Low mass DARK SECTOR SEARCHES with deuteron photodisintegration

Cornelis J.G. Mommers,

Phys. Rev. D 109, 095010 & Phys. Lett. B 858 139031

Group Marc Vanderhaeghen, Johannes Gutenberg University Mainz

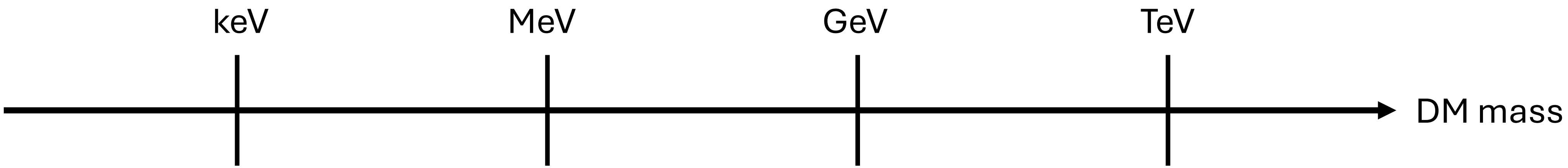
Low mass

DARK SECTOR SEARCHES

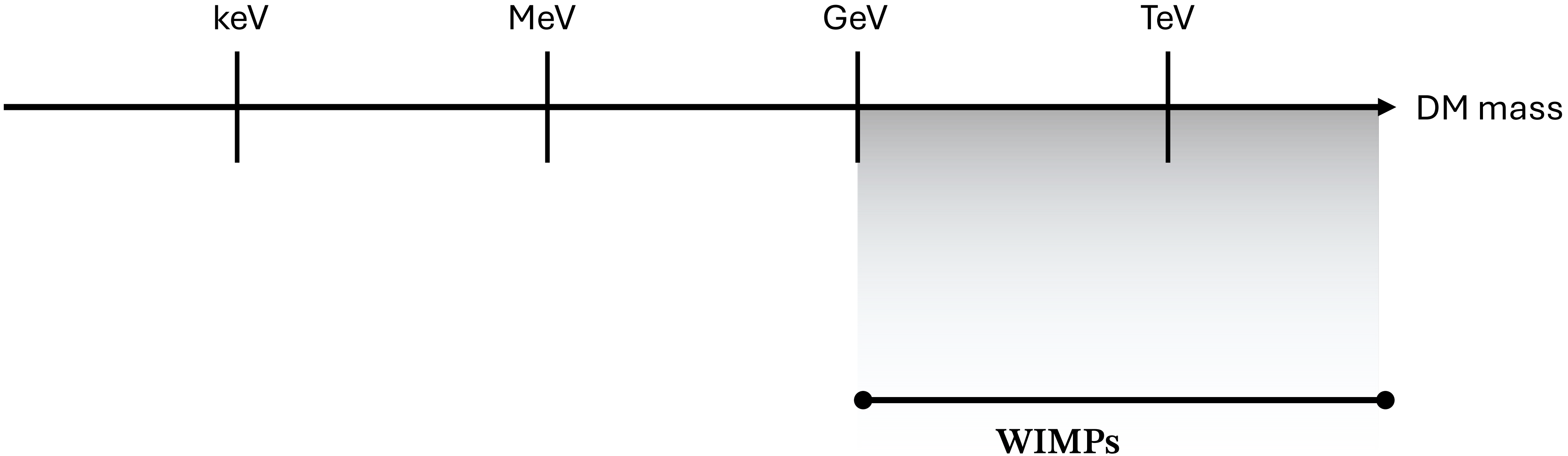
with deuteron photodisintegration

Why?

A shifting paradigm?



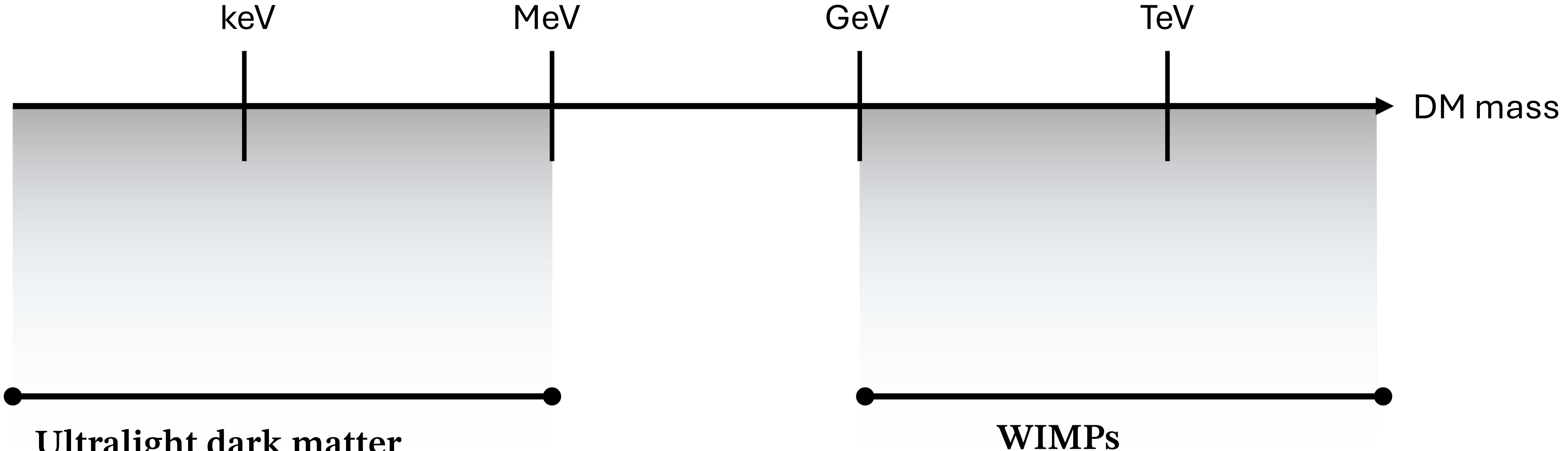
A shifting paradigm?



WIMPs

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

A shifting paradigm?



Ultralight dark matter
- **Searches with atomic and nuclear systems**
- **No clear signal yet**

WIMPs
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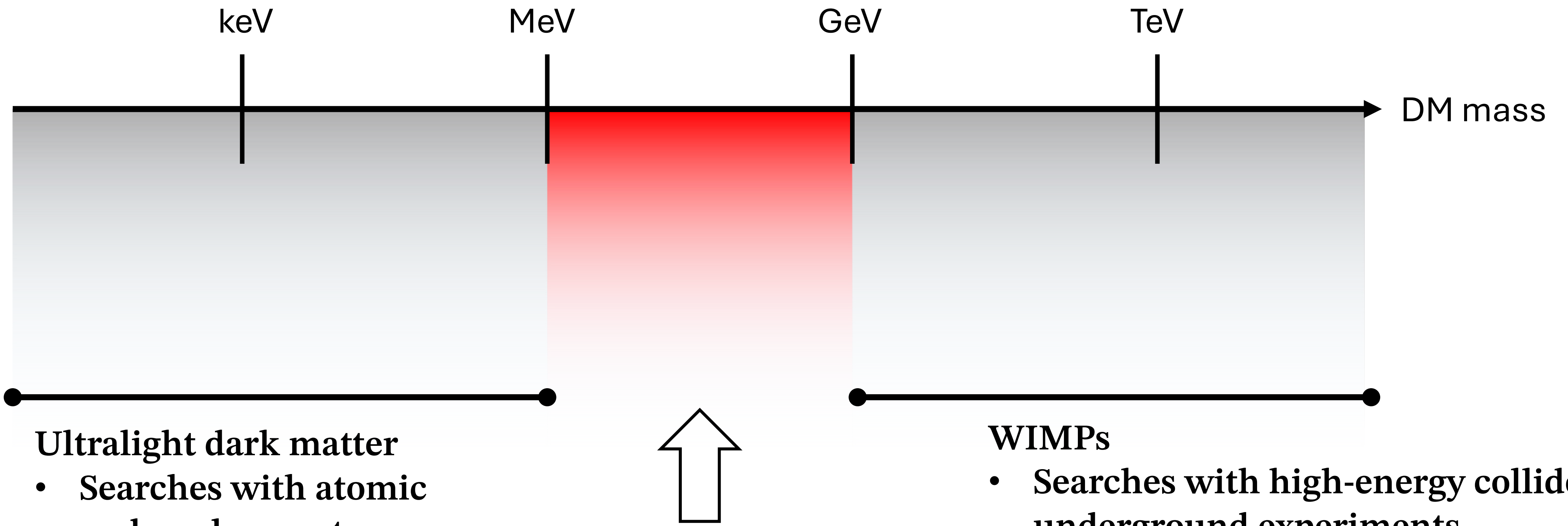

Ultralight dark matter
- Searches with atomic and nuclear systems
- No clear signal yet

- Searches with low energy, high intensity
- Increasing interest

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

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Strong interest in light bosons

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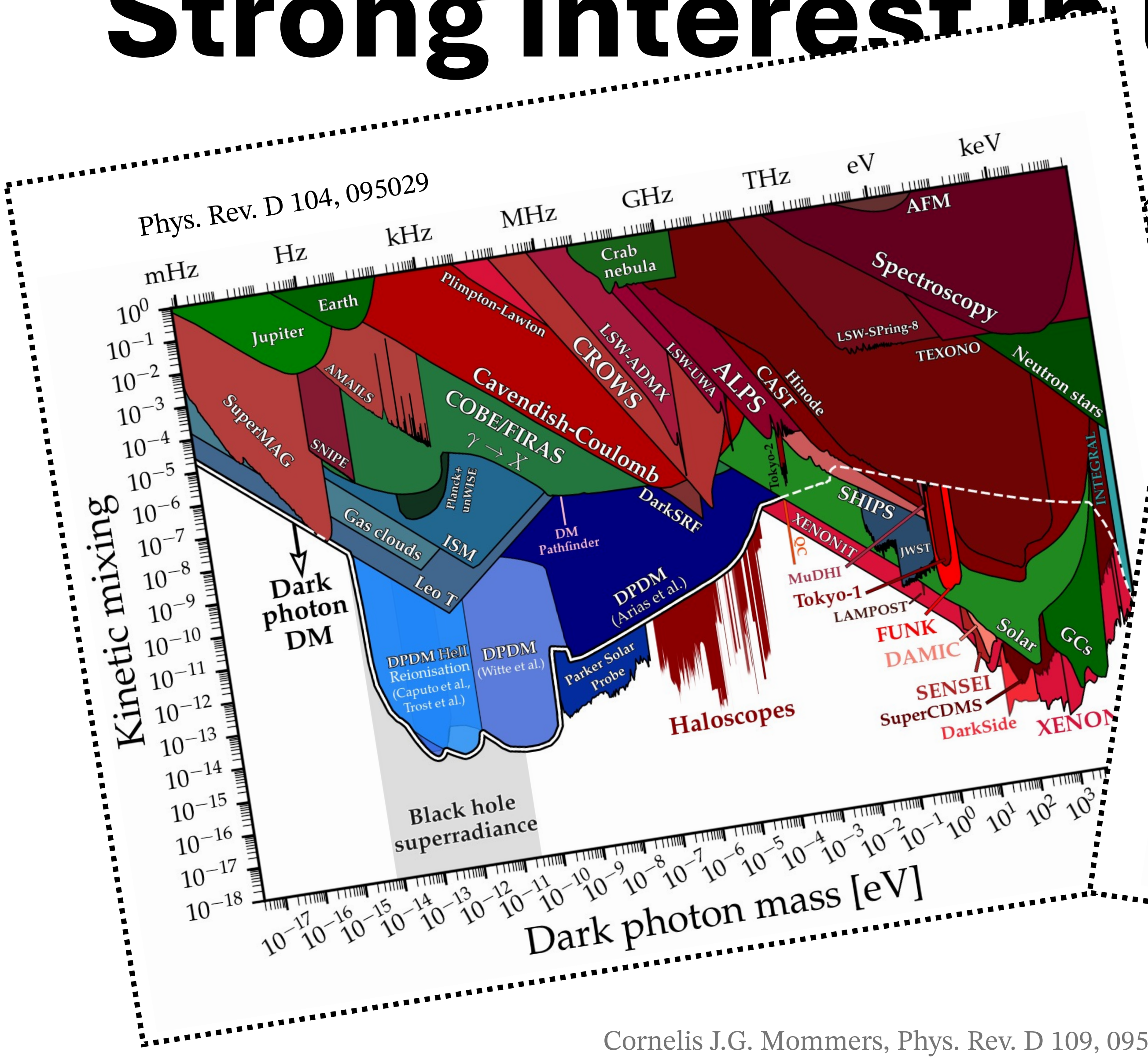

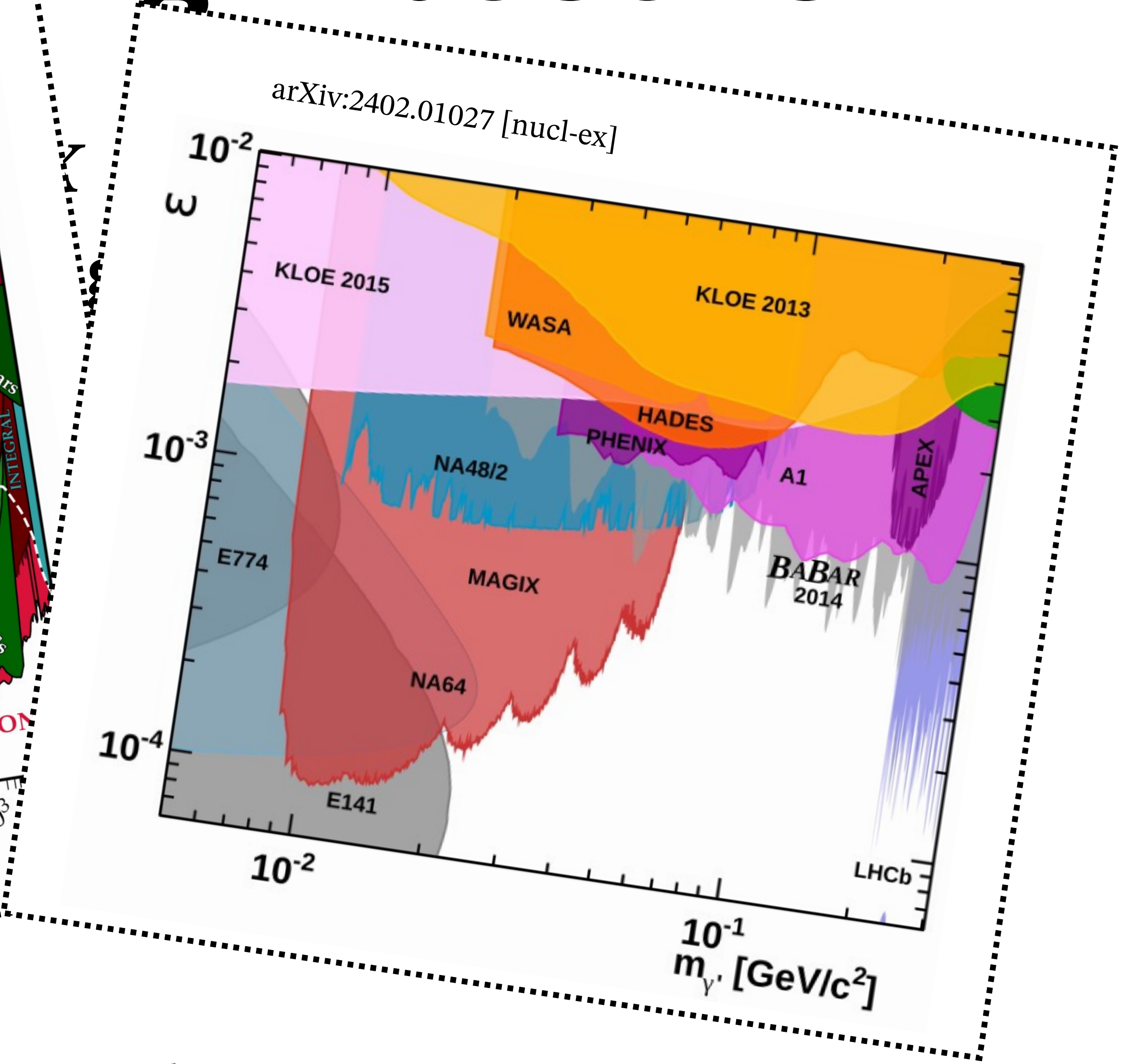

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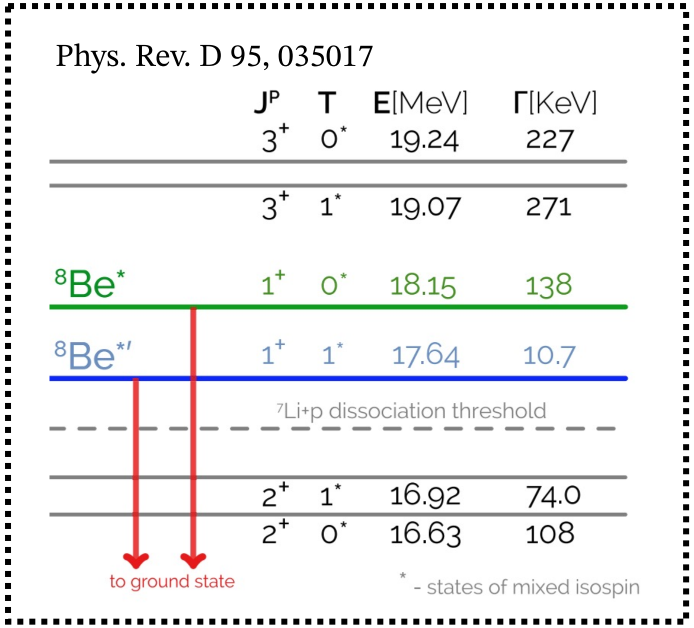
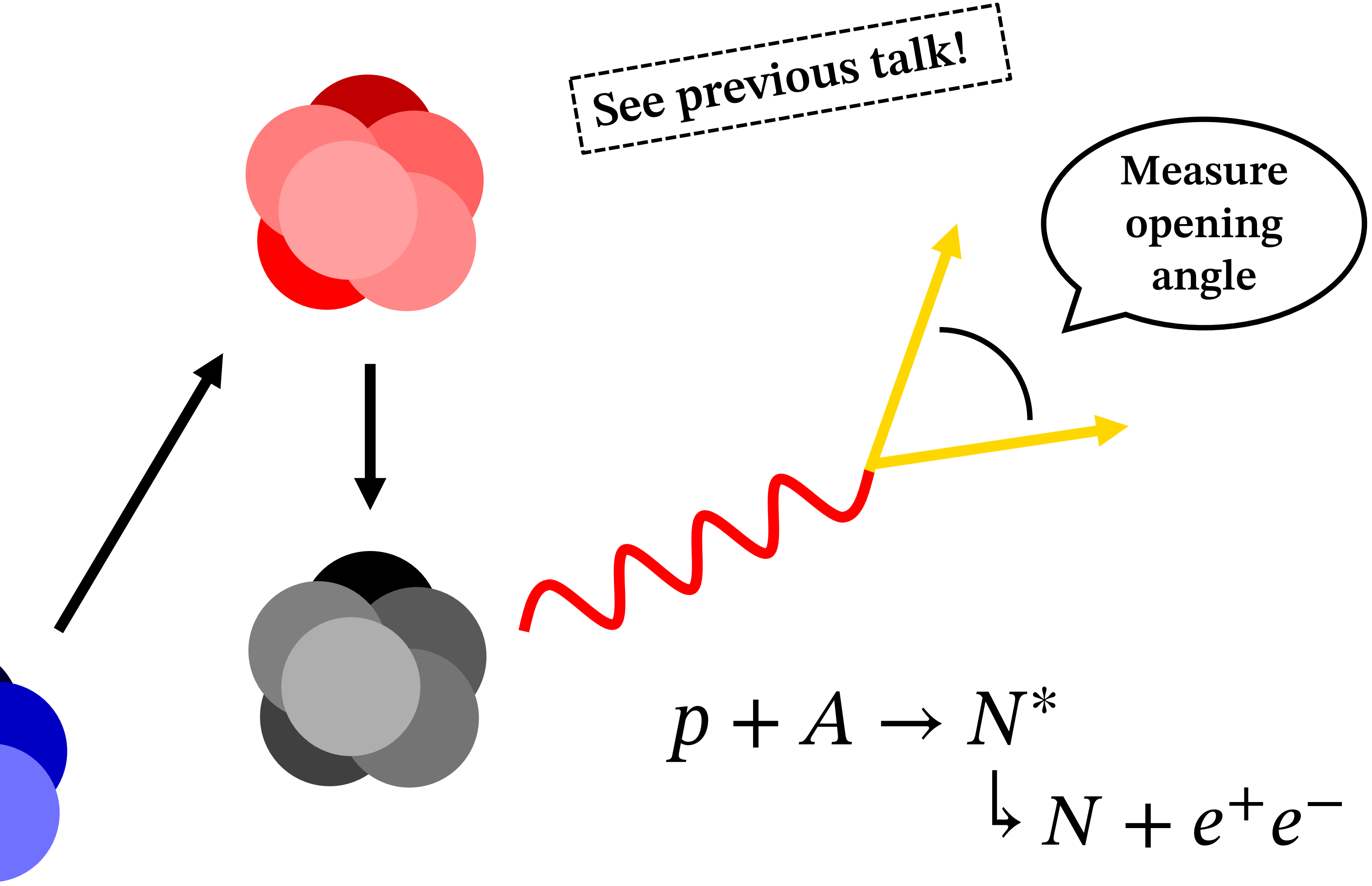
- **However, few constraints on *just* the neutron coupling *in 10-100 MeV mass range***
- **Reason: hard to probe, no free neutron target**
- **But bounds would be useful:**
  Probe flavor-dependent couplings $g_{u/d} \sim (2g_{p/n} - g_{n/p})/3$
  Constrain X17?

ATOMKI anomaly: X17





$$p + A \to N^*$$
$$\hookrightarrow N + e^+e^-$$

Timeline: X17 + theory

Disclaimer: timeline not exhaustive, many relevant & important papers left out!

ATOMKI group reports anomalous signals in…

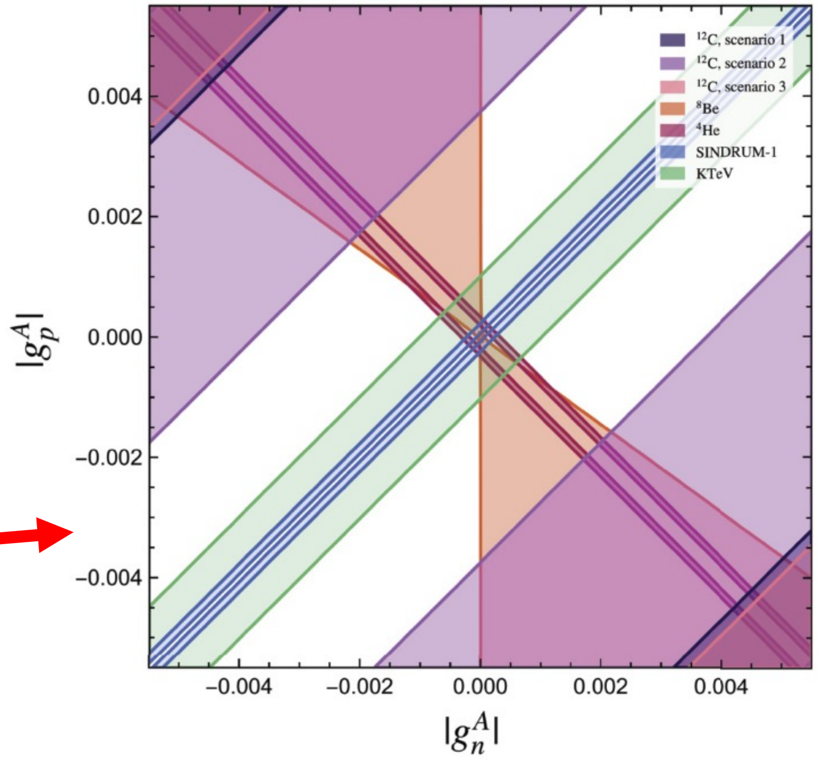
2016	• ^{8}Be decays	Phys. Rev. Lett. 116, 042501 (2016)
2021	• ^{4}He decays	Phys. Rev. C 104, 044003 (2021)
2022	• ^{12}C decays	Phys. Rev. C 106, L061601 (2022)

2022-now Tensions in theory?

See JHEP 02 154 (202

All colored regions should overlap at least at one point, but they don't!

Phys. Lett. B 858 139031 (2024)



More theory developments...

Now

On the Atomki nuclear anomaly after the MEG-II result

D. Barducci,[a] D. Germani,[b] M. Nardecchia,[b] S. Scacco,[b] C. Toni[c,d]

ABSTRACT: Recent experimental results from the Atomki collaboration have reported the observation of anomalous effects in Beryllium, Helium and Carbon nuclear transitions that could hint at physics beyond the Standard Model. However, the MEG-II experiment has recently found no significant anomalous signal in the Beryllium transition $^8\text{Be}^\star \to {}^8\text{Be} + e^+e^-$. In view of this result, we critically re-examine the possible theoretical interpretations of the anomalies observed by the Atomki experiment in terms of a new boson X with mass around 17 MeV. The present work aims to study the phenomenology of a spin-2 state and revisit the possibility of a pure CP-even scalar, which was initially dismissed due to its inability to explain the Beryllium anomalous signal. Our analysis shows that a spin-2 state is highly disfavoured by the SINDRUM constraint while a scalar boson could explain the Helium and Carbon anomalies while being compatible with other experimental constraints.

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  Use quasi-free neutrons!

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- How to measure the neutron coupling?
  Use quasi-free neutrons!
- How to measure quasi-free neutrons?
  Deuteron photodisintegration!
- Previously: similar measurements for extraction neutron polarizability (Phys. Rev. Lett. 88, 162301)

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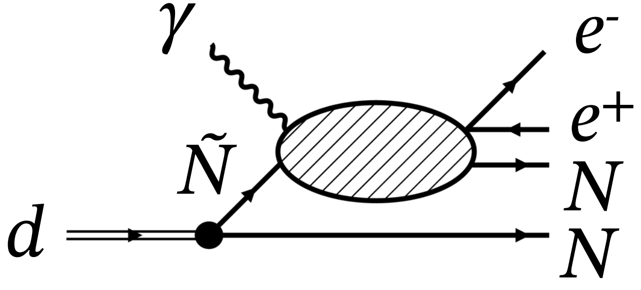
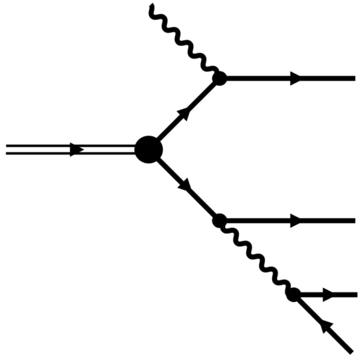
Diagram topologies to one loop

Pole diagrams





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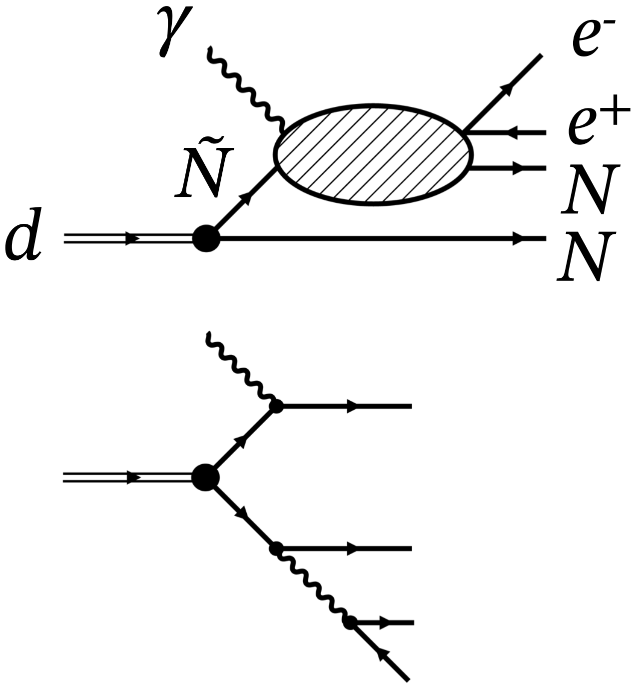
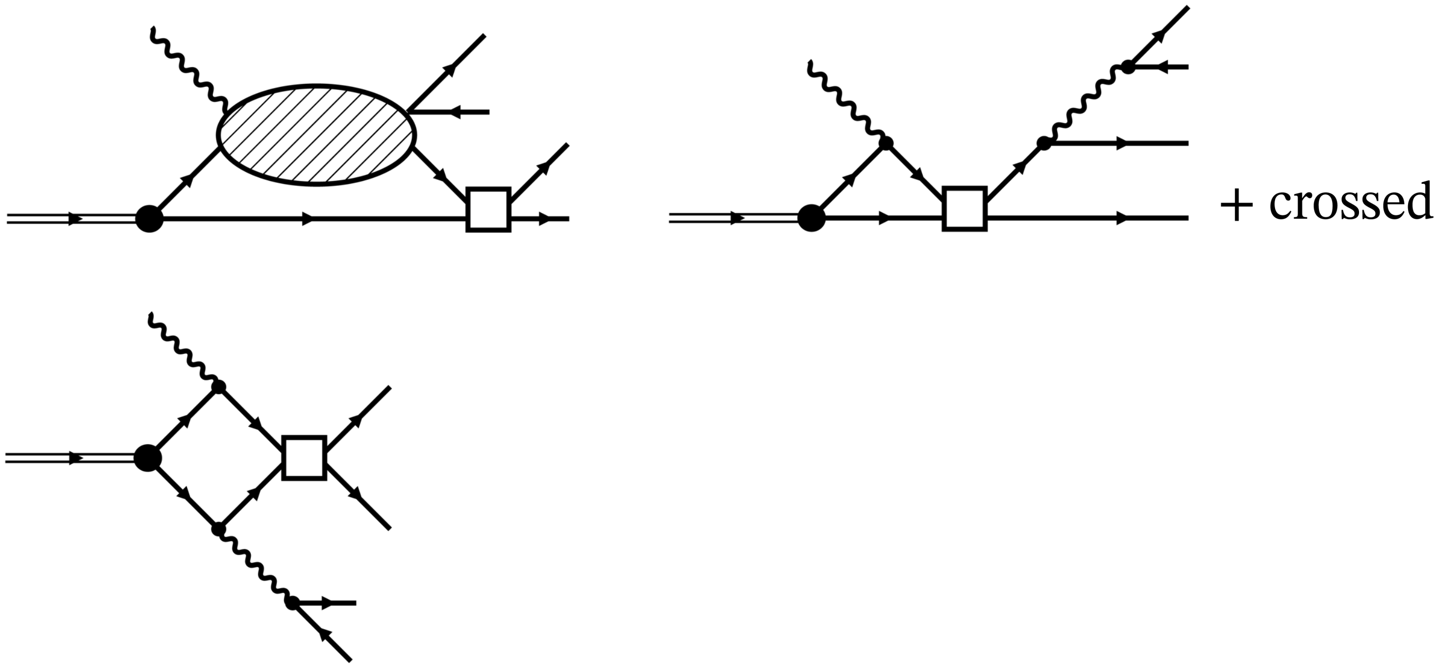


Rescattering diagrams



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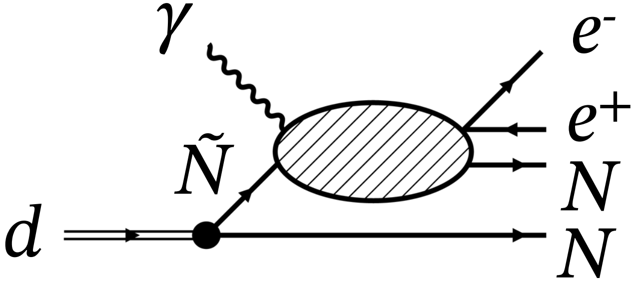

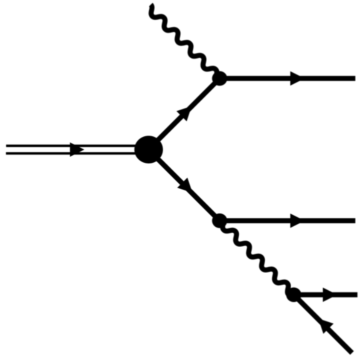

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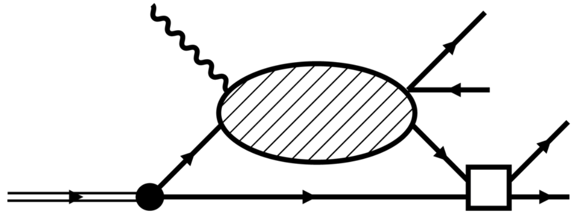
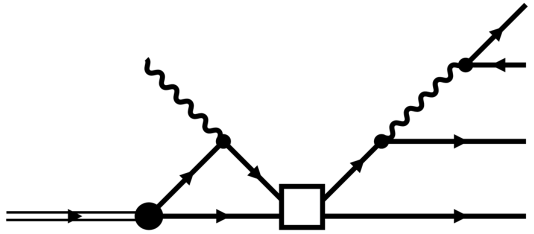
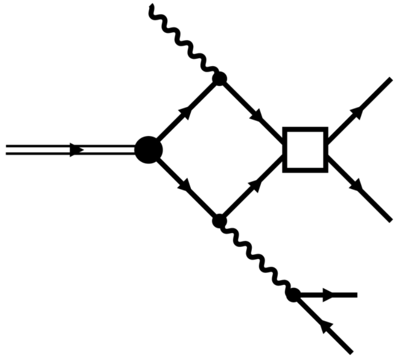
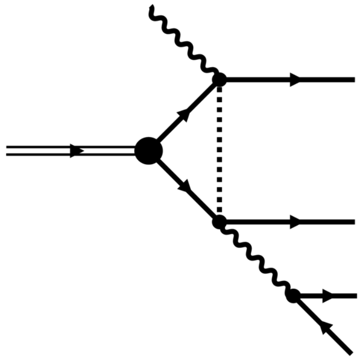


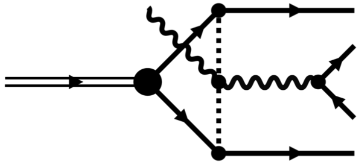


+ crossed



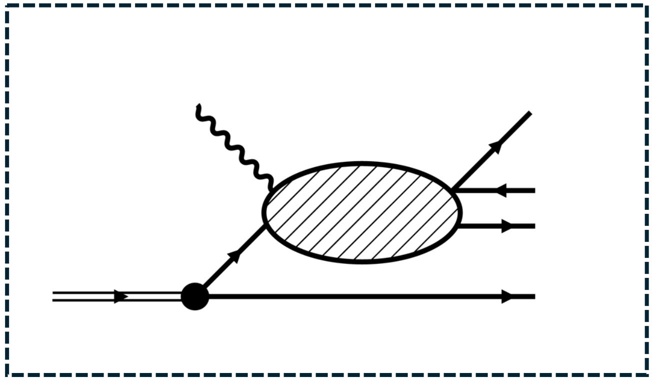
MEC diagrams





Dominant diagram topologies

Pole diagrams



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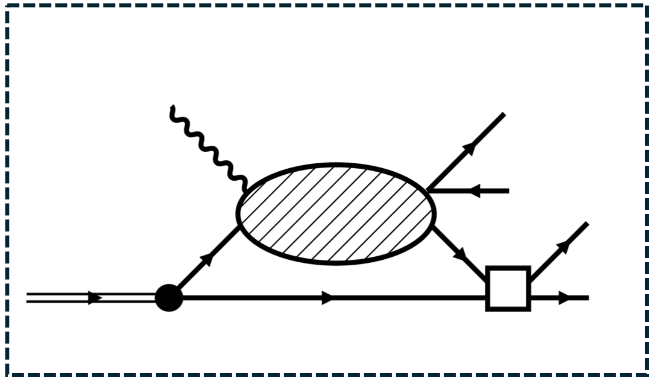

Plane wave

Distorted wave

Only plane wave: PWIA

Plane wave + distorted waved: DWIA

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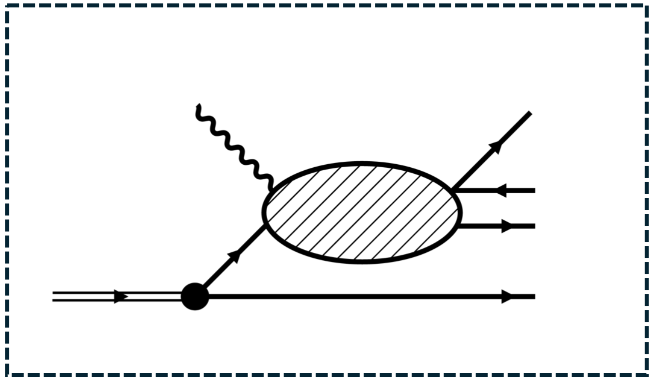

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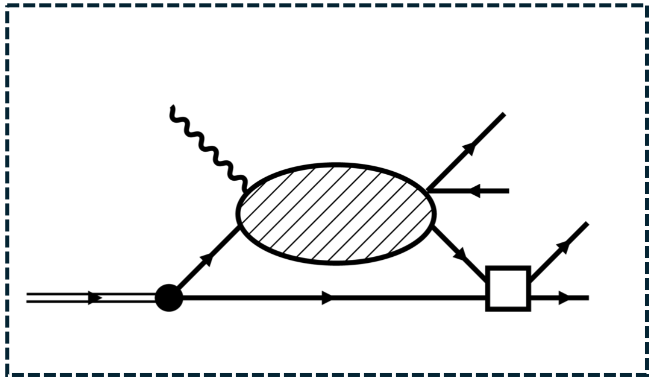
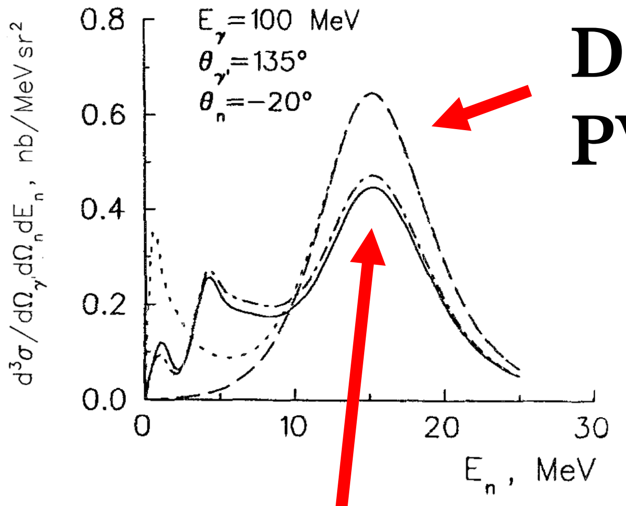


Distorted wave

Few-Body Systems 16, 101-125 (1994)



Dashed: PWIA

Only plane wave: PWIA

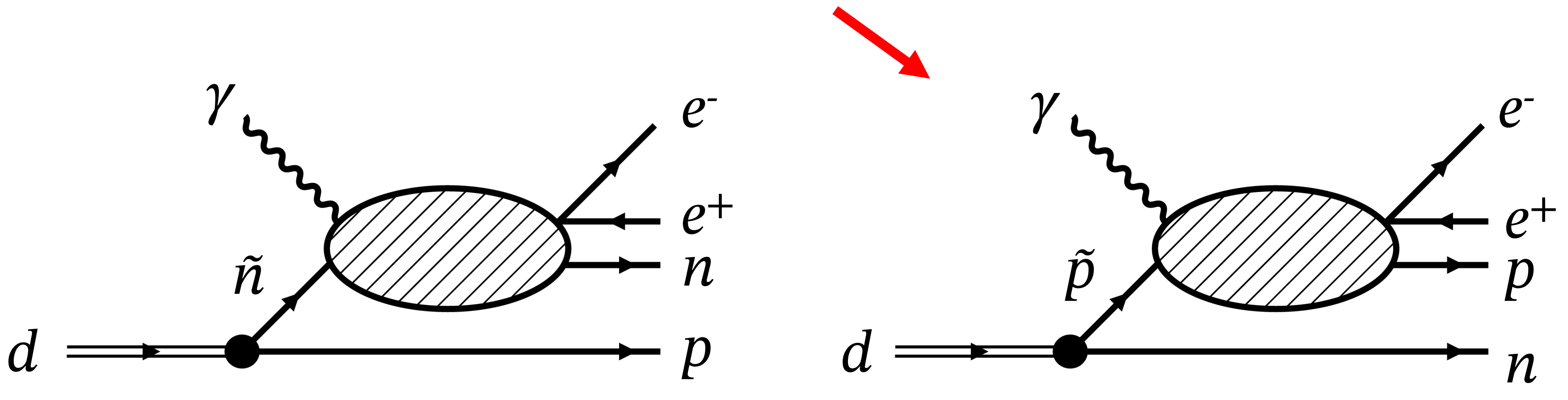
Plane wave + distorted waved: DWIA

Dash-dot: DWIA

Solid: DWIA + MEC

Suppressing proton contributions

- As a first step consider only PWIA (currently calculating DWIA + MEC)
- Goal: extract neutron observables
- Question: how to suppress proton plane-wave contribution?



Neutron quasi-free peak

- **In deuteron rest frame can show:**
  - $\mathcal{M}^{n}_{\mathrm{PWIA}} \propto \Psi_d(\mathbf{p}_p)$
  - $\mathcal{M}^{p}_{\mathrm{PWIA}} \propto \Psi_d(-\mathbf{p}_n)$

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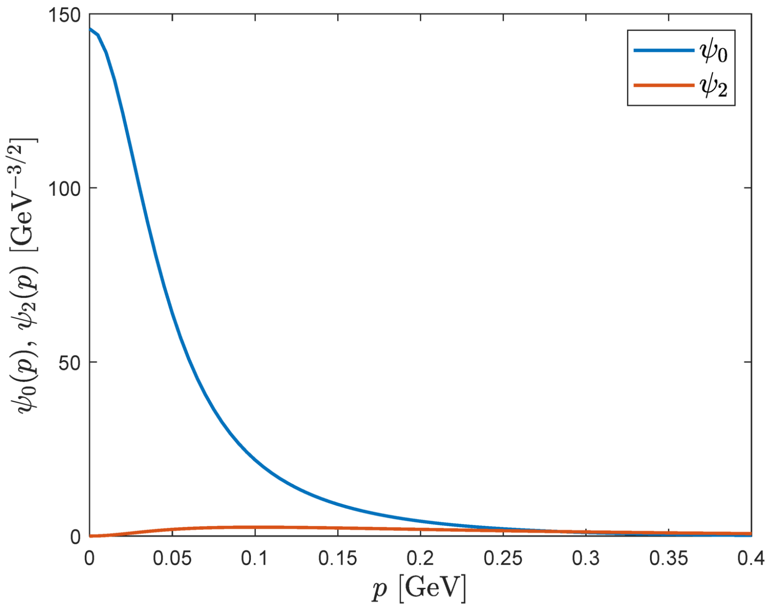

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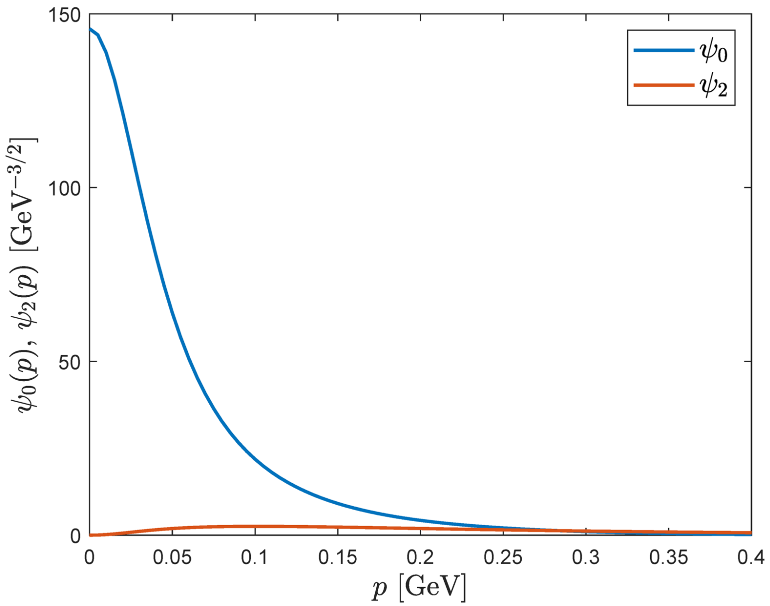
- **Go to region $|\mathbf{p}_p| \to 0$**



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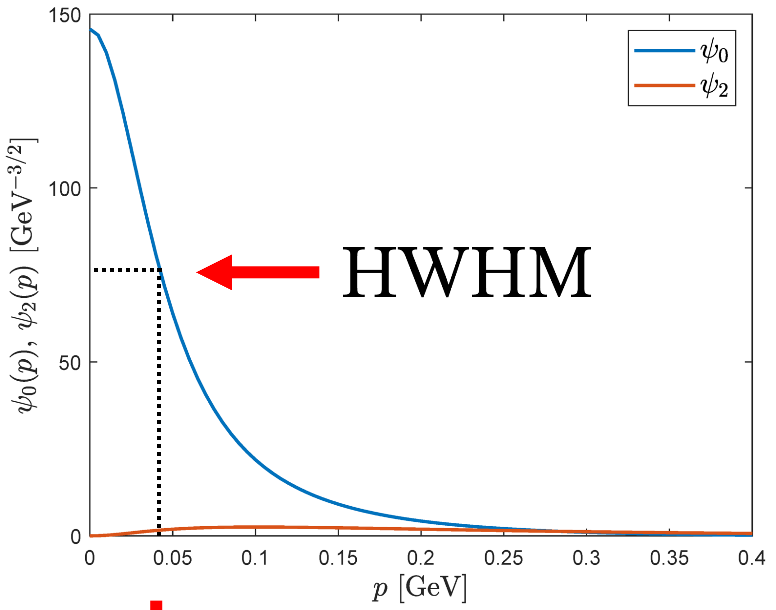
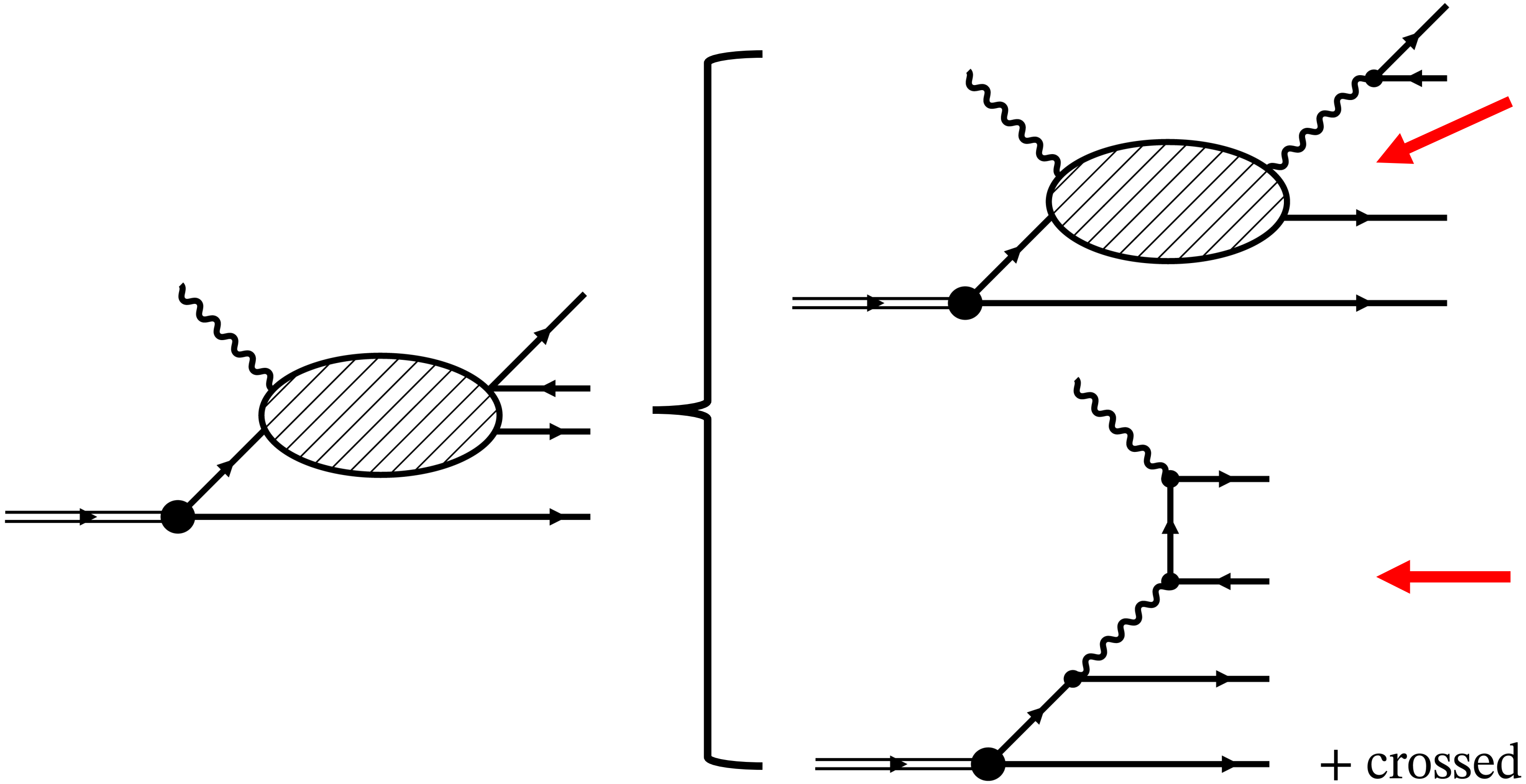
- Go to region $|\mathbf{p}_p| \to 0$
- $\Delta \approx 2.2$ MeV deuteron binding energy



$$|\mathbf{p}_p| \lesssim \sqrt{\Delta m_N} \approx 45.7 \text{ MeV/c}$$

Signal (I)

- Consider PWIA in more detail:



Time-like nucleon Compton

- Born
- π^0 *t*-channel exchange
- Neutron scalar polarizability

Bethe-Heitler

Signal (II)

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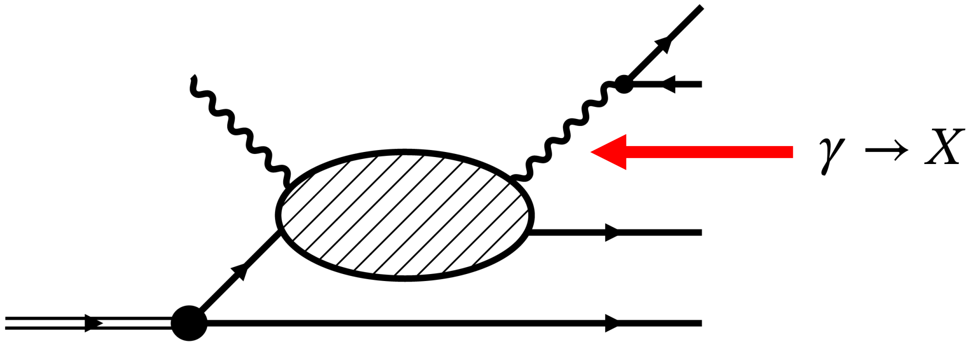

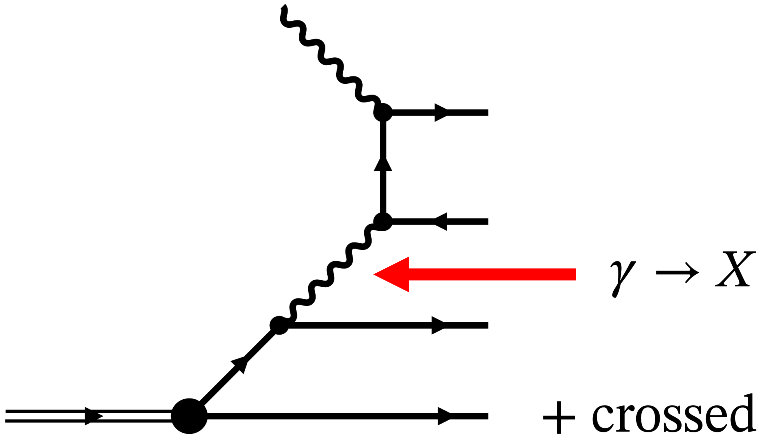

- New boson X can appear as narrow resonance on top of QED background
- Restrict kinematics s.t.

$$(p_+ + p_-)^2 = p^2_{e^+e^-} = m_X^2$$

- Then: BH negligible

Binning data

- **Real world: cannot set** $(p_+ + p_-)^2 = p^2_{e^+e^-} = m_X^2$ **exactly**
- **Bin data:**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi} \to \overline{\frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}} = \frac{1}{\delta m_{ee}} \int_{m_X - \delta m_{ee}/2}^{m_X + \delta m_{ee}/2} \mathrm{d}m_{ee} \, \frac{\mathrm{d}\sigma}{\mathrm{d}\Pi}$$

  with bin width δm_{ee}

- **N.B. possible**
  $\delta m_{ee} \sim \mathcal{O}(0.1\ \mathrm{MeV}/c^2)$

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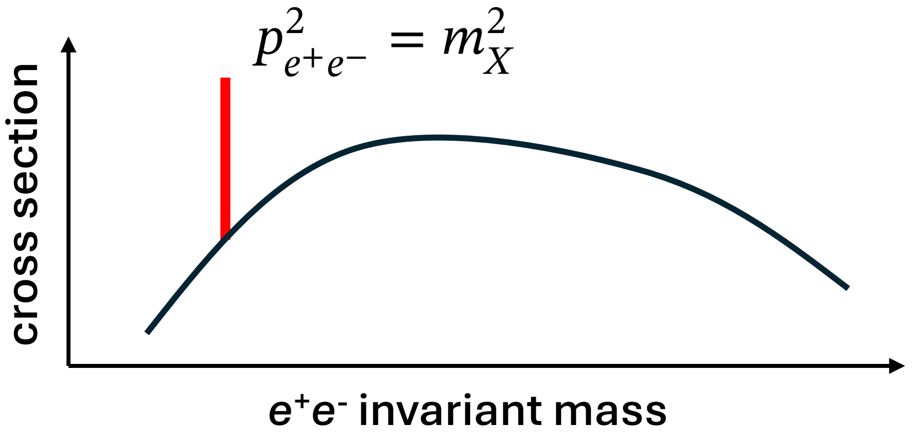

Binning data

- **Real world: cannot set** $(p_+ + p_-)^2 = p^2_{e^+e^-} = m^2_{X}$ ... **y**
- **Bin data:**

What kinematic regions is NQFP condition valid and X on resonance?

$\mathrm{d}\Pi$

with ... δm_{ee}

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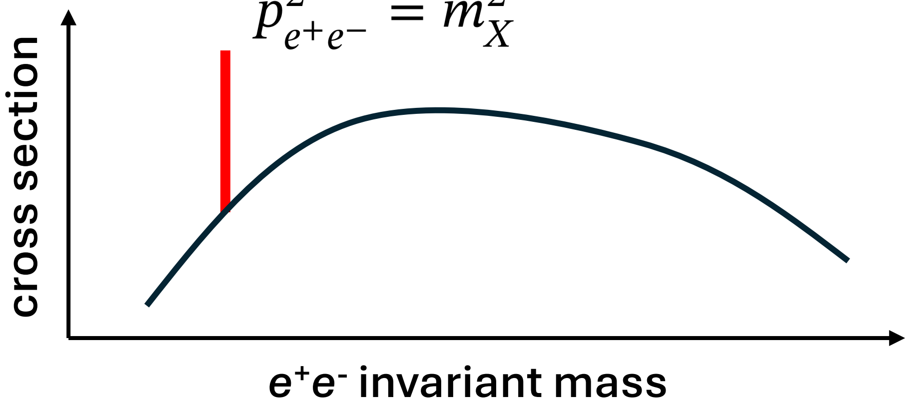
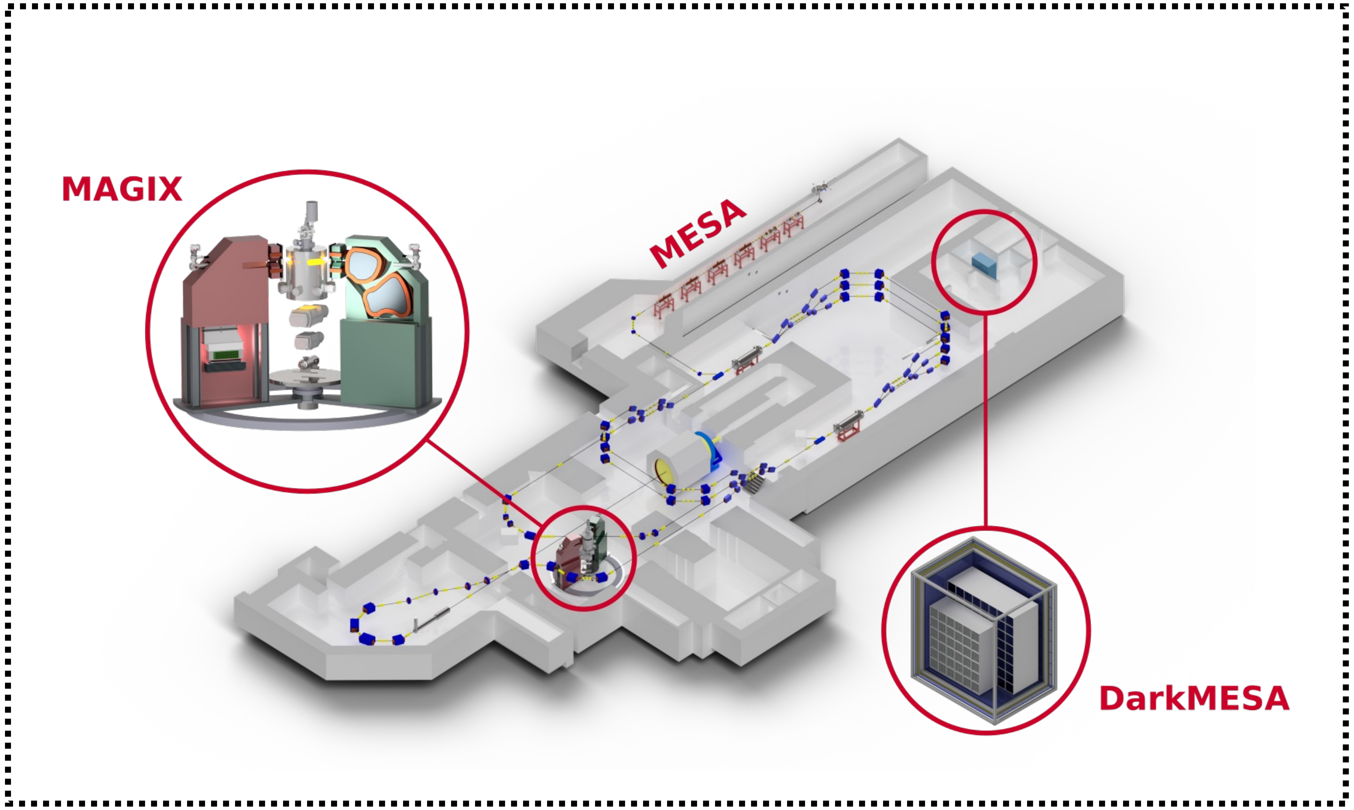


MESA

- Mainz Energy-Recovering Superconducting Accelerator



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- **MAGIX is a pair of multipurpose spectrometers, expected precision** $\delta m_{ee} < 0.1\ \text{MeV}/c^2$

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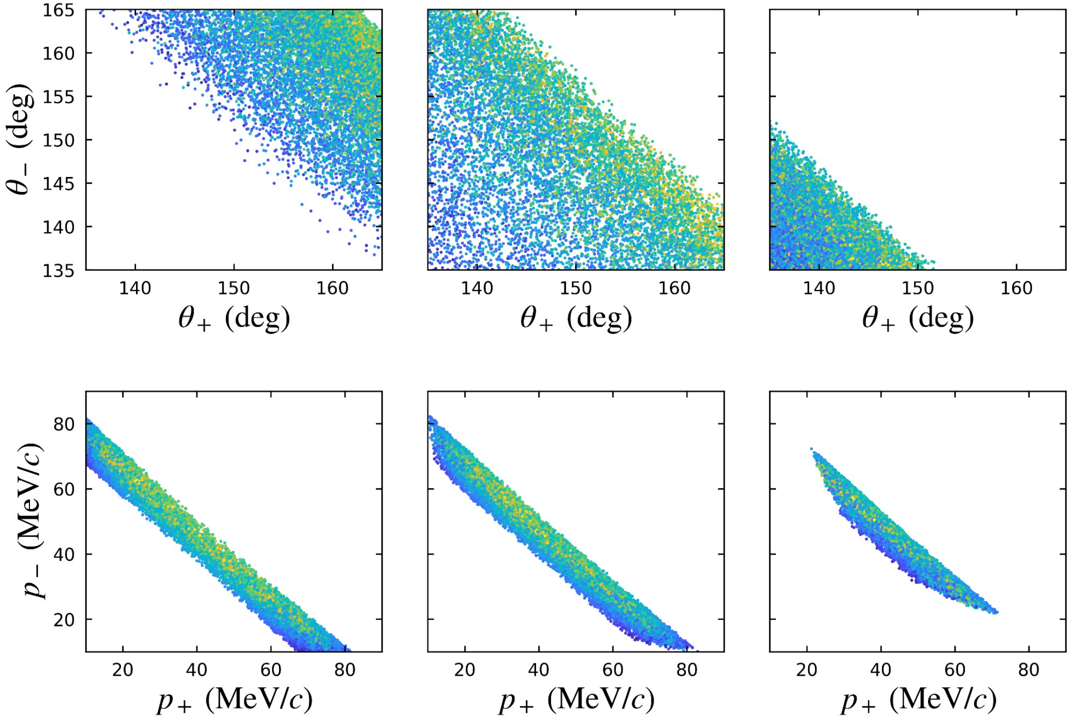
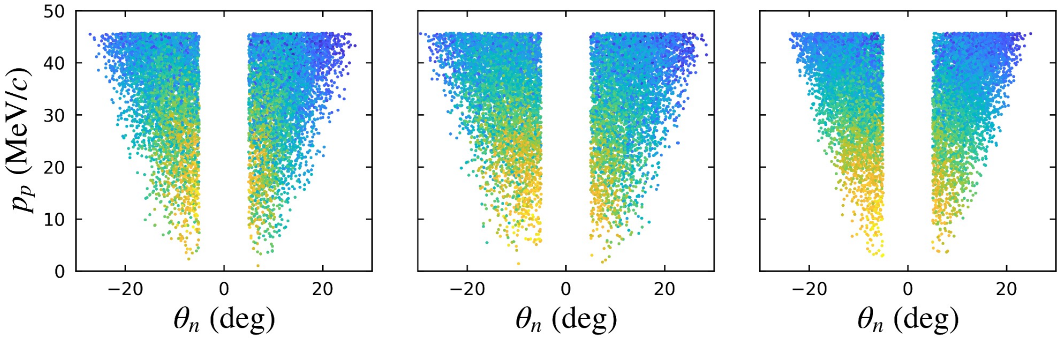
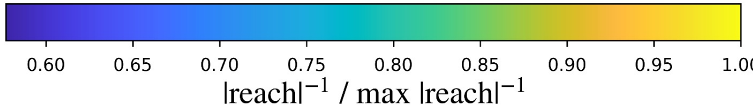
Projections MAGIX@MESA (I)

$m_{ee} =$ 25 MeV/c^2 40 MeV/c^2 55 MeV/c^2 25 MeV/c^2 40 MeV/c^2 55 MeV/c^2

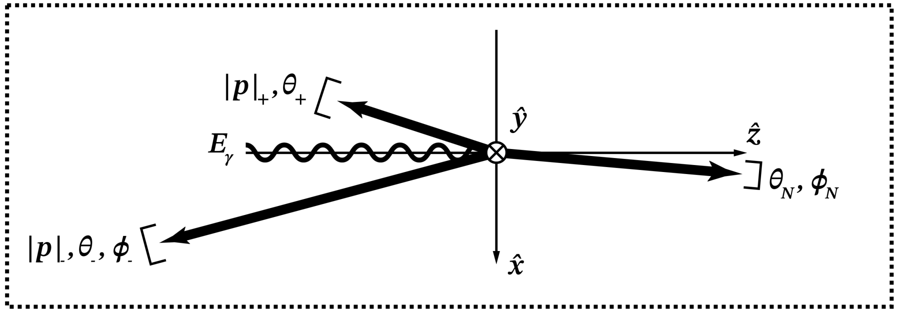






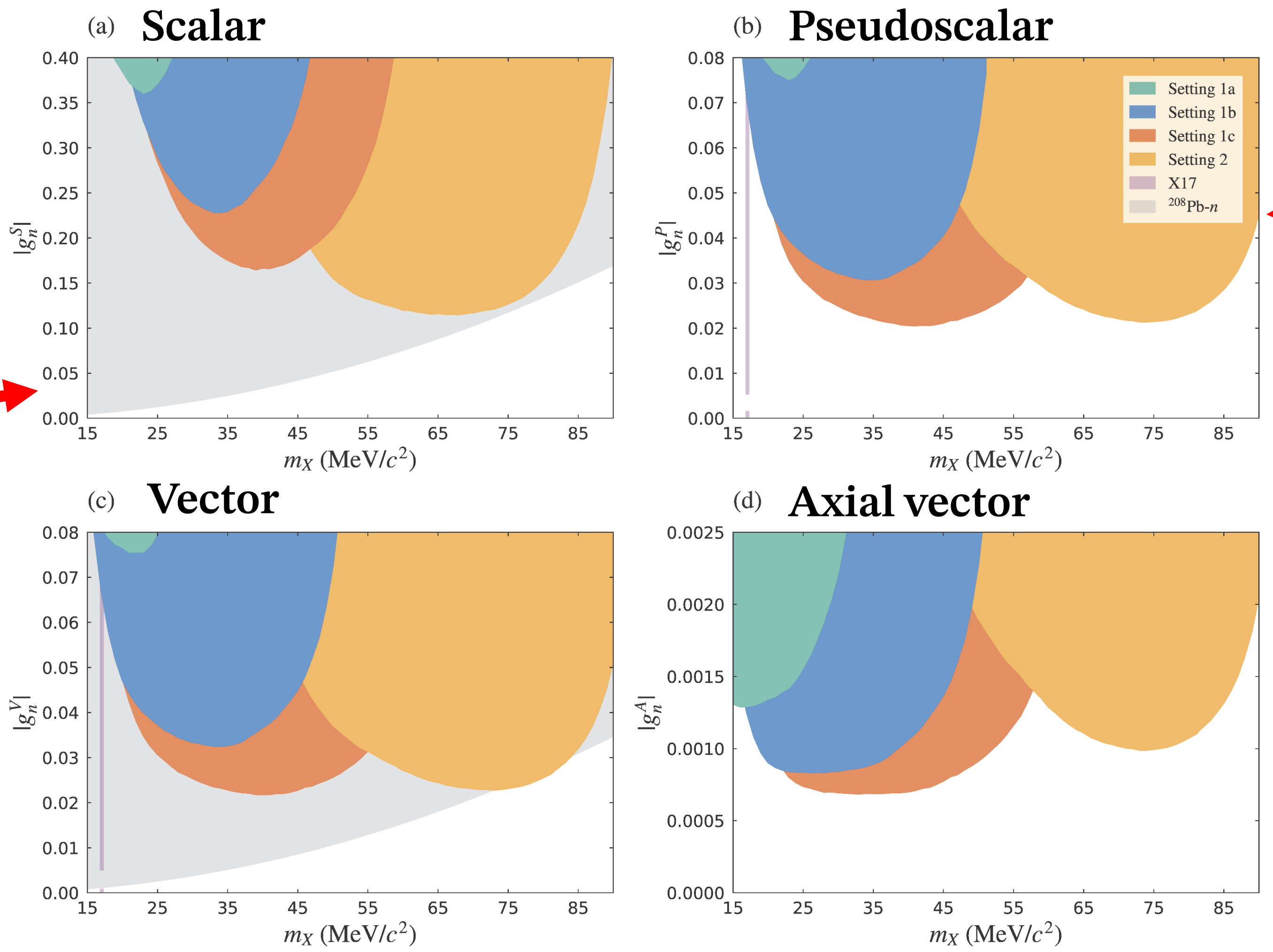
yellow = better

$E_\gamma = 105$ MeV



Projections MAGIX@MESA (II)

Pre-existing constraints



Different kinematics @MESA

Competitive constraints for pseudoscalar or axial vector?

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Conclusion & outlook

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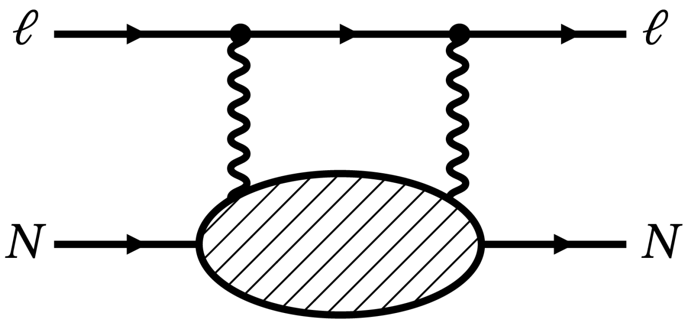
- Neutron observables not as constrained
- Access neutron observables with deuteron photodisintegration + tagging, previously successful
- Extensions:
  - same principles w/ more neutron-rich system, enhan nal
  - if no signal, neutron polarizabilities? (currently WI

Theory | **Experiment**

	$\Delta E_{TPE} \pm \delta_{theo}\ (\Delta E_{TPE})$	Ref.	$\delta_{exp}(\Delta_{LS})$	Ref.
μH	33 μeV $\pm$ 2 μeV	Antognini et al. (2013)	2.3 μeV	Antognini et al. (2013)
μD	1710 μeV $\pm$ 15 μeV	Krauth et al. (2015)	3.4 μeV	Pohl et al. (2016)
μ^3He^+	15.30 meV $\pm$ 0.52 meV	Franke et al. (2017)	0.05 meV	
μ^4He^+	9.34 meV $\pm$ 0.25 meV -0.15 meV $\pm$ 0.15 meV (3PE)	Diepold et al. (2018) Pachucki et al. (2018)	0.05 meV	Krauth et al. (2020)



Low mass
DARK SECTOR SEARCHES
with deuteron photodisintegration

Cornelis J.G. Mommers,
Phys. Rev. D 109, 095010 & Phys. Lett. B 858 139031
Group Marc Vanderhaeghen, Johannes Gutenberg University Mainz

Backup slides

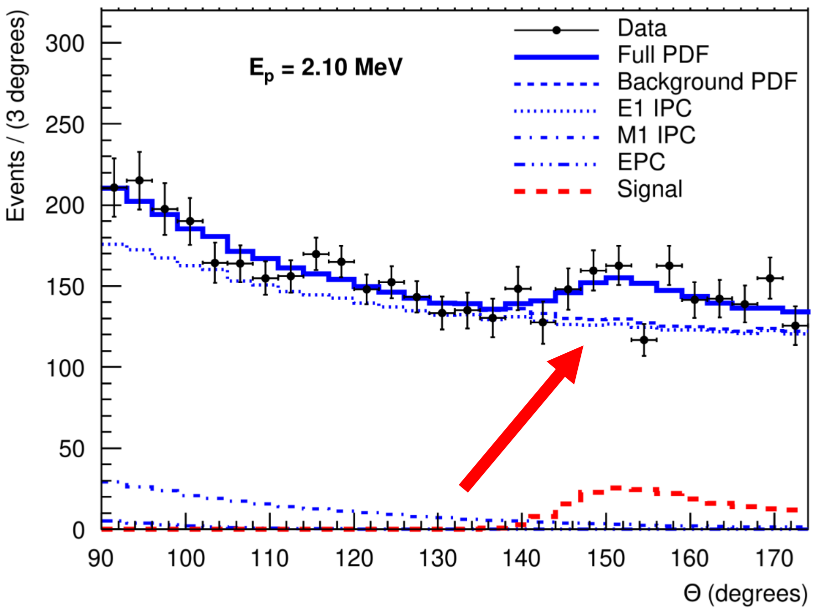
Timeline: X17 + theory

Disclaimer: timeline not exhaustive, many relevant & important papers left out!

ATOMKI group reports anomalous signals in…

- 2016 — ^{8}Be decays — Phys. Rev. Lett. 116, 042501 (2016)
- 2021 — ^{4}He decays — Phys. Rev. C 104, 044003 (2021)
- 2022 — ^{12}C decays — Phys. Rev. C 106, L061601 (2022)

Phys. Rev. C 106, L061601 (2022)



Timeline: X17 + theory

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ATOMKI group reports anomalous signals in…

2016 • ^{8}Be decays Phys. Rev. Lett. 116, 042501 (2016)

2021 • ^{4}He decays Phys. Rev. C 104, 044003 (2021)

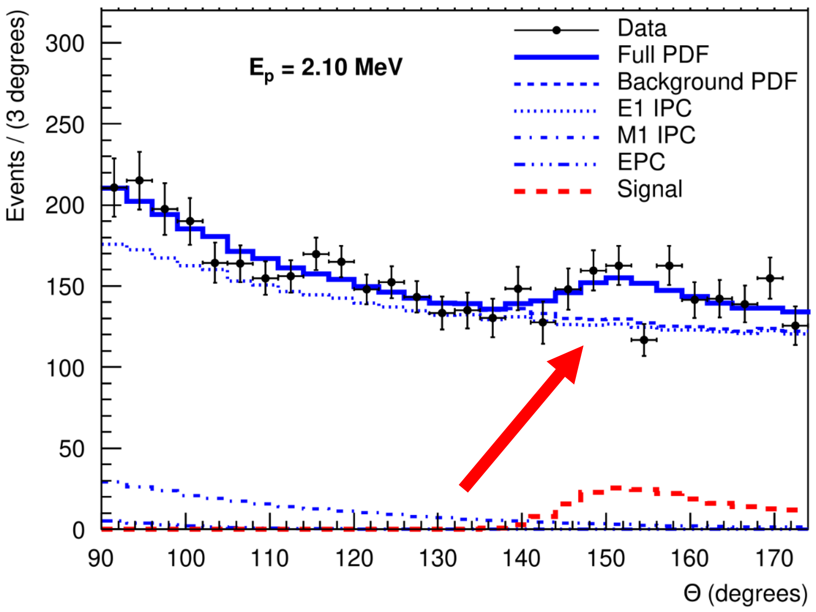
2022 • ^{12}C decays Phys. Rev. C 106, L061601 (2022)

2022-now

Tensions in theory?

See JHEP 02 154 (2023),
Phys. Rev. D 108, 015009 (2023),
Phys. Rev. D 108, 055011 (2023),
Phys. Lett. B 858 139031 (2024),
and *many* others!

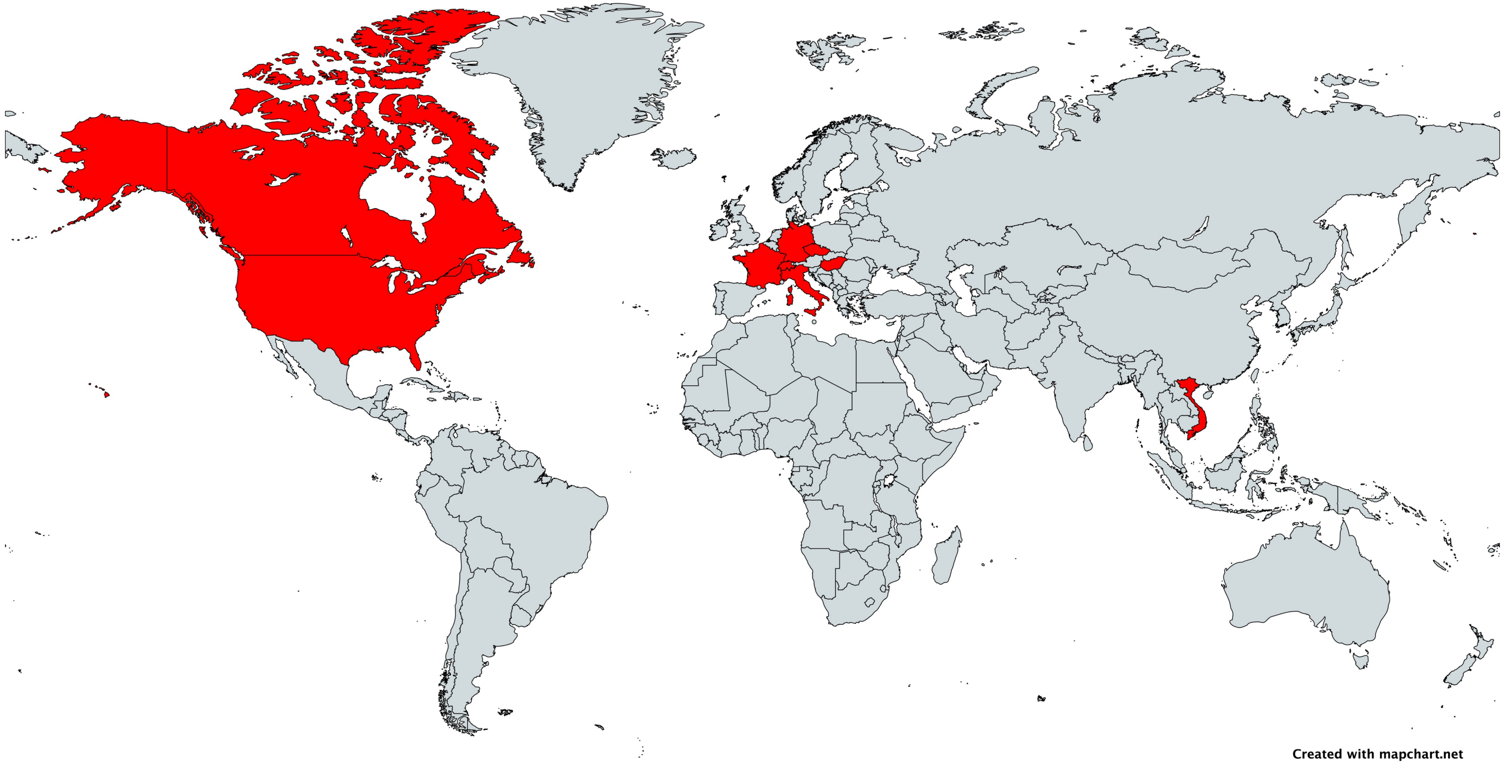
Phys. Rev. C 106, L061601 (2022)



Meanwhile, in experiment...

Disclaimer: list of planned & current experiments not exhaustive!

ATOMKI (HU)
VNU (VN)
MEG-II (CH)
PADME (IT)
CCPAC (CA)
MAGIX (DE)
JLAB (US)
NEW JEDI (FR)
n_TOF (CH)
CTU (CZ)
Others...



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MAGIX (DE)
JLAB (US)
NEW JEDI (FR)
n_TOF (CH)
CTU (CZ)
Others…

universe MDPI

Article

Checking the ^{8}Be Anomaly with a Two-Arm Electron Positron Pair Spectrometer

Tran The Anh [1], Tran Dinh Trong [2,*], Attila J. Krasznahorkay [3], Attila Krasznahorkay [3], József Molnár [3], Zoltán Pintye [3], Nguyen Ai Viet [1], Nguyen The Nghia [1,*], Do Thi Khanh Linh [4], Bui Thi Hoa [1], Le Xuan Chung [4] and Nguyen Tuan Anh [5]

Abstract: We have repeated the experiment performed recently by ATOMKI Laboratory (Debrecen, Hungary), which may indicate a new particle called X17 in the literature. In order to obtain a reliable and independent result, we used a different structure of the electron–positron pair spectrometer at the VNU University of Science. The spectrometer has two arms and simpler acceptance and efficiency as a function of the correlation angle, but the other conditions of the experiment were very similar to the published ones. We could confirm the presence of the anomaly measured at E_p = 1225 keV, which is above the E_p = 1040 keV resonance.

Meanwhile, in experiment…

Disclaimer: list of planned & current experiments not exhaustive!

- ATOMKI (HU)
- VNU (VN)
- **MEG-II (CH)**
- PADME (IT)
- CCPAC (CA)
- MAGIX (DE)
- JLAB (US)
- NEW JEDI (FR)
- n_TOF (CH)
- CTU (CZ)
- Others…

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Search for the X17 particle in $^7\mathrm{Li}(\mathrm{p}, \mathrm{e}^+\mathrm{e}^-)^8\mathrm{Be}$ processes with the MEG II detector.

The MEG II collaboration

See previous talk!

Abstract The observation of a resonance structure in the opening angle of the electron-positron pairs in the $^7\mathrm{Li}(\mathrm{p,e}^+\mathrm{e}^-)$ $^8\mathrm{Be}$ reaction was claimed and interpreted as the production and subsequent decay of a hypothetical particle (X17). Similar excesses, consistent with this particle, were later observed in processes involving $^4\mathrm{He}$ and $^{12}\mathrm{C}$ nuclei with the same experimental technique. The MEG II apparatus at PSI, designed to search for the $\mu^+ \to \mathrm{e}^+\gamma$ decay, can be exploited to investigate the existence of this particle and study its nature. Protons from a Cockroft-Walton accelerator, with an energy up to 1.1 MeV, were delivered on a dedicated Li-based target. The γ and the $\mathrm{e}^+\mathrm{e}^-$ pair emerging from the $^8\mathrm{Be}^*$ transitions were studied with calorimeters and a spectrometer, featuring a broader angular acceptance than previous experiments. We present in this paper the analysis of a four-week data-taking in 2023 with a beam energy of 1080 keV, resulting in the excitation of two different resonances with Q-value 17.6 MeV and 18.1 MeV. No significant signal was found, and limits at 90 % C.L. on the branching ratios (relative to the γ emission) of the two resonances to X17 were set, $R_{17.6} < 1.8 \times 10^{-6}$ and $R_{18.1} < 1.2 \times 10^{-5}$.

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Some key observations

- Mass X17 ~ 17 MeV/c^2
- Parity analysis: (J^P)

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^-	✓		✓	✓

- X17 couples (at least) to protons, neutrons and electrons
- Existing constraints from NA48/2,
  may imply a vector X17 couples weakly to protons
  ("protophobia") $\pi^0 \to \gamma(X \to e^+e^-)$

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Projections MAGIX@MESA

- **Assuming we see a signal (bump), what is the smallest value of the neutron coupling we would be able to exclude (=reach)**

- **Recall relation no. events and cross section,** $N = \sigma \int_0^T \mathrm{d}t\mathcal{L} = \sigma L$
- **Poisson statistics,** $\mathrm{SD} = s = \sqrt{N}$
- **So,** $\sigma_S/\sigma_B = N_S/N_B = n_\sigma s_B/N_B = n_\sigma/\sqrt{N_B} = n_\sigma/\sqrt{\sigma_B L}$

- **Finally,** $\sigma_S = \sigma_X = g_n^2\bar{\sigma}_X \;\Rightarrow\; \text{reach} = |g_n| = \left[\frac{\sigma_{\text{QED}}}{\bar{\sigma}_X}\frac{n_\sigma}{\sqrt{L\sigma_{\text{QED}}}}\right]^{1/2}$

Kinematics

- $\mathcal{M}_{n\leftarrow 2}$ Lorentz scalar $\Rightarrow 3n-4$ independent variables
- Pick following eight variables (in deuteron rest frame):
  - E_γ
  - $|\mathbf{p}|_\pm, \theta_\pm, \phi_-$
  - θ_N, ϕ_N

  where N is the tagged nucleon

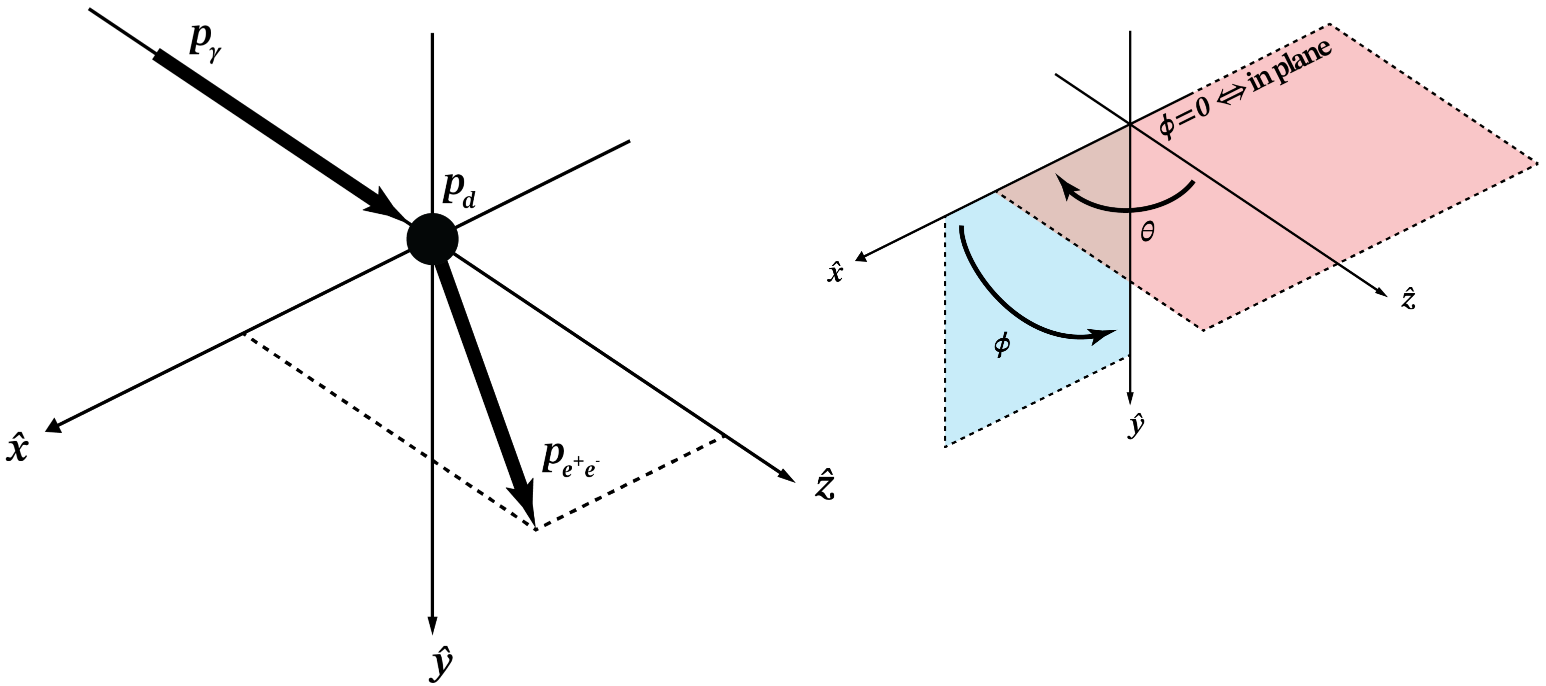

Table ATOMKI decays

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

Theory analysis

- Assume definite parity (J^P)
- Example: ^{8}Be(18.15), 1^+
- $A \to XB$

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

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

$$\mathbf{S}_X = \mathbf{0} \implies |L-1| \leq 0 \leq L+1 \implies L = 1$$
$$\mathbf{S}_X = \mathbf{1} \implies |L-1| \leq 1 \leq L+1 \implies L = 0, 1, 2$$

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

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Theory analysis

- Assume definite parity (J^P)

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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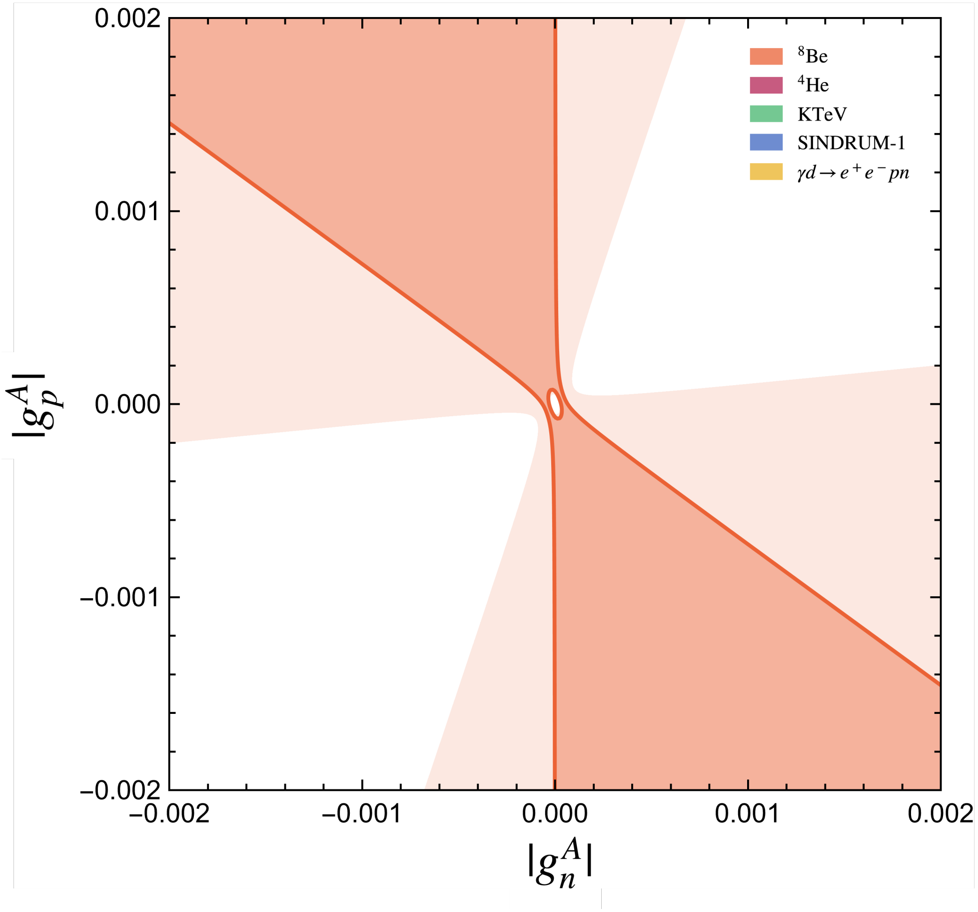
Projections for the reach

Projections for the reach



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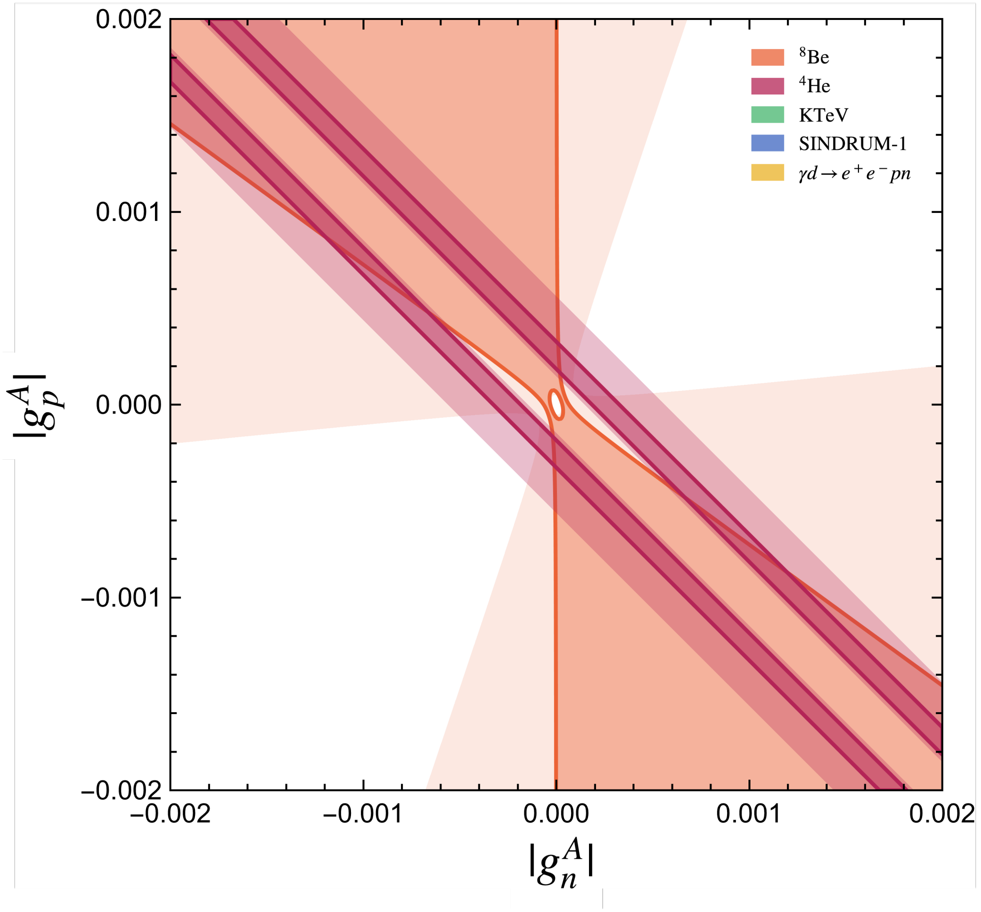
Projections for the reach



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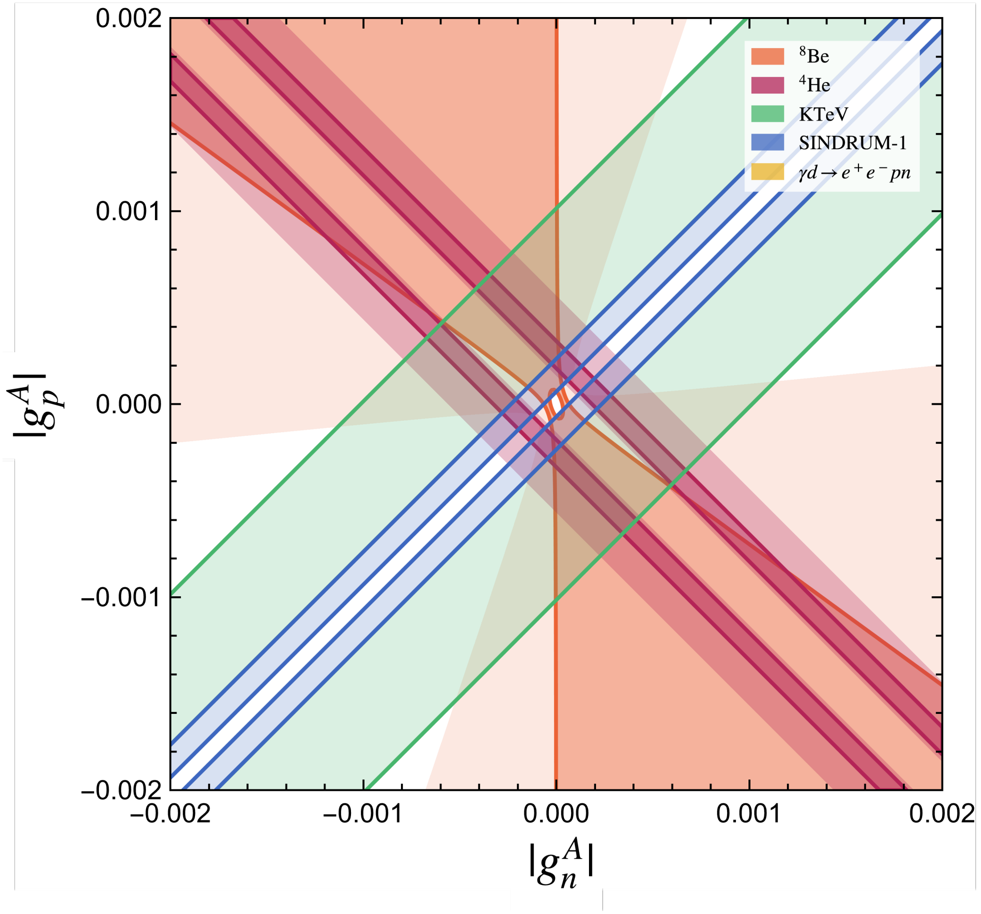

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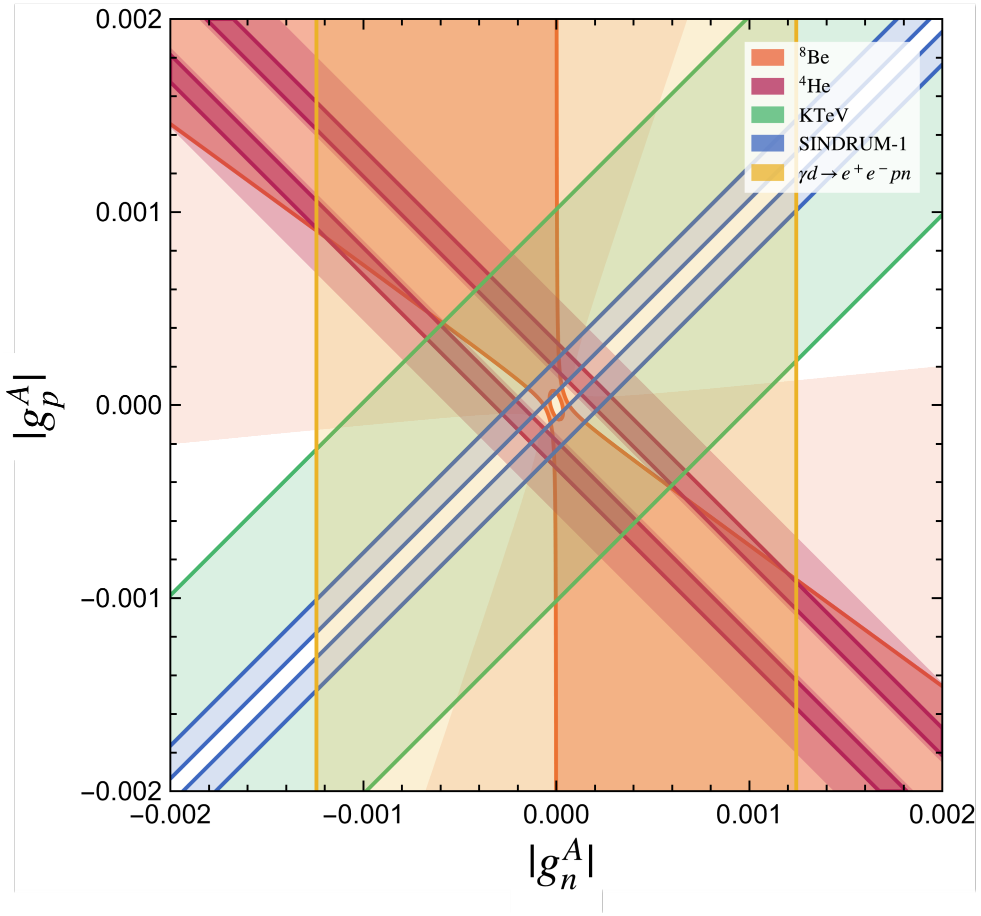

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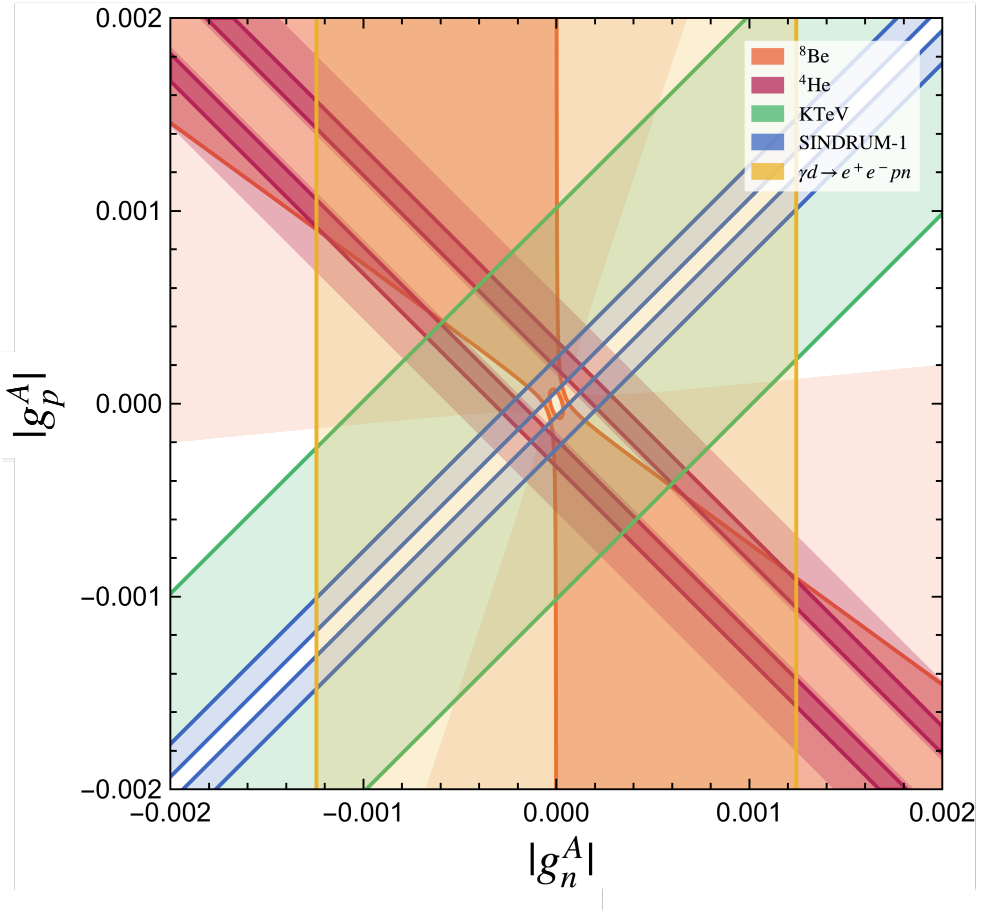
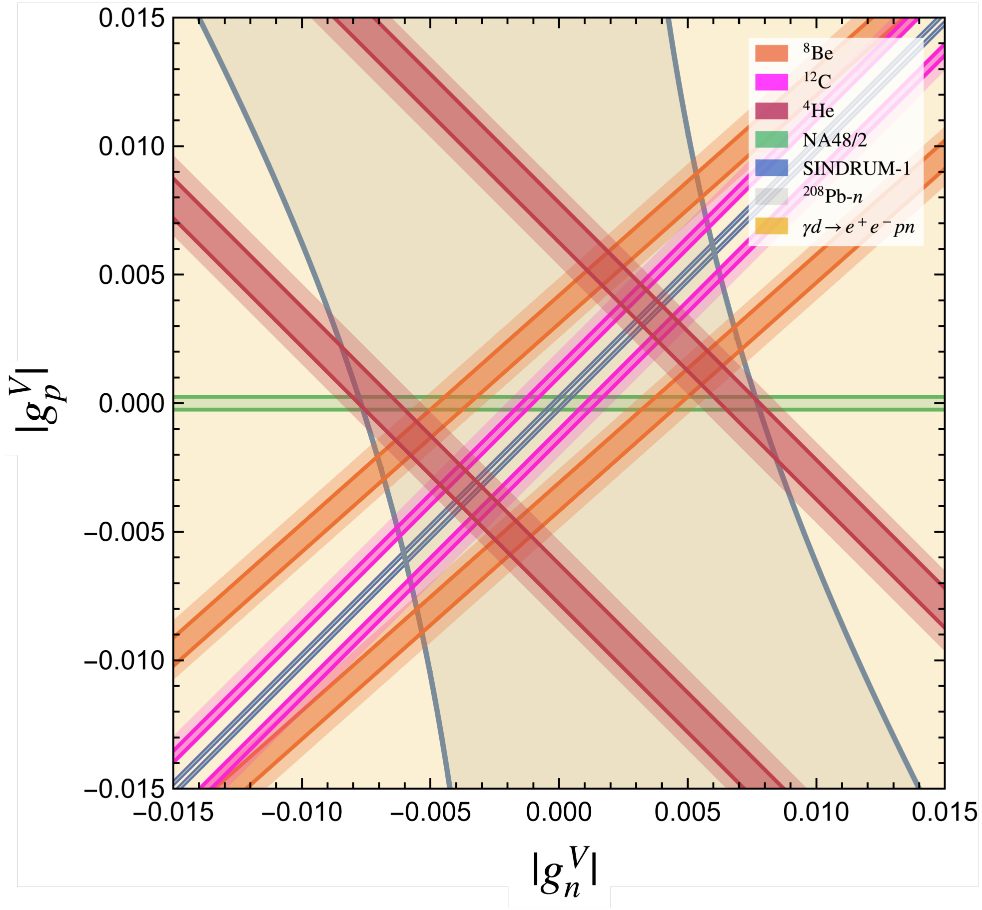
Projections for the reach





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Diagrams in detail (QED)

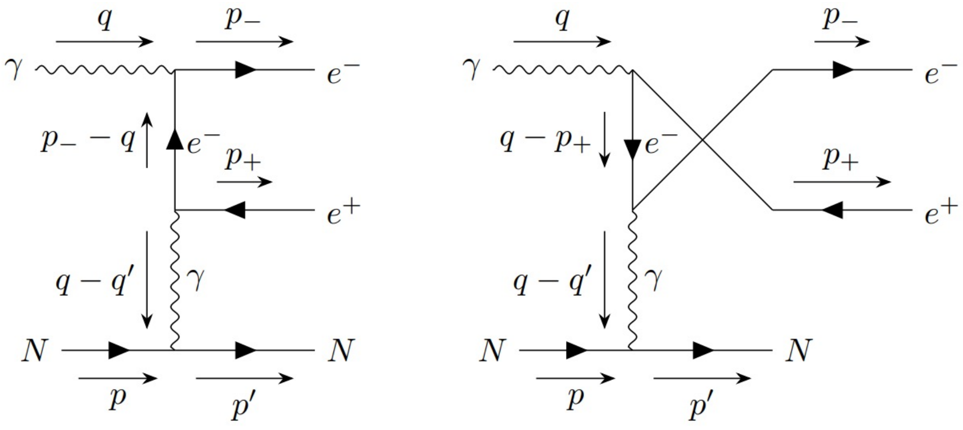

Figure 2: The direct and crossed diagram for the BH process.

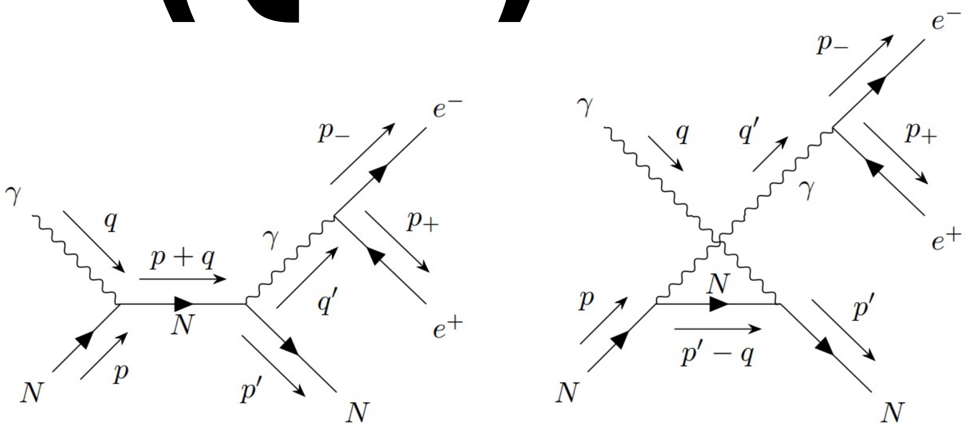

Figure 1: The direct and crossed diagram for the Born process.

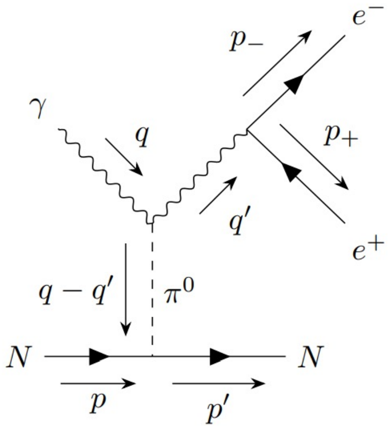

Figure 3: The diagram for the pion-pole amplitude.

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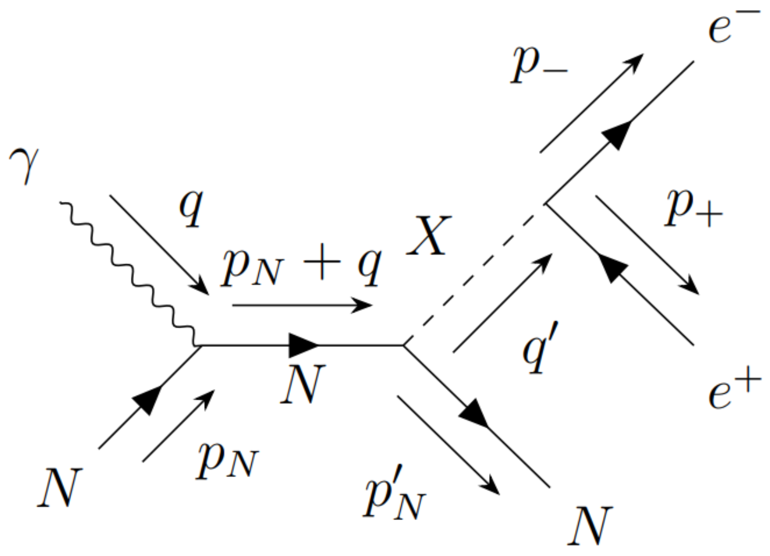
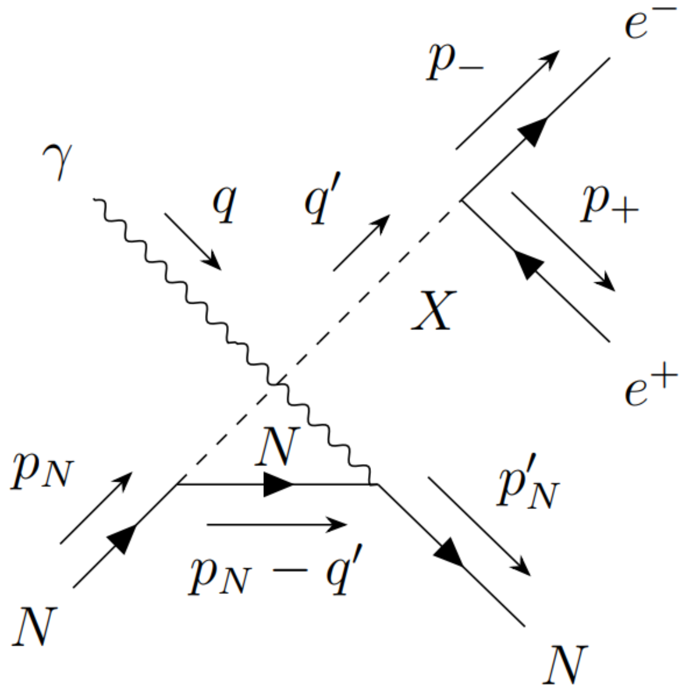
Diagrams in detail (signal)



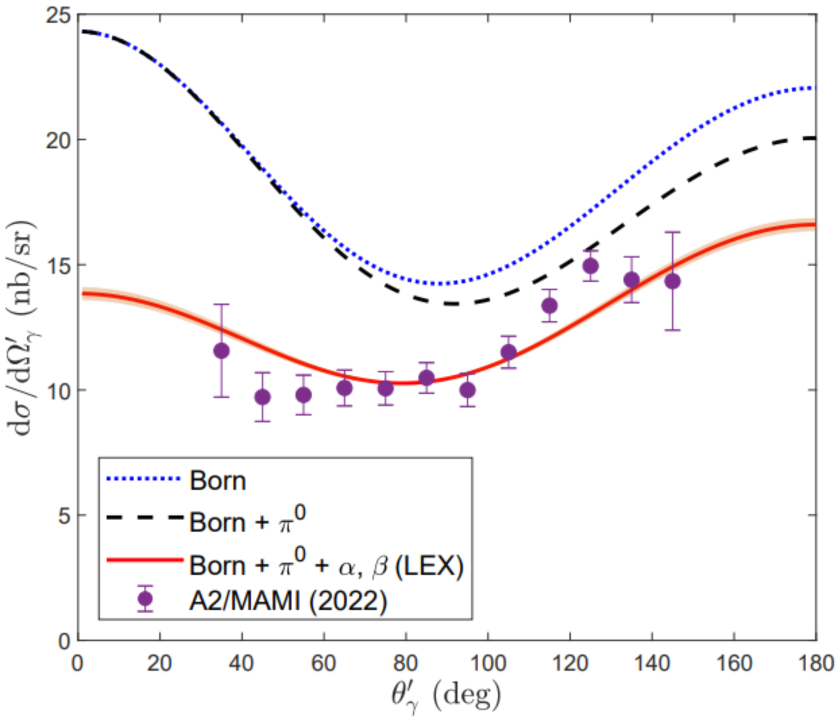


Projections MAGIX@MESA (II)

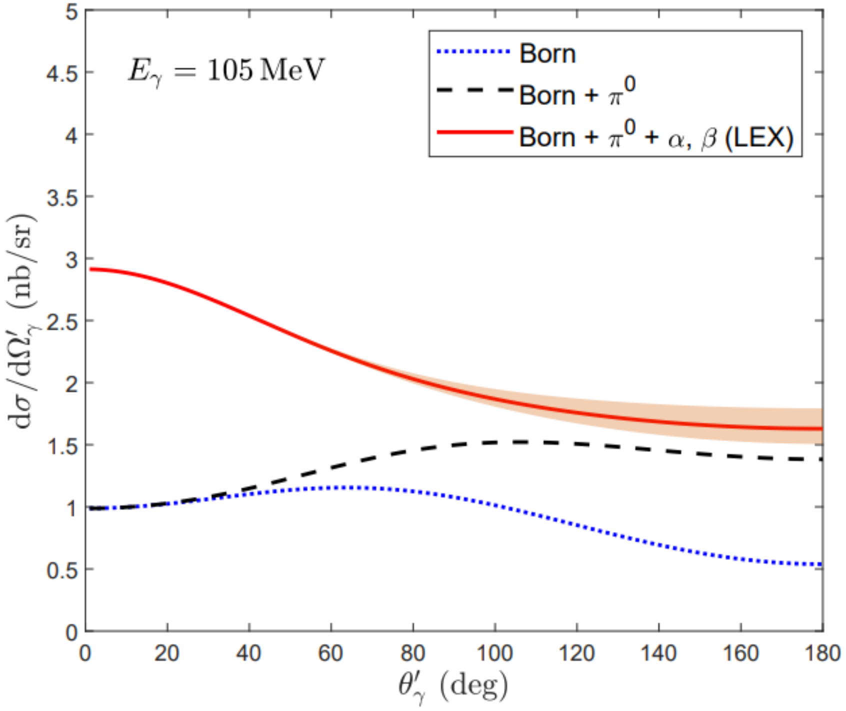
- **Assuming we see a signal (bump), what is the smallest value of the neutron coupling we would be able to exclude (=reach)**

- **Recall relation no. events and cross section,** $N = \sigma \int_0^T \mathrm{d}t\mathcal{L} = \sigma L$
- **Poisson statistics,** $\mathrm{SD} = s = \sqrt{N}$
- **Then,** $\sigma_{S+B}/\sigma_B \approx \sigma_S/\sigma_B + 1 \;\Rightarrow\;$ Sensitivity $S = \sigma_{S+B}/\sigma_B - 1 = \sigma_S/\sigma_B$
- **So,** $S = N_S/N_B = n_\sigma s_B/N_B = n_\sigma/\sqrt{N_B} = n_\sigma/\sqrt{\sigma_B L}$
- **Finally,** $\sigma_S = \sigma_X = g_n^2\overline{\sigma}_X \;\Rightarrow\;$ reach $= |g_n| = \left[\dfrac{\sigma_{\mathrm{QED}}}{\overline{\sigma}_X}\dfrac{n_\sigma}{\sqrt{L\sigma_{\mathrm{QED}}}}\right]^{1/2}$

Verifying the QED background (I)



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



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

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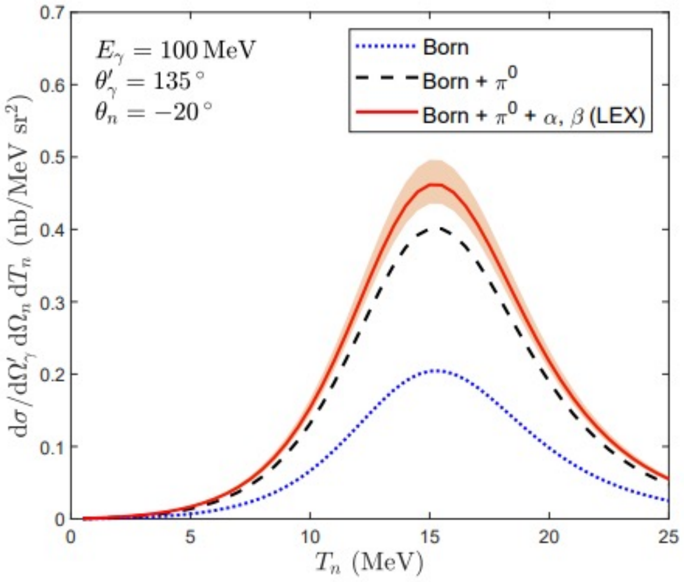
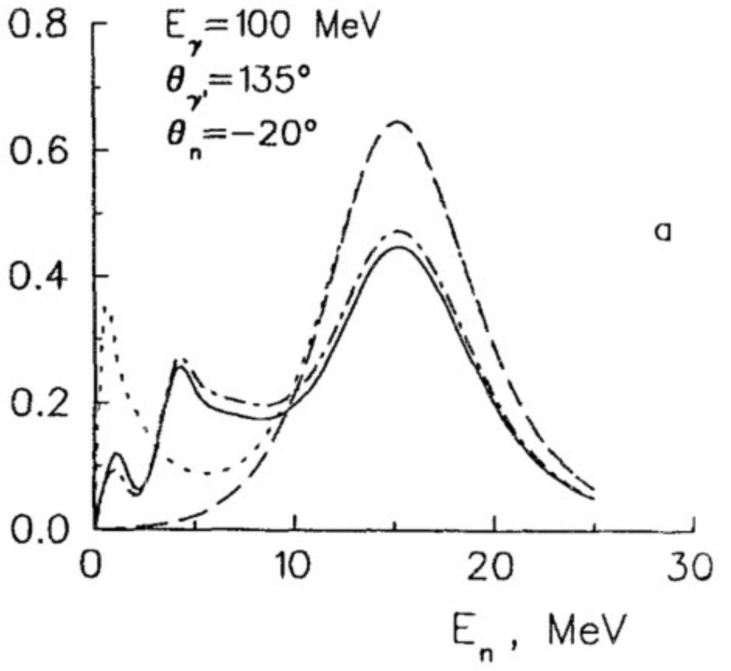
Verifying the QED background (II)

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])

Influence phase space reach

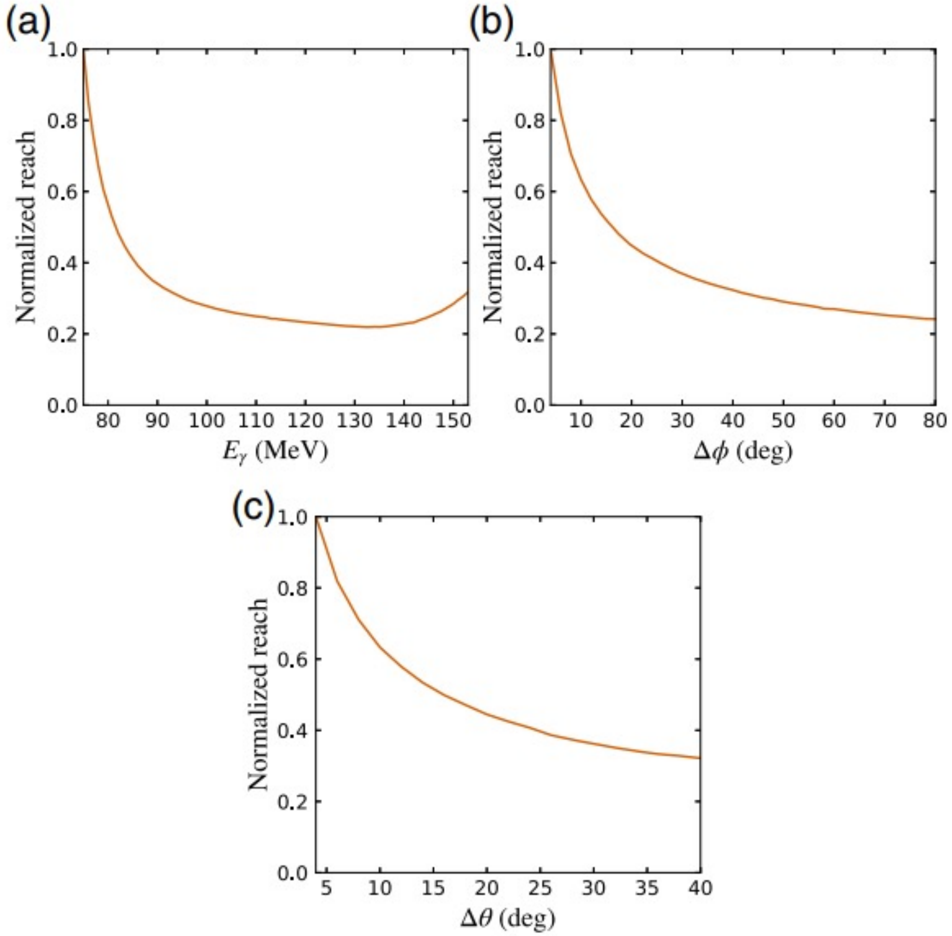


FIG. 9. The dependence of the reach on the size of the integrated phase space for a vectorlike X normalized to its value at the start of the x-axis. Here we vary (a) E_γ, (b) $\phi_\pm$ or (c) $\theta_\pm$ while keeping the rest of the kinematic variables fixed to detector setting 2 (see text). We set $m_X = 65\ \mathrm{MeV}/c^2$ and $\delta m_X = 0.1\ \mathrm{MeV}/c^2$.