Resonant FIP searches with positrons

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IP2I – CNRS
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Based on 2209.09261 and 2211.xxxx with M. Raggi and E. Nardi

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Outline

Introduction: using resonant production

Two experimental strategies for positron beams

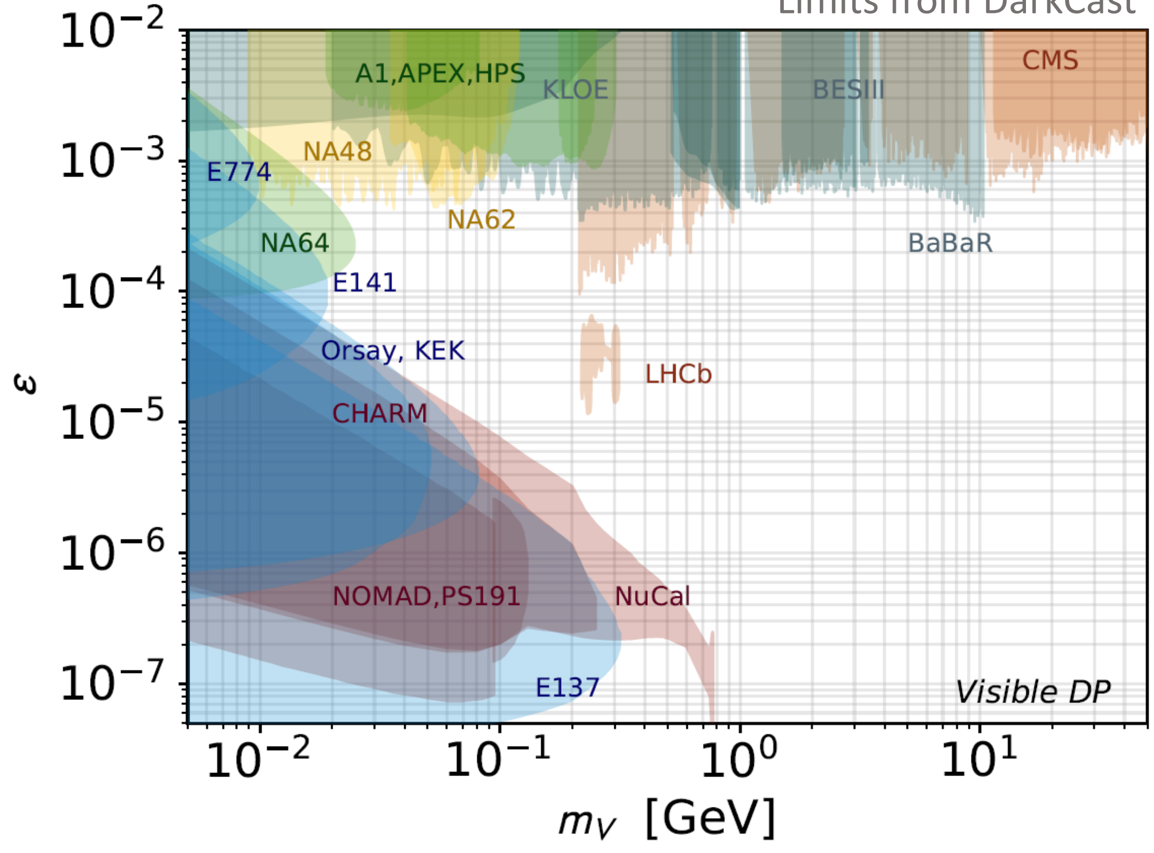
Searches for X17 in PADME

Building the e^-/e^+ fixed target of the future ?

- Many proposals for a next-generation electron fixed target/beam dump machines

  →For the long-lived limit, we want to do better than experiments from the 80s-90s …

Limits from DarkCast



Building the e^-/e^+ fixed target of the future ?

- Many proposals for a next-generation electron fixed target/beam dump machines

  →For the long-lived limit, we want to do better than experiments from the 80s-90s …

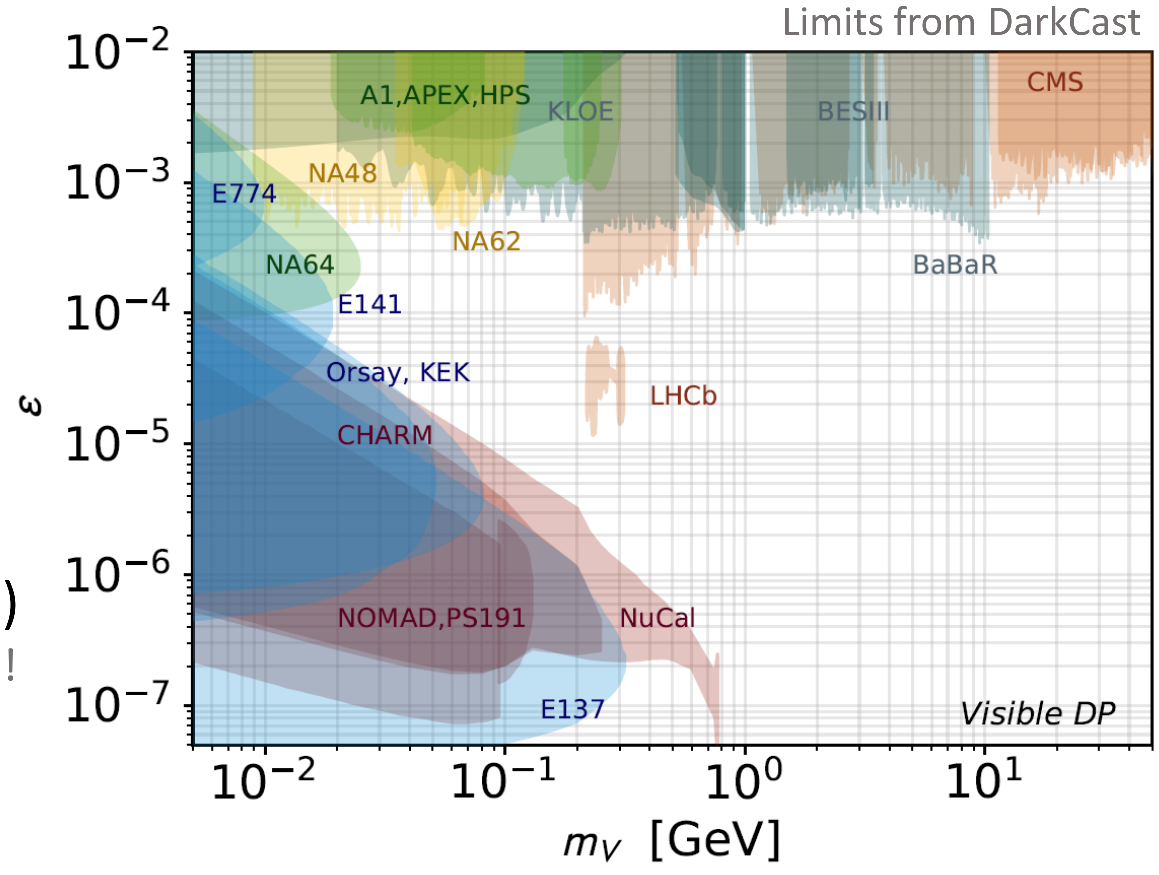
- Many experimental strategies pursued closing the (in)-famous Mont's gap

  → Higher boost factor (FPF, SHIP, etc…)

  → Smaller beam dump size (NA64) / Displaced vertices (LHCb)

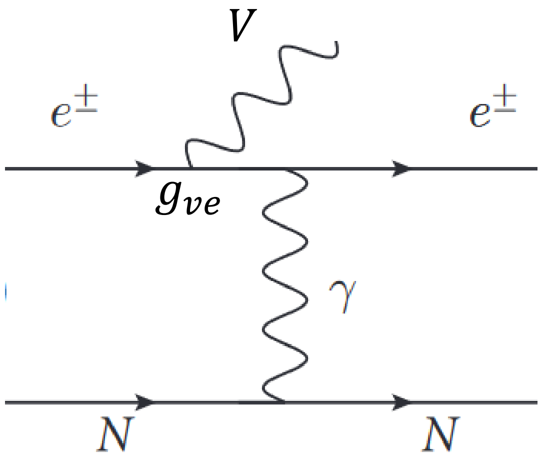
  → More statistics for bump-search method (Belle-II)

… and many others !



This talk → use a different production mechanism

Going resonant …



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

Bremsstrahlung process

→Cross-section scales as Z^2

→FIP carries away most of the beam energy: sensitivity up to $m_V \sim E_{e^+}$

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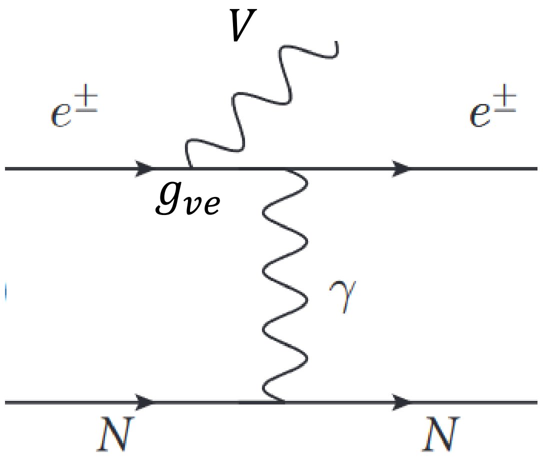

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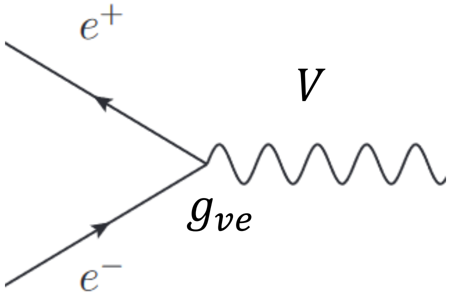


Resonant process

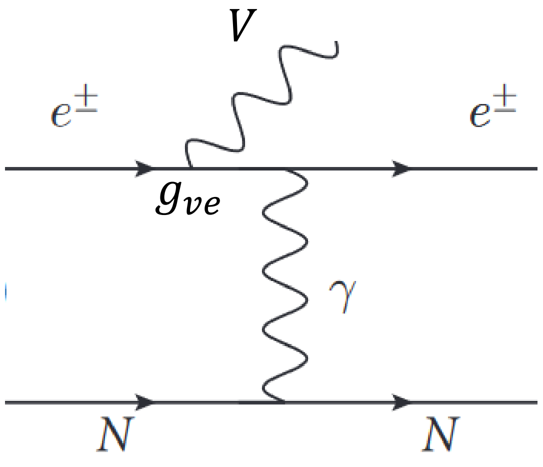
→ Cross-section x100 times larger

→Scales as Z only

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

Also significantly larger than $e^+e^- \to \gamma V$

Going resonant …



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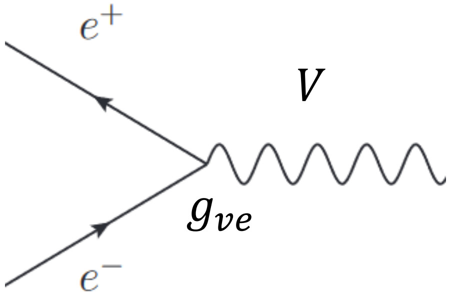

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Also significantly larger than $e^+e^- \rightarrow \gamma V$

- What are the trade-offs for resonant production ?
  - → First, we need to find positrons somewhere. Typically, this implies a certain loss in energy + beam intensity
  - → Then we need to hit the resonant energy (works mostly for 10-100 MeV range)

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

How to get to the exact energy ?

- Study models with large invisible width Γ_V^{inv} → Typically extremely important for DM-motivated models !

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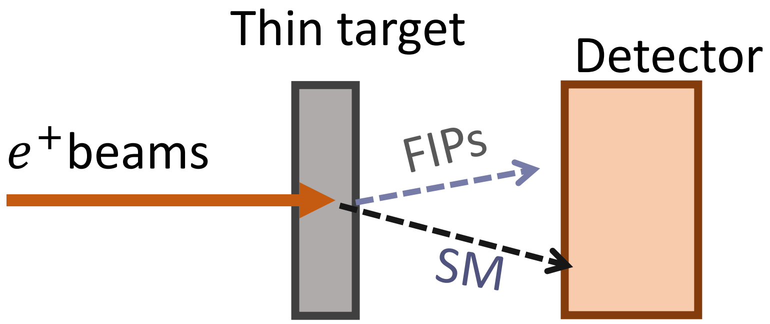
  - Vary the beam energy

  → "Scanning" procedure is required, varying the beam energy on non-negligible range   See e.g. 1802.04756



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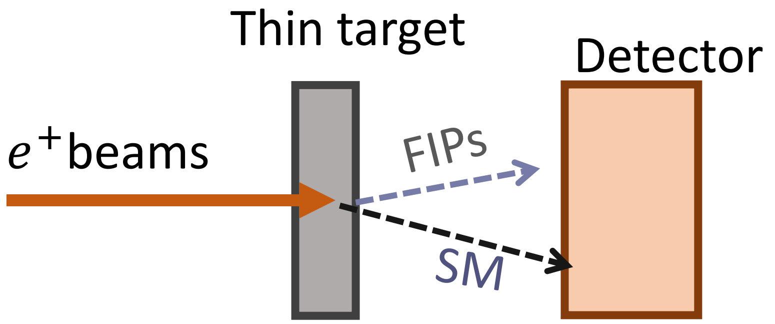
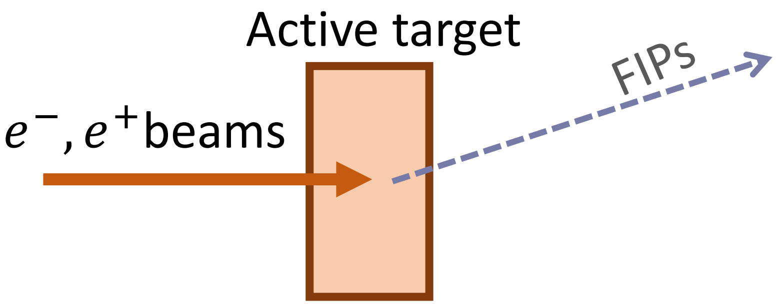


- Use energy loss and secondary e^+ production in the target to "scan" naturally various positron energies

→Requires a "not-too-thin" target to allow some evolution of the beam

→ Works to a certain extent also in electron-based machines

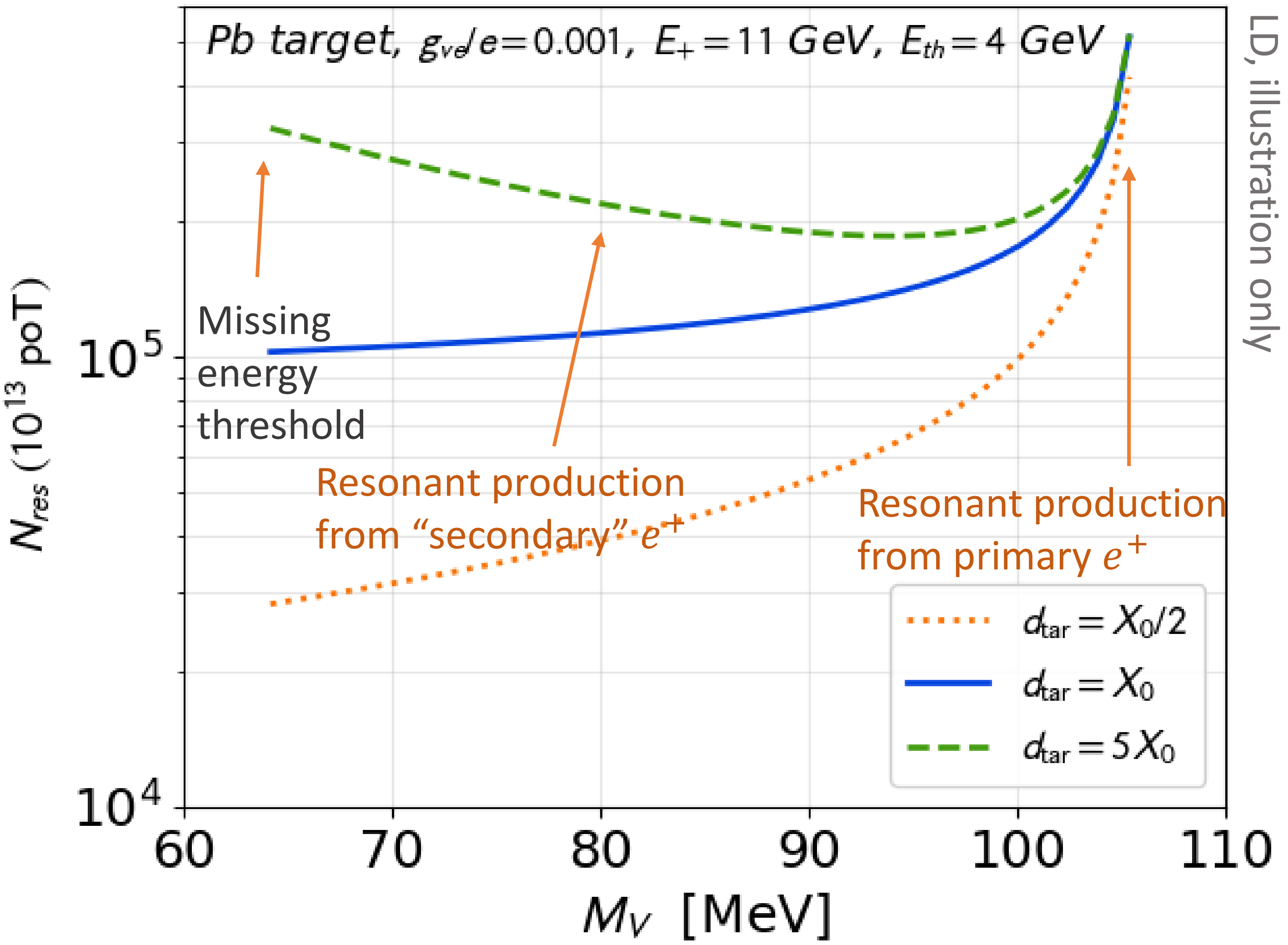
See e.g. 1802.03794, 2105.04540, 2206.03101



The thick target approach

- Use straggling and bremsstrahlung process degrades the beam energy

- Effective to probe a large range of masses without varying the beam energy too much

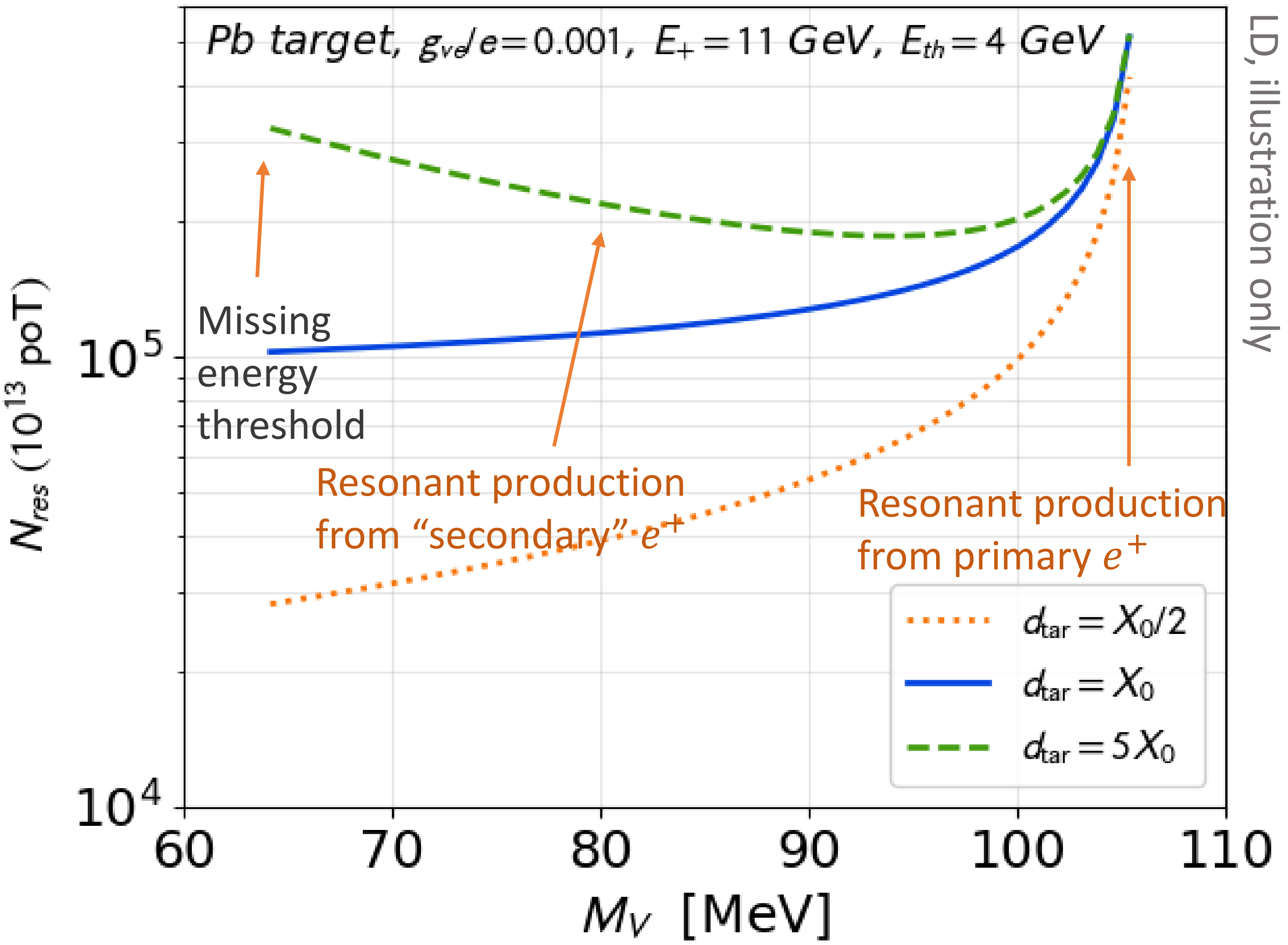


The thick target approach

- Use straggling and bremsstrahlung processes to degrad the beam energy

- Effective to probe a large range of masses without varying the beam energy too much

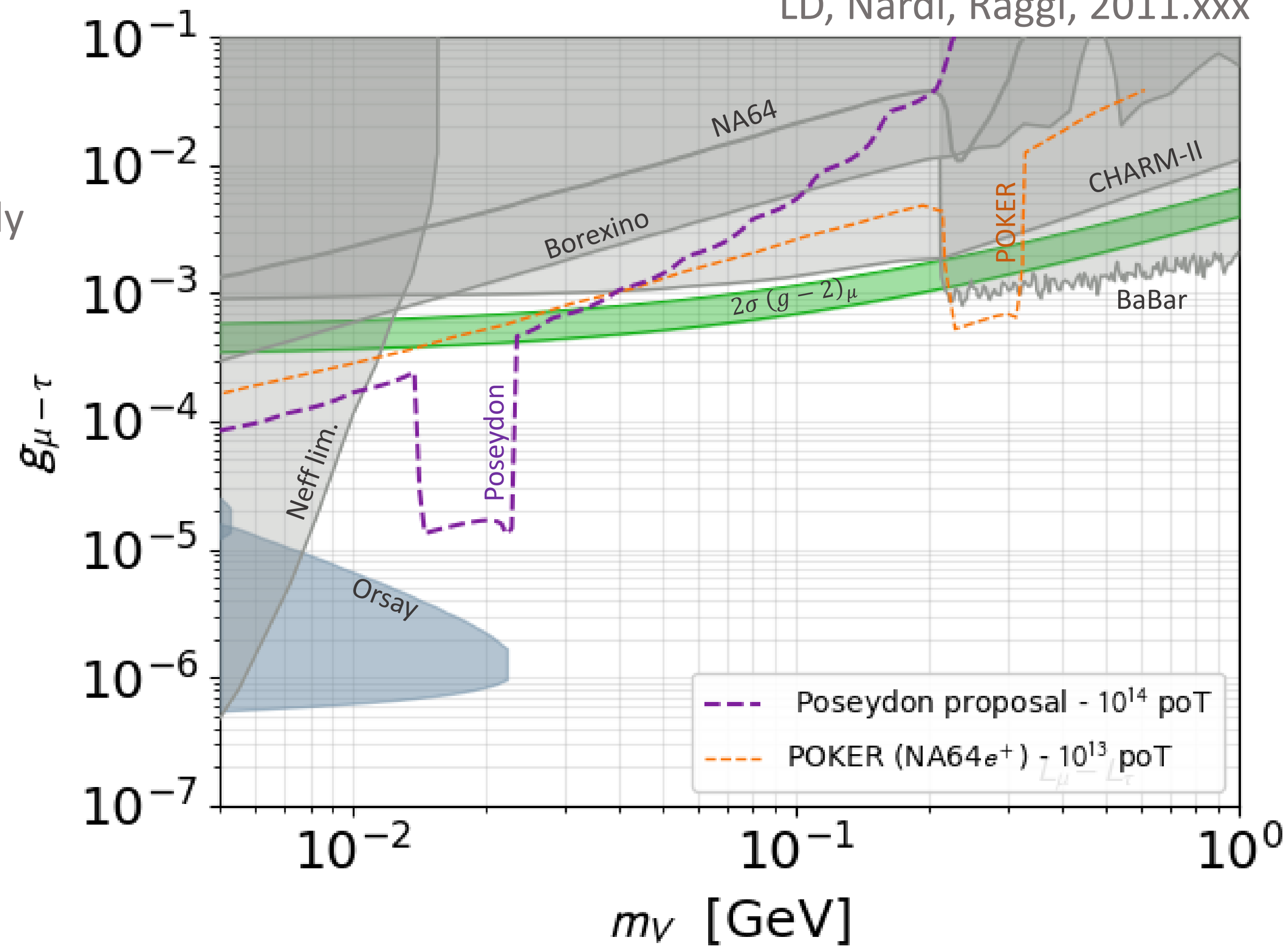
- But FIP production occurs directly in the shower
  - →Requires either a displaced signal or missing energy to escape background
  - →This works as soon as we have a coupling to neutrinos …



In practice: limits on $L_\mu - L_\tau$ gauge boson

- Use radiatively generated kinetic mixing for the production stage + decay into neutrinos   Cf, e.g., Patrick's talk yesterady
  - →Recent limits from NA64 promising !
- Projections for
  - →Poseydon (based on the e^+ LNF beam at 0.5 GeV)
  - → NA64-e^+ (POKER, with ~150 GeV beam)   From 2206.03101

LD, Nardi, Raggi, 2011.xxx



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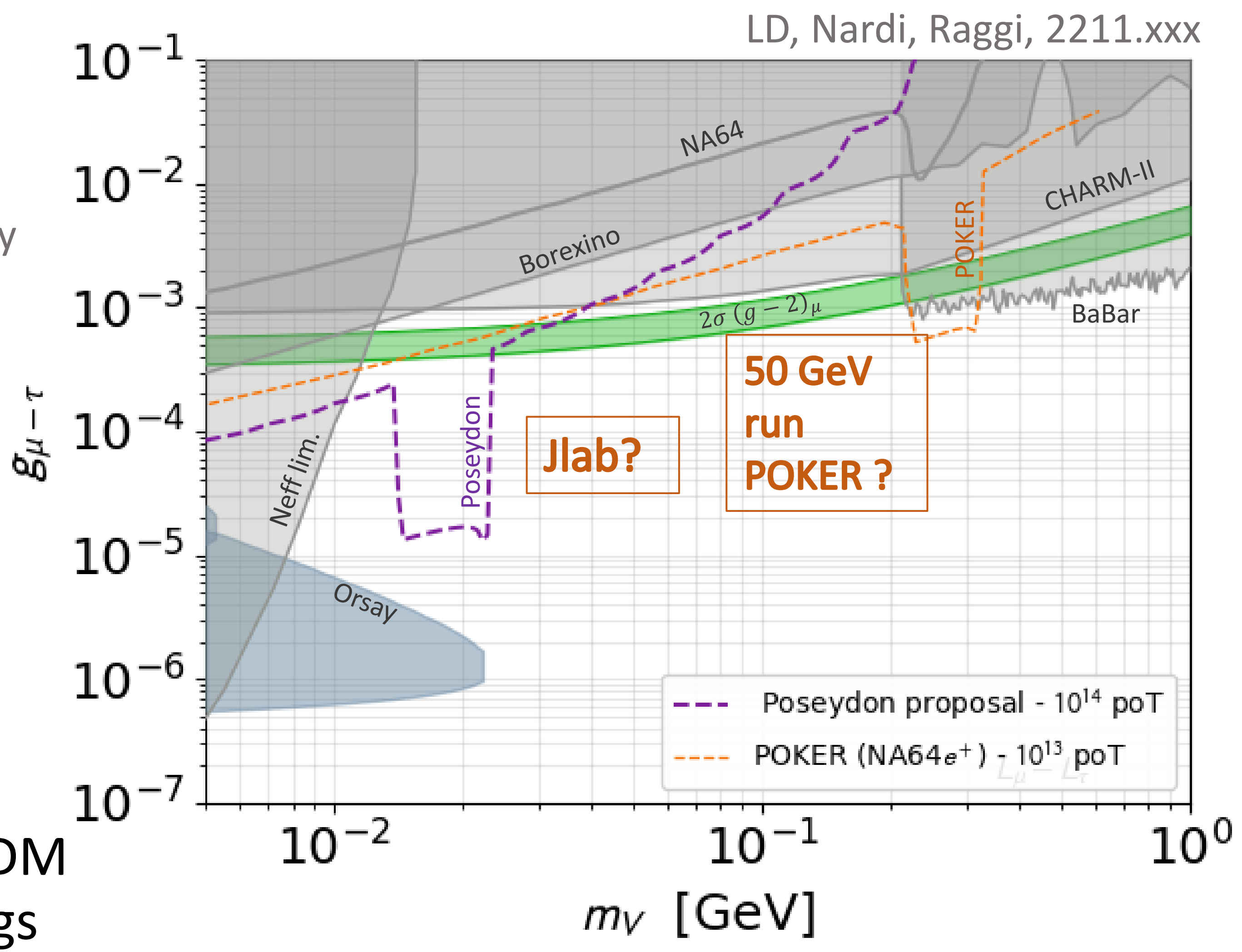
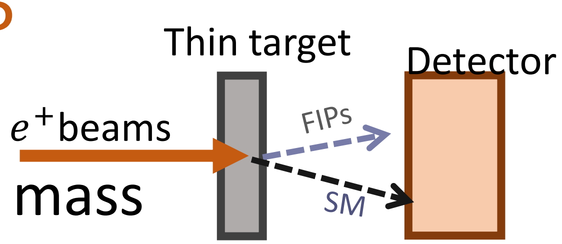
- Of course, even better constraints on DM scenarios with "tree-level" $e^\pm$ couplings



Resonant production: thin target

- Main idea: use resonant production and search for visible FIP decay in a noisy environment

  → Mostly relevant with e^+e^- final states (hard to produce a FIP with mass above the di-muon threshold resonantly)



- Vary the beam energy, fit the background, and look for resonance

  → Simple analysis strategy

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

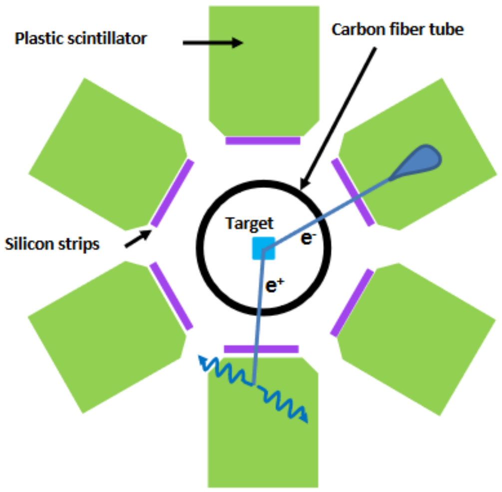
With f the beam spread, typically modelised by a Gaussian distribution with spread δE

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

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

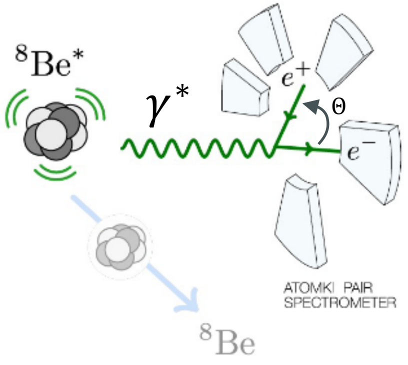
The X17 anomaly

- The signal: a possible 17 MeV boson in the ATOMKI spectrometer?
  → Production in excited nuclei ^{12}C, ^{8}Be and ^{4}He, followed by radiative decay $N^* \to N\,\gamma^* \to N\,e^+e^-$

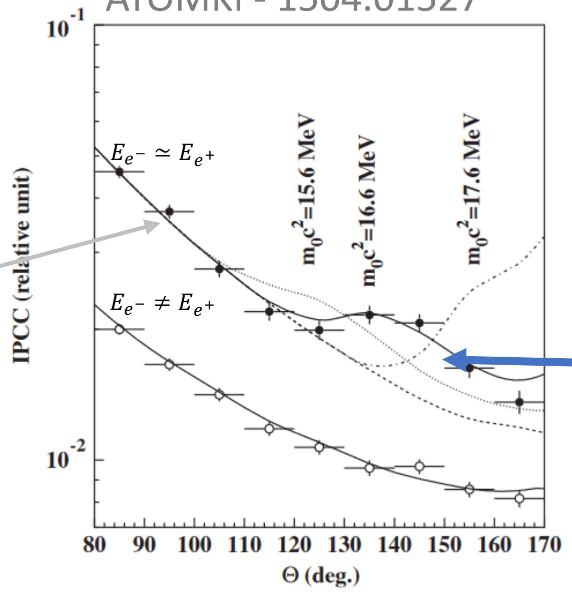


2209.10795, 2104.10075, 1504.01527

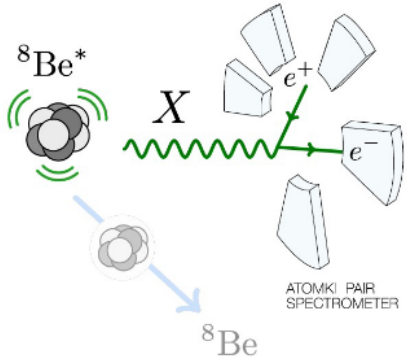
The SM signal: $N^* \to N\,\gamma^* \to N\,e^+e^-$



ATOMKI - 1504.01527



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



PADME and the X17 boson, the perfect target

- Large coupling to quarks required + protophobia to avoid NA48 π^0 decay limits
  - → sizeable coupling to electron also required to allow prompt decay

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

$$M_X = \begin{cases} 16.70 \pm 0.35 \pm 0.50 \text{ MeV} \\ 17.01 \pm 0.16 \text{ MeV} \\ 16.94 \pm 0.12 \pm 0.21 \text{ MeV} \end{cases}$$

← ^{8}Be 1504.01527 + cds.cern.ch/record/2312578

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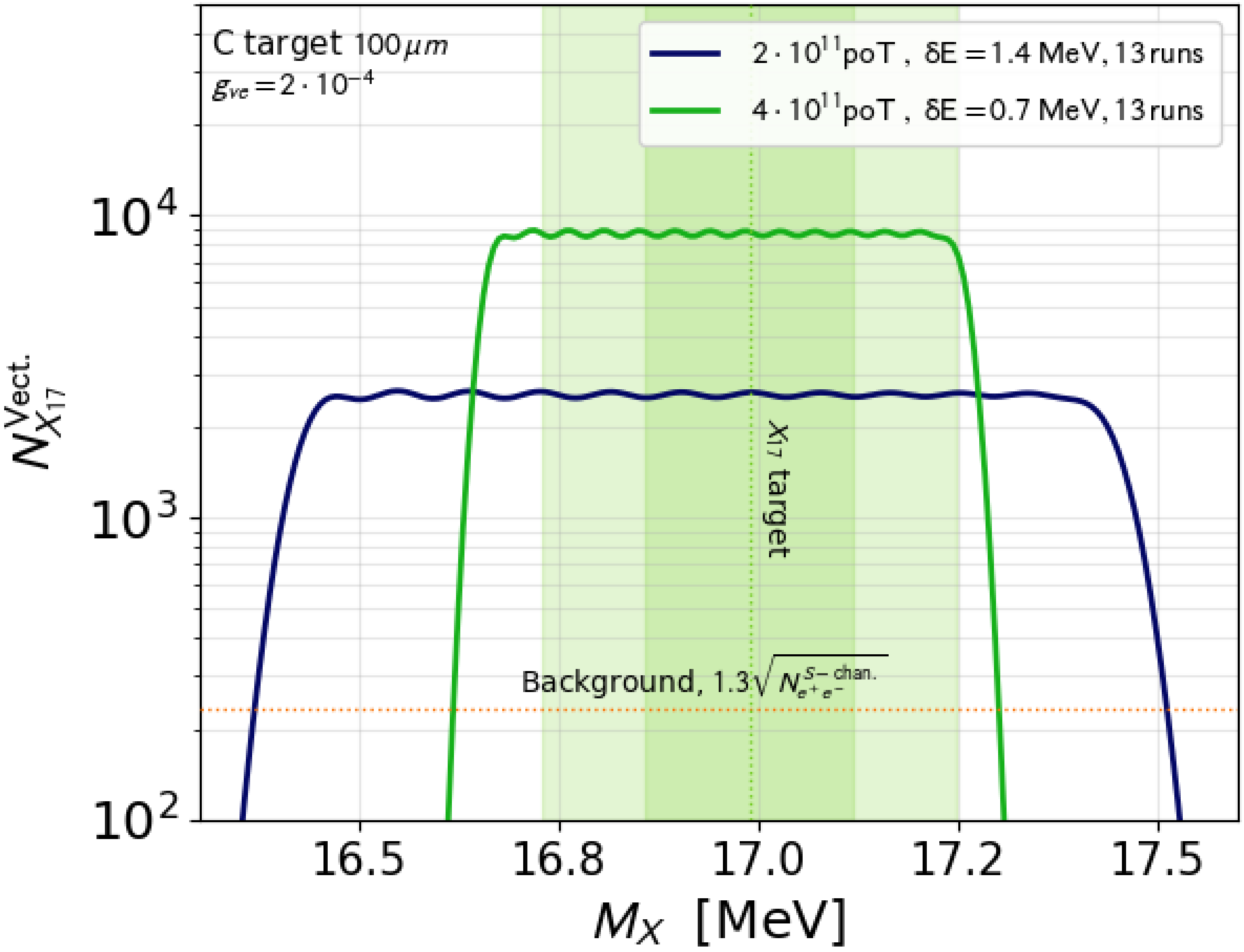
- The narrow mass range plus model-independent $e^\pm$ couplings makes this anomaly a perfect target for a resonant search !

- The target energy range is [270 - 290] MeV → perfectly adapted to e^+ beam in Frascati

Scanning strategy

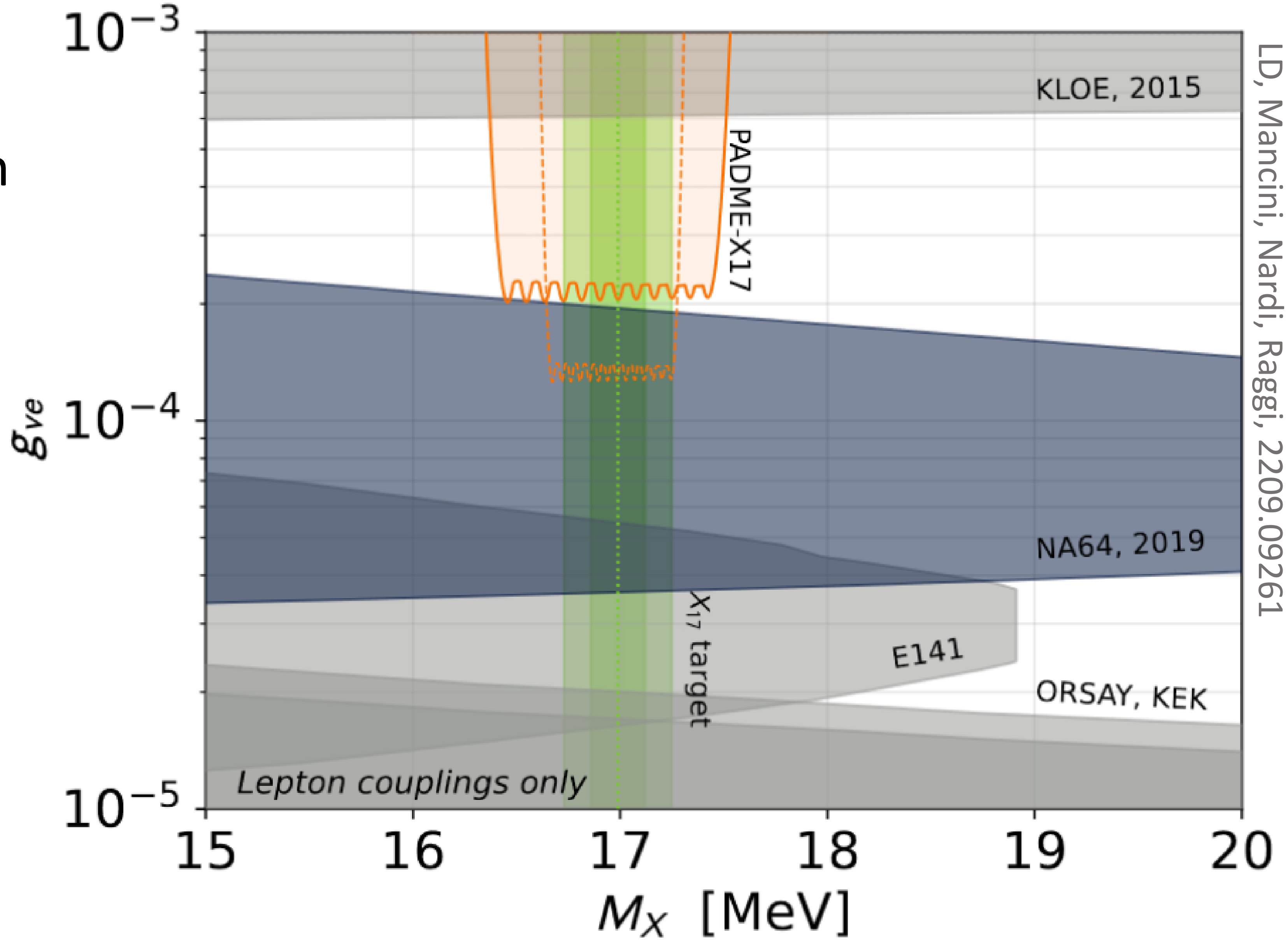
- Several runs depending on the beam spread δE
  - →Smaller spread implies lower background as the signal a “bump” with spread δE
  - →Currently only LNF’s accelerator complex can provide a positron beam and vary its energy
- Include radiative return effects with use of NLO $e^+e^- \to (\gamma)X$, with soft photon emission



LD, Mancini, Nardi, Raggi, 2209.09261

Projections for PADME – X17

- More details in this afternoon's presentation by M. Raggi
- Complete simulation based on the current PADME setup
  - → Conservative: $2 \cdot 10^{11}$ PoT, a 0.5% beam spread
  - →Aggressive: $4 \cdot 10^{11}$ total PoT, a 0.25% beam spread
- Serve as a first "test run" for these kind of analysis



LD, Mancini, Nardi, Raggi, 2209.09261

Conclusion

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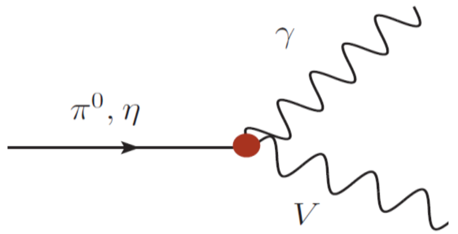
- Positron-based facilities allow to leverage resonant production to increase significantly signal rates
  - → With the cost of having to scan over a large energy ranges
- Current planned strategies are
  - → Either thick target + missing energy (works both for DM-models and for neutrino decays)
  - → Or thin target with visible decays + scan in beam energy
- First experimental example of the later strategy will be completed shortly by the PADME collaboration, with the X17 anomaly as a target

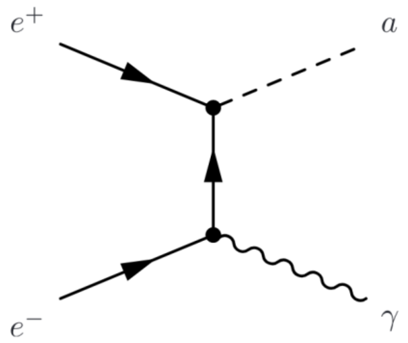
Backup

Accelerator facilities (currently) available

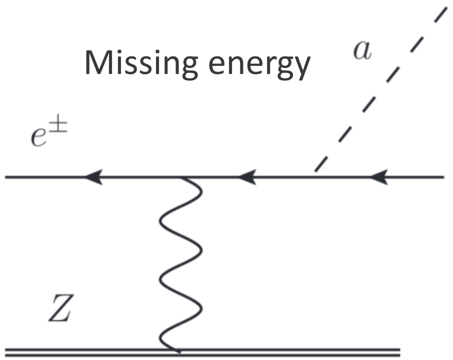
- Intensity beam dumps: typically, p machines (beam neutrinos exp, SHiP).
  - Large backgrounds + protophobia of X17 + far away detectors → Challenging for X17



- e^+e^- colliders (BaBaR, Belle-II …)
  - Good production rates, large luminosity, but also background control and the small p_T for the e^+e^- pair → Still interesting avenue for X17 (displaced vertices?)



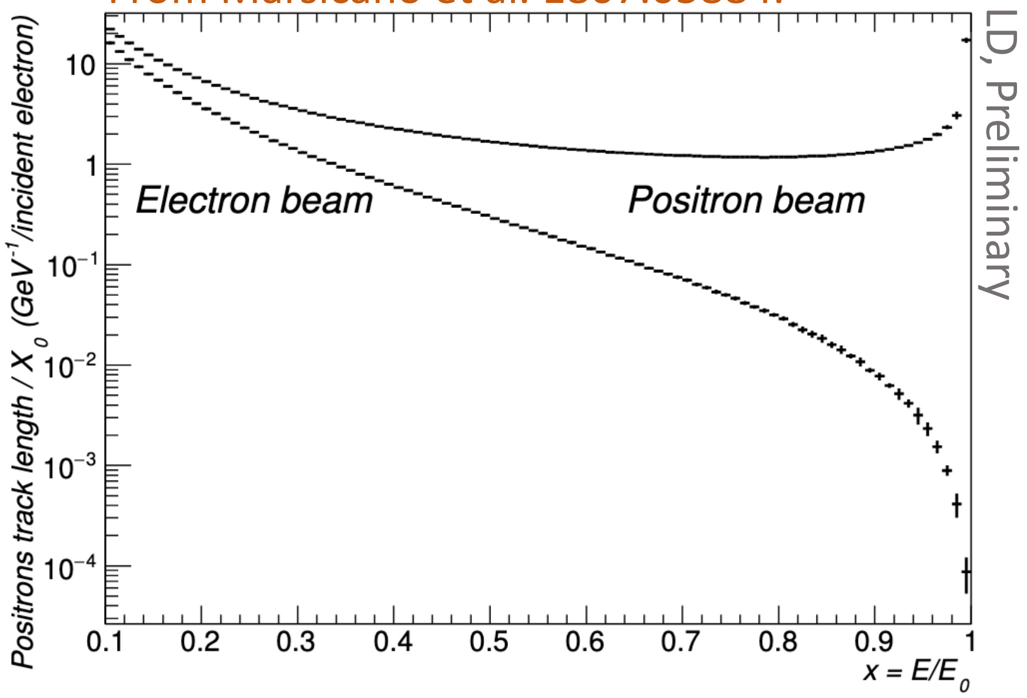
- e^+e^- beam dumps: typically, e^+ or e^- machine (NA64, PADME, MAGIX, etc…)
  - Large production rates, can search for displaced vertices or reconstruct the e^+e^- pair → particularly suitable



- Rare meson/lepton decays → Promising, but with model-dependence

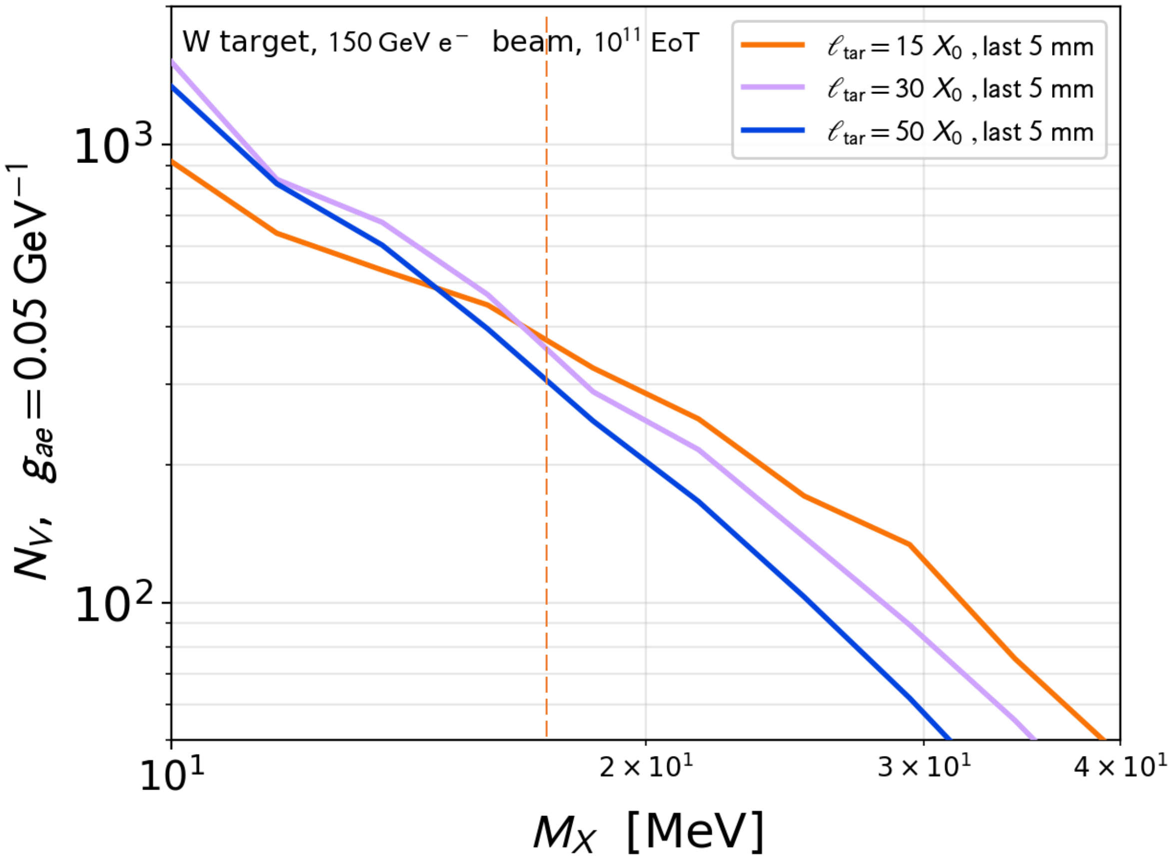
Secondary positron production

From Marsicano et al. 1807.05884.



- A secondary positron population build up the shower "convert energy to statistics"

$$N_{e^+}^{X17} \sim \frac{E_{ini}/2}{280\ MeV} N_{e^-}^{ini}$$



→ X17 resonant production occurs at any point in the target, including at the end

→ Background from the residual shower likely to swamp the signal

.. but energy matters for decay lengths!

- Bremsstrahlung extracts most of the energy of the beam

$$\gamma_{X17}\ell_{X17} \sim 3\text{ cm}\left(\frac{E_{X17}}{100\text{ GeV}}\right)\left(\frac{17\text{ MeV}}{m_{X17}}\right)\left(\frac{3\cdot 10^{-4}}{g_{Xe}}\right)^2 \quad \text{(Vector)}$$

$$\gamma_{X17}\ell_{X17} \sim 3\text{ cm}\left(\frac{E_{X17}}{100\text{ GeV}}\right)\left(\frac{17\text{ MeV}}{m_{X17}}\right)\left(\frac{0.5\text{ GeV}^{-1}}{g_{Xe}}\right)^2 \quad \text{(ALP)}$$

➡ Make displaced signatures viable for higher energy experiments

- By contrast, X17 from resonant production have relatively low energy

$$E_{X17}^{\text{res}} = \frac{m_{X17}^2}{2\,m_e} \simeq 280\text{ MeV} \;\Rightarrow\; \gamma_{X17}^{\text{res}} \simeq 15$$

➡ Displaced signatures viable only for the lowest allowed couplings

- However, resonant production implies that the decay production satisfy precisely both $E_{X17}^{\text{res}} \simeq 280\text{ MeV}$ and $m_{ee} \simeq m_{X17}$

Fixing notations: explicit Lagrangians for X17

- 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 Daniele Alves's talk

- 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 $e\varepsilon_f$ in Jonathan Feng's and Tim Tait's talks

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

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

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

The X17: the couplings

- Need a large couplings to quarks, but the actual couplings target depends on the X17 nature

  → As a reference for the vector case

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

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

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

→ Huge couplings ! Protophobia needed to escape NA48

- It has to decay (mostly) visibly into e^+e^-

  → For ATOMKI result, coupling with electron constrained only by a lower limit to ensure decay length smaller than ~cm (we will discuss it in detail in this talk)

  → Can have an invisible BR to e.g. a new dark sector particles but leads to even larger coupling to quarks

  → Strong constraints on neutrinos interactions from $\nu_e e^-$ scattering experiments

X17: widths and productions

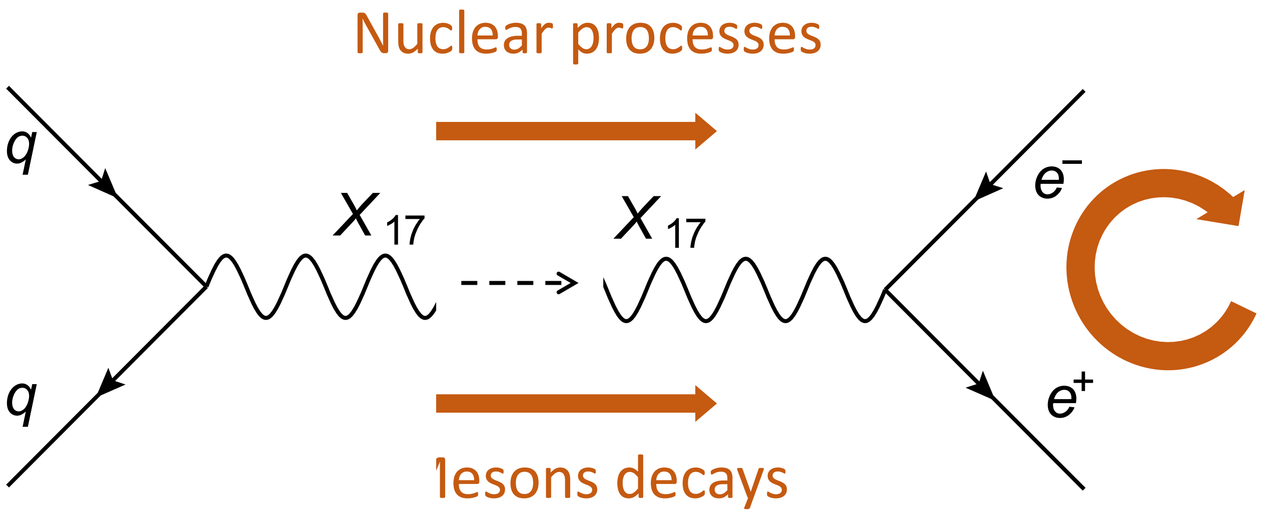
- Combined, the above requirements imply that the X17 must have a tiny width, mostly driven by the e^+e^- decay

Vector case

$$\Gamma_X \sim \frac{g_{Ve}^2}{12\pi} M_V \sim 0.5\ \text{eV}\ \times \left(\frac{g_{Ve}}{0.001}\right)^2$$

→ More challenging to produce it on resonance

- Altogether we have the following situation



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

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 (cf Ann-Kathrin’s talk)