Tales From The "Dark Side" of Particle Physics

(The Dark-Light Connection)

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

Viewer Discretion Advised

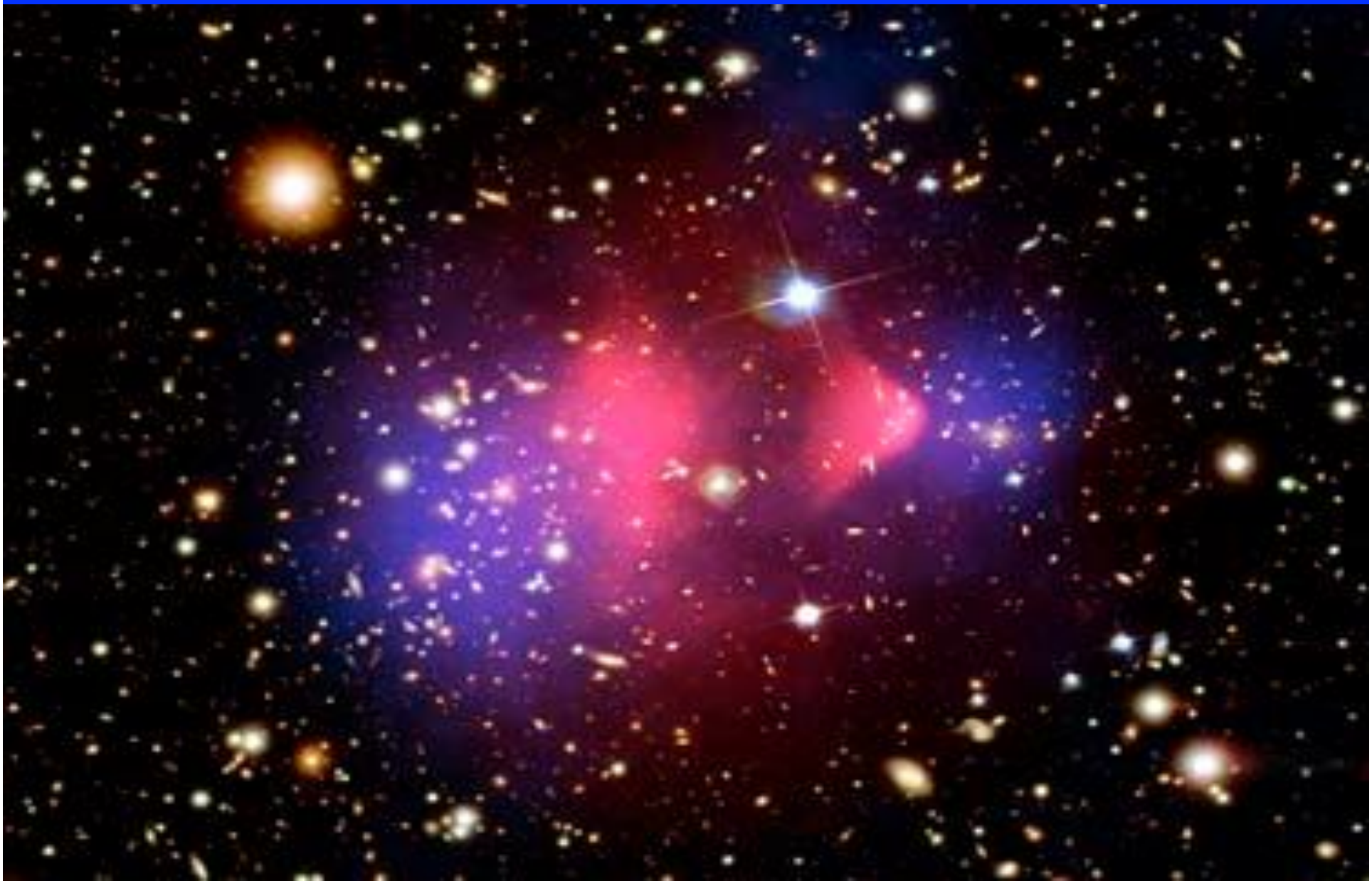
Beware the Ides of March!

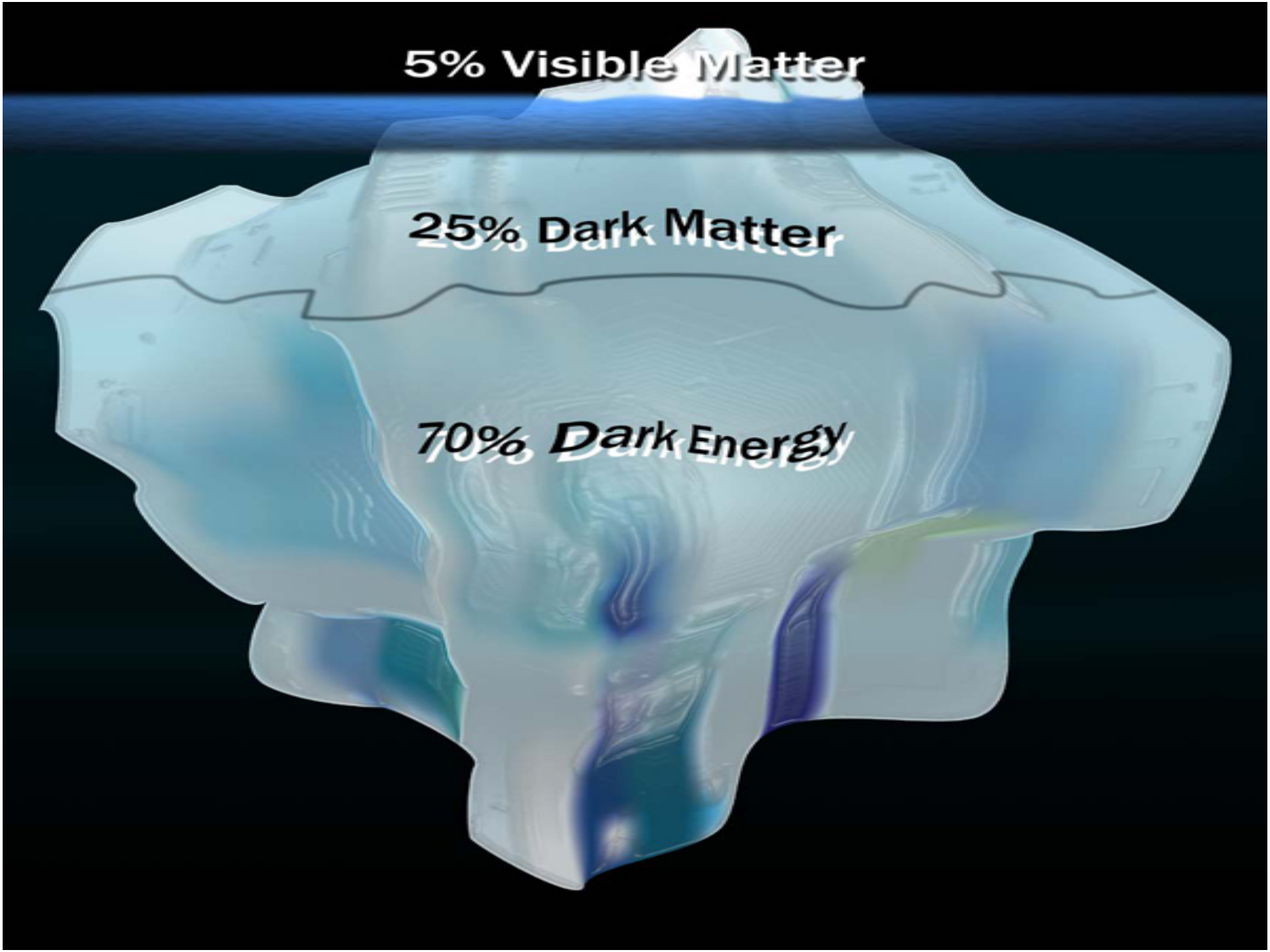
William J. Marciano

The Best of Times or The Worst of Times?

(March 15, 2012)

Bullet Galaxy Cluster




5% Visible Matter
25% Dark Matter
70% Dark Energy

Visible Matter

- Elementary Particle Physics
- $SU(3)_C x SU(2)_L x U(1)_Y$ Standard Model

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

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

  e,ν_e,u,d μ,ν_μ,c,s τ,ν_τ,t,b ($m_t/m_\nu > 10^{13}$!!)

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

Almost Complete! Where's the Higgs (H)?

Remnant of Particle Mass Origin

How did we arrive at the Standard Model?

What Else Is There? New Particles? Interactions?

How does dark matter fit in?

Ancient History - At a Glance

Maxwells Equations (E&M) 1861

1897 ***Electron*** Discovered

Quantum Mechanics (γ photon) – Special Relativity

1919 ***Proton*** Discovered

Spin, Atomic Physics (magnetic moment $\boldsymbol{\mu}_e = g_e e/2m_e \mathbf{S}$) , $g_e = 2$

1928 The Dirac Equation ***The Genius of Dirac***

QM+Special Rel.+Spin+EM Gauge Invariance

First Order Equation

$\mathbf{i(\partial_\mu - ieA_\mu(x))\gamma^\mu \psi(x) = m_e \psi(x)}$, $\mathbf{g_e = 2}$ **(automatic!)**

4x4 γ^μ (Dirac) matrices: $\gamma^\mu \gamma^\nu + \gamma^\nu \gamma^\mu = 2g^{\mu\nu}I$

Dirac predicts positron, antiproton, antihydrogen…

1929 Electromagnetic Gauge Invariance – H. Weyl

1930 Pauli Proposes the ***Neutrino*** (weak interactions)

1931 ***Neutron*** Discovered (strong interactions)

1932 ***Positron*** Discovered (*Anti-Matter Exists!*)

Antimatter Discovery Dirac's crowning glory!

Doubled Fermion Particle Spectrum ($e^- p^+ + e^+ p^-$)!

Why is the Universe Matter-Antimatter Asymmetric?

What happened to the antimatter?

Baryogenesis! Leptogenesis!

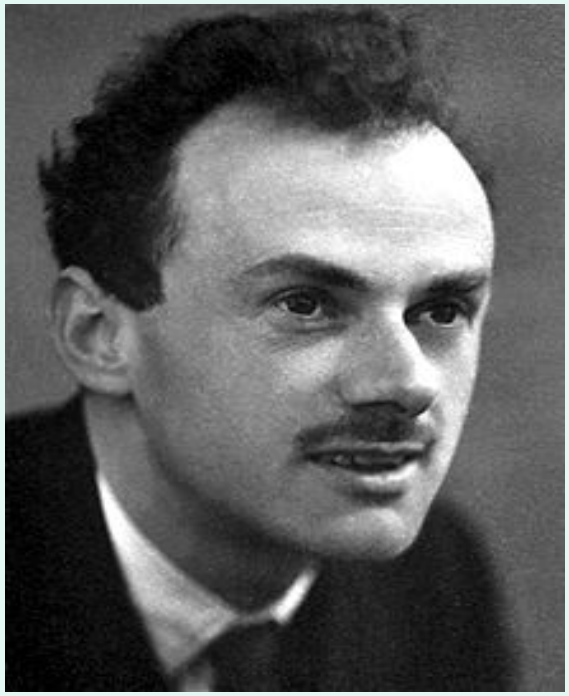
"New Physics" Source of CP Violation Needed!

Supersymmetry, 4th Generation, Multi-Higgs…

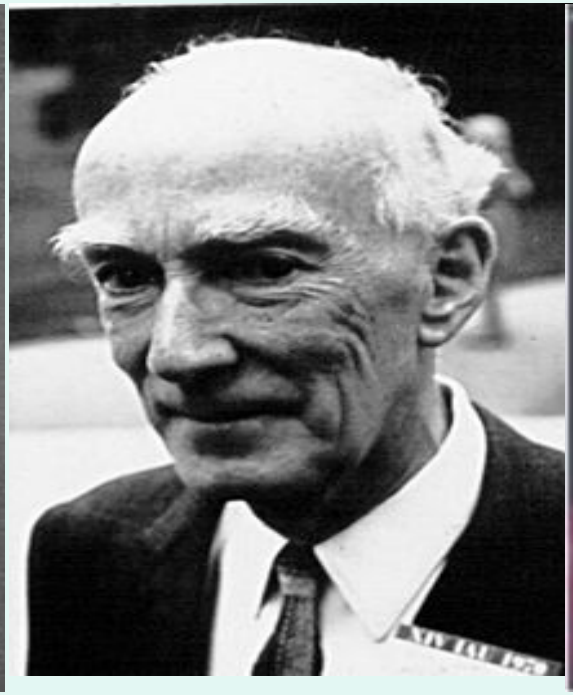
1932-33's Astronomers start to see "Dark Matter" Evidence!

Jan Ort & Fritz Zwicky

Dirac



Ort



Zwicky

Post WWII Developments (1947-48)

1947 Lamb measures the $2P_{½}$-$2S_{½}$ splitting

vacuum polarization, electron self-interaction

1948 Schwinger Calculates: $a_e=(g_e-2)/2=\alpha/2\pi\approx 0.00116$

$(\alpha=e^2/4\pi=1/137)$

Agreed with measurement of Kusch & Foley**!**

a_e and Lamb shift start of QED (Quantum Electrodynamics)

Current Status of $a_e=(g_e-2)/2$

a_e(exp)=0.001159652180 73(28)

g_e(exp)=2.002319304361 46(56) *13 significant figures!*

QED tested at the $(\alpha/\pi)^5$ level!

$\alpha^{-1}(a_e)$=137.035999084(51) Best Determination

Mount Auburn Cemetery

Muon Physics

1947 Muon established $m_\mu \approx 207 m_e$ "Who ordered that?"

$\tau_\mu = 2.2 \times 10^{-6}$ sec *very long*

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 287(63)(49) \times 10^{-11}$ (*3.6σ!*) very large deviation!

Muonic Hydrogen Lamb Shift Exp – QED deviates by 5-8σ!

Signs of "New Physics"?

Precision Measurements Probe:

"High and Low Scales" Supersymmetry – Dark Bosons

Electroweak Unification - Glashow & Weinberg

- **1954 Yang – Mills SU(2) Theory (BNL Paper)**
- **1957 Schwinger SO(3) (W^+, γ, W^-) triplet**

- **"It really doesn't matter what your thesis subject is. What counts is your choice of an advisor"**

S.L. Glashow

Glashow (1961) SU(2)xU(1) (**W^+, W^0, W^-) B^0**

"No Higgs Mechanism"

m_W & m_Z arbitrary (put in by hand)

$\gamma = B\cos\theta + W^0\sin\theta$ massless photon

$Z = W^0\cos\theta - B\sin\theta$ massive neutral gauge boson

$e=g\sin\theta$ *birth of the weak mixing angle*

(Given Little Attention)

- **Weinberg**(1967) SU(2)xU(1) + Higgs Mechanism

  generates $W^{\pm}$&Z masses

  spontaneous sym. Breaking

  via complex scalar doublet

$$m_W = m_Z \cos\theta \;\&\; e = g\sin\theta$$

Z Boson: ***New Source of Parity Violation!***

Weak Neutral Currents

Flavor Changing Weak Neutral Currents $s \rightarrow d\mu^+\mu^-$

Largely ignored until 'tHooft proved renormalizability (1971)

Weak Neutral Currents Discovered (1972) Neutrino scattering!

$\theta \rightarrow \theta_W$ **Weinberg or Glashow or Weak Mixing Angle**

Most important Electroweak Parameter!

A Beautiful Relation

$SU(2)_L xU(1)_Y$ + Higgs Doublet + Renormalizability

- ***$\sin^2\theta^0_W = 1-(m^0_W/m^0_Z)^2 = (e^0/g^0)^2$ Natural Bare Relation***
  Quantum (Loop) Corrections - Finite & Calculable!

$\sin^2\theta_W$, m_W, m_Z, e, g interrelated

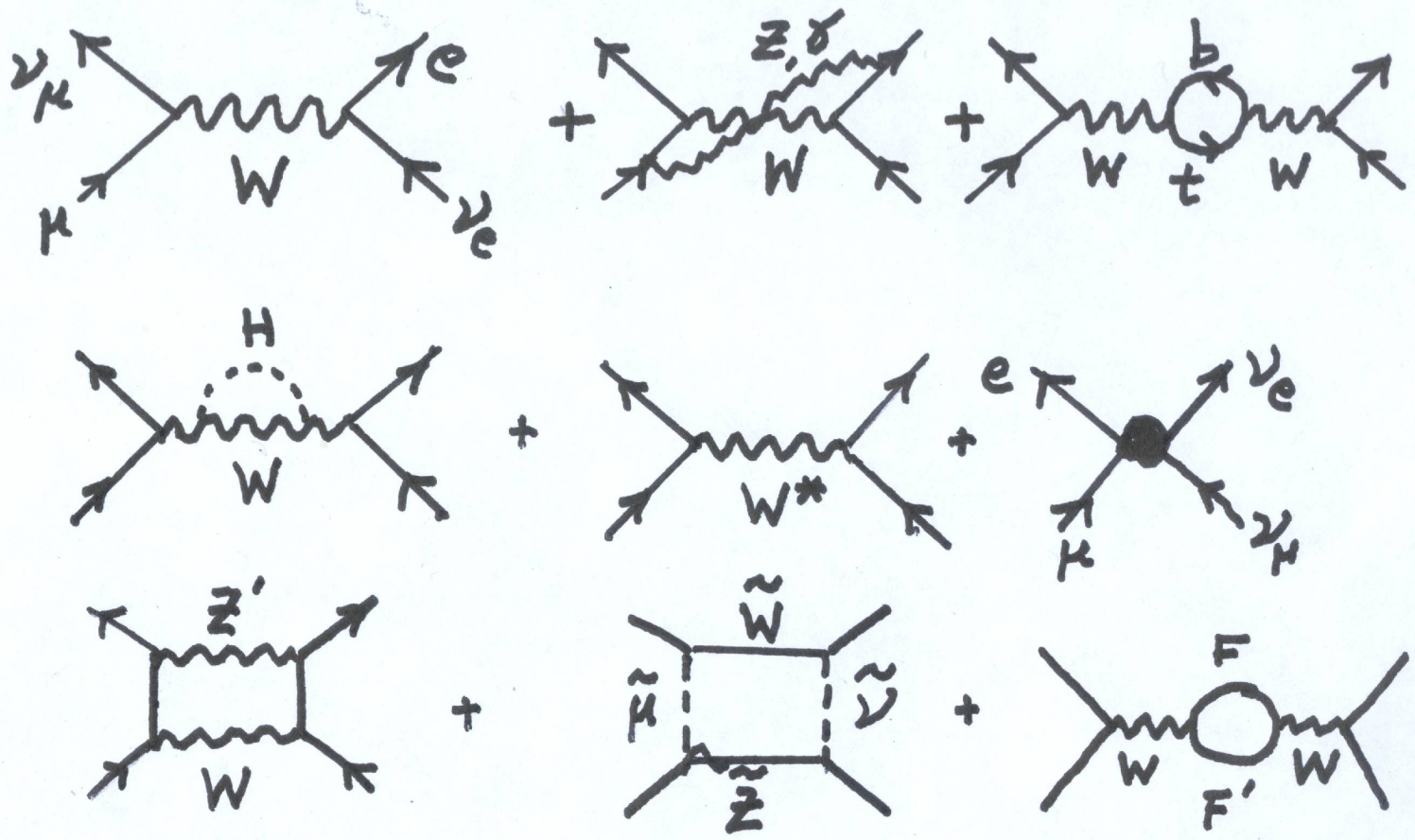
$\alpha = e^2/4\pi$ **$G_\mu = g^2/4\sqrt{2}m_W^2$ (Fermi Constant)**

Precision Measurements probe quantum loops

$$\Delta r(\text{SM},\text{“New Physics”})_{MS} = 1-\pi\alpha/\sqrt{2}G_\mu m_W^2 \sin^2\theta_W(m_Z)_{MS}$$

$$\Delta r(\text{SM},\mathbf{m_H},\text{”New Physics”}) = 1-\pi\alpha/\sqrt{2}G_\mu m_W^2(1-m_W^2/m_Z^2)$$

Loop and Tree Level Corrections to Muon Decay



+ . . .

New Precise Muon (μ^+) Lifetime

$\tau_{\mu+}$=2.1969803(22)x10^{-6}sec MuLAN at PSI (2010)

(Most precise lifetime measurement ever!)

Previous World Average $\tau_{\mu+}$=2.1970190(210)x10^{-6}sec

improved by a factor of 10! 1.8 sigma shift!

$$\tau_\mu^{-1} = \Gamma(\mu^+ \rightarrow e^+ \nu_e \nu_\mu(\gamma)) = G_\mu^2 m_\mu^5 f(m_e^2/m_\mu^2)[1+RC]/192\pi^3$$

$$RC = \alpha/2\pi(25/4-\pi^2)(1+\alpha/\pi[2/3\ln(m_\mu/m_e)-3.7)\ldots]$$ Fermi Th.

Other SM and "New Physics" radiative corrections absorbed into G_μ. Eg. Top Mass, Higgs Mass, Technicolor, Susy, W*…

G_μ=1.16637887(7)x10^{-5}GeV^{-2} precise & important

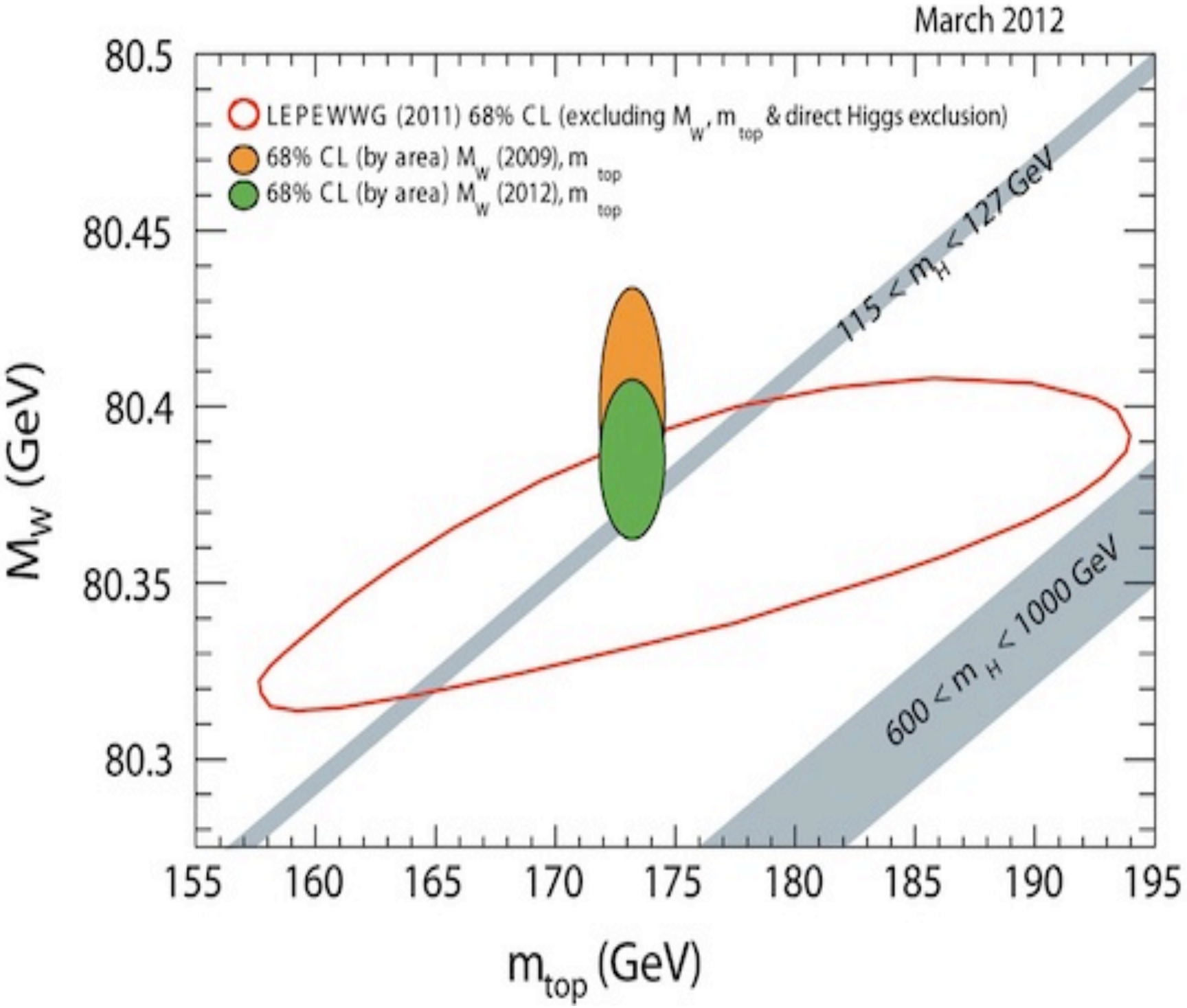
Precision Parameters (status):

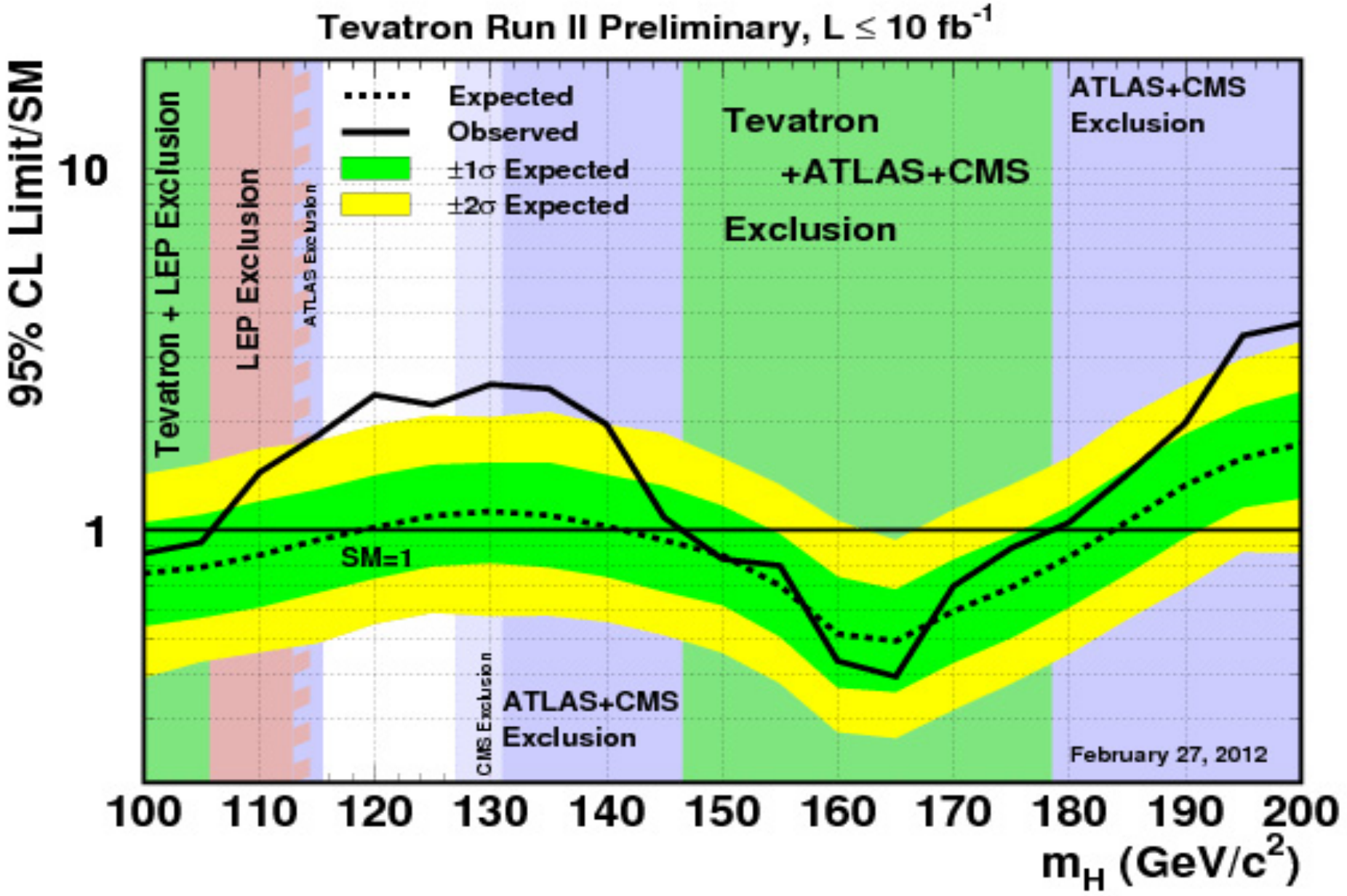
Quantity	2006 Value		2011 Value	Comment
α^{-1}	137.035999710(96)		137.035999084(51)	g_e-2
G_μ	$1.16637(1)\times10^{-5}GeV^{-2}$		$1.1663788(7)\times10^{-5}GeV^{-2}$	PSI
m_Z	91 .1875(21)GeV		91.1876(21)GeV	-
*m_t	171.4(2.1)GeV	→	173.2(0.9)GeV	FNAL
m_W	80.410(32)GeV	→	80.399(25)GeV	LEP2/FNAL
$\sin^2\theta_W(m_Z)$	0.23125(16)		0.23125(16)	Ave.

m_H=90GeV central prediction 114GeV<m_H<140GeV

2012 shift m_W = 80.399(25)GeV ➔80.387(19)GeV CDF

80.375(23)GeV DO


March 2012
LEPEWWG (2011) 68% CL (excluding M_W, m_{top} & direct Higgs exclusion)
68% CL (by area) M_W (2009), m_{top}
68% CL (by area) M_W (2012), m_{top}
$115 < m_H < 127$ GeV
$600 < m_H < 1000$ GeV
M_W (GeV)
m_{top} (GeV)
80.5
80.45
80.4
80.35
80.3
155
160
165
170
175
180
185
190
195


Tevatron Run II Preliminary, L ≤ 10 fb-1
95% CL Limit/SM
10
1
Tevatron + LEP Exclusion
LEP Exclusion
ATLAS Exclusion
CMS Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron
+ATLAS+CMS
Exclusion
ATLAS+CMS
Exclusion
SM=1
ATLAS+CMS
Exclusion
February 27, 2012
100 110 120 130 140 150 160 170 180 190 200
mH (GeV/c2)

What About $\sin^2\theta_W$?

$\sin^2\theta_W(Q^2)$ = Physical Running Angle

Continuous

Incorporates γZ mixing loops: quarks, leptons, $W^{\pm}$

Precision measurements at the Z Pole ($e^+e^- \rightarrow Z \rightarrow ff$)

Best Determinations

$\sin^2\theta_W(m_Z)_{MS} = 0.23070(26)$ A_{LR} (SLAC)

$\sin^2\theta_W(m_Z)_{MS} = 0.23193(29)$ $A_{FB}(bb)$ (CERN)

(3.2 sigma difference!)

- **Leptonic vs Hadronic Z Pole Averages**

$\sin^2\theta_W(m_Z)_{MS}$ = 0.23085(21) Leptonic

$\sin^2\theta_W(m_Z)_{MS}$ = 0.23194(27) Hadronic

(Also differ by > 3sigma)

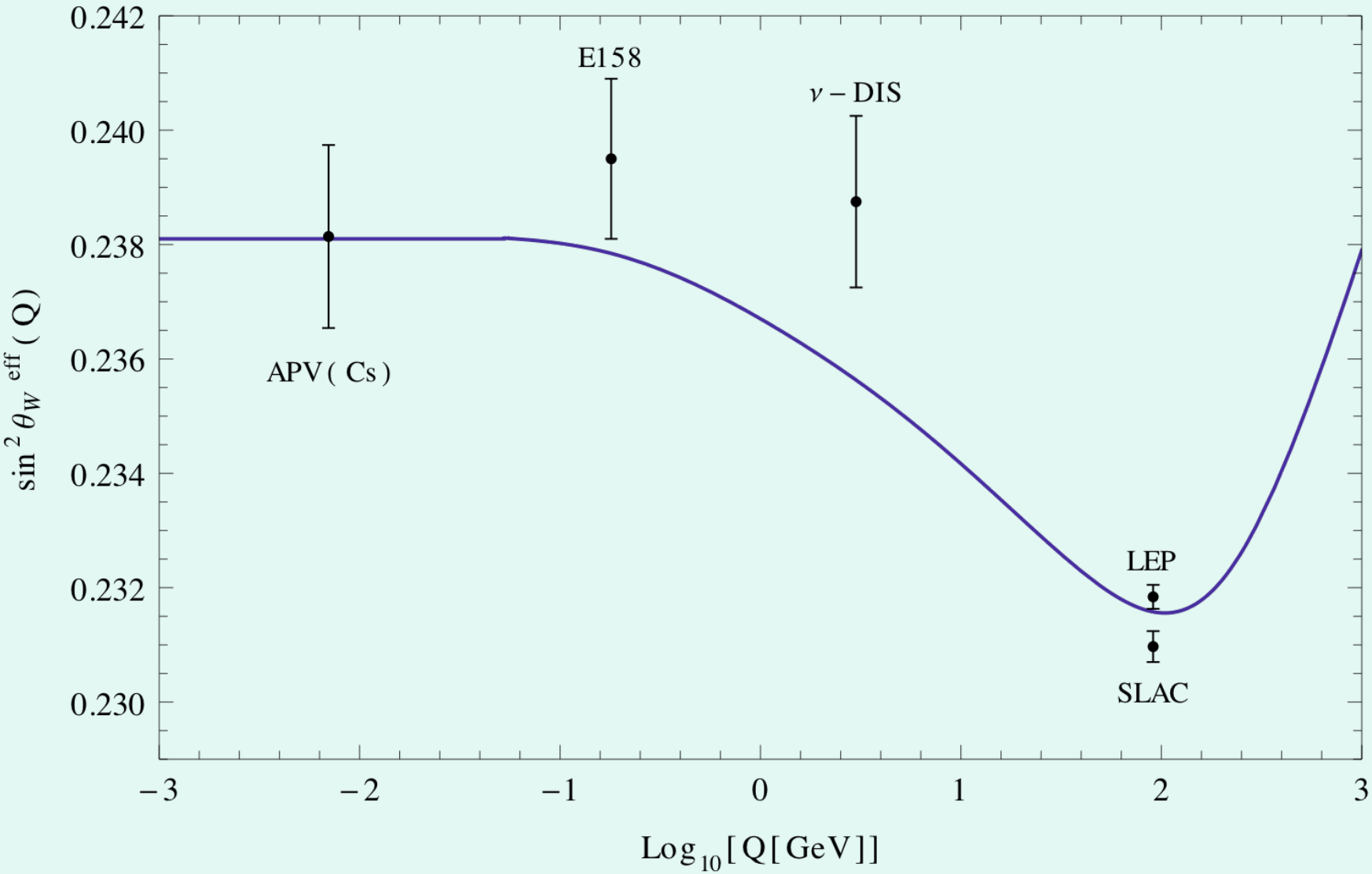
World Average: **$\sin^2\theta_W(m_Z)_{MS}$=0.23125(16)**

IS IT CORRECT?

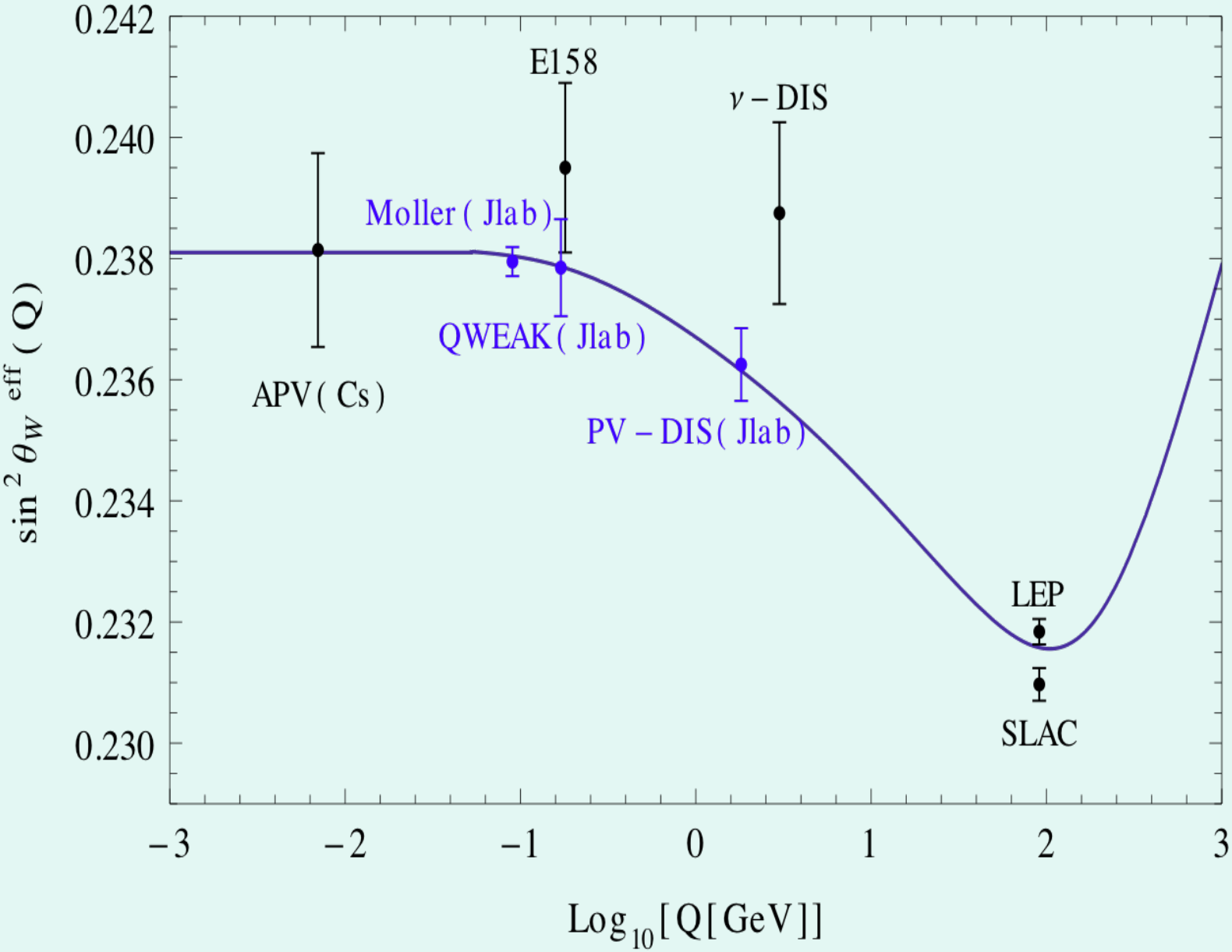
(Major Implications) Higgs & "New Physics"

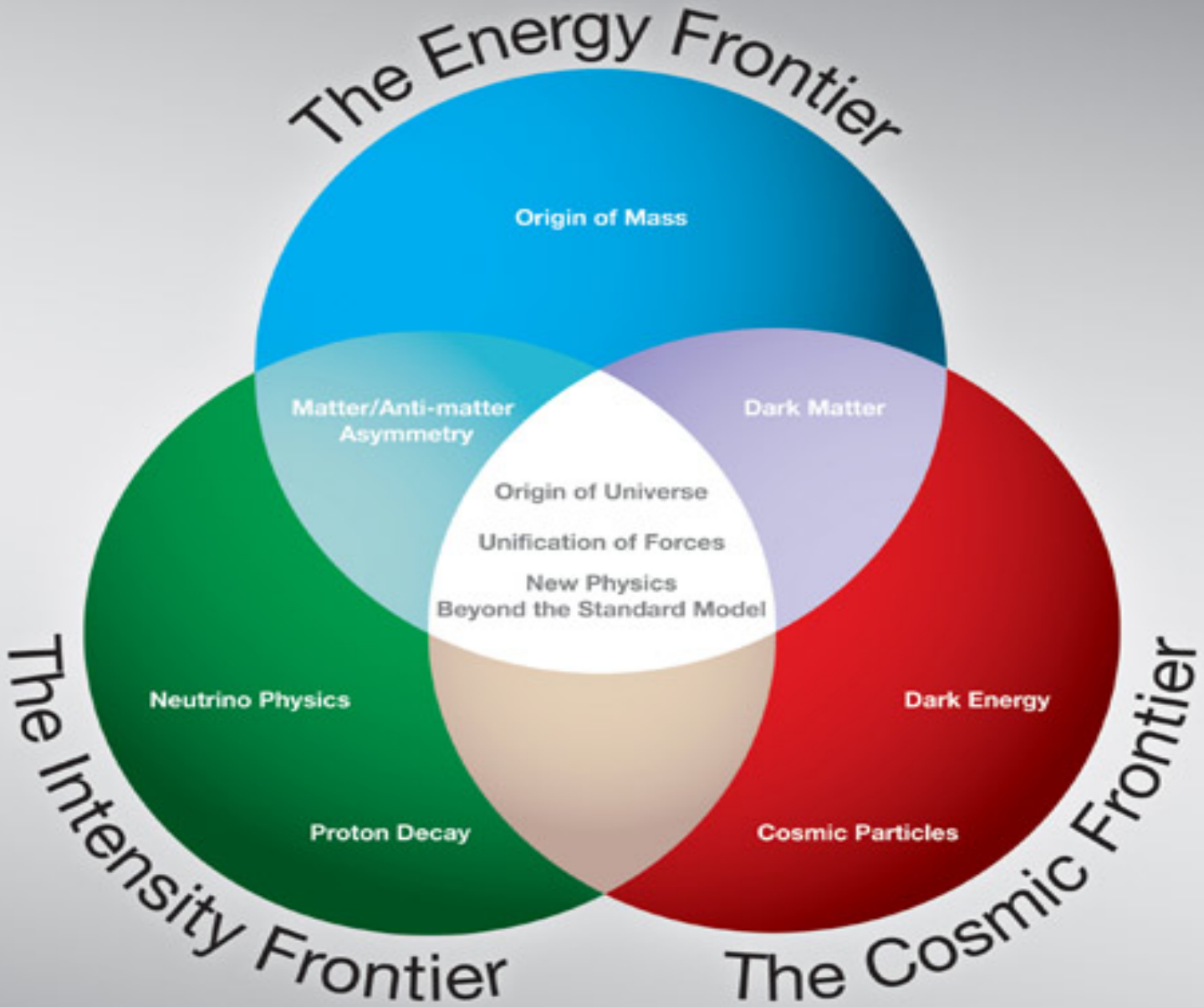
Average → $m_H \approx$ 115GeV

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



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




The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

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

Hints of m_H≈125GeV 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}

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

Pretty 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 Dark Boson
A Portal to Dark Matter

- Searches for Dark Matter Particles (Mainly WIMPS)

  Astrophysics - Possible Hints

  LHC (Supersymmetry) No sign yet

  Underground Scattering – Conflicting Experiments

Is dark matter just a single particle?

Are there many dark particles (most unstable)

Does Dark Matter have gauge symmetries? Dark Charge?

What if $U(1)_d$ ➔ Z_d $10MeV<m_{Zd}<10GeV$?

(Sometimes called Dark Photon or Dark Z)

Z_d coupling to our particle world

- Kinetic Mixing (Bob Holdom) $U(1)_Y$ & $U(1)_d$

  $\rightarrow \varepsilon/2\, F_{\mu\nu} Z_d^{\mu\nu} \rightarrow \varepsilon e Z_d^{\mu} J_{\mu}^{em}$ no J_{μ}^{NC} coupling!

  $\varepsilon \leq$ few x 10^{-3} 10MeV $\leq m_d \leq$ few GeV

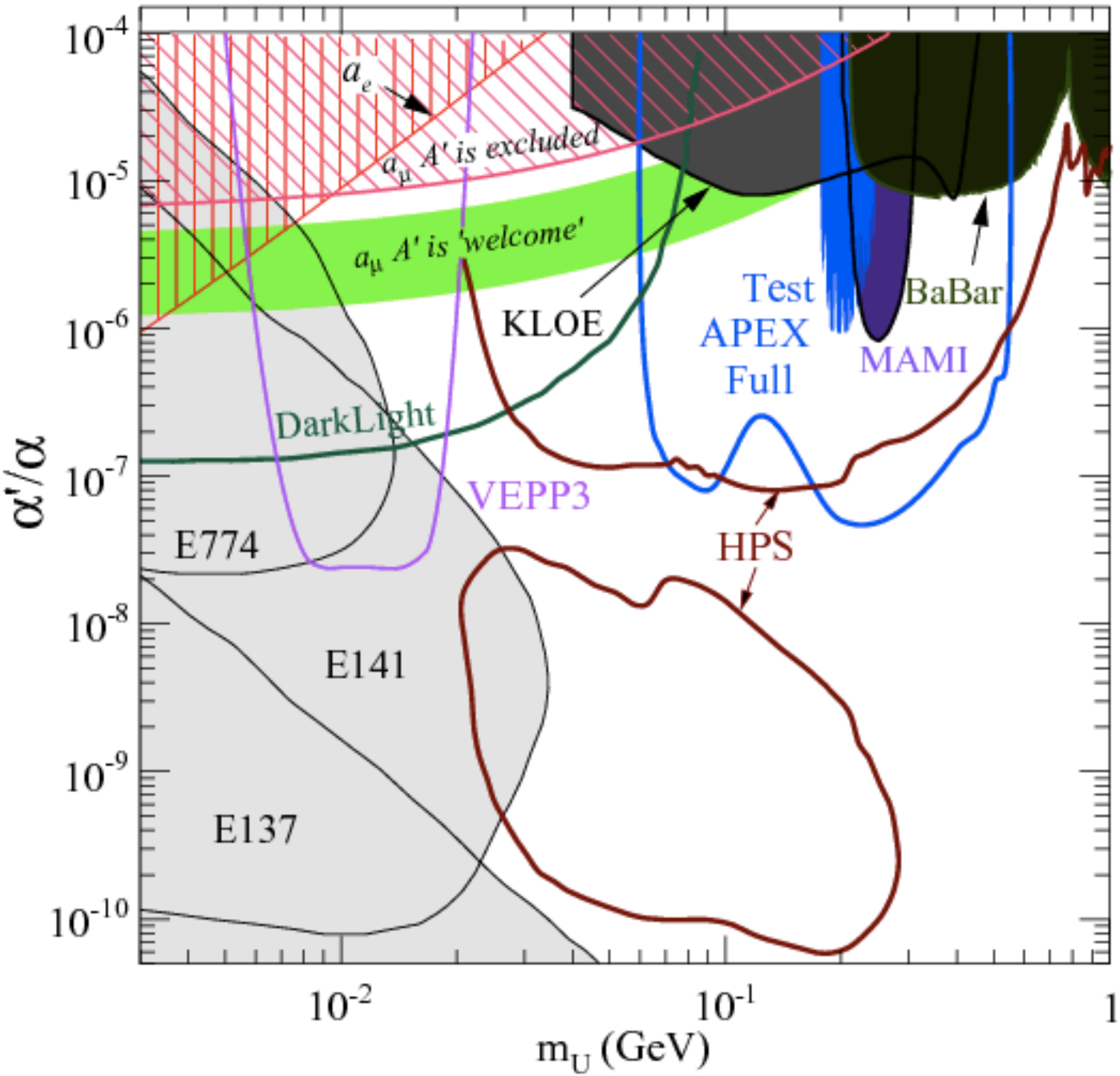
  $\alpha'/\alpha = \varepsilon^2$

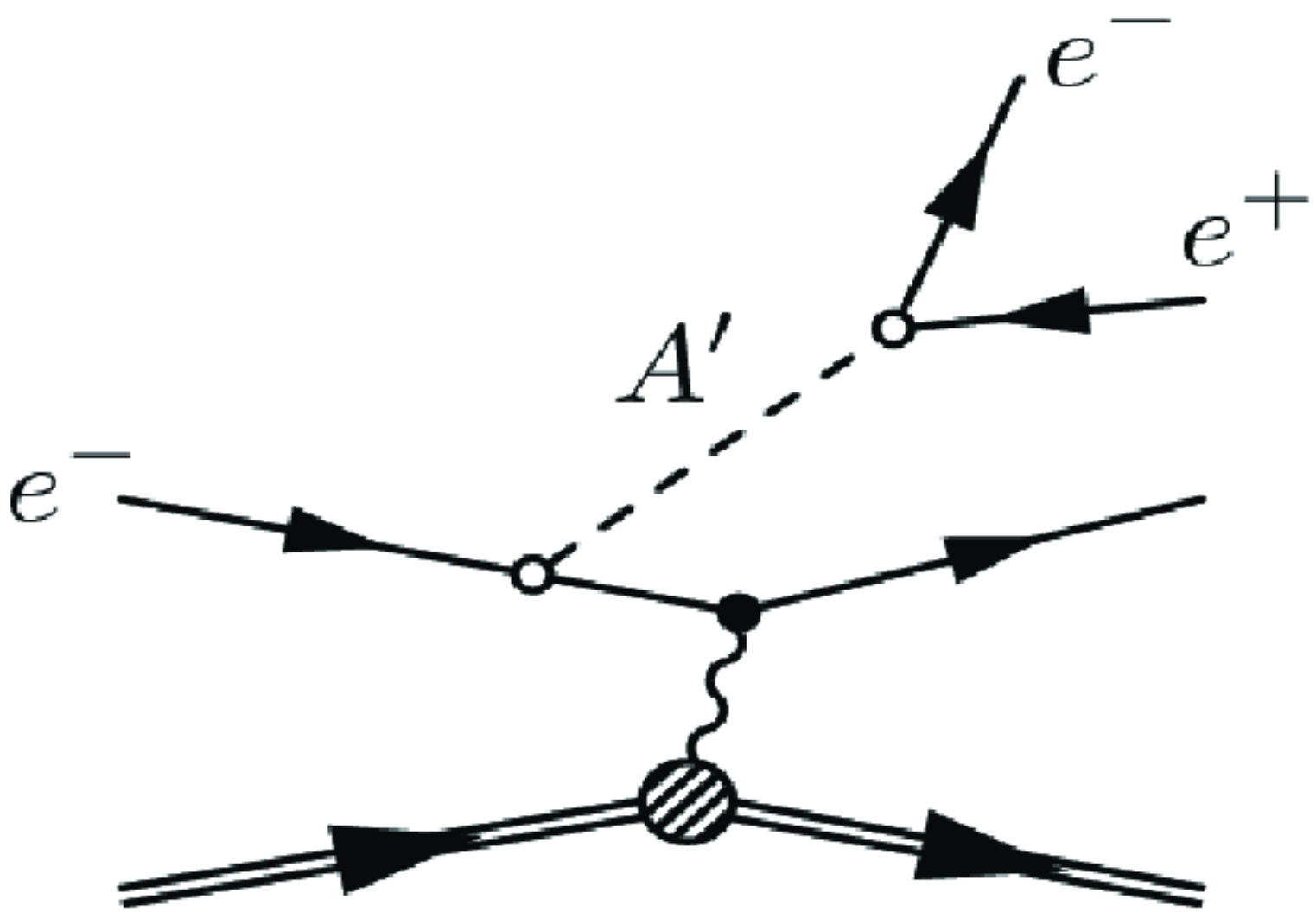
$\varepsilon \approx 2 \times 10^{-3}$ & $m_d \approx$ 10-200MeV resolves a_μ discrepency!

produce in electron scattering

detect $Z_d \rightarrow e^+e^-$

Experiments at JLAB and MAMI (Mainz)


a_e
a_μ A' is excluded
a_μ A' is 'welcome'
KLOE
Test
APEX
Full
BaBar
MAMI
DarkLight
VEPP3
HPS
E774
E141
E137
α'/α
m_U (GeV)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-2}
10^{-1}
1


e^-
e^+
A'
e^-

Z-Z_d Mass Mixing H.Davoudiasl, H-S Lee & WJM arXiv:1203.2947

- $M^2 = \begin{matrix} m_Z^2 & m_{Zd}m_Z\delta \\ m_{Zd}m_Z\delta & m_{Zd}^2 \end{matrix}$ $\delta^2 << 1$

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

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

New Effects from δ

- New Parity Violation: Atomic PV & Polarized ee &ep

Flavor Changing Decays $K \rightarrow \pi Z_d$, $Z_d \rightarrow e^+e^-$ or $\nu\nu$

$B \rightarrow K Z_d$ " "

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

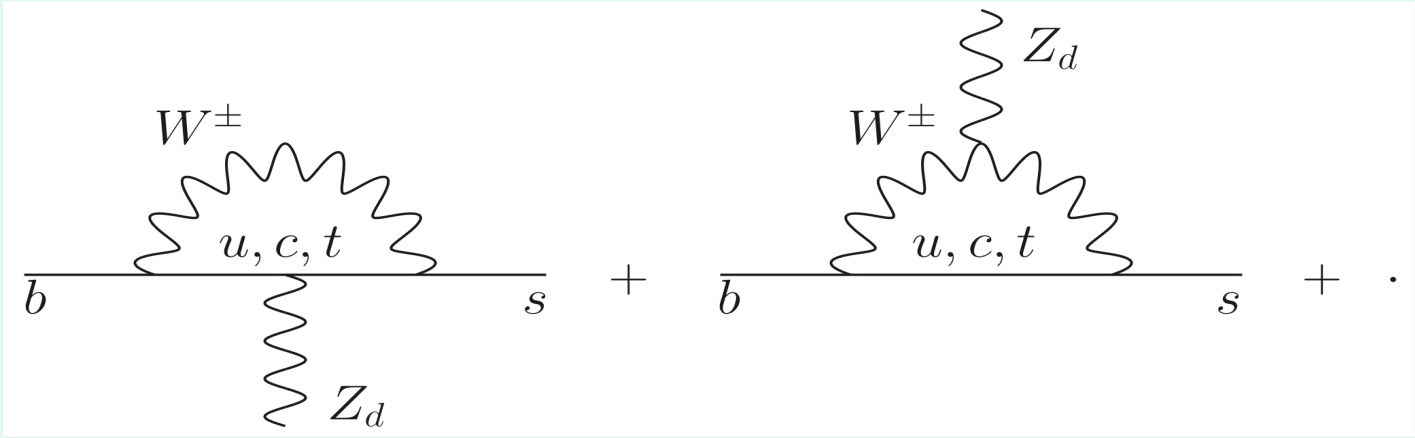
Longitudinal Z_d

All are enhanced by E/m_{Zd} overcomes m_{Zd}/m_Z suppression

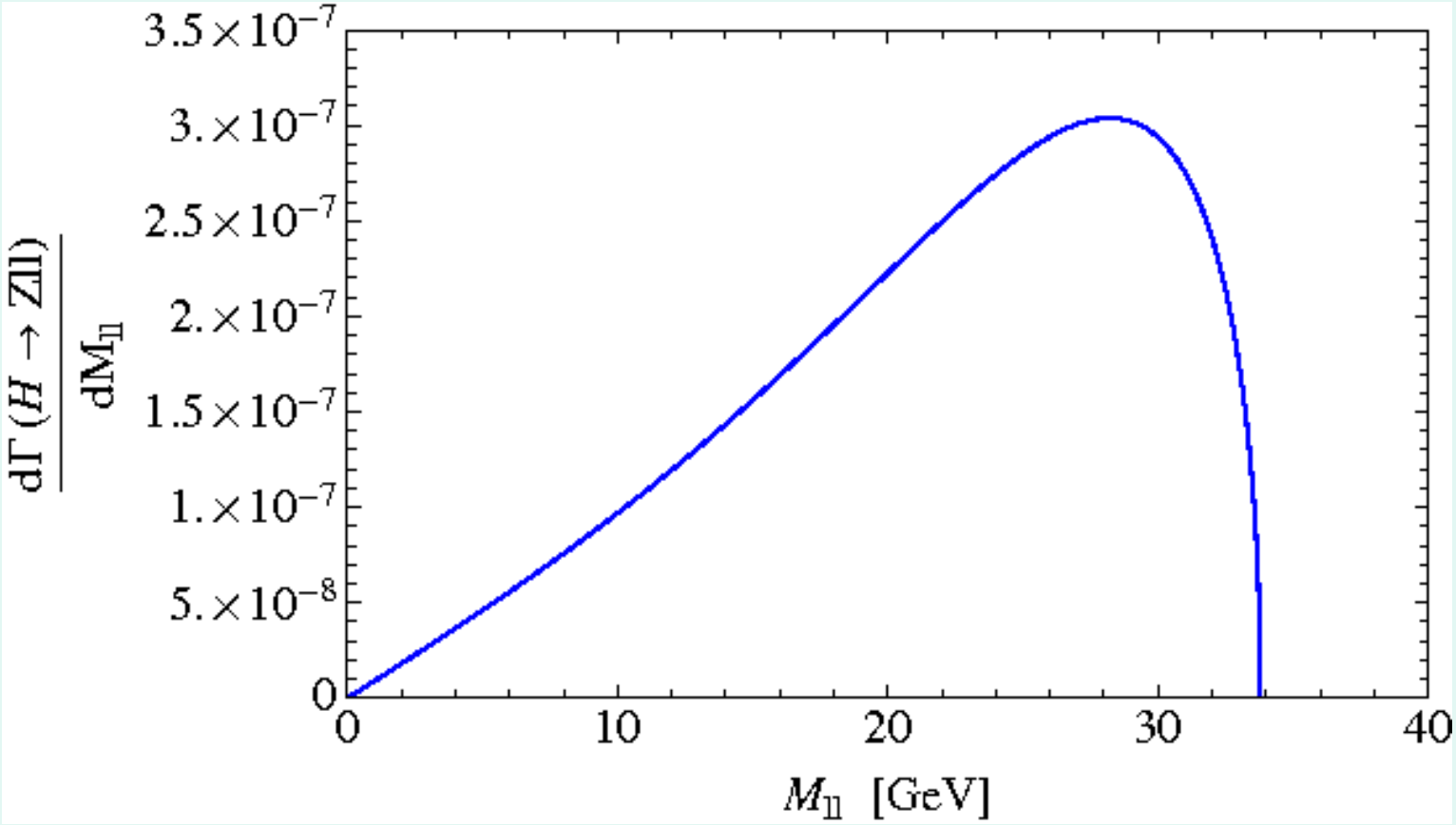
Experimental sensitivities δ below 10^{-3}! (B & K decays)

Should be pushed as far as possible!

Flavor Changing neutral current decays



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



Conclusions

- **Precision measurements seem to be starting to pinpoint $m_H \approx$ 100-125 GeV with little room for "New Physics"**

  Standard Model Higgs – Is that all there is?

  So far no real sign of "New Physics" at the LHC

  Where is supersymmetry?

  Strong Cosmic Evidence for Dark Matter

  We need Laboratory Evidence!

  Look for Z_d wherever possible – Portal to Dark Matter

  Parity Violation, Rare K, B & H Decays