Effects of atomic electron momentum distribution on resonant dark sector production

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based on

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

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

42ND INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

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Outline

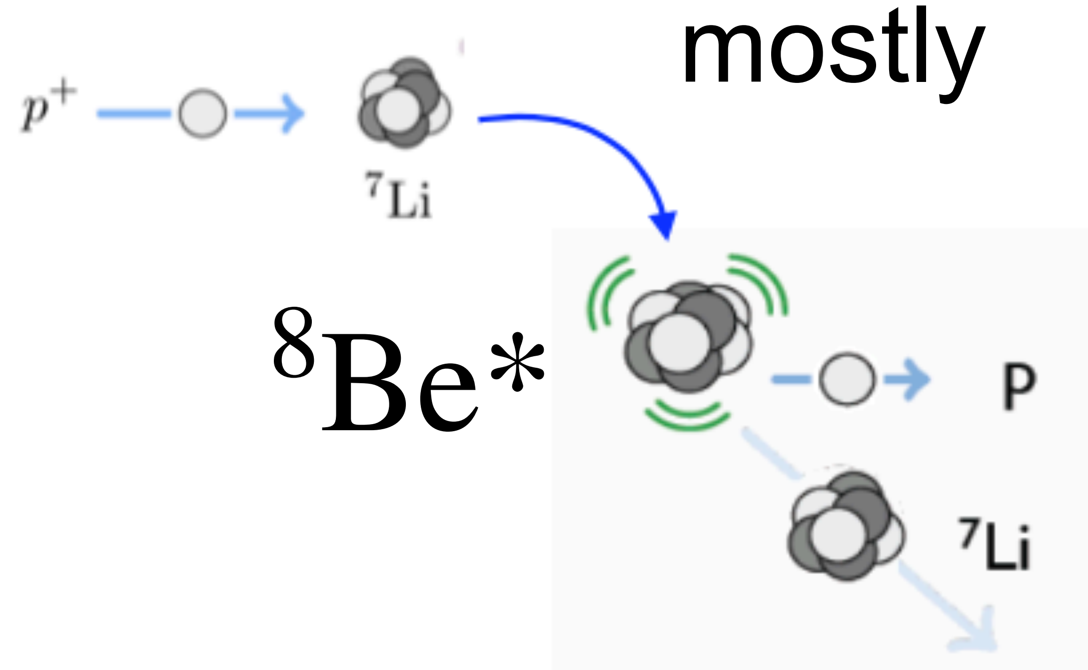
1. Motivation
2. Dark sector resonant production
3. The problem
4. The solution
5. Atoms as particle accelerators

   Searches for dark sector particles

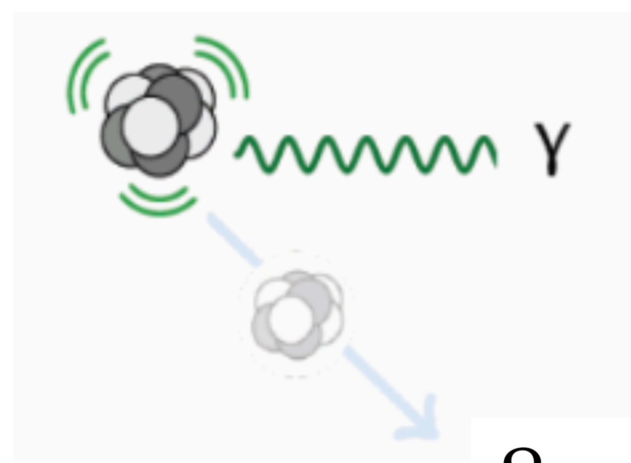
   Measuring σ_{had}?

Motivation

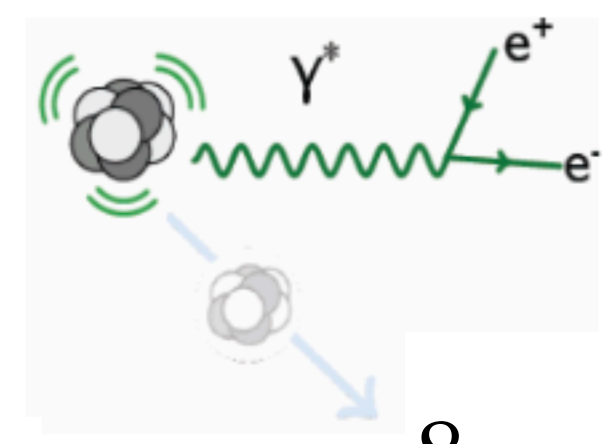
The X_{17} saga



mostly



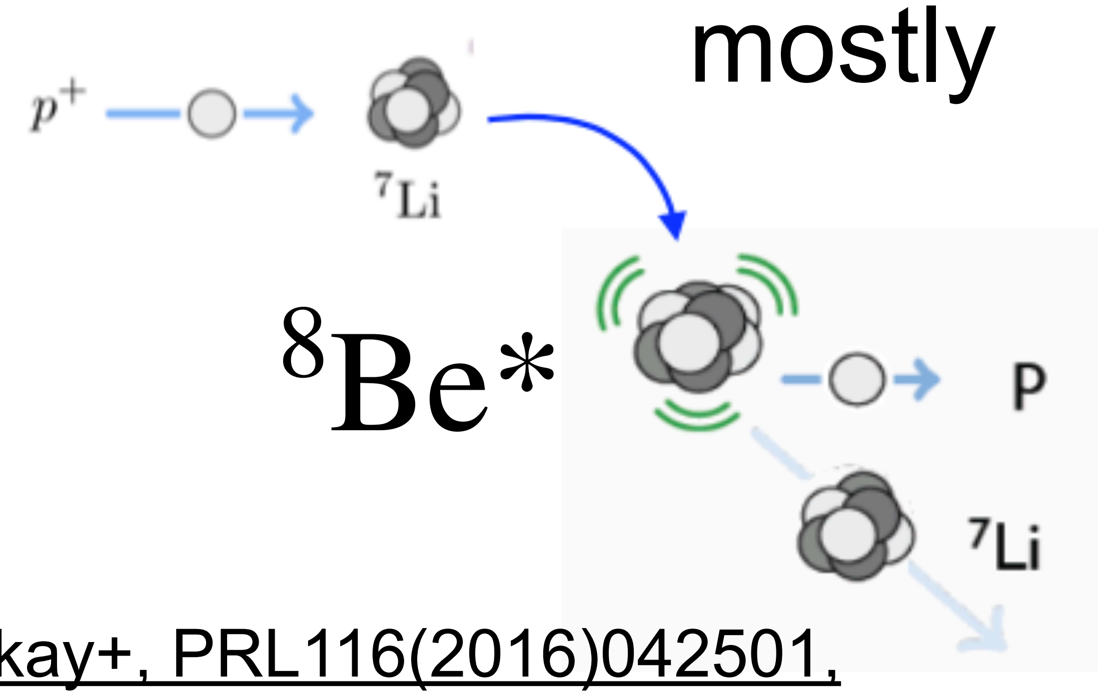
$B_\gamma \simeq 10^{-5}$

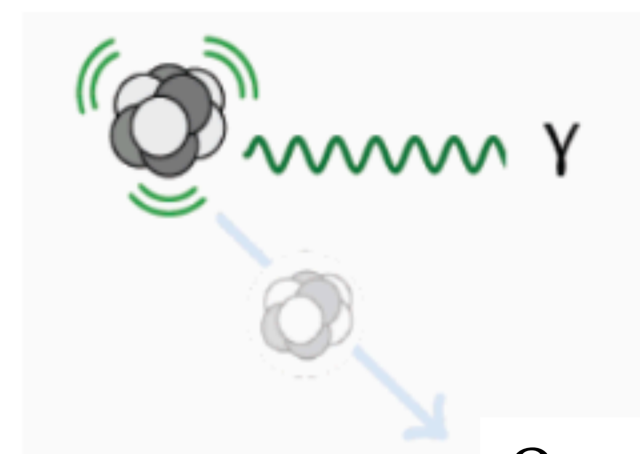


$B_{e^\pm} \simeq 10^{-3} B_\gamma$

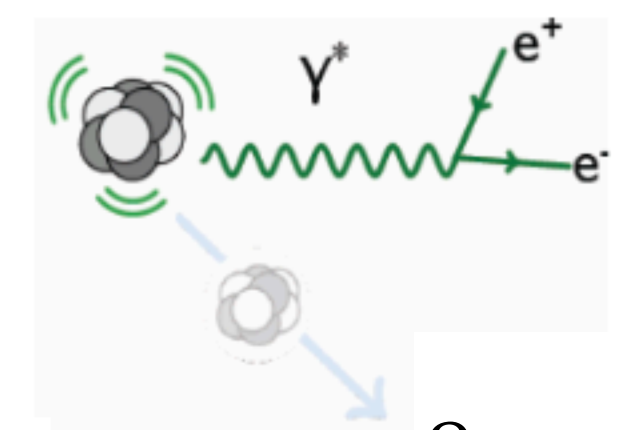
The X_{17} saga

mostly | $\mathrm{B}_\gamma \simeq 10^{-5}$ | $\mathrm{B}_{e^\pm} \simeq 10^{-3}\mathrm{B}_\gamma$ | $\mathrm{B}_X \simeq ?$





^{8}Be



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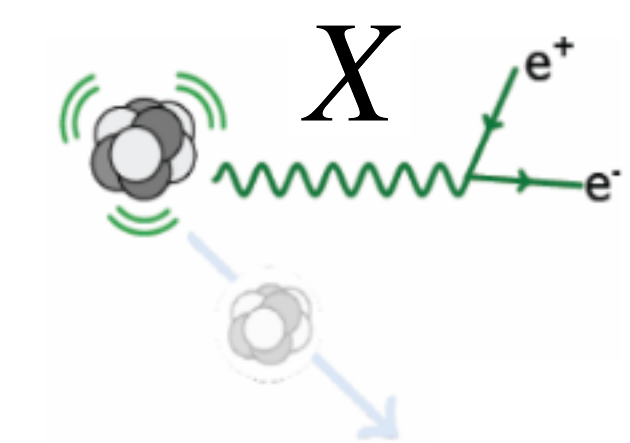
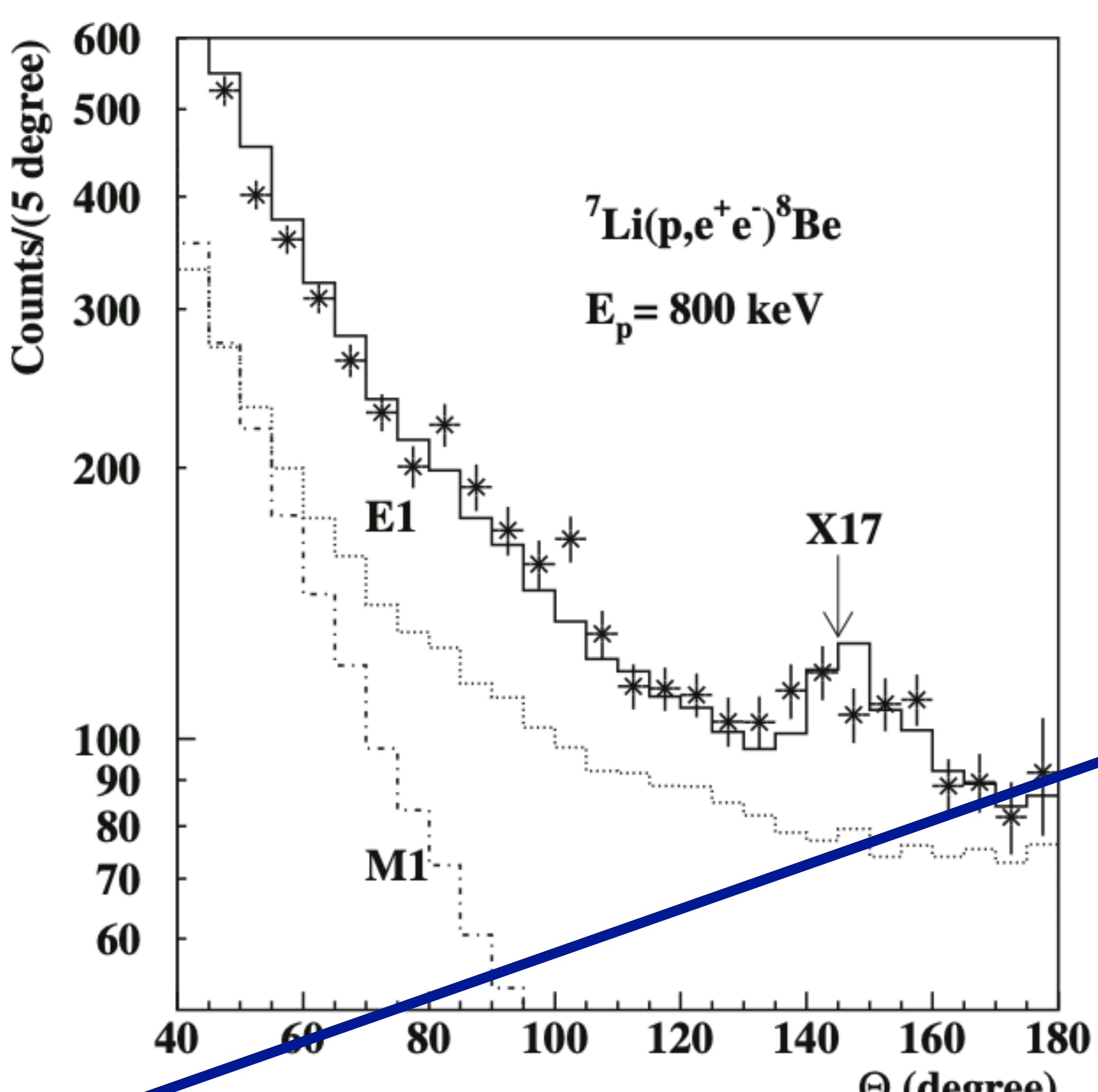
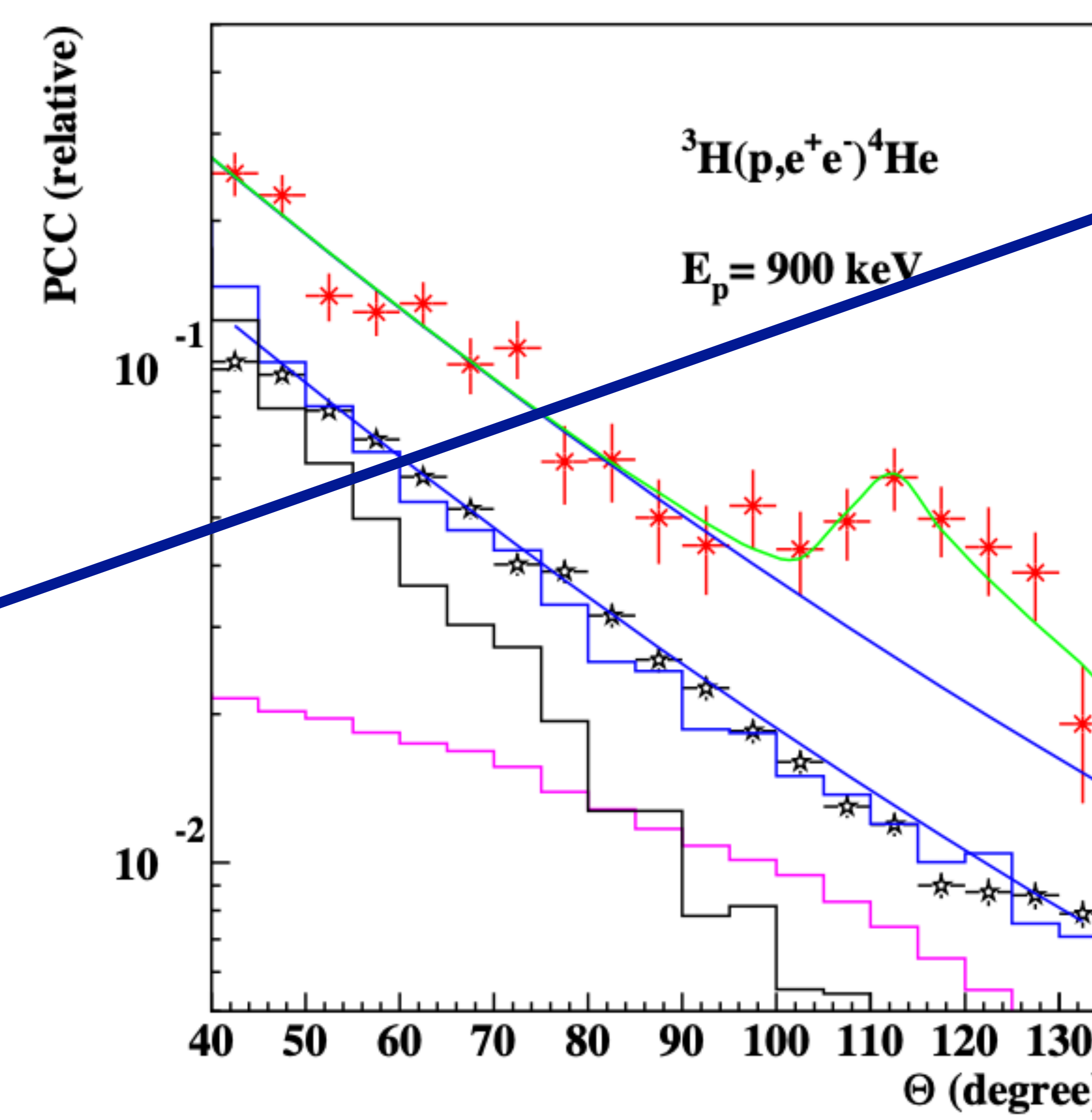


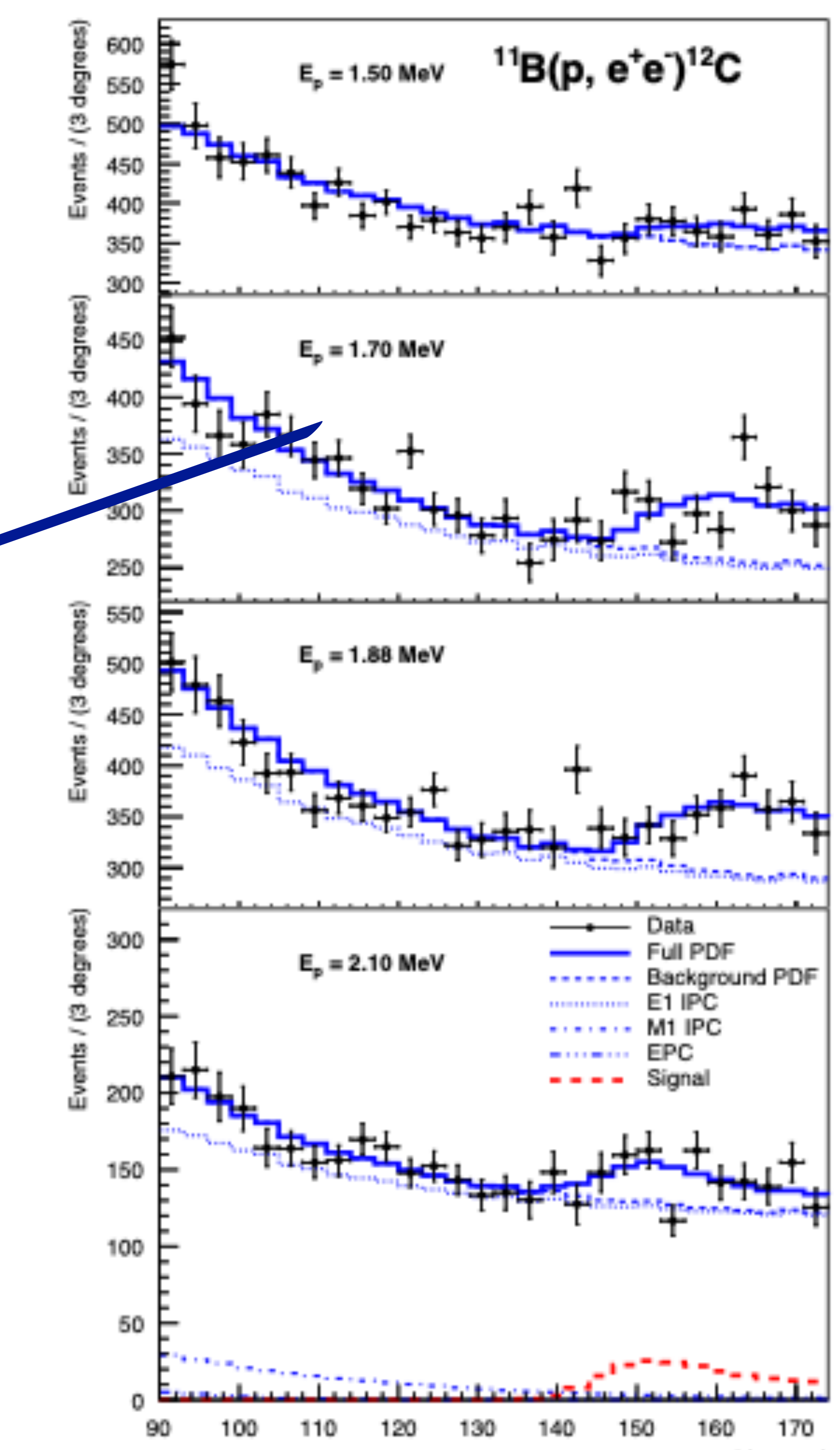
^{8}Be

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

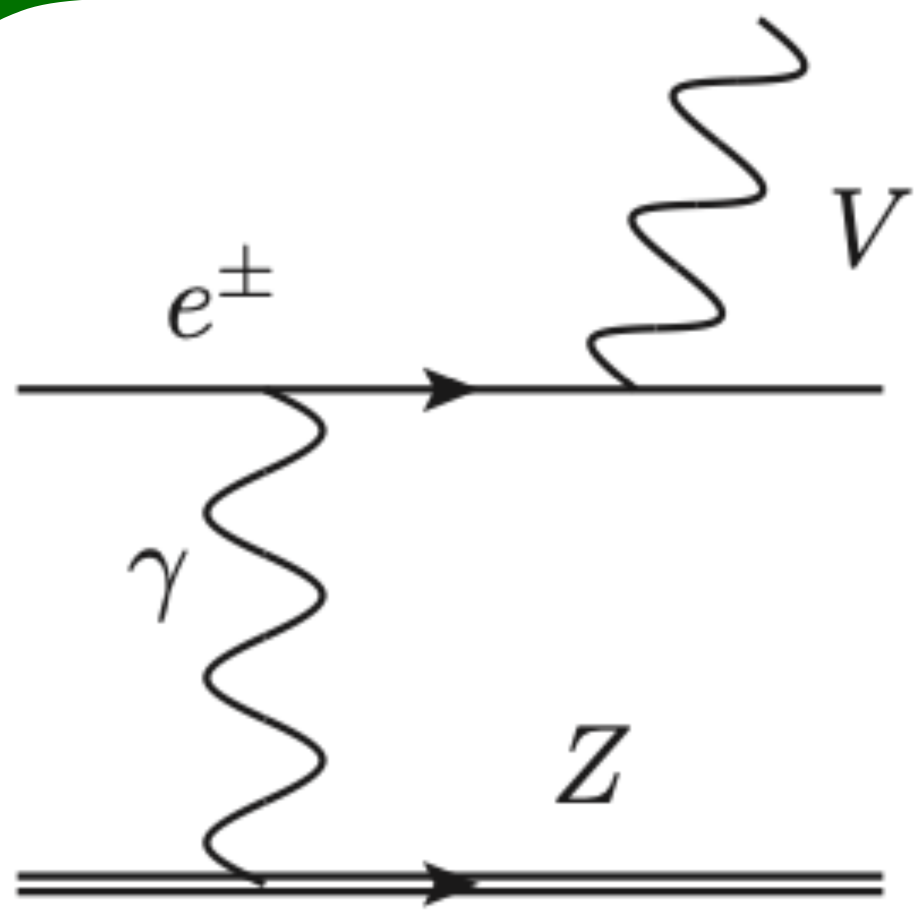
Anomaly observation in ^{8}Be, ^{4}He and ^{12}C transitions





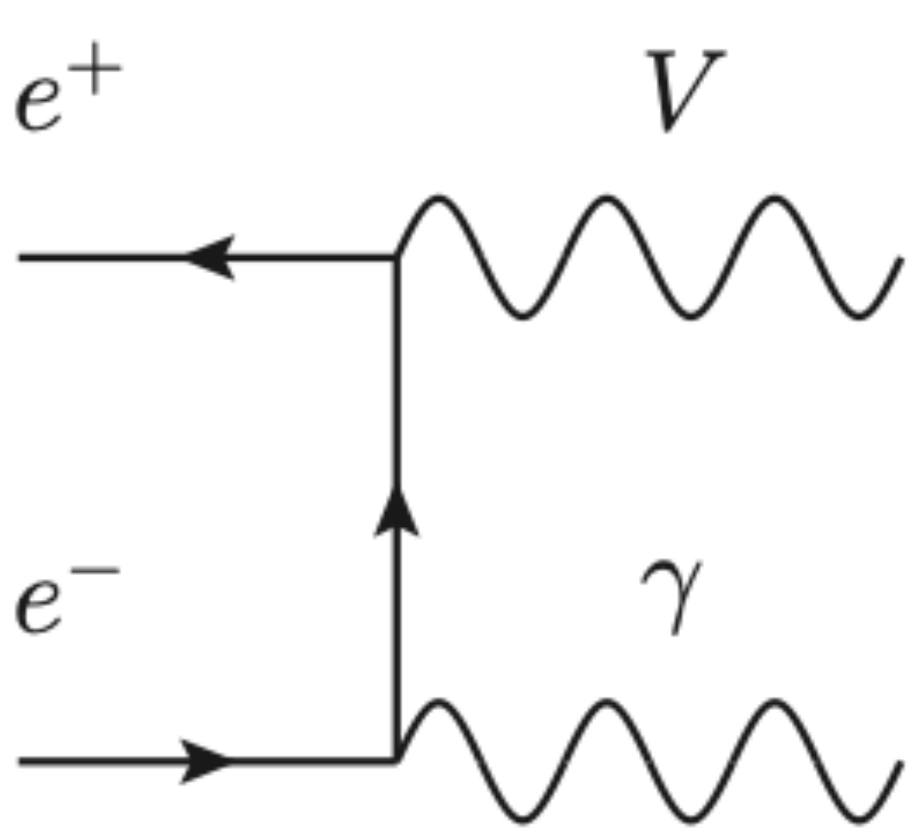


Searches at fixed target exp.



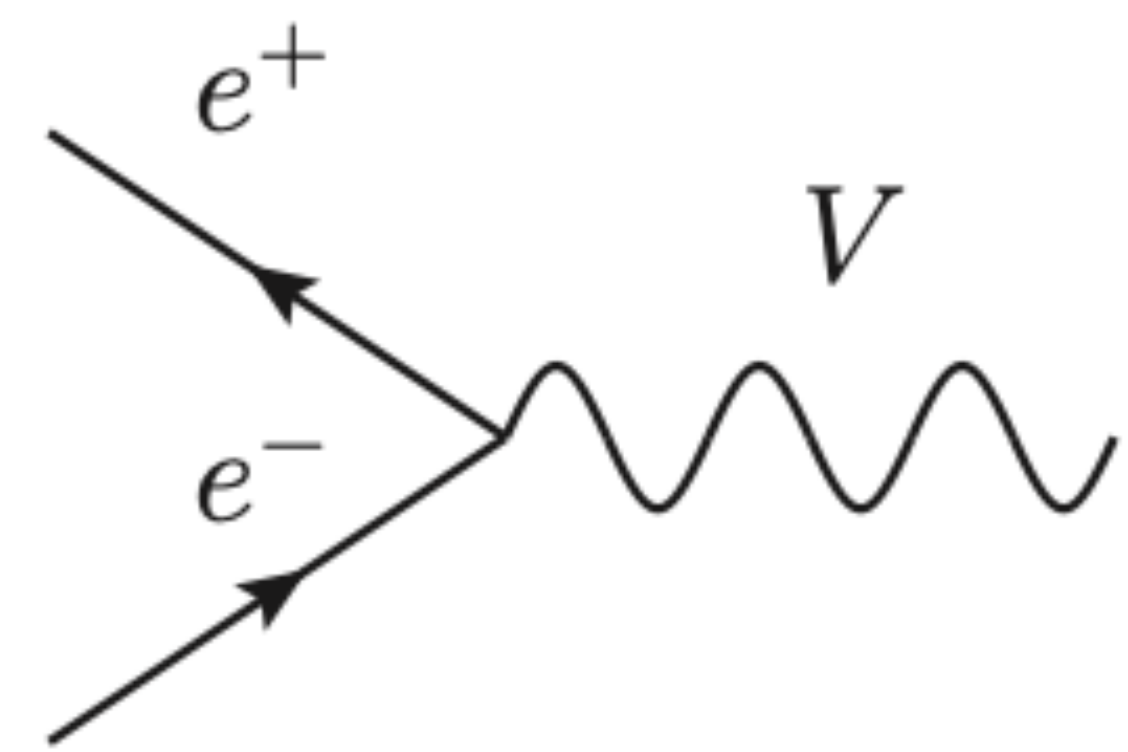
Electron/positron beam fixed target experiments

Dark photon production via Bremsstrahlung: APEX, NA64, …



Positron beams fixed target experiments

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



Positron beam fixed target experiments

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

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

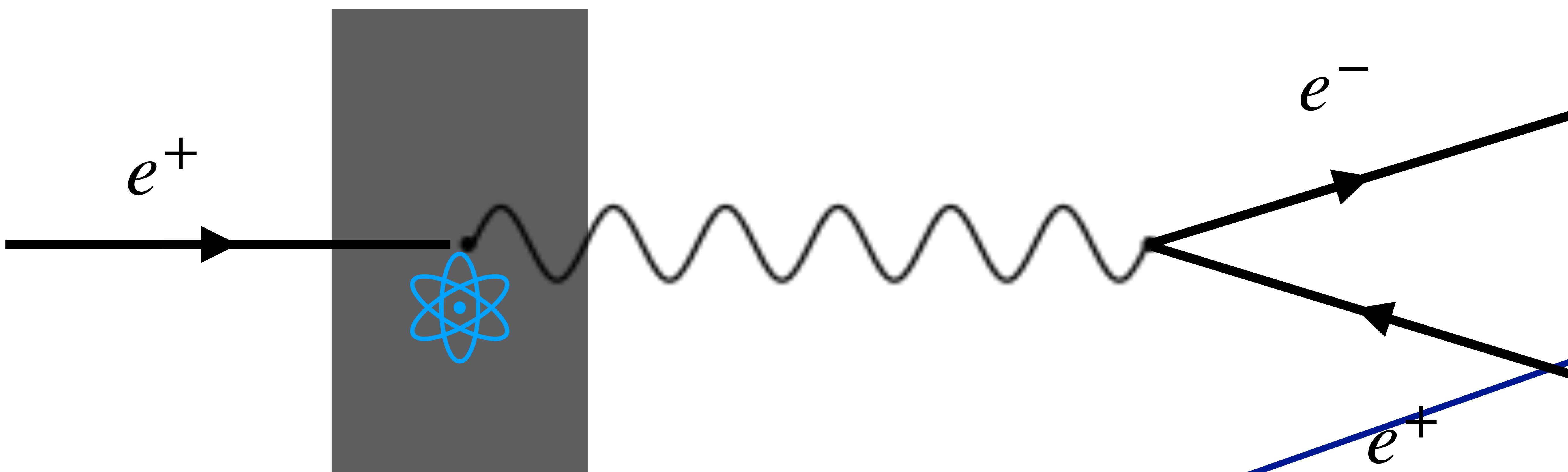
Dark Sector resonant production

Resonant production

Thick fixed target

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

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

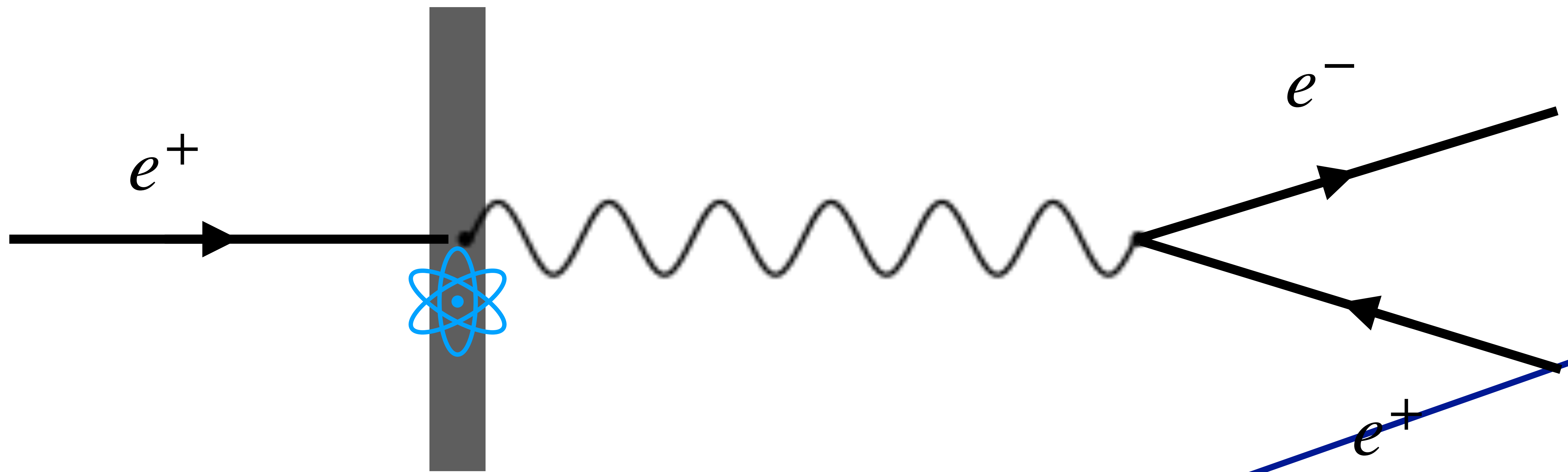


Take advantage of energy loss of the positrons propagating through matter, effectively scanning in energy until hitting the resonance.

Resonant production

Thin fixed target

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



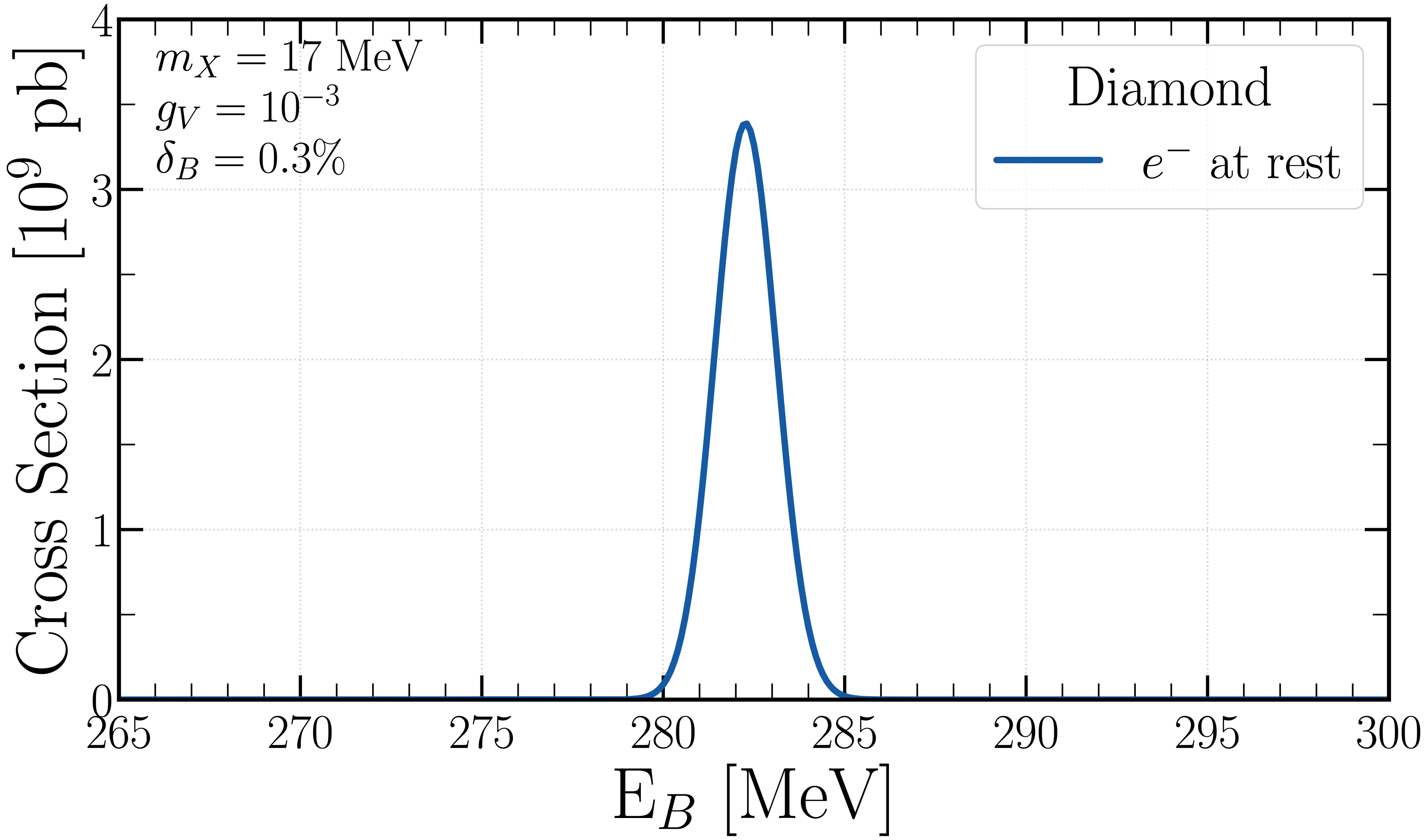
Negligible energy loss, need to physically vary the beam energy

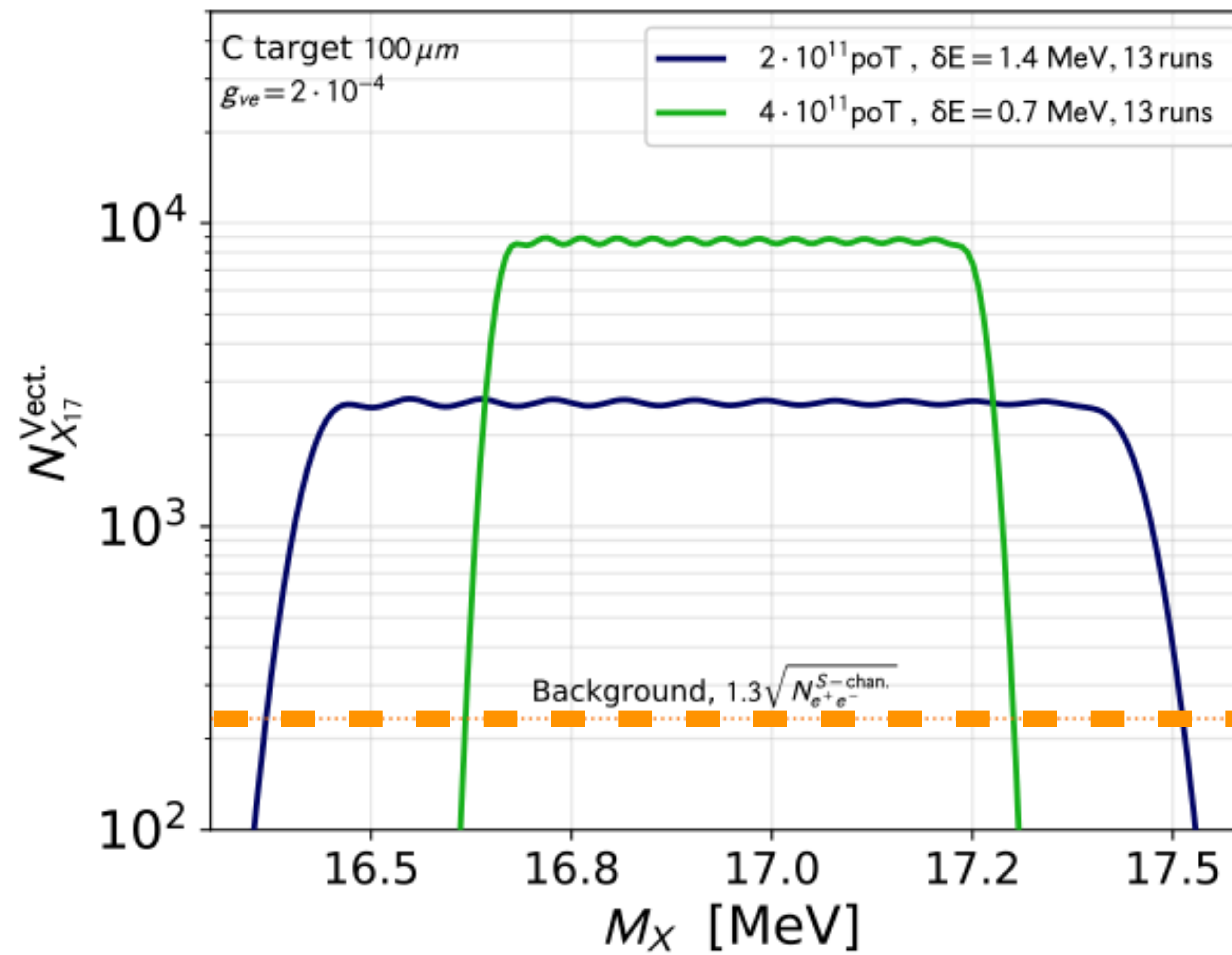
Resonant production

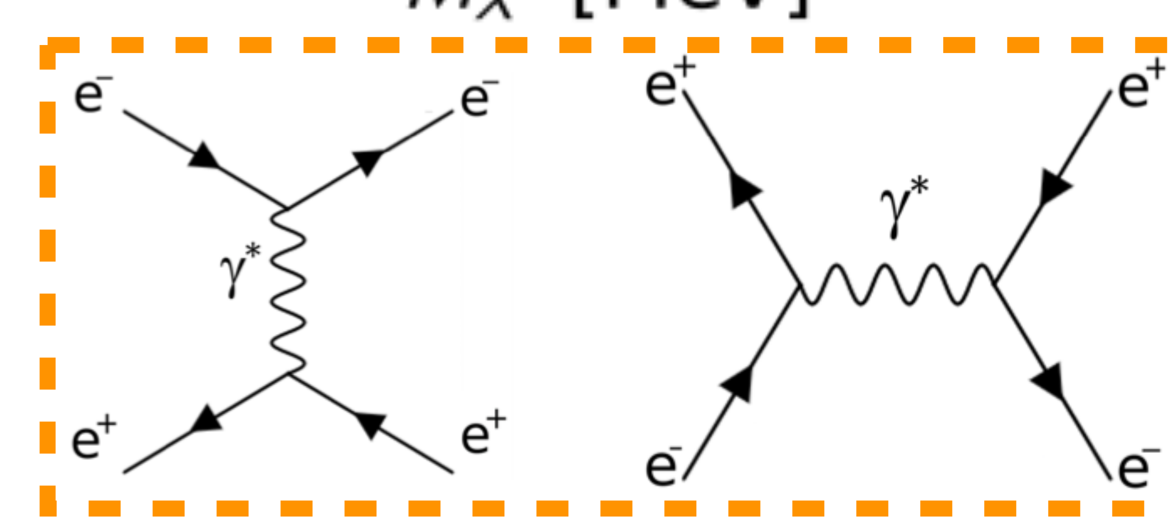
PADME strategy for the X_{17} search [Darmé+, PRD106(2022)115036]

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

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







Resonant production

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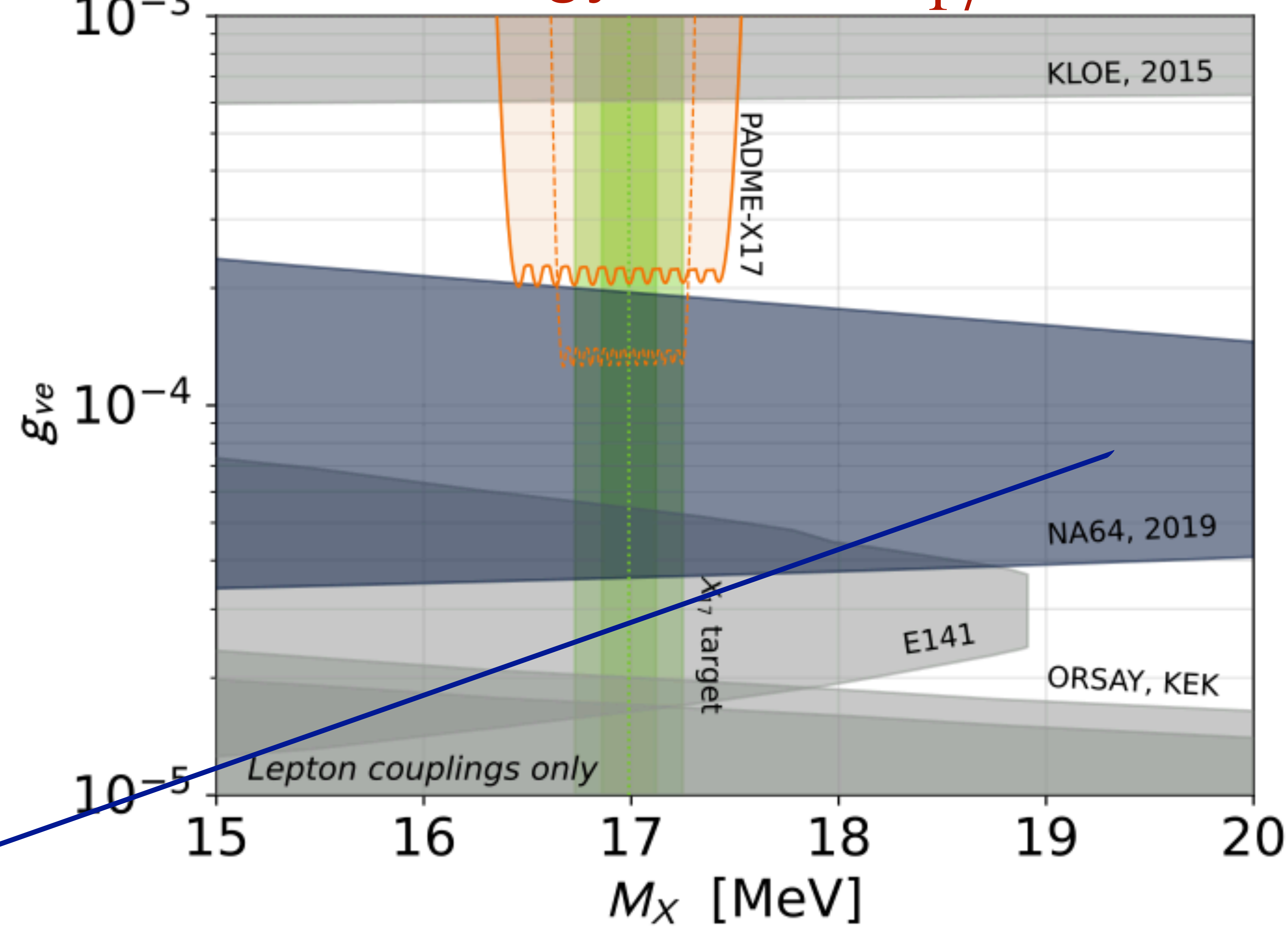
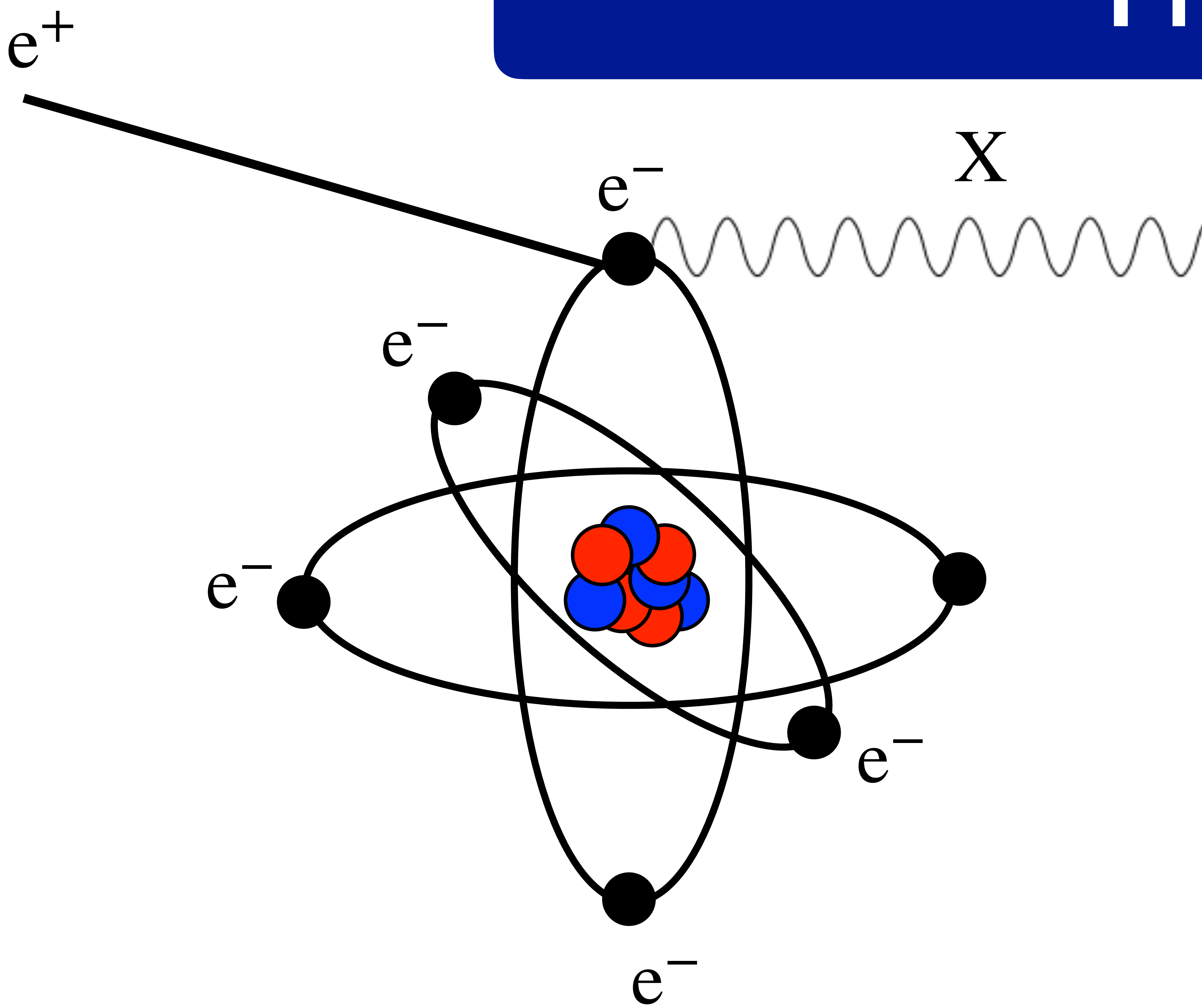


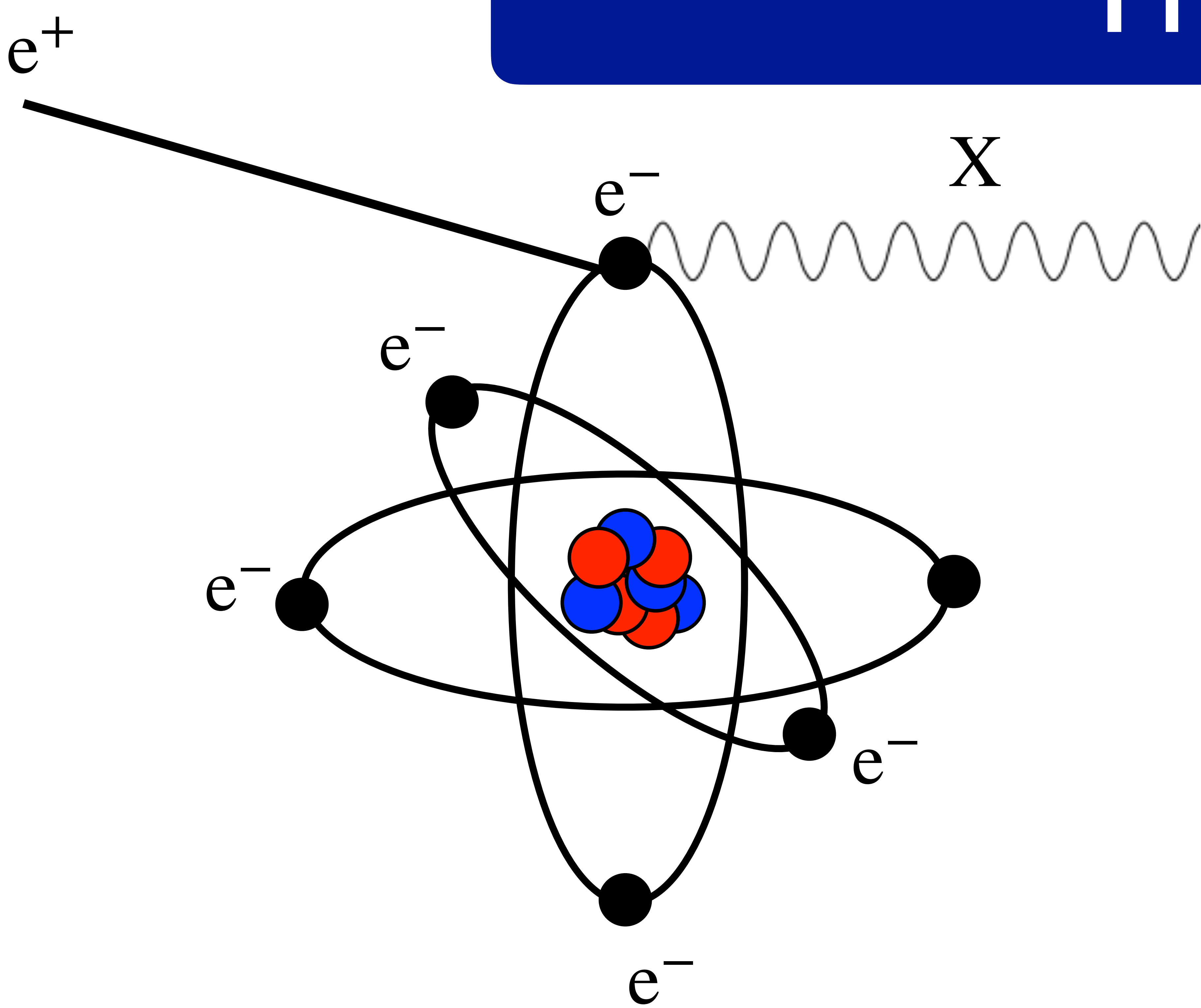
The problem

The problem



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

The problem



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

Naive estimate:

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

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

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

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

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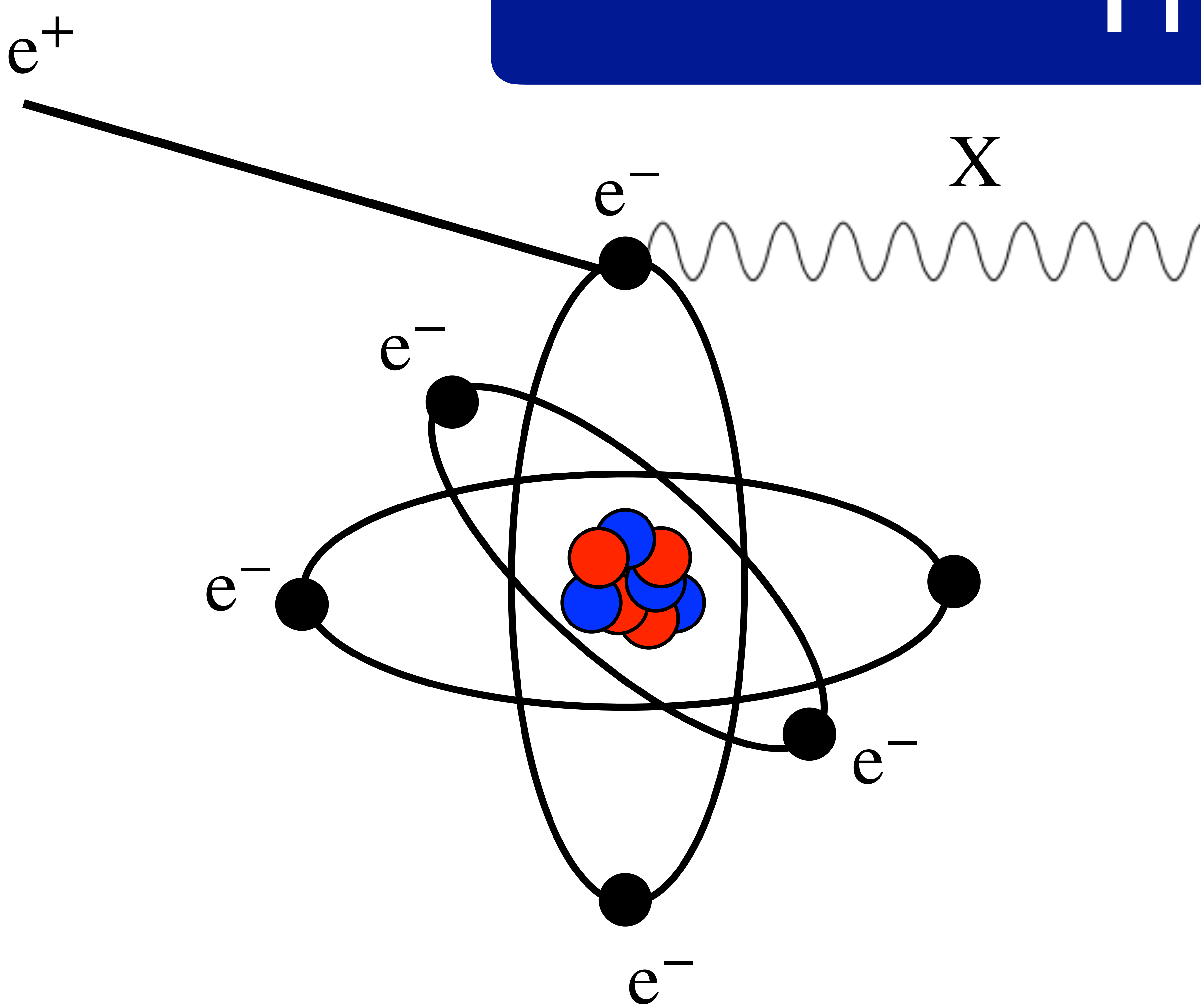

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using $\beta = \langle \beta_{1s} \rangle = 0.04$

$\sqrt{s} = 16.99\,\mathrm{MeV}$ $\quad (E_b \sim 282.0\ \mathrm{MeV})$

$\sqrt{s'_+} = 17.33\,\mathrm{MeV}$ $\quad (E_b \sim 293.5\ \mathrm{MeV})$

$\sqrt{s'_-} = 16.66\,\mathrm{MeV}$ $\quad (E_b \sim 271.5\ \mathrm{MeV})$

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

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

The solution

What should we compute?

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

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

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→ theory

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

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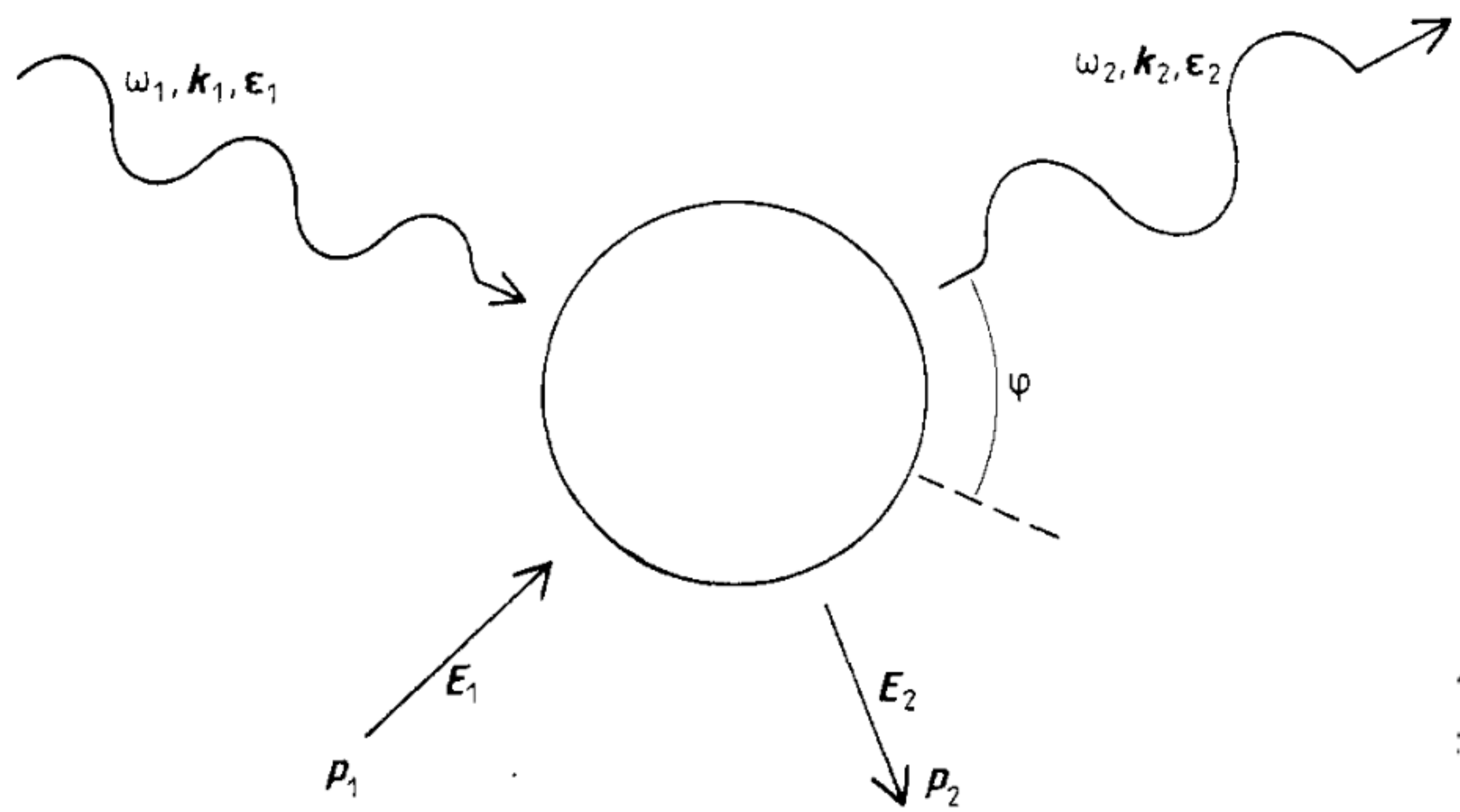
theory: use Slater Type Orbitals, hybridization, Hartree Fock computations for atomic carbon, …

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

Compton Profile

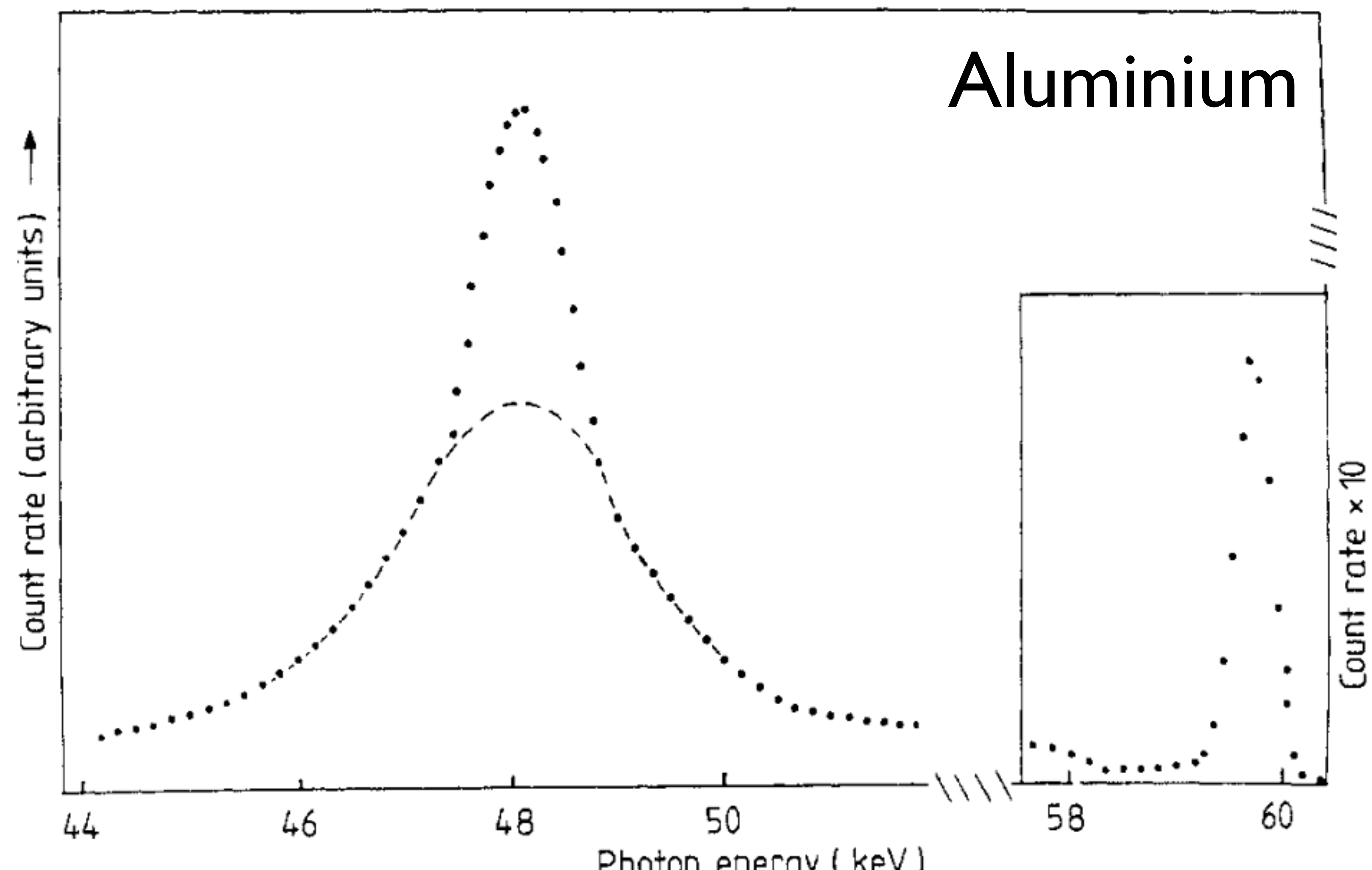


$$\omega_1 - \omega_2 = \frac{1}{2} m_e [\vec{p} + (\vec{k}_1 - \vec{k}_2)]^2 - \frac{|\vec{p}|^2}{2m_e}$$

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

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

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



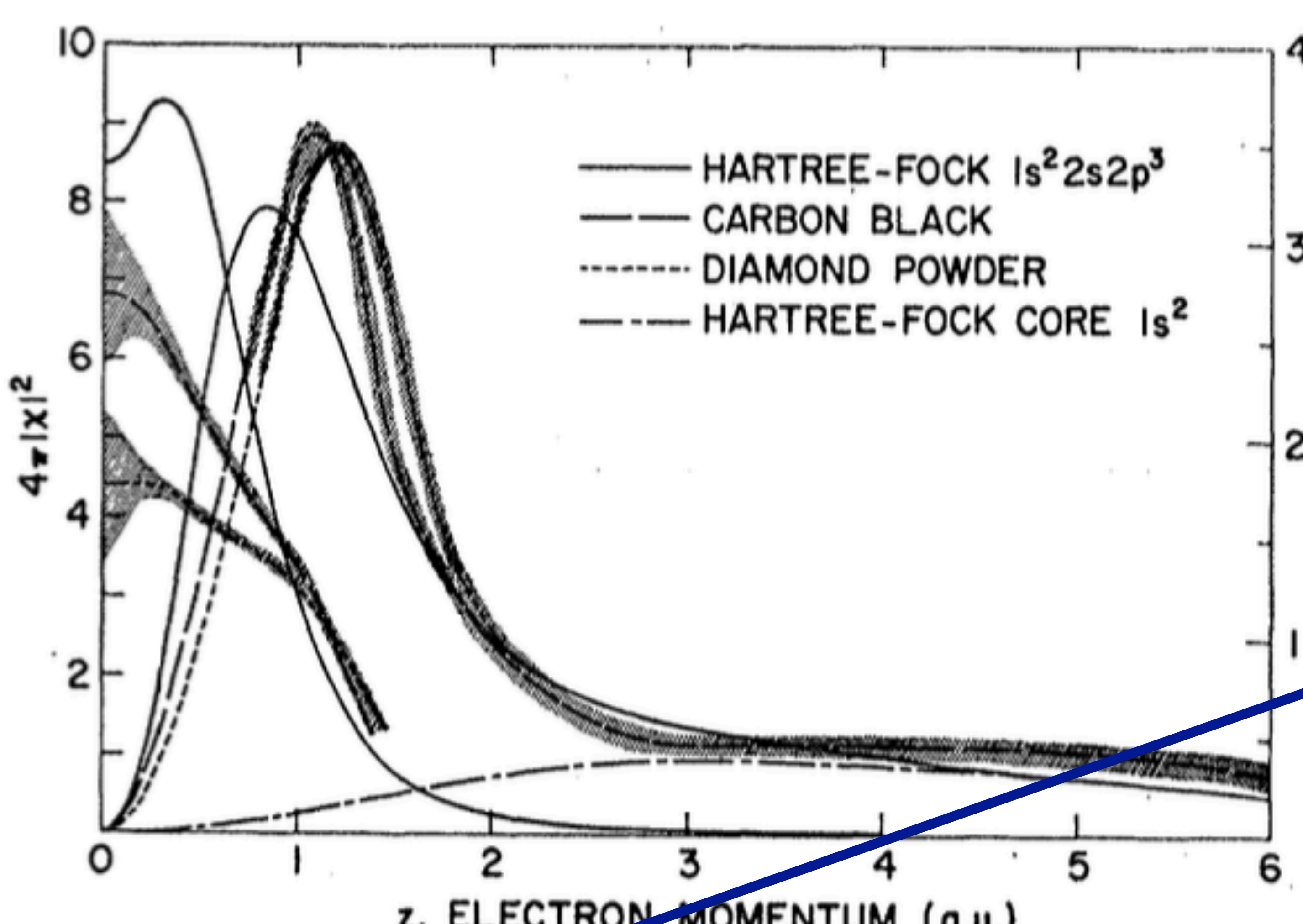
Compton Profile

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

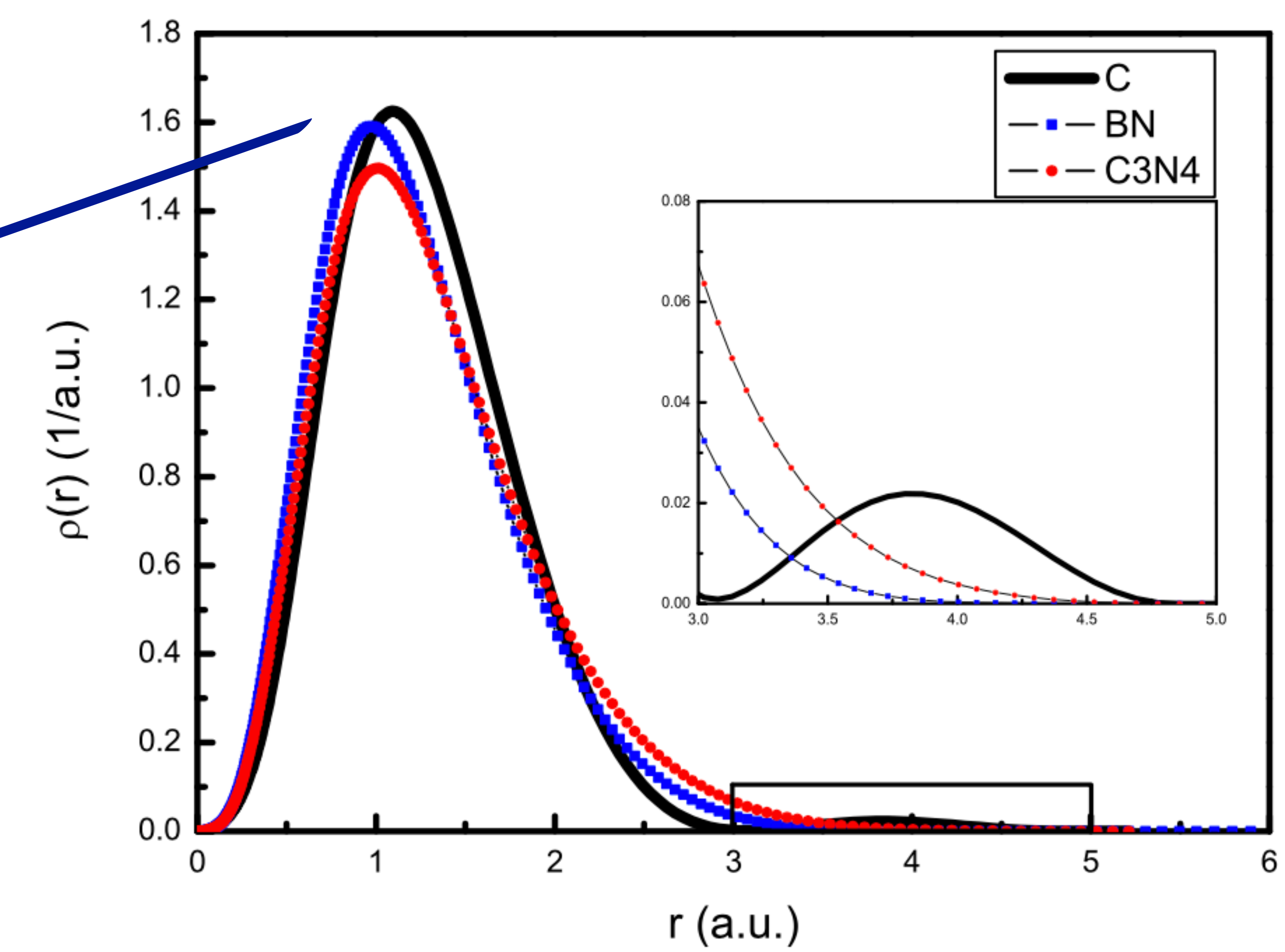
assuming isotropy

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

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

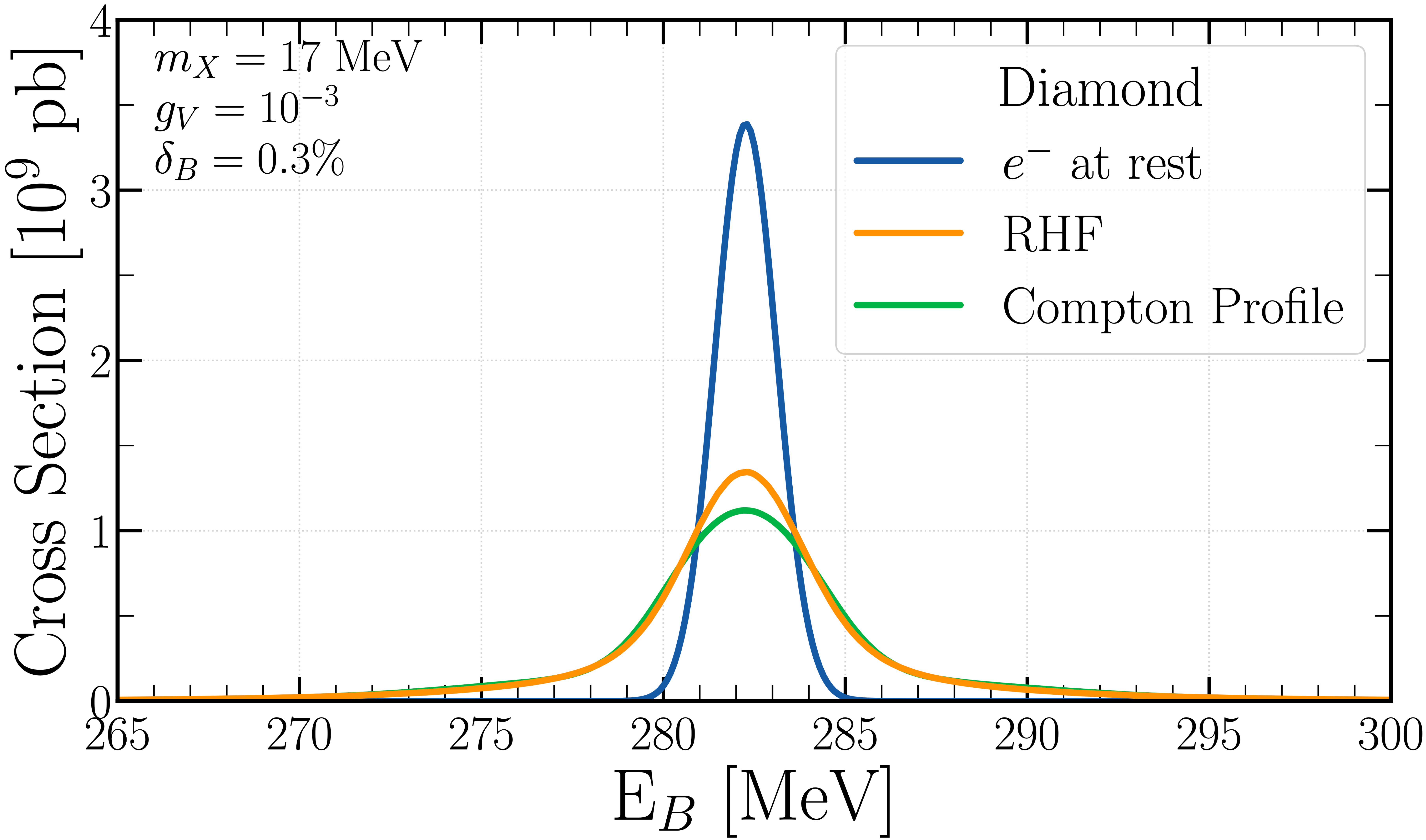


[Phys. Rev. 176 (1968) 900]



[Physica B 521 (2017) 361-364]

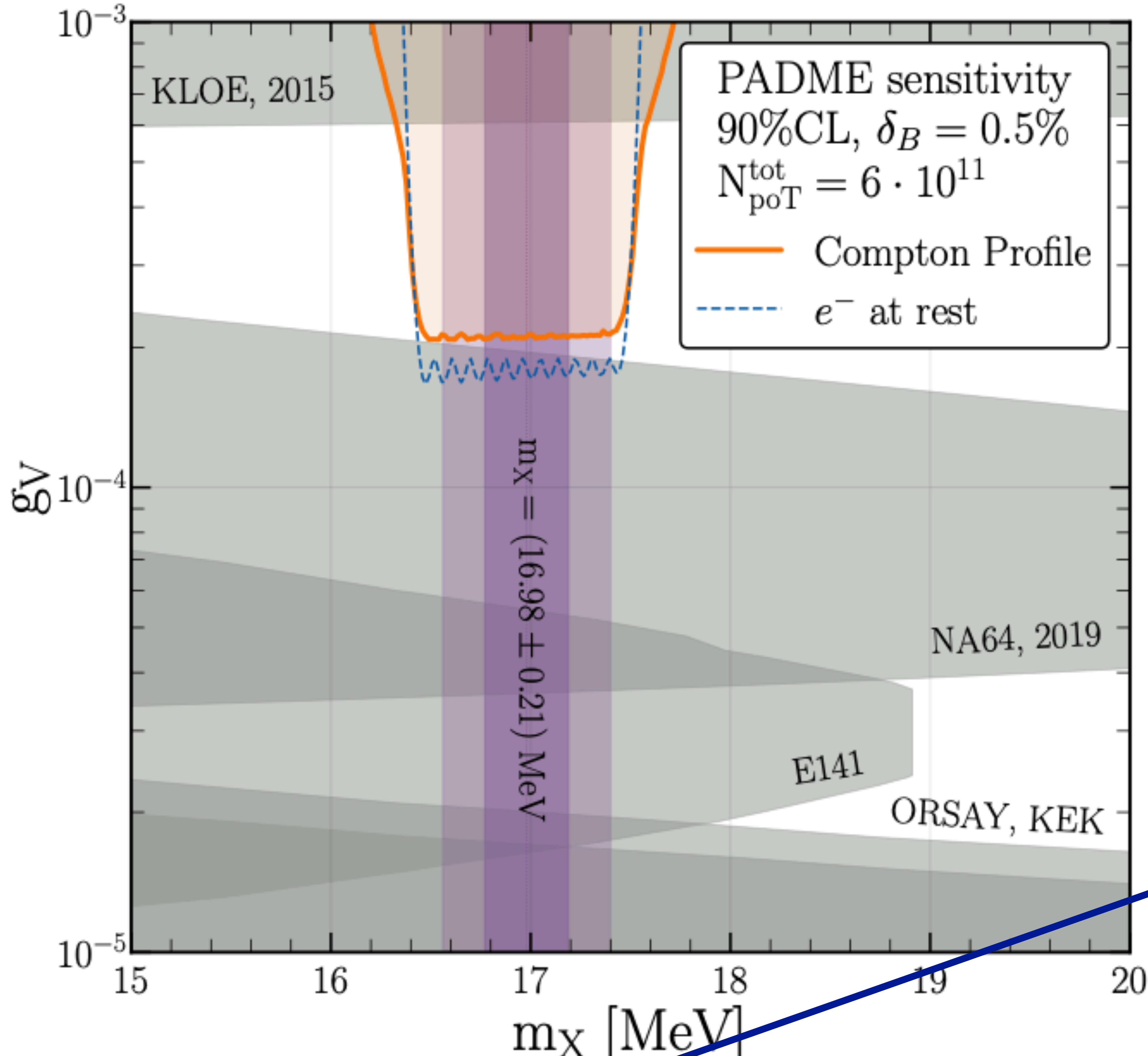
Comparison

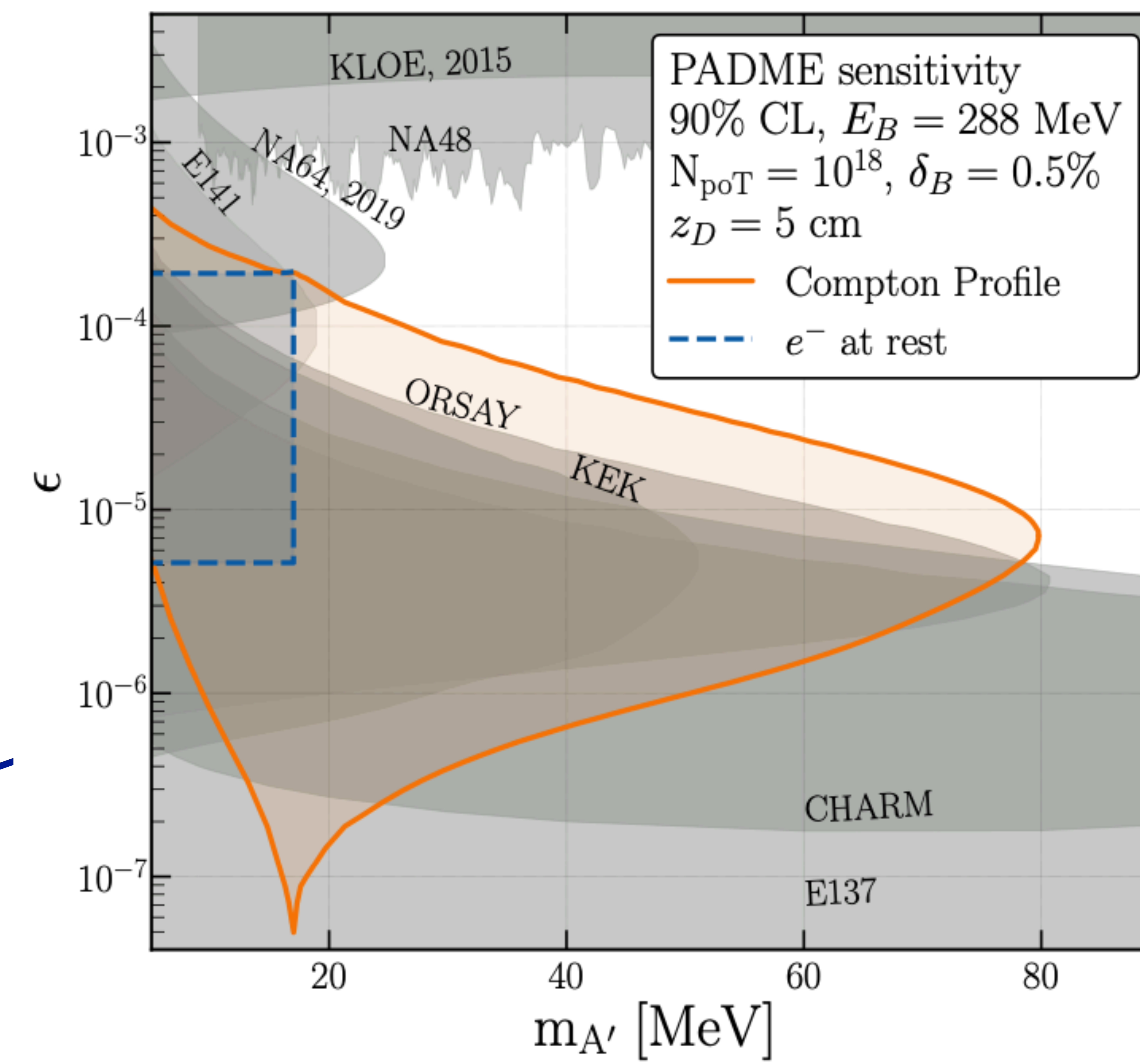

$m_X = 17$ MeV
$g_V = 10^{-3}$
$\delta_B = 0.3\%$
Diamond
e^- at rest
RHF
Compton Profile
Cross Section [10^9 pb]
0
1
2
3
4
265
270
275
280
285
290
295
300
E_B [MeV]

Atoms as particle accelerators

Dark vector/photon sensitivity

negligible systematics [Arias-Aragon, Darmé, G^2dC, Nardi PRL]





see PADME talk by V. Kozhuharov

Hadron vacuum polarization

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

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

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

Hadron vacuum polarization

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PROPOSAL:

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

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

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, to appear soon]

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

Hadron vacuum polarization

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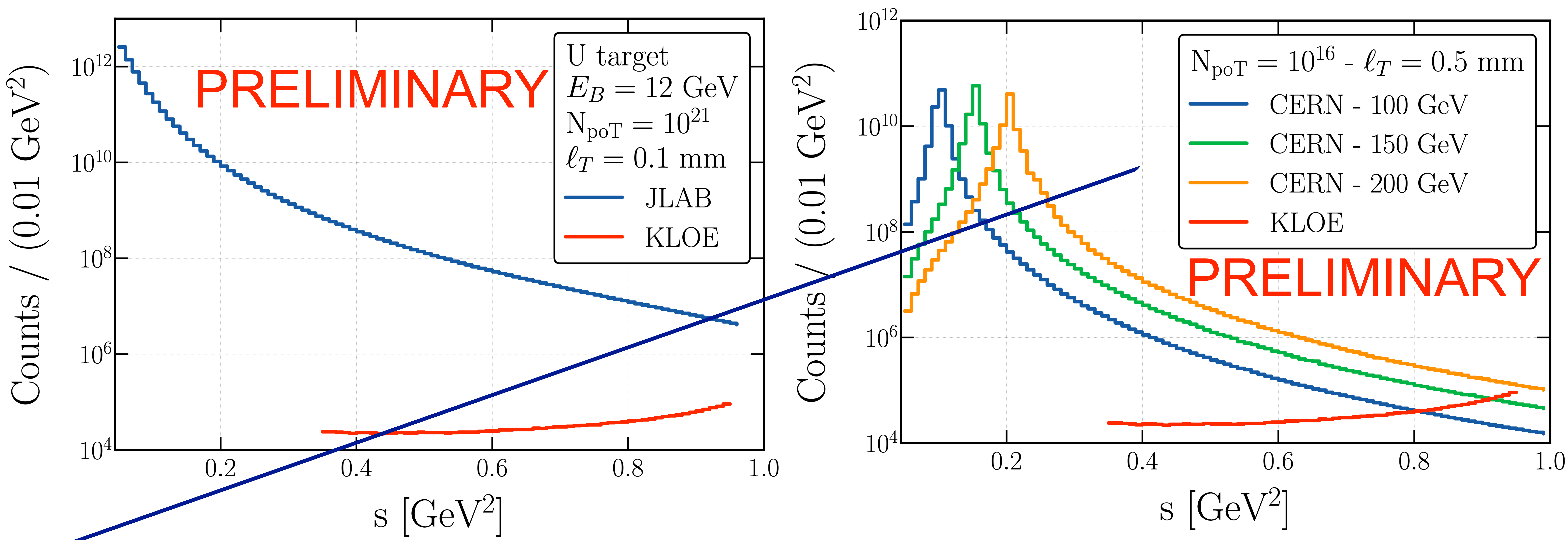
$$\sigma_{\rm had} \simeq \sigma_{\pi\pi} = \frac{N_{\pi\pi}}{N_{\mu\mu}}\sigma^0_{\mu\mu}$$

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



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 and on dark sector particle searches at fixed target experiments;
- Opens up new perspectives on positron annihilation on fixed targets: new stronger constraints, hadron cross section measurement, impact on MUonE…