Hunting Dark Matter at Accelerators

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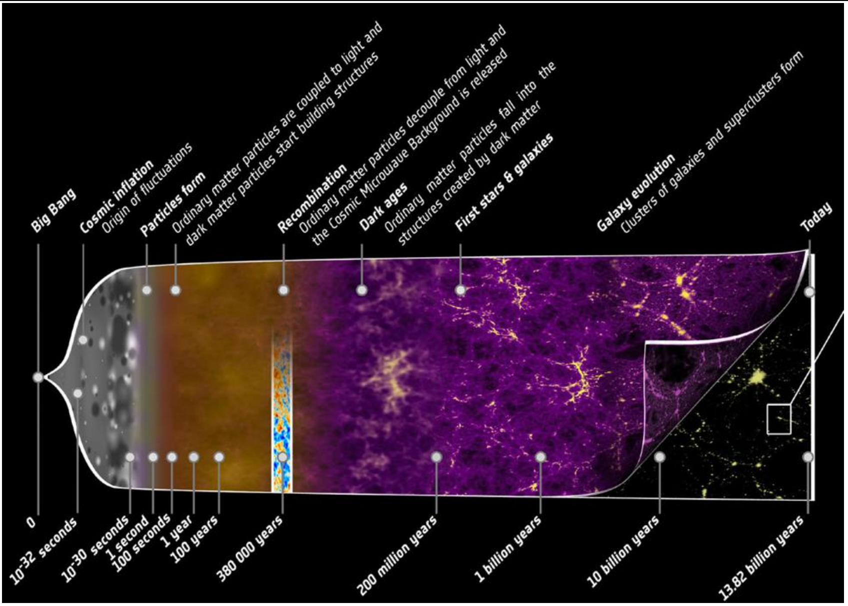
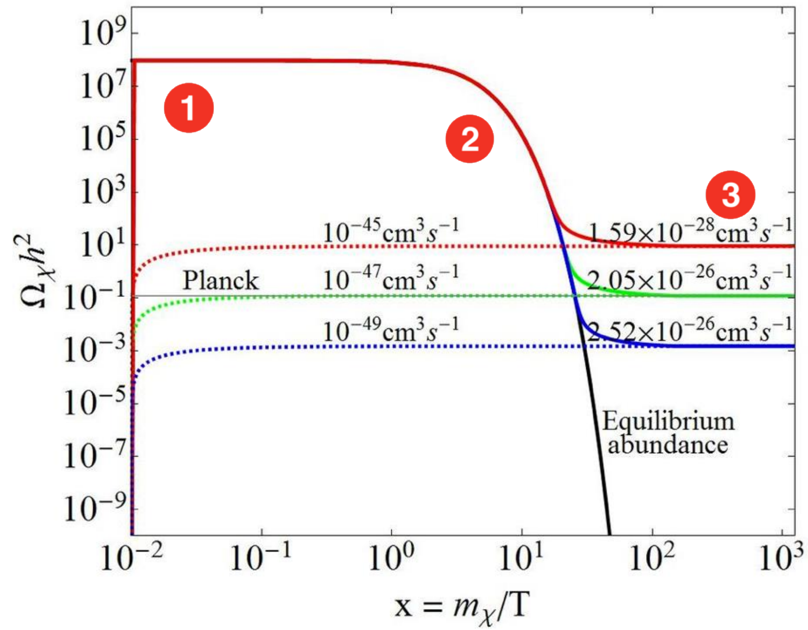
Universe and the dark matter

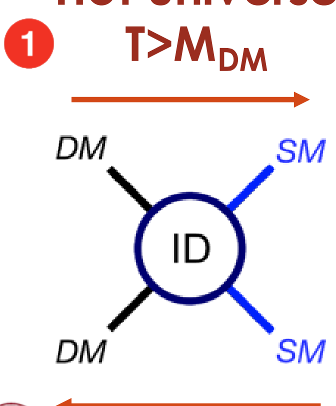


DM freezeout mechanism

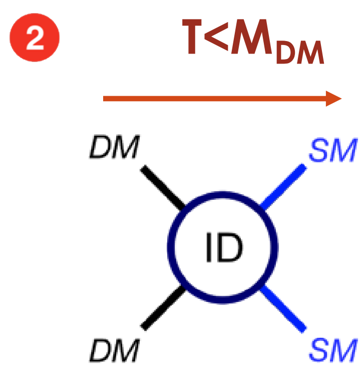


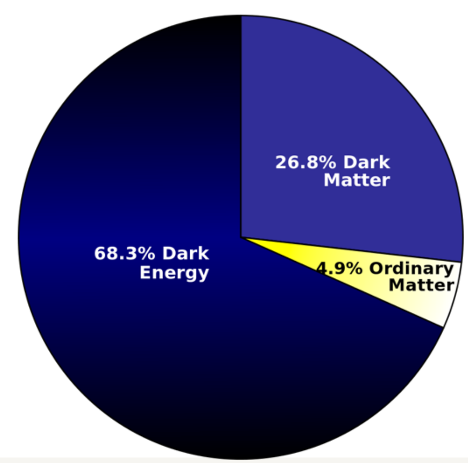
Thermal dark matter production

Hot universe
$T>M_{DM}$



Cold universe
$T<M_{DM}$





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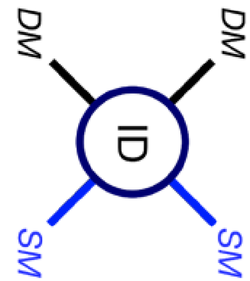
The wimp miracle

The relic density is set by the **annihilation cross-section:**

$$\Omega_{DM} h^2 \sim \frac{3 \cdot 10^{-27} cm^3 s^{-1}}{\langle \sigma v \rangle}$$



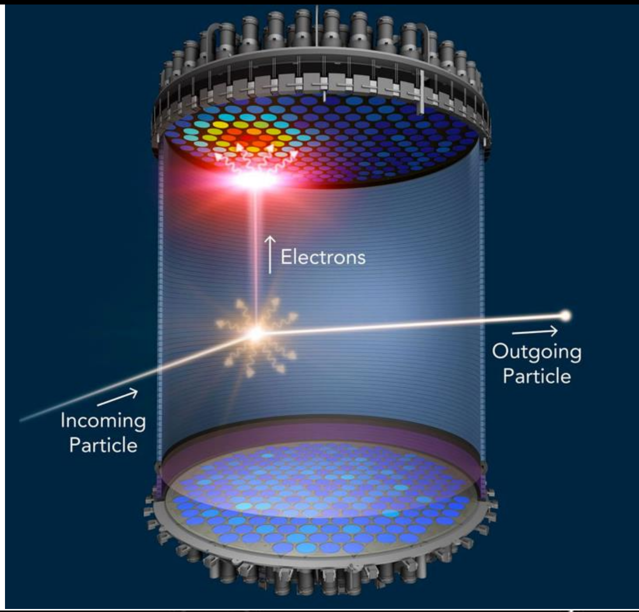
From CMB we can fit the relic density value

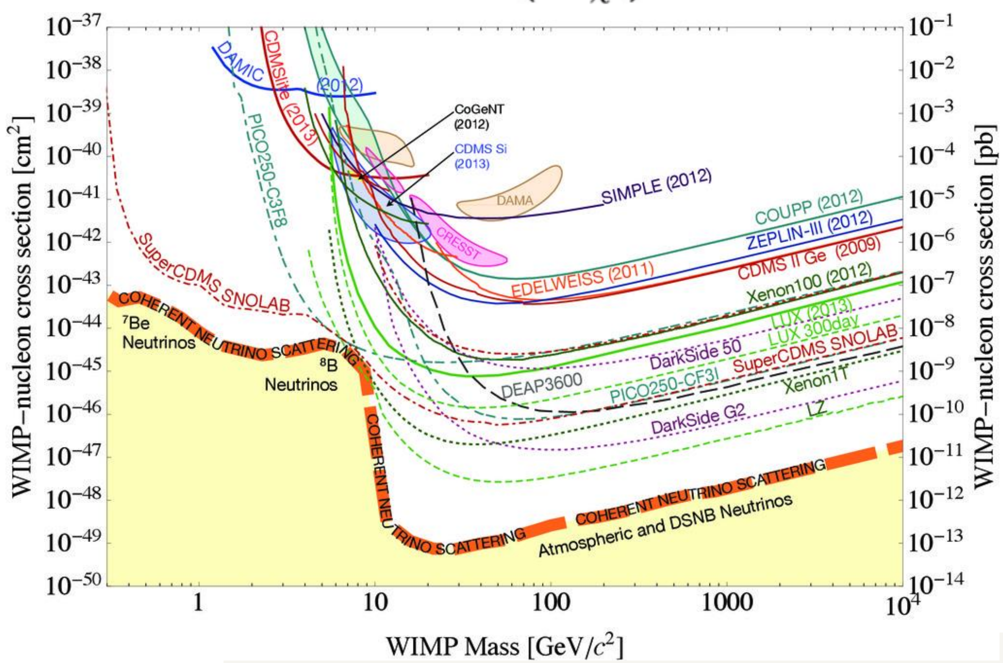
$\Omega_{DM} h^2 \simeq 0.1$, hence:

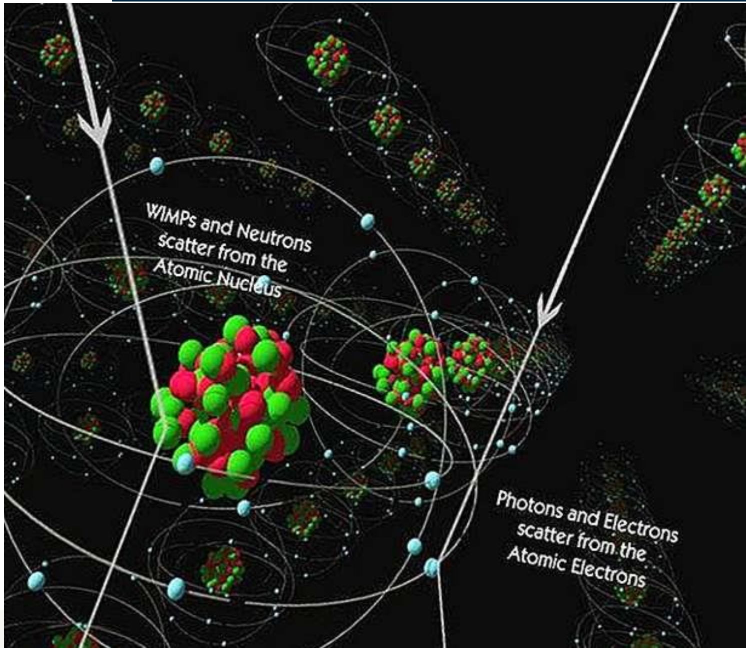
$\langle \sigma v \rangle \simeq 3 \cdot 10^{-26} cm^3 s^{-1}$

corresponding to weakly coupled GeV TeV mass particle:

$$\langle \sigma v \rangle_{\rm WIMP} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1} \left(\frac{\rm TeV}{m_\chi} \right)^2$$

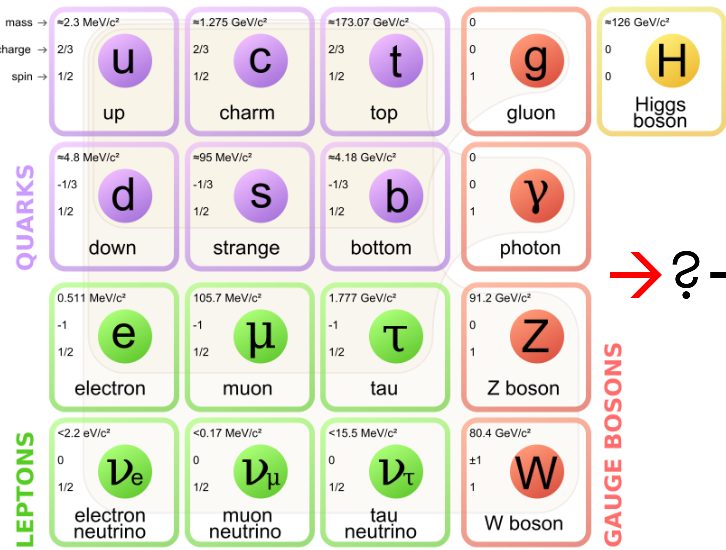


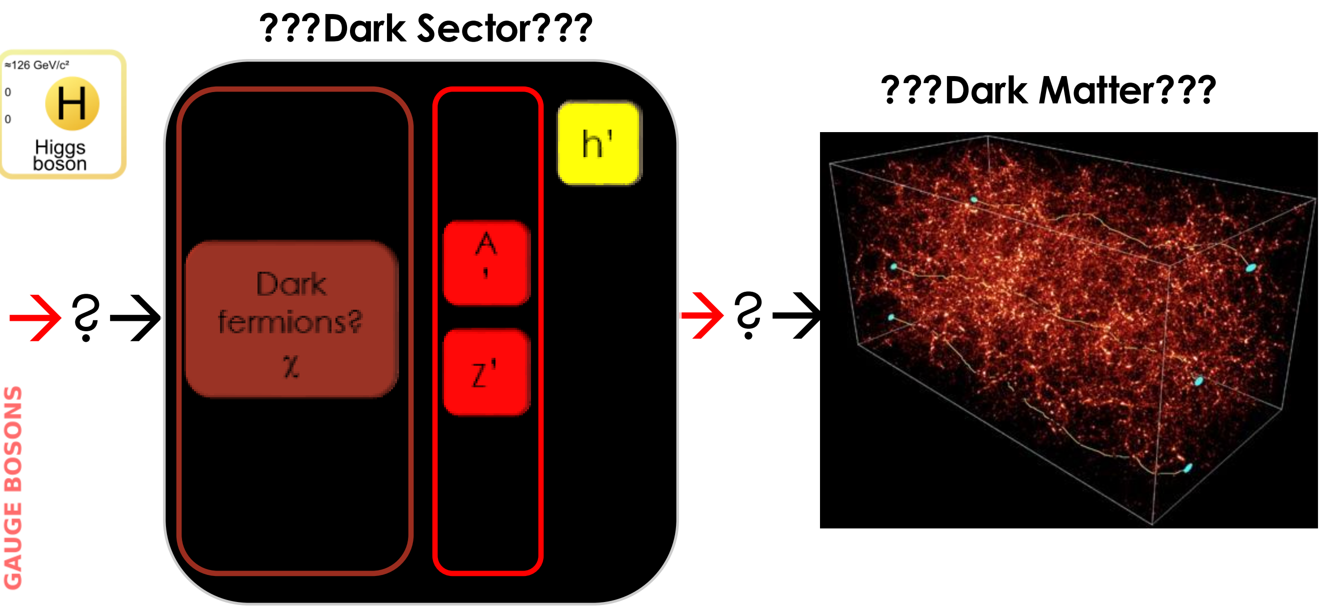




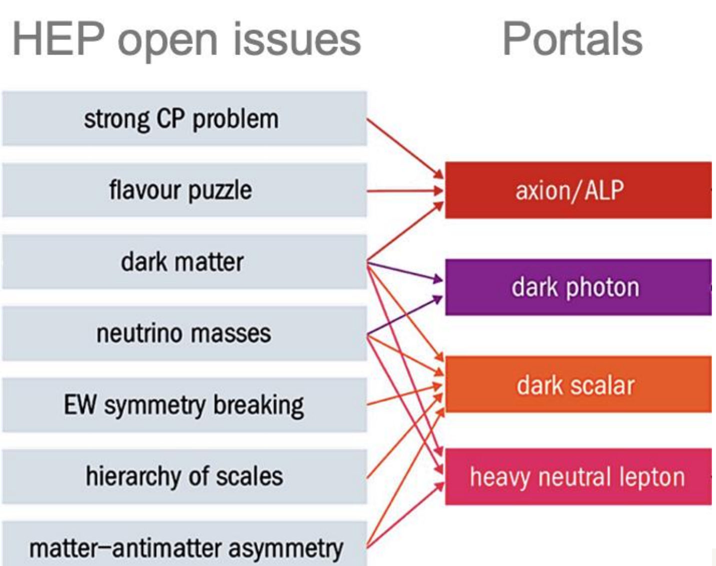
Dark sector dark matter?

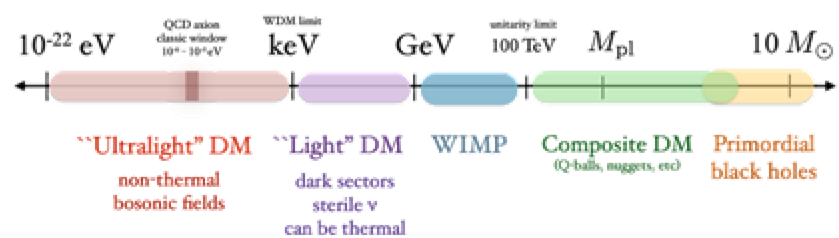
Standard model



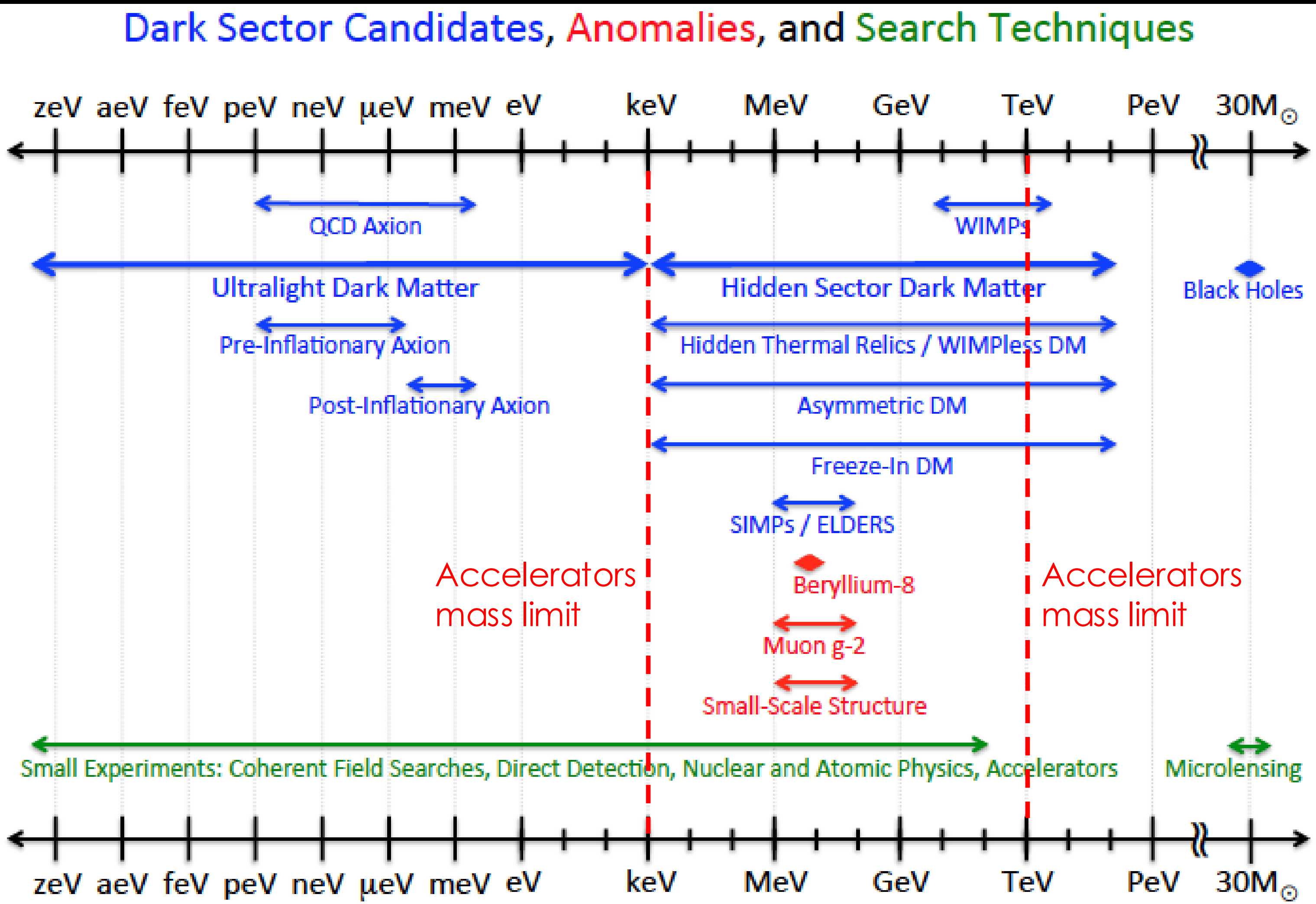


- Dark sector candidates can explain SM anomalies: (g-2)μ, ^{8}Be, proton radius
- The mediator can have a **small mass (MeV - 100 MeV)**
- Due to its **small mass** the mediator can be **produced in fixed target experiments**
- It can **decay back to ordinary matter "visible"** on **not "invisible"**





Which mass region is accessible

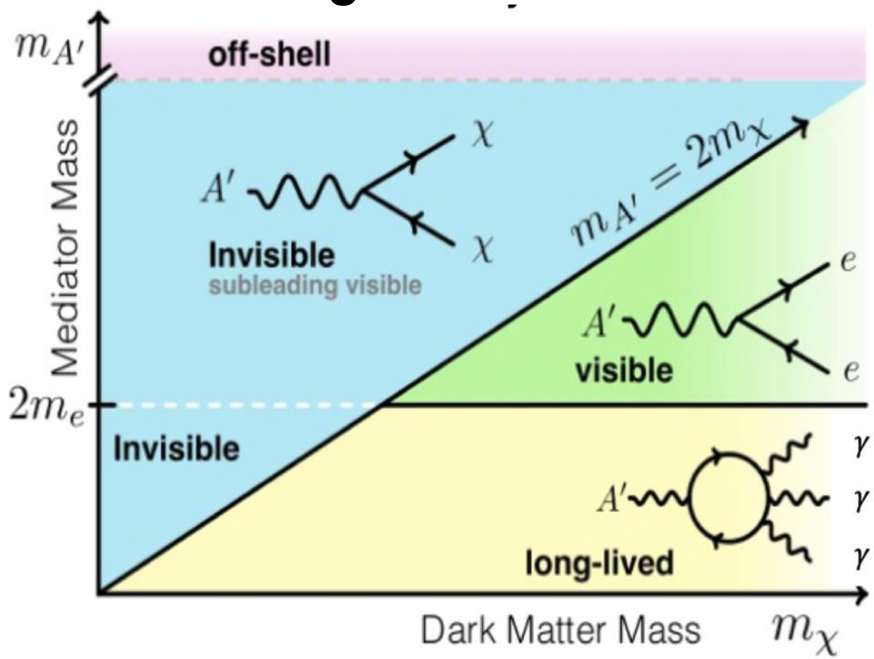


Accelerator limit energy scale ~1 TeV allows to access most of the models

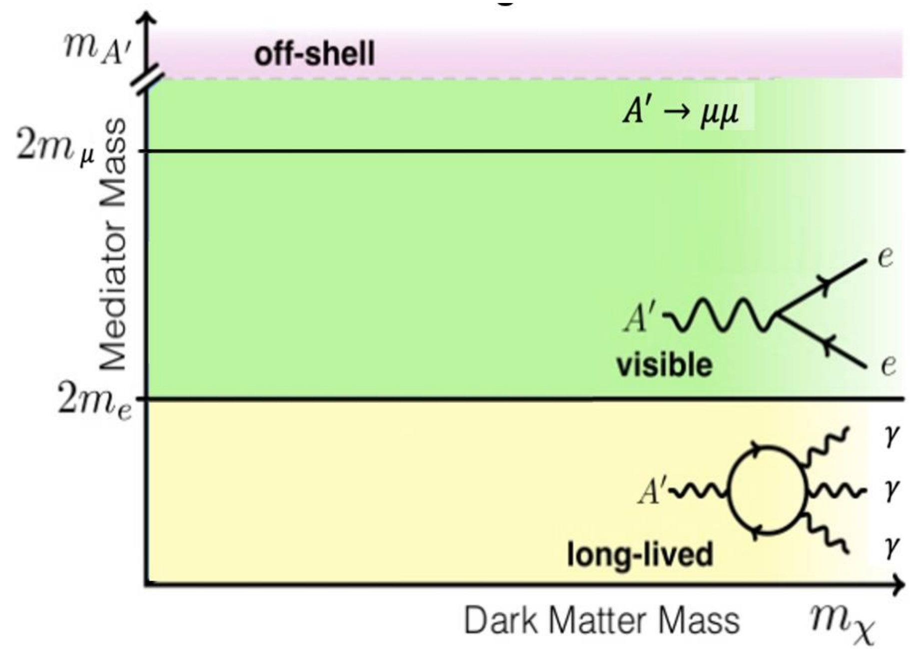
SM anomalies at low energy guide the eye in this region

Visible or invisible?

Light dark matter



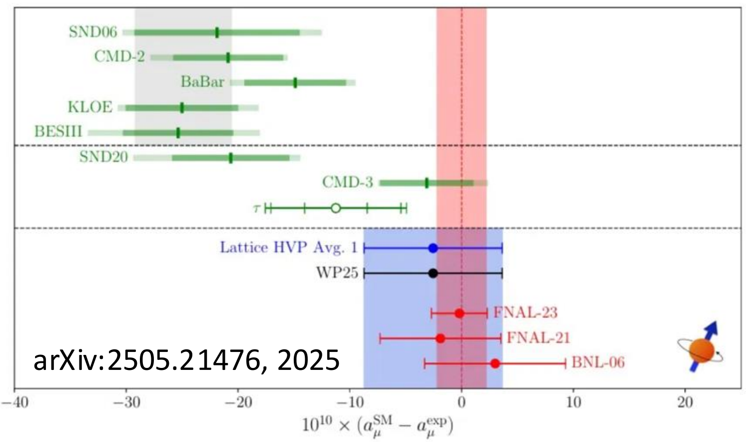
Massive dark matter



- X particle decays **in dark matter χ** if there are **light dark matter** particles ($m_\chi<m_X/2$)
  - Subdominant SM decays are suppressed coup^2
- **“Invisible” decays are dominant.**

- X particle decays **into SM particles** if dark matter is massive $m_\chi>m_X/2$.
  - SM decays are the only allowed
- **Visible decay scenario**

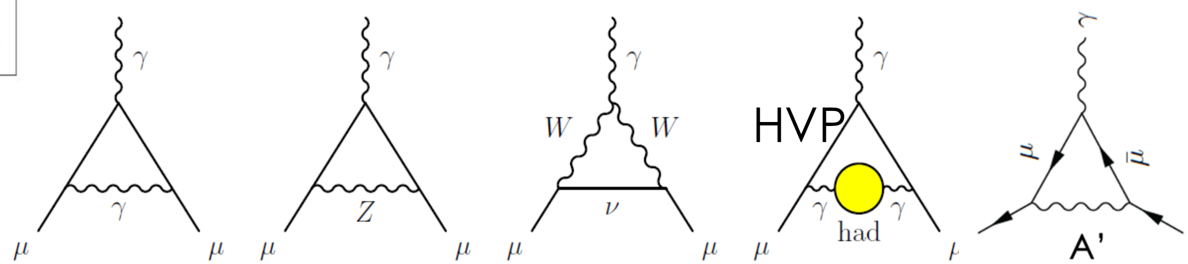
Muon g-2 anomaly and dark sectors

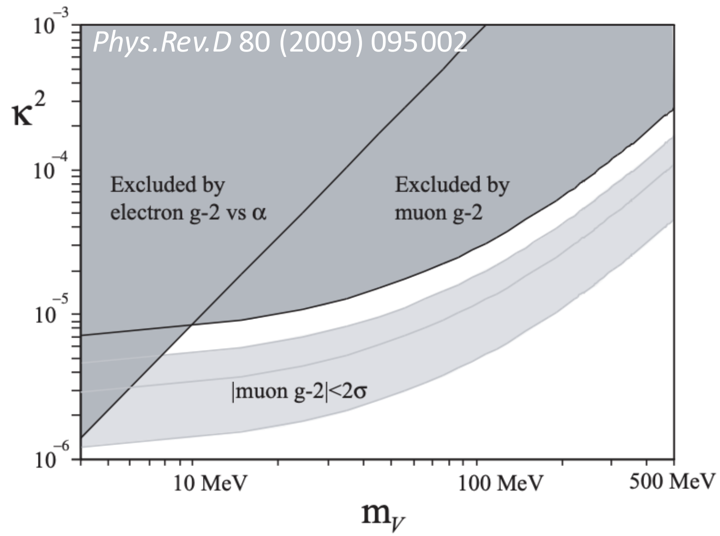


g-2 puzzle in the standard model

- ~3σ discrepancy between dispersive theory and experiments
- Fixed by recent lattice QCD results
- Lattice is still in tension with dispersive theory and experiment

SM contribution **DS**





Additional diagram with dark photon exchange can contribute to fix the discrepancy (with sub GeV A' masses)

$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F(m_V/m_\mu)\,, \qquad (17)$$

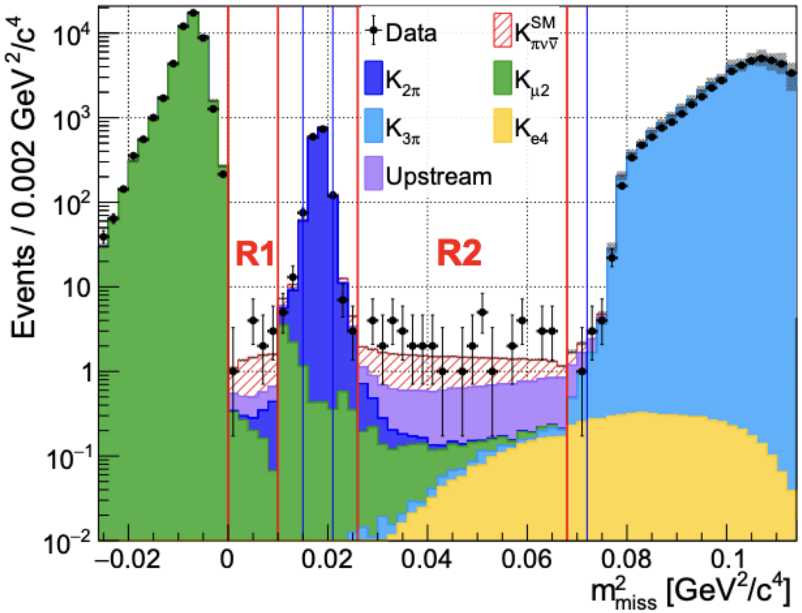
where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z]\,dz$. For values of $\varepsilon \sim 1\text{–}2 \cdot 10^{-3}$ and $m_V \sim 10\text{–}100\,\text{MeV}$, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon $g-2$ discrepancy. Searches for the dark

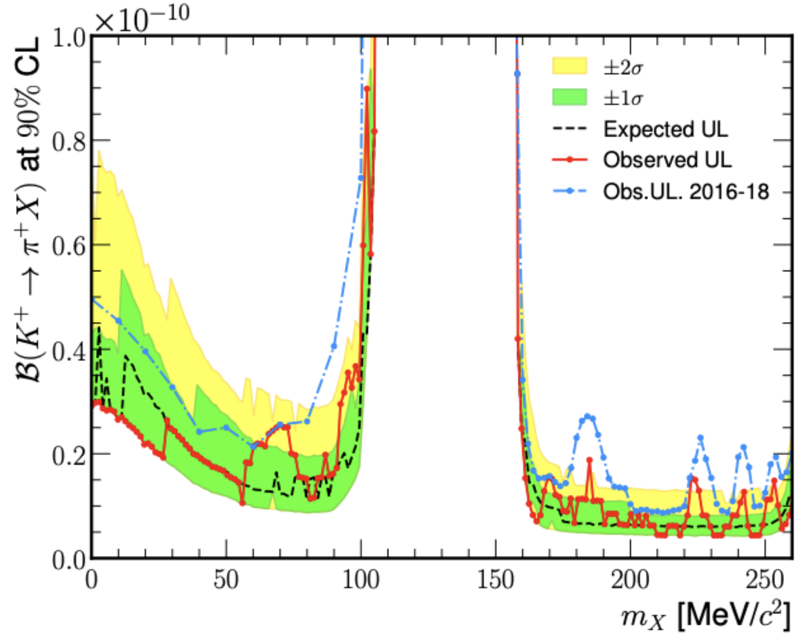
This possibility has now been ruled out or very severely constrained by lattice results.

Searches for DM in flavor factories

- **Rare Decays (on shell mediator or DM):**
  - Flavour experiments are sensitive to new physics in rare processes, such as rare B and K meson decays, whose rate could be modified by the production of an on shell dark mediator or dark matter particles.
- **Flavor Violating Interactions (LFV or LNV throug Z'):**
  - Flavored dark matter models introduce new flavor-violating interactions, that are not allowed in the SM. These new interactions provide unique signatures in rare meson and lepton decays.
- **Precision Measurements (off shell mediator):**
  - Besides directly producing DM or mediators, DM could influence the SM decay rates through virtual effects. Flavor experiments can study these effects by precisely measuring decay rates.

From $K^+ \to \pi^+\nu\nu$ to $K^+ \to \pi^+ X$, X–>invisible



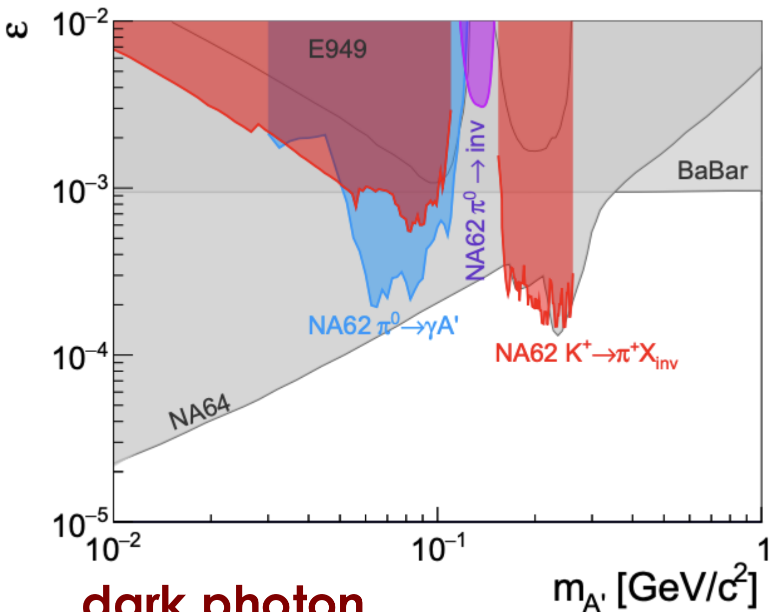


- Start from the m^2_{miss} spectrum used for the NA62 $K^+ \to \pi^+\nu\nu$ searches on 2016-22 data [JHEP 02 (2025) 191]
- Obtain the UL on the BR($K^+ \to \pi^+ X$) as function of X mass (p_X mom of X in the K rest frame):

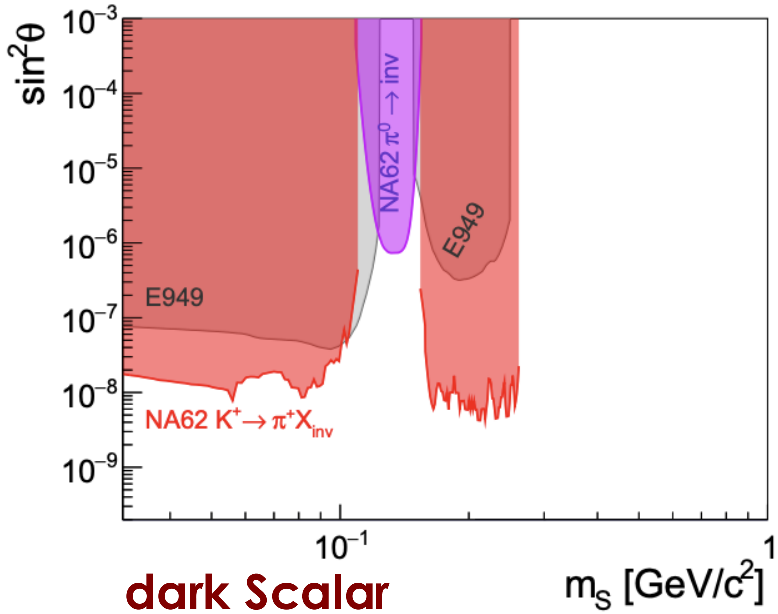
$$\mathcal{B}(K^+ \to \pi^+ X) = \frac{p_X}{8\pi\Gamma_K m_K^2}|\mathcal{M}|^2 \qquad \Gamma_K = 5.32 \times 10^{-14}\,\text{MeV}$$

- Recast the limit under different model assumptions (Vector, scalar, pseudoscalar) changing $|M|^2$
  - Add lifetime corrections to obtain visible decay limits for the same model.

Constraints on invisible particles



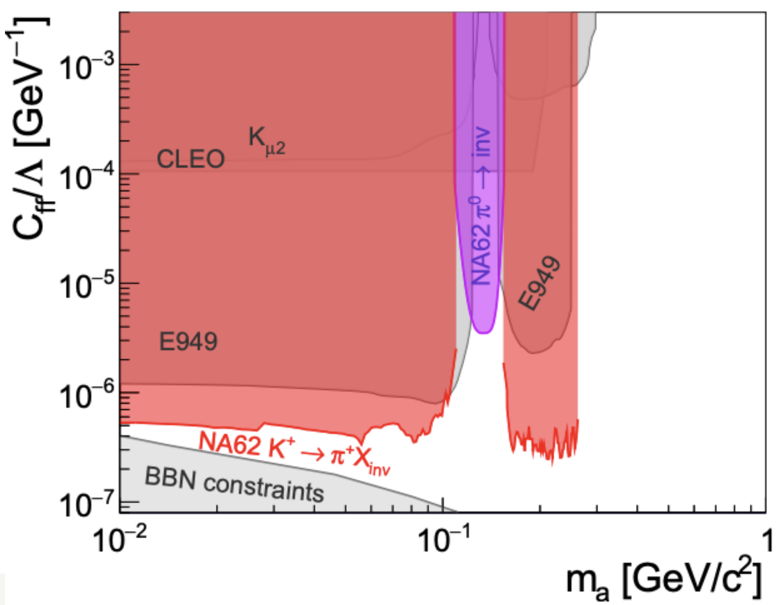
dark photon



dark Scalar

dominant bounds < M_K for several DS scenario

[arXiv:2507.17286](https://arxiv.org/abs/2507.17286)



ALPs with fermion coupling

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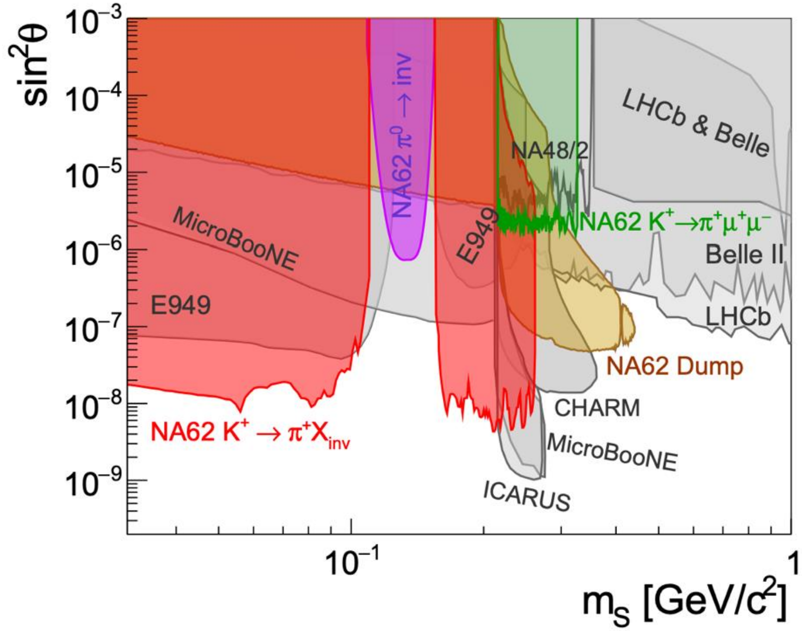
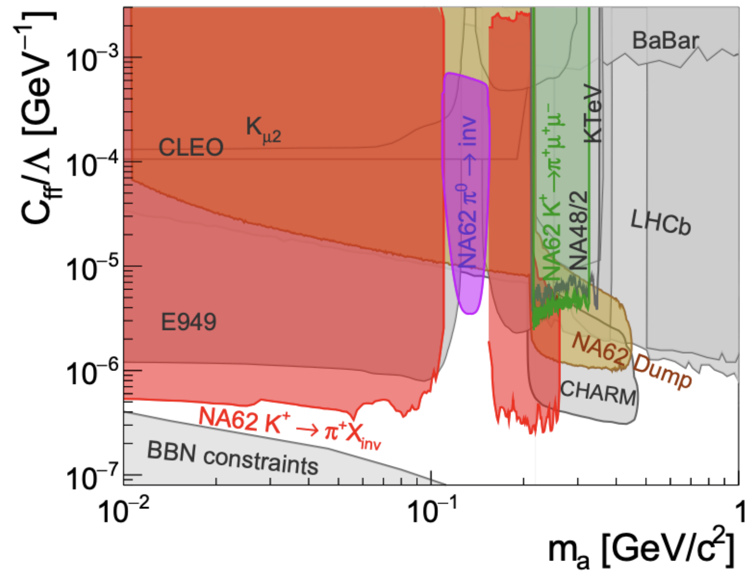
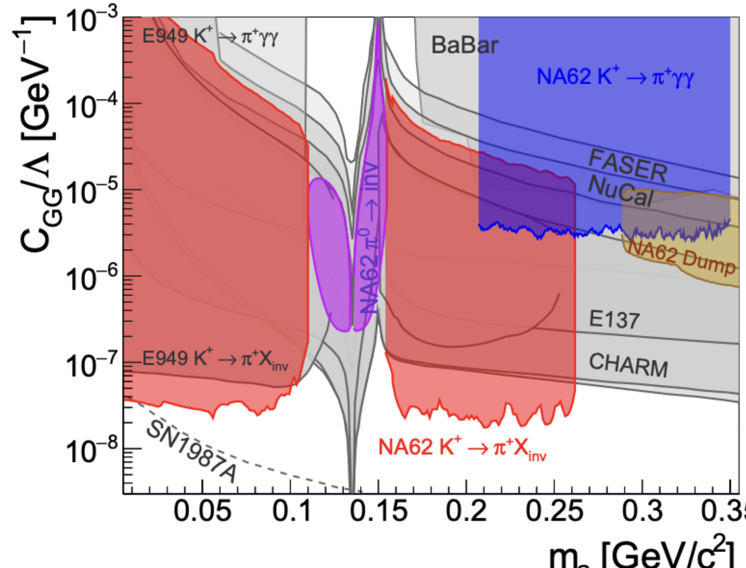
Constraints on visible decay searches







Dominant limits on all scenarios form $K^+ \to \pi^+ X$

Additional limits from several K^+ decays even if not world leading

arXiv:2507.17286

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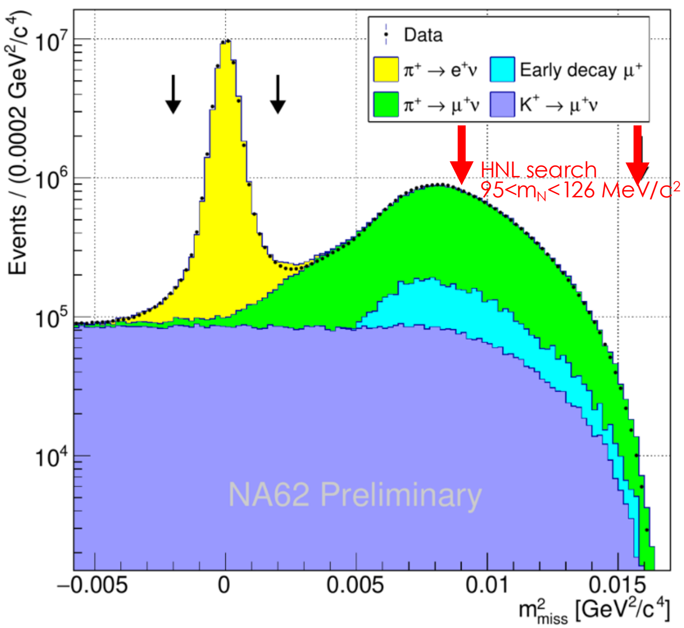
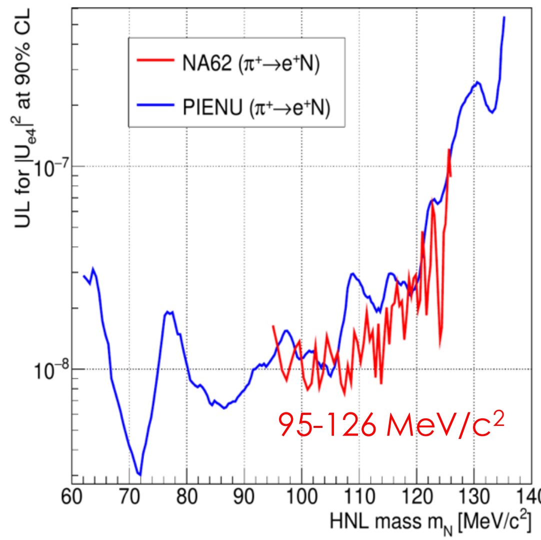
NA62 limits on HNL π,K decay: $K^+,\pi^+ \to e^+N$

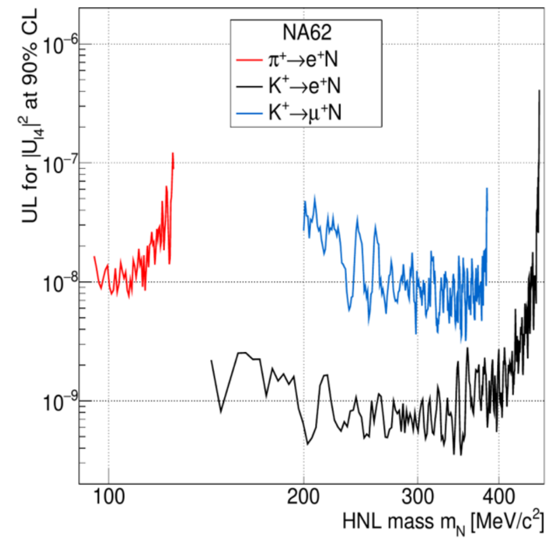
Single e^+ with no other activity



e⁺ dominance BC6



Univ. lepton coupling



ArXiv:2507.07345v1

- $K^+,\pi^+ \to e^+N$ with N HNL decaying to invisible.
  - Searches in both K and beam pion decays.
- Experimental searches at NA62
  - NA62 : $K^+ \to e^+N$ (2016–2018 data) [Phys.Lett.B 807 (2020) 135599]
  - NA62 : $K^+ \to \mu^+N$ (2016–2018 data) [Phys.Lett.B 816 (2021) 136259]
  - NA62 : $\pi^+ \to e^+N$ [ArXiv: 2507.07345v1]

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The Be or X17 anomaly

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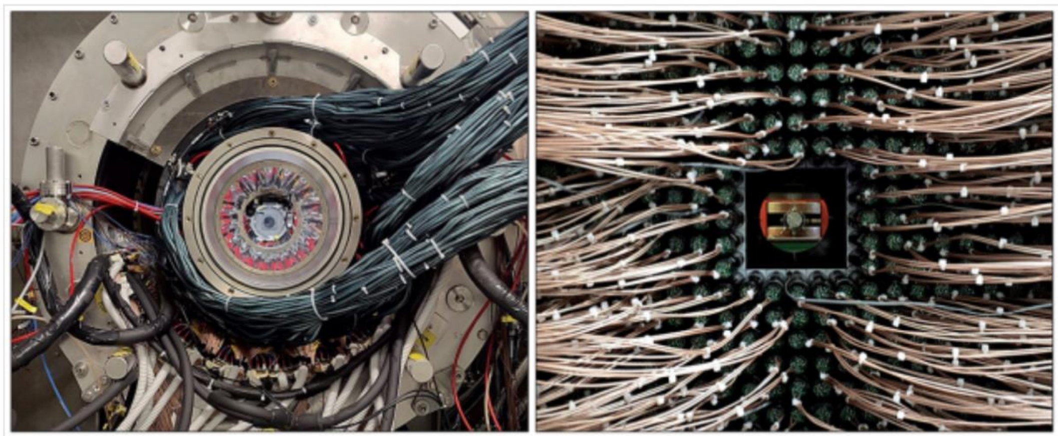
Mixed signals from X17

9 September 2025



Square peg in a round hole Independent checks by the MEG II (left) and PADME (right) experiments report conflicting early indications on the true nature of the ATOMKI anomaly. Credit: INFN

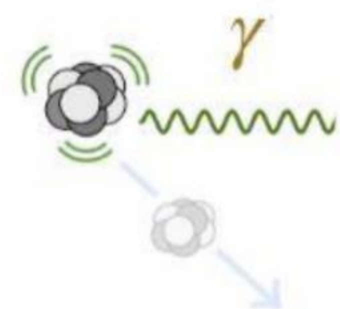
https://cerncourier.com/a/mixed-signals-from-x17/

New Physics in nuclear transitions?

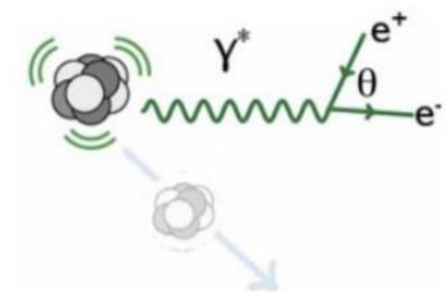
Excite the nucleus by proton capture:
choose the level by using appropriate p energy (few MeV)

Standard Model deexcitation mechanisms:
a) γ emission
b) Internal Pair Creation (IPC):
- emit an off-shell photon γ^*
- γ^* decays to ee pair

γ emission



IPC



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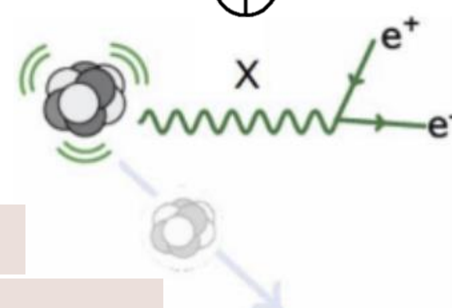


New Physics (NP) deexcitation mechanisms:
- Produce an intermediate on shell new particle X (mass M_X)
- X decays to e^+e^- pair

Need nuclei having transitions with $\Delta E > M_X$

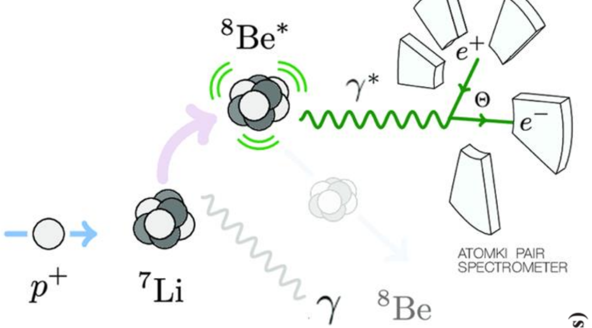
New Particles will produce enhanced IPC rate

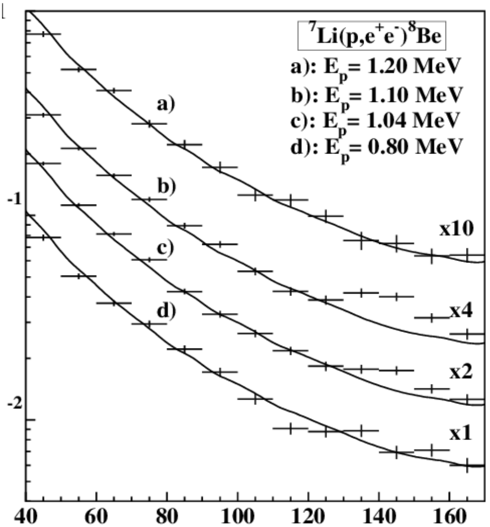
New particle will appear as a peak in the θ_{ee} distribution

The ATOMKY anomaly

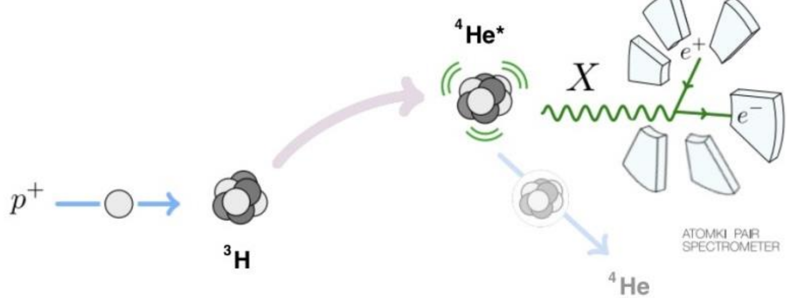
PRL **116,** 042501 (2016)

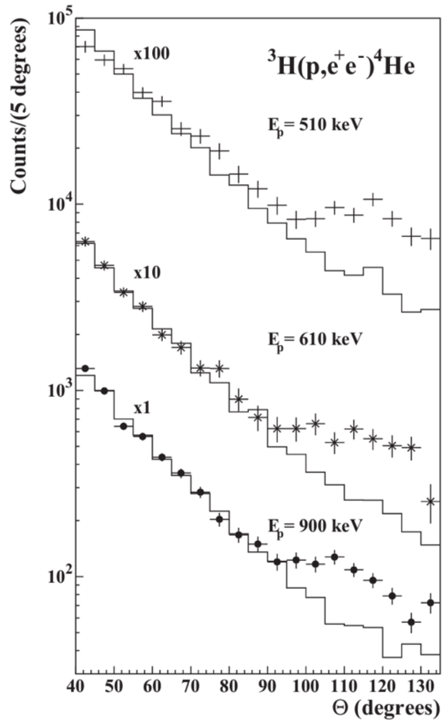
A. J. Krasznahorkay, et al.



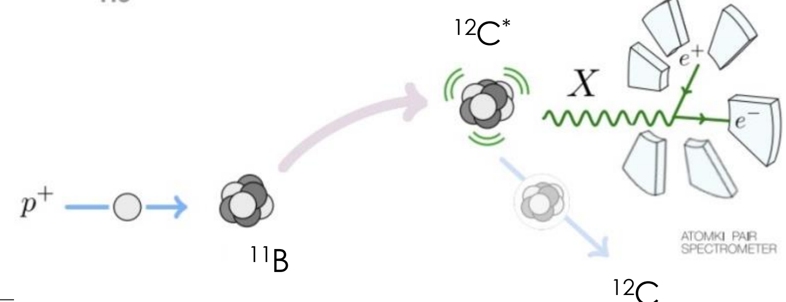


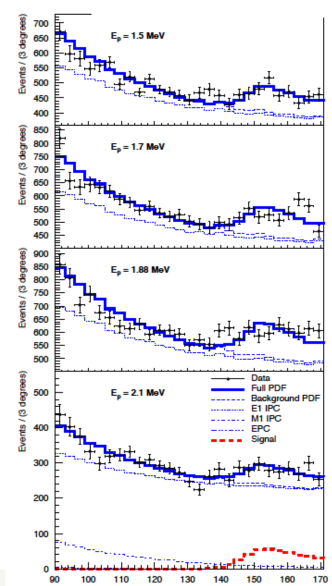
PHYSICAL REVIEW C **104**, 044003 (2021)



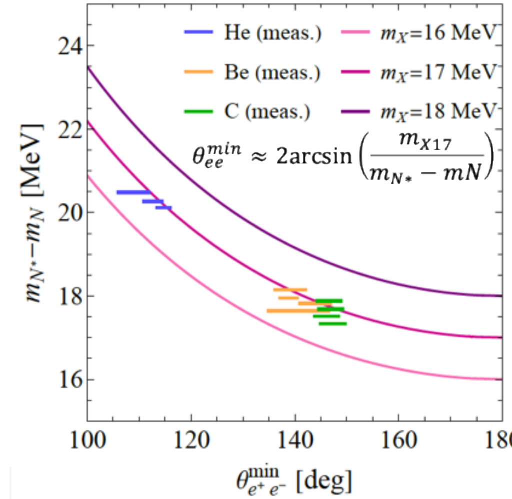


PHYSICAL REVIEW C **106**, L061601 (2022)





PHYS.REV. D 108, 015009 (2023)



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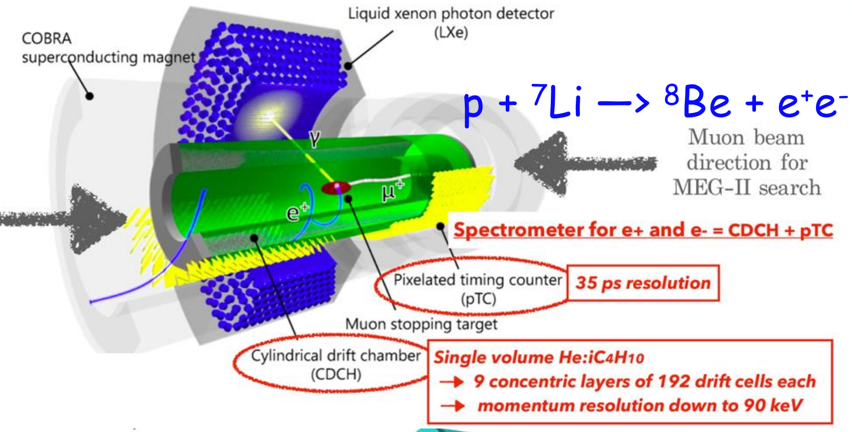
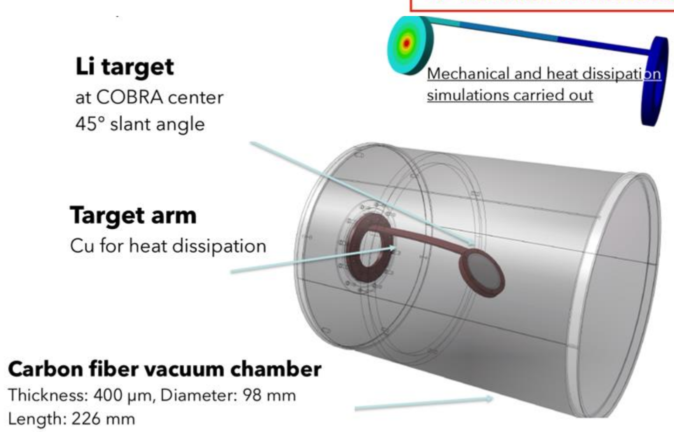
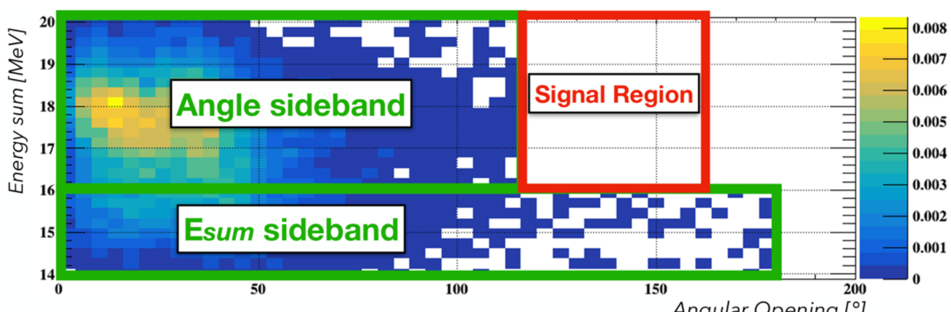
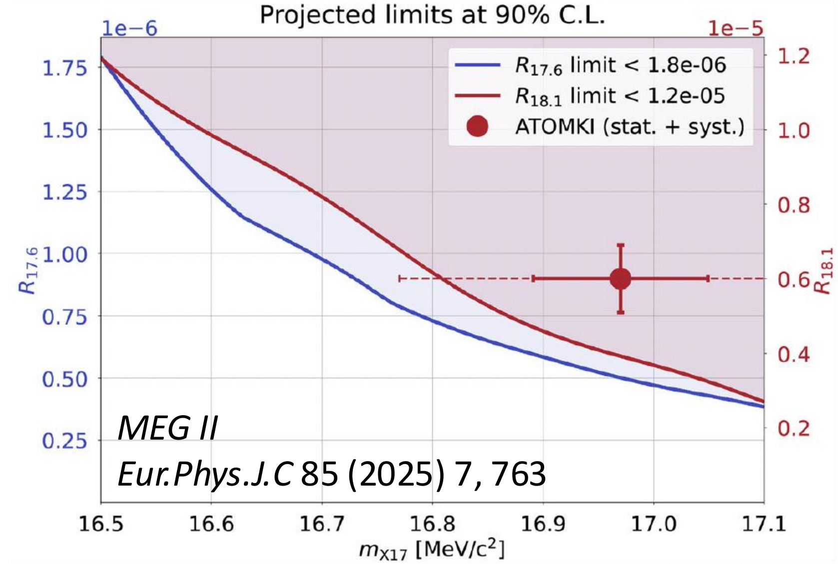
^{8}Be anomaly at MEG II PSI

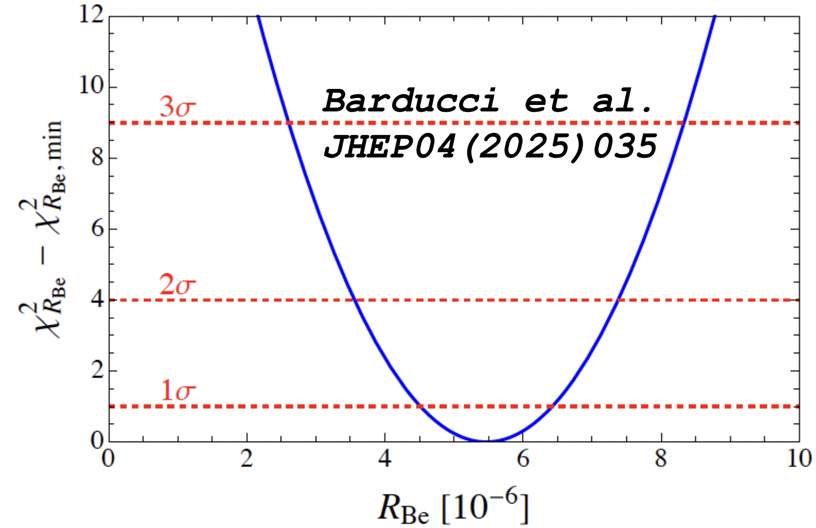
In February 2023, X17 physics run for 4 weeks at E_p = 1080 keV











contrast to the Atomki results. Nevertheless, the Beryllium anomaly cannot be definitively excluded, as MEG-II reports its result to be compatible with the Atomki ones within 1.5σ.

Pure dark photon: excluded by NA48/2

For genuine A' $\varepsilon_f = \varepsilon q_f$ Feng et. al from the X17 rate:

$$\frac{B(^8\text{Be}^* \to {}^8\text{Be}\,X)}{B(^8\text{Be}^* \to {}^8\text{Be}\,\gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\vec{p}_X|^3}{|\vec{p}_\gamma|^3} \approx 5.8 \times 10^{-6}$$

[PRL 117, 071803 (2016)]

$$|\varepsilon_p + \varepsilon_n| \approx 0.011,$$

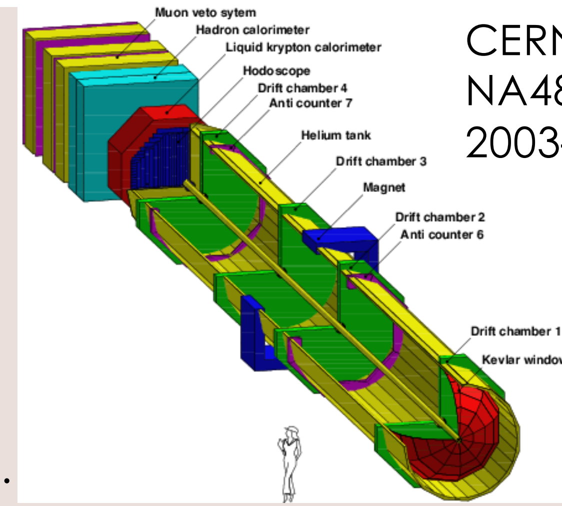
NA48/2 experiment limits for **A' in $K^{\pm}_{2pD}$**:

$K^\pm \to \pi^\pm \pi^0_D$ with $\pi^0_D = \gamma e^+ e^-$ [PLB 746 (2015) 178-185]

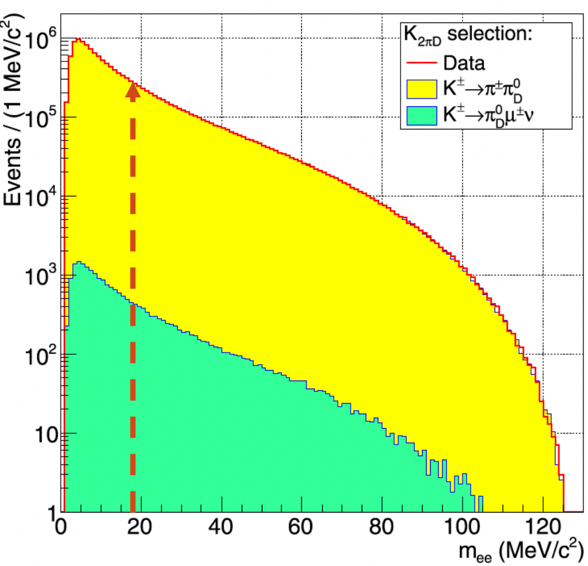
In case X17 is a dark photon we should have in addition:

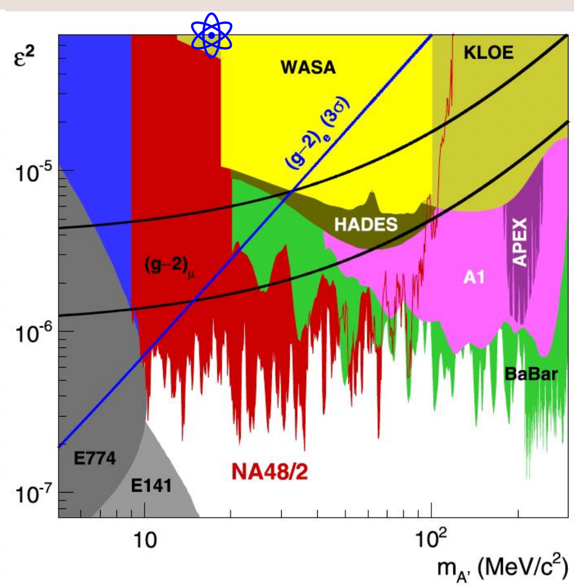
$\pi^0 \to \gamma X17 \to \gamma e^+ e^-$

X17 should appear as a peak at 17 MeV in the m_{ee} spectrum.



CERN NA48/2 2003-4

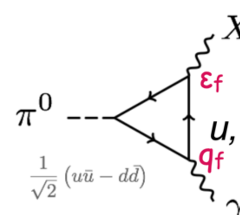




Universal coupled vector hypothesis A' firmly excluded

π-phobic/P-phobic vector particle:

[PRL 117, 071803 (2016)]



$\pi^0 \to X\gamma$: $|2\varepsilon_u + \varepsilon_d| < 8 \times 10^{-4}$ (NA48/2)

B_{X17}/B_γ: $|\varepsilon_u + \varepsilon_d| \approx 4 \times 10^{-3}$ (Atomki)

$\varepsilon_d \approx -2\,\varepsilon_u$ (±10%) ==> $\varepsilon_p = 2\varepsilon_u + \varepsilon_d \approx 0$;

$2\varepsilon_u + \varepsilon_d \approx 0$ ==> $\pi^0 \to X\gamma = 0$ forbidden

π-phobic vector still alive!

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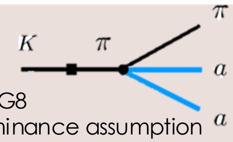
X17 as QCD Axion: excluded by NA62

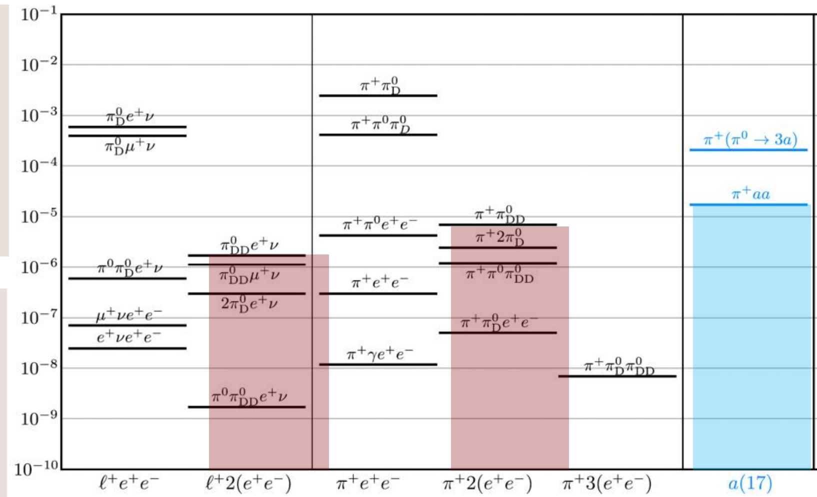
M. Pospelov noted: [PRD 105, 015017 (2022)]

$$BR(K^+ \to \pi^+ aa) \simeq 1.7 \times 10^{-5}$$

If a=X17 X17–>e^+e^- and we have π^+4e final state
a) main SM background $K^+ \to \pi^+\pi^0_{DD}$ has lower rate
b) $m_{ee} = m_a$ is a strong kinematical constraint



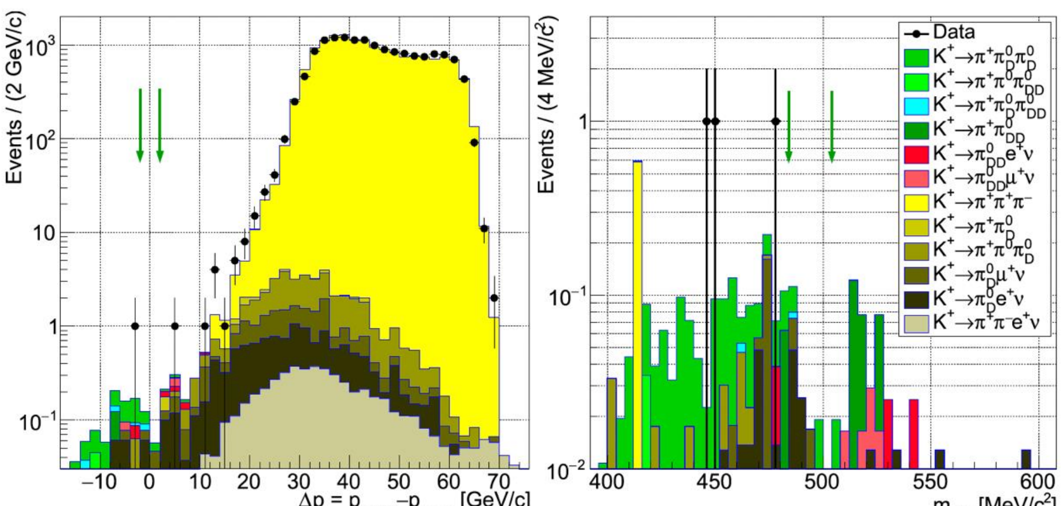
χPT G8 dominance assumption



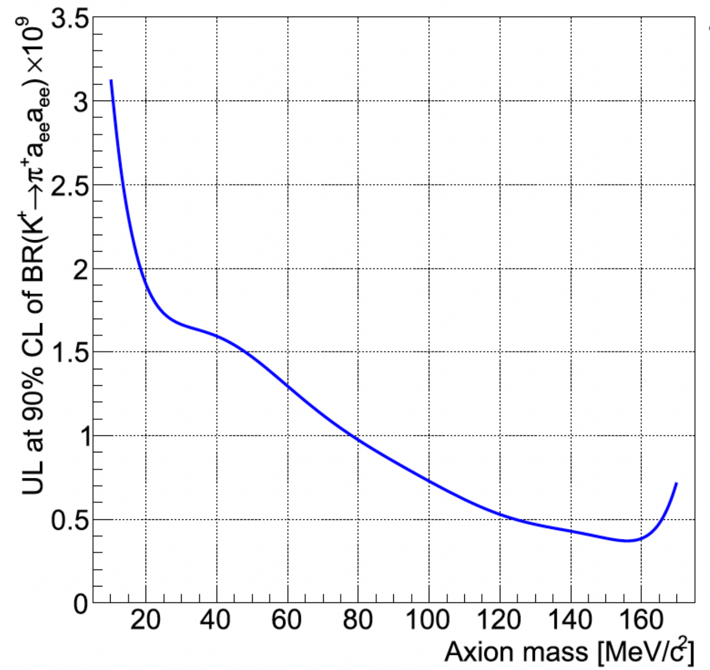
NA62 Search for $K^+ \to \pi^+ aa \to \pi^+ e^+e^-e^+e^-$ [PLB 846 (2023) 138193]

- Full NA62cdata set collected in 2017–2018
- Expected BG = 0.18±0.14 events
- No events are observed in the signal region $m_{\pi 4e} \sim m_{K+}$
- NA62 obtained: $$BR(K^+ \to \pi^+ aa) \leq 2.1 \times 10^{-9} \; at \; 90\% \; CL$$

which rules out **the QCD axion hypothesis for the X17**.



[PLB 846 (2023) 138193]



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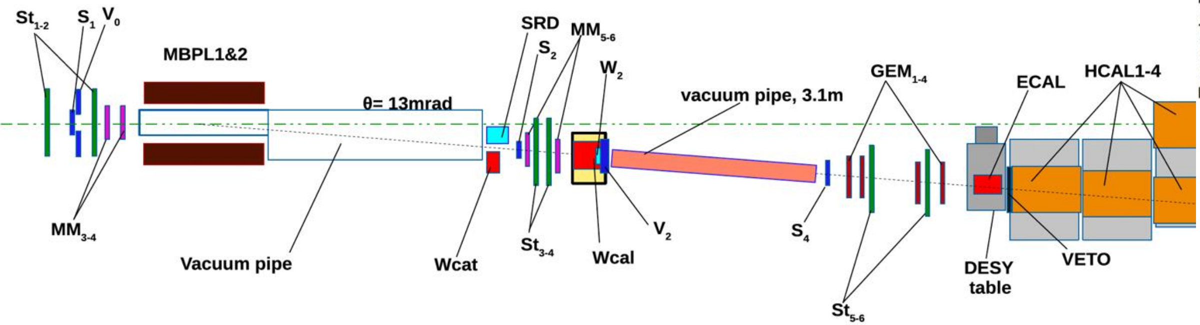
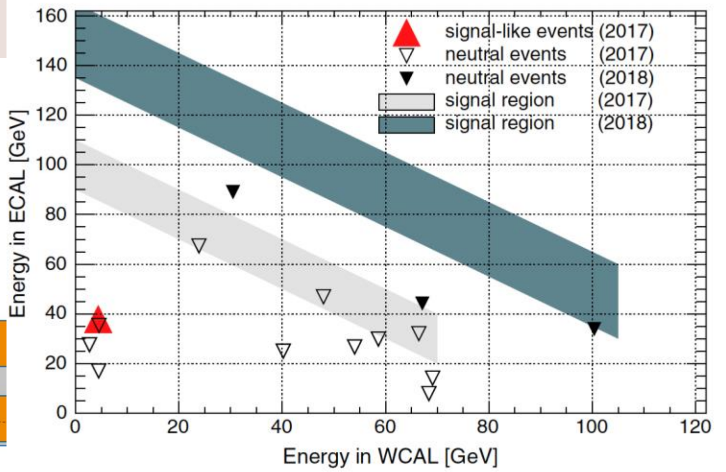
Generical vector constraints NA64

NA64 CERN NA, uses 150 GeV e⁻ beam on thick target.

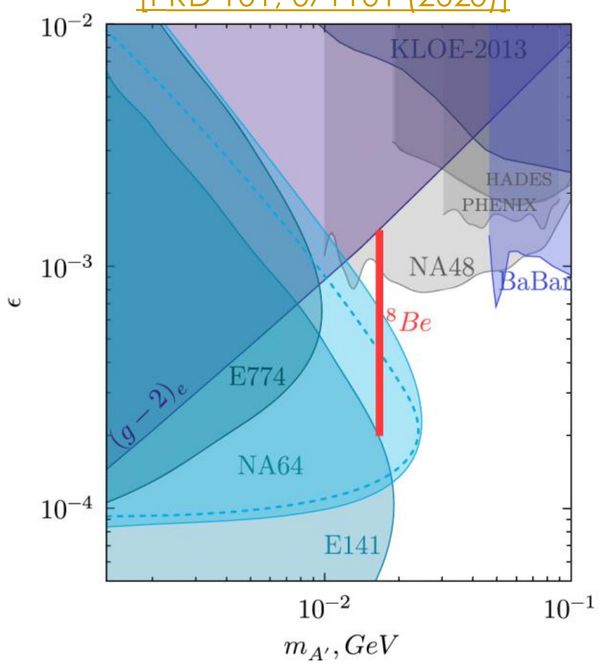
$$e^- + Z \rightarrow e^- + Z + A'(X), \qquad A'(X) \rightarrow e^+e^-$$

only e⁻ -> no problem with extra couplings!





[PRD 101, 071101 (2020)]



How it works:

1) Beam e⁻ losses part of its energy in W_{cal} before radiating.
2) After radiating A' is absrobed by W_{cal} depsiting all of its energy.
3) A' is radiated and decays after the W_{cal}
4) Energy of the ee pair from the A' decay is measured by ECal

Dump experiment:

- limited in the high ε values by X17 lifetime
- No possibility to measure mass of eventually observed events
- just counts general event excess

Collider constraints: KLOE

Physics Letters B 750 (2015) 633–637

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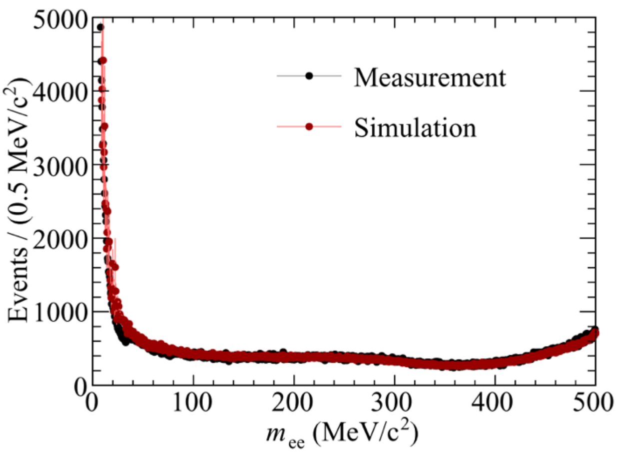
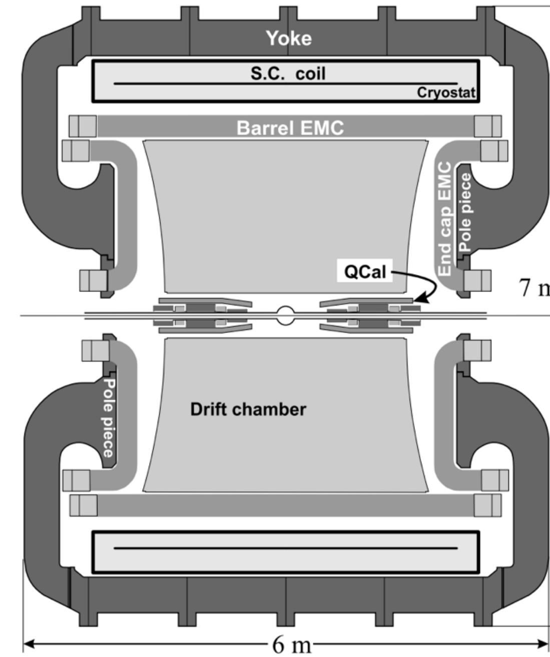
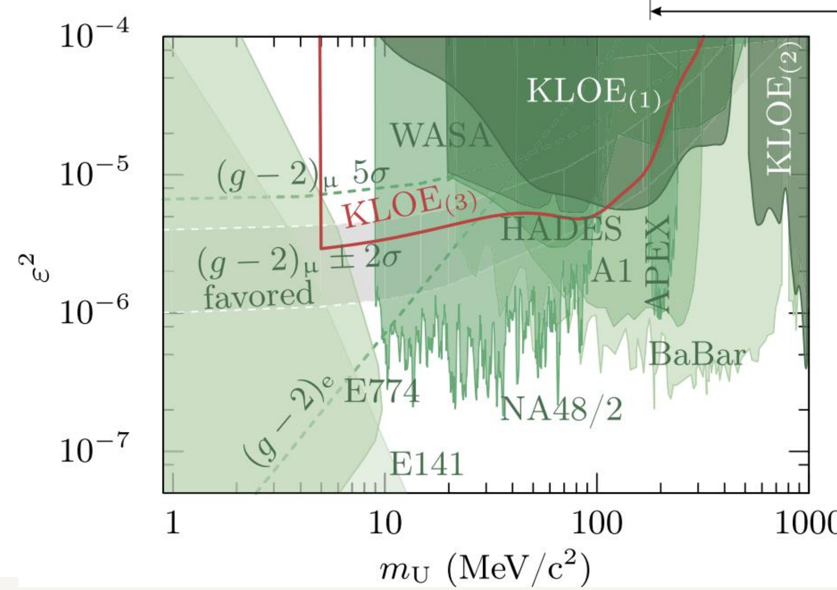
Limit on the production of a low-mass vector boson in $e^+e^- \to U\gamma$, $U \to e^+e^-$ with the KLOE experiment



$$\varepsilon^2(m_{ee}) = \frac{N_U(m_{ee})}{\epsilon_{\text{eff}}(m_{ee})} \frac{1}{H(m_{ee})\ I(m_{ee})\ L}$$





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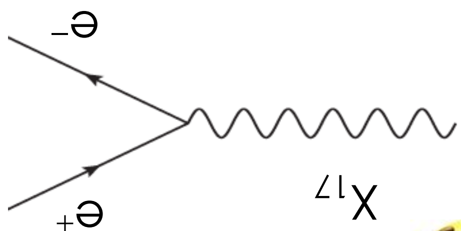
As simple as possible: the resonance search

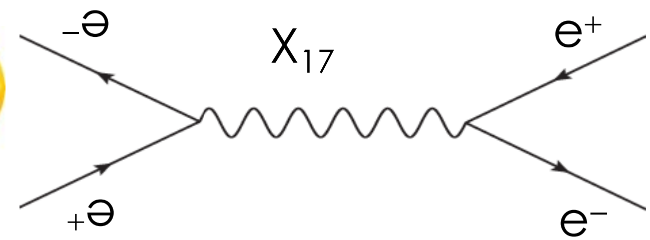
Atomki X_{17}

[M.R., E. Nardi et al. PRD 97, 095004 (2018)]

Just flip the diagram



and connect!



No model dependence just electron coupling!

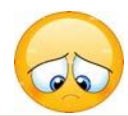
Extremely high production rate Breit-Wigner enhancement

$$\sigma_{\rm res}(E_e) = \sigma_{\rm peak}\frac{\Gamma^2_{A'}/4}{(\sqrt{s}-m_{A'})^2+\Gamma^2_{A'}/4} \qquad \sigma_{\rm peak} = 12\pi/m^2_{A'}$$

Lowest possible α suppression

E. Nardi M.R. et al. *Phys.Rev.D 97 (2018) 9, 095004*

Extremely small Γ_{X17} $\Gamma_{A'} \simeq \epsilon^2 \alpha m_{A'}/3$ <10^{-2} eV



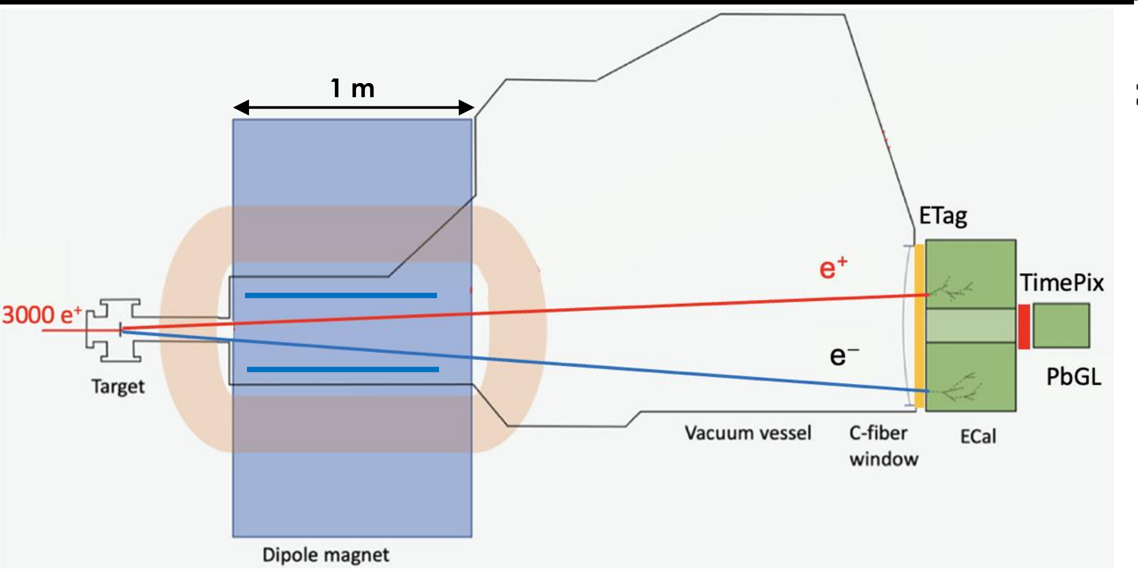
We need a lot of positrons in very limited COM energy range

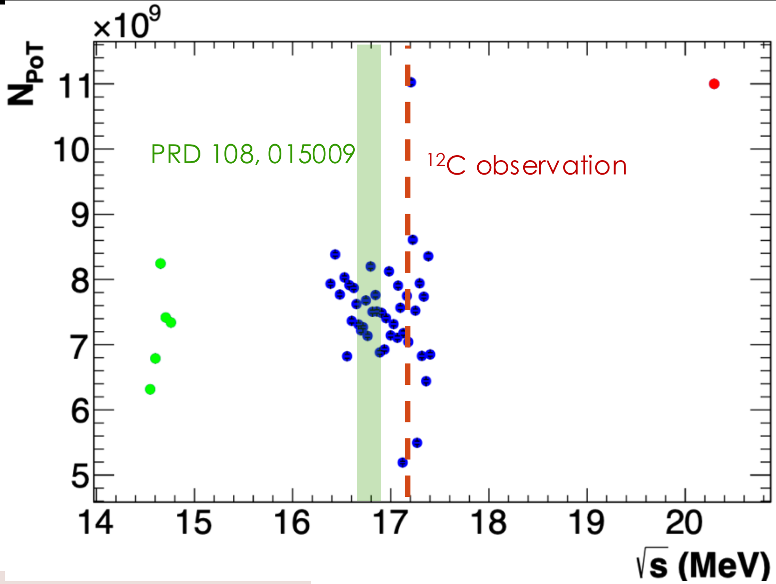
We can **have >1E10 e⁺ in 20KeV** CoM energy at LNF!

Ok **let's do that at PADME**!

[L. Darmé E. Nardi, Mancini M.R. et al. PRD 106,115036]

PADME detector in Run III 2022





2022 Run-III setup adapted for the X17 search:

- **Active target, CVD polycrystalline diamond with X,Y coordinates**
- **ECal, 616 21x21x230 mm³ BGO crystals**
- **Newly built ETag in front of Ecal for e/γ**
- **Timepix silicon-pixel detector for beam spot imaging**
- **Lead-glass beam catcher (NA62 LAV spare block)**

On resonance points **spaced** by **~ 0.75 MeV**
Point spacing equal to the energy resolution
- Mass region 16.4 MeV <M_{X17}< 17.5 MeV
- Statistics ~1x10^{10} NPoT per point

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Observed limit after box opening

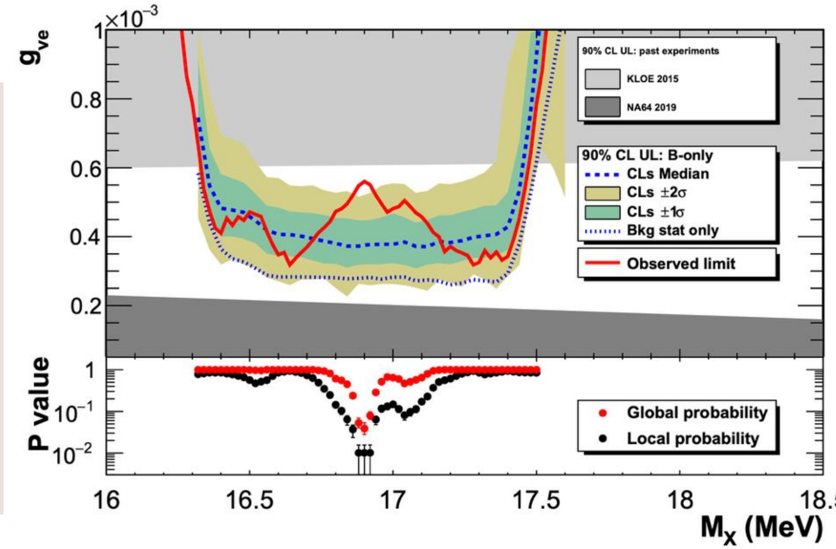
An **excess** is observed **beyond the 2σ local coverage** (**2.5 σ local**)

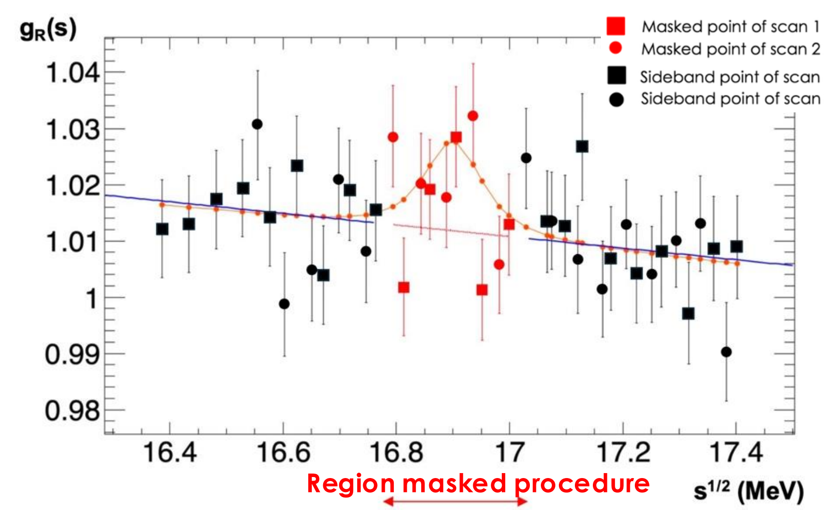
At **M_X = 16.90(2) MeV**, **g_{ve} ~ 5.6 x 10^{-4}**, the global probability dip reaches $3.9_{-1.1}^{+1.5}$ %, corresponding to (1.77±0.15) σ one-sided
(look-elsewhere calculated exactly from the toy pseudo-events)

A second excess is present at larger masses ~ 17.1 MeV, but the absolute probability there is ~ 40%

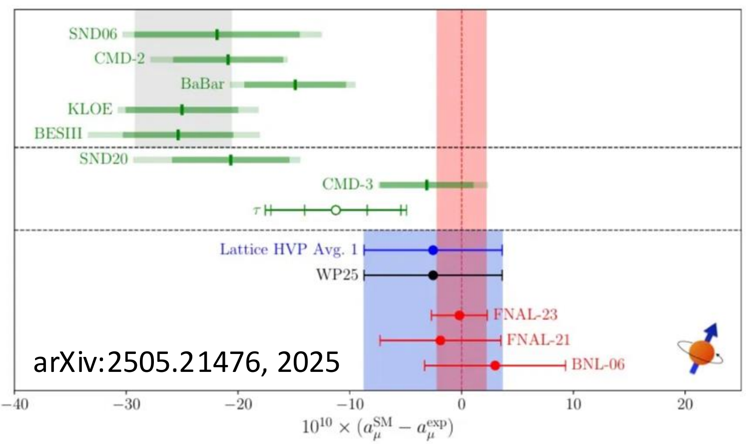
If a 3σ interval is assumed for observation following the estimate M_X = 16.85(4) of PRD 108, 015009 (2023),

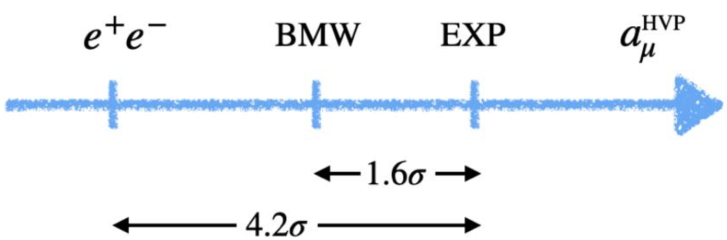
the p-value dip deepens to $2.2_{-0.8}^{+1.2}$% corresponding to (2.0±0.2) σ one-sided





New possibilities?





needed to explain Δa_μ can be divided in two regions: *i*) $m_{Z'} \gtrsim 0.3$ GeV which requires $|\epsilon| \approx 10^{-2}$ and $\gamma \gtrsim 10^{-3}$ and *ii*) $m_{Z'} \lesssim 0.3$ GeV which requires $|\epsilon| \approx 10^{-2}$ and basically no relevant constraint on γ (as evident from Eq. (13)). We note that in principle it could be possible to directly observe (with a dedicated scanning analysis) the new resonance in e^+e^- data for particular choices of the Z' mass and width parameters. However, since there

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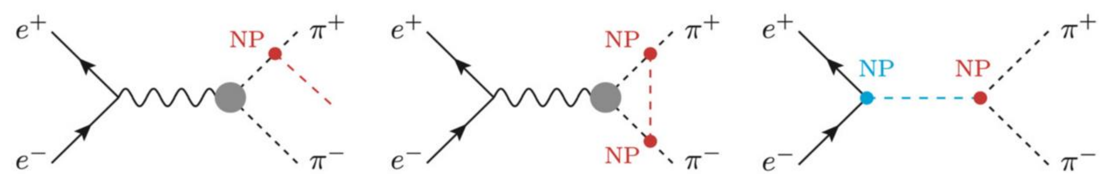
Physics Letters B

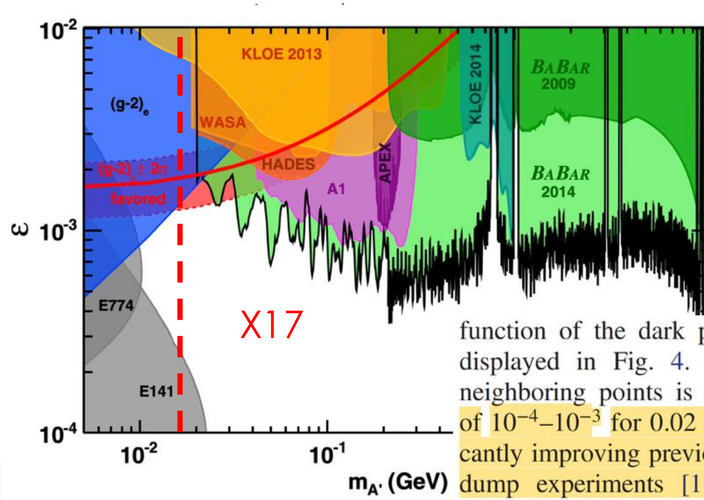
Volume 829, 10 June 2022, 137037

New physics behind the new muon g-2 puzzle?

Luca Di Luzio [a b], Antonio Masiero [a b], Paride Paradisi [a b], Massimo Passera [b]



2. Leptonic processes. The Z' coupling to electrons is also tightly constrained. In particular, the non-observation at BaBar of the process $e^+e^- \to \gamma Z'$ followed by the decay $Z' \to e^+e^-$ yields $g_V^e \lesssim 2 \cdot 10^{-4}$ [42] if the Z' decays dominantly into electrons. Therefore, in our framework, this bound applies only for $m_{Z'} \lesssim 0.3$



PRL 113, 201801 (2014)

function of the dark photon mass [10]. The results are displayed in Fig. 4. The average correlation between neighboring points is around 90%. Bounds at the level of 10^{-4}–10^{-3} for $0.02 < m_{A'} < 10.2$ GeV are set, significantly improving previous constraints derived from beam-dump experiments [11,12,18], the electron anomalous

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More on X17 and g-2$_e$

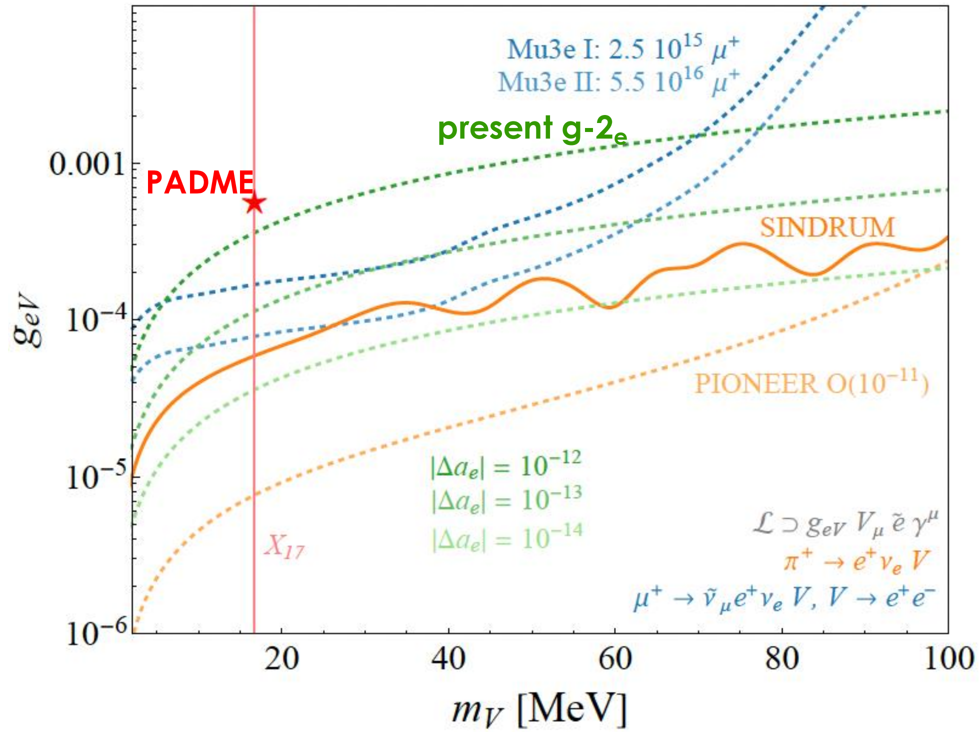
Hunting for a 17 MeV particle coupled to electrons

arXiv:2504.14014v2

Luca Di Luzio,[1,*] Paride Paradisi,[2,1,†] and Nudžeim Selimović[1,‡]

$$\Delta a_e^X = \frac{g_{eX}^2}{4\pi^2}\frac{m_e^2}{m_X^2} L_X \qquad L_V = \frac{1}{3}$$

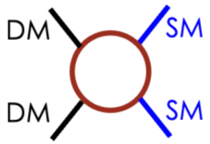
$$\Delta a_e^V \approx 2.4\times 10^{-12}\left(\frac{g_{eV}}{5.6\times 10^{-4}}\right)^2\left(\frac{17\,\text{MeV}}{m_V}\right)^2$$



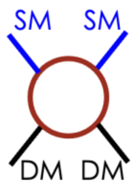
other beam-dump experiments. We have shown that the e^+e^- PADME excess is already in tension with the electron g-2, as well as exotic pion decay data from SINDRUM, although it remains marginally viable and testable.

Conclusions

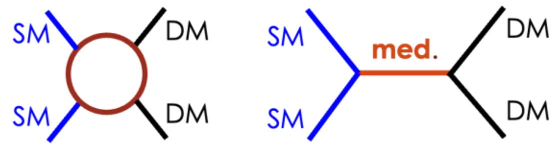
- Low energy physics it's an important player in dark matter searches
  - Flavor factories, dump experiments, precision measurements.
- Flavor physics is a excellent testing ground for dark sector searches
  - NA62 recently delibred would leading results for:
    Dark Photons, dark scalars, ALPs and HNL.
- Searches for X17 particle after 10 years may be facing a crucial stage
  - MEG II and PADME able to clarify the situation in the next 2-3 years
- Contribution of postulated X17 to the g-2 puzzle needs deeper scrutiny.



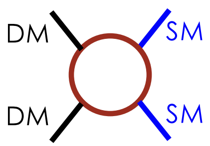
Indirect detection



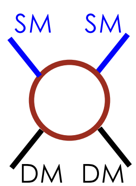
Direct detection



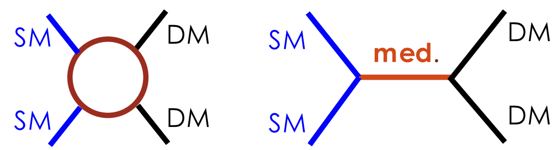
Colliders



Indirect detection



Direct detection



Colliders