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An updated view on the X17 hypothesis

based on the work with Daniele Barducci
published in JHEP 02 (2023) 154

Claudio Toni

XXXVII Convegno Nazionale di Fisica Teorica, 28/09/2023

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

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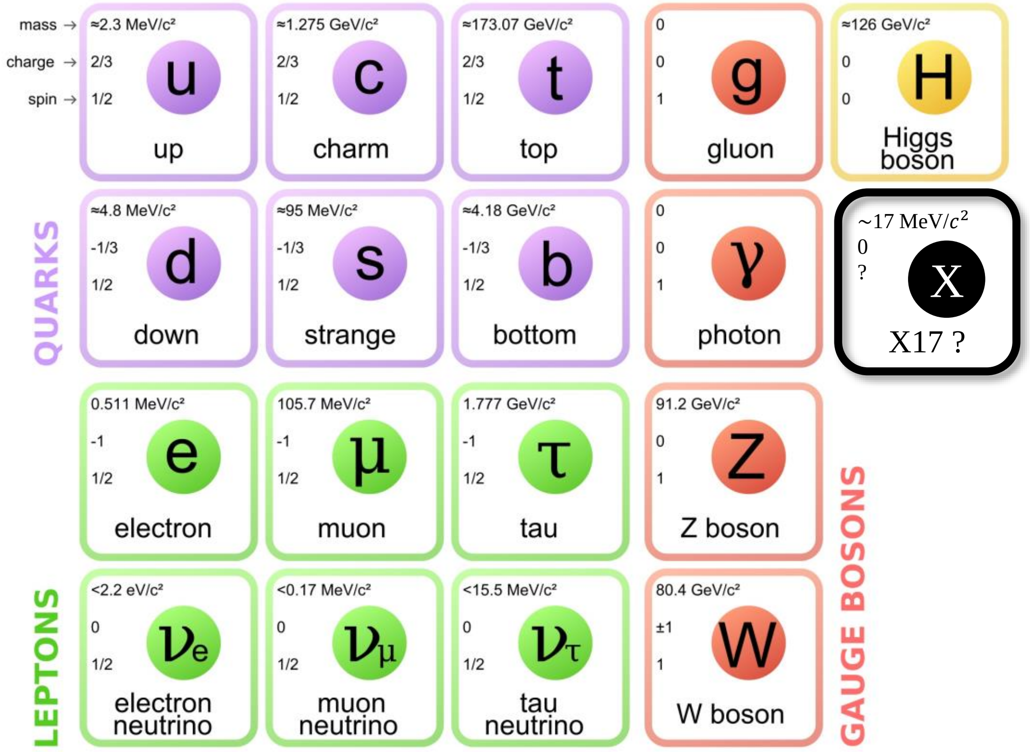
(Received 7 April 2015; published 26 January 2016)

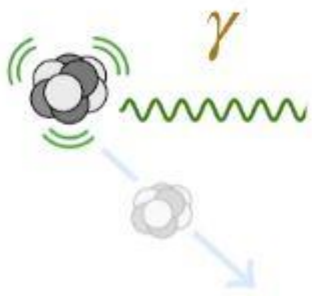
Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement 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 $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV$/c^2$ and $J^\pi = 1^+$ was created.



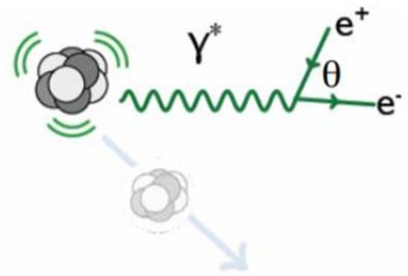
ATOMKI search

- ATOMKI collaboration focused on the Internal Pair Creation (IPC) decay channel of excited nuclei.
- Rare nuclear processes can be affected by New Physics (NP) even if weakly coupled.

QED processes:



~ first order in QED coupling,



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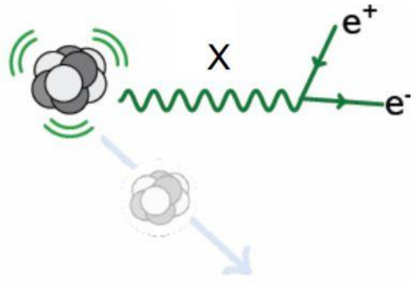
NP processes:

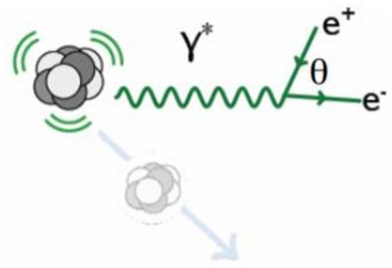


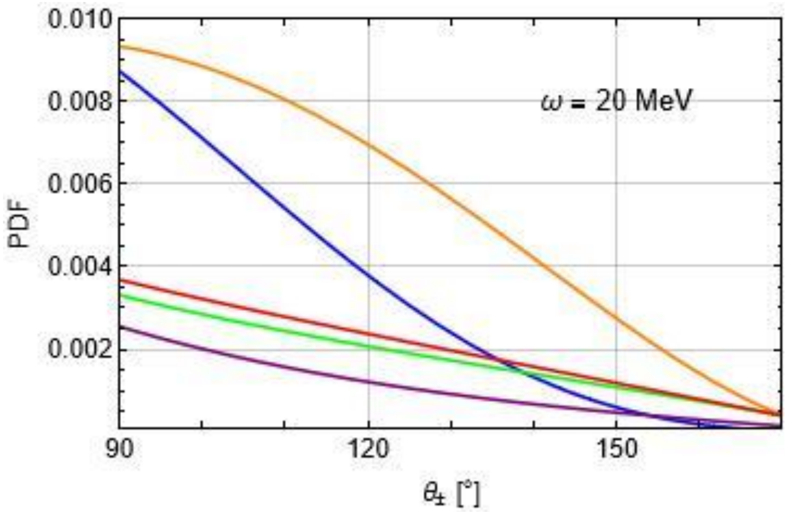
~ first order in NP coupling

ATOMKI search

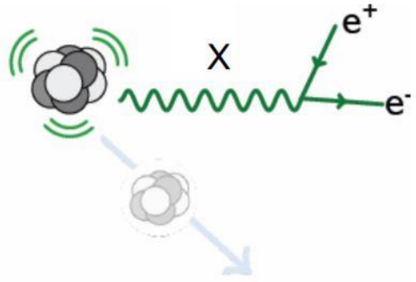
- ATOMKI collaboration looks for light NP in the angular correlation distribution of $e^- e^+$.
- At large angles, QED predicts that the angular correlation drops rapidly.

QED:





NP:

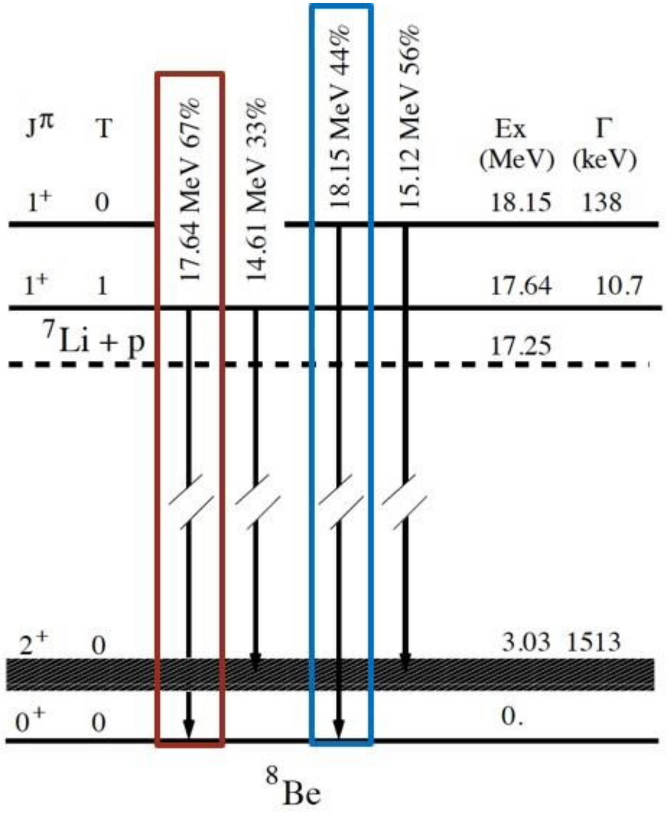


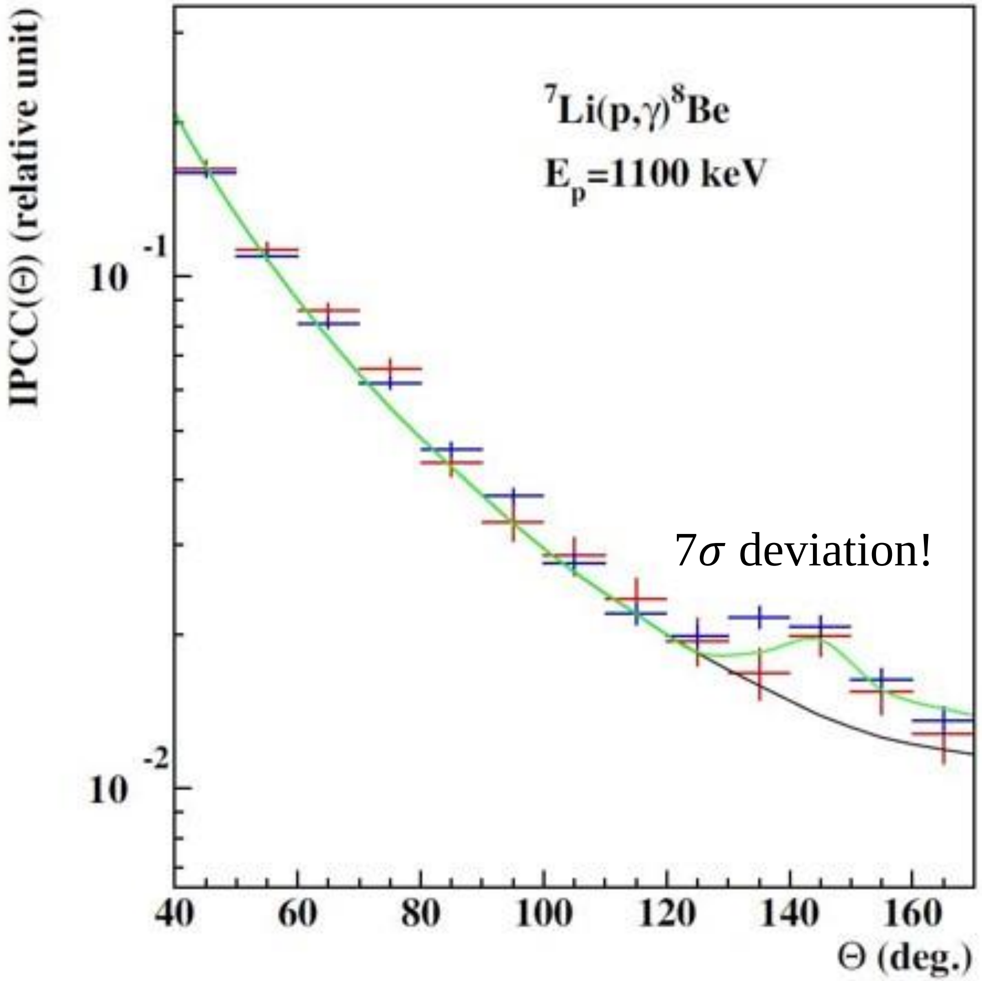
Bump-like distribution!

Beryllium anomaly (2016)

- In 2016 and 2018 ATOMKI 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

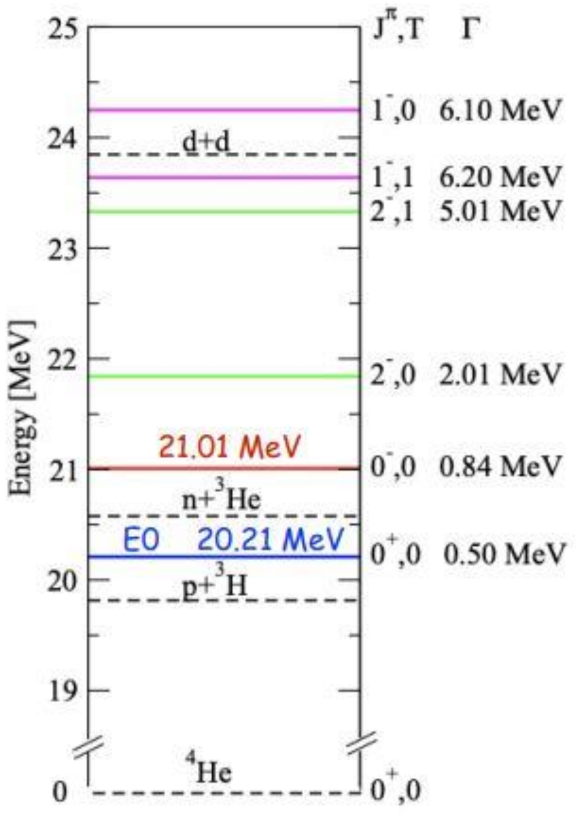


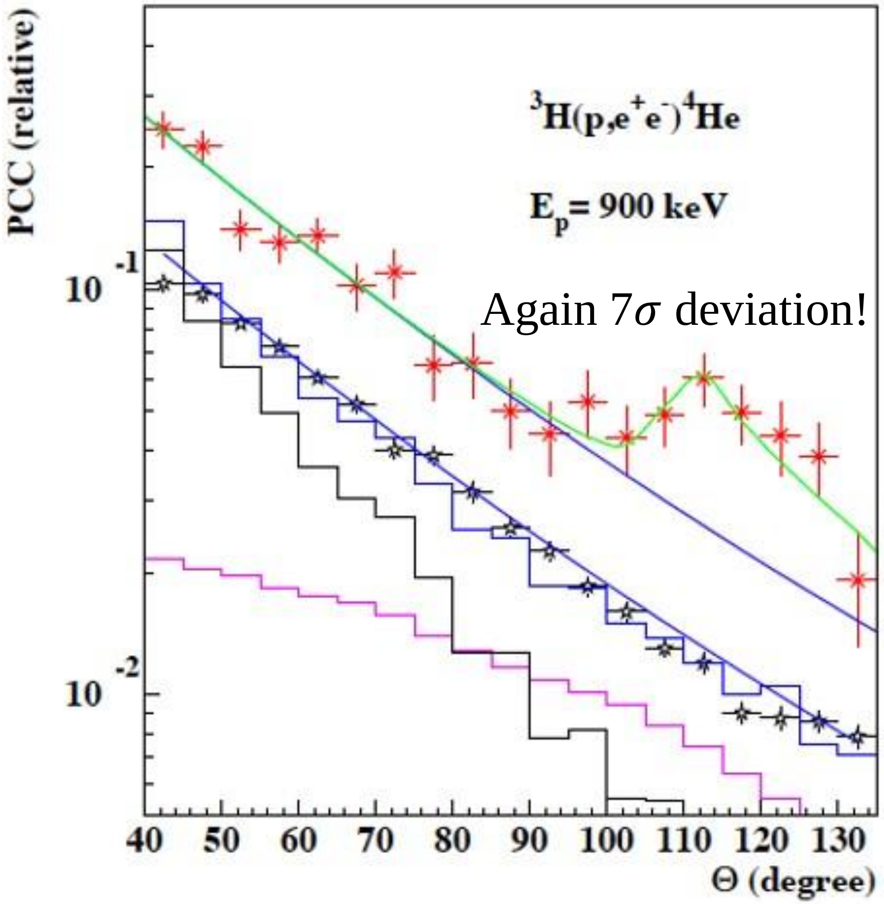


Helium anomaly (2019)

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

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





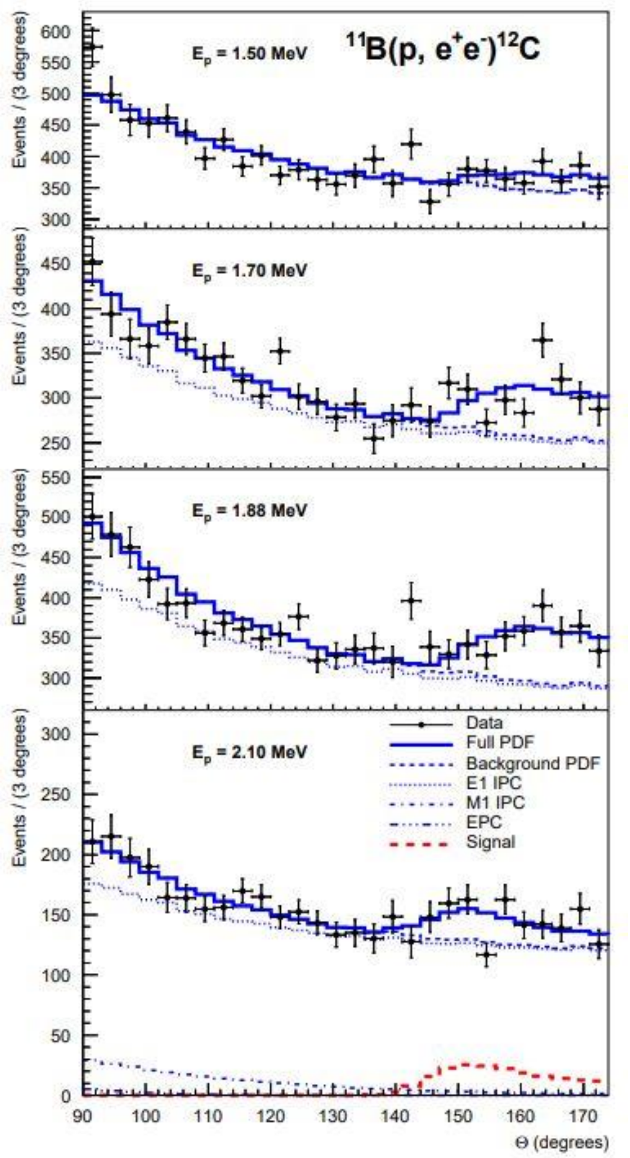
Again 7σ deviation!

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.

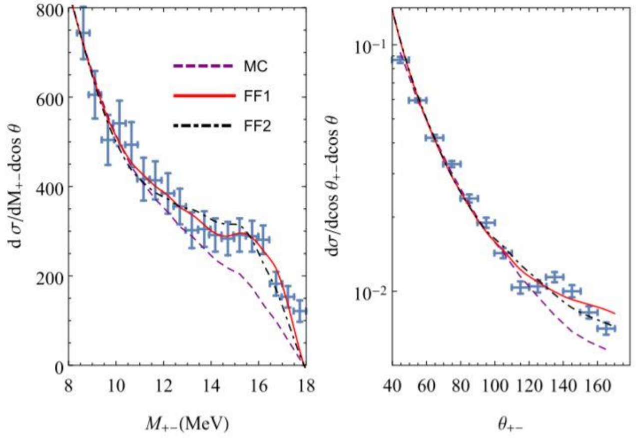
E_p (MeV)	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	
Predicted [30]	3.0		



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

SM explanation

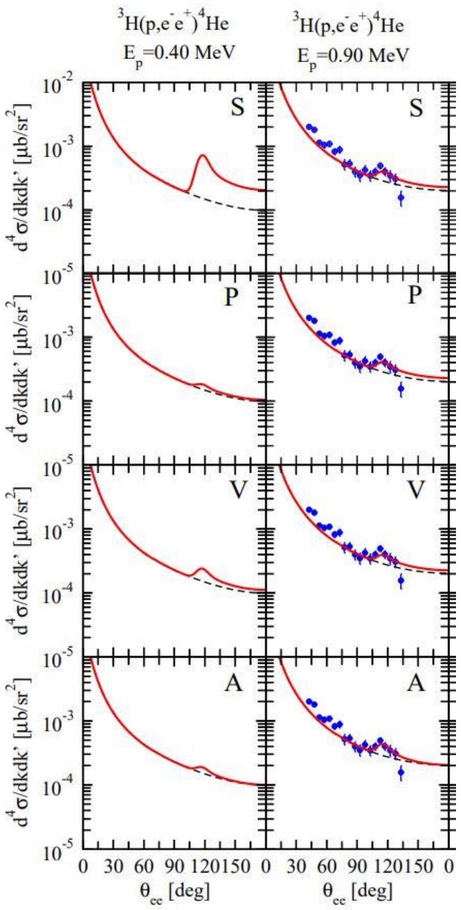
- Improvement of the Be nuclear model used by Atomki is not enough to explain the anomaly.
- Unknown nuclear effect is also excluded.
- The length scale of the needed form factor is in contrast with the experimental observation.



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.

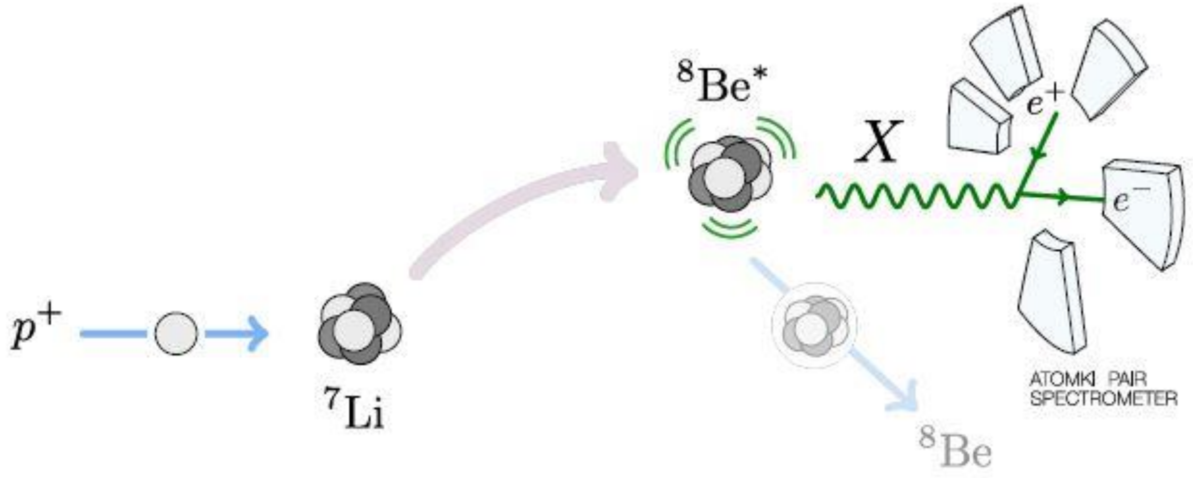
Viviani et al., PRC 105 (2022) 1, 014001



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

Features of X17

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



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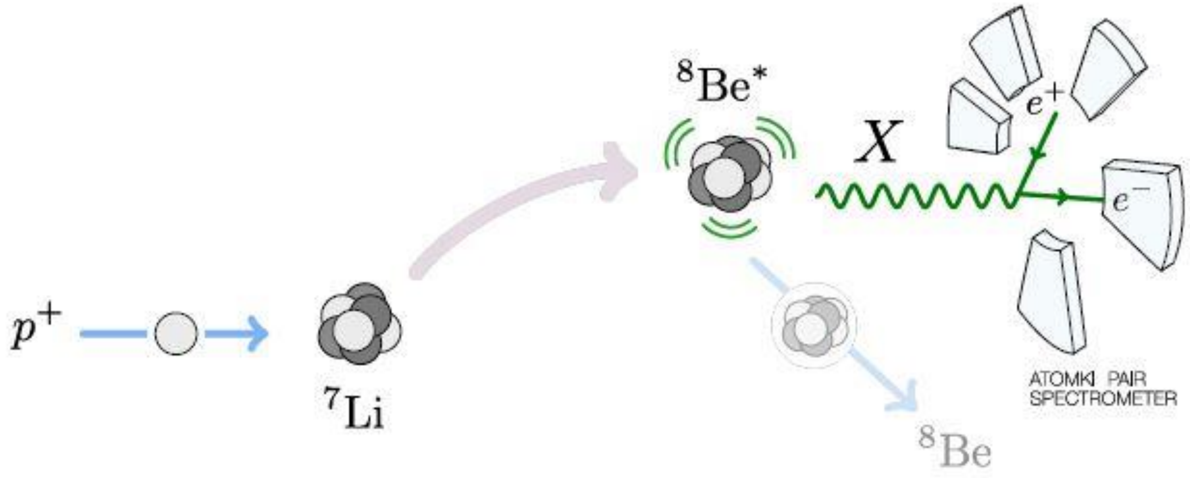

- Best fit mass values give ∼17 MeV.
- The particle must be a neutral boson.
- It propagates less then 1 cm in the apparatus ⇒ short-lived boson

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

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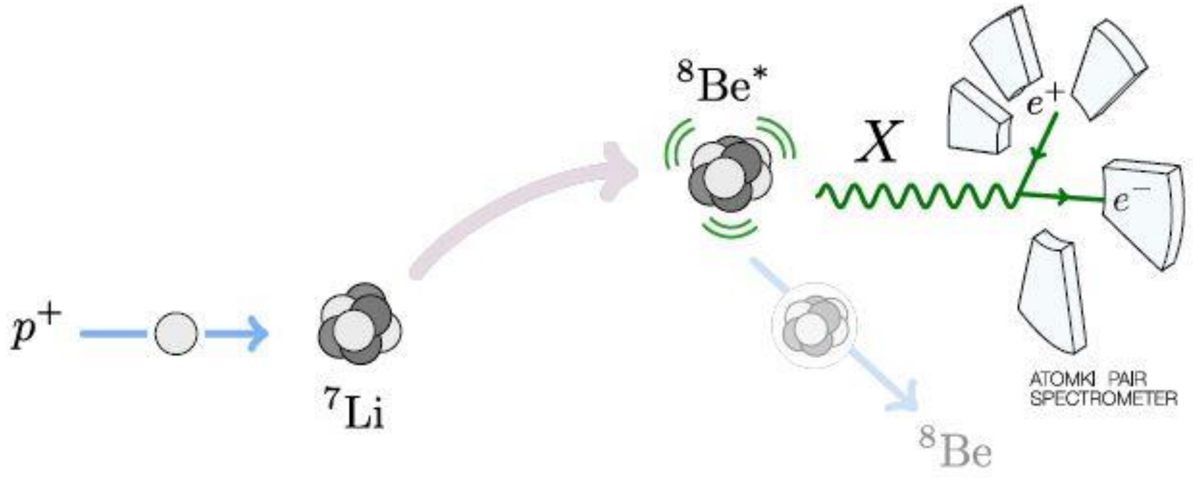

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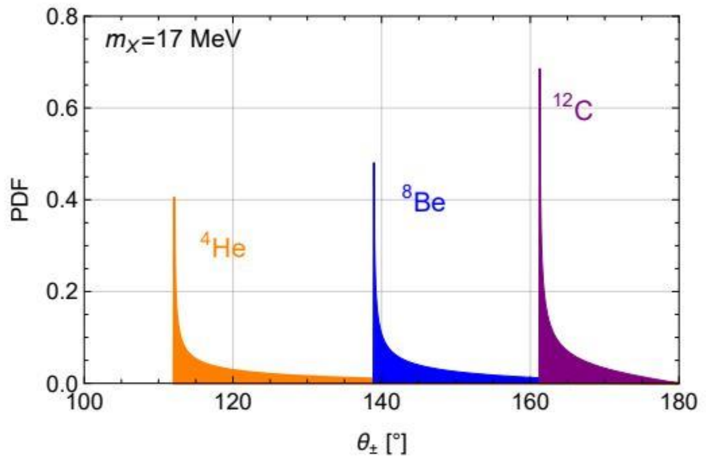
$$\gamma v \tau \lesssim 1\,\mathrm{cm}$$

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

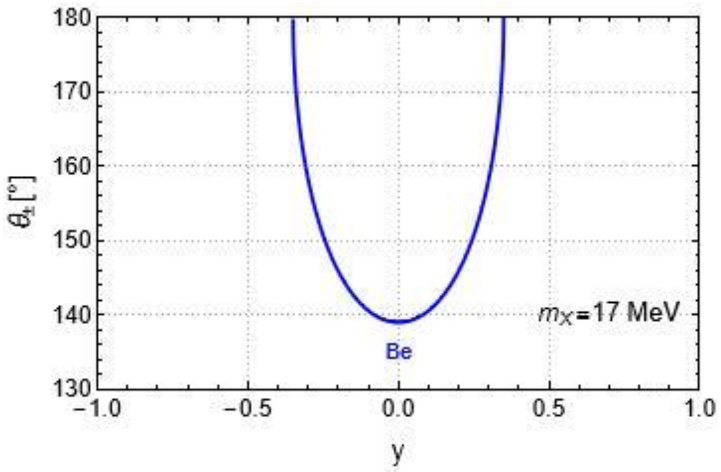
X17 kinematics

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

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.
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



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

Orbital angular momentum L of the X17

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

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$^8\text{Be}(17.64) \to {}^8\text{Be}$	1	0, 2	1	/
$^4\text{He}(21.01) \to {}^4\text{He}$	/	1	0	/
$^4\text{He}(20.21) \to {}^4\text{He}$	1	/	/	0
$^{12}\text{C}(17.23) \to {}^{12}\text{C}$	0, 2	1	/	1

Orbital angular momentum L of the X17

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- The X17 hypothesis is *kinematically* consistent for all the anomalies.
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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	***X* boson spin parity**			
$N^* \to N$	$S^{\pi} = 1^{-}$	$S^{\pi} = 1^{+}$	$S^{\pi} = 0^{-}$	$S^{\pi} = 0^{+}$
$^{8}\text{Be}(18.15) \to {}^{8}\text{Be}$	1	0, 2	1	/
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$^{12}\text{C}(17.23) \to {}^{12}\text{C}$	0, 2	1	/	1

Orbital angular momentum L of the X17

X17 dynamics

After the C anomaly,
two main scenarios to test:

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

Atomki best fit values

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

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

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

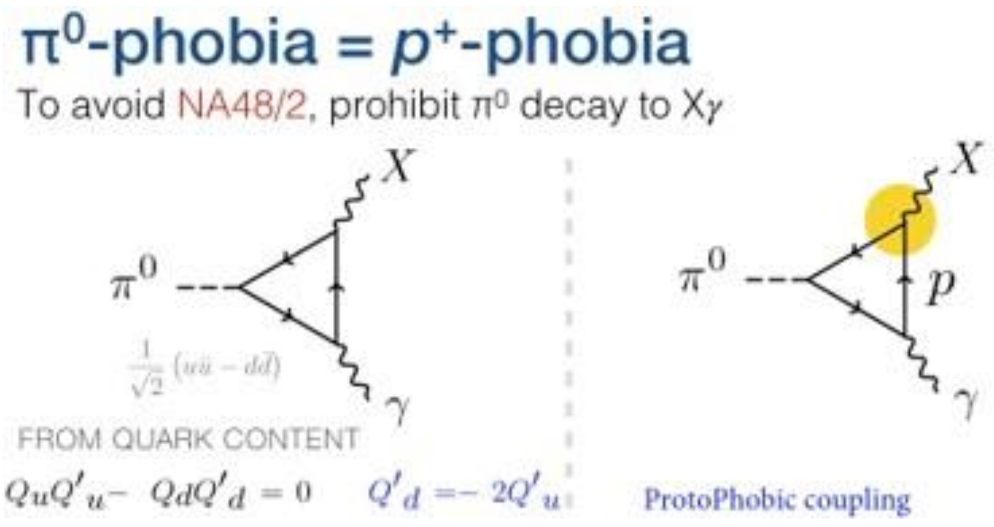
$$\frac{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + X)}{\Gamma(^{12}\mathrm{C}(17.23) \to {}^{12}\mathrm{C} + \gamma)} = (3.6 \pm 0.3) \times 10^{-6}$$

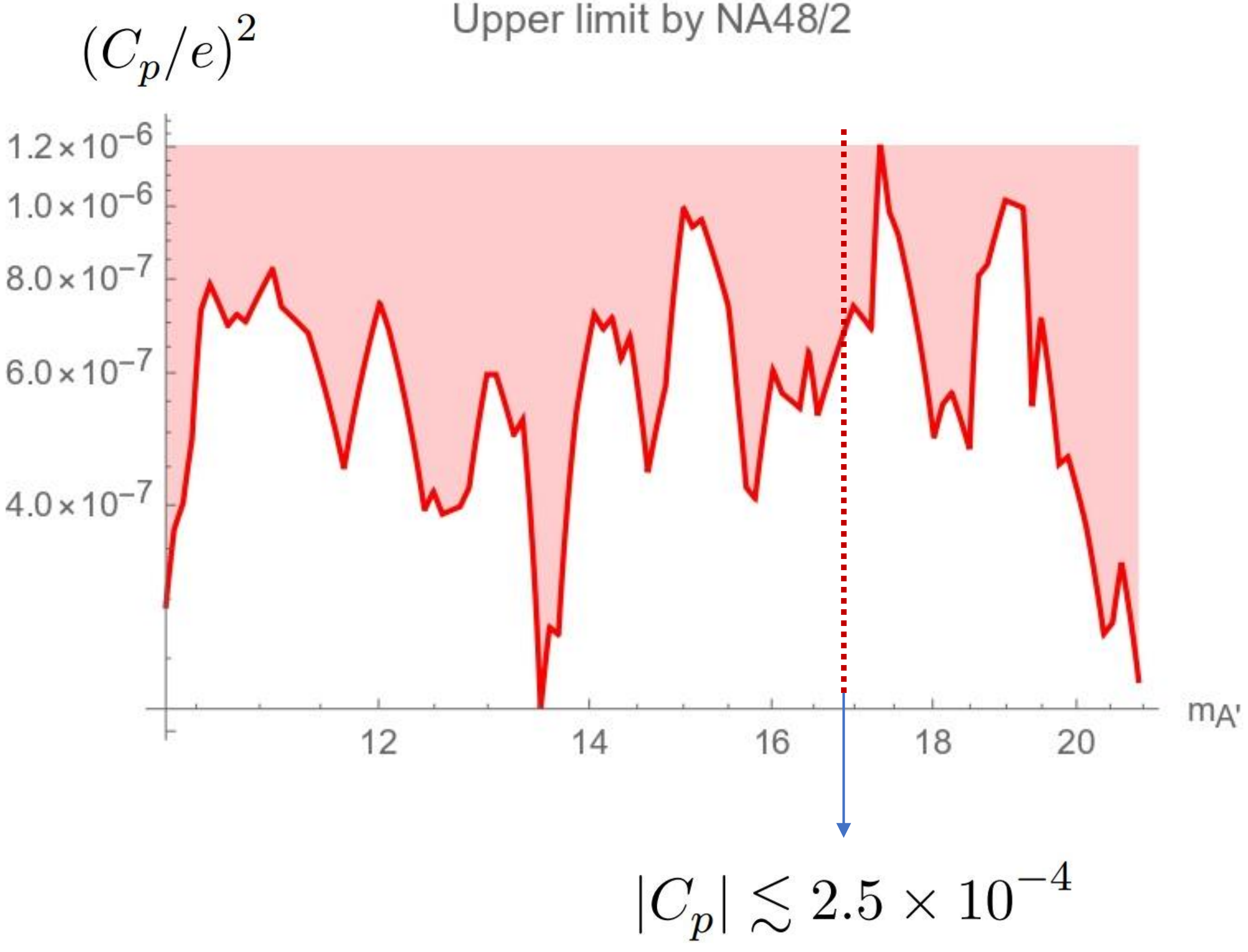
By matching the data to the theoretical prediction, one extracts the nucleon couplings to X17

Vector X17: protophobia

NA48 coll., PLB 746 (2015) 178-185

- Among the constraints from experimental search, the strongest comes from the dark photon search of NA48.
- A suppressed proton coupling is required to avoid the constraint.

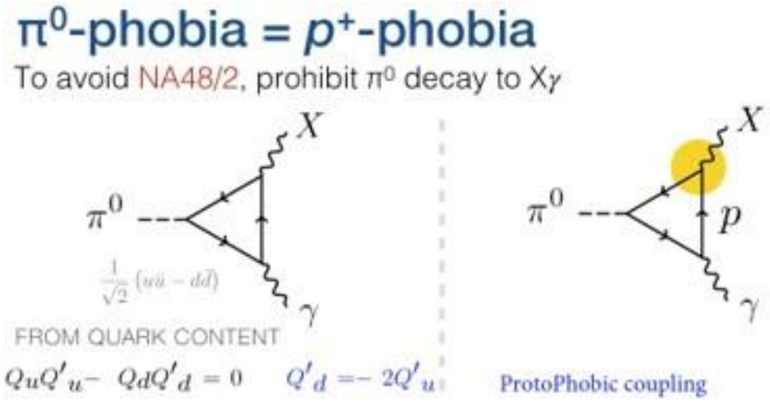


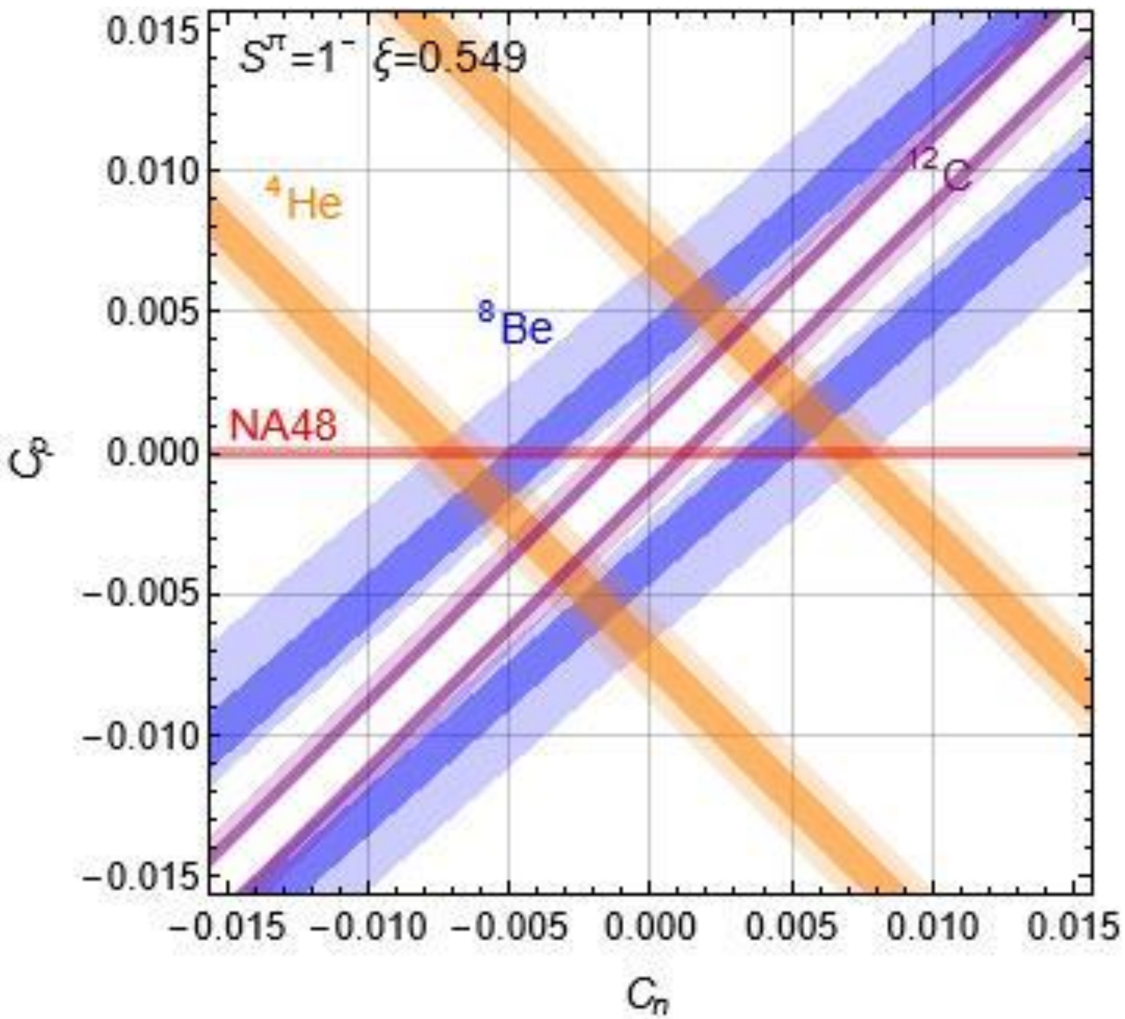


Vector X17

Barducci and Toni, JHEP 02 (2023) 154

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





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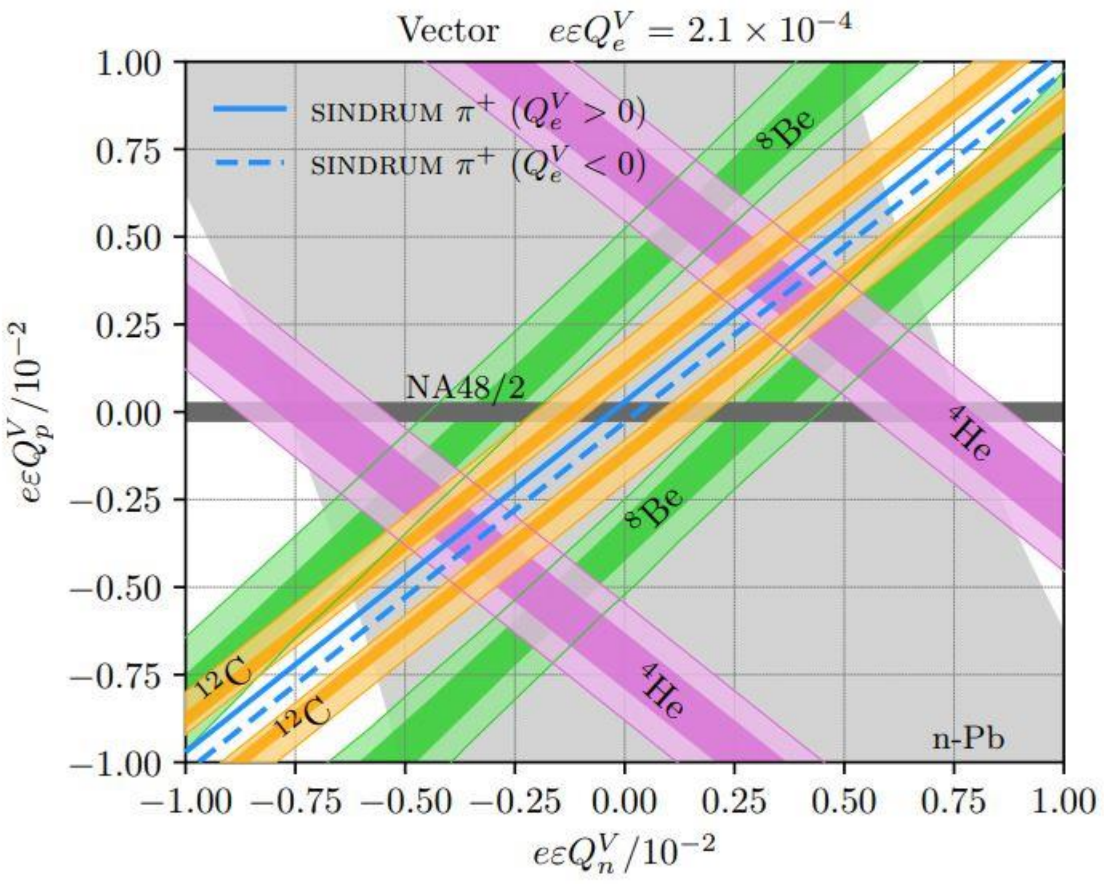


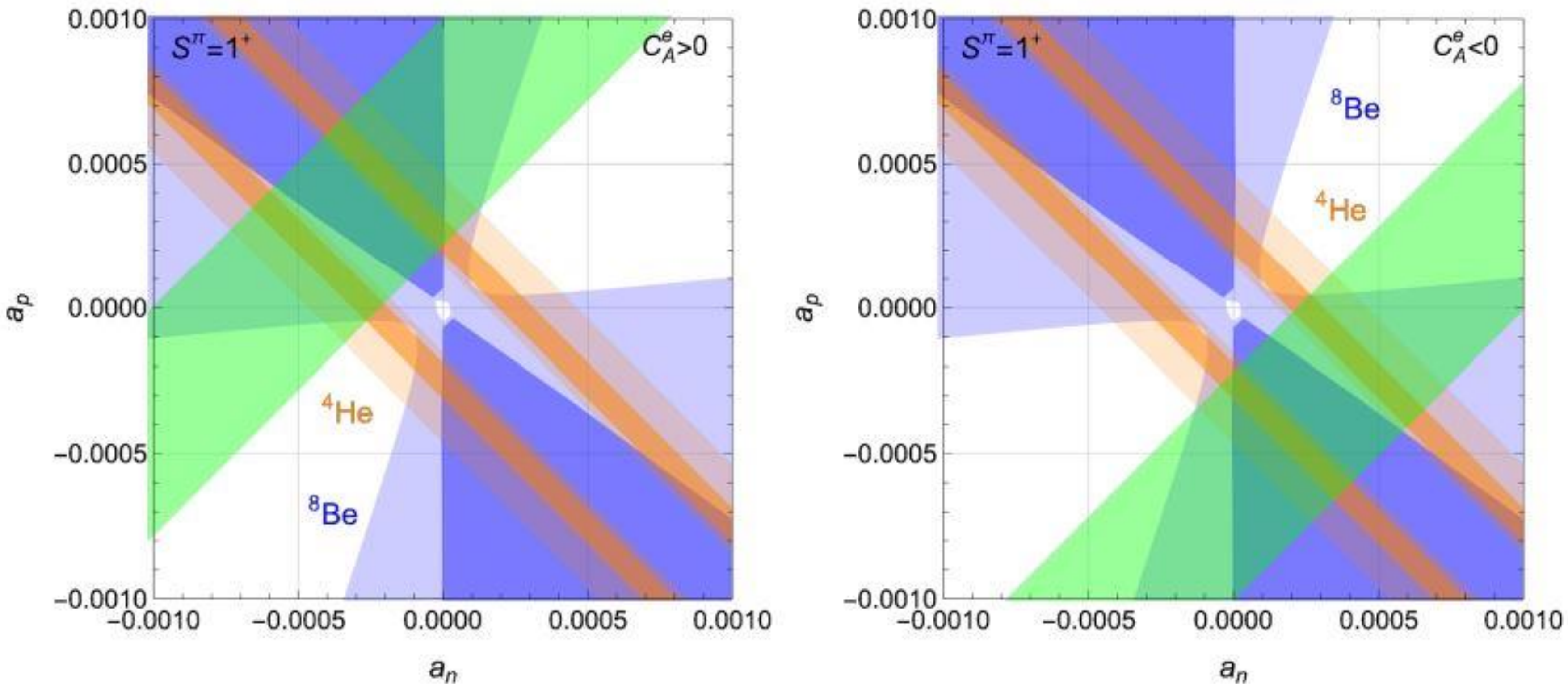
- Recently Hostert and Pospelov calculated the constraints to a spin-1 X17 coming from the SINDRUM search of $\pi^+ \to e^+ \nu_e X$.
- All together, it seems that the vector case is almost excluded.

Hostert and Pospelov , arxiv:2306.15077

Axial-vector X17

[Barducci and Toni, JHEP 02 (2023) 154]

- An axial-vector X17 is dynamically consistent for Helium and Beryllium.
- No strong bound applies on the parameter space.
- An order of magnitude estimate of the Carbon anomaly seems to indicate that axial-vector solution is possible.



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

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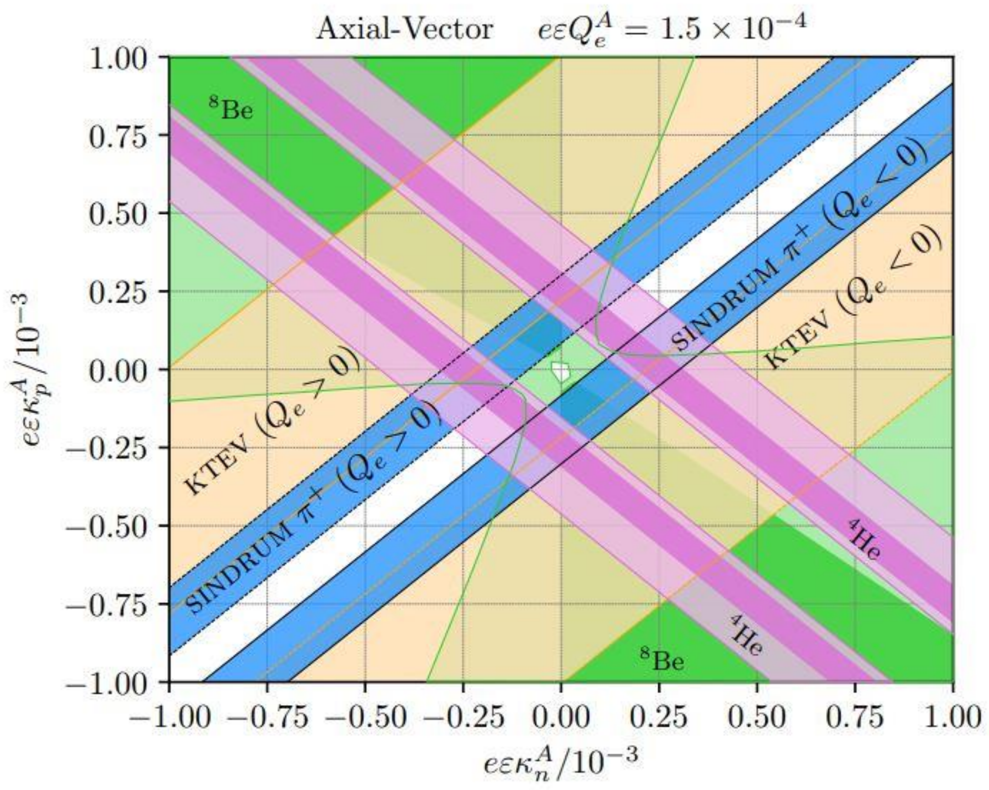

- Recently Hostert and Pospelov calculated the constraints to a spin-1 X17 coming from the SINDRUM search of $\pi^+ \to e^+\nu_e X$.
- All together, it seems that the axial case is still open but the allowed region is quite small.

Hostert and Pospelov , arxiv:2306.15077

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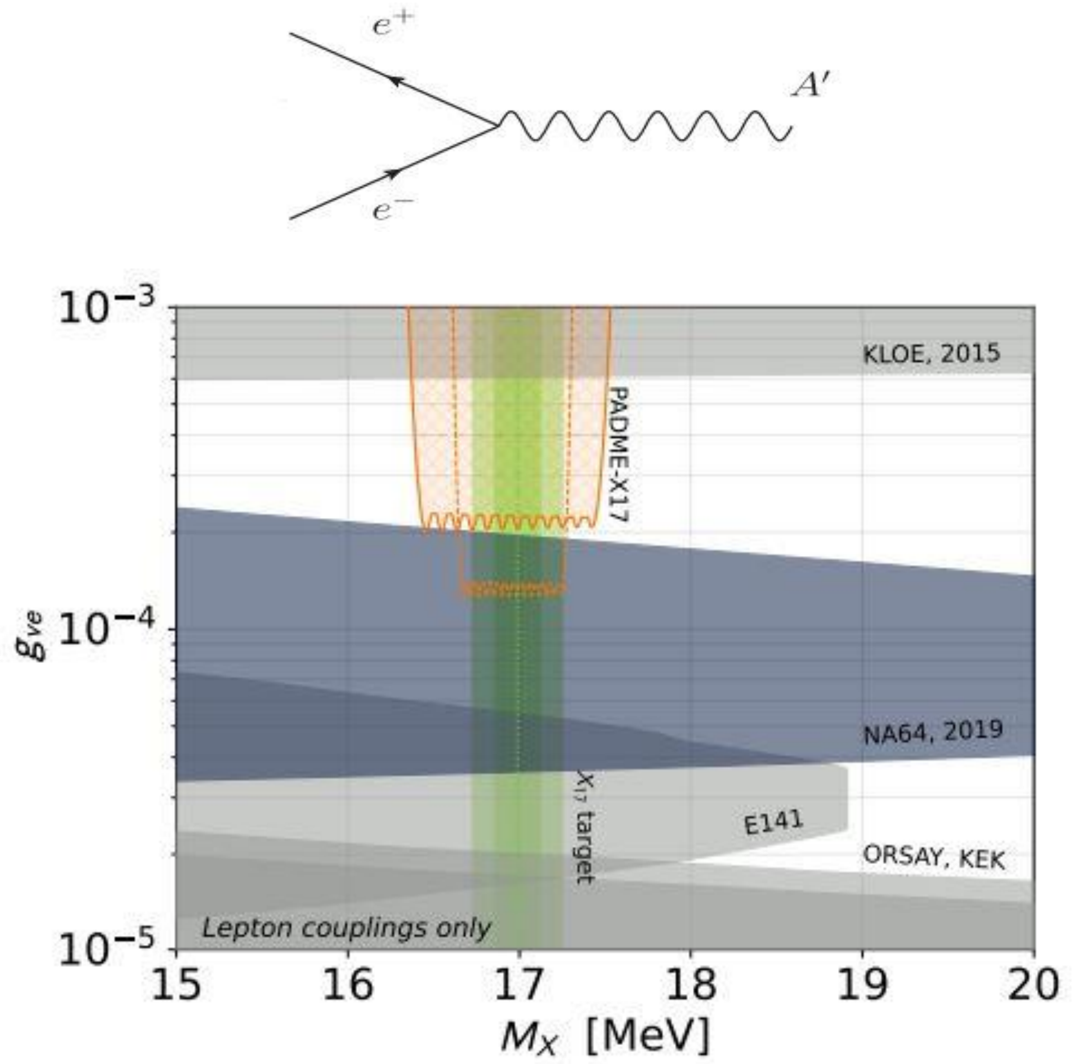
Spin-1 X17 at Padme

- 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!



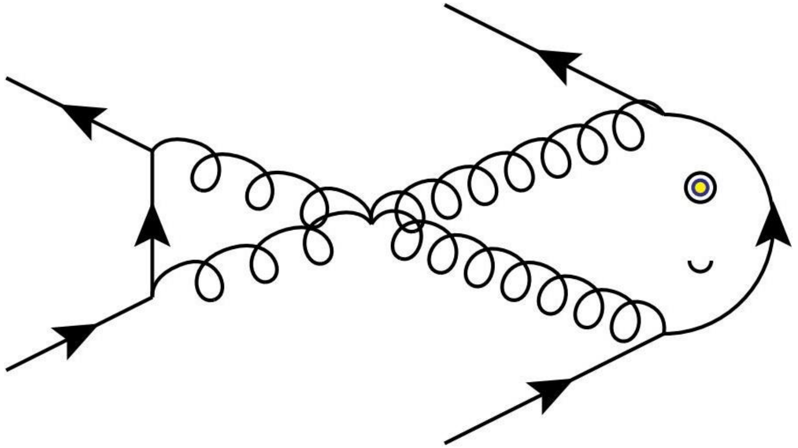
PRD 106 (2022) 11, 115036
L. Darmé, M. Mancini,
M. Raggi and E. Nardi

Summary

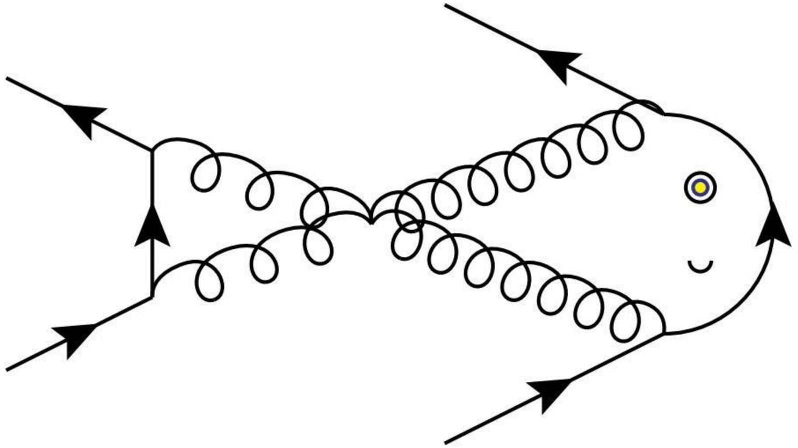
- Three anomalies observed in nuclear transitions appear to be consistent with a new particle explanation, the X17.
- The statistical significance is very strong, nearly 7σ for each nucleus.
- The X17 is kinematically consistent with all the anomalies.
- Parity conservation disfavored spin-0 solutions.
- An axial vector X17 could accommodate other experimental anomalies, like KTeV and $(g-2)_e$.
- Padme will test the X17 hypothesis, almost closing the spin-1 parameter space.

Waiting for new results from experimental searches!

The End



THANK YOU FOR THE ATTENTION!



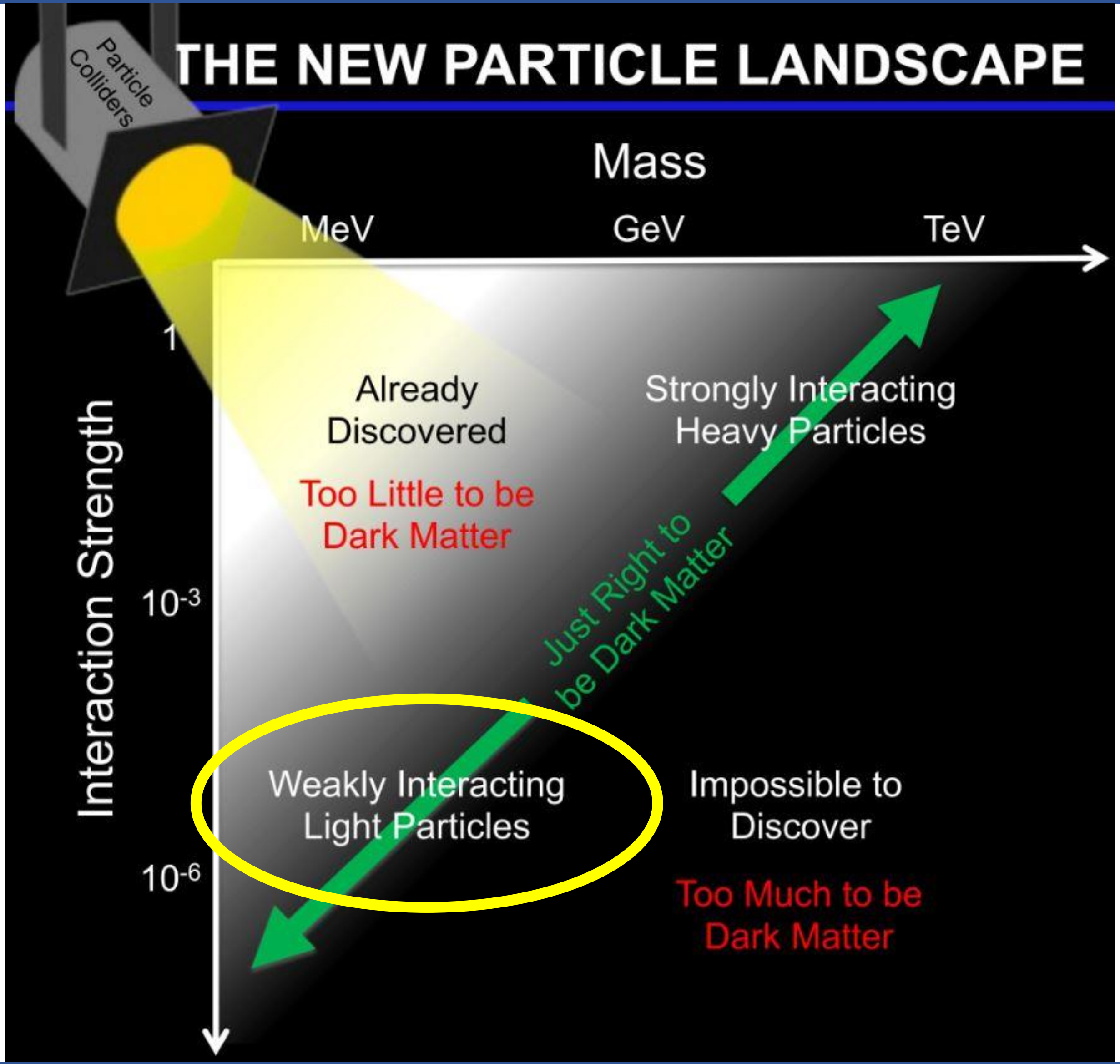
BACK UP SLIDES

Light New Physics frontier

Even if unexpected,
a X17-like particle is well welcome

- Light (sub-GeV) and weakly coupled particles are well studied nowadays.
- Recently, light and weakly coupled new physics have raised considerable interest due to the null result of TeV scale research at particle colliders.
- BSM physics and cosmology motivate the presence of light and weakly-coupled particles.

Examples: dark photons, axion, …



X17 kinematics

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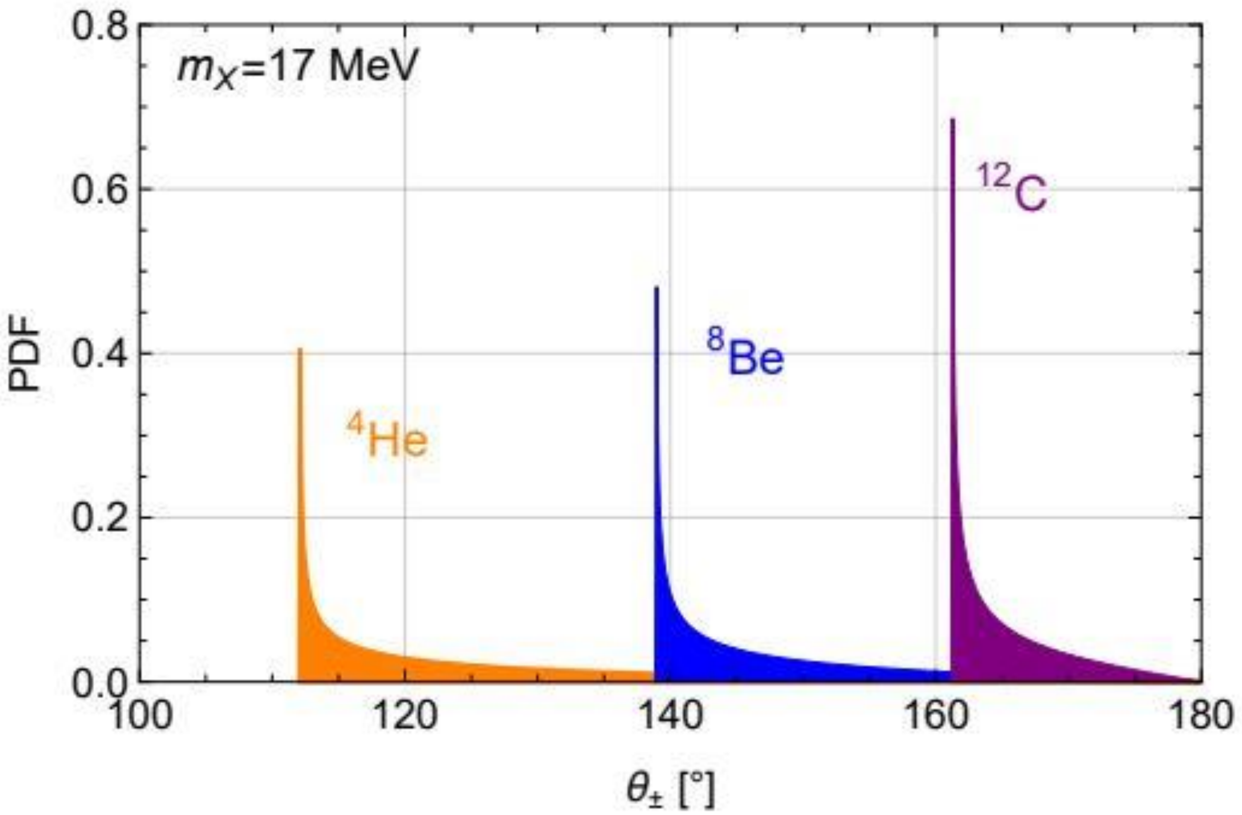

- Theoretical PDFs due to phase space effects, i.e. to the process kinematics.
- The measured values of the peak angles are in according with the theoretical prediction.

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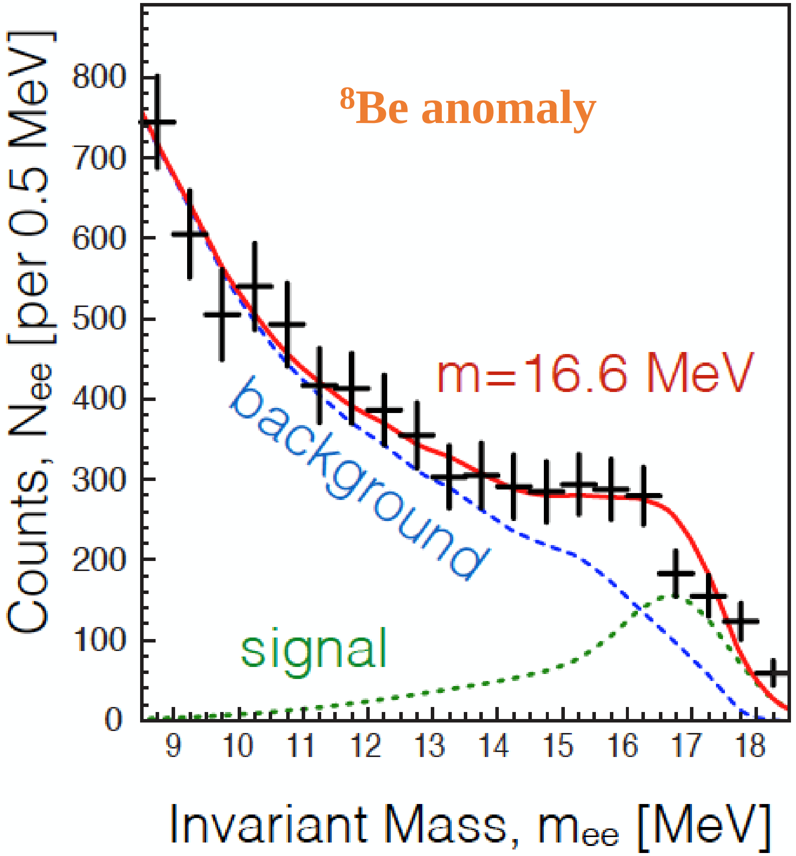
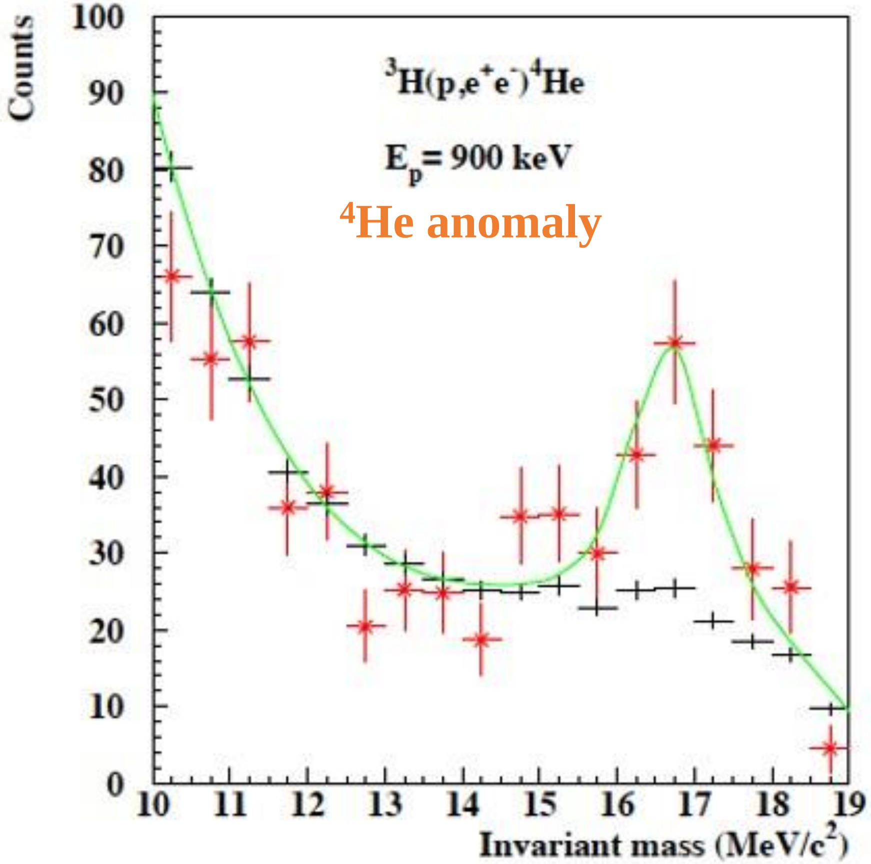
The ATOMKI anomalies show simple but well defined features, naturally explained by the kinematics of the X17 hypothesis.

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

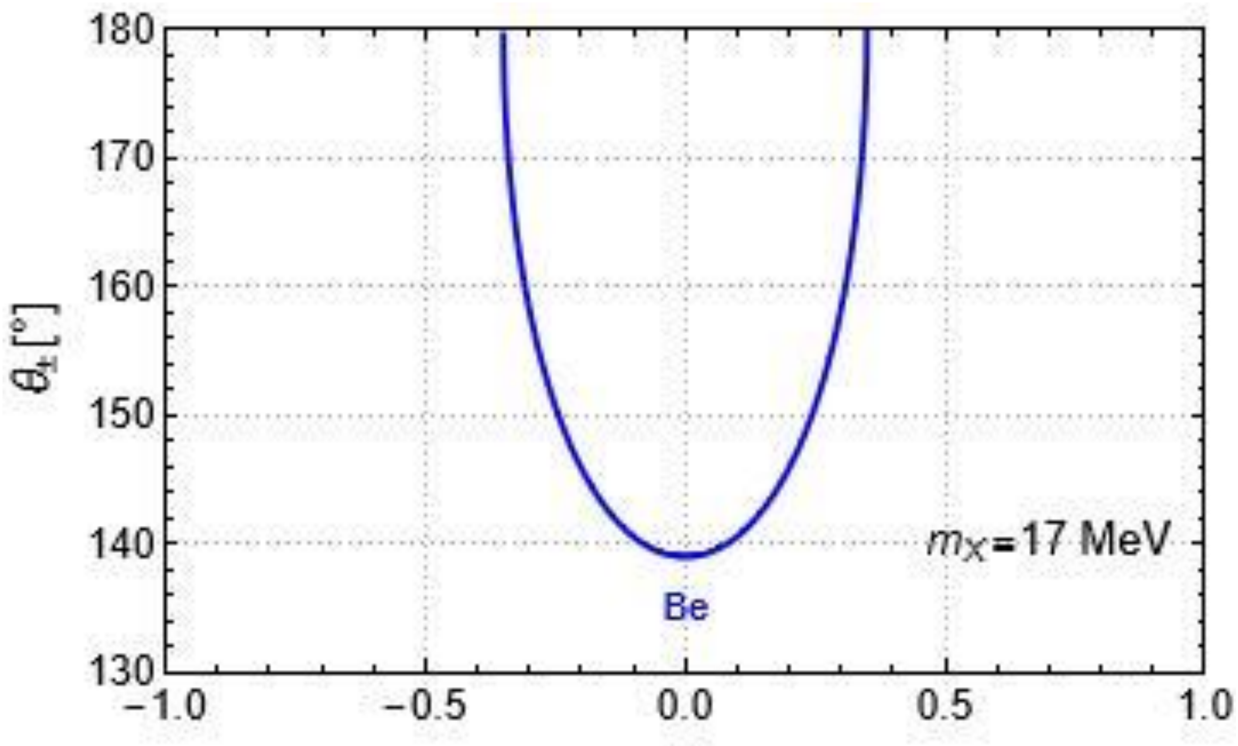




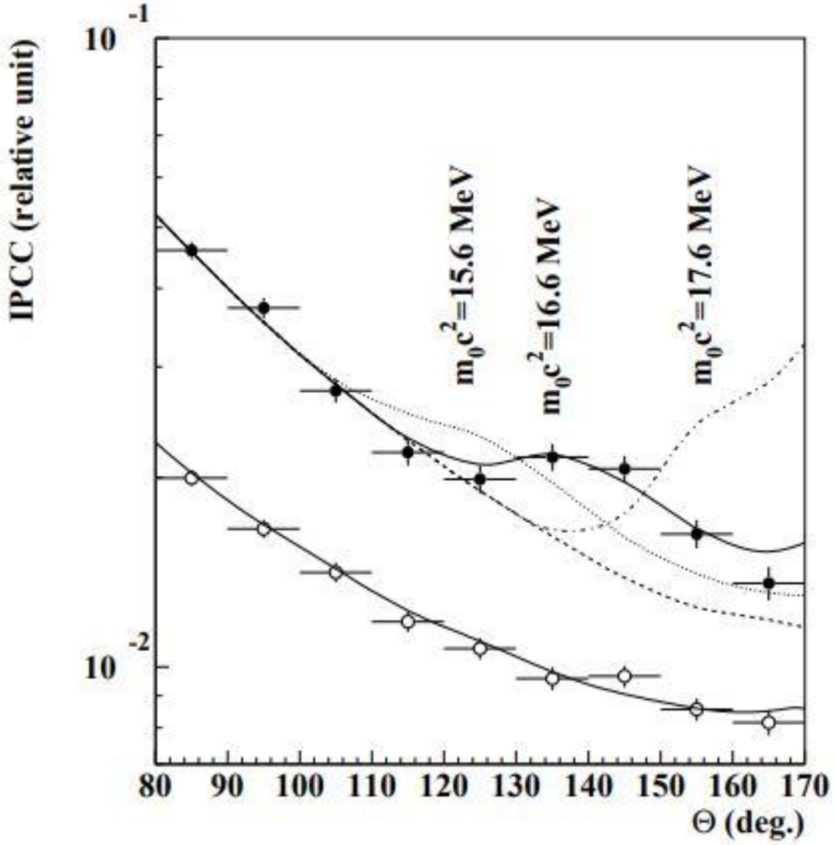
X17 kinematics

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

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.



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

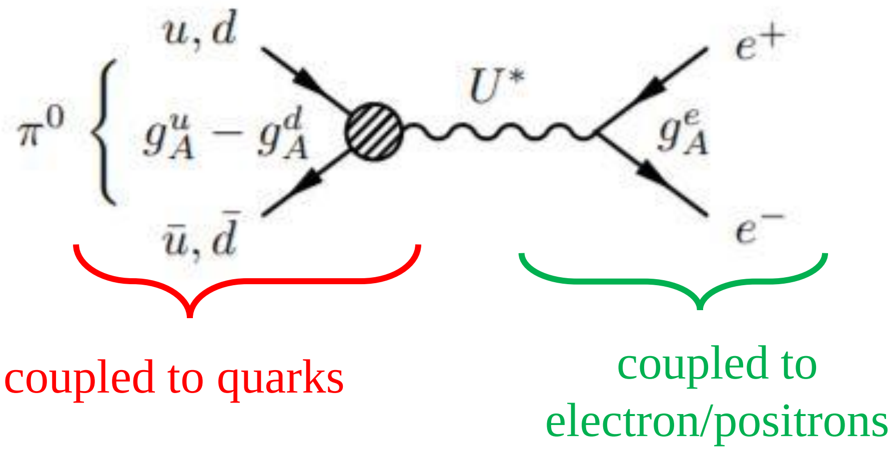


Axial-vector X17: KTeV anomaly

$$B^{\text{meas}}(\pi^0 \to e^+e^-) = (7.48 \pm 0.29 \pm 0.25) \times 10^{-8}$$

$$B^{\text{SM}}(\pi^0 \to e^+e^-) = (6.2 \pm 0.1) \times 10^{-8}$$

- The KTeV collaboration observed a 3.2σ deviation in the pion decay to electron/positron pair
- Khan, Schmitt and Tait (JHEP 05 (2017) 002) suggested that the KTeV anomaly could be explained by the introduction of a light axial boson.
- The axial boson should couple to the light quarks and to the electrons/positrons.

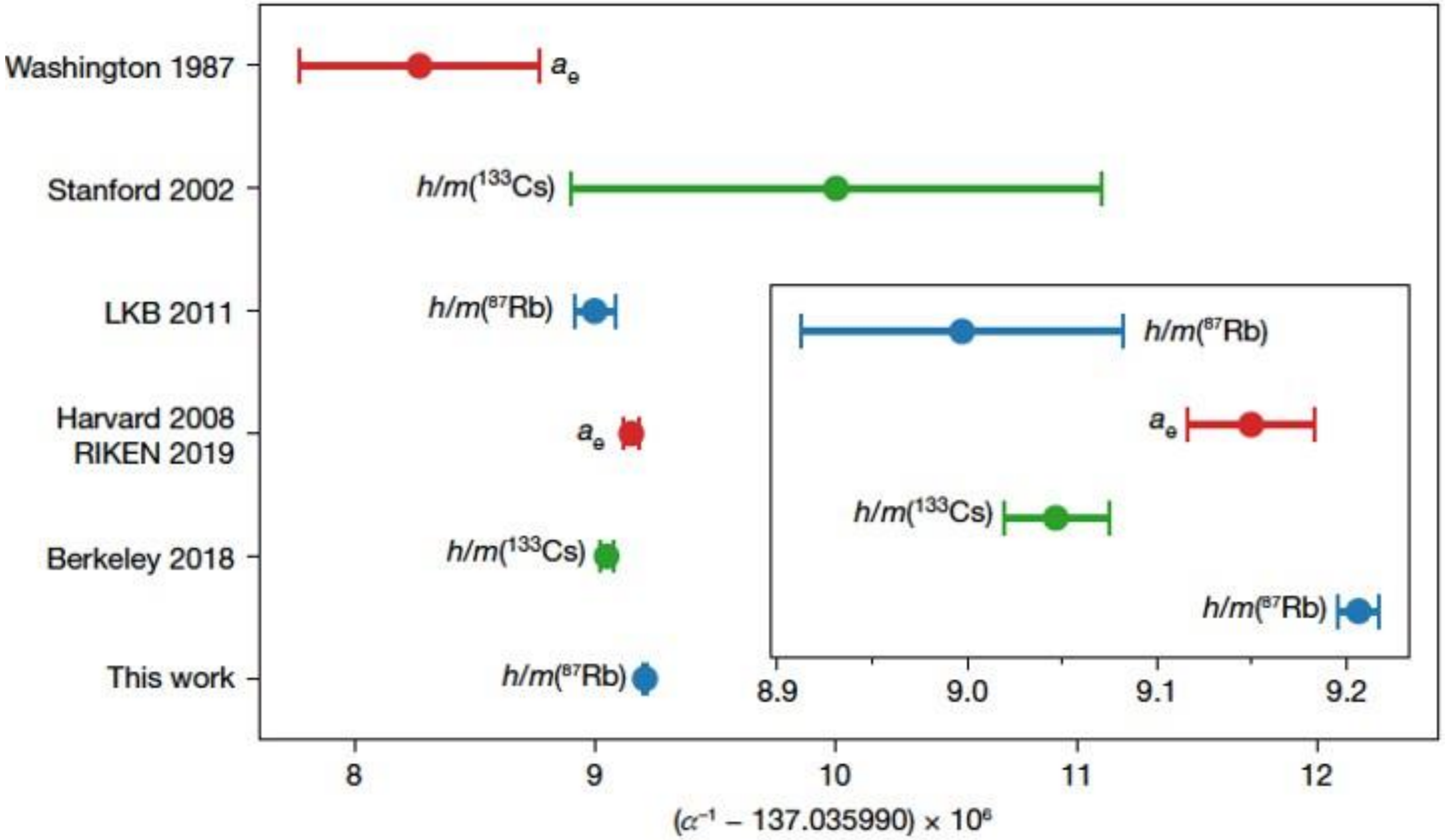


$$\frac{(g_A^u - g_A^d)g_A^e}{m_U^2} = (4.0 \pm 1.8) \times 10^{-10}\ \text{MeV}^{-2}$$

Axial X17 couplings $\Rightarrow$ $$\frac{(g_A^u - g_A^d)g_A^e}{m_U^2} \sim 10^{-10}\ \text{MeV}^{-2}$$

Electron's g-2

- The recent measurement changes the sign of the anomalous value of electron's g-2.
- The δ(SM) has been moved from (-) to (+) and the vector hypothesis is now favored by Rb measurement.
- Instead, the Cs measurement would prefer an axial boson.



^{133}Cs~9.045±0.03
^{87}Rb~9.21±0.01

Difference ~0.16
Sigma ~0.03

difference >5σ

something is wrong

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:

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