New Physics Searches via Beam Normal Spin Asymmetry in Bhabha Scattering

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LEEPP@JLab Workshop

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

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Research Unit FOR 5327
Photon-photon interactions in the Standard Model and beyond
Exploiting the discovery potential from MESA to the LHC

Motivation

Potential

Searches for BSM Interference Terms in Unpolarized and Polarized Bhabha Scattering

Dave Mack (Jefferson Lab)
Hadron 2030
Paris, France
Oct 24, 2024

Largely motivated by Dave Mack's at "Hardon 2030"...

...and we are very much interested in the next talk

A region between beam dumps and collider experiments remains **unexplored so far**

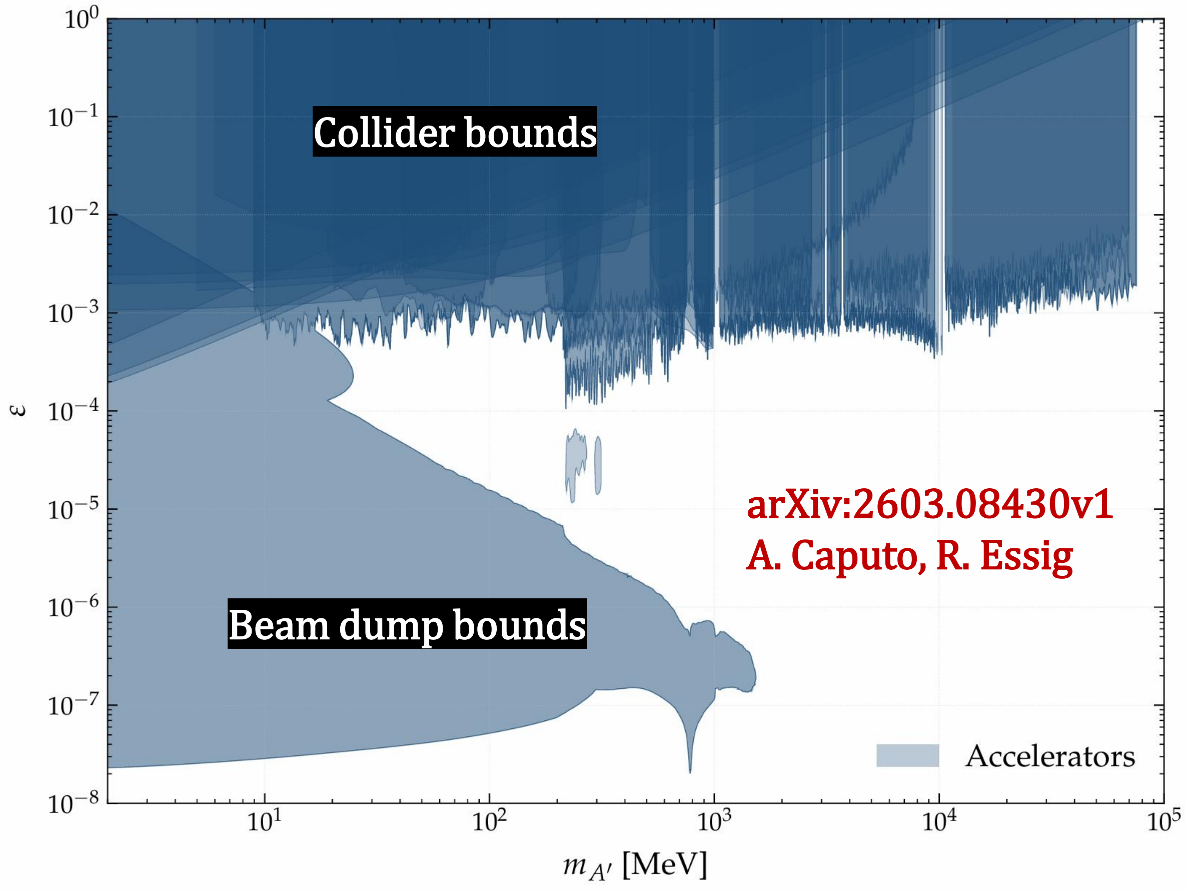
- $\varepsilon \sim 10^{-5} \div 10^{-3}$ – natural parameter space for the dark photon

Dashed box: potentially accessible at Jlab

Other potential implications include:

- X17 searches
- Scalar dark sector
- Axion-like particles

Complementary to other low-energy precision experiments, such as **MAGIX@MESA** (Mainz), PIONEER (PSI), ...



Dark photon kinetic mixing constrains (visible decays)

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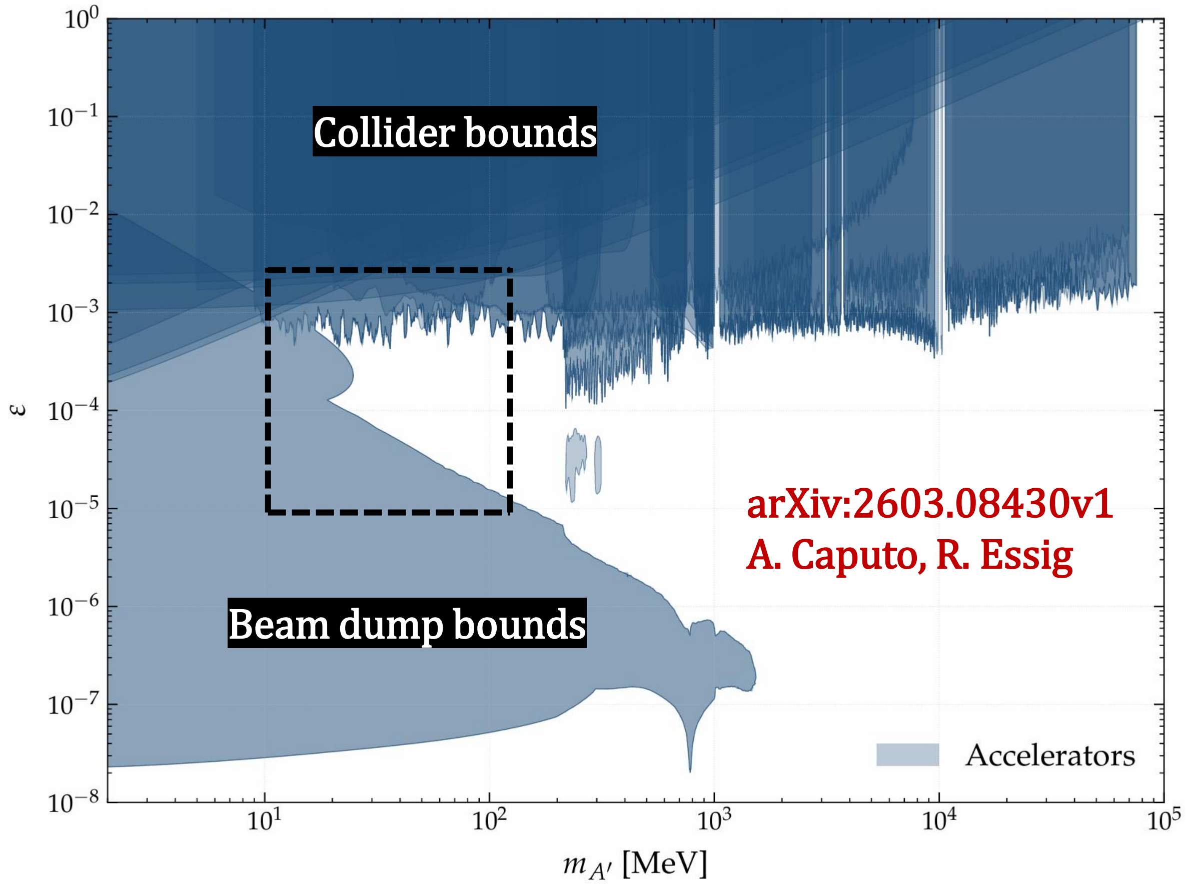
Uncovered BSM parameter space



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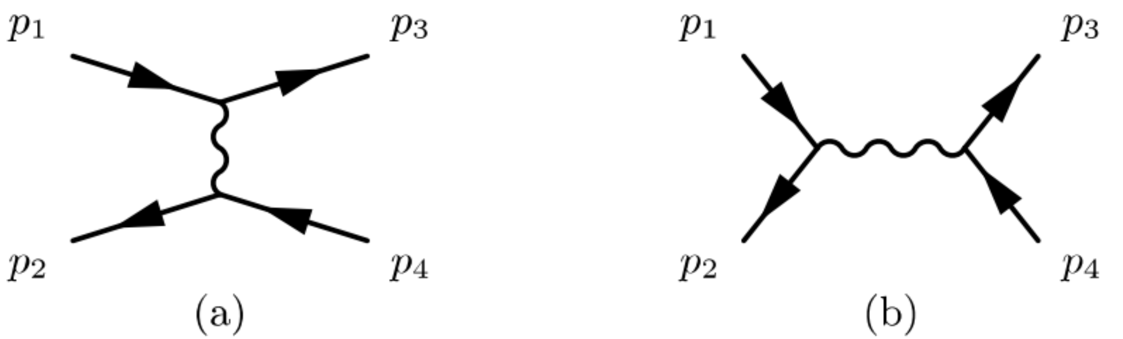
Tree-level Bhabha scattering

Let's make use of the 11 GeV polarized positron beam



- Scattering against **atomic electrons**, $\sqrt{s} \approx 106$ MeV
- No hadroproduction – **exceptionally clean theoretically**
- Bhabha $e^+e^- \to e^+e^-$ process, scattering ***t*-channel** (a) and annihilation ***s*-channel** (b) contributions

$$\mathcal{M}_t = \frac{ie^2}{t}\, \bar{u}_3 \gamma_\mu u_1\, \bar{v}_2 \gamma^\mu v_4$$

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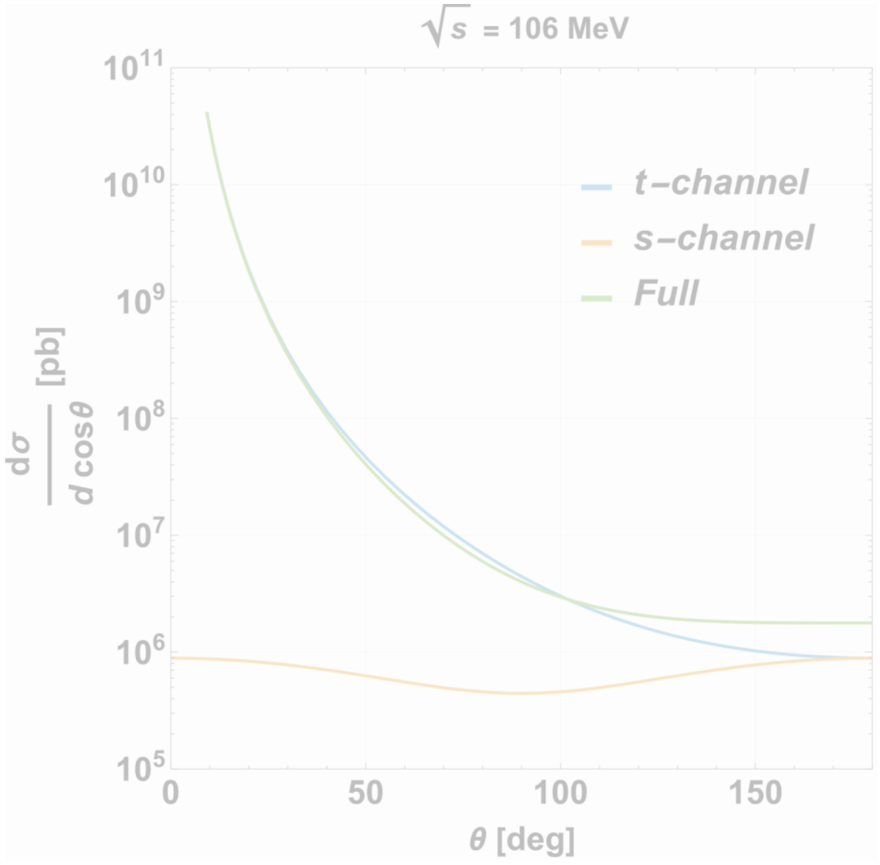
Other than SM photon γ, **BSM particles can be exchanged**

BSM signal crossing the resonance ⇒ large ***t*-channel** QED amplitude may serve as an **amplifier**, even at backward c.m. angles (forward in lab)



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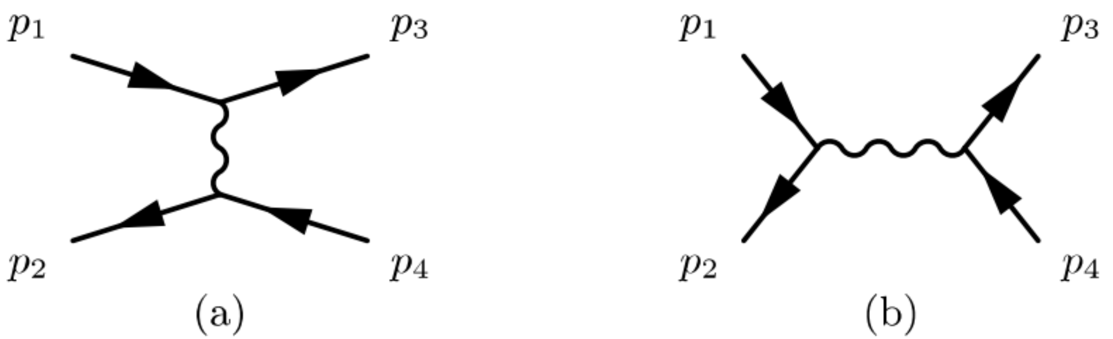

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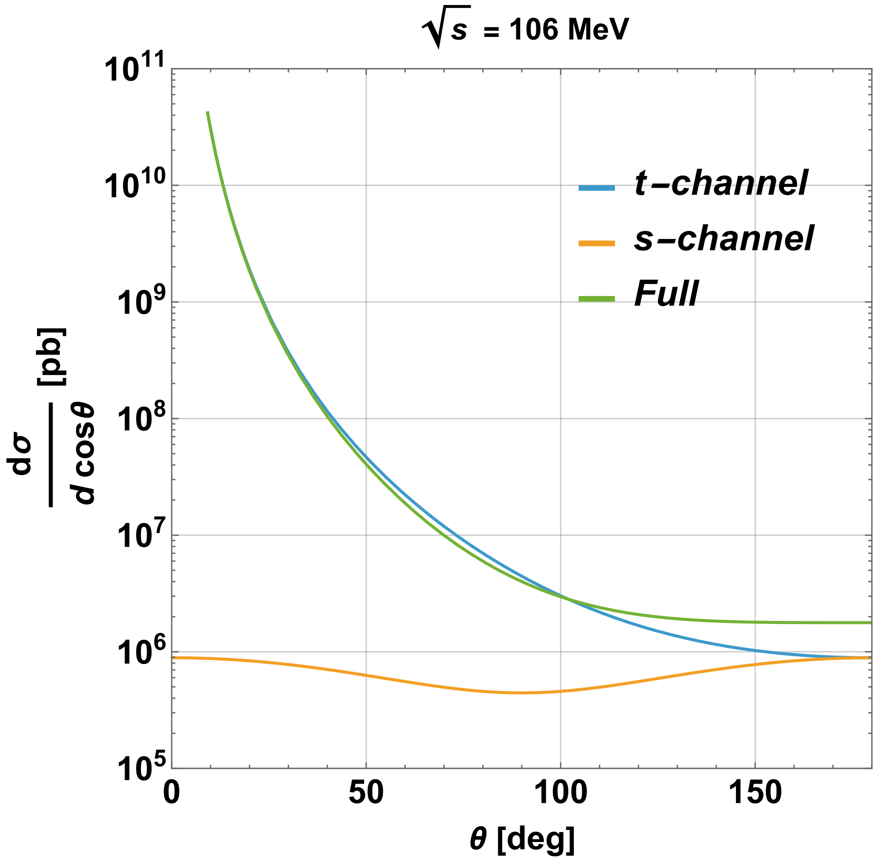

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- P-, T- and C-invariance: only five independent helicity amplitudes $\mathcal{M}_{s_+ s_-, s'_+ s'_-}$ enter the process

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Can be mapped onto five Dirac bilinears

$$\mathcal{M} = \sum_{i=S,P,V,A,T} A_i(s,t) \cdot \bar{v}\Gamma_i v' \cdot \bar{u}'\Gamma_i u$$

$$\Gamma_S = \mathbb{1}, \quad \Gamma_P = \gamma^5, \quad \Gamma_V = \gamma^\mu,$$
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M.L. Goldberger, Y. Nambu and R. Oehme, Ann. of Phys. 2, 226 (1957)

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Relations among helicity amplitudes imposed by parity (P), time reversal (T), and charge conjugation (C) invariance for Bhabha scattering

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- ***t*-channel** and ***s*-channel** are related via Fierz identities

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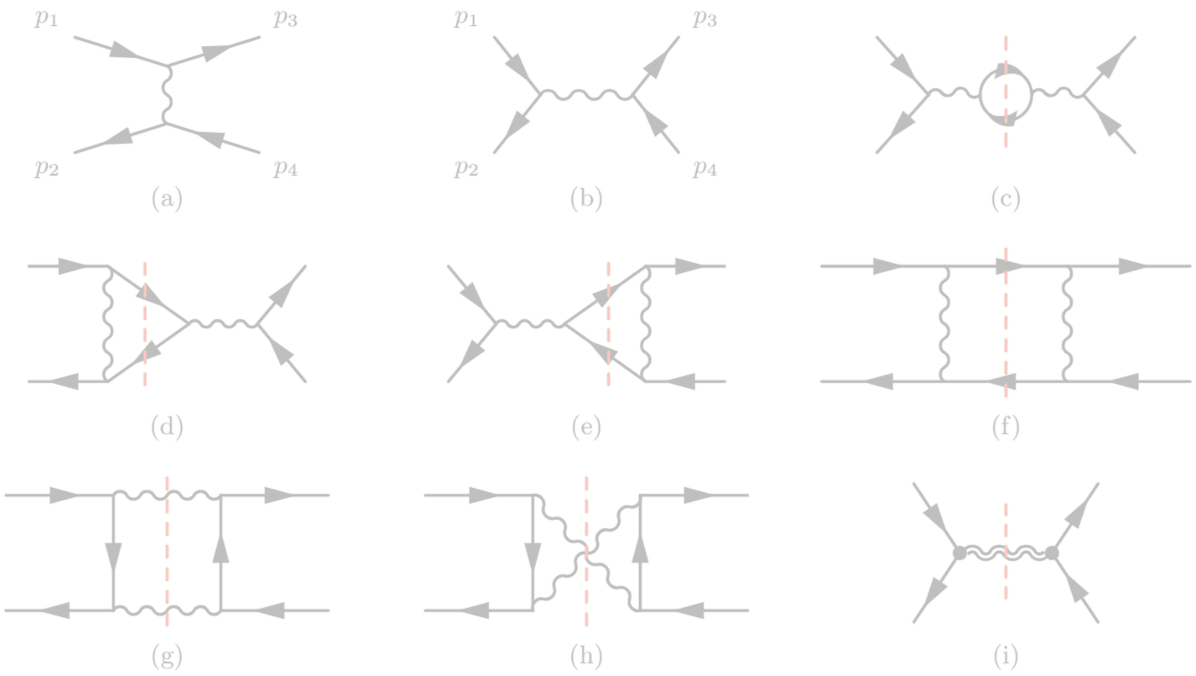
S_+^μ – positron spin
$n^\mu = (0, \boldsymbol{n})$ & $\boldsymbol{n} \perp$ scattering plane

$$B_n \equiv \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

$$= (S_+ \cdot n) \frac{\sqrt{stu}}{4\pi s \sigma_0} \mathrm{Im}[(A_S - A_A)(A_V^* + 2A_T^*)]$$

- Fix the sign of the asymmetry: set $(S_+ \cdot n) = 1$
- No transverse contribution: C-, P-, T- are respected ✓

Leading order: interference between tree-level QED and imaginary parts of 1-loop QED/tree-level BSM



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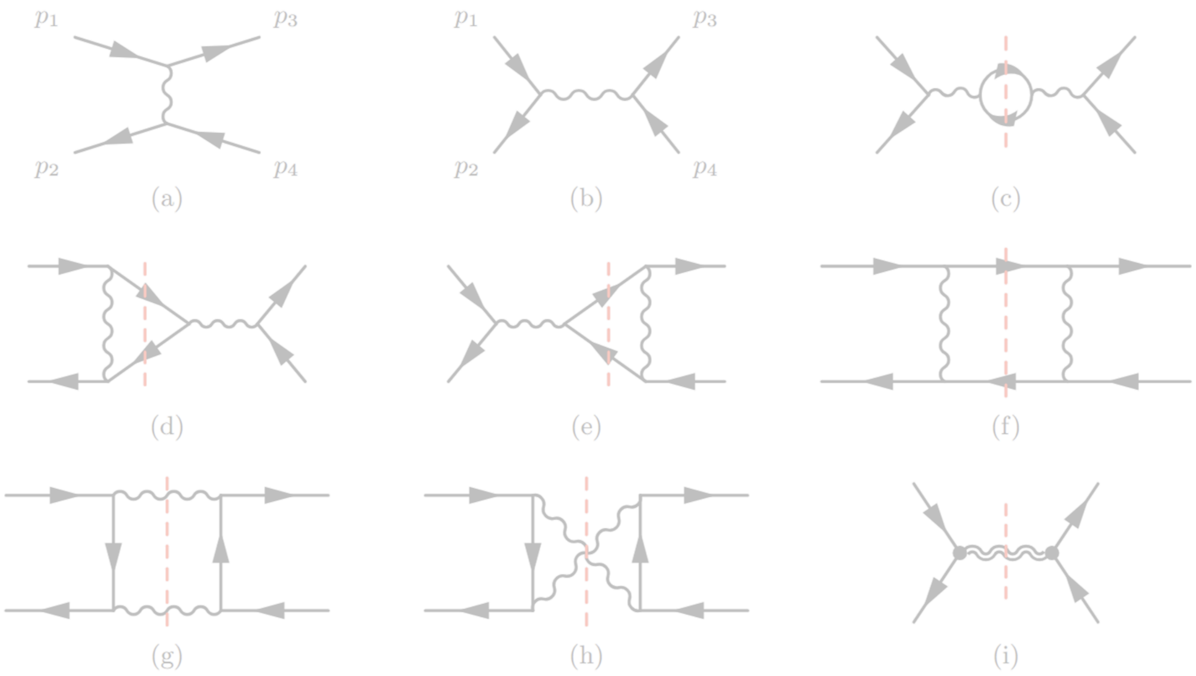

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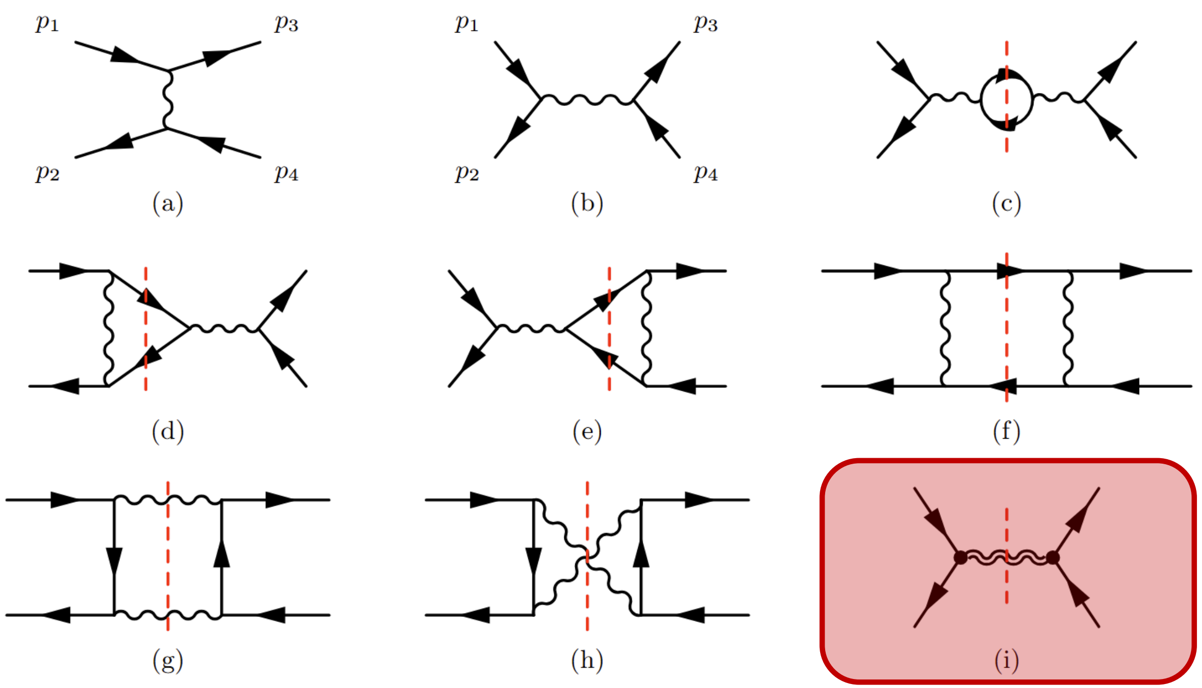

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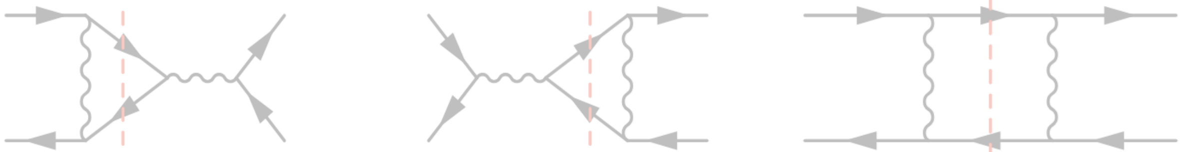
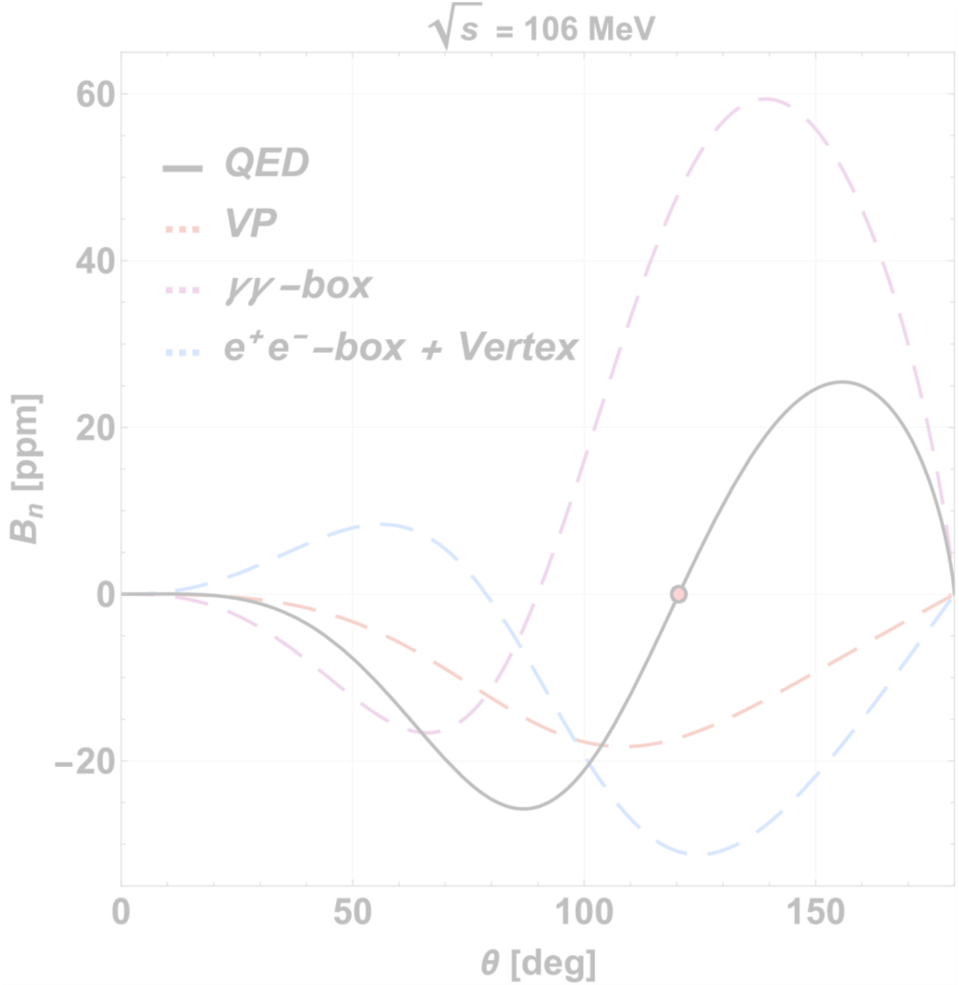
Verified
C. Fronsdal and B. Jakšić
Phys. Rev. 121, 916 (1961)

where $x = \sin\theta/2$, scattering angle in the c.m. frame

- m_γ^2 **cancellation** between ***s*-vertex** and ***t*-channel box** at the observable level



- The **largest contribution** to B_n is **two-photon box**



Cancellations between different discontinuities – zero crossing, background-free kinematic point

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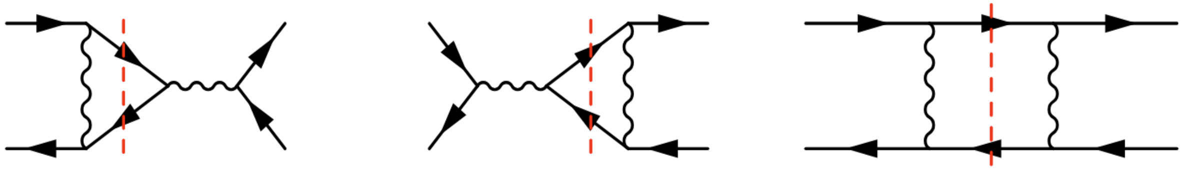

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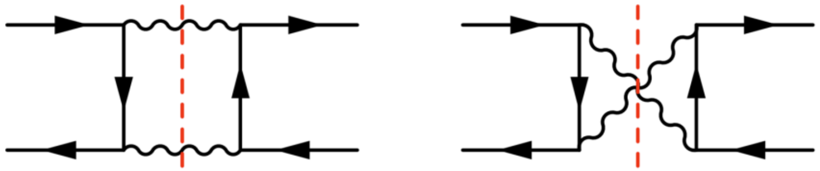

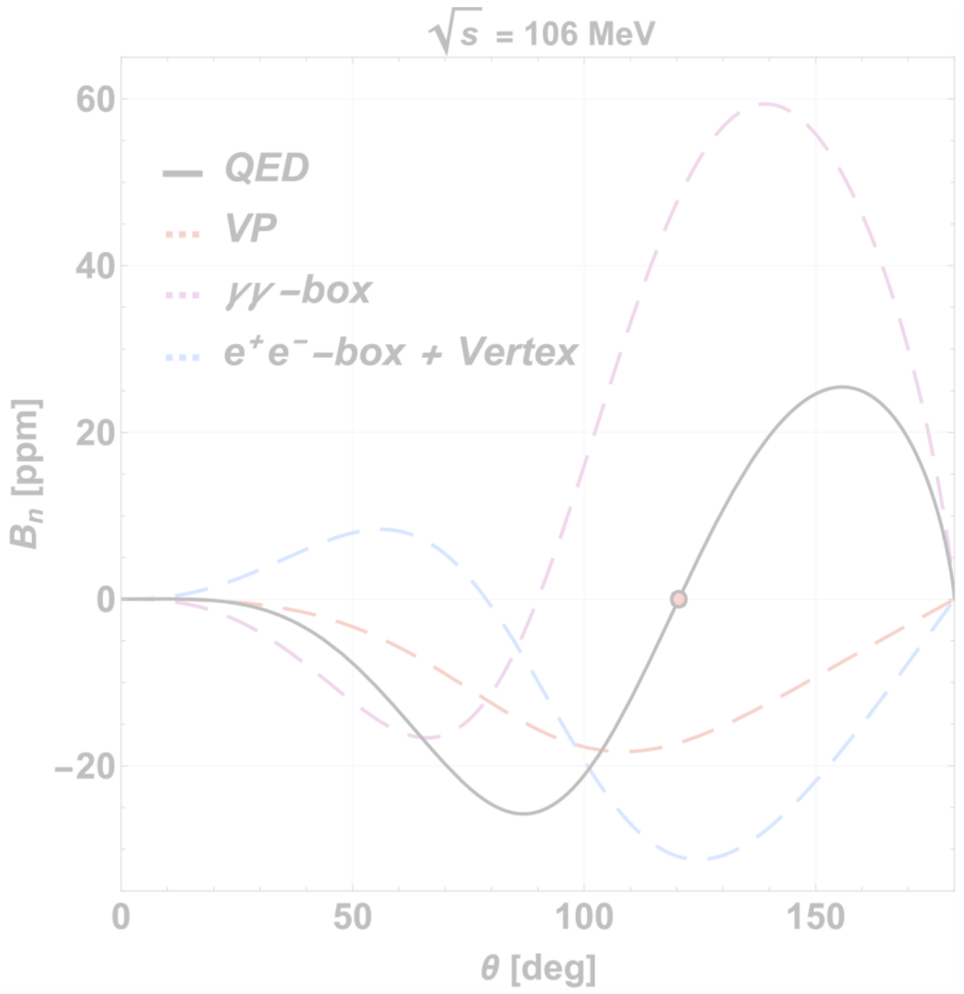

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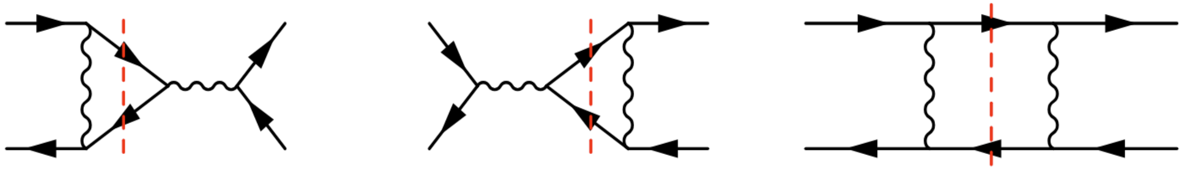

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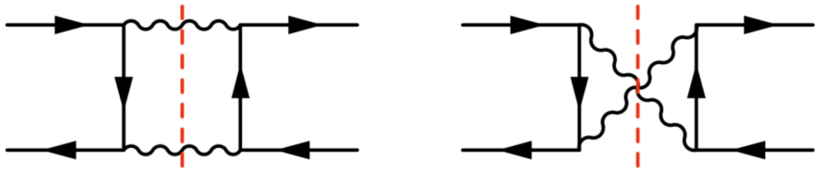

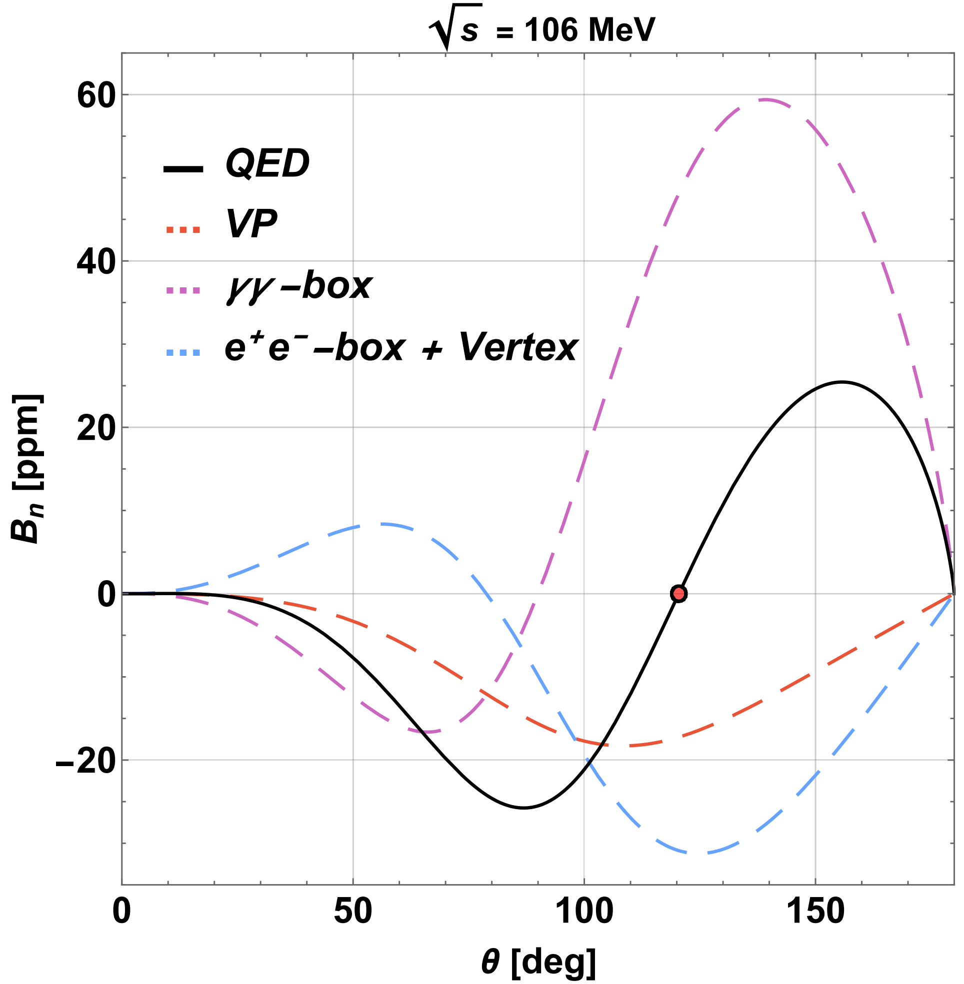

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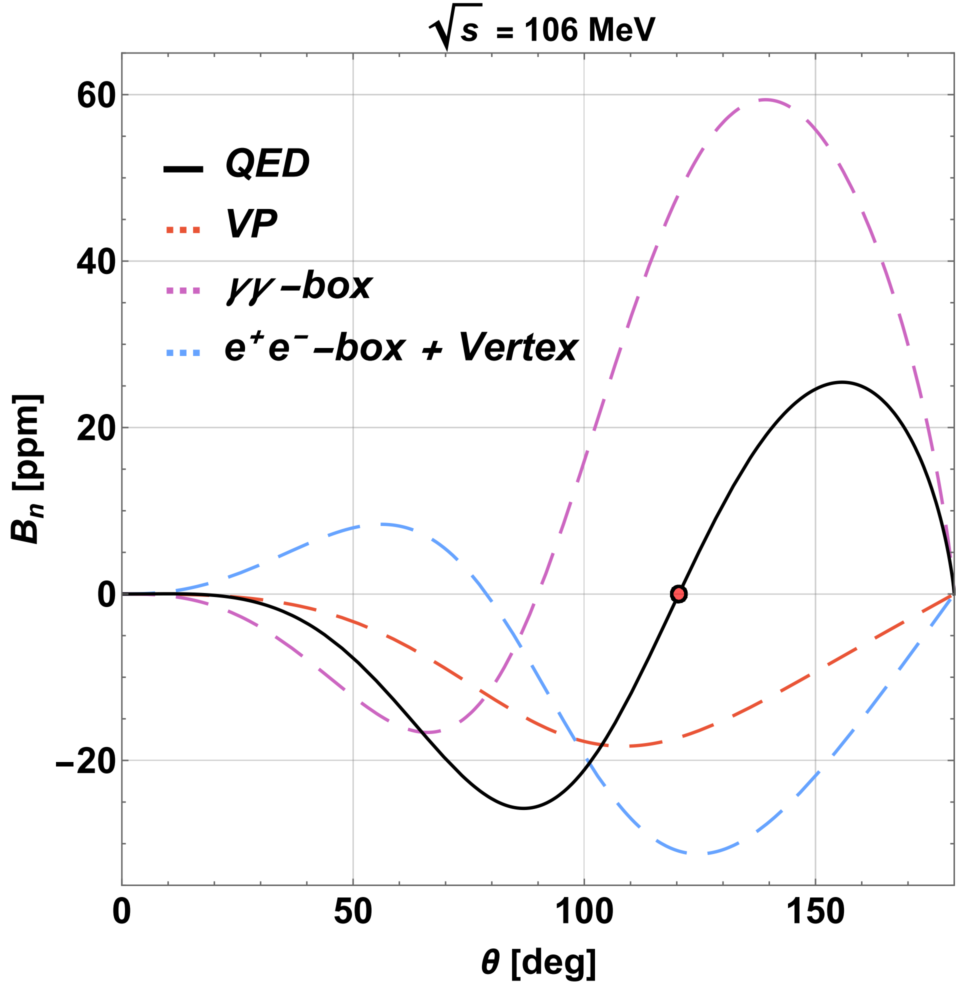
- **$\ln m_e^2$** also **cancel out** in the final result
- Only kinematic dependance: helicity flipping $m_e/\sqrt{s}$ prefactor ⇒ **zero crossing does not move** in c.m. frame
- Any **BSM contribution around it,** $\theta \approx 120.4°$, would provide a distinct signal
- **Never been measured before**



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Experimental input

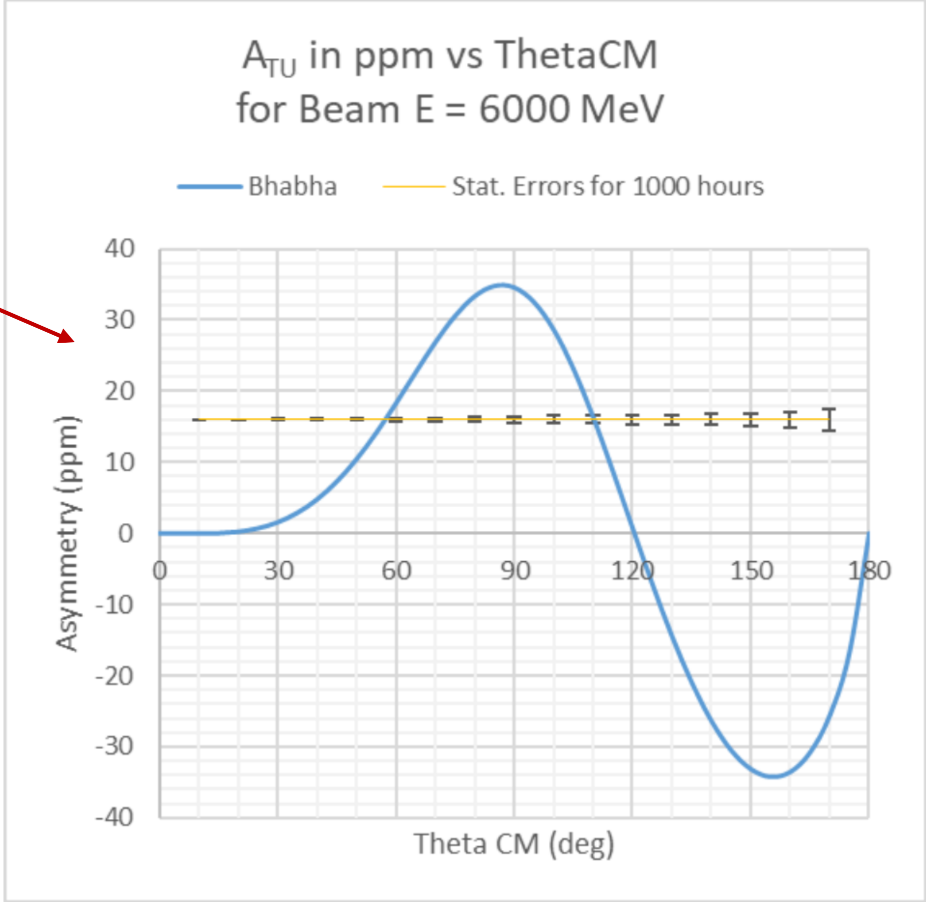
The ultimate **reach on BSM coupling will depend on**

- **Jlab precision** on B_n measurements: estimated as 1 ppm based on talk by Dave Mack at "Hadron 2030"

- **Angular resolution**: integrating the QED background over a symmetric bin centered on the zero-crossing cancels to the first order < 0.1 ppm for $10°$ bin

- **Bin resolution** for e^+e^- invariant mass – crucial for BSM searches, reach scales as **coupling² ∝ BinSize**

Other potential backgrounds (e.g. from $e^+N \to e^+N$) can be eliminated by requiring a coincidence detection of the final state e^+e^- pair



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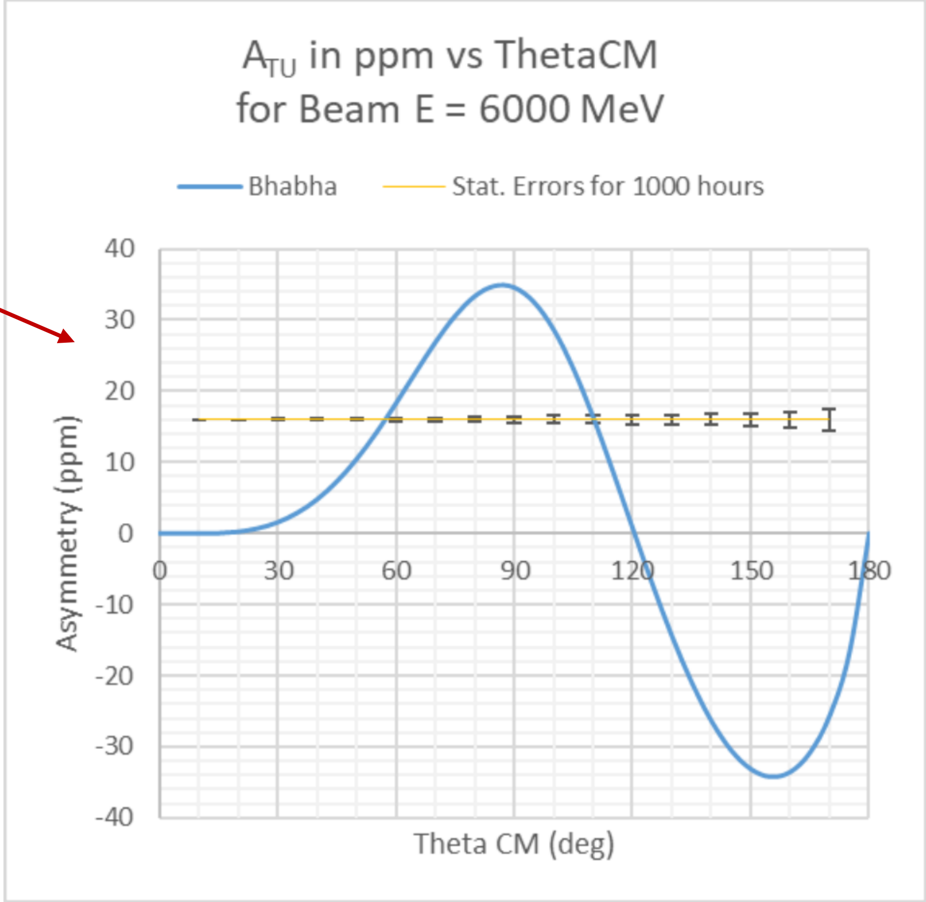

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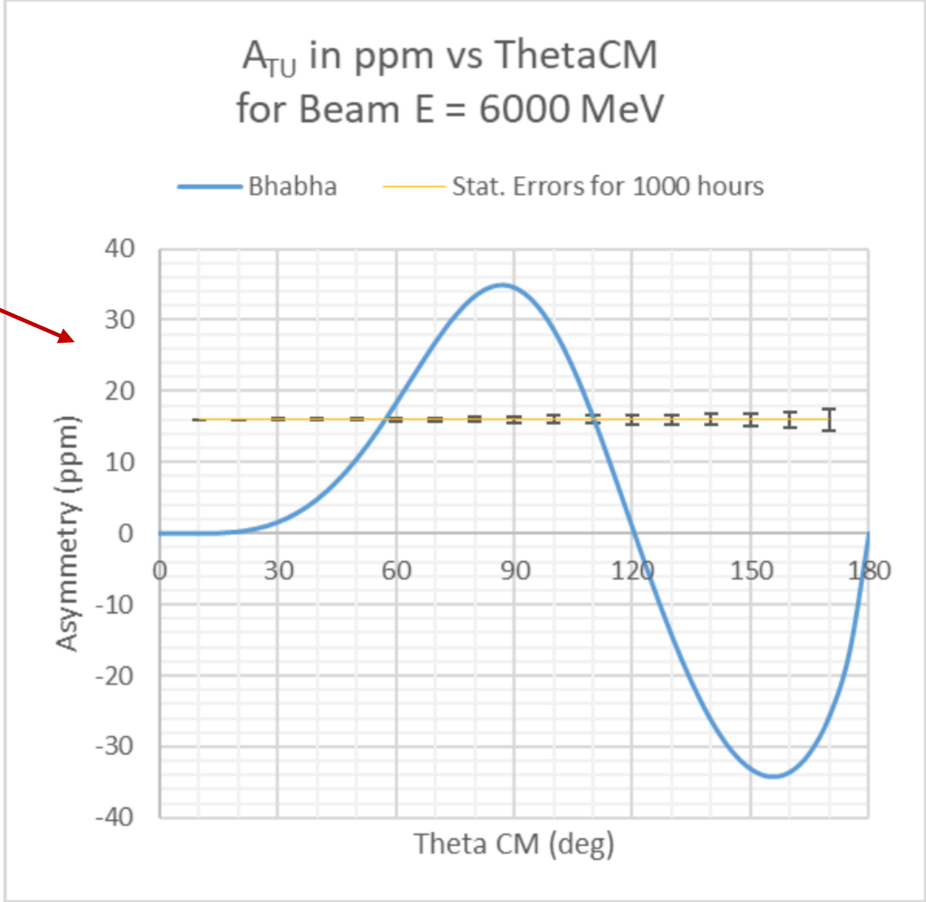
- **Jlab precision** on B_n measurements: estimated as 1 ppm based on talk by Dave Mack at "Hadron 2030"

- **Angular resolution**: integrating the QED background over a symmetric bin centered on the zero-crossing cancels to the first order
  < 0.1 ppm for $10°$ bin

- **Bin resolution** for e^+e^- invariant mass – crucial for BSM searches, reach scales as **coupling² ∝ BinSize**

Other potential backgrounds (e.g. from $e^+N \to e^+N$) can be eliminated by requiring a coincidence detection of the final state e^+e^- pair



Example statistical errors are shown for 1000 hours of 50 nA of 60% polarized beam on an e- target consisting of $0.10*X_0$ beryllium, and assume 100% acceptance in 10 degree CM angle bins.

Experimental input

Q: zero crossing is $\theta \approx 120.4°$ in the c. m. frame, how realistic is that in the lab frame?

A: the boost factor $\gamma \approx 100$, lab frame angle is $\theta_L \approx 1°$

As example: PRad (JLab) used Forward ECL **HyCal + GEM**: **lab angles down to** $\approx 0.7°$ in e^-e^- and e^-p scattering

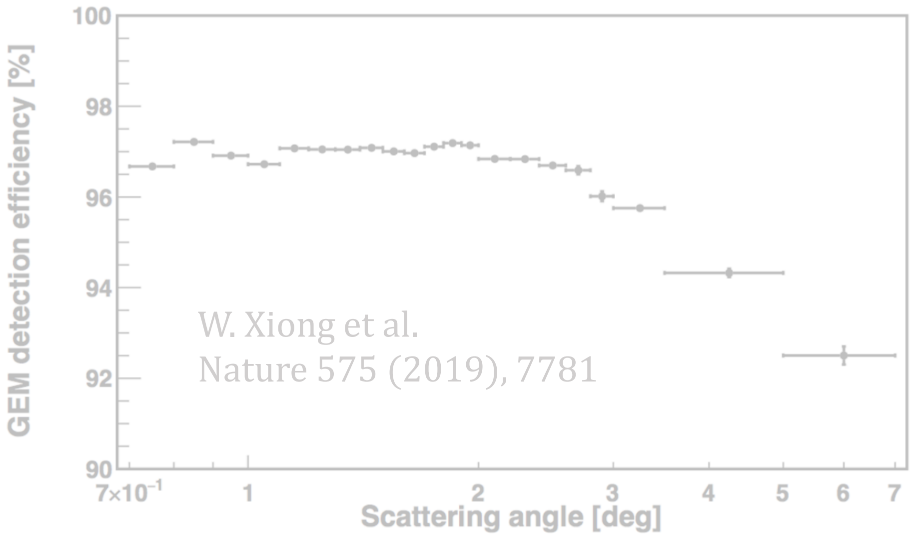
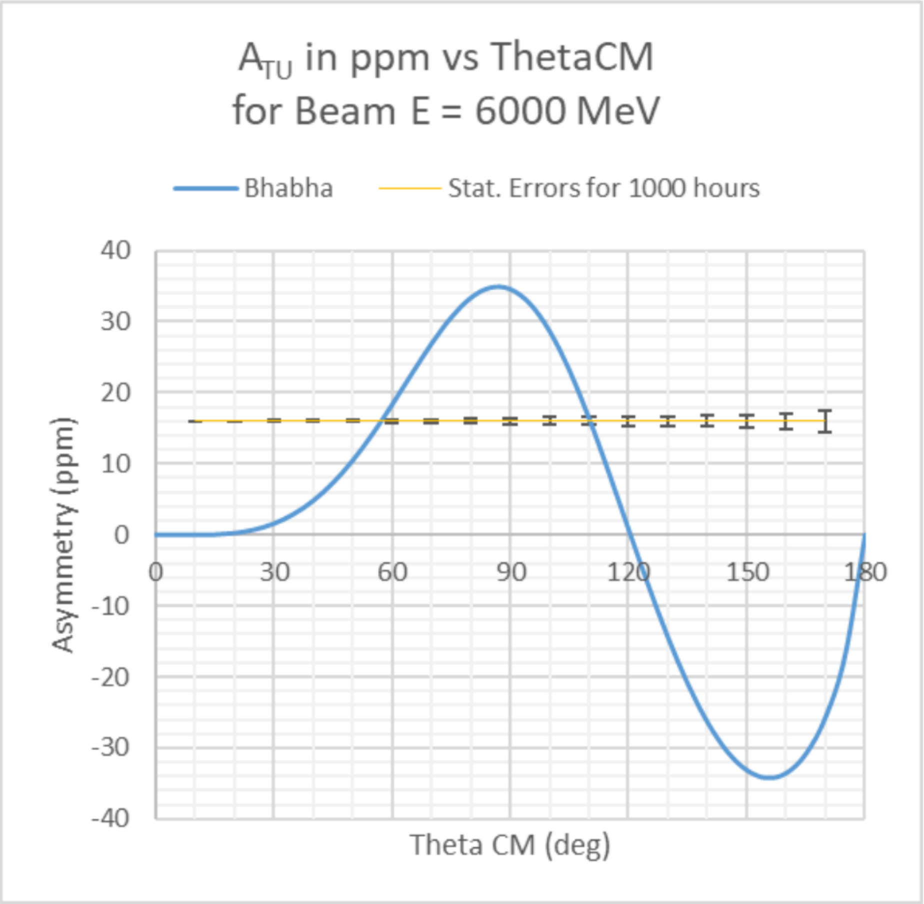


Figure S5: The GEM detector efficiency as a function of the scattering angle. The statistical uncertainty of each point is included but is smaller than the marker size.



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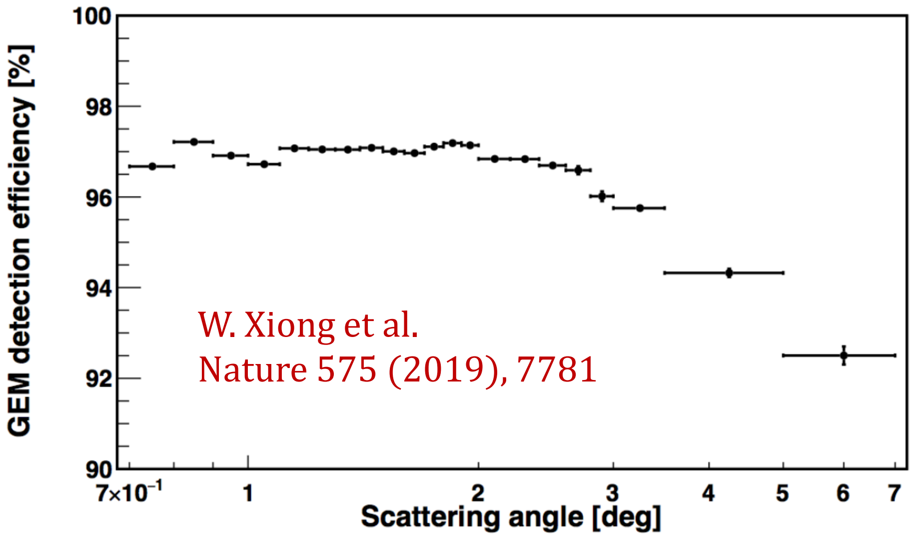

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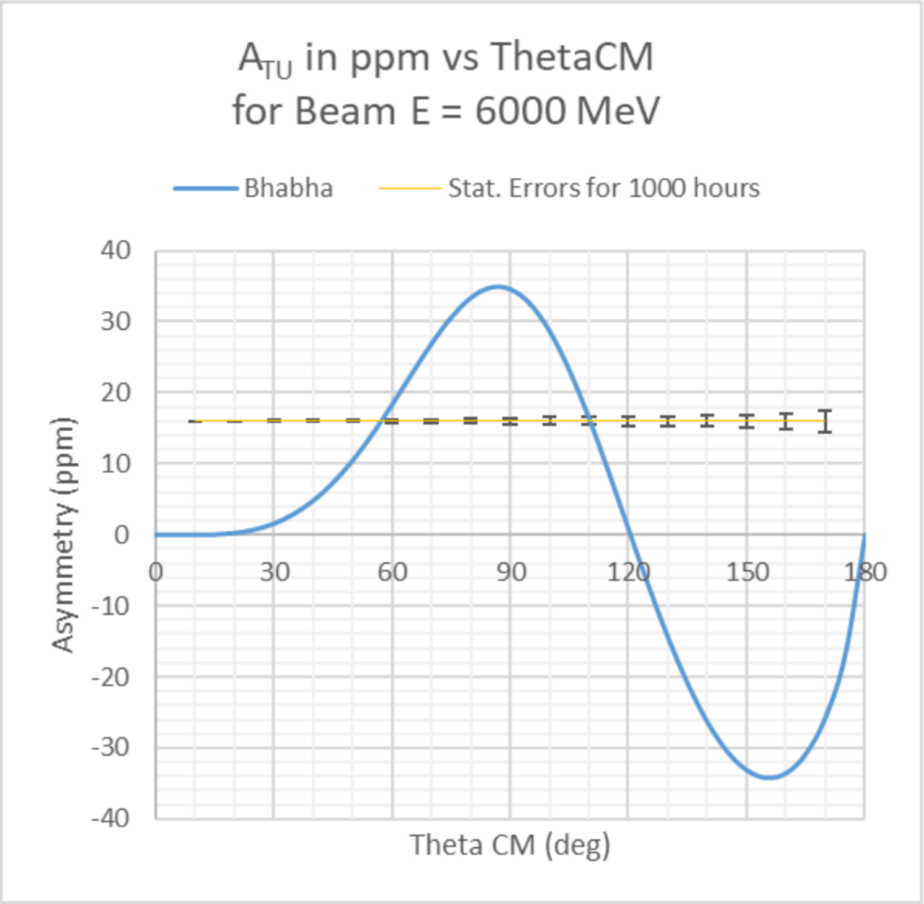

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BSM contributions

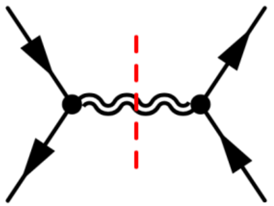
- Pseudoscalar doesn't contribute
- Symmetric tensor doesn't couple via dim-4 operators

⇒ we consider scalar, vector and axial vector mediators

$$\mathcal{L}_S = -\,g\,S\,\bar{\ell}\ell,$$

$$\mathcal{L}_V = -\,e\,\epsilon\,\bar{\ell}\,\not{V}\,\ell,$$

$$\mathcal{L}_A = -\,e\,\epsilon\,\bar{\ell}\,\gamma^5\not{A}\,\ell,$$



The imaginary part: from propagator $\dfrac{1}{s - m_X^2 + i m_X \Gamma_X}$

Resulting in: $$\bar{B}_n^{\mathrm{BSM}} = \frac{\sqrt{s}}{\delta E_+}\,\frac{x\sqrt{1-x^2}}{8}\,\frac{N_i}{(1-x^2+x^4)^2}$$

$$N_S = \frac{g^2}{\alpha}\,x^2\left(1-2x^2\right),$$

$$N_V = -4\pi\epsilon^2\,3x^2,$$

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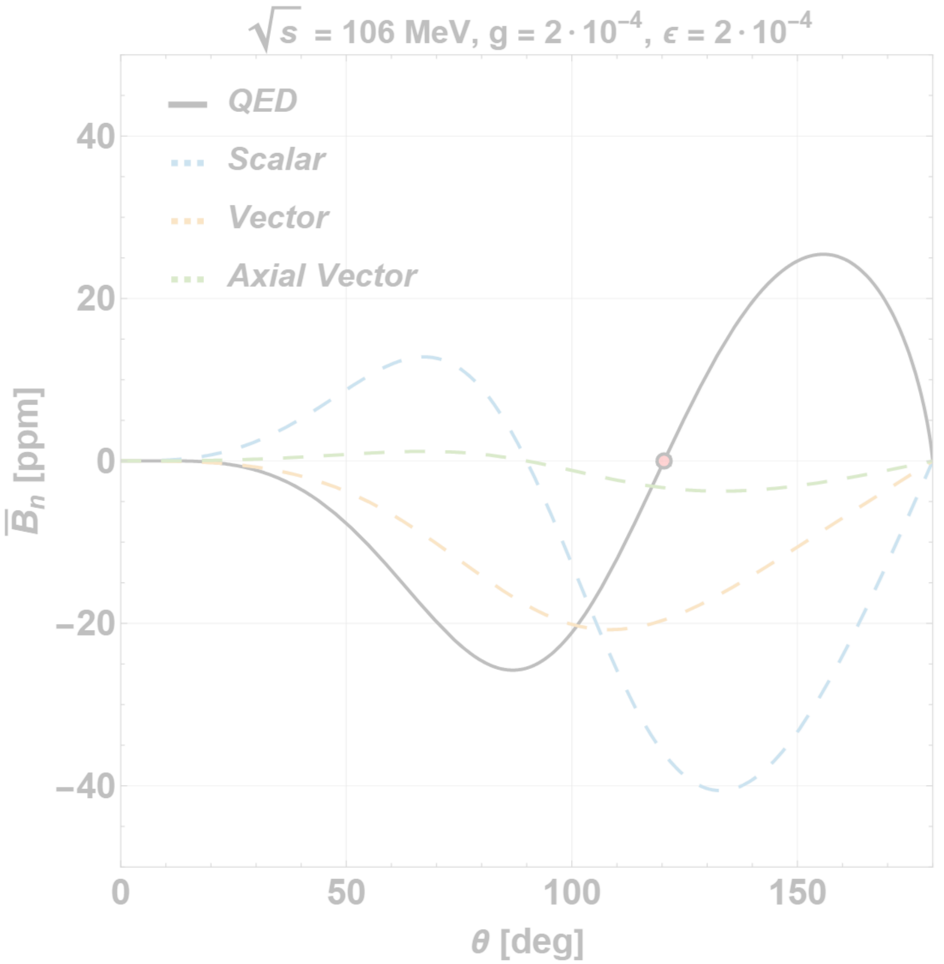
$\bar{B}_n$ – integrated over the beam energy spread 0.5 MeV



The BSM effects in the vicinity of the QED zero can be sizable compared to the ppm-level experimental precision

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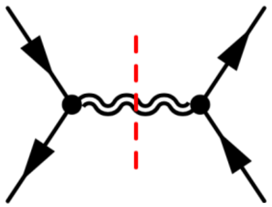

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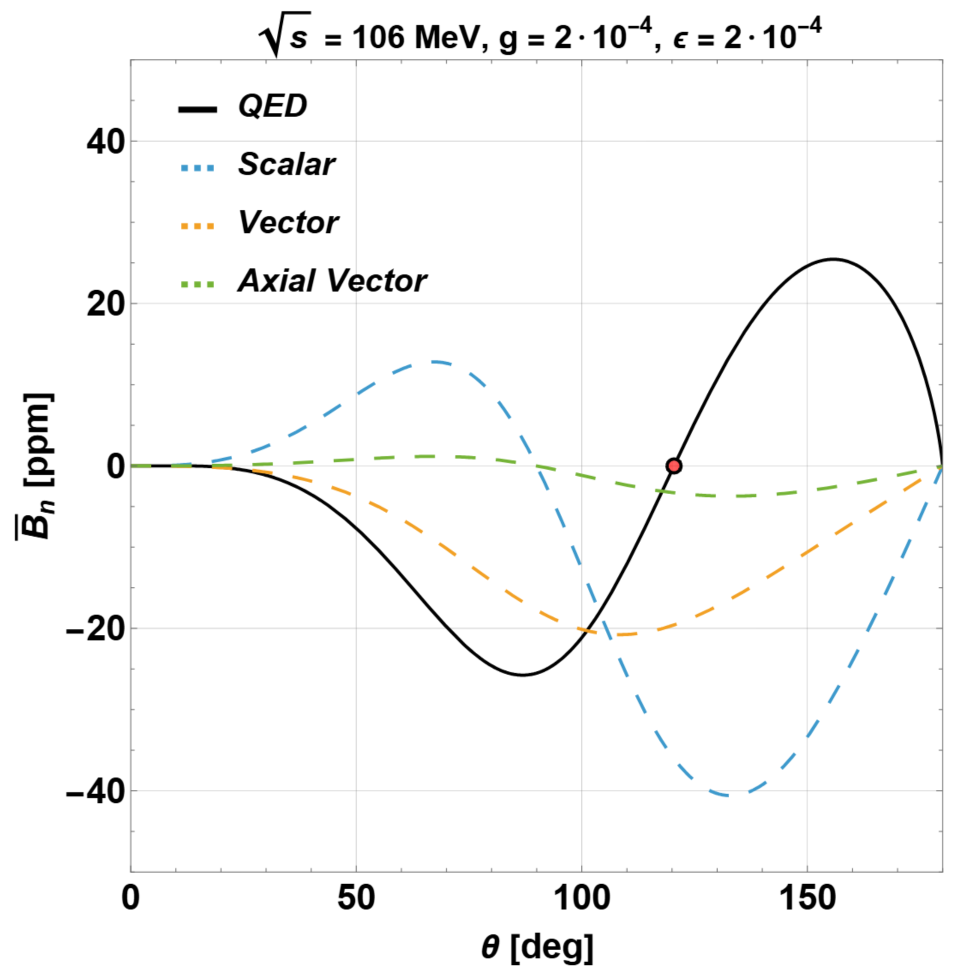

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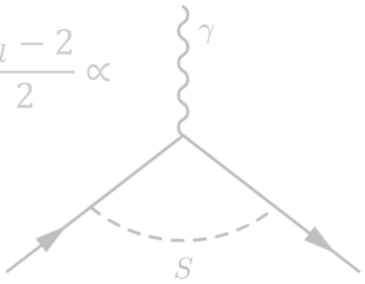
Scalar mediator

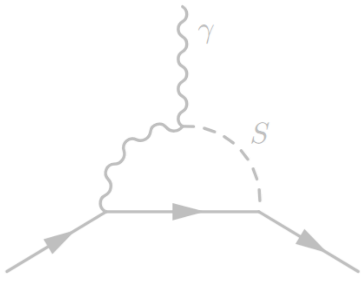
Direct probe of electron-scalar coupling in the region, where not so many reliable bounds are known:

- SINDRUM (1989) results are likely overestimated
- NA64 is the reinterpretation of dark photon bounds
- $(g-2)_e$ is subject to potential Barr-Zee correction, which might be substantial

$a_l = \frac{g_l - 2}{2} \propto$

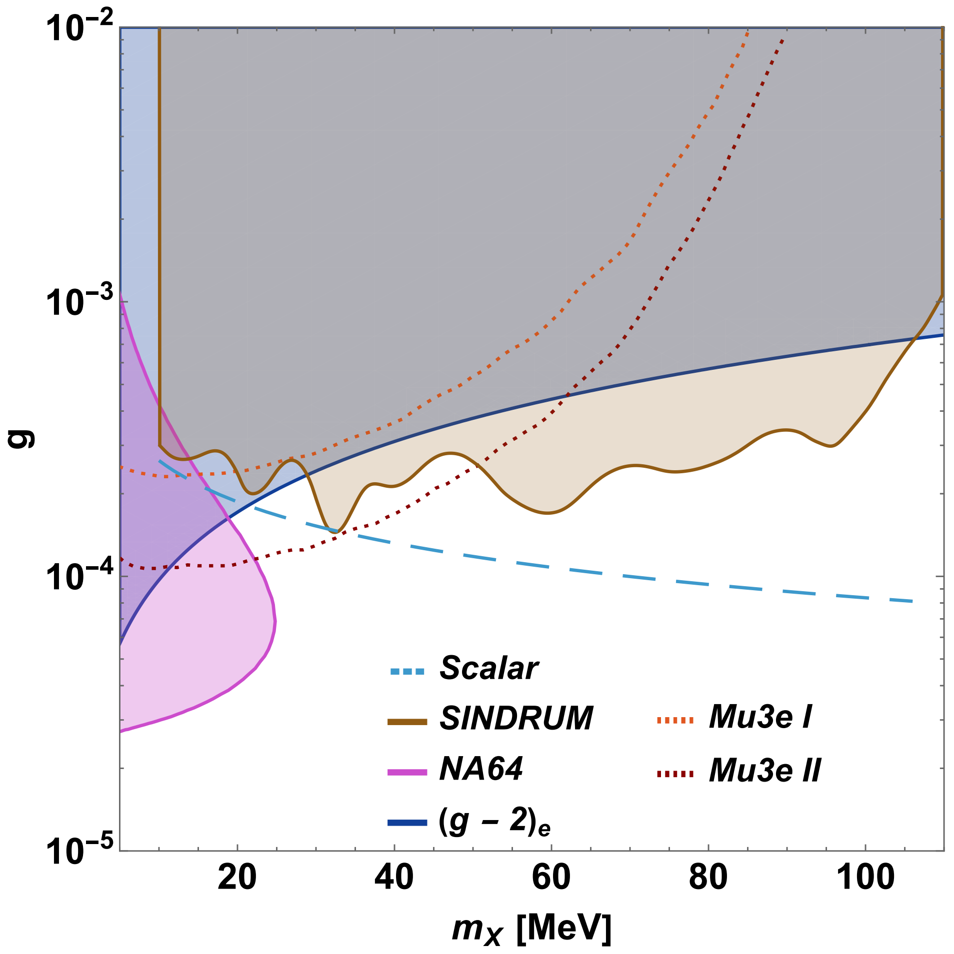


Yukawa type



Barr-Zee type

- In contrast, branching ratio effects due to possible photon coupling at JLab kinematics are negligible



Constraints on the scalar parameter space from $(g-2)_e$ and visible e^+e^- decays.
JLab projection assumes a **1 ppm precision** on B_n and **2σ signal**. Near-future experiments are shown as dotted lines.

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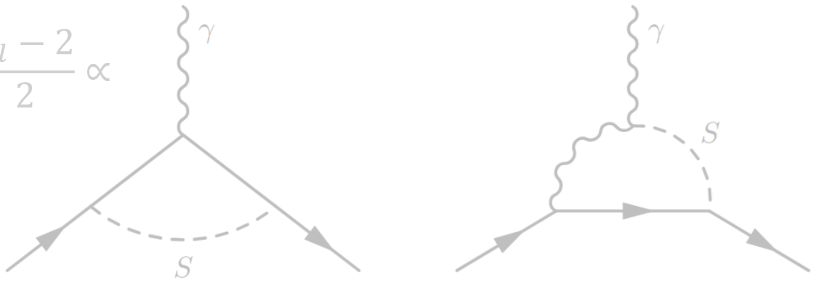

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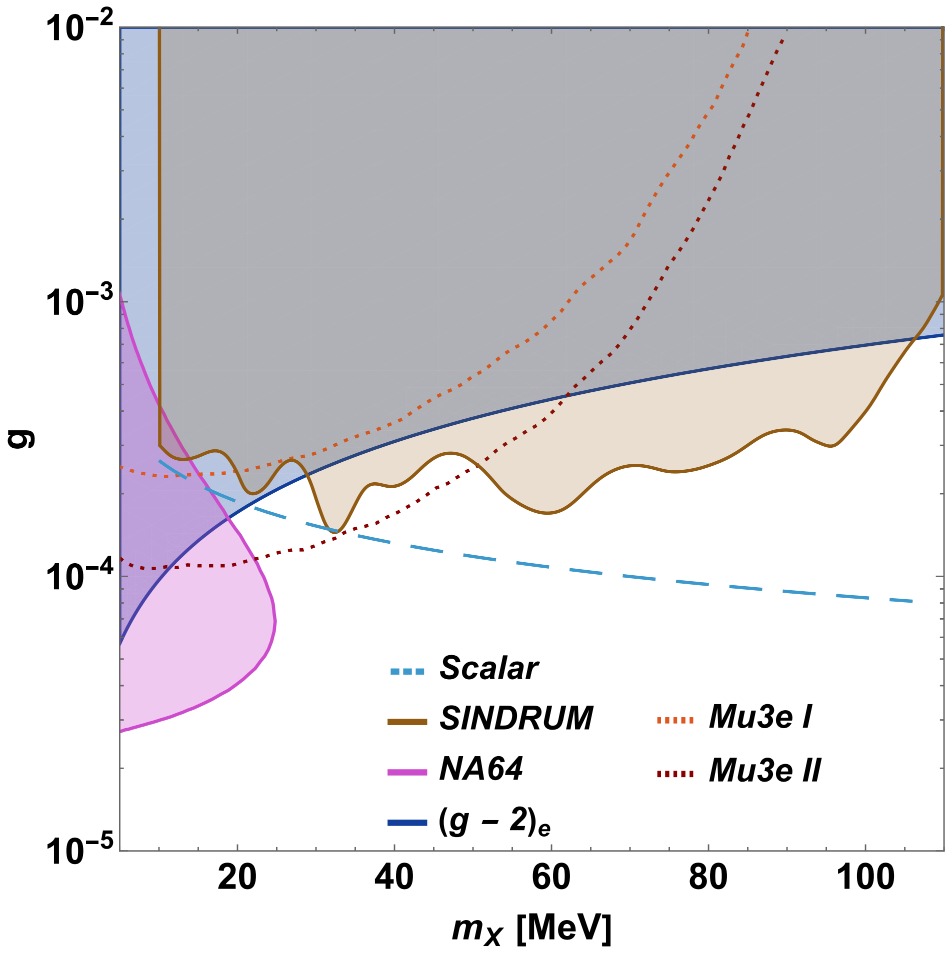

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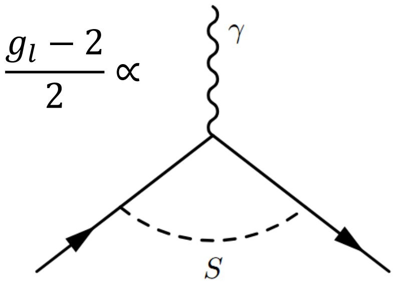

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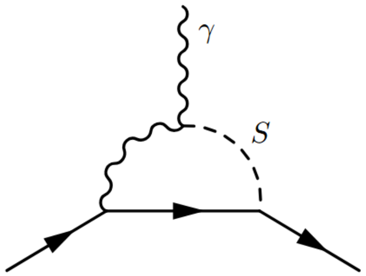

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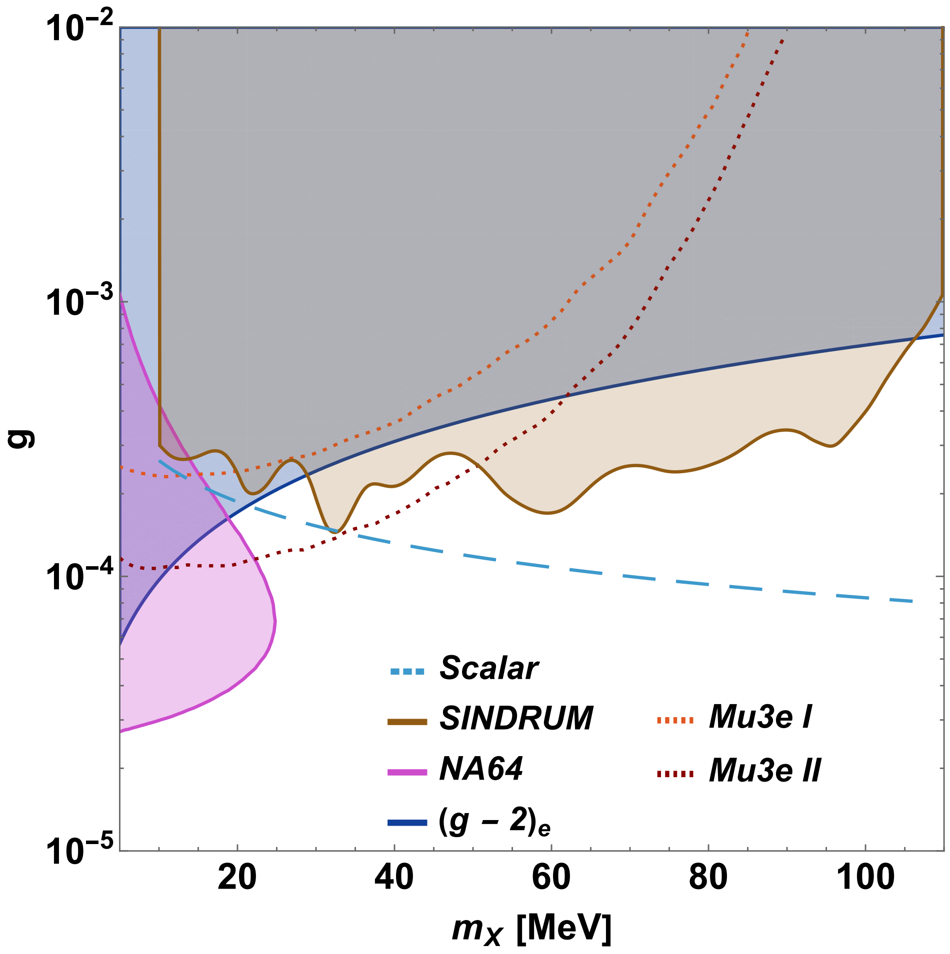

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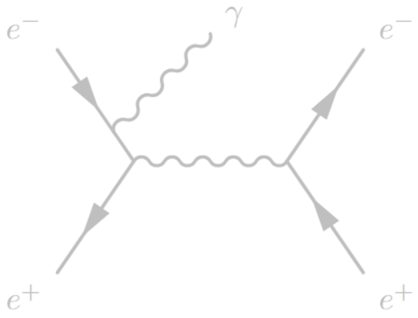
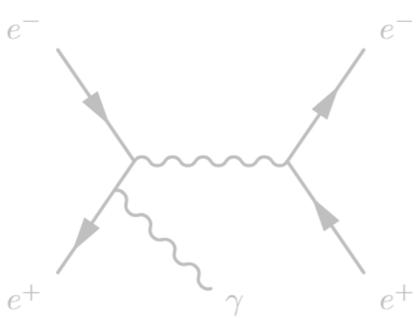
Substantial improvement even for vector-like mediators:

– Improve upon Belle II projections (50 ab^{-1})

Up to an order of magnitude under conservative assumptions about setup and without further model-dependence…

…but a study of ISR is required to go beyond a pilot measurement





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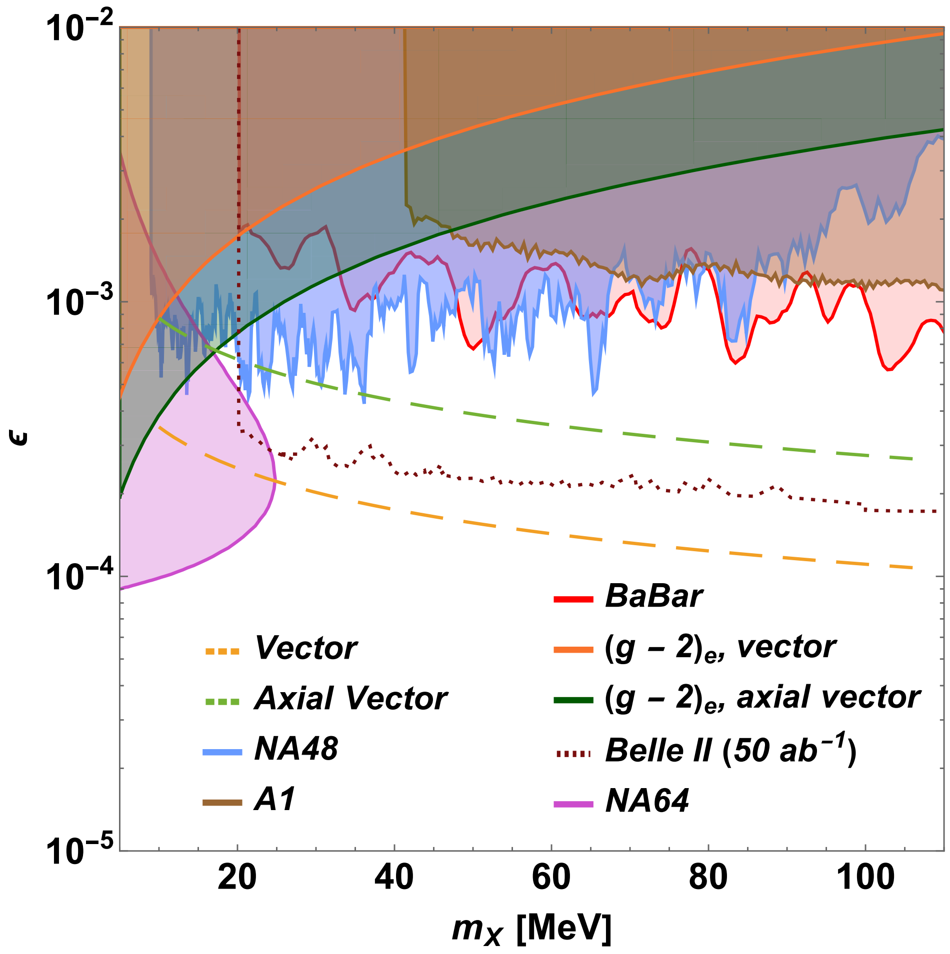

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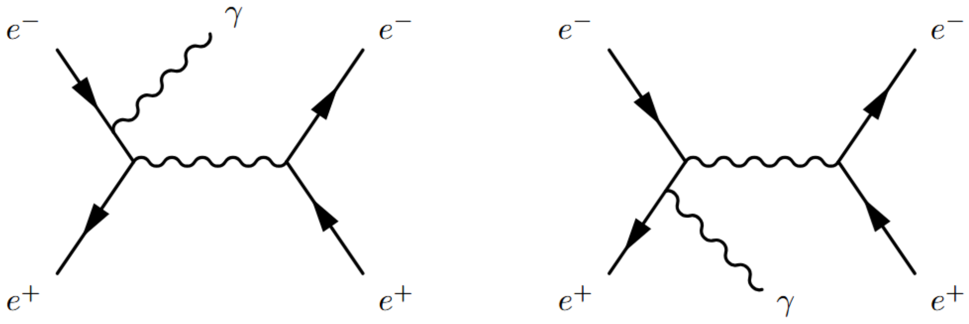

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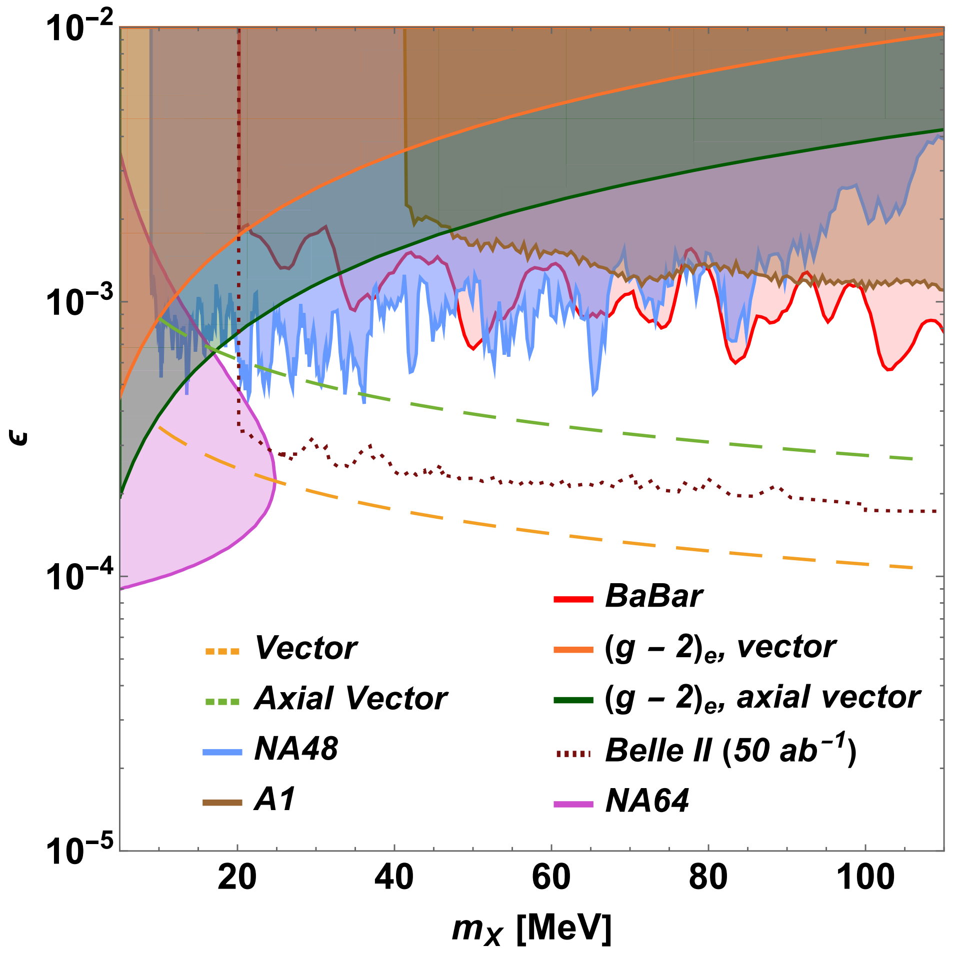

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Double spin asymmetry

An aside on the double-transverse asymmetry:

$$A_{TT} \equiv \frac{(\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow}) - (\sigma_{\uparrow\downarrow} + \sigma_{\downarrow\uparrow})}{(\sigma_{\uparrow\uparrow} + \sigma_{\downarrow\downarrow}) + (\sigma_{\uparrow\downarrow} + \sigma_{\downarrow\uparrow})}$$

Contains helicity-suppressed and unsuppressed parts:

$$A_{TT} \propto \left(A_{TT}^{(0)} + {m_e^2}/{s} \cdot A_{TT}^{(2)}\right) \times (S_+ S_-)$$

- Involves the product of positron/electron spins $S_\pm$
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Measures the real part of the 1-loop/BSM amplitudes

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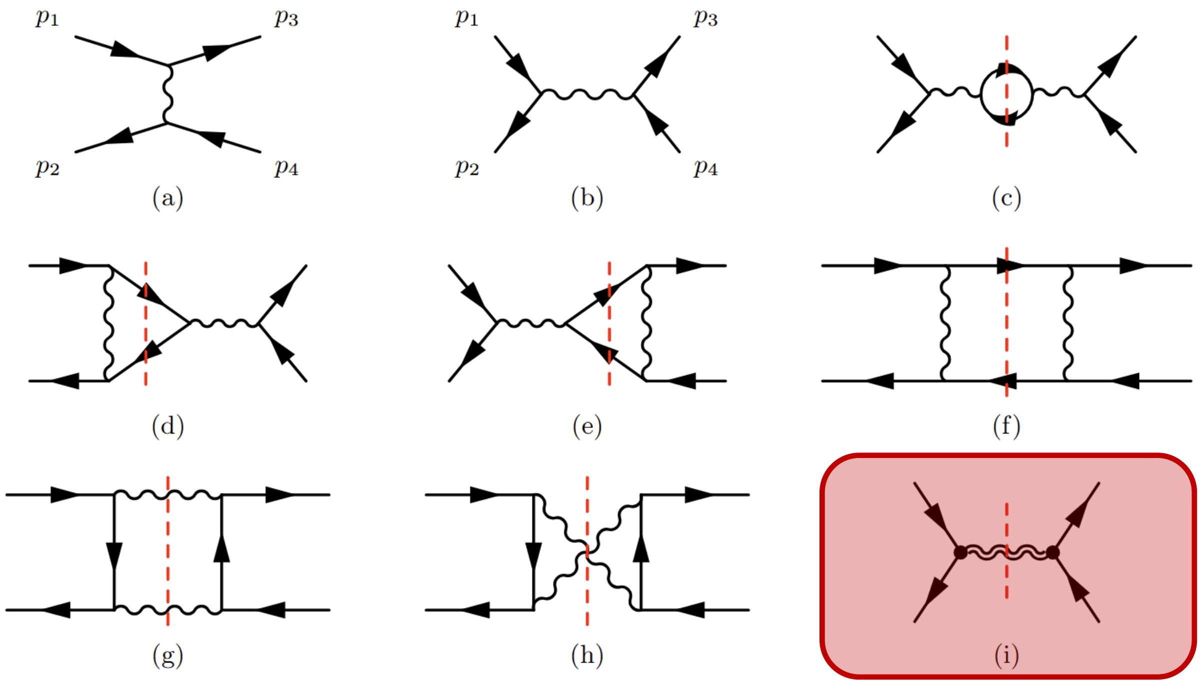

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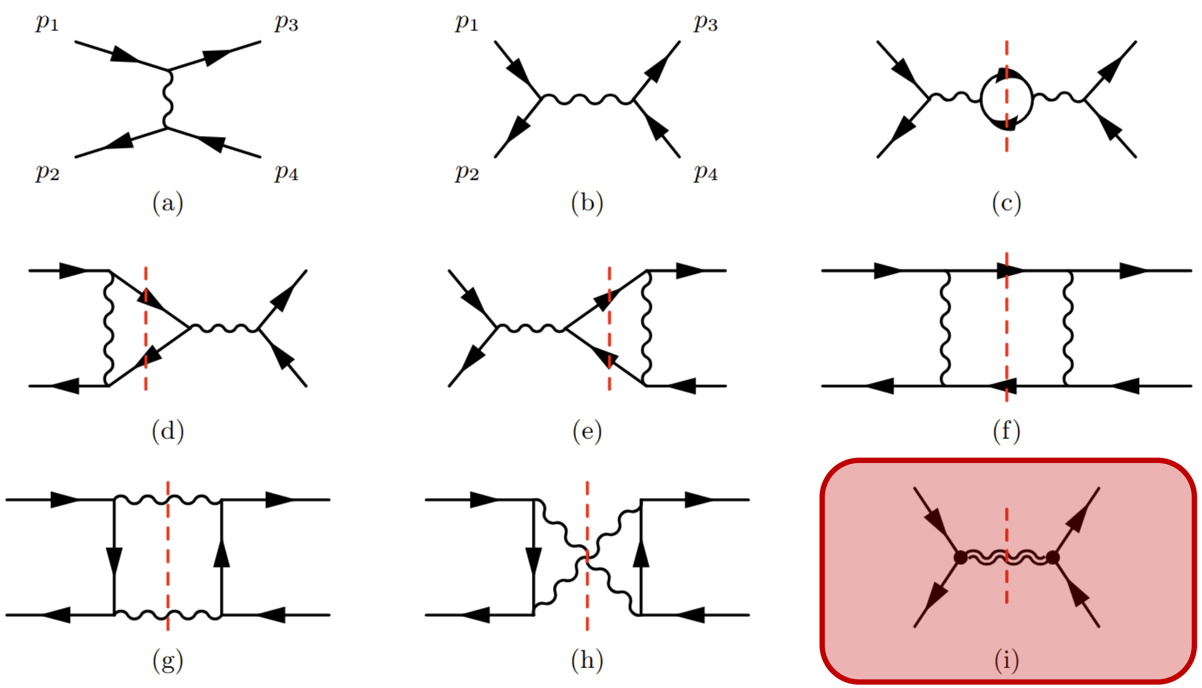

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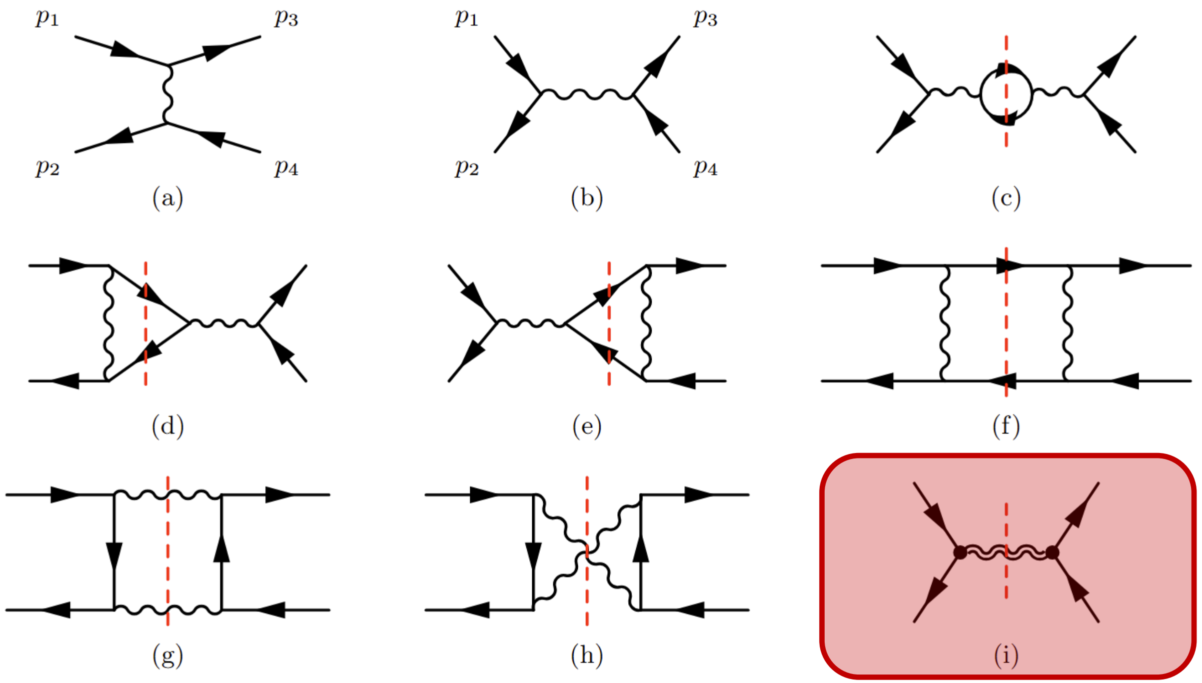

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Postdoc position? Please contact me: apustynt@uni-mainz.de

(skilled in many topics)

Thank you *very much* for your attention!