X_{17} and anomalies in particle physics

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Overview

- Introduction
- ATOMKI anomaly and vector boson solution
- Lepton magnetic moment
- Lamb shift
- W mass
- Conclusion

The following presentation is based on:" A. Capolupo, A. Quaranta, R. Serao, Phys. Dark Univ. 47 101748 (2025)"

The Standard Model

A remarkably successful theory describing electromagnetic, weak, and strong interactions. Extensively confirmed by experiments, it forms the cornerstone of modern particle physics.

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A remarkably successful theory describing electromagnetic, weak, and strong interactions. Extensively confirmed by experiments, it forms the cornerstone of modern particle physics.

Yet, it is far from complete:

- No gravity, no true grand unification
- 19 free parameters fixed by data
- Neutrino masses: origin and nature (Dirac/Majorana) unknown
- Open questions in flavor physics: 3 generations, mixing?
- No explanation for dark matter or dark energy

Experimental Anomalies

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- Muon $g - 2$
- Proton radius (Lamb shift)
- **ATOMKI anomaly**

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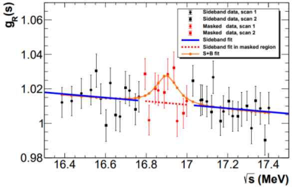
Possible hints of physics beyond the SM:

- Discrepancies suggesting new interactions or particles
- Proposed extensions often introduce **dark sector** candidates

ATOMKI Anomaly

- Normally, pair distributions decrease smoothly with θ and $m_{e^+e^-}$.
- ATOMKI observed **peaks at $\theta \simeq 140°$** and $m_{e^+e^-} \simeq 17.6$ **MeV**.
- Similar anomalies reported in **C** and **He** decays.
- The current status remains unclear:
  - **MEG II (PSI):** against
  - **PADME (Frascati):** in favor

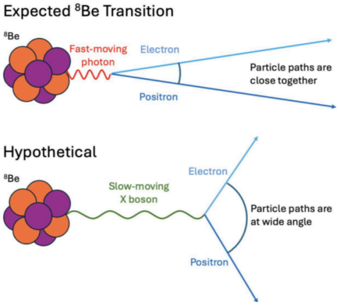


Number of $e^+e^- \to e^+e^-$ events normalized to background (PADME Run III).

PADME Collaboration, arXiv:2505.24797 (2025)

A new vector boson

- A rather natural explanation is represented by a new intermediate particle X^2 with mass around $\simeq 17$ MeV
- The new particle must be a vector boson with distinct nucleon couplings
- X_{17} may fit into abelian extensions of the SM ($U(1)_D$, $U(1)_{B-L}$) as well as non-abelian extensions ($SU(2)_{\text{dark}}$)

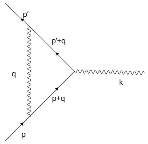


Sketch of the X boson solution[1]

1: C. Gustavino et al., *Nuclear Instruments and Methods in Physics Research A* **1072**, 170087 (2025)
2:J.L. Feng et al. PRL 117,071803 (2016)

There is a discrepancy between the observed value of $(g-2) = 2a_\mu$ and its SM prediction, with a significance of around $4.2\,\sigma$:

$$\delta a_\mu = a_{\mu,\mathrm{EXP}} - a_{\mu,\mathrm{SM}} \simeq (2.51 \pm 0.59) \times 10^{-9}.$$



One-loop contribution of X_{17} to the lepton magnetic moment.

X_{17} may account for the anomaly if it has direct couplings to SM leptons:

$$\mathcal{L} \supset -\epsilon_l X_\nu \bar{l} \gamma^\nu l, \qquad l = e, \mu, \tau.$$

Main contribution from the one-loop diagram

$$\delta\Gamma^\mu(q) = \int \frac{d^4 q}{(2\pi)^4}\, \bar{u}(p')(-i\epsilon_l \gamma^\lambda) \frac{i(\not{p}' + \not{q} + m_l)}{(p'+q)^2 - m_l^2} (e\gamma^\mu) \frac{i(\not{p} + \not{q} + m_l)}{(p+q)^2 - m_l^2}$$

$$\times (-i\epsilon_l \gamma^\nu) \frac{i}{q^2 + M_X^2} \left(-g^{\nu\lambda} + \frac{q^\nu q^\lambda}{M_X^2} \right) u(p)$$

X_{17} and muon $g-2$

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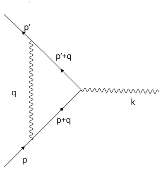

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Form Factor Correction

$$a_l^X = \frac{\alpha}{2\pi}(\epsilon_l m_l)^2 \int_0^1 dx \, \frac{x^2(1-x)}{m_l^2 x^2 + M_X^2(1-x)}$$

- The correction is **independent of the sign** of ϵ_l.
- Experimental data on the **electron** magnetic moment constrain:

$$\delta a_e = a_{e,\text{EXP}} - a_{e,\text{SM}} \leq 4.8\times10^{-13} \Rightarrow |\epsilon_e| \leq 1.0\times10^{-4} \quad (M_X = 17\ \text{MeV})$$

- The **muon** discrepancy can be accommodated with:

$$|\epsilon_\mu| \simeq (2.1 \pm 0.3) \times 10^{-4}$$

X_{17} can explain $(g-2)_\mu$ while remaining consistent with $(g-2)_e$.

Comments and Physical Implications

Key Observations

- The correction is **insensitive to the sign** of ϵ_l: we cannot determine the leptons charge under the new $U(1)$ symmetry.
- The effect scales as $(m_l/M_X)^2$: negligible for the **electron**, visible for the **muon**, and potentially dominant for the **tau**.
- Dark couplings could in principle be **flavor-blind** or **flavor-dependent**. However, flavor-blind interactions would induce **unobserved charged-lepton oscillations** therefore we assume **flavor-dependent couplings**.

A consistent picture emerges only if the dark sector distinguishes lepton flavor.

X_{17} and the Anomalous Lamb Shift

- Precision spectroscopy of **muonic atoms** (such as muonic hydrogen and deuterium) shows a discrepancy with the SM prediction for the Lamb shift:

$$\delta E_\mu^H = (-0.363, -0.251)\,\text{meV}, \qquad \delta E_\mu^D = (-0.475, -0.337)\,\text{meV}.$$

- The exchange of the hypothetical X_{17} **boson** generates an additional **Yukawa-like potential** in the nonrelativistic limit:

$$V_X(r) = \frac{\epsilon_\mu \epsilon_p}{e^2} \frac{\alpha\, e^{-M_X r}}{r},$$

acting as a short-range *fifth force* between the muon and the proton.

This new interaction could explain the energy shift observed in muonic atoms.

Energy-Level Shift from X_{17} Exchange

- The potential $V_X(r)$ produces a correction to the $2S_{1/2} - 2P_{3/2}$ **splitting** via standard perturbation theory:

$$\delta E_X^H = \int dr\, r^2\, V_X(r)\big(|R_{20}(r)|^2 - |R_{21}(r)|^2\big) = \frac{\alpha}{2a_H^3}\left(\frac{\epsilon_\mu \epsilon_p}{e^2}\right)\frac{f(a_H M_X)}{M_X^2}.$$

- Here:

$$a_H = (\alpha\, \mu_{mp})^{-1}, \qquad \mu_{mp} = \frac{m_\mu m_p}{m_\mu + m_p}, \qquad f(x) = \frac{x^4}{1+x^4}.$$

The X_{17} contribution can naturally account for the observed μH Lamb shift anomaly.

Muonic Deuterium and the X_{17} Boson

- The same mechanism applies to **muonic deuterium**, where both the proton and neutron contribute to the interaction.
- The exchange of the hypothetical X_{17} boson induces a **Yukawa-like potential** in the nonrelativistic limit:

$$V_X(r) = \frac{\epsilon_\mu(\epsilon_p + \epsilon_n)}{e^2} \frac{\alpha e^{-M_X r}}{r}.$$

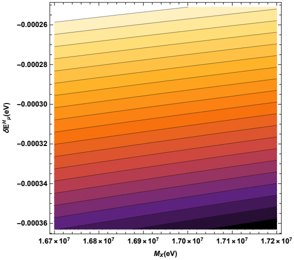
- The corresponding contribution to the $2S_{1/2} - 2P_{3/2}$ Lamb shift is:

$$\delta E_X^D = \frac{\alpha}{2a_D^3} \left(\frac{\epsilon_\mu(\epsilon_p + \epsilon_n)}{e^2} \right) \frac{f(a_D M_X)}{M_X^2},$$

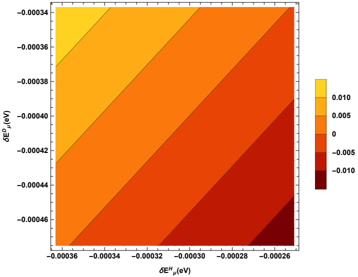
with

$$a_D = (\alpha\, \mu_{\mu D})^{-1}, \qquad \mu_{\mu D} = \frac{m_\mu m_D}{m_\mu + m_D}, \qquad f(x) = \frac{x^4}{1 + x^4}.$$

X_{17} exchange may explain the observed Lamb-shift discrepancy.



Upper bound on X_{17}–proton coupling vs. mass and muonic hydrogen data.



Upper bound on X_{17}–proton coupling vs. hydrogen and deuterium data.

Comments

- There remains an overall sign ambiguity due to the unresolved sign of ϵ_μ.
- To accommodate both discrepancies, ϵ_p and ϵ_n may have either **the same or opposite sign**, depending on the range considered.

W Mass Anomaly (CDF 2022)

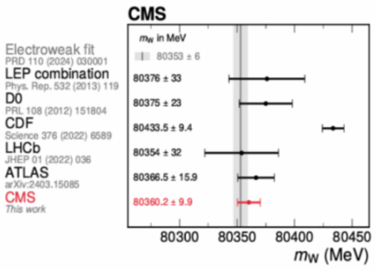
- In **2022**, the **CDF Collaboration**[1] reported a precise measurement of the W boson mass:

$$m_W^{\text{CDF}} = 80.4335 \pm 0.0084 \text{ GeV}.$$

- This value shows a 7σ discrepancy with the SM prediction:

$$m_W^{\text{SM}} = 80.379 \pm 0.006 \text{ GeV}.$$

- The result triggered wide discussion about possible **BSM effects** in electroweak observables.



CDF 2022 result compared with previous determinations.

[1] T. Aaltonen *et al.* (CDF Collaboration), *Science* **376**, 170 (2022).

W Mass Anomaly (CMS 2024 and Outlook)

- In **late 2024**, the **CMS Collaboration**[1] announced a new measurement with comparable precision, reporting a value **much closer to the SM prediction**.
- The overall experimental picture currently:
  - favors a W mass slightly above the SM value;
  - remains **consistent within uncertainties**.
- Future measurements at LHC Run 3 and future colliders will be crucial to determine whether this tension persists.
- Electroweak precision observables like m_W are extremely sensitive probes of new physics beyond the SM.

Future high-precision data will clarify the nature of this discrepancy.

[1] CMS Collaboration, `arXiv:2412.13872`

Oblique Corrections to the W Mass (1/2)

- The tree-level W mass is determined by the Higgs mechanism ($c = \cos\theta_W$):

$$m_W = \frac{gv}{2} = c m_Z$$

- At higher order, m_W receives vertex and box corrections from SM interactions. Additionally, it receives contributions from vacuum polarization diagrams, called **oblique corrections**[2], which are very sensitive to BSM effects.

- The basic polarization amplitudes $\Pi_{XY}(q^2)$ can be approximated as

$$\Pi_{jj}(q^2) \simeq \Pi_{jj}(0) + q^2\Pi'_{jj}(0), \quad j = 1, 2, 3$$

$$\Pi_{QQ}(q^2) \simeq q^2\Pi'_{QQ}(0), \quad \Pi_{3Q}(q^2) \simeq q^2\Pi'_{3Q}(0)$$

[2] M.E. Peskin and T. Takeuchi, Phys. Rev. D **46**, 1 (1992)

Oblique Corrections to the W Mass (2/2)

- The **oblique parameters** are defined as:

$$S = 16\pi \left(\Pi'_{33}(0) - \Pi'_{3Q}(0)\right)$$

$$T = \frac{4\pi}{s^2 c^2 m_Z^2} \left(\Pi_{11}(0) - \Pi_{33}(0)\right)$$

$$U = 16\pi \left(\Pi'_{11}(0) - \Pi'_{33}(0)\right)$$

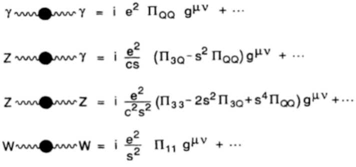


Illustration of oblique corrections in the electroweak sector.

Kinetic Mixing (1/2)

- BSM contributions to m_W enter via the oblique parameters:

$$m_W^2 = m_W^{\text{SM}} \left[1 + \frac{\alpha c^2}{c^2 - s^2} \left(-\frac{1}{2} S + c^2 T + \frac{c^2 - s^2}{4s^2} U \right) \right]$$

- $S, T, U = 0$ corresponds to the Standard Model.
- A minimal explanation of the W mass anomaly is provided by a **dark vector boson** X kinetically mixing with the hypercharge boson B:

$$\mathcal{L} \supset \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + \frac{\xi}{2c} X_{\mu\nu} B^{\mu\nu} + \frac{1}{2} M_{X,0}^2 X^\mu X_\mu$$

- $M_{X,0}$ is the bare mass parameter; ξ is the kinetic mixing.

Kinetic Mixing (2/2)

- The oblique parameters in terms of the kinetic mixing ξ are:

$$S = \frac{4s^2(c^2 - s^2)}{\alpha}\left(\frac{\xi}{1 - r^2}\right)^2,$$

$$T = -\frac{s^2 r^2}{c^2\alpha}\left(\frac{\xi^2}{1 - r^2}\right)^2,$$

$$U = \frac{4s^2}{\alpha}\left(\frac{\xi^2}{1 - r^2}\right)^2,$$

where $r = \frac{M_X}{M_Z}$.

- This shows explicitly how the kinetic mixing ξ affects the electroweak precision observables, and can provide a minimal explanation for a shift in m_W.

Kinetic Mixing of X_{17}

Dark Vector Contribution

$$\delta m_W = -\frac{m_W^{\rm SM} s^2 \xi^2}{2(c^2 - s^2)(1 - r^2)}$$

Comments:

- A heavy dark photon ($M_X > M_Z \Rightarrow r > 1$) can account for a **positive shift** in m_W.
- For the X_{17}, with $M_X \simeq 17\,\text{MeV} \ll M_Z$, the contribution is instead **negative**.
- The experimental uncertainty from the CMS measurement ($\Delta m_W \simeq 10\,\text{MeV}$) imposes a stringent bound on the kinetic mixing:

$$|\xi| < 2.2 \times 10^{-2}$$

Even a tiny kinetic mixing leaves measurable traces in electroweak precision tests.

Conclusions

- The Standard Model remains highly successful, but several **experimental tensions** persist.
- A light vector boson ($M_X \simeq 17$ MeV) could explain the **ATOMKI anomaly**, $(g-2)_\mu$, and the **Lamb shift**.
- The W **mass data** impose strong bounds on its kinetic mixing.
- The X_{17} might act as a **portal to a dark sector**.
- Future measurements will clarify its **viability**.

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The search for new physics continues.