# Dark $Z$ and New Parity Violating Processes

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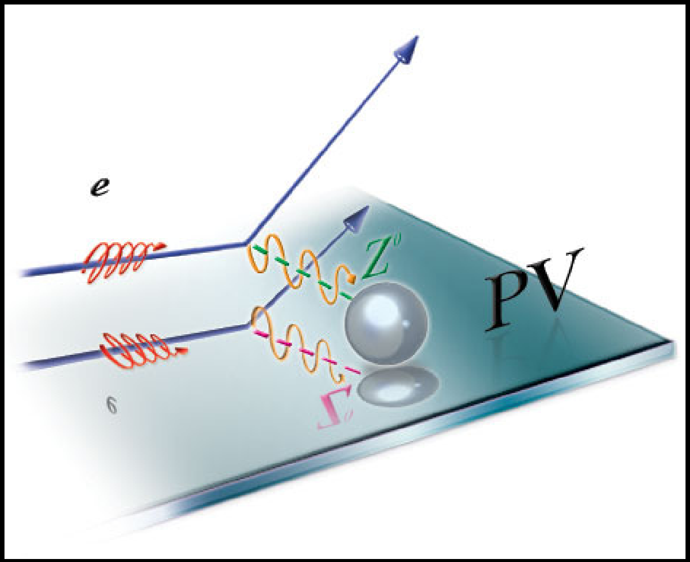


INT 22-81W: “Parity-Violation and other Electroweak Physics at JLab 12 GeV and Beyond”

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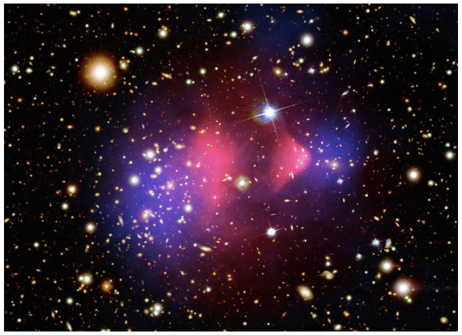
# Twilight of WIMPs?



- Dark matter (DM): a mystery
  - Comprises $\sim 27\%$ of cosmic energy density
  - Substance with feeble coupling to visible matter
  - One of the strongest motivations for new physics

- Longstanding DM candidate: weakly interacting massive particles (WIMPs)
  - Masses $\sim 1$ TeV and couplings $\sim 1$
  - Correct typical annihilation cross section for thermal relic DM
  - Fits in with solutions to the *hierarchy problem* (why weak scale $\ll M_P$?)

- However, no beyond SM evidence after $\sim 140$ fb$^{-1}$ of LHC data

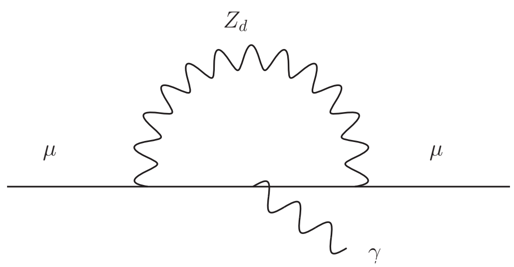
- Perhaps DM could be lighter, from a dark sector
  - No direct coupling to SM
  - Feeble interactions with visible sector: probed by intense sources
  - Analogy with SM: dark sector may contain matter and forces

# Example of a Dark Sector

- Minimal scenario: dark $U(1)_d$ force (dark photon/$Z$)
- Mediated by vector boson $Z_d$ with coupling $g_d$
- Interaction with SM via kinetic and mass mixing
- Could allow DM interpretation of some astrophysical data

Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- Signals in rare meson decays, dark parity violation, rare Higgs decays, . . .
- May have a role in explaining potential anomalies in $g-2$ of the electron or muon



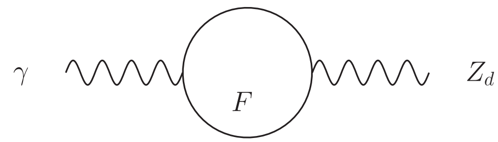
# Dark Photon

- Kinetic mixing: $Z_{d\mu}$ of $U(1)_d$ and $B_\mu$ of SM $U(1)_Y$ Holdom, 1986

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}\mathbf{B}_{\mu\nu}\mathbf{Z}_d^{\mu\nu} - \frac{1}{4}\mathbf{Z}_{d\mu\nu}\mathbf{Z}_d^{\mu\nu}$$

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$

  - May be loop induced: $\varepsilon \sim e g_d/(4\pi)^2 \lesssim 10^{-3}$




- Remove cross term, via field redefinition
  - $B_\mu \to B_\mu + \frac{\varepsilon}{\cos\theta_W} Z_{d\mu}$
  - $Z$-$Z_d$ mass matrix digonalization

- After redefinition, $Z_d$ couples to EM current $J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$

$$\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$$

  - Like a photon, but $\varepsilon$-suppressed couplings: "dark" photon

- Neutral current coupling suppressed further by $O(m_{Z_d}/m_Z) \ll 1$

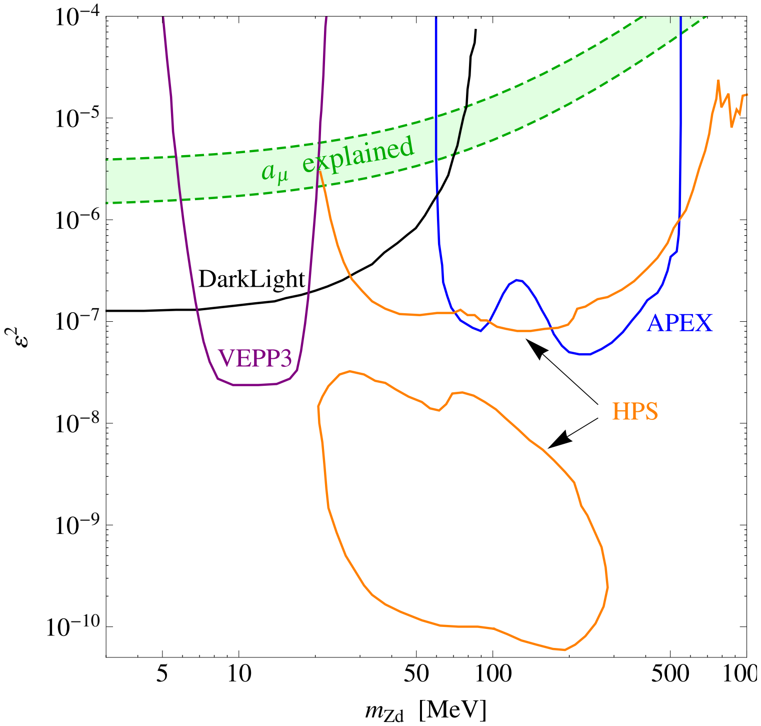
- Active experimental program to search for dark photon

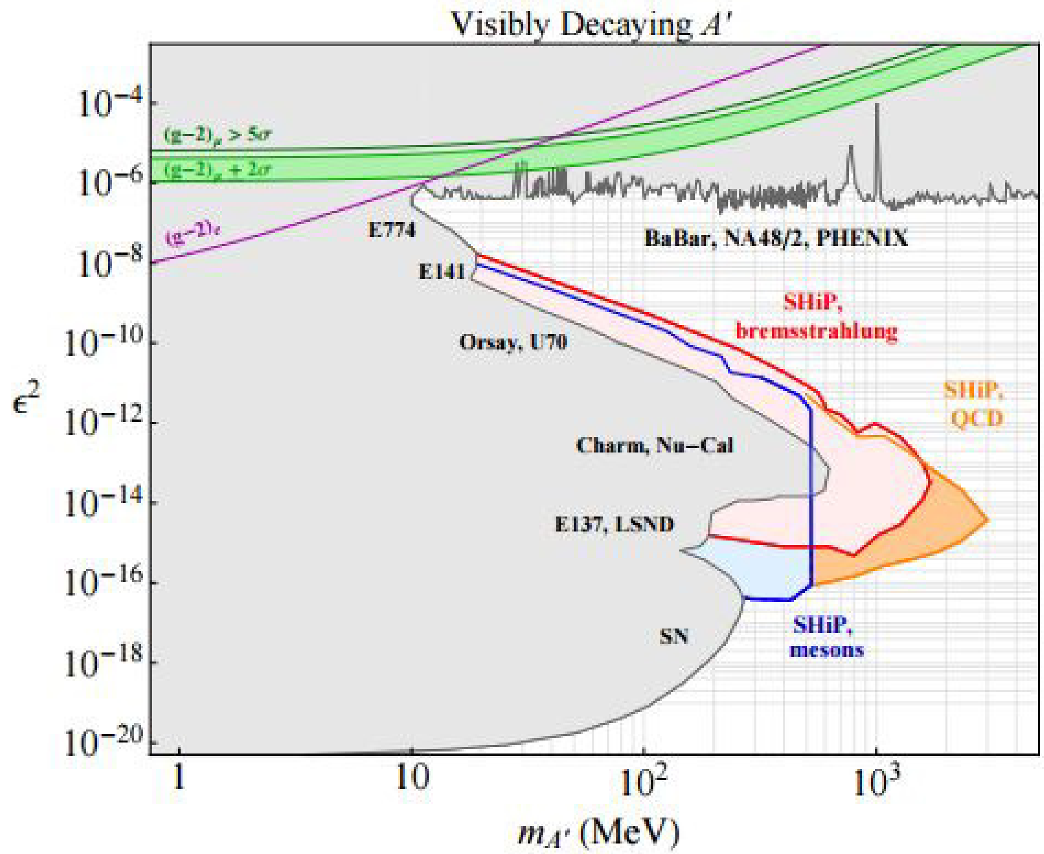
Pioneering work by Bjorken, Essig, Schuster, Toro, 2009

- An early experimental target: $g_\mu - 2$ parameter space

Fayet, 2007 (direct coupling)  Pospelov, 2008 (kinetic mixing)

Future Prospects



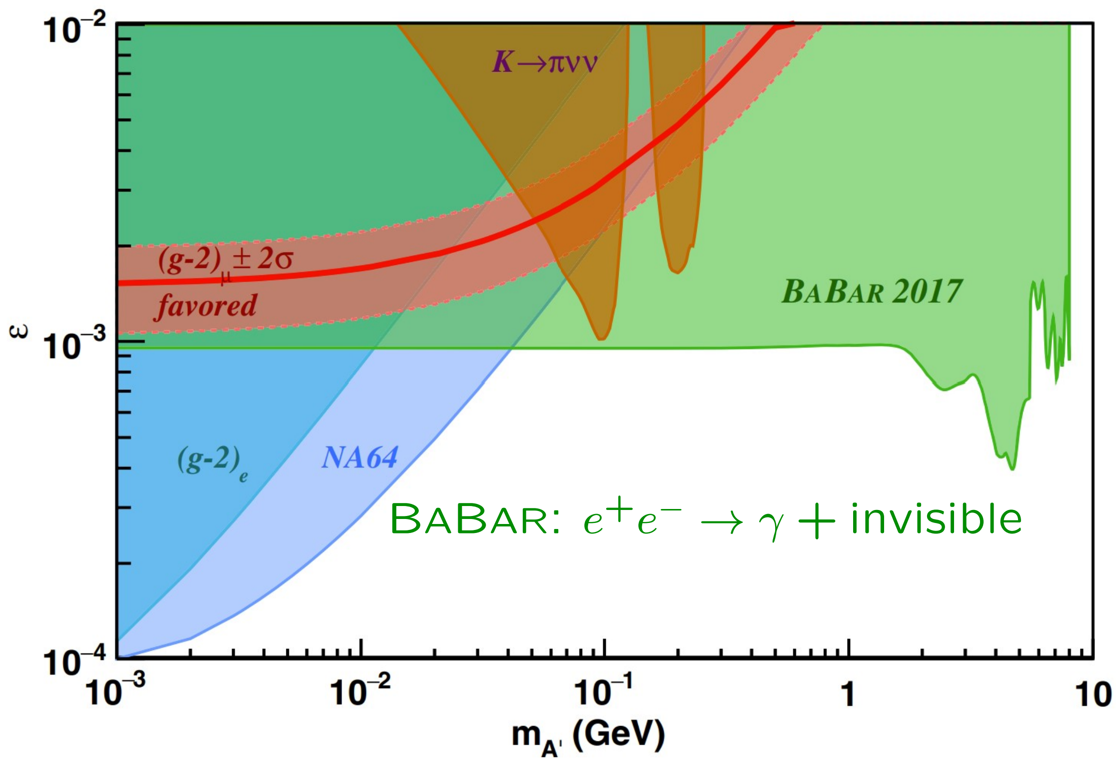




S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

Visibly decaying $Z_d$ nearly ruled out as $g_\mu - 2$ explanation

# "Invisible" Dark Photon

- $\exists$ dark $X$ with $m_X < m_{Z_d}/2$ and $Q_d g_d \gg e\varepsilon \Rightarrow$ Br$(Z_d \to X\bar{X}) \simeq 1$




90% CL bound from BABAR Collaboration, Phys.Rev.Lett. 119 (2017) 13, 131804; 1702.03327

GeV-scale "invisible" dark photon $g_\mu - 2$ solution ruled out

- Possible loop hole: semi-visible decays

Mohlabeng, Phys.Rev.D 99 (2019) 11, 115001; 1902.05075

- Possible production and detection of *DM beams* in experiments

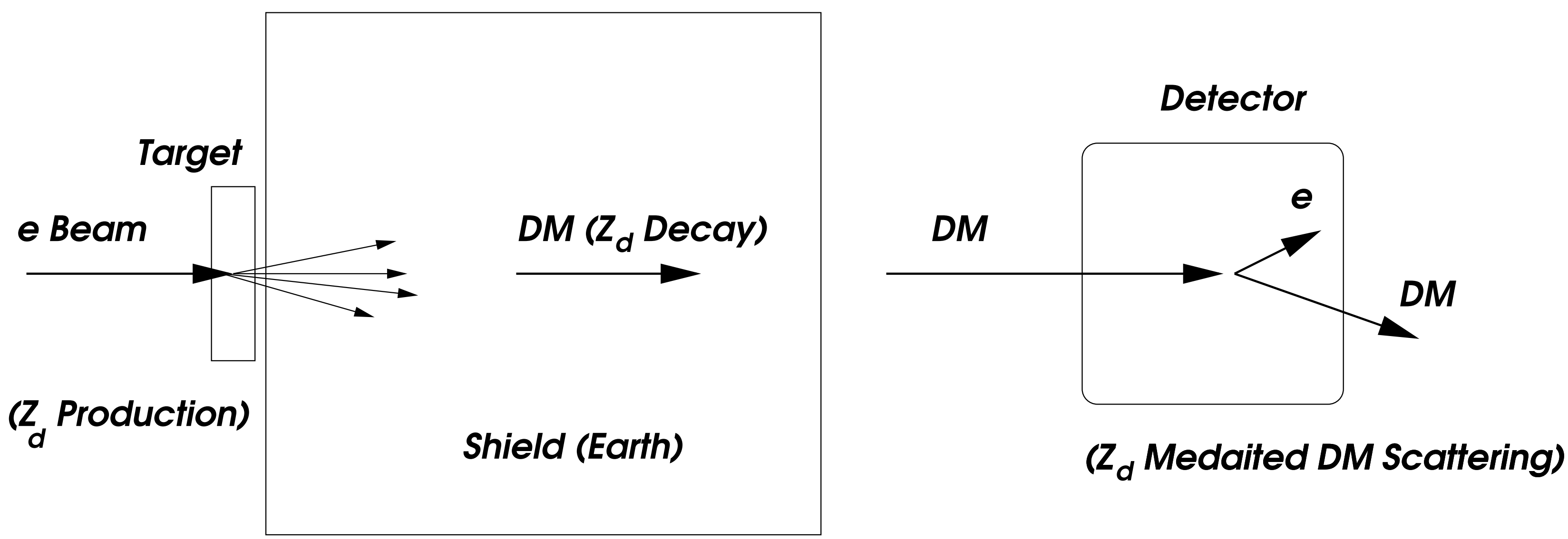
- $p$ or $e$ on fixed target $\Rightarrow$ production of $Z_d$ (meson decays, bremsstrahlung,...)

Batell, Pospelov, Ritz, 2009 ($p$ beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 ($e$ beam dump)

- Relativistic $Z_d$ beam decays into DM particles

- DM interactions with detector via $Z_d$ exchange

*Example*:



# Dark $Z$

HD, Lee, Marciano, 1203.2947

- $Z_d$ may also have mass mixing with SM $Z$

$$M_0^2 = m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z_d}^2/m_Z^2 \end{pmatrix}$$

$$\boxed{\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta}$$

$\delta \ll 1$ a model-dependent parameter

- $M_0$ leads to $Z$-$Z_d$ mixing angle $\xi$ given by: $\tan 2\xi \simeq 2\frac{m_{Z_d}}{m_Z}\delta = 2\varepsilon_Z$
- Induced interactions with kinetic and mass mixing

$$\mathcal{L}_{\text{int}} = \left(-e\varepsilon J_\mu^{em} - \frac{g}{2\cos\theta_W}\varepsilon_Z J_\mu^{NC}\right) Z_d^\mu$$

$J_\mu^{NC} = \sum_f (T_{3f} - 2Q_f \sin^2\theta_W)\bar{f}\gamma_\mu f - T_{3f}\bar{f}\gamma_\mu\gamma_5 f$ ; $T_{3f} = \pm 1/2$ and $\sin^2\theta_W \simeq 0.23$

- Neutral current coupling of $Z_d$ like a $Z$, suppressed by $\varepsilon_Z$: "dark" $Z$

*Notation: $Z_d$ dark photon or dark $Z$, depending on the context*

# A Concrete Dark $Z$ Model

- Mass mixing can naturally occur in a 2HDM

- Type I 2HDM: $H_1$ and $H_2$, where only $H_1$ has $Q_d \neq 0$
  - $U(1)_d$ as protective symmetry for FCNCs instead of the usual $\mathbb{Z}_2$
  - SM fermions only couple to $H_2$ (SM-like); $\langle H_i \rangle = v_i$
  - Generally, also a dark sector Higgs particle $\phi$ with $\langle \phi \rangle = v_d$

$$m_Z \simeq \frac{g}{2\cos\theta_W}\sqrt{v_1^2 + v_2^2} \quad \text{and} \quad m_{Z_d} \simeq g_d Q_d \sqrt{v_d^2 + v_1^2}$$

- With $\tan\beta = v_2/v_1$ and $\tan\beta_d = v_d/v_1$ we get

$$\varepsilon_Z \simeq (m_{Z_d}/m_Z)\cos\beta\cos\beta_d \Rightarrow \delta \simeq \cos\beta\cos\beta_d$$

- $H_1$ has $Q_Y Q_d \neq 0$ $\rightarrow$ generally also expect kinetic mixing

# Dark $Z$ Phenomenology

HD, Lee, Marciano, 2012

- "Dark" parity violation [independent of $\mathrm{Br}(\mathrm{Z_d} \to \mathrm{visible})$]

Polarized electron scattering, atomic parity violation, . . .

- Flavor physics ($m_{Z_d} < m_{\mathrm{meson}}$)

- Longitudinal $Z_d$ enhancement $\sim E/m_{Z_d}$

$\{\mathrm{Br}(\mathrm{K}^+ \to \pi^+ \mathrm{Z_d})_{\mathrm{long}} \simeq 4 \times 10^{-4}\delta^2 \quad ; \quad \mathrm{Br}(\mathrm{B} \to \mathrm{K Z_d})_{\mathrm{long}} \simeq 0.1\delta^2\} \to |\delta| \lesssim 5 \times 10^{-4}$

PDG 2022

\- Depending on visible branching fraction of $Z_d$

- Rare Higgs decays, *e.g.* $H \to Z Z_d$ ($m_{Z_d} \ll m_Z$, on-shell $Z_d$)

- In 2HDM realization there could be other signals

- Dominant $H^\pm \to W^\pm Z_d$ (tree-level) for $m_{H^\pm} \lesssim m_t$

HD, Marciano, Ramos, Sher, 2014

Lee, Kong, Park, 2014

# Dark $Z$ and Parity Violation

- Low $Q^2$ ($< m_{Z_d}^2$) parity violation from $Z - Z_d$ mixing

- $Z_d$ effects can be parameterized by    HD, Lee, Marciano, 2012

$$G_F \to \rho_d G_F \quad \text{and} \quad \sin^2\theta_W \to \kappa_d \sin^2\theta_W$$

$$\text{with } \rho_d = 1 + \delta^2 \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2} \quad \text{and} \quad \kappa_d = 1 - \varepsilon\delta \frac{m_Z}{m_{Z_d}} \frac{\cos\theta_W}{\sin\theta_W} \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$$

- $\kappa_d$ effect enhanced for $m_{Z_d} \ll m_Z$

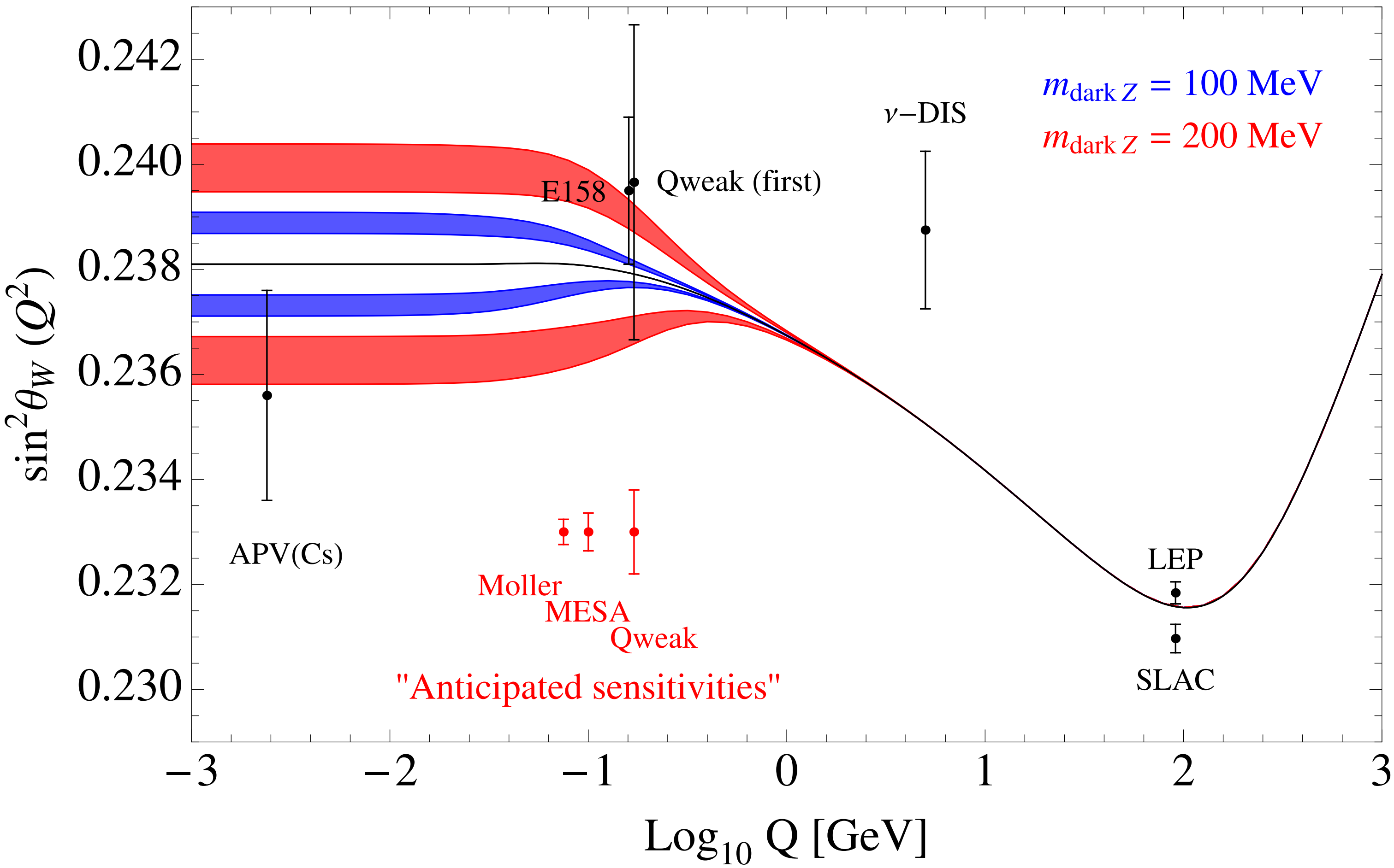
- Leads to variation of $\sin^2\theta_W$ with $Q^2$:

$$\boxed{\Delta \sin^2\theta_W(Q^2) = -\varepsilon\delta \frac{m_Z}{m_{Z_d}} \sin\theta_W \cos\theta_W f\left(Q^2/m_{Z_d}^2\right)}$$

$f\left(Q^2/m_{Z_d}^2\right) = 1/(1 + Q^2/m_{Z_d}^2)$

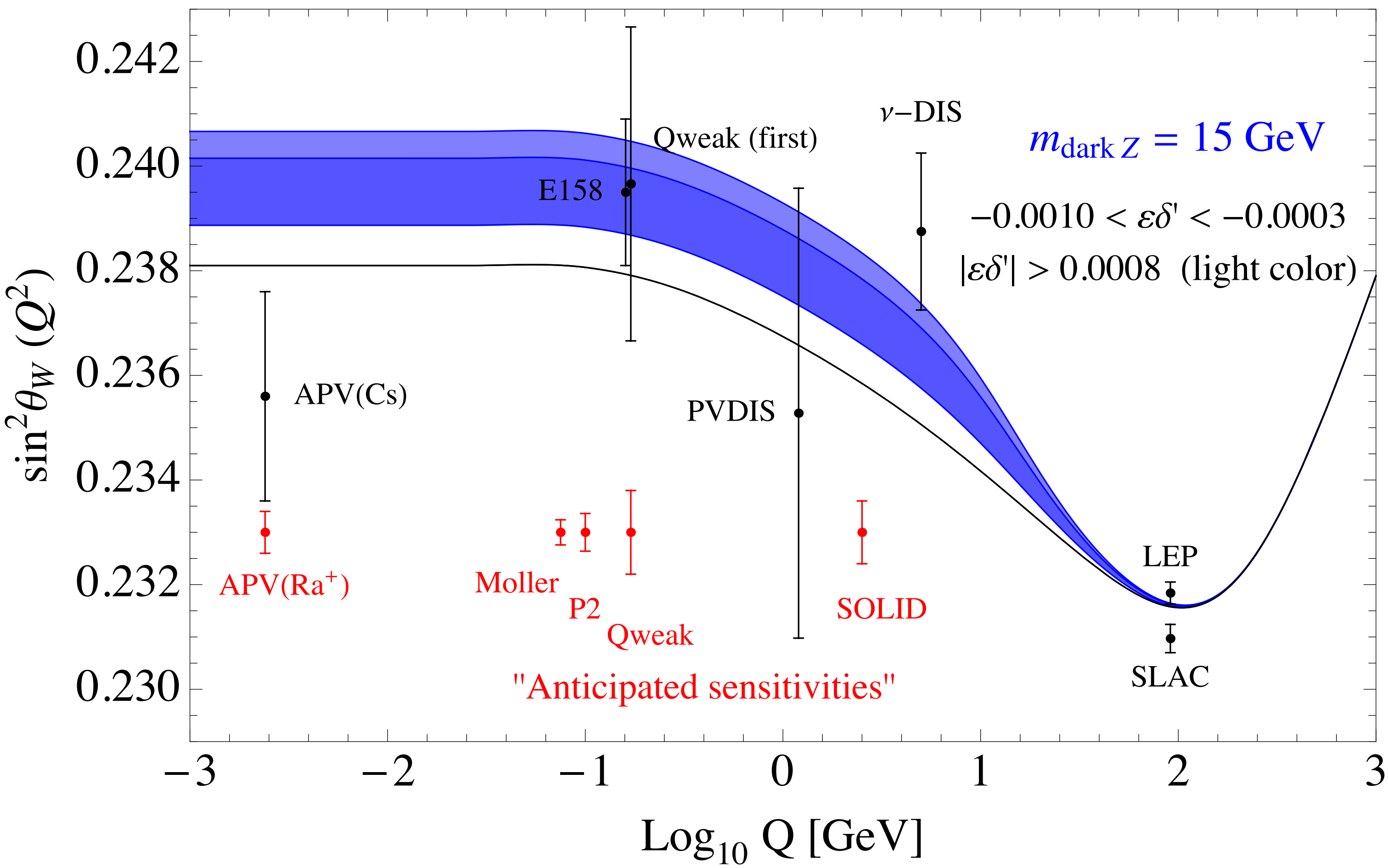
# Running of $\sin^2\theta_W$ with $Q^2$

From HD, Lee, Marciano, Phys. Rev. D **89**, no. 9, 095006 (2014)




- Black curve: SM running   Marciano, Sirlin, 1981; Czarnecki, Marciano, 1996
- $Z_d$ parameters: $|\varepsilon| \sim |\delta| \sim$ few $\times\, 10^{-3}$   (for $g_\mu - 2$)
- Two branches corresponding to $\varepsilon\delta$ sign ambiguity ($\Delta\sin^2\theta_W \propto \varepsilon\delta$)

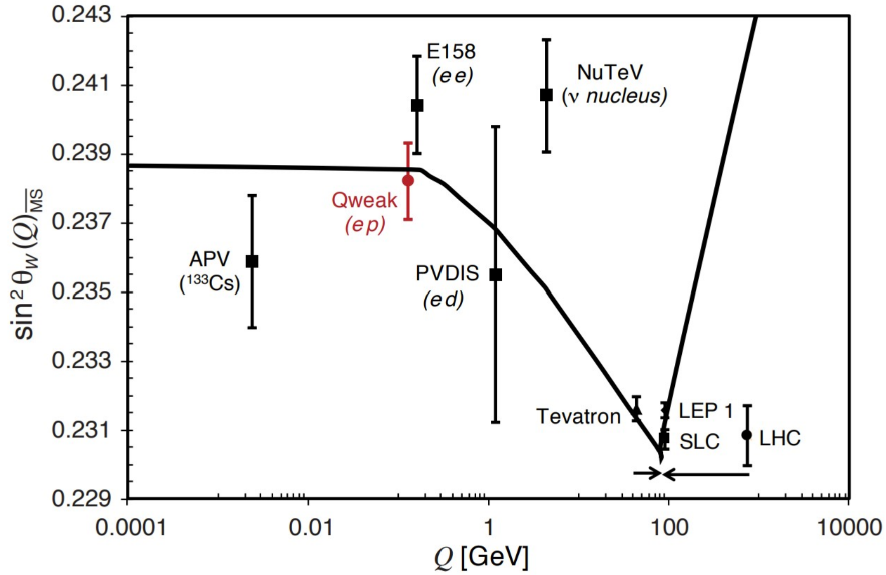
From HD, Lee, Marciano, Phys. Rev. D **92**, no. 5, 055005 (2015)



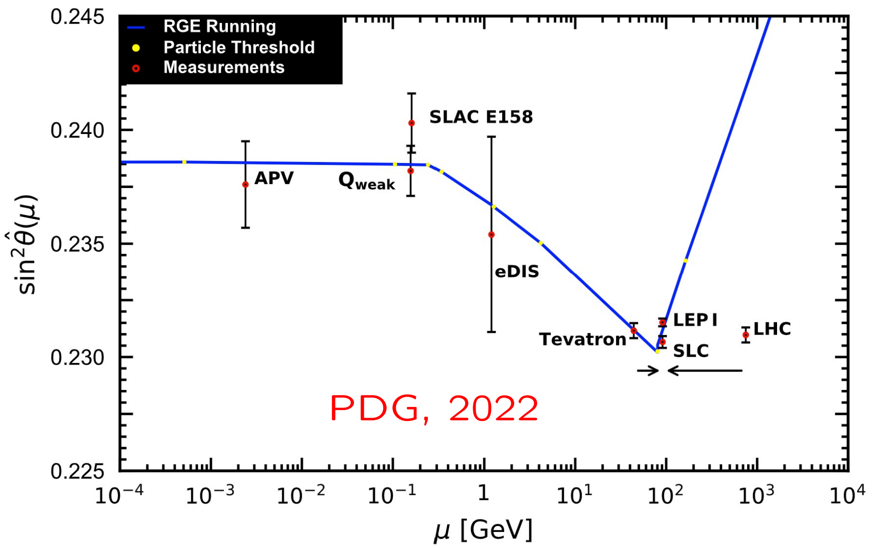

- $\varepsilon\delta' < 0$ range corresponds to 1 $\sigma$ band for $\sin^2\theta_W$ deviation (circa 2015)
- Qweak and APV values have been updated
- LHC updates on $\delta$ can disfavor the assumed $\varepsilon\delta' < 0$ (depending on $Z_d$ decay BR)

- Qweak (experimental) and APV (theory input) updates:

Toh *et al.*, 2019




Qweak Collaboration, Nature 557 (2018) 7704, 207-211, 1905.08283



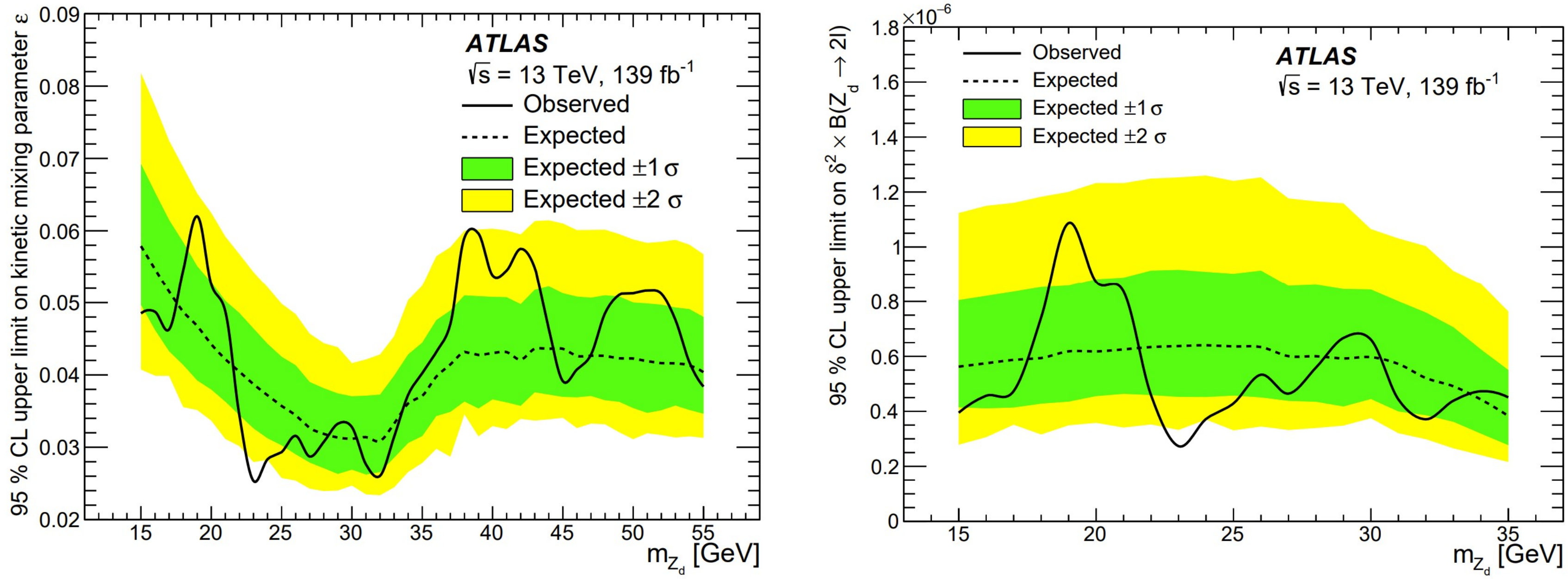
# Rare Higgs Decay $H \to ZZ_d$

- ATLAS search for $m_{Z_d} > 15$ GeV (no lepton jets)
- Non-negligible $m_{Z_d}$: $\delta' \equiv \delta + \varepsilon\,(m_{Z_d}/m_Z)\tan\theta_W$
- $\mathrm{Br}(\mathrm{H} \to \mathrm{ZZ_d}) \approx (16 - 18)\delta'^2$
- EW precision constraints: $\varepsilon \lesssim 0.03$

Hook, Izaguirre, Wacker, 2010

Curtin, Essig, Gori, Shelton, 2014

- $\mathrm{Br}(\mathrm{Z_d} \to \ell^+\ell^-) \sim 0.3$ for $\mathrm{Br}(\mathrm{Z_d} \to \mathrm{SM}) = 1$
- Br $\ll 0.3$ if $Z_d \to$ dark states




From G. Aad *et al.* [ATLAS], JHEP **03**, 041 (2022), [arXiv:2110.13673 [hep-ex]]

- ATLAS ($m_{Z_d} = 15$ GeV):

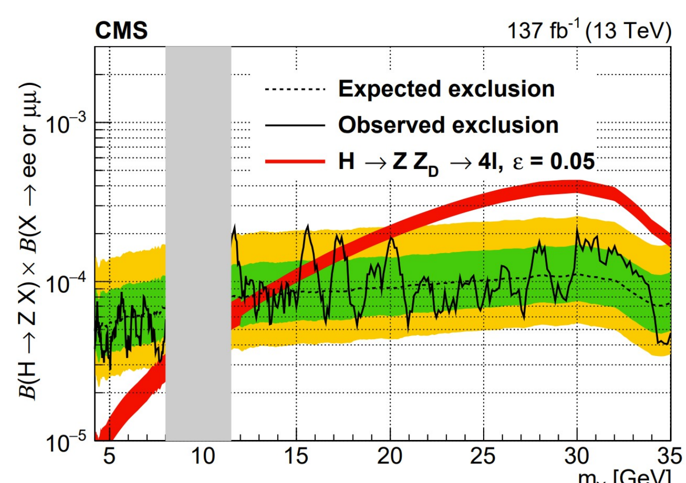
$\mathrm{Br}(\mathrm{Z_d} \to \ell^+\ell^-) \sim 0.3$ (mostly visible) $\Rightarrow |\varepsilon\delta'| \lesssim 4 \times 10^{-5}$

$\mathrm{Br}(\mathrm{Z_d} \to \ell^+\ell^-) \sim 0.003$ (mostly invisible) $\Rightarrow |\varepsilon\delta'| \lesssim 3 \times 10^{-4}$

From A. Tumasyan *et al.* [CMS],
Eur. Phys. J. C **82**, no.4, 290 (2022),
[arXiv:2111.01299 [hep-ex]] (95% CL)

- CMS ($m_{Z_d} = 15$ GeV):

$|\varepsilon\delta'| \lesssim 1 \times 10^{-4}$ (mostly visible)



# Exploring Dark Parity at Future Colliders

- Polarized electron beam of the future electron ion collider (EIC) a potential probe

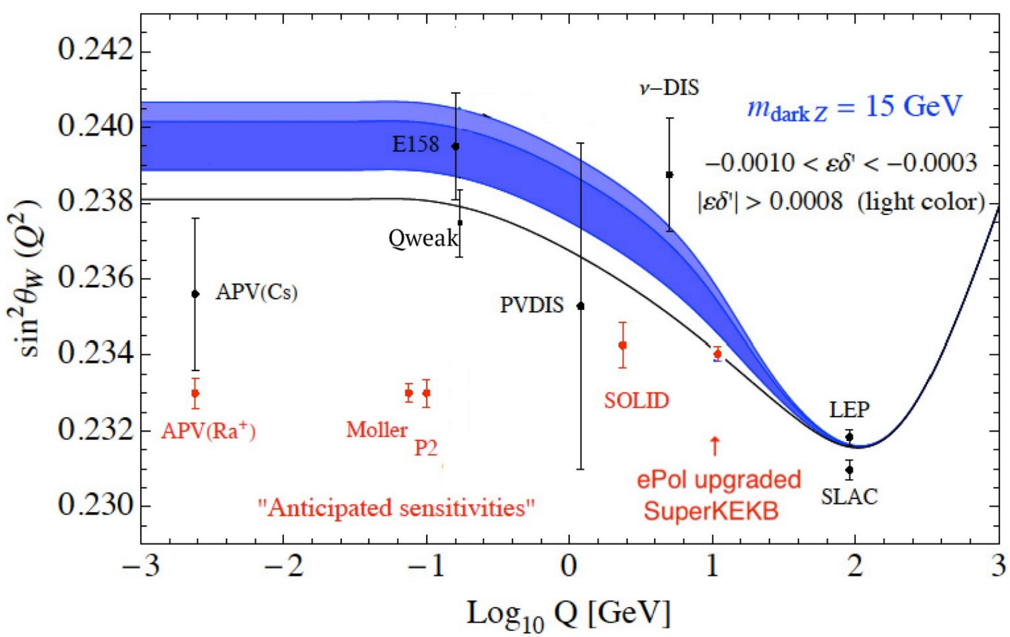
- Production of $Z_d$ in coherent $Z^2$-enhanced electron-ion scattering

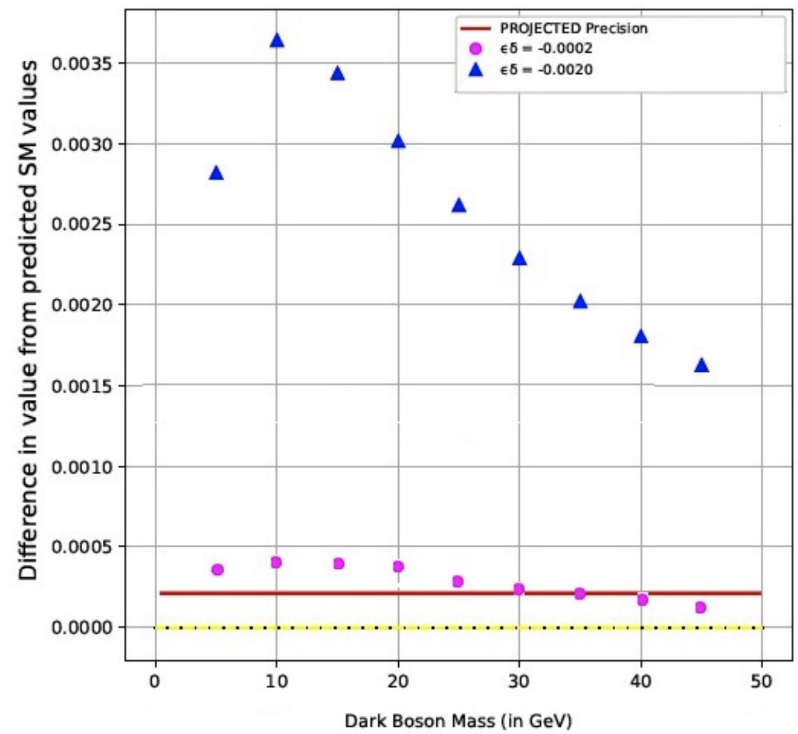
HD, Marcarelli, Neil, work in progress

- Precision on $\sin^2\theta_W$ based on 40 ab$^{-1}$ of "Chiral Belle" data: $\pm 0.00018$

- Approximately 70% longitudinally polarized electron beam; $Q^2 = (10.58\ \text{GeV})^2$

- Possible sensitivity [mostly invisible; $\text{Br}(Z_d \to \ell^+\ell^-) \sim 0.003$]: $|\varepsilon\delta'| \lesssim 3\times10^{-4} \Rightarrow \Delta\sin^2\theta_W \lesssim 5\times10^{-4}$




From: S. Banerjee *et al.* [US Belle II Group and Belle II/SuperKEKB e-Polarization Upgrade Working Group], 2205.12847

# Concluding Remarks

- Dark sector may have its own forces, mediated by dark bosons
- $Z_d$ from a $U(1)_d$
- Dark Higgs $\phi$, possibly associated with $U(1)_d$ breaking

- Kinetic mixing: dark photon
- Simple extension that could address $g_\mu - 2$; $m_{Z_d} \lesssim 1$ GeV

- Mass-mixing with $Z$: dark $Z$
- Production (direct) and precision (indirect) signals
- New low energy source of parity violation: $\Delta \sin^2 \theta_W(Q^2)$
- Opportunities for polarized electron scattering experiments

- Perhaps also at the future EIC or a proposed polarized SuperKEKB

- Potential correlated signals in *rare Higgs decays*