Explanation of the Beryllium anomaly through a dark Z’

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Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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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 $16.70 \pm 0.35(\mathrm{stat}) \pm 0.5(\mathrm{syst})\ \mathrm{MeV}/c^2$ and $J^\pi = 1^+$ was created.

Outline

1. The Atomki experiment and the Beryllium anomaly

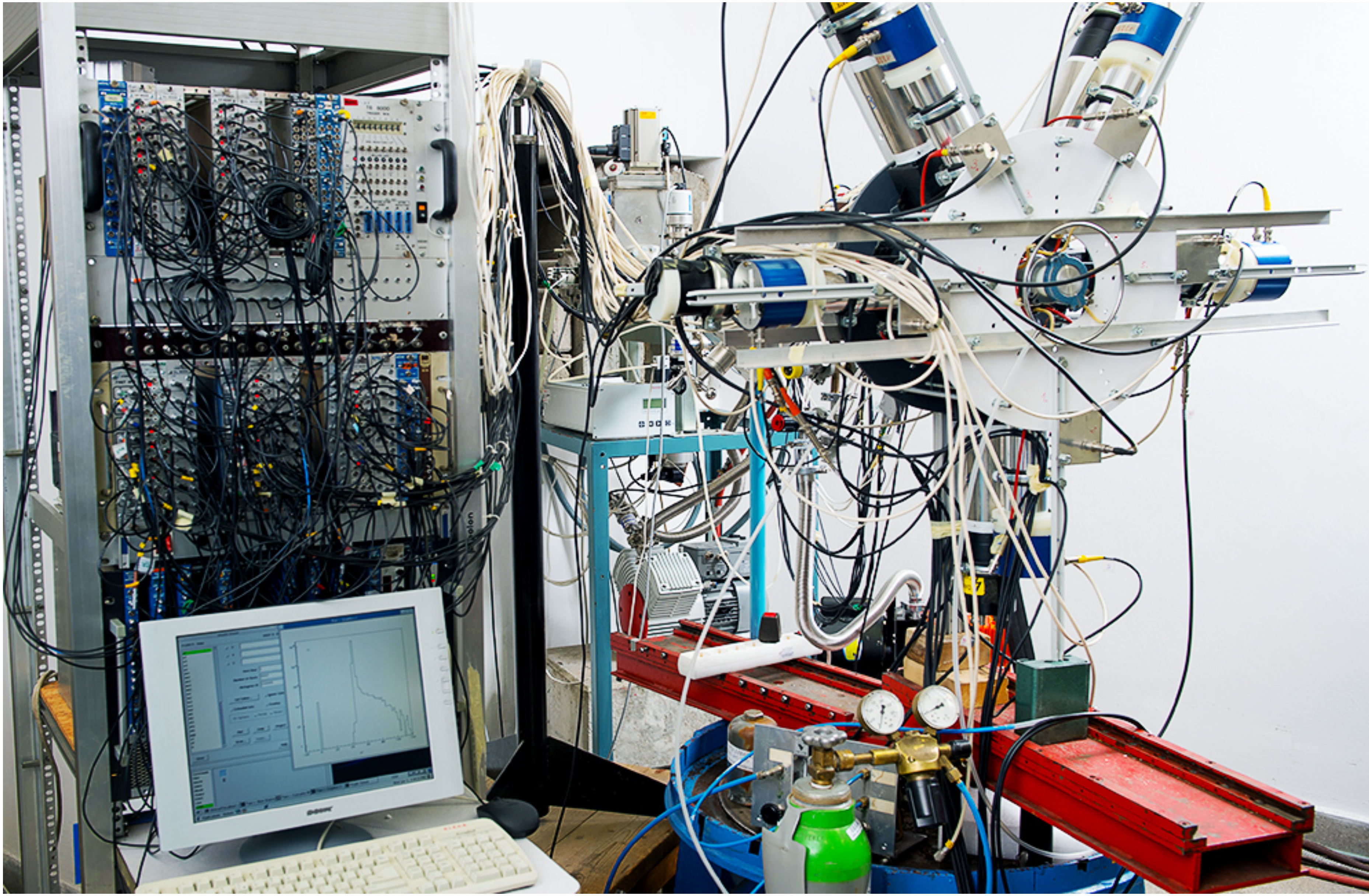
2. Experimental constraints on the lepton and quark couplings to a vector boson

3. Model building

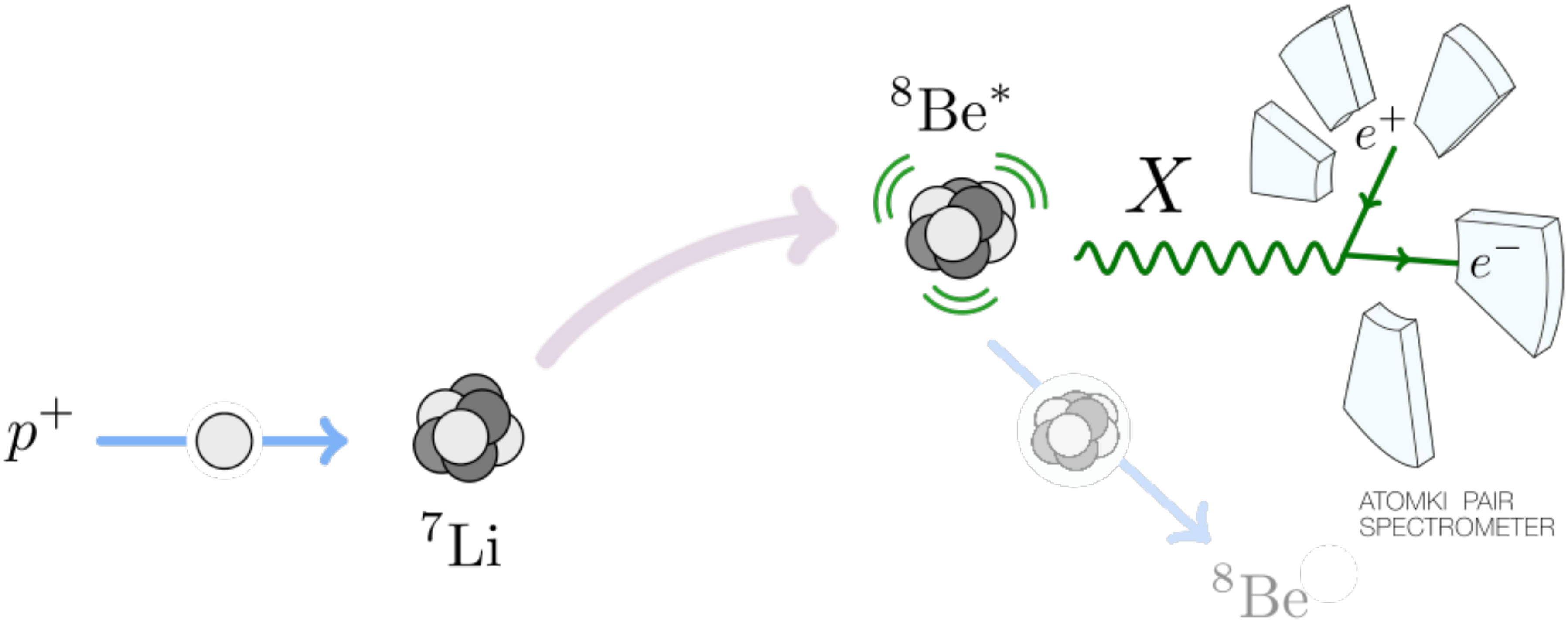
    1. Z’ with vector interactions

    2. Z’ with vector and axial-vector interactions (*general case*)

The Atomki experiment



The Atomki experiment



arXiv:1608.03591

The Atomki pair spectrometer experiment was set up for searching e^+e^- internal pair creation in the decay of excited ^{8}Be nuclei, the latter being produced with help of a beam of protons directed on a ^{7}Li target. The proton beam was tuned in such a way that the different ^{8}Be excitations could be separated with high accuracy.

^{8}Be decay modes

- Hadronic decay (BR ~ 1)

$$^8\mathrm{Be}^* \to {}^7\mathrm{Li} + p$$

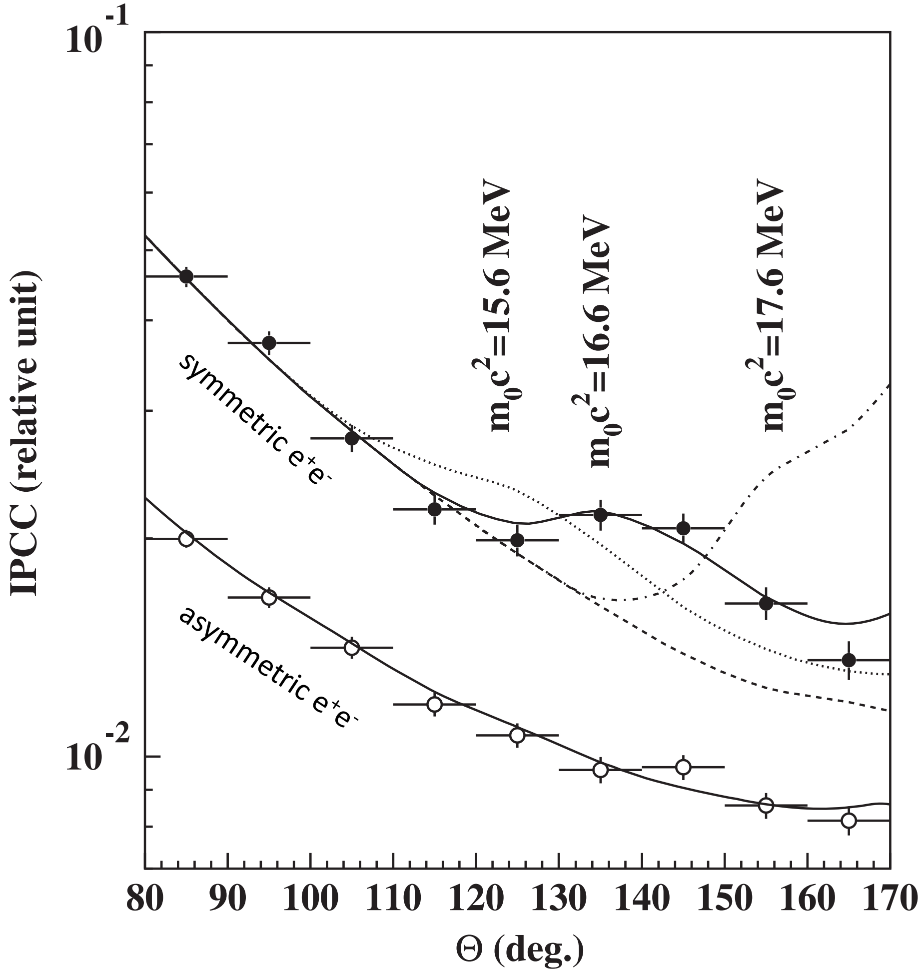
- Electromagnetic decay (BR ~ 1.5 x 10^{-5})

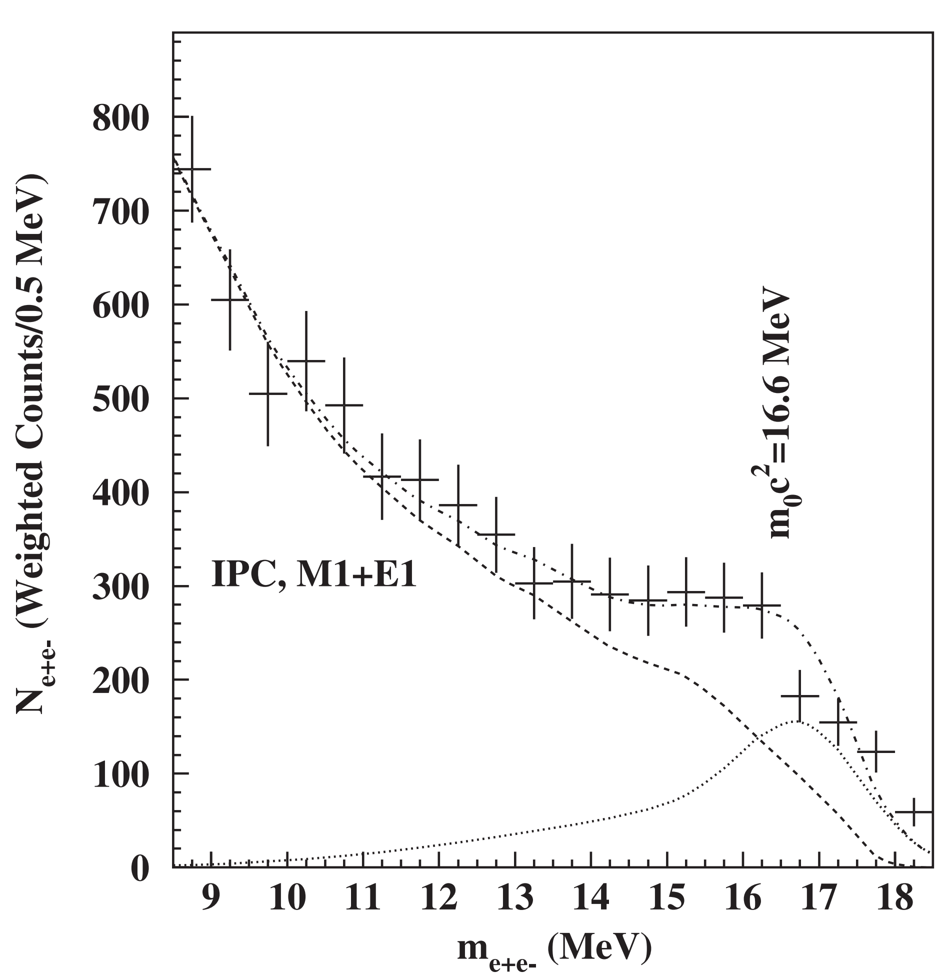
$$^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma$$

- Internal pair creation (BR ~ 5.5 x 10^{-8})

$$^8\mathrm{Be}^* \to {}^8\mathrm{Be} + \gamma^* \to {}^8\mathrm{Be} + e^+ e^-$$

^{8}Be anomaly





arXiv:1504.01527

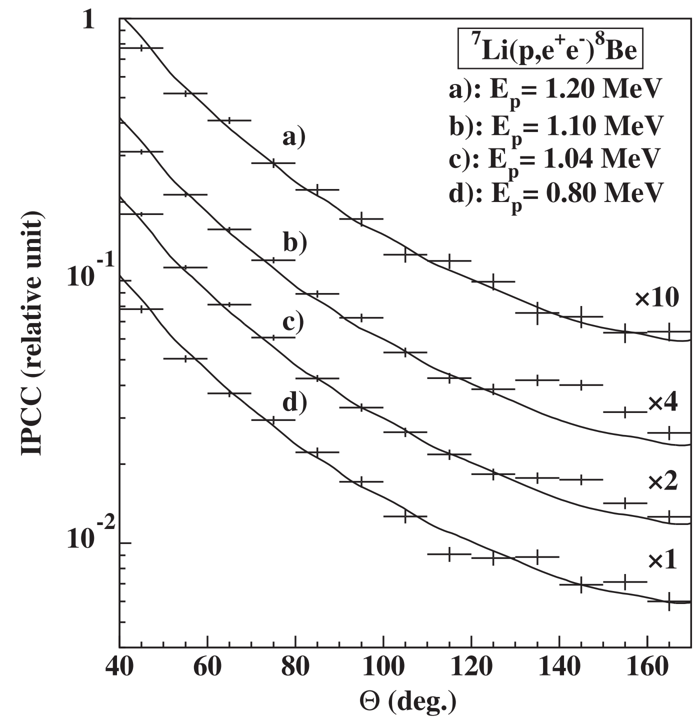
$$M_X = 16.7 \pm 0.35\ (\mathrm{stat})\ \pm 0.5\ (\mathrm{sys})\ \mathrm{MeV}$$

$$\frac{\mathrm{BR}(^8\mathrm{Be}^* \to X + {}^8\mathrm{Be})}{\mathrm{BR}(^8\mathrm{Be}^* \to \gamma + {}^8\mathrm{Be})} \times \mathrm{BR}(X \to e^+e^-) = 5.8 \times 10^{-6}$$

Statistical significance of the excess of about 6.8 σ

Signal characteristics and consistency checks

- Both the opening angle and invariant mass distributions present the characteristics of an excess consistent with an intermediate boson
- The signal appears as a bump over the monotonically decreasing background from QED
- The bump disappears off resonance
- The bump appears only for symmetric energies of e^+e^- (as expected from an on-shell non-relativistic particle)



Possible explanations of the ^{8}Be anomaly

1. The $X \to e^+e^-$ decay implies that X is a boson

2. Candidates:

   a) **Scalars** $(J^P = 0^+)$
   not allowed since $1^+ \to 0^+0^+$ *would imply L = 1 and (-1)*^{L}

   b) **Pseudoscalars** $(J^P = 0^-)$
   decay width $\sim |k|^3/m_X^3$ implies new Yukawa couplings $Y \sim 0.3\ Y_{SM}$

   c) **Vectors** $(J^P = 1^-)$
   decay width $\sim |k|^3/m_X^3$ implies g' ~ 10^{-3}

   d) **Axial-vectors** $(J^P = 1^+)$
   nuclear matrix elements have been computed only recently (arXiv:1612.01525)
   decay width $\sim |k|/m_X$ implies g' ~ 10^{-4}

   e) **Vector + Axial-vector spin-1 bosons**
   strongly constrained by atomic parity violation

The spin - 1 case

We consider a *generic* abelian extension of the SM described by the abelian group U(1)’

$$J^{\mu}_{Z'} = \sum_f \bar{\psi}_f \gamma^\mu \left(C_{f,V} + \gamma^5 \, C_{f,A}\right) \psi_f$$

Experimental constraints on the lepton couplings

- The Z' decays into e^+e^- inside the Atomki detector: $c\tau \lesssim 1cm$
- Electron beam dump experiment (SLAC E141)
- Parity-violating Moller scattering (SLAC E158)
- Magnetic moments of electron and muon
- Electron-positron colliders, like KLOE2 searching for $e^+e^- \to \gamma Z', Z' \to e^+e^-$
- Neutrino-electron scattering

Experimental constraints on the quark couplings

- Neutral pion decay (NA48/2), $\pi^0 \to Z'\gamma, Z' \to e^+e^-$
- Atomic parity violation in Cesium
- Rare η decay, $\eta \to \mu^+\mu^-$
- Search for $\phi \to Z'\eta, Z' \to e^+e^-$ at KLOE2
- Charged kaon decay (NA48/2), $K^+ \to Z'\pi^+, Z' \to e^+e^-$
- Neutron–neutron scattering
- Proton fixed target experiments

Experimental constraints on the quark couplings

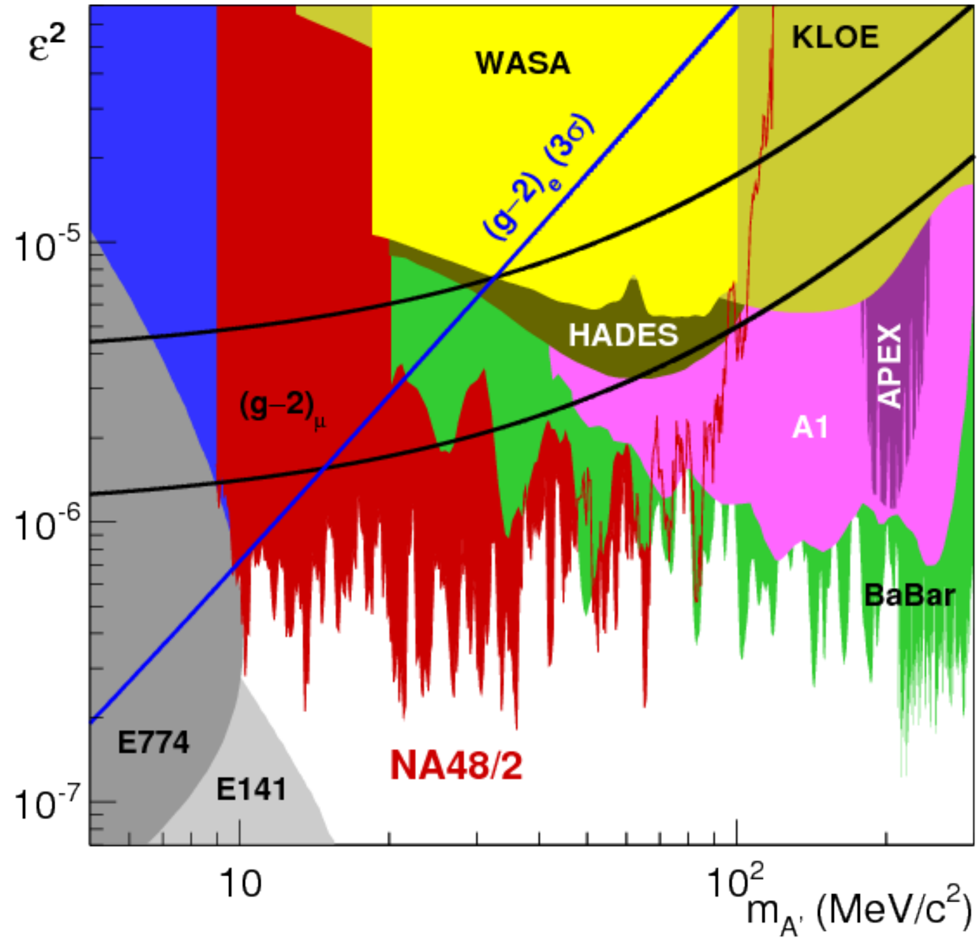
Neutral pion decay (NA48/2), $\pi^0 \to Z'\gamma, Z' \to e^+e^-$

The process is proportional to the anomaly factor

$$N_\pi \equiv (C_{u,V}\, q_u - C_{d,V}\, q_d)^2$$
$$= \frac{1}{9}(2C_{u,V} + C_{d,V})^2$$

there is no contribution from the axial couplings up to chiral-symmetry breaking effects proportional to the quark masses

$$|2C_{u,V} + C_{d,V}| \lesssim \frac{0.36\times 10^{-3}}{\sqrt{\mathrm{BR}(Z' \to e^+e^-)}}$$



arXiv:1508.01307

Experimental constraints on the quark couplings

Atomic parity violation in Cesium

- It provides an accurate test of the low-energy electroweak sector of the SM
- It also confirmed the low-energy running of the electroweak coupling constants

Very strong constraints on a light *Z'* can be extracted from the measurement of the effective weak charge of the Cs atom

$$\Delta Q_W = -\frac{2\sqrt{2}}{G_F} C_{e,A} \left[C_{u,V}(2Z+N) + C_{d,V}(Z+2N) \right] \frac{K(M_{Z'})}{M_{Z'}^2}$$

where $|\Delta Q_W| \lesssim 0.71$ at 2σ

$K(M_{Z'})$ is a correction factor taking into account the Yukawa-like potential generated by the exchange of a massive boson between the nucleus and the atomic electrons
$K(M_{Z'}) \simeq 0.8$ for $M_{Z'} \simeq$ 17 MeV

arXiv:0902.0335
arXiv:1203.2947
arXiv:hep-ph/0410260

Model Building

U(1)' abelian extension of the SM

We consider a *generic* abelian extension of the SM described by the abelian group U(1)'

Due to the presence of the abelian groups $U(1)_Y$ x U(1)' the most general kinetic Lagrangian of the corresponding abelian fields is

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'^{\mu\nu} - \frac{\kappa}{2}\hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}$$

It is particular convenient to recast the kinetic Lagrangian into a diagonal form by a transformation (rotation + rescaling) of the fields. This affects the structure of the gauge covariant derivative

$$\mathcal{D}_\mu = \partial_\mu + \ldots + i g_1 Y B_\mu + i(\tilde{g} Y + g' z) B'_\mu$$

Two gauge couplings $\tilde{g},\ g'$ for the new abelian field

The EW symmetry breaking and the Z' mass

Consider the simplest extension: *an additional U(1)' with the same Higgs potential*

The neutral gauge boson mass matrix can be extracted from the Higgs Lagrangian

$$-\mathcal{L}_{\text{Higgs}} = \frac{v^2}{8}(g_2 W^3_\mu - g_1 B_\mu - \bar{g}_H B'_\mu)^2 + \frac{m^2_{B'}}{2} B'^2_\mu + \ldots$$

where $\bar{g}_H = \tilde{g} + 2 z_H g'$ induces a *Z-Z'* mixing:

$$\begin{pmatrix} B^\mu \\ W_3^\mu \\ B'^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & -\sin\theta_w\cos\theta' & \sin\theta_w \sin\theta' \\ \sin\theta_w & \cos\theta_w \cos\theta' & -\cos\theta_w \sin\theta' \\ 0 & \sin\theta' & \cos\theta' \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \\ Z'^\mu \end{pmatrix}$$

$$\tan 2\theta' = \frac{2\bar{g}_H g_Z}{\bar{g}_H^2 + 4 m^2_{B'}/v^2 - g_Z^2}$$

for $g', \tilde{g} \ll 1 \quad m^2_{B'} \ll v^2$ one obtains $M_Z^2 \simeq \frac{1}{4} g_Z^2 v^2 \,, \qquad M^2_{Z'} \simeq m^2_{B'}$

if we assume that m_B is generated through SSB by the vev *v'* of an extra scalar we find v' ~ 10 GeV with g' ~ 10^{-3}

The Z' interactions

The interactions between the Z' gauge boson and the SM fermions are described by the gauge current

$$J^{\mu}_{Z'} = \sum_f \bar{\psi}_f \gamma^{\mu} \left(C_{f,L} P_L + C_{f,R} P_R \right) \psi_f$$

where the Left- and Right-handed coefficients are

$$C_{f,L} = -g_Z s' \left(T^3_f - s^2_w Q_f \right) + \bar{g}_{f,L} \, c' \qquad\qquad C_{f,R} = g_Z s^2_w s' Q_f + \bar{g}_{f,R} \, c'$$

with $\quad \bar{g}_{f,L/R} = \tilde{g} Y_{f,L/R} + g' z_{f,L/R}$

in the limit $\quad \tilde{g}, g' \ll 1$

$$C_{f,V} \simeq \tilde{g} c^2_W \, Q_f + g' \left[z_\Phi (T^3_f - 2 s^2_W Q_f) + z_{f,V} \right] ,$$
$$C_{f,A} \simeq g' \left[-z_\Phi \, T^3_f + z_{f,A} \right] ,$$

The Z’ interactions

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with $\bar g_{f,L/R} = \tilde g Y_{f,L/R} + g' z_{f,L/R}$

in the limit $\tilde g, g' \ll 1$

$$\begin{aligned} C_{f,V} &\simeq \tilde g c^2_W Q_f + g' \left[z_\Phi (T^3_f - 2 s^2_W Q_f) + z_{f,V} \right] , \\ C_{f,A} &\simeq g' \left[- z_\Phi T^3_f + z_{f,A} \right] , \end{aligned}$$

- ***Dark photon***
- ***Dark Z***
- ***Z’ interactions***

Theoretical constraints

We build on top of the SM

1. Gauge invariance
2. Anomaly-free model
3. Flavour universality
4. Minimal matter content (*compatibly with 1 and 2*)

In particular, the gauge invariance of the SM Yukawa Lagrangian

$$-\mathcal{L}^{\mathrm{SM}}_{\mathrm{Yuk}} = \bar{Q}_L Y_u \tilde{H} u_R + \bar{Q}_L Y_d H d_R + \bar{L}_L Y_e H e_R + \mathrm{h.c.}$$

implies

$$z_\Phi \equiv z_H = z_Q - z_d = -z_Q + z_u = z_L - z_e$$

and therefore

$$\boxed{C_{f,A} \simeq g' \left[-z_\Phi T^3_f + z_{f,A}\right] = 0}$$

Theoretical constraints

To summarise: we can identify two situations discriminated by the scalar content of the model

1. The SM is extended by an additional abelian gauge group U(1)’ and the SM scalar sector is unchanged

   The Z’ has only vector interactions with the SM fermions
   (the only exception is the left-handed neutrino coupling to a V-A current)

2. The SM is extended by an additional abelian gauge group U(1)’ and the scalar sector is extended (for instance by an additional Higgs doublet)

   The Z’ has both vector and axial-vector interactions with the SM fermions

Z’ with vector interactions only – *dark photon*

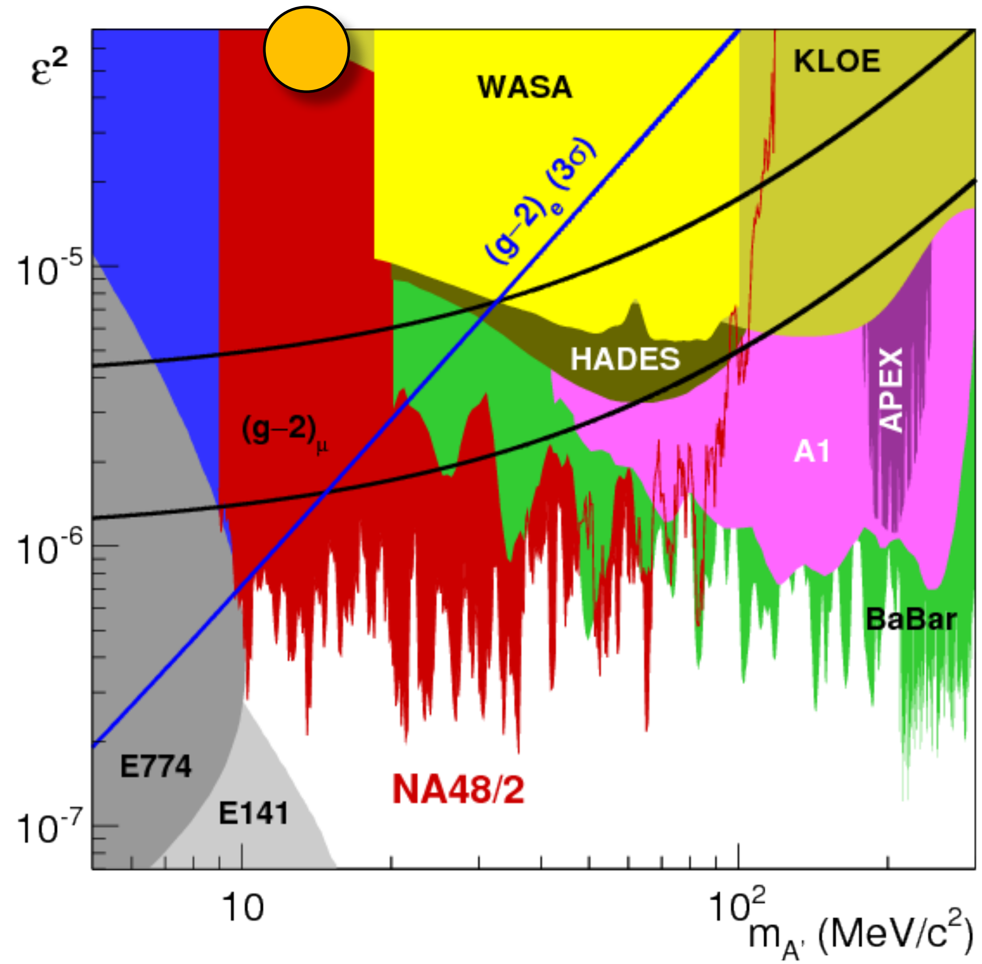
The first attempt: *dark photon*
a vector portal between the SM and a hidden sector interacting with the SM e.m. charged fields through kinetic mixing $-\frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu}$

only one free parameter $\tilde{\varepsilon}$

$\varepsilon' = 0 \qquad (\varepsilon_n = 0, \quad \varepsilon_p = \tilde{\varepsilon} = 0.011)$

NA48/2 $\quad \pi^0 \to Z'\,\gamma$

$$N_\pi \equiv (\varepsilon_u q_u - \varepsilon_d q_d)^2 = \frac{1}{9}(2\varepsilon_u + \varepsilon_d)^2 = \frac{\varepsilon_p^2}{9}$$



arXiv:1508.01307

the Z’ must be *protophobic*:
it couples to neutron but not to protons

Z' with vector interactions only – *general case*

To summarise:

$$\begin{aligned} |\varepsilon_n| &= (2-10)\times 10^{-3} \\ |\varepsilon_p| &\lesssim 1.2\times 10^{-3} \\ |\varepsilon_e| &= (0.2-1.4)\times 10^{-3} \\ \sqrt{|\varepsilon_e \varepsilon_\nu|} &\lesssim 3\times 10^{-4}\ . \end{aligned}$$

arXiv:1608.03591

- ε_n is determined by the ^{8}Be signal rate
- ε_p is bounded by NA48/2 experiment
- ε_e is bounded from below by beam dump experiments and from above by $(g\text{-}2)_e$ and KLOE2
- $\varepsilon_\nu\ \varepsilon_e$ is bounded by neutrino-electron scattering experiment (TEXONO)

In a *minimal* gauge invariant, anomaly free and flavour universal model with a single Higgs doublet we obtain: $\varepsilon_\nu = \varepsilon_n$ and the last bound is incompatible with the others!!!

The EW symmetry breaking and the Z' mass in a 2HDM

Consider *an additional U(1)' with an extended Higgs potential (two Higgs doublets)*

The neutral gauge boson mass matrix can be extracted from the Higgs Lagrangian

$$-\mathcal{L}_{\rm Higgs} = \frac{v_1^2}{8}(g_2 W^3_\mu - g_1 B_\mu - \bar{g}_{\Phi_1} B'_\mu)^2 + \frac{v_2^2}{8}(g_2 W^3_\mu - g_1 B_\mu - \bar{g}_{\Phi_2} B'_\mu)^2 + \frac{m^2_{B'}}{2} B'^2_\mu + \ldots$$

$$\tan 2\theta' = \frac{2\bar{g}_\Phi g_Z}{\bar{k}^2 + 4 m^2_{B'}/v^2 - g_Z^2}$$

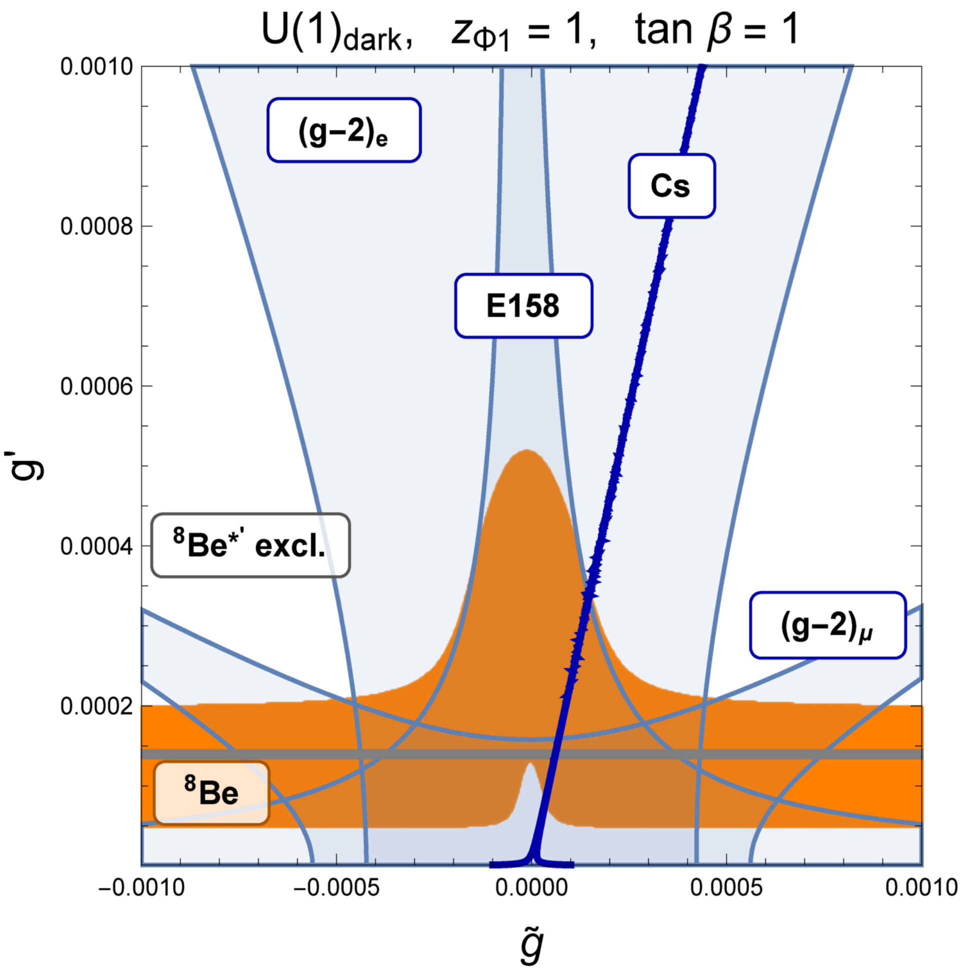
$$\bar{g}_\Phi = \bar{g}_{\Phi_1}\cos^2\beta + \bar{g}_{\Phi_2}\sin^2\beta$$
$$\bar{k}^2 = \bar{g}^2_{\Phi_1}\cos^2\beta + \bar{g}^2_{\Phi_2}\sin^2\beta$$
$$\bar{g}_{\Phi_n} = \tilde{g} + 2 g' z_{\Phi_n}$$

for $g', \tilde{g} \ll 1 \quad m^2_{B'} \ll v^2$

$$\boxed{M^2_{Z'} \simeq m^2_{B'} + \frac{v^2}{4} g'^2 (z_{\Phi_1} - z_{\Phi_2})^2 \sin^2(2\beta)}$$

Even if $m_{B'} = 0$, we can generate the 17 mass from EWSB (with $g' \sim 10^{-4}$) by the same EW mass scale v = 246 GeV, as for the Z and W bosons

$U(1)_{dark}$ – type I - 2HDM



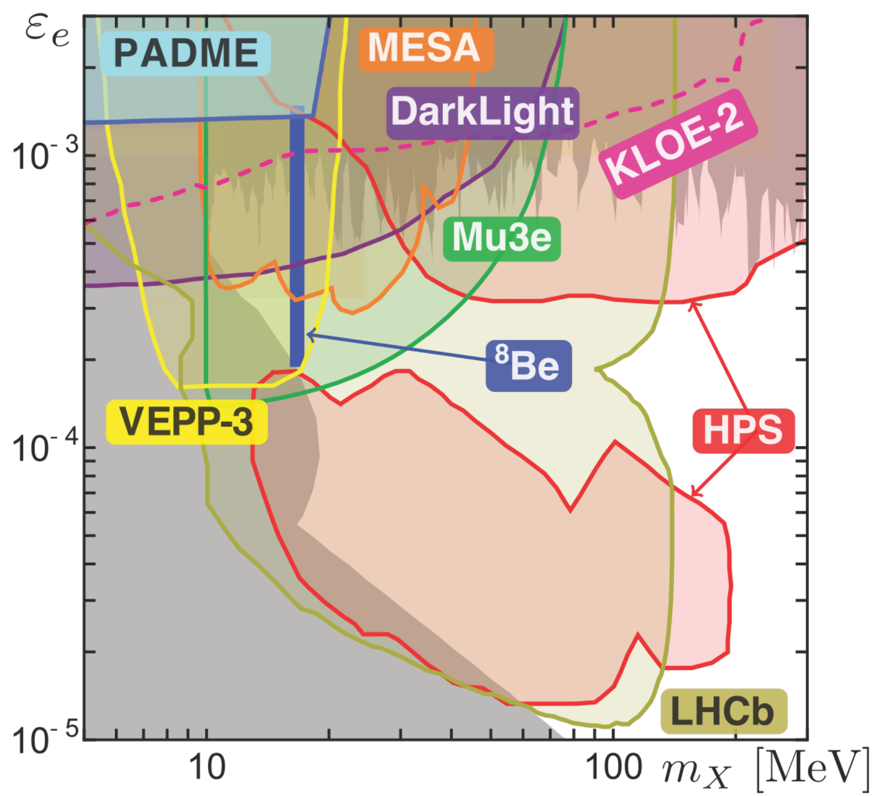
Future prospects

Experimental side

- Other experimental groups may independently verify the Atomki result

- Search for other nuclear transitions

- Other experiments searching for dark photons
  (LHCb search for $D^*(2007)^0 \rightarrow D^0 X$)



arXiv:1608.03591

Theoretical side

- Improving the computation of the nuclear matrix elements of an axial current

- Classification of UV complete models explaining low-scale physics

Conclusions

- There is an anomaly in the IPC decay mode of an excited state of the Beryllium with a statistical significance of 6.8 σ

$$M_X = 16.7 \pm 0.35 \text{ (stat) } \pm 0.5 \text{ (sys) MeV}$$

$$\frac{\mathrm{BR}(^8\mathrm{Be}^* \to X + {}^8\mathrm{Be})}{\mathrm{BR}(^8\mathrm{Be}^* \to \gamma + {}^8\mathrm{Be})} \times \mathrm{BR}(X \to e^+ e^-) = 5.8 \times 10^{-6}$$

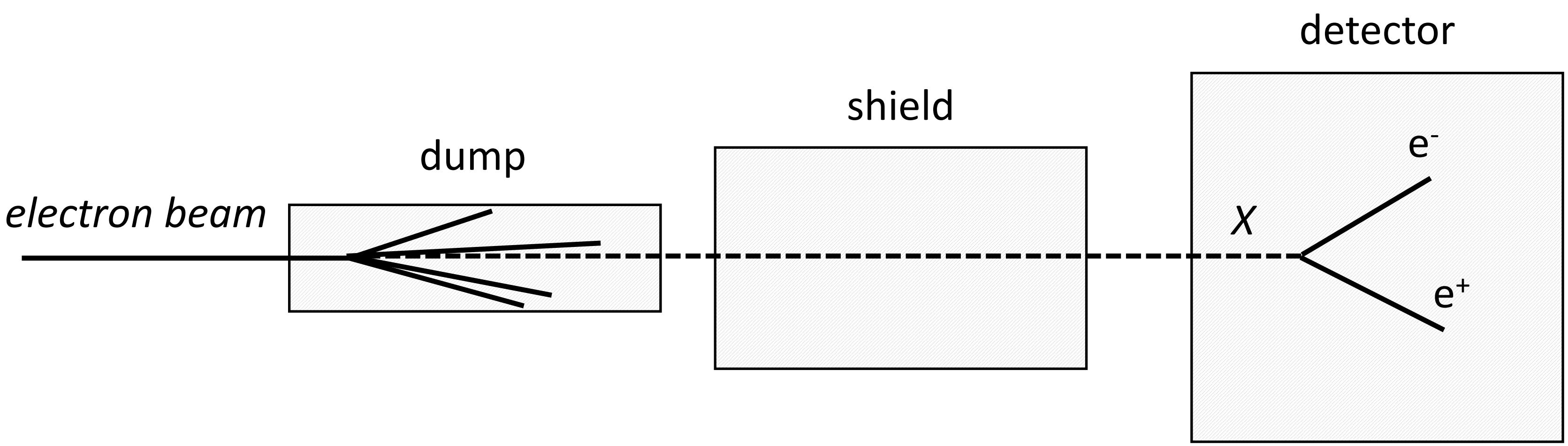
- Build a UV complete model explaining the excess is quite challenging: many bounds from low-energy physics experiments (e.g. parity violations)

- The SM electroweak symmetry breaking may account for the mass of this light Z' boson without introducing any new mass scale

Backup slides

Experimental constraints on the lepton couplings

Electron beam dump experiment (SLAC E141)

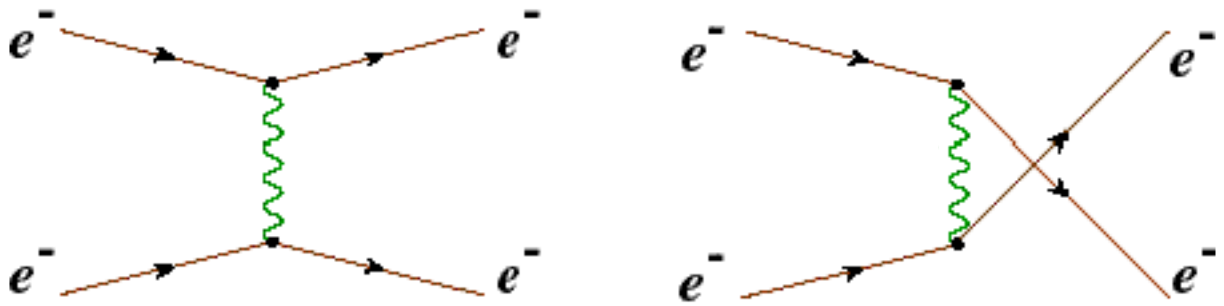


We have not seen the *Z'* in these experiments

- the *Z'* has not been produced $C_{e,V}^2 + C_{e,A}^2 < 10^{-17}$
- the *Z'* has been caught in the dump $\dfrac{C_{e,V}^2 + C_{e,A}^2}{\mathrm{BR}(Z' \to e^+ e^-)} \gtrsim 3.7 \times 10^{-9}$

Experimental constraints on the lepton couplings

Parity-violating Moller scattering (SLAC E158)



the new Z' boson contributes to the left-right asymmetry $A_{PV} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$

which can be used to constrain the vector and axial-vector couplings

$$|C_{e,V} C_{e,A}| \lesssim 10^{-8}$$

Experimental constraints on the lepton couplings

Magnetic moments of electron and muon

$$\Delta a_e = a_e^{\mathrm{EXP}} - a_e^{\mathrm{SM}} = -10.5\,(8.1) \times 10^{-13}$$

$$\Delta a_\mu = a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}} = 2.90\,(90) \times 10^{-9}$$

Contributions from a *Z':*

$$\delta a_l = \frac{C_{l,V}^2}{4\pi^2} \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x) r_l^2} - \frac{C_{l,A}^2}{4\pi^2} \frac{1}{r_l^2} \int_0^1 dx \frac{2x^3 + (x - x^2)(4-x) r_l^2}{x^2 + (1-x) r_l^2}$$

$$r_l = M_{Z'}/m_l$$

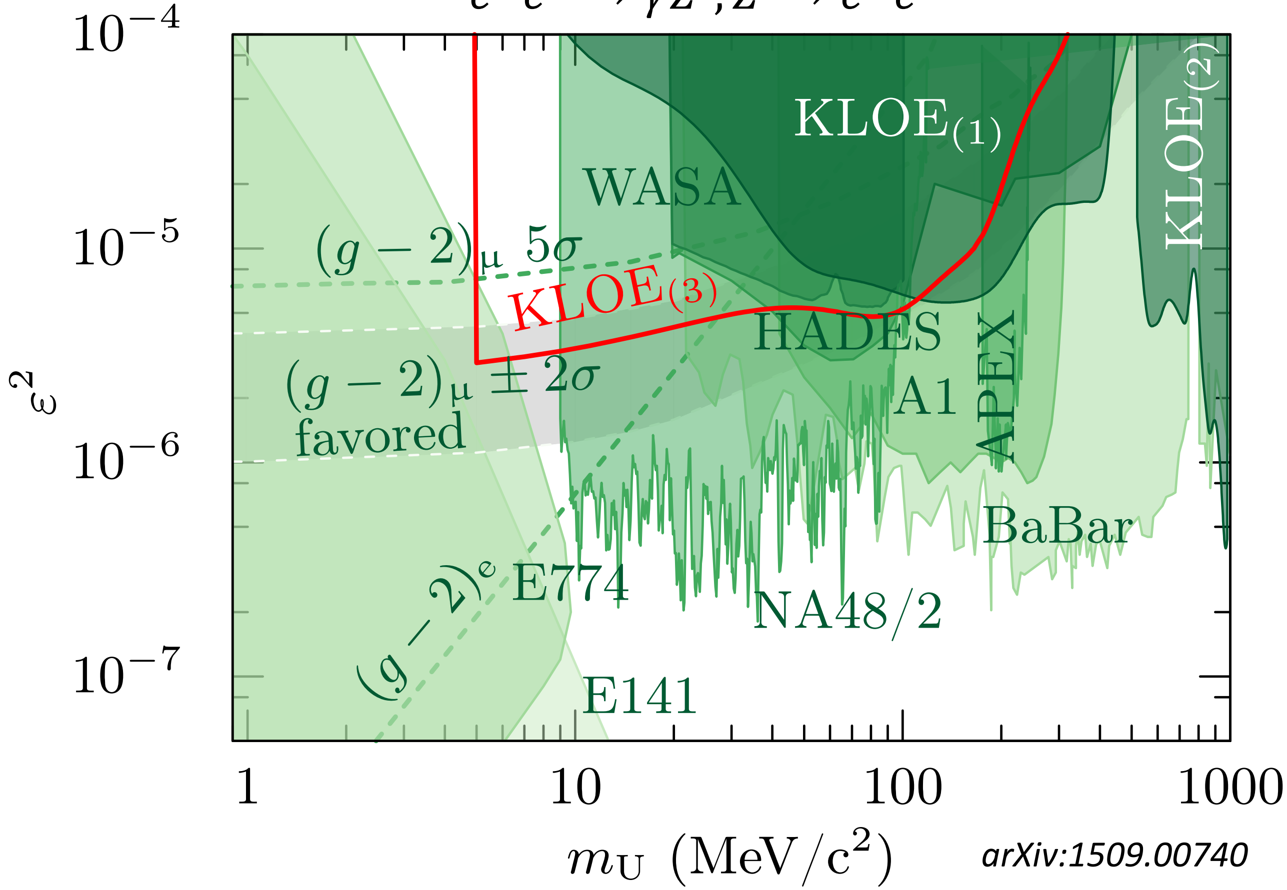
$$\delta a_e = 7.6 \times 10^{-6}\, C_{e,V}^2 - 3.8 \times 10^{-5}\, C_{e,A}^2$$

$$\delta a_\mu = 0.009\, C_{\mu,V}^2 - C_{\mu,A}^2$$

Experimental constraints on the lepton couplings

Electron-positron colliders (KLOE2)

$e^+e^- \to \gamma Z', Z' \to e^+e^-$

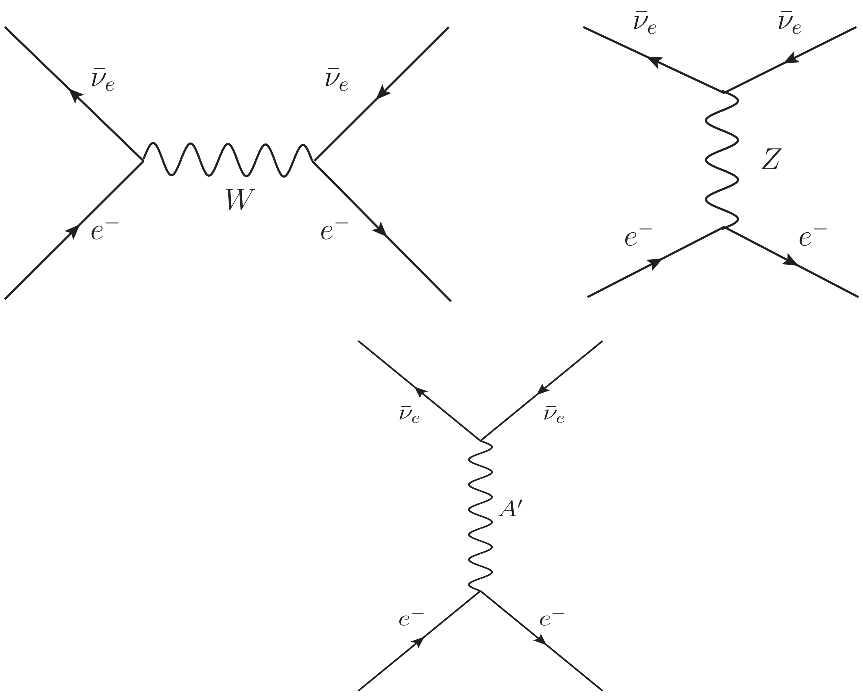


arXiv:1509.00740

$$(C_{e,V}^2 + C_{e,A}^2)\,\mathrm{BR}(Z' \to e^+e^-) \lesssim 3.7 \times 10^{-7}$$

Experimental constraints on the lepton couplings

Neutrino-electron scattering



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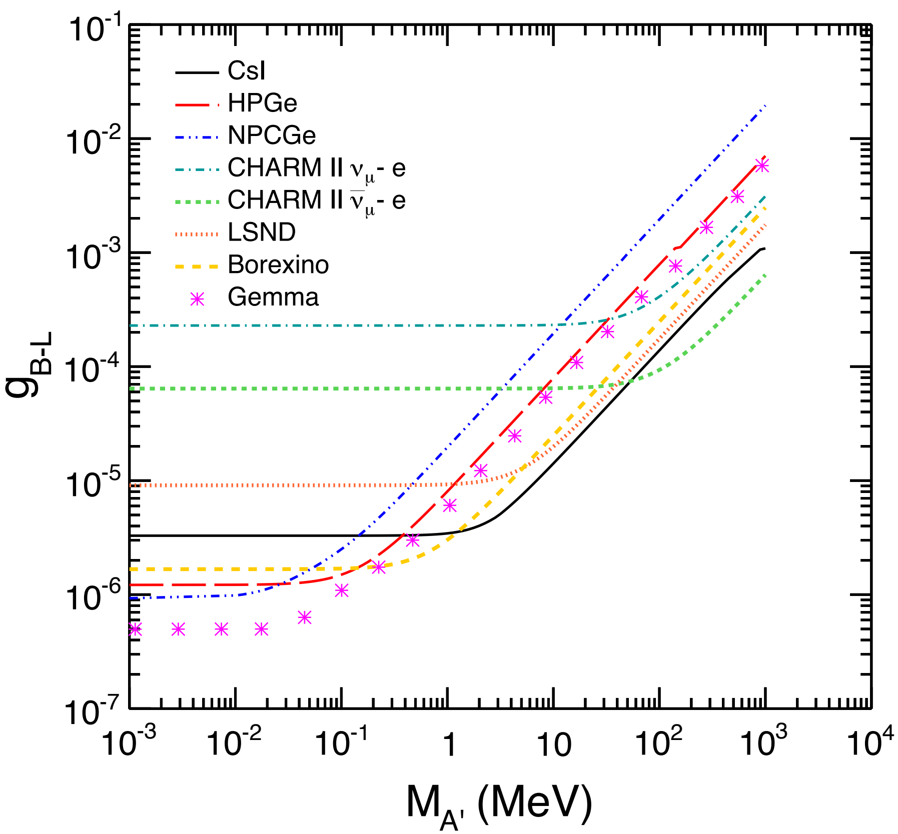

it implies a bound on the product of the electron and neutrino couplings to the Z'

Z' with vector interactions only

The *simplest solution:* one Higgs doublet and a vector-like Z'

$$C_{f,V} \simeq \tilde{g}\, c_w^2\, Q_f + g'\, z_f\,,$$

$$C_{f,A} \simeq 0\,.$$

The couplings are usually written as multiples of the positron charge *e* as

$$J^{\mu}_{Z'} = e \sum_f \left(\tilde{\varepsilon}\, Q_f + \varepsilon'\, z_f\right) \bar{\psi}_f \gamma^{\mu} \psi_f \equiv \sum_f \varepsilon_f\, \bar{\psi}_f \gamma^{\mu} \psi_f$$

$$\boxed{\varepsilon_n = \varepsilon_u + 2\varepsilon_d = \varepsilon'} \qquad \boxed{\varepsilon_p = 2\varepsilon_u + \varepsilon_d = \varepsilon' + \tilde{\varepsilon}}$$

The decay width of the excited state of ^{8}Be is given by

$$\frac{\Gamma(\,^8\mathrm{Be}^* \to \,^8\mathrm{Be}\, X)}{\Gamma(\,^8\mathrm{Be}^* \to \,^8\mathrm{Be}\, \gamma)} = (\varepsilon_p + \varepsilon_n)^2 \frac{|\mathbf{k}_X|^3}{|\mathbf{k}_\gamma|^3} = (\varepsilon_p + \varepsilon_n)^2 \left[1 - \left(\frac{m_X}{18.15\ \mathrm{MeV}}\right)^2\right]^{3/2}$$

nuclear matrix elements cancel in the ratio

which implies $\quad |\varepsilon_p + \varepsilon_n| \approx 0.011 \quad$ or $\quad |\varepsilon_u + \varepsilon_d| \approx 3.7 \times 10^{-3}$

assuming BR(Z' -> e^+e^-) = 1