"Dark" Photons: Lepton Magnetic Moments
Rare Dark K Decays
Dark Parity Violation

$K \rightarrow \pi\gamma_d$ $\gamma_d \rightarrow$ "missing energy"

Implications for $\sin^2\theta_W(Q^2)$

Based on work by:

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Outline

1. ***Dark Matter & $U(1)_d$ Symmetry***
   - ***i) Underground Detection vs Positron & γ-ray Excesses***
   - ****ii) (Very) Light Dark Matter (≤100MeV?)***
   - ***iii) Dark Bosons*** *(Dark Photon(γ_d), Dark Z(Z_d), U, Secluded…)*
2. ***Kinetic $U(1)_Y$ x $U(1)_d$ Mixing*** **$\frac{1}{2}\varepsilon/\cos\theta_W B_{\mu\nu} D^{\mu\nu}$**
   - **i) $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(80) \times 10^{-11}$ (*<u>3.6σ discrepancy!</u>*)**
     $\Delta a_e = a_e^{exp} - a_e^{SM} = -105(81) \times 10^{-14}$ (1000x more precise)
   - ***ii) <u>The Dark Photon Solution:</u>*** **$\varepsilon e \gamma_d^\mu J_\mu^{em}$**
   - ***iii) γ_d Searches ($\gamma_d \rightarrow e^+e^-$) ($m_{Zd}$, ε parameter space)***
     $m_{\gamma d} \approx 50$MeV, $\varepsilon \approx 2 \times 10^{-3}$ (being cornered?)

3. *Z-γ_d mass mixing (General Discussion) ➔Z_d & Z*
Non-Conserved Currents $\varepsilon_Z g/2\cos\theta_W Z_d^{\mu} J_{\mu}^{NC}$

. **i) Atomic PV & Polarized Electron Scattering*

**ii) Rare K & B Decays (eg. K➔πZ_d, B➔KZ_d)*

K➔πZ_d➔πe^+e^- or π+"missing energy"

iii) Higgs Decay H➔ZZ_d ➔4 charged leptons

**4. K➔πZ_d➔ π+"missing energy"*
Kinetic Mixing (Pospolov) ~ Mass Mixing (DLM)
(Implications for dark photon searches)

**5. Dark Parity Violation & Running $\sin^2\theta_W(Q)$ New*

6. Outlook

1. Dark Matter & $U(1)_d$ Symmetry

i) Underground Detection vs Positron & γ-ray Excesses

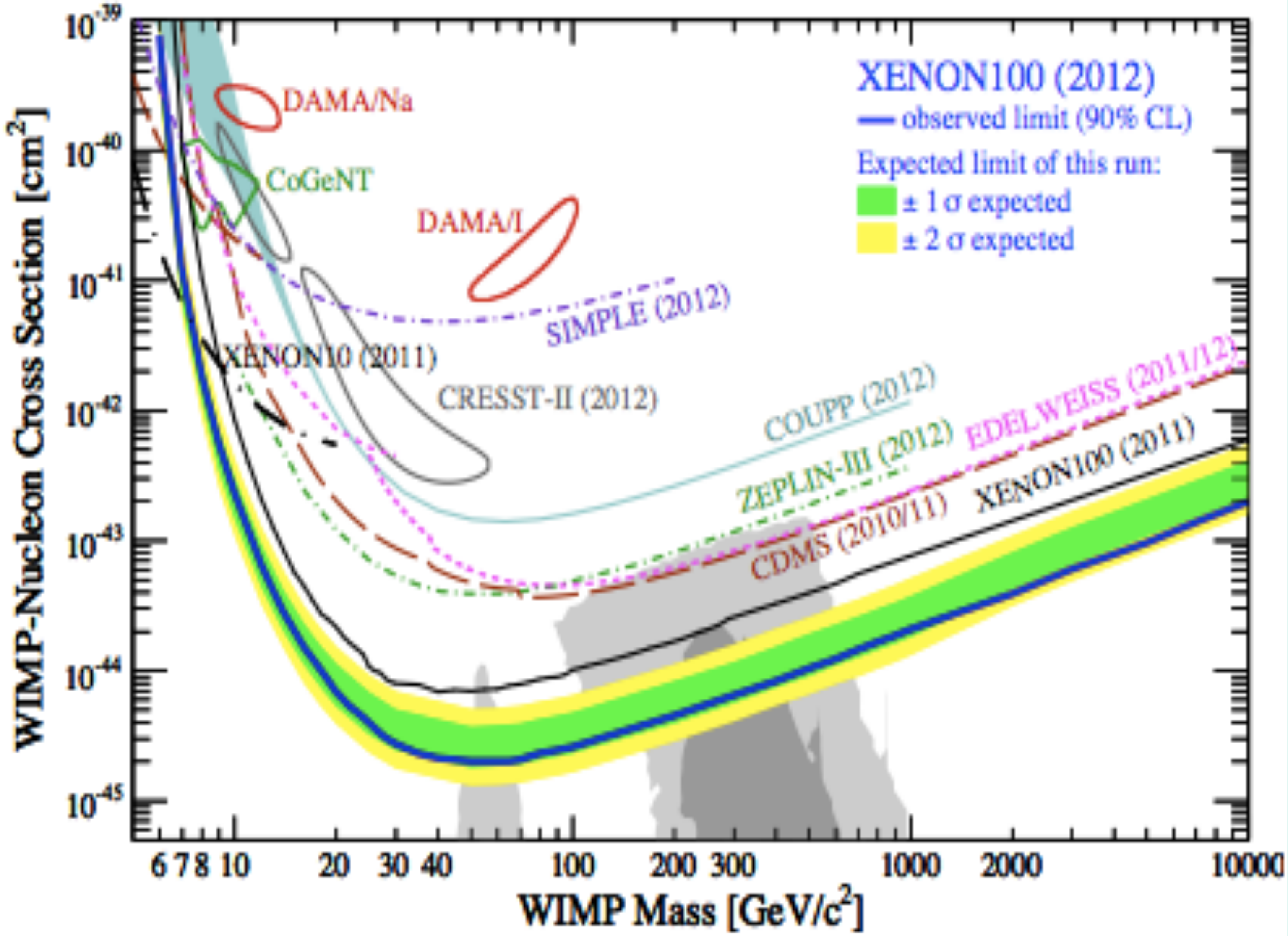
The Hunt For Dark Particles (~80% of all Matter!)

- **Underground Searches** for Dark Matter Particles (WIMPS) $m_\chi \sim 100 GeV$
  Search via coherent elastic scattering off nuclei (Z exchange) ***Recoil***

(Interactions may be spin/isospin dependent)

CDMSII(Si) ***3 events $m_\chi \sim 8.6 GeV$, $\sigma \sim 2 \times 10^{-41} cm^2$***

Consistent with Dama & CoGent but XENON100 Tension



XENON100 (2012)
observed limit (90% CL)
Expected limit of this run:
± 1 σ expected
± 2 σ expected
DAMA/Na
CoGeNT
DAMA/I
SIMPLE (2012)
XENON10 (2011)
CRESST-II (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011/12)
XENON100 (2011)
CDMS (2010/11)
WIMP-Nucleon Cross Section [cm²]
WIMP Mass [GeV/c²]

Astrophysics: Hints of Dark Particle Annihilations

Light or Heavy Dark Matter Particles?

Positron (e^+) Excesses at high energies(?)

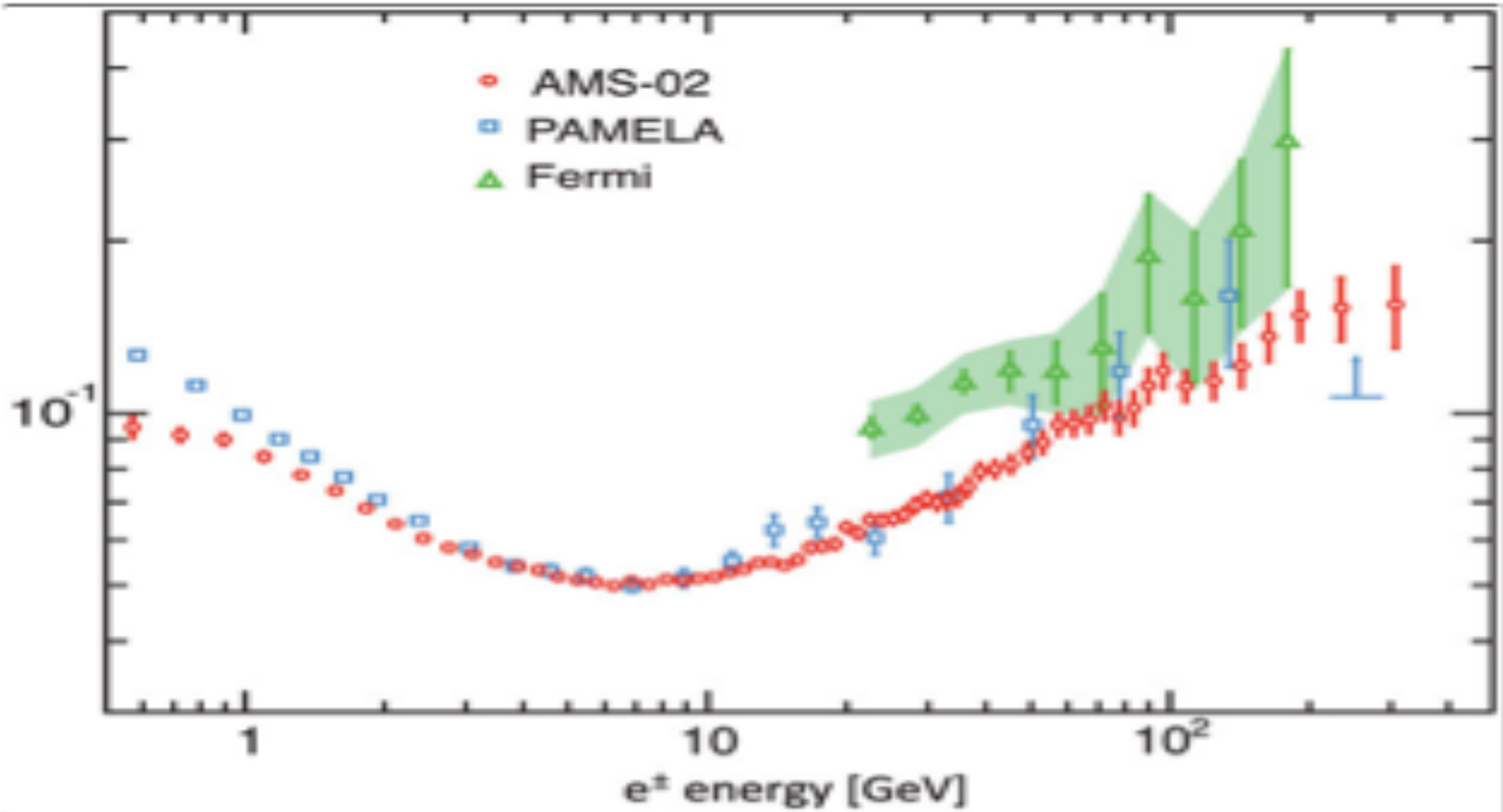
Pamela, Fermi, AMS (Heavy Dark Matter)>TeV? (Unlikely Interpretation?)

Fermi γ-ray Excess from Gallactic Center

Light ~10GeV Dark matter annihilations (➔ e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$)

Both Interesting Effects

Interpretations?



e positron fraction as measured by the AMS (red circles) from 1 to 350 GeV. (Courtesy: *Phys. v. Lett.* **110** 141102)

close or Esc Key

observed.

The Dark Boson – A Portal to Dark Matter

What if some dark **sector** particles interact with one another via a new massive but relatively "light" $\boldsymbol{Z_d}$ (Dark Boson)?
$U(1)_d$ local gauge symmetry of the Dark Sector

Introduced for 1) Sommerfeld Enhancement

2) $Z_d \rightarrow e^+e^-$ (source of positrons, ***γ-rays)***

3) Cosmic Stability $U(1)_d$

eg Wimp Number (S. Weinberg)

*4) Muon Anomalous Magnetic Moment

****5) Light (< GeV) Dark Matter Abundance***

Can we find direct evidence for such a particle (boson)?

Dark Symmetry & Our World

*1. Kinetic $U(1)_Y$ x $U(1)_d$ Mixing (B. Holdom): $B_{\mu\nu}D^{\mu\nu}$

*2. Z-γ_d mass mixing (DLM)

3. $U(1)_d$ = B-L, L_μ-L_τ, L_e-L_μ, L_e-L_τ…

(All or some ordinary particles have dark charge)

$U(1)_d$ Vector Like Small or Large Unquantized Couplings

2. Kinetic $U(1)_Y$ x $U(1)_d$ Mixing (Holdom)

$L_{U(1)YxU(1)d} = -\frac{1}{4}(B_{\mu\nu}B^{\mu\nu} - 2\varepsilon/\cos\theta_W B_{\mu\nu}D^{\mu\nu} + D_{\mu\nu}D^{\mu\nu})$

$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \quad D_{\mu\nu} = \partial_\mu \gamma_{d\nu} - \partial_\nu \gamma_{d\mu}$

$\varepsilon = O(\text{few } x10^{-3})$ or smaller loop effect

Remove Mixing by field redefinitions

$B_\mu \rightarrow B_\mu + \varepsilon/\cos\theta_W \gamma_{d\mu}$ or in terms of γ & Z

$A_\mu \rightarrow A_\mu + \varepsilon\gamma_{d\mu} \quad Z_\mu \rightarrow Z_\mu + \varepsilon\tan\theta_W \gamma_{d\mu}$

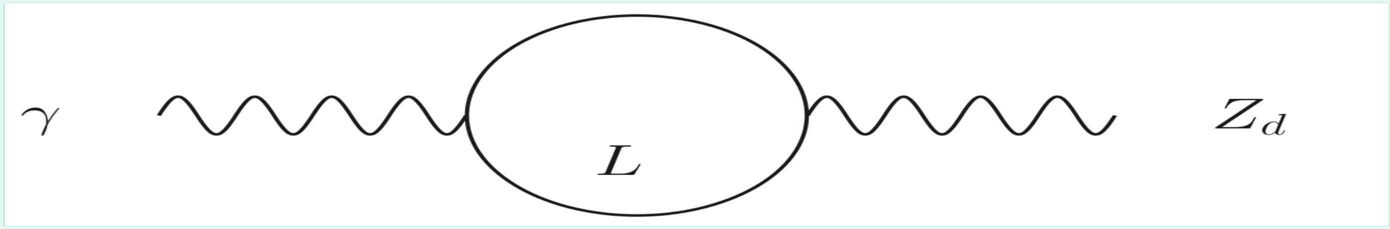
$L_{int} = -e\varepsilon(J_\mu^{em} - 1/2\cos^2\theta_W J_\mu^{NC})\ \gamma_d^\mu$

Second term largely cancelled by Z-γ_d mass matrix diagonalization! (Suppressed at low Q^2)

Remaining Z-γ_d mixing $O(\varepsilon m_{Zd}^2/m_Z^2)$ very small ~10^{-7}-10^{-9}!

Example

One Loop gamma-γ_d Kinetic Mixing
(Through Heavy Charged Leptons)
That also carry $U(1)_d$ charge
Expect $\varepsilon \sim e g_d / 8\pi^2 \approx O(10^{-3})$



The Muon Anomalous Magnetic Moment

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(63)(49) \times 10^{-11}$ **(PDG 2014)**

$288(80) \times 10^{-11}$ (*3.6σ discrepancy!*)

Includes Recent **(Aoyama, Hayakawa, Kinoshita & Nio)*

Note? $\Delta a_e = a_e^{exp} - a_e^{SM} = -105(81) \times 10^{-14}$ **(1000x more precise)**

Interpretations

***Generic 1 loop SUSY Contribution*:**

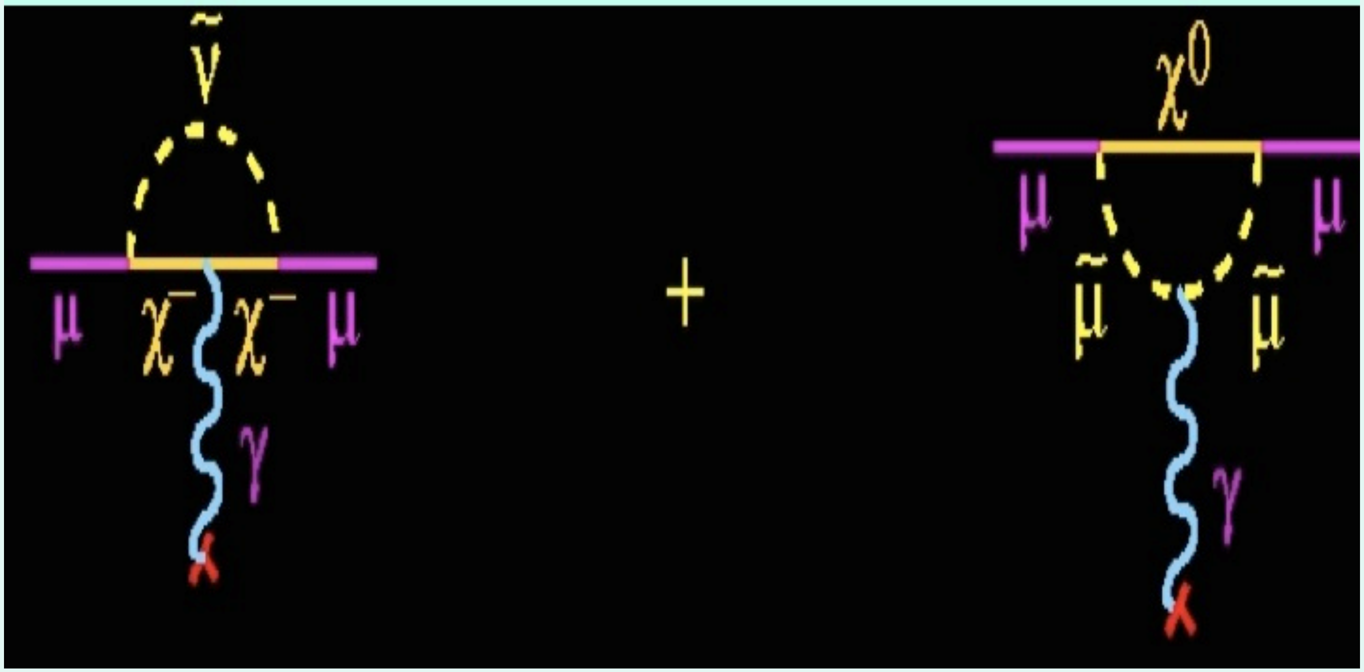
$a_\mu^{SUSY} = (\text{sgn}\mu) 130 \times 10^{-11} (100\text{GeV}/m_{susy})^2 \tan\beta$

$\tan\beta \approx 3\text{-}40$, $m_{susy} \approx 100\text{-}500\text{GeV}$ ***Some LHC Tension***

3.2 “New Physics” Effects

_SUSY 1 loop a_μ Corrections

(Most Likely Scenario)



Other Explanations: ***Hadronic e^+e^- Data? HLBL (3loop)?***

Multi-Higgs Models (2 loop)

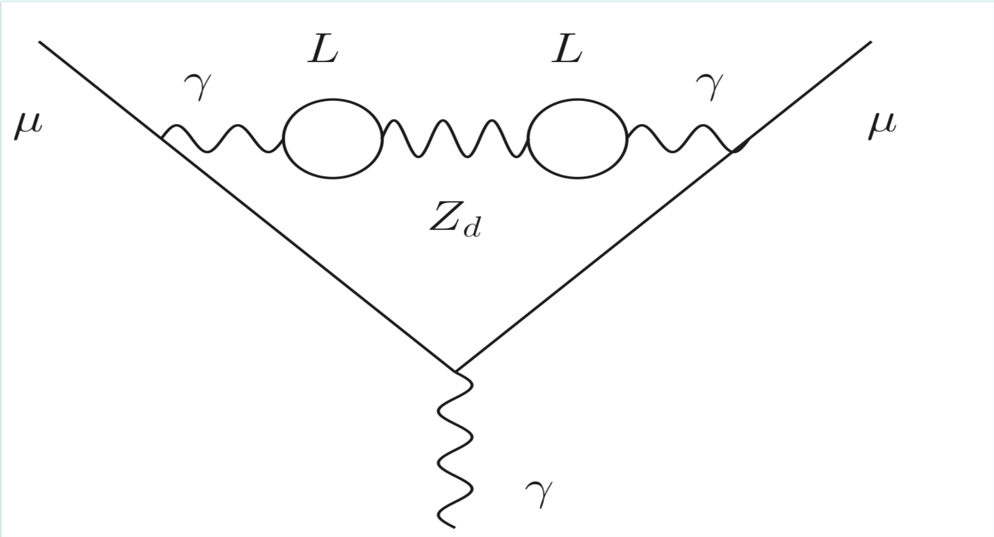
Extra Dimensions<2TeV, Heavy Z', Dynamics…

Light Higgs Like Scalar <10MeV?

* ***Dark Photons (Fayet, Pospelov…)***

$a_\mu^{Zd}=\alpha/2\pi\varepsilon^2 F(m_{Zd}/m_\mu)$, $F(0)=1$ solves g-2 discrepancy

for $\varepsilon^2 \approx 10^{-6}$-$10^{-4}$ & $m_{Zd} \approx$ 10-500MeV (see figure)



Z_d contribution to a_e

- **$a_e^{Zd}=\alpha/2\pi\varepsilon^2F(m_{Zd}/m_e)>0$ (Vector Interaction)**

a_e(exp) − a_e(theory) = −1.05 (0.81) × 10^{-12} (sign!) <1.4x10^{-12}

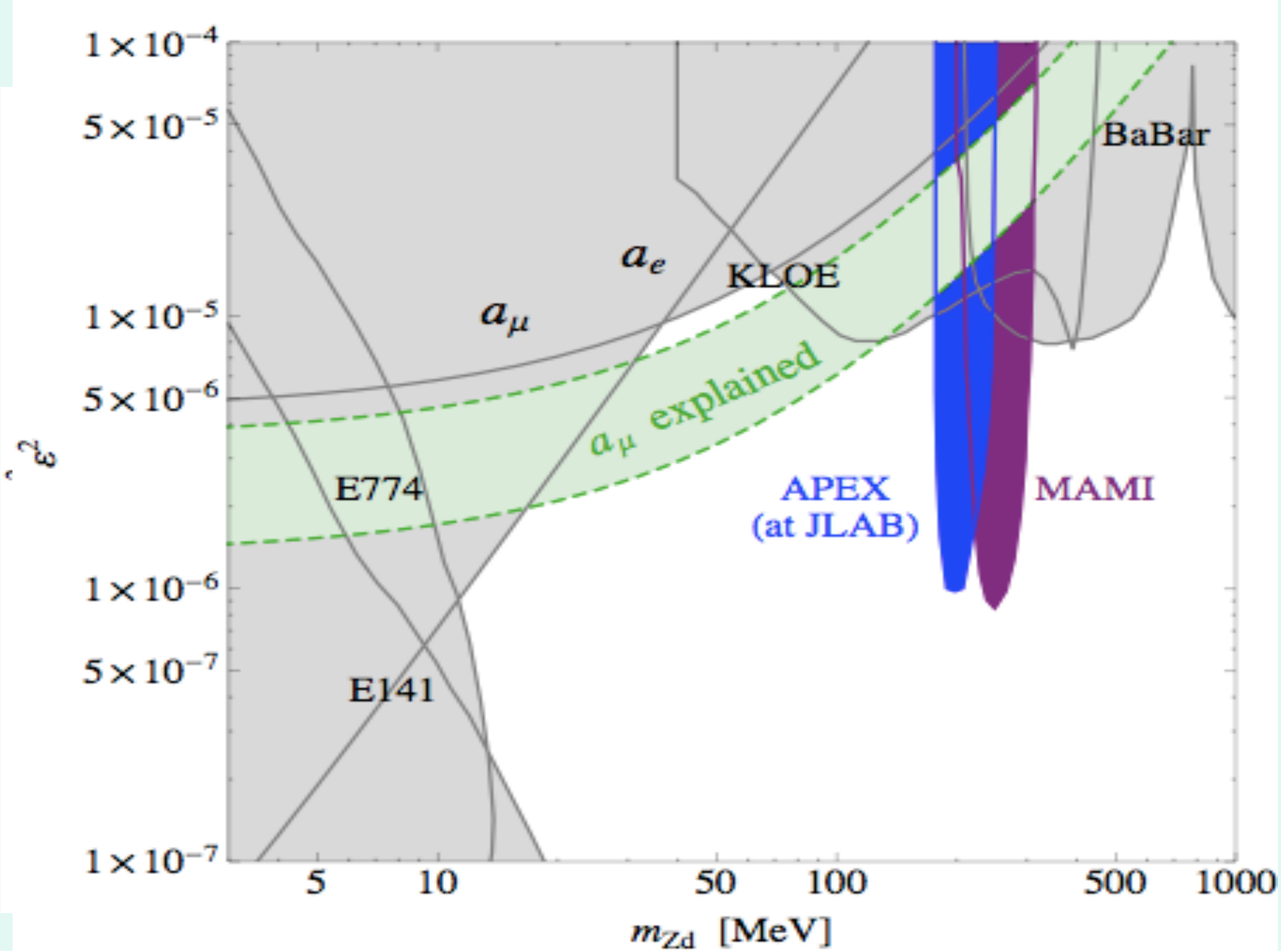
3 sigma CONSTRAINS "NEW PHYSICS" (eg Dark Photon)

Important Recent Improvement: Needs further scrutiny:

α^{-1}(^{87}Rb)=137.035999049(90) R. Bouchendira et al. (2011)

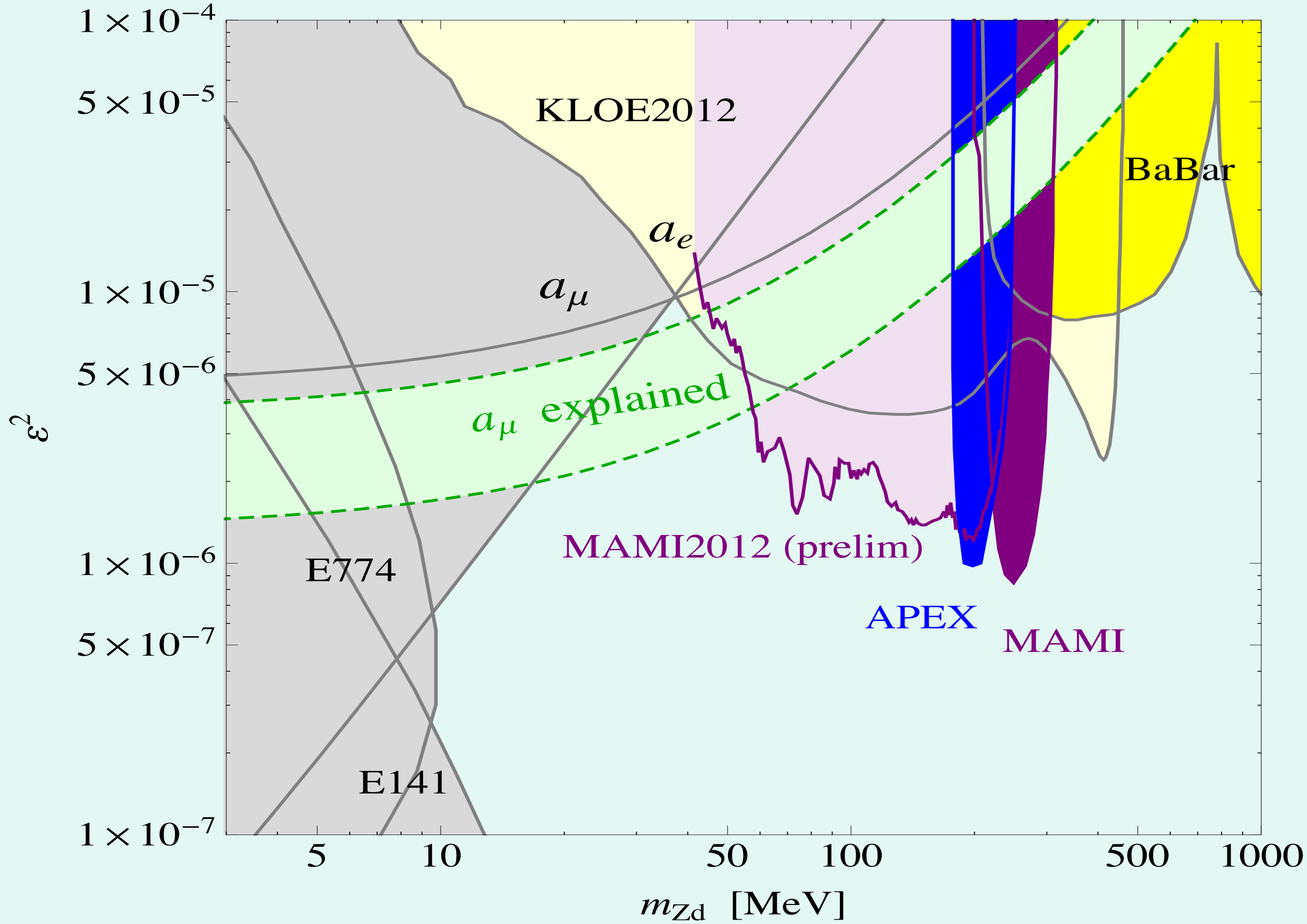
Future Improvement? (factor 3!)

Dark Photon Exclusion Early 2012
(Some assume BR(Z_d → e^+e^- ~ 1)



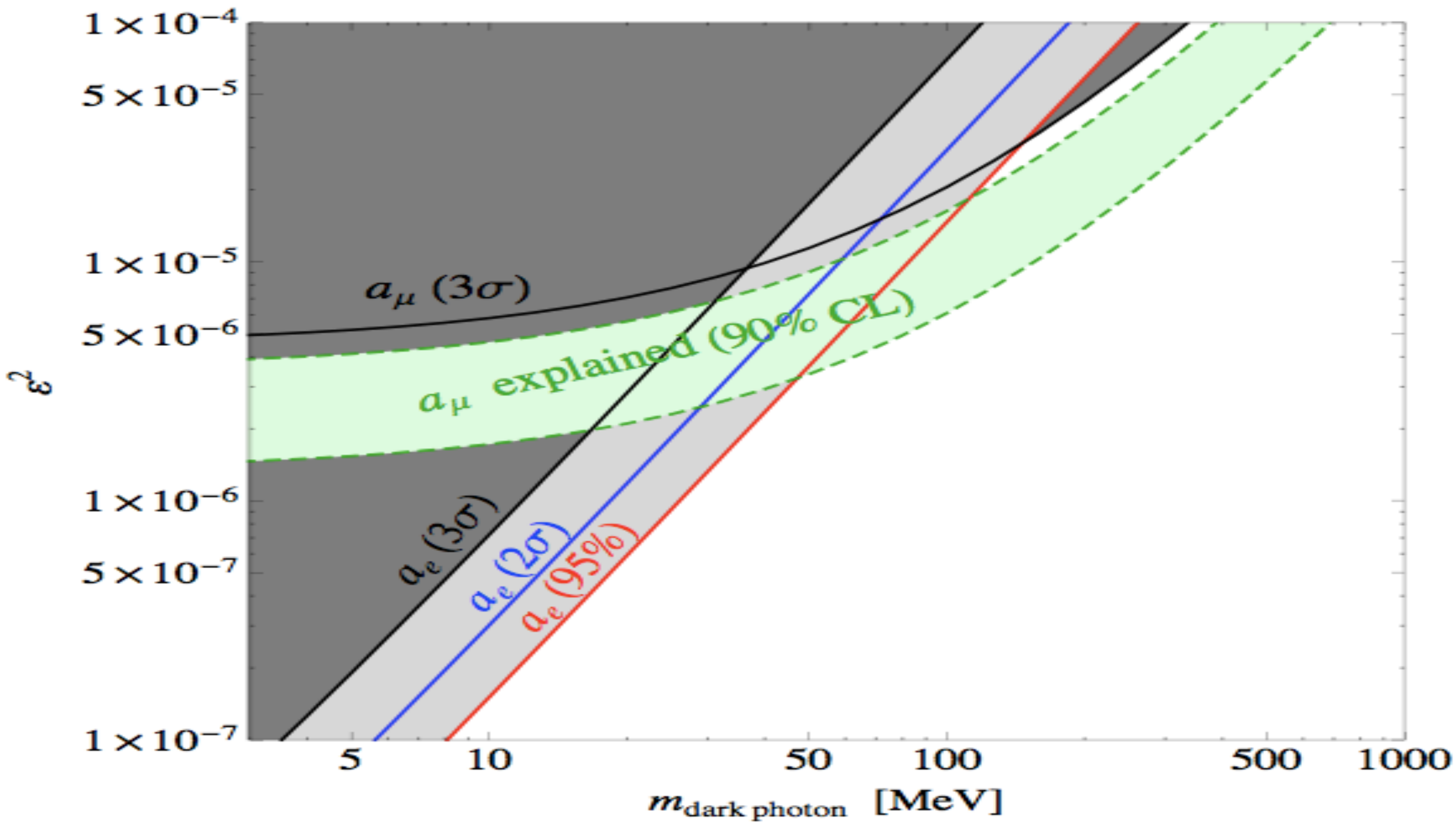
Recent Updates➔20MeV-50MeV Left

2013 COSY π^0➔γZ_d➔e^+e^- Not Shown



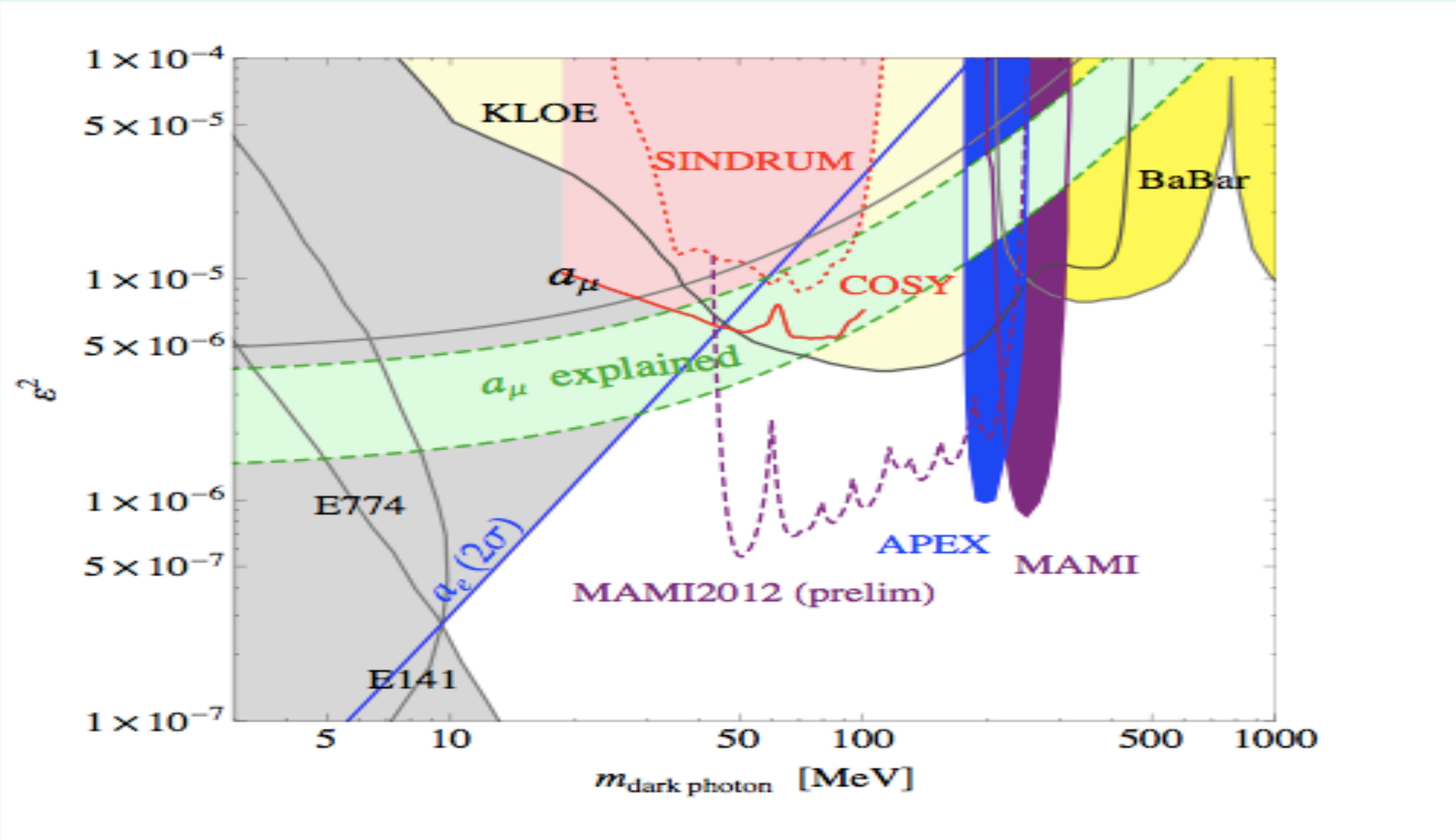
Lepton Magnetic Moment Constraints on the Dark Photon

(Green Band Correspods to a_μ^{exp}-a_μ^{SM}=288(63)(49)x10^{-11}) 90% CL

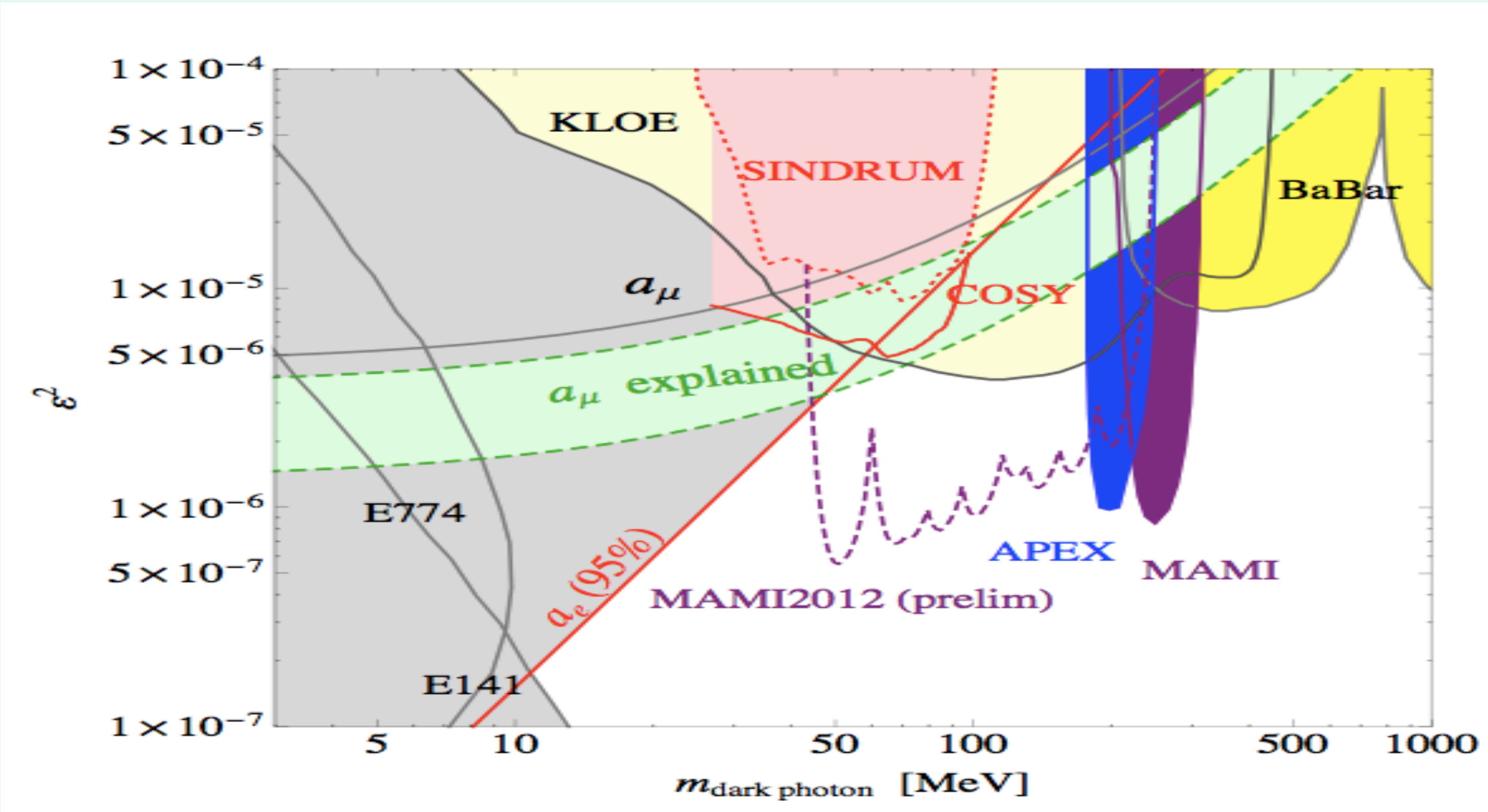


Updated Dark Photon Constraints

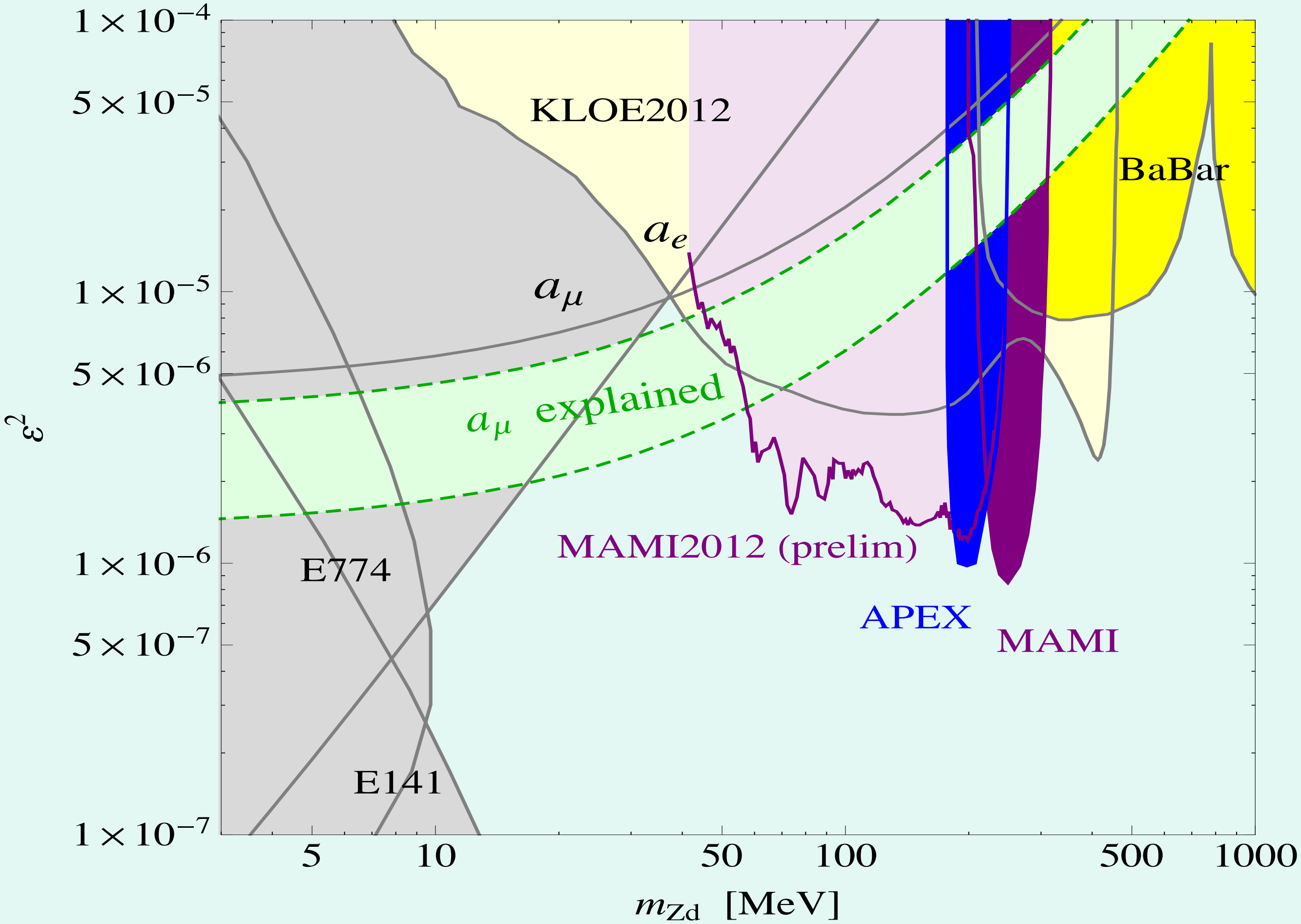
(Some assume BR(Zd➔e⁺e⁻ ~ 1)



Updated Dark Photon Constraints
(Some assume BR(Zd→e⁺e⁻ ~ 1)
a_e at 95% CL

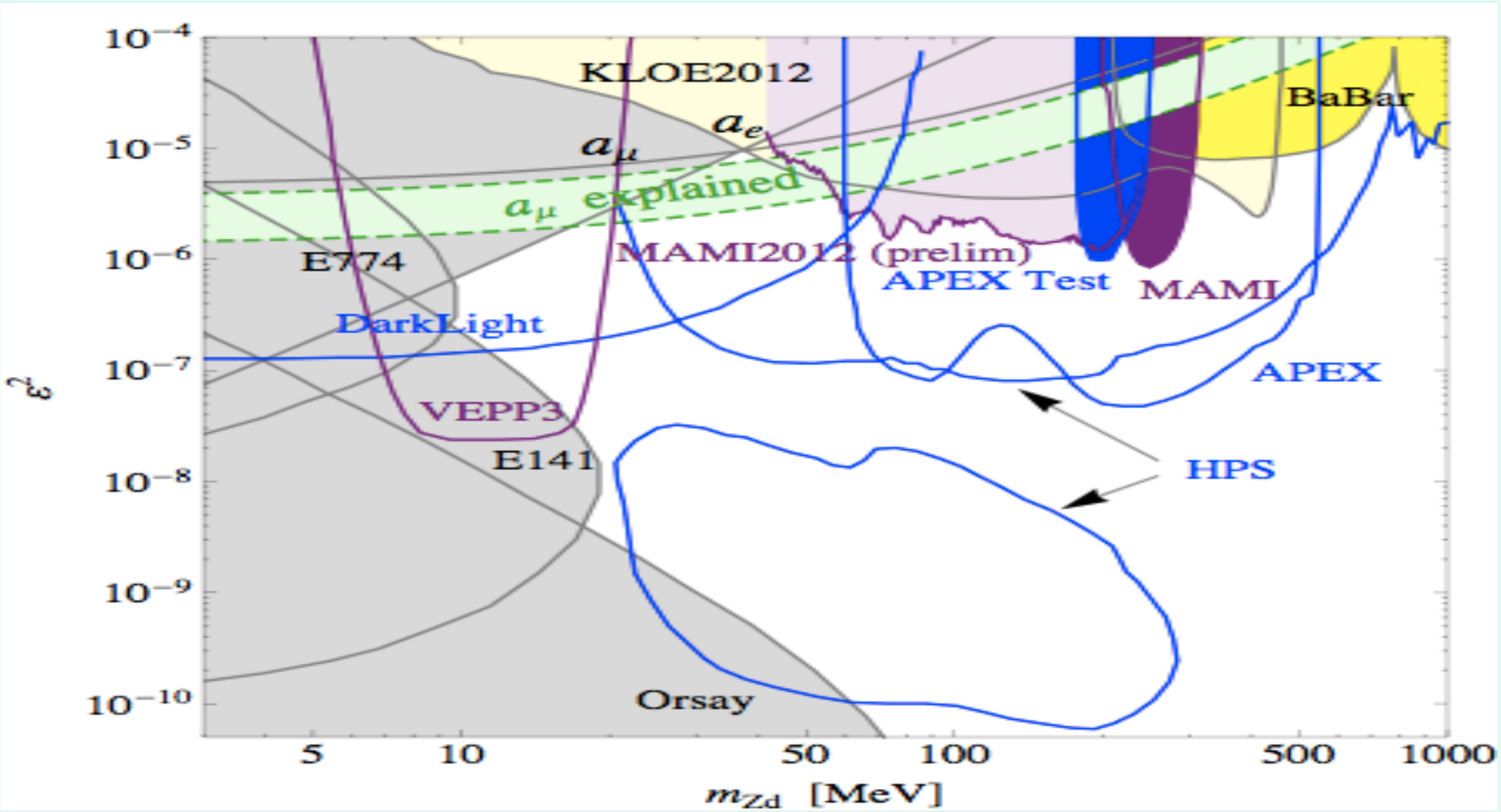


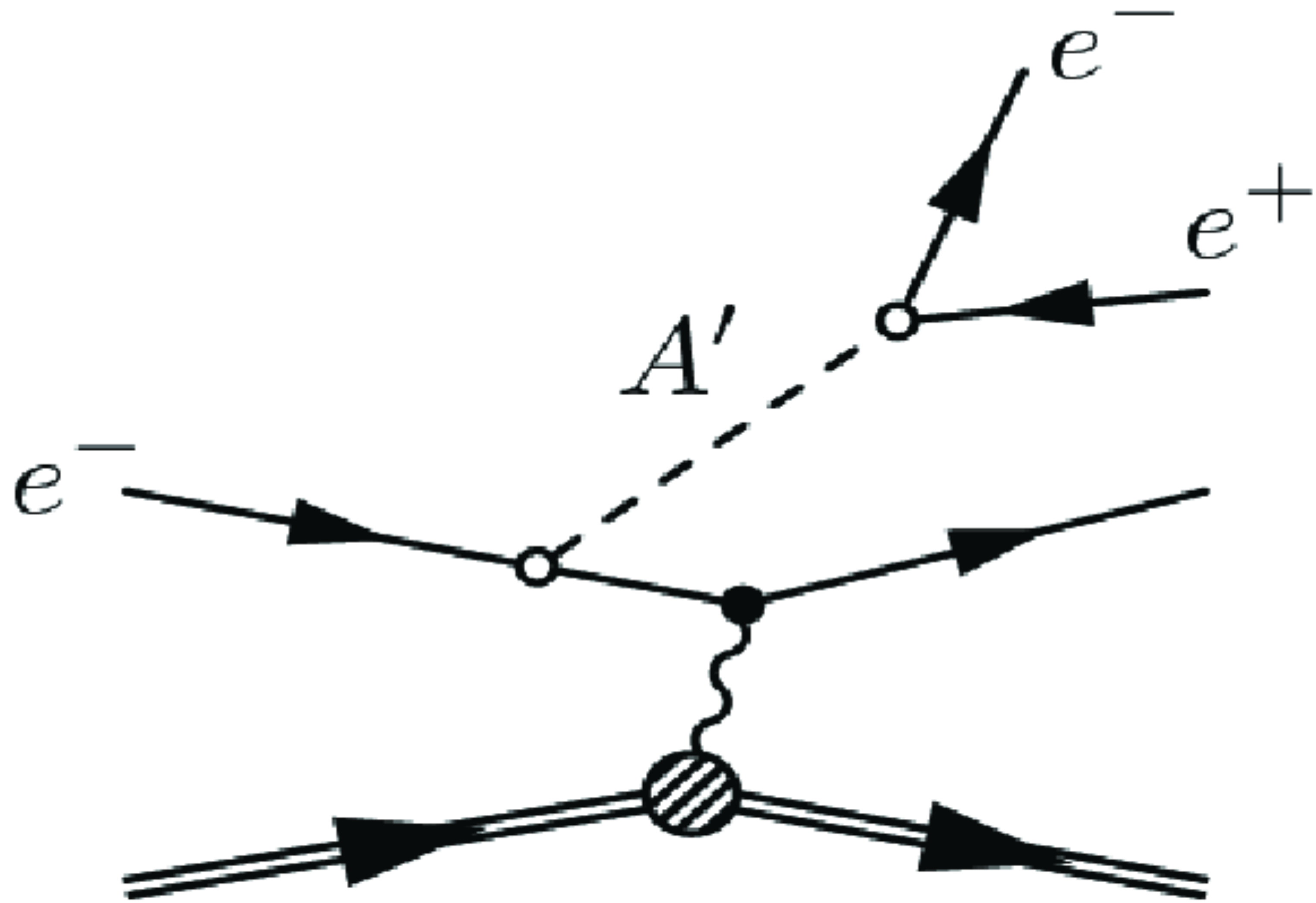
Recent Updates➔20MeV-50MeV Left
2013 COSY π^0➔γZ_d➔e^+e^- Not Shown



Current Bounds & Future Dark Photon Sensitivity

Assumes Br(Z_d→e^+e^-)=1 What if Z_d→missing energy?




e^-
e^+
A'
e^-

Light Dark Matter Alternative

Very light Dark Matter (10-100-few hundred MeV) can be a viable scenario (Fayet, Pospelov …)

Needs Dark Photon!

May require strong dark coupling g_d~10e!

Strong Dynamics?

We examine the consequences of

BR(Z_d➔light dark matter) ~1. Invisible Decays

Pospelov et al: Light Dark Matter may be part of accelerator produced neutrino beams.

BR(π^0➔γ +Z_d)~O(10^{-5}-10^{-6}) Z_d➔light Dark matter

MiniBoone Proposal

3. ***Z-Z_d mass mixing***

$\varepsilon_Z = m_{Zd}/m_Z\delta \rightarrow \varepsilon_Z g/2\cos\theta_W Z_d^{\mu} J_{\mu}^{NC}$

Neglecting Kinetic Mixing ε

$$M^2 = \begin{bmatrix} m_Z^2 & -m_{Zd}m_Z\delta \\ -m_{Zd}m_Z\delta & m_{Zd}^2 \end{bmatrix}$$

$0 \leq |\delta| < 1$

$\delta \approx (m_{Zd}/m_Z) << 1$

Mixing angle $\approx \varepsilon_Z = m_{Zd}/m_Z\delta \sim (m_{Zd}/m_Z)^2 \sim 10^{-6}$

Gives rise to: $g/2\cos\theta_W(m_{Zd}/m_Z\delta)J_{\mu}^{NC}$

Like a Z with smaller mass and couplings

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

Extended Higgs Example

1st Higgs Doublet $<\phi_1>=v_1$ ➔ $W^{\pm}$, Z, fermion masses

2nd Higgs Doublet $<\Phi_2>=v_2$ dark charge (Portal) $W^{\pm}$,Z, Z_d masses

3rd Higgs Singlet $<\phi_d>=v_d$ carries dark charge: Z_d mass

$\tan\beta = v_2/v_1 \quad \tan\beta_d=v_2/v_d$

$\varepsilon_Z=m_{Zd}/m_Z \sin\beta \sin\beta_d \approx m_{Zd}/m_Z\, v_2^2/v_1 v_d$ **(very small)**

➔ **parity violation (like ordinary Z but suppressed by ε_Z)**

longitudinal Z_d like an axion E/m_{Zd} coupling!

At High Energies Z_d Axion Like but spin 1!

Dark Parity Violation

Effect of ε & ε_Z together: (at low $Q^2 << m_Z^2$)

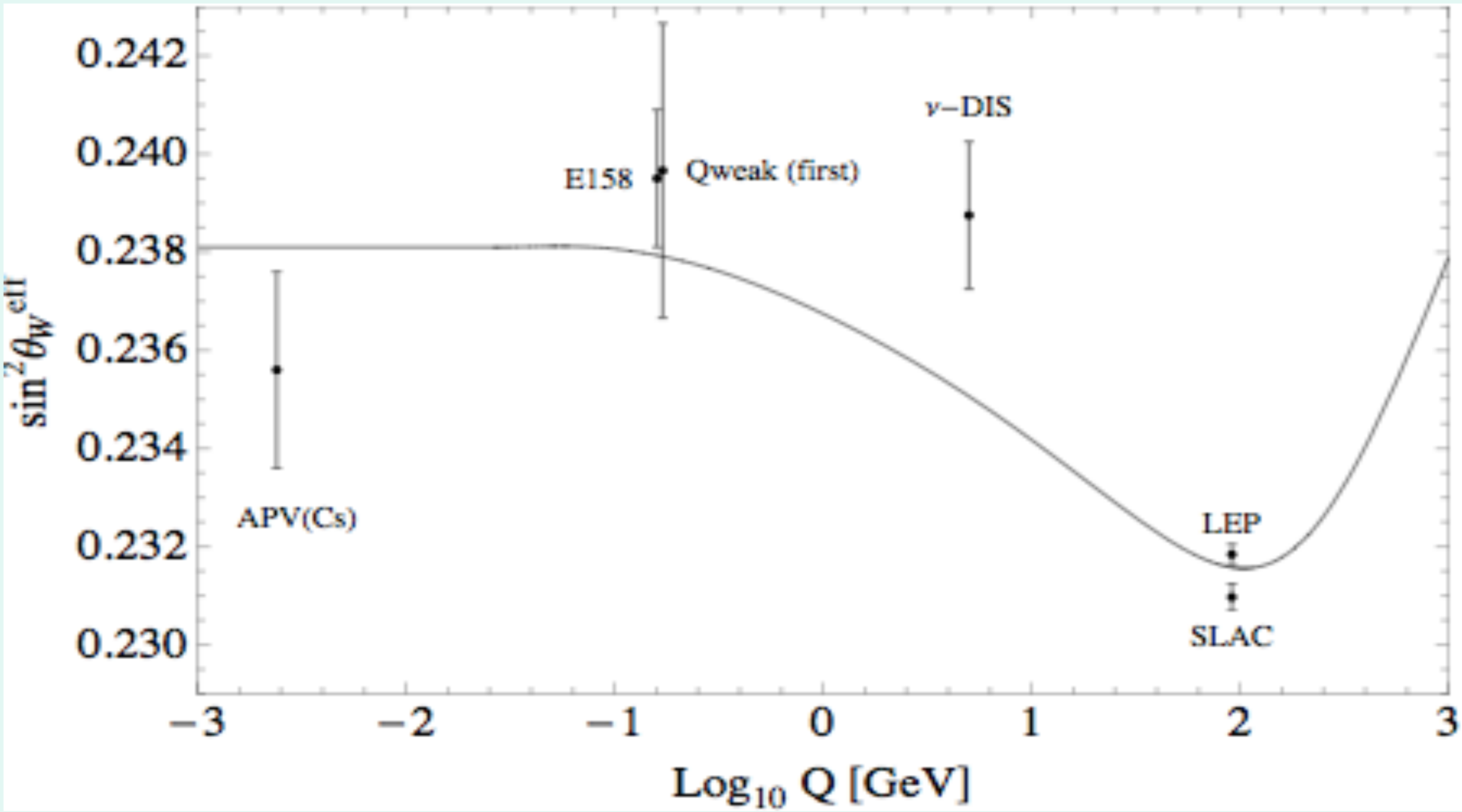
$\Delta\sin^2\theta_W(Q^2) = 0.42\varepsilon\delta m_Z m_{Zd}/(Q^2+m_{Zd}^2) \approx 0.42\varepsilon m_{Zd}^2/(Q^2+m_{Zd}^2)$

Shift largest at small $Q^2 < m_{Zd}^2$

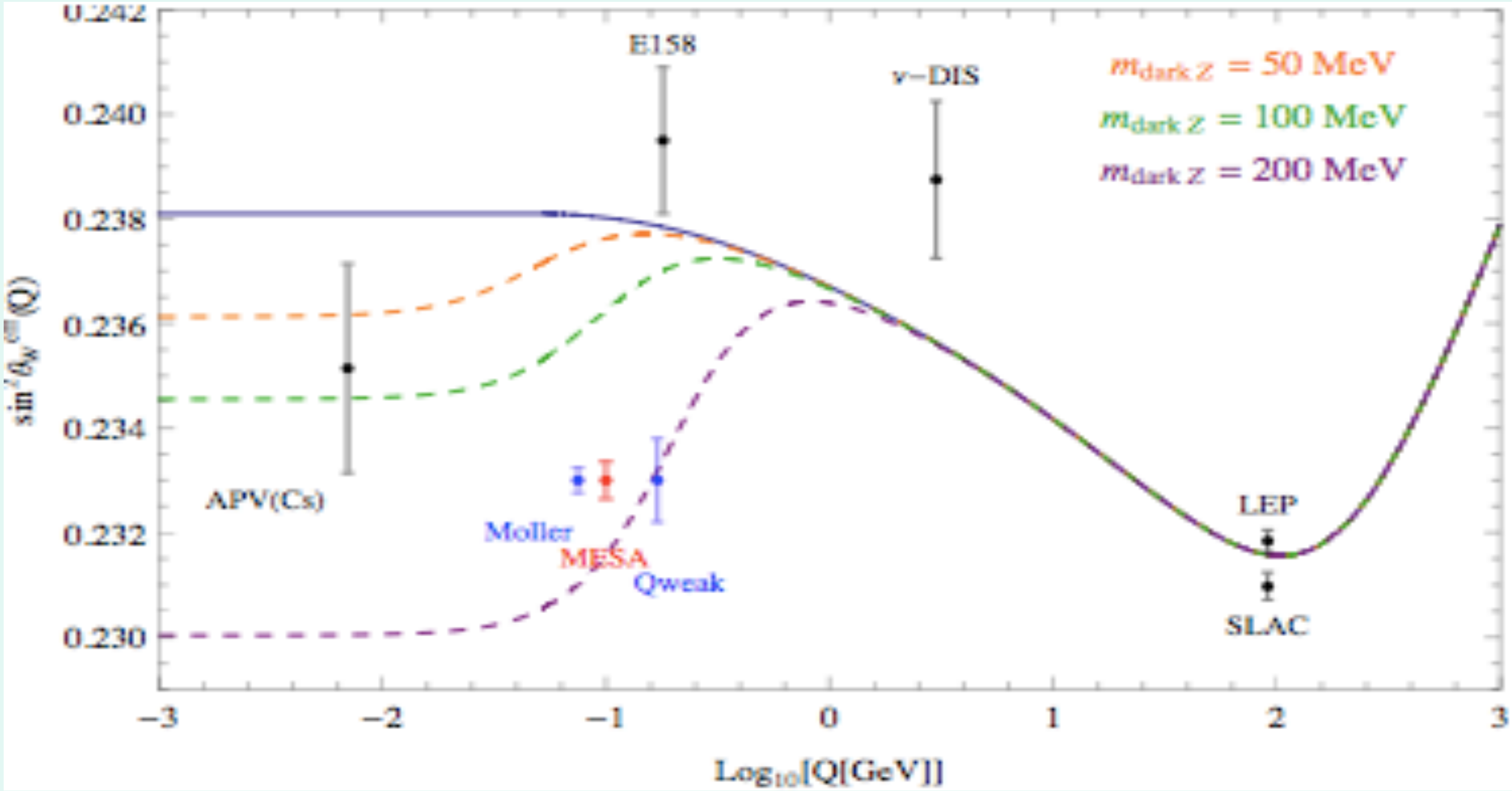
APV & **m_{Zd} *=50MeV*➔ $\sin^2\theta_W(Q \approx 75\text{MeV})$ shift by <u>0.0010</u>!**

<u>Negligible effect at the Z Pole!</u>

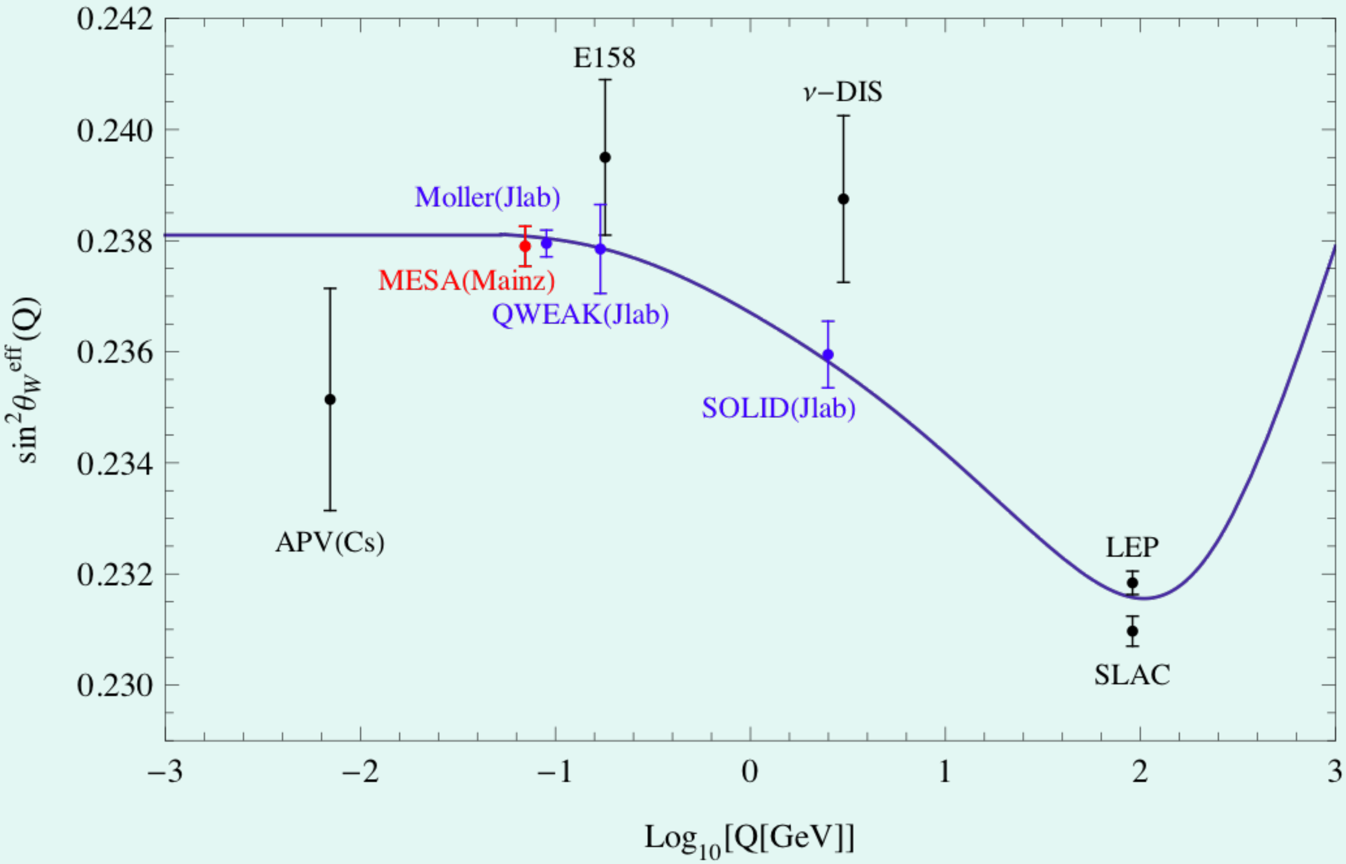
Current Status of Running weak mixing angle



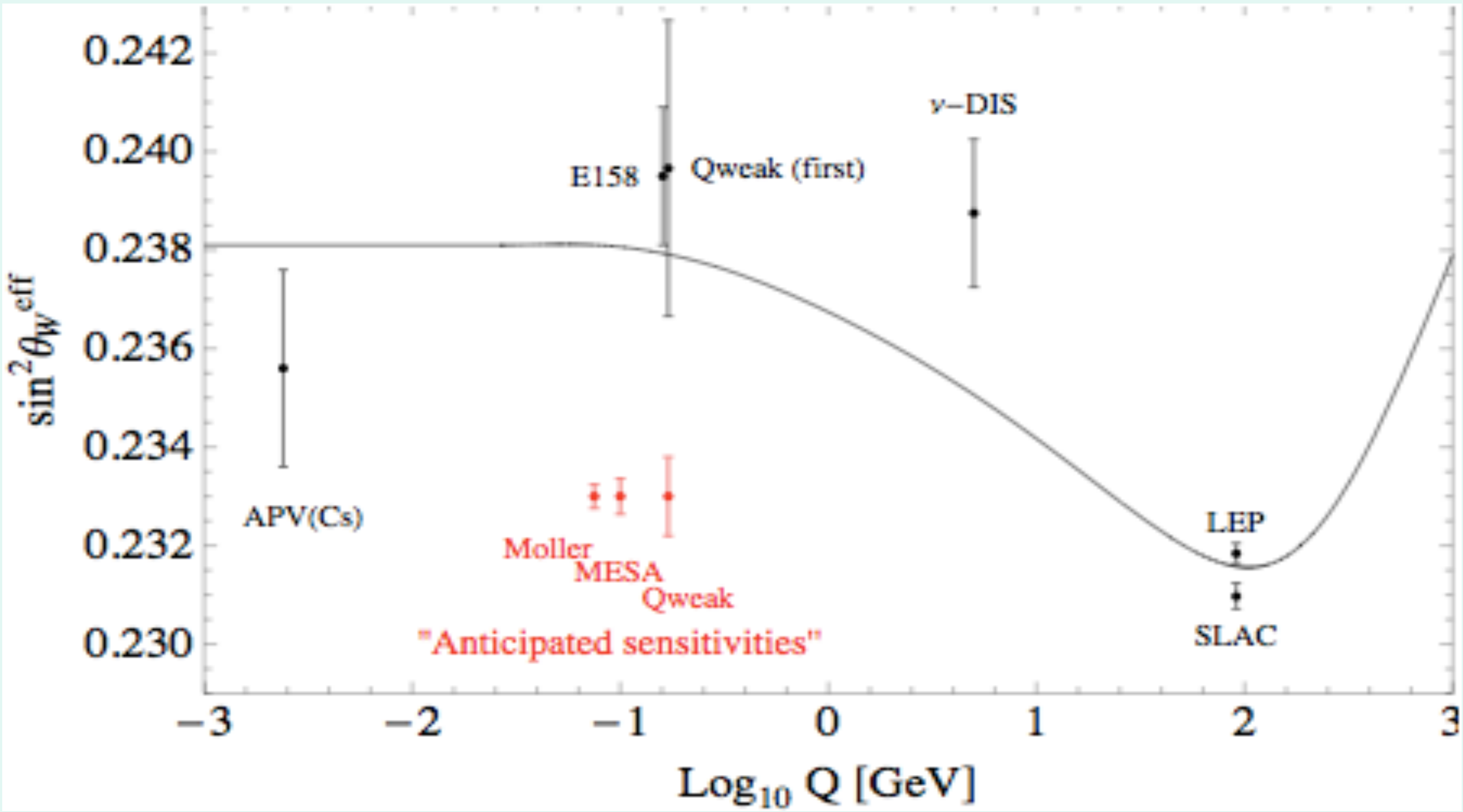
Examples of Possible Dark Parity Violation



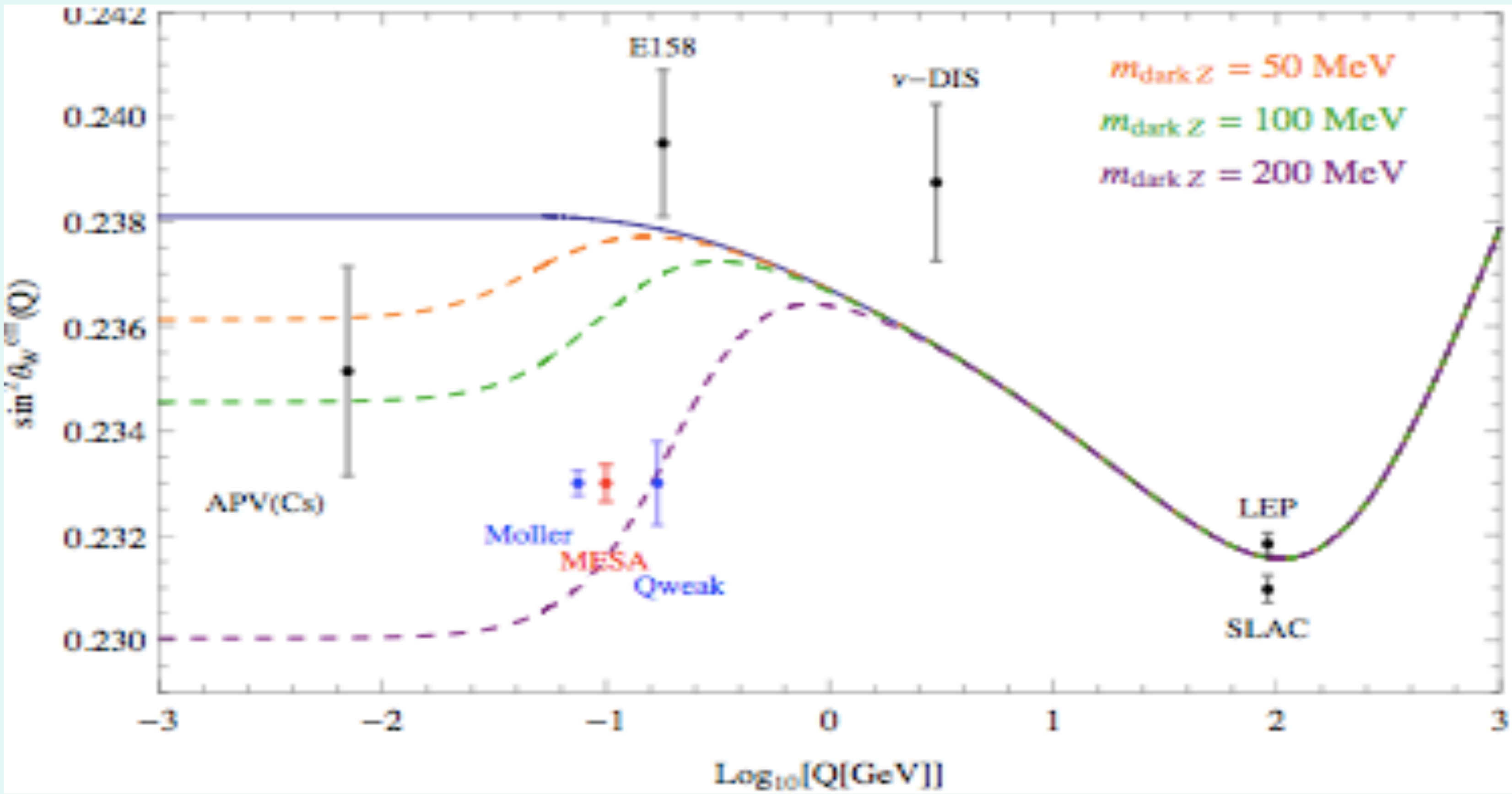
APV Update & MESA



Future Measurements



Examples of Possible Dark Parity Violation



3ii) ***Rare K & B Decays (eg. $K \rightarrow \pi Z_d$) $\delta^2 \rightarrow 10^{-6}$!***

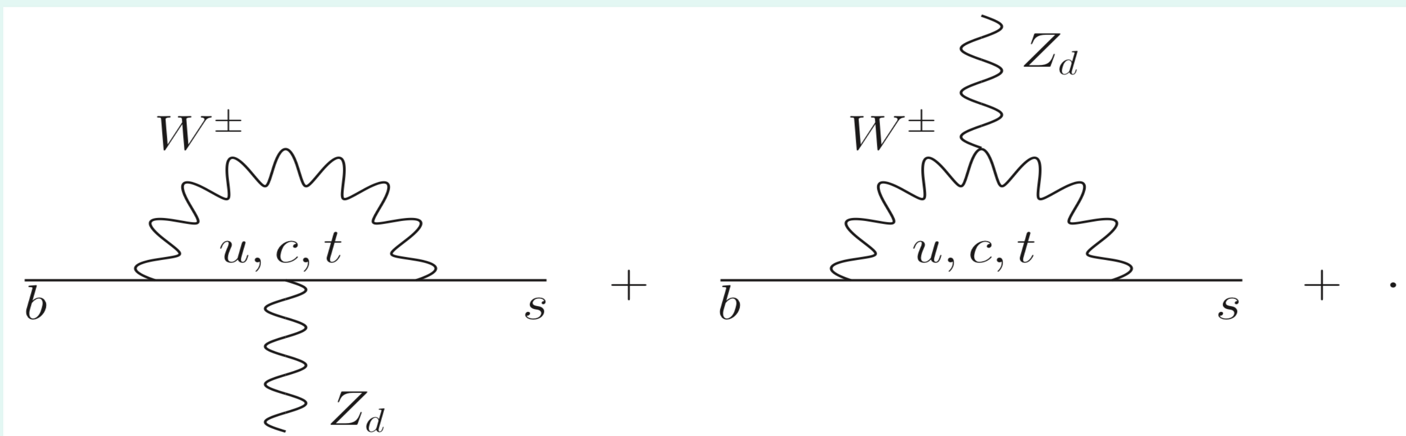
- With Z-Z_d mixing ➔ $Z_d^{\mu} f \gamma_\mu \gamma_5 f$ coupling non-conserved
  Loop Induced Effects: eg Zsd or Zbs $Z \rightarrow \varepsilon_Z Z_d$
  Longitudinal Z_d couples strongest to heavy particles eg t, b…
  Flavor Changing Neutral Currents: $Z_d sd$ & $Z_d bs$
  Proportional to $g^2(m_t/m_W)^2 x\ |V_{ts}V^*_{td}|$ or $|V_{tb}V^*_{ts}|$

$BR(K \rightarrow \pi Z_d) \approx 4 \times 10^{-4} \delta^2$ $Z_d \rightarrow e^+e^-$, $\mu^+\mu^-$, or neutrinos
light dark matter?

$BR(B \rightarrow K Z_d) \approx 0.1 \delta^2$

Some Model Dependence

Flavor Changing neutral current decays and ε_Z



K & B Decay Bounds

$BR(K^+ \rightarrow \pi^+ e^+ e^-)_{exp} = 3.00(9) \times 10^{-7}$ probes $\delta^2 \approx 10^{-4}$

$BR(K^+ \rightarrow \pi^+ \mu^+ \mu^-)_{exp} = 9.4(6) \times 10^{-8}$ probes $\delta^2 \approx 10^{-4}$

$BR(K^+ \rightarrow \pi^+ \nu\nu)_{exp} = 1.7(1.1) \times 10^{-10}$ probes $\delta^2 \approx 10^{-6}$

SM Expectation ~ 0.8×10^{-10}

Depends on m_{Zd} and Z_d Branching Ratios

K_L potentially better $BR(K_L \rightarrow \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$ KTeV!

$BR(B^+ \rightarrow K Z_d) < 10^{-7}$ probes $\delta^2 \approx 10^{-6}$ Can do even better!

B decays – Look for e^+e^- pairs at m_{Zd} Super B Factories

4. $K \rightarrow \pi Z_d \rightarrow \pi e^+e^-$ or π+"missing energy"

M. Pospolov(2009) Kinetic γ-Z_d Mixing $\rightarrow K \rightarrow \pi Z_d$

$$BR(K \rightarrow \pi Z_d) = 1.6 x 10^{-3} |V_{cd} V_{cs}^*|^2 \varepsilon^2 (m_{Zd}/100 MeV)^2$$

$$\approx 8 x 10^{-5} \varepsilon^2 (m_{Zd}/100 MeV)^2$$

$$BR(K \rightarrow \pi Z_d) \approx 2 x 10^3 |V_{td} V_{ts}^*|^2 \delta^2$$ (Z-Z_d mixing) DLM

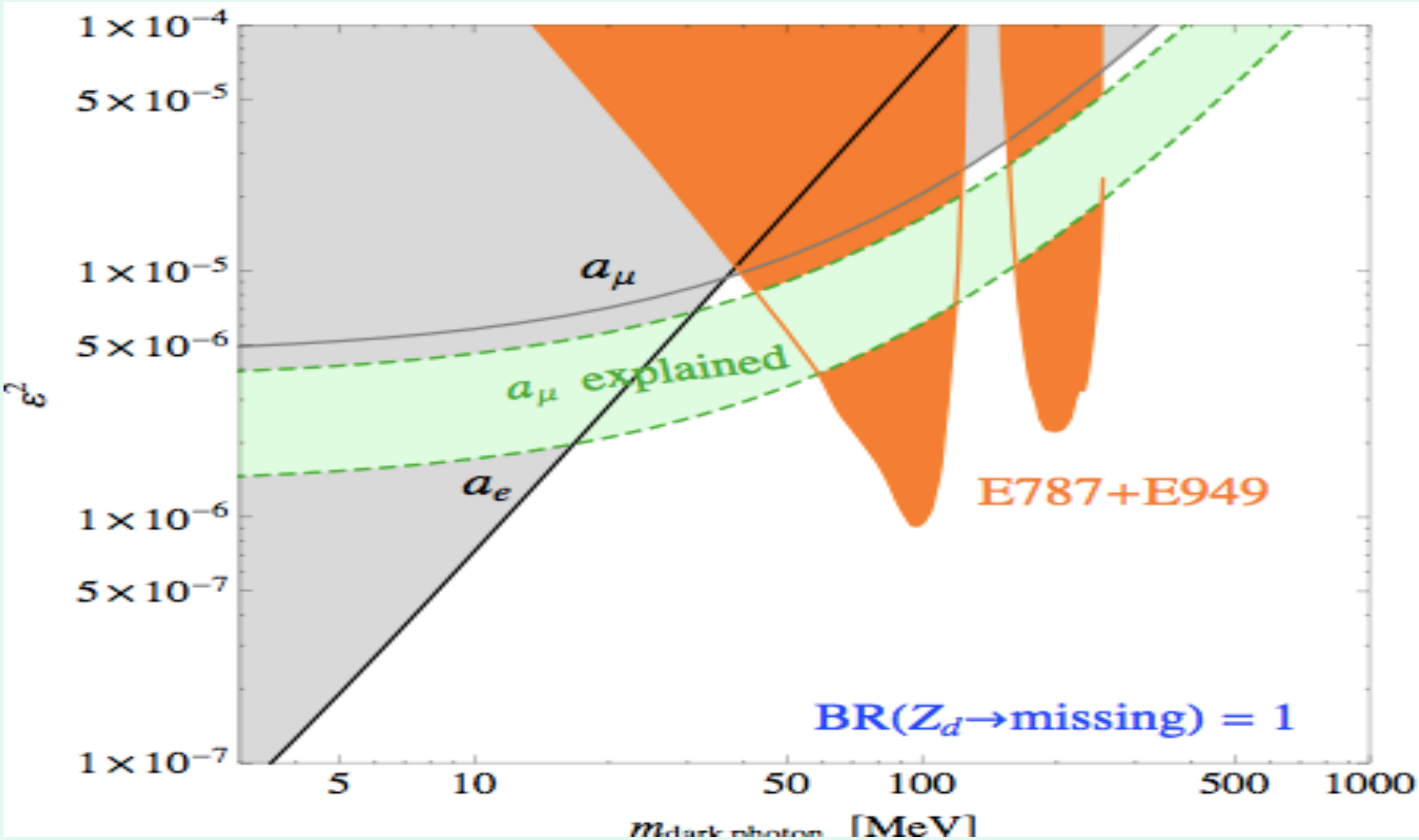
$$\approx 4 x 10^{-4} \delta^2$$ similar magnitudes for $\delta \approx m_{Zd}/m_Z$

Amplitudes could interfere constructively or destructively

Can be searched for in $K \rightarrow \pi e^+e^-$ or π+"missing energy"

Dark Photon Constraints for BR(γ_d ➔ *dark matter)*

$m_{\gamma d}$=100, 200MeV ruled out



What if $Br(Z_d \rightarrow e^+e^-) << 1$? , $Br(Z_d \rightarrow e^+e^-) << Br(Z_d \rightarrow \text{missing energy}) = 1$ For $m_{Zd} < 200\text{MeV}$

- **Pospelov**: Kinetic Mixing and $K^+ \rightarrow \pi^+ Z_d$

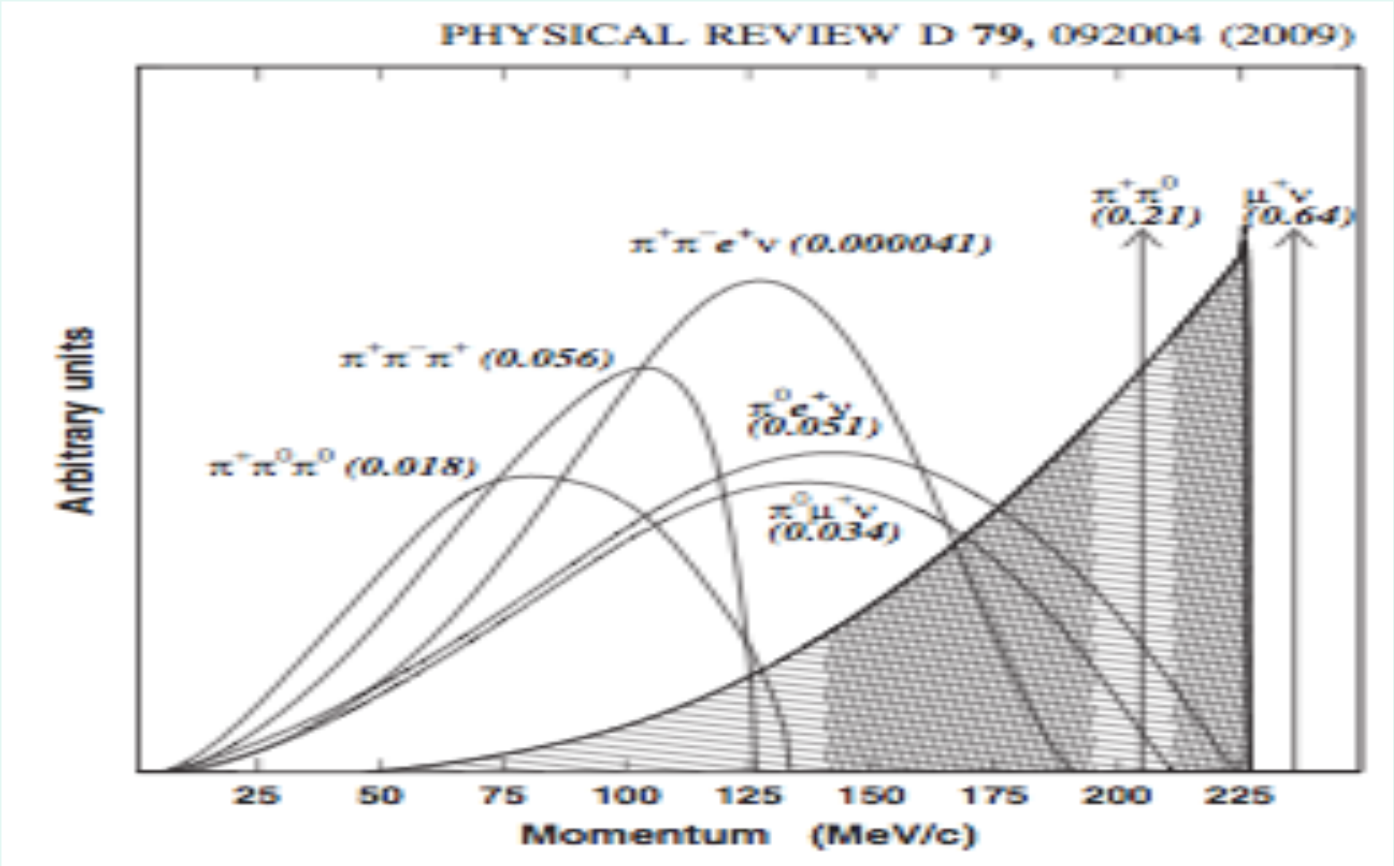
$BR(K^+ \rightarrow \pi^+ Z_d) = 8\text{x}10^{-5} \varepsilon^2 (m_{Zd}/100\text{MeV})^2$

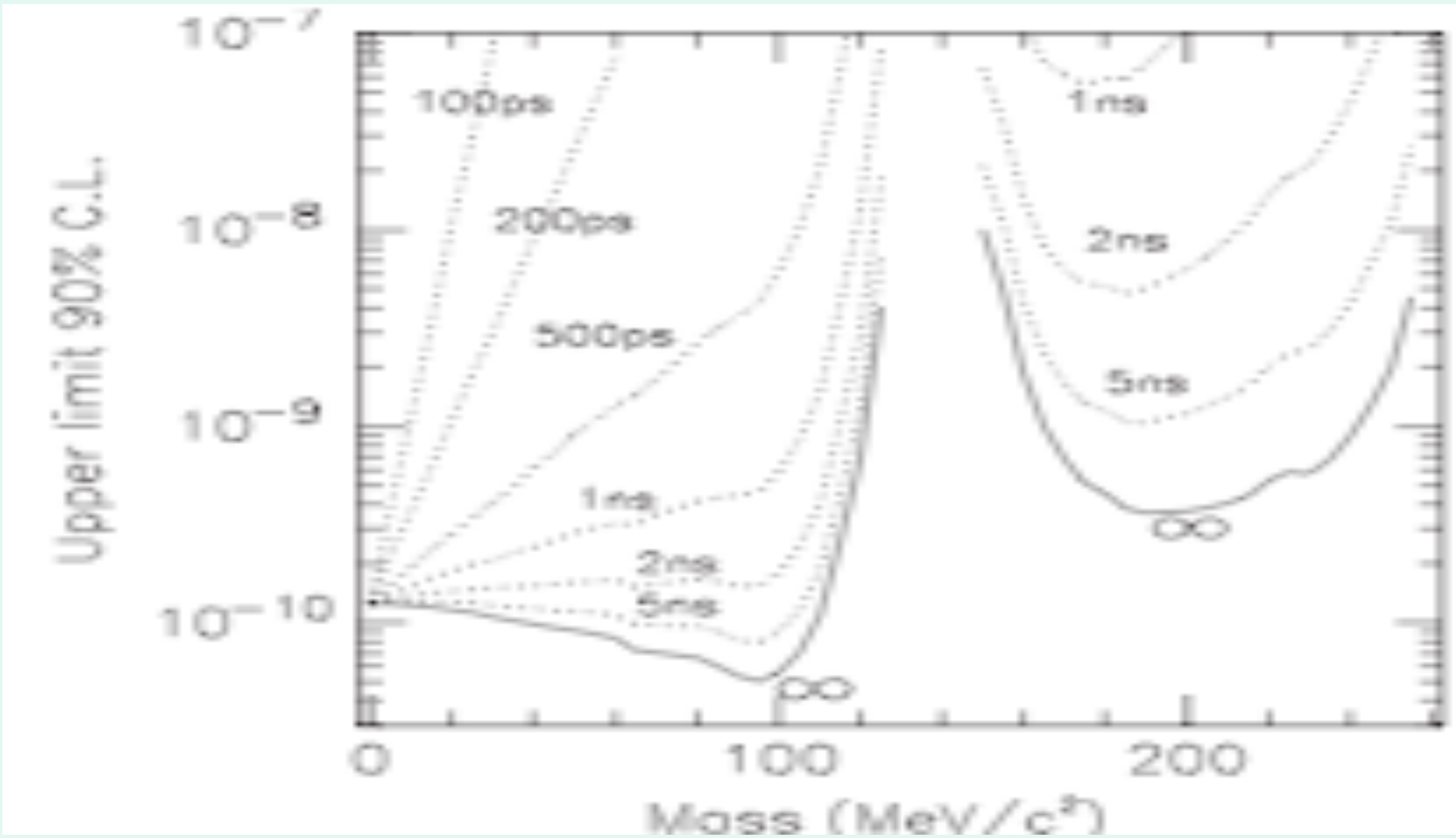
E787/949 at BNL sensitive to $BR(K^+ \rightarrow \pi^+ + \text{missing energy})$ down to $5\text{x}10^{-11}$ at $m_{Zd}=100\text{MeV}$ $\rightarrow$ $\varepsilon < 8\text{x}10^{-4}$!

For $BR(Z_d \rightarrow \text{missing energy}) = 1$ leaves mainly

$20\text{MeV} < m_{Zd} < 50\text{MeV}$ & $m_{Zd} \sim m_\pi$

BNL E787/949 sensitivity to BR($K^+ \rightarrow \pi^+$+nothing) as a function of π^+ momentum

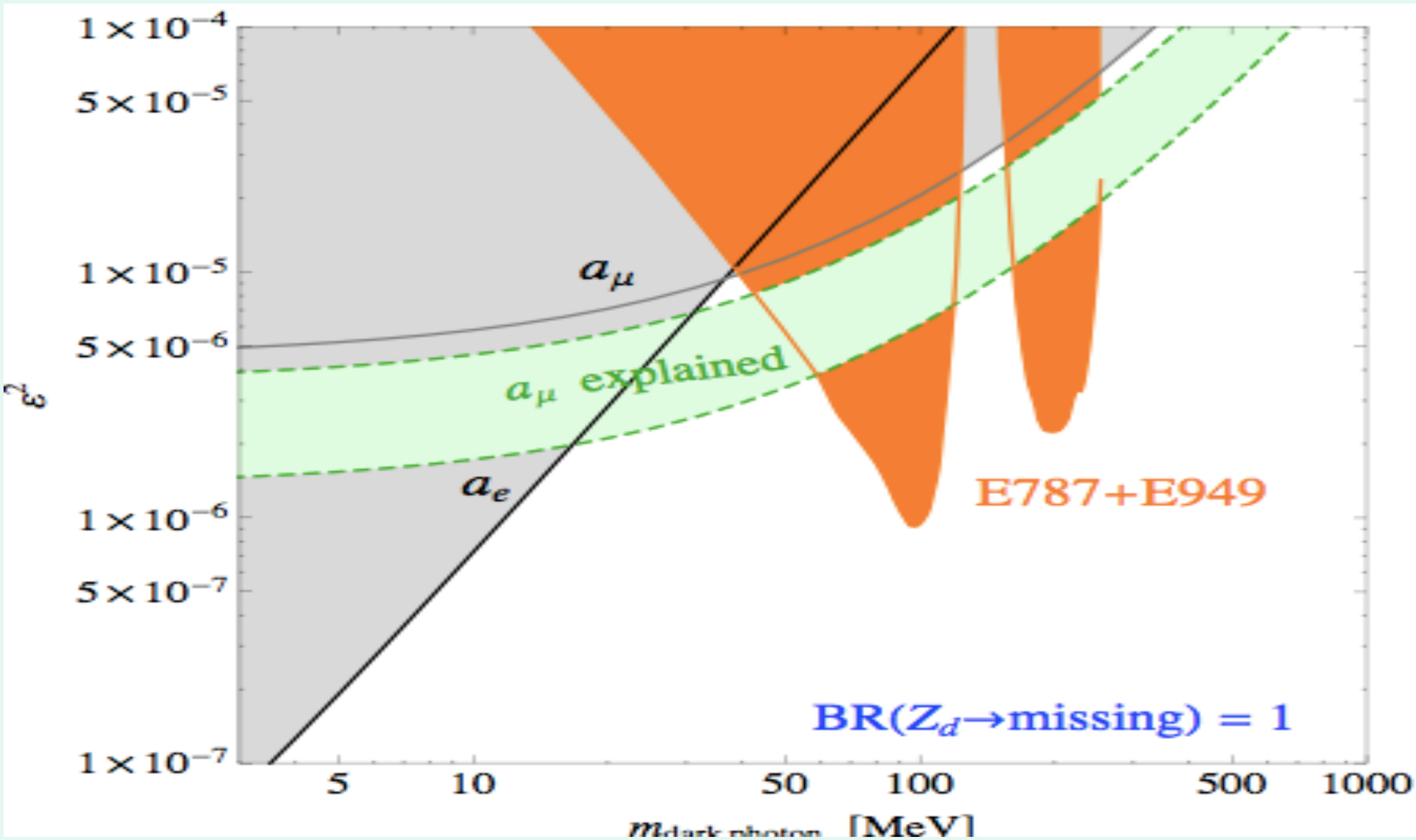




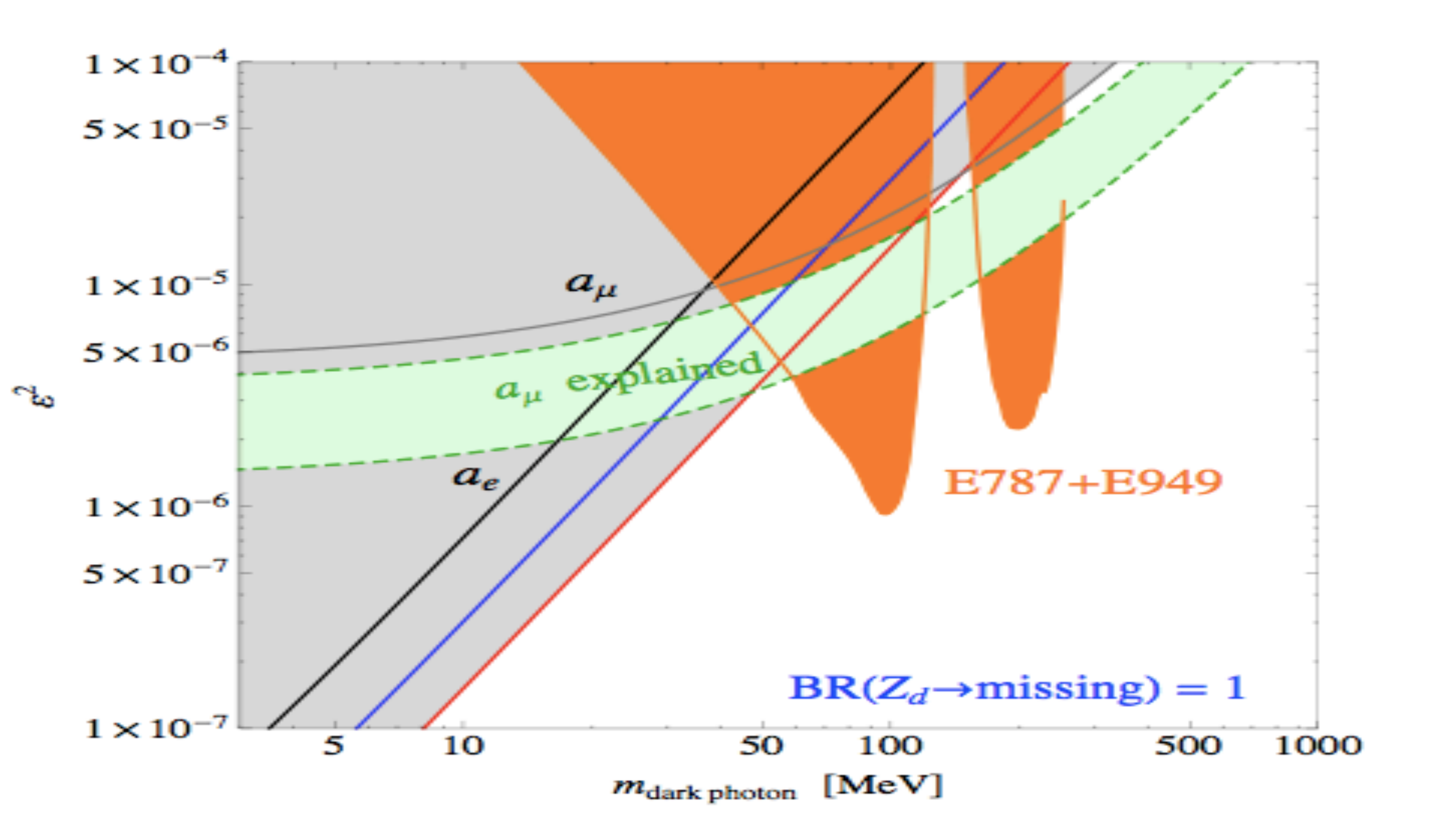
Upper limit 90% C.L.
Mass (MeV/c²)
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
0
100
200
100ps
200ps
500ps
1ns
2ns
5ns
∞
1ns
2ns
5ns
∞

Dark Photon Constraints for BR(γ_d→*dark matter)*

$m_{\gamma d}$=100, 200MeV ruled out



Dark Photon Constraints & a_e



Z-Z_d Mass Mixing ➔ $\varepsilon_Z = \delta m_{Zd}/m_Z \approx (m_{Zd}/m_Z)^2$

- Potentially Observable Effects (for $\delta \geq 10^{-3}$)

APV & Polarized Electron Scattering at low <Q>

$BR(K \to \pi Z_d) \approx 4 \times 10^{-4} \delta^2$ $BR(B \to K Z_d) \approx 0.1 \delta^2$

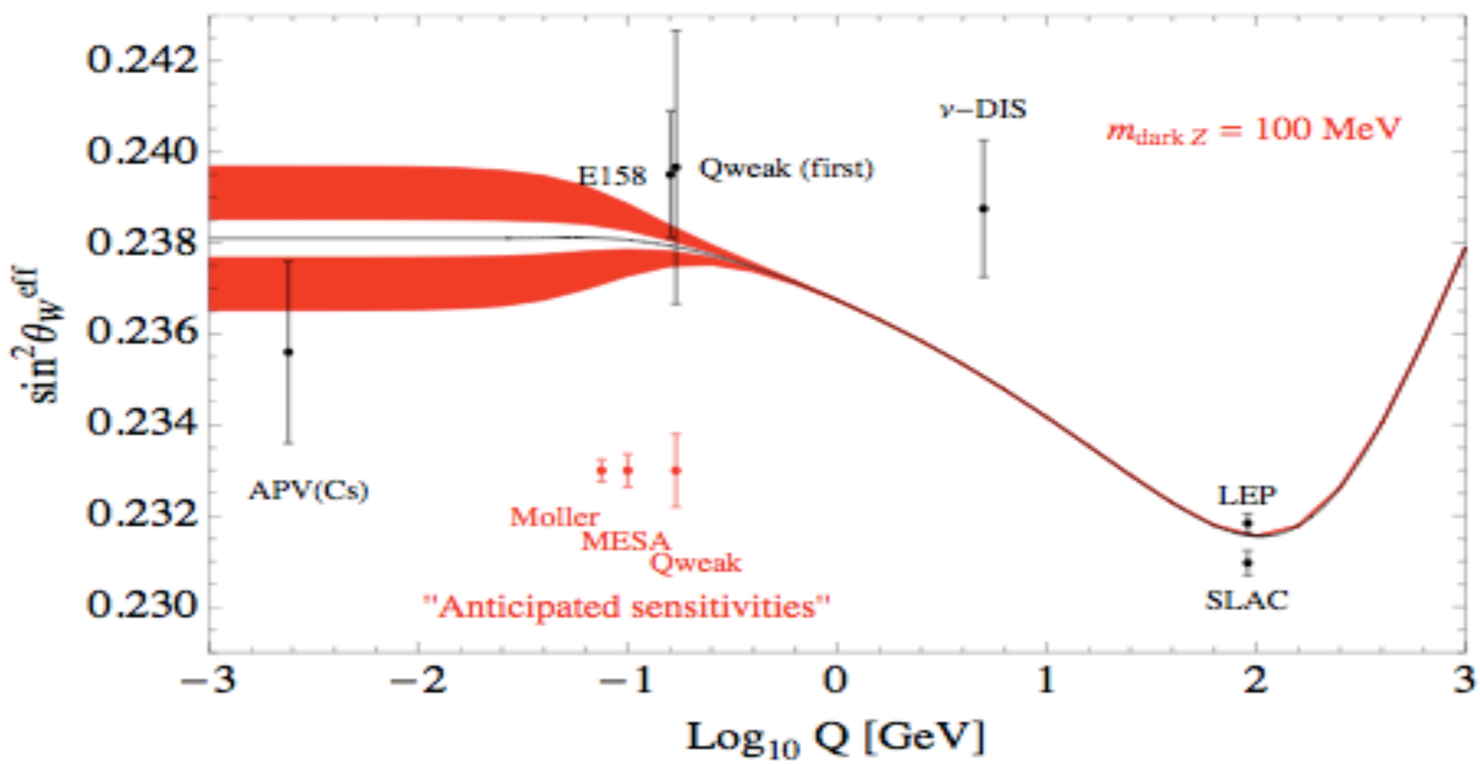
δ^2 roughly probed to 10^{-6}

$K \to \pi Z_d \to \pi$+"missing energy"

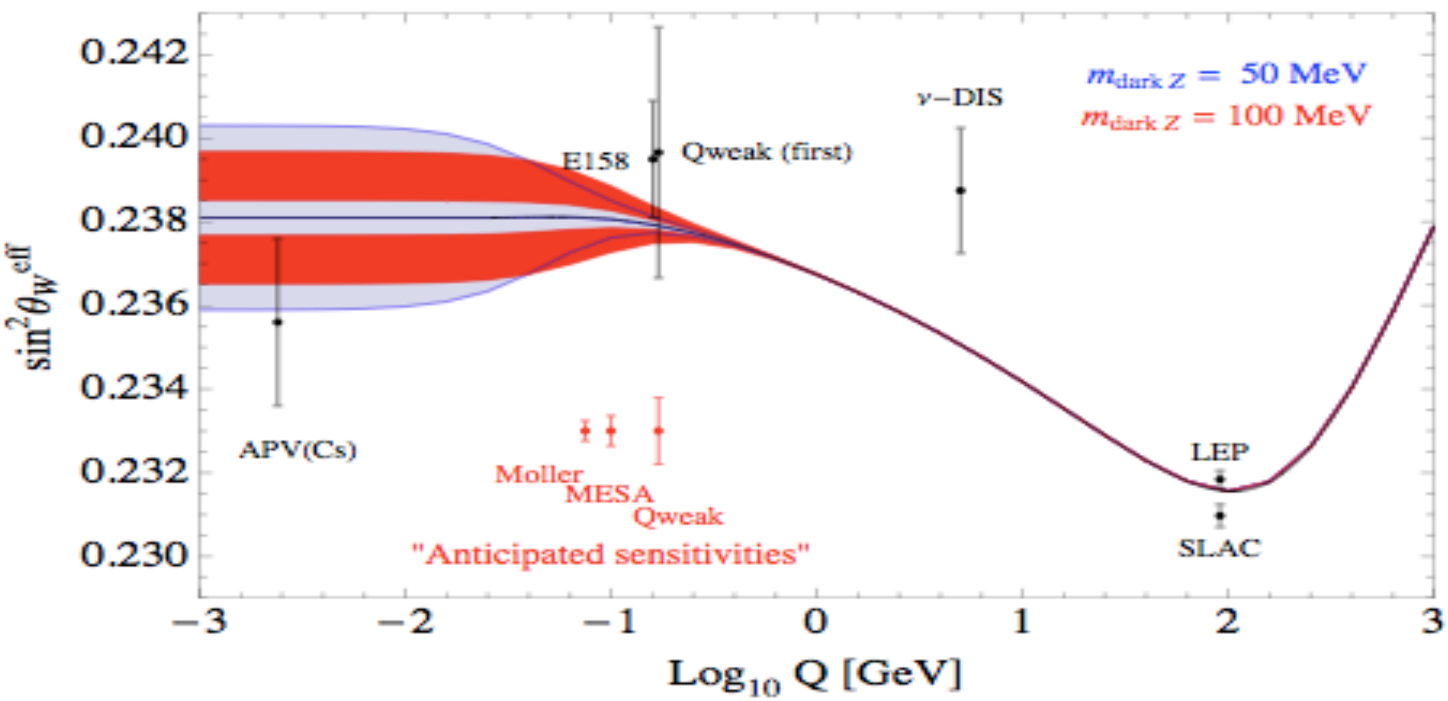
ε and δ effects could partially cancel!

Suppression by ~1/6 allows Z_d~100MeV

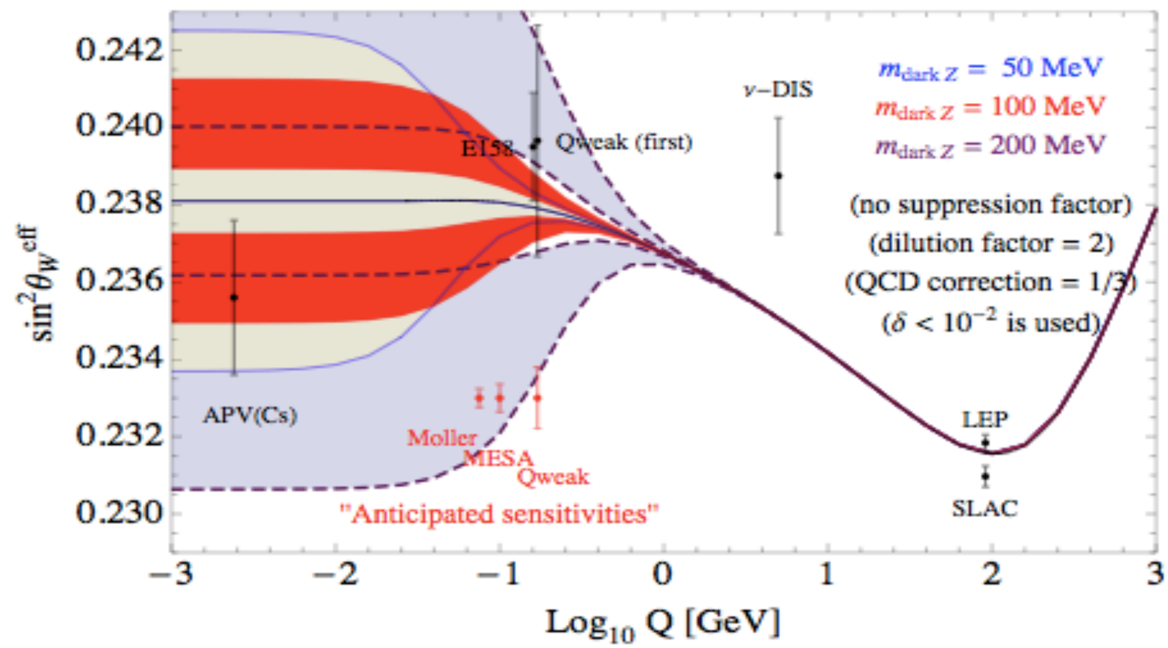
Combined with muon g-2 ➔ observable dark PV Band



0.242
0.240
0.238
0.236
0.234
0.232
0.230
$\sin^2\theta_W{}^{\rm eff}$
−3
−2
−1
0
1
2
3
Log_{10} Q [GeV]
E158
Qweak (first)
ν−DIS
$m_{\rm dark\ Z}$ = 100 MeV
APV(Cs)
Moller
MESA
Qweak
"Anticipated sensitivities"
LEP
SLAC



0.242
0.240
0.238
0.236
0.234
0.232
0.230
$\sin^2\theta_W^{eff}$
−3
−2
−1
0
1
2
3
Log10 Q [GeV]
$m_{dark\ Z}$ = 50 MeV
$m_{dark\ Z}$ = 100 MeV
E158
Qweak (first)
ν−DIS
APV(Cs)
Moller
MESA
Qweak
"Anticipated sensitivities"
LEP
SLAC



0.242
0.240
0.238
0.236
0.234
0.232
0.230
$\sin^2\theta_W{}^{\text{eff}}$
−3
−2
−1
0
1
2
3
Log_{10} Q [GeV]
$m_{\text{dark Z}}$ = 50 MeV
$m_{\text{dark Z}}$ = 100 MeV
$m_{\text{dark Z}}$ = 200 MeV
(no suppression factor)
(dilution factor = 2)
(QCD correction = 1/3)
($\delta < 10^{-2}$ is used)
ν−DIS
E158
Qweak (first)
APV(Cs)
Moller
MESA
Qweak
"Anticipated sensitivities"
LEP
SLAC

6.Outlook

- Light Dark Photon – Under some tension (e^+e^- decays)
- Light Dark Boson + Light Dark Matter (avoid e^+e^- constraints)
- ($K \rightarrow \pi Z_d$) $Z_d \rightarrow$ light dark matter constraint tension for m_{Zd}~100 & 200MeV (kinetic - mass mixing suppression)

Predictive Bands for dark parity violation

NA62 starts running in 2014: ~20x more K^+ sensitivity

~100x more $\pi \rightarrow \gamma Z_d$ sensitivity

Z_d Discovery would revolutionize particle physics

The End or "New Physics" Beginning!!