An Updated View on Parity-Conserving X17 Scenarios

Claudio Toni

based on the works:
-Barducci and CT, arxiv:2212.06453
-Barducci, Germani, Nardecchia, Scacco and CT, arixiv:2501.05507

«The X17 particle, status and new ideas?» workshop, ECT*, 26/03/2026

Arguments of the talk

1) Brief comment on experimental results

2) X17 hypothesis and kinematics

3) X17 dynamics

4) Conclusion

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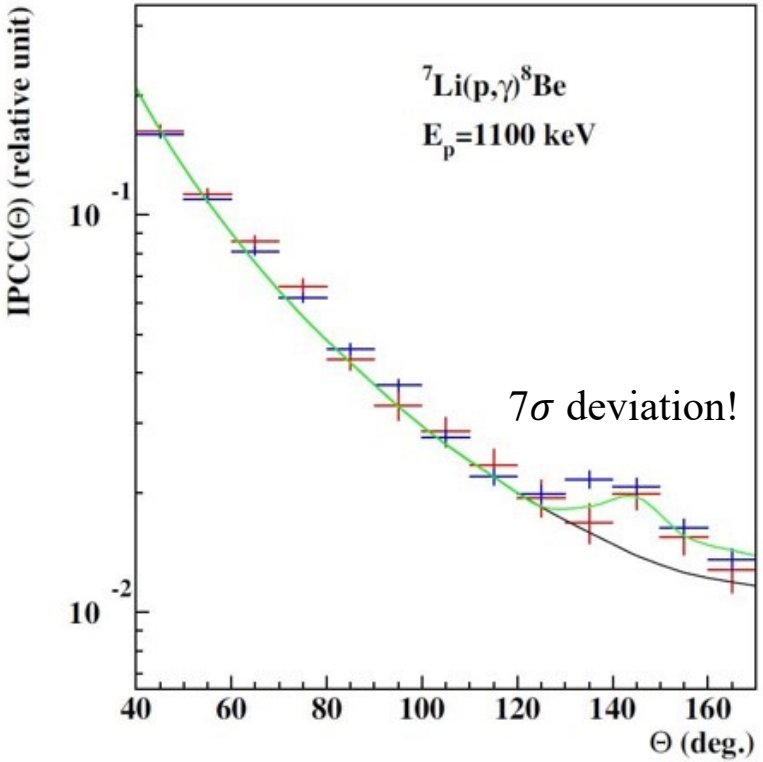
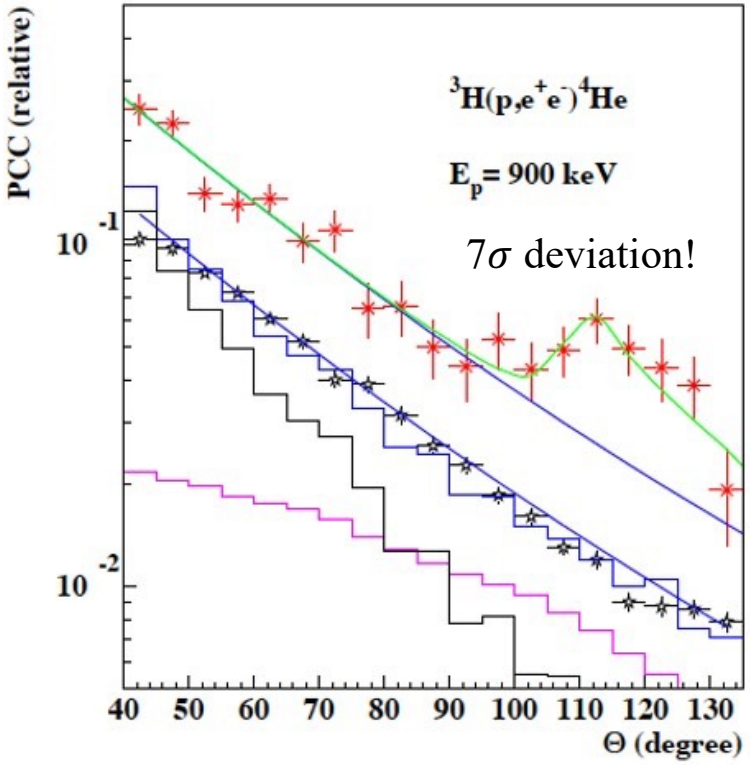
ATOMKI search

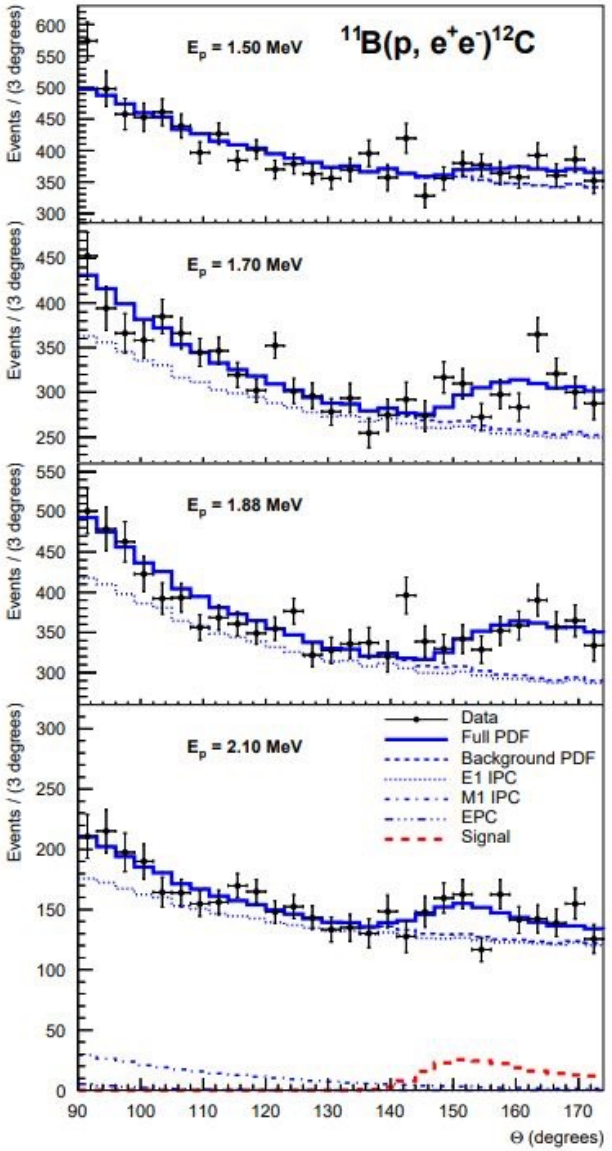
ATOMKI proposal: looking for New Physics at the MeV scale trough nuclear transitions!

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



Phys.Rev.C 104 (2021) 4, 044003





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

ATOMKI search

Assuming only production from the nuclear resonances, ATOMKI provided best-fit values of the anomalous branching ratios:

J. Phys.: Conf. Ser. 1056 012028

Beryllium (R_{Be})

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

Phys.Rev.C 104 (2021) 4, 044003

Helium (R_{He})

$$\frac{\Gamma(^4\mathrm{He}(20.21) \to {}^4\mathrm{He} + X)}{\Gamma(^4\mathrm{He}(20.21) \to {}^4\mathrm{He} + e^+e^-)}\,\mathrm{BR}(X \to e^+e^-) = 0.20 \pm 0.03 \qquad \text{If } S^\pi = 0^+,1^-,2^+,\ldots$$

$$\frac{\Gamma(^4\mathrm{He}(21.01) \to {}^4\mathrm{He} + X)}{\Gamma(^4\mathrm{He}(20.21) \to {}^4\mathrm{He} + e^+e^-)}\,\mathrm{BR}(X \to e^+e^-) = 0.87 \pm 0.14 \qquad \text{If } S^\pi = 0^-,1^+,2^-,\ldots$$

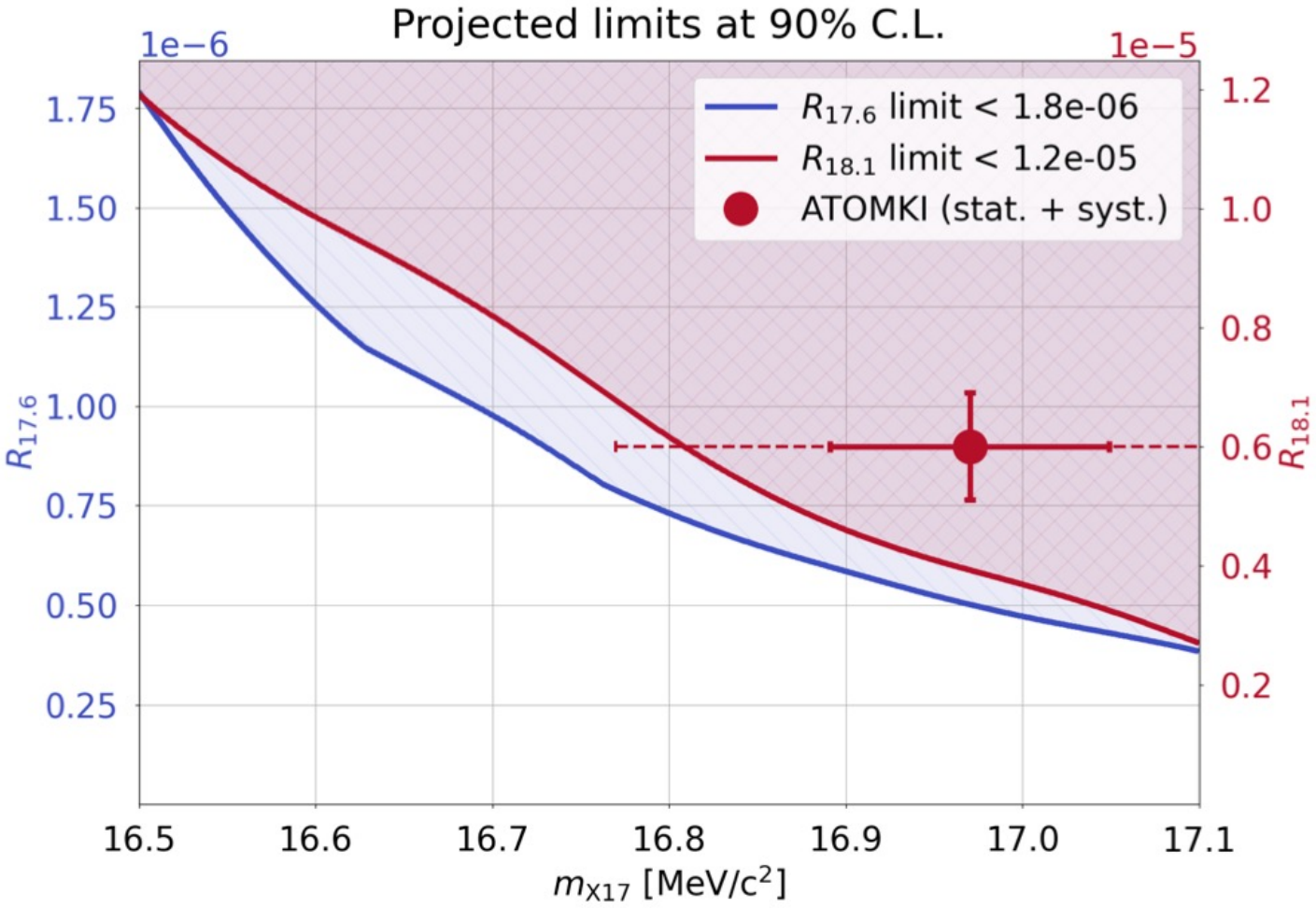
Phys.Rev.C 106 (2022) 6, L061601

Carbon (R_C)

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

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)

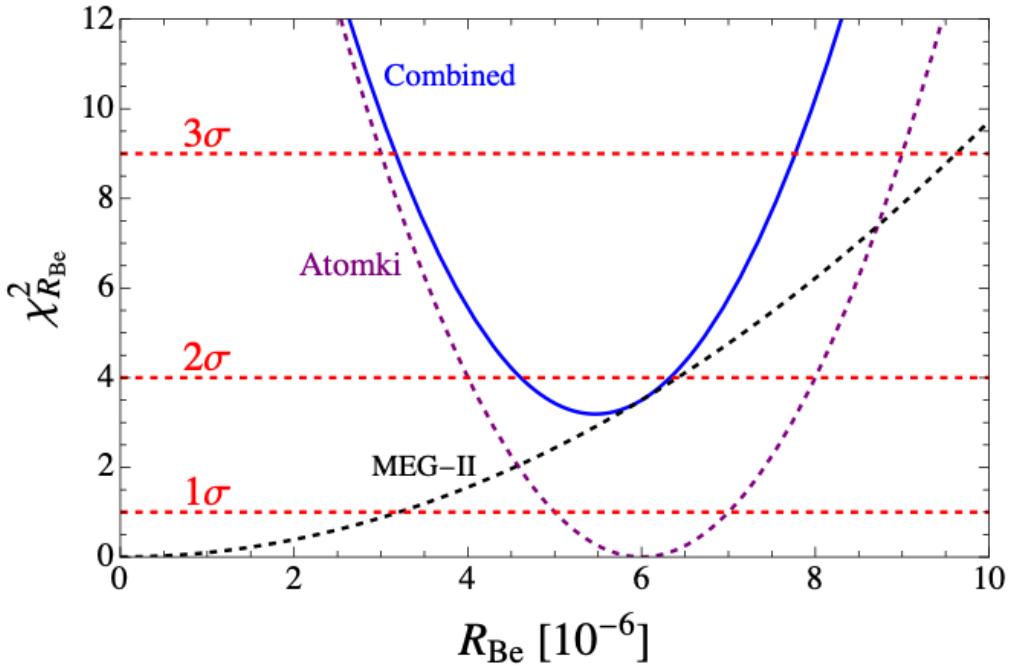


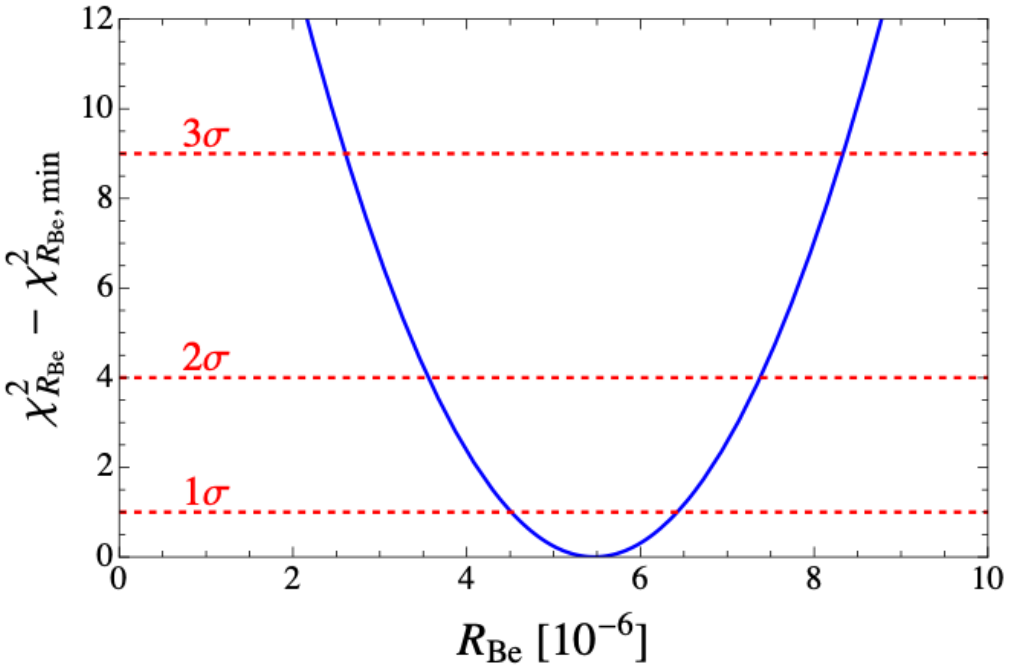
Confronting Atomki and MEG-II

- 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(Delton and Gehrlein arxiv:2304.09877)

	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

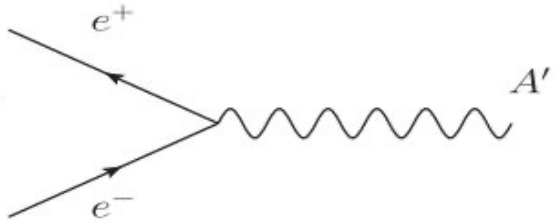


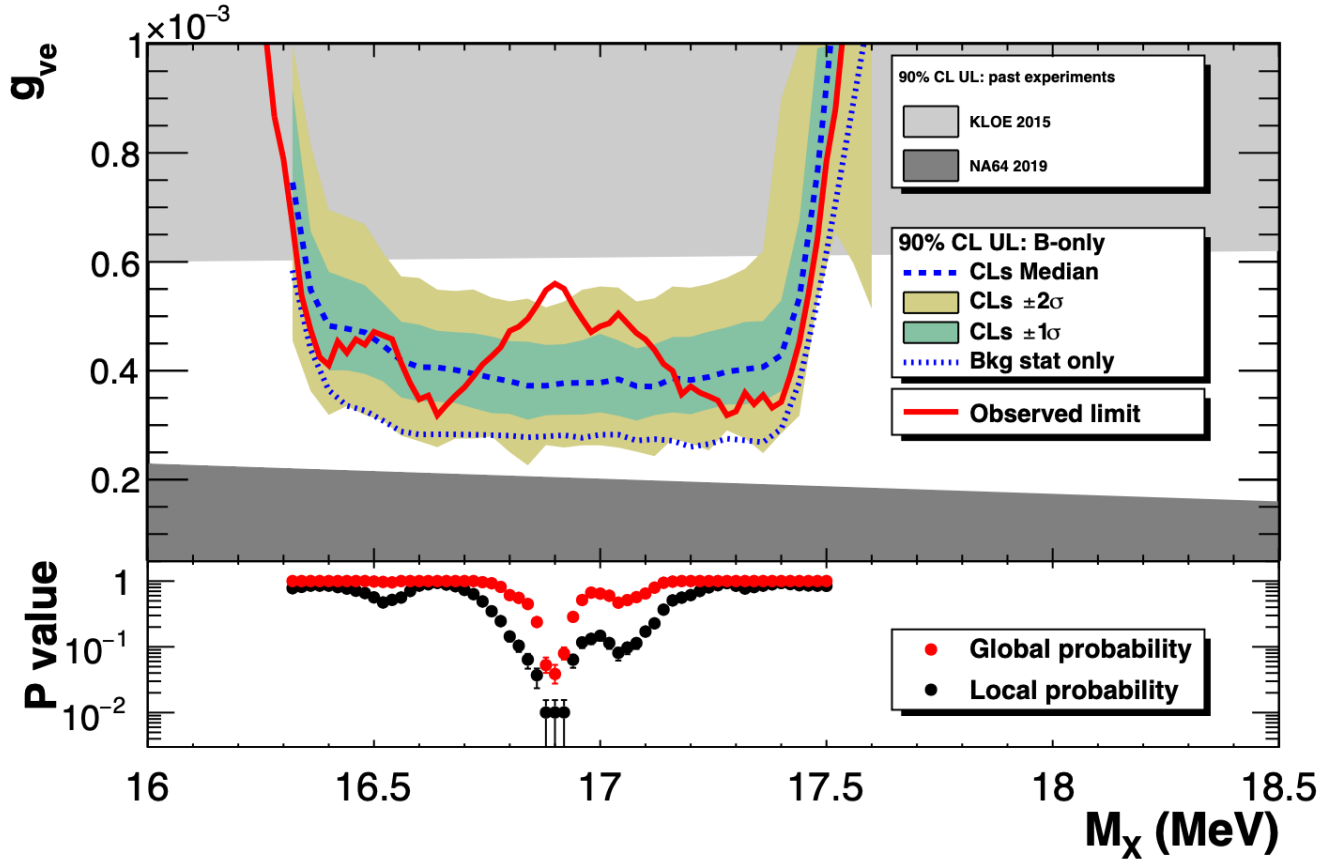


X17 at Padme

- 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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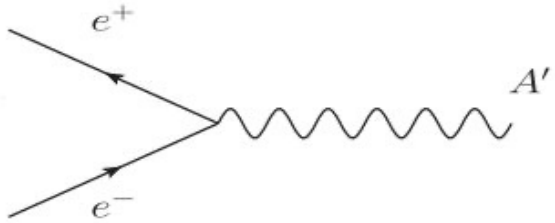

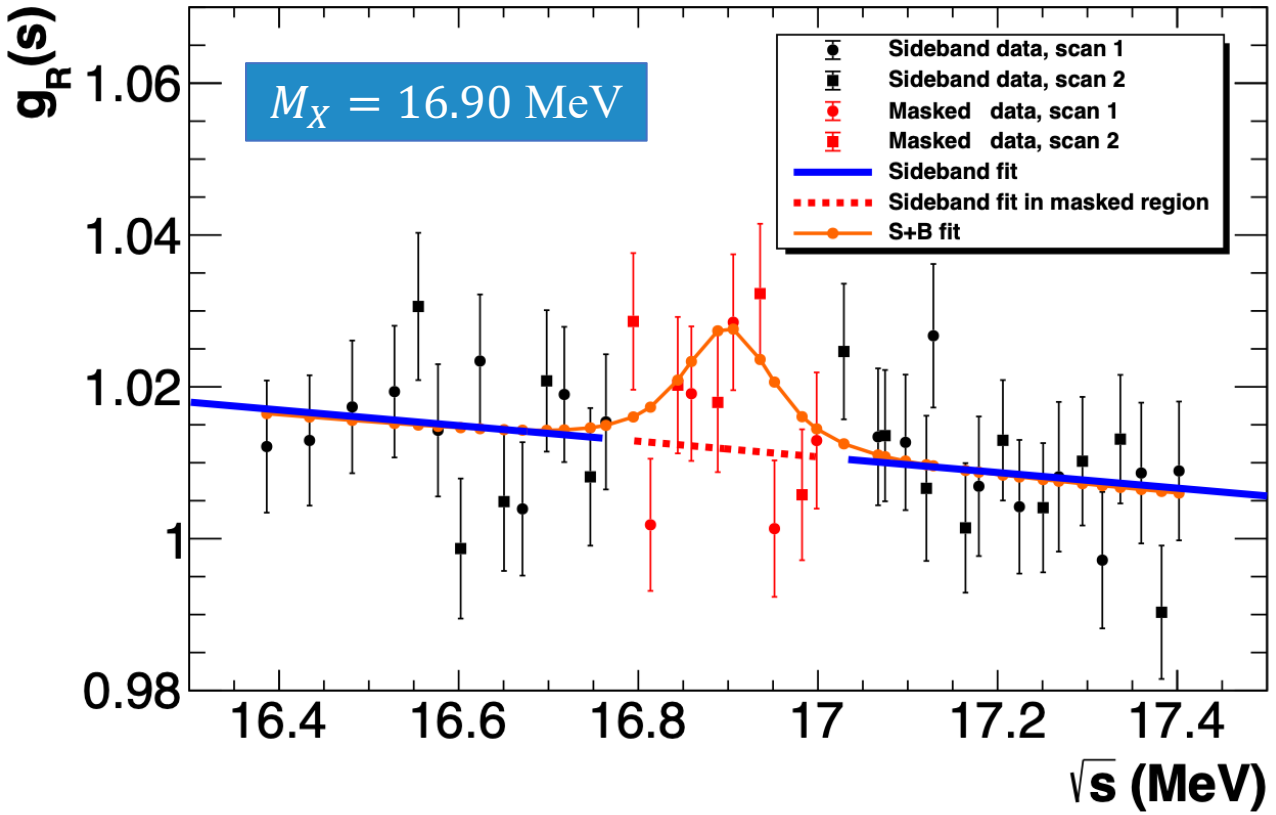

Padme impact on mass extrapolation

If taken seriously, PADME result allows for a precise determination of the new particle mass

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

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 $m_{X_{17}} = 16.78 \pm 0.12\,\text{MeV}$ (1σ uncertainty)[1]. After including the PADME mass determination, the uncertainty gets reduced by more than a factor of two, giving $m_{X_{17}} = 16.88 \pm 0.05\,\text{MeV}$.

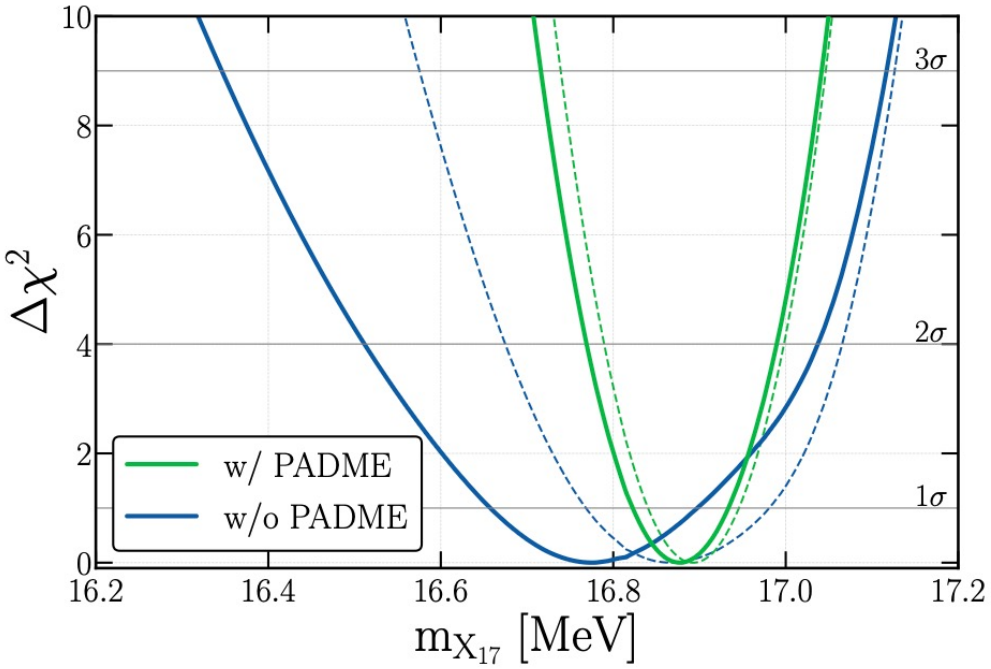

Figure 2 Value of the $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$ for the X_{17} mass marginalized over $R_{\rm Be}$. Green (blue) lines are with (without) the inclusion of the PADME measurement. Continuous (dashed) lines correspond to assuming fully correlated (uncorrelated) systematic uncertainties for the nuclear physics results. The gray horizontal lines corresponds to the 1σ, 2σ and 3σ of a χ^2 variable with one degree of freedom.

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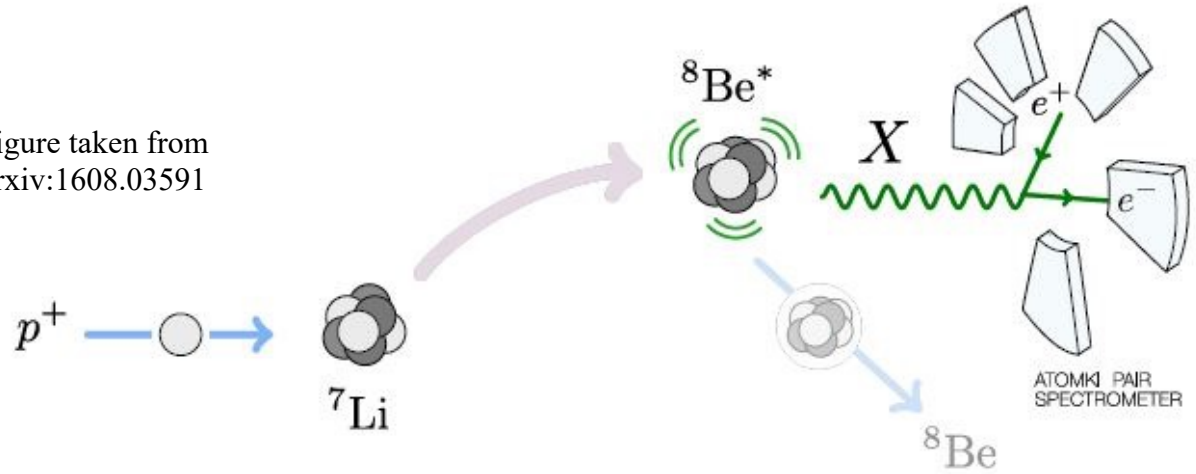
Features of X17

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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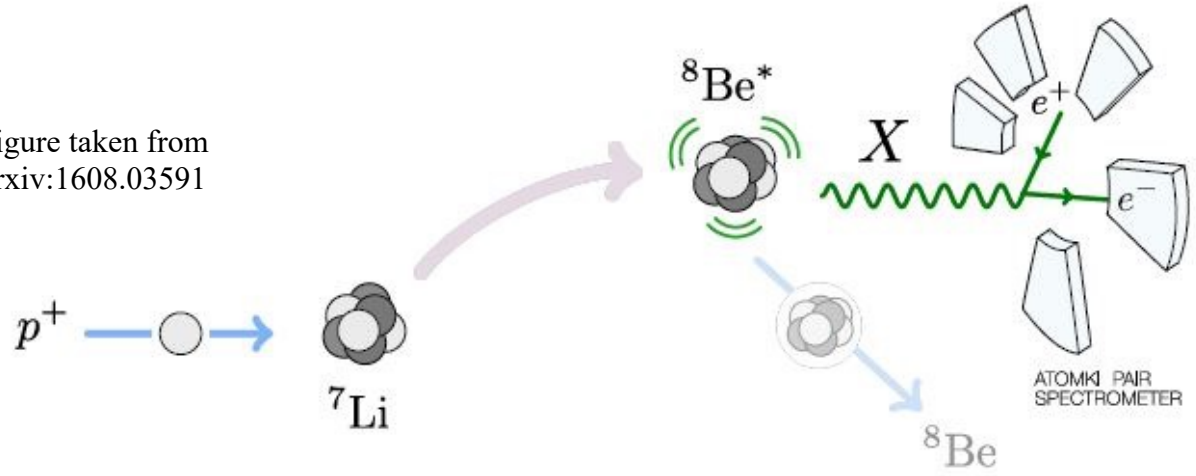

- Best fit mass values give ~17 MeV.
- The particle must be a neutral boson.
- It propagates less then 1 cm in the apparatus ⇒ short-lived boson

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

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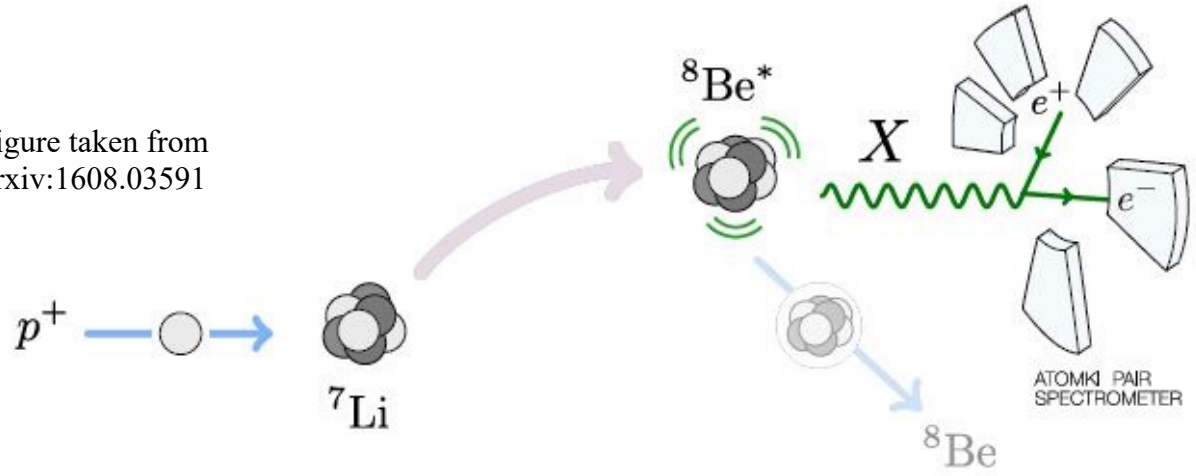

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$$\text{Signal Rate} = \underbrace{\sigma(N^* \to N + X)}_{\text{coupled to nuclear matter, i.e. quarks and gluons}} \times \underbrace{\mathrm{BR}(X \to e^+e^-)}_{\text{coupled to electron/positrons}}$$

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

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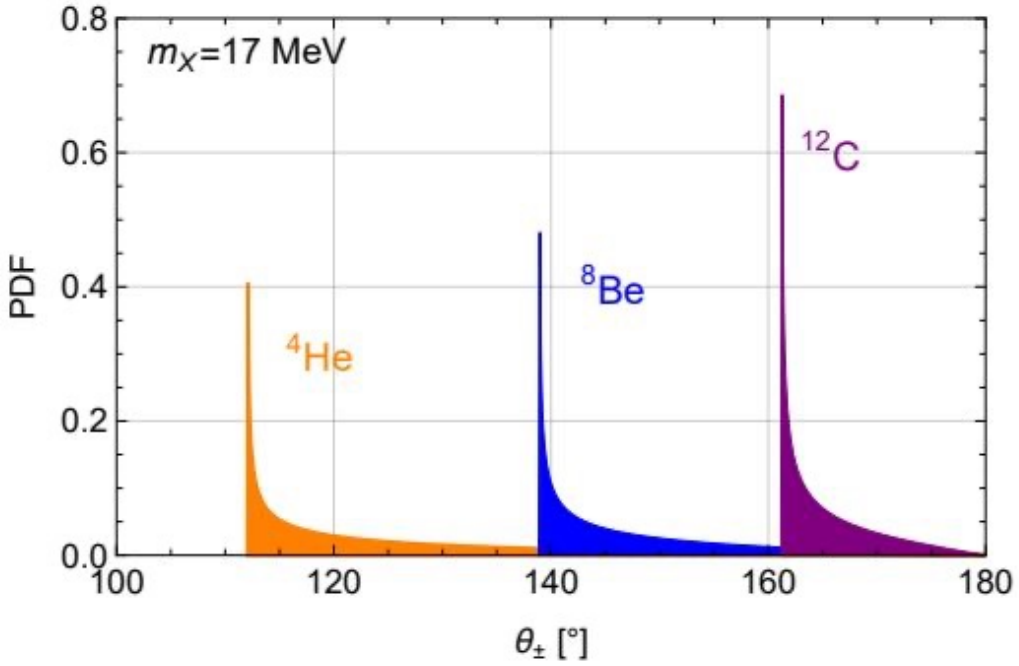
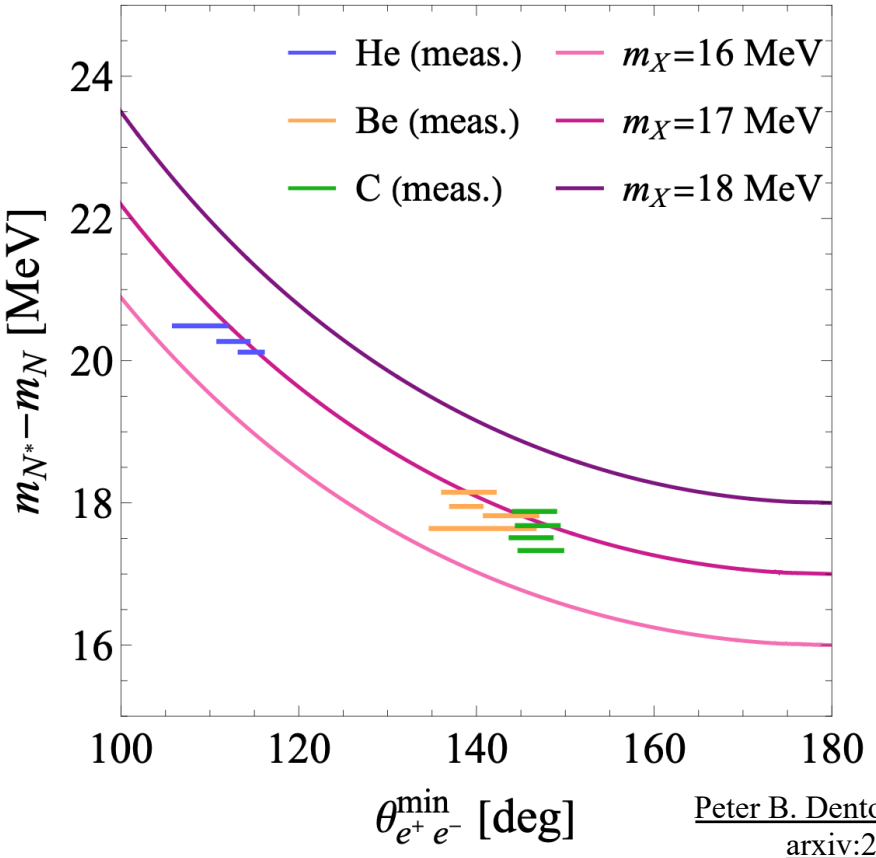
1) the e+e− opening angles of the anomalous peaks are located around 140°, 115° and 155°−160°, respectively, for the 8Be, 4He and 12C anomaly.





Peter B. Denton, Julia Gehrlein, arxiv:2304.09877

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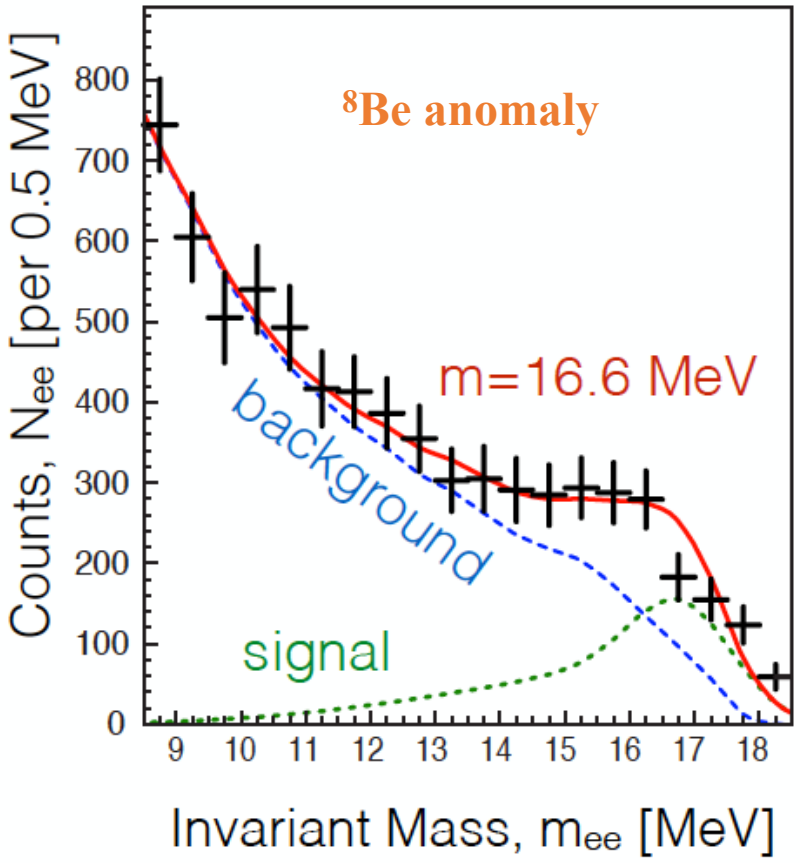
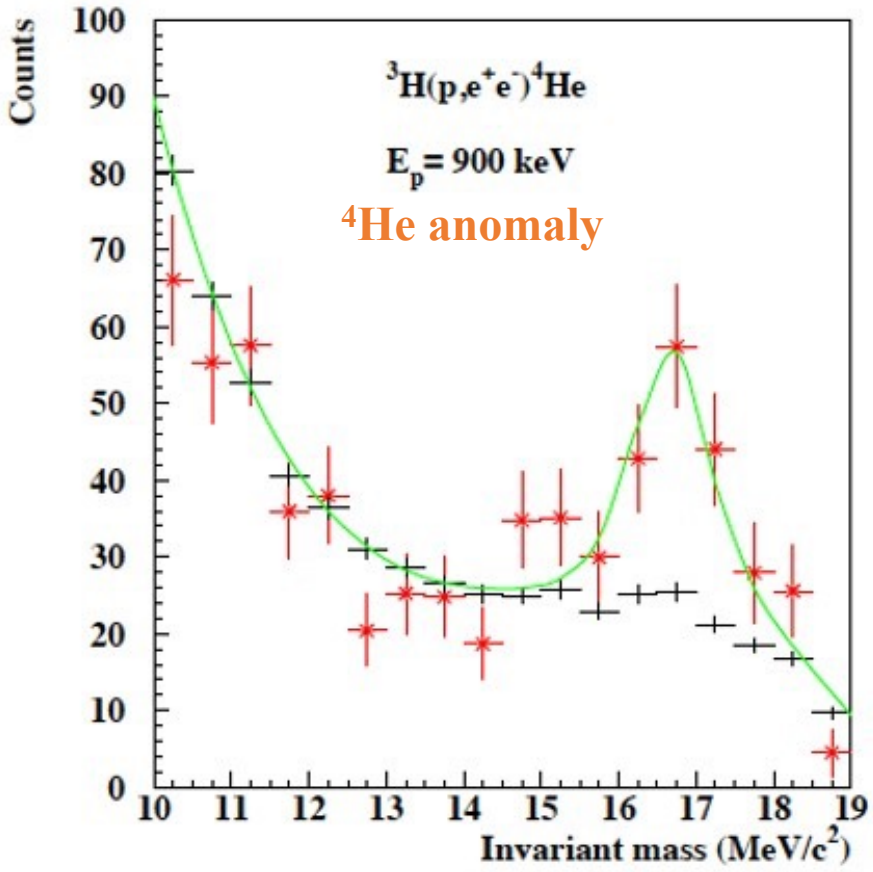
2) The excesses are resonant bumps located at the same e+e− invariant mass for all the 8Be and 4He transitions.





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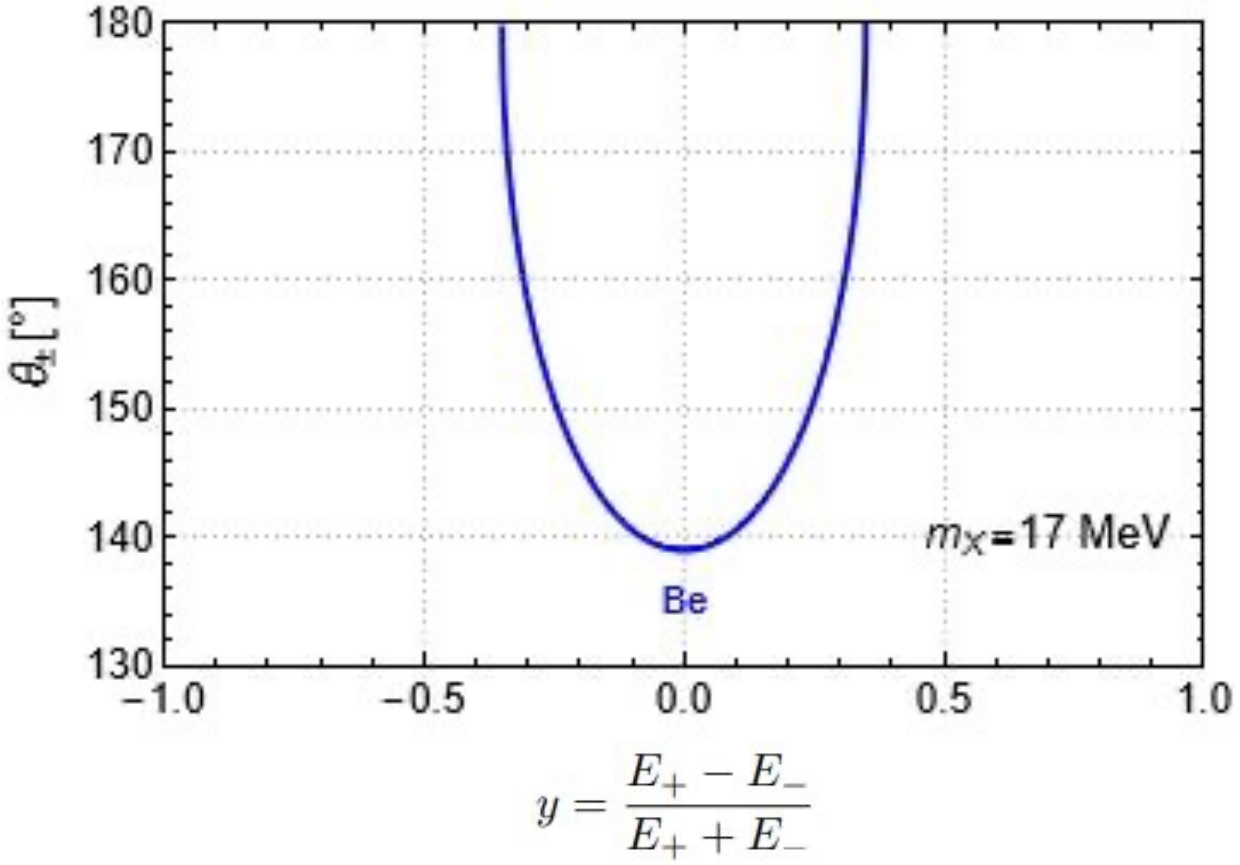
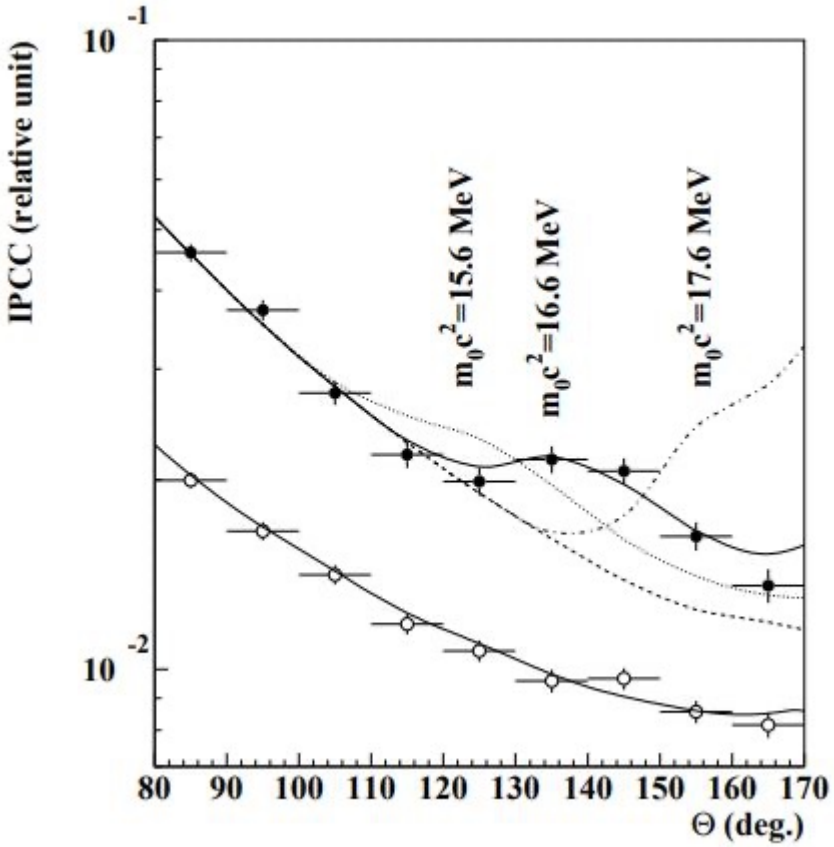
3) the anomalous signal in the 8Be transition have been observed only inside the kinematic region given by $|y| < 0.5$, where y is energy asymmetry.





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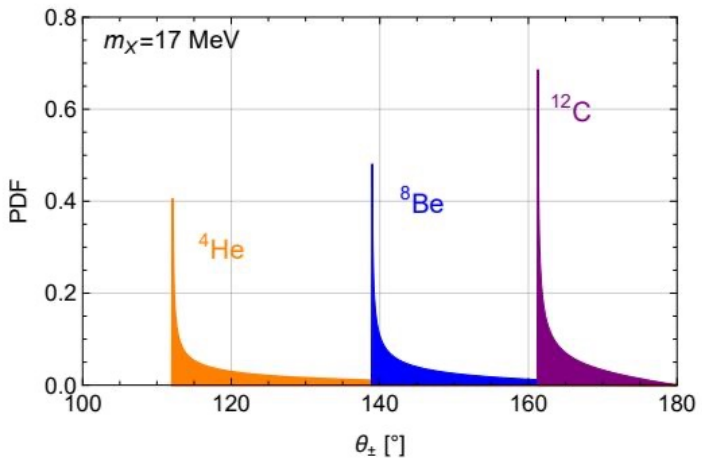
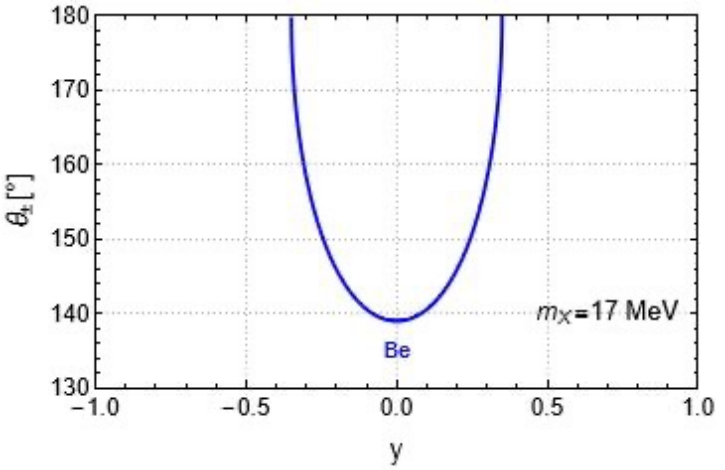
2) The excesses are resonant bumps located at the same e+e− invariant mass for all the 8Be and 4He transitions.
3) The anomalous signal in the 8Be transition have been observed only inside the kinematic region given by $|y| < 0.5$, where y is energy asymmetry.



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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A lot of works on the possible origin of such a boson, e.g.

- Dark U(1) gauge boson (see e.g. Feng et al. arxiv:1608.03591 and many others, or Stefano Moretti's talk)
- QCD axion (Daniele Alves arxiv:2009.05578)
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However, regardless of its UV origin, what can we say on the X17 based only on the Atomki data?

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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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Working assumption: we assume X17 production predominantly coming from the nuclear resonance transition!

(Perhaps a lazy choice but it was/is what we were able to do it. I will comment on this again at the end of the talk.)

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

- The scalar scenario is excluded by parity conservation in Beryllium transitions (see also Feng at al. arxiv:2006.01151).

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^{12}C(17.23) $\to$ ^{12}C	0, 2	1	/	1

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

- The scalar scenario is excluded by parity conservation in Beryllium transitions (see also Feng at al. arxiv:2006.01151).
- The pseudoscalar scenario is excluded by parity conservation in Carbon transition.

Process	***X* boson spin parity**			
$N^* \to N$	$S^\pi = 1^-$	$S^\pi = 1^+$	$S^\pi = 0^-$	$S^\pi = 0^+$
$^8\mathrm{Be}(18.15) \to {}^8\mathrm{Be}$	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})

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

Helium (R_{He})

$$\frac{\Gamma(^4\mathrm{He}(20.21) \to {}^4\mathrm{He} + X)}{\Gamma(^4\mathrm{He}(20.21) \to {}^4\mathrm{He} + e^+e^-)}\,\mathrm{BR}(X \to e^+e^-) = 0.20 \pm 0.03 \quad \text{If } S^\pi = 0^+,1^-,2^+,\ldots$$

$$\frac{\Gamma(^4\mathrm{He}(21.01) \to {}^4\mathrm{He} + X)}{\Gamma(^4\mathrm{He}(20.21) \to {}^4\mathrm{He} + e^+e^-)}\,\mathrm{BR}(X \to e^+e^-) = 0.87 \pm 0.14 \quad \text{If } S^\pi = 0^-,1^+,2^-,\ldots$$

Carbon (R_{C})

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

Theoretical decay rates are evaluated within a multipole expansion method (see Cornelis's talk) up to nuclear matrix elements we took from the literature

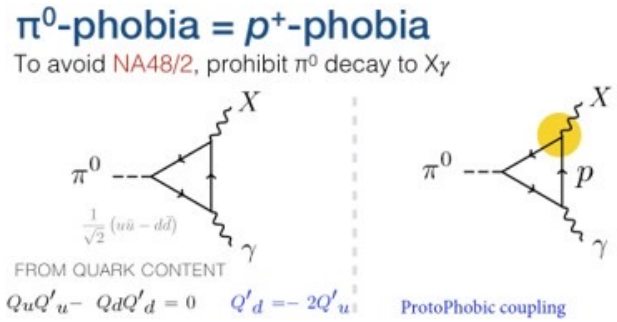
By matching the data to the theoretical prediction, one extracts the nucleon couplings to X17

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

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

Vector X17

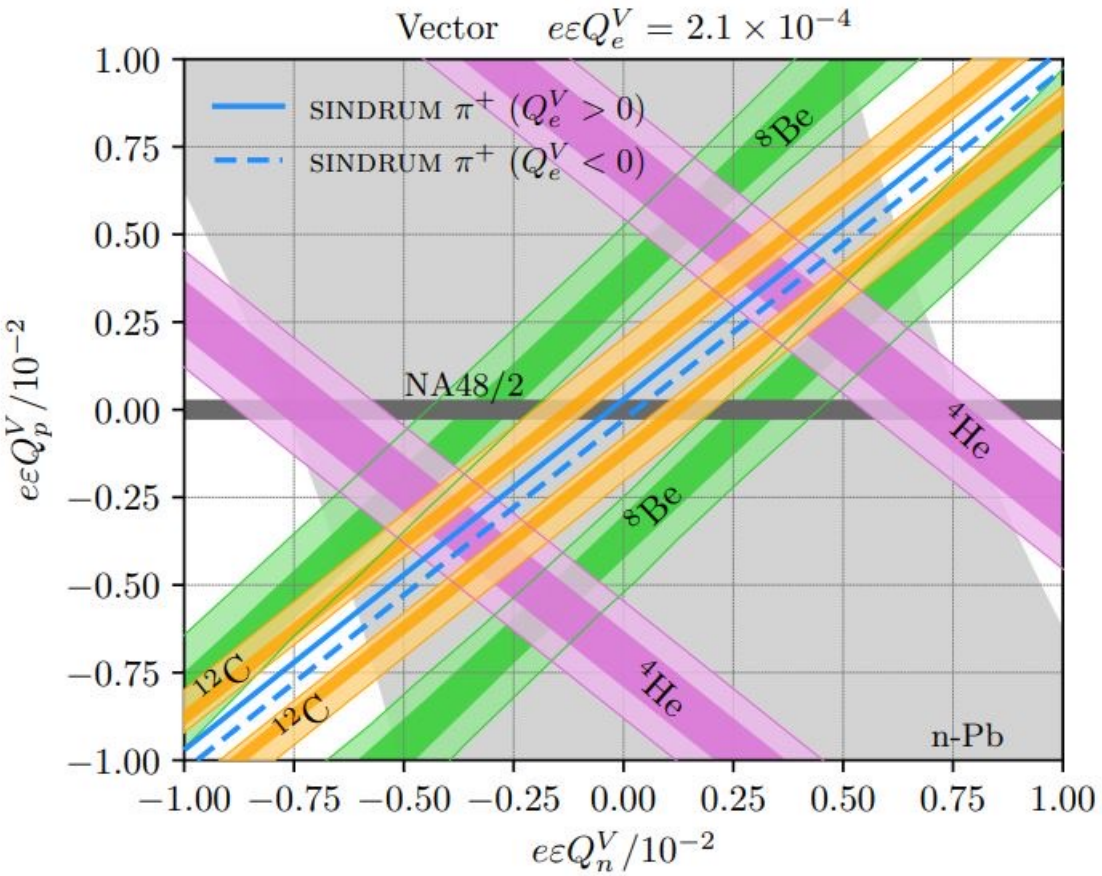
- The Carbon anomaly is in tension with a combined explanation of the Beryllium and Helium anomalies and the NA48 constraint.



- 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 (before)

- An axial-vector X17 is dynamically consistent for Helium and Beryllium.
- The needed nuclear matrix element for the Carbon transition is absent in literature.
- Recently, Hostert and Pospelov calculated the constraints to a spin-1 X17 coming from the SINDRUM search of $\pi^+ \to e^+ \nu_e X$.

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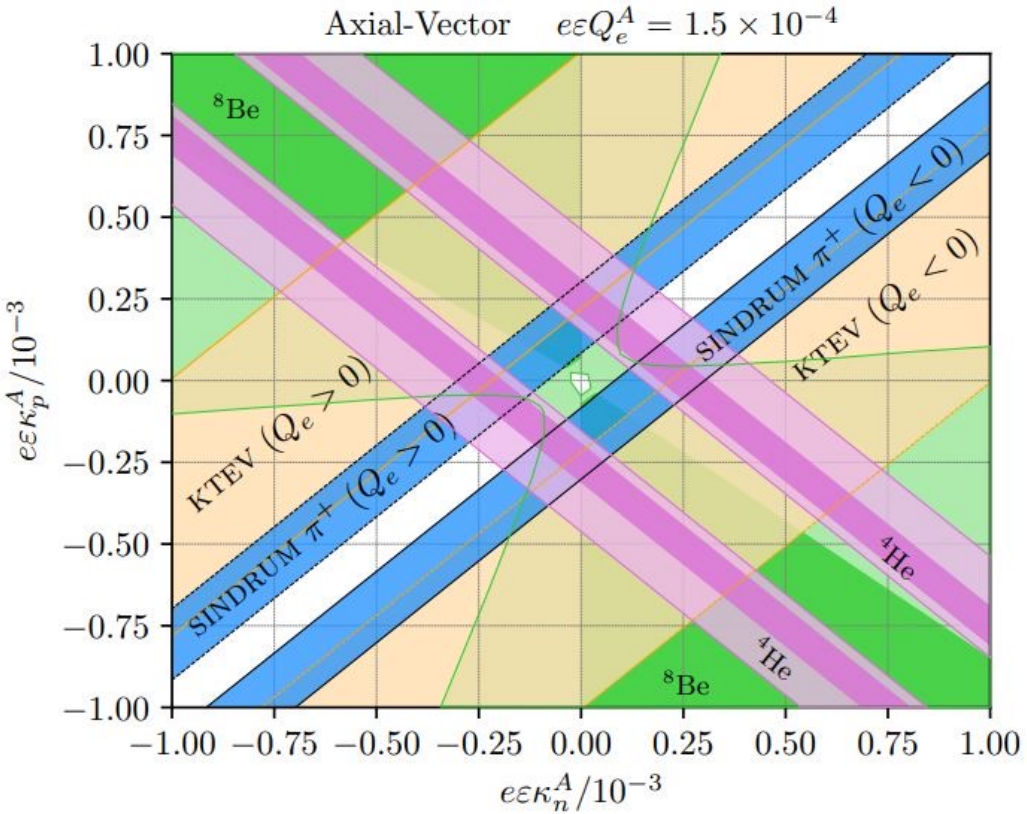


Intriguingly, other experimental anomalies can be simultaneously satisfied:
KTeV measurement of $\pi^0 \to e^+e^-$ and electron's g-2

Axial-vector X17 (now)

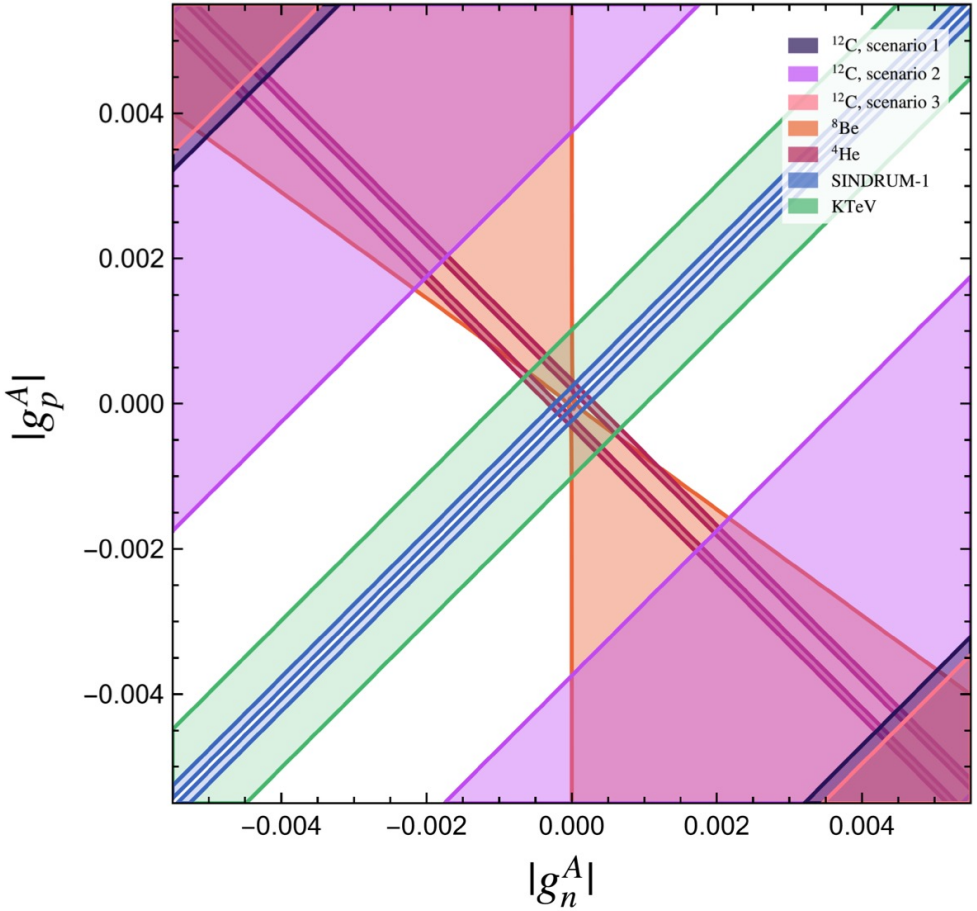
Particle-hole shell model approximation for Carbon excited state:

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

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

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

Mommers and Vanderhaeghen, arxiv:2406.08143



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

See Cornelis Mommers's talk from yesterday

Further bounds from Kaon decays…

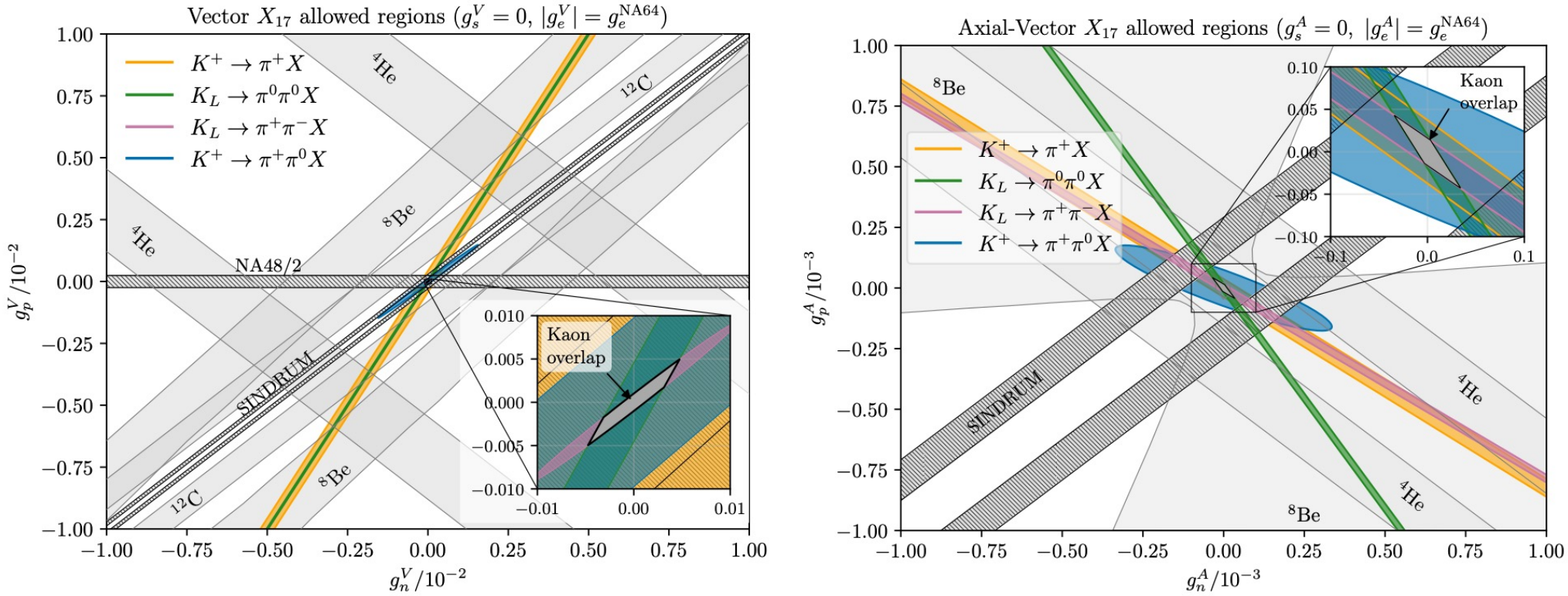


FIG. 5. The allowed regions in the 17 MeV spin-1 boson coupled to a vector (left) or axial-vector (right) current for $g_s^{V,A} = 0$, setting the electron coupling to saturate the lower bound from NA64 [25]. The 90% CL allowed regions for different kaon decay channels are shown in color, together with their overlap, which is highlighted by the inset axis. Constraints from pion decays are shown as dark grey bands. For SINDRUM, the two bands correspond to different sign choices for g_e^V (left) or g_e^V (right). The 2σ allowed regions for the ^{4}He, ^{8}Be, ^{12}C ATOMKI anomalies are shown as light shaded grey (from [56]). The preference regions for ^{12}C in the axial-vector case are beyond the axis boundaries [29].

Hostert, Pospelov and Thompson, arXiv:2602.19479

See Adrian Thompson's talk from yesterday

X17 dynamics (again)

- Atomki and MEG-II are still in agreement at 2σ, so no exclusion established!
- The question then remains the same: is the X17 hypothesis *dynamically* consistent for all the anomalies?
- If so, which is the most promising spin-parity assignment?

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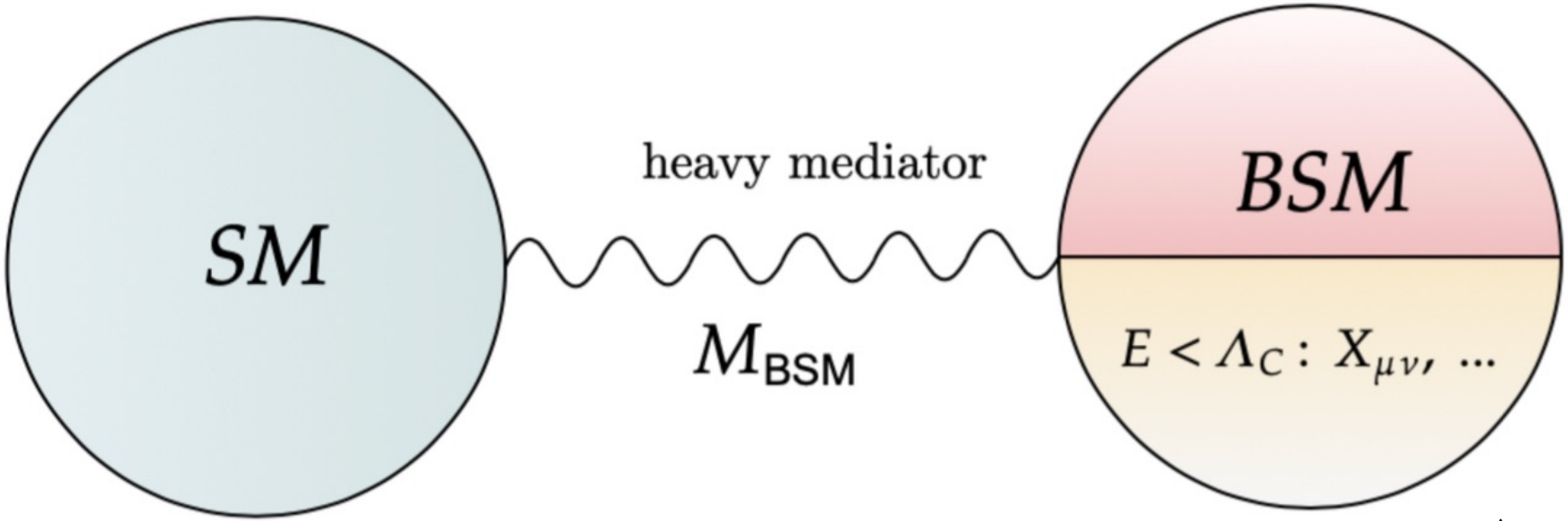

$\Lambda_c = 4\pi m_X \approx 200$ MeV

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

$$+ \tilde{C}_f \left[\gamma_\mu \gamma_5 \left(\frac{p' + p}{4} \right)_\nu + \gamma_\nu \gamma_5 \left(\frac{p' + p}{4} \right)_\mu \right]$$

Axial-tensor X17 $J^\pi = 2^-$

$$+ \quad + \quad \Bigg\} u(p, \sigma) \; [\epsilon_a^{\mu\nu}(p - p')]^*$$

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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 combined with electron's (g-2)

Spin-2 scenarios are out too!

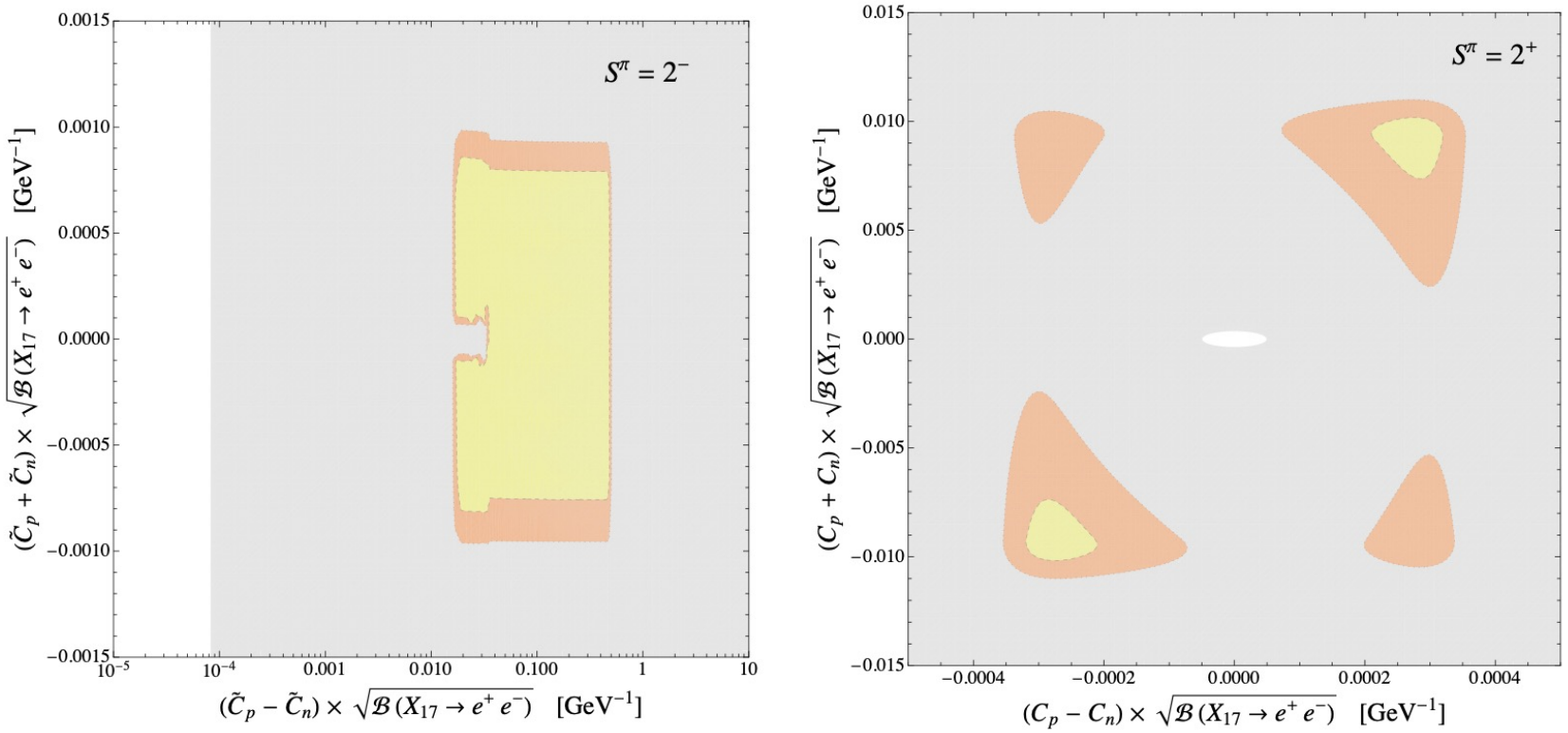

Figure 3 Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\text{profiled}} < 2.28, 5.99, 11.62$, for an axial tensor (left) and tensor (right) boson. The gray region is excluded by SINDRUM search at 90% CL.

Arguments of the talk

1) Brief comment on experimental results

2) X17 hypothesis and kinematics

3) X17 dynamics

4) Conclusion

A brief recap

- We studied all the possible scenarios of parity-conserving X17 states with spin≤ 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
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See Max Fieg's talk from today
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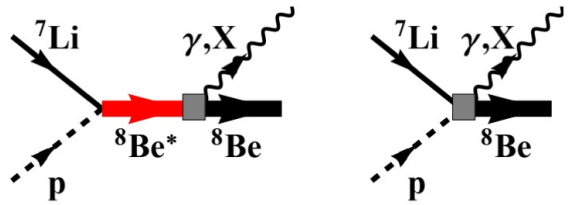
…or refine the analysis including the direct proton capture!



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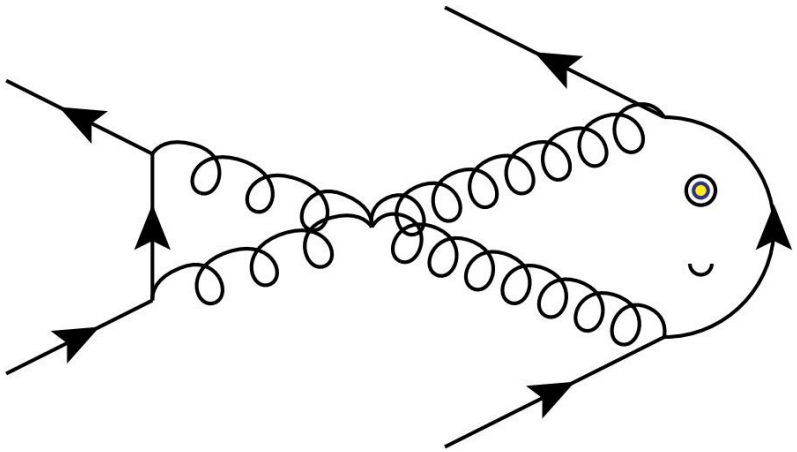
A joint effort of experimentalists and theorists, from both nuclear and particle sectors, helps advance our understanding of what's going on. Opportunities for exchange like this workshop are invaluable.

The End



THANK YOU
FOR THE
ATTENTION!