Cornering the X_{17} at PADME

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Third Italian Workshop on the Physics at High Intensity

Bologna, November 15 2024

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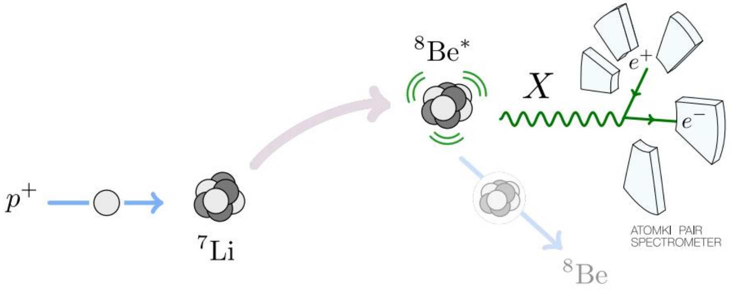
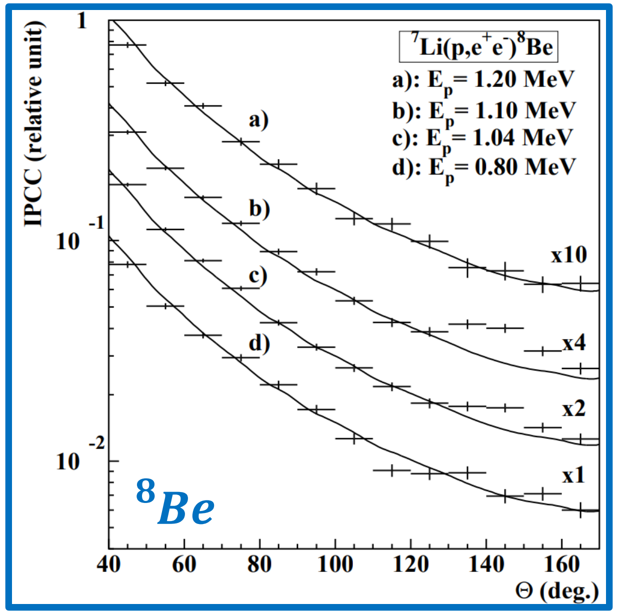
X17 anomaly @ ATOMKI

- Anomalous excesses in angular correlation of e^+e^- couples produced via IPC of ^8Be, ^4He e ^{12}C observed by the ATOMKI collaboration.

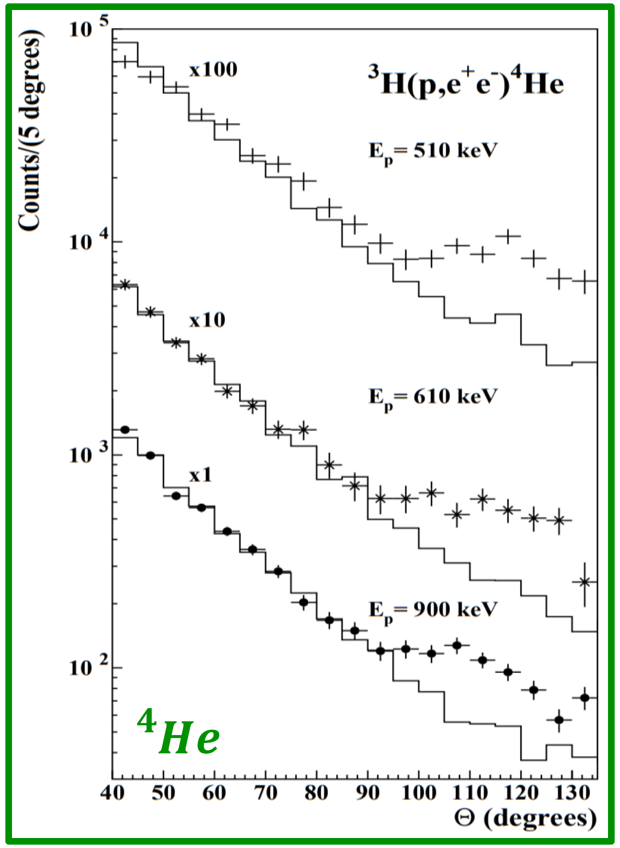
- The anomaly seems to be compatible with the production and successive decay of a **new ~17 MeV mass particle**



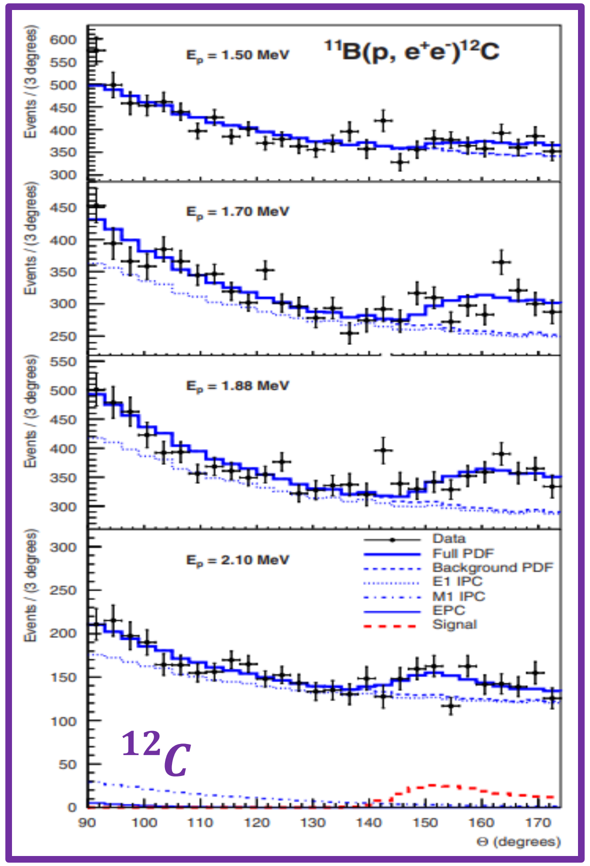
Phys.Rev.Lett. 116 (2016) 4, 042501



Phys.Rev.C, 104(4):044003



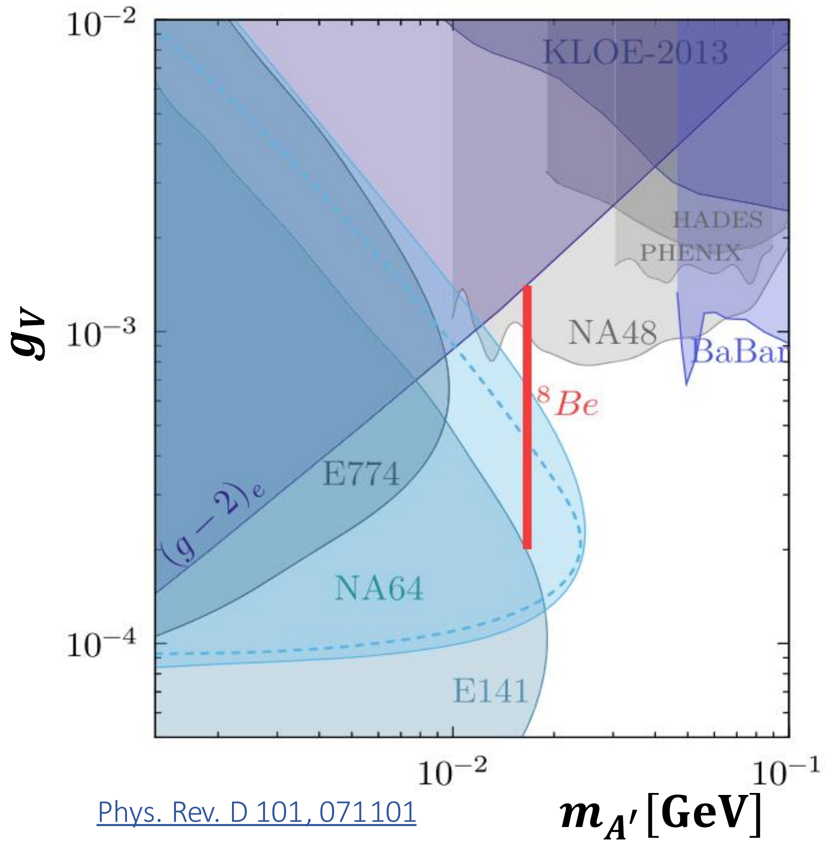
Phys. Rev. C 106, L061601



X17 as a vector or pseudo-scalar state

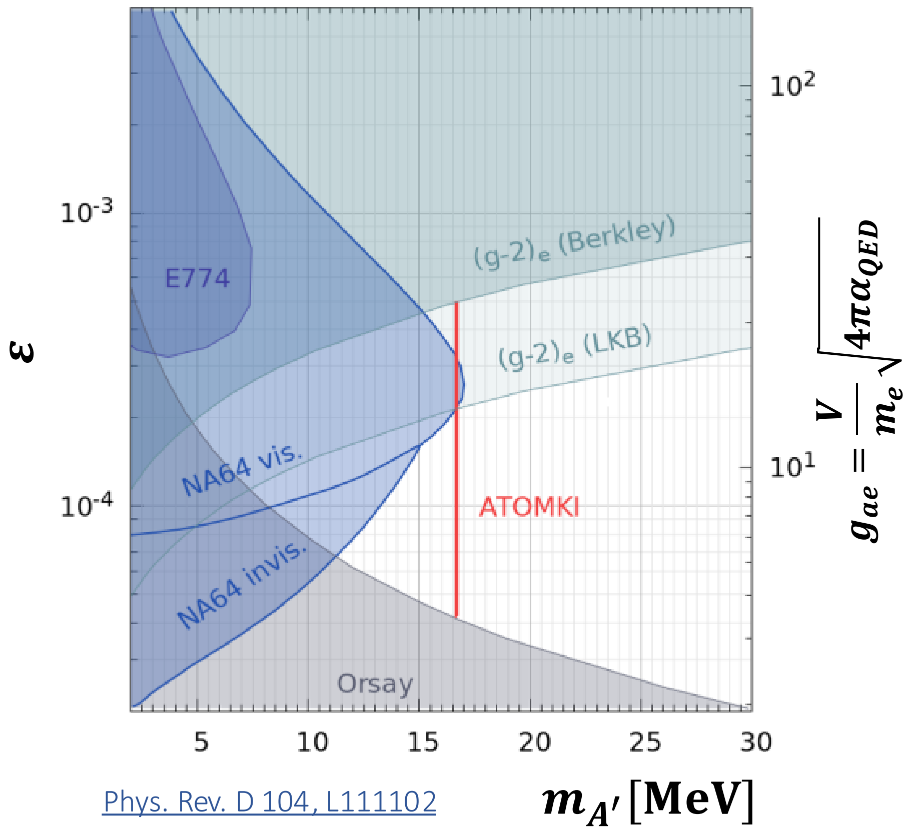
- New physics interpretations not fully excluded → still some phase-space available
- The PADME experiment is sensible to this mass range

Vector



Phys. Rev. D 101, 071101

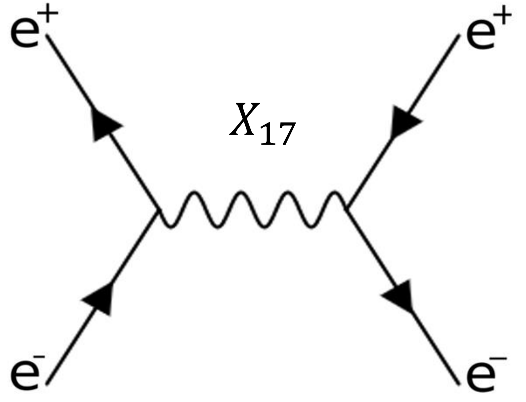
Pseudoscalar



Phys. Rev. D 104, L111102

Resonant search on fixed thin target

- $\sigma_{res} \propto \frac{g^2_{Ve}}{2m_e} \pi Z\, \delta(E_{res} - E_{beam})$ 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 scan procedure with the e^+ beam → expected enhancement in $\sqrt{s}$ over the standard model background



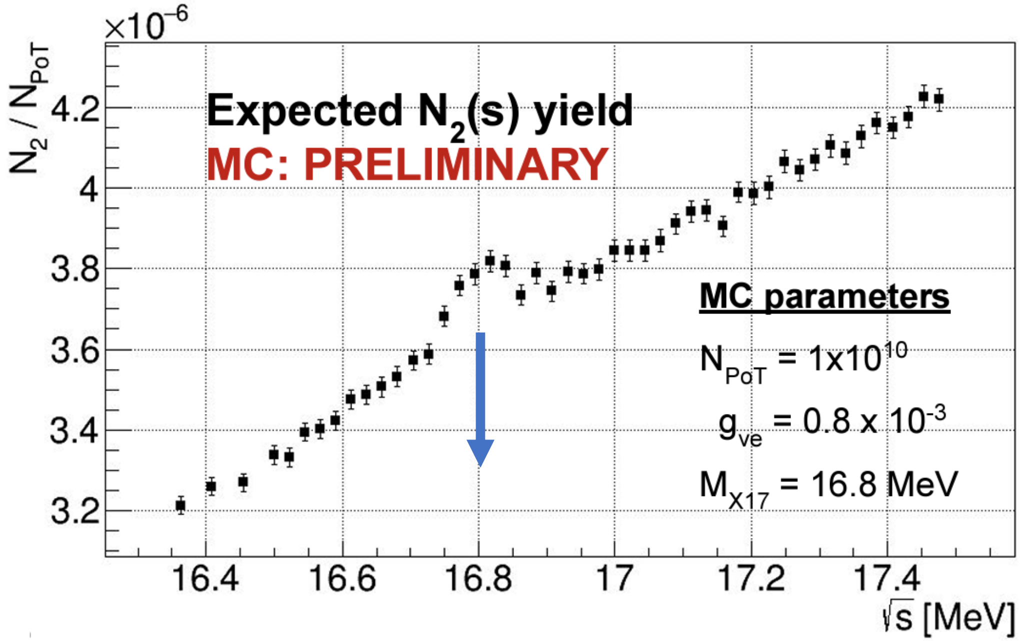
At PADME, X_{17} produced through resonant annihilation in diamond target:
Scan around $E(e^+)$ ~ 283 MeV with the aim to measure two-body final state yield N_2

$$N_2(s) = N_{POT}(s) \times [\, B(s) + S(s;\, M_X, g)\; e_S(s) \,]$$

to be compared to $N_2(s) = N_{POT}(s) \times B(s)$

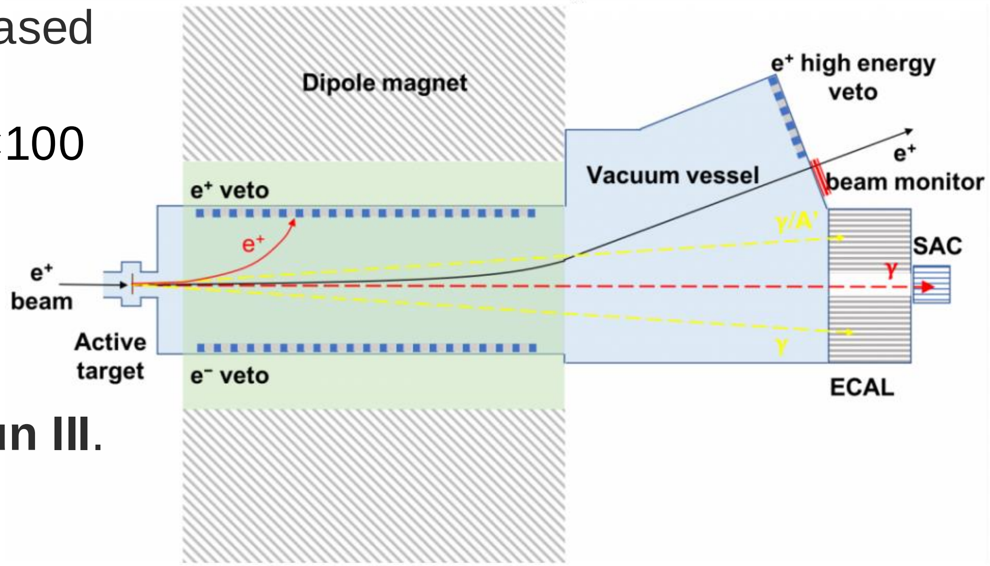
Inputs:

- $N_{POT}(s)$ number of e+ on target from beam-catcher calorimeter
- $B(s)$ background yield expected per POT
- $S(s; M_X, g)$ signal production expected for {mass, coupling} = $\{M_X, g\}$
- $e_S(s)$ signal acceptance and selection efficiency



The PADME experiment

- Positron Annihilation into Dark Matter Experiment: $e^+e^- \rightarrow \gamma A'$ based @ Frascati National Laboratories (LNF-INFN).
- e^+beam (E<550 MeV) on a diamond active target 2 cm × 2 cm ×100 μm
- Measure of ΔM^2_{miss} using a BGO ECal.
- Could be sensitive to sub-GeV new physics (e.g. ALPs)



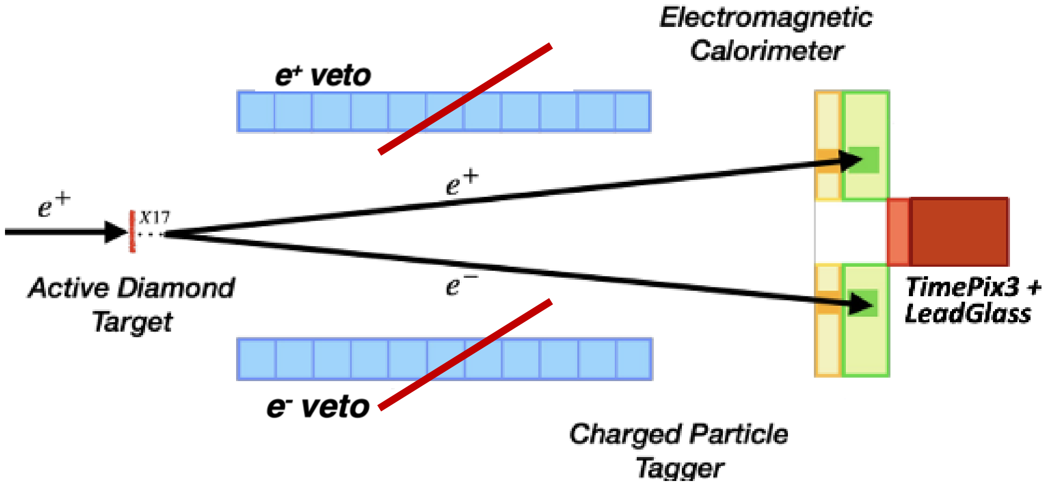
Can exploit the resonant production of X17 → fine scan: **PADME Run III**.

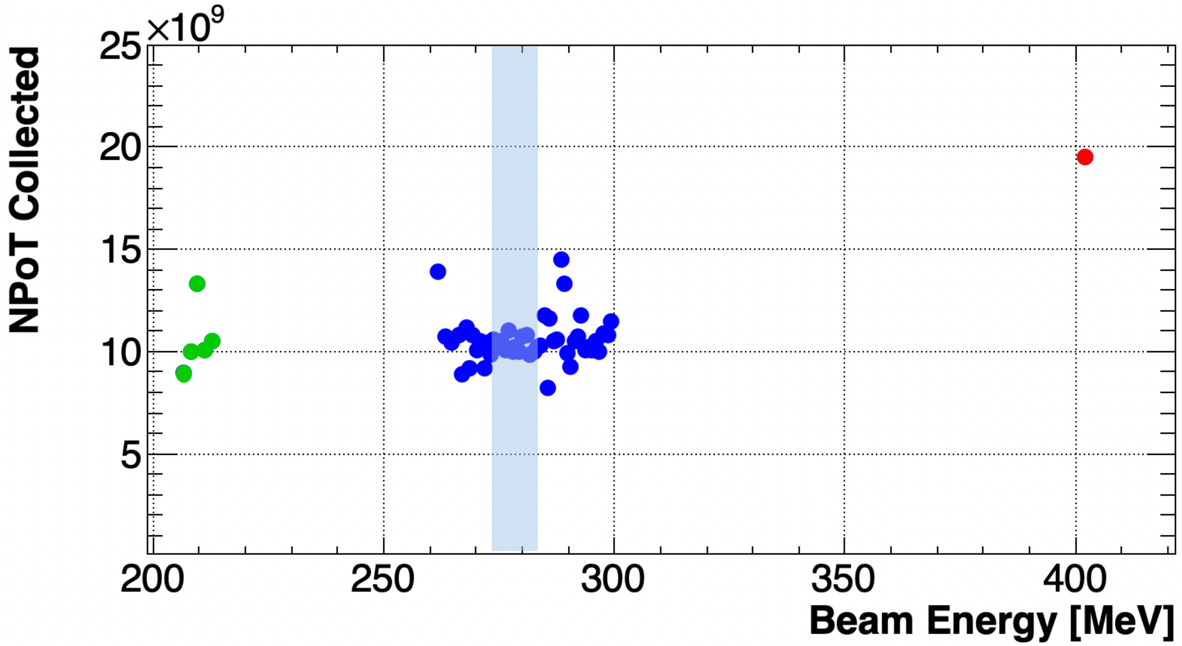
- Some modification to the setup were necessary

PADME Run III

Main SM background are Bhabha scatterings and $\gamma\gamma$ pairs productions, fitted directly from data → needed some setup optimization:

- PADME dipole turned
- ETagger added to identify charged particles
- SAC replaced with a TimePix3 beam monitor and a Leadglass luminometer





Light blue zone: mass interval from fit results in [Phys. Rev. D 108, 015009 (2023)]

Data-taking divided in 3 parts:

- ➢ **On resonance: 47 points @ (263-299) MeV**
- ➢ **Below resonance: 5 points @ (205-211) MeV**
- ➢ **Over resonance: 5 points @ 402.5 MeV**

Beam monitoring

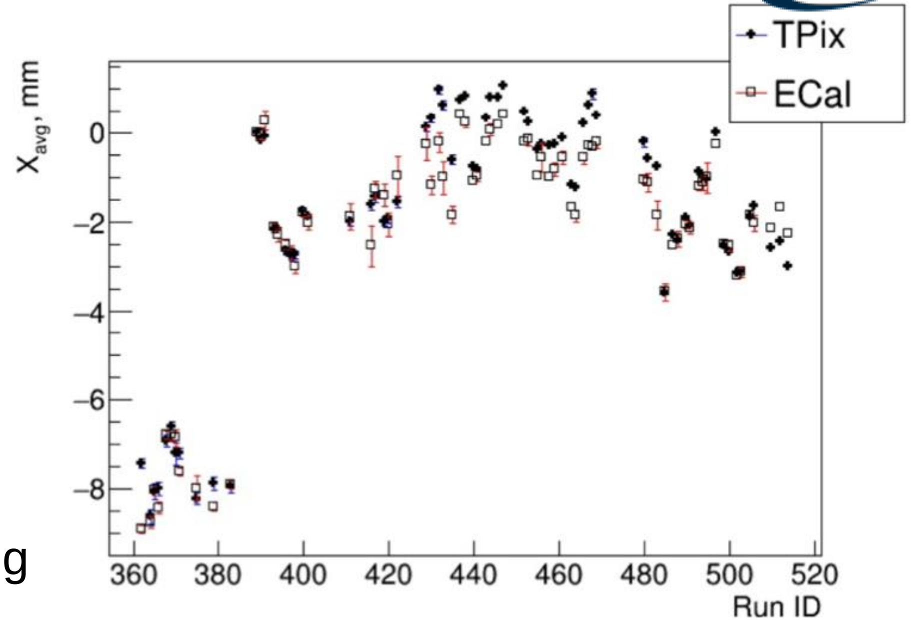
Selection algorithm as independent as possible on beam and detector conditions

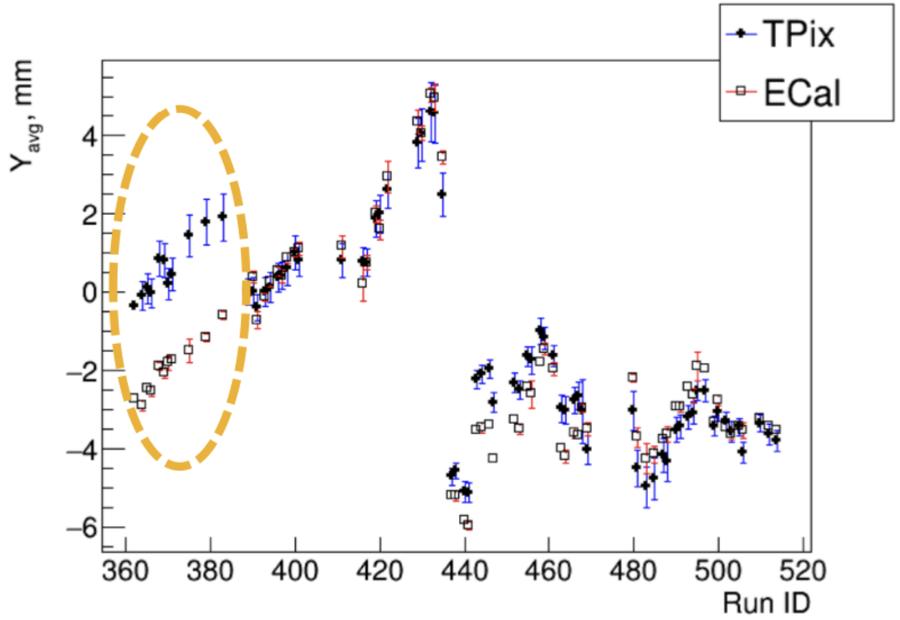
- **Beam position measured run by run** in data from the center of gravity (COG) of 2 EM clusters at ECAL

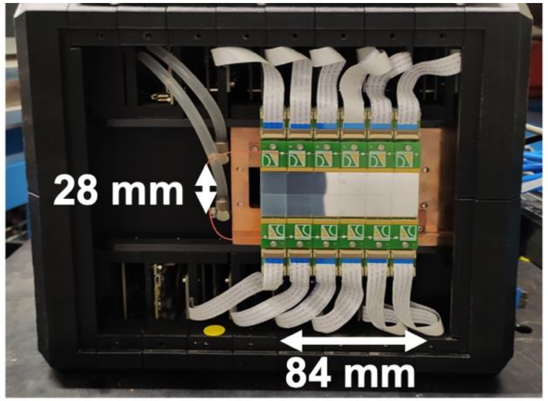
$$x_i^{COG} = \frac{x_i^1 E_1 + x_i^2 E_2}{E_1 + E_2}$$

The beam position slightly moves run by run

- Focus kept ~ at target, minimum fine tuning to increase data taking efficiency
- Cross-checked using a downstream silicon pixel detector (TimePix) (55 µm square pixels, 84 x 28 mm2 active area)
- Beam spot at TimePix used to model beam emittance in MC



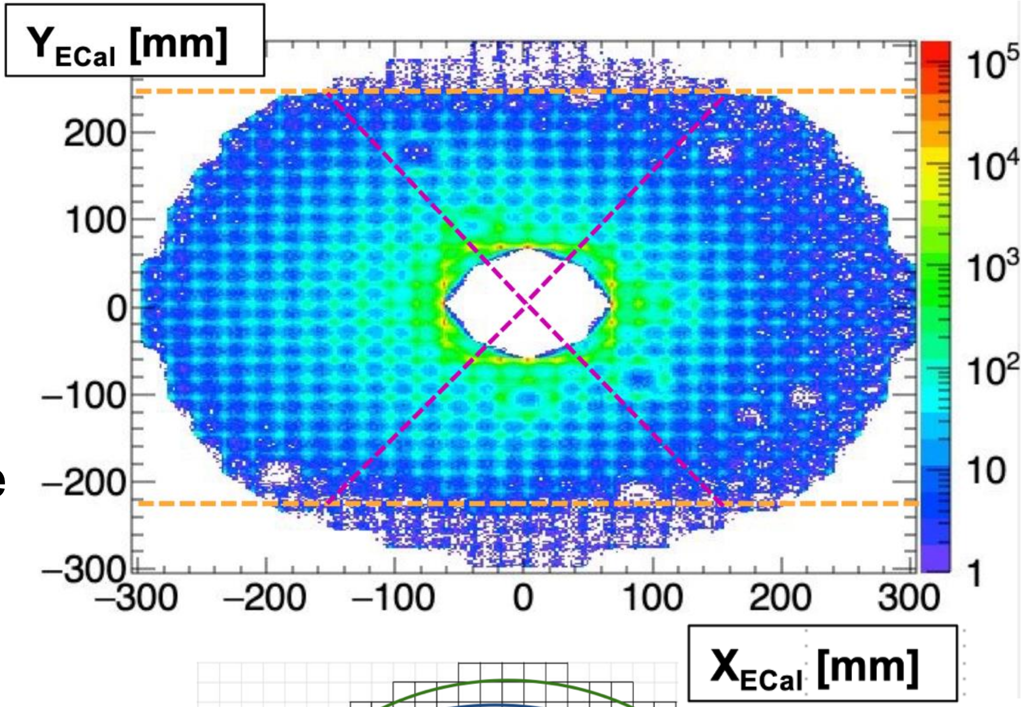


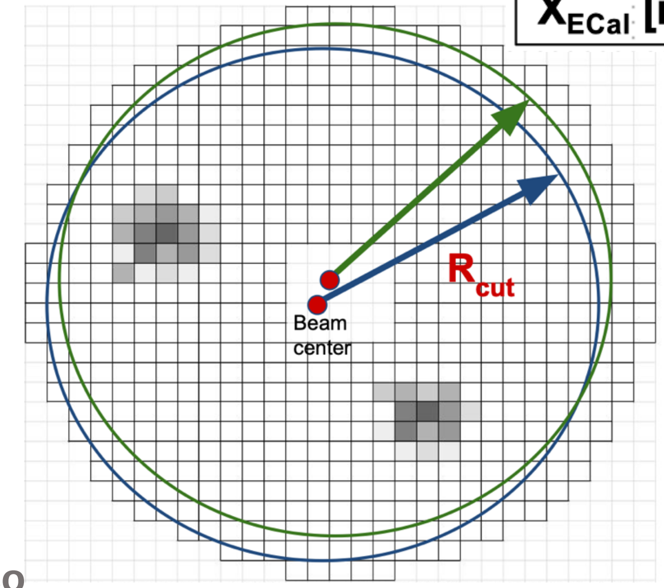


PADME Two clusters selection cuts

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

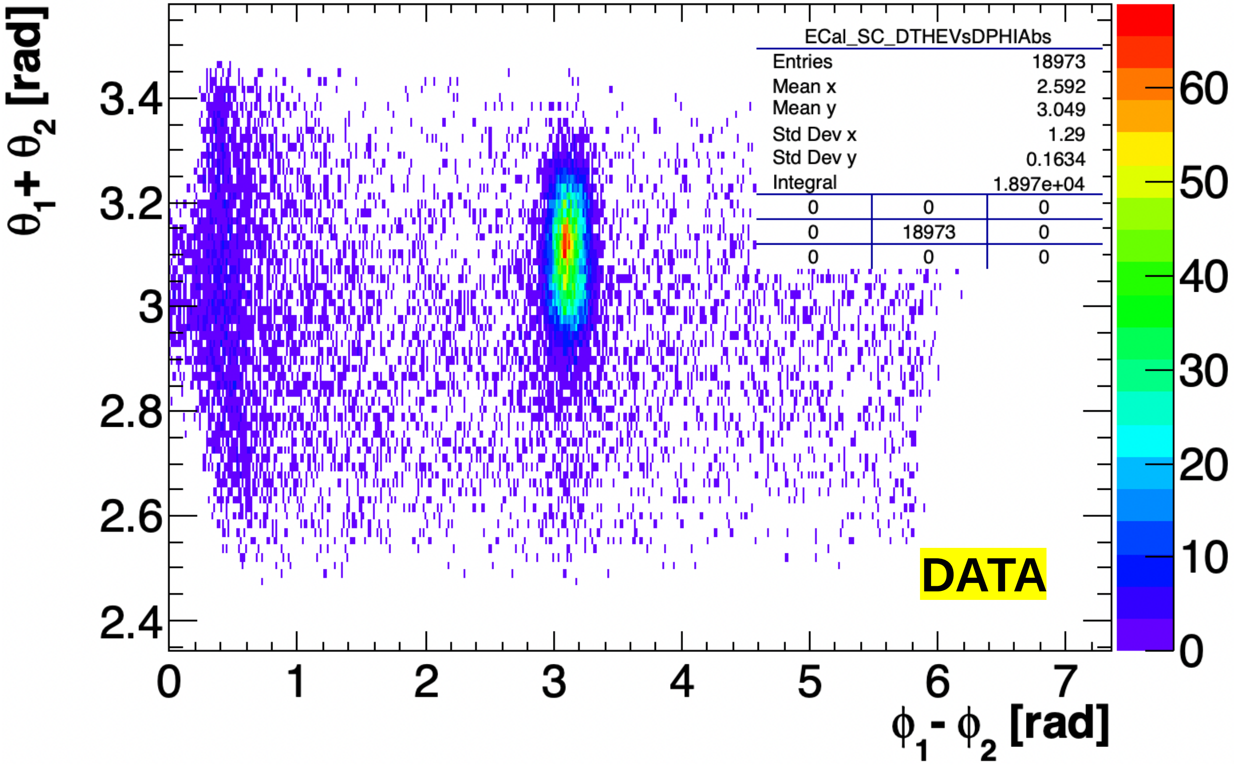
- **Selected a cluster pair with the following criteria**
  - Maximum radius defined by ECAL dimensions
  - Energy within the “two-cluster” kinematic range
  - Minimum radius within the “two-cluster” kinematic range → following the beam center conditions
  - Illumination clearly affected by material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

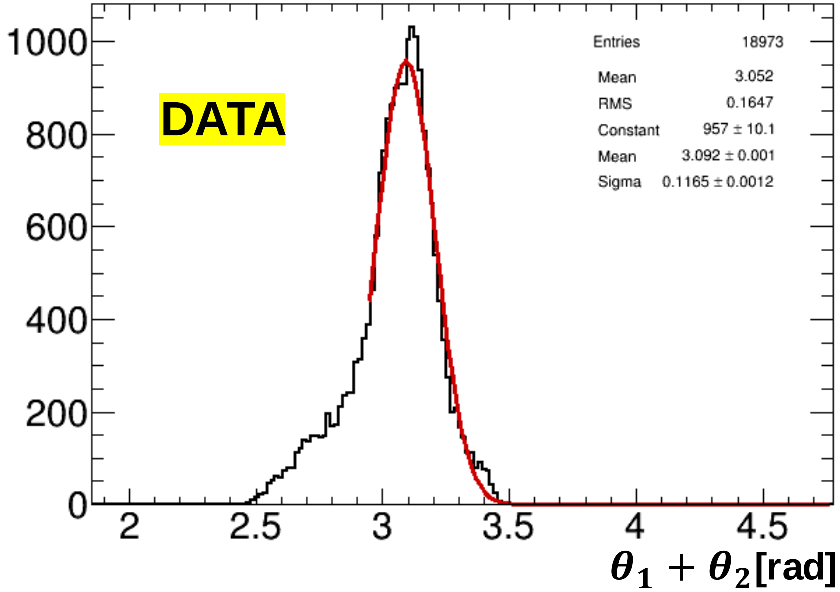


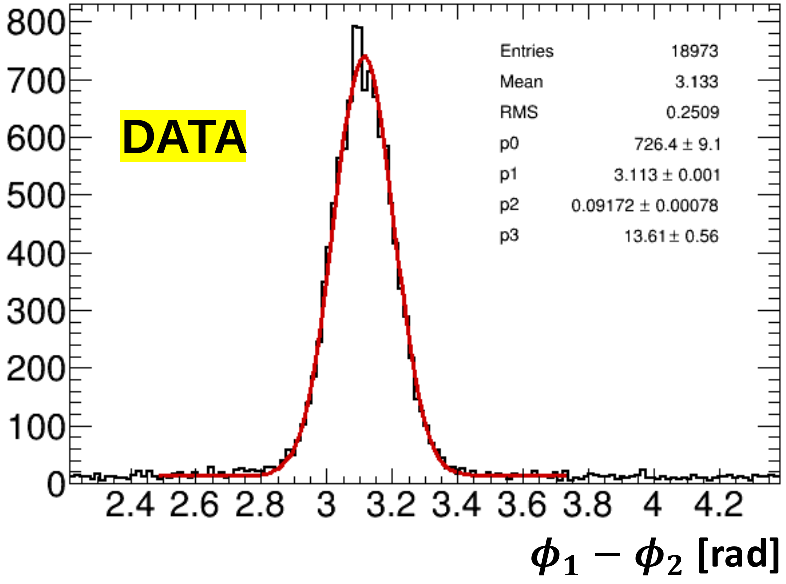


$\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$

- $\phi_1 - \phi_2$ vs $\theta_1 + \theta_2$ cut isolates the signal
- **Cut range**: 3σ around the mean value
  - ➢Flat beam bkg in $\phi_1 - \phi_2$ coordinates
  - ➢Gaussian+Costant fit → bkg level ~4%

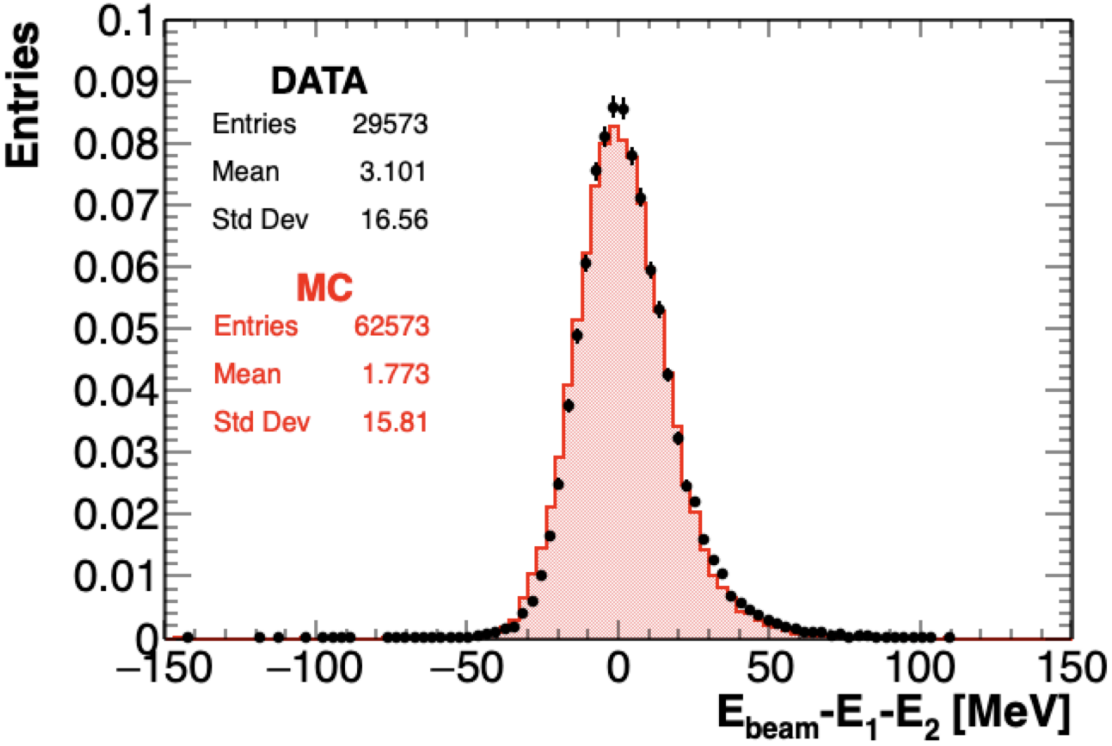


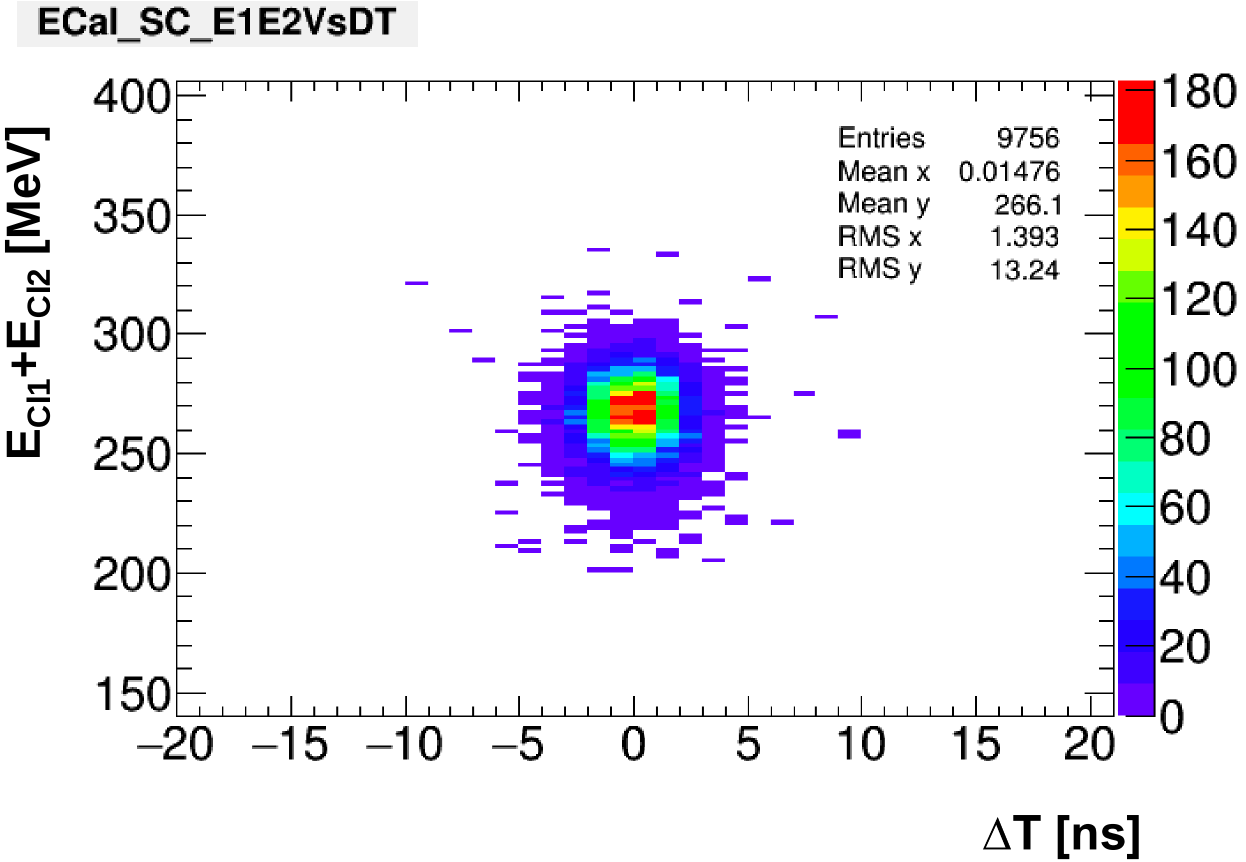




Events selected

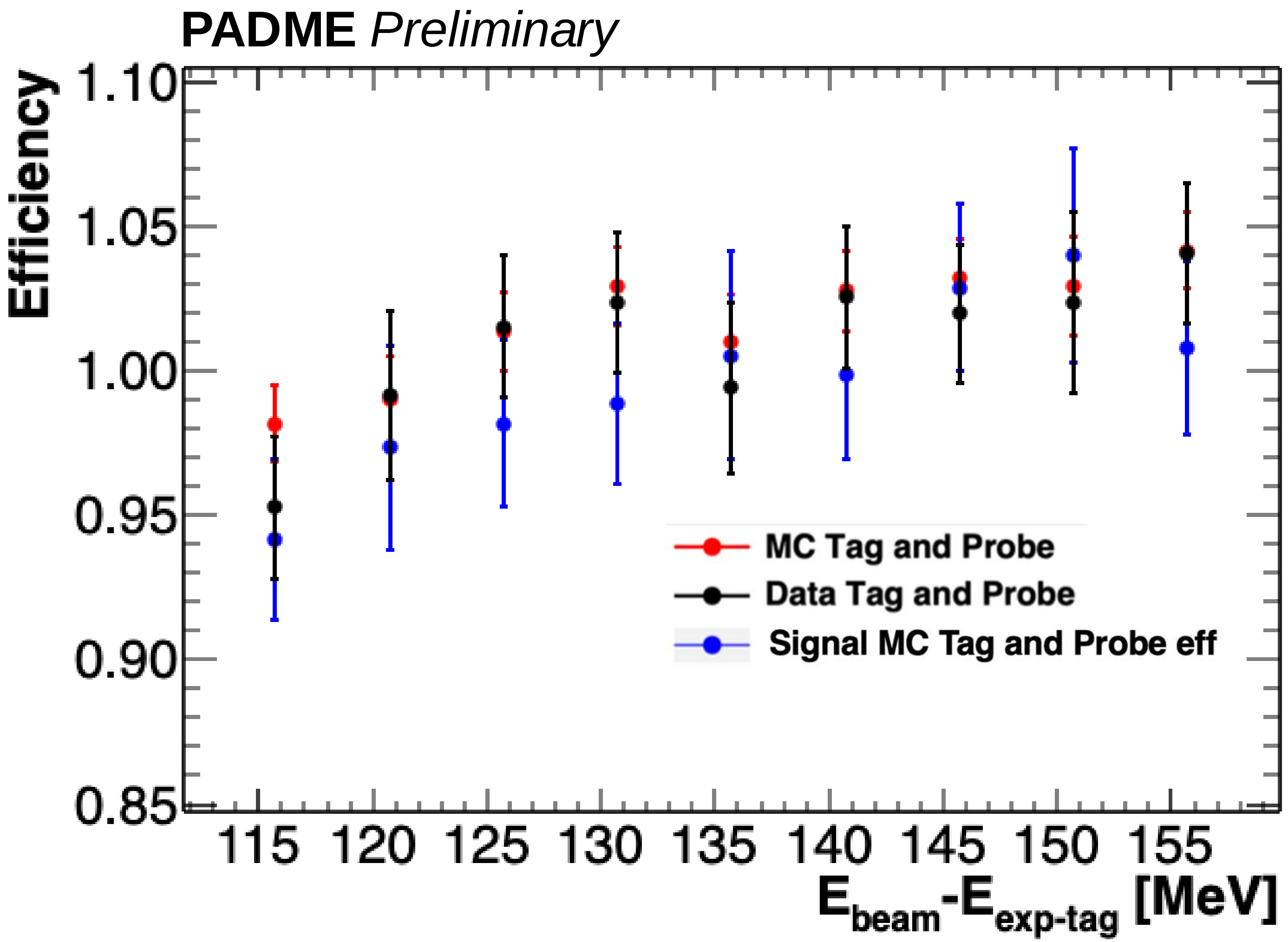
- Events surviving the whole set of cuts, also related to the time difference of the 2 Clusters
- Energy sum of the 2 clusters selected gives back the beam energy (as expected for a two-body final state)
- ECAL relative energy resolution ~ 5%





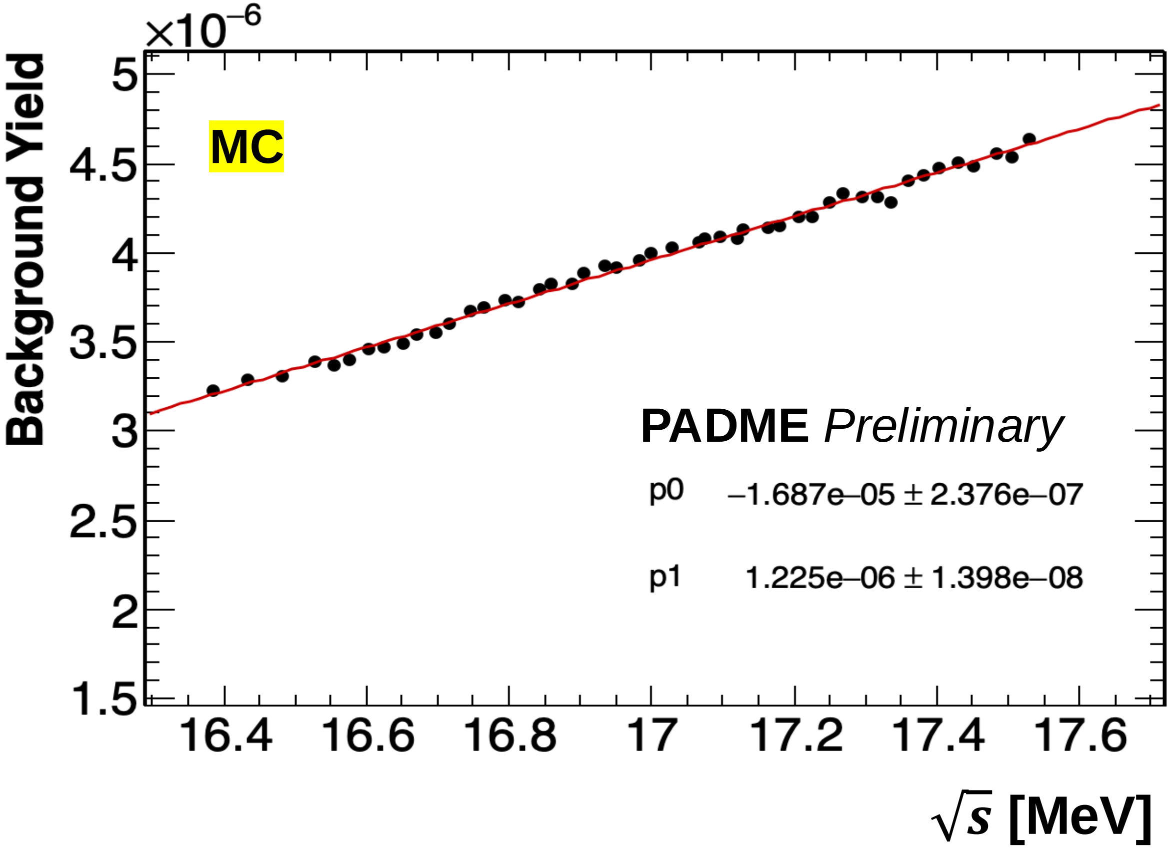
ECAL efficiency: Tag and Probe

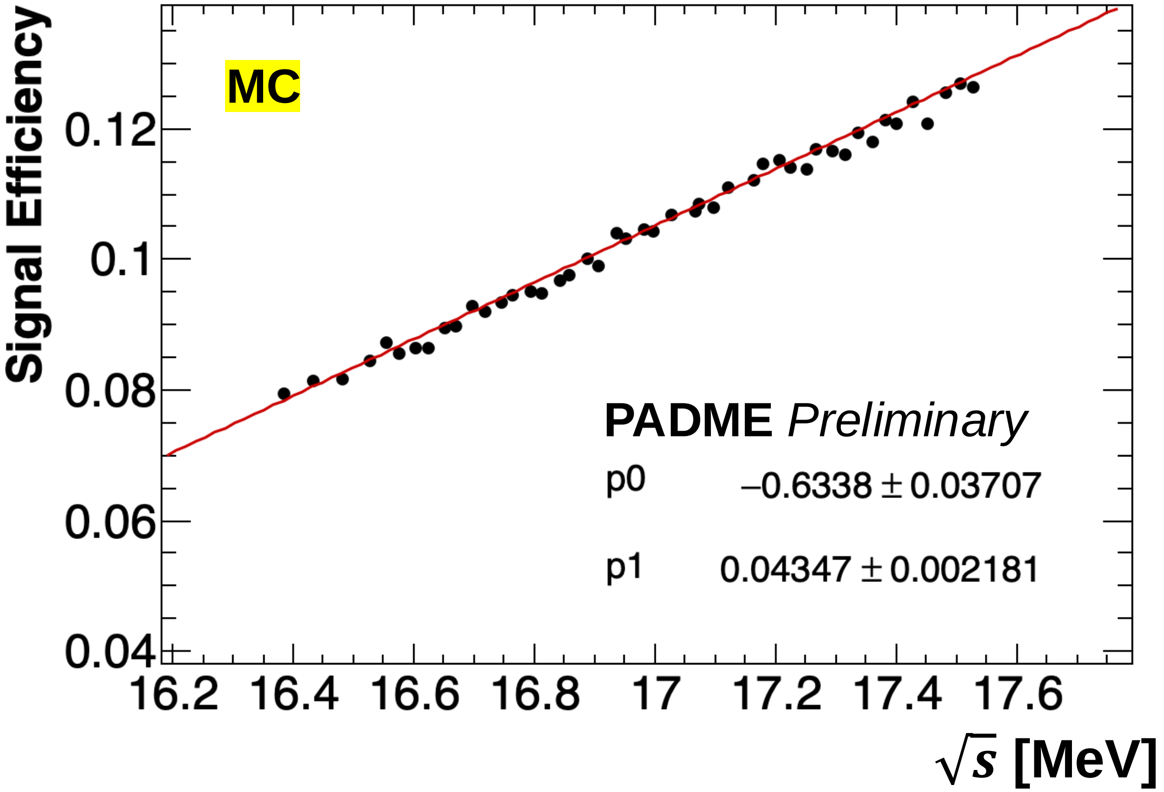
- ECAL efficiency evaluated using the **Tag and Probe** method.
- Low energy inefficiency is mainly due to the hit energy threshold applied during the reconstruction phase **(15 MeV)**
- **Still some residual issue for background subtraction in the Tag evaluation**
- The MC correction to be applied on data is expected at % level



MC bkg yield and signal efficiency

Selection algorithm provides a degree of cancellation of systematic uncertainties
- A data/MC correction to ECal reconstruction largely cancels in the ratio **$B(s)$ / $e_S(s)$**
- Quantitatively: a 15% slope correction in energy per cluster ~ 0.2% in **$B(s)$ / $e_S(s)$**

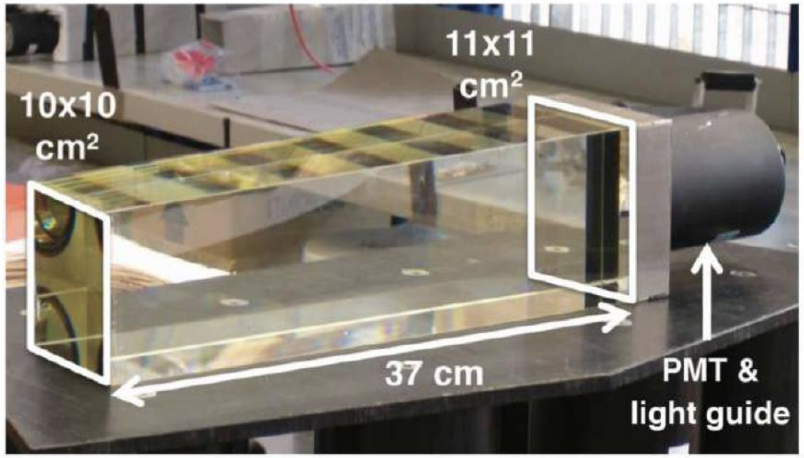


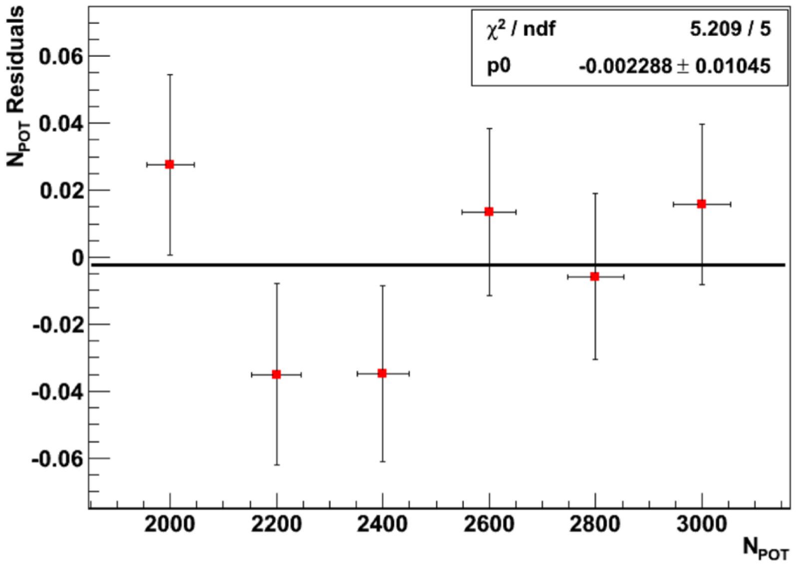


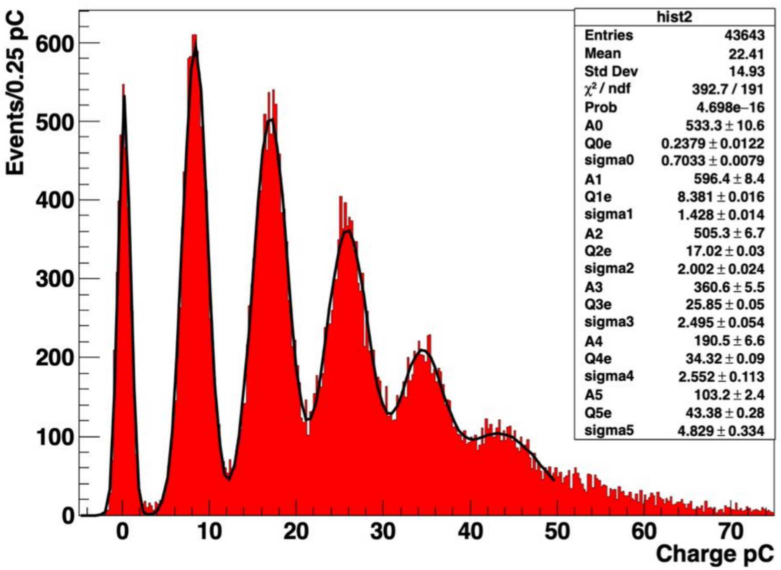
- The individual uncertainties behave mostly like the POT scale uncertainty
- The non-correlated part of the uncertainty is < ~ 0.5%

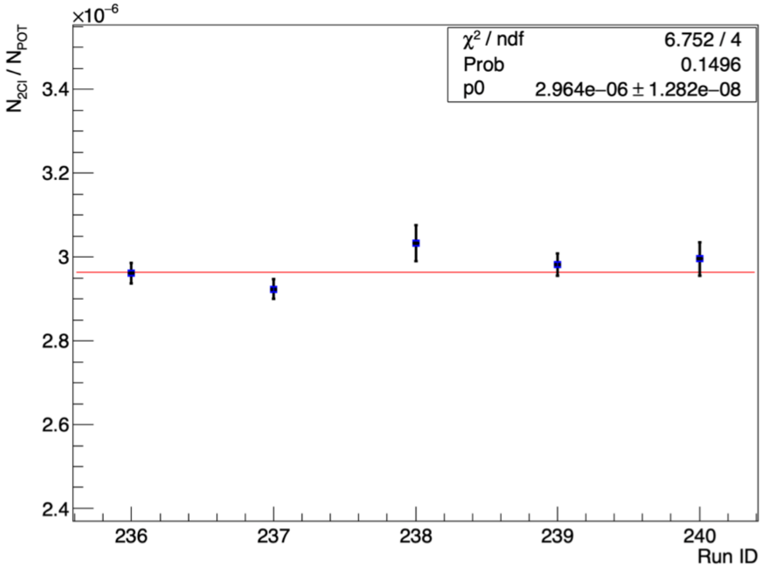
Luminosity measurement

- POT measured from a beam catcher lead-glass block operated at low HV [650 V] to avoid saturation at 3000 e+
- **Cross-calibrated** against pixel-based detector for un-deviated beam **at 2%**
- Independent calibration performed with single e+ at ~1000 V → gain curve is OK, but uncertainty is 8%
- Once the PbGL was placed at the end-of-line, corrected run by run for leakage: **error ~ 0.5%**



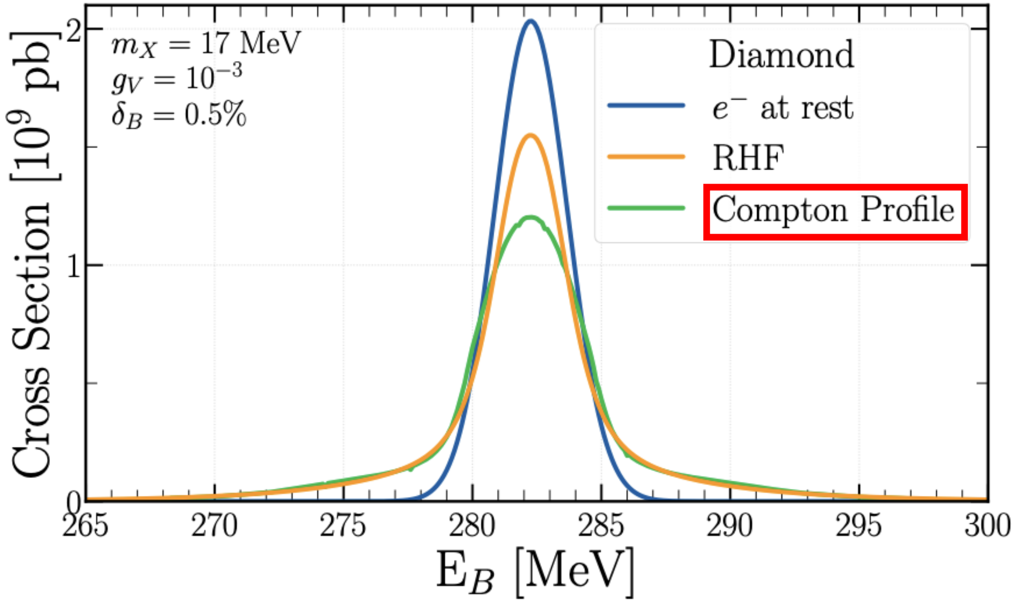


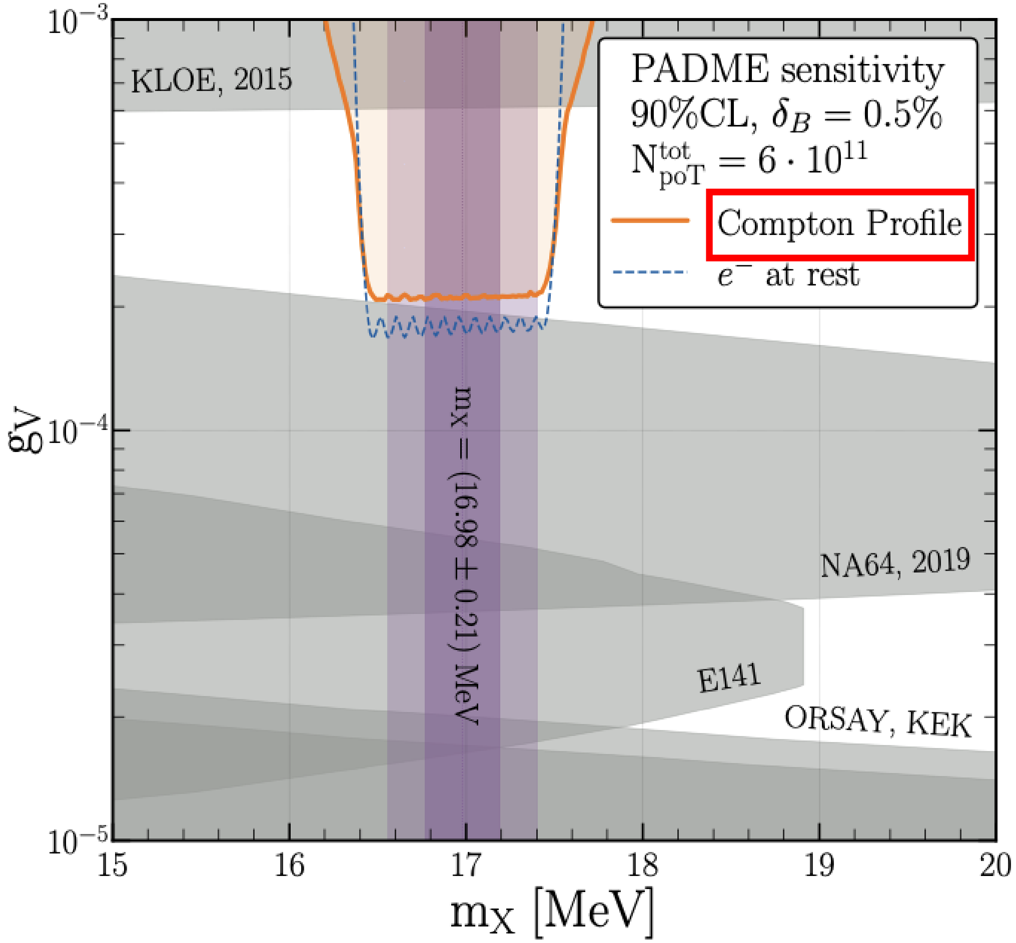




Target electron motion effect

- The electron motion inside the diamond target causes not negligible effects in the resonance lineshape and cross section
- This has many effects on the data already collected:
  1. Signal yield down by a factor 3.5, S/B by a factor 2
  2. Side bands for background scaling down by x4
  3. Sensitivity reachable strictly **depending on the systematic error**
  4. The theory error on the expected signal yield is below 3%



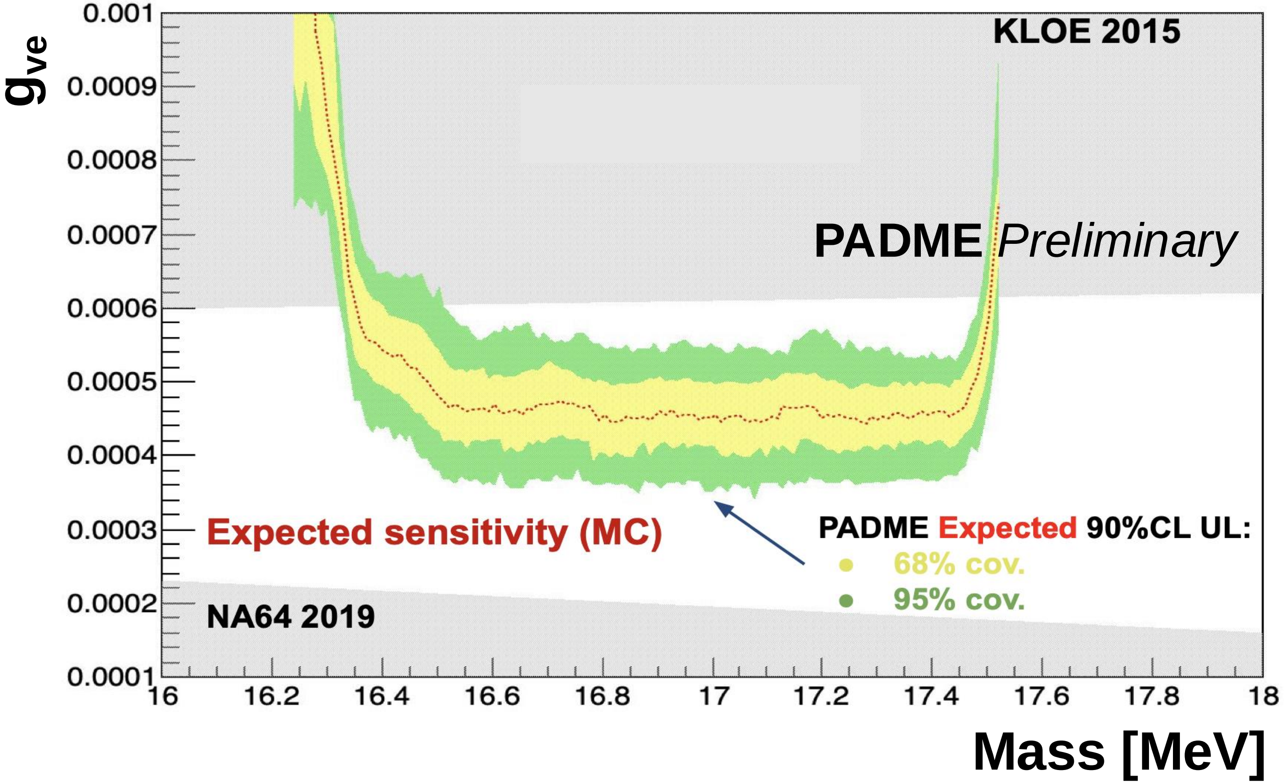


Phys.Rev.Lett. 132 (2024) 26, 261801

PADME Expected sensitivity

Expected 90% CL upper limits are obtained with the CLs method:

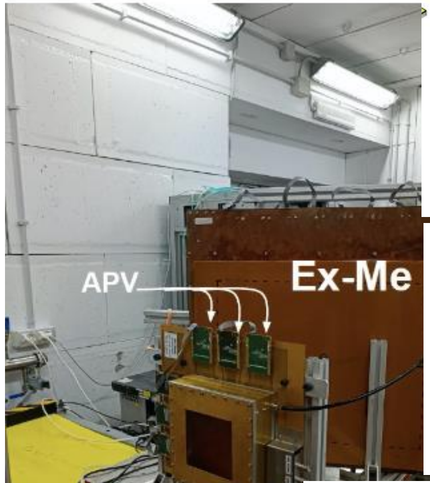
- Modified frequentist approach, LEP-style test statistic
- **Likelihood fits** performed for the separate assumptions of **signal + background vs background only**
- $Q_{statistics} = -2\ln(Lsb/Lb)$

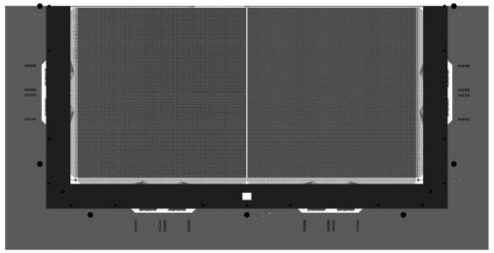


- Pseudo data (SM background) is generated accounting for the expected uncertainties of nuisance parameters + statistical fluctuations
- **147 Nuisance parameters:**
  - NPoT of each scan point
  - Common error on NPoT (scale error)
  - Signal efficiency for each scan point
  - Background yield for each scan point
  - Signal shape parameters: theoretical input and beam energy spread

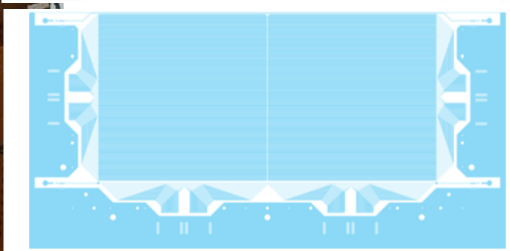
PADME Run IV

- Idea to close the X17 parameter space with a new run, so-called Run IV
- Main pillars of the new run:
  - Wrong e^+e^- tagging must be under control → ETag is limited by rate capability
  - Substitute the ETag with a micromega-based tracker to **evaluate N(e^+e^-)/N($\gamma\gamma$)** vs $\sqrt{s}$ instead of N(e^+e^- / $\gamma\gamma$)/NPoT
  - **Decrease by x2 the number of points in $\sqrt{s}$, take 4x statistics per point**
  - Precisely evaluate the beam features (beam spot, angle, energy, beam focus) per point using TimePix
- **Micro pattern gas detector:**
  - High segmentation
  - Able to track
  - Low material budget
  - Great XY resolution
- Already tested @ the LNF Beam Test Facility di LNF in May and July 2024, now almost ready to be installed.

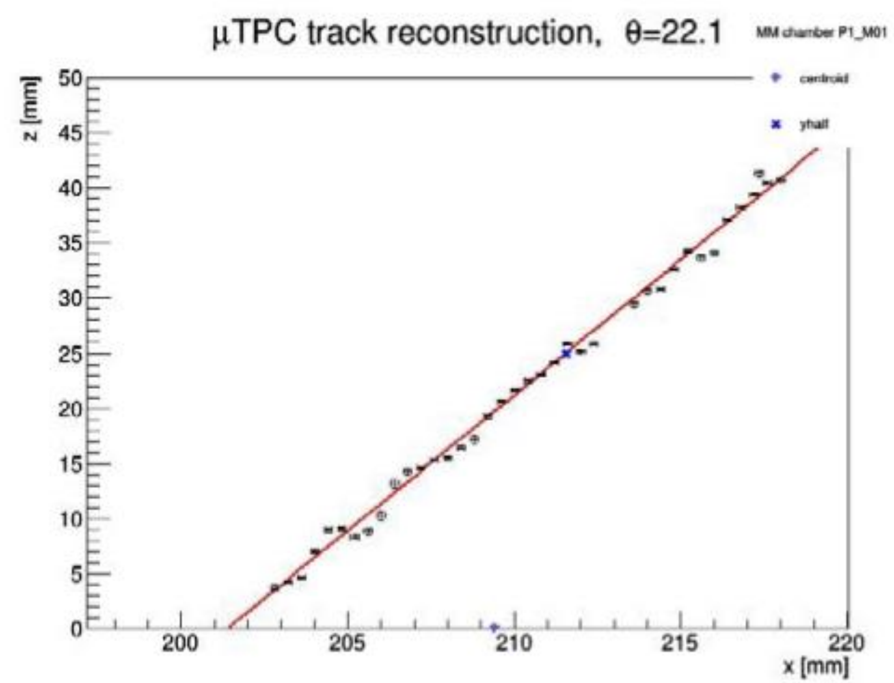




Strip layout



Diamond layout



Conclusions

- PADME performed 53 (47 on-resonance + 6 off-resonance) cross section measurements of the SM allowed processes: Bhabha scattering and $\gamma\gamma$-production
- Quality of the Run III data meet expectations for X17 searches → <1% systematic error is achievable
- Data are still blind, but PADME aims to set limits on both vector and pseudoscalar model
- The presence of the electron motion effect worsened the global significance for the X17 search, however it could be exploit to improve BSM searches
- A new Run period (PADME Run IV) is already scheduled at the beginning of 2025 → Collect x2 Run III statistics to close the gap in vector model parameter space
- In case an excess is observed on Run III data sample → Focused Run IV in restricted s range

Backup slides

MEG results

- Hypothesis of a X17 with mass > 16.97 MeV now excluded (great result!)
- For the whole mass range available the actual exclusion is:

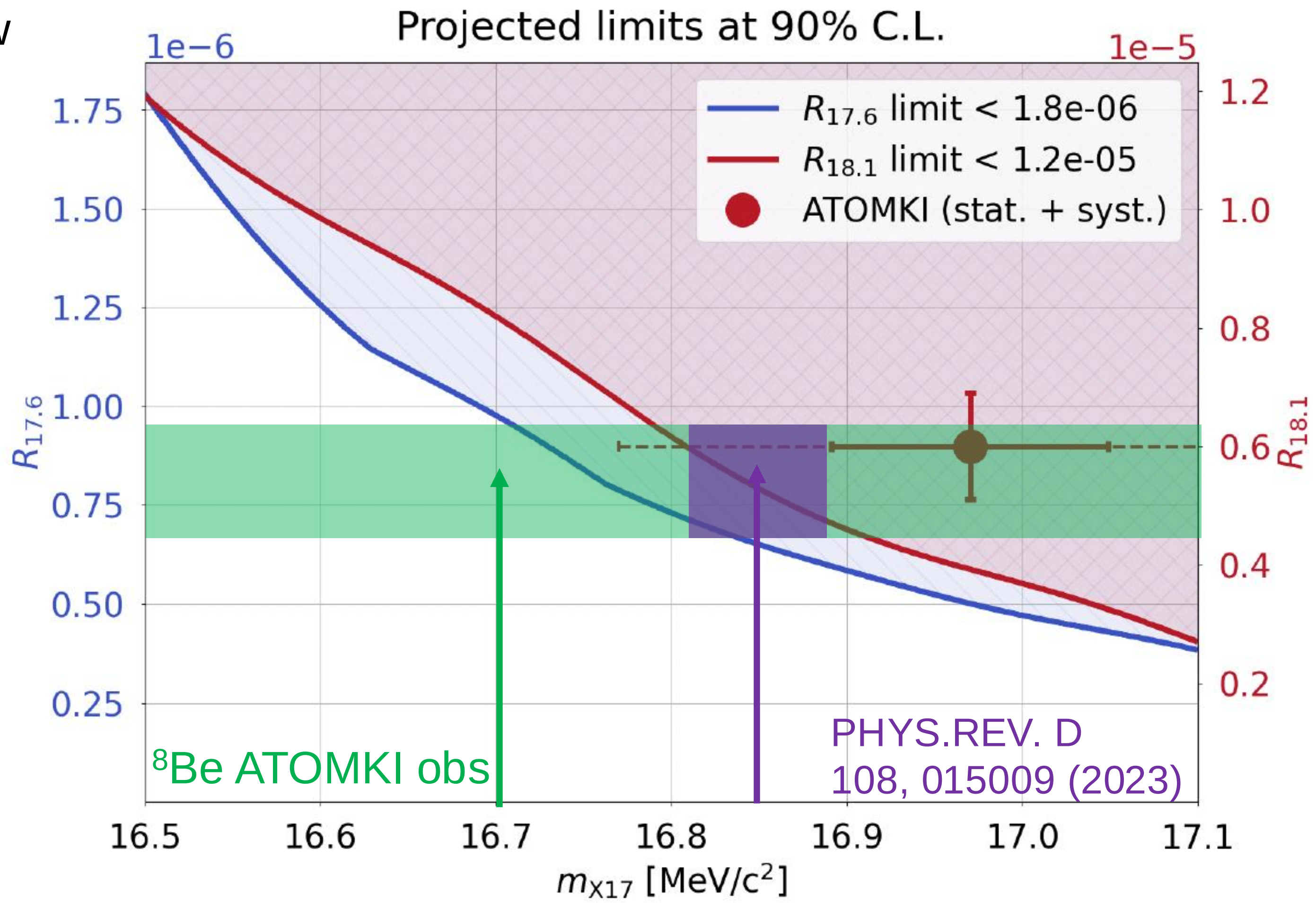
$$R_{18.1} < 1.2 \times 10^{-5} \text{ and } R_{17.6} < 1.8 \times 10^{-6}$$

- From fits in **PHYS.REV. D 108, 015009 (2023)** the best mass candidate combining ATOMKI results in:

$M_{X17} = 16.85 \pm 0.04$ MeV

- The result from **ATOMKI ^{8}Be measurement** (only one comparable to MEG results) is instead:

$M_{X17} = 16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV.
with $R_{18.1} = 5.8 \times 10^{-6}$



Ricercare A' nelle reazioni elettrone-positrone

Il Fotone Oscuro A' può essere descritto come un portale massivo e neutro tra il Modello Standard e il Settore Oscuro:

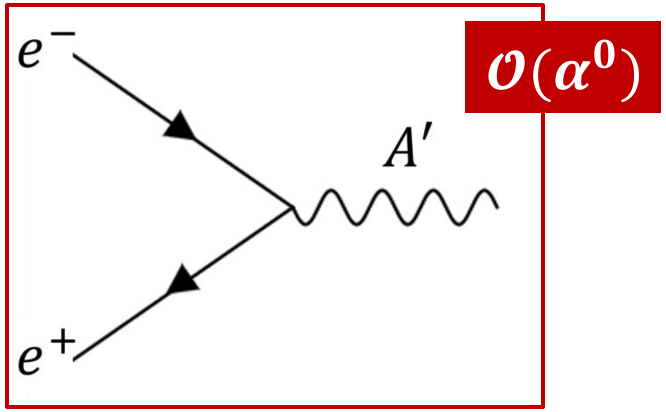
$$\mathcal{L} \sim g_V q_f \bar{\psi}_f \gamma^\mu \psi_f A'_\mu$$

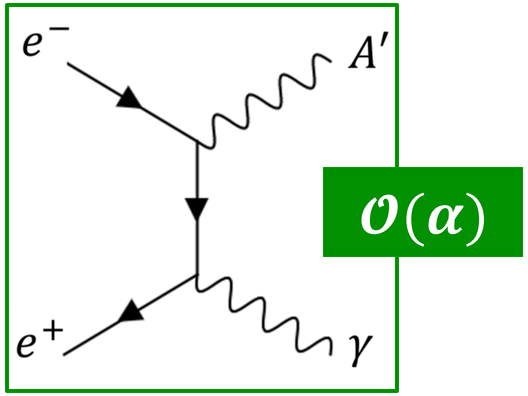
$g_V \ll 1$ → nascosto/oscuro

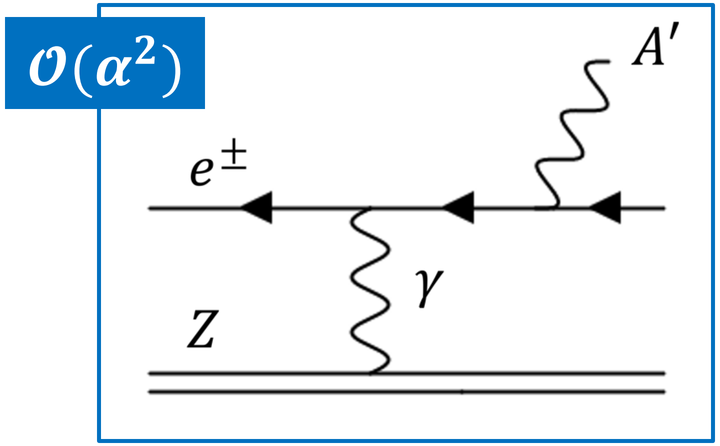
Produzione di A' tramite due differenti meccanismi, annichilazione ed emissione:

- **Annichilazione risonante:** $e^+e^- \to A'$ → $\sigma_{res}(E_{e^+}) = \frac{12\pi}{m_{A'}^2} \frac{\Gamma_{A'}^2/4}{(\sqrt{s}-m_{A'})^2+\Gamma_{A'}^2/4}$ Nardi et al. Phys. Rev. D 97, 095004
- **Produzione associata:** $e^+e^- \to \gamma A'$
- **Emissione radiativa A'-strahlung:** $e^\pm Z \to e^\pm Z A'$

L'annichilazione risonante è accessibile solo tramite esperimenti con fascio di positroni





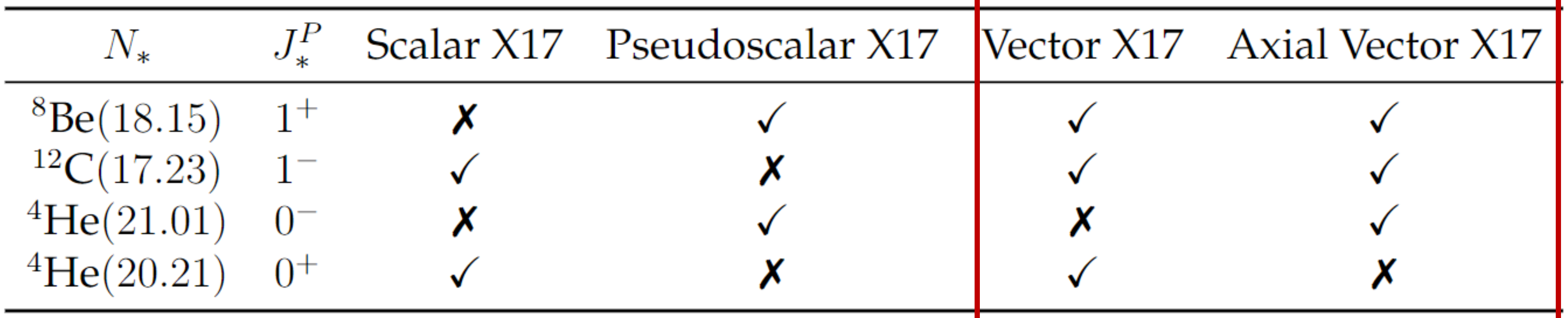


The X17 particle

According to the ATOMKI observations, the main properties of the new X_{17} particle are:

- $m_{X_{17}} \sim 17\ \mathrm{MeV}$
- $Br(e^+e^- \to X_{17}) \simeq 5 \times 10^{-6} Br(e^+e^- \to \gamma\gamma)$
- $\Gamma_V = 0.5 \left(\frac{g_V}{0.001}\right)^2$ eV for the vector case

The spin-parity selection rules $J_* = L \oplus J_0 \oplus J_X$ and $P_* = (-1)^L P_0 P_X$ are required to identify the nature of the new mediator



N_*	J_*^P	Scalar X17	Pseudoscalar X17	Vector X17	Axial Vector X17
^{8}Be(18.15)	1^+	✗	✓	✓	✓
^{12}C(17.23)	1^-	✓	✗	✓	✓
^{4}He(21.01)	0^-	✗	✓	✗	✓
^{4}He(20.21)	0^+	✓	✗	✓	✗

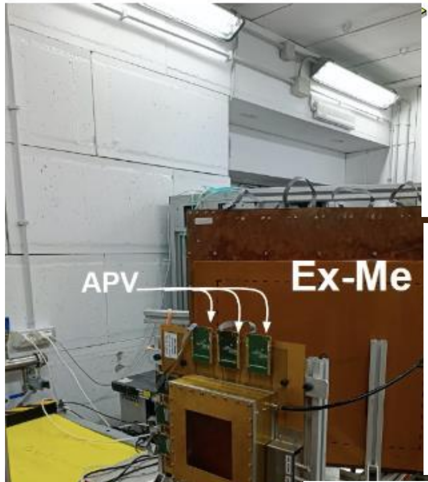
Phys.Rev.D 102 (2020) 3, 036016

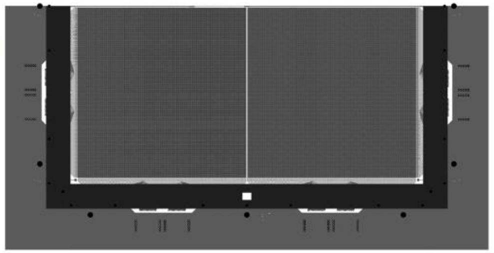
^{12}C Last results

Phys. Rev. C 106, L061601

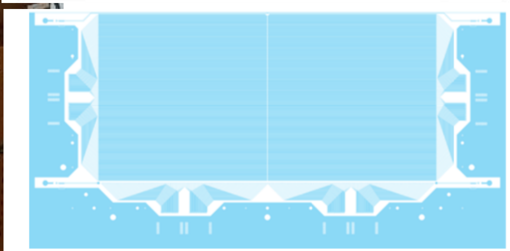
PADME New run, new tagger

- New tracker for e^+e^- invariant mass evaluation
- From the analysis point of view is better to use N(e^+e^-)/N($\gamma\gamma$) instead of N(e^+e^- / $\gamma\gamma$)/POT
- Wrong e^+e^- tagging must be under control → ETag is limited by rate capability
- **Idea: micro pattern gas detector:**
  - High segmanetation
  - Able to track
  - Low material budget
  - Great XY resolution
- Already tested @ the LNF Beam Test Facility di LNF in May 2024.

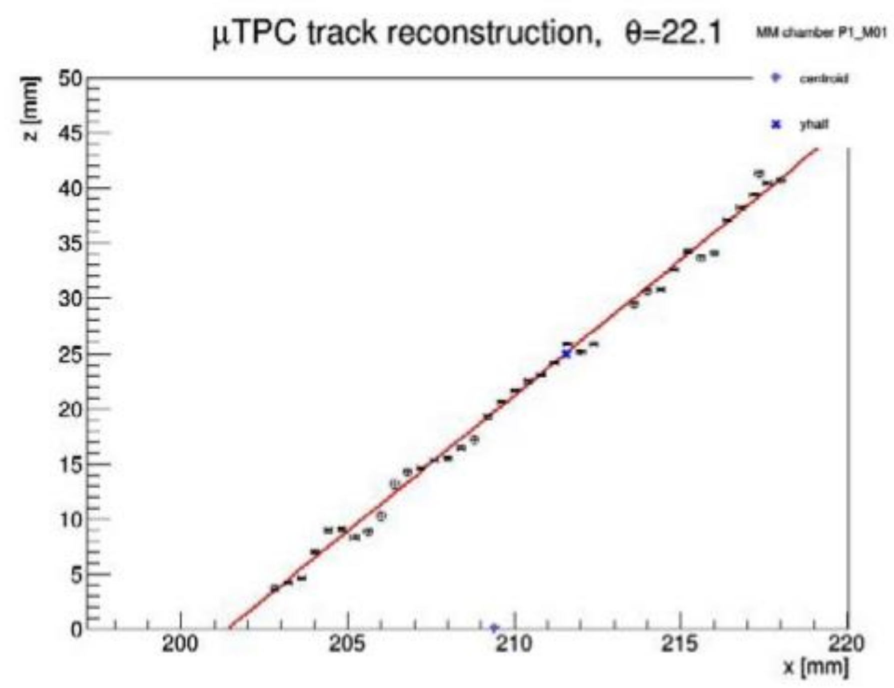




Strip layout



Diamond layout



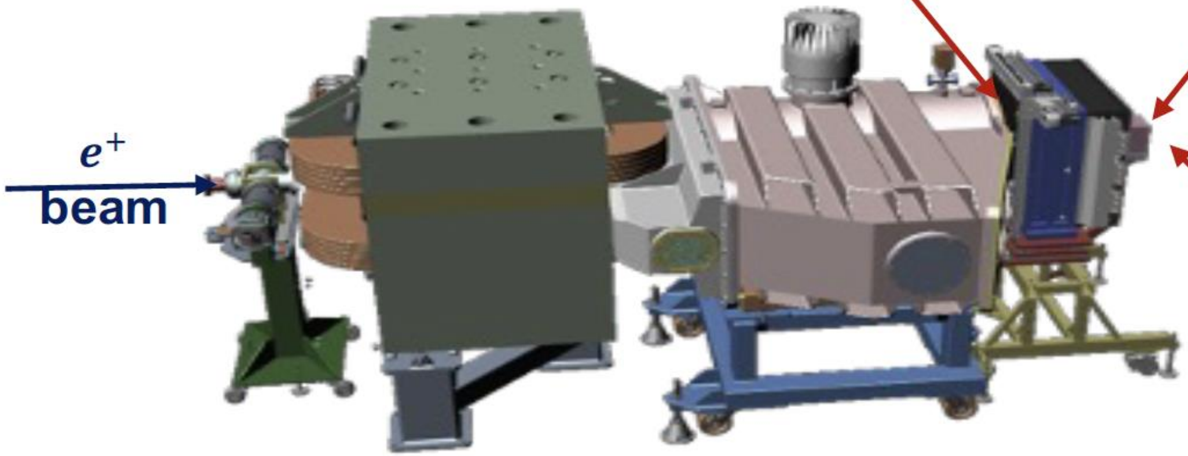
PoT determination

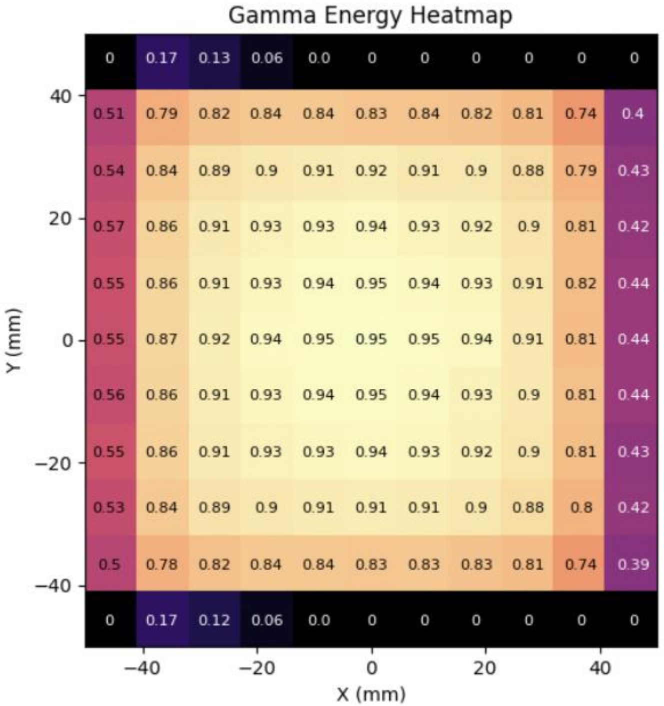
Absolute scale of POT is not relevant for X17, this is only needed for absolute xs
We know the absolute is better than 10%, working to improve it
The beam variations induce a correction point-by-point of **several %**

Carbon fiber window

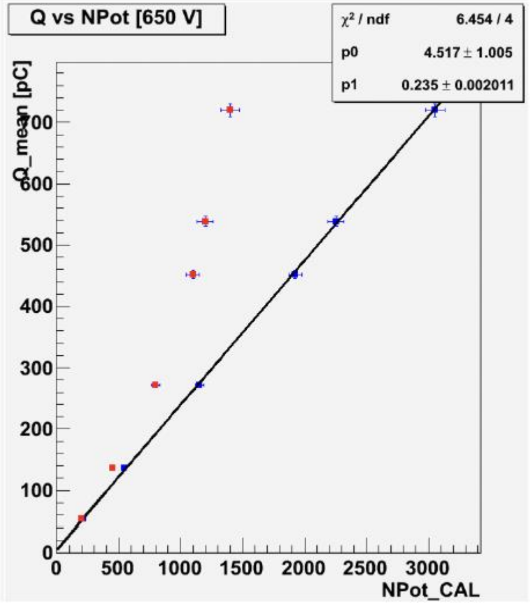
PbGl luminometer

TimePix3 + support structure





0	0.17	0.13	0.06	0.0	0	0	0	0	0	0
0.51	0.79	0.82	0.84	0.84	0.83	0.84	0.82	0.81	0.74	0.4
0.54	0.84	0.89	0.9	0.91	0.92	0.91	0.9	0.88	0.79	0.43
0.57	0.86	0.91	0.93	0.93	0.94	0.93	0.92	0.9	0.81	0.42
0.55	0.86	0.91	0.93	0.94	0.95	0.94	0.93	0.91	0.82	0.44
0.55	0.87	0.92	0.94	0.95	0.95	0.95	0.94	0.91	0.81	0.44
0.56	0.86	0.91	0.93	0.94	0.95	0.94	0.93	0.9	0.81	0.44
0.55	0.86	0.91	0.93	0.93	0.94	0.93	0.92	0.9	0.81	0.43
0.53	0.84	0.89	0.9	0.91	0.91	0.91	0.9	0.88	0.8	0.42
0.5	0.78	0.82	0.84	0.84	0.83	0.83	0.83	0.81	0.74	0.39
0	0.17	0.12	0.06	0.0	0	0	0	0	0	0



Basic assumptions [counting experiment]

Statistics collected (after data quality cuts): O(10^{10} POT) / point

Beam momentum spread: σ_E = 0.7 MeV/c → 0.25% relative beam spread

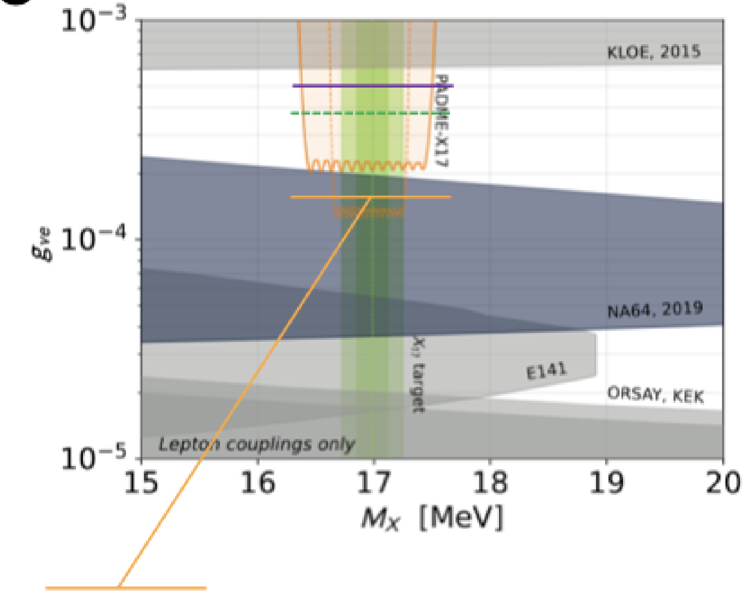
47 points spaced by ΔE = 0.75 MeV/c ~ σ_E, reduce span due to binning

- **Signal counts (S) expected per point: $S = 350 \times (g_{ve} / 2 \times 10^{-4})^2$**
- **Background (B) expected per point: B ~ 45000 events**

$S / \sqrt{B} \sim 1.6 \times (g_{ve} / 2 \times 10^{-4})^2$

- **5σ discovery for $g_{ve} > 3.5 \times 10^{-4}$**
- **If no signal, 90% CL excl. for $g_{ve} > 0.9 \times 10^{-4}$**

Systematic σ_B negligible if $\sigma_B / B \ll 1/\sqrt{B} = 0.5\%$

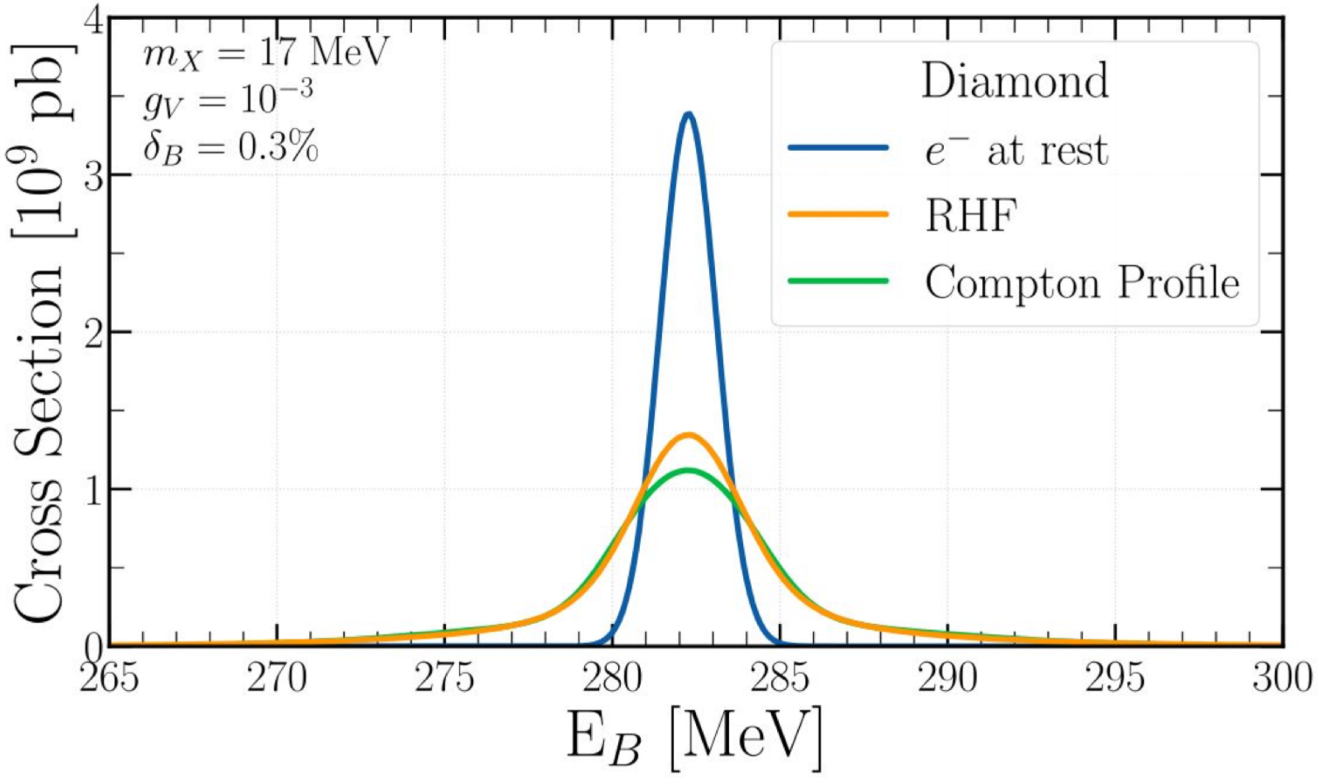


If σ_B / B = 1%:

- **sensitivity worsens by $\sqrt{3}$ → 5σ, 3σ obs. 5 (3.8) × 10^{-4}, excl. 1.5 × 10^{-4}**
- **expected exclusion in absence of NP would remain within NA64**

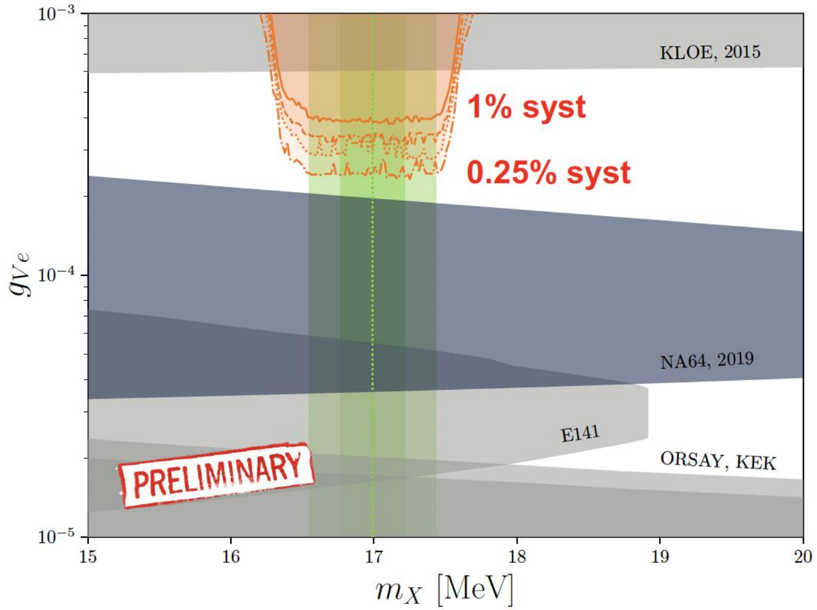
Sensitivity estimation

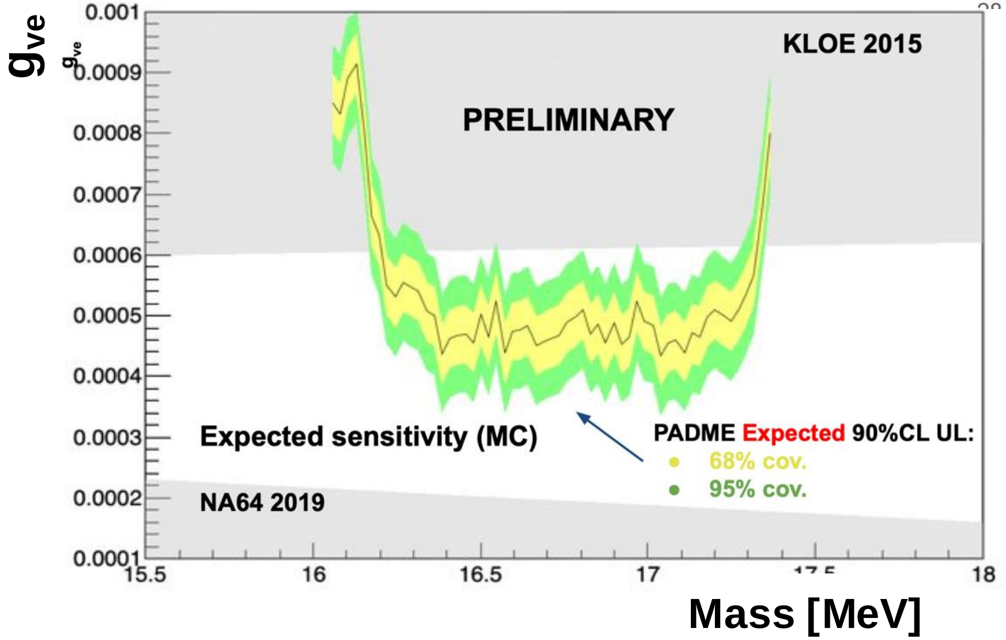
- Sensitivity depends on S/B and the uncertainty on the background determination
  - Statistical (N_B), 47 points with O(10^{10}) PoT, ΔE = 0.75 MeV
  - Systematics (e.g. N_{poT})
  - Background: N_B ~ 45000 events per point
  - Signal acceptance



- **Sources of systematics**
  - Relative PoT estimation O(0.5%)
  - Acceptance 0.75%
  - Beam energy spread 0.05 %
  - Signal shape uncertainty
  - Beam
  - Time dependent ECal efficiency
  - Beam energy uncertainty - controlled by Hall probes < 10^{-3}
  - ECal calibration
- **Normalization systematics**
  - absolute PoT - 5 %

PADME MC sensitivity estimate for RUN III





- Expected 90% CL upper limits are obtained with the CLs method
    - modified frequentist approach, LEP-style test statistic
- Likelihood fits performed for the separate assumptions of signal + background vs background only

$$Q_{\text{statistics}} = -2\,\ln\,(L_{s+b} / L_b)$$

- Pseudo data (SM background) is generated accounting for the expected uncertainties of nuisance parameters + statistical fluctuations
- 150 Nuisance parameters:
    - POT of each scan point
    - Common error on POT (scale error)
    - Signal efficiency for each scan point
    - Background yield for each scan point
    - Signal shape parameters: signal yield @ a given X17 mass and g_{ve}
    - Signal shape parameter: beam-energy spread