Results from PADME Experiment

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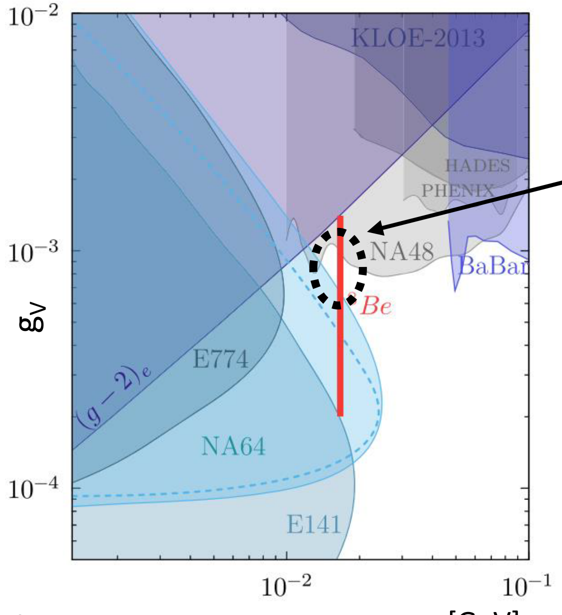
Search for X17 resonance

ATOMKI Collaboration observed anomalies in the angular correlation of e^+e^- pairs emitted via internal pair conversion in the ^{8}Be, ^{4}He and ^{12}C nuclear de-excitation

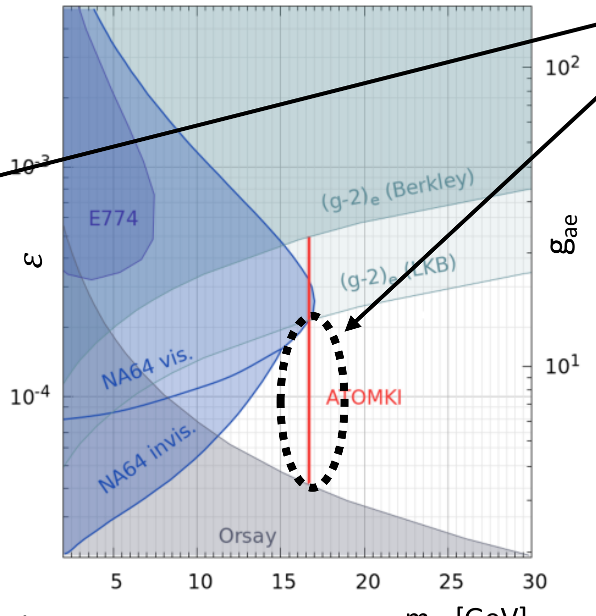
→ results compatible with a new neutral mediator called X17

Vector coupling



Phys. Rev. D101, 071101

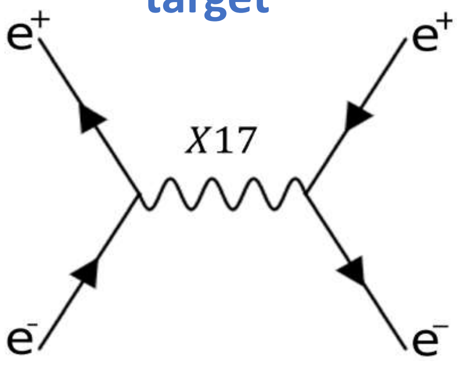
Pseudo-scalar coupling



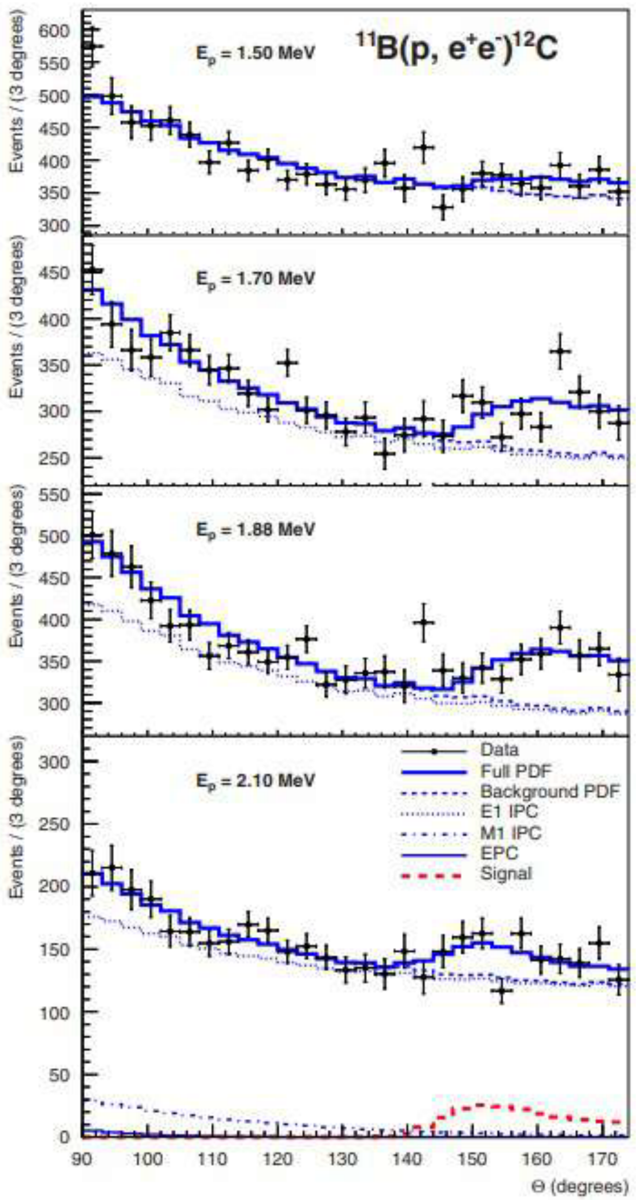
Phys. Rev. D104, L111102

There is still room in the phase space for New Physics interpretation!

Resonant search on fixed target



e^+e^- annihilation is the main production process



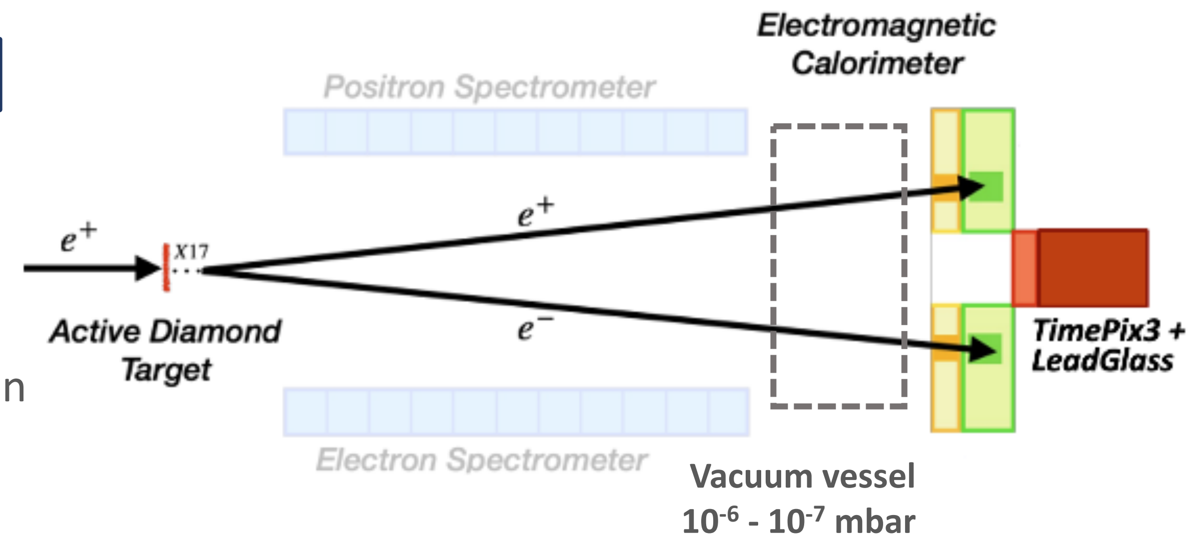
PADME measurement idea: perform a very fine scan of √s around the hypothetical mass resonance using positron beam with E_{beam} ~ 283 MeV on target → measure a 2-body final state

PADME Experiment in Run III

Experimental setup

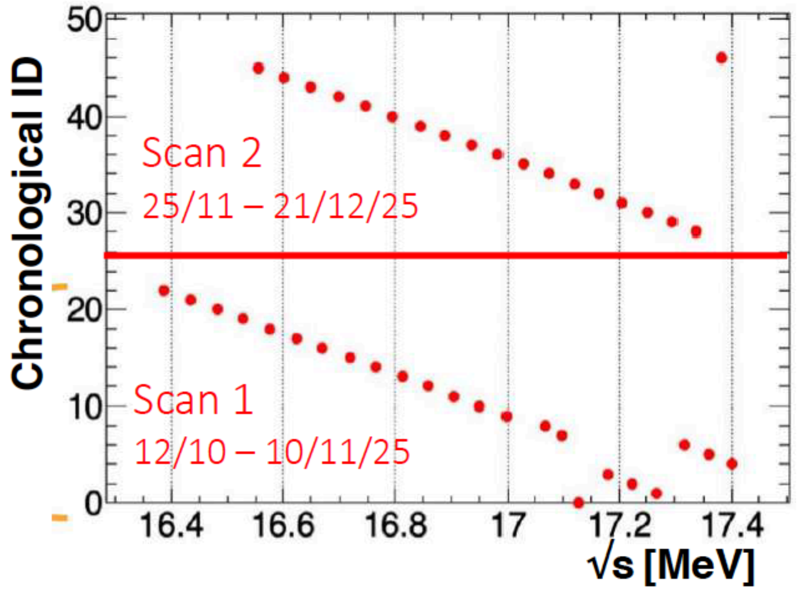
- Active target polycrystalline diamond
- ECal: 616 BGO crystals, each 21x21x230 mm^3
- ETagger (scintillator detector) in front of ECal for e/γ discrimination
- TimePix3 high granularity silicon-based detector for beam spot
- LeadGlass luminometer (NA62 Large Angle Veto spare block)

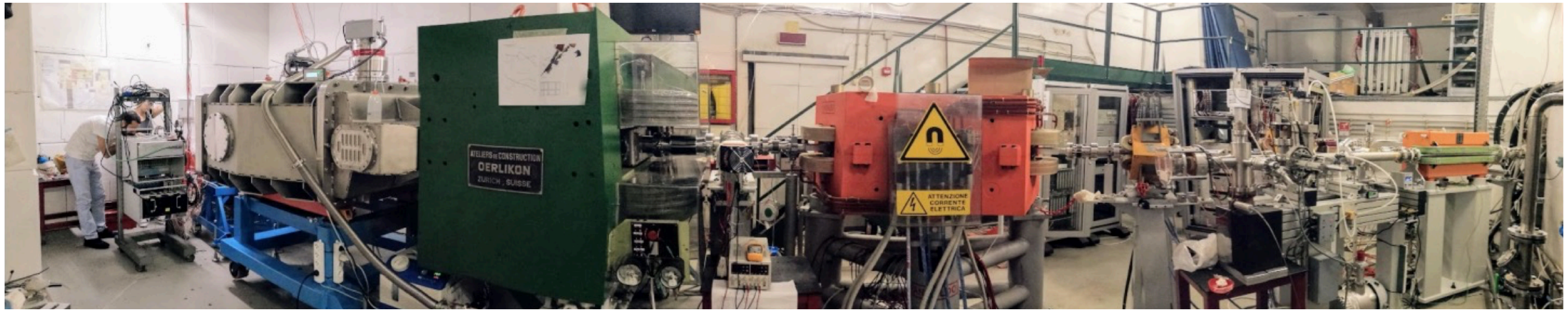
Elements not used: charged particle veto and magnetic field (residual 12.5 G)



Run III Dataset ~ 6x10^{11} PoT (~10^{10} PoT per $\sqrt{s}$ point)

- 47 on-resonance points in 2 scans: E_{beam} @(263, 299) MeV ($\sqrt{s}$ steps of ~20 keV)
- 6 out-of-resonance points: X17 production forbidden
  - 5 points with ~ 10^{10} PoT each and E_{beam} @(205, 211) MeV
  - 1 point with ~ 2x10^{10} PoT and E_{beam} = 402 MeV





Analysis Strategy

Goal is to measure a two-body final state to establish if the rate is compatible with SM expectation or with the presence of an hypothetical X17 signal

- The primary analysis observable is $g_R(s)$ → the ratio between the number of observed events with a two-body final state, $N_2(s)$, and the expected number of background events, $N_{PoT}(s) \cdot B(s)$
  - with X17 signal: $g_R(s) = \left[1 + \frac{S(s;M_X,g_{Ve}) \cdot \varepsilon_{Sig}(s)}{B(s)}\right]$
  - without X17 signal: $g_R(s) = 1$

  Several theoretical and experimental effects may induce deviations from unity → accounted with a scale factor $K(s)$.

Observable to measure

Hypothesis test to perform

$$g_R(s) = \frac{N_2(s)}{N_{PoT}(s) \cdot B(s)} =$$

Signal + Background hyptothesis

$$\boxed{K(s)\left[1 + \frac{S(s;M_X,g_{Ve}) \cdot \varepsilon_{Sig}(s)}{B(s)}\right]}$$

vs

Background only hypothesis

$$\boxed{K(s)}$$

Crucial to determine the systematic errors on the measured quantities: N_2 clusters, N_{PoT}, Bkg yields

Event selection

Estimation of N_2

Selection algorithm as independent as possible on beam and detector conditions

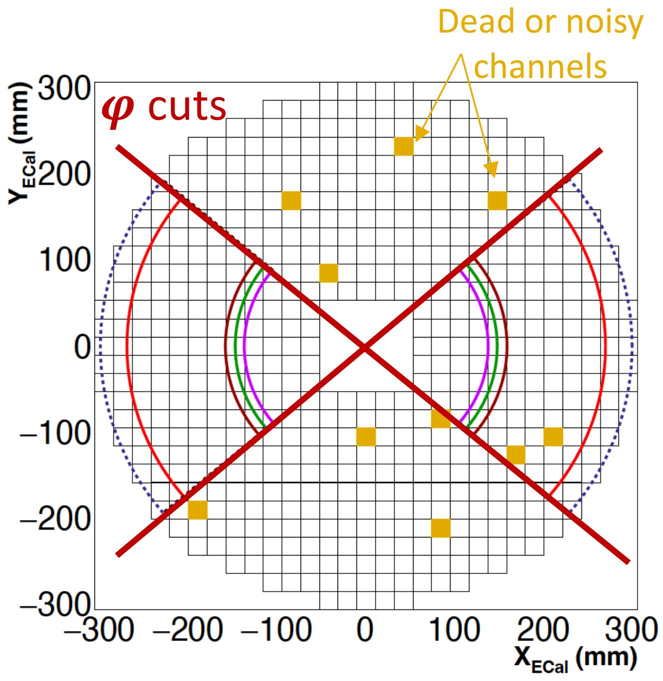
- Require 2 clusters within ECal geometric acceptance
  - R_{max} defined by ECal dimensions and R_{min} by the CoM energy
  - Limited energy range for each cluster, depending on CoM energy
  - Illumination affected by the presence of the magnet → Cut regions in φ
    - about 30% loss in acceptance
- Mutual cluster conditions
  - Time and spatial distance: $\Delta T < 5$ ns & $\Delta R > 60$ mm
  - $\phi 1 - \phi 2$ vs $\theta 1 + \theta 2$ cut in the center of mass frame isolates the signal

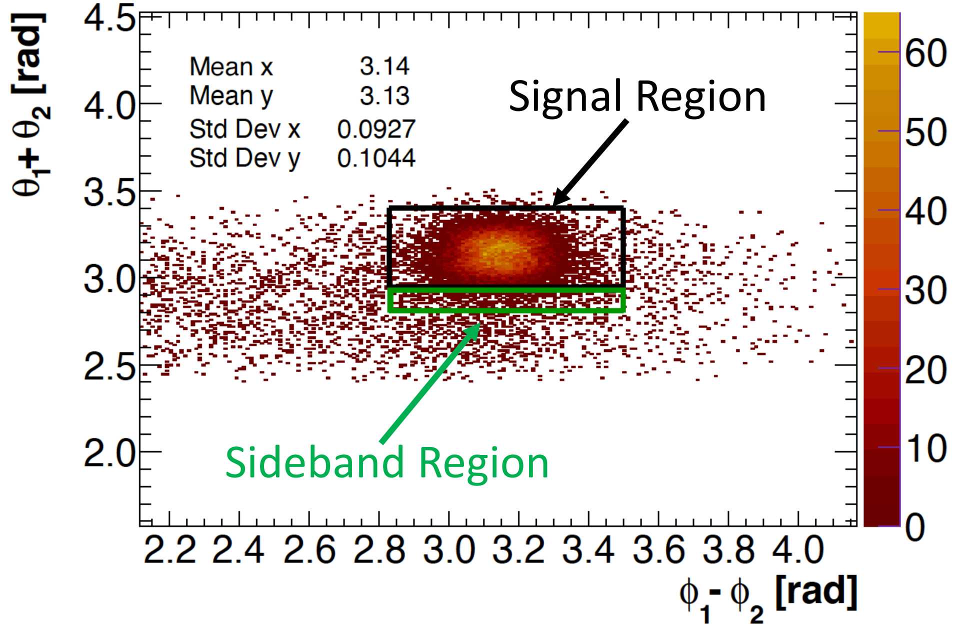
    → Signal Region is 3σ around the mean value

    → Sideband Region to determine background normalization

    ~ 4% originating from Bremsstrahlung radiation in the target subtracted to obtain the final N_2 estimation

Source of uncertainty	Error on N_2 [%]
Statistics	0.6 – 0.7
Background subtraction	0.3
Total (uncorrelated)	0.65





SM Background

Estimation of B

The main background sources are the Bhabha scattering and $\gamma\gamma$ annihilation.

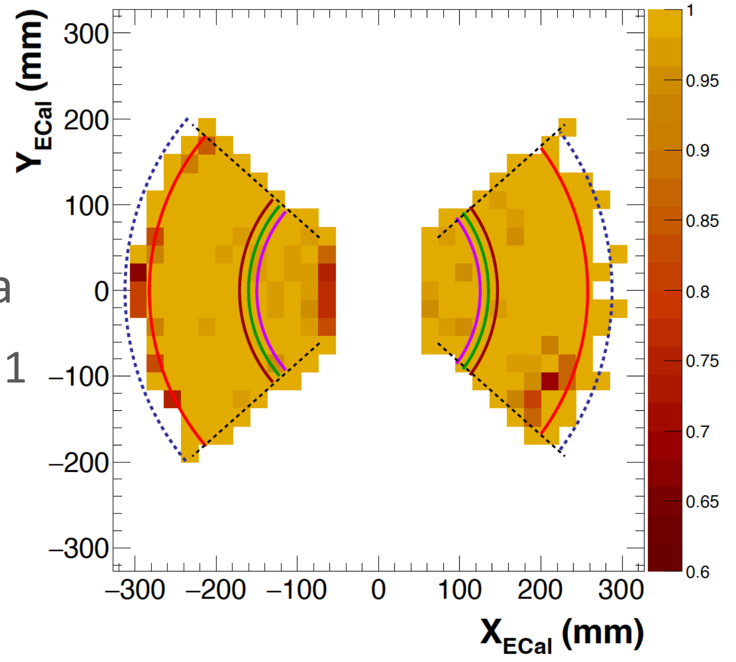
The expected background yield per PoT is determined with MC → validate with data

- Reconstruction efficiency estimated with Tag&Probe method → data/MC compatible with 1

Effects that spoils the B estimation:

- 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}

Tag & Probe efficiency

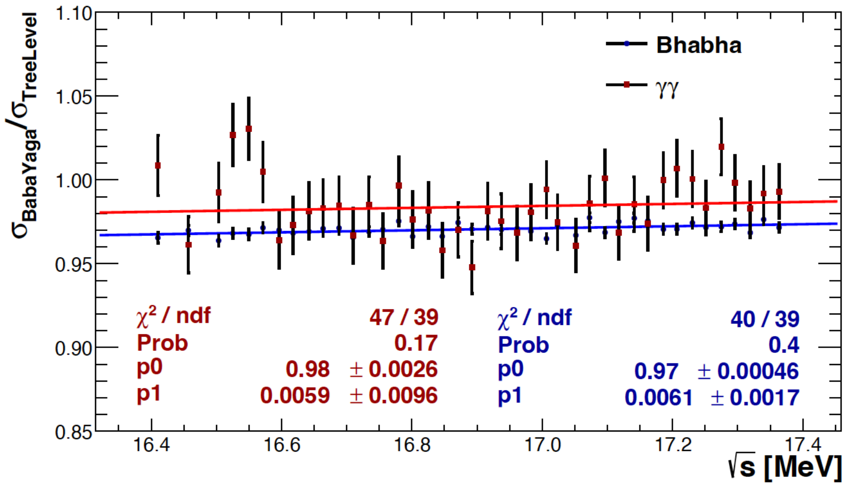


Source of uncertainty	Error on B [%]
MC statistics	0.4
Tag & Probe eff.	0.35
Beam spot variations	0.05
Cut stability	0.04
Total (uncorrelated)	0.54
Absolute B yield (correlated, affect K(s))	1.8

B yield normalized to below-resonance energy points
→ improve systematic uncertainty

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}

Radiative Corrections



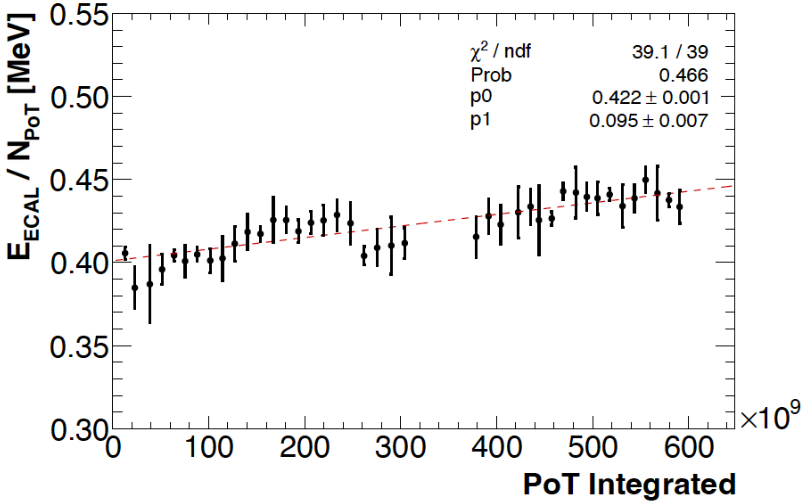
Positron on target

Estimation of N_{PoT}

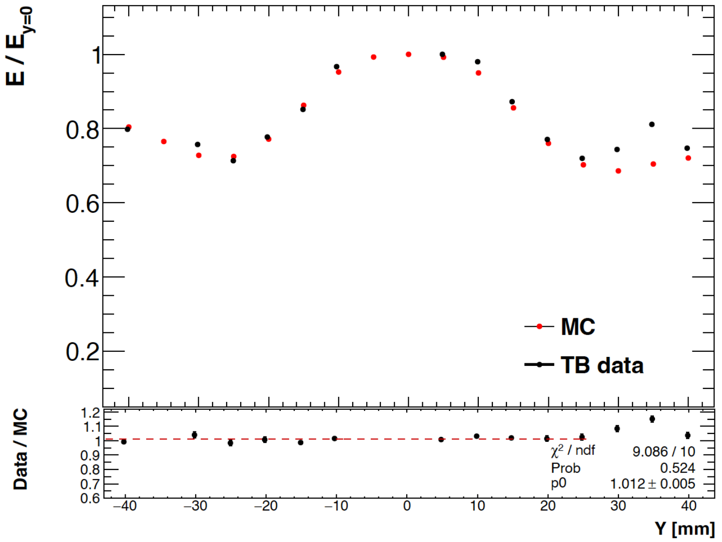
The number of PoT per bunch is determined using the LeadGlass calorimeter charge.

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

Radiation induced loss



Energy loss in passive material



Corrections for precise estimation of N_{PoT}

- Radiation induced loss
  - Run III dose ~ 2.5 krad → transparency changes for O(krad)
  - Estimated from 2 flux proxy observables: Q_{target} , E_{ECal}

    → show a linear energy dependence on the integrated flux → LG yield decreases by 0.097 ± 0.007 → N_{PoT} flux corrected for this effect
  - 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 to check goodness of MC simulation → evaluate the overall energy loss for the specific beam conditions → for each energy point N_{PoT} flux corrected

Source of uncertainty	Error on N_{PoT} [%]
Radiation Loss. slope (uncorrelated)	Variable ~ 0.35
Common errors on N_{PoT} (affect K(s))	
LG Calibration pC/MeV	2.0
Energy Loss	0.5
Radiation Loss, const. term	0.3
Total (correlated)	2.1

Signal modelling & efficiency

Estimation of S and ε_{Sig}/B

Signal yield estimation

The width of the expected excess receive contributions by the beam energy spread and from 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)%

Signal efficiency

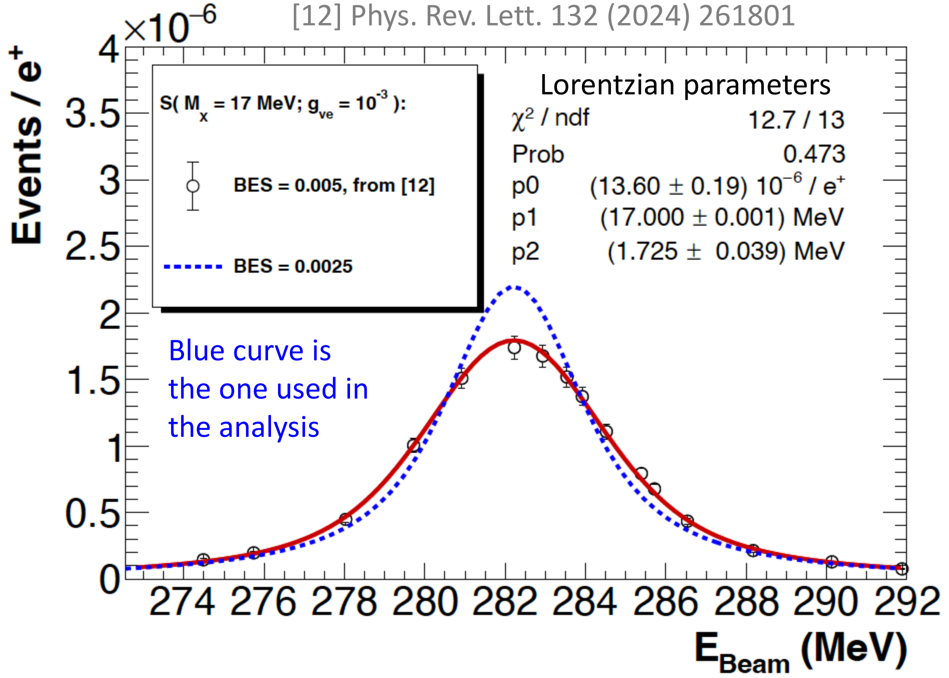
Expected signal efficiency ε_{Sig} determined from MC:

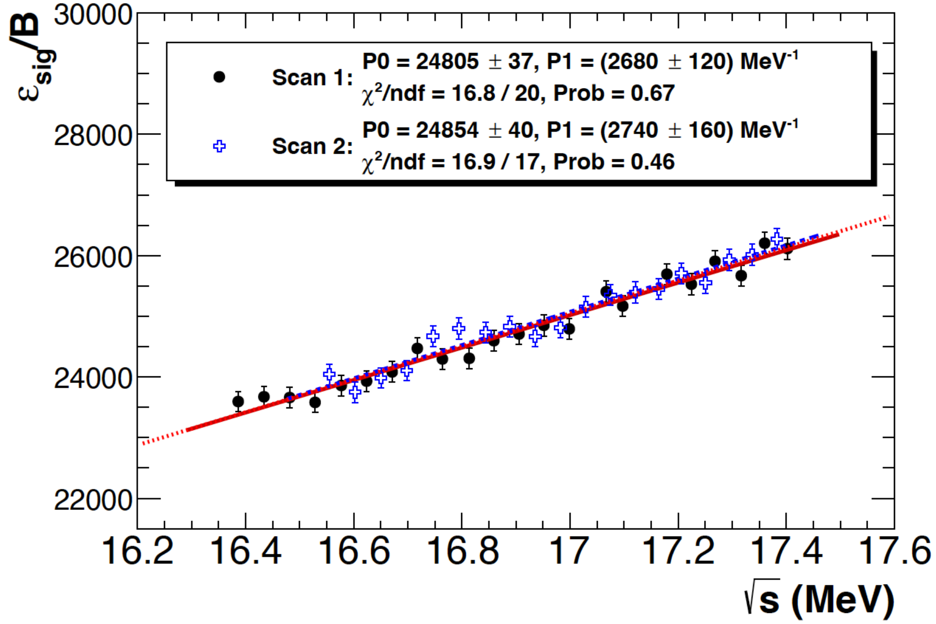
- Use of the ratio ε_{Sig}/B significantly reduces detector-related systematic uncertainties (similar detector illumination for both signal and background).

→ Fit ε_{Sig}/B with a straight line → fit parameters as nuisances:

  - Errors: $\Delta P0/P0$ ~0.1%, $\Delta P1/P1$ = 3%, correlation = -1.8%

[12] Phys. Rev. Lett. 132 (2024) 261801





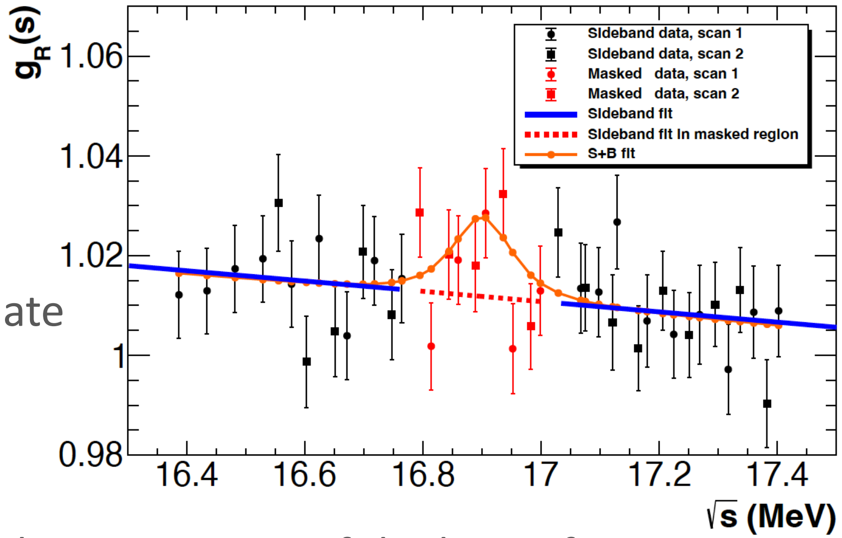
The Run III Results

Blind - unbliding procedure

Large expected X17 mass resolution → no sideband region in √s can be defined to validate the statistical approach → Validation procedure described in 2503.05650 were used

- Aim to blindly define a sideband in gR(s), excluding 10 periods of the scan
- Define the masked periods by optimizing the probability of a linear fit in s

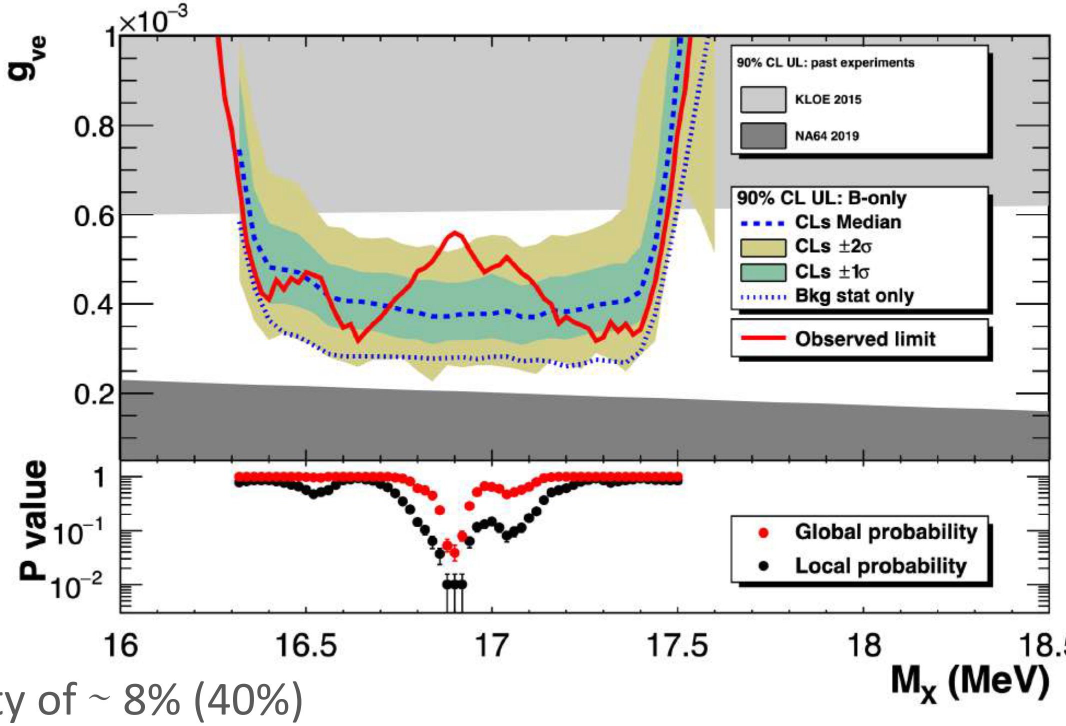
Data validation criteria are based on the fit quality, the distribution of the fit pulls, and the parameters of the linear fit



Statistical treatment

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

- For a given M_X, $CL_s = \frac{P_S}{(1-P_B)}$ is used to define the upper limit on g_{ve}



Run III Results

Excess observed, 2.5 σ local, 1.8(2) σ global significance

corresponding to mass $M_X = 16.9\ MeV$ and a coupling

$g_{ve} = 5 \times 10^{-4}$

Second excess present at $M_X \cong 17.1\ MeV$, with a local (global) probability of ~ 8% (40%)

PADME Upgrade for Run IV

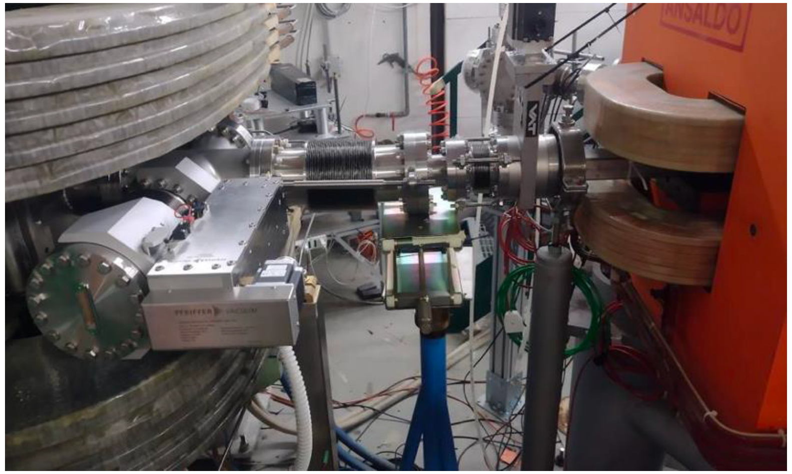
The goal of Run IV is to increase sensibility to confirm/disprove Run III result

- Diamond target position moved downstream by ~30 cm + position readout changed
- Passive material removed and PADME Magnet fully degaussed
- Radiation loss monitor system for online LG calibration

- New detectors
  - PadMMe MicroMegas chamber replaced the ETagger
  - TMM Micromegas replace the TimePix beam monitor

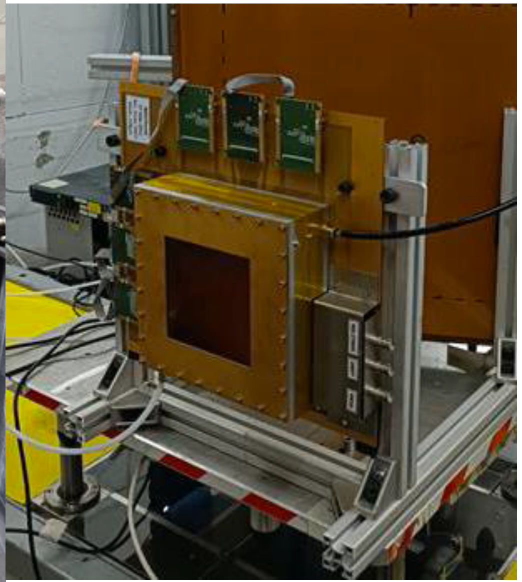
Source	Uncertainty		Improvement
	Run III	Run IV	
N_2	0.6	0.3	New target position → **acceptance increased**
B	0.54	0.3	PadMMe → **ee/$\gamma\gamma$ discrimination** + angular-momentum resolution increasing
N_{PoT}	0.35	0.3	**3 different beam spot monitor** (Target-PadMMe-TMM) + **online LG calibration system**
Total	**0.88**	**0.5**	

Diamond target moved



PadMMe

TMM



Pad*MMe*: Micromegas tracker

Micropatter gas detector operated in TPC mode

- Detector dimensions **88 × 88 cm²**
- Two drift gaps of **5 cm** each (~3 kV)
- Amplification gap ~ 128 μm

Novel diamond-shaped readout

- Able to read both x and y coordinates with reduced coupling

Readout Electronics: **APV25**

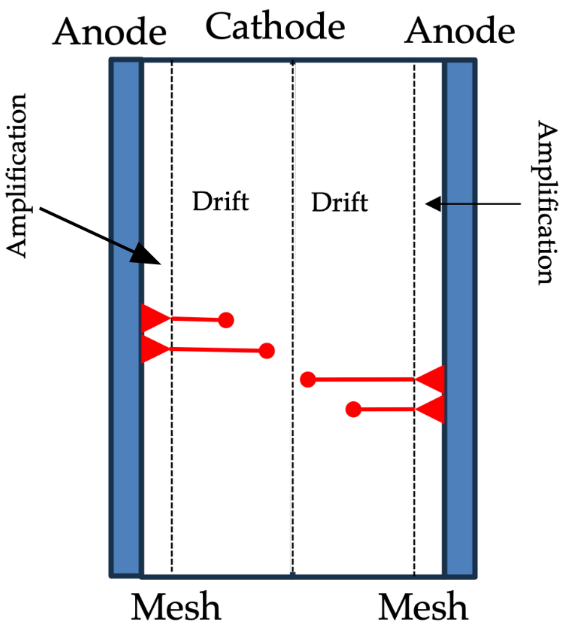
- Time window up to 675 ns ns to read the entire drift time ~500 ns

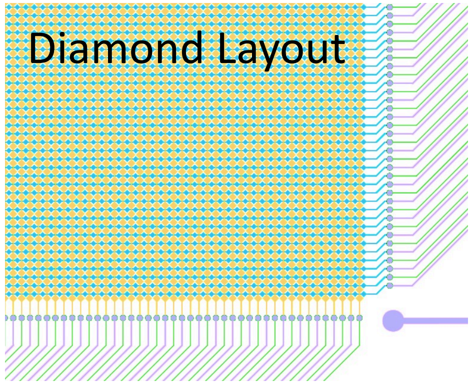
Gas Mixture **Ar:CF_4:Isobutane** (88:10:2)

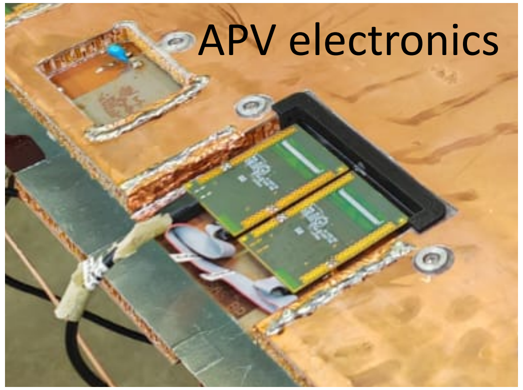
- Drift velocity ~ 10.5 cm/μs

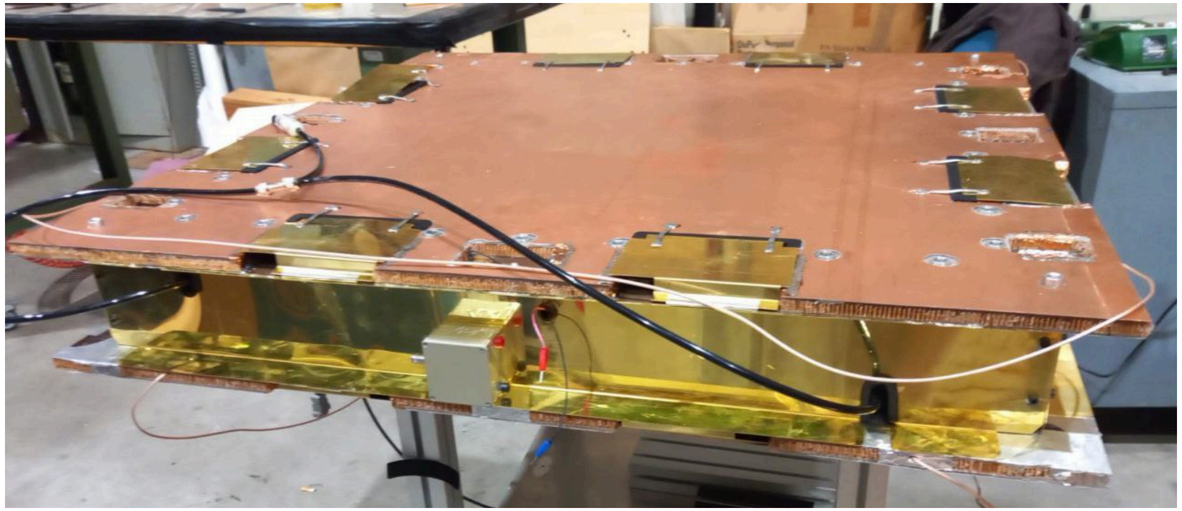
3 HV regions to be able to have a better control on the amplification in the ”beam” region

- External regions operating at 490 V
- Inner regions operating at 350 V (no amplification)







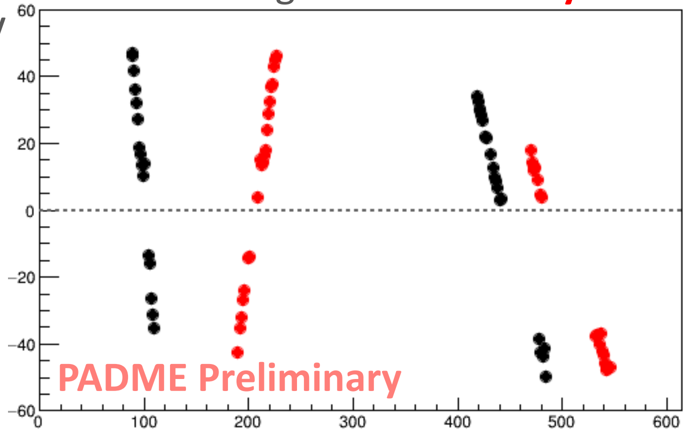


Pad*MMe* preliminary performance

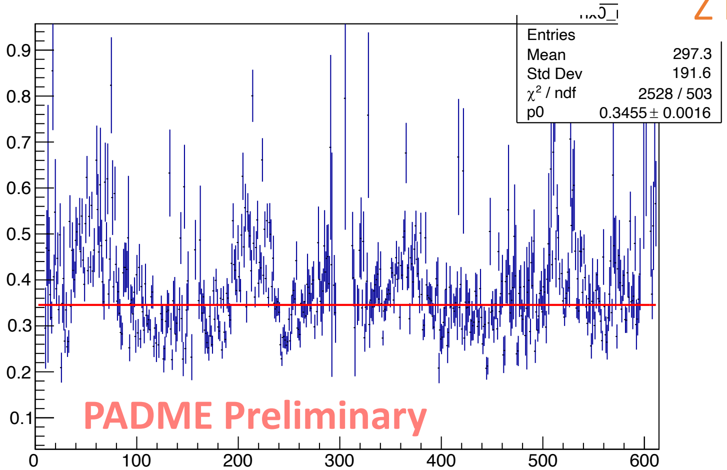
Preliminary results with cosmic data

- TPC for track reconstruction
- Hit efficiency **> 90%** @ 500 V
- Spatial Resolution
  - $\sigma_{x,y}$ ~ **350 µm**
  - σ_z ~ **2 mm** → can improve with better time calibration

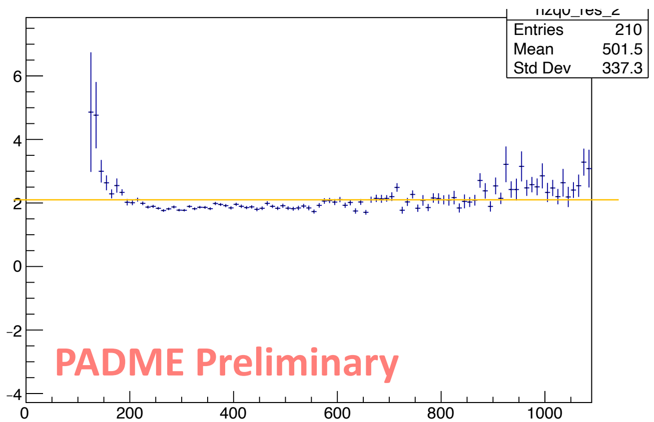
Tracking for both **x** and **y**



X,Y Resolution



Z Resolution as function of the charge

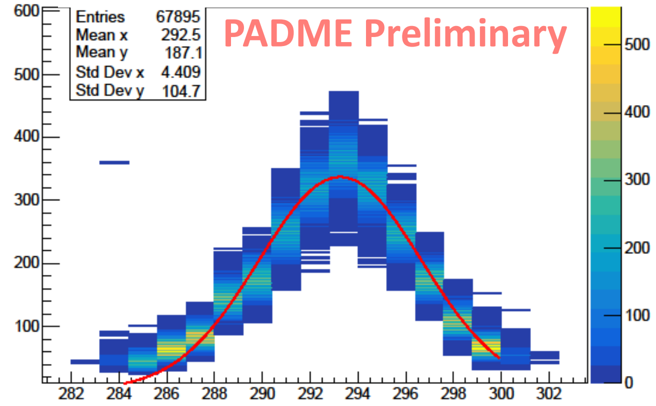


Beam Monitoring & Tracking in PADME

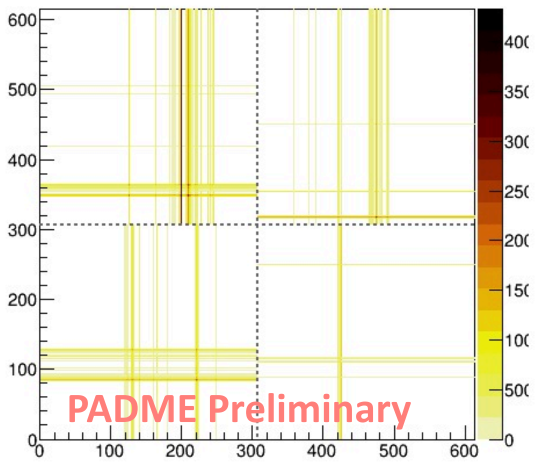
- Able to reconstruct the beam spot position and spread up to σ ~ **3.5 mm**
- Tracking in beam conditions, occupancy as high as 50%

→ **working for a robust track reconstruction**

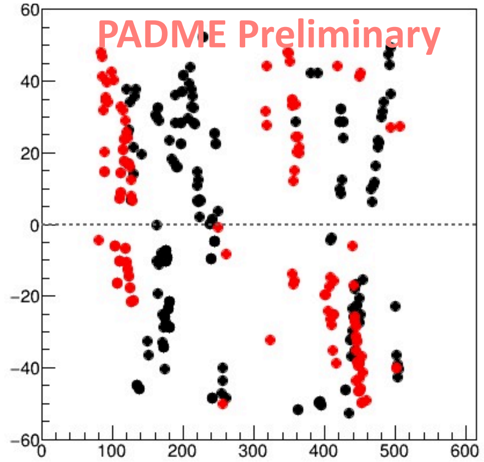
Charge vs position



P1_panel_frame



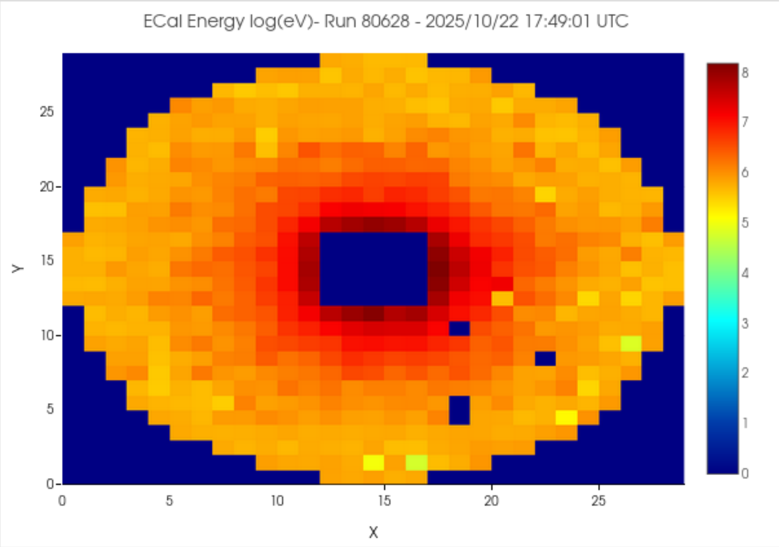
Tracks for 3k particles

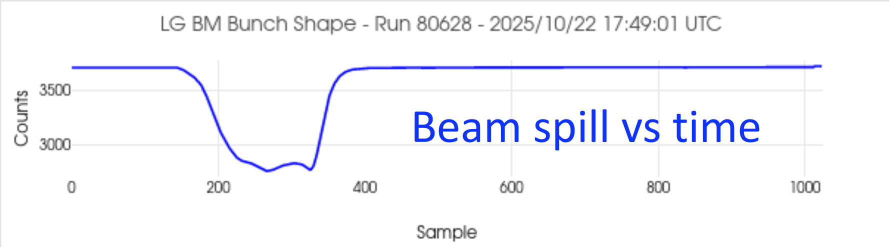


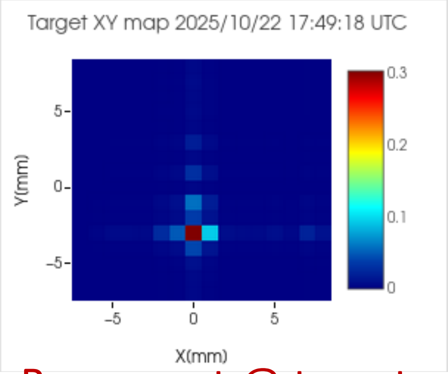
Run IV Status

Some online monitoring plots of the on-going data taking

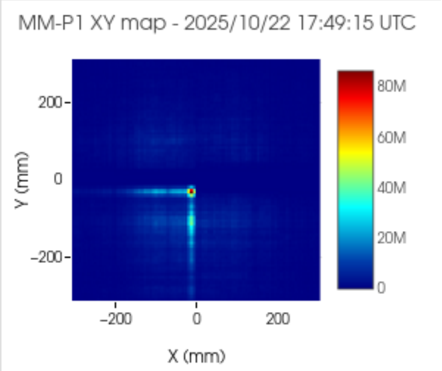
full ECal acceptance available thanks to th target movement



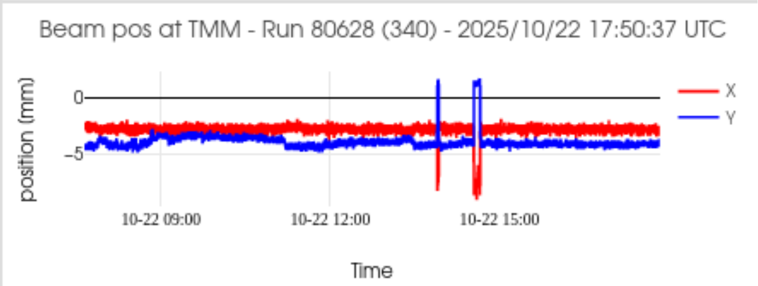




Beam spot @ target

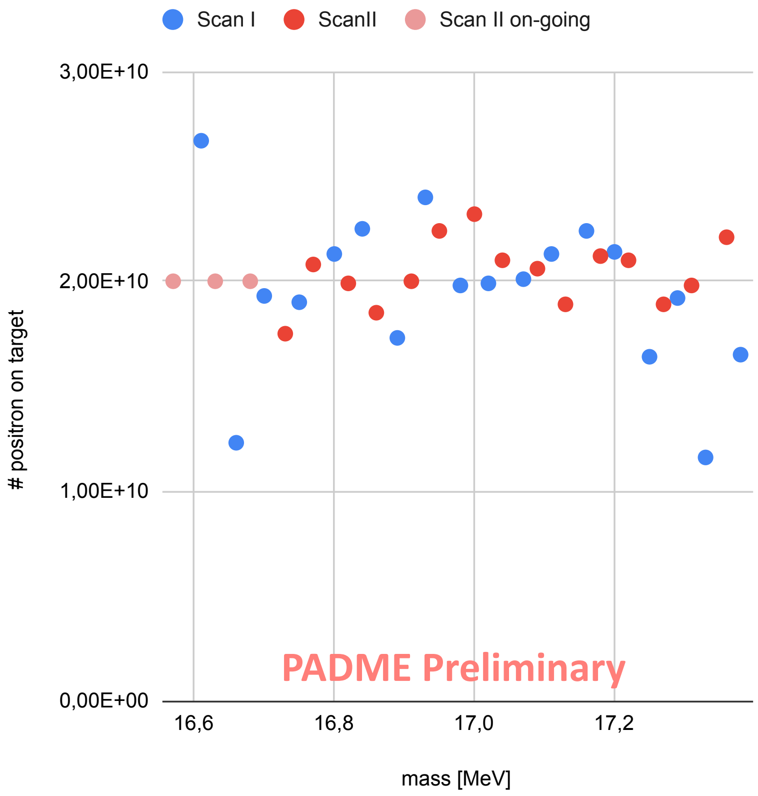


Beam spot @ PadMMe



Beam position @ TMM

Run IV **Scan I** already finished, while **Scan II** is on-going



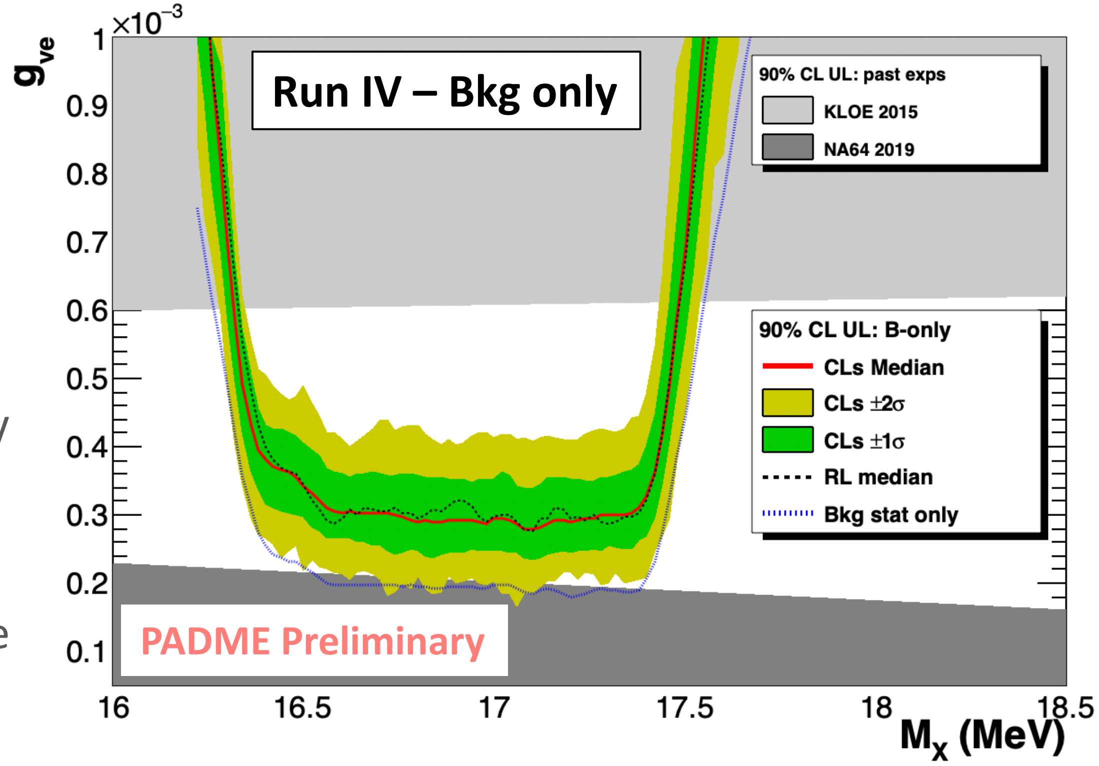
Conclusions

The **Run III** data analysis has been successfully blessed using the “blind-unblinding” procedure

- Overall uncertainties ~ 0.9% per energy point
- No indications of X17 well beyond two-sigma-equivalent global p-values
- An excess has been observed @ 16.9 MeV, with global p-value equivalent to 1.8(2)σ arXiv:2505.24797

The **Run IV** data needed to clarify

- New Micromegas tracker were installed to measure the absolute ee/$\gamma\gamma$ cross section allowing combined analysis + TMM to the end of the line for beam monitor
- Run IV-part 1 data already in the books
  - 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 → √s= (16.60, 17.36) MeV
- Run IV-part 2 on-going since September
  - 18-20 scan points + out-of-resonance below 16 MeV and above 18 MeV



Backup

Other Experiments

Recent result from MEG II, arXiv:2411.07994 still to be published

- Measurement on ^{7}Li target to reproduce ^{8}Be ATOMKI
  - → no signal found
- ULs on $\frac{\Gamma(^8Be^* \to {}^8Be\, X_{17}(ee))}{\Gamma(^8Be^* \to {}^8Be\, \gamma)}$ for 17.6 and 18.1 MeV transitions

MEG II result compatible at 1.5 σ with the **ATOMKI combination**
M_X = 16.85(4) MeV [Barducci, et al. , JHEP 04 (2025) 035]

Further attempts to verify:

AN2000 facility @INFN-LNL [data taking ongoing]

n_TOF EAR2 neutron line @CERN [2025 proposal]

Tandem accelerator @Montreal [JPC Ser. 2391 (2022) 012008]

Van de Graaf accelerator @IEAP Prague [NIM. A 1047 (2023) 167858]