X(17): a theory overview

Claudio Toni

Outline

1) Could this be new physics?

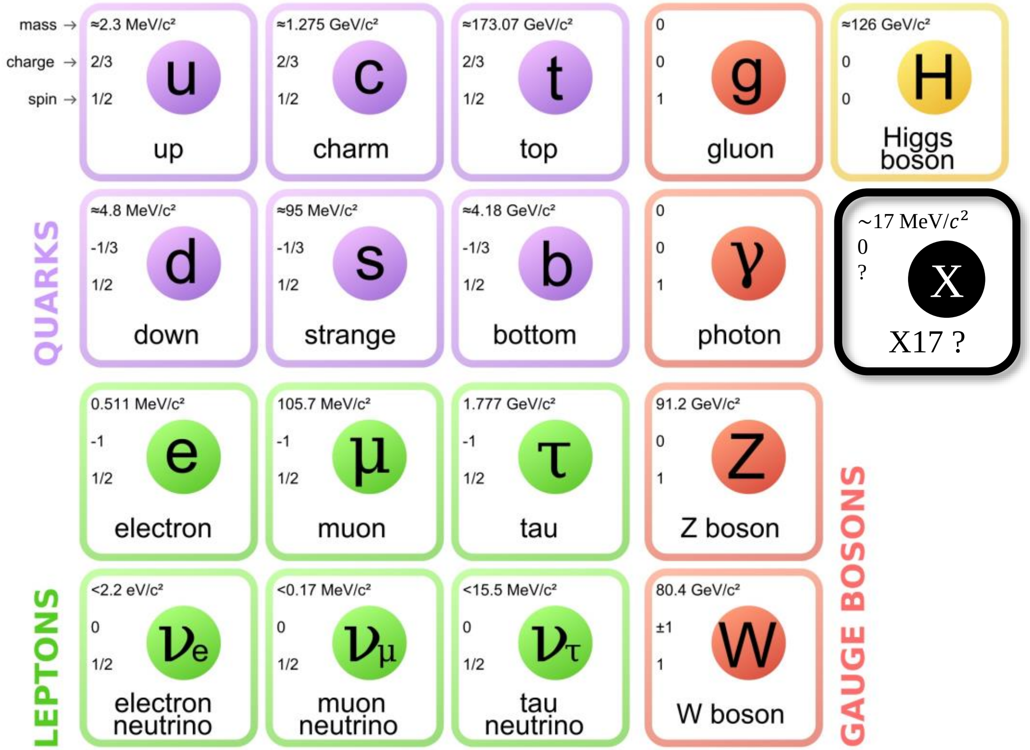
2) X17 features and kinematic

3) X17 dynamics:

I. Vector boson and protophobia

II. Axial vector boson and the KTeV anomalies

4) X17 coupling to electron/positron



The Atomki anomalies

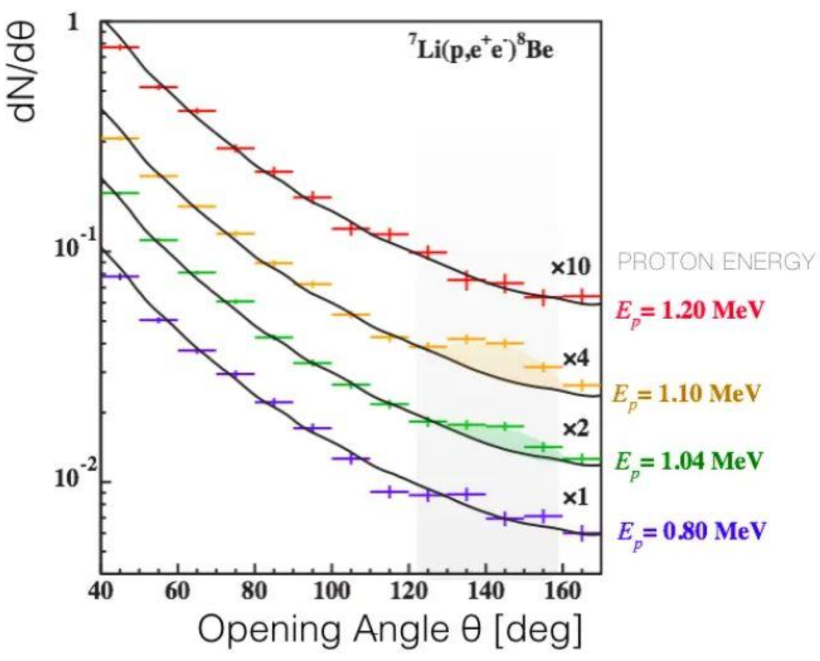
<u>Some key considerations on the Atomki anomalies:</u>

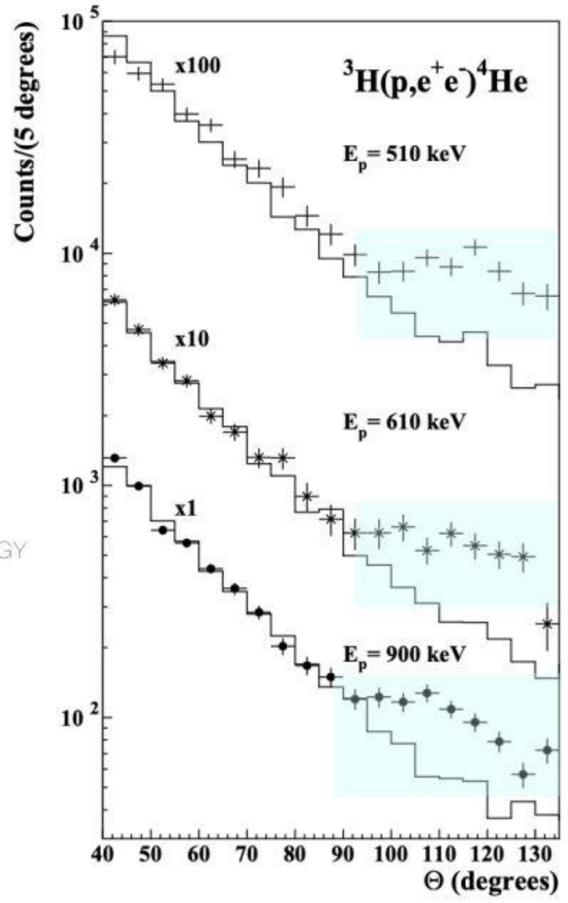
- $\sim 7\sigma$ statistical significances in all the anomalies, not a matter of statistics.
- No experimental problem identified.
- It's a bump, not a general excess.
- Fit improves drastically with the introduction of a new particle.
- 8Be, 4He and 12C support each others.

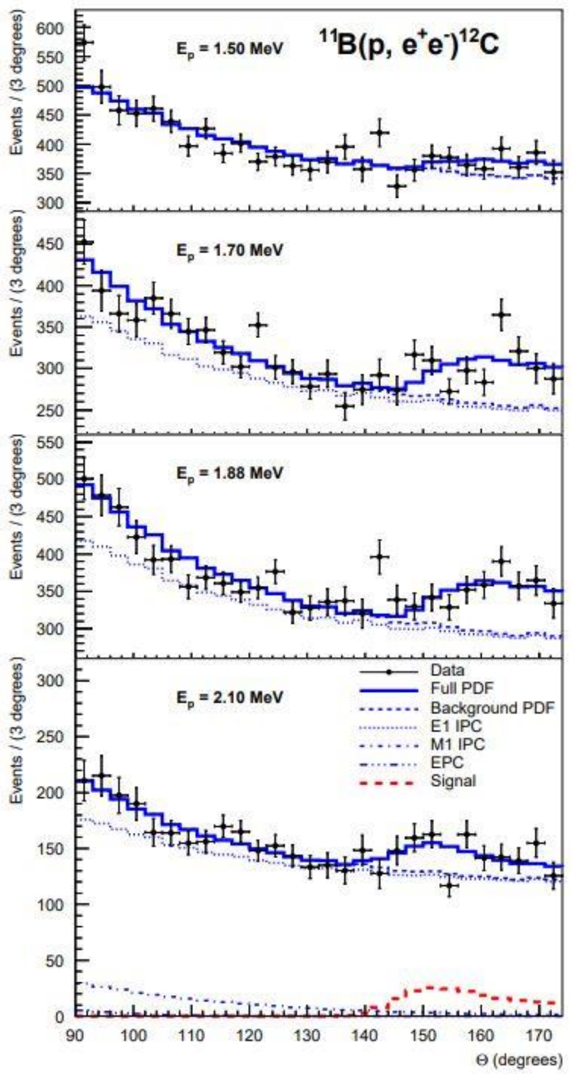
Be: PRL 116 (2016) 4, 042501

He: PRC 104 (2021) 4, 044003

C: PRC 106, L061601

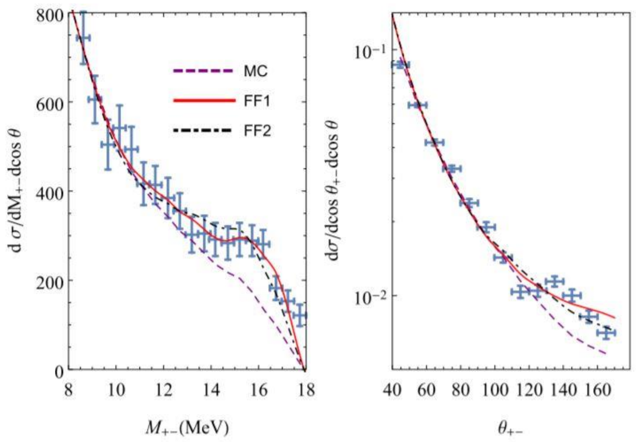






SM explanation

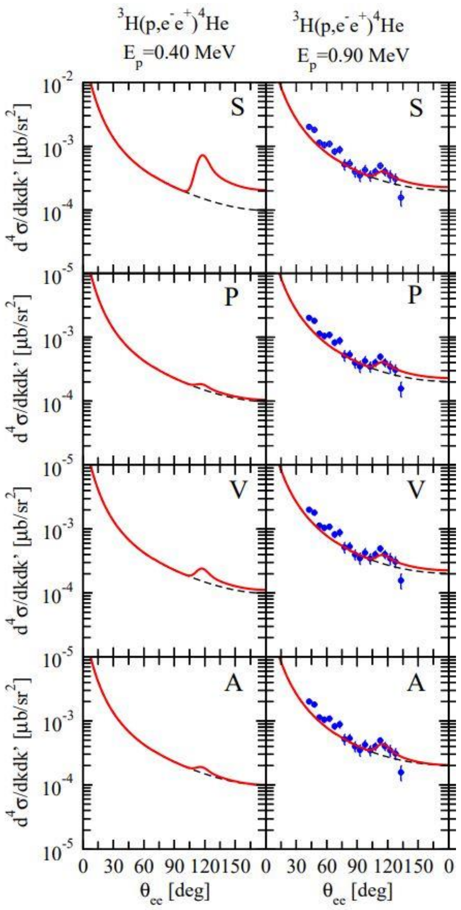
- Improvement of the Be nuclear model used by Atomki is not enough to explain the anomaly.
- Unknown nuclear effect is also excluded.
- The length scale of the needed form factor is in contrast with the experimental observation.



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



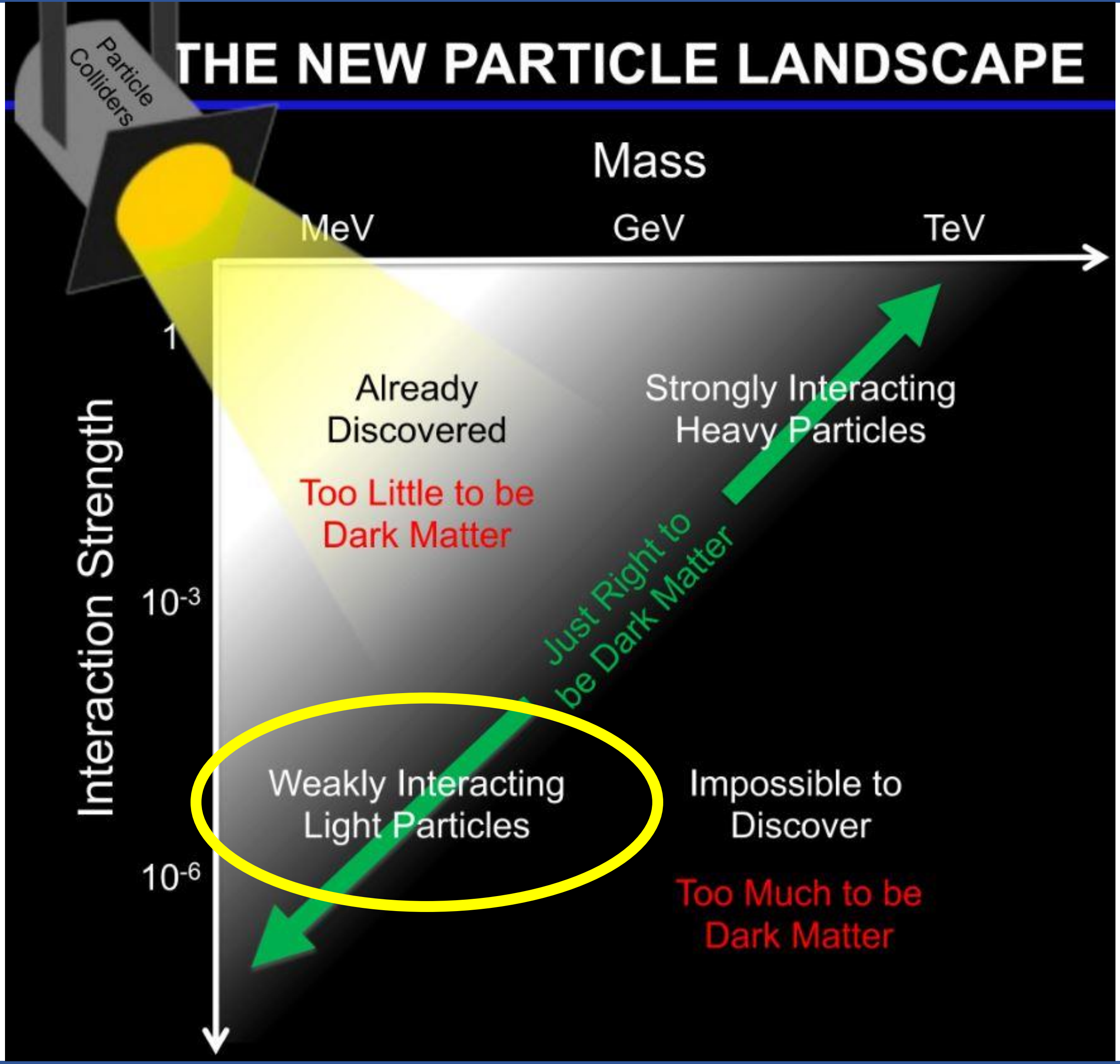
Many other proposals but, in conclusion, no compelling SM explanation so far.

New physics?

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

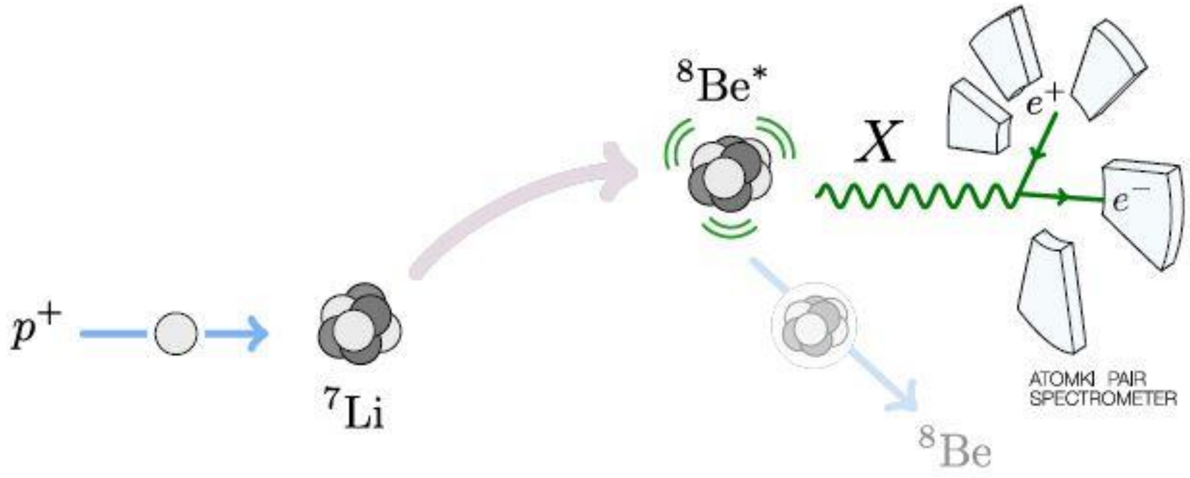
- Light (sub-GeV) and weakly coupled particles are well studied nowadays.
- Recently, light and weakly coupled new physics have raised considerable interest due to the null result of TeV scale research at particle colliders.
- BSM physics and cosmology motivate the presence of light and weakly-coupled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

Examples: dark photons, axion, …



Features of X17

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



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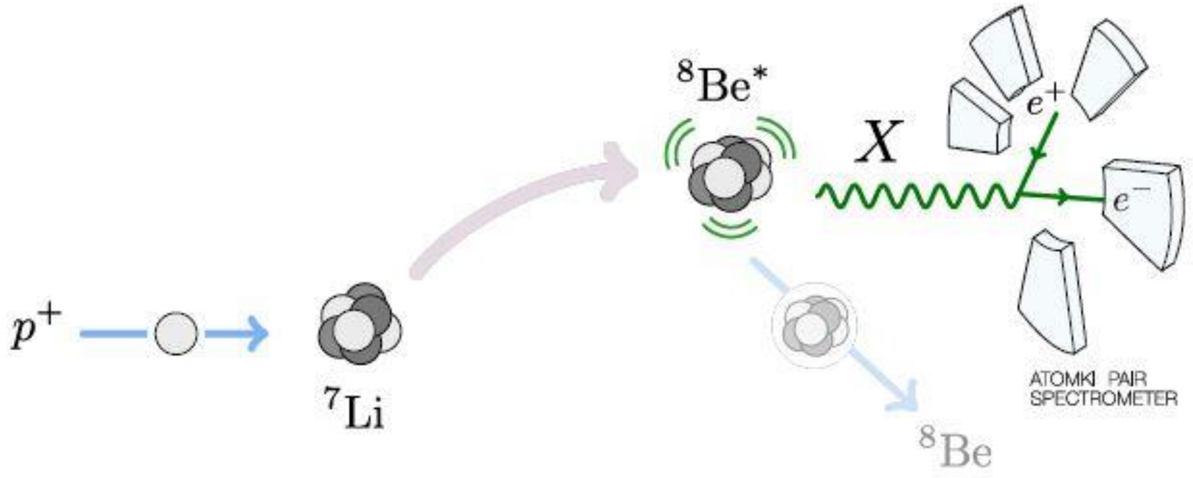

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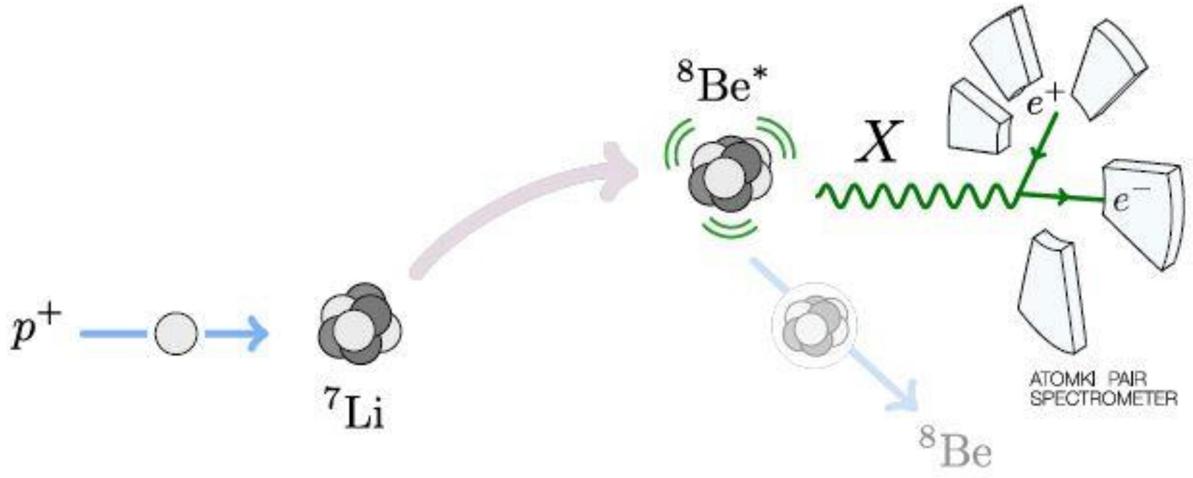

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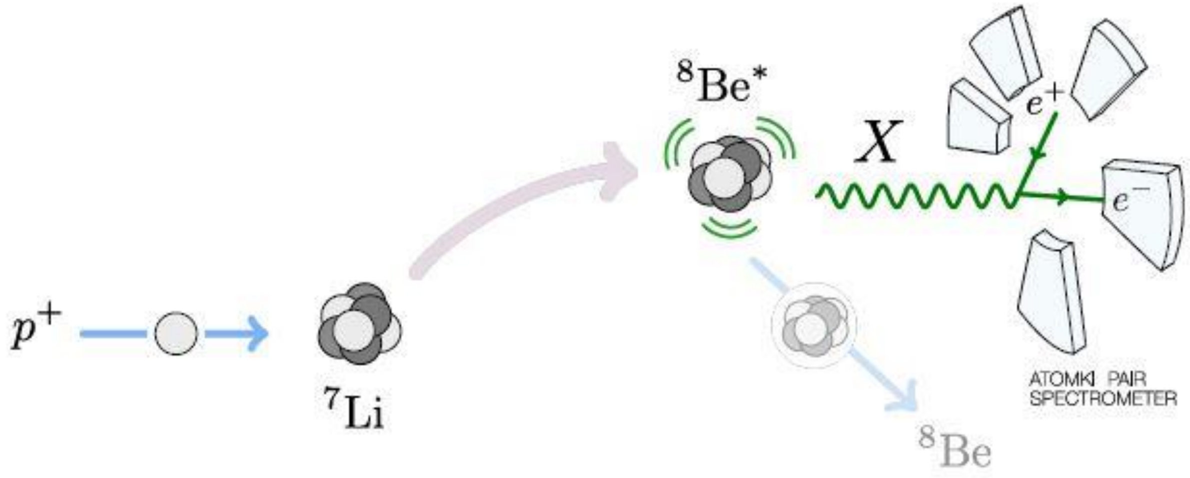

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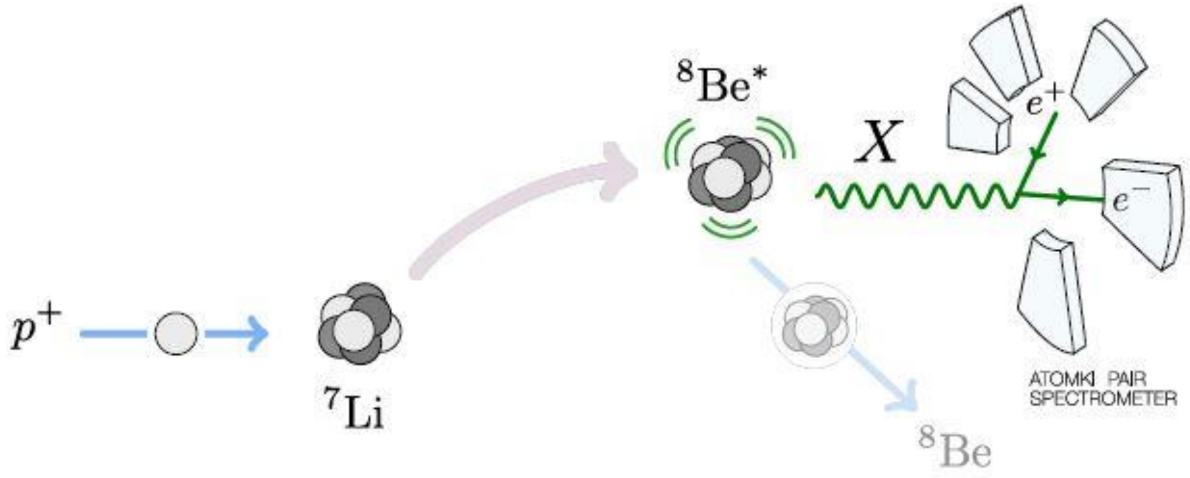

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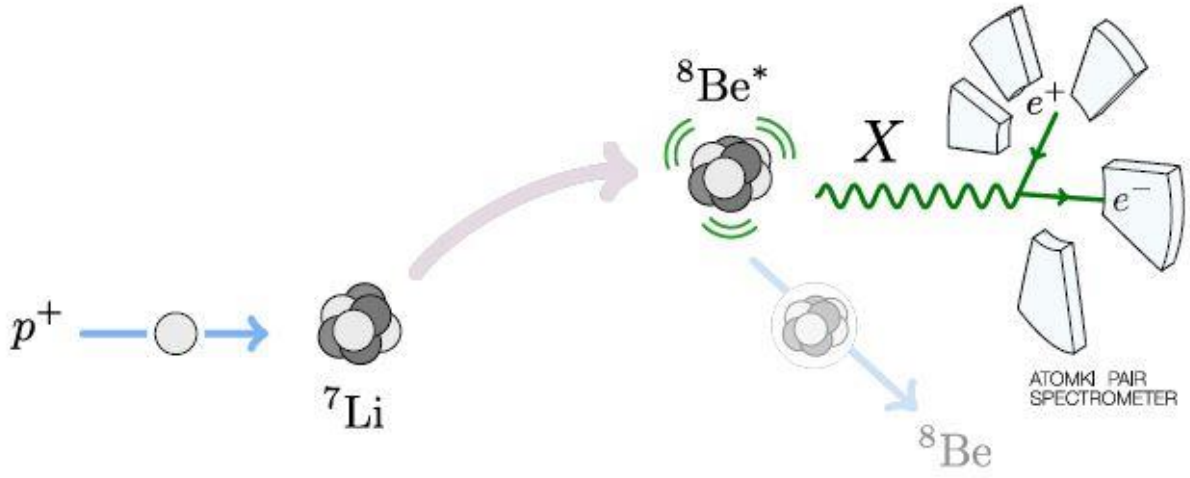

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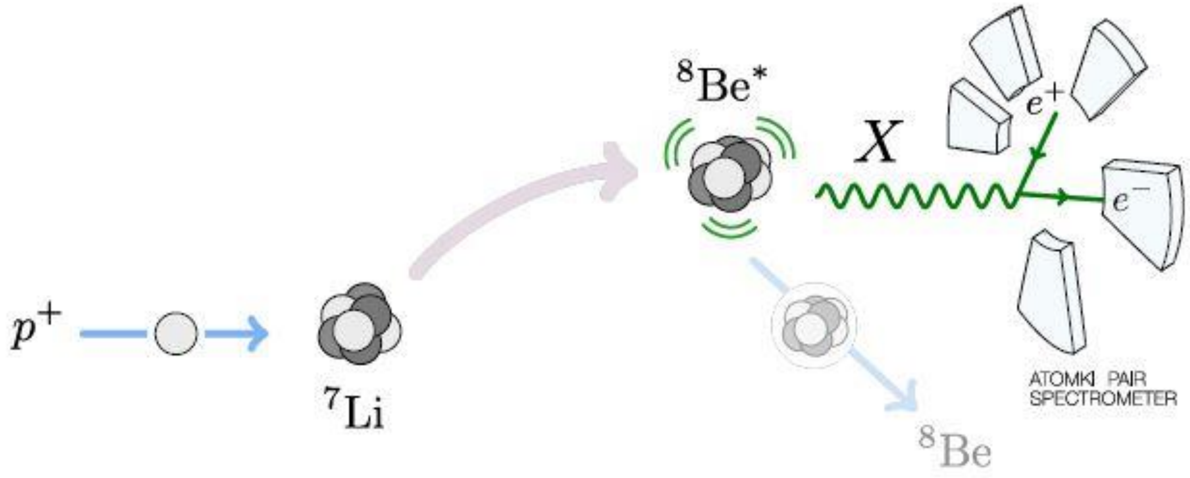

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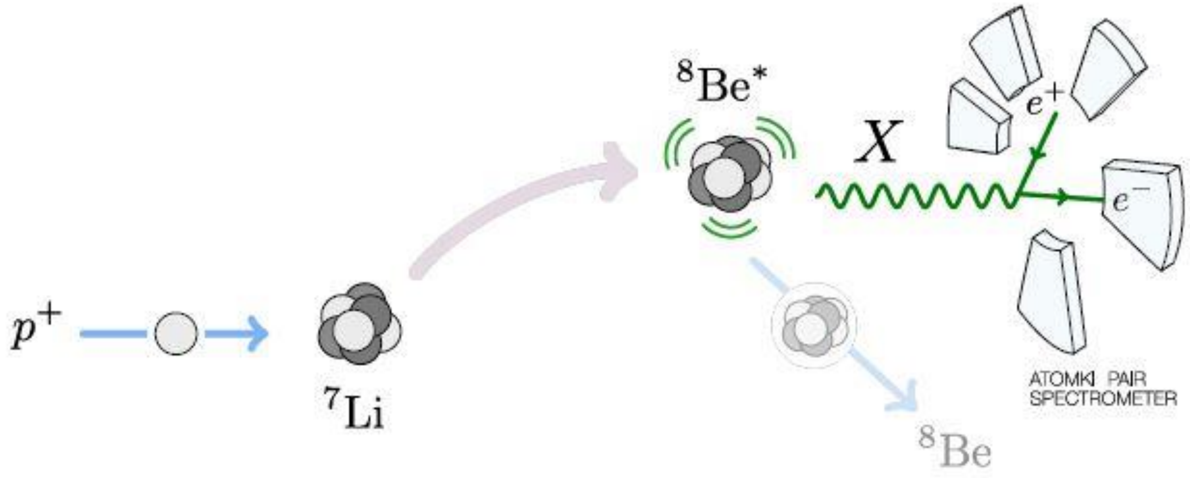

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Other decays are possible ($X \to \nu\bar{\nu}, DM, \ldots$) but it is reasonable to assume $\mathrm{BR}(X \to e^+ e^-) = 1$

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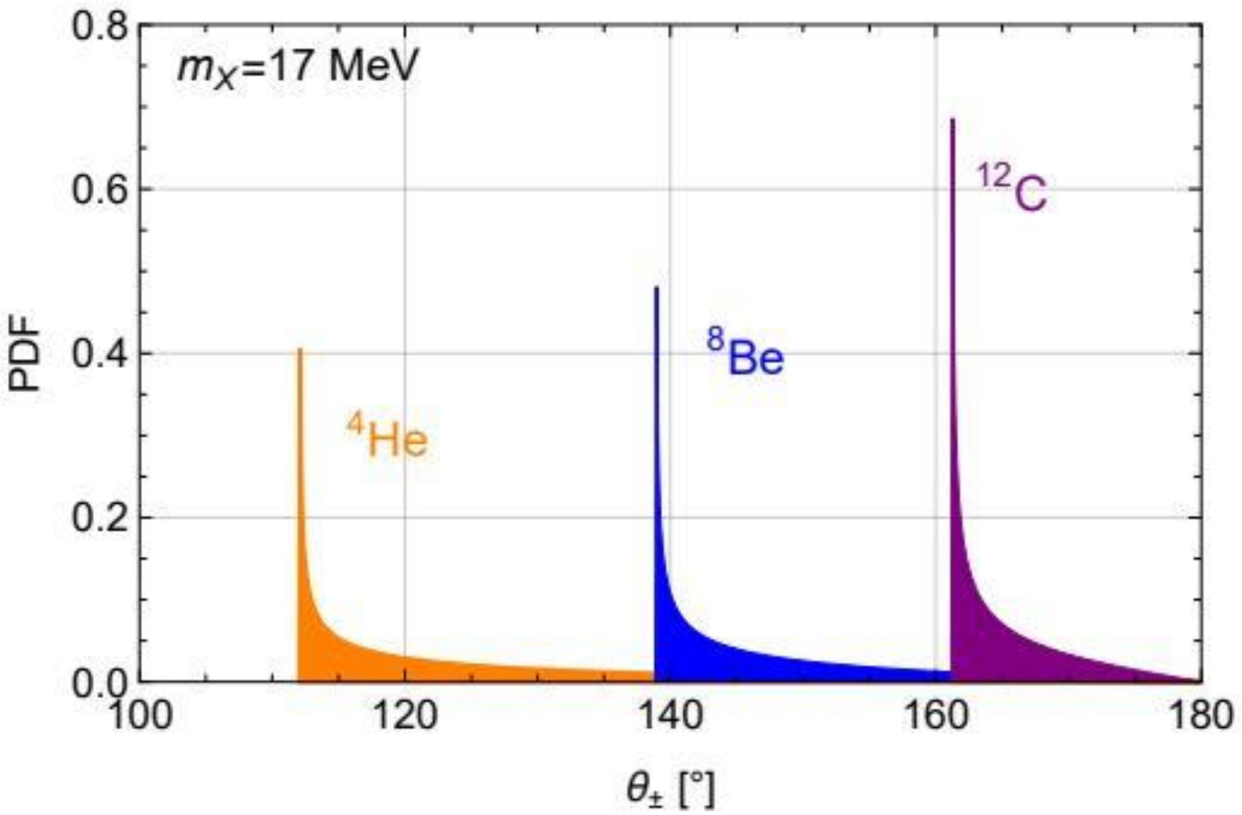

- Theoretical PDFs due to phase space effects, i.e. to the process kinematics.
- The measured values of the peak angles are in according with the theoretical prediction.

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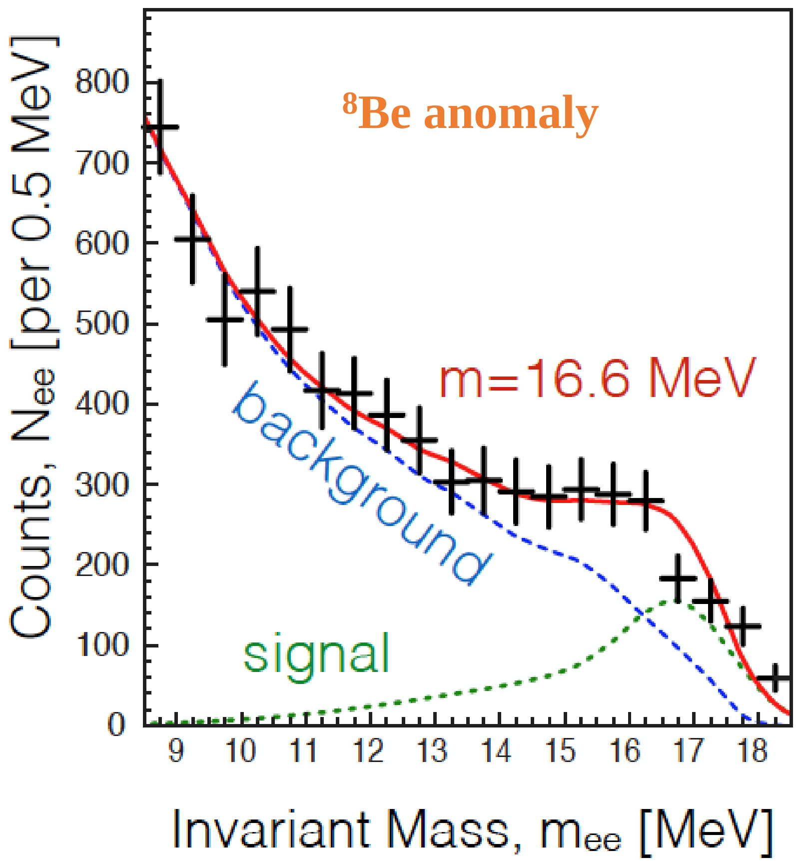
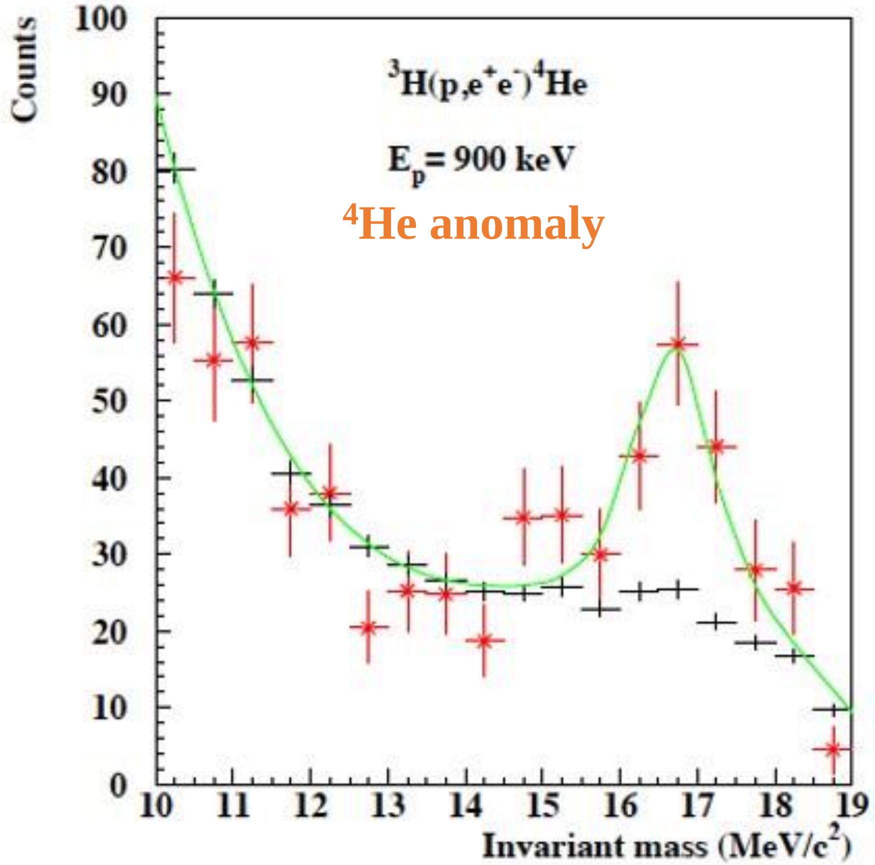
2) The excesses are resonant bumps located at the same e+e− invariant mass for all the 8Be and 4He transitions.





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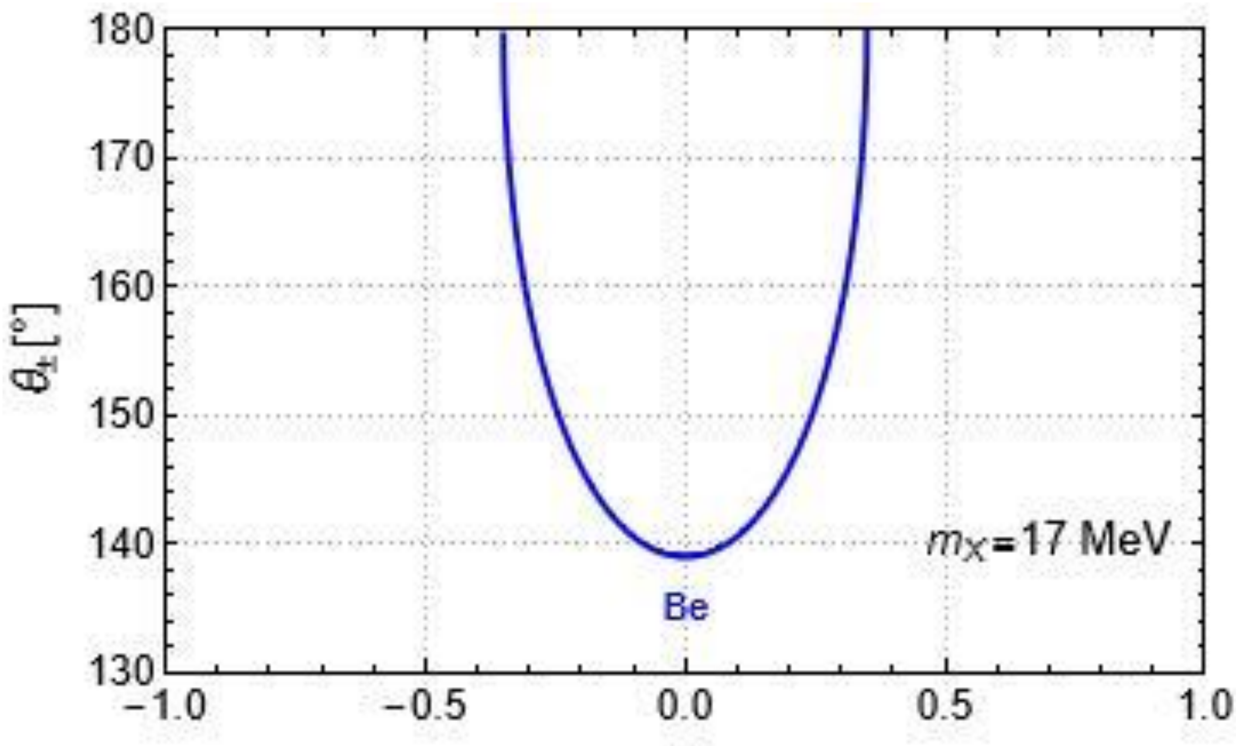
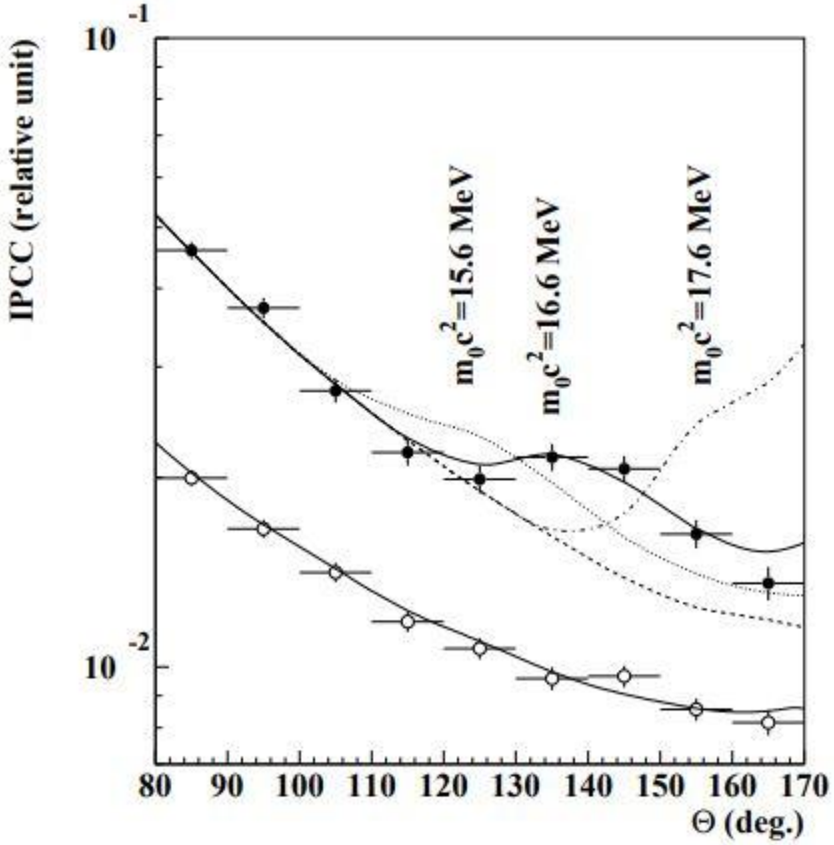
3) the anomalous signal in the 8Be transition have been observed only inside the kinematic region given by |y| < 0.5, where y is energy asymmetry.



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



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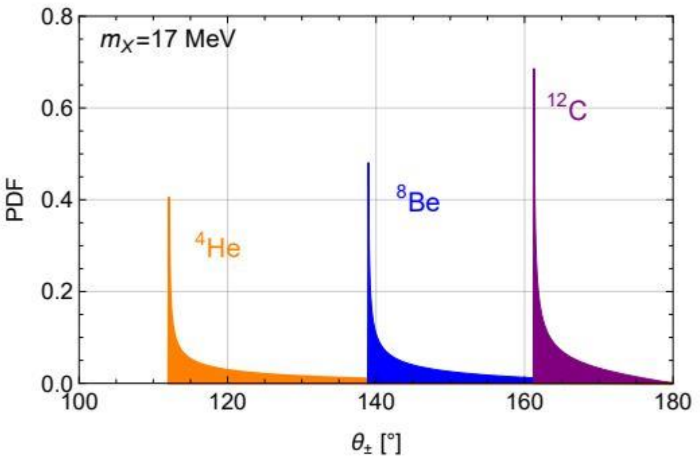
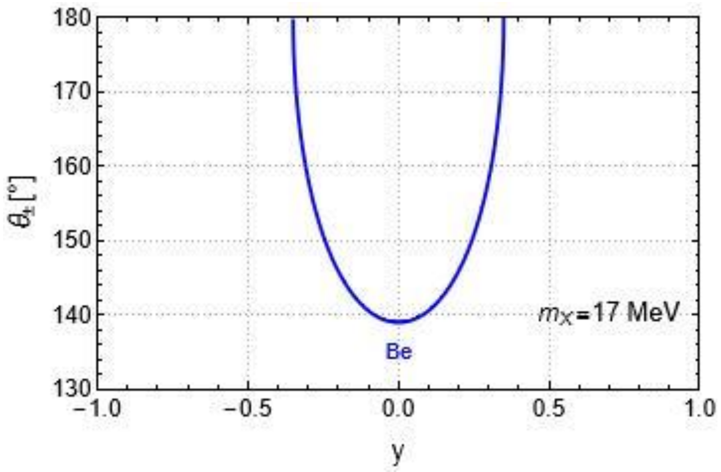


The agreement of the data with the X17 kinematic is a strong argument in favor of the new particle interpretation of the Atomki anomalies



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- 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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- A common assumption in phenomenological analysis is to assume the validity of *nuclear narrow width approximation*

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- In a EFT approach, the X17 nucleon coupling with effective interacting operators, depending on the spin-parity of the boson.

$$\begin{aligned}
\mathcal{L}_{S^\pi=0^+} &= z_p \bar{p} p X + z_n \bar{n} n X \ , \\
\mathcal{L}_{S^\pi=0^-} &= i h_p \bar{p} \gamma^5 p X + i h_n \bar{n} \gamma^5 n X \ , \\
\mathcal{L}_{S^\pi=1^-} &= C_p \bar{p} \gamma^\mu p X_\mu + C_n \bar{n} \gamma^\mu n X_\mu + \frac{\kappa_p}{2m_p} \partial_\nu (\bar{p} \sigma^{\mu\nu} p) X_\mu + \frac{\kappa_n}{2m_n} \partial_\nu (\bar{n} \sigma^{\mu\nu} n) X_\mu \ , \\
\mathcal{L}_{S^\pi=1^+} &= \ a_p \bar{p} \gamma^\mu \gamma^5 p X_\mu + \ a_n \bar{n} \gamma^\mu \gamma^5 n X_\mu \ ,
\end{aligned}$$

Model building of a complete UV theory of X17 appears a bit difficult
(Delle Rose et al., PRD 96 (2017) 11, 115024)

X17 dynamics: solutions that don't work

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

Orbital angular momentum L of the X17

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- Dark photon with kinetic mixing induced interaction – the needed ε value is already excluded by experimental searches. → $-\frac{\sin\varepsilon}{2} B_{\mu\nu}\hat{X}^{\mu\nu}$

- Vector with no definite parity – disfavored by atomic parity violation experiments. → assuming definite parity is reasonable!

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

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

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Orbital angular momentum L of the X17

X17 dynamics: what's been done

- From the first anomaly, a lot of work has been done:

Vector X17

Feng et al.: PRL 117 (2016) 7, 071803; PRD 95 (2017) 3, 035017; PRD 102 (2020) 3, 036016.
Delle Rose, Khalil and Moretti: PRD 96 (2017) 11, 115024.
Chen, Lin, Lin and Xu: PRD 95 (2017) 1, 015008

Axial-vector X17

Kahn, Krjaic, Mishra-Sharma and Tait: JHEP 05 (2017) 002.
Kozaczuk, Morrissey and Stroberg: PRD 95 (2017) 11, 115024.

Pseudoscalar or QCD axion X17

Ellwanger and Moretti: JHEP 11 (2016) 039.
Alves and Weiner: JHEP 07 (2018) 092.
Alves: PRD 103 (2021) 5, 055018.

X17 dynamics

After the C anomaly,
two main scenario to test:

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Atomki best fit values

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

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

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

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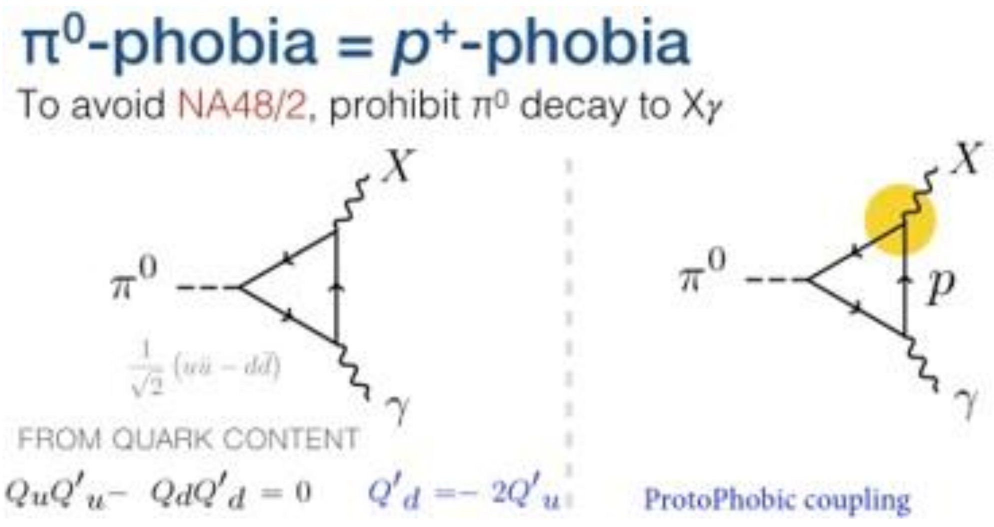
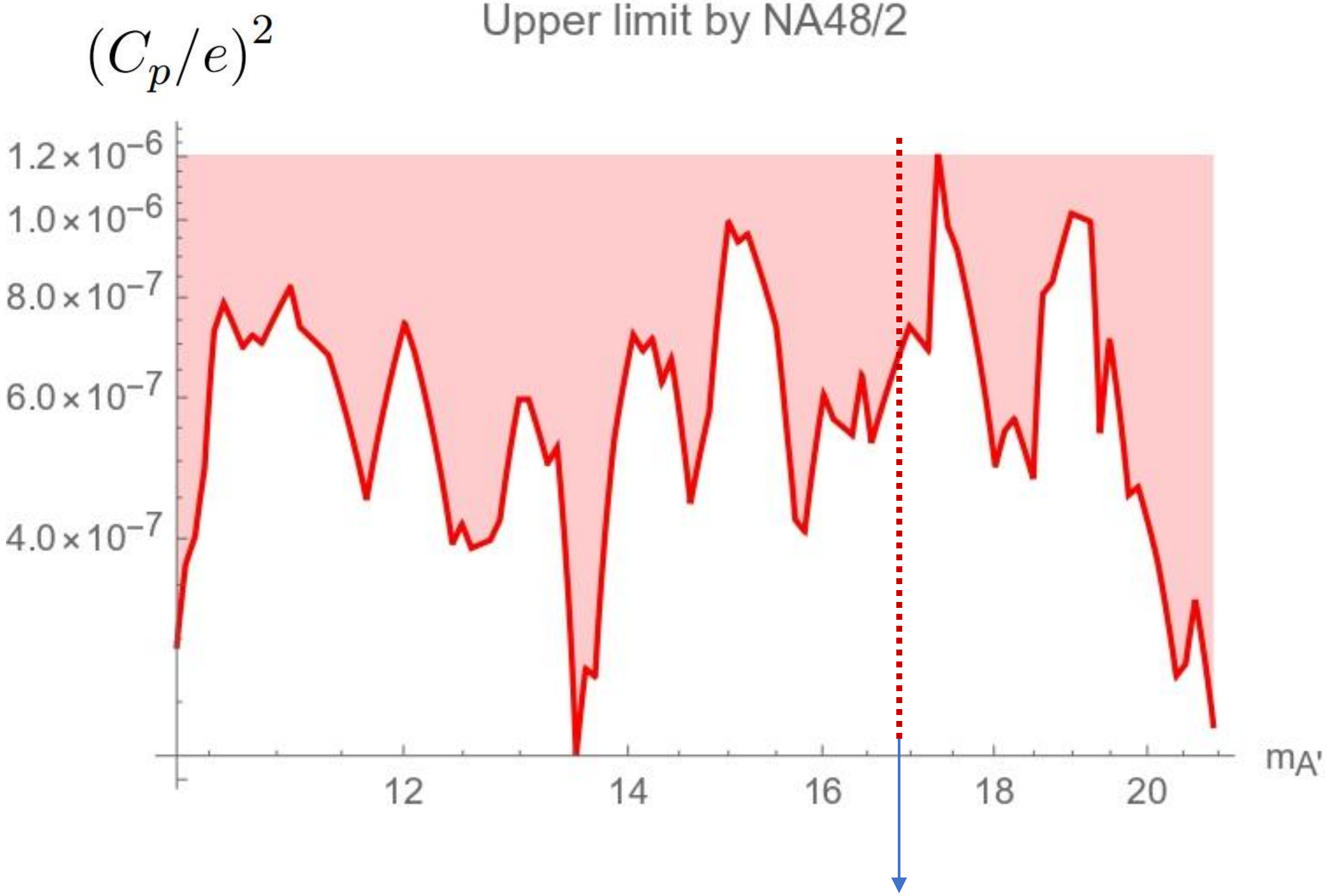
By matching the data to the theoretical prediction, one extract the nucleon couplings to X17

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.



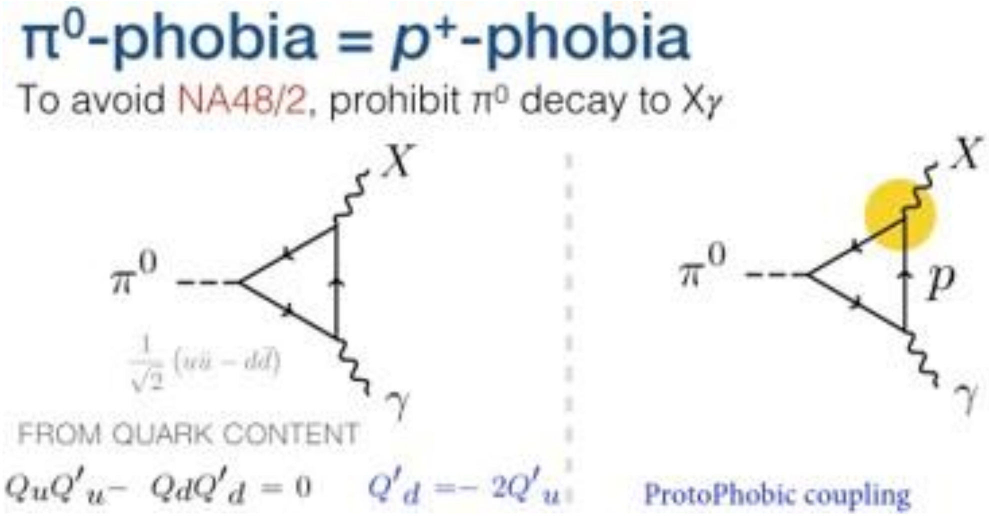


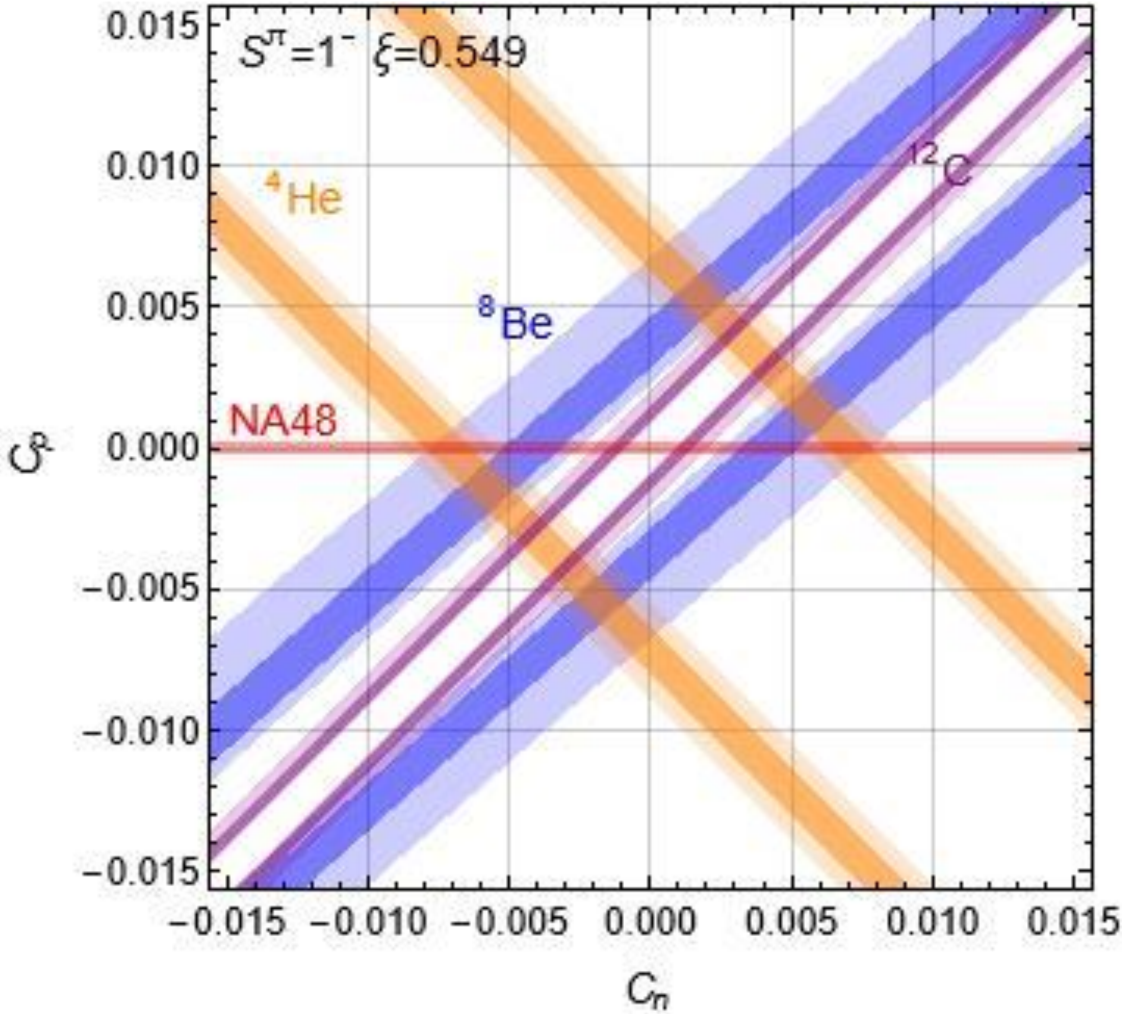
$$|C_p| \lesssim 2.5 \times 10^{-4}$$

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.

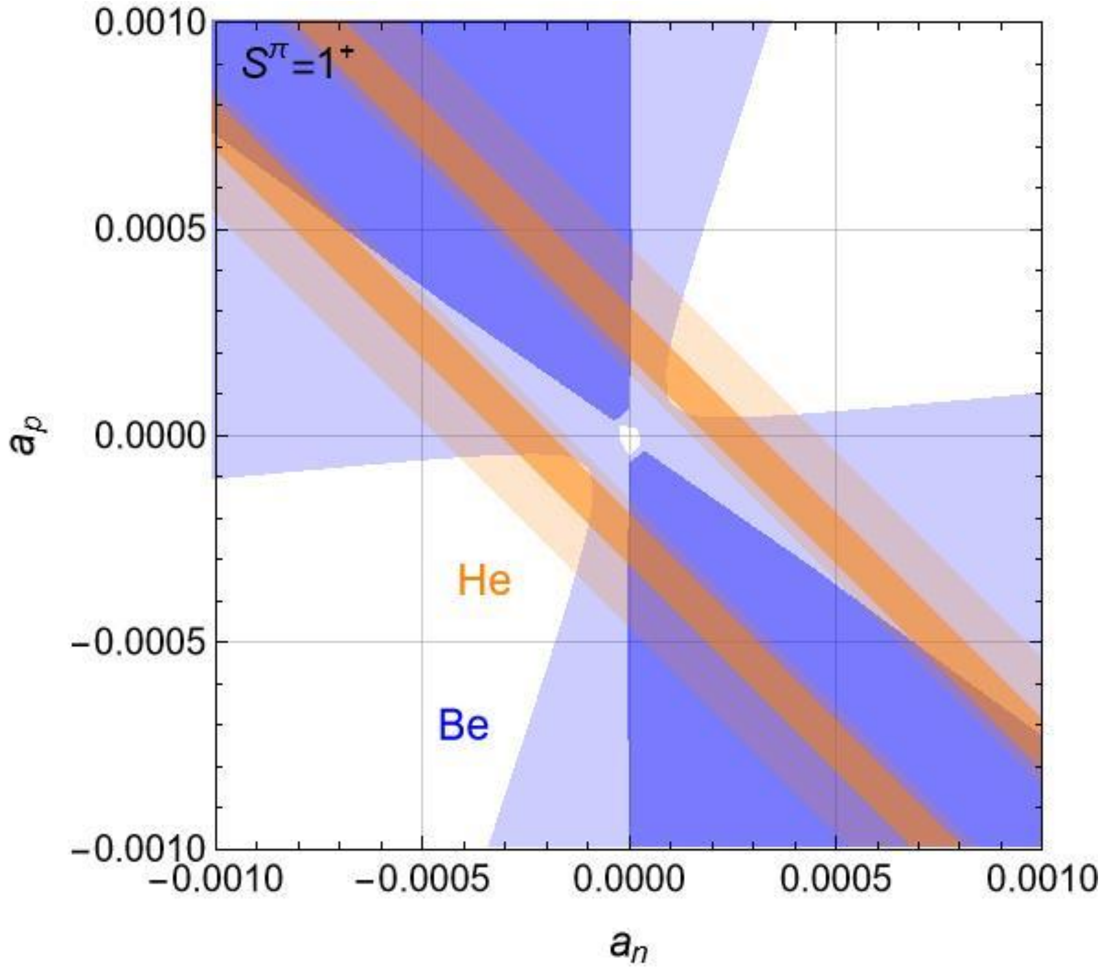




Axial-vector X17

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.



Large uncertainties on the 8Be axial nuclear matrix element

12C axial nuclear matrix element is missing in literature

Axial-vector X17: KTeV anomaly

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

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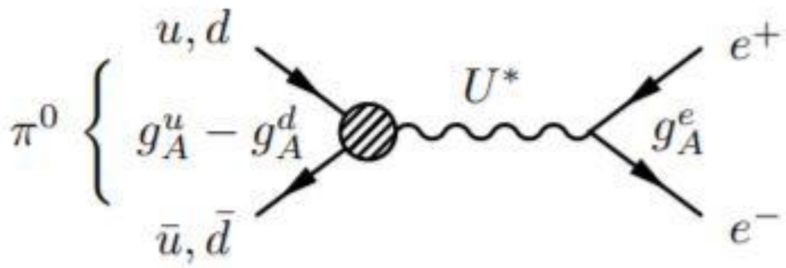

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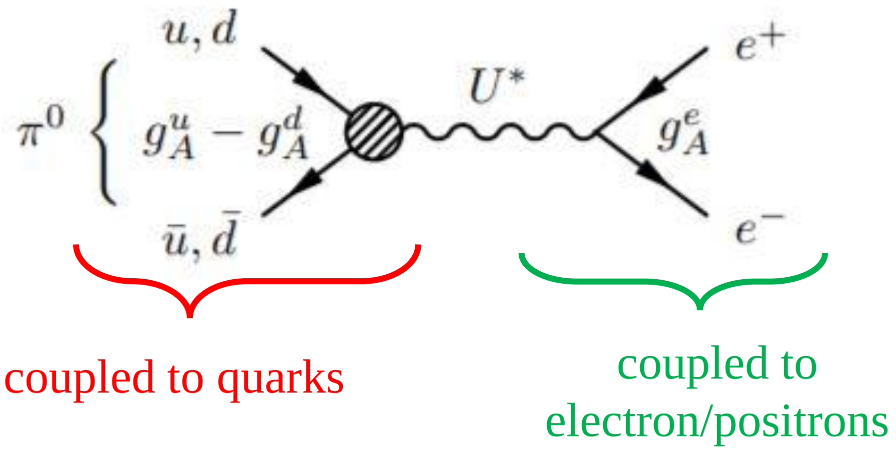
- The axial boson should couple to the light quarks and to the electrons/positrons.



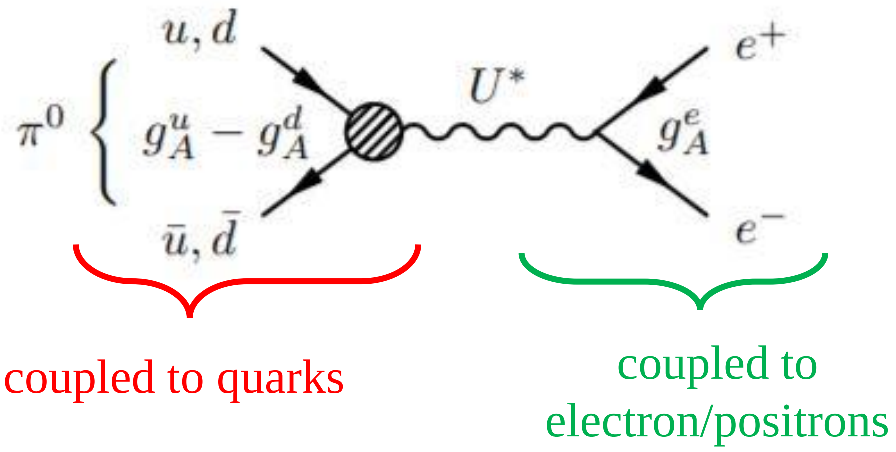
$$\frac{(g_A^u - g_A^d)g_A^e}{m_U^2} = (4.0 \pm 1.8) \times 10^{-10}\ \text{MeV}^{-2}$$

Axial-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.



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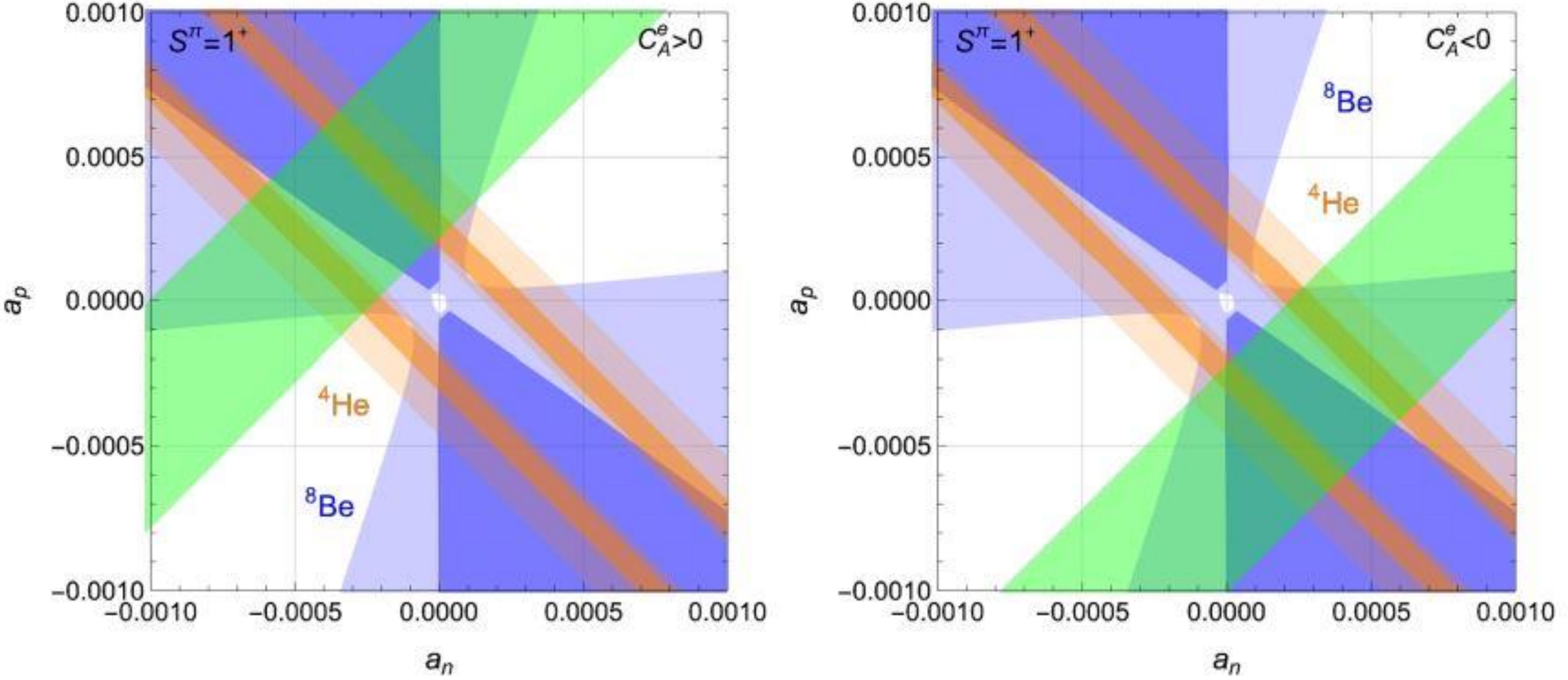
Axial X17 couplings → $\frac{(g_A^u - g_A^d)g_A^e}{m_U^2} \sim 10^{-10}\ \text{MeV}^{-2}$

Axial-vector X17

- 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.

KTeV anomaly in $\pi^0 \to e^+e^-$

$\delta a_e^{\rm BSM}(Cs)$

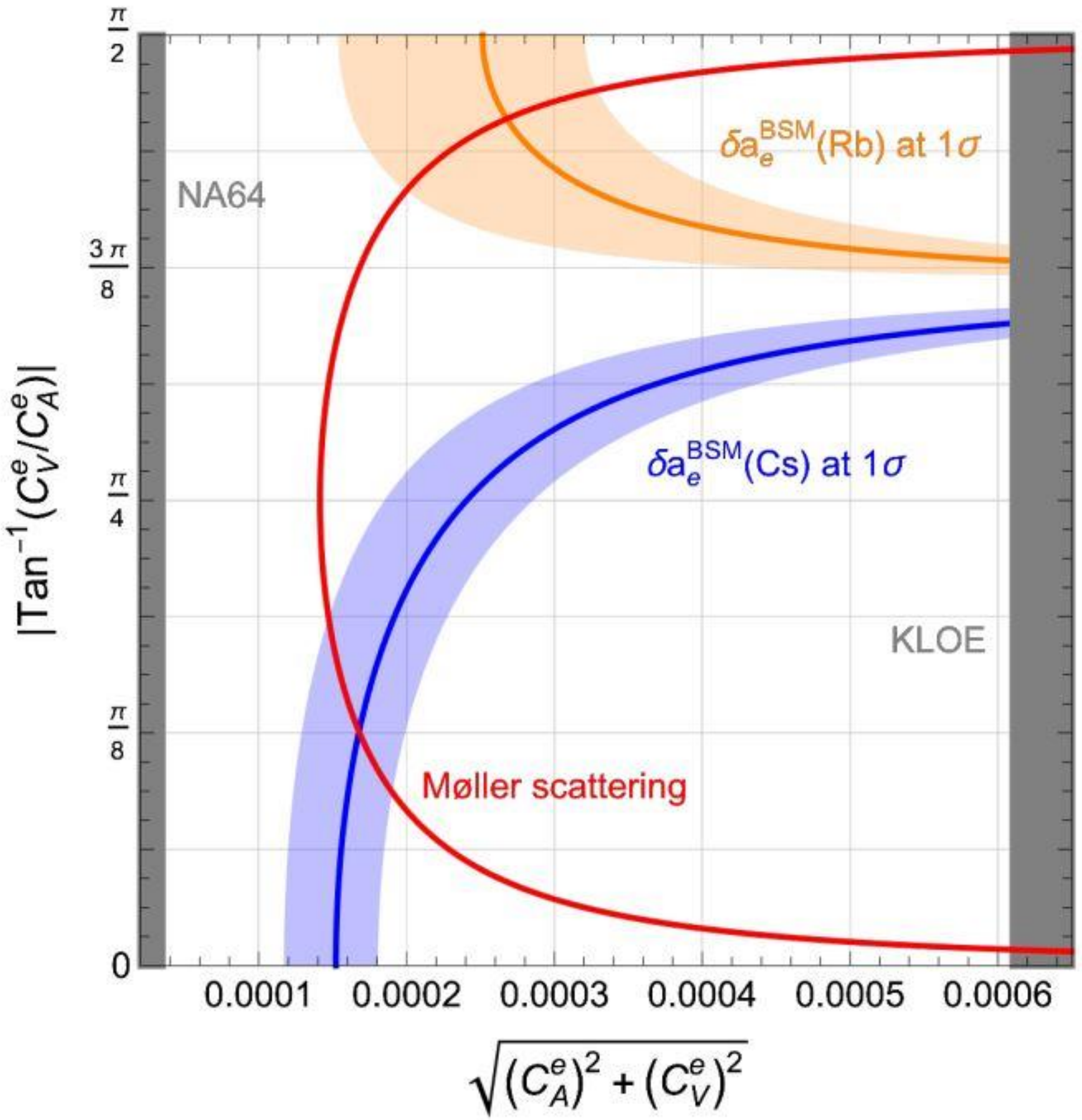


X17 coupling to electron/positrons

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

- 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:

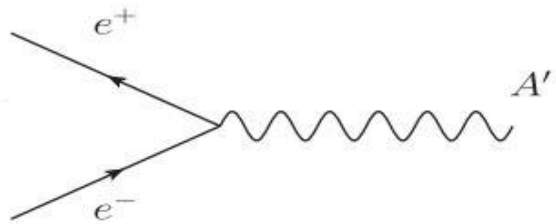
$$\sqrt{(C_V^e)^2 + (C_A^e)^2} \gtrsim 3 \times 10^{-7}$$

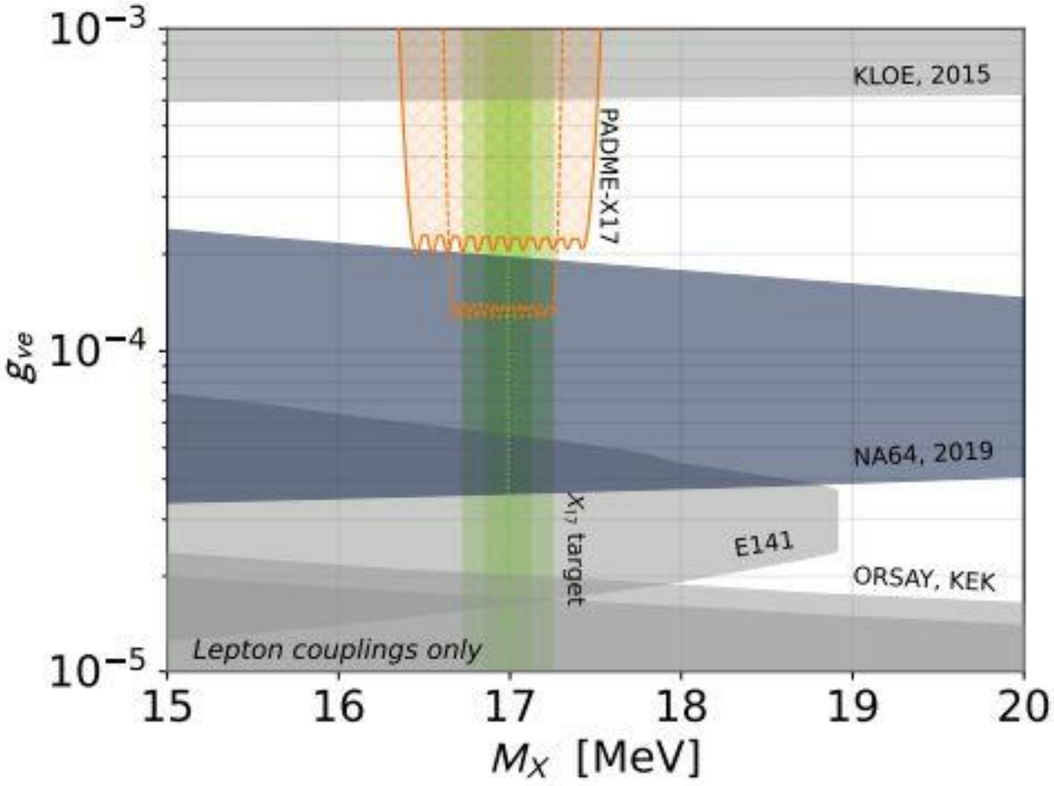


Spin-1 X17 at Padme

- 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.

Summary

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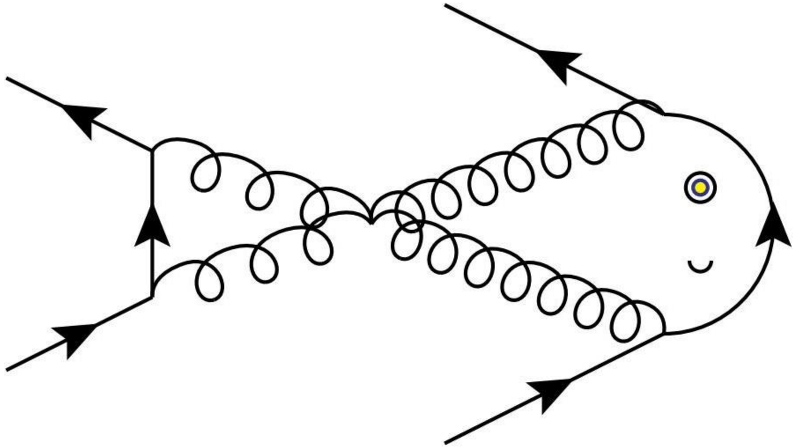
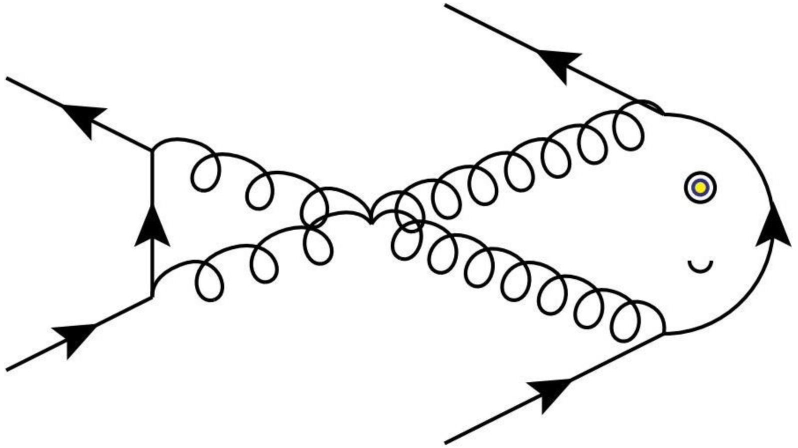
Waiting for new results from experimental searches!



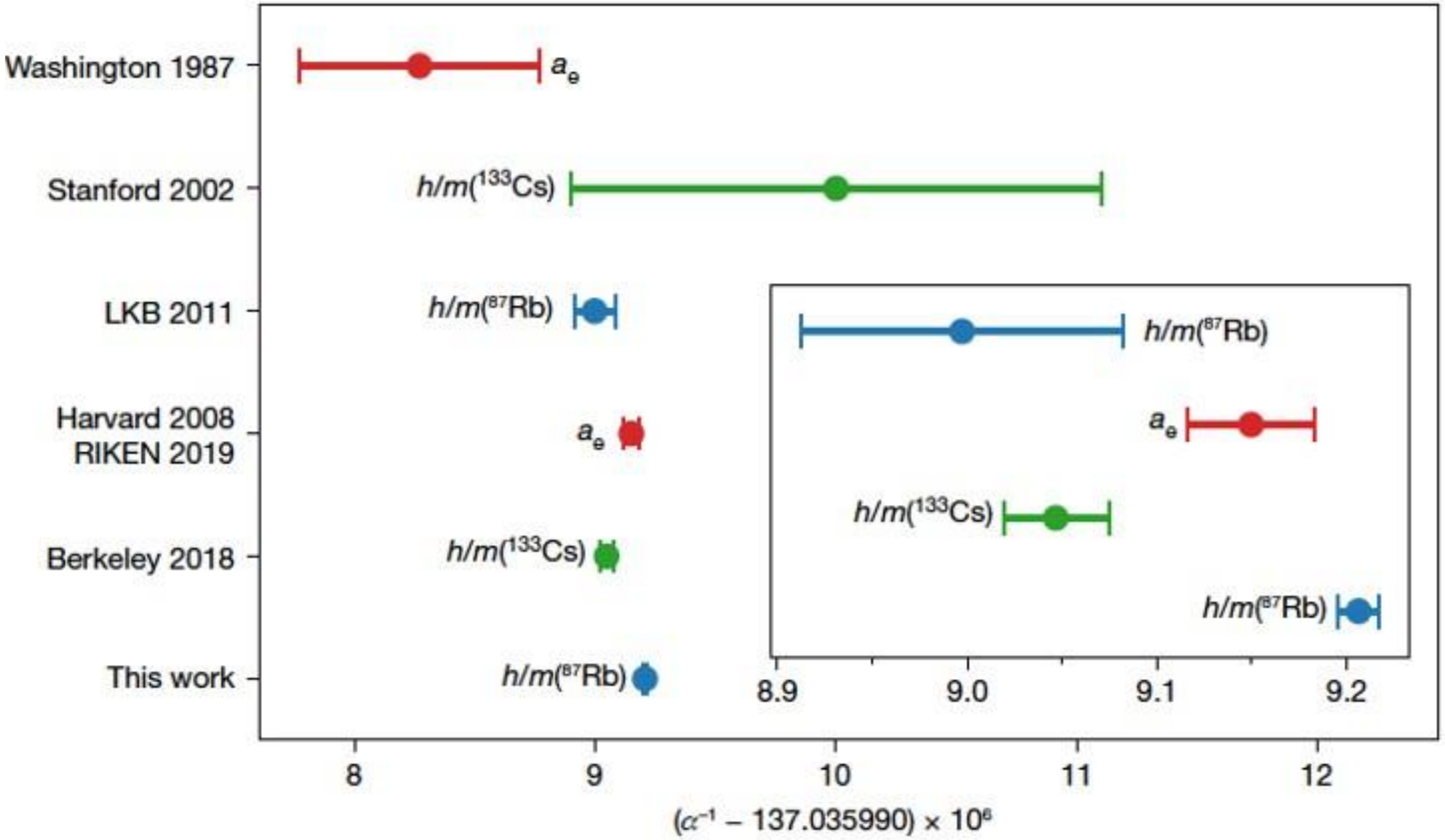
THANK YOU FOR THE ATTENTION!



BACK UP SLIDES

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.



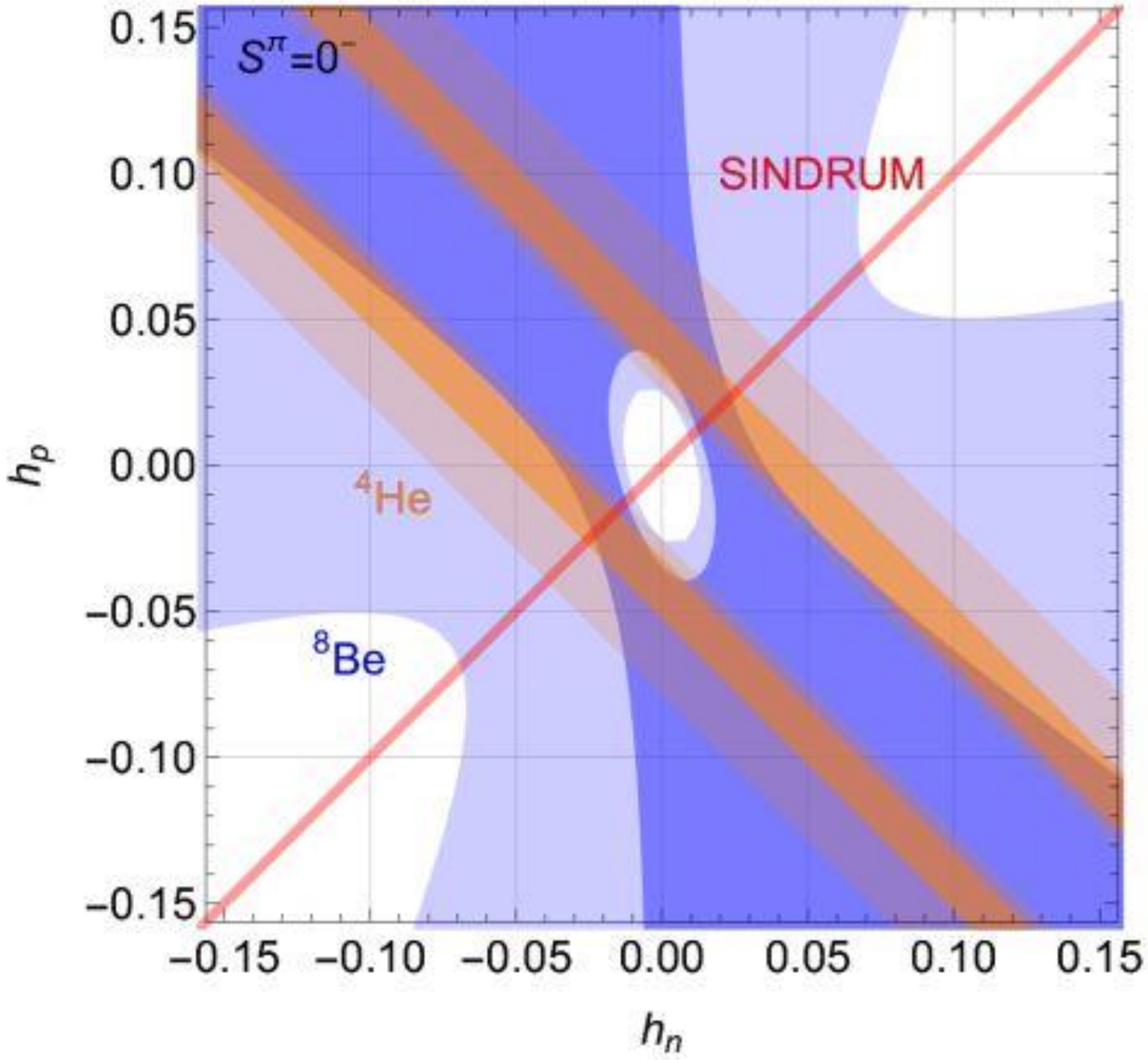
^{133}Cs~9.045±0.03
^{87}Rb~9.21±0.01

Difference ~0.16
Sigma ~0.03

difference >5σ

something is wrong

Pseudoscalar X17

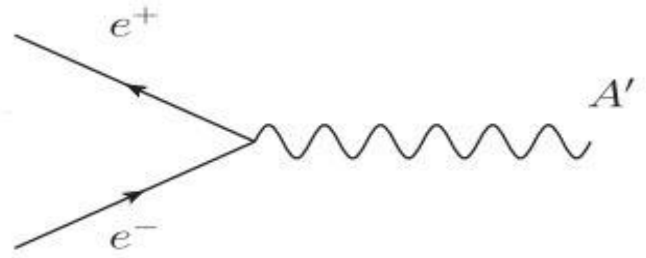


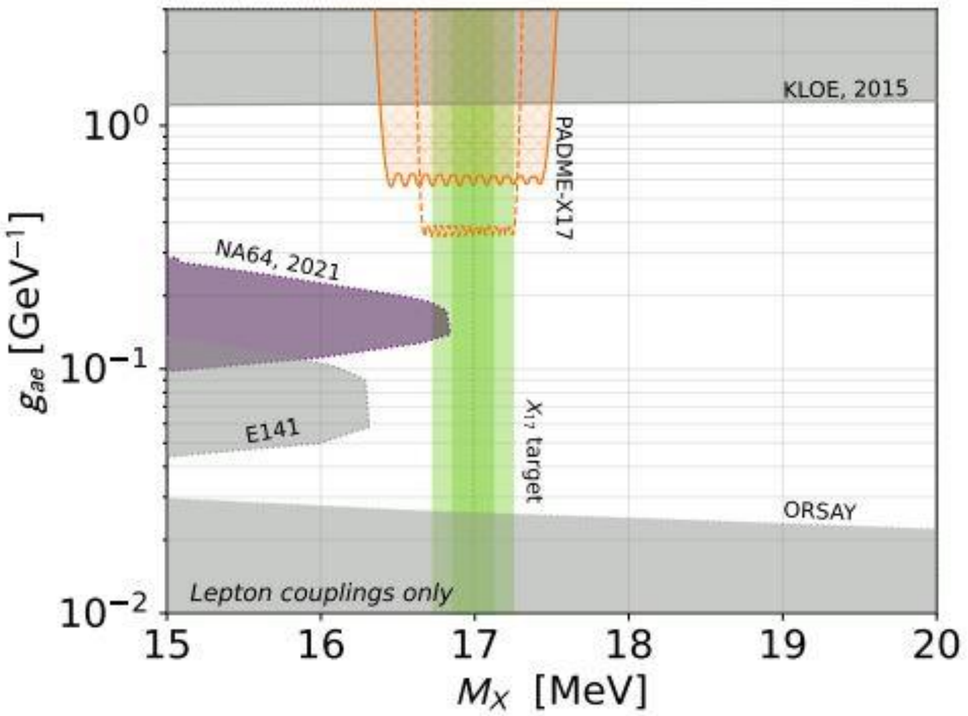
SINDRUM bound from $\pi^+ \to e^+ \nu_e X$ decay

- A pseudoscalar X17 is dynamically consistent for Helium and Beryllium anomalies with nuclear couplings of order $\sim 10^{-2}$.
- However, the Carbon anomaly excludes this possibility.

Pseudoscalar X17 at Padme

- Regardless the need of an independent confirm of the ATOMKI anomalies, the PADME experiment allows for a strong test of the new particle hypothesis.
- A positron beam dump experiment like Padme can resonantly produce the X17.
- Data taking has been already performed and data analysis is starting now.





Pseudoscalar X17

Arxiv:2209.09261
L. Darmé, M. Mancini, M. Raggi and E. Nardi

QCD axion X17 issue

Novel multi-lepton signatures of dark sectors in light meson decays

Matheus Hostert (Minnesota U. and Perimeter Inst. Theor. Phys.), Maxim Pospelov (Minnesota U.) (Dec 3, 2020)

e-Print: 2012.02142 [hep-ph]

- Hostert and Pospelov point out that a viable QCD axion with mass near 17 MeV would produce a large branching ratio of the neutral pion decay to three axion. However, such value has not been observed so far.
- A dedicated search would potentially exclude this model.

$$\mathcal{B}(\pi^0 \to 3a \to 3(e^+e^-))\big|_{m_a=17\,\mathrm{MeV}} = 1.0 \times 10^{-3}. \quad (48)$$

It would be appropriate to say that this is a gigantic rate, and it would be indeed the third largest branching after $\gamma\gamma(0.99)$ and $\gamma e^+e^-(0.01)$, exceeding the SM double-Dalitz decay by a factor of 30. We believe that such a large rate should have been noticed, *e.g.* in the studies of $\pi^0 \to 2(e^+e^-)$ via capture of π^- [73]. (In that work, double-Dalitz and single-Dalitz decays were observed by human examination of photographs from a bubble chamber, and missing very frequent 6-track decays seems implausible.)