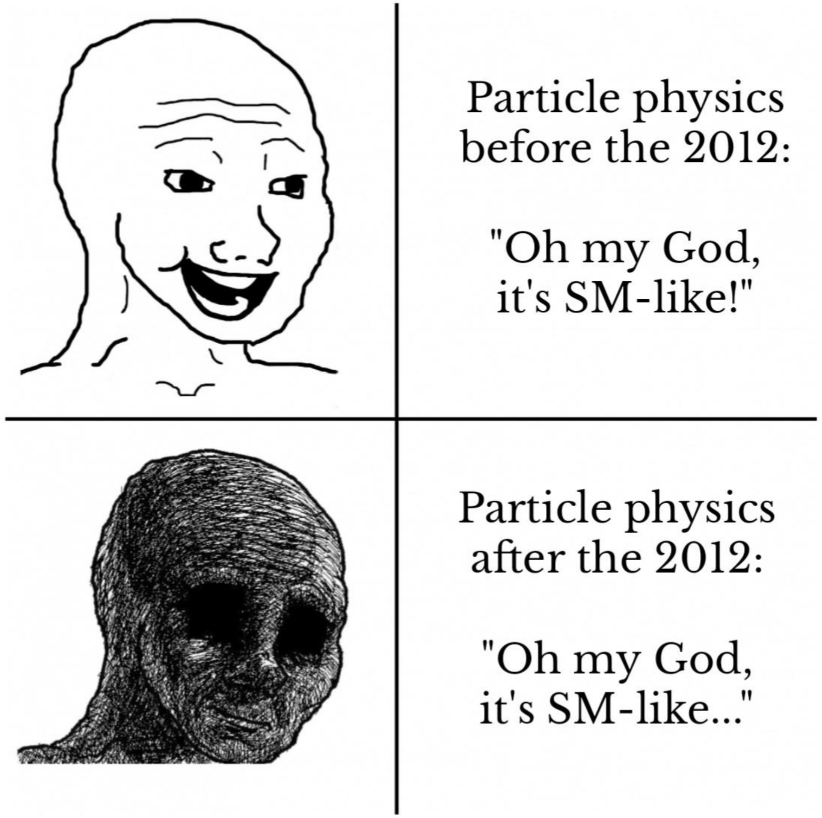
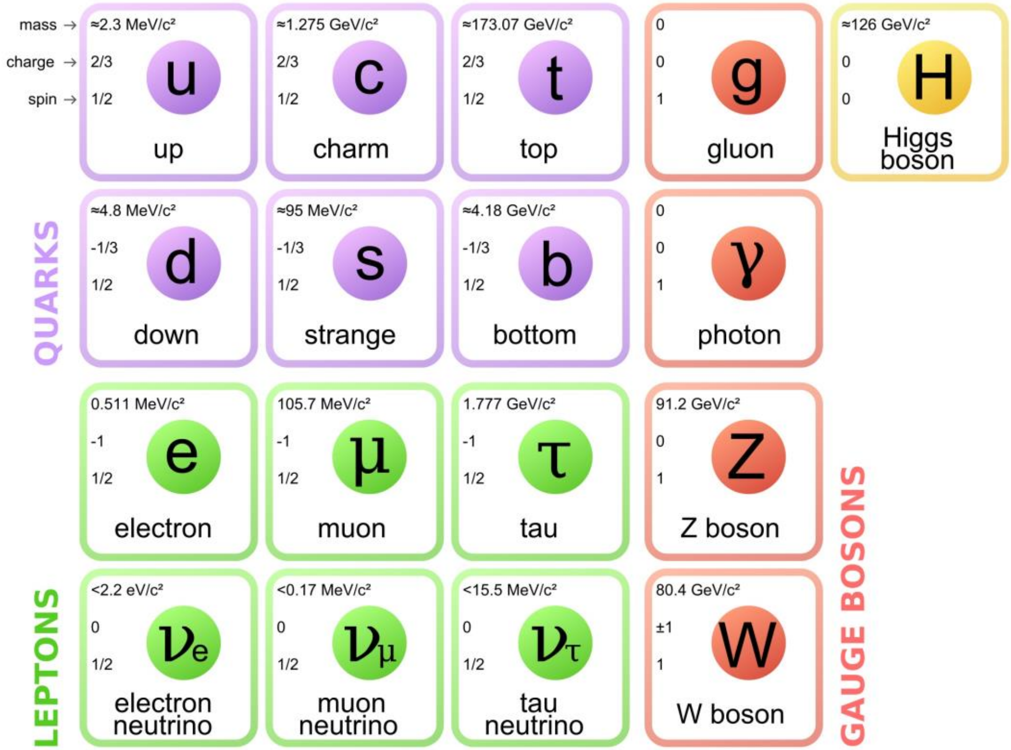
The Atomki anomalies and the X17

Claudio Toni

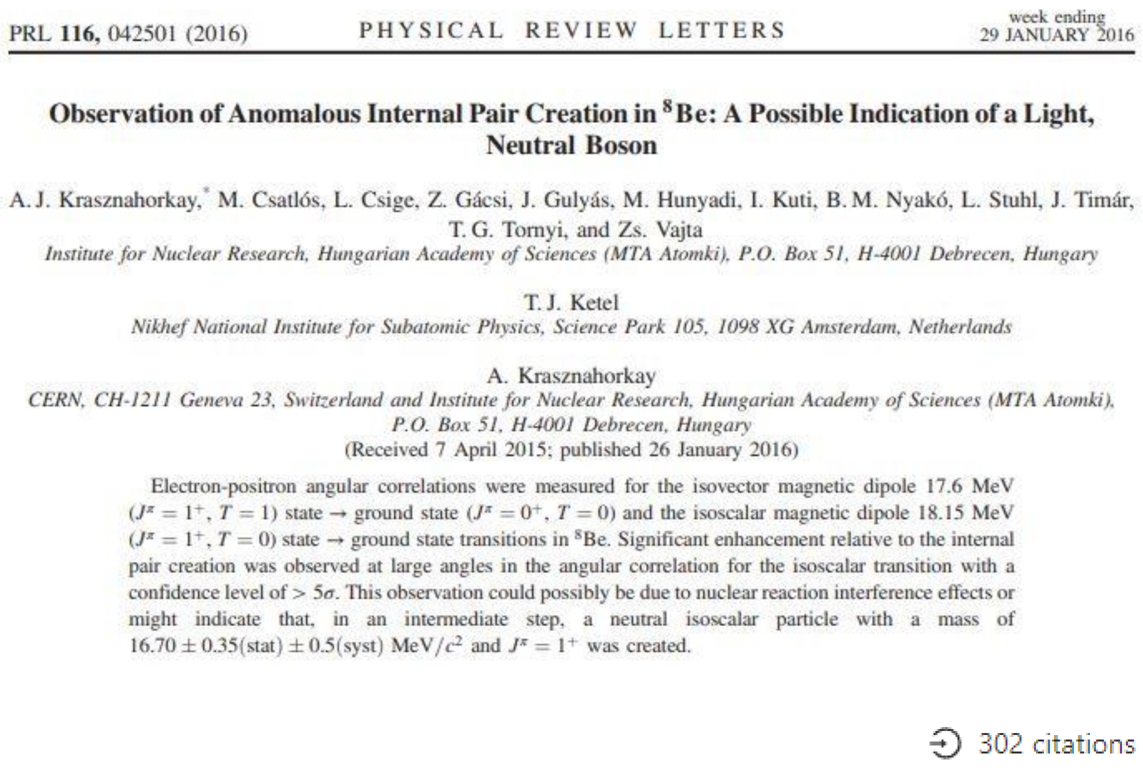
PhD seminar, 03/05/2023

There is life beyond the SM?





There is 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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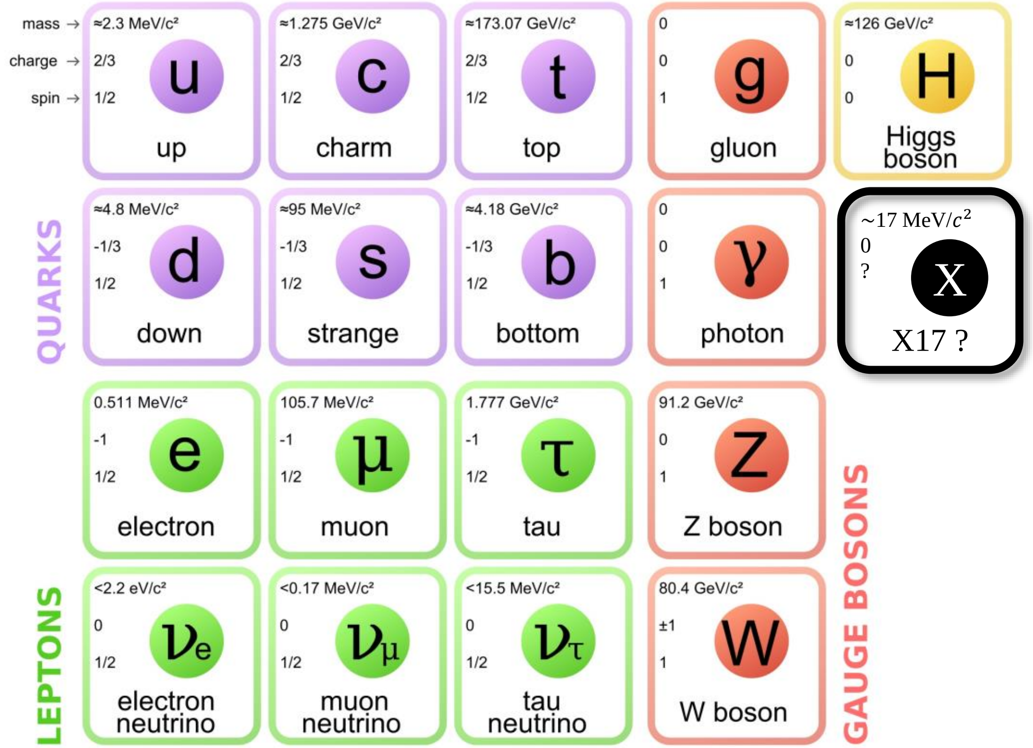
(Received 7 April 2015; published 26 January 2016)

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.

302 citations

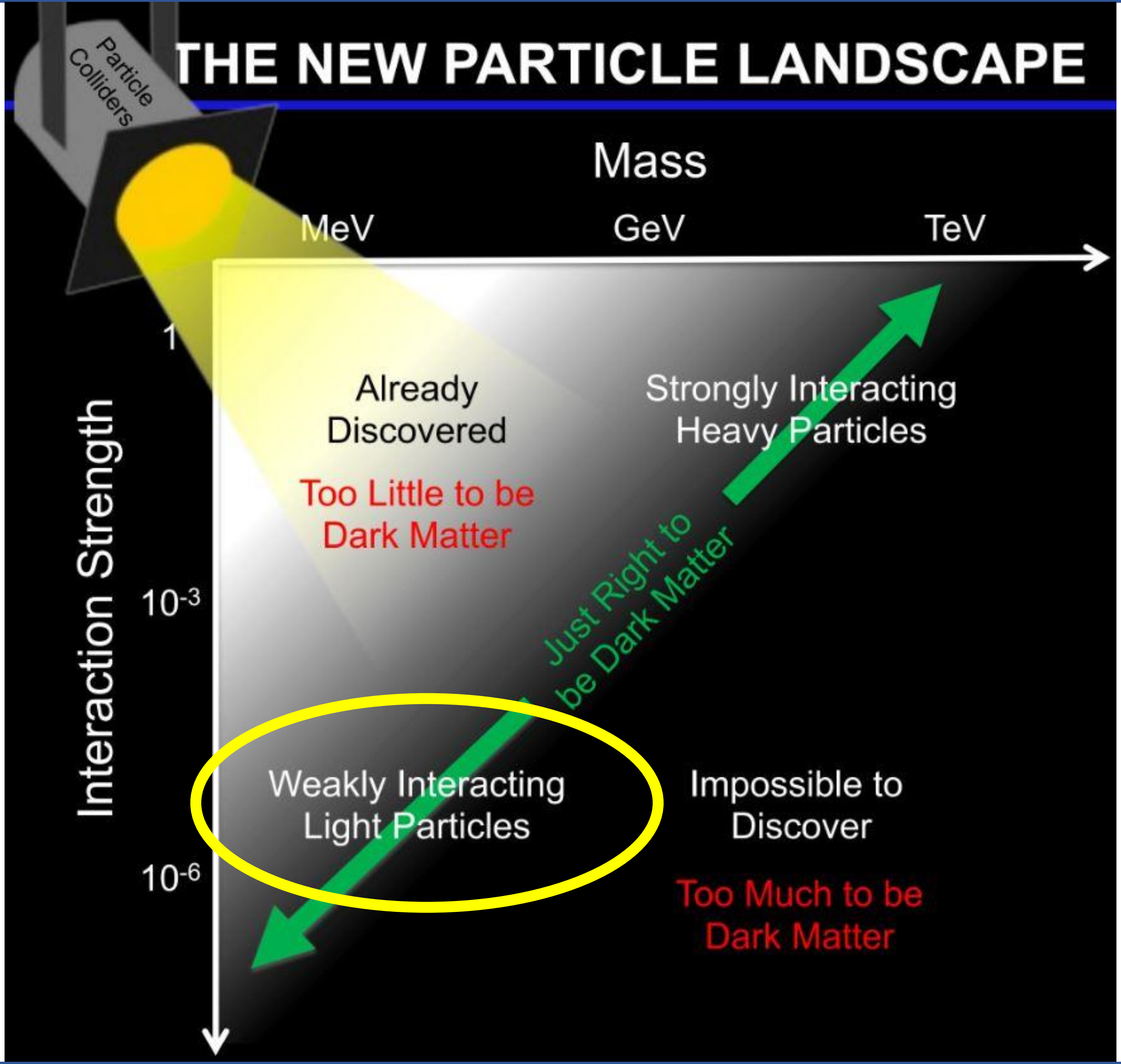


Could X17 be New Physics?

**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.

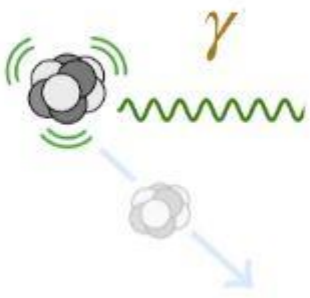
Examples: dark photons, axion, …



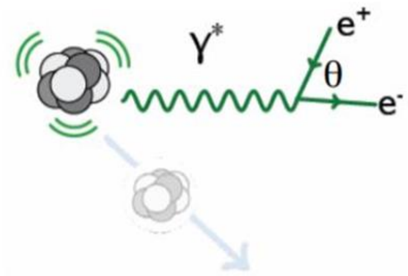
ATOMKI search

- Nuclear transitions provides a good tool to observe new particles at MeV scale.
- A nuclear transition occurs when an excited nucleus decays into a lower energy level of the same nucleus.
- Within the SM, only the QED can mediated nuclear transition.

<u>QED processes:</u>



γ emission

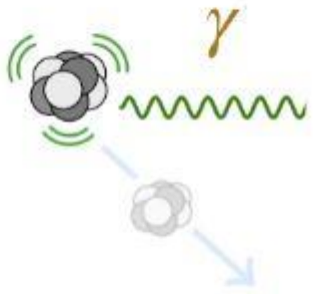


Internal pair creation

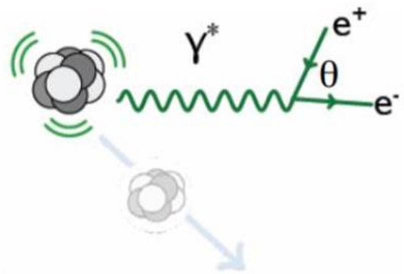
ATOMKI search

- 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:

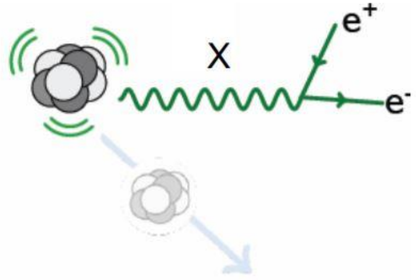


~ first order in QED coupling,



~ second order in QED coupling

NP processes:

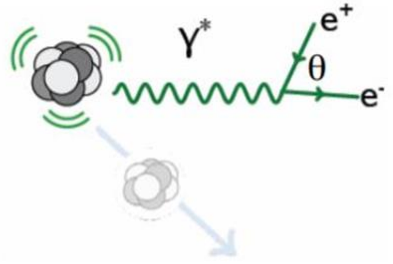


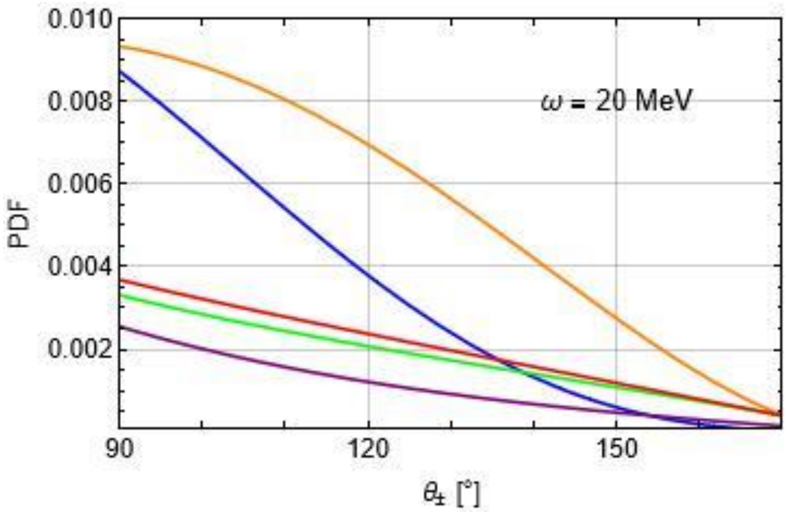
~ first order in NP coupling

ATOMKI search

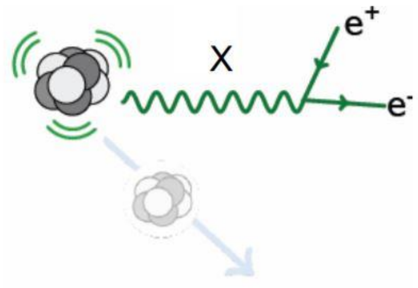
- ATOMKI collaboration looks for light NP in the angular correlation distribution of $e^- e^+$.
- At large angles, QED predicts that the angular correlation drops rapidly.

QED:





NP:

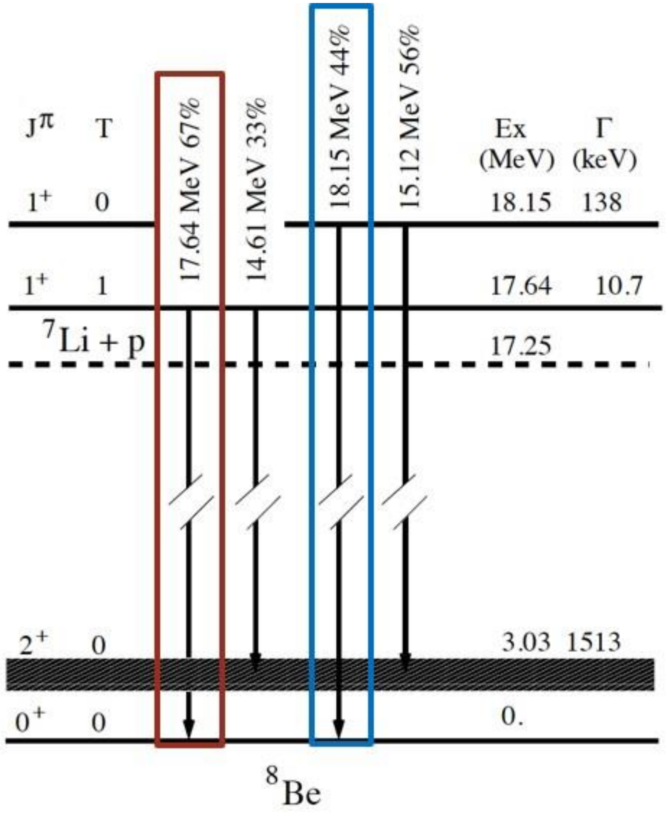


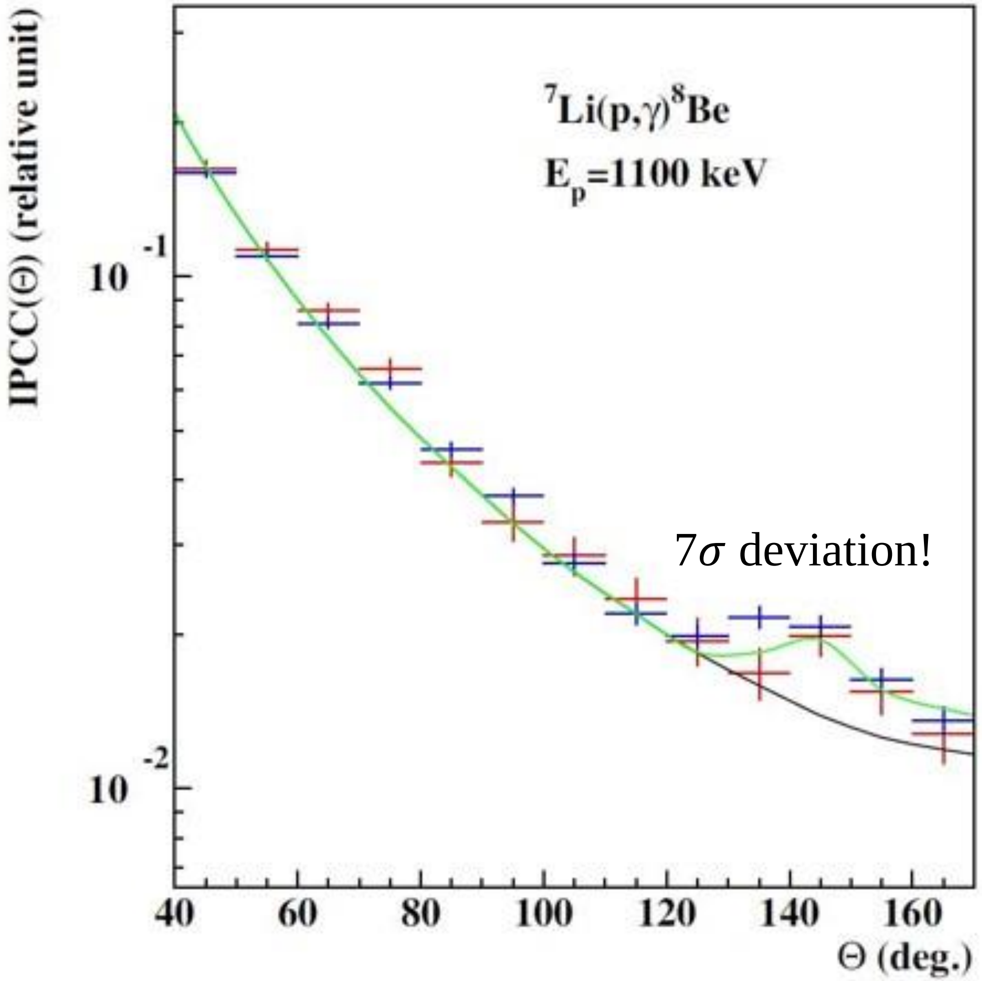
Bump-like distribution!

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



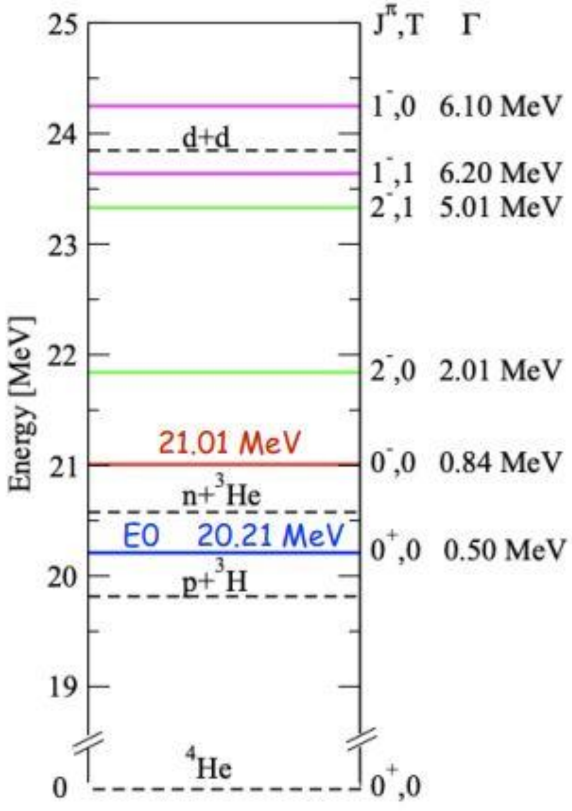


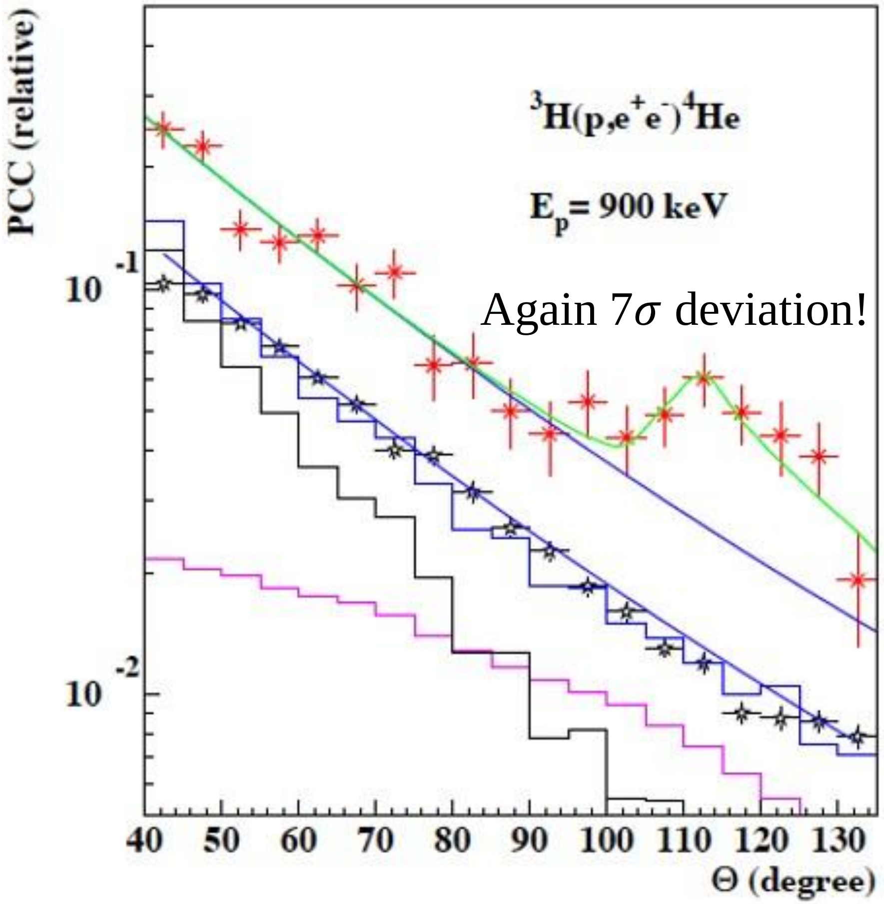
7σ deviation!

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





Again 7σ deviation!

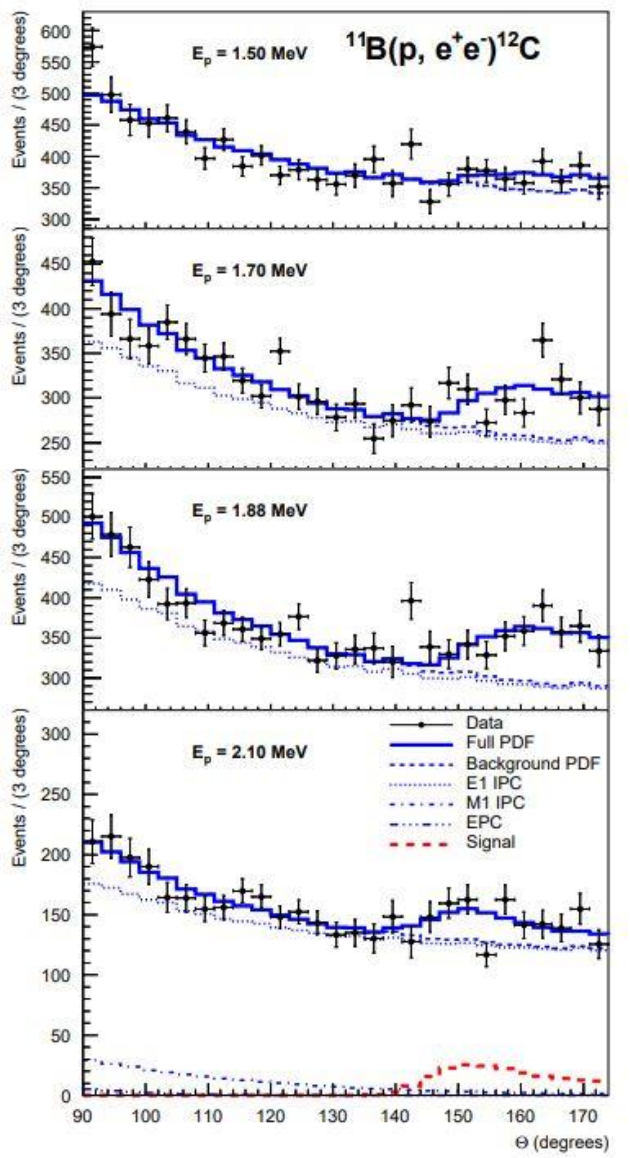
Carbon anomaly (2022)

- 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.

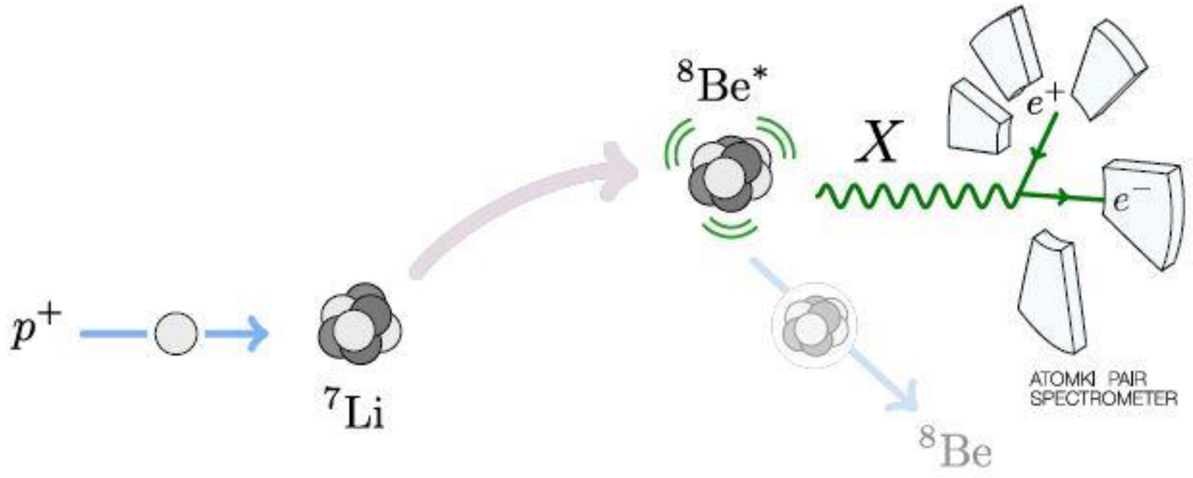
E_p (MeV)	B_x $\times 10^{-6}$	Mass (MeV/c^2)	Confidence
1.50	1.1(6)	16.81(15)	3σ
1.70	3.3(7)	16.93(8)	7σ
1.88	3.9(7)	17.13(10)	8σ
2.10	4.9(21)	17.06(10)	3σ
Averages	3.6(3)	17.03(11)	
Previous [14]	5.8	16.70(30)	
Previous [28]	5.1	16.94(12)	
Predicted [30]	3.0		

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



Features of X17

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



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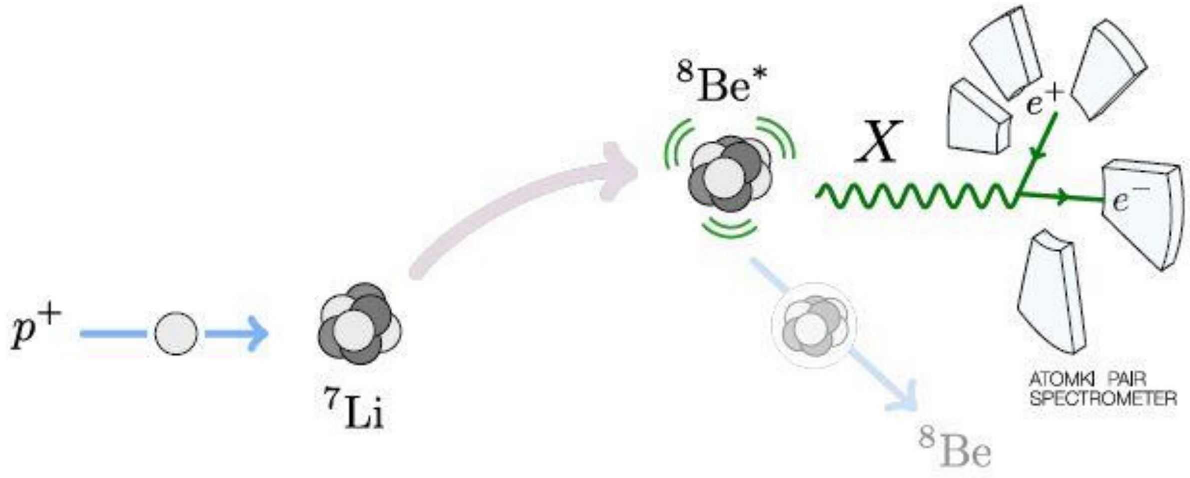

- Best fit mass values give ∼17 MeV.
- The particle must be a neutral boson.
- It propagates less then 1 cm in the apparatus ⇒ short-lived boson

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

Features of X17

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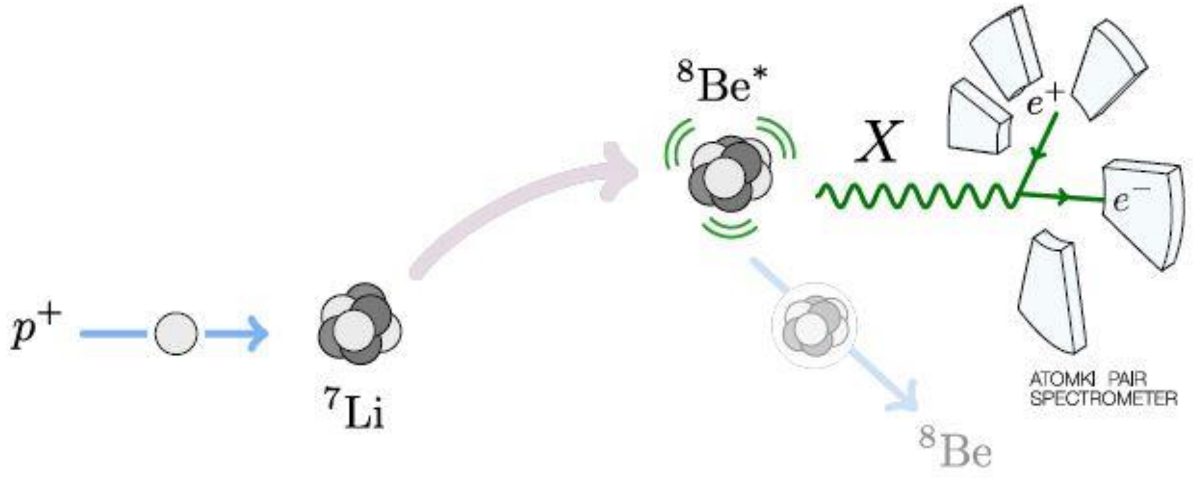

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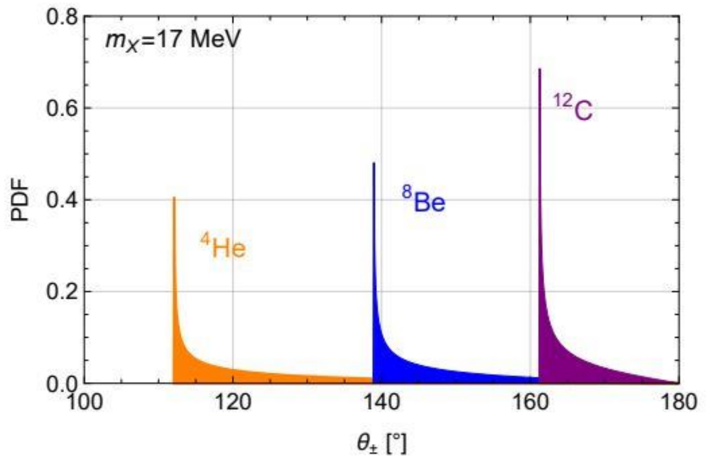
$$\text{Signal Rate} = \underbrace{\sigma(N^* \to N + X)}_{\text{coupled to nuclear matter, i.e. quarks and gluons}} \times \underbrace{\mathrm{BR}(X \to e^+ e^-)}_{\text{coupled to electron/positrons}}$$

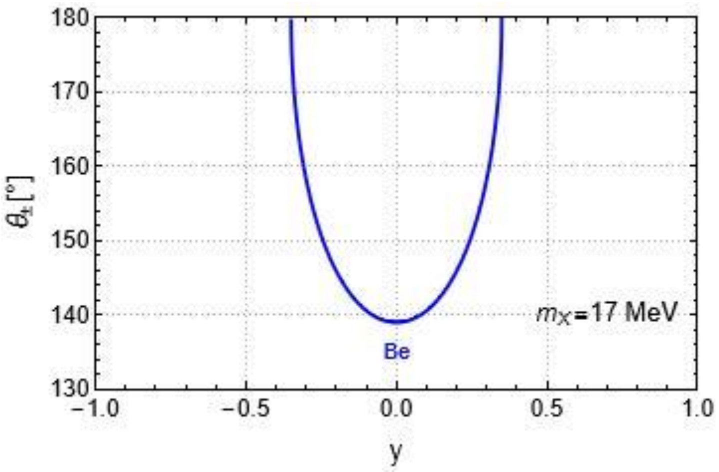
X17 kinematics

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?

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

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Process	X boson spin parity			
$N^* \to N$	$S^\pi = 1^-$	$S^\pi = 1^+$	$S^\pi = 0^-$	$S^\pi = 0^+$
$^8Be(18.15) \to {}^8Be$	1	0, 2	1	/
$^8Be(17.64) \to {}^8Be$	1	0, 2	1	/
$^4He(21.01) \to {}^4He$	/	1	0	/
$^4He(20.21) \to {}^4He$	1	/	/	0
$^{12}C(17.23) \to {}^{12}C$	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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Vector X17 $J^\pi = 1^-$	Scalar X17 $J^\pi = 0^+$	Axial-vector X17 $J^\pi = 1^+$	Pseudoscalar X17 $J^\pi = 0^-$

- 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}Be(18.15) $\to$ ^{8}Be	1	0, 2	1	/
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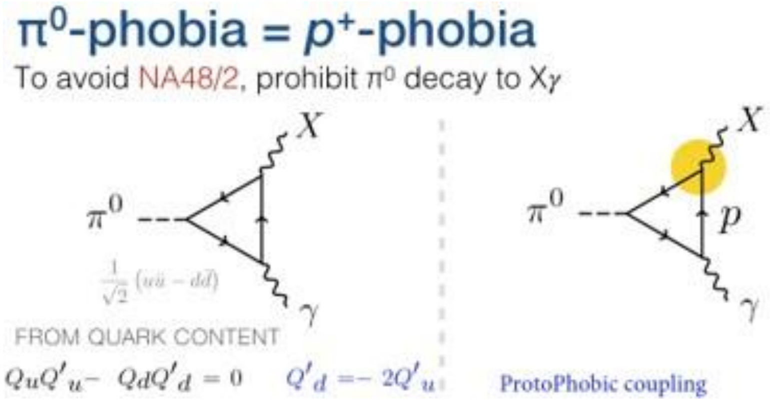
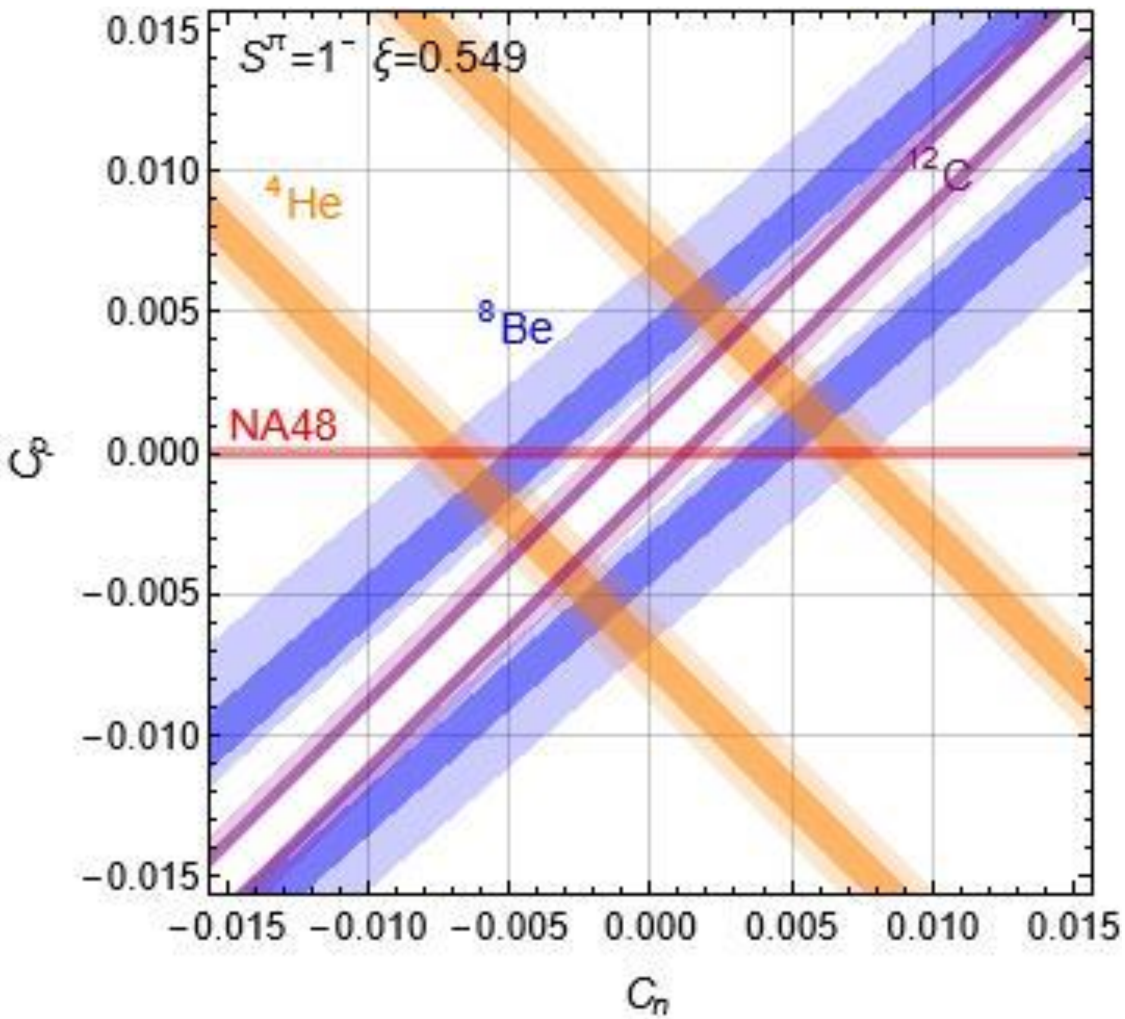
Orbital angular momentum L of the X17

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.

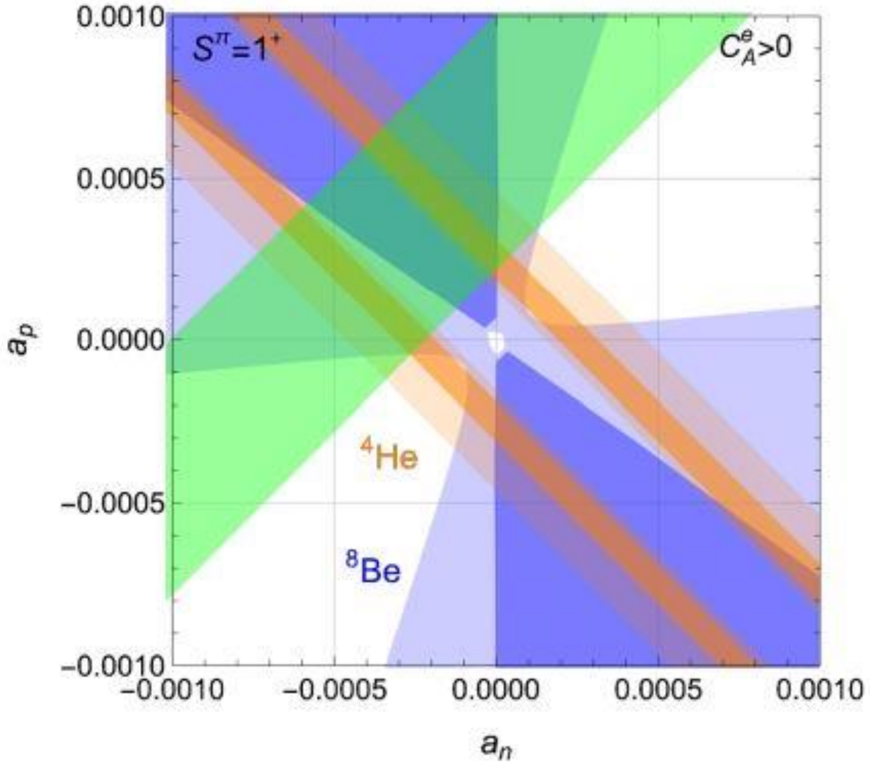


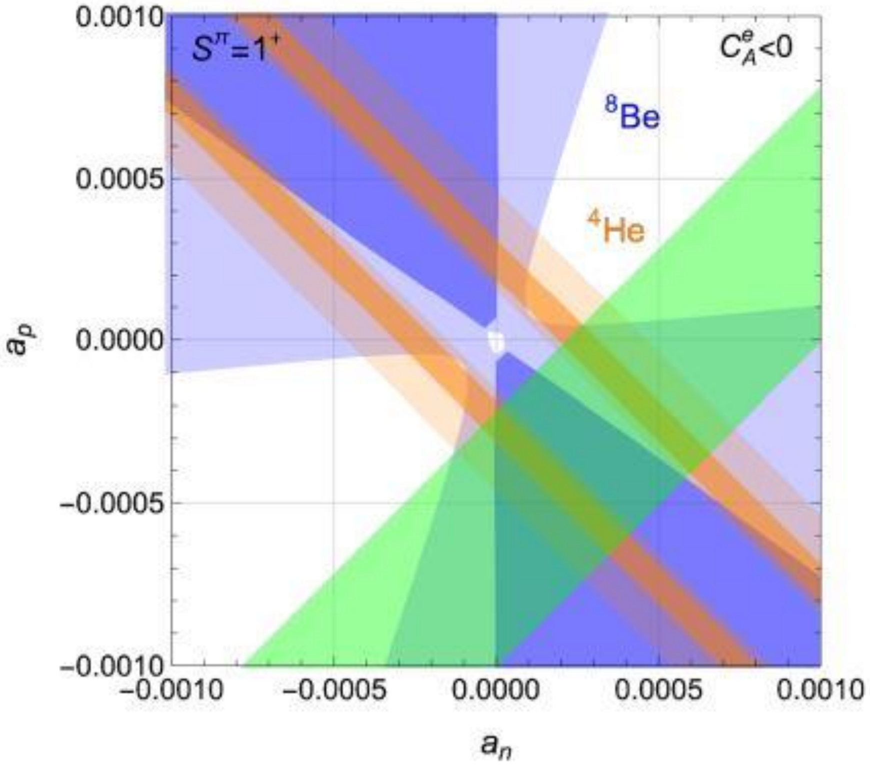


Axial-vector X17

Barducci and Toni, JHEP 02 (2023) 154

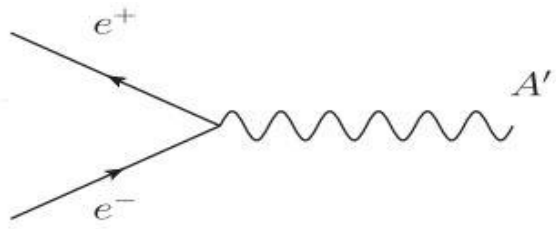
- An axial-vector X17 is dynamically consistent for Helium and Beryllium.
- No strong bound applies on the parameter space.
- An order of magnitude estimate of the Carbon anomaly seems to indicate that axial-vector solution is favored.
- Intriguingly, other experimental anomalies can be simultaneously satisfied.

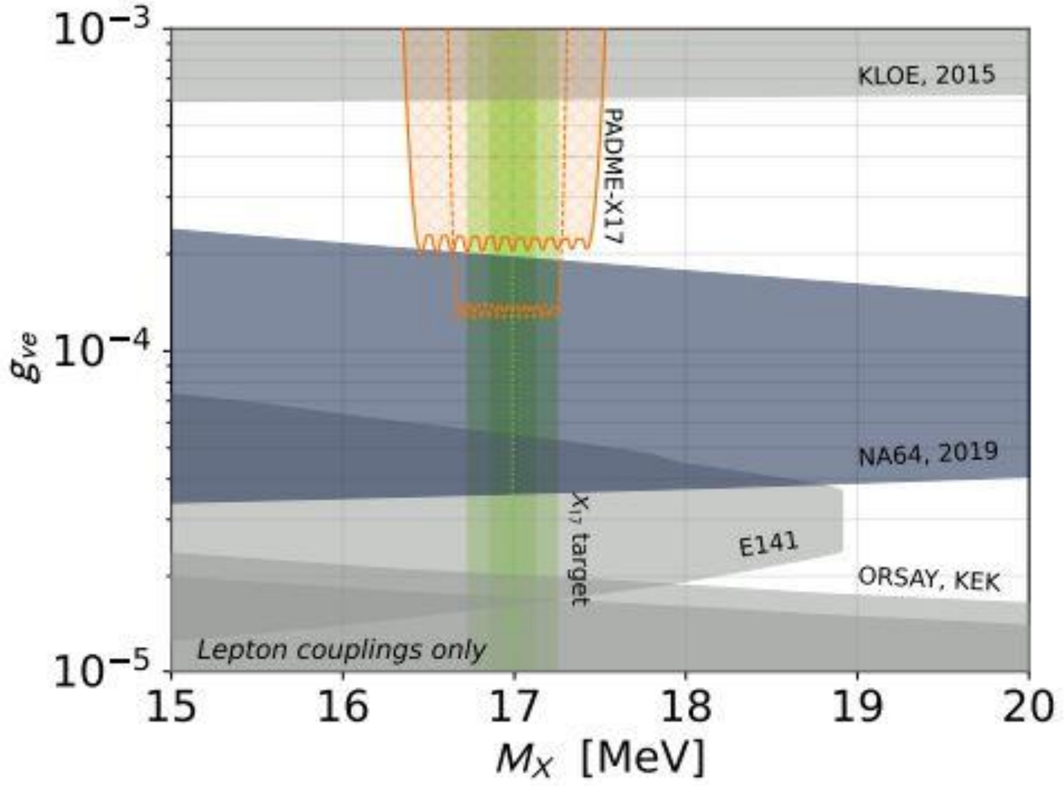




Spin-1 X17 at Padme

- 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!





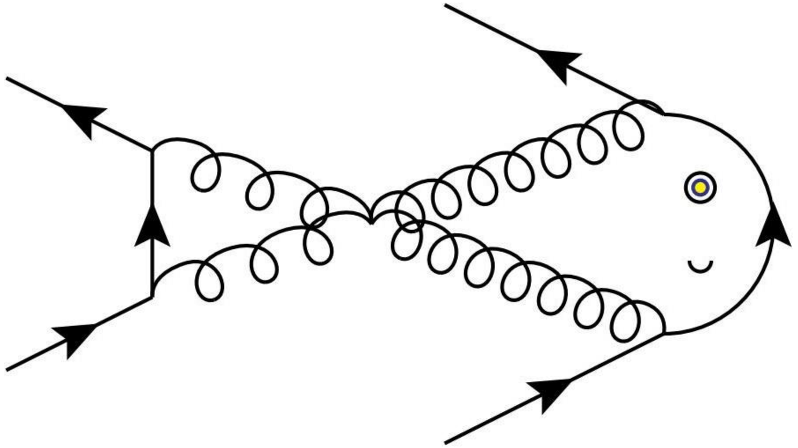
PRD 106 (2022) 11, 115036
L. Darmé, M. Mancini,
M. Raggi and E. Nardi

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.

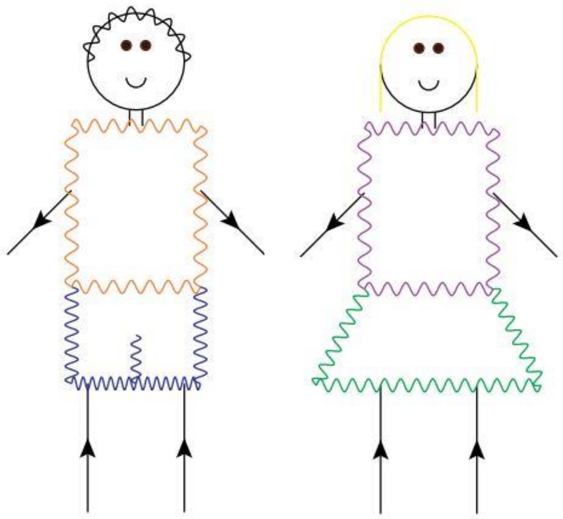
Waiting for new results from experimental searches!

The End

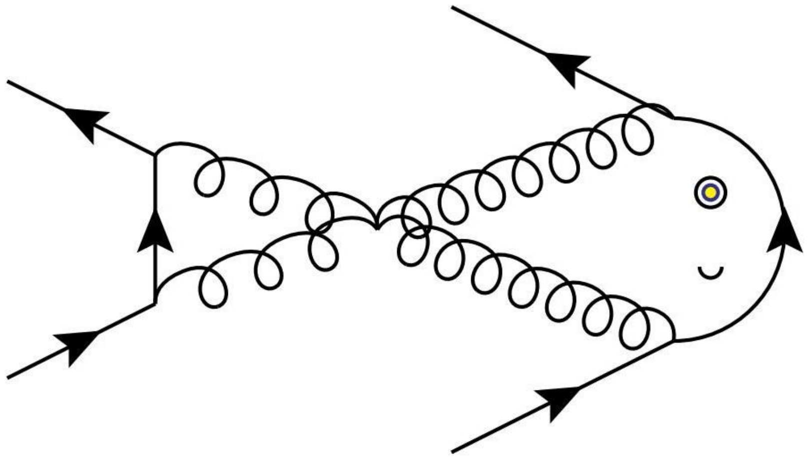


THANK YOU FOR THE ATTENTION!

An important question



Do you actually believe
on the existence of the X17?



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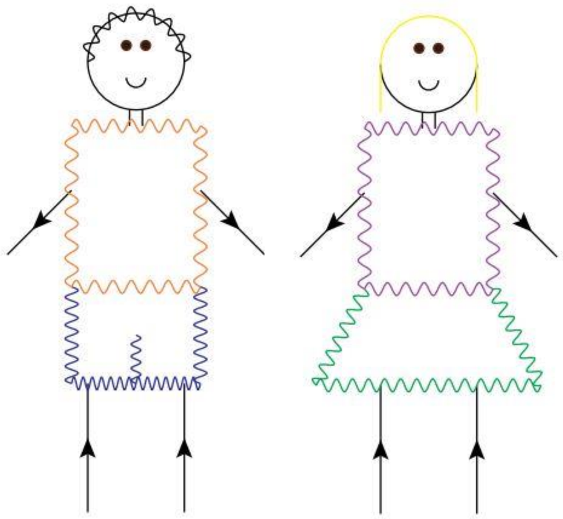

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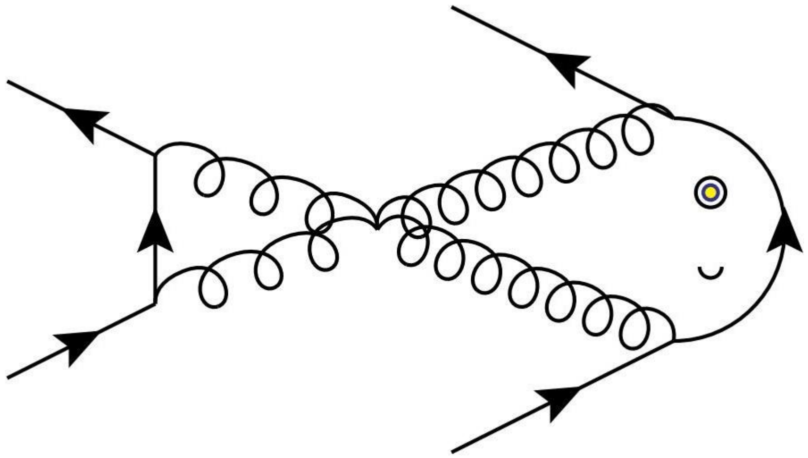

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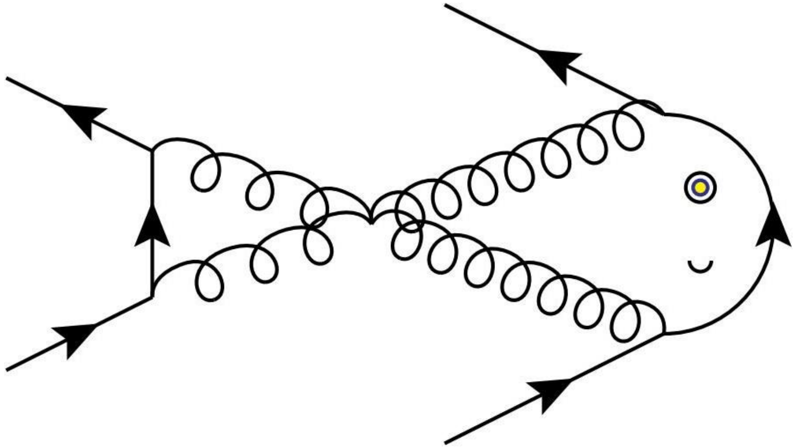
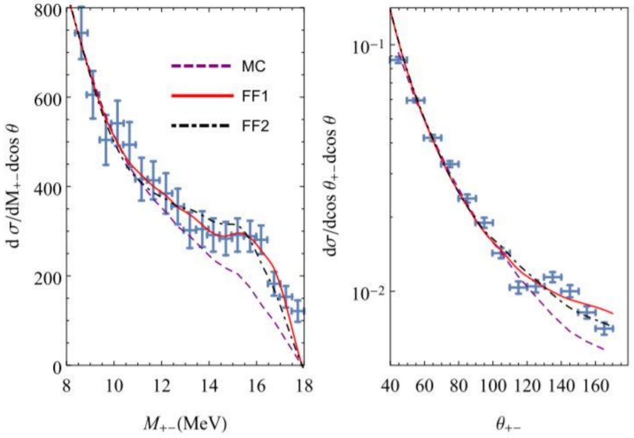


BACK UP SLIDES

SM explanation

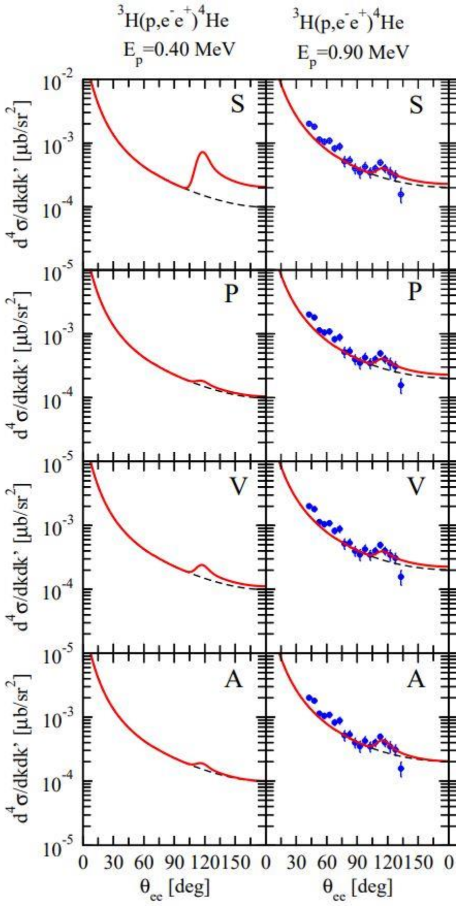
- Improvement of the Be nuclear model used by Atomki is not enough to explain the anomaly.
- Unknown nuclear effect is also excluded.
- The length scale of the needed form factor is in contrast with the experimental observation.



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.

X17 kinematics

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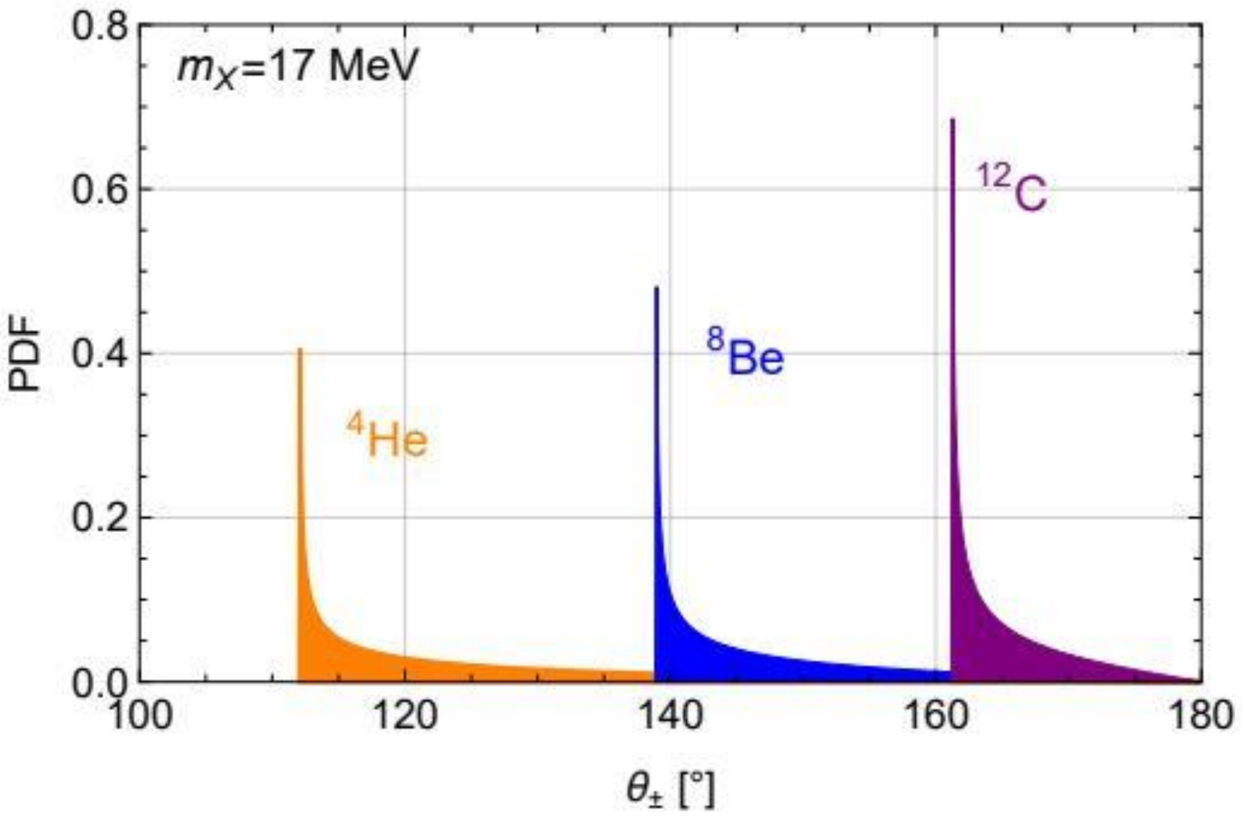

- Theoretical PDFs due to phase space effects, i.e. to the process kinematics.
- The measured values of the peak angles are in according with the theoretical prediction.

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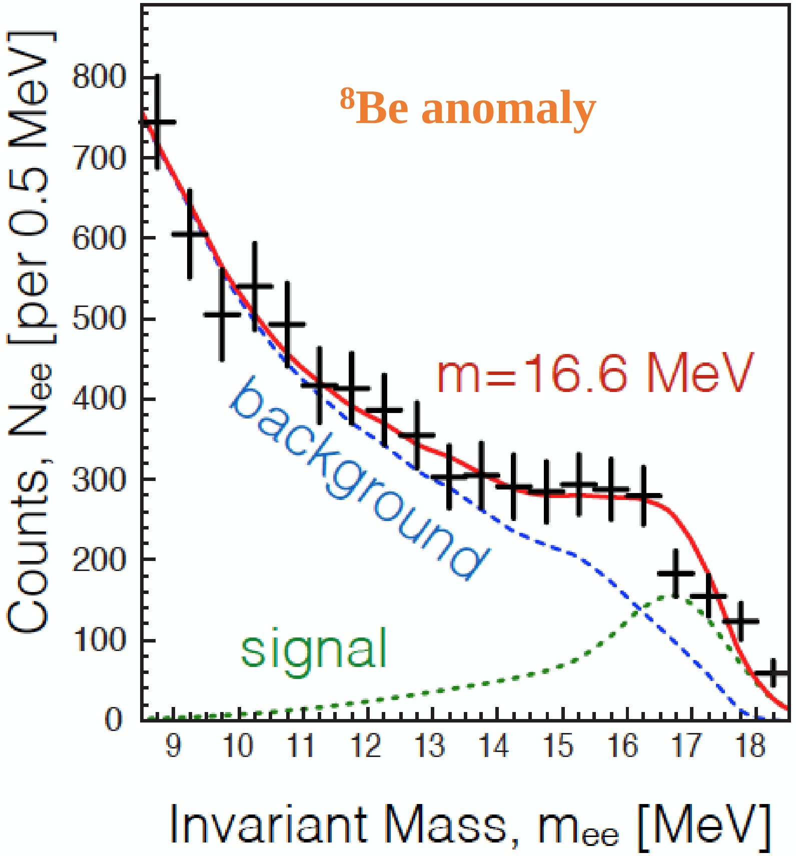

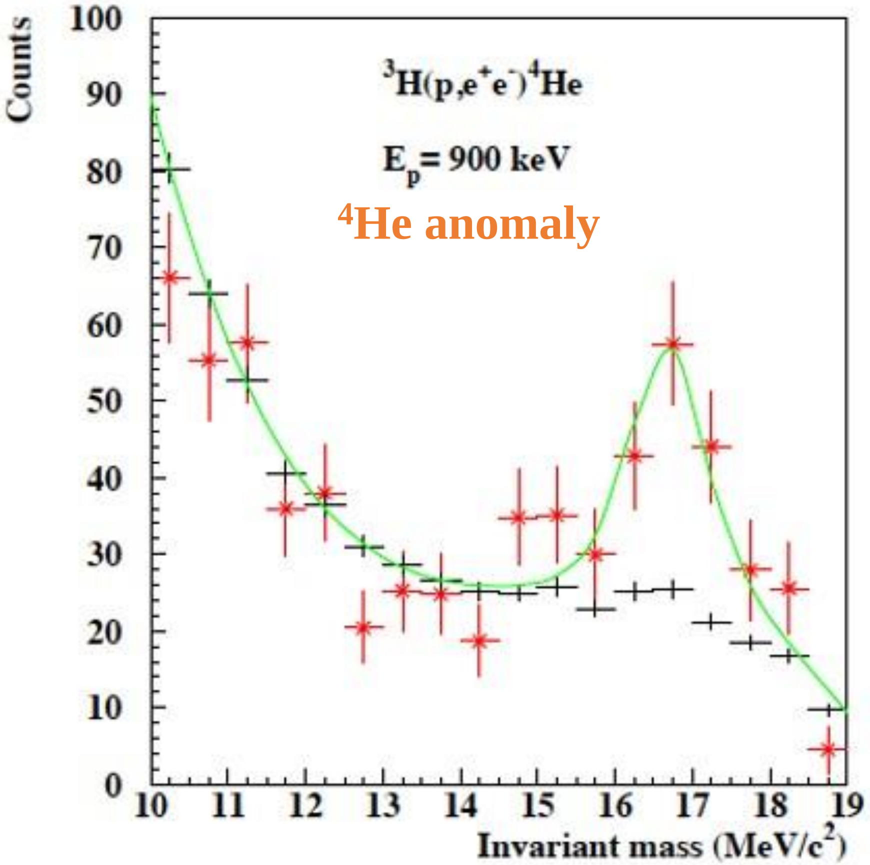

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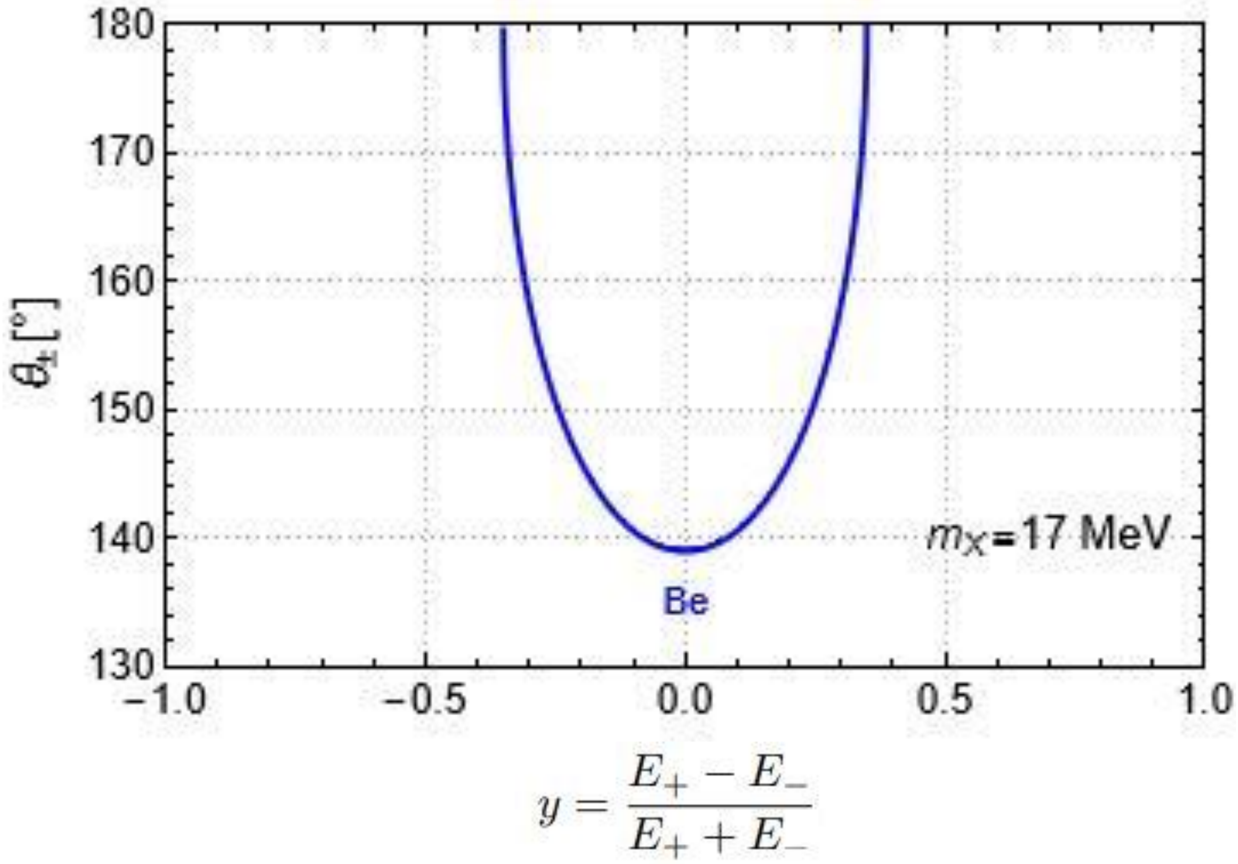
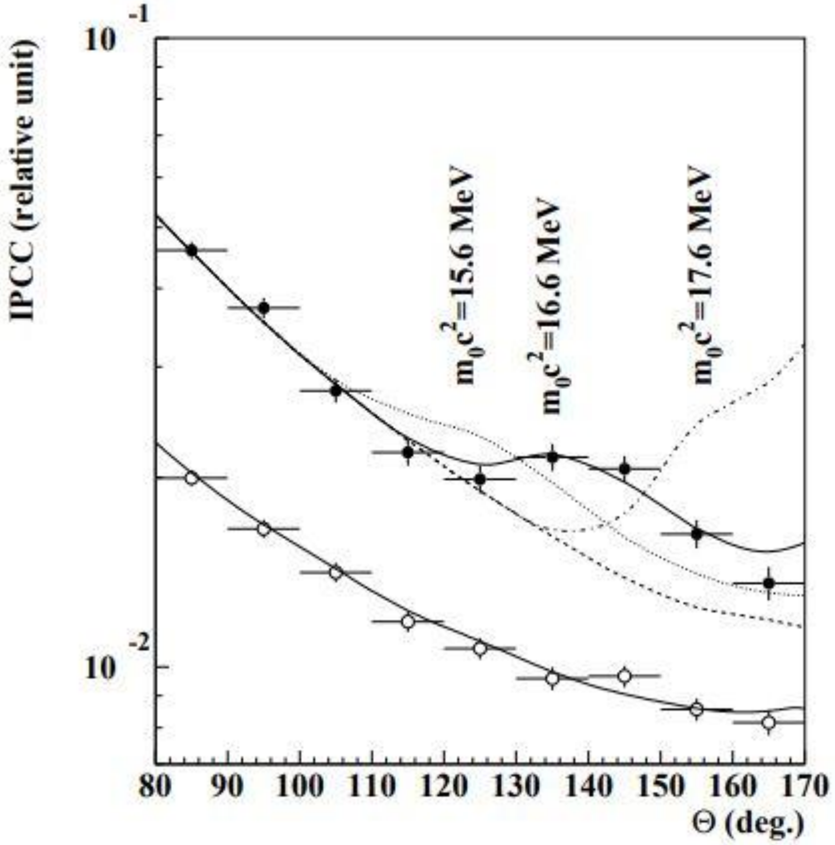


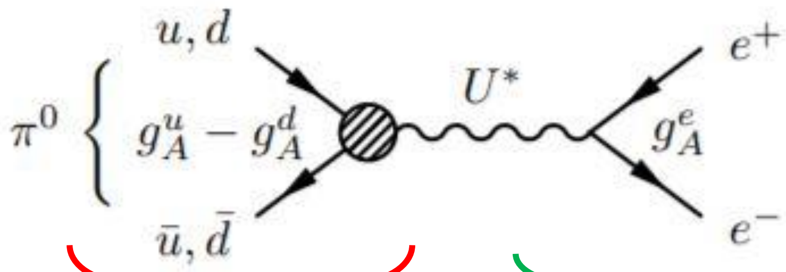


Axial-vector X17: KTeV anomaly

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

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

- 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.



coupled to quarks

coupled to electron/positrons

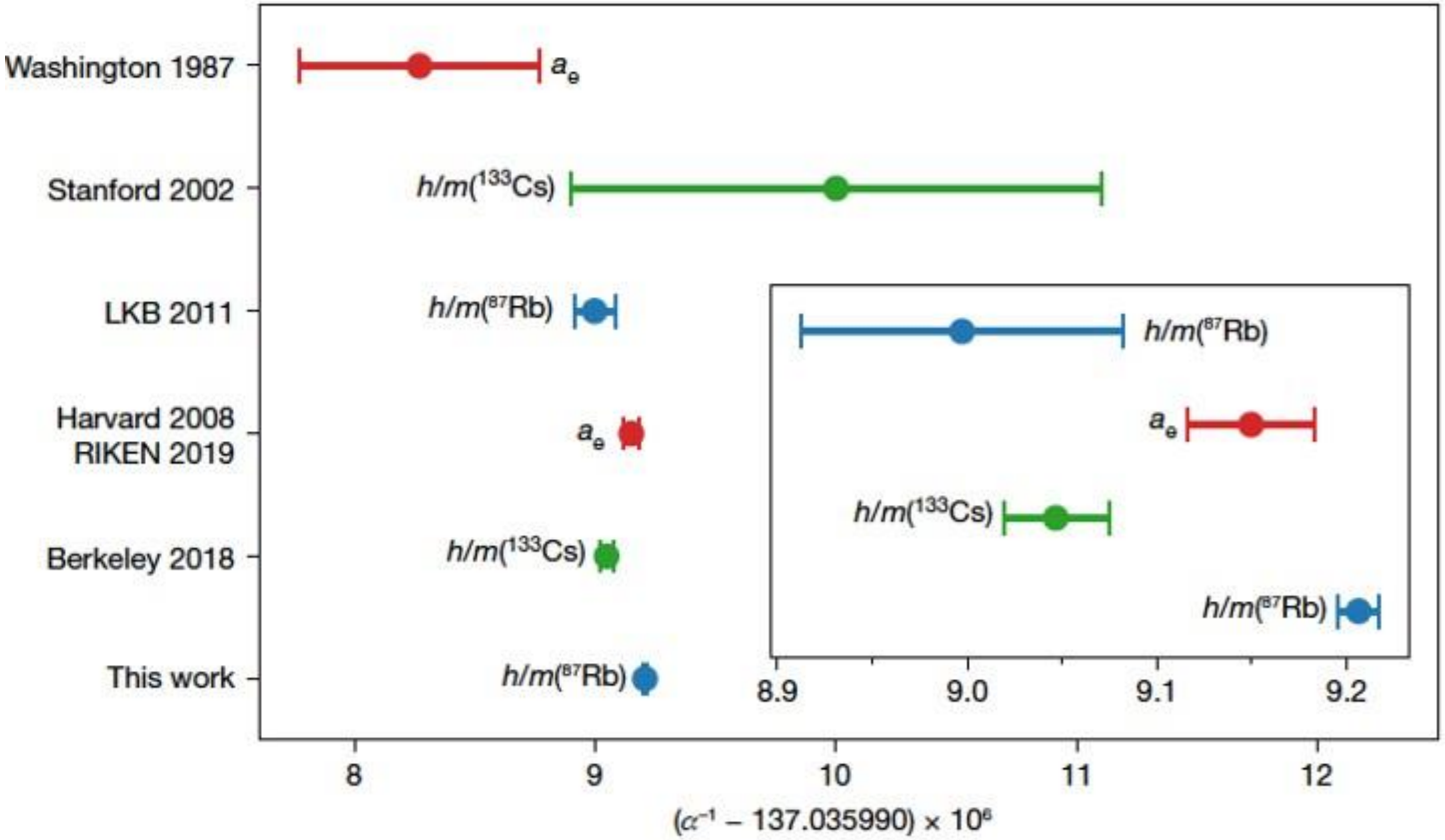
$$\frac{(g_A^u - g_A^d)g_A^e}{m_U^2} = (4.0 \pm 1.8) \times 10^{-10}\ \text{MeV}^{-2}$$

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:

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