QCD@Work
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PADME Results on X17 search

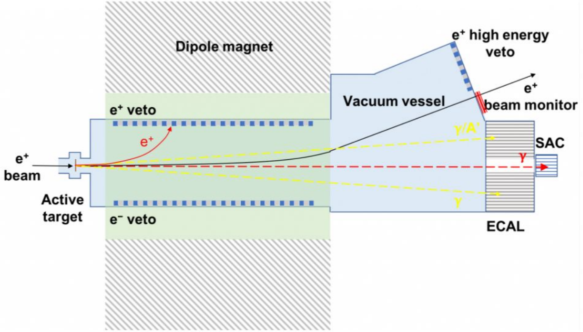
Katerina Kostova*
on behalf of the PADME collaboration
*Faculty of Physics, Sofia University, katerina@phys.uni-sofia.bg

The PADME experiment

Positron **A**nnihilation into **D**ark **M**atter **E**xperiment

@ National Laboratory of Frascati (LNF-INFN)

$$e^+ + e^- \rightarrow \gamma A'$$



- Fixed target experiment originally planned for searching the dark photon via associate production in positron-on-target annihilation - **Run I** and **Run II**
- **Run III** and **Run IV** - search for the resonant production of the hypothetical X17 boson

$$e^+ + e^- \rightarrow X17 \rightarrow e^+ + e^-$$

X17 anomaly

- Study of the nuclear decay of the **^{8}Be*** by internal pair creation (IPC) at ATOMKI in Debrecen, Hungary

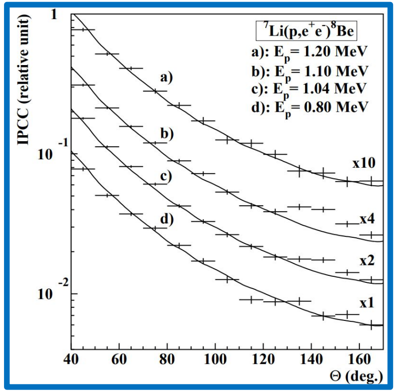
- Anomalous excess in angular correlation of $e^{+}e^{-}$ pairs produced via IPC in **^{8}Be**, **^{4}He** and **^{12}C** nuclei is observed

- The anomaly seems to be compatible with the production and successive decay of a **new ~17 MeV mass neutral particle**

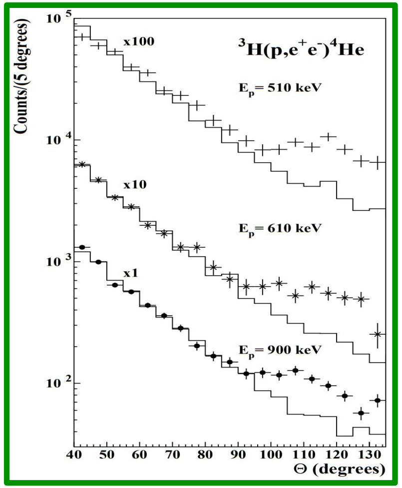
- If X17 is a vector boson particle, extend the Standard Model Lagrangian with a new term, corresponding to X17 coupling to electrons/positrons:

$$\mathcal{L} \supset g_{ve}\, X_{17}^{\mu}\, \bar{e}\, \gamma_{\mu}\, e$$

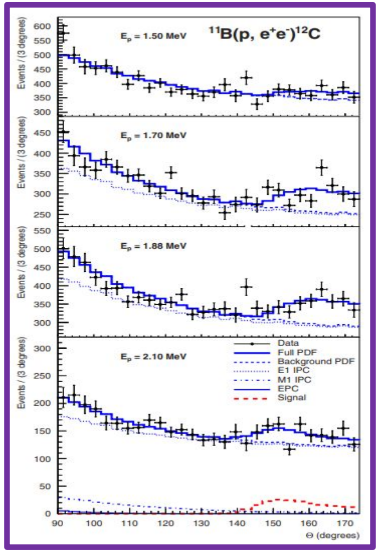
PhysRevLett 116 (2016) 042501

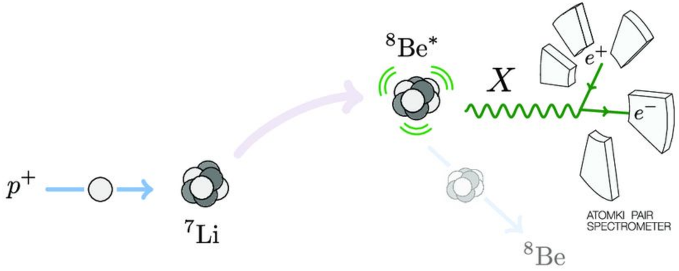


PhysRevC 104 (2021) 044003



PhysRevC 106 (2022) L061601





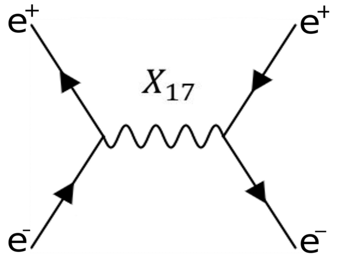
physrevd.95.035017

→ **Test of the X17 hypothesis by many ongoing and new experiments**

Resonant X17 search on fixed target experiment

- $\sigma_{res} \propto \frac{g_{Ve}^2}{2m_e}\pi Z\delta(E_{res} - E_{beam})$ goes with ***Z*** → dominant process with respect to alternative signal production processes

- $\sqrt{s}$ has to be as close as possible to the expected mass
  → fine energy scan procedure with positron beam
  → expected enhancement over the SM background



At PADME X17 to be produced via resonant annihilation in diamond target: $e^+ + e^- \rightarrow X17 \rightarrow e^+ + e^-$

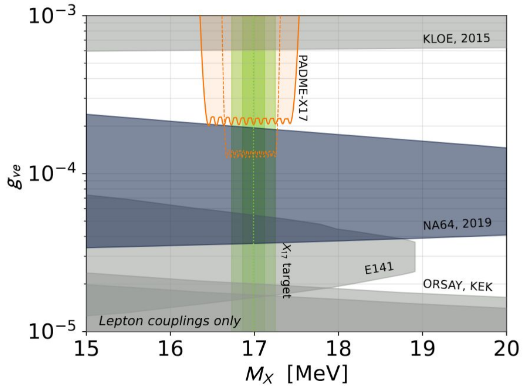
Beam energy scan in the range $\mathbf{E_{beam}}$ **= [262, 296] MeV** → corresponding to center-of-mass energy range for the e^+e^- pair of **√s = [16.4, 17.4] MeV**

→ aiming to measure an enhancement in the 2-body final state yield $N_2(s)$ due to X17 events

$$\mathcal{N}_{X_{17}}^{\text{per poT}}(E) = \frac{\mathcal{N}_A Z \rho}{A} \ell_{\text{tar}} \frac{g_{ve}^2 \pi}{2m_e} f(E_{\text{res}}, E)$$

$$\mathcal{N}_{X_{17}}^{\text{Vect.}} \simeq 1.8 \cdot 10^{-7} \times \left(\frac{g_{ve}}{2 \cdot 10^{-4}}\right)^2 \left(\frac{1 \text{ MeV}}{\sigma_E}\right)$$

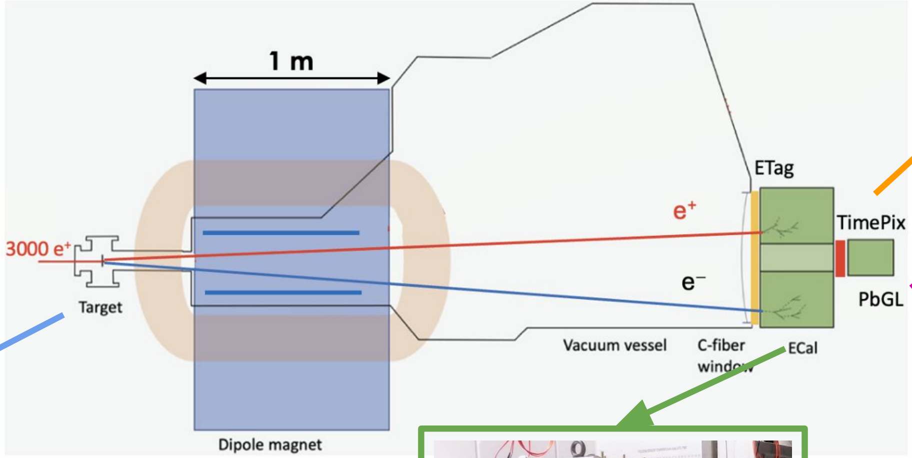
PRD 106 (2022) 11, 115036

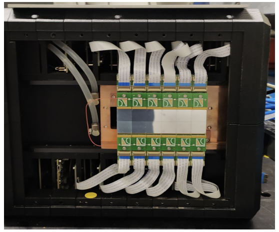


PADME Run III detector setup

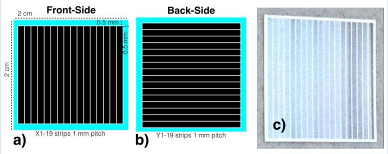
for the X17 search

Beam: 3000 e^+/bunch
[262 MeV – 296 MeV]
Bunch length ~200 ns



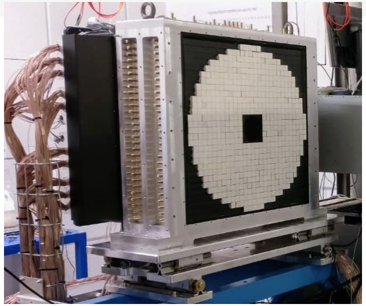


TimePix3
(Si-based detector for beam monitoring)

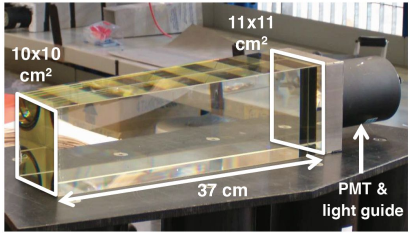


Active diamond target
(measure beam spot position)

PADME dipole magnet OFF



ECAL
(616 BGO crystals 21×21×230 mm^3)



LeadGlass calorimeter
(measure N_{PoT} and beam catcher)

Run III data analysis strategy

Signal+Background hypothesis:

$N_2(s) = N_{PoT}(s)\,[B(s) + S(s;\, M_X,\, g_{Ve})\ \varepsilon_S(s)]$

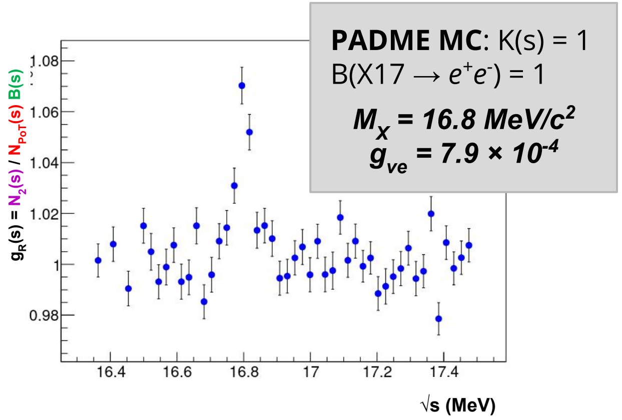
vs.

Background-only hypothesis:

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

Analysis inputs:

- $N_2(s)$ → Number of 2-particle final state events in ECAL
- $N_{PoT}(s)$ → Number of Positrons-on-Target from LG beam-catcher
- $B(s)$ → Expected background yield per PoT
- $S(s;\, M_X,\, g_{Ve})$ → Expected signal per PoT for $\{M_X, g_{Ve}\}$
- $\varepsilon_S(s)$ → Signal acceptance and selection efficiency



Define the main analysis observable as the ratio between the number of observed and expected events:

$$g_R(s) = N_2(s) \,/\, N_{PoT}(s)\ B(s)$$

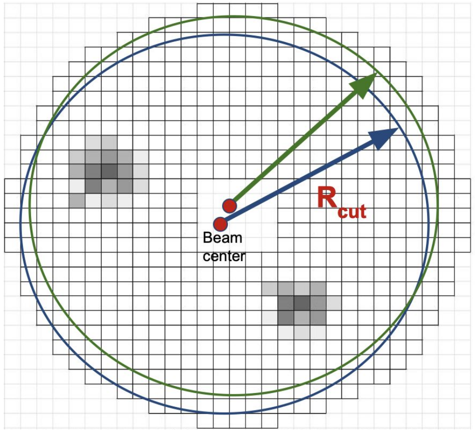
In the B-only hypothesis deviation of $g_R(s)$ wrt 1 allowed up to a linear function **K(s) - accounting for uncertainties in radiative corrections, bkg systematics etc.*

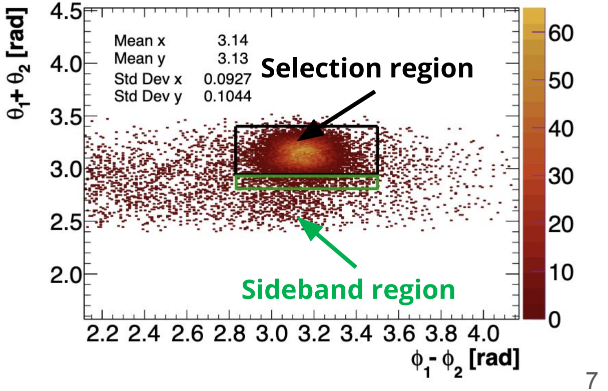
$N_2(s)$ selection and Bremsstrahlung cut

Select 2-body final states in the ECAL acceptance

- R_{max} away from the ECAL edges by ~1.5 crystals
- **Identify two spatially separated in-time energy clusters:**
  - $\Delta t < 5$ ns
  - $\Delta R > 60$ mm (min. 2 cluster difference)
  - $E_1 + E_2 = E_{beam}$ (2-body final state process)
- **Beam movement** within 10 mm
  → beam center determination run by run with TimePix beam monitor and ECAL center-of-gravity (CoG) position (better than mm precision)
- **In the center-of-mass (CoM) frame signal region centers around** $\boldsymbol{\theta_1 + \theta_2 \simeq \pi}$ ***and*** $\boldsymbol{\phi_1 - \phi_2 \simeq \pi}$
- Bremsstrahlung tail in $\theta_1 + \theta_2$ due to residual magnetic field in the PADME dipole magnet → subtracted from the final $N_2(s)$ yield by using MC shape on the sideband

→ **Statistical error: δN_2 ~ 0.60%**





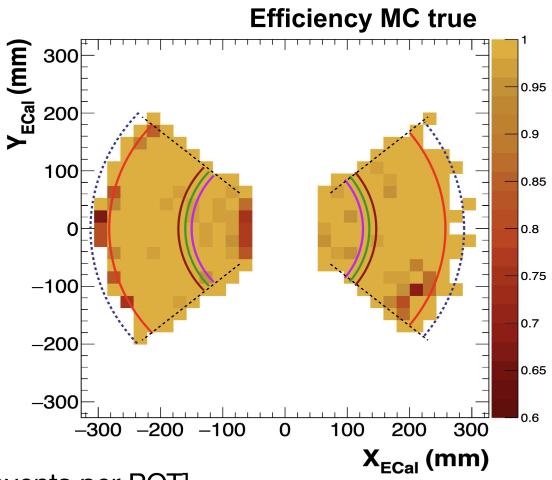
Expected SM background yield B(s)

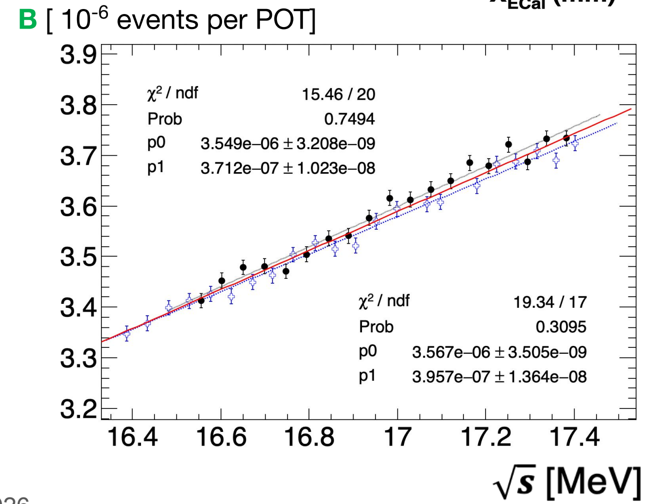
B(s) is determined with MC + data-driven checks

- Reconstruction efficiency → Tag&Probe method
- Systematic shifts in beam spot position - largest effect in Y due to acceptance limitations → 0.05% acceptance systematic error
- Expected **B(s)** evaluated from MC simulation and compared to below resonance points, improving the systematic uncertainty
- Fit on **B(s)** with a straight line (used only as a check)

$B(s)$ uncorrelated error

Source	Uncertainty (% per energy point)
MC statistics	0.40
Tag and probe efficiency	0.35
Cut stability	0.04
Beam spot variations	0.05
Total on $B(s)$	0.54





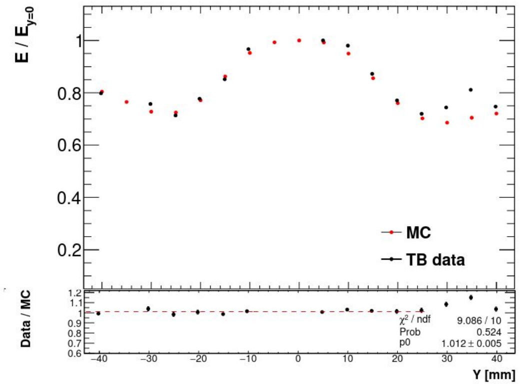
Precise determination of the N_{PoT}

→ ***N_{PoT}* measured by the lead-glass calorimeter**

Several test beam campaigns for calibration and cross-check with other detectors → **two types of corrections applied:**

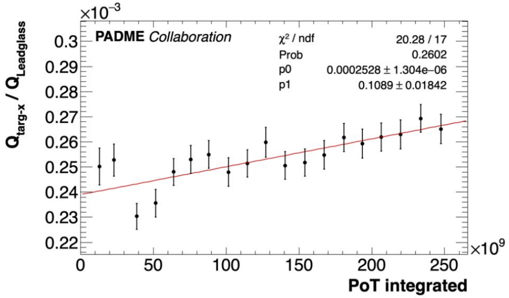
1. Energy loss correction due to variable upstream material and beam movements

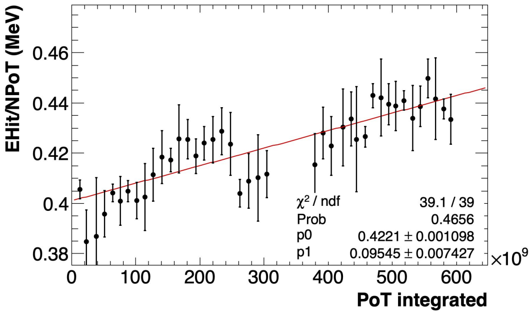
- Good agreement between data and MC simulation → validation of the profile shape in Y



2. Light yield correction due to radiation-induced loss

- Throughout Run III a total of 7×10^{11} PoT (of ~300 MeV each) has passed through the LG block corresponding to a TID of 25 Gy (2.5 krad)
- Effect estimate with Q_{tar} and total energy in ECAL



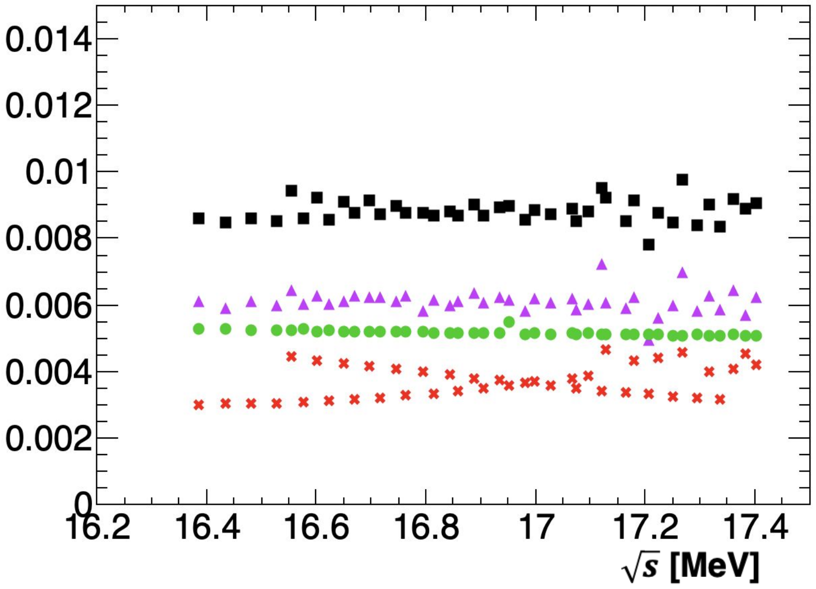


[JHEP 11 (2025) 007](#)

Run III systematic error budget

JHEP 11 (2025) 007

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

Total uncorrelated uncertainty on **$g_R(s)$ = 0.88%** and on **K(s) = 2.8%**

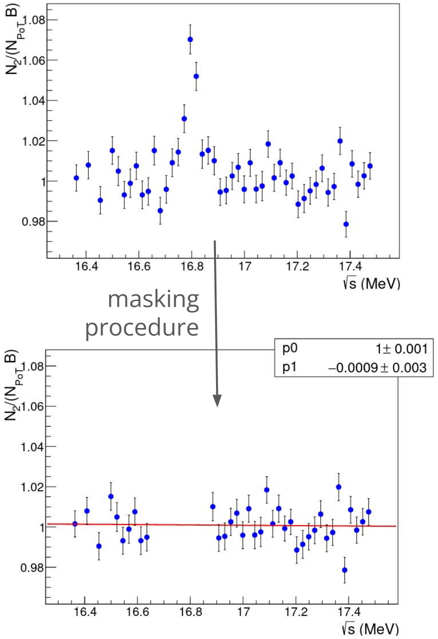
Blind unblinding procedure

→ Data self-consistency check procedure defined in *JHEP 06 (2025) 040*

Define a side-band region in $g_R(s)$, excluding 10 consecutive in √s periods of the scan by maximizing the probability for a linear fit.

Define criteria to be respected by the remaining data points before proceeding to box opening:

1. **Fit quality:** Threshold on the χ^2 fit in side-band is $P(\chi^2) = 20\%$, defined through 90% acceptance probability (reject 10% of the times)
2. **Fit parameter reliability:** Check if the fit pulls with respect to the line fit follow a Gaussian distribution
3. **Gaussian fit pulls:** Check if a straight-line fit of the pulls has no slope in √s (within 2σ)
4. **Correlated systematic errors on the fit pulls:** Check if the constant term and slope of the linear fit for K(s) are within two sigma of the expectations, i.e.: 1.0 ± 4% for the constant, ± 2% MeV^{-1} for the slope



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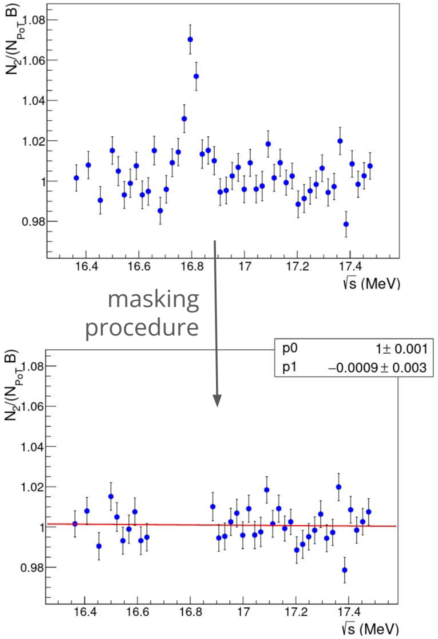


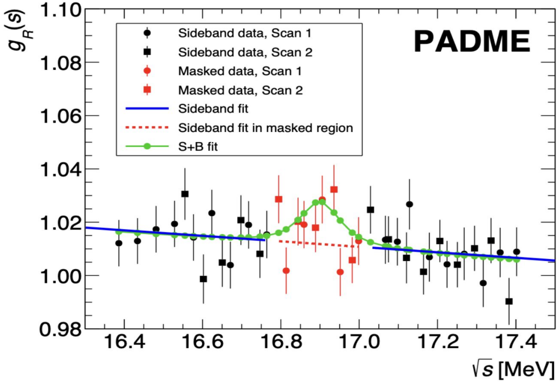
Successfully applied to data: JHEP 11 (2025) 007

✅ 1. $P(\chi^2)$ = 74%
✅ 2. Pulls gaussian fit probability = 60%
✅ 3. Slope of pulls consistent with zero
✅ 4. Constant term: 1.012(2), slope: (-0.010 ± 0.005) MeV^{-1}

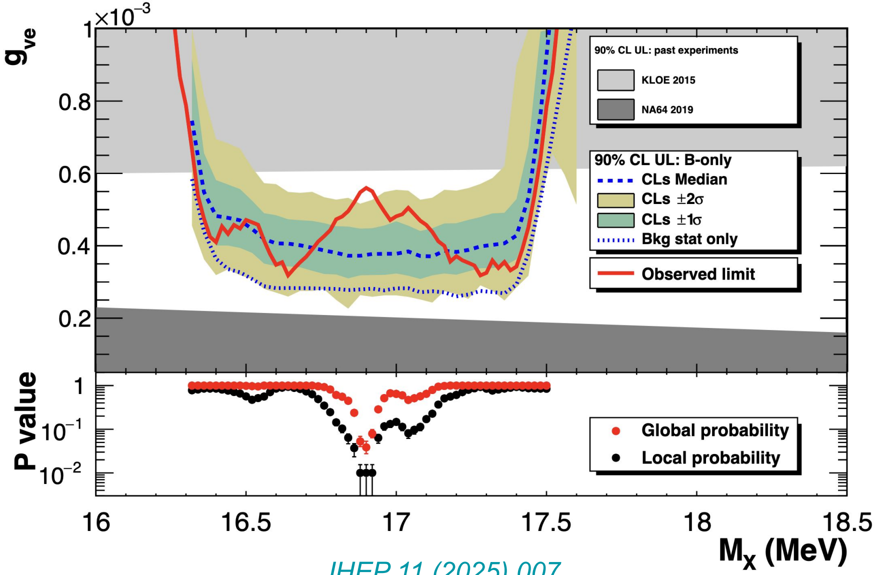
Ready to unblind!

PADME Run III result

- A modified frequentist approach (CL_s) is used, the test statistic compares the likelihood functions between the S+B and the B-only scenarios.
- **A local excess at ~2.5σ local coverage is observed *@ M_X = 16.90(2) MeV, g_{Ve} = 5.6×10^{-4}***
- The global probability dip reaches **$3.9_{-1.1}^{+1.5}$ %**, corresponding to an excess of **(1.77 ± 0.15)σ** one-sided
- The observed limit is consistent with the expected within 1σ in most of the scan points



No statistically significant signal beyond 3σ was observed



JHEP 11 (2025) 007

Result not conclusive!
Need for more data → Run IV in 2025

Run IV improvements

→ **for increased sensibility to confirm/disprove Run III result**

- **Total N_{PoT} × 2 wrt Run III - reduce statistical uncertainty**
- **Active diamond target** position moved downstream → **increase acceptance**
- Passive material removed and magnet fully degaussed → B_{PADME} < 1 G
- Radiation-induced loss monitor system for the LG detector
- **2 new gaseous tracking detectors:**

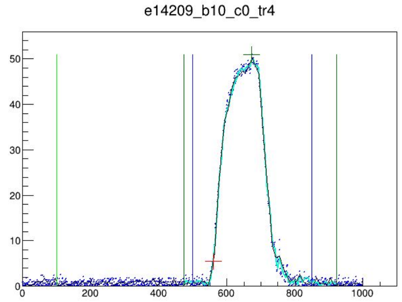
  TMM Micromegas replace the TimePix3 beam monitor
  - 10cm x 10cm MM gas chamber, with x-y strips readout, with ~250 μm pitch for beam shape and spot monitor
  - greater active area wrt TimePix and less passive material

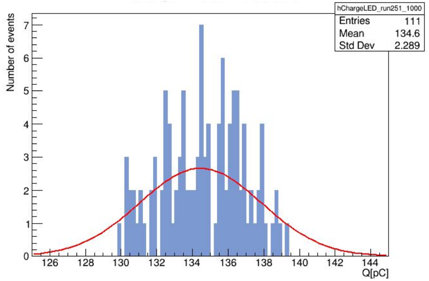
  PadMMe Micromegas chamber in front of ECAL
  - e/γ discrimination
  - spatial resolution ~350 μm
  - used to tune the beam parameters during data-taking

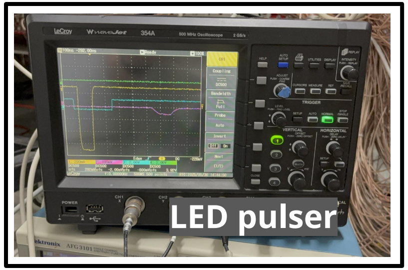
Run IV improvements

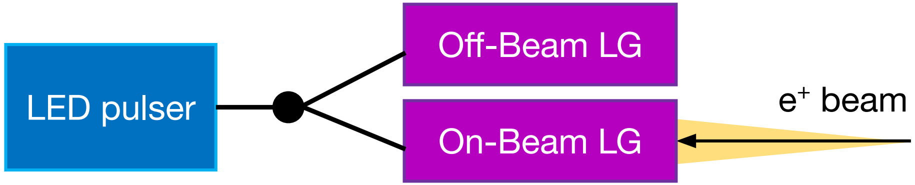
LED pulse generator + 2nd lead-glass detector

- **LED pulser** Tektronix AFG3101 to control the radiation induced loss of the lead-glass calorimeter
- Independent trigger included in the DAQ system
- A **2nd lead-glass block** installed (out of the acceptance and only acquiring the LED signals)
- Online LG response renormalized to the non-fired-block
  → monitor and calibration
  → reference for light yield response





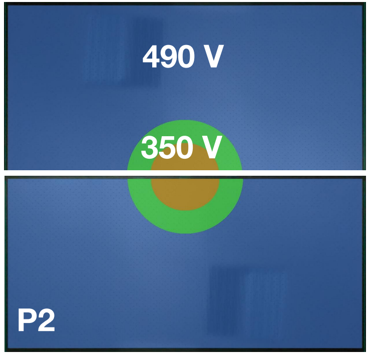


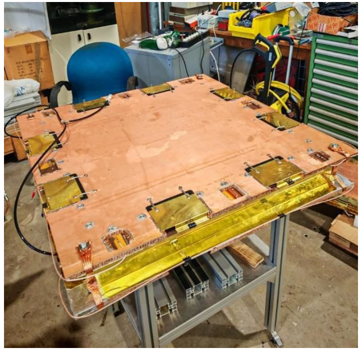


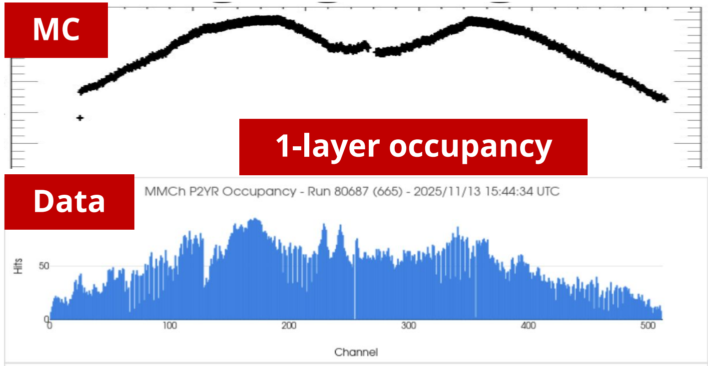
LED independent Trigger $\mathcal{O}$(2-4 Hz)

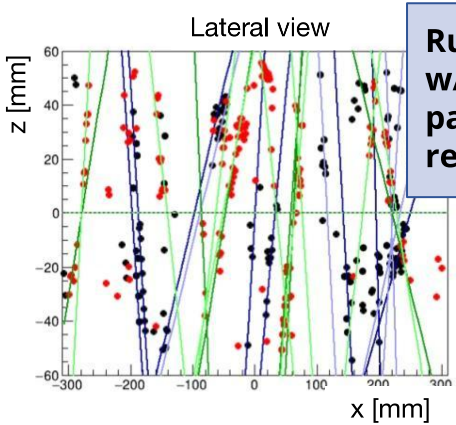
PadMMe - MicroMegas tracker

- e/γ discrimination □ bkg reduced by 20% - charged final states only
- Access to different observables N_2/N_{PoT}, ee/N_{PoT}, ee/γγ
- Tag and probe improves
- Main features:
  - 65x65x10 cm^3 - gas mixture (Ar:CF4:Iso=88:10:2)
  - 2 RO planes divided into 2 PCBs vertically (horizontally) separated P1(P2)
  - Hit efficiency > 90%
- **Beam monitor capability** □ central region at low gain (orange+green)
  - Used as online monitor during Run IV data taking
- **Need to face very high occupancy**









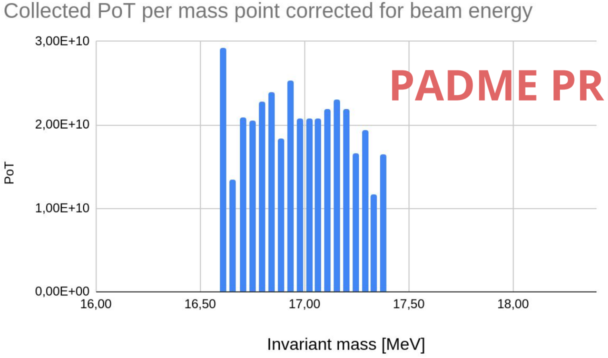
Run IV data w/ standart pattern recognition

Run IV data-taking

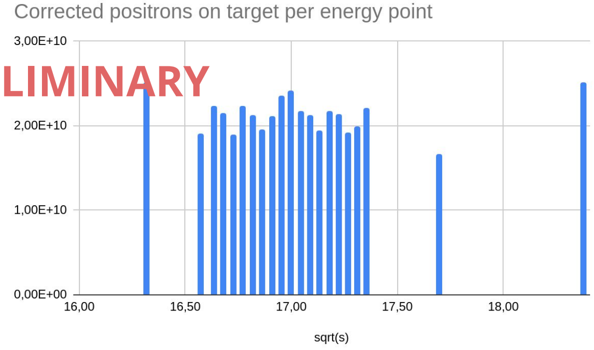
→ Energy scan technique as in Run III

- 36 energy scan points collected (~2×10^{10} PoT each) equally separated by 0.75 MeV in the resonance region
- 3 out-of-resonance energy points @ 260,300, 330 MeV
- 15 no-target (for multiple scattering bkg evaluation)

→ **signal yield ×2.5 wrt Run III**



PADME PRELIMINARY



Source	Uncertainty [%]	
	Run III	Run IV target
N_2	0.6	0.3
B	0.35	0.3
N_{PoT}	0.55	0.3
TOTAL	**0.88**	0.5

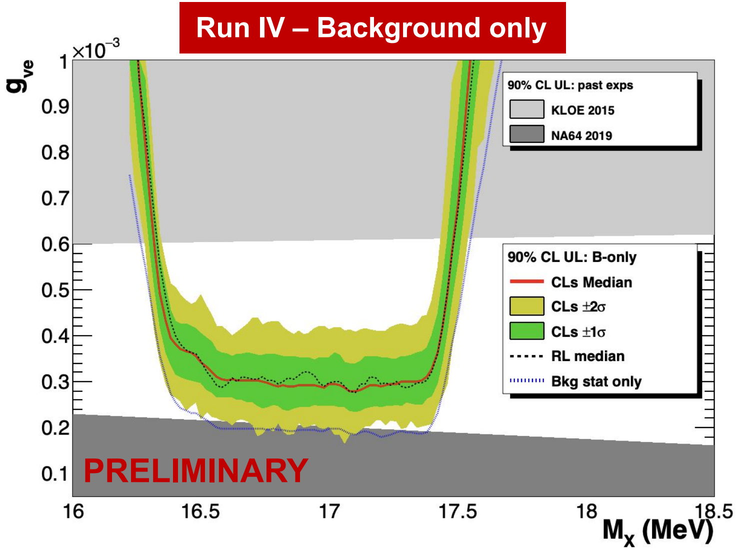
→ **Overall uncertainty aiming to be reduced from 0.9% to ~0.5%**

Conclusions

- **PADME Run III X17 analysis completed**
  - Overall systematic uncertainty achieved is below ~0.9 % for the entire Run III dataset
  - No statistically significant indications for X17 signal observed - excess at M_X = 16.90 MeV with 2.5σ local and 1.8σ global p-value

- **PADME Run IV data-taking completed with major improvements to the detector setup**
  - 36 energy scan points (≥ 2×10^{10} PoT each) equally separated by 0.75 MeV in the around resonance region
    → signal yield ×2.5 wrt Run III
  - New detectors for beam monitoring and final states identification
  - Run IV analysis currently ongoing
    → redundant beam parameter measurements
    → MC simulation of the experiment and track matching

Stay tuned for new results!



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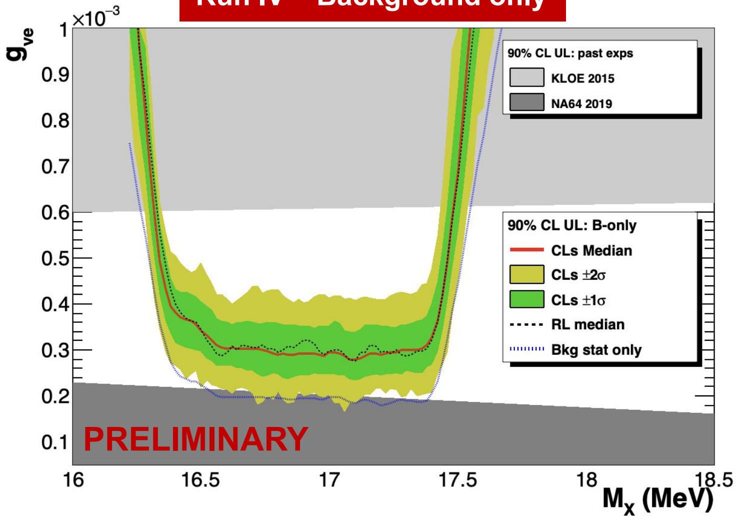
Run IV – Background only



Thank you for your attention!

Back-up

About X17 nature

- The X17 hypothesis is *kinematically* consistent for all the anomalies
- The question about the X17 hypothesis being *dynamically* consistent for all the anomalies is still open

Assuming definite parity (and parity conservation) for simplicity there are four possible scenarios.

→ The scalar scenario is excluded by parity conservation in ^{8}Be transitions.
→ The pseudoscalar scenario is excluded by parity conservation in ^{12}C transition.

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)	…

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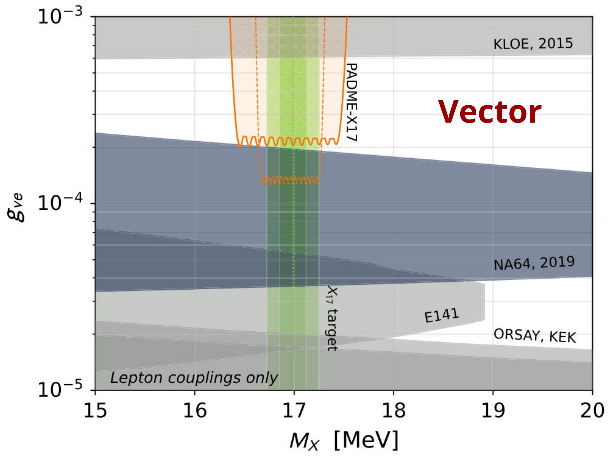
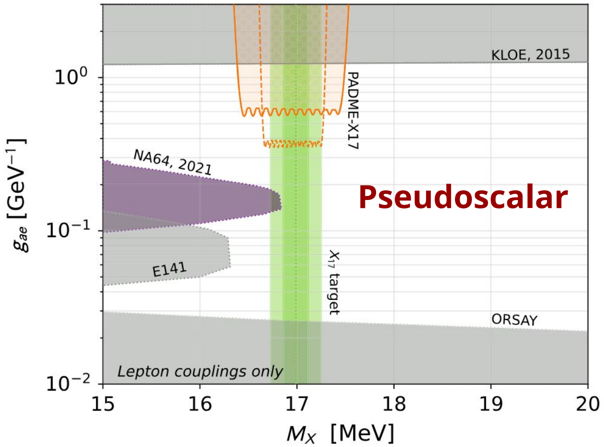




Run III dataset

Total amount of collected data is ~ 6×10^{11} PoT, i.e. **~ 10^{10} PoT per √s point:**

- 42 points in ***263 MeV < E_{beam} < 292 MeV*** and ***δE_{beam} ~ 0.75 MeV*** energy step in the on-resonance region
  → corresponding to ***16.4 MeV < √s < 17.4 MeV*** in CoM energy
- 6 points out-of-resonance, where the X17 production is forbidden:
  - 5 points **@ (205 - 212) MeV** with ~ 10^{10} PoT each
  - 1 point **@ 402 MeV** with ~ 2×10^{10} PoT

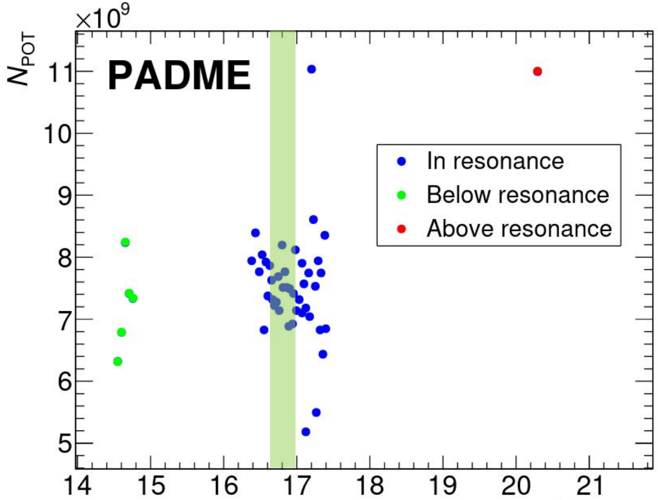
Some terminology:

- **Period**: a scan point at a fixed beam energy, typically lasting 24 hours
- **Scan**: a chronological set of periods typically decreasing in energy

Scan 1 and 2 periods spaced 1.5 MeV but relatively interspersed

- **Scan 1**: 12/10/2022 – 10/11/2022
- **Scan 2**: 25/11/2022 – 21/12/2022

Detailed Geant4-based MC performed for each period!

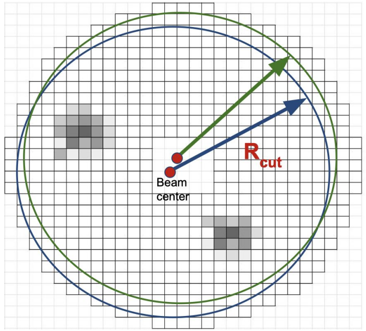


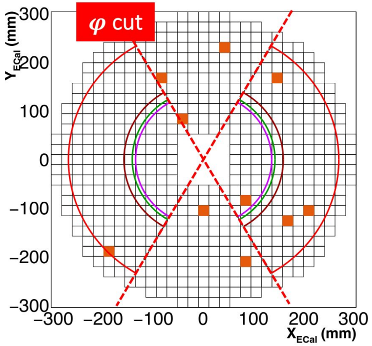
$m_{X_{17}}$ = (16.85 ± 0.04) MeV

$N_2(s)$ selection and Bremsstrahlung cut

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
    → Cut regions in φ



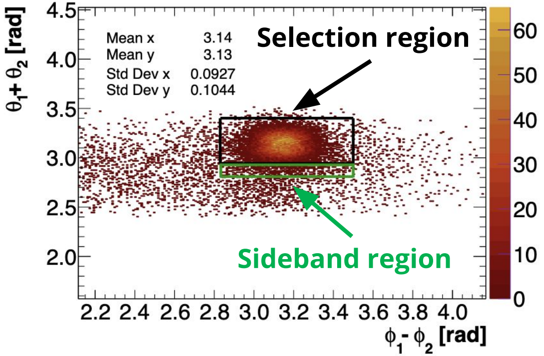


- **Mutual cluster conditions:**
  - $\Delta T < 5$ ns
  - $\Delta R > 60$ mm (min. 2 cluster diff.)
  - $E_1 + E_2 = E_{beam}$ (2-body final state process)

$\phi_1 - \phi_2$ vs. $\theta_1 + \theta_2$ cut in the center of mass frame isolates the signal
Flat beam bkg in $\phi_1 - \phi_2$ → bkg level < 4%

- Bremsstrahlung tail in $\theta_1 + \theta_2$ subtracted by using MC shape on the sideband

→ Statistical error: $\delta N_2 \sim 0.60\%$
→ Systematic uncertainty due to bkg subtraction: $\delta N_2 \sim 0.30\%$



SM **B(s)** uncorrelated error budget

The expected background yield **B(s)** is determined with MC + data-driven checks

Reconstruction efficiency:

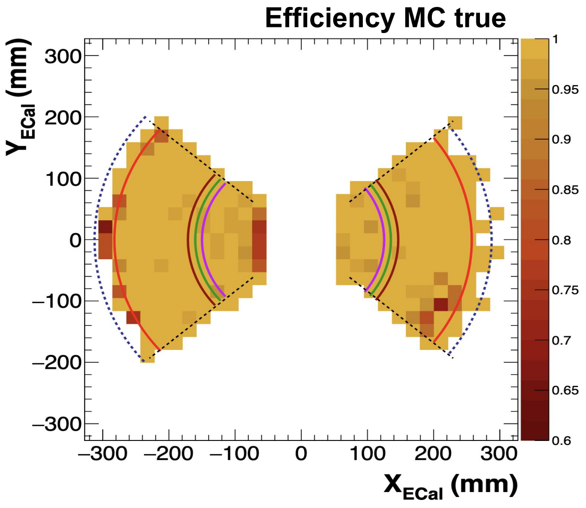
- Data/MC efficiency - Tag&Probe method
- Background subtraction at tag level dominated the systematic error → **δB = 0.35%**

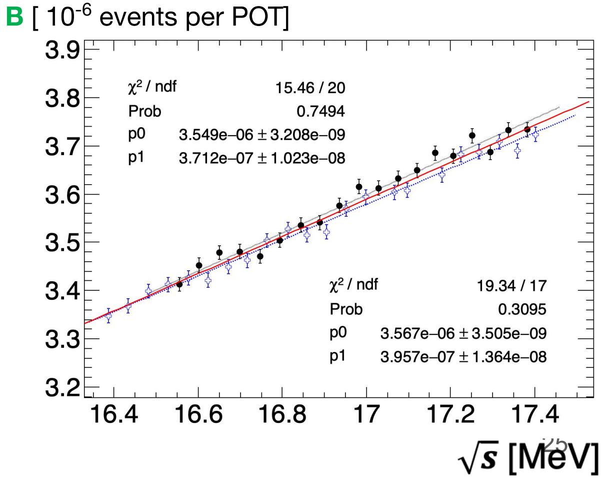
The selection relies on the expected beam direction: spot measured at the target and the Center of Gravity (COG) of 2 body final states at ECal

- 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 $s^{1/2}$ = (16.4, 17.3) MeV

$B(s)$ uncorrelated error

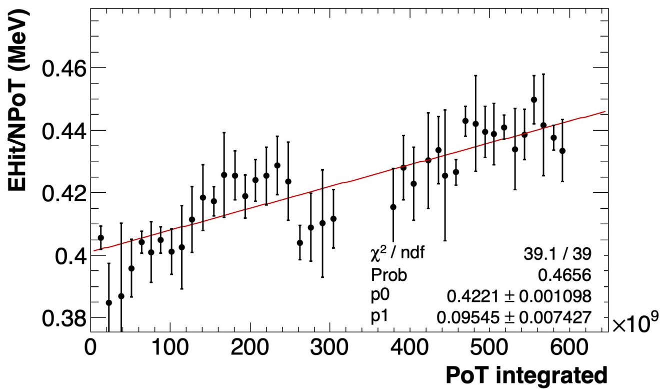
Source	Uncertainty (% per energy point)
MC statistics	0.40
Tag and probe efficiency	0.35
Cut stability	0.04
Beam spot variations	0.05
Total on $B(s)$	0.54

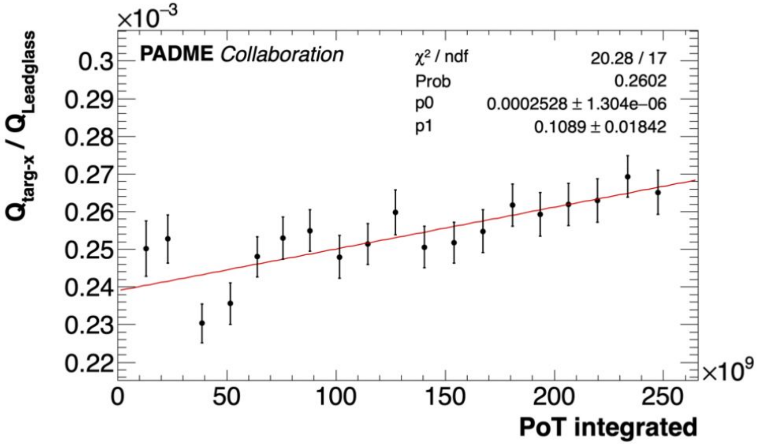




Systematic error of the N_{PoT}

→ after the corrections applied on the beam monitor





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**

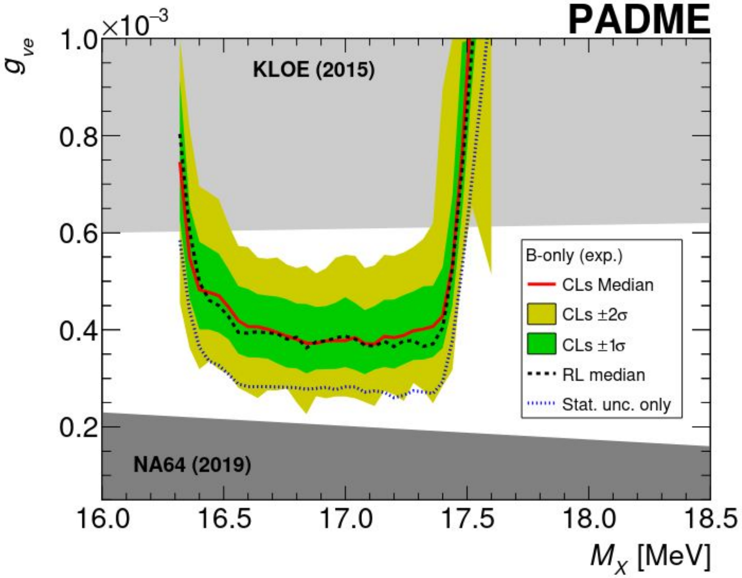
Common systematic errors

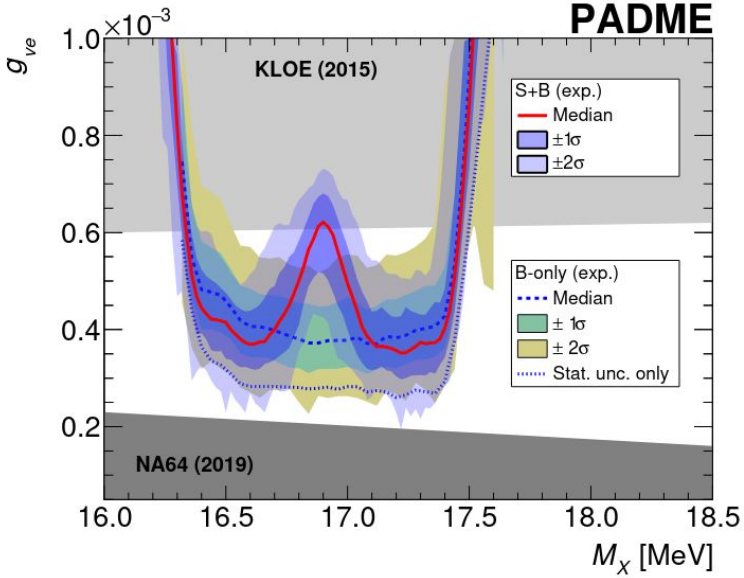
Source	Common error [%]
pC / MeV (JHEP 08 (2024) 121)	2.0
Energy Loss, data/MC	0.5
Rad. induced loss	0.3
Total	**2.1**

Run III expected sensitivity

Expected 90% CL upper limit in absence of signal (left) and in presence of signal (left):

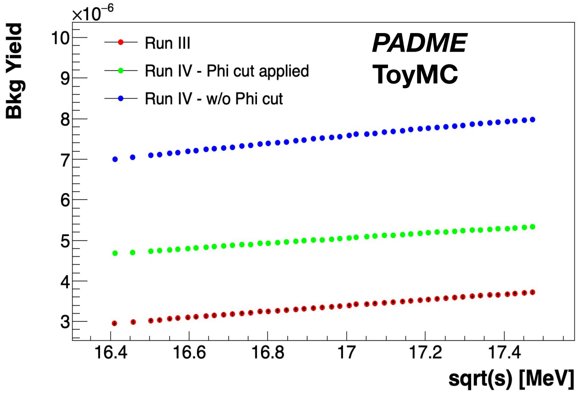
- Modified frequentist approach, LEP-stype test statistics; Likelihood fits performed for signal + background vs. background-only
- Total error budget: 0.88% on g_R(s) and 2.8% on K(s)



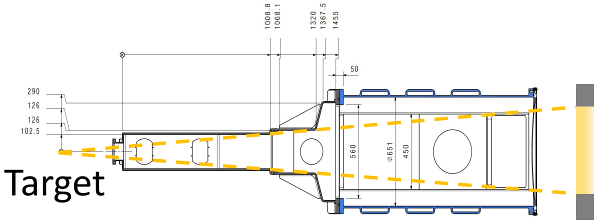


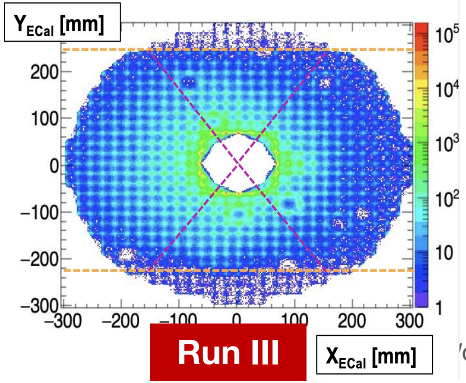
Run IV increased acceptance

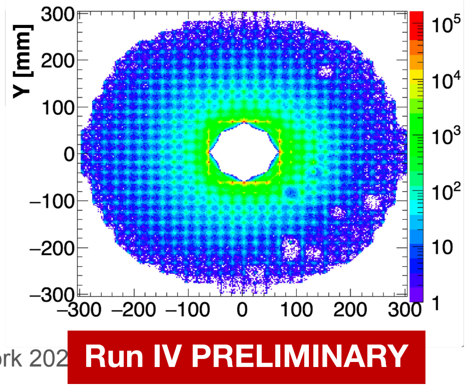
- Target thickness measurement dedicated data taking campaign
- Phi-cut can be totally removed or adapted
- Acceptance region widened → $\frac{Sig}{\sqrt{Bkg}}$ increases
- Run-by-run Run IV integrated luminosity increases by a factor of ~ 2.5 wrt Run III
    - Run III: $N_2 = 3.705\times10^{-6}$ (evaluated over 0.78×10^{10} PoT)
    - Run IV: $N_2 = 9.948\times10^{-6}$ (evaluated over 10^{10} PoT)



Run period	Target-ECal [mm]	Scattering θ_{lab} [mrad]	Magnet bore shadow
Run III	3700	24 - 73	249 mm
Run IV	3360	27 - 82	268 mm







TMM - MM beam monitor detector

- **A 10x10x5 cm^3 micromegas** detector:
  - Connected in series to the padMMe - same gas mixture (Ar:CF4:Iso=88:10:2)
  - HV 350 V, Drift 300 V
  - Chamber placed in front of the LG
- Larger and uniform active area wrt TimePix and less passive material budget
- Beam spot and flux monitor