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On the Atomki nuclear anomaly after the MEG-II result

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Summary of this talk

- **Brief history of X17**
  - Atomki experiment ←
  - Preliminary phenomenology
  - MEG-II result
- **Spin 2 hypothesis**
  - Model
  - Atomki signal
  - SINDRUM constraint
  - Results
- **Spin parity 0^+ hypothesis**
  - Model
  - Constraints
  - Results
- **Future prospects for X17**

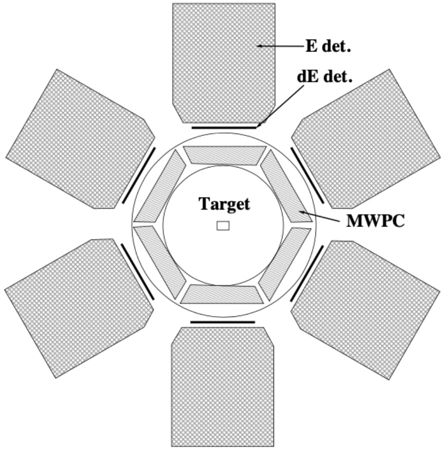
The discovery of the X17 anomaly

Atomki experiment (Hungary)

Process observed: $p + A \to N^* \to N + e^+e^-$.

Nuclear transition IPC

Apparatus [4]:



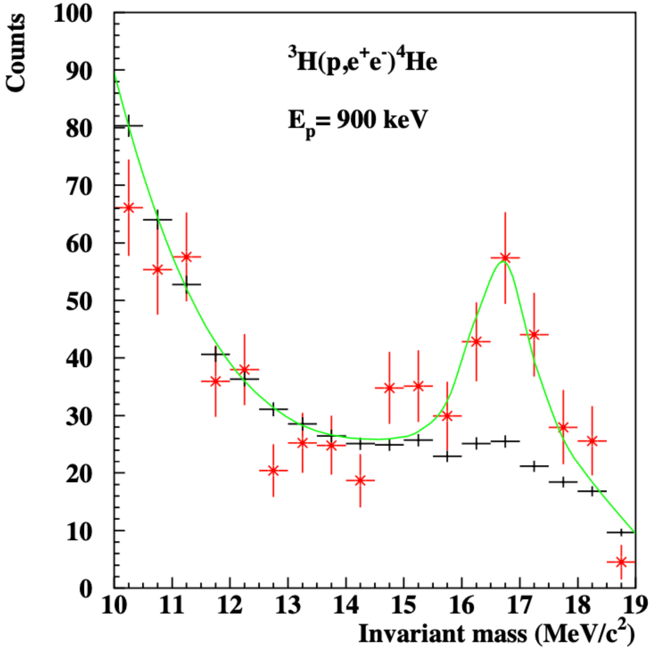


FIG. 3. *Invariant mass distribution derived for the 20.49 MeV transition in ^4He.*

Several nuclei tested: ^8Be [1], ^4He [2], ^{12}C [3] $\to$ peak at about 17 MeV (X17 resonance!)

Decay detected: $X \to e^+e^-$

Atomki observables

Invariant mass of lepton pair [5]

$$m_{ee}^2 = \frac{\omega^2}{2}\left[1 - y^2 + \delta^2 - \cos\theta_{\pm}\sqrt{(1-\delta^2+y^2)^2 - 4y^2}\right] \qquad \omega = \frac{E_{\text{CM}} - m_X^2 - m_N^2}{2E_{\text{CM}}}, \qquad y = \frac{E_+ - E_-}{E_+ + E_-}, \qquad \delta = \frac{2m_e}{\omega}$$

Signals [5]

Beryllium (R_{Be})

$$\frac{\Gamma(^8\text{Be}(18.15) \to {}^8\text{Be} + X)}{\Gamma(^8\text{Be}(18.15) \to {}^8\text{Be} + \gamma)}\,\text{BR}(X \to e^+e^-) = (6 \pm 1) \times 10^{-6}.$$

Helium (R_{He})

$$\frac{\Gamma(^4\text{He}(20.21) \to {}^4\text{He} + X)}{\Gamma(^4\text{He}(20.21) \to {}^4\text{He} + e^+e^-)}\,\text{BR}(X \to e^+e^-) = 0.20 \pm 0.03$$

If $S^\pi = 0^+, 1^-, 2^+, \ldots$

$$\frac{\Gamma(^4\text{He}(21.01) \to {}^4\text{He} + X)}{\Gamma(^4\text{He}(20.21) \to {}^4\text{He} + e^+e^-)}\,\text{BR}(X \to e^+e^-) = 0.87 \pm 0.14$$

If $S^\pi = 0^-, 1^+, 2^-, \ldots$

Carbon (R_{C})

$$\frac{\Gamma(^{12}\text{C}(17.23) \to {}^{12}\text{C} + X)}{\Gamma(^{12}\text{C}(17.23) \to {}^{12}\text{C} + \gamma)}\,\text{BR}(X \to e^+e^-) = 3.6(3) \times 10^{-6}$$

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The axial vector hypothesis (1)

Many models to explain X17 (fifth-force mediation, axion, nuclear resonance model, QCD meson, QED meson…)

However → phenomenologically, what can X17 be?
"An updated view on the ATOMKI nuclear anomaly" (Barducci, Toni) [5]

N	N^*	S^π	I	$\Gamma(\text{keV})$	$\Gamma_\gamma(\text{eV})$
^{8}Be		0^+	0	5.57 ± 0.25	
	^{8}Be(18.15)	1^+	0^*	138 ± 6	1.9 ± 0.4
	^{8}Be(17.64)	1^+	1^*	10.7 ± 0.5	15.0 ± 1.8
^{4}He		0^+	0	Stable	
	^{4}He(21.01)	0^-	0	0.84	0
	^{4}He(20.21)	0^+	0	0.50	0
^{12}C		0^+	0	Stable	
	^{12}C(17.23)	1^-	1	1150	44

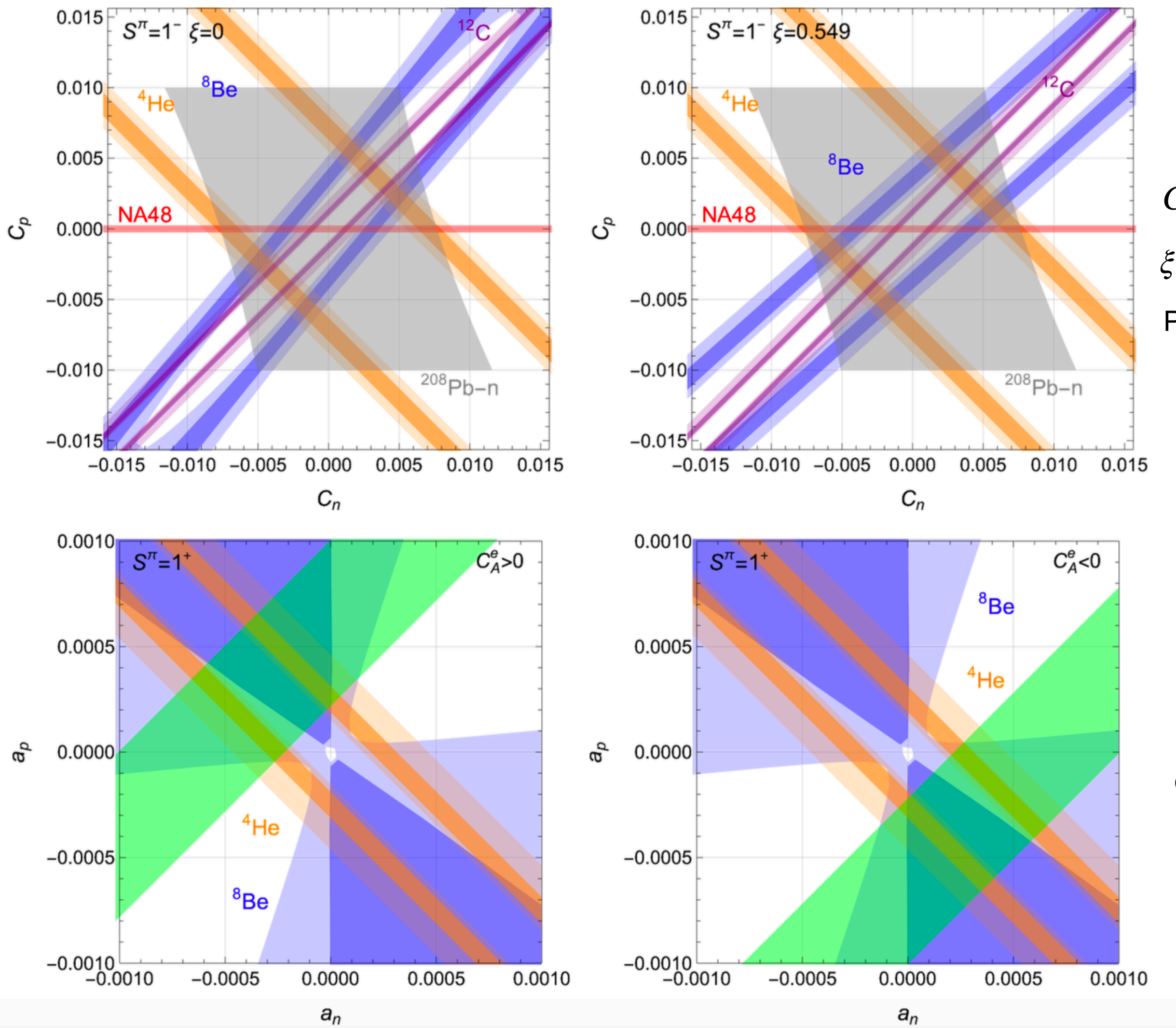
Table 1. Spin-parity J^π and isospin I quantum numbers, total decay widths Γ and γ-decay widths $\Gamma_\gamma = \Gamma(N^* \to N\gamma)$ for the nuclei used in the ATOMKI experiment: ^{8}Be [7], ^{4}He [8, 9] and ^{12}C [10, 11] nuclei. Asterisks on isospin assignments indicate states with significant isospin mixing.

Process $N^* \to N$	X boson spin parity $S^\pi = 1^-$	$S^\pi = 1^+$	$S^\pi = 0^-$	$S^\pi = 0^+$
^{8}Be(18.15) → ^{8}Be	1	0, 2	1	/
^{8}Be(17.64) → ^{8}Be	1	0, 2	1	/
^{4}He(21.01) → ^{4}He	/	1	0	/
^{4}He(20.21) → ^{4}He	1	/	/	0
^{12}C(17.23) → ^{12}C	0, 2	1	/	1

Table 2. Relative angular momentum between the X boson and N in the various decays, based on its possible parity-spin assignments. Note that parity conservation prohibits a pure scalar solution to the Beryllium anomaly.

Spin 0 excluded by angular momentum conservation!

The axial vector hypothesis (2)



$\longrightarrow$ $S^\pi = 1^-$

C_p, C_n vector couplings

ξ parametrizes isospin breaking effects in Beryllium

Protophobia constraint from NA48

Only a 2σ agreement

$\longrightarrow$ $S^\pi = 1^+$

a_p, a_n axial couplings

Green area KTeV anomaly for $\pi^0 \to e^+e^-$ decay

Favoured hypothesis

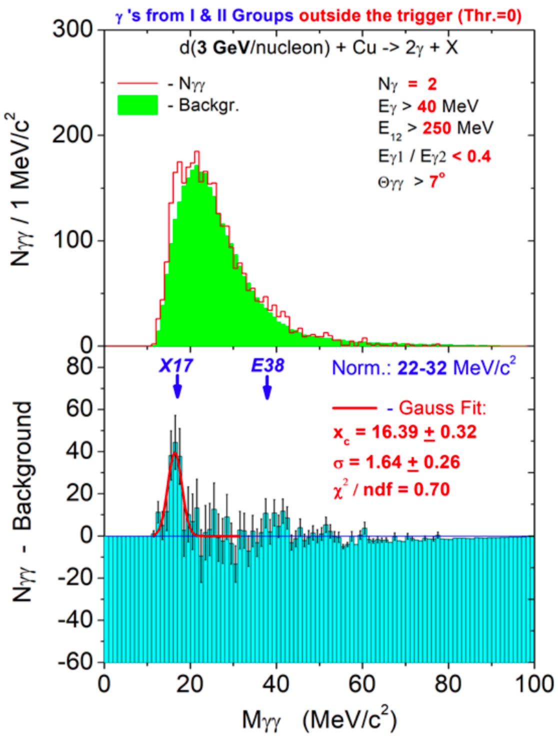
The “independent” confirmation

JINR experiment (Russia)

Process observed: $p + N \to \gamma\gamma + \text{else}$

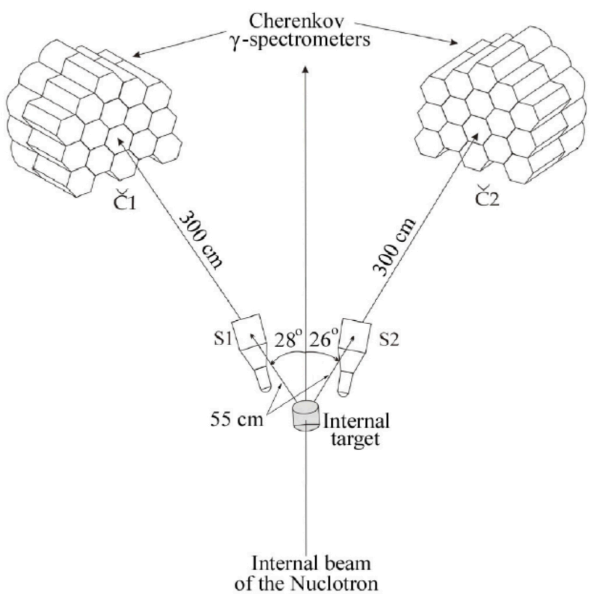
Observation of structures at ~ 17 and ~ 38 MeV/c^2 in the $\gamma\gamma$ invariant mass spectra in pC, dC, and dCu collisions at p_{lab} of a few GeV/c per nucleon

Kh.U. Abraamyan[1,2*], Ch. Austin[3], M.I. Baznat[4], K.K. Gudima[4], M.A. Kozhin[1], S.G. Reznikov[1], and A.S. Sorin[1,5]



Decay detected:

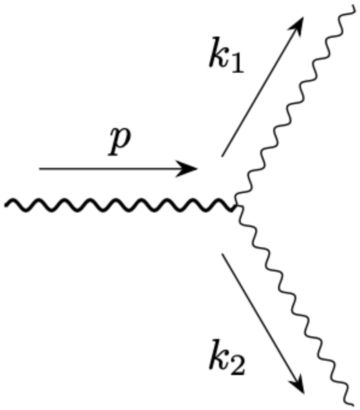
$$X \to \gamma\gamma$$



Apparatus [6]

This negates the spin 1 hypothesis!

Landau-Yang theorem



Theorem:

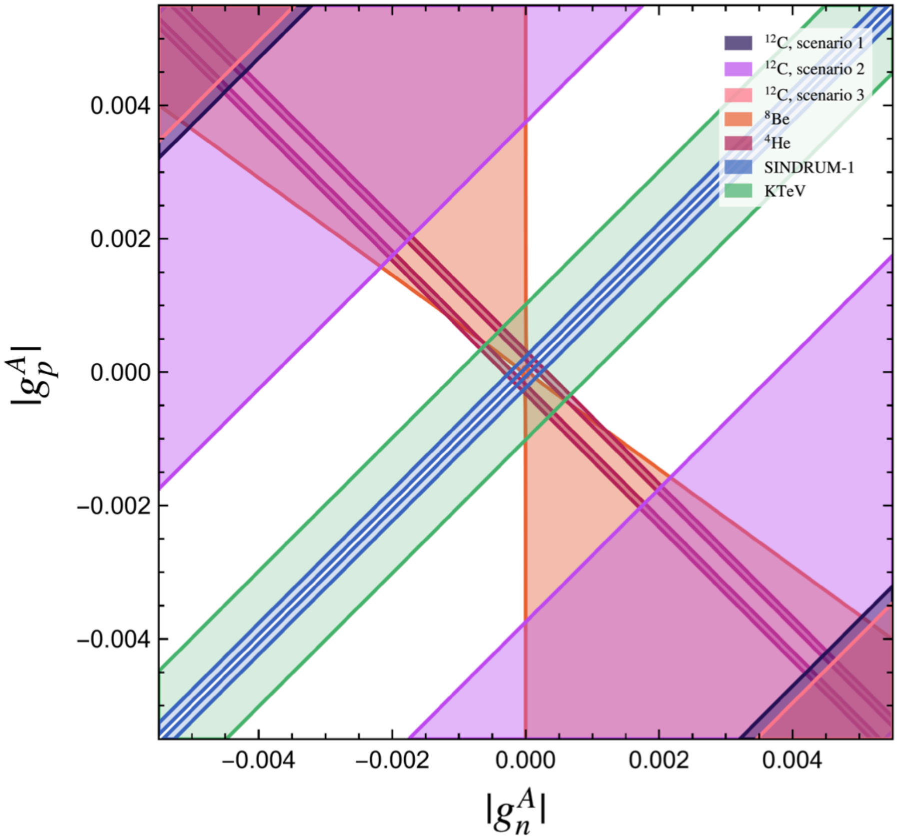
“It is impossible for any massive, odd spin state to decay into two massless bosons.”

Exclusion of spin 1 hypothesis for X17 altogether?

However → Atomki did search for 2 photon channels, but found nothing

Constraining axial vector hypothesis

C. J. G. Mommers, M. Vanderhaeghen (2024), "Constraining the axial-vector X17 interpretation with ^{12}C data" [7]



Estimation of Carbon matrix element with particle-hole approximation.

Addition of SINDRUM constraint

Only a 2σ agreement

If spin 0 and spin 1 are excluded, can X17 be spin 2?

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The MEG-II null result [8]

MEG-II experiment at PSI (Switzerland)

Apparatus readapted for X17 search with Beryllium [8]

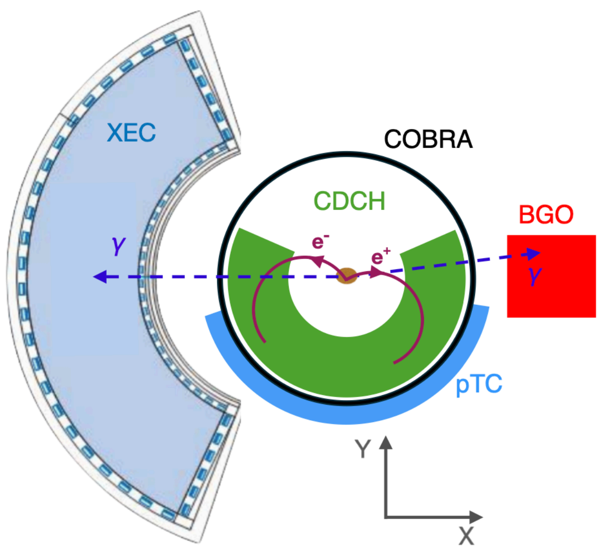

Fig. 1 Representation of the MEG II apparatus employed for this work. The Cockroft-Walton proton accelerator is located at a *z* position several meters away from the COBRA center.

Null result for Beryllium → **Atomki hypothesis excluded at 1.5σ**

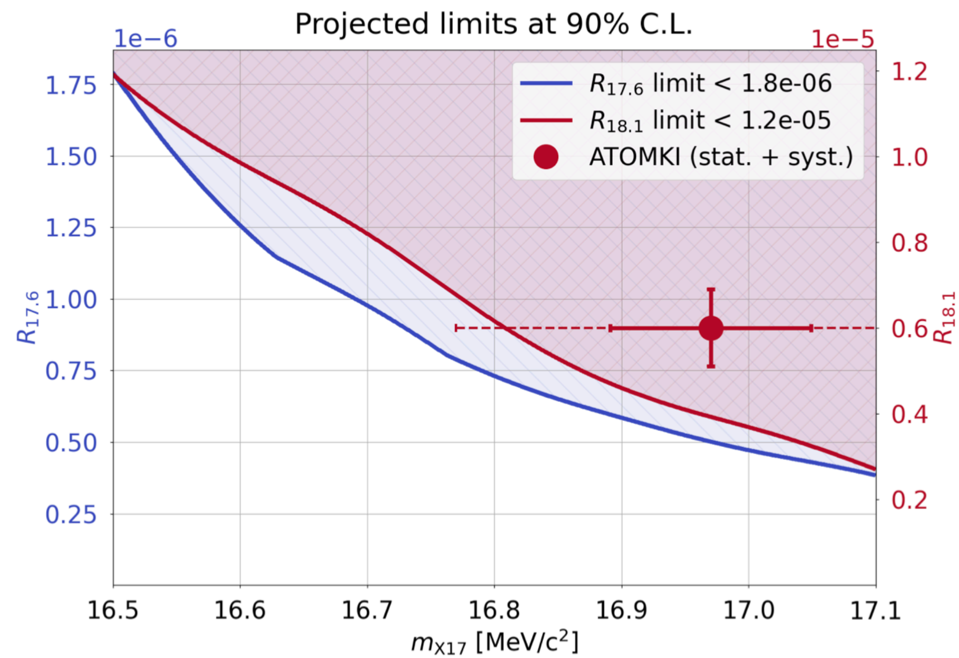

Fig. 9 ~~Left: 3D upper limits on $R_{17.6}$, $R_{18.1}$ and m_{X17} at 90 % C.L.~~ Right: 90 % C.L. limit projections of $R_{17.6}$ (blue) and $R_{18.1}$ (red) within the allowed mass range. The hatched area represents the excluded region. The red point represents the measured branching ratio at ATOMKI. The dashed error bar represents the systematic error on the X17 mass.

How to treat an inconclusive result?

Remark: actual X17 mass is (16.85 ± 0.04) MeV [9] → Atomki signal is "almost" compatible with MEG-II result

Either combine them…

	R_{Be} $[10^{-6}]$
Atomki	6 ± 1 [1, 2]
MEG-II	< 5.3 at 90% CL [38]
Combined	5.5 ± 1.0

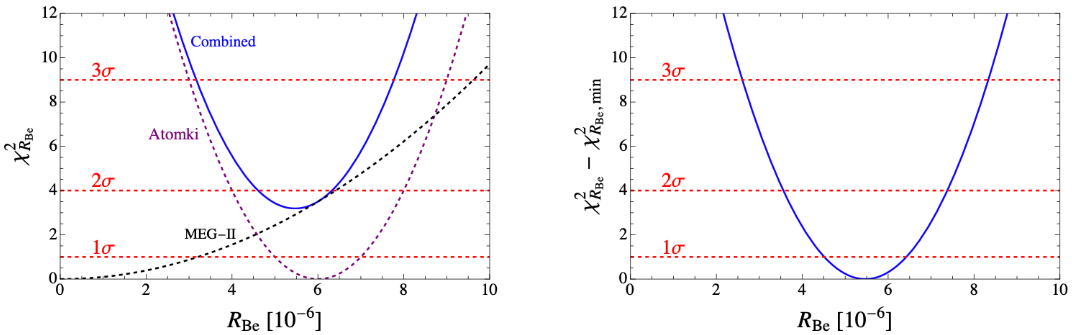

Figure 1. *Left panel:* Value of the χ^2 of the Atomki (black dashed line) and MEG-II (purple dashed line) measurements and the sum of them (blue line). The red dashed lines denotes the 68%, 95%, 99% values of a χ^2 variable with 1 degree of freedom. *Right panel:* Value of the total χ^2 around its minimal value.

… or exclude Beryllium signal

↓

0^+ hypothesis may work

↓

Phenomenological analysis required

Both scenarios explored in our work

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Method of analysis

1) Choose a spin parity assignment for X17.

2) Write down the most general Lagrangian/amplitudes.

3) Identify interactions and relevant couplings.

4) Compute Atomki observables as a function of those couplings.

5) Compute other relevant constraints (*i.e.* SINDRUM, NA48, electron g-2, decay rates…)

6) Gather everything into exclusion plots.

Spin 2 on shell model (1)

Complications from off shell contact terms ⟶ No Lagrangian approach

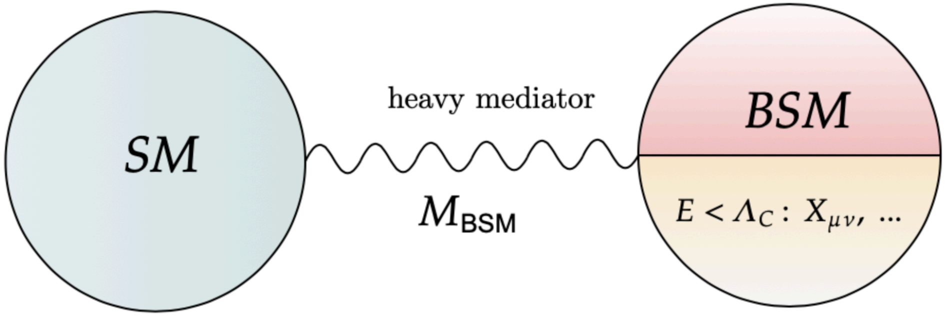
Following [10], from most general on shell amplitudes

$$\begin{aligned}\mathcal{A}(f \to f'X) = \overline{u}(p',\sigma')\Big\{ & C_f\left[\gamma_\mu\left(\frac{p'+p}{4}\right)_\nu + \gamma_\nu\left(\frac{p'+p}{4}\right)_\mu\right] \\ & +\tilde{C}_f\left[\gamma_\mu\gamma_5\left(\frac{p'+p}{4}\right)_\nu + \gamma_\nu\gamma_5\left(\frac{p'+p}{4}\right)_\mu\right] \\ & +D_f\,(p'+p)_\mu\,(p'+p)_\nu \\ & +\tilde{D}_f\,(p'+p)_\mu\,(p'+p)_\nu\, i\gamma_5\Big\} u(p,\sigma)\;[\epsilon_a^{\mu\nu}(p-p')]^*\end{aligned}$$

$$\begin{aligned}\mathcal{A}(X \to \gamma\gamma) = 2i\Big\{ & C_\gamma\left[(\epsilon_1^*\cdot\epsilon_2^*)q_{1\mu}q_{2\nu} - (\epsilon_2^*\cdot q_1)\epsilon_{1\mu}^* q_{2\nu} - (\epsilon_1^*\cdot q_2)\epsilon_{2\mu}^* q_{1\nu} + (q_1\cdot q_2)\epsilon_{1\mu}^*\epsilon_{2\nu}^*\right] \\ & +D_\gamma\, q_{1\mu}q_{2\nu}\left[(\epsilon_1^*\cdot\epsilon_2^*)(q_1\cdot q_2) - (\epsilon_1^*\cdot k_2)(\epsilon_2^*\cdot k_1)\right] \\ & +\tilde{D}_\gamma\, q_{1\mu}q_{2\nu}\, \varepsilon^{\alpha\rho\beta\sigma}\, q_{1\alpha}q_{2\beta}\epsilon_{1\rho}^*\epsilon_{2\sigma}^*\Big\}\epsilon_a^{\mu\nu}(q_1+q_2)\;,\end{aligned}$$

Spin 2 on shell model (2)

Massive spin 2 requires EFT



$$C_f \sim \tilde{C}_f \sim \mathcal{O}(M_{\text{BSM}}^{-1}) \quad \text{and} \quad D_f \sim \tilde{D}_f \sim \mathcal{O}(M_{\text{BSM}}^{-2}) \ .$$

$$C_\gamma \sim \mathcal{O}(M_{\text{BSM}}^{-1}) \quad \text{and} \quad D_\gamma \sim \tilde{D}_\gamma \sim \mathcal{O}(M_{\text{BSM}}^{-3})$$

At lowest order, parameters are C_p, C_n, C_e for 2^+, and $\tilde{C}_p, \tilde{C}_n, \tilde{C}_e$ for 2^-.
No couplings to neutrinos.

In the most conservative way, $\Lambda_c = 4\pi m_X \approx 200$ MeV

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Atomki signal computation (1)

Nuclear interaction described by

$$H^s_{\rm int} = \int d^3\vec{r}\, \mathcal{H}_{\mu\nu}(\vec{r}) X^{\mu\nu}(\vec{r})$$

In the interaction picture

$$\mathcal{T}^s_{fi} = \langle N, X | H^s_{\rm int} | N^\star \rangle = \langle N | \int d^3\vec{r} [\epsilon^{\mu\nu}_a(\vec{k})]^* \mathcal{H}_{\mu\nu}(\vec{r}) e^{-i\vec{k}\cdot\vec{r}} | N^\star \rangle$$

$\mathscr{H}_{\mu\nu}$ expanded in non-relativistic limit, in powers of $\langle p_N \rangle^2 / m_N^2 \approx 0.06$

$$\mathcal{H}^{\mu\nu} = \begin{pmatrix} \mathcal{E} & \vec{\mathcal{P}}^T \\ \vec{\mathcal{P}} & \hat{\mathcal{W}} \end{pmatrix}$$

$$\begin{aligned}
\mathcal{E}(\vec{r}) =& \sum_{s=1}^{A} m_s C_s \delta_{\vec{r},\vec{r}_s} \\
&+ \sum_{s=1}^{A} \sum_i \frac{C_s}{8m_s} \left[p^i_s p^i_s \delta_{\vec{r},\vec{r}_s} + 2 p^i_s \delta_{\vec{r},\vec{r}_s} p^i_s + \delta_{\vec{r},\vec{r}_s} p^i_s p^i_s \right] , \\
\vec{\mathcal{P}}(\vec{r}) =& \frac{1}{2} \sum_{s=1}^{A} C_s \left[\vec{p}_s \delta_{\vec{r},\vec{r}_s} + \delta_{\vec{r},\vec{r}_s} \vec{p}_s \right] + \vec{\nabla} \times \left(\frac{1}{4} \sum_{s=1}^{A} C_s \vec{\sigma}_s \delta_{\vec{r},\vec{r}_s} \right) , \\
\hat{\mathcal{W}}^{ij}(\vec{r}) =& \sum_{s=1}^{A} \frac{C_s}{4m_s} \left[p^i_s p^j_s \delta_{\vec{r},\vec{r}_s} + p^i_s \delta_{\vec{r},\vec{r}_s} p^j_s + p^j_s \delta_{\vec{r},\vec{r}_s} p^i_s + \delta_{\vec{r},\vec{r}_s} p^i_s p^j_s \right] \\
&- \sum_{s=1}^{A} \frac{C_s}{4m_s} (\vec{\sigma}_s \times \vec{\nabla})^j \left[p^i_s \delta_{\vec{r},\vec{r}_s} + \delta_{\vec{r},\vec{r}_s} p^i_s \right] \\
&- \sum_{s=1}^{A} \frac{C_s}{4m_s} (\vec{\sigma}_s \times \vec{\nabla})^i \left[p^j_s \delta_{\vec{r},\vec{r}_s} + \delta_{\vec{r},\vec{r}_s} p^j_s \right] ,
\end{aligned}$$

Tensor boson 2^+

$$\begin{aligned}
\mathcal{E}(\vec{r}) =& \frac{1}{2} \sum_{s=1}^{A} \tilde{C}_s \left[\vec{p}_s \delta_{\vec{r},\vec{r}_s} + \delta_{\vec{r},\vec{r}_s} \vec{p}_s \right] \cdot \vec{\sigma}_s , \\
\vec{\mathcal{P}}(\vec{r}) =& \frac{1}{2} \sum_{s=1}^{A} m_s \tilde{C}_s \vec{\sigma}_s \delta_{\vec{r},\vec{r}_s} , \\
\hat{\mathcal{W}}^{ij}(\vec{r}) =& \frac{1}{4} \sum_{s=1}^{A} \tilde{C}_s \left[p^i_s \delta_{\vec{r},\vec{r}_s} + \delta_{\vec{r},\vec{r}_s} p^i_s \right] \sigma^j_s \\
&+ \frac{1}{4} \sum_{s=1}^{A} \tilde{C}_s \left[p^j_s \delta_{\vec{r},\vec{r}_s} + \delta_{\vec{r},\vec{r}_s} p^j_s \right] \sigma^i_s .
\end{aligned}$$

Axial tensor boson 2^-

Atomki signal computation (2)

Since $kr \approx 0.1$ ⟶ Long wavelength approximation

$$e^{-i\vec{k}\cdot\vec{r}} \approx 1 - i\vec{k}\cdot\vec{r} - \frac{1}{2}(\vec{k}\cdot\vec{r})^2 + \ldots$$

- Apply parity and angular momentum selection rules.
- Keep lowest order terms in both expansion.

Transition amplitude expressed as

$$\mathcal{T}^s_{fi} = \langle N| \sum_{\mathcal{O}} \sum_{JM} \mathcal{O}_{JM} |N^\star\rangle$$

Simplified through Wigner-Eckart theorem

$$\langle J_f M_f|\mathcal{O}_{J,-M}|J_i M_i\rangle = \frac{(-1)^{J_i - M_i}}{\sqrt{2J+1}} C^{J,-M}_{J_f,M_f;J_i,-M_i} \langle J_f||\mathcal{O}_J||J_i\rangle$$

For Helium and Carbon, isospin conservation:

$$\sum_N m_N C_N \approx \frac{m_N}{2}\left(C_p + C_n\right)\mathbf{I} + \frac{m_N}{2}\left(C_p - C_n\right)\tau_z$$

$$\sum_N m_N \tilde{C}_N \approx \frac{m_N}{2}\left(\tilde{C}_p + \tilde{C}_n\right)\mathbf{I} + \frac{m_N}{2}\left(\tilde{C}_p - \tilde{C}_n\right)\tau_z$$

Atomki signal computation (3)

Final rate

$$\Gamma(N^\star \to NX) = \frac{1}{2J_i+1}\frac{k}{2\pi}\sum_{\text{pol.}}\left|\mathcal{T}^s_{fi}\right|^2$$

Atomki observables

$$R_{\rm Be} = \frac{k m_X^2}{18\pi}\left|\sqrt{\frac{4\pi}{3}}[(-\alpha_1+\beta_1\xi)M1^\gamma_{I=1}(C_p-C_n)+\beta_1 M1^\gamma_{I=0}(C_p+C_n)]\right.$$
$$-\frac{1}{2}(5C_p-4C_n)\langle{}^8\text{Be}||\hat\sigma^{(p)}||{}^8\text{Be}(18.15)\rangle$$
$$\left.+\frac{1}{2}(4C_p-5C_n)\langle{}^8\text{Be}||\hat\sigma^{(n)}||{}^8\text{Be}(18.15)\rangle\right|^2\frac{\text{BR}(X\to e^+e^-)}{\Gamma({}^8\text{Be}(18.15)\to{}^8\text{Be}+\gamma)}\,,$$
$$R_{\rm He} = \frac{m_N^2}{\alpha^2}\frac{5}{4}\frac{k m_X^4}{\omega^5}(C_p+C_n)^2\left|1-\left(3-2\frac{k^2}{m_X^2}\right)r_{\rm He}\right|^2\text{BR}(X\to e^+e^-)\,,$$
$$R_{\rm C} = \frac{m_N^2}{12\pi\alpha}\frac{m_X^4}{k\omega^3}\left[1+6r_{\rm C}^2\right](C_p-C_n)^2\,\text{BR}(X\to e^+e^-)\,,$$

Tensor boson 2^+

$$R_{\rm Be} = \frac{m_N^2 k^3}{18\pi m_X^2}\left|\tilde C_p\langle{}^8\text{Be}||\hat\sigma^{(p)}||{}^8\text{Be}(18.15)\rangle+\tilde C_n\langle{}^8\text{Be}||\hat\sigma^{(n)}||{}^8\text{Be}(18.15)\rangle\right|^2$$
$$\times\left(1+\frac{2}{3}\frac{\omega^2}{m_X^2}\right)\frac{\text{BR}(X\to e^+e^-)}{\Gamma({}^8\text{Be}(18.15)\to{}^8\text{Be}+\gamma)}\,,$$
$$R_{\rm C} = \frac{m_N^2}{32\pi\alpha}\frac{k^5}{m_X^2\omega^3}\left(\tilde C_p-\tilde C_n\right)^2|\tilde r_{\rm C}|^2\,,$$
$$R_{\rm He} = \frac{80 m_N^2}{\alpha^2}\frac{\sigma_-\Gamma_+}{\sigma_+\Gamma_-}\left(\frac{k}{\omega}\right)^5\left(\tilde C_p+\tilde C_n\right)^2|\tilde r_{\rm He}|^2\text{BR}(X\to e^+e^-)\,,$$

Axial tensor boson 2^-

Parameters not found in literature are only estimated

$r_{\rm He}$	$\tilde r_{\rm He}$	$r_{\rm C}$	$\tilde r_{\rm C}$
~ 4.6	~ 7.7	~ 5.5	~ 1

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SINDRUM constraint (1)

SINDRUM experiment [11, 12]: $\pi^+ \to e^+\nu_e(X \to e^+e^-)$

BR$(\pi^+ \to e^+\nu_e X) \times$ BR$(X \to e^+e^-) < 6.0 \times 10^{-10}$

Calculation method (from [12])

χPT framework. At lowest order:

$$U = \exp\left\{\frac{i}{f_\pi}\begin{pmatrix}\pi^0 & \sqrt{2}\pi^+ \\ \sqrt{2}\pi^- & -\pi^0\end{pmatrix}\right\} \longrightarrow \mathcal{L}_{\chi\mathrm{PT}} = \frac{f_\pi^2}{4}\mathrm{Tr}\left[(D^\mu U)^\dagger D_\mu U\right] + \frac{f_\pi^2}{4}\mathrm{Tr}\left[U^\dagger\chi + \chi^\dagger U\right]$$

Spin 2 interaction as external current $\chi_L^{\mu\nu} \to g_L \chi_L^{\mu\nu} g_L^\dagger$ and $\chi_R^{\mu\nu} \to g_R \chi_R^{\mu\nu} g_R^\dagger$

$$\begin{aligned}\mathcal{L}_{\chi\mathrm{PT}} + \Delta\mathcal{L}_{\chi\mathrm{PT}}^{\text{spin-2}} \supset\ & (\partial_\mu\pi^+)(\partial^\mu\pi^-) - m_\pi^2\pi^+\pi^- \\ & + \eta_3(C_u + C_d)X^{\mu\nu}(\partial_\mu\pi^+)(\partial_\nu\pi^-) \\ & + \frac{gf_\pi}{2}\eta_3(C_u + C_d)X^{\mu\nu}(V_{ud}W_\mu^+\partial_\nu\pi^- + V_{ud}^*W_\mu^-\partial_\nu\pi^+) \\ & - i\frac{gf_\pi}{2}\eta_2(C_u - C_d)X^{\mu\nu}(V_{ud}W_\mu^+\partial_\nu\pi^- - V_{ud}^*W_\mu^-\partial_\nu\pi^+) \\ & + i\frac{gf_\pi}{2}\eta_2(\tilde{C}_u - \tilde{C}_d)X^{\mu\nu}(V_{ud}W_\mu^+\partial_\nu\pi^- - V_{ud}^*W_\mu^-\partial_\nu\pi^+) \\ & + \frac{gf_\pi}{2}(V_{ud}W_\mu^+\partial_\nu\pi^- + V_{ud}^*W_\mu^-\partial_\nu\pi^+) + \dots\ ,\end{aligned}$$

SINDRUM constraint (2)

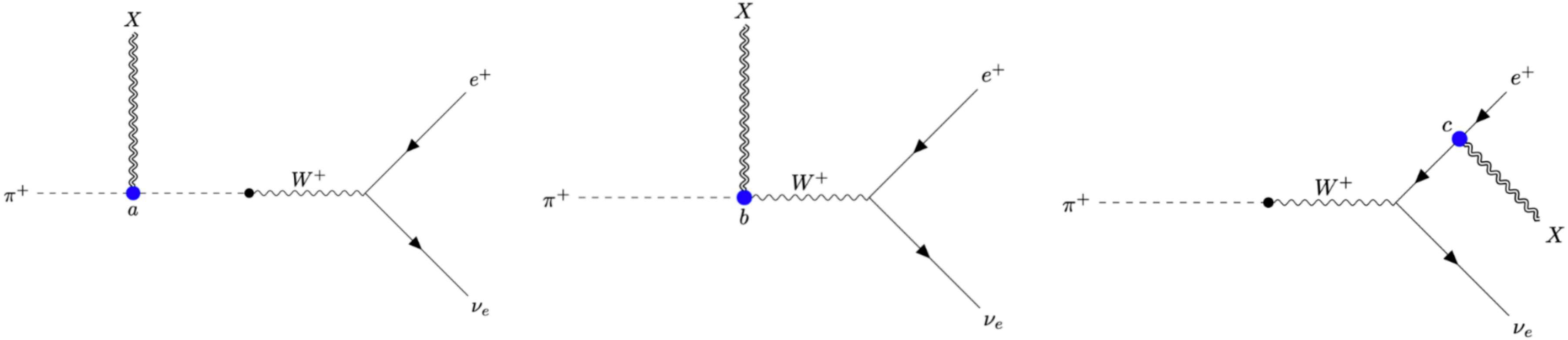

Figure 4. Diagrams of internal bremsstrahlung of the charged decay pion.

$$\mathrm{BR}(\pi^+ \to e^+\nu_e X) = \frac{m_\pi^{12}\left(10\left(\eta_2^2(C_d-C_u)^2+\eta_3^2(C_u+C_d)^2\right)+3C_e^2-10C_e\eta_3(C_u+C_d)\right)}{2^8\ 3^3\ 5\pi^2 m_\mu^2 m_X^4\left(m_\pi^2-m_\mu^2\right)^2}$$

Tensor boson 2^+

$$\mathrm{BR}(\pi^+ \to e^+\nu_e X) = \frac{m_\pi^{12}\left(10\eta_2^2(\tilde{C}_d-\tilde{C}_u)^2+3\tilde{C}_e^2\right)}{2^8\ 3^3\ 5\pi^2 m_\mu^2 m_X^4\left(m_\pi^2-m_\mu^2\right)^2}$$

Axial tensor boson 2^-

SINDRUM constraint (3)

From quark couplings to nucleon couplings

Static quark model [13].
Nucleons as quark states $|q_1 \uparrow, q_2 \uparrow, q_3 \downarrow\rangle$. Identical quarks in $J = 1$ state.

$$\left|\frac{1}{2},\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}\left|1,1;\ \frac{1}{2},-\frac{1}{2}\right\rangle - \sqrt{\frac{1}{3}}\left|1,0;\ \frac{1}{2},\frac{1}{2}\right\rangle$$

Tensor boson 2^+

$\mathcal{E} \approx m_s C_s \mathbf{1}$ Non-relativistically

$$C_p = \frac{1}{m_N}\langle p|\,\mathcal{E}\,|p\rangle = \frac{2}{3}\frac{2m_u^{\rm eff}C_u + m_d^{\rm eff}C_d}{m_N} + \frac{1}{3}\frac{2m_u^{\rm eff}C_u + m_d^{\rm eff}C_d}{m_N} = \frac{2}{3}C_u + \frac{1}{3}C_d$$

$$C_n = \frac{1}{m_N}\langle n|\,\mathcal{E}\,|n\rangle = \frac{2}{3}\frac{m_u^{\rm eff}C_u + 2m_d^{\rm eff}C_d}{m_N} + \frac{1}{3}\frac{m_u^{\rm eff}C_u + 2m_d^{\rm eff}C_d}{m_N} = \frac{1}{3}C_u + \frac{2}{3}C_d$$

Axial tensor boson 2^-

$\vec{\mathcal{P}} \approx m_s \tilde{C}_s \vec{\sigma}_s$ Non-relativistically

$$\tilde{C}_p = \frac{1}{m_N}\langle p|\,\mathcal{P}\,|p\rangle = \frac{2}{3}\frac{2m_u^{\rm eff}\tilde{C}_u - m_d^{\rm eff}\tilde{C}_d}{m_N} + \frac{1}{3}\frac{m_d^{\rm eff}\tilde{C}_d}{m_N} = \frac{4}{9}\tilde{C}_u - \frac{1}{9}\tilde{C}_d$$

$$\tilde{C}_n = \frac{1}{m_N}\langle n|\,\mathcal{P}\,|n\rangle = \frac{2}{3}\frac{-m_u^{\rm eff}\tilde{C}_u + 2m_d^{\rm eff}\tilde{C}_d}{m_N} + \frac{1}{3}\frac{m_u^{\rm eff}\tilde{C}_u}{m_N} = -\frac{1}{9}\tilde{C}_u + \frac{4}{9}\tilde{C}_d$$

$$\mathrm{BR}(\pi^+ \to e^+\nu_e X) = \frac{m_\pi^{12}\left(90\left(\eta_2^2(C_p - C_n)^2 + \eta_3^2(C_p + C_n)^2\right) + 3C_e^2 + 10C_e\eta_3(C_p + C_n)\right)}{2^8\ 3^3\ 5\pi^2 m_\mu^2 m_X^4\left(m_\pi^2 - m_\mu^2\right)^2}$$

Tensor boson 2^+

$$\mathrm{BR}(\pi^+ \to e^+\nu_e X) = \frac{m_\pi^{12}\left(54\eta_2^2(\tilde{C}_p - \tilde{C}_n)^2 + 5\tilde{C}_e^2\right)}{2^8\ 3^2\ 5^2\pi^2 m_\mu^2 m_X^4\left(m_\pi^2 - m_\mu^2\right)^2}$$

Axial tensor boson 2^-

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- **Spin parity 0^+ hypothesis**
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Spin 2 boson exclusion plots

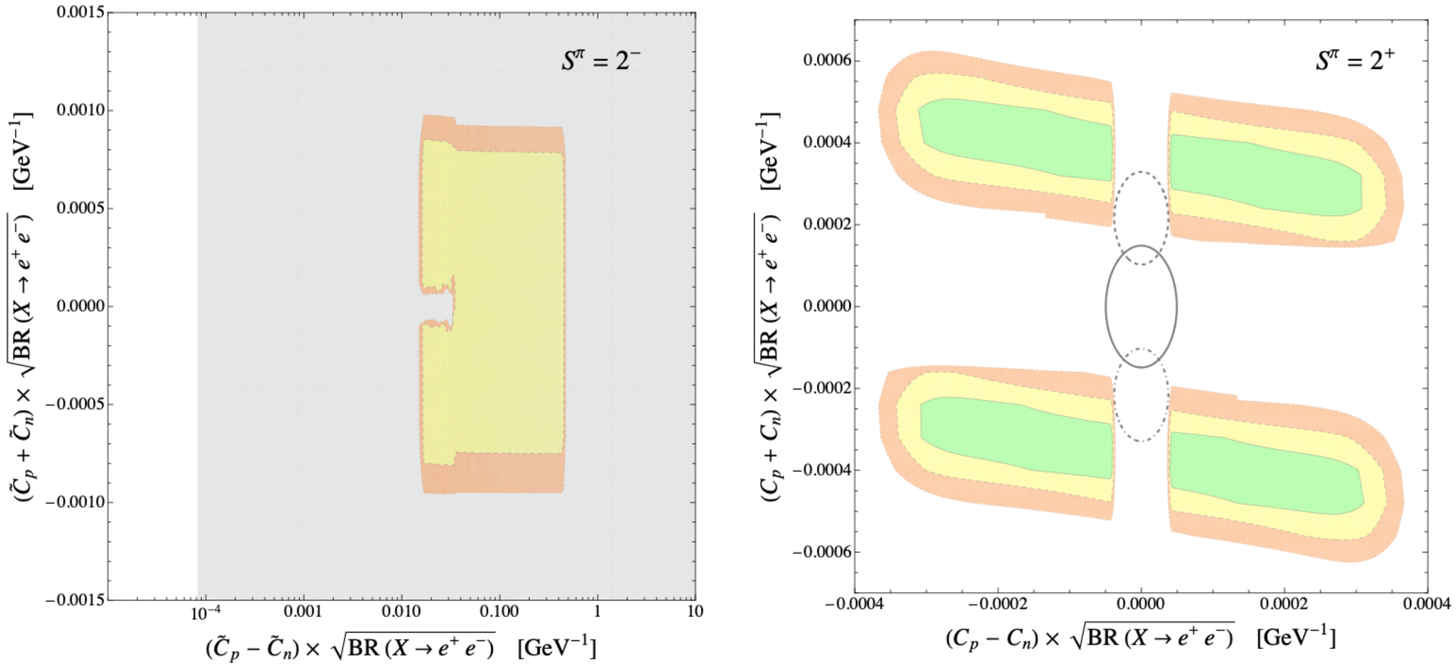

Figure 2. *Left panel:* Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\mathrm{profiled}} < 2.28, 5.99, 11.62$, for an axial tensor boson. The gray region is excluded by SINDRUM search. *Right panel:* Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\mathrm{profiled}} < 2.28, 5.99, 11.62$, for a tensor boson. The regions outside the solid, dashed and dot-dashed gray lines are excluded by the SINDUM search at 90% CL respectively for $C_e = 0$, $C_e = -0.001$ GeV^{-1} and $C_e = 0.001$ GeV^{-1}.

At least at 3σ exclusion for both models!

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Lagrangian for 0^+

At renormalizable level

$$\mathcal{L}_{\rm int}^{d\leq 4} = z_p \bar{p} p X + z_n \bar{n} n X + z_e \bar{e} e X$$

Photon coupling is effective

$$\mathcal{L}_{\rm int}^{d=5} = \frac{\alpha}{8\pi} \frac{X}{f_\gamma} F_{\mu\nu} F^{\mu\nu}$$

Only relevant couplings are z_e, z_p, z_n.
No neutrino couplings.

Decay rate

$$\Gamma = \Gamma(X \to e^+ e^-) = \frac{z_e^2 m_X}{8\pi} \left(1 - \frac{4m_e^2}{m_X^2}\right)^{3/2}$$

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Signal and constraints

Prompt decay in Atomki

Geometrical constraint for decay rate in Atomki apparatus

$$\Gamma \geq 1.3 \times 10^{-4}\ \text{eV} \longrightarrow |z_e| \geq 1.4 \times 10^{-5}$$

$g-2$ of electron [14]

$$\delta a_e^{\text{BSM}} \approx \frac{z_e^2}{4\pi^2}\frac{m_e^2}{m_X^2}\left[\ln\frac{m_X}{m_e} - \frac{7}{12}\right] \longrightarrow |z_e| \leq 10^{-4}$$

Atomki observables [5]

Same method already described

$$R_{\text{He}} = \frac{1}{\alpha^2}\frac{15}{8}\left(\frac{k}{\omega}\right)^5 (z_p + z_n)^2 \left|1 + 3r_{\text{He}}\right|^2 \text{BR}(X \to e^+e^-) ,$$

$$R_{\text{C}} = \left(\frac{k}{\omega}\right)^3 \frac{(z_p - z_n)^2}{8\pi\alpha_e}\text{BR}(X \to e^+e^-) ,$$

SINDRUM constraint (1)

χPT framework. Spin 0 boson included in $\chi = 2B_0(s + ip)$

$$s + ip = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix} - X \begin{pmatrix} z_u & 0 \\ 0 & z_d \end{pmatrix}$$

Need $\mathcal{O}(p^4)$ Lagrangian [15]

$$\begin{aligned}
\mathcal{L}_{\chi\mathrm{PT}}^{\mathrm{NLO}} =& L_1 \mathrm{Tr}\left[D_\mu U^\dagger D^\mu U\right]^2 + L_2 \mathrm{Tr}\left[D_\mu U^\dagger D_\nu U\right] \mathrm{Tr}\left[D^\mu U^\dagger D^\nu U\right] \\
&+ L_3 \mathrm{Tr}\left[D_\mu U^\dagger D^\mu U D_\nu U^\dagger D^\nu U\right] + L_4 \mathrm{Tr}\left[D_\mu U^\dagger D^\mu U\right] \mathrm{Tr}\left[U^\dagger \chi + \chi^\dagger U\right] \\
&+ L_5 \mathrm{Tr}\left[D_\mu U^\dagger D^\mu U (U^\dagger \chi + \chi^\dagger U)\right] + L_6 \mathrm{Tr}\left[U^\dagger \chi + \chi^\dagger U\right]^2 \\
&+ L_7 \mathrm{Tr}\left[U^\dagger \chi - \chi^\dagger U\right]^2 + L_8 \mathrm{Tr}\left[U^\dagger \chi U^\dagger \chi + \chi^\dagger U \chi^\dagger U\right] + \dots \, ,
\end{aligned}$$

After NLO corrections to kinetic term and m_π

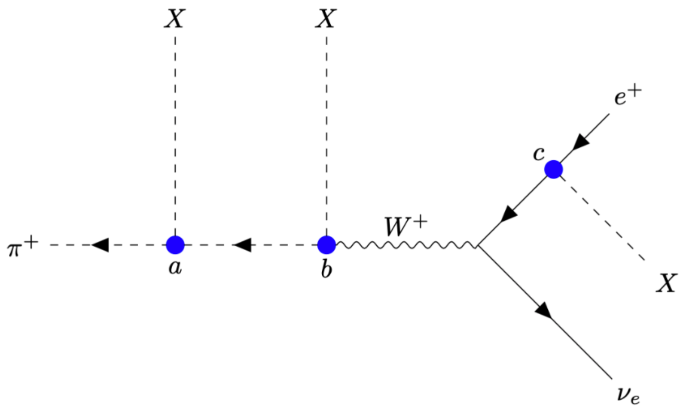
$$\begin{aligned}
\mathcal{L}_{\chi\mathrm{PT}} + \mathcal{L}_{\chi\mathrm{PT}}^{\mathrm{NLO}} \,|_{\mathrm{rescaled}} \supset \;& (\partial_\mu \pi^+)(\partial^\mu \pi^-) - m_\pi^2 \pi^+ \pi^- \\
&+ (1 + \delta_1) m_\pi^2 \frac{z_u + z_d}{m_u + m_d} X \pi^+ \pi^- \\
&- 2\delta_2 \frac{z_u + z_d}{m_u + m_d} X (\partial_\mu \pi^+)(\partial^\mu \pi^-) \\
&- \delta_2 g f_\pi \frac{z_u + z_d}{m_u + m_d} X (V_{ud} W_\mu^+ \partial^\mu \pi^- + V_{ud}^* W_\mu^- \partial^\mu \pi^+) \\
&+ \frac{g f_\pi}{2} (1 + \delta_2)(V_{ud} W_\mu^+ \partial_\nu \pi^- + V_{ud}^* W_\mu^- \partial_\nu \pi^+) + \dots \, ,
\end{aligned}$$

$$\delta_1 = 16 \frac{m_\pi^2}{f_\pi^2} \left[2L_6(m_\pi) + L_8(m_\pi)\right]$$

$$\delta_2 = 4 \frac{m_\pi^2}{f_\pi^2} \left[2L_4(m_\pi) + L_5(m_\pi)\right]$$

SINDRUM constraint (2)

Same diagrams as in spin 2



Final result

$$\Gamma(\pi^+ \to e^+\nu_e X) = \frac{G_F^2 f^2 |V_{ud}|^2 m_\pi^3}{32(2\pi)^3}\left[(z_u+z_d)^2 F_1 + z_e(z_u+z_d)F_2 + z_e^2 F_3\right]$$

$$F_1 \cong 0.024 \qquad F_2 \cong -0.143 \qquad F_3 \cong 0.676$$

Derivation of z_p, z_n from z_u, z_d described in [5].

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0^+ boson exclusion plots

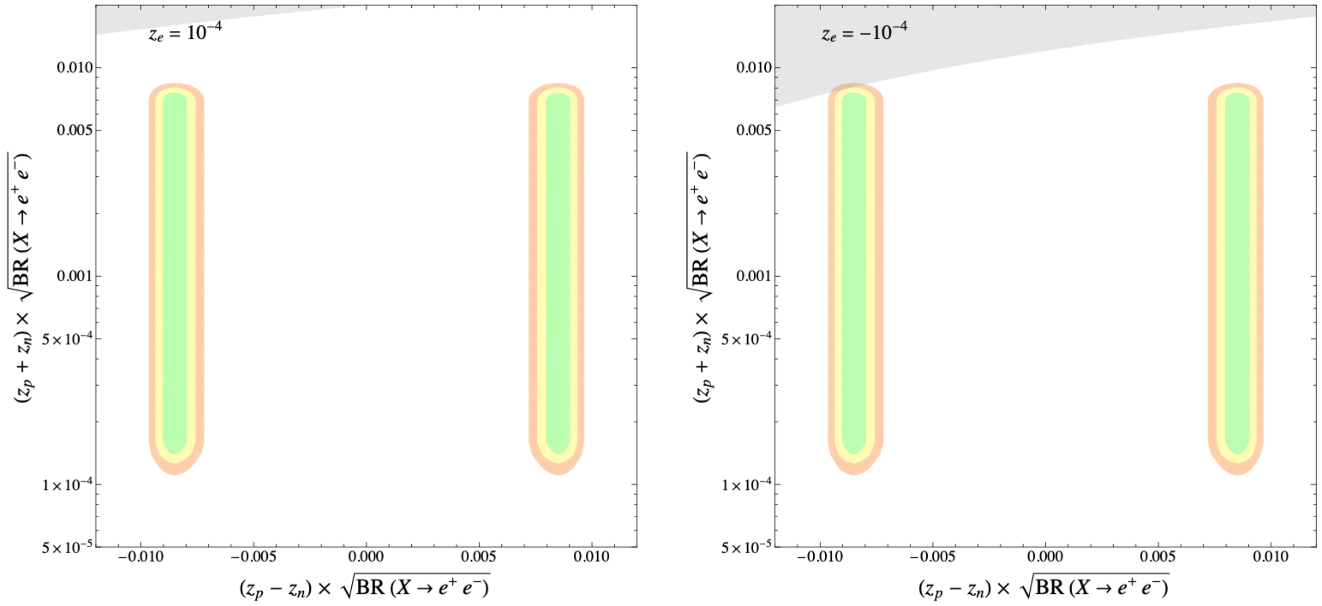

Figure 3. Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\text{profiled}} < 2.28, 5.99, 11.62$, for a scalar boson. The gray region is excluded by SINDRUM search fixing $z_e = 10^{-4}$ (left panel) and $z_e = -10^{-4}$ (right panel).

0^+ hypothesis works if MEG-II excludes Beryllium anomaly

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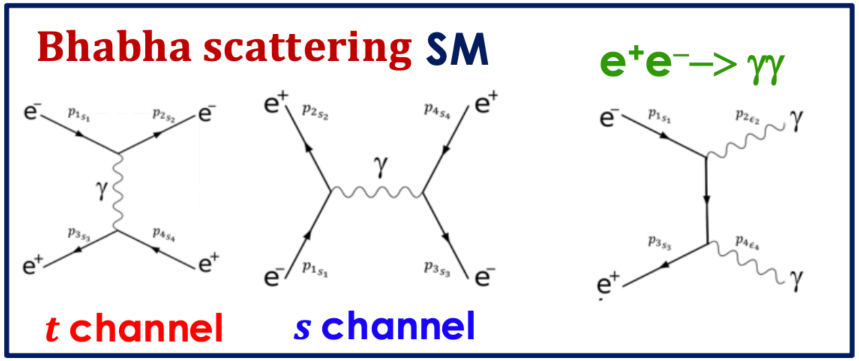
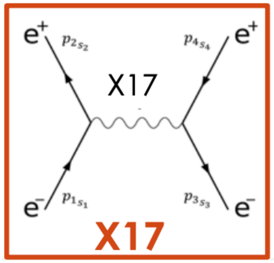
PADME's (unexpected) result

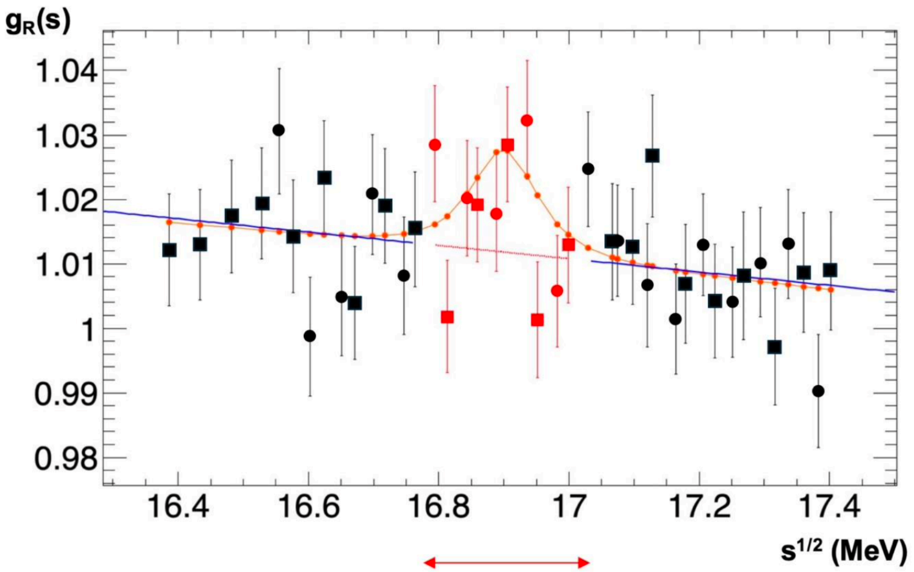
[1] **PADME** Collab., ***JHEP* 08 (2024) 121**
[2] **PADME** Collab., ***2505.24797***

Positron beam against diamond target apparatus [1, 2]:





BSM



Region masked by automatic procedure

PADME announced a local 2.5σ excess at 17 MeV at LDMA (April 2025)

Courtesy of Mauro Raggi

Conclusion

“X17 is dead! Long live X17!”

(Claudio Toni)

Excesses compatible X17 are observed left and right

BUT

No phenomenological model works so far

References (1)

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[9] P. B. Denton, J. Gehrlein (2023), "Neutrino Constraints and the ATOMKI X17 Anomaly". Phys. Rev. D 108 (2023), no. 1 015009, arXiv:2304.09877.

[10] G. Panico, L. Vecchi, A. Wulzer (2016), "Resonant Diphoton Phenomenology Simplified". JHEP 06 (2016) 184, arXiv:1603.04248.

References (2)

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[13] http://webusers.fis.uniroma3.it/ ceradini/dispense.pdf.

[14] F. Jegerlehner, A. Nyffeler (2009), “Muon g-2”. Phys. Rept. 477 (2009) 1–110, arXiv:0902.3360.

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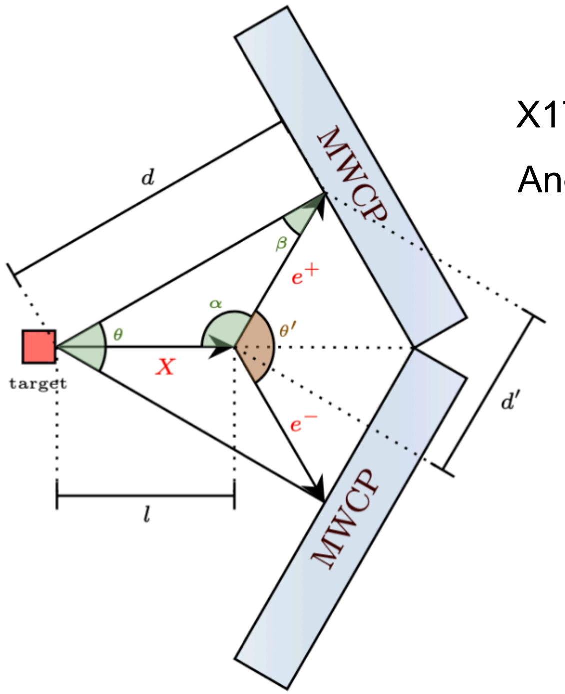
Thanks for your attention!

Additional material

Prompt decay in Atomki



X17 measured mass dependent on true angular opening θ'

Angular resolution: $\Delta\theta_{\text{exp}} = 2^\circ$ ⟶ $\Delta\theta = \theta' - \theta < \Delta\theta_{\text{exp}}$

Constraint on length l ⟶ Constraint on width Γ

Helium experiment most constraining:

$$\Gamma \geq 1.3 \times 10^{-4} \text{ eV}$$

By comparison, mean lifetime of:

- J/ψ: $\Gamma = 92.6$ keV
- B meson: $\Gamma = 4.1 \times 10^{-4}$ eV
- Muon: $\Gamma = 3.0 \times 10^{-10}$ eV

Total decay width:

$$\Gamma = \Gamma(X \to e^+e^-) + \Gamma(X \to \gamma\gamma) \geq 1.3 \times 10^{-4} \text{ eV}$$

How to build a massive spin 2 model

1. Choice of notation

Pauli notation

- Metric: $\delta_{\mu\nu} = \text{diag}(1,1,1,1)$
- Imaginary time: $p_\mu = (\vec{p}, ip_4)$
- Hermitian gamma matrices

→ FORM tool for algebraic manipulations

2. Free Lagrangian

Fierz - Pauli Lagrangian [7]:

$$\mathcal{L} = \frac{1}{2}\partial_\mu X_{\nu\rho}\,\partial_\mu X_{\nu\rho} + \frac{m_X^2}{2} X_{\nu\rho}\,X_{\nu\rho}$$

$X_{\mu\nu}$ symmetric, traceless field tensor.

3. Free propagator

Sum over polarisations:

$$\sum_{\lambda=1}^{5} \varepsilon_{\mu\nu}(\vec{k},\lambda)\,\varepsilon^*_{\rho\sigma}(\vec{k},\lambda) = \frac{1}{2}\left(P_{\mu\rho}P_{\nu\sigma} + P_{\mu\sigma}P_{\nu\rho}\right) - \frac{1}{3}P_{\mu\nu}P_{\rho\sigma} = N_{\mu\nu\rho\sigma}(k)$$

$$\text{where} \quad P_{\mu\nu}(k) = \delta_{\mu\nu} + \frac{k_\mu k_\nu}{m_X^2}$$

Momentum space propagator:

$$D_{\mu\nu\rho\sigma}(p) = \frac{N_{\mu\nu\rho\sigma}(p)}{p^2 + m_X^2 - i\epsilon}$$

How to build a spin 2 EFT

4. Interacting Lagrangian

$$\mathcal{L}_{\text{matter}} = \frac{1}{\Lambda} X_{\mu\nu} T_{\mu\nu} \longrightarrow T_{\mu\nu} = \frac{\partial \mathcal{L}}{\partial\left(\partial_\mu \phi_i\right)} \partial_\nu \phi_i - \delta_{\mu\nu} \mathcal{L}$$

Dimensional coupling

Stress-energy tensor

Coupling to electrons and photons:

$$\mathcal{L} = X_{\mu\nu} \left[-\frac{1}{\Lambda_\gamma} F_{\mu\alpha} F_{\nu\alpha} + \frac{1}{\Lambda_e} \bar{\psi} \gamma_\mu \partial_\nu \psi \right] = \frac{1}{\Lambda_\gamma} X_{\mu\nu} T^{\gamma}_{\mu\nu} + \frac{1}{\Lambda_e} X_{\mu\nu} T^{e}_{\mu\nu}$$

5. Cutoff energy Λ_c

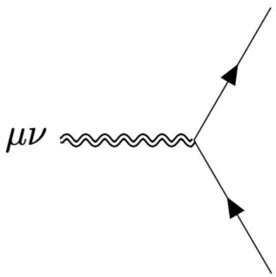
Only dimensional quantity is mass of X17 m_X $\longrightarrow$ $\Lambda_c = k m_X$ with $2 < k < 4\pi$

$\Lambda_c \sim 100$ MeV

6. Finite width Γ effects

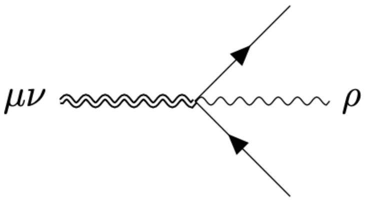
$$D_{\mu\nu\rho\sigma}(p) = \frac{N_{\mu\nu\rho\sigma}(p)}{p^2 + m_X^2 - i m_X \Gamma}$$

Feynman rules



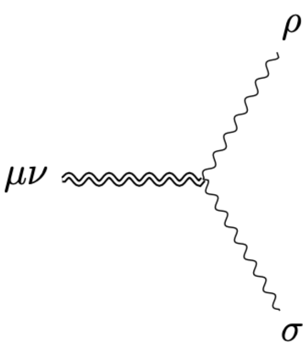
$$= \frac{i}{4\Lambda_e}\left[\gamma_\mu\left(k_\nu^- - k_\nu^+\right) + \gamma_\nu\left(k_\mu^- - k_\mu^+\right)\right]$$

$k_\mu^\pm$ outward fermion momenta



$$= \frac{-ie}{2\Lambda_e}\left[\gamma_\mu\,\delta_{\nu\rho} + \gamma_\nu\,\delta_{\mu\rho}\right]$$

From covariant derivative



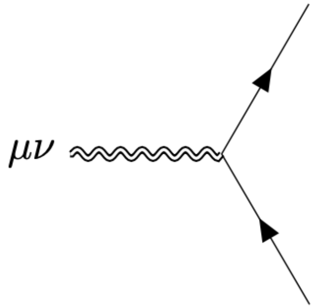
$$= \frac{1}{\Lambda_\gamma}\,\Pi^\xi_{\mu\nu\rho\sigma}(k_1, k_2)$$

$$\begin{aligned}\Pi^\xi_{\mu\nu\rho\sigma}(k_1,k_2) = {}& \delta_{\rho\sigma}\,\left(k_{1,\mu}\,k_{2,\nu} + k_{1,\nu}\,k_{2,\mu}\right) - \delta_{\mu\rho}\,k_{1,\sigma}\,k_{2,\nu} - \delta_{\mu\sigma}\,k_{1,\nu}\,k_{2,\rho} \\ & - \delta_{\nu\sigma}\,k_{1,\mu}\,k_{2,\rho} - \delta_{\nu\rho}\,k_{1,\sigma}\,k_{2,\mu} + k_1\cdot k_2\,\left(\delta_{\mu\sigma}\,\delta_{\nu\rho} + \delta_{\nu\sigma}\,\delta_{\mu\rho}\right) \\ & + \frac{1}{\xi}\left[-\delta_{\mu\rho}\,k_{2,\sigma}\,k_{2,\nu} - \delta_{\mu\sigma}\,k_{1,\nu}\,k_{1,\rho} - \delta_{\nu\sigma}\,k_{1,\mu}\,k_{1,\rho} - \delta_{\nu\rho}\,k_{2,\sigma}\,k_{2,\mu}\right]\end{aligned}$$

ξ gauge parameter

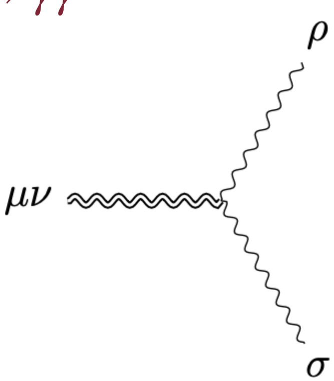
Decay rates [8]

$X \to e^+e^-$



$$\Gamma(X \to e^+e^-) = \frac{1}{\Lambda_e^2}\frac{m_X^3}{160\pi}\left[1 - \frac{4m_e^2}{m_X^2}\right]^{3/2}\left[1 + \frac{8}{3}\frac{m_e^2}{m_X^2}\right]$$

$X \to \gamma\gamma$



$$\Gamma(X \to \gamma\gamma) = \frac{1}{\Lambda_\gamma^2}\frac{m_X^3}{80\pi}$$

FORM tool for algebraic manipulations

For this thesis, FORM tool was used.
User's manual can be found here.

All codes can be found in this GitHub repository.

FORM employs **Pauli notation**

Example: $e^+e^- \to \mu^+\mu^-$ squared matrix element:

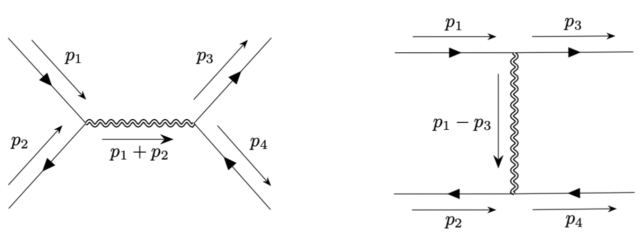
```
Vectors k1, k2, p1, p2;
Symbols s, t, u, e;
Indices mu, nu, rho, sigma;
*
Local   M2 =
*       electron line
          e^2 * g_(1, k1, rho, k2, sigma) *
*       photon propagator
          d_(rho,mu) * d_(sigma,nu) / s^2 *
*       muon spin line
          e^2 * g_(2, p1, mu, p2, nu)
        ;
Trace4,1;
Trace4,2;
```

```
id k1.k2 = s/2;
id p1.p2 = s/2;
id k1.p1 = -t/2;
id k2.p2 = -t/2;
id k1.p2 = -u/2;
id k2.p1 = -u/2;
Bracket e,s;
Print;
.end
```

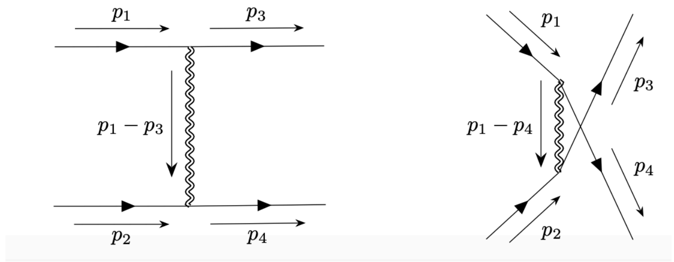
```
M2 =
    + s^-2*e^4 * ( 8*t^2 + 8*u^2 );
```

Diagrams for X17 mediated QED processes

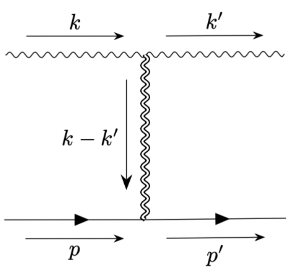
Tree level diagrams for the following processes:



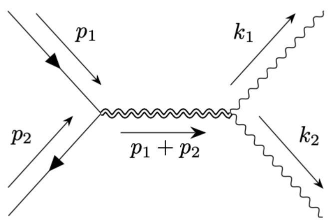
Bhabha scattering



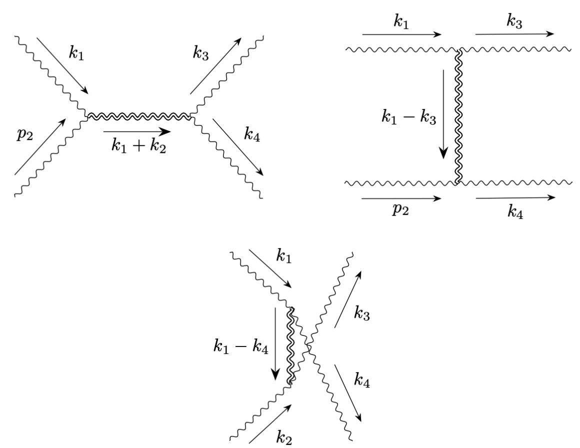
Møller scattering



Compton scattering



Annihilation into
Two photons



Photon-photon elastic scattering

Constraining cross sections → **Constraining couplings**

Example result: Bhabha scattering

$$
\begin{aligned}
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\Bigg\{ & \frac{1}{s^2}\left[u^2+t^2-8m_e^2(u+t)+24m_e^4\right]+\frac{1}{t^2}\left[u^2+s^2-8m_e^2(u+s)+24m_e^4\right]+\frac{2}{st}\left[u^2-8m_e^2u+12m_e^4\right]\Bigg\} \\
+\frac{\alpha}{\pi}\frac{1}{48\Lambda_e^2}\frac{1}{s}\Bigg\{ & \left(\frac{t-u}{s}\right)\frac{s-m_X^2}{\left(s-m_X^2\right)^2+m_X^2\Gamma^2}\left[ut+\left(s+4m_e^2\right)\left(s-4m_e^2\right)\right] \\
& +\left(\frac{s-u}{t}\right)\frac{t-m_X^2}{\left(t-m_X^2\right)^2+m_X^2\Gamma^2}\left[us+\left(t+4m_e^2\right)\left(t-4m_e^2\right)\right] \\
& +\frac{s-m_X^2}{t\left[\left(s-m_X^2\right)^2+m_X^2\Gamma^2\right]}\left[u^2(s-t)+10m_e^2ut-6m_e^2\left(s-2m_e^2\right)\left(s-6m_e^2\right)-24m_e^6\right] \\
& +\frac{t-m_X^2}{s\left[\left(t-m_X^2\right)^2+m_X^2\Gamma^2\right]}\left[u^2(t-s)+10m_e^2us-6m_e^2\left(t-2m_e^2\right)\left(t-6m_e^2\right)-24m_e^6\right]\Bigg\} \\
+\frac{1}{4608\pi^2\Lambda_e^4\,s}\Bigg\{ & \frac{(s-4m_e^2)^4+2u^2t^2+4m_e^2\left(s-4m_e^2\right)\left[2(s-4m_e^2)^2+ut\right]+48m_e^4\left[(s-4m_e^2)^2-ut\right]}{\left(s-m_X^2\right)^2+m_X^2\Gamma^2} \\
& +\frac{(t-4m_e^2)^4+2u^2s^2+4m_e^2\left(t-4m_e^2\right)\left[2(t-4m_e^2)^2+us\right]+48m_e^4\left[(t-4m_e^2)^2-us\right]}{\left(t-m_X^2\right)^2+m_X^2\Gamma^2} \\
& +\frac{-2u\left(s-m_X^2\right)\left(t-m_X^2\right)\left[u(u+2s)^2-2m_e^2\left(s^2+9us+2u^2\right)+8m_e^4(2u+s)\right]}{\left[\left(s-m_X^2\right)^2+m_X^2\Gamma^2\right]\left[\left(t-m_X^2\right)^2+m_X^2\Gamma^2\right]}\Bigg\} \qquad (1.4)
\end{aligned}
$$

→ QED result (first line)

→ Interference QED - spin 2 correction (second group of terms)

→ Spin 2 squared modulus (third group of terms)

$s = -(p_1+p_2)^2 \quad t = -(p_1-p_2)^2 \quad u = -(p_1-p_4)^2$ → Mandelstam variables

Resulting cross sections

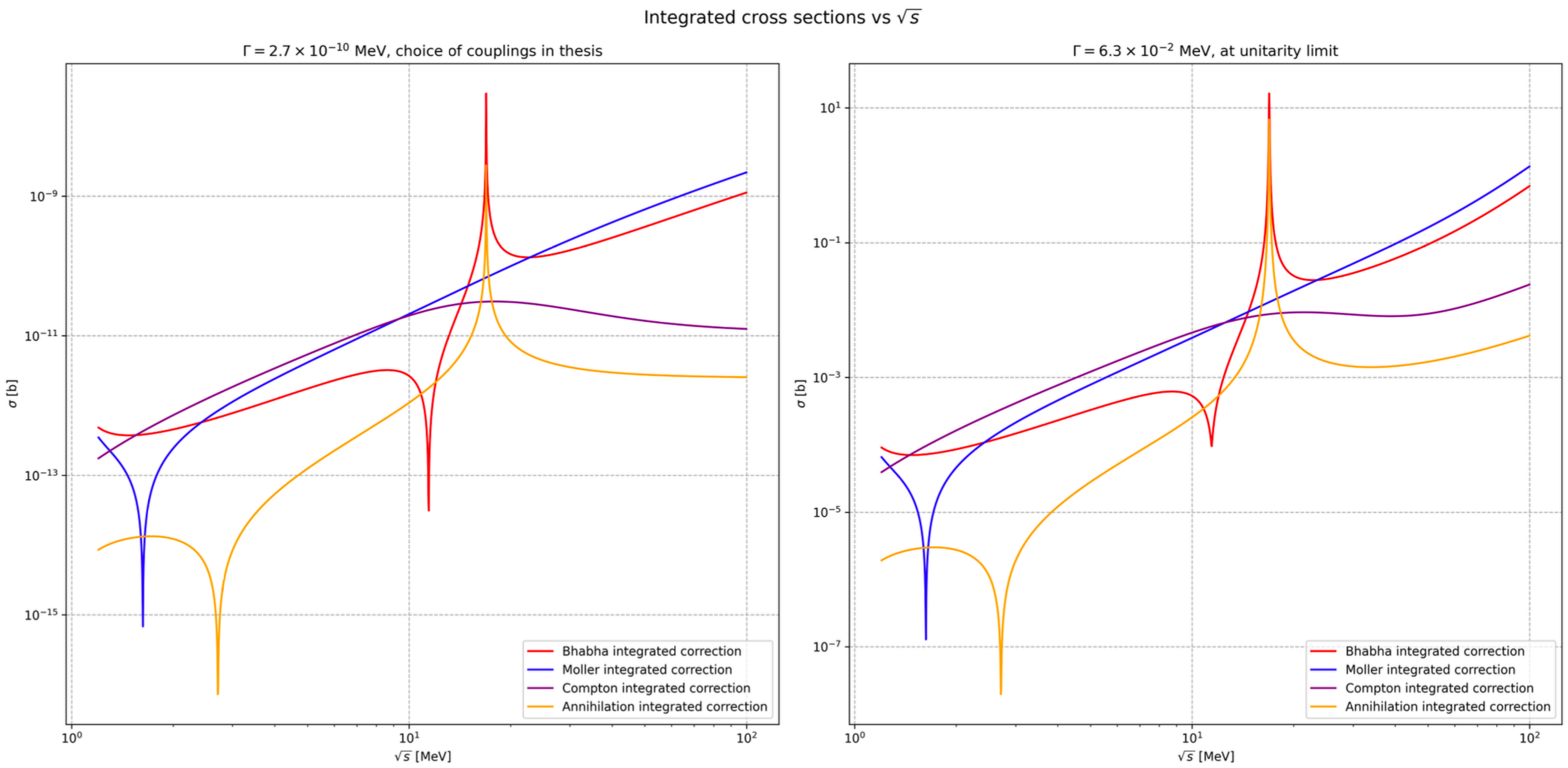
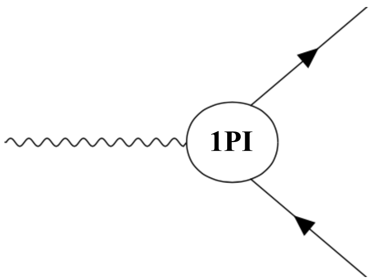


Figure 27: Graph of behavior of absolute value of integrated cross sections, for all processes, from 1.2 MeV to 100 MeV, for different values of Γ, as function of $\sqrt{s}$. Graphs are in log scale. On the left, $1/\Lambda_e = 3.8 \times 10^{-6}\,\mathrm{MeV}^{-1}$ and $1/\Lambda_\gamma = 2.7 \times 10^{-6}\,\mathrm{MeV}^{-1}$ are assumed. On the right, $1/\Lambda_e = 5.2 \times 10^{-2}\,\mathrm{MeV}^{-1}$ and $1/\Lambda_\gamma = 4.4 \times 10^{-2}\,\mathrm{MeV}^{-1}$ are assumed. Different choices of couplings scale cross sections differently.

Other constraints: $g-2$ of electron

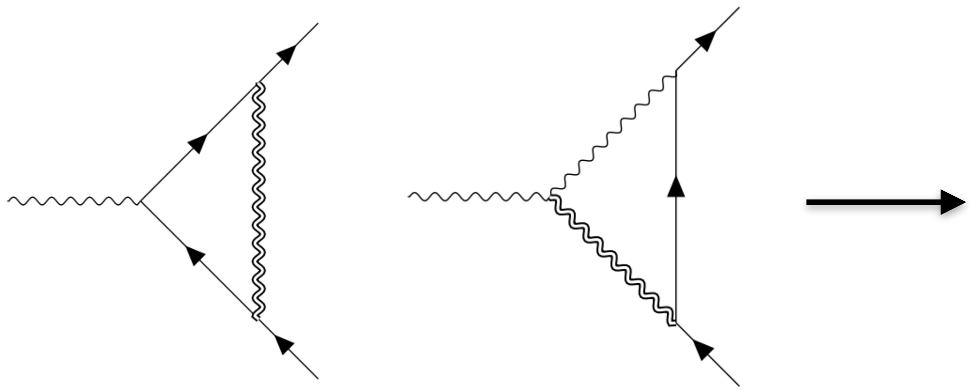
Gyromagnetic ratio of the electron: $\gamma = \frac{|\vec{\mu}|}{|\vec{L}|} = \frac{g_e e}{2m_e}$

QED prediction from vertex correction:



g_e one of the most precise measurements in physics [9]: $a_e = \frac{g_e - 2}{2} = 0.001\,159\,652\,180\,73\,(28)$

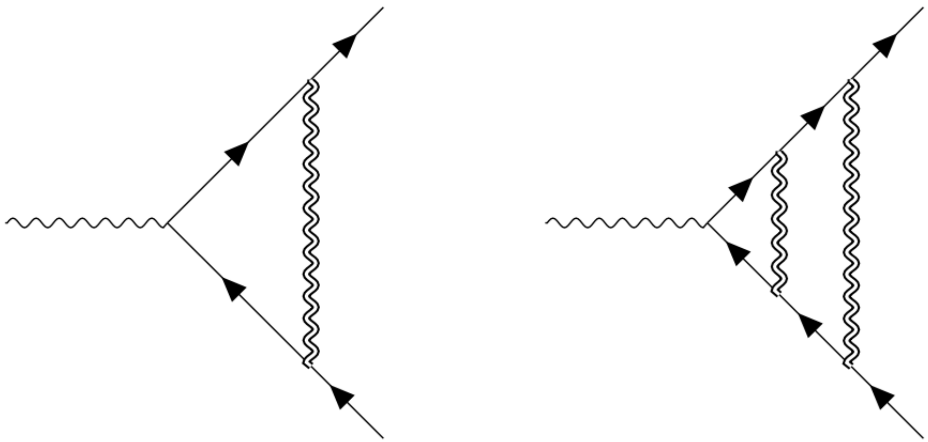
Affected in our EFT at loop level [10]:



$$\delta a_e = \frac{m_e^2}{48\pi^2}\left(\frac{\Lambda_c}{m_X}\right)^4 \frac{1}{\Lambda_e}\left(\frac{1}{\Lambda_e} - \frac{2}{\Lambda_\gamma}\right)$$

Other constraints: Perturbativity

Spin 2 model must be *perturbative*!



$$\Delta a_e^{(1)} \approx \frac{1}{16\pi^2}\frac{m_e^2}{\Lambda_e^2}\frac{\Lambda_c^4}{m_X^4} \qquad \Delta a_e^{(2)} \approx \left(\frac{1}{16\pi^2}\right)^2 \frac{m_e^2}{\Lambda_e^4}\frac{\Lambda_c^{10}}{m_X^8}$$

If $\Lambda_c = k m_X$

$$\boldsymbol{k = 4\pi:} \qquad \frac{1}{\Lambda_e}, \frac{1}{\Lambda_\gamma} < 3.7 \times 10^{-4}\,\mathrm{MeV}^{-1}$$

$$\boldsymbol{k = 2:} \qquad \frac{1}{\Lambda_e}, \frac{1}{\Lambda_\gamma} < 9.3 \times 10^{-2}\,\mathrm{MeV}^{-1}$$

Other constraints: Unitarity

Spin 2 model must be *unitary*! ⟶ S matrix must be unitary: $\mathbb{1} = S^\dagger S = \mathbb{1} - i(T^\dagger - T) + T^\dagger T$

1 - Unitarity implies optical theorem. Taking a, b initial and final state:

$$-i\left[\mathcal{M}_{ba} - (\mathcal{M})^\dagger_{ba}\right] \geq \sum_c \frac{2^{-\delta_c}|\vec{q}_c|}{16\pi^2\sqrt{s}} \int d\Omega_c \, \mathcal{M}_{ca} \, \mathcal{M}^*_{cb}$$

2 - Expanding amplitudes in partial waves: $\mathcal{M}_{ba} = 16\pi \sum_{J=0}^{\infty} (2J+1)\, P_J(z_b)\, \hat{a}^J_{ba}(s)$

$$-\frac{i}{2}\left[a^J_{ba} - a^{\dagger J}_{ba}\right] \geq a^J_{ca}\, a^{*J}_{cb} = a^{\dagger J}_{bc}\, a^J_{ca} = \left(a^\dagger a\right)^J_{ba} \longrightarrow \mathrm{Im}(a^J_i) \geq |a^J_i|^2 = \mathrm{Re}(a^J_i)^2 + \mathrm{Im}(a^J_i)^2$$

3 - Choosing $i = 0$: Unitarity constraint

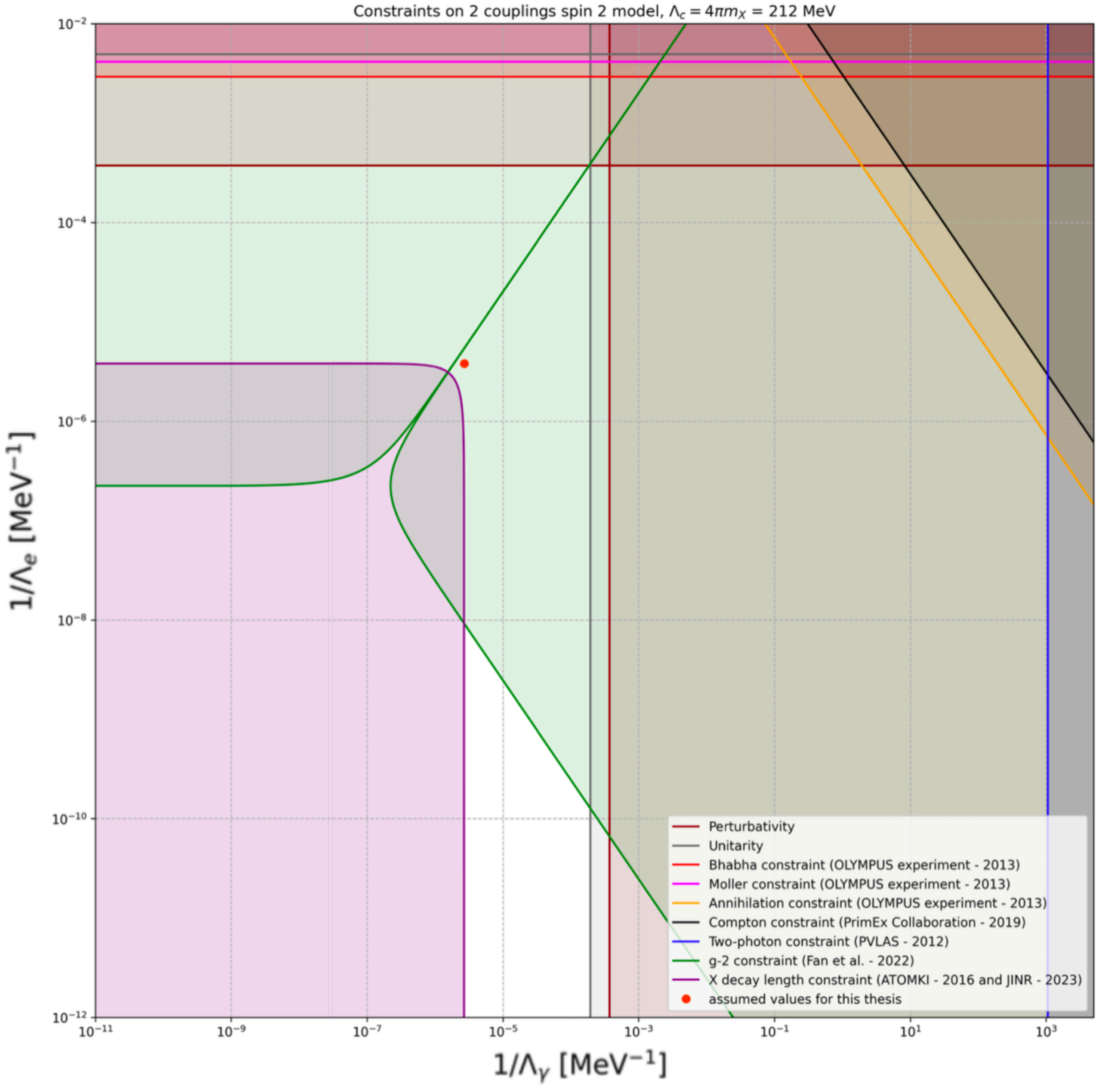
$$\mathrm{Re}\left[a_0(\sqrt{s})\right] \leq \frac{1}{2}$$

4 - Applying this constraint to $e^+e^- \to e^+e^-$ binds Λ_e^{-1}

5 - Applying this constraint to $\gamma\gamma \to \gamma\gamma$ binds Λ_γ^{-1}

Put all constraints together!

Spin 2 model exclusion plot



Best experimental result constraining each process.

Center of mass energy $\sqrt{s} < \Lambda_c$

Valid parameter region is white

Best constraints:

- Decay length (purple)
- Unitarity constraint (gray)
- Electron $g-2$ (green)