

Status of the PADME X17 Search

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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 ^8Be , ^4He and ^{12}C nuclear de-excitation

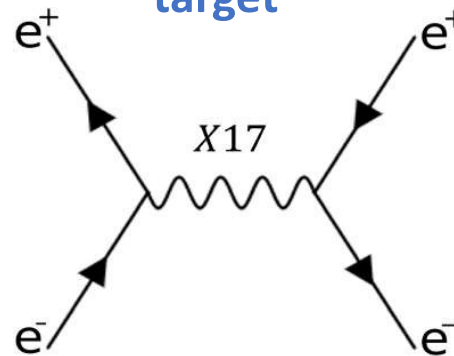
→ results compatible with a new neutral mediator called X17

Vector coupling

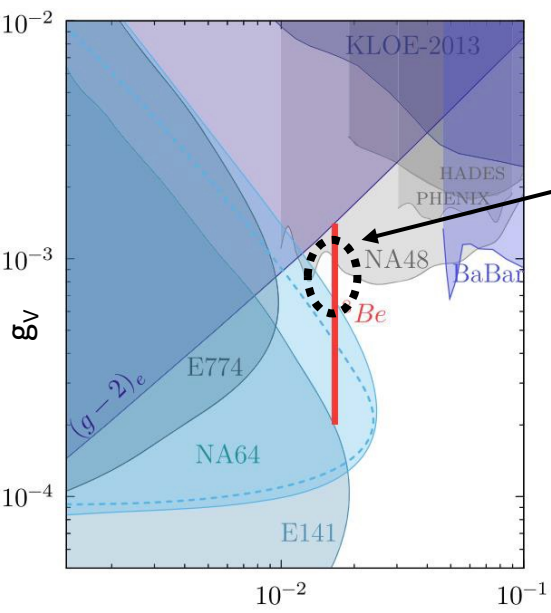
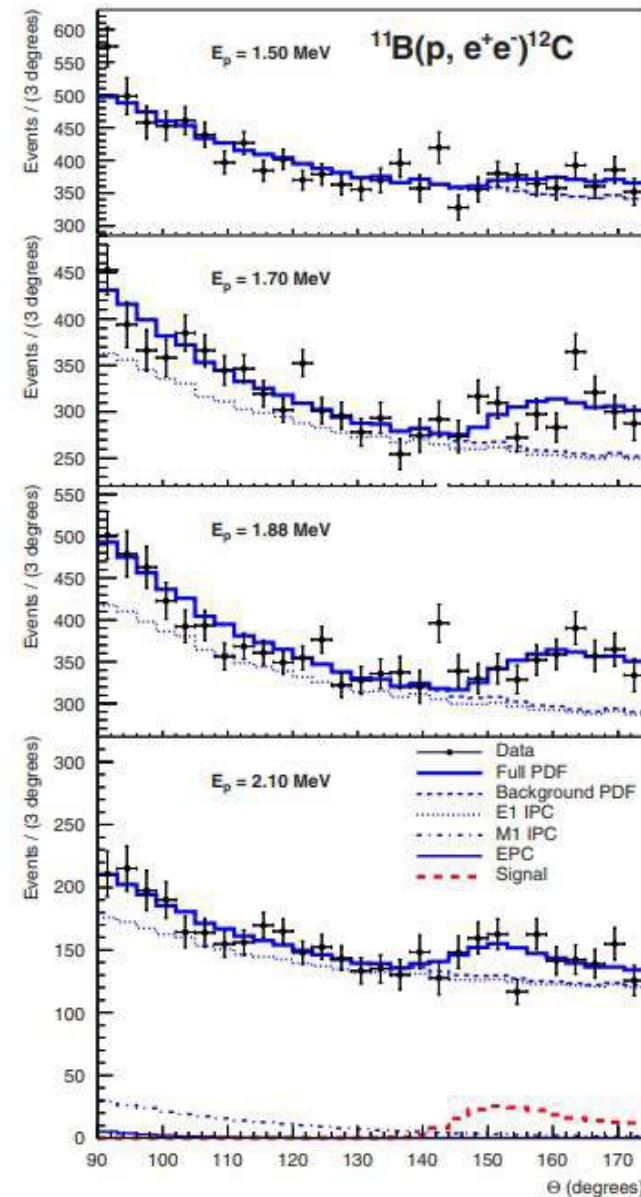
Pseudo-scalar coupling

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

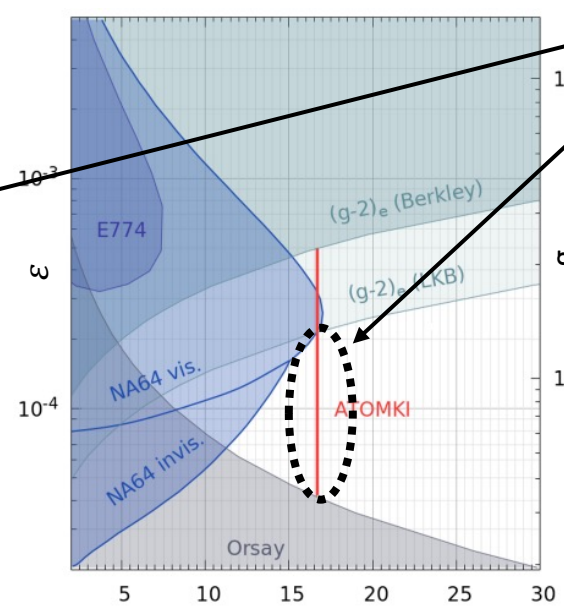
Resonant search on fixed target



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



Phys. Rev. D101, 071101 $m_{A'} [\text{GeV}]$



Phys. Rev. D104, L111102 $m_{A'} [\text{GeV}]$

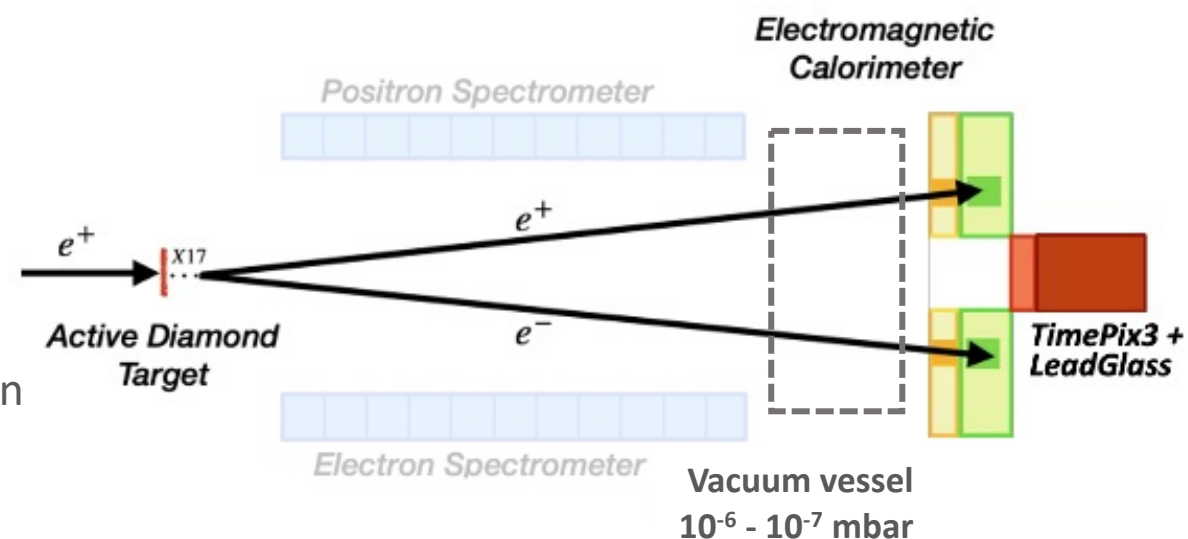
PADME measurement idea: perform a very fine scan of ν_s around the hypothetical mass resonance using positron beam with $E_{\text{beam}} \sim 283$ MeV on target → measure a 2-body final state

PADME Experiment in Run III

Experimental setup

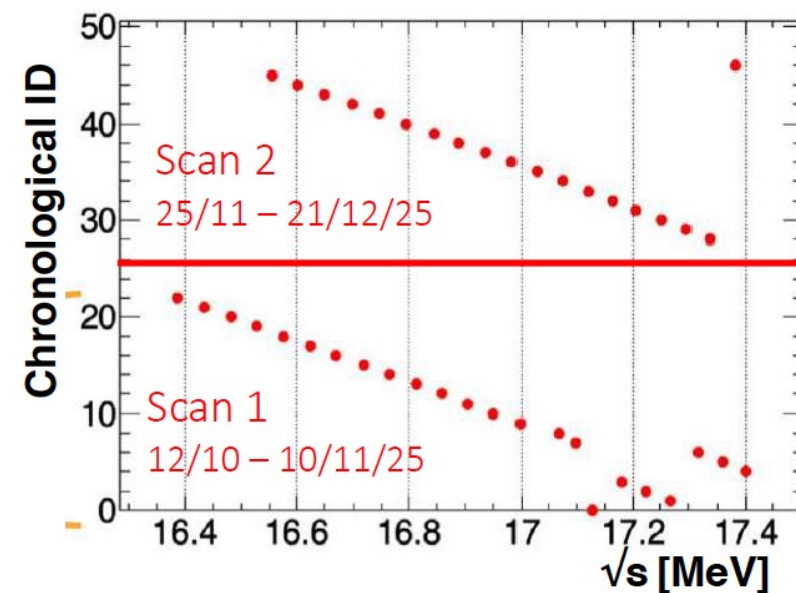
- **Active target** polycrystalline diamond
- **ECal**: 616 BGO crystals, each 21x21x230 mm³
- **ETagger** (scintillator detector) in front of ECal for e/ γ discrimination
- **TimePix3** high granularity silicon-based detector for beam spot
- **LeadGlass** luminometer (NA62 Large Angle Veto spare block)

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



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

- **42 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 $\sim 10^{10}$ PoT each and E_{beam} @(205, 211) MeV
 - 1 point with $\sim 2 \times 10^{10}$ PoT and $E_{\text{beam}} = 402$ MeV

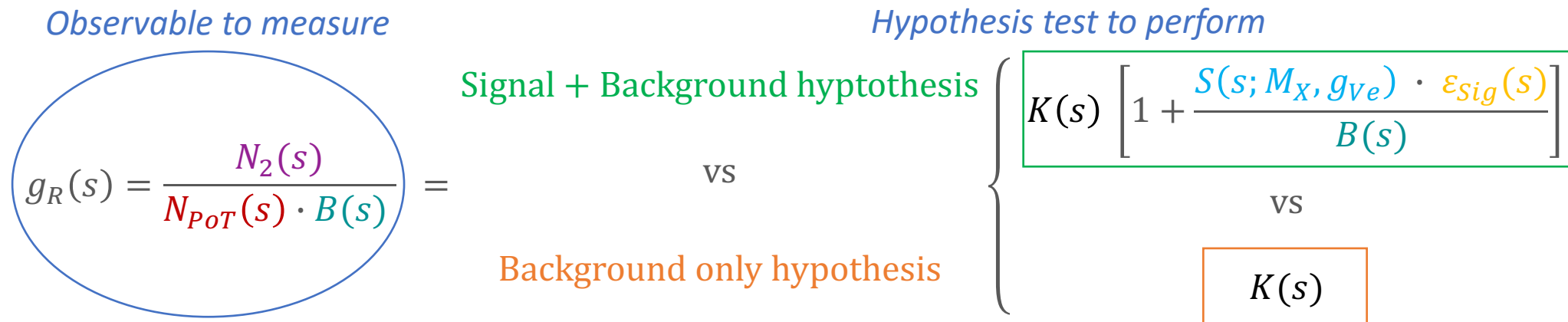


Run III Analysis Strategy

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: $g_R(s) = \left[1 + \frac{S(s; M_X, g_{Ve}) \cdot \epsilon_{Sig}(s)}{B(s)} \right]$
 - without X17 signal: $g_R(s) = 1$

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

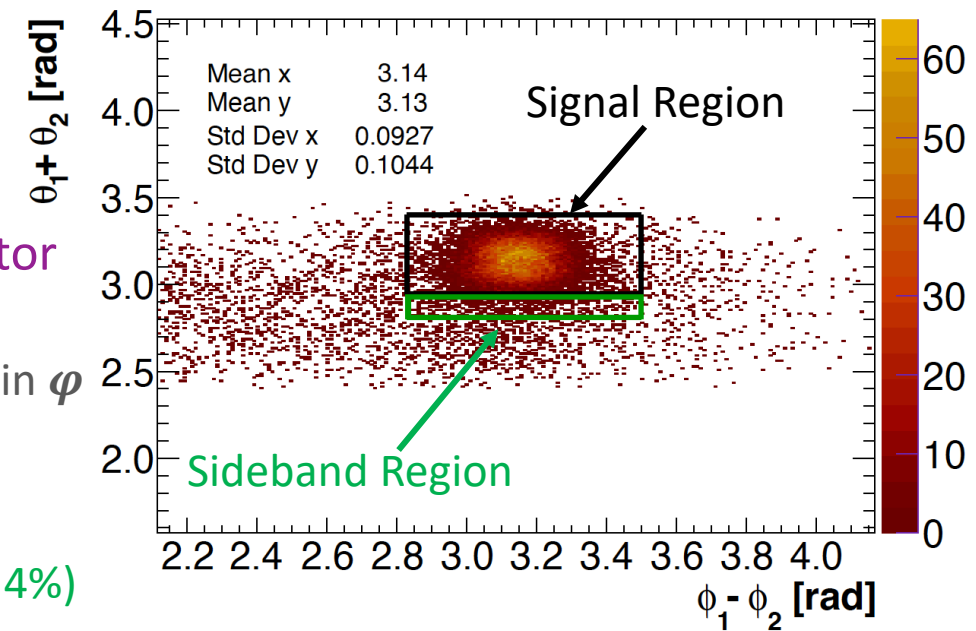


Crucial to determine the systematic errors on the measured quantities: N_2 clusters, N_{PoT} , Bkg yields

Run III Analysis Strategy

N_2 : selection algorithm as independent as possible on beam and detector conditions: required 2 clusters in ECal

- Acceptance reduced by 30% due the presence of the magnet \rightarrow Cut regions in ϕ
- $\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ cut in the center of mass to define the signal region
 - \rightarrow Signal Region is 3σ around the mean value
 - \rightarrow Sideband Region for Bremsstrahlung background normalization ($\sim 4\%$)



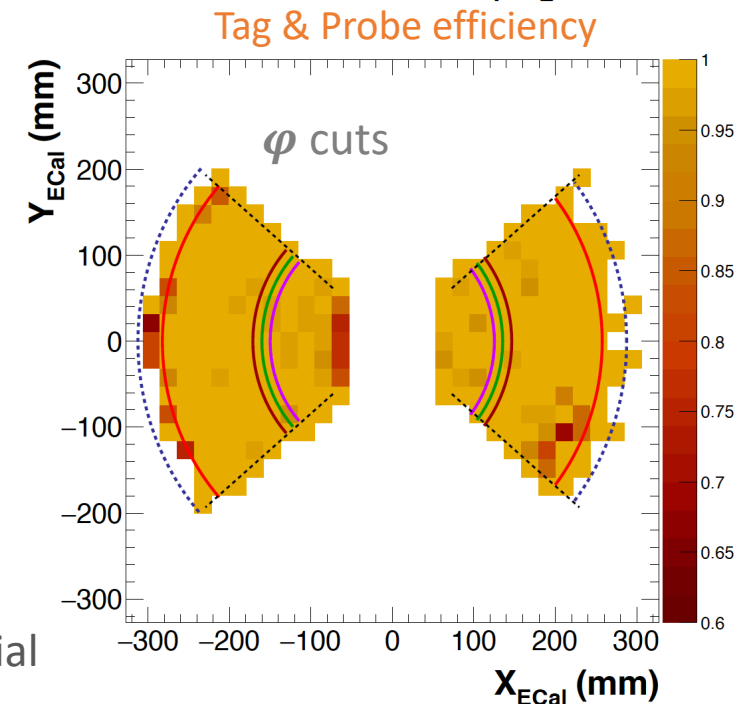
B : main backgrounds are Bhabha scattering and $\gamma\gamma$ annihilation.

- The expected background yield per PoT is determined with MC and reconstruction efficiency estimated with Tag&Probe method \rightarrow data/MC compatible with 1
- B yield normalized to below-resonance energy points to improve systematic uncertainty
- Radiative corrections $e+e-(\gamma)$ and $\gamma\gamma(\gamma)$ evaluated using BabaYaga

N_{PoT} : The number of positron on target per bunch is determined using the LeadGlass calorimeter charge.

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

- Estimation corrected for radiation induced loss and the energy loss in the passive material



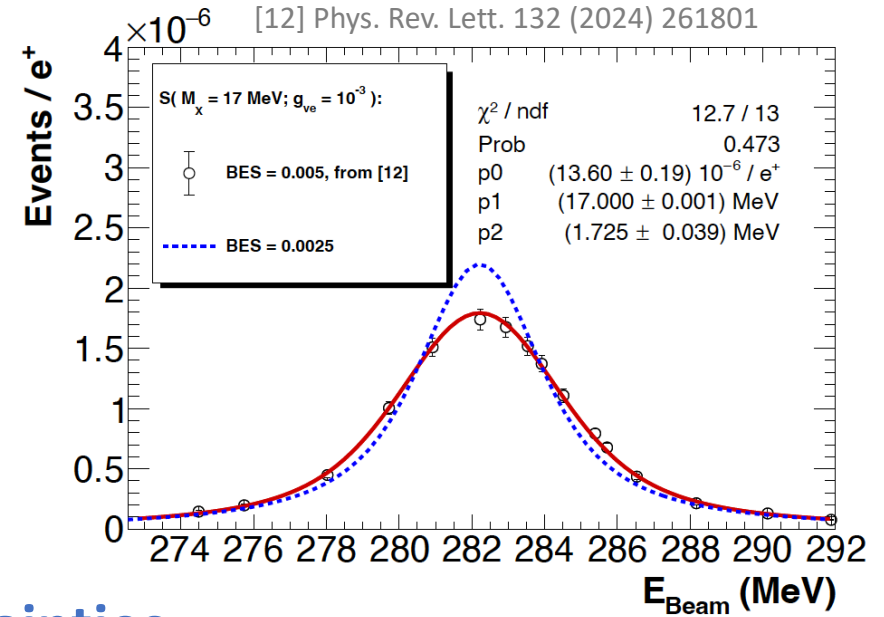
Run III Analysis Strategy

S : the width of the expected excess receive contributions by the beam energy spread and from the electron motion in the target.

- Convolution of the Gaussian for the BES with a Lorentzian

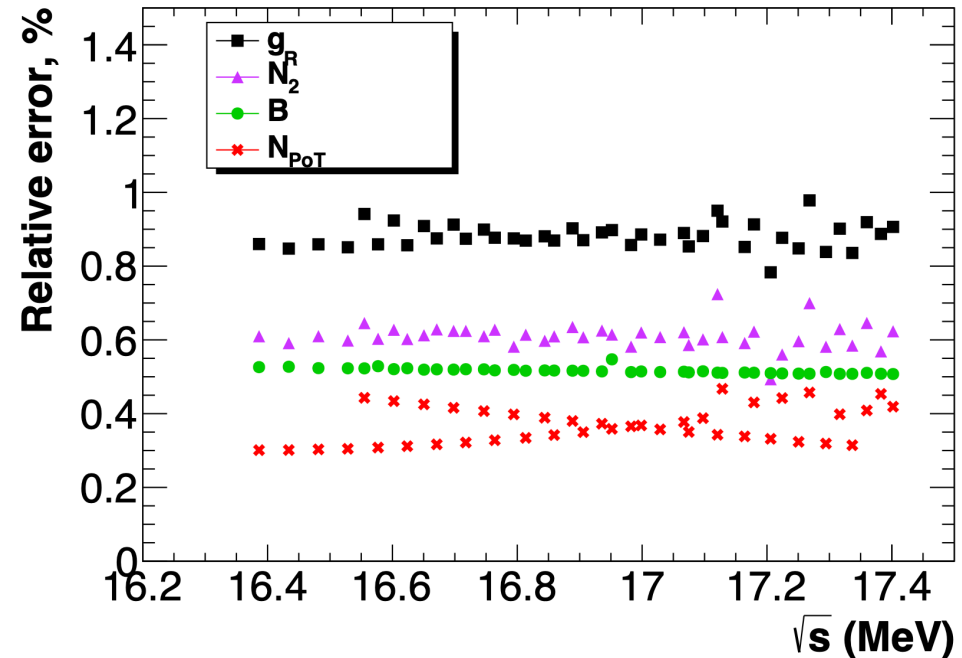
ε_{sig} : signal efficiency determined from MC

- Use of the ratio ε_{sig}/B significantly reduces detector-related systematic



Summary of the systematic uncertainties

Uncorrelated errors	
Source	Uncertainty (% per energy point)
$N_2(s)$	0.60
$B(s)$	0.54
$N_{PoT}(s)$	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



Run III Results

Blind - unblinding procedure

Large expected X17 mass resolution \rightarrow no sideband region in \sqrt{s} can be defined to validate the statistical approach \rightarrow Validation procedure described in 2503.05650 were 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

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

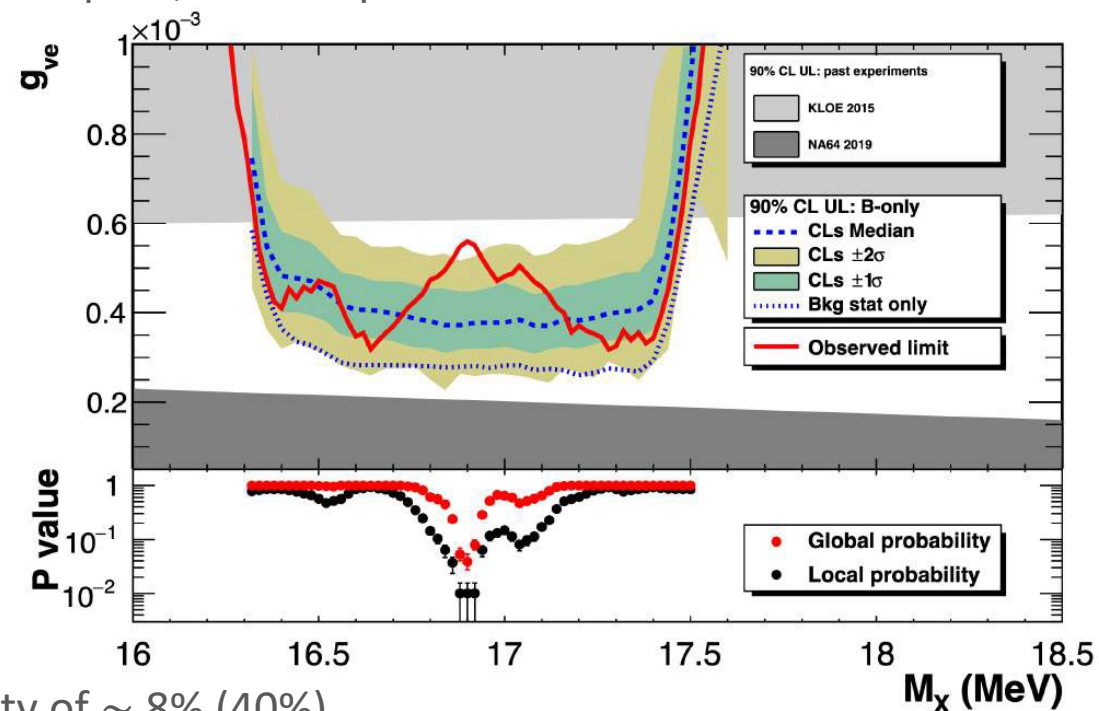
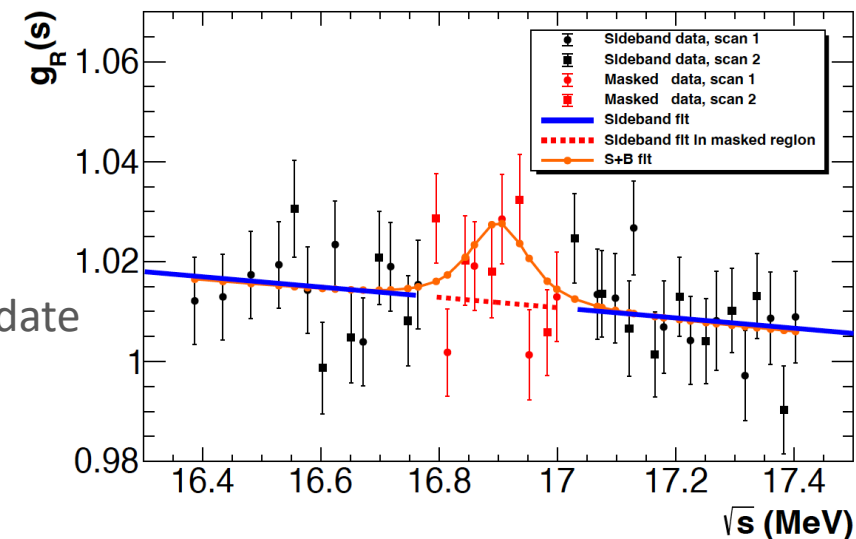
Run III Results

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

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

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

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

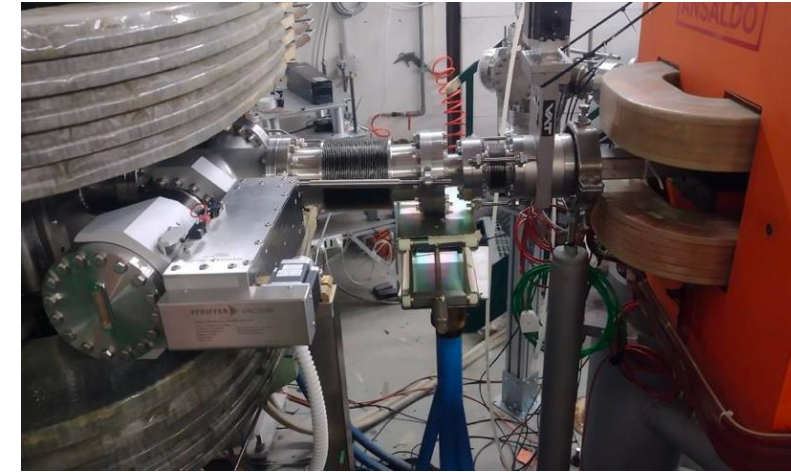


PADME Upgrade for Run IV

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

Diamond target moved



PadMMe



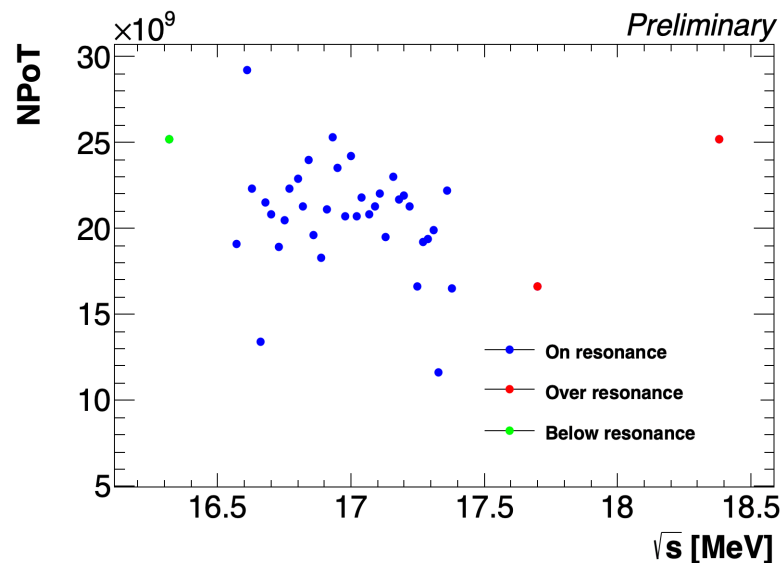
TMM



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/γγ 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	

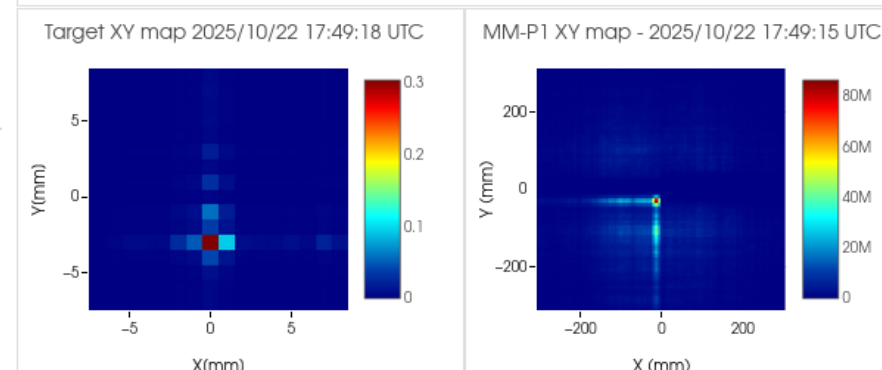
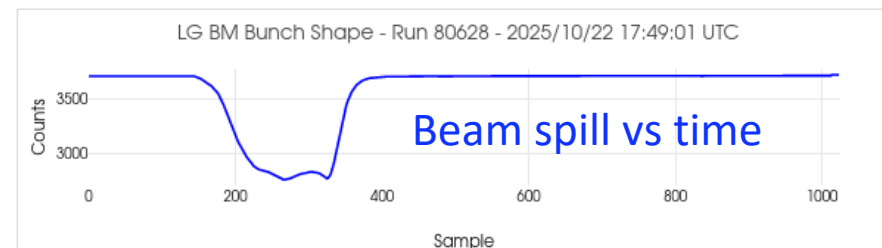
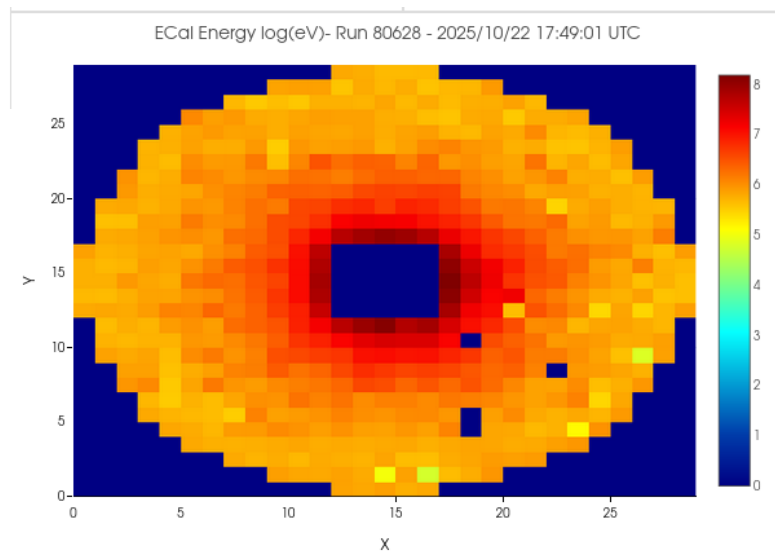
Run IV Data Taking

36 points: Scan 1 and 2 18 points each
$\sim 2.2 \times 10^{10}$ PoT per point
268-295 MeV range, with 0.75 MeV spacing
1 point @ 260 MeV
2 points @ 300 and 330 MeV

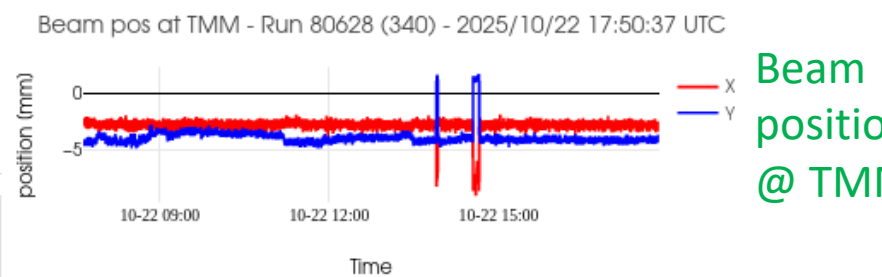


Some online monitoring plots of the data taking

full ECal acceptance available thanks to th target movement



Beam spot @ target Beam spot @ PadMME



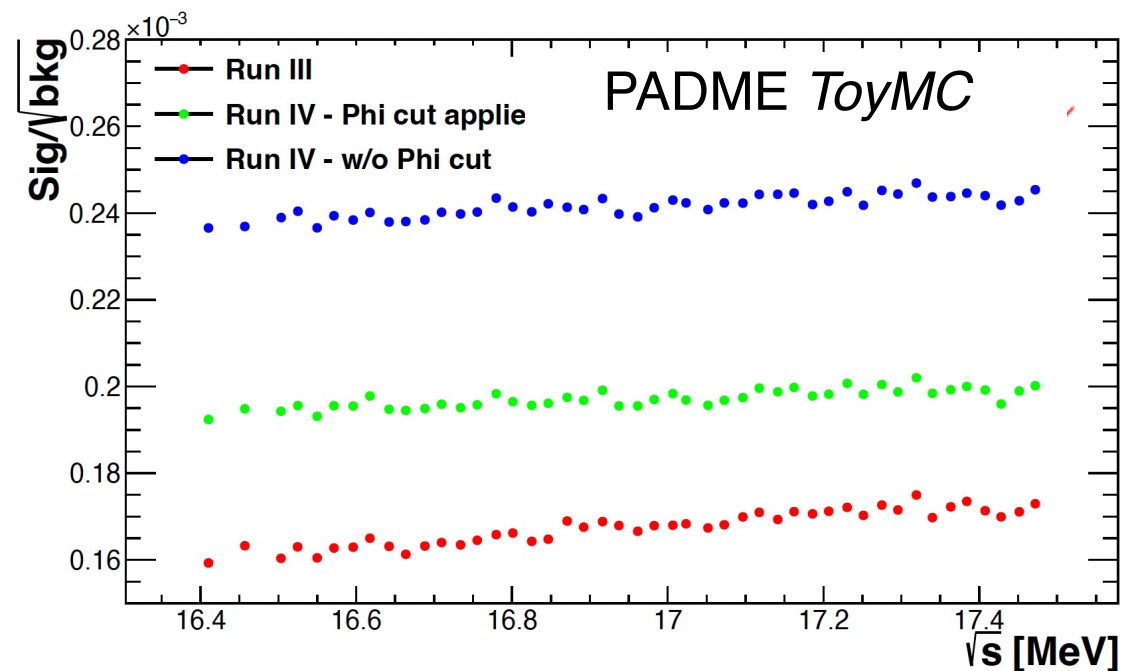
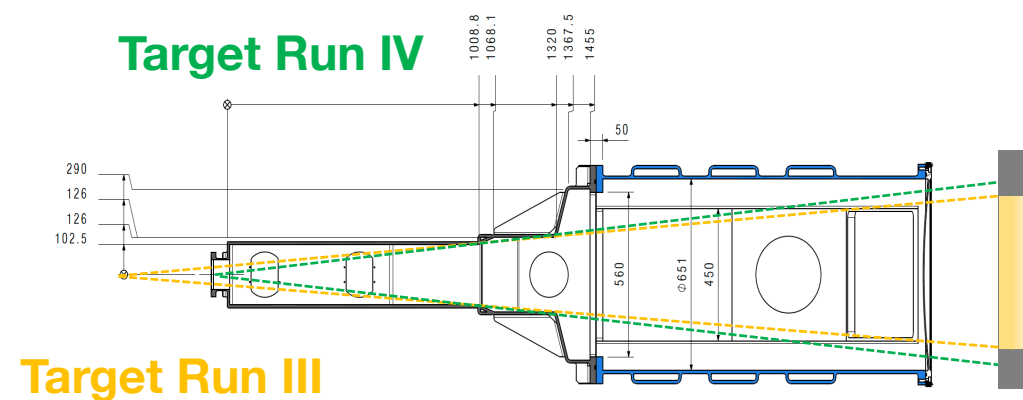
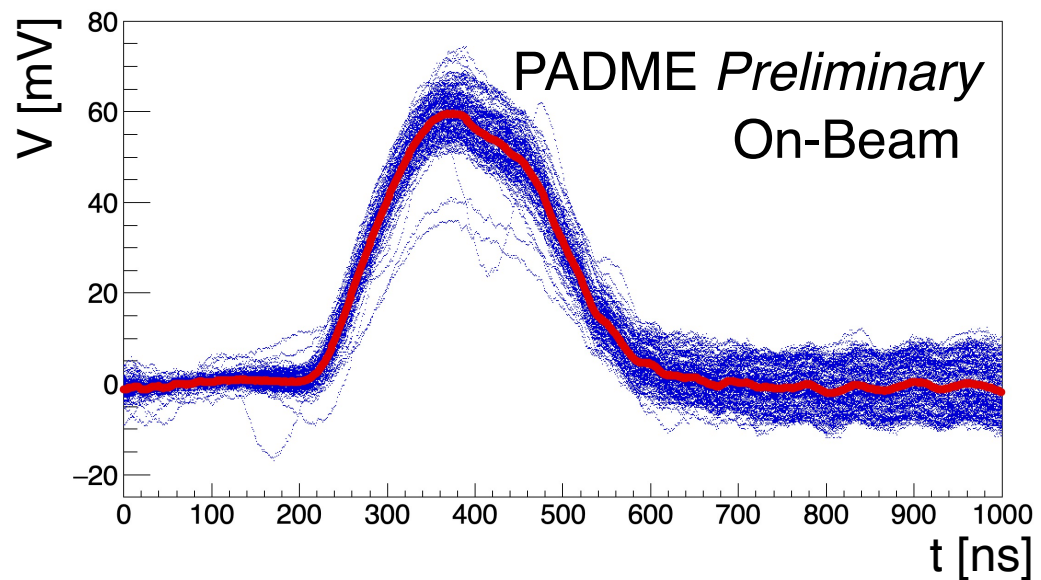
Diamond Target

Target position changed from 3.70 m to 3.36 m

- ϕ_{lab} -cut can be totally removed or adapted
- Acceptance region enlarged \rightarrow luminosity increases by a factor of 2.5

Reconstruction optimization

- Target waveform affected by common-mode noise
 \rightarrow Average over $\mathcal{O}(100)$ waveforms
- Beam multiplicity $\propto Q = \sum_{t_{start}}^{t_{stop}} \frac{V(t)}{Z}$



PadMMe: Micromegas tracker

Micropattern gas detector operated in TPC mode

- Detector dimensions $88 \times 88 \text{ cm}^2$
- Two drift gaps of 5 cm each ($\sim 3 \text{ kV}$)
- Amplification gap $\sim 128 \mu\text{m}$

Novel diamond-shaped readout

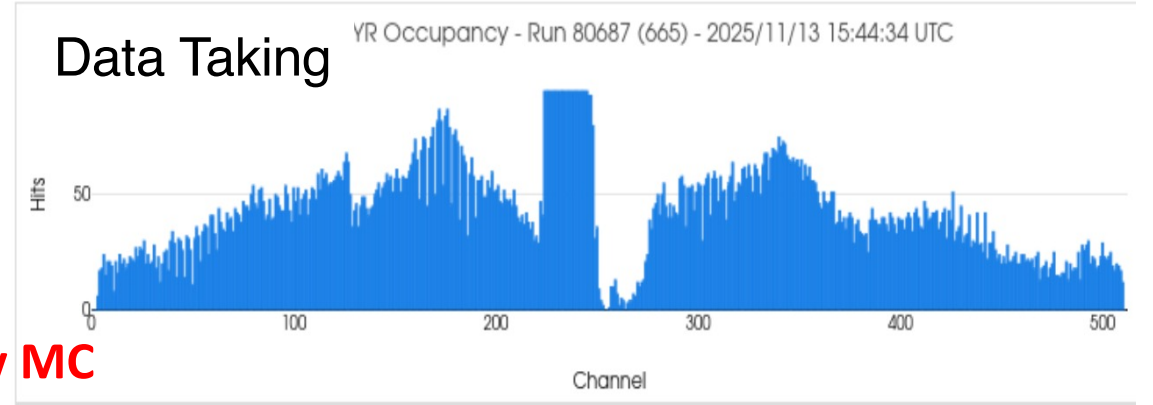
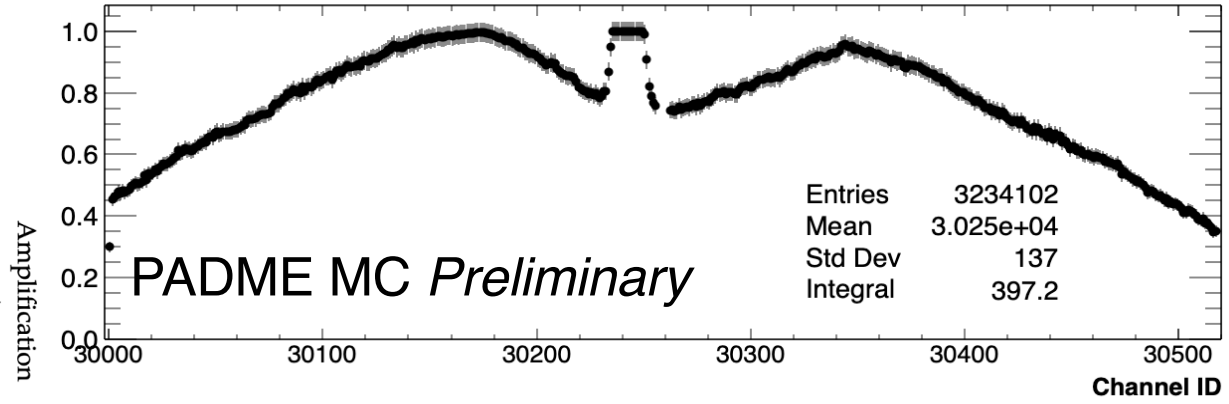
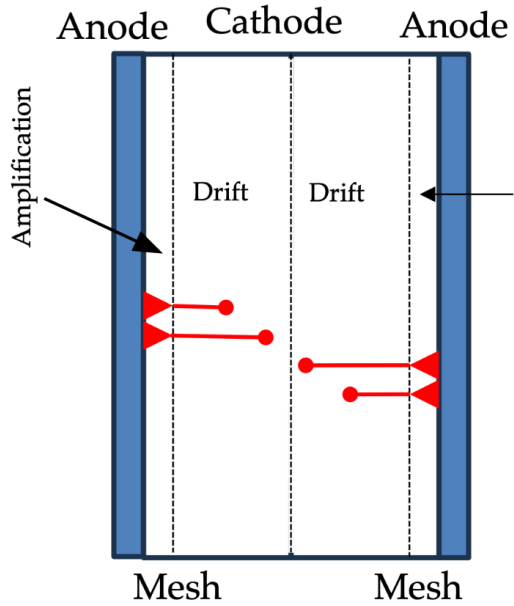
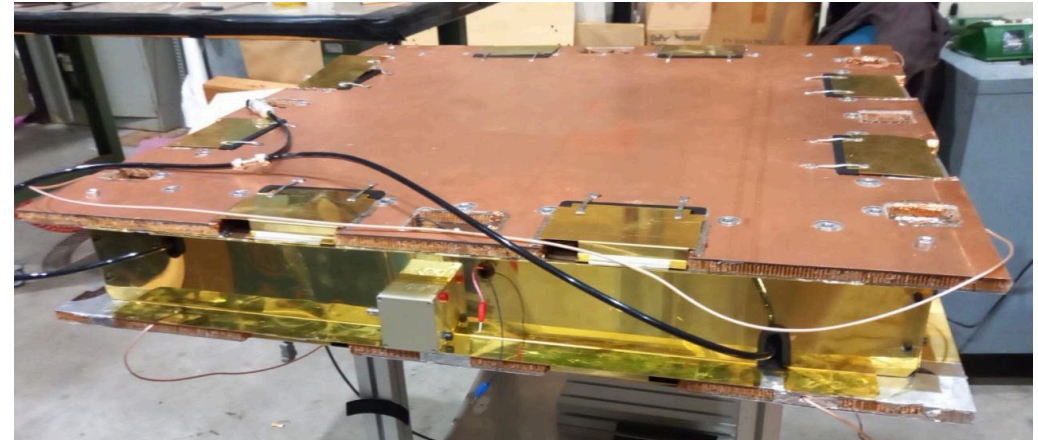
- Able to read both x and y coordinates with reduced coupling

Readout Electronics: APV25

- Time window up to 675 ns (drift time $\sim 500 \text{ ns}$)

Gas Mixture Ar:CF₄:Isobutane (88:10:2)

- Drift velocity $\sim 10.5 \text{ cm}/\mu\text{s}$
- **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)



Need to face very high occupancy (85%) → well reproduced by MC

PadMMe Preliminary Performance

Huge combinatory in pattern recognition

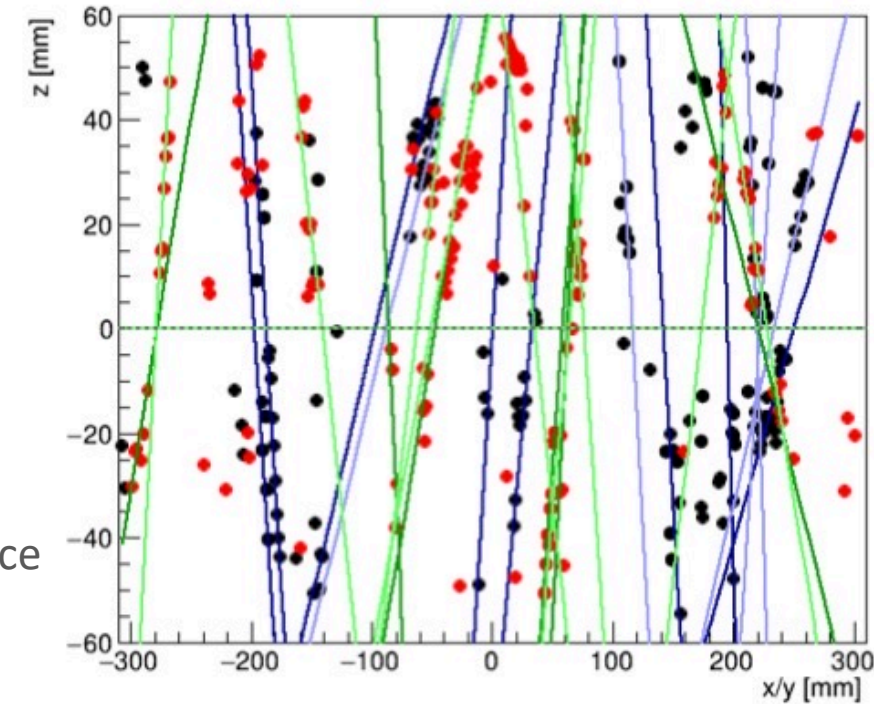
~200 track candidates found without Interaction Point (IP) constraint

→ IP oriented pattern recognition algorithm

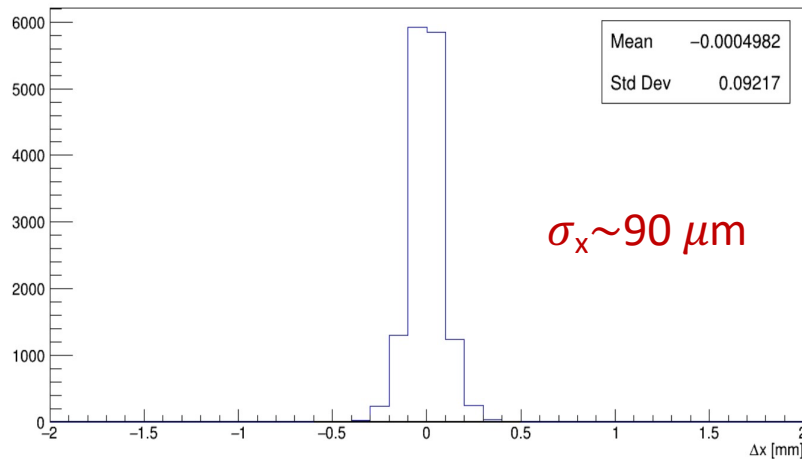
Each charged particle measured in 2 planes – both X and Y coordinates

- **Level-0 tracks** correspond to track segments in each plane and coordinate
 - High efficiency but also high fakes level: need at least 2/3 out of 4 coincidence
 - **Level-1 track: 2 planes coincidence**
- Requiring the **matching with ECal clusters** fakes are further reduced

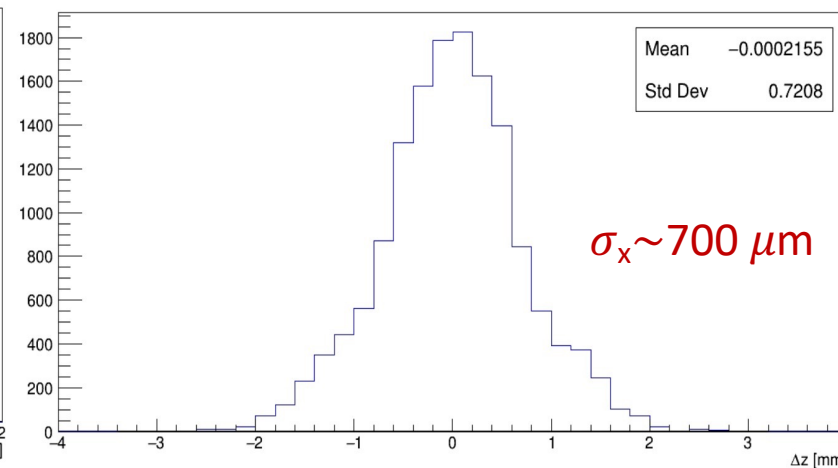
Lateral view



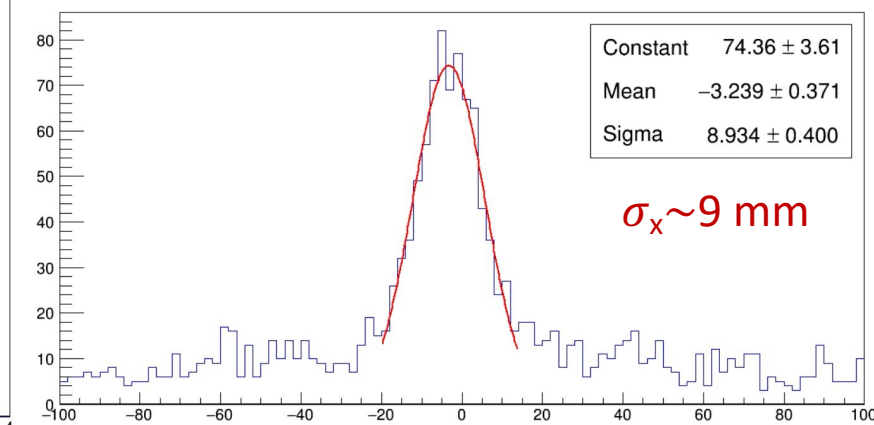
X direction track residual



Z direction track residual



Track to cluster association



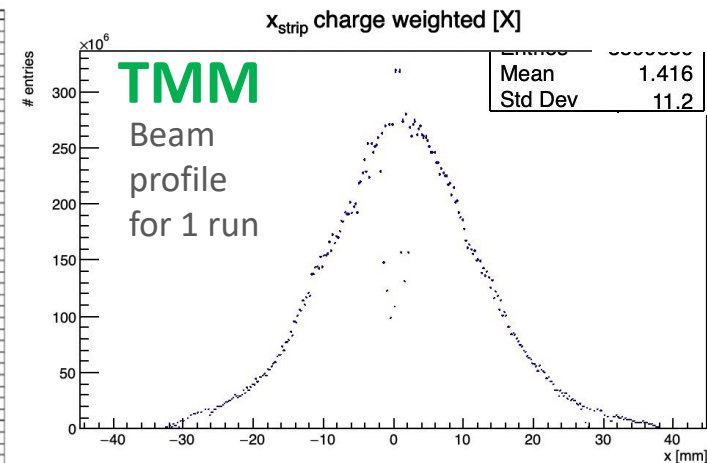
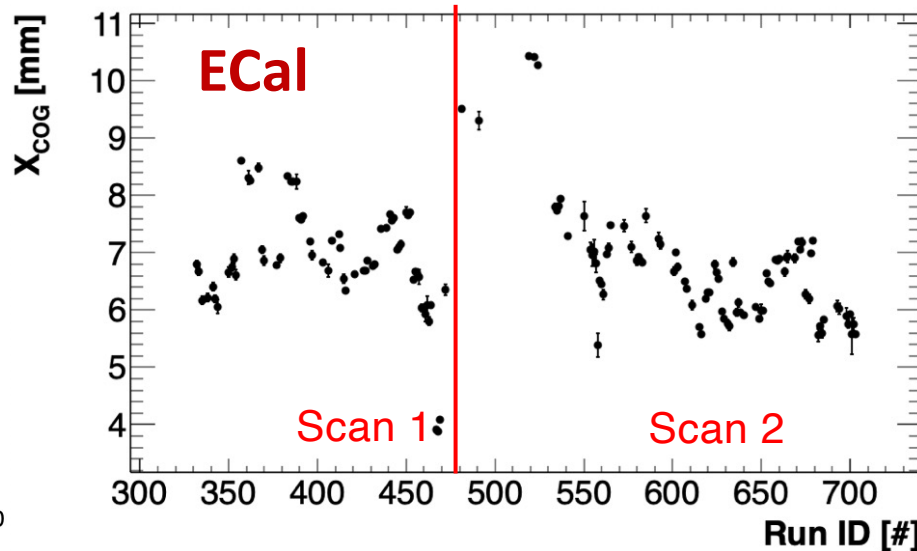
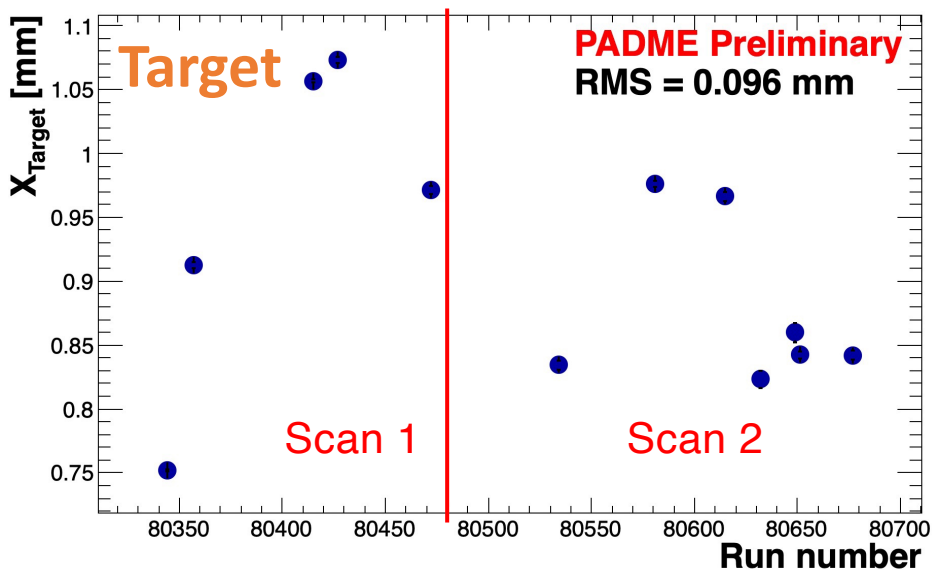
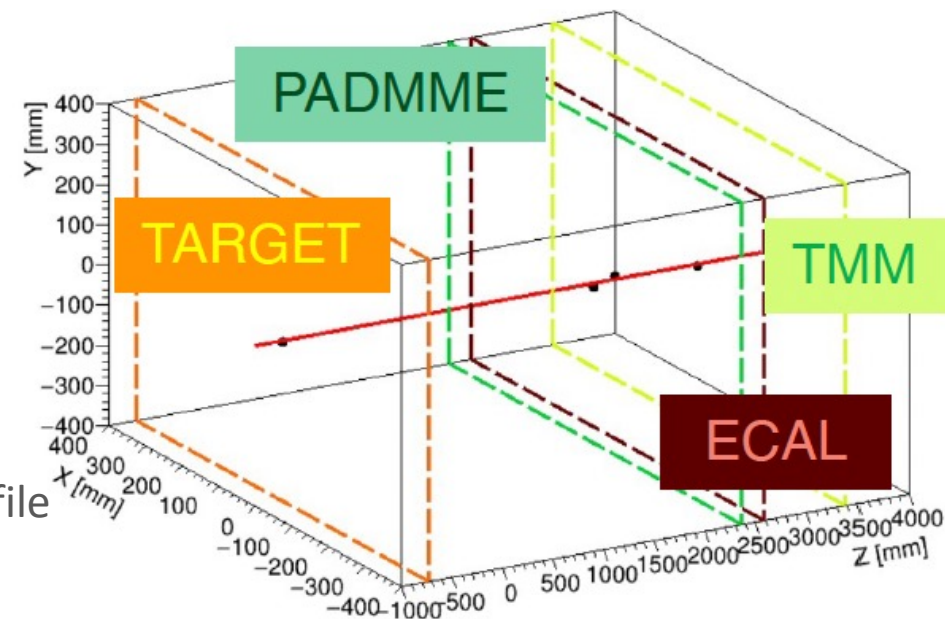
Beam Conditions

Beam monitor at 4 different levels using different methods to measure position, angle, beam spread and beam divergence

Target: charged-weighted mean over the 3 fired strips: beam position stable within 100-150 μm . Full scan evaluation ongoing

PadMMe and **TMM** analysis ongoing: preliminary estimation of the beam profile from weighted position with strip charge \rightarrow work on strip charge calibration

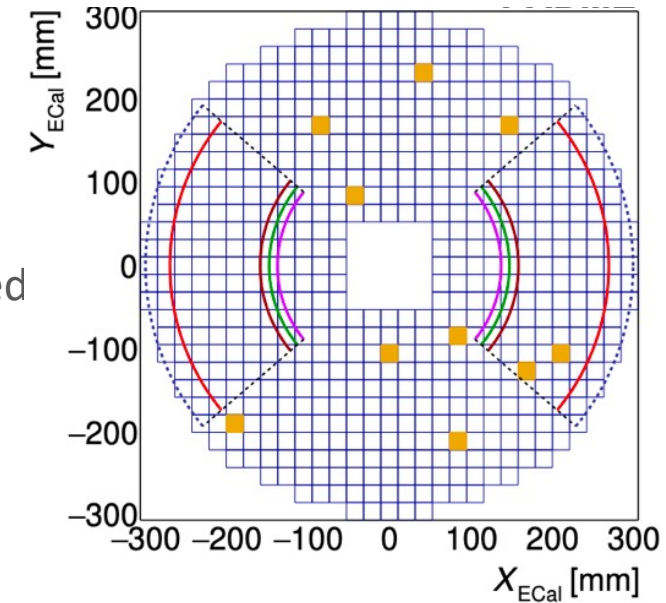
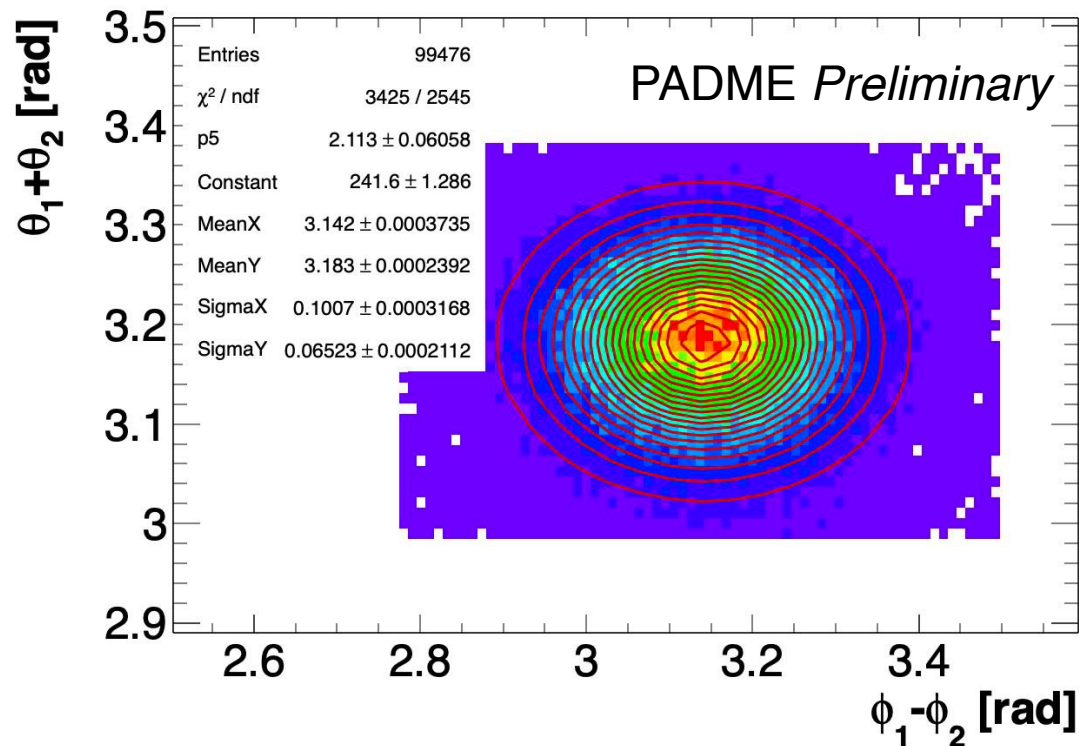
ECAL: beam parameters estimated using the two-clusters center of gravity (CoG): beam position stable at few mm level in X and at cm level in Y



Run IV Preliminary Event Selection and Background

As for Run III, two body final states selected using ECal clusters position information **Acceptance study** with some preliminary estimations without Bremsstrahlung subtraction and missing lead-glass calibration:

- With ϕ_{lab} cut: yield increases $\times 1.5$ (as expected from MC studies)
- No ϕ_{lab} cut: yield increases $> \times 2.5$ and enlarging the low-energy cluster acceptance (expected 2.3 from ToyMC)



Preliminary flat background estimation

- Selected events signal can be fitted with a 2D Gaussian + constant
- Preliminary Flat Bkg $\sim 7\%$ (was 4% at Run III)
- Improvement in $S/V(S+B)$ by a factor 1.5 wrt to RunIII
- Stat error on the yield aimed at $\sim 0.35\%$ for 1×10^{10} POT

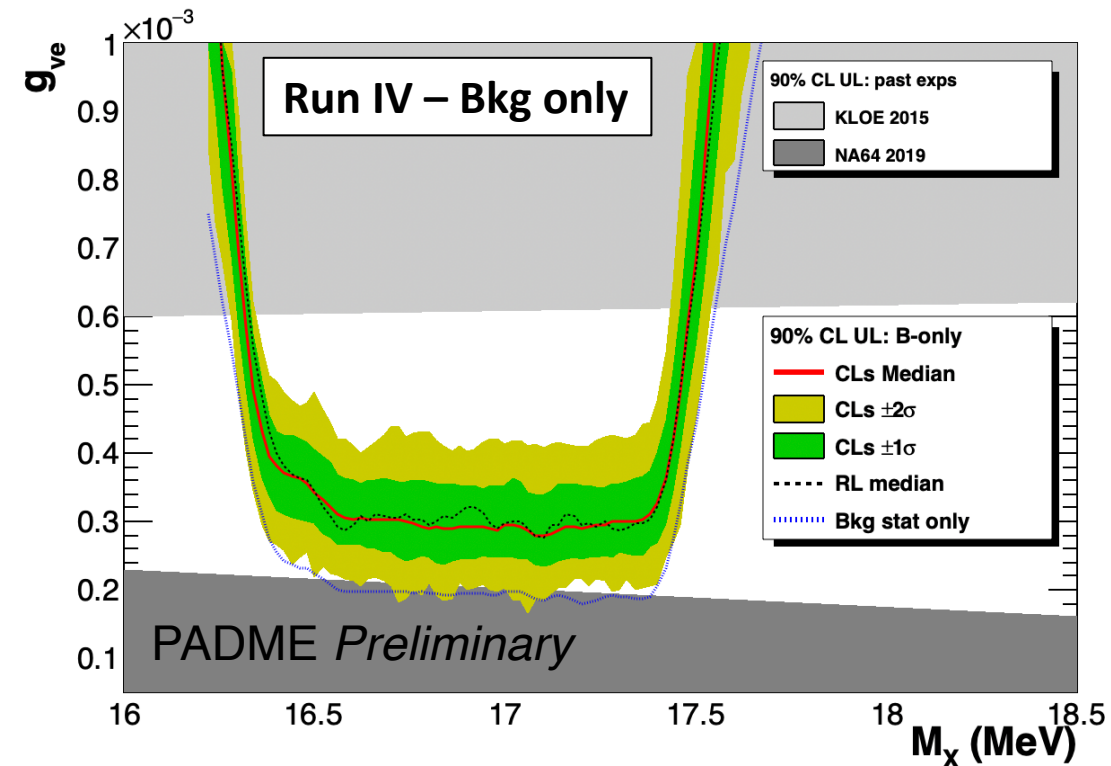
Conclusions

The **Run III** data analysis shows an excess @ 16.9 MeV, with global p-value equivalent to $1.8(2)\sigma$

- Overall uncertainties $\sim 0.9\%$ per energy point
- No indications of X17 well beyond 2σ -equivalent global p-values

The **Run IV** data needed to clarify

- Improve sensitivity (higher statistics and better control of systematics) aiming at a factor of 2 error reduction
- New Micromegas tracker were installed to measure the absolute $ee/\gamma\gamma$ cross section allowing combined analysis
- Redundant beam parameter measurements also with TMM to the end of the line for beam monitor
- Signal yield increased by a factor of ~ 2.5 wrt Run III



On the basis of the ongoing analysis of Run IV and during the test runs, we are currently evaluating the possibilities to significantly increase the sensitivity of the experiment in future running campaign (using lighter materials for target, reduce passive material in the tracker to mitigate multiple scattering)

The image is a composite background. At the bottom, there is a silhouette of a city skyline at sunset, with a warm orange and yellow glow. The skyline includes a prominent cathedral with many spires on the left and several skyscrapers. One skyscraper has the word 'CNET' visible on its side. Above the skyline, the background transitions into a vast, dark space filled with a network of glowing blue lines connecting numerous small, bright stars. In the upper left quadrant, two large, dark, circular black holes are depicted, each surrounded by a bright, glowing purple and white ring of light. The overall scene is a blend of urban architecture, celestial phenomena, and a futuristic network of light.

Backup

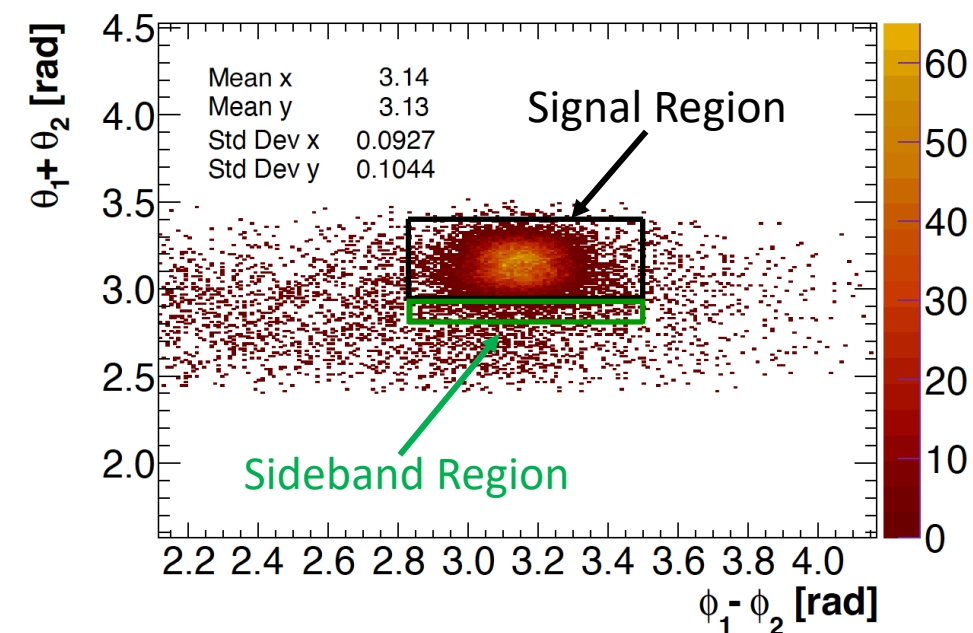
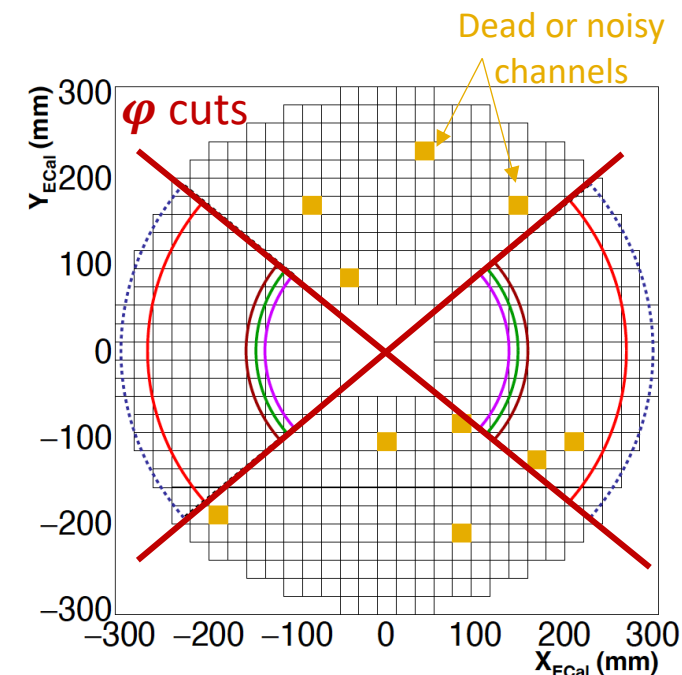
Event selection

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

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

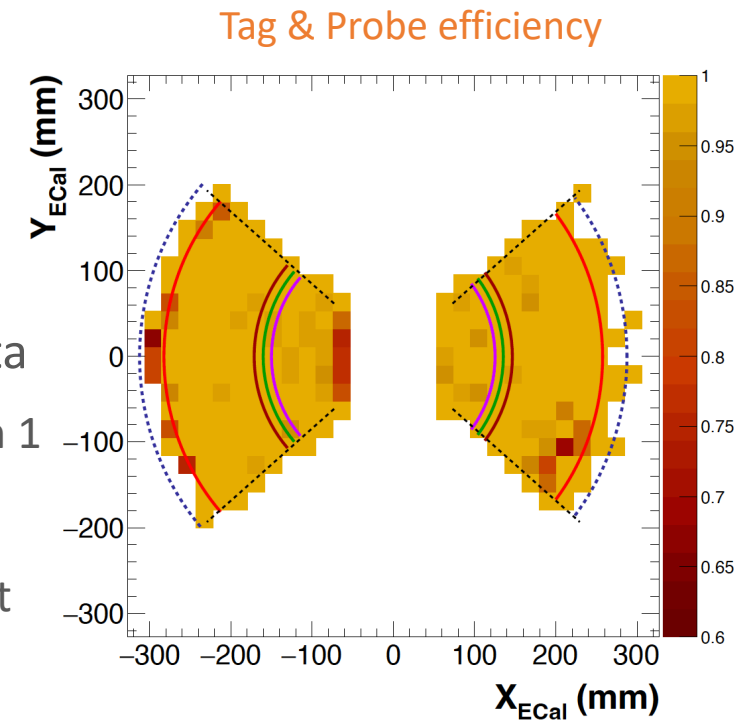
The main background sources are the Bhabha scattering and $\gamma\gamma$ annihilation.

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

- **Reconstruction efficiency** estimated with Tag&Probe method \rightarrow data/MC compatible with 1

Effects that spoils the B estimation:

- **Beam spot direction & shape** \rightarrow acceptance variation of 0.08% - 0.1%/ mm of vertical shift
- **Stability of cuts** due to acceptance edge effects and leakage \rightarrow estimated by varying R_{\max}



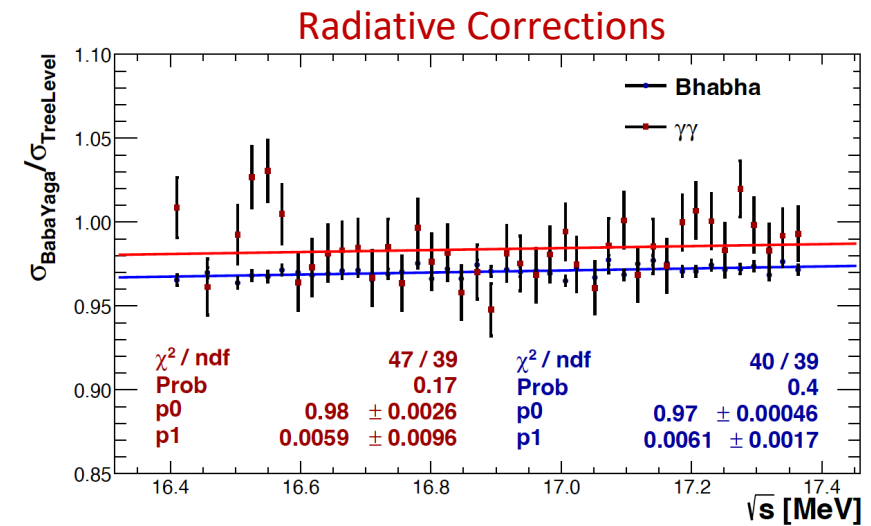
Source of uncertainty	Error on B [%]
MC statistics	0.4
Tag & Probe eff.	0.35
Beam spot variations	0.05
Cut stability	0.04
Total (uncorrelated)	0.54
Absolute B yield (correlated, affect K(s))	1.8

B yield normalized to below-resonance energy points

\rightarrow improve systematic uncertainty

Radiative corrections
 $e+e-(\gamma)$ and $\gamma\gamma(\gamma)$

evaluated using BabaYaga
 \rightarrow 3% decrease in the total cross section @ 16.92 MeV and a \sqrt{s} slope of -0.6(6) % MeV $^{-1}$

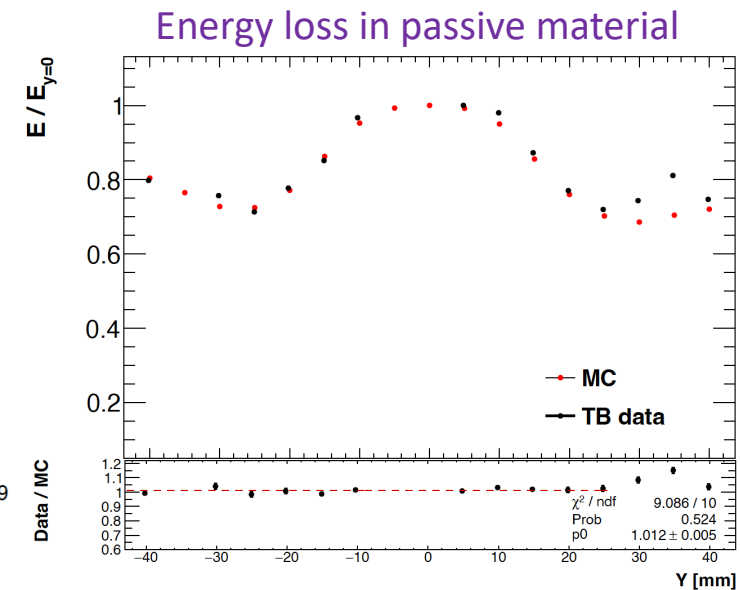
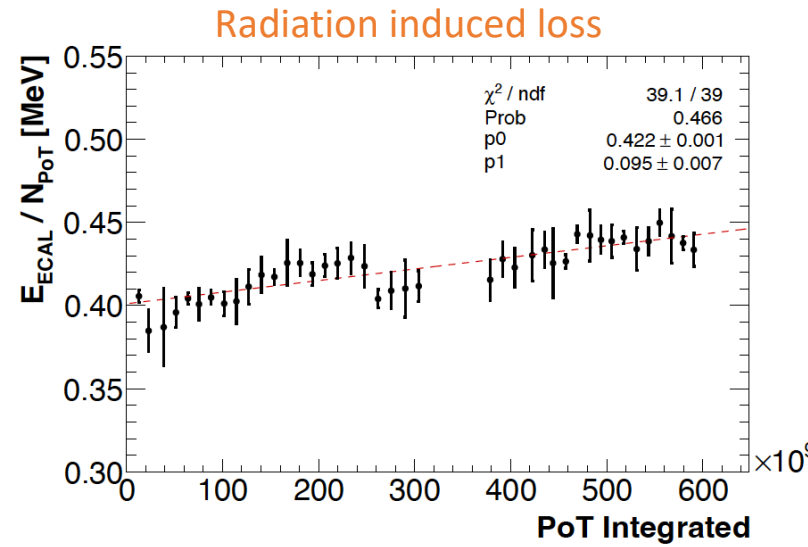


Positron on target

Estimation of N_{PoT}

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

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



Corrections for precise estimation of N_{PoT}

- Radiation induced loss

- Run III dose ~ 2.5 krad \rightarrow transparency changes for O(krad)
- Estimated from 2 flux proxy observables: Q_{target} , E_{ECAL}
 \rightarrow show a linear energy dependence on the integrated flux \rightarrow LG yield decreases by $0.097 \pm 0.007 \rightarrow N_{PoT}$ 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 \rightarrow passive material crossing (TimePix cooling system)
- Test beam to check goodness of MC simulation \rightarrow evaluate the overall energy loss for the specific beam conditions \rightarrow 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: 0.25(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: $\Delta P0/P0 \sim 0.1\%$, $\Delta P1/P1 = 3\%$, correlation = -1.8%

