Precision Electroweak Physics
Featuring
Radiative Corrections & Natural Relations
Muon Properties & Puzzles: $g_\mu-2$, $r_p$ & $\Delta r$
“The Dark Photon”
Part II

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From Lecture I

- $\Delta a_{\mu} = a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = +288(80) \times 10^{-11}$ (3.6$\sigma$ Discrepancy)
- $\Delta a_{e} = a_{e}^{\text{exp}} - a_{e}^{\text{SM}} = -105(81) \times 10^{-14}$ (1000x more precise)

$\Delta a_{e}$ has become a major constraint on the “Dark Photon” solution to the $\Delta a_{\mu}$ discrepancy

Seems to rule out $m_{\gamma_d} < 20\text{MeV}$ in the green band

Implications for the Proton Radius Puzzle!
Lepton Magnetic Moment Constraints on the Dark Photon

Green Band Corresponds to $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 288(63)(49) \times 10^{-11}$ 90% CL

Recent $g_e - 2$ Constraint (Davoudiasl, Lee, WJM)

$a_e^{\text{exp}} - a_e^{\text{theory}} = -1.05 (0.81) \times 10^{-12}$ wrong sign!
Updated Dark Photon Constraints
(Some assume $\text{BR}(Z_d \rightarrow e^+e^- \sim 1)$
Approx. MAMI2013 Sensitivity Shown
**Muonic Hydrogen Lamb Shift**

In an effort to precisely determine $r_p$

**PSI $\mu p$ atomic Lamb shift experiment**

$\Delta E(2P_{3/2} - 2S_{1/2}) = 209.9779(49) - 5.2262r_p^2 + 0.0347r_p^3 \text{ meV}$

*R. Pohl, A. Antognini et al. Nature July 2010*

**Very Elegant!**

Stop $\mu^-$ in Hydrogen, About 1% populate 2S $(1\mu\text{sec})$

Excite resonance with laser to $2P \rightarrow 1S$

$\mu p$ atomic Lamb Shift *very* sensitive to $r_p$

$(m_\mu/m_e)^3 = 8 \times 10^6$ enhancement

Proton Finite Size $\approx -2\%$

**20 ppm experiment**

12 years in the making (1998-2010)

$\Delta E(2P_{3/2} - 2S_{1/2})^{\text{exp}} = 206.2949 \pm 0.0032 \text{ meV}$
\[ r_p = 0.84184(67) \text{fm} \quad (\mu p \text{ atom}) \]

10x More Precise & 5 sigma below ep value!

\[ r_p \approx 0.8768(69) \text{fm} \quad (ep \text{ atom}) \]

Confirmation from ep scattering

\[ r_p \approx 0.879(8) \text{fm} \quad \text{(Mainz)} \]

\[ r_p \approx 0.875(10) \text{fm} \quad \text{(JLAB)} \]

**Electron Average:** \[ r_p = 0.8772(46) \text{fm} \]

8 sigma below \( \mu p \) atom!
From Pohl, Gilman, Miller & Pachucki Ann. Rev. NPS
$R_p(ep \text{ atom})$ vs $R_p(\mu p \text{ atom})$
From Pohl, Gilman, Miller & Pachucki Ann. Rev. NPS
$R_p(\text{ep scattering & atom})$ vs $R_p(\mu p \text{ atom})$
Atomic ep Theory? Rydberg Constant ($R_\infty$) (Off by 5σ?)

$R_\infty$ known to 13 significant figures!

$$= 1.0973731568527(73) \times 10^7 \text{m}^{-1}$$

"One of the Two most accurately measured fundamental physical constants".

Could $R_\infty$ really be wrong?

also

What about ep scattering? Wrong!

Perhaps the most likely solution
µp atomic theory or experiment wrong?

Proton Polarizability? QED Corrections (γγ)?
µp Experiment? (seems solid)
Follow up Experimental & Theoretical Work appear to confirm original results!

Can all three \( r_p \) determinations be correct?
2 out of 3 correct?...
New “Light” Vector Boson Solution?

Light Vector Boson with coupling $e' = \frac{e'}{4\pi} = \alpha' \ll \alpha = 1/137$

New Vector Boson Interaction Shifts Atomic Spectrum in a way that mimics a proton charge radius

$\Delta r_p/r_p \sim -2\alpha'/\alpha^3(1+m_V/\alpha m_\mu)^2$  Experiment $\rightarrow \Delta r_p/r_p \sim -4\%$

A. Czarnecki Calculation

example $\alpha' = 3 \times 10^{-6} \alpha$, $m_V \leq 1 \text{MeV}$ works

(Heavier $m_V$ requires larger coupling)

Can it be the “Dark Photon”?

Light gauge boson from Dark Matter Sector that mixes with the photon (small coupling) $\varepsilon^2 \approx 3 \times 10^{-6}$
No! light dark photon (O(1MeV)) should have also led to $g_e-2$ discrepancy

$$\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} > +10^{-9} >> 10^{-12} \text{ (bound)}!$$

Possible Solution: violate e-$\mu$ Universality

Egs Gauge B-3L$_{\mu}$ or B-3/2(L$_{\mu}$ + L$_{\tau}$)… (Lee & Ma symmetries)

Anomaly Free, couples to baryons, **not electrons**

So, a light $m_\nu \sim \text{MeV} & \alpha' \sim 3\times10^{-6}\alpha$ alleviates both $r_p$ and $a_\mu$ problems if it doesn’t couple (directly) to electrons!

What about neutrino physics? ($\nu_\mu \text{ vs } \nu_e$) Matter effect!
**Neutrino Oscillations in Matter** \((\nu_\mu \text{ vs } \nu_e)\)

New Vector Interaction Different for \(\nu_\mu \text{ & } \nu_e\)

Eg, if we gauge B-3L\(_\mu\) with \(\alpha' \sim 3 \times 10^{-6} \alpha\)?

Implies new matter effect on the \(\nu_\mu\) index of refraction

Of \(O(10^4 G_F N_B (1 \text{MeV}/m_V)^2)\) **Very Large**!

\(m_V=1\text{MeV} \text{ Ruled Out! Quenches Oscillations!} \text{ By a factor } > 10,000!!\)

Very hard to simultaneously solve \(r_p\), \(a_\mu\) and \(\nu_\mu\) matter osc

Neutrino Matter Effects are a **great** probe of long distance physics  Oscillation Interferometry

Batell, McKeen & Pospelov: Gauge only \(\mu_R\) (not neutrinos or \(e_R\))

*(creative but has other issues)*
3 $r_p$ determinations: ep atom, ep scattering, $\mu p$ atom
something likely wrong but which one(s)?

Rydberg Constant Vulnerable

What if it shifts by 5 sigma?
but ep remains a problem?

Other constraints? $a_e$?, neutrino osc….

Precision QED remains interesting & timely

Stay Tuned For Future Developments
**Electron Electric Dipole Moment EDM**

\[ d_e^{\text{SM}} \approx 10^{-38} \text{e-cm} \approx a_e (\text{EW})e/2m_e \times 10^{-14}! \]

highly suppressed 4 loop effect

\[ |d_e^{\exp}| < 1 \times 10^{-27} \text{e-cm} \approx 1 \times 10^{-16} e/2m_e \]

*The electron edm is a very good probe of New (short distance) CP Violating Physics*

\[ d_e (\text{new physics}) = a_e (\text{new physics}) e/2m_e \tan \phi^{\text{NP}} \]

\[ \Lambda^{\text{edm}} > 50 \text{TeV} (C \tan \phi^{\text{NP}})^{1/2} \]

future \(10^2-10^3\) improved \(d_e\) sensitivity expected

(maybe much more!)
General Formalism (Spin1/2 Form Factors)

\[ <f(p')|J_{\mu}^{em}|f(p)> = u_f(p')\Gamma_{\mu} u_f(p) \]

\[ \Gamma_{\mu} = F_1(q^2)\gamma_{\mu} + iF_2(q^2)\sigma_{\mu\nu}q^{\nu} - F_3(q^2)\gamma_5\sigma_{\mu\nu}q^{\nu} \ldots \]

\[ F_1(0) = Q_f e \quad \text{electric charge} \]

\[ F_2(0) = a_f Q_f e / 2m_f \quad \text{anom. mag. mom.} \]

\[ F_3(0) = d_f Q_f \quad \text{el. dipole mom.} \]

Effective Dim. 5 Dipole Operators

\[ H_{\text{dipole}} = -1/2[F_2 f(x)\sigma_{\mu\nu} f(x) + iF_3 f(x)\sigma_{\mu\nu}\gamma_5 f(x)]F^{\mu\nu}(x) \]

\[ F_2 \& F_3 \text{ Real, Finite & Calculable in Ren. QFT} \]

\[ (\text{No Counterterms!}) \]
Complex Formalism: \( F_D = F_2 + iF_3 \)

\[
H_{\text{dipole}} = -\frac{1}{2} [F_D f_L \sigma_{\mu\nu} f_R + F_D^* f_R \sigma_{\mu\nu} f_L] F^{\mu\nu}
\]

\( F_D = |F_D| e^{i\phi} \) (Relative to \( m_f \))

\( |F_D| = (F_2^2 + F_3^2)^{1/2}, \tan\phi = F_3/F_2 \)

\( \tan\phi = \text{Relative Degree of CP Violation} \)

e.g.s. \( |\tan\phi_e|^{SM} \approx 10^{-24} \), \( |\tan\phi_n|^{SM} \approx 10^{-20} \)

Can \( \phi \) be removed by a chiral rotation?

\( f \rightarrow \exp(i\gamma_5 \phi/2) f \) (Dirac Confusion)

No, it makes the mass \( m_f \) complex

(\( EDM = \text{relative phase!} \)
Anomalous Dipole Moments

<table>
<thead>
<tr>
<th>Fermion</th>
<th>$a_f^{\text{exp}}$</th>
<th>$d_f (e/2m_f)^{\text{exp}} (\phi)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>0.00115965218073(28)</td>
<td>$&lt;1 \times 10^{-16}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.00116592089(63)</td>
<td>$&lt;3 \times 10^{-6}$</td>
</tr>
<tr>
<td>$p$</td>
<td>1.792158142(28)</td>
<td>$&lt;3 \times 10^{-12}$ (new $d_{\text{Hg}}$)</td>
</tr>
<tr>
<td>$n$</td>
<td>-1.9130427(5)</td>
<td>$&lt;1 \times 10^{-13}$</td>
</tr>
</tbody>
</table>

“Heavy New Physics” expected to scale as $(m_f/\Lambda)^2$
$(m_\mu/m_e)^2 \approx 43000$ Muon only $a_f$ sensitive to high $\Lambda$!

All $d_f$ sensitive to “New Physics” if $\tan^\phi_{\text{NP}}$ not too small
Great Future Expectations

- $d_n \rightarrow 10^{-27}$-$10^{-28}$ e-cm Neutron Spallation/Reactor Sources
- $d_e \rightarrow 10^{-29}$ e-cm or better!
- $d_p$ & $d_D \rightarrow 10^{-28}$-$10^{-29}$ e-cm Storage Ring Proposal (BNL/COSY)

Pave the way for a new generation of storage ring experiments $d_p$, $d_D$, $d(^3\text{He})$, $d$(radioactive nuclei), $d_\mu$

Several orders of magnitude improvement expected
New Physics Loops or Pseuoscalar Mixing etc.

New CP Violation Source (eg. Voloshin)

\[ aH F_{\mu \nu} F_{\mu \nu} + b^{1/2} \epsilon_{\mu \nu \alpha \beta} H F_{\mu \nu} F_{\alpha \beta} \text{ (CP odd)} \]
$a_f$ vs $d_f$ (very roughly)

- Two loop Higgs contribution: $a_\mu(H) \approx \text{few} \times 10^{-11}$
  $a_e(H) \approx 5 \times 10^{-16}$

  **Unobservably Small!**

  Two Loop Higgs contribution: $d_e(H) \approx 10^{-26} \sin\phi$ e−cm
  $|d_n(H)| \approx |d_p(H)| \approx 3 \times 10^{-26} \sin\phi$ e−cm

Already $d_e$ bound implies $\sin\phi \leq 0.1$ (smaller?)

**CP violation in $H \rightarrow \gamma\gamma$** $\sin^2\phi \leq 0.01$

*Unlikely to be observable, but edm experiments can Explore down to $\sin\phi \approx O(10^{-3})$!* **Unique!**
7.) **The Standard Model** – \( SU(3)_C \times SU(2)_L \times U(1)_Y \)

Beautiful Standard Model Natural Relations:
\[
e_0^2/g_0^2 = \sin^2 \theta_W^0 = 1 - (m_W^0/m_Z^0)^2
\]

**Radiative Corrections (Loops) Finite & Calculable**

\( m_t \) prediction \( \approx 160-180 \text{GeV} \), \( m_H < 150 \text{GeV} \) (95%CL)!

**Deviation** → ”New Physics”: SUSY, Technicolor, \( W^* \)…

* 

**MUON LIFETIME PARTICULARLY IMPORTANT** → \( G_\mu \)
**Muon ($\mu^+$) Lifetime**

MuLAN experiment at PSI:
$$\tau_{\mu^+} = 2.1969803(22) \times 10^{-6} \text{sec} \text{ MuLAN 2010}$$

*(Most precise lifetime measurement ever!)*

*Improved Previous World Average by error/20!*

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

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

Other SM and “New Physics” radiative corrections absorbed into $G_\mu$. Eg. Top Mass, Higgs Mass, Technicolor, Susy, $W^*$…

$$G_\mu = 1.1663787(6) \times 10^{-5} \text{GeV}^{-2} \text{ precise & important}$$

*Normalizes all weak interaction amplitudes*
Loop and Tree Level Corrections to Muon Decay

\[ \nu_\mu \rightarrow e \]  
\[ \mu \rightarrow \nu_e \]  
\[ W \]  
\[ z' \]  
\[ \beta \]  
\[ t \]  
\[ W \]  
\[ H \]  
\[ e \]  
\[ \nu_e \]  
\[\tilde{W} \]  
\[\tilde{Z} \]  
\[\tilde{H} \]  
\[ F \]  
\[ F' \]  
\[ W \]  

\text{Z'} Boson}  
\text{SUSY}  
\text{Technicolor}  

+ \ldots
## Precision EW Parameters (status):

<table>
<thead>
<tr>
<th>Quantity</th>
<th>2008 Value</th>
<th>2013 Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha^{-1}$</td>
<td>137.035999084(51)</td>
<td><strong>137.035999049(90)</strong></td>
<td>$\alpha^{-1}(a_e)$ vs $\alpha^{-1}(Rb)$</td>
</tr>
<tr>
<td>$G_{\mu}$</td>
<td>1.16637(1)x10^{-5}GeV^{-2}</td>
<td>1.1663787(6)x10^{-5}GeV^{-2}</td>
<td>PSI</td>
</tr>
<tr>
<td>$m_Z$</td>
<td>91.1875(21)GeV</td>
<td>91.1876(21)GeV</td>
<td>-</td>
</tr>
<tr>
<td>*$m_t$</td>
<td>171.4(2.1)GeV</td>
<td><strong>173.3(0.8)GeV</strong></td>
<td>FNAL/LHC</td>
</tr>
<tr>
<td>$m_H$</td>
<td>&gt;114GeV</td>
<td>125-126GeV</td>
<td>LEP2/FNAL</td>
</tr>
<tr>
<td>$m_W$</td>
<td>80.410(32)GeV</td>
<td><strong>80.385(15)GeV</strong></td>
<td></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>
<tr>
<td>$\sin^2\theta_W(m_Z)$</td>
<td>0.23070(26)</td>
<td>0.23070(26)</td>
<td>$A_{LR}$</td>
</tr>
<tr>
<td>$\sin^2\theta_W(m_Z)$</td>
<td>0.23193(29)</td>
<td>0.23193(29)</td>
<td>$A_{FB}(bb)$</td>
</tr>
</tbody>
</table>

(3 sigma difference?)
**S Parameter**

Use $\alpha$, $G_\mu$, $m_W$, and $\sin^2\theta_W(m_Z)_{\text{MS}} \rightarrow S$ (Counts $N_D$) & $m_{W^*}$

eg. $G_\mu (1-\Delta r(m_Z)_{\text{MS}}) = \frac{\pi \alpha}{\sqrt{2} m_W^2} \sin^2\theta_W(m_Z)_{\text{MS}}$

$\Delta r(m_Z)_{\text{MS}} = 0.0696 + 0.0085S + \delta(1)(m_w/m_{W^*})^2 + \ldots$

$m_W = 80.385(15)\text{GeV} \quad \sin^2\theta_W(m_Z)_{\text{MS}} = 0.23125(16)\text{ Ave}$

$\rightarrow S = 0.07(9) \quad \& \quad M_{W^*} > 2-3\text{TeV}$

No Sign of “New Physics”!
The importance of $\sin^2\theta_W(m_Z)$

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2\theta_W(m_Z)_{\text{MS}}$</th>
<th>$\Delta S$</th>
<th>$S$</th>
<th>$N_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.23125(16)</td>
<td>-0.04(8)</td>
<td>+0.07(9)</td>
<td>2(2)</td>
</tr>
<tr>
<td>$A_{LR}$</td>
<td>0.23070(26)</td>
<td>-0.32(13)</td>
<td>-0.21(15)</td>
<td>(SUSY)</td>
</tr>
<tr>
<td>$A_{FB}(bb)$</td>
<td>0.23193(29)</td>
<td>+0.32(15)</td>
<td>+0.39(17)</td>
<td>9(3)!</td>
</tr>
</tbody>
</table>

If $A_{LR}$ had never been measured: $\sin^2\theta_W(m_Z)_{\text{MS}}=0.23158(20)$

That would imply $S=+0.26(12)\rightarrow N_D\sim 6\pm 2.4!!$

Technicolor, 4th Generation, $m_{W^*}\sim 1.6\text{TeV}$…)

We would be waiting for 4th Generation, Technicolor, Extra Dim.

We missed our chance to nail $\sin^2\theta_W(m_Z)_{\text{MS}}$ at the Z pole!

Future $\sin^2\theta_W(m_Z)_{\text{MS}}$ **Precision: Low energy polarized e⁻**
\[ m_W & \sin^2 \theta_W(m_Z)_{MS} \] Predictions

\[ m_W = 80.362(6) \text{GeV}[1-0.0036S+0.0056T] \]
\[ m_W = 80.385(15) \text{GeV} \] (experiment)  somewhat high

\[ \sin^2 \theta_W(m_Z)_{MS} = 0.23124(6)[1+0.0157S-0.0112T] \]
\[ \sin^2 \theta_W(m_Z)_{MS} = 0.23125(16) \] (Z pole experimental ave.)

\[ S = 0.07\pm0.09 \text{ and } T = 0.10\pm0.09 \]

Very dependent on \( \sin^2 \theta_W(m_Z)_{MS} \) value!

Significantly Constrains: 4\textsuperscript{th} Generation, Technicolor, SUSY…
Low $Q^2$ Measurements of $\sin^2\theta_W(m_Z)_{\overline{MS}}$

\[
\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2283(20) \quad \text{Cs APV at } \langle Q \rangle \approx 2.4 \text{ MeV}
\]

*Dzuba, Berengut, Flambaum, Roberts 2012 PRL*

$Q_W(Cs) \rightarrow -72.58(29)(32)_{th}$ Update vs SM -73.24(5)

*(1.5 sigma APV deviation)*

\[
\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2329(13) \quad \text{Møller } A_{PV} \text{ at } \langle Q \rangle \approx 160 \text{ MeV}
\]

$A_{RL}(ee) = -131(14)(10) \times 10^{-9} \alpha (1-4\sin^2\theta_W)$

Measured to $\pm 12\% \rightarrow \sin^2\theta_W$ to $\pm 0.6\%$

\[
\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2356(16) \quad \nu_\mu N \text{ at } \langle Q \rangle \approx 5 \text{ GeV}
\]

Needs Reanalysis
Comparison of (static) weak charges

\[ Q_W(e) = -0.0435(9) [1 + 0.25T - 0.34S + 0.7X(Q^2) + 7m^2_Z/m^2_{Zx}] \]

\[ Q_W(p) = 0.0707(9) [1 + 0.15T - 0.21S + 0.43X(Q^2) + 4.3m^2_Z/m^2_{Zx}] \]

\[ Q_W(^{133}\text{Cs}) = -73.24(5) [1 + 0.011S - 0.023X(Q^2) - 0.9m^2_Z/m^2_{Zx}] \]

Long Term Exp. Goals: \( Q_W(e) \pm 2.5\%, Q_W(p) \pm 1.5\% \),
**Polarized ee, ep Asymmetries**

- \( A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \)  Parity Violating \( \alpha Q^2 \) very small

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(&lt;Q&gt;) MeV</th>
<th>( \Delta \sin^2 \theta_W )</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs APV</td>
<td>2.4</td>
<td>±0.0020</td>
<td>Atomic Theory</td>
</tr>
<tr>
<td>E158 SLAC</td>
<td>160</td>
<td>±0.0013</td>
<td>ee Completed</td>
</tr>
<tr>
<td>Q_{weak} JLAB</td>
<td>160</td>
<td>±0.0008</td>
<td>ep in analysis</td>
</tr>
<tr>
<td>Moller JLAB</td>
<td>75</td>
<td>±0.00029</td>
<td>ee approved</td>
</tr>
<tr>
<td>MESA (ep) P2</td>
<td>100?</td>
<td>±0.00037</td>
<td>ep Low Energy</td>
</tr>
</tbody>
</table>
Current Status of Running weak mixing angle
**Dark Parity Violation**

- $U(1)_d$ gauge symmetry from the Dark Sector

  *Dark Photon, $U$ Boson, Secluded … Dark $Z$ ($Z_d$)*

**Interaction with our world:**

*Induced by heavy fermion loops & extended Higgs*

1) Kinetic Mixing $U(1)_\gamma \times U(1)_d$

  $$\varepsilon e Z_d^\mu J_\mu^{em} \approx \alpha/\pi \approx 2 \times 10^{-3}$$

2) $Z-Z_d$ Mass Mixing

  $$\varepsilon Z g/2\cos\theta_w Z_d^\mu J_\mu^{NC}$$

  $$\varepsilon Z = m_{Z_d}/m_Z \delta = O(m_{Z_d}/m_Z)^2 \approx 10^{-6}$$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(80) \times 10^{-11}$$

*3.6σ discrepancy!*

$$\approx \frac{1}{4}(\alpha/\pi)^3$$

(Effective light 3 loop physics)
**Dark Parity Violation**

Effect of $\varepsilon$ & $\varepsilon_z$ together: (at low $Q^2<<m_Z^2$)

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

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

Shift largest at small $Q^2<m_{Zd}^2$ ($\approx O(1\%)!$ Eg APV)

*1.5 sigma APV deviation* fit $\Rightarrow \varepsilon \delta = 4 \times 10^{-6}$

or $\varepsilon \approx \delta \approx 2 \times 10^{-3}$ for $(g_\mu-2)$ & APV $\Rightarrow m_{Zd} \approx 50$MeV region

$\sin^2 \theta_W(Q\approx 75$MeV) shift by $\pm O(0.5-1\%)!!$

$\delta$ down to $\approx 10^{-3}$ Potentially Observable

$A_{RL}(ee)$ & $A_{RL}(ep)$ at low $Q^2$ Potentially Important
Dark Parity Violation

Effect of $\epsilon$ & $\epsilon_Z$ together: (at low $Q^2 << m_Z^2$)

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

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

$APV \ & m_{Zd} = 50\text{MeV} \Rightarrow \sin^2 \theta_W(Q \approx 75\text{MeV})$ shift by 0.0010!

Negligible effect at the Z Pole!
Current Status of Running weak mixing angle
Future Measurements
Examples of Possible Dark Parity Violation
$m_{\text{dark } Z} = 100 \text{ MeV}$
Outlook

- Light Dark Photon – Under some tension ($e^+e^-$ decays)
- Light Dark Photon + Light Dark Matter (avoid $e^+e^-$ constraints)
- $(K \rightarrow \pi Z_d) \quad Z_d \rightarrow \text{light dark matter constraint tension for}$
  \[ m_{Z_d} \sim 100 \, \text{MeV} \quad \text{and} \quad 200 \, \text{MeV} \]  
  (kinetic - mass mixing suppression)

  **Predictive Bands for dark parity violation**

  \[ \varepsilon \approx \delta \approx \text{few} \times 10^{-3} \]

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!!