Physics of Dark Z boson

a variant of Dark Photon

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(CERN since August 2014)

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Dark gauge boson

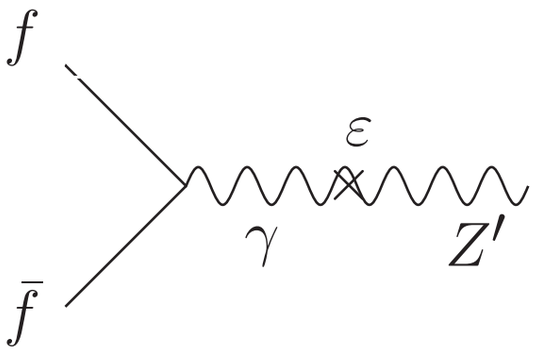
Dark gauge boson : Gauge boson with very small mass and very small coupling, motivated from the dark matter physics [e.g. positron excess] and others [e.g. g_μ-2 anomaly (weakened by now)].

Z'
(Dark Force carrier)

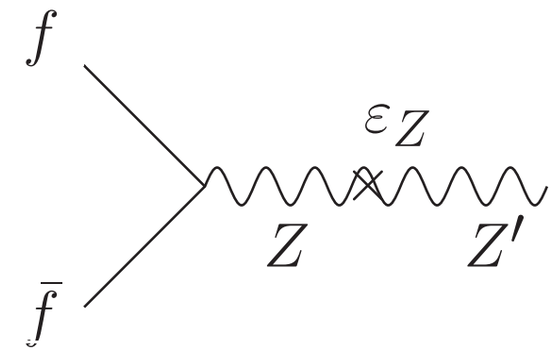
- Roughly, O(1) GeV scale
- Extremely weak couplings to the SM particles

[See Brian's talk for some related topics.]

In this talk, I will compare two models "Dark Photon" and "Dark Z boson".



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 axial coupling)

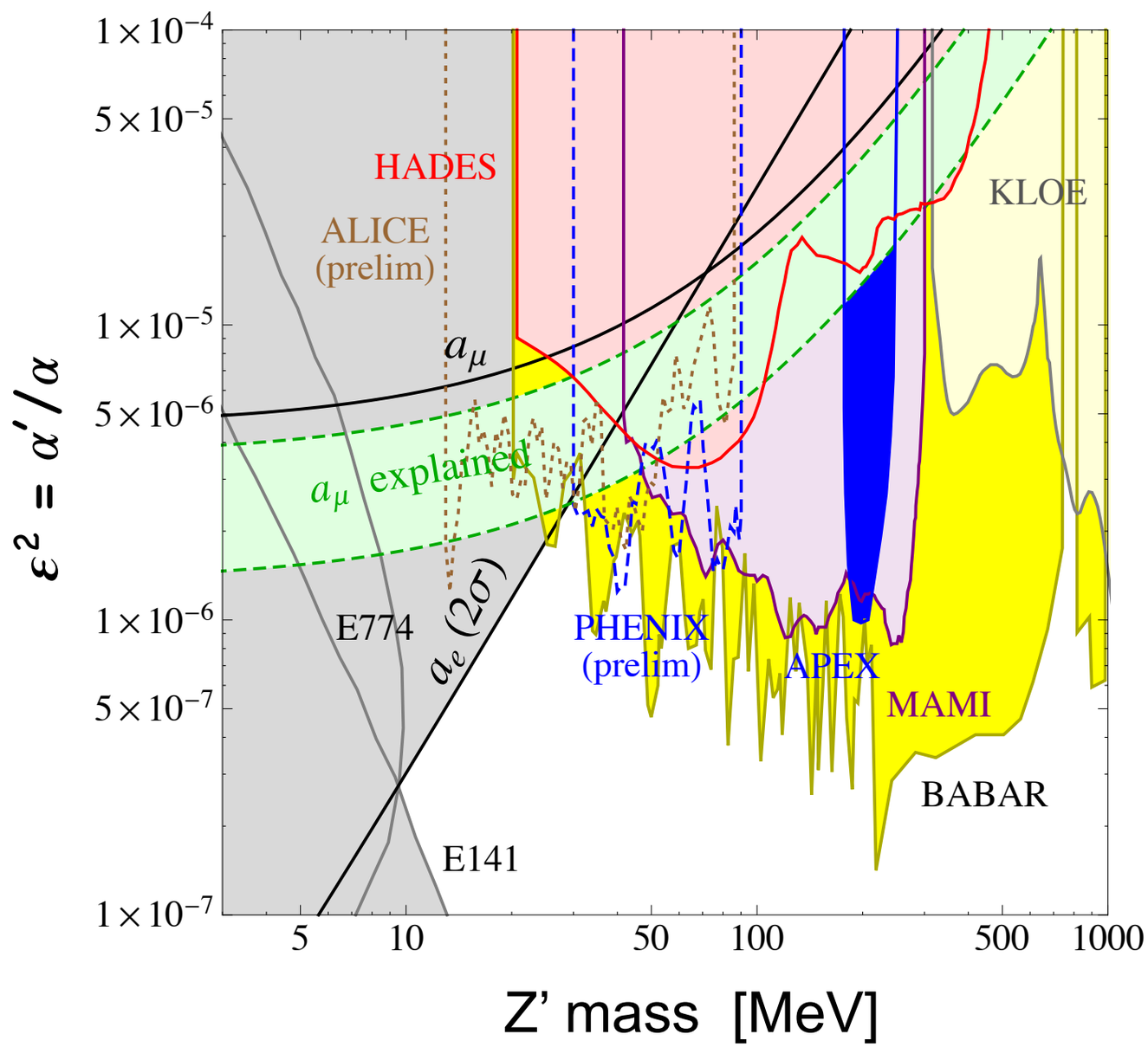
Constraints on the Parameter Space

Mostly from the Z' → $\ell^+\ell^-$ searches

(i) Electron, Muon g-2
(ii) Beam-dumps
(iii) Meson (quarkonium) decays
(iv) e+e- collision
(v) Fixed target experiments

News of 2014: Whole green band (g_μ-2 favored) is excluded now !

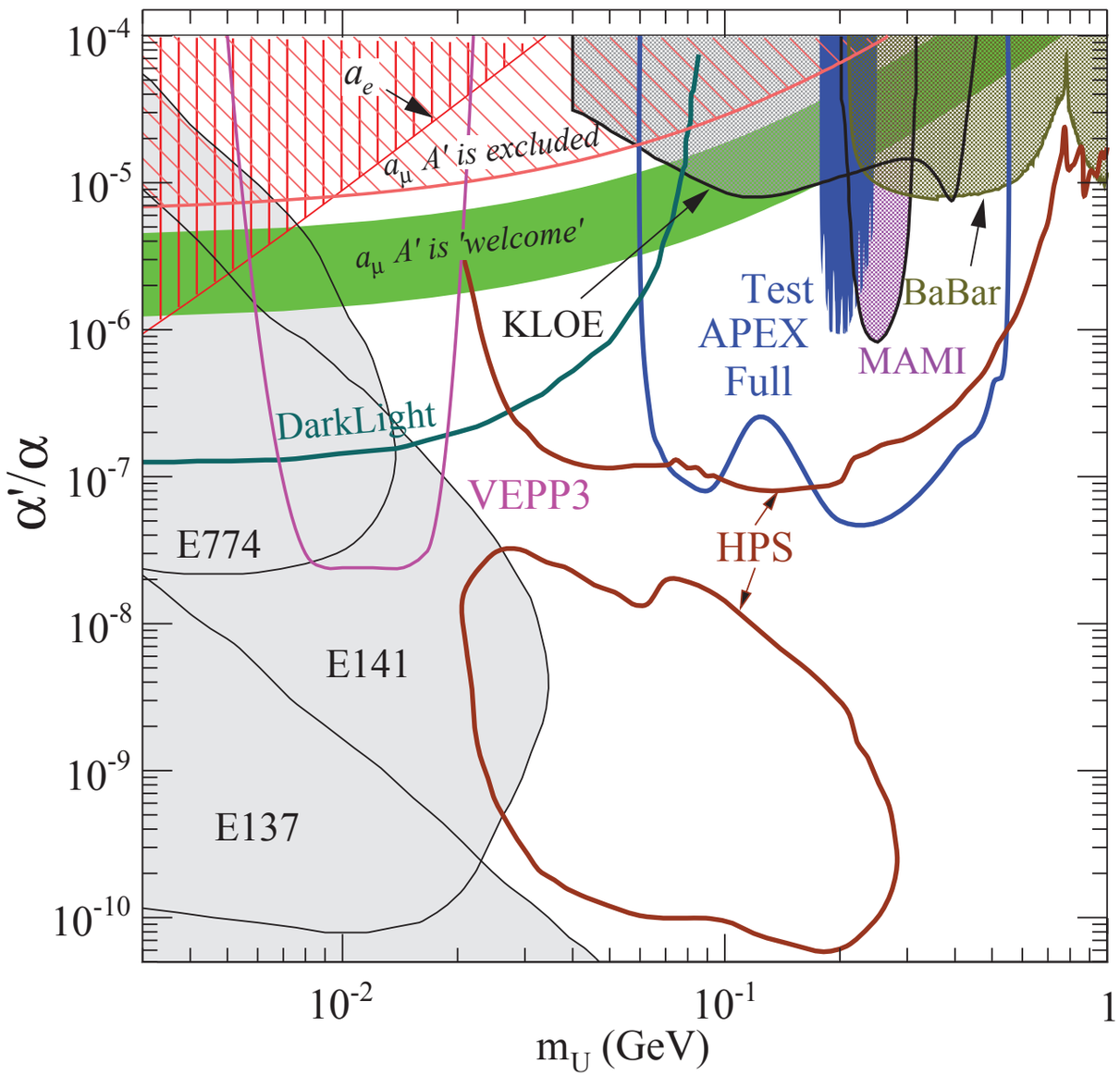
[2014 constraints]



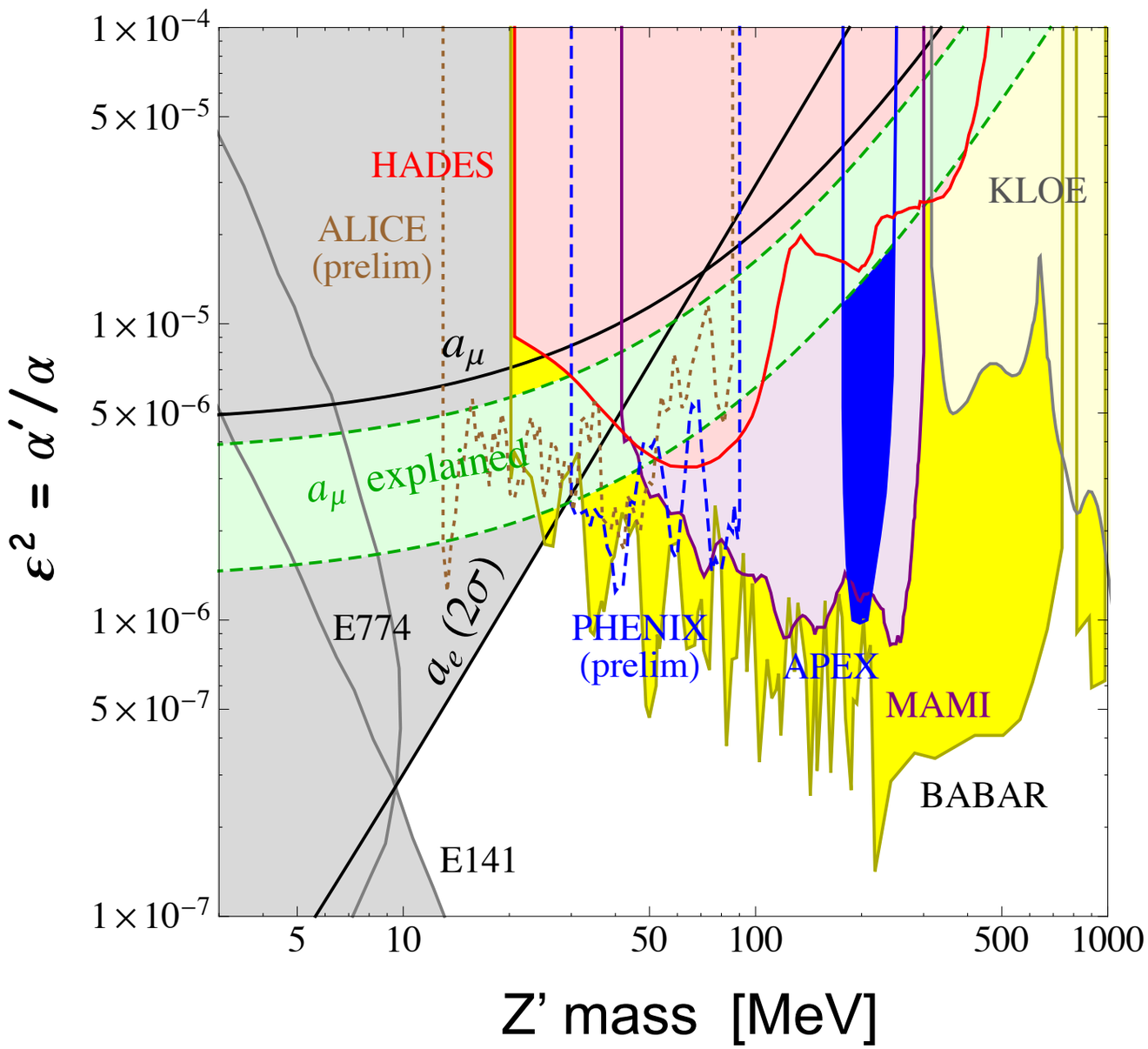
[Dark Photon & Dark Z boson]

Constraints on the Parameter Space

[2011 constraints and plans]



[2014 constraints]



"Dark Gauge Interaction" is a rapidly-developing field.

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)

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

- Dark Z: (Example) additional Higgs doublet (+ singlet) gives mass to Z'

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

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

(Example) Dark Photon case

: Z-Z' kinetic mixing is cancelled by Z-Z' mass mixing (which is "induced by kinetic mixing") at Leading Order.

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

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

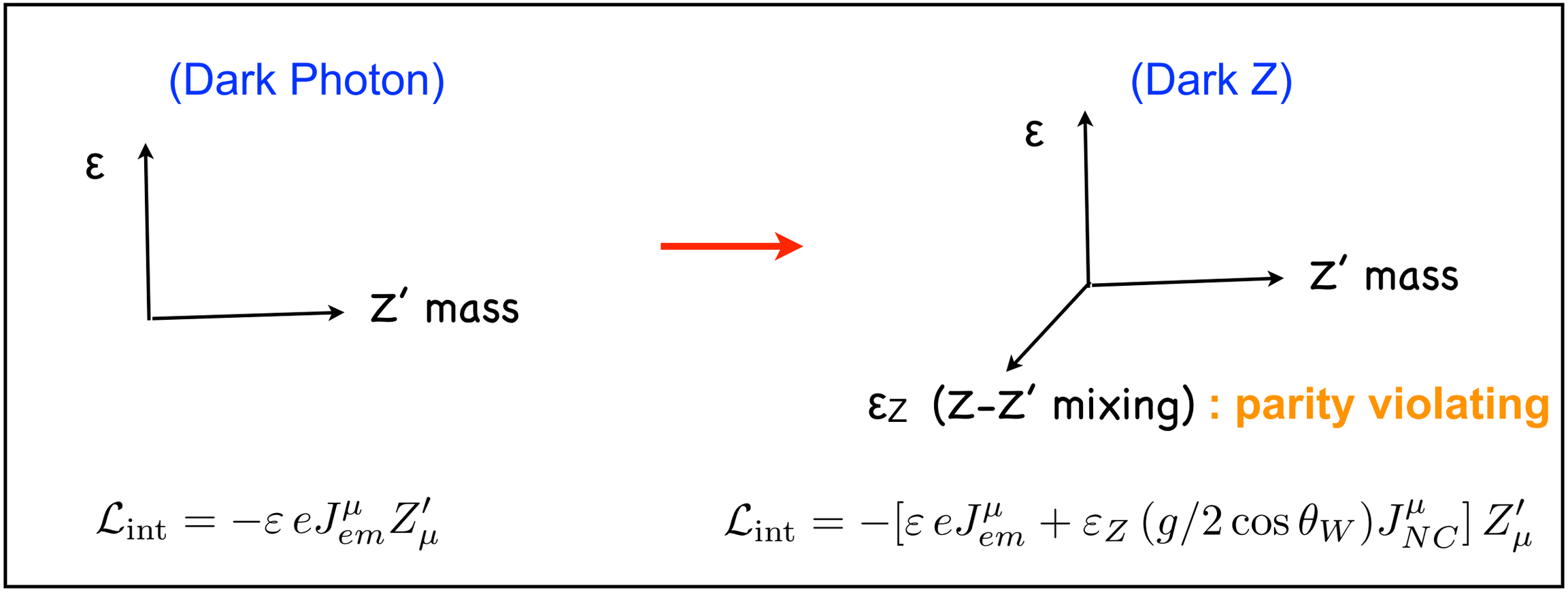
(Z-Z' mass matrix diagonalization) $\rightarrow -e J^{\mu}_{em}[A_{\mu} + \varepsilon Z'_{\mu}] - (g/2\cos\theta_W) J^{\mu}_{NC} Z_{\mu}$

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

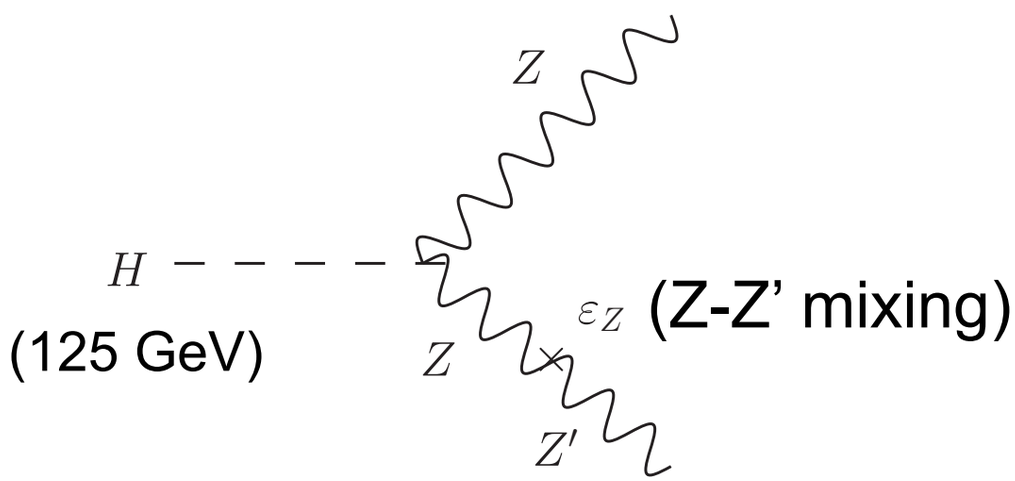
Some experiments irrelevant to Dark Photon searches <u>become relevant</u> to Dark Z searches. They include

(1) Rare Higgs decay (Z–Z' mixing),

(2) Rare Top decay ($H^{\pm} \to W\, Z'$ or $W\, Z'Z'$ as the dominant $H^{\pm}$ decay),

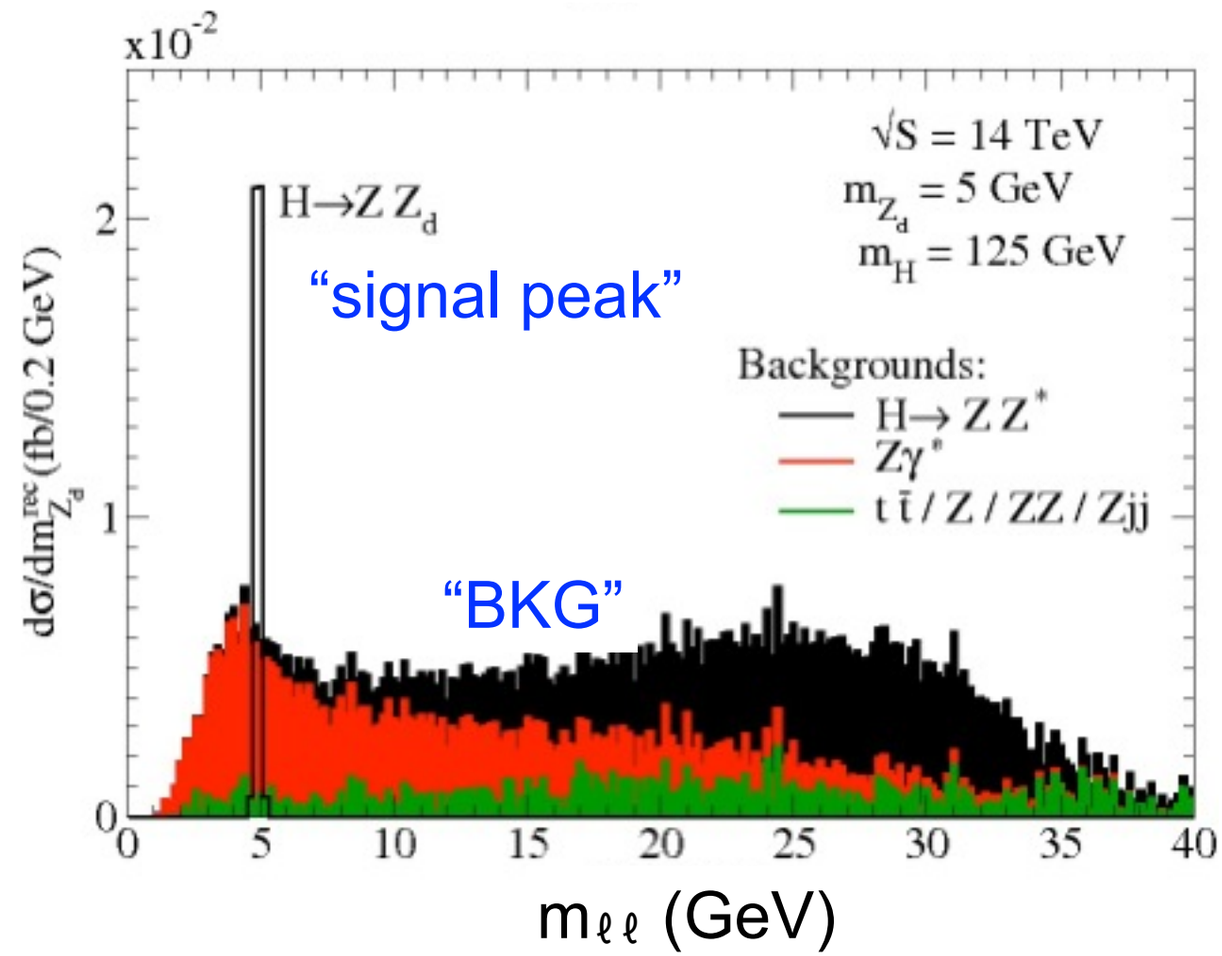
(3) Low–Q^2 parity violation (in Polarized electron scattering).

(1) Higgs-to-Dark decay at the LHC



[Higgs → Z Z' in Dark Z model]

[Davoudiasl, LEE, Lewis, Marciano (2013)]



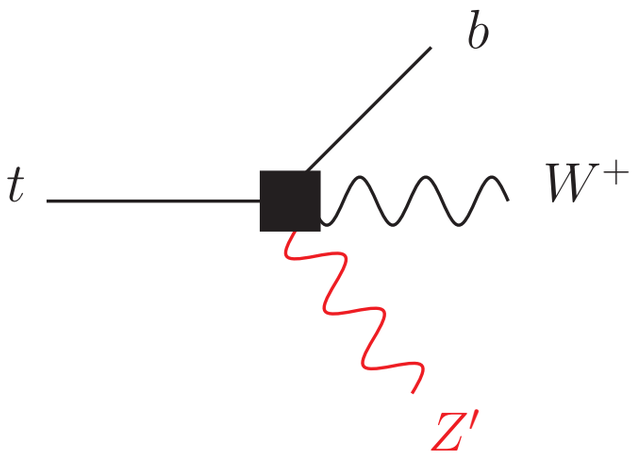
[Reconstructed Z' (dilepton) events after some cuts]

- Signal: H → Z Z' → 4-leptons
- Major BKG: Z γ*, H → Z Z*

The 14 TeV LHC can make a 5σ discovery of Z' through a rare Higgs decay for L ≈ (a few) × 100 fb^{-1}.

(2) Top-to-Dark decay at the LHC

[Kong, LEE, Park (Jan. 2014)]

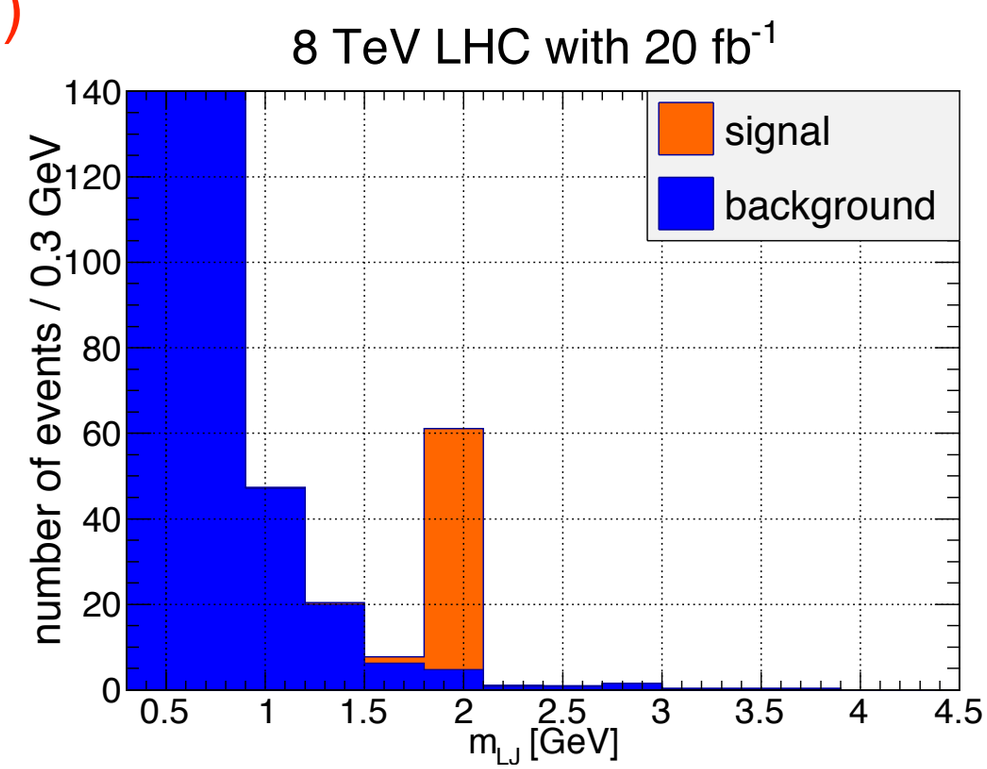


Top may decay into Z' (through a light charged Higgs)
t → bH⁺ → bW + Z's (on-shell decay)
: dominant top decay products (bW) + elusive Z's
[easily mis-identifiable as t → bW]

- Signal: t tbar → bW bH⁺ → bW bW + Z' (dilepton)
- Major BKG: t tbar → bW bW + γ*/Z (dilepton)

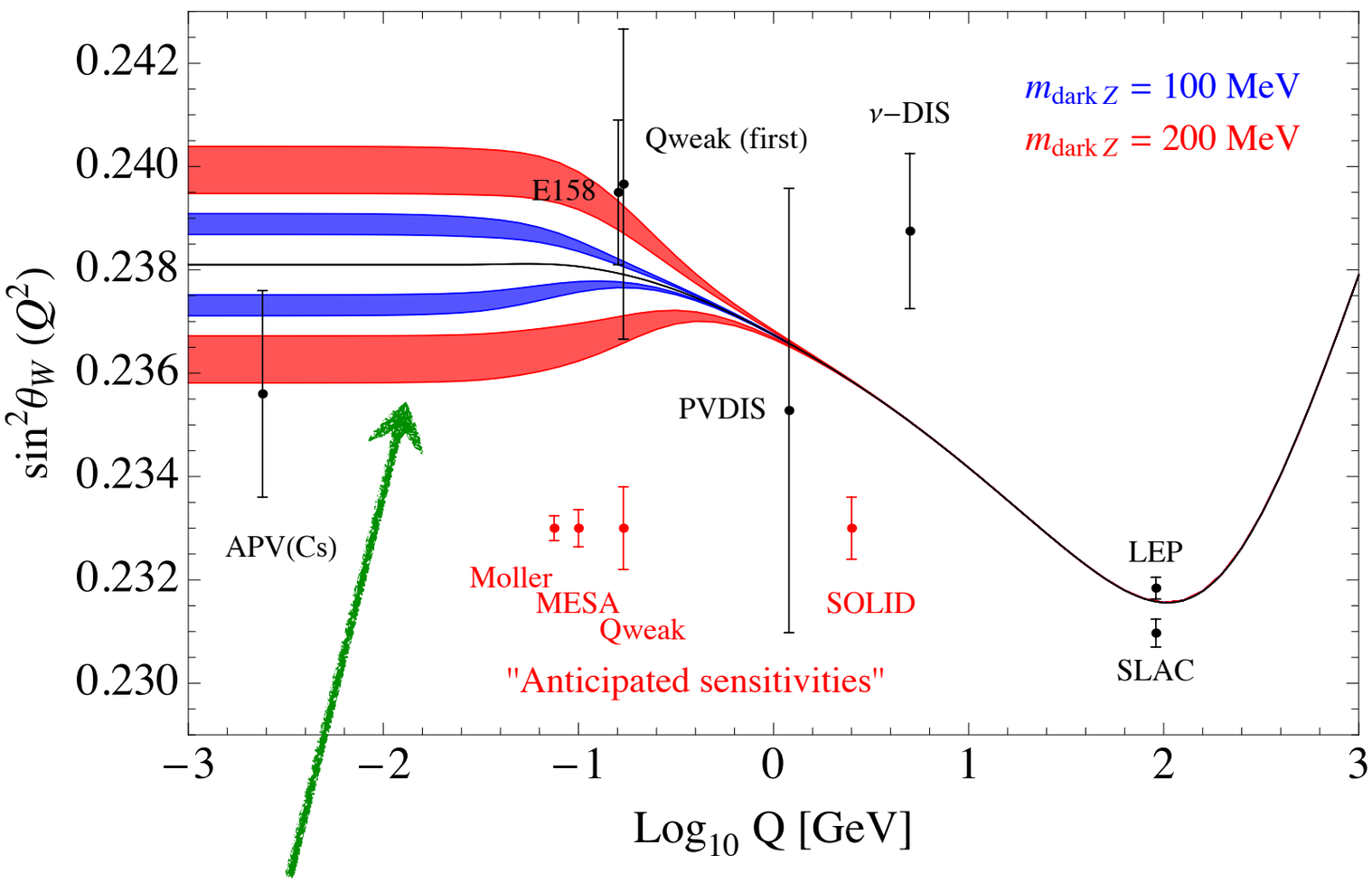
(Ex) With Lepton-jet analysis
for BR(t → bW + Z') = 10^{-3} and
BR(Z' → ℓ ℓ) = 0.2

We suggest re-analysis of the "existing" 8 TeV t tbar data (L_{tot} = 20 fb^{-1}) may give a discovery (at 15σ level) now!



(3) Weinberg angle shift in Low-Q^2

[Davoudiasl, LEE, Marciano (Feb. 2014)]



Dark Z modifies the effective Lagrangian of the weak Neutral Current scattering.

→ Effectively changes Weinberg angle for low momentum transfer (Q ≲ mZ').

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

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

<u>For the Low-Q^2 Parity Test</u> (measuring Weinberg angle), we can use

(i) Atomic Parity Violation (Cs, …)

(ii) Low-Q^2 Polarized Electron Scattering (E158, Qweak, MESA P2, Moller, …)

independent of Z' decay BR (good for both visibly/invisibly decaying Z').

Summary

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

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

Typical Dark Force searches in the Dark Photon model (visible case)

(i) Electron, Muon g-2
(ii) Beam-dumps
(iii) Meson (quarkonium) decays
(iv) e+e- collision
(v) Fixed target experiments

Additional Dark Force searches in the Dark Z model

(1) Rare Higgs decay ($H \to ZZ'$)
(2) Rare Top decay ($t \to bH^+ \to bW + Z$'s)
(3) Low-energy polarized electron scattering (JLab Moller, Mainz P2)

What I still work on include : **modeling and suggesting new channels to search for new light particles**

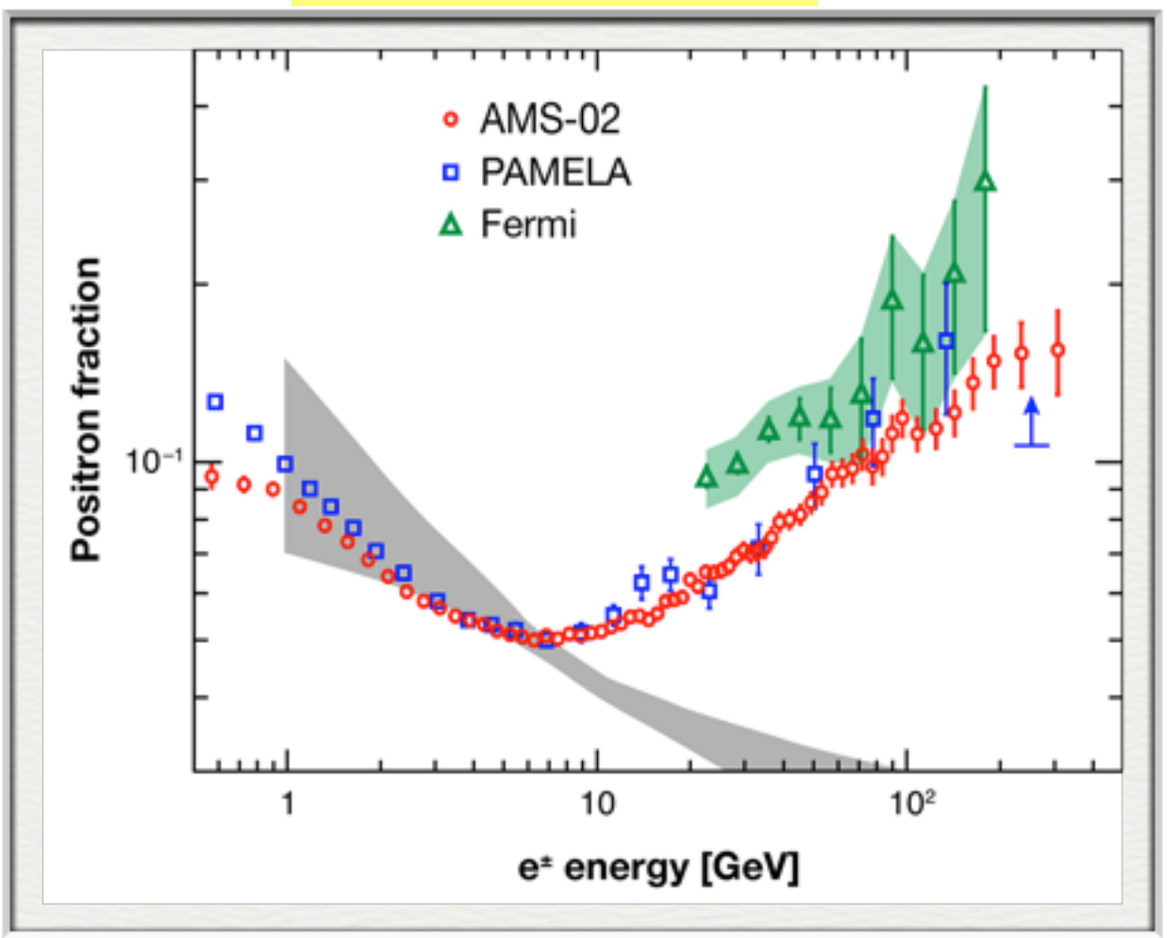
Backup Slides

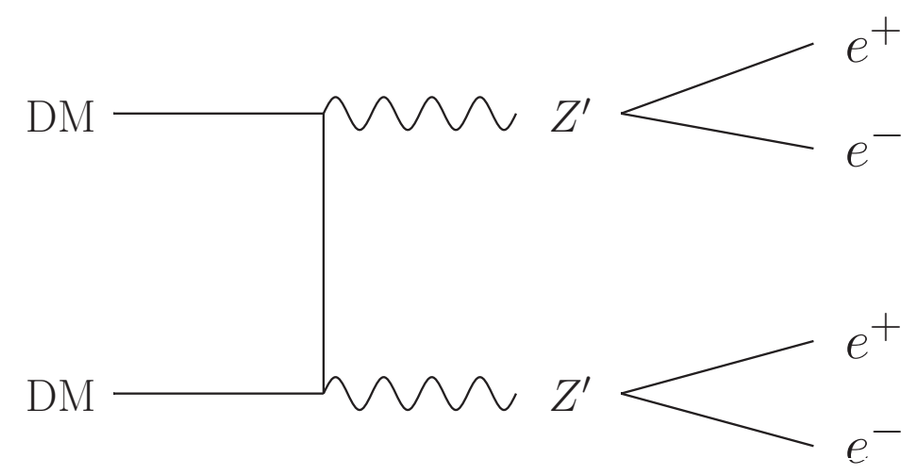
Dark Force (Force among Dark Matters)

Z'
(Dark Force carrier)

- New gauge boson of O(1) GeV scale *(cf. Proton: 1 GeV)*
- Extremely weak couplings to the SM particles

Positron excess



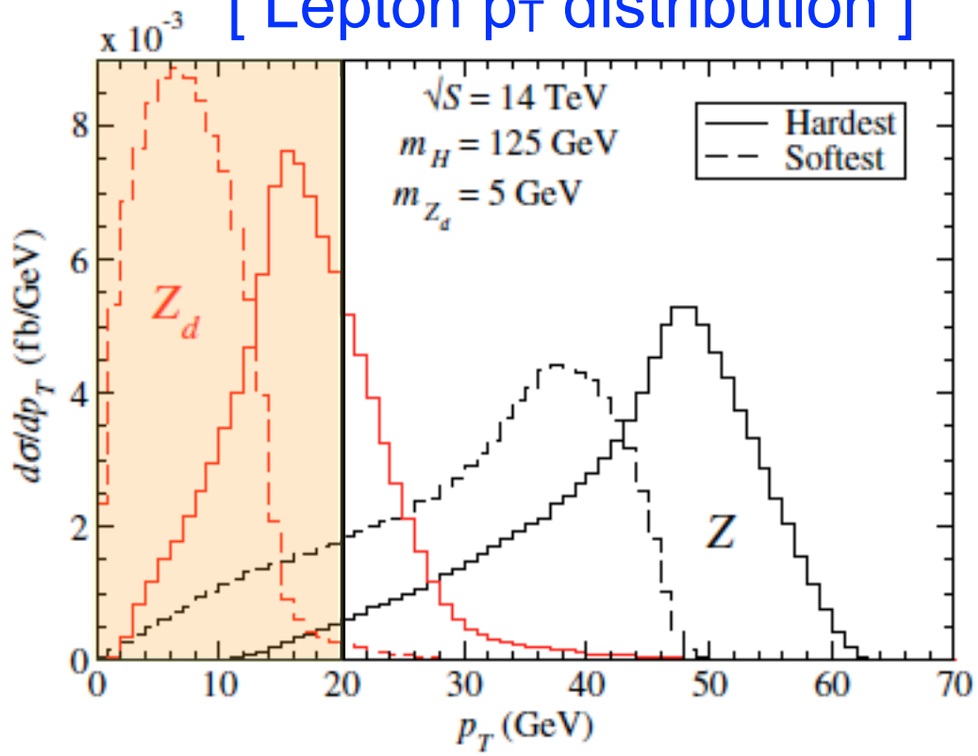


Dark Matter annihilations with Dark Force can explain anomalies including the positron excess.
[Arkani-Hamed *et al* (2008); and others].

No corresponding antiproton excess
: Typical DM annihilation would produce both e+e- and p+p-

Higgs-to-Dark decay at the LHC

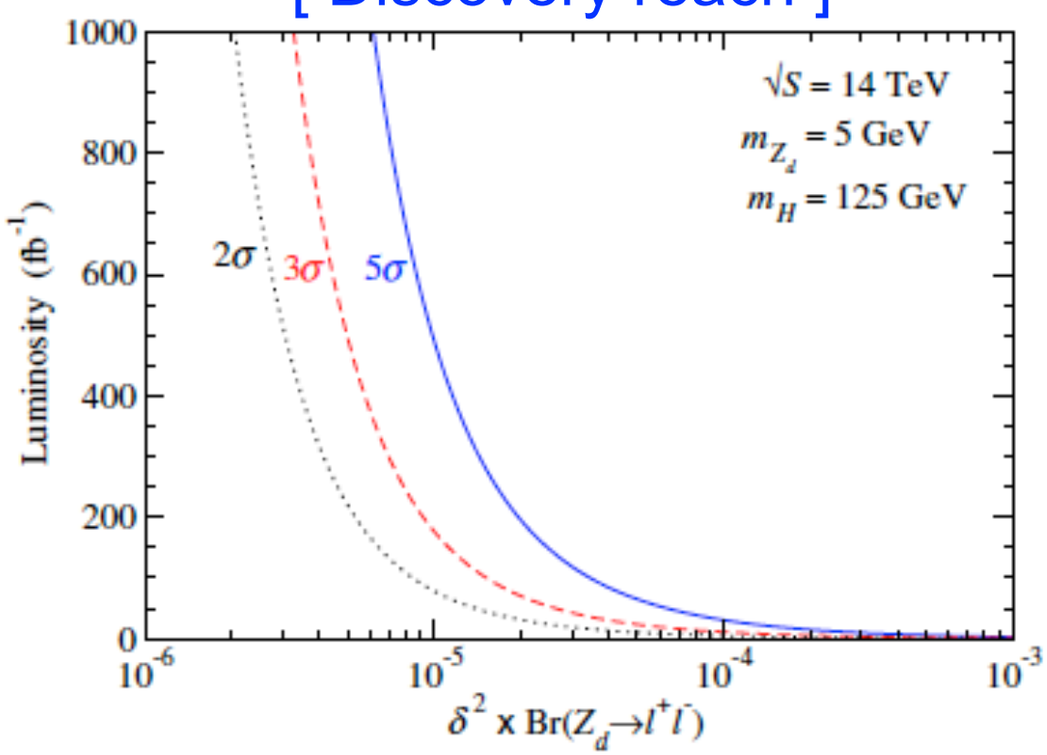
[Lepton p_T distribution]



Typical searches may miss our signal.
(Lepton p_T > 20 GeV, for SM Higgs search $H \to Z Z^* \to 4L$ to avoid $Z \gamma^*$ BKG.)

We suggest lower p_T > 4 GeV,
with invariant mass windows (4L–resonance at mH, 2L–resonance at mZ, 2L–resonance at mZ'.)

[Discovery reach]



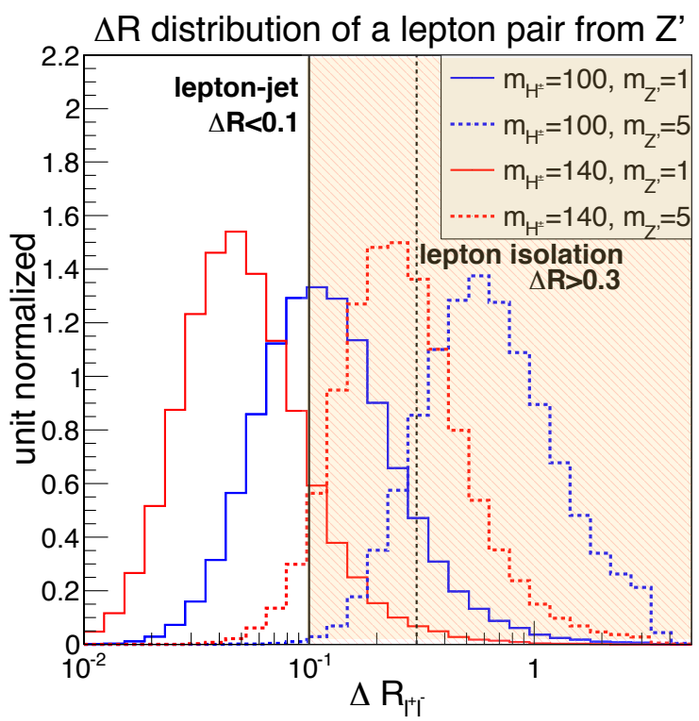
Signal is not very large [$Br(H \to Z Z') \approx 20\ \delta^2$], but mass windows cut out most BKG (S/B ~ 1.5).

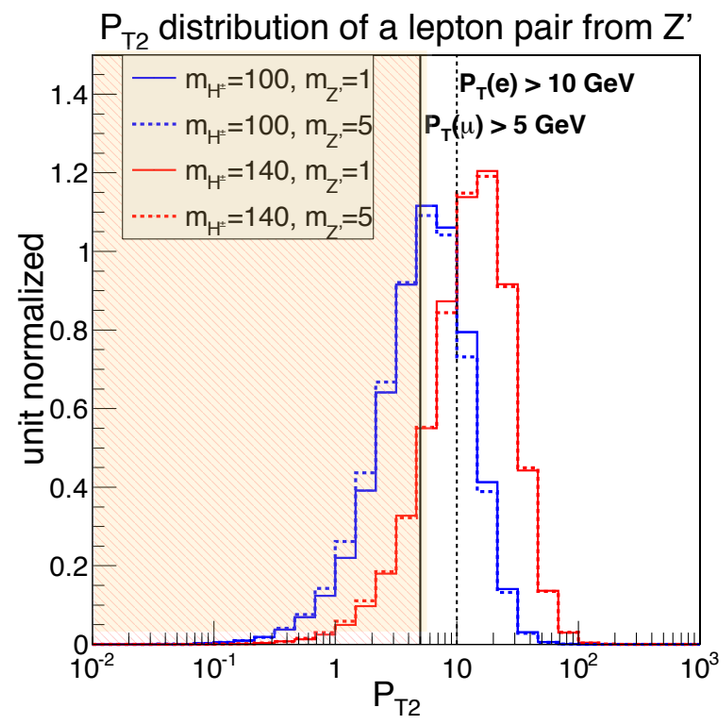
Luminosity ≈ (a few) × 100 fb^{-1} can make 5σ discovery (LHC 14 TeV).

[~ a few years of time]

Top-to-Dark decay at the LHC

Lepton-jet tagging efficiency (in t-decay): Higher for lighter Z', heavier $H^{\pm}$.
(Ex) 45% [mZ' = 1 GeV, $mH^{\pm}$ = 140 GeV], 0.03% [mZ' = 5 GeV, $mH^{\pm}$ = 100 GeV].





Lepton-jet (highly collimated leptons) is a good object developed to analyze the highly boosted Z' decaying into a lepton pair [Arkani-Hamed, Weiner (2008); Cheung, et al (2009)].

We take

1. At least 2 same flavor leptons (e, μ) with p_T > 10 (e), 5 (μ) [in a cone of ΔR < 0.1]
2. Hadronic and leptonic isolation of p_T < 3 [in 0.1 < ΔR < 0.3]
3. |mLJ - mZ'| < 0.2×mZ'

“Dark Z” effects on Weak Neutral Current phenomenology

[Davoudiasl, LEE, Marciano (2012)]

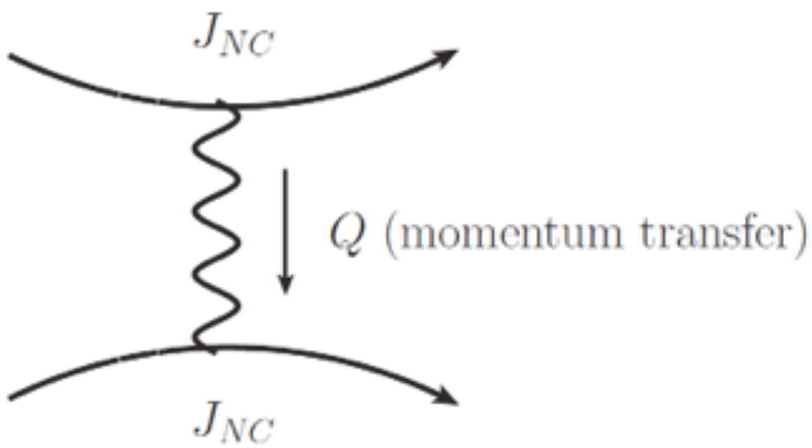
Dark Z : $\mathcal{L}_{\rm int} = -[\varepsilon\, e J^\mu_{em} + \varepsilon_Z\, (g/2\cos\theta_W) J^\mu_{NC}]\, Z'_\mu$

Dark Z **modifies** the effective Lagrangian of <u>Weak Neutral Current scattering</u>.

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

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

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



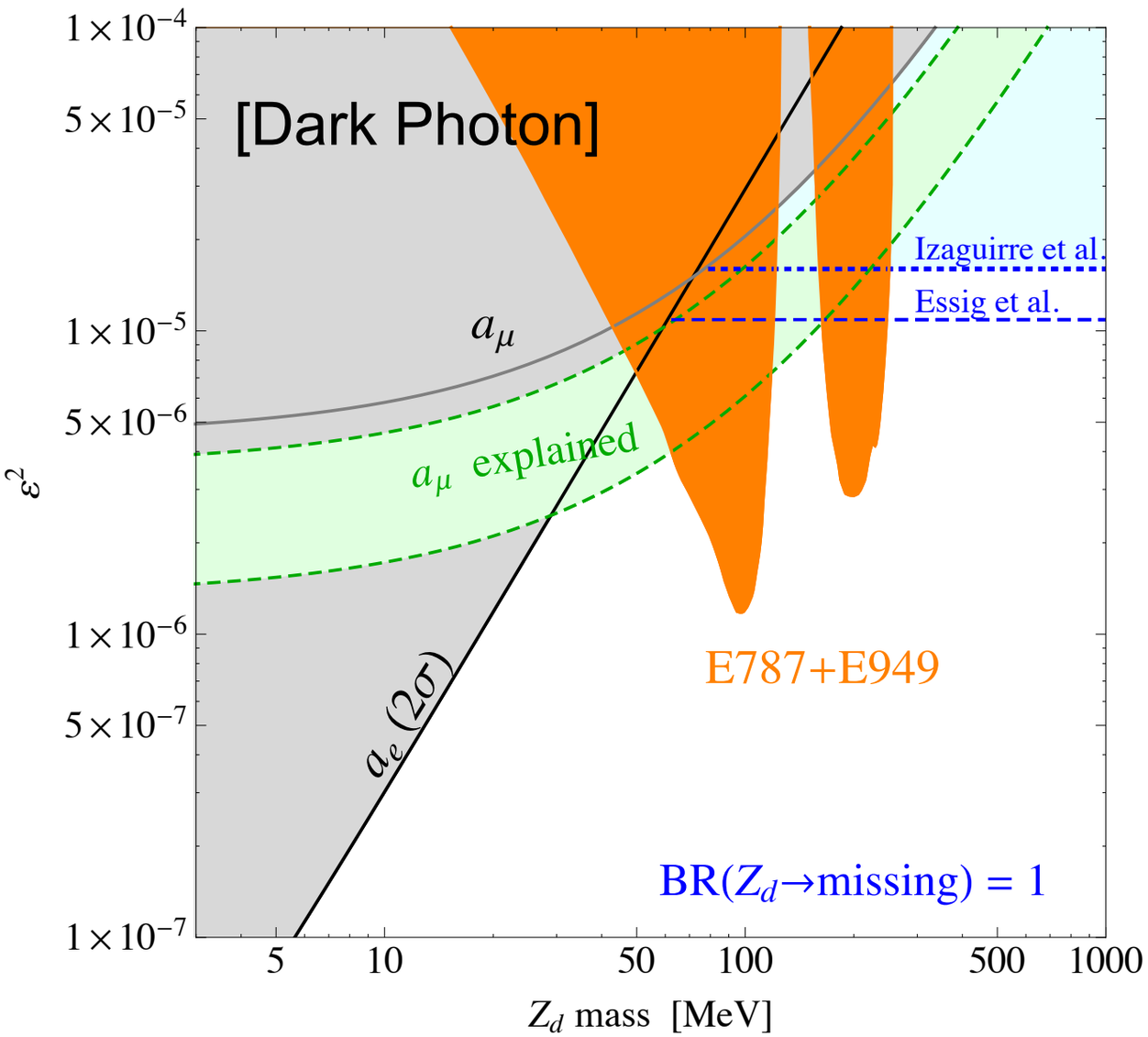
- <u>Sensitive only to Low-Q^2 (momentum transfer).</u> (Effect negligible for $Q^2 >> mZ'^2$)
- Low-Q^2 Parity-Violating experiments (measuring Weinberg angle) are good place to look.

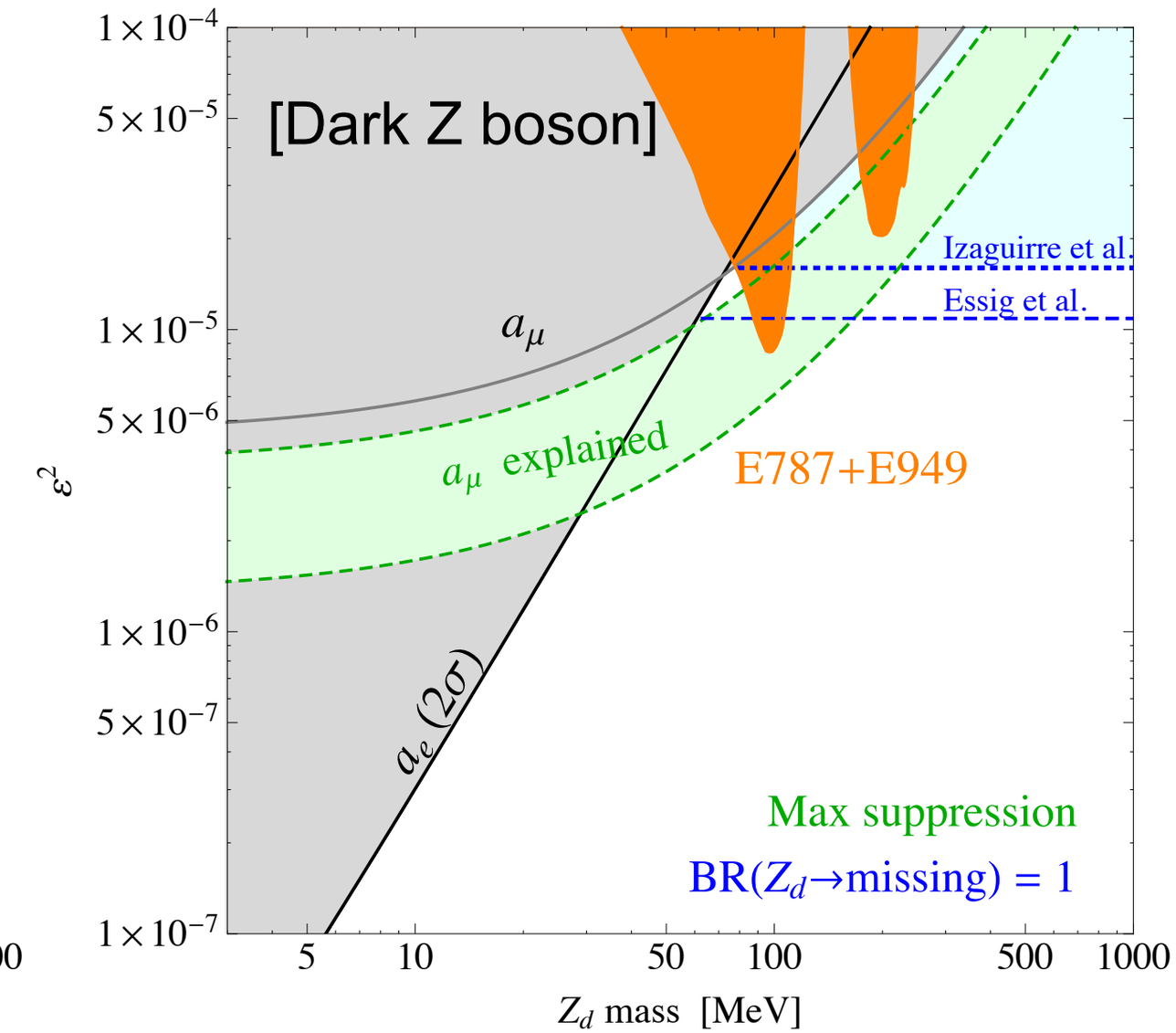
Dark Z effectively changes the weak neutral current scattering (including parity), but only for the “Low” momentum transfer (Q).

Invisibly decaying Dark gauge boson

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

[Davoudiasl, LEE, Marciano (2014)]

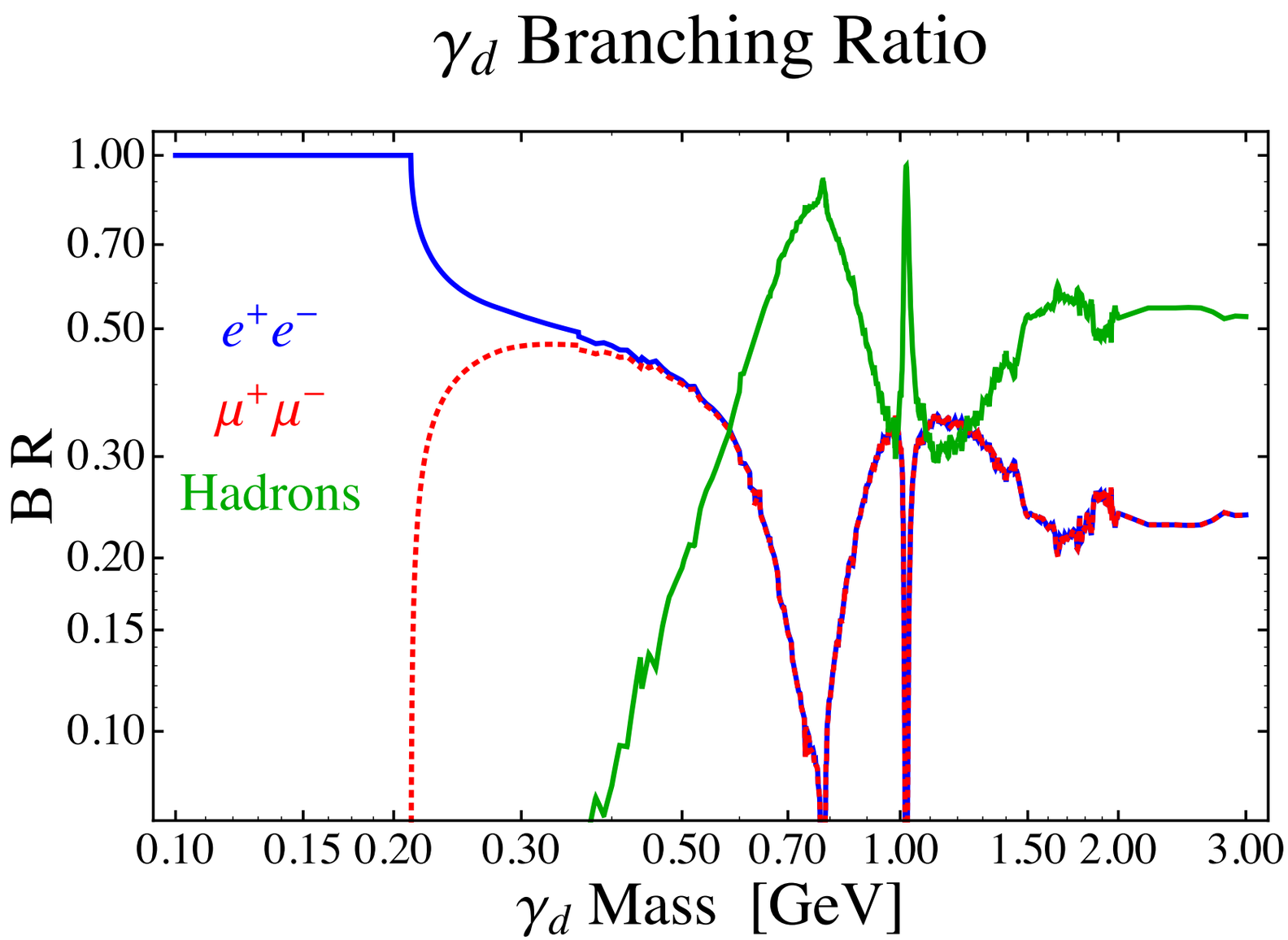




In Dark Z model, because of the additional term (ε_Z term), there can be a sizable interference in the flavor-changing meson decays.

The "K → π + Z' (nothing)" <u>constraints (orange) can be much weaker</u> (1/7 times).

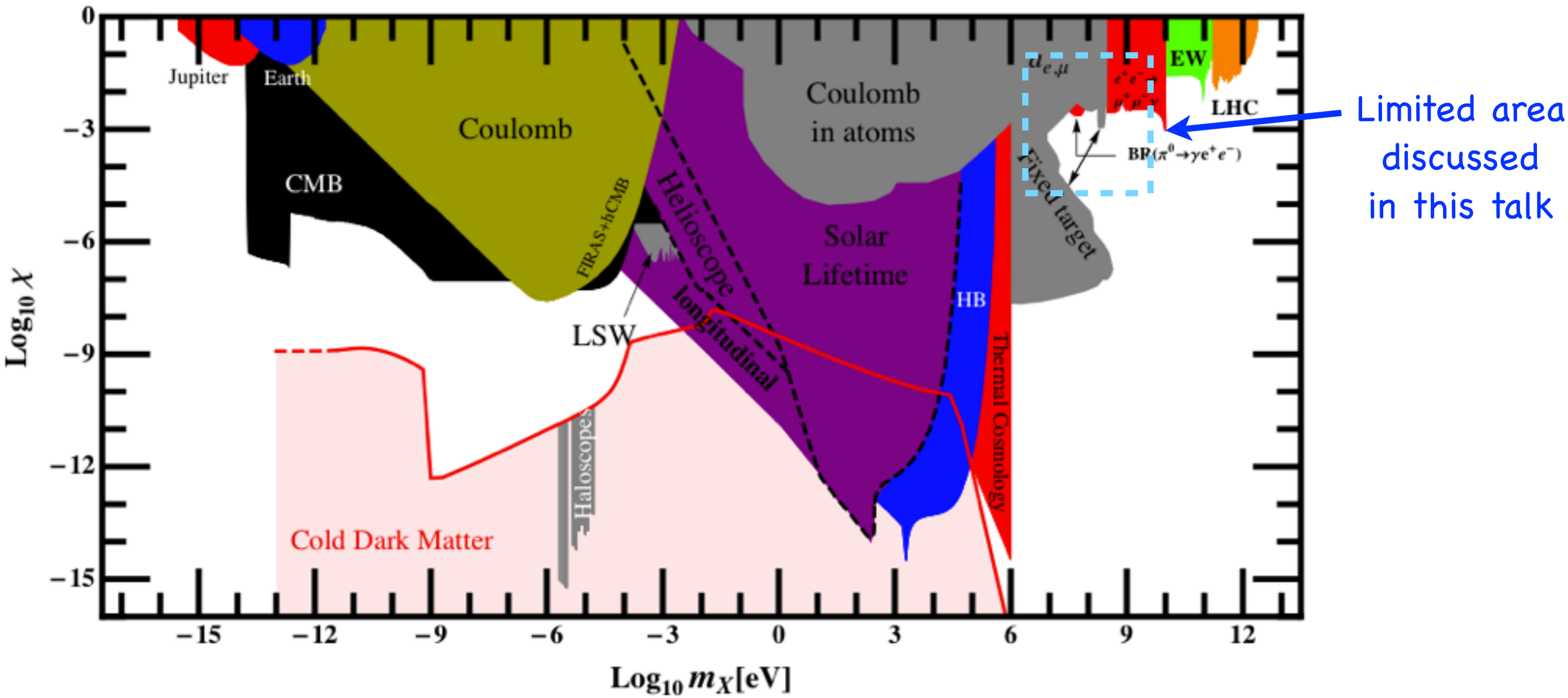
Dark Photon decay branching ratio



[Batell, Pospelov, Ritz (2009)]
[Falkowski, *et al* (2010)]

rho (775 MeV), phi (1 GeV)

Extended range of parameters (of Dark Photon)



[Jaeckel (2013)]

Not entire parameter space is necessarily able to explain some puzzles (positron excess, muon g-2, …), but there are **vast unexplored space** waiting for us.

(Its exploration requires new ideas and experimental innovations.)

Bounds on δ (in Dark Z)

Process	Current (future) bound on δ	Comment
Low Energy Parity Violation	$\lvert\delta\rvert \lesssim 0.08 - 0.01$ (0.001)	Fairly independent of m_{Z_d}. Depends on ε.
Rare K Decays	$\lvert\delta\rvert \lesssim 0.01 - 0.001$ (0.0003)	$m_\pi^2 < m_{Z_d}^2 \ll m_K^2$. Depends on BR($Z_d$).
Rare B Decays	$\lvert\delta\rvert \lesssim 0.02 - 0.001$ (0.0003)	$m_\pi^2 < m_{Z_d}^2 \ll m_B^2$. Depends on BR($Z_d$). Some mass gap ~ 3 GeV.
$H \to ZZ_d$	$\lvert\delta\rvert \lesssim (0.003 - 0.001)$	$m_{Z_d}^2 \ll (m_H - m_Z)^2$. Depends on BR($Z_d$) and background.

TABLE II: Rough ranges of current (future) constraints on δ from various processes examined along with commentary on applicability of the bounds. These processes have negligible sensitivity to pure kinetic mixing effects.

$$\left(\varepsilon_Z = \frac{m_{Z'}}{m_Z}\delta\right)$$