X17 discovery potential from $\gamma d \to e^+ e^- p n$ with neutron tagging

Cornelis J.G. Mommers & Marc Vanderhaeghen
Johannes Gutenberg-Universität Mainz
arXiv:2307.02181 [hep-ph]

Outline

1. What is X17?
2. Neutron tagging at MESA
3. X17 signal and QED background
4. Outlook
5. Questions

What is X17?

- ATOMKI experiment:

$$p + A \rightarrow N^* \rightarrow N + e^+e^-$$

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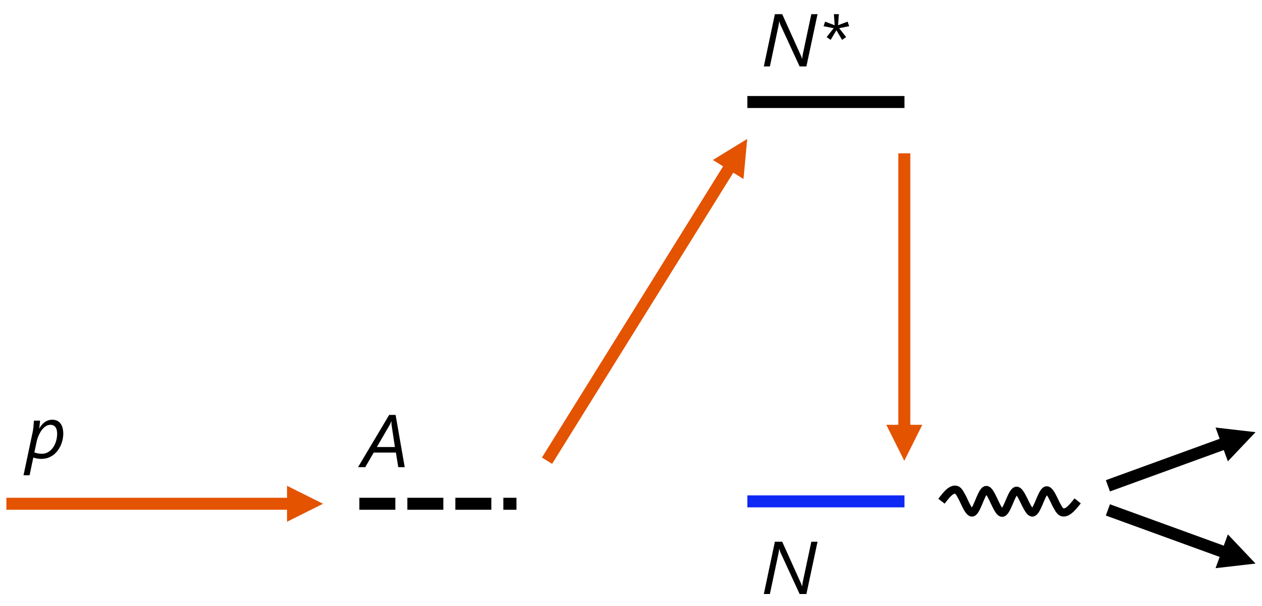
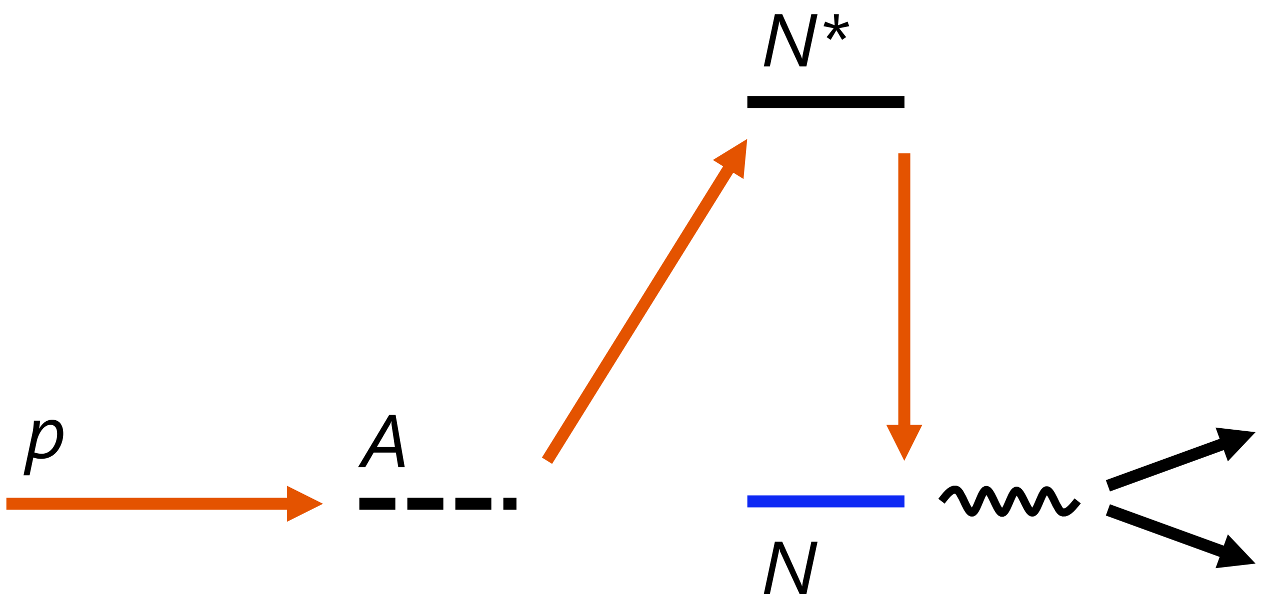


What is X17?

- ATOMKI experiment:

$$p + A \rightarrow N^* \rightarrow N + e^+e^-$$

- $^7Li(p,\gamma)^8Be$
- $^3H(p,\gamma)^4He$
- $^{11}B(p,\gamma)^{12}C$



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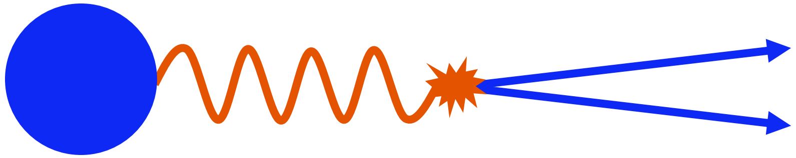

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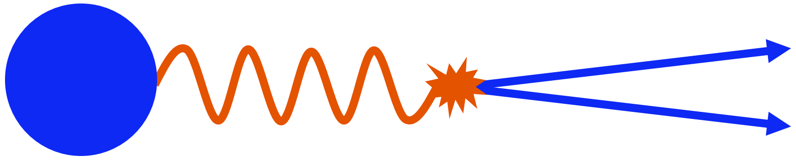
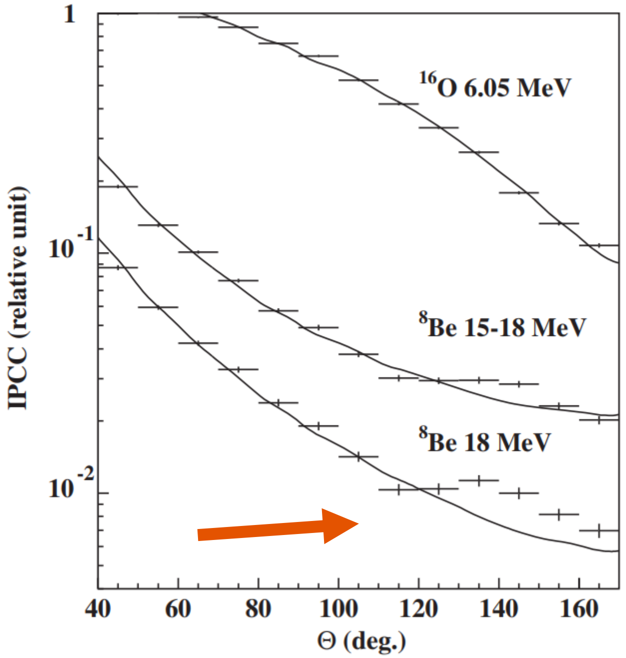


Phys. Rev. Lett. 116, 042501 (2016)



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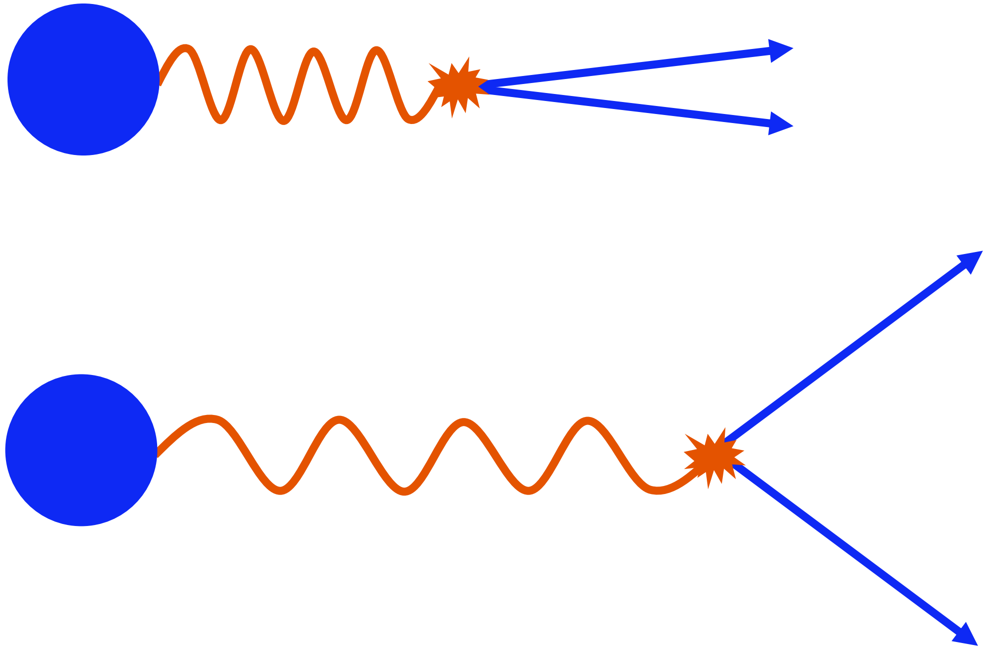

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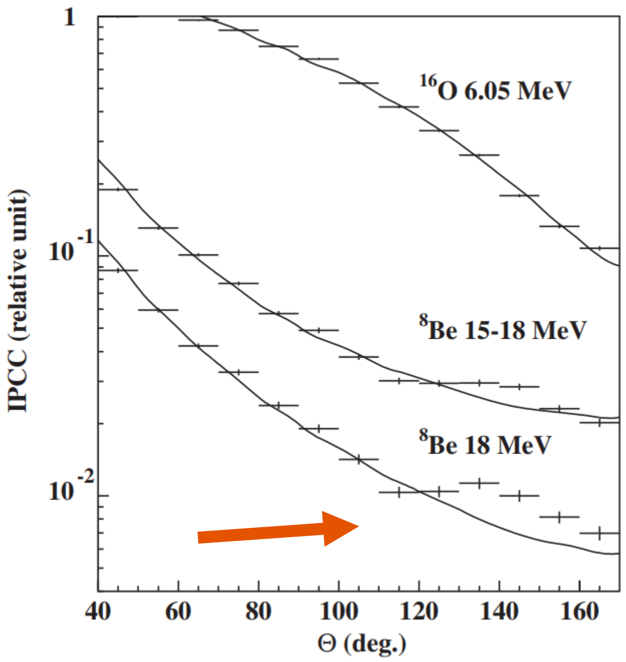

What is X17?

- ~17 MeV boson also fits the other data (!)

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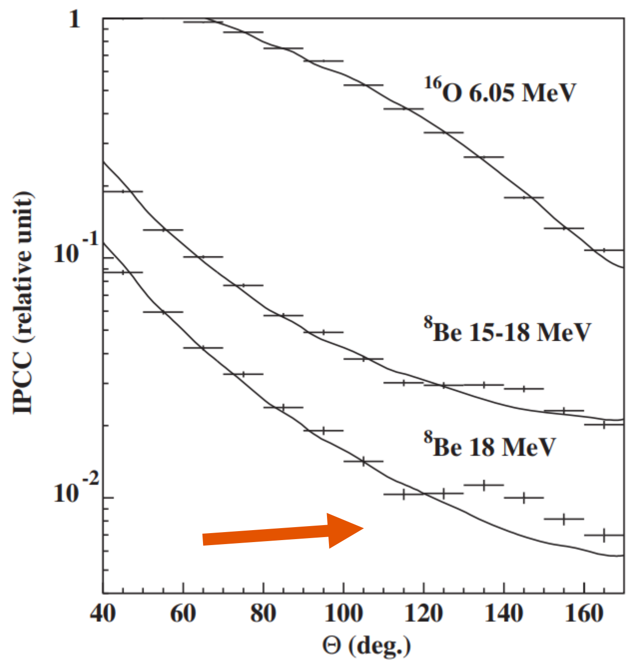

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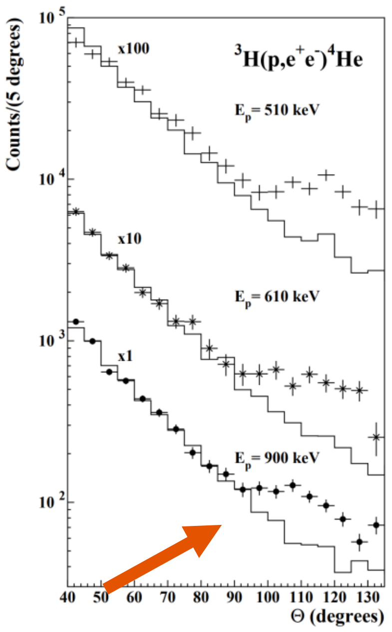
Phys. Rev. C 104, 044003 (2021)



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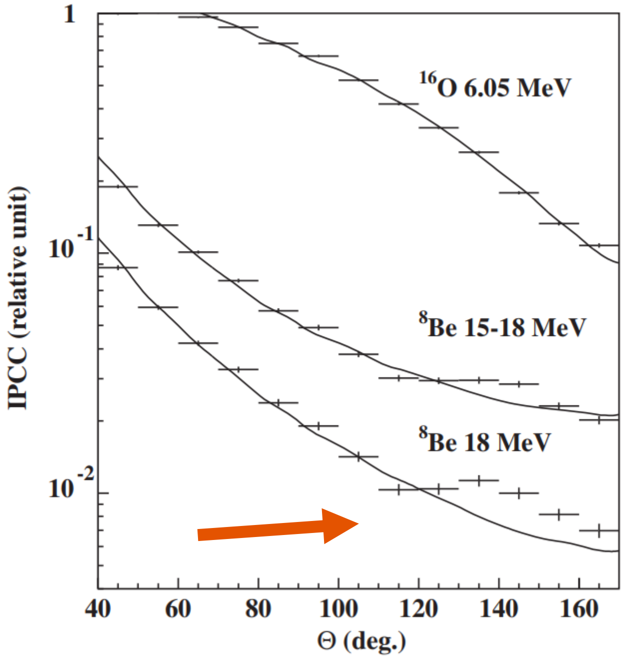

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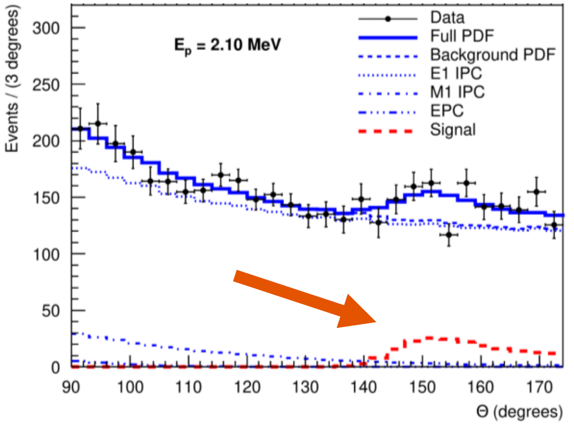
Phys. Rev. C 106, L061601 (2022)



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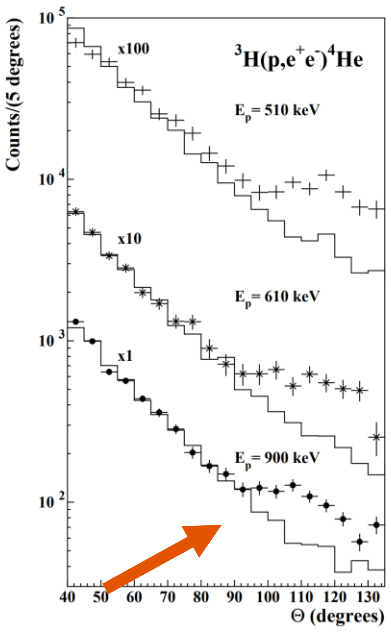

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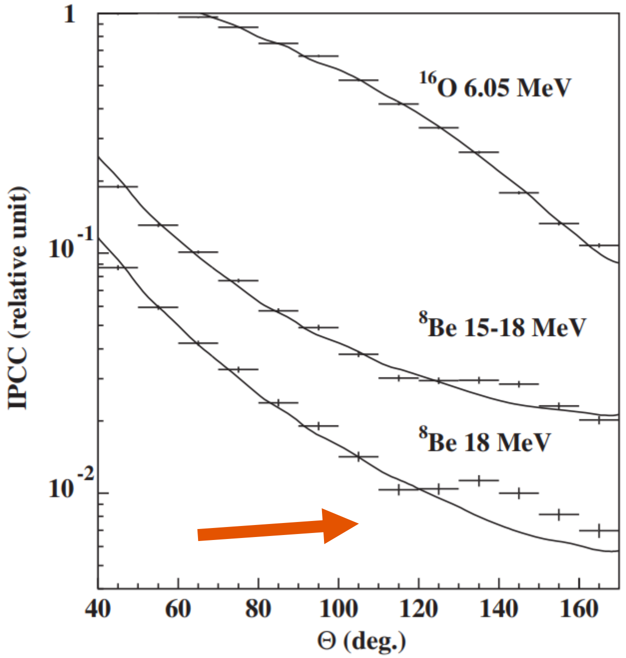

Continued interest...

PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
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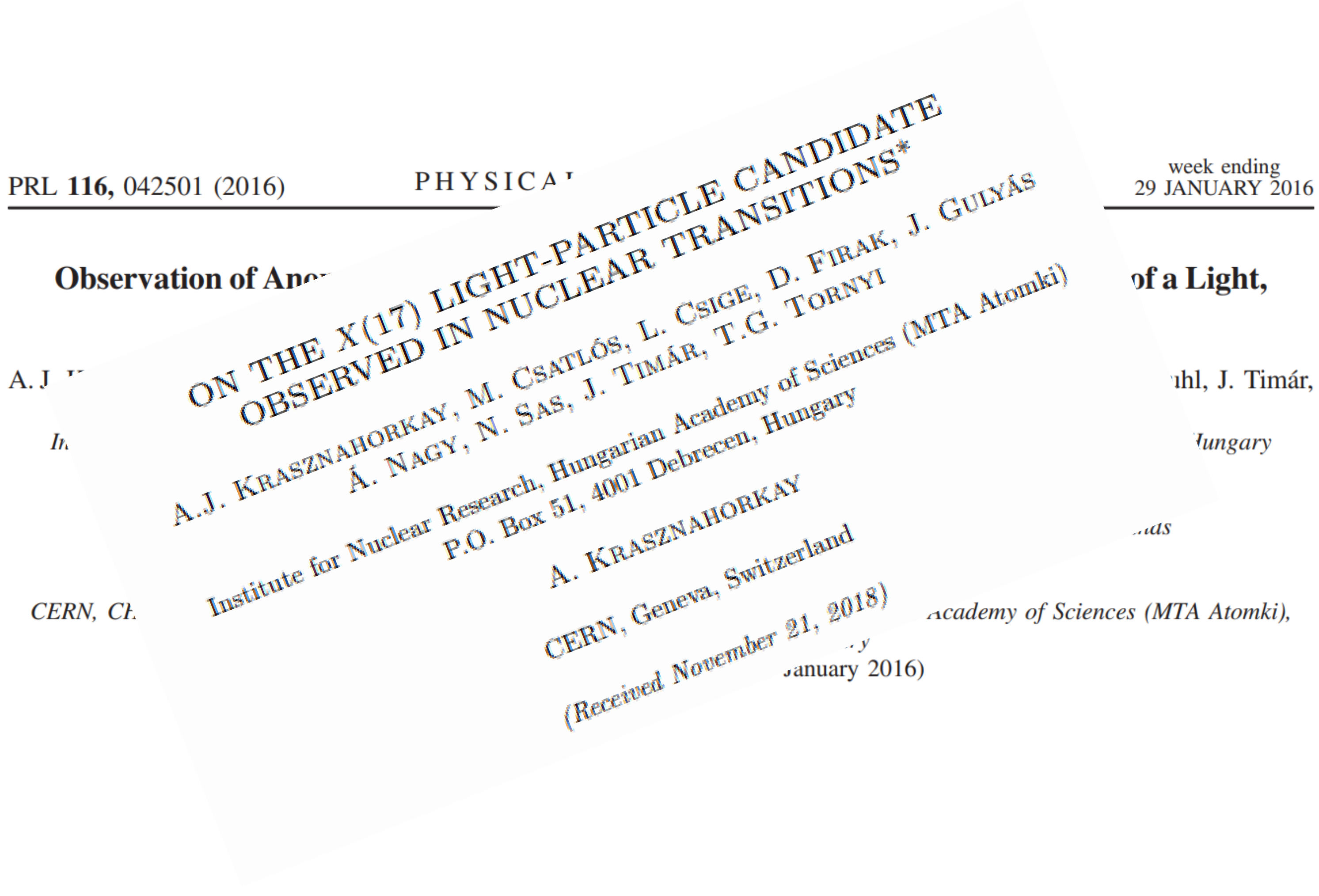
(Received 7 April 2015; published 26 January 2016)

Continued interest...



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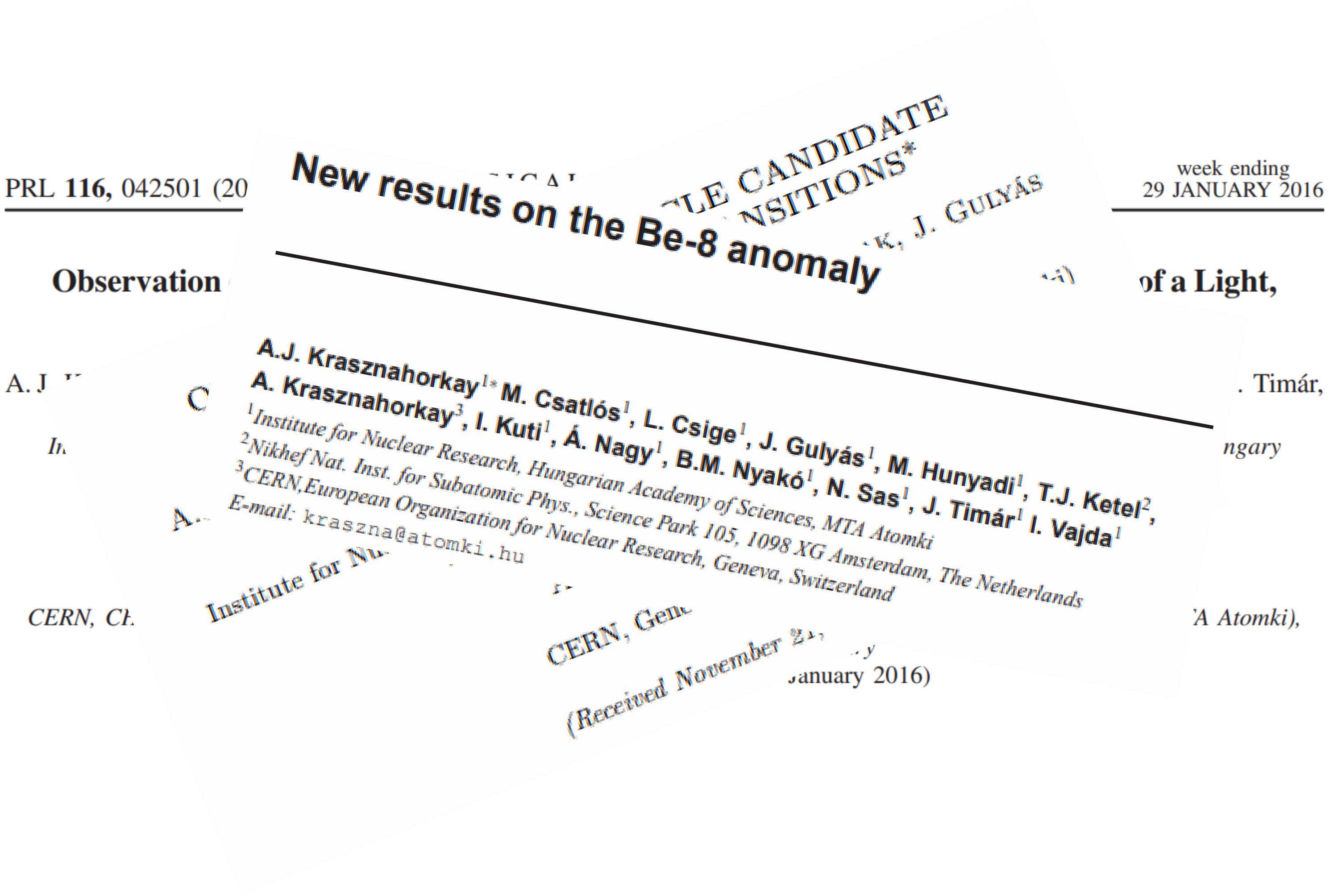

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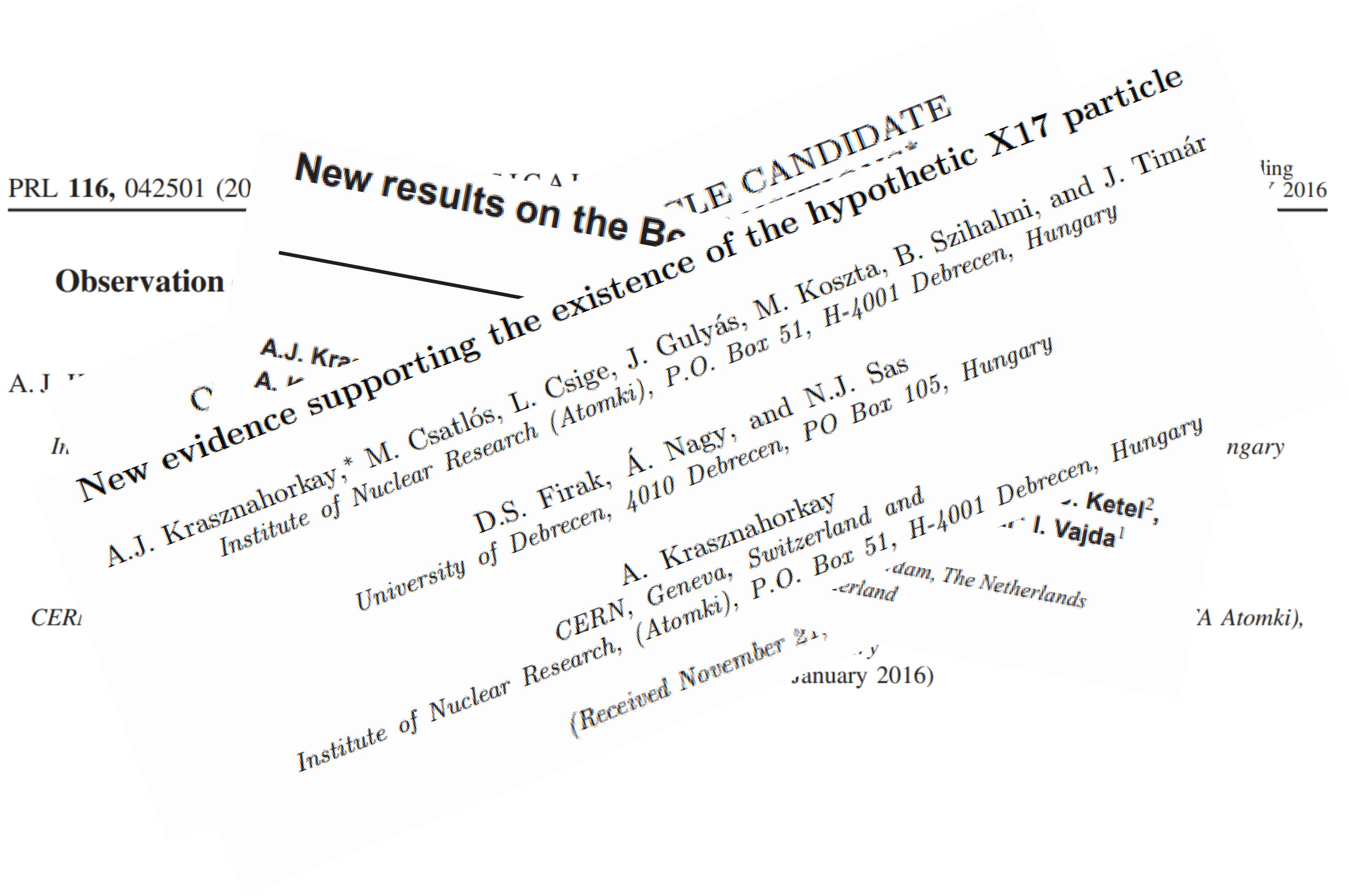

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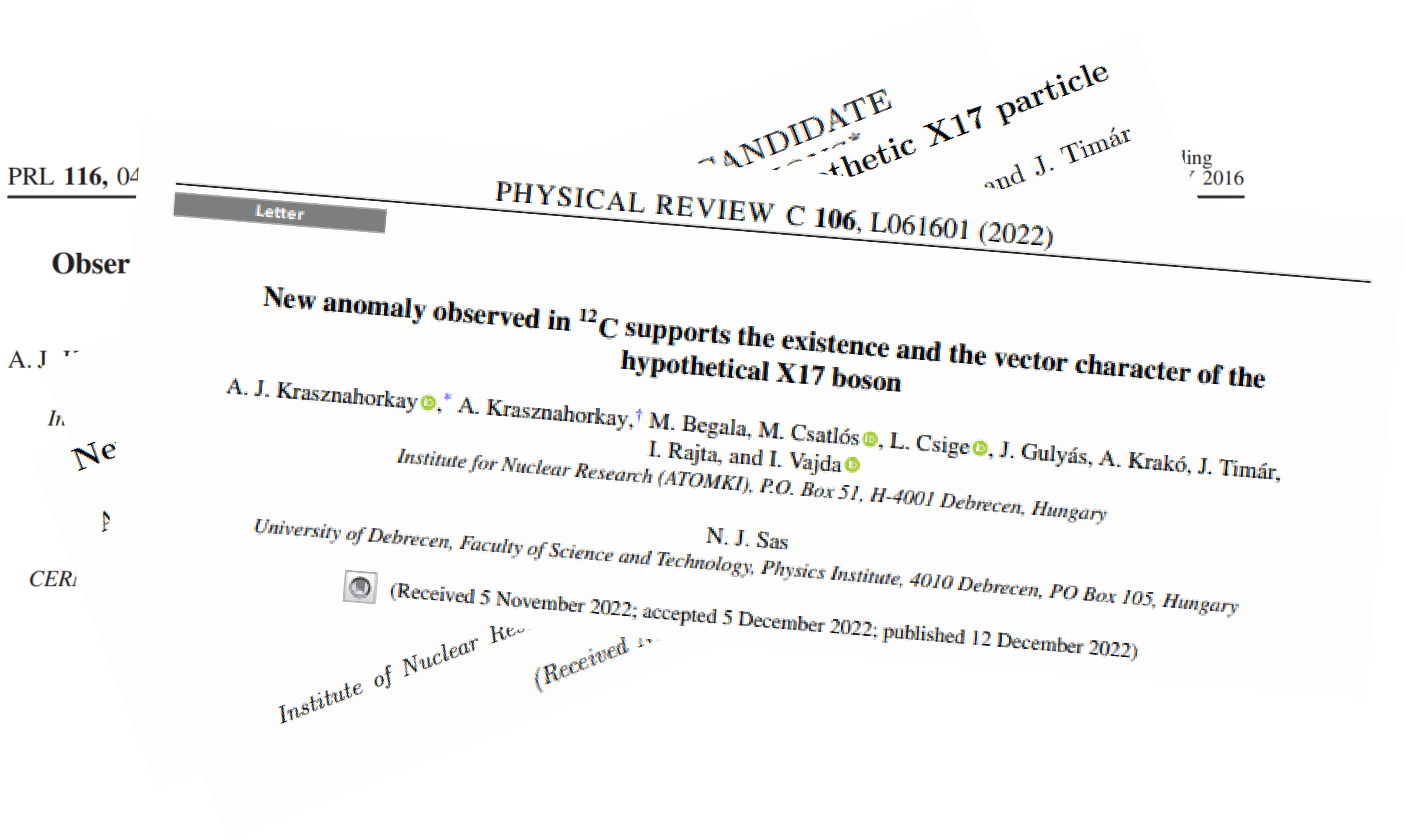

PHYSICAL REVIEW C **106**, L061601 (2022)

Letter

New anomaly observed in ^{12}C supports the existence and the vector character of the hypothetical X17 boson

A. J. Krasznahorkay,* A. Krasznahorkay,† M. Begala, M. Csatlós, L. Csige, J. Gulyás, A. Krakó, J. Timár, I. Rajta, and I. Vajda

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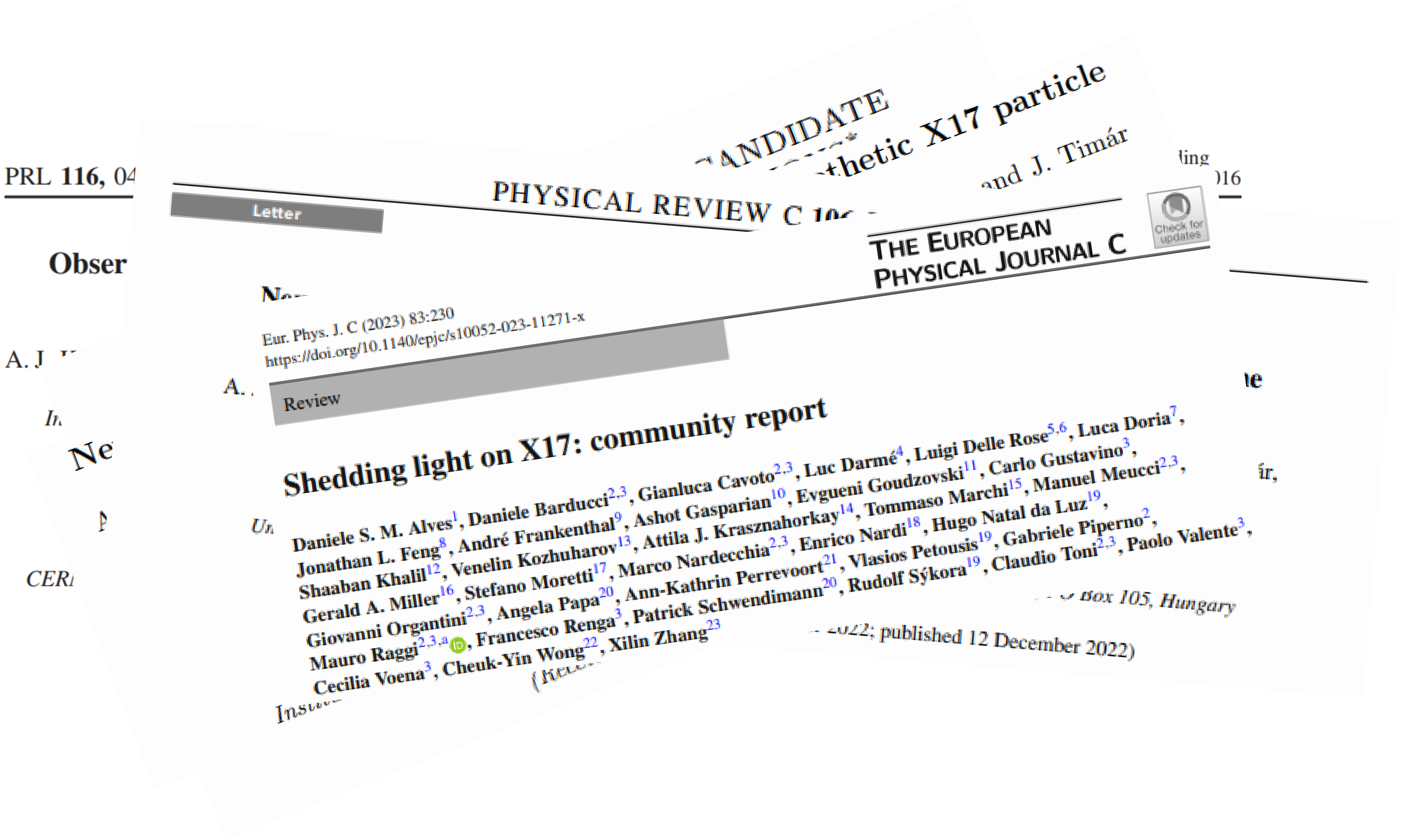
N. J. Sas

University of Debrecen, Faculty of Science and Technology, Physics Institute, 4010 Debrecen, PO Box 105, Hungary

(Received 5 November 2022; accepted 5 December 2022; published 12 December 2022)

Continued interest…



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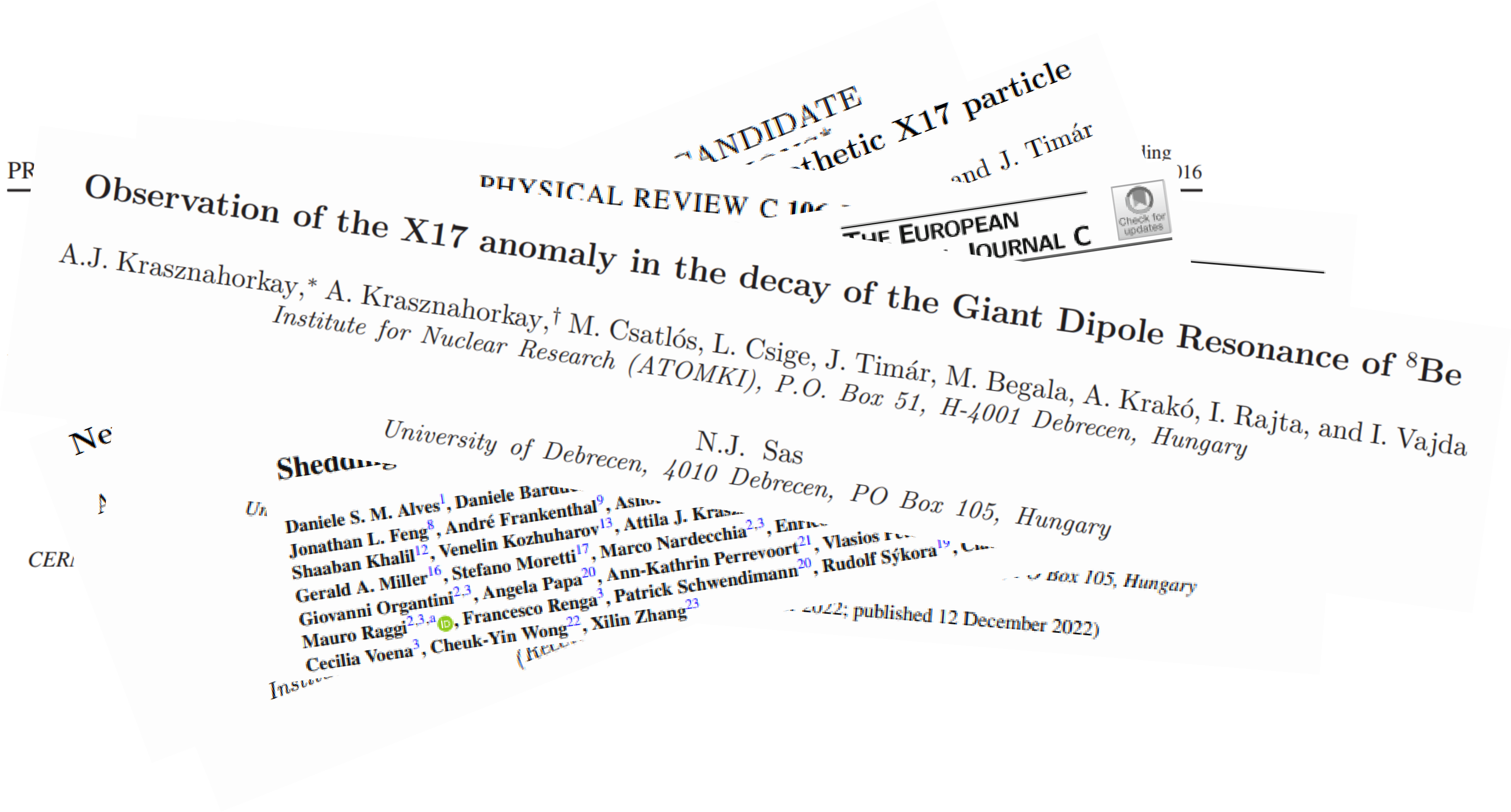

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$$\mathbf{1} = \mathbf{S}_X + \mathbf{0} + \mathbf{L} \qquad +1 = P_X \times (+1) \times (-1)^L$$

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

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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^-				

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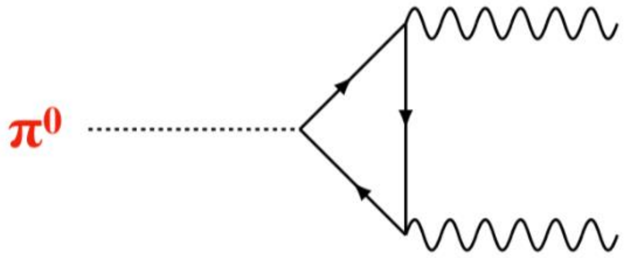
^{8}Be(17.64), 1^+		✓	✓	✓
^{4}He(21.01), 0^-		✓		✓
^{4}He(20.21), 0^+	✓		✓	
^{12}C(17.23), 1^-	✓		✓	✓

Theory analysis

- For vector X17 proton coupling bounded by NA48/2 (protophobic, see Phys. Rev. D 95, 035017 [2017])

$$\pi^0 \to \gamma(X \to e^+e^-)$$



$$\propto |2\varepsilon_u + \varepsilon_d| = |\varepsilon_p|$$

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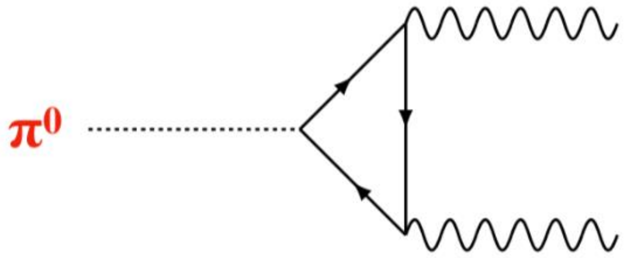
- For vector X17 proton coupling bounded by NA48/2 (protophobic, see Phys. Rev. D 95, 035017 [2017])
- Derive limits on neutron coupling

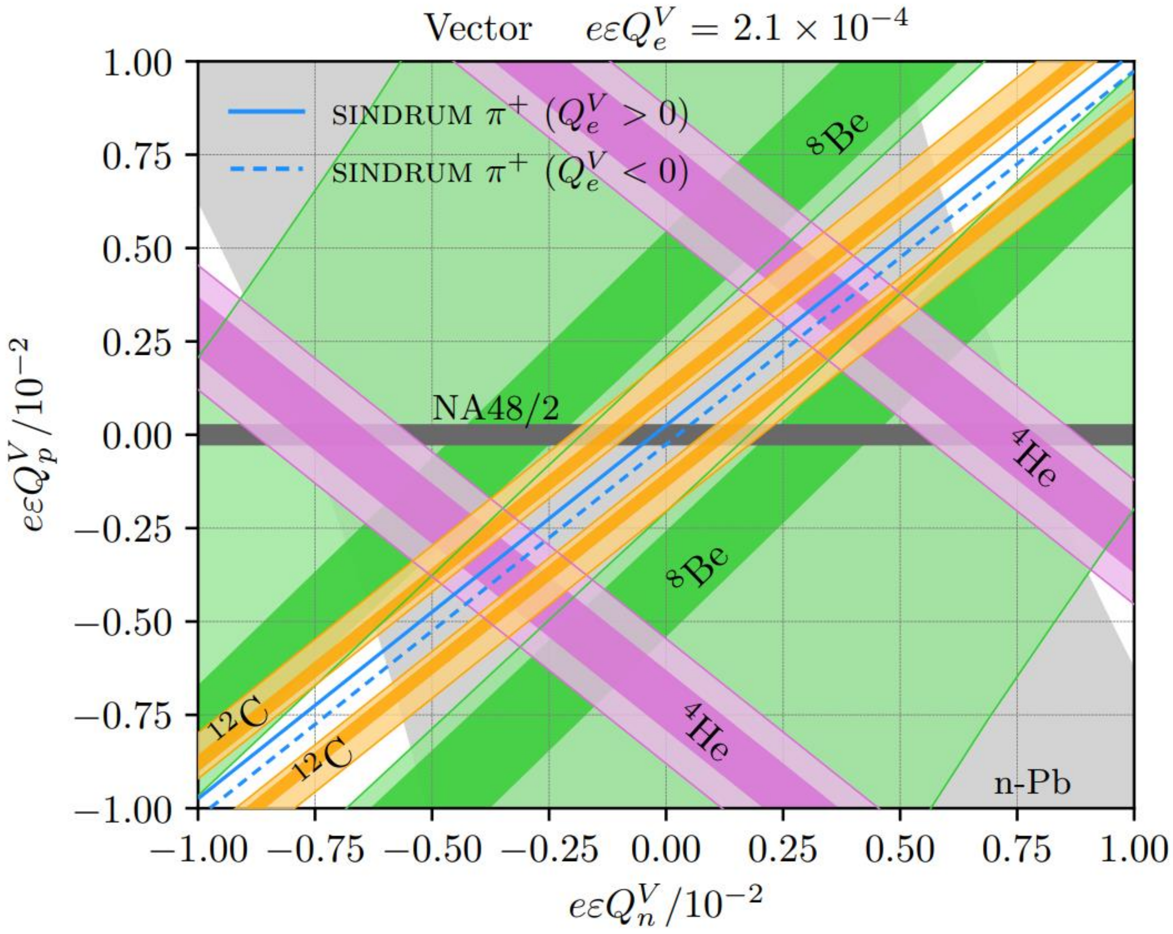
$$\pi^0 \to \gamma(X \to e^+ e^-)$$



$$\propto |2\varepsilon_u + \varepsilon_d| = |\varepsilon_p|$$

Many open questions

Phys. Rev. D 108, 055011 (20230



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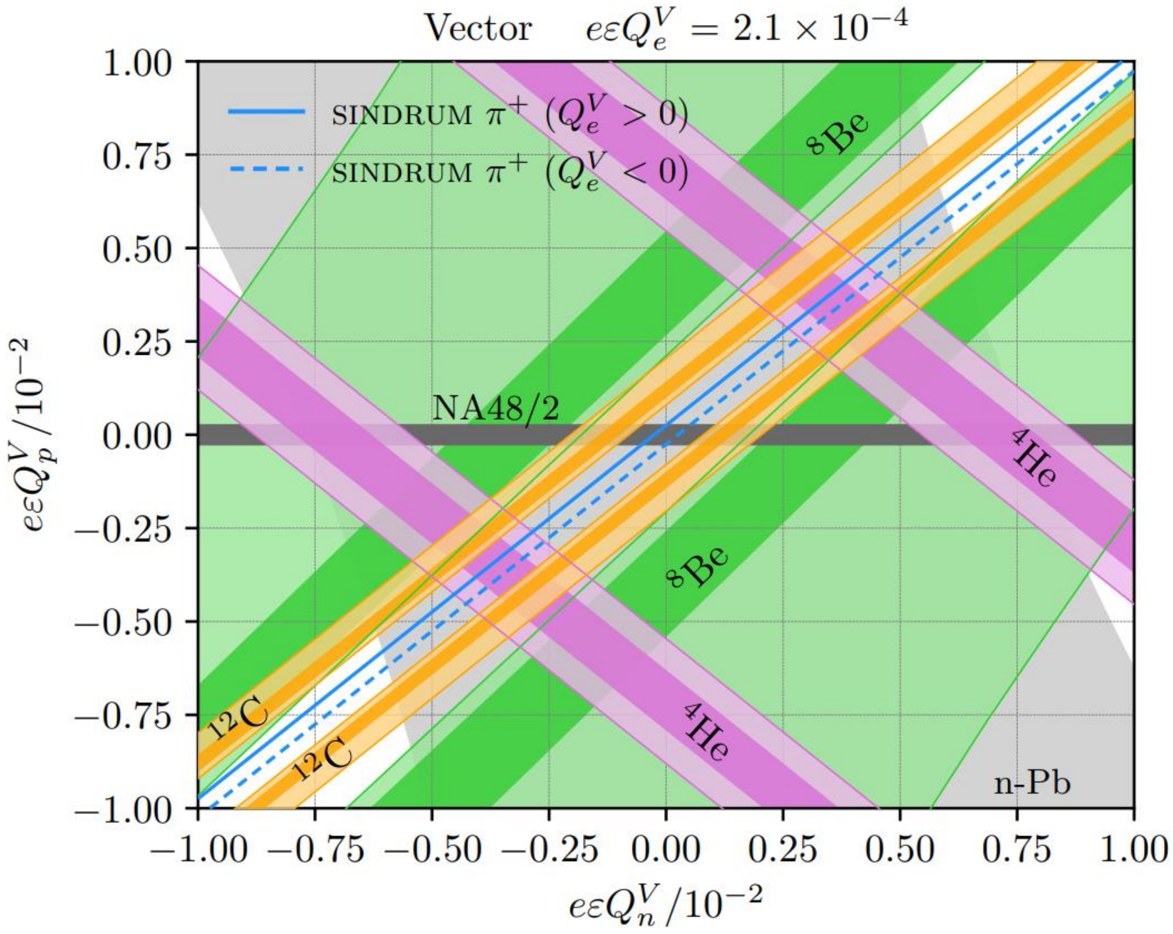
Phys. Rev. D 108, 055011 (20230



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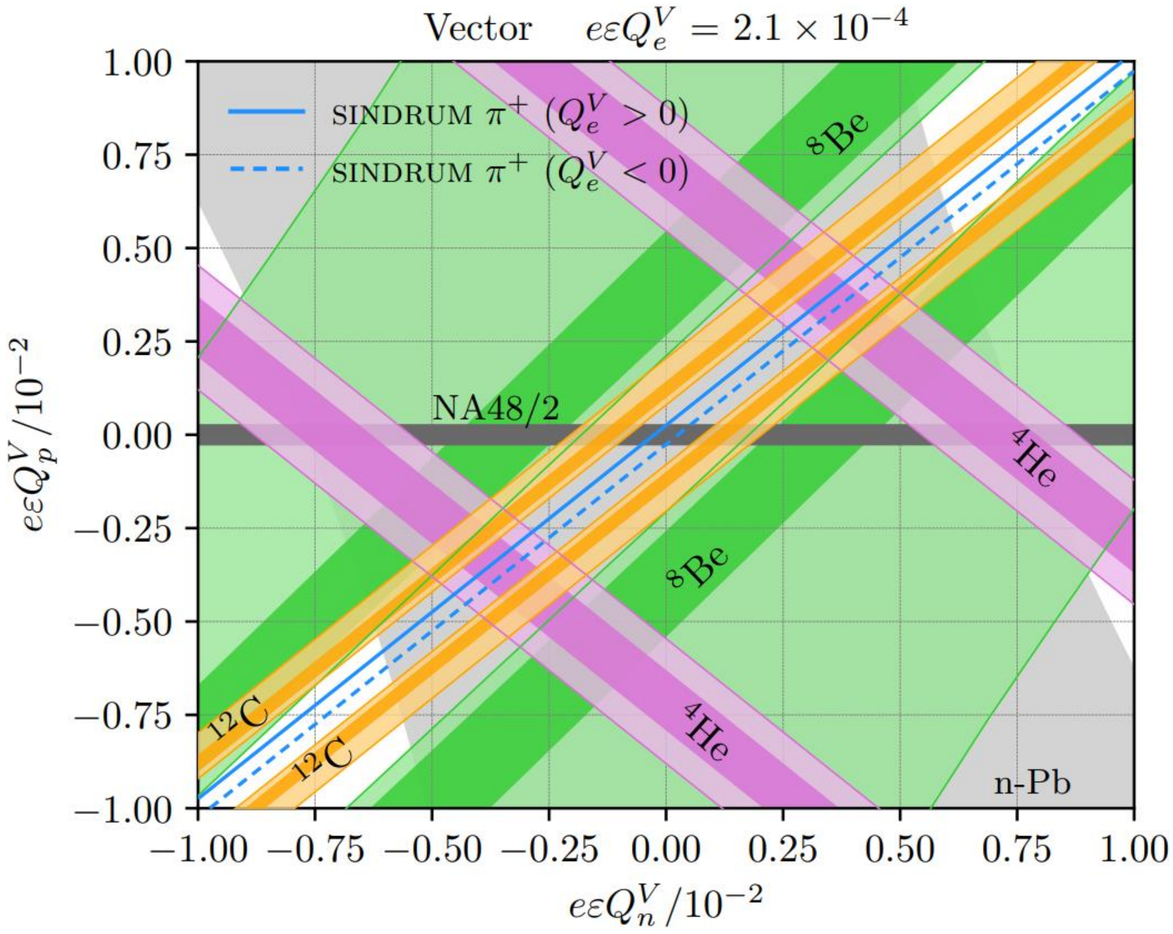

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- Ongoing/planned experiments at JLAB, CCPAC (Montreal), PADME and others (see Eur.Phys.J.C 83 (2023) 3, 230)

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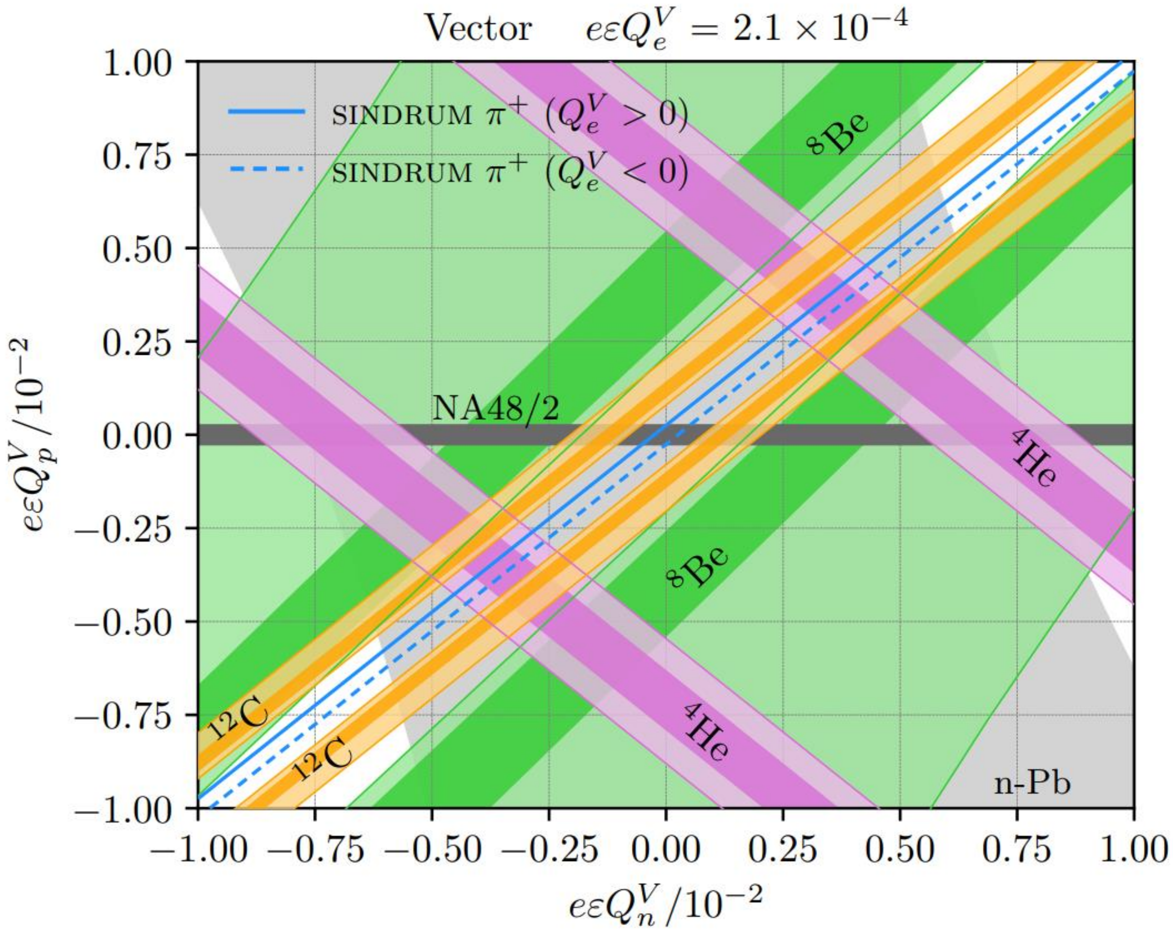
Phys. Rev. D 108, 055011 (20230



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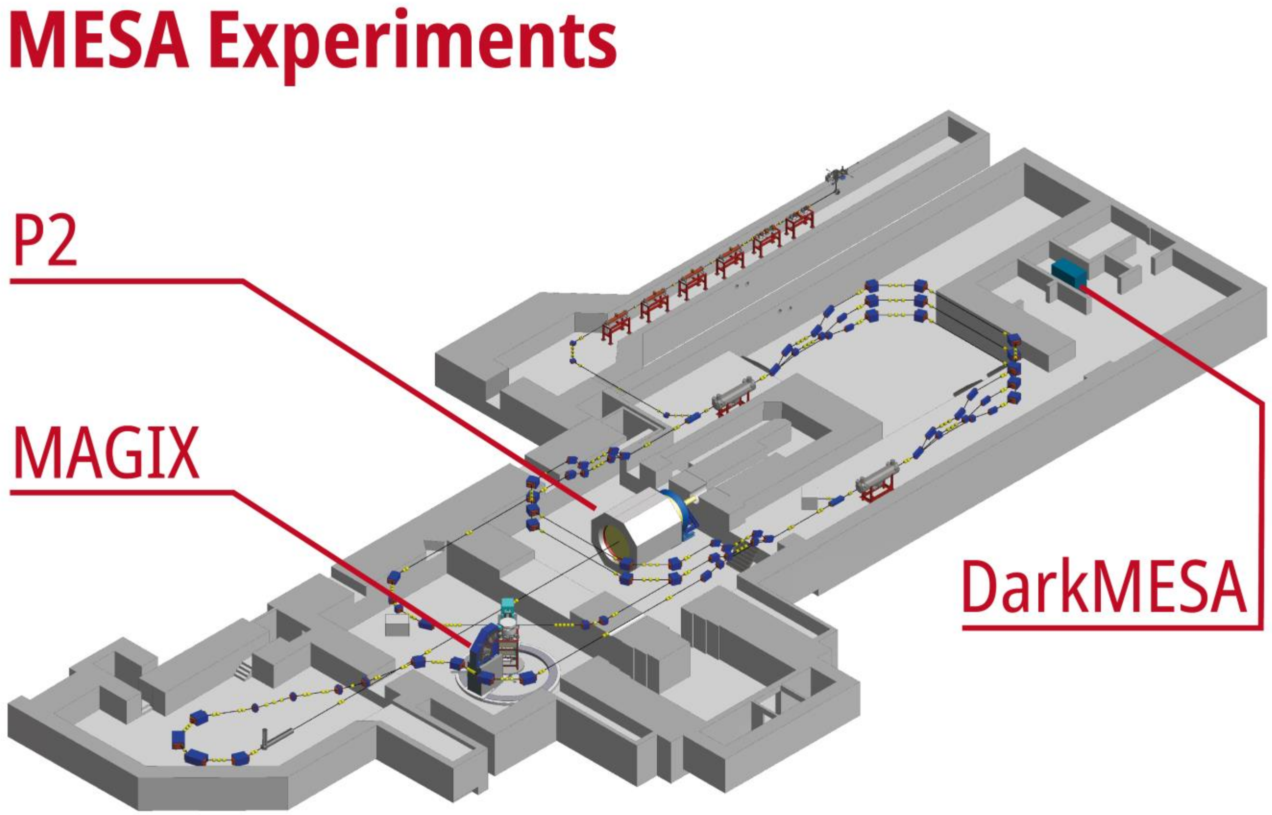
- We propose a direct search at MAGIX experiment at MESA

MAGIX@MESA

- MESA is a linear accelerator under construction in Mainz



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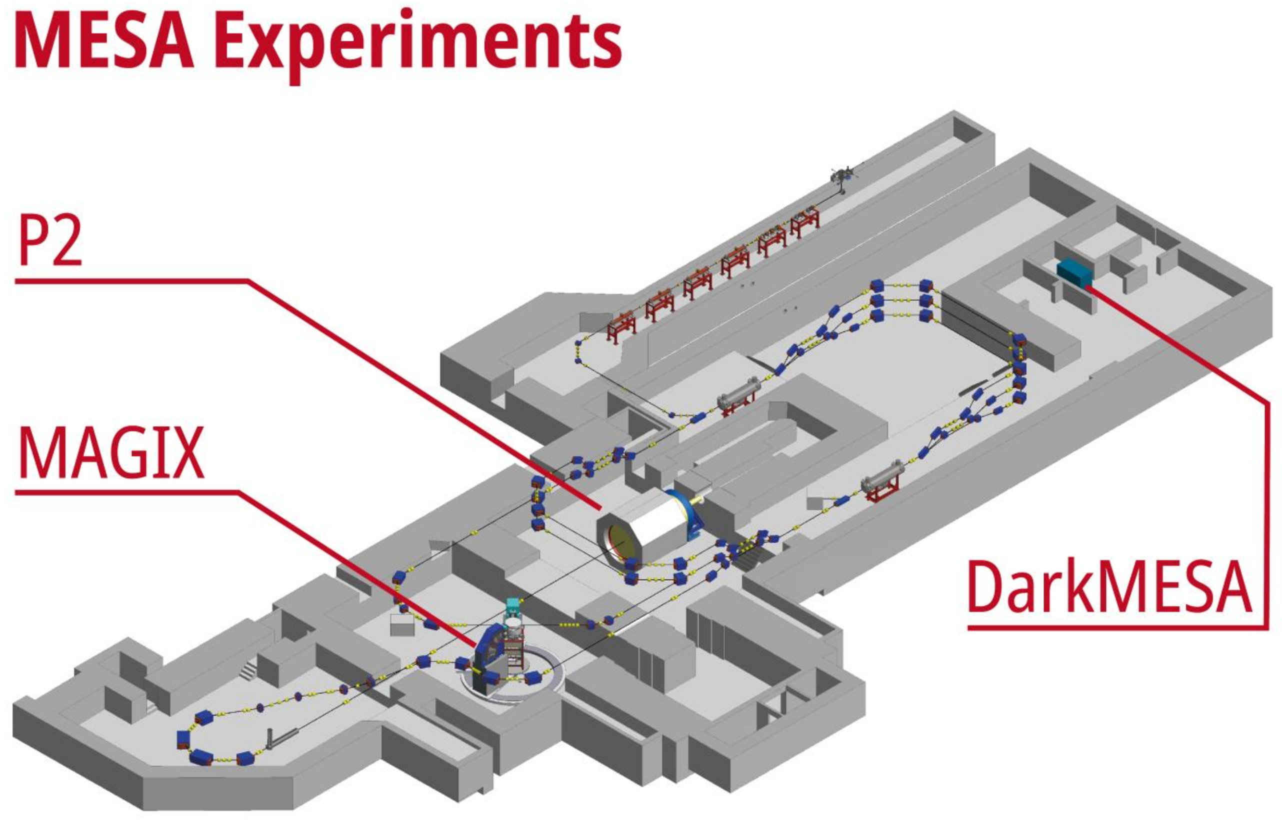
- Low energy, high intensity electron beam ~105 MeV



MAGIX@MESA

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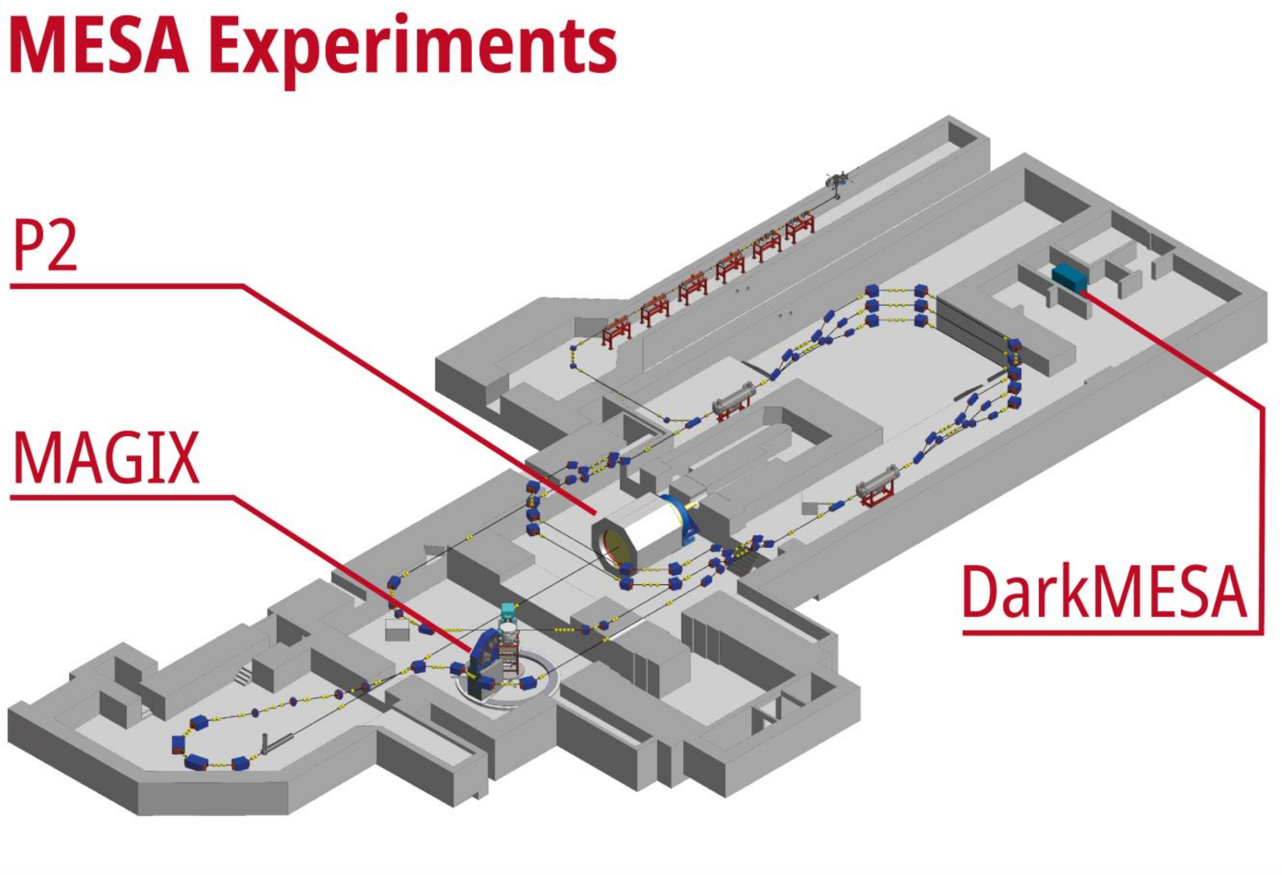
- Low energy, high intensity electron beam ~105 MeV
- MAGIX is a pair of multipurpose spectrometers, expected to measure m_{ee} with precision of 0.1 MeV



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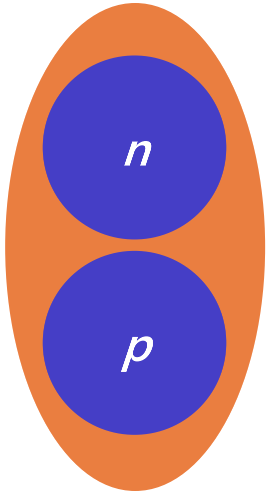

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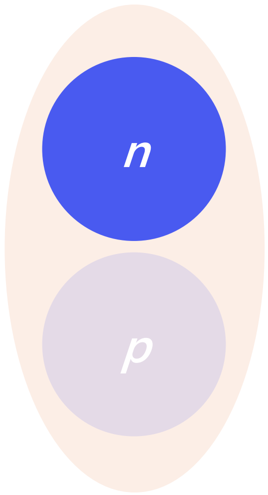

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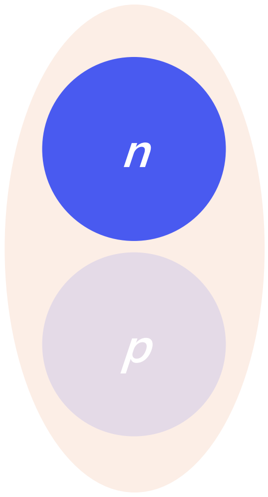
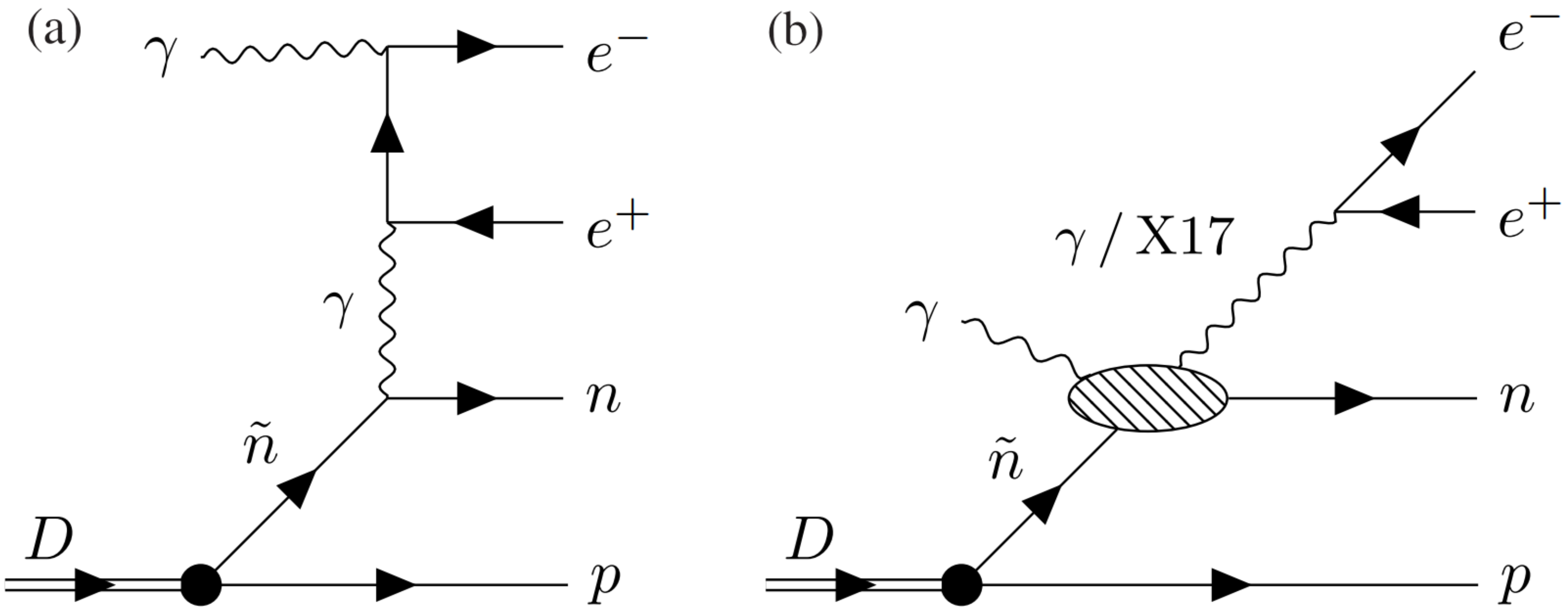
- Work within plane-wave impulse approximation:

$$\mathcal{M}(\gamma D \to e^+ e^- pn) \propto \psi_D \times \mathcal{M}(\gamma n \to e^+ e^- n) + \psi_D \times \mathcal{M}(\gamma p \to e^+ e^- p)$$



X17 discovery potential from $\gamma d \to e^+ e^- pn$, Cornelis J.G. Mommers & Marc Vanderhaeghen, arXiv:2307.02181 [hep-ph]

Relevant diagrams



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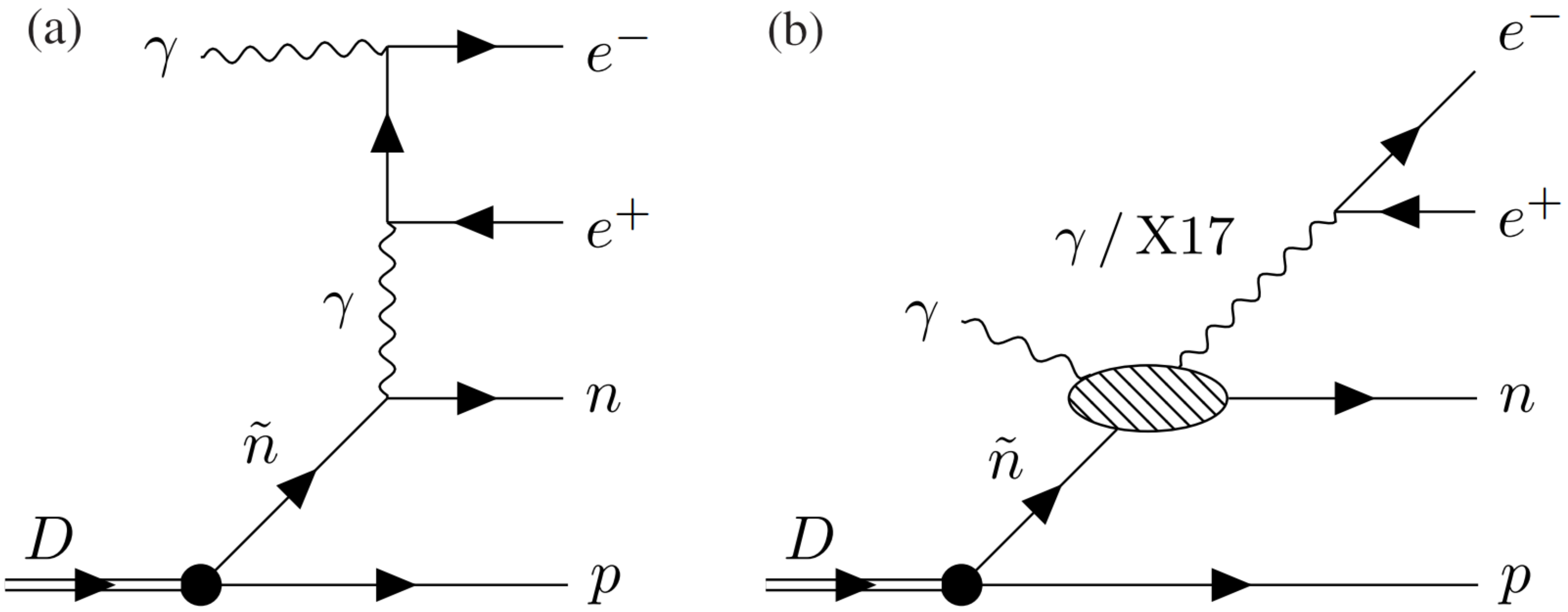
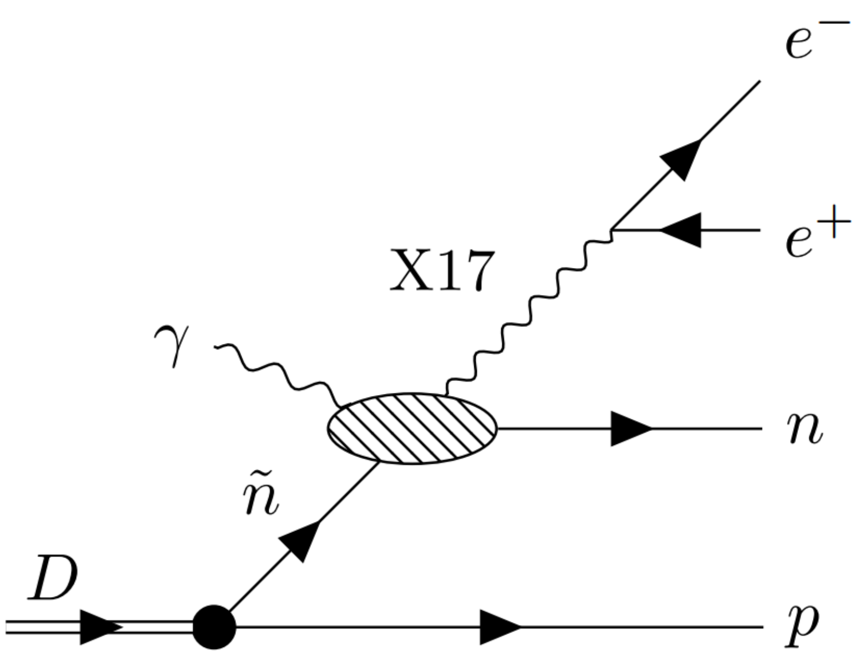


- Higher-order corrections ~25%, tree level sufficient for this work

Signal optimization



- Optimize kinematics such that X17 signal is visible over QED background, subject to constraints

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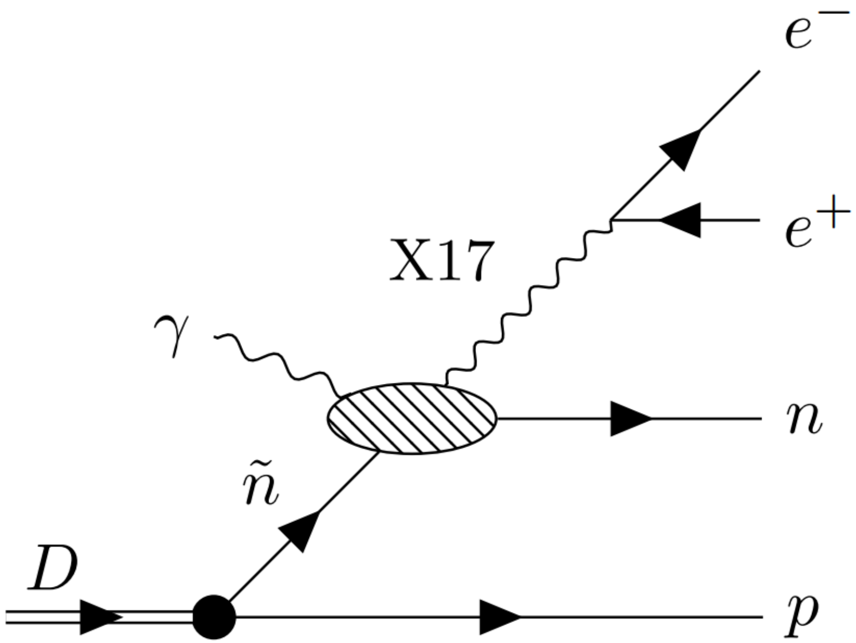

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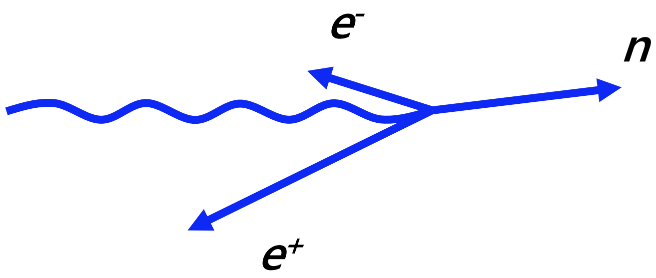

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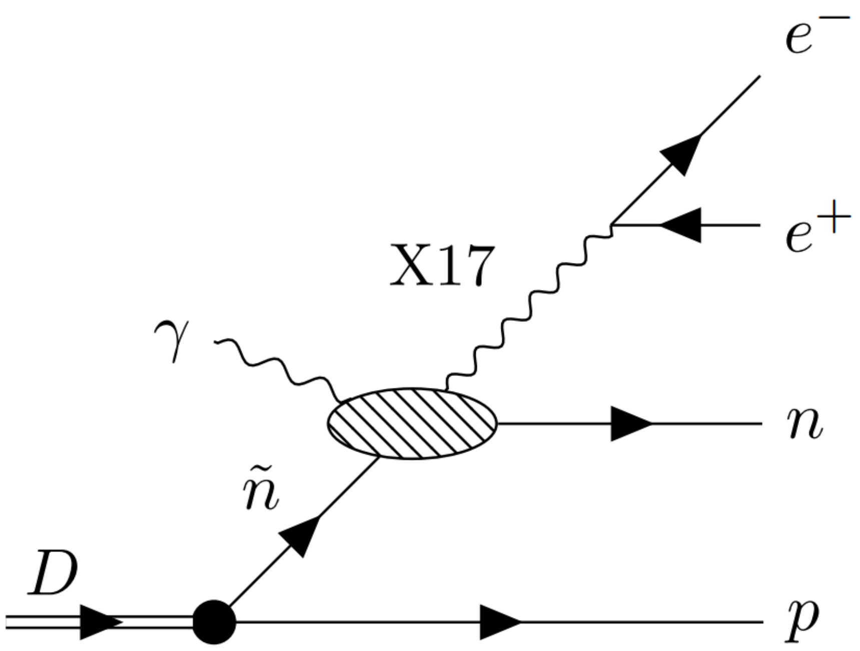

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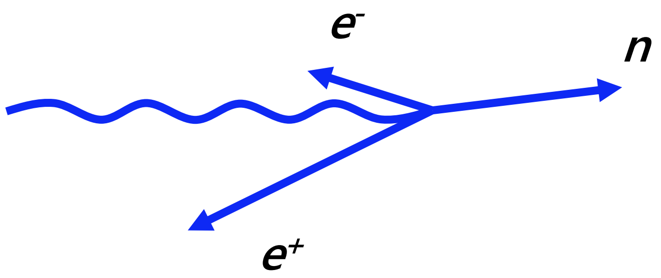
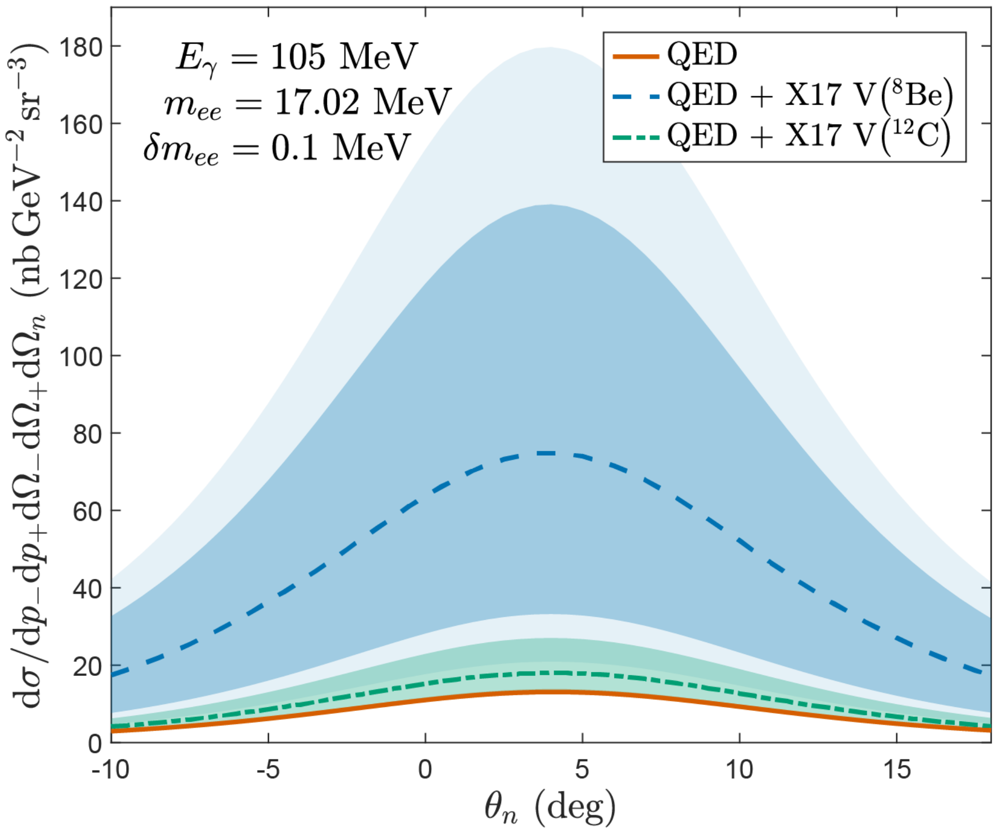
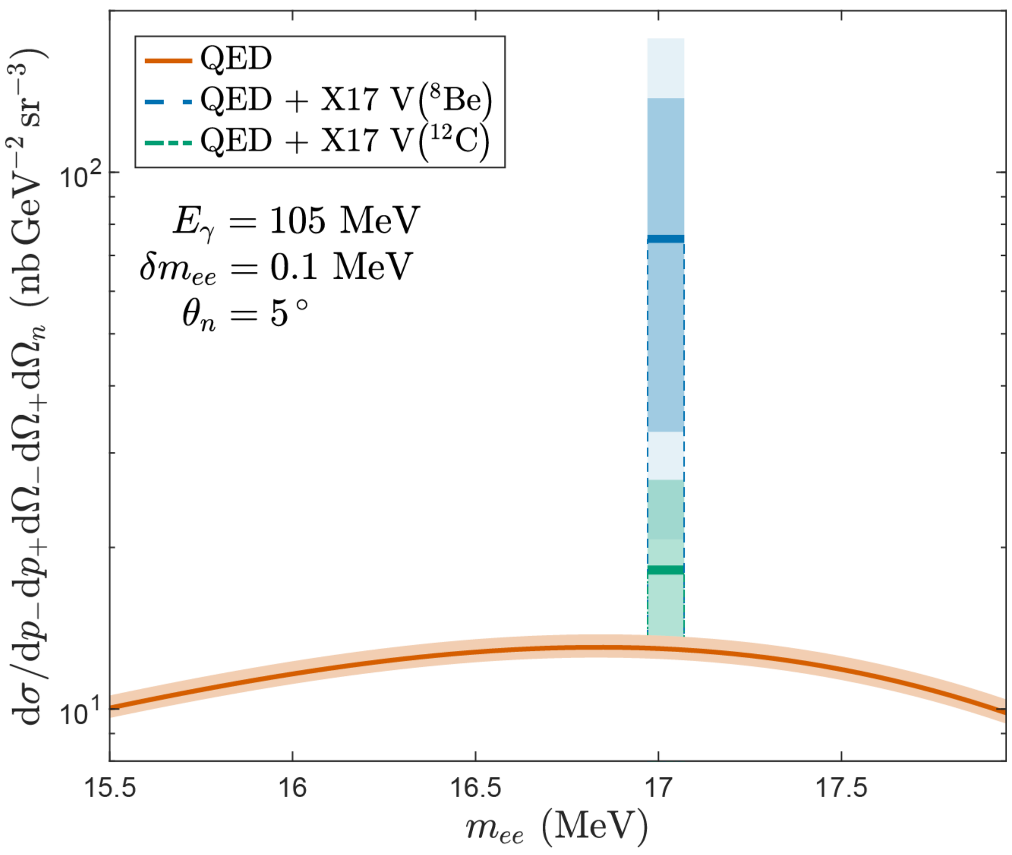


- Sensitivity MESA: δm_{ee} = 0.1 MeV

Results (I)

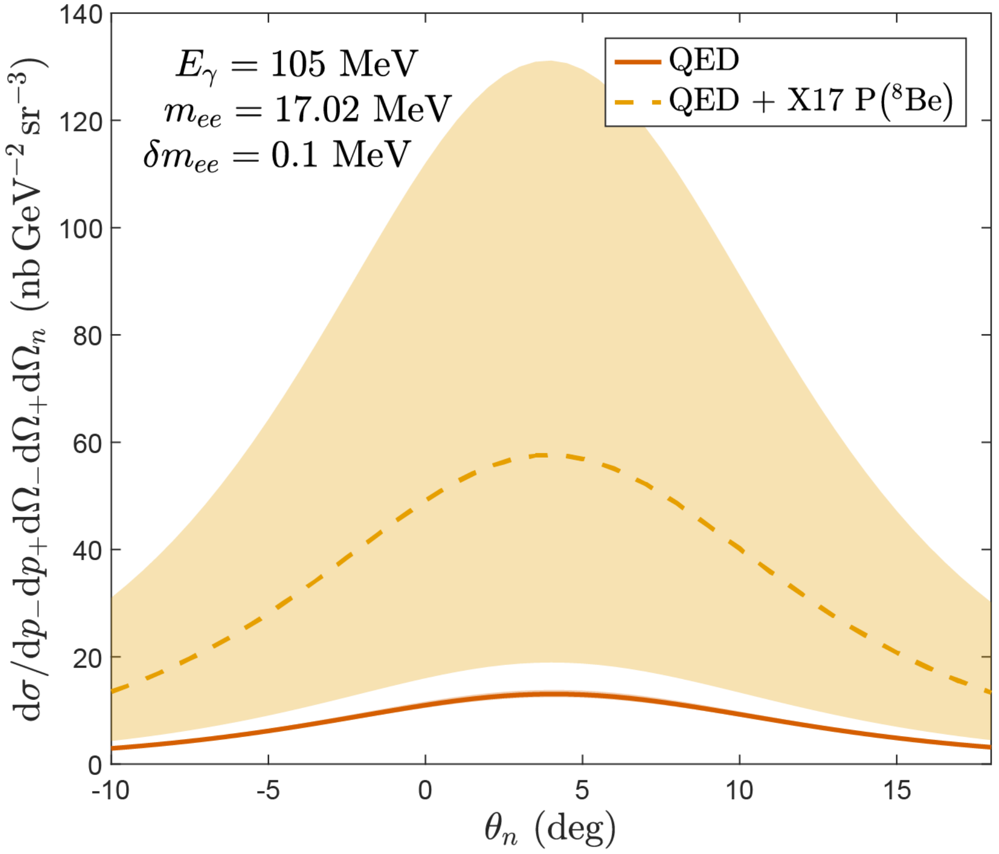


$E_\gamma = 105$ MeV
$m_{ee} = 17.02$ MeV
$\delta m_{ee} = 0.1$ MeV
QED
QED + X17 V(^{8}Be)
QED + X17 V(^{12}C)
$d\sigma/dp_- dp_+ d\Omega_- d\Omega_+ d\Omega_n$ (nb GeV^{-2} sr^{-3})
θ_n (deg)



QED
QED + X17 V(^{8}Be)
QED + X17 V(^{12}C)
$E_\gamma = 105$ MeV
$\delta m_{ee} = 0.1$ MeV
$\theta_n = 5°$
$d\sigma/dp_- dp_+ d\Omega_- d\Omega_+ d\Omega_n$ (nb GeV^{-2} sr^{-3})
m_{ee} (MeV)

Results (II)



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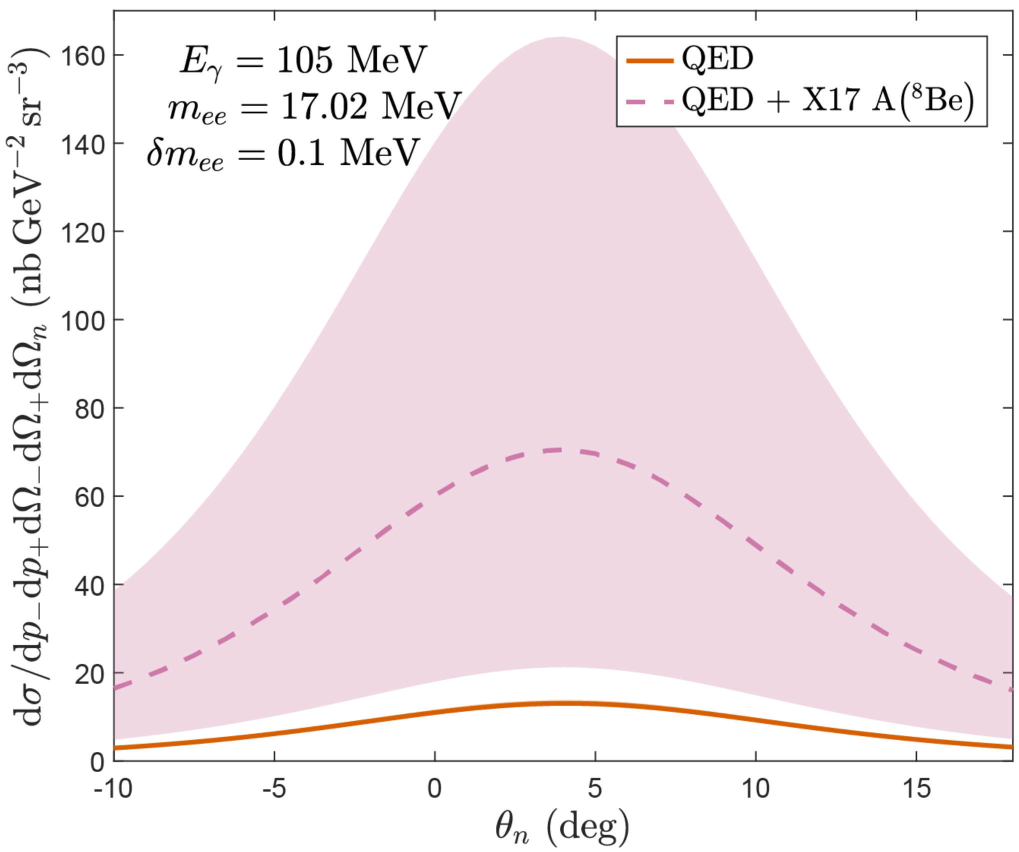
QED
QED + X17 P(^{8}Be)
$d\sigma/dp_- dp_+ d\Omega_- d\Omega_+ d\Omega_n$ (nb GeV^{-2} sr^{-3})
θ_n (deg)
140
120
100
80
60
40
20
0
-10
-5
0
5
10
15



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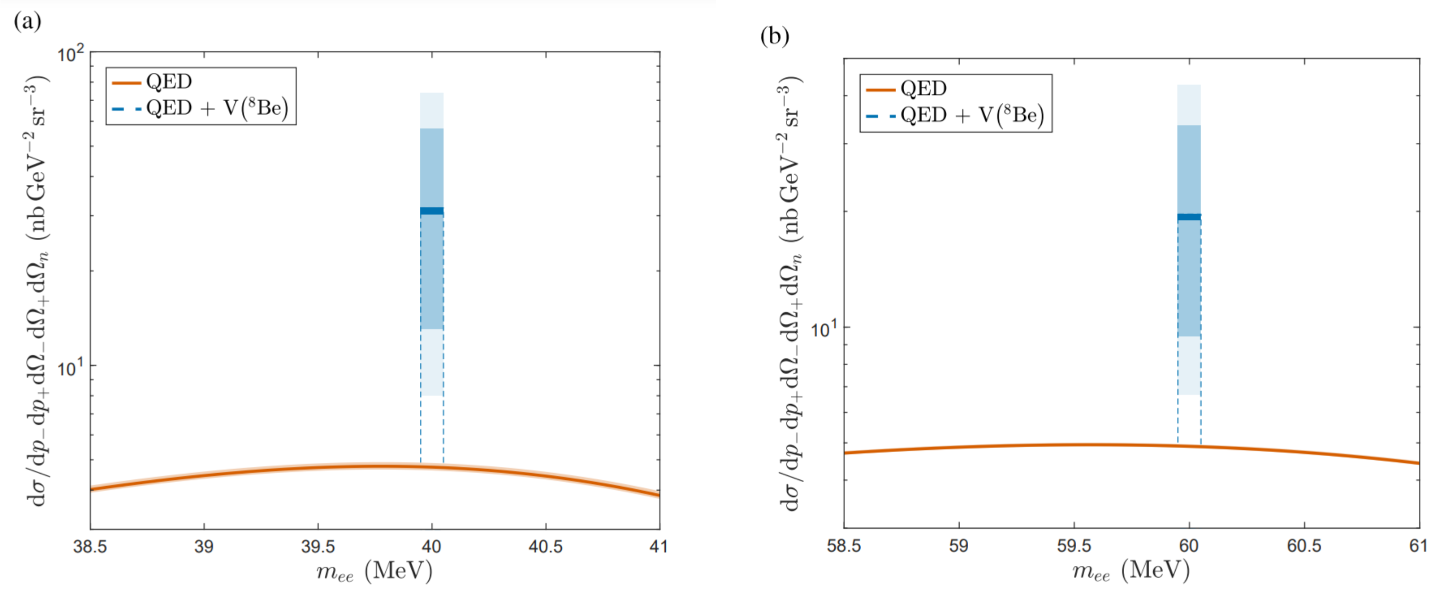
$\delta m_{ee} = 0.1$ MeV
QED
QED + X17 A(^{8}Be)
$d\sigma/dp_- dp_+ d\Omega_- d\Omega_+ d\Omega_n$ (nb GeV^{-2} sr^{-3})
θ_n (deg)
160
140
120
100
80
60
40
20
0
-10
-5
0
5
10
15

Outlook

- Not limited to X17 – can draw exclusion limits (see e.g., Phys. Rev. D 89, 055006 [2014])



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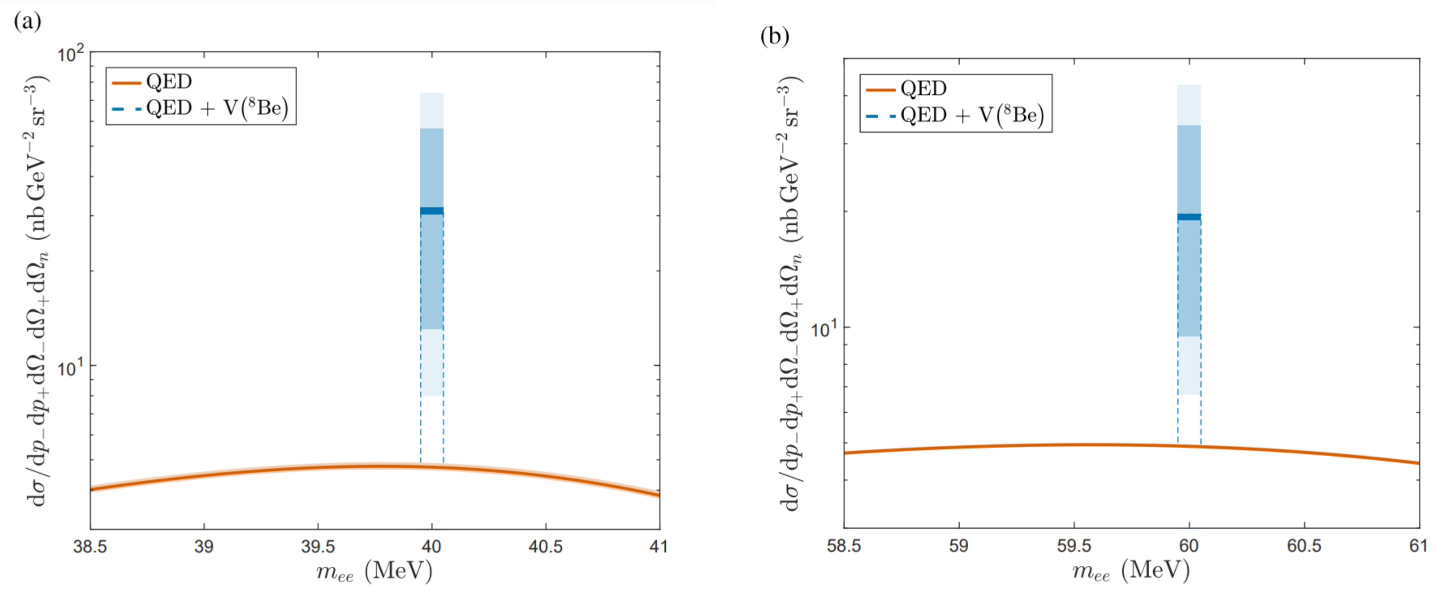

$$\varepsilon_u = (2\varepsilon_p - \varepsilon_n)/3 \quad \varepsilon_d = (2\varepsilon_n - \varepsilon_p)/3$$

Outlook

- Potential spin-off:
  using same measurement data to get neutron polarizabilities

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  Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$
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- *n*:

$$\text{Electric polarizability } \alpha = (11.8 \pm 1.1) \times 10^{-4}\ \text{fm}^3$$
$$\text{Magnetic polarizability } \beta = (3.7 \pm 1.2) \times 10^{-4}\ \text{fm}^3$$

PDG

Outlook

- Potential spin-off:
  using same measurement data to get neutron polarizabilities

Photon Scattering on Quasi-Free Neutrons in the Reaction $\gamma d \to \gamma' np$ and Neutron Polarizabilities

M. I. Levchuk[1], A. I. L'vov[2], and V. A. Petrun'kin[2]

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[2] P. N. Lebedev Physical Institute, Russian Academy of Sciences, Leninsky Prospect 53, Moscow 117924, Russia

Neutron Polarizabilities Investigated by Quasifree Compton Scattering from the Deuteron

K. Kossert,[1] M. Camen,[1] F. Wissmann,[1] J. Ahrens,[2] J. R. M. Annand,[3] H.-J Arends,[2] R. Beck,[2] G. Caselotti,[2] P. Grabmayr,[4] O. Jahn,[2] P. Jennewein,[2] M. I. Levchuk,[5] A. I. L'vov,[6] J. C. McGeorge,[3] A. Natter,[4] V. Olmos de León,[2] V. A. Petrun'kin,[6] G. Rosner,[3] M. Schumacher,[1] B. Seitz,[1] F. Smend,[1] A. Thomas,[2] W. Weihofen,[1] and F. Zapadtka[1]

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[6]*P. N. Lebedev Physical Institute, 117924 Moscow, Russia*
(Received 23 November 2001; published 8 April 2002)

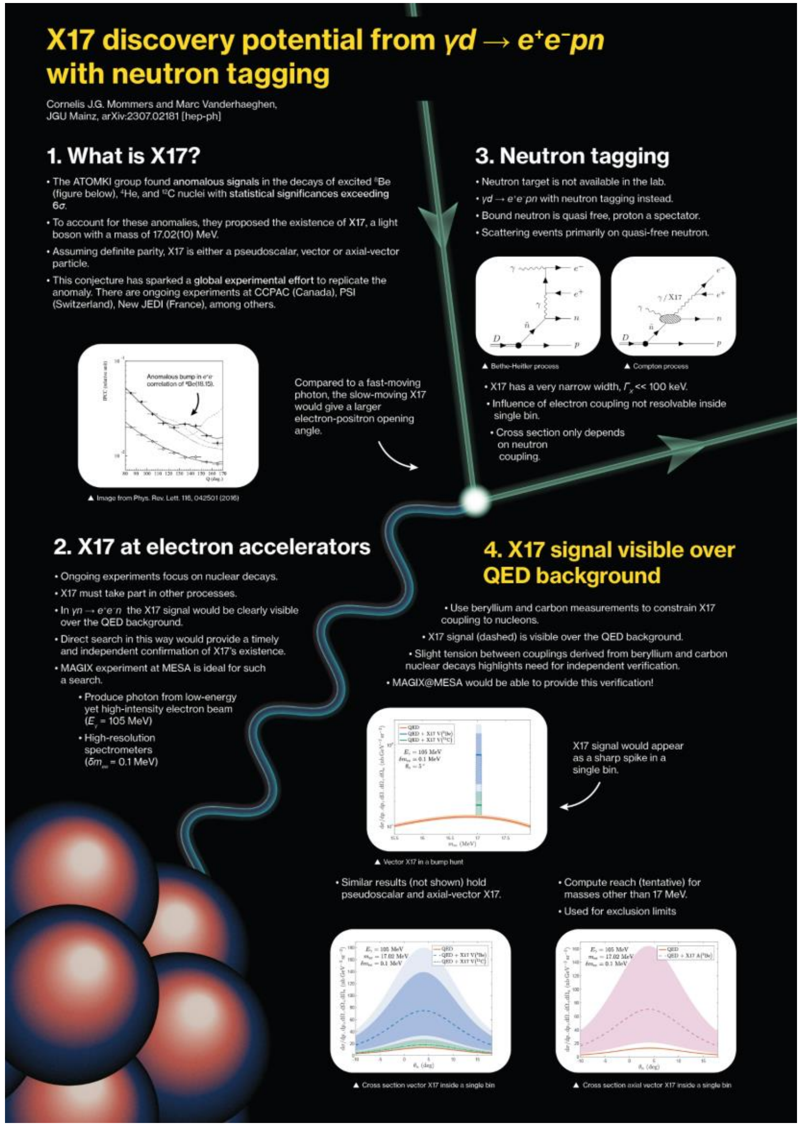
Summary

- ATOMKI anomaly is a smoking gun
- Much is still unclear, clear need for independent experiments
- MAGIX experiment at MESA is uniquely suited for a direct search using neutron tagging
- Calculation may be extended for exclusion plots

X17 discovery potential from $\gamma d \to e^+e^-pn$ with neutron tagging

Cornelis J.G. Mommers & Marc Vanderhaeghen
Johannes Gutenberg-Universität Mainz

arXiv:2307.02181 [hep-ph]



Bonus slides

Table ATOMKI decays

Ref.	State (MeV)	Transition (J^P)	
[2]–[4], [6]	^{8}Be(18.15)	$1^+ \to 0^+$	(M1, isoscalar)
[2]–[4], [6]	^{8}Be(17.64)	$1^+ \to 0^+$	(M1, isovector)
[5], [7]–[9]	^{4}He(21.01)	$0^- \to 0^+$	(M0)
[5], [7]–[9]	^{4}He(20.21)	$0^+ \to 0^+$	(E0)
[10]	^{12}C(17.23)	$1^- \to 0^+$	(E1, isovector)

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)	$17.03 \pm 0.11(\text{stat}) \pm 0.20(\text{syst})$	$1.6(1) \times 10^{-4}$	$3.6(3) \times 10^{-6}$

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: $\frac{\Gamma^{^8\mathrm{Be}}_X}{\Gamma^{\mathrm{M1}}_\gamma} = \frac{1}{2\pi\alpha} \left(\frac{g^{(0)}_{XNN}\cos\theta_{1+} - g^{(1)}_{XNN}\sin\theta_{1+}}{[\mu^{(0)} - \eta^{(0)}]\cos\theta_{1+} - [\mu^{(1)} - \eta^{(1)}]\sin\theta_{1+}} \right)^2 \left(\frac{k_X}{k_\gamma} \right)^3$

Deriving limits on couplings (V)

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

- 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)

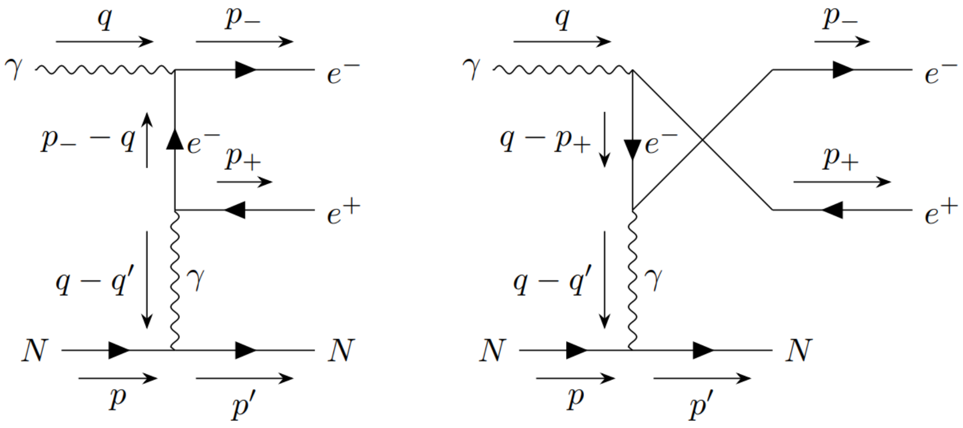


Figure 2: The direct and crossed diagram for the BH process.

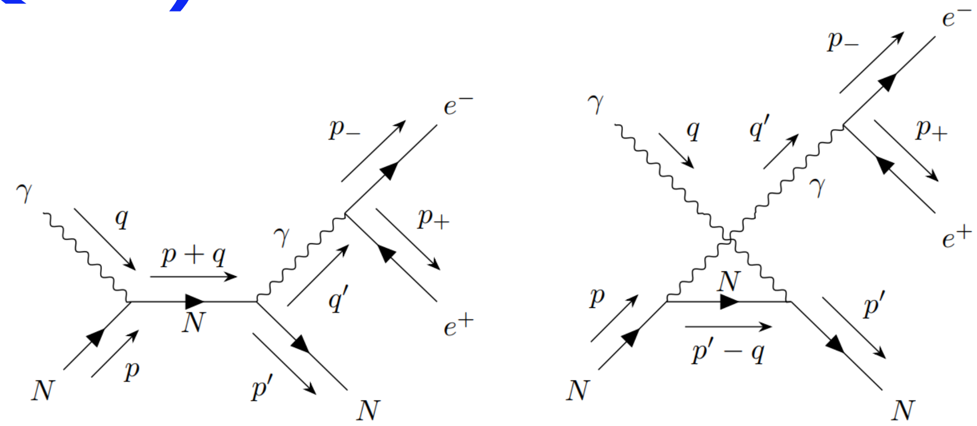


Figure 1: The direct and crossed diagram for the Born process.

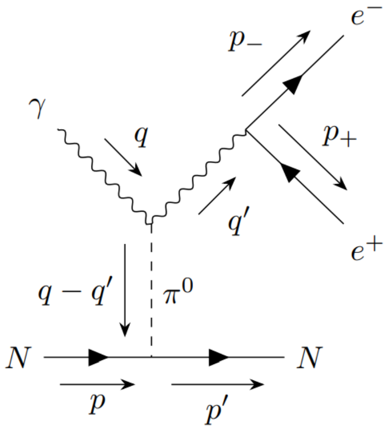
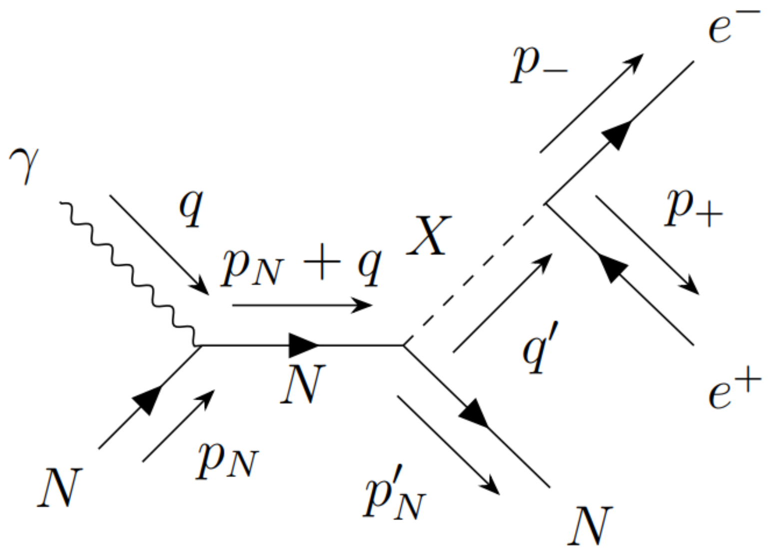
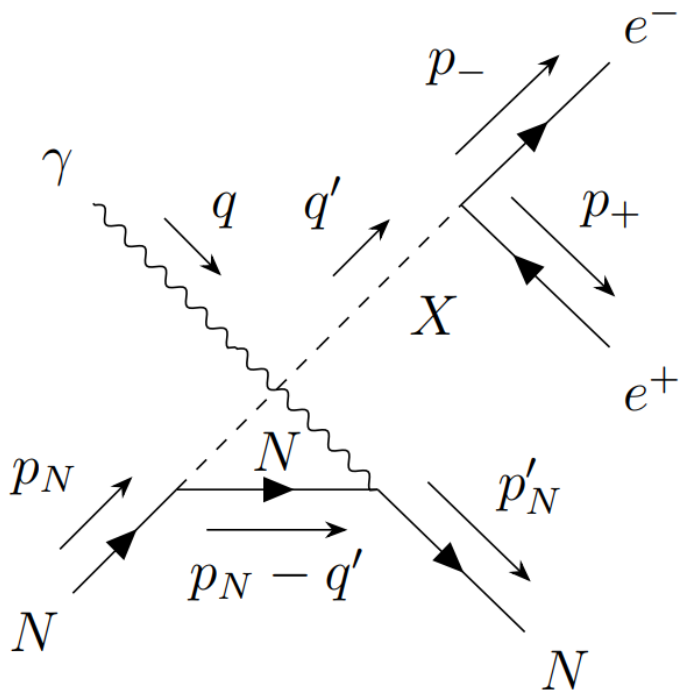


Figure 3: The diagram for the pion-pole amplitude.

X17 discovery potential from $\gamma d \to e^+ e^- pn$, Cornelis J.G. Mommers & Marc Vanderhaeghen, arXiv:2307.02181 [hep-ph]

Diagrams in detail (signal)

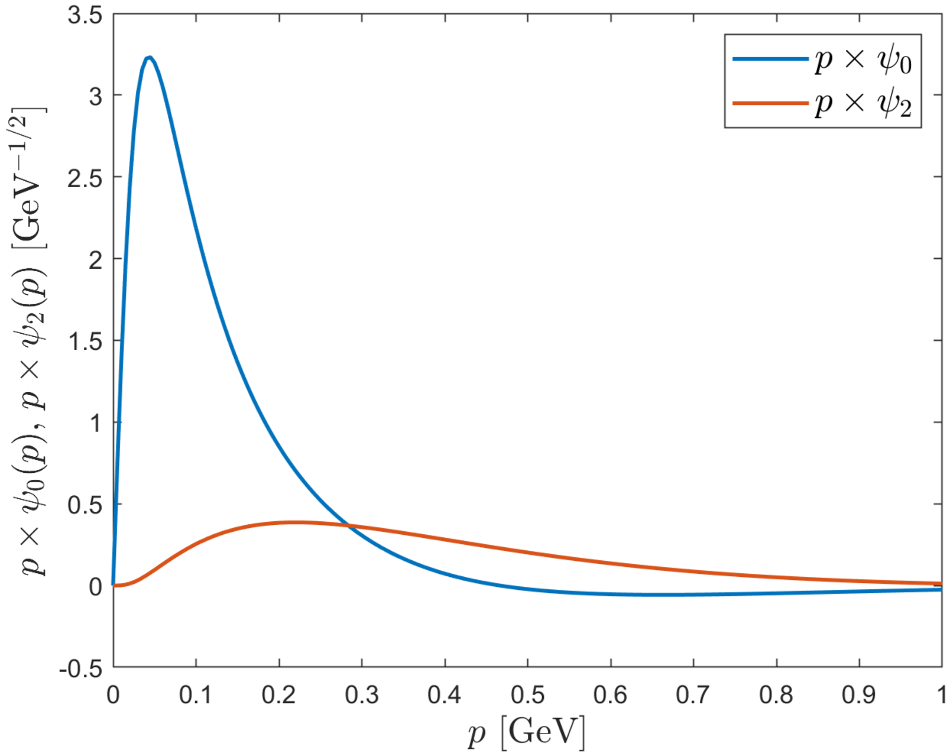




Deuteron wave function

- Use CD-Bonn wave function in momentum space (DOI: [10.1103/PhysRevC.63.024001](https://doi.org/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

$$\mathcal{M}^{\text{lab}}_{\text{IA}}(d\gamma \to e^+e^-pn) = \frac{(2\pi)^{3/2}(2m_d)^{1/2}}{\sqrt{2}}$$

$$\times \Bigg\{ \left(\frac{E^{(n)}_{p_n}}{E^{(p)}_{p_n}}\right)^{1/2} \Bigg[\mathcal{M}\left(\gamma(\boldsymbol{q},\lambda)\, p(-\boldsymbol{p}_n, m_d - s_n) \to e^-(\boldsymbol{p}_-, s_-)\, e^+(\boldsymbol{p}_+, s_+)\, p(\boldsymbol{p}_p, s_p)\right)$$

$$\times \frac{1}{\sqrt{4\pi}}\psi_0(p_n)\, \langle \tfrac{1}{2}\,\tfrac{1}{2}\,;\, m_d - s_n\, s_n \,|\, 1 m_d\rangle$$

$$- \sum_{m_s=-1}^{+1} \mathcal{M}\left(\gamma(\boldsymbol{q},\lambda)\, p(-\boldsymbol{p}_n, m_s - s_n) \to e^-(\boldsymbol{p}_-, s_-)\, e^+(\boldsymbol{p}_+, s_+)\, p(\boldsymbol{p}_p, s_p)\right)$$

$$\times Y_2^{m_d - m_s}(-\hat{\mathbf{p}}_n)\psi_2(p_n)\, \langle 2\, 1\,;\, m_d - m_s\, m_s \,|\, 1\, m_d\rangle\, \langle \tfrac{1}{2}\,\tfrac{1}{2}\,;\, m_s - s_n\, s_n \,|\, 1\, m_s\rangle \Bigg]$$

$$+ \left(\frac{E^{(p)}_{p_p}}{E^{(n)}_{p_p}}\right)^{1/2} \Bigg[\mathcal{M}\left(\gamma(\boldsymbol{q},\lambda)\, n(-\boldsymbol{p}_p, m_d - s_p) \to e^-(\boldsymbol{p}_-, s_-)\, e^+(\boldsymbol{p}_+, s_+)\, n(\boldsymbol{p}_n, s_n)\right)$$

$$\times \frac{1}{\sqrt{4\pi}}\psi_0(p_p)\, \langle \tfrac{1}{2}\,\tfrac{1}{2}\,;\, s_p\, m_d - s_p \,|\, 1 m_d\rangle$$

$$- \sum_{m_s=-1}^{+1} \mathcal{M}\left(\gamma(\boldsymbol{q},\lambda)\, n(-\boldsymbol{p}_p, m_s - s_p) \to e^-(\boldsymbol{p}_-, s_-)\, e^+(\boldsymbol{p}_+, s_+)\, n(\boldsymbol{p}_n, s_n)\right)$$

$$\times Y_2^{m_d - m_s}(\hat{\mathbf{p}}_p)\psi_2(p_p)\, \langle 2\, 1\,;\, m_d - m_s\, m_s \,|\, 1\, m_d\rangle\, \langle \tfrac{1}{2}\,\tfrac{1}{2}\,;\, s_p\, m_s - s_p \,|\, 1\, m_s\rangle \Bigg]\Bigg\}.$$

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

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

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

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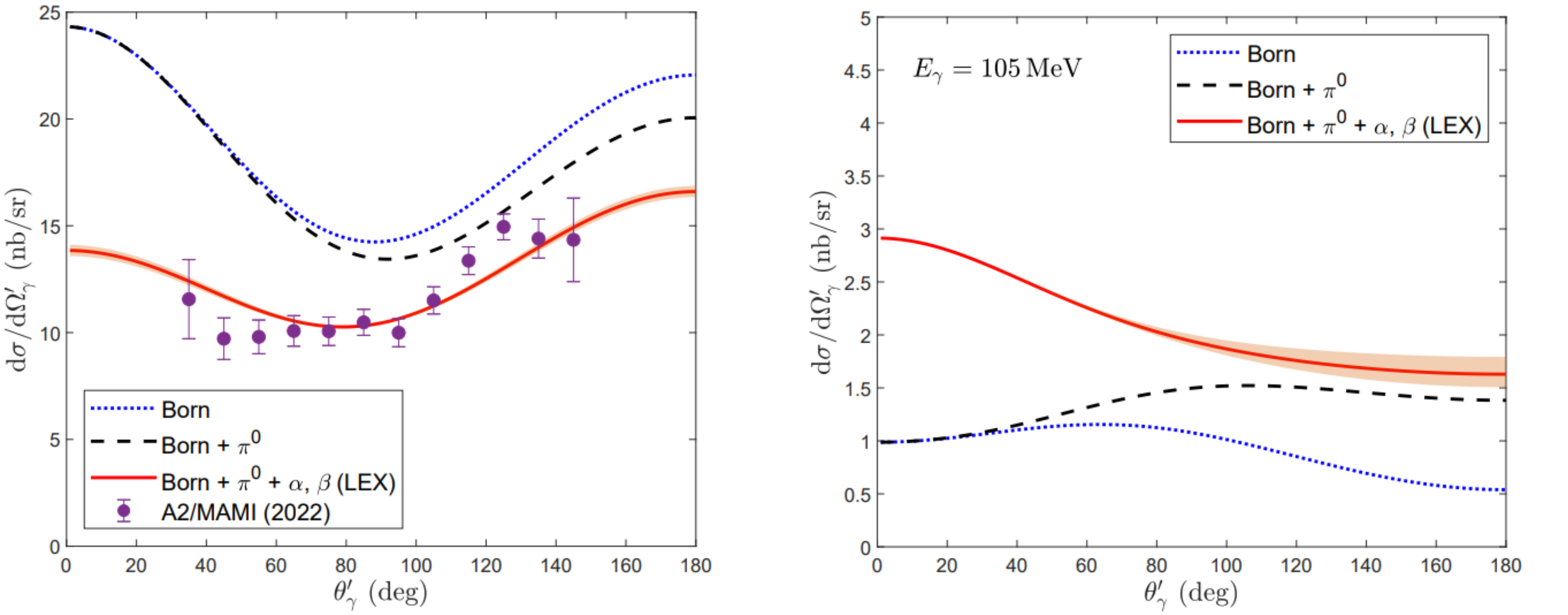
$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}\right|_{\text{measured}}$$

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

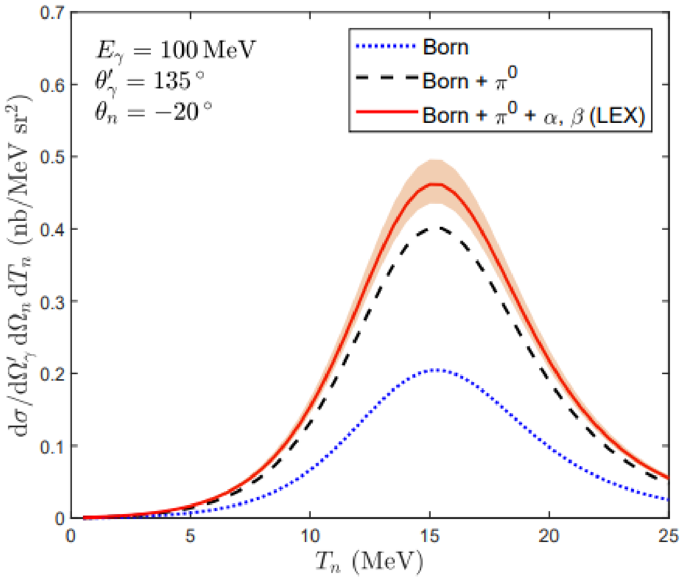
Verifying the QED background (I)



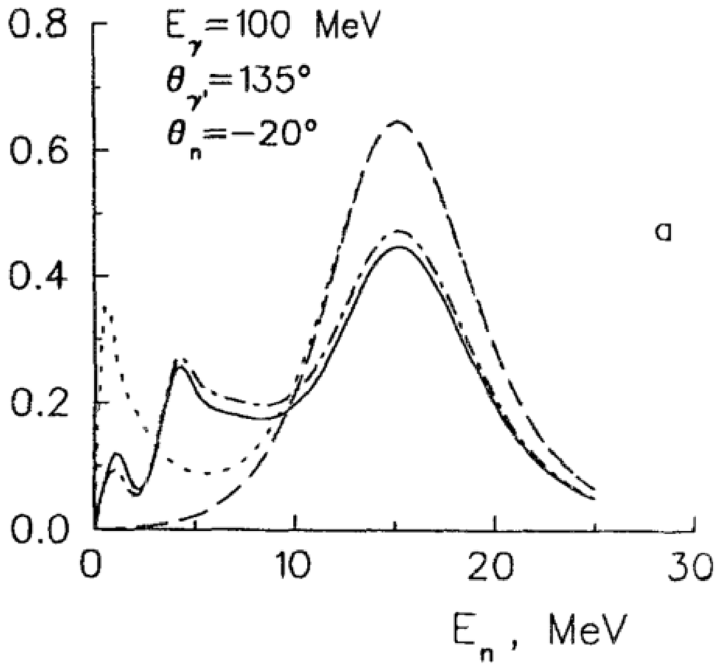
(a) $\gamma p \to \gamma p$ (b) $\gamma n \to \gamma n$

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])

Optimizing kinematics

1. $|\boldsymbol{p}_p| < (m_N\,\Delta)^{1/2} \sim 45.7$ MeV/c
2. $15\,° < |\theta_i| < 165\,°$, $i = +, -$
3. $5\,° < |\theta_n| < 165\,°$,
4. $|\boldsymbol{p}_\pm| > 20$ MeV/c

- Scan parameter range
- Find maximum
- Fine tune parameters