Searching for a new light boson with PADME

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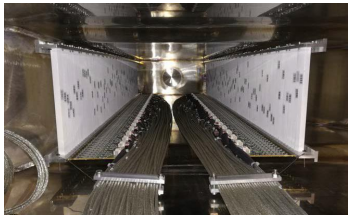
LA THUILE 2026 - Les Rencontres de Physique de la Vallée d'Aoste
Mar 01 – 07, 2026
La Thuile, Italy

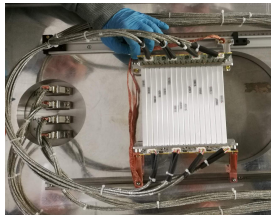
** partially supported by BNSF KP-06-COST/25 from 16.12.2024, COST Action COSMIC WISPers CA21106*

The PADME Experiment

Charged particle veto system

96 + 96 (90) + 16 (x2) plastic scintillator-WLS-SiPM RO channels
Segmentation provides momentum measurement down to ~5 MeV resolution



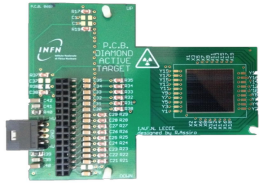


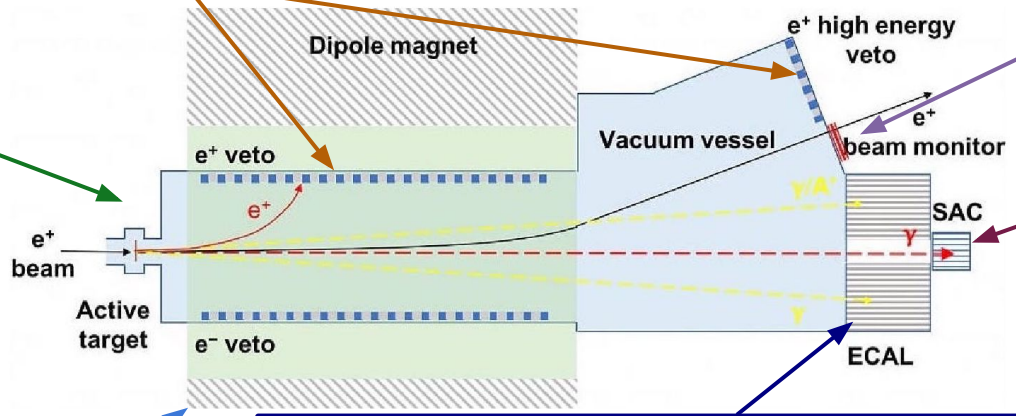
TimePix3 beam monitor at beam exit window

Matrix of 2 x 6 detectors for a total of 1536 x 512 pixels

Active diamond target

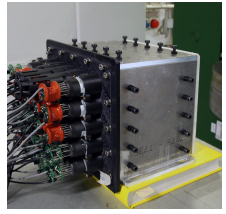
2 × 16 graphite electrodes: XY beam profile and multiplicity



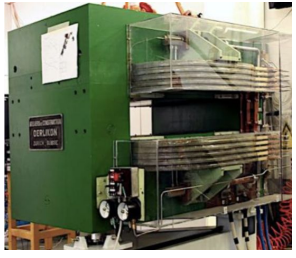


Small-angle calorimeter (SAC)

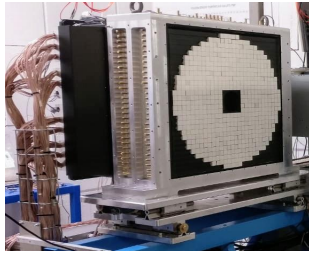
25 crystals - 5 x 5 matrix, Cherenkov PbF_2



Dipole magnet



Electromagnetic calorimeter (ECal)

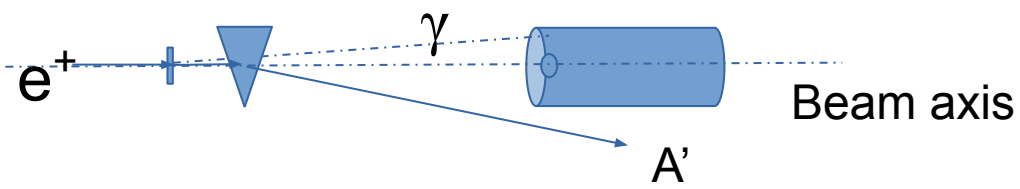


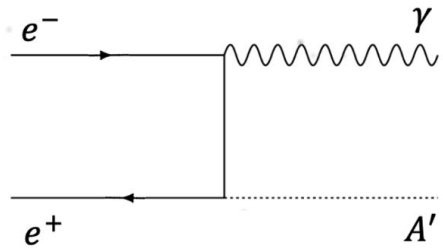
616 BGO crystals, 2.1 × 2.1 × 23 cm^3
BGO covered with diffuse reflective TiO_2 paint; additional optical isolation: 50 – 100 μm black tedlar foils
Scintillation light decay time – O(300 ns)

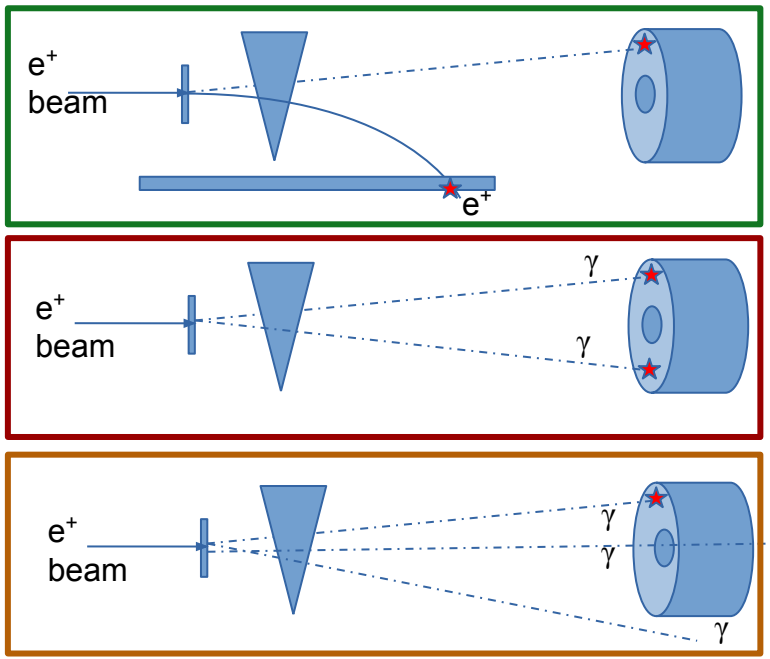
PADME Run II Dark Photon search

Associated production: $e^+ e^- \rightarrow A' \gamma$
Search for single photon events and calculate the missing mass

$$M_{miss}^2 = (p_{pos} + p_{elec} - p_\gamma)^2$$







Background composition:

- **Bremsstrahlung in the field of the target nuclei:** Photons mostly @ low energy, background dominates the high missing masses
- **2 photon annihilation**: Peaks at $M_{miss} = 0$
- **3 photon annihilation**: symmetry is lost – decrease in the vetoing capabilities
- **Radiative Bhabha scattering**

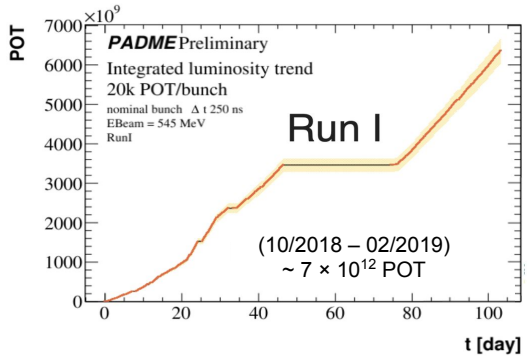
Run II data taking and results

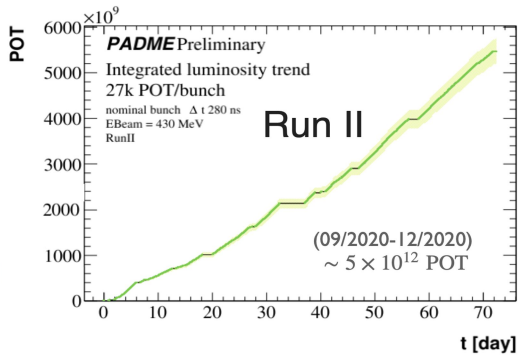
Run I and PADME commissioning

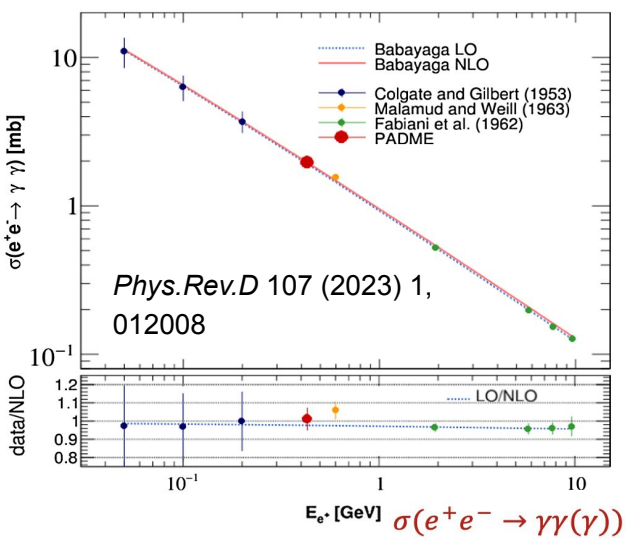
- Started in Autumn 2018 and ended on February 25th
  - ~7 x 10^{12} PoT recorded with secondary beam
  - PADME DAQ, Detector, beam, collaboration commissioning
  - Data quality and detector calibration
- PADME test beam data
  - July 2019, few days of valuable data: certification of the primary beam
  - Detector performance/calibration checks
  - Primary beam with E_{beam} = 490 MeV

Run II: primary beam

- July 2020
  - New environment/detector parameter monitoring and control system
  - Remote operation confirmation
- Autumn 2020:
  - A long data taking period with O(5x10^{12}) e^+ on target
  - E_{beam} = 430 MeV







$e^+e^- \rightarrow \gamma\gamma$ cross section

- Using 10% of Run II sample
- Tag-and-probe method on two back-to-back clusters
- Exploit energy-angle correlation

$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.930 \pm 0.029(\text{stat}) \pm 0.099(\text{syst})$ mb

Run II Dark Photon Analysis

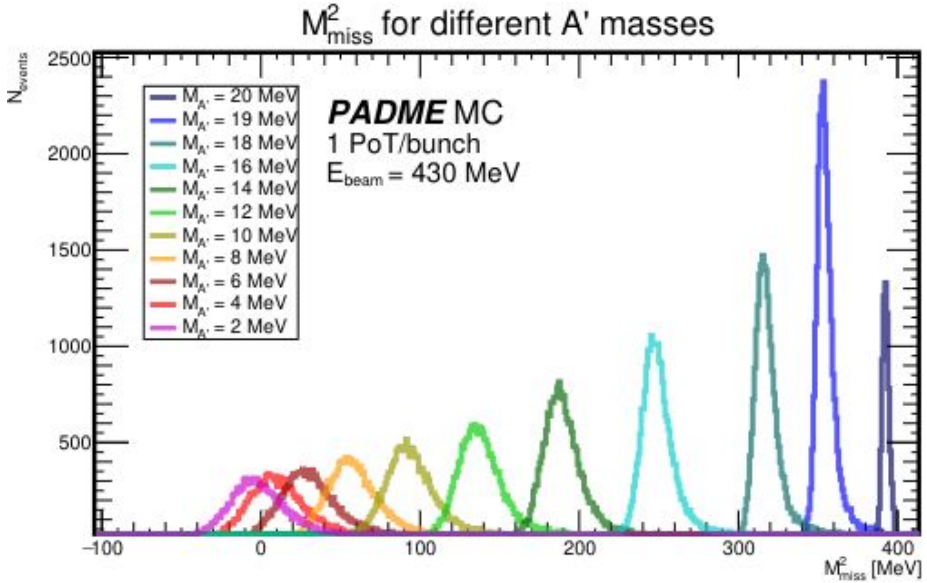
$$N_{A'} = N_{pots}\sigma(\epsilon)\frac{\rho d \mathcal{N}_A Z}{M}$$

5 x 10^{12} for Run II

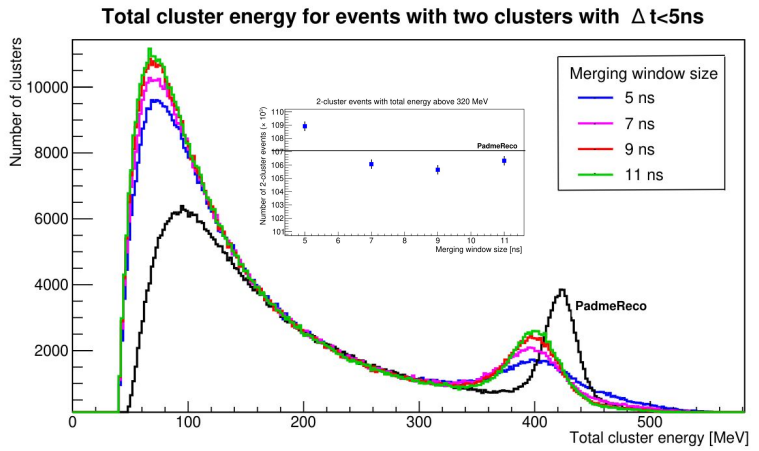
0.0106/barn (number of e^-/unit of area of the target)

Check obtained cross-section values using γγ result

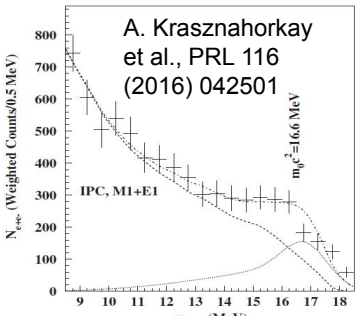
$$\frac{\sigma(e^+e^- \to U\gamma)}{\sigma(e^+e^- \to \gamma\gamma)} = \epsilon^2 * \delta$$



Machine learning models were tested for the reconstruction of e+e-→γγ events in Run II data and compared to the conventional reconstruction

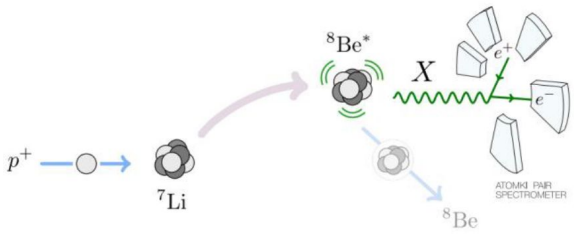


The X17 anomaly

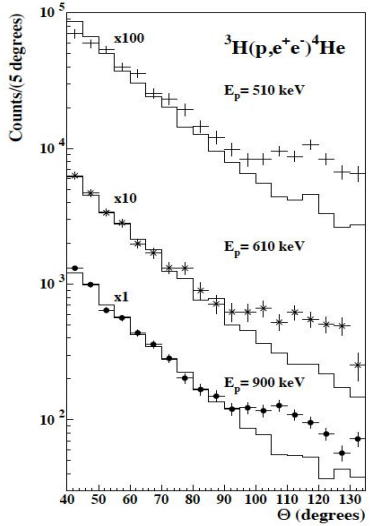


Excess in e^+e^- pairs angular correlation:

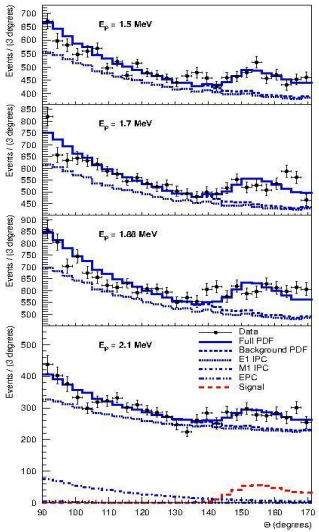
- Similar physics observables in ^{8}Be, ^{4}He and ^{12}C experiments: 2 leptons in the final state, produced via internal pair conversion
- Kinematics properties determined by the mass of a decaying X particle, compatible with $M_X \sim 17$ MeV



Phys.Rev.C 104, 044003 (2021)



Phys. Rev. C 106, L061601 (2022)



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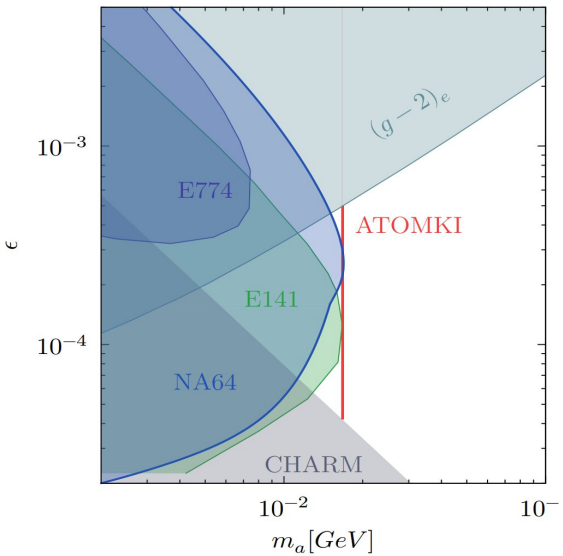
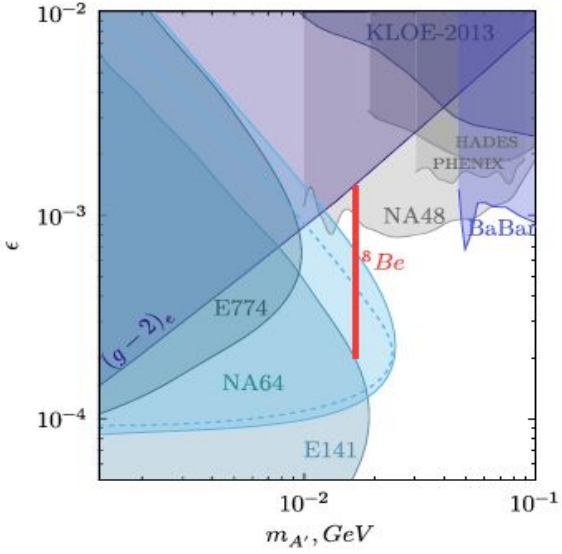
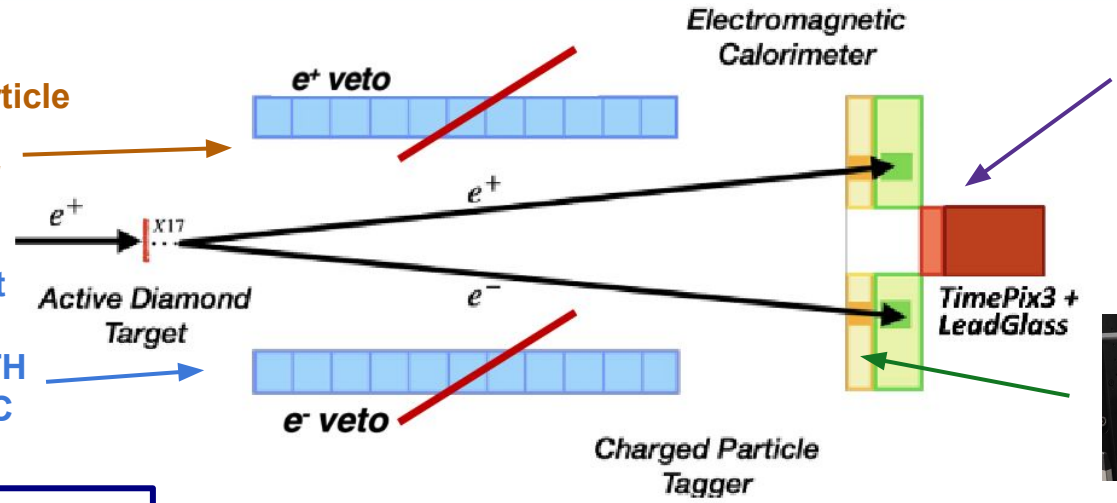


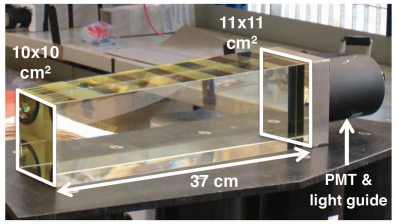
Phys. Rev. D 104, L111102 (2021)



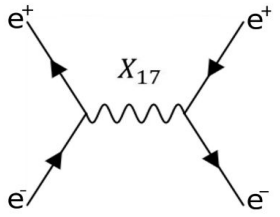
PADME X17 Search



SAC replaced with TimePix3 + Lead Glass beam monitoring system



Charged particle tagger (ETag) placed in front of the ECal (plastic scintillator array)

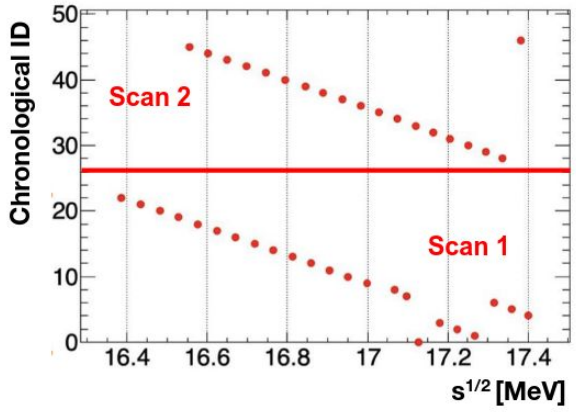


Search for resonant X17 production and subsequent decay: $e^+e^- \rightarrow X17 \rightarrow e^+e^-$

Goal: measure the e^+e^- final state and look for excess above the SM background

Data-taking divided in 3 parts:

- ➢ Nominal scan: 47 points (scan 1 and 2) @ (263-299) MeV, corresponding to $\sqrt{s}$= [16.4, 17.4] MeV
- ➢ Below resonance: 5 points @ (205-211) MeV
- ➢ Above resonance: 5 points @ 402.5 MeV



Run III analysis strategy

Main analysis observable: the ratio $g_R(s)$ between the number of observed events with a two-body final state and the expected number of background events

$$g_R(s) = \frac{N_2(s)}{N_{POT}(s) \cdot B(s)} = \begin{cases} K(s)[1 + \dfrac{S(s; M_X, g_{V_e}) \cdot \varepsilon_{sig}(s)}{B(s)}] \\ K(s) \end{cases}$$

Signal + background hypothesis

Background-only hypothesis

$N_2(S)$ - number of two-cluster events selected

$N_{PoT}(S)$ - number of positrons on target

$B(S)$ - expected background yield per POT

$S(s; M_X, g_{V_e})$ - expected signal production for mass M_X and coupling g_{Ve}

$\varepsilon_{sig}(s)$ - signal acceptance and selection efficiency

$K(s)$ - DATA-MC scale factor with a possible additional linear dependence on sqrt(s)

Goal: measure the two-body final state and evaluate systematic errors. Establish if the obtained rate is compatible with SM expectation or with the presence of an hypothetical X17 signal

N_2 selection

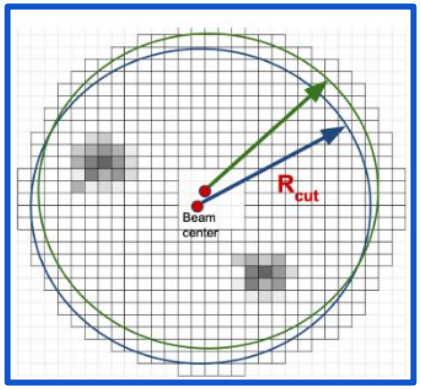
Selection of two-cluster events in the ECal - algorithm as independent as possible on beam and detector conditions:

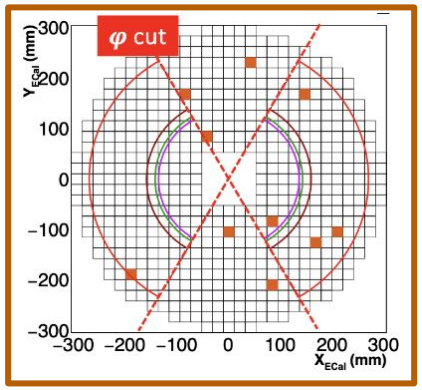
- Maximum radius defined by ECAL dimensions
- Minimum radius within the "two-cluster" kinematic range → following the beam center conditions
- Energy within the "two-cluster" kinematic range
- ECAL illumination affected by material along the beam line (below flange) → Cut regions in φ

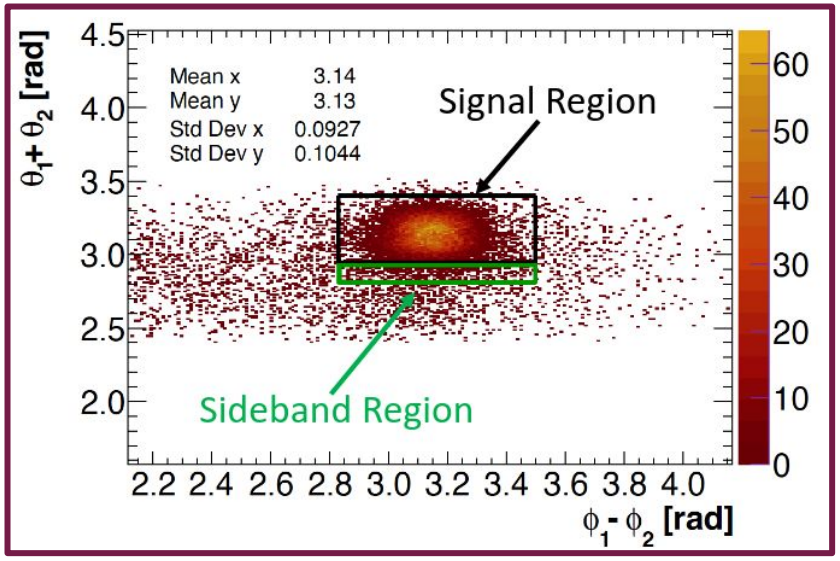
Two cluster selection cuts:

- Time difference $\Delta T < 5$ ns
- Distance $\Delta R > 60$ mm (minimum GG difference)
- $\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ cut in the center of mass frame isolates the signal

Source	Error on N_2 [%]
Statistics	~ 0.6
Background subtraction	0.3
Total	**0.65**







N_{PoT} estimation

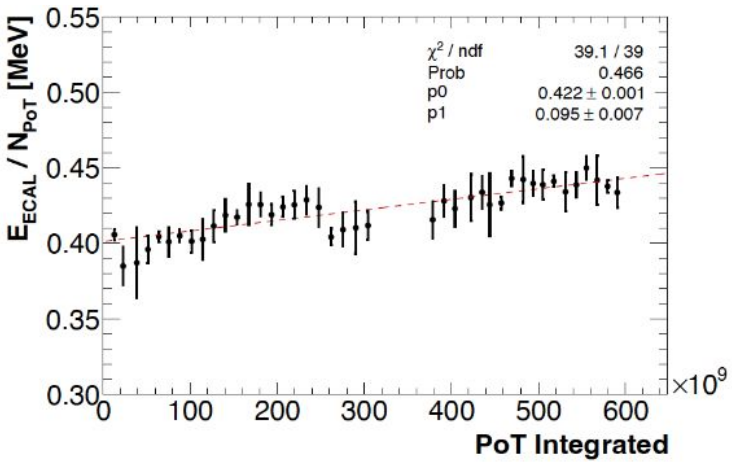
PoTs measured with the end-of-line lead glass calorimeter:

$$N_{PoT} = \frac{Q_{LG}}{Q_{1e^+,402[MeV]}} \times \frac{402}{E_{beam}[MeV]}$$

Uncorrelated systematic errors	
Source	Error on N_{PoT} [%]
Statistics, ped subtraction	negligible
Energy scale from BES	0.3
Rad. induced loss, slope	Variable, ~0.35
Total	**0.45**
Common systematic errors	
Source	Common error [%]
pC / MeV (JHEP 08 (2024) 121)	2.0
Energy Loss, data/MC	0.5
Rad. induced loss	0.3
Total	**2.1**

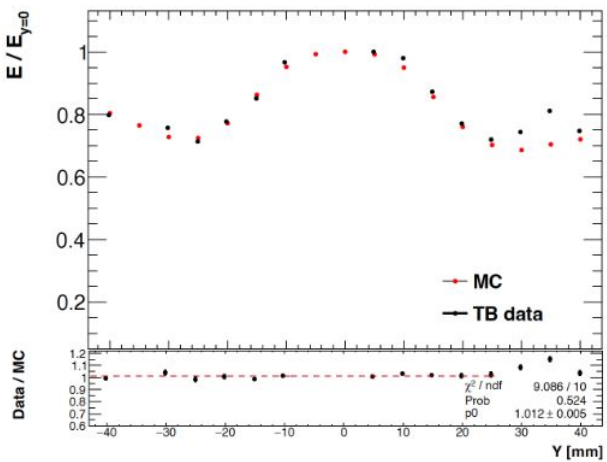
Radiation induced loss

- Run III dose ~ 2.5 krad → transparency changes for O(krad)
- Linear energy dependence on the integrated flux → LG yield decreases by 0.097 ± 0.007 → NPoT flux corrected
- Error associated both to the constant term and to the slope of the correction



Energy loss in passive material

- Beam movements → passive material crossing (TimePix cooling system)
- Test beam: evaluate the overall energy loss for the specific beam conditions → flux corrected for each energy point



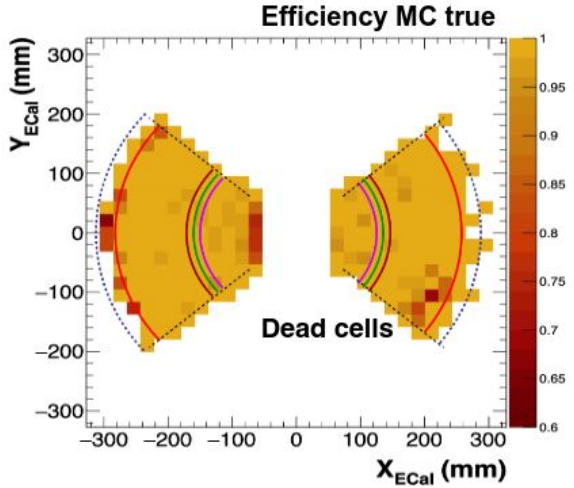
Expected background B(s)

The expected background / e+, B(s), is determined with MC and validated with data-driven checks.

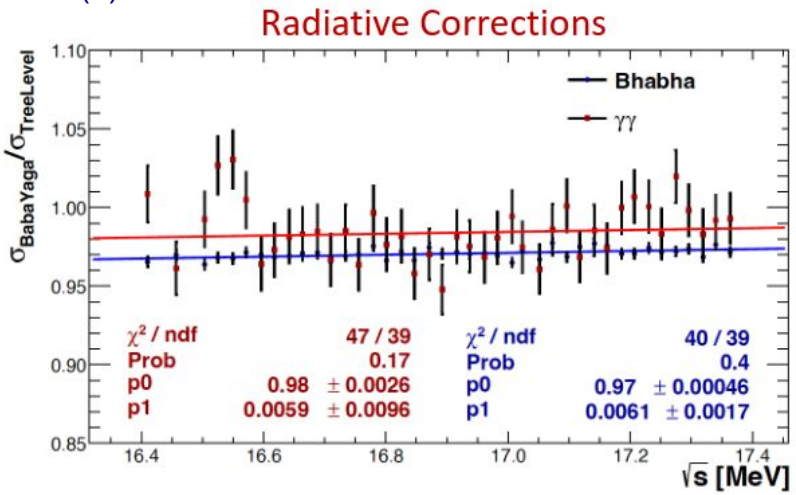
- Reconstruction efficiency estimated with Tag&Probe method
- Background subtraction at tag level dominates the statistical-systematic error → **δB = 0.35%**
- Beam spot direction & shape → acceptance variation of 0.08% - 0.1% / mm of vertical shift
- Stability of cuts due to acceptance edge effects and leakage → estimated by varying R_{max}

Source of uncertainty	Error on B [%]
MC statistics	0.40
Data/MC efficiency (Tag&Probe)	0.35
Cut stability	0.04
Beam spot variations	0.05
Total	**0.54**

Data/MC efficiency with tag-and-probe technique

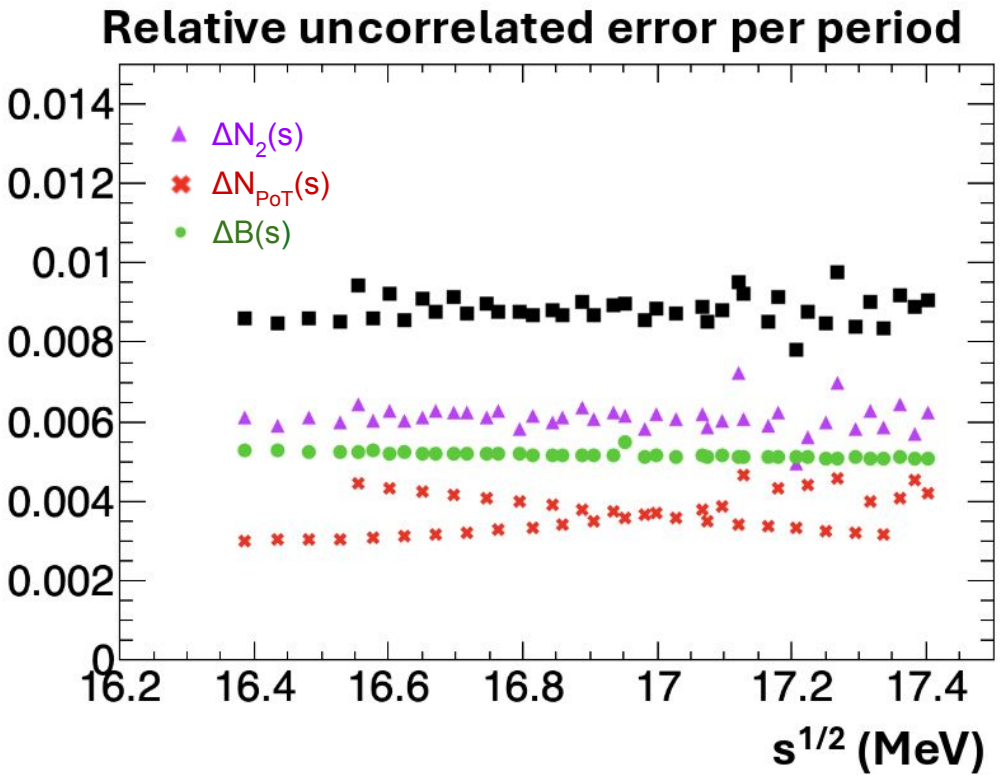


Radiative corrections e+e-(γ) and $\gamma\gamma(\gamma)$ evaluated using BabaYaga → 3% decrease in the total cross section @ 16.92 MeV and a √s slope of -0.6(6) % MeV^{-1}



Total error budget

Uncorrelated uncertainty on $g_R(s) = N_2(s) / (N_{PoT}(s) B(s))$:



Uncorrelated errors

Source	Uncertainty (% per energy point)
$N_2(s)$	0.60
$B(s)$	0.54
$N_{\mathrm{PoT}}(s)$	0.35
Total on $g_R(s)$	0.88

$K(s)$, constant term

Source	Uncertainty (%)
Lead-glass calibration	2.0
Absolute B yield	1.8
Energy-loss correction to N_{PoT}	0.5
Radiation-induced correction to N_{PoT}	0.3
Total	2.8

$K(s)$, $\sqrt{s}$-slope

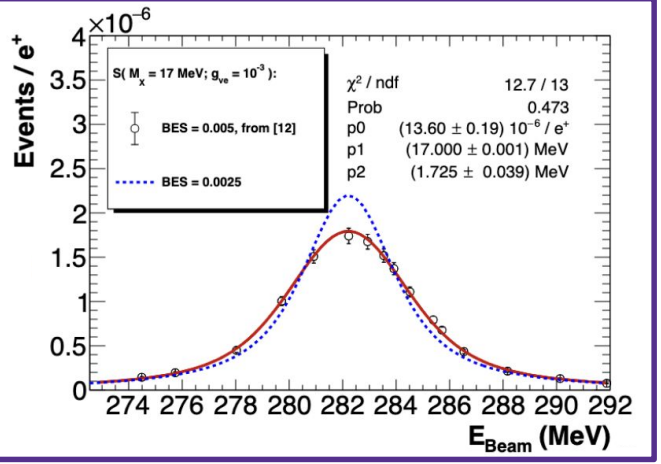
Source	Expected value (%/MeV)
Radiative corrections	$-0.6 \pm 0.2 \pm 0.6$
Total	-0.6 ± 0.6

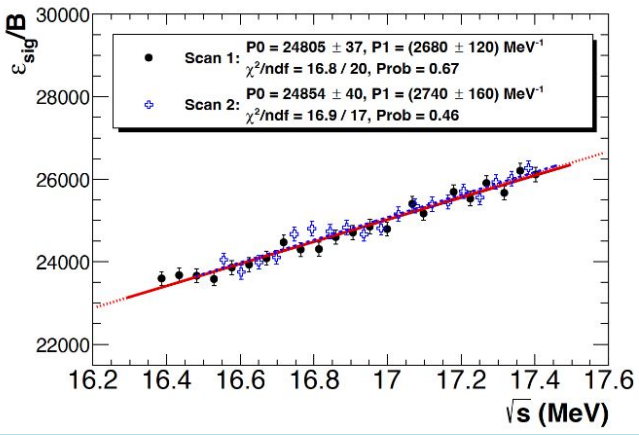
Next step: is $g_R(s)$ compatible with ***1*** or ***1 + (S(s) ε(s) / B(s))***?

Signal yield S(s; M,g_v) and efficiency ε_{Sig}/B

Signal yield: the width of the expected excess depends on the beam energy spread (BES) the electron motion in the target.
Functional form is a Voigt distribution parametrized as function of the beam energy: **convolution of the Gaussian for the BES with a Lorentzian →**
Uncertainty in the curve parameters as nuisances:

- Lorentzian width around the resonance energy: 1.72(4) MeV
- Relative BES: 0.025(5)%



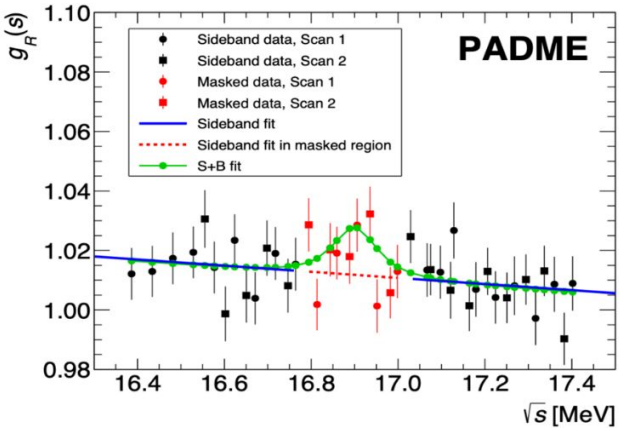


Expected signal efficiency determined from MC:

Use of the ratio ε_{sig}/B significantly reduces detector-related systematic uncertainties (similar detector illumination for both signal and background).
→ Fit ε_{sig}/B with a straight line → fit parameters as nuisances:

- Errors: ΔP0/P0 ~0.1%, ΔP1/P1 = 3%, correlation = -1.8

Run III results



Blind - unblinding procedure

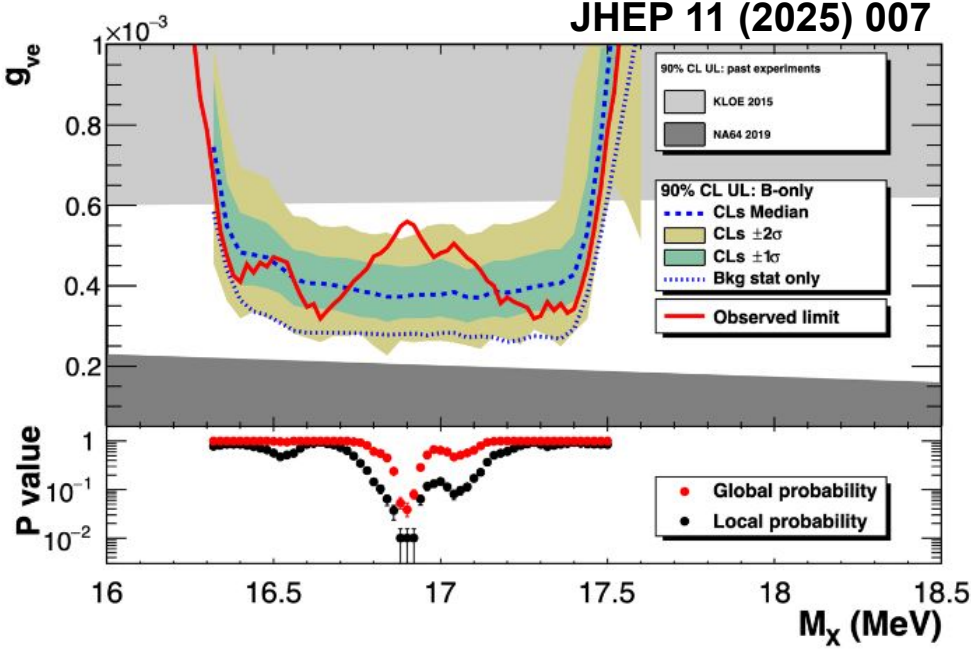
Large expected X17 mass resolution → no sideband region in √s can be defined to validate the statistical approach → Validation procedure described in *JHEP 06 (2025) 040* was used

- Aim to blindly define a sideband in $g_R(s)$, excluding 10 periods of the scan
- Define the masked periods by optimizing the probability of a linear fit in s
- Data validation criteria are based on the fit quality, the distribution of the fit pulls, and the parameters of the linear fit

Statistical treatment

Test statistic based on likelihood ratio between S+B and B-only and includes terms for each nuisance parameter

Upper limit on g_{ve} defined as $CL_S = \frac{P_S}{(1-P_B)}$ for a given M_X



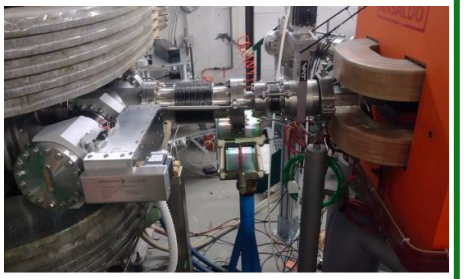
Results

- **The observed limit is consistent with the expected for most of the parameter space**
- **Slight excess observed, 2.5 σ local, 1.8(2) σ global significance corresponding to mass M_X = 16.9 MeV and a coupling $g_{ve} = 5 \times 10^{-4}$**

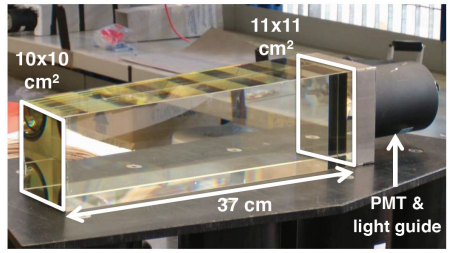
PADME Run IV improvements

PADME Run IV realized in 2025: optimized setup with increased sensibility to confirm/disprove Run III result

- Diamond target moved downstream by ~30 cm
- Passive material removed and PADME Magnet fully degaussed → B < 1 G
- Beam stable in the central position along the whole data taking → NO LATERAL LEAKAGE on the beam catcher
- Led pulser Tektronix AFG3101 to control the radiation induced loss
  - Independent trigger included in the DAQ
  - A second LG block installed (out of the acceptance and only acquiring the LED trigger)
  - Online LG response renormalized to the not-fired-block
  - Almost instant reference for light yield response



Diamond target moved downstream by ~30 cm



Led pulser to control the radiation induced loss

Source	Uncertainty [%]		Improvement
	Run III	Run IV	
N_2	0.6	0.3	New target position → acceptance increased
B	0.35	0.3	PadMMe → ee/γγ discrimination + better angular momentum resolution
N_{PoT}	0.55	0.3	Three different beam spot monitor (target-PadMMe-TMM) + online LG calibration system
Total	**0.88**	**0.5**	

PADME Run IV improvements

PadMMe MicroMegas chamber (replaced the Etagger):

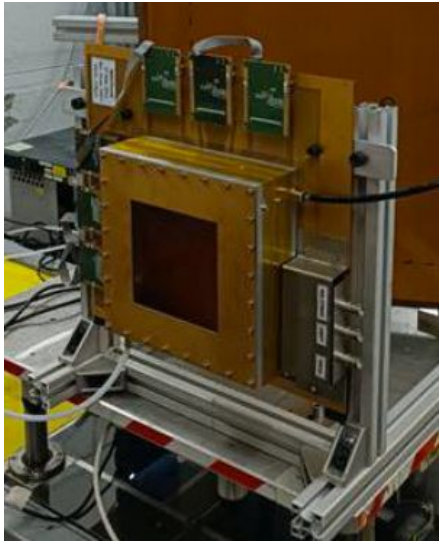
- e/γ discrimination → possible normalization to $e^+e^- \rightarrow \gamma\gamma$ process
- Spatial resolution ~ 350 μm → angle disentanglement
- Multitrack events can be collected
- Beam spot monitor → Implemented in the Run IV online monitor
- 3 HV regions for a better control on the amplification in the ”beam” region
- Gas Mixture Ar:CF4:Isobutane (88:10:2)

TMM MicroMegas (replaced the TimePix beam monitor)

- Greater active area wrt TimePix and less passive material budget
- Beam shape and spot monitor

PadMMe MicroMegas chamber

TMM MicroMegas

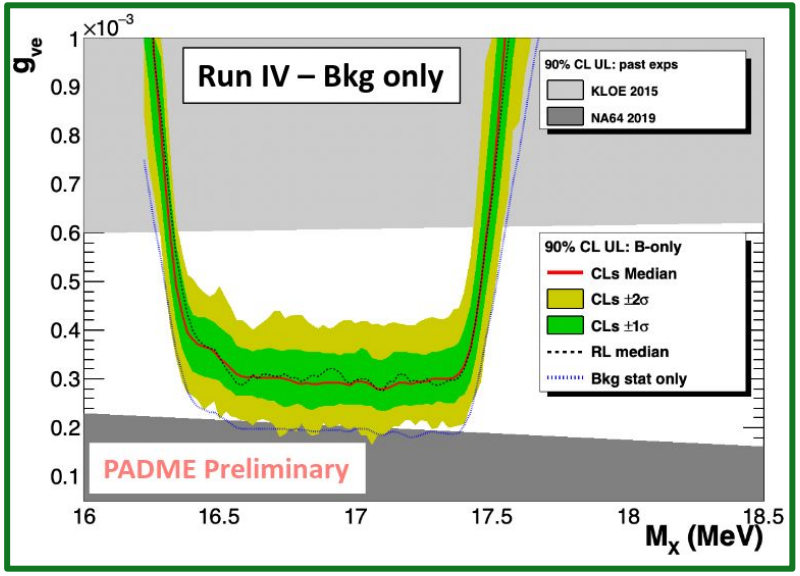


Conclusions

Run II
- About 5x10^{12} PoT with primary positron beam collected
- $e^+e^- \rightarrow \gamma\gamma$ cross section at E_{e+} = 430 MeV measured with ~5% uncertainty
- Analysis for Dark Photon search currently ongoing

Run III
- Analysis has been completed: no indications of X17 well beyond two-sigma, slight excess has been observed at M_X = 16.9 MeV, with global p-value equivalent to 1.77(15)σ

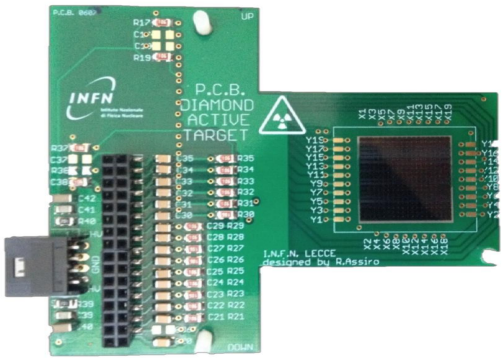
Run IV
- Improved setup: new Micromegas tracker installed to measure the absolute ee/$\gamma\gamma$ cross section + TMM to the end of the line for beam monitor
- Run IV-part 1 completed in July 2025
  - 18 energy scan points collected (~2×10^{10} PoTs each) equally separated by 1.5 MeV in the range of E_{beam}= (269.5, 295) MeV→ $\sqrt{s}$ = (16.60, 17.36) MeV
- Run IV-part 2 completed in November 2025
  - 18 scan points interspersing part 1 ones
  - Out-of-resonance: $\sqrt{s}$ below 16 MeV and above 18 MeV

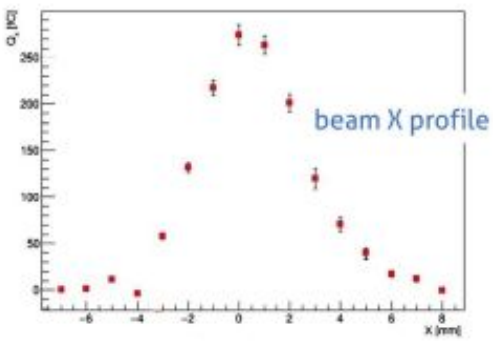


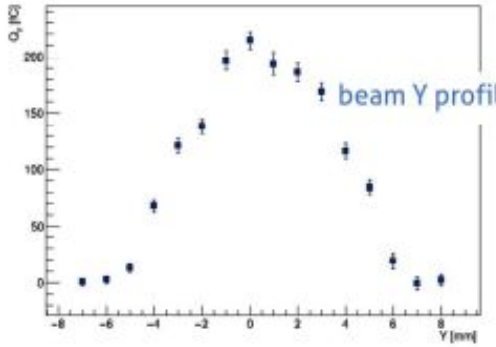
Backup slides

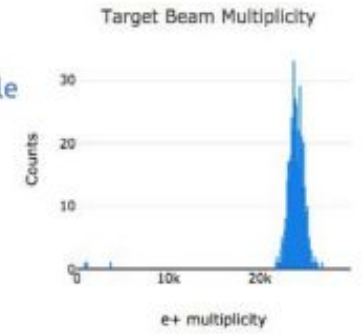
The PADME Experiment

Active target

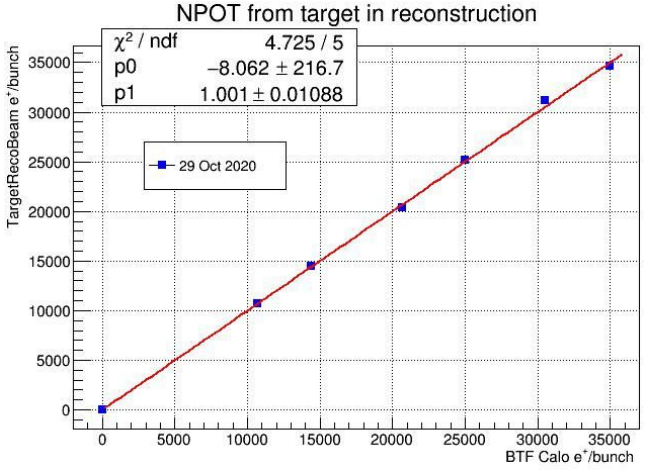


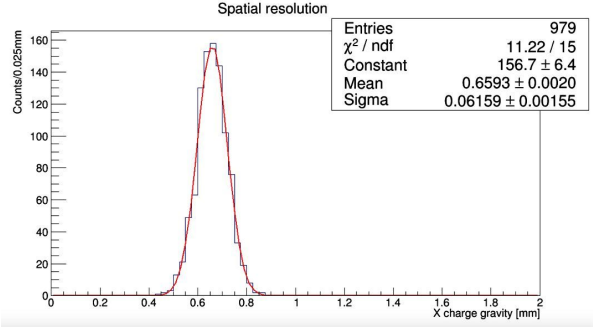






- Polycrystalline diamond:
  - 100 μm thickness:
  - 2 × 16 × 1 mm strips provide X-Y readout in a single detector: graphite electrodes using excimer laser
  - Beam XY profile and multiplicity





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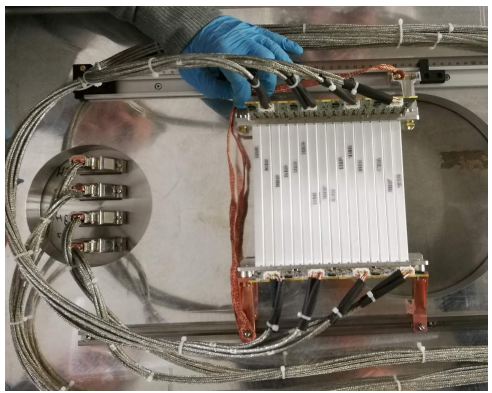
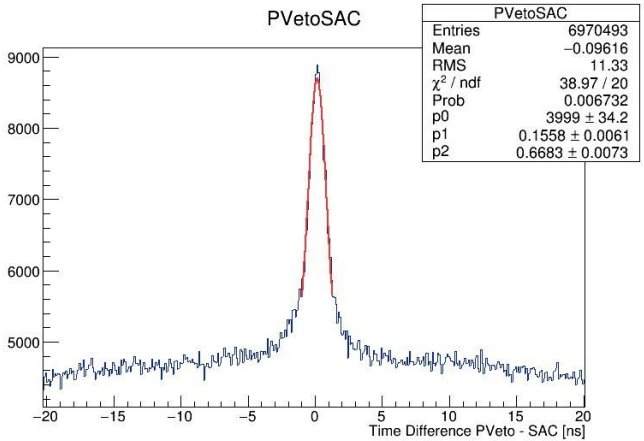
The PADME Experiment

Charged particle detectors



- Three sets of detectors detect the charged particles from the PADME target:
  - **PVeto**: positrons with 50 MeV < p_{e+} < 450 MeV
  - **HEPVeto**: positrons with 450 MeV < p_{e+} < 500 MeV
  - **EVeto**: electrons with 50 MeV < p_{e+} < 450 MeV
- 96 + 96 (90) + 16 (x2) plastic scintillator-WLS-SiPM RO channels
- Segmentation provides momentum measurement down to ~ 5 MeV resolution

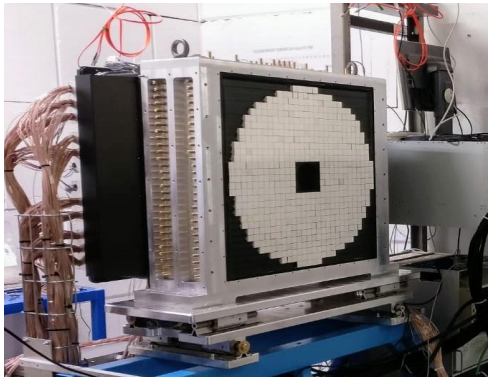
- Custom SiPM electronics, Hamamatsu S13360 3 mm, 25μm pixel SiPM
- Differential signals to the controllers, HV, thermal and current monitoring
- Online time resolution: ~ 2 ns
- Offline time resolution after fine T_0 calculation – better than 1 ns

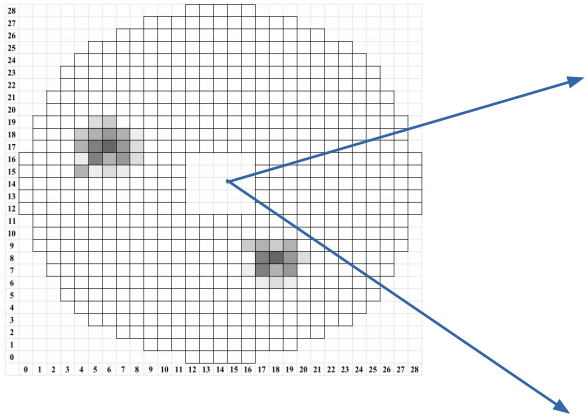


Time calibration with SAC using Bremsstrahlung events

The PADME Experiment

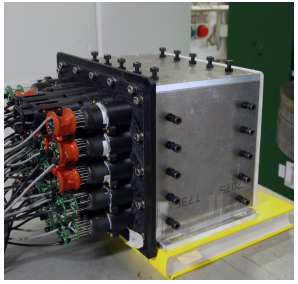
Electromagnetic calorimeter (ECal)





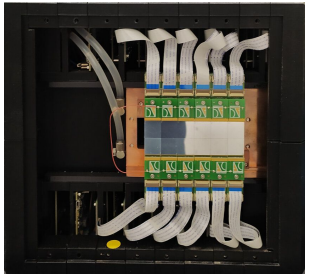
- 616 BGO crystals, 2.1 × 2.1 × 23 cm^3
- BGO covered with diffuse reflective TiO_2 paint
  - additional optical isolation: 50 – 100 μm black tedlar foils
- Scintillation light decay time – O(300 ns)

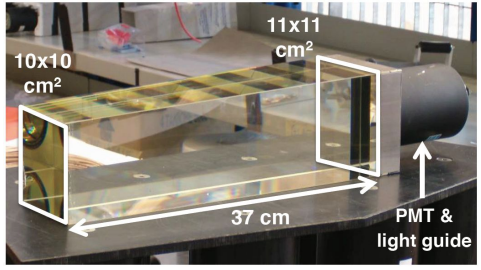
Run I and II: Small-angle calorimeter (SAC)



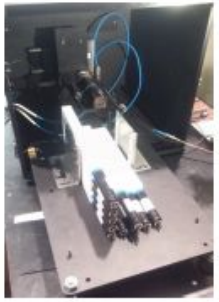
- 25 crystals - 5 x 5 matrix, Cherenkov PbF_2
- Time resolution: < 100 ps
- Angular acceptance: [0,19] mrad

Run III: Beam monitoring system: TimePix3 + Lead Glass Calorimeter



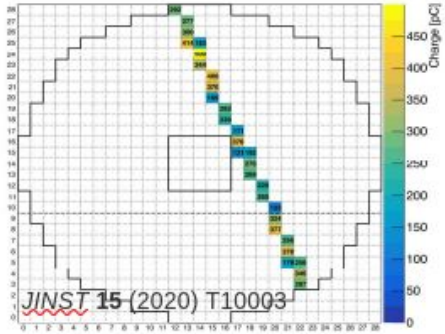


The PADME Experiment



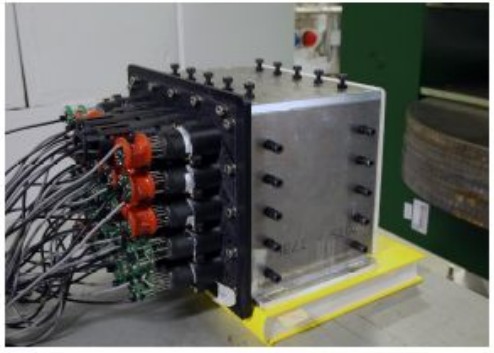
ECAL: The heart of PADME

- 616 BGO crystals, 2.1 x 2.1 x 23 cm^3
- BGO covered with diffuse reflective TiO_2 paint
- additional optical isolation: 50 – 100 μm black tedlar foils



Calibration at several stages:

- BGO + PMT equalization with ^{22}Na source before construction
- Cosmic rays calibration using the MPV of the spectrum
- Temperature monitoring



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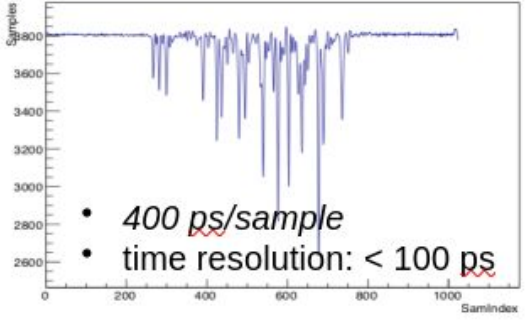
Small Angle Calorimeter (SAC)

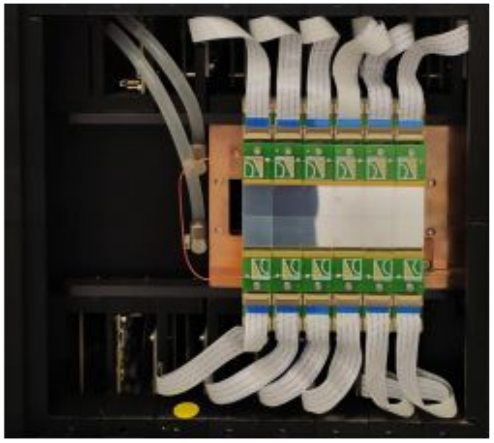
- 25 crystals - 5 x 5 matrix, Cherenkov PbF_2
- Dimensions of each crystal: 3 × 3 × 14 cm^3
- 50 cm behind ECal
- PMT readout: Hamamatsu R13478UV with custom dividers
- Angular acceptance: [0,19] mrad

Recorded bunch



- *400 ps/sample*
- time resolution: < 100 ps

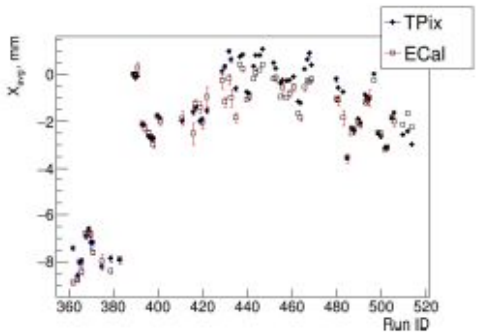
TimePix3 beam monitor

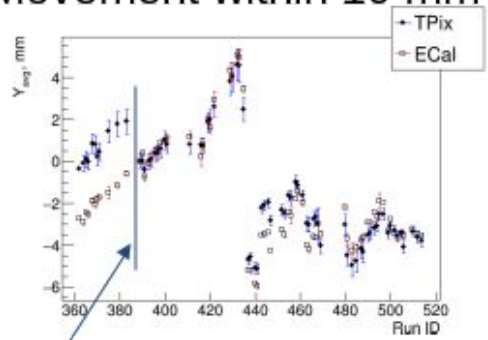


- Matrix of 2 x 6 Timepix3 detectors
  - each 256x256 pixels
- Operated in 2 modes:
  - image mode, integrating
  - streaming mode, feeding ToT and ToA for each fired pixel

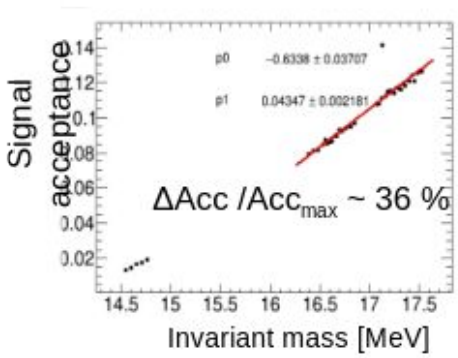
COG at the ECal front face from 2 cluster events

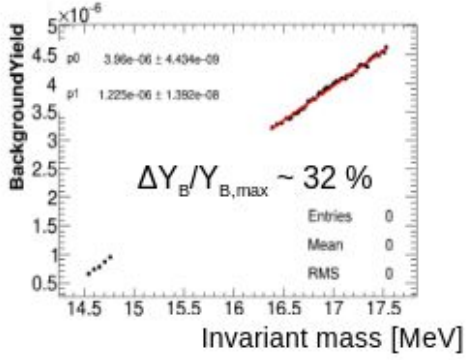
Movement within 10 mm





Timepix was moved by 1.8 mm





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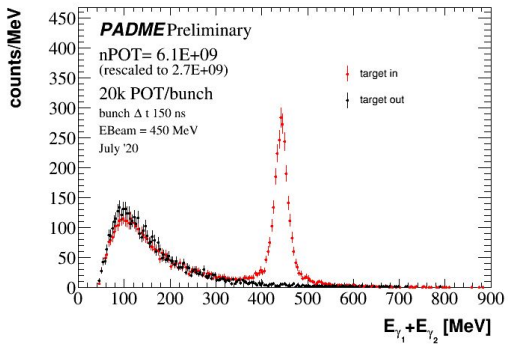
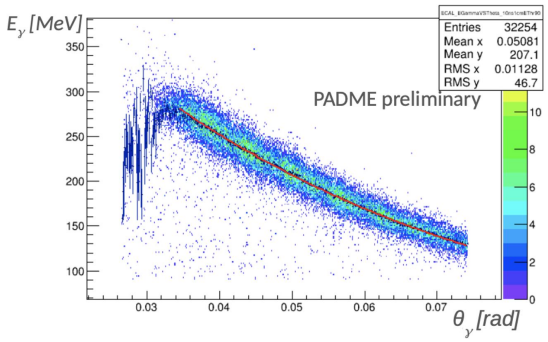
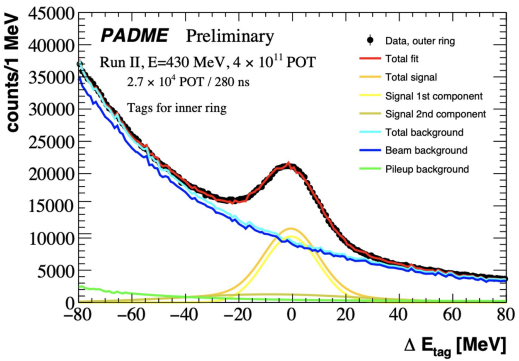
$e^+e^- \rightarrow \gamma\gamma$ cross-section



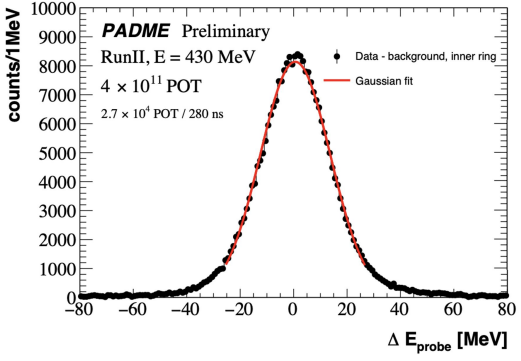


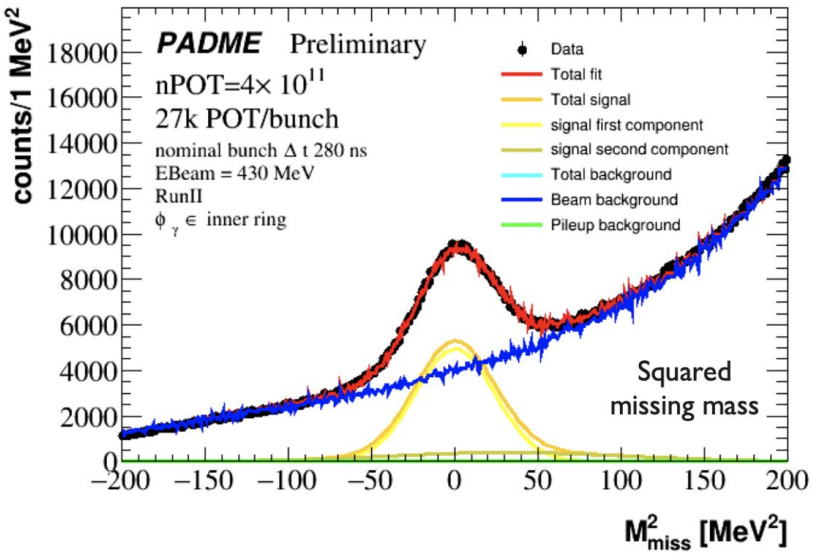
- Below 0.6 GeV known only with 20% accuracy
- Can be sensitive to sub-GeV new physics (e.g. ALPs)
- Using 10% of Run II sample
- Tag-and-probe method on two back-to-back clusters
- Exploit energy-angle correlation

Tag photons selection



Probe photons

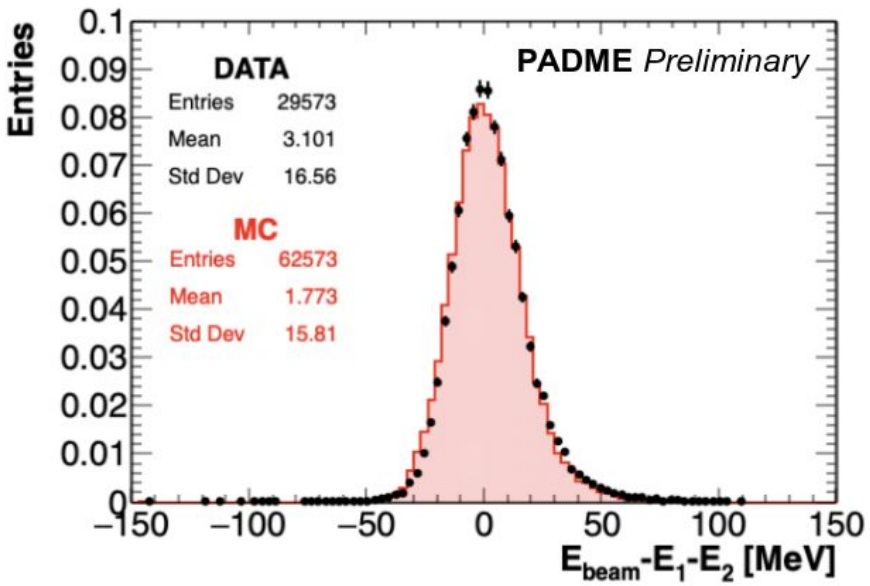


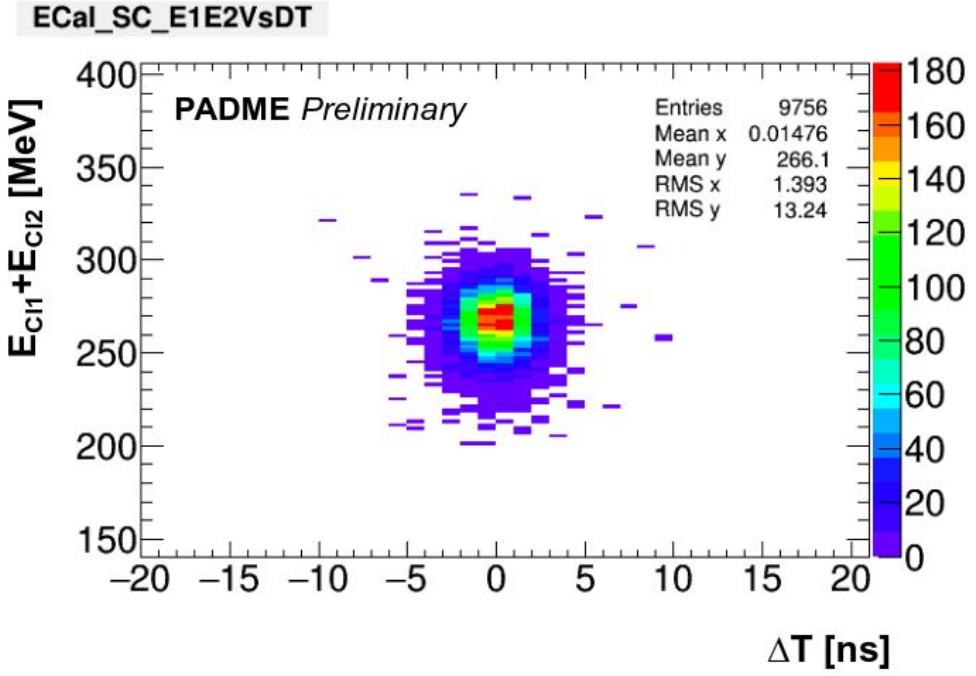


N_2 selection

Events selected → N_2(s)

- Events surviving the whole set of cuts, also related to the time difference of the 2 Clusters
- Energy sum of the 2 clusters selected gives back the beam energy (as expected for a two-body final state)
- ECAL relative energy resolution ~ 5%

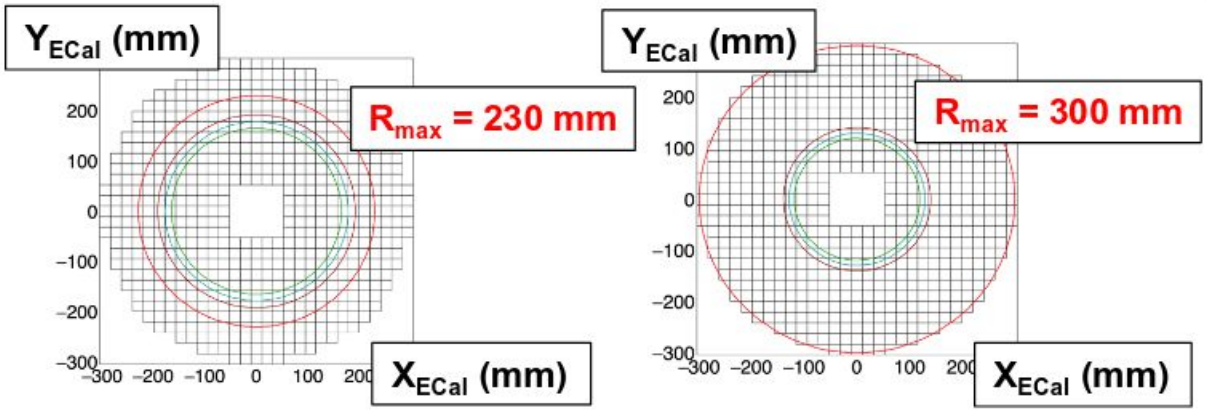


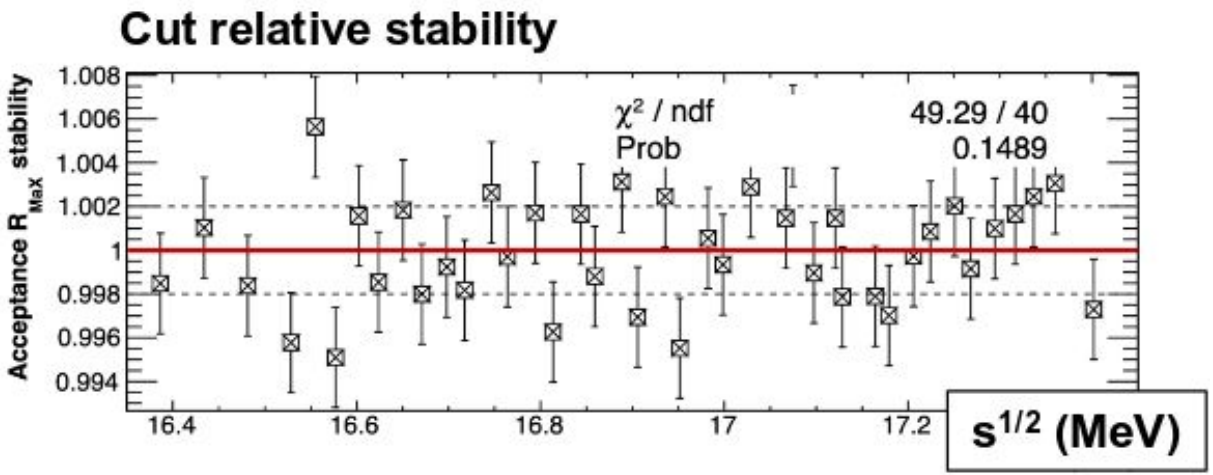


N_2 selection

Stability of R_{max} cuts

- Check if MC and data yields stable vs R_{min}, R_{max} (edge effects, leakage)
- Vary R_{max} by +-2 ECal cells around nominal cut of 270 mm: 230 mm → 300 mm
  - Yield variation: ~10%
  - Uncorrelated error 0.3%
- Stability is observed within a coverage band of +-0.2%, add 0.035% uncorrelated systematic error on B

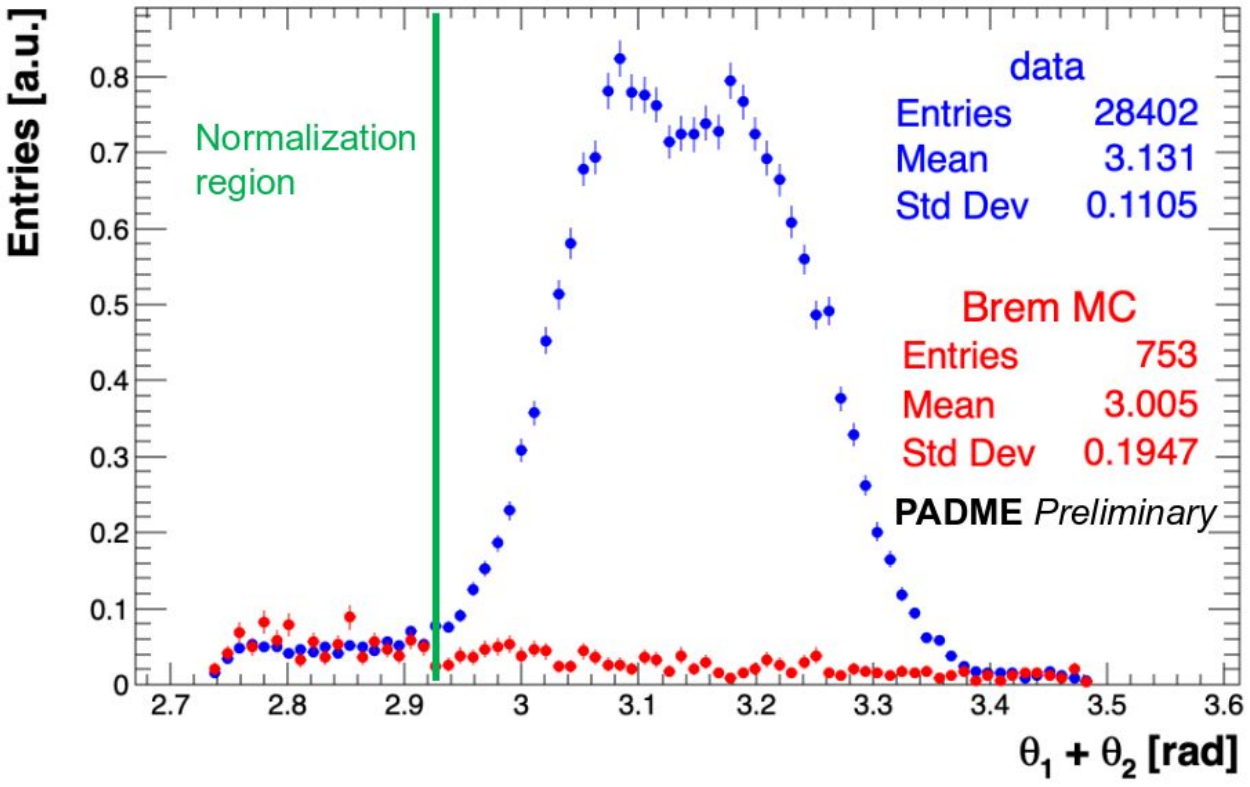




N_2 selection

Bremsstrahlung background removal

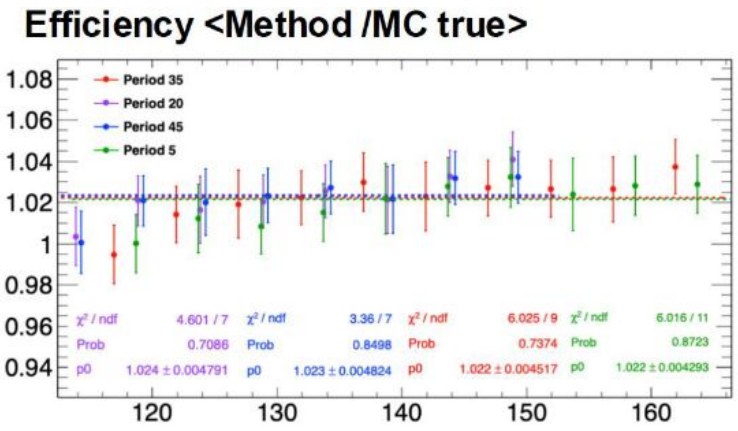
- In the θcm_1 + θcm_2 distribution of the selected event in data and MC shows a Brem tail in outside the signal
- By normalizing in the (0, 2.94 rad) regions and then using the ratio between the (2.94 rad, 4 rad) integrals it is possible to get an estimate of the Brem events under the signal

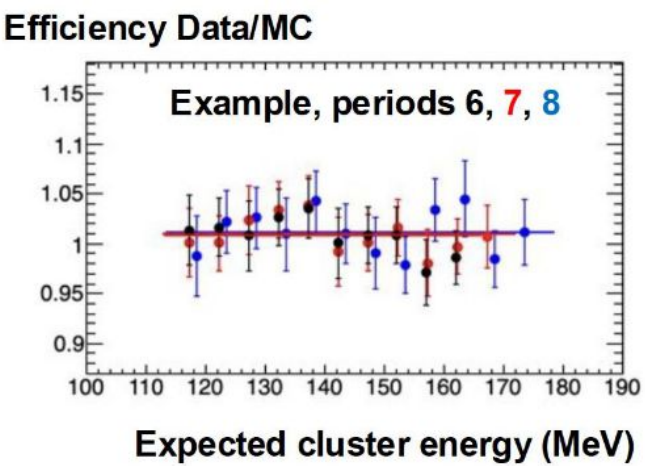


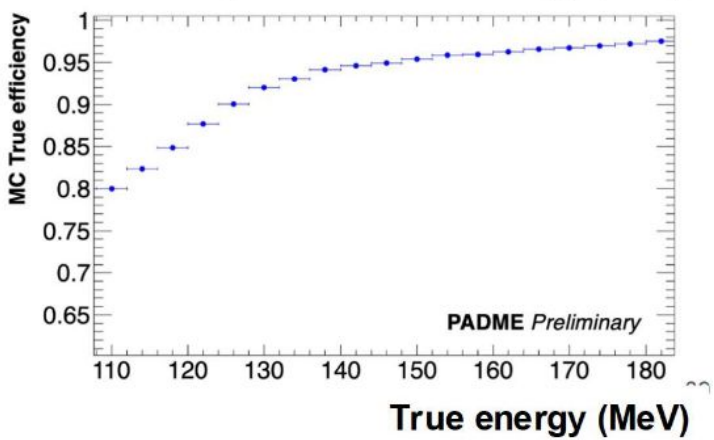
N_2 selection

Tag and Probe → Reco efficiency

- Efficiency around 1 within few % except in specific regions (Ecal edges, dead cells)
- Tag & probe: method-induced bias 2.3(2)%, stable along the data set
- Data/MC method efficiency stable along the data set and at the few per mil



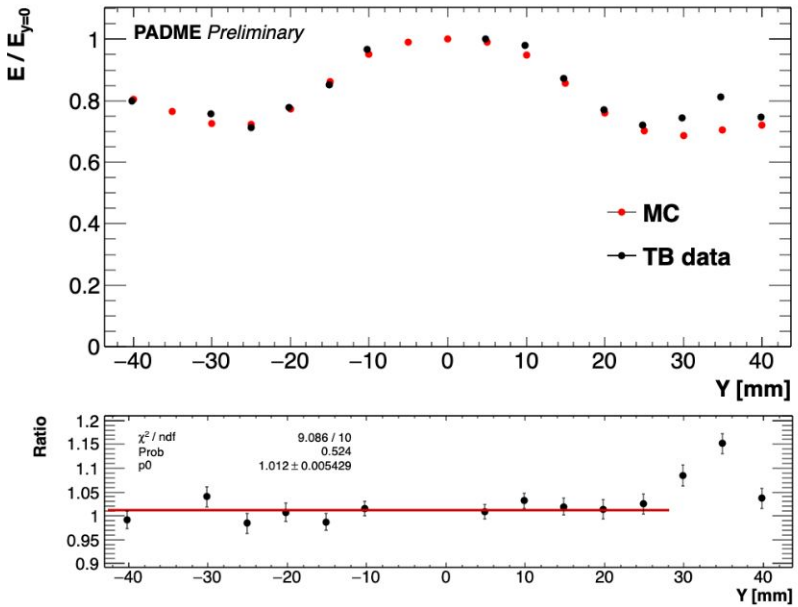


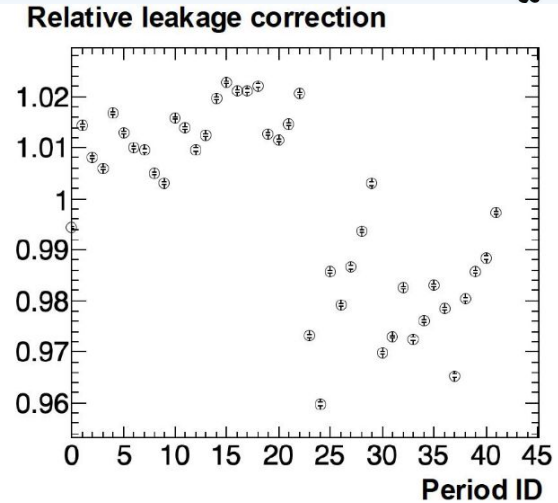


N_{PoT} estimation

PbGl energy loss in passive material

- TimePix cooling geometry (mostly Cu) was described in detail in the MC simulation
- Replicate the loss due to the beam passing in the Cu in Run III is possible by using the beam spot
- Beam spot from TimePix is not available for all the periods → used the COG instead considering the Timepix-ECAL offsets and the intrinsic difference in resolution





Significant period-by-period correction variation: -4% to +2%

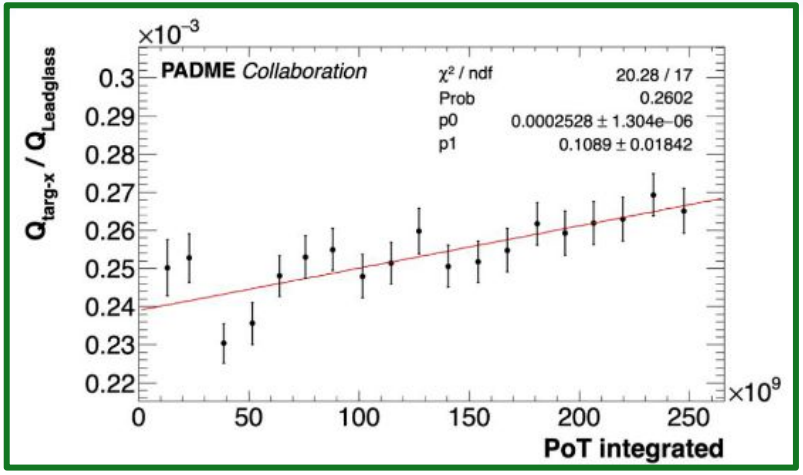
How much do we trust the correction?

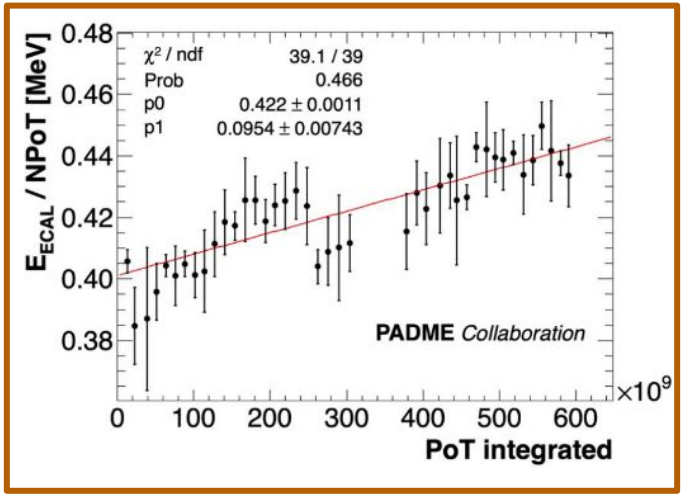
- Dedicated test beam taking a Y scan at PbGl level. We tried to replicate it with the MC simulation
- Good Data/MC agreement in the region where the beam was scanned during Run III
- 1.2% overall scale correction (included in the $g_R(s)$ scale) with a 0.5% error

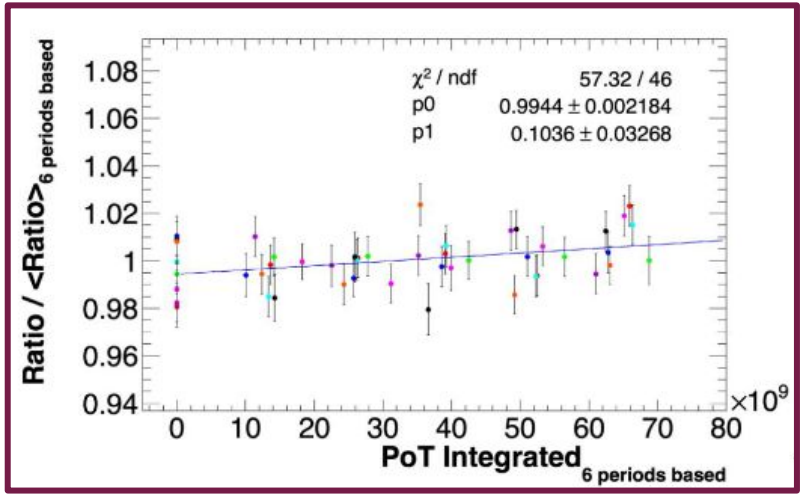
N_{PoT} estimation

Radiation damage

- Throughout Run III a total of 7e11 PoT(of ~300 MeV each) has passed through the PbGl block corresponding to a TID of 25 Gy (2.5 krad)
- The SF57 transmittance loss was never measured in literature, however for similar blocks (SF5-SF6) a significant loss is shown, especially near Cherenkov wavelengths
- Proof of loss of LY:
  - Target X strips are way more sensible than Y → their charge can be used for quantitative checks. **10% slope found**
  - The overall energy on ECAL over the NPoT should be a stable quantity, also here **we see a 10% slope**
  - Looking at the Data/MC ratio on resetting every 6 periods a compatible slope is found



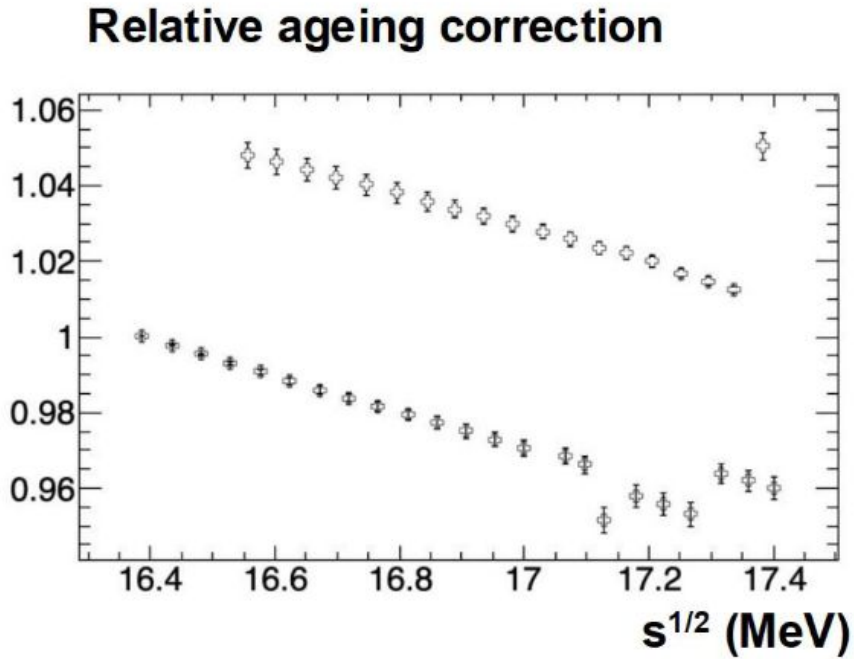


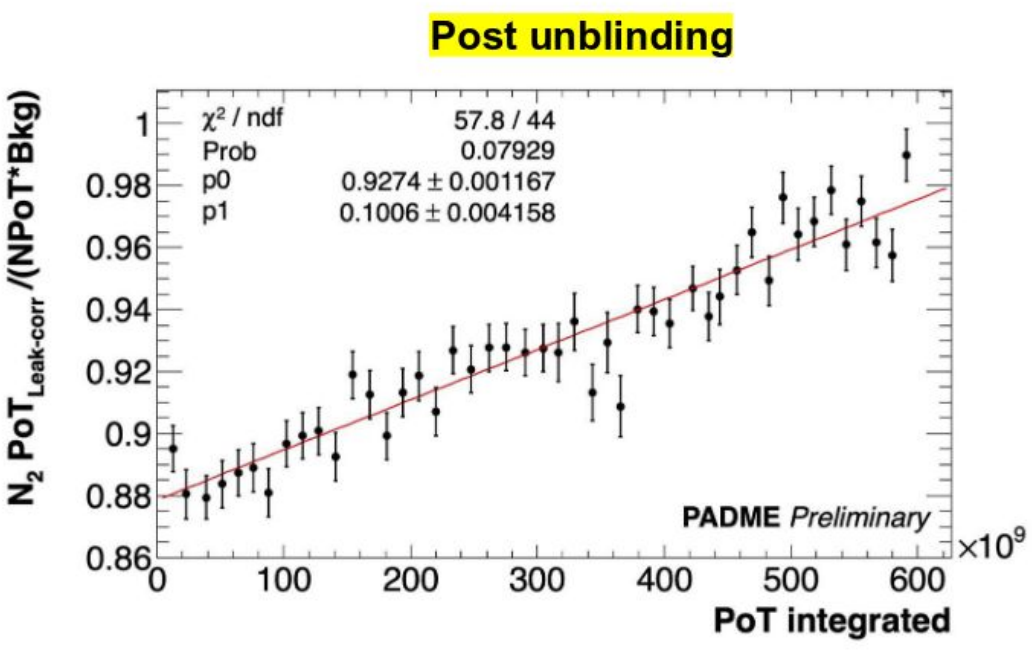


N_{PoT} estimation

Radiation damage

- PbGl yield decreases with relative PoT slope of 0.097(7)
- Constant term uncertainty of 0.3% added as scale error
- Slope error included in PoT uncertainty
- Checked the slope value on $g_R(s)$ after the unblinding→ totally compatible results





Unblinding procedure

To validate the error estimate, we applied the procedure in 2503.05650 [hep-ex]

- Aim to blindly define a side-band in $g_R(s)$, excluding 10 periods of the scan
- Define the masked periods by optimizing the probability of a linear fit in $s^{1/2}$

1. Threshold on the χ^2 fit in side-band is $P(\chi^2) = 20\%$, corresponding to reject 10% of the times
2. If OK, check if the fit pulls are gaussian
3. If OK, check if a straight-line fit of the pulls has no slope in $s^{1/2}$ (within 2 sigma)
4. If OK, check if constant term and slope of the linear fit for $N_2(s)/B(s)$ are within two sigma of the expectations, i.e.: ±4% for the constant, ±2% MeV -1 for the slope

Successfully applied:

1. **$P(\chi^2) = 74\%$**
2. **Pulls gaussian fit probability 60%**
3. **Slope of pulls consistent with zero**
4. **Constant term = 1.0116(16), Slope = (-0.010 +- 0.005) MeV^{-1}**

→ **Ready to unblind**

Run III results

After box opening, check of the ageing correction applied, slope was 0.097(7)

- Fully consistent (observed excess alters only marginally)
- The slope has been used to correct for the radiation-induced effect, acting as a separate nuisance
- Again no significant change in the location of the excess and in the global p-value