Muon and Electron g-2, Proton and Cesium Weak Charges Implications on Dark Z_d Models

Carlo Giunti

INFN, Torino, Italy

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M. Cadeddu,[1, a] N. Cargioli,[2, 1, b] F. Dordei,[1, c] C. Giunti,[3, d] and E. Picciau[2, 1, e]

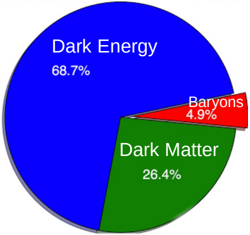
[1] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Cagliari, Complesso Universitario di Monserrato - S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*

[2] *Dipartimento di Fisica, Università degli Studi di Cagliari, Complesso Universitario di Monserrato - S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy*

[3] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I–10125 Torino, Italy*

[arXiv:2104.03280]

Dark Z_d models



- It is very likely that the energy of the Universe is composed by:
  - about 70% of Dark Energy,
  - about 25% of non-baryonic Dark Matter,
  - about 5% of baryonic matter.
- Therefore, there is a Dark Sector made of unknown particles and interactions.
- There are many models of all types, many based on new symmetries.
- A simple and attractive new symmetry (present in many models) is a broken $U(1)_d$ gauge symmetry in the Dark Sector.
- The associated low-mass gauge boson is called:
  - dark photon (A') if it couples only with J^μ_{EM} (kinetic mixing with $F_{\mu\nu}$);
  - dark Z (Z_d) if it couples with J^μ_{EM} and J^μ_{NC} (in the past: Z', U, V, ...).
- We consider a Z_d with mass between about 10 MeV and 10 GeV.
- This Z_d is a force mediator in the Dark Sector, not the Dark Matter, because it decays very quickly.
- Vector Portal: Z_d has a rich low-energy phenomenology.

- Low-energy Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4}\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu} - \frac{1}{4}\widehat{D}_{\mu\nu}\widehat{D}^{\mu\nu} \boxed{- \frac{\sin\eta}{2}\widehat{B}_{\mu\nu}\widehat{D}^{\mu\nu}}$$

kinetic mixing

$$+\frac{1}{2}\widehat{M}_Z^2\,\widehat{Z}_\mu\widehat{Z}^\mu + \frac{1}{2}\widehat{M}_D^2\,\widehat{D}_\mu\widehat{D}^\mu \boxed{- \delta\,\widehat{M}_Z\widehat{M}_D\,\widehat{Z}_\mu\widehat{D}^\mu}$$

mass mixing

$$-e\,J^\mu_{\text{EM}}\widehat{A}_\mu - \frac{g}{2\cos\theta_W}\,J^\mu_{\text{NC}}\widehat{Z}_\mu$$

$$\widehat{B}_{\mu\nu} = \partial_\mu\widehat{B}_\nu - \partial_\nu\widehat{B}_\mu \quad \leftarrow U(1)_Y$$

$$\widehat{D}_{\mu\nu} = \partial_\mu\widehat{D}_\nu - \partial_\nu\widehat{D}_\mu \quad \leftarrow U(1)_d$$

$$\widehat{Z}^\mu = \cos\theta_W\,W_3^\mu - \sin\theta_W\,\widehat{B}^\mu \qquad g\sin\theta_W = g'\cos\theta_W = e$$

$$\widehat{A}^\mu = \sin\theta_W\,W_3^\mu + \cos\theta_W\,\widehat{B}^\mu \qquad \leftarrow \text{massless}$$

- Diagonalization of kinetic term: [see Babu, Kolda, March-Russell, hep-ph/9710441]

$$\widehat{B}_\mu = B_\mu - \tan\eta\, D_\mu \qquad \widehat{D}_\mu = \frac{1}{\cos\eta}\, D_\mu$$

$$\begin{aligned}\widehat{Z}^\mu = {} & \cos\theta_W W_3^\mu - \sin\theta_W B^\mu + \sin\theta_W \tan\eta D^\mu \\ & = \widetilde{Z}^\mu + \sin\theta_W \tan\eta D^\mu\end{aligned}$$

$$\begin{aligned}\widehat{A}^\mu = {} & \sin\theta_W W_3^\mu + \cos\theta_W B^\mu - \cos\theta_W \tan\eta D^\mu \\ & = A^\mu - \cos\theta_W \tan\eta D^\mu \qquad \longleftarrow \text{massless}\end{aligned}$$

- Low-energy Lagrangian:

$$
\begin{aligned}
\mathcal{L} \supset & +\frac{1}{2}\,\widehat{M}_Z^2\,\widetilde{Z}_\mu \widetilde{Z}^\mu \\
& +\frac{1}{2}\left[\frac{\widehat{M}_D^2}{\cos^2\eta} + \widehat{M}_Z^2 \sin^2\theta_W \tan^2\eta - 2\delta\,\widehat{M}_Z \widehat{M}_D \sin\theta_W \frac{\tan\eta}{\cos\eta}\right] D_\mu D^\mu \\
& \boxed{+\left[\widehat{M}_Z^2 \sin\theta_W \tan\eta - \delta\,\frac{\widehat{M}_Z \widehat{M}_D}{\cos\eta}\right] \widetilde{Z}_\mu D^\mu} \quad \text{mass mixing} \\
& -e\,J^\mu_{\text{EM}} A_\mu \\
& +e\,\cos\theta_W \tan\eta\, J^\mu_{\text{EM}} D_\mu \\
& -\frac{g}{2\cos\theta_W}\, J^\mu_{\text{NC}} \widetilde{Z}_\mu \\
& -\frac{g}{2\cos\theta_W}\, \sin\theta_W \tan\eta\, J^\mu_{\text{NC}} D_\mu
\end{aligned}
$$

- Diagonalization of mass term: [see Babu, Kolda, March-Russell, hep-ph/9710441]

$$\begin{pmatrix} \widetilde{Z}^\mu \\ D^\mu \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} Z^\mu \\ Z_d^\mu \end{pmatrix}$$

$$\tan 2\xi = \frac{-2\cos\eta \left(\widehat{M}_Z^2 \sin\theta_W \sin\eta - \delta\, \widehat{M}_Z \widehat{M}_D + \right)}{\widehat{M}_D^2 + \widehat{M}_Z^2 \left(\sin^2\theta_W \sin^2\eta - \cos^2\eta\right) - 2\delta\, \widehat{M}_Z \widehat{M}_D \sin\theta_W \sin\eta}$$

$$\widehat{M}_Z^2 = m_Z^2 \left[1 - \sin^2\xi \left(1 - \frac{m_{Z_d}}{m_Z} \right) \right]$$

- $\sin\eta, \delta \ll 1 \implies \sin\xi \simeq \dfrac{m_Z^2 \sin\theta_W \sin\eta - \delta\, m_Z m_{Z_d}}{m_Z^2 - m_{Z_d}^2}$

$$m_Z^2 \simeq \widehat{M}_Z^2 \left[1 + \sin^2\xi \left(1 - \frac{\widehat{M}_D}{\widehat{M}_Z} \right) \right]$$

$$m_{Z_d}^2 \simeq \widehat{M}_D^2 \left[1 + \sin^2\xi \left(1 - \frac{\widehat{M}_Z}{\widehat{M}_D} \right) + \sin^2\eta \left(1 + \sin^2\theta_W \frac{\widehat{M}_Z}{\widehat{M}_D} \right) - 2\delta \sin\xi \sin\theta_W \frac{m_Z}{m_{Z_d}} \right]$$

- Low-energy Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} D_{\mu\nu} D^{\mu\nu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu + \frac{1}{2} m_{Z_d}^2 Z_{d\mu} Z_d^\mu - e\, J_{\mathrm{EM}}^\mu A_\mu$$
$$- \frac{g}{2\cos\theta_W} (\cos\xi + \sin\theta_W \tan\eta \sin\xi)\, J_{\mathrm{NC}}^\mu Z_\mu$$
$$+ e\, \cos\theta_W \tan\eta \sin\xi\, J_{\mathrm{EM}}^\mu Z_\mu \qquad \leftarrow \text{quadratically suppressed}$$
$$+ e\, \cos\theta_W \tan\eta \cos\xi\, J_{\mathrm{EM}}^\mu Z_{d\mu} \qquad \leftarrow Z_d \text{ EM interactions}$$
$$- \frac{g}{2\cos\theta_W} (\sin\theta_W \tan\eta \cos\xi - \sin\xi)\, J_{\mathrm{NC}}^\mu Z_{d\mu} \qquad \leftarrow Z_d \text{ NC interactions}$$

- Common convenient definition:

$$\boxed{\mathcal{L}_{Z_d}^{\text{EM}} = -e\,\varepsilon\, J_{\text{EM}}^{\mu} Z_{d\mu}} \implies \tan\eta\cos\xi = -\frac{\varepsilon}{\cos\theta_W}$$

- Neutral-Current interaction:

$$\mathcal{L}_{Z_d}^{\text{NC}} = -\frac{g}{2\cos\theta_W}\left(-\varepsilon\tan\theta_W - \sin\xi\right) J_{\text{NC}}^{\mu} Z_{d\mu}$$

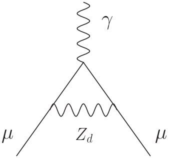
- $\sin\eta, \delta \ll 1 \Rightarrow \sin\eta \simeq -\dfrac{\varepsilon}{\cos\theta_W} \Rightarrow \sin\xi \simeq -\dfrac{m_Z^2\tan\theta_W\varepsilon + \delta\, m_Z m_{Z_d}}{m_Z^2 - m_{Z_d}^2}$

$$\boxed{\mathcal{L}_{Z_d}^{\text{NC}} = -\frac{g}{2\cos\theta_W}\frac{m_{Z_d}}{m_Z}\delta'\, J_{\text{NC}}^{\mu} Z_{d\mu}}$$

with $$\delta' \simeq \left(\delta + \frac{m_{Z_d}}{m_Z}\varepsilon\tan\theta_W\right)\left(1 - \frac{m_{Z_d}^2}{m_Z^2}\right)^{-1}$$

- $m_{Z_d} \ll m_Z \implies \boxed{\delta' \simeq \delta + \dfrac{m_{Z_d}}{m_Z}\varepsilon\tan\theta_W}$ [Davoudiasl, Lee, Marciano, arXiv:1507.00352]

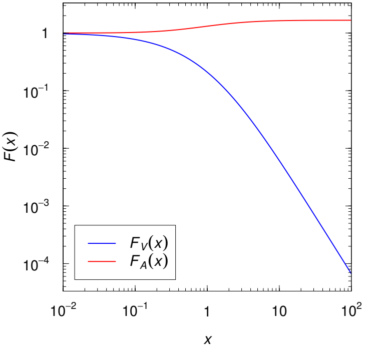
Anomalous Magnetic Moments of Charged Leptons



$$a_{\ell,V}^{Z_d} = \frac{\alpha}{2\pi} \left(\varepsilon + \frac{m_{Z_d}}{m_Z} \delta' \frac{1 - 4\sin^2\theta_W}{4\sin\theta_W \cos\theta_W} \right)^2 F_V\left(\frac{m_{Z_d}}{m_\ell}\right)$$

$$a_{\ell,A}^{Z_d} = -\frac{G_F m_\ell^2}{8\sqrt{2}\pi^2} \delta'^2 F_A\left(\frac{m_{Z_d}}{m_\ell}\right) \qquad \ell = e, \mu$$

[Boehm, Fayet, hep-ph/0305261; Pospelov, arXiv:0811.1030; Davoudiasl, Lee, Marciano, arXiv:1205.2709]



- $m_{Z_d} \ll m_Z \implies \delta'$ contribution to $a_{\ell,V}^{Z_d}$ is negligible
- $a_{\ell,V}^{Z_d}$ is suppressed for $m_{Z_d} \gg m_\ell$
- $a_{\ell,A}^{Z_d}$ is negligible:

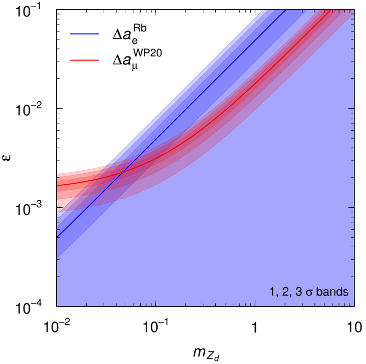
$$\frac{G_F m_\mu^2}{8\sqrt{2}\pi^2} \simeq 1.2 \times 10^{-9} \ll \frac{\alpha}{2\pi} \simeq 1.2 \times 10^{-3}$$

- Electron Anomalous Magnetic Moment: [Hanneke, Fogwell, Gabrielse, arXiv:0801.1134] [LKB20, Nature 588 (2020) 7836]

$$\Delta a_e^{\mathrm{Rb}} = a_e^{\mathrm{exp}} - a_e^{\mathrm{Rb}} = 0.48(30) \times 10^{-12} \qquad (1.6\,\sigma)$$

- Muon Anomalous Magnetic Moment: [WP20, arXiv:2006.04822] [FNAL Muon g-2, arXiv:2104.03281]

$$\Delta a_\mu^{\mathrm{WP20}} = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{WP20}} = 251(59) \times 10^{-11} \qquad (4.2\,\sigma)$$



- Positive deviations from SM can be explained by positive $a_{\ell,V}^{Z_d}$.
- Note that negative [Berkeley, arXiv:1812.04130]

$$\Delta a_e^{\mathrm{Cs}} = -0.88(36) \times 10^{-12}$$

cannot be explained by positive $a_{e,V}^{Z_d}$.

Z_d Neutral Current Interactions

At low Q^2 momentum transfer: [Davoudiasl, Lee, Marciano, arXiv:1507.00352]

- $G_F \to \rho_d \, G_F$ with $$\rho_d = 1 + \delta'^2 \, f\left(\frac{Q^2}{m_{Z_d}^2}\right) = 1 + \left(\delta + \frac{m_{Z_d}}{m_Z} \varepsilon \tan\theta_W\right)^2 f\left(\frac{Q^2}{m_{Z_d}^2}\right)$$
- $\sin^2\theta_W(Q^2) \to \kappa_d \sin^2\theta_W(Q^2)$ with

$$\kappa_d = 1 - \varepsilon \, \delta' \, \frac{m_{Z_d}}{m_Z} \cot\theta_W \, f\left(\frac{Q^2}{m_{Z_d}^2}\right)$$

$$= 1 - \varepsilon \left(\delta + \frac{m_{Z_d}}{m_Z} \varepsilon \tan\theta_W\right) \frac{m_Z}{m_{Z_d}} \cot\theta_W \, f\left(\frac{Q^2}{m_{Z_d}^2}\right)$$

$$\simeq 1 - \varepsilon \, \delta \, \frac{m_Z}{m_{Z_d}} \cot\theta_W \, f\left(\frac{Q^2}{m_{Z_d}^2}\right)$$ ← dominant for $m_{Z_d} \ll m_Z$

We consider the low-energy Neutral Current measurements:

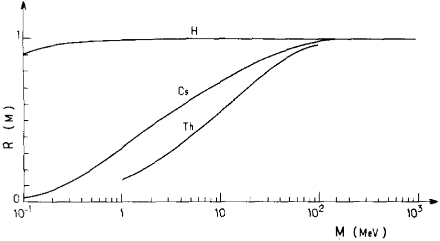
- $\mathrm{Q_{weak}}$ measurement of proton weak charge Q_W^p at $Q^2 = (157\,\mathrm{MeV})^2$:

$$f\left(\frac{Q^2}{m_{Z_d}^2}\right) = \frac{m_{Z_d}^2}{m_{Z_d}^2 + Q^2} \to \begin{cases} 1 & \text{for } m_{Z_d}^2 \gg Q^2 \\ 0 & \text{for } m_{Z_d}^2 \ll Q^2 \end{cases}$$

- APV (Atomic Parity Violation) measurement of the $^{133}\mathrm{Cs}$ weak charge $Q_W^{^{133}\mathrm{Cs}}$ at $Q^2 \approx (2.4\,\mathrm{MeV})^2$:

$$f\left(\frac{Q^2}{m_{Z_d}^2}\right) = R(m_{Z_d})$$

nuclear structure effect



[Bouchiat, Piketty, PLB 128 (1983) 73]
[see also Bouchiat, Fayet, hep-ph/0410260]

- Then, the dominant effect of κ_d to $\sin^2\theta_W(Q^2)$ is maximal at

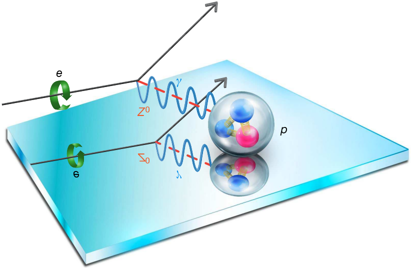
$$m_{Z_d}^2 \simeq Q^2$$

Q_{weak} Proton Weak Charge Measurement

[arXiv:1905.08283]

Parity-violating asymmetry in the scattering of polarized electrons on protons:

$$A_{ep} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} Q_W^p$$



$$\boxed{Q_W^{p,\text{exp}} = 0.0719\,(45)}$$

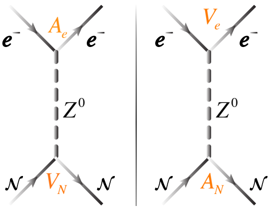
$$\boxed{Q_W^{p,\text{SM}} = -2\,g_{AV}^{ep}(\sin^2\theta_W)\left(1 - \frac{\alpha}{2\pi}\right) = 0.0711\,(2)}$$

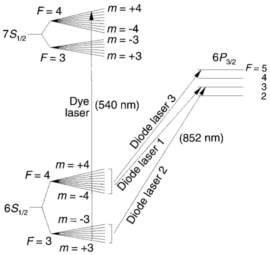
$$g_{AV}^{ep}(\sin^2\theta_W) = -0.0357 \approx -\frac{1}{2} + 2\sin^2\theta_W$$

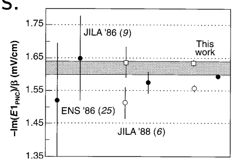
$$\boxed{Q_W^{p,Z_d} = -2\,\rho_d\,g_{AV}^{ep}(\kappa_d \sin^2\theta_W)\left(1 - \frac{\alpha}{2\pi}\right)}$$

Atomic Parity Violation

- Amplitude of the Parity Non-Conserving (PNC) transition between the 6S and 7S states of Cesium.
- Why Cesium? The atomic structure is the most accurately known (1%): a single valence electron outside of a tightly bound Xe-like inner core.
- Electric-dipole (E1) transitions are forbidden between the equal-parity 6S and 7S states.
- Parity-violating NC electron-nucleus interactions generate a very small ($\sim 10^{-11}$) admixture of states with opposite parity: 6P states mix with 6S and with 7S states, leading to very small E1 transitions.







$$\frac{\mathrm{Im}\,E_{\mathrm{PNC}}}{\beta} = -21.5935\,(56)\ \mathrm{mV/cm}$$

[Boulder, Wood et al, Science 275 (1997) 1759]

β: Stark vector transition polarizability

$$Q_W^{^{133}\mathrm{Cs,exp}} = N_{^{133}\mathrm{Cs}} \left(\frac{\mathrm{Im}\,E_{\mathrm{PNC}}}{\beta}\right)_{\mathrm{exp}} \left(\frac{Q_W^{^{133}\mathrm{Cs}}}{N_{^{133}\mathrm{Cs}}\mathrm{Im}\,E_{\mathrm{PNC}}(R_n)}\right)_{\mathrm{th}} \beta_{\mathrm{exp+th}}$$

$N_{^{133}\mathrm{Cs}} = 78$ neutron number of $^{133}\mathrm{Cs}$

$$\left(\frac{\mathrm{Im}\,E_{\mathrm{PNC}}}{\beta}\right)_{\mathrm{exp}} = -1.5924 \pm 0.0055\,\mathrm{mV/cm}$$

$$= (-3.0967 \pm 0.0107) \times 10^{-13}\, e/a_B^2$$

[Boulder + physics/0412017]

$$\beta_{\mathrm{exp+th}} = (27.064 \pm 0.033)\, a_B^3$$

[hep-ph/0204134 + 1905.02768]

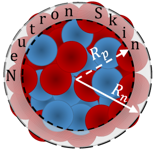
[PDG 2020]

Without neutron skin of $^{133}\mathrm{Cs}$ (i.e $R_n = R_p$):

$$\left(\frac{N_{^{133}\mathrm{Cs}}\mathrm{Im}\,E_{\mathrm{PNC}}(R_n)}{Q_W^{^{133}\mathrm{Cs}}}\right)_{\mathrm{th}}^{\mathrm{w.n.s.}} = (0.8995 \pm 0.0040) \times 10^{-11}\, e\, a_B$$

[Dzuba, Berengut, Flambaum, Roberts, arXiv:1207.5864]

- Neutron skin: $\Delta R_{np} \equiv R_n - R_p$.



- Previous determinations of $Q_W^{^{133}\text{Cs,exp}}$ used the value of $\Delta R_{np}(^{133}\text{Cs})$ given by the empirical relation obtained from the fit of hadronic measurements:

$$\Delta R_{np}^{\text{had}} = (-0.04 \pm 0.03) + (1.01 \pm 0.15)\,\frac{N - Z}{A}\,\text{fm}$$

- This gives $\Delta R_{np}^{\text{had}}(^{133}\text{Cs}) = 0.13 \pm 0.04\,\text{fm}$

- $R_p(^{133}\text{Cs}) = 4.807 \pm 0.001\,\text{fm} \implies R_n^{\text{had}}(^{133}\text{Cs}) = 4.94 \pm 0.04\,\text{fm}$

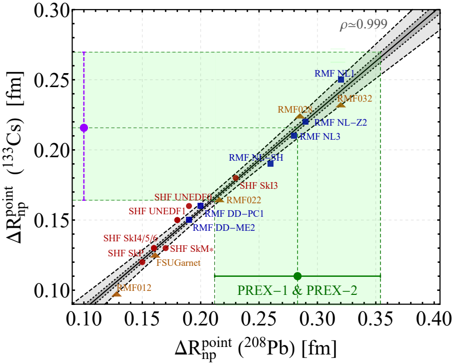
- This hadronic determination of ΔR_{np} is affected by considerable model dependencies and uncontrolled approximations

[see: Thiel, Sfienti, Piekarewicz, Horowitz, Vanderhaeghen, arXiv:1904.12269]

- This determination of $R_n(^{133}\text{Cs})$ gives $Q_W^{^{133}\text{Cs,exp}} = -72.82 \pm 0.42$

[PDG 2020]

- We determined $\Delta R_{np}^{\text{had}}(^{133}\text{Cs})$ in a practically model-independent way by extrapolating the recent measurement of $\Delta R_{np}^{\text{had}}(^{208}\text{Pb})$ of the PREX-1 and PREX-2 experiments [arXiv:1202.1468; arXiv:2102.10767]
- The PREX measurements of $\Delta R_{np}^{\text{had}}(^{208}\text{Pb})$ are robust because done with parity-violating electron scattering due to neutral-current weak interactions.



$$\frac{\Delta R_{np}^{\text{point}}(^{133}\text{Cs})}{\Delta R_{np}^{\text{point}}(^{208}\text{Pb})} \simeq 0.71 \pm 0.02$$

$$\frac{[(N-Z)/A]_{^{133}\text{Cs}}}{[(N-Z)/A]_{^{208}\text{Pb}}} \simeq 0.8$$

$$\Delta R_{np}^{\text{point}}(^{208}\text{Pb}) = 0.283 \pm 0.071 \text{ fm}$$

$$\Downarrow$$

$$\Delta R_{np}^{\text{point}}(^{133}\text{Cs}) = 0.22 \pm 0.05 \text{ fm}$$

$$\Downarrow$$

$$R_n(^{133}\text{Cs}) = 5.03 \pm 0.05 \text{ fm}$$

$$\Downarrow$$

$$Q_W^{^{133}\text{Cs,exp}} = -72.94 \pm 0.43$$

$$Q_W^{^{133}\text{Cs,exp}} = -72.94 \pm 0.43$$

$$Q_W^{^{133}\text{Cs,SM}} = -2\Big[Z_{^{133}\text{Cs}} \left(g_{AV}^{ep}(\sin^2\theta_W) + 0.00005\right) + N_{^{133}\text{Cs}} \left(g_{AV}^{en} + 0.00006\right)\Big] \left(1 - \frac{\alpha}{2\pi}\right)$$

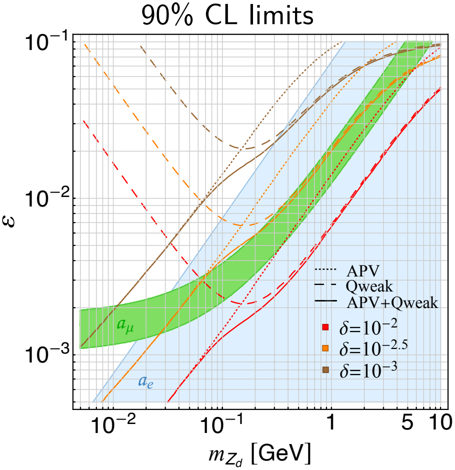
$$Z_{^{133}\text{Cs}} = 55 \qquad g_{AV}^{ep}(\sin^2\theta_W) = -0.0357 \approx -\frac{1}{2} + 2\sin^2\theta_W$$

$$N_{^{133}\text{Cs}} = 78 \qquad g_{AV}^{en} = 0.495 \approx \frac{1}{2}$$

$$Q_W^{^{133}\text{Cs,SM}} = -73.23 \pm 0.01$$

[PDG 2020]

$$Q_W^{^{133}\text{Cs},Z_d} = -2\,\rho_d\Big[Z_{^{133}\text{Cs}} \left(g_{AV}^{ep}(\kappa_d \sin^2\theta_W) + 0.00005\right) + N_{^{133}\text{Cs}} \left(g_{AV}^{en} + 0.00006\right)\Big] \left(1 - \frac{\alpha}{2\pi}\right)$$



- $$\chi_i^2 = \frac{\left[X_i^{\text{exp}} - X_i^{\text{th}}(\varepsilon, \delta, m_{Z_d})\right]^2}{\sigma_i^2}$$

  $$X_i^{\text{exp}} = a_\mu^{\text{exp}},\ a_e^{\text{exp}},\ Q_W^{p,\text{exp}},\ Q_W^{^{133}\text{Cs},\text{exp}}$$

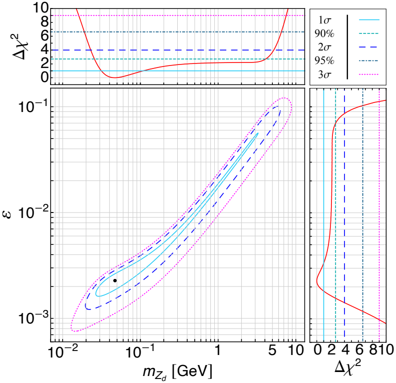
  $$X_i^{\text{th}} = a_\mu^{Z_d},\ a_e^{Z_d},\ Q_W^{p,Z_d},\ Q_W^{^{133}\text{Cs},Z_d}$$

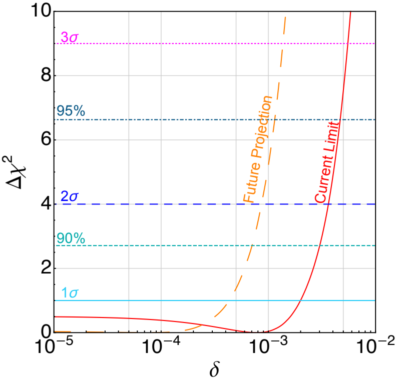
- $Q^2(\text{Q}_{\text{weak}}) = (157\,\text{MeV})^2$

  $Q^2(\text{APV}) \approx (2.4\,\text{MeV})^2$

- Q_{weak} and APV constraints depend strongly on δ

- For $\delta > 10^{-2}$ the Z_d explanation of a_μ^{exp} is disfavored by APV and more strongly by Q_{weak} + APV

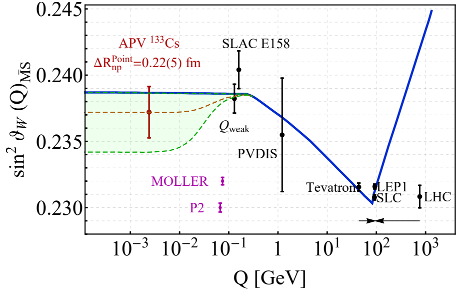




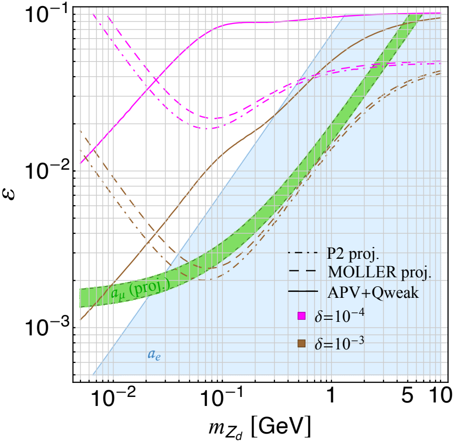
$$m_{Z_d} = 47^{+61}_{-16}\ \text{MeV}$$

$$\varepsilon = 2.3^{+1.1}_{-0.4} \times 10^{-3}$$

$$\delta < 2 \times 10^{-3}$$



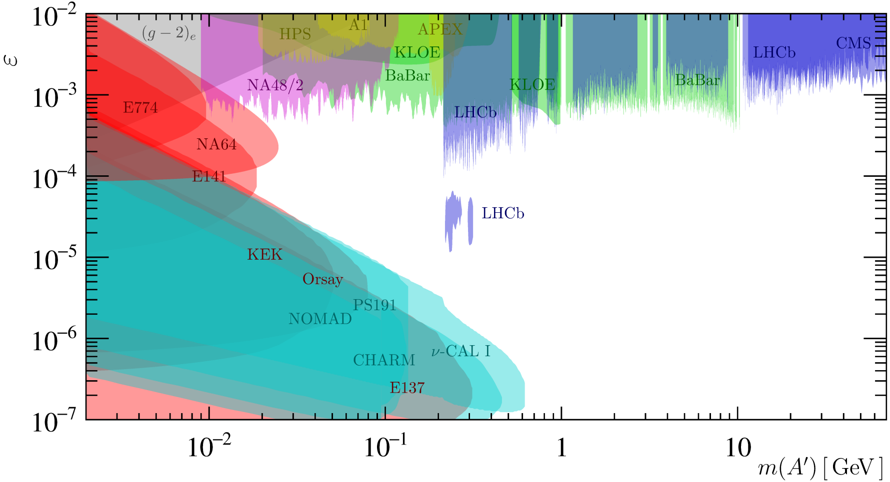
Future prospects



- MOLLER@JLab: Measurement Of a Lepton Lepton Electroweak Reaction [arXiv:1411.4088]
  Precise measurement ($\approx \pm 3 \times 10^{-4}$) of $\sin^2\theta_W$ at $Q^2 \approx (70\,\text{MeV})^2$ with parity-violating asymmetry in polarized electron-electron (Møller) scattering (Q_W^e)

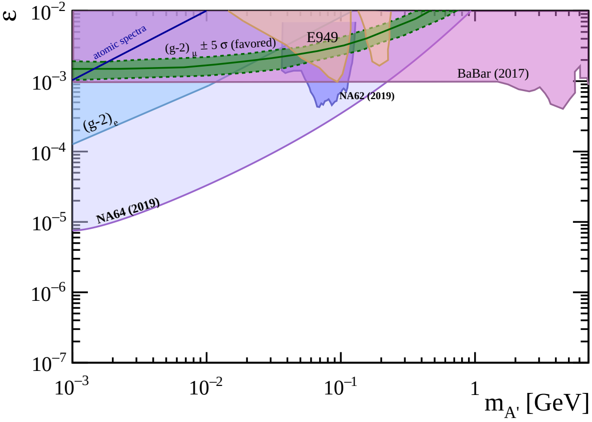
- P2@MESA (Mainz): [arXiv:1802.04759]
  Precise measurement ($\approx \pm 3 \times 10^{-4}$) of $\sin^2\theta_W$ at $Q^2 \approx (70\,\text{MeV})^2$ with parity-violating asymmetry in polarized electron-proton scattering (Q_W^p)

Dark Photon Constraints

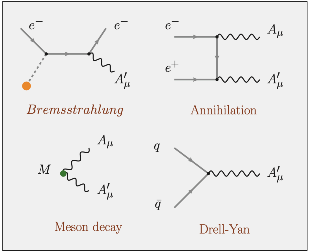


Constraints on visible A' decays from electron beam dumps, proton beam dumps, e^+e^- colliders, pp collisions, meson decays, and electron on fixed target experiments.

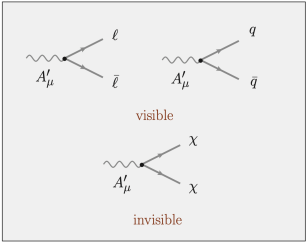
[Graham, Hearty, Williams, arXiv:2104.10280, adapted from Ilten, Soreq, Williams, Xue, arXiv:1801.04847]



Production



Decay

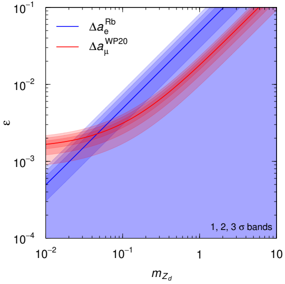


Constraints on invisible A' decays

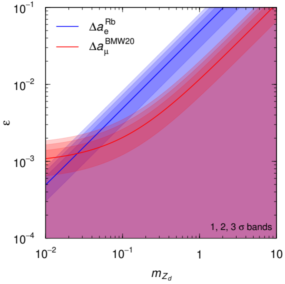
[Fabbrichesi, Gabrielli, Lanfranchi, arXiv:2005.01515]

$(g-2)_\mu$ What Ifs

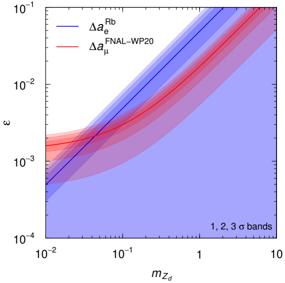
Standard FNAL+BNL – WP20



FNAL+BNL – BMW20



FNAL – WP20



$$\Delta a_\mu^{\text{WP20}} = 251 \pm 59 \quad (4.2\,\sigma)$$

$$\Delta a_\mu^{\text{BMW20}} = 107 \pm 69 \quad (1.6\,\sigma)$$

$$\Delta a_\mu^{\text{FNAL-WP20}} = 230 \pm 69 \quad (3.3\,\sigma)$$

[WP20, arXiv:2006.04822]
[FNAL Muon g-2, arXiv:2104.03281]
[BMW20, Borsanyi et al, arXiv:2002.12347]

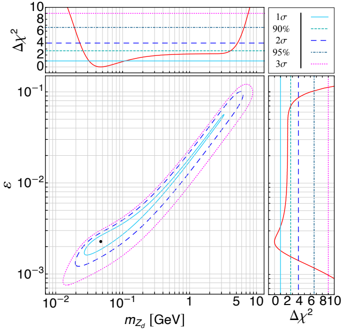
Conclusions

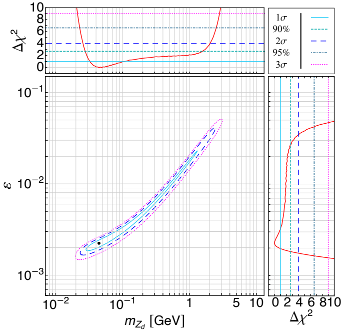
- A light Dark Z_d is an attractive Vector Portal to the Dark Sector.
- Z_d couples with the EM current J^μ_{EM} and the weak NC J^μ_{NC}
- 3 parameters: ε (kinetic mixing), δ (mass mixing), and m_{Z_d}
- Z_d effects are observable in low-Q^2 processes
- Z_d can explain positive lepton $g-2$ anomalies
- We considered the low-energy NC constraints from
  - Q_{weak} measurement of proton weak charge Q_W^p at $Q^2 = (157\,\text{MeV})^2$
  - APV measurement of the ^{133}Cs weak charge $Q_W^{^{133}\text{Cs}}$ at $Q^2 = (157\,\text{MeV})^2$
- We found a preferred region at

$$m_{Z_d} = 47^{+61}_{-16}\,\text{MeV}, \quad \varepsilon = 2.3^{+1.1}_{-0.4} \times 10^{-3}, \quad \delta < 2 \times 10^{-3}$$

- Dark-photon-like constraints from other experiments need further study.

Extra Slides





- Present: combined fit of Q_{weak}, APV, a_e, and a_μ experimental results:

$$m_{Z_d} = 47^{+61}_{-16}\ \text{MeV}$$

$$\varepsilon = 2.3^{+1.1}_{-0.4} \times 10^{-3}$$

$$\delta < 2 \times 10^{-3}$$

- Future: combined fit of Q_{weak}, APV, and a_e experimental results, the projections for P2 and MOLLER, and future a_μ expected sensitivity:

$$m_{Z_d} = 44^{+63}_{-12}\ \text{MeV}$$

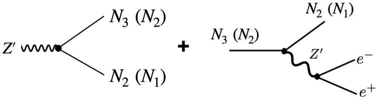
$$\varepsilon = 2.2^{+1.0}_{-0.3} \times 10^{-3}$$

$$\delta < 4 \times 10^{-4}$$

Revised constraints on semi-visible DP

Scenario 3: Heavy Neutral Leptons ($Z' \to N_1 N_2$ AND $Z' \to N_3 N_2$)

AA, M.Hostert, S.Pascoli
arXiv: 2007.11813

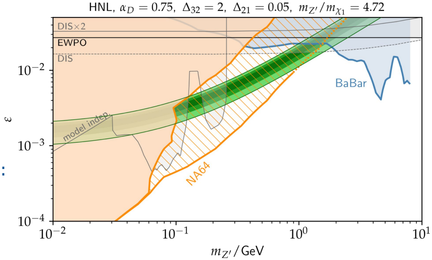


Pair of dark fermions + 1 sterile neutrino:

1) **Approximate L ↔ R symmetry** suppresses diagonal couplings

2) Compatible with light neutrino masses

3) Possible solution to other anomalies (e.g. MiniBooNe)



Possibility of opening up large regions of (g-2) parameter space!

Note: subject to NA64 analysis efficiencies

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[Asli M. Abdullahi @ Invisibles21 Workshop]

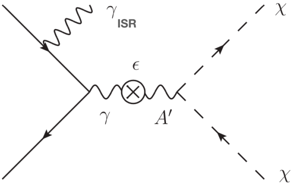
Dark Photon at Belle II

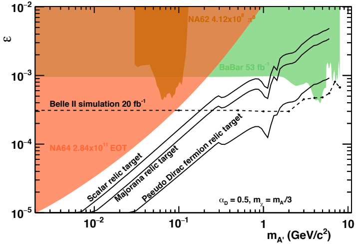
What?

- Dark sector mediator which couples to SM photon

How?

- Belle II looks into $e^+e^- \to \gamma_{ISR}\ A';\ \ A' \to \chi\chi$
- Final state: Single γ + Missing Energy
- $m^2_{A'} = 4E^*_{beam}(E^*_{beam} - E^*_{\gamma_{ISR}})$; Easy to find A' mass
- Newly designed trigger allows sensitivity down to 0.5 GeV of single photon



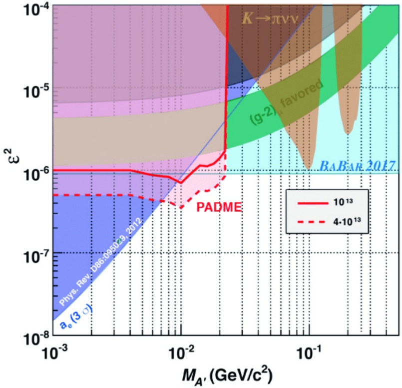


Based on M. Graham, C. Hearty, M. Williams, Annu. Rev. Nucl. Part. Sci. 2021. 71:37

[Miho Wakai @ Invisibles21 Workshop]

Physics goals

- Dark photons: $e^+e^- \to \gamma A'$
  - Final states:
    - Visible $A' \to e^+e^-$
    - Invisible $A' \to \chi\chi$



[Elizabeth Long @ Invisibles21 Workshop]