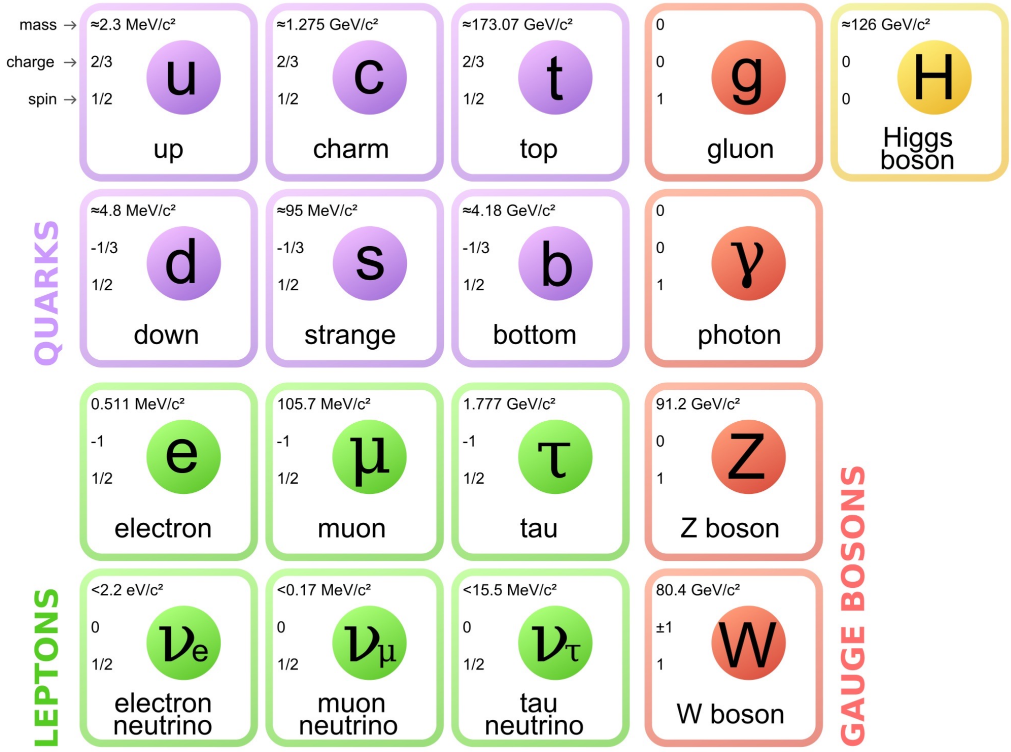
The X17 from the Atomki anomalies to the recent PADME result

Claudio Toni

IP2I Seminar, 17/06/2025

Life beyond the SM? The X17



Life beyond the SM? The X17

PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

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

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
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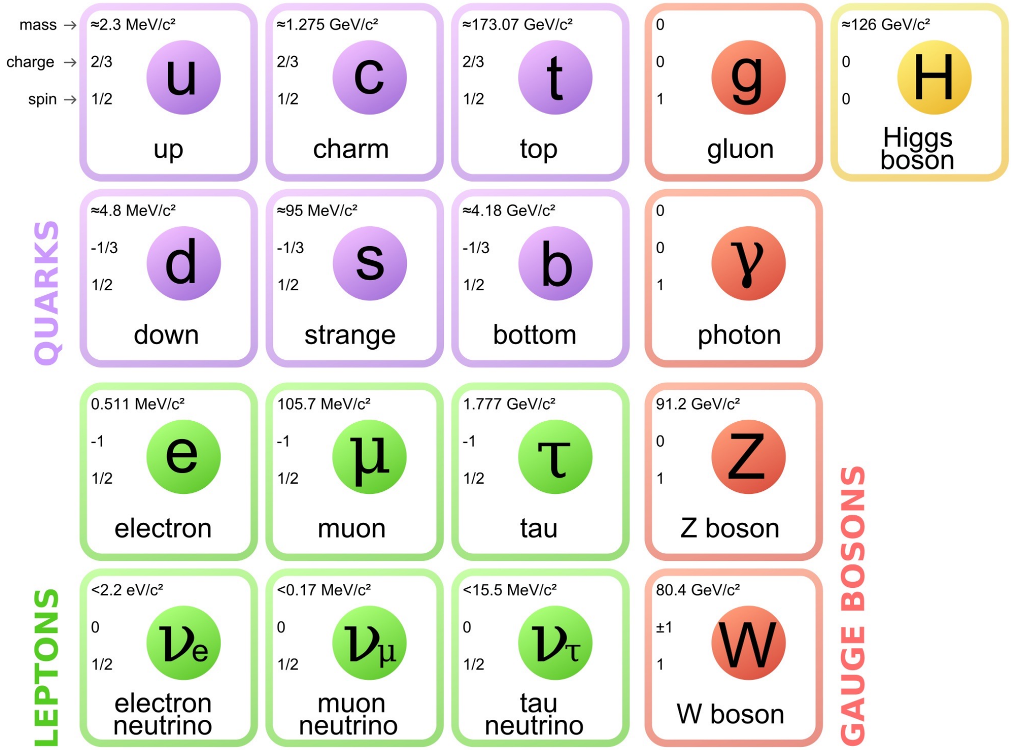
(Received 7 April 2015; published 26 January 2016)

Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\mathrm{stat}) \pm 0.5(\mathrm{syst})$ MeV/c^2 and $J^\pi = 1^+$ was created.



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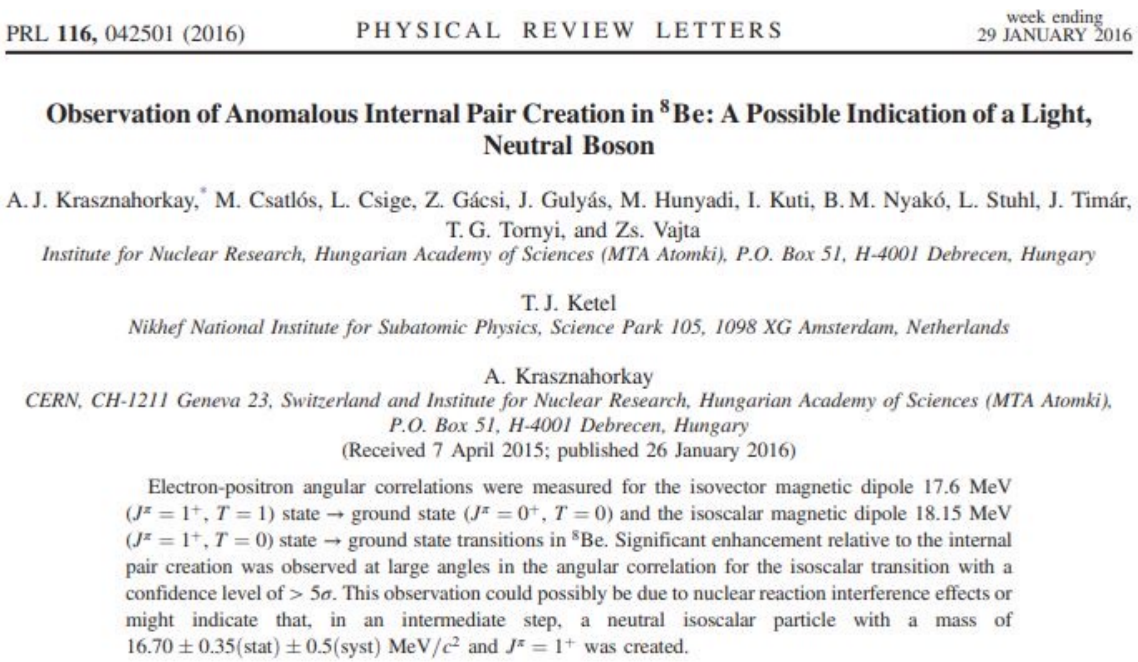
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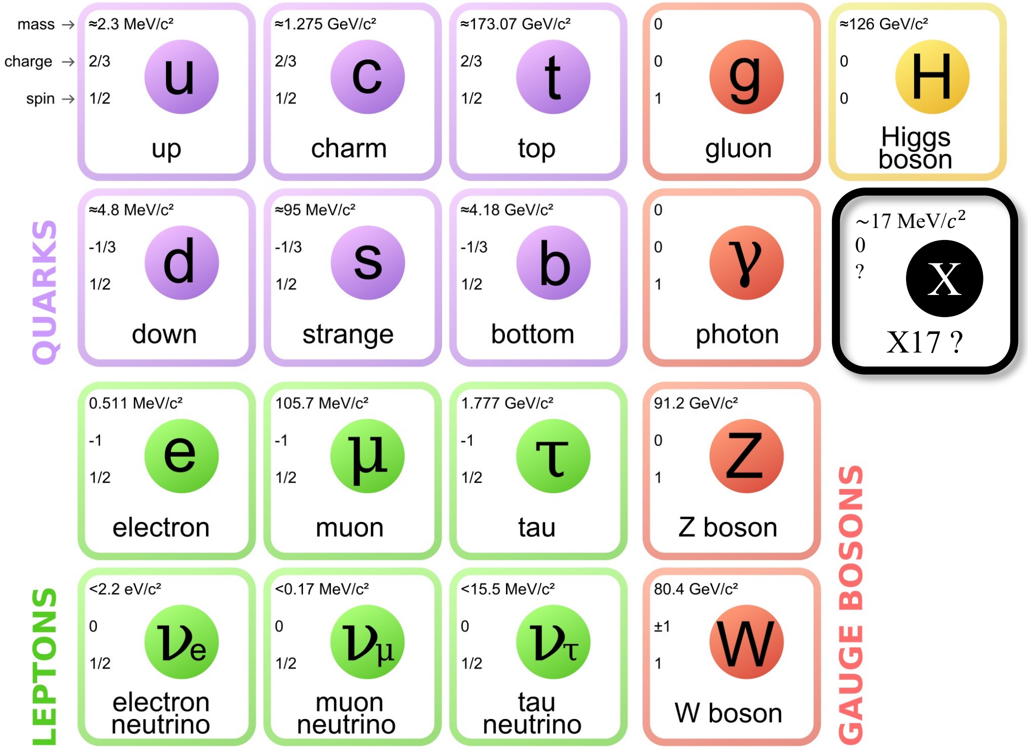

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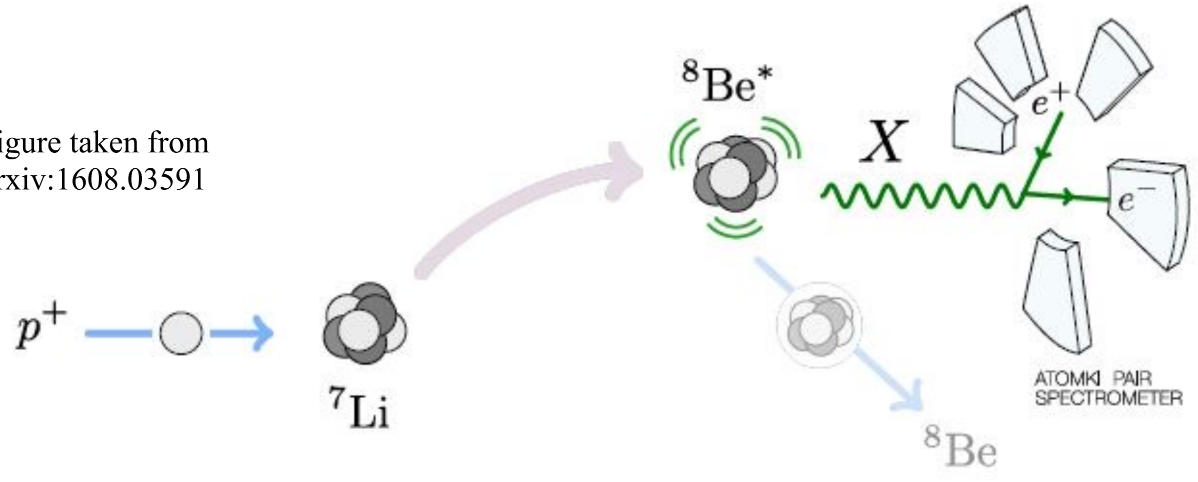
ATOMKI search

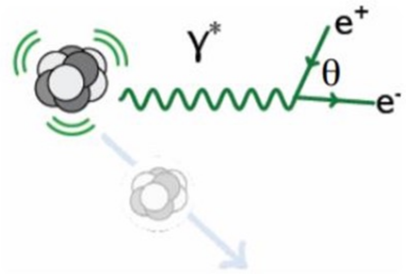
ATOMKI proposal: looking for New Physics at the MeV scale trough nuclear transitions!

Figure taken from
arxiv:1608.03591



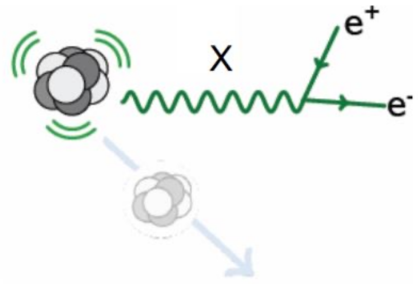
Energy released in nuclear transitions is $O(1-10)$ MeV

QED processes:



~ second order in QED coupling

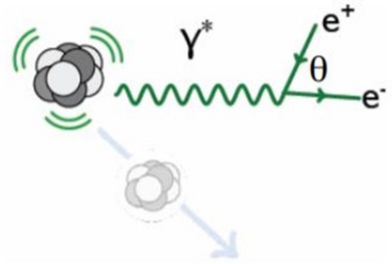
NP processes:

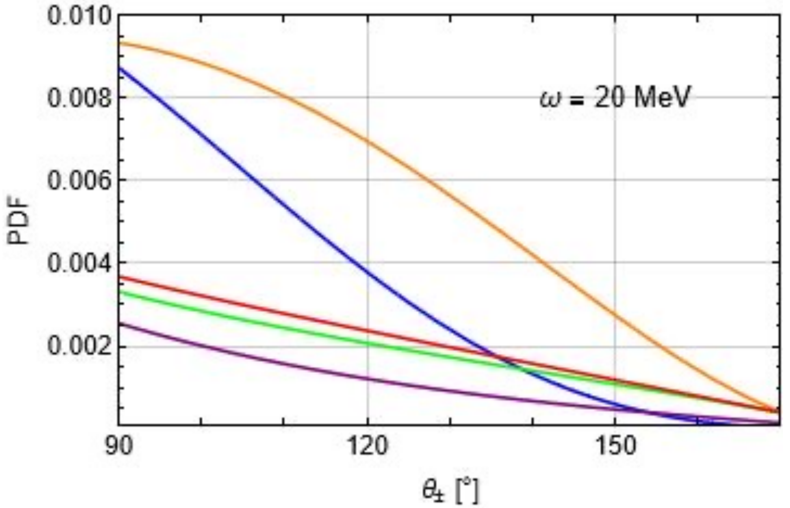


~ first order in NP coupling

ATOMKI search

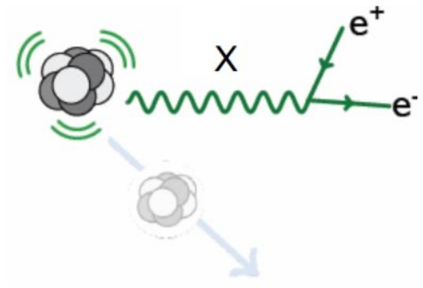
QED:

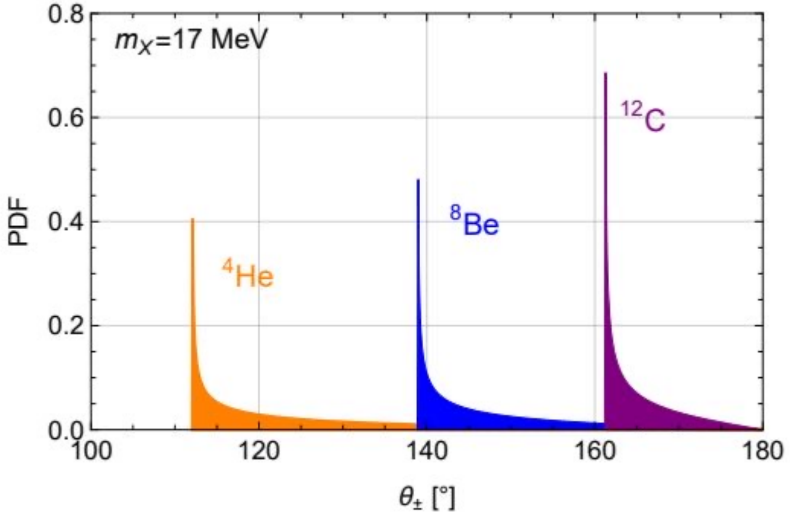




At large angles, QED predicts that the angular correlation of lepton pairs drops rapidly.

NP:



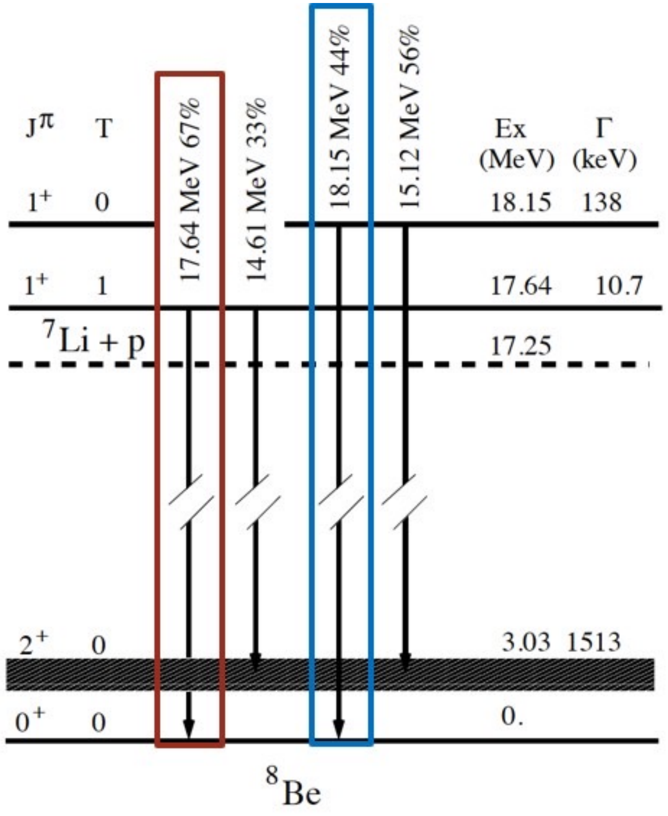


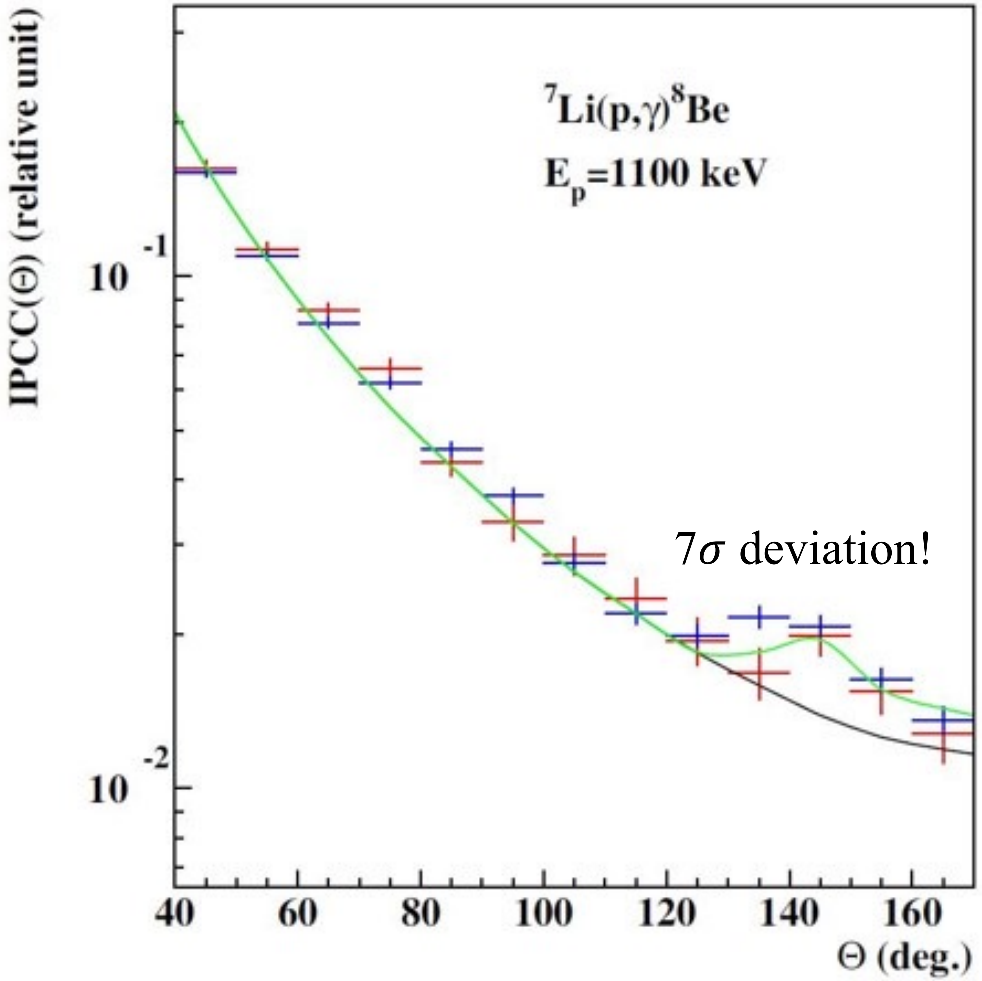
Bump-like distribution peaked at large angles!

Beryllium anomaly (2016)

- In 2016 and 2018 the ATOMKI collaboration investigated the 18.15 MeV energy level of Beryllium8.
- They observed an anomalous peak of events in both the measurements.

Phys.Rev.Lett. 116 (2016) 4, 042501
J. Phys.: Conf. Ser. 1056 012028



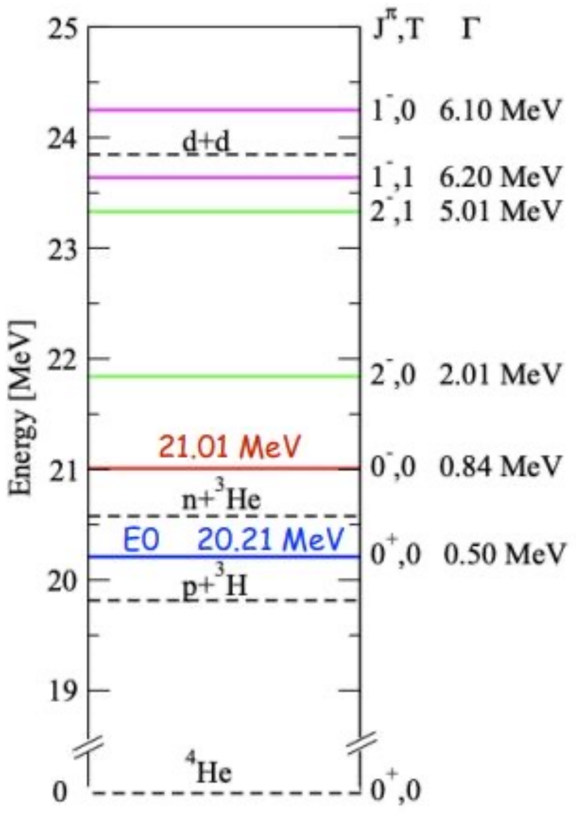


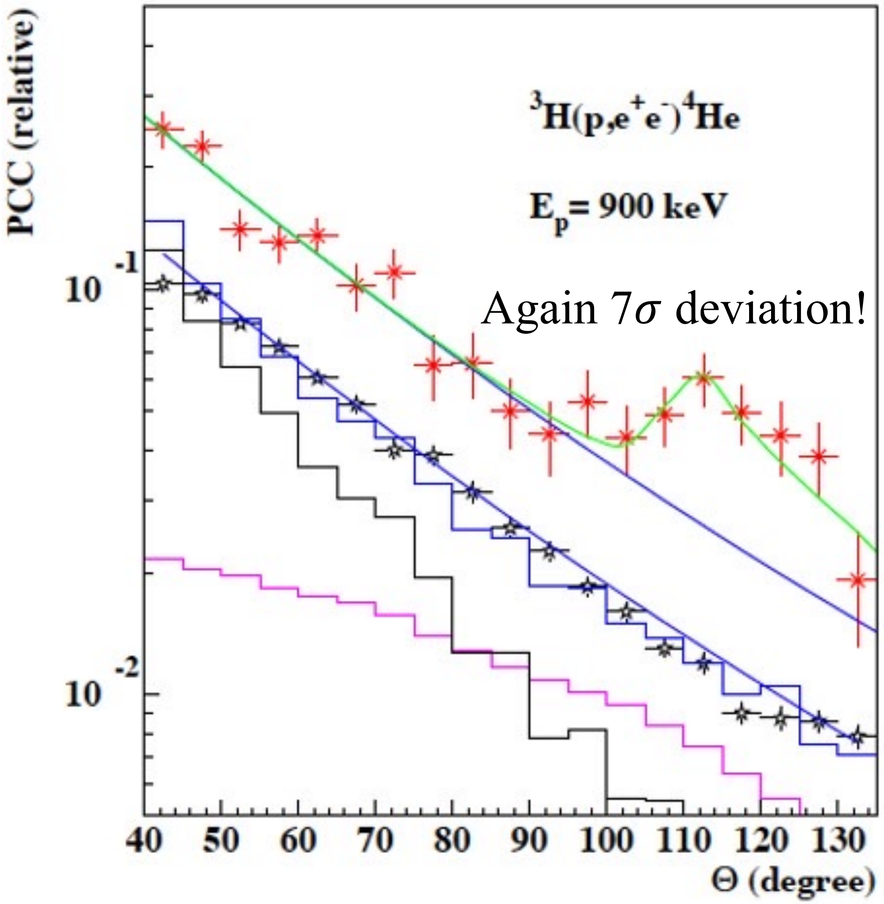
7σ deviation!

Helium anomaly (2019)

- In 2019 and 2021 ATOMKI investigated the 20.21 MeV and 21.01 MeV energy levels of Helium4.
- They observed an new anomalous peak of events.

Phys.Rev.C 104 (2021) 4, 044003
Arxiv:1910.10459





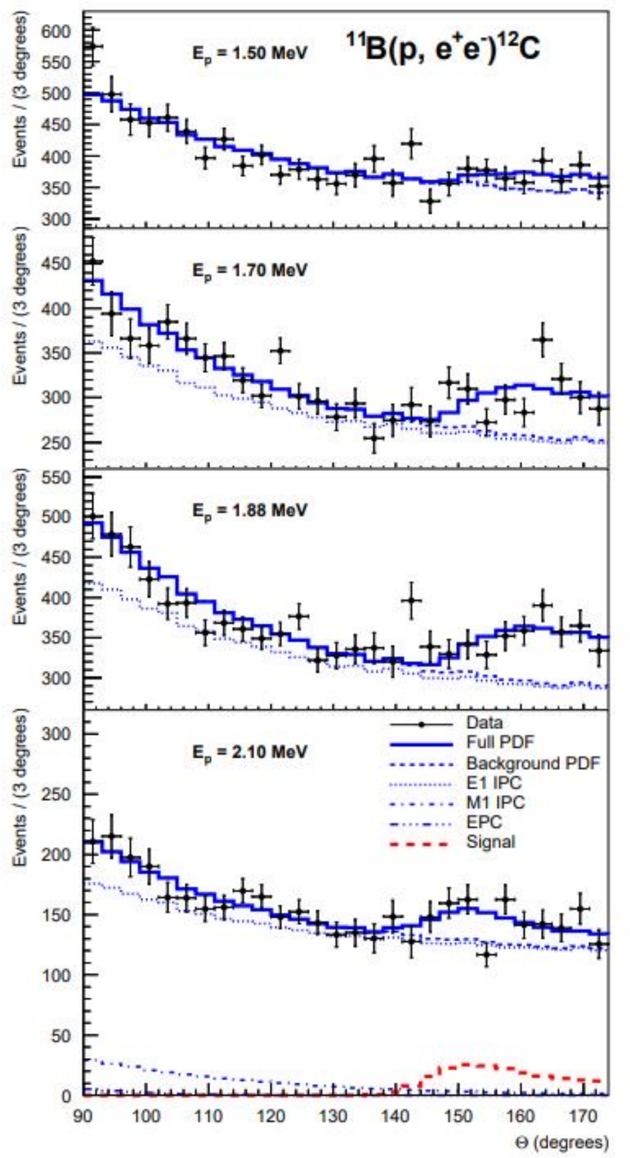
Carbon anomaly (2022)

- In 2022 ATOMKI investigated the 17.2 MeV energy level of Carbon12.
- They again observed a new anomalous peak of events.

TABLE I. X17 branching ratios (B_x), masses, and confidences derived from the fits.

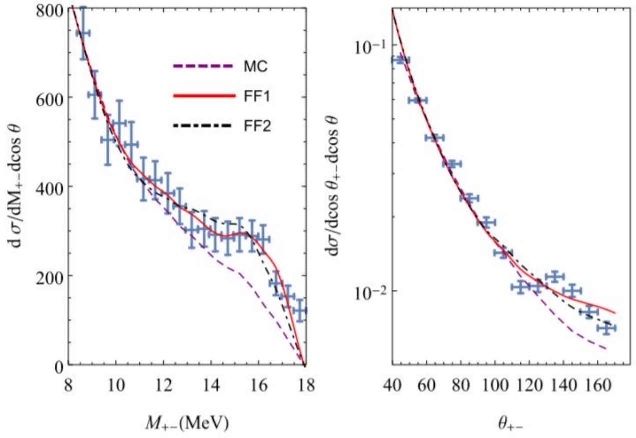
E_p	B_x	Mass	Confidence
(MeV)	$\times 10^{-6}$	(MeV/c^2)	
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	
Predicted [30]	3.0		

Phys.Rev.C 106 (2022) 6, L061601



SM explanation

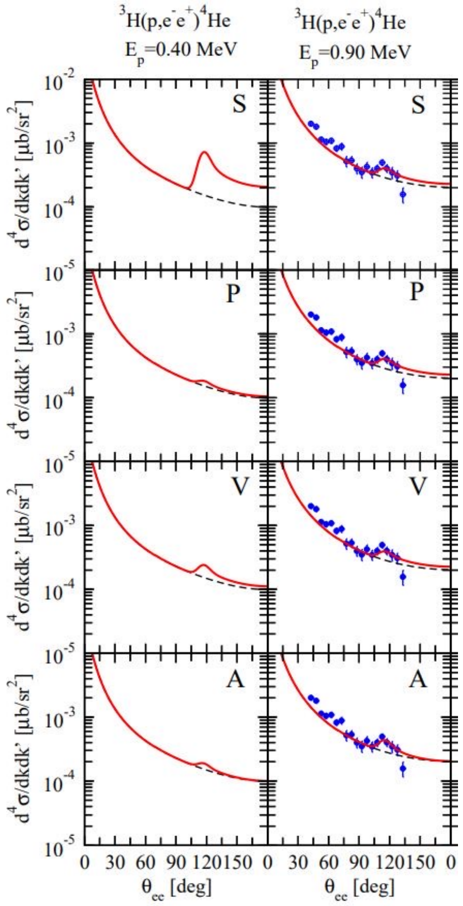
- Improvement of the Be nuclear model used by Atomki is not enough to explain the anomaly.
- Unknown nuclear effect is also excluded.
- The length scale of the needed form factor is in contrast with the experimental observation.



Zhang and Miller, PLB 773 (2017) 159-165

- Ab-initio calculations of the SM prediction in the 4He transitions.
- The predicted cross sections are monotonically decreasing.
- Absence of any resonance-like structure.

Viviani et al., PRC 105 (2022) 1, 014001



Many other proposals but, in conclusion, no compelling SM explanation so far.

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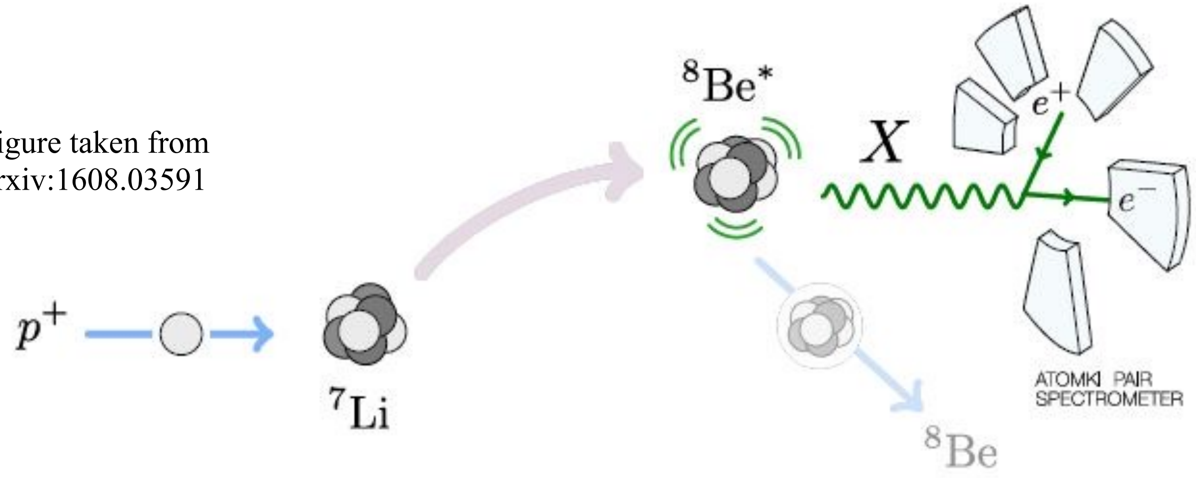
Features of X17

ATOMKI claim: a new particle decaying into a lepton pair is produced in the experiment!

Figure taken from
arxiv:1608.03591



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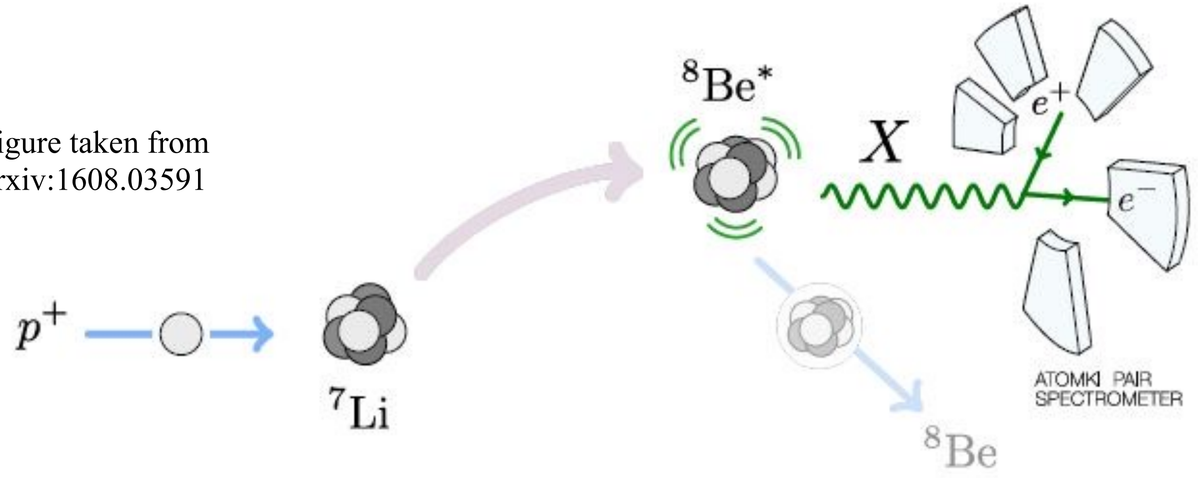

- Best fit mass values give ~17 MeV.
- The particle must be a neutral boson.
- It propagates less then 1 cm in the apparatus ⇒ short-lived boson

$$\gamma v \tau \lesssim 1\,\mathrm{cm}$$

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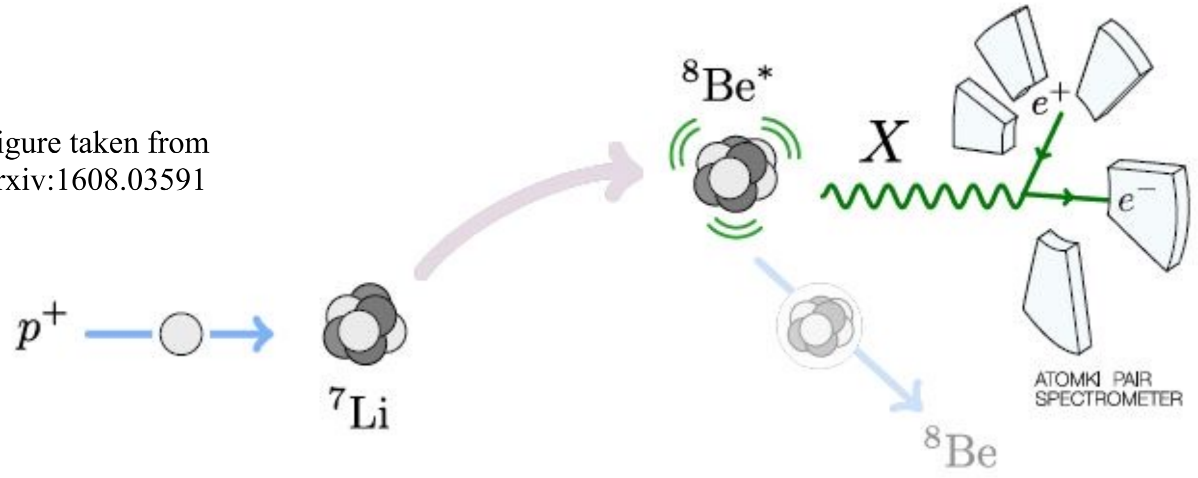

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$$\gamma v \tau \lesssim 1\,\mathrm{cm}$$

$$\text{Signal Rate} = \sigma(N^* \to N + X) \times \mathrm{BR}(X \to e^+ e^-)$$

coupled to nuclear matter, i.e. quarks and gluons

coupled to electron/positrons

X17 kinematics

The ATOMKI anomalies show simple but well defined features, naturally explained by the kinematics of the X17 hypothesis.

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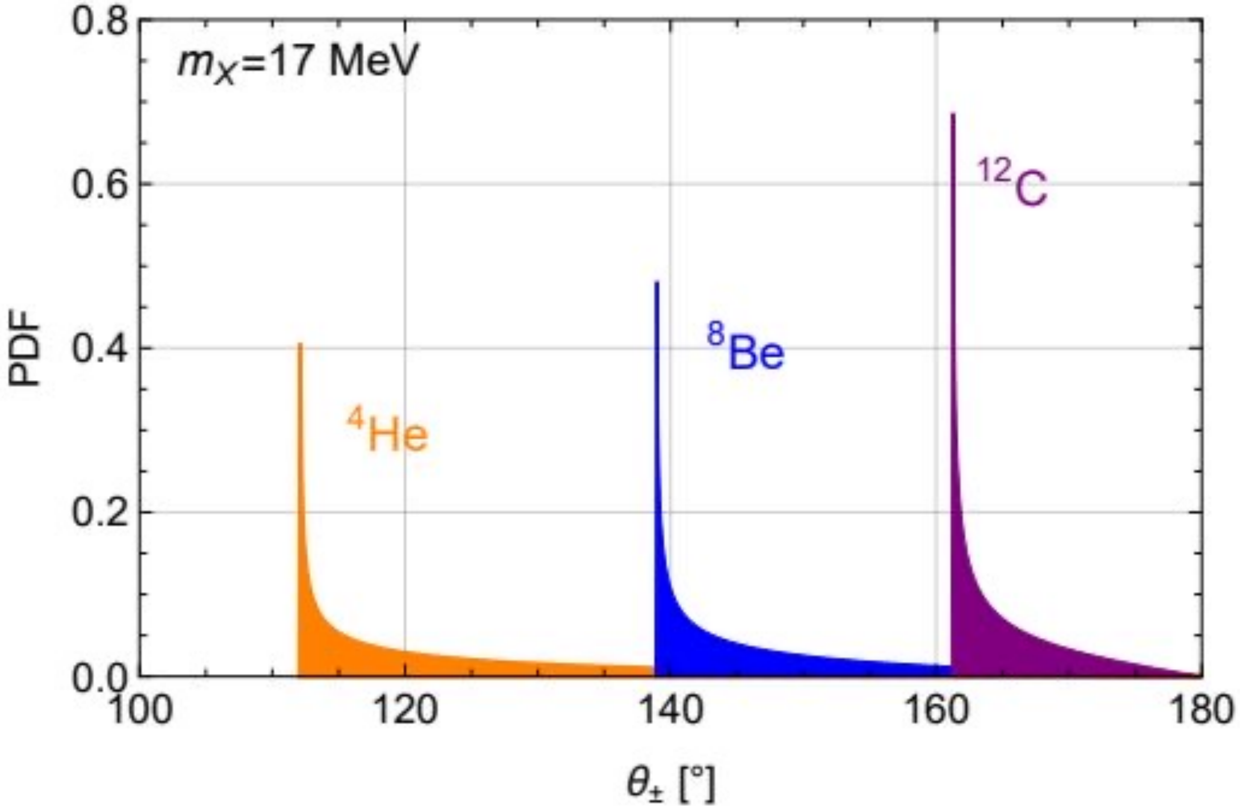
1) the e+e− opening angles of the anomalous peaks are located around 140°, 115° and 155°−160°, respectively, for the 8Be, 4He and 12C anomaly.



- Theoretical PDFs due to phase space effects, i.e. to the process kinematics.
- The measured values of the peak angles are in according with the theoretical prediction.

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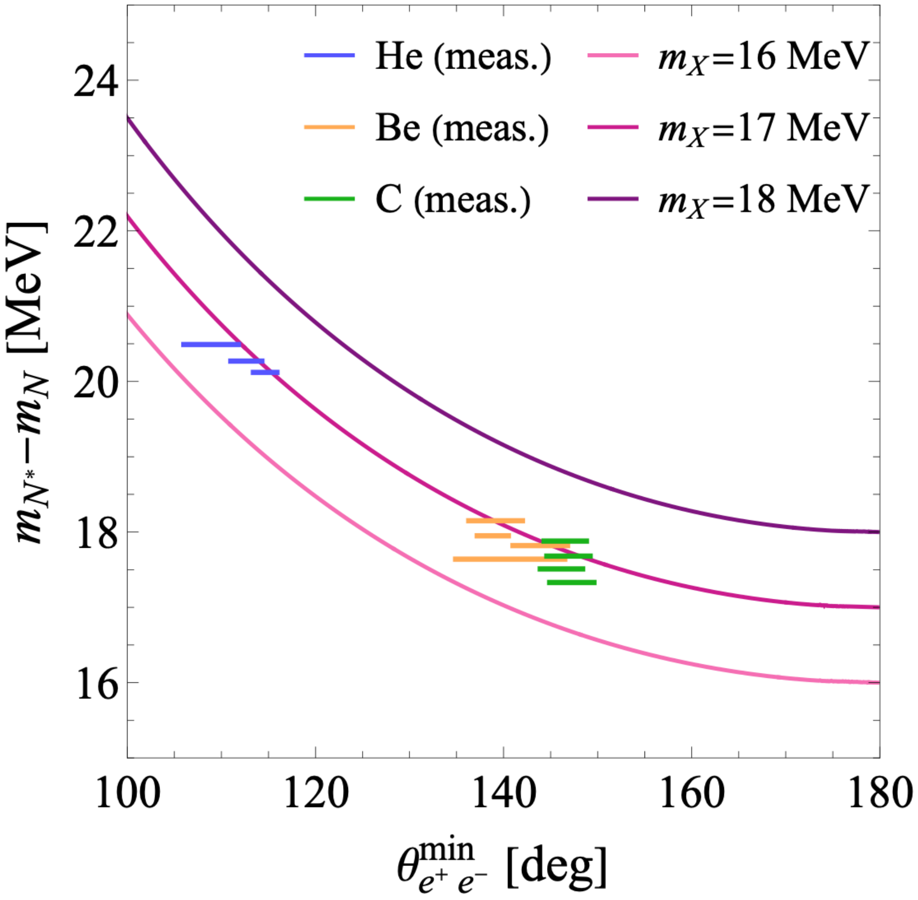
An analysis with the angular data alone of 11 different measurements finds that the data is well described by a new particle of mass $m_X = 16.85 \pm 0.04$ MeV with an internal goodness-of-fit of 1.8σ calculated from Wilks' theorem at $\chi^2/dof = 17.3/10$. We use only the best fit

Peter B. Denton, Julia Gehrlein, arxiv:2304.09877



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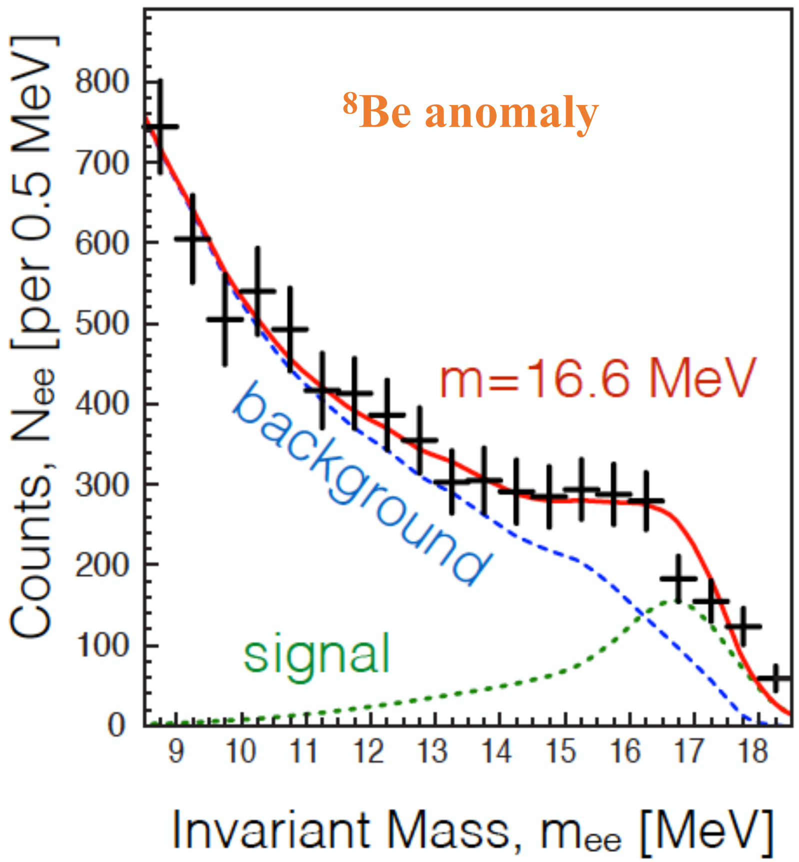

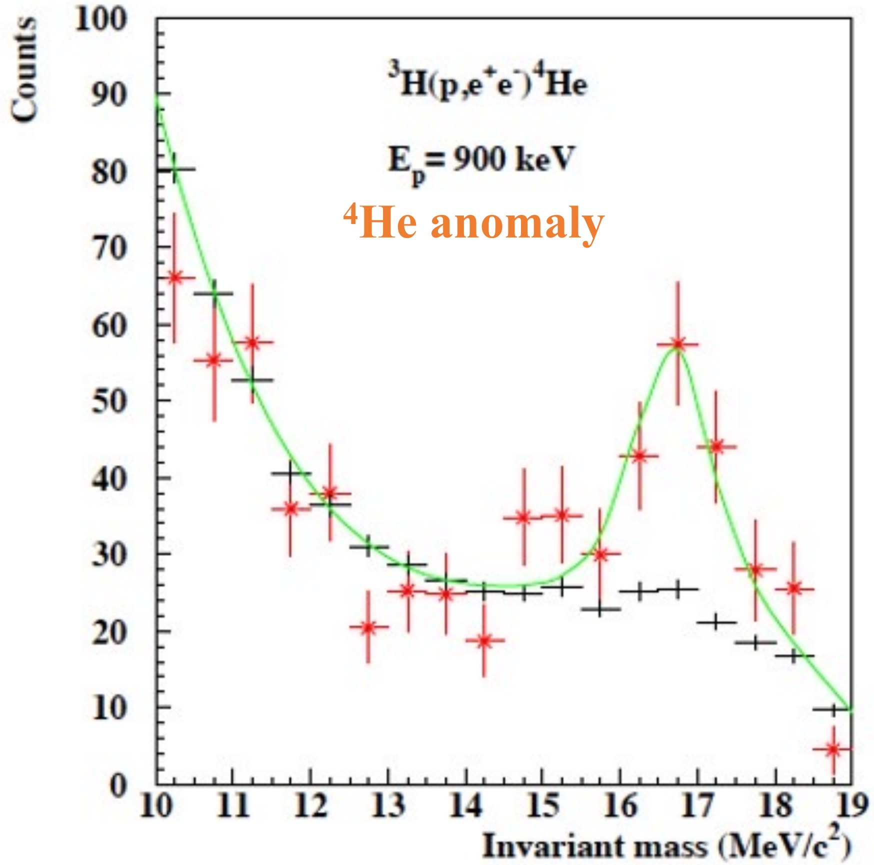

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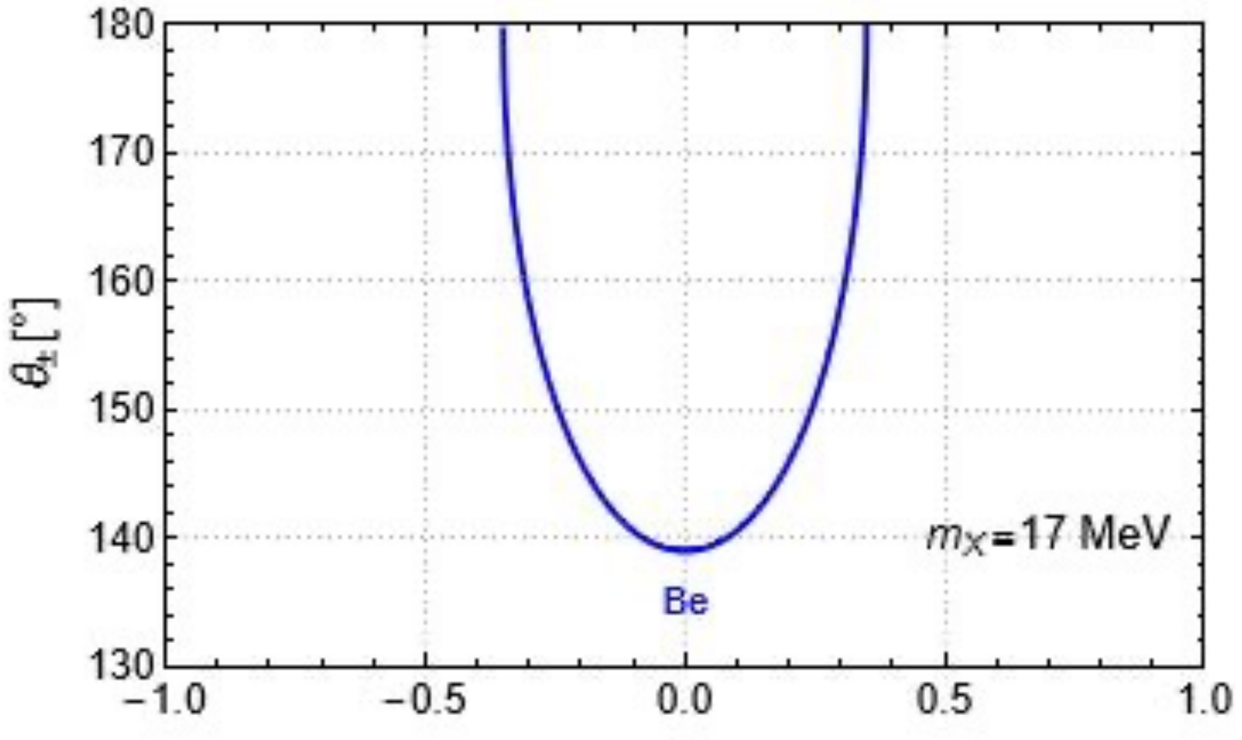
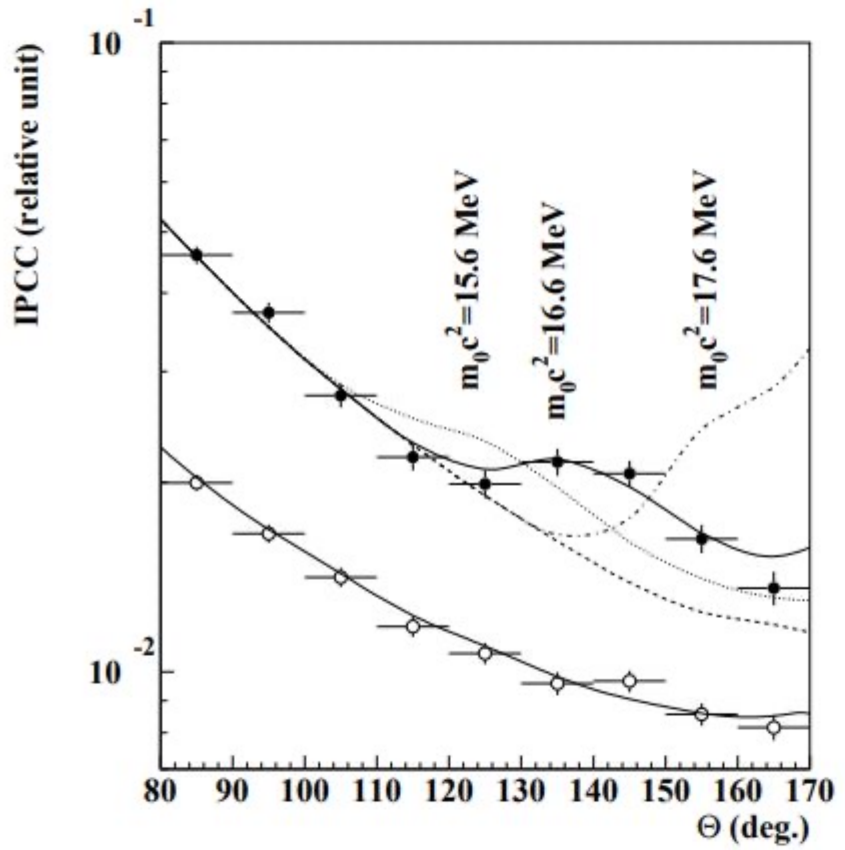


$$y = \frac{E_+ - E_-}{E_+ + E_-}$$



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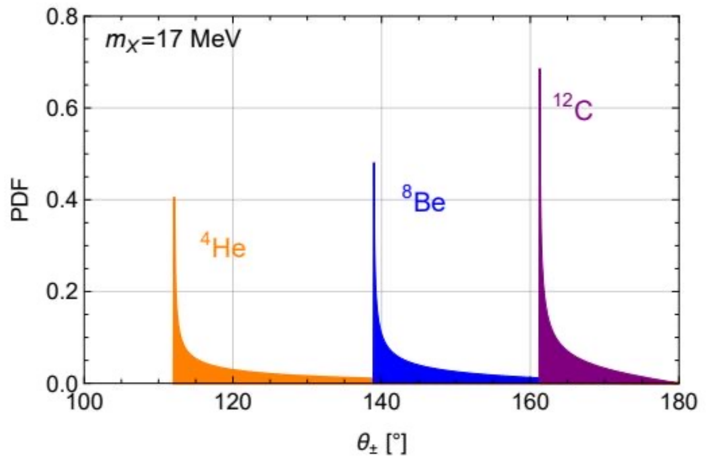
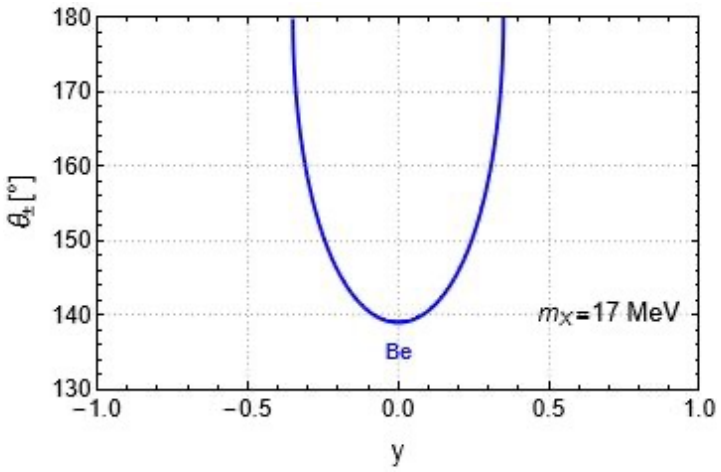


The agreement of the data with the X17 kinematic is a strong argument in favor of the new particle interpretation of the Atomki anomalies



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X17 dynamics

- The X17 hypothesis is *kinematically* consistent for all the anomalies.
- The question then become: is the X17 hypothesis *dynamically* consistent for all the anomalies?
- If so, which is the most promising spin-parity assignment?

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Vector X17 $J^\pi = 1^-$	Scalar X17 $J^\pi = 0^+$	Axial-vector X17 $J^\pi = 1^+$	Pseudoscalar X17 $J^\pi = 0^-$

Assuming definite parity for simplicity, there are four possible scenarios.

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Relying on an EFT approach, effective X17-nucleon coupling terms depends on the spin-parity of the boson.

$$\mathcal{L}_{S^\pi=0^+} = z_p \bar{p} p X + z_n \bar{n} n X \ ,$$

$$\mathcal{L}_{S^\pi=0^-} = i h_p \bar{p} \gamma^5 p X + i h_n \bar{n} \gamma^5 n X \ ,$$

$$\mathcal{L}_{S^\pi=1^-} = C_p \bar{p} \gamma^\mu p X_\mu + C_n \bar{n} \gamma^\mu n X_\mu + \frac{\kappa_p}{2m_p} \partial_\nu (\bar{p} \sigma^{\mu\nu} p) X_\mu + \frac{\kappa_n}{2m_n} \partial_\nu (\bar{n} \sigma^{\mu\nu} n) X_\mu \ ,$$

$$\mathcal{L}_{S^\pi=1^+} = a_p \bar{p} \gamma^\mu \gamma^5 p X_\mu + a_n \bar{n} \gamma^\mu \gamma^5 n X_\mu \ ,$$

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

Orbital angular momentum L of the X17

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^{4}He(21.01) $\to$ ^{4}He	/	1	0	/
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Vector X17 $J^\pi = 1^-$	Scalar X17 $J^\pi = 0^+$	Axial-vector X17 $J^\pi = 1^+$	Pseudoscalar X17 $J^\pi = 0^-$

Assuming definite parity for simplicity, there are four possible scenarios.

- The scalar scenario is excluded by parity conservation in Beryllium transitions.
- The pseudoscalar scenario is excluded by parity conservation in Carbon transition.

Process $N^* \to N$	X boson spin parity $S^\pi = 1^-$	$S^\pi = 1^+$	$S^\pi = 0^-$	$S^\pi = 0^+$
^{8}Be(18.15) $\to$ ^{8}Be	1	0, 2	1	/
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Orbital angular momentum L of the X17

X17 dynamics

Vector X17 $J^\pi = 1^-$

Axial-vector X17 $J^\pi = 1^+$

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)

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

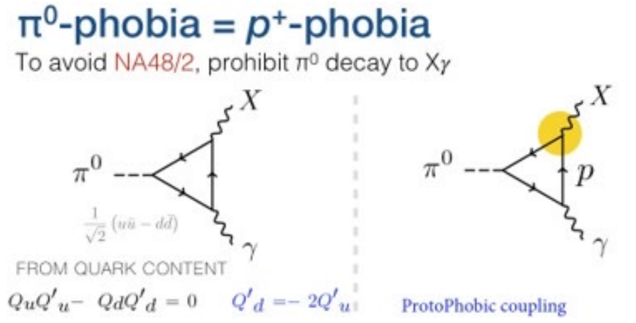
By matching the data to the theoretical prediction, one extracts the nucleon couplings to X17

We assume for simplicity no or suppressed coupling to neutrinos such that

$$\text{BR}(X \to e^+e^-) = 1$$

Vector X17

- The Carbon anomaly is in tension with a combined explanation of the Beryllium and Helium anomalies and the NA48 constraint.

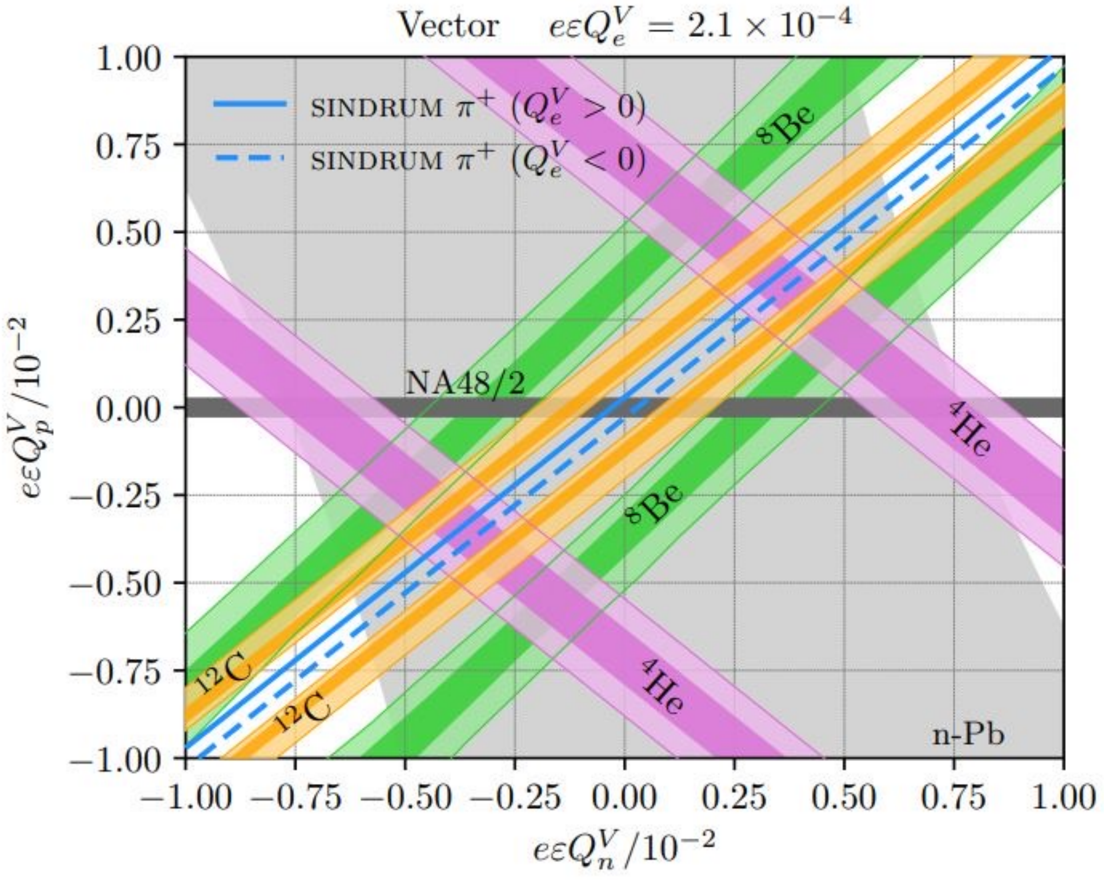


- Additionally, Hostert and Pospelov calculated the constraints to a spin-1 X17 coming from the SINDRUM search of $\pi^+ \to e^+ \nu_e X$.

- Putting all together, the vector case is almost excluded.

Barducci and Toni, JHEP 02 (2023) 154

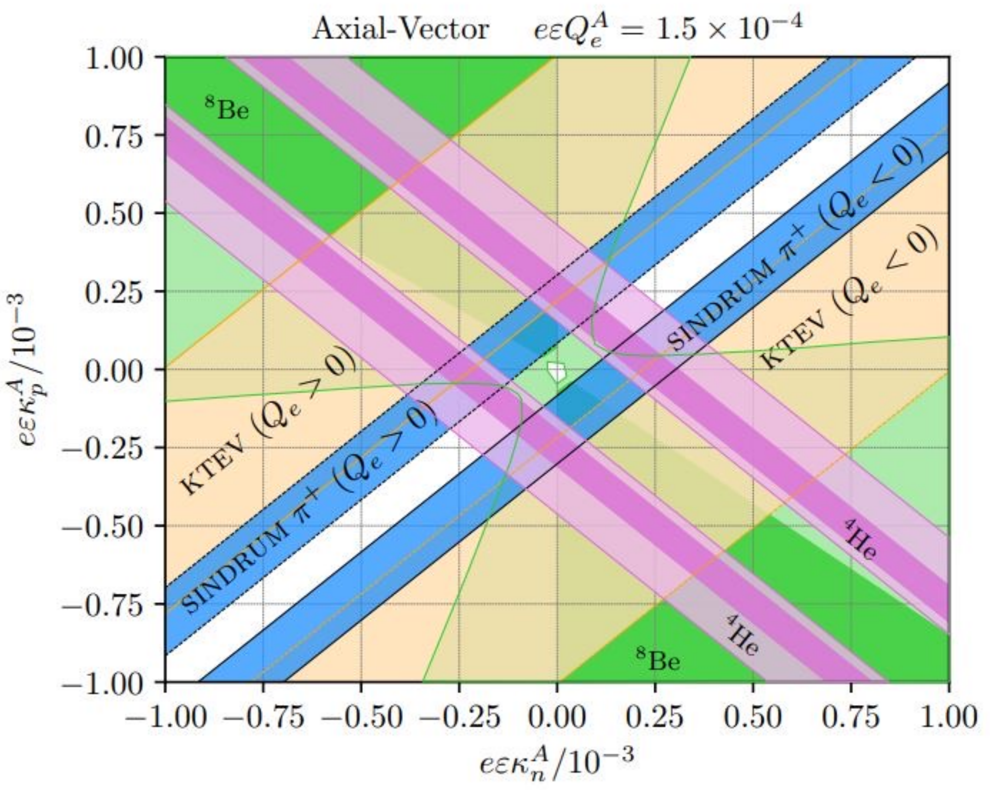
Hostert and Pospelov , arxiv:2306.15077



Axial-vector X17

Barducci and Toni, JHEP 02 (2023) 154 Hostert and Pospelov , arxiv:2306.15077

- An axial-vector X17 is dynamically consistent for Helium and Beryllium.
- An order of magnitude estimate of the Carbon anomaly seems to indicate that axial-vector solution is possible.
- Recently, Hostert and Pospelov calculated the constraints to a spin-1 X17 coming from the SINDRUM search of $\pi^+ \to e^+ \nu_e X$.
- In conclusion, the axial solution is the most promising spin-parity assignment for the X17!



Intriguingly, other experimental anomalies can be simultaneously satisfied: KTeV measurement of $\pi^0 \to e^+e^-$ and electron's g-2

Axial-vector X17: two years later

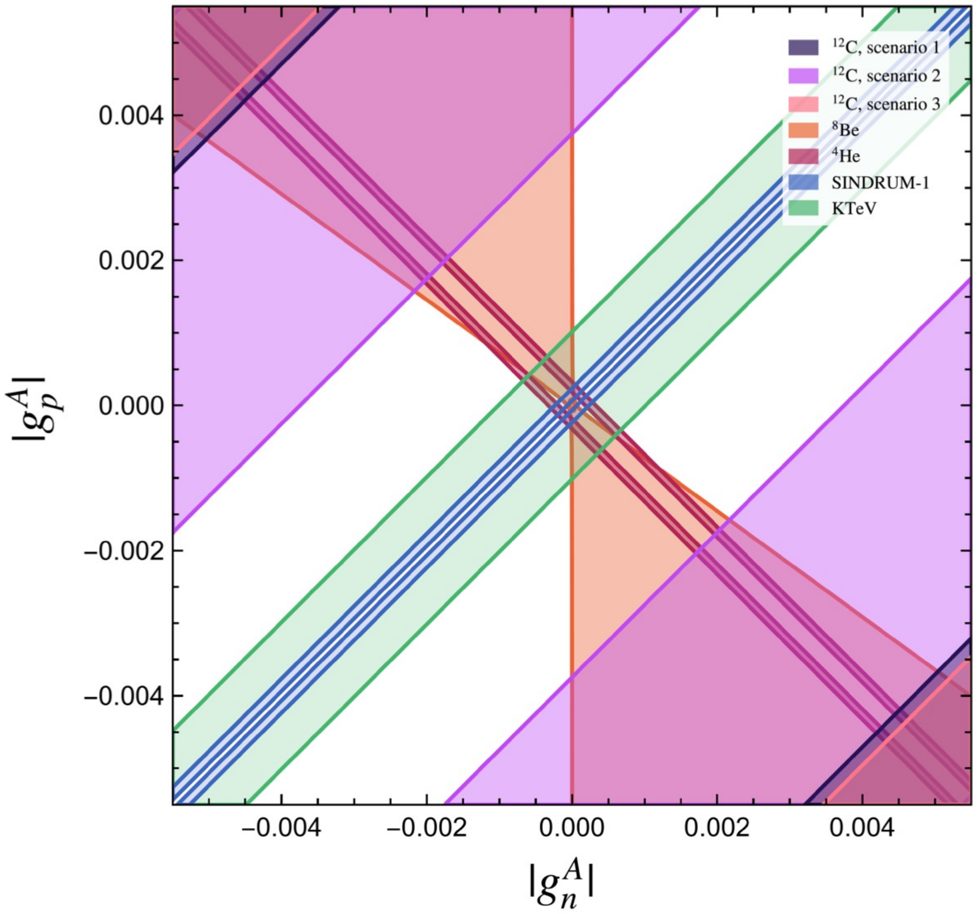
Mommers and Vanderhaeghen, arxiv:2406.08143

Particle-hole shell model approximation for Carbon excited state:

$$\left|{}^{12}\mathrm{C}(17.23)\right\rangle = \left|2s_{1/2}1p_{3/2}^{-1}; 1M1M_T\right\rangle = \left[c^{\dagger}_{2s_{1/2}}\tilde{c}_{1p_{3/2}}\right]^{1M_T}_{1M}\left|{}^{12}\mathrm{C(g.s.)}\right\rangle$$

$$\Gamma\left[{}^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C(g.s.)} + \mathrm{X17}\right] = \frac{|\mathbf{k}_X|^3}{162\pi}(g_p^A - g_n^A)^2\left|\mathcal{R}^{(1)}_{1p,2s}\right|^2, \quad (22)$$

$$\Gamma\left[{}^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C(g.s.)} + \gamma\right] = \frac{2e^2E_\gamma^3}{81\pi}(Q_p - Q_n)^2\left|\mathcal{R}^{(1)}_{1p,2s}\right|^2. \quad (23)$$



The shell model estimate indicates tension in the axial-vector scenario!

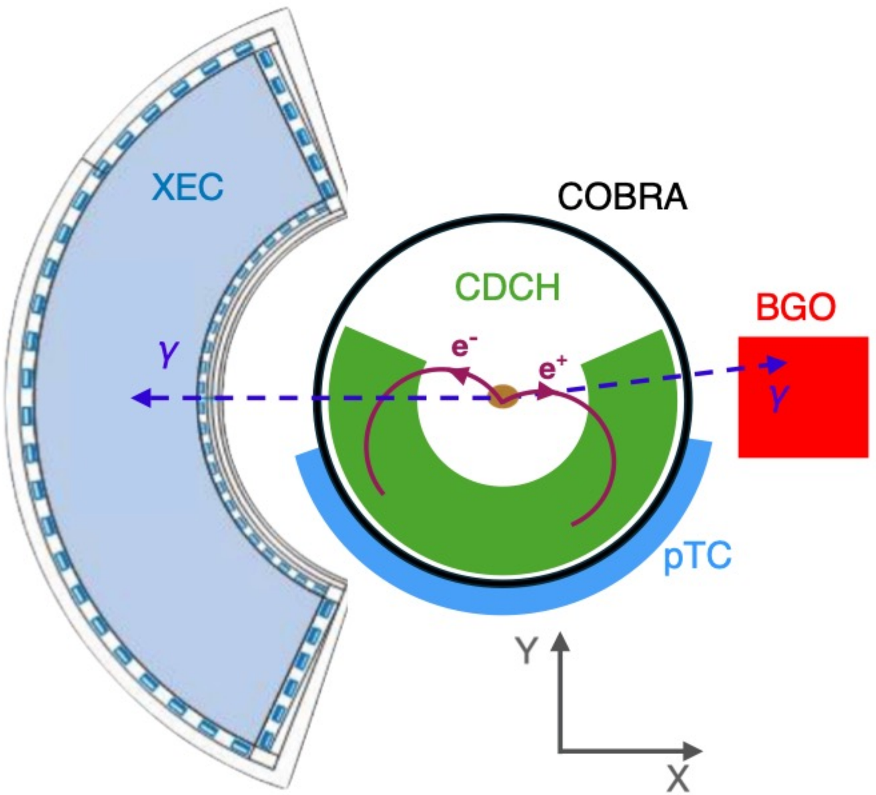
Arguments of the talk

1) ATOMKI search and anomalies (2016-2022)
2) X17 hypothesis
3) First phenomenological analysis (2022)
4) MEG-II search and results (end of 2024)
5) Second phenomenological analysis (early 2025)
6) Padme search and results (few months ago)

X17 at MEG-II (2024)

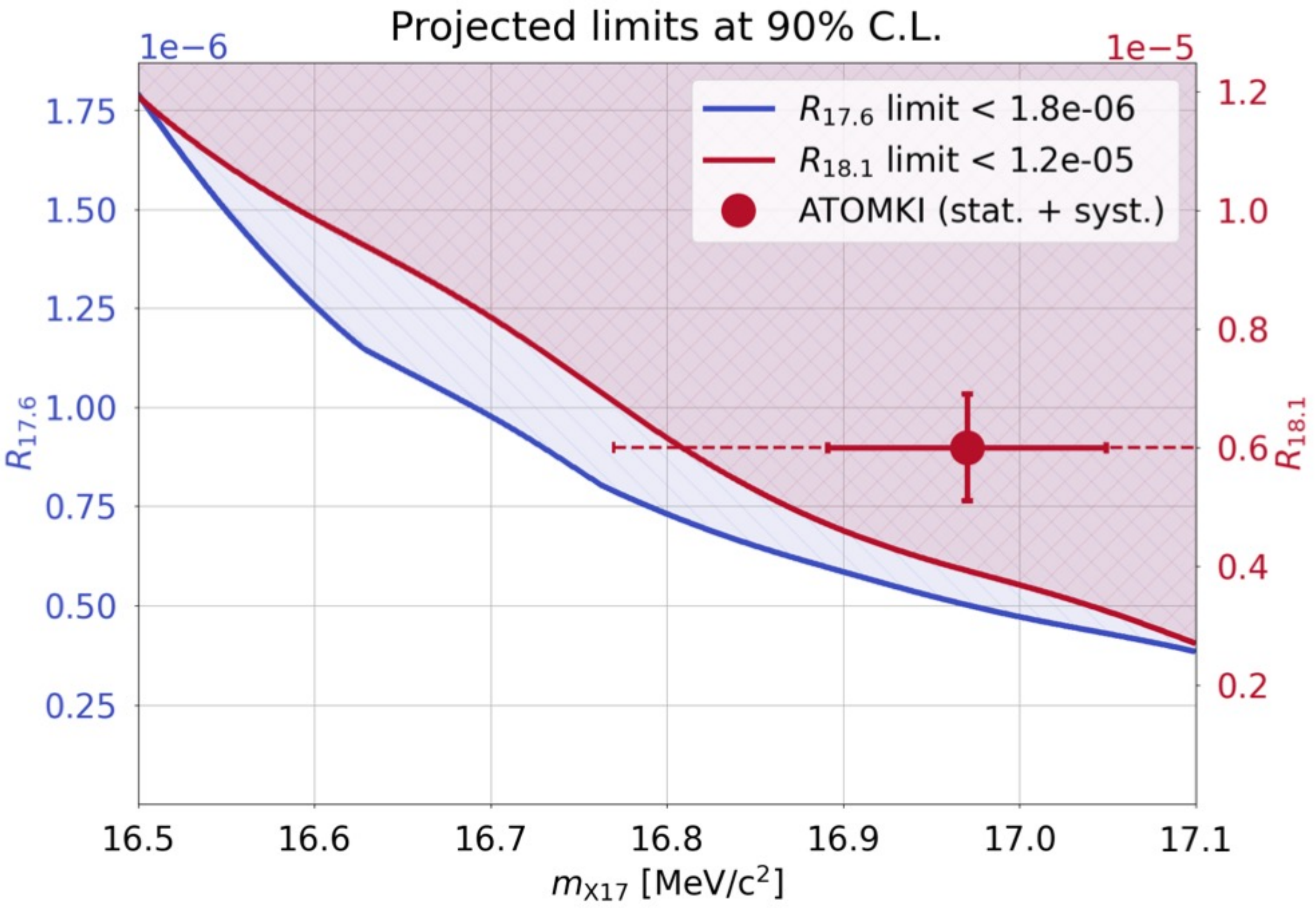
- In order to confirm the Atomki anomaly, MEG-II re-measured the Beryllium transitions at the PSI

- They took data during 2023 with energy beam at 1080 keV.



X17 at MEG-II (2024)

- In order to confirm the Atomki anomaly, MEG-II re-measured the Beryllium transitions at the PSI
- They took data during 2023 with energy beam at 1080 keV.
- Their results show no significant signal.
- They conclude that their measurement agrees with Atomki result with a *p*-value of 6% (1.5σ)

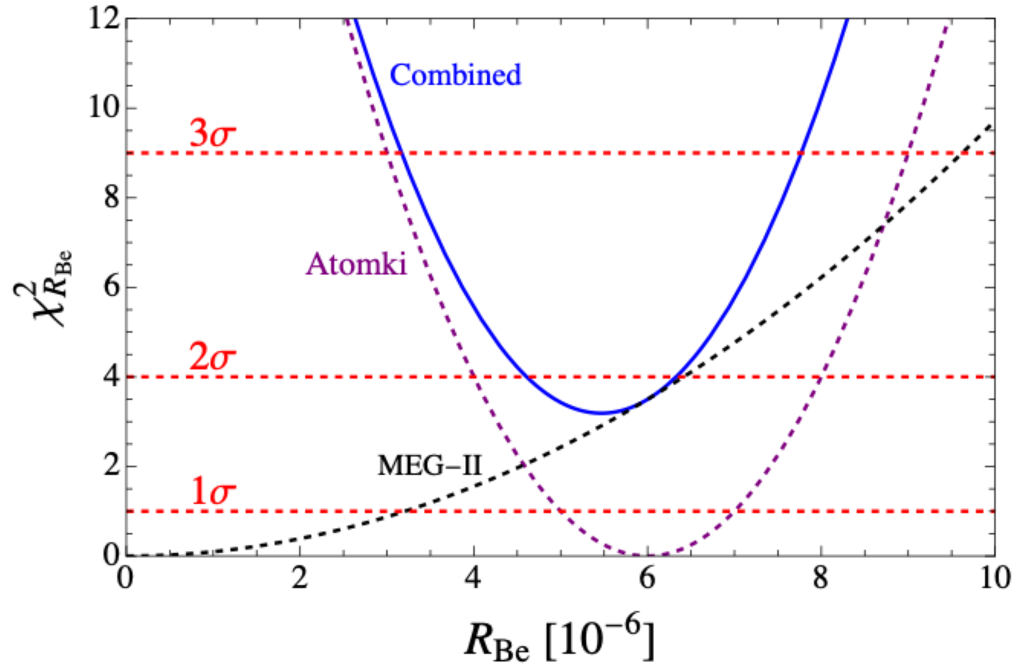


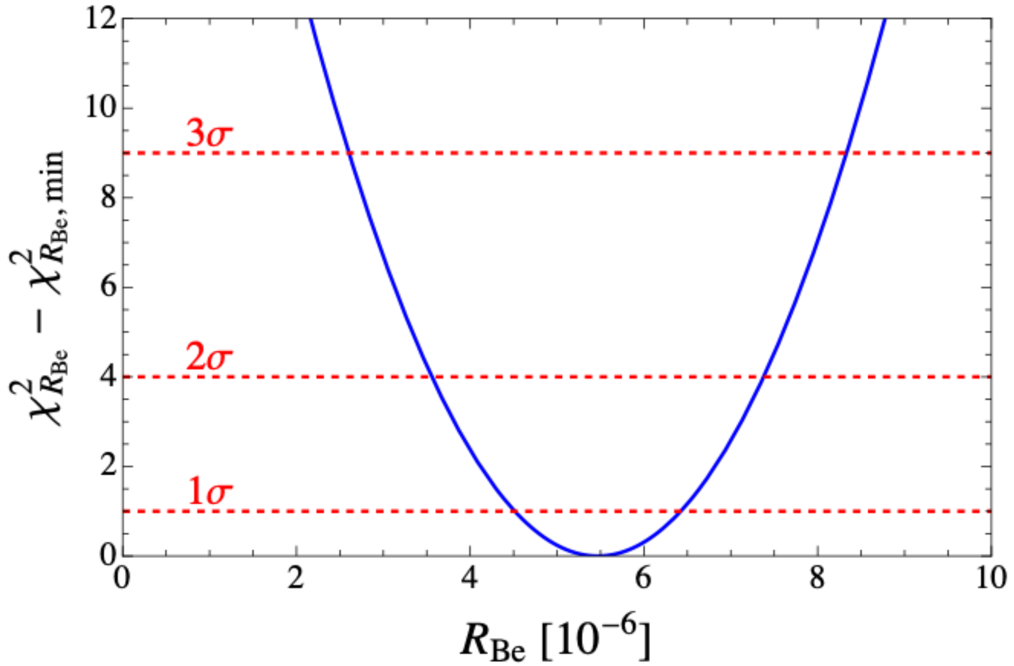
Combining Atomki and MEG-II

- Despite the null result from MEG-II, no final exclusion is established as there is still agreement at 2σ
- We combined the two measurement by a simple chi squared analysis for a mass value of 16.85 MeV

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

Barducci et al., arxiv:2501.05507





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X17 dynamics (again)

- Atomki and MEG-II are still in agreement at 2σ, so no exclusion established!
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- If so, which is the most promising spin-parity assignment?

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What about a spin-2 scenario instead?

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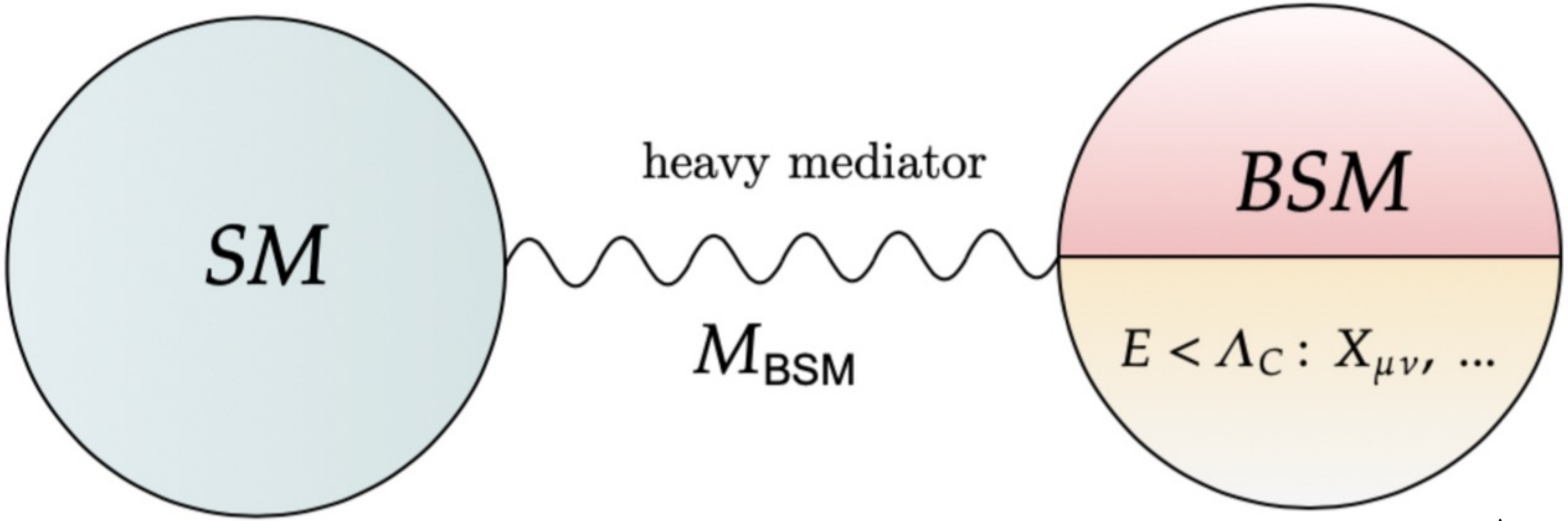

$\Lambda_c = 4\pi m_X \approx 200$ MeV

Spin-2 couplings to fermions

- A Lagrangian approach to massive spin-2 is difficult due to the large number of unphysical degrees of freedom one needs to introduce
- On-shell amplitude appears a more natural and easier way to write down the couplings

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$$
\begin{aligned}
\mathcal{A}(f \to f'X) = \overline{u}(p',\sigma')\Bigg\{ & 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 \left(p'+p\right)_\mu \left(p'+p\right)_\nu \\
& + \tilde{D}_f \left(p'+p\right)_\mu \left(p'+p\right)_\nu i\gamma_5 \Bigg\} u(p,\sigma)\ \left[\epsilon_a^{\mu\nu}(p-p')\right]^*
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- By naive dimensional analysis: $C_f \sim \tilde{C}_f \sim \mathcal{O}(M_{\text{BSM}}^{-1})$ and $D_f \sim \tilde{D}_f \sim \mathcal{O}(M_{\text{BSM}}^{-2})$

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Vector-tensor X17 $J^\pi = 2^+$

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Vector-tensor and axial-tensor X17

Barducci et al., arxiv:2501.05507

- The axial-tensor scenario could accommodate all the anomalies at most at 2σ but it is completely excluded by the SINDRUM bound

- The vector-tensor scenario could accommodate all the anomalies within 1σ but it is highly disfavoured by the SINDRUM bound

Spin-2 scenarios are out too!

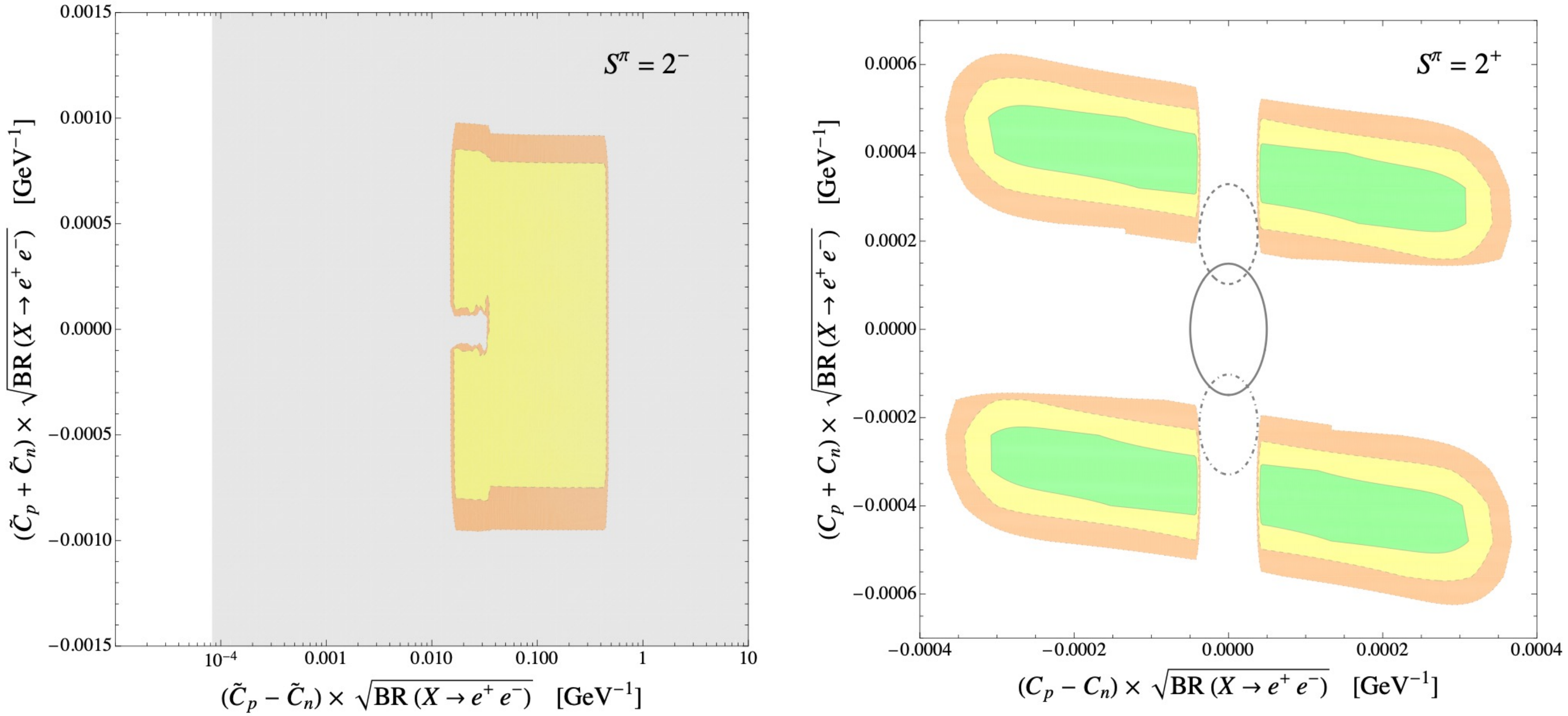

Figure 2. *Left panel:* Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\text{profiled}} < 2.28, 5.99, 11.62$, for an axial tensor boson. The gray region is excluded by SINDRUM search. *Right panel:* Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\text{profiled}} < 2.28, 5.99, 11.62$, 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 $C_e = 0$, $C_e = -0.001\ \text{GeV}^{-1}$ and $C_e = 0.001\ \text{GeV}^{-1}$.

A brief theory recap

- We studied all the possible scenarios of parity-conserving X17 states with spin$\leq$ 2.
- We found out that none of them provides a viable model.

- Scalar X17 $J^{\pi} = 0^{+}$: It cannot mediate the Beryllium transition
- Pseudoscalar X17 $J^{\pi} = 0^{-}$: It cannot mediate the Carbon transition
- Vector X17 $J^{\pi} = 1^{-}$: Tension among data and SINDRUM and NA48 constraint
- Axial-vector X17 $J^{\pi} = 1^{+}$: Tension among Carbon data and SINDRUM constraint
- Vector-tensor X17 $J^{\pi} = 2^{+}$: Excluded by SINDRUM constraint
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Perhaps we need to start to consider parity-violating states…

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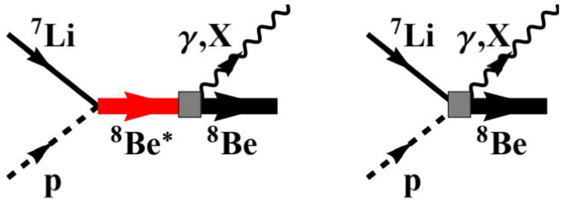
Perhaps we need to start to consider parity-violating states…

…or refine the analysis including the direct proton capture!



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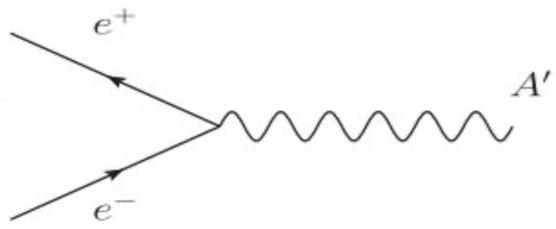
X17 at Padme

- PADME experiment allows for a strong test of the new particle hypothesis.

- A positron beam dump experiment like Padme can resonantly produce the X17.



Arxiv:1802.04756
Nardi, Carvajal, Groshal, Meloni, Raggi

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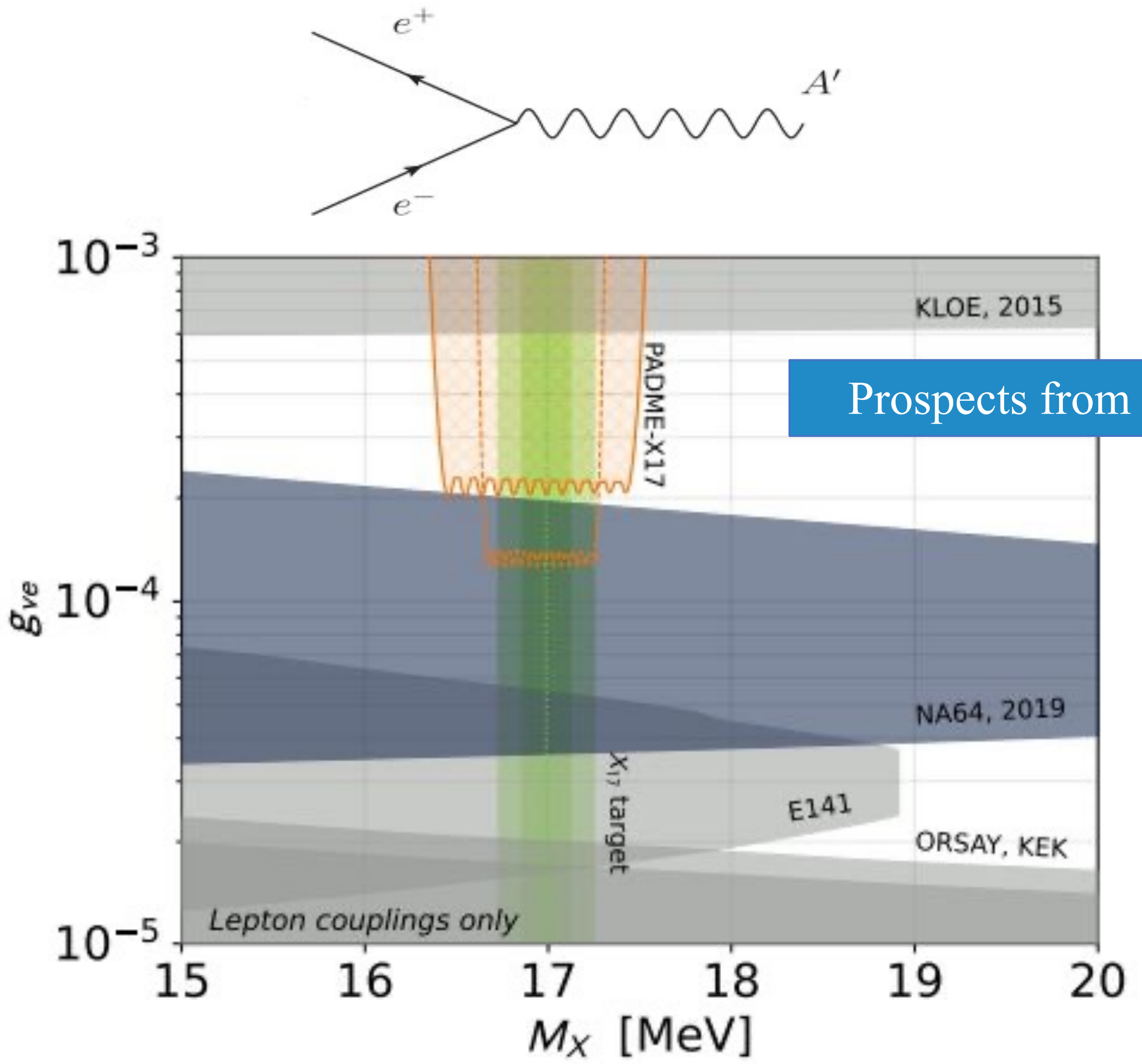
- PADME was expected to close the spin-1 parameter space!

PRD 106 (2022) 11, 115036
L. Darmé, M. Mancini,
M. Raggi and E. Nardi

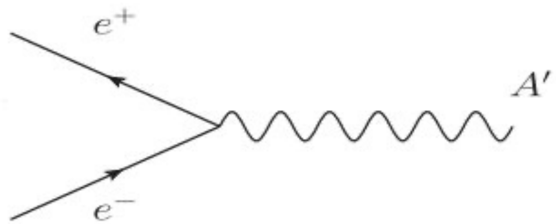


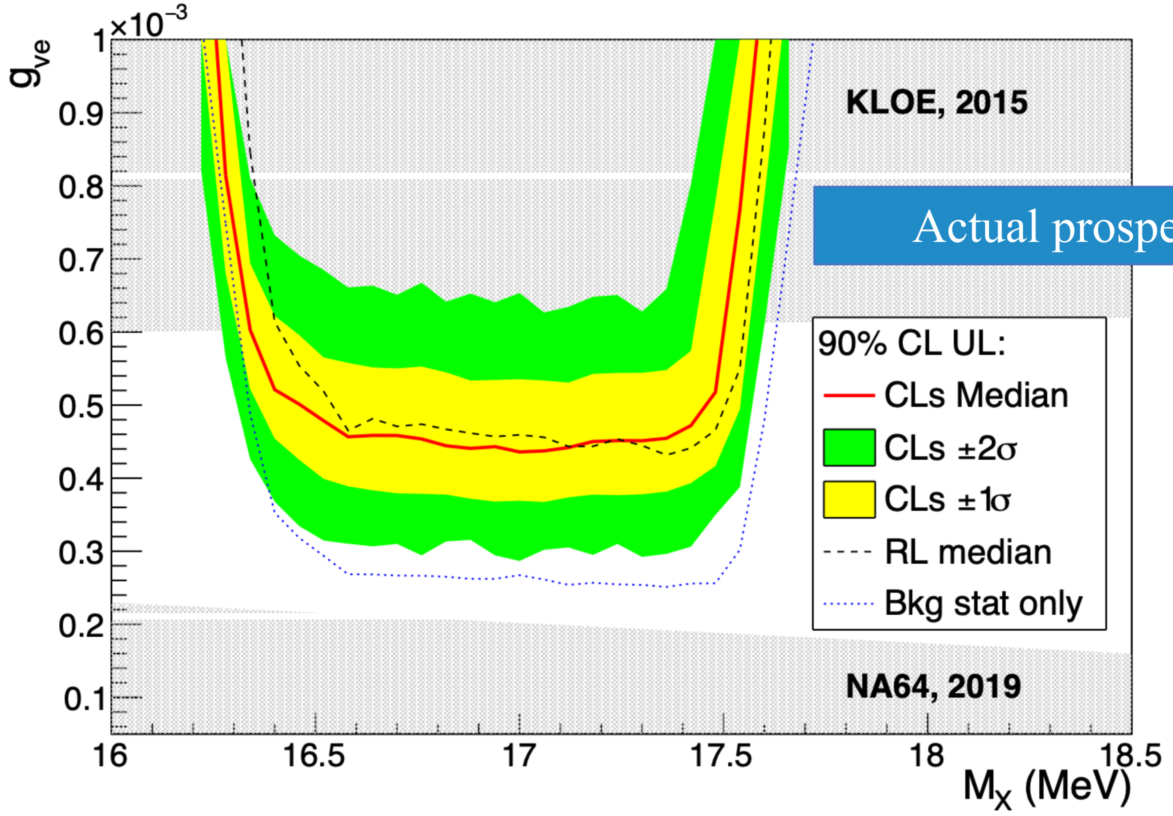
Prospects from 2022

X17 at Padme

- PADME experiment allows for a strong test of the new particle hypothesis.
- A positron beam dump experiment like Padme can resonantly produce the X17.
- PADME is expected to test a large portion the spin-1 parameter space but not closing it!

Bertelli et al., arxiv:2503.05650



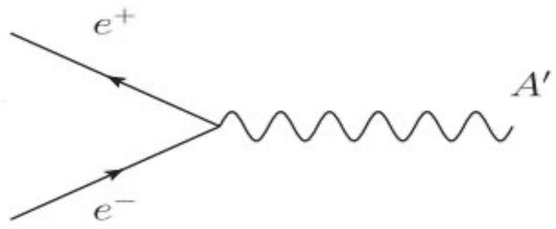


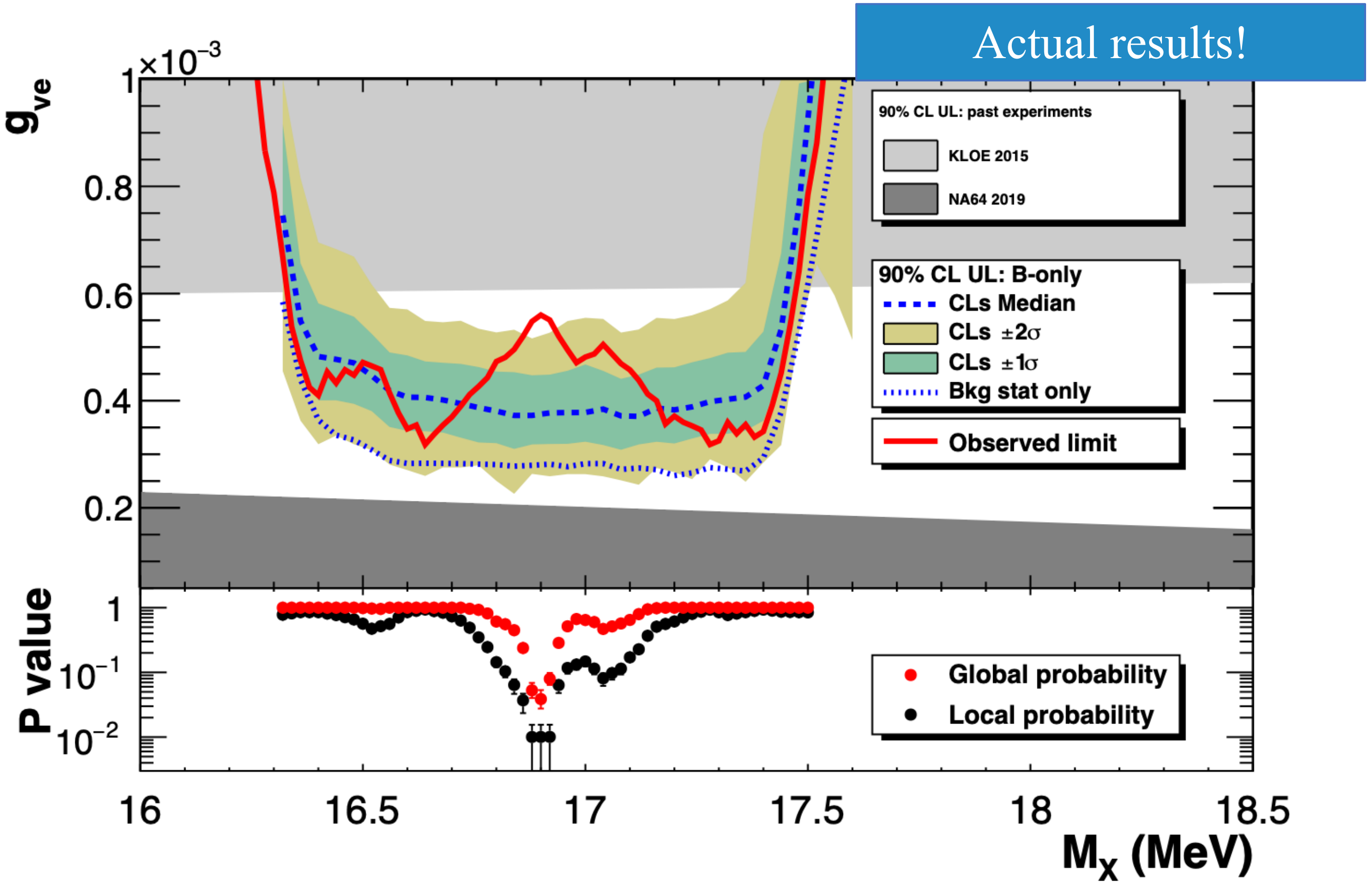
Actual prospects

X17 at Padme

- PADME experiment allows for a strong test of the new particle hypothesis.
- A positron beam dump experiment like Padme can resonantly produce the X17.
- 1.77σ global deviation at the minimum of the p-value at 16.90 MeV!

Bertelli et al., arxiv:2505.24797





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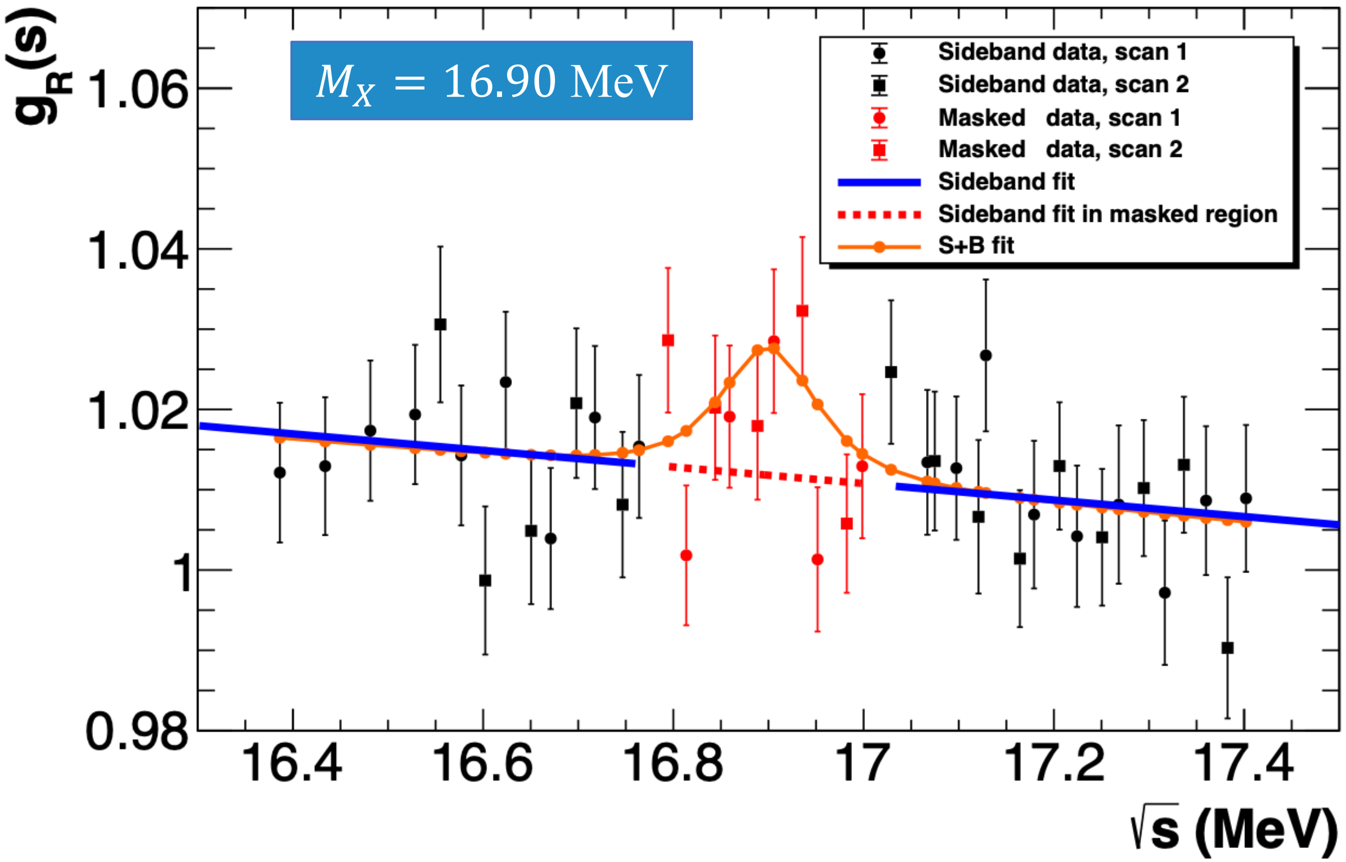


Bertelli et al., arxiv:2505.24797

Padme result from a pheno point of view

PADME result allows for a precise determination of the new particle mass

Nucleus (MeV)	m_X (MeV)	Experiment	Ref.
^{8}Be*(18.15)	$16.86 \pm 0.06 \pm 0.50$	Atomki	[2, 6]
^{8}Be*(18.15)	$17.17 \pm 0.07 \pm 0.20$	Atomki	[6]
^{4}He*(20.21/21.01)	$16.94 \pm 0.12 \pm 0.21$	Atomki	[9]
^{12}C*(17.23)	$17.03 \pm 0.11 \pm 0.20$	Atomki	[10]
^{8}Be*(GDR)	$16.95 \pm 0.48 \pm 0.35$	Atomki	[11, 12]
^{8}Be*(18.15)	$16.66 \pm 0.47 \pm 0.35$	VNU-UoS	[13]
^{8}Be*(17.64/18.15)	< 16.81 [$R_{\rm Be} = 6 \cdot 10^{-6}$]	MEG II	[17]
$e^+e^- \to X_{17}$	$16.90 \pm 0.02 \pm 0.05$	PADME	[20, 21]

izing over $R_{\rm Be}$. For the nuclear physics only case we obtain $m_{X_{17}} = 16.78 \pm 0.12\,{\rm MeV}$ (1σ uncertainty)[1]. After including the PADME mass determination, the uncertainty gets reduced by more than a factor of two, giving $m_{X_{17}} = 16.88 \pm 0.05\,{\rm MeV}$.

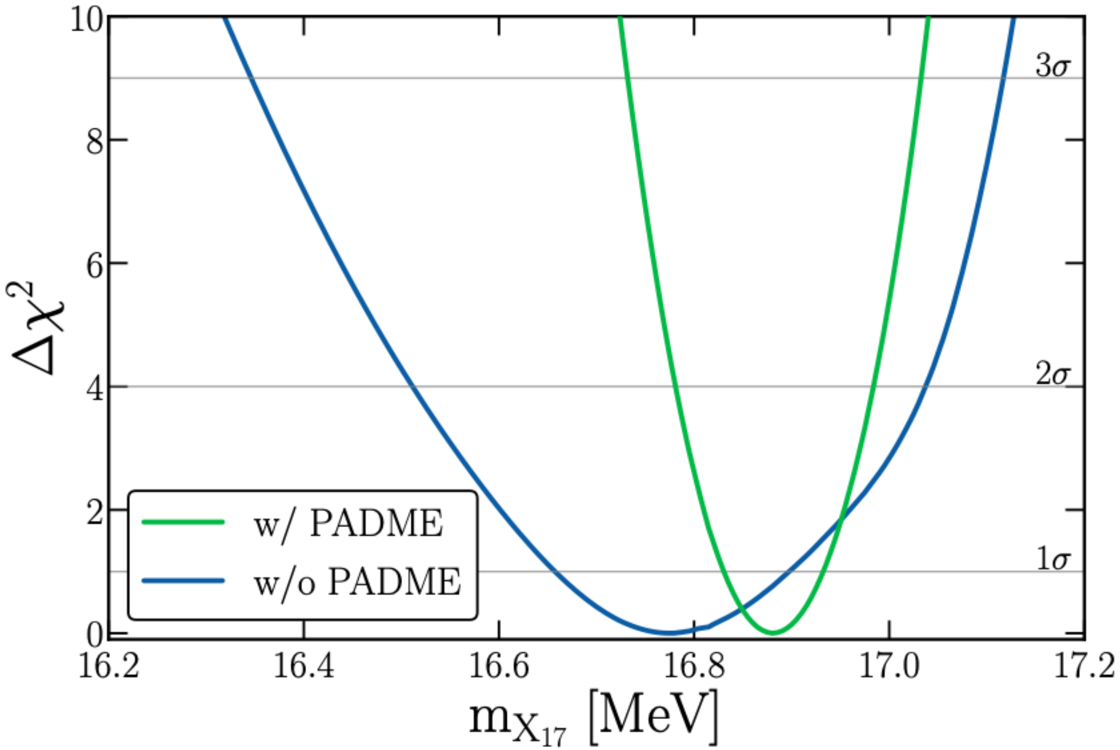
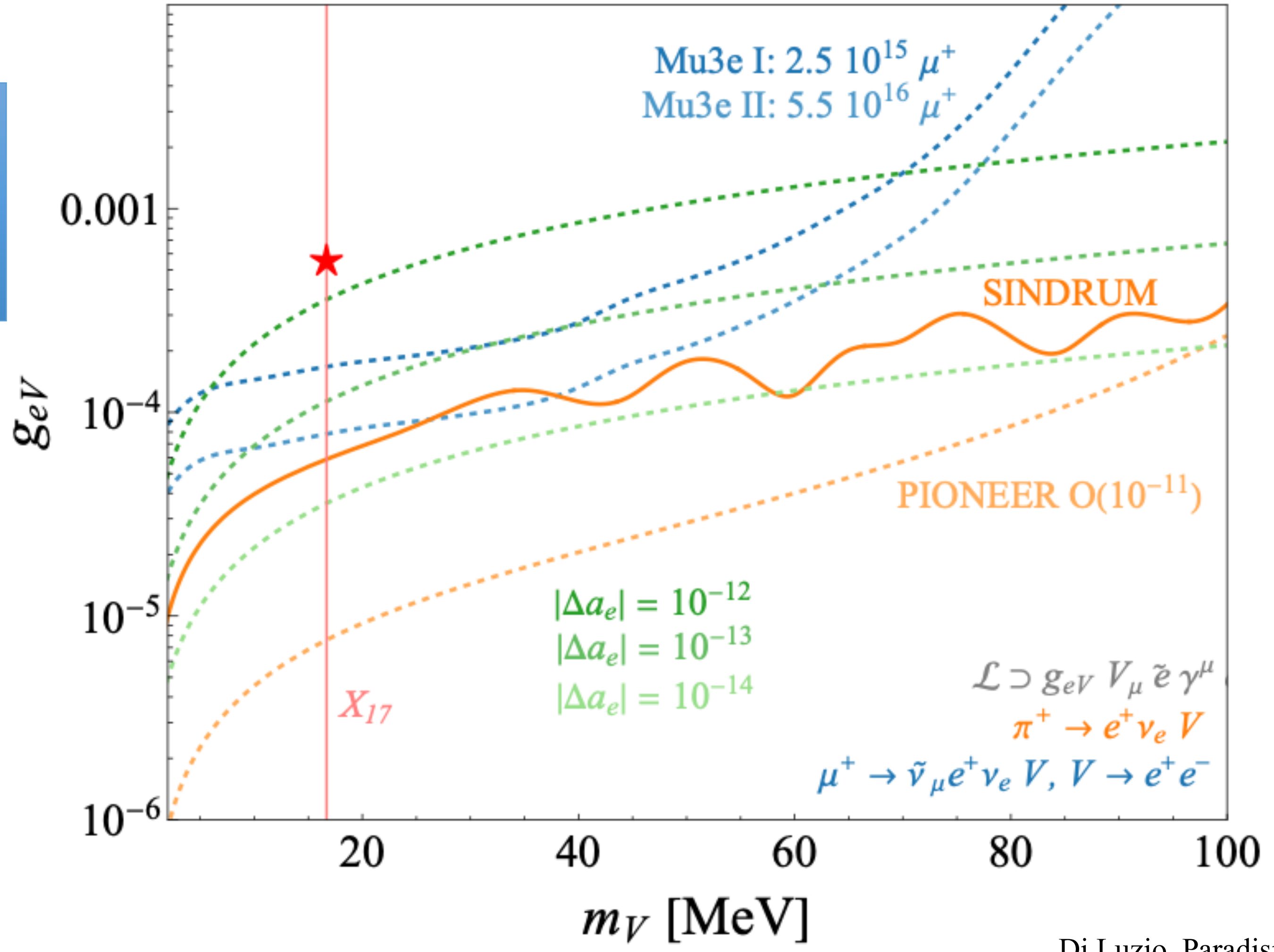


FIG. 2. Value of the $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$ for the X_{17} mass marginalized over $R_{\rm Be}$. The gray horizontal lines corresponds to the 1σ, 2σ and 3σ of a χ^2 variable with 1 degree of freedom.

Arias-Aragon, Grilli Di Cortona, Nardi, Toni, Arxiv:2505.24797

Padme result from a pheno point of view

PADME best fit of the coupling seems in tension with other observables, in particular (g-2)



Di Luzio, Paradisi, Selimovic, arxiv:2504.14014

FIG. 1. Present constraints (solid lines) and expected sensitivities (dashed lines) for a light $X = S, P, V, A$ particle coupled to electrons in the 1–100 MeV mass range. The vertical, red line at $m_X = 16.9$ MeV denotes the X_{17} benchmark, with the red star (in the vector case) representing the PADME best-fit value $g_{eV} = 5.6 \times 10^{-4}$.

Conclusions

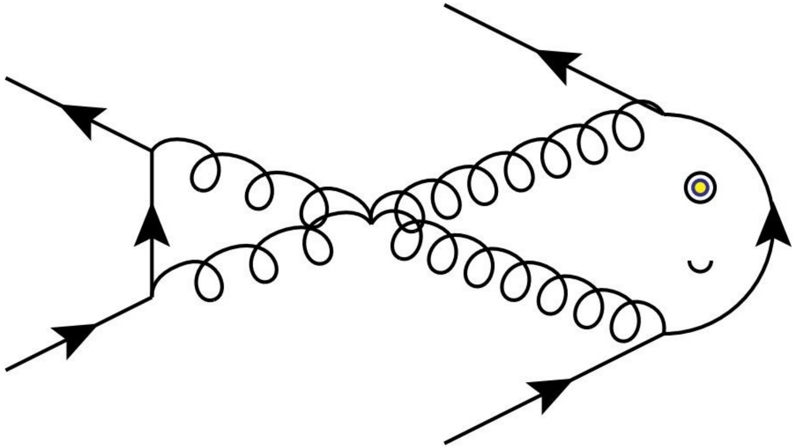
Experiments

- Atomki reported a series of anomalies kinematically consistent with a new particle interpretation.
- MEG-II observed no significant signal in Be but no exclusion is established.
- PADME observed a 1.77σ global deviation at mass 16.90 MeV. They already started a new run of data taking.
- Laboratory of Legnano plans to redo the Atomki experiment (see Tommaso Marchi's talk at "Light Dark Matter 2025" workshop)

Theory

- No theoretical explanation within the SM so far
- Parity-conserving scenarios are excluded or disfavored with spin up to 2 (parity-violating X17?)
- The best fit value of Padme for electron coupling seems disfavored by other observables as (g-2)

The End



THANK YOU
FOR THE
ATTENTION!