Atoms as electron accelerators

Leveraging atomic electron momentum distribution in fixed target experiments

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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, PRL134(2025)061802

F. Arias Aragon, G^{2}dC, E. Nardi and L. Veissière, 2504.00100

Light Dark Matter @ Accelerators 2025 - 9/4/2025

Outline

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

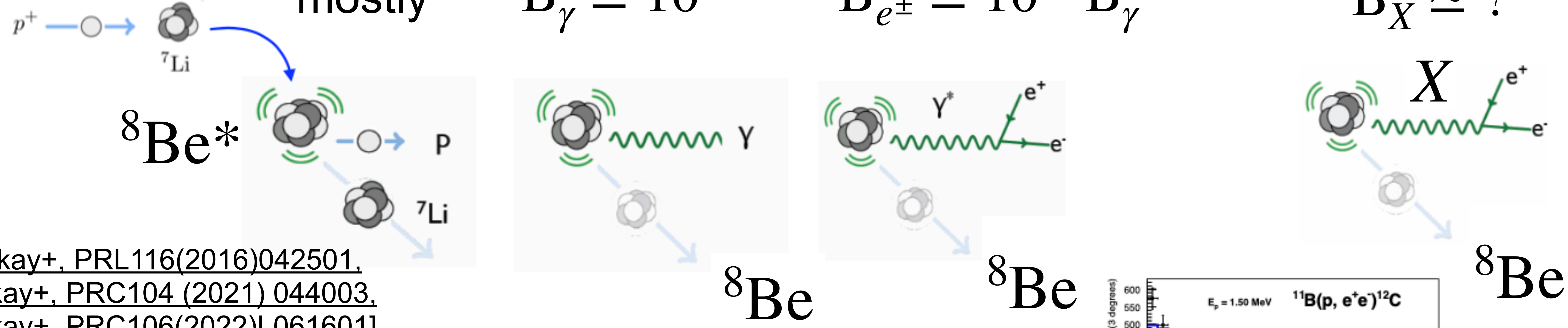
Motivation

[see Arias-Aragon's talk yesterday]

The X_{17} saga

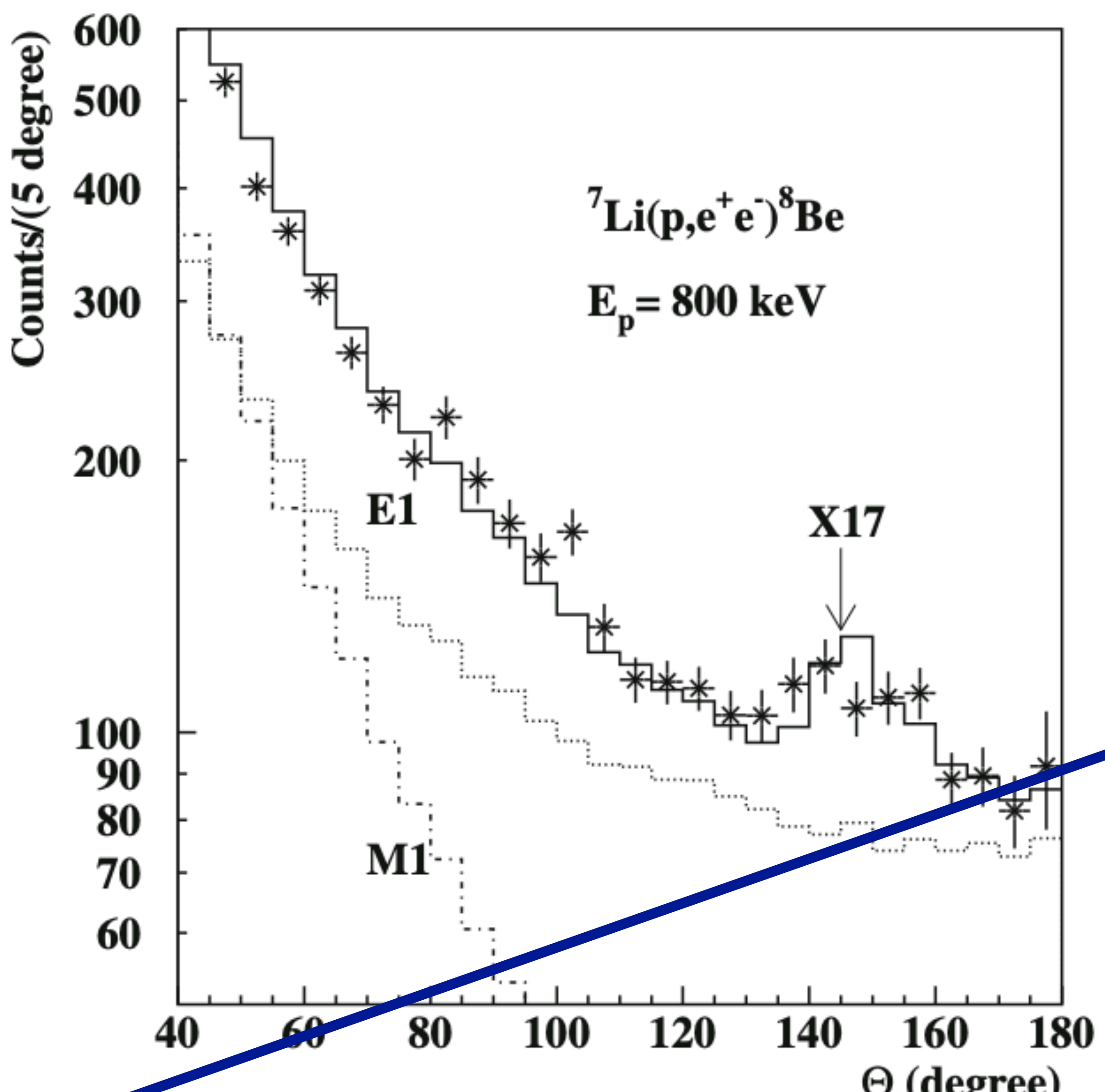
[tomorrow's X17 session]

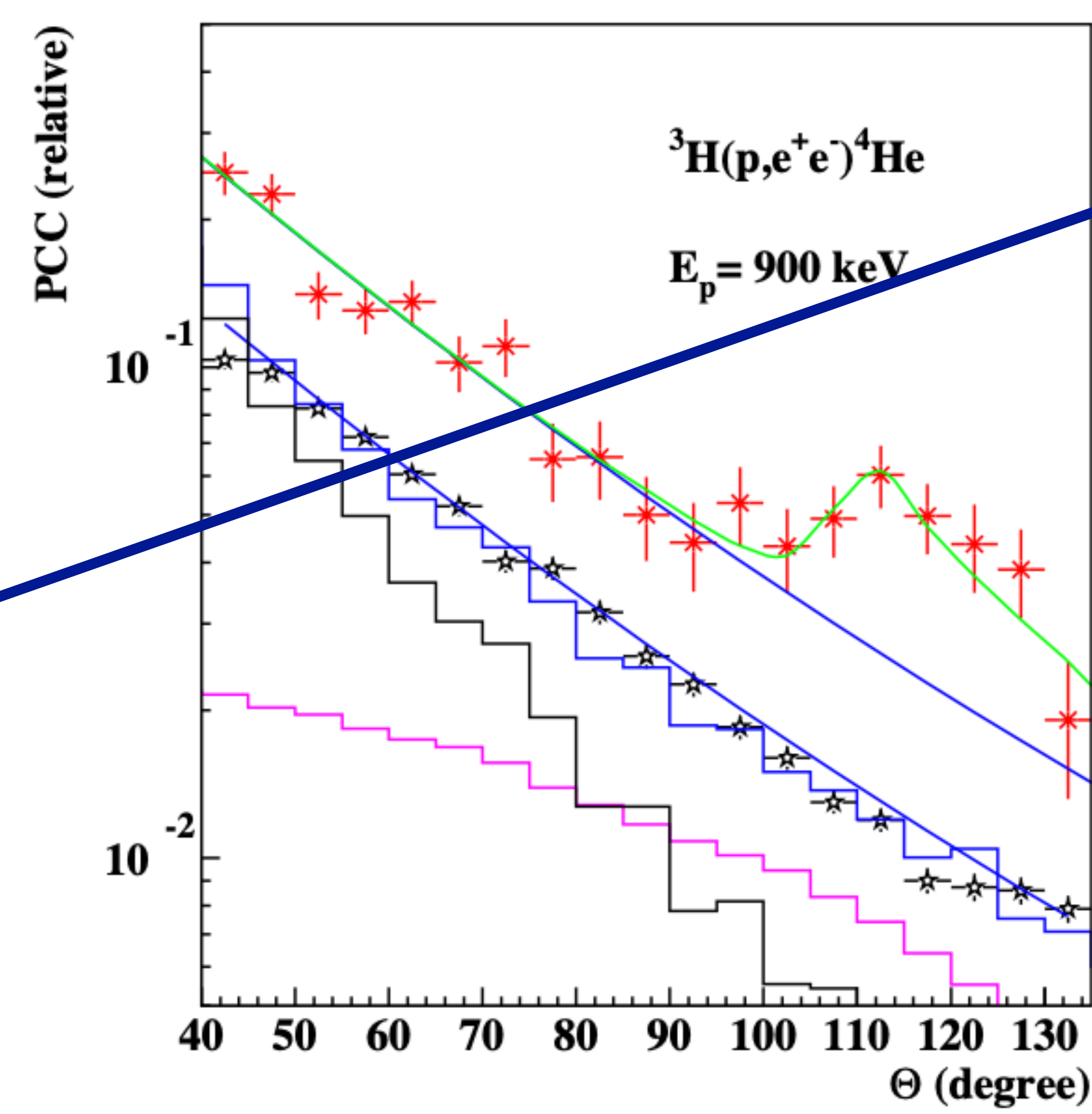
mostly $\quad B_\gamma \simeq 10^{-5} \quad B_{e^\pm} \simeq 10^{-3} B_\gamma \quad B_X \simeq ?$

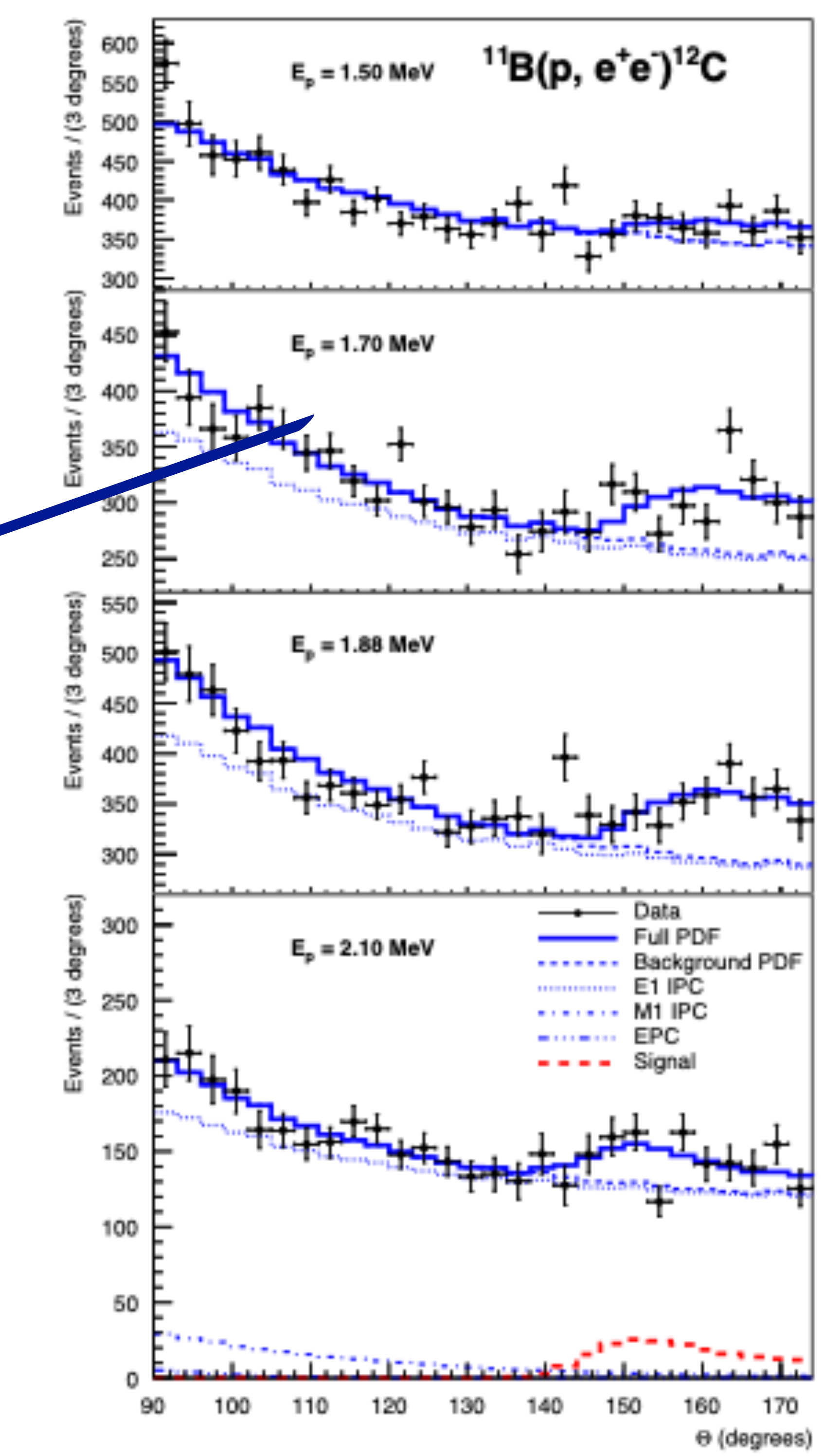


[Krasznahorkay+, PRL116(2016)042501,
Krasznahorkay+, PRC104 (2021) 044003,
Krasznahorkay+, PRC106(2022)L061601]

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

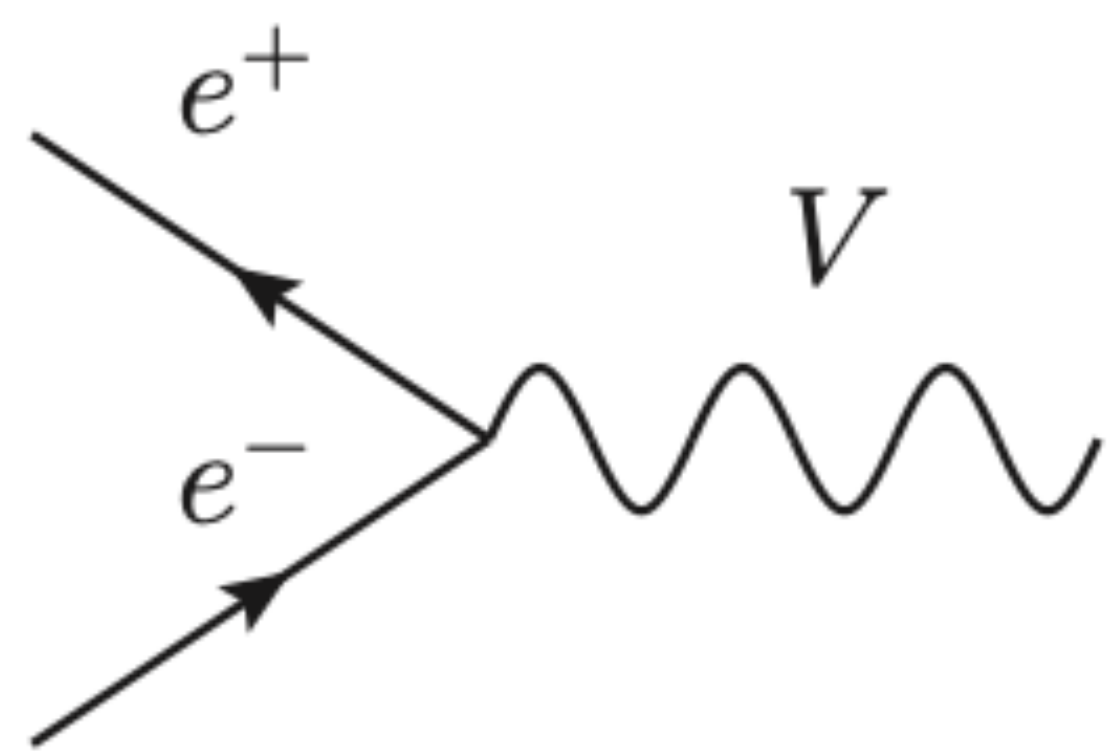






Dark Sector resonant production

Resonant production



Positron beam fixed target experiments

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

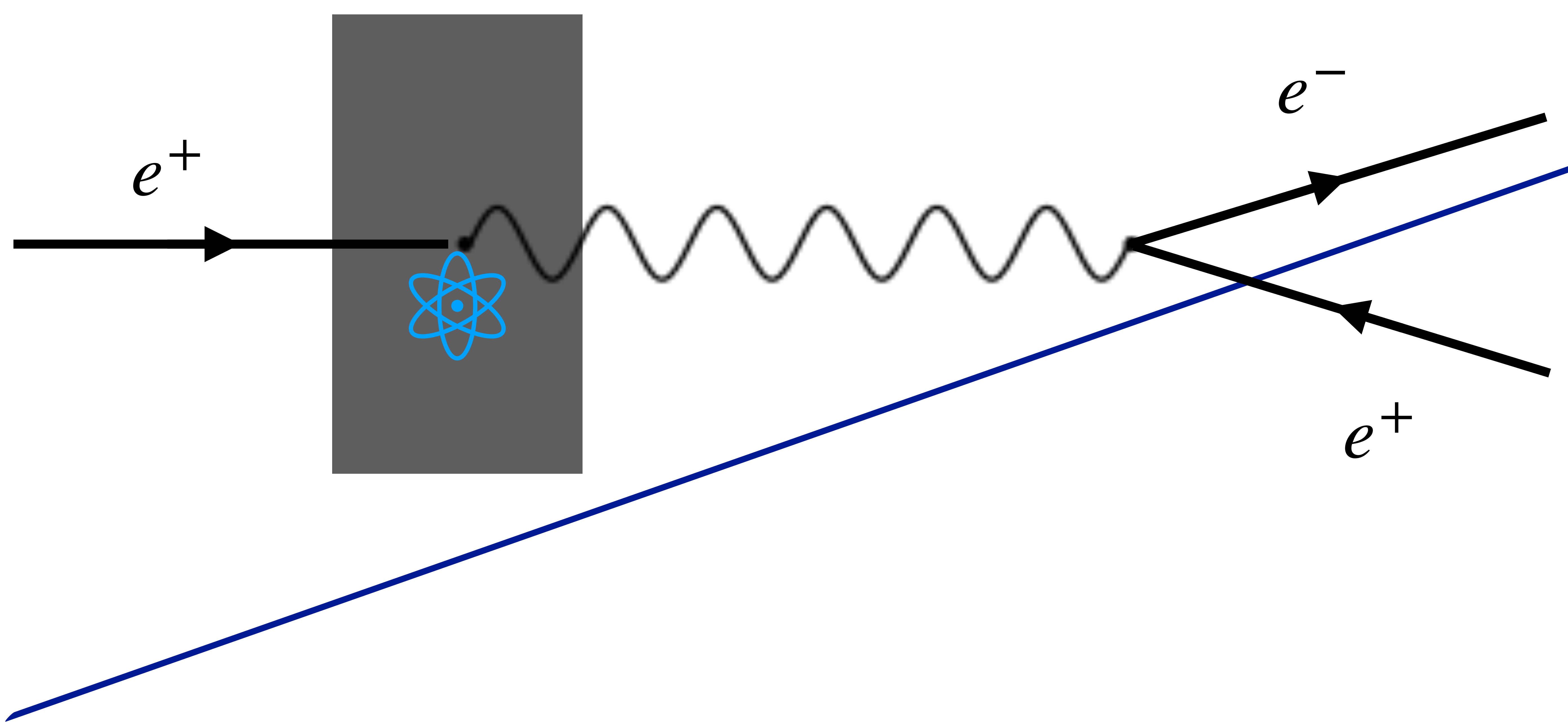
[Nardi et al., Phys. Rev. D (2018) 9, 095004]

Resonant production

Thick fixed target

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

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



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

Resonant production

Thick fixed target

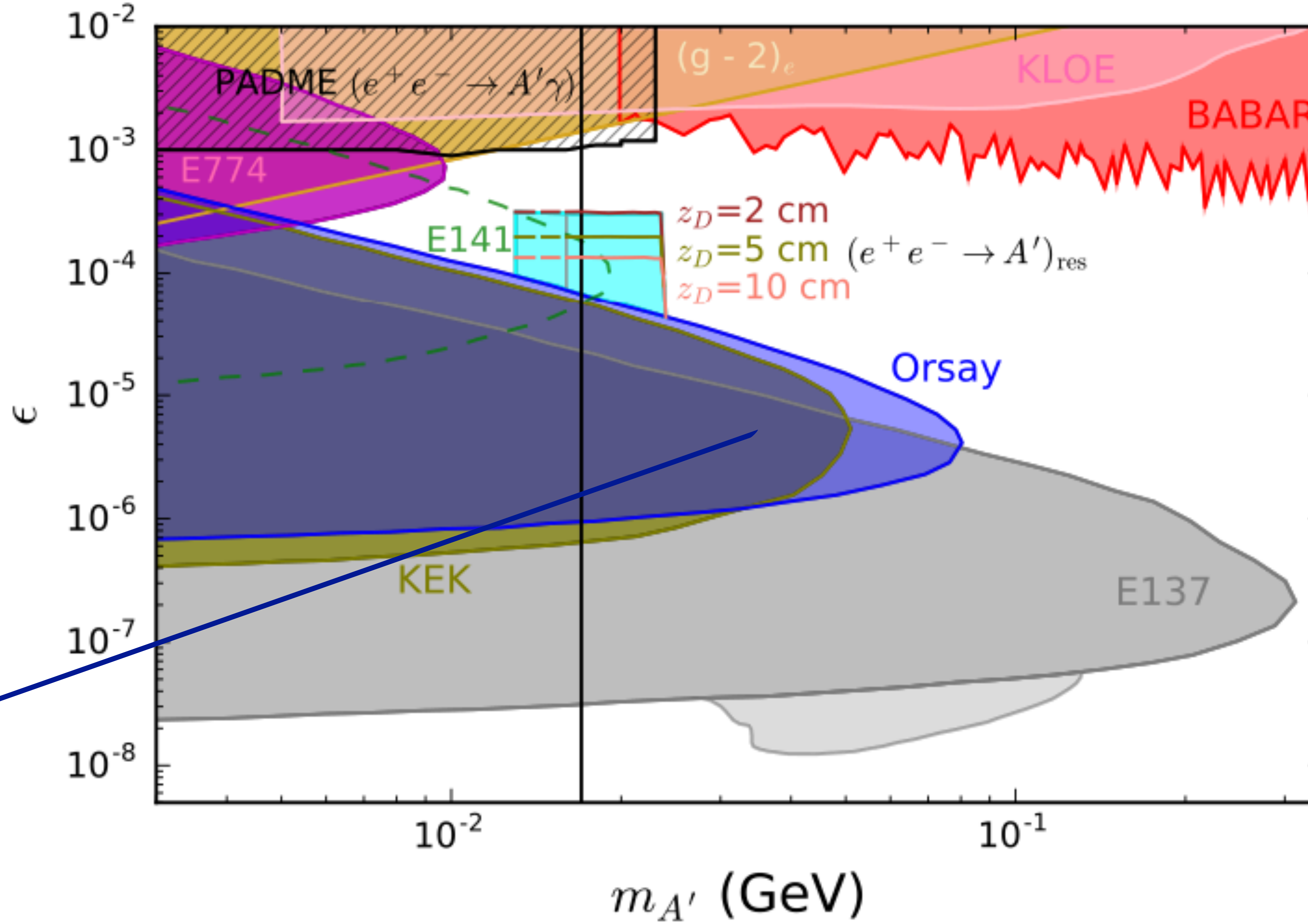
[Nardi et al., Phys. Rev. D (2018) 9, 095004]

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

$E_B \simeq 282$ MeV

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

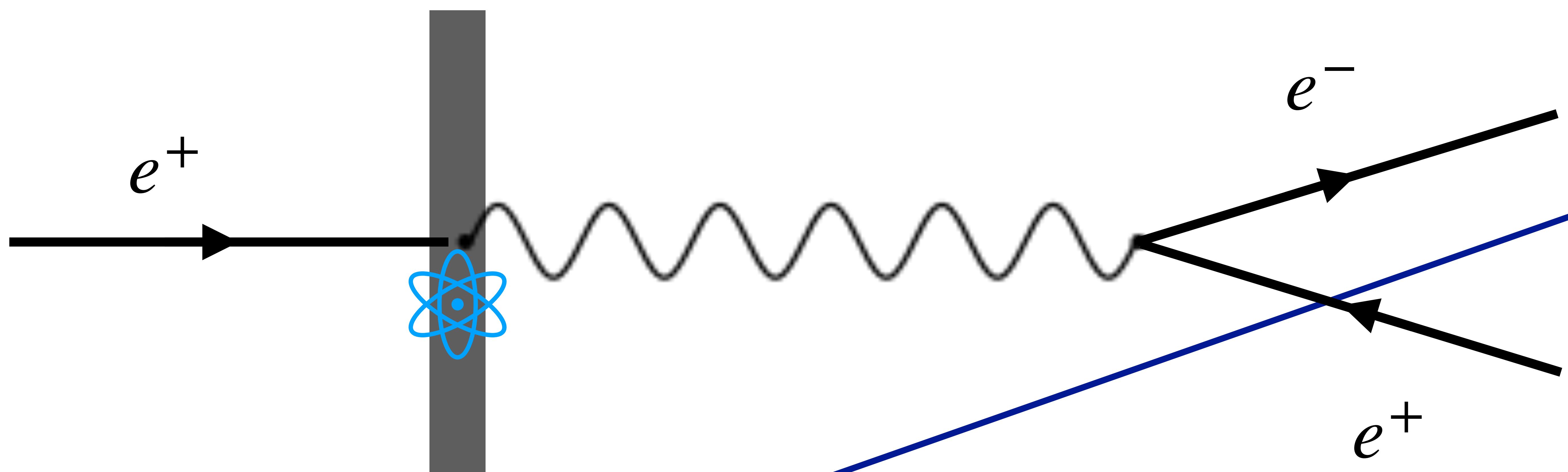
2-10 cm of tungsten



Resonant production

Thin fixed target

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



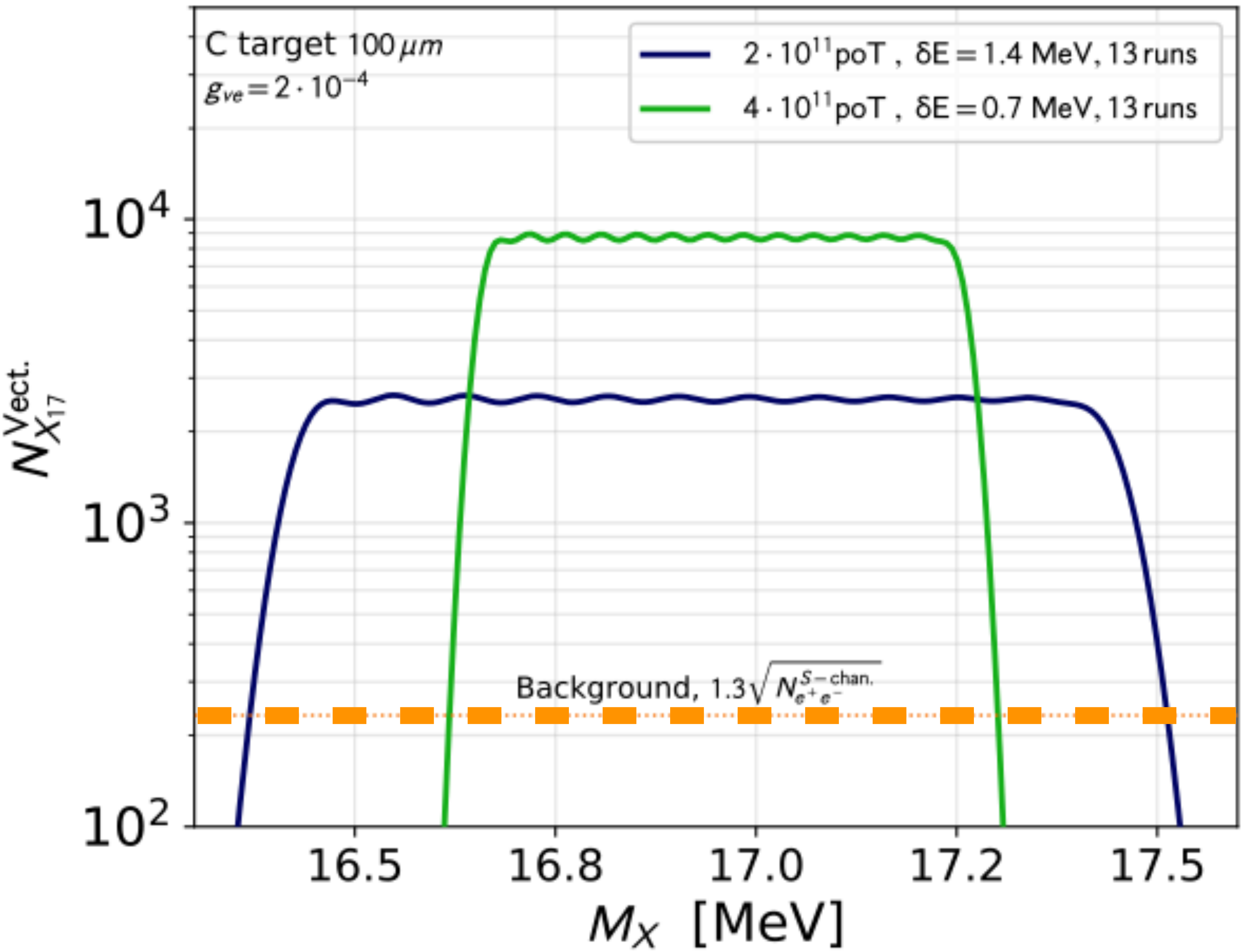
Negligible energy loss, need to physically vary the beam energy

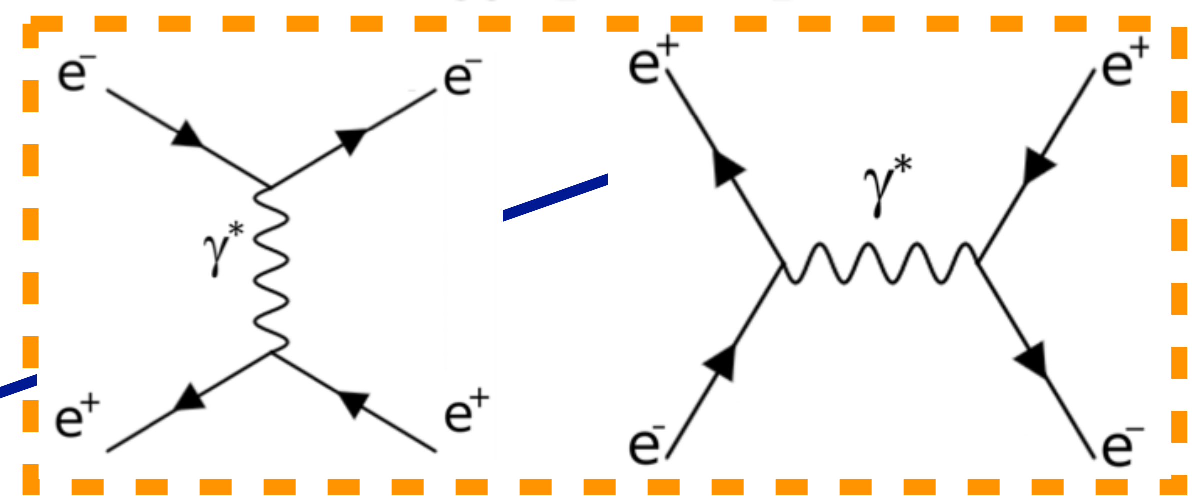
Resonant production

[see Spadaro's talk tomorrow]

PADME strategy for the X_{17} search

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





Resonant production

[see Spadaro's talk tomorrow]

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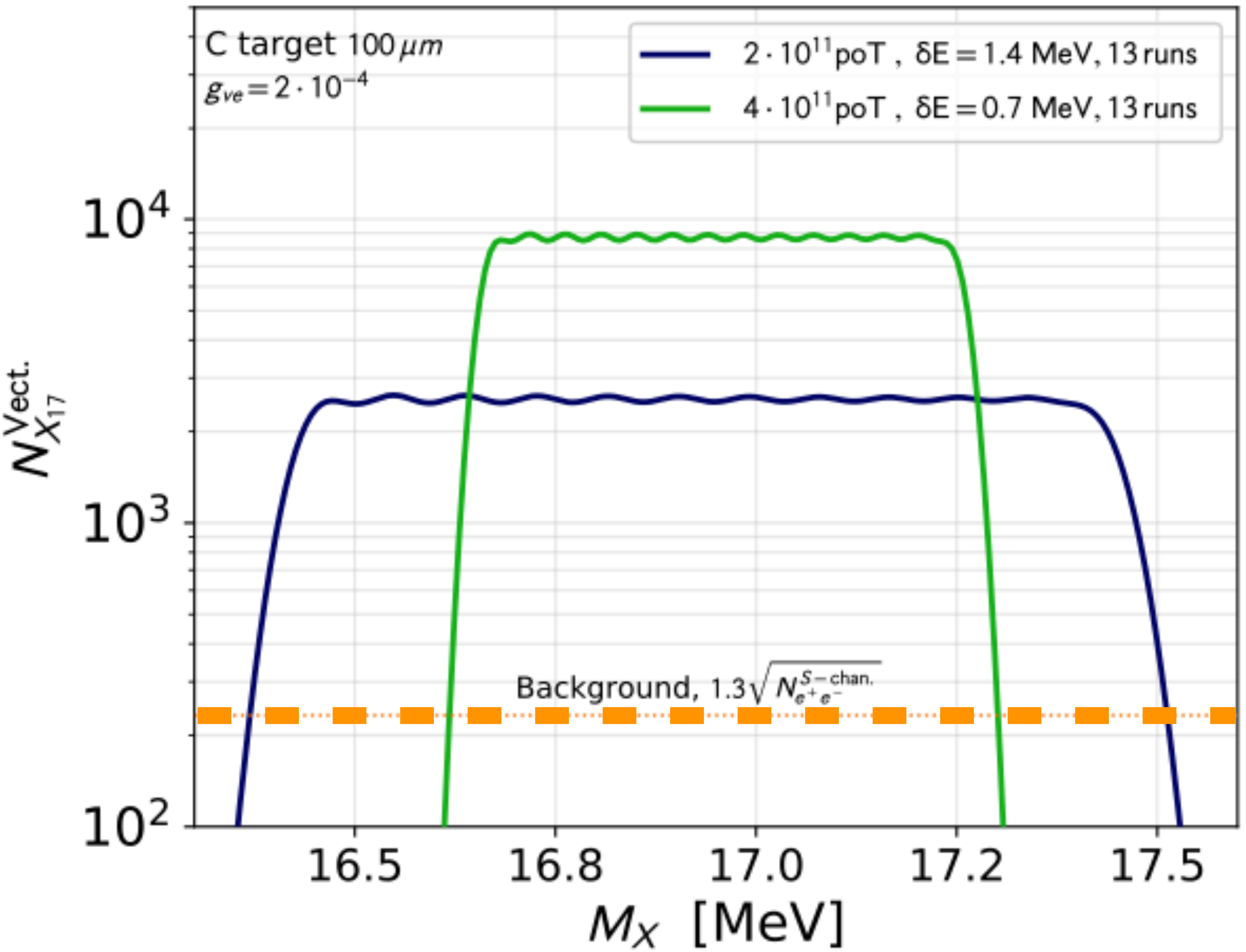
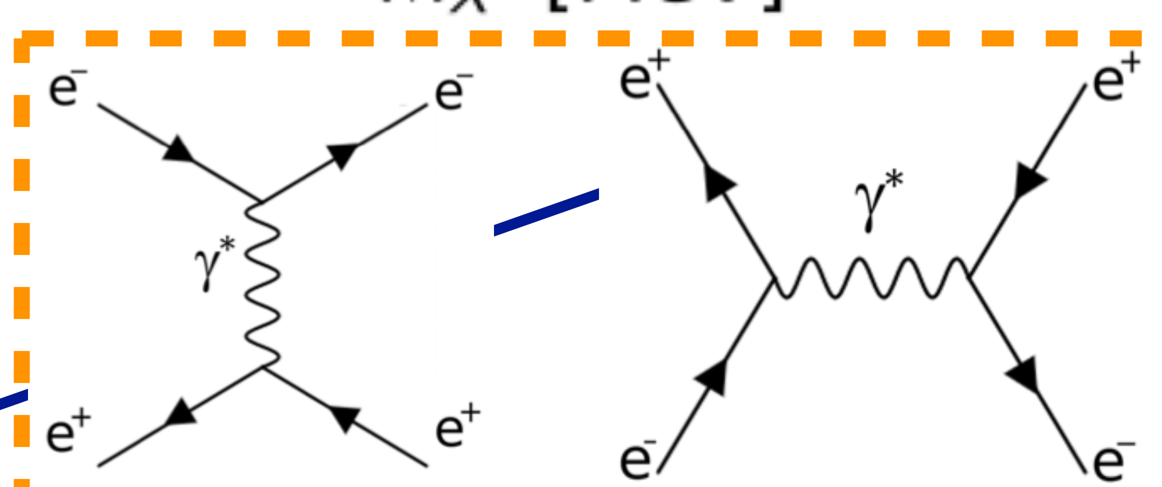
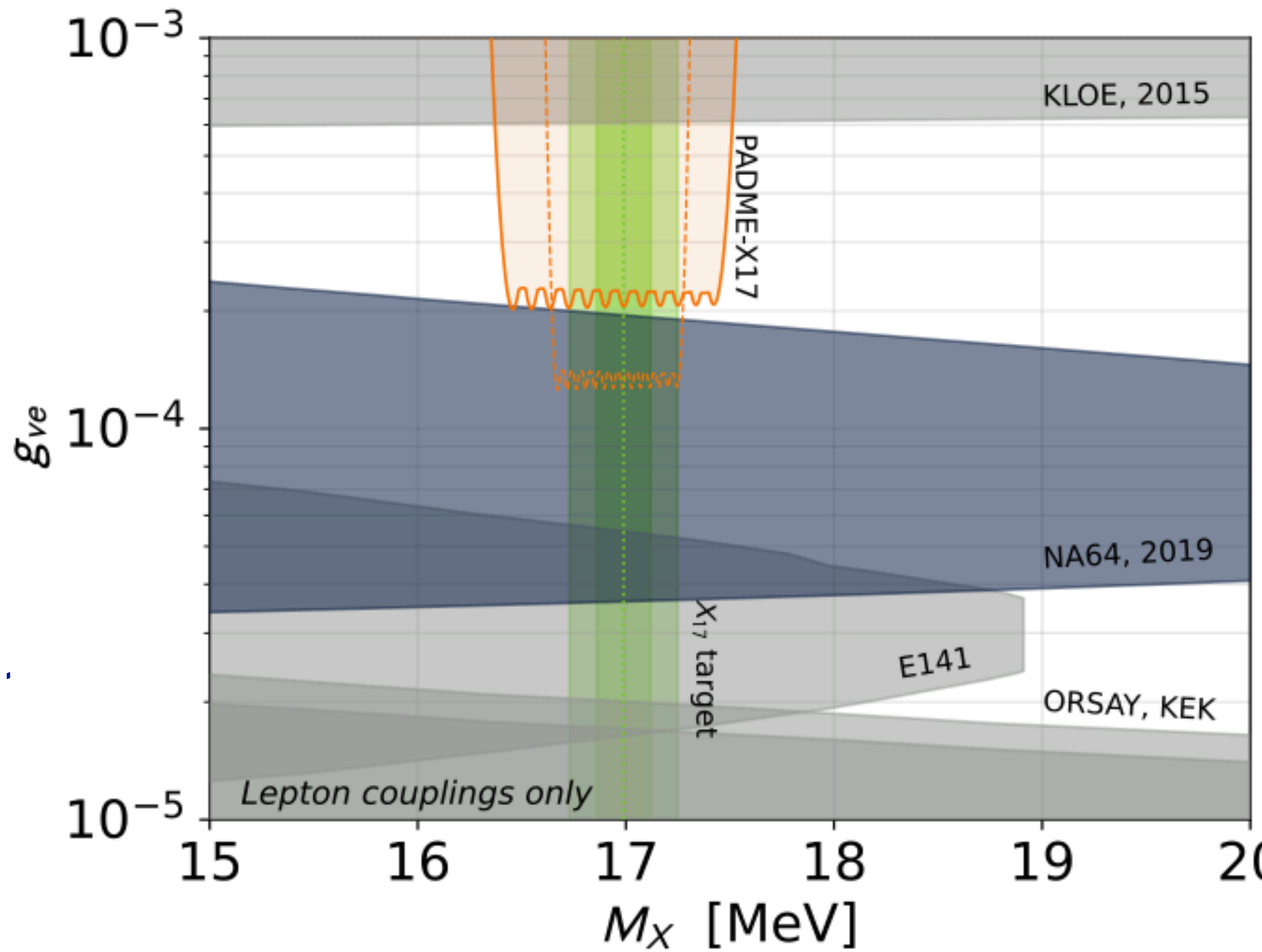




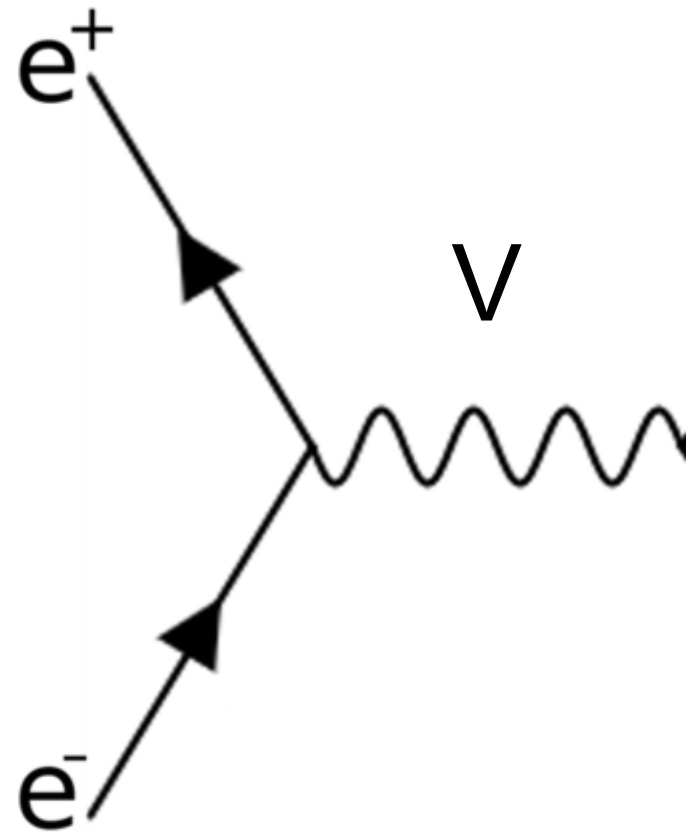
[Darmé, Mancini, Nardi, Raggi, Phys. Rev. D 106 (2022) 11, 115036]



Free electrons at rest approximation

Resonant production

Free electron at rest approximation

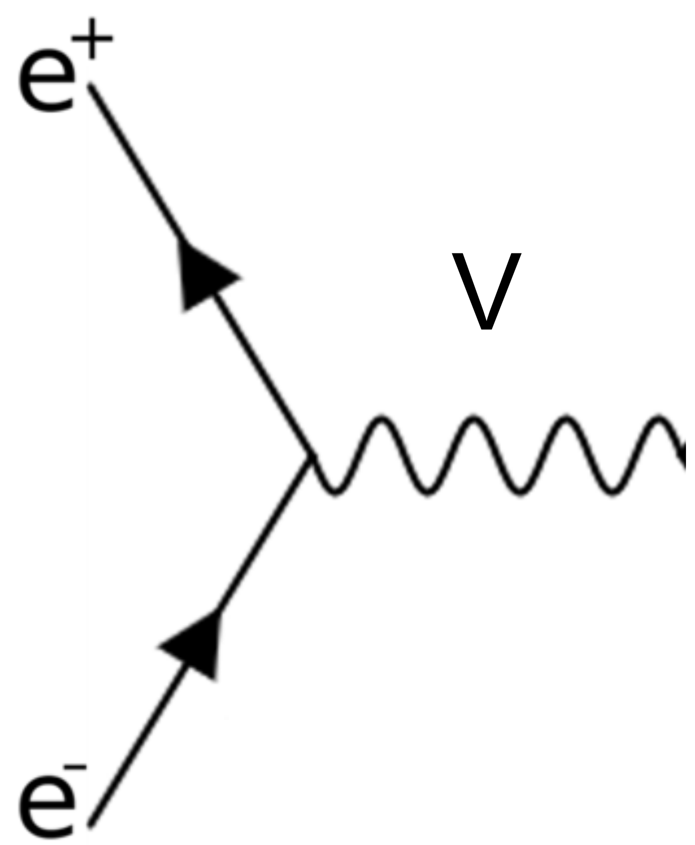


$$\sigma_{\rm res}(E) \simeq \frac{\pi g_V^2}{2m_e}\mathcal{G}(E, E_{\rm res}, \sigma_{E_B})$$

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

Resonant production

Free electron at rest approximation



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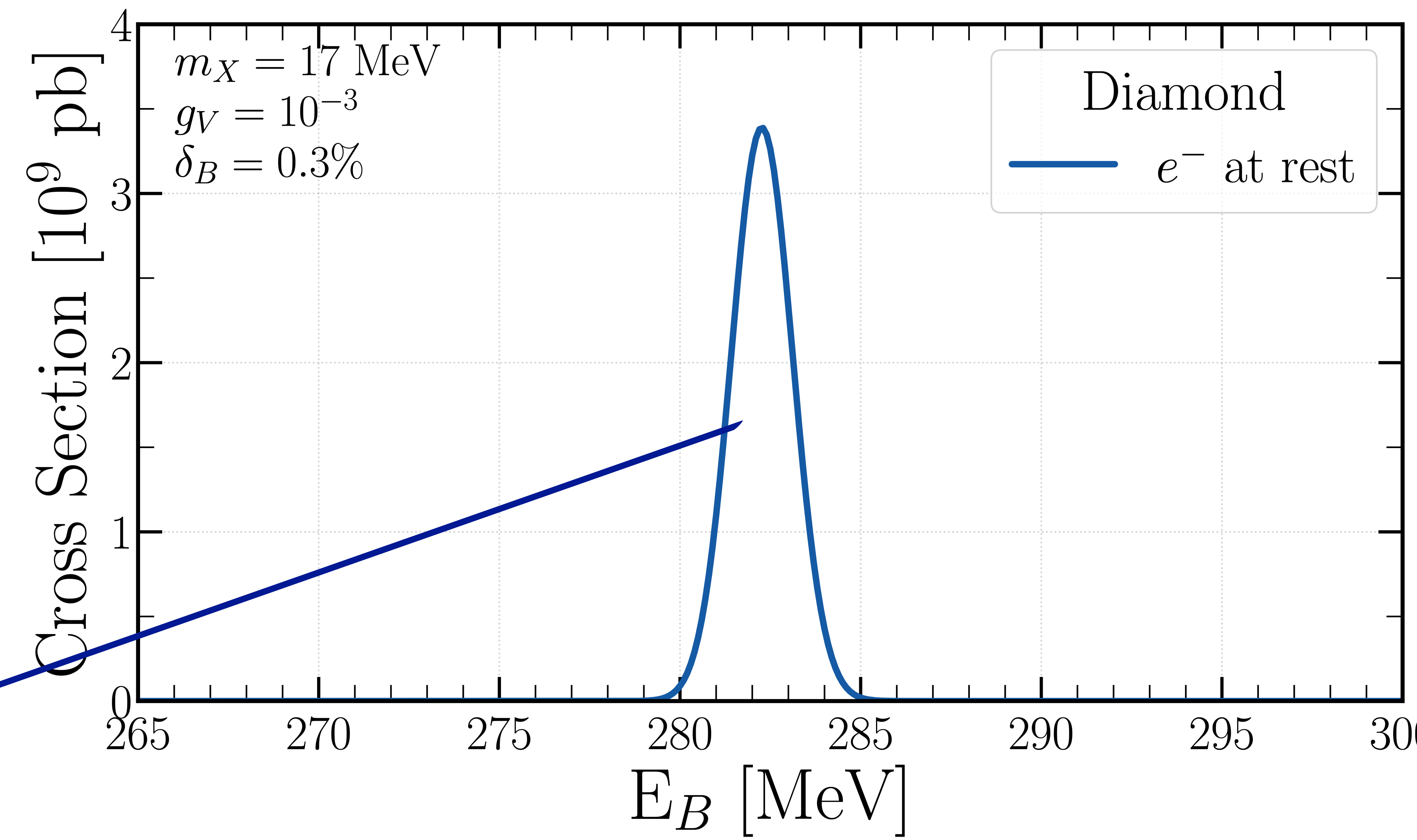
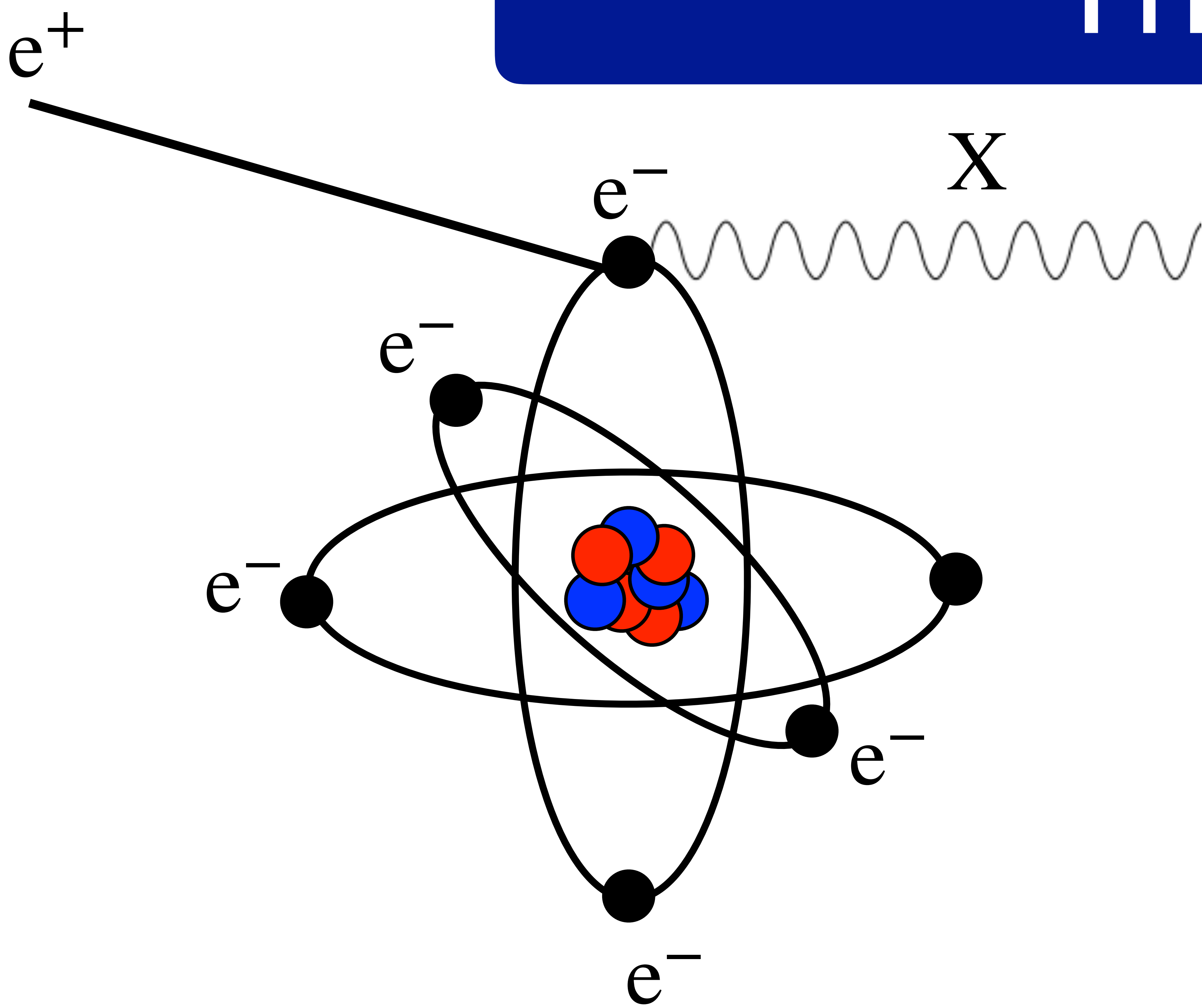
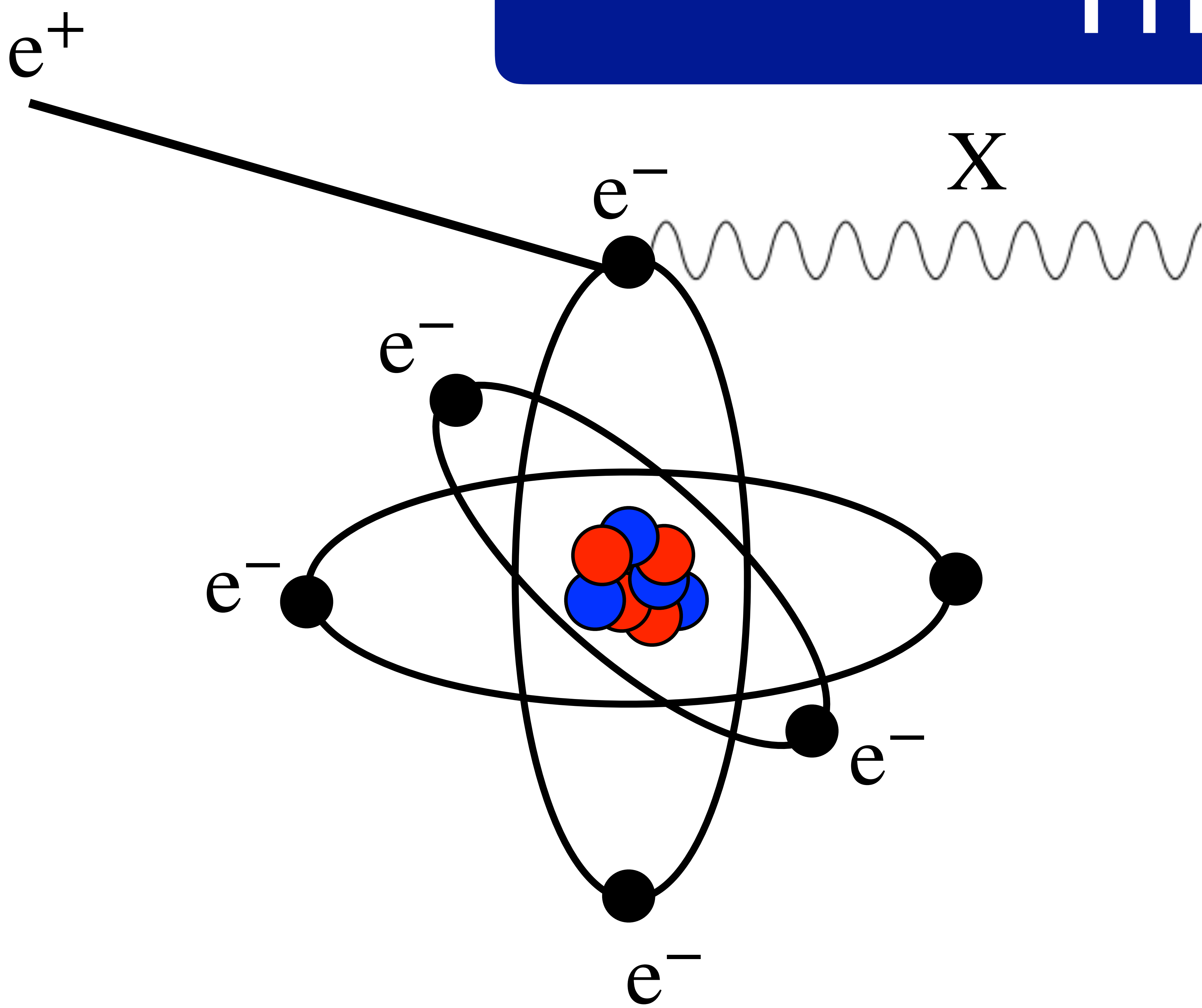


The problem



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

The problem



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

Naive estimate:

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

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

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

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

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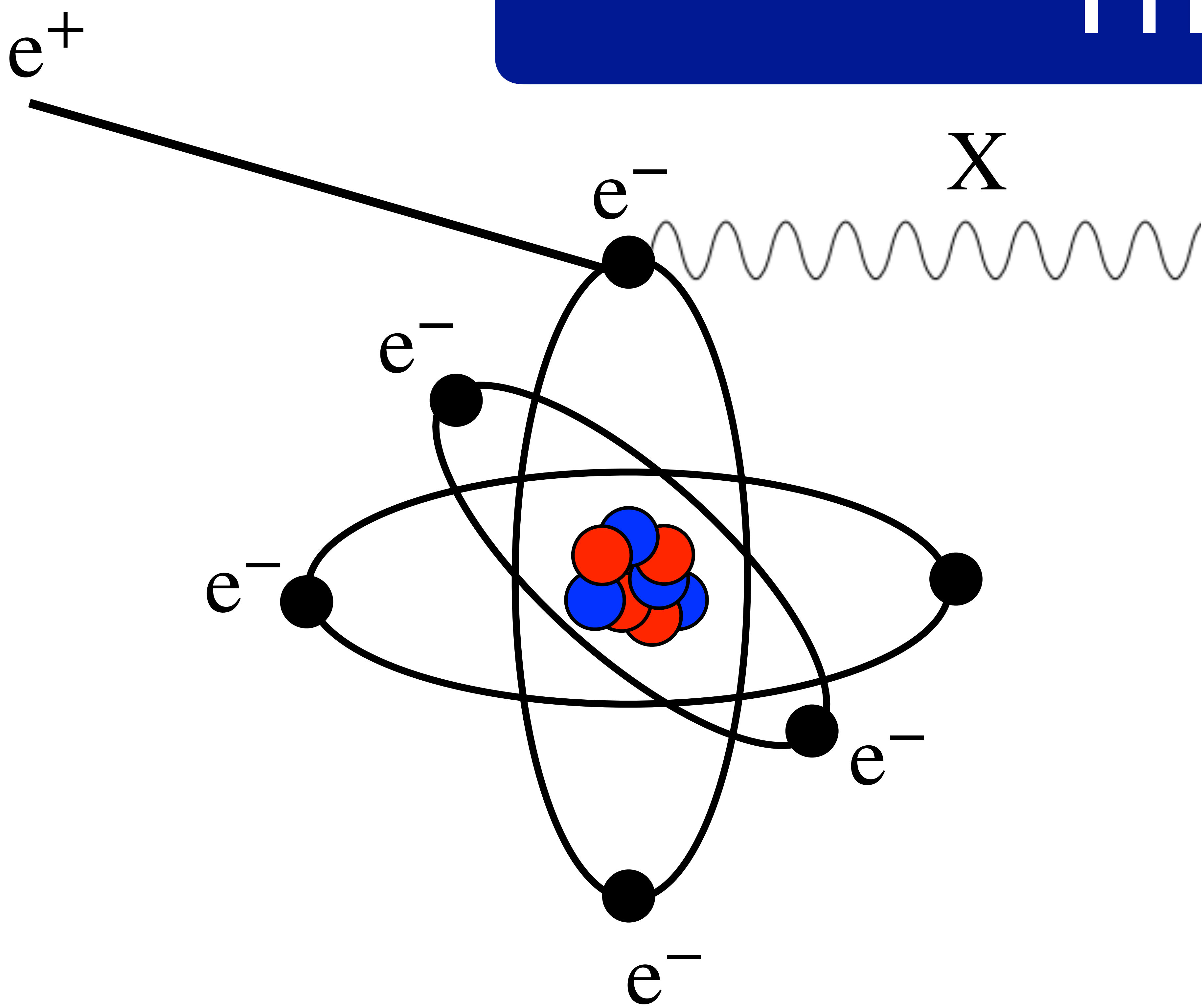

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using $\beta = \langle \beta_{1s} \rangle = 0.04$

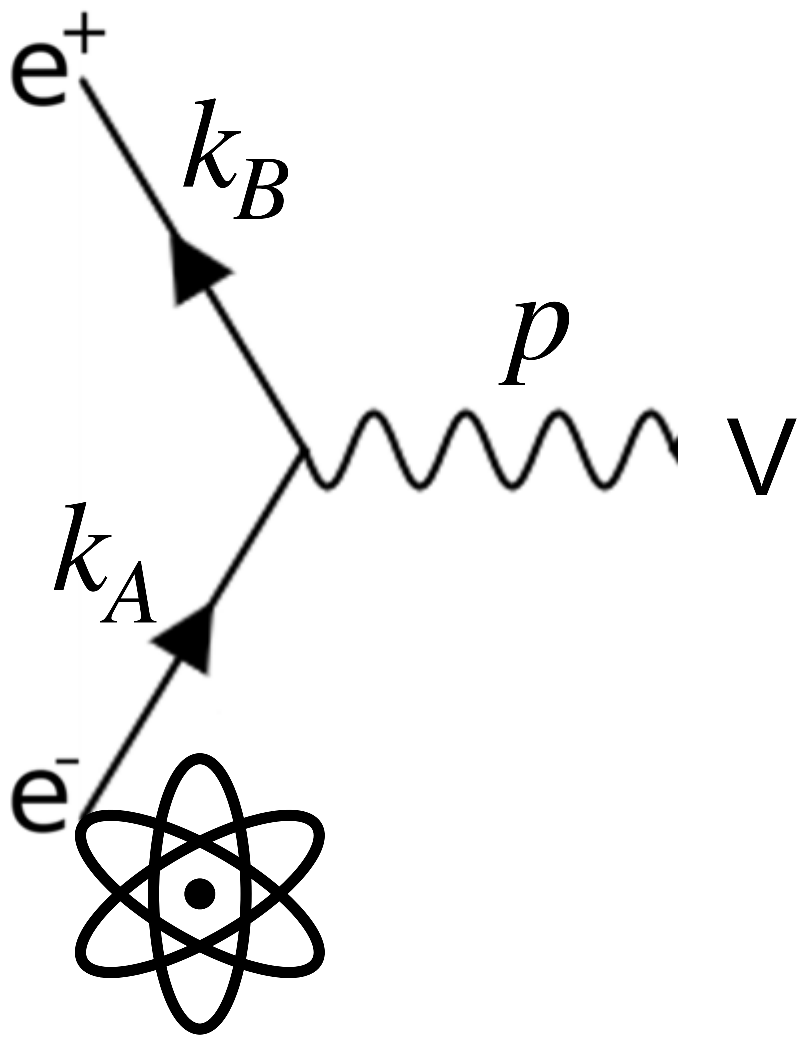
$$\sqrt{s} \simeq 17.0\,\text{MeV} \qquad (E_b \sim 282.2 \text{ MeV})$$
$$\sqrt{s'_+} = 17.3\,\text{MeV} \qquad (E_b \sim 293.5 \text{ MeV})$$
$$\sqrt{s'_-} = 16.7\,\text{MeV} \qquad (E_b \sim 270.9 \text{ MeV})$$

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

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

Atomic electron motion

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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$$E_A \simeq m_e$$

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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

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theory

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

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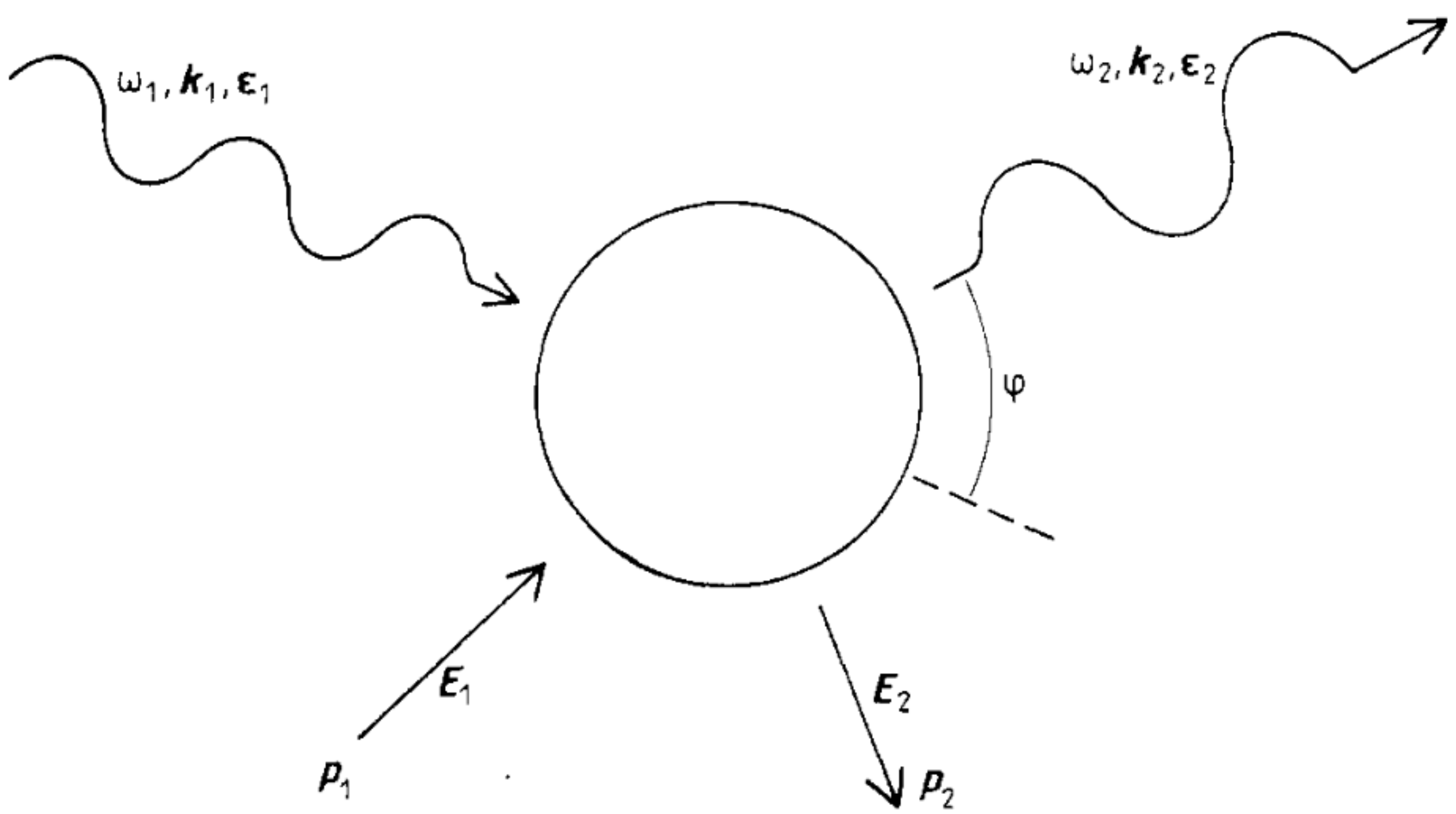
theory: use Slater Type Orbitals, hybridization, Hartree Fock computations for atomic carbon, …

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

Compton Profile

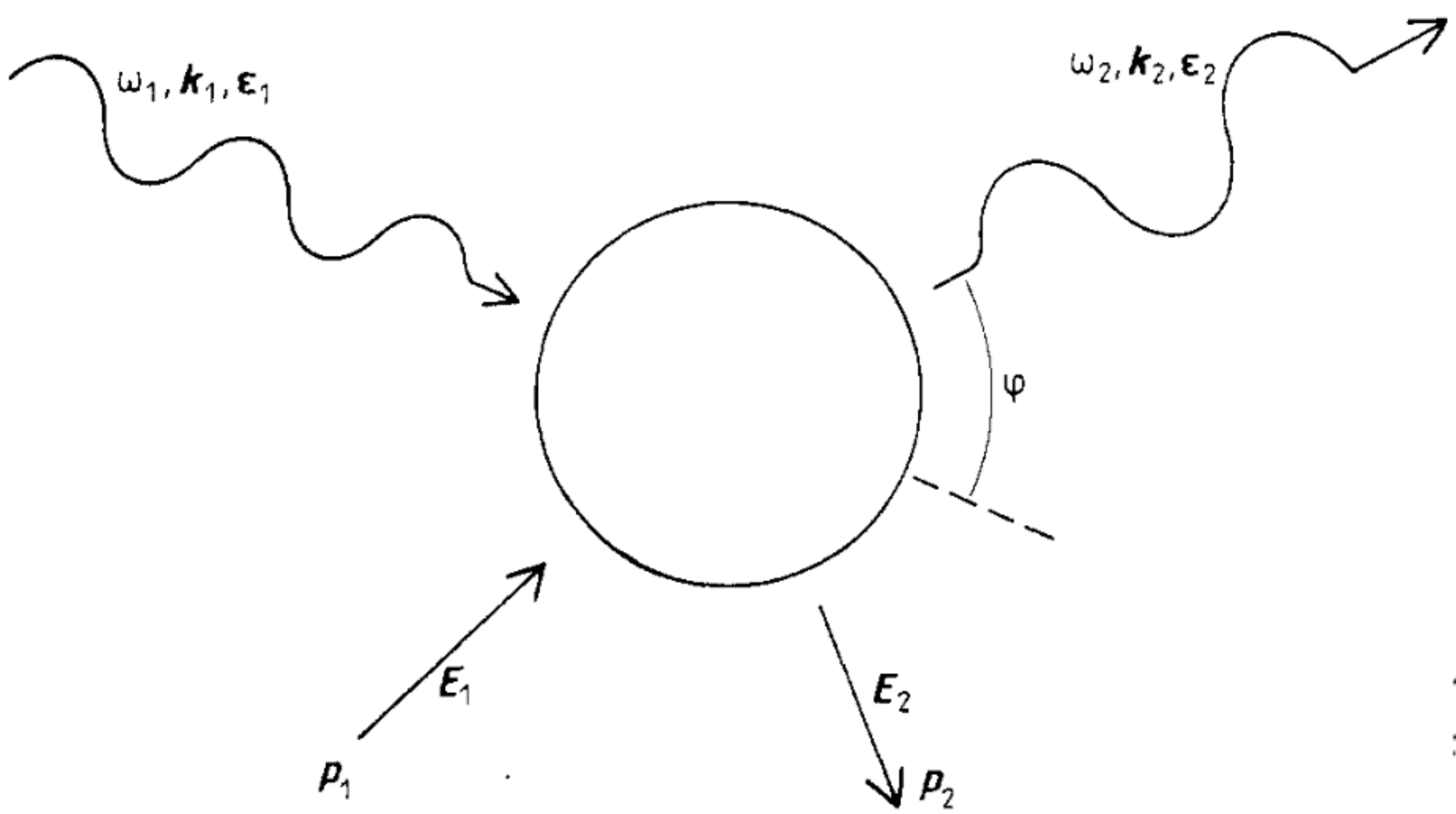


$$\omega_1 - \omega_2 = \frac{1}{2}m_e\,[\vec{p} + (\vec{k}_1 - \vec{k}_2)]^2 - \frac{|\vec{p}\,|^2}{2m_e}$$

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

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

Compton Profile



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

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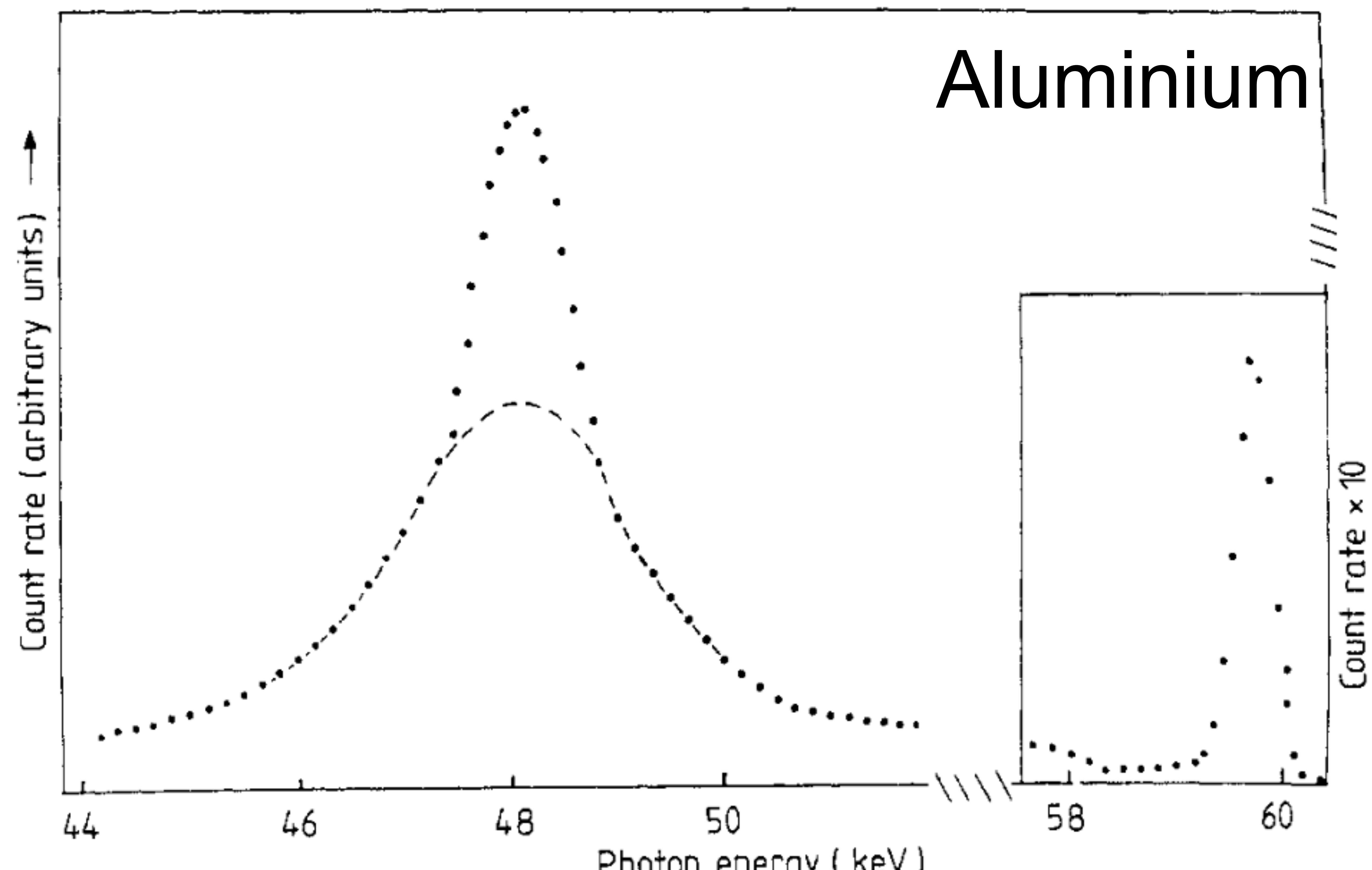
M J Cooper 1985 Rep. Prog. Phys. 48 415



Compton Profile

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

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

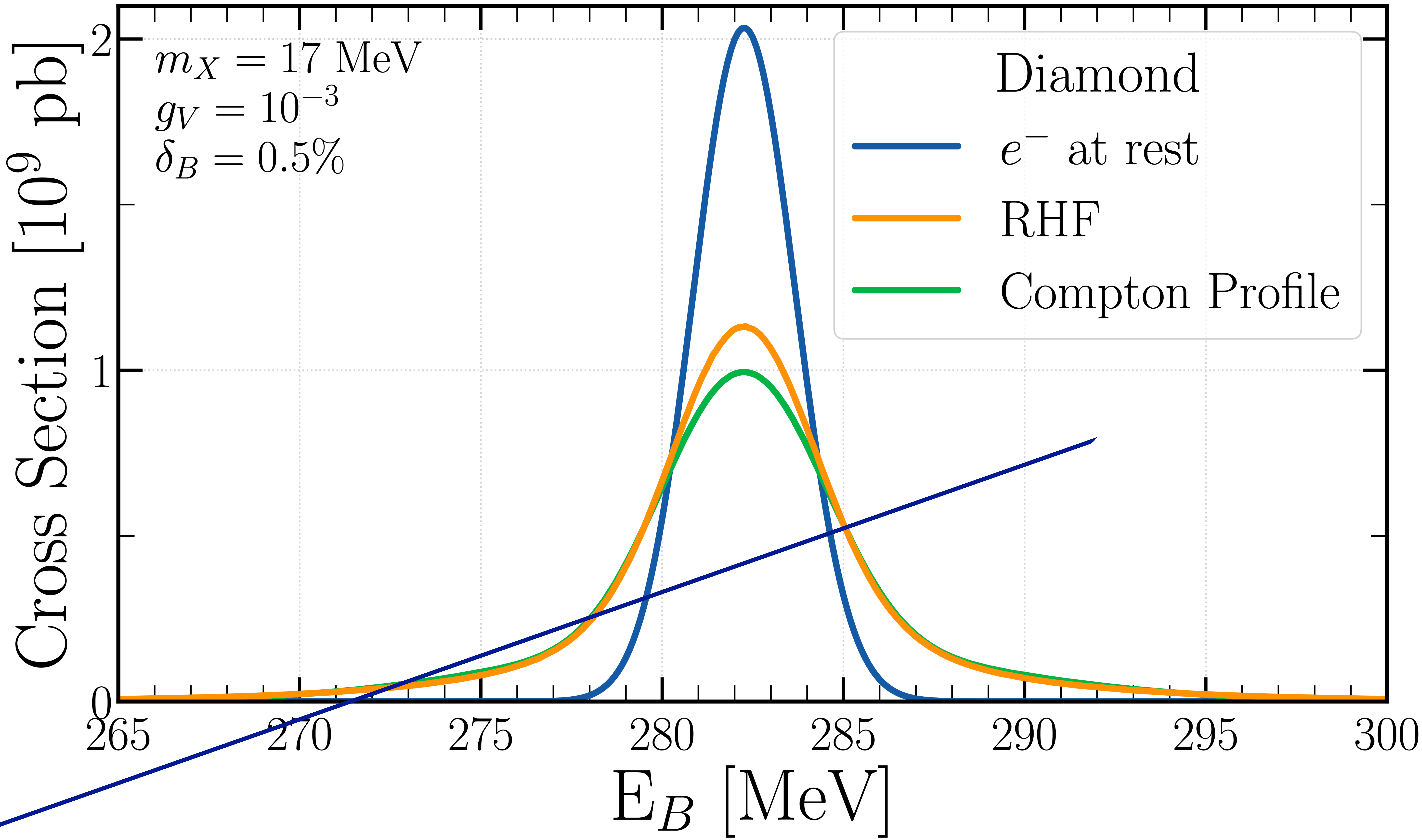
assuming isotropy

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

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

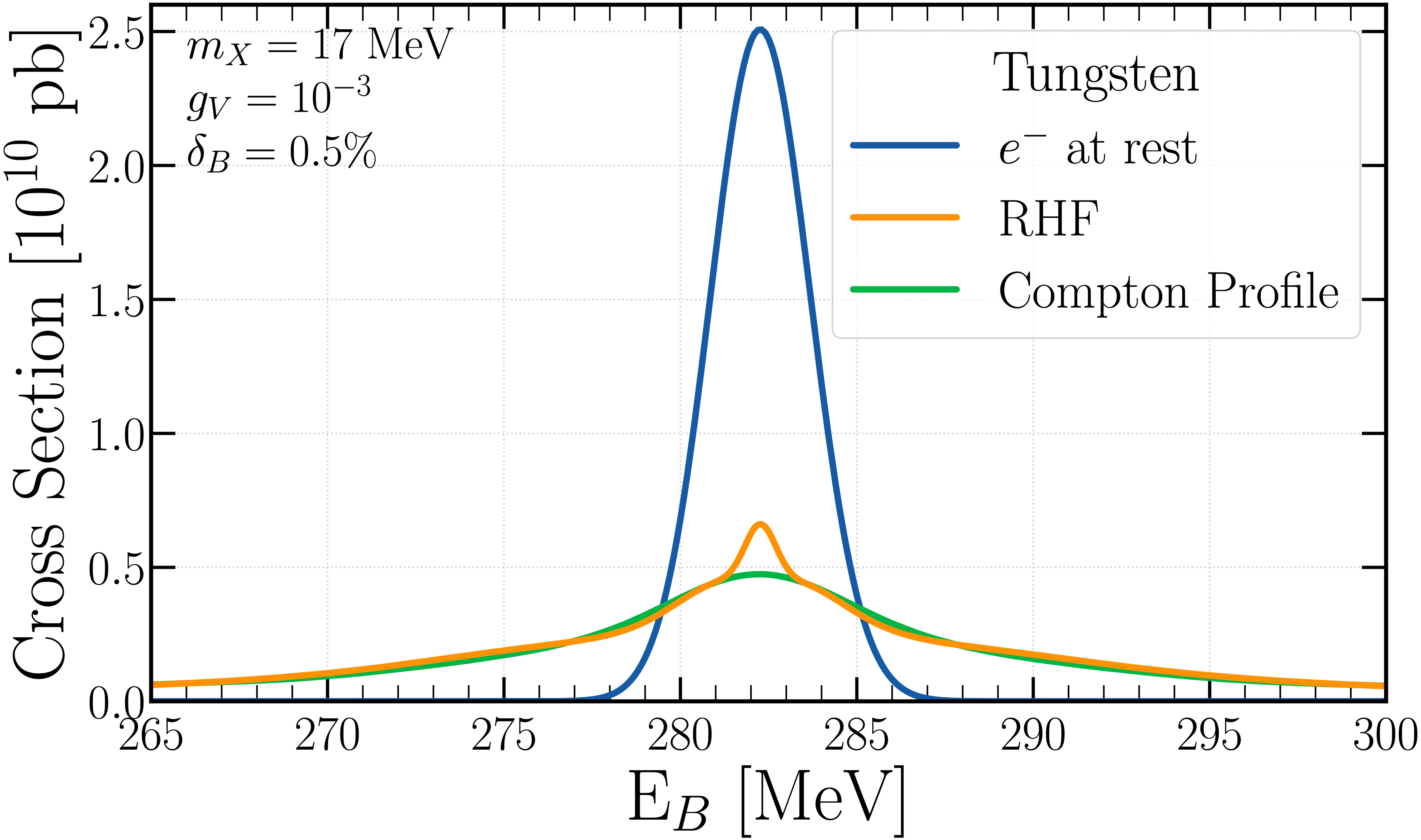
$$n(k) = -\frac{(2\pi)^2}{k}\left|\frac{dJ(k)}{dk}\right|$$

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]
2
1
0
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]

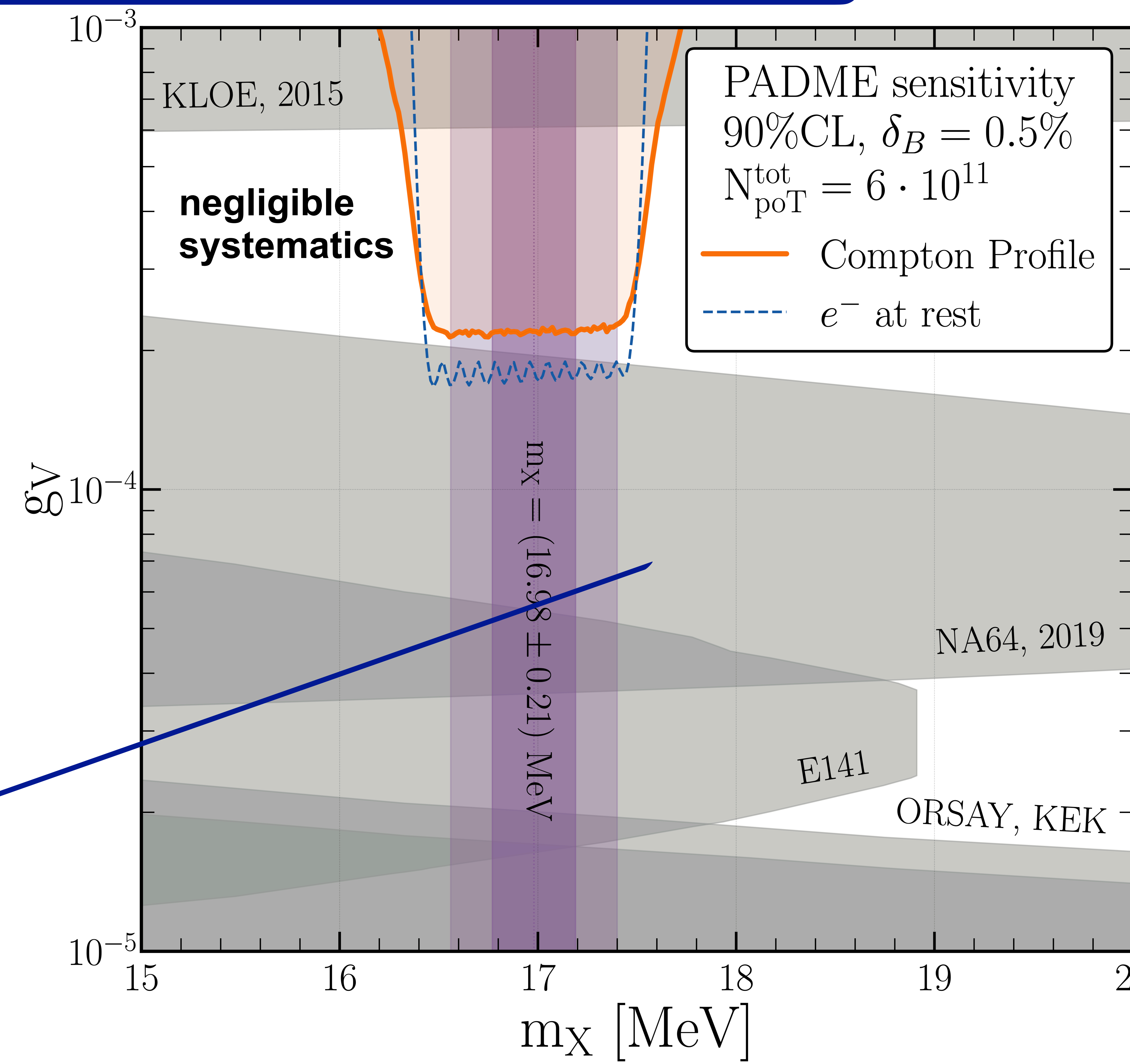
Atoms as electron accelerators: new physics

X17 sensitivity @PADME

[see Spadaro's talk tomorrow]

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

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



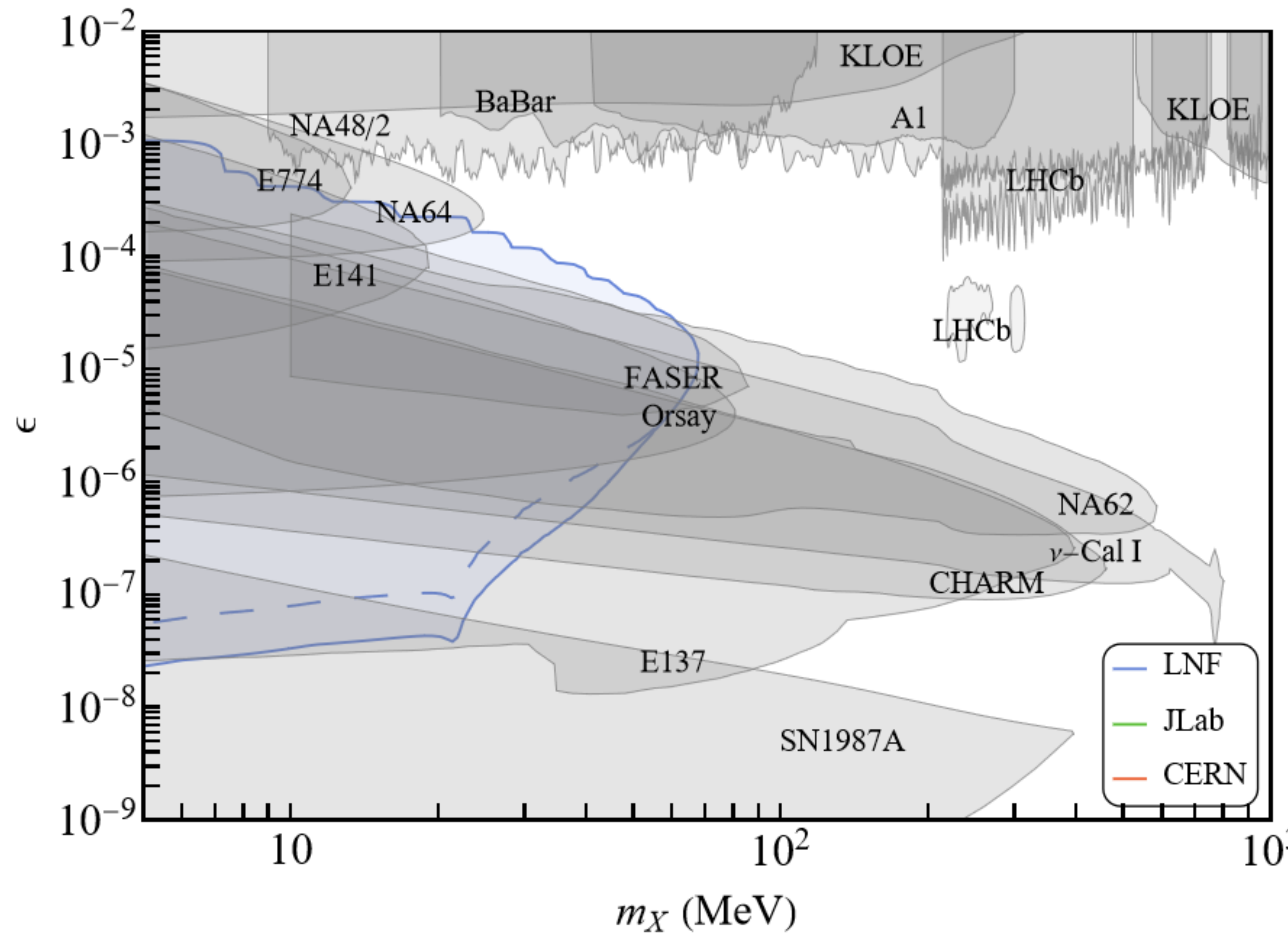
Dark photons

[Arias-Aragon, G^{2}dC, Nardi, Veissière, 2504.00100]

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

5 cm tungsten thick target

LNF: 450 MeV, $10^{18}\, e^+$oT



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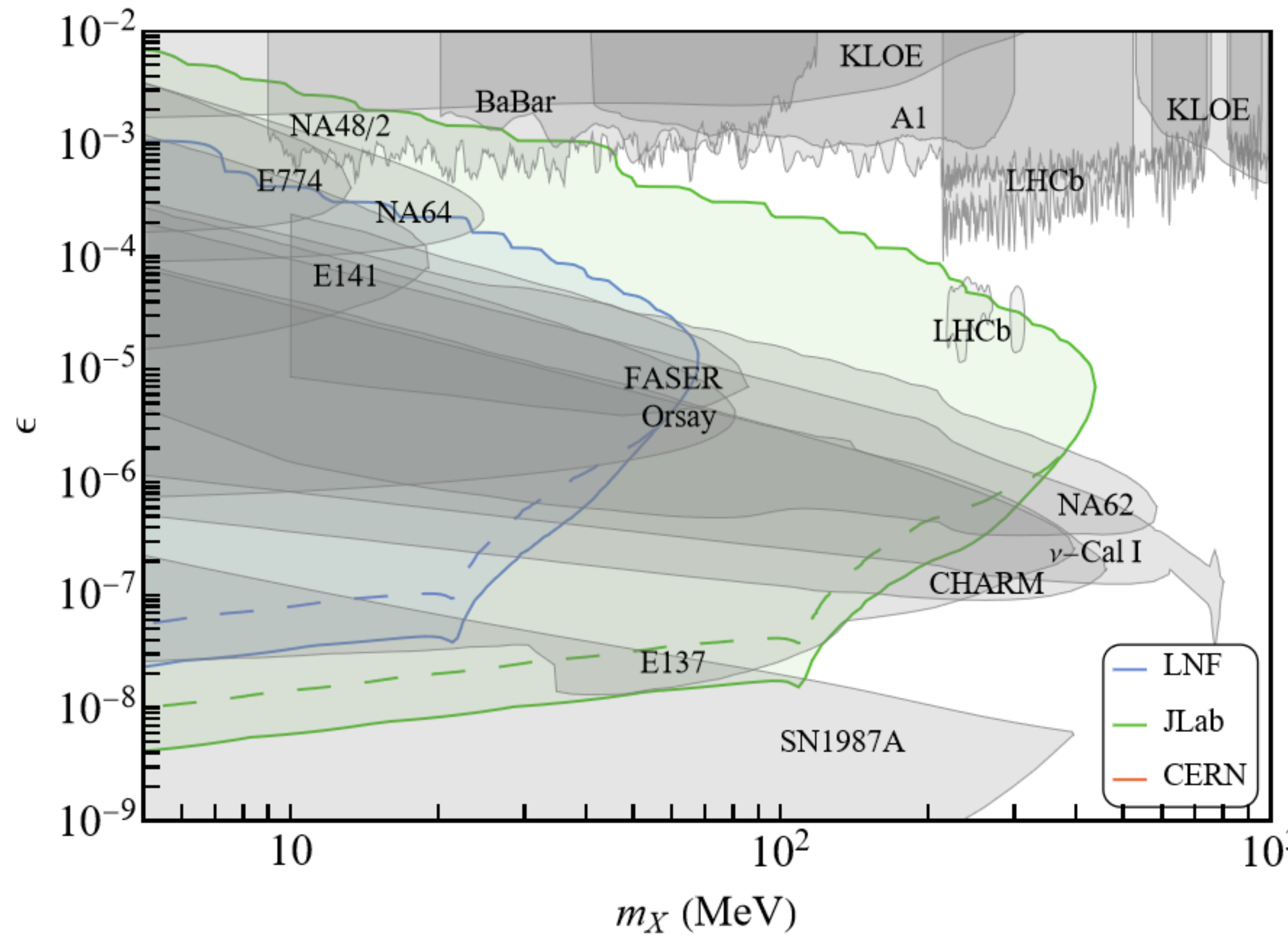

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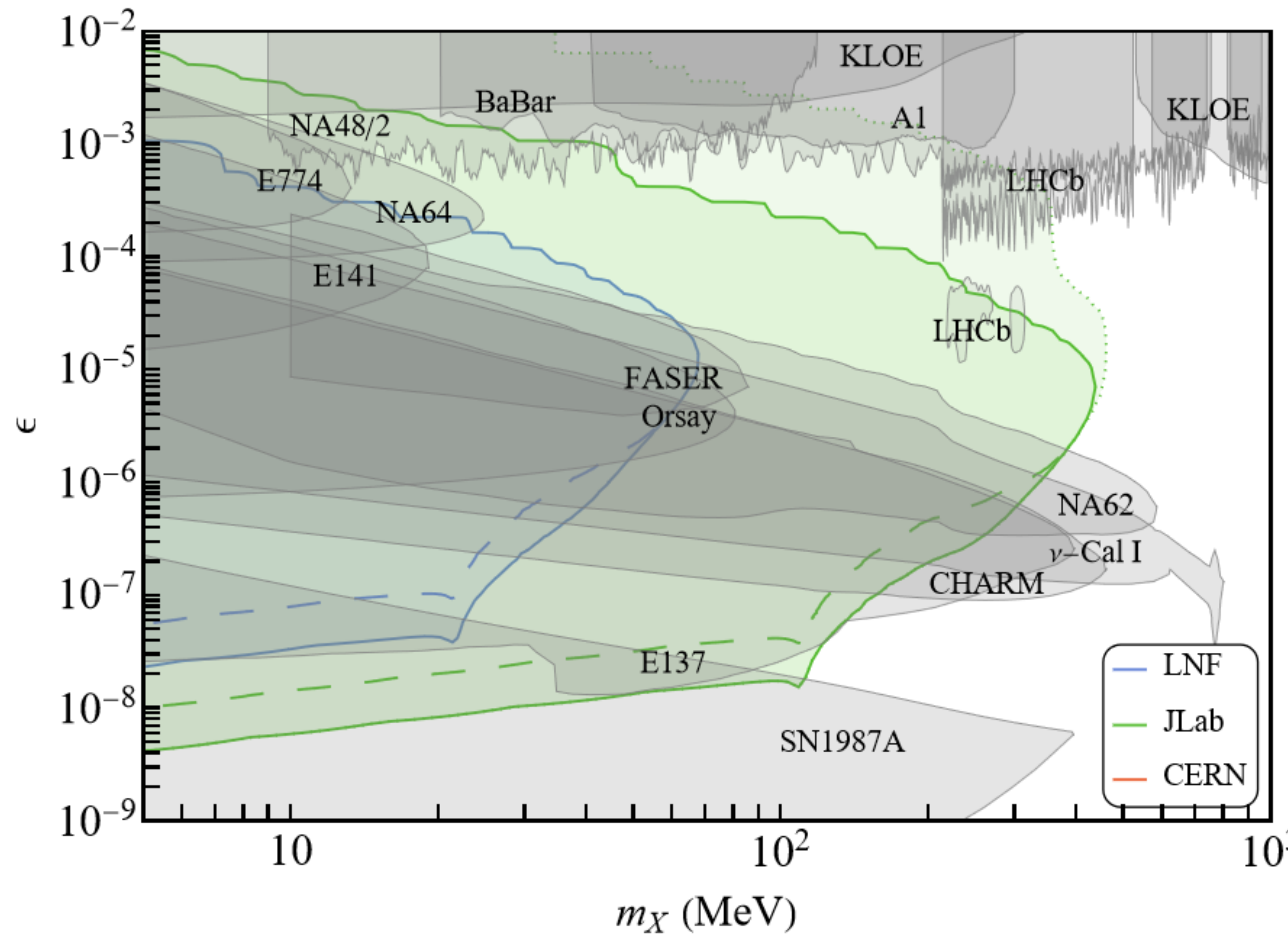

Dark photons

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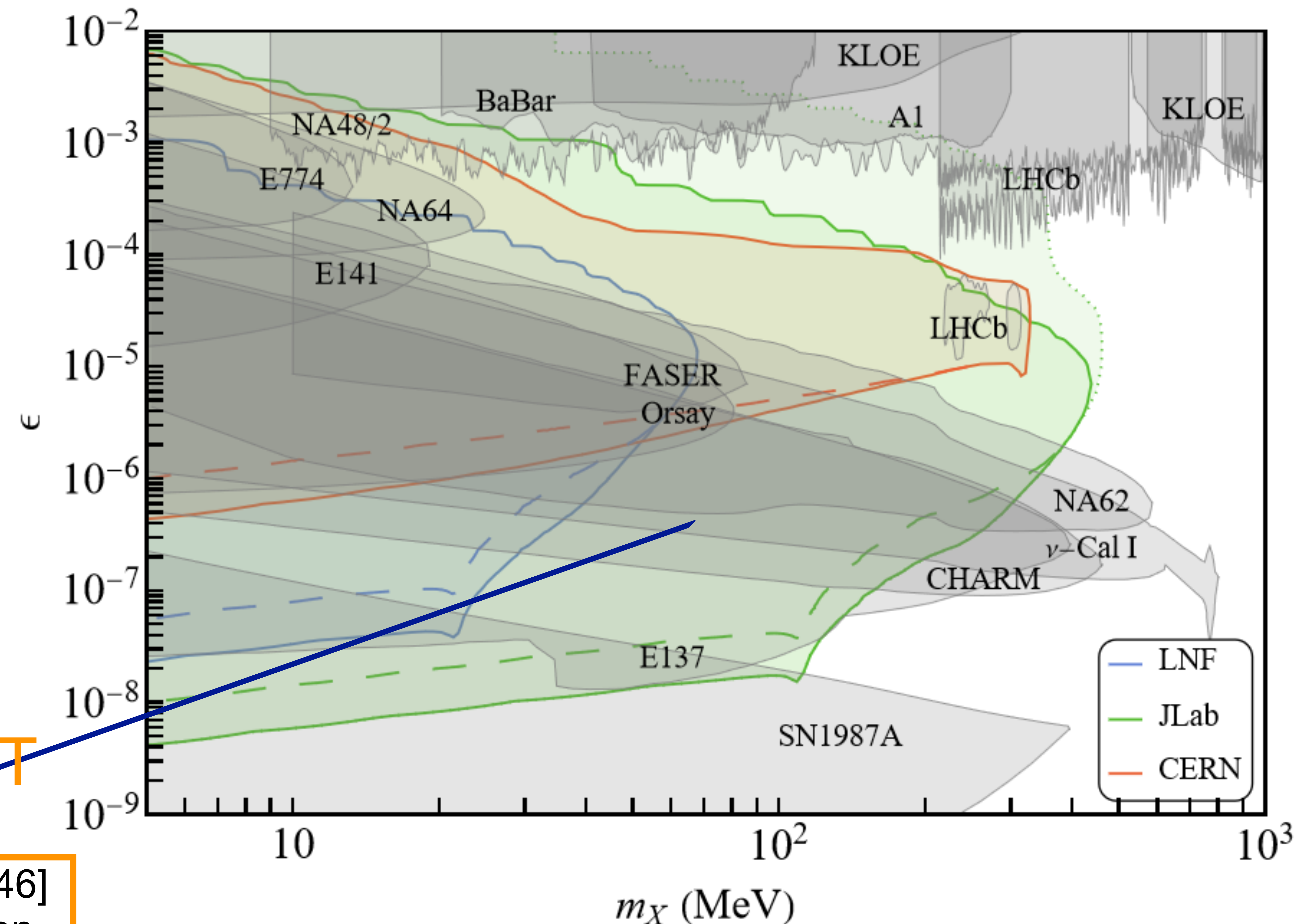
$$\mathscr{L} \supset -i\,\epsilon\, e\,\bar{\psi}_e \gamma^\mu \psi_e A'_\mu$$

5 cm tungsten thick target

LNF: 450 MeV, $10^{18}\, e^+$oT

JLAB: 12 GeV, $10^{21}\, e^+$oT

CERN: 100 GeV, $10^{13}\, e^+$oT

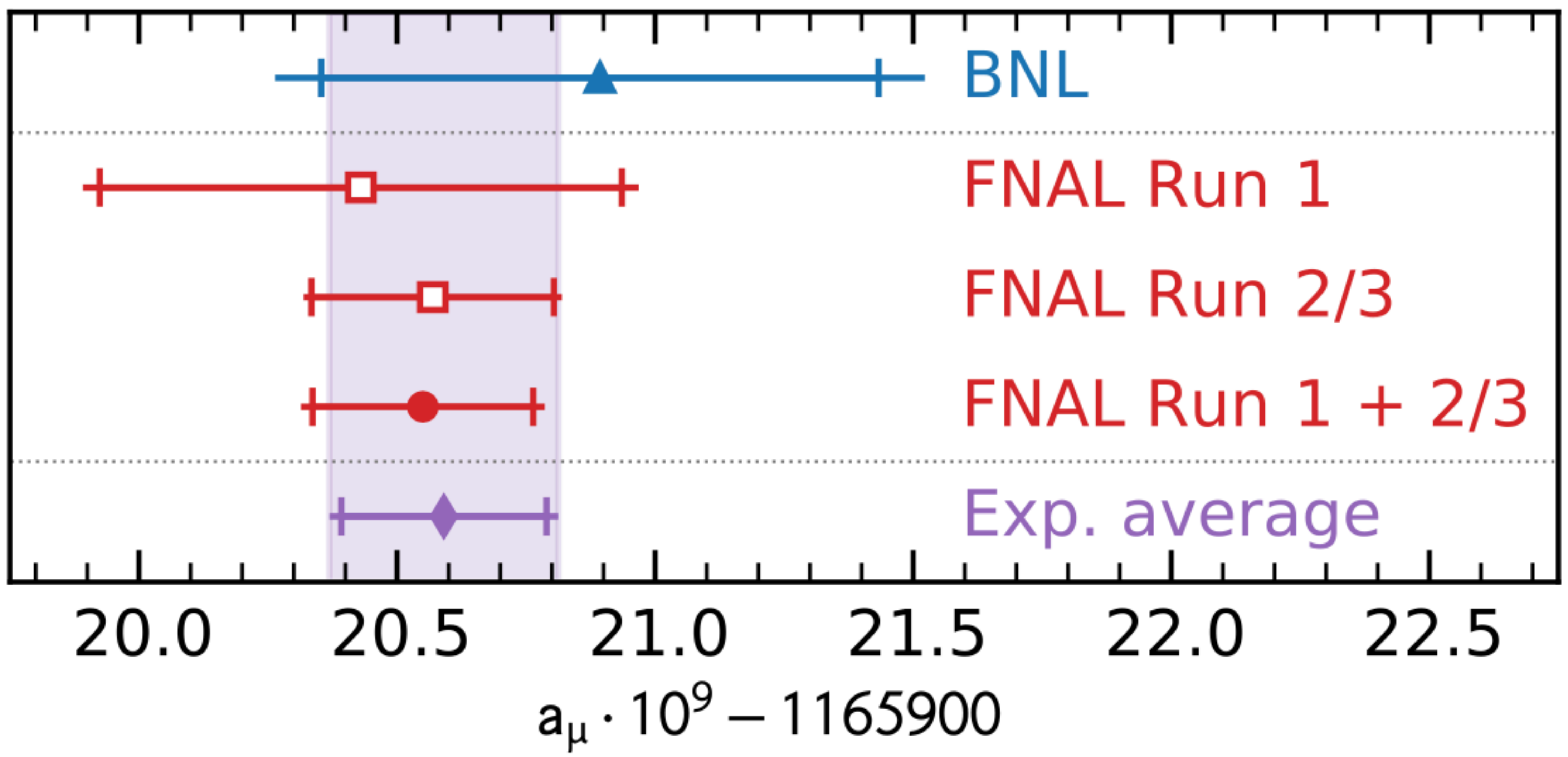


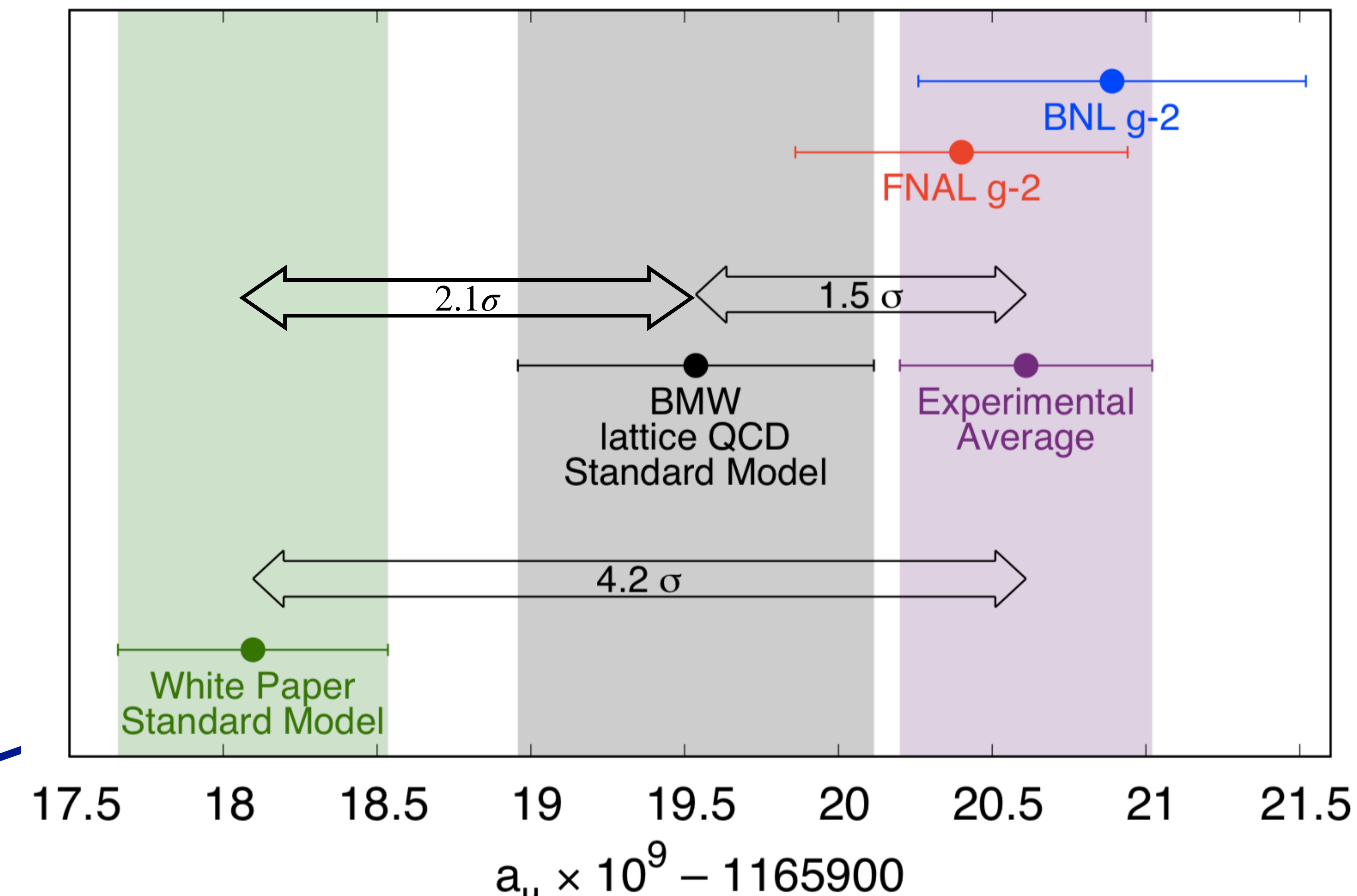
see however [Arias-Aragon+ 2502.10346] for the possibility to increase the positron intensity at CERN

Atoms as electron accelerators: σ_{had}

The muon magnetic moment

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





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

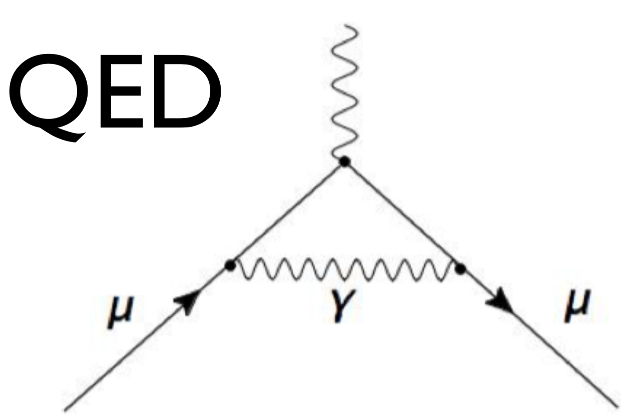
The muon magnetic moment

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

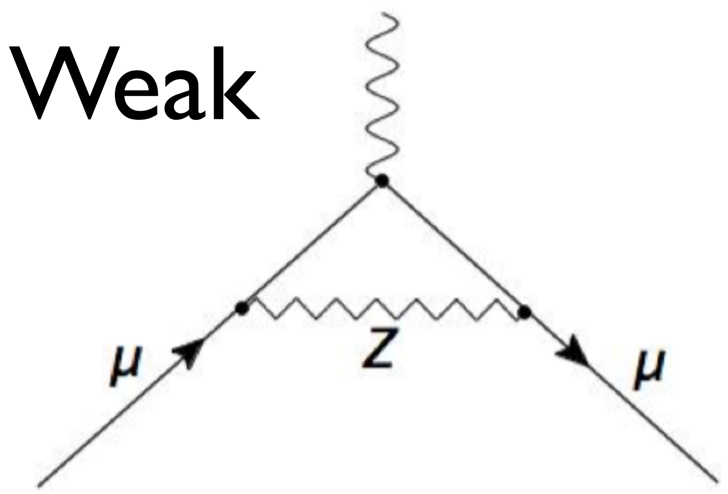
$116584718.9(1) \cdot 10^{-11}$

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

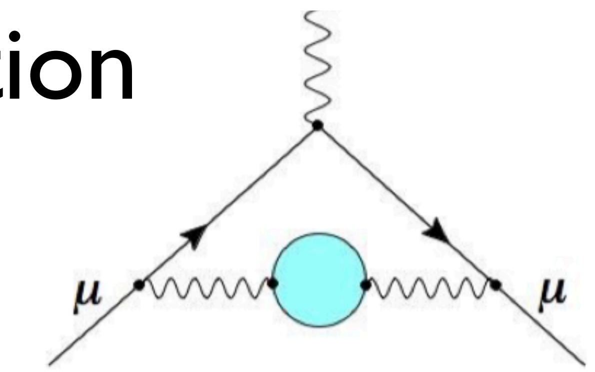
QED



Weak

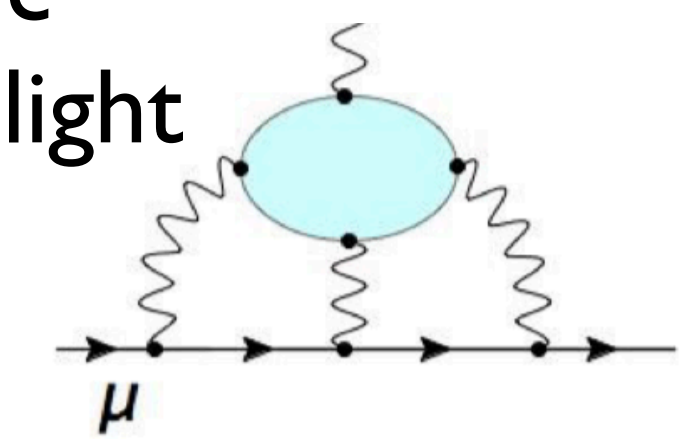


Hadronic vacuum polarization



$+\ldots$

Hadronic light-by-light

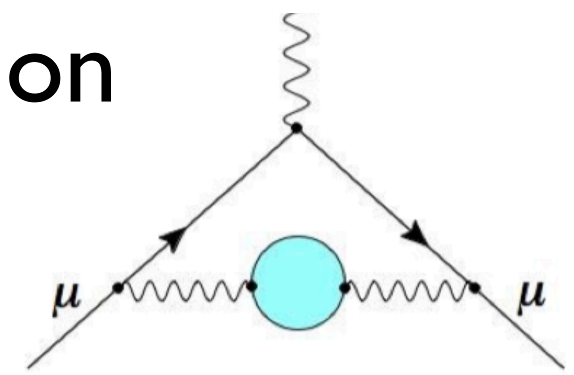


$153.6(1.0) \cdot 10^{-11}$

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

Hadronic cross section

Hadronic vacuum polarization

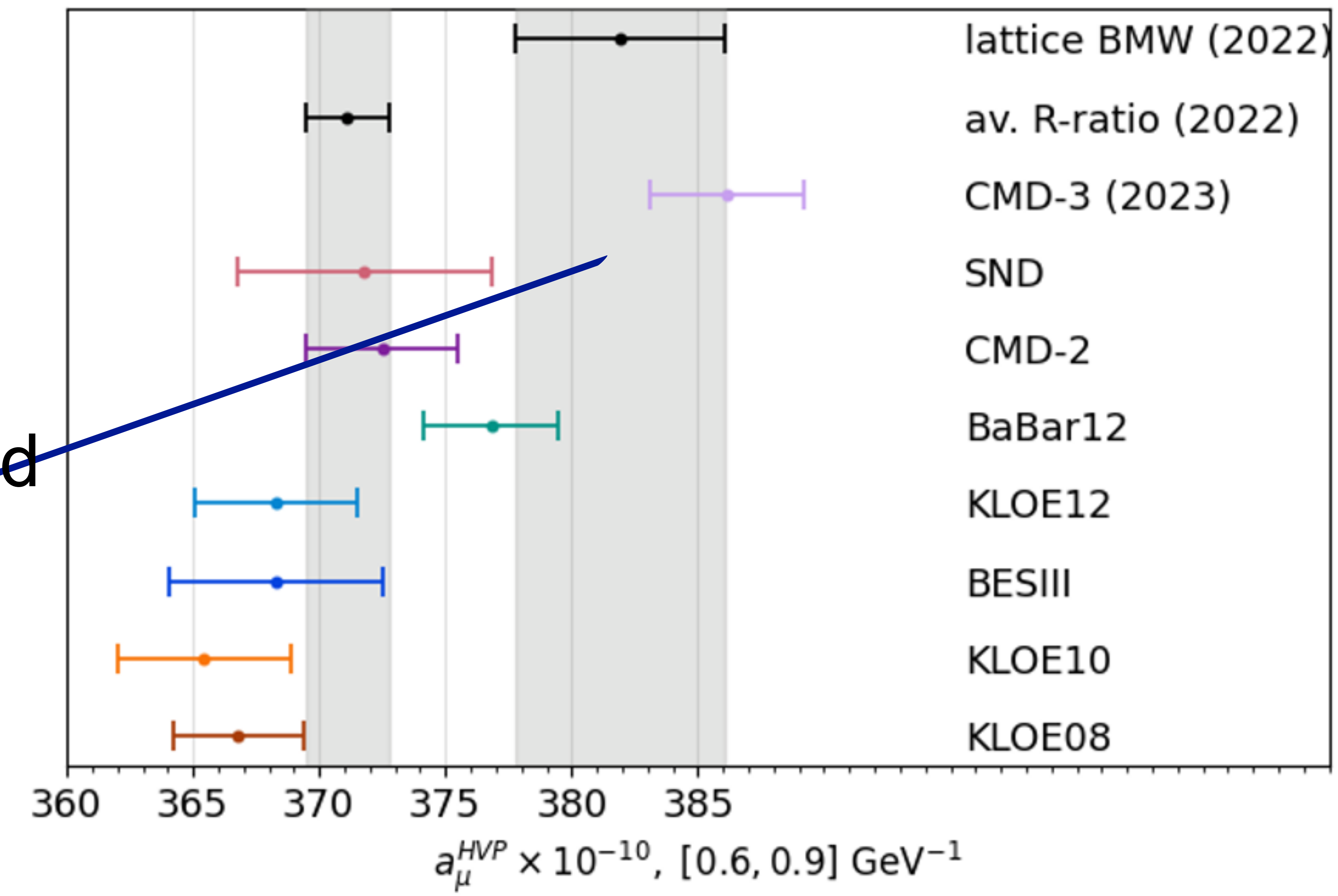


$6845(40) \cdot 10^{-11}$

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

σ_{had} measured at colliders

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



Hadronic cross section

PROPOSAL:

[Arias-Aragon, Darmé, G^2dC, Nardi, PRL134(2025)061802 , arXiv: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.

Hadronic cross section

[Arias-Aragon, Darmé, G^{2}dC, Nardi, PRL134(2025)061802 , arXiv: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

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

Hadronic cross section

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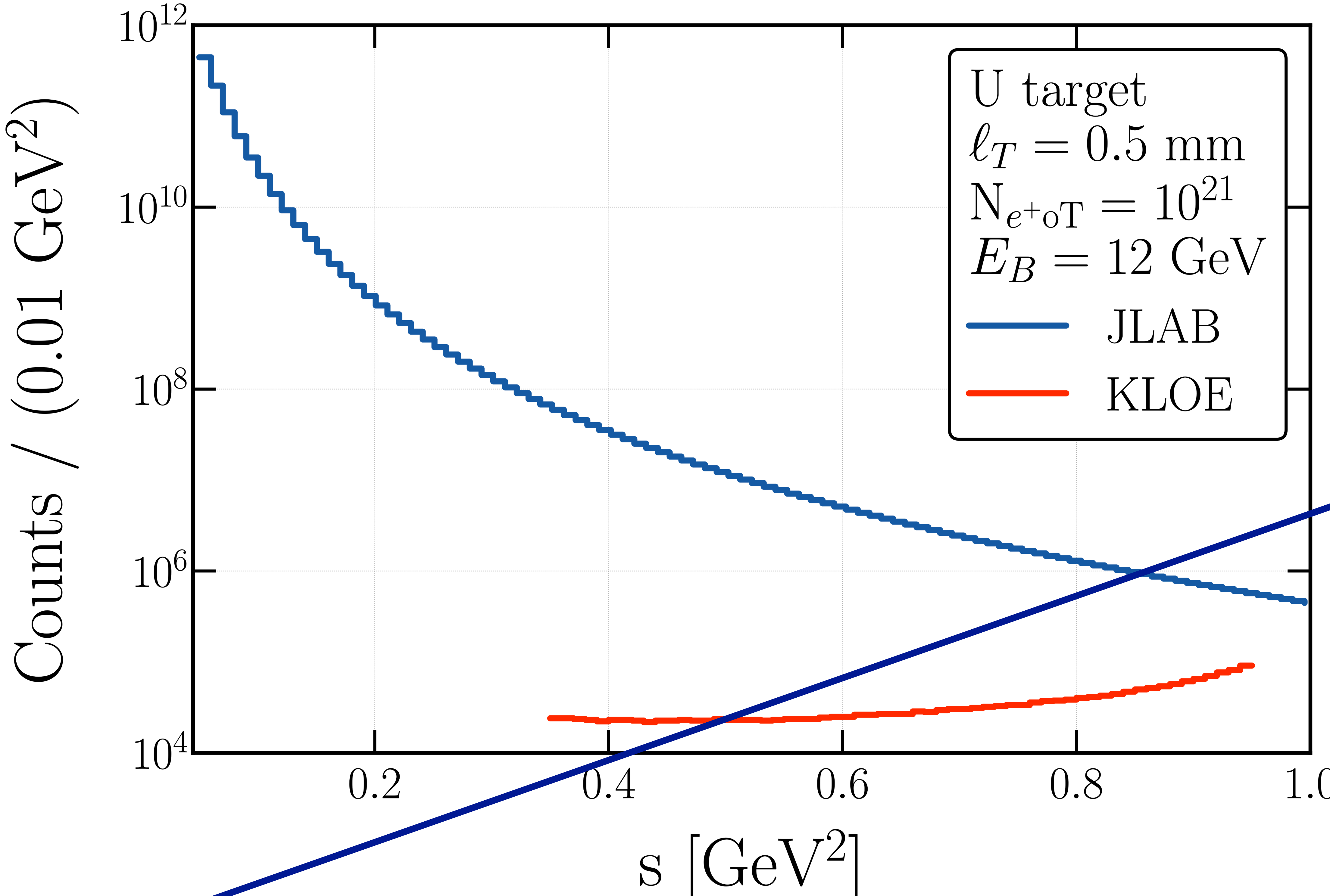
KLOE = $N_{\mu\mu\gamma}$ [Phys. Lett. B 720 (2013) 336-343]



Hadronic cross section

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Two possible beam-lines:

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

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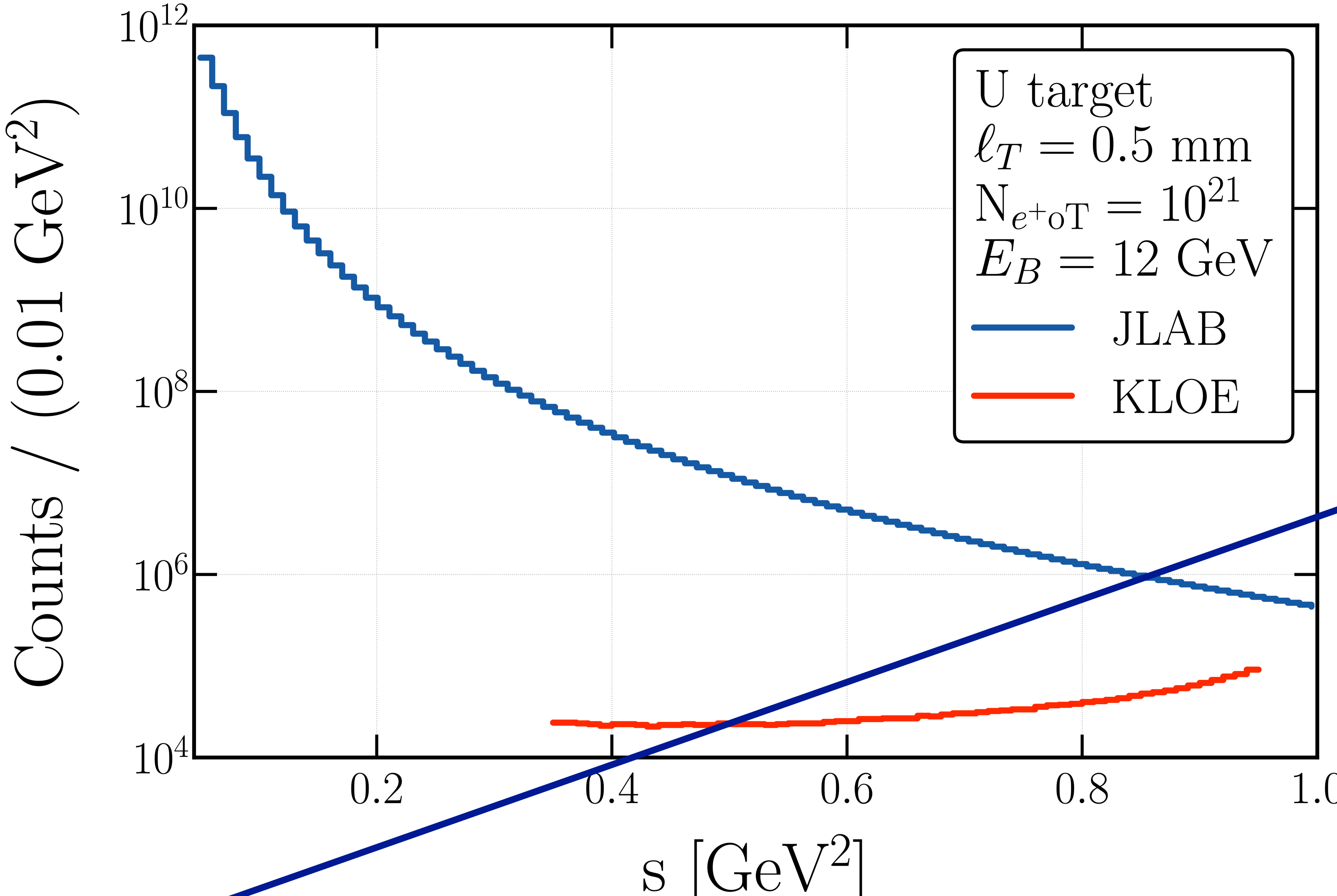

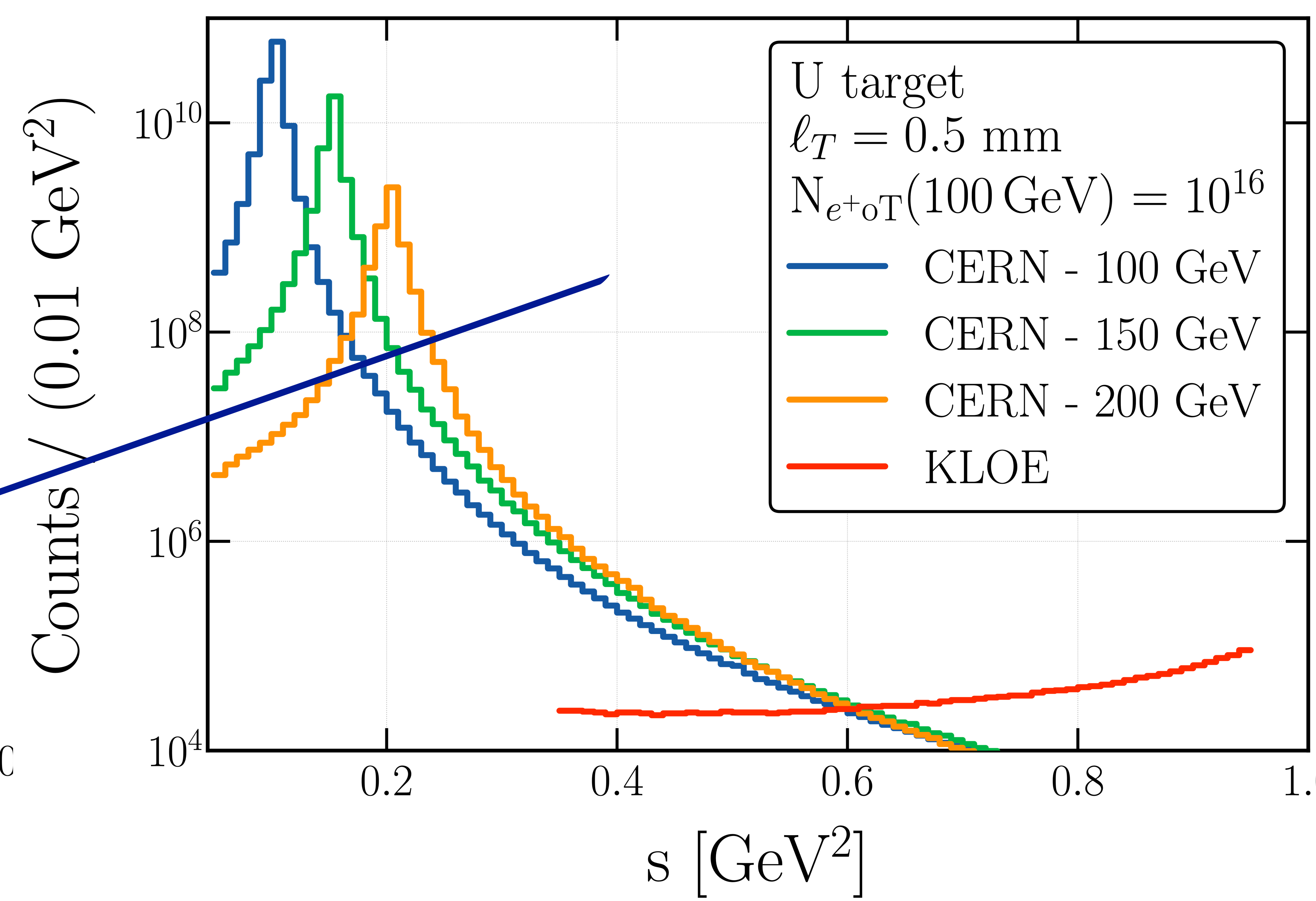

Conclusions

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- 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>); [see Spadaro's talk tomorrow]
- Opens up new perspectives on positron annihilation on fixed targets: increased sensitivity for BSM theories, hadronic cross section measurement, impact on MUonE…

Dark pseudo-scalars

[Arias-Aragon, G^{2}dC, Nardi, Veissière, 2504.00100]

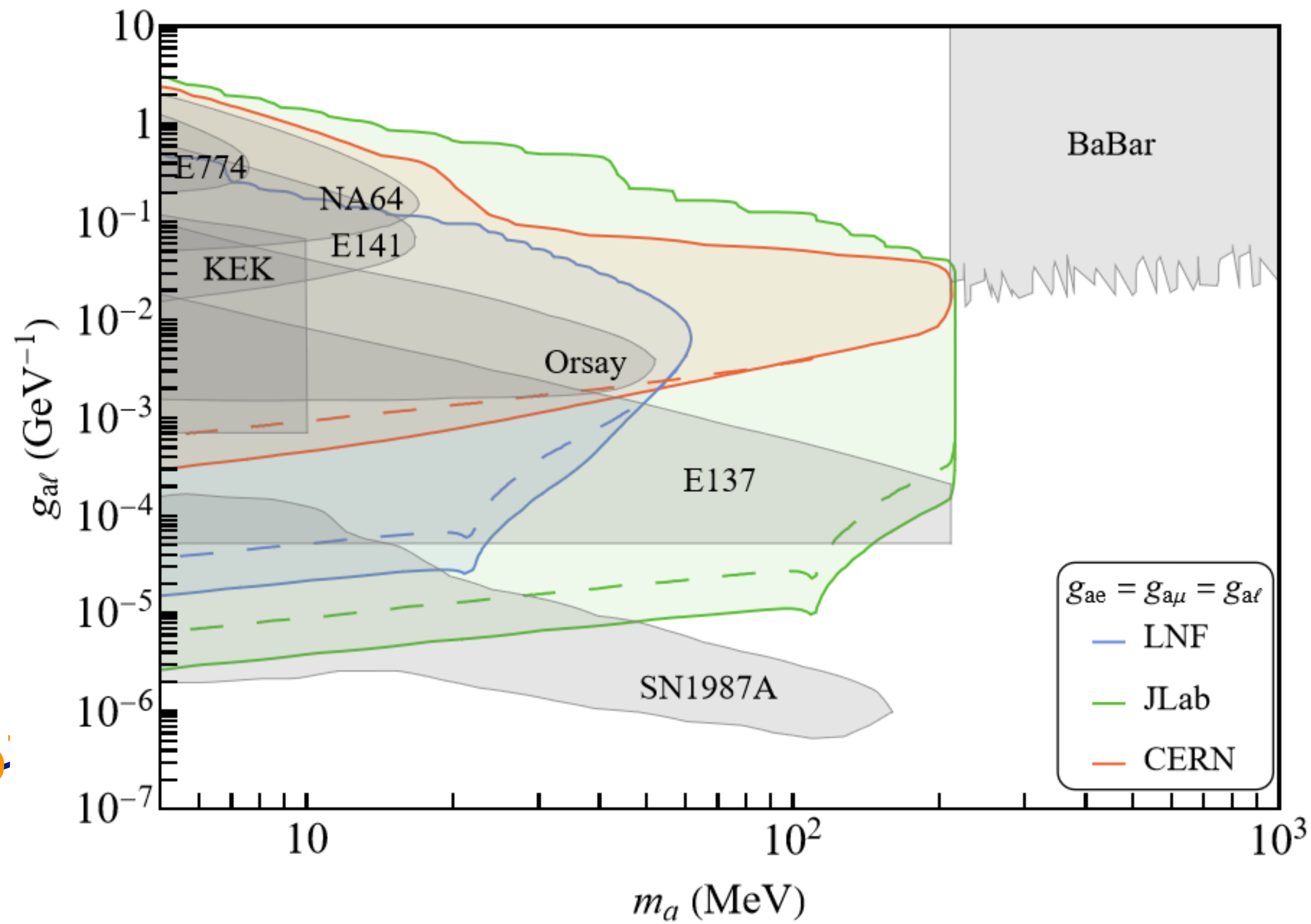
$$\mathscr{L} \supset i\, m_e\, g_{ae}\, a\, \bar{\psi}_e \gamma_5 \psi_e$$

5 cm tungsten thick target

LNF: 450 MeV, $10^{18}\ e^+$oT

JLAB: 12 GeV, $10^{21}\ e^+$oT

CERN: 100 GeV, $10^{13}\ e^+$oT



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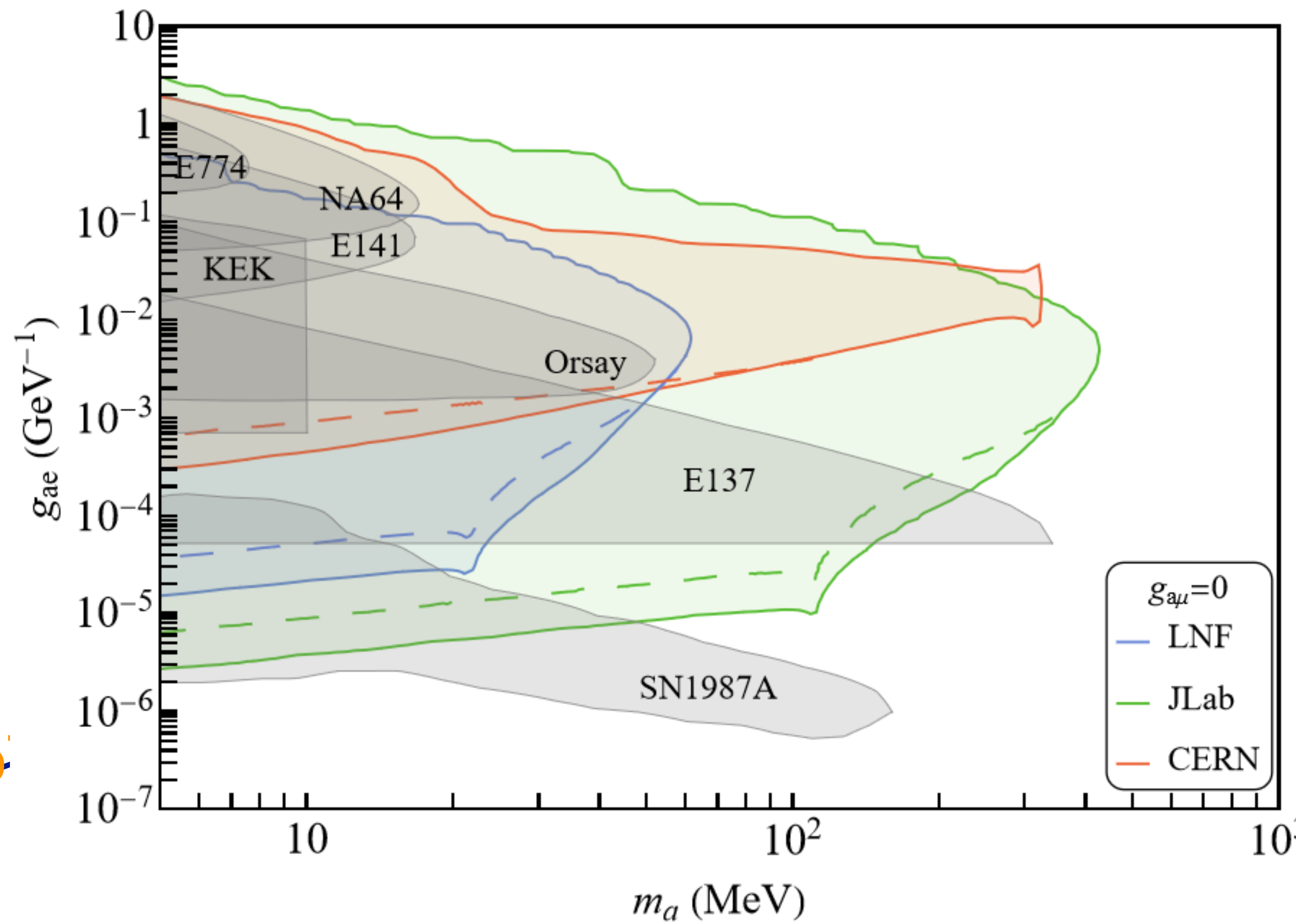
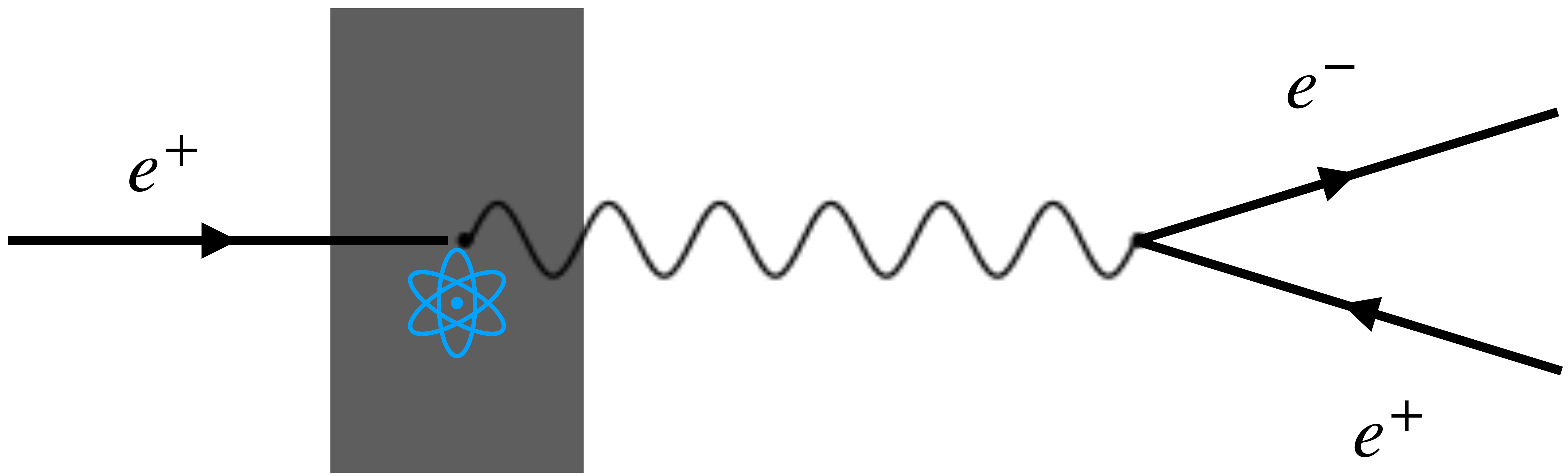


Resonant production

[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.

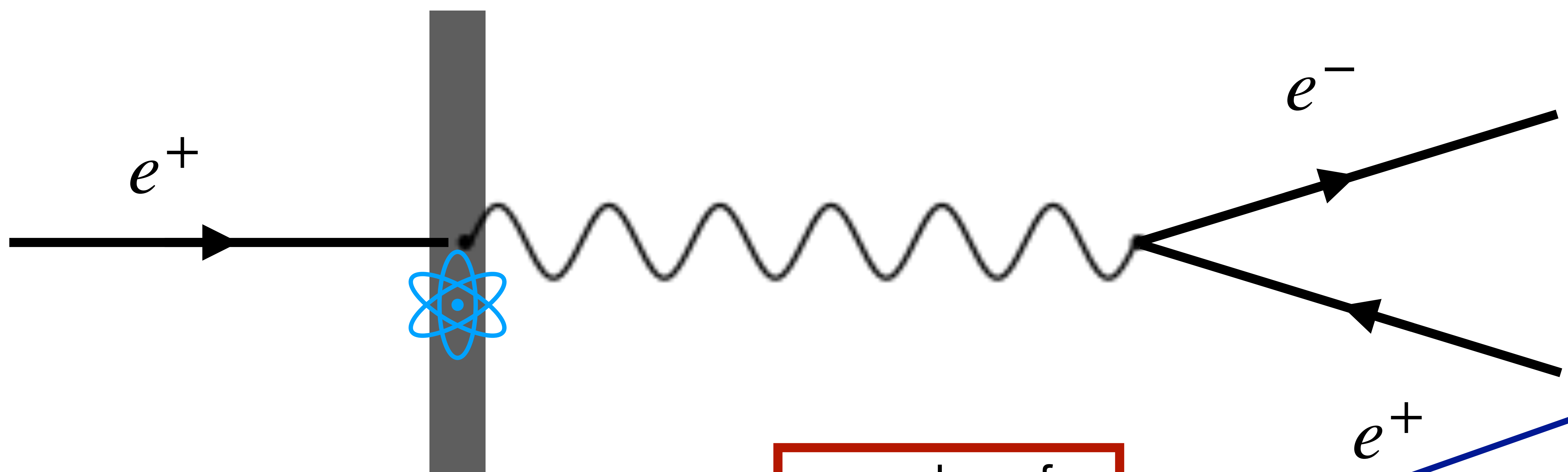
$$N_{A'} = \left(1 - e^{\frac{z_D - z_{\text{det}}}{\ell_\epsilon}}\right) \frac{N_{\text{poT}} N_{\text{Av}} Z \rho X_0}{A} \int_0^T dt \frac{d\mathscr{P}(t, z_D, \ell_\epsilon)}{dt} \int dE_e \int dE\, \mathscr{G}(E, E_B, \sigma_B)\, I(E, E_e, t)\, \sigma(E_e)$$

- $\left(1 - e^{\frac{z_D - z_{\text{det}}}{\ell_\epsilon}}\right)$, $\frac{d\mathscr{P}(t, z_D, \ell_\epsilon)}{dt}$: probability that the dark photon decays before the detector but outside the target
- $\frac{N_{\text{Av}} Z \rho}{A}$: number of target electrons
- $\mathscr{G}(E, E_B, \sigma_B)$: Gaussian beam energy spread
- $I(E, E_e, t)$: probability of finding a positron with energy E_e after passing through t radiation lengths

Resonant production

Thin fixed target

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



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