Atoms as electron accelerators

Leveraging atomic electron momentum distribution in fixed target experiments

Istituto Nazionale di Fisica Nucleare
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based on

F. Arias Aragon, L. Darmé, G^{2}dC and E. Nardi, 2403.15387, PRL132(2024)261801

F. Arias Aragon, L. Darmé, G^{2}dC and E. Nardi, 2407.15941

F. Arias Aragon, L. Darmé, G^{2}dC, E. Nardi and L. Veissière, in preparation

LNF General Seminar - 16/10/2024

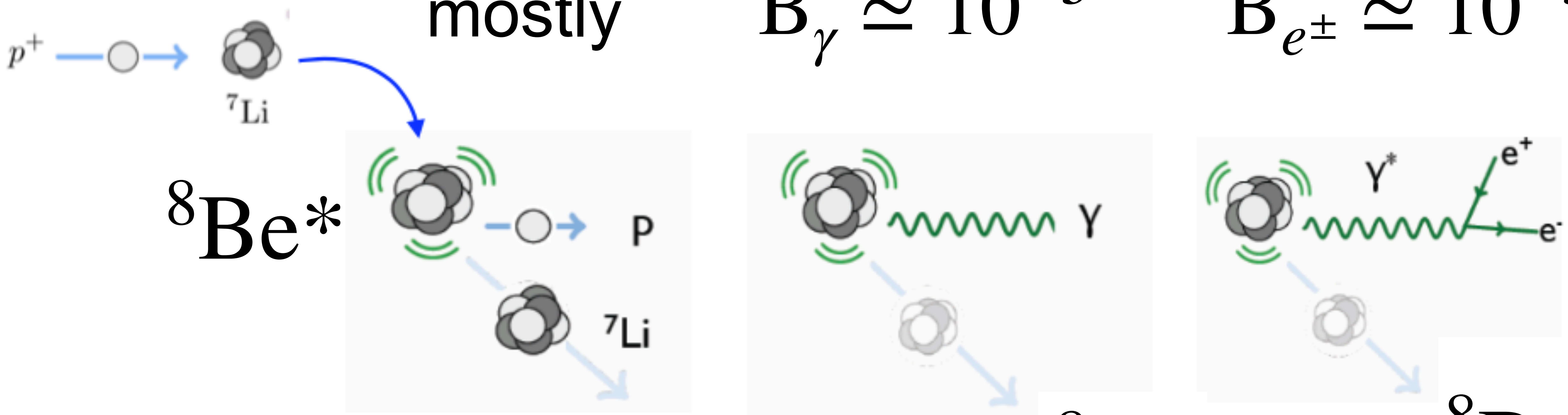
Outline

1. Motivation
2. Dark sector resonant production
   Thick target
   Thin target
3. Free electrons at rest approximation
4. The computation with bound moving electrons
5. Atoms as electron accelerators
   Search for the X_{17} at PADME
   New physics searches
   A proposal to measure the hadronic cross section

Motivation

The X_{17} saga

mostly $\quad B_\gamma \simeq 10^{-5} \quad B_{e^\pm} \simeq 10^{-3} B_\gamma$

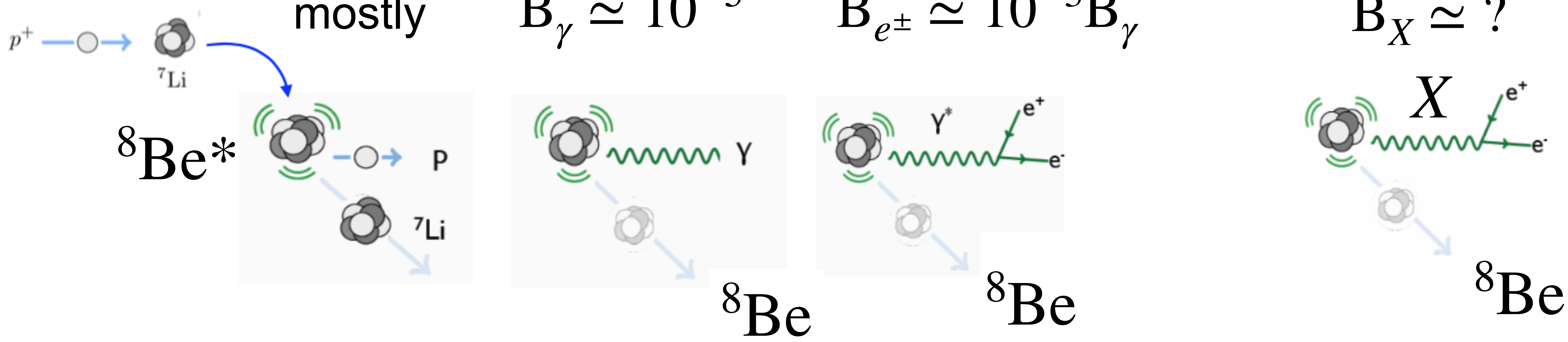


$^8\mathrm{Be}^*$

$^8\mathrm{Be}$ $\quad$ $^8\mathrm{Be}$

The X_{17} saga

mostly $\quad B_\gamma \simeq 10^{-5} \quad B_{e^\pm} \simeq 10^{-3} B_\gamma \quad B_X \simeq ?$



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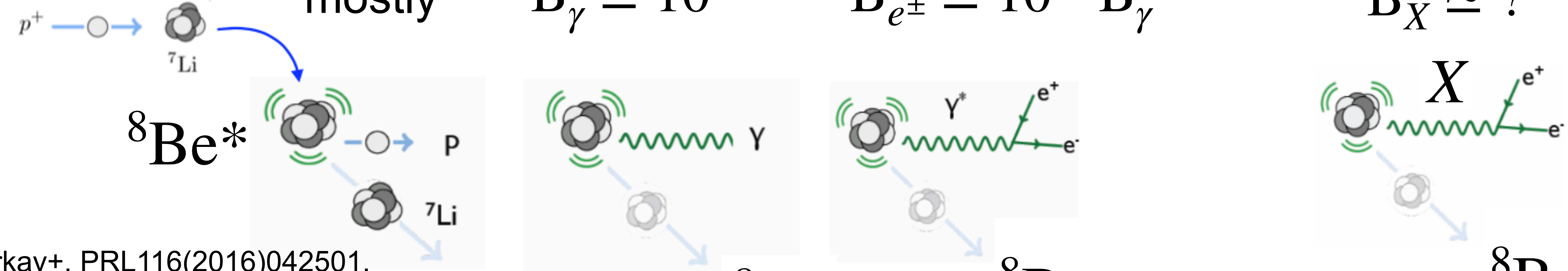
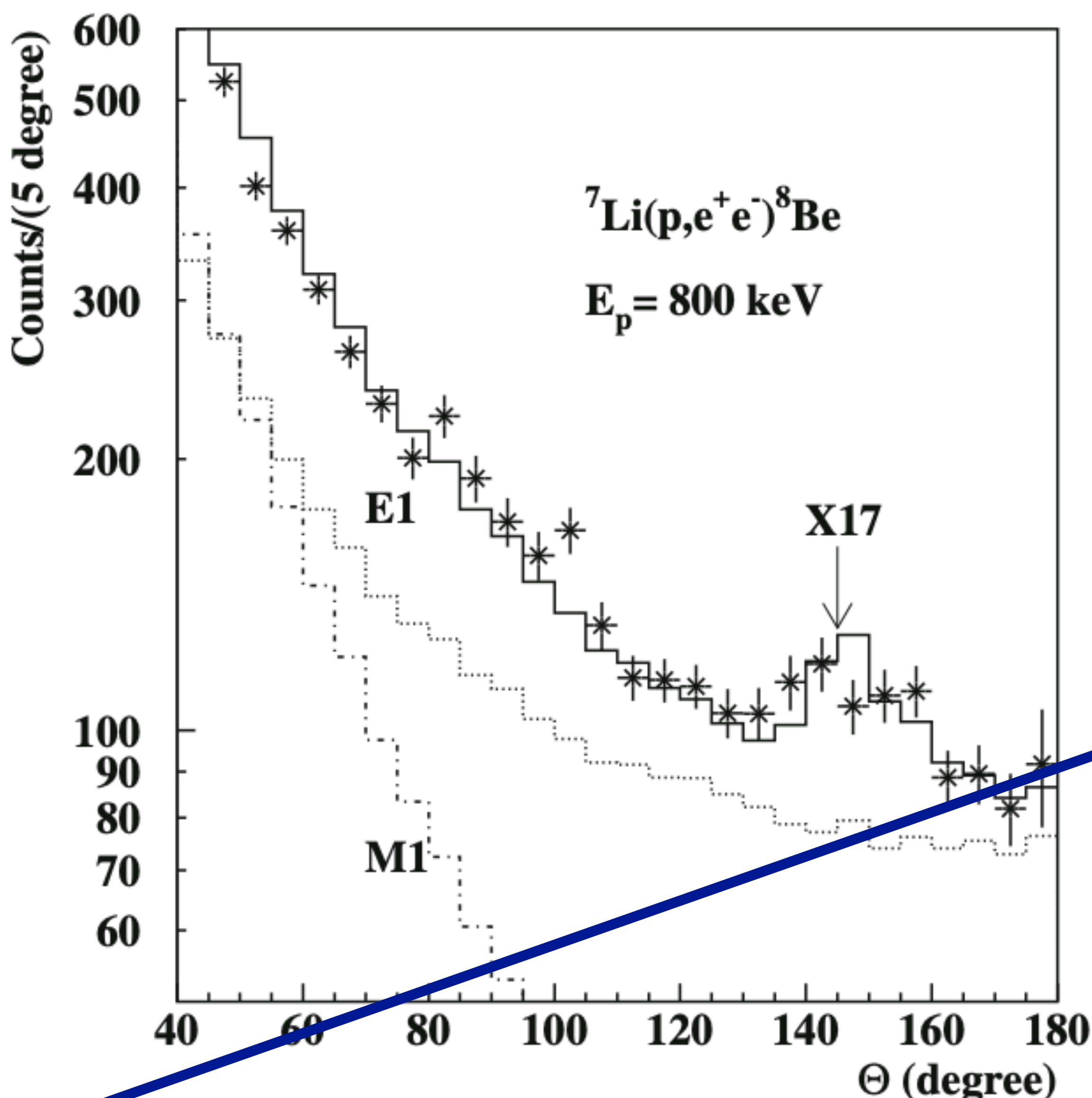
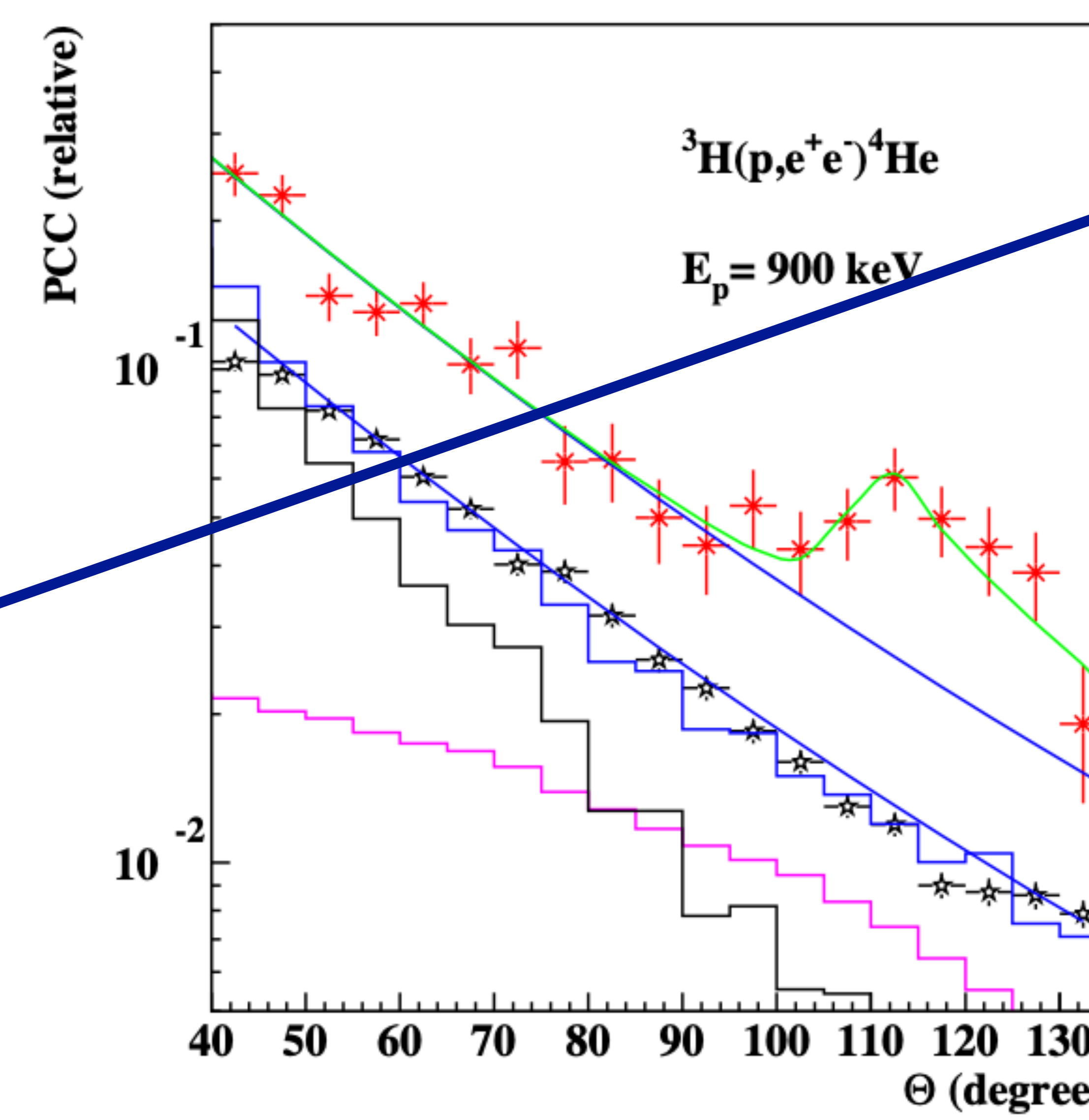


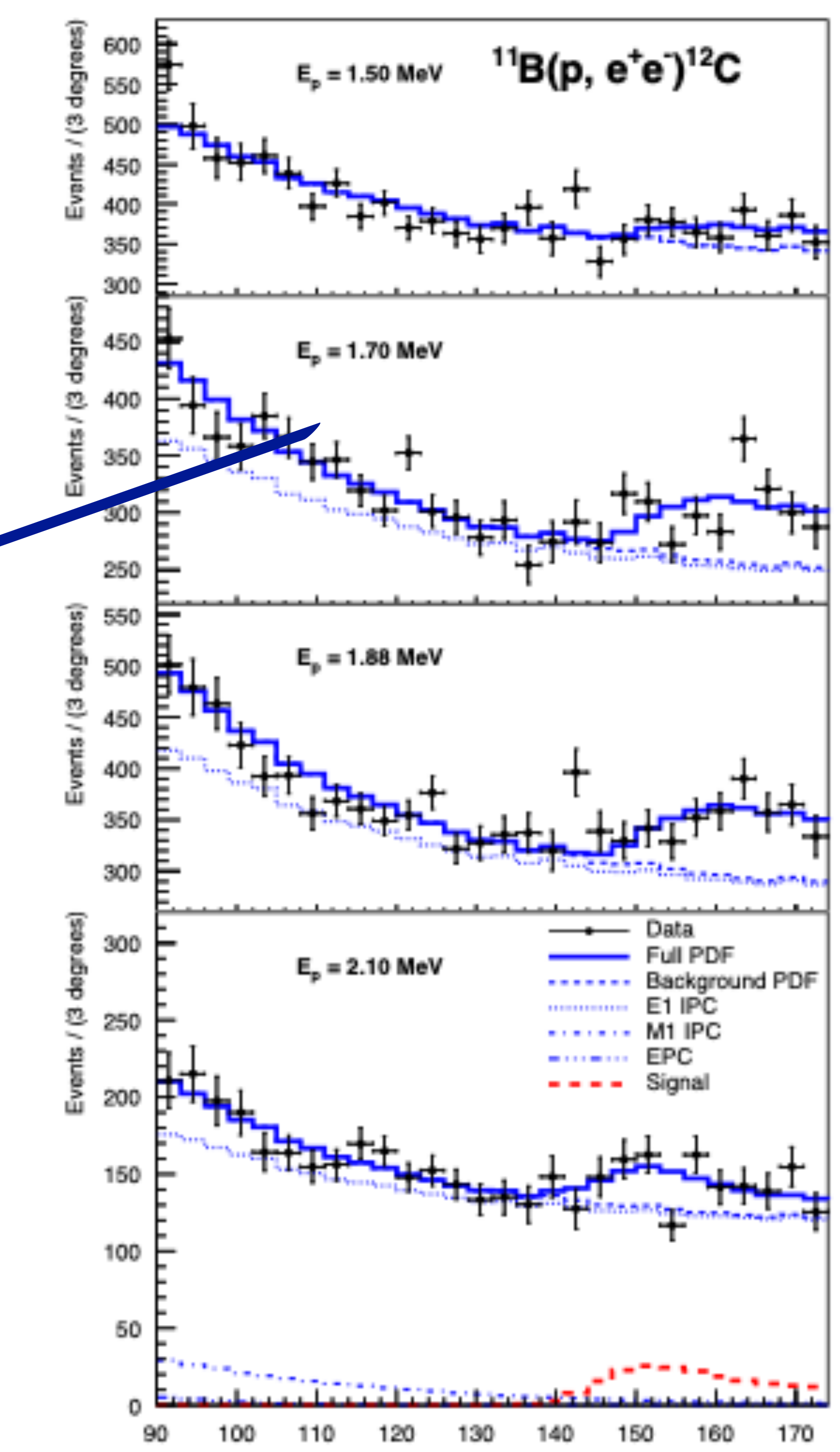
^{8}Be $\quad$ ^{8}Be $\quad$ ^{8}Be

[Krasznahorkay+, PRL116(2016)042501,
Krasznahorkay+, PRC104 (2021) 044003,
Krasznahorkay+, PRC106(2022)L061601]

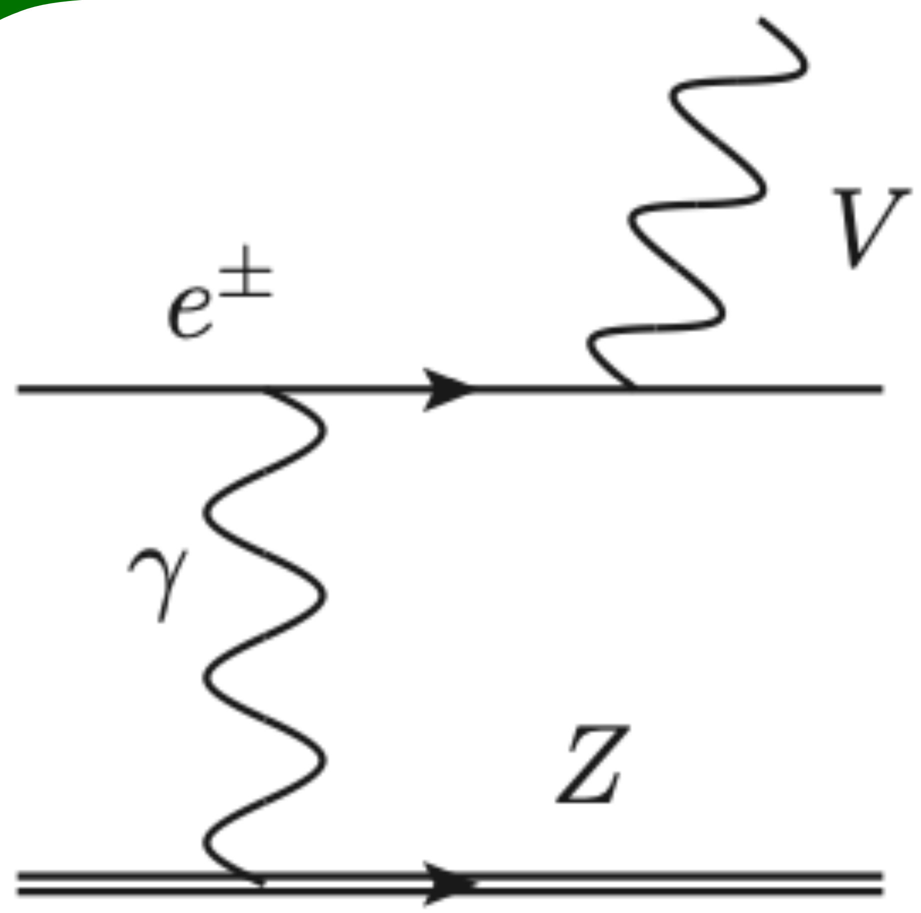
Anomaly observation in ^{8}Be, ^{4}He and ^{12}C transitions







Searches at fixed target exp.



Electron/positron beam fixed target experiments

Dark photon production
via Bremsstrahlung:
APEX, NA64, …

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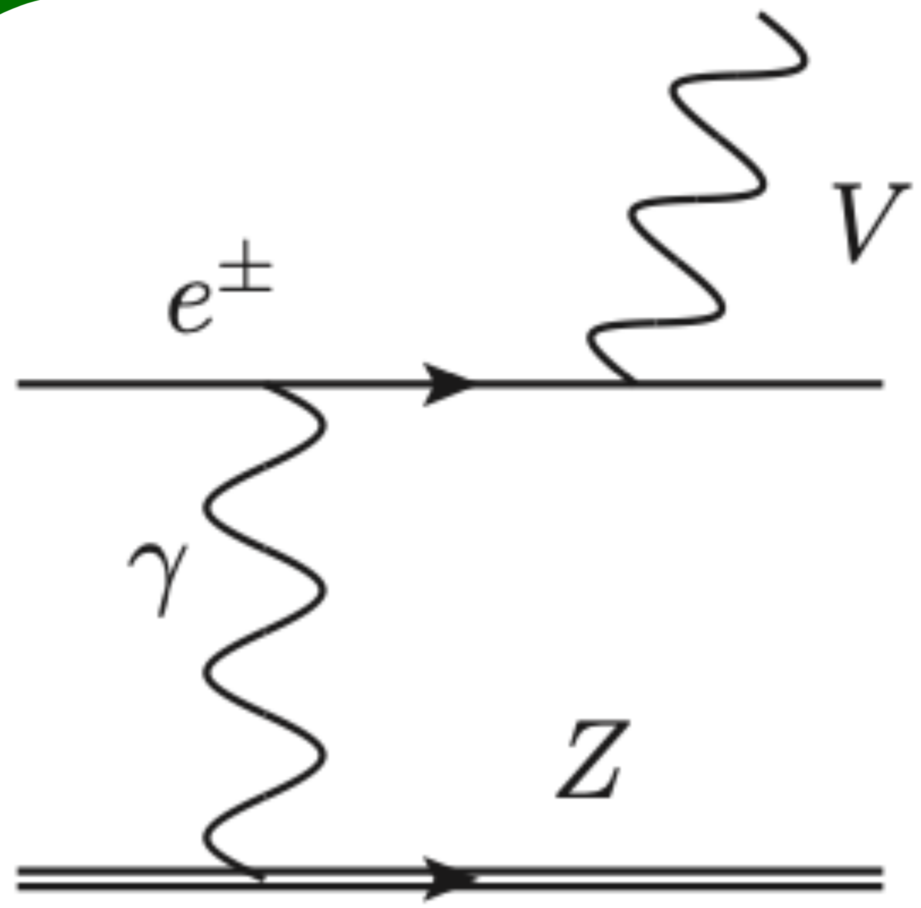

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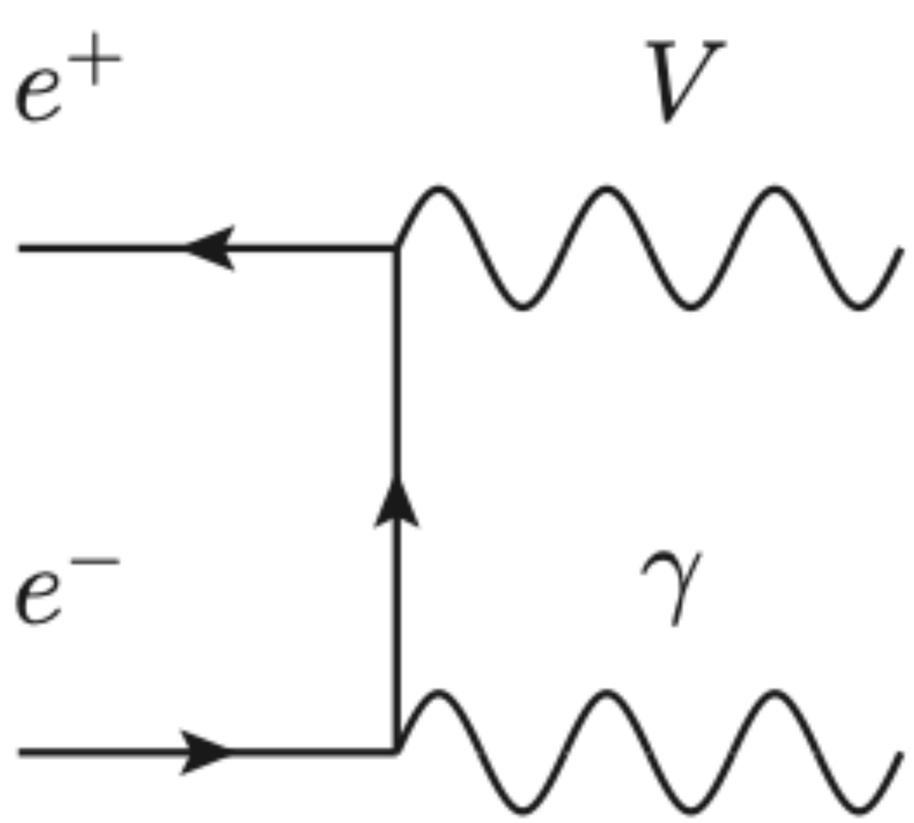

Positron beams fixed target experiments

Dark photon associate production: PADME (Frascati National Lab.), VEPP3, …

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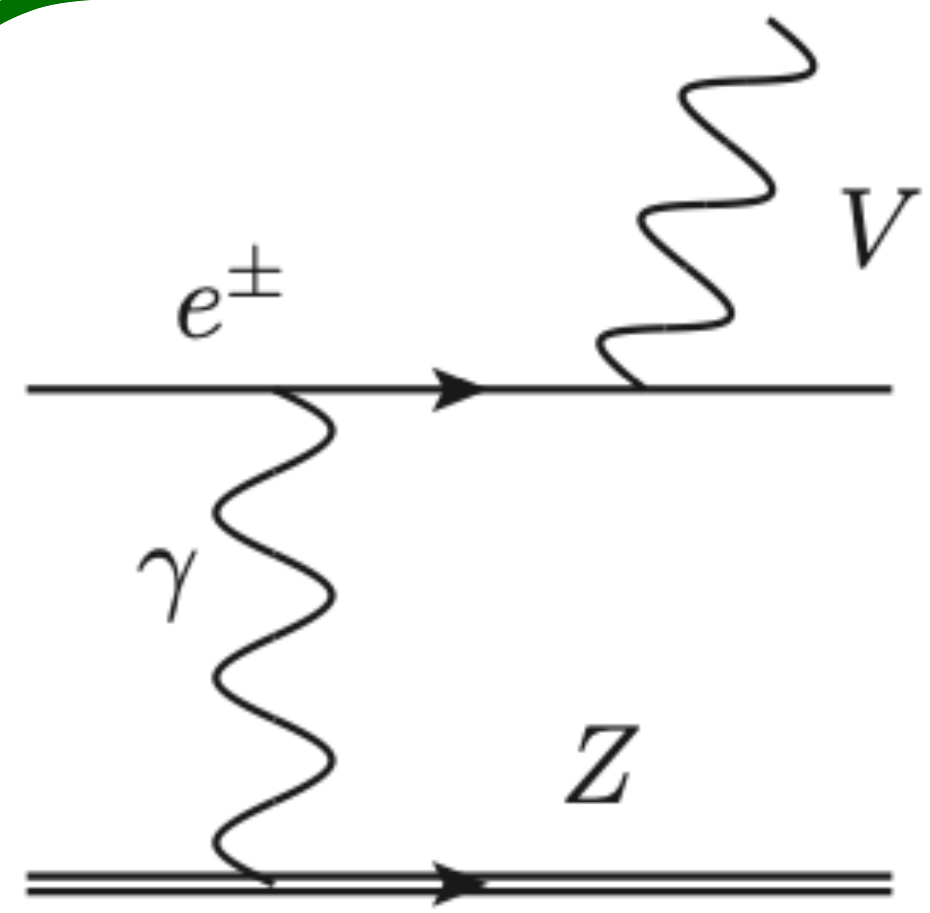

Electron/positron beam fixed target experiments

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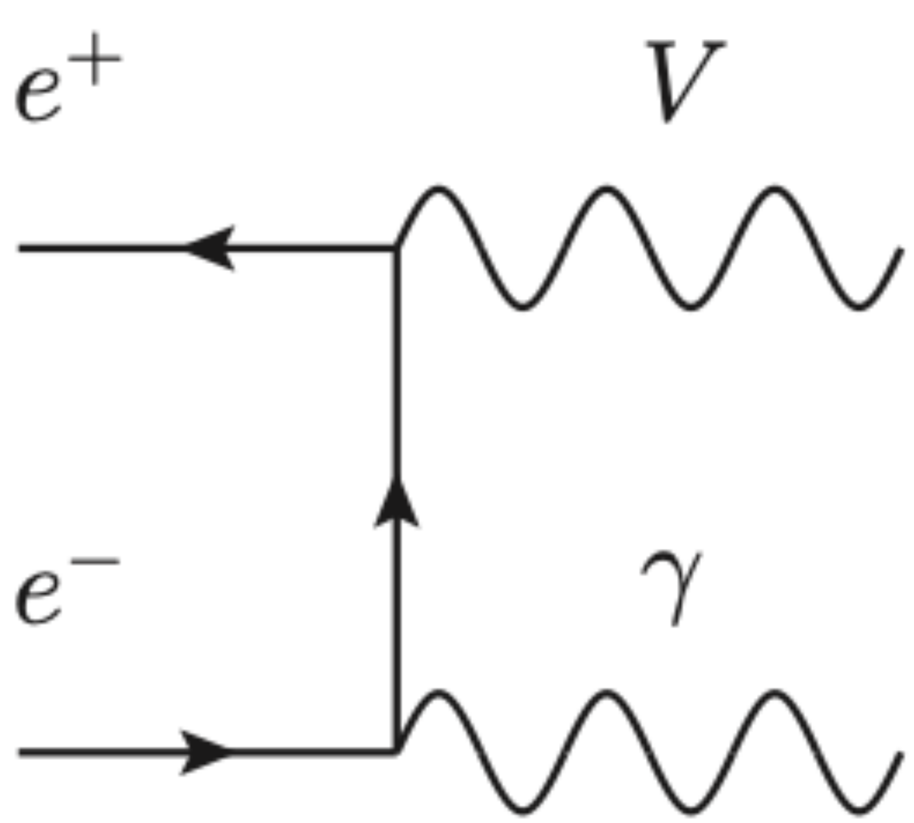

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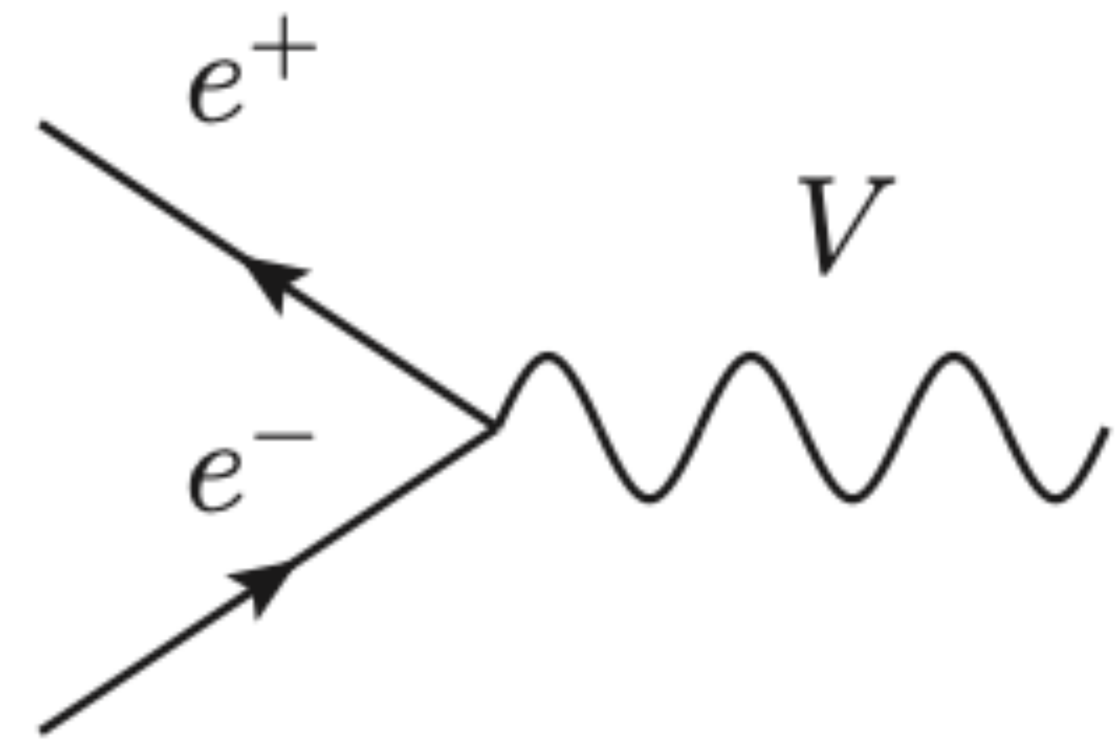


Positron beam fixed target experiments

Positron - electron resonant annihilation $e^+e^- \to A'$:

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

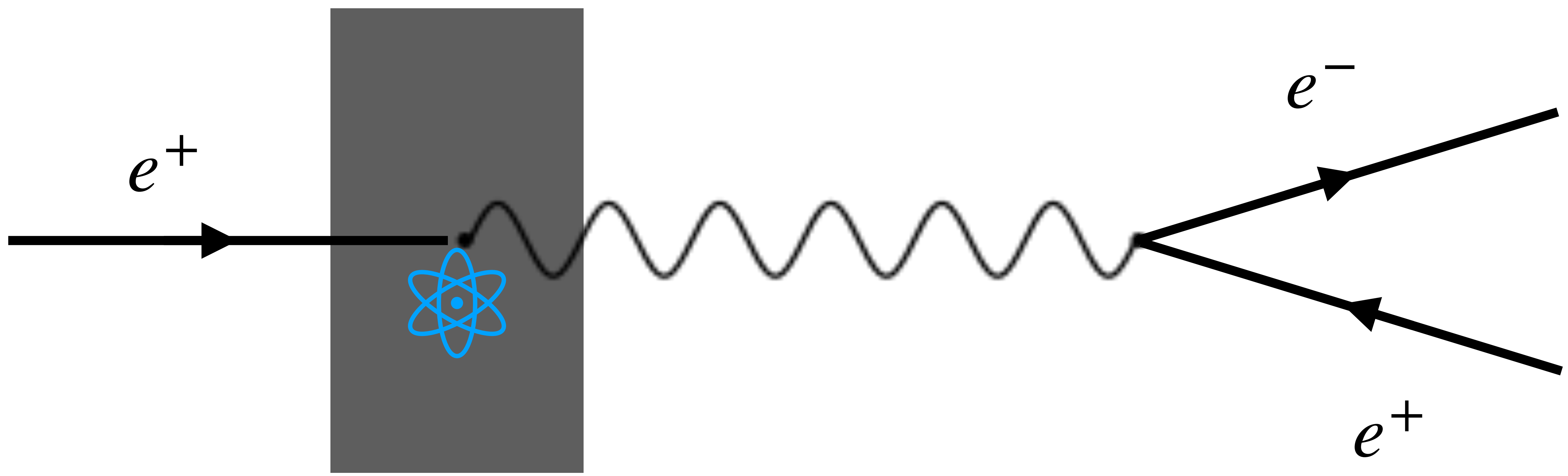
Dark Sector resonant production

Resonant production

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

Thick fixed target

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



Take advantage of energy loss of the positrons propagating through matter, effectively scanning in energy until hitting the resonance.

Resonant production

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

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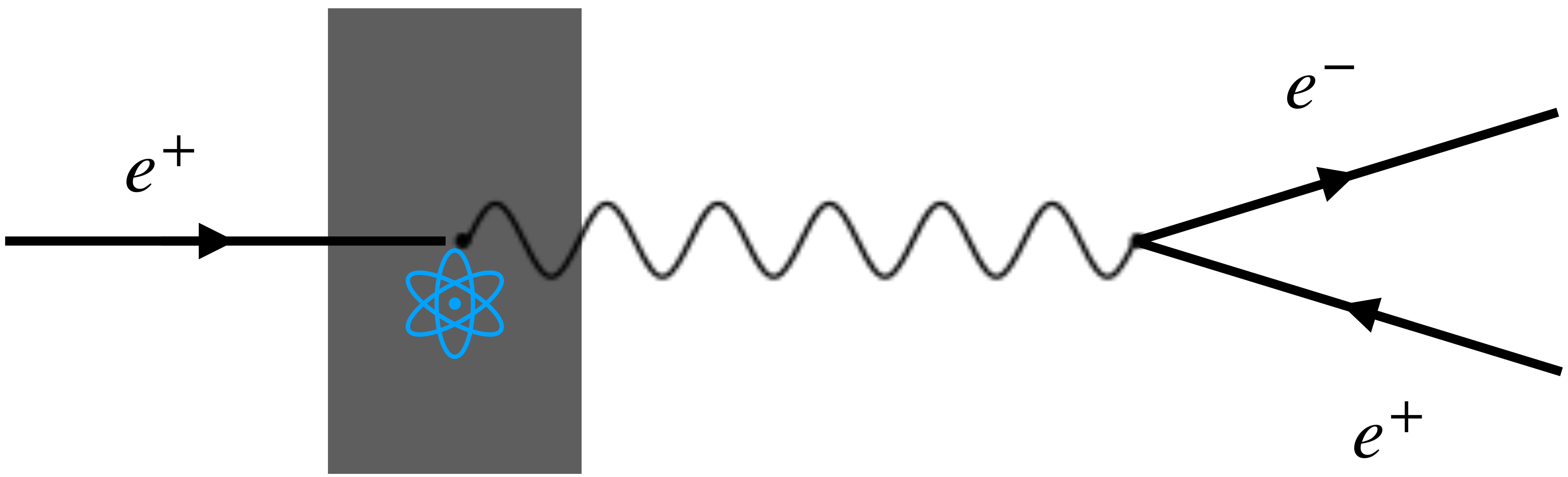


Take advantage of energy loss of the positrons propagating through matter, effectively scanning in energy until hitting the resonance.

number of target electrons

Gaussian beam energy spread

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

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

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

Resonant production

Thick fixed target

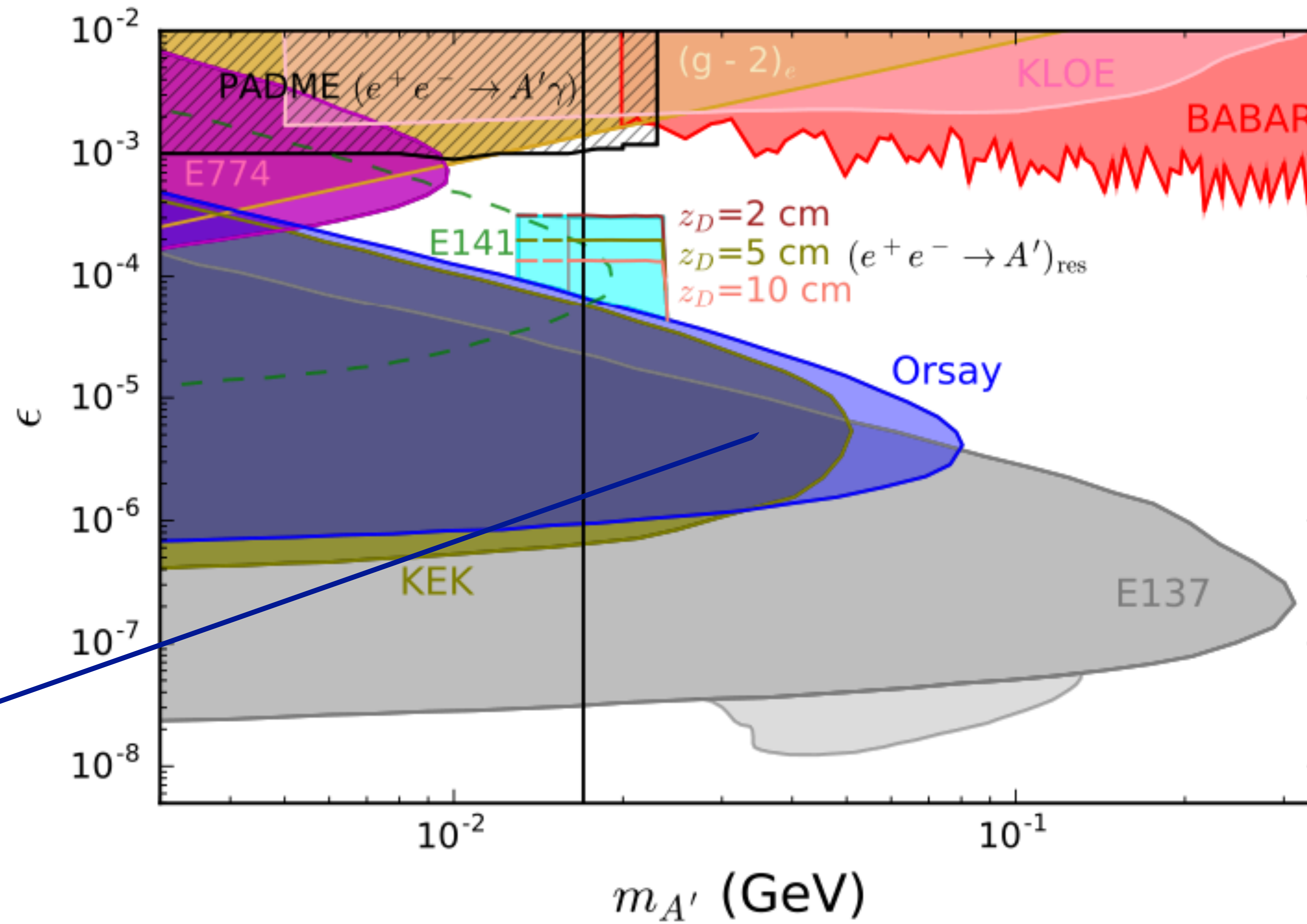
[Nardi et al., Phys. Rev. D (2018) 9, 095004]

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

$E_B \simeq 282$ MeV

$N_{\rm poT} = 10^{18}$

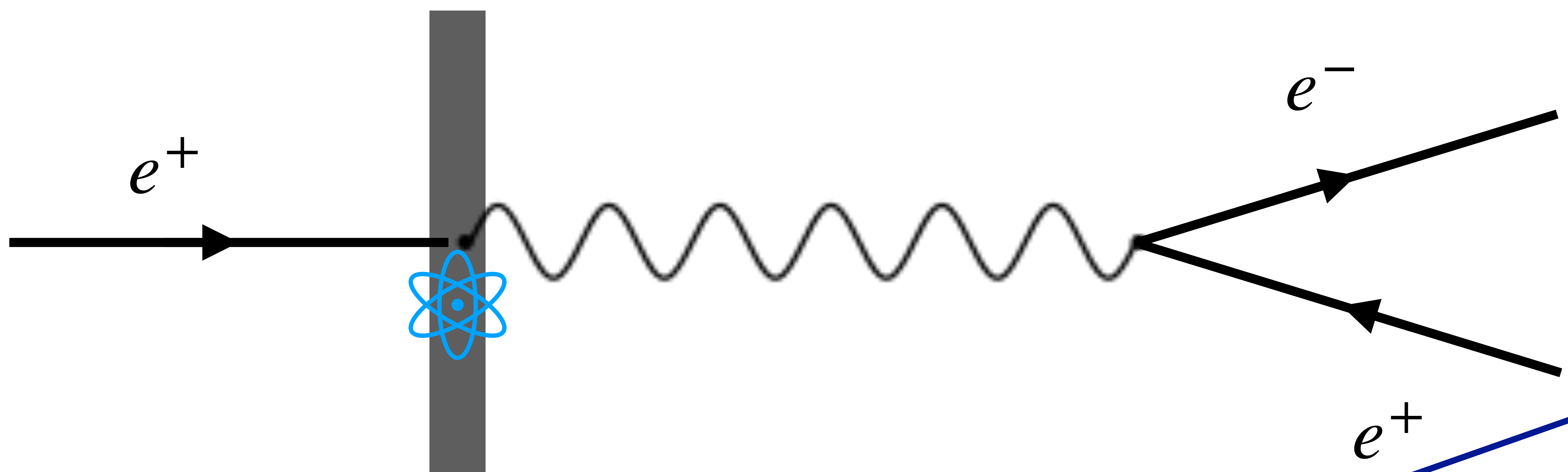
2-10 cm of tungsten



Resonant production

Thin fixed target

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



Negligible energy loss, need to physically vary the beam energy

Resonant production

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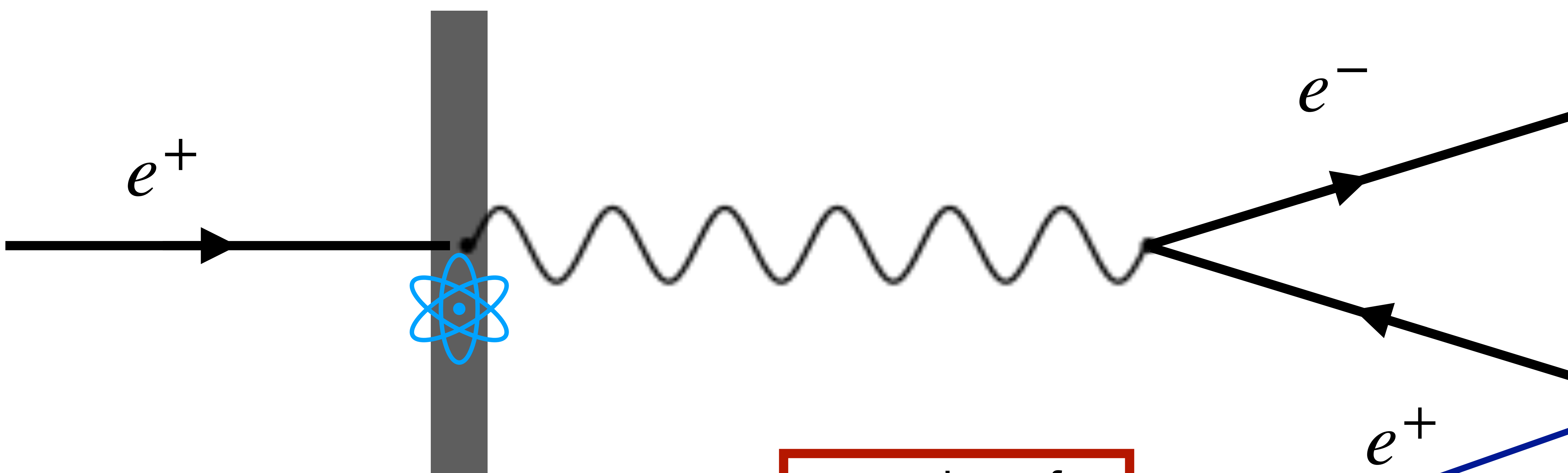


Negligible energy loss, need to physically vary the beam energy

number of target electrons

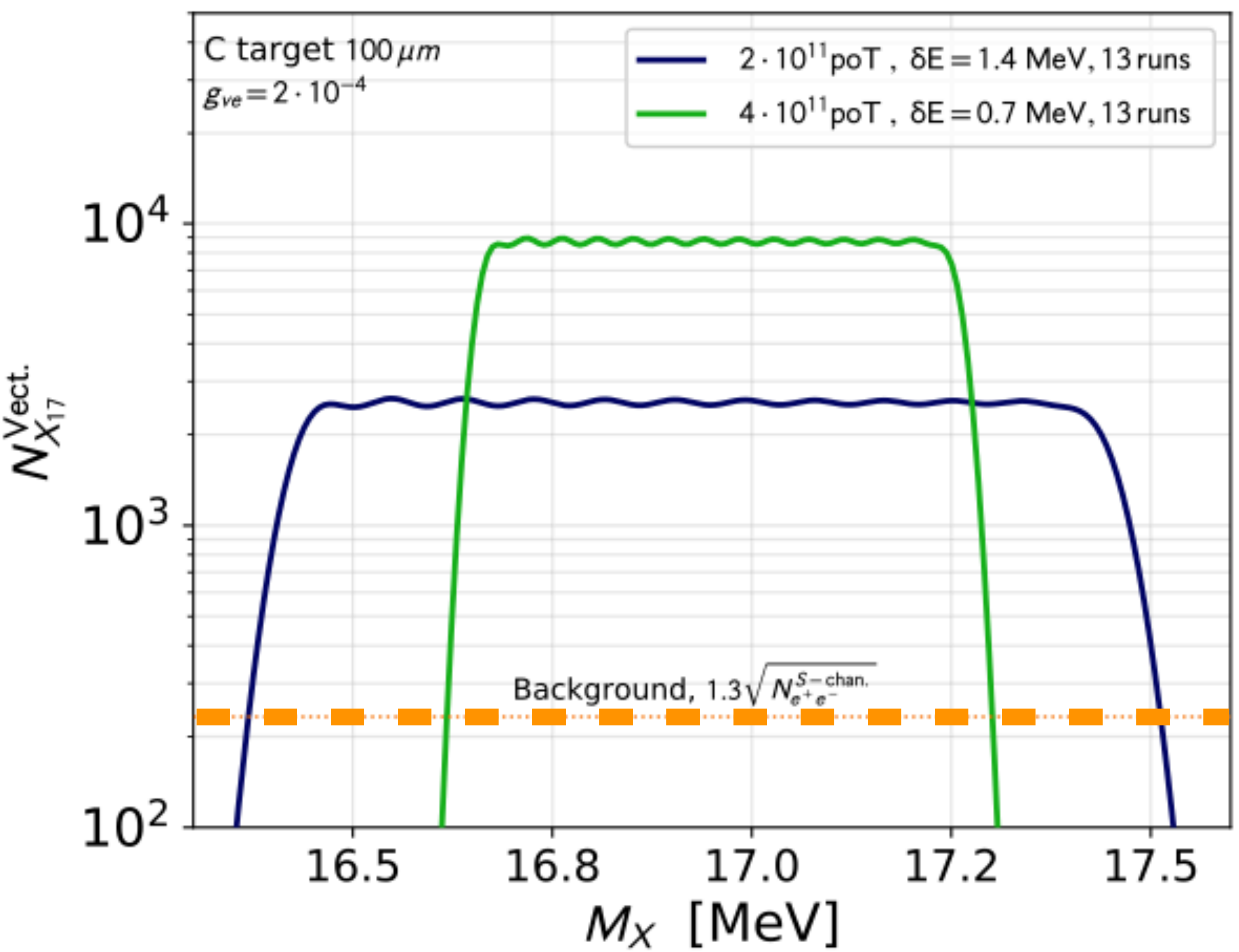
$$N_{A'} = N_{\text{poT}} \frac{N_{\text{Av}} Z \rho}{A} \ell_{\text{target}} \int dE \, \mathcal{G}(E, E_B, \sigma_B) \, \sigma(E)$$

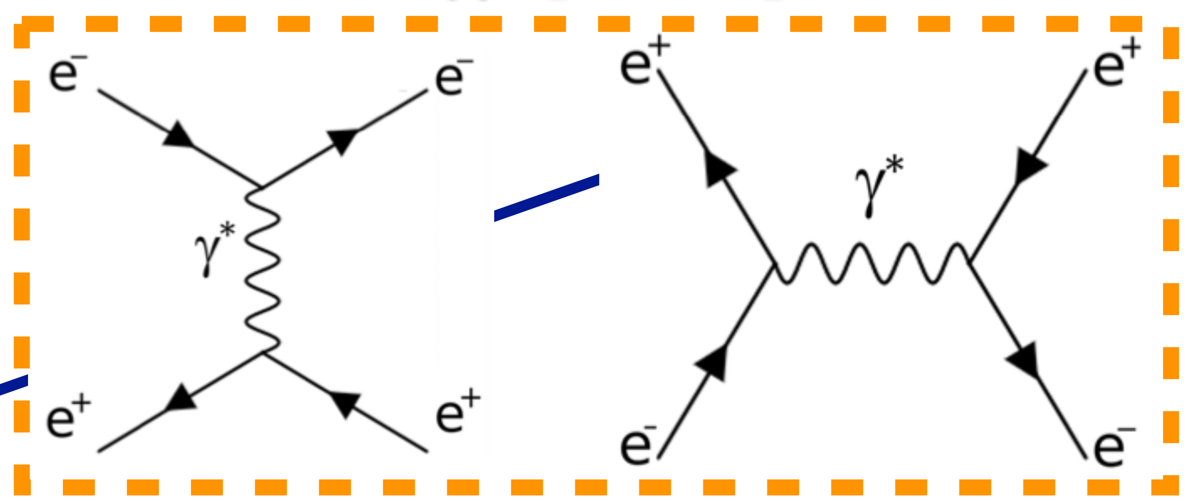
Gaussian beam energy spread

Resonant production

PADME strategy for the X_{17} search

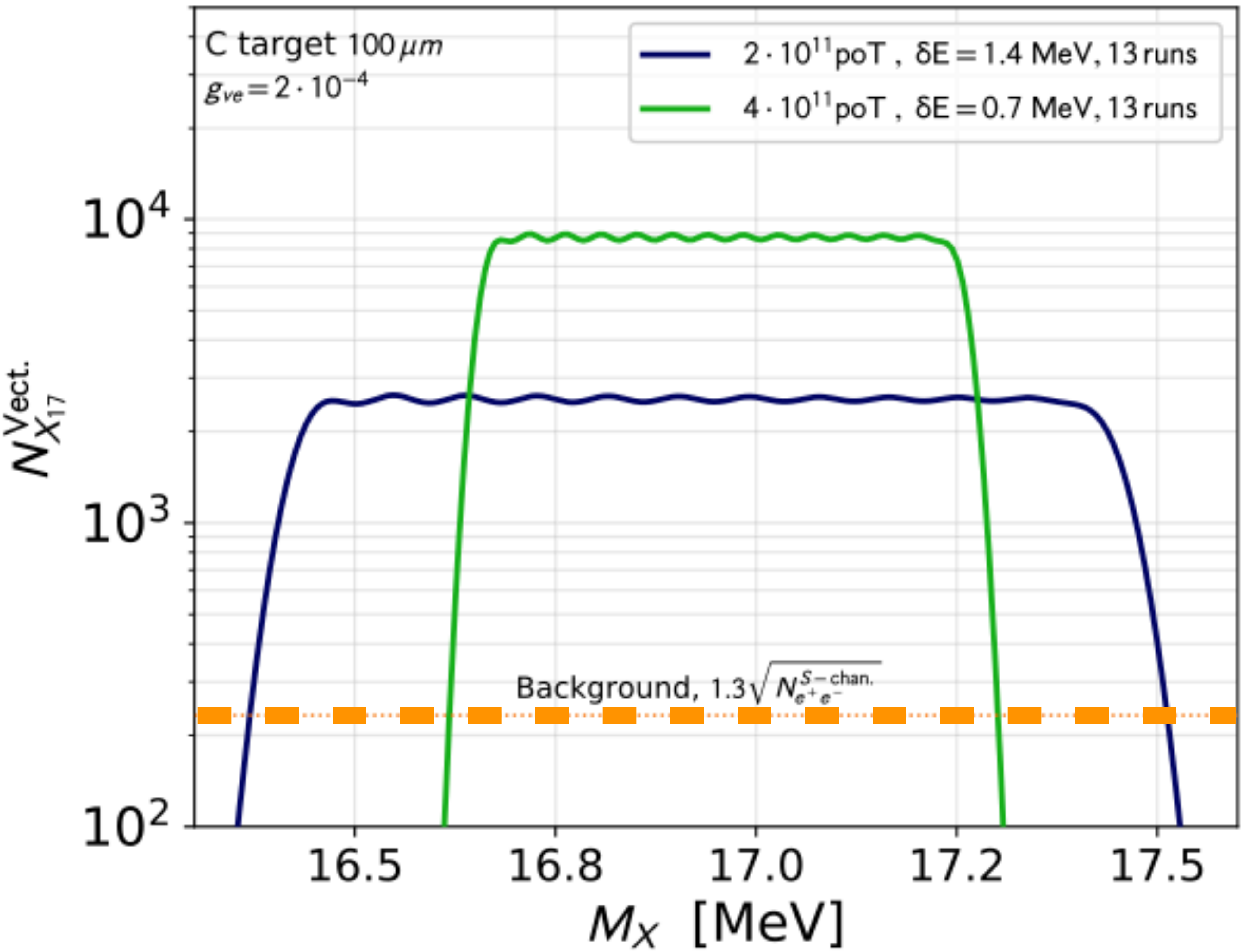
[Darmé, Mancini, Nardi, Raggi, Phys. Rev. D 106 (2022) 11, 115036]





Resonant production

PADME strategy for the X_{17} search



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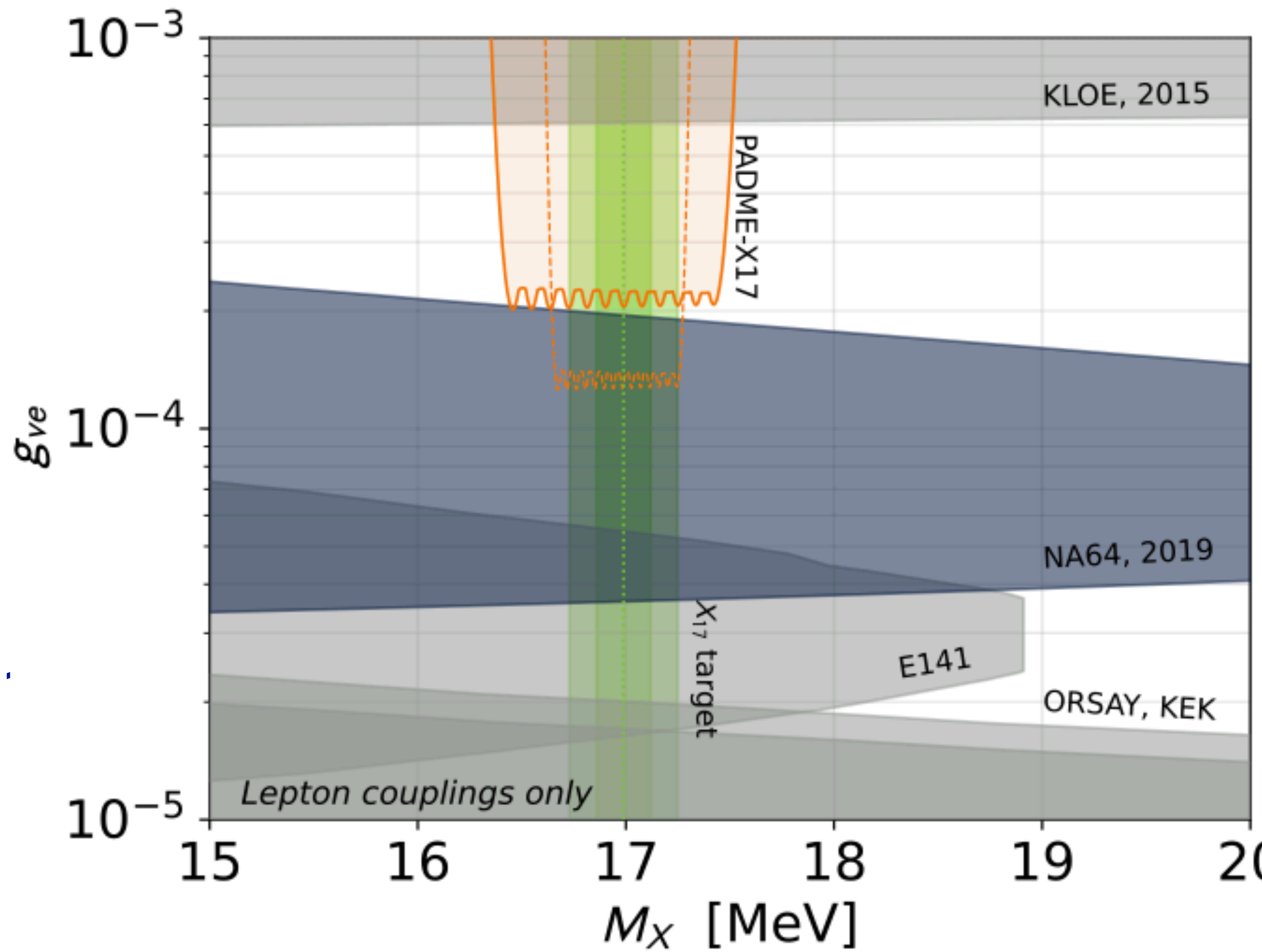
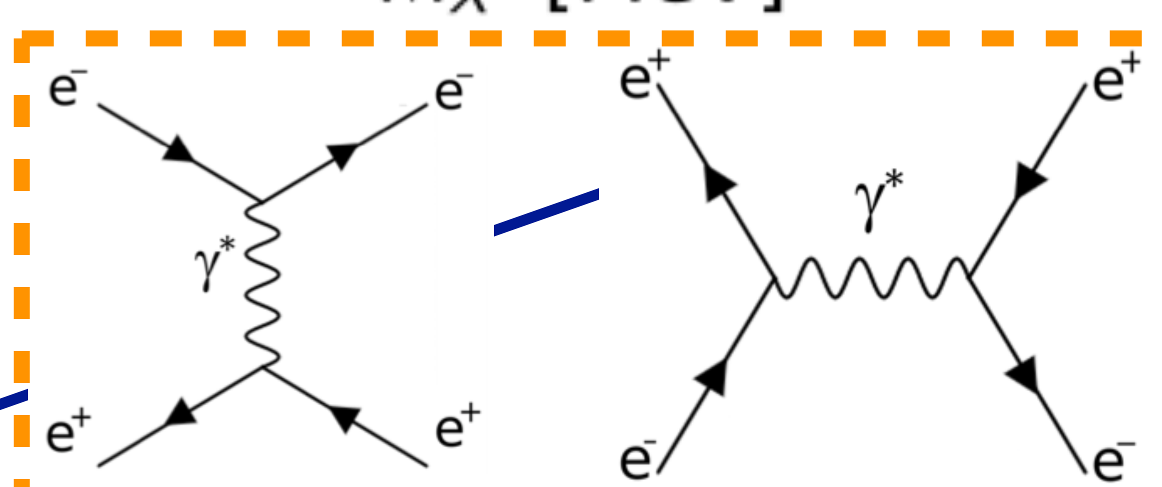
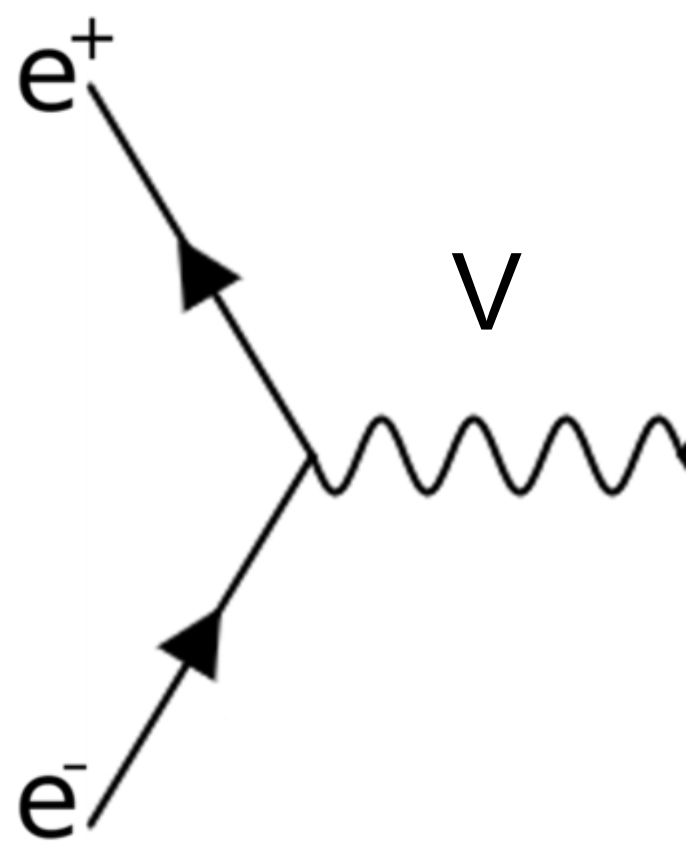




Free electrons at rest approximation

Resonant production

Free electron at rest (FEAR) approximation

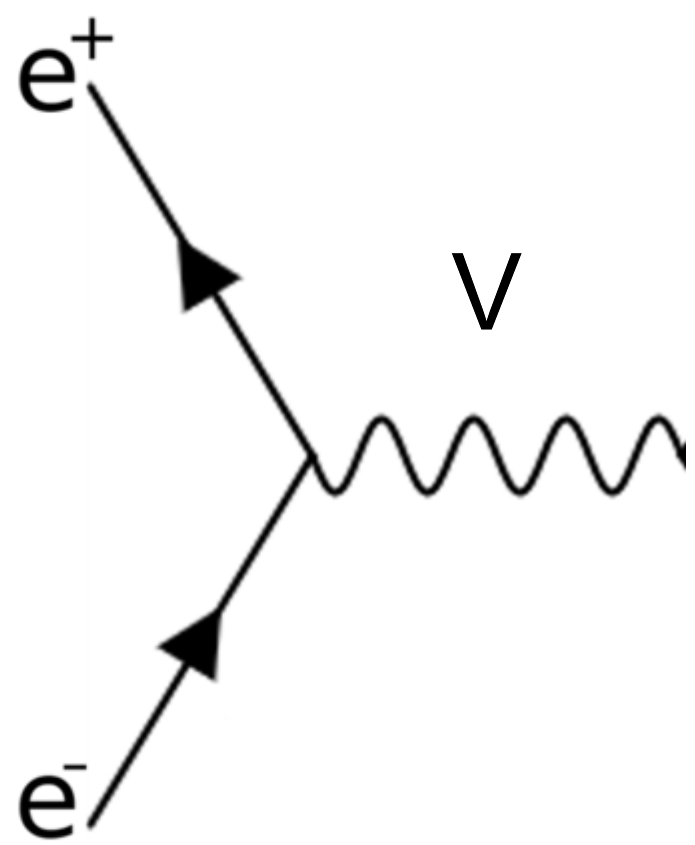


$$\sigma_{\rm res}(E) \simeq \frac{\pi g_V^2}{2m_e}\mathcal{G}(E, E_{\rm res}, \sigma_{E_B})$$

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

Resonant production

Free electron at rest (FEAR) approximation



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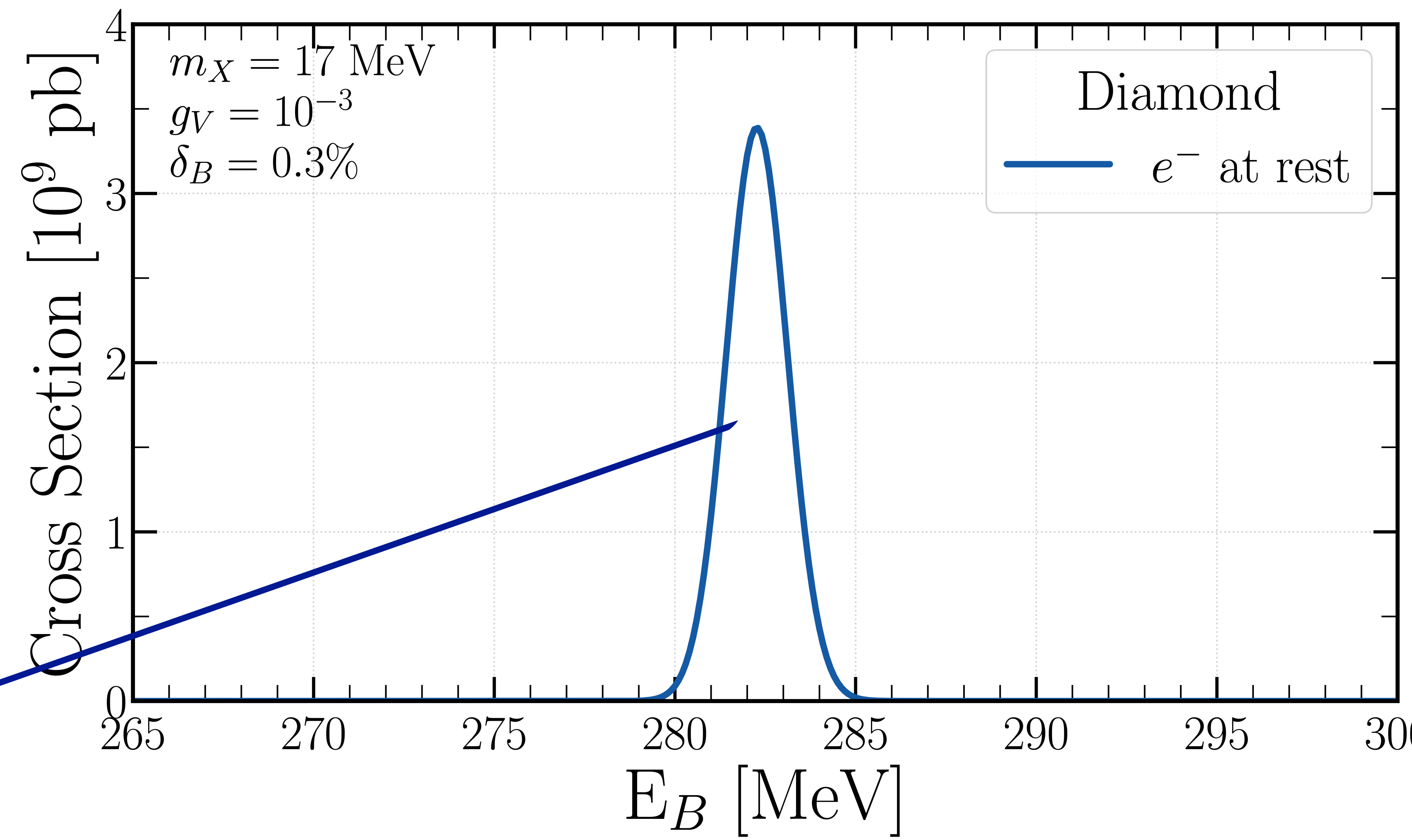
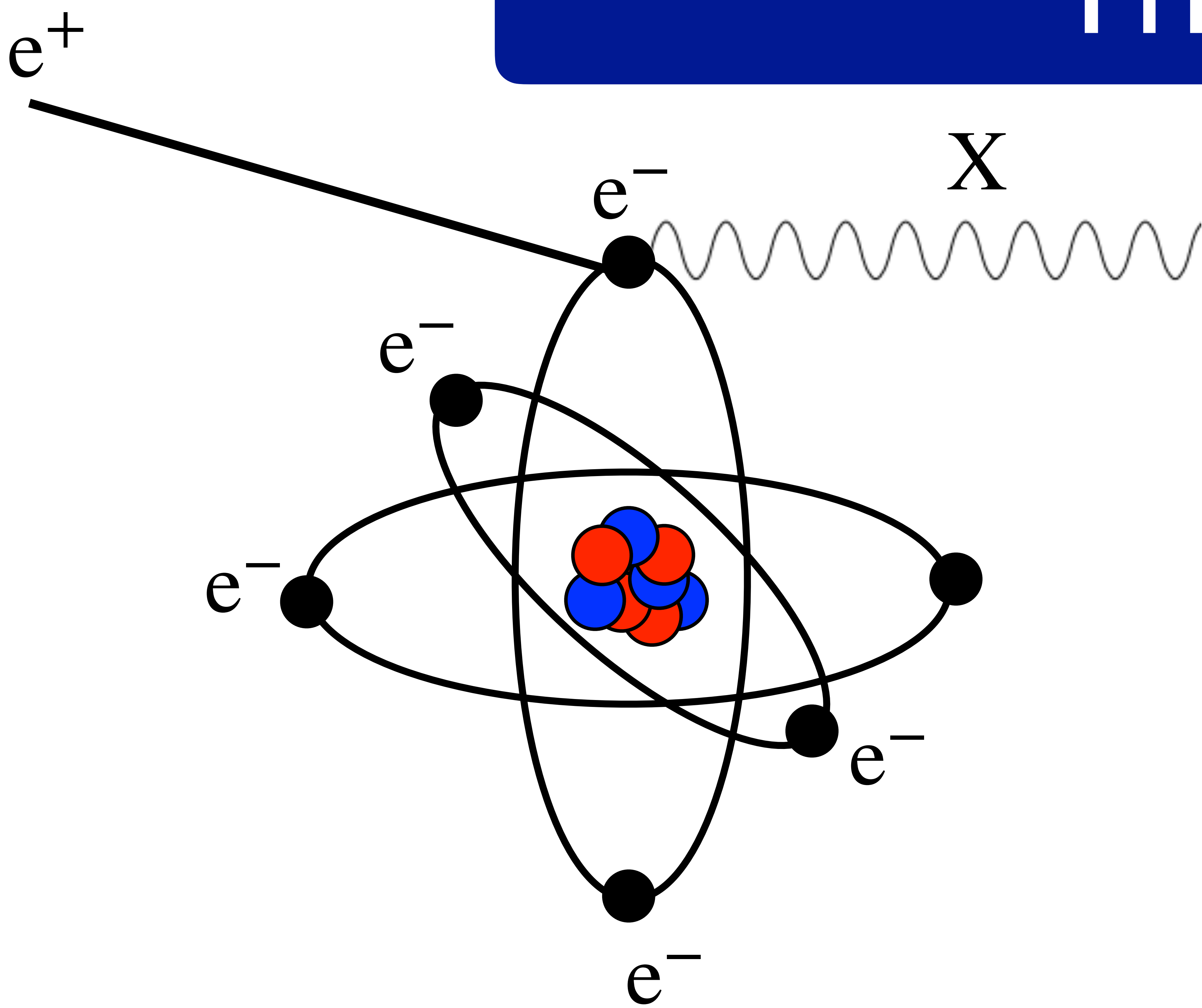
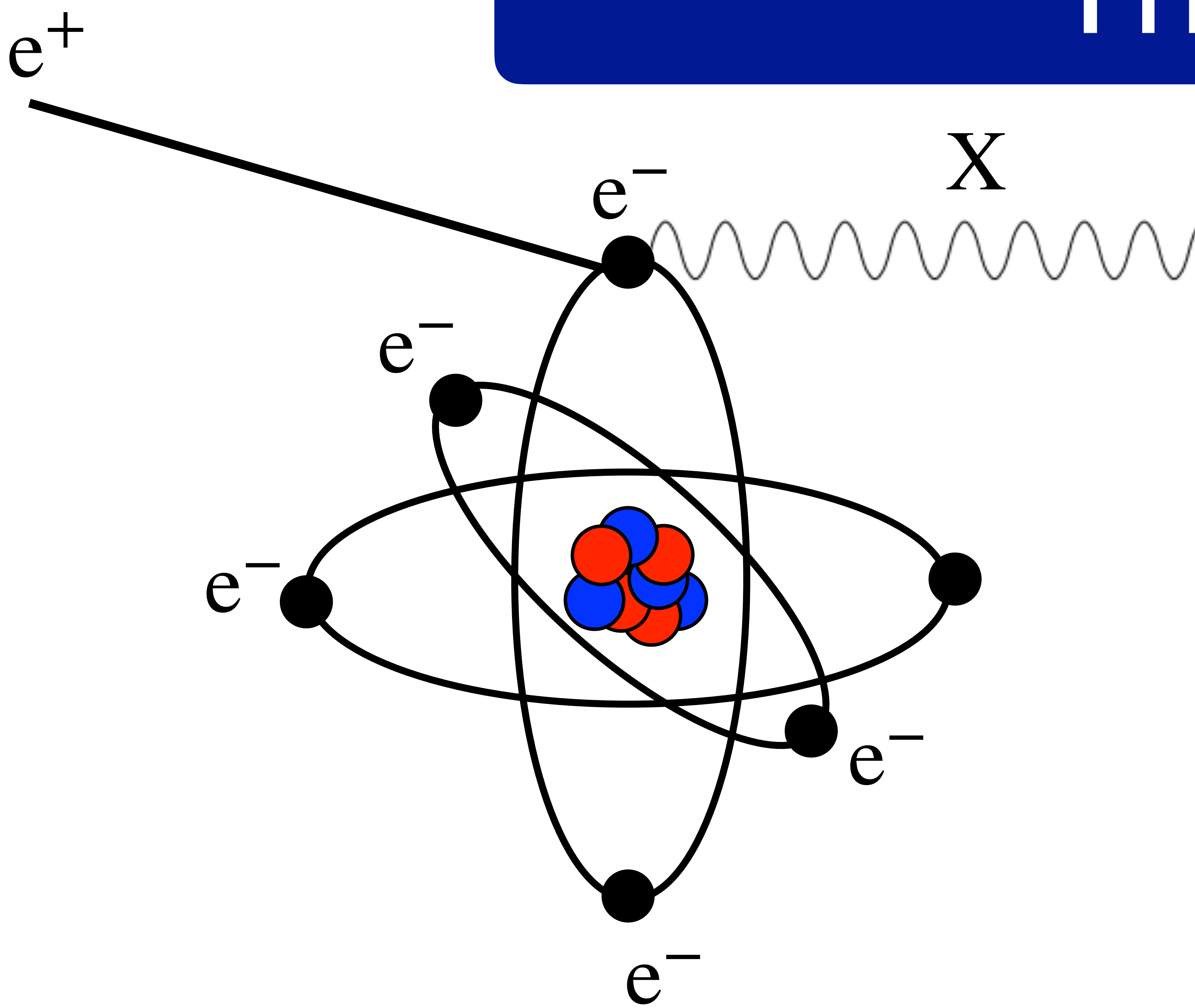


The problem



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

The problem



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

Naive estimate:

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

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

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

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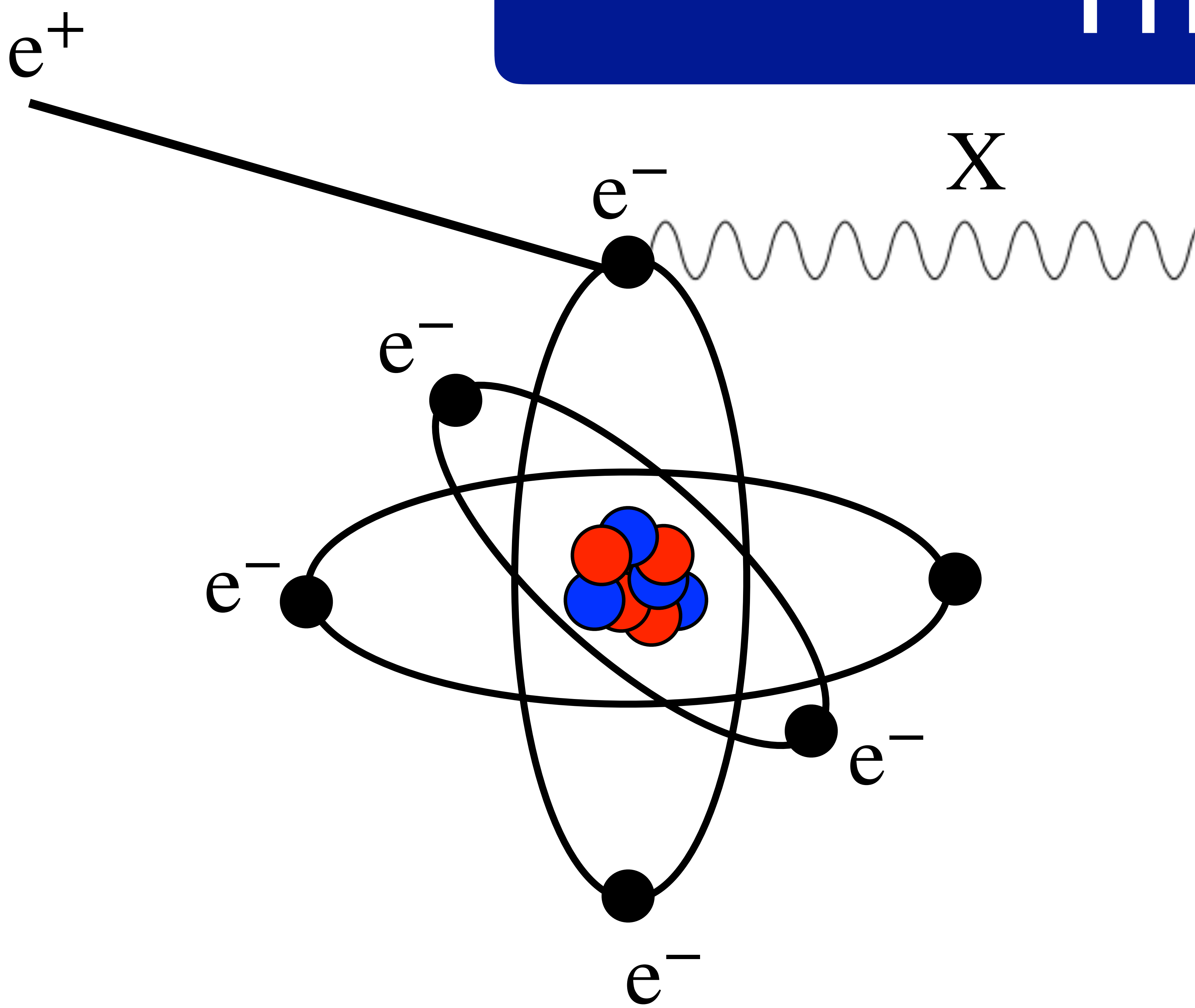

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using $\beta = \langle \beta_{1s} \rangle = 0.04$

$\sqrt{s} \simeq 17.0\,\mathrm{MeV}$ $\quad (E_b \sim 282.2\ \mathrm{MeV})$

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

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

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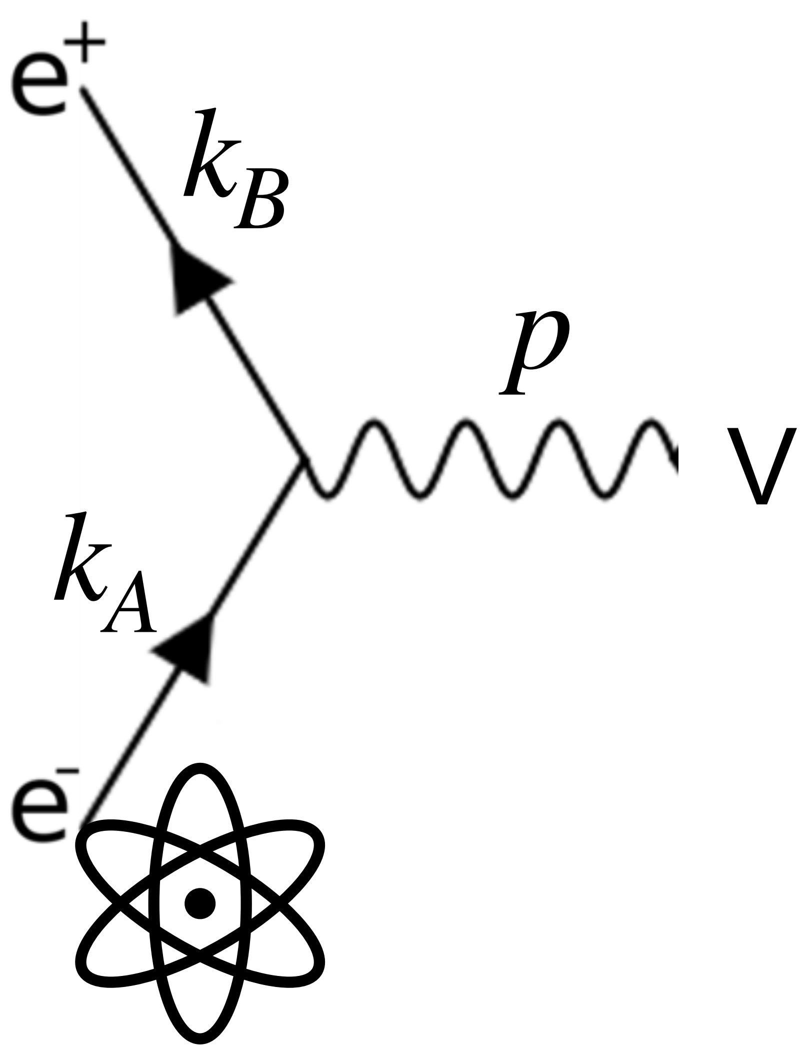
$$s' = m_e^2(2 - \beta^2\gamma^2) + 2\gamma m_e E_b (1 \pm \beta)$$

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

Bound moving electrons

The cross-section



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

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

wave-functions

matrix element

atomic electron quantum numbers

Assumptions

1. Positrons in the beam as free particles with well defined momentum p_B

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

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3. isotropic electron momentum distribution

The cross-section

$$d\sigma = \frac{d^3p_X}{(2\pi)^3}\int\frac{d^3k_A}{(2\pi)^3}\frac{(2\pi)^4}{8E_XE_{k_A}E_B|v_A - v_B|}n\left(\vec{k}_A\right)|\mathscr{M}|^2\delta(E_A + E_B - E_X)\delta^{(3)}(\vec{k}_A + \vec{p}_B - \vec{p}_X)$$

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

The cross-section

$$d\sigma = \frac{d^3 p_X}{(2\pi)^3} \int \frac{d^3 k_A}{(2\pi)^3} \frac{(2\pi)^4}{8 E_X E_{k_A} E_B \,|\, v_A - v_B \,|} n\left(\vec{k}_A\right) |\, \mathscr{M} \,|^2 \delta(E_A + E_B - E_X) \delta^{(3)}(\vec{k}_A + \vec{p}_B - \vec{p}_X)$$

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→ theory

use Slater Type Orbitals, hybridization, Hartree Fock computations for atomic carbon, …

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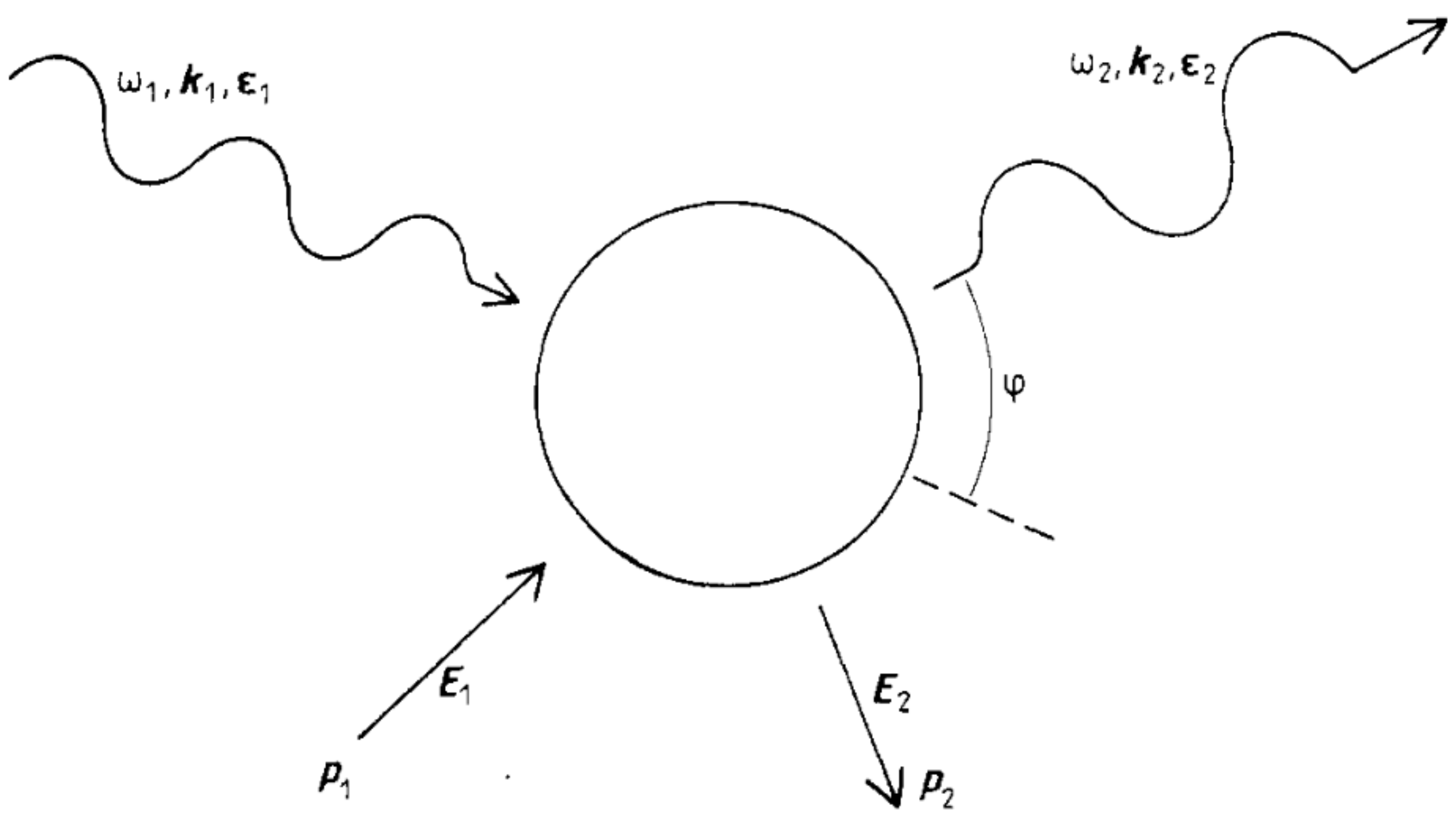
theory: use Slater Type Orbitals, hybridization, Hartree Fock computations for atomic carbon, …

data: obtain $n(k)$ from data: Compton Profile

Compton Profile

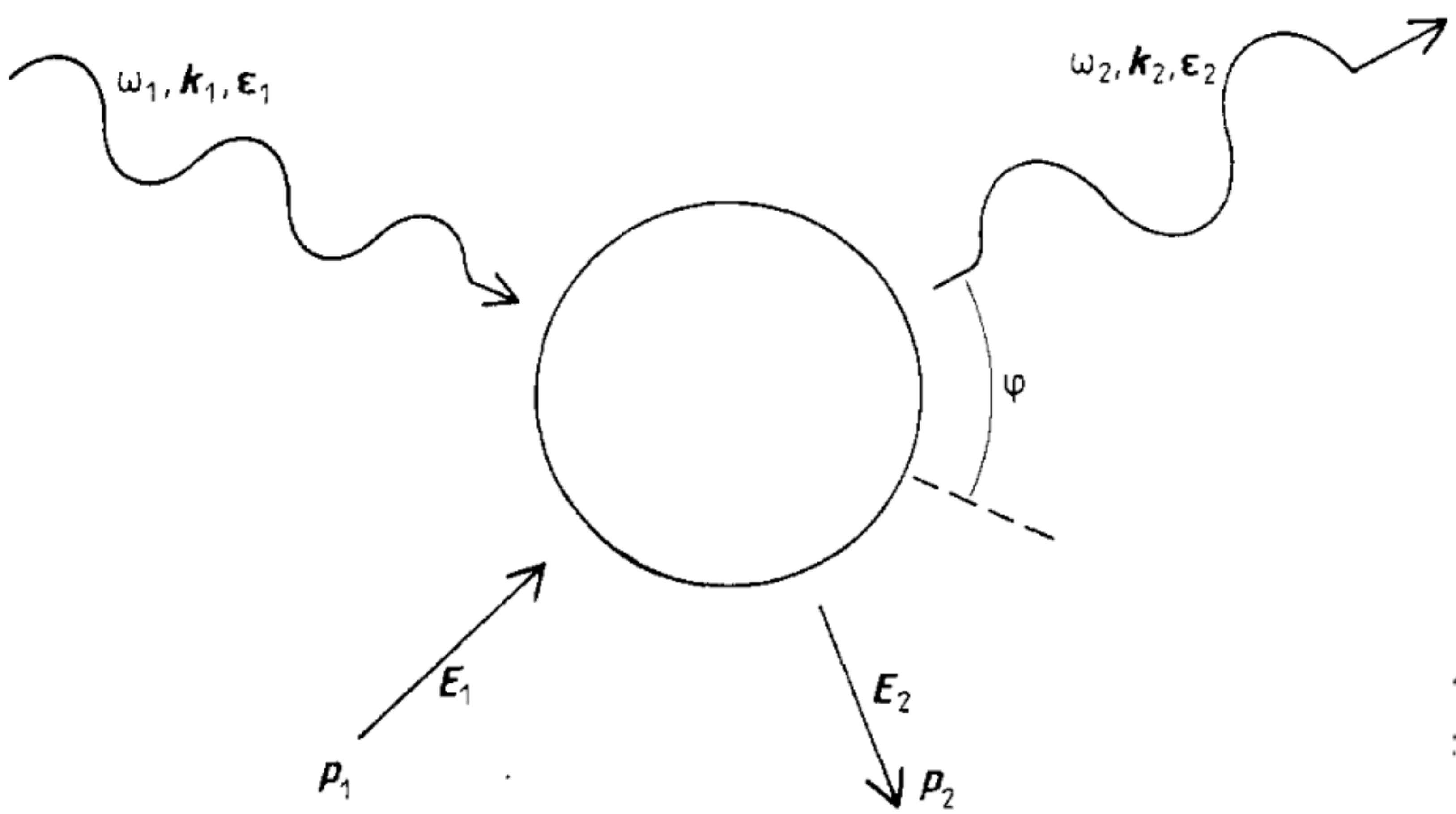


$$\omega_1 - \omega_2 = \frac{1}{2} m_e [\vec{p} + (\vec{k}_1 - \vec{k}_2)]^2 - \frac{|\vec{p}|^2}{2m_e}$$

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

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

Compton Profile



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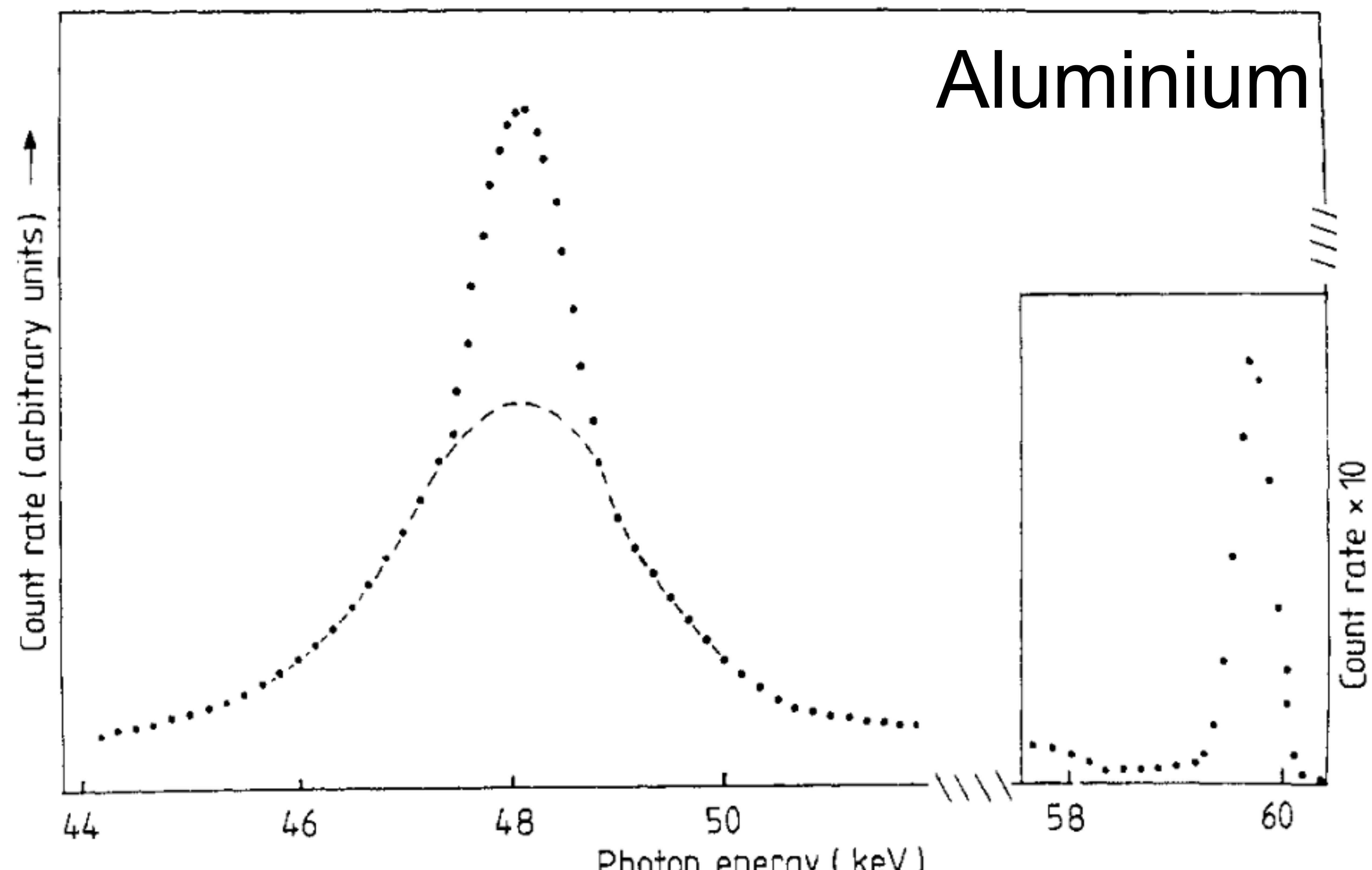
M J Cooper 1985 Rep. Prog. Phys. 48 415



Compton Profile

The Compton Profile is the Radon transform of the electronic momentum distribution along the scattering vector k_z

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

assuming isotropy

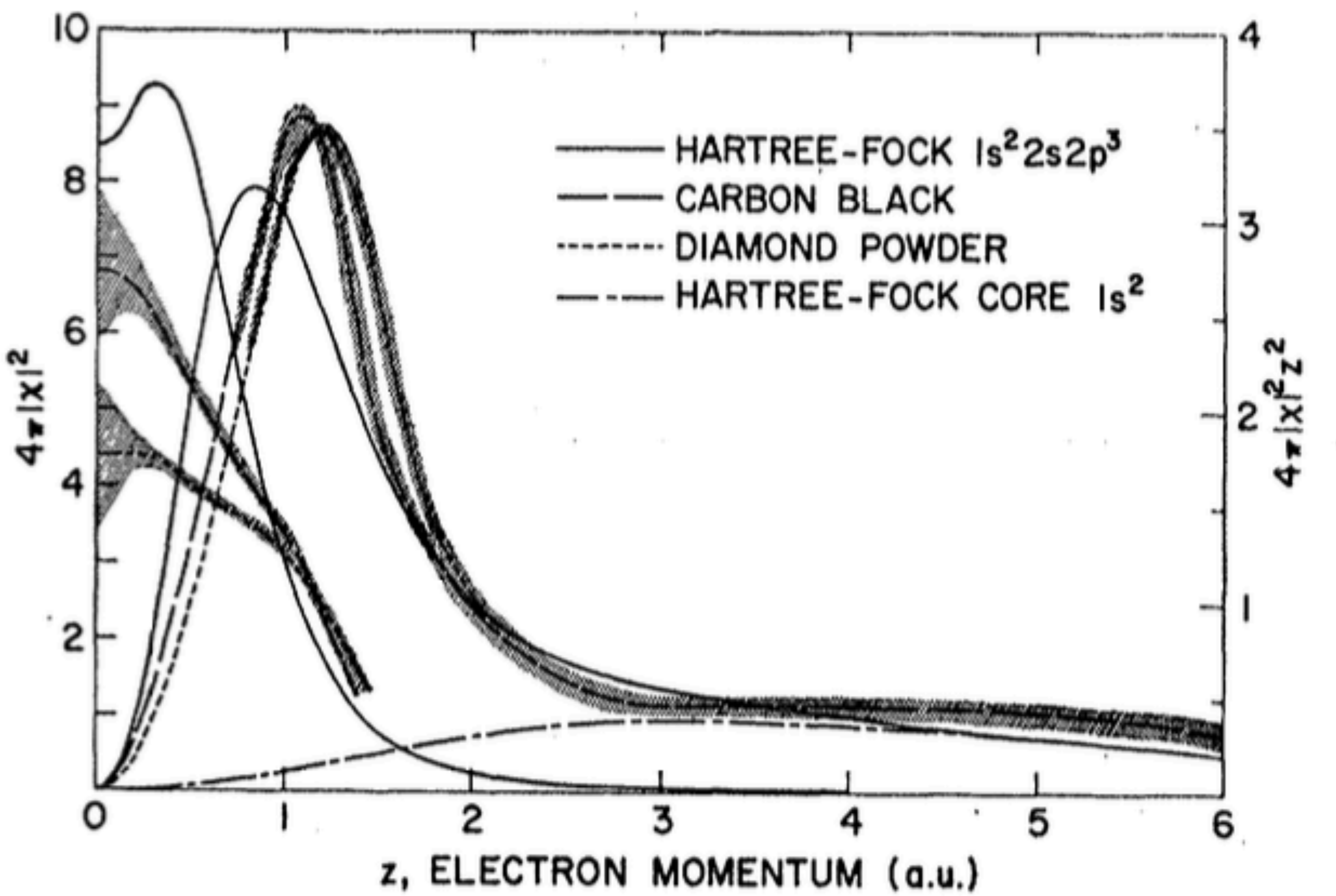
$$J(q) = \frac{1}{4\pi^2}\int_{|q|}^{\infty} n(k)\, k\, dk$$

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

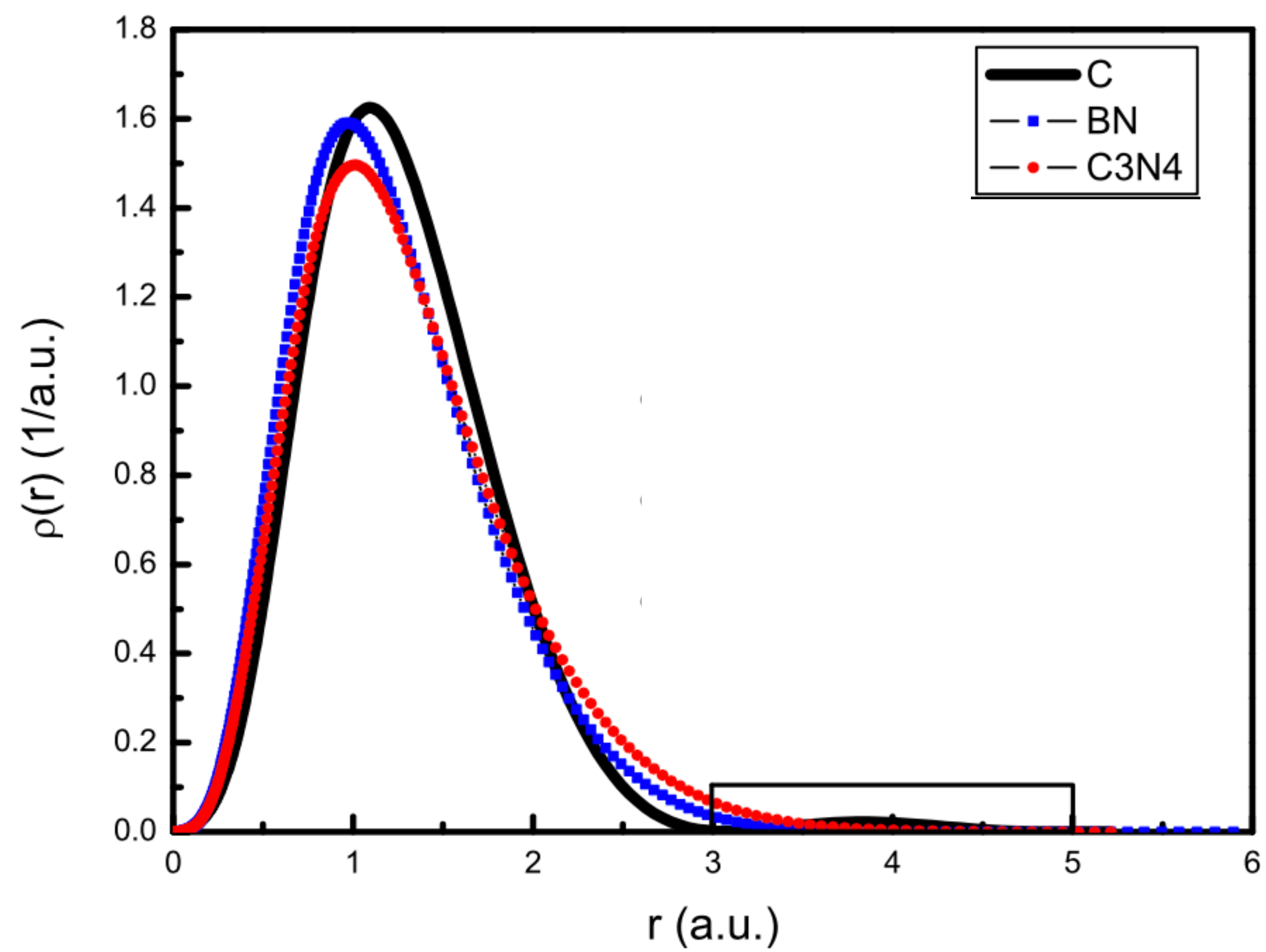
$$n(k) = -\frac{(2\pi)^2}{k}\left|\frac{dJ(k)}{dk}\right|$$

Data and theory

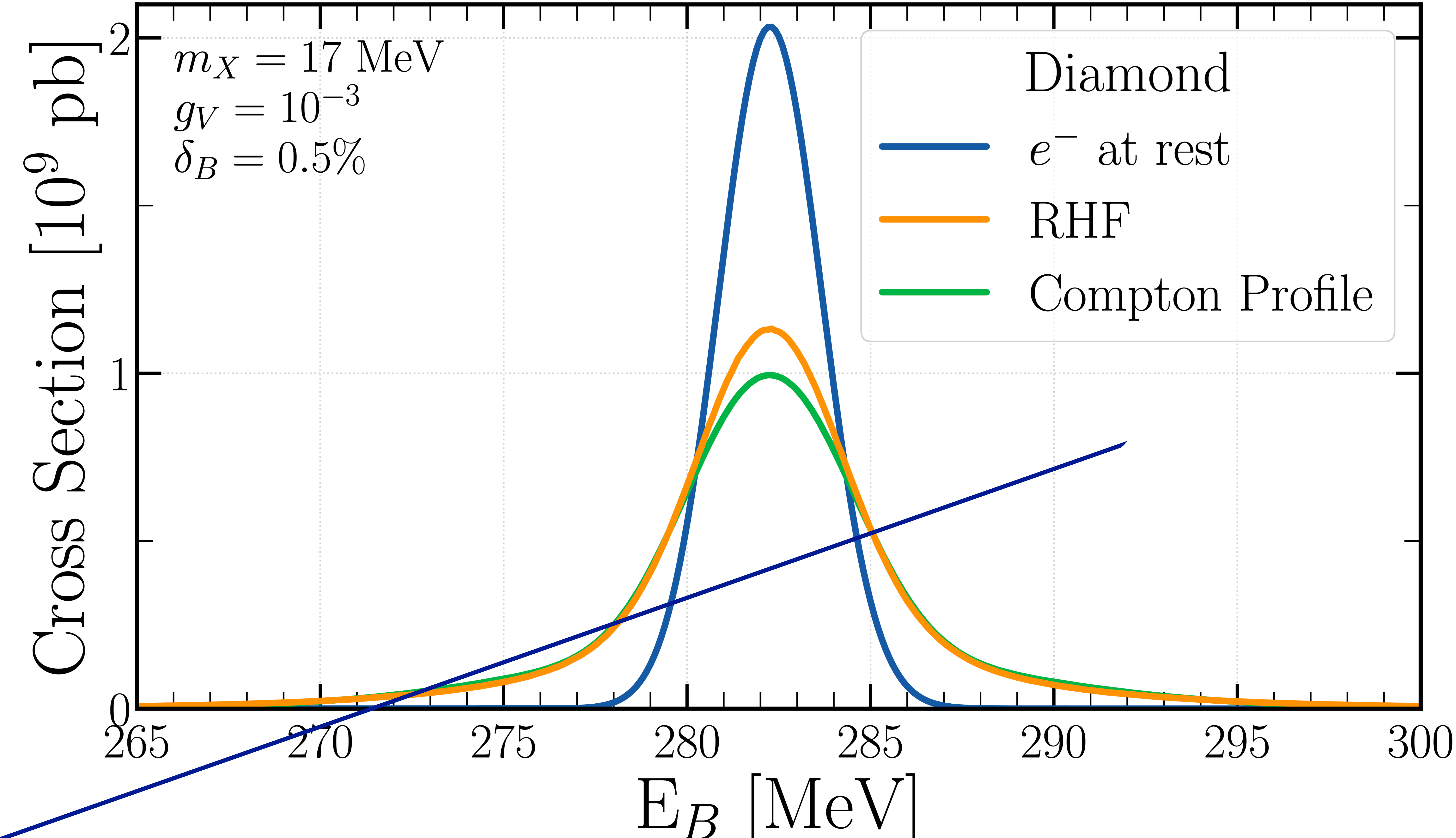
X-Ray determination of the Electron Momentum Density in Diamond, Graphite and Carbon Black
[Phys. Rev. 176 (1968) 900]



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

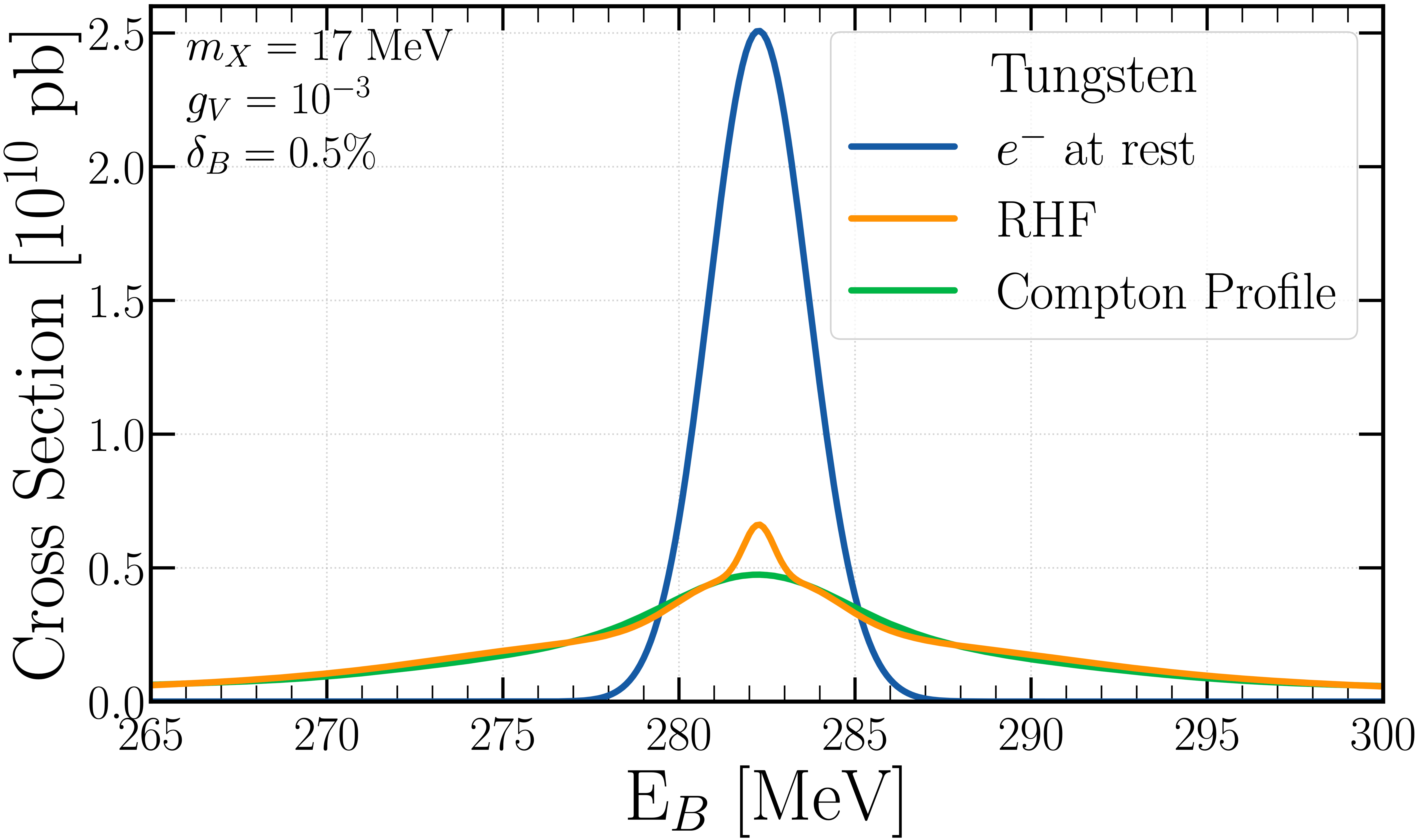


Comparison



$m_X = 17$ MeV
$g_V = 10^{-3}$
$\delta_B = 0.5\%$
Diamond
e^- at rest
RHF
Compton Profile
Cross Section [10^9 pb]
0
1
2
265
270
275
280
285
290
295
300
E_B [MeV]

Comparison



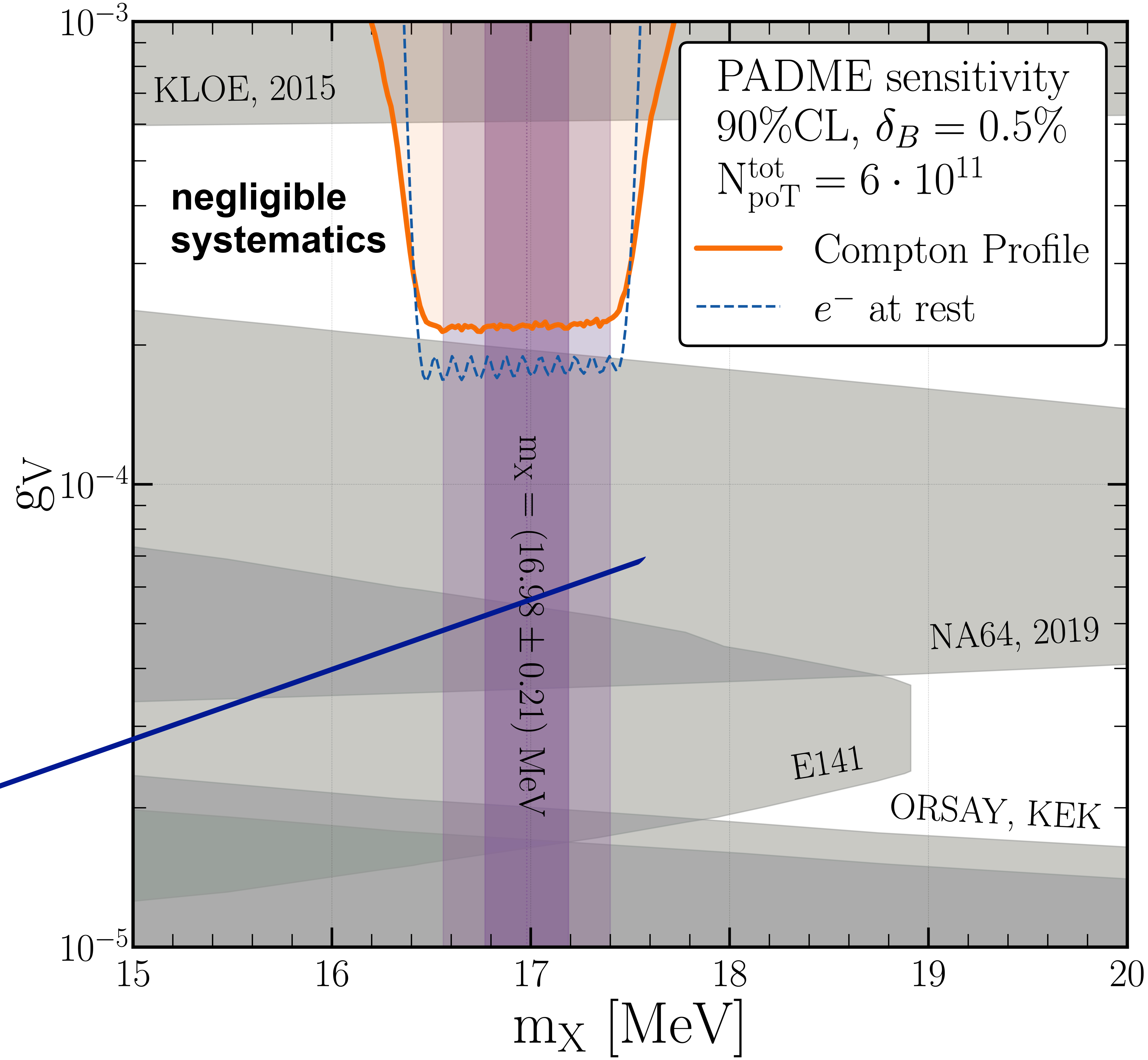
$m_X = 17$ MeV
$g_V = 10^{-3}$
$\delta_B = 0.5\%$
Tungsten
e^- at rest
RHF
Compton Profile
Cross Section [10^{10} pb]
0.0
0.5
1.0
1.5
2.0
2.5
265
270
275
280
285
290
295
300
E_B [MeV]

Atoms as electron accelerators: new physics

X17 sensitivity @PADME

[Arias-Aragon, Darmé, G^{2}dC, Nardi, PRL132(2024)261801, arXiv:2403.15387]

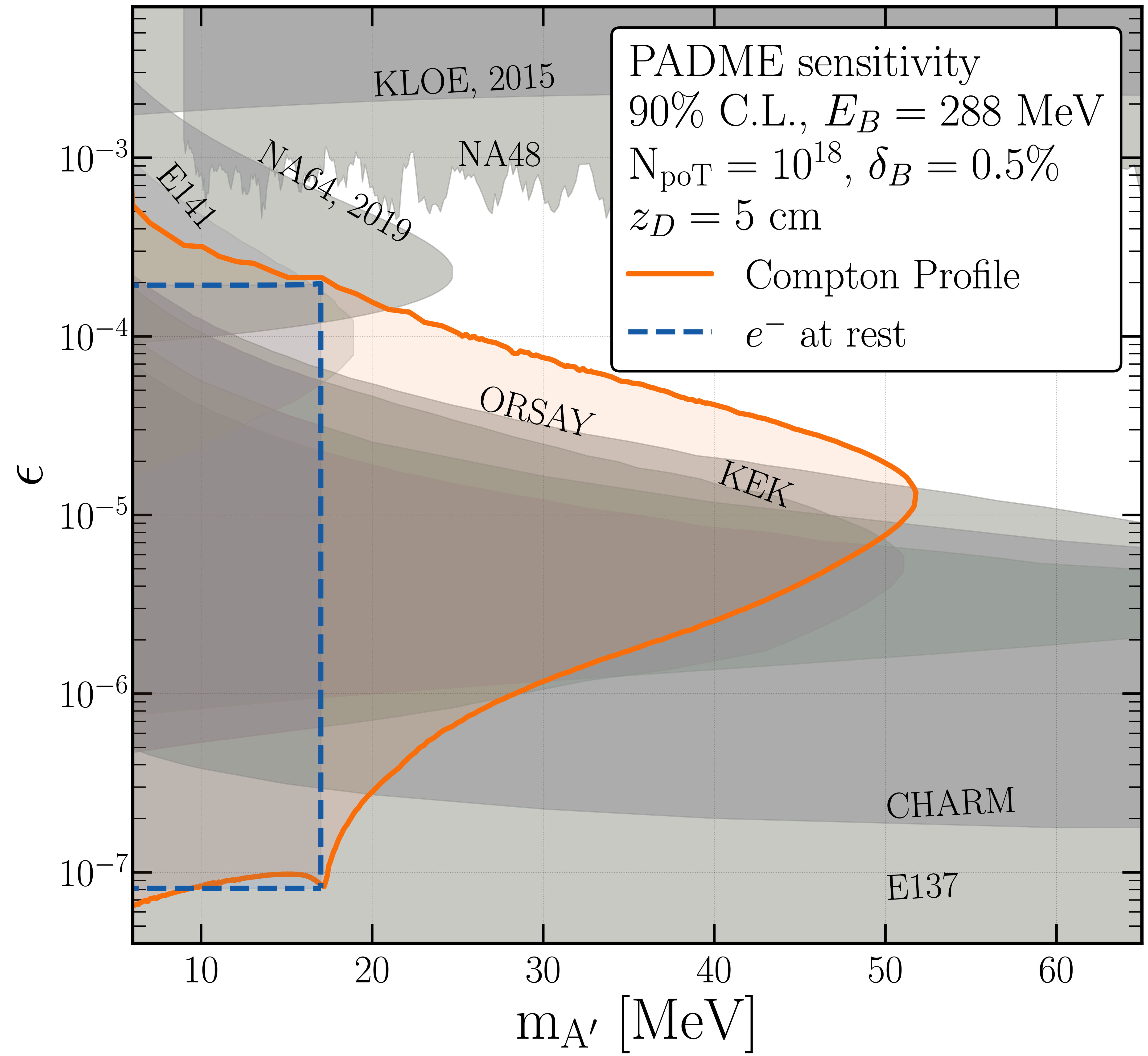
$$\mathscr{L} \supset -i\, g_V\, \bar{\psi}_e \gamma^\mu \psi_e\, V_\mu$$



Dark photons

[Arias-Aragon, Darmé, G^{2}dC, Nardi, PRL132(2024)261801, arXiv:2403.15387]

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

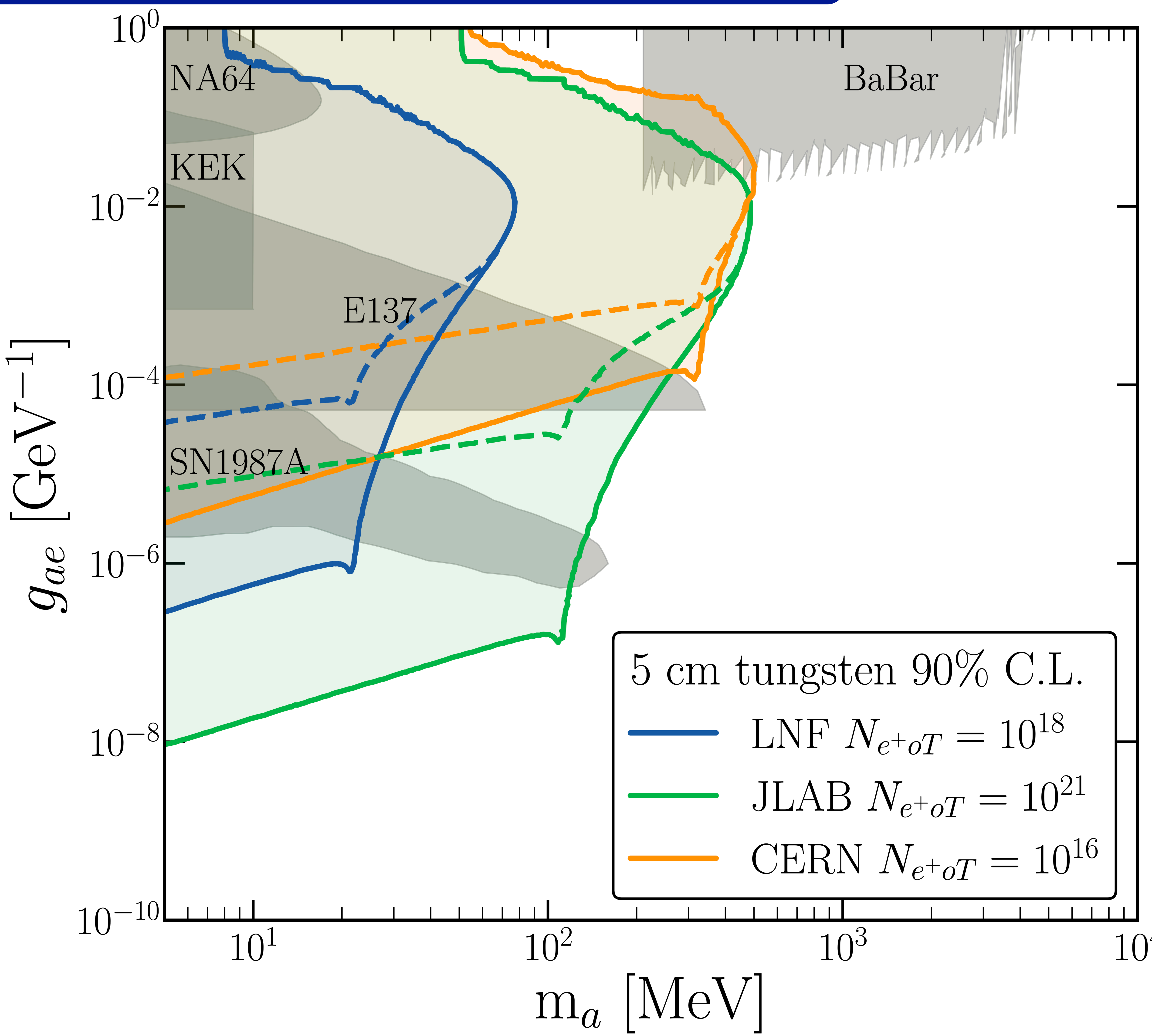


Dark pseudo-scalars

[Arias-Aragon, Darmé, G^{2}dC, Nardi, Veissière, in preparation]

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

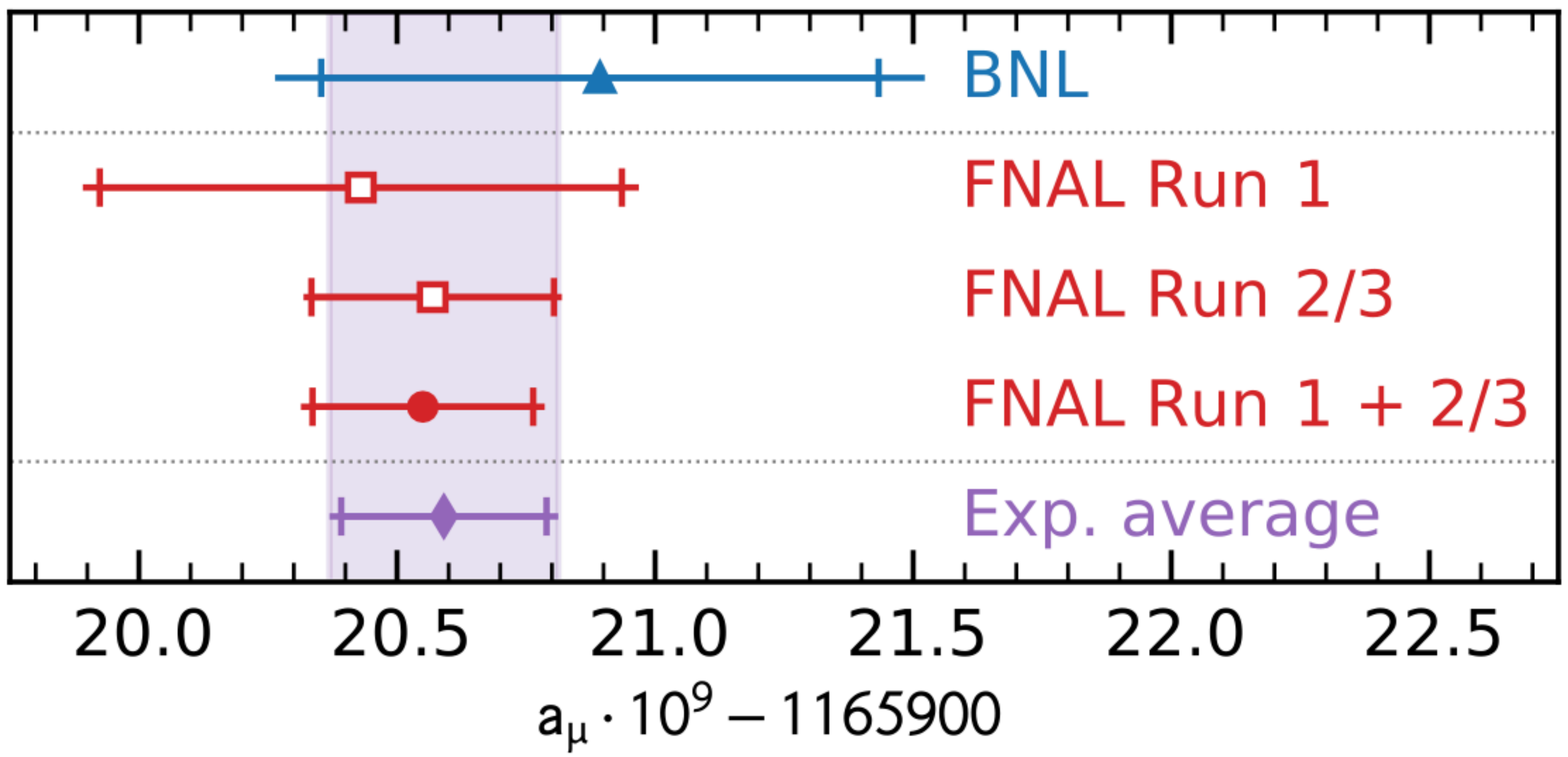
LNF: 450 MeV
JLAB: 12 GeV
CERN: 100 GeV

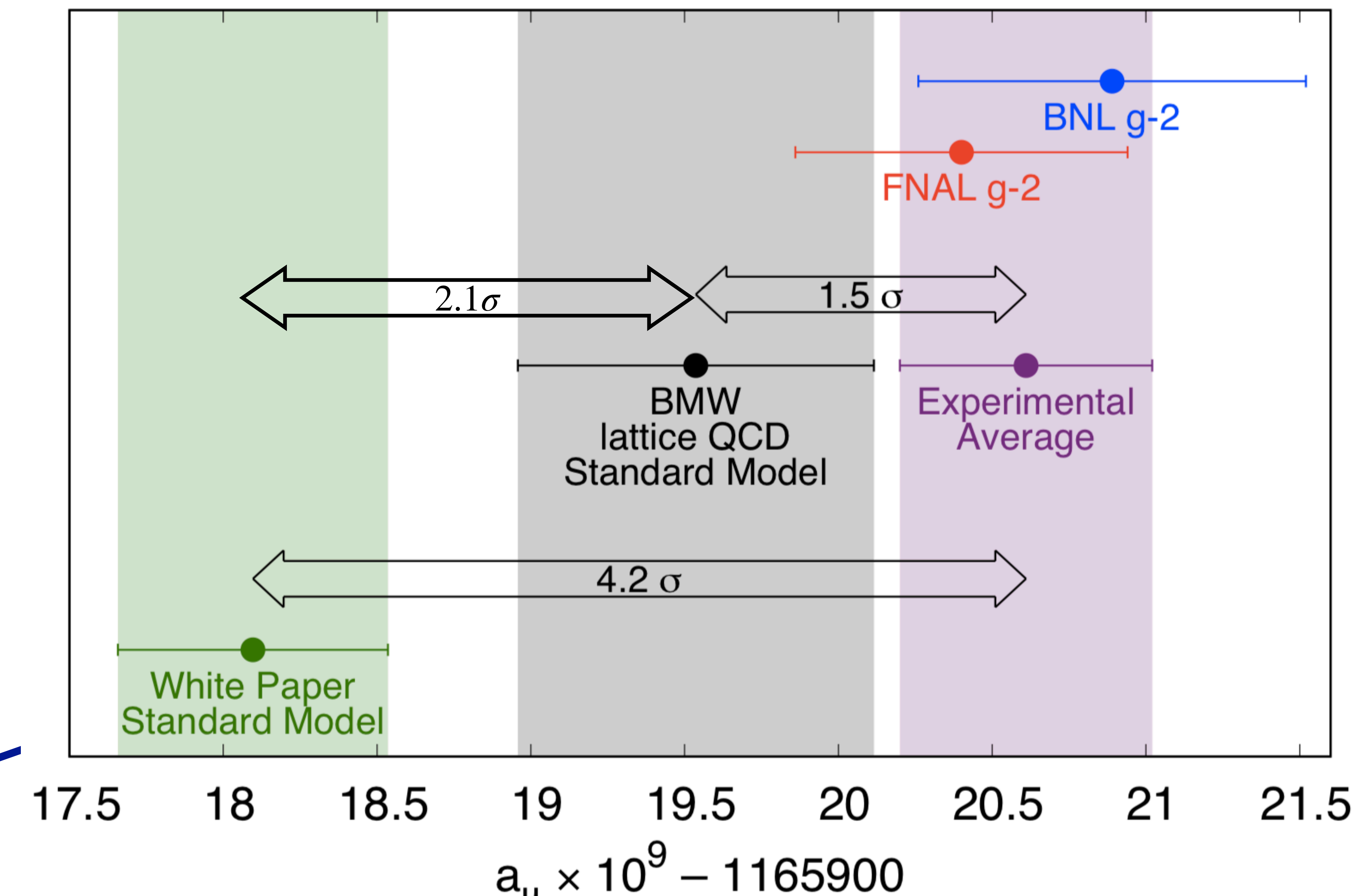


Atoms as electron accelerators: σ_{had}

Hadron vacuum polarization

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





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

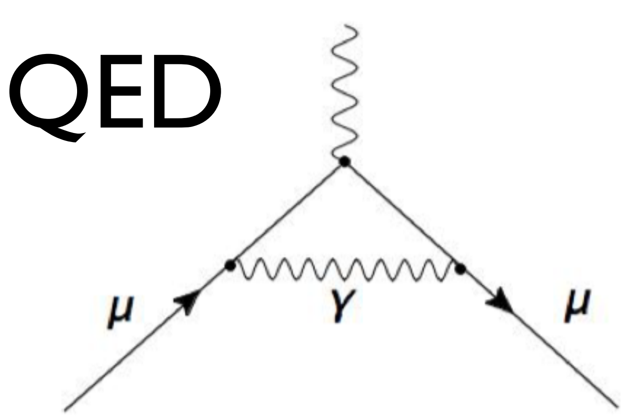
Hadron vacuum polarization

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

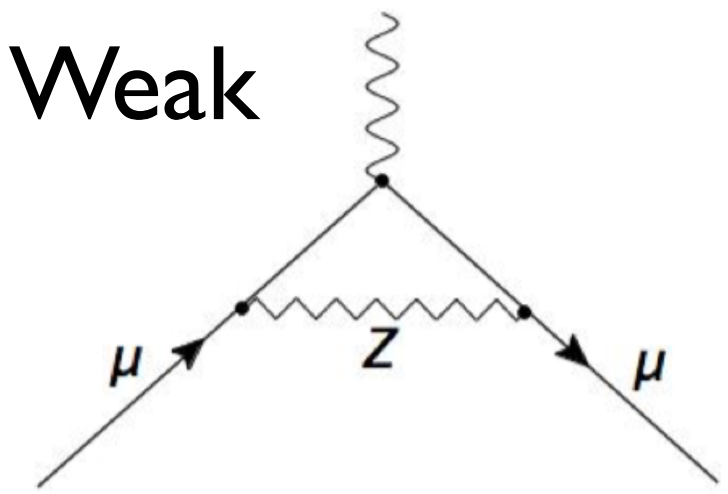
$116584718.9(1) \cdot 10^{-11}$

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

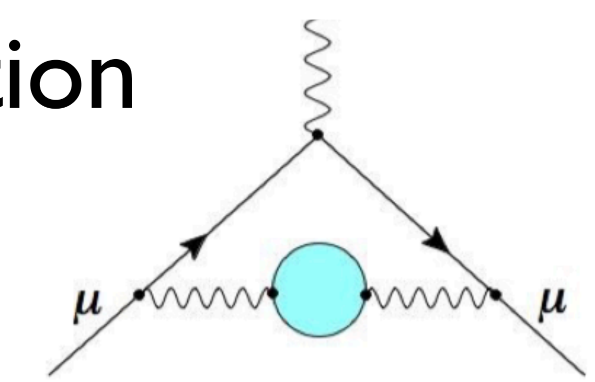
QED



Weak

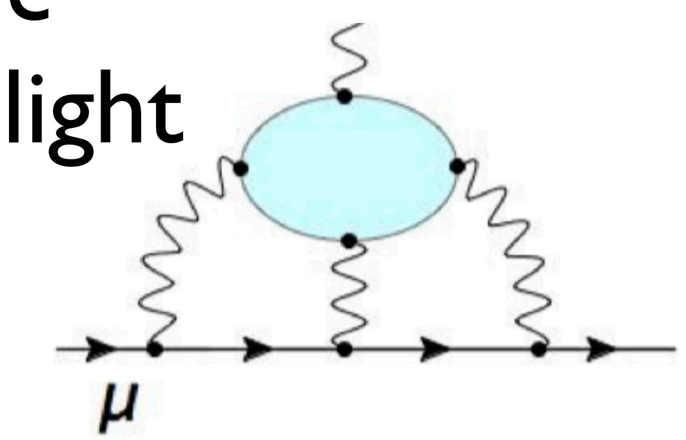


Hadronic vacuum polarization



$+ \ldots$

Hadronic light-by-light

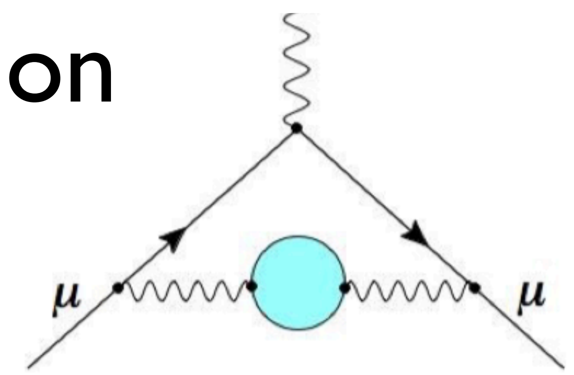


$153.6(1.0) \cdot 10^{-11}$

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

Hadron vacuum polarization

Hadronic vacuum polarization

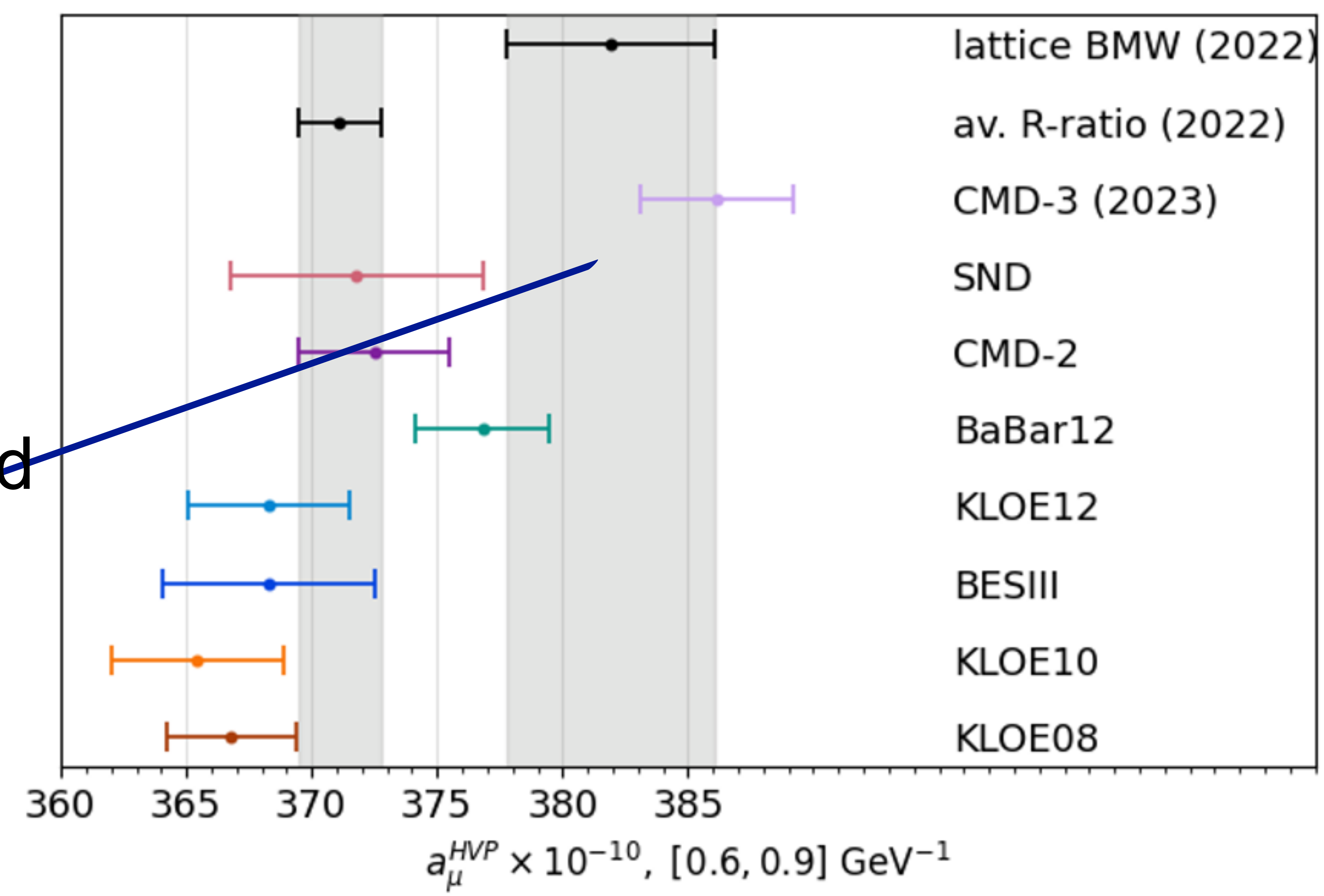


$$6845(40) \cdot 10^{-11}$$

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

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

1. employing a scanning method
2. employing the radiative return method



Hadron vacuum polarization

PROPOSAL:

[Arias-Aragon, Darmé, G^2dC, Nardi, 2407.15941]

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

Hadron vacuum polarization

[Arias-Aragon, Darmé, G^2dC, Nardi, 2407.15941]

Two possible beam-lines:

1. JLAB: $E_B = 12$ GeV, $10^{21} e^+$oT
2. CERN H4 beam-line: $E_B = (100 - 200)$ GeV, $(2.3 - 0.2) \times 10^{13}\ e^+$oT

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

Hadron vacuum polarization

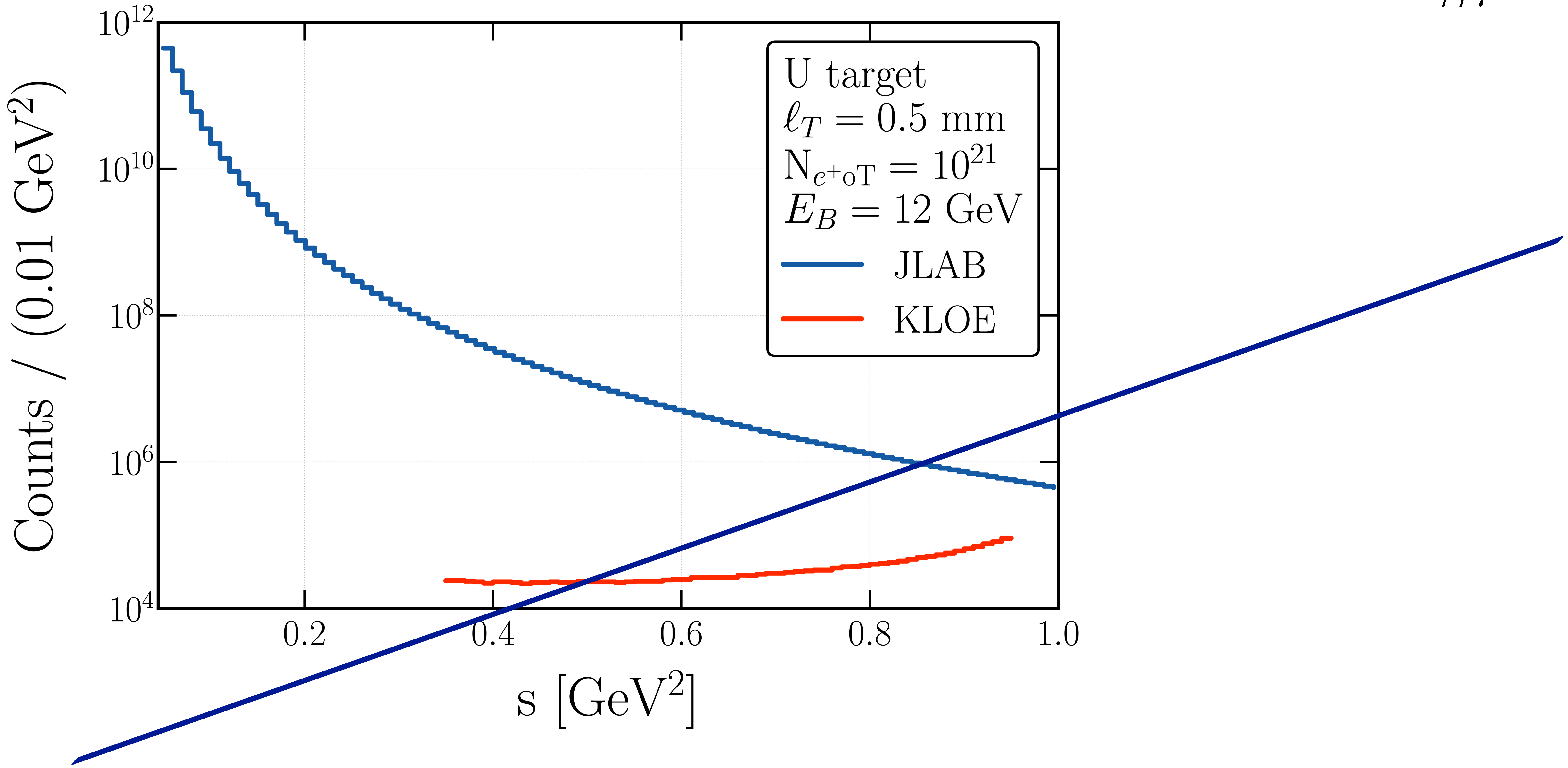
Two possible beam-lines:

1. JLAB: $E_B = 12$ GeV, $10^{21} e^+$oT
2. CERN H4 beam-line: $E_B = (100 - 200)$ GeV, order 10^{16} e^+oT needed

[Arias-Aragon, Darmé, G^{2}dC, Nardi, 2407.15941]

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

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



Hadron vacuum polarization

[Arias-Aragon, Darmé, G^{2}dC, Nardi, 2407.15941]

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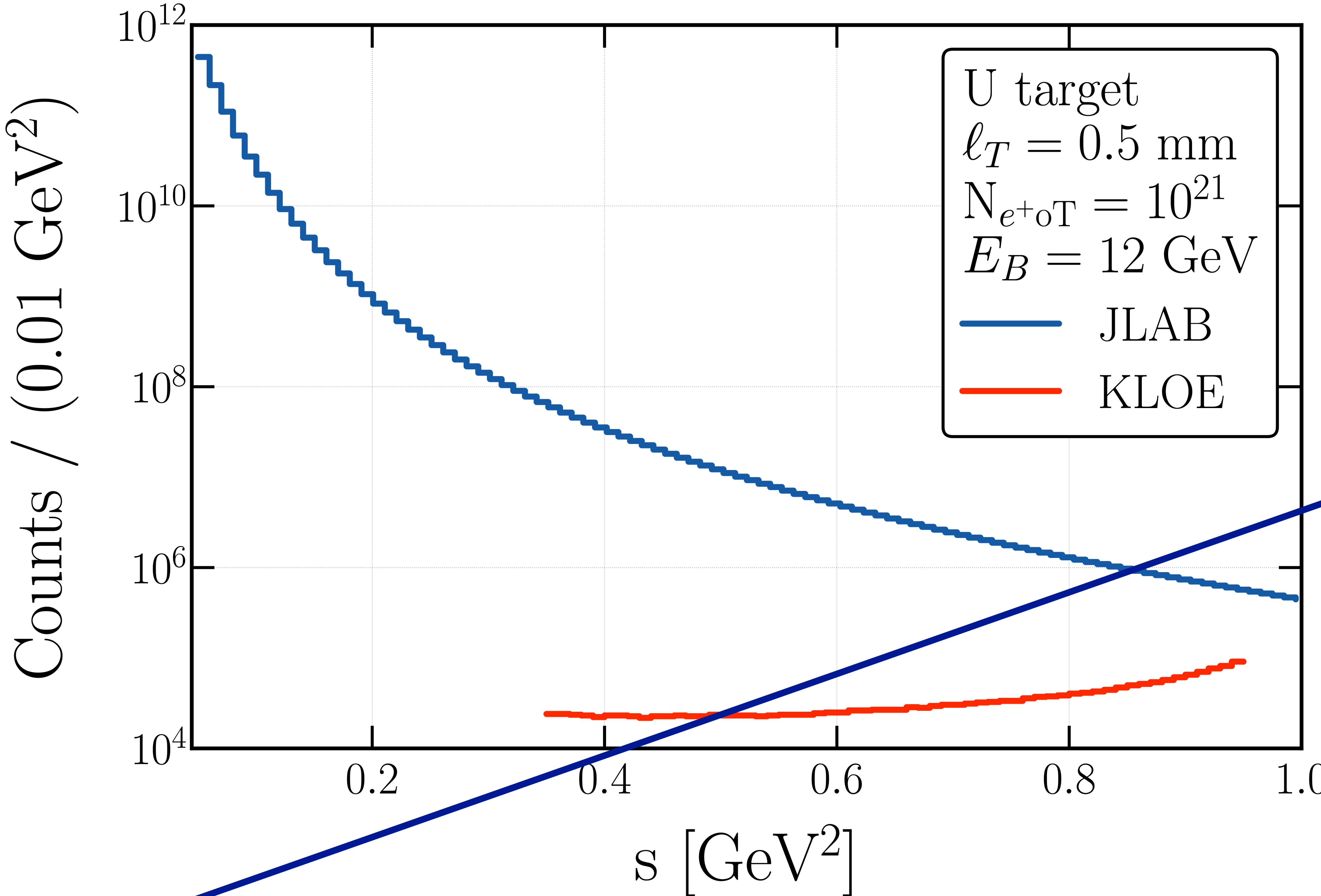

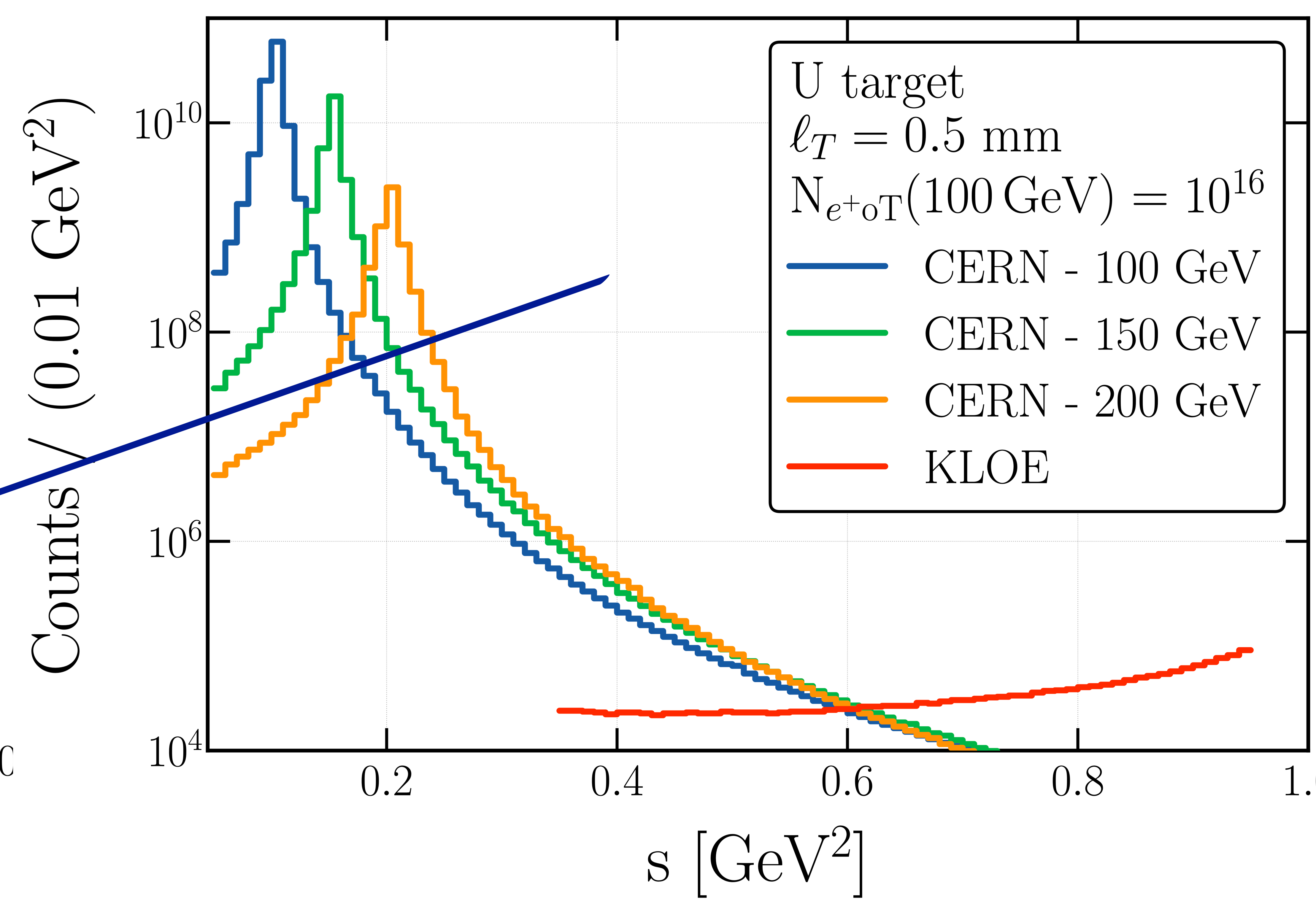

Conclusions

Conclusions

- Prescription on how to account for non-zero momentum of electrons in the target taking advantage of Compton profiles;
- Impact of the atomic electron motion on the X17 search at PADME (but <u>not limited to PADME</u>);
- Opens up new perspectives on positron annihilation on fixed targets: increased sensitivity for BSM theories, hadron cross section measurement, impact on MUonE…