Muon g-2 and Dark Parity Violation

(based on works with H. Davoudiasl and W. Marciano)

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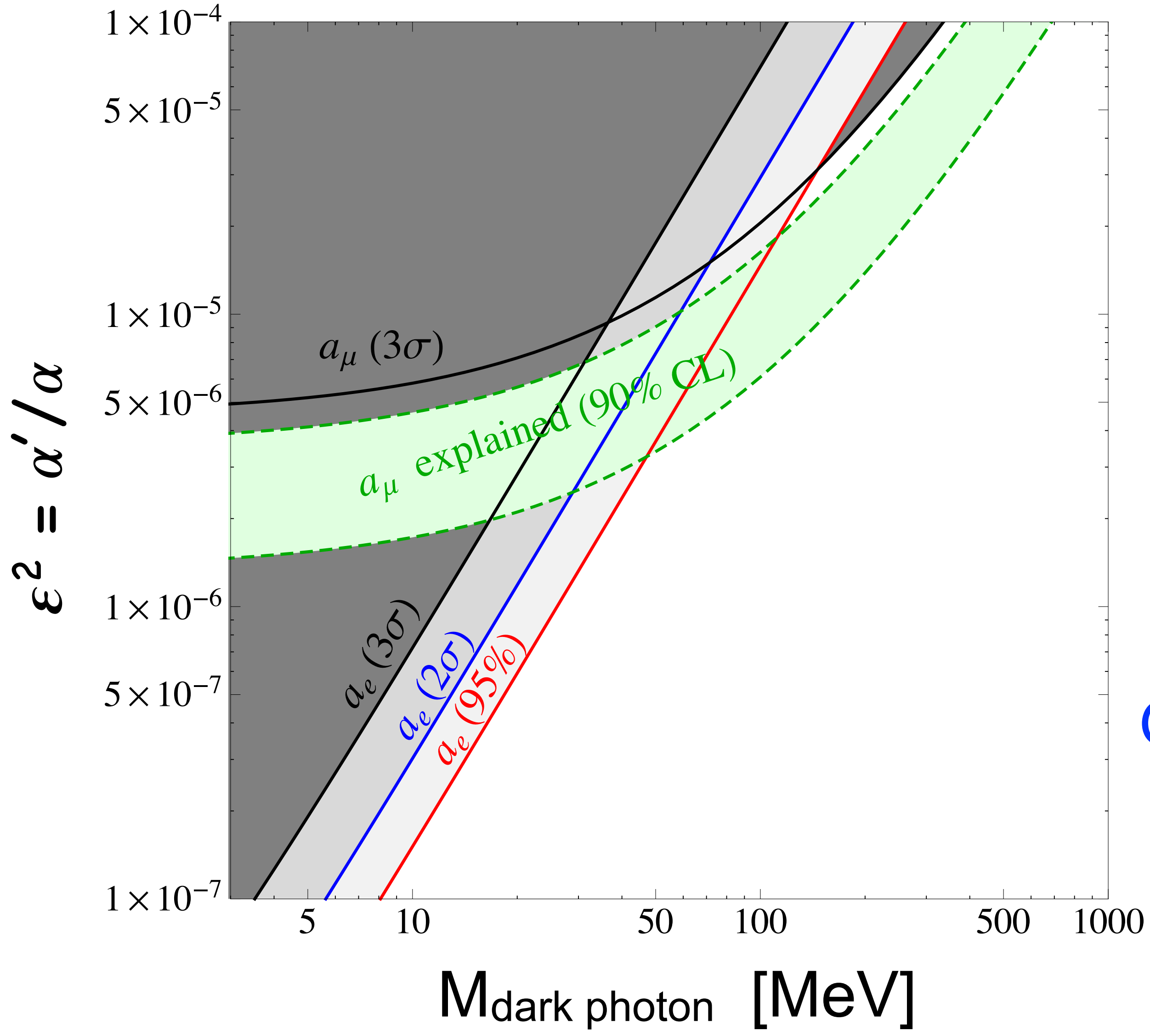
Muon g-2 and Dark gauge interaction

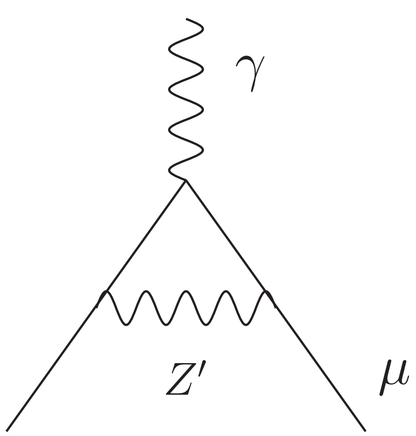
Anomalous Magnetic Moment

a_μ **= (g_μ - 2) / 2** : Always an important motivation/constraint for New Physics.

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (288 \pm 80) \times 10^{-11}$$ 3.6σ level discrepancy

- One of the major motivations for the light Dark gauge boson (Z').
- Unlike other motivations, it is independent of the unknown Dark Matter properties.
- It is independent of the Z' decay branching ratios.





$$(\text{magnetic moment}) = -\frac{g\mu_B S}{\hbar}$$

Green band: explains the 3.6σ deviation in a_μ (possibly early hint of Dark Force)

[Pospelov (2008); and others]

Anomalous Magnetic Moment

The Z' coupling to muons, to explain the Δa_μ = 288(80) × 10^{-11},

$$a_\mu^{Z'} = (\underbrace{\text{vector coupling contribution}}_{\text{Right sign (+)}}) + (\underbrace{\text{axial coupling contribution}}_{\text{Wrong sign (–)}})$$

Either (i) only vector coupling
or (ii) dominant vector coupling + smaller axial coupling

Some Dark Force models for each case and their couplings <u>(at LO)</u>

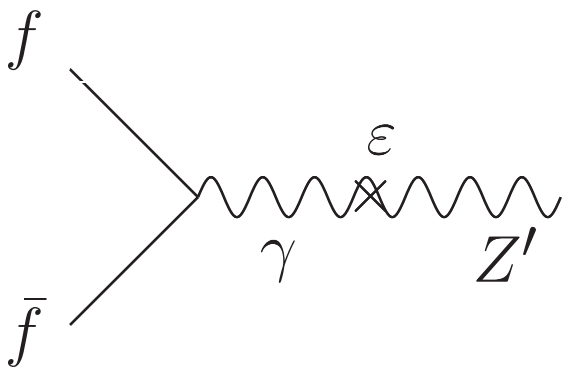
(i) Dark Photon : $\mathcal{L}_{\text{int}} = -\varepsilon\, e J^\mu_{em} Z'_\mu$

(vector coupling)

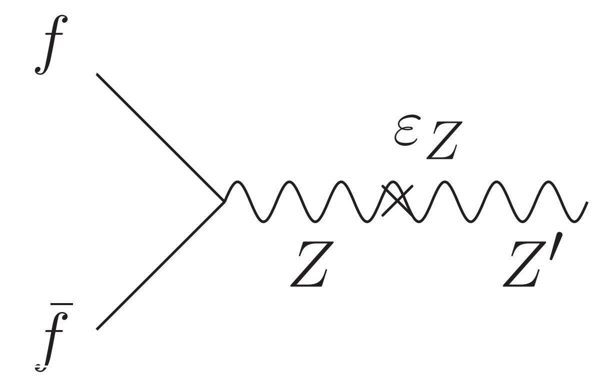
(ii) Dark Z : $\mathcal{L}_{\text{int}} = -[\varepsilon\, e J^\mu_{em} + \varepsilon_Z\, (g/2\cos\theta_W) J^\mu_{NC}]\, Z'_\mu$

(vector coupling) + (axial coupling)

$$J^{NC}_\mu = (T_{3f} - 2Q_f \sin^2\theta_W)\, \bar{f}\gamma_\mu f - (T_{3f})\, \bar{f}\gamma_\mu\gamma_5 f$$



Types of Dark Force



It may interact with DM, but SM particles have zero charges

Both models commonly assume the kinetic mixing of $U(1)_Y$ and $U(1)_{dark}$.

[Holdom (1986)]

$$\mathcal{L}_{\rm kin} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W} B_{\mu\nu} Z'^{\mu\nu} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}$$

$$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$$

(i) Popular Model: **"Dark Photon"** [Arkani-Hamed *et al* (2008); and others]

mass ≈ O(1) GeV

coupling = ε×(Photon coupling)

$$\mathcal{L}_{\rm int} = -\varepsilon\, e J^\mu_{em} Z'_\mu$$

(ii) New Model: **"Dark Z"** [Davoudiasl, LEE, Marciano (2012)]

mass ≈ O(1) GeV

coupling = ε×(Photon coupling) + ε_Z×(Z coupling)

$$\mathcal{L}_{\rm int} = -[\varepsilon\, e J^\mu_{em} + \varepsilon_Z\,(g/2\cos\theta_W) J^\mu_{NC}]\, Z'_\mu$$

inherits properties of Z boson (including the parity violation)

Higgs structure matters

Model-dependence in coupling comes from **how Z' gets mass** (or Higgs sector).

- Dark Photon: (Example) additional Higgs singlet gives mass to Z'
  coupling = ε×(Photon coupling)
- Dark Z: (Example) additional Higgs doublet (+ singlet) gives mass to Z'
  coupling = ε×(Photon coupling) + ε_Z×(Z coupling)

(Example) Dark Photon case
: Z-Z' kinetic mixing is cancelled by Z-Z' mass mixing (which is "induced by kinetic mixing") at Leading order.

$$\mathcal{L}_{\text{int}} \sim -eJ^{\mu}_{em}A_{\mu} - (g/2\cos\theta_W)J^{\mu}_{NC}Z_{\mu}$$

(Kinetic mixing diagonalization) $\rightarrow -eJ^{\mu}_{em}[A_{\mu} + \varepsilon Z'_{\mu}] - (g/2\cos\theta_W)J^{\mu}_{NC}[Z_{\mu} + O(\varepsilon)Z'_{\mu}]$

(Z-Z' mass matrix diagonalization) $\rightarrow -eJ^{\mu}_{em}[A_{\mu} + \varepsilon Z'_{\mu}] - (g/2\cos\theta_W)J^{\mu}_{NC}Z_{\mu}$

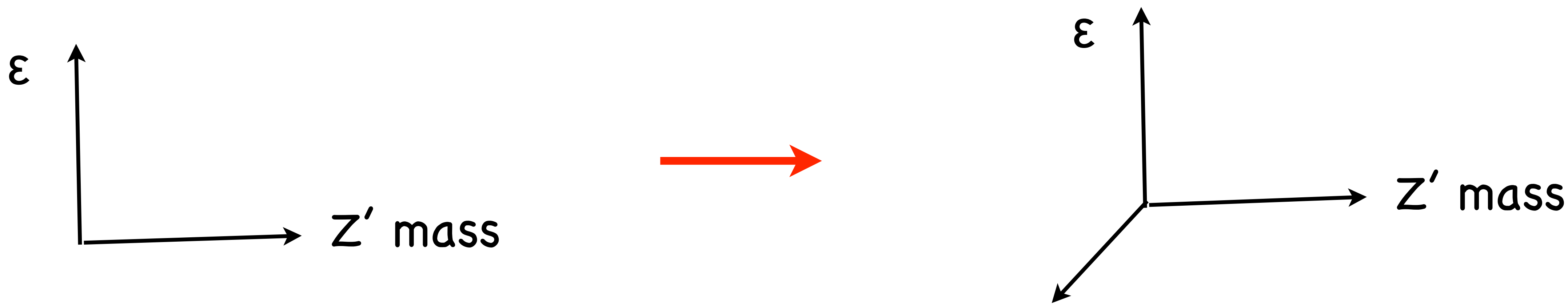
(depends on Higgs sector) *(for Higgs singlet)*

Dark Force couplings depend on "Higgs sector".

Effects of New Model (Dark Z)

Parameter space (Z' mass and coupling to the SM) is extended from 2D to 3D.

(Dark Photon) (Dark Z)



ε_Z (Z-Z′ mixing) : **parity violating**

$$\mathcal{L}_{\rm int} = -\varepsilon\, e J^{\mu}_{em} Z'_{\mu}$$

$$\mathcal{L}_{\rm int} = -[\varepsilon\, e J^{\mu}_{em} + \varepsilon_Z\, (g/2\cos\theta_W) J^{\mu}_{NC}]\, Z'_{\mu}$$

- Dark Z = Dark Photon with a more general coupling.
- Dark Photon = a special case of Dark Z (ε_Z = 0 limit).

Some experiments irrelevant to Dark Photon searches become relevant to Dark Z searches. They include the **"Low-energy Parity Test"**.

$$\mathcal{L}_{\rm int}({\rm SM}) = -e J^{\mu}_{em} A_{\mu} - (g/2\cos\theta_W) J^{\mu}_{NC} Z_{\mu}$$

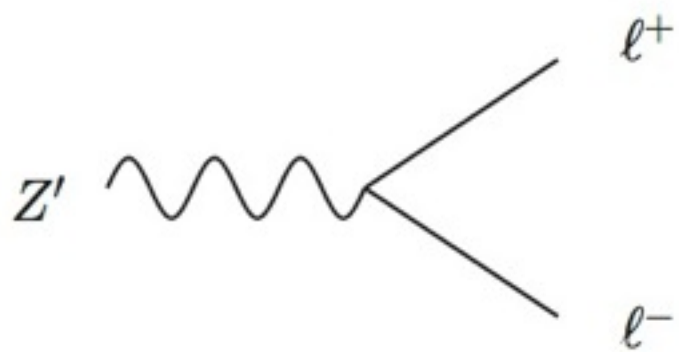
Typical Dark Force Searches in the Labs

(although covered by many previous talks)

Visible/Invisible decay of Dark gauge boson

Typical searches in the labs:

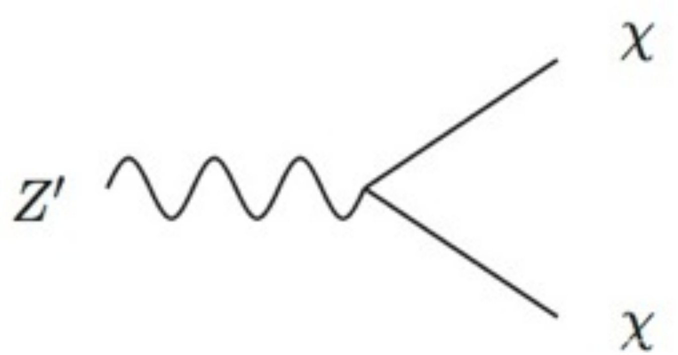
(i) "Dilepton Resonance" search



For Z' $\rightarrow \ell^+\ell^-$ is the major decay mode

(Fixed targets, beam dumps, meson decays, …)

(ii) "Missing Energy" search

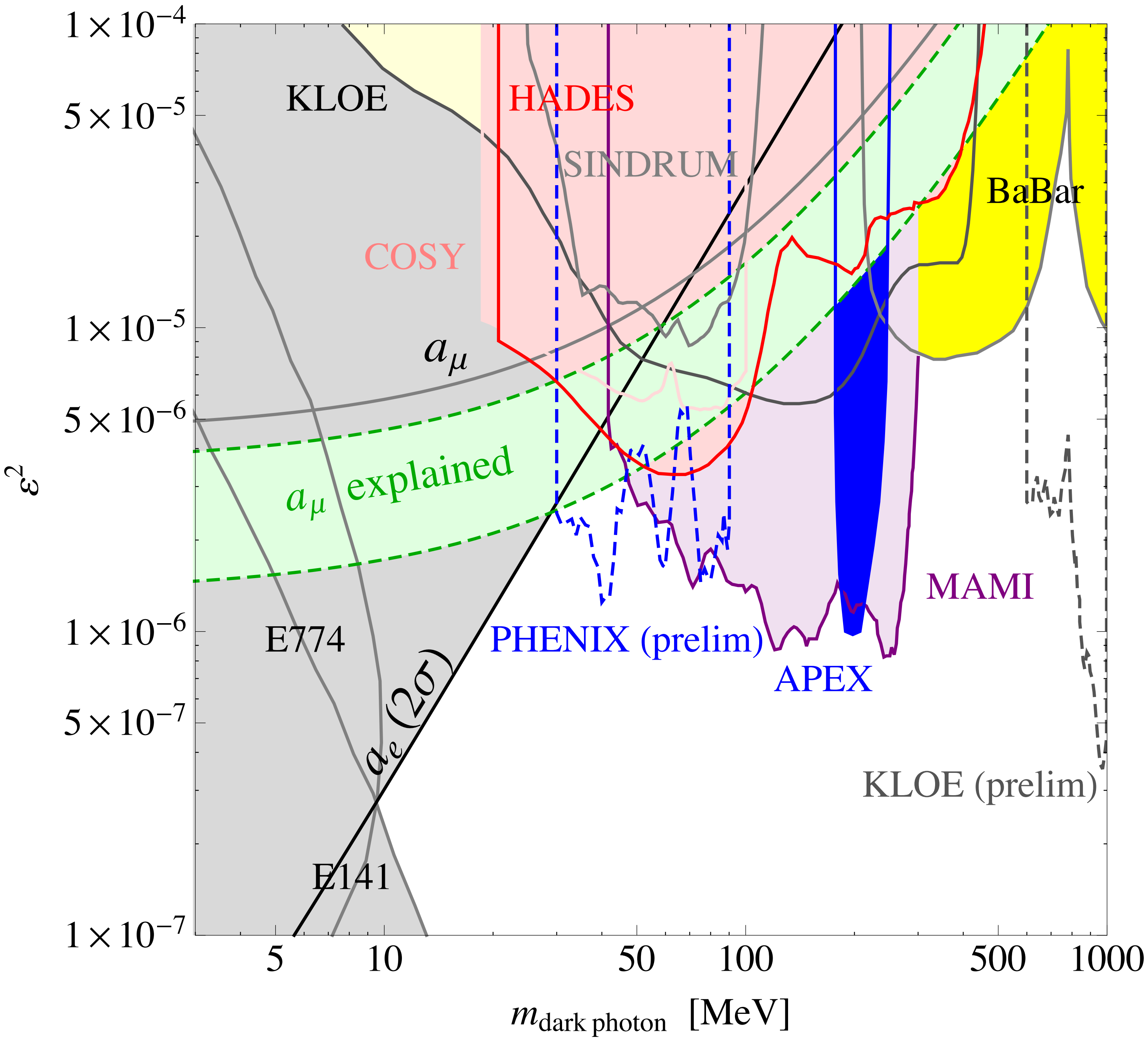


For Z' $\rightarrow \chi\chi$ (very light dark sector particles) is the major decay mode

($e^+e^- \rightarrow \gamma$ + nothing, K $\rightarrow$ π + nothing, …)

Visibly decaying Dark gauge boson

(i) Dilepton Bump ($Z' \to \ell^+\ell^-$) searches



[Dark Photon and Dark Z boson]

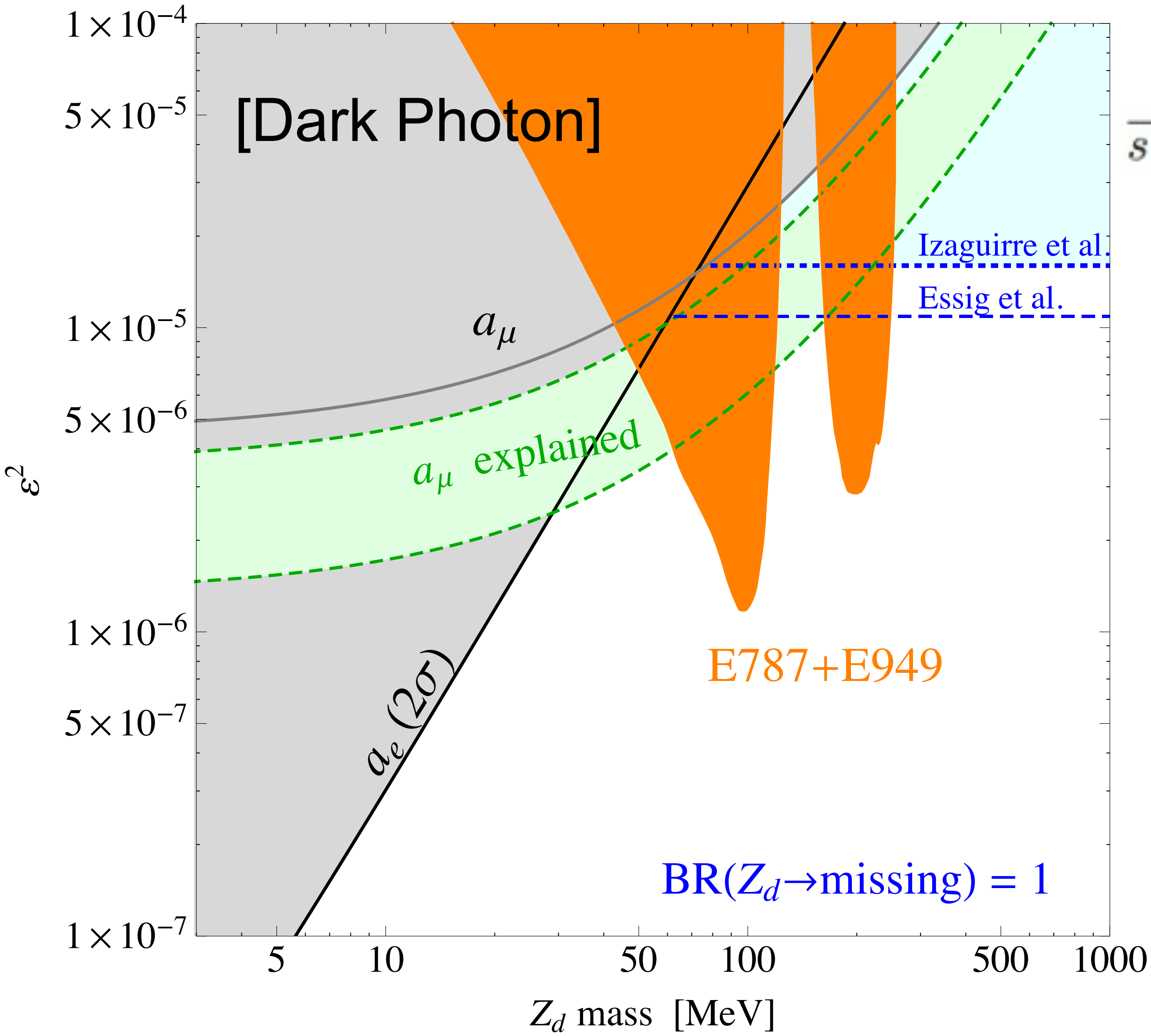
Up-to-dated constraints including PHENIX prelim and new MAMI
[DNP 2013 meeting] [April 2014]

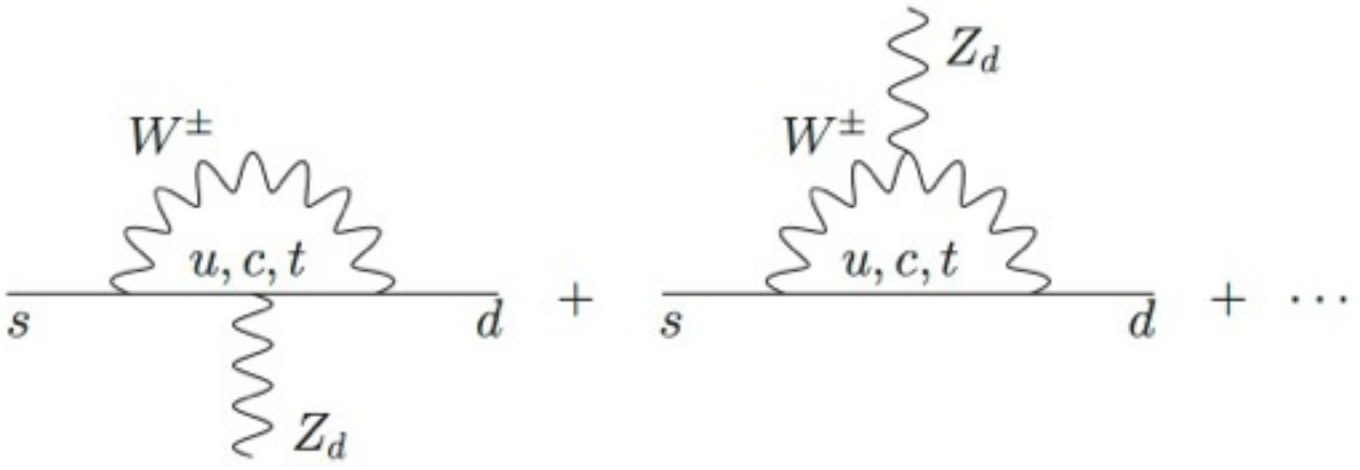
(Beam-dumps
Meson (quarkonium) decays
Fixed target experiments)

Whole green band (g_μ-2 favored) is almost excluded !
(weakening a major motivation of the light Dark gauge boson)

Invisibly decaying Dark gauge boson

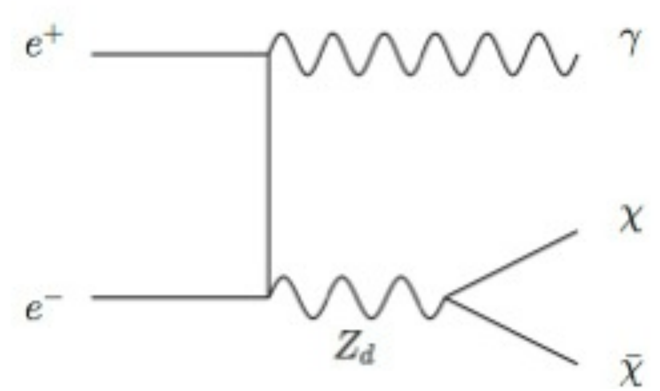
(ii) Missing Energy ($Z' \to \chi\chi$) searches





K⁺ → π⁺ + nothing (BNL E787+E949)

[Pospelov (2009); and others]



$e^+e^- \to \gamma$ + nothing (BaBaR)

[Izaguirre *et al* (2013); Essig *et al* (2013)]

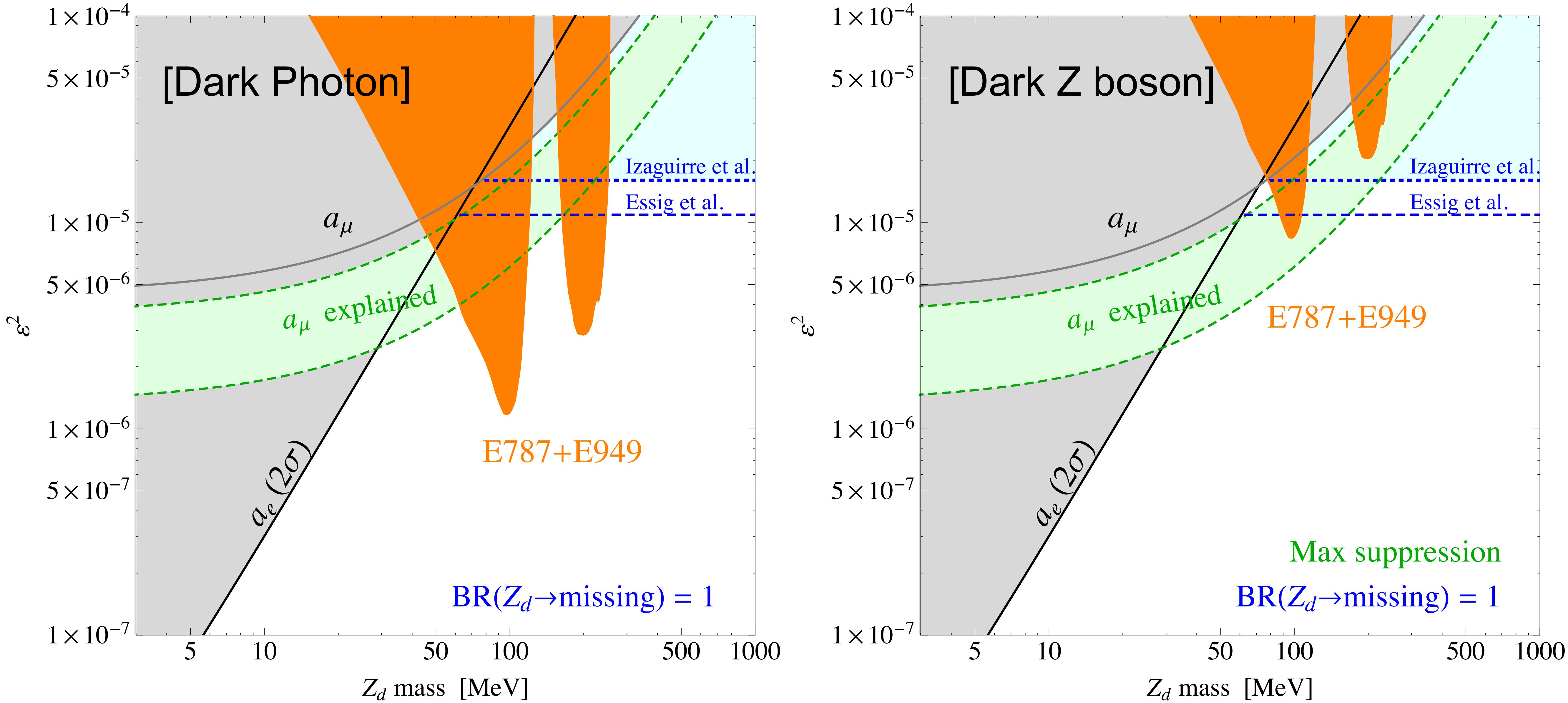
(More constraints may be possible through χ interaction in detectors.)

In Dark Photon model, only small portion of the green band survives the constraints.

Invisibly decaying Dark gauge boson

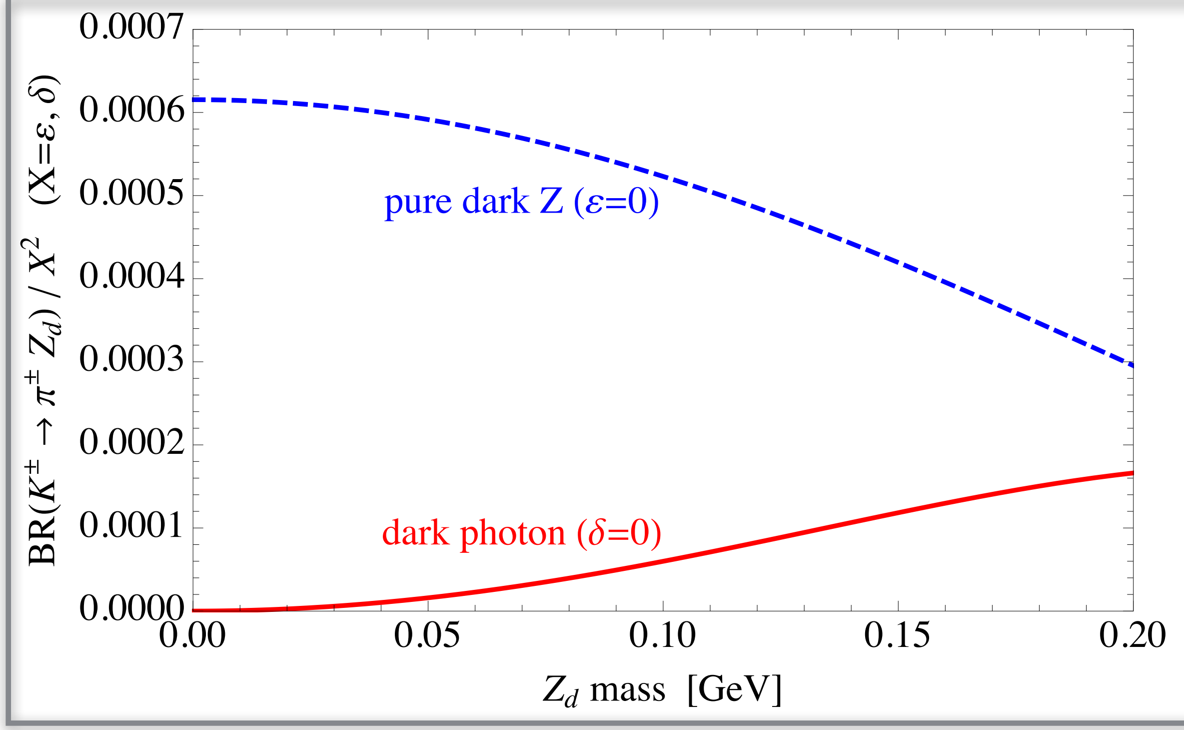
(ii) Missing Energy (Z' → $\chi\chi$) searches

[Davoudiasl, LEE, Marciano (2014)]



In Dark Z model, because of the additional term (ε_Z term), there can be a sizable interference in the flavor-changing meson decays.
The "K → π + Z' (nothing)" <u>constraints (orange) can be much weaker</u> (1/7 times).

K → π + Z’



$$\Gamma(K^+ \to \pi^+ Z_d) = 4\pi \frac{\sqrt{\lambda(m_K^2, m_\pi^2, m_{Z_d}^2)}}{64\pi^2\, m_K^3} \sum_{\mathrm{pol}} |\mathcal{M}|^2$$

with $$\sum_{\mathrm{pol}} |\mathcal{M}|^2 = \frac{1}{4}(f_+)^2 \left[\left(\frac{m_K^2 - m_\pi^2}{m_{Z_d}} \right)^2 - \left(2m_K^2 + 2m_\pi^2 - m_{Z_d}^2\right) \right] \left| \varepsilon m_{Z_d}^2 A \pm \delta \frac{m_{Z_d}}{m_Z} B \right|^2$$

Additional term of Dark Z model

- Dark Photon :
 (loop-suppression with γ)×(small ε)

- pure Dark Z :
 (loop-suppression with Z)×(small ε_Z)×(enhancement factor)

(enhancement factor) = E / mZ’, at amplitude level, applies to the longitudinally polarized Z’, which happens when mZ’ << mB, mK.
Longitudinally polarized Z’ behaves as an “axion” (for production), which couples strongly to heavy particles (Top-quark). [Goldstone Boson Equivalence Theorem]

Dark Force Searches through Low-Energy Parity Test

“Dark Z” effects on Weak Neutral Current phenomenology

[Davoudiasl, LEE, Marciano (2012)]

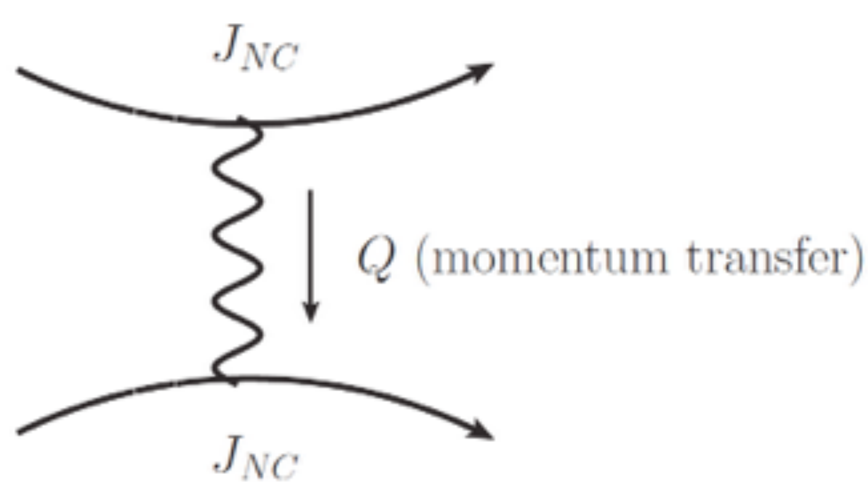
Dark Z : $\mathcal{L}_{\rm int} = -[\varepsilon\, e J^\mu_{em} + \varepsilon_Z\, (g/2\cos\theta_W) J^\mu_{NC}]\, Z'_\mu$

Dark Z **modifies** the effective Lagrangian of Weak Neutral Current scattering.

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} J^\mu_{NC}(\sin^2\theta_W) J^{NC}_\mu(\sin^2\theta_W)$$

$$G_F \to \left(1 + \delta^2 \frac{1}{1+Q^2/m^2_{Z'}}\right) G_F \quad \left(\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta\right)$$

$$\sin^2\theta_W \to \left(1 - \varepsilon\delta \frac{m_Z}{m_{Z'}} \frac{\cos\theta_W}{\sin\theta_W} \frac{1}{1+Q^2/m^2_{Z'}}\right) \sin^2\theta_W$$

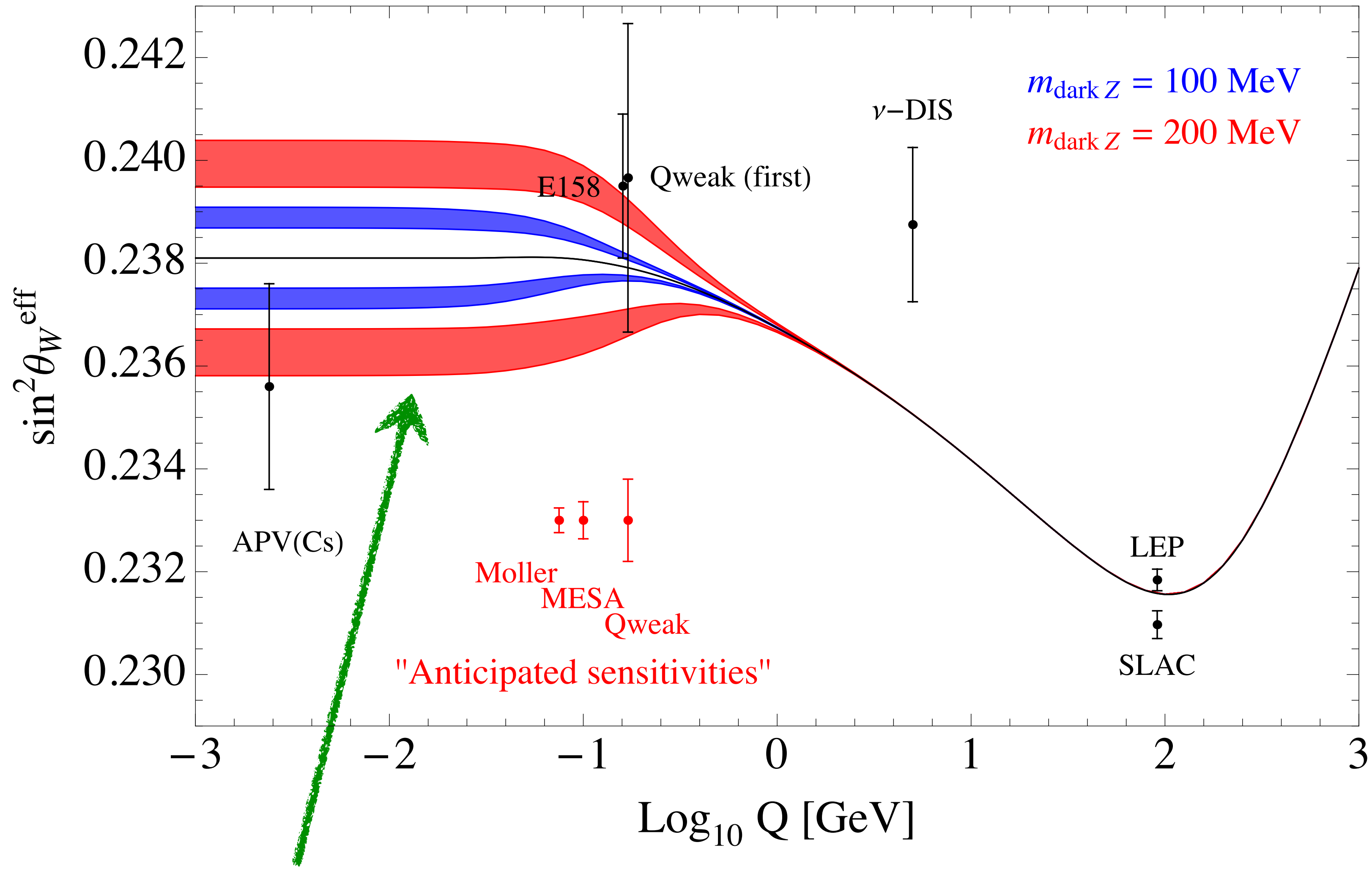


- Sensitive only to Low-Q^2 (momentum transfer). (Effect negligible for $Q^2 >> mZ'^2$)
- Low-Q^2 Parity-Violating experiments (measuring Weinberg angle) are good place to look.

Dark Z effectively changes the weak neutral current scattering (including parity), but only for the “Low” momentum transfer (Q).

Weinberg angle shift in Low-Q^2

[Davoudiasl, LEE, Marciano (2012)]



(Example)
For invisibly-decaying Dark Z.

Colored regions are predictions for the Weinberg angle shift by the Δa_μ solution (green band).

$$\Delta \sin^2 \theta_W(Q^2) \simeq -0.42\,\varepsilon\delta\,\frac{m_Z}{m_{Z'}}\,\frac{1}{1+Q^2/m_{Z'}^2}$$

Deviations from the SM prediction (due to Dark Z) can appear **"only" in the Low-E experiments.**

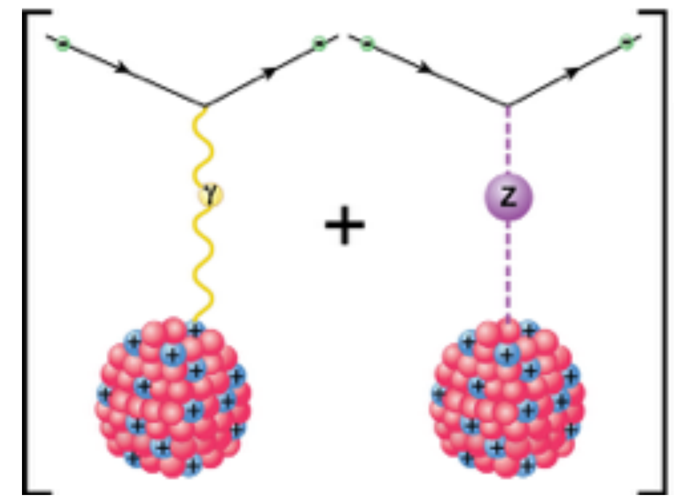
For the Low-Q^2 Parity Test (measuring Weinberg angle), we can use
- (i) Atomic Parity Violation (Cs)
- (ii) Low-Q^2 Polarized Electron Scattering (E158, Qweak, MESA, Moller)

independent of Z' decay BR.

Low-Energy Parity-Violating Experiments

(i) **Atomic Parity Violation** [Weak nuclear charge $Q_W(Z,N) \simeq -N+Z(1-4\sin^2\theta_W)$]

Cesium (^{133}Cs) Experiment [C. Wieman *et al* (1980's)]

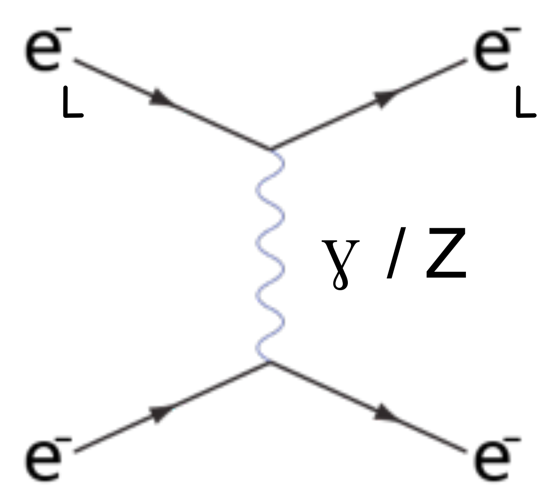


(ii) **Polarized Electron Scattering** [Left-Right asymmetry. $A_{LR} = \sigma_L - \sigma_R / \sigma_L + \sigma_R$]

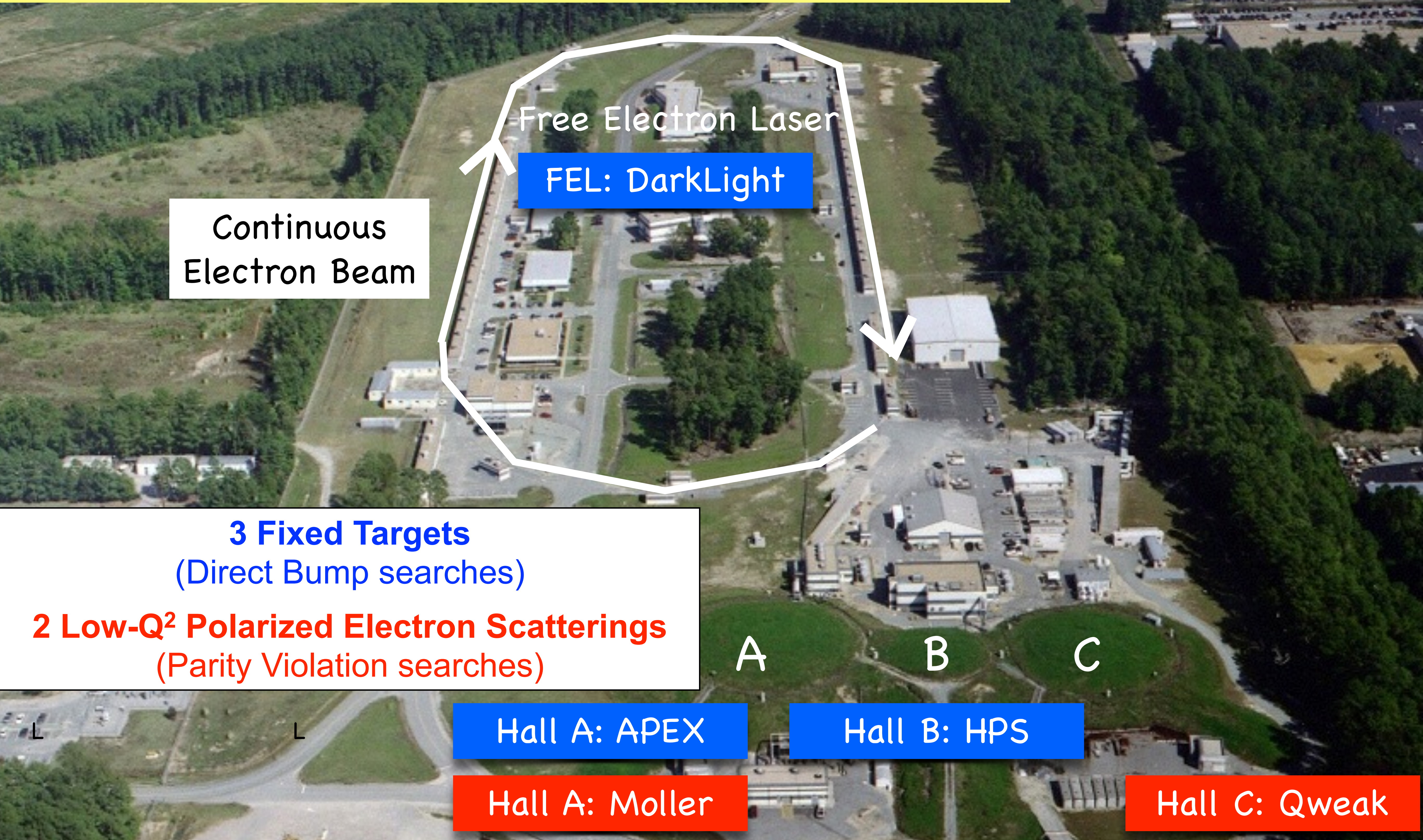
SLAC E158 (2005), JLab Qweak (ongoing analysis), JLab Moller, Mainz MESA

Experiment	Type	$\langle Q \rangle$	$\sin^2\theta_W(m_Z)$
Cesium APV	Cs	2.4 MeV	0.2356(20)
E158 (SLAC)	*ee*	160 MeV	0.2329(13)
Qweak (JLAB)	*ep*	170 MeV	±0.0007
Moller (JLAB)	*ee*	75 MeV	±0.00029
MESA* (Mainz)	*ep*	100 MeV	±0.00037

(*MESA parameters uncertain, but comparable to Moller)

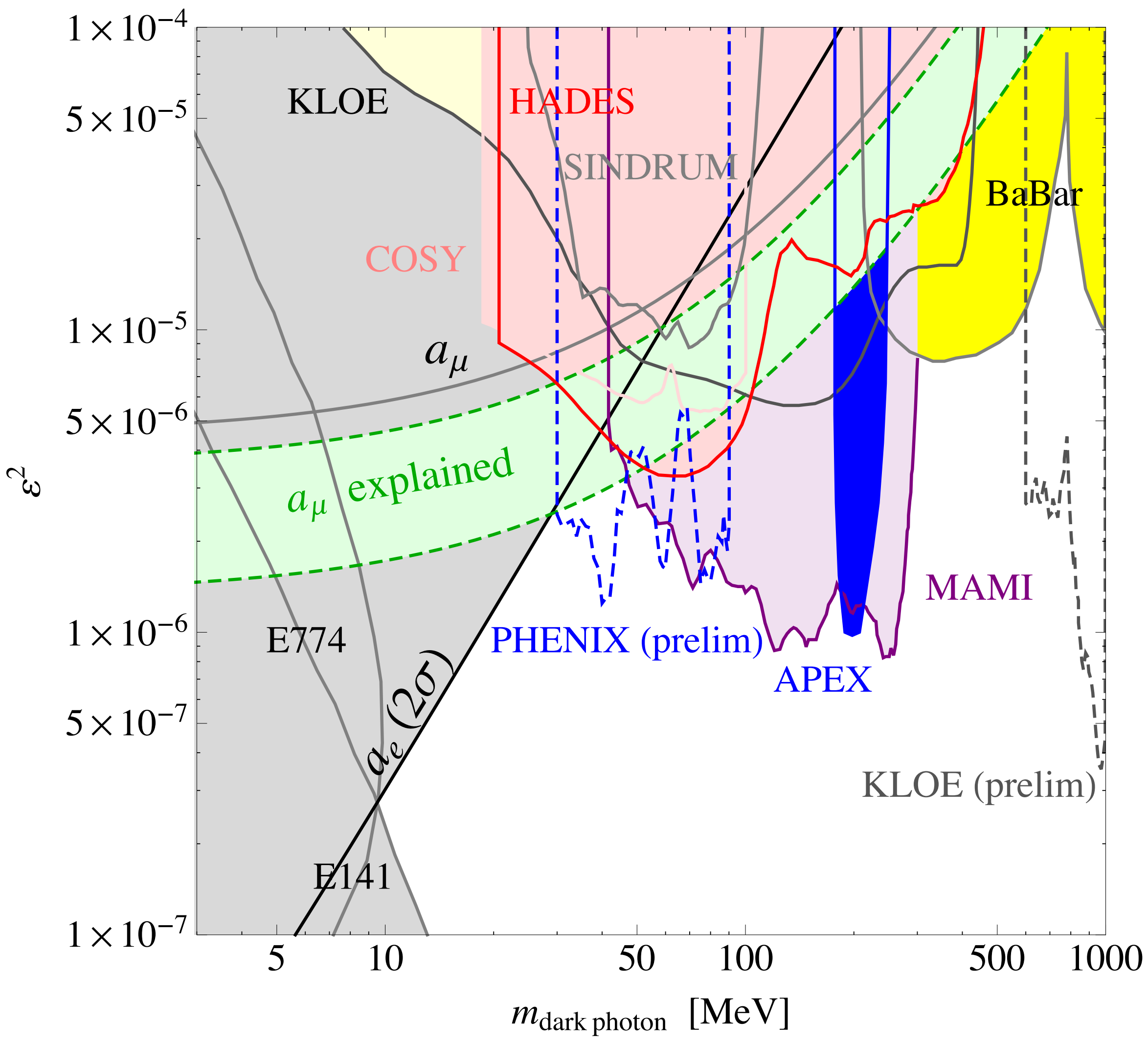


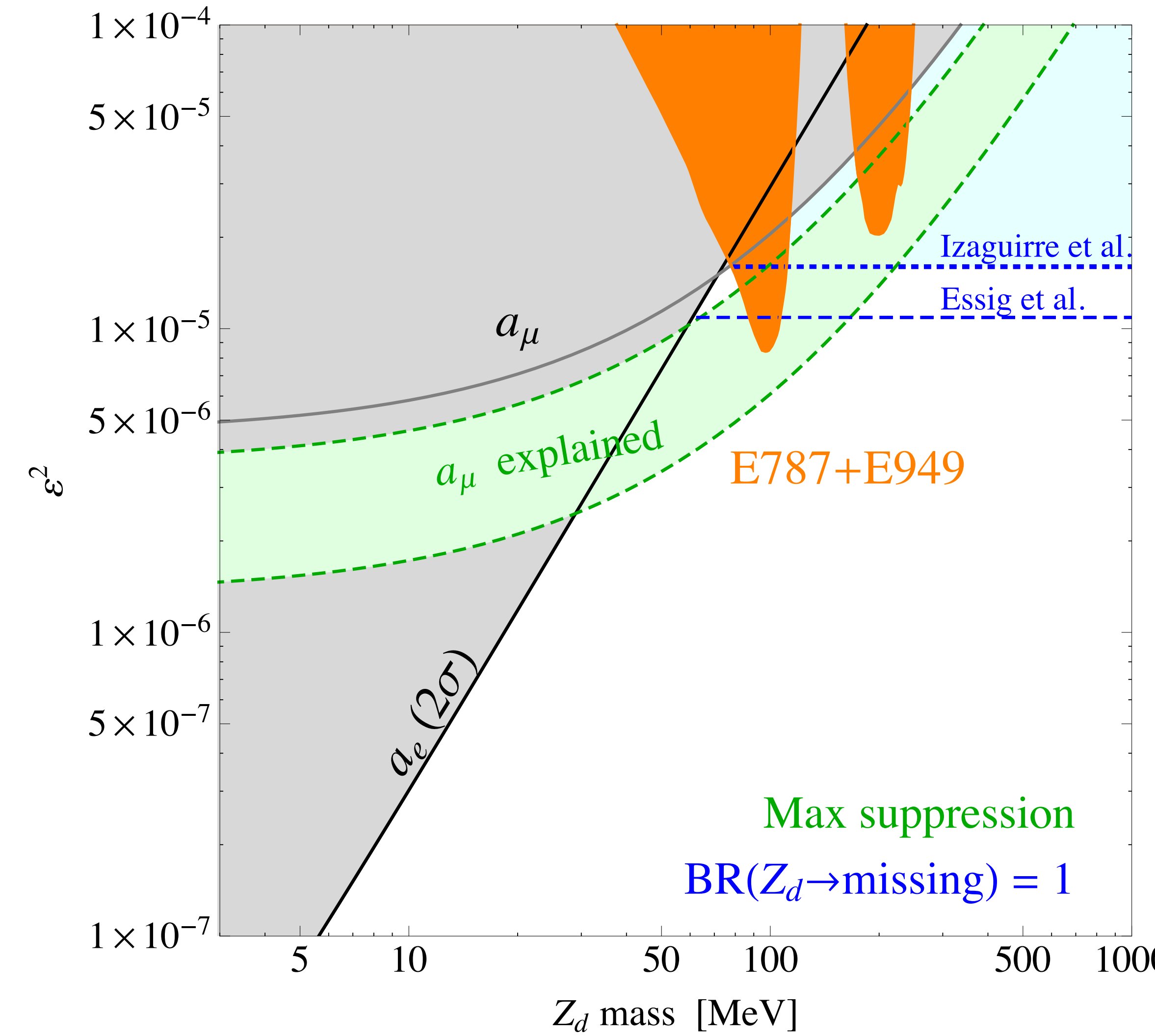
Dark Force searches at Jefferson Lab



With the possibility of small axial coupling (Dark Z), 2 more JLab experiments are relevant to Dark Force search.

Summary





Dark gauge interaction searches include

(i) g-2 : 3.6σ deviation in a_μ may be explained by Dark gauge boson (Green band).

(ii) Z' → $\ell^+\ell^-$: Direct bump searches. (Green band is almost excluded.)

(iii) Z' → MET : Requires light Dark particles (mχ ≲ mZ'/2). (Green band survives.)

(iv) Low-Energy Parity Test (APV, Polarized Electron Scattering) **:**

Another excellent probe. It is independent of Z' decay BR and small axial coupling may be present (Dark Z model).