X17 production mechanisms at accelerators

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Use inputs from 2012.11150 with Frederica Giacchino, Enrico Nardi and Mauro Raggi
and from 2105.04540 with Battaglieri et al.

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Outline

Introduction: X17 properties

X17 production strategies: an overview

The case of resonant production

The X17, stating the obvious first

- We look for a boson with mass:
  - $16.94 \pm 0.12(stat) \pm 0.21(syst)$ MeV ← ^{4}He 2104.10075
  - 16.70 ± 0.35 (stat) ± 0.5 (sys) MeV ← ^{8}Be 1504.01527

- The small mass implies
  → No need for large $\sqrt{s}$ to produce a X17, makes beam dump experiments competitive. In particular, in "worst case" of e^+ driven processes on atomic electron

$$\sqrt{s} = \sqrt{2 m_e E_b} \sim 30 \text{ MeV} \times \sqrt{\frac{E_b}{1 \text{ GeV}}}$$

➡ Positrons below the GeV are still energetic enough to produce a X17 in $e^- e^+$ annihilation

→ Accessible in decay of low mass particles e.g. π^0, μ with large rates from small SM decay width

→ But also from excited flavoured mesons ➡
- $M_{D^*} - M_D \simeq 140$ MeV
- $M_{B^*} - M_B \simeq 45$ MeV
- Etc…

See e.g. 2101.01865

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.

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

→ 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

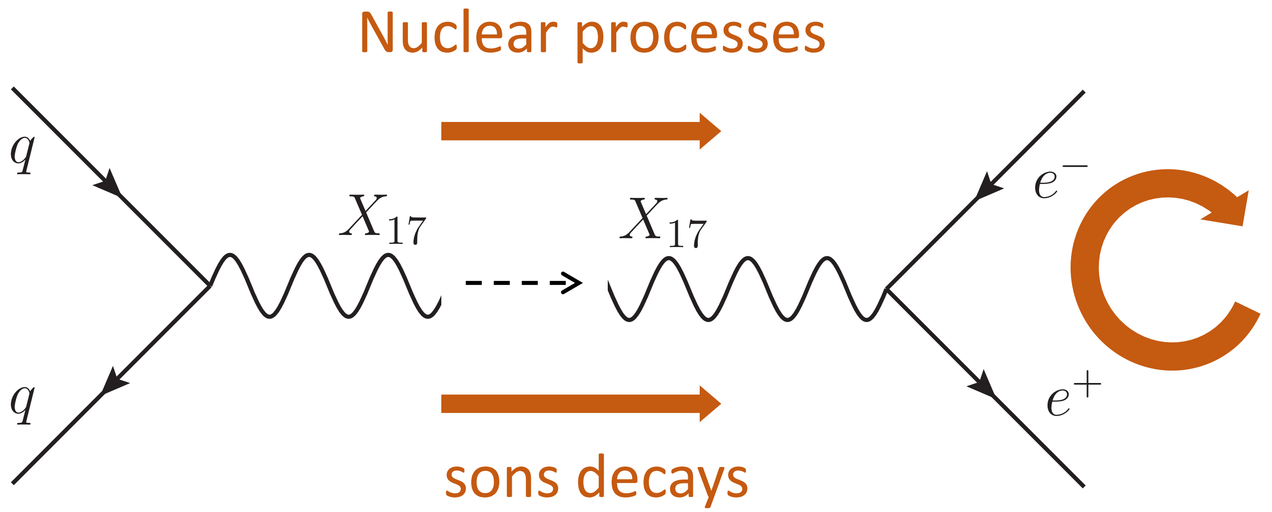
- Combined, the above requirements imply that the X17 must have a tiny width, mostly driven by the e^+e^- decay

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

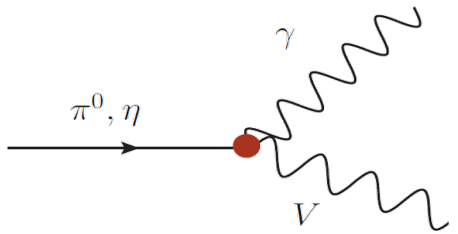


- e^+/e^- beam dump and e^+/e^- collider
- $e^{(*)} \to e\,X$ emission

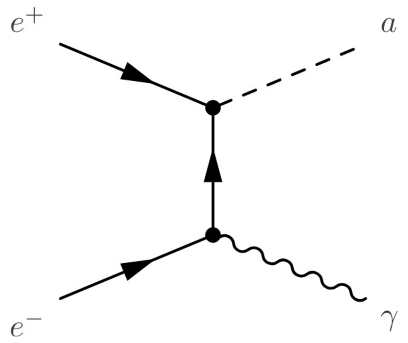
X17 production strategies at accelerators: an overview

Accelerator facilities (currently) available

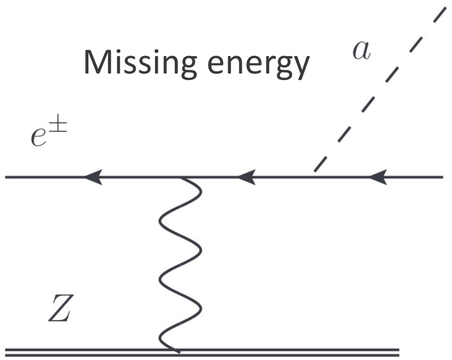
- Intensity beam dumps: typically, p machines (beam neutrinos exp, SHiP).
  - Large backgrounds + protophobia of X17 + far away detectors → Challenging for X17



- 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

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. 1710.03763, 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)

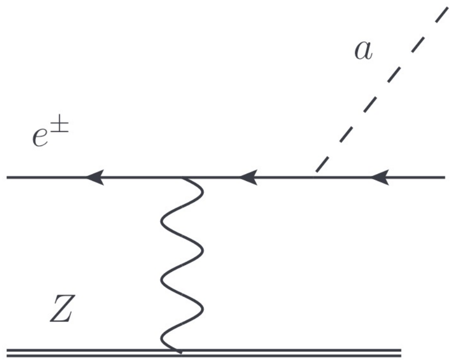
X17 production in e^+/e^- machines

- Lepton-induced production is currently focused on Bremsstrahlung

→ Electron-only machine mostly rely on Bremsstrahlung process

Bremsstrahlung

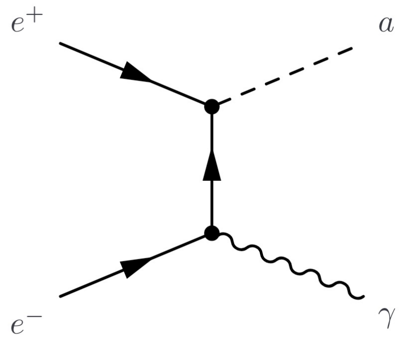
$$\sigma_{ae} \propto \alpha_{\rm em}^2 g_{ae}^2 \frac{m_e^2}{m_a^2}$$



For an ALP/axion X17

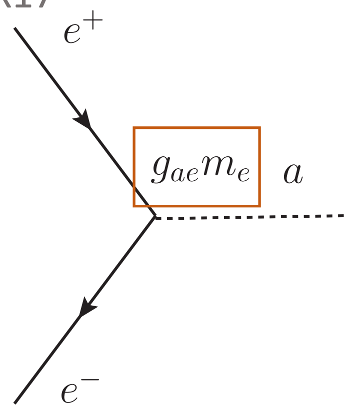
→ Positron machine have more channels (annihilation on beam target's electrons)

For an ALP/axion X17



Associated/mono-γ

$$\sigma_{ae} \sim \alpha_{\rm em} g_{ae}^2 \frac{m_e^2}{2s} \log\left(\frac{s}{m_e^2}\right)$$



etc…

Resonant

$$\sigma_{res} \sim \pi g_{ae}^2 m_e \delta(E_+ - E_{res})$$

Beam energy dependence

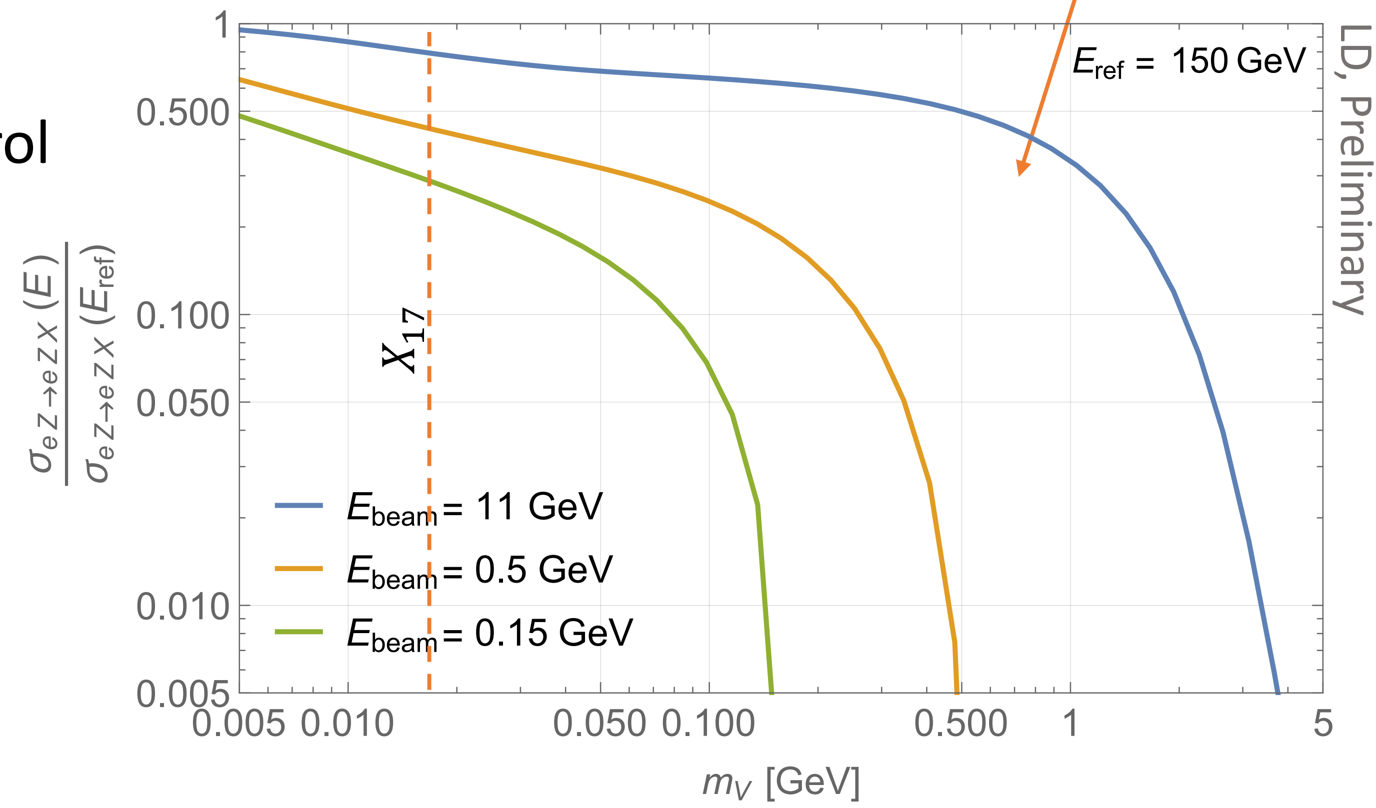
- Bremsstrahlung CS depends only feebly on the actual e^+/e^- energy
  - Intensity, signal efficiencies, and control of the background are the important parameters!
- For resonant production one needs to meet the resonance condition

$$E_+ = \frac{m_V^2}{2m_e}$$

  - For masses in the tens of MeV, low energies are required …

$$E_{res}^{X17} \simeq 280 \text{ MeV}$$

Significant reduction only near beam energy



- For associated production: the smaller the better since $\sigma \propto \frac{log(s)}{s}$, as long as $E \gg E_{res}^{X17}$

.. but energy matters for decay lengths!

- Bremsstrahlung extracts most of the energy of the beam

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

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

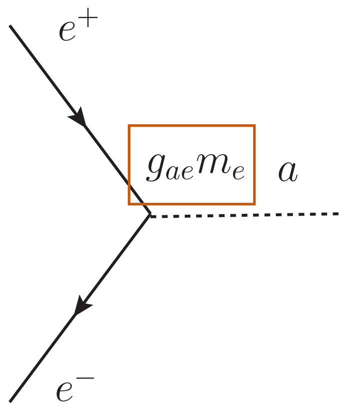
→ Make displaced signatures viable for higher energy experiments

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

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

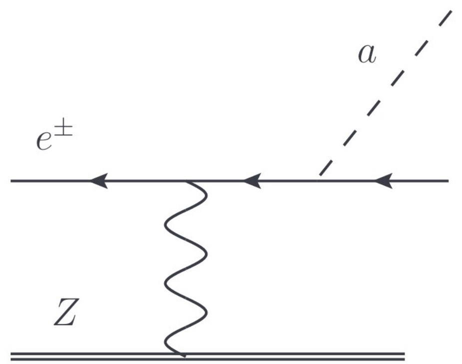
The case of resonant production



Going resonant …

- What are the trade-offs of going to resonant production ?

  → First, we need to find positrons somewhere (use a positron beam, rely on secondary positron production in a thick target, etc…). Typically, this implies a certain loss in energy + beam intensity

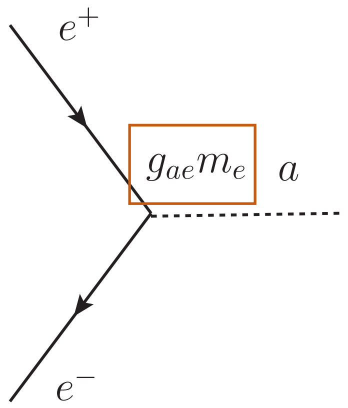


$$\sigma_{ae} \propto \alpha_{\rm em}^2 g_{ae}^2 \frac{m_e^2}{m_a^2}$$

Bremsstrahlung process

→Cross-section scales as Z^2

→ALP/DP carries away most of the beam energy: sensitivity up to $m_a \sim E_{e^+}$



Resonant process

→Cross-section x100-1000 times larger

→Fixed positron energy required

$$\sigma_{res} \sim \pi g_{ae}^2 m_e \delta(E_+ - E_{res})$$

However the gain in cross-section is enormous!

How to get to the exact energy ?

- Study models with large invisible width Γ_V^{inv} → not possible for the X17

- Vary the beam energy (+ radiative return) See e.g. 1802.04756

→ X17 has a narrow mass range, less than a MeV, only the narrow range [270 MeV, 290 MeV] needs to be probed

→ "Scanning" procedure is required (possible only with the DAΦNE beam at LNF currently?)

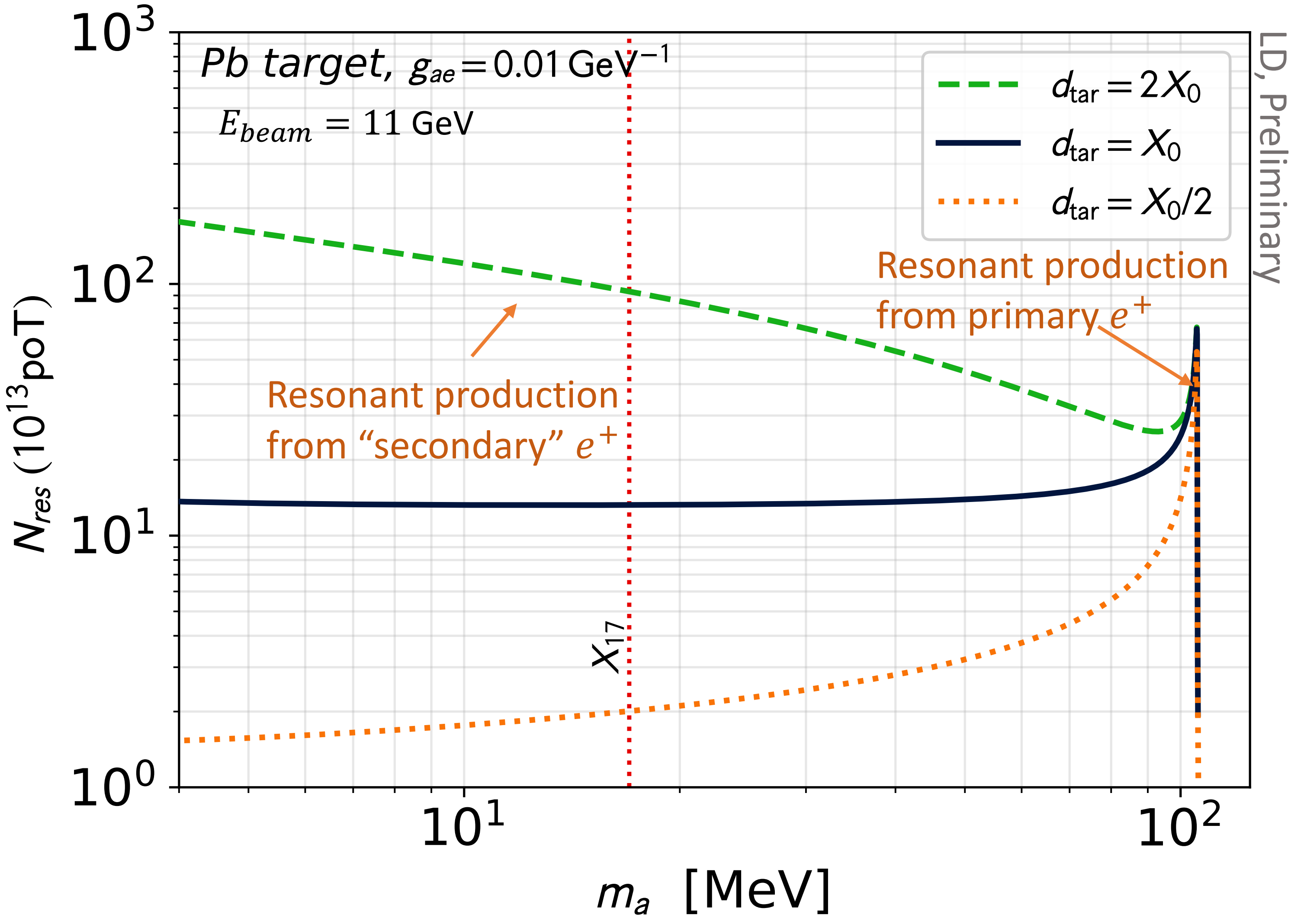
- Use energy loss and secondary e^+ production in the target to "scan" naturally various positron energies

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

See e.g. 1802.03794, 2105.04540

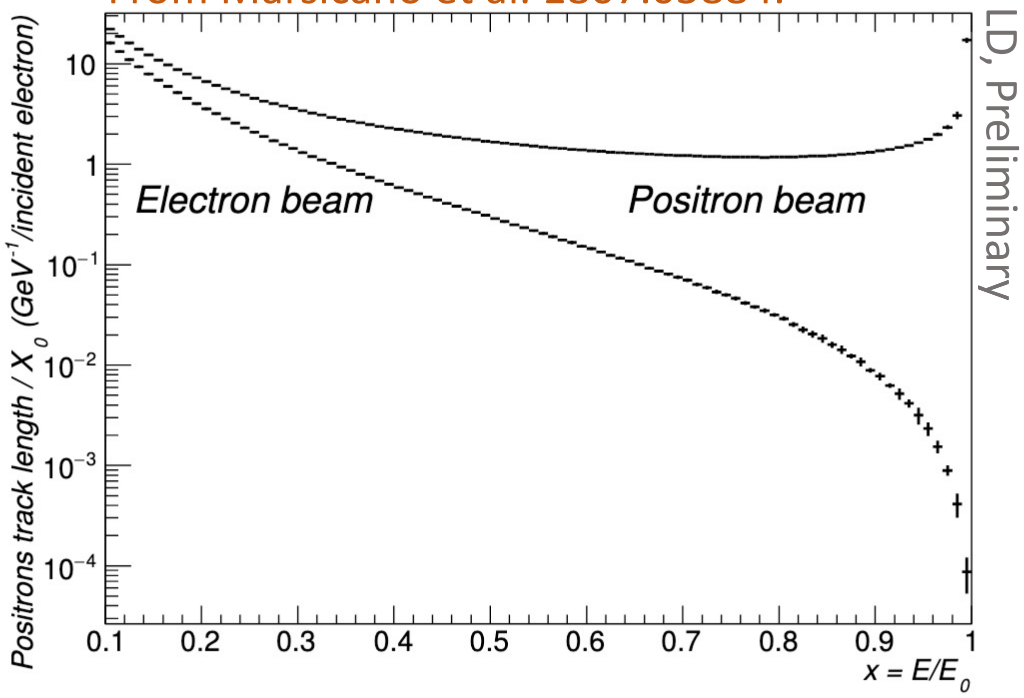
The thick target approach – positron beam

- Effective to probe a large range of masses
- Since the X17 decay visibly + no large boost → Relatively thin target required
- If the primary beam energy energy is significantly larger than $E_{X17,res}$ → marginal production gain of having a primary e^+ beam.



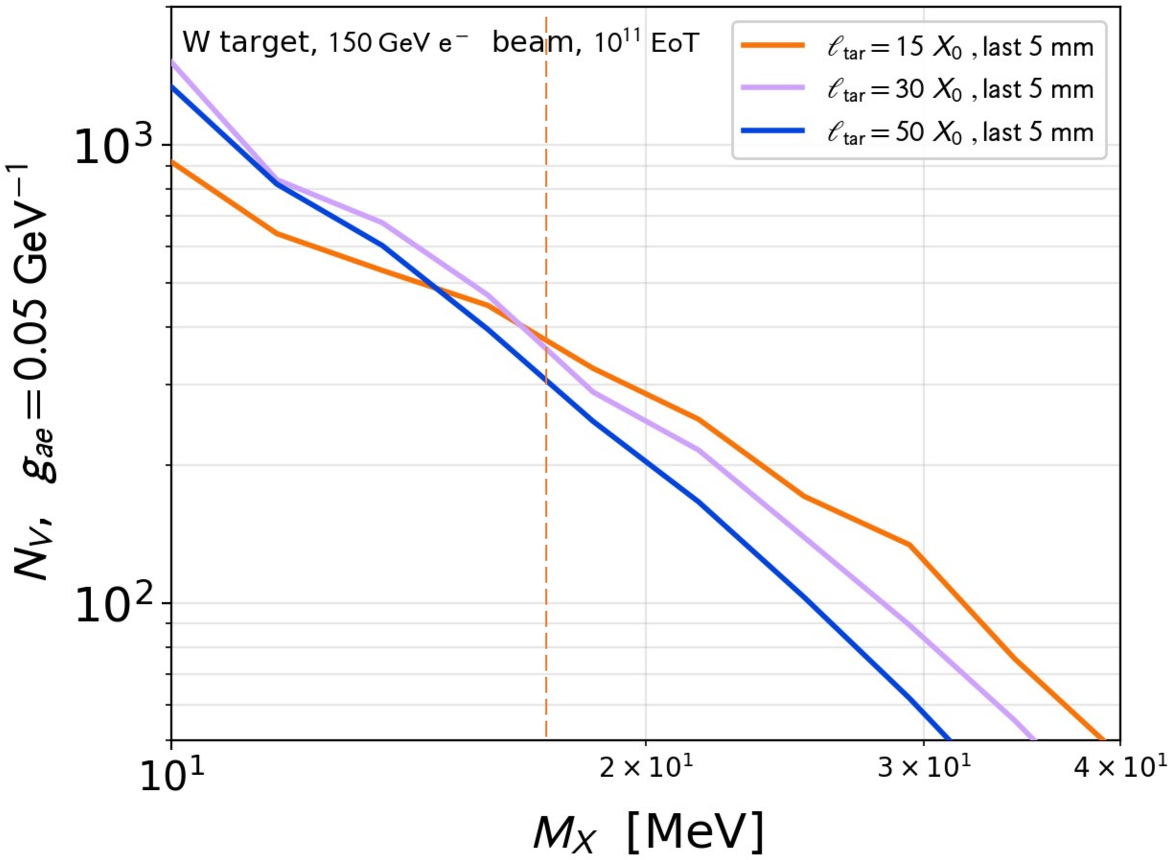
Secondary positron production

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

Resonant production: thin target

- In a thin target environment, the positron beam must be very near the resonant energy of $\sim 270 - 290$ MeV
  - The windows is directly related to the uncertainty in the X17 mass

  → Typical beam spread of 1 MeV or below imply that at least ten different energies should be probed
- Extremely large production rates are expected when near the resonance

$$N_V = N_{tot}\frac{N_{av}\rho_{Si}}{A_{Si}}\times Z_{Si}\times f(E_{res})\times\tilde{\sigma}\times L_{tar} \simeq 10\, g_{Ve}^2\, N_{tot}$$

$\frac{N_{av}\rho_{Si}}{A_{Si}}$: $7\cdot 10^{23} cm^{-3}$

$f(E_{res})$: $\sim {}^{1}/_{\sqrt{2\pi}\delta E} \sim 400\ GeV^{-1}$ (Gaussian distribution for the beam energy)

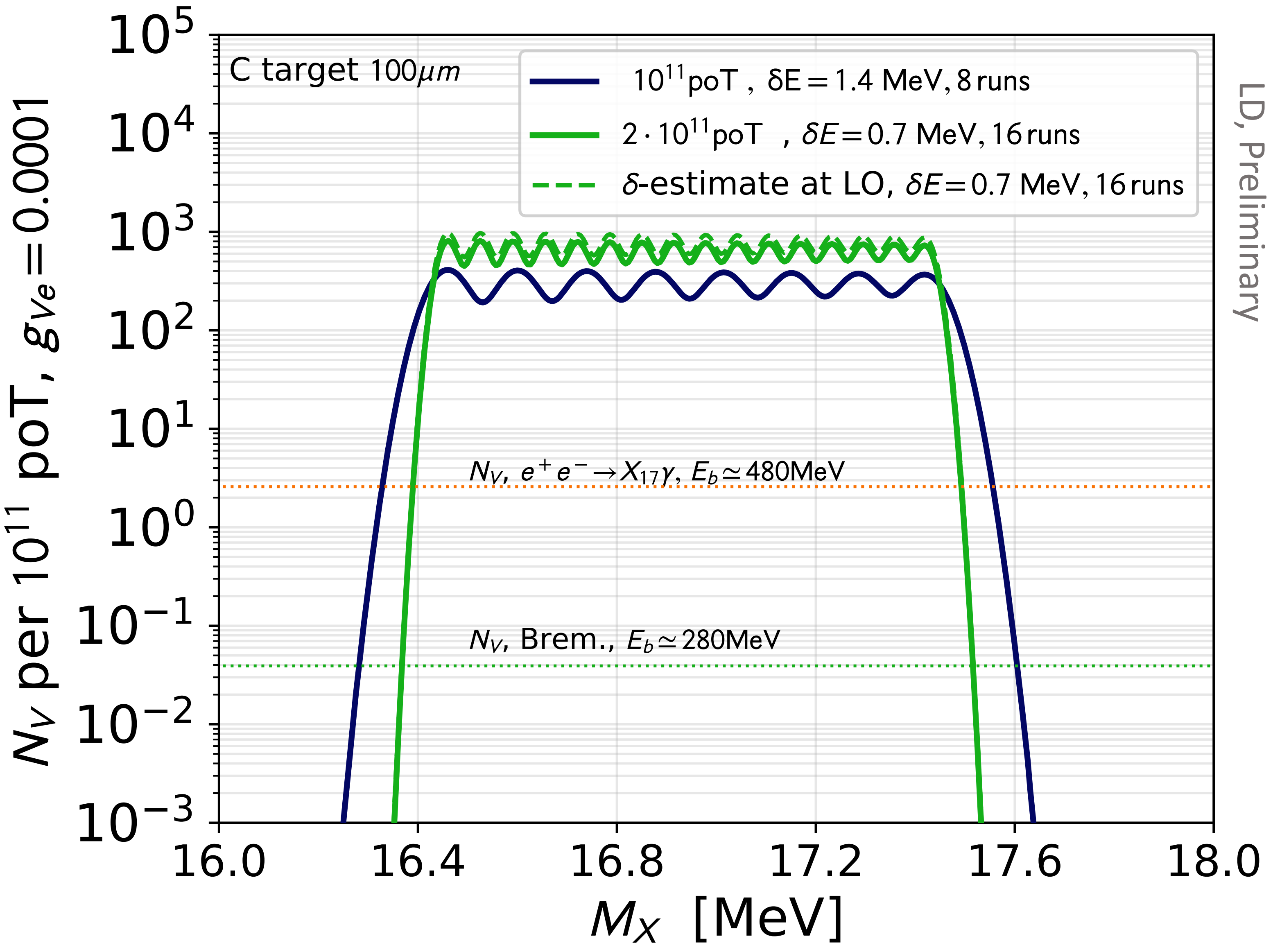
$\tilde{\sigma}$: $\sim 3000\ g_{Ve}^2\ GeV^{-1}$

L_{tar}: $\sim 0.03\ cm$

- When not on the resonance, the signal will disappear -> bump search

Scanning strategy

- Several runs depending on the beam spread
  → more precision on X17 mass means less beam time
  → Smaller spread implies lower background
  → 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



Conclusion

Conclusion

- X17's "light" mass means that there are many complementary ways of producing the X17
  - →can provide an independent cross-check to the nuclear decay results
- Electron/positron-based facilities provide a relatively model-independent way of testing the existence of this particle
- Resonant production mechanism can play an important role in producing the X17, using of the fact that its possible mass is precisely known.

Backup

X17, some technical details

$e^{\pm}Z, pZ$ → Mesons: $f_{\pi^0}, f_{\eta}, f_K, \ldots$ / EM processes: $T_{e^{\pm}}, T_{\gamma}$ →

e^+e^-, pp →

Flavoured mesons decay
$B \to K\, X, K \to \pi X, K \to inv$ or $D, B, J/\Psi \to \ell N$ etc …

Light mesons decay
$\pi^0, \eta \to \gamma\, X$ or $\pi^0 \to a$; $\pi^0, \eta \to \chi\chi$ etc …

EM-derived processes
$e^+e^- \to X\gamma, a\,\gamma$; $e\,N \to e\,N\,X$, etc …

→ Flavoured interactions

→ Vector portal, ALP portal

- Mesons decays estimations
  - No automatic tool available (new light states: not possible to apply standard WET-based tools)

  → Analytical calculation required. BR usually estimated by standard techniques (χPT, Vector Meson Dominance, …) For VMD, see e.g. Fujiwara et al. (1985)

→ Limit on rare BR, $B \to K, K \to \pi$, $\pi \to inv.$, etc…

- EM-derived processes
  - For collider experiments: standard MC tools can be used (MG5_aMC@NLO, Alwall et al. 2014 CalcHEP, etc…) Belyaev et al. 2012
  - For beam dump → must include the track-lengths information, nucleus form factors…

→ Limits on mono-photon search @ BaBar/NA64/LEP

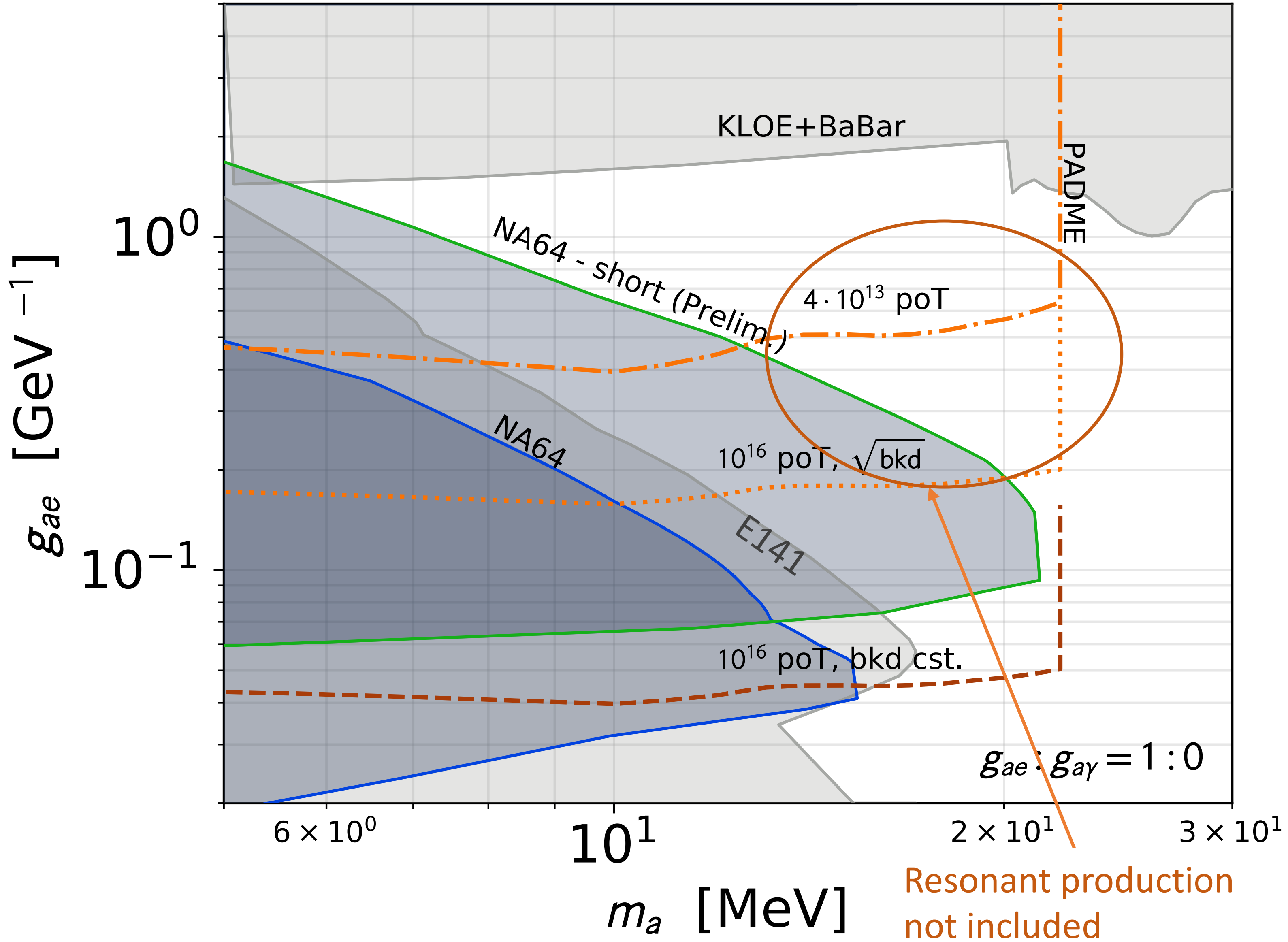
ALP visible decay at PADME

- No NA48 limits (as from $\pi^0 \to \gamma V$ decays)
- Larger available parameter space for X17 than in the vector case
- Good prospects also for PADME with :
  $e^+e^- \to a\,\gamma \to e^+e^-\,\gamma$

Assuming large luminosity increases

--> It is likely that the current dataset could improve on KLOE

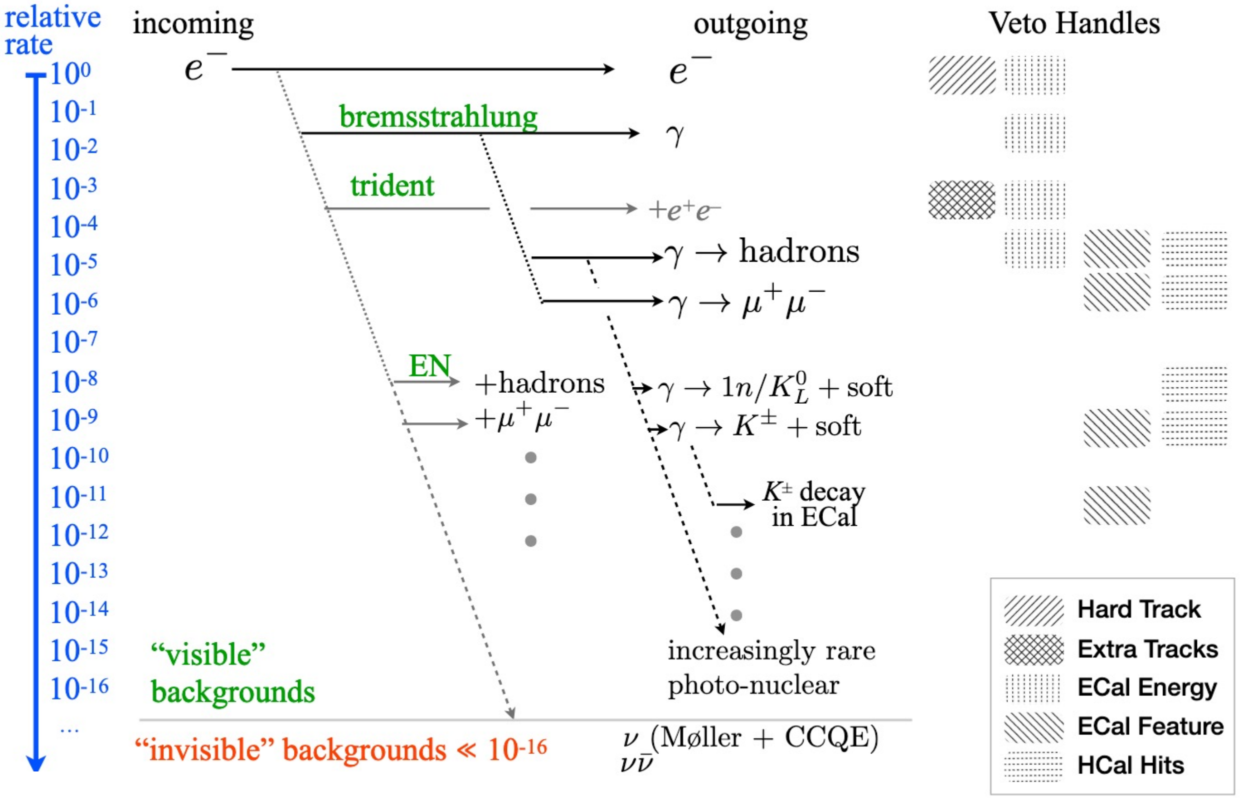
From 1710.03764 + NA64 recast of dark photon (naive → see true result 2104.13342)



Resonant production not included

Example of background processes, estimated by LDMX

LDMX collaboration 1808.05219



LDMX collaboration 1808.05219

	Photo-nuclear		Muon conversion	
	Target-area	**ECal**	**Target-area**	**ECal**
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track with $p < 1.2$ GeV	2×10^{7}	2.34×10^{8}	3.1×10^{4}	1.5×10^{8}
ECal BDT (> 0.99)	9.4×10^{5}	1.32×10^{5}	< 1	< 1
HCal max PE < 5	< 1	10	< 1	< 1
ECal MIP tracks = 0	< 1	< 1	< 1	< 1