PADME Run III analysis results

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The X_{17} anomaly @ATOMKI

Anomaly in the angular correlation of e^+e^- pairs emitted via IPC in the ^{8}Be, ^{4}He and ^{12}C nuclear de-excitation.

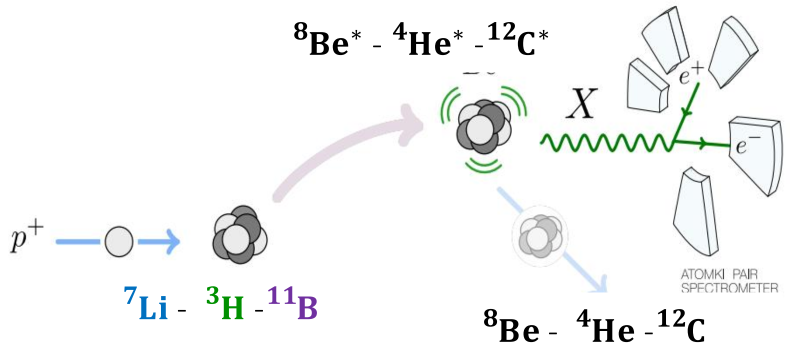
It seems to be compatible with a **new neutral mediator called X_{17}**:

- $m_{X_{17}} \sim 17$ MeV
- $\Gamma_{X_{17}} \simeq \frac{\epsilon^2 \alpha m_{X_{17}}}{3} \rightarrow$ (vector) $\Gamma_V = 0.5 \left(\frac{g_V}{0.001}\right)^2$ eV
- Observation at ATOMKI (Hungary) + HUS (Vietnam)

Phys. Rev. C 106, L061601

Neutrino Constraints and the ATOMKI X17 Anomaly

An analysis with the angular data alone of 11 different measurements finds that the data is well described by a new particle of mass $m_X = 16.85 \pm 0.04$ MeV with an internal goodness-of-fit of 1.8σ calculated from Wilks' theorem at $\chi^2/dof = 17.3/10$. We use only the best fit



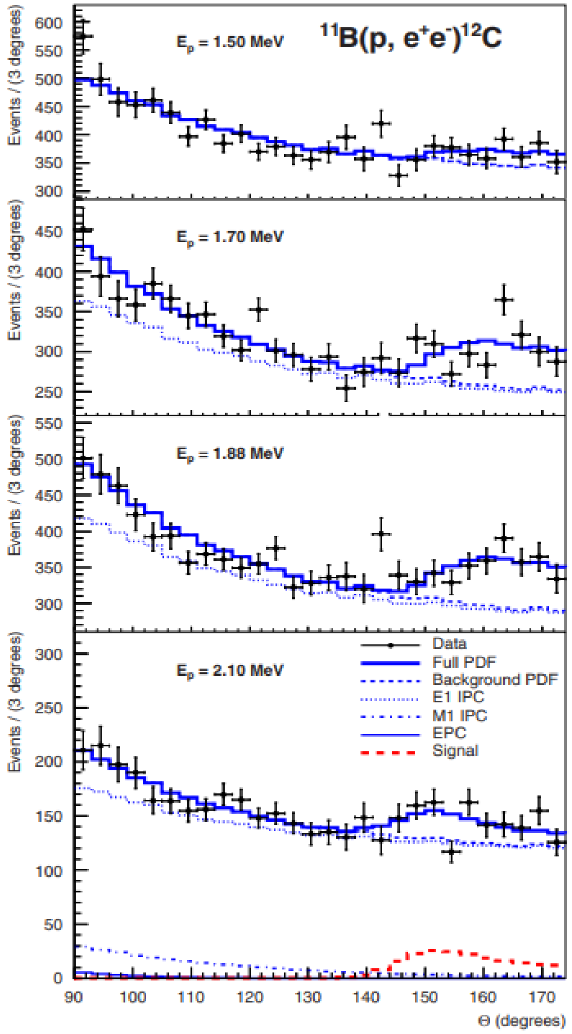


TABLE III. Nuclear excited states N_*, their spin-parity $J_*^{P_*}$, and the possibilities for X (scalar, pseudoscalar, vector, axial vector) allowed by angular momentum and parity conservation, along with the operators that mediate the decay and references to the equation numbers where these operators are defined. The operator subscripts label the operator's dimension and the partial wave of the decay, and the superscript labels the X spin. For example, $\mathcal{O}_{4P}^{(0)}$ is a dimension-four operator that mediates a P-wave decay to a spin-0 X boson.

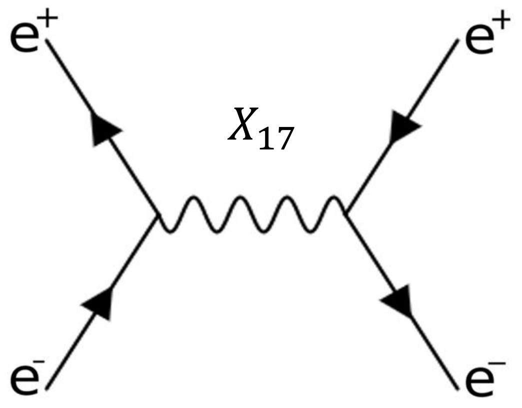
N_*	$J_*^{P_*}$	Scalar X	Pseudoscalar X	Vector X	Axial Vector X
^{8}Be(18.15)	1^+	...	$\mathcal{O}_{4P}^{(0)}$ (27)	$\mathcal{O}_{5P}^{(1)}$ (37)	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)
^{12}C(17.23)	1^-	$\mathcal{O}_{4P}^{(0)}$ (27)	...	$\mathcal{O}_{3S}^{(1)}$ (29), $\mathcal{O}_{5D}^{(1)}$ (34)	$\mathcal{O}_{5P}^{(1)}$ (37)
^{4}He(21.01)	0^-	...	$\mathcal{O}_{3S}^{(0)}$ (39)	...	$\mathcal{O}_{4P}^{(1)}$ (40)
^{4}He(20.21)	0^+	$\mathcal{O}_{3S}^{(0)}$ (39)	...	$\mathcal{O}_{4P}^{(1)}$ (40)	...

Resonant X_{17} search @PADME Run III

- $\sigma_{res} \propto \frac{g_{V_e}^2}{2m_e} \pi Z\, \delta(E_{res} - E_{beam})$ → dominant wrt other signal production processes
- $\sqrt{s} \simeq m_X$ → fine scan with the e^+-beam looking for an excess over SM BKG

  @PADME: X_{17} production through resonant annihilation in diamond target: scan $E(e^+) \sim 282$ MeV aiming to measure 2 body final state yield **$N_2(s)$**

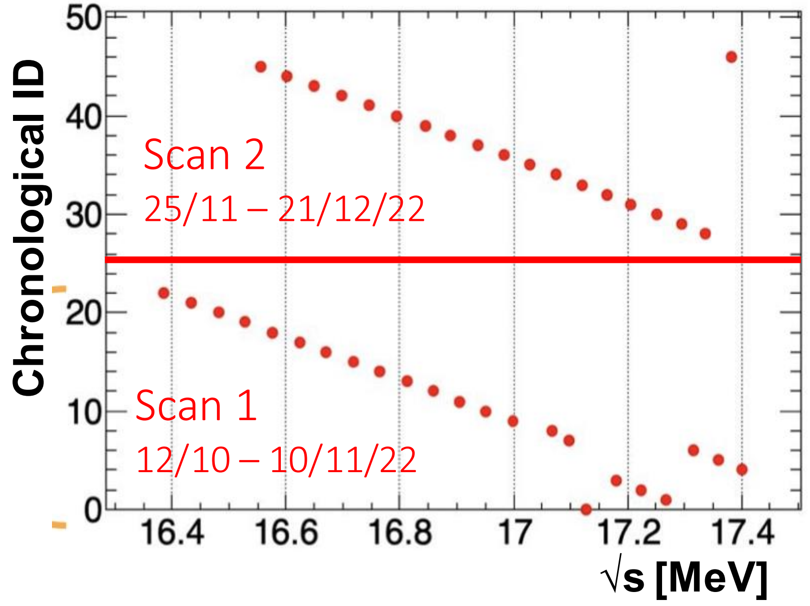
  [*PRD* 106 (2022) 11, 115036]



Run III collected data ~ **6x10^{11} PoT** ~ 10^{10} PoT per $\sqrt{s}$ point:

- **47 on-resonance points:** E_{beam} @(263, 299) MeV, δE_{beam} ~0.75 MeV energy step
  - 2 different scan in time → Scan 1 and 2
- **6 out-of-resonance points:** X_{17} production forbidden → SM studies & sideband

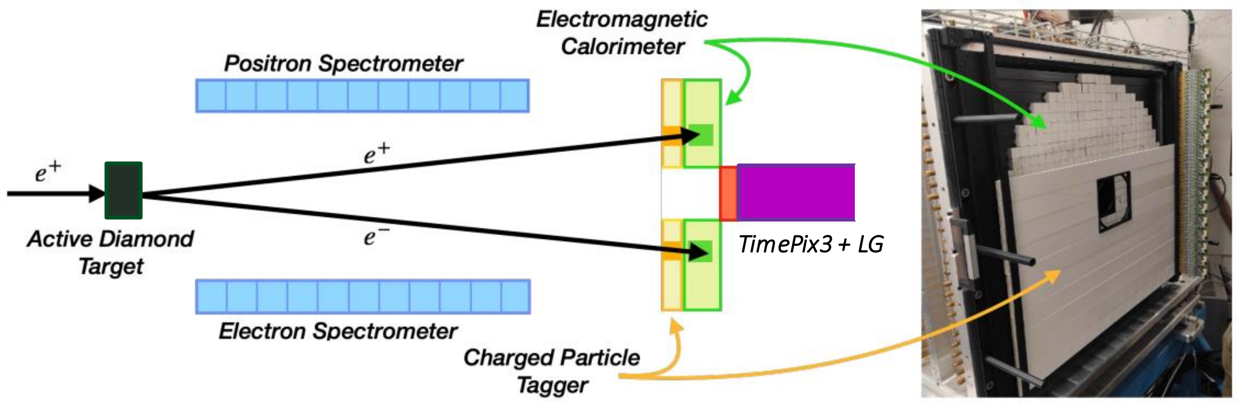
[*JHEP* 08 (2024) 121]

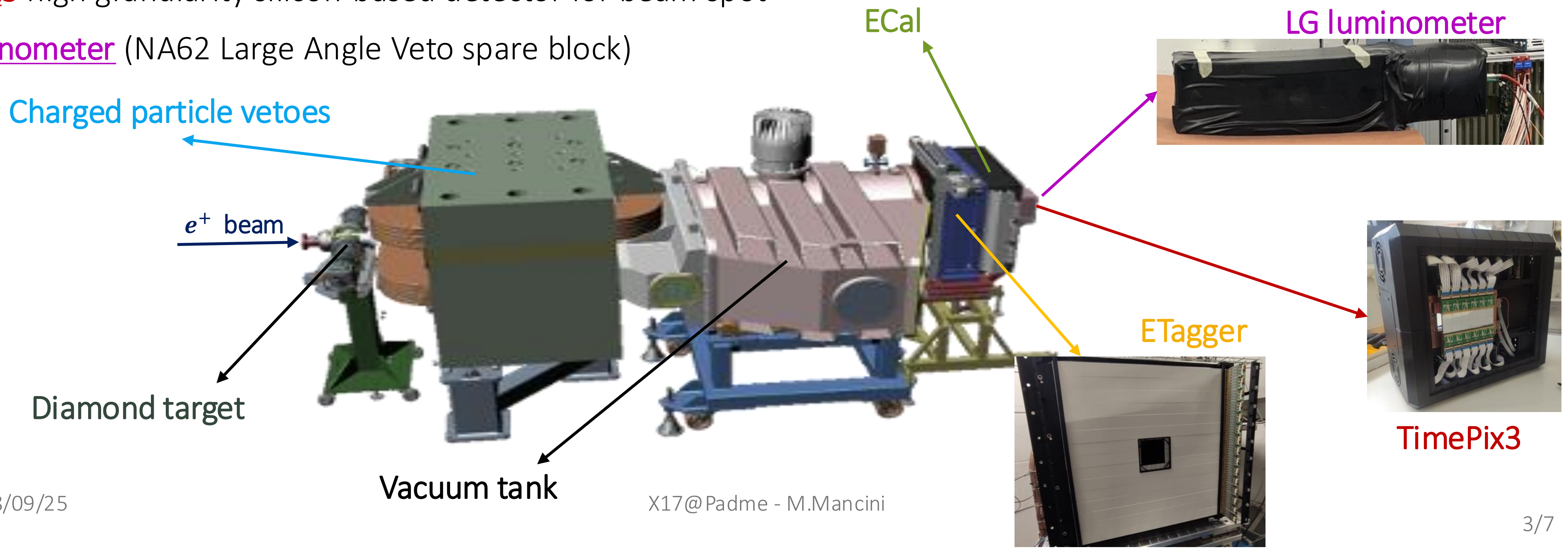


The PADME Run III experimental setup

Run III experimental setup for the X_{17} search:

- Active target polycrystalline diamond
- PADME magnetic field off
- ECal: 616 BGO crystals, each 21x21x230 mm^3
- Charged particle vetoes not used
- ETagger (scintillator detector) in front of ECal for e/γ discrimination
- TimePix3 high granularity silicon-based detector for beam spot
- LG luminometer (NA62 Large Angle Veto spare block)





Analysis inputs & final error budget

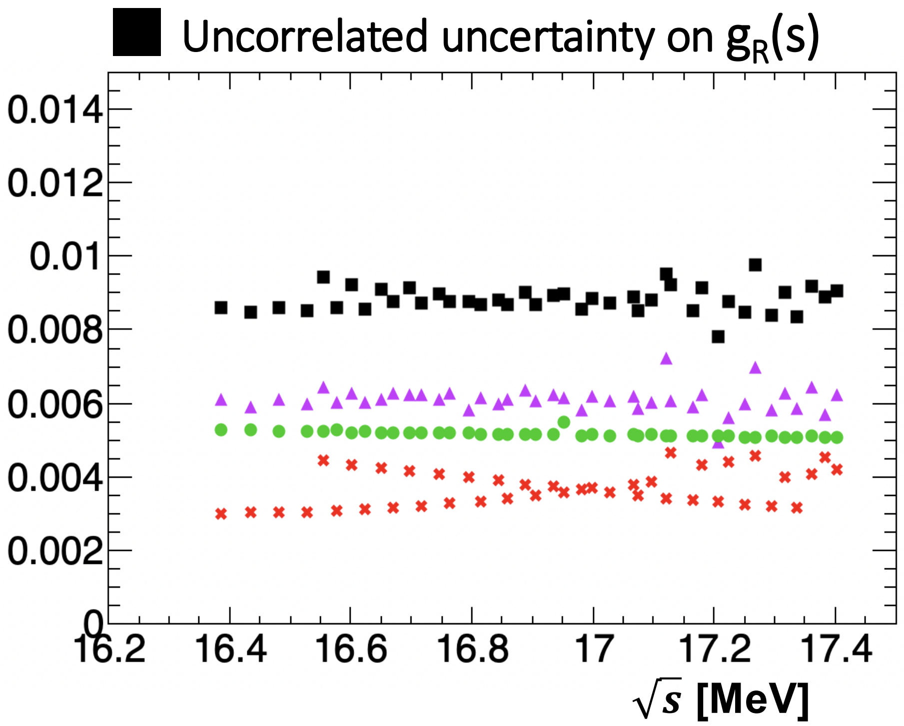
Signal + bkg hypothesis → $N_2(s)$ / $N_{PoT}(s)$ $B(s)$ = $g_R(s)$ = $K(s)[1 + S(s; M_X, g_{Ve})\ \varepsilon_S(s)/ B(s)]$

To be compated with

Bkg only hypothesis → $N_2(s)$ / $N_{PoT}(s)$ $B(s)$ = $K(s)$

Analysis inputs:

- $K(s)$ → DATA-MC scale factor
- $N_2(s)$ → 2-body final states in ECal ▲
- $N_{PoT}(s)$ → e^+ on target from LG beam-catcher ✖
- $B(s)$ → expected bkg yield per PoT ●
- $S(s; M_X, g_{Ve})$ → expected signal production for {mass, coupling} = $\{M_X, g_{Ve}\}$
- $\varepsilon(s)$ → signal acceptance and selection efficiency



$K(s)$, 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

Uncorrelated errors

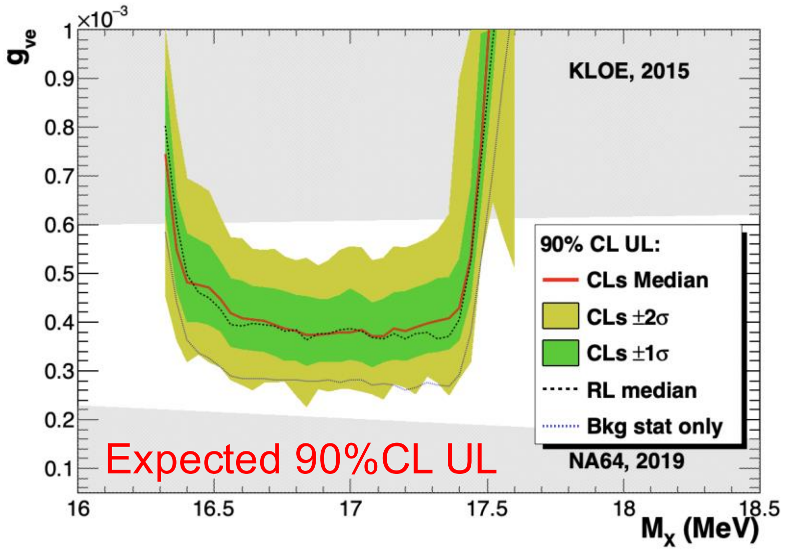
Source	Uncertainty (% per energy point)
$N_2(s)$	0.60
$B(s)$	0.54
$N_{PoT}(s)$	0.35
Total on $g_R(s)$	0.88

arXiv:2505.24797 [hep-ex]

The blind unblinding

Expected 90% CL UL in absence of signal:

- **Likelihood fits** performed for **signal + background** vs **background** only
- Total error budget: δg(r) = 0.88% - δK(s)=2.1%
- For a M_X: $CLs = \frac{P_S}{1-P_B}$ to define the UL on g_{Ve}



Before box opening, error estimate validation (JHEP 06 (2025) 040):

- 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 $\sqrt{s}$
  1. Threshold on the χ^2 fit in side-band is P(χ^2) = 20%
  2. If ✅, check if the fit pulls are gaussian
  3. If ✅, check if a straight-line fit of the pulls has no slope in $\sqrt{s}$ (within 2 sigma)
  4. If ✅, check if constant term and slope of the linear fit for $N_2(s)/B(s)$ are within two sigma of the expectations

Successfully applied:

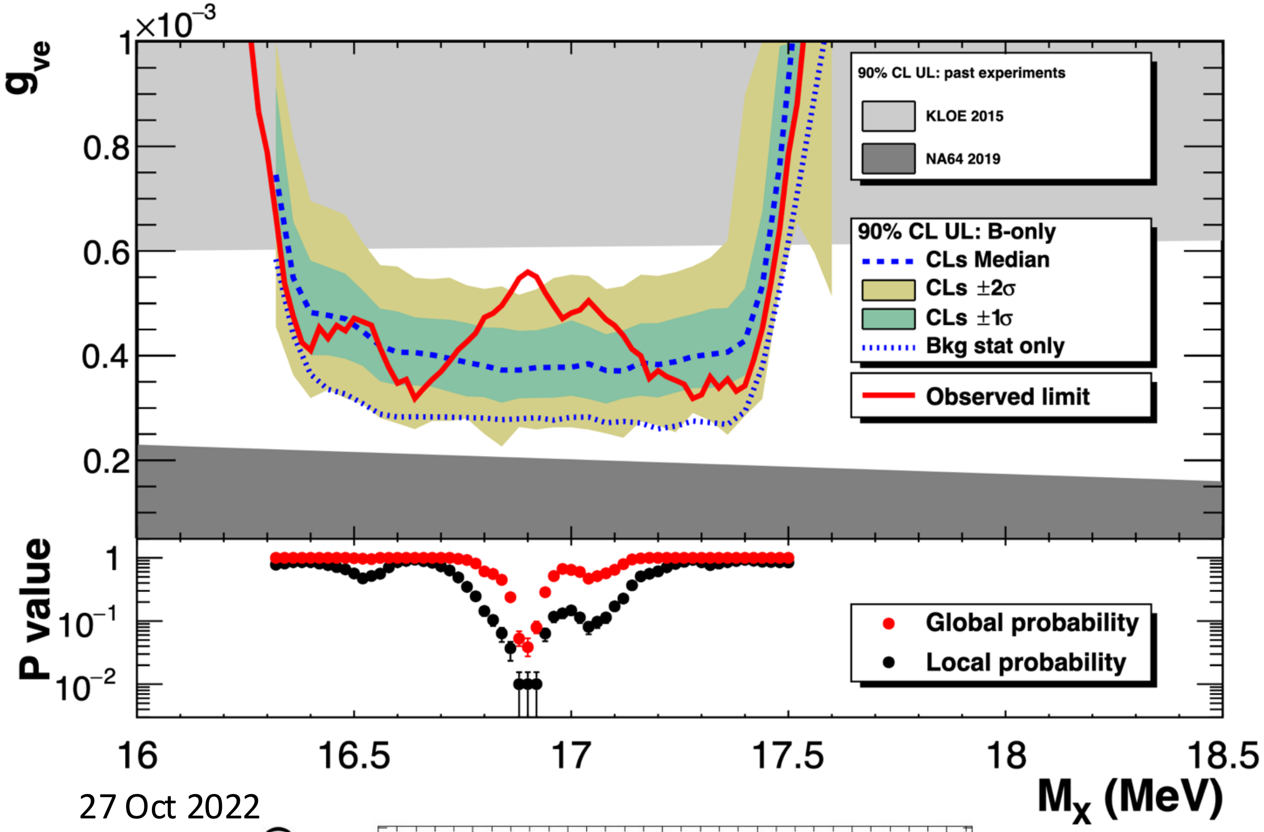
1. P(χ^2) = 74%,
2. Pulls gaussian fit probability: 60%
3. Slope of pulls consistent with zero
4. Constant term: 1.0116(16), Slope: (-0.010 ± 0.005) MeV^{-1}

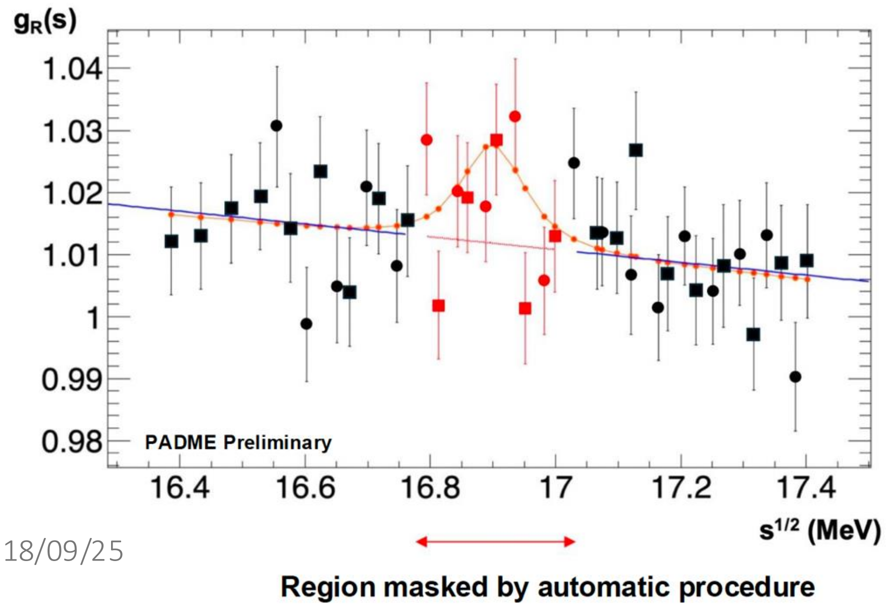
→ **Ready to unblind**

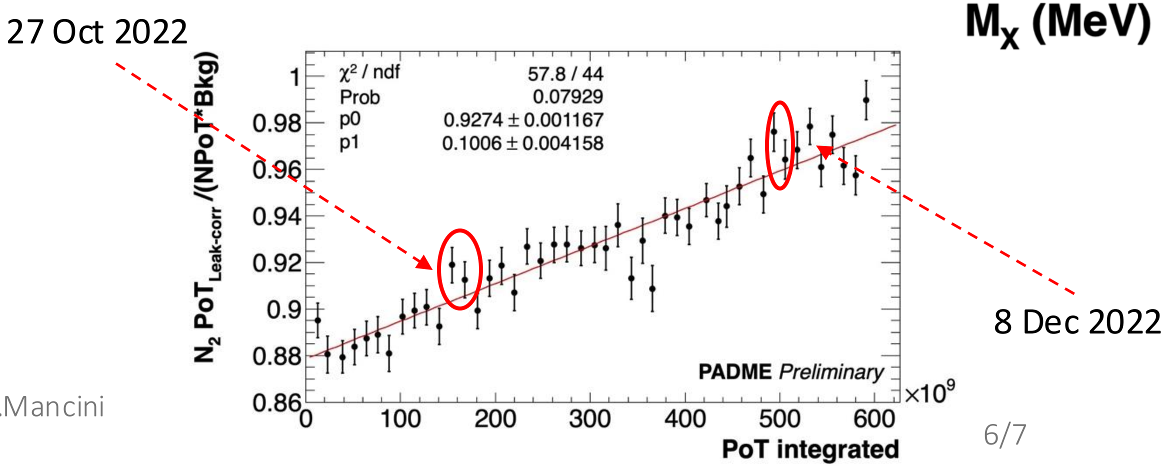
PADME Run III result and outcome

Some excess is observed around 2σ global coverage (2.5σ local) ArXiv:2505.24797 [hep-ex]

- At M_X = 16.90(2) MeV, $g_{ve} = 5.6 \times 10^{-4}$, the global probability dip reaches $3.9_{-1.1}^{+1.5}$ **%**, corresponding to **(1.8 ± 0.2) σ** one-sided
- A 2nd excess is present at ~17.1 MeV, but disfavoured (general probability 40%)
- If a 3 σ interval is assumed for observation following the estimate M_X = 16.85(4) MeV of PRD 108, 015009 (2023), the p-value dip deepens to $2.2_{-0.8}^{+1.2}$ % corresponding to (2.0 ± 0.2) σ one-sided

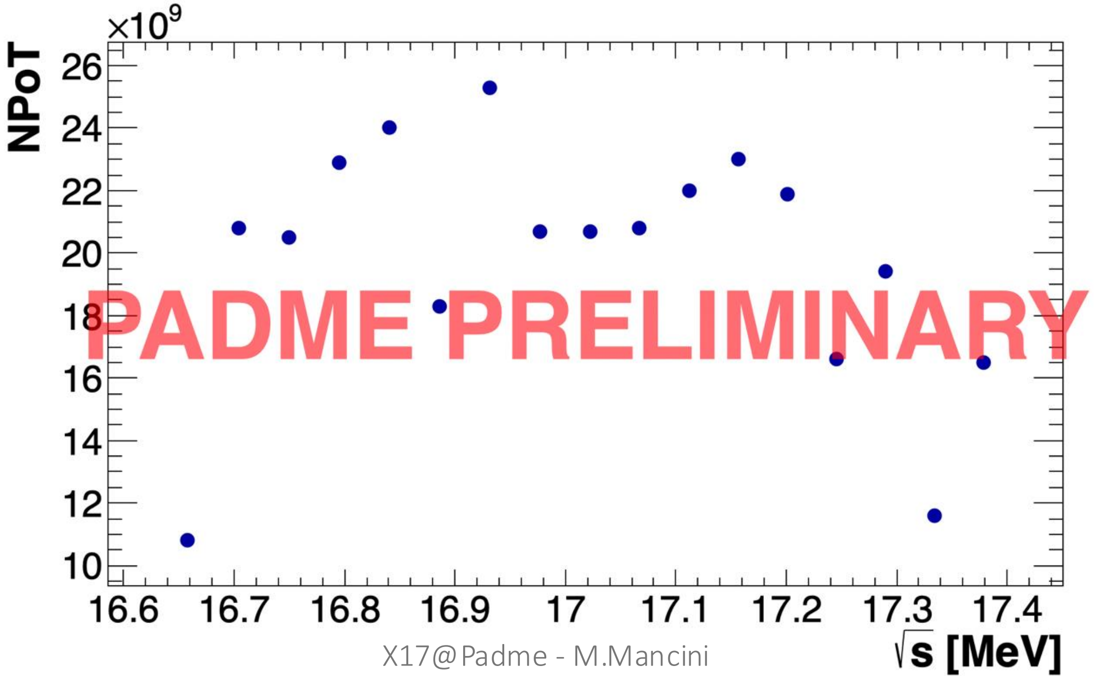






Conclusions

- The analysis has been successfully blessed using the “blind unblinding” procedure
- **Overall uncertainties at 0.9% or slightly better**
- No indications of X_{17} well beyond two-sigma-equivalent global p-values
- An excess has been observed, with global p-value equivalent to 1.8(2)σ
- New data acquired to better clarify:
  - 2 new micromegas-based tracker installed to measure the absolute ee/$\gamma\gamma$ cross section allowing combined analysis
  - Run IV-part 1 data already in the books: 18 energy scan points collected (∼2e10 PoTs each) equally separated by 1.5 MeV in the the E_{beam} = (269.5, 295) MeV / $\sqrt{s}$ = (16.60, 17.36) MeV region
  - Run IV-part 2 already scheduled for fall 2025 → 18-20 scan points + out-of-resonance below 16 MeV and above 18 MeV



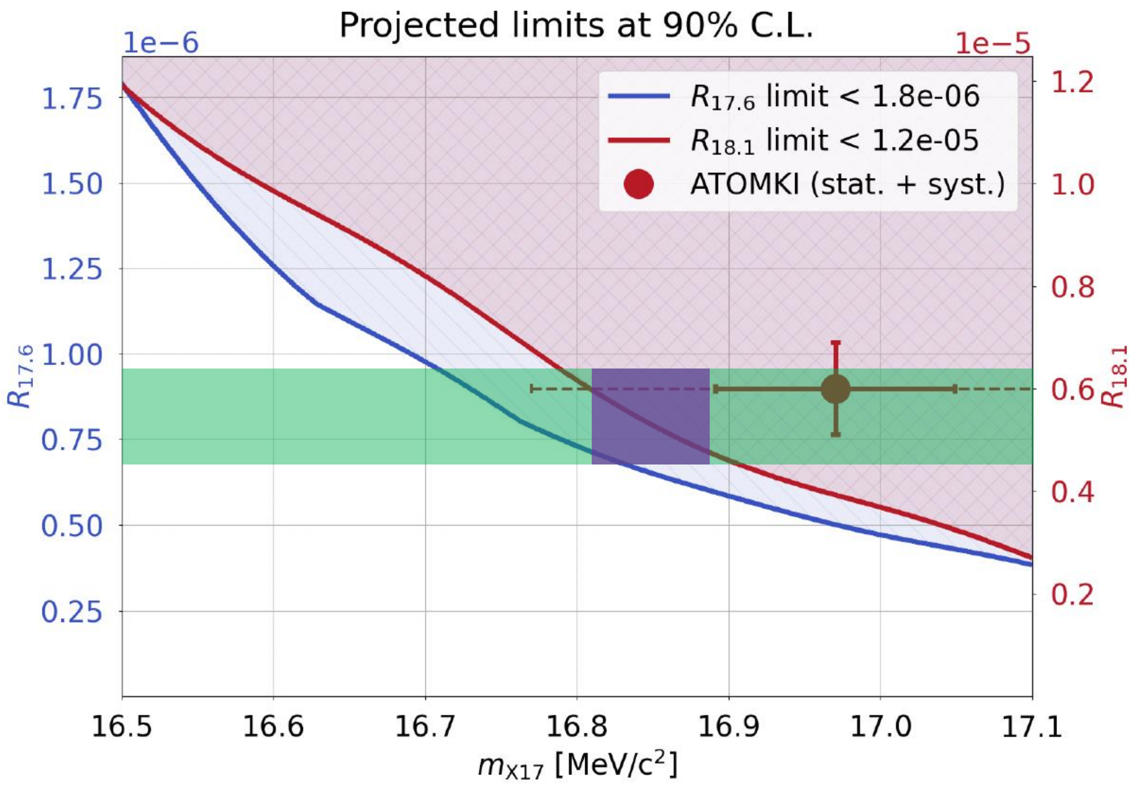
Back-up slides

Other experiments in the race

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 $\frac{\Gamma(^{8}Be^{*} \rightarrow {}^{8}Be\, X_{17}(ee))}{\Gamma(^{8}Be^{*} \rightarrow {}^{8}Be\, \gamma)}$ 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]

Draft of expected Run IV exclusion limit

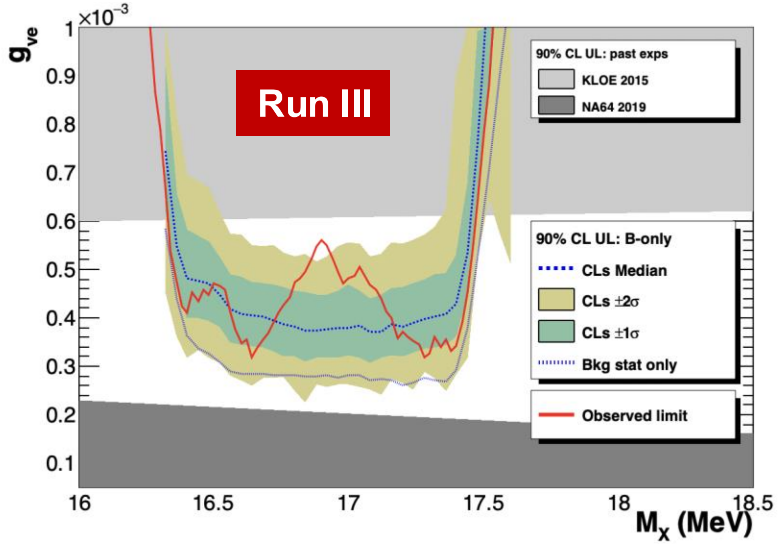
Lessons for Run IV to improve:

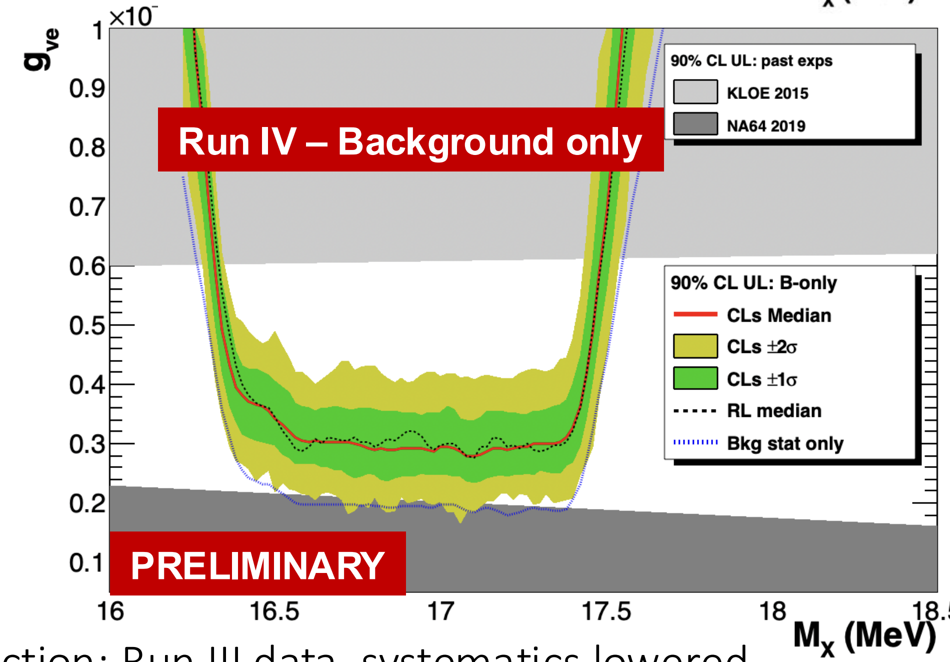
- Increase monitoring power and redundancy: guarantee better stability
- Alternative flux determination: γγ, new flux monitor system, target, chambers
- Increase acceptance: allow even safer treatment for edge effects
- Increase statistics per energy points

Assumptions for Run IV:

- x2 acceptance increase (target closer to ECal + Phi-cut removal)
- x2 statistics increase, 1.5 x 10^{10} POT per energy point
- 2 days for data collection, 3000 e^+ / spill as in Run III
- Points divided into 2 scans: 16—20 points per scan (summer – autumn)
- Stable beam condition + no target runs for bkg studies

Source	Uncertainty [%]	
	Run III	Run IV
N_2	0.6	0.3
N_{PoT}	0.35	0.3
B	0.55	0.3
Total on g_R	0.89	0.5



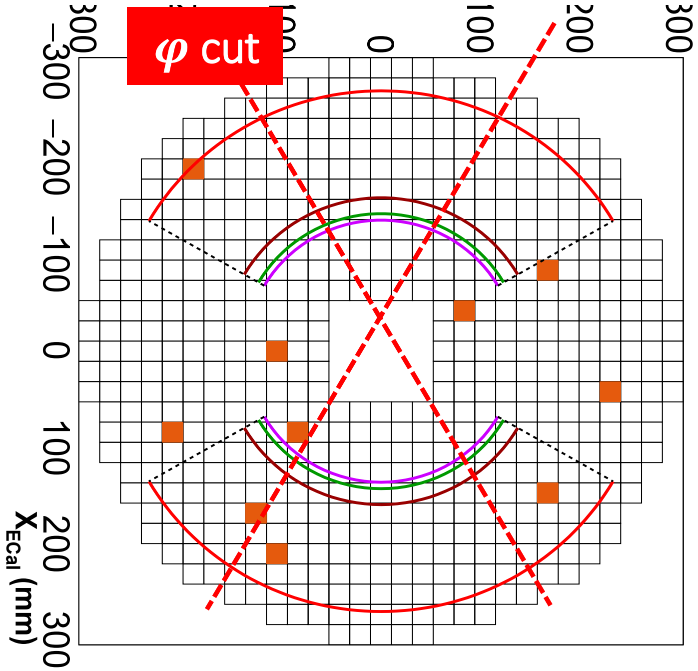


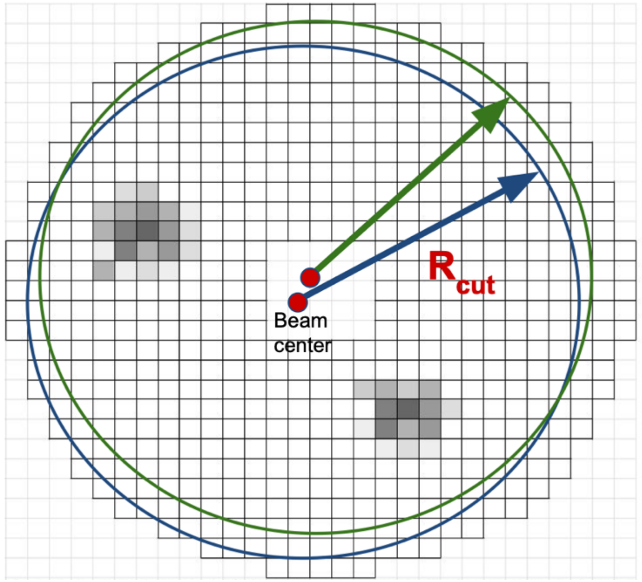
Projection: Run III data, systematics lowered

N_2 selection cuts

Selection algorithm as independent as possible on beam and detector conditions:

- Selected a cluster pair with the following criteria
  - Maximum radius defined by ECal dimensions
  - Energy within the "two-cluster" kinematic range
  - Minimum radius within the "two-cluster" kinematic range → following the beam center conditions
  - Illumination clearly affected by material along the beam line (magnet bore) → Cut regions in φ
- Mutual cluster conditions:
  - ΔT (clu0-clu1) < 5 ns
  - ΔR (clu0-clu1) > 60 mm (Minimum 2CL difference)
  - $\boldsymbol{\phi_1 - \phi_2}$ vs $\boldsymbol{\theta_1 + \theta_2}$ cut in the center of mass frame isolates the signal





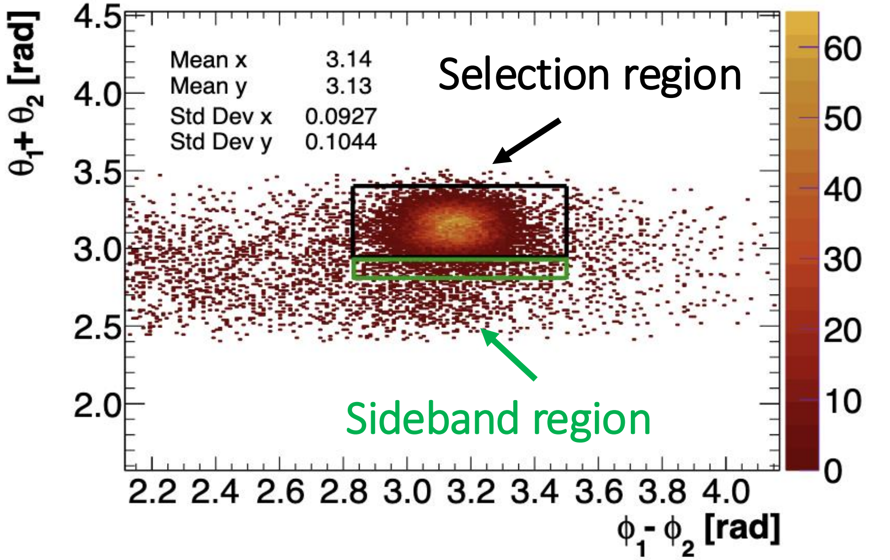
N_2 selection and Bremsstrahlung substraction

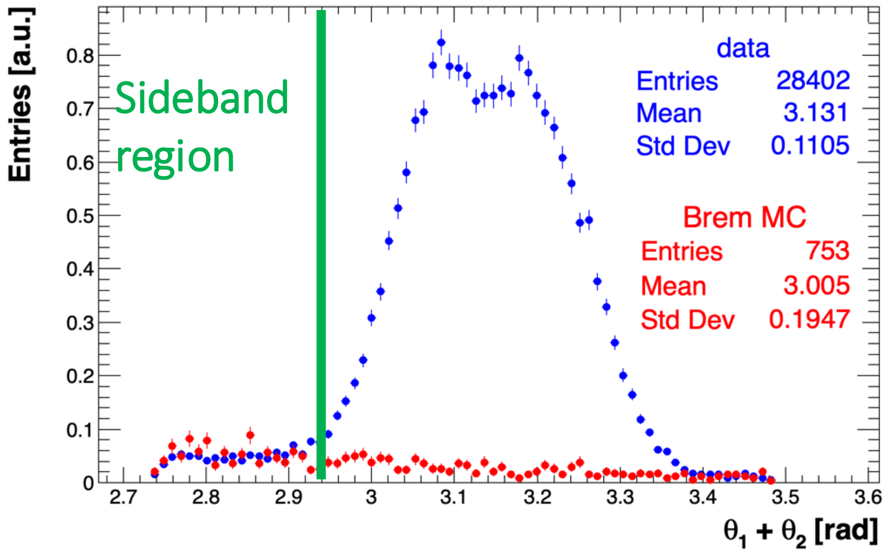
- $\boldsymbol{\phi_1 - \phi_2}$ vs $\boldsymbol{\theta_1 + \theta_2}$ cut isolates the signal→ 3σ around the mean value
- 2 Clusters event surviving the whole set of cuts:
  - $E_1 + E_2 = E_{beam}$ as expected for a 2-body final state process
  - Time coincidence verified
- Flat beam bkg in $\boldsymbol{\phi_1 - \phi_2}$ → bkg level < 4%
- Bremsstrahlung tail in $\boldsymbol{\theta_1 + \theta_2}$ subtracted by using MC shape on the sideband

→ Statistical error: δN_2 ~0.6% up to 0.7%

→ Systematic uncertainty due to bkg subtraction: δN_2 ~ 0.3%

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

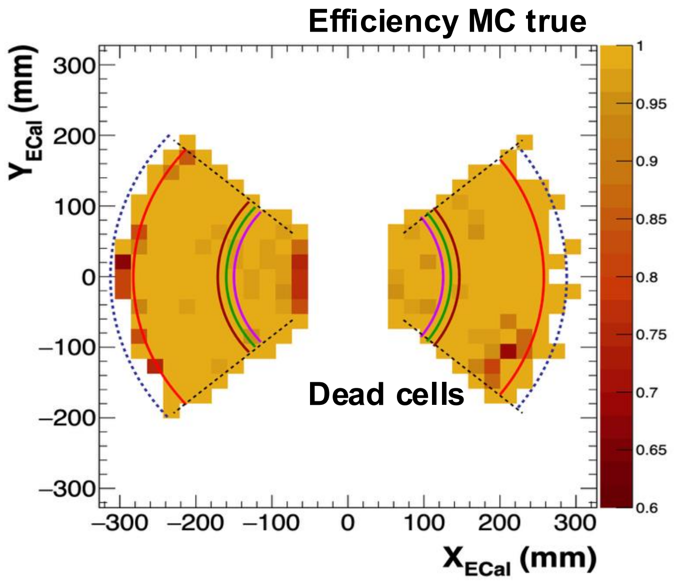




Shape of ee signal due to residual PADME magnetic field
→ Fully modelled using MC + detailed map

The SM bkg B uncorrelated error budget

The expected background yield B is determined with MC + data-driven checks

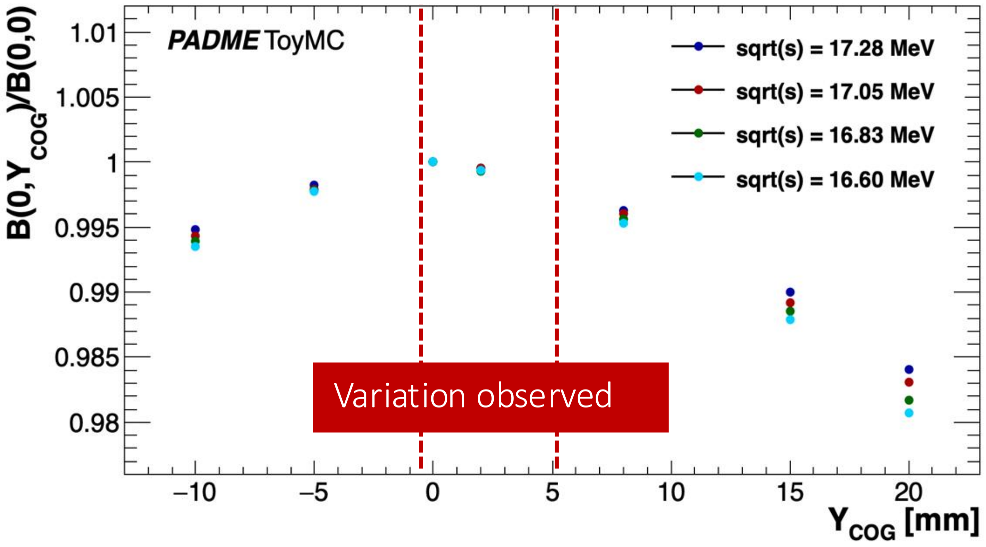


Reconstruction efficiency:

- Data/MC efficiency with tag-and-probe technique
- bkg subtraction at tag level dominates the statistical-systematic error → $\delta B = 0.35\%$

The selection relies on the expected beam direction: spot measured at the target and the Center of Gravity (COG) of 2 body final states at ECal

- Systematic shifts in the COG position → acceptance systematic errors
- Largest effect in y due to acceptance limitations (magnet bore)
- Fractional variations range from 0.08% to 0.1% mm^{-1} for $\sqrt{s}$ = (16.4, 17.3) MeV



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

The N_{PoT} error budget

Flux N_{PoT} determined using LG detector charge: $N_{PoT} = \frac{Q_{LG}}{Q_{1e^+,402\,[\mathrm{MeV}]}} \times \frac{402\ \mathrm{MeV}}{E_{beam}\ [\mathrm{MeV}]}$ → common systematic error @2%

2 main effects: **radiation induced loss** + **energy loss in passive material**

- Run III radiation dose ~ 2.5 krad → transparency changes for O(krad)
  - Estimated from 3 flux proxy observables: $Q_{target\text{-}x}$, $\langle E_{ECal}\rangle$, period multiplets
  - LG yield decreases with relative PoT slope of 0.097(7) → Slope error included **δN_{PoT}= 0.35%** (after correction applied)
  - Constant term uncertainty of **δN_{PoT}=0.3%** added as scale error
- Loss due to beam movements during the whole Run III → passive material crossing
  - Checked against data of October test beam + MC simulation → systematic correlated error **δN_{PoT}=0.5%**

Uncorrelated systematic errors on N_{PoT}

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

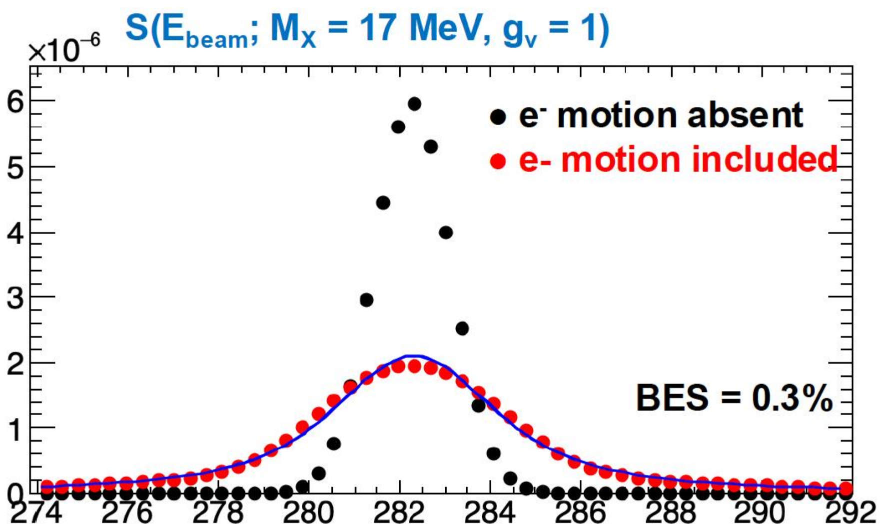
Common systematic errors on N_{PoT}

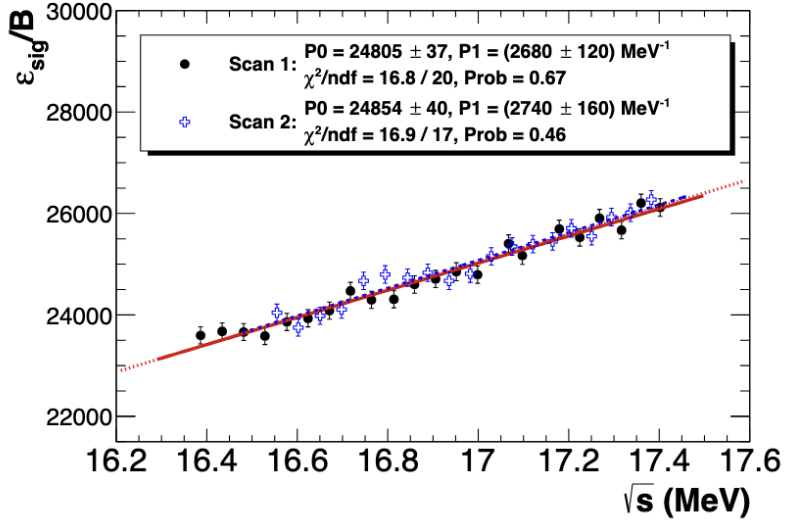
Source	Common error on N_{POT} [%]
pC / MeV (JHEP 08 (2024) 121)	2.0
Energy loss, data/MC	0.5
Rad. induced loss, const. term	0.3
Total	2.1

Signal shape and ε/B

Electron motion inside the target changes significantly the resonance shape → not anymore just a gaussian with σ equal to the beam energy spread

- Signal parametrized vs E_{beam} with a **Voigt** function:
  - Convolution of the gaussian BES with the 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 ***ε*** determined from MC:
  - Large cancellation of systematic errors if using ***ε*** /B
- Fit **ε(s)/B(s)** with a straight line → fit parameters as nuisances:
  - **Errors:** δP0/P0 ~ 0.1%, δP1/P1 = 3%, correlation = -2.5%

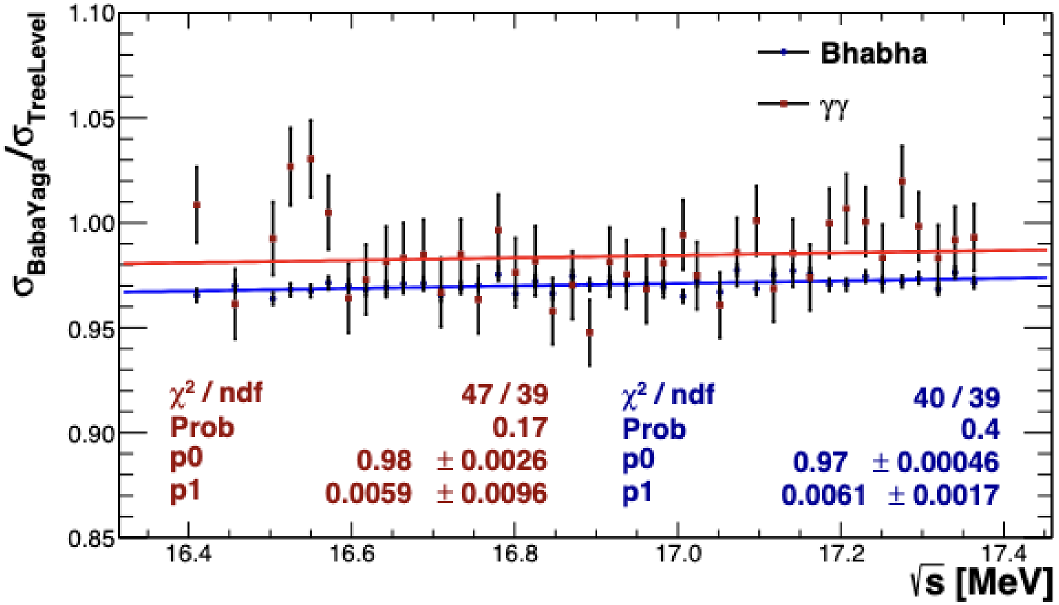


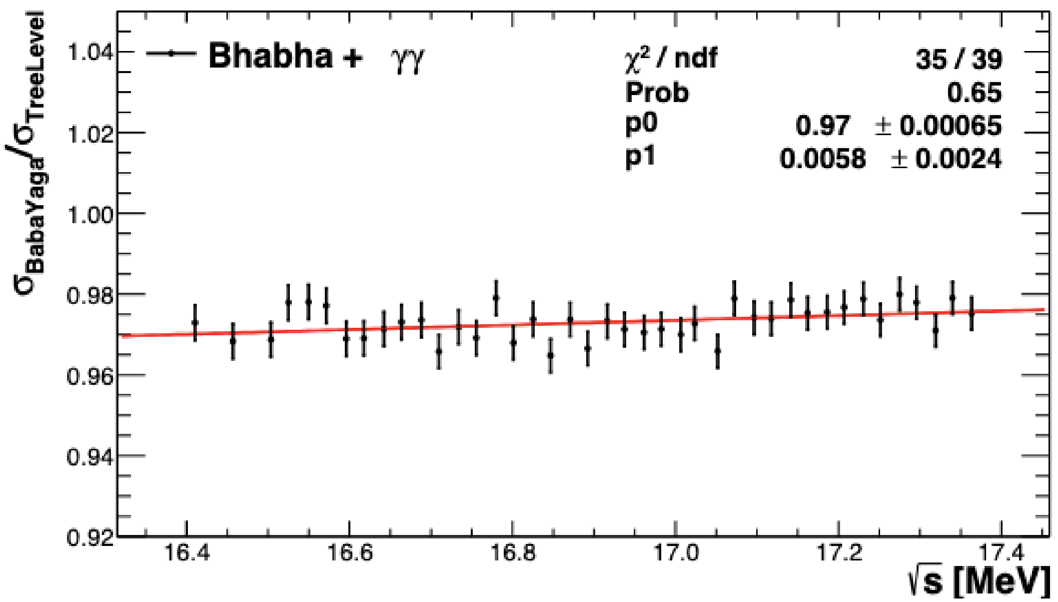


PRL 132 (2024) 261801

Possible scale effects – K(s)

Radiative corrections evaluated using BabaYaga → $e^+e^-(\gamma)$ and $\gamma\gamma(\gamma)$ (Nucl. Phys. B 758 (2006) 227, Phys. Lett B 663 (2008) 209)





Possible offset → -2.8% @ 16.92 MeV

Possible slope with $\sqrt{s}$ → -0.6(6)% MeV^{-1}

The scaling with the below resonance is affected by a -1.5(1.5)% shift because of radiative correction, but the expected total error covers for it: 1.8%(B) + 2.1%(N_{PoT}) = 2.8%

Insertion of Babayaga-generated events in the MC (up to 10 γ's)
→ no effect on ε(s)

$K(s)$, 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