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**The PADME experiment and the extraction of
annihilation cross section**

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The annihilation in two photons is a very important SM candle process for PADME. Gaining a good knowledge of this process allows to monitor with a physics candle the energy scale, the number of positrons hitting the target and detector geometry. In addition, it allows to exercise on a easy test case the strategy to fight the background for the dark search. The signature of this process in the experiment consists in the presence of two photons in the electromagnetic calorimeters. Since the SAC detector is overwhelmed by Bremsstrahlung photons, only the main calorimeter, ECAL, is used to perform this analysis. The goal of this study is to measure the cross section of $e^+e^- \rightarrow \gamma\gamma$ using the data collected by the experiment during RunII. In this chapter the entire strategy is described, including a very important and challenging step that is measurement of the efficiency. The technique applied is first described, then validated on dedicated MC samples and applied to data. Nowadays no measurements of the cross section exist at the PADME energy scale. A small review on the two photons annihilation cross section measurement at energies close to $\sqrt{s} \approx 21$ MeV is given in Appendix ??.

1.1 The cross section measurement strategy

The total cross section, σ_T , for the process $e^+e^- \rightarrow \gamma\gamma(\gamma)$ can be measured in PADME using the following relation:

$$\sigma(e^+e^- \rightarrow \gamma\gamma) = \frac{N_{sig}}{N_{POT} \times A \times \epsilon \times N_{\frac{e}{s}}} \quad (1.1)$$

where

- $N_{\frac{e}{s}}$ is the number of atomic electrons per unit surface in the PADME target. It is estimated as $N_{\frac{e}{s}} = \frac{\rho \times N_A \times Z \times d}{M_w} = 0,0105 \text{ b}^{-1}$, where $\rho = 3,52 \text{ g/cm}^3$ is the Diamond density, N_A is the Avogadro number, Z the atomic number, $d = 100 \text{ }\mu\text{m}$ is the target thickness and M_w is the atomic weigh;
- N_{sig} is the number of signal processes observed after a selection based on the kinematic correlations typical of annihilation events once subtracted of the background component. In this thesis work several selection procedures for the annihilation process have been considered. In addition to searches based on the identification of a pair of photons,

event selection using only one photon have been studied. The choice among the various possibilities has been taken balancing the difficulty in estimating the background from physics process and from spurious beam interaction and the difficulty in evaluating the overall selection efficiency;

- N_{POT} is the total number of positrons hitting the target measured with the active Diamond target;
- A is the acceptance of the PADME detector and of the selection criteria applied. Therefore, it results from both geometric and kinematic constraints. The determination of the acceptance will be described in Section 1.5.1. The acceptance allows to relate the total cross section σ_T to the so called fiducial cross section σ_F , corresponding to the fraction of the cross section directly visible in the experimental apparatus and lying within the kinematic selection requirements $\sigma_T = \sigma_F/A$;
- ϵ is the overall efficiency to identify signal processes. It represents the combination of the detection efficiency of the PADME calorimeter, the photon reconstruction and identification efficiency for both photons and the event selection efficiency. Therefore, when N_{sig} is measured with a selection requiring two photons in ECAL, the efficiency ϵ is the product of the identification efficiencies, $\epsilon(\gamma_1)$ and $\epsilon(\gamma_2)$ of the two photons.

Detector defects and asymmetries often prevent the performance of photon reconstruction algorithms to be uniform. Therefore, the event efficiency varies depending on the regions of the detector where the photons have been detected and, in general, the efficiency ϵ cannot be applied as a constant term in Eq. 1.1, unless it is estimated as an average value over the data sample.

Several procedures can be applied to generalize 1.1 taking into account these problems. An approach consists in measuring the fiducial cross section as follows:

$$\sigma_F = \sigma(\theta_0 < \theta_{\gamma_{1,2}} < \theta_1) = \frac{N_{\gamma\gamma}^W}{N_{POT} \cdot n_{\frac{e}{S}}} \quad (1.2)$$

$N_{\gamma\gamma}^W$ is the number of weighted annihilation events. Each candidate contributes to the counting with a weight accounting for all the efficiency factors that determine the probability of such event to be selected. The quantity $N_{\gamma\gamma}^W$ is then estimated after correcting the weighted number of candidates for the number of background events passing the selection: $N_{\gamma\gamma}^W = N_{sel}^W - N_{bkg}$. For the candidate annihilation event i , the weight W_i is given by the inverse probability to identify the two photons in the event:

$$W_i = P^{-1}(\theta_{\gamma_{i_1}}, \theta_{\gamma_{i_2}}) = [A_{eff}(\theta_{\gamma_{i_1}}, \theta_{\gamma_{i_2}}) \times \epsilon(\theta_{i_1}, \phi_{i_1}) \times \epsilon(\theta_{i_2}, \phi_{i_2})]^{-1} \quad (1.3)$$

where $\epsilon(\theta_{i_1,2}, \phi_{i_1,2})$ is the efficiency as a function of the position in the calorimeter for the first or second photon. The factor $A_{eff}(\theta_{\gamma_{i_1}}, \theta_{\gamma_{i_2}})$ is the visible acceptance and it represents a correction to the acceptance that takes into account resolution effects causing the migration of events from

the acceptance region to the outside and vice versa. It will be discussed in more details and estimated in Section 1.5.2.

The efficiency values used in Eq. 1.2 can be estimated with simulation or can be directly measured in data if a suitable sample of reference photons can be defined and used to measure the fraction of them that is successfully detected and identified. Section [reference](#) describes that data-driven determination of the efficiency that is used in the cross section measurement, exploiting the approach of Eq. 1.2.

Data-driven efficiency measurements may be affected by biases. On the other hand, simulations are often affected by residual mismodeling of the detector response and geometry and of the beam features. Another strategy, meant to address these problems, consists in using a global efficiency factor C , replacing ϵ in Eq. 1.1, predicted by the simulation as the ratio of simulated to generated events inside the fiducial requirements, and corrected for mismodelling with scale factors defined as the ratio between the event dependent efficiency measured in data $\epsilon^{data}(\theta, \phi)$ and in simulation $\epsilon^{MC}(\theta, \phi)$, the latter being obtained with exactly the same method applied in the case of data. In practice,

$$\sigma_F = \frac{N_{sel}}{C \cdot N_{POT} \cdot n_{\frac{e}{S}}}, \quad (1.4)$$

$$C_{\gamma\gamma} = \frac{N_W^{MC,gen}(\theta_{min} < \theta_{\gamma_1, \gamma_2} < \theta_{max})}{N^{gen}(\theta_{min} < \theta_{\gamma_1, \gamma_2} < \theta_{max})}, \quad (1.5)$$

$$N_W^{MC,gen}(\theta_{min} < \theta_{\gamma_1, \gamma_2} < \theta_{max}) = \sum_i f_i^{data/MC}, \quad (1.6)$$

$$f_i^{data/MC} = \prod_j f_{i,j}^{data/MC} \quad (1.7)$$

where $f_{ij}^{data/MC}$ is the data-simulation scale factor for any efficiency contribution, for example the efficiency for photon 1 in event i leads to a scale factor $f_{i1} = \epsilon_{DD}^{data}(\theta_1, \phi_1) / \epsilon_{DD}^{MC}(\theta_1, \phi_1)$, where the efficiency $\epsilon_{DD}^{data}(\theta_1, \phi_1)$ is measured with a data driven (DD) method both in data and in Monte Carlo. The quantity N_W^{MC} therefore represents the number of signal events selected in the simulation, but corrected for local mismodelling of data, and N^{gen} is the number of simulated signal events that at generator level fall in within the acceptance of the selection. Finally, the factor C would correspond to purely MC based efficiency for the selection if all scale factors were equal to 1.

In this work the cross section measurement will be derived relying on a data-driven determination of the photon selection efficiency. The possible biases of the methods are studied in dedicated simulations and found to be negligible or mitigated by compensation effects. This topic will be discussed in Section [reference](#) where the cancellation due to compensation effects will be described and in Section [reference](#) where a careful implementation of the data driven method will be shown to leave no sign of biases.

1.2 Theory prediction

1.3 Data sample, simulation and reconstruction

1.3.1 Data sample

The data used for this measurement have been chosen among the sample collected during RunII, because of the smallest background level, as seen in Chapter [data taking](#). During this run the energy of the beam was $E_{beam} = 430$ MeV and the beam density ~ 100 POT/ns. A summary of the runs used for the analysis with their main features is collected in Table 1.1. The total number of positrons on target corresponding to the sample is $N_{POT}^{tot} = 3,97 \times 10^{11}$. In Figure

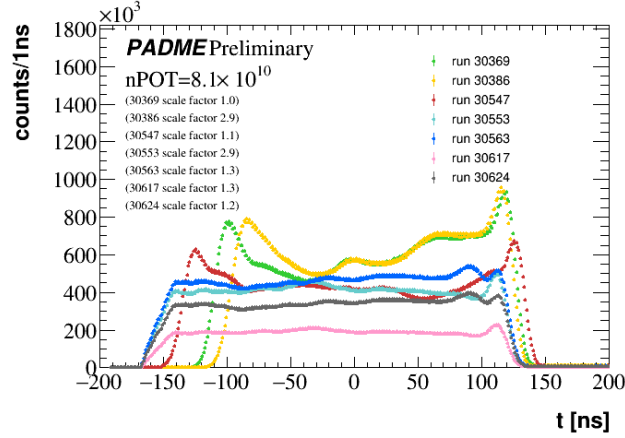


Figure 1.1: Bunch structure for each run analysed recorded with SAC.

1.1 structure in time of the bunch is shown. As highlighted by Table and Figure the runs have different features not only in multiplicity per bunch but also in bunch structure, meaning that the runs are collected with different beam configurations. This selection of runs was chosen because of a good stability of the beam intensity in time within the each run. Indeed a data quality monitor processing of the data shows that the number of positrons on target measured by the Diamond is very stable as is shown in Figure 1.2 for run $N = 30617$.

A special data sample consisting of two runs, recorded with the target out of the beam line, has also been used. This sample allows to study the beam related background observed in PADME.

With a total of $N_{POT} = 4 \times 10^{11}$, assuming a product of acceptance and efficiency of the order of $\sim 5\%$ the number of detected annihilation events is about ~ 521000 ; if background was negligible or compatible with the signal, the relative statistical error on the cross section measurement would be $\sim 1\%$ and even if the background rate was ten times larger than the signal, the statistical uncertainty would be $\leq 1\%$ which is unlikely to be larger than the systematic uncertainties affecting the measurement. Therefore the sample selected is adequate in size to the measurement.

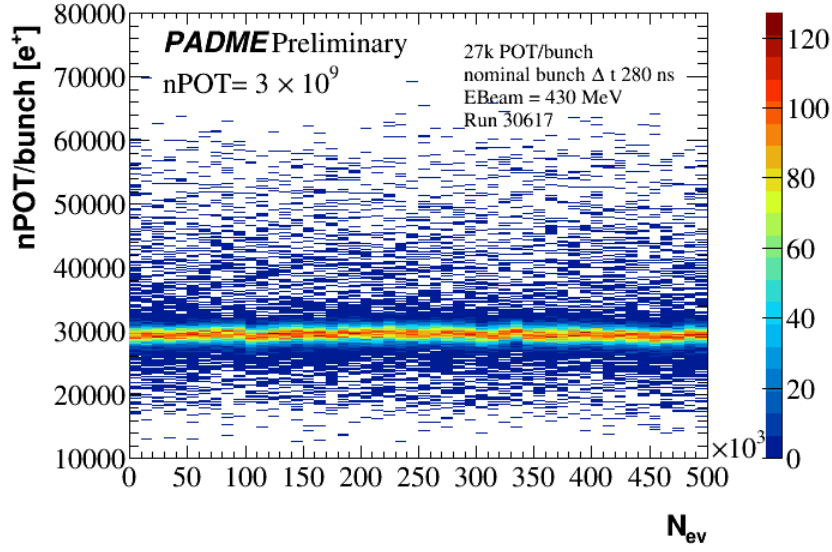


Figure 1.2: Number of positrons per bunch as a function of the event number for run 30617.

Table 1.1: Main features of the analysed runs: run number, total N_{POT} measured by target, mean and sigma of a gaussian fit to the peak of the N_{POT} distribution, bunch length and month of data taking.

Run number	$N_{POT}/10^{10}$	$\mu(N_{POT})$	$\sigma(N_{POT})$	bunch length [ns]	Date
30369	8, 2	26993	1738	260	Sept
30386	2, 8	19057	1385	240	Sept
30547	7, 1	31480	1402	270	Oct.
30553	2, 8	35729	1314	260	Oct.
30563	6, 0	26785	1231	270	Oct.
30617	6, 1	27380	1496	270	Nov.
30624	6, 6	29515	2070	270	Nov.
30654	/	~ 27000	/	~ 270	Nov. no target
30662	/	~ 27000	/	~ 270	Nov. no target

1.3.2 Simulation samples

The PADME MC is based on a GEANT4 [?] simulation of the experimental apparatus and of the beam. Annihilation processes are simulated when the positrons of the beam cross the Diamond target along with the other dominant QED processes: Bremsstrahlung in particular, Bhabha scattering, and others minor effects. However, similarly to what happens in PADME, a large number of positrons per bunch must be simulated in order to achieve a reasonable statistics of annihilation processes, therefore the final state from a $e^+e^- \rightarrow \gamma\gamma$ event often overlaps with other photons in the the calorimeter, and moreover, the signal photons are not labelled to be easily distinguished. In order to study the kinematics of annihilation events either

in a background free simulation, or flagging the final state particles, the CalcHEP generator was used. From the $e^+e^- \rightarrow \gamma\gamma$ generation, a text file was saved with the four-momenta of all particles involved in the process. A special functionality in PADMEMC allows to plug the two photons from an event generated by CALCHEP in a point of the target where a positron from the incoming beam is killed. The photons are then propagated through the detectors like any particle managed by GEANT4.

Several MC data samples were used across the analysis:

1. CalcHEP event generator samples, used to study the MC truth and generator level properties;
2. CalcHEP samples simulated with PADMEMC with a beam consisting of a single positron. In this case the final state of each event contains only two photons from e^+e^- annihilation that can fall inside or outside the detector geometrical acceptance;
3. CalcHEP samples simulated with PADMEMC as in case two but with a beam of 25×10^3 positrons in average in a bunch. This kind of simulation allows to investigate the effect of pileup of the signal event with physics background processes originated from beam interactions in the target.

The CalcHEP generator performs all calculations in the LO approximation for the final state selected by the user, that can be in our case, $\gamma\gamma$ or $\gamma\gamma\gamma$. The same techniques was used to plug annihilation events generated by Babayaga at the NLO approximation in the PADME MC. Therefore a Babayaga generation output at LO was used to check the consistency with CalcHEP and another generation at NLO was used to evaluate the acceptance of the annihilation.

1.3.3 Event reconstruction

The selection of annihilation events uses only the PADME BGO electromagnetic calorimeter. Therefore, here a brief reminder of the main features of the reconstruction of clusters in ECAL is given, while an extensive description of the algorithms is given in Chapter [reference](#).

The multi hit reconstruction, described in Chapter [??](#) Section [??](#), was used. For each waveform up to three hits can be identified, with energy and time estimated with a fit with a signal template obtained from clean waveforms recorded in a single positron run. The template allows to naturally account and correct for problems related to the data acquisition like the limited acquisition time window and the saturation. For signals where only one hit is identified in the waveform, energy and time determination follow the same logic applied in the single hit reconstruction, described in Chapter [??](#) Section [??](#).

Once the hit collection is defined, clusters are reconstructed merging hits in nearby crystals in time coincidence. The energy required for the cluster seed is 20 MeV, while hits contributing to the cluster must have energy above 1 MeV, a distance from the seed not exceeding three crystals, and a maximum distance in time from the seed of 6 ns.

The cross section measurement requires the determination of the number of POT. This was estimated using the calibration procedure described in Section [verify that in padme chapter](#)

161 **there is the description.** This procedures rely on the absolute energy calibration of the BTF
 162 calorimeter that is verified to 5%. The systematic uncertainty on the N_{POT} measurement arises
 163 from the calibration procedure, and can be assessed by studying the stability and consistency
 164 with the energy seen in other detectors, in particular in the SAC, that collects all forward
 165 Bremsstrahlung photons produced by interactions of the beam in the target.

166 1.4 Experimental signature of annihilation events

167 The selection of annihilation processes is based on the constrained photon-photon kinematics.
 168 In the assumption of a final state consisting of exactly two photons sharing the energy and
 169 momentum of the initial state, several relationships between the energies E_1 and E_2 , the polar
 170 angles¹ θ_1 , θ_2 , and the azimuthal angles² ϕ_1 , ϕ_2 of the photons, can be exploited. The most
 171 relevant of them are listed in the following, adopting the convention of using the the index 1
 172 for the most energetic photon in the pair:

- 173 1. the sum of the energies $E_1 + E_2$ is equal to the beam energy with very good approximation;
- 174 2. the transverse momenta of the photons are back to back, therefore $\phi_1 + \pi = \phi_2$
- 175 3. for each photon the polar angle θ is a function of the energy;
- 176 4. As a consequence of properties 1 and 3 the polar angle of the two photons are strictly
 177 correlated;
- 178 5. The previous considerations also imply that knowing E_1 sets the value the polar angle of
 179 the second photon θ_2 ; the same is true if the role of the two photons is exchanged;
- 180 6. The momentum balance implies also the following relation between the coordinates of the
 181 impact point of the two photons in a transverse plane

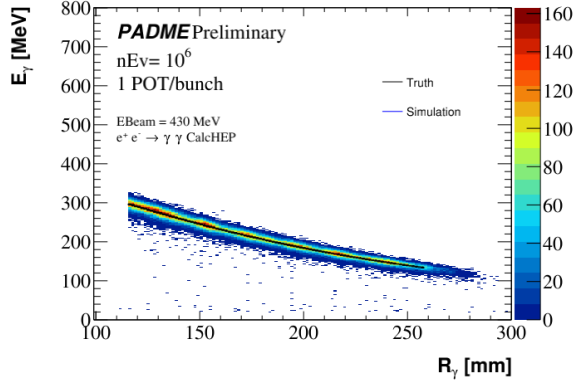
$$x(y)_{CoG} = \frac{x(y)_1 E_1 + x(y)_2 E_2}{E_1 + E_2} \sim 0. \quad (1.8)$$

182 In Figure 1.3 the correlation between the energy and the polar angle θ of the two photons is
 183 reported along with the two photons energy correlation and the distance in ϕ between a photon
 184 and the other extrapolated in the backward direction. Figure 1.4 shows the X and Y center of
 185 gravity for a sample **specify sample used** are also reported.

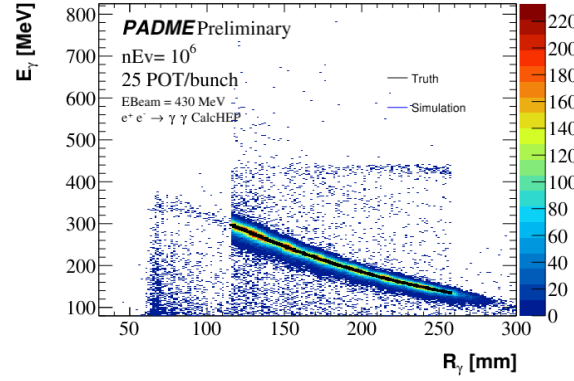
186 When the beam intensity is of the order of 25k POT/bunch, the pair of photons in time co-
 187 incidence produced by an annihilation event is overlapped to energy deposits in the calorimeters
 188 and hits in the veto detectors that are produced by the physics background processes due to

¹The polar angle θ is defined as the angle between the photon direction and the z axis of the PADME reference frame, which is assumed to match the direction of the incoming positron beam.

²The azimuthal angle ϕ is the angle between the direction of a photon in the plane perpendicular to the beam and a reference axis conventionally chosen to be the x axis.

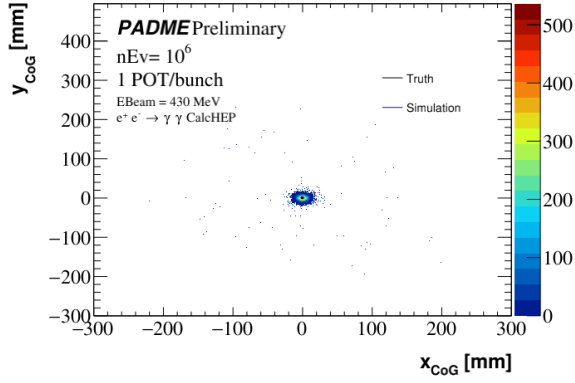


(a)

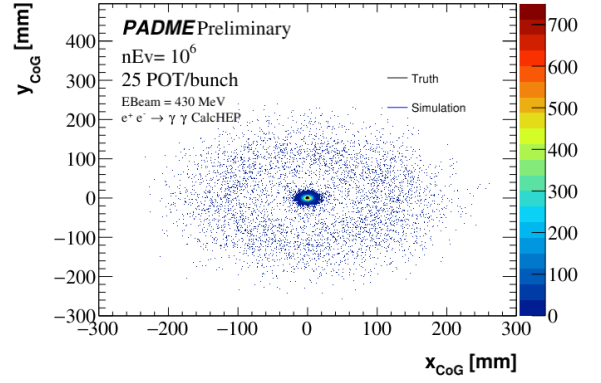


(b)

Figure 1.3: Correlation between energy and radius of the photon for pure annihilation simulation (a) and adding pileup (b).



(a)



(b)

Figure 1.4: X and Y CoG map for pure annihilation simulation (a) and adding pileup (b).

interactions of other positrons in the bunch with the target. The background photons, positrons and possibly electrons seen in the detectors are distributed within the 250 ns time width of the bunch. Therefore, the time coincidence between the two signal photons is a powerful handle to suppress the background which can be used along with the kinematic correlations. Fig. xx, yy, zz ask show the distributions of the same variables shown in Fig. xx-nopileup - zz-nopileup for a sample of annihilation events generated with calchep and simulated in PADMEMC along with 25000 positrons.

In the PADME data the pictures is complicated by the beam induced background, which due to the high rate imply a high probability of accidental two-photon coincidence, and in general accidental occurrence of the kinematic correlations typical of annihilation events.

The annihilation yield, i.e. the number of annihilation processes seen in the PADME detector, can be measured starting from the distribution of the sum of the two photon energies, from

the CoG distributions or from the difference in the azimuthal angle $\Delta\phi = \phi_1 + 180^\circ - \phi_2$. In all these distributions a peak corresponding to the signal events will emerge over the combinatorial background, if the other correlations are used to select the signal and suppress the background, provided the background rate is below a certain level. Additional selection criteria efficient for the signal consist in setting a minimum photon energy threshold and requiring that the photon has an energy close to the value compatible with its polar angle: $|\Delta E| = |E_\gamma - E(\theta_\gamma)| < \Delta E_E^{Max}$.

In the following a sequence of selection cuts, summarized in Table 1.2, will be used to show how the annihilation signal emerges in RunII data.

Table 1.2: *Annihilation selection cut, threshold applied on each variables and cut flow for CalcHEP simulation with pileup from 25000 positrons per bunch and for data (run 30563).*

Cut description		Threshold	Simulation	data
Time coincidence	$|t_{\gamma_1} - t_{\gamma_2}|$	< 10 ns		
γ_1 in FR	R_{γ_1}	$\in]115.82 \text{ mm}, 258 \text{ mm}[$	0, 70	0, 73
CoG	$|x_{CoG}|$	< 50 mm	1, 00	0, 87
CoG	$|y_{CoG}|$	< 50 mm	1, 00	0, 96
γ energy	$E_{\gamma_1}, E_{\gamma_2}$	$\in [90 \text{ MeV}, 400 \text{ MeV}]$	1, 00	1, 00
sum of γ energies	$E_{\gamma_1} + E_{\gamma_2}$	$\in [300 \text{ MeV}, 600 \text{ MeV}]$	1.00	0, 98
γ_2 in FR	R_{γ_2}	$\in]115.82 \text{ mm}, 258 \text{ mm}[$	0, 96	0, 96

Where the energy thresholds are defined studying the CalcHEP truth, see Figure 1.5.

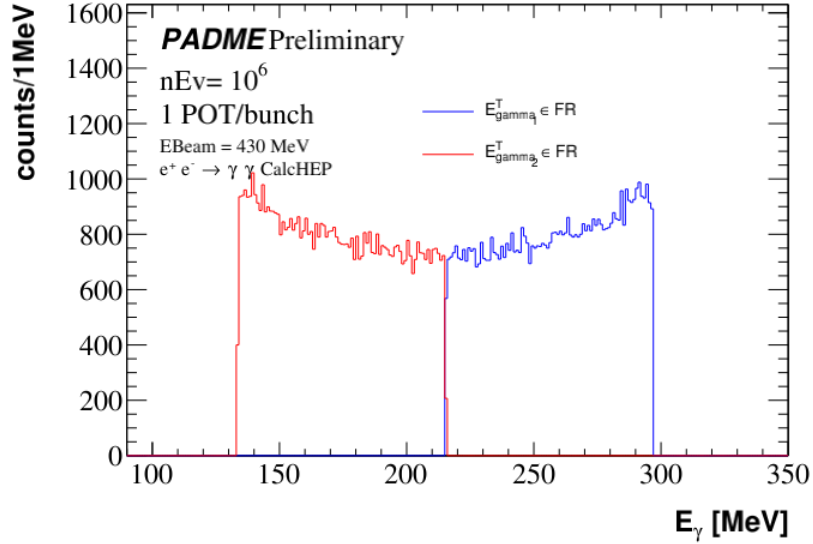


Figure 1.5: *Photon energy distributions in blue for the first photon (in energy) and in red for the second photon.*

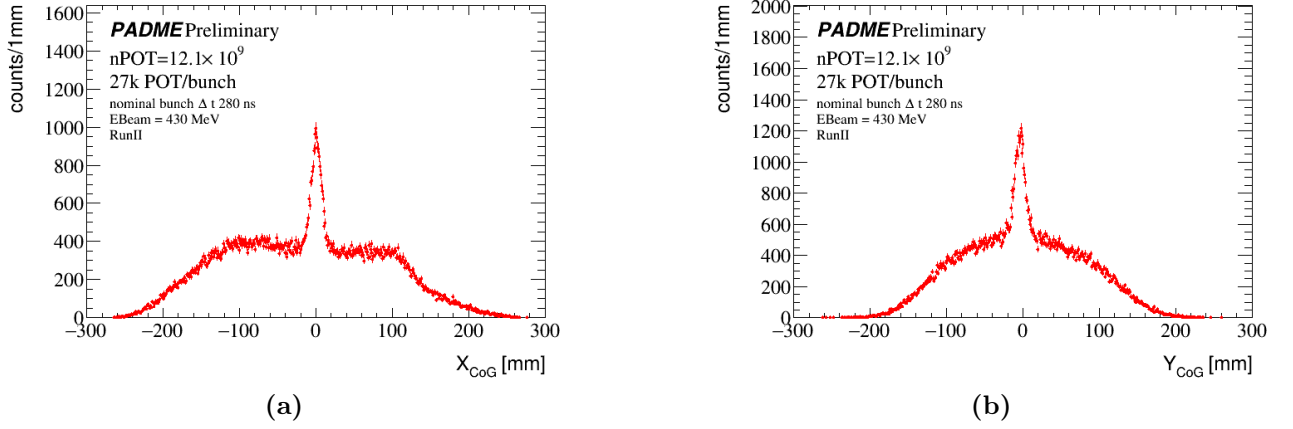


Figure 1.6: Distribution of the Center Of Gravity variables for the events that satisfy the following cuts, described in Table 1.2: time coincidence and first photon in FR. On the left (a) the distribution of X_{CoG} , on the right (b) the distribution of the Y_{CoG} .

Ci vuole un plot di Delta T nei dati la selezione di fig 1,3 per esempio, ovviamente senza taglio in Dt e con $|COG| < 50$ + commento Ci vuole un plot di Delta Phi nei dati la selezione di fig 1,3 per esempio, ovviamente senza taglio in DPhi e con $|COG| < 50$ + commento In addition to the cuts on the kinematic variables and on the time coincidence, a geometrical requirement is introduced to ensure a reliable reconstruction of the photons. Indeed, the position of the clusters in ECAL must be at distance from the inner and from the outer border of the calorimeter equal to at least twice the width of a BGO crystal. This ensures limited shower leakage and therefore a good determination of the energy and position. Adding in sequence selection cuts improves the background rejection as demonstrated by Figure 1.7 where the sum of the energy of the two selected photons $E_{\gamma_1} + E_{\gamma_2}$ is shown the red distribution corresponds to events passing the time coincidence and the fiducial region requirement for the most energetic photon γ_1 . The amount of background is strongly reduced adding the CoG request (blue distribution). The energy cuts applied to each photon help to further reduce the background. The population of events under the peak, clearly corresponding to annihilation processes, is not significantly reduced by the cuts.

Figure 1.8 (a) shows that the additional cut of the FR on the second photon (the less energetic one) reduces (of $\sim 5\%$) the yield of the annihilation. In Figure 1.8 (b) only the most energetic photon is required to be in the FR. It's interesting to notice that, because of the cut in the inner radius for the leading photon, E_{γ_1} is constrained to be > 100 MeV, on the other hand the energy of the second photon is not subject to sharp cuts, and ranges from about 50 MeV up to 300 MeV. Most of the studies performed are done with two analysis variant: selecting only events with the first photon in the FR or selecting events with both photons in the FR.

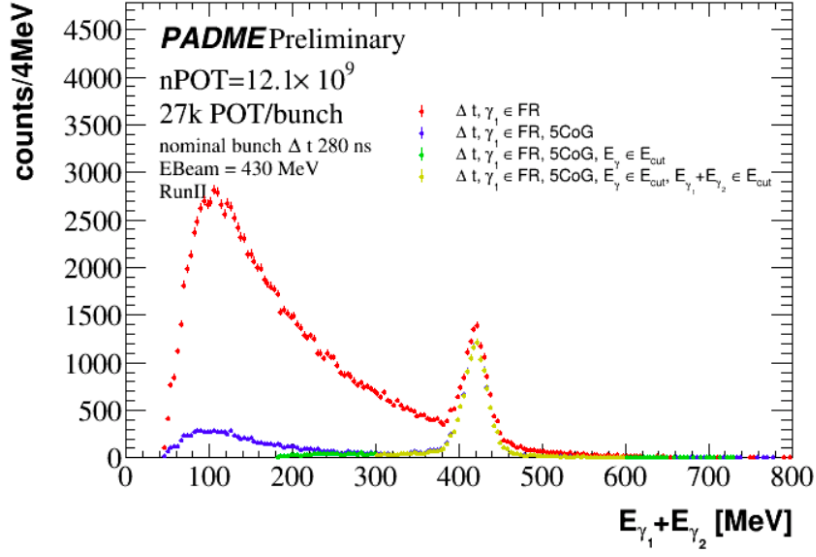
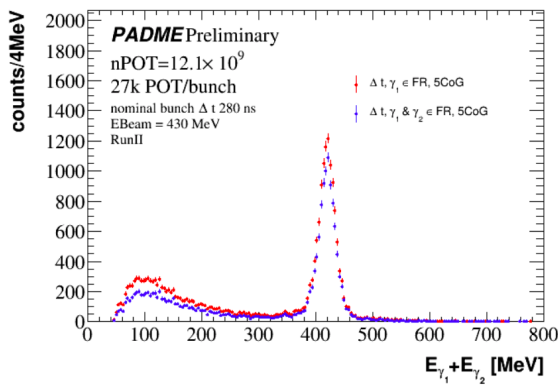
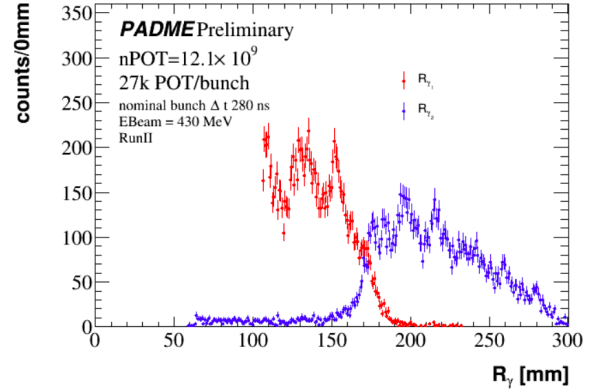


Figure 1.7: Distribution of $E_{\gamma_1} + E_{\gamma_2}$ for pairs of photons passing various sets of cuts. In red events that pass the time coincidence request with the first photon in the FR; in blue the distribution for events passing also the CoG cut (5 cm). Finally in green (yellow) events satisfy also the energy requirements for one photon (both photons).



(a)



(b)

Figure 1.8: (a) Distribution of the sum of $E_{\gamma_1} + E_{\gamma_2}$ for the events that pass the cuts on time coincidence and CoG. In red the request of FR is applied only to the most energetic photon, while in blue on both photons. (b) Radius distribution for the most energetic photon γ_1 in red and for the less energetic one γ_2 in blue for the events that pass the time coincidence, FR on the most energetic photon, CoG, energetic cuts.

1.5 Acceptance

The acceptance has been introduced in Equation 1.1 as a global factor describing the fraction of events corresponding to the process under study that can be detected with the experimental

apparatus of PADME and the kinematic requirements applied in the event selection procedure. This concept is based on the assumption of full efficiency of the PADME detectors, DAQ and data reconstruction algorithms. Indeed, in Equation 1.1 all the motivations that can lead to a loss of signal in the data of PADME related to instrumental effects are described through the efficiency term ϵ . As a consequence, the determination of the acceptance must be based on a generator-level simulation of the signal process, before any efficiency, resolution, miscalibration effect plays any role.

The selection cuts described in Table 1.2 are all applied to kinematic properties, involving energies and momenta, except for the requirement that the most energetic photon (or both photons) fall inside a fiducial region of the electromagnetic calorimeter described by an inner and an outer radius. This cut, apparently defined as a geometrical criterion, is dictated by the ECAL geometry but it also has an impact on the energy distribution of the signal photons due to the completely closed kinematics of the two-photon final state in a e^+e^- annihilation process. This requirement is also the only selection cut shaping the phase space of the annihilation process. Indeed, all other cuts are dictated by considerations related to the detector and reconstruction resolution. In summary, if PADME would measure with infinite resolution the photon energies, and positions, each of the selection cut, except for the FR requirement, would have no effect on any signal event with exactly two photons. Therefore, the assessment of the acceptance is strictly related to the definition of the boundaries of the fiducial region.

These boundaries need to be set inside the geometrical boundaries of the calorimeter in order to minimize the effect of the shower leakage. In addition the strong correlation of the two photons implies that for a given value of the beam energy, setting a constraint on the region where, for example, the most energetic photon can be found, directly defines the corresponding region where the second most energetic photon can lie. In order to choose a consistent definition of the fiducial region and estimate the corresponding acceptance a dedicated study was done using CALCHEP and Babayaga simulations at generator level or simulated with a single positron per bunch.

The CalcHEP generator has been used to produce a sample of 10^6 annihilation events according to the LO approximation for the process $e^+e^- \rightarrow \gamma\gamma$, with an electron momentum $\vec{P}_{e^-} \sim 0$ MeV/c and a positron energy equal to the energy of the beam $E_{e^+} = 430$ MeV. The three components of the momenta \vec{P} of the two photons of the final state are saved on a text file and used directly to study the events before any detector effect. The same events simulated in PADMEMC allow to assess detector and resolutions effects. The truth information can easily be compared with the simulated event.

A crucial quantity is the radial distance from the original beam direction of the cluster produced by the photon in the calorimeter. In data and in simulation this quantity is computed from the energy weighed position of the BGO crystals in the cluster (see Section [reconstruction..](#) for a detailed discussion).

The measured R_γ allows to measure the polar angle of the photon through the relation

$$R_\gamma = \tan(\theta) \times D = \frac{p_T}{p_z} \times D \quad (1.9)$$

where p_T and p_z are the transverse and longitudinal components of the photon momentum and

D is the distance between the target and the plane perpendicular to the z axis representing the ECAL measurement plane.

The parameter D does not match the distance between the target and the entrance surface of the crystals in ECAL. The position of the target and of the ECAL calorimeter in the PADME reference framework are known from design and from survey measurement. The first is $z_{Target} = 1030$ mm and, due to the fact that the thickness of the target is very small it is also considered as the distance of the annihilation production point and the origin of the z axis of PADME that is defined as the center on the dipole magnet. Concerning the z coordinate of ECAL, there are three options to consider: the ECAL front face, the plane where the shower reaches the maximum development and the one corresponding to the mean multiplicity of charged particles in the shower. In Figure 1.9 the distribution of the z coordinates of the GEANT4 hits produced by charged particles in the electromagnetic shower is shown. Thus the options for

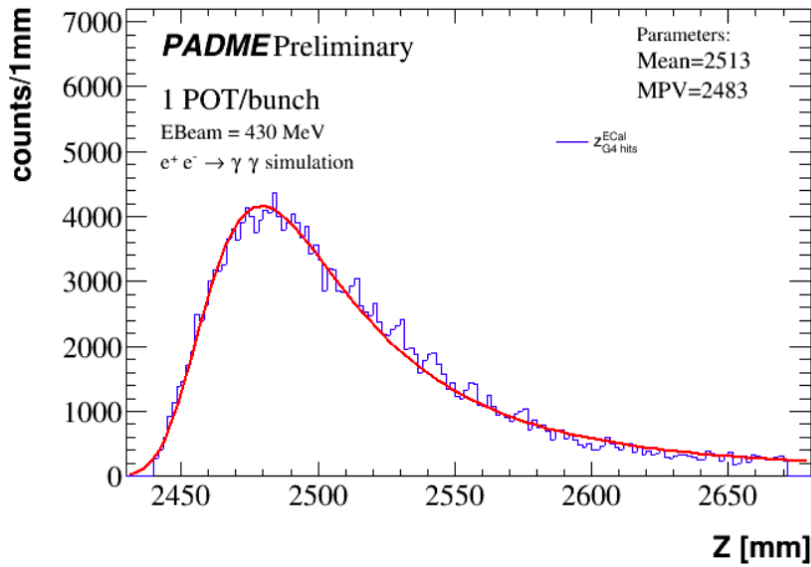


Figure 1.9: Distribution of the z coordinate of all the hits generated in the BGO crystals of ECAL superimposed by a fit using a landau function. The simulation used CalcHEP events simulated in PADMEMC.

the coordinate of the ECAL measurement plane are:

- target - ECAL front face, equal to 2440 mm;
- target - most probable value of the shower maximum, equal to 2483 mm, obtained from a fit of the shower longitudinal profile with a landau function;
- target - mean of the shower profile, equal to 2513 mm.

The value of the distance $D = 1030 + 2513$ mm using the mean of the shower z profile if finally chosen. This value statistically guarantees a good match between the radius R_γ computed from

the true photon directly with Equation 1.9 and the R_γ corresponding to the cluster position in the simulation. The distributions of the differences between $R_{truth}(3543 \text{ mm})$ and $R_{cluster}$ for the most energetic photon and the least energetic one are shown in Figure 1.10 right and left respectively. Both the distributions, for this value of D , have the mean of the gaussian fit close to 0 and a standard deviation of $\sim 5 \text{ mm}$.

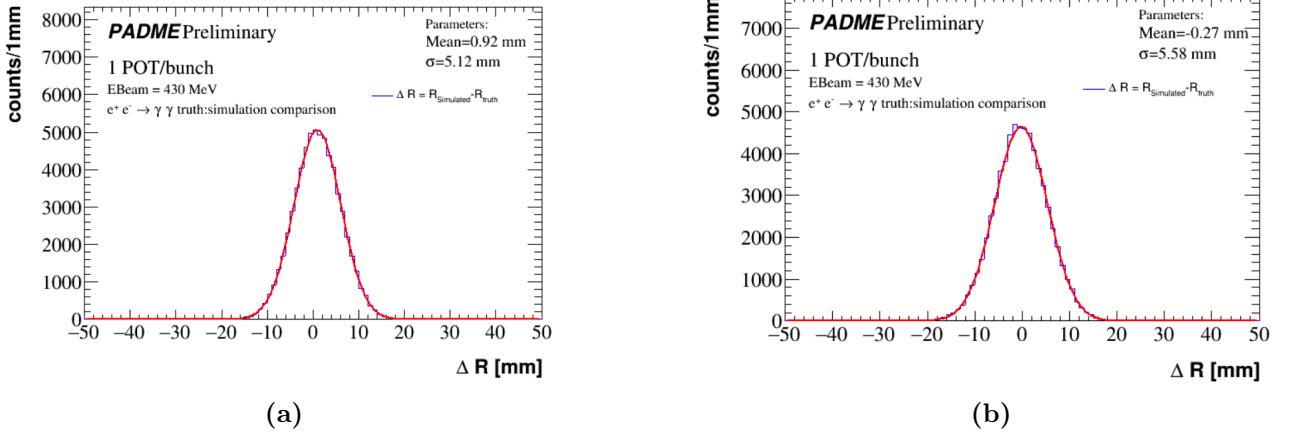


Figure 1.10: Distribution of the difference between the radius of the photon simulated in PADMEMC and the radius of the truth in the plane at a distance $D = 3543 \text{ mm}$ from the diamond target for the most energetic photon (a) and for the second energetic photon (b).

Clusters in ECAL may be used as photon candidates if the measured energy and position are reliable. For photons hitting the calorimeter in a peripheral regions, energy and positions are likely biased. The features of the clusterization algorithm implemented in the reconstruction suggest that the bias due to transversal shower leakage is small if the cluster position (computed as the energy weighted position of the crystals contributing to the cluster, that must be at a distance from the seed of no more than two crystals) is reconstructed at a distance at least equal to twice the pitch of the BGO crystal matrix. Using this criterion, the maximum radius of a reliable cluster is equal to 258 mm. Due to the fact that the first and the second photon are correlated in energy, thus in space, the corresponding minimum radius is constrained by the kinematics. In practice it is extracted with a scan on R_{min} studying the number of γ_1 and γ_2 with radius inside the range according to MC truth in a CALCHEP $e^+e^- \rightarrow \gamma\gamma$ sample. The value of R_{min} that gives a number of first (most energetic) photons equal to the number of second photon is chosen. As a result the fiducial region for the selection of annihilation photons in the PADME calorimeter is defined as the interval $FR = [115.82, 258] \text{ mm}$. Another important parameter is the value of the radius $R_{mid} = R_{\gamma_1}(E_{mid}) = R_{\gamma_2}(E_{mid})$ where the two photons have the same energy and therefore the same radius. This parameter, for an energy of the beam $E_{beam} = 430 \text{ MeV}$, is equal to $R_{mid} = 172.83 \text{ mm}$. Table 1.3 reports the number of γ_1 and γ_2 ($N_{\gamma_{1(2)}}$) found in ECAL regions defined in terms of the parameters R_{min} , R_{max} and R_{mid} . The counters shows the consistency of the definition for the three parameters, since the number of N_{γ_1} is equal to N_{γ_2} , and all the most energetic photons fall in the inner ring of

ECAL while all those with a lower energy fall in the outer ring as expected by kinematics. In addition in Table 1.3 the number of photons in the upper and lower ECAL region are reported. This number show as for each γ_1 correspond a γ_2 in the opposite ECAL region (e.g. all the γ_1 belonging to the inner ring of ECAL and the upper region have a corresponding γ_2 in the outer ring in the lower region of ECAL).

Table 1.3: Yield of the most energetic photon γ_1 and the less energetic one γ_2 in the ECAL regions. The radius range $]115.82, 258[$ mm is considered be the fiducial region, the radius $R_{mid} = 172.83$ mm is the radius where the two photon has the same energy. The counters are reported also for the upper and lower parts of the detector.

Cuts	N_{γ_1}	N_{γ_2}
$\gamma \in]115.82, 258[$ mm	65320	65318
$\gamma \in]115.82, 172, 83[$ mm	65320	0
$\gamma \in [172, 83, 258[$ mm	0	65318

A confirmation that the distance target-ECAL considered is the appropriated, is given by the fact that the the same value for R_{mid} is determined by applying the same considerations to the CALCHEP sample simulated in PADMEMC. Figure 1.11 shows the distribution of R_γ for the first (most energetic) and the second photon. Two selections of events are represented: the first defined by the request that $R_{\gamma_1}^T$, i.e. the true radius of the first photon is in the FR (i.e. in the range R_{min}, R_{max}); the second defined by the request that $R_{\gamma_1}^R$, i.e. the radius of the first photon as reconstructed in simulation is in the FR. For the first case the distribution of $R_{\gamma_1}^T$ and $R_{\gamma_2}^T$ are shown in blue by the solid and dotted line respectively. The two distributions do not overlap and span the entire range of the FR with the first (second) photon well contained below (above) R_{mid} . For the second selection, the distributions of $R_{\gamma_1}^R$ and $R_{\gamma_2}^R$ are shown by the green solid and dotted line respectively. As expected, the distribution of $R_{\gamma_1}^R$ is sharply defined at R_{min} , but some migration above R_{mid} is induced by resolution; similarly, the corresponding $R_{\gamma_2}^R$ distribution starts before R_{mid} and ends after R_{max} . Finally, for the second selection the distributions of $R_{\gamma_1}^T$ and $R_{\gamma_2}^T$ are shown by the cyan histograms with solid and dotted line respectively, showing migration of events at the edges of the FR due to resolution.

The same correlation between the radius of the first and second photon predicted by the simulation should be observed if beam energy and detector geometry are well known. In Figure 1.12 the points show R_{γ_2} as a function of R_{γ_1} in PADME annihilation events. The annihilation photon candidates are selected with the application of the cuts presented in the Section 1.4 (in particular cuts a,b,c,d,e are applied). The black continuous line is correlation between observed in CalcHEP sample using MC truth. The agreement is a check of the good description of the geometry.

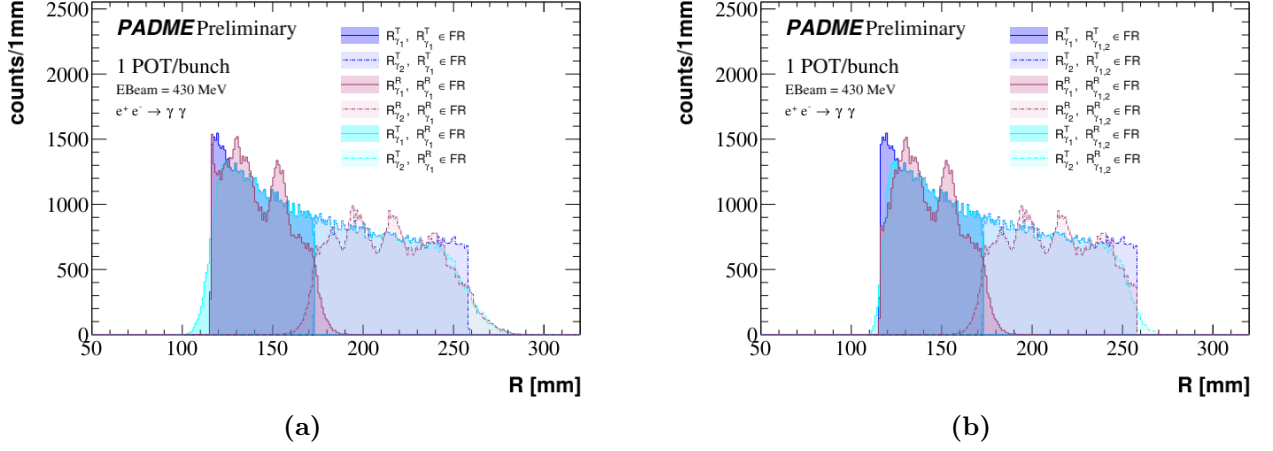


Figure 1.11: Distribution of true and reconstructed radius of photons from annihilation events. Continuous lines refer to the most energetic photon γ_1 , dotted lines to the other photon γ_2 . Events are selected either for the first photon (a) and both (b) belonging to the fiducial region at MC truth level or at reconstruction level.

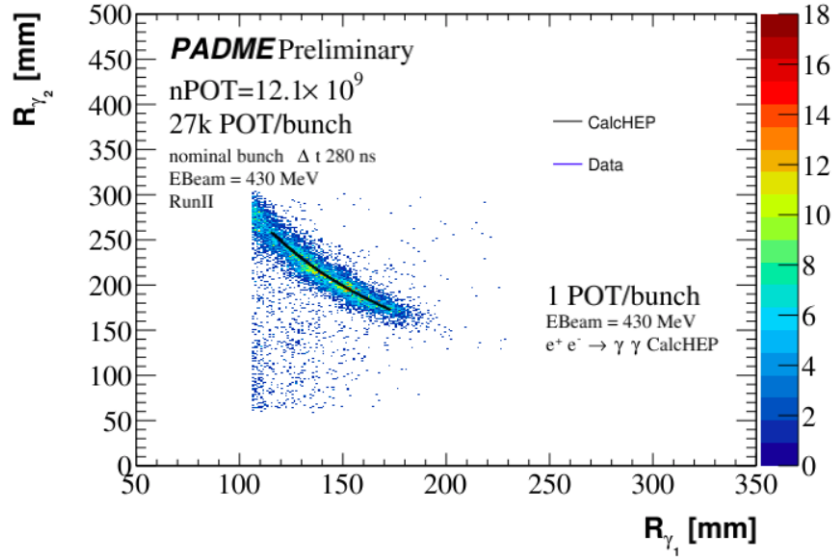


Figure 1.12: Correlation between the radius of the first and second photon. Points are PADME data after a tight selection of annihilation events, corresponding to cuts a,b,c,d,e presented in Section 1.4. The black line is the same correlation according to MC truth in CalHEP.

1.5.1 The acceptance at leading order

The acceptance of the fiducial region defined for the measurement was extracted as a global factor telling what fraction of the annihilation events reach ECAL in the FR. The effect of event migration at the boundary of the FR, which instead is a function of polar angle of the

350 photons, will be estimated later and treated as a correction to the efficiency.

351 The global acceptance is given by

$$acc = \frac{N_{\gamma\gamma}^{gen} \in FR}{N_{\gamma\gamma}^{gen}} \quad (1.10)$$

352 where $N_{\gamma\gamma}^{gen} \in FR$ if the number of the annihilation events generated by CalcHEP generation
 353 that fall in the FR, and $N_{\gamma\gamma}^{gen}$ is the total number of the generated events. The sample used
 354 for this study consist of 10^6 annihilation events, and the number of the annihilation events
 355 observed in the FR is $\sim 65,3 \times 10^3$, thus the global acceptance is $A = 0.0653 \pm 0.0003$ where
 356 the error comes from the statics of the MC sample.

357 1.5.2 A correction for migration effects

358 In the PADME data the cut used to decide if an event belongs to the FR are applied to values
 359 of R_γ that are reconstructed from quantities measured by the detector. The simulation of the
 360 CALCHEP sample can be used to understand how the number of events that are truly in the
 361 FR, $N_{\gamma\gamma}^{gen} \in FR$, relates to the number of events that are reconstructed, in the assumption of
 362 full efficiency, within the FR, $N_{\gamma\gamma}^{reco} \in FR$. The ratio,

$$A_{mig}(\theta_1, \theta_2) = \frac{N_{\gamma\gamma}^{reco} \in FR}{N_{\gamma\gamma}^{gen} \in FR} \quad (1.11)$$

363 will need to multiply the event dependent efficiency at the denominator of Equation 1.1.

364 In order to disentangle the efficiency effects from migration effects, the correction A_{mig} has
 365 been estimated using a smearing of the polar angle of the photons from the MC truth and
 366 comparing with distributions at generator level. The gaussian smearing was defined using the
 367 data, and looking at the width of the distribution of the reconstructed polar angle of a given
 368 photon, once the value of theta for the other is set to a constant value. This width of the
 369 distribution was found to have a negligible dependence on the polar angle and to be equal to
 370 $\sigma_\theta = 2.04$ mrad. After that, the following samples of events are in hands:

- 371 1. annihilation at generator le events from CalcHEP in the entire phase space;
- 372 2. annihilation at generator leevents from CalcHEP in the entire phase space with both
- 373 photon polar angles smeared by σ_θ .

374 The correction is measured as:

$$A_{mig}(\theta) = \frac{N_{\gamma\gamma}^{smeared}(\theta_i)}{N_{\gamma\gamma}(\theta_i)} \quad (1.12)$$

375 where $N_{\gamma\gamma}^{smeared}(\theta_i)$ is the number of photons of the smeared sample with a polar angle equal to
 376 θ_i , and $N_{\gamma\gamma}(\theta_i)$ is the number of photons generated with a polar angle equal to θ_i .

377 The first step is to select all the events in the samples 1. and 2. that have $R_{\gamma_1} \in FR$ and
 378 study the distributions of the polar angle of both photons. These are shown in Figure 1.13 (a),

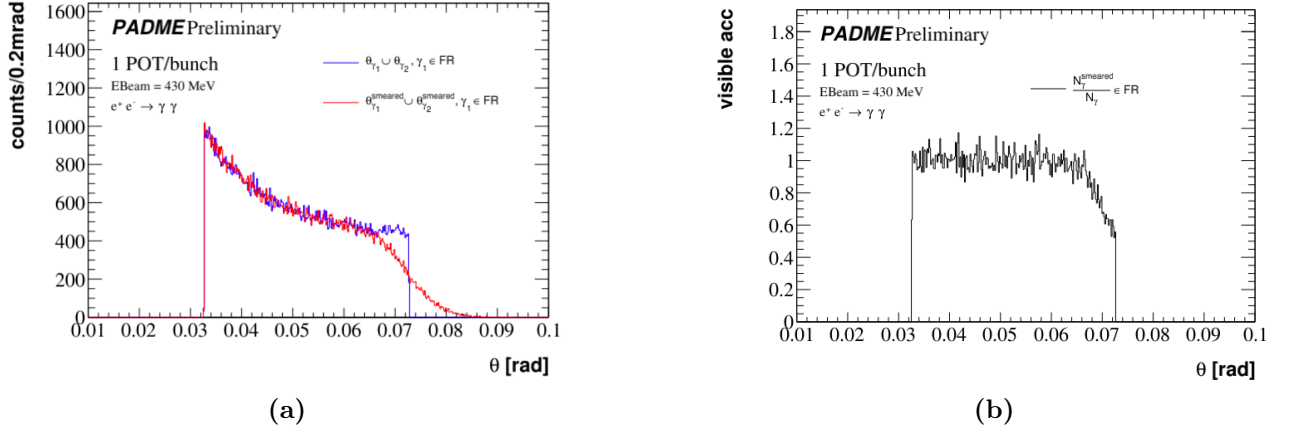


Figure 1.13: (a) Distribution of the polar angle of the two photons of the annihilation sample, in blue the CalchEP generation, in red the same sample after the smearing in θ . The selection for this events is $R_{\gamma_1} \in \text{FR}$. (b) The visible acceptance calculated as the ratio between the number of annihilation in a single bin for the sample with the smearing over the sample from the generator (red line / blue line of the Figure (a)).

in blue for MC truth and in red for the smeared sample. The ratio of the two distribution, as described in Equation 1.12, is represented in Figure 1.13 (b). This shows that if the event selection enforces the FR cut corresponding to the acceptance through a request applied only to one photon³, in this case the most energetic one, the correction for migration effects it be applied as function of θ_{γ_1} is always compatible to one.

On the other hand if the event selection requires that both photons are reconstructed in the FR, the correction for migration effects, applied again per event as a function of θ_{γ_1} (or θ_{γ_2}), depends on the event topology, as shown in Figure 1.14. Here, the distributions of the polar angles for both photons are shown after selecting all the events in both smeared and MC truth samples with both photons in the FR. The ratio of the two distributions, as described in Equation 1.12, is shown in Figure 1.14 (b). In this case, the correction is not identically equal to one.

1.5.3 In order acceptance at NLO

The CalchEP generator produces annihilation events, with exactly two photons in the final state, at the leading order in the perturbative expansion. It can also be used to produce the process $e^+e^- \rightarrow \gamma\gamma(\gamma)$ at the leading order approximation; Eventually the two samples might be combined to derive a general estimate for the inclusive cross section for the process e^+e^- to photons, however this procedure is prone to theoretical inaccuracies. On the other hand, Babayaga is NLO event generator for the $e^+e^- \rightarrow \gamma\gamma$ process, which means that the

³One has to remember that in terms of acceptance, i.e. when considering generator level quantities, requiring only one photons in the FR is perfectly equivalent to requiring both photons in the FR.

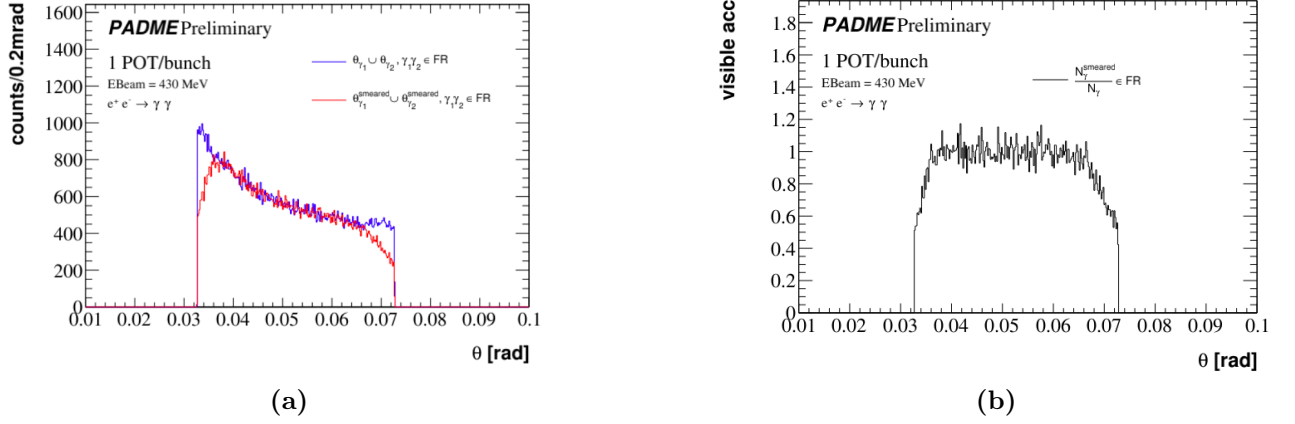


Figure 1.14: (a) Distribution of the polar angle of the two photons of the annihilation sample, for CalcHEP generation (blue) and after the smearing in polar angle (red). The selection for this events is both the photon $R_{\gamma_1}, R_{\gamma_2} \in FR$. (b) Visible acceptance calculated as the ratio between the number of annihilation in a single bin for the sample with the smearing over the truth sample (red line / blue line of the Figure (a).)

production of two and three photons are consistently managed over the phase space. In addition, Babayaga can be configured to run in the LO approximation, therefore a first check done to verify the compatibility of the LO predictions from the two generators. The total cross sections obtained are $\sigma(e^+e^- \rightarrow \gamma\gamma)^{CalcHEP} = 1.91218$ mb and $\sigma(e^+e^- \rightarrow \gamma\gamma)^{Babayaga} = 1.91096 \pm 0.00036$ mb with a relative difference of 0.06%. Another check was done to compare the kinematics measuring the global acceptance of the process. In this case the one measured with Babayaga is $acc^{Babayaga} = 0.0651$, thus there is a relative difference of -0.4% with the acceptance measured with CalcHEP. After these preliminary check a sample of the process $e^+e^- \rightarrow \gamma\gamma(\gamma)$ was generated. When running Babayaga at NLO up to three photons can be generated and the three photon final state is not anymore fully constrained. In this case the spatial resolution of ECAL should be considered if a soft photon falls close to another one, they may be reconstructed as a single cluster. To take into account this clustering effect photons from Babayaga are merged if the second lies at a distance in X or Y from the other compatible with the clusterization algorithm. In this case the resulting merged photon is assigned an energy equal to the sum of the two original energies and a position computed as an energy weighted average of the original positions. After this procedure, the photons are requested to pass the kinematic cuts that will be applied in the event selection: $E_{\gamma} > 90$ MeV and $|\Delta E| = |E_{\gamma} - E(\theta_g)| < 100$ MeV. Notice that these conditions in a LO simulation are trivially satisfied, therefore they are not applied to estimate the Acceptance in the LO approximation. The events where at least one pair of photons passing the kinematic cuts and lying both inside the FR are counted as events inside the acceptance. The ratio of this number to the total number of events produced by Babayaga is used to assess the acceptance that is measured to be: $A = 0.06341 \pm 0.00026$ that is relative 2.6% lower than the acceptance at the leading order.

This is used to measure the cross section as described in the next sections.

The systematics that can affect the acceptance come from perturbative approximation and the error on the distance between the target and the ECAL detector. For the first of them the NNLO correction is quoted be of the order of 0.1% **put reference**, hence it can be neglected. For the second the variations of the acceptance when changing the distance between ECAL and target have been estimated and they are summarized in Table 1.4 . Since the systematic error

Table 1.4: *Acceptance calculation obtained varying the distance between ECAL and target.*

Variation [mm]	$acc^{Babayaga}$	$\frac{acc^{Babayaga}}{acc_0^{Babayaga}}$
-15	0.0627771	0.990
-10	0.0629869	0.993
-5	0.0632111	0.997
0	0.0634096	1.000
+5	0.0632002	0.997
+10	0.0629825	0.993
+15	0.0627801	0.990

the measurement of the distance from the survey of the PADME apparatus is $\sim few$ mm, also this systematic uncertainty can be neglected.

1.6 Efficiency determination and closure tests

The photon efficiency was measured on data by developing a tag and probe technique exploiting the closed kinematics of annihilation events. Typically data driven efficiency measurements benefit from another auxiliary detector that allows to observe a sample of reference particles (probes), sometimes identified as belonging to a specific category of interest thanks to a tagging criterion. Then, the efficiency for reconstructing and identifying that category of particles with the detector and procedure under test is measured as the number of probes that are actually matched a particle reconstructed by the detector or procedure under test. For example, in a detector with a central spectrometer IS tracking all charged particles and an outer spectrometer OS for muons, the OS efficiency can be measured by looking for a well reconstructed muon reconstructed (tag) that combined with a track (probe) reconstructed in the IS gives an invariant mass corresponding to the J/Psi mass; the OS efficiency is given by the number of probes that have a matching muon track in the OS divided by the total number of probes. In the case of annihilation events in PADME calorimeter is a destructive detector and there is no other tagging detector to confirm the presence of a photon. Therefore the redundancy of kinematic constraints in the annihilation process is used to define a tag, a probe and to test if the probe is matched.

1.6.1 Tag and probe with annihilation events in PADME

As already extensively discussed, the two photons produced in the final state of $e^+e^- \rightarrow \gamma\gamma$ are correlated in energy and in space. Figure 1.15 shows that the polar angle of an annihilation photon predicts its energy, through an analytical function $E = f(\theta)$. Therefore, if a photon in ECAL comes from annihilation:

- its energy is compatible with $E_\gamma = f(\theta_\gamma)$;
- a second photon must exist back to back in phi to the first with $E_{\gamma_2} = E_{beam} - E_{\gamma_1}$;
- the energy of the second photon is also compatible with $E_{\gamma_2} = f(\theta_{\gamma_2})$.

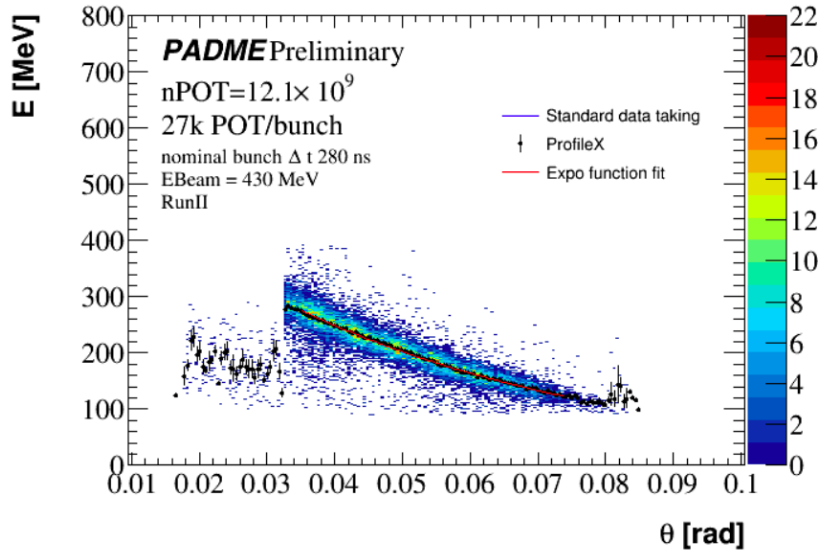


Figure 1.15: Correlation between the energy E and the polar angle θ of annihilation photons. For the plot are used data of run II and events that pass the selection: a,b,c,d,e, described in Section 1.4, to be background free. To extract the function $f(\theta_g)$ used in this studies to extract the predicted energy of the photon, a profileX was done, thus an exponential fit on a good region of it (fitted in $[0.035, 0.074]$ rad to exclude the problematic points). The parameters extracted are used to convert the polar angle in energy.

Therefore, the tag is identified as a cluster in the FR of ECal with:

$$\Delta E_{tag} = E_{Tag} - f(\theta_{Tag}) \quad (1.13)$$

close to zero. All the clusters in the FR with $|\Delta E_{Tag}| < 100$ MeV are considered tag candidates. This is a very loose cut considering that the resolution on ΔE_{Tag} is of the order of ~ 15 MeV.

When a tag candidate is found, the probe is defined as the “expected second photon” from the annihilation therefore, the number of probes is equal to the number of tags.

Finally, a matched probe candidate is defined as a cluster with features similar to the probe hypothesis; this means with $|\phi - \phi_{Probe}| < 25$ Deg, with $|\Delta E_{Probe}| < 100$ MeV, where $\Delta E_{Probe} = E_{Probe} - f(\theta_{Probe})$, and with $|\Delta E_{TP}| < 100$ MeV, where $\Delta E_{TP} = E - E_{beam} + f(\theta_{Tag})$. In addition, a matched probe is requested to be in time with the tag photon within 7 ns.

If more than one cluster seems to match a given tag, a choice must be taken; this is done by selecting the candidate matched probe with the minimum χ^2 defined as follows:

$$\chi^2 = \frac{\Delta E^2 + \Delta E_{probe}^2}{\sigma^2} = \frac{\Delta E_{Probe}^2 + \Delta E_{TP}^2}{\sigma(E_{\gamma_1})^2 + \sigma(E_{\gamma_2})^2} \quad (1.14)$$

was estimated, where $\sigma(E_{\gamma_i})$ for $i = 1, 2$ is the energy resolution of the calorimeter and it is considered equal to 15 MeV for all the clusters. An additional analysis was made requesting the belonging of the second photon in the FR. In the following studies, in order to understand each element of the analysis, the efficiency and the corrected annihilation yields are reported for both the selections: γ_1 in FR and γ_1, γ_2 in FR.

Finally, given the sample of tag candidates the counting of the “signal candidates” N_{Tag}^{sig} , i.e. of the photons that are really originating from an annihilation, requires the subtraction of a large background; similarly, the counting of the matched probes, N_{Probe}^{sig} , in the sample of candidates requires the subtraction of a background that, in this case, is very small.

The efficiency is therefore computed as follows:

$$\epsilon \pm \sigma = \frac{N_{probe}^{sig}}{N_{tag}^{sig}} \pm \sqrt{\frac{N_{probe}^{sig}}{(N_{tag}^{sig})^2} + \left(\frac{N_{probe}^{sig}}{(N_{tag}^{sig})^2}\right)^2} \times N_{tag}^{sig} \quad (1.15)$$

The error takes into account the poissonian fluctuation of both counters because the background, dominating the selection of tag candidates, washes out the correlation of numerator and denominator that would require a binomial treatment. Indeed the subtraction of the background contaminating the sample of candidate tags and the determination of the number of signal tags is the most critical step in the procedure and several approaches have been adopted. The first strategy consists in modelling the background using the sideband or a control data sample, applying a gaussian fit to the signal peak to estimate its standard deviation; The number of tags is then computed as the integral of the background subtracted distribution in the range corresponding to 3 sigma. The same procedure is applied to count the number of matched probes in the sample of candidates. An assessment of the systematic error affecting the efficiency determination is obtained by estimating the number of tags and probes consistently as the integral within 1 or 5 sigma of the background subtracted candidate distribution.

This method has been applied to measure the efficiency in 16 bins covering the ECAL geometry, two radial bins and 8 azimuthal bins.

1.6.2 Validation in MC

All the methodology was tested on MC samples of pure annihilation simulated without any defect in the calorimeter, with pure or in pileup annihilation when the calorimeter is affected by dead crystals.

493 Truth efficiency

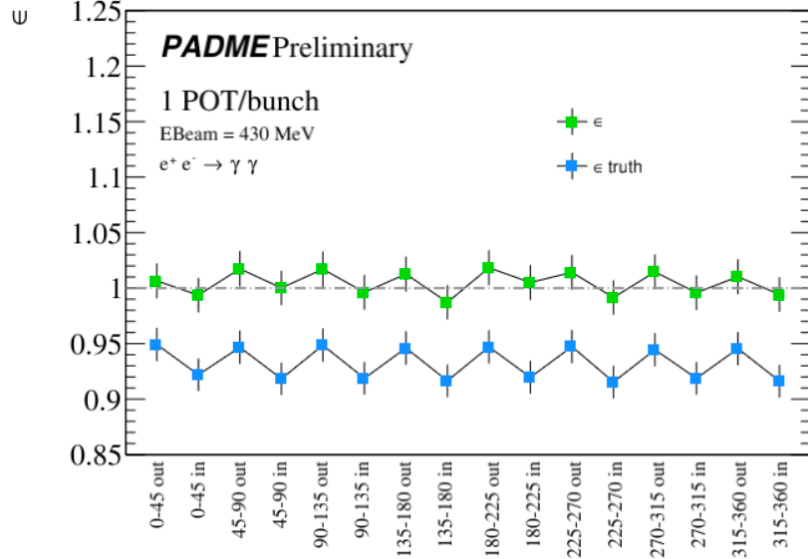


Figure 1.16: Efficiency extracted with a comparison of the CalcHEP truth generation and the same events simulated in PADMEMC. The study was done splitting ECAL in 8 azimuthal slices, each one is subdivided in two radius ranges: inner range if $R_\gamma \in]R_{min}^{FR}, R_{mid}]$, outer range if $R_\gamma \in [R_{mid}, R_{max}^{FR}]$. In green is represented the photon efficiency extracted as the number of clusters in that bin over the number of photons generated in the same bin. In azure the number of cluster in bin that has the truth in the same bin over the number of photons generated that fall in the bin. The shape observed is due to the migration effect. *change layout*

To study the reconstruction efficiency, ECAL was divided in 8 azimuthal slices and each one in two radius ranges: $R_{min} - R_{mid}$ and $R_{mid} - R_{max}$ *maybe a scheme to explain*. For each event are studied the spatial coordinate from the truth information and from the CalcHEP sample simulated with PADMEMC and reconstructed. The variables studied are

- reconstruction efficiency, given by the ratio between the number of simulated photons and generated once that fall in each bin. In Figure 1.16, computed is reported the variable:

$$\epsilon = \frac{N_\gamma^{sim}}{N_\gamma^{gen}}; \quad (1.16)$$

for each bin (green dots), where N_γ^{sim} is the number of annihilations observed in that bin analysing the simulated sample and N_γ^{gen} is the number of annihilation recorded in the same bin studying the truth information. A first observation is that for some bins the efficiency is higher than 1, this is a migration effect, when the truth is simulated the photon's coordinates are changed by the resolution, by the segmentation of the detector and by the presence in the experiment of all the components. The other effect is that the bins representing the outer radius range has an efficiency higher than the inner one. This

is due to the fact that in the inner radius range the number of clusters with the truth out of the bin but simulated with a radius in, has an average number of 626, while the number of the clusters simulated in bin but with a truth radius out of it is 546. This imply that the reconstruction efficiency of the inner part of ECAL is smaller than the outer one;

- truth efficiency, given by the ratio between the number of the simulated photons having the truth and the simulated spatial coordinates falling in a bin and the number of the generated γ that fall in the same bin. In figure 1.16 are reported also the variable:

$$\epsilon^{truth} = \frac{N_{\gamma}^{sim}(\gamma^{gen})}{N_{\gamma}^{gen}} \quad (1.17)$$

where $N_{\gamma}^{sim}(\gamma^{gen})$ is the number of the annihilations having truth and simulated coordinates in the bin. The truth efficiency in the outer radius range ($R_{mid} - R_{max}$) is higher of the once in the inner radius range ($R_{min} - R_{mid}$), this is due to the fact that in the inner part is more evident the effect of the migration. In fact the average number of the clusters reconstructed with a radius out of the radius range is 669, while for the outer range it is 432. This means that in mean, when the truth is in the bin, the photons related to that truth have a higher migration effect for the inner radius range, this imply that for the same bins the efficiency should decrease.

In Tables 1.5 (for inner ring) and 1.6 (for outer ECAL ring) are reported for all the azimuthal ranges the truth efficiency ϵ^{truth} , efficiency ϵ , the ratio of the clusters simulated in that bin but with the truth with $R_{\gamma} < R_{min}^{range}$ with the number of clusters in the bin (feed thorough in), the number of clusters simulated with a radius $R_{cl} < R_{min}^{range}$ but with the truth with radius in the bin (loss in), the ratio of the clusters simulated in that bin but with the truth with $R_{\gamma} > R_{max}^{range}$ with the number of clusters in the bin (feed thorough out), the number of clusters simulated with a radius $R_{cl} > R_{max}^{range}$ but with the truth with radius in the bin (loss out). The two ranges studied are: $]R_{min}^{FR}, R_{mid}[$, parameters in Table 1.5, $[R_{mid}, R_{max}^{FR}[$, parameters in Table 1.6.

Tag and probe on MC

A first study was done simulating CalcHEP pure annihilation in to photons sample recorded in the detector ECAL that do not present problems, thus without died crystals. For this reason in the selection of the tag and matched probe there is not background. In this case the number of tags (matched probes) will be the integration in 3σ of the tag (same for matched probe) peak in the distribution of ΔE_{tag} (ΔE_{probe}). The systematic errors are given as described in section 1.6.1. In the Figure 1.17 are shown the two efficiency extracted with only tag in the FR (blue dots) and also the probe in FR (red dots). As is shown the requirement of both the photons in the fiducial region should decrease the efficiency. For each point in the graph there is the statistic error, represented as a line, and the $\sigma \oplus \sigma_{sys}$, represented as a band over it. In this section a deeper understanding of the two efficiencies are described.

Table 1.5: Photon radius range $]R_{min}^{FR}, R_{mid}[$ for each azimuthal slice are reported the truth efficiency ϵ^{truth} , efficiency ϵ , the ratio of the clusters simulated in that bin but with the truth with $R_\gamma < R_{min}^{range}$ with the number of clusters in the bin (feed thorough in), the number of clusters simulated with a radius $R_{cl} < R_{min}^{range}$ but with the truth with radius in the bin (loss in), the ratio of the clusters simulated in that bin but with the truth with $R_\gamma > R_{max}^{range}$ with the number of clusters in the bin (feed thorough out), the number of clusters simulated with a radius $R_{cl} > R_{max}^{range}$ but with the truth with radius in the bin (loss out).

Angle range	ϵ^{truth} ± 0.015	ϵ ± 0.016	feed through in ± 0.002	loss in ± 0.002	feed through out ± 0.002	loss out ± 0.002
[0, 45[	0,923	0,994	0,046	0,044	0,030	0,034
[45, 90[	0,918	1,000	0,050	0,046	0,029	0,037
[90, 135[	0,919	0,996	0,047	0,045	0,028	0,037
[135, 180[	0,917	0,987	0,047	0,050	0,031	0,033
[180, 225[	0,920	1,005	0,047	0,044	0,029	0,036
[225, 270[	0,915	0,994	0,049	0,048	0,028	0,036
[270, 315[	0,919	0,996	0,048	0,050	0,034	0,033
[315, 360[	0,916	0,994	0,046	0,049	0,029	0,035

Table 1.6: Photon radius range $[R_{mid}, R_{max}^{FR}[$ for each azimuthal slice are reported the truth efficiency ϵ^{truth} , efficiency ϵ , the ratio of the clusters simulated in that bin but with the truth with $R_\gamma < R_{min}^{range}$ with the number of clusters in the bin (feed thorough in), the number of clusters simulated with a radius $R_{cl} < R_{min}^{range}$ but with the truth with radius in the bin (loss in), the ratio of the clusters simulated in that bin but with the truth with $R_\gamma > R_{max}^{range}$ with the number of clusters in the bin (feed thorough out), the number of clusters simulated with a radius $R_{cl} > R_{max}^{range}$ but with the truth with radius in the bin (loss out).

Angle range	ϵ^{truth} ± 0.015	ϵ ± 0.016	feed through in ± 0.002	loss in ± 0.002	feed through out ± 0.002	loss out ± 0.002
[0, 45[	0,949	1,020	0,035	0,030	0,027	0,021
[45, 90[	0,947	1,017	0,040	0,027	0,030	0,026
[90, 135[	0,949	1,017	0,039	0,026	0,033	0,026
[135, 180[	0,946	1,013	0,034	0,030	0,027	0,024
[180, 225[	0,947	1,018	0,036	0,029	0,027	0,024
[225, 270[	0,947	1,014	0,037	0,024	0,033	0,028
[270, 315[	0,945	1,015	0,035	0,031	0,032	0,024
[315, 360[	0,946	1,010	0,035	0,028	0,027	0,026

Comparison truth and tag and probe efficiency on CalcHEP sample

The truth efficiency in Figure 1.16 shape is different by the one represented in Figure 1.17. In particular the two photon efficiencies that can be comparable, due to the same requirements,

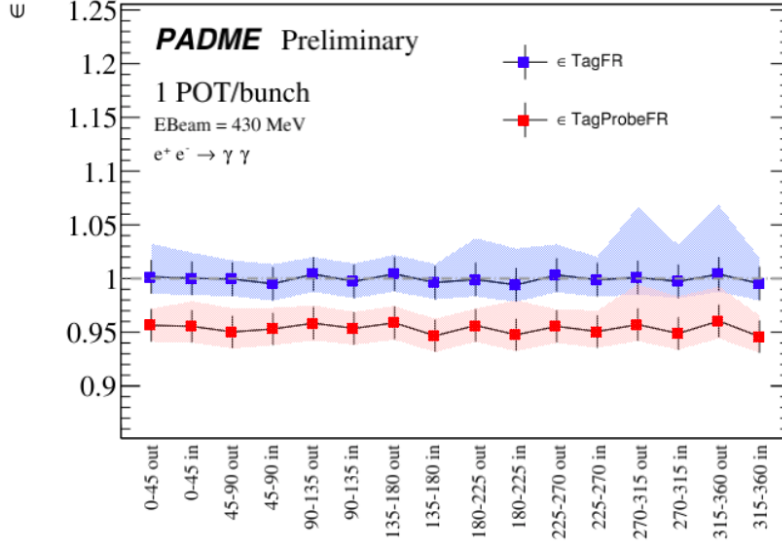


Figure 1.17: Efficiency extracted using the tag and probe method on $e^+e^- \rightarrow \gamma\gamma$ CalcHEP simulated sample. In blue the efficiency ϵ extracted requiring only to tag the belonging to the FR. In red the efficiency ϵ' extracted when both the photons are in FR. *change layout + eps TagFR -> eps and eps TagProbeFR -> eps'*

are the $\epsilon^{truth} = \frac{NClusters_i}{NTruth_i}$ of the Figure 1.16 (green dots), and for the second the one extracted with the request of the FR only to the tag $\epsilon^{TP} = \frac{nProbe_i}{nTag \in bin_j}$. In this nomenclature the subscript i means the bin in which ECAL efficiency is studied, while j is the bin with opposite azimuthal angle and opposite radius range (constrain given by the kinematics of the annihilation). As it is said in 1.6.2, the differences between the inner radius range and the outer one of Figure 1.16 is due to the migration effect. In the efficiency trend extracted using tag and probe this effect is reduced. In addition the efficiency is never higher than 1, this because the existence of a probe is constrained to the existence of a tag, so also when the number of tags are less than the number of clusters in the opposite bin (case of tag in the inner radius range as is described in 1.6.2), the number of probes can't be different from the number of tags. When the number of tags is higher than the clusters in the opposite bin (case of the tag in the inner radius range bins) the absence of a radius range cut for the probe allow to find a matched probe, so the efficiency is still close to one. From these considerations it follows that the efficiency extracted from tag and probe is not effected by migration. The small differences visible in the tag and probe efficiency trend is a result of the cluster reconstruction effect.

In Table 1.7 is reported the ratio between the truth efficiency and the one measured with the tag and probe (TP):

$$\alpha = \frac{\epsilon^{truth}}{\epsilon^{TP}} = \frac{\frac{NClusters}{NTruth}}{\frac{NProbe}{NTag}}. \quad (1.18)$$

for all the phi slices, inner and outer rings. From the α factors emerges that the inner ring bins have the truth and TP equal within the 1%, while in the outer ring the truth efficiency is

564 higher than the TP one because more affected by migration effects.

Table 1.7: *Ratio between the truth and TP efficiency.*

Angle range	α	α
	inner ring	outer ring
[0, 45[	0,994	1,018
[45, 90[	1,004	1,018
[90, 135[	0,999	1,013
[135, 180[	0,991	1,009
[180, 225[	1,011	1,019
[225, 270[	0,995	1,011
[270, 315[	0,999	1,014
[315, 360[	0,999	1,006

565 1.6.3 A closure test of the annihilation yield measurement

566 To test how the tag and probe efficiency depend on detector problems, the CalcHEP sample
 567 $e^+e^- \rightarrow \gamma\gamma$ was simulated adding to ECAL four died crystals having $\phi \in [45, 90]^\circ$ to localise the
 effects. In Figure 1.18 is reported the map of the annihilation photons for this special sample.

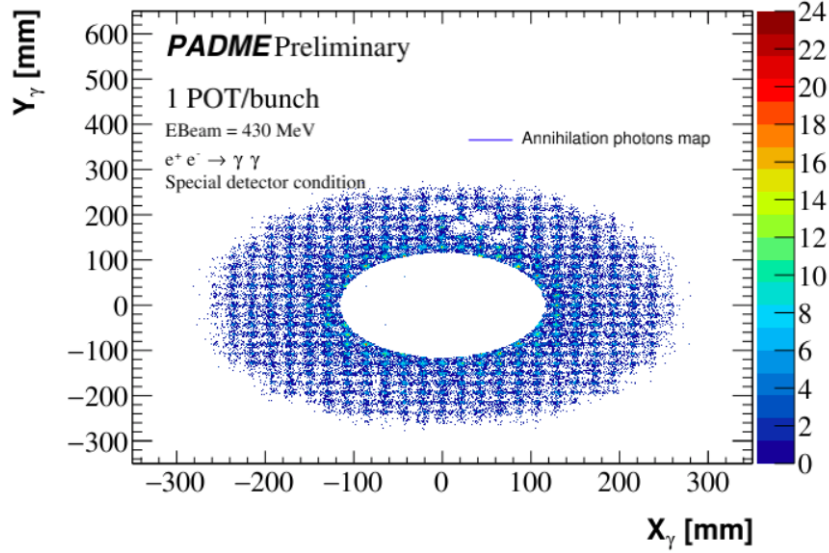


Figure 1.18: *Map of the annihilation photons selected with only the time coincidence requirement and the application of the FR to the most energetic photon. This a special simulation in which there are four died crystals, made to test the tag and probe efficiency.*

568 First the truth efficiency for this special sample was extracted as described in section 1.6.2,
 569 and the efficiency trend are reported in Figure (a) of 1.21. As expected the efficiency decrease
 570

where the detector has problems, represented in this case by the presence of died crystals. Then the ΔE_{Tag} and ΔE_{Probe} were studied to extract the efficiency trend. The distribution of these variables for the special sample are not a gaussian distributions for all the bins, in fact where there is the died crystals the energy of the cluster was missing of the energy ratio that fall in the died crystal. In Figure 1.19 is shown a distribution of ΔE_{tag} for tags reconstructed in the

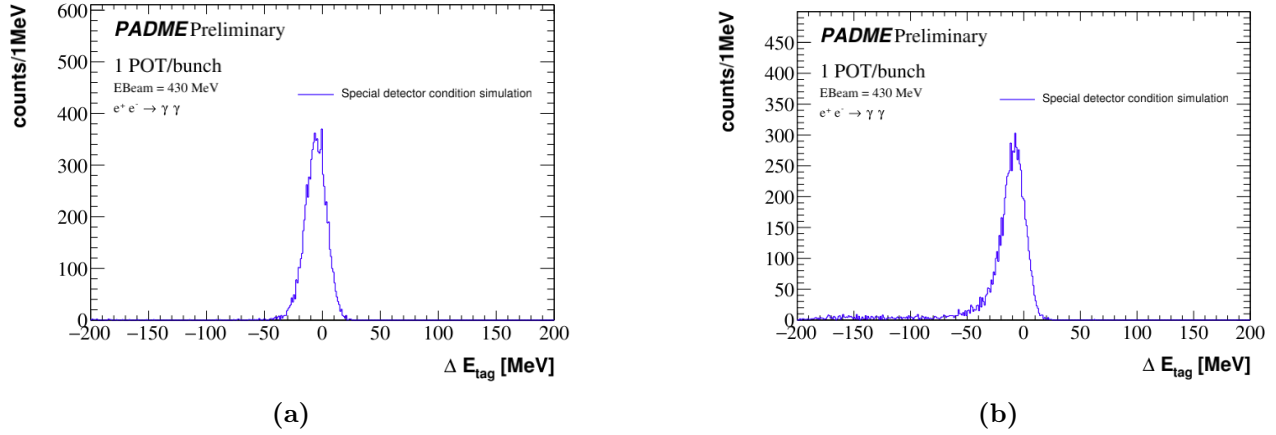


Figure 1.19: ΔE_{Tag} distribution for the MC simulation of pure annihilation with a special detector condition. On the left the distribution is plotted for a bin without died crystals, on the right the same distribution for tags reconstructed in the bin with died crystals. *add spatial cuts to the plots*

bin without problems $\phi \in [180, 225]$ Deg , $R \in]R_{min}$ and $R_{mid}[$ while in Figure 1.19 (b) the same distribution extracted for the problematic bin with $\phi \in [45, 90]$ deg and $R \in]R_{min}, R_{mid}[$. The probe distributions are affected by the same problem. In Figure 1.20 are reported for the same bins the ΔE_{Probe} distribution. Also for this variable is visible the presence of a tail in the ΔE_{probe} distribution where there are died crystals, Figure 1.20 (b). The process performed to extract the tag and probe efficiency is the same as the one described in the previous section and the efficiency extracted is reported in Figure 1.21 (b). In the ECAL slice where four died crystals were simulated the efficiency is strongly reduced, obtaining $\epsilon \sim 0.86$. The correspondent increasing of the efficiency in the opposite phi slice is an evidence that the efficiency extracted using the tag and probe is biased. This is due to the following consequence of the method applied:

- to extract the efficiency where there is a detector problem, like in the inner ring of the phi slice $[45, 90[$ Deg the number of probes are less. The tags belonging in the opposite bin (outer ring of $[225, 270[$ Deg) are not effected of any deficit and consequentially of any decreasing. The overall effect is an underestimation of the efficiency;
- to extract the efficiency in the opposite side of the detector problem allocation, like in the inner ring of the phi slice $[225, 270[$ Deg the number of probes are not effected of deficit, while the tags belonging in the opposite bin (outer ring of $[45, 90[$ Deg) are invalidate by the died crystals. The overall effect is an overestimation of the efficiency.

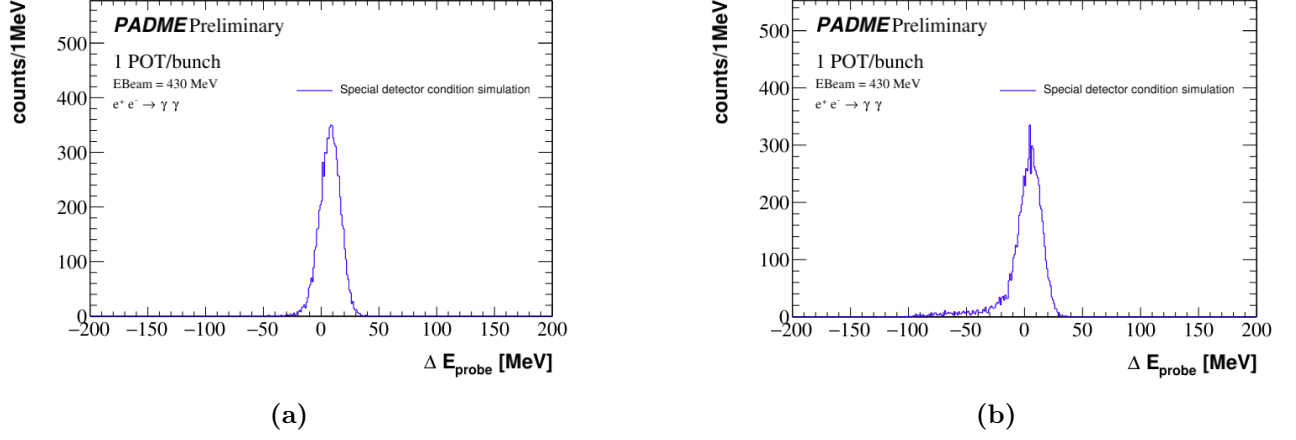


Figure 1.20: ΔE_{Probe} distribution for the MC simulation of pure annihilation with a special detector condition. On the left the distribution is plotted for a bin without died crystals, on the right the same distribution for tags reconstructed in the bin with died crystals. *add spatial cuts to the plots*

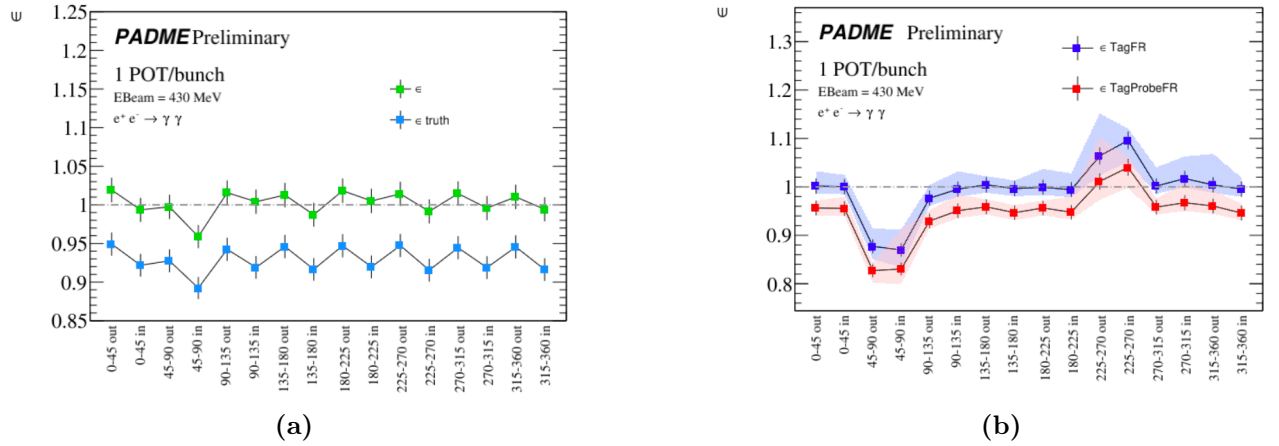


Figure 1.21: Efficiencies extracted on a simulation with a special ECal condition. On the left: truth efficiency. On the right: Efficiency extracted using the tag and probe technique. *change layout*

Due to this bias the efficiency measured for each bin can not be considered as photon efficiency, however since the correction of the annihilation yield will be done using $\epsilon(\gamma_1) \times \epsilon(\gamma_2)$ the bias will disappear. In fact in the problematic region the efficiency is $0,86 \times 1,08 = 0,93 < 1$. In Figure 1.22 (a) is shown the event efficiency for both truth and TP one, where the truth event efficiency is represented in green while the tag and probe in blue. As in showed by the graph for the event efficiency extracted using the tag and probe in the problematic bins is lower than the truth event efficiency. This is an expected effect because in the truth efficiency there is any consideration of the cluster energy, therefore a photon that hit a died crystal produce a small signal in the nearest scintillator bars, and if the tag and probe reject this cluster (because is not

comparable with the expected energy), the clusters counter should increase with an increasing of the truth efficiency. If an energy threshold was applied in the selection of the clusters to extract the truth efficiency, the two efficiency are statistically the same, as is shown in Figure 1.22 (b).

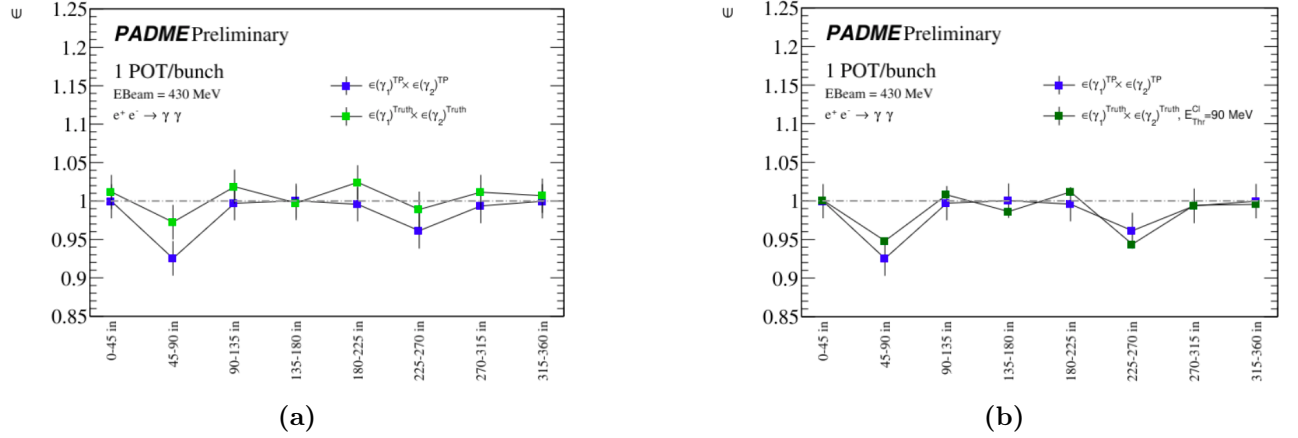


Figure 1.22: Event efficiency given by $\epsilon(\gamma_1) \times \epsilon(\gamma_2)$. Due to the strong correlation of the two photons the event efficiency is well defined: if one photon fall in the bin i , the other falls in the opposite bin, i with opposite phi and radius range.

1.6.4 Application of data-driven efficiency on CalcHEP simulation sample without pileup

The calcchep simulation is used to verify the consistency of the corrected yields. In this section the results obtained from the application of the method on calcchep simulation with a special detector condition, four died crystals, is reported. The tag and probe single photon efficiency for this sample is shown in Figure 1.21. The weight to the annihilation events are applied as reported in 1.22. The efficiency associated to the first photon (that is required to be in the FR) is always the one extracted without the FR belonging request to probe ϵ_{TP} that it is equivalent to constrain the tag to belong in a bin and leave the probe to be or not in the FR. To the second photon, the efficiency was applied as a function of the selection: if the second photon is not required to be in the FR, the efficiency used is the ϵ_{TP} , while if it is requested to be in the FR the efficiency to be used is the one extracted with the additional request of $R_{probe} \in FR$: $\epsilon_{TP,probe \in FR}$. In fact in this latest case to the efficiency factor the visible acceptance is added, factor induced by the request of second photon FR belonging. To have a confirmation of the fact that the $\epsilon_{TP,probe \in FR}$ is equal to the product of the photon efficiency and the visible acceptance, for the analysis $\gamma_1, \gamma_2 \in FR$ was also applied a weight given by the two photons efficiency times the visible acceptance extracted in the Section 1.5.2.

The yield of the annihilation, for this no background sample, is given by the integration in a fixed energy range $[300, 600]$ MeV in the $ECAL_{g1} + E_{\gamma_2}$ spectrum. In Figure 1.23 is shown the

annihilation peak of all the events that pass the time selection, with the first photon in the FR and that has the CoG coordinates in 5 cm. All the yields extracted are reported in table 1.8.

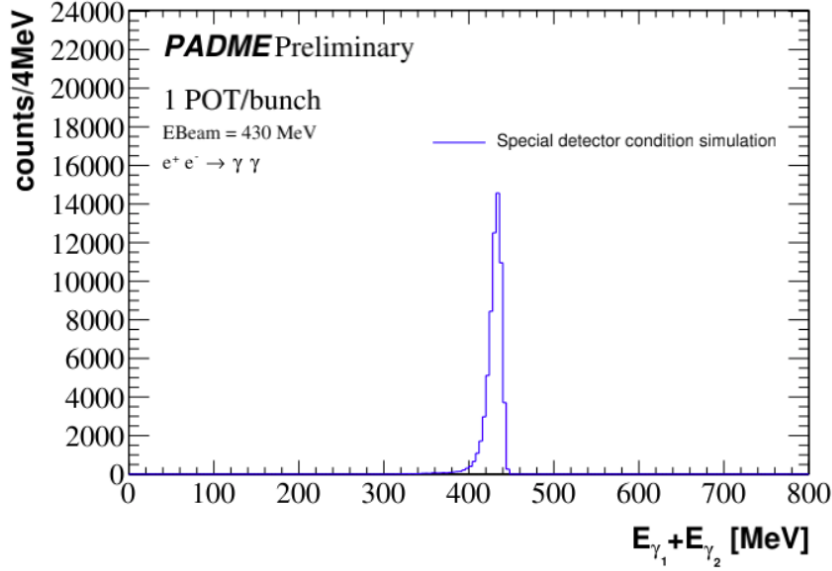


Figure 1.23: Distribution of the sum of the two photons energy $E_{\gamma_1} + E_{\gamma_2}$ for all the events that pass the time selection, with the first photon in the FR and that has the CoG coordinates inside 5 cm for a sample simulated with a special detector conditions (four died crystals).

As is shown the correction improve the measurement and return an yield close to the expected

Table 1.8: Yield extracted from the annihilation distribution obtained analysing the special detector CalcHEP simulation. The yields were extracted integrating the $E_{\gamma_1} + E_{\gamma_2}$ spectrum in the fixed range [300, 600] MeV. It is also reported the yield obtained counting the number of events in the FR of the CalcHEP generation, this will represent the expected yield.

Sample and cut	$\gamma_1 \in FR$	$\gamma_1, \gamma_2 \in FR$
CalcHEP generation (expectation)		
$\in FR$	65320	65318
CalcHEP simulation		
$\in FR, |CoG| < 5$ cm	64006	61041
$\in FR, |CoG| < 5$ cm, $\epsilon_{TP} \times \epsilon_{TP} (\times \epsilon_{TP, probe \in FR})$ application	65057	65088
$\in FR, |CoG| < 5$ cm, $\epsilon_{TP} \times \epsilon_{TP} \times Acc(\theta_{\gamma_1})$ application		65649

one from CalcHEP in $< 0.5\%$.

1.6.5 Pileup and detector defects

Another strategy is to use the MC simulation to extract the scale factor that normalise the simulation to data, then using this factors is possible to correct data and extract the annihilation yield.

Samples definition

Due to the presence of the four died crystals only in a specific side of ECal, the sample was divided in two sub-samples defined as “data” and “MC”:

- all the reconstruction that involve the ECal region along x axis $\pm 45^\circ$ is defined as “MC” because there are no inefficiencies;
- all the reconstruction that involve the ECal region along y axis $\pm 45^\circ$ is defined as “data” due to the presence of the four died crystals;

in Figure 1.24 is represented a schematic view of the division, where sub-sample 1 is the “data” one and the second sub-sample is defined as “MC”. For this two sub-samples the yield was

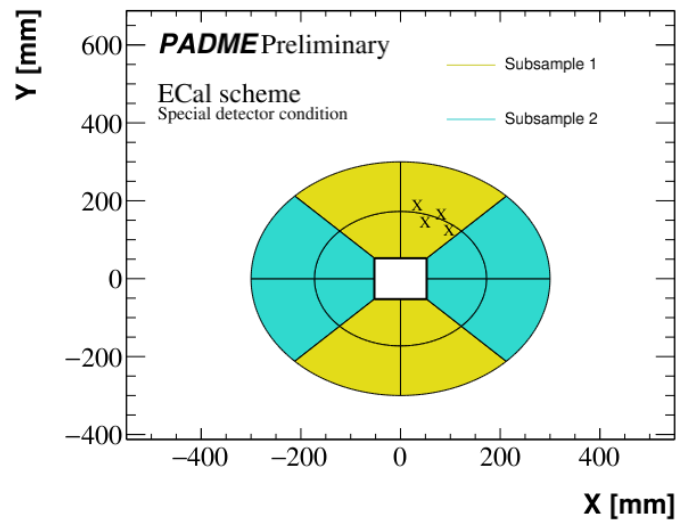


Figure 1.24: Graphic representation of the two sub-samples. *adjust X positions*

extracted applying directly the tag and probe efficiency and applying the scale factors method. From CalcHEP generation the expected yields are reported in Table 1.9.

The impact of detector defects

The first sample used is the simulation of CalcHEP events in PADME with the special detector condition with a single positron into the bunch that produce an annihilation final state. The sample was divided in two sub-samples as described before. The numbers of events that pass the selection without any weight applied is reported in table 1.10.

Table 1.9: *Expected yields in the data and MC sub-samples from CalcHEP generation.*

Sub-sample	Yield
Data	32649
MC	32671

Table 1.10: *Yield extracted from the annihilation distribution obtained analysing the special detector calcchep simulation. The yields were extracted integrating the $E_{\gamma_1} + E_{\gamma_2}$ spectrum in a fixed range $[300, 600]$ MeV).*

Sample	Cut	$\gamma_1 \in FR$	$\gamma_1, \gamma_2 \in FR$
Data	$|\Delta t| < 10$ ns, $|X(Y)_{CoG}| < 5$ cm	31443	29940
MC	$|\Delta t| < 10$ ns, $|X(Y)_{CoG}| < 5$ cm	32537	31088

Check of the data-driven efficiency correction

For each event that pass the selection of $|\Delta t| < 10$ ns, $|X(Y)_{CoG}| < 5$ cm with the first or both the photons in the FR, was applied a weight given by formula 1.3. The so corrected yields obtained are reported in table 1.11 and it is in agreement with the expectation less than the 1%. It is needed to observe that the data sub-sample, where there are the died crystals, the

Table 1.11: *Yield extracted from the annihilation distribution obtained analysing the special detector calcchep simulation and corrected for the weights as described in formula 1.3. The yields were extracted integrating the $E_{\gamma_1} + E_{\gamma_2}$ spectrum in a fixed range $[300, 600]$ MeV).*

Sample	Cut	$\gamma_1 \in FR$	$\frac{\gamma_1 \in FR}{expetation}$	$\gamma_1, \gamma_2 \in FR$	$\frac{\gamma_1, \gamma_2 \in FR}{expetation}$
Data	$|\Delta t| < 10$ ns, $|CoG| < 5$ cm	32429	0.993	32477	0.995
MC	$|\Delta t| < 10$ ns, $|CoG| < 5$ cm	32598	0.998	32594	0.998

yield corrected extracted is in agreement with the expectation, a confirmation that the bias of the efficiency is compensated in the product $\epsilon(\gamma_1) \times \epsilon(\gamma_2)$.

Application of the scale factors correction

In this sample, the data and the MC is a sub-sample of the same simulation, thus the application of the scale factors described at the beginning of this Chapter will be adapted to the problem. For this reason the weight defined as:

$$f_i = \frac{\epsilon^{TP}(data|\phi_i, R_i)}{\epsilon^{TP}(MC|\phi_i, R_i)} \quad (1.19)$$

was adapted to use the same simulation, but using the two defined sub-samples:

$$f'_i = \frac{\epsilon^{TP}(MC|\phi_i + 90, R_i)}{\epsilon^{TP}(MC|\phi_i, R_i)} \quad (1.20)$$

in this way the data efficiency corresponds to the efficiency of the bin in the same radial range but in the damage region of ECAL, thus efficiency of $\phi + 90^\circ$ as azimuthal angle. The f'_i factors was applied only to MC sub-sample. Then integrating the $E_{\gamma_1} + E_{\gamma_2}$ signal distribution in $[300, 600]$ MeV energy range the $C_{\gamma\gamma}$ factors were compiled. This was done for the two analysis related to the request of only most energetic photon in the fiducial region or both the photons in FR. The factors $C_{\gamma\gamma}$ and the corrected yields are:

- $C_{\gamma\gamma}^{\gamma_1 \in FR}$: it is given by the annihilation yield in MC sample after the application of the scale factors (31627) divided by the number of generated annihilation: $C_{\gamma\gamma}^{\gamma_1 \in FR} = \frac{31627}{32671} = 0.968$. Since the data yield not weighted, if there is only the first photon in the fiducial region is 31443, the application of the correction imply that the corrected yield for data is $D = \frac{31443}{0.968} = 32480$. The ratio of D with the prediction is equal to 0.995;
- $C_{\gamma\gamma}^{\gamma_1, \gamma_2 \in FR}$: it is given by the annihilation yield in MC sample after the application of the scale factors (30065) divided by the number of generated annihilation: $C_{\gamma\gamma}^{\gamma_1 \in FR} = \frac{30065}{32671} = 0.920$. Since the data yield not weighted, if both the photons are in the fiducial region is 29940, the application of the correction imply that the corrected data yield is $D = \frac{29940}{0.920} = 32535$. The ratio of D with the prediction is equal to 0.997.

Applying this method it is obtained an yield close to the expected within 0,5%.

Application of the methods on CalcHEP simulation sample with pileup

The simulation used in this check is the annihilation from CalcHEP in addition to the GEANT4 simulation coming from the interaction of 25000 POT/bunch with the target. Using this sample there is a uncertainty on the determination of the annihilation generated number. To be sure of this number, an identification process was developed to study only the reconstructed CalcHEP events was taken. The consistency selection of the events with the CalcHEP truth was done adding a tool in the analysis frame able to extract the truth from the CalcHEP output and compare it with its simulation. The consistency check was tested with a pure annihilation simulation without any dead crystals. The variables used to analyse the events chosen was the energy and the azimuthal angle, in particular was studied the difference in energy and in ϕ of the truth photon with the simulated one for all the events that pass the selection cuts a, b and c described in Section 1.4. The distribution of $\Delta E = E_\gamma - E_{cl}$ and $\Delta\phi = \phi_\gamma - \phi_{cl}$ are reported in Figure 1.25, where $ECAL_g$ and ϕ_g is respectively the energy and the azimuthal angle of the truth photon. The first variable is all contained in $|\Delta E| < 50$ MeV, thus the events that satisfy this cut for both the photons can be considered coming from CalcHEP generation. To reduce the probability that also GEANT4 events pass the identification, also on $\Delta\phi$ was applied a selection. Considering the Figure 1.25 (b) there are three different situations:

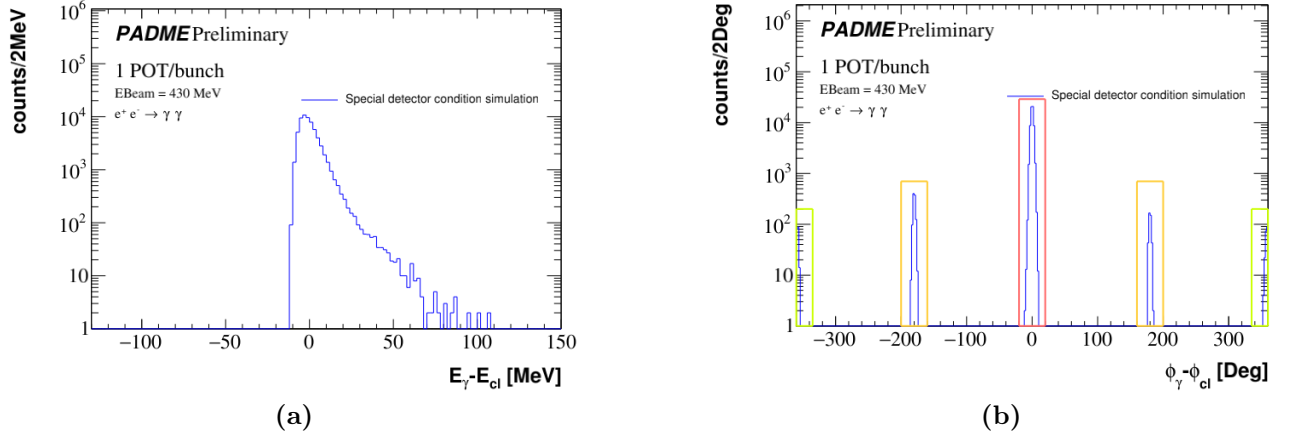


Figure 1.25: Left: distribution of $\Delta E = E_\gamma - E_{cl}$ for the events that pass the selection cuts *a*, *b* and *c* described in 1.4 for a pure annihilation simulation.

- $|\Delta\phi| = 180$ Deg: it represent the expected $\Delta\phi$, where the generation and the simulation have the same azimuthal angle;
- $|\Delta\phi| = 180^\circ$: in this particular situation the two photons have the same energy, and due to the resolution, the role of the most energetic and the less energetic are inverted;
- $|\Delta\phi| = 360^\circ$: due to resolution problem the cluster having $\phi = 0$ can be reconstructed with a $\phi = 360$, producing an high difference.

Due to these features the azimuthal selection was applied as follow:

- $|\Delta\phi| < 50^\circ$ on both the photons (including the red peak);
- $|\Delta\phi| = |\phi_{\gamma_i} - \phi_{cl_j}| < 50^\circ$ for *i* and *j* equal to 1 or 2 (including the orange peak);
- $|\Delta\phi| = |\phi_{\gamma_i} - \phi_{cl_i}| < 50^\circ$ and $|\Delta\phi| - 360 = |\phi_{\gamma_i} - \phi_{cl_i}| - 360 < 50^\circ$ for *i* and *j* equal to 1 or 2 (including the green peak);

Applying this selection, the number of annihilation recognised as CalcHEP simulation was 65067 in stead of 65172, only the 0.2% is lose in absence of pileup and without any detector problems. In presence of pileup (25×10^3 POT/bunch) the number of annihilation that pass the consistency check is 65342, the 0.3% more than the expected (65172) that represent the GEANT4 contamination.

Check of consistency process on CalcHEP samples simulated without pileup and with the special ECal detector condition

The second check was done with the introduction of the four died crystals, to study the efficiency if the consistency selection. The check was done on the two sub-samples defined as “data”

and “MC” described in Section 1.6.5. The check was done with and without the consistency for all the event that pass the time coincidence request and the CoG cut. The yields are reported in Table 1.12. From the table is clear that in the sub-sample in which there is

Table 1.12: Yield extracted from the annihilation distribution obtained analysing the special detector calchep simulation in order to extract the performance on the consistency selection.

Sample	$\gamma_1 \in FR$		$\gamma_1, \gamma_2 \in FR$	
	Without consistency	Consistency applied	Without consistency	Consistency applied
Data	31443	30809	29940	29313
MC	32537	32489	31088	31042

no problem, the consistency imply the same efficiency of before, but when were added some detector imperfections, like the four died crystals, the efficiency of the consistency, for the two selection with one or two photons in the FR, has an efficiency of $\beta = \frac{30809}{31443} = \frac{29313}{29940} = 0.98$. To verify the results using TP method, the efficiencies shown in Figure 1.22 are used. The results obtained applying or not the CalcHEP consistency are reported in Table 1.13. As it is visible,

Table 1.13: Yield extracted from the annihilation distribution obtained analysing the special detector calchep simulation with and without the consistency check corrected for the tag and probe efficiency.

Sample	$\gamma_1 \in FR$		$\gamma_1, \gamma_2 \in FR$	
	Weighted w/o consistency	Weighted, Consistency applied	Weighted w/o consistency	Weighted, Consistency applied
Data	32429	31765	32477	32553
MC	32598	31784	32594	32548

the corrected yield obtained with the events if it is not applied the consistency check is very close to the expectation, while a higher discrepancy is observed in the data sub-sample after the consistency check. Considering that this events has an intrinsic inefficiency related to the comparison procedure with the truth, the yield should be corrected for the β factor, obtaining consequentially the expected yield ~ 32400 for both the selections.

The corrected yield was extracted also applying the scale factors method obtaining:

- Not applying a consistency check:

- The $C_{\gamma\gamma}^{\gamma_1 \in FR}$ is obtained by dividing the annihilation yield after the application of the scale factors (31627) with the expected one extarcted from the truth: $C_{\gamma\gamma}^{\gamma_1 \in FR} = \frac{31627}{32671} = 0.968$. Since the data yield not weighted, if there is only the most energetic photon in the fiducial region is 31443, the application of the correction imply that the data corrected yield is $D = \frac{31443}{0.968} = 32516$. The ratio of D with the prediction is equal to 0.995;

- The second scale factor obtained is $C_{\gamma\gamma}^{\gamma_1, \gamma_2 \in FR} = \frac{30065}{32671} = 0.920$. Since the data yield not weighted, if both the photons are in the fiducial region is 29940, the application of the correction imply that the corrected data yield is $D = \frac{29940}{0.920} = 32535$. The ratio of D with the prediction is equal to 0.997;

- Applying a consistency check gives the same results if the yield of data is corrected by the β factor:

- $C_{\gamma\gamma}^{\gamma_1 \in FR} = \frac{31583}{32671} = 0.967$, the data yield not weighted, if there is only the first photon in the fiducial region is 30809, that corrected for the β factor become $D' = \frac{30809}{\beta} = 31443$, the application of the correction imply that the corrected data yield is $D = \frac{31443}{0.968} = 32516$. The ratio of D with the prediction is equal to 0.995 as in the previous case;

- $C_{\gamma\gamma}^{\gamma_1, \gamma_2 \in FR} = \frac{30022}{32671} = 0.919$, the data yield not weighted, if both the photons are in the fiducial region is 29313, that corrected for the β becomes 29940 and as before the application of $C_{\gamma\gamma}^{\gamma_1, \gamma_2 \in FR}$ gives a value in agreement with the prediction of the 99.7%.

As is shown, for both the weight (tag and probe efficiency directly application and from scale factors) in both the region (with died crystals or an ideal detector simulation) the number of annihilation extracted is compatible with the expectation.

Introduction of the pileup

The introduction of the pileup imply a presence in the distribution of background produced by the interaction of the positrons with the experiment components. The simulation that is used so far is produced at the target level, thus no beam line components was simulated. The implication is that the source of background coming from the line is not simulated. The prediction of the background, thus its subtraction from all the distributions, was made with a simulation having the target out the beam line, thus the positrons don't interact with the diamond. In the simulation of the beam at the target level however the clean beam pass throughout the magnetic field and it is bent out the experiment without any background production in the calorimeter. In a first approximation, to obtain a background with a shape similar to the one observed in the standard simulation, was used a MC simulation of the experiment starting from the Beryllium window and the beam line in the configuration of the data took in 2019 (see Chapter [data](#)). An important point is the simulation of the background MC in the same detector condition of the standard simulation, thus also for the background the four died crystals were simulated. A summary of the background simulation features is reported below:

- $E_{beam} = 490$ MeV;
- $N_{POT}/Bunch = 20 \times 10^3$;
- $\Delta t_{bunch} = 250$ ns;

- target position out of the beam line, $X_{Diamond} = -52$ mm
- beam line and Beryllium window activate;
- four died crystals in ECal ($\phi_{died} \in [45, 90]$ deg).

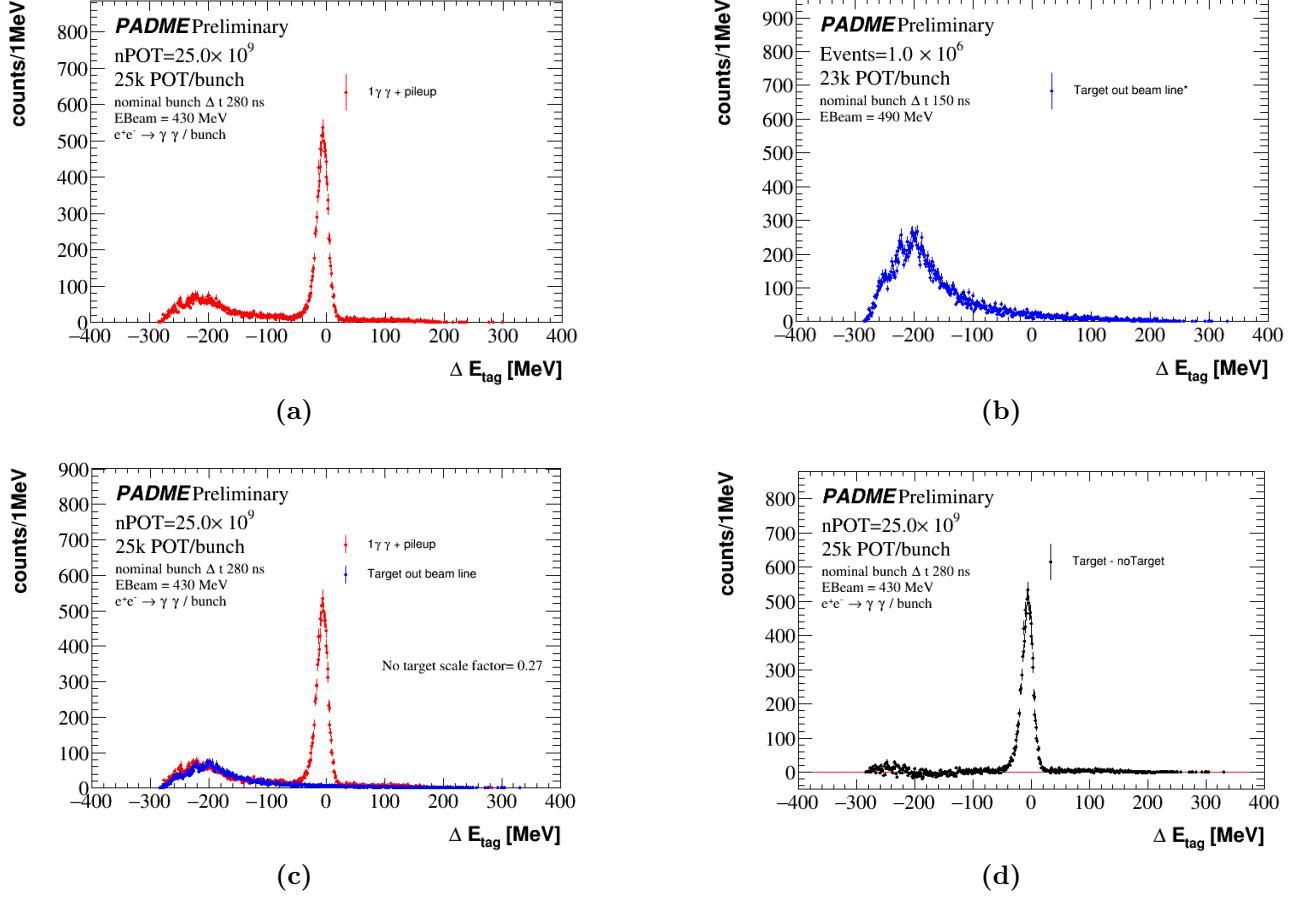


Figure 1.26: (a): Distribution of the $\Delta E = E_{cl} - f(\theta)$ of the tag distribution for the CalcHEP simulation in pileup. (b): Distribution of the $\Delta E = E_{cl} - f(\theta)$ for MC simulation of background (made with the target out of the beam line). (c): Comparison of (a) and scaled (b). (d) : Tag yield, obtained from the subtraction of the background to the signal.

The MC that is used in these tests is not the one related to the data collected during RunII. Since the simulation of the new beam line is not completed, the analysis was conducted with the simulation of the old beam line. In most of the bins studied the background shape (predicted by the no target run in RunII, thus with the new beam line) is the same of the background in the signal. A difference is only in the bins with $\phi = 0 \pm 45$ Deg outer where the presence of the beam line and Beryllium window produce an higher level of background. To solve this problem a background of the bin with $\phi \in [180, 225]$ Deg was used.

The selection of tag and probe distribution is done as described in section 1.6.1, for both the samples: the CalcHEP simulation submerged in the pileup and the no target simulation. The distribution of the tag are show in Figure 1.26.

The probe matching the tag have not background and the distribution are reported in Figure 1.27.

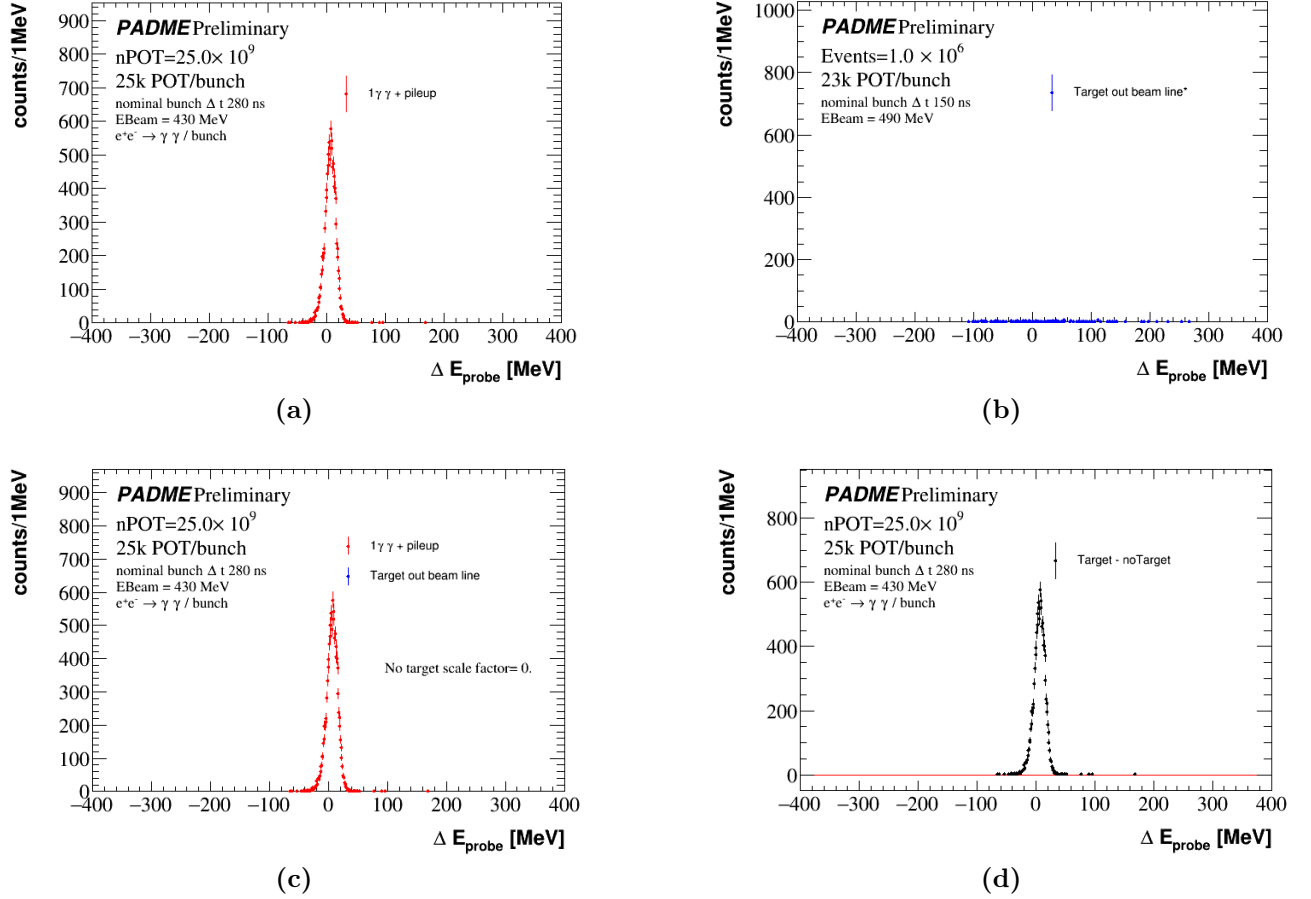


Figure 1.27: *P(a): Distribution of the $|\Delta E_{\text{Probe}} = E_{\text{cl}} - (E_{\text{Beam}} - f(\theta_{\text{Tag}}))$ of the probe matched distribution in the CalcHEP simulation with the pileup. (b): Distribution of the ΔE_{Probe} for MC background (target out of the beam line). (c): Comparison of (a) and scaled (b). (d) : Probe yield, obtained from the subtraction of the background on the signal.*

1.7 Early selection studies

The analysis was run using the longest and stablest runs took during the second PADME run. For all the runs the energy of the beam is $E_{beam} = 430$ MeV, the pulse duration is $\Delta t \sim 280$ ns and the mean of the beam multiplicity is $N_{POT}/bunch \sim 27 \times 10^3$. The special runs took with

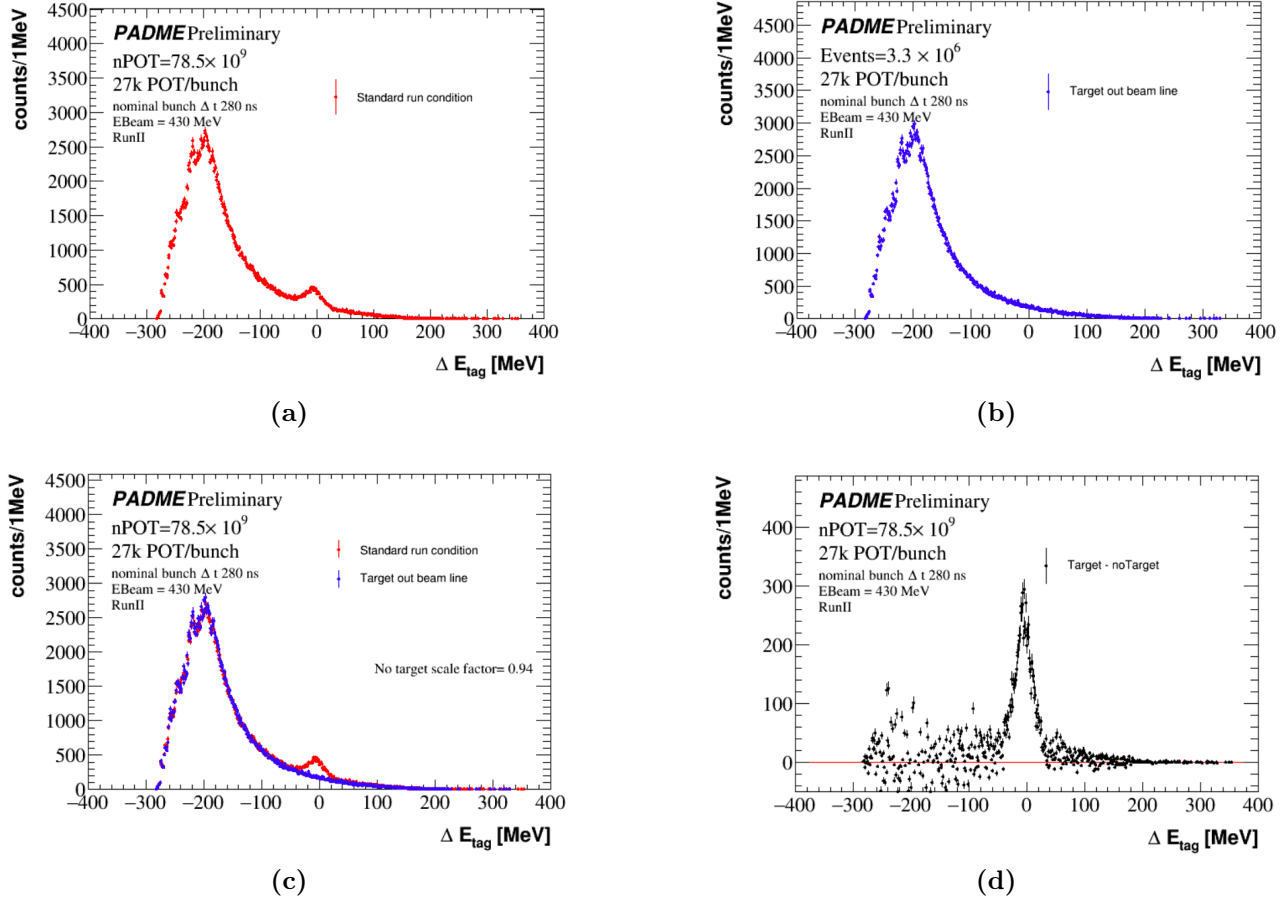


Figure 1.28: (a): Distribution of the $\Delta E = E_d - f(\theta)$ of the tag distribution in a standard run condition. (b): Distribution of the $\Delta E = E_d - f(\theta)$ for background, distribution of the events taken with the target out of the beam line. (c): Comparison of (a) and scaled (b). (d) : Tag yield, obtained from the subtraction of the background on the signal.

the beam out of the beam line allow the prediction of the beam related background. These runs were used to subtract the background from tag, probe, and annihilation distributions. These runs was token in the middle of the RunII, thus the features of the standard beam don't change much.

1.7.1 Tag and probe on data sample

The extraction of the tag and probe efficiency for the data sample procedure is the same that is described in the previous sections. The main difference with the calchep simulation is the presence of a huge background in the tag distribution. Thus the number of tag is give by the

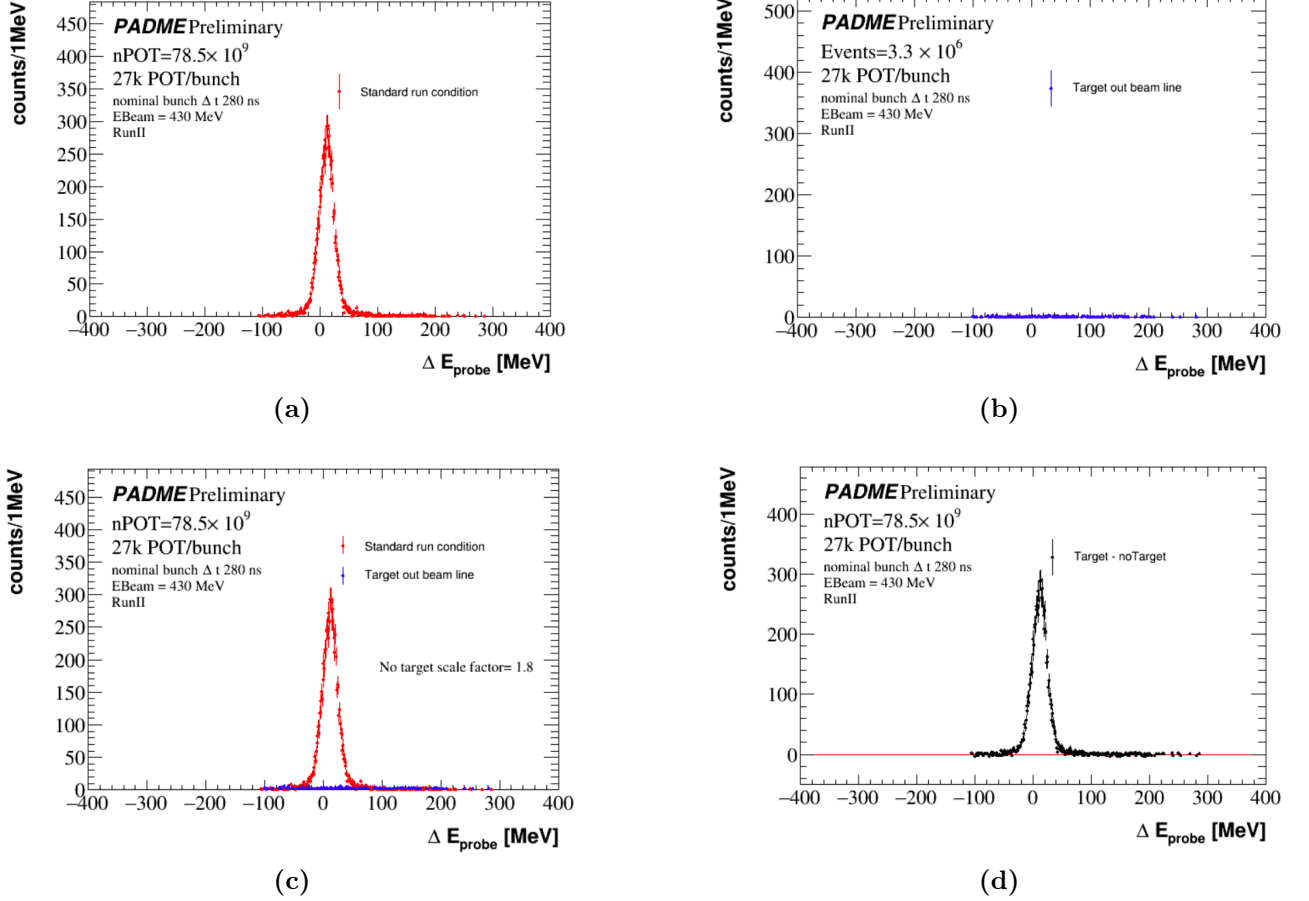


Figure 1.29: (a): Distribution of the $\Delta E_{Probe} = E_{cl} - (E_{Beam} - f(\theta_{Tag}))$ of the probe matched distribution in a standard run condition. (b): Distribution of the ΔE_{Probe} for background, distribution of the events taken with the target out of the beam line. (c): Comparison of (a) and scaled (b). (d) : Probe yield, obtained from the subtraction of the background on the signal.

signal subtracted of the background:

$$N_{Tag}^{sig} = N_{Tag} - N_{Tag}^{bkg}. \quad (1.21)$$

The prediction of the background is made normalising the distribution obtained analysing the special runs with the target out of the beam line in the range $\Delta E_{Tag} \in [-150, -90]$ MeV.

In Figure 1.28 (a) is shown the distribution of the ΔE_{Tag} for the data sample use, in (b) is represented the background for the same distribution. A comparison of the tag distribution

and the normalised background is in (c), thus its subtraction on the standard distribution in (c). The yield of tag is extracted integrating the distribution in $k\sigma$, where $k = 1, 3, 5$. The distribution of the probe, shown in Figure 1.29 (a), is background free (b), however in Figure (c) is reported the signal and the normalised background, in (d) the signal subtracted of the background.

The number of tags (probe) obtained is:

$$N_{tag(probe)} = (N_{inRangeTarget} - N_{inRangeNoTarget} \times f) \pm \sqrt{N_{inRangeTarget}^2 + N_{inRangeNoTarget}^2 \times f^2} \quad (1.22)$$

where $N_{inRangeTarget}$ is the number of events under the peak in the integrated range in the spectrum obtained analysing the runs token with a standard run condition, while $N_{inRangeNoTarget} \times f$ is the one extracted from background runs normalised with f scale factor.

1.7.2 Efficiency distribution

The efficiency is defined as:

$$\epsilon = \frac{N_{sig}^{probe}}{N_{sig}^{tag}} \pm \sqrt{\frac{\sigma_{probe}^2}{(N_{sig}^{tag})^2} + \left(\frac{N_{sig}^{probe}}{(N_{sig}^{tag})^2}\right)^2 \times \sigma_{tag}^2} \quad (1.23)$$

and is represented in Figure 1.30: (a) representation of the efficiency and the efficiency times the visible acceptance ϵ' for each bin of ECAL, (b) schematic view of the data efficiency. From

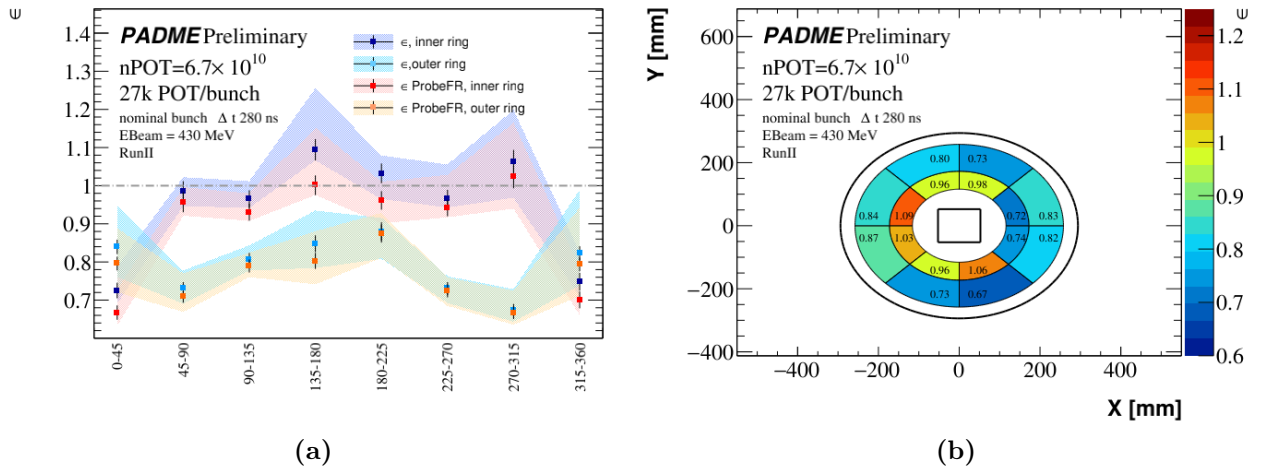


Figure 1.30: (a): Trend of the efficiency for bins in the inner ring in blue and outer once in light blue; in addition is reported the efficiency time the visible acceptance extracted requiring the probe in the FR (red for inner ring bins and orange for outer ring bins); (b) schematic view of the measured efficiency. *eps ProbeFR -> eps'*

the main features of the detector and the background occupancy described in Chapter [data](#), it is expected that the inner range bins should have an higher efficiency since there is no detector problems, with the exception of bins $\phi \in [0, 45[$ Deg and $\phi \in [315, 360[$ Deg where a huge background reach ECAL . In addition the bins with $\phi \in [270, 315[$ Deg and $\phi \in [315, 360[$ Deg share a died crystal. Regarding the outer efficiencies of upper and lower ECAL region, it is expected to observe a reduction of the efficiency due to the shadow, also with a different effect as the upper part is less affected. In addition the efficiency in bins with $\phi \in [270, 315[$ Deg and $\phi \in [315, 360[$ Deg have efficiency invalidated by the presence of a died crystal for each bin.

1.7.3 Early results

The cross section measurement was performed with both the analysis: the most energetic photon in FR and both in FR, applying the selection a.c. of Section 1.4. The N_{sig} is extracted integrating the $E_{\gamma_1} + E_{\gamma_2}$ sum of the two photons energy distribution for events that pass the annihilation selection for data subtracted of the normalised beam background obtained with the no target runs. The cross section measurement were:

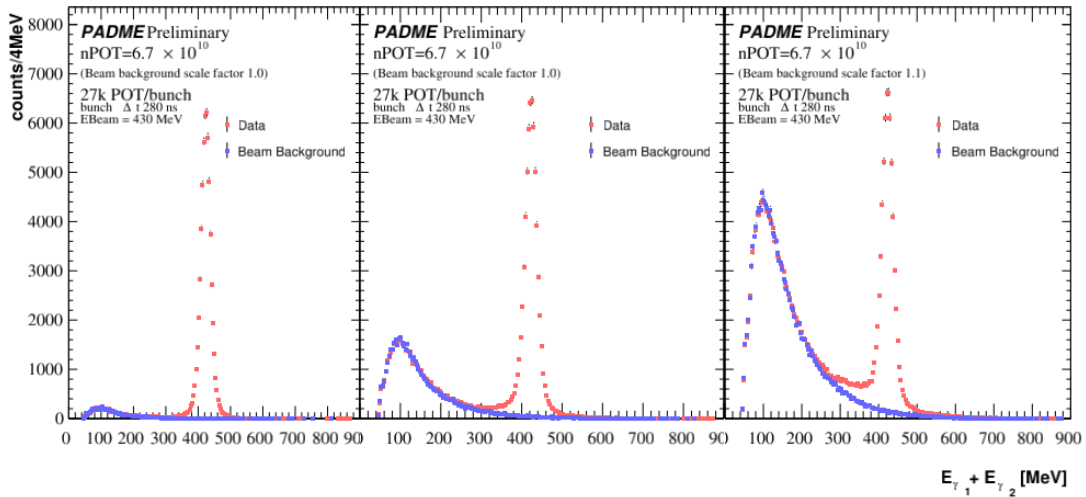


Figure 1.31: Distribution of $E_{\gamma_1} + E_{\gamma_2}$ of the two photons that pass the selection a.b. described in Section 1.4 for standard run (red dots) and special one with target out of the target beam (blue dots). (a) additional selection CoG cut of 20 mm; (b) additional selection CoG cut of 50 mm; (c) additional selection CoG cut of 80 mm.

- adding b. selection : $\sigma(e^+e^- \rightarrow \gamma\gamma) = 1.841 \pm 0.003$ mb;

- adding b.d. selections: $\sigma(e^+e^- \rightarrow \gamma\gamma) = 1.817 \pm 0.003$ mb;

with an extraction of the signal to this value, systematic errors should be added for:

- yield Tag:

- integration of the tag and probe signals in $1, 3, 5\sigma$, quoted $+10\% - 14\%$ of the cross section measurements for both the analysis;
- different normalisation range for the no target sample (default integration range $[-150, -90]$ MeV), quoted $+14\% - 13\%$ of the cross section measurements for both the analysis.

- Annihilation yield:

- systematic due to the 5 cm cut on CoG distribution. In Figure 1.31 is reported the distribution of the sum of the two photons energy passing different CoG cut: 2, 5, 8 cm. As is visible from the distribution the beam related background approximated using the no target special run, and normalising the two distribution in the range $[0, 200]$ MeV, is not able to reproduce the signal background with the choose of a larger CoG cut. Using these three points a systematic was extracted and quoted $+11\% - 10\%$;
- systematic due to the integration of the signal in different $E_{\gamma_1} + E_{\gamma_2}$ ranges (default integration range $[300, 700]$ MeV), it is extracted changing the normalisation range and is quoted $+4\% - 1\%$ of the cross section measurement for both the analysis.

The high systematics on the measurements is mainly due to the high uncertainty on the tag signal, thus a hard work was done and reported to reduce all these systematics.

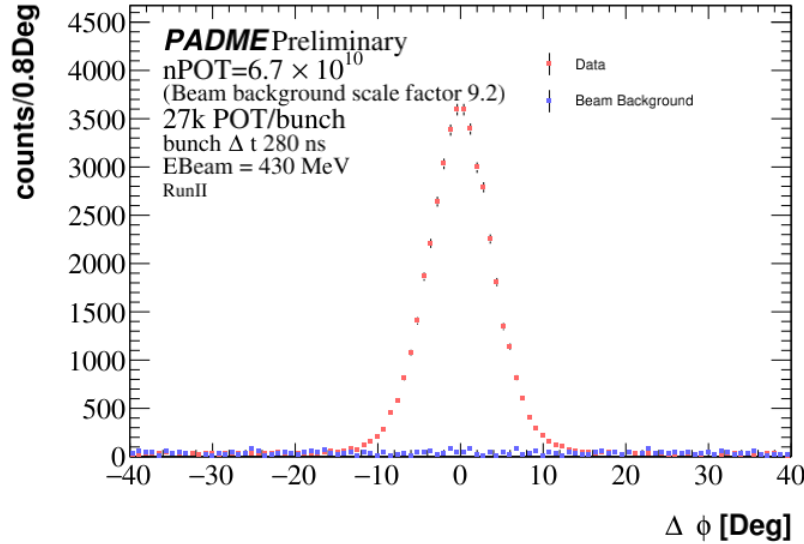


Figure 1.32: Distribution of $\Delta\phi = \phi_{\gamma_1} - \phi_{\gamma_2} - 180$ Deg of the two photons that pass the selection a.b.c. described in Section 1.4 for standard run (red dots) and special one with target out of the target beam (blue dots).

Since there is agreement in the analyses performed with the most energetic photon in FR and both the photons in FR, and since it is proved that the ϵ' measured with both the photons

in FR is given by the product of the efficiency and the visible acceptance, the following study was done only requiring the most energetic photon belonging FR.

1.8 Event selection and Results

1.8.1 Pre-selection

A first screening of the events was done in order to chose only events where a beam bunch arrives in the experiment, this is possible by choosing event triggered by the hardware trigger of the BTF beam.

However, even when the PADME trigger board receives the BFT trigger signal, it can happen that the event is empty, typically because of a late update of the BFT trigger signal after beam loss.

In addition, another problem can be observed looking at Figure 1.33 where the N_{POT} distribution for the events triggered by the BTF signal is shown for run $N = 30563$. Up to

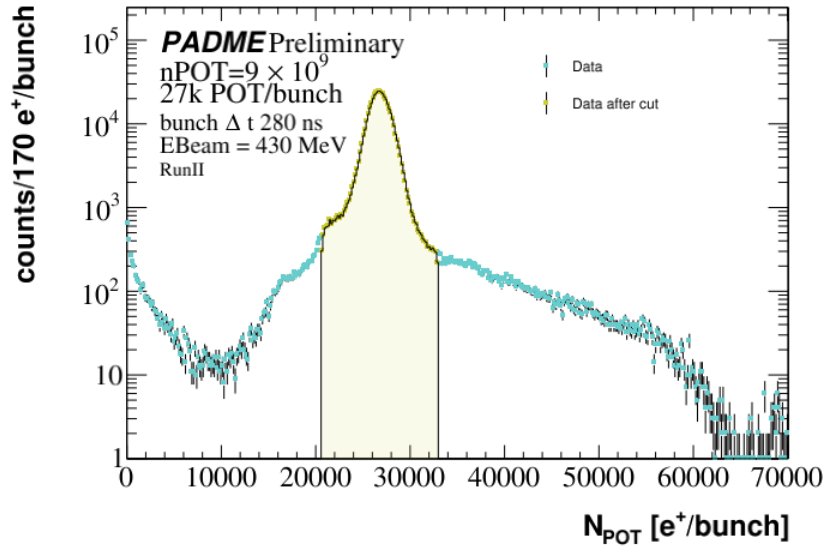


Figure 1.33: Distribution of the Number of Positrons On Target per bunch for run $N = 30563$ (azure distribution). In yellow is reported the N_{POT}/bunch distribution of the events that pass the multiplicity selection.

70 kPOT/bunch were estimated in a few cases. To solve both these problems in each run, events with a measured number of positrons in the bunch above or below five sigma from the average bunch multiplicity have been discarded. The reason of this cut lie the fact that if the target is reconstructing correctly the bunch multiplicity, events out the 5σ have a different beam background level and are affected by the pileup differently with respect to a typical event. On the other hand, instead events where the signals readout from the strips of the Diamond target lead to an extremely low or unrealistically high measurement of the total charge lead to

a wrong assessment of the number of positrons in the bunch. Although the occurrence of such events is low, they may introduce biases in the measurement of the total number of positrons on target.

Table 1.14: For each run analysed the number of events triggered by the BTF trigger signal, the number of events passing the luminosity selection and their ratio are reported.

Run number	N_{ev}^{BTF}	$N_{ev}^{5\sigma}$	$\frac{N_{ev}^{5\sigma}}{N_{ev}}$
30369	2961470	2820916	0,953
30386	1437248	1307072	0,909
30547	2232745	2140028	0,958
30553	785728	746250	0,95
30563	2243220	2101791	0,937
30617	2206172	2086402	0,946
30624	2234949	2106551	0,943
All	14000000	13300000	0,95

In Table 1.14 the number of events for each runs before and after the luminosity selection are reported along with the fraction of events retained.

1.8.2 Photon pre-selection

In Chapter [data taking](#)) it has been shown that even in RunII the PADME electromagnetic calorimeter receives a high rate of background particles, from beam related spurious interactions. Most of the times the resulting energy deposits have low energy, therefore the features of the corresponding clusters are statistically different from those of photons of energy above about 90 MeV that, as we will see later, are involved with the annihilation process. Therefore a cluster selection is applied in order to reduce the contamination of the cluster collection and improve the rejection of background.

Cluster quality requirements

Several features of the clusters corresponding to a tight selection of annihilation events have been studied and contrasted with the same quantities observed in the overall sample of clusters. The selection of annihilation photon candidates was based in the following requirements: at least two clusters must be found in ECAL with $|t_{\gamma_1} - t_{\gamma_2}| < 10$ ns, $|\Delta\phi| = |\phi_{\gamma_1} + 180^\circ - \phi_{\gamma_2}| < 25^\circ$, $|CoG_{X(Y)}| < 5$ cm, $300 < E_{\gamma_1} + E_{\gamma_2} < 500$ MeV⁴. In addition the most energetic cluster in the pair was requested to be at a radial distance with respect to the direction of the incoming beam bigger than 115.82 mm.

The distributions (with arbitrary relative normalization) of the variables studied are reported in Figure 1.34 for all clusters (azure distribution) and for annihilation candidate pho-

⁴The definition of x, y_{CoG} and the motivations of these cuts will be explained in Section 1.4

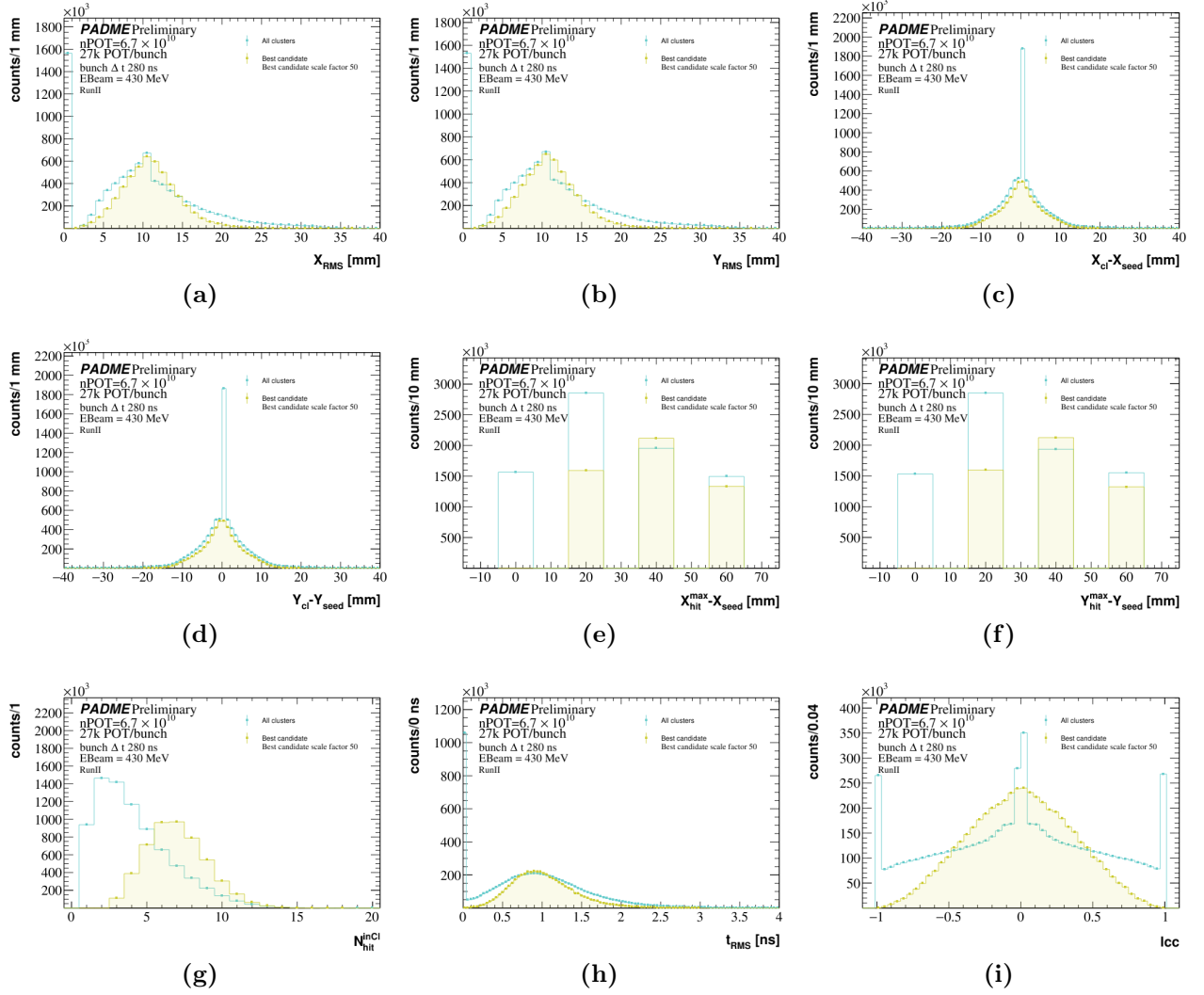


Figure 1.34: Cluster features, used to improve the quality and reduce the background contamination of the cluster sample, for all clusters (azure distributions) and annihilation candidate photons (yellow distribution): (a) RMS of X coordinates for hits in cluster, (b) RMS of Y coordinates for hits in cluster, (c) distance of cluster position from its seed in the X and Y (d) direction (e) maximum distance between a hit in the cluster and the seed in the X and Y (f) direction, (g) cluster size, (h) time RMS, (i) linear correlation coefficient of hits in the cluster.

tons. For each variable, a loose cleanup cut was defined to avoid compromising significantly the efficiency for signal photon. In the following the relevance of each variable is briefly described:

- the distance between the cluster position and its seed is peaked at zero in both the X and Y directions (see Figure 1.34 (c) and (d)), large distances may only be due to anomalous situations related for example by pileup; therefore only clusters with $R_{cl-seed} = (X_{cl} - X_{seed})^2 + (Y_{cl} - Y_{seed})^2 < 20$ mm are retained;

Table 1.15: Cluster quality requirements and fraction of clusters passing each cut with respect to those passing the previous cut.

Quality cut	$\frac{N_i}{N_{i-1}}$
$R_{Cl-seed} < 20$ mm	0.96
$X_{RMS} \geq 1$ mm	0.79
$Y_{RMS} \geq 1$ mm	0.90
$\Delta X^{max} \geq 1$ mm	1.
$\Delta Y^{max} \geq 1$ mm	1.
$|l_{cc}| \leq 0.99$ mm	0.92
t_{RMS}	0.996
Isolation	0.85

- X and Y RMS, defined as

$$\sqrt{\frac{\sum_{i=0}^{n_{hit \in Cl}} (X(Y)_i - X(Y)_{Cl})^2 E_i}{\sum_{i=0}^{n_{hit \in Cl}} E_i}}, \quad (1.24)$$

are shown in Figure 1.34 (a) for X and (b) for Y RMS. A comparison between generic clusters and annihilation candidates suggest to reject clusters with $X(Y)_{RMS} \leq 1$ mm;

- the maximum distance between hits in a cluster and the cluster position along X and Y axis (Figure 1.34 (e) and (f)) is requested to be $\Delta X(Y)^{max} \geq 1$ mm in order to discard the occurrence of signals from noise in an isolated crystal;
- the cluster distribution size, reported in Figure 1.34 (g), shows that candidate photons have an average multiplicity of 7 hits per cluster, thus a threshold was defined $N_{hits}^{inCL} > 1$;
- the RMS of the time distribution of hits in a cluster, defined similarly to the X(Y) RMS, is shown in Figure 1.34 (h) and a value not exceeding 3 ns is requested;
- the linear correlation coefficient of hits in the cluster given by

$$l_{cc} = \frac{\sum_{i=0}^{n_{hit}} (X_i - X_{cl})(Y_i - Y_{cl}) E_i}{\sum_{i=0}^{n_{hit}} E_i \times X_{RMS} \times Y_{RMS}} \quad (1.25)$$

is reported in Figure 1.34 (i); only values below 0.99 are accepted;

- finally an isolation requirement is applied: a photon is rejected if another cluster in a time within 10 ns is found closer than 200 mm.

The sequence of cuts applied to the ECAL clusters rejects 53,8% of them with the relative efficiency cut flow reported in Table 1.15. The fraction of the signal rejected is the 10% given by (number of probe that pass NPOTselection and ClQuality / number of probe that pass only NPOTselection)/2 - I divided for 2 to consider also the number of tag, since I select a probe if I found the tag....How I can explain this now?.

1.8.3 Choice of the event selection requirements

In order to correct the annihilation yield with the efficiency extracted from tag and probe technique, the same preliminary selection that it is applied in the searching of the matched probe was applied to the photon: $E_\gamma > 90$ MeV and $|\Delta E| = |E_\gamma - E(\theta_g)| < 100$ MeV.

As discussed the extraction of the two photons annihilation yield measurement is characterised by a not negligible systematic, this is due to the technique used in the extraction of the signal (integration of the signal subtracted of the background in a fixed range) and on the selection that is used to identify the annihilation events. In order to erase the systematic due the CoG cut, the selection used for the following analysis is just the a. and b. cuts described in Section 1.4. Aiming to reduce the systematic due to the yield extraction other variables was studied. In particular it is searched a variable with a flat background, as can be the $\Delta t = t_{\gamma_1} - t_{\gamma_2}$, but as is shown in Figure [Figure 1.32](#), the beam related background has a bump at zero. For this reason and since the annihilation has a constrained kinematic, the variable $\Delta\phi = \phi_{\gamma_1} - \phi_{\gamma_2} - 180^\circ$ is studied. As is represented in Figure 1.32 the beam related background has a flat distribution in $\Delta\phi$. In addition, to be coherent with the efficiency measurement, to each photon is required to pass an annihilation pre-selection: $E_\gamma > 90$ MeV and $|\Delta E| = |E_\gamma - f(\theta_g)| < 100$ MeV. The two photons annihilation yield extraction is consequentially done fitting the $\Delta\phi$ with a background and signal function represented by a polynomial of second degree and a gaussian. Then using the background prediction function the yield is extracted as:

$$N_{Sig} = N_{ev} - N_{Bkg}^{fit}. \quad (1.26)$$

A data-driven geometry correction

In order to verify the consistency of the annihilation, the ECAL calorimeter is divided in 8 azimuthal angle slices. In Table 1.16 are reported the yields of the annihilation for each bin, where the belonging to the bin is defined by the bin of the most energetic photon. The run analysed is the numbered 30563.

Apparently the annihilation center seems shifted towards negative x and y coordinates. This is in agreement with the measurement done in a survey, where emerges that the ECAL center is located in $(x_c, y_c) = (-3.13, -3.86)$ mm in the PADME framework. In addition the run took in account has a global Center Of Gravity shifted with respect to the zero of PADME, in fact a fit on the gaussian peak over the background shown a spatial centroid in $CoG = (X_{CoG}, Y_{CoG}) = (0.86, 0.67)$ mm. The annihilation axis is then shifted in order to be the same of the PADME one. The position of all the photons were shifted of:

$$X_\gamma = X_\gamma^{PADME} + X_c - X_{CoG}. \quad (1.27)$$

After the alignment of the detector with the annihilation physic the so obtained annihilation yields are reported in Table 1.17 divided in azimuthal slices (bin belonging is defined by the bin of the most energetic photon). In Figure 1.35 are shown the ratio between the maximum yield measured in the ECAL bins and the yields of each azimuthal slice for (a) clusters not shifted,

Table 1.16: *Annihilation yields measured fitting the background of the $\Delta\phi$ distribution for each azimuthal ECAL bin and the relative ratio of the yields with to respect the higher one.*

ϕ Deg range	N_{sig}	$\frac{N_{sig}}{N_{sig}^{max}}$
[0, 45]	1227	0.85
[45, 90]	899	0.62
[90, 135]	866	0.60
[135, 180]	1316	0.91
[180, 225]	1451	1
[225, 270]	1290	0.90
[270, 315]	1091	0.75
[315, 360]	1334	0.92

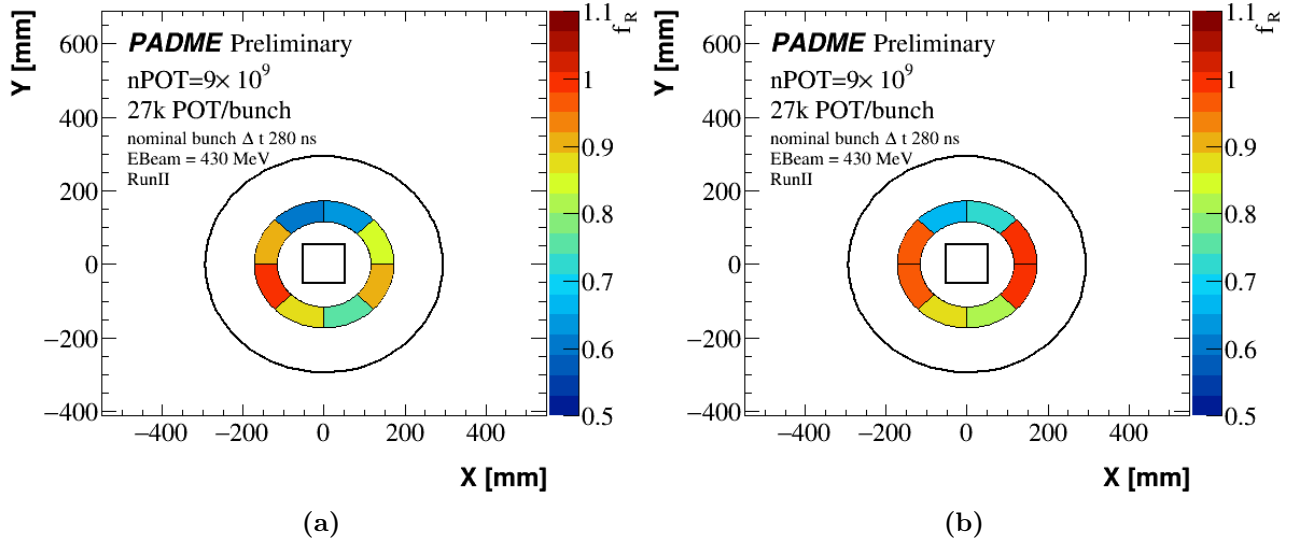


Figure 1.35: (a) Schematic view of the ratio between the bin maximum annihilation yield and the signals observed in each bin f_R . The belonging to this latest is defined by the most energetic photon. (b) f_R observed after the cluster position correction.

(b) adding the shift of Equation 1.27. As is visible after the correction the yields are consistent with the ECAL features, in fact along the x axis, where there are not detector problem, the ratio of the yields are uniform. The bins along the y axis have a low yield with to respect the other bins, and this is due to the shadow of the magnet, and since this effect is different between the top and the bottom of ECAL , the yields are different between the two ECAL regions. In addition a difference due to the died crystals is observed.

Table 1.17: Annihilation yields after the cluster position correction measured fitting the background of the $\Delta\phi$ distribution for each azimuthal ECAL bin and the relative ratio of the yields with to respect the higher one.

ϕ Deg range	N_{sig}	$\frac{N_{sig}}{N_{sig}^{max}}$
[0, 45]	1352	1
[45, 90]	966	0.71
[90, 135]	901	0.67
[135, 180]	1295	0.96
[180, 225]	1294	0.96
[225, 270]	1182	0.87
[270, 315]	1089	0.81
[315, 360]	1332	0.99

1.8.4 Improving on tag modelling

The major problem in the tag yield extraction is the modelling of the background. A cleaning of the background was done with the pre-selection. The reduction of background in the tag samples is shown in Figure 1.36 where are reported the distribution of ΔE_{tag} identified tag belonging the fiducial region without any selection in blue, for the events that pass the nPOT selection in grey and in red the events that pass the nPOT selection and photons that pass the cluster quality one.

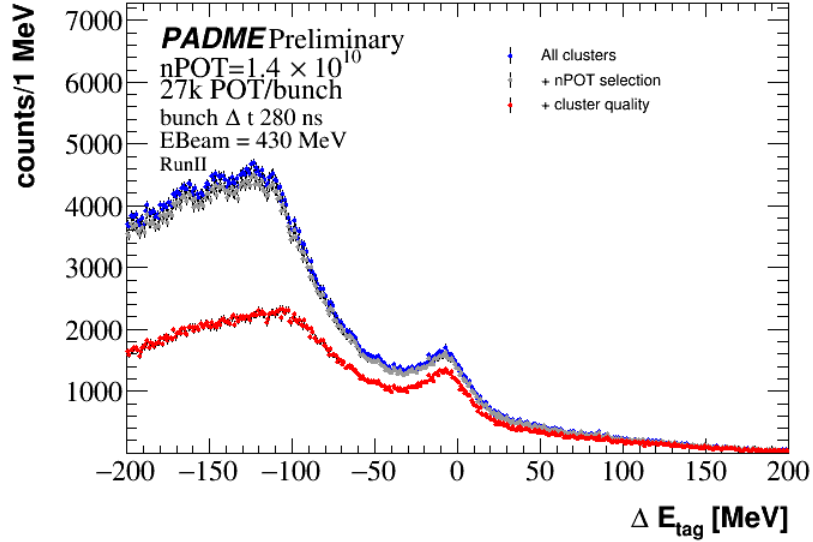


Figure 1.36: ΔE_{Tag} distribution of r identified tag belonging the fiducial region in blue. The same distribution is reported in grey for events that pass the nPOT selection and in red the photons that pass also the cluster quality cuts.

The main contribution to the background in data sample comes from the beam related background and the pileup one. The first one, as specified before, is predicted by the no target run, instead the simulation of pure annihilation in a bunch of $25000e^+$ is used to predict the pileup background. From the total spectrum of ΔE_{tag} , the annihilation peak was removed and

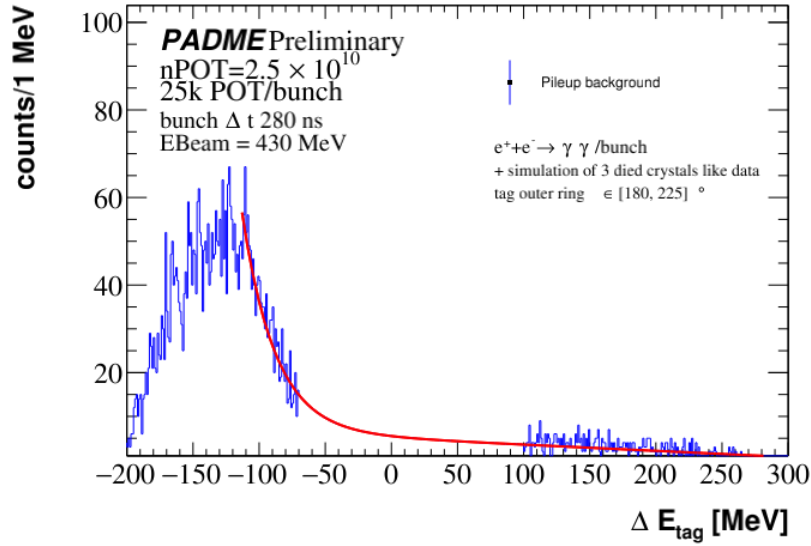


Figure 1.37: Distribution of pileup background in the tag distribution extracted using MC simulation of one annihilation events generated by CalCHEP and predict the signal region fitting with an exponential and polynomial of one order degree functions.

the empty region was fit with a exponential added to a polynomial of one degree function. Once obtained the function $f(\Delta E_{Tag}^i)$. In Figure 1.40 is reported an example of pileup background used for the tag yield extraction for photons with $R \in [172.82, 258[$ mm and $\phi \in [180, 225[$ Deg.

Consequently the fit of the tag distribution was performed fitting the ΔE_{Tag} spectrum in the range $[-100, 100]$ MeV fitted using for the description of the background the two samples just described and for the signal two gaussian function. In Figure ?? (a) is shown an example of fit made for the tag belonging the inner ring of ECAL and with $\phi \in [180, 225[$ Deg, (b) example of fit made for the tag belonging the outer ring of ECAL and with $\phi \in [45, 90[$ Deg . The first was optimised using RooFit [add reference](#), that allow to use the background distributions as probability function. The fit from which the signal was extracted is the one with the function parameters set have the minimum in the Negative Logarithmic Likelihood and of the error on the signal.

In the plot are reported all the contributions on data represented with the black dot: the red solid line represent the total fit, the orange line represent the total signal, given by the sum of the two gaussian component (yellows distributions). The total background prediction is reported in cyan, that is given by the sum of beam background (blue) and the pileup one (green). The fit parameters are 7: fraction of the total signal over the total background $f_{s/b}$, the fraction of the pileup over the beam related background, the faction of a gaussin over the

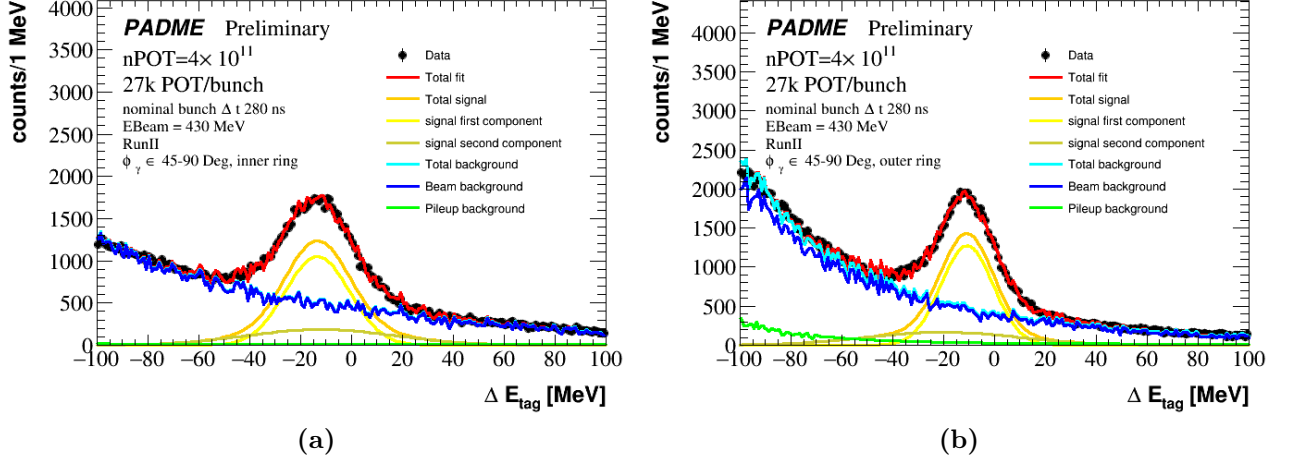


Figure 1.38: Fit of the ΔE_{Tag} distribution for photon belonging (a) $R \in [115.8, 172.82[$ mm and $\phi \in [180, 225[$ Deg, (b) $R \in [172.82, 258[$ mm and $\phi \in [45, 90[$ Deg. The data (black dots) is fitted with a total function (red line) given by the sum of a total signal component in orange (composed by two gaussian function in yellow) and a total background component in cyan (given by the sum of pileup effect in green and the beam related background in blue).

total signal, mean and sigma of the two gaussian functions. From the fraction $f_{s/b}$ it is possible the extraction of the tag yield:

$$N_{tag} = f_{s/b} \times N \pm \sqrt{(f_{s/b} \times \sqrt{N})^2 + (N \times \Delta f_{s/b})^2} \quad (1.28)$$

where N is the total number of events in the fit range and $\Delta f_{s/b}$ is the error on the fraction extracted from fit. The estimation of the yield using this technique, integrating in a large range, fix the bias observed integrating in the 3σ , thus the $\epsilon(R_\gamma, \theta_g)$ represent a photon efficiency.

1.9 Cross section measurement after multiplicity selection

Using the modelling of the distribution ΔE_{Tag} described in Section 1.8.4 and applying the multiplicity selection, the efficiency was extracted as:

$$\epsilon = \left[\frac{N_{probe}^{3\sigma}}{N_{tag}^{RF}} \right]_{N_{POT} selection} \quad (1.29)$$

where the tag yields were extracted fitting with RooFit and the probe yields form the integration in 3σ in the ΔE_{probe} distribution. The efficiency measured is reported in Table 1.18 for each of the eight phi bins with probe belonging the inner ring and the eight phi bins with the probe in the outer ring. The efficiency trend is also shown in Figure 1.39 (a), a schematic view in Figure 1.39 (b).

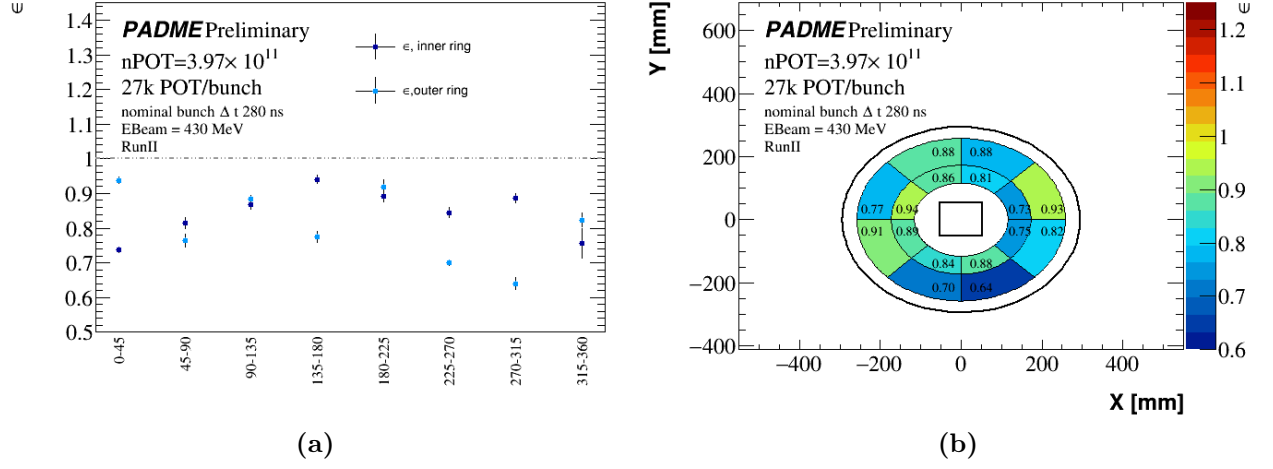


Figure 1.39: (a): Trend of the efficiency for bins in the inner ring in blue and outer once in light blue obtained requiring the multiplicity selection; (b) schematic view of the measured efficiency.

Table 1.18: Number of tag yield N_{Tag} and its error ΔN_{Tag} , number of probe N_{Probe} with the error ΔN_{Probe} and the efficiency ϵ measured from the ratio of the probe over the tag yield with the error $\Delta\epsilon$ obtained applying the propagation of the tag and probe errors. The yields are obtained with events that pass the multiplicity selection.

ϕ [Deg]	N_{Tag}	ΔN_{Tag}	N_{Probe}	ΔN_{Probe}	ϵ	$\Delta\epsilon$
Inner ring						
[0, 45]	62318	648	45968	214	0,738	0,008
[45, 90]	42433	816	34575	186	0,815	0,016
[90, 135]	37141	545	32266	180	0,869	0,014
[135, 180]	47867	580	45034	212	0,941	0,012
[180, 225]	53620	910	47780	219	0,891	0,016
[225, 270]	50830	813	42960	207	0,845	0,014
[270, 315]	46465	617	41207	203	0,887	0,013
[315, 360]	57955	337	43815	209	0,756	0,006
Outer ring						
[0, 45]	48803	481	45787	214	0,938	0,01
[45, 90]	56531	1400	43167	208	0,764	0,019
[90, 135]	46797	457	41402	203	0,885	0,01
[135, 180]	57192	1084	44342	211	0,775	0,015
[180, 225]	51248	1078	47112	217	0,919	0,02
[225, 270]	51337	530	35982	190	0,701	0,008
[270, 315]	53048	1416	33954	184	0,640	0,017
[315, 360]	55798	1253	45976	214	0,824	0,019

From the cross section definition reported in Equation 1.1, multiplying it for a factor $g = 8$ to obtain the total cross section, the cross sections for each bins were extracted. For the measurement it is used:

- $N_{POT} = 3.97 \times 10^{11}$ extracted using the corrected target calibration **maybe it is needed a section where is described the changes in me nPOT measurement. NB: all the previous plots and estimations were done with the first approximation of nPOT.**;
- $Acc = 0.0634$ extracted using the NLO Babayaga sample for a positron energy of $E_{e^+} = 430$ MeV;
- ϵ : each yield is corrected using the efficiency of the bins where the photons falls, the values used are reported in Table 1.18.

The measurement was done using the two photons yield obtained fitting the distribution of $\Delta\phi$ for events that has two photons passing the annihilation pre-selection, time coincidence of 10 ns request and having the most energetic photon in the FR. As cross check of the cross section

Table 1.19: *Cross sections measured with the yields of one (Tag in the inner ring and Tag in the outer ring) and two photons as a function of them azimuthal angles. The cross sections are obtained with events that pass the multiplicity selection.*

ϕ [Deg]	$\sigma_{\Delta\phi}$ [mb]	σ_{TagIn} [mb]	σ_{TagOut} [mb]
[0, 45]	$2,127 \pm 0,051$	$2,104 \pm 0,05$	$1,732 \pm 0,035$
[45, 90]	$1,843 \pm 0,043$	$1,908 \pm 0,042$	$2,015 \pm 0,06$
[90, 135]	$1,76 \pm 0,055$	$1,849 \pm 0,058$	$1,59 \pm 0,028$
[135, 180]	$1,73 \pm 0,045$	$1,796 \pm 0,046$	$2,265 \pm 0,046$
[180, 225]	$1,707 \pm 0,036$	$1,659 \pm 0,034$	$2,054 \pm 0,05$
[225, 270]	$2,051 \pm 0,061$	$2,027 \pm 0,06$	$1,834 \pm 0,041$
[270, 315]	$1,65 \pm 0,033$	$1,598 \pm 0,028$	$1,758 \pm 0,053$
[315, 360]	$2,3 \pm 0,048$	$2,292 \pm 0,047$	$1,76 \pm 0,046$

measurement is also extracted using the yields of the single photon obtained form the ΔE_{Tag} distributions (photons are corrected with the efficiency of the belonging bin) for the inner ring and outer one. The cross sections obtained are reported in Table 1.19. A trend of them as a function of the phi slice is reported in Figure 1.40, where the measurement obtained with two photons and a single photon is reported: in violet is reported the measurement obtained with the two photons yield extracted with the $\Delta\phi$ distribution, in orange it is reported the measurement obtained with the tag yields for the inner ring and in azure the cross section obtained form the tag yields belonging the outer ring and sorting them as a function of the most energetic photon phi (the photon in [0, 45] Deg and outer ring has the most energetic photon in the inner ring of [180, 225] Deg, thus it is allocated to this latest bin. This is done to observe coherent cross sections).

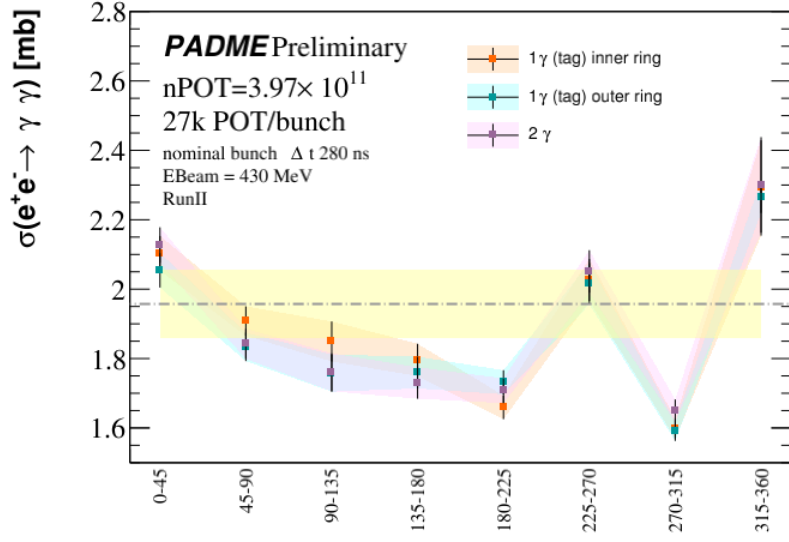


Figure 1.40: Trend of the cross section as a function of the phi slice (the annihilation photon belong to a phi bin if the respective most energetic photon belong to that bin). The yellow strip represent the uncertainty of 5% on the multiplicity measurement. The orange dots are the cross section measurement done with a single photon obtained from tag yields in the inner ring, the azure one is the cross section trend obtained from the single photon from tags in the outer rings, the violet are the cross sections obtained with the two photons (selection: annihilation pre-selection, most energetic photon in FR and time coincidence of 10 ns).

1.10 Results

1.10.1 Phi dependence

Another cross section measurement was done for events that pass the multiplicity selection and photons that pass the cluster quality cuts. A preliminary step is to measure the selection efficiency, thus for each of 16 bins was measured the efficiency as:

$$\epsilon = \left[\frac{N_{Probe}^{3\sigma}}{N_{Tag}^{RF}} \right]_{N_{POT} \text{selection and cluster quality}} \quad (1.30)$$

where the $N_{Probe}^{3\sigma}$ correspond to the matched probe yield obtained integrating ΔE_{Probe} in 3σ from the mean value and N_{Tag}^{RF} is the tag yield obtained fitting the ΔE_{tag} with RooFit.

The yields and the corresponding efficiencies is reported in Table 1.20 for each phi slice, both inner and outer ring. In Figure 1.41 (a) is shown the trend efficiency as a function of the azimuthal angle for the inner and outer ring of ECAL, in figure 1.41 (b) a schematic view of them. As is visible the efficiency is lower than the one obtained with only the multiplicity selection, but it appear as more stable. For this selection the cross section for the single photon was extracted also fitting the missing mass squared, in fact the M_{miss}^2 variable (it will be used

Table 1.20: Number of tag yield N_{Tag} and its error ΔN_{Tag} , number of probe N_{Probe} with the error ΔN_{Probe} and the efficiency ϵ measured from the ratio of the probe over the tag yield with the error $\Delta\epsilon$ obtained applying the propagation of the tag and probe errors. The yields are obtained with events that pass the multiplicity selection and photons that pass the cluster quality cuts.

ϕ [Deg]	N_{Tag}	ΔN_{Tag}	N_{Probe}	ΔN_{Probe}	ϵ	$\Delta\epsilon$
Inner ring						
[0, 45]	51972	1076	37459	194	0,721	0,015
[45, 90]	38315	575	28423	169	0,742	0,012
[90, 135]	32427	372	26629	163	0,821	0,011
[135, 180]	50356	1659	36394	191	0,723	0,024
[180, 225]	56982	1273	38890	197	0,682	0,016
[225, 270]	45297	470	35562	189	0,785	0,009
[270, 315]	46322	803	33608	183	0,726	0,013
[315, 360]	51591	819	35279	189	0,684	0,011
Outer ring						
[0, 45]	44848	868	37872	195	0,844	0,017
[45, 90]	47468	732	35524	188	0,748	0,012
[90, 135]	45301	778	33984	184	0,75	0,014
[135, 180]	45687	837	35608	189	0,779	0,015
[180, 225]	46946	759	38162	195	0,813	0,014
[225, 270]	46732	520	29428	172	0,63	0,008
[270, 315]	53746	1421	27660	166	0,515	0,014
[315, 360]	45774	439	36687	192	0,801	0,009

to verify the existence of the dark photon) return, in case of annihilation photon, a value equal to 0 MeV. In Figure 1.42 the missing mass squared for photons with $R \in [115.8, 172.82[$ mm and $\phi \in [45, 90[$ Deg is shown. Superimposed to the data reported with the back dots, there is the total fit in red, composed by the background contribution in cyan (pileup effect in green summed with the beam related background in blue) and the signal contribution in orange (two yellows gaussian contributions). As for the tag, the single photon yield is given by the sum of the two gaussian functions. The two photons annihilation yield and consequentially cross section with ΔE_{tag} and M_{miss}^2 for inner and outer ring is measured to check the yields consistency along with the efficiency measured. In fact the four distribution, although they are composed by the same events in same phi and radius bin, they have a different representation of the background. In Figure 1.43 there is the comparison between the (a) ΔE_{tag} and (b) M_{miss}^2 distributions between the inner ring in blue and outer one in pink for photons with $R \in]115.8, 172.82[$ mm and $\phi \in [180, 225[$ Deg. As is shown the two distributions of both the variables have different modelling of background and also of the signal. As described in previous section, the yields of two photons and from single photon were corrected with the efficiency $\epsilon(R, \phi)$ and the cross section was extracted as a function of the azimuthal angle dividing them for the other constants.

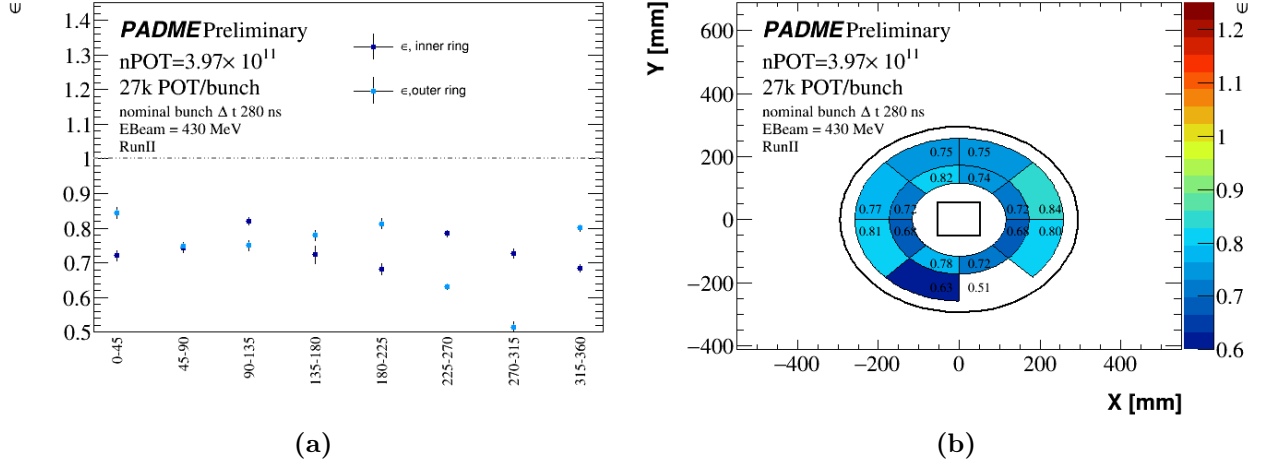


Figure 1.41: (a): Trend of the efficiency for bins in the inner ring in blue and outer once in light blue obtained requiring the multiplicity selection and cluster quality cuts; (b) schematic view of the measured efficiency.

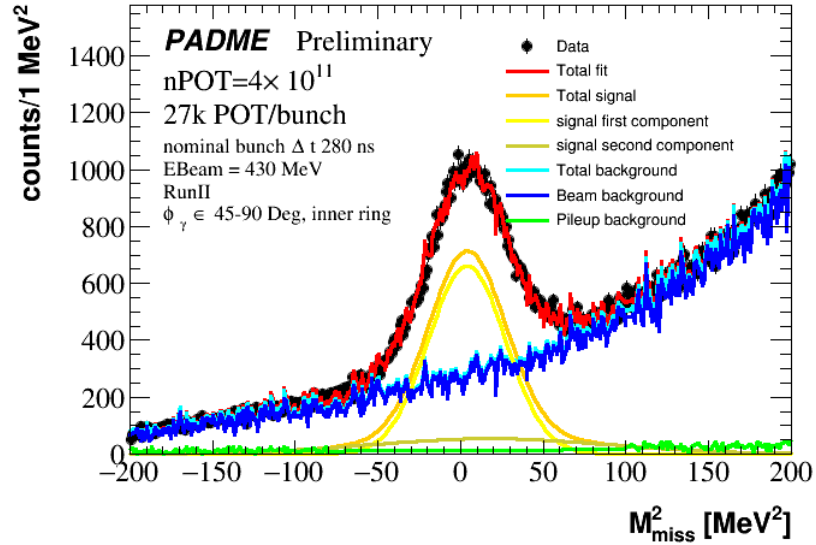


Figure 1.42: Fit of the missing mass squared distribution for photon belonging $R \in [115.8, 172.82[$ mm and $\phi \in [45, 90[$ Deg. The data (black dots) is fitted with a total function (red line) given by the sum of a total signal component in orange (composed by two gaussian function in yellow) and a total background component in cyan (given by the sum of pileup effect in green and the beam related background in blue).

1061 The measurements are reported in Table 1.21 for all the annihilation: two photons yield from
 1062 the $\Delta\phi$ distribution and the single photon yield from tag and missing mass squared in both
 1063 inner and outer ring. All the measurements were plotted as a function of the azimuthal bin in
 1064 Figure 1.44, where the two photon cross section measurement is reported in violet (selection:

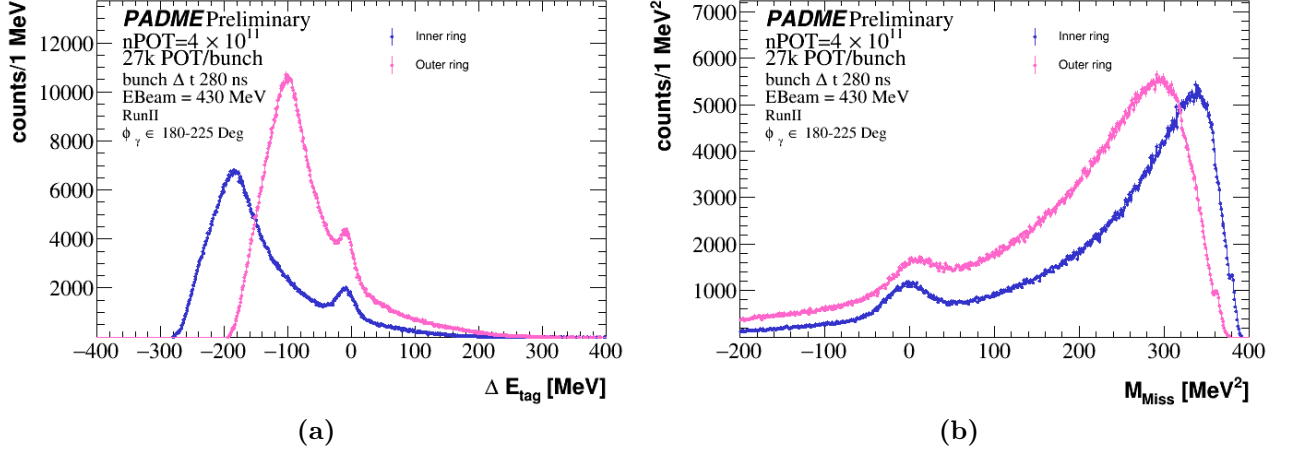


Figure 1.43: Comparison between the (a) ΔE_{tag} and (b) M_{miss}^2 in inner (blue dots) and outer (pink dots) ring belonging. The variables are extracted from photons with $R \in [115.8, 172.82[$ mm and $\phi \in [180, 225[$ Deg.

Table 1.21: Cross sections measured with the yields of one (Tag and missing mass squared in the inner ring and Tag and missing mass squared in the outer ring) and two photons as a function of them azimuthal angles. The cross sections are obtained with events that pass the multiplicity selection and photons that pass the cluster quality cuts.

ϕ [Deg]	$\sigma_{\Delta\phi}$ [mb]	$\sigma_{\Delta E_{In}}$ [mb]	$\sigma_{\Delta E_{Out}}$ [mb]	$\sigma_{MM_{In}^2}$ [mb]	$\sigma_{MM_{Out}^2}$ [mb]
[0, 45]	$2,005 \pm 0,056$	$1,972 \pm 0,052$	$2,045 \pm 0,062$	$1,971 \pm 0,056$	$2,067 \pm 0,048$
[45, 90]	$1,856 \pm 0,041$	$1,908 \pm 0,037$	$1,834 \pm 0,035$	$1,989 \pm 0,035$	$1,865 \pm 0,037$
[90, 135]	$1,899 \pm 0,06$	$1,983 \pm 0,059$	$1,871 \pm 0,048$	$1,846 \pm 0,042$	$1,889 \pm 0,039$
[135, 180]	$1,959 \pm 0,068$	$1,918 \pm 0,066$	$2,006 \pm 0,05$	$2,025 \pm 0,069$	$2,056 \pm 0,043$
[180, 225]	$2,039 \pm 0,065$	$1,992 \pm 0,061$	$1,936 \pm 0,052$	$2,103 \pm 0,052$	$1,862 \pm 0,045$
[225, 270]	$1,873 \pm 0,04$	$1,832 \pm 0,035$	$1,842 \pm 0,036$	$1,814 \pm 0,053$	$1,892 \pm 0,031$
[270, 315]	$1,964 \pm 0,052$	$1,89 \pm 0,047$	$1,907 \pm 0,056$	$1,836 \pm 0,038$	$1,927 \pm 0,055$
[315, 360]	$2,05 \pm 0,051$	$2,023 \pm 0,049$	$1,904 \pm 0,066$	$2,056 \pm 0,084$	$1,741 \pm 0,033$

most energetic photon in FR and time coincidence of 10 ns), the single photon in: orange for tag in the inner ring, azure for tag in the outer ring, missing mass yield in pink for inner ring and green for outer ring.

1.10.2 Run dependence

To study the stability of the result as a function of the pileup, beam background and beam structure, the cross section was extracted as a function of the run: for each run it was extracted a global efficiency for the inner ring and a global efficiency for the outer one. In Table 1.22

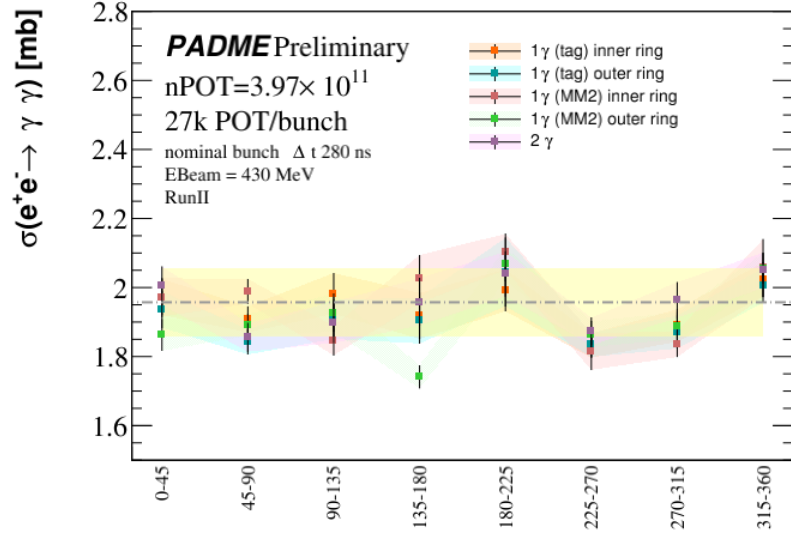


Figure 1.44: Trend of the cross section as a function of the phi slice (the annihilation photon belong to a phi bin if the respective most energetic photon belong to that bin). The yellow strip represent the uncertainty of 5% on the multiplicity measurement. The orange dots are the cross section measurement done with a single photon obtained from tag yields in the inner ring, the azure one is the cross section trend obtained from the single photon form tags in the outer rings, the pink dots correspond to the cross section obtained from the missing mass squared of photons in the inner ring, the green are from photons measured from missing mass squared spectrum for clusters in outer ring and the violet are the cross sections obtained with the two photons (selection: most energetic photon in FR and time coincidence of 10 ns).

are reported the tag and probe yields and the efficiency $\epsilon(R)$ for each run used. An efficiency trend is also reported in Figure 1.45 for a global inner ring efficiency in blue and a global outer ring efficiency in light blue. The latest point of the trend correspond to the whole statistic, where it is extracted a global efficiency as a function of the photon radius. Having the efficiency for each run, the cross section can be obtained correcting for the beam condition. As before, the yield measured were the one of the two photon annihilation and the other one related to the single photon annihilation. For this latest measurement the tag yields were used. This time the cross sections were extracted using for each run its number of POT and in the total cross section it is not included the factor $g = 8$ that it is used for the cross section as a function of phi. The resulted measurement were summarised in Table 1.23 and represented in Figure 1.46.

1.10.3 Systematics

The central value of the annihilation in two photons cross section is defined to be the one measured using the two photons selection, since the $\delta\phi$ has a flat background, thus less subjected to background modelling errors, all phi slices together, fitting all the statistic and using the average efficiency. The measurement is $\sigma(e^+e^- \rightarrow \gamma\gamma) = 1,973 \pm 0,030$ mb, where the error is

Table 1.22: Number of tag yield N_{Tag} and its error ΔN_{Tag} , number of probe N_{Probe} with the error ΔN_{Probe} and the efficiency ϵ measured from the ratio of the probe over the tag yield with the error $\Delta\epsilon$ obtained applying the propagation of the tag and probe errors. as a function of the run. The yields are obtained with events that pass the multiplicity selection and photons that pass the cluster quality cuts.

Run number	N_{Tag}	ΔN_{Tag}	N_{Probe}	ΔN_{Probe}	ϵ	$\Delta\epsilon$
Inner ring						
30369	71134	1678	52342	229	0,736	0,018
30386	26007	437	20540	143	0,790	0,014
30547	66487	928	49152	222	0,739	0,011
30553	25134	1966	18106	135	0,720	0,057
30563	55459	3493	40371	201	0,728	0,046
30617	56665	4407	41912	205	0,740	0,058
30624	61268	3005	44042	210	0,719	0,035
All runs	36000	4252	267373	517	0,743	0,009
Outer ring						
30369	74918	1106	52684	230	0,703	0,011
30386	27854	1038	20631	144	0,741	0,028
30547	67095	1839	49476	222	0,737	0,02
30553	26343	877	18171	135	0,690	0,024
30563	56505	1356	40587	201	0,718	0,018
30617	57951	1830	41805	204	0,721	0,023
30624	63696	1425	44355	211	0,696	0,016
All runs	37562	2951	268098	518	0,714	0,006

Table 1.23: Cross sections measured with the yields of one (Tag in the inner ring and Tag in the outer ring) and two photons as a function of run number. The cross sections are obtained with events that pass the multiplicity selection and cluster quality cuts.

Run number	$\sigma_{\Delta\phi}$ [mb]	$\sigma_{\Delta E_{In}}$ [mb]	$\sigma_{\Delta E_{Out}}$ [mb]
30369	$1,941 \pm 0,057$	$1,872 \pm 0,053$	$1,861 \pm 0,053$
30386	$1,98 \pm 0,082$	$1,904 \pm 0,079$	$1,896 \pm 0,078$
30547	$1,988 \pm 0,063$	$1,911 \pm 0,06$	$1,899 \pm 0,058$
30553	$2,051 \pm 0,178$	$1,959 \pm 0,168$	$1,95 \pm 0,167$
30563	$2,012 \pm 0,139$	$1,936 \pm 0,131$	$1,926 \pm 0,131$
30617	$1,989 \pm 0,168$	$1,92 \pm 0,162$	$1,927 \pm 0,162$
30624	$2,07 \pm 0,112$	$2,006 \pm 0,107$	$1,993 \pm 0,108$
All runs	$1,973 \pm 0,03$	$1,914 \pm 0,028$	$1,909 \pm 0,028$

1087 due to the statistical error on yield and to statistical error on efficiency.

1088 The systematic error due to the efficiency determination on detector defects and uneven

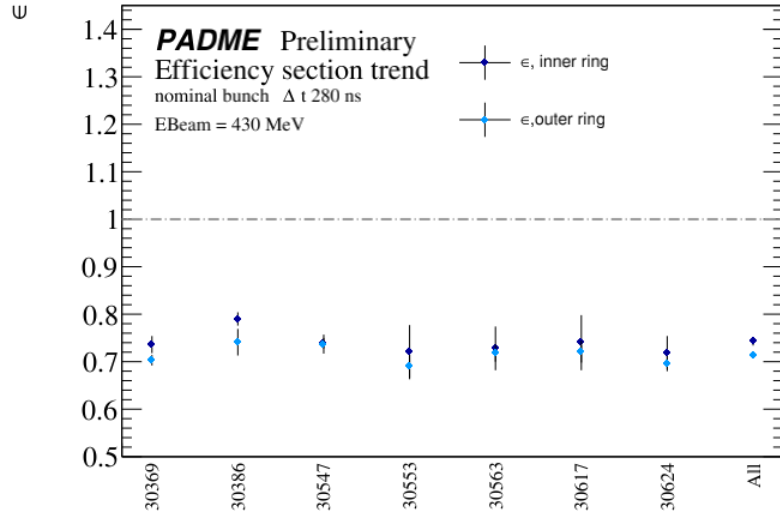


Figure 1.45: Trend of the efficiency for inner ring in blue and outer one in light blue obtained requiring the multiplicity selection and cluster quality cuts extracted for each run. The last point represent the global efficiency of the whole data taking

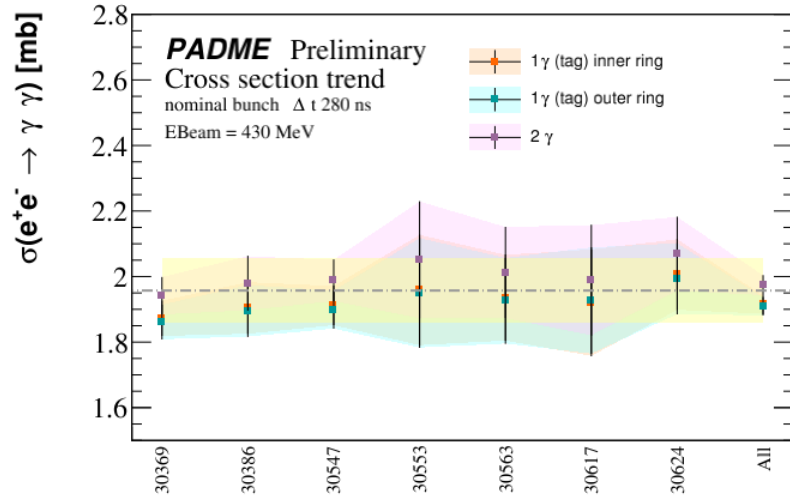


Figure 1.46: Trend of the cross section as a function of the run. The yellow strip represent the uncertainty of 5% on the multiplicity measurement. The orange dots are the cross section measurement done with a single photon obtained from tag yields in the inner ring, the azure one is the cross section trend obtained from the single photon form tags in the outer rings, the violet are the cross sections obtained with the two photons (selection: most energetic photon in FR and time coincidence of 10 ns).

1089 background distribution in ECAL is extracted from the stability of the two photons cross
 1090 section in phi slices, and extracted measuring the RMS of all the measurements weighted with

the errors, thus once estimated the weighted cross section mean as $\sigma_\mu = \frac{\sum \sigma_i / \Delta \sigma_i^2}{1 / \Delta \sigma_i^2}$, the RMS is extracted as:

$$\sqrt{\frac{\sum ((\sigma_i - \sigma_\mu) / \Delta \sigma_i)^2}{\sum 1 / (\Delta \sigma_i)^2}} \quad (1.31)$$

where $\Delta \sigma$ is the error on the cross section. The resulting systematic error is 0.073 mb.

The systematic error due to the background conditions is measured from the stability of the cross section as a function of the run. Also for this systematic the average cross section was extracted as $\sigma_\mu = \frac{\sum \sigma_i / \Delta \sigma_i^2}{1 / \Delta \sigma_i^2}$ and then measured the weighted RMS as:

$$\sqrt{\frac{\sum ((\sigma_i - \sigma_\mu) / \Delta \sigma_i)^2}{\sum 1 / (\Delta \sigma_i)^2}} \quad (1.32)$$

obtaining a systematic error of 0.0382 mb.

Another systematic error can be introduced in order to take into account the calorimeter granularity and of the definition of the minimum and maximum radii of the fiducial region: this can be extracted using the cross section extracted with single photon yield in the inner and outer ring of ECAL : $1.914 - 1.909 = 0,005$ mb.

The systematic errors due to the acceptance can come from the theoretical error, that since the measurement was done at NLO was negligible, and from the dependency on the knowledge of the distance between ECAL and target, that as discussed in Section [put ref](#) is negligible. Another systematic can be due to the energy scale, but introducing a variation of the energy scale of $\pm 0,3\%$ the acceptance change of $< 0,1\%$, thus also this can be negligible.

The total systematic error due to the sum of the defect and background correction (phi stability), background and pileup condition (run stability) and ECAL granularity and FR assumption (comparison ΔE_{In} and ΔE_{Out}) is $0.073 + 0.038 + 0.005 = 0,082$ mb.

An additional systematic error is due to the N_{POT} measurement, and it is quoted to be of the 5%.

The final measurement is:

$$\sigma(e^+e^- \rightarrow \gamma\gamma) = 1,973 \pm 0,030 \text{ (stat)} \pm 0,082 \text{ (syst)} \pm 0,098 \text{ (lumi)} \text{ mb} \quad (1.33)$$

that is compatible with the measurement of Babayaga at NLO $\sigma = 1.9573 \pm 0.0051$ mb (for reference Babayaga estimation at LO is $\sigma = 1.9110 \pm 0.0004$ mb).

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