PADME Run III

Theoretical perspective and expected sensitivity

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Outline

Targeting the X_{17} anomaly

PADME Run-3: a “resonant” fixed target experiment

Run III projections

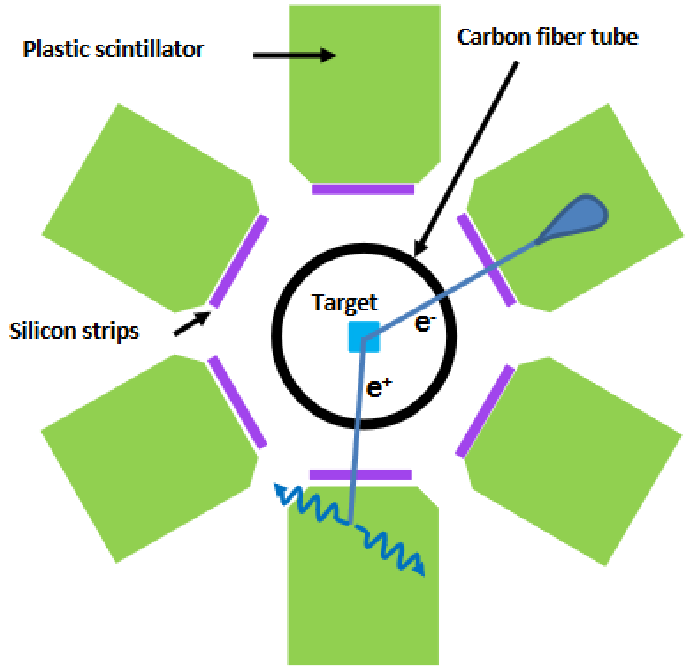
The X17 anomaly

- The signal: a 17 MeV boson in the ATOMKI spectrometer?

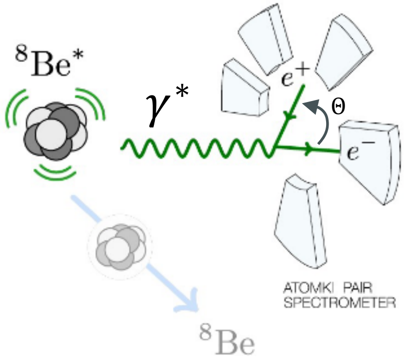
2209.10795 1504.01527 2104.10075

→ Production of excited nuclei ^{12}C, ^{8}Be and ^{4}He, followed by radiative decay $N^* \to N\,\gamma^* \to N\,e^+e^-$

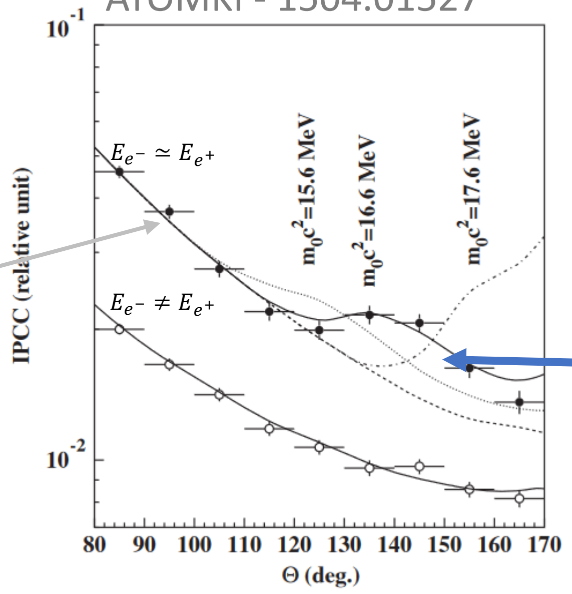
→ Very large excess, cannot be statistical. But from one collaboration only.



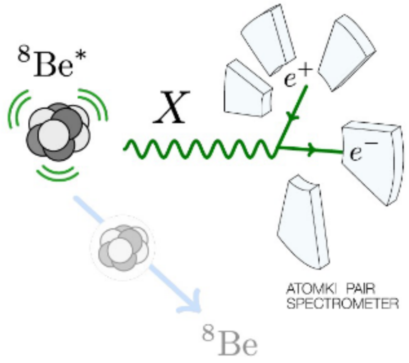
The SM signal: $N^* \to N\,\gamma^* \to N\,e^+e^-$



ATOMKI - 1504.01527



NP sigma: $N^* \to N\,V \to N\,e^+e^-$



Which NP bosons for the X17 ?

- No current nuclear physics explanation
- Use spin-parity analysis for hints of possible NP candidate
  - → Scalar (0+) excluded by ^{8}Be data
  - → ^{4}He data mixes 0+ and 0- excited nuclei

$N^* \to N\, V$

$J_* = L \oplus J_X$

$P_* = (-1)^L P_X$

N_* \ V	0^+	0^-	1^-	1^+
^{4}He 0^+	S	—	—	P
^{4}He 0^-	—	S	P	—
^{8}Be 1^+	—	P	P	S, D

T. Tait from Feng et al. 2016-2020

- The most obvious requirements is on the mass !

$$m_{X_{17}} = \begin{cases} 16.70 \pm 0.35 \pm 0.50 \text{ MeV} & (^8\text{Be ATOMKI 2015}) \\ 17.01 \pm 0.16 \text{ MeV} \quad ? & (^8\text{Be proceedings 2018}) \\ 16.94 \pm 0.12 \pm 0.21 \text{ MeV} & (^4\text{He ATOMKI 2021}) \\ 17.03 \pm 0.11 \pm 0.20 \text{ MeV} & (^{12}\text{C ATOMKI 2022}) \end{cases}$$

Re-analysis but no systematics !

Exp1	Exp2	Average
16.86(6)	17.17(7)	17.01(16)

Keeping the 2015 systematics for ^{8}Be + naive combination of both ^{8}Be measurements and of ^{4}He and ^{12}C

$$m_{X_{17}} \simeq 16.99 \pm 0.04\,(stat) \pm 0.21(syst) \text{ MeV}$$

Fixing notations: explicit Lagrangian

- X17 as a light vector V^μ, potentially with both vector and axial couplings

$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}M_V^2\, V_\mu V^\mu + \sum_{f=\ell,q} V_\mu\, \bar{f}\,(g_{Vf} + \gamma^5 g_{Af})f$$

$\longrightarrow$ g_{Vf} corresponds to $eq_f\varepsilon$ in dark photon models

- X17 as an axion-like particle (ALP) a, interacting via $\bar{f}\gamma^\mu\gamma^5 f$

$$\mathcal{L} \subset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + \sum_{f=\ell,q} \frac{g_{af}}{2}(\partial_\mu a)\,\bar{f}\,\gamma^\mu\gamma^5 f$$

$\longrightarrow$ g_{af} corresponds to $\frac{Q_{af}}{f_a}$ in the literature

Most of the e^+/e^--driven production rates shown in the rest of the talk satisfy approximately:

$$m_\ell g_{a\ell} \longleftrightarrow g_{V\ell}$$

$\Rightarrow$ e^+/e^--driven production rates are pretty agnostic concerning the X17 nature/couplings

The X17 couplings

- Need coupling to e^+e^- AND a large couplings to quarks to fit the excess

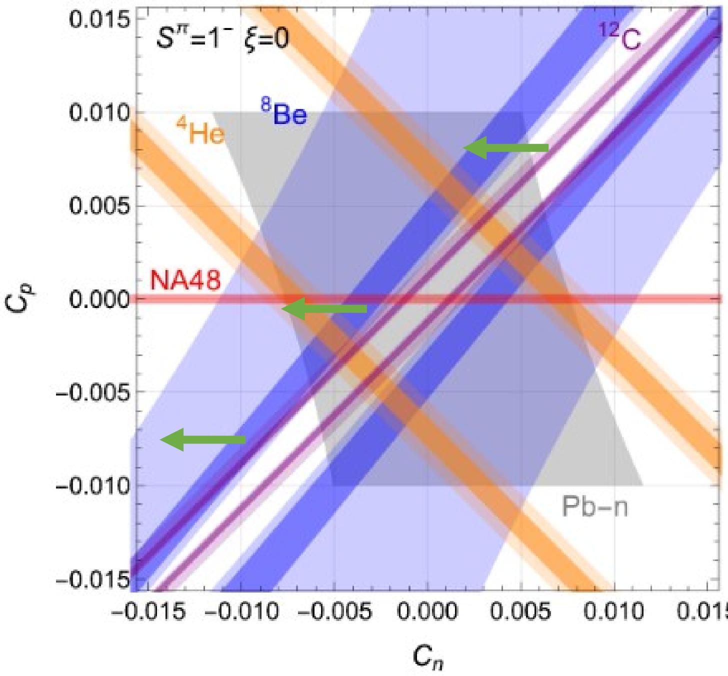
$$|g_{Vu} + 2\, g_{Vd}| \sim [0.6 \cdot 10^{-3}, 3 \cdot 10^{-3}]$$

See e.g. 1608.03591, assumed BR_{ee} at 1.

Protophobia needed to escape NA48 $\pi^0 \to \gamma\, V$

$$|2 g_{Vu} + g_{Vd}| \lesssim 0.4 \cdot 10^{-3}$$

- The couplings and mass both enters in fitting the excess → simultaneous fit of ^{12}C, ^{8}Be and ^{4}He required, not available yet with the latest data

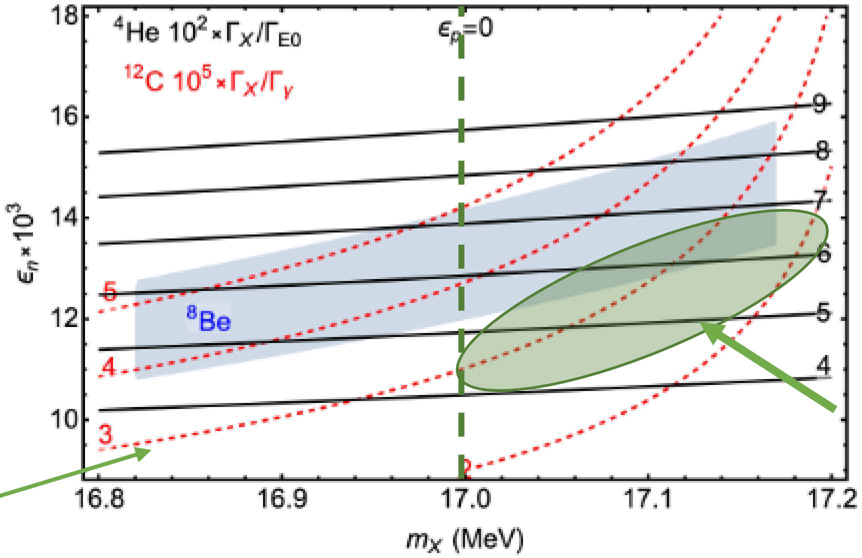


Barducci and Toni 2212.06453

It may be that the central value for the mass will move to accomodate the fit in couplings!

Measured ^{12}C is just below this line

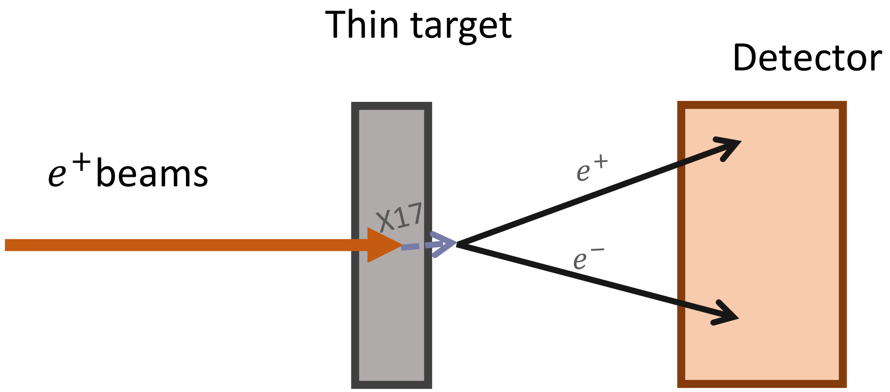
Feng et al. 2006.01151



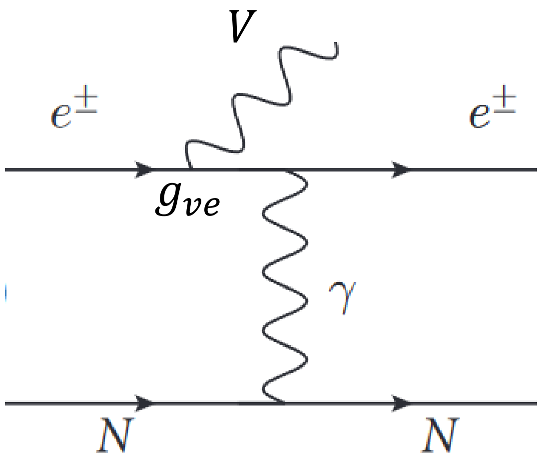
A full mass + couplings fit would put us around here ?

Resonant X17 production on a thin target

- Main idea: use resonant production and search for visible X17 decay in e^+e^-
- This is more or less the PADME setup, but no missing energy in the final state

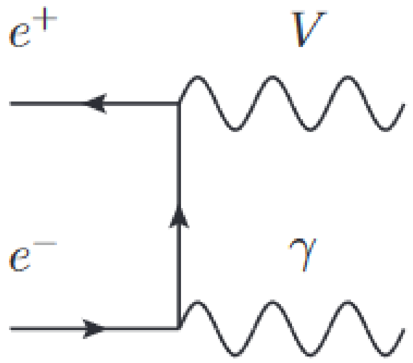


Bremsstrahlung process

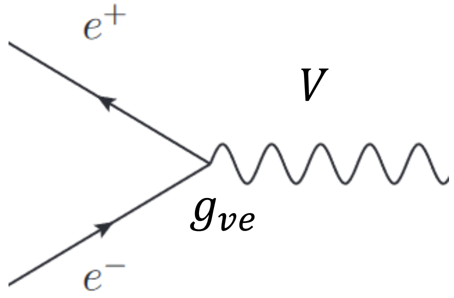


$$\sigma_{brem} \sim \frac{g_{ve}^2}{M_V^2}\, \alpha^2\, Z^2$$

Associated annihilation process



$$\sigma_{assoc} \sim \frac{g_{ve}^2}{2 m_e E_+}\, \alpha\, Z$$



Resonant process

→ Cross-section x100 times larger

→Scales as Z only

$$\sigma_{res} \sim \frac{g_{ve}^2}{2\, m_e} \pi\, Z\, \delta(E_+ - E_{res})$$

Scanning on energies

- To use resonant production, you need to start with positrons AND get to the resonant energies

$$E_{res} = \frac{M_V^2}{2\, m_e}$$

A "scanning" procedure is required

- Analysis strategy: vary the beam energy, fit the background, calibrate the luminosity and look for resonance

  → The resonance shape is exactly the one of the beam energy distribution !

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

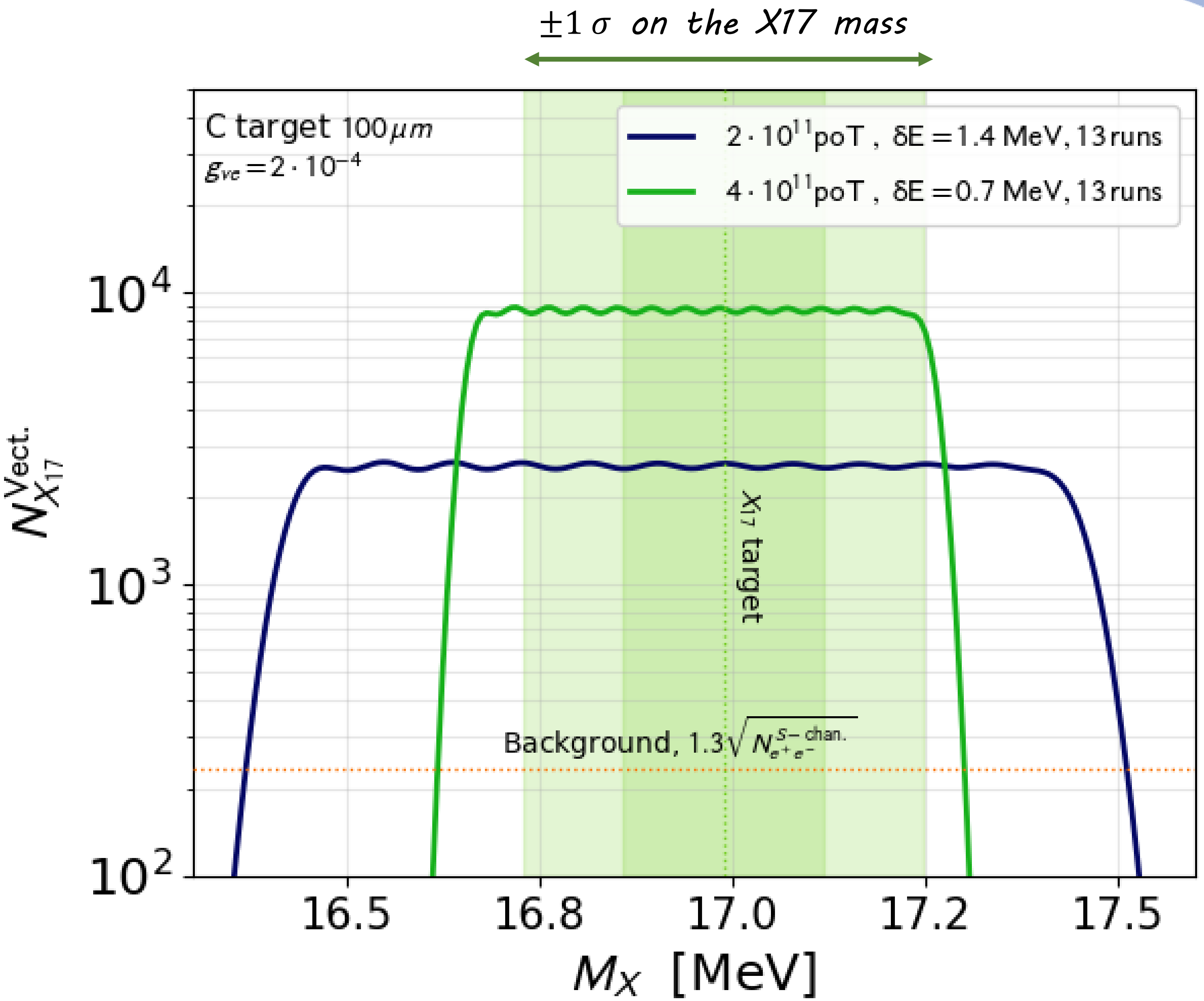
With f the beam spread, typically modelised by a Gaussian distribution with spread δE

- Main background is from Bhabha scattering, fitted directly from the data

  → "Large angular acceptance" detector important to reduce the t-channel contribution

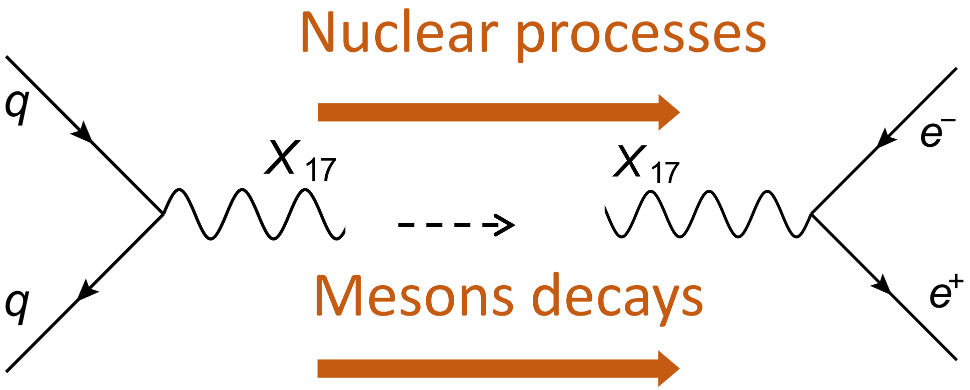
Production rates

- The beam energies used must be adapted depending on the beam spread δE
  - → Smaller spread implies lower background as the signal a "bump" with spread δE
- In PADME, better resolution on the beam energy steps than on e^+e^- invariant mass
  - → Each individual run at a given energy is used as a data point



LD, Mancini, Nardi, Raggi, 2209.09261

PADME and the X17 boson, the perfect target



- e^+/e^- beam dump and e^+/e^- collider
- $e^{(*)} \to e\, X$ emission

Model independent + test NP origin of the signal

- We look for a light boson decaying to mostly to e^+e^- with mass:

$$m_{X_{17}} \simeq 16.99 \pm 0.04\,(stat) \pm 0.21(syst)\ \text{MeV}$$

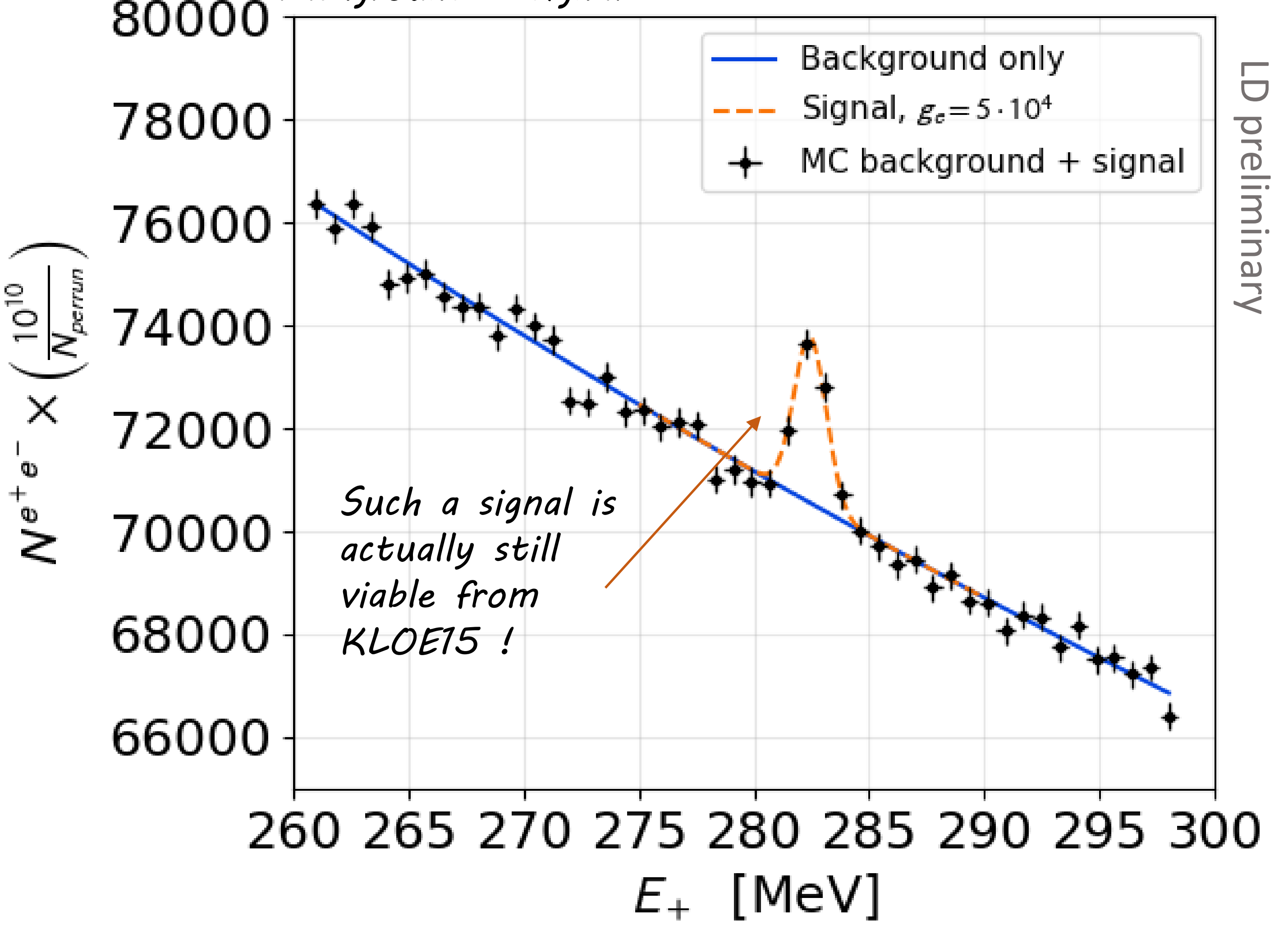
- The narrow mass range plus model-independent $e^{\pm}$ couplings makes this anomaly a perfect target for a resonant search !
- The target energy range is [260 - 300] MeV → perfectly adapted to e^+ beam at LNF

$$\mathcal{N}_{X_{17}}^{\text{per poT}} \simeq 3.8 \cdot 10^{-7} \times \left(\frac{g_e}{3 \cdot 10^{-4}}\right)^2 \left(\frac{1\ \text{MeV}}{\delta E}\right)$$

What would a perfect signal look like …

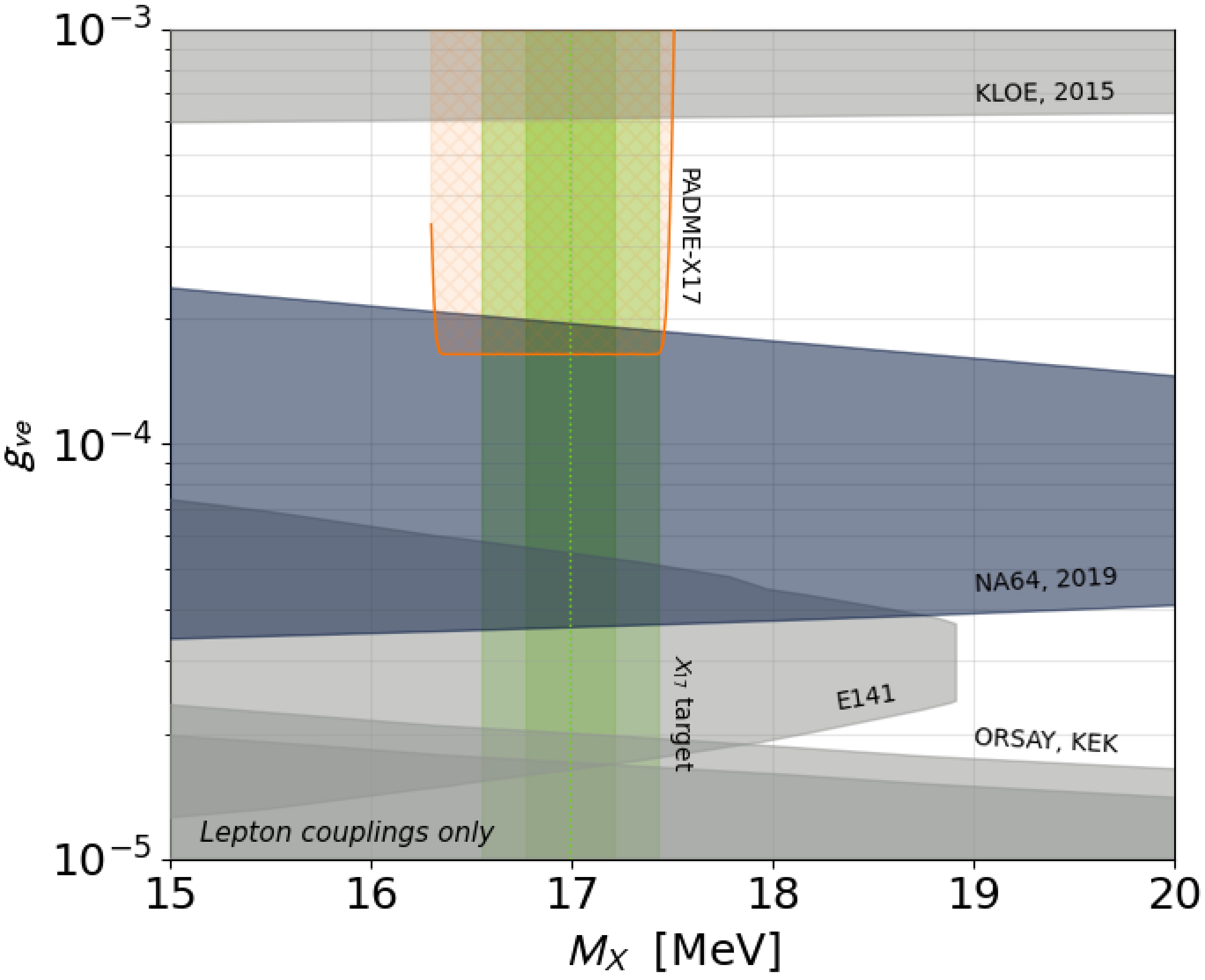
- Take a (slightly) idealised Run-3 dataset
  - → $4.9 \cdot 10^{11}$ PoT, a 0.25% beam spread
  - → [261 , 298] MeV range of energy with a 0.75 MeV energy step
- Assume the luminosity uncertainty has been controlled below the statistical error (i.e ~ 0.5 % level or so)
  - → Normalise each point to 10^{10}
- The beam spread implies that the signal will turn up in several data-point
  - → Full bump-search approach required

Toy dataset with statistical errors only for background + signal



Projections for PADME – X17

- Complete simulation based on the current PADME setup
  - →If all goes to plan the vector X17 hypothesis will be fully covered !)
  - →Not enough for the scalar case due to reduced NA64 limit
- Serve as a first "test run" for these kind of analysis
  - → Will also provide best constraints on dark photon in this (narrow) mass range, beating NA48



LD, Mancini, Nardi, Raggi, 2209.09261

Conclusion

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- Positron-based facilities allow to leverage resonant production to significantly increase signal rates

  →With the cost of having to scan over a large energy range

- PADME-Run III is (also) a proof-of-concept for a $e^-e^+ \to X, X \to e^+e^-$ experimental strategy for a feebly coupled new particle

- The X17 vector explanation (the most probable one given ^{12}C data) could be fully covered!

  →(provided experimental errors stay nicely where expected)

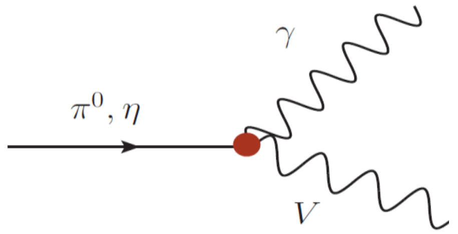
Backup

Accelerator facilities (currently) available

Intensity beam dumps

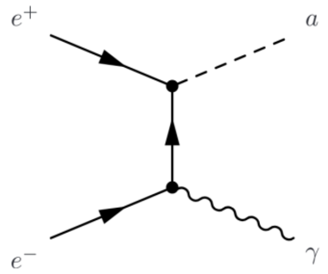
→ p machines (beam neutrinos exp, SHiP).

- Large backgrounds + far away detectors



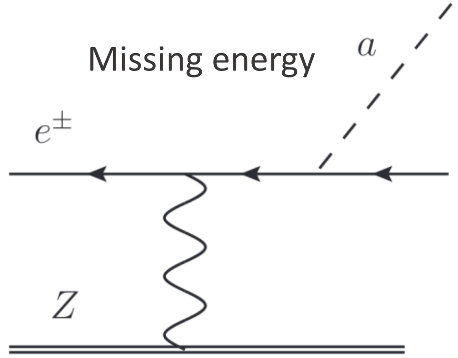
e^+e^- colliders

→ Higher energy but smaller luminosity



e^- "precision"fixed targets (NA64 ...)

→ Small luminosity but no background



- PADME Run-3 is also the first try at a new concept : e^+ "precision" beam dumps → Rely on resonant production for x10-100 improvement in production rates

Rare decays searches

- Rare decays probes are both extremely effective in probing X17, often at the price of a large model dependence
- Mesons decay probes (example from mostly last year)

Vector state

- $\pi^0 \to \gamma V_{17}$, for vector states: NA48 bounds implies proto-phobic (hep-ex/0610072) — Feng et al. (1604.07411,1608.03591) 2006.01151
- J/Ψ decays, charm couplings only — Ban et al. 2012.04190
- $B^* \to B\, V_{17}, D^* \to D\, V_{17}$ for vector states — Castro and Quintero 2101.01865

Axion

- $\pi^0 \to a_{17} \to e^+e^-, K \to \pi(\pi)a_{17}, K \to \mu\nu\, a_{17}$ — e.g Alves et al. 1710.03764, 2009.05578
- $\pi^0 \to a_{17}\, a_{17}\, a_{17}$ and other multi-leptons final states — Hostert and Pospelov 2012.02142

- If flavour-violation, many more available channels both in lepton decays and in “standard” flavoured meson decay.
- Also radiative emission from μ decay

ALP case

- The « tip » of the NA64 search does not cover the relevant range

→ Not much is required, shoud be much better with new data