

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

Cornelis J.G. Mommers & Marc Vanderhaeghen

Johannes Gutenberg-Universität Mainz

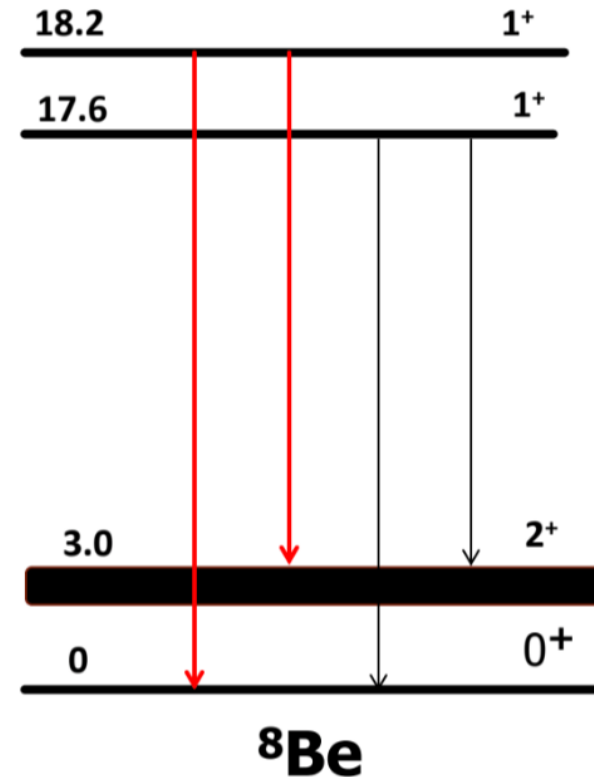
arXiv:2307.02181 [hep-ph]

# Outline

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

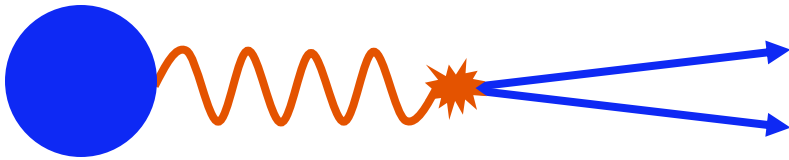
# What is X17?

- New particle conjectured to explain ATOMKI anomaly in  ${}^7\text{Li}(p,\gamma){}^8\text{Be}$  with  $1^+$  state of  ${}^8\text{Be}(18.15)$



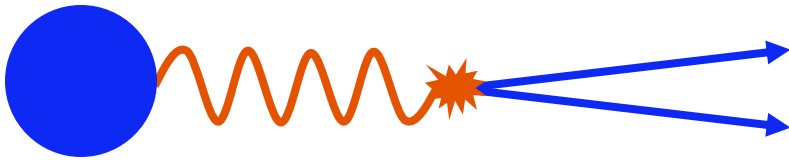
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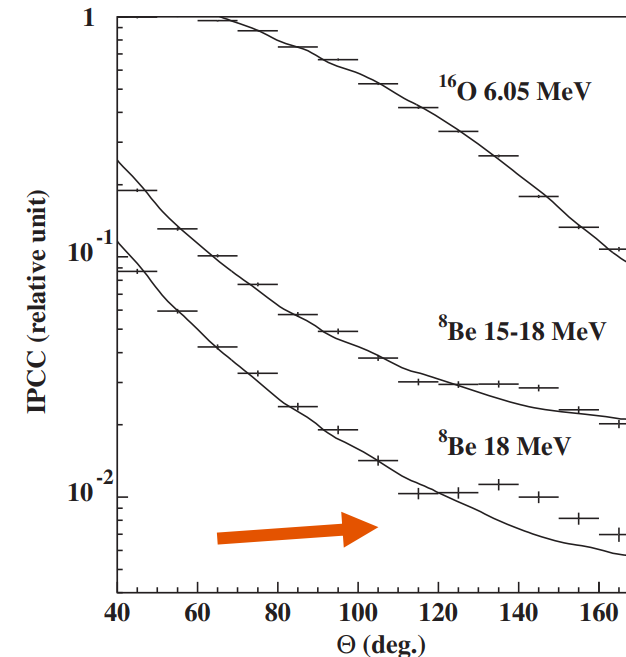


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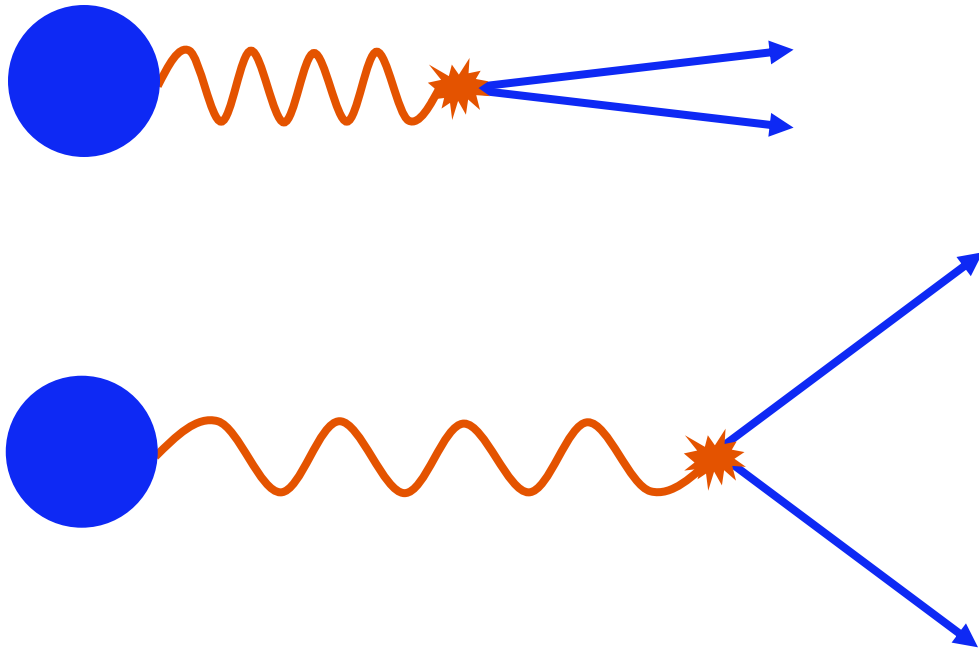


Phys. Rev. Lett. 116, 042501 (2016)

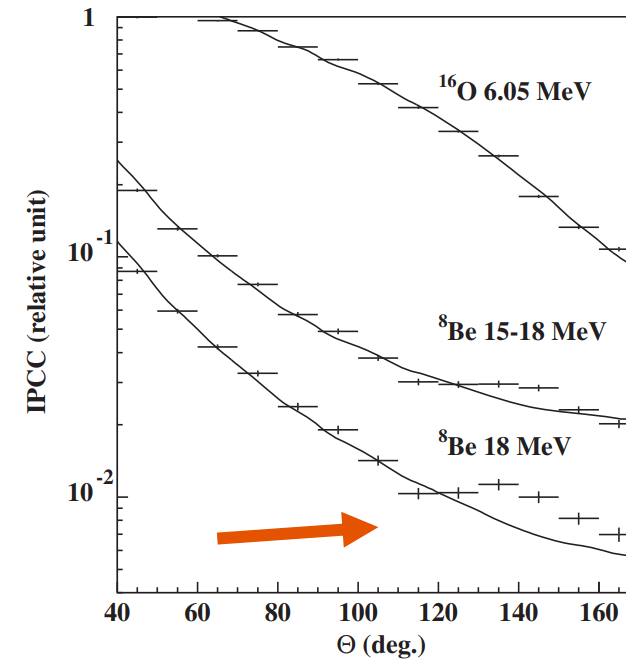


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# Continued interest...

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  
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(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. Krasznahorkay

et al.

Timár, J. Timár,

Hungary

CERN, CH

A.J. KRASZNAHORKAY, M. CSATLÓS, L. CSIGE, D. FIRAK, J. GULYÁS  
Á. NAGY, N. SAS, J. TIMÁR, T.G. TORNYI  
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et al.

A. KRASZNAHORKAY  
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(Received November 21, 2015)

January 2016)



# Continued interest...

PRL 116, 042501 (2016)

Observation

A. J. Krasznahorkay

Institute for Nuclear Research, Hungarian Academy of Sciences, MTA Atomki

CERN, Geneva

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

week ending  
29 JANUARY 2016

of a Light,

J. Timár,

Institute for Nuclear Research, Hungarian Academy of Sciences, MTA Atomki

CERN, Geneva

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>  
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CERN, Geneva

(Received November 22, 2015  
January 2016)

# Continued interest...

PRL 116, 042501 (2016)

Observation

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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**

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D.S. Firak, Á. Nagy, and N.J. Sas  
University of Debrecen, 4010 Debrecen, PO Box 105, Hungary

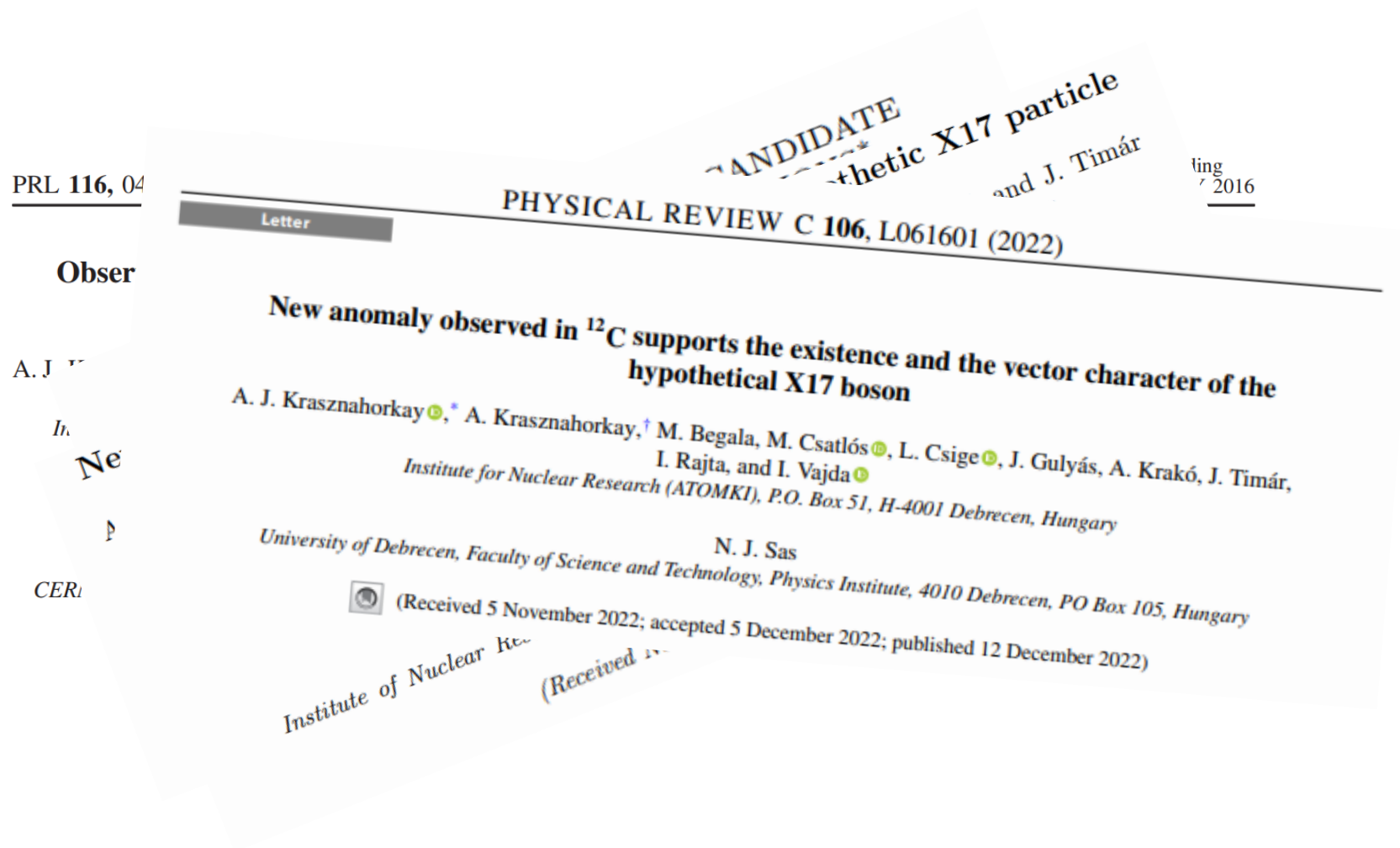
A. Krasznahorkay  
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I. Vajda<sup>1</sup>,  
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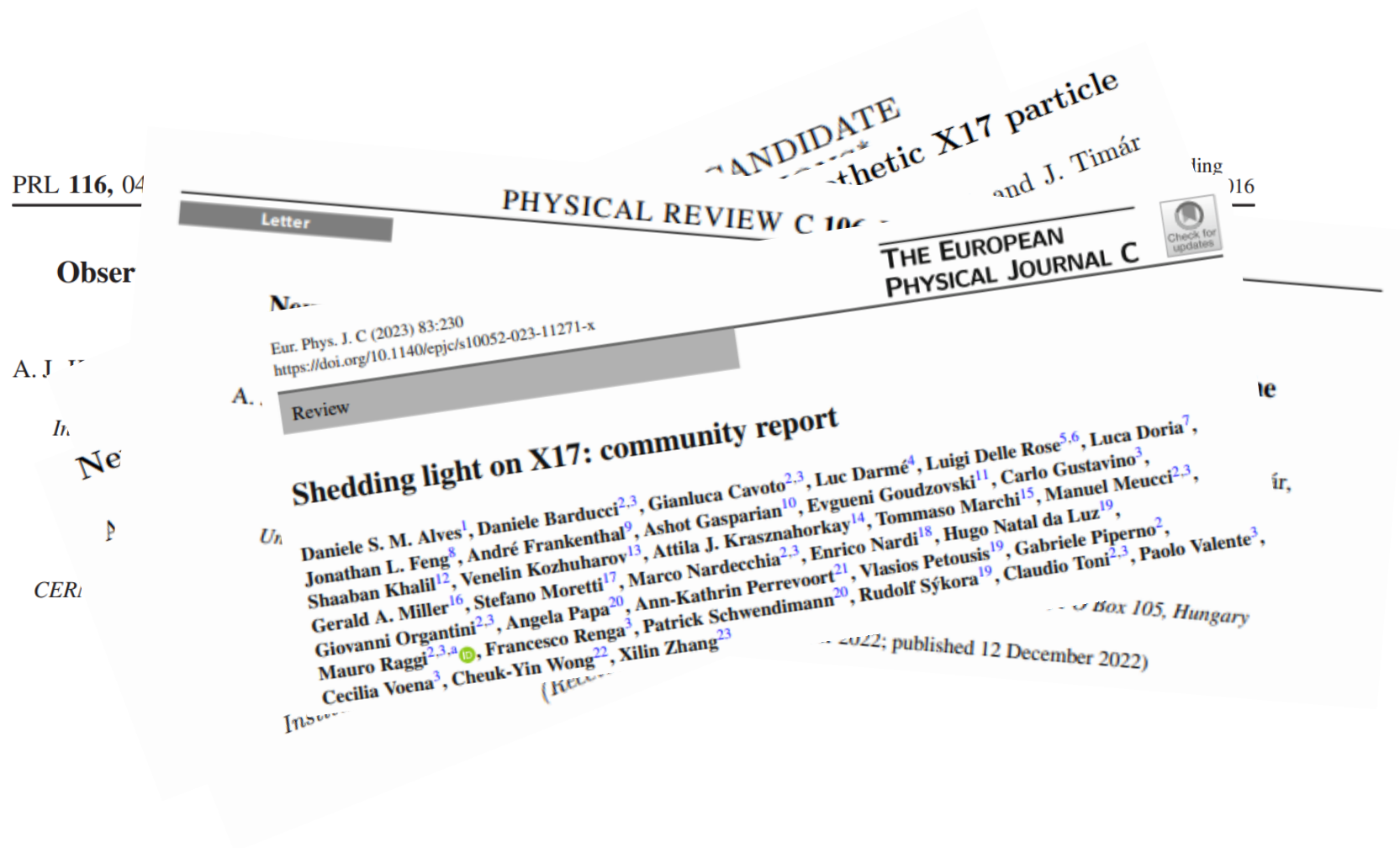
(Received November 2, 2015)  
(January 2016)

January 2016

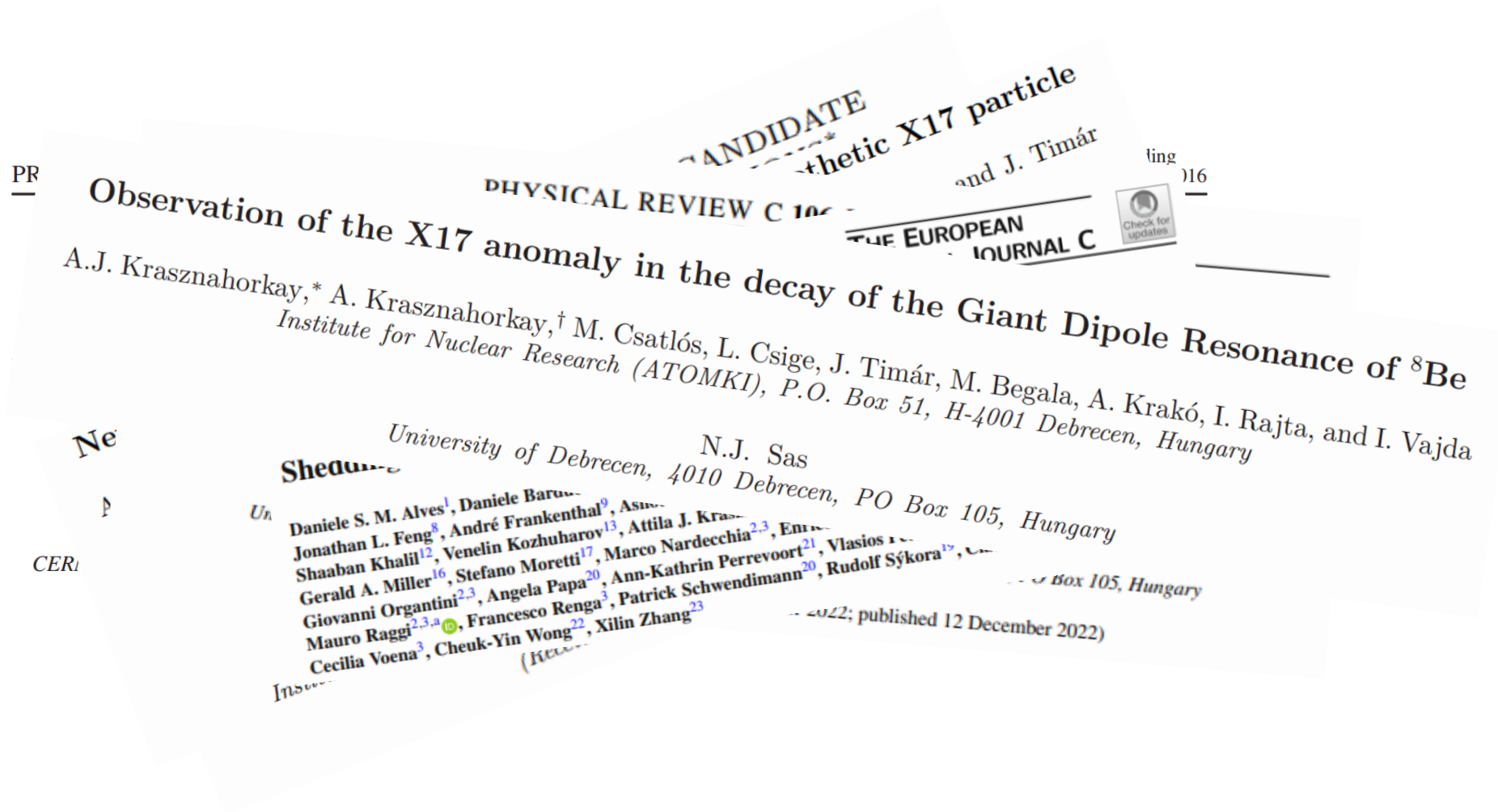
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# Theory analysis

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

# Theory analysis

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

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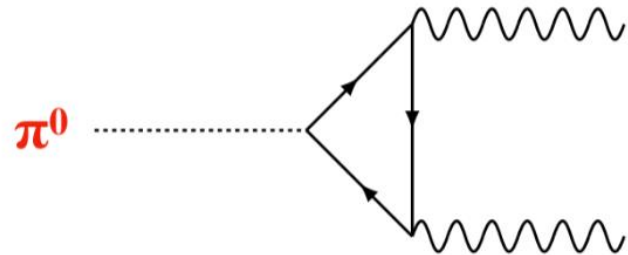
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$^4\text{He}(20.21), 0^+$	✓		✓	
$^{12}\text{C}(17.23), 1^-$	✓		✓	✓

# Theory analysis

- Proton coupling bounded by SINDRUM, NA48/2 (protophobic), derive limits on neutron coupling

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

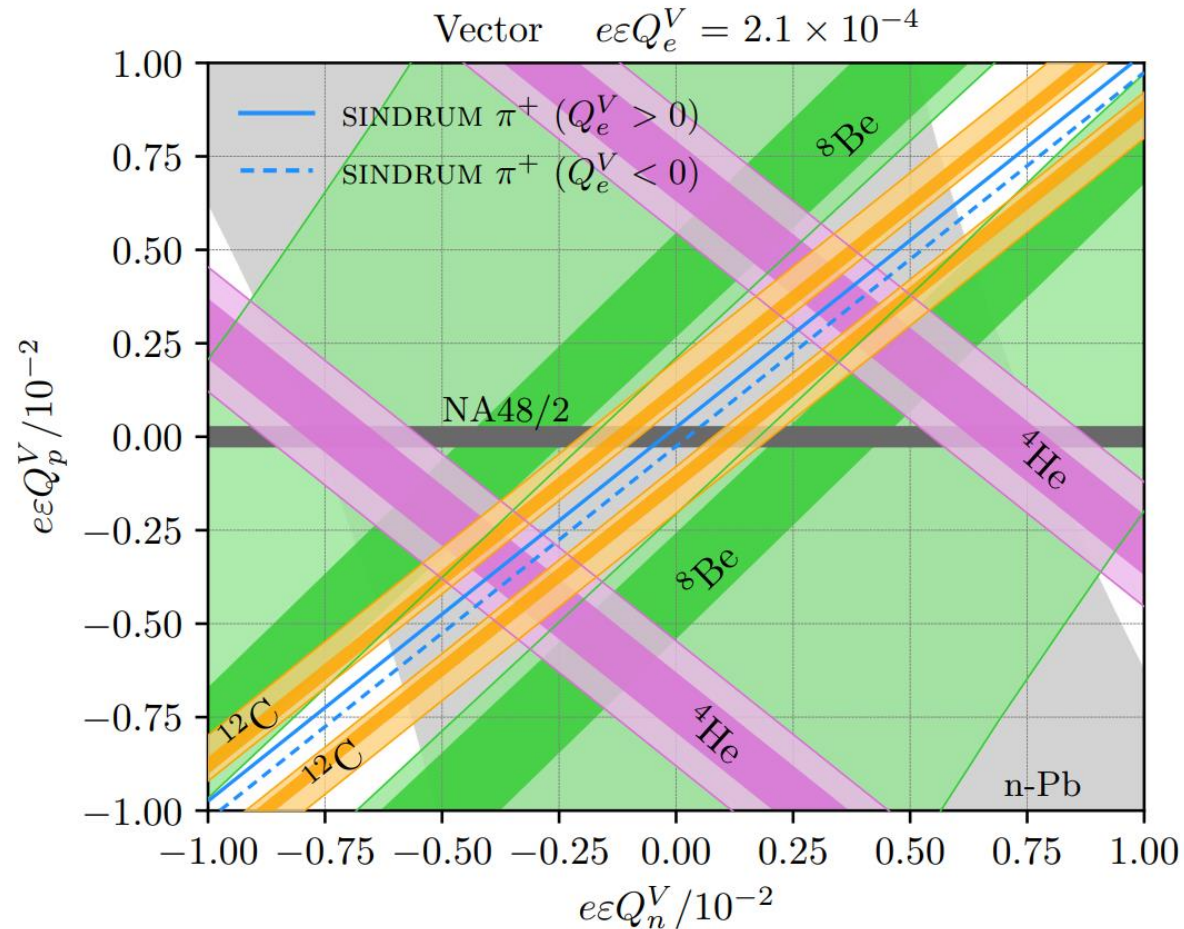


$$\propto |2\varepsilon_u + \varepsilon_d| = |\varepsilon_p|$$



# Many open questions

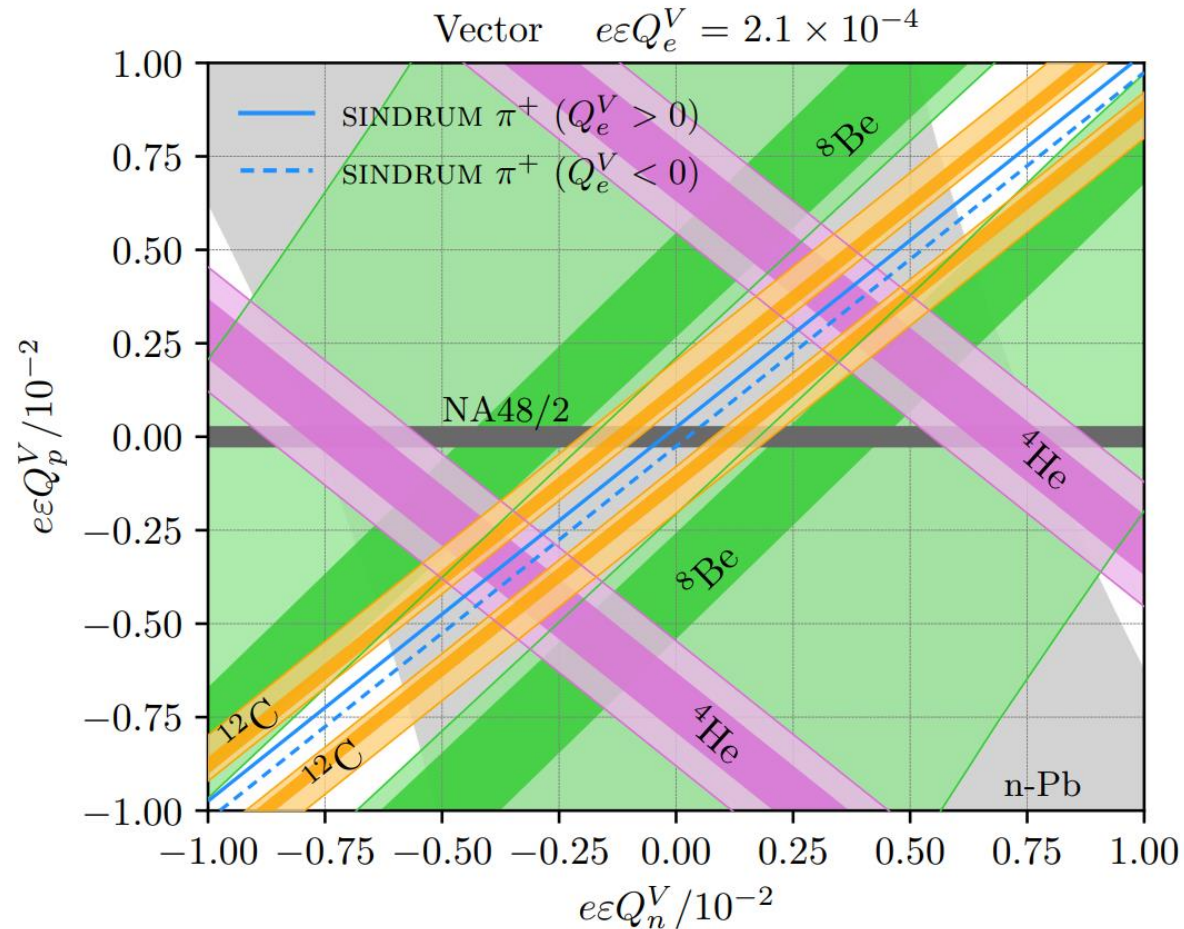
arXiv:2306.15077 [hep-ph]



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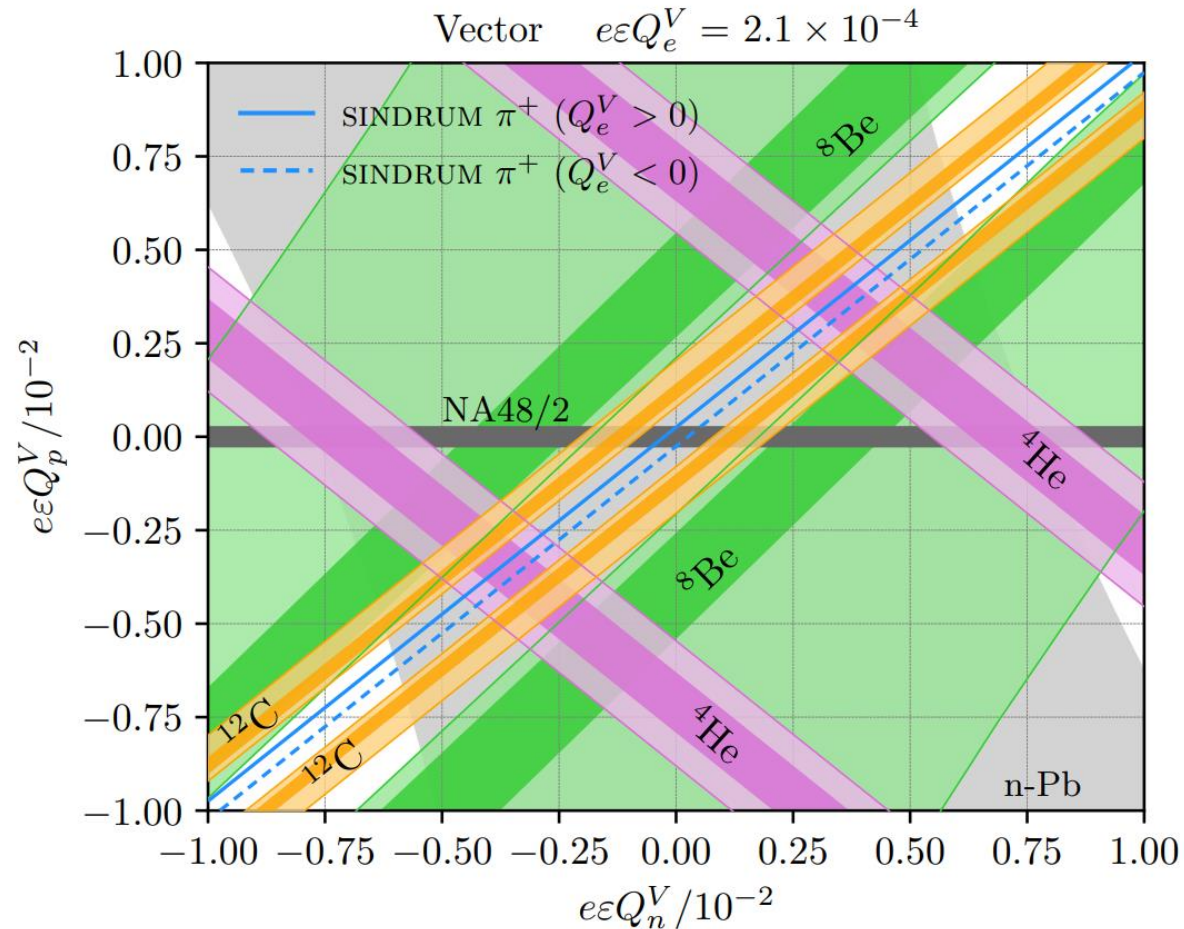
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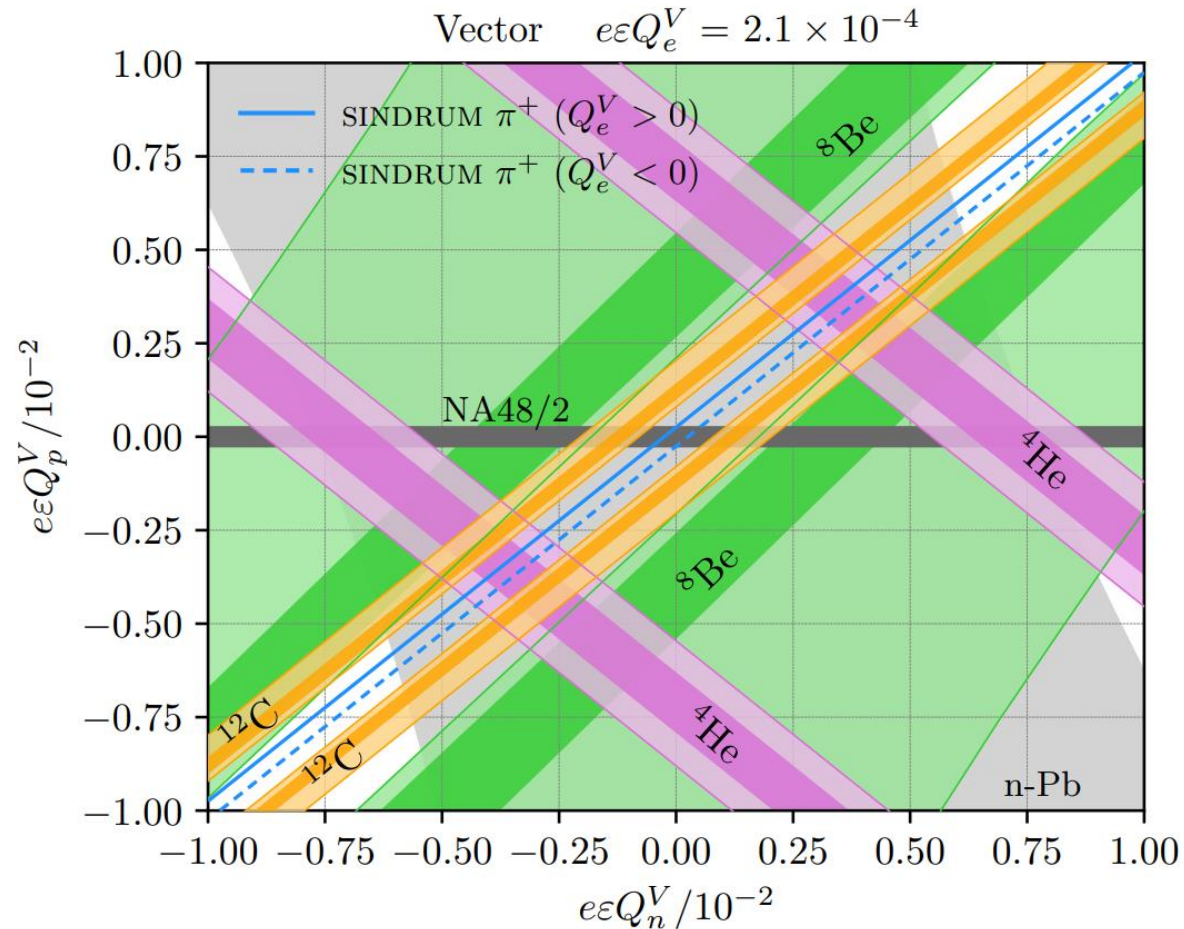
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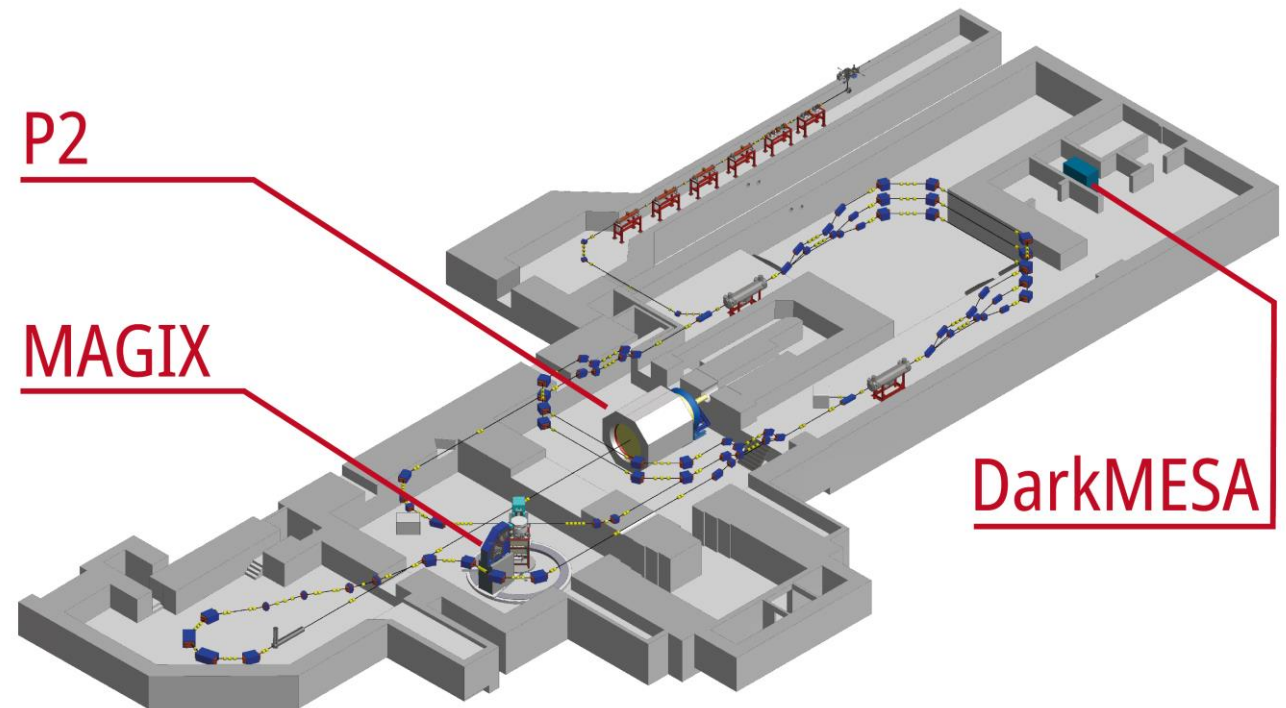


- Parity etc. still unclear
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- We propose a direct search at MAGIX experiment at MESA

# MAGIX@MESA

- MESA is a linear accelerator under construction in Mainz

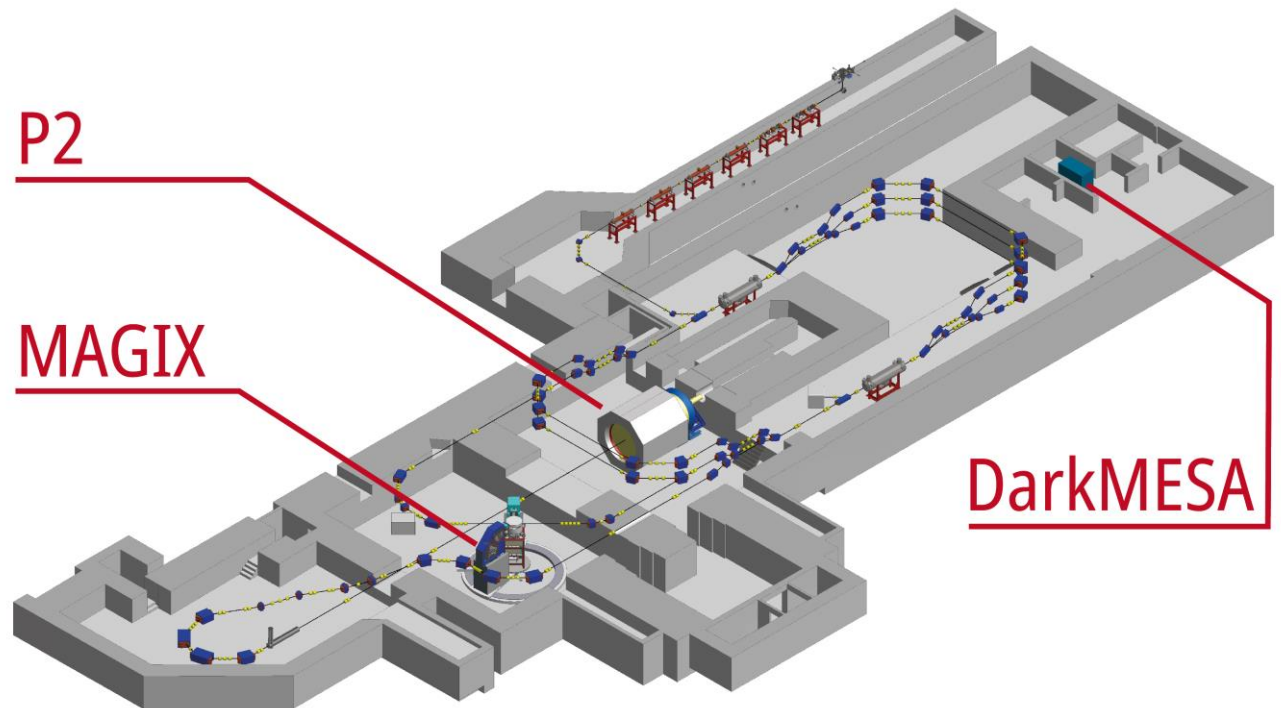
## MESA Experiments



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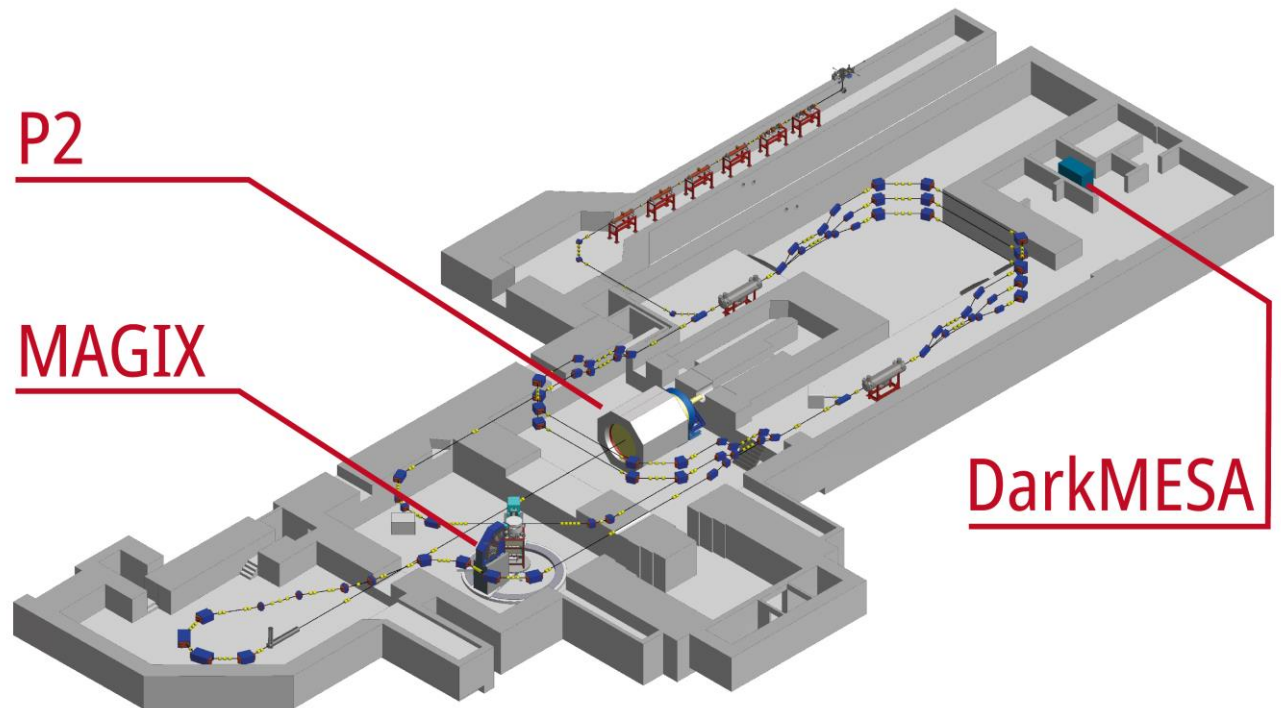
## MESA Experiments



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

## MESA Experiments



# Deuteron with neutron tagging

- Direct search using  $\gamma N \rightarrow Ne^+e^-$



# Deuteron with neutron tagging

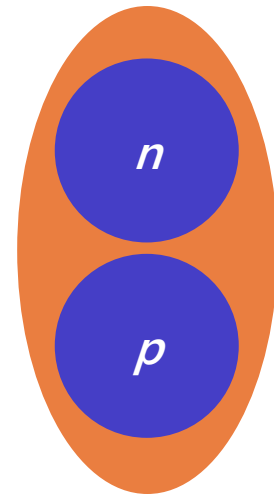
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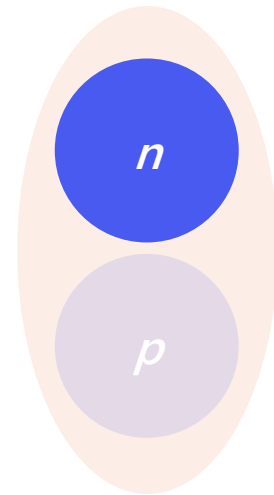
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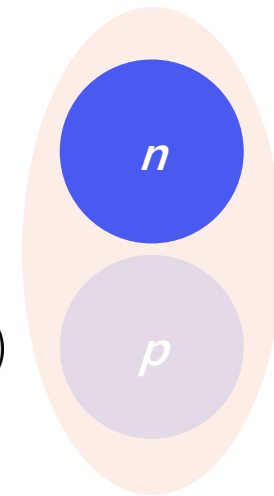
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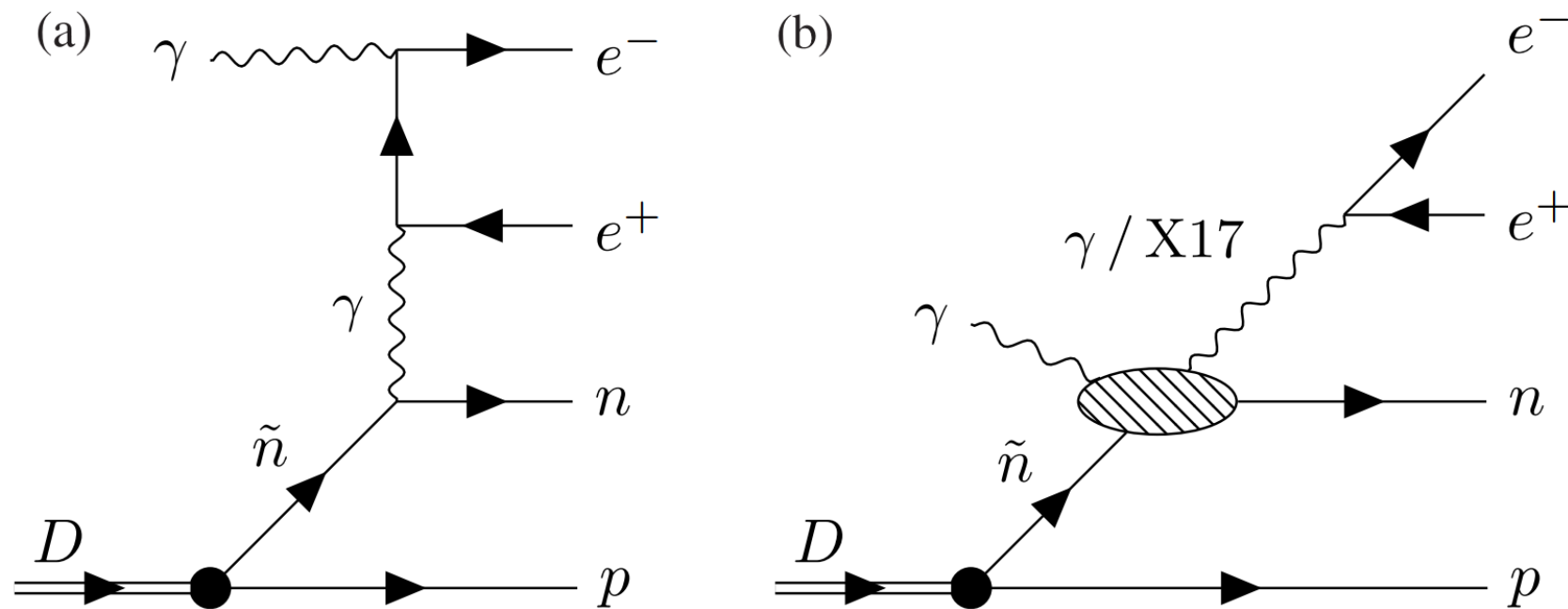


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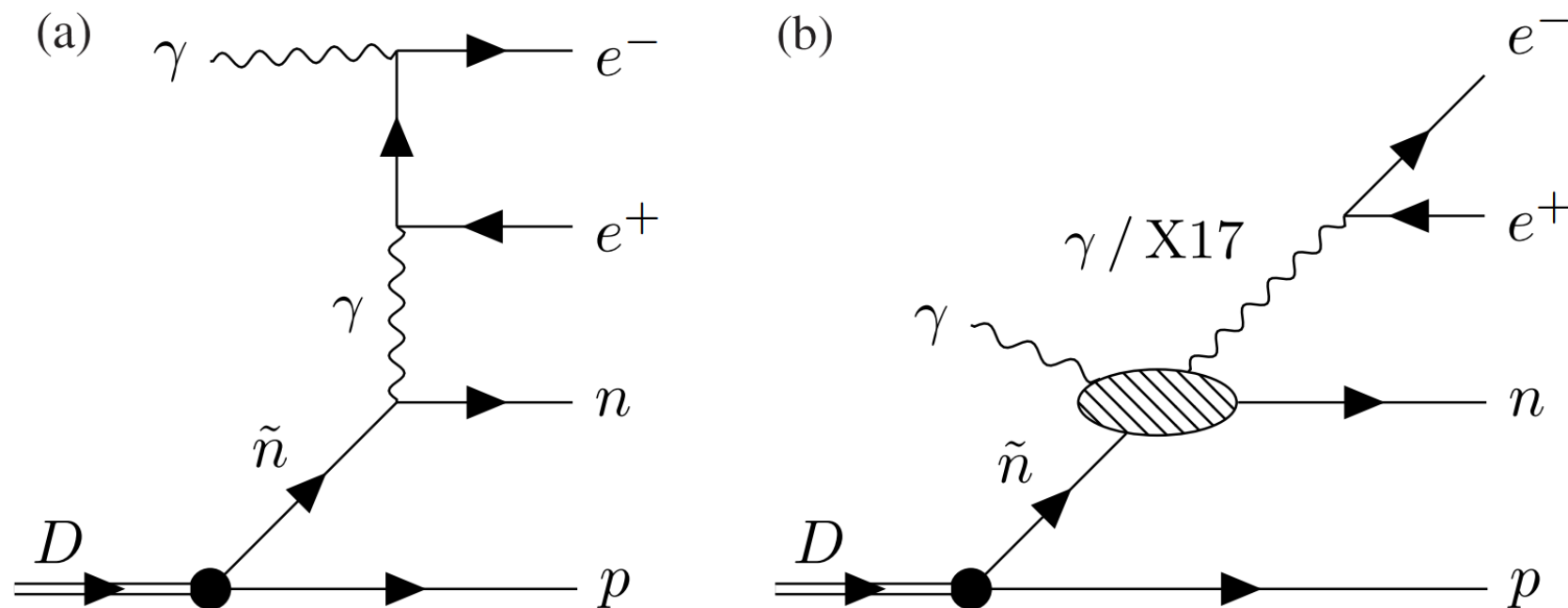
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- Work within plane-wave impulse approximation:  
$$\mathcal{M}(\gamma D \rightarrow e^+e^-pn) \propto \psi_D \times \mathcal{M}(\gamma n \rightarrow e^+e^-n) + \psi_D \times \mathcal{M}(\gamma p \rightarrow e^+e^-p)$$



# Relevant diagrams

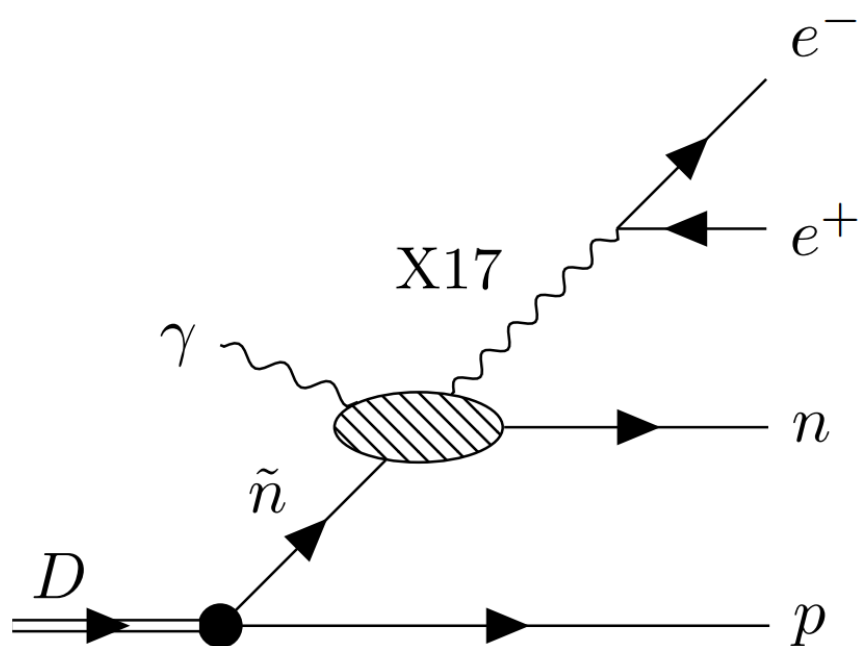


# Relevant diagrams



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

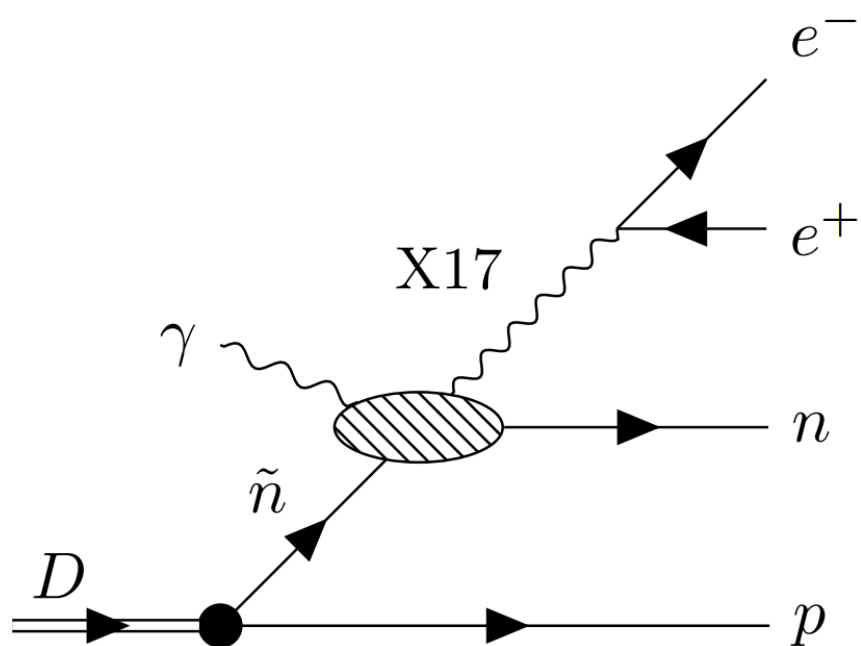
# Signal optimization



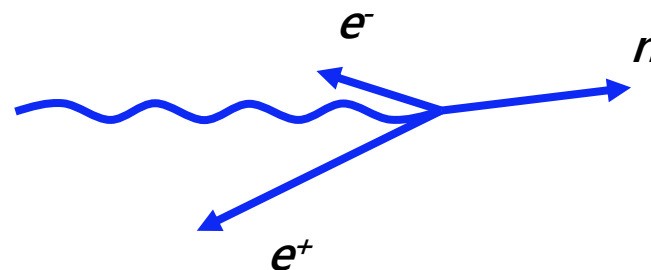
- Optimize kinematics such that X17 signal is visible over QED background, subject to constraints



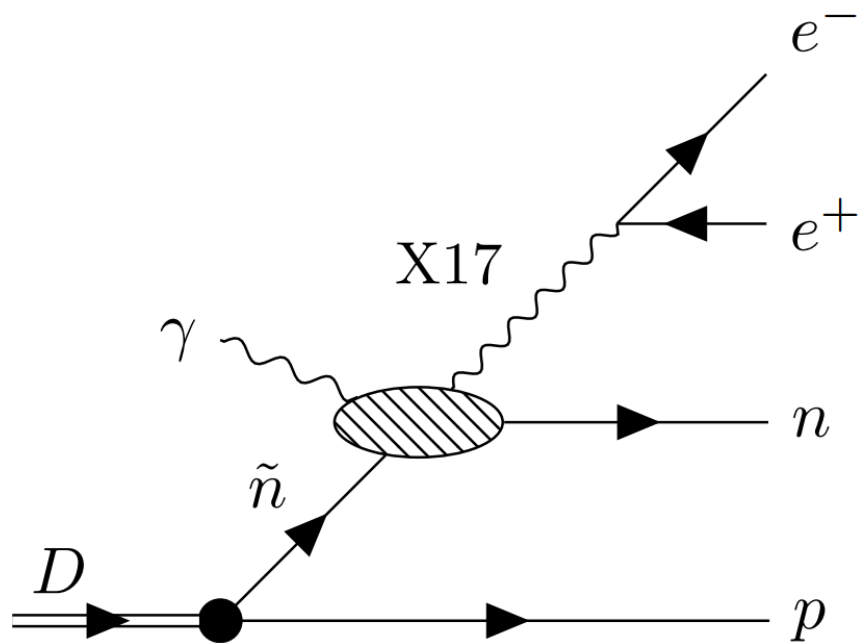
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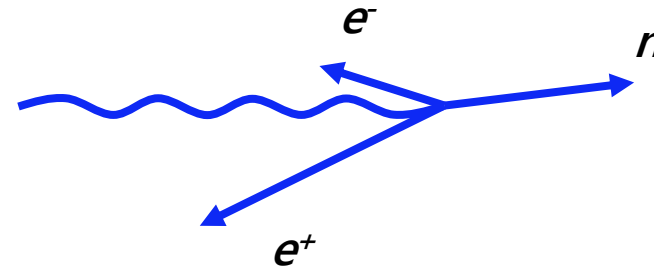
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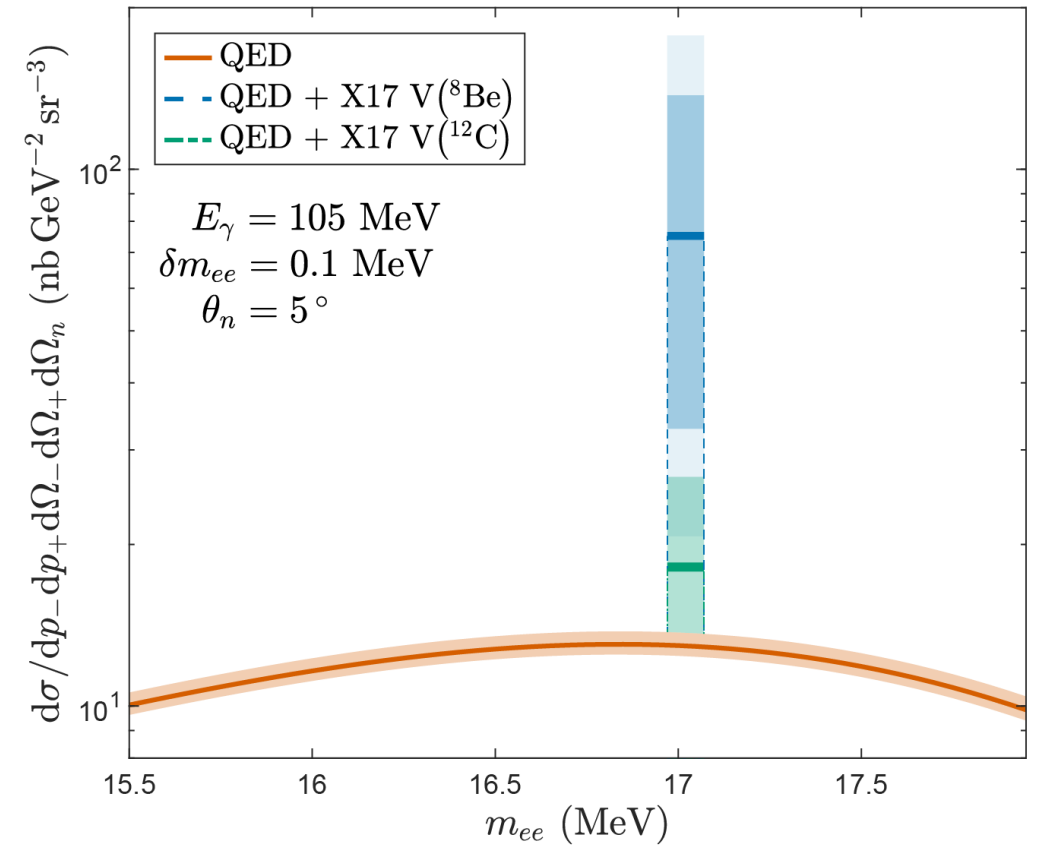
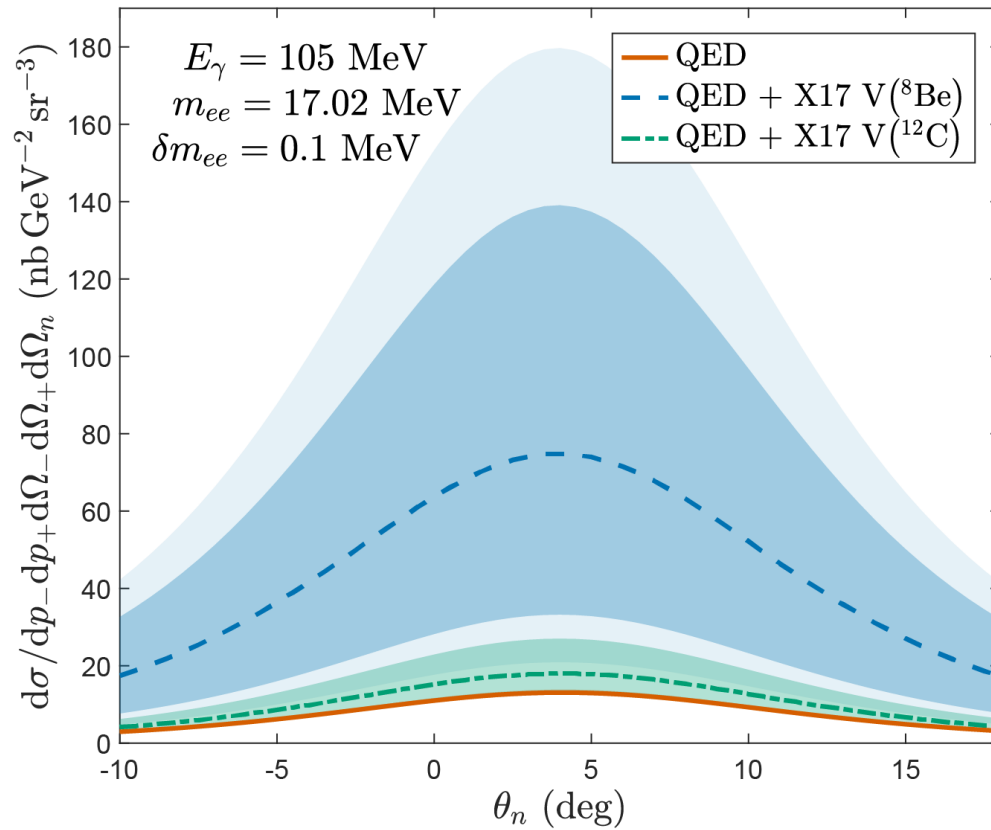


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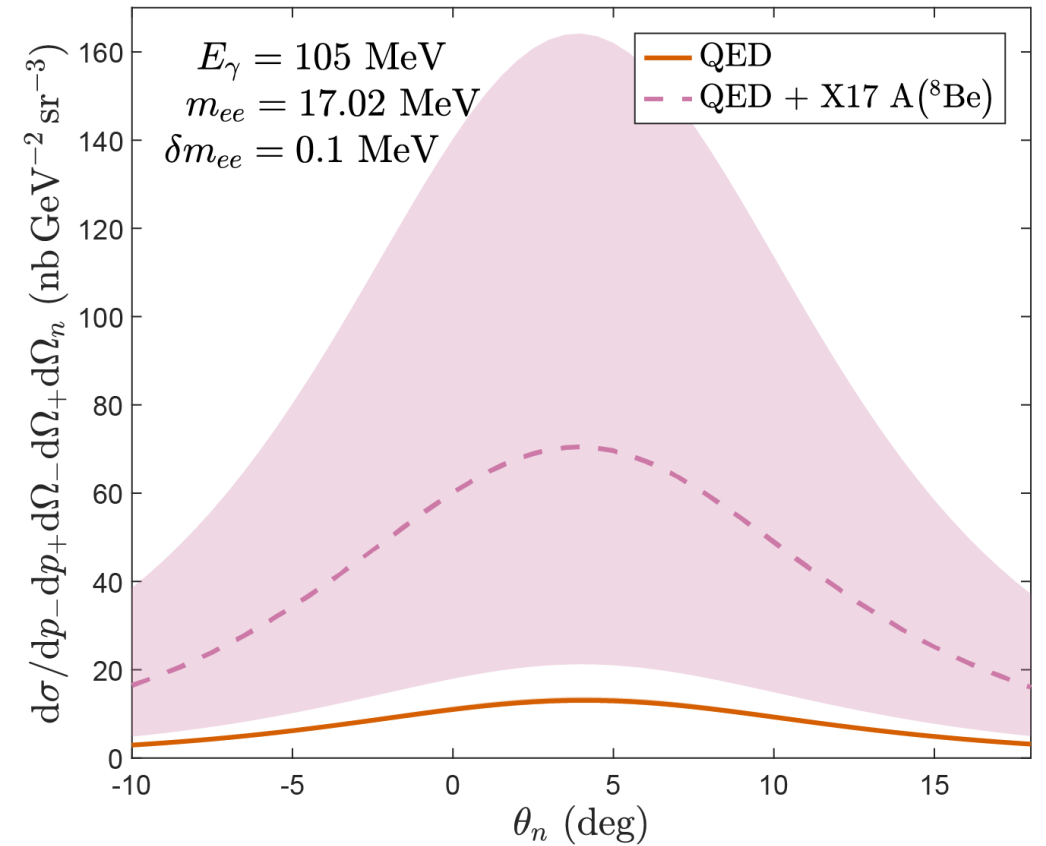
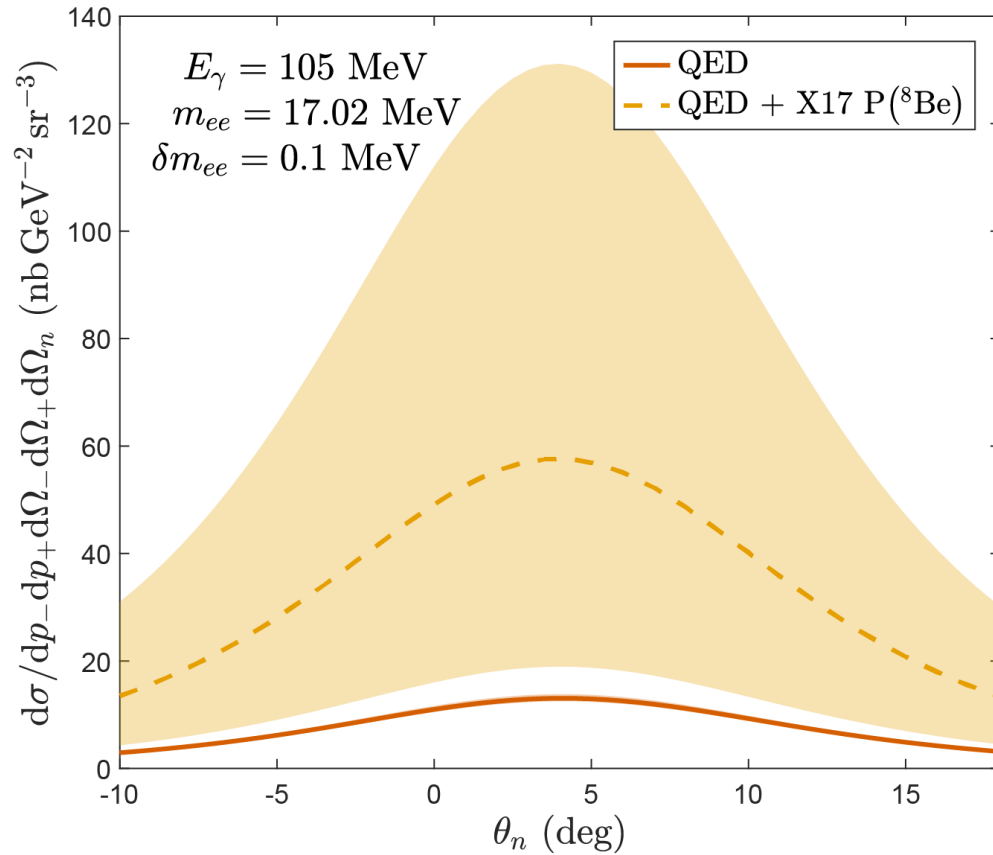


- Sensitivity MESA:  $\delta m_{ee} = 0.1 \text{ MeV}$

# Results (I)



# Results (II)



# Outlook

- Not limited to X17 – can draw exclusion limits

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- Not limited to X17 – can draw exclusion limits
- Use same measurement data to get neutron polarizabilities

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

M. I. Levchuk<sup>1</sup>, A. I. L'vov<sup>2</sup>, and V. A. Petrun'kin<sup>2</sup>

<sup>1</sup> B. I. Stepanov Institute of Physics, Belorussian Academy of Sciences, F. Scarina Prospect 70, 220602 Minsk, Belarus

<sup>2</sup> P. N. Lebedev Physical Institute, Russian Academy of Sciences, Leninsky Prospect 53, Moscow 117924, Russia

# 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

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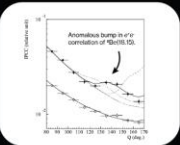
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### 1. What is X17?

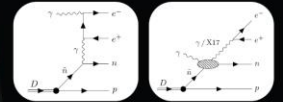
- The ATOMKI group found anomalous signals in the decays of excited  $^8\text{Be}$  (figure below),  $^4\text{He}$ , and  $^{12}\text{C}$  nuclei with statistical significances exceeding  $6\sigma$ .
- To account for these anomalies, they proposed the existence of X17, a light boson with a mass of 17.02(10) 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

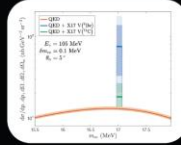
- X17 has a very narrow width,  $\Gamma_{\gamma} \ll 100$  keV.
- Influence of electron coupling not resolvable inside single bin.
- Cross section only depends on neutron coupling.

### 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

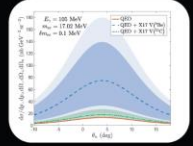
- Use beryllium and carbon measurements to constrain X17 coupling to nucleons.
- X17 signal (dashed) is visible over the QED background.
- Slight tension between couplings derived from beryllium and carbon nuclear decays highlights need for independent verification.
- MAGIX@MESA would be able to provide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



▲ Vector X17 in a bump hunt

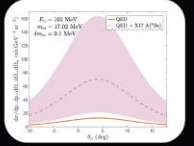
X17 signal would appear as a sharp spike in a single bin.

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)

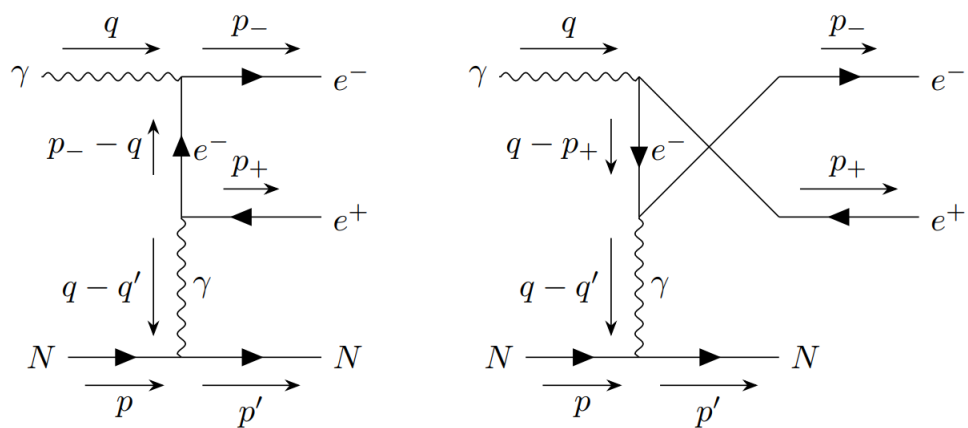


Figure 2: The direct and crossed diagram for the BH process.

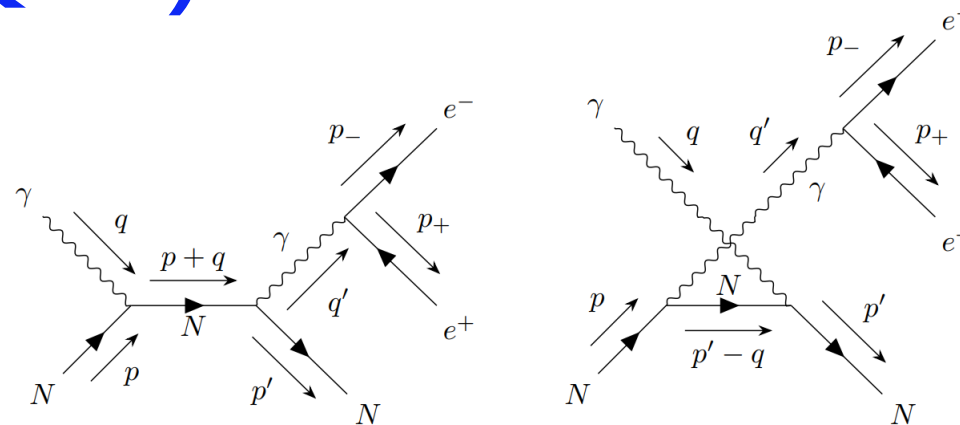


Figure 1: The direct and crossed diagram for the Born process.

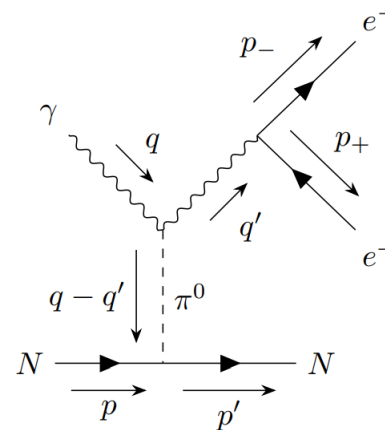
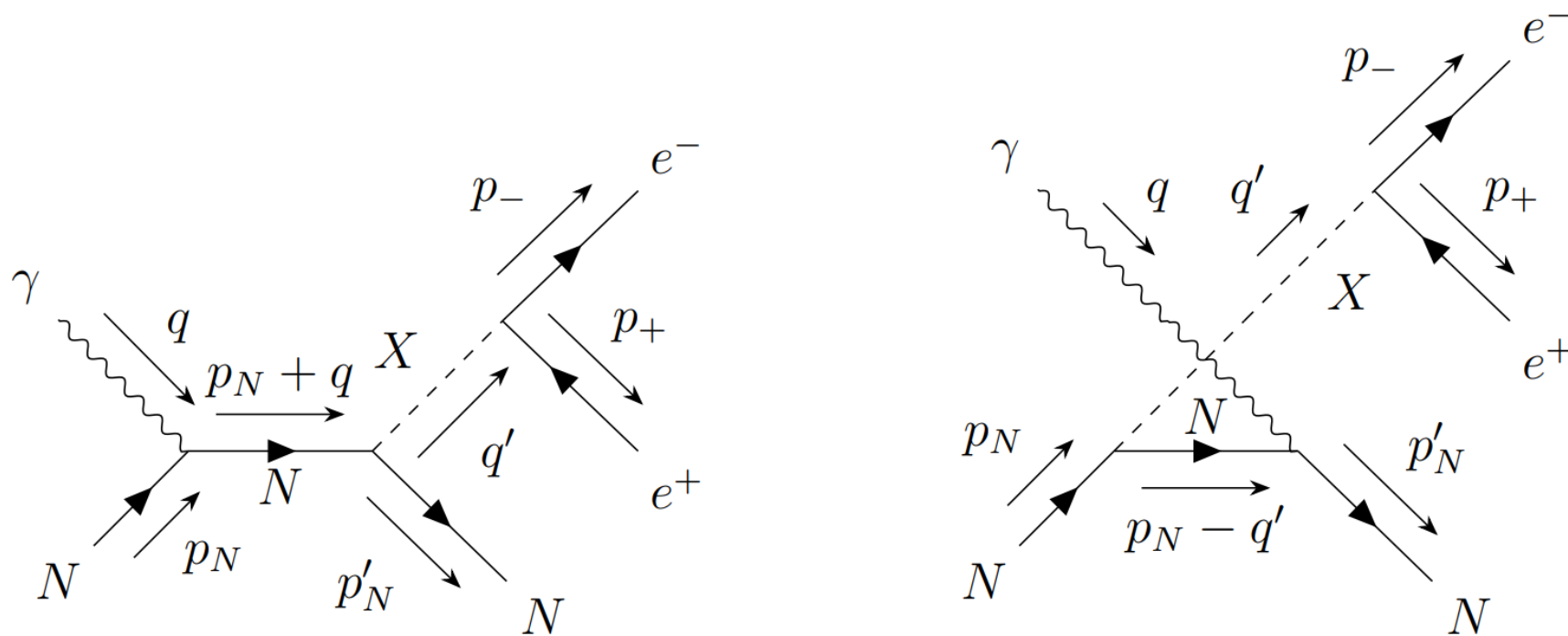


Figure 3: The diagram for the pion-pole amplitude.

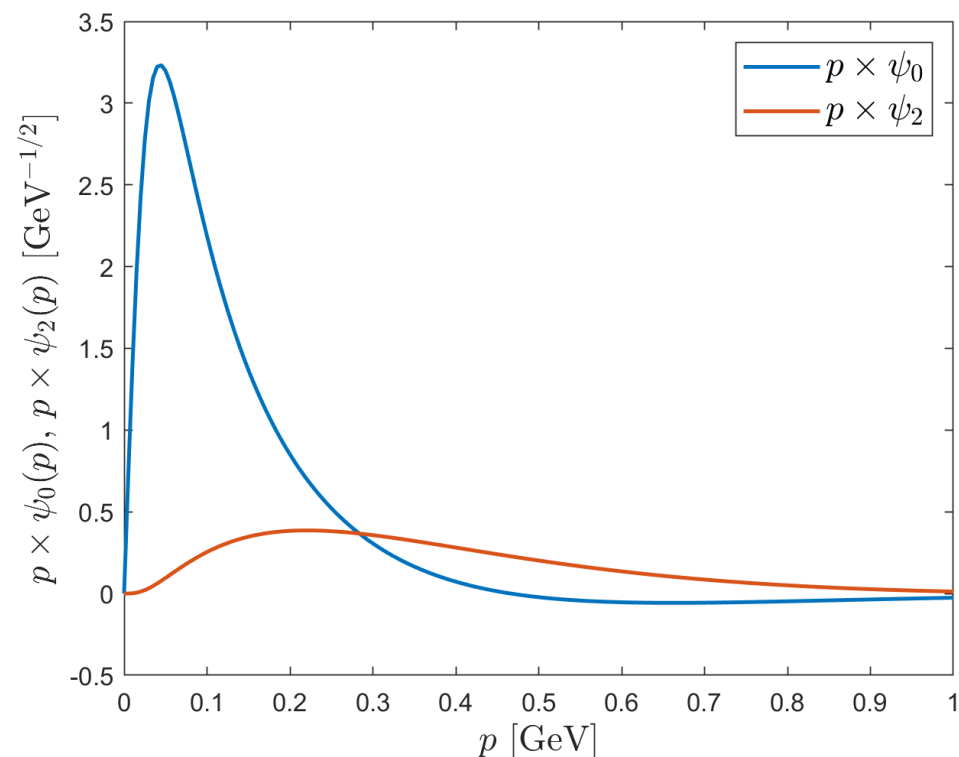
# Diagrams in detail (signal)



# 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

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

# 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

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

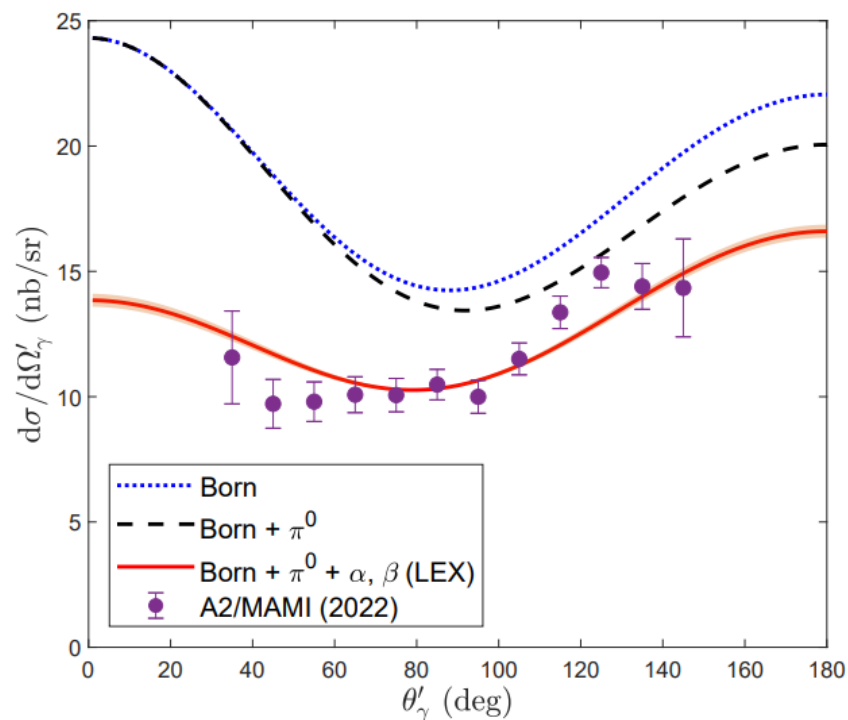
We have

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

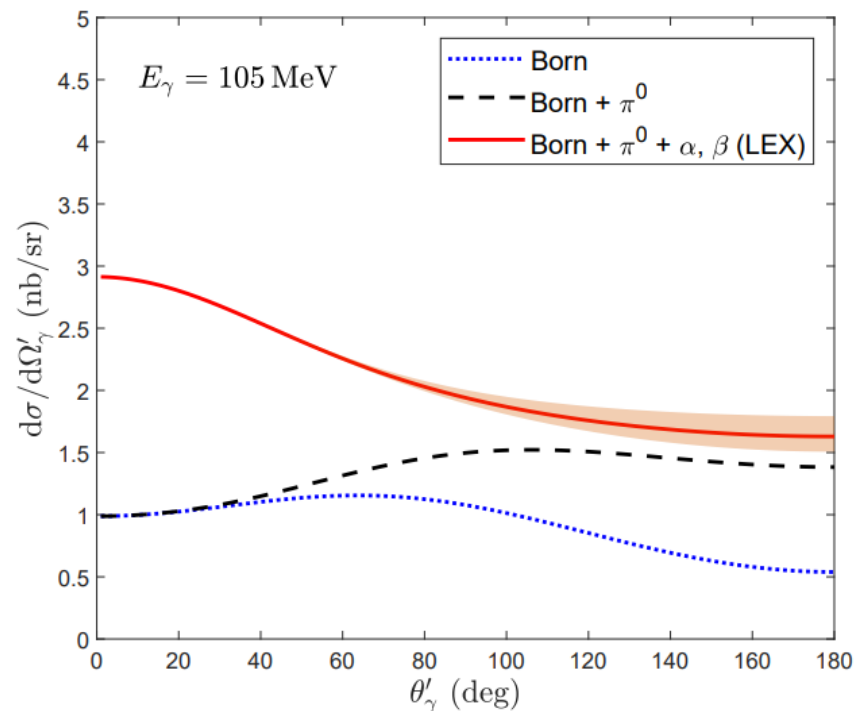
$$\frac{1}{q'^2} \left( \frac{d\sigma}{d\Pi} \right) \frac{[(q'^2 - m_X^2)^2 + (m_X \Gamma_X)^2]}{g_{Xee}^2} \approx \text{constant between } \left[ m_X - \frac{\delta m_X}{2}, m_X + \frac{\delta m_X}{2} \right]$$

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

# Verifying the QED background (I)



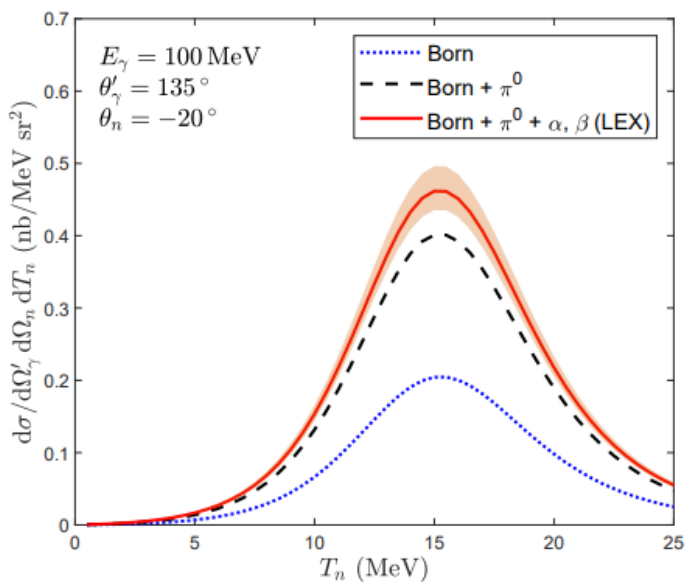
(a)  $\gamma p \rightarrow \gamma p$



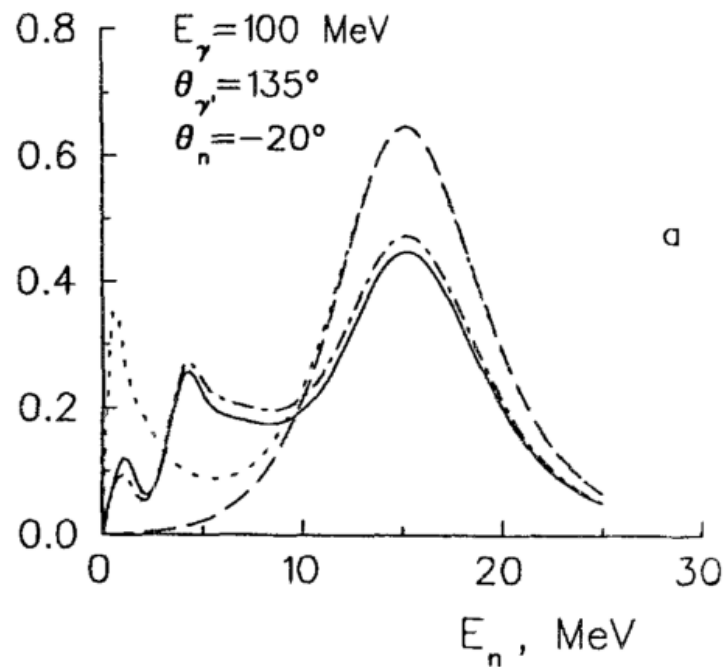
(b)  $\gamma n \rightarrow \gamma n$

# 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