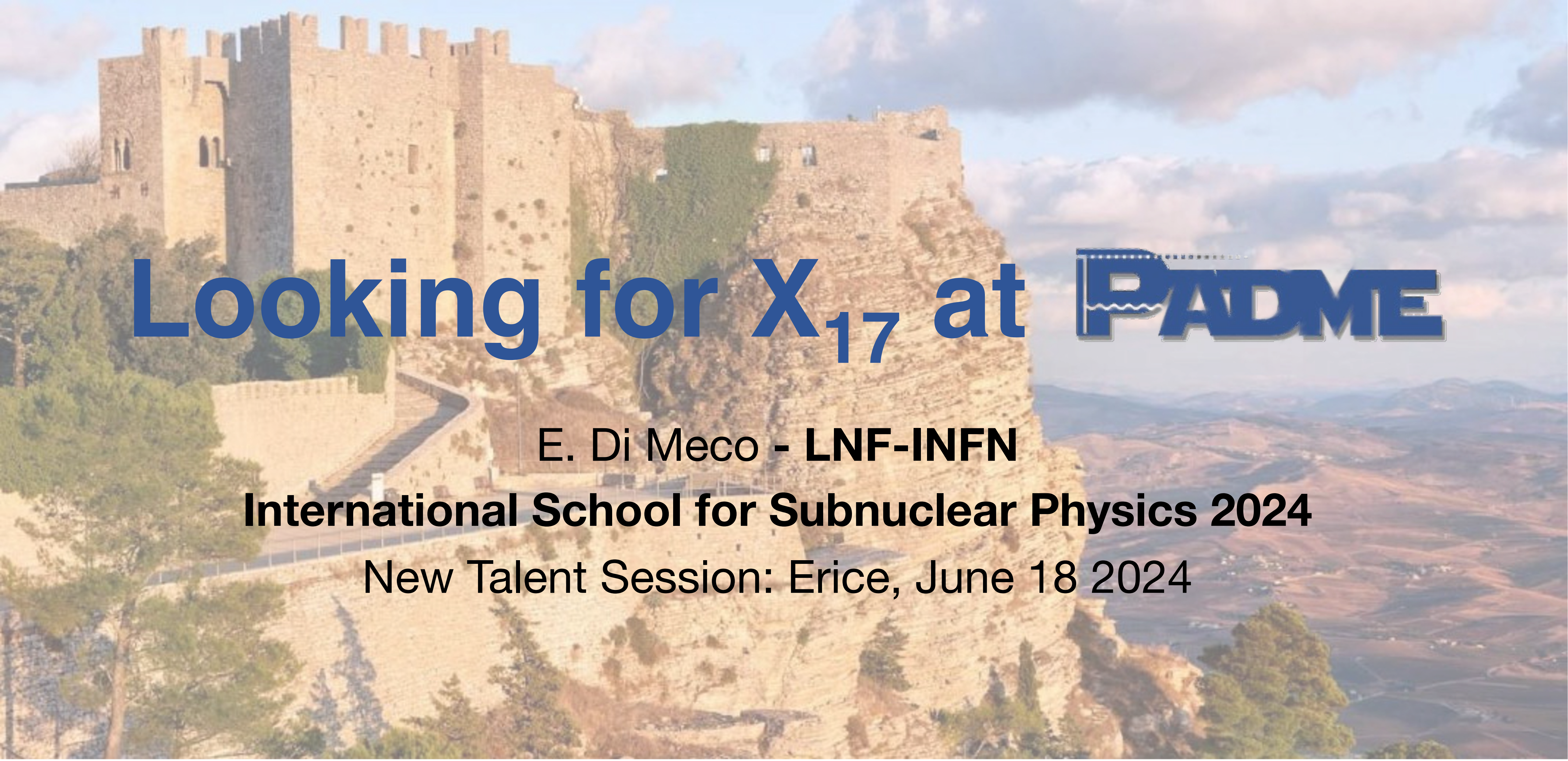
Looking for X_{17} at PADME

E. Di Meco - **LNF-INFN**

International School for Subnuclear Physics 2024

New Talent Session: Erice, June 18 2024



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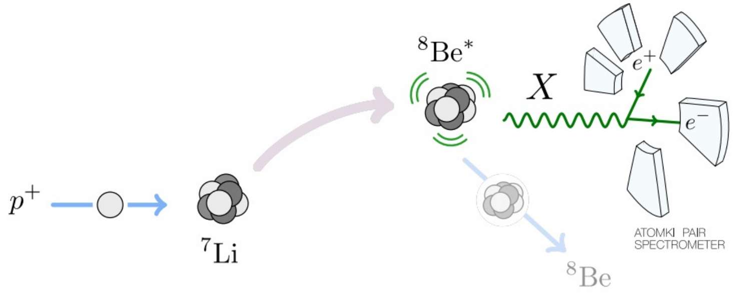
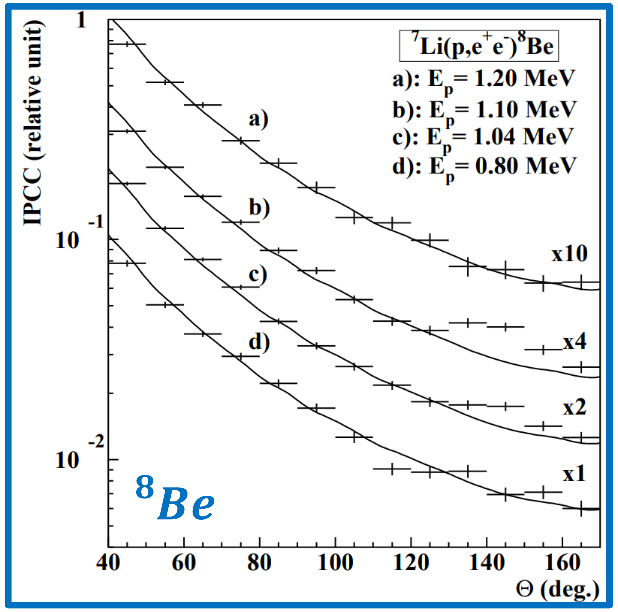
X17 anomaly @ ATOMKI

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

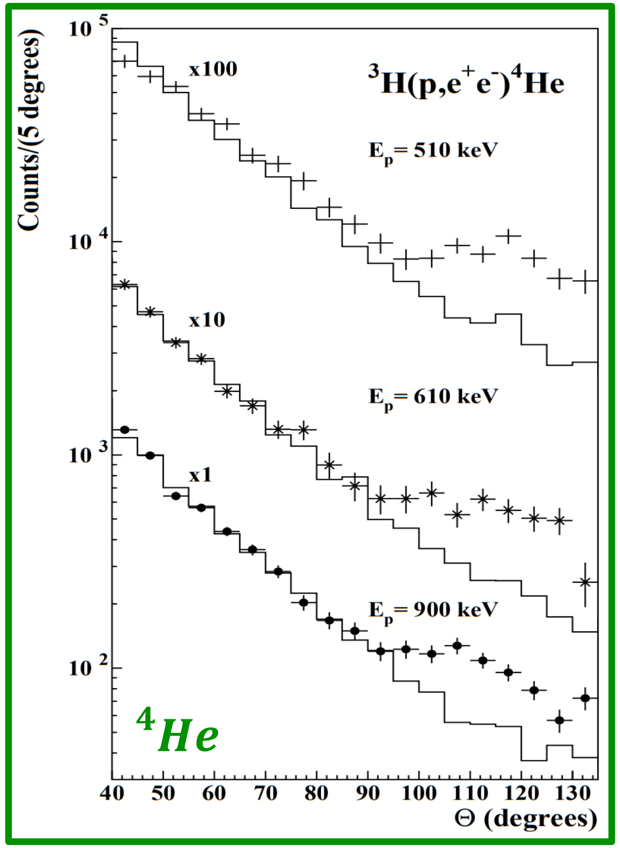
- The anomaly seems to be compatible with the production and successive decay of a **new ~17 MeV mass particle**



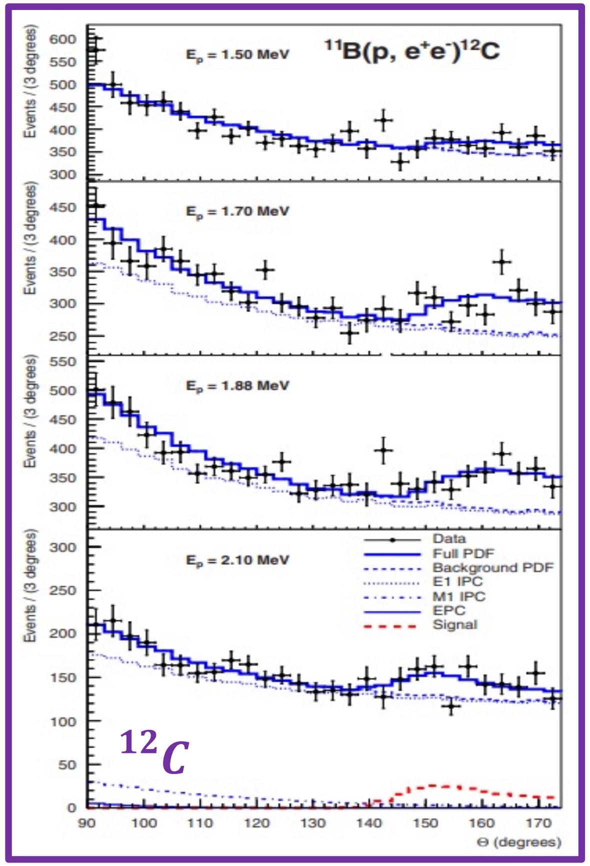
Phys.Rev.Lett. 116 (2016) 4, 042501



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



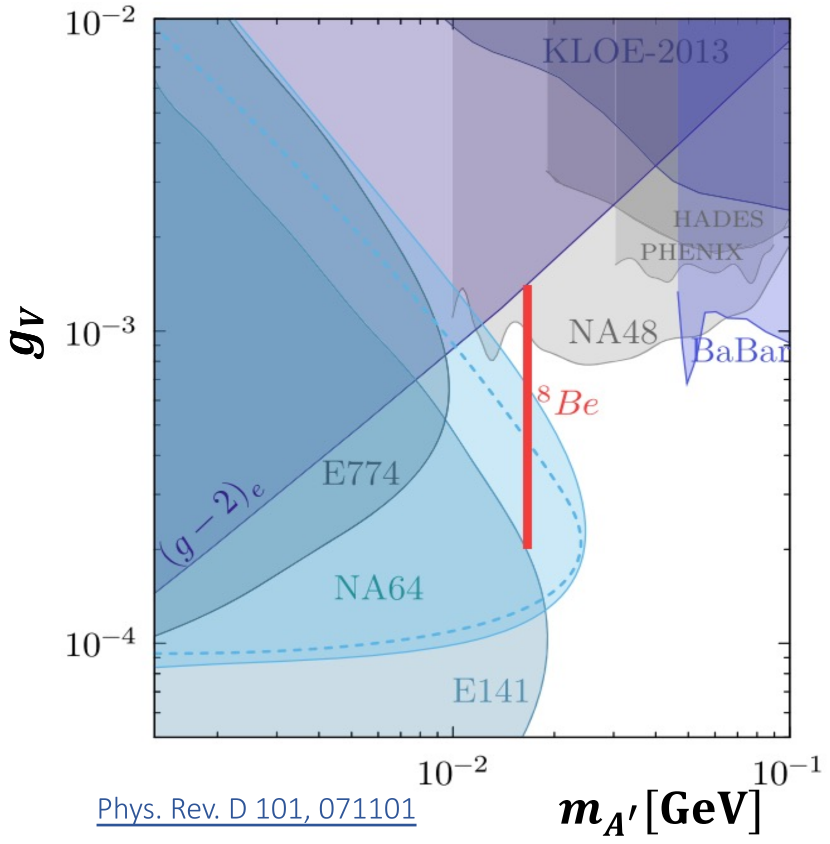
Phys. Rev. C 106, L061601



X17 as a vector or pseudo-scalar state

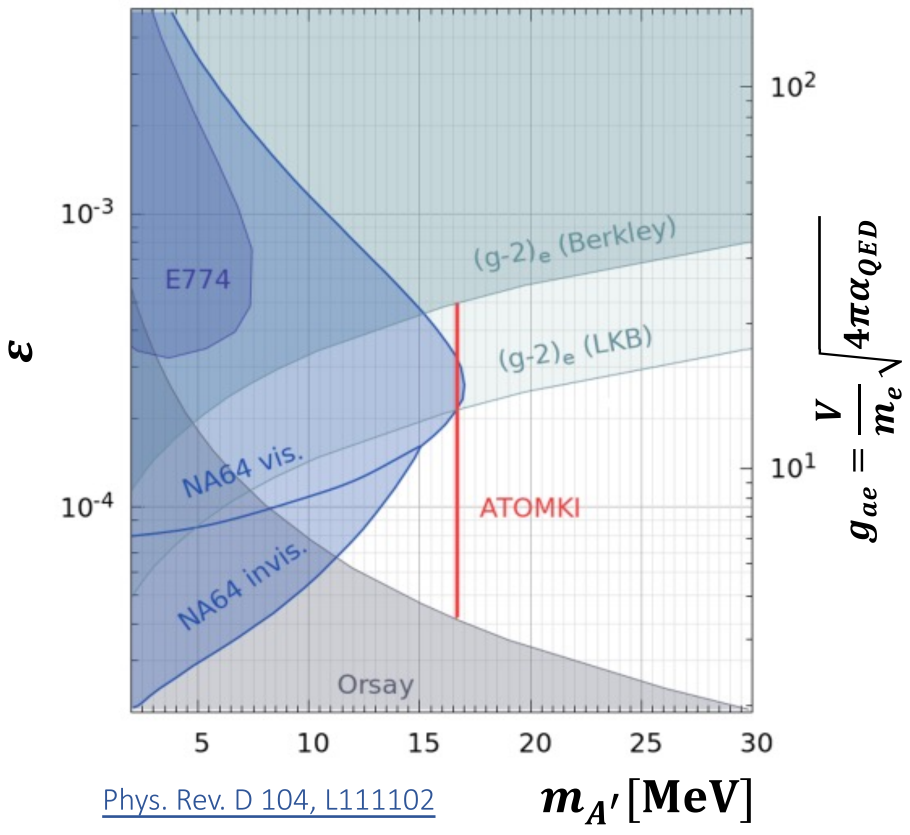
- New physics interpretations not fully excluded → still some phase-space available
- The PADME experiment is sensible to this mass range

Vector



Phys. Rev. D 101, 071101

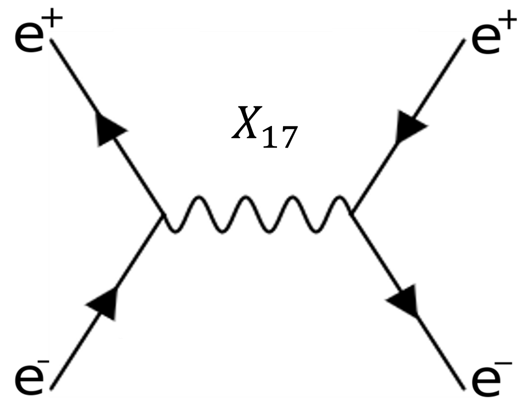
Pseudoscalar



Phys. Rev. D 104, L111102

Resonant search on fixed thin target

- Possible approach: use resonant production and search for visible X_{17} decay in e^+e^-
- $\sigma_{res} \propto \frac{g_{V_e}^2}{2m_e} \pi Z\, \delta(E_{res} - E_{beam})$ 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 scan procedure with the e^+ beam



Analysis strategy:

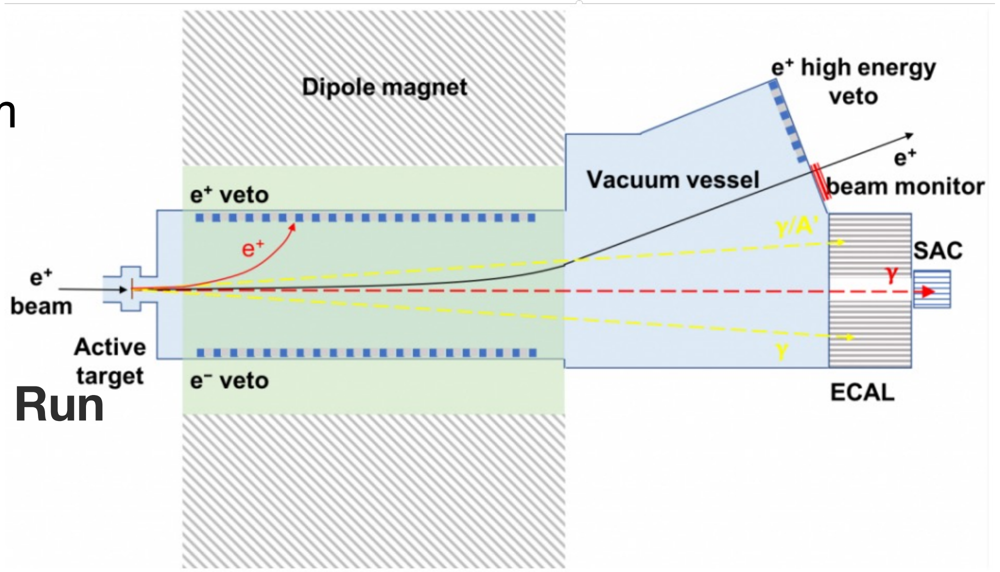
1. Change beam energy
2. Fit the background
3. Calibrate luminosity
4. Look for the resonance

$$\boldsymbol{N_{X_{17}}^{perPoT}} \propto \frac{g_{V_e}^2}{2m_e} \ell_{tar} \frac{N_A \rho Z}{A} f(E_{res}, E_{beam})$$

$f(E_{res}, E_{beam})$ is the beam spread → gaussian distribution with **spread $\boldsymbol{\delta E}$**

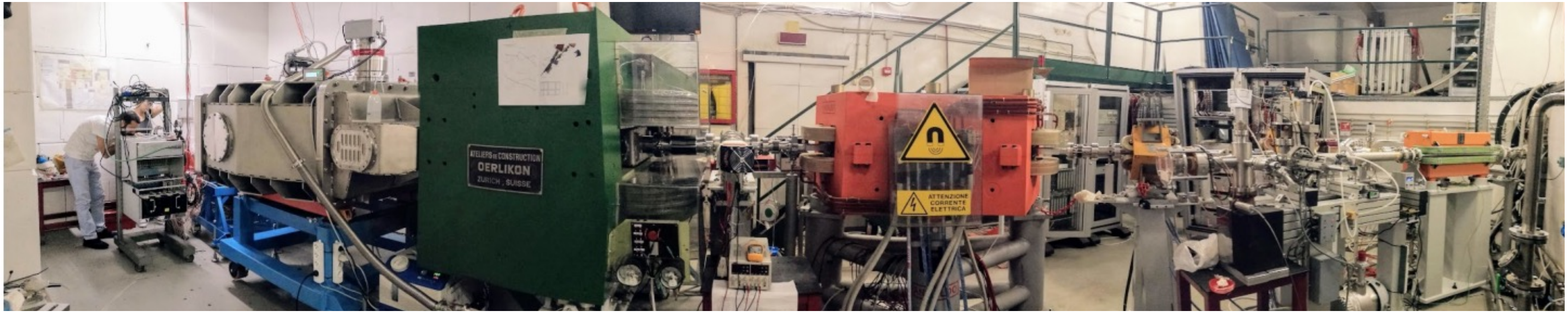
The PADME experiment

- 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**.

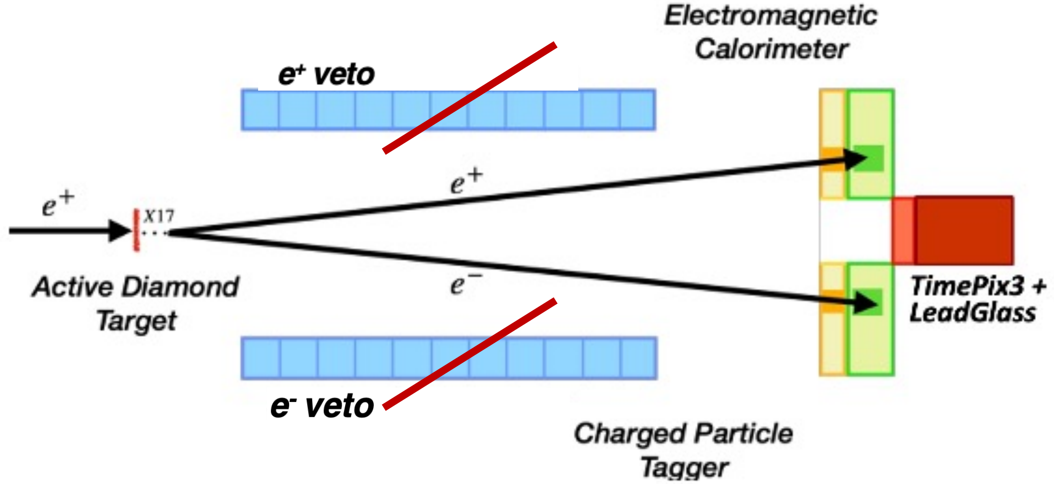
- Some modification to the setup were necessary



PADME Run III

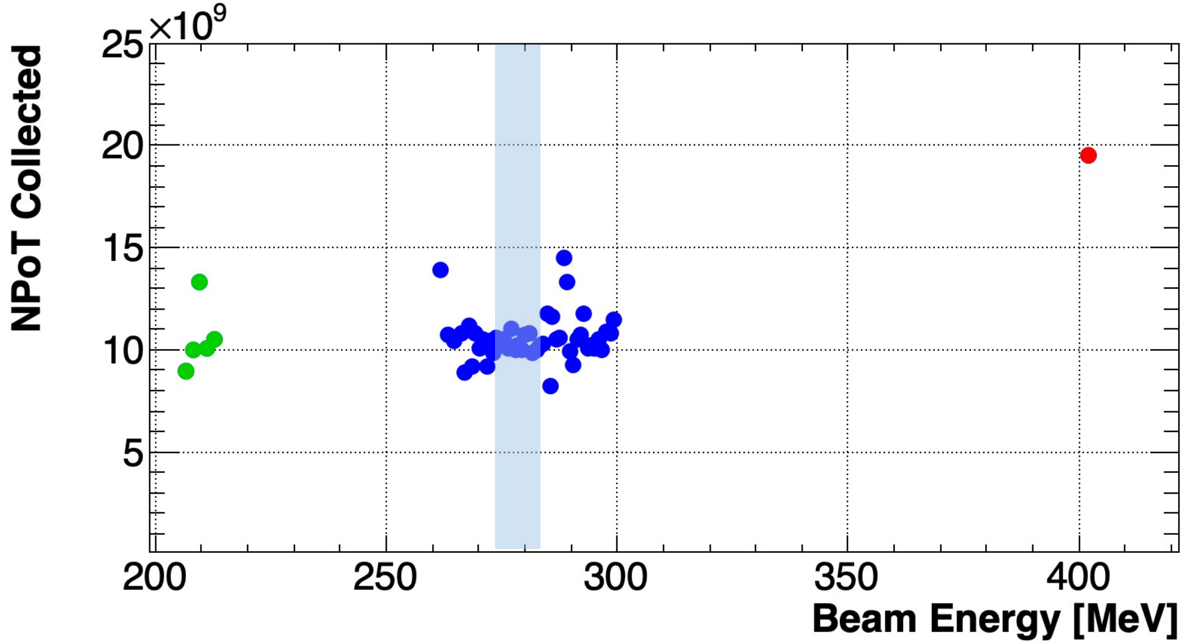
Main SM background are Bhabha scatterings and $\gamma\gamma$ pairs productions, fitted directly from data → needed some setup optimization:

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



Data-taking divided in 3 parts:

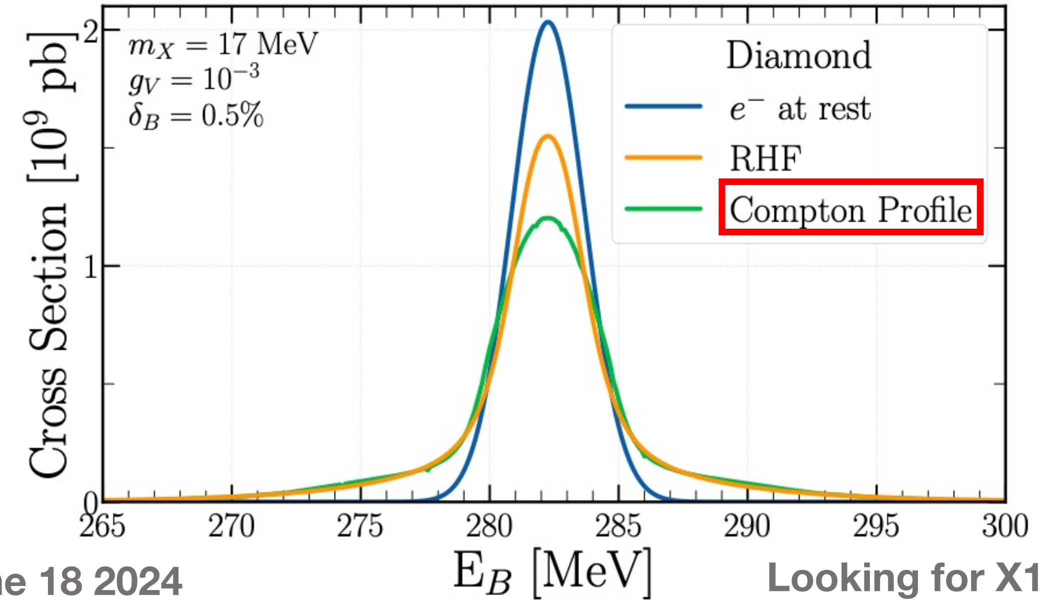
- **On resonance: 47 points @ (263-299) MeV**
- **Below resonance: 5 points @ (205-211) MeV**
- **Over resonance: 5 points @ 402.5 MeV**

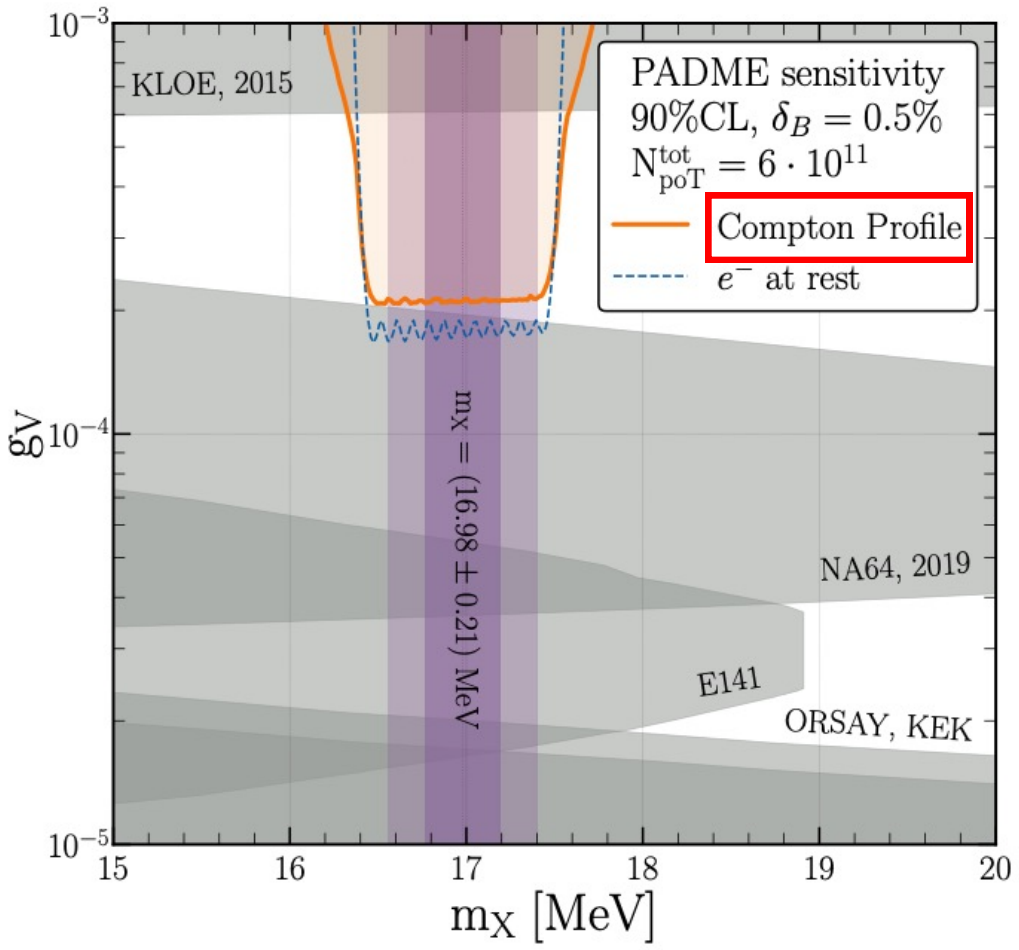


Light blue zone: mass interval from fit results in Phys. Rev. D 108, 015009 (2023)

PADME 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. Peak down by a factor 3, the S/B by a factor 2
  2. Side bands for background scaling down by x4
  3. Sensitivity strictly **depending on the systematic error**, it **should be kept below 0.3 %** to be able to close the available phase space zone.

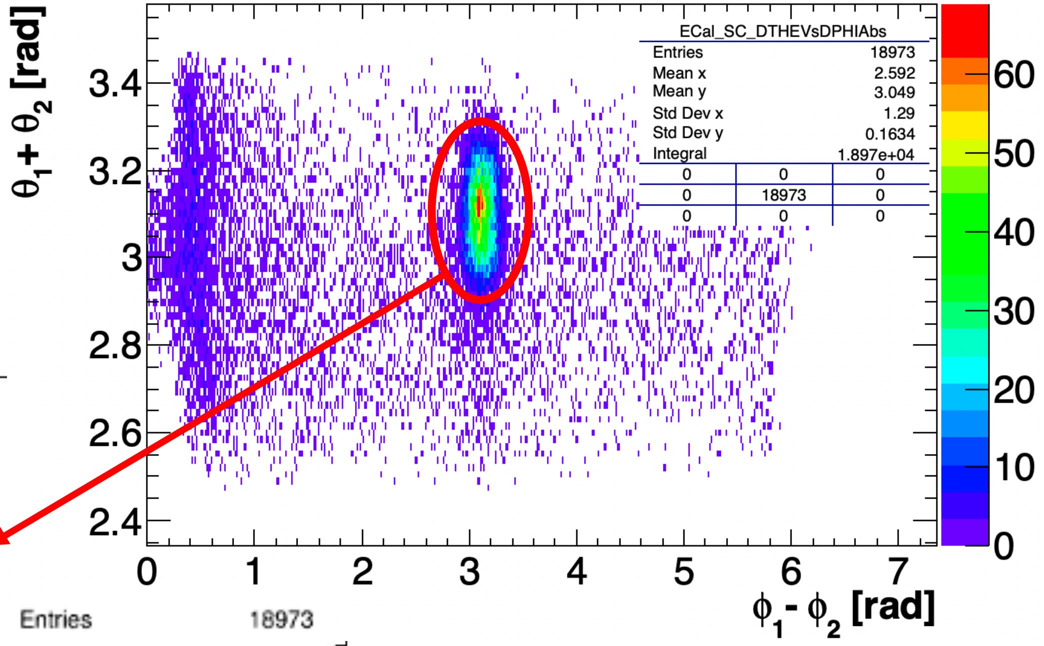


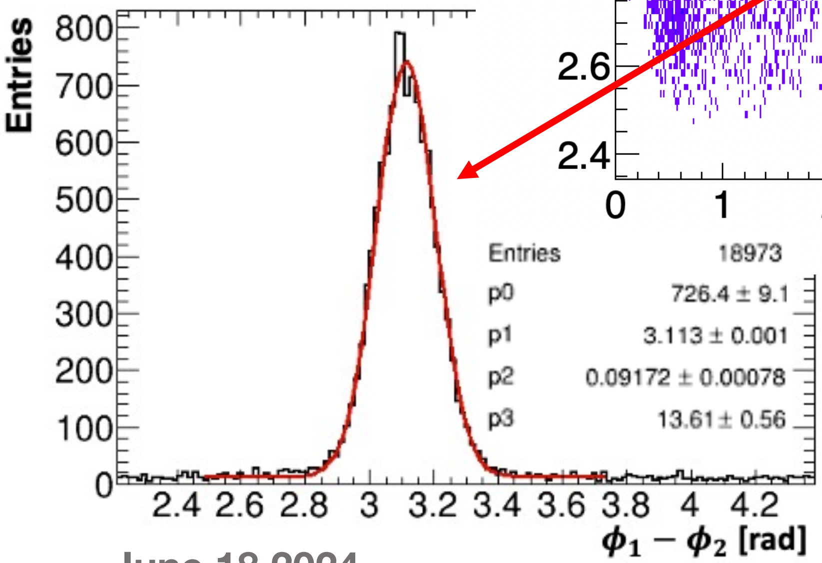


https://arxiv.org/pdf/2403.15387.pdf

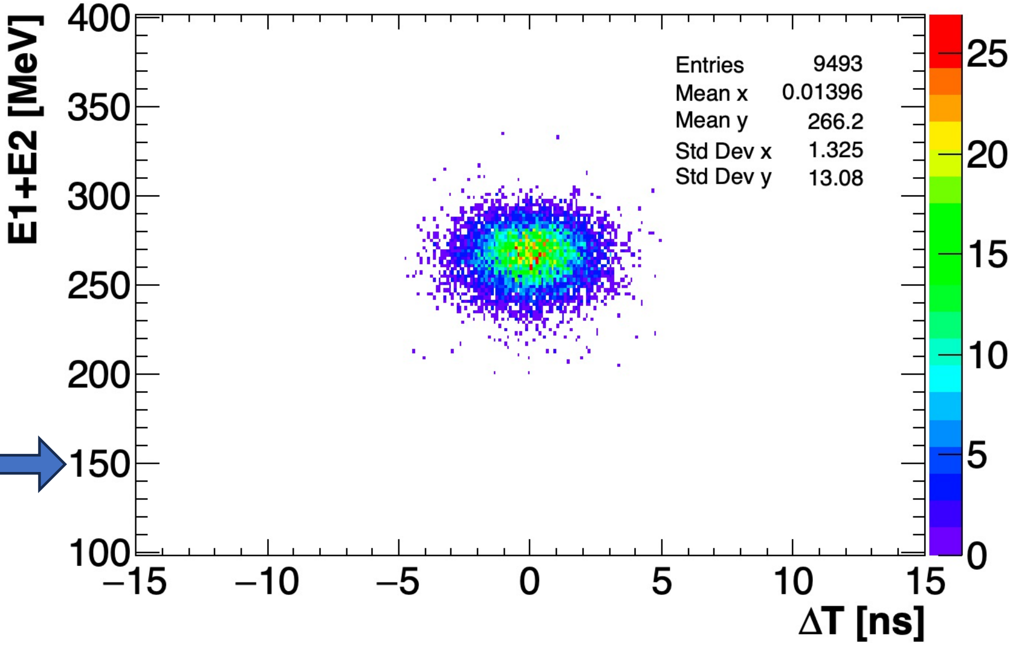
Run III: signal candidate selection

- ECAL is the main detector for this analysis → **request of two in-time clusters (5 ns)**
- Selection based on the **angular correlation of a two-body decay in the center-of-mass frame** → does not depend on the ECAL energy.



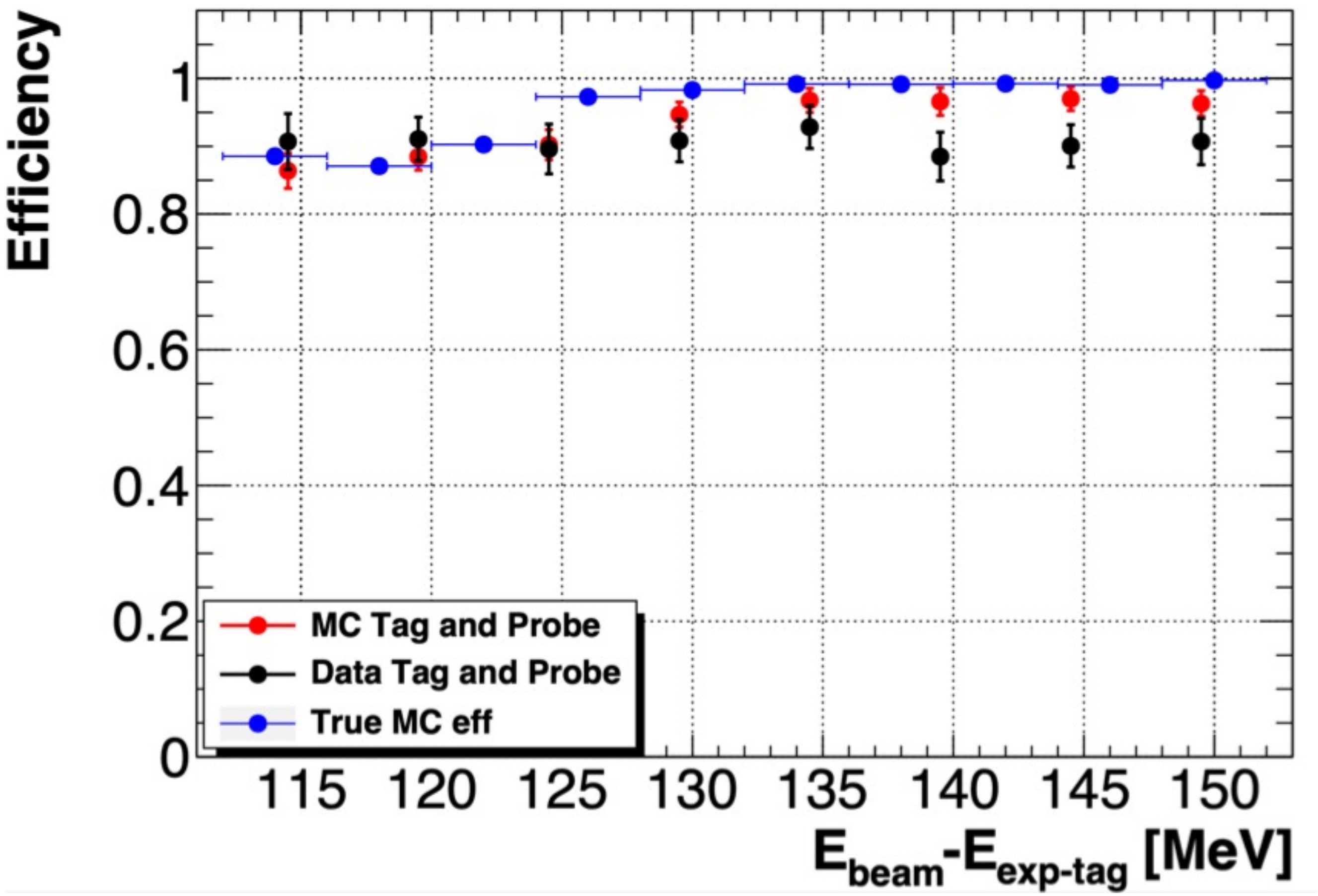


Remaining bkg order of 4%
(beam halo e Bremstralung)



PADME Run III: ECAL efficiency

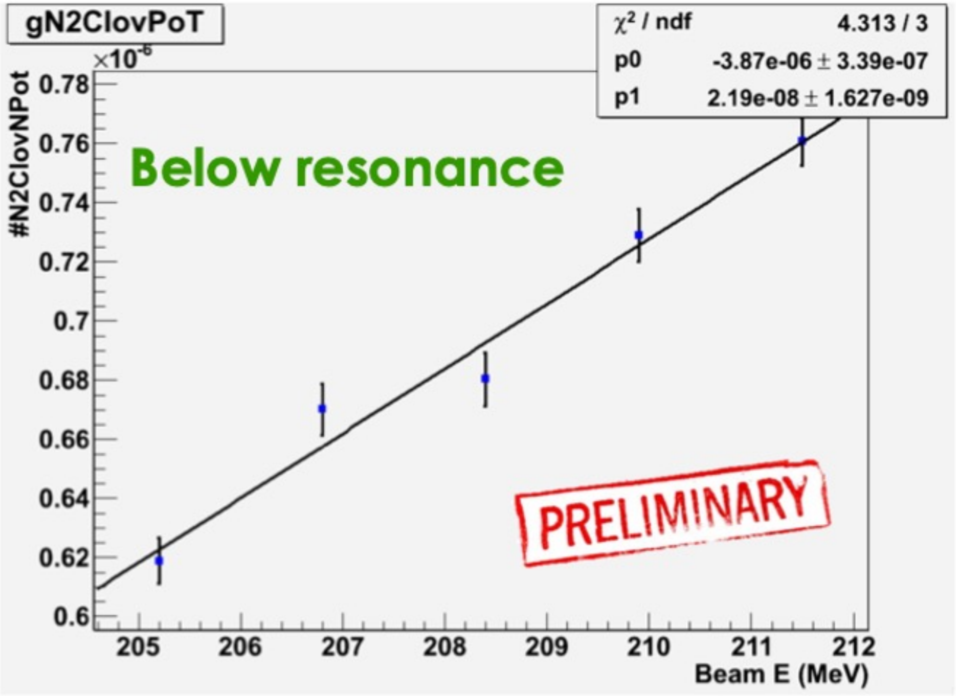
- ECAL is the main detector of this analysis→ efficiency has to be evaluated
- Method choice: **Tag and Probe**
- Low energy inefficiency dominated by the hit energy threshold during the reconstruction process
- Good agreement between MC Truth and MC Tag and Probe → low method bias
- MC correction to be applied on data of the order of %.

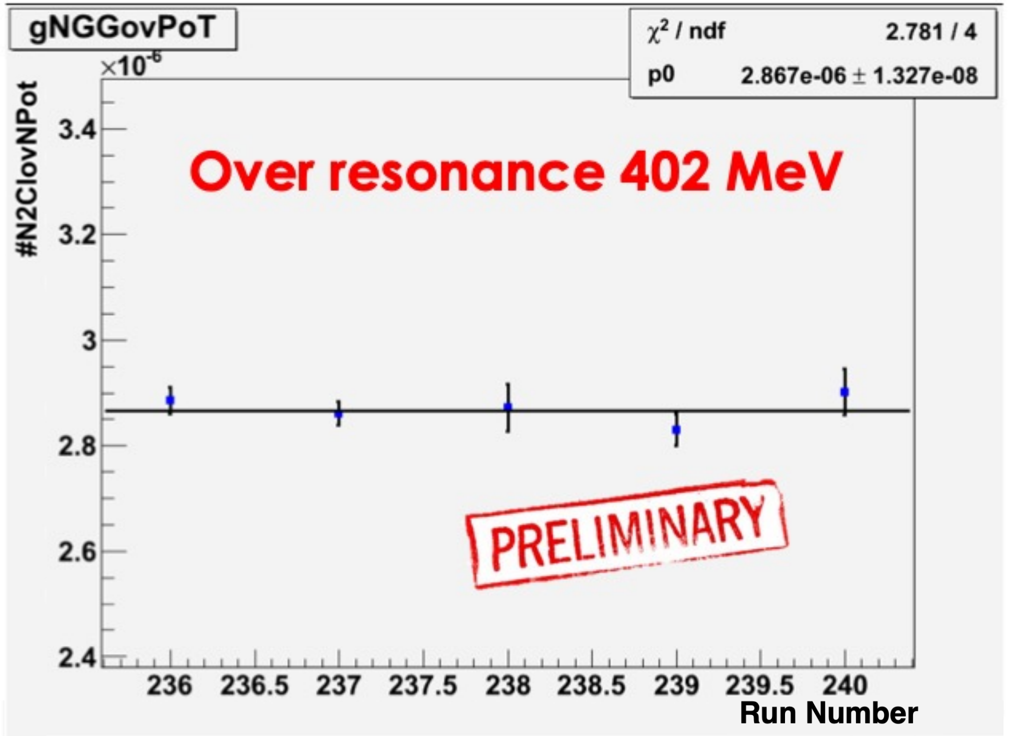


Run III: signal stability

Signal stability: evaluated as the ratio between the number of 2 clusters couples and the number of Positron on Target.

- **Below resonance (5 energy points):**
  - ➢ RMS <1% wrt fit residuals
  - ➢ Good χ^2 , the slope is due to the acceptance and is reproduced also in the MC



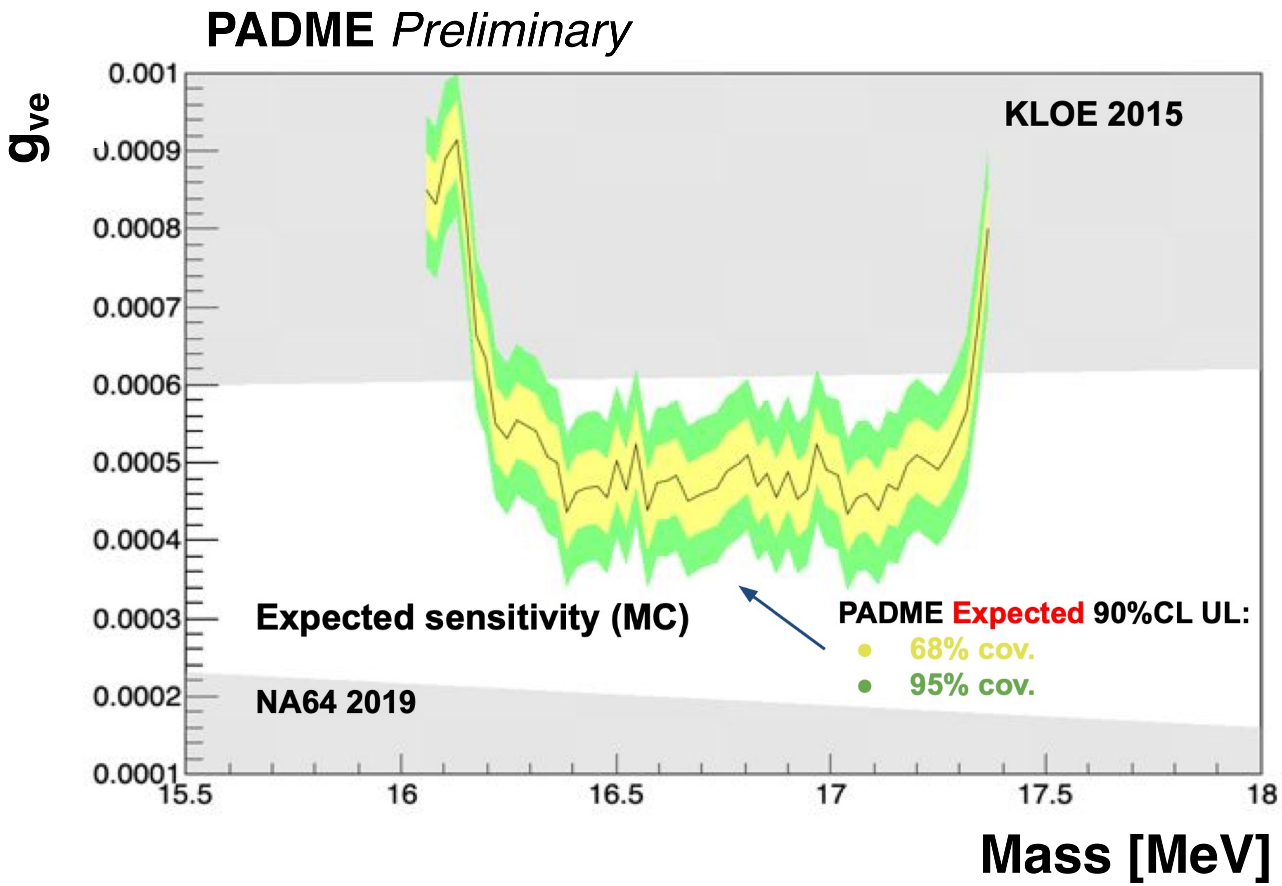


- **Over resonance (5 runs at the same energy):**
  - ➢ RMS <0.7% compatible with the purely statistical error
  - ➢ Good χ^2 systematics looks absent even without acceptace corrections

Stability→ 1% level on out of resonance points

Conclusions

- Run III data are in line with the expectations for X17 research→ 1% systematic error is reachable
- The unblinding procedure will be ultimate by the end of the summer, unfortunately the sensitivity will be lower than the one estimated before the run and we will not be able to close the free phase-space.
- A new run will be needed, we also need precise measurement of ee/$\gamma\gamma$, meaning that new changes to the setup are needed
- We will need 4 times the Run III statistics



Backup slides

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:

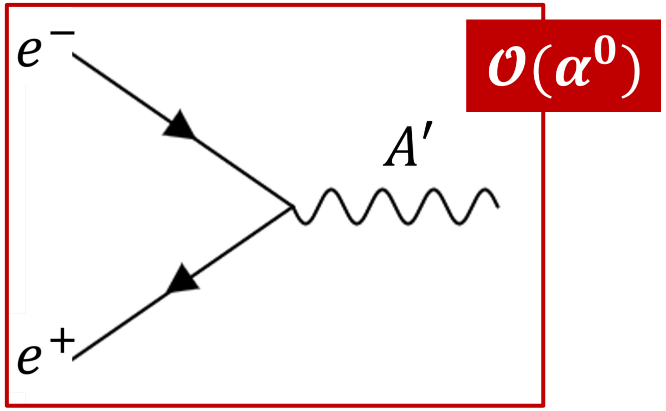
$$\mathcal{L} \sim g_V q_f \bar{\psi}_f \gamma^\mu \psi_f A'_\mu$$

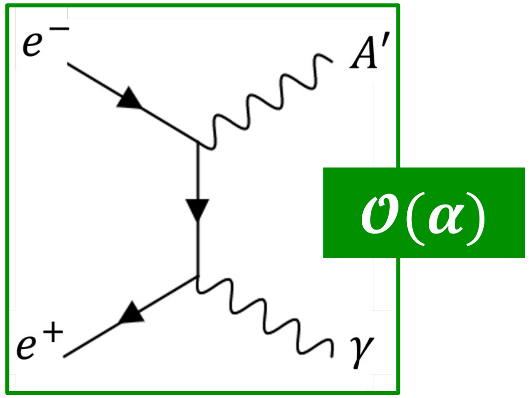
$g_V \ll 1$ → nascosto/oscuro

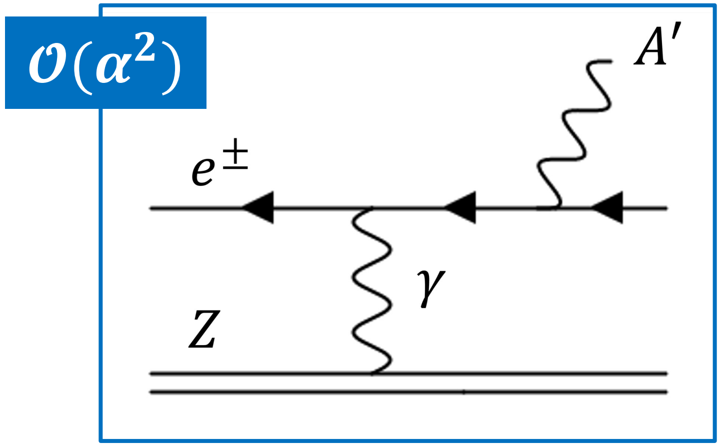
Produzione di A' tramite due differenti meccanismi, annichilazione ed emissione:

- **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:

- $m_{X_{17}} \sim 17$ 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^+	✓	✗	✓	✗

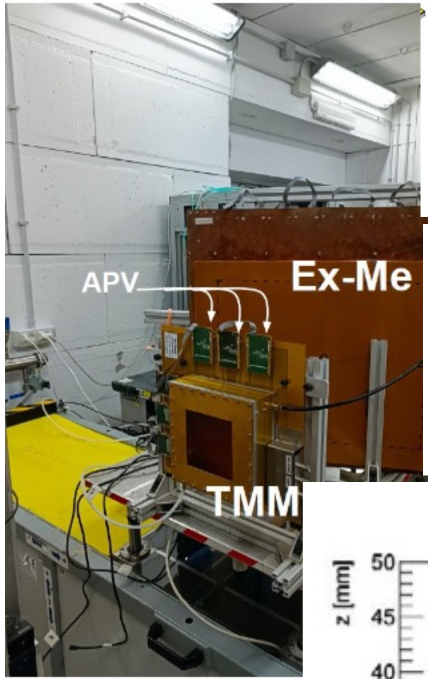
Phys.Rev.D 102 (2020) 3, 036016

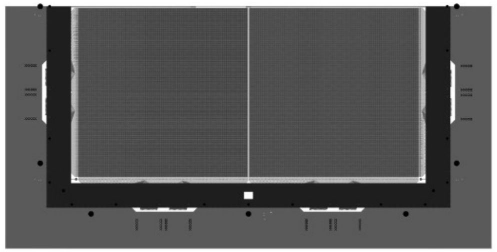
^{12}C Last results

Phys. Rev. C 106, L061601

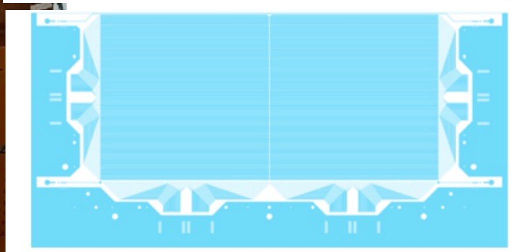
PADME New run, new tagger

- 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.

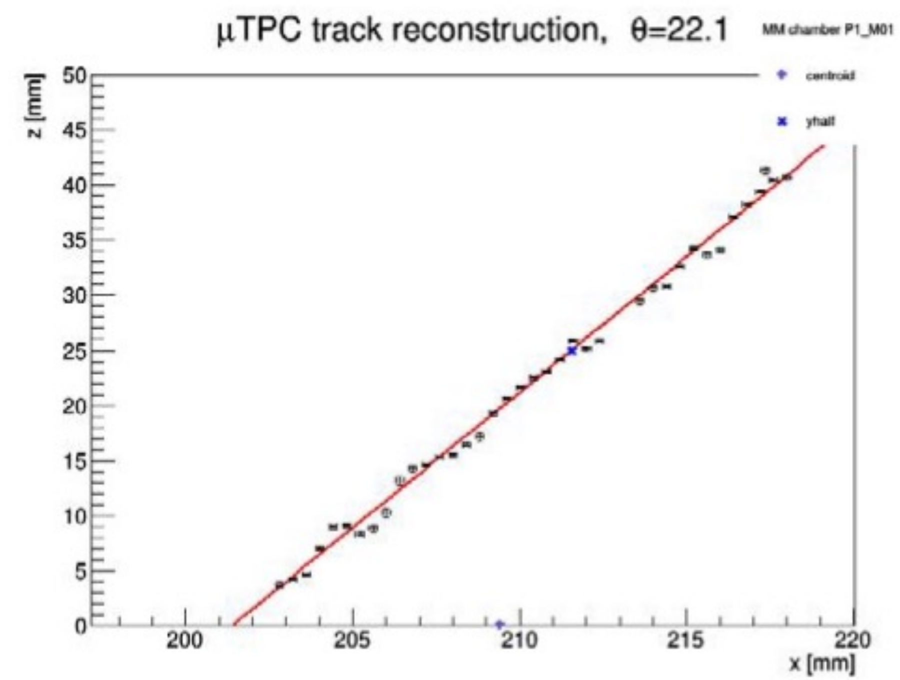




Strip layout

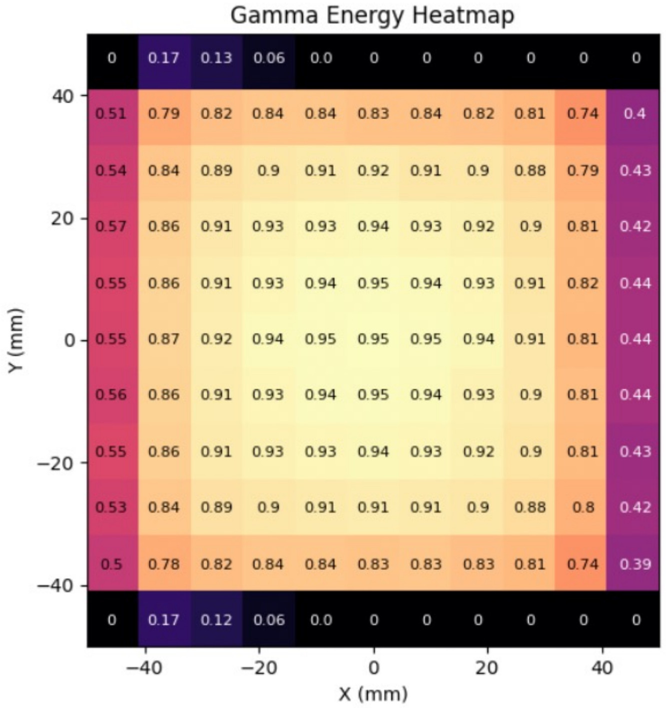


Diamond layout



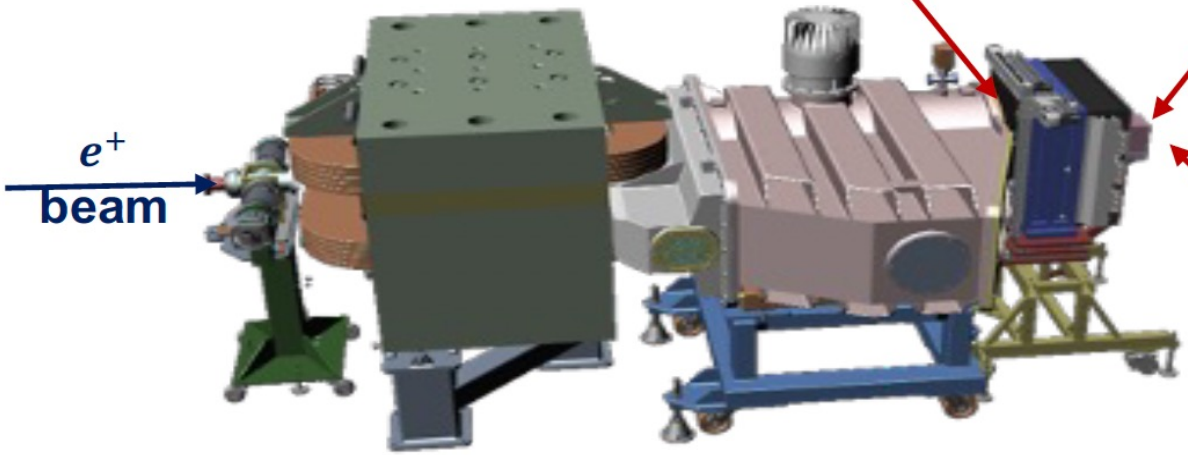
PoT determination

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 %**

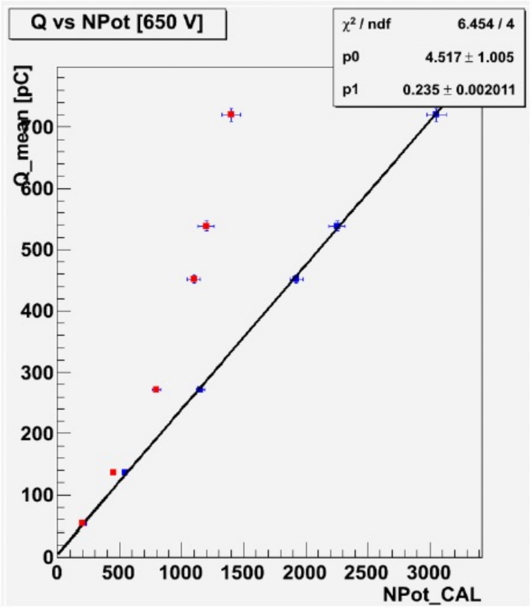


Carbon fiber window

PbGl luminometer



TimePix3 + support structure



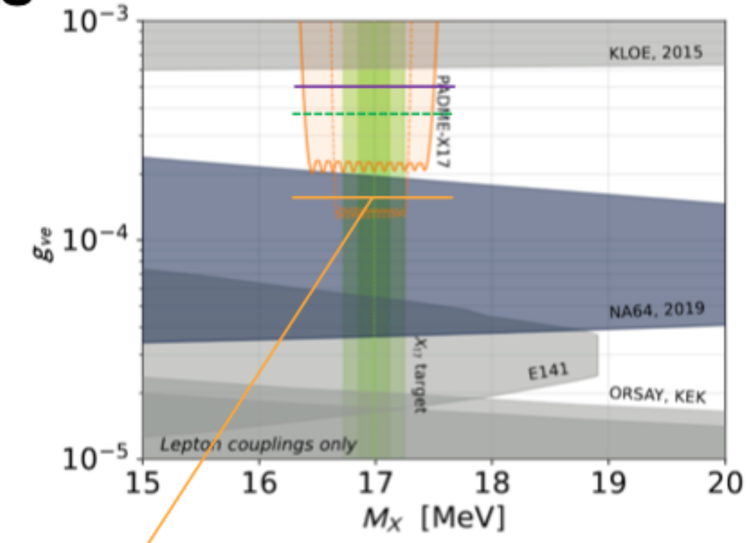
Basic assumptions [counting experiment]

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 $g_{ve} > 0.9 \times 10^{-4}$

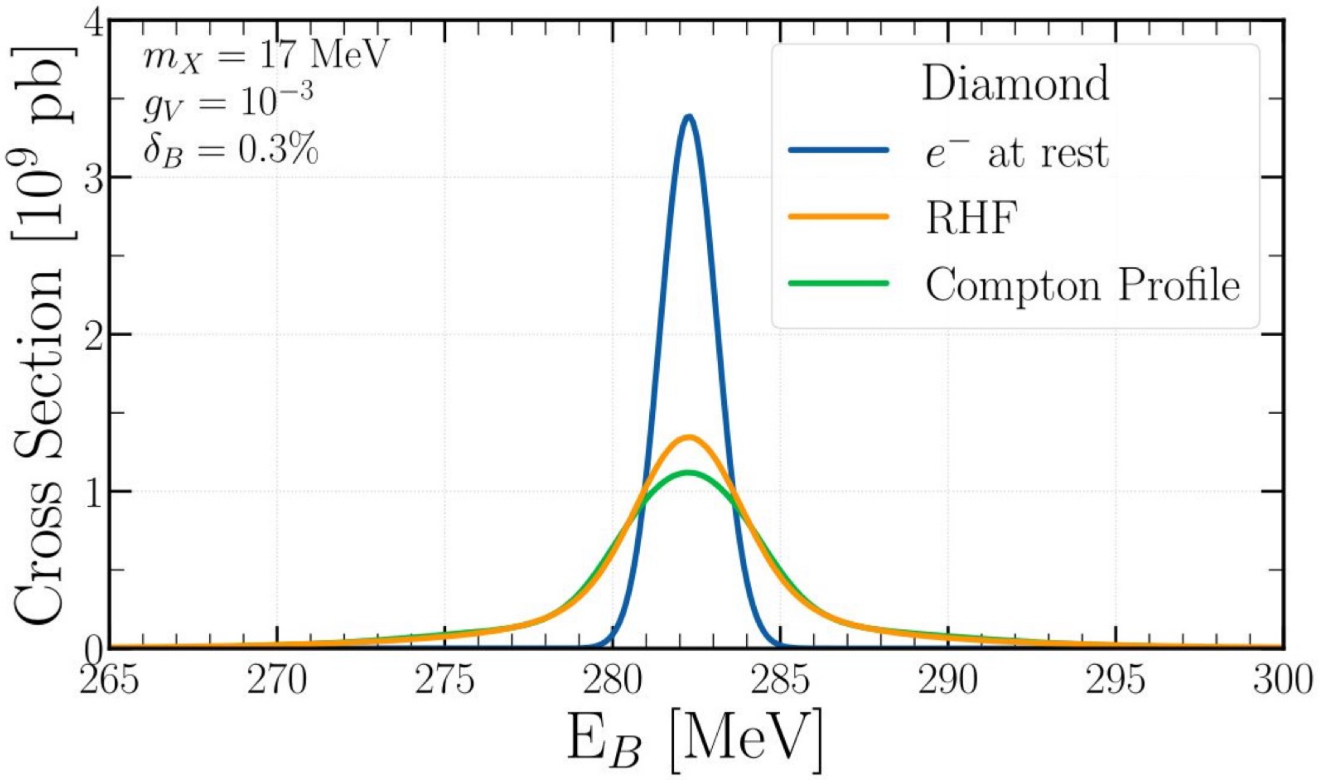
Systematic σ_B negligible if $\sigma_B / B \ll 1/\sqrt{B} = 0.5\%$

If $\sigma_B / B = 1\%$:

- 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

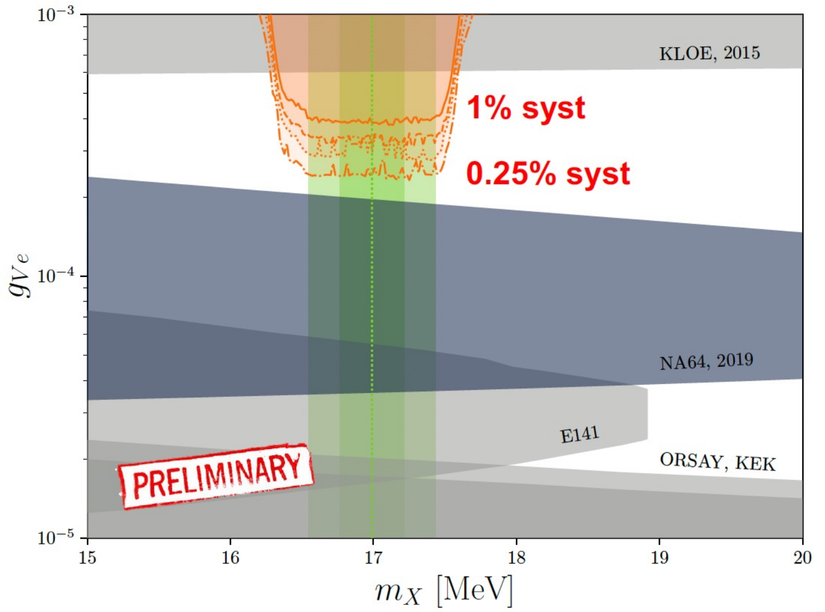
Sensitivity estimation

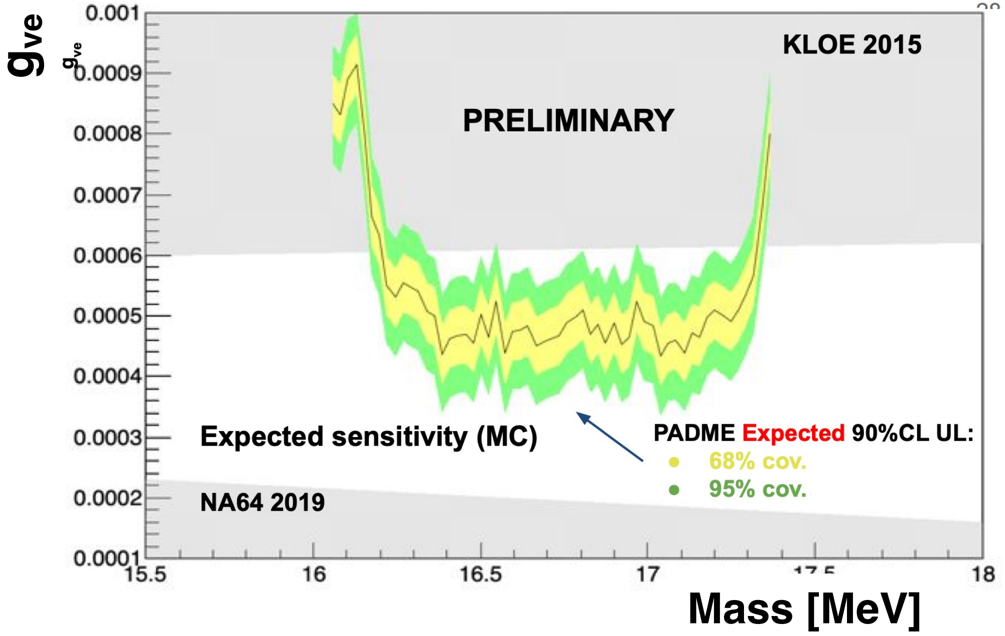
- Sensitivity depends on S/B and the uncertainty on the background determination
  - Statistical (N_B), 47 points with $O(10^{10})$ PoT, ΔE = 0.75 MeV
  - Systematics (e.g. N_{poT})
  - Background: N_B ~ 45000 events per point
  - Signal acceptance



- **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

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

- 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