X17 searches with deuteron photodisintegration

Cornelis J.G. Mommers, Group Marc Vanderhaeghen,

University of Mainz

Phys. Rev. D 109, 095010 (10 May 2024)

The ATOMKI experiments

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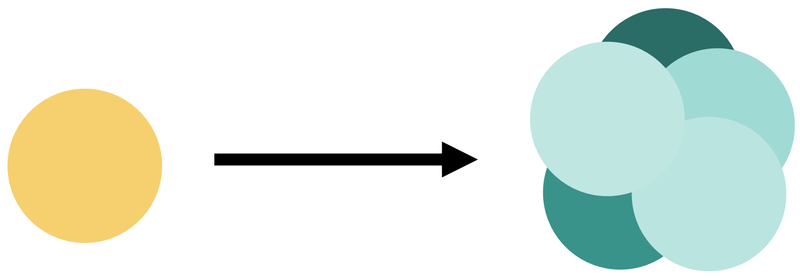

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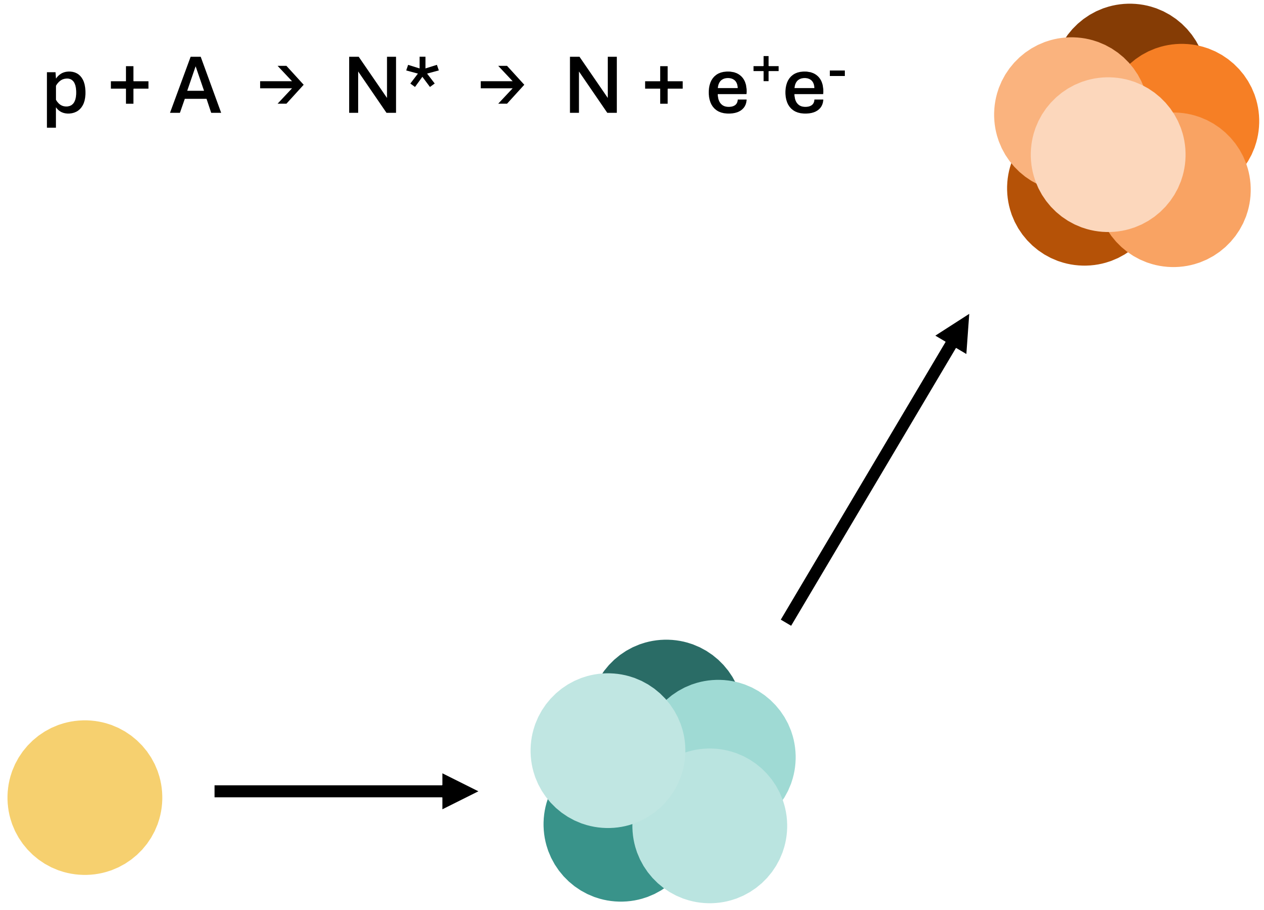

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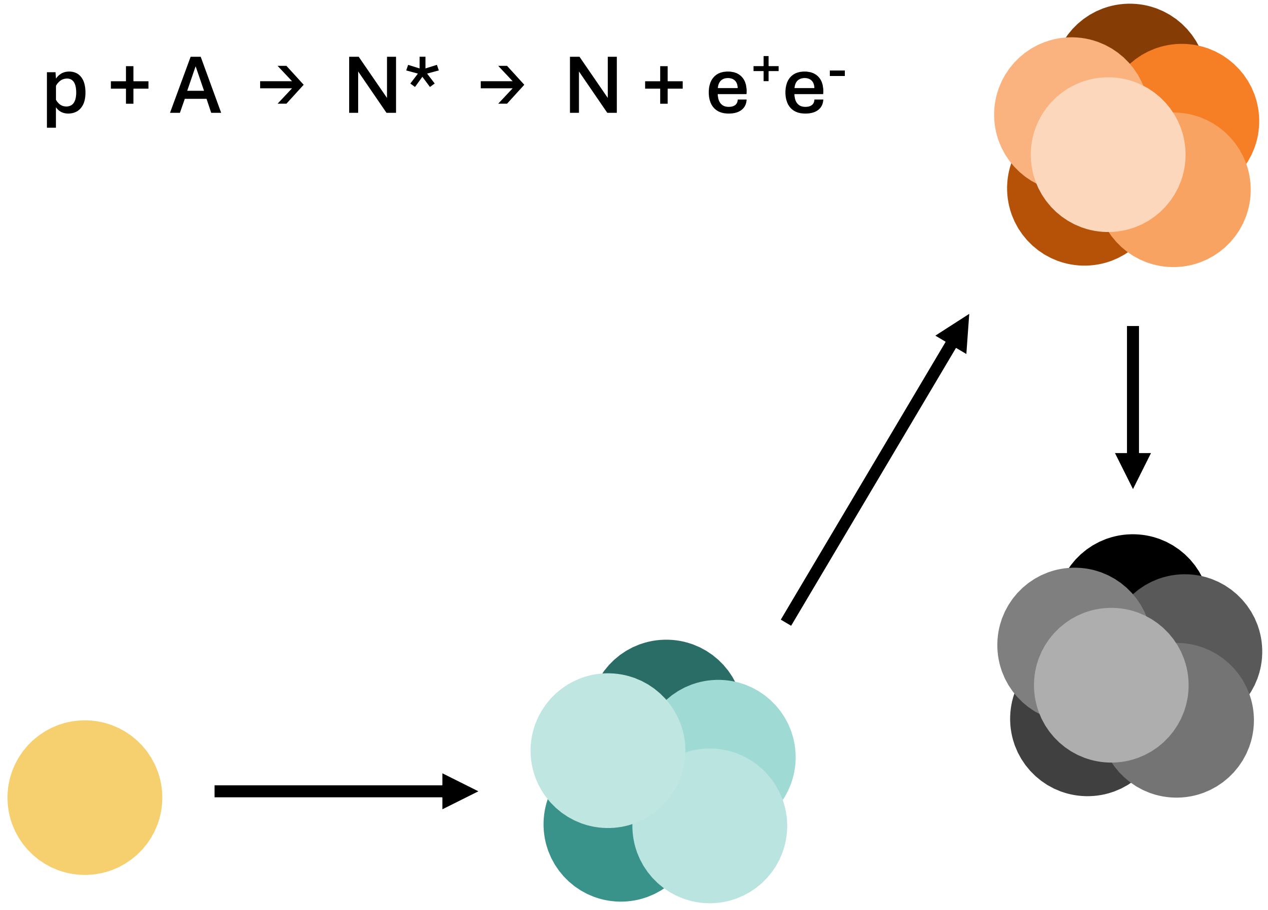

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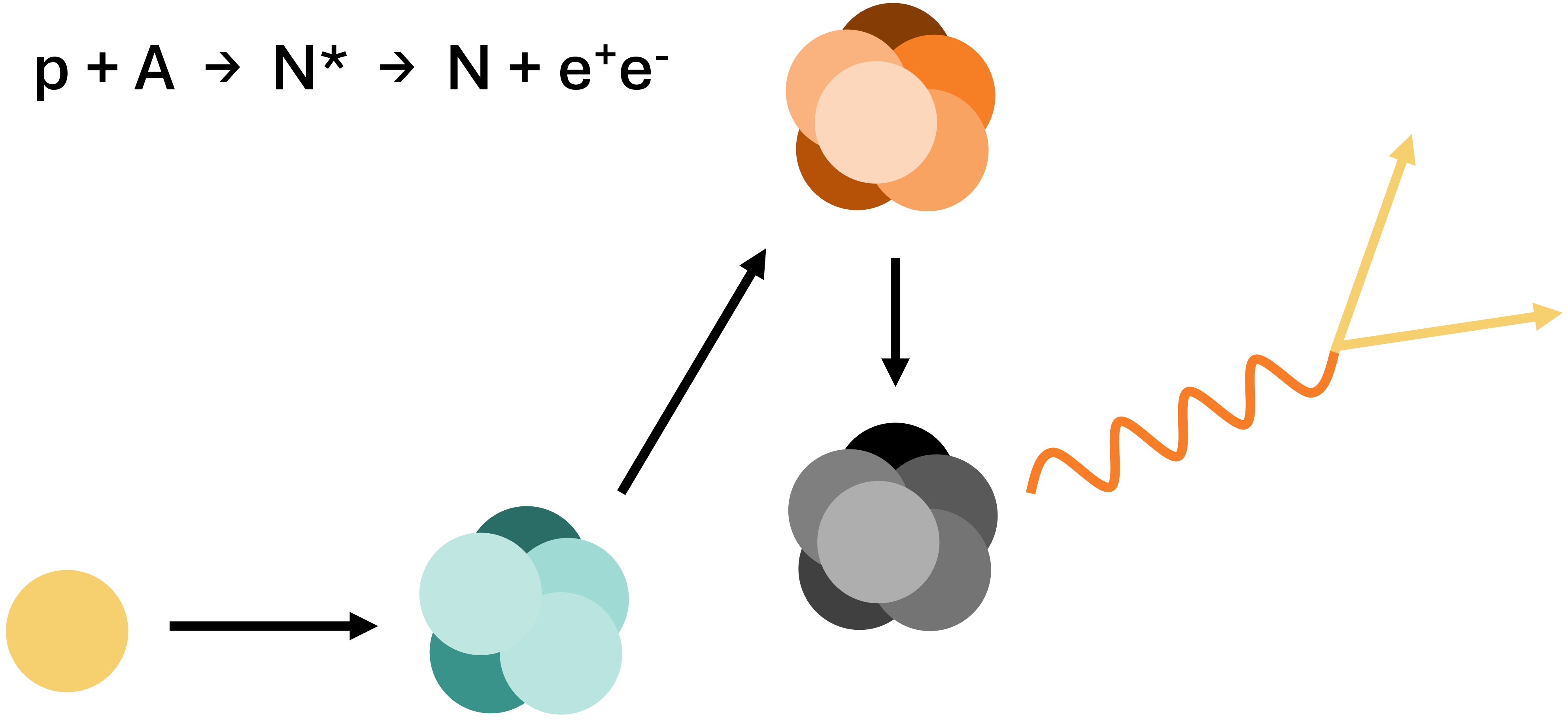

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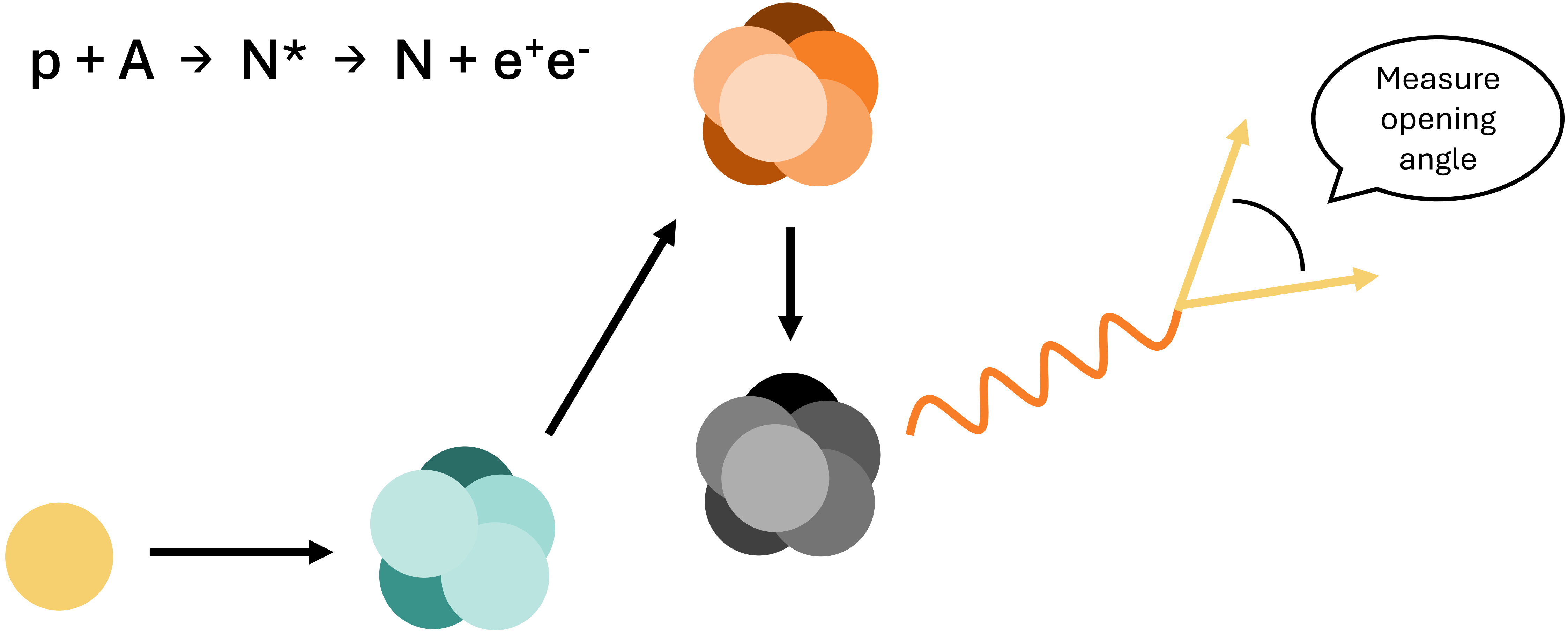
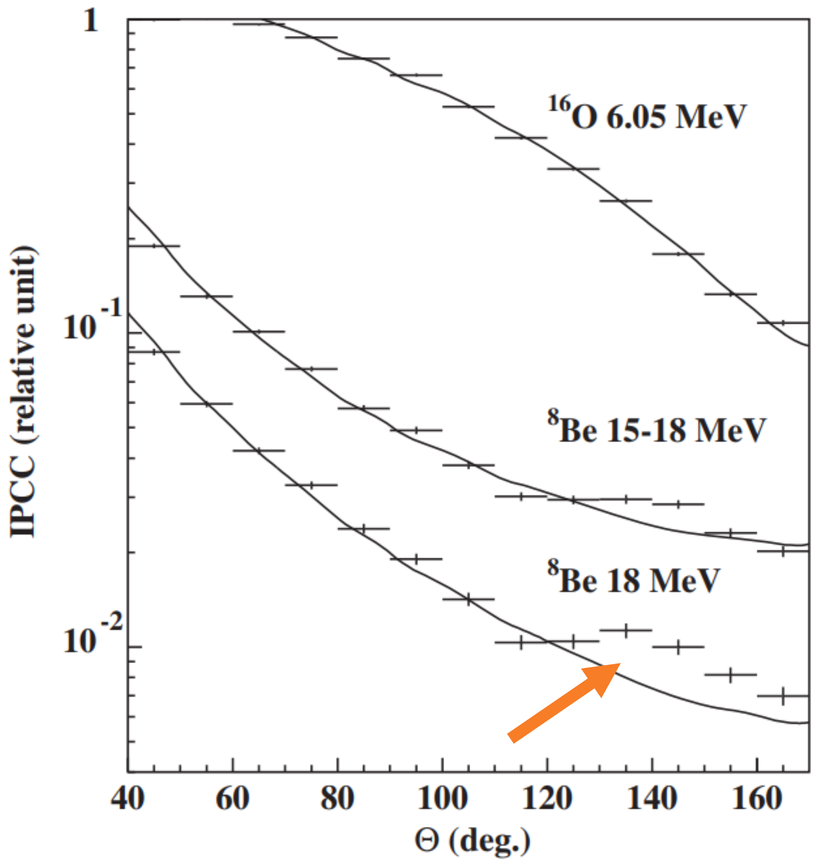


X17, an anomalous signal?

Phys. Rev. Lett. 116, 042501 (2016)



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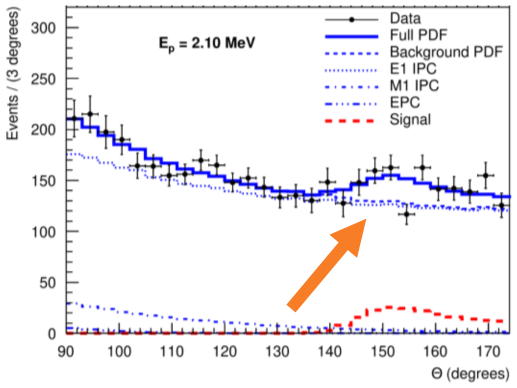
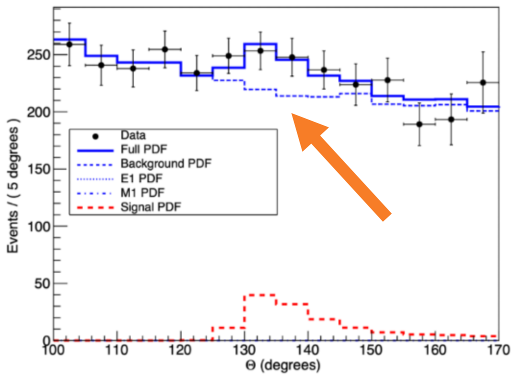


Universe 2024, 10(4), 168



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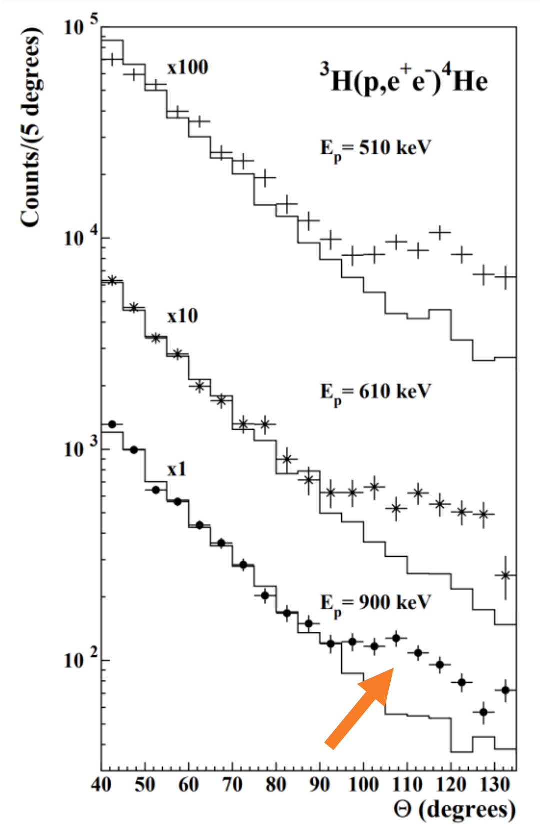

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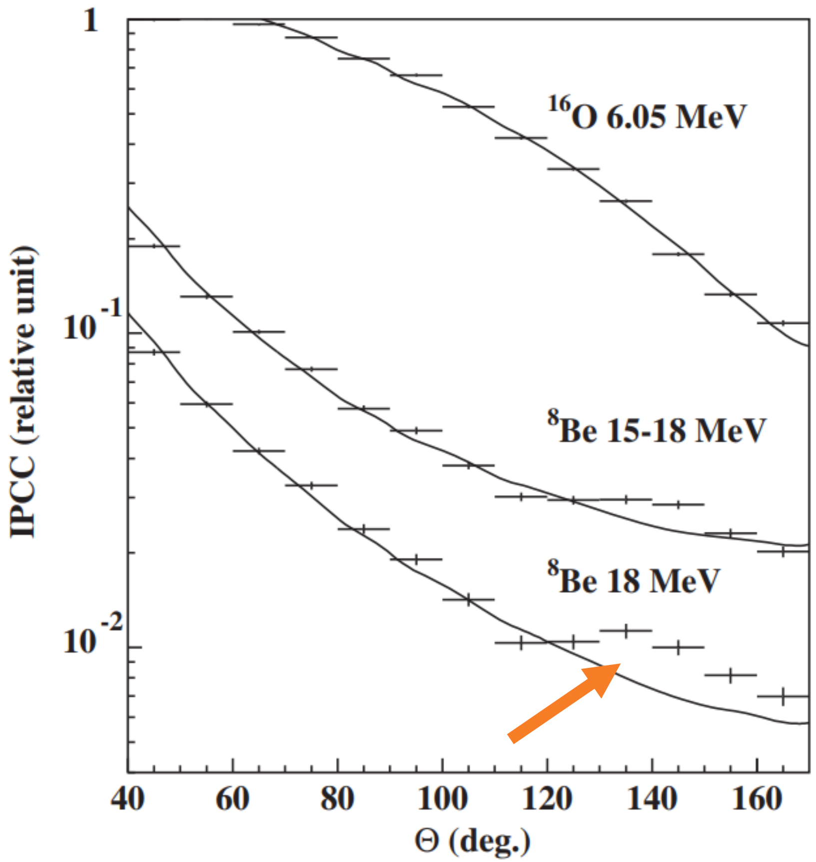

Some key observations

- Parity analysis: X17 is
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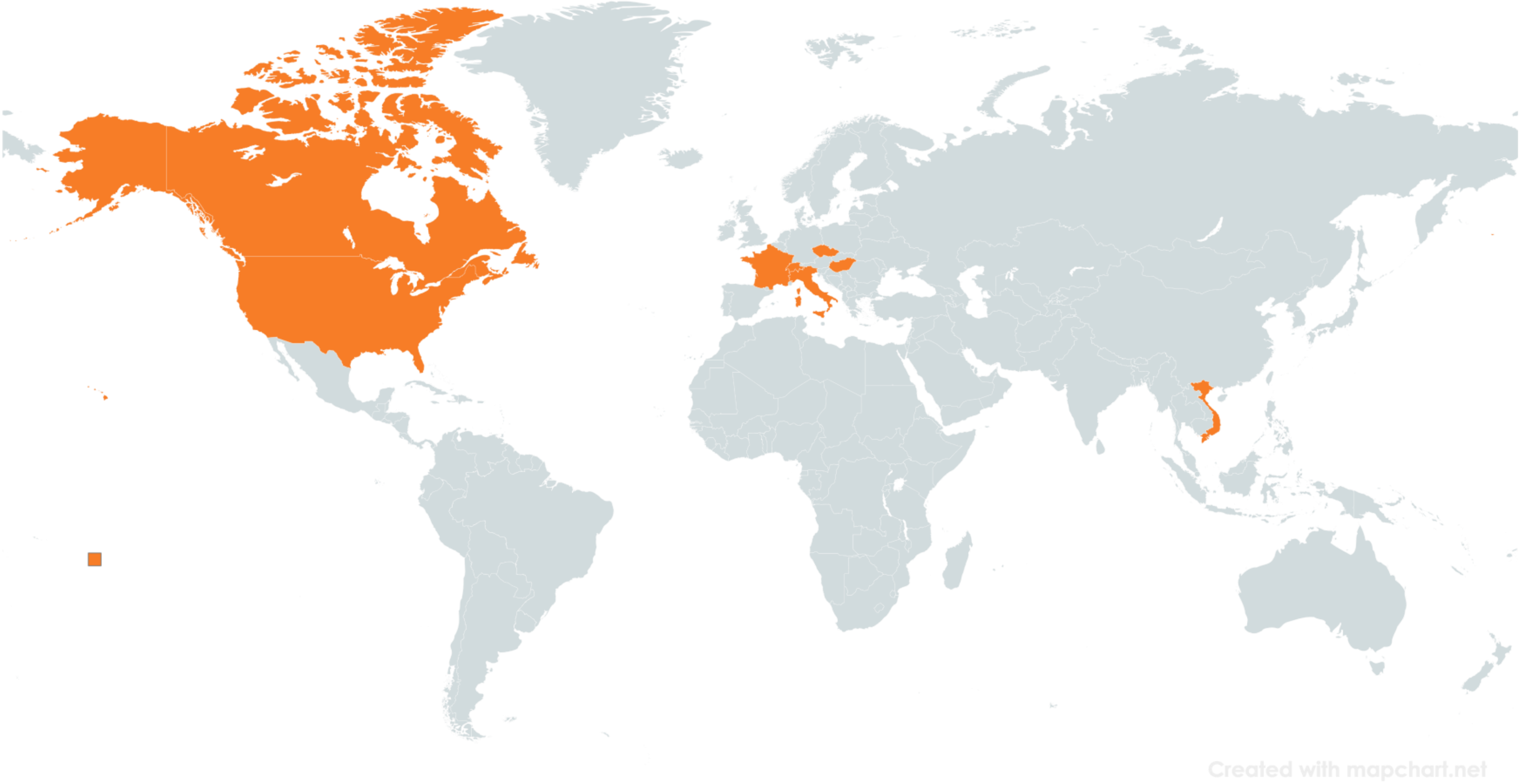
- X17 couples (at least) to protons, neutrons and electrons

- Existing constraints from NA48/2, $\pi^0 \to \gamma \left(X \to e^+e^-\right)$ imply a vector X17 couples weakly to protons ("protophobia")

A global search



MAGIX@MESA

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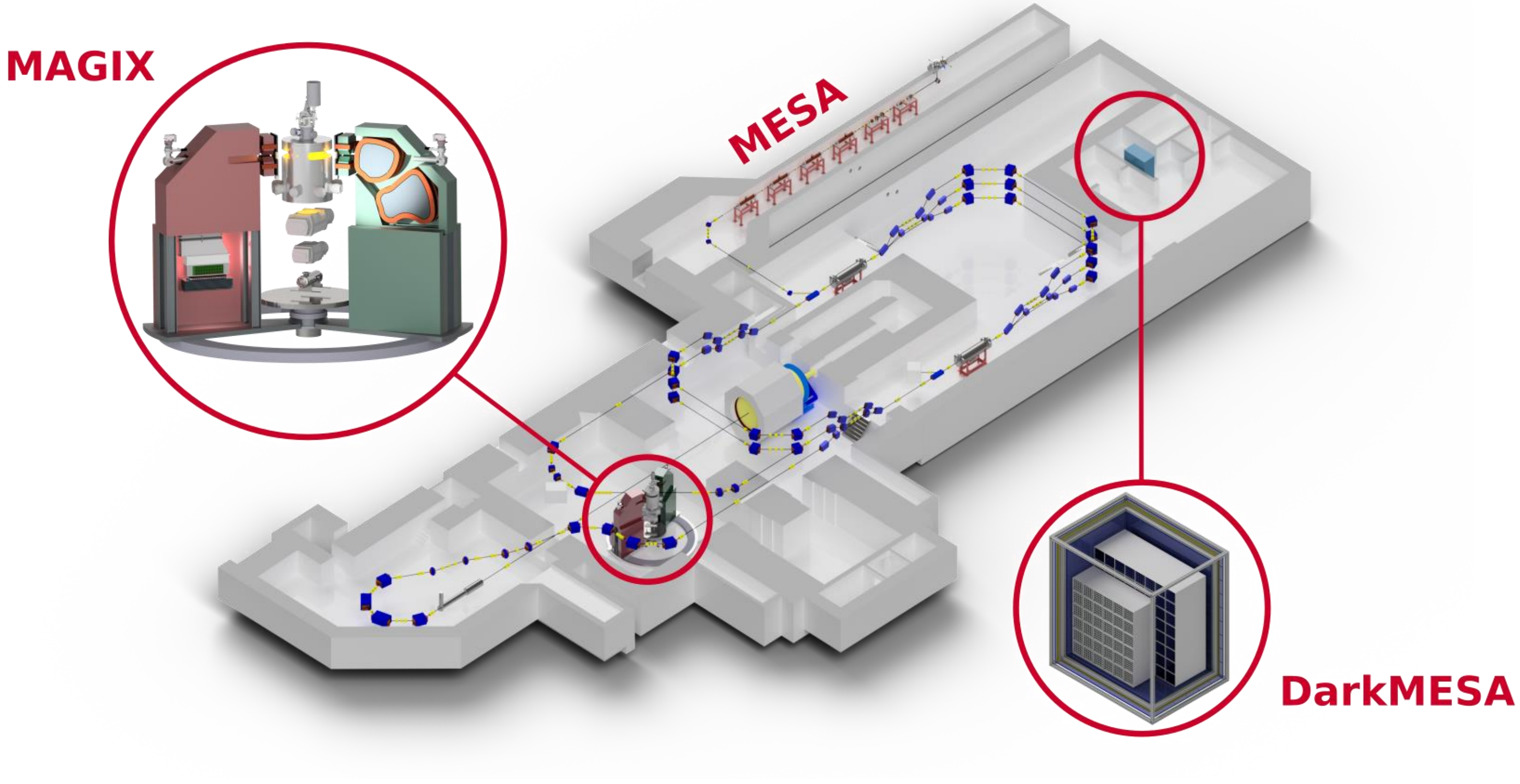

MAGIX@MESA

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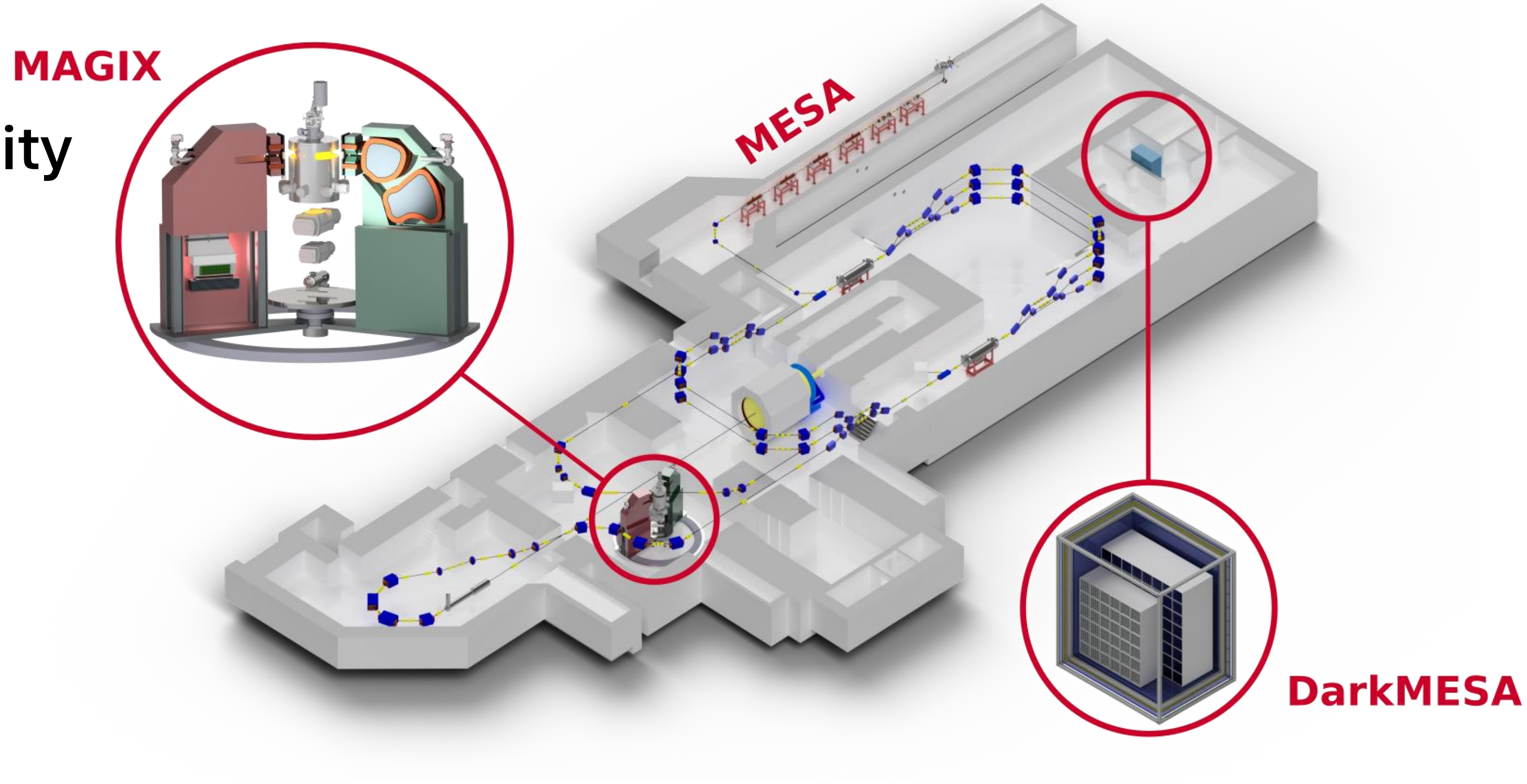
- Low energy, high intensity electron beam + gas jet target
  - $E \sim 105$ MeV
  - $L \sim 10^{35}\ cm^{-2}s^{-1}$



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- Low energy, high intensity electron beam + gas jet target
    - E ~ 105 MeV
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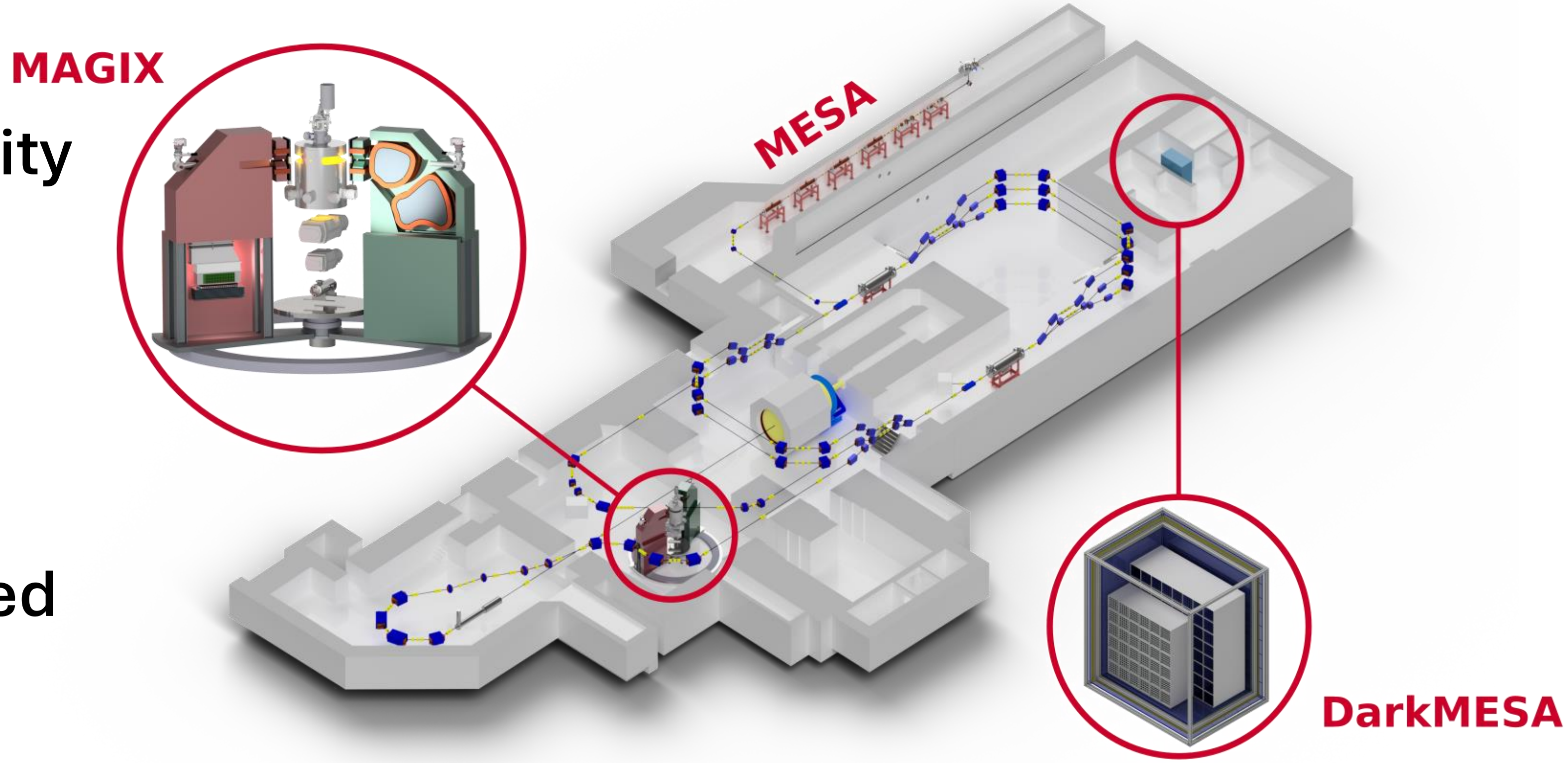
- MAGIX is a pair of multipurpose spectrometers, expected to measure m_{ee} with precision of >0.1 MeV



How to detect X17?

Use Bremsstrahlung to get a photon beam and measure $\gamma p \to e^+ e^- p$!

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But X17 might be protophobic!

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But X17 might be protophobic!

Measure $\gamma n \rightarrow e^+ e^- n$ instead!

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But we don't have free neutron targets!

…

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Use $\gamma d \to e^+ e^- p n$ with nucleon tagging instead!

Huh?

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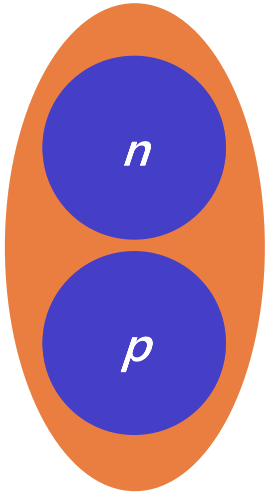
Deuteron with nucleon tagging

- Consider neutron bound in deuteron, $\gamma d \to e^+e^- pn$



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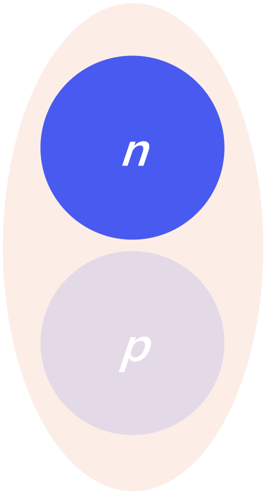

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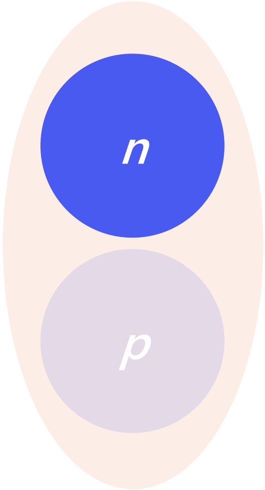

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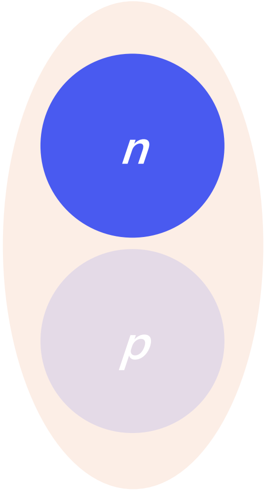

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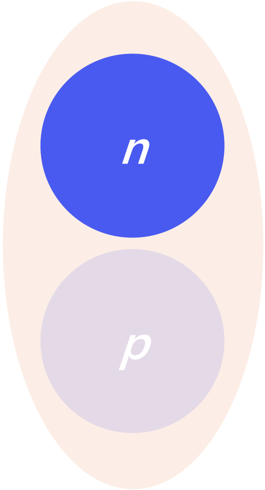
- MAMI@Mainz has measured $\gamma d \to \gamma pn$ already Eur.Phys.J.A16:259-273,2003



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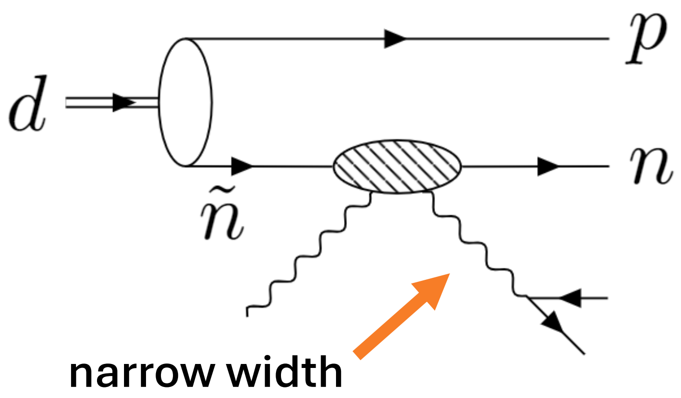

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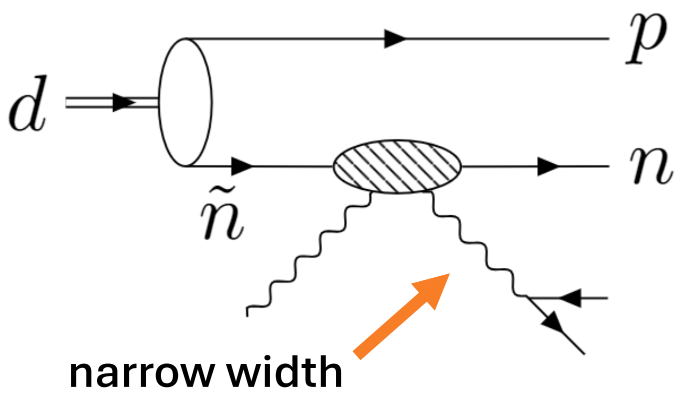

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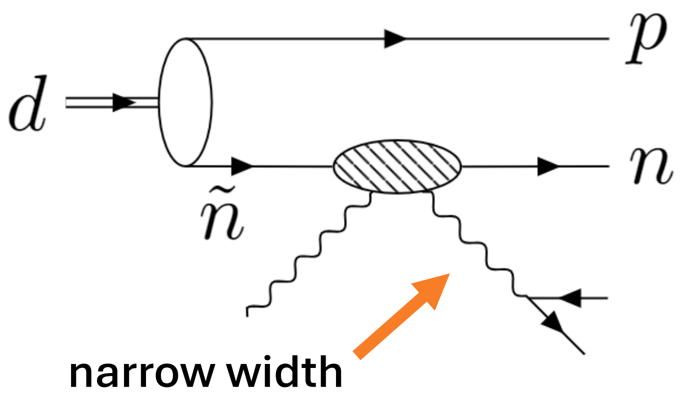

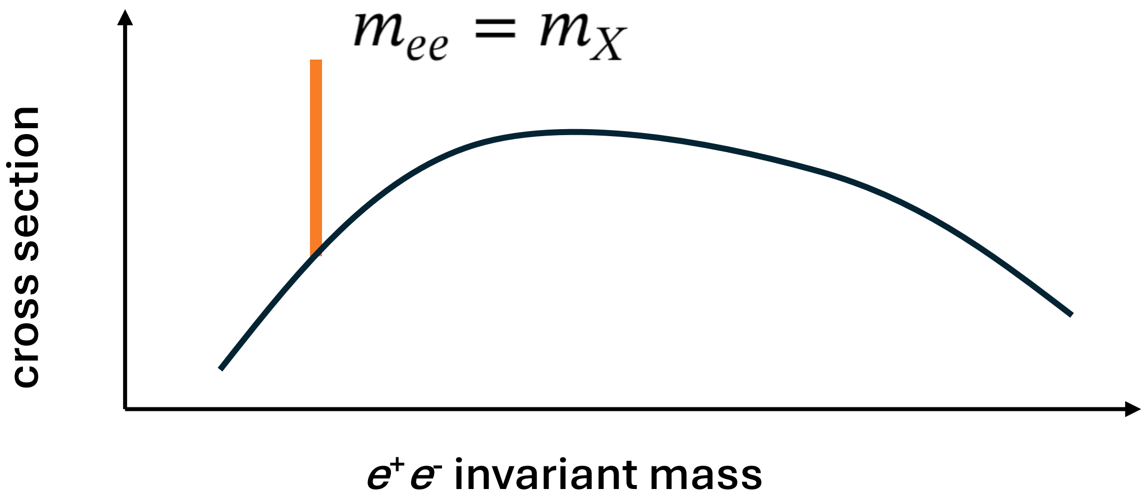

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- If we see nothing, what is the smallest coupling we can exclude?

$$|g_n| = \left(\frac{\Delta\sigma_{\mathrm{QED}}}{\Delta\sigma_X|_{g_n=1}} \frac{n_\sigma}{\sqrt{L \times \Delta\sigma_{\mathrm{QED}}}} \right)^{1/2}$$

- Compute projections reach for different detector settings

Projections for the reach

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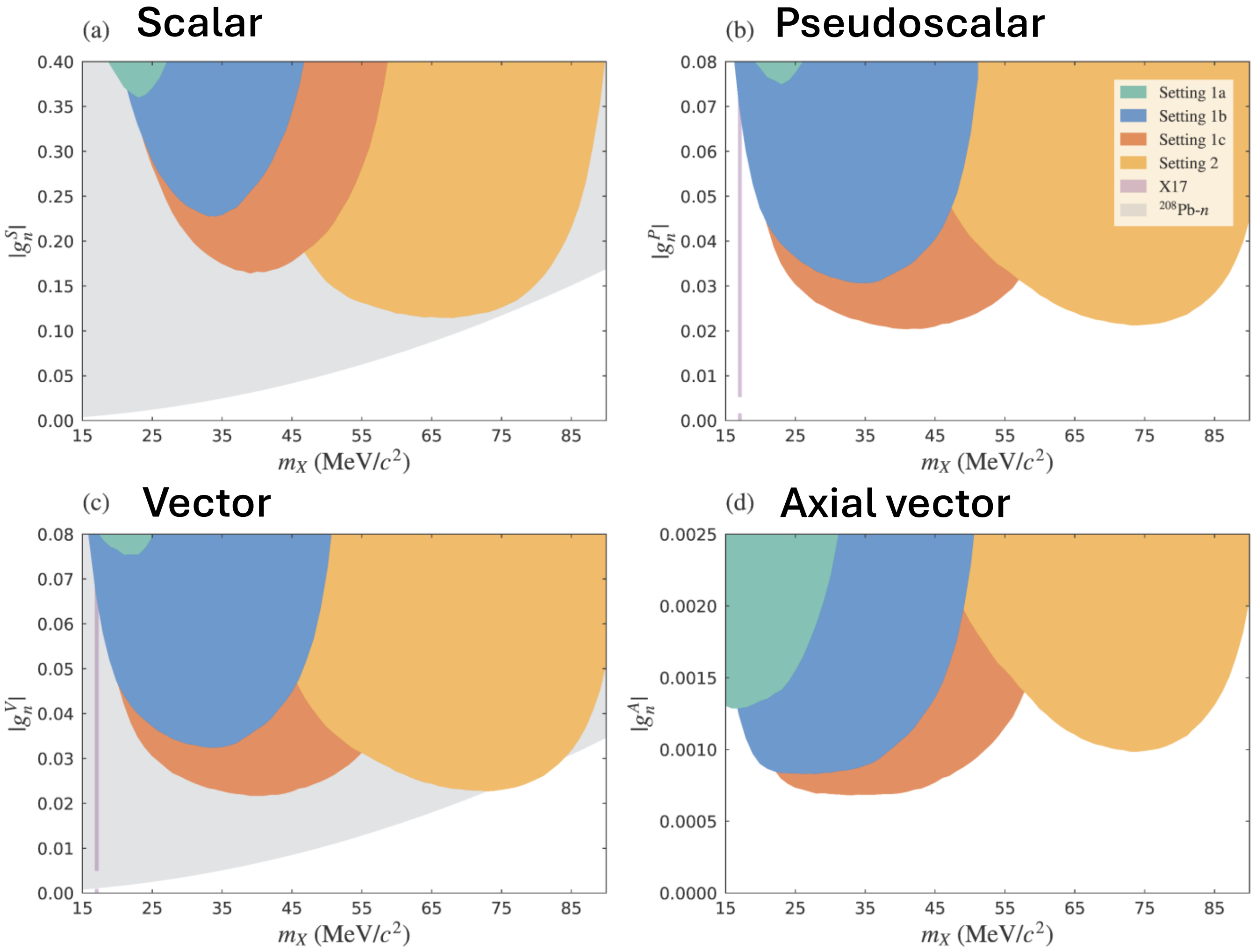

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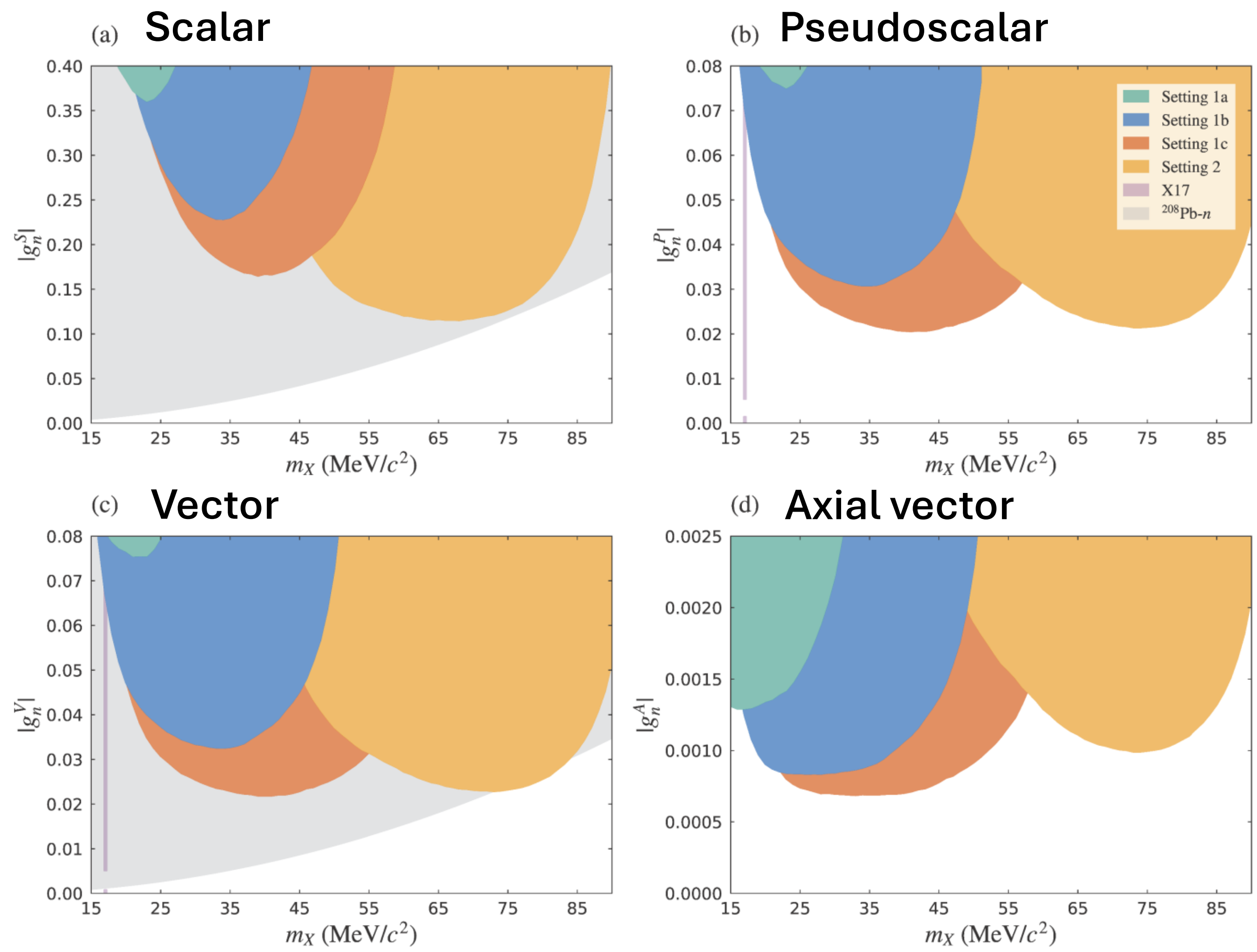

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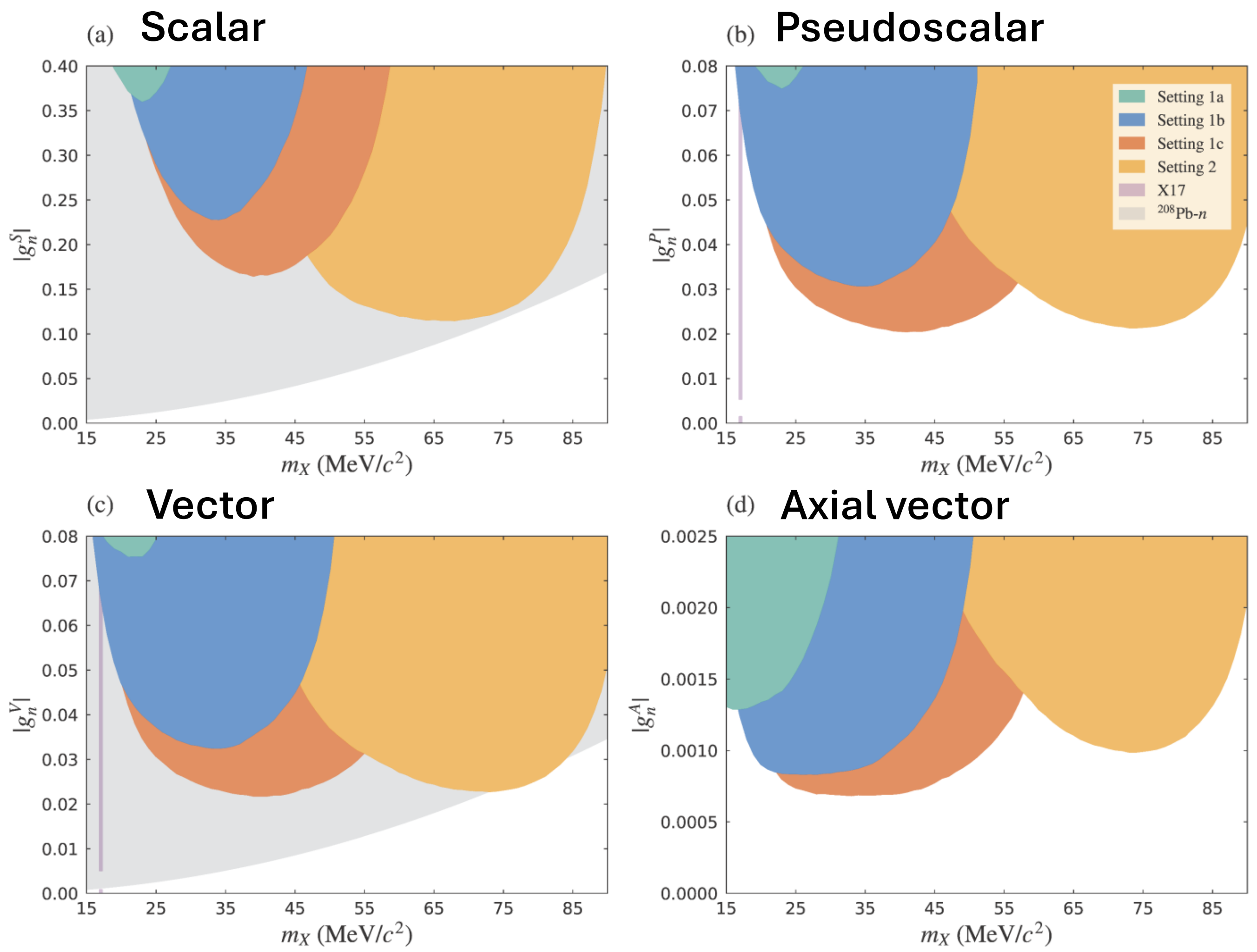

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- Axial vector and pseudoscalar constraints competitive

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- Many details left out, see paper!

Thank you for your attention! Questions?

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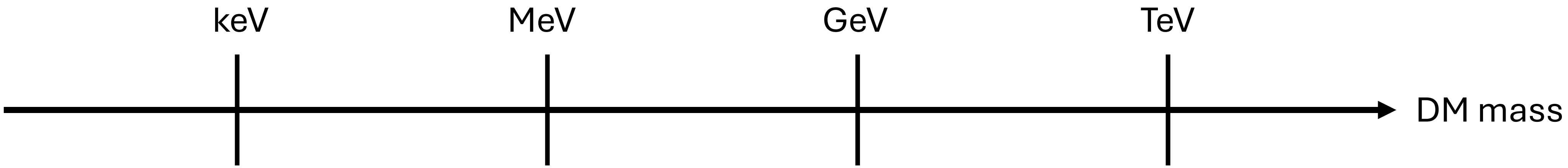
A shifting paradigm?



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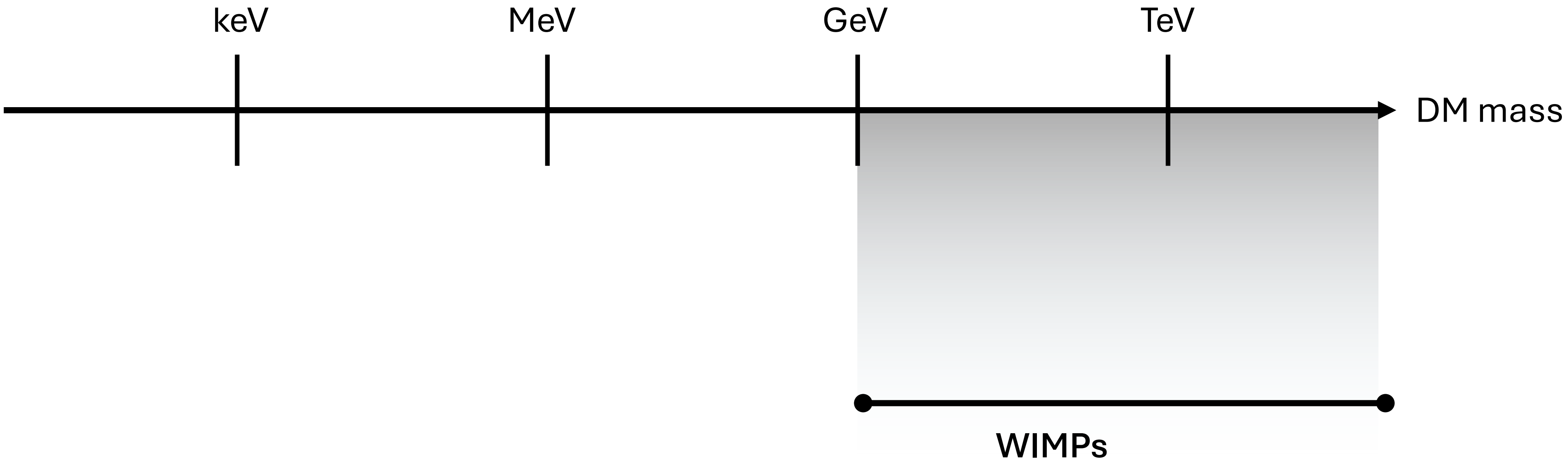

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- Searches with high-energy colliders, underground experiments
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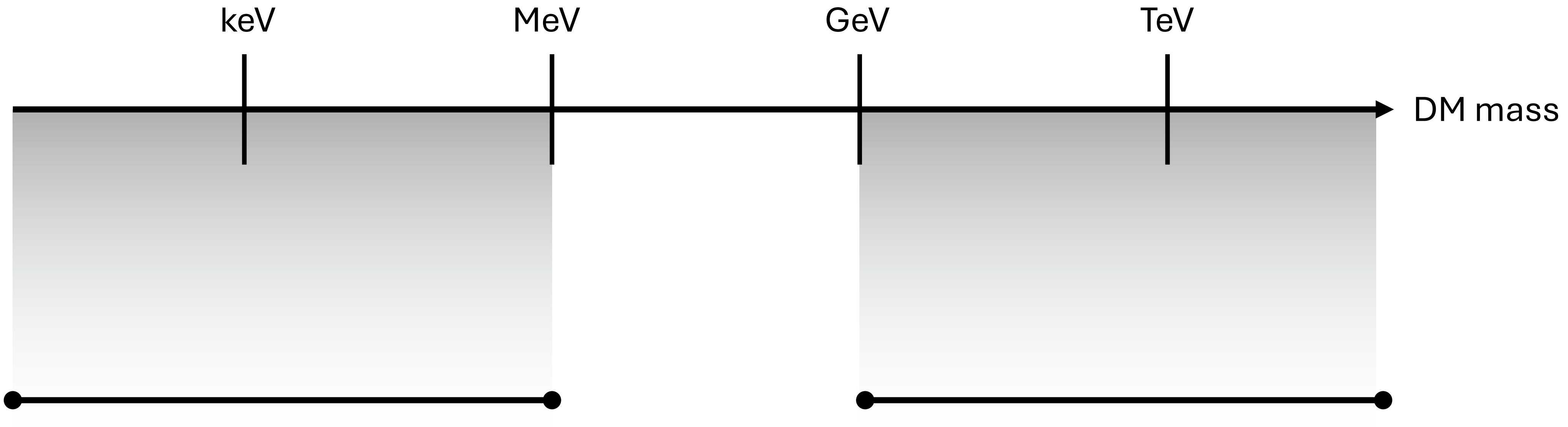

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- Searches with atomic and nuclear systems
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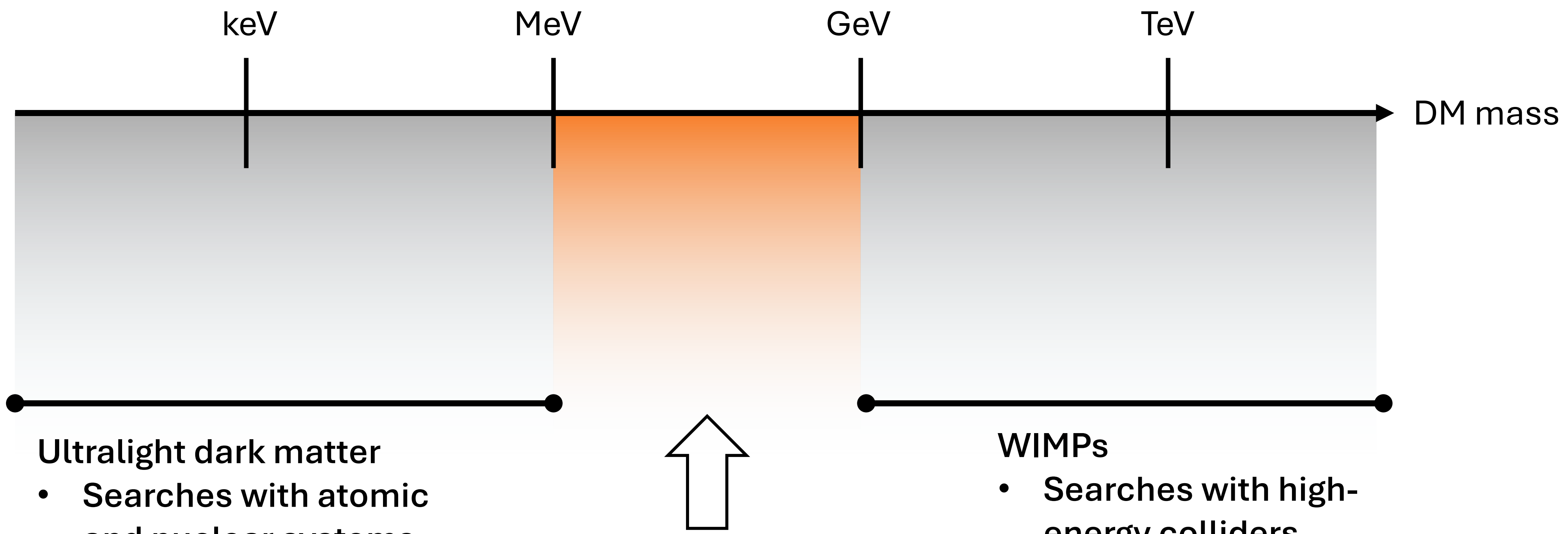

Ultralight dark matter
- Searches with atomic and nuclear systems
- Strict bounds

- Searches with low energy, high intensity
- Increasing interest (X17)

WIMPs
- Searches with high-energy colliders, underground experiments
- No clear signal yet

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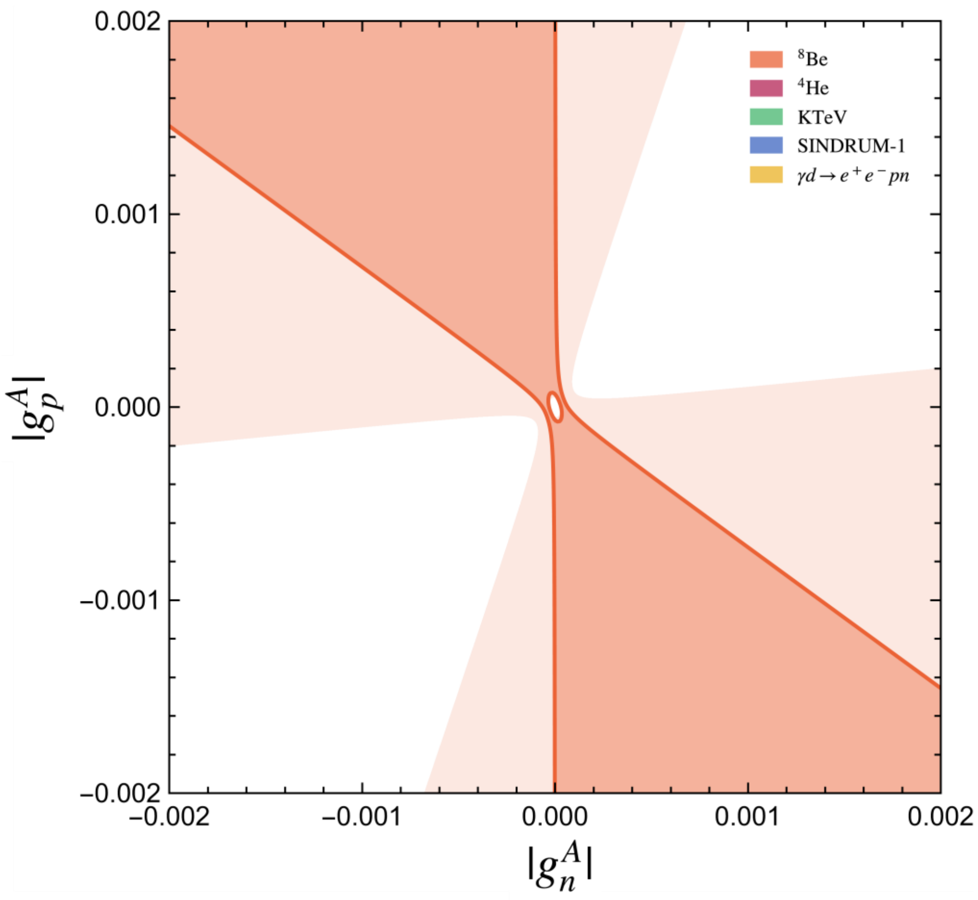

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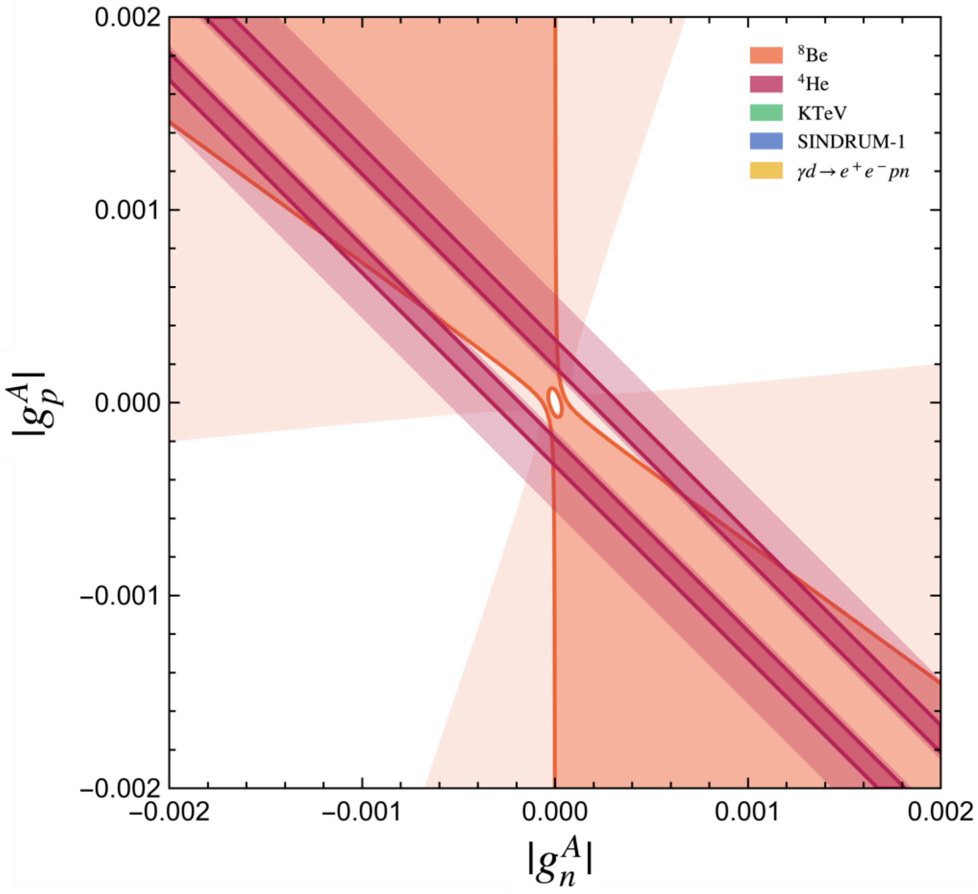

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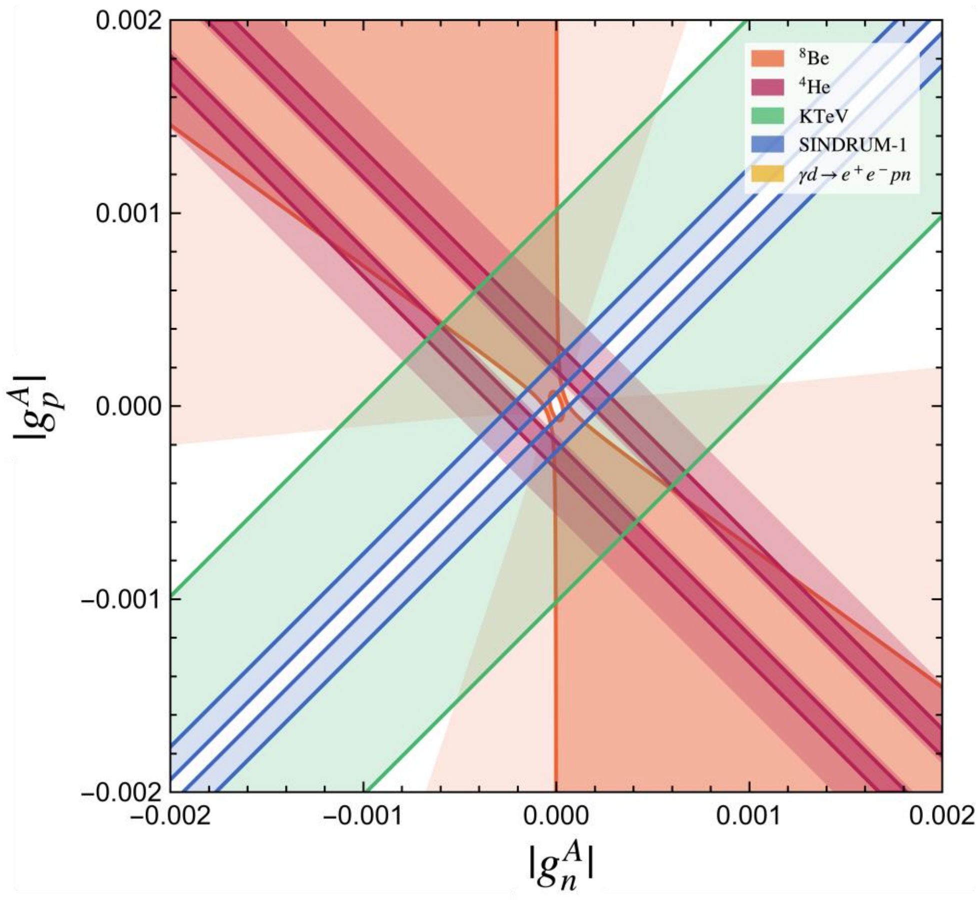

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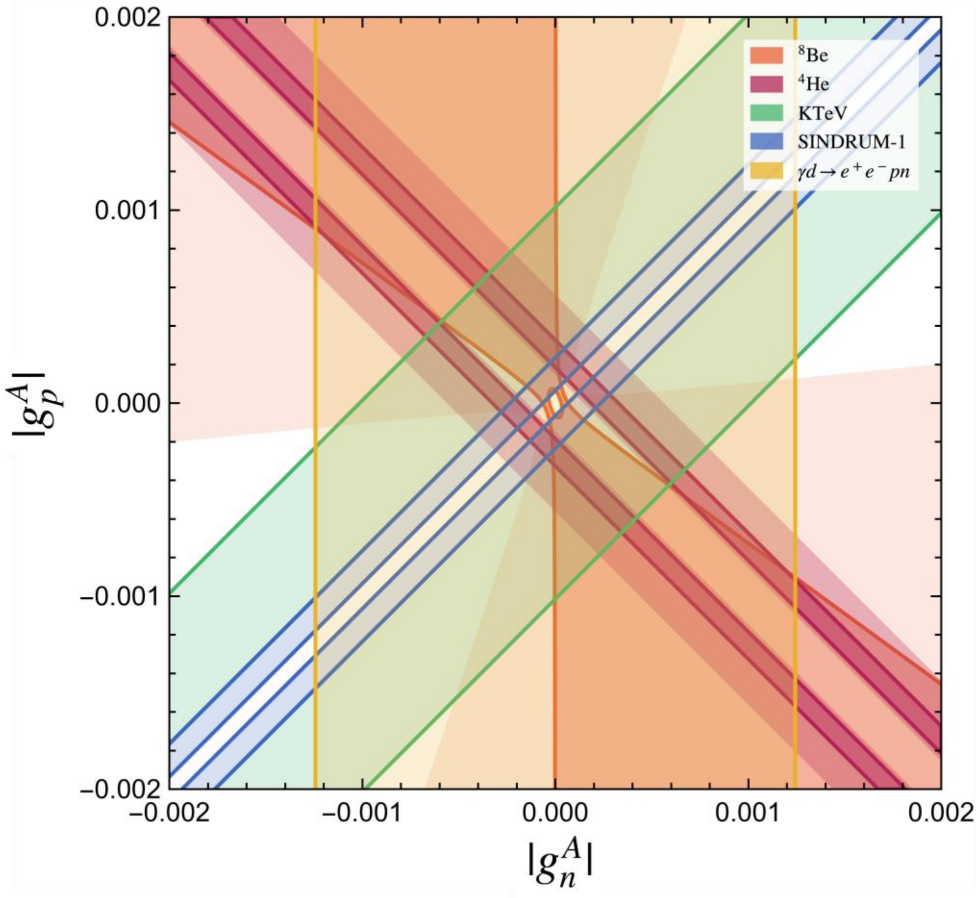

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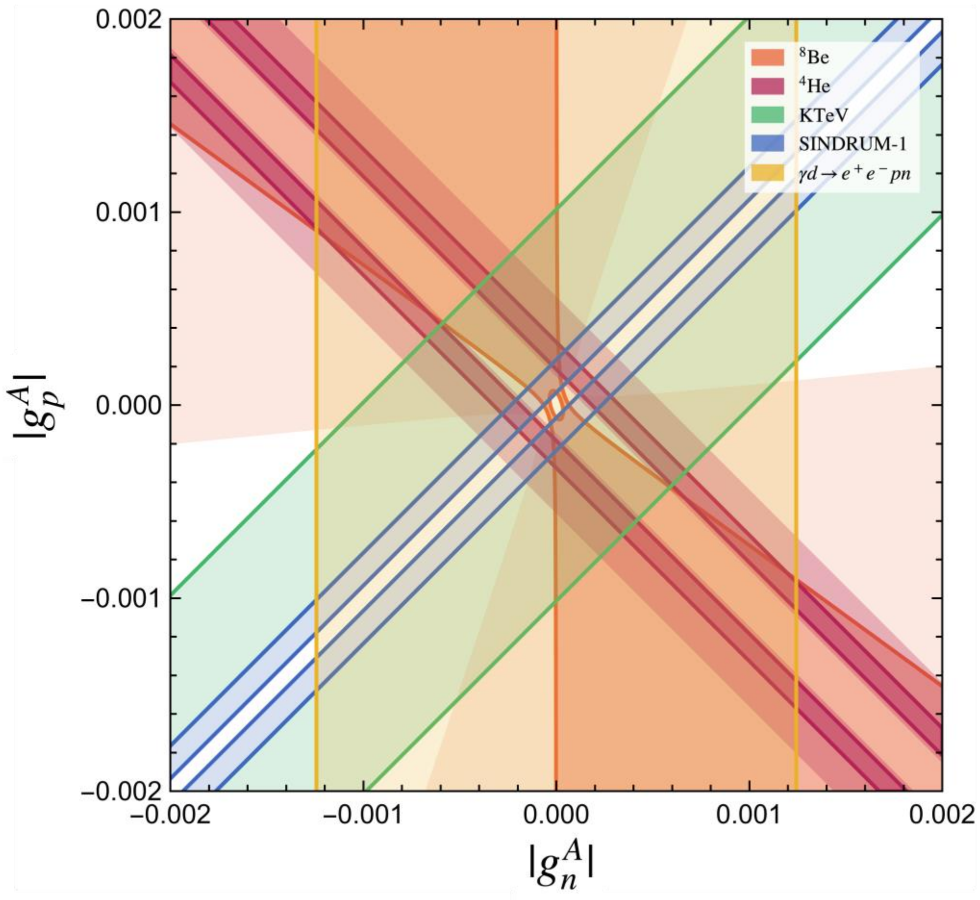
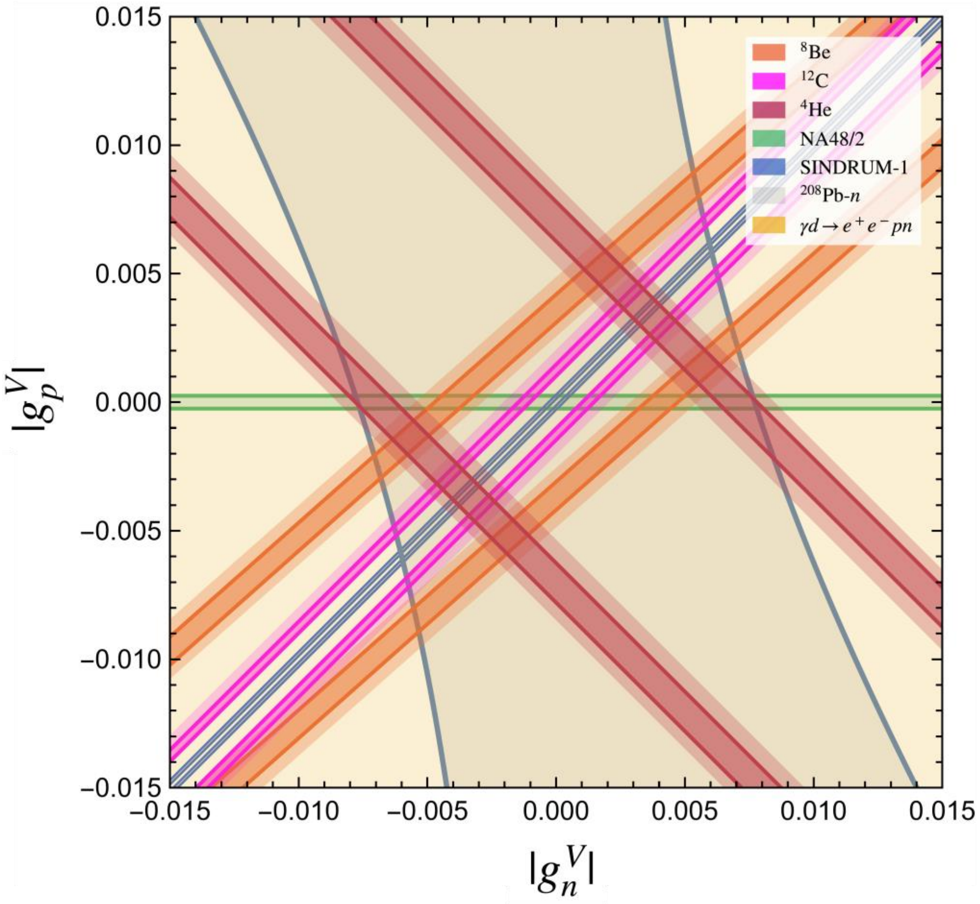
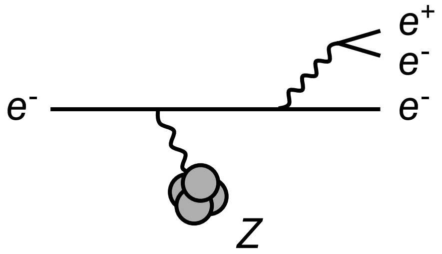


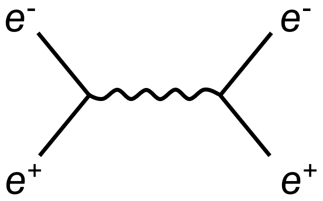


(some) other accelerator experiments

- JLAB, DarkLight: (A, Z) → γ^*(A, Z) to $\gamma^* e^- \rightarrow e^+ e^- e^-$
  arXiv:2301.08768 [nucl-ex], doi.org/10.1088/1742-6596/2391/1/012010



- PADME: $e^+ e^- \rightarrow$ X17 → $e^+ e^-$
  arXiv:2209.09261 [hep-ph]



(some) other nuclear experiments

- ATOMKI: ^{7}Li(p, X17)^{8}Be, ^{3}H(p, $e^{+}e^{-}$)^{4}He, ^{11}B(p, $e^{+}e^{-}$)^{12}C
  (for Refs. see previous slides)
- VNU: ^{7}Li(p, X17)^{8}Be
  arXiv:2401.11676 [nucl-ex]
- CCPAC: ^{7}Li(p, X17)^{8}Be, ^{7}Li(^{3}He, X17)^{10}Be
  arXiv:2211.11900 [physics.ins-det]
- MEG-II : ^{7}Li(p, X17)^{8}Be
  doi.org/10.22323/1.402.0120
- NEW JEDI: ^{7}Li(p, X17)^{8}Be, ^{3}H(p, $e^{+}e^{-}$)^{4}He
  doi.org/10.1051/epjconf/202327501012
- n_TOF: ^{3}H(n, $e^{+}e^{-}$)^{4}He
  doi.org/10.1051/epjconf/202327913007
- CTU Prague: ^{7}Li(p, X17)^{8}Be
  doi.org/10.1016/j.nima.2022.167858

Table ATOMKI decays

State (MeV)	Transition (J^P)	
^{8}Be(18.15)	$1^+ \to 0^+$	(M1, isoscalar)
^{8}Be(17.64)	$1^+ \to 0^+$	(M1, isovector)
^{4}He(21.01)	$0^- \to 0^+$	(M0)
^{4}He(20.21)	$0^+ \to 0^+$	(E0)
^{12}C(17.23)	$1^- \to 0^+$	(E1, isovector)

EL ~ $(-1)^L$

ML ~ $(-1)^{L+1}$

States (MeV)	m_X (MeV)	Γ_X (eV)	$\mathcal{B}$
^{8}Be(18.15)	$16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$	$1.1(2) \times 10^{-5}$	5.8×10^{-6}
^{8}Be(18.15), ^{8}Be(17.64)	17.01(16)	$1.2(2) \times 10^{-5}$	$6(1) \times 10^{-6}$
^{4}He(21.01), ^{4}He(20.21)	$16.94 \pm 0.12(\text{stat}) \pm 0.21(\text{syst})$		
^{4}He(21.01), ^{4}He(20.21)	$16.84 \pm 0.16(\text{stat}) \pm 0.20(\text{syst})$	3.9×10^{-5}	$1.2(4) \times 10^{-1}$
^{12}C(17.23)	$17.03 \pm 0.11(\text{stat}) \pm 0.20(\text{syst})$	$1.6(1) \times 10^{-4}$	$3.6(3) \times 10^{-6}$

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$$\mathbf{J}_A = \mathbf{S}_X + \mathbf{S}_B + \mathbf{L} \qquad P_A = P_X \times P_B \times (-1)^L$$

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$$\mathbf{S}_X = \mathbf{0} \implies |L-1| \leq 0 \leq L+1 \implies L = 1$$

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$$J^P = 0^-, 1^+, 1^-$$

Theory analysis

- Assume definite parity (J^P)

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State (MeV)	Scalar (0^+)	Pseudoscalar (0^-)	Vector (1^-)	Axial vector (1^+)
^{8}Be(18.15), 1^+		✓	✓	✓
^{8}Be(17.64), 1^+		✓	✓	✓
^{4}He(21.01), 0^-		✓		✓
^{4}He(20.21), 0^+	✓		✓	
^{12}C(17.23), 1^-	✓		✓	✓

Deriving limits on couplings (P)

$$\mathcal{L}_{0^-} = i\bar{N}\gamma_5 \left(g^{(0)}_{XNN} + g^{(1)}_{XNN}\tau^3\right) NX$$

- SINDRUM: $|g^{(1)}_{XNN}| \lesssim 0.6 \times 10^{-3}$ (Phys. Lett. B 175, 101 (1986))
- Multipole: $\frac{\Gamma_X^{^8\mathrm{Be}}}{\Gamma_\gamma^{\mathrm{M1}}} = \frac{1}{2\pi\alpha}\left(\frac{g^{(0)}_{XNN}\cos\theta_{1+} - g^{(1)}_{XNN}\sin\theta_{1+}}{[\mu^{(0)} - \eta^{(0)}]\cos\theta_{1+} - [\mu^{(1)} - \eta^{(1)}]\sin\theta_{1+}}\right)^2 \left(\frac{k_X}{k_\gamma}\right)^3$

Deriving limits on couplings (V)

$$\mathcal{L}_{\rm V} = -eX_\mu \sum_{N=p,n} \varepsilon_N \bar{N}\gamma^\mu N$$

- **NA48/2:** $|\varepsilon_p| \lesssim \frac{(0.8-1.2)\times 10^{-3}}{\sqrt{\mathcal{B}(X\to e^+e^-)}}$ (Phys. Lett. B 746, 178 (2015))

- **Multipole:** $\frac{\Gamma_X^{^8\mathrm{Be}}}{\Gamma_\gamma^{\mathrm{M1}}} = \frac{|(\varepsilon_p+\varepsilon_n)\cos\theta_{1^+}M1_{1,T=0} + (\varepsilon_p-\varepsilon_n)(-\sin\theta_{1^+}M1_{1,T=1} + \cos\theta_{1^+}\kappa M1_{1,T=1})|^2}{|\cos\theta_{1^+}M1_{1,T=0} - \sin\theta_{1^+}M1_{1,T=1} + \cos\theta_{1^+}\kappa M1_{1,T=1}|^2}\left(\frac{k_X}{k_\gamma}\right)^3$

$$\frac{\Gamma_{X,V}^{^{12}\mathrm{C}(17.23)}}{\Gamma_\gamma^{\mathrm{E1}}} = \frac{k}{\Delta E}\left(1+\frac{m_X^2}{2\Delta E^2}\right)|\varepsilon_p-\varepsilon_n|^2$$

Deriving limits on couplings (A)

$$\mathcal{L}_{\mathrm{A}} = -X_\mu \sum_{N=p,n} a_N \bar{N}\gamma^\mu\gamma_5 N$$

- Matrix elements from Phys. Rev. D 95, 115024
- Multipole: $\frac{\Gamma_{X,A}^{^8\mathrm{Be}(18.15)}}{\Gamma_\gamma^{\mathrm{M1}}} = \frac{1}{\Gamma_\gamma(^8\mathrm{Be}(18.15))}\frac{k_X}{18\pi}\left[2+\left(\frac{\Delta E}{m_X}\right)^2\right] |\langle f||a_p\hat{\sigma}_M^{(p)} + a_n\hat{\sigma}_M^{(n)}||i_*\rangle|^2$

Diagrams in detail (QED)

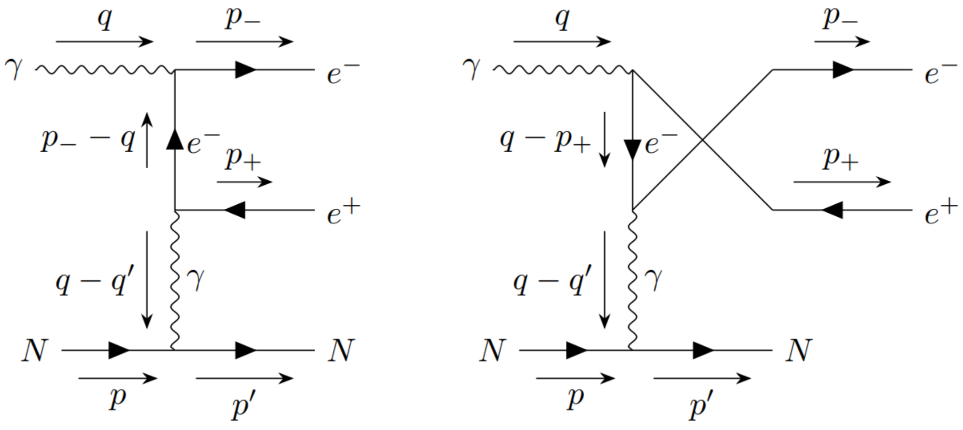


Figure 2: The direct and crossed diagram for the BH process.

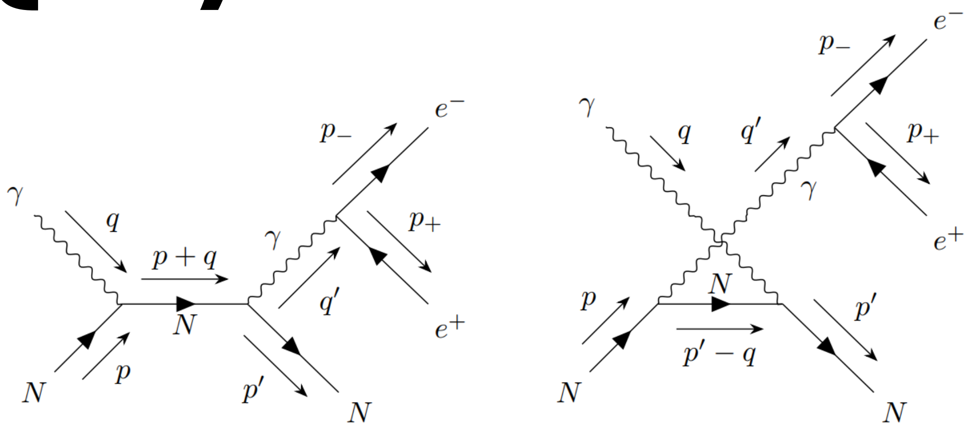


Figure 1: The direct and crossed diagram for the Born process.

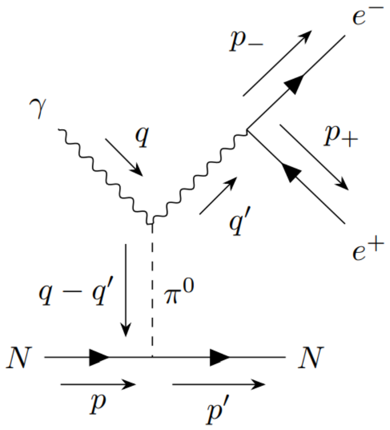
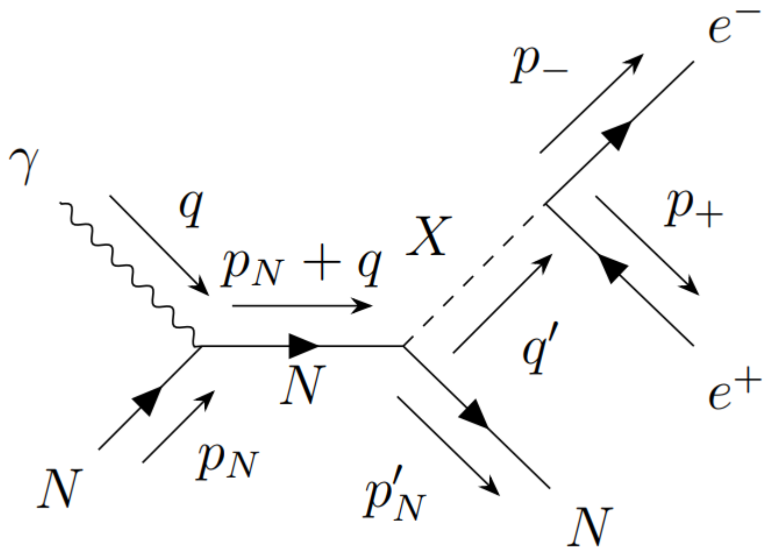
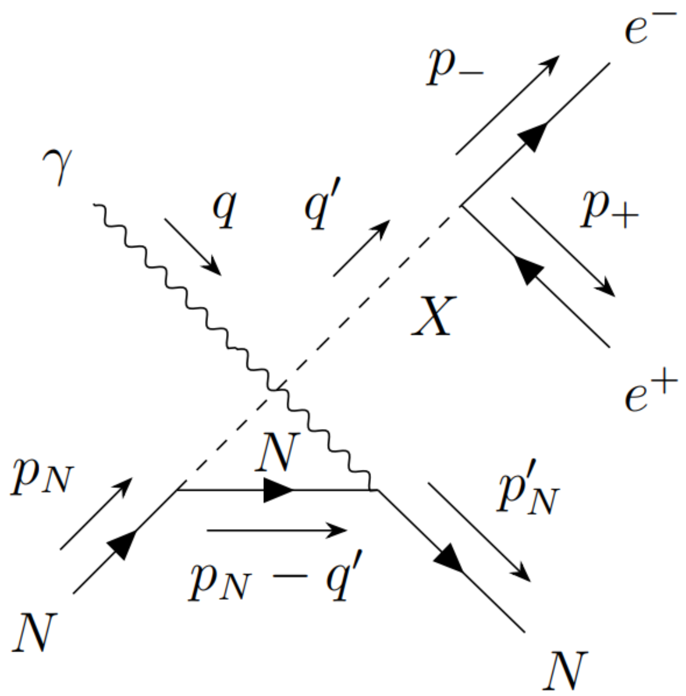


Figure 3: The diagram for the pion-pole amplitude.

Diagrams in detail (signal)

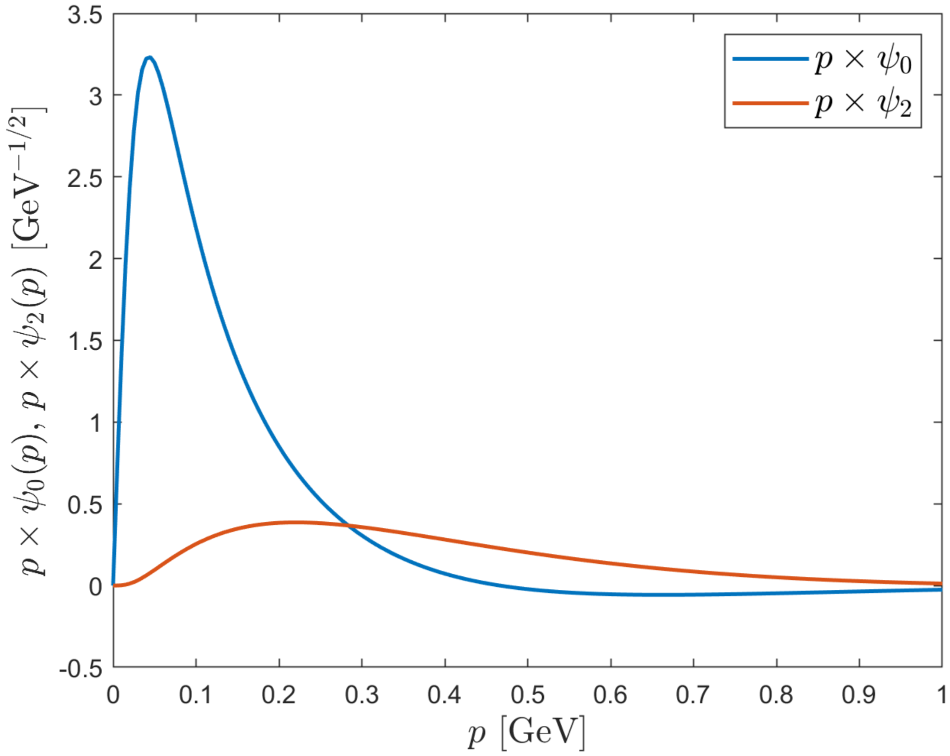




Deuteron wave function

- Use CD-Bonn wave function in momentum space (10.1103/PhysRevC.63.024001)

$$\tilde{\Psi}_d^{M_d}(\boldsymbol{p}) = \frac{(2\pi)^{3/2}}{\sqrt{4\pi}} \left[\psi_0(p) - \frac{1}{\sqrt{8}} \psi_2(p) S_{12}(\hat{\boldsymbol{p}}) \right] \chi_1^{M_d}$$



PWIA

$$\mathcal{M}_{\text{IA}}^{\text{lab}}(d\gamma \to e^+e^-pn) = \frac{(2\pi)^{3/2}(2m_d)^{1/2}}{\sqrt{2}}$$
$$\times \Bigg\{ \left(\frac{E_{p_n}^{(n)}}{E_{p_n}^{(p)}}\right)^{1/2} \Bigg[\mathcal{M}\left(\gamma(\boldsymbol{q},\lambda)\, p(-\boldsymbol{p}_n, m_d - s_n) \to e^-(\boldsymbol{p}_-, s_-)\, e^+(\boldsymbol{p}_+, s_+)\, p(\boldsymbol{p}_p, s_p)\right)$$
$$\times \frac{1}{\sqrt{4\pi}}\psi_0(p_n)\, \langle \tfrac{1}{2}\, \tfrac{1}{2}\,;\, m_d - s_n\, s_n \,|\, 1 m_d\rangle$$
$$- \sum_{m_s=-1}^{+1} \mathcal{M}\left(\gamma(\boldsymbol{q},\lambda)\, p(-\boldsymbol{p}_n, m_s - s_n) \to e^-(\boldsymbol{p}_-, s_-)\, e^+(\boldsymbol{p}_+, s_+)\, p(\boldsymbol{p}_p, s_p)\right)$$
$$\times Y_2^{m_d - m_s}(-\hat{\boldsymbol{p}}_n)\psi_2(p_n)\, \langle 2\, 1\,;\, m_d - m_s\, m_s \,|\, 1\, m_d\rangle\, \langle \tfrac{1}{2}\, \tfrac{1}{2}\,;\, m_s - s_n\, s_n \,|\, 1\, m_s\rangle \Bigg]$$
$$+ \left(\frac{E_{p_p}^{(p)}}{E_{p_p}^{(n)}}\right)^{1/2} \Bigg[\mathcal{M}\left(\gamma(\boldsymbol{q},\lambda)\, n(-\boldsymbol{p}_p, m_d - s_p) \to e^-(\boldsymbol{p}_-, s_-)\, e^+(\boldsymbol{p}_+, s_+)\, n(\boldsymbol{p}_n, s_n)\right)$$
$$\times \frac{1}{\sqrt{4\pi}}\psi_0(p_p)\, \langle \tfrac{1}{2}\, \tfrac{1}{2}\,;\, s_p\, m_d - s_p \,|\, 1 m_d\rangle$$
$$- \sum_{m_s=-1}^{+1} \mathcal{M}\left(\gamma(\boldsymbol{q},\lambda)\, n(-\boldsymbol{p}_p, m_s - s_p) \to e^-(\boldsymbol{p}_-, s_-)\, e^+(\boldsymbol{p}_+, s_+)\, n(\boldsymbol{p}_n, s_n)\right)$$
$$\times Y_2^{m_d - m_s}(\hat{\boldsymbol{p}}_p)\psi_2(p_p)\, \langle 2\, 1\,;\, m_d - m_s\, m_s \,|\, 1\, m_d\rangle\, \langle \tfrac{1}{2}\, \tfrac{1}{2}\,;\, s_p\, m_s - s_p \,|\, 1\, m_s\rangle \Bigg]\Bigg\}.$$

Averaging the signal

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|\boldsymbol{p}_+|\,\mathrm{d}|\boldsymbol{p}_-|\,\mathrm{d}\Omega_n\,\mathrm{d}\Omega_-\,\mathrm{d}\Omega_+} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}.$$

We have

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}\right|_{\text{measured}} = \frac{1}{\delta m_X}\int_{m_X-\delta m_X/2}^{m_X+\delta m_X/2} \mathrm{d}\sqrt{q'^2}\,\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}.$$

Averaging the signal

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|\boldsymbol{p}_+|\,\mathrm{d}|\boldsymbol{p}_-|\,\mathrm{d}\Omega_n\,\mathrm{d}\Omega_-\,\mathrm{d}\Omega_+} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}.$$

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$$\frac{1}{q'^2}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}\right)\frac{\left[(q'^2-m_X^2)^2+(m_X\Gamma_X)^2\right]}{g_{Xee}^2} \approx \text{ constant between } \left[m_X-\frac{\delta m_X}{2}, m_X+\frac{\delta m_X}{2}\right]$$

Averaging the signal

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|\boldsymbol{p}_+|\,\mathrm{d}|\boldsymbol{p}_-|\,\mathrm{d}\Omega_n\,\mathrm{d}\Omega_-\,\mathrm{d}\Omega_+} = \frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}.$$

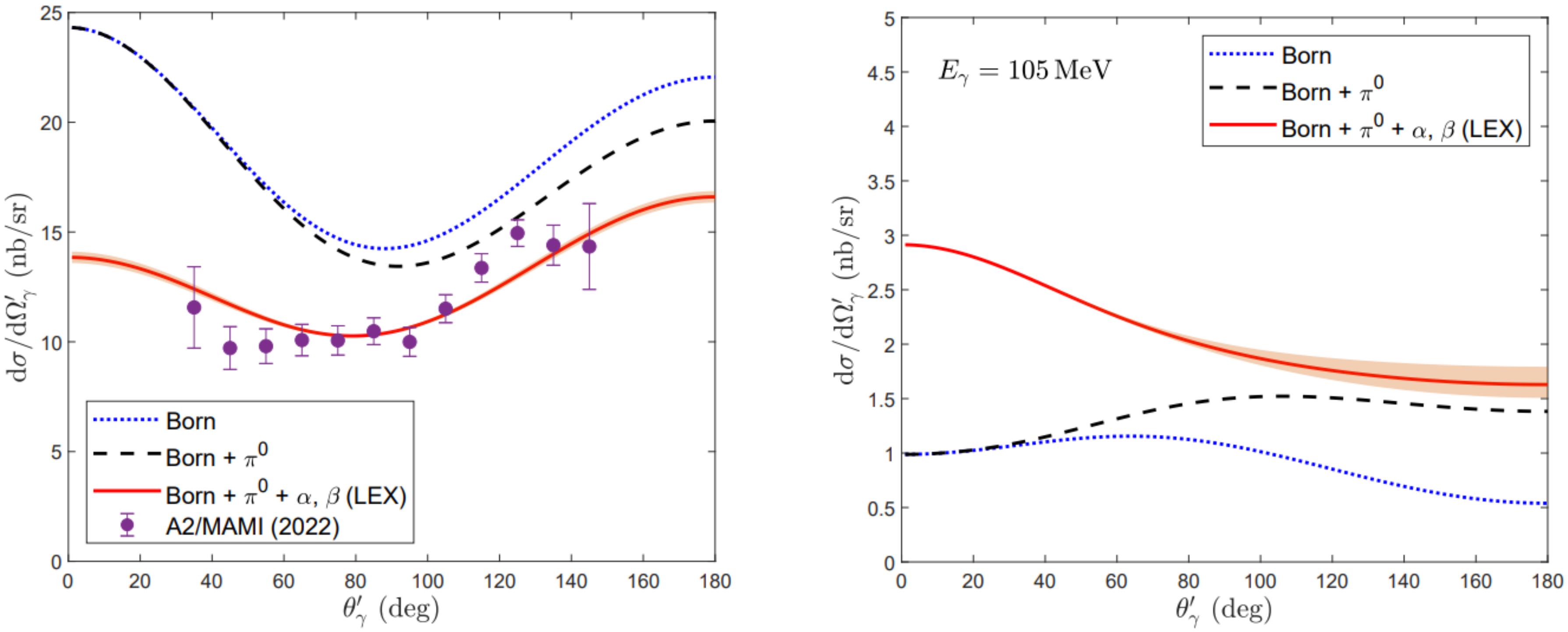
We have

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}\right|_{\text{measured}} = \frac{1}{\delta m_X}\int_{m_X-\delta m_X/2}^{m_X+\delta m_X/2} \mathrm{d}\sqrt{q'^2}\,\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}.$$

$$\frac{1}{q'^2}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}\right)\frac{\left[(q'^2-m_X^2)^2+(m_X\Gamma_X)^2\right]}{g_{Xee}^2} \approx \text{ constant between } \left[m_X-\frac{\delta m_X}{2}, m_X+\frac{\delta m_X}{2}\right]$$

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}\right|_{\text{measured}}$$
$$\approx \left.\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}\right)\right|_{q'^2=m_X^2,\ \varepsilon_e^2=1,\ \Gamma_X=1} \frac{1}{\delta m_X}\frac{6\pi^2}{e^2 m_X}\left(1+\frac{2m_e^2}{m_X^2}\right)^{-1}\left(1-\frac{4m_e^2}{m_X^2}\right)^{-1/2}\mathcal{B}(a\to e^+e^-),$$

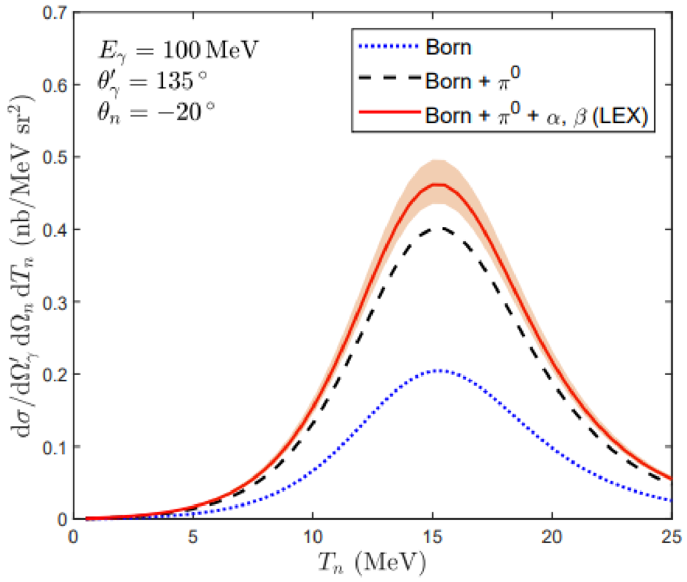
Verifying the QED background (I)



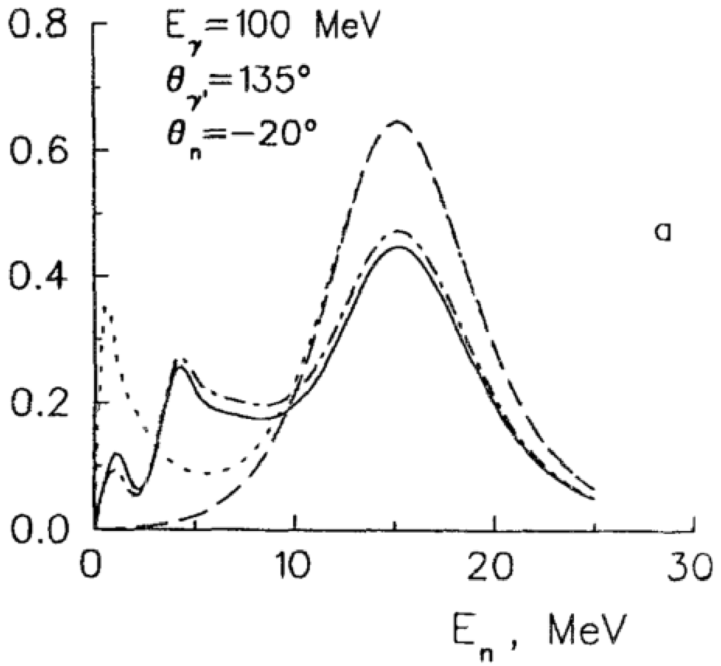
(a) $\gamma p \to \gamma p$ (b) $\gamma n \to \gamma n$

Verifying the QED background (II)

Few Body Syst. 16 (1994) 101-125
DOI: 10.1007/BF01355284

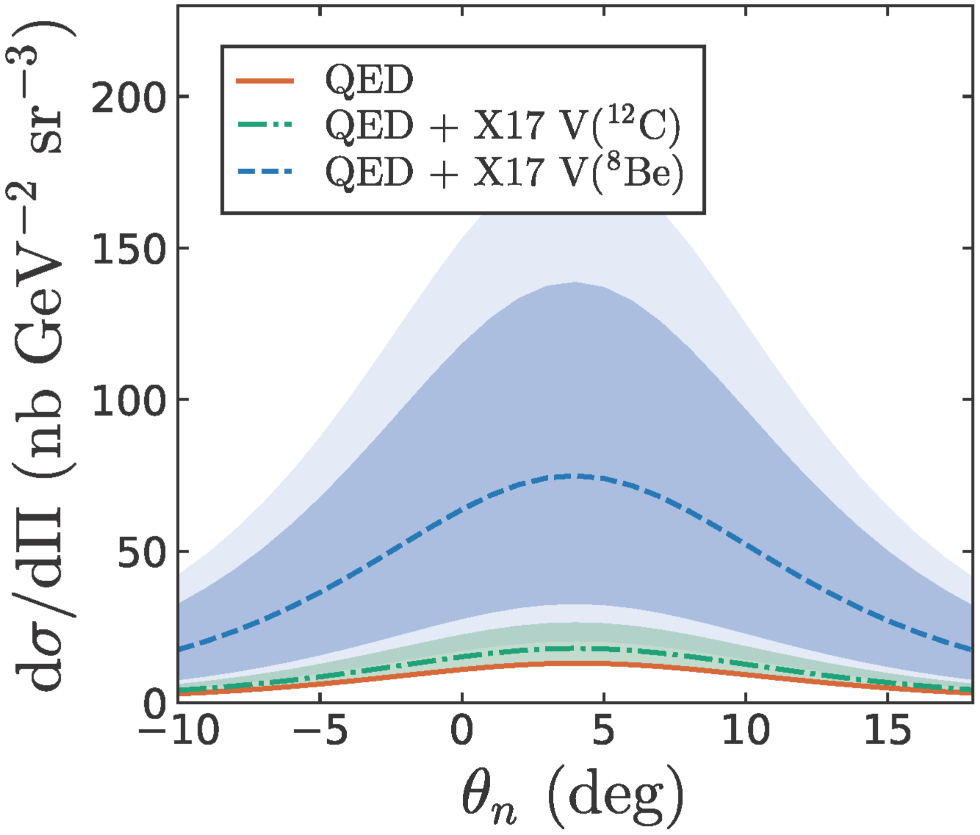


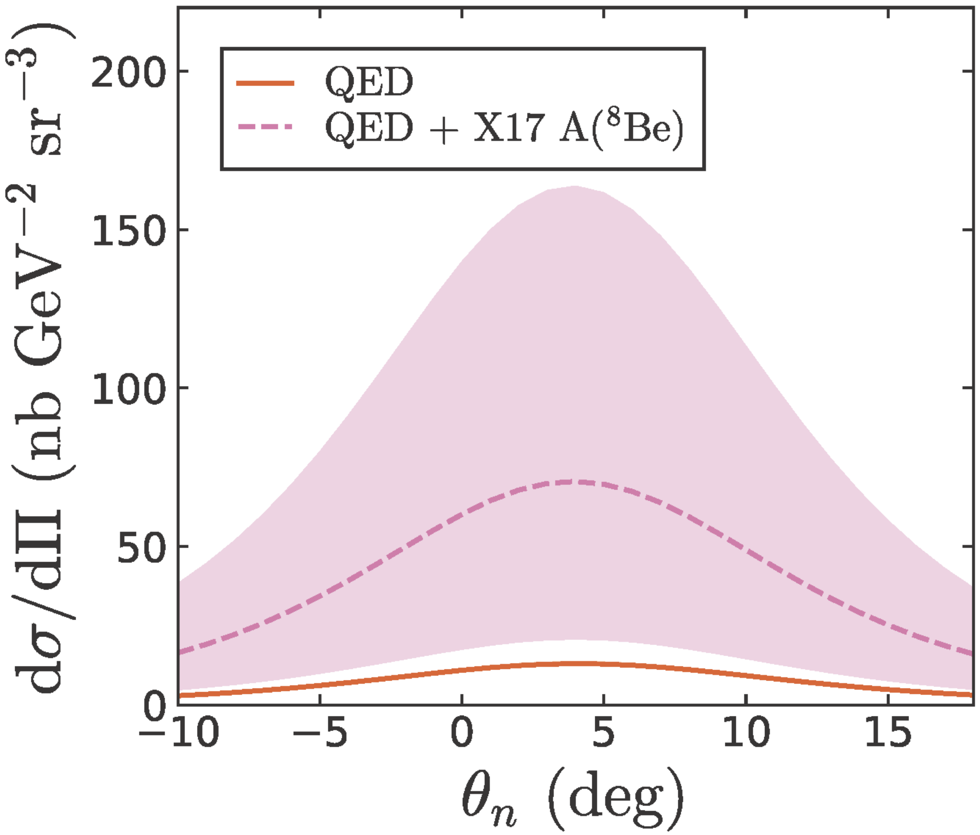
(a) $\gamma D \to \gamma pn$ (mine, PWIA)



(b) $\gamma D \to \gamma pn$ (Levchuk, PWIA [dashed], DWIA [dash-dot], DWIA + MEC [full])

Results


QED
QED + X17 V(^{12}C)
QED + X17 V(^{8}Be)
dσ/dΠ (nb GeV^{-2} sr^{-3})
θ_n (deg)
0
50
100
150
200
−10
−5
0
5
10
15


QED
QED + X17 A(^{8}Be)
dσ/dΠ (nb GeV^{-2} sr^{-3})
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0
50
100
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200
−10
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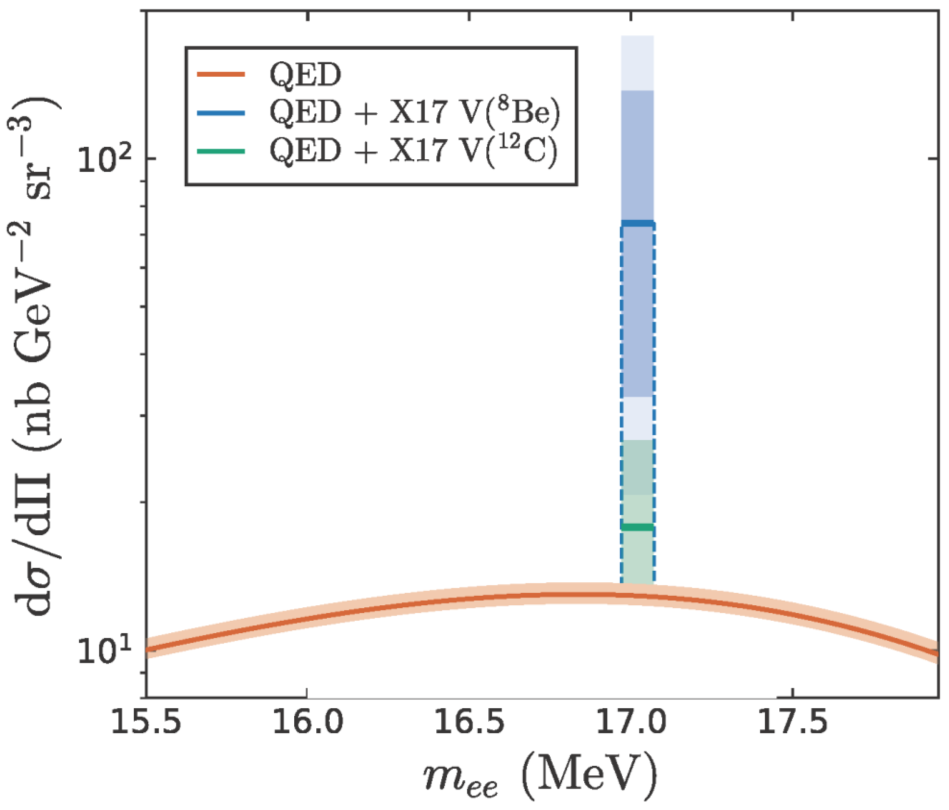
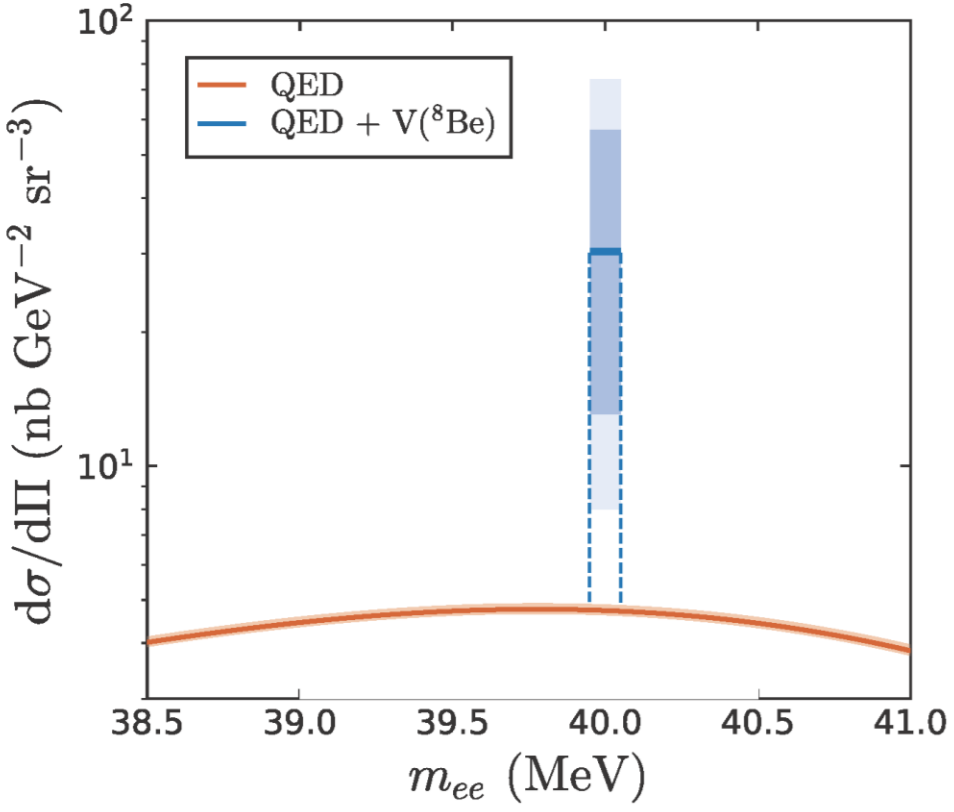
Results





Phys. Rev. D 109, 095010, Cornelis J.G. Mommers, Group Marc Vanderhaeghen, University of Mainz

Results