The X17 Journey: From Nuclear Experiments to Atomic Electron Motion

Fernando Arias Aragón

June, 25th, 2025

Based on:

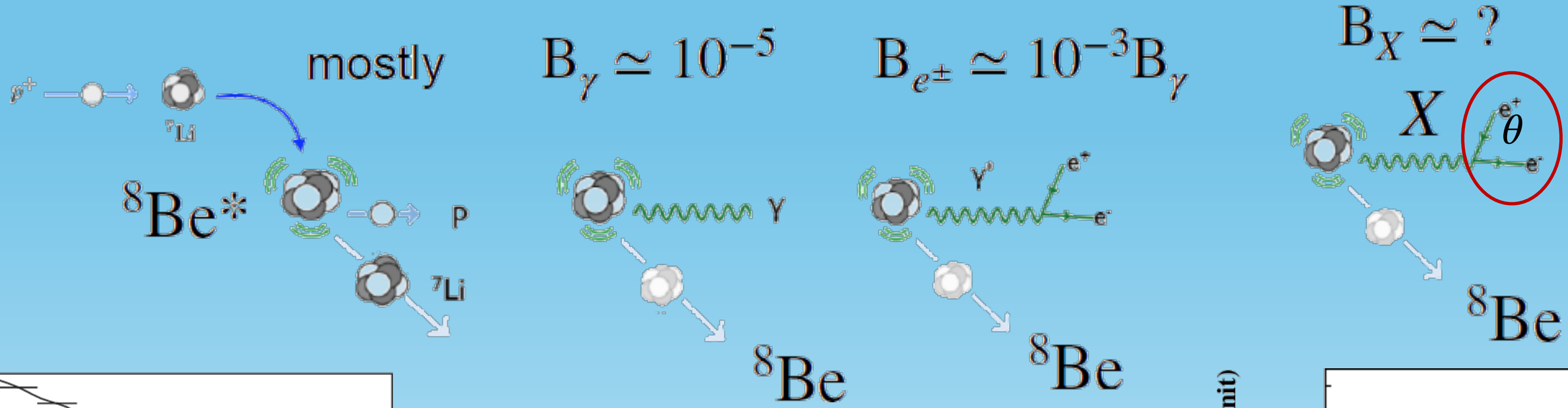
FAA, L. Darmé, G. Grilli di Cortona, E. Nardi, 2403.15387, PRL132(2024)261801
FAA, L. Darmé, G. Grilli di Cortona, E. Nardi, 2407.15941, PRL134(2025)061802
FAA, G. Grilli di Cortona, E. Nardi, L. Veissière, 2504.00100, JHEP06(2025)199
FAA, G. Grilli di Cortona, E. Nardi, C. Toni, 2504.11439

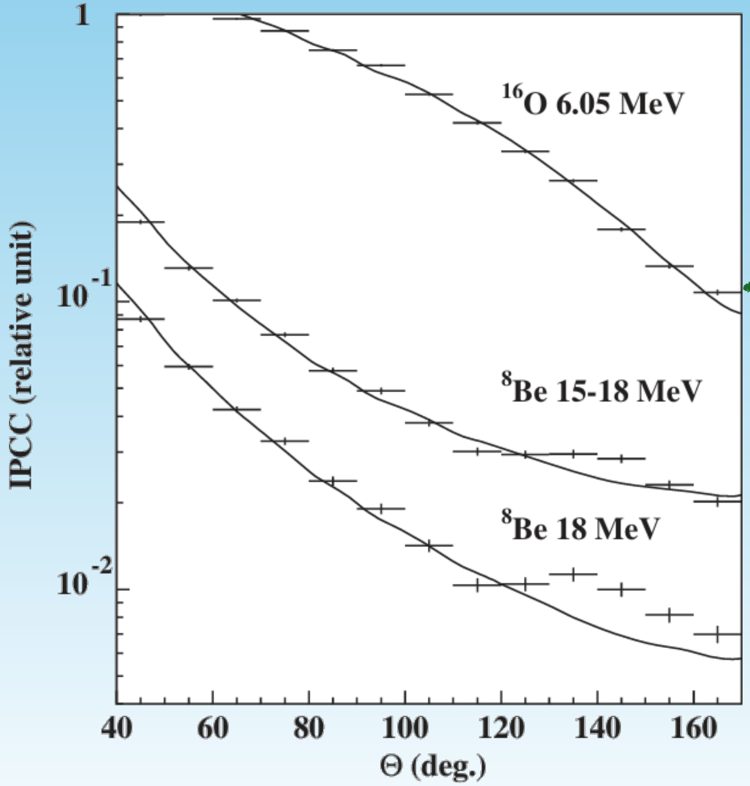
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Overview

- The X17 particle
  - Anomalies in Nuclear Transitions
  - Consistency and Explanation
- A particle physics probe: PADME
  - Resonant Production of the X17
  - Signal Shape: Atomic Electron Motion
  - The PADME Excess
- Atoms as Electron Accelerators
  - a_μ
  - New Physics Searches

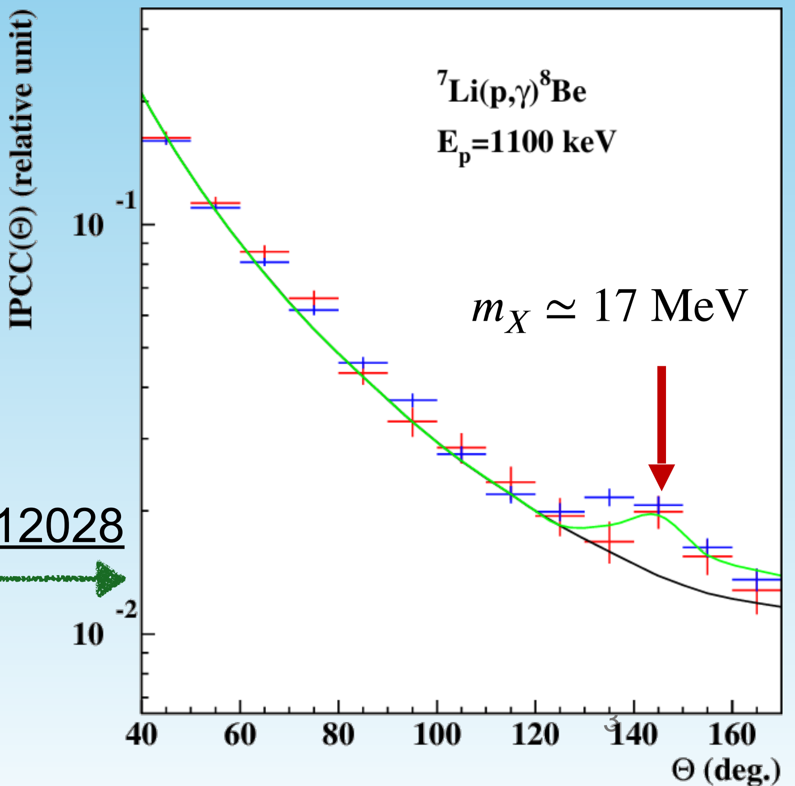
The X17 Particle – Nuclear Anomalies





Krasznahorkay et al., PRL116(2016)042501

Krasznahorkay et al., J.Phys.Conf.Ser.1056 012028



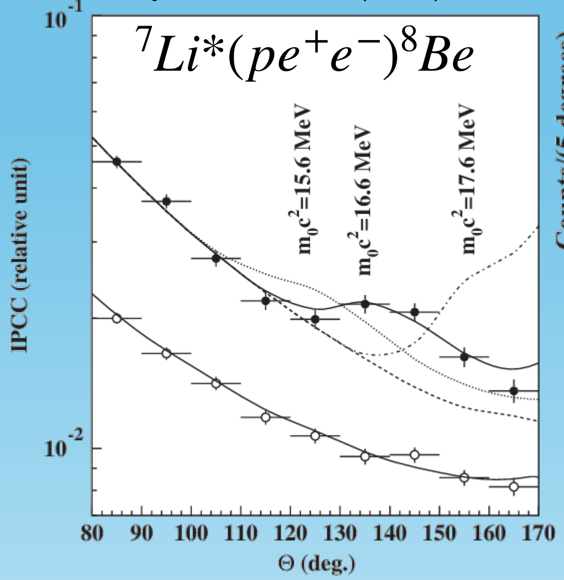
The X17 Particle – Nuclear Anomalies

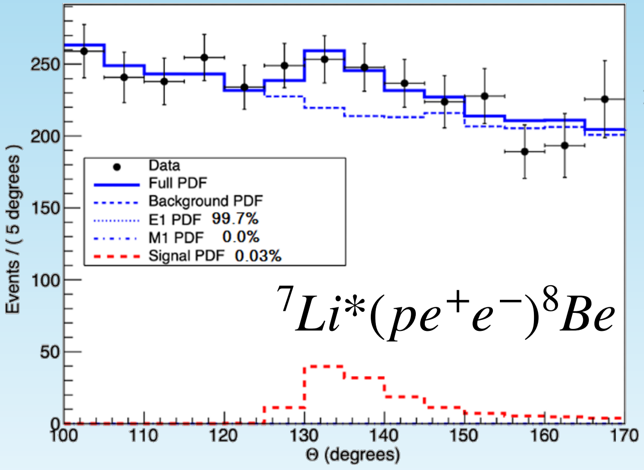
Timeline:

- **2015**: First anomaly observed in $^{8}Be^{*}(18.15\ MeV) \rightarrow g.s.$ Krasznahorkay et al., PRL116(2016)042501
- **2017**: Improved setup, similar anomaly in $^{8}Be^{*}(17.64\ MeV) \rightarrow g.s.$ Krasznahorkay et al., EPJ WebConf. 142(2017)01019
- **2018**: ^{8}Be result confirmed, hint at anomaly $^{4}He^{*}(21\ MeV)$ Zakopane Conf., Acta Phys.Polon.B 50(2019)3, 675
- **2019**: Confirmation of ^{4}He excess $(7{,}2\sigma)$ consistent with X17 Krasznahorkay et al., Phys.Rev.C 104(2021)4, 044003
- **2021**: Preliminary results for $^{12}C^{*}(17.2\ MeV)$: large angle excess Krasznahorkay, "Shedding light on X17" workshop
- **2022**: Confirmation of ^{12}C excess Krasznahorkay et al., Phys.Rev.C106(2022)6, L061601
- **04/2023**: Giant dipole resonance anomaly observed in $^{7}Li^{*}(pe^{+}e^{-})^{8}Be$ Krasznahorkay et al., 2308.06473
- **08/2023**: Observation of the ^{8}Be anomaly in a different spectrometer Tran The Anh et al., Universe 10(2024)4, 168
- **11/2024**: MEG-II sees no significant signal at $1{,}5\sigma$ Afanaciev et al., 2411.07994 nucl-ex
- **05/2025**: PADME sees an excess around 17 MeV in $e^{+}e^{-}$ final state Bossi et al., 2505.24797 hep-ex

The X17 Particle – Nuclear Anomalies

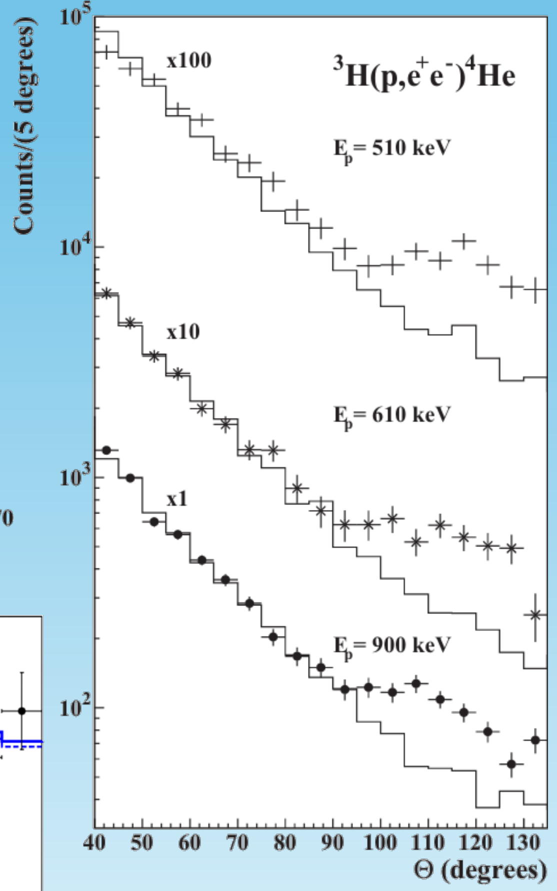
Krasznahorkay et al., PRL116(2016)042501



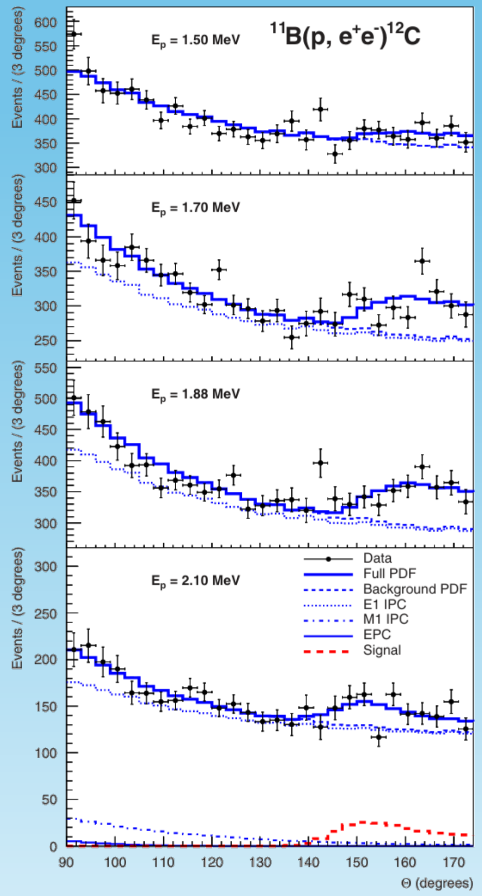


Tran The Anh et al., Universe 10(2024)4, 168

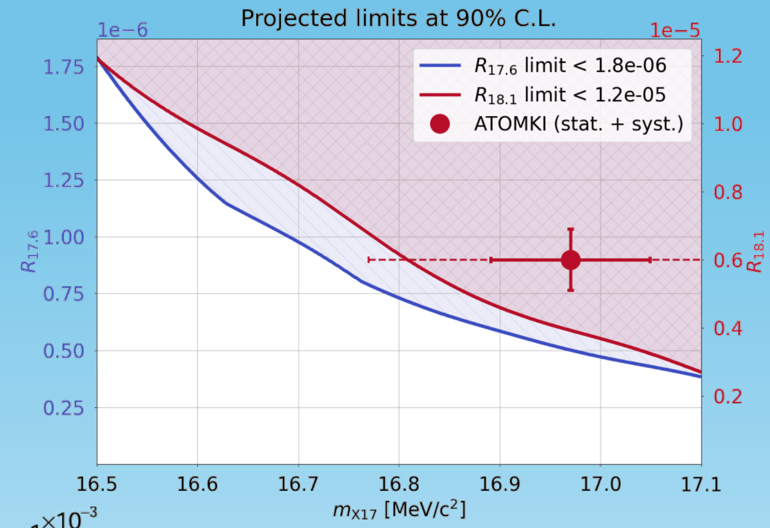
Krasznahorkay et al., Phys.Rev.C 104(2021)4, 044003

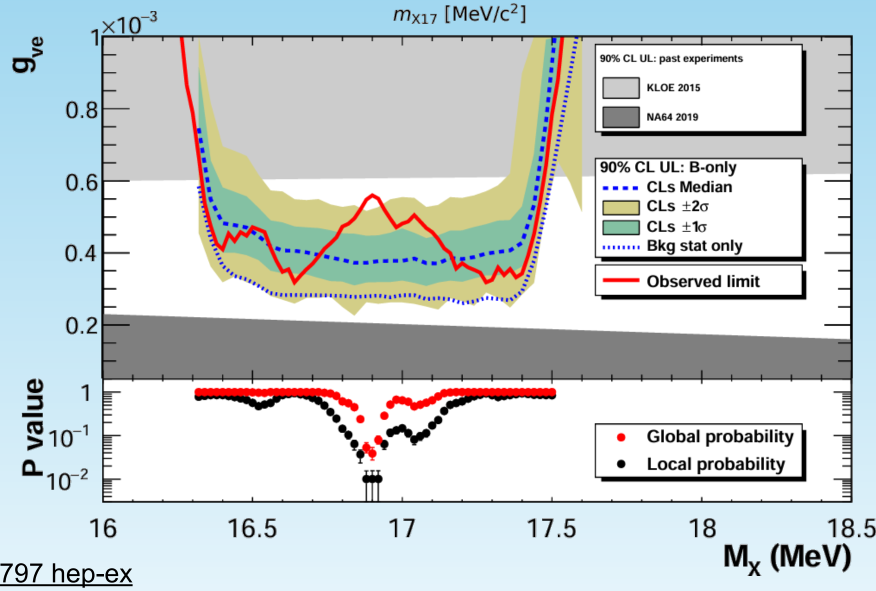


Krasznahorkay et al., Phys.Rev.C 106 (2022) 6, L061601



Afanaciev et al., 2411.07994 nucl-ex

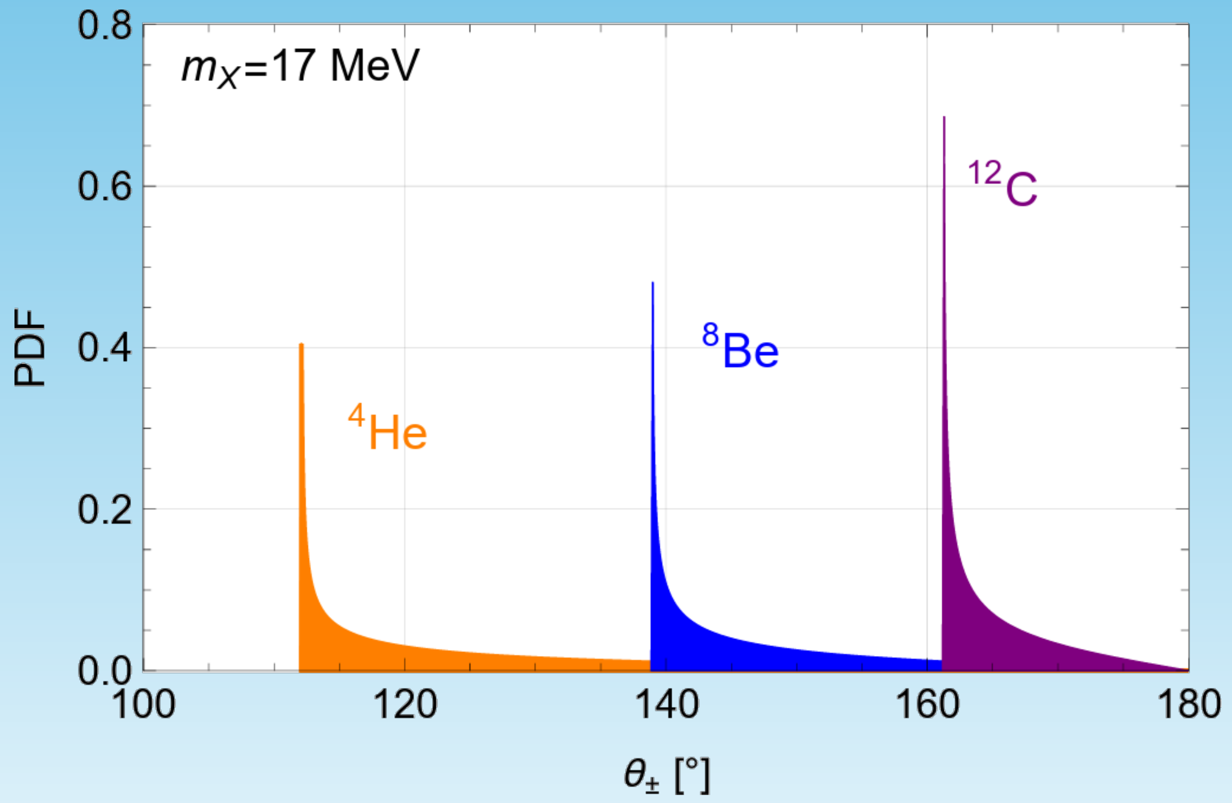




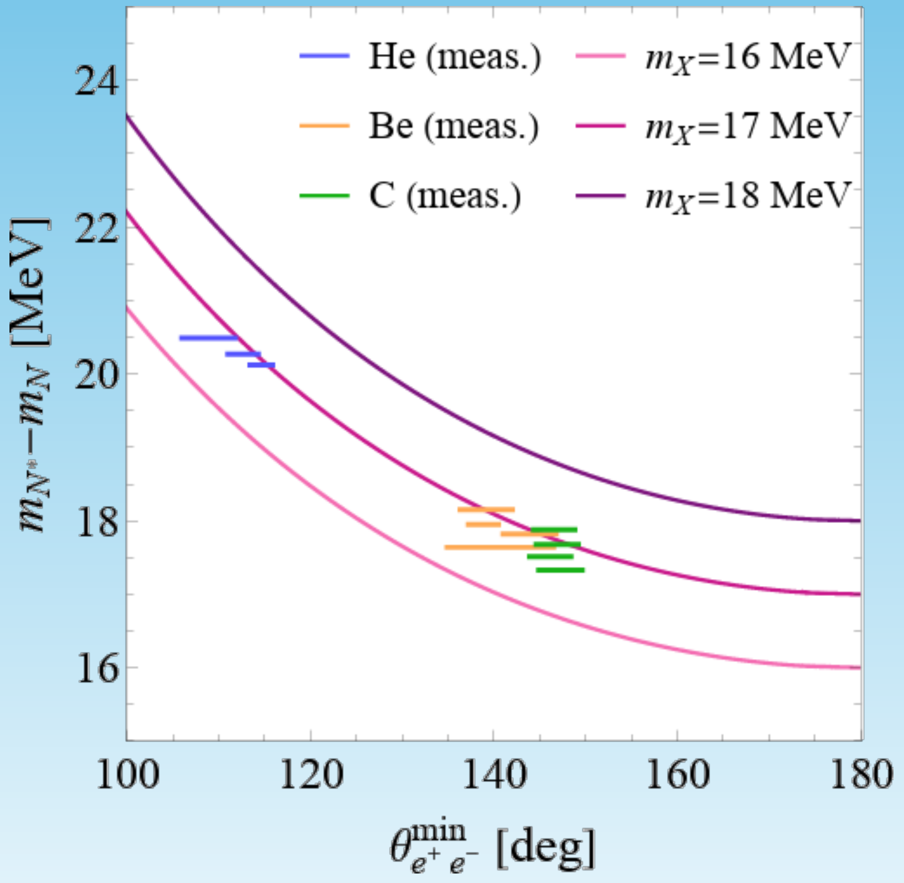
Bossi et al., 2505.24797 hep-ex

The X17 Particle – Consistency and Explanation

- e^+e^- angle θ correlated to mass m_X of single new particle



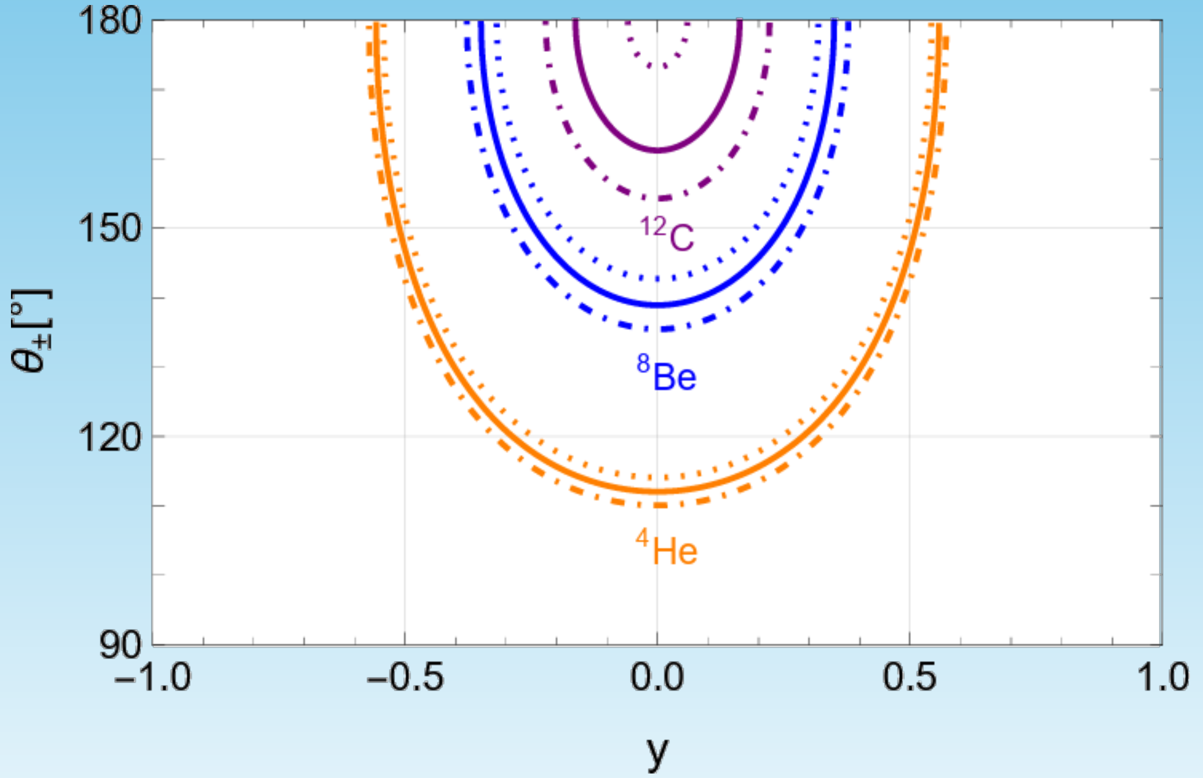
D. Barducci and C. Toni, JHEP 02 (2023) 154



P. B. Denton and J. Gehrlein, Phys.Rev.D 108 (2023) 1, 015009

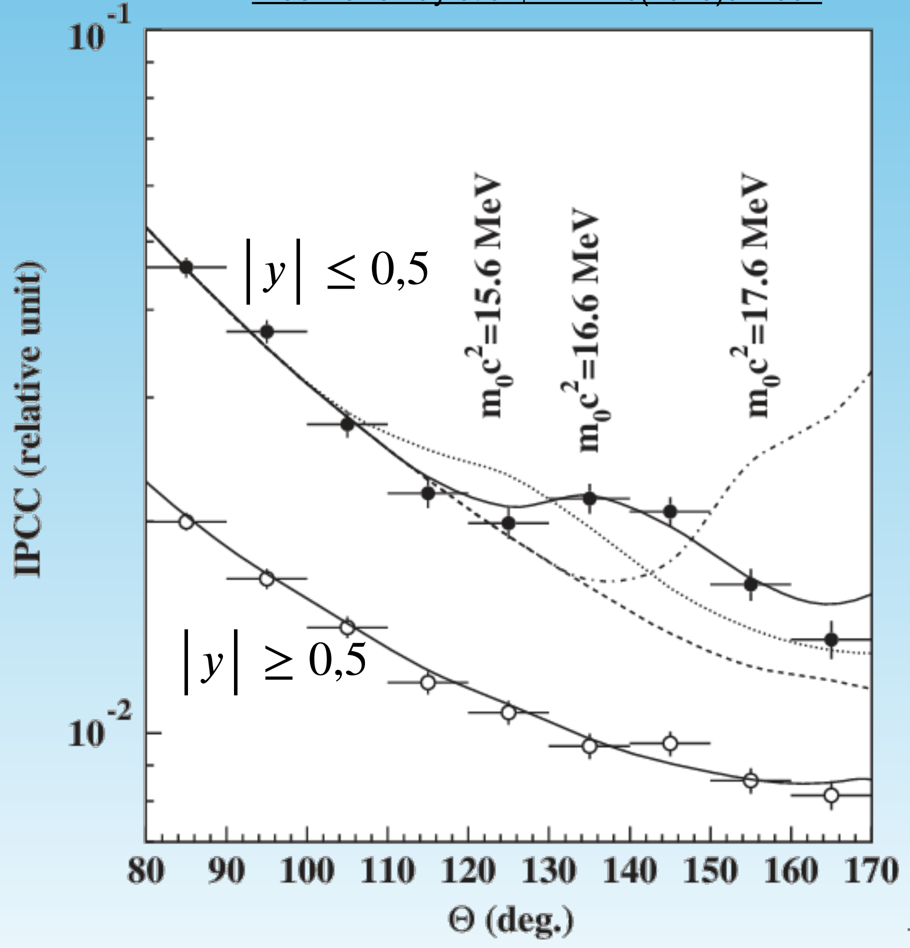
The X17 Particle – Consistency and Explanation

- e^+e^- energy asymmetry $y = \frac{E_- - E_+}{E_- + E_+}$ expected $|y| \leq 0{,}5$ for X17 emission



D. Barducci and C. Toni, JHEP 02 (2023) 154

Krasznahorkay et al., PRL116(2016)042501



The X17 Particle – Consistency and Explanation

- Can the SM explain these anomalies?
  - Multipole interference ✗ Zhang and Miller, Phys.Lett.B 773 (2017) 159-165
  - Nuclear chain reaction ✗ B. Koch, Nucl.Phys.A 1008 (2021) 122143
  - Higher order processes: peaked distributions ? P. Kálmán and T. Keszthelyi, Eur.Phys.J.A 56 (2020) 8, 205
  - Full second-order calculation ✓ (for ^{8}Be) Aleksejevs et al., 2102.01127
  - *Ab-initio* No-Core Shell Model with Continuum: consistent with ATOMKI background ✗ Gysbers et al., Phys.Rev.C 110 (2024) 1, 015503
  - *Ab-initio* detailed study of ^{4}He reaction: no bumps in SM ✗ Viviani et al., Phys.Rev.C 105 (2022) 1, 014001

<u>No conclusive explanation within the SM</u>

The X17 Particle – Consistency and Explanation

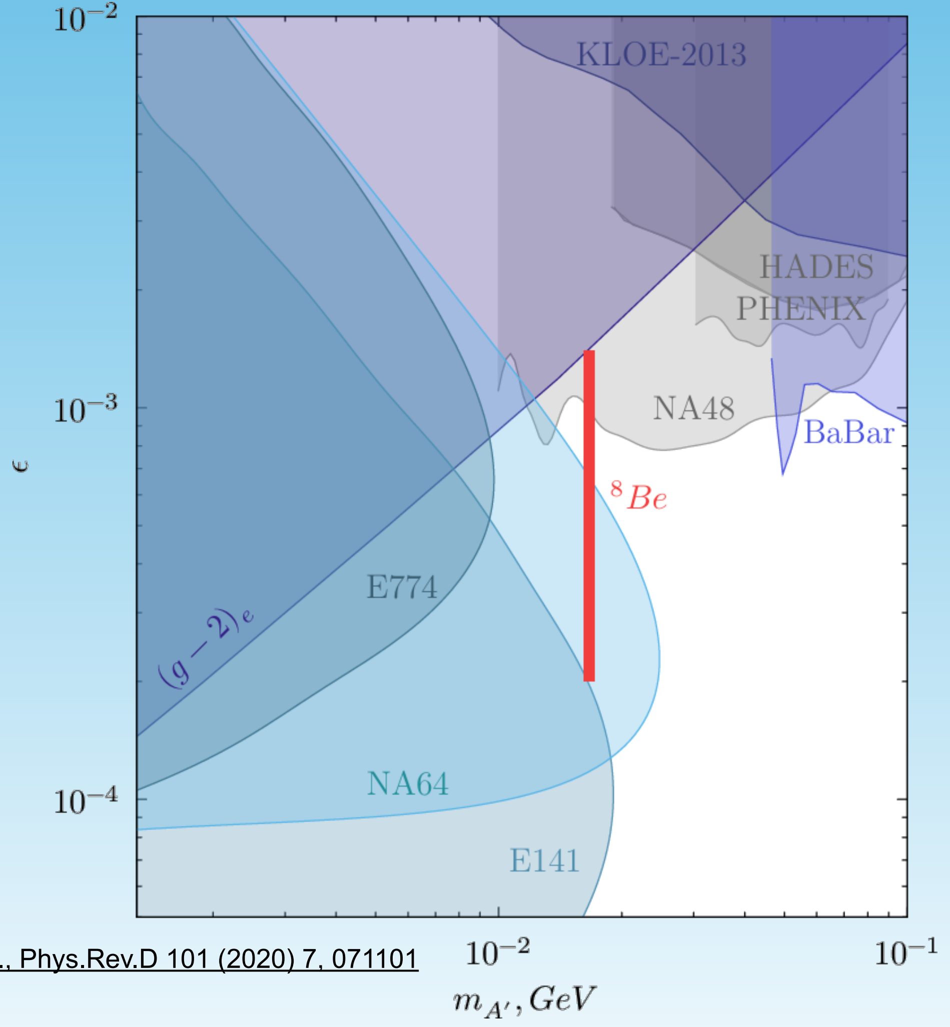
- If not SM, then what?

Process $N^* \to N$	X boson spin parity: Axialvector	Vector	Pseudoscalar	Scalar
$^{8}Be(18.15) \to {}^{8}Be$	1	0, 2	1	/
$^{8}Be(17.64) \to {}^{8}Be$	1	0, 2	1	/
$^{4}He(21.01) \to {}^{4}He$	/	1	0	/
$^{4}He(20.21) \to {}^{4}He$	1	/	/	0
$^{12}C(17.23) \to {}^{12}C$	0, 2	1	/	1

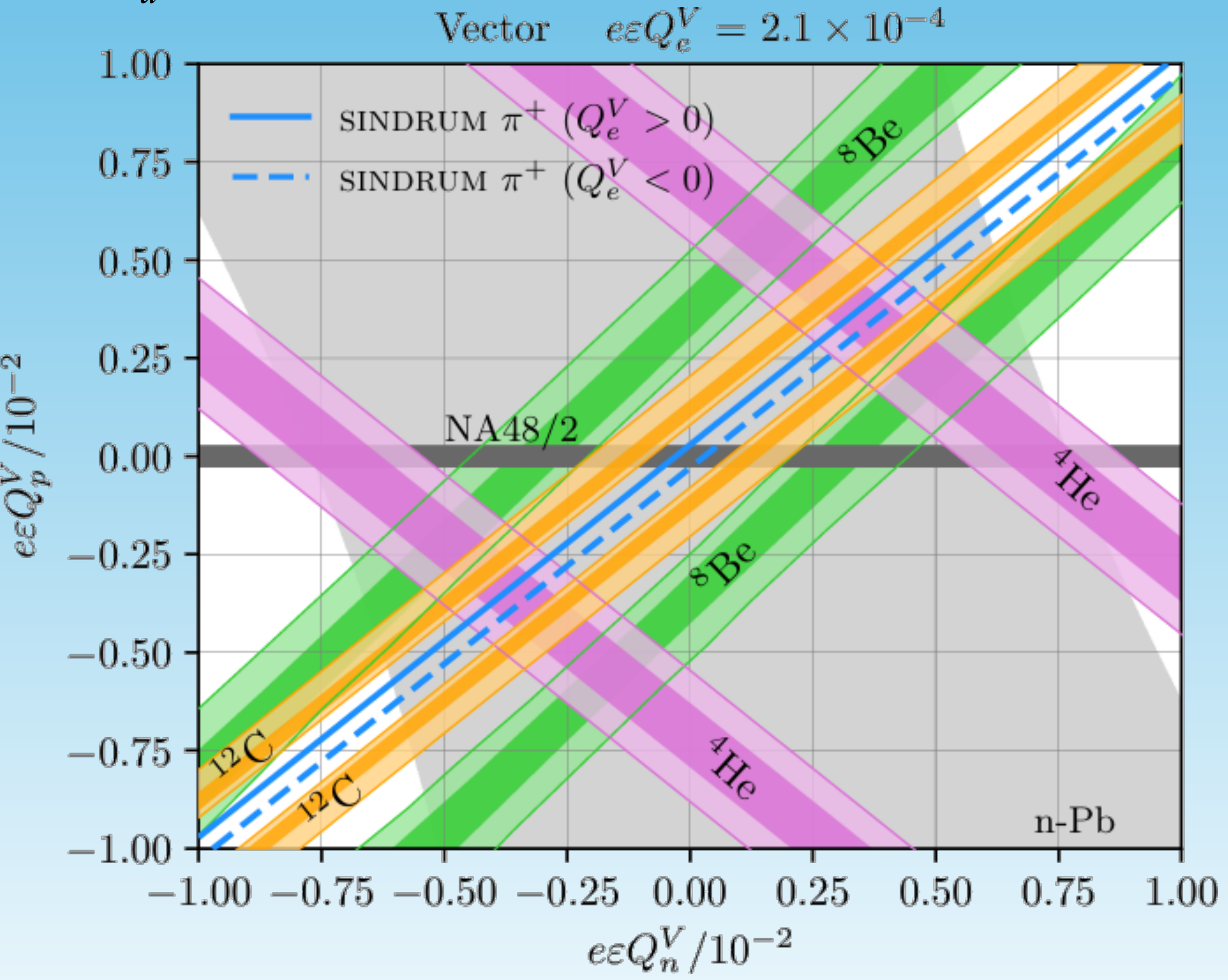
Adapted from D. Barducci and C. Toni, JHEP 02 (2023) 154

The X17 Particle – Consistency and Explanation

- $\pi \to X + \gamma$ requires pion/protophobia: $\varepsilon_d \approx -2\varepsilon_u$



NA64 Collab., Phys.Rev.D 101 (2020) 7, 071101



M. Hostert and M. Pospelov, Phys.Rev.D 108 (2023) 5, 05501

The X17 Particle – Summary

- Anomalies seen in three different nuclei, two *independent* experiments
- Not single or last bin effects: clear bumps
- A single new particle greatly improves fits
- SM fails to give conclusive explanations
- (Axial)vector kinematically (θ and y) and dynamically (coupling and BR) robust

A test independent of nuclear physics? → PADME

PADME – Resonant Production

- Beam Test Facility @ Laboratori Nazionali di Frascati: positron accelerator

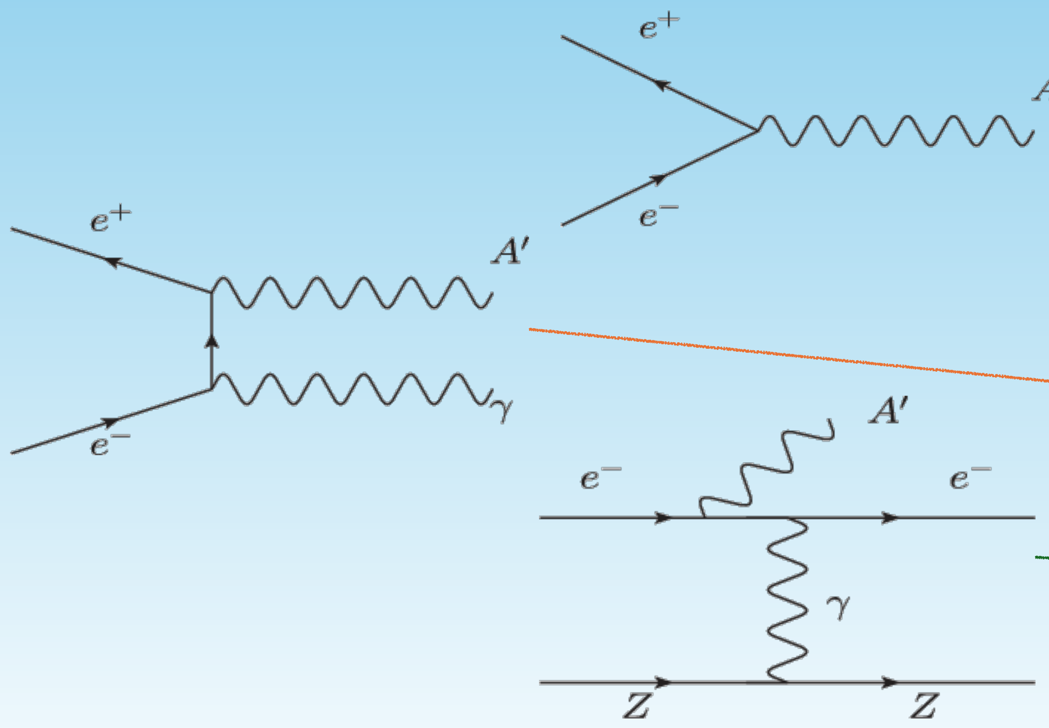
$$E_+ \in [150{,}500]\ \text{MeV} \rightarrow \sqrt{s} \in [12.5,\ 22.5]\ \text{MeV}$$

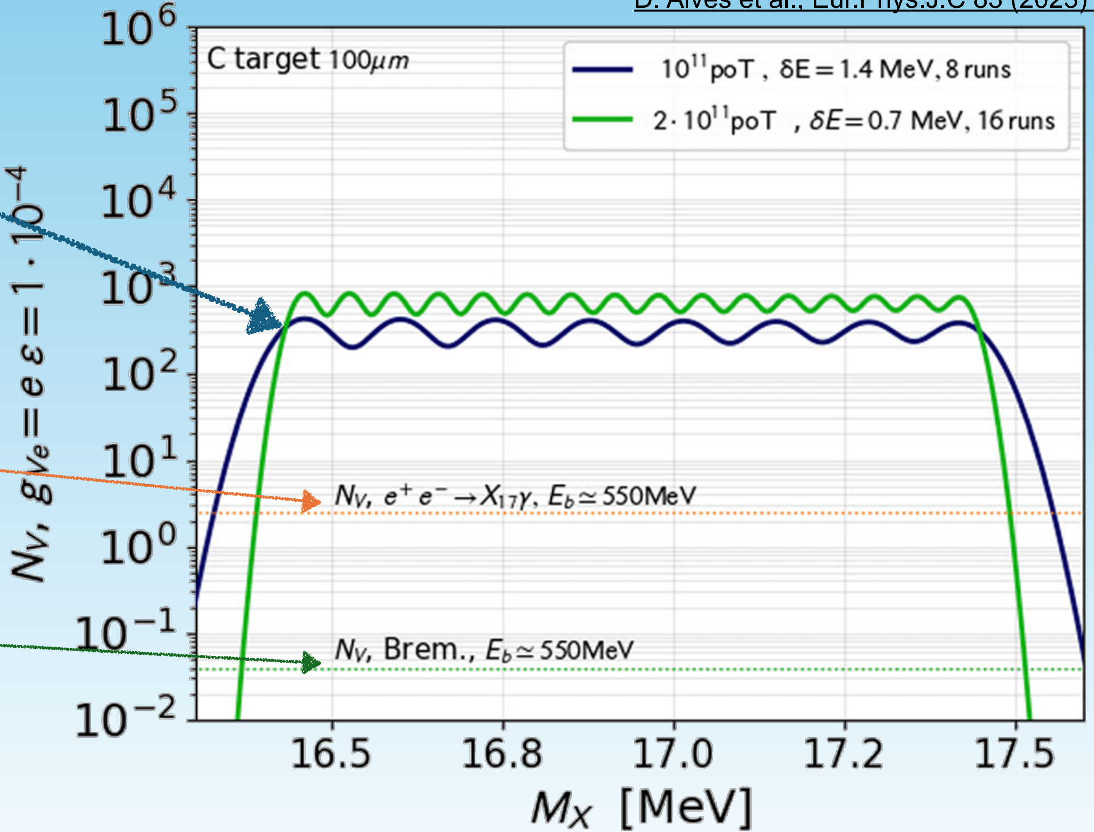
Perfect for X17!

- Resonant e^+e^- annihilation into the X17

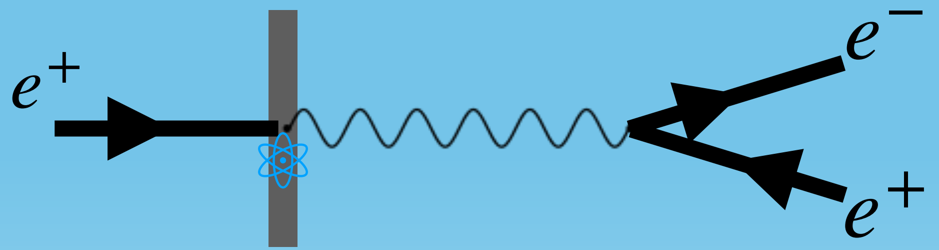
Nardi, Carvajal, Ghoshal, Meloni and Raggi, Phys.Rev.D 97 (2018) 9, 095004

D. Alves et al., Eur.Phys.J.C 83 (2023) 3, 230





PADME – Resonant Production



Thin target

Energy loss negligible, must change beam energy

$$\ell_{\text{target}} \ll X_0$$

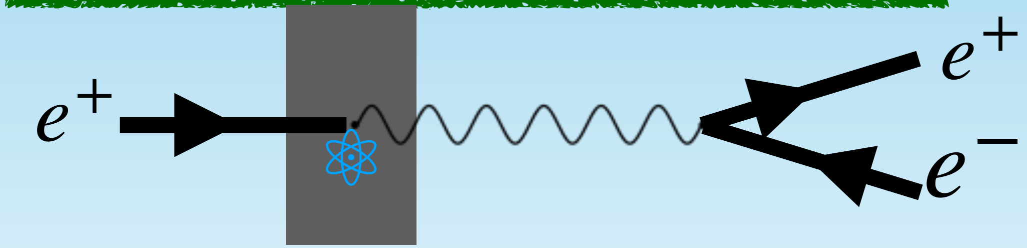
$$N_{A'} = N_{\text{poT}} \frac{N_{\text{Av}} Z \rho}{A} \ell_{\text{target}} \int dE\, \mathcal{G}(E, E_B, \sigma_B)\, \sigma(E)$$

Number of target electrons

Gaussian beam energy spread

Probability that the dark photon decays before the detector but outside the target

Probability of finding a positron with E_e after passing through t radiation lengths



Thick target

Energy loss as scanning method

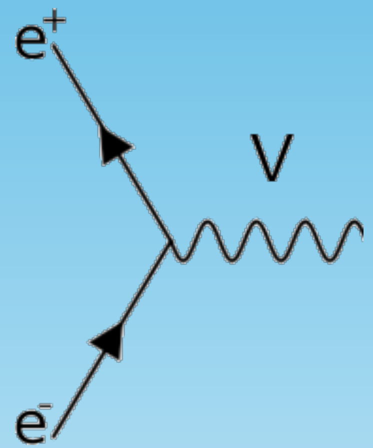
$$\ell_{\text{target}} \gtrsim X_0$$

$$N_{A'} = \left(1 - e^{\frac{z_D - z_{\text{det}}}{\ell_\epsilon}}\right) \frac{N_{\text{poT}} N_{\text{Av}} Z \rho X_0}{A} \int_0^T dt \frac{d\mathcal{P}(t, z_D, \ell_\epsilon)}{dt} \int dE_e \int dE\, \mathcal{G}(E, E_B, \sigma_B)\, I(E, E_e, t)\, \sigma(E_e)$$

[Nardi et al., Phys. Rev. D (2018) 9, 095004]

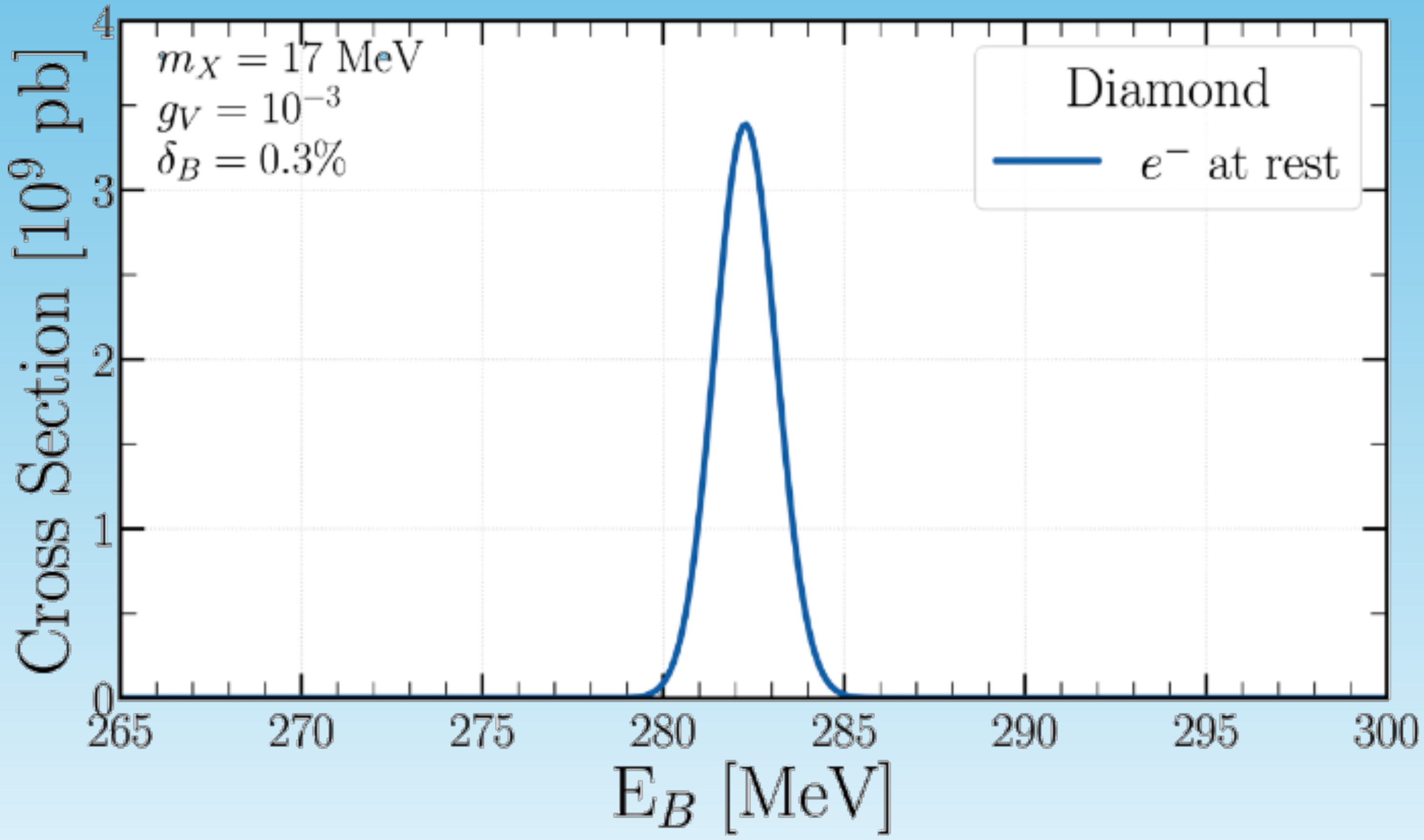
PADME – Resonant Production

Free-electron-at-rest (**FEAR**) approximation



$$\sigma_{\rm res}(E_B) \simeq \frac{\pi g_V^2}{2m_e}\mathcal{G}(E_B, E_{\rm res}, \sigma_{E_B})$$

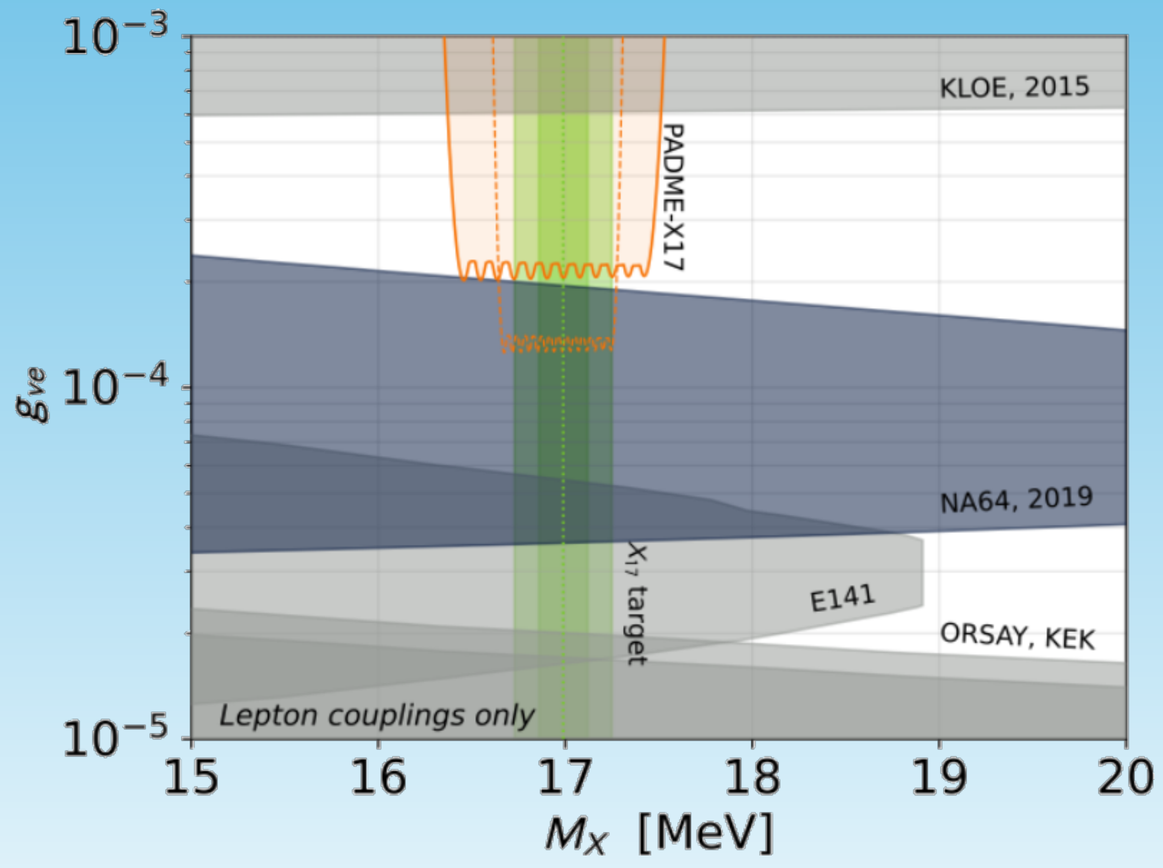
$$E_{\rm res} = \frac{m_V^2}{2m_e} - m_e$$



PADME – Resonant Production

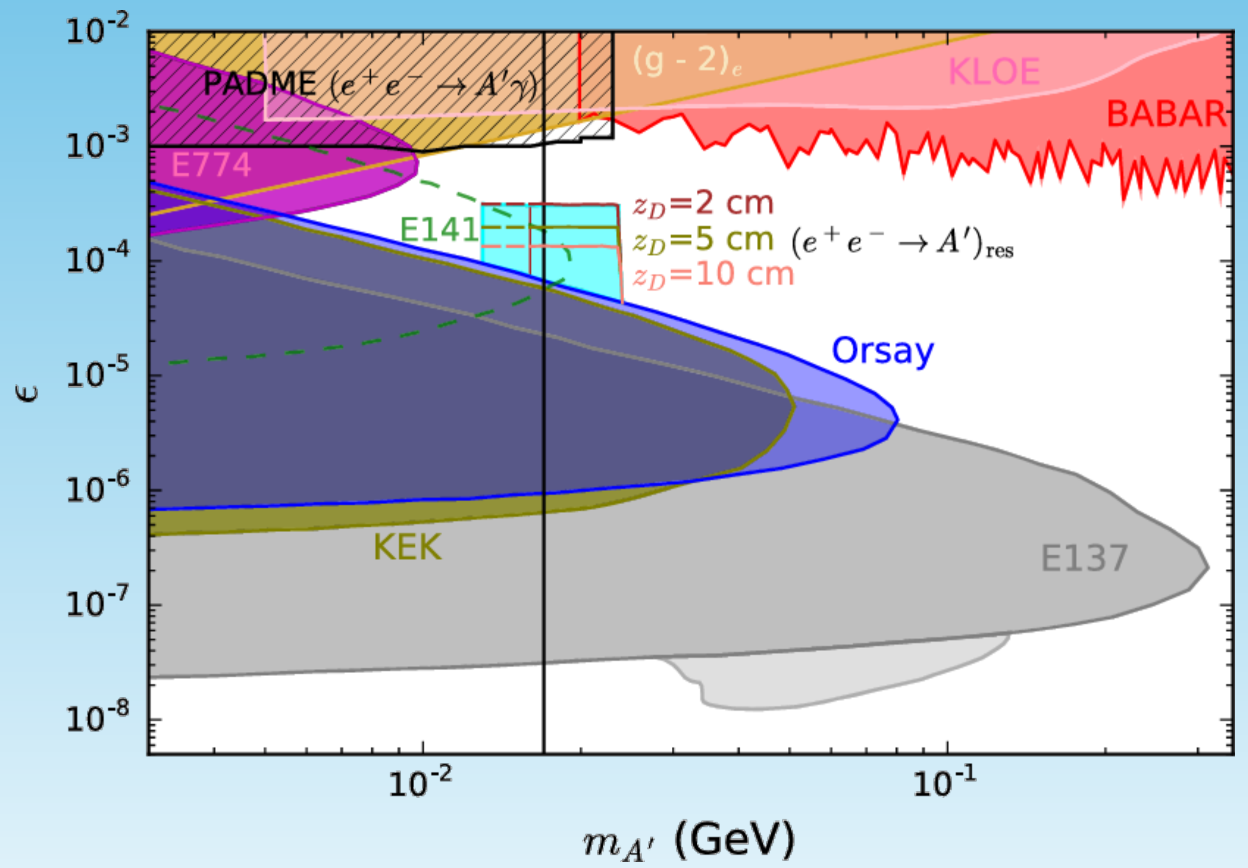
PADME strategy for the X_{17} search

[Darmé, Mancini, Nardi, Raggi, Phys. Rev. D 106 (2022) 11, 115036]



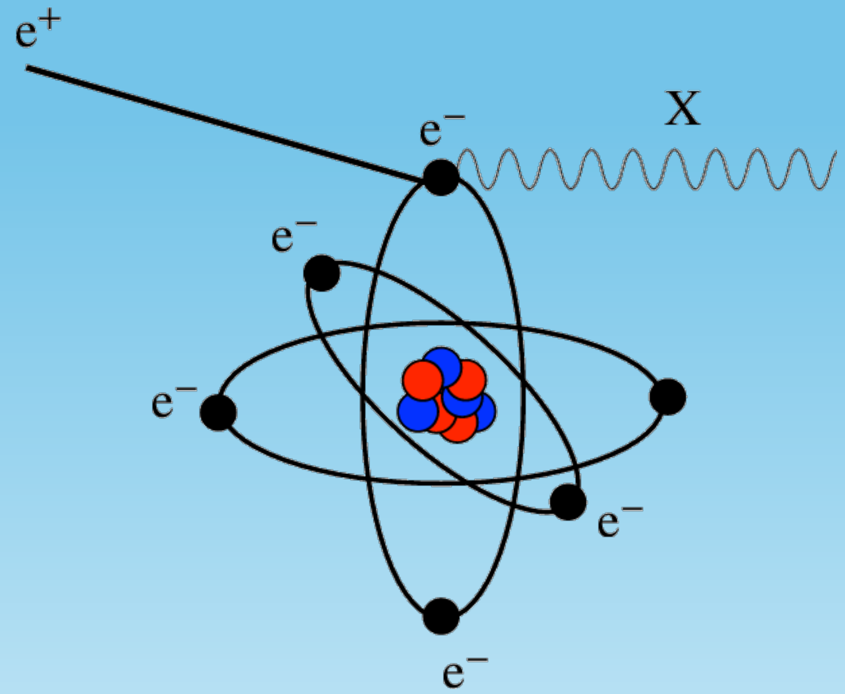
Thin target

Nardi te al., Phys. Rev. D (2018) 9, 09504]



Thick target

PADME – Atomic Electron Motion



Naive estimate:

$\langle \beta_{n\ell} \rangle = \alpha Z_{\text{eff}}^{n\ell}$

[J. Chem. Phys. 47 (1967) 4 1300-1307]

$Z_{\text{eff}}^{1s} = 5.67 \qquad \langle \beta_{1s} \rangle = 0.041$

$Z_{\text{eff}}^{2s} = 3.22 \qquad \langle \beta_{2s} \rangle = 0.024$

$Z_{\text{eff}}^{2p} = 3.14 \qquad \langle \beta_{2p} \rangle = 0.023$

using $\beta = \langle \beta_{1s} \rangle = 0.04$

$\sqrt{s} \simeq 17.0\,\text{MeV} \qquad (E_b \sim 282.2\ \text{MeV})$

$\sqrt{s'_+} = 17.3\,\text{MeV} \qquad (E_b \sim 293.5\ \text{MeV})$

$\sqrt{s'_-} = 16.7\,\text{MeV} \qquad (E_b \sim 270.9\ \text{MeV})$

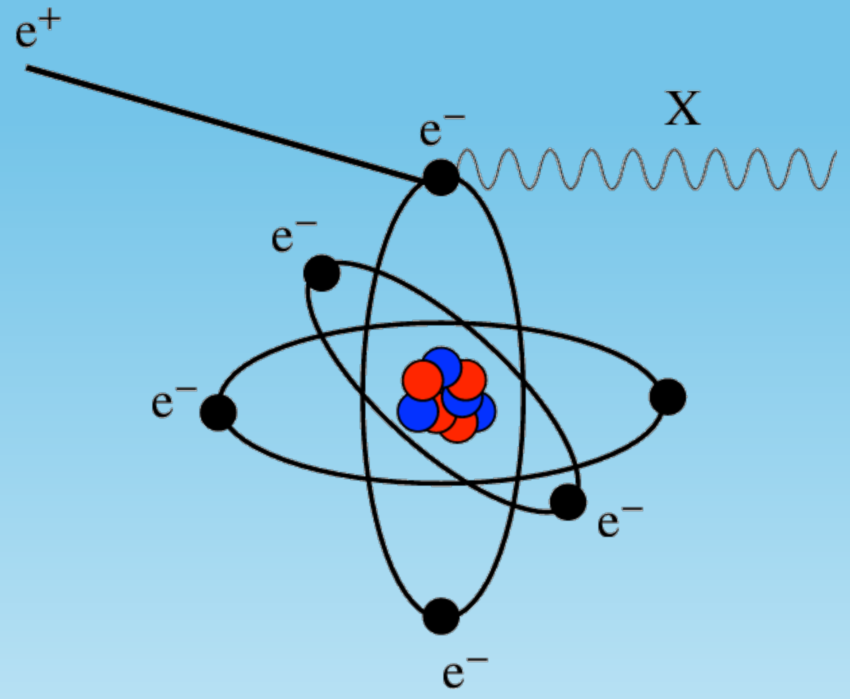
$p^+ \simeq (E_b, E_b)$

$p^- = (m_e, \pm \gamma m_e \beta)$

$s' = m_e^2(2 - \beta^2\gamma^2) + 2\gamma m_e E_b(1 \pm \beta)$

The centre of mass energy for positron annihilation can differ sizeably with respect to the electrons at rest assumption!

PADME – Atomic Electron Motion



Attempt using the virial theorem

Plestid and Wise, Phys.Rev.D 110 (2024) 5, 056032

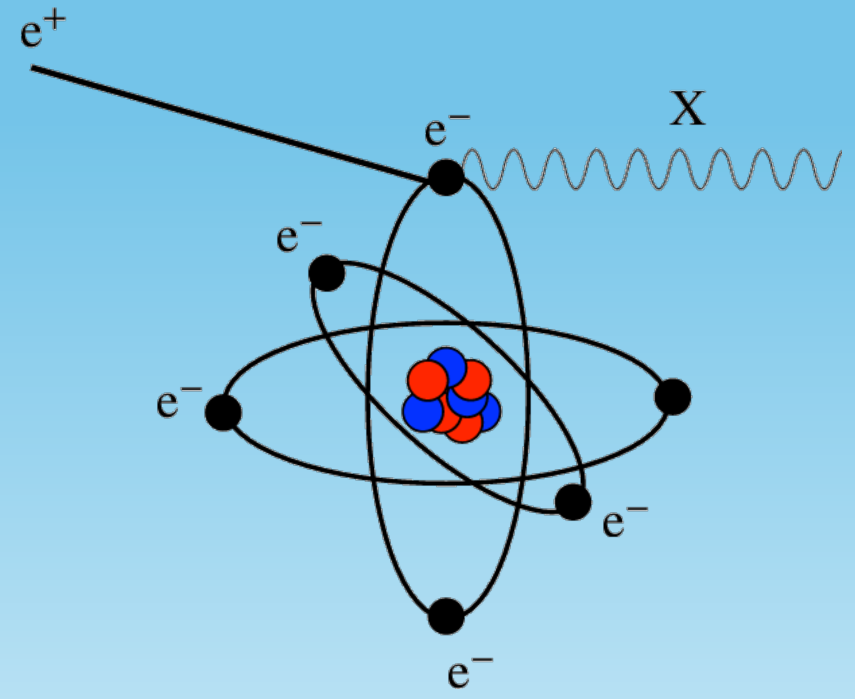
$$\mathrm{d}\sigma \simeq \mathrm{d}\sigma_0 + \mathrm{d}\sigma_{\mathcal{B}}$$

$$\mathrm{d}\sigma_{\mathcal{B}} = \frac{1}{Z_A m_e}\left(-\frac{7}{3}\epsilon_A - \langle \hat{V}_1 \rangle_A\right)\mathrm{d}\sigma_0$$

$$\langle \hat{V}_1 \rangle_A = Z_A \times \int \mathrm{d}^3 r \quad n_A(\mathbf{r})\left(\frac{-Z_A \alpha}{|\mathbf{r}|}\right)$$

Virial theorem does not account for fast electrons

PADME – Atomic Electron Motion

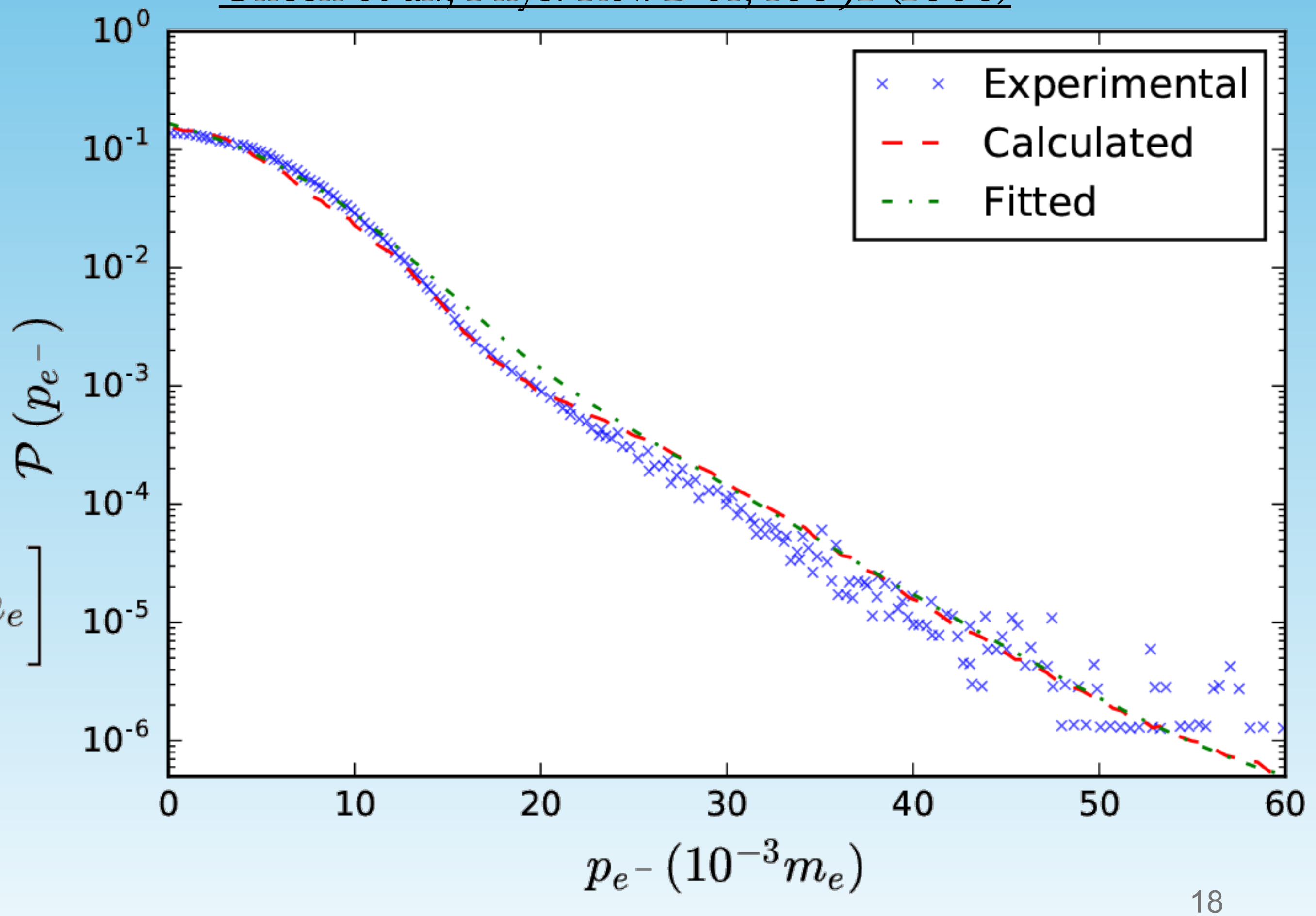


$$s(v_e,\chi) = 2m_e\left[E_e\left(1-\mathcal{P}(v_e)v_e\frac{1}{2}s_\chi c_\chi\right)+m_e\right]$$

Nardi et al., Phys.Rev.D 97 (2018) 9, 095004

Ad-hoc inclusion of electron motion

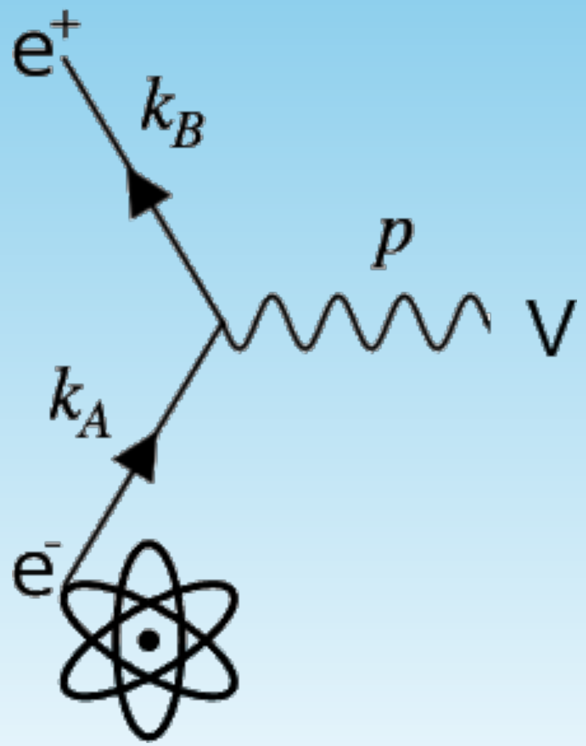
Ghosh et al., Phys. Rev. B 61, 10092 (2000)



PADME – Atomic Electron Motion

[Peskin-Schroeder (or any other text-book)]

$$d\sigma_q = \frac{d^3p}{(2\pi)^3} \int \frac{d^3k_A}{(2\pi)^3} \int \frac{d^3k_B}{(2\pi)^3} \frac{(2\pi)^4 \delta(E_A + E_B - E_X)\delta^{(3)}(\vec{k}_A + \vec{k}_B - \vec{p})}{2E_X 2E_{k_A} 2E_B \left| v_A - v_B \right|} \left| \phi_{A,q}(\vec{k}_A) \right|^2 \left| \mathcal{M}(k_A, k_B \to p) \right|^2 \left| \phi_B(\vec{k}_B) \right|^2$$



Atomic electron quantum numbers

Wavefunctions

Matrix element

PADME – Atomic Electron Motion

[Peskin-Schroeder (or any other text-book)]

$$d\sigma_q = \frac{d^3p}{(2\pi)^3} \int \frac{d^3k_A}{(2\pi)^3} \int \frac{d^3k_B}{(2\pi)^3} \frac{(2\pi)^4 \delta(E_A + E_B - E_X)\delta^{(3)}(\vec{k}_A + \vec{k}_B - \vec{p})}{2E_X 2E_{k_A} 2E_B \left| v_A - v_B \right|} \left| \phi_{A,q}(\vec{k}_A) \right|^2 \left| \mathcal{M}(k_A, k_B \to p) \right|^2 \left| \phi_B(\vec{k}_B) \right|^2$$

- Beam positrons are free with momentum p_B

$$\int \frac{dk_B^3}{(2\pi)^3} \left| \phi_B(\vec{k}_B) \right|^2 = 1, \quad \left| \phi_B(\vec{k}_B) \right|^2 = (2\pi)^3 \delta^3 \left(\vec{p}_B - \vec{k}_B \right)$$

- Neglect binding energies

$$E_A \simeq m_e$$

- Isotropic electron momentum distribution

PADME – Atomic Electron Motion

$$\sigma = \int_{k_A^{\min}}^{k_A^{\max}} dk_A \frac{|\mathcal{M}|^2 \, k_A n(k_A)}{16\pi p_B |E_B k_A x_0(k_A) - E_{k_A} p_B|}$$

$$x_0(k_A) = \frac{2E_A E_B + 2m_e^2 - m_X^2 - k_A^2}{2k_A p_B}$$

$$k_A^{\max,\min} = \left| p_B \pm \sqrt{(E_A + E_B)^2 - m_X^2} \right|$$

$$n(\vec{k}_A) = \sum_{n,\ell} |\phi_{n,\ell}(\vec{k}_A)|^2$$

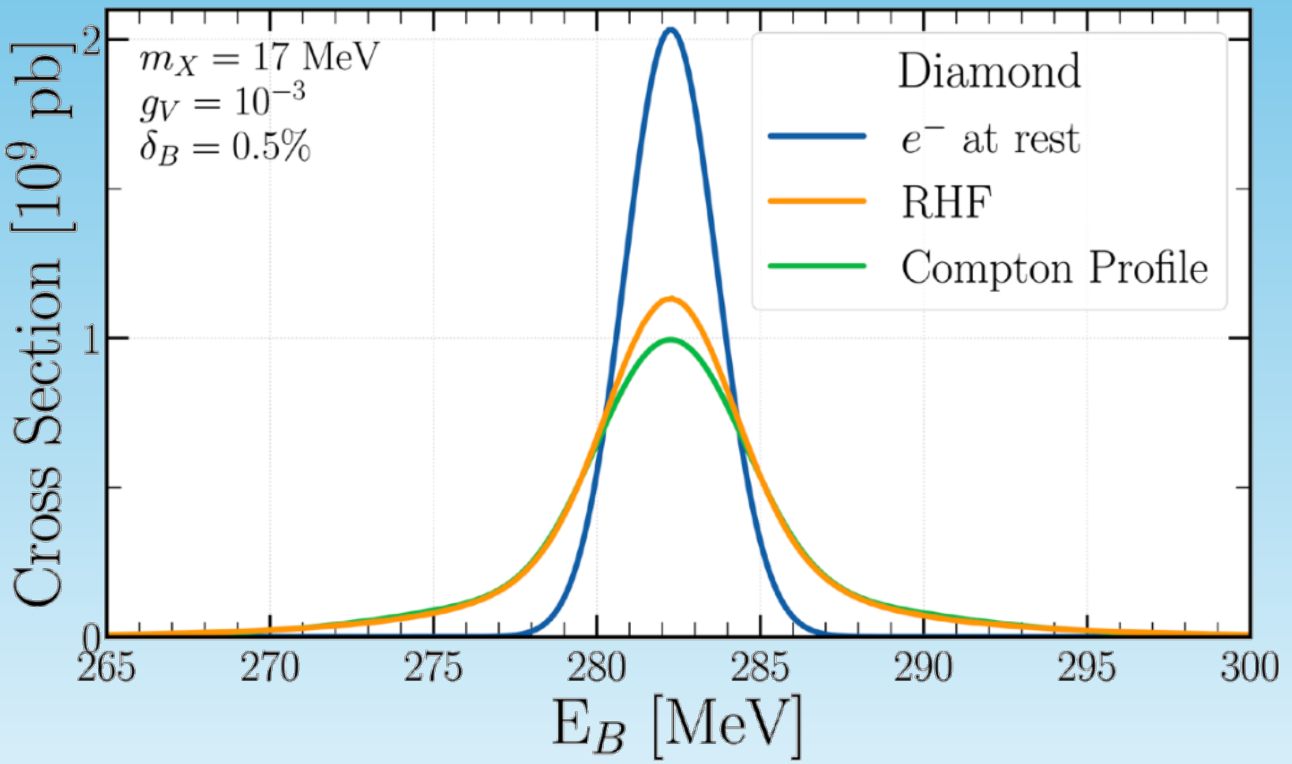
Theory Slater Type Orbitals, hybridization, Hartree Fock computations, etc

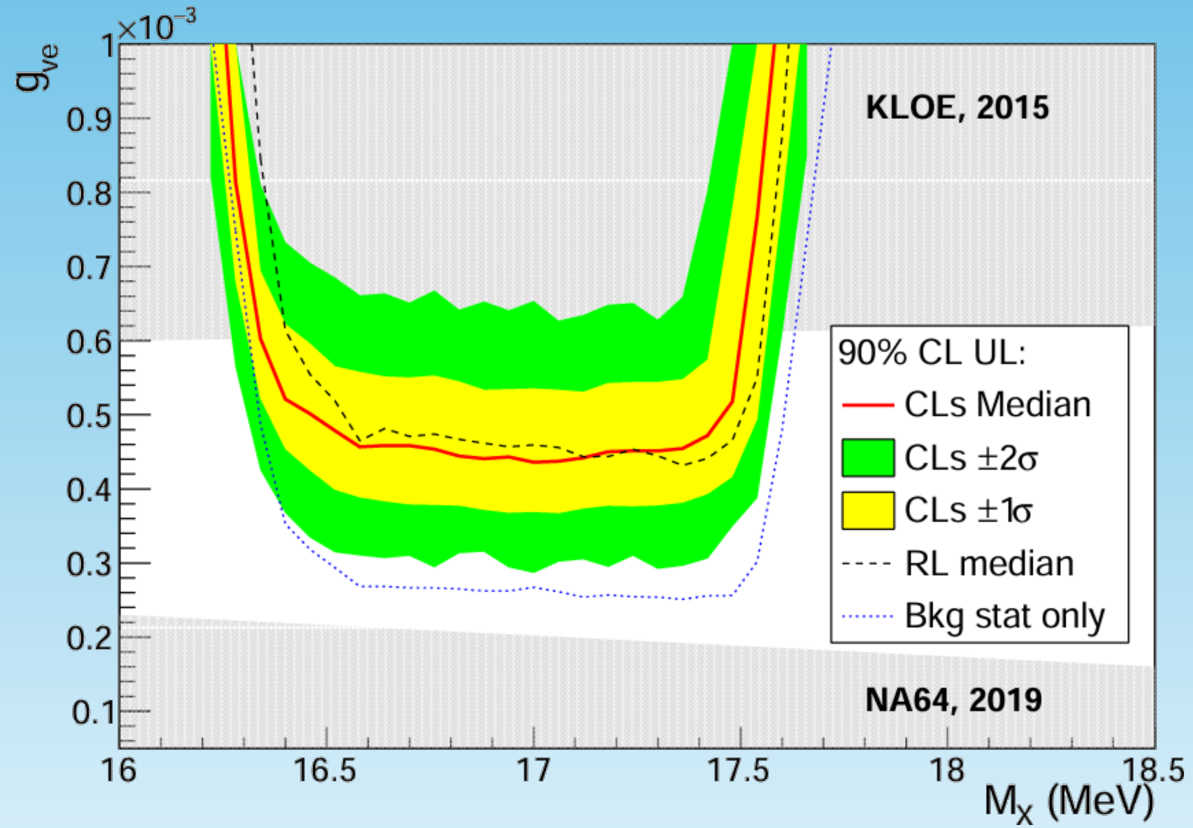
Data Compton Profile

PADME – Atomic Electron Motion

[PADME Collaboration + **FAA**, Darmé, Grilli di Cortona, Nardi, JHEP 06(2025)040]

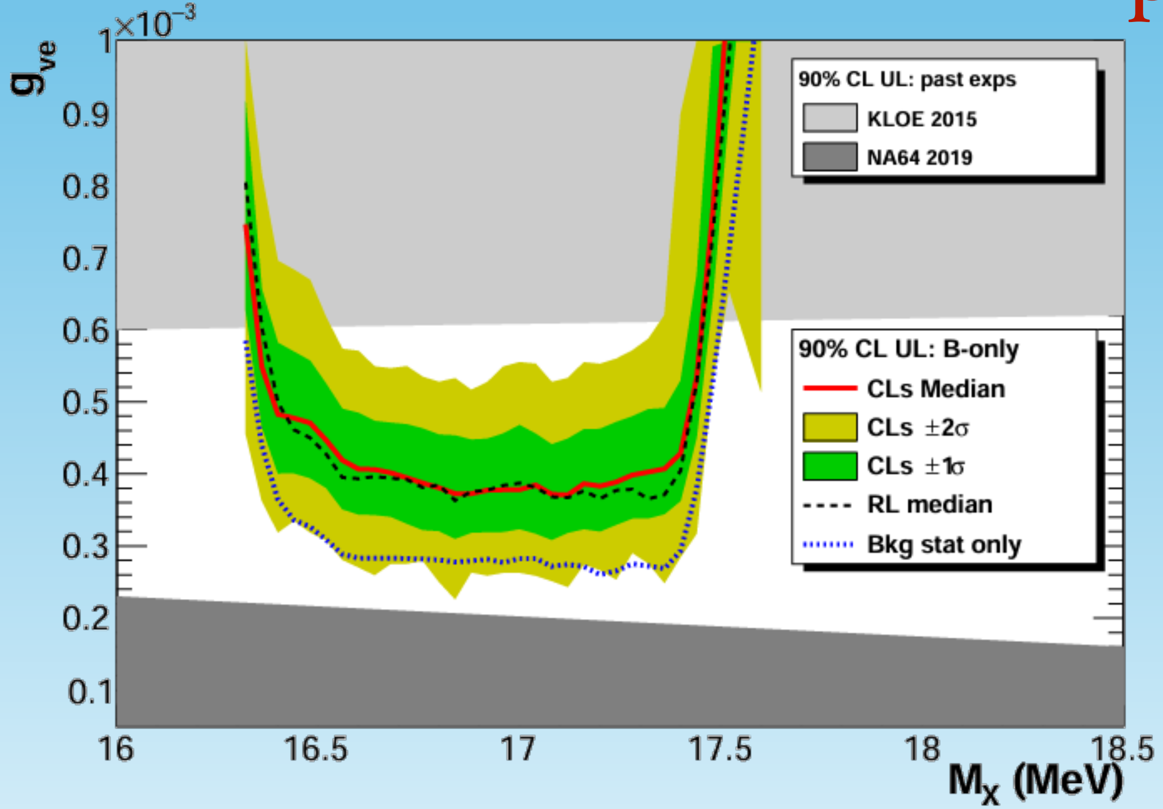
[**FAA**, Darmé, Grilli di Cortona, Nardi, PRL132(2024)261801, arXiv:2403.15387]



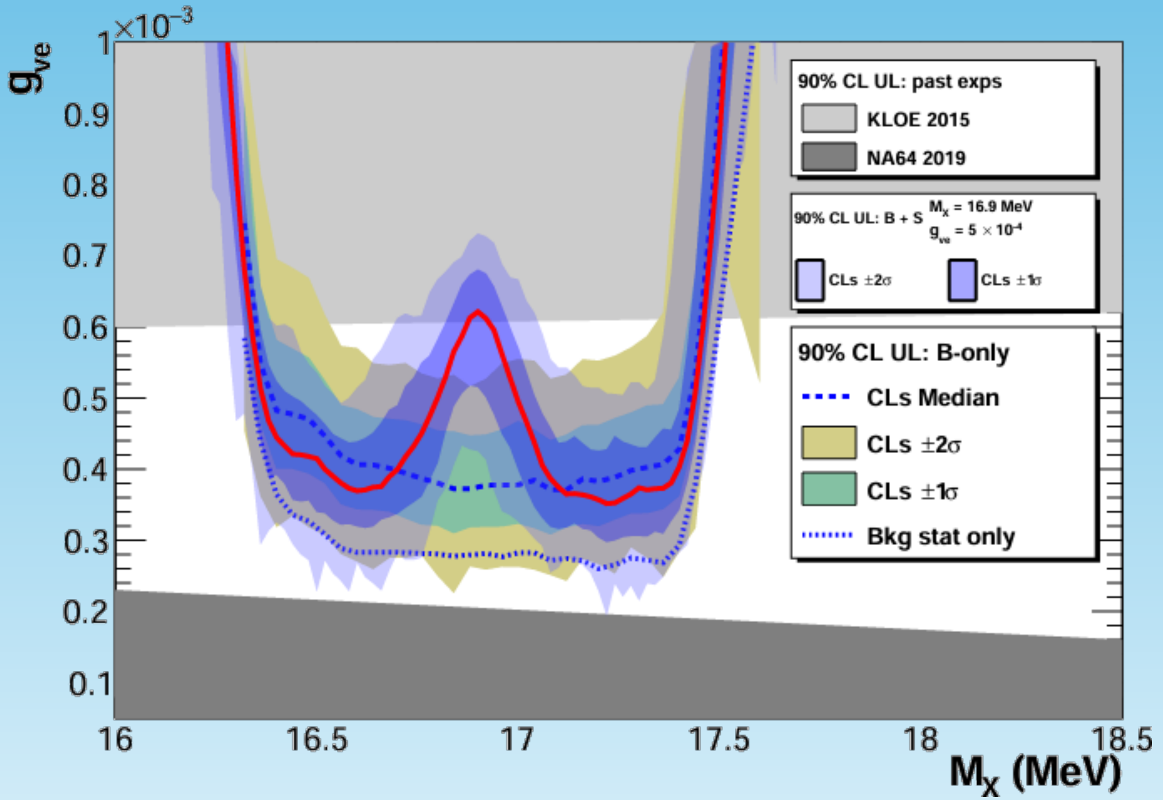


The Excess at PADME

Expectation



Without signal



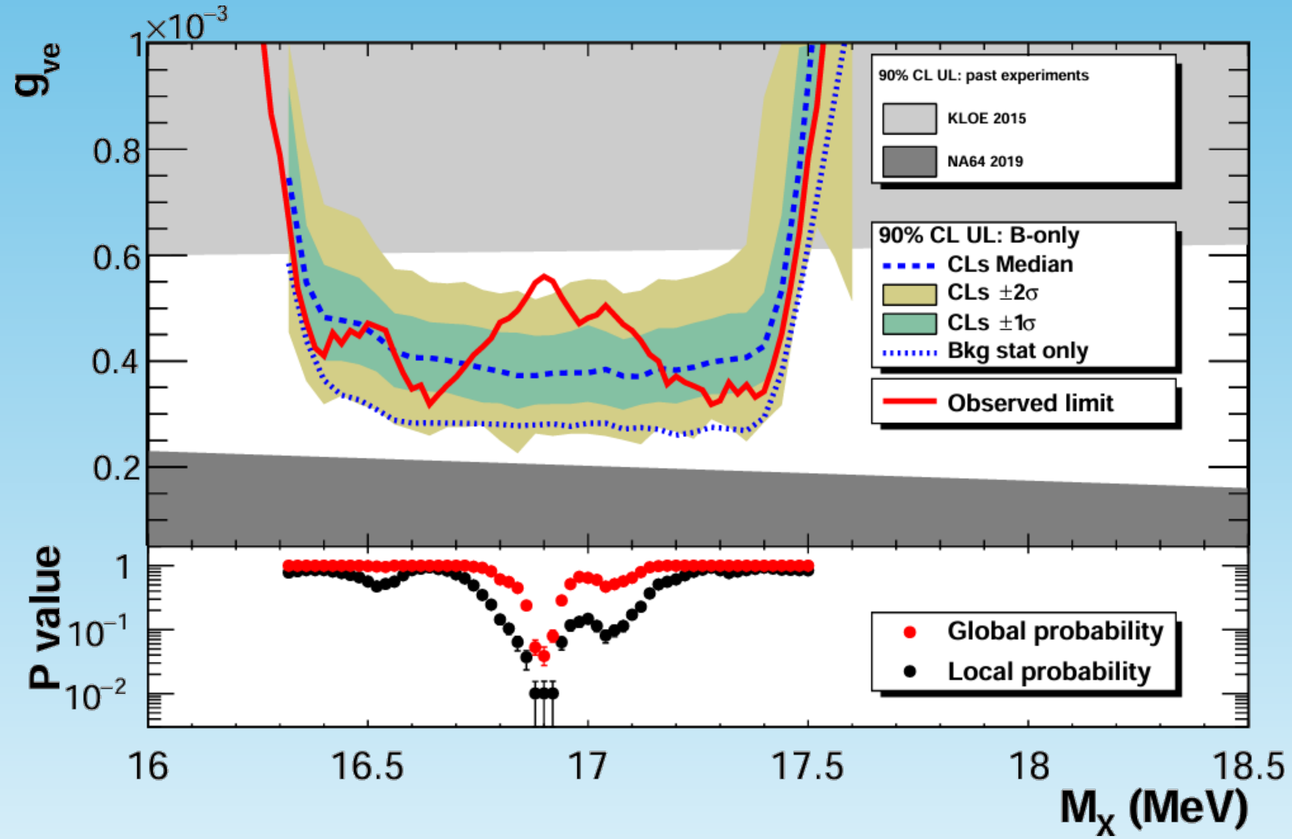
With signal

Bossi et al., 2505.24797 hep-ex

The Excess at PADME

Local 2.5σ excess at $m_X = 16.90\ MeV$

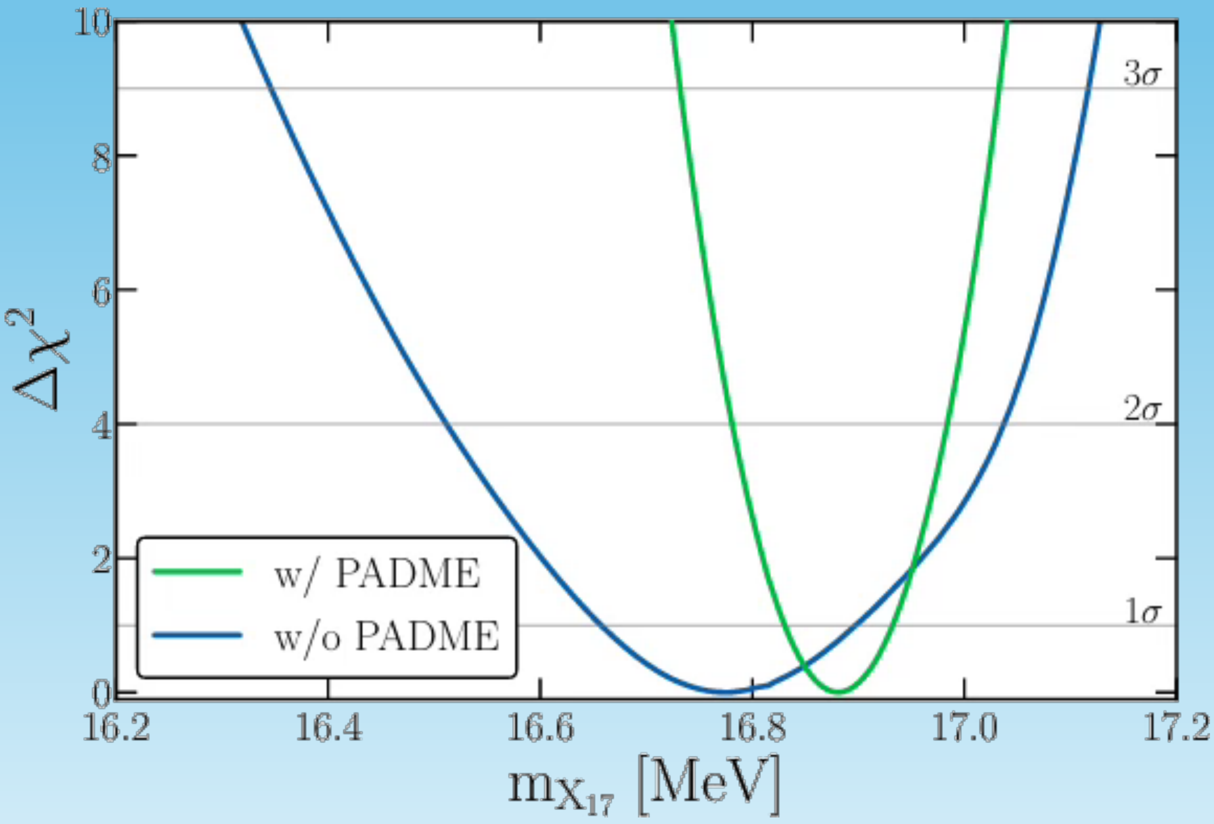
Measured



Bossi et al., 2505.24797 hep-ex

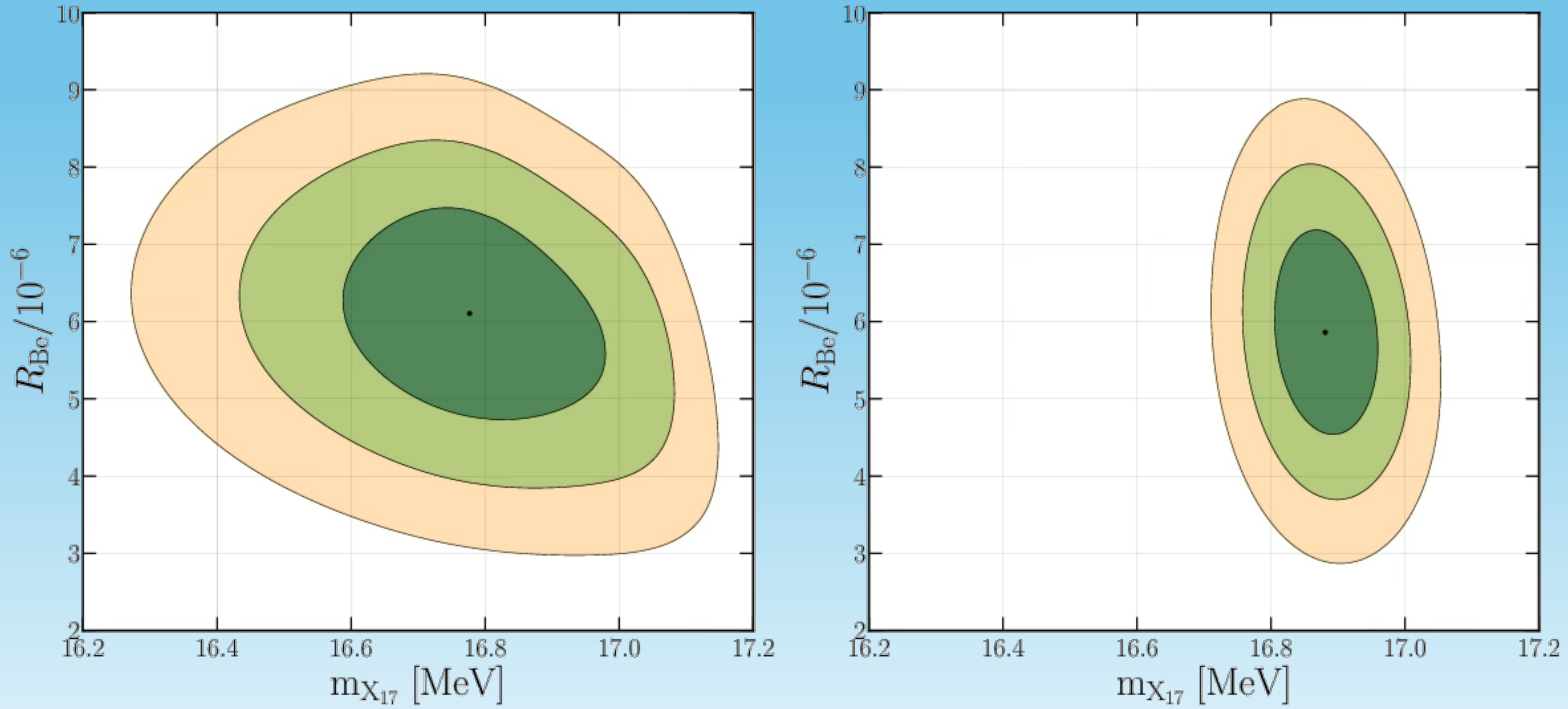
The Excess at PADME

Nucleus (MeV)	m_X (MeV)	Experiment
$^{8}Be^{*}(18.15)$	$16.86 \pm 0.06 \pm 0.50$	Atomki
$^{8}Be^{*}(18.15)$	$17.17 \pm 0.07 \pm 0.20$	Atomki
$^{4}He^{*}(20.21/21.01)$	$16.94 \pm 0.12 \pm 0.21$	Atomki
$^{12}C^{*}(17.23)$	$17.03 \pm 0.11 \pm 0.20$	Atomki
$^{8}Be^{*}(GDR)$	$16.95 \pm 0.48 \pm 0.35$	Atomki
$^{8}Be^{*}(18.15)$	$16.66 \pm 0.47 \pm 0.35$	VNU-UoS
$^{8}Be^{*}(17.64/18.15)$	< 16.81 $[R_{Be} = 6 \cdot 10^{-6}]$	MEG II
$e^+e^- \to X_{17}$	$16.90 \pm 0.02 \pm 0.05$	PADME



FAA, G. Grilli di Cortona, E. Nardi, C. Toni, 2504.11439

The Excess at PADME



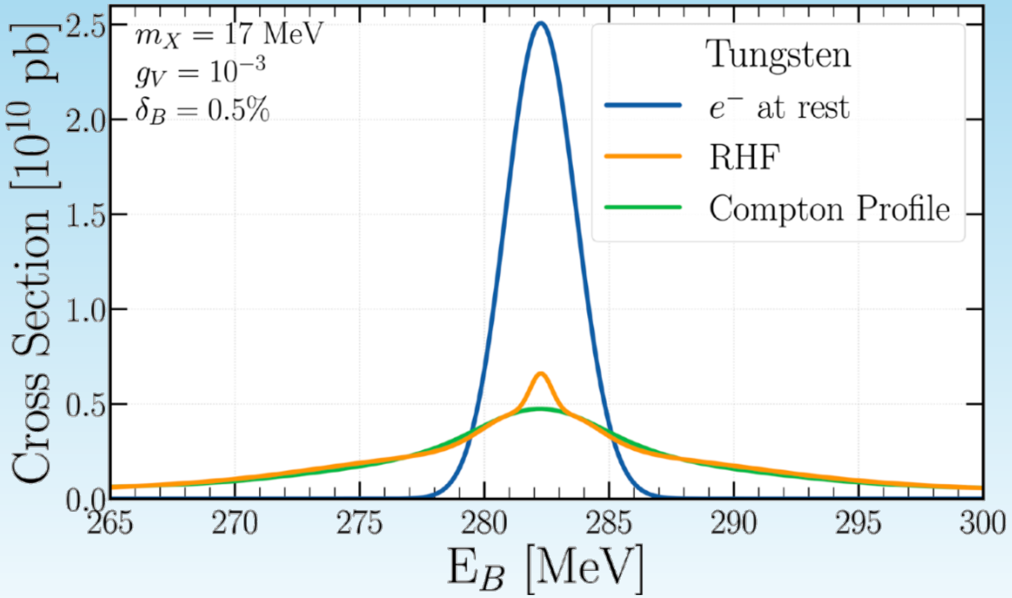
FAA, G. Grilli di Cortona, E. Nardi, C. Toni, 2504,11439

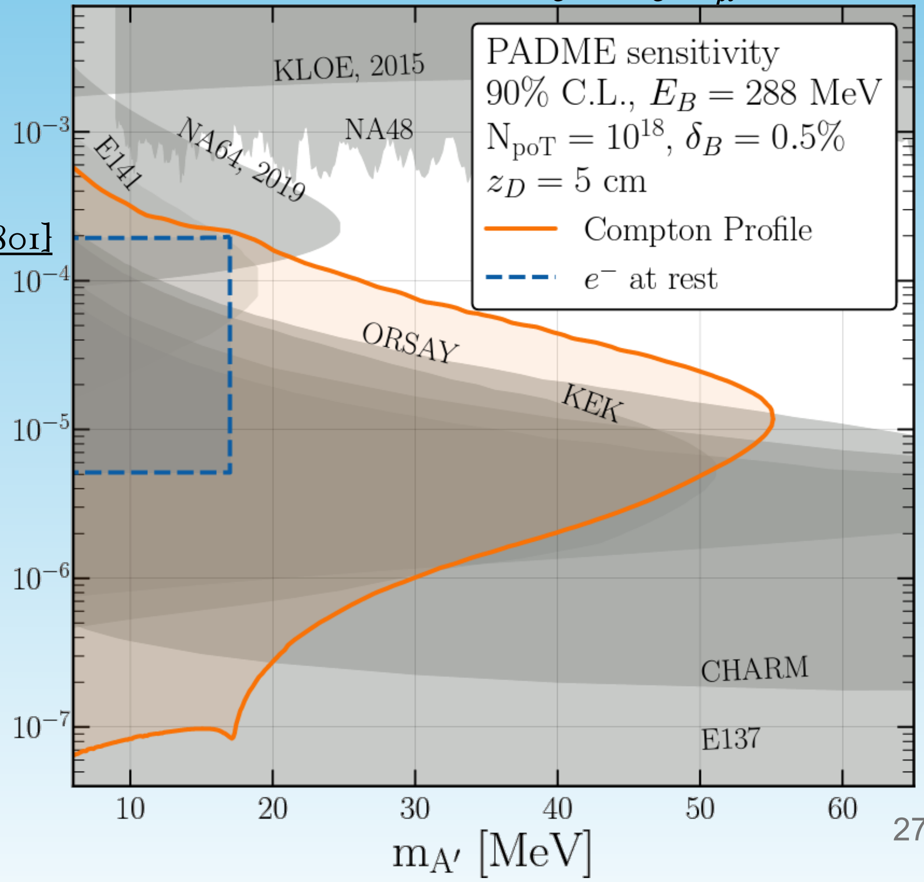
Atoms as Electron Accelerators

- Electron motions *smears* cross sections
- Resonant production lower at the minimum, but wider range of masses
- Effective as a new energy scanning method
- Exploits large Z materials and very intense beams

$$\mathscr{L} \supset -i\,\epsilon\, e\, \bar{\psi}_e \gamma^\mu \psi_e A'_\mu$$

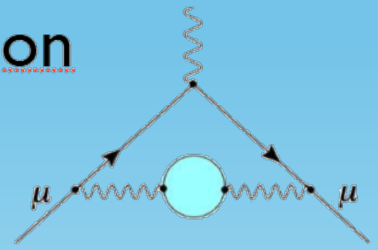
[**FAA**, Darmé, Grilli di Cortona, Nardi, PRL132(2024)261801]

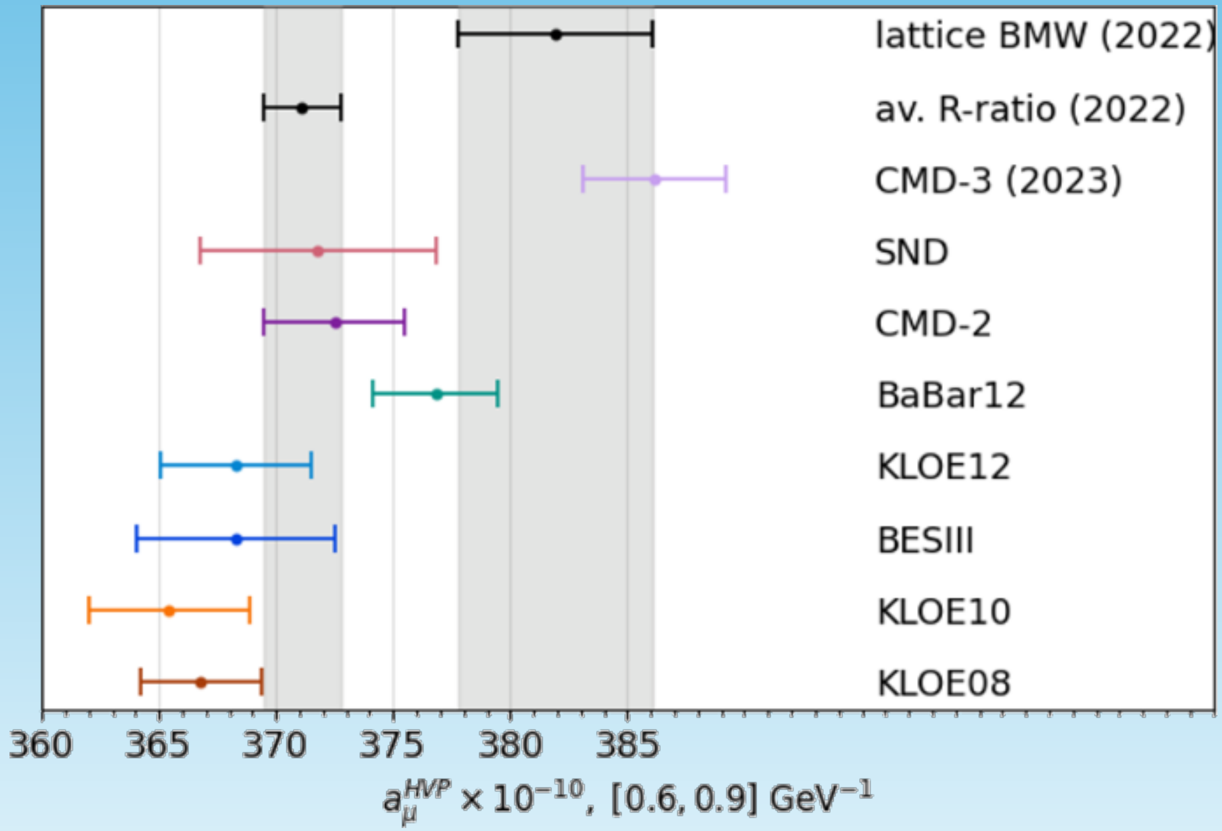




Atoms as Electron Accelerators - a_μ

Hadronic vacuum polarization





$$a_\mu^{HVP} = \frac{1}{4\pi^3}\int_{s_{th}} ds\, \sigma_{\rm had}(s)\, K(s)$$

$$\sigma_{\rm had} \simeq \sigma_{\pi\pi} = \frac{N_{\pi\pi}}{N_{\mu\mu}}\sigma^0_{\mu\mu}$$

$\sigma_{\rm had}$ measured at colliders

1. Scanning method
2. Radiative return method

Atoms as Electron Accelerators - a_μ

PROPOSAL:

[**FAA**, Darmé, Grilli di Cortona, Nardi, PRL134(2025)061802]

Positron annihilation on atomic electrons of a fixed target with high Z (e.g. ^{92}U).
The $\sigma_{\text{had}}(s)$ energy dependence is scanned by the relativistic electron velocity of the inner atomic shells.

- Resonant annihilation: 2 → 1 process

$$\sigma = \int_{k_A^{\min}}^{k_A^{\max}} dk_A \frac{|\mathcal{M}|^2 k_A n(k_A)}{16\pi p_B |E_B k_A x_0(k_A) - E_{k_A} p_B|}$$

- $e^+e^- \to \mu^+\mu^-$: 2 → 2, more complex phase space

$$\sigma = \int_0^\infty dp_2 \int_0^\infty dk_A \int_0^\pi d\theta_2 \int_0^\pi d\theta_A \frac{p_2 k_A |\phi(k_A)|^2}{2^8 \pi^5 E_2} (2\pi - \arccos x_0) \cdot \frac{|\mathcal{M}_{free}(k_A, p_B \to k_A + p_B - p_2, p_2))|^2}{\sqrt{1 - x_0^2} |E_B k_A c_{\theta_A} - E_{k_A} p_B|} \Pi\left(\frac{x_0}{2}\right)$$

$$x_0 = \frac{m_1^2 + k_A^2 + p_2^2 + p_B^2 + 2k_A p_B c_{\theta_A} - 2p_2 c_{\theta_2}(p_B + k_A c_{\theta_A}) - (E_A + E_B - E_2)^2}{2k_A p_2 s_{\theta_A} s_{\theta_2}}$$

Atoms as Electron Accelerators - a_μ

PROPOSAL: [**FAA**, Darmé, Grilli di Cortona, Nardi, PRL134(2025)061802]

Positron annihilation on atomic electrons of a fixed target with high Z (e.g. ^{92}U).
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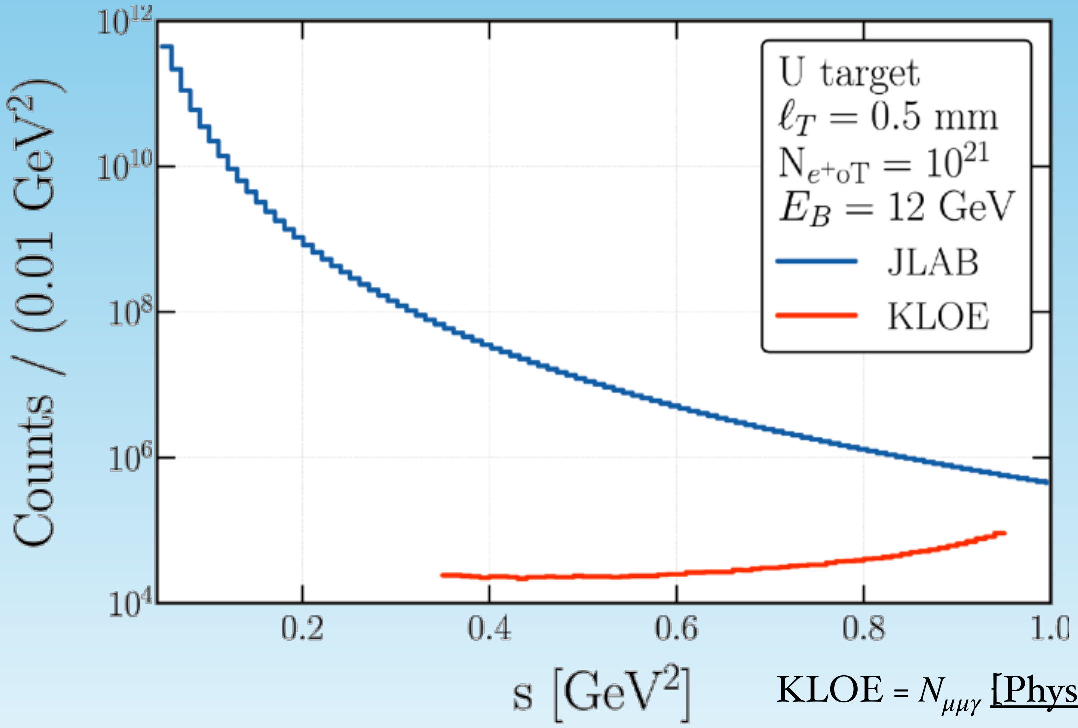
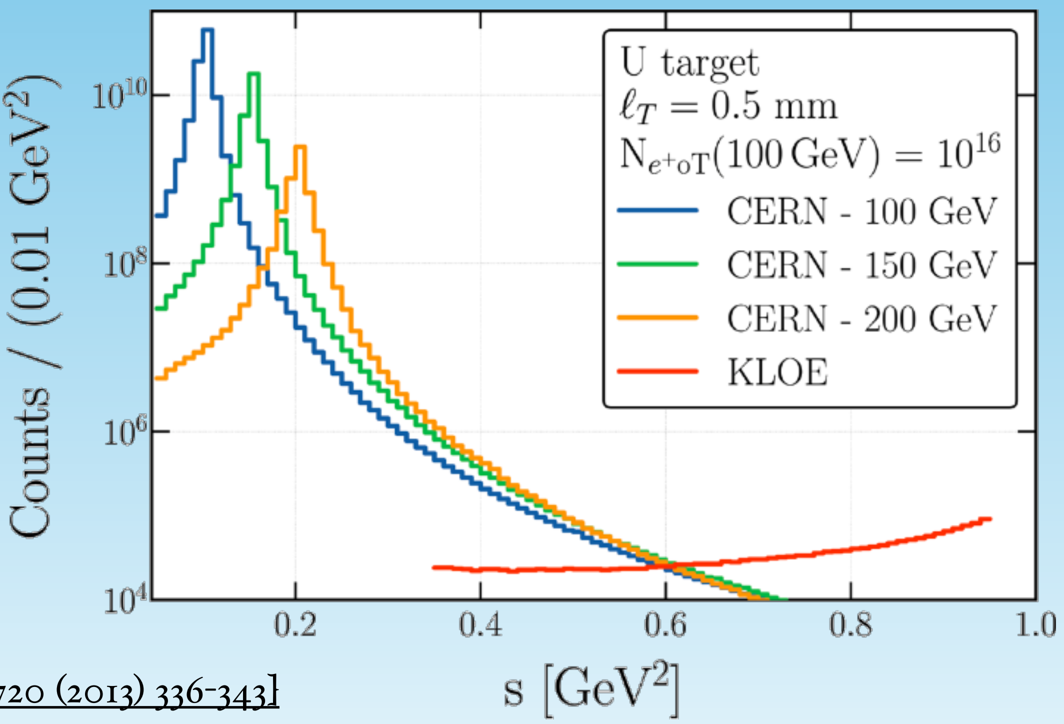


KLOE = $N_{\mu\mu\gamma}$ [Phys. Lett. B 720 (2013) 336-343]

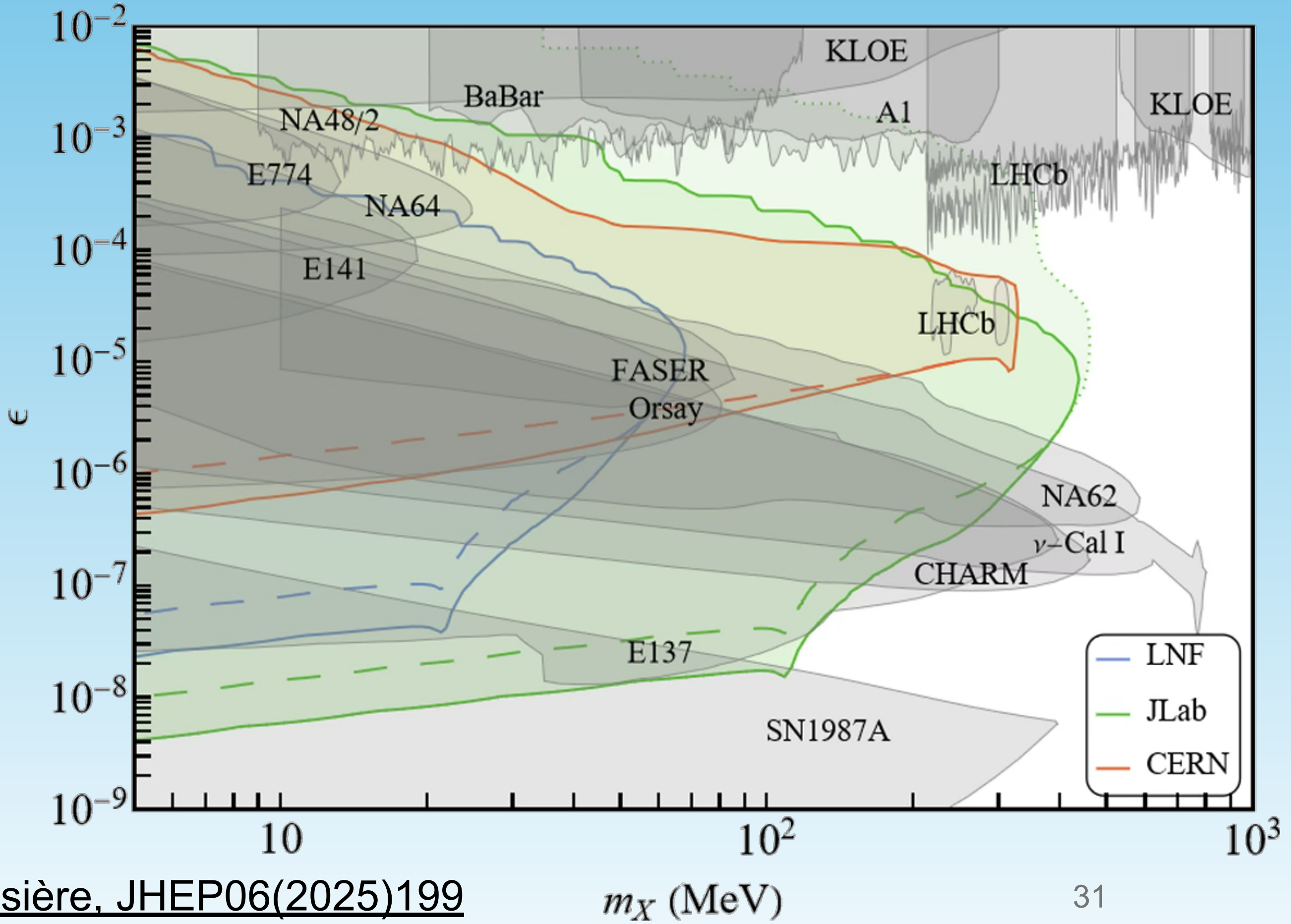


Atoms as Electron Accelerators - NP Searches

- New Intensity vs Energy dynamics
- Can reach difficult parts of some parameter spaces

	$N_{e^+ oT}$/year	E_B	^{74}W target	z_D
LNF	10^{18}	450 MeV	5 cm	3 m–100 m
JLab	10^{21}	12 GeV	1 cm – 5 cm	3 m–100 m
CERN	10^{13}	100 GeV	5 cm	3 m–100 m

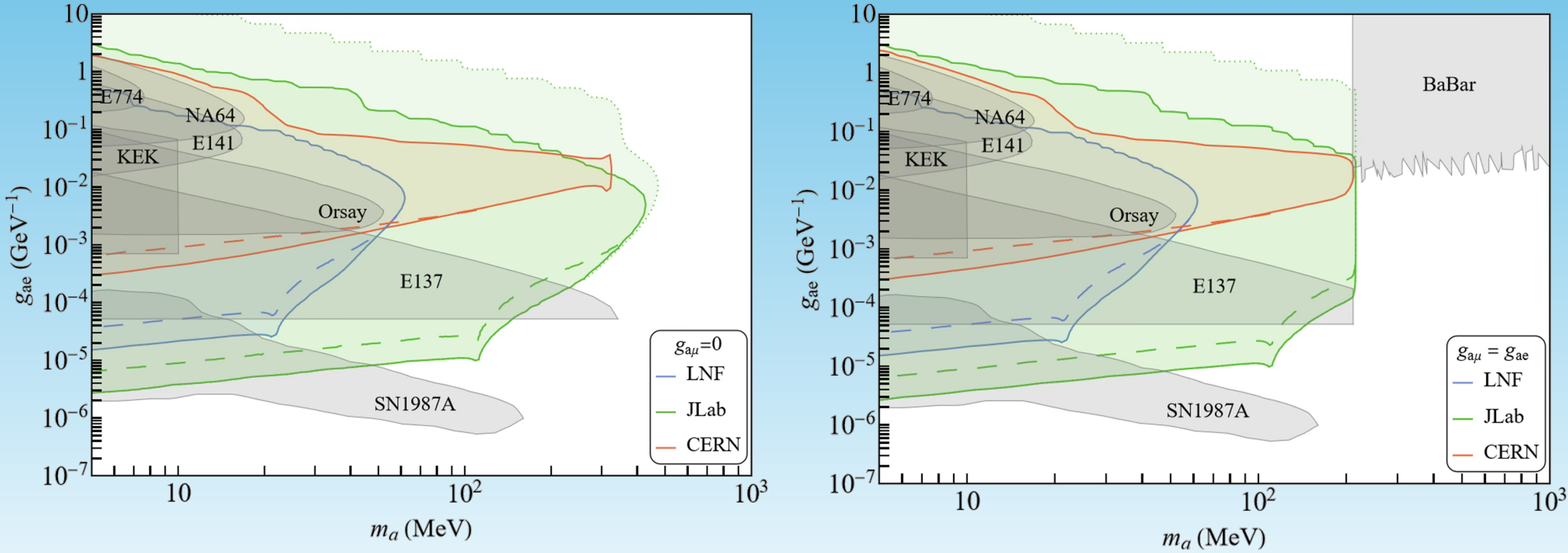
$$\mathscr{L} \supset -i\,\epsilon\, e\, \bar{\psi}_e \gamma^\mu \psi_e A'_\mu$$



FAA, G. Grilli di Cortona, E. Nardi, L. Veissière, JHEP06(2025)199

Atoms as Electron Accelerators - NP Searches

$$\mathscr{L} \supset i\, m_e\, g_{ae}\, a\, \bar{\psi}_e \gamma_5 \psi_e$$



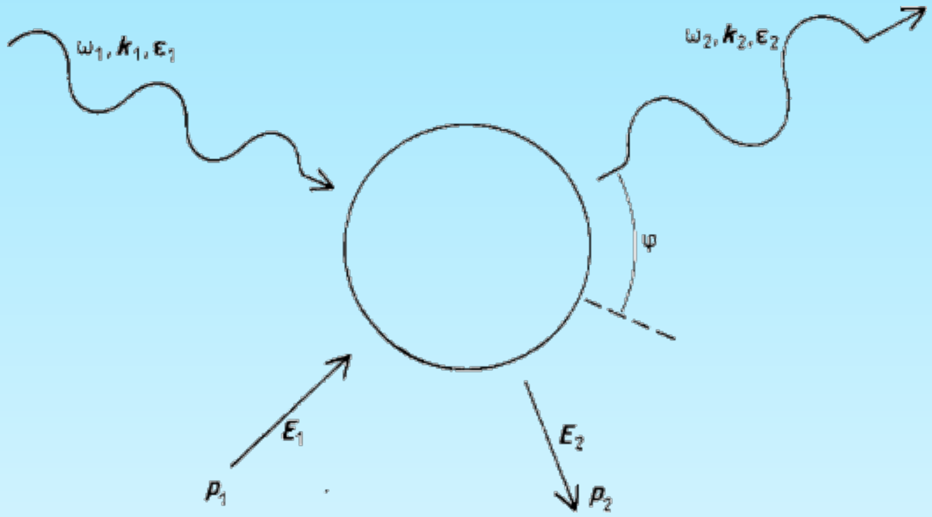
FAA, G. Grilli di Cortona, E. Nardi, L. Veissière, JHEP06(2025)199

Conclusions

- Anomalies from 3 different nuclei point towards the same invariant mass
- SM does not provide satisfying explanations
- A single new (axial)vector may be *hidden* behind the anomalies
- PADME is the ideal particle experiments to produce the X17
- Given its narrow with, electron motion effects are crucial for the signal shape
- A local 2.5σ excess was observed at the precisely expected mass
- Atomic electron motion shows potential for SM and New Physics

THANK YOU FOR YOUR ATTENTION

Beyond FEAR - Compton Profile

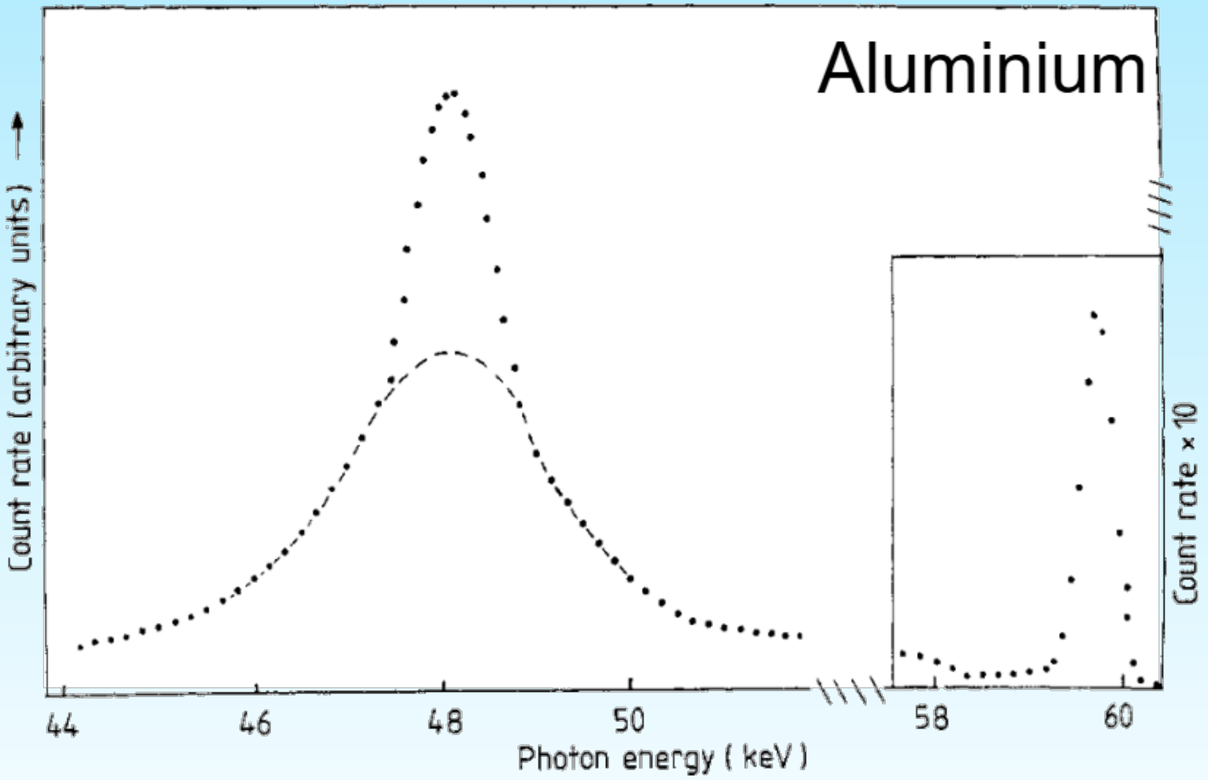


$$\omega_1 - \omega_2 = \frac{1}{2} m_e [\vec{p} + (\vec{k}_1 - \vec{k}_2)]^2 - \frac{|\vec{p}\,|^2}{2m_e}$$

$$= \frac{|\vec{k}_1 - \vec{k}_2|^2}{2m_e} + \frac{(\vec{k}_1 - \vec{k}_2) \cdot \vec{p}}{m_e}$$

$$\simeq \frac{2\omega_1}{m_e} \sin(\phi/2) p_z$$

M J Cooper 1985 Rep. Prog. Phys. 48 415



Beyond FEAR - Compton profile

Compton profile: Radon transform of the electron momentum distribution function along a certain direction

$$J(k_z) = \int\int dk_x\, dk_y\, n(k_x, k_y, k_z)$$

$$J(q) = \frac{1}{4\pi^2}\int_{|q|}^{\infty} n(k)\, k\, dk$$

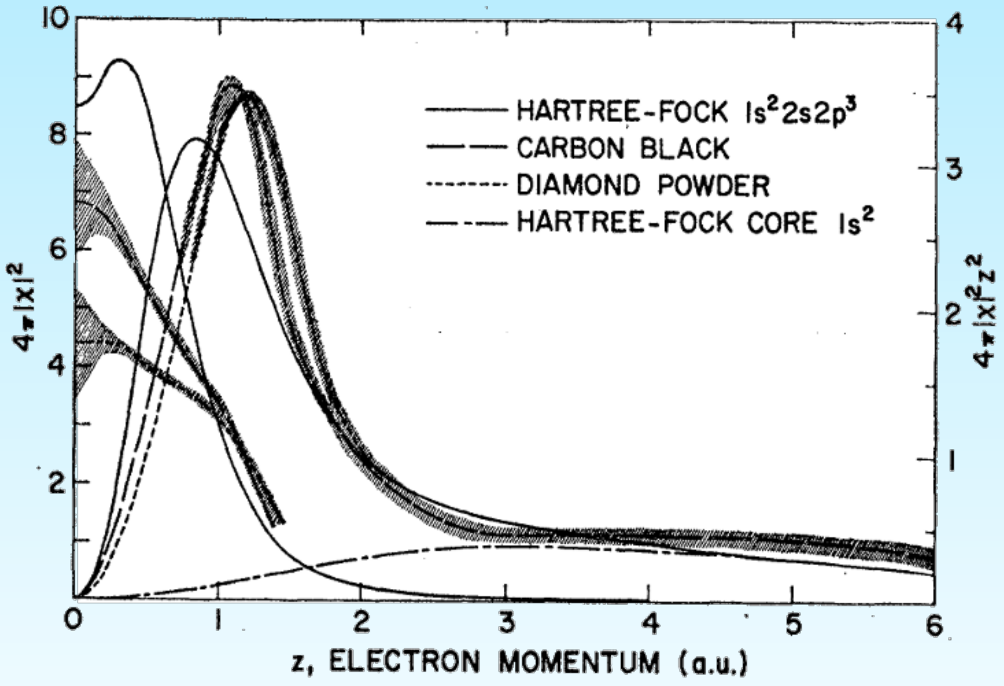
+isotropy

$$\int_{-\infty}^{+\infty} J(q)\, dq = Z$$

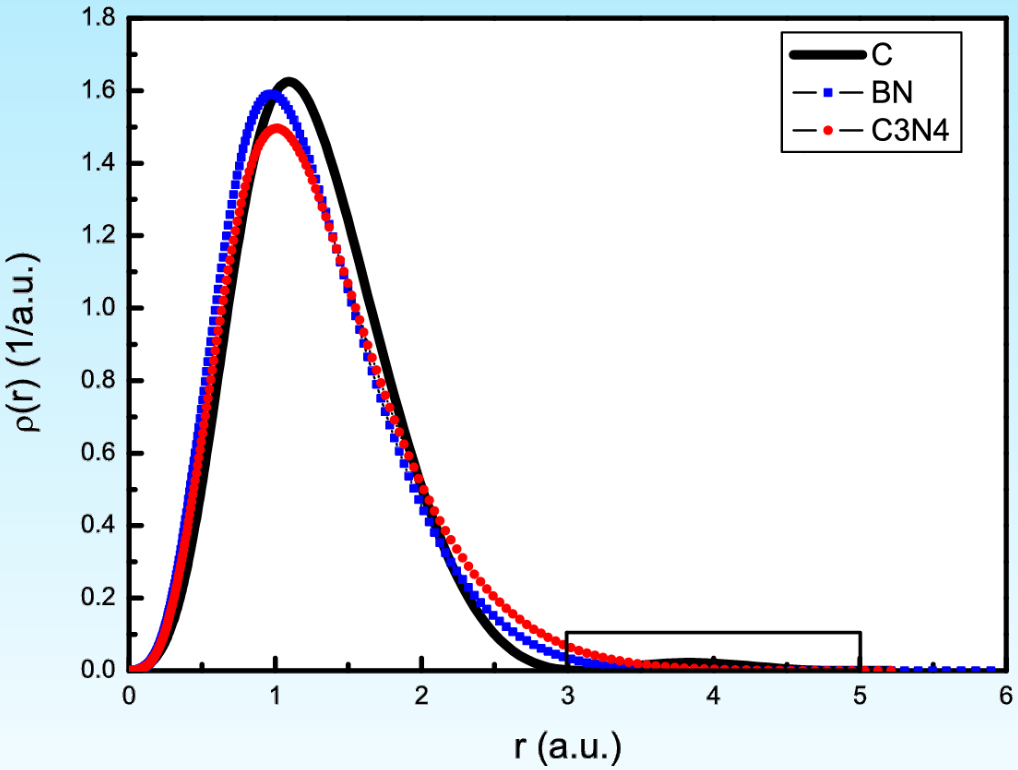
$$n(k) = -\frac{(2\pi)^2}{k}\left|\frac{dJ(k)}{dk}\right|$$

Beyond FEAR - Data and Theory

X-Ray determination of the Electron Momentum Density in Diamond, Graphite and Carbon Black
[Phys. Rev. 176 (1968) 900]

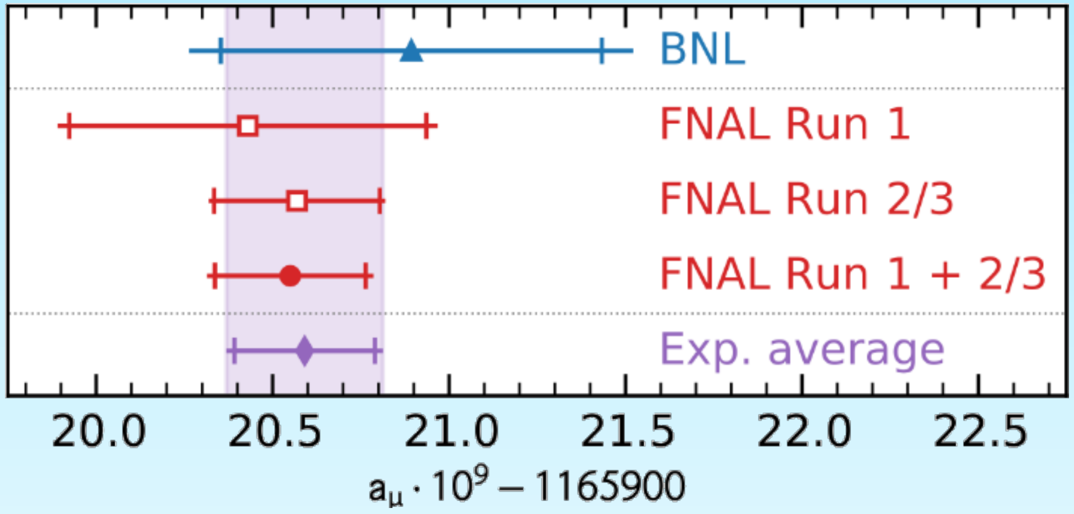


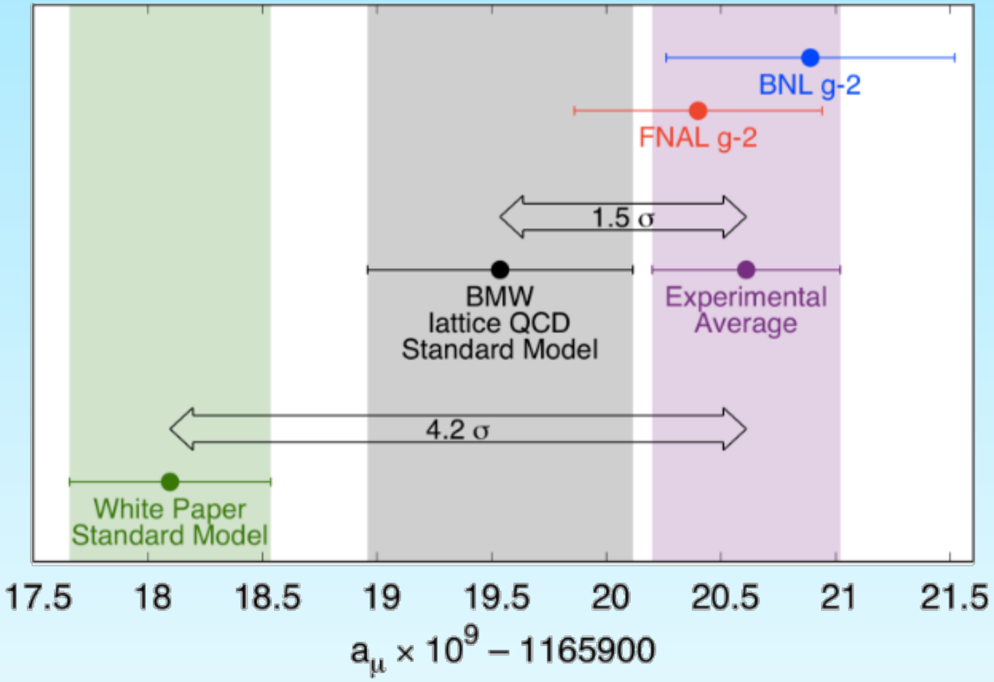
Theoretical Compton profile of diamond, boron nitride and carbon nitride
[Physica B 521 (2017) 361-364]



New obtention of the HVP

[Muon g-2 Coll. *Phys.Rev.D* 110 (2024) 3, 032009]





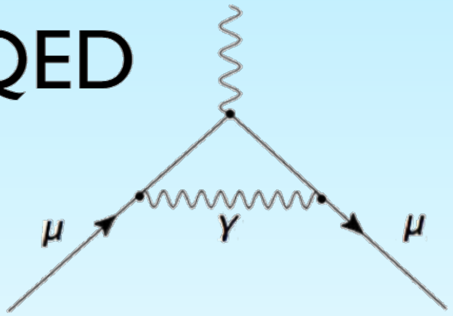
$$a_\mu^{\text{exp}} = (116592059 \pm 22) \cdot 10^{-11}$$

New obtention of the HVP

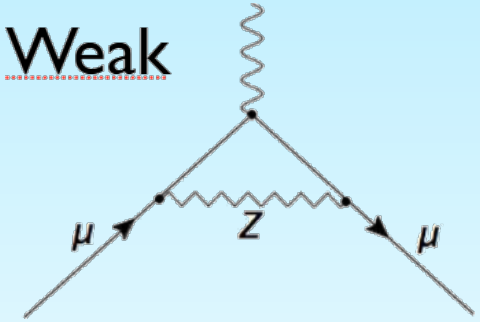
[Aoyama et al., 2006.04822, Phys. Rept. 887 (2020) 1-166]

$116584718.9(1) \cdot 10^{-11}$

QED



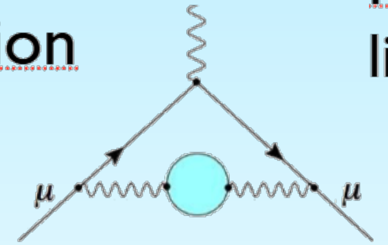
Weak



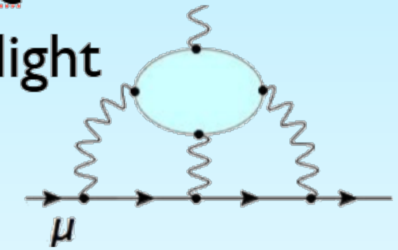
$153.6(1.0) \cdot 10^{-11}$

$6845(40) \cdot 10^{-11}$

Hadronic vacuum polarization



Hadronic light-by-light



$92(18) \cdot 10^{-11}$