The X17 boson: status and prospects

Claudio Toni

LDMA 2025, 10/04/2025

Arguments of the talk

1) ATOMKI search and anomalies

2) X17 hypothesis and kinematics

3) X17 dynamics and spin/parity

4) Recent development from MEG-II and Padme

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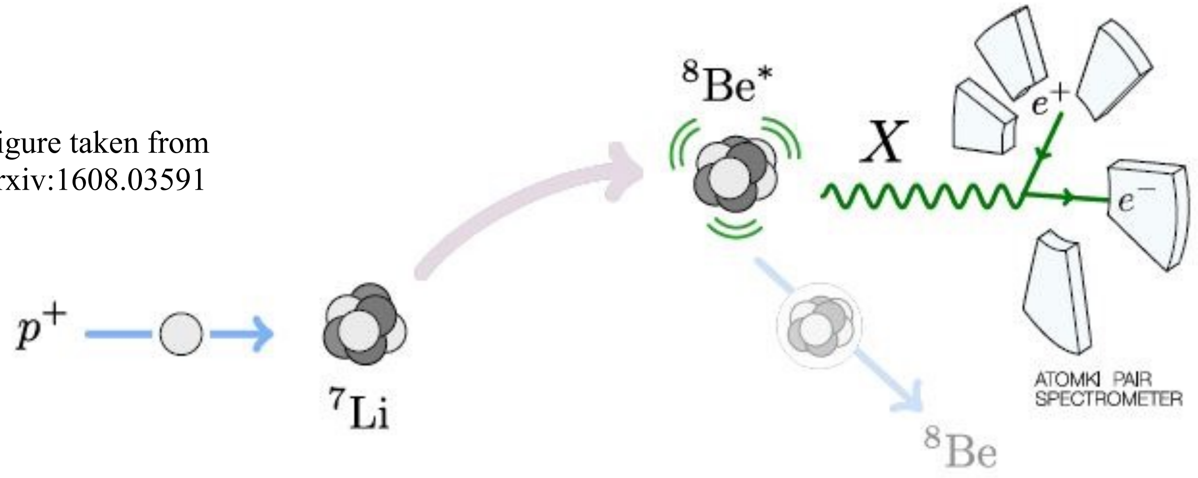
ATOMKI search

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

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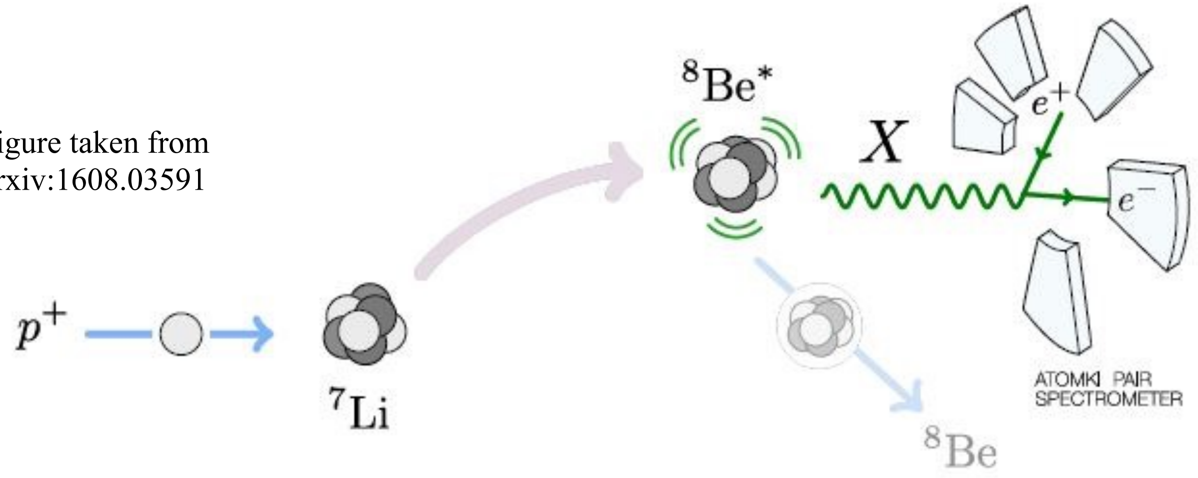

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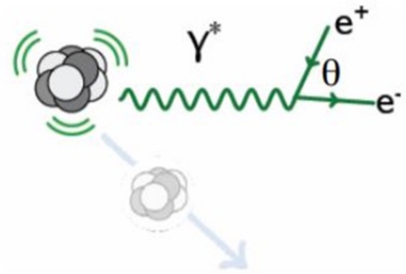
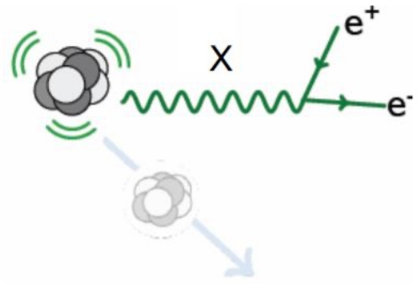
QED processes:



~ second order in QED coupling

NP processes:



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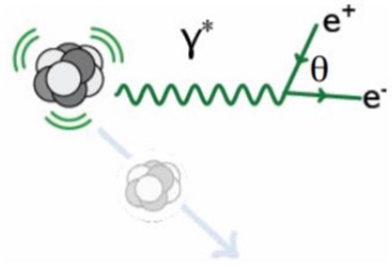
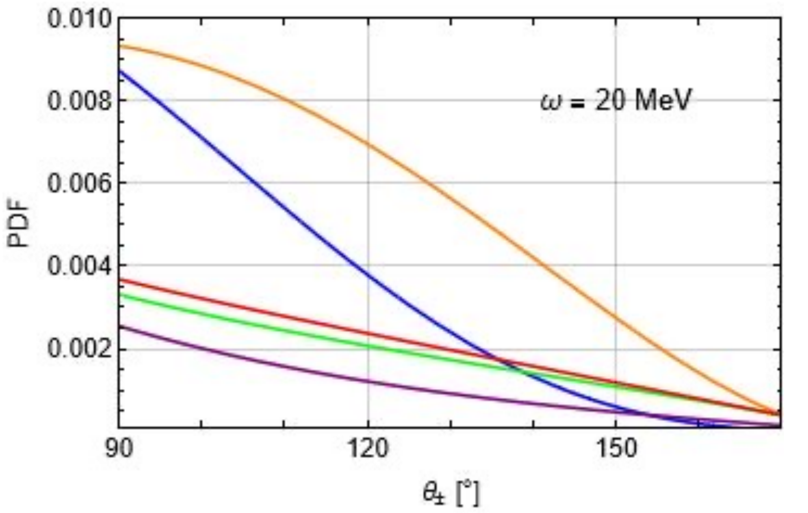
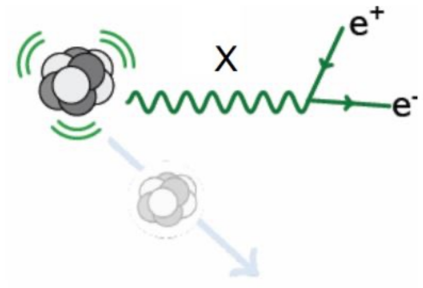
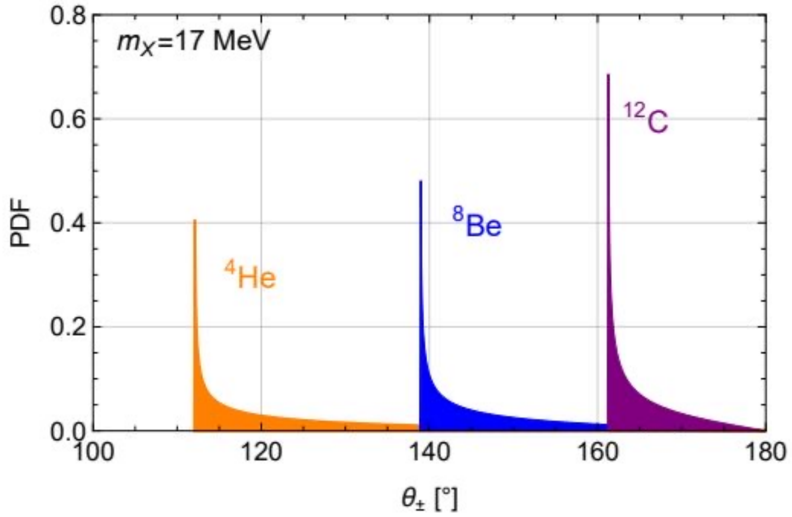




At large angles, QED predicts that the angular correlation of lepton pairs drops rapidly.

NP:



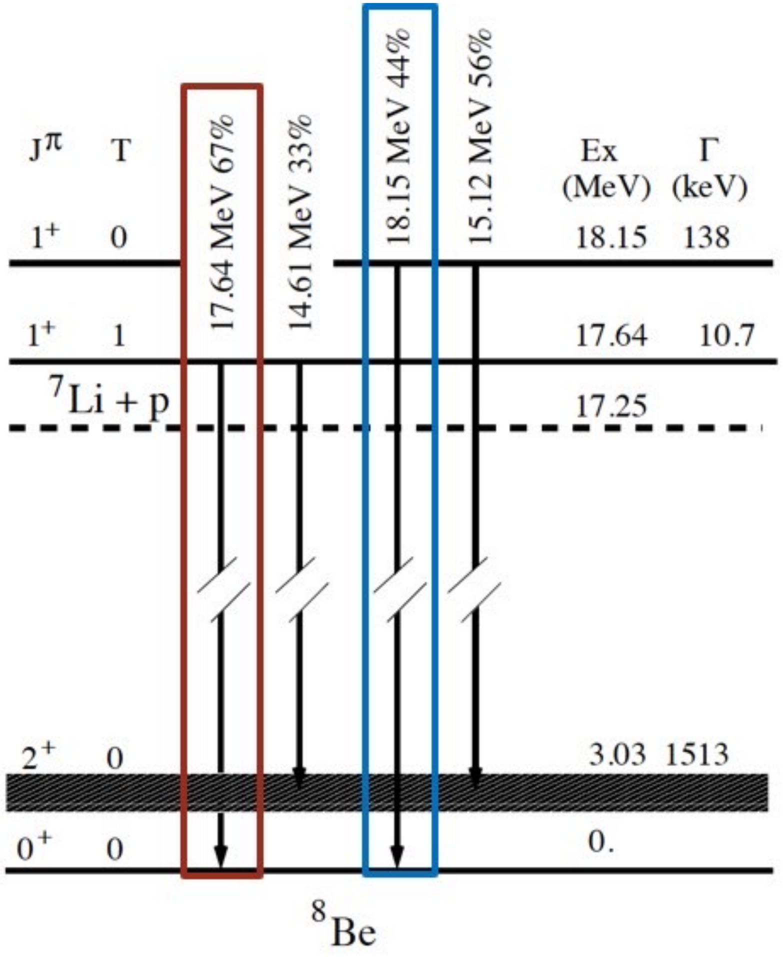


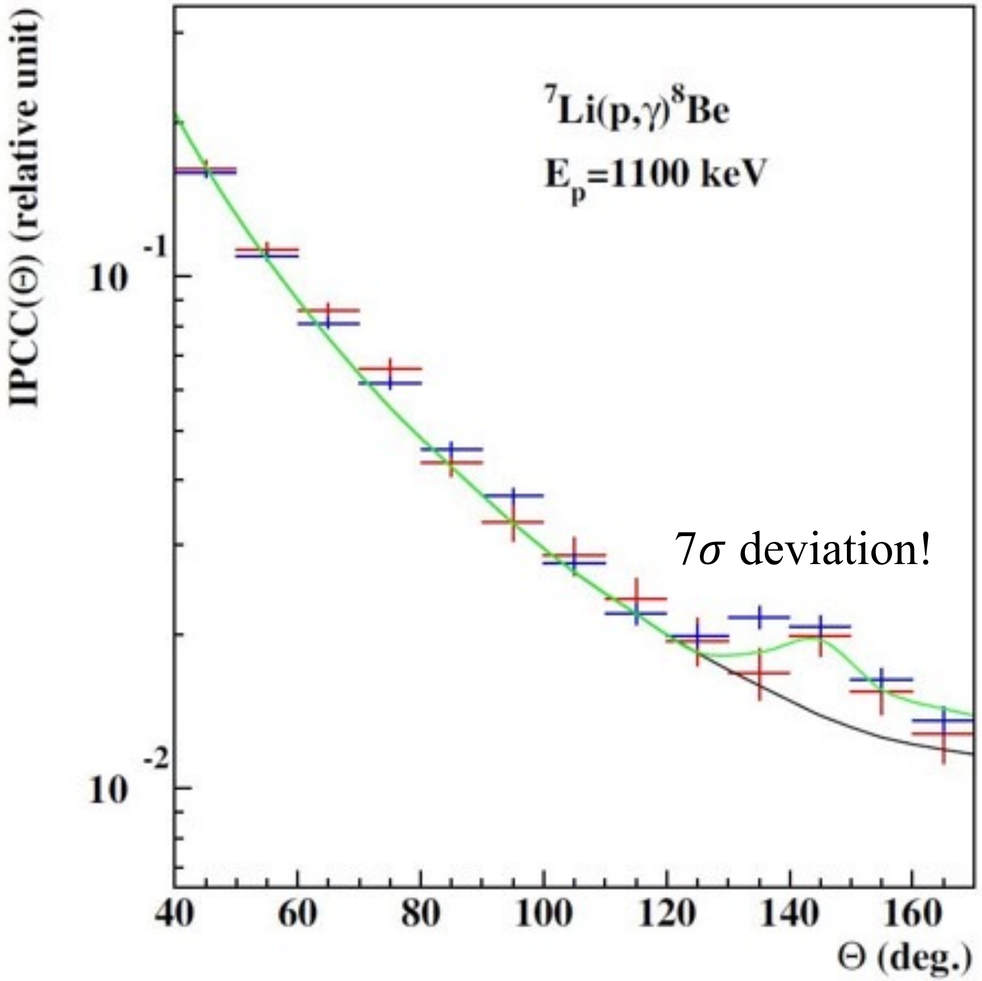
Bump-like distribution peaked at large angles!

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.

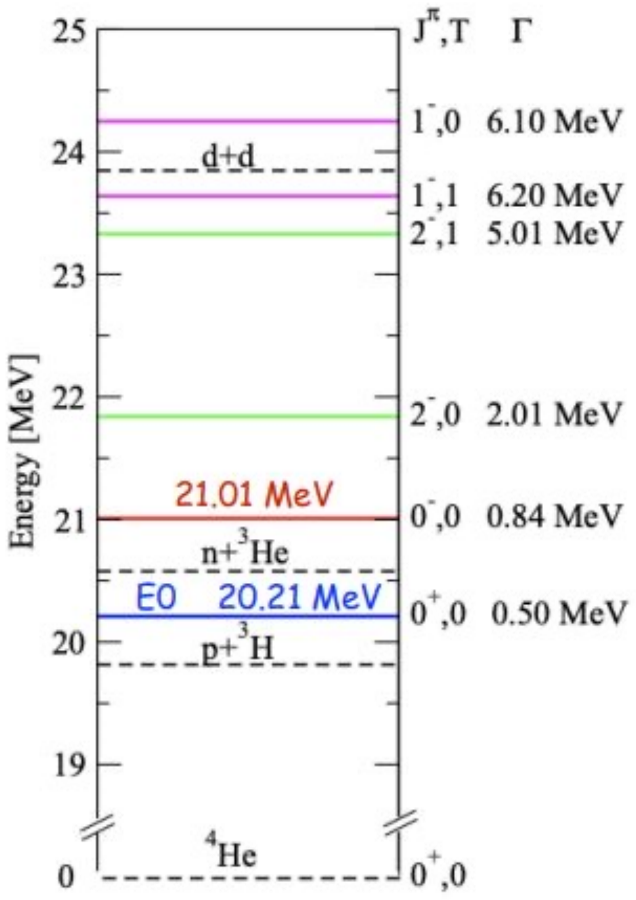
Phys.Rev.Lett. 116 (2016) 4, 042501
J. Phys.: Conf. Ser. 1056 012028

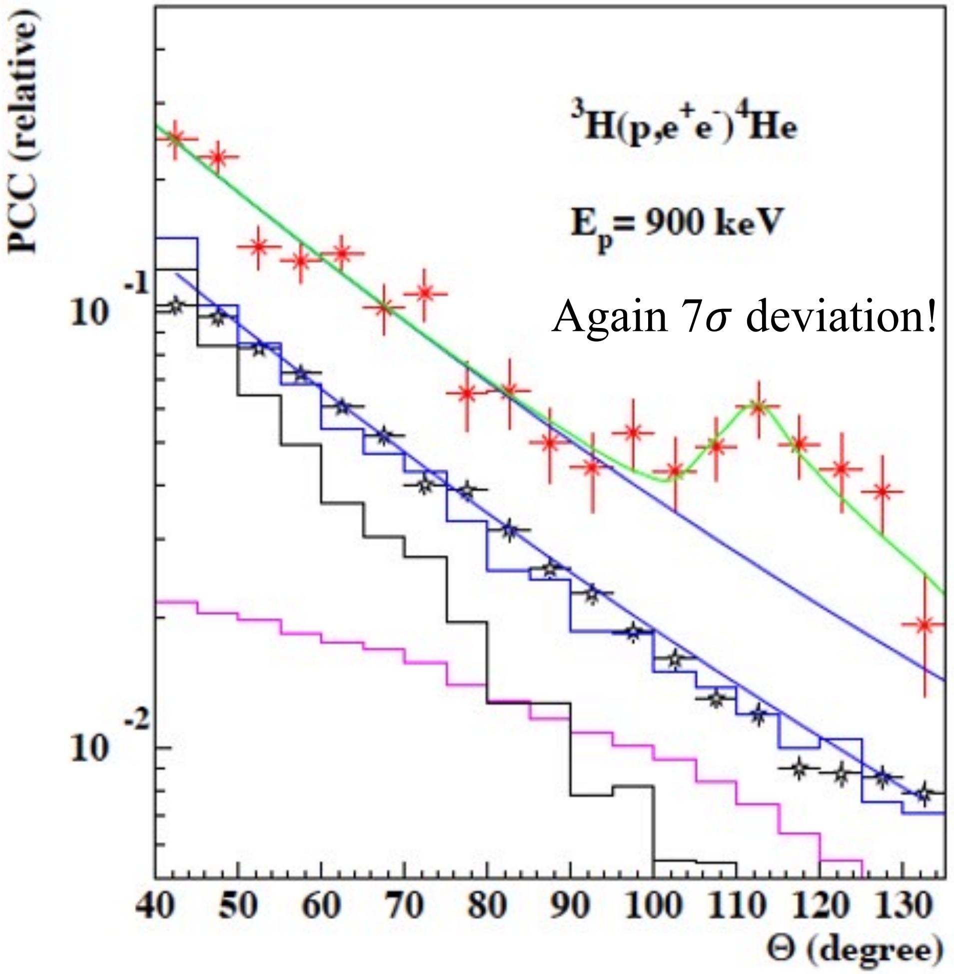




Helium anomaly (2019)

- In 2019 and 2021 ATOMKI investigated the 20.21 MeV and 21.01 MeV energy levels of Helium4. *Phys.Rev.C* 104 (2021) 4, 044003
- They observed a new anomalous peak of events. Arxiv:1910.10459





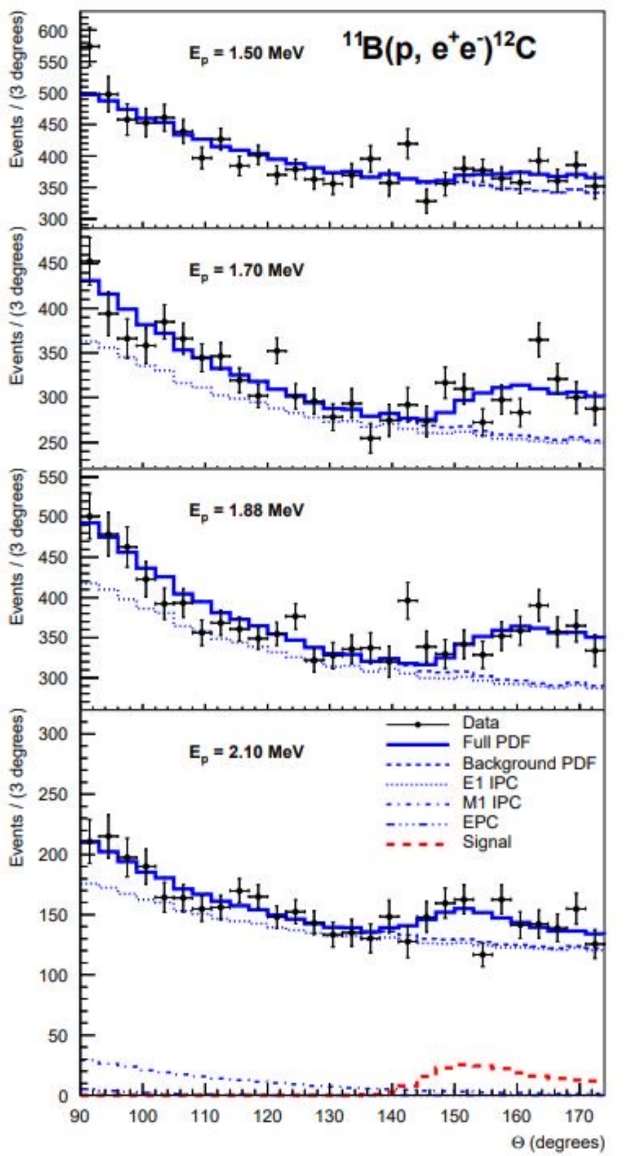
Carbon anomaly (2022)

- 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 (MeV)	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
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



Can SM explain Atomki?

Many attempts in this direction but…

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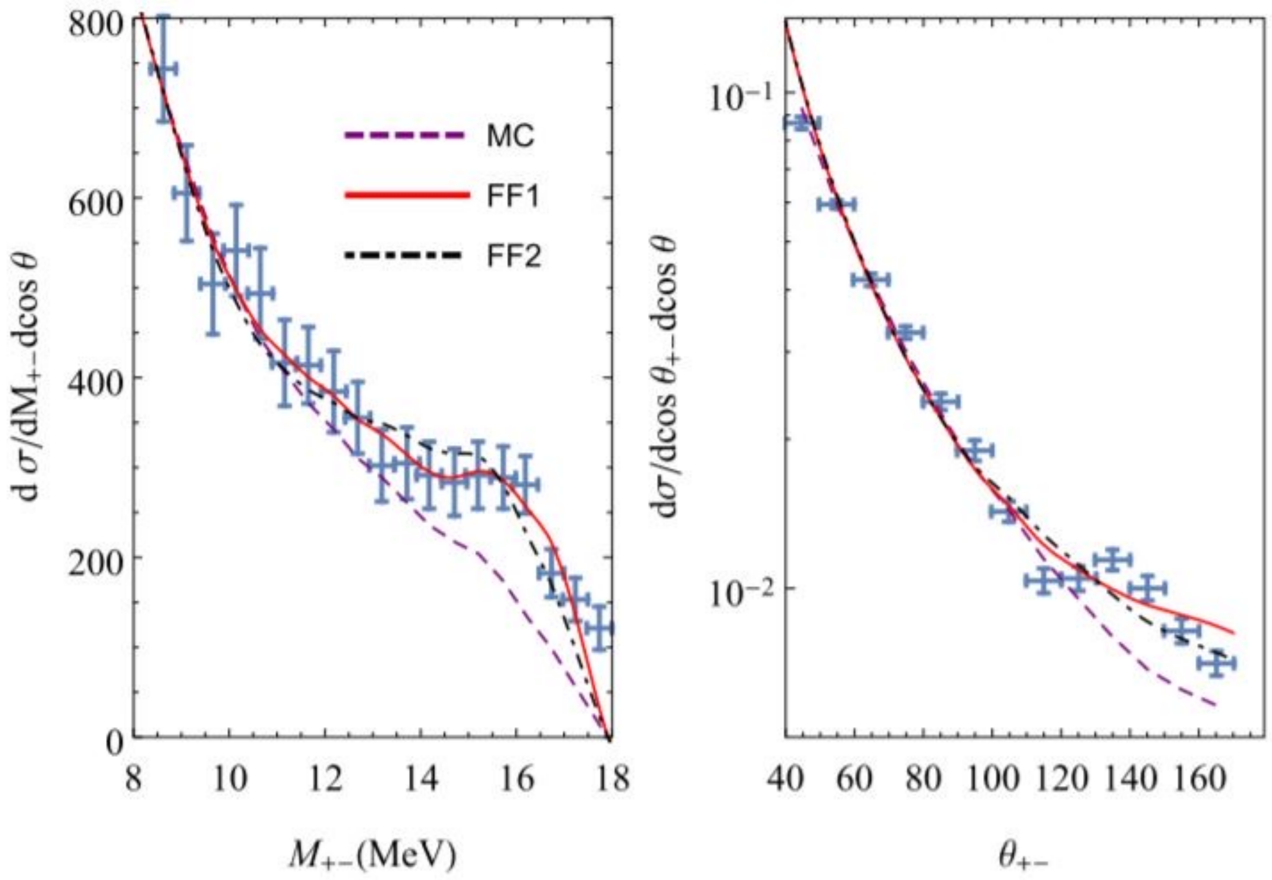
Zhang and Miller, PLB 773 (2017) 159-165

An example for ^{8}Be anomaly

- What if Atomki anomaly is due to some hard nuclear effect we are not able to understand?

$$f(M_{+-}^2) \equiv 1 + f_1 r + f_2 r^2 + f_3 r^3 \text{ with } r \equiv M_{+-}^2/\tilde{\Lambda}^2 \text{ and } \tilde{\Lambda} = 20 \text{ MeV}.$$

- The length scale of the needed form factor is in contrast with the experimental observation.



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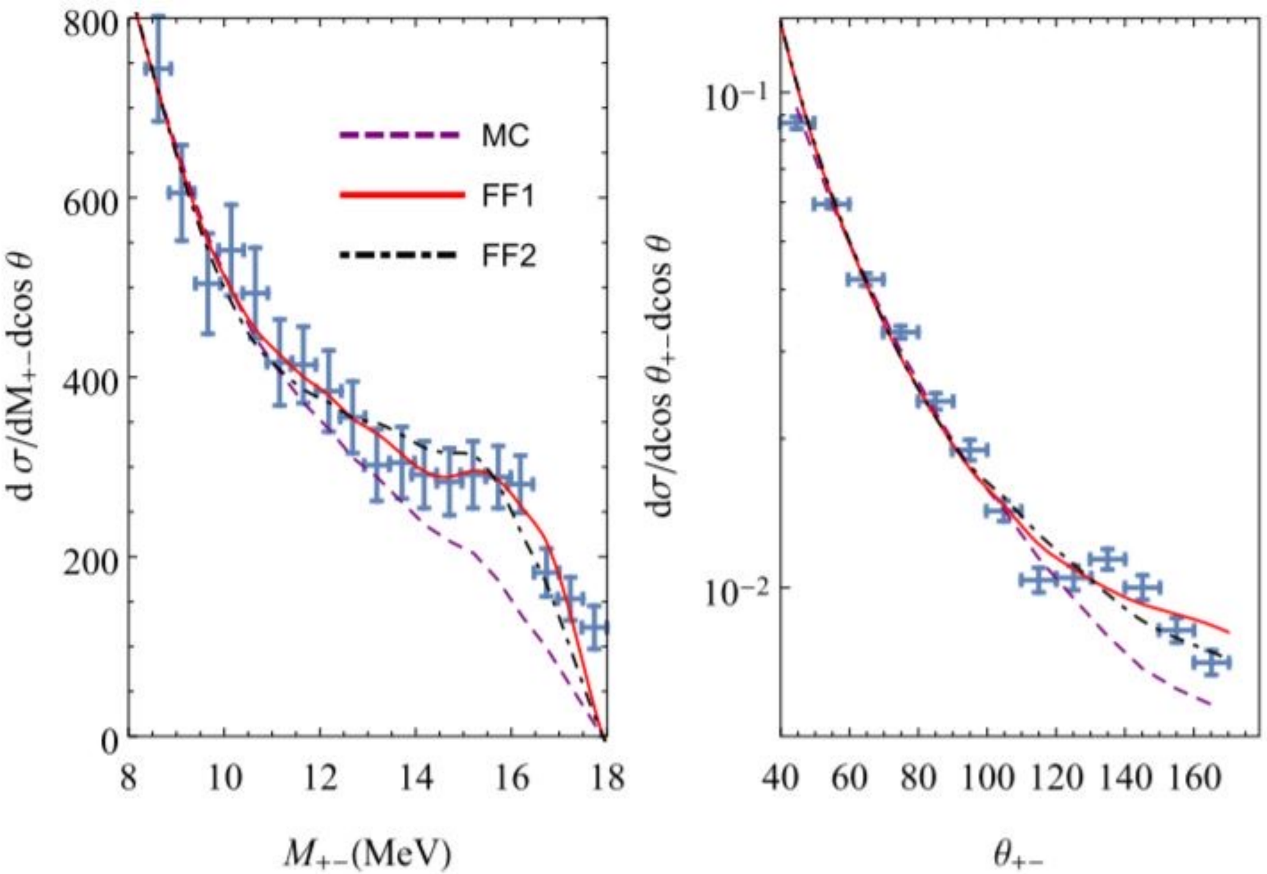

…in conclusion, no compelling SM explanation so far.

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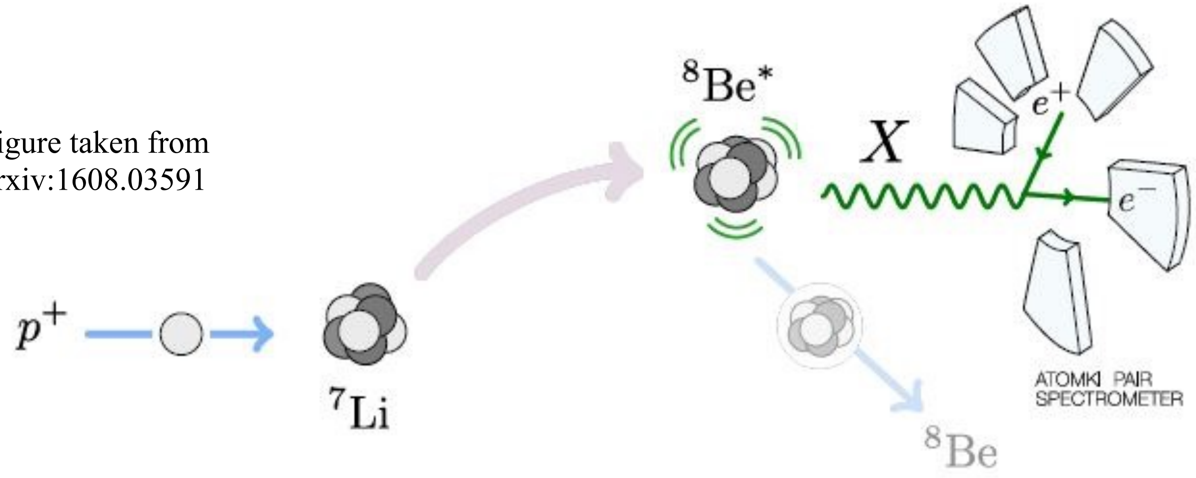
The X17

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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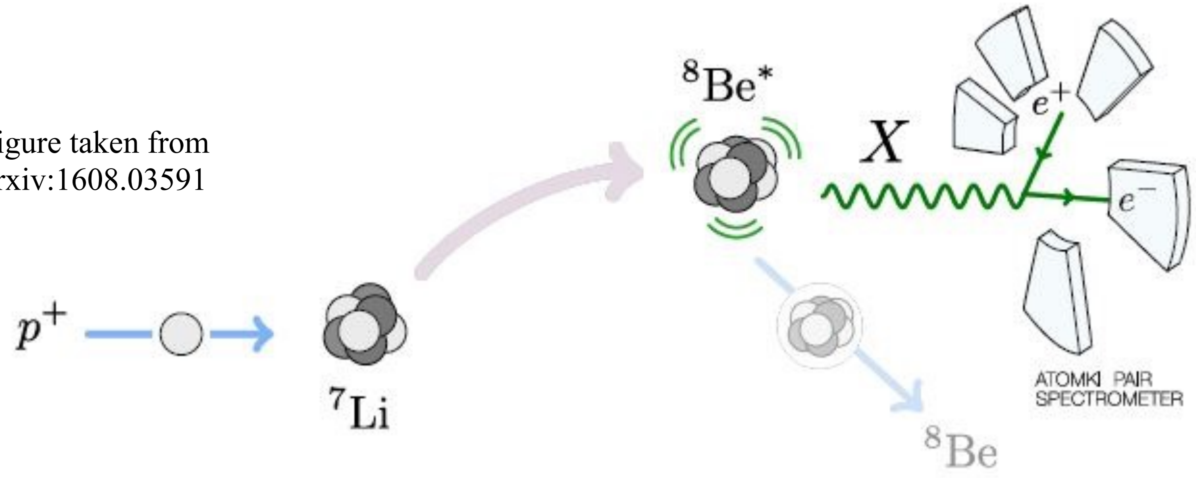

- Best fit mass values give ~17 MeV.
- The particle must be a neutral boson.
- It propagates less then 1 cm in the apparatus ⇒ short-lived boson

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

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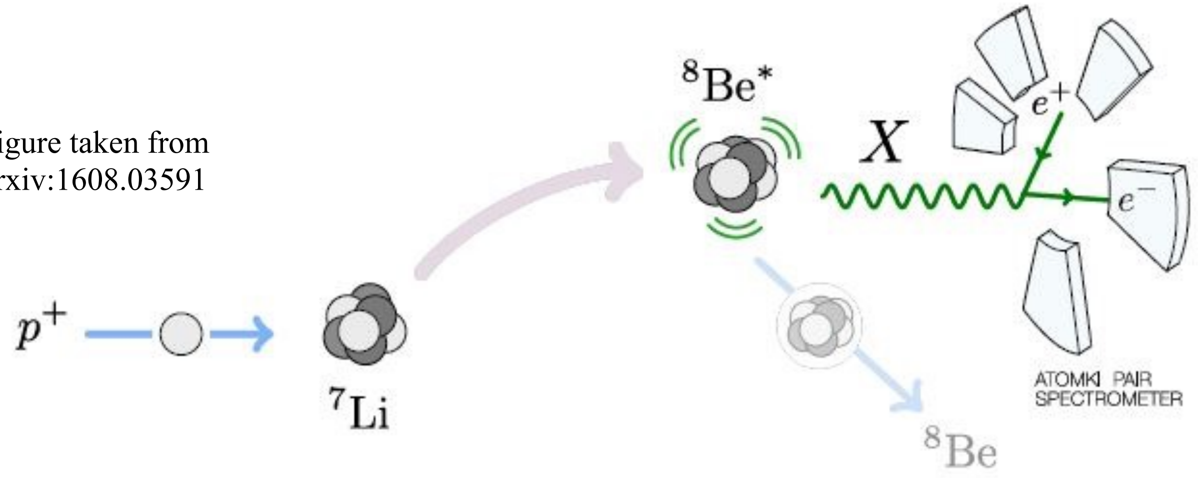

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$$\text{Signal Rate} = \underbrace{\sigma(N^* \to N + X)}_{\text{coupled to nuclear matter, i.e. quarks and gluons}} \times \underbrace{\mathrm{BR}(X \to e^+ e^-)}_{\text{coupled to electrons/positrons}}$$

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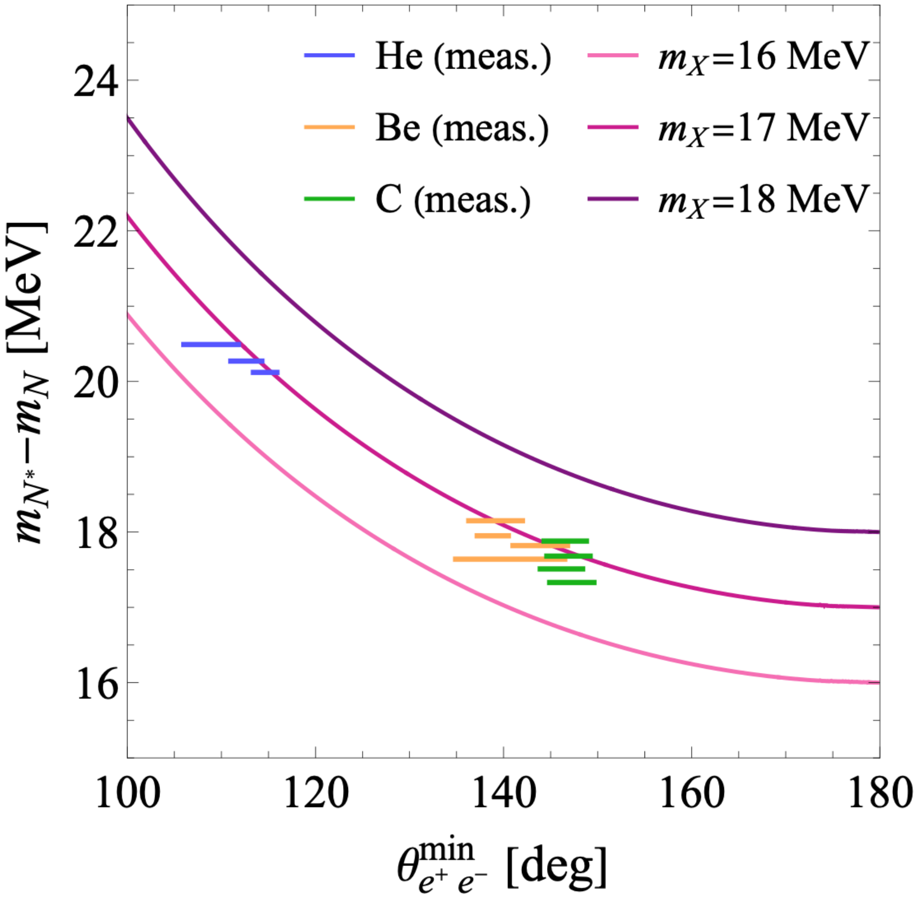
1) the e+e− opening angles of the anomalous peaks are located around 140°, 115° and 155°−160°, respectively, for the 8Be, 4He and 12C anomaly.

- The measured values of the peak angles are in agreement with the theoretical prediction.

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

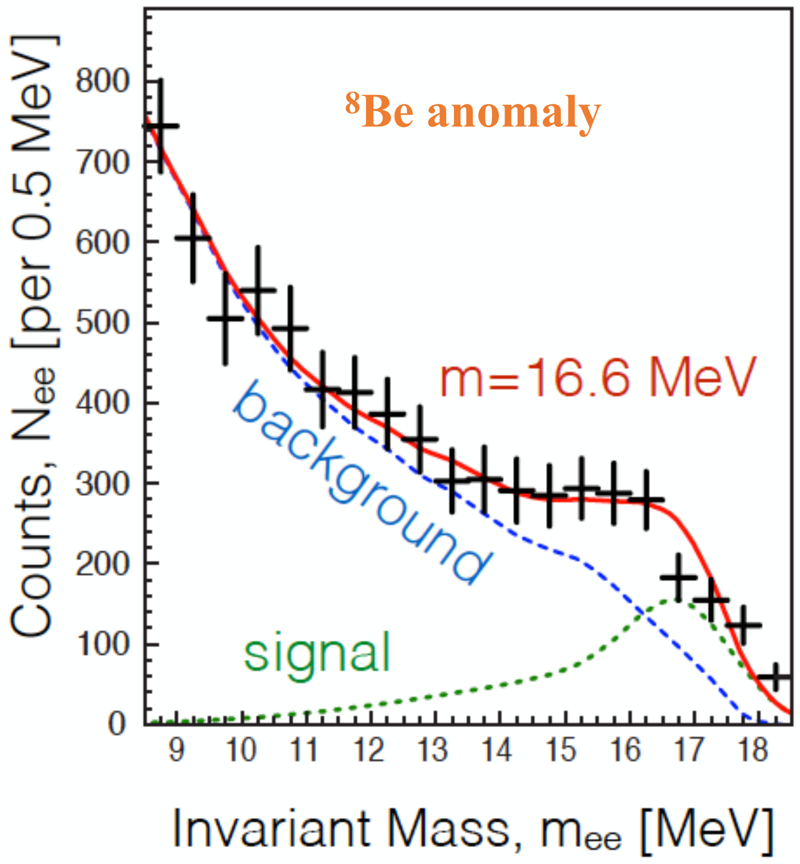


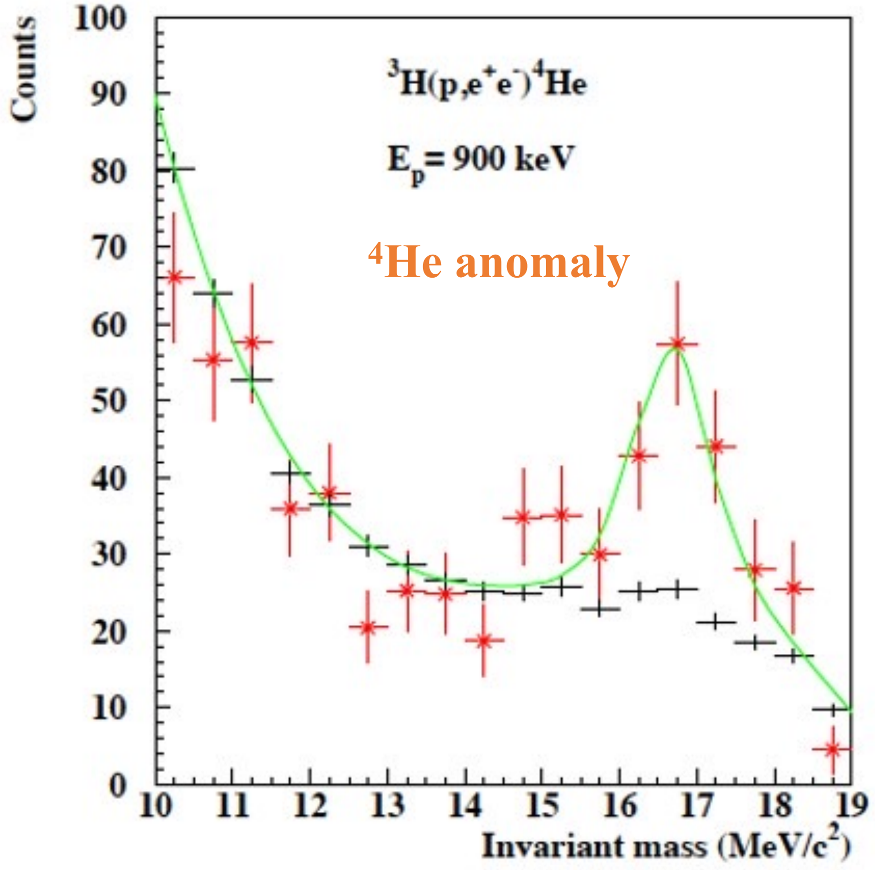
Peter B. Denton, Julia Gehrlein, arxiv:2304.09877
(see also Feng et al. arxiv:1608.03591)

X17 kinematics

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

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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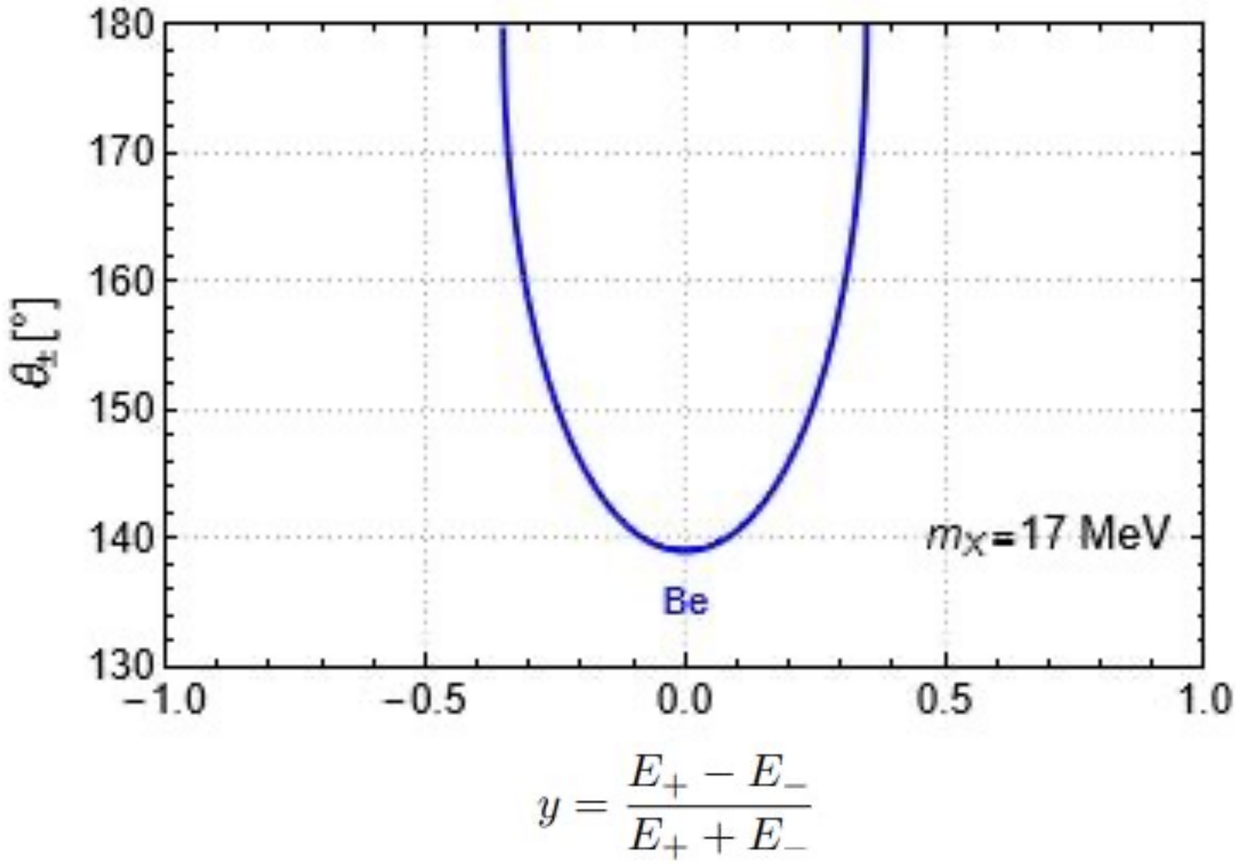

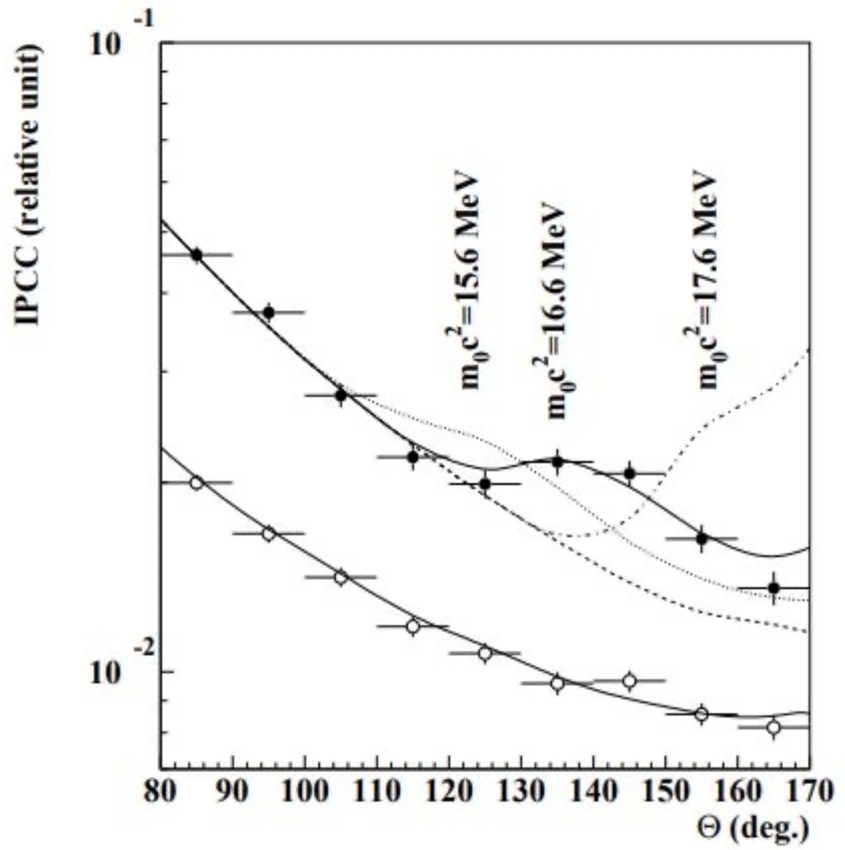

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1) The e+e− opening angles of the anomalous peaks are located around 140°, 115° and 155°−160°, respectively, for the 8Be, 4He and 12C anomaly.
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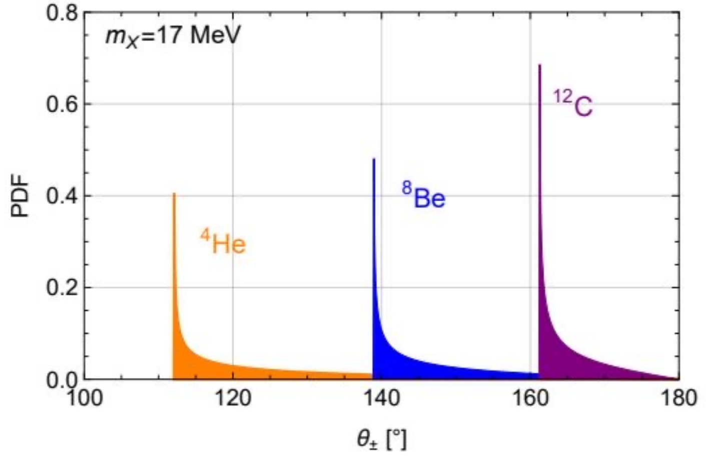
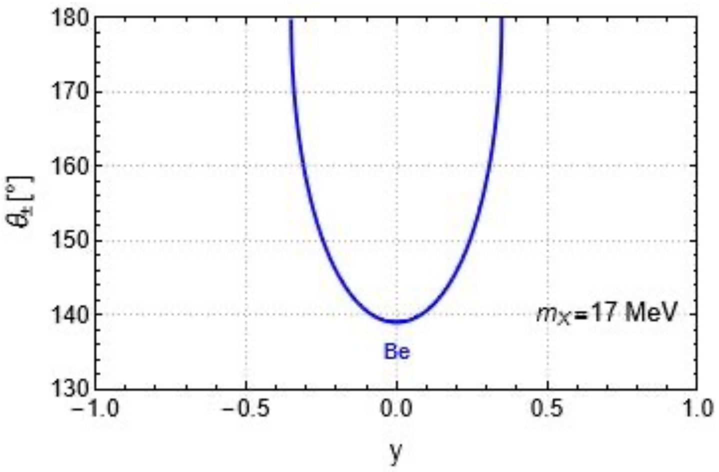


The agreement of the data with the X17 kinematic is a strong argument in favor of the new particle interpretation of the Atomki anomalies



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X17 dynamics

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

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

- Dark U(1) gauge boson (Feng et al. arxiv:1608.03591)
- QCD axion (Daniele Alves arxiv:2009.05578)
- QED meson (Cheuk-Yin Wong arxiv:2201.09764)

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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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Barducci and Toni, JHEP 02 (2023) 154

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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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 $N^* \to N$	X **boson spin parity** $S^\pi = 1^-$	$S^\pi = 1^+$	$S^\pi = 0^-$	$S^\pi = 0^+$
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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})

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

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

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

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

Carbon (R_C)

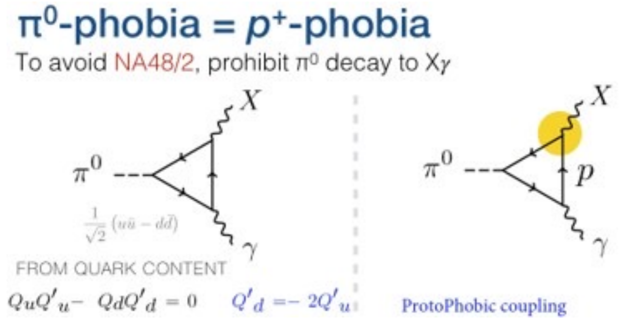
$$\frac{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + X)}{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + \gamma)} \mathrm{BR}(X \to e^+e^-) = 3.6(3) \times 10^{-6}$$

- Up to a nuclear matrix element we must take from the literature, we are able to calculate the theoretical rates
- By matching the data to our prediction, one extracts the nucleon couplings to X17
- We assume for simplicity none or suppressed coupling to neutrinos such that

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

Vector X17

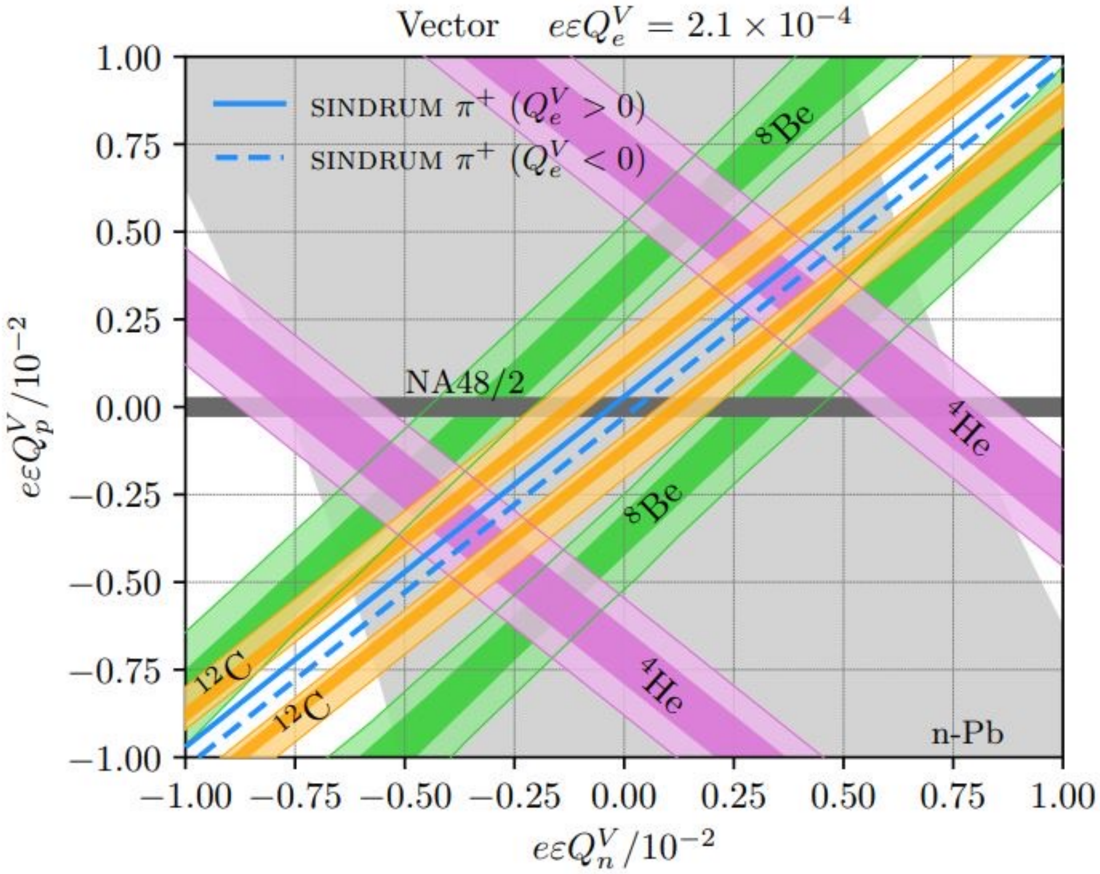
➢ The Carbon anomaly is in tension with a combined explanation of the Beryllium and Helium anomalies and the NA48 constraint.



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

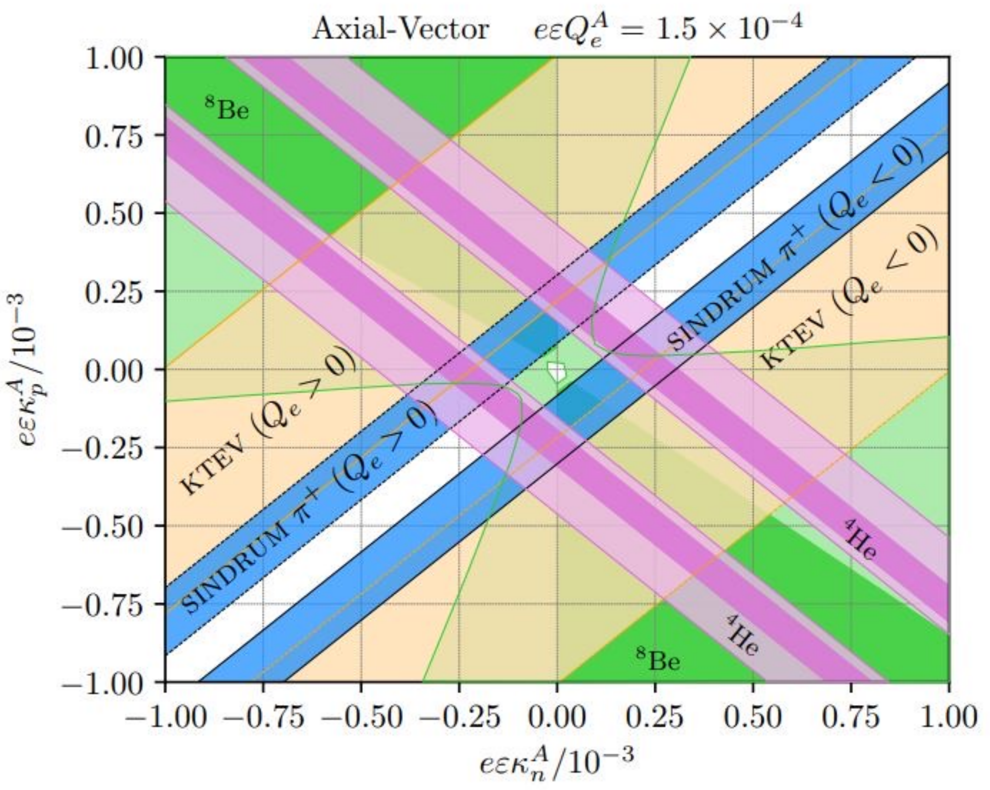
➢ Putting all together, the vector case is almost excluded.

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



Axial-vector X17: two years ago

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.
- After our work, Hostert and Pospelov calculated the constraints to a spin-1 X17 coming from the SINDRUM search of $\pi^+ \to e^+\nu_e X$.
- We claimed that the axial solution was 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: now

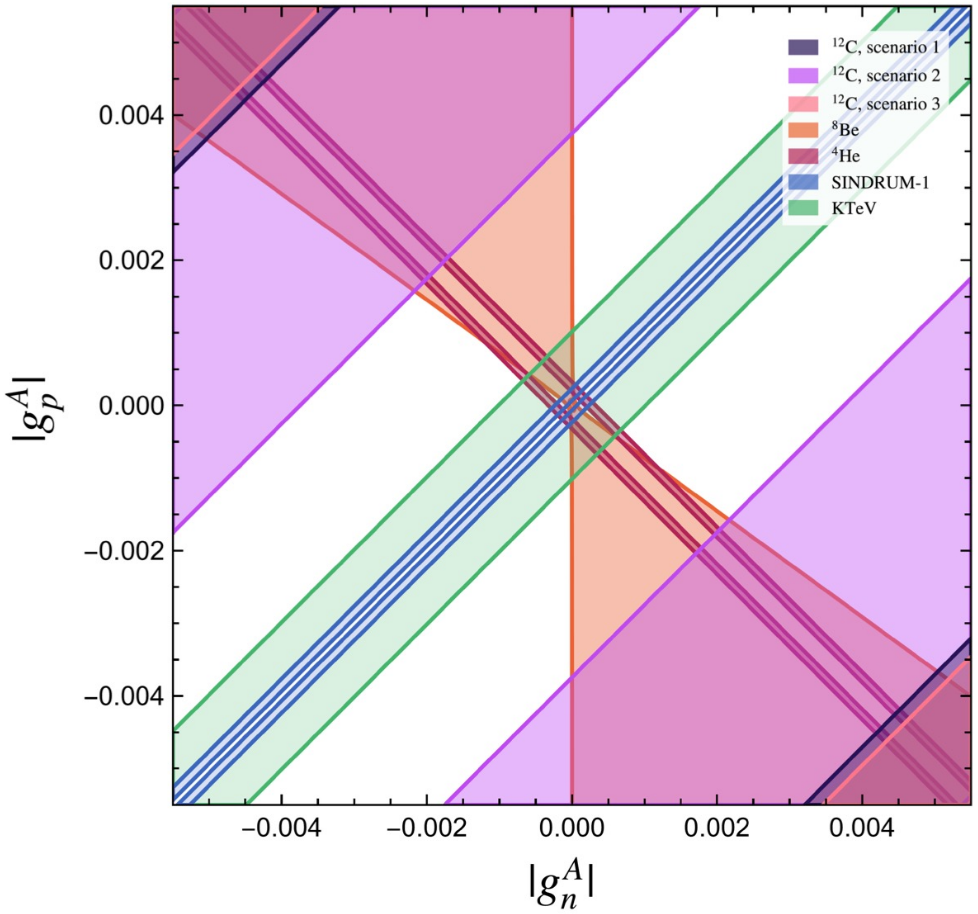
Mommers and Vanderhaeghen, arxiv:2406.08143

Particle-hole shell model approximation for Carbon excited state:

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

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

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



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

A brief recap

- All the possible scenarios of parity-conserving X17 states with spin ≤ 1 have been investigated.

- 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 constraints
- Axial-vector X17 $J^{\pi} = 1^{+}$: Tension among Carbon data and SINDRUM constraint

A brief recap

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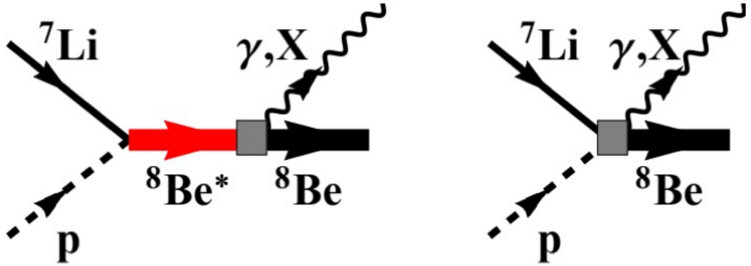
Possible new lines of research:

- Scenarios with parity violating states → parity violation constraints
- Inclusion of the contribution from direct proton capture (see again Viviani et al., arxiv:2408.16744 and Gysbers et al. arxiv:2308.13751) → need of ab-initio calculation for all the transitions



Arguments of the talk

1) ATOMKI search and anomalies

2) X17 hypothesis and kinematics

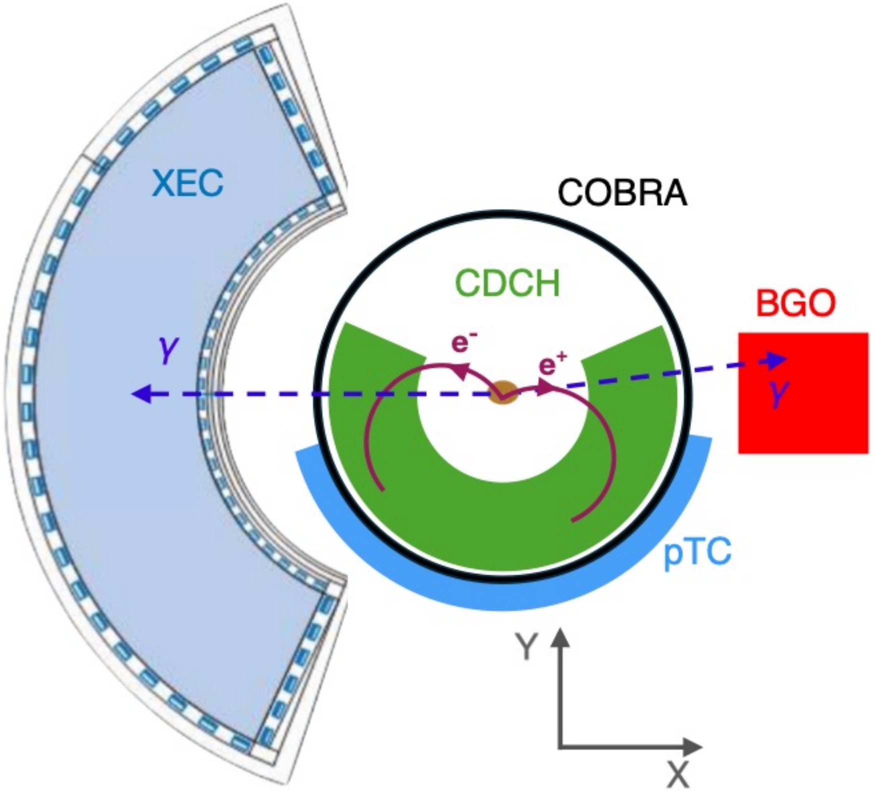
3) X17 dynamics and spin/parity

4) Recent development from MEG-II and Padme

X17 at MEG-II (2024)

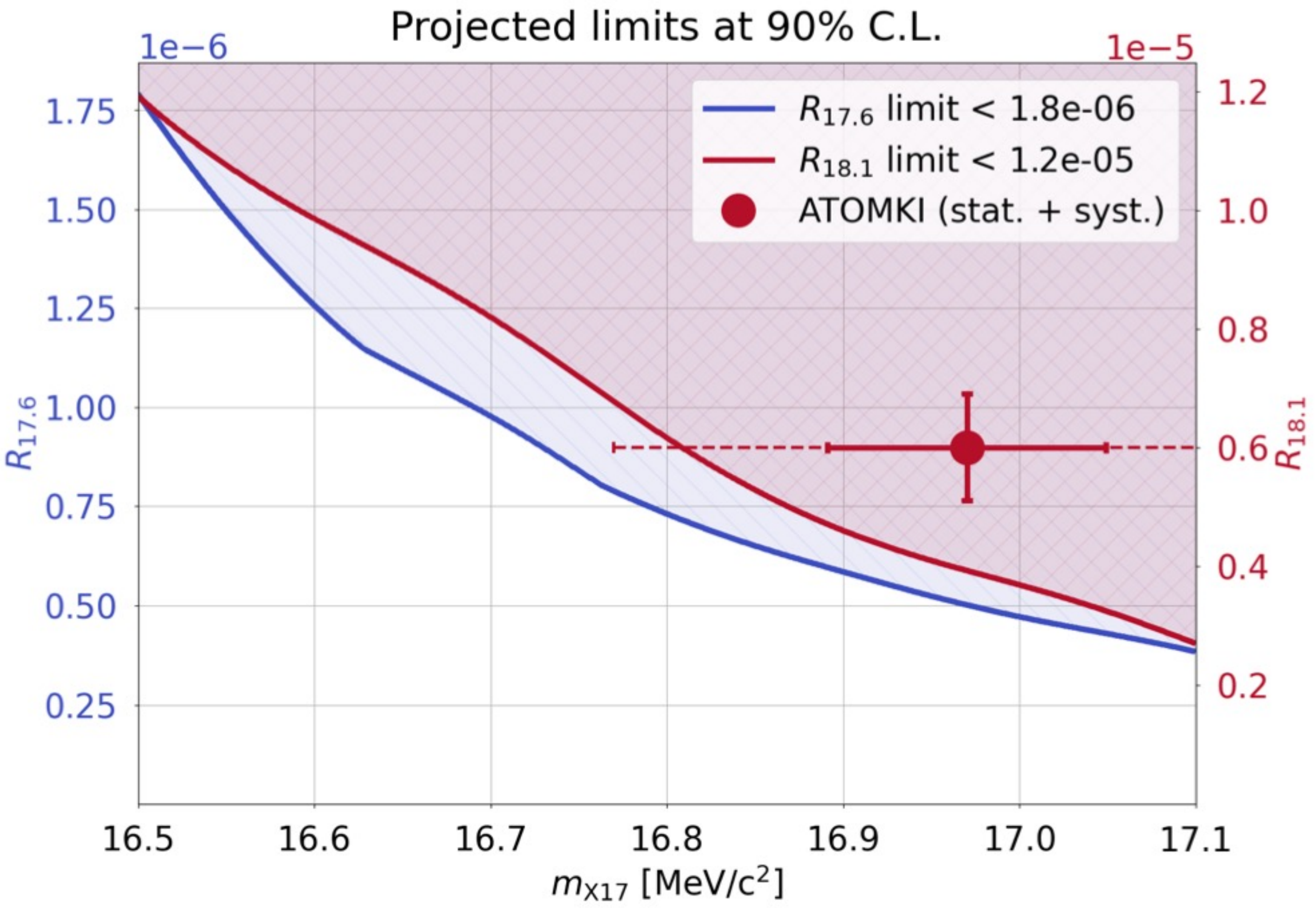
- In order to confirm the Atomki anomaly, MEG-II re-measured the Beryllium transitions at the PSI

- 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)

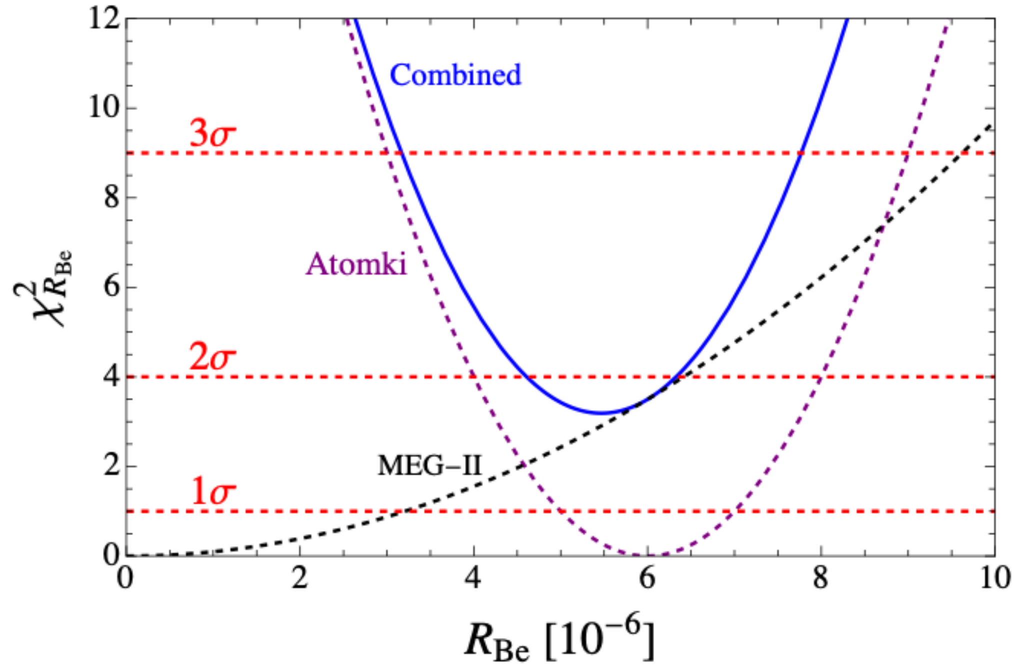


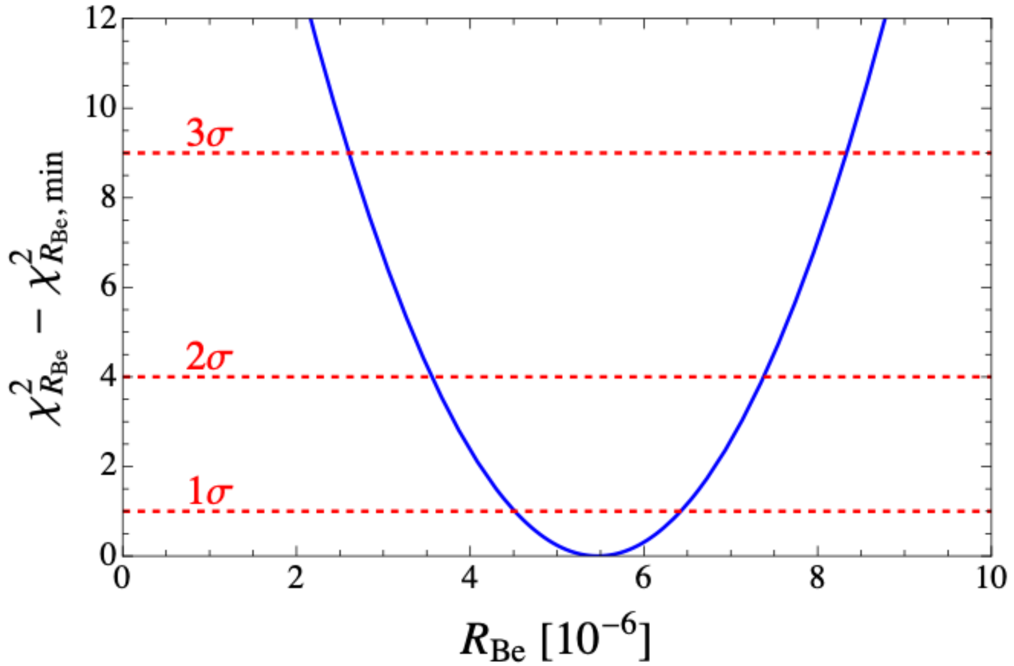
Combining Atomki and MEG-II

- 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

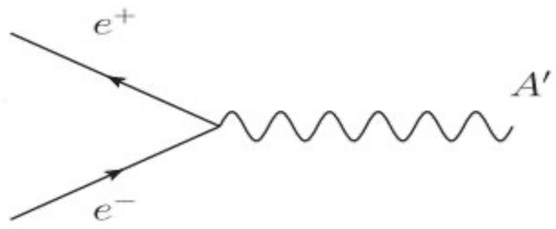
Barducci et al., arxiv:2501.05507





X17 at Padme

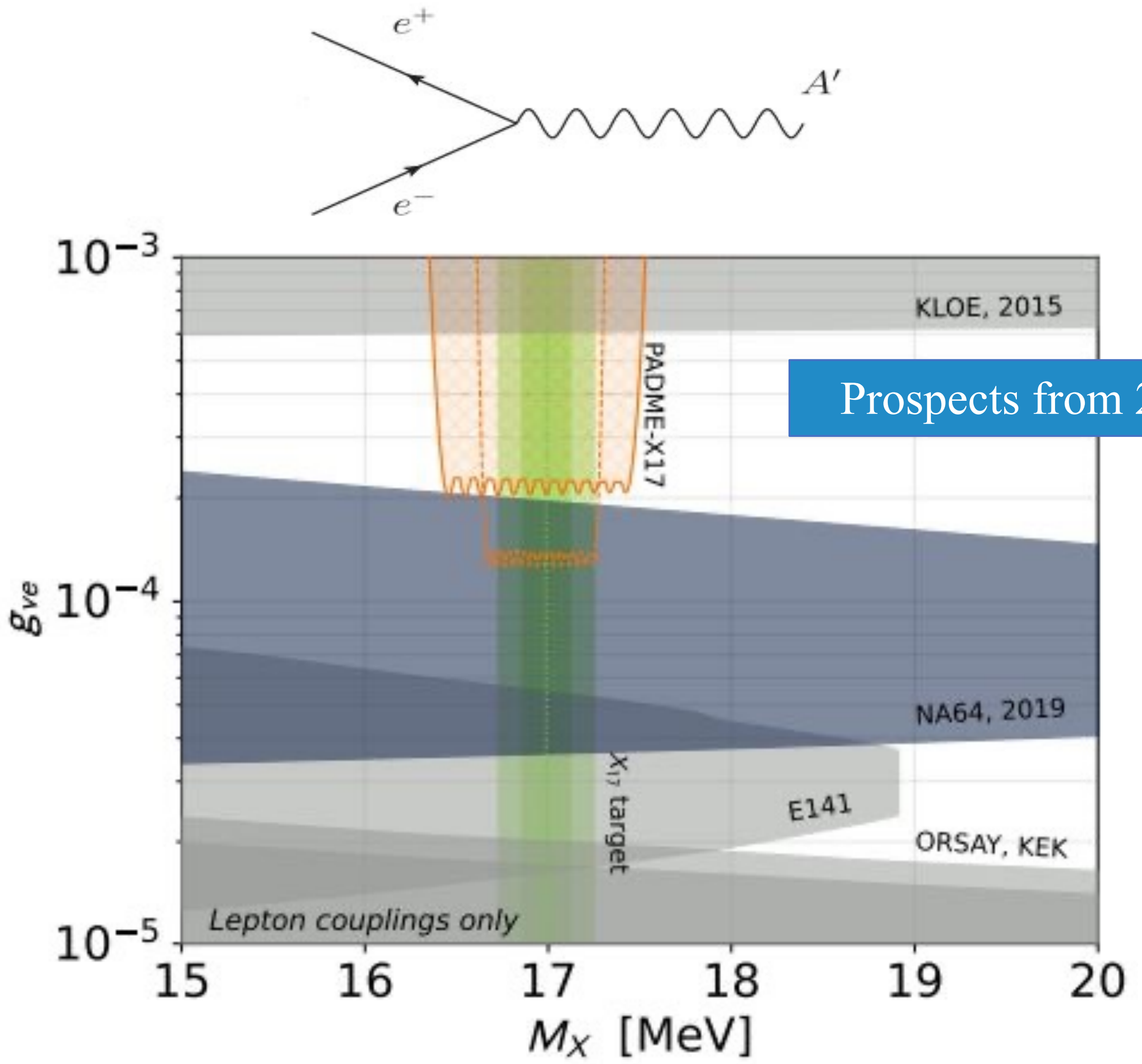
- PADME experiment allows for a strong test of the new particle hypothesis.
- A positron beam dump experiment like Padme can resonantly produce the X17.



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

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 close the spin-1 parameter space!



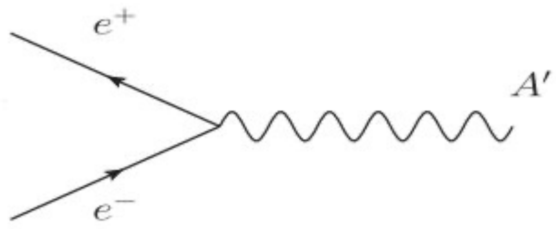
Prospects from 2022!

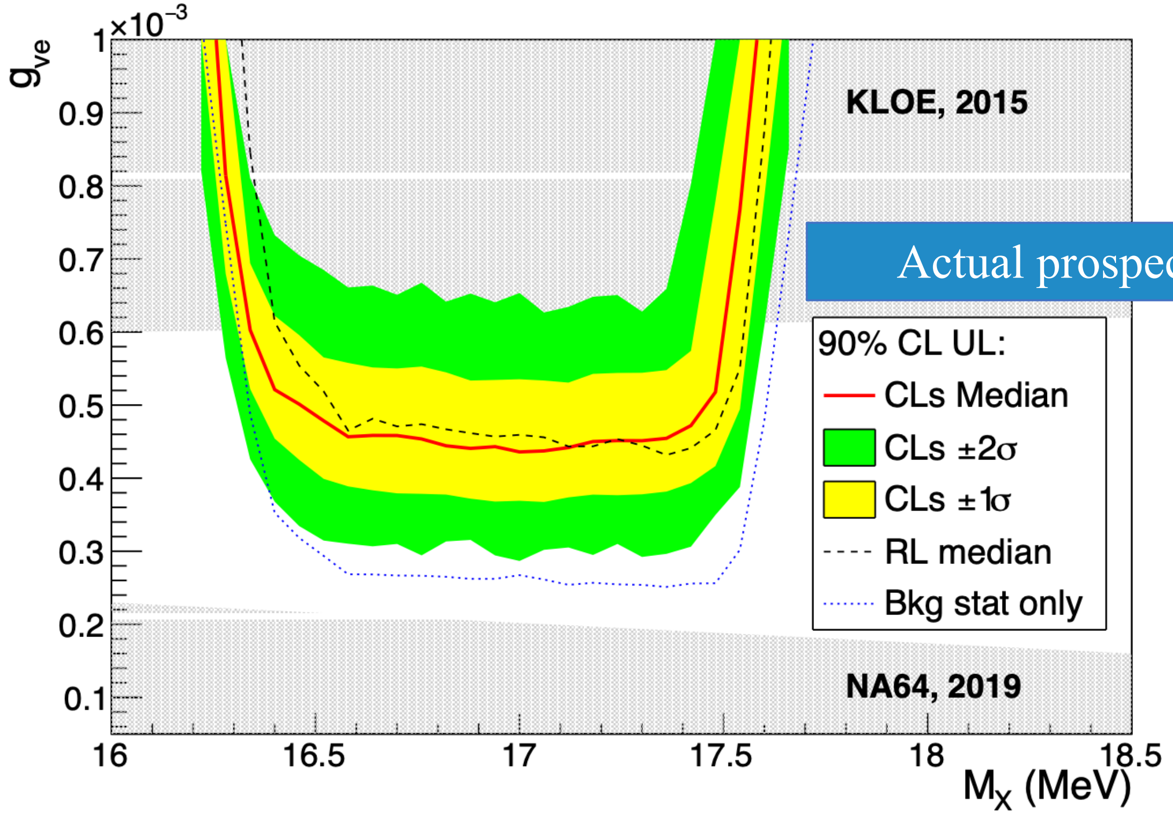
PRD 106 (2022) 11, 115036
L. Darmé, M. Mancini,
M. Raggi and E. Nardi

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!

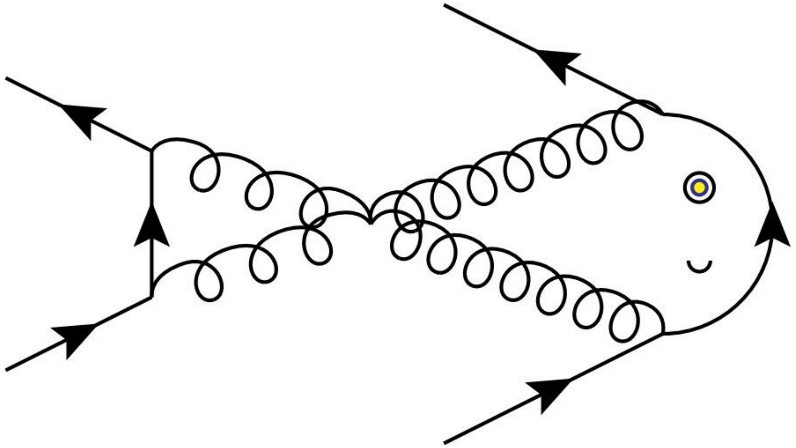
Bertelli et al., arxiv:2503.05650



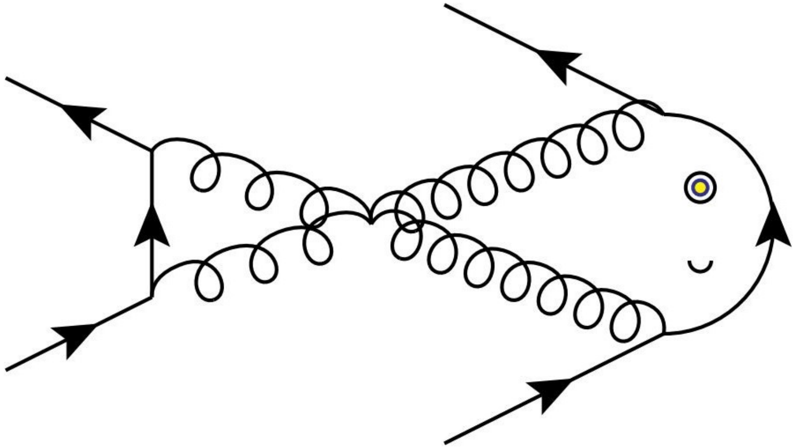


Actual prospects!

The End



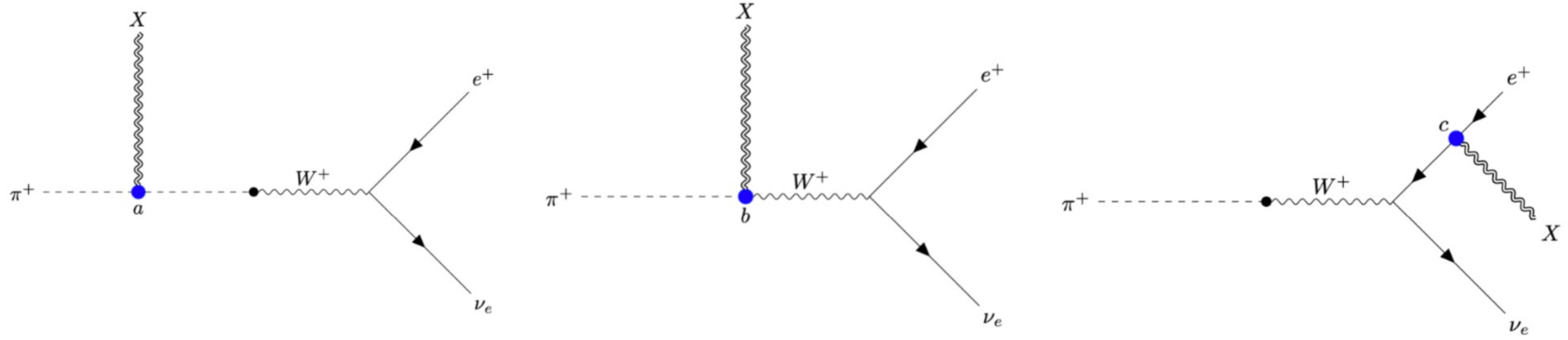
THANK YOU FOR THE ATTENTION!



BACK UP SLIDES

SINDRUM

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

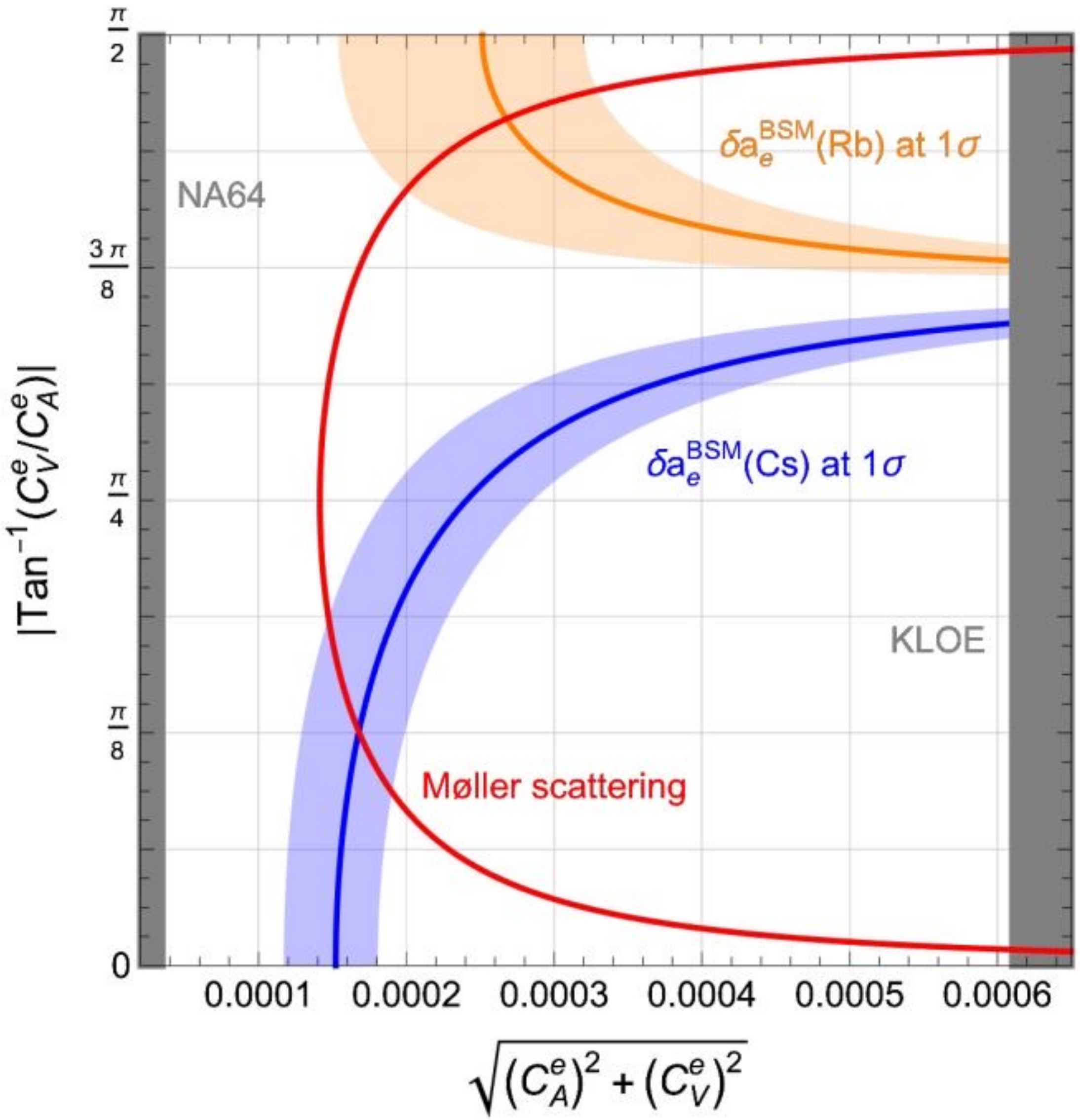


Spin-1 X17 coupling to electron/positrons

$$\mathcal{L}_{Xee} = X_\mu \overline{\psi}_e \left(C_V^e \gamma^\mu + C_A^e \gamma^5 \right) \psi_e$$

- Here the main bounds for a spin-1 boson with mass 17 MeV coupled to the electron field are recollected.
- Recalling that the lifetime is less than 1 cm leads to a lower bound on the X17 couplings to electrons:

$$\sqrt{(C_V^e)^2 + (C_A^e)^2} \gtrsim 3 \times 10^{-7}$$



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!

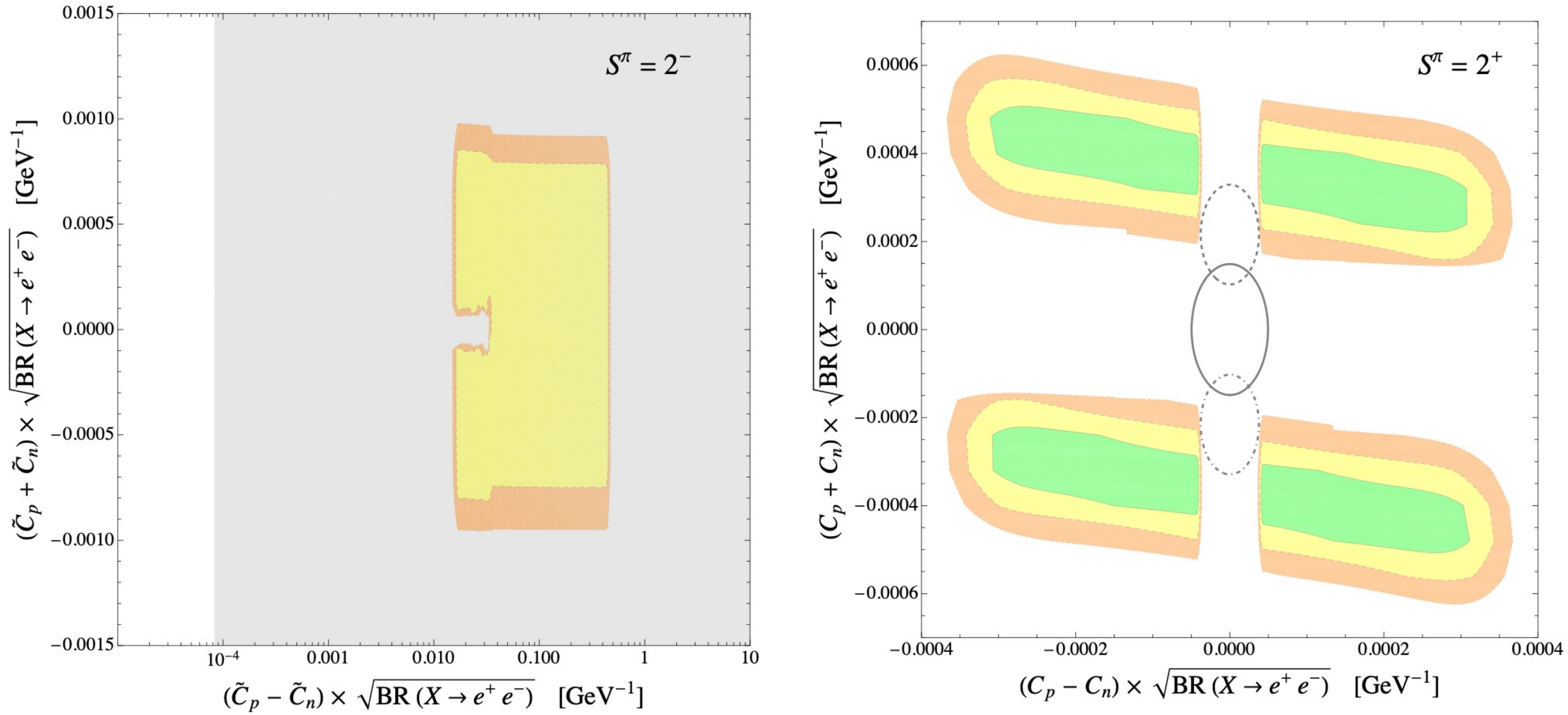
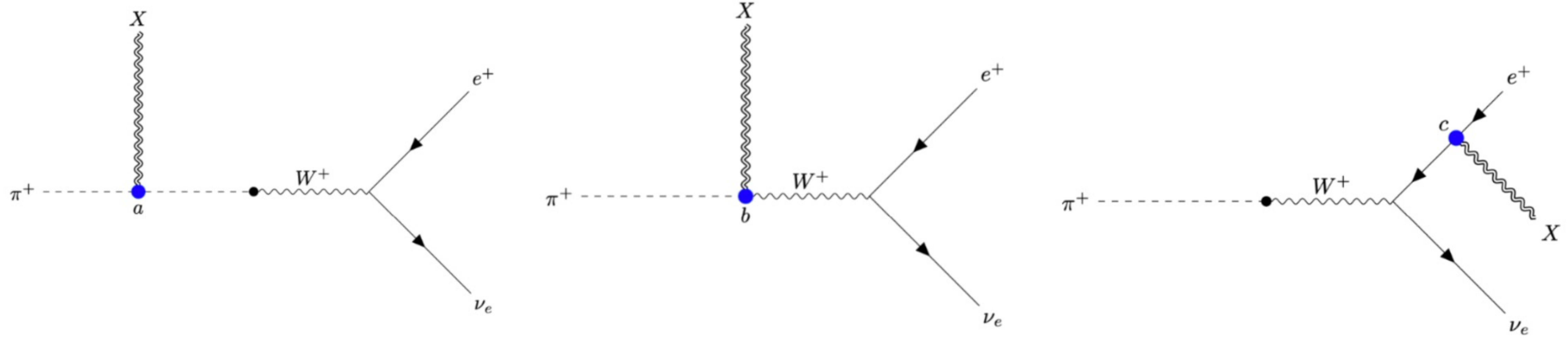


Figure 2. *Left panel:* Green, yellow, orange areas correspond to the $1\sigma, 2\sigma, 3\sigma$ compatibility regions, defined by the requirement $\chi^2_{\text{profiled}} < 2.28, 5.99, 11.62$, for an axial tensor boson. The gray region is excluded by SINDRUM search. *Right panel:* Green, yellow, orange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

SINDRUM

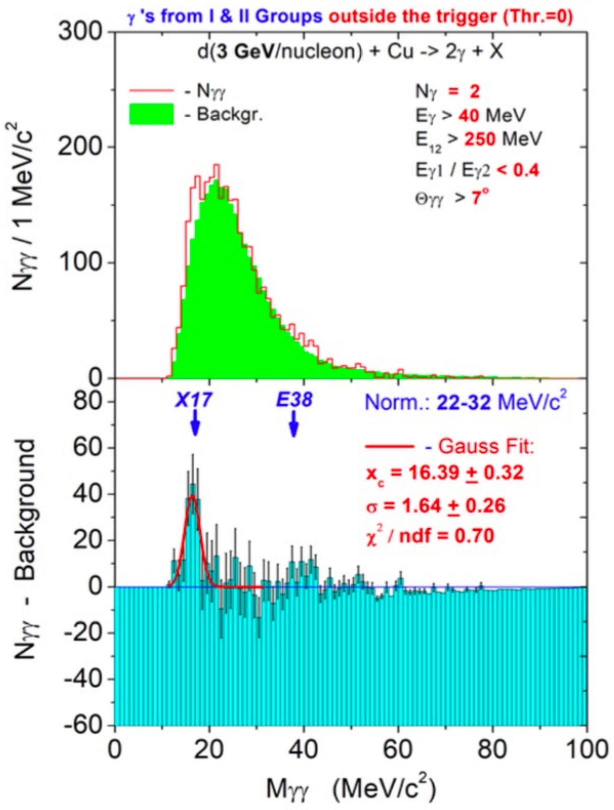
$$\mathrm{BR}(\pi^+ \to e^+\nu_e X) \times \mathrm{BR}(X \to e^+e^-) < 6.0 \times 10^{-10}$$



JINR experiment

JINR experiment (Russia)

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



Decay detected:

$X \rightarrow \gamma\gamma$

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]