Prospects for Dark Photons and ALPs with improved e^+/e^- beam

Luc Darmé

INFN – LNF

13/01/2021

Istituto Nazionale di Fisica Nucleare

Partially based on 2012.02245 with F. Giacchino, E. Nardi and M. Raggi

Outline

Introduction: FIPs physics

The PADME road: γX production

The missing momentum road: pure "X" production rates

Feebly-Interacting Particles

- FIPs= "new neutral particle which interact with the SM via suppressed new interactions"
- Appear in various NP models aiming at dark matter, neutrino masses, strong CP problem, flavour etc …

	SM operator		FIPs / dark sector	examples …
Scalar portal	$\lvert H\rvert^2 \quad (d=2)\,,$	$\longleftrightarrow$	$\lvert S\rvert^2$	Dark Higgs
Vector portal	$F_{\mu\nu} \quad (d=2)\,,$	$\longleftrightarrow$	$F'^{\mu\nu}$	Dark photon
Neutrino portal	$LH \quad (d=5/2)$	$\longleftrightarrow$	N	HNL
Axion portal	$\bar{f}_i\, \Gamma^\mu f_j \quad (d=3)$	$\nearrow$	$\partial_\mu a$	Axion/ALP
/ fermion portal		$\searrow$	$\Psi \Gamma_\mu \Psi$	Dark fermions

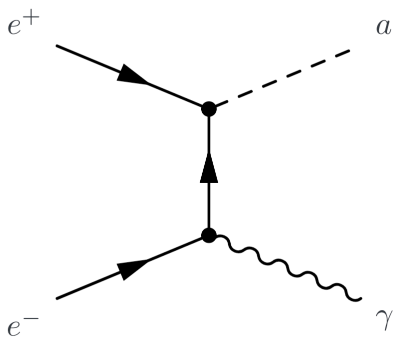
Can be produced with light SM fields, no need to high energy

Dark photon/ALP production

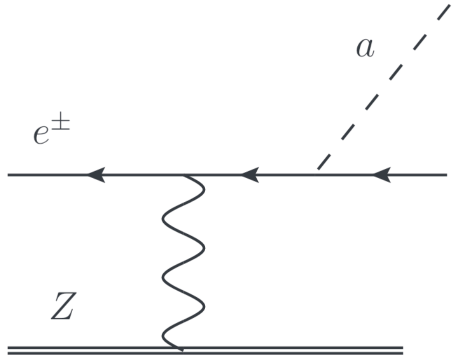
- FIPs are typically produced in a beam dump setups via either q or ℓ/γ coupling
  - Quark couplings

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

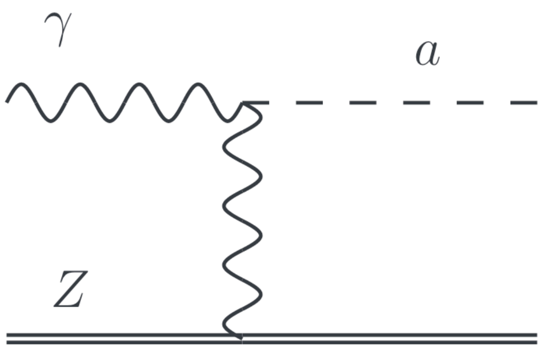
    →Light mesons process
    $\pi^0, \eta \to \gamma\, V$; $\rho, \omega \to V$ or $\pi^0 \to a$; $\pi^0, \eta \to \chi\chi$ etc …
  - Lepton/photon couplings lead to



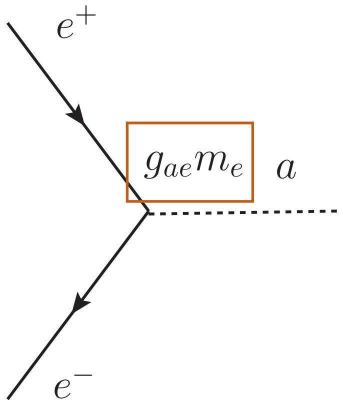
Associated



Bremsstrahlung



Primakoff (ALP)



Resonant

etc…

→ Depending on the models, very large range of possible mechanisms,

Light dark matter models

iDM
hep-ph/0101138, …

Secluded DM
0711.4866, …

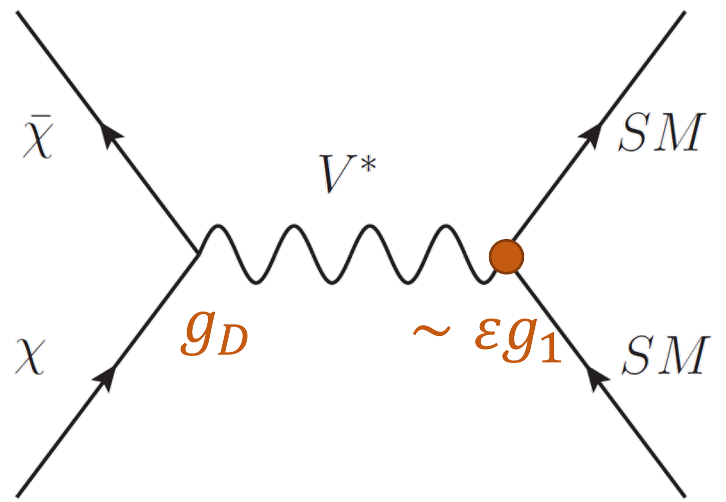
Semi-annihilating DM
1003.5912, …

…and many more recent

- Interest in FIPs also driven from strong theoretical developments toward building models of thermal sub-GeV DM

- Works typically with dark photon/vector portal
  - Relic density: sub-GeV particles requires $\varepsilon \sim 10^{-3}$ suppression

$$\Omega h^2 \sim 0.1 \times \left(\frac{10^{-3}}{\varepsilon}\right)^2 \left(\frac{0.1}{\alpha_D}\right)\left(\frac{25\ \mathrm{MeV}}{M_\chi}\right)^2 \left(\frac{M_V}{75\ \mathrm{MeV}}\right)^4$$



- Various way of avoiding CMB limits: e.g. use a pseudo-Dirac DM candidate χ_1, χ_2 with small mass splitting $\delta_{chi} = m_2 - m_1$

Following the PADME approach

using “$\gamma\ FIP$” production

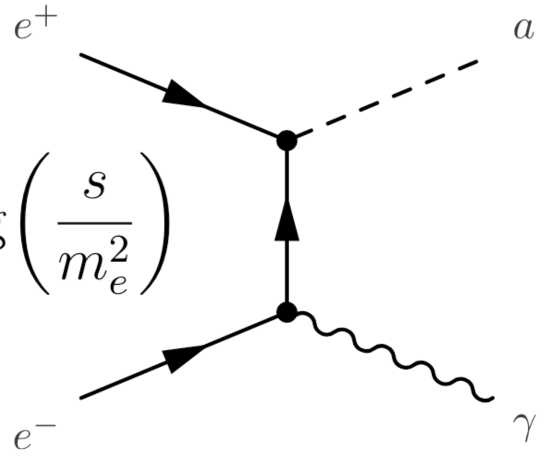
Mono-photon search at PADME

- PADME relies on associated production

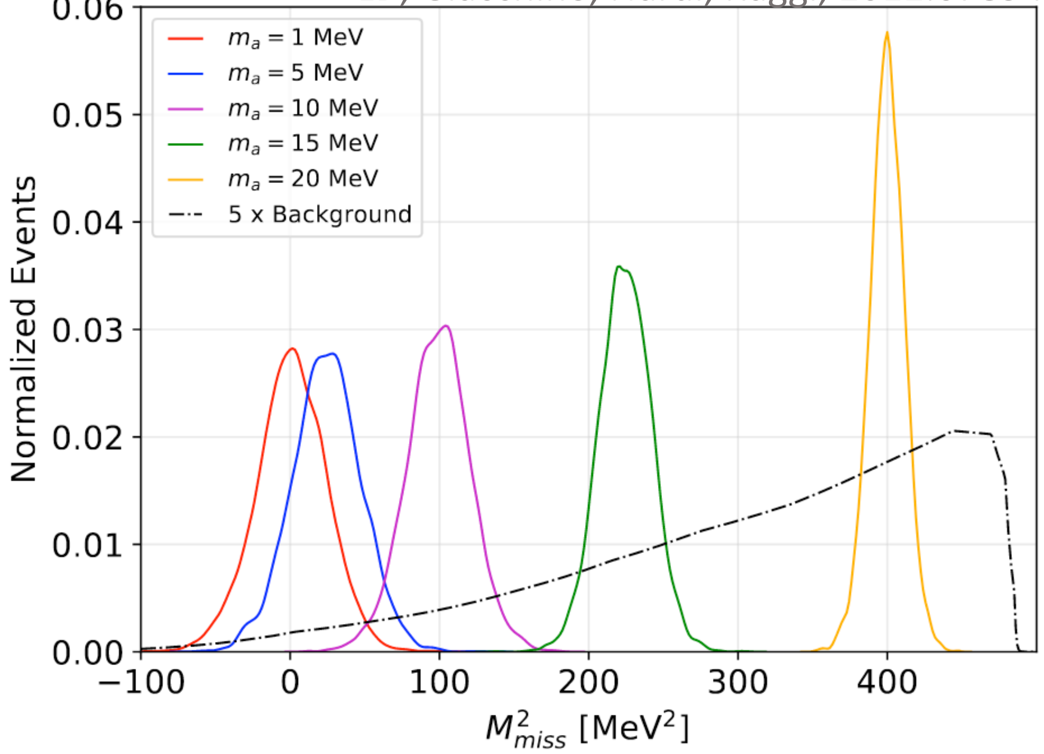
→Use photon four-momentum to track missing mass

→ Potentially including visible ALP decay

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



LD, Giacchino, Nardi, Raggi, 2012.07894



- In missing mass mode: “bump search” so limit on signal event scales as

$$N_{lim} \sim g_{ae}^2 \sim \sqrt{bkd}$$

  - The current projected limit is background-dominated

  →$\sim$ 40k events at $4 \cdot 10^{13}$ poT

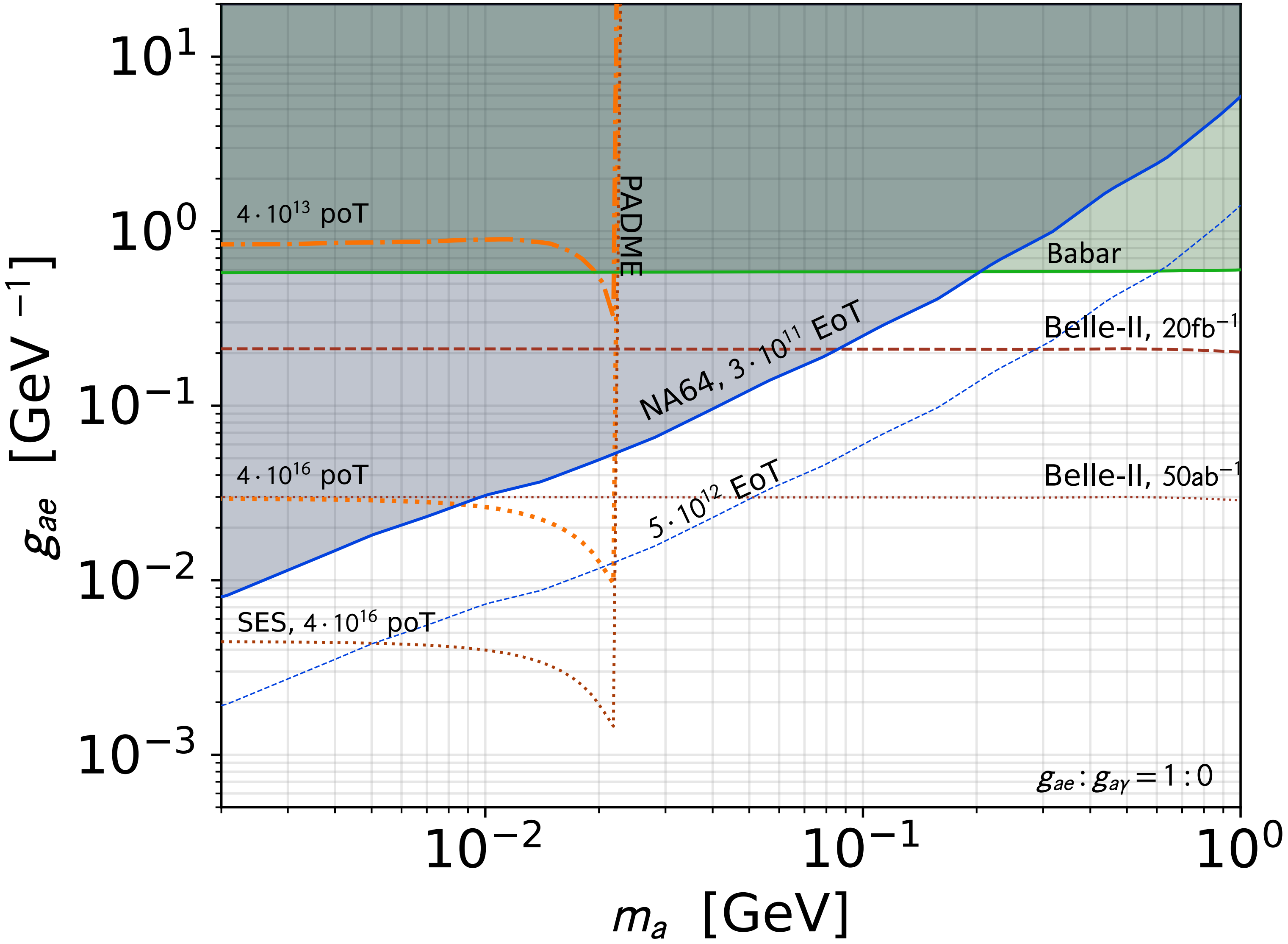
  →$\sim$ 10M events at 10^{16} poT

- Any reduction of the background will be useful

Invisible ALP search at PADME

- PADME typically probes the electron coupling, focus on electrophilic ALPs
- NA64, $5 \cdot 10^{12}$ EoT (limit for constant background) should be reached around 2024
  - Another order of magnitude at LDMX → ~10 years horizon
- Prospect for $\sim$2 year runs with POSEYDON machine
  - With 100 signal events (equiv. current requirements at PADME) and 2.3 (Single Event Sensitivity)

PADME projection from 2012.07894



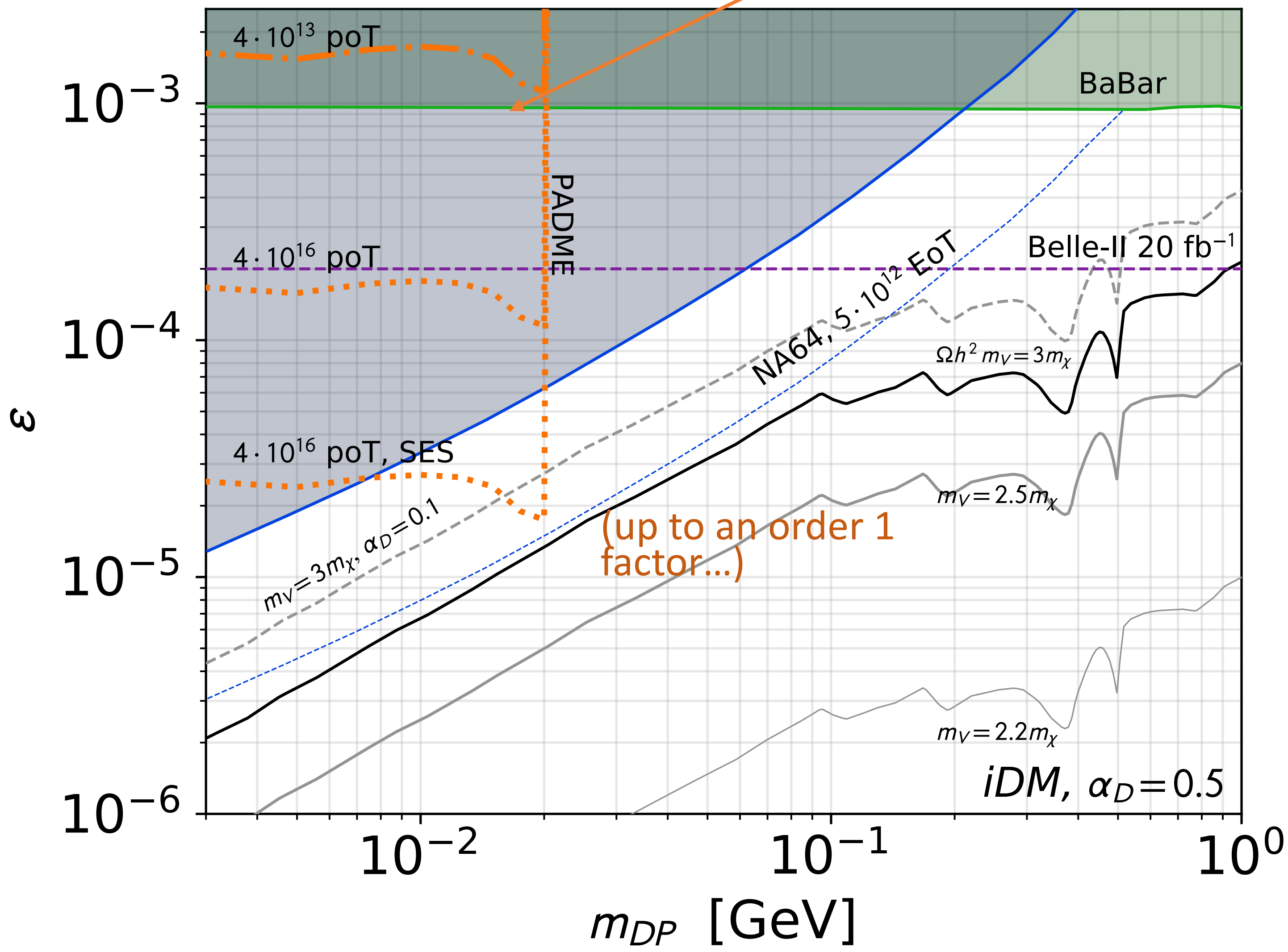
Invisible DP search at PADME

Projection extracted from 1501.01867:
Conservative estimate…

- ALP and DP production (mostly) similar

$$g_{ae} m_e \longleftrightarrow \sqrt{4\pi\alpha}\ \varepsilon$$

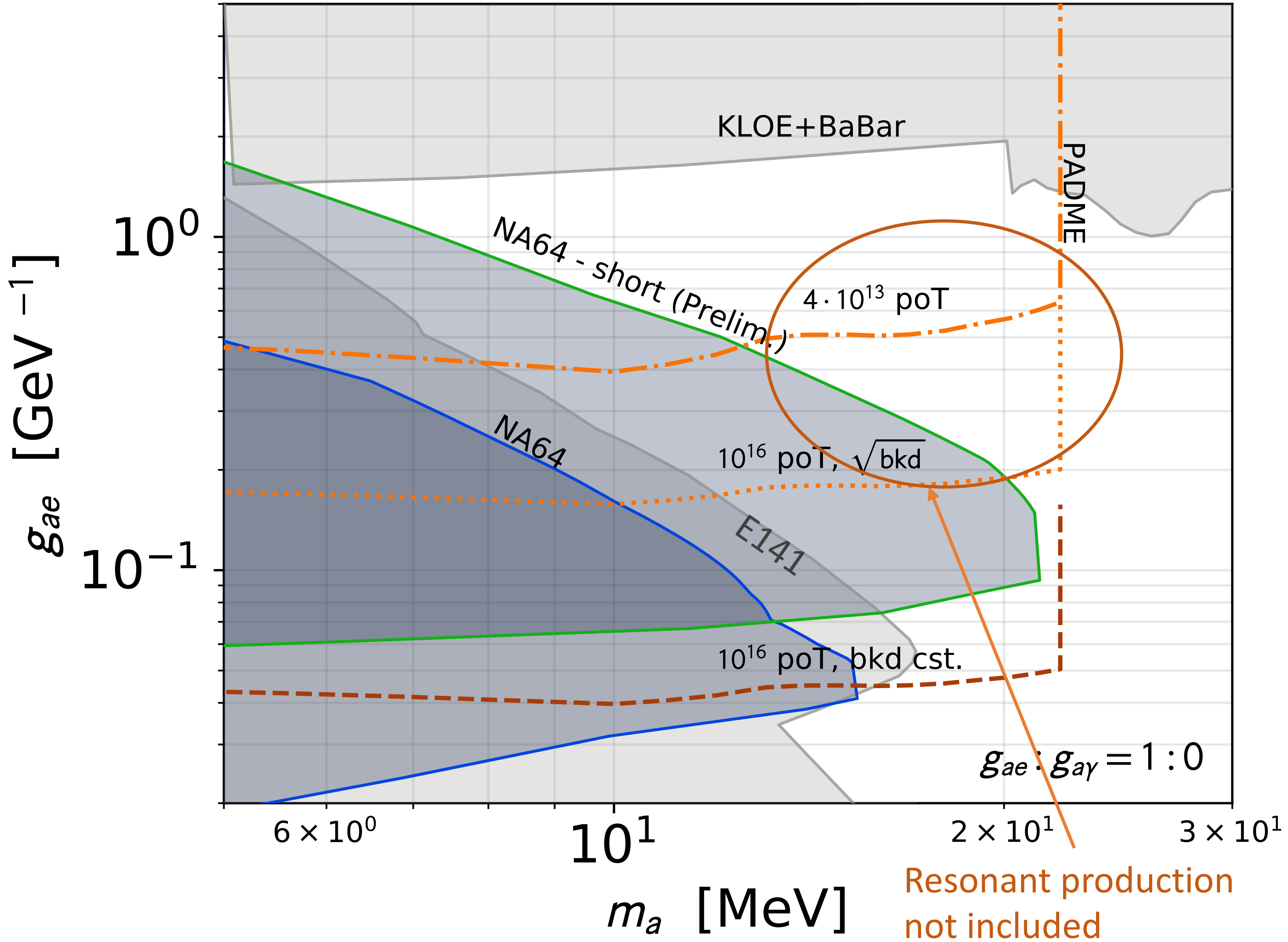
- Relic density lines are function of model parameters
  → Showing the worst case scenario
  iDM, with tiny splitting and large α_D
  → Part of parameter space still out of reach



ALP visible decay at PADME

- PADME relies on: $e^+e^- \to a\,\gamma \to e^+e^-\,\gamma$
- No NA48 limits (as from $\pi^0 \to \gamma V$ decays)
- Two different NA64 analysis
  - Include recast of which focused on X17 boson
- Excellent prospects for PADME

From 1710.03764 + NA64 recast

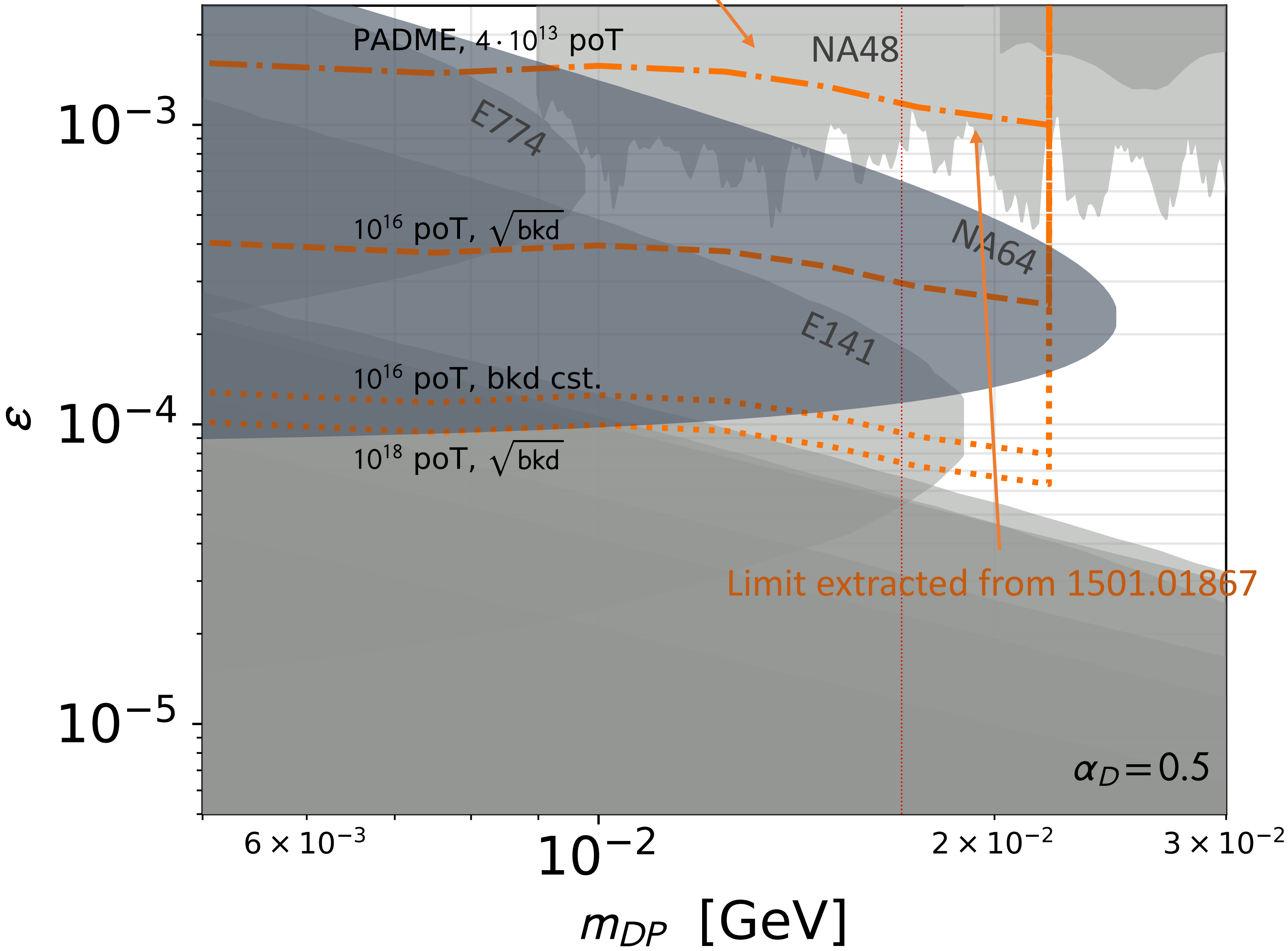


Resonant production not included

DP visible decay at PADME

- Limits from NA48 vanishes for a leptophilic dark photon …
- Recent NA64 limits for X17 boson.
  - Uses a different analysis, 1912.11389, than the ”main” NA64 experiment, based on a purely beam dump setup.
  - Use a 17cm tungsten calorimeter as target

No NA48 for leptophilic dark photon

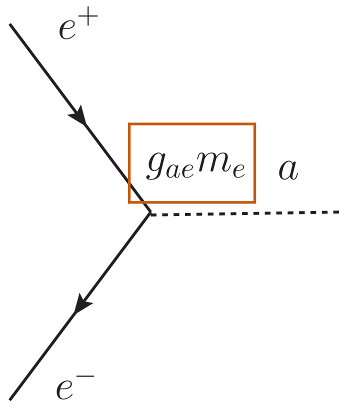


Limit extracted from 1501.01867

Beyond associated production

Using pure "FIP" channels

Pure dark photon/ALP   production

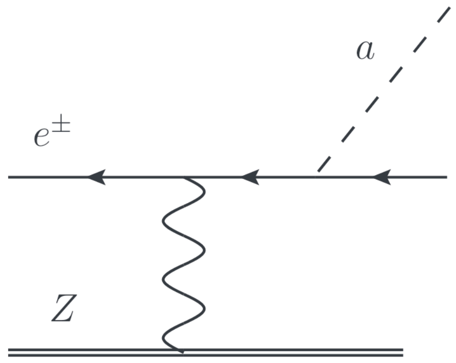


Resonant process

→Cross-section x1000 times larger than associated $e^+e^- \to V\gamma$

→Fixed positron energy required

$$\sigma_{\rm res} = \frac{2\pi^2\varepsilon^2\alpha_{\rm em}}{m_e}\delta(E_+ - \frac{m_V^2}{2m_e}) \,.$$



Bremsstrahlung process

→Cross-section scales as Z^2

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

$$\sigma \approx \frac{4}{3}\frac{\alpha_{\rm em}^3\epsilon^2\mathcal{F}\beta_V}{m_V^2}\log\left(\frac{1}{(1-x)_c}\right)$$

- But no photon “signal”… instead we can
  - Tag some initial radiation from the e^+
  - Look for a missing positron/missing momentum…

→ For resonant production, the missing energy is completely fixed, with a narrow peak at

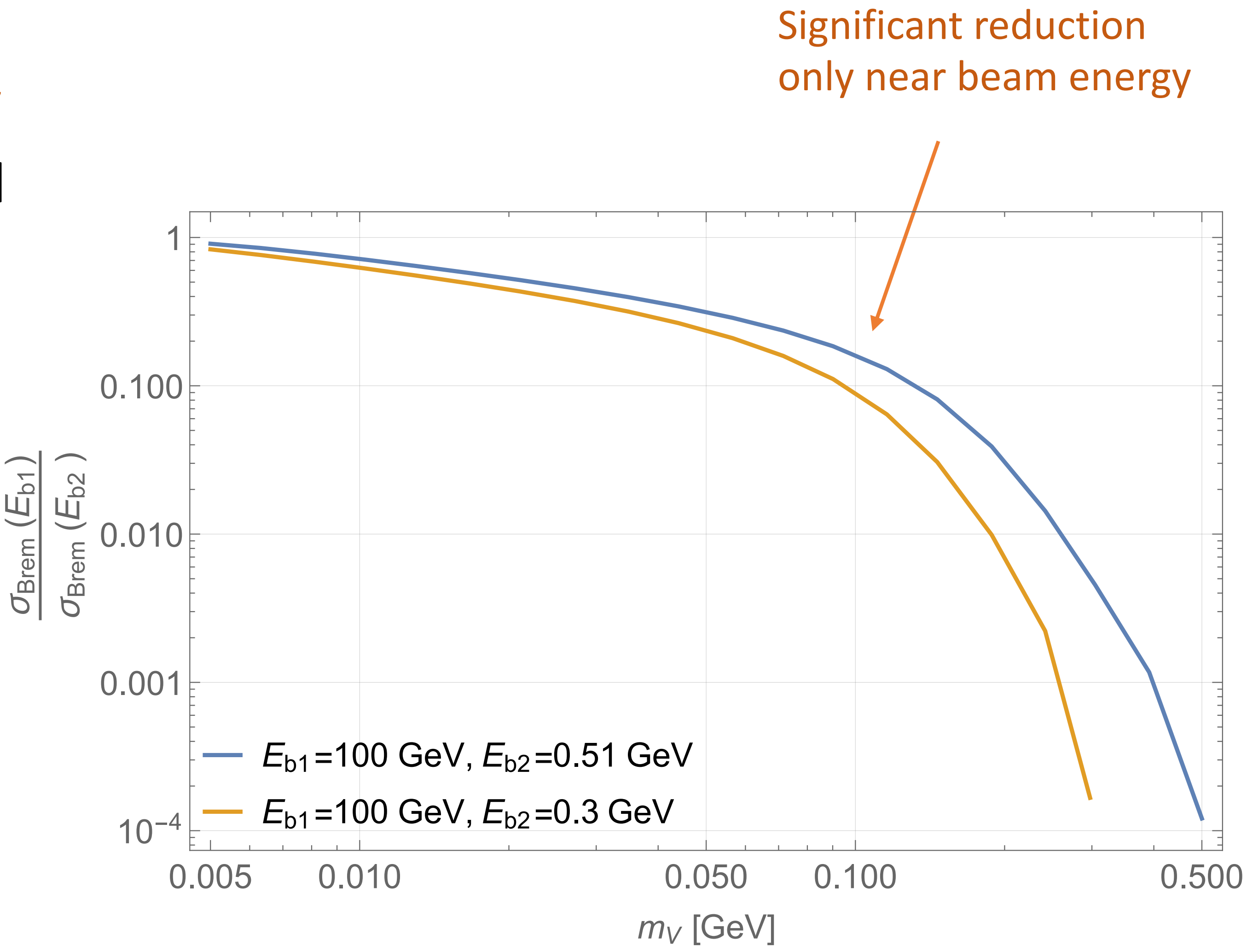
$$E_V^{\rm res} = \frac{m_V^2}{2m_e}$$

Beam energy does not really matter…

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

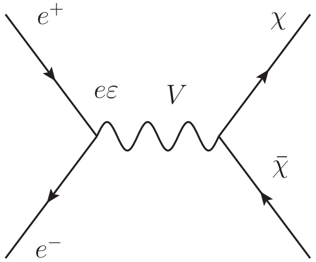
$$E_+ = \frac{m_V^2}{2m_e}$$

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



Resonant production and production rates

- How to get to the exact energy?
  - Study models with large invisible width Γ_V^{inv} → typical for dark photon with light dark matter



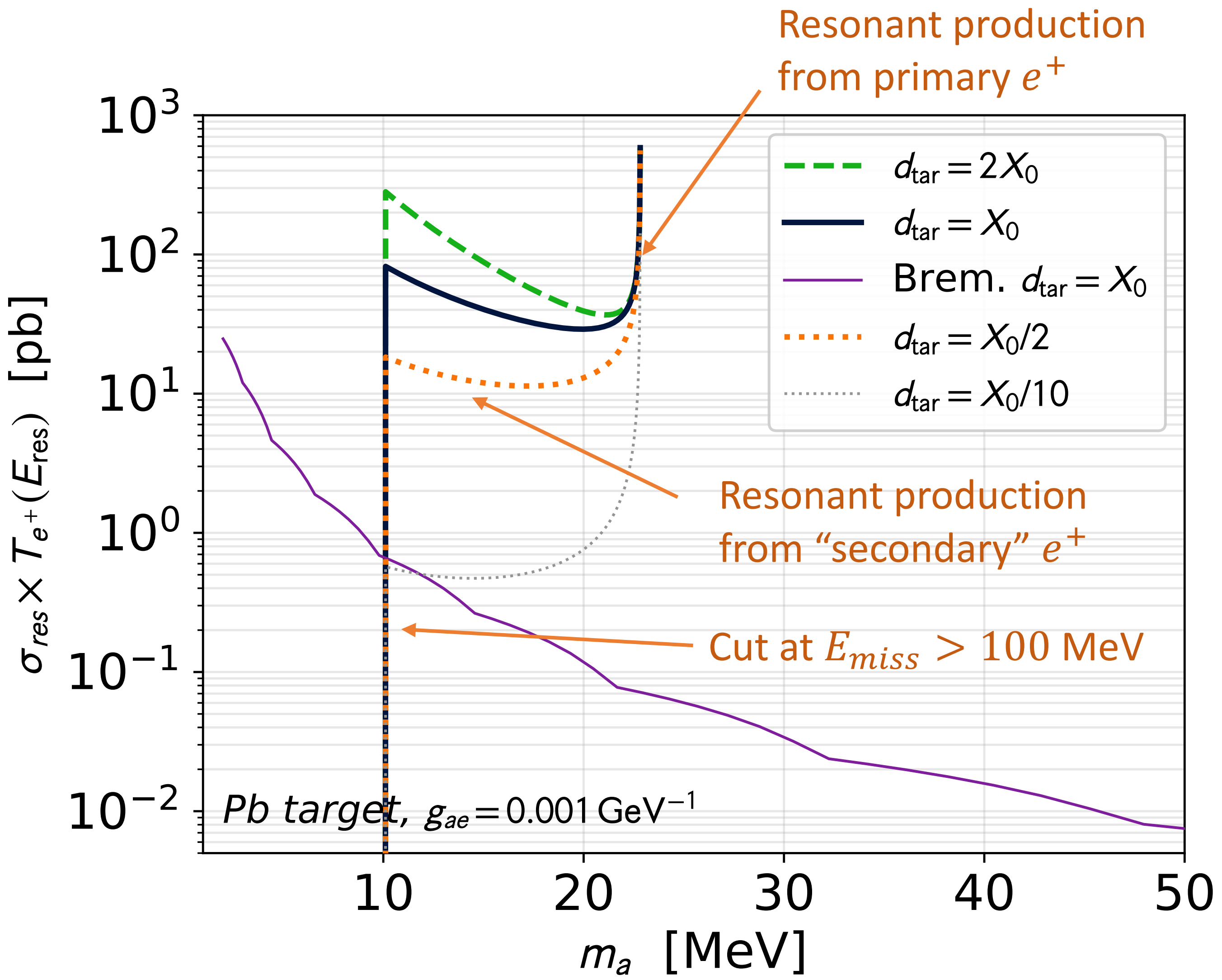
- Vary the beam energy (+ extra factor, e.g. atomic electron velocity)

  See e.g. 1802.04756

- Use energy loss in the target to "scan" naturally various positron energy

  See e.g. 1802.03794

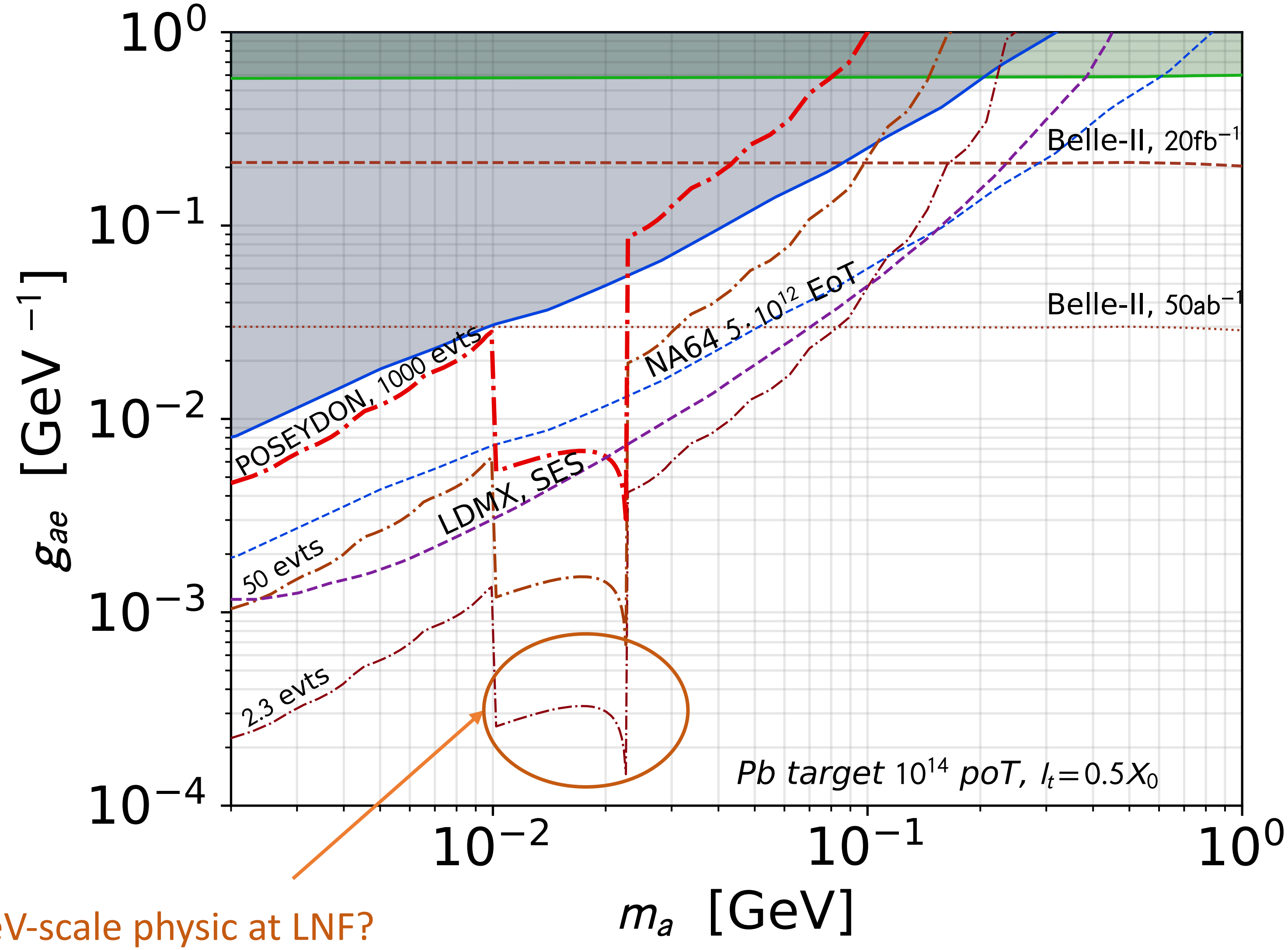
- Just rely on Bremsstrahlung → no resonance …



Missing momentum production rates

- Production only, high-Z target, around $0.5X_0$ (just as an example)
- Show the 2.3, 50 and 1000 events lines
  - NOT projective limits…
  - Assume 10^{14} positrons on target
  - Work in “single positron” on target mode
- Weak dependence of the beam energy

  → Changing the energy will move the resonant peak

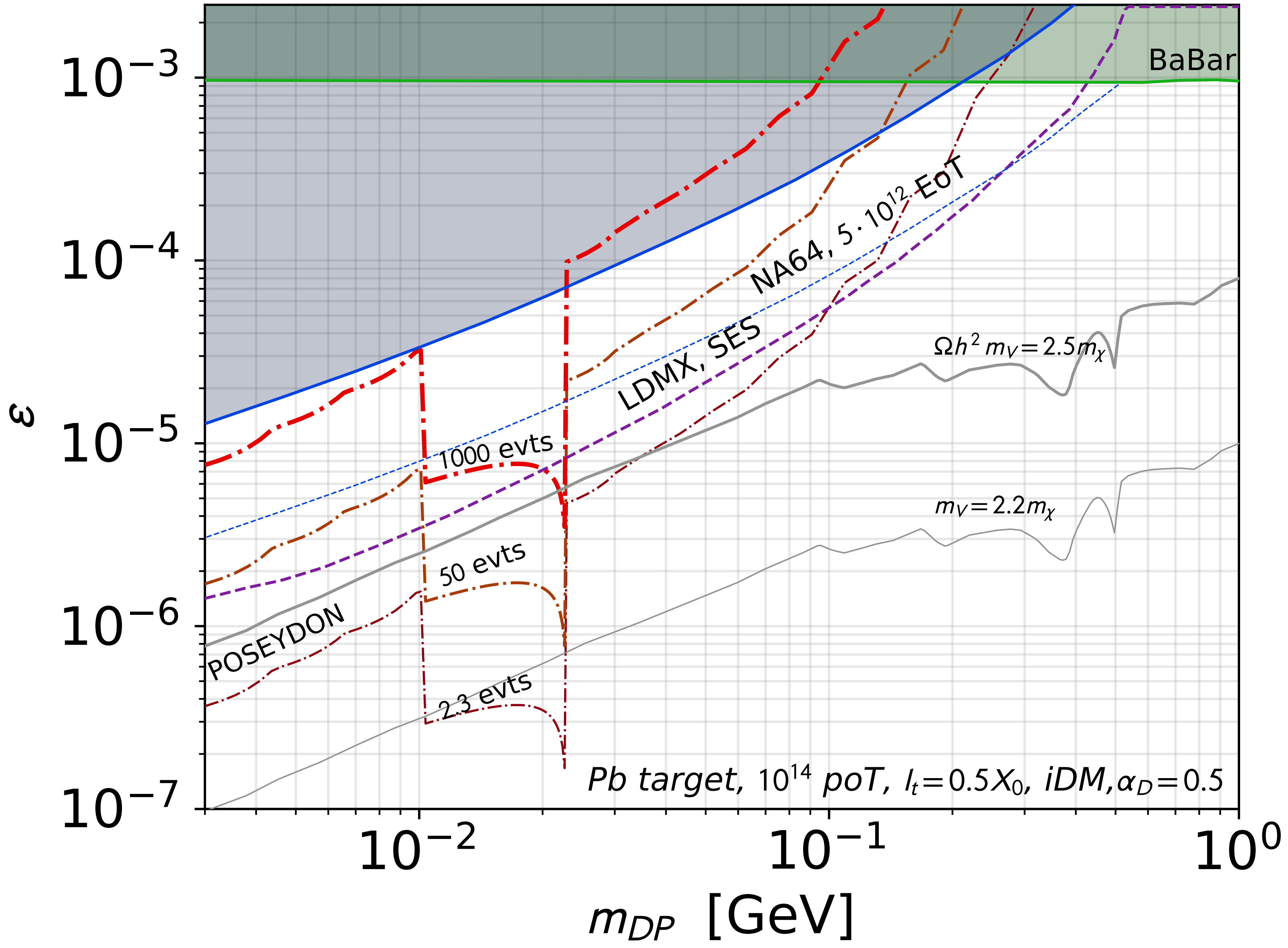


TeV-scale physic at LNF?

Dark photon search at PADME in missing mass

- Extremely large production rates expected in the DM-relevant region
- 17 MeV resonance in the resonant region…

→ Of course visible search strategies still viable



Conclusions

- Prospects for PADME with/without POSEYDON
  - In the short run: visible searches for leptophilic ALP/dark photon
  - For $X\gamma$ strategy to be competitive, $\sim 10^{16}$ positrons with POSEYDON, background reduction is critical

- Going to a missing energy/momentum (pure "X") with not so thin target dramatically help production rates.
  - Many production mode available (resonant, brem)
  - Visible searches with displaced vertices could still be available (e.g. dark Higgs + dark photon search, etc…)

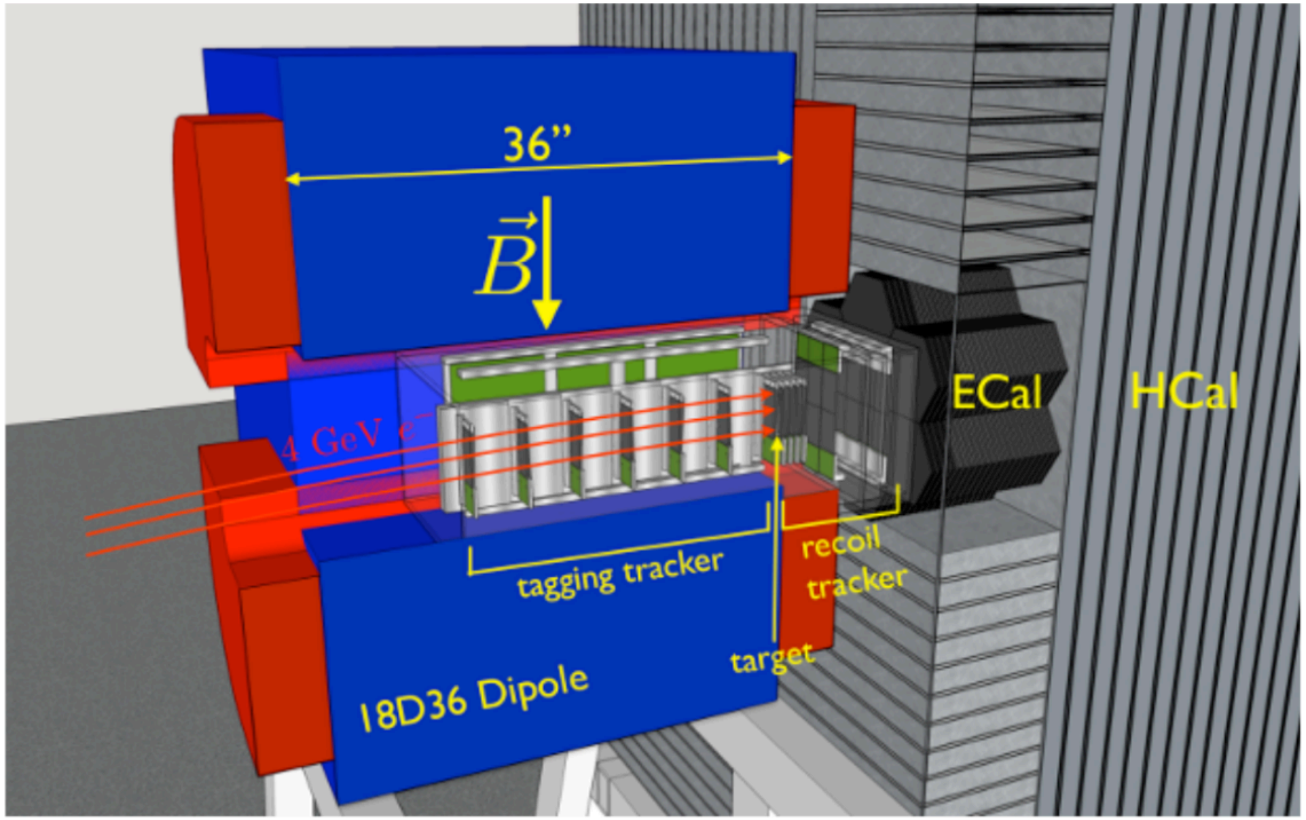
- Beam energy does not matter for the production rates

→ a 500 MeV machine is as viable as a 100 GeV one in terms of FIP production

Backup slides

LDMX proposal

- Target is $0.1X_0$ tungsten
- Designed for single events sensitivity



LDMX background

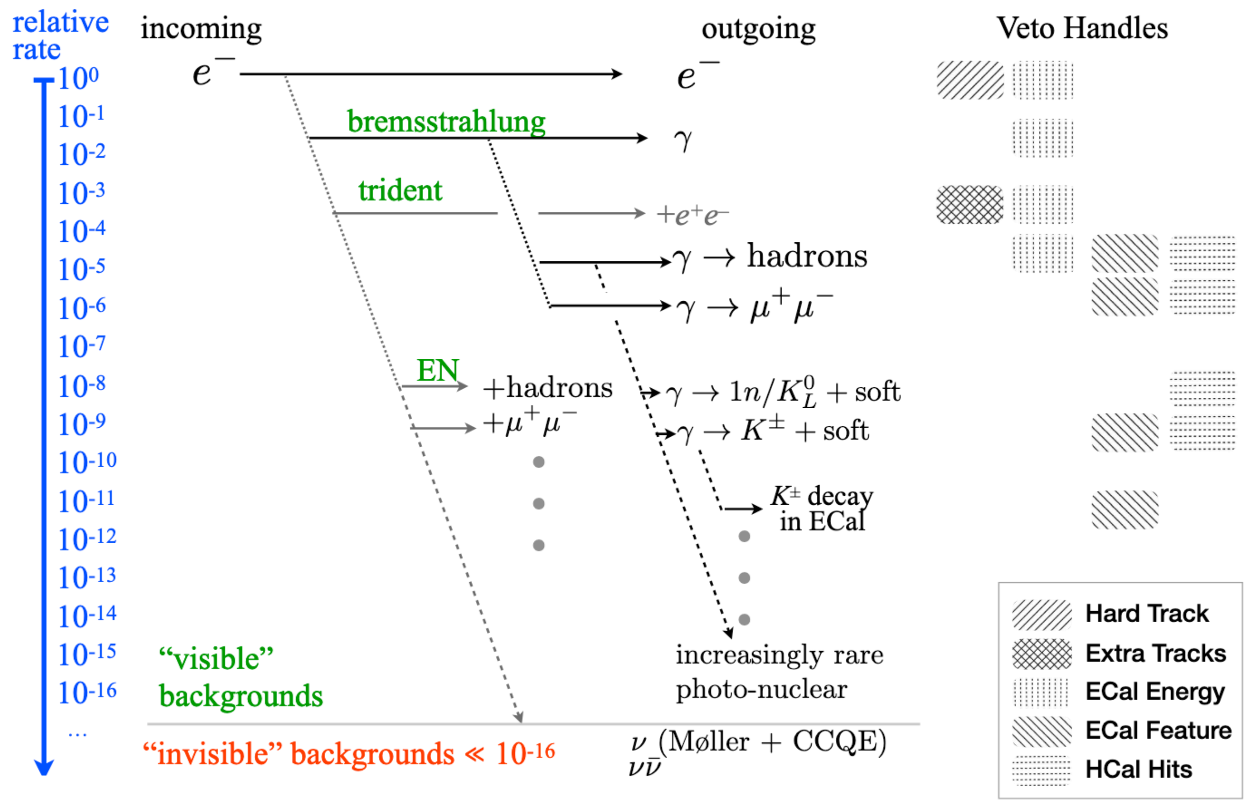
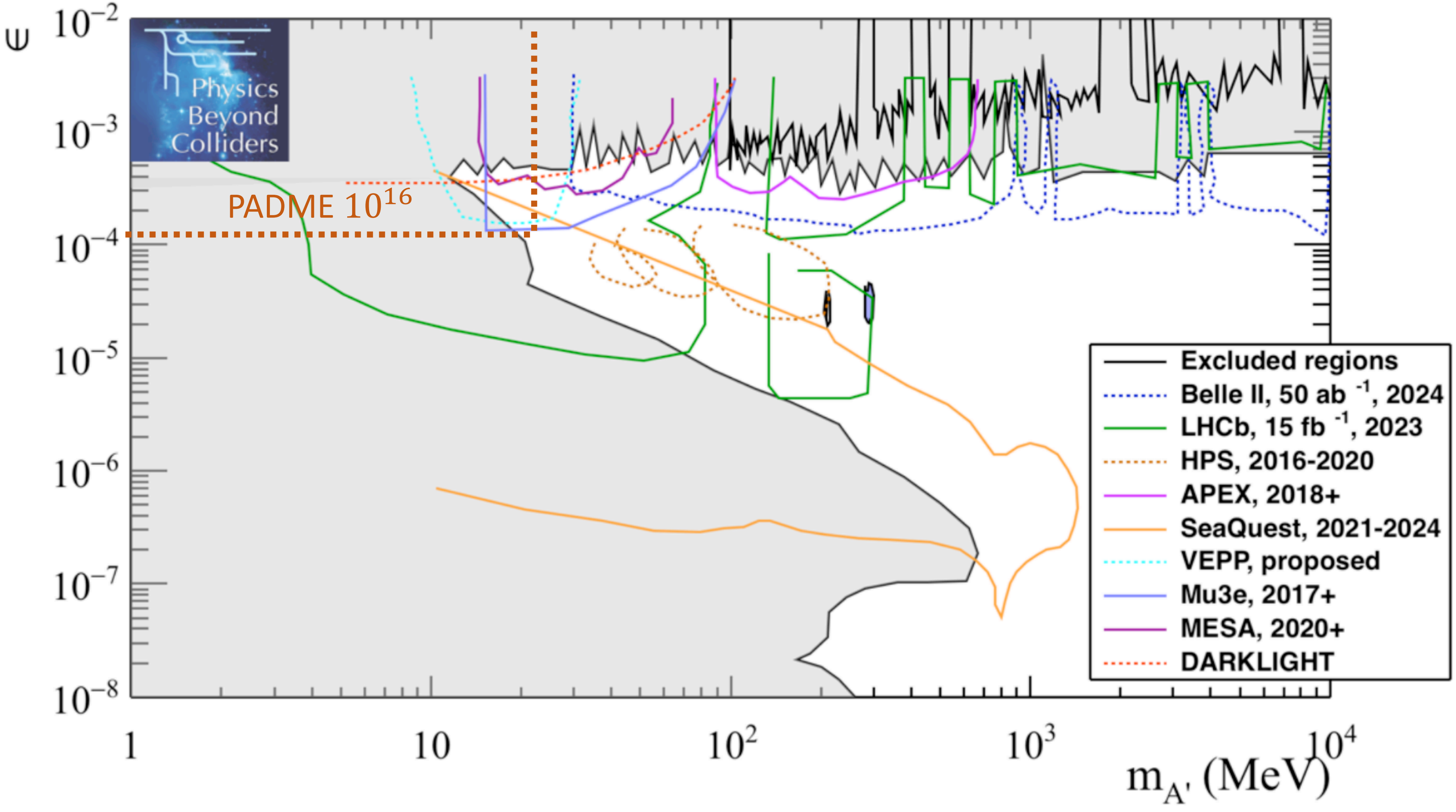


	Photo-nuclear		Muon conversion	
	Target-area	**ECal**	**Target-area**	**ECal**
EoT equivalent	4×10^{14}	2.1×10^{14}	8.2×10^{14}	2.4×10^{15}
Total events simulated	8.8×10^{11}	4.65×10^{11}	6.27×10^{8}	8×10^{10}
Trigger, ECal total energy < 1.5 GeV	1×10^{8}	2.63×10^{8}	1.6×10^{7}	1.6×10^{8}
Single track 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

The big picture, dark photon visible



Anomalous magnetic moment

- Controversy concerning the values for $(g-2)_e$

$$\Delta a_e \equiv a_e^{\mathrm{SM}} - a_e = +(4.8 \pm 3.0) \cdot 10^{-13}$$
$$(\mathrm{LKB}-2020)$$

$$\Delta a_e \equiv a_e^{\mathrm{SM}} - a_e = -(8.7 \pm 3.6) \cdot 10^{-13}$$
$$(\mathrm{Berkeley\text{-}2018})$$

- In any case, observables with very strong dependence on UV physics …