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)

BROOKHAVEN NATIONAL LABORATORY
Bullet Galaxy Cluster
5% Visible Matter

25% Dark Matter

70% Dark Energy
Visible Matter

- Elementary Particle Physics
- $SU(3)_C \times SU(2)_L \times U(1)_Y$ Standard Model
  - 8 gluons + $W^\pm$, $Z$, $\gamma$ (spin 1) gauge bosons
  - 3 generations of quarks & leptons (mix->CP violation)
    - $e, \nu_e, u, d \quad \mu, \nu_\mu, c, s \quad \tau, \nu_\tau, t, b$ (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

Maxwell's Equations (E&M) 1861

1897 *Electron* Discovered
  Quantum Mechanics (\(\gamma\) photon) – Special Relativity

1919 *Proton* Discovered
  Spin, Atomic Physics (magnetic moment \(\mu_e = g_e e / 2m_e S\)) , \(g_e = 2\)

1928 The Dirac Equation  *The Genius of Dirac*
  QM+Special Rel.+Spin+EM Gauge Invariance
  First Order Equation
  \[i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m_e\psi(x), \quad g_e = 2\ (\text{automatic!})\]
  4x4 \(\gamma^\mu\) (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
Post WWII Developments (1947-48)

1947 Lamb measures the $2P_{1/2}-2S_{1/2}$ 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 $a_e = (g_e - 2)/2$

$a_e(\text{exp}) = 0.00115965218073(28)$
$g_e(\text{exp}) = 2.00231930436146(56)$  13 significant figures!

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

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

\[ \frac{\alpha}{2\pi} \]

JULIAN SCHWINGER
2.12.1918 — 7.16.1994
Muon Physics

1947 Muon established \( m_\mu \approx 207 m_e \) “Who ordered that?”
\( \tau_\mu = 2.2 \times 10^{-6} \text{sec} \) very long

\[ \Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 287(63)(49) \times 10^{-11} (3.6\sigma!) \] very large deviation!

Muonic Hydrogen Lamb Shift Exp – QED deviates by 5-8\( \sigma \)!

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) \((W^+, \gamma, W^-)\) triplet

• "It really doesn’t matter what your thesis subject is. What counts is your choice of an advisor”
  
S.L. Glashow

Glashow (1961) \(SU(2) \times U(1)\) \((W^+, W^0, W^-) B^0\)

“No Higgs Mechanism”

\(m_W & m_Z \text{ arbitrary}\) (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 symmetry breaking via complex scalar doublet

$$m_W = m_Z \cos \theta \quad \text{and} \quad e = g \sin \theta$$

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

**Weak Neutral Currents**

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

Largely ignored until 't Hooft proved renormalizability (1971)

Weak Neutral Currents Discovered (1972) Neutrino scattering!

$$\theta \rightarrow \theta_W \quad \text{Weinberg or Glashow or Weak Mixing Angle}$$

**Most important Electroweak Parameter!**
A Beautiful Relation

SU(2)_L \times U(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!

\[ \sin^2 \theta_W, m_W, m_Z, e, g \text{ interrelated} \]
\[ \alpha = e^2/4\pi \quad G_\mu = g^2/4\sqrt{2}m_W^2 \text{ (Fermi Constant)} \]

Precision Measurements probe quantum loops

\[ \Delta r(\text{SM}, \text{"New Physics"})_{\text{MS}} = 1 - \pi\alpha/\sqrt{2}G_\mu m_W^2\sin^2 \theta_W(m_Z)_{\text{MS}} \]
\[ \Delta r(\text{SM}, m_H, \text{"New Physics"}) = 1 - \pi\alpha/\sqrt{2}G_\mu m_W^2(1 - m_W^2/m_Z^2) \]
Loop and Tree Level Corrections to Muon Decay

\[ \nu_\mu \rightarrow e + Z + W + H + \tilde{Z} + F \]

\[ \mu \rightarrow e + W + t \]

\[ \nu_e \]

\[ \tilde{Z} \]

\[ \text{Z' Boson} \]

\[ \text{SUSY} \]

\[ \text{Technicolor} \]

\[ + \ldots \]
New Precise Muon ($\mu^+$) Lifetime

$\tau_{\mu^+} = 2.1969803(22) \times 10^{-6}$ sec  MuLAN at PSI (2010)
(Most precise lifetime measurement ever!)

Previous World Average $\tau_{\mu^+} = 2.1970190(210) \times 10^{-6}$ 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 $= \frac{\alpha}{2\pi}(25/4-\pi^2)(1+\alpha/\pi[2/3\ln(m_\mu/m_e)-3.7])$… Fermi Th.
Other SM and “New Physics” radiative corrections absorbed into $G_\mu$. Eg. Top Mass, Higgs Mass, Technicolor, Susy, W*…

$G_\mu = 1.16637887(7) \times 10^{-5}$ GeV$^{-2}$ precise & important
### Precision Parameters (status):

<table>
<thead>
<tr>
<th>Quantity</th>
<th>2006 Value</th>
<th>2011 Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha^{-1}$</td>
<td>137.035999710(96)</td>
<td><strong>137.035999084(51)</strong></td>
<td>$g_e^{-2}$</td>
</tr>
<tr>
<td>$G_\mu$</td>
<td>1.16637(1)x10^{-5}\text{GeV}^{-2}$</td>
<td><strong>1.1663788(7)x10^{-5}\text{GeV}^{-2}</strong></td>
<td>PSI</td>
</tr>
<tr>
<td>$m_Z$</td>
<td>91.1875(21)\text{GeV}</td>
<td>91.1876(21)\text{GeV}</td>
<td>-</td>
</tr>
<tr>
<td>*$m_t$</td>
<td>171.4(2.1)\text{GeV}</td>
<td><strong>173.2(0.9)\text{GeV}</strong></td>
<td>FNAL</td>
</tr>
<tr>
<td>$m_W$</td>
<td>80.410(32)\text{GeV}</td>
<td><strong>80.399(25)\text{GeV}</strong></td>
<td>LEP2/FNAL</td>
</tr>
<tr>
<td>$\sin^2\theta_W(m_Z)$</td>
<td>0.23125(16)</td>
<td>0.23125(16)</td>
<td>Ave.</td>
</tr>
</tbody>
</table>

$m_H=90\text{GeV central prediction}$ \hspace{1cm} 114\text{GeV}<m_H<140\text{GeV}

2012 shift $m_W = \underline{80.399(25)\text{GeV}} \rightarrow 80.387(19)\text{GeV}$ CDF

80.375(23)\text{GeV}$ DO
March 2012

LEPE WWG (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)
Tevatron Run II Preliminary, $L \leq 10 \text{ fb}^{-1}$

- 95\% CL Limit/SM
- Tevatron
- LEP Exclusion
- ATLAS+CMS Exclusion

$\pm 1\sigma$ Expected
$\pm 2\sigma$ Expected

$M_H$ (GeV/c$^2$)

February 27, 2012
What About $\sin^2 \theta_W$?

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

Continuous

Incorporates $\gamma Z$ mixing loops: quarks, leptons, $W^\pm$

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

**Best Determinations**

\[
\begin{align*}
\sin^2 \theta_W(m_Z)_{\text{MS}} &= 0.23070(26) & A_{LR} \quad (\text{SLAC}) \\
\sin^2 \theta_W(m_Z)_{\text{MS}} &= 0.23193(29) & A_{FB}(bb) \quad (\text{CERN})
\end{align*}
\]

(3.2 sigma difference!)
• Leptonic vs Hadronic Z Pole Averages

\[ \sin^2 \theta_W(m_Z)_{\text{MS}} = 0.23085(21) \quad \text{Leptonic} \]
\[ \sin^2 \theta_W(m_Z)_{\text{MS}} = 0.23194(27) \quad \text{Hadronic} \]

(Also differ by > 3sigma)

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

IS IT CORRECT?

(Major Implications) Higgs & “New Physics”

Average \( \Rightarrow m_H \approx 115 \text{GeV} \)
Running $\sin^2 \theta_W(Q^2)$
Running of $\sin^2 \theta_W(Q)$
The Higgs Search Has Narrowed: $115\text{GeV}<m_{H}<135\text{GeV}$
Hints of $m_{H}\approx 125\text{GeV}$ at CERN
$H \rightarrow \gamma\gamma, WW^*, ZZ^*$
Approx 75,000 $H$/exp!

<table>
<thead>
<tr>
<th>$H$ Decay Channel</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{b}b$</td>
<td>0.578</td>
</tr>
<tr>
<td>$WW^*$</td>
<td>0.215</td>
</tr>
<tr>
<td>$gg$</td>
<td>0.086</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>0.063</td>
</tr>
<tr>
<td>$c\bar{c}$</td>
<td>0.029</td>
</tr>
<tr>
<td>$ZZ^*$</td>
<td>0.026</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>$2.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow \ell_1^+\ell_1^-\ell_2^+\ell_2^-$</td>
<td>$1.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\nu\bar{\nu}$</td>
<td>$3.6 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
What if $m_H=125\text{GeV}$?

Implies: $m_W = \underline{80.361(10)}\text{GeV} \text{ vs } 80.384(17)\text{GeV}$ now

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

Pretty Good Agreement!

Not much room for “New Physics”

So far: No direct evidence for Supersymmetry, Extra Dimensions, 4$^{\text{th}}$ 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 $U(1)_d \rightarrow Z_d$ 10MeV<$m_{Zd}$<10GeV ?
(Sometimes called Dark Photon or Dark Z)
**Z\textsubscript{d} coupling to our particle world**

- Kinetic Mixing (Bob Holdom) U(1)\textsubscript{Y} & U(1)\textsubscript{d}
  \[ \epsilon/2 \, F_{\mu\nu} Z_\text{d}^{\mu\nu} \Rightarrow \epsilon e Z_\text{d}^{\mu} J_\mu^{\text{em}} \] no J\textsubscript{\mu}^{\text{NC}} coupling!

  \[
  \epsilon \leq \text{few } 10^{-3} \quad 10\text{MeV} \leq m_\text{d} \leq \text{few GeV} \\
  \alpha'/\alpha = \epsilon^2
  \]

\[ \epsilon \approx 2 \times 10^{-3} \] \& \[ m_\text{d} \approx 10-200\text{MeV} \] resolves \[^{\text{a}}\mu\] discrepancy!

produce in electron scattering

detect \[ Z_\text{d} \Rightarrow e^+e^- \]

Experiments at JLAB and MAMI (Mainz)
Z-\(Z_d\) Mass Mixing H. Davoudiasl, H-S Lee & WJM
arXiv:1203.2947

\[
m_Z^2, m_{Zd}m_Z\delta
\]

- \(M^2 = \delta^2 << 1\)
  
  \[
m_{Zd}m_Z\delta, m_{Zd}^2
\]

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 $\delta$

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

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

$B \rightarrow KZ_d$

$H \rightarrow ZZ_d$  $Z_d \rightarrow l^+ l^-$ (l=e or $\mu$) or “missing energy”

**Longitudinal $Z_d$**

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

Experimental sensitivities $\delta$ below $10^{-3}$! (B & K decays)
Should be pushed as far as possible!
Flavor Changing neutral current decays
$H \rightarrow ZZ^* \rightarrow Z \ell^+\ell^-$
Conclusions

- Precision measurements seem to be starting to pinpoint \( m_H \approx 100-125 \text{ GeV} \) 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