

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

Cornelis J.G. Mommers & Marc Vanderhaeghen

Johannes Gutenberg-Universität Mainz

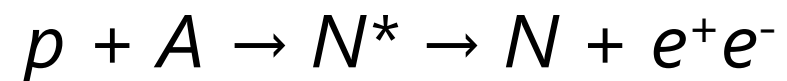
arXiv:2307.02181 [hep-ph]

# Outline

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

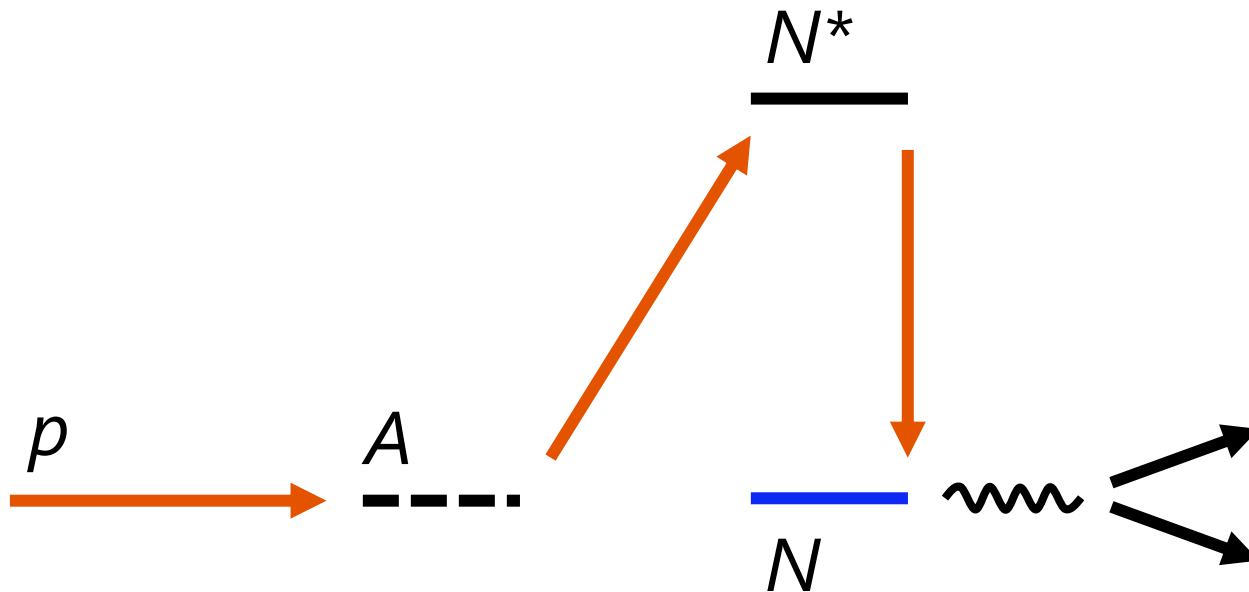
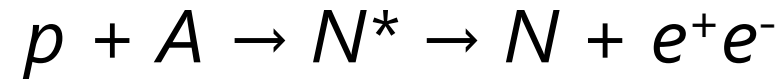
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- ATOMKI experiment:



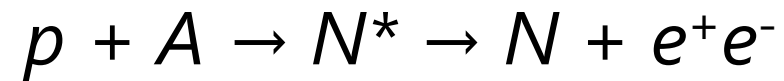
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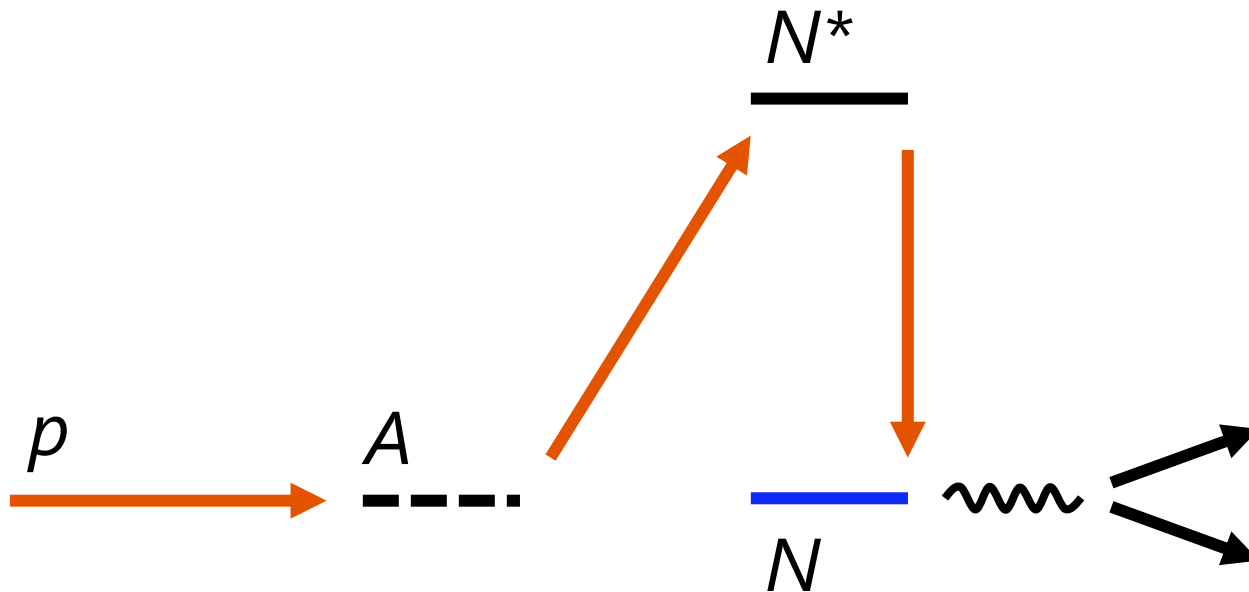


# What is X17?

- ATOMKI experiment:



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



# What is X17?

- New particle conjectured to explain ATOMKI anomaly

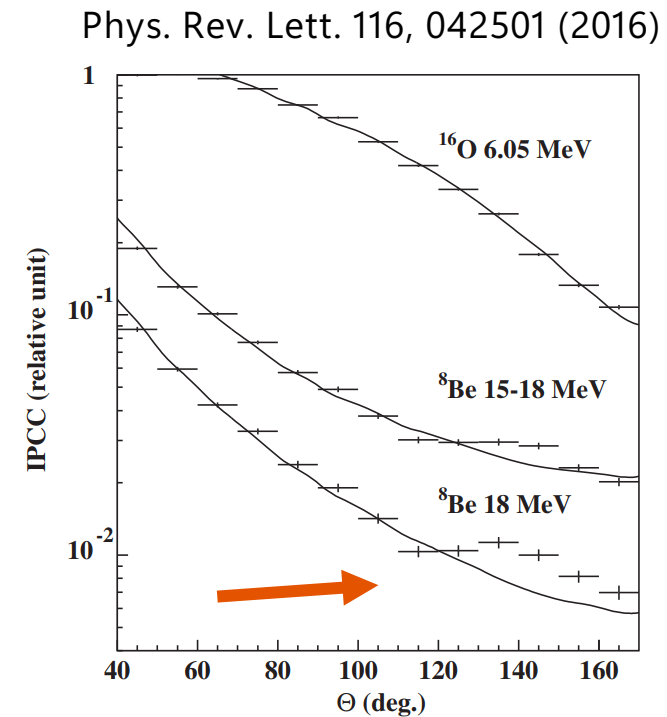
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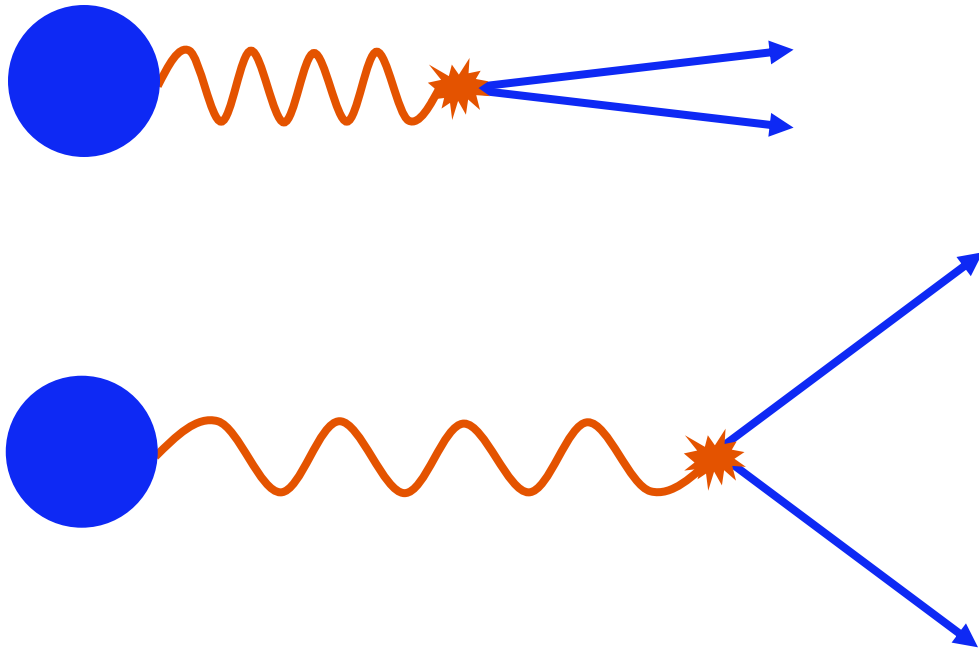
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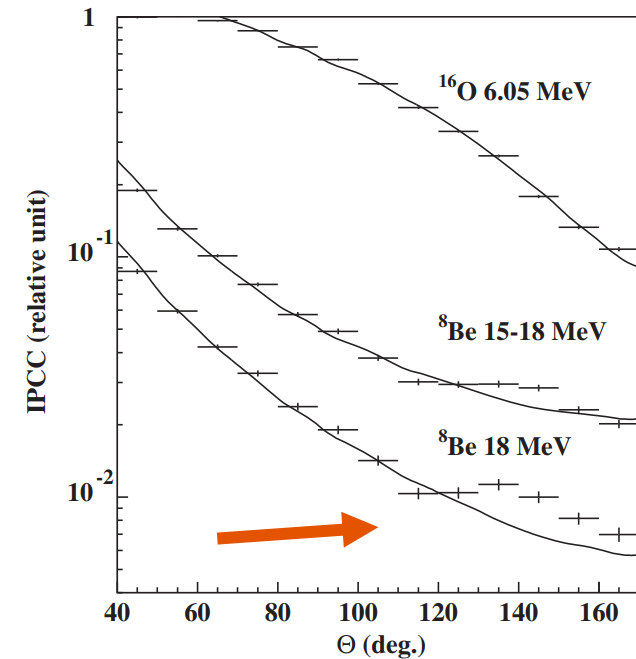


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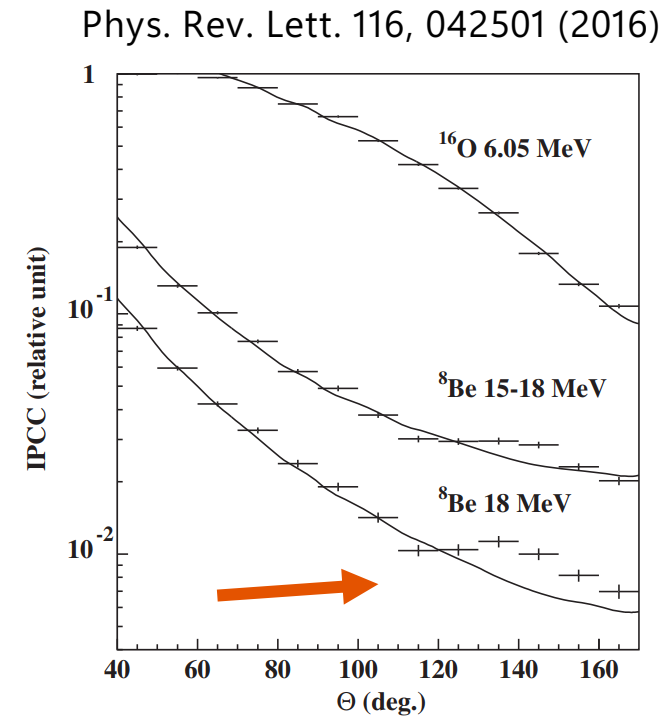


Phys. Rev. Lett. 116, 042501 (2016)



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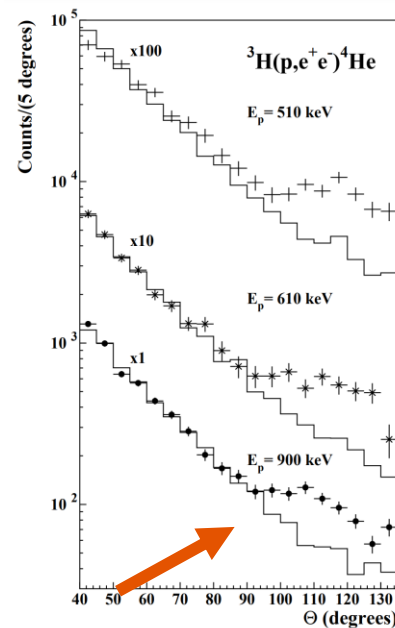
- $\sim 17$  MeV boson also fits the other data (!)



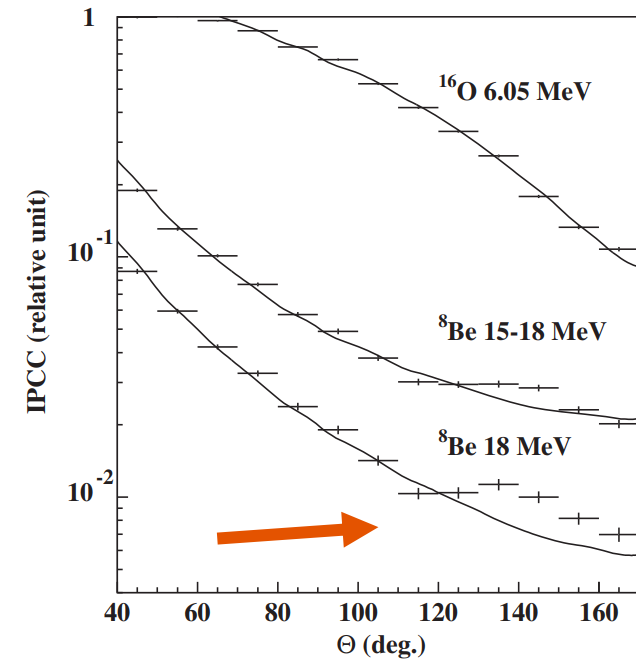
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Phys. Rev. C 104, 044003 (2021)



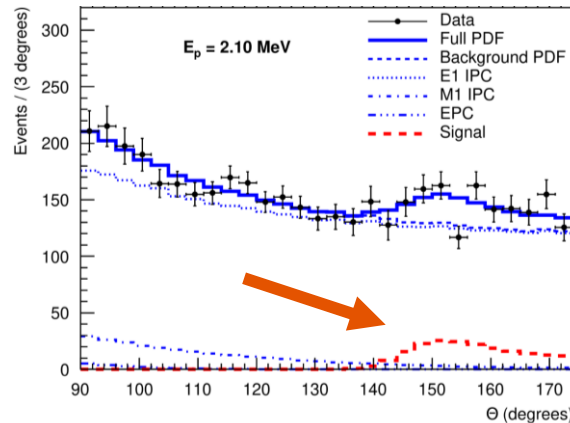
Phys. Rev. Lett. 116, 042501 (2016)



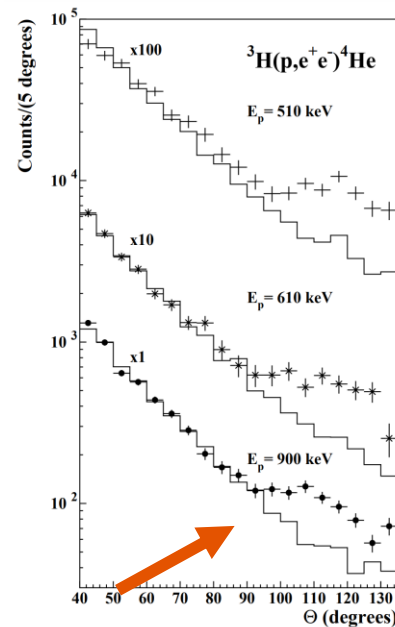
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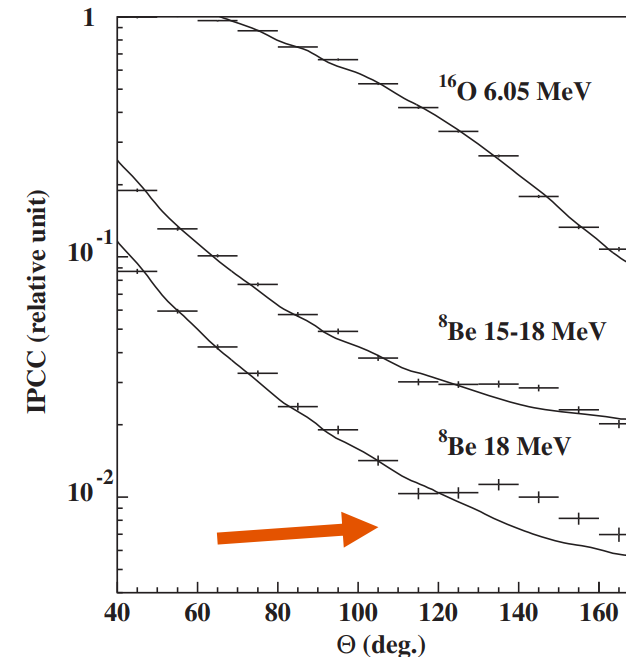
Phys. Rev. C 106, L061601 (2022)



Phys. Rev. C 104, 044003 (2021)



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



# Continued interest...

PRL **116**, 042501 (2016)

PHYSICAL REVIEW LETTERS

week ending  
29 JANUARY 2016

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

A. J. Krasznahorkay,<sup>\*</sup> M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyai, and Zs. Vajta  
*Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary*

T. J. Ketel  
*Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands*

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*CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary*  
(Received 7 April 2015; published 26 January 2016)

# Continued interest...

PRL 116, 042501 (2016)

PHYSICAL

week ending  
29 JANUARY 2016

Observation of Anomalous

ON THE X(17) LIGHT-PARTICLE CANDIDATE  
OBSERVED IN NUCLEAR TRANSITIONS\*

of a Light,

A. J. Timár

In

Timár, J. Timár,

Hungary

A.J. KRASZNAHORKAY, M. CSATLÓS, L. CSIGE, D. FIRAK, J. GULYÁS  
Á. NAGY, N. SAS, J. TIMÁR, T.G. TORNYI  
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki)  
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and

CERN, CH

A. KRASZNAHORKAY  
CERN, Geneva, Switzerland

Hungarian Academy of Sciences (MTA Atomki),

(Received November 21, 2015)

January 2016)

# Continued interest...

PRL 116, 042501 (2016)

Observation

A. J. ...

In

CERN, CH

PREPRINT  
PHYSICAL CANDIDATE  
TRANSITIONS\*  
K, J. GULYÁS  
**New results on the Be-8 anomaly**

week ending  
29 JANUARY 2016

of a Light,

. Timár,

ngary

A Atomki),

A.J. Krasznahorkay<sup>1\*</sup>, M. Csatlós<sup>1</sup>, L. Csige<sup>1</sup>, J. Gulyás<sup>1</sup>, M. Hunyadi<sup>1</sup>, T.J. Ketel<sup>2</sup>,  
A. Krasznahorkay<sup>3</sup>, I. Kuti<sup>1</sup>, Á. Nagy<sup>1</sup>, B.M. Nyakó<sup>1</sup>, N. Sas<sup>1</sup>, J. Timár<sup>1</sup>, I. Vajda<sup>1</sup>  
<sup>1</sup>Institute for Nuclear Research, Hungarian Academy of Sciences, MTA Atomki  
<sup>2</sup>Nikhef Nat. Inst. for Subatomic Phys., Science Park 105, 1098 XG Amsterdam, The Netherlands  
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E-mail: kraszna@atomki.hu

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CERN, Gen

(Received November 2015  
January 2016)

# Continued interest...

PRL 116, 042501 (2016)

Observation

A. J. Krasznahorkay  
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CERN

**New results on the B<sub>s</sub> meson candidate**  
**New evidence supporting the existence of the hypothetical X17 particle**

A.J. Krasznahorkay\*, M. Csatlós, L. Csige, J. Gulyás, M. Koszta, B. Szihalmi, and J. Timár  
Institute of Nuclear Research (Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

D.S. Firak, Á. Nagy, and N.J. Sas  
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A. Krasznahorkay  
CERN, Geneva, Switzerland and  
Institute of Nuclear Research, (Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

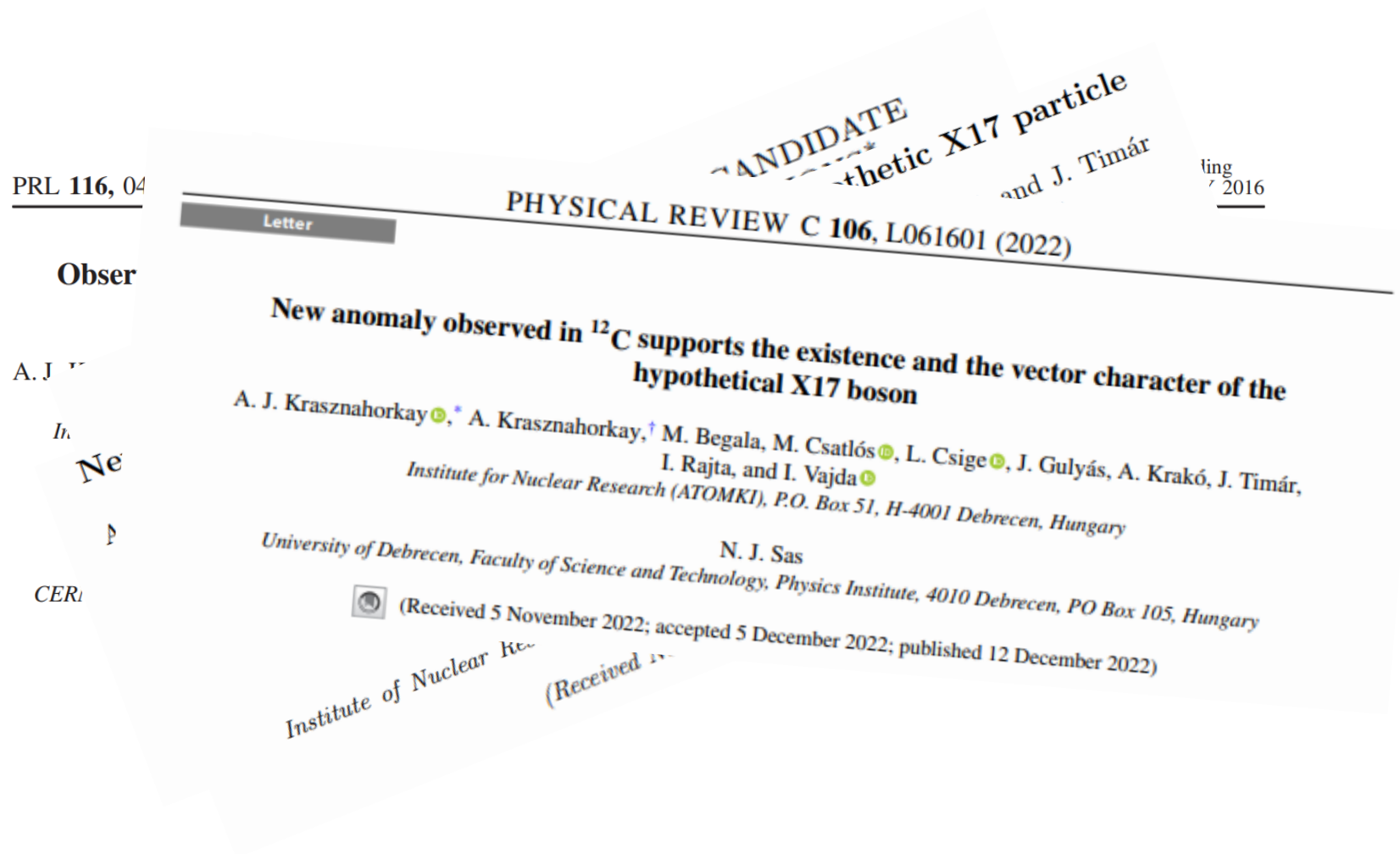
I. Vajda<sup>1</sup>,  
Radboud University Nijmegen, The Netherlands

(Received November 2, 2015)  
(January 2016)

January 2016



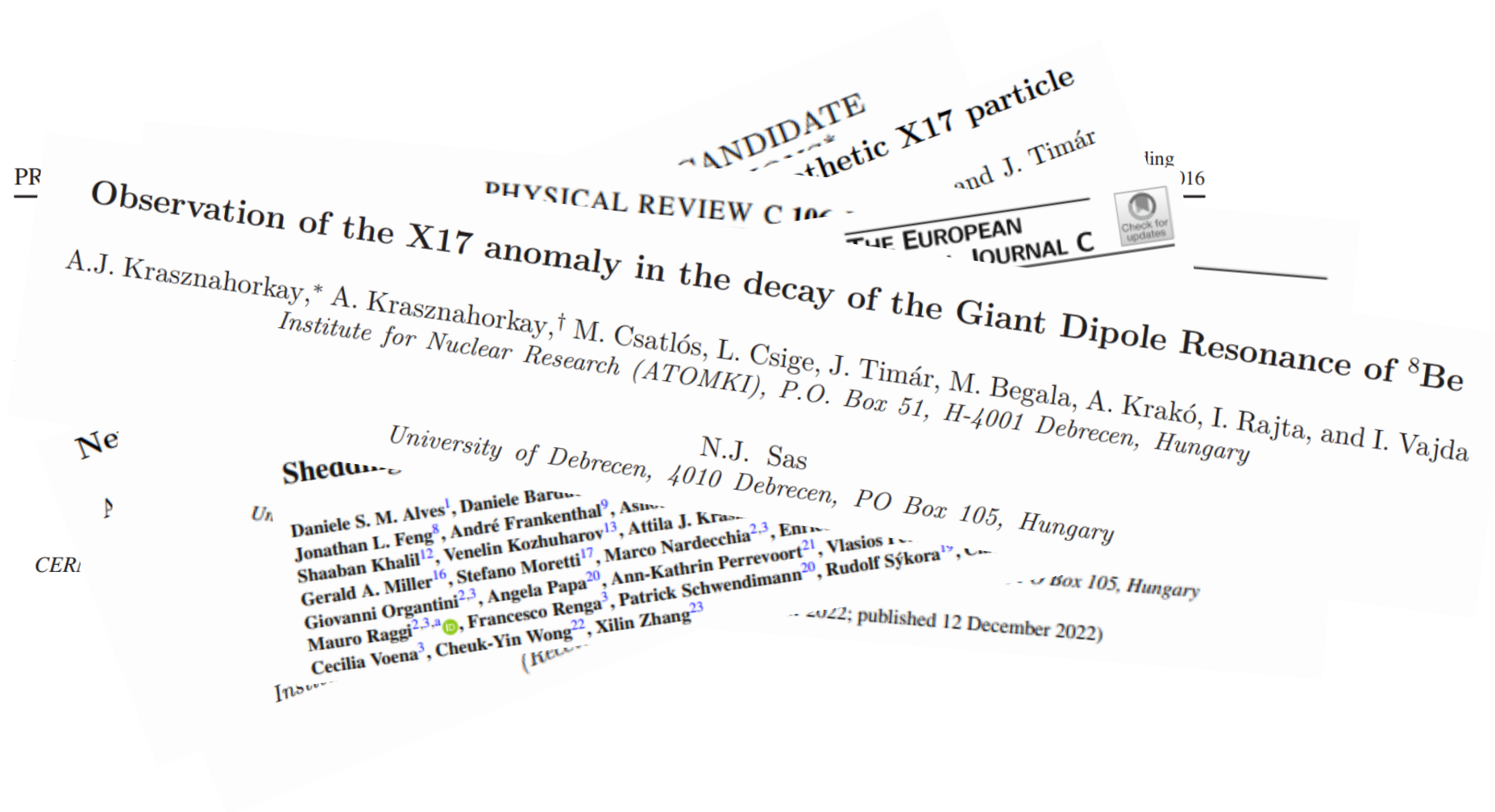
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$$J^P = 0^-, 1^+, 1^-$$

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

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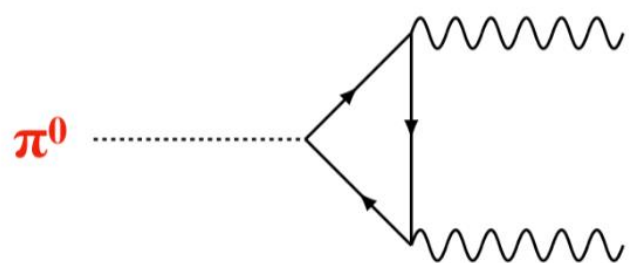
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${}^{12}\text{C}(17.23), 1^-$	✓		✓	✓

# Theory analysis

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

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

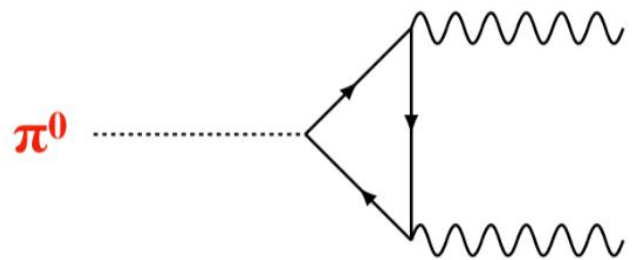


$$\propto |2\varepsilon_u + \varepsilon_d| = |\varepsilon_p|$$

# Theory analysis

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

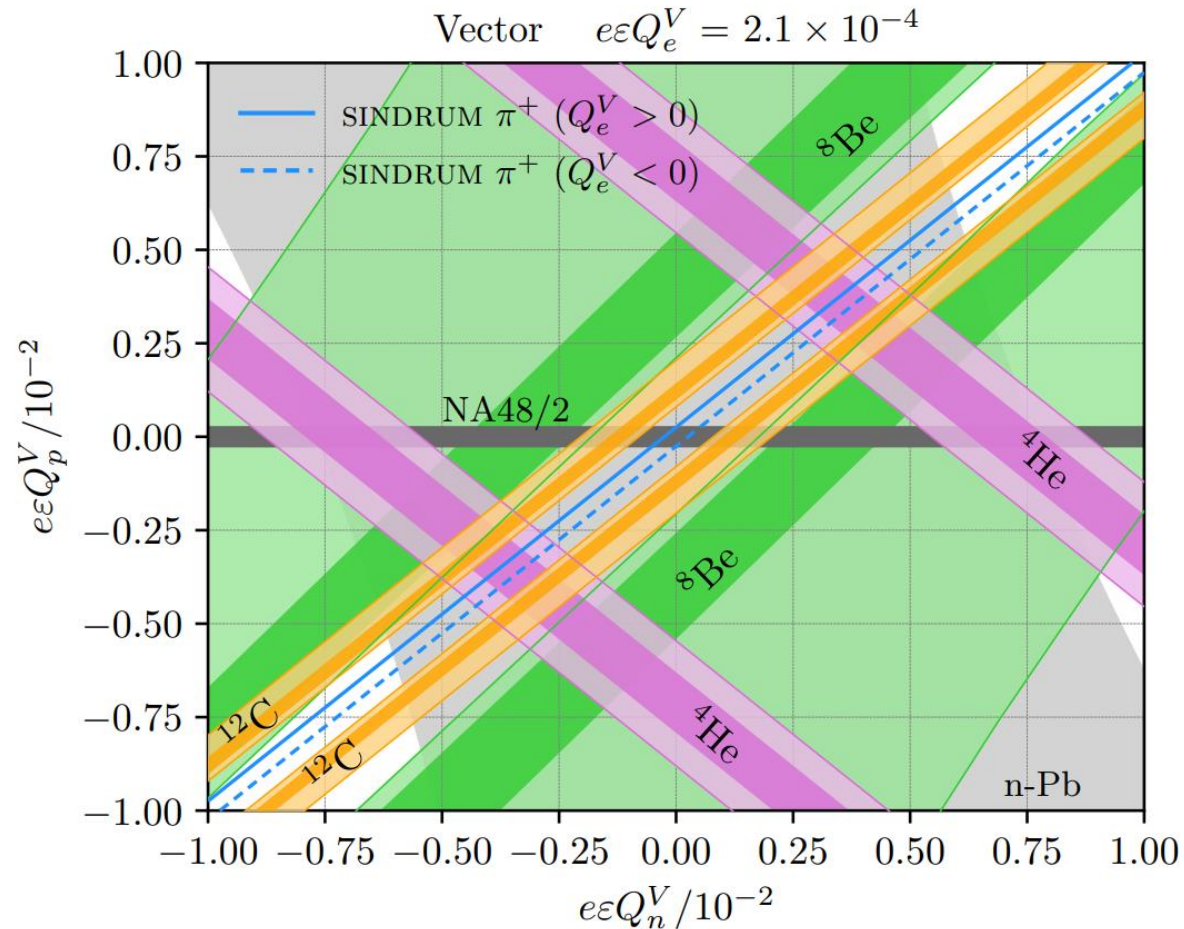
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# Many open questions

Phys. Rev. D 108, 055011 (20230)

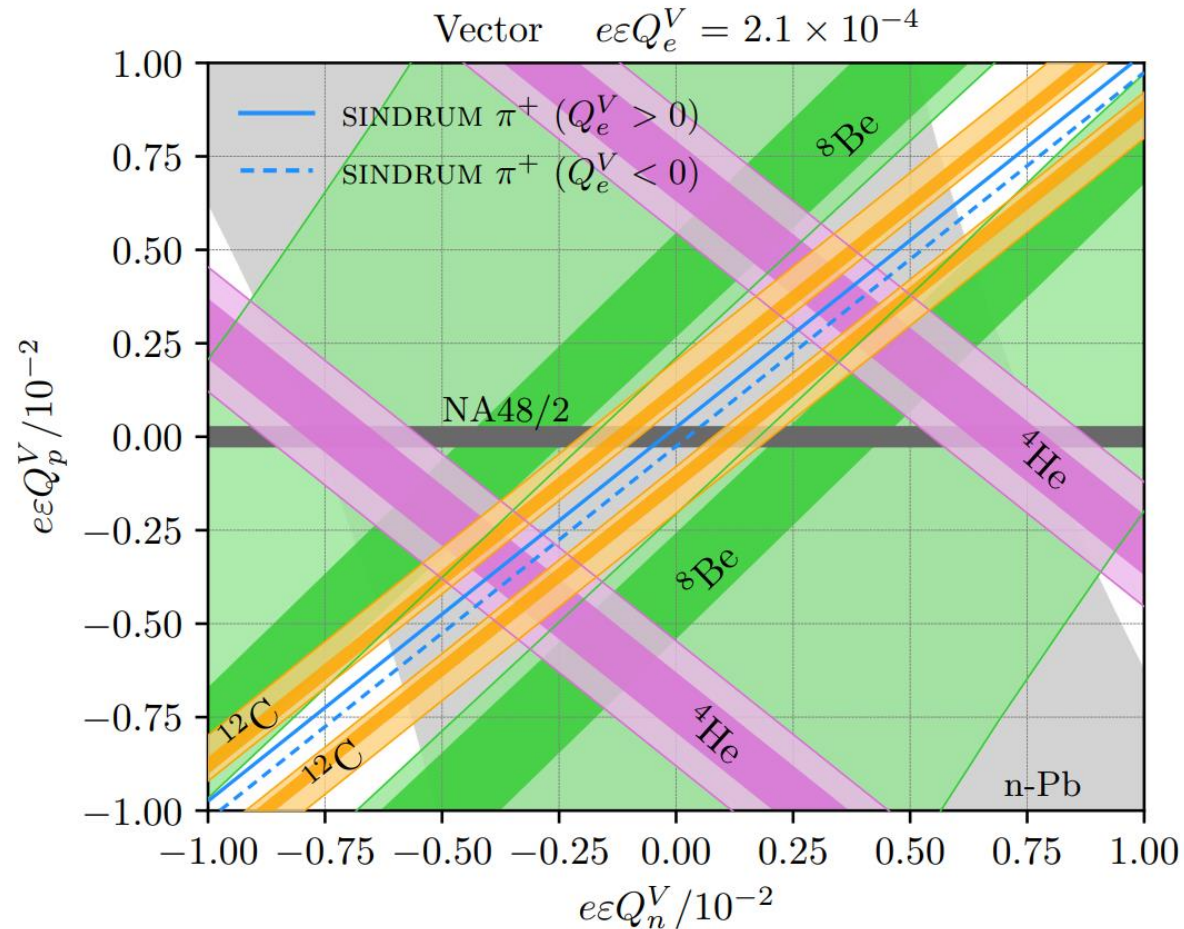


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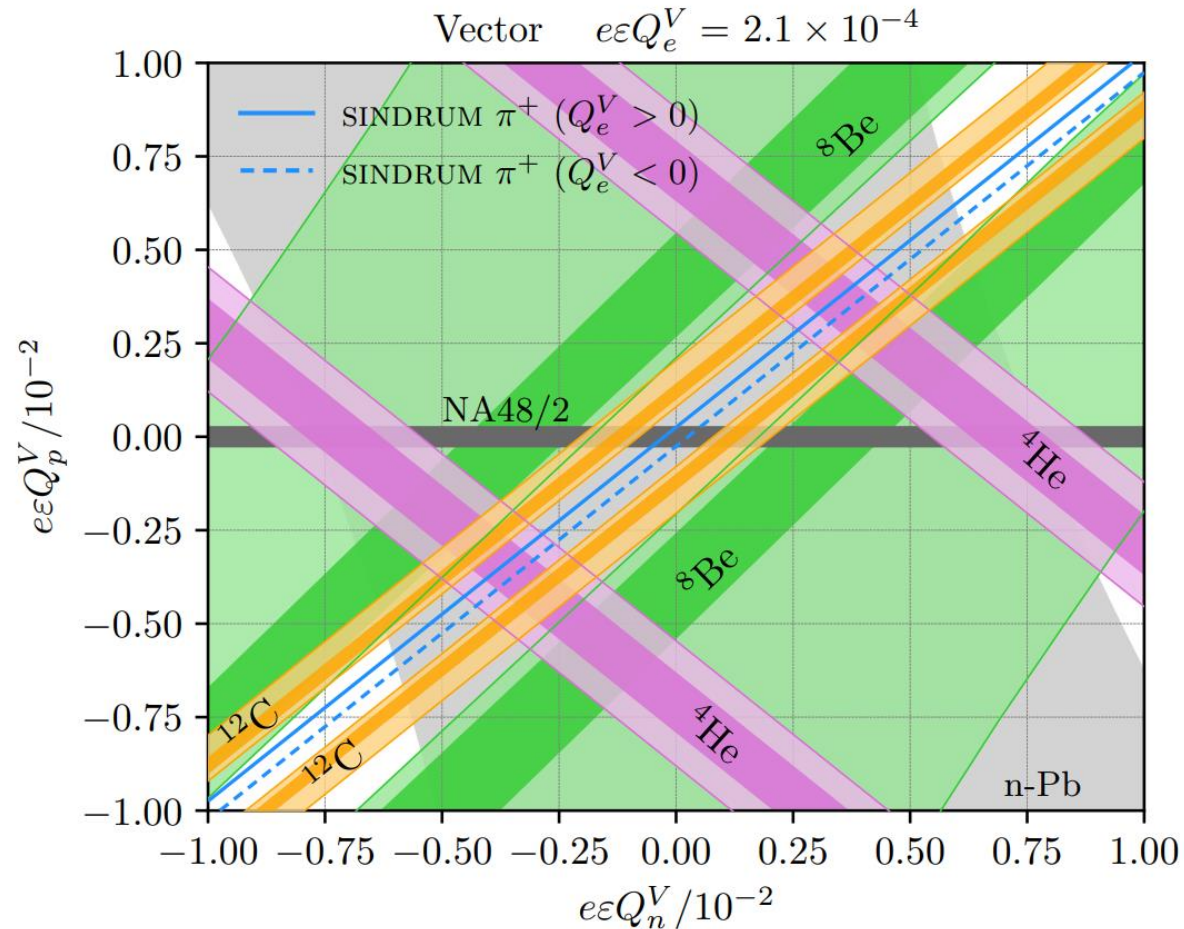
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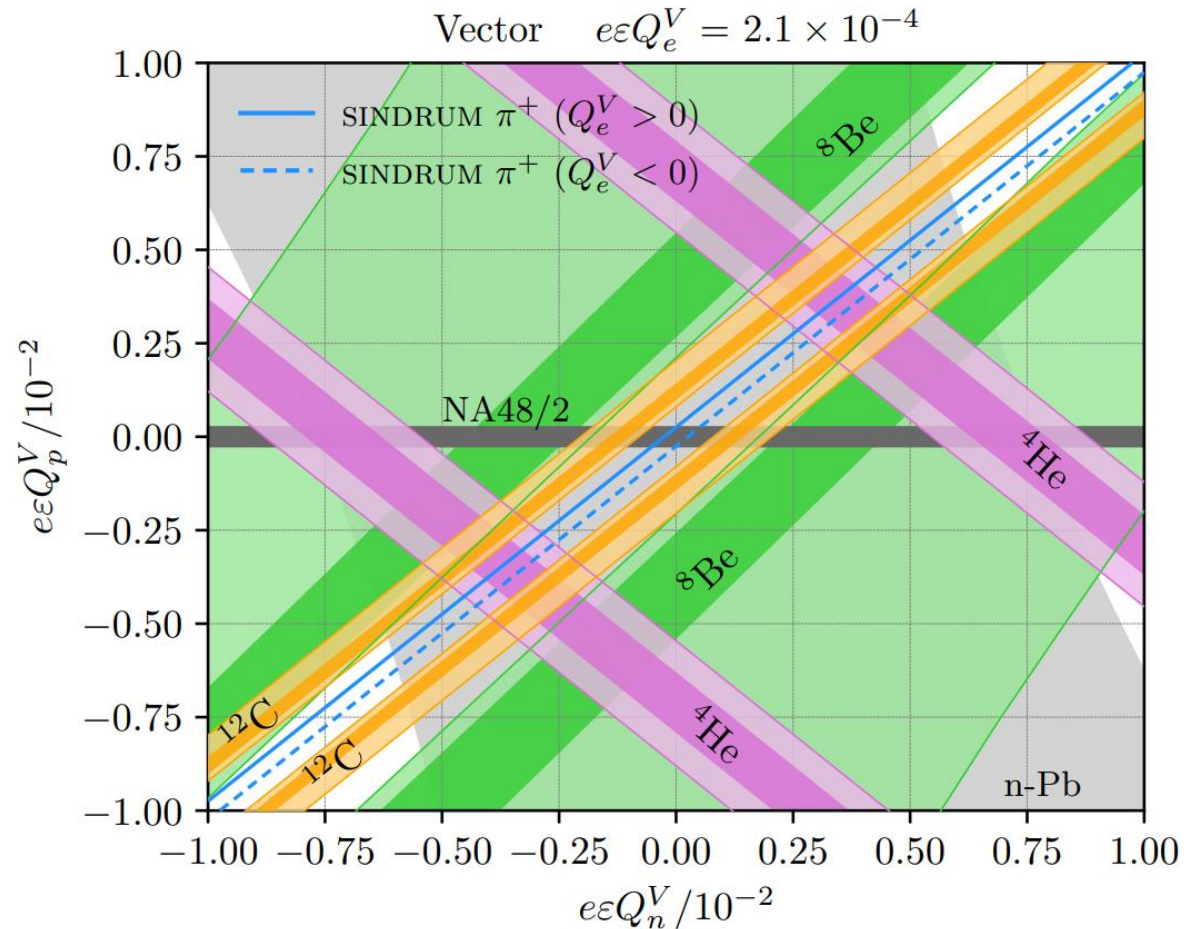
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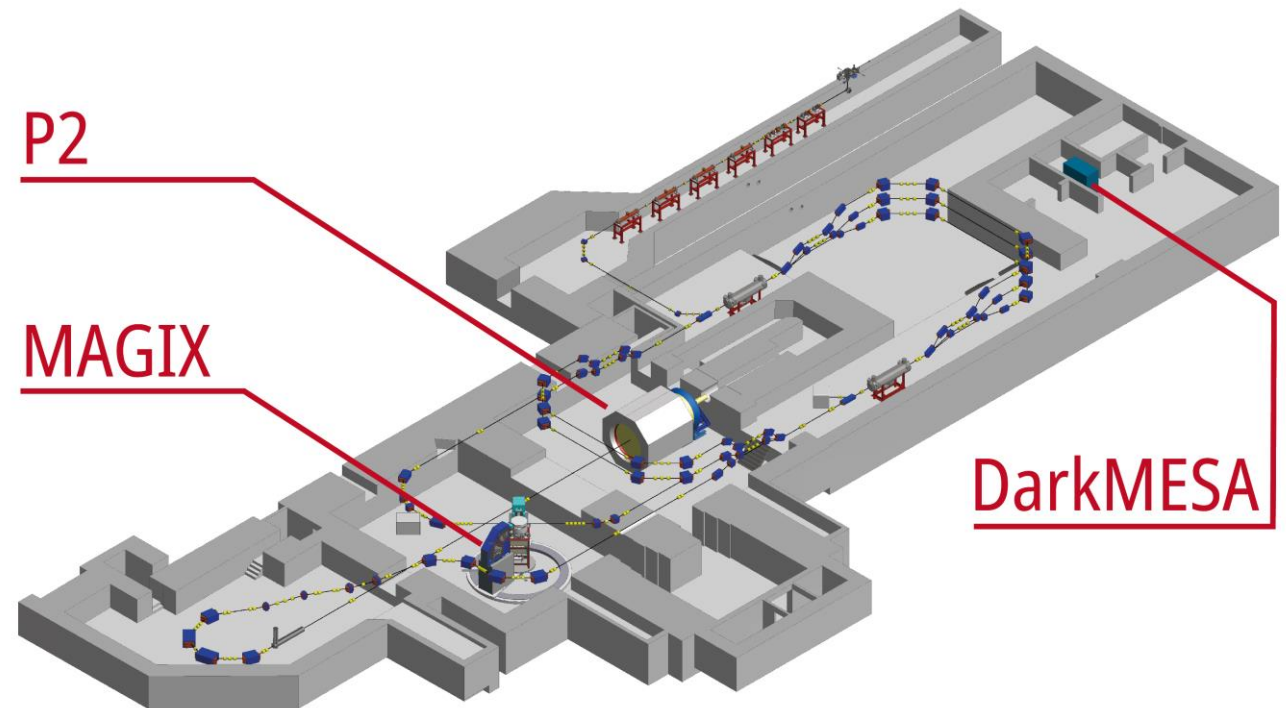


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- We propose a direct search at MAGIX experiment at MESA

# MAGIX@MESA

- MESA is a linear accelerator under construction in Mainz

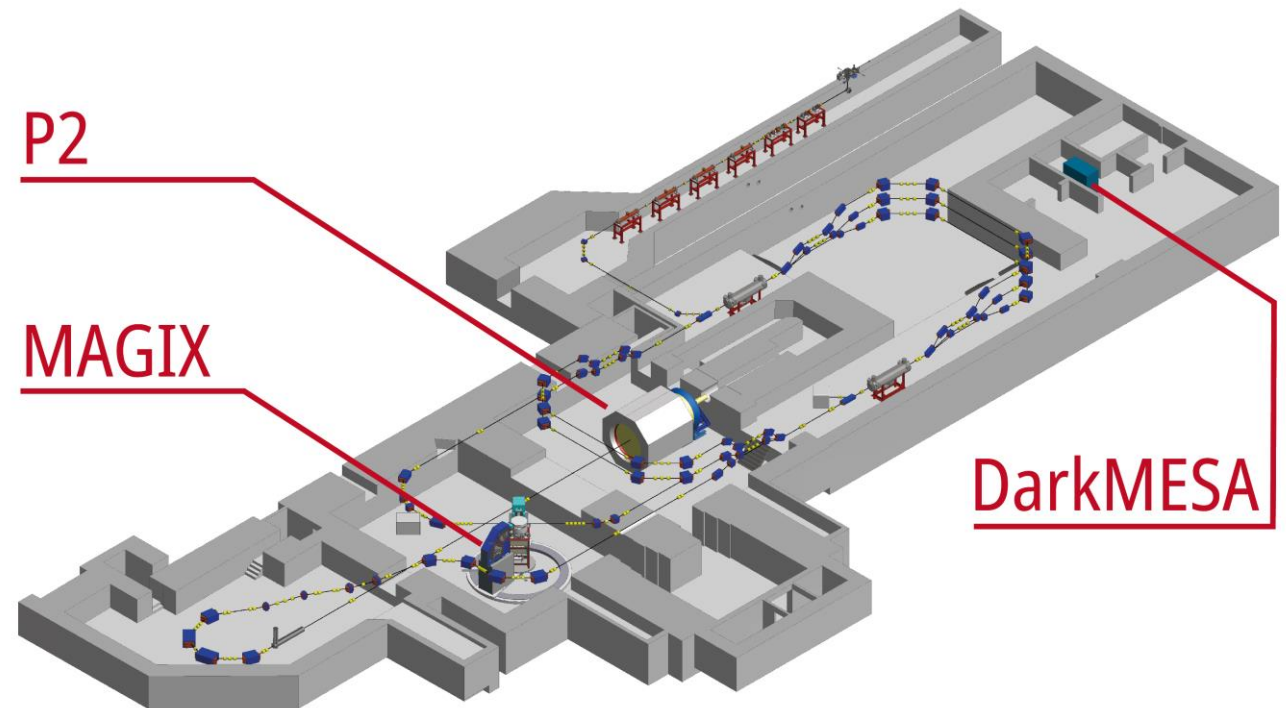
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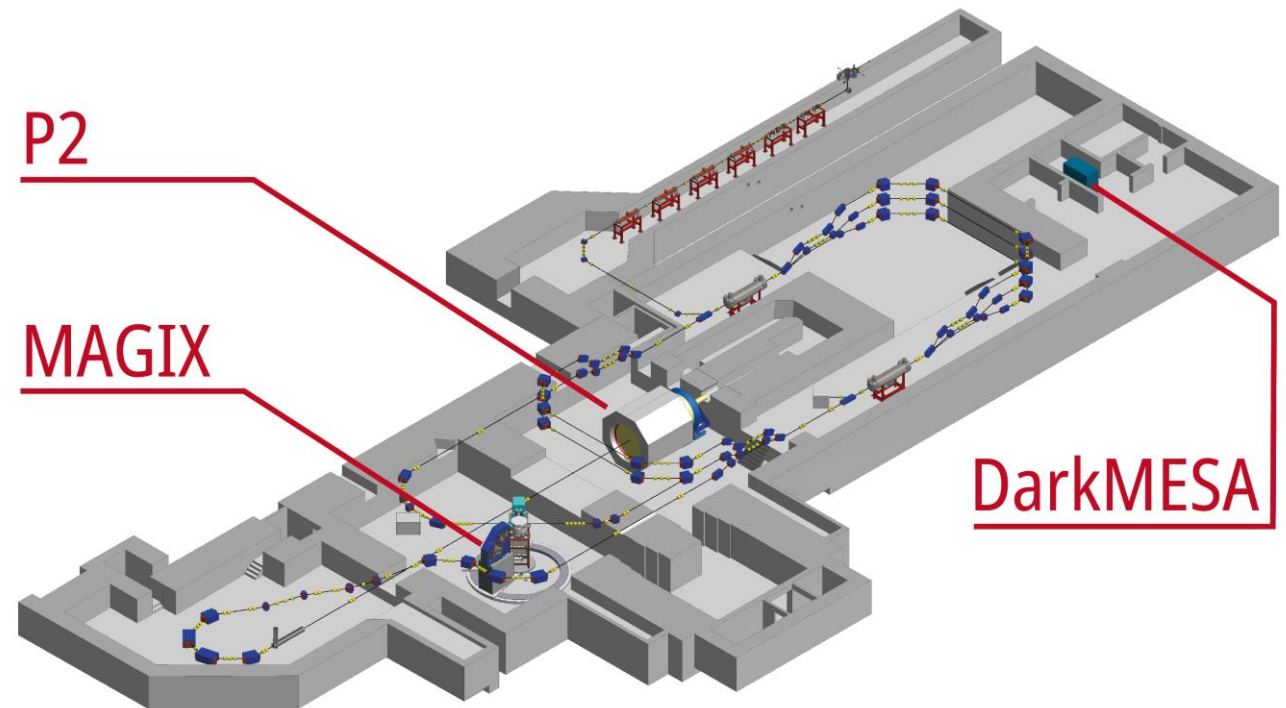
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- Low energy, high intensity electron beam  $\sim 105$  MeV
- MAGIX is a pair of multipurpose spectrometers, expected to measure  $m_{ee}$  with precision of 0.1 MeV

## MESA Experiments



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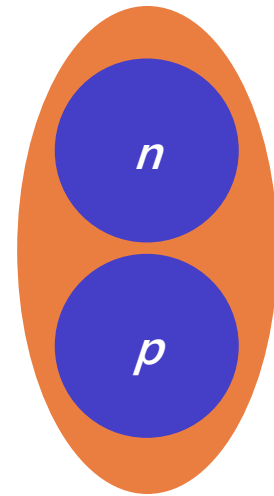


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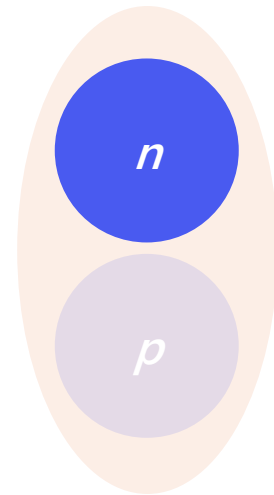
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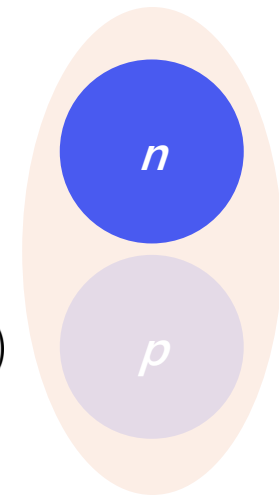
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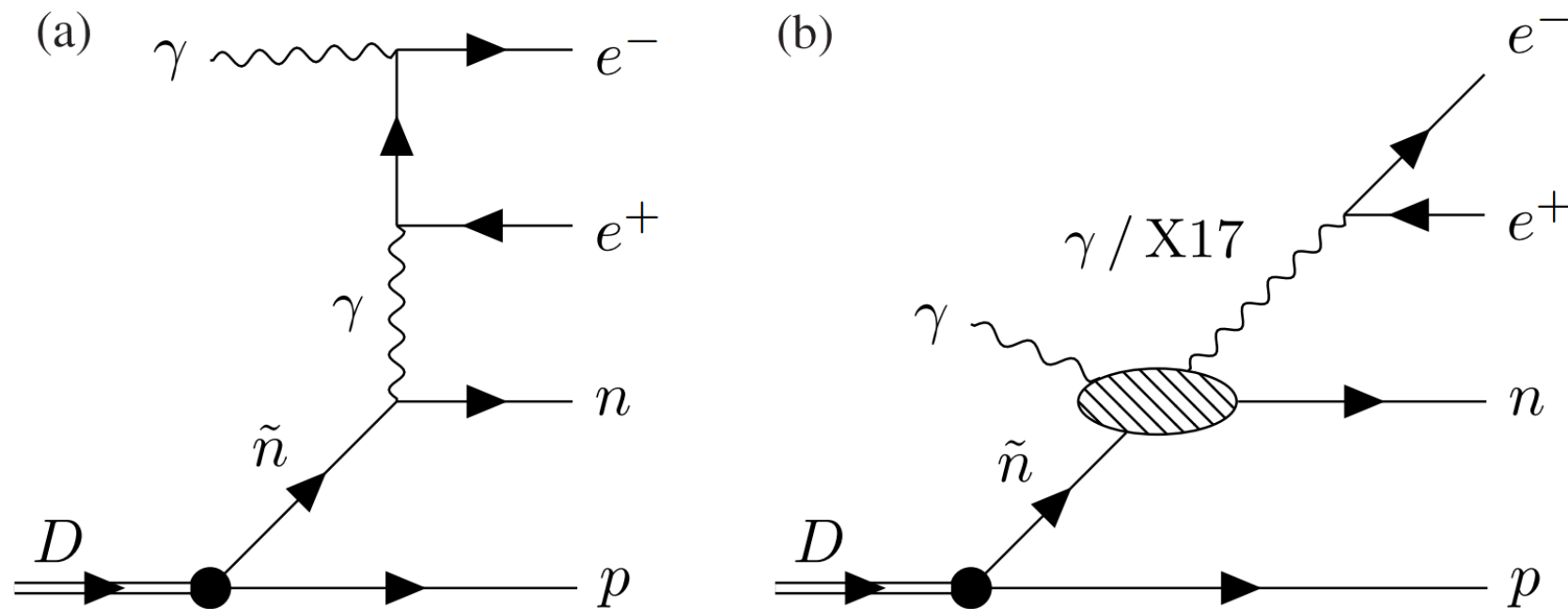


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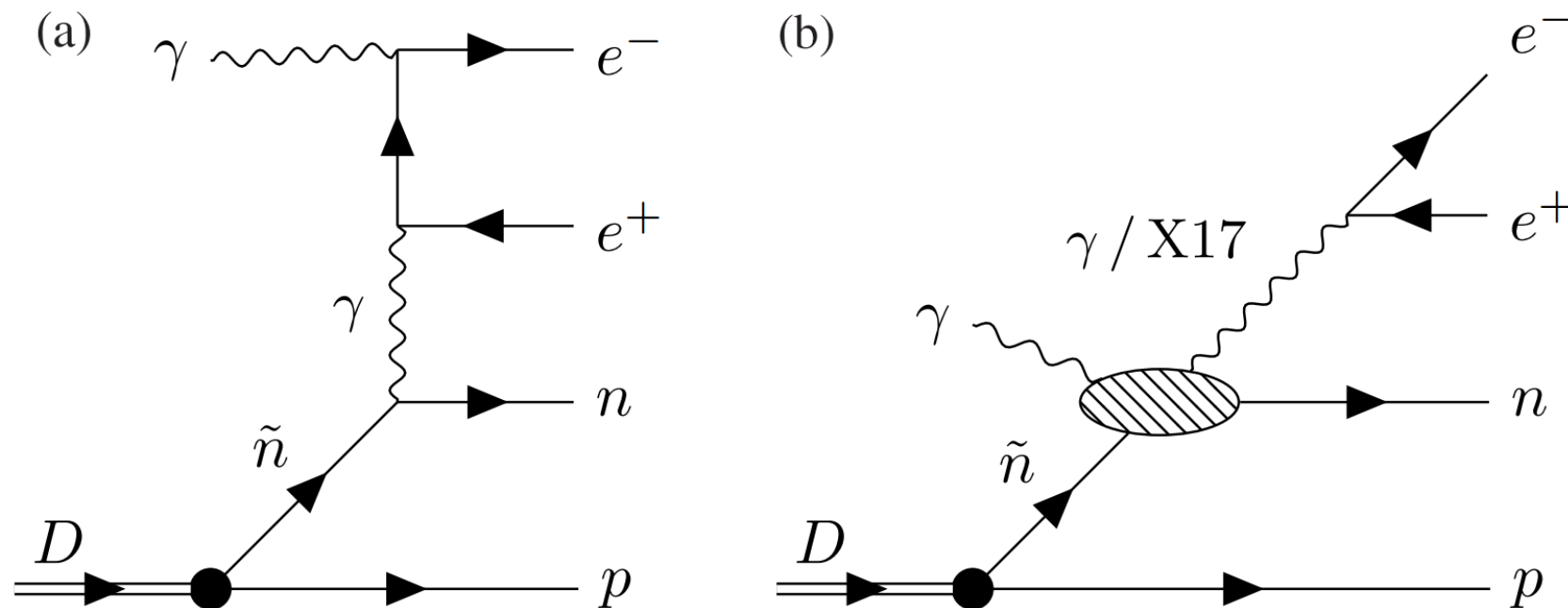
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- Consider neutron bound in deuteron,  $\gamma d \rightarrow e^+e^-pn$
- Pick kinematics where neutron is "quasi-free"
- Work within plane-wave impulse approximation:  
$$\mathcal{M}(\gamma D \rightarrow e^+e^-pn) \propto \psi_D \times \mathcal{M}(\gamma n \rightarrow e^+e^-n) + \psi_D \times \mathcal{M}(\gamma p \rightarrow e^+e^-p)$$



# Relevant diagrams

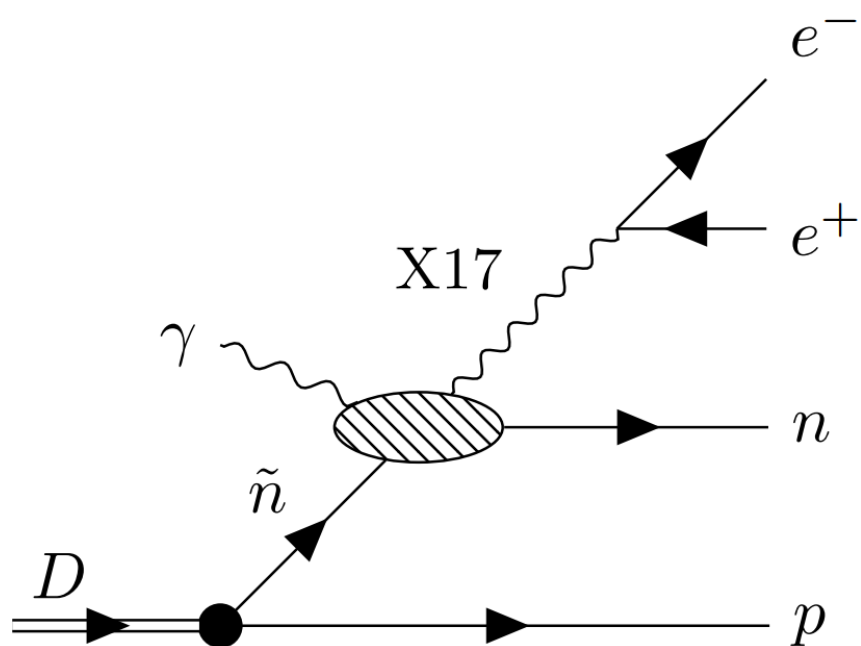


# Relevant diagrams



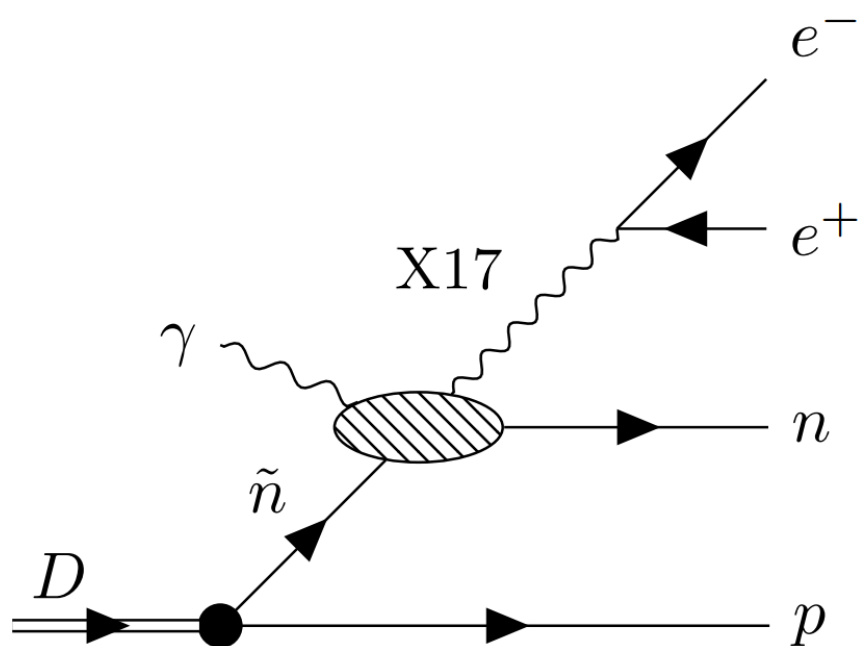
- Higher-order corrections  $\sim 25\%$ , tree level sufficient for this work

# Signal optimization

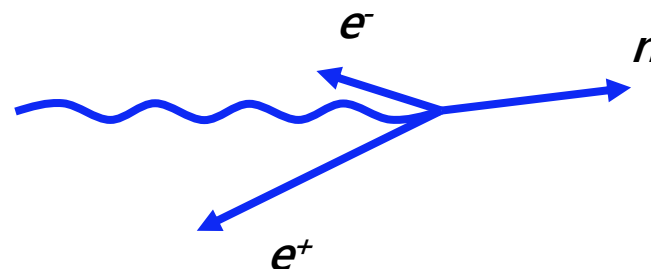


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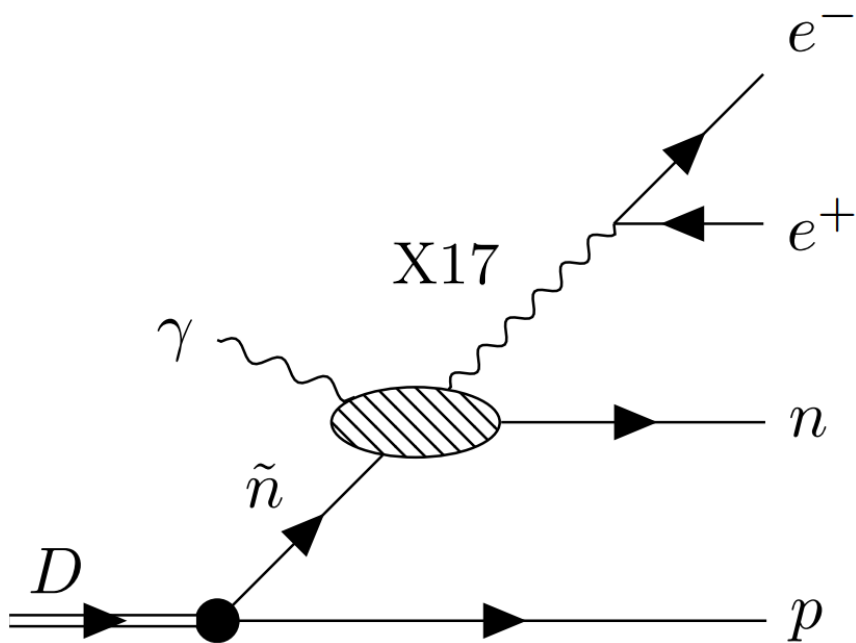


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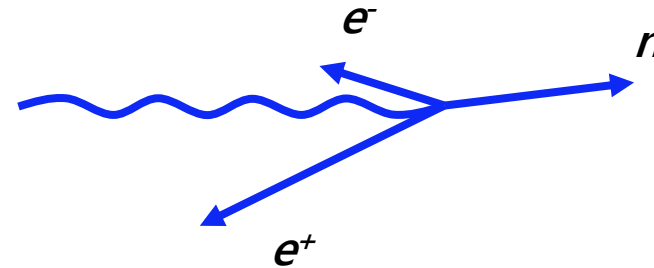




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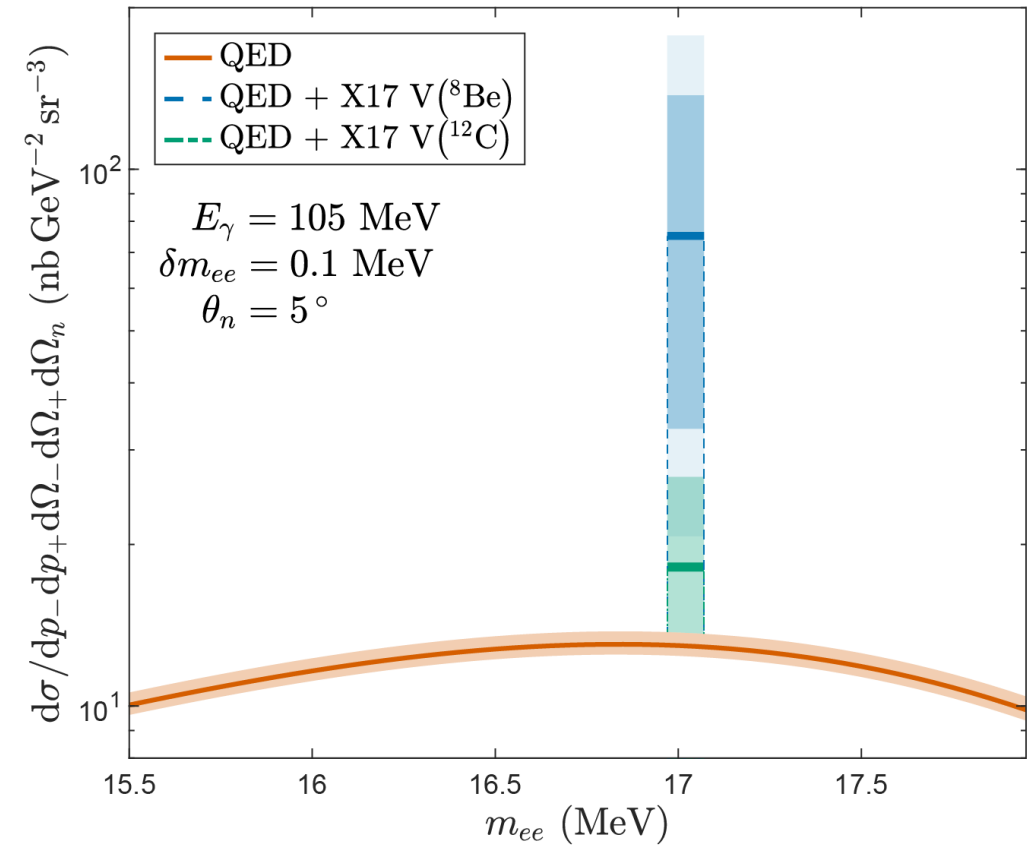
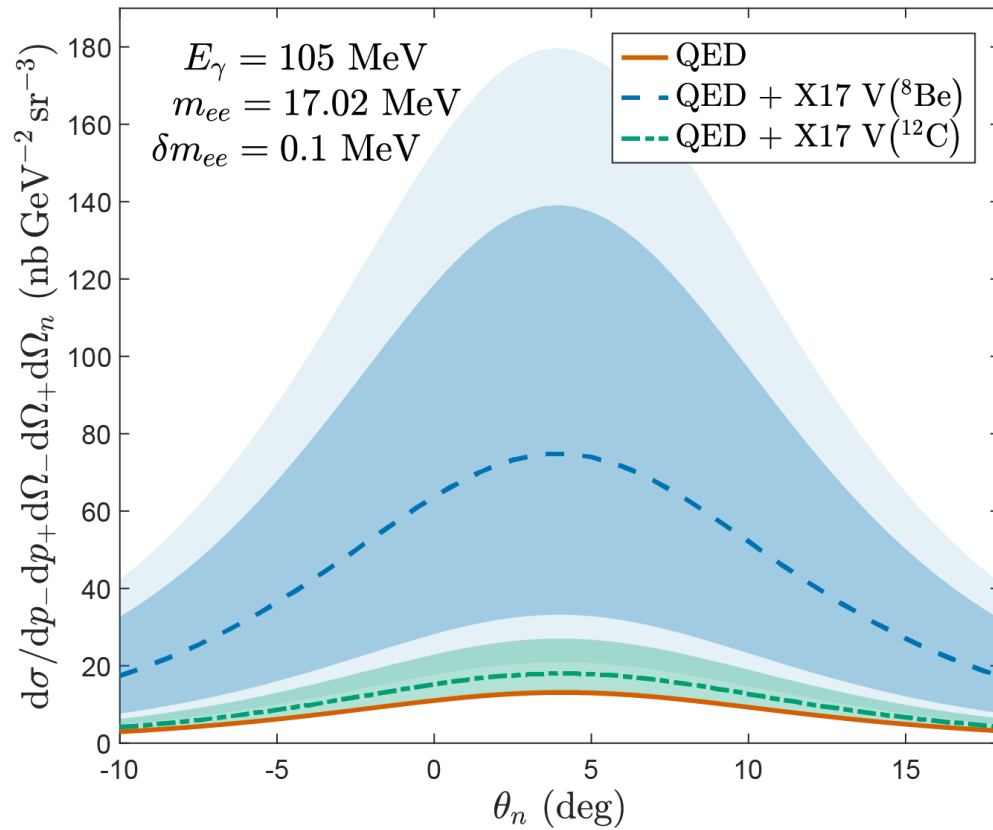


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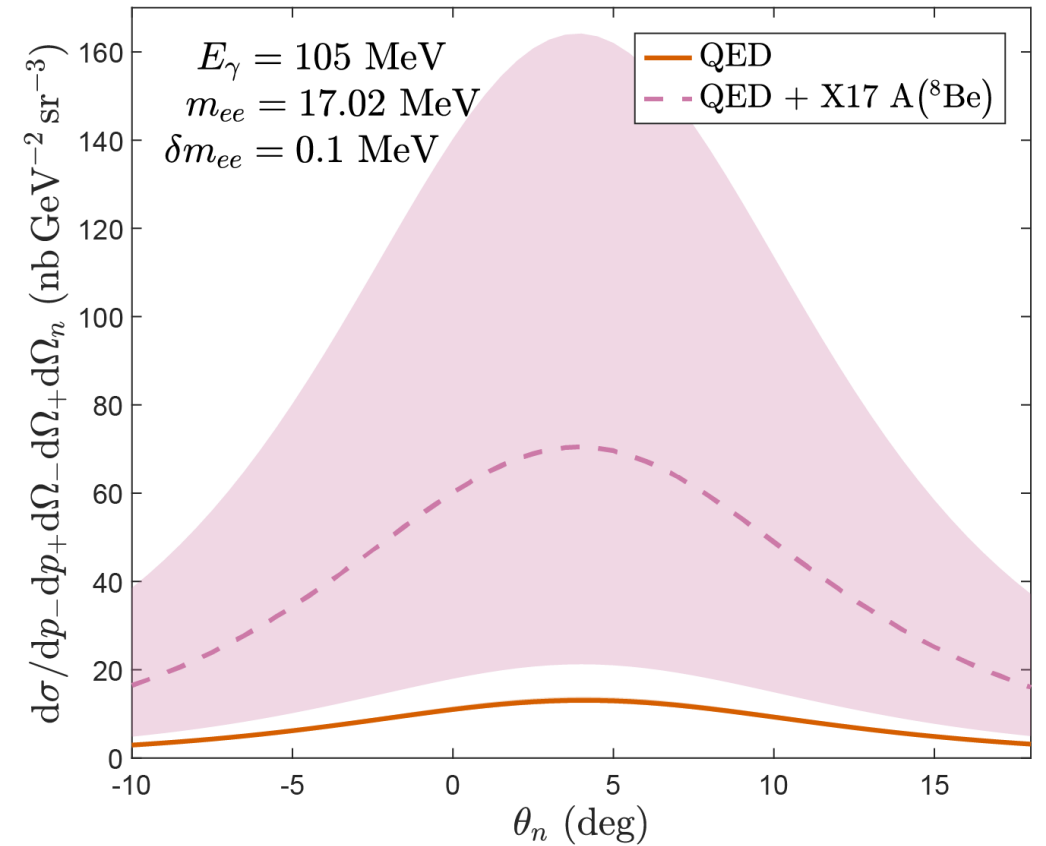
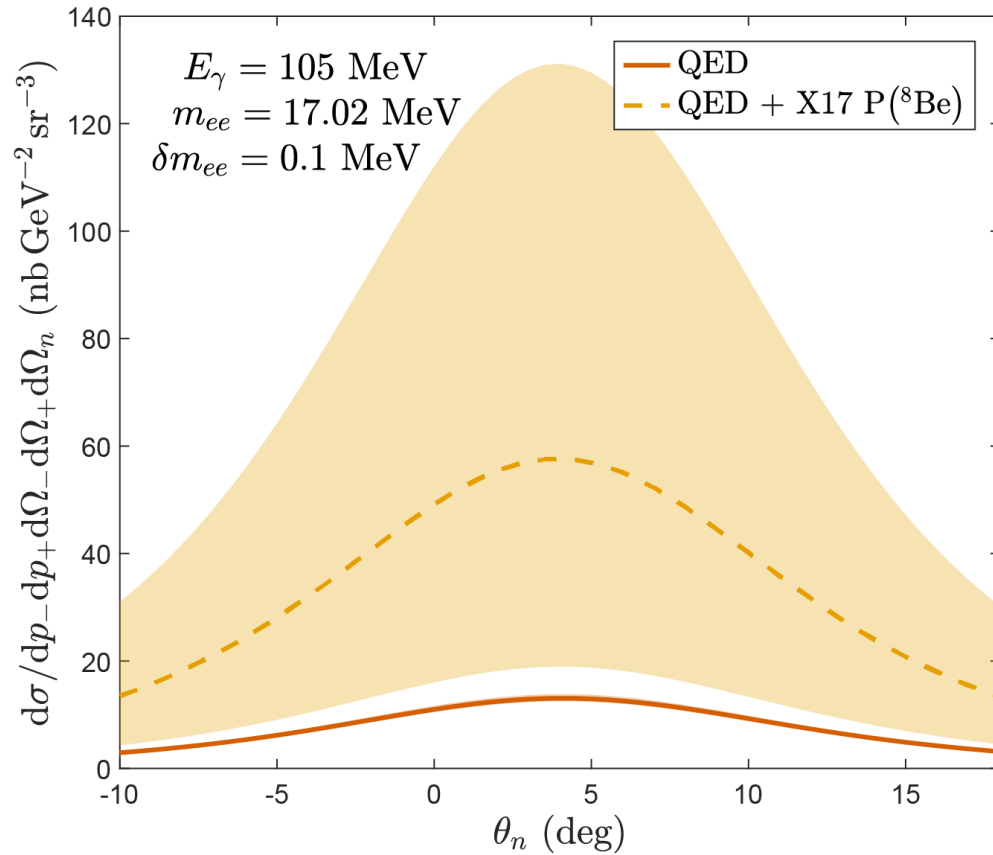


- Sensitivity MESA:  $\delta m_{ee} = 0.1 \text{ MeV}$

# Results (I)

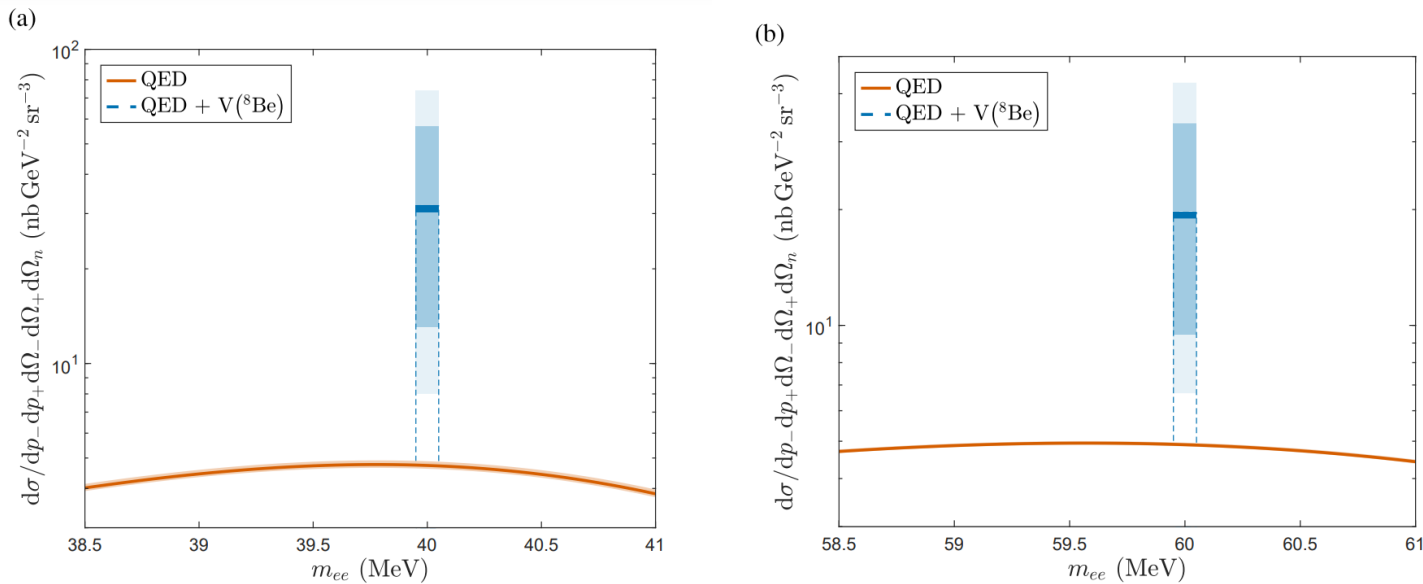


# Results (II)



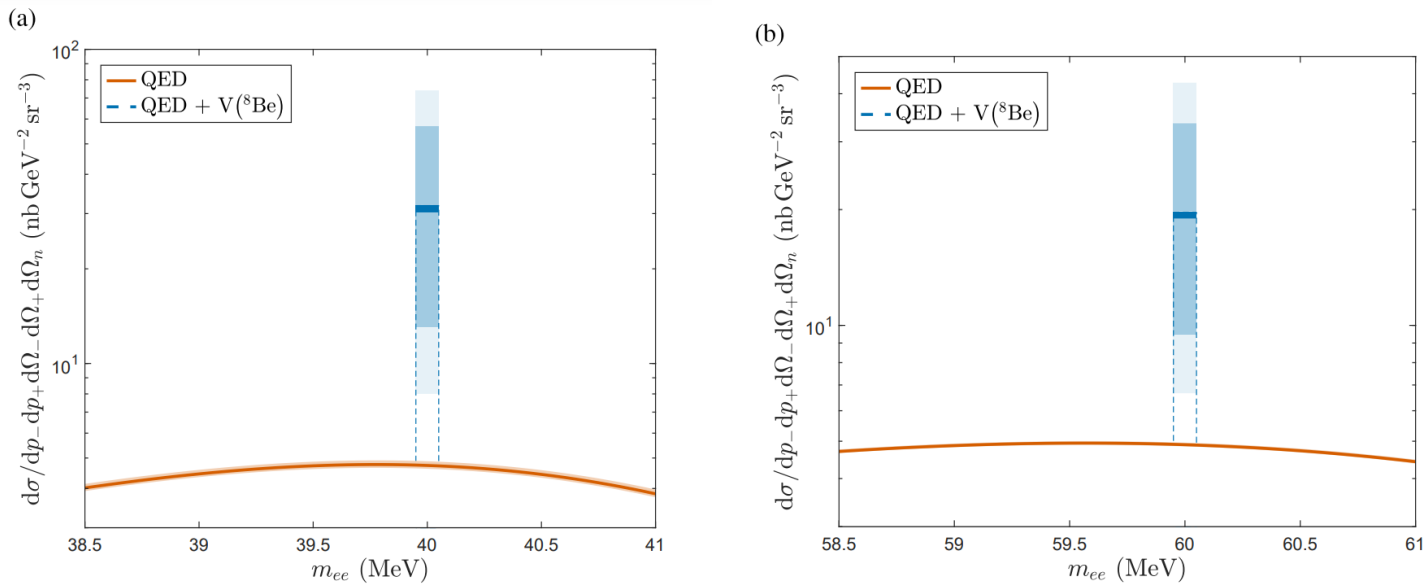
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$$\varepsilon_u = (2\varepsilon_p - \varepsilon_n)/3 \quad \varepsilon_d = (2\varepsilon_n - \varepsilon_p)/3$$

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

PDG



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

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

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## Neutron Polarizabilities Investigated by Quasifree Compton Scattering from the Deuteron

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# 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 $\gamma d \rightarrow e^+ e^- pn$ with neutron tagging

Cornelis J.G. Mommers & Marc Vanderhaeghen

Johannes Gutenberg-Universität Mainz

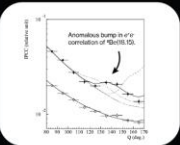
arXiv:2307.02181 [hep-ph]

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

Cornelis J.G. Mommers and Marc Vanderhaeghen, JGU Mainz, arXiv:2307.02181 [hep-ph]

### 1. What is X17?

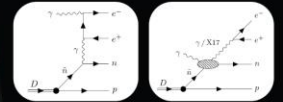
- The ATOMKI group found anomalous signals in the decays of excited  $^8\text{Be}$  (figure below),  $^4\text{He}$ , and  $^{12}\text{C}$  nuclei with statistical significances exceeding  $6\sigma$ .
- To account for these anomalies, they proposed the existence of X17, a light boson with a mass of 17.02(10) MeV.
- Assuming definite parity, X17 is either a pseudoscalar, vector or axial-vector particle.
- This conjecture has sparked a global experimental effort to replicate the anomaly. There are ongoing experiments at CCPAC (Canada), PSI (Switzerland), New JEDI (France), among others.



▲ Image from Phys. Rev. Lett. 118, 042501 (2009)

### 3. Neutron tagging

- Neutron target is not available in the lab.
- $\gamma d \rightarrow e^+ e^- pn$  with neutron tagging instead.
- Bound neutron is quasi free, proton a spectator.
- Scattering events primarily on quasi-free neutron.



▲ Bethe-Heitler process    ▲ Compton process

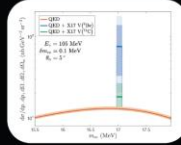
- X17 has a very narrow width,  $\Gamma_{\gamma} \ll 100$  keV.
- Influence of electron coupling not resolvable inside single bin.
- Cross section only depends on neutron coupling.

### 2. X17 at electron accelerators

- Ongoing experiments focus on nuclear decays.
- X17 must take part in other processes.
- In  $\gamma n \rightarrow e^+ e^- n$  the X17 signal would be clearly visible over the QED background.
- Direct search in this way would provide a timely and independent confirmation of X17's existence.
- MAGIX experiment at MESA is ideal for such a search.
  - Produce photon from low-energy yet high-intensity electron beam ( $E_e = 105$  MeV)
  - High-resolution spectrometers ( $\delta\theta_{\text{min}} = 0.1$  MeV)

### 4. X17 signal visible over QED background

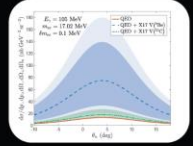
- Use beryllium and carbon measurements to constrain X17 coupling to nucleons.
- X17 signal (dashed) is visible over the QED background.
- Slight tension between couplings derived from beryllium and carbon nuclear decays highlights need for independent verification.
- MAGIX@MESA would be able to provide this verification!



▲ Vector X17 in a bump hunt

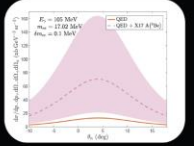
X17 signal would appear as a sharp spike in a single bin.

Similar results (not shown) hold pseudoscalar and axial-vector X17.



▲ Cross section vector X17 inside a single bin

Compute reach (tentative) for masses other than 17 MeV. Used for exclusion limits.



▲ Cross section axial vector X17 inside a single bin

**Bonus slides**

# Table ATOMKI decays

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

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

# Deriving limits on couplings (P)

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

- SINDRUM:  $|g_{XNN}^{(1)}| \lesssim 0.6 \times 10^{-3}$  (Phys. Lett. B 175, 101 (1986))

- Multipole: 
$$\frac{\Gamma_X^{8\text{Be}}}{\Gamma_\gamma^{\text{M1}}} = \frac{1}{2\pi\alpha} \left( \frac{g_{XNN}^{(0)} \cos \theta_{1+} - g_{XNN}^{(1)} \sin \theta_{1+}}{[\mu^{(0)} - \eta^{(0)}] \cos \theta_{1+} - [\mu^{(1)} - \eta^{(1)}] \sin \theta_{1+}} \right)^2 \left( \frac{k_X}{k_\gamma} \right)^3$$

# Deriving limits on couplings (V)

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

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

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

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

# Deriving limits on couplings (A)

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

- Matrix elements from Phys. Rev. D 95, 115024

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



# Diagrams in detail (QED)

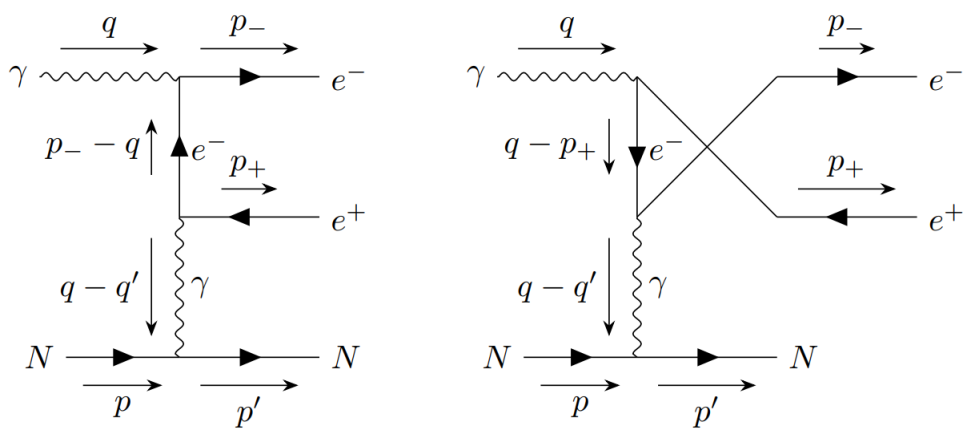


Figure 2: The direct and crossed diagram for the BH process.

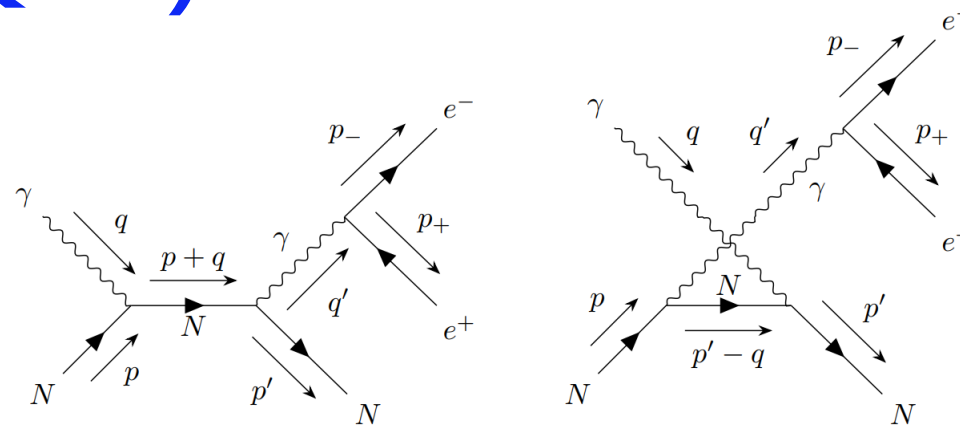


Figure 1: The direct and crossed diagram for the Born process.

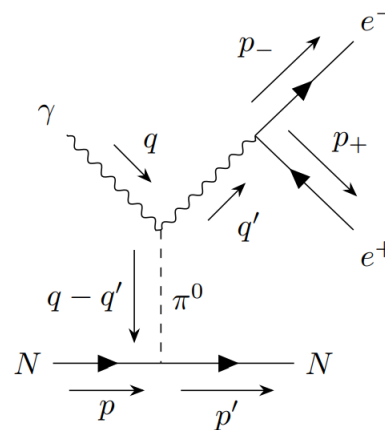
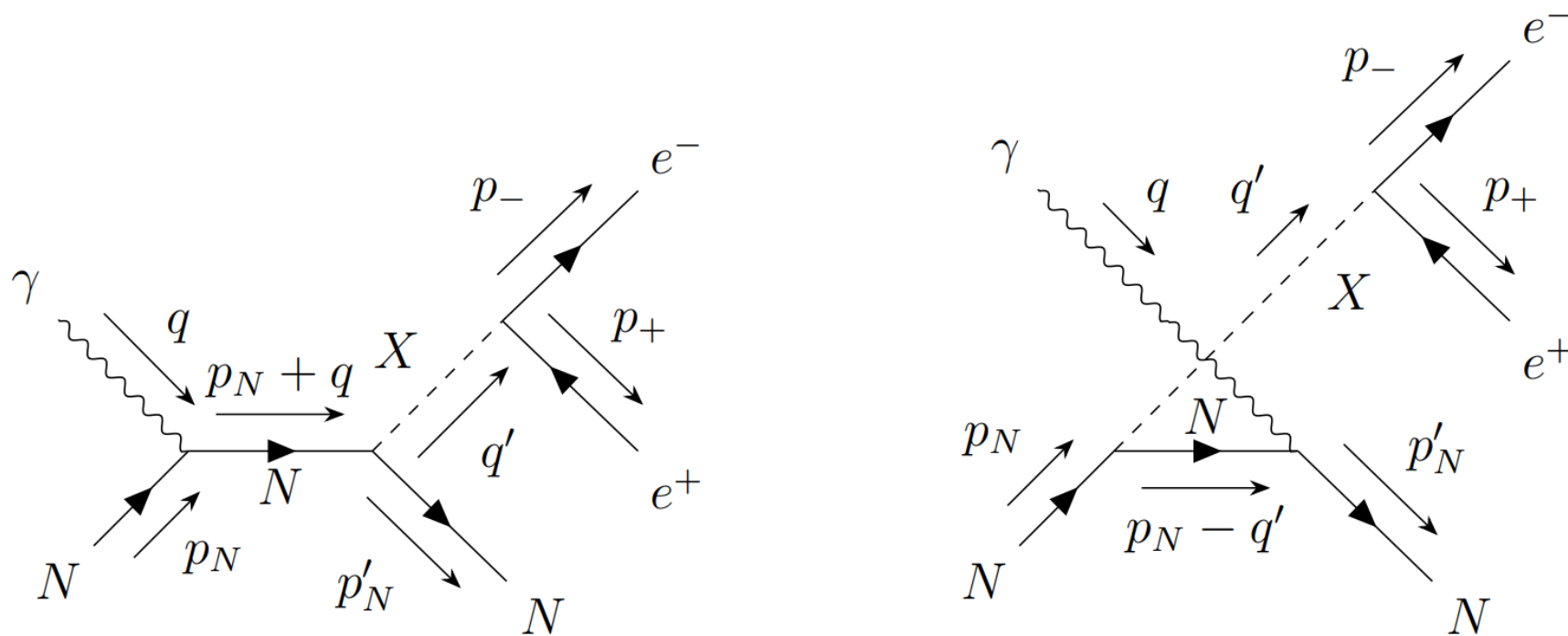


Figure 3: The diagram for the pion-pole amplitude.

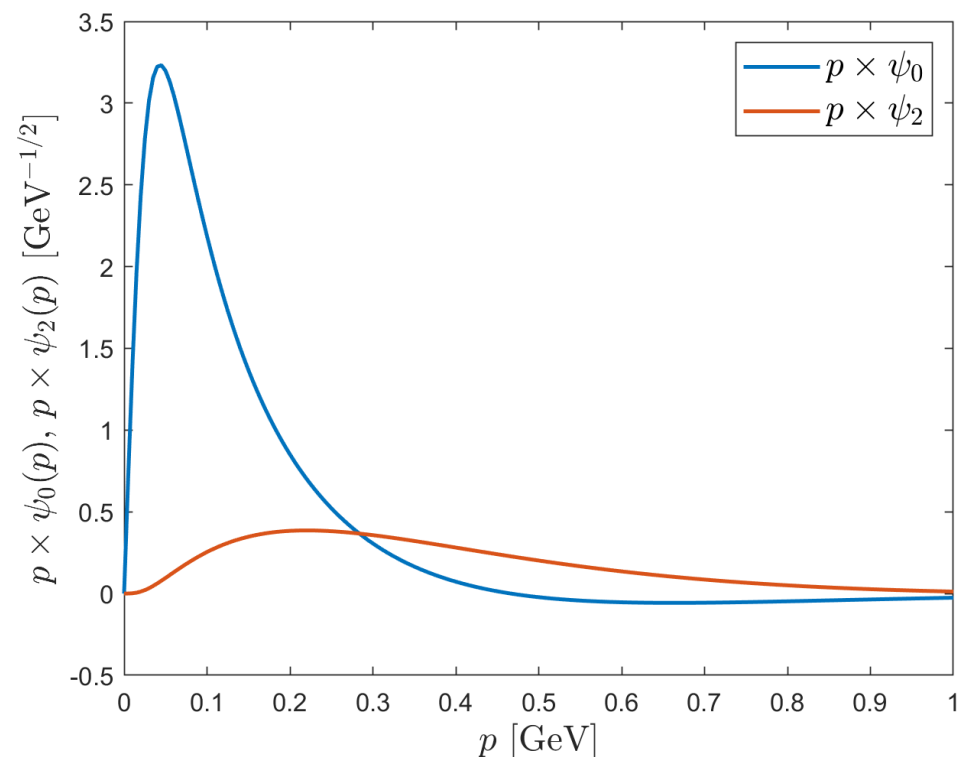
# Diagrams in detail (signal)



# Deuteron wave function

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

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



# PWIA

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

# Averaging the signal

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

We have

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

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

# Averaging the signal

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

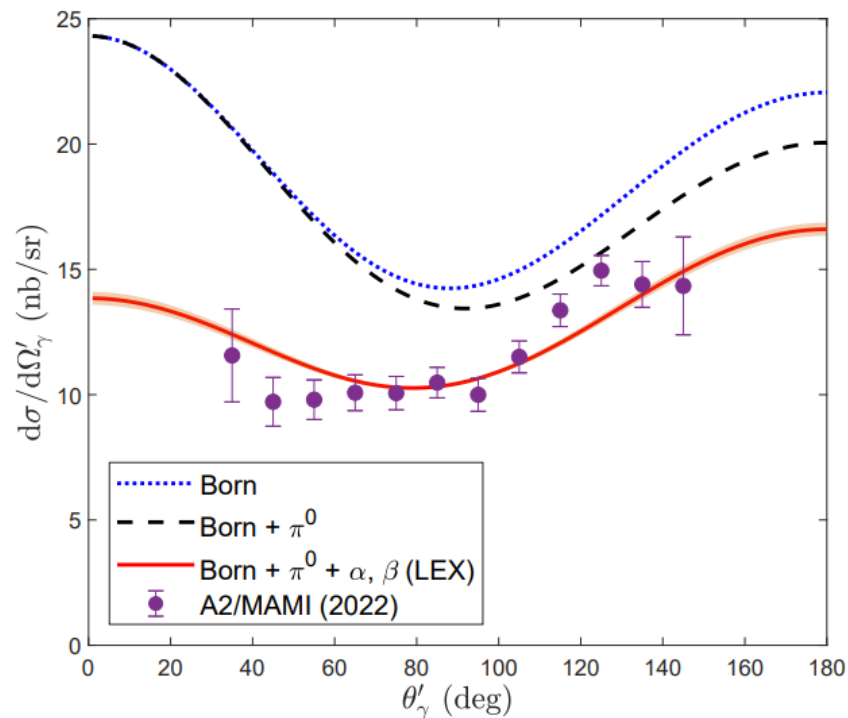
We have

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

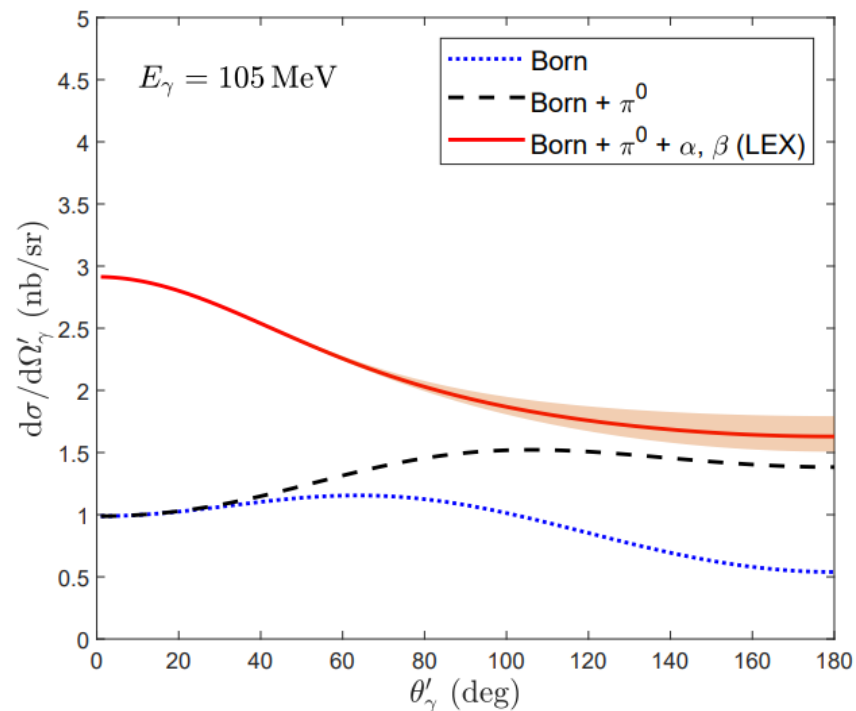
$$\frac{1}{q'^2} \left( \frac{d\sigma}{d\Pi} \right) \frac{[(q'^2 - m_X^2)^2 + (m_X \Gamma_X)^2]}{g_{Xee}^2} \approx \text{constant between } \left[ m_X - \frac{\delta m_X}{2}, m_X + \frac{\delta m_X}{2} \right]$$

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

# Verifying the QED background (I)



(a)  $\gamma p \rightarrow \gamma p$

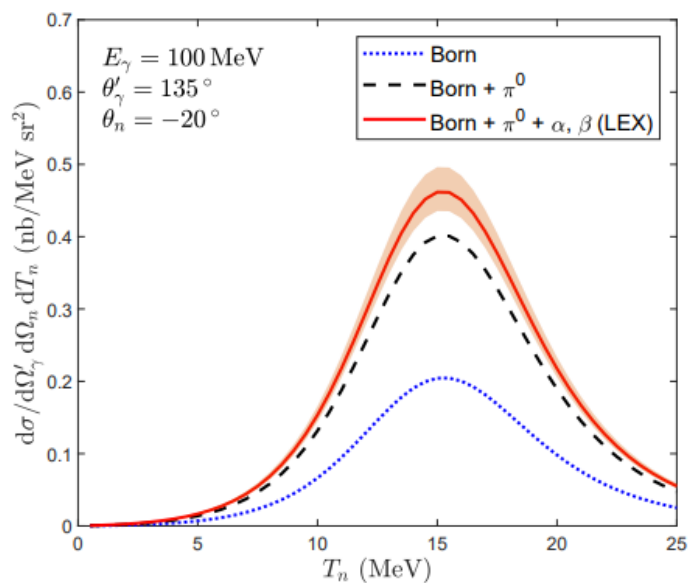


(b)  $\gamma n \rightarrow \gamma n$

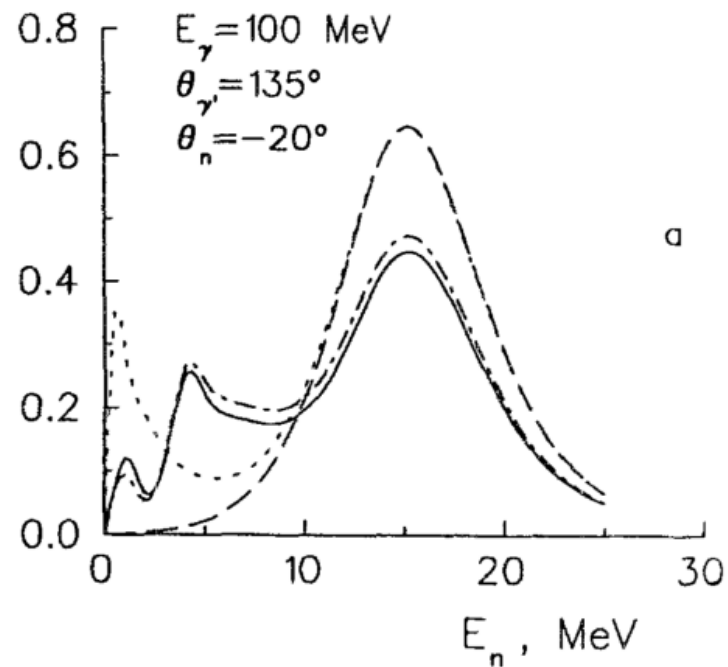


# Verifying the QED background (II)

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



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



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

# Optimizing kinematics

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

- Scan parameter range
- Find maximum
- Fine tune parameters