“Dark” Symmetries

Based on H. Davoudiasl, H-S Lee & WJM
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Outline

1. ***Introductory Remarks ➔ Dark Symmetries***
2. ***Kinetic $U(1)_Y$ x $U(1)_d$ Mixing***

   $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(80) \times 10^{-11}$ (*3.6σ discrepancy!*)

   The Dark Photon Solution: **$\varepsilon e Z_d^\mu J_\mu^{em}$**

   10MeV$<m_{Zd}<$500MeV, $\varepsilon^2 \approx 10^{-6}$-$10^{-4}$

*3. ***Z-Z_d mass mixing ➔ Axial Current!***

   Dark Parity Violation & Non-Conserved

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

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

   iii) Higgs Decay H➔ZZ_d➔4 charged leptons

4. ***Outlook***

1. Introductory Remarks → Dark Symmetries

1928 *The Dirac Equation*

QM+Special Rel.+Spin+EM Gauge Invariance $U(1)_{em}$

First Order Differential Equation

$$i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m_e\psi(x)$$

Dirac Predicts Antiparticles!

1932 Positron Discovered!

followed by antiproton → antihydrogen…

Why is the Universe Matter-Antimatter Asymmetric?

What happened to the antimatter after the Big Bang?

Baryogenesis! Leptogenesis!

"New Physics" – New CP Violation (edms!)

- **Today: $SU(3)_C xSU(2)_L xU(1)_Y$ Standard Model**

8 gluons + $W^{\pm}$, Z, γ ***gauge bosons (spin 1)***

3 generations of *quarks & leptons (mix->CP violation)*

e,ν_e,u,d μ,ν_μ,c,s τ,ν_τ,t,b (m_t/m_ν >10^{13}!!) *(spin ½)*

Scalar Doublet: $S^{\pm}$,S^0,H source of mass *(spin 0)*

Waiting for the Higgs (125GeV?)

Many Symmetries, Interactions, P & CP Violation...?

1932-33's Astronomers start to see "Dark Matter" Evidence!

Now established -7 x Visible Matter!

What is Dark Matter?

Massive Cosmologically Stable Elementary Particle?

Candidates Models: SUSY(LSP), Kaluza-Klein…

Spin: 0, **1/2** 1, 3/2   Mass: O(5 - 100GeV)? WIMPS?

Several Particles?   Dark Matter-Antimatter Asymmetry?

Weak (Broken) Gauge Interactions?

P & CP Violation?

New $U(1)_d$ Interaction among dark particles? Dark Force?

Fayet, Pospelov, Weiner, Arkani-Hamed…

***Spin 1 gauge boson*: U, Secluded, Dark Photon, Dark Z…**

Dark Boson Interactions with our World?

Dark Symmetry & Our World

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

****2. Z-Z_d mass mixing (Higgs Portal)***

3. d = B-L, L_μ-L_τ, L_e-L_μ, L_e-L_τ…
(All or Some particles have dark charge)
(Vector Interactions?) Bouchiat & Fayet

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

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

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

ε= small (infinite) counterterm

Remove Mixing by field redefinitions

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

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

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

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

Z_d couples to conserved vector current J_μ^{em} of our world!

Z_d=Dark Photon

Effects suppressed by $\varepsilon \approx 10^{-2}$-$10^{-3}$ or smaller

Light gauge boson motivated by Dark Matter

Positron excesses $Z_d \rightarrow e^+e^-$, Dark Matter Annihilations…

Some superstring models → Extra U(1)s

- Searches for Dark Matter Particles (Mainly WIMPS)

  LHC (Supersymmetry) No sign yet

  Underground Scattering – Conflicting Experiments

The Muon Anomalous Magnetic Moment

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 286(63)(49)\times 10^{-11}$

$286(80)\times 10^{-11}$ (***3.6σ discrepancy!***)

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

Interpretations

***Generic 1 loop SUSY Conribution*:**

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

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

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

Multi-Higgs Models

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

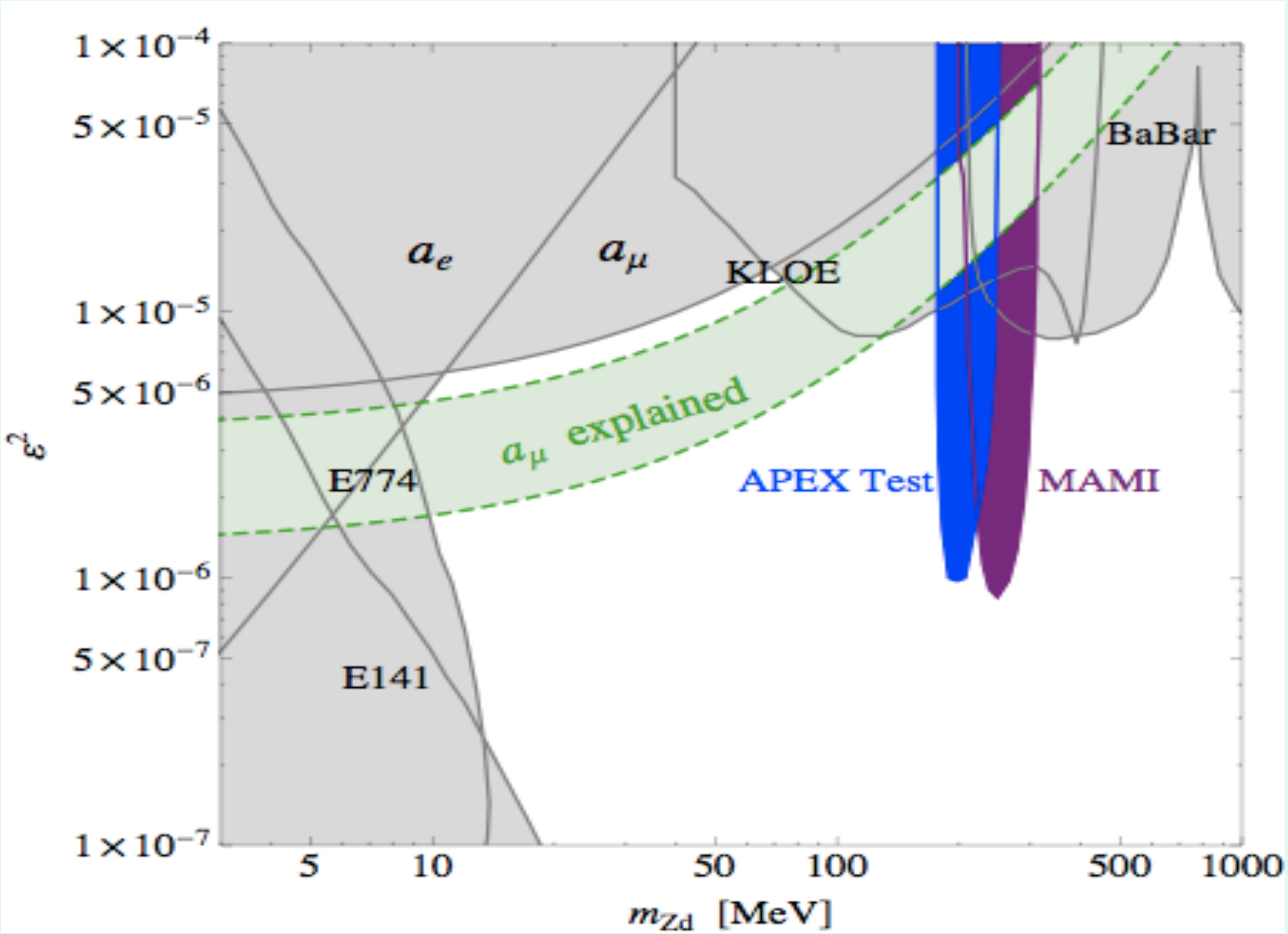
Light Higgs Like Scalar <10MeV?

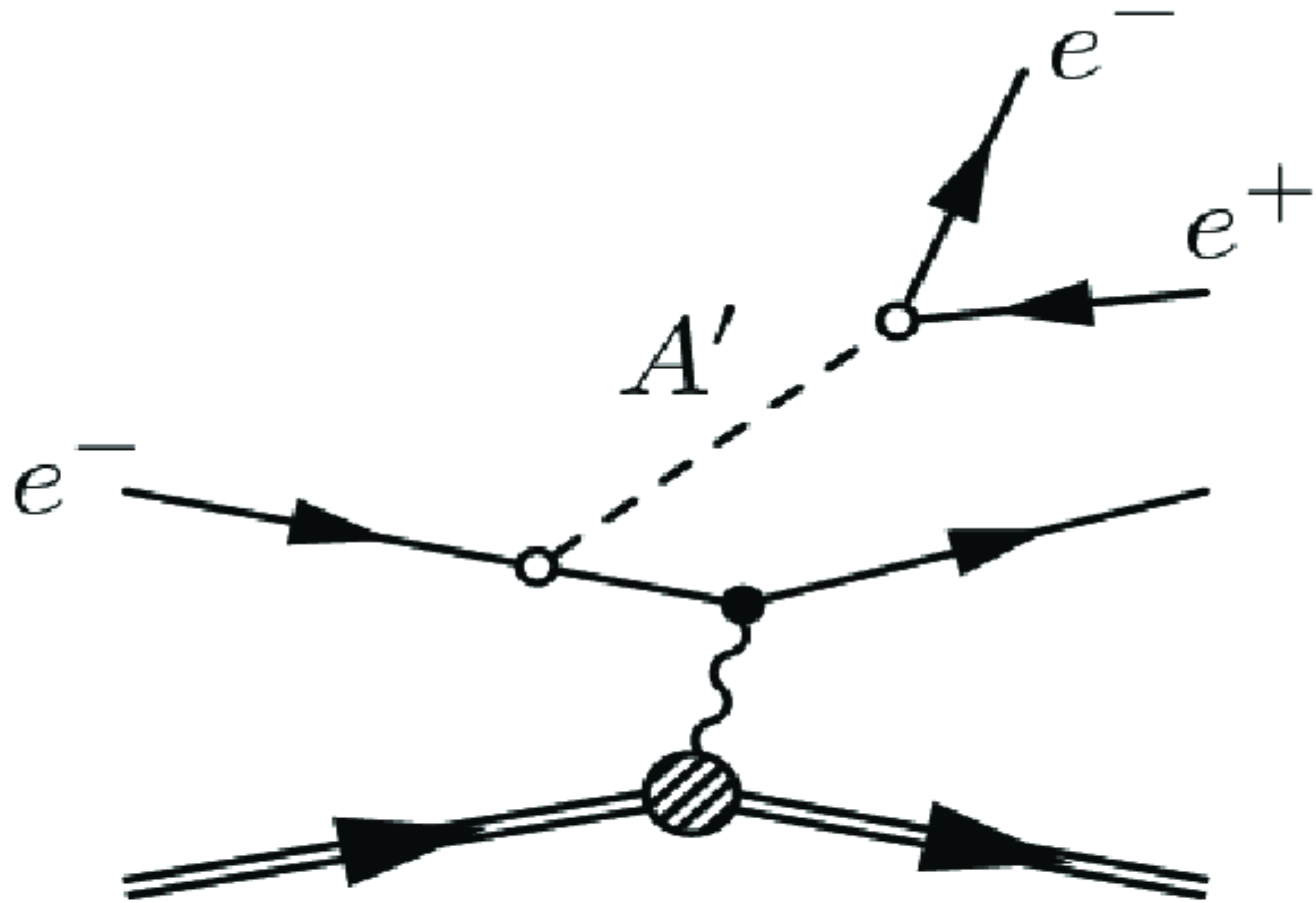
* ***Dark Photons (Fayet, Pospelov…)***

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

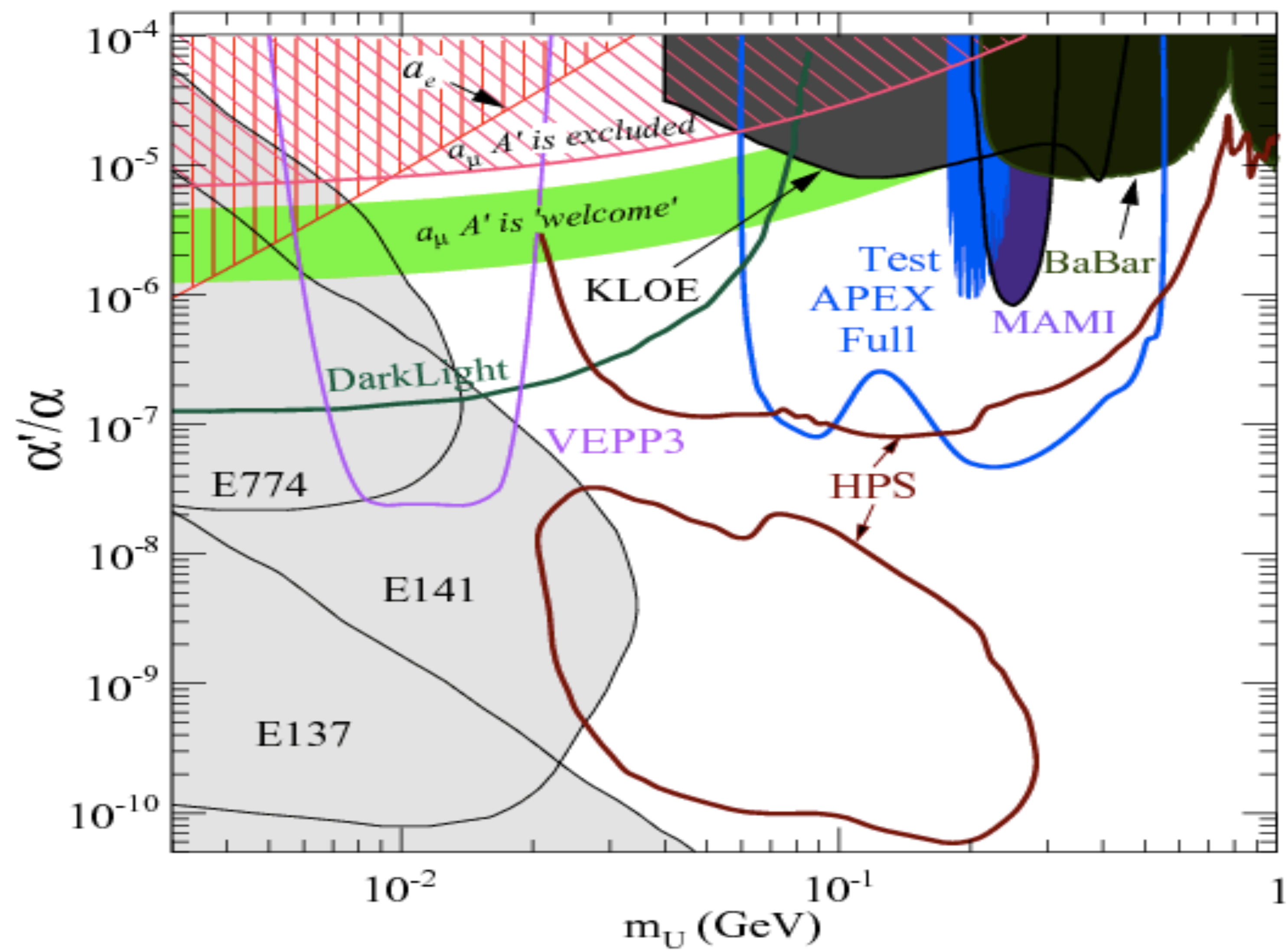
for $\varepsilon^2 \approx 10^{-6}$-$10^{-4}$ & $m_{Zd} \approx 10$-500MeV (see figure)

Dark Photon Exclusion




e^-
e^+
A'
e^-

JLab Future – R. McKeown (Similar Mainz Goals)



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

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

$0 \le |\delta| < 1$

$\delta^2 << 1$

Mixing angle $\approx \varepsilon_Z = m_{Zd}/m_Z\delta << 1$

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

Like a Z with smaller mass (10MeV-10GeV) 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

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

$\delta=\sin\beta\sin\beta_d$ ➔ $\varepsilon_Z=m_{Zd}/m_Z \sin\beta \sin\beta_d$ (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 $Q^2 << m_Z^2$)

$a_\mu(Z_d) = \alpha/2\pi(\varepsilon + 0.02\varepsilon_Z)^2 F(m_{Zd}/m_\mu) - 117\times10^{-11}\delta^2$

essentially no change from ε alone solution

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

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

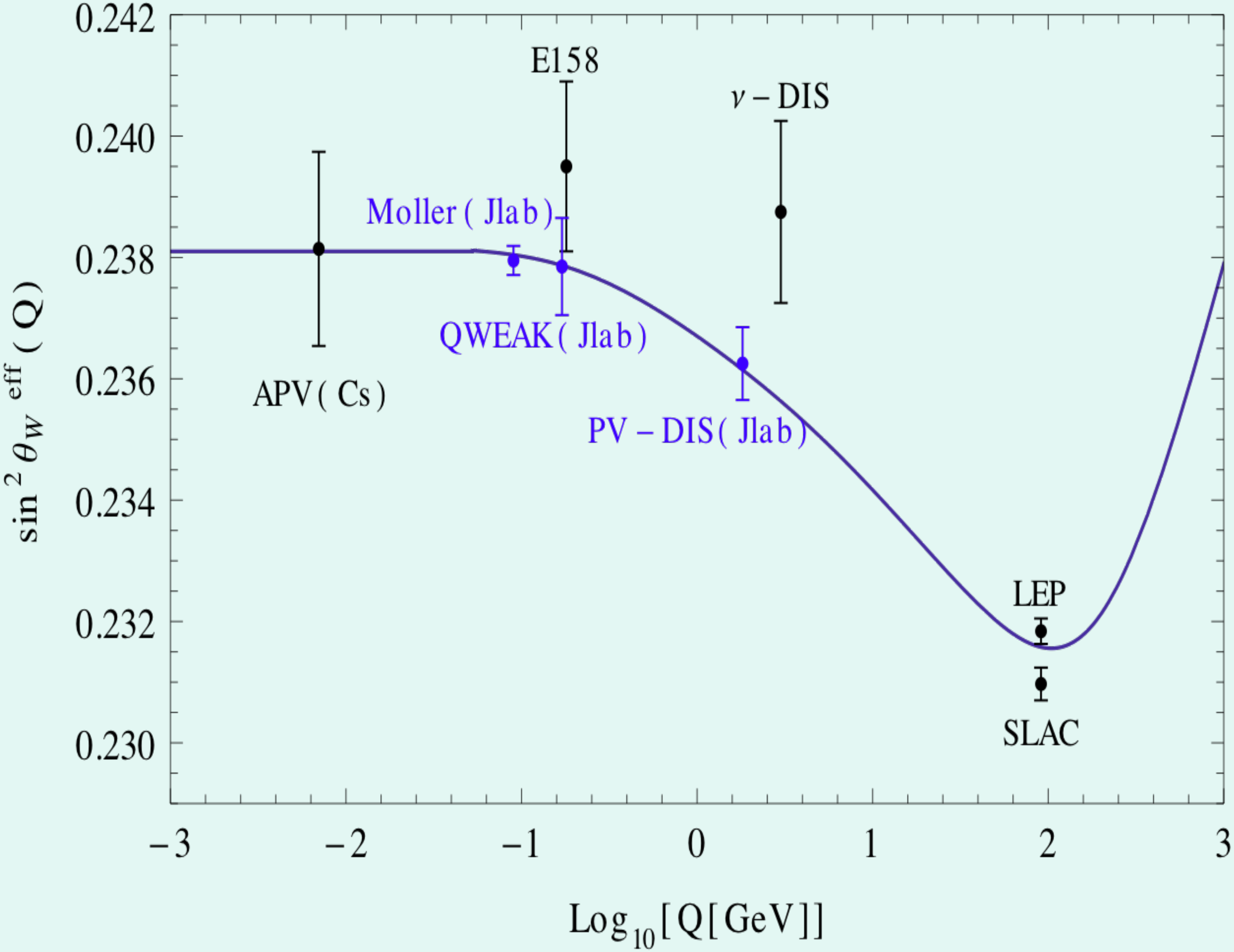
Atomic PV in Cesium $\langle Q\rangle \approx 2.4$MeV

$|\Delta\sin^2\theta_W(Q=2.4\text{MeV})| < 0.0026$ **90% CL**

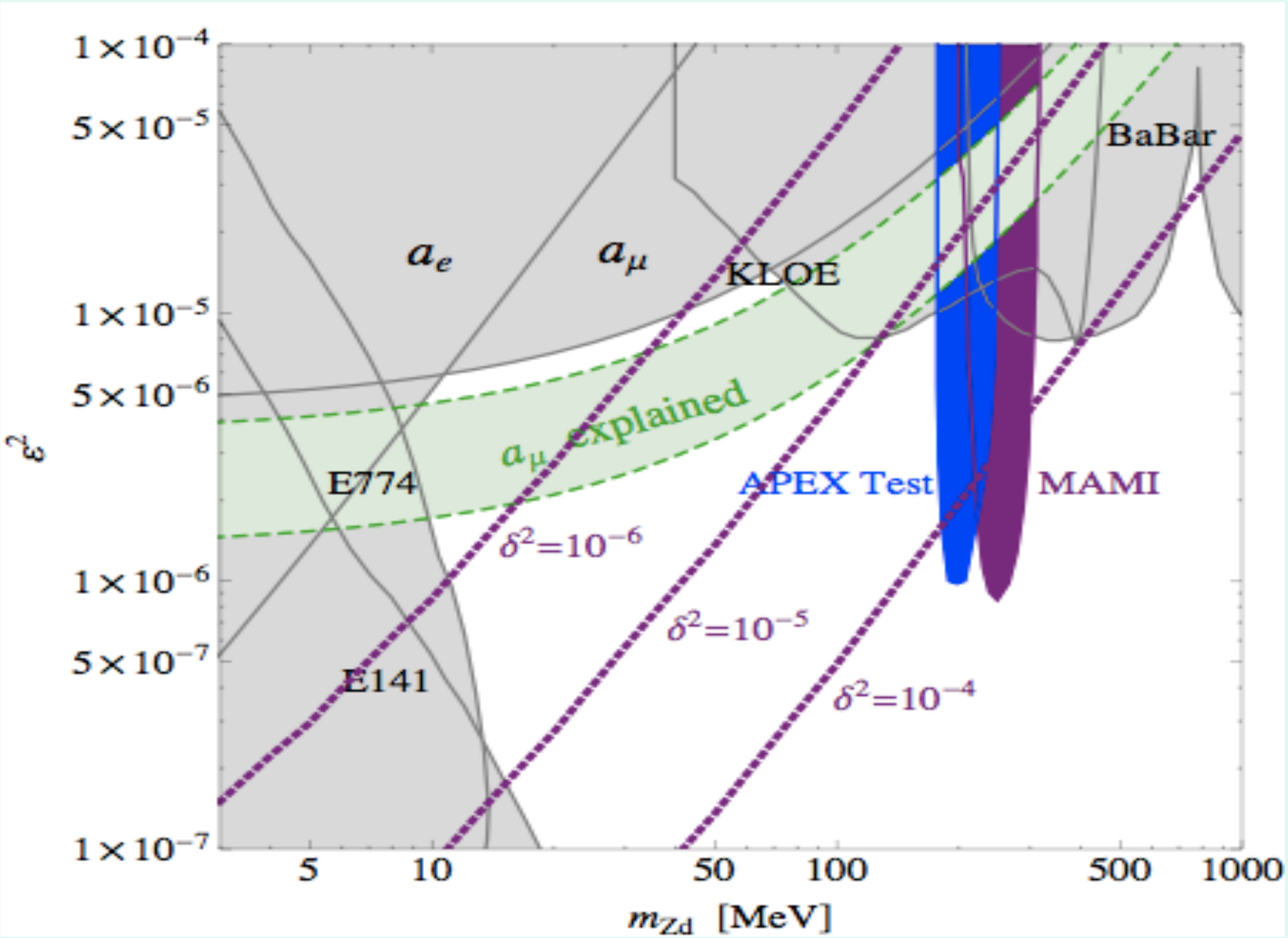
or for $m_{Zd} \geq 10$MeV $\varepsilon\delta < 7\times10^{-5}(m_{Zd}/\text{GeV})$

δ must be very small for g-2 solution $\varepsilon \approx 10^{-3}-10^{-2}$

Running of $sin^2\theta_W(Q)$



Atomic Parity Violation Constraints



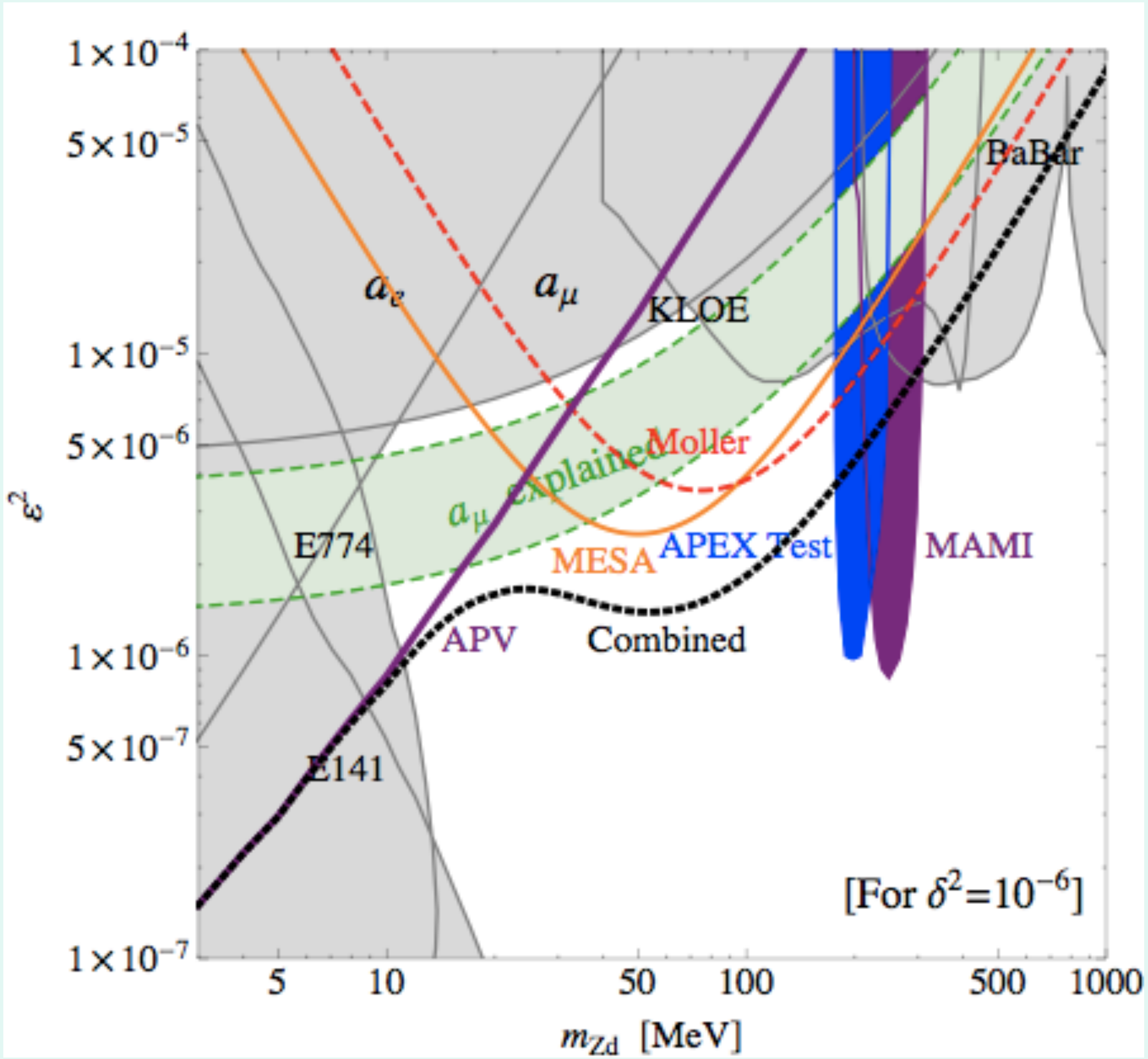
Polarized ee, ep, eC Asymmetries

- $A_{LR}=\sigma_L-\sigma_R/\sigma_L+\sigma_R$ Parity Violating α Q^2 very small

Experiment	<Q>MeV	$\Delta\sin^2\theta_W$	Measurement
Cs APV	2.4	±0.0016	Completed
E158 SLAC	160	±0.0013	ee Completed
Q_{weak} JLAB	170	±0.0007/8	ep in progress
Moller JLAB	75	±0.00029	ee approved
MESA (Mainz)	50-150?	±0.00037	ep proposed
eC	low?	±0.0010?	eC Bosen 2009

Experiments will actually probe a range of Q^2

APV Sets Normalization – Francium, Isotopes, Trapped Ions



1×10⁻⁴
5×10⁻⁵
1×10⁻⁵
5×10⁻⁶
1×10⁻⁶
5×10⁻⁷
1×10⁻⁷
ε^2
5
10
50
100
500
1000
m_{Zd} [MeV]
a_e
a_μ
KLOE
BaBar
Moller
a_μ explained
E774
MESA
APEX Test
MAMI
APV
Combined
E141
[For $\delta^2=10^{-6}$]

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

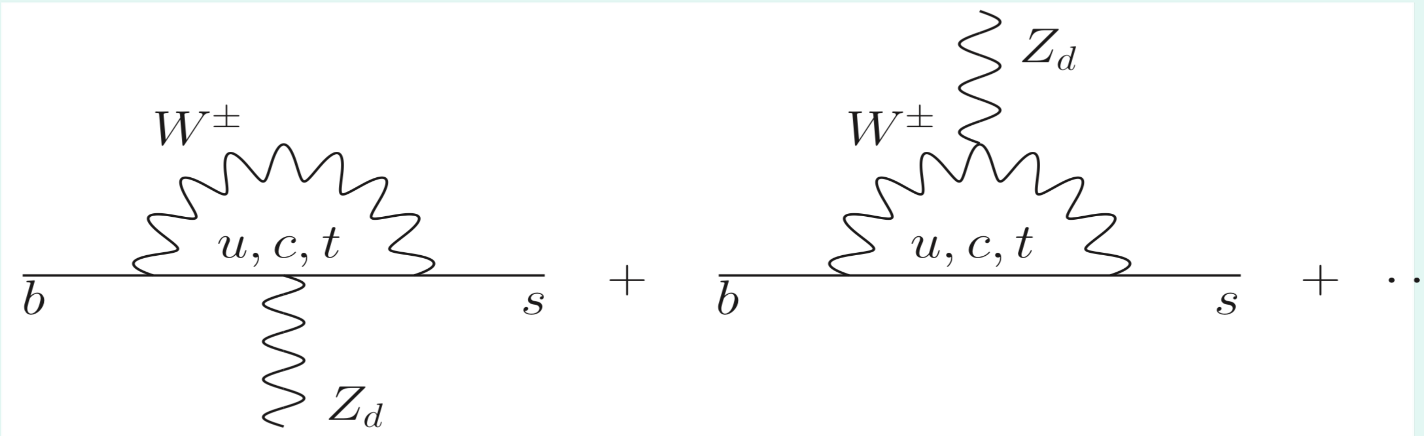
- With Z-Z_d mixing ➔ $Z_d^{\mu} f \gamma_{\mu} \gamma_5 f$ coupling non-conserved
  Loop Induced Effects: eg Zsd or Zbs $Z \rightarrow \varepsilon_Z Z_d$

Longitudinal Z_d couples strongest to heavy particles eg t, b…
Flavor Changing Neutral Currents: $Z_d sd$ & $Z_d bs$

$BR(K \rightarrow \pi Z_d) \approx 4\text{x}10^{-4}\delta^2$ $Z_d \rightarrow e^+e^-$, $\mu^+\mu^-$, or neutrinos
similarly
$BR(B \rightarrow K Z_d) \approx 0.1\delta^2$

Comment – Little Sensitivity at $m_{Zd} < m_{\pi}$ (Dalitz $\pi^0 \rightarrow e^+e^-\gamma$)
Some Model Dependence

Flavor Changing neutral current decays



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 $\delta^2 \approx 10^{-6}$

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!

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

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

- ***Also***: $\mu \rightarrow e^+ e^- e^+$ 10^{-15}-10^{-16} Sensitivity
- $\tau \rightarrow \mu\mu\mu$, $\tau \rightarrow eee$ $\tau \rightarrow \mu ee$ $\tau \rightarrow e\mu\mu$ $10^{-10}(10^{-11})$!

3ii. ***Higgs Decay $H \rightarrow ZZ_d \rightarrow$ 4 charged leptons***

What if m_H=125GeV? Implies:

m_W = 80.361(10)GeV vs 80.384(17)GeV now

$\sin^2\theta_W(m_Z)$ = 0.23130(10) vs 0.23125(16) now

Very Good Agreement!

Not much room for "New Physics"

So far: No direct evidence for Supersymmetry, Extra Dimensions, 4th Generation, New Dynamics…

At The LHC!

The Higgs – Last Particle Ever Discovered?

The Higgs Search Has Narrowed: 115GeV<m_H<135GeV

Hints of $m_H \approx 125$GeV at CERN

H➔γγ, WW*, ZZ*

Approx 75,000 H/exp!

H Decay Channel	Branching Ratio
$b\bar{b}$	0.578
WW^*	0.215
gg	0.086
$\tau^+\tau^-$	0.063
$c\bar{c}$	0.029
ZZ^*	0.026
$\gamma\gamma$	2.3×10^{-3}
$Z\gamma$	1.5×10^{-3}
$H \to ZZ^* \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$	1.2×10^{-4}
$H \to ZZ^* \to \ell^+\ell^-\nu\bar{\nu}$	3.6×10^{-4}

New Effects from δ

HZZ coupling of SM large $H \rightarrow ZZ \approx g^2 m_H^3/m_Z^2$ if allowed

Longitudinal Z Bosons – Goldstone Equivalence Theorem

m_H=125GeV $H \rightarrow ZZ^*$ 4 charged leptons BR $\approx 10^{-4}$

HZZ_d coupling $\varepsilon_Z = m_{Zd}/m_Z \delta$ suppressed

But Longitudinal Z_d

Enhanced by E/m_{Zd} overcomes m_{Zd}/m_Z suppression

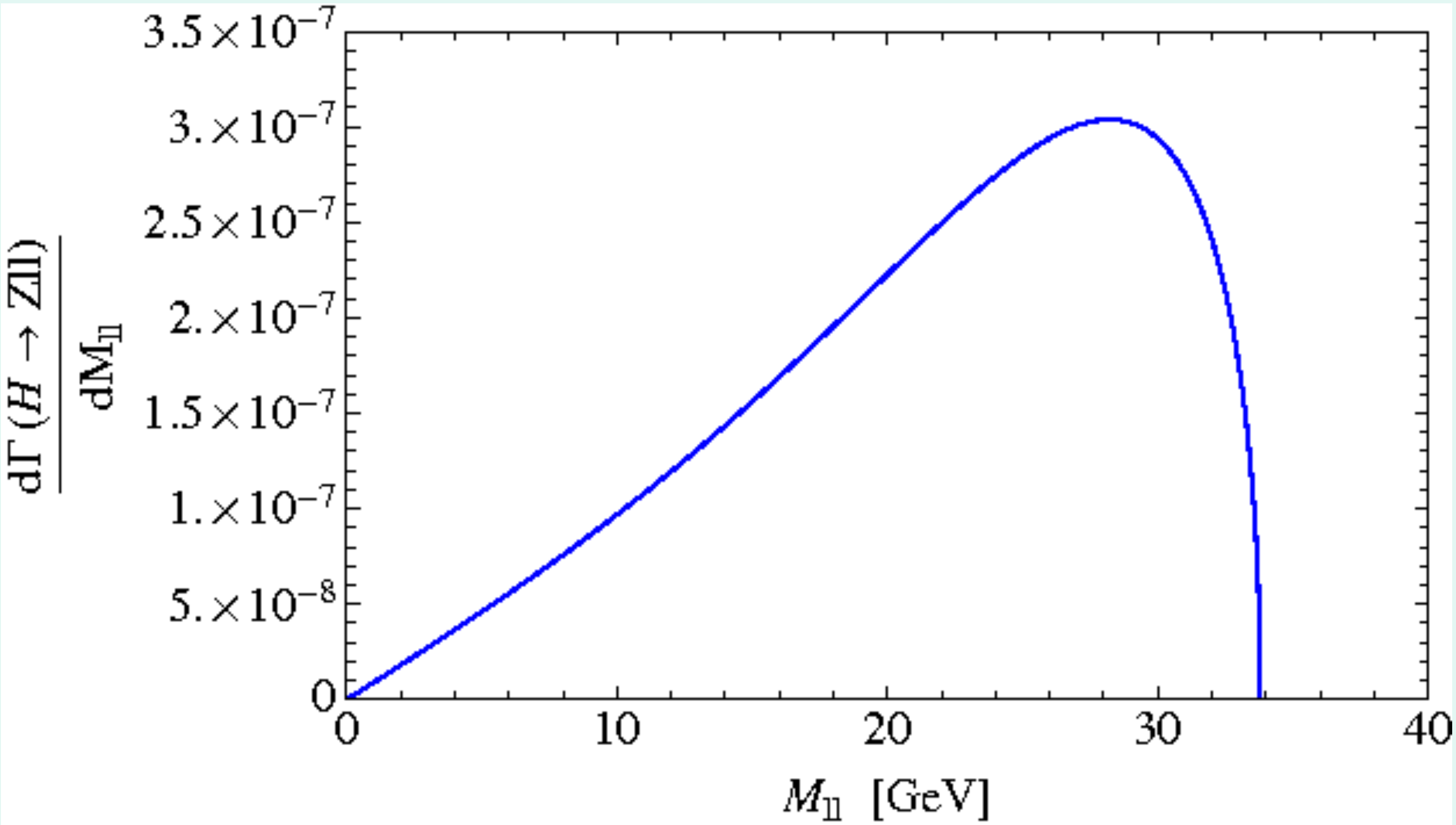
$H \rightarrow ZZ_d$ $Z_d \rightarrow l^+l^-$ (l=e or μ) or "missing energy"

$\Gamma(H \rightarrow ZZ_d)/\Gamma_H(125\text{GeV})_{SM} = 16\delta^2$

Potential experimental sensitivity to $\delta^2 \approx 10^{-6}$

Should be pushed as far as possible!

$H \rightarrow ZZ^* \rightarrow Z\, l^+l^-$



4. Outlook

Strong Cosmic Evidence for Dark Matter
But, we need Laboratory Studies!

LHC – No SUSY or Other "New Physics" Yet
Underground WIMP Searches (Some Controversey)
Astrophysical Antimatter (positron) Excesses?

Possible Z_d Effects → Portal to Dark Matter
g-2 Hint, Direct Searches $Z_d \to e^+e^-$,
Parity Violation, Rare K, B (μ & τ) & H Decays

Z_d Discovery would revolutionize particle physics!