Title: The Standard Model Experiment: Electroweak Tests

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Abstract:

The Standard Model: Experiment

(Elecroweak Tests)

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Third Lecture

In this third lecture, I will focus on providing an overview of various tests of electroweak theory, with a short introduction on the implications of the choice of gauge group for the SM

I normally spend many hours on this in a graduate phenomenology course. I will not have time to do an exhaustive tour of electroweak tests and will not be able to present in detail the tests that I do present.

I will continue with electroweak physics and cover Higgs physics in the fourth lecture

*Many plots from LEP Electroweak Working Group

SU(2) (quick review)

Consider a system with two fermion fields q_1 and q_2 and demand that it possesses symmetry under transformations that mix them together:

$$q_1 \rightarrow q_1' = \alpha q_1 + \beta q_2$$
$$q_2 \rightarrow q_2' = \gamma q_1 + \delta q_2$$

The $\alpha, \beta, \ldots$ are complex

Keep normalization: $\langle q_i' | q_i' \rangle = \langle q_1 | q_1 \rangle = 1$ etc.

$$\Rightarrow |\alpha|^2 + |\beta|^2 = |\gamma|^2 + |\delta|^2 = 1$$

Keep orthogonality: $\langle \psi_1' | \psi_2' \rangle = 0$

$$\Rightarrow \alpha^* \delta + \beta^* \gamma = 0$$

in 2D component form:

$$q = \begin{pmatrix} q_1 \\ q_2 \end{pmatrix} \rightarrow q' = \begin{pmatrix} q_1' \\ q_2' \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}$$

SU(2) (quick review)

$\begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix}$ is unitary : $\begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \begin{pmatrix} \alpha^* & \gamma^* \\ \beta^* & \delta^* \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

A 2×2 Unitary matrix has 4 free parameters and we can write:

$$U = e^{i\alpha_0 + \underbrace{i\alpha_1 \tau_1 + i\alpha_2 \tau_2 + i\alpha_3 \tau_3}_{V}}$$

τ_i are the Pauli matrices:

$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $\tau_2 \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$, $\tau_3 \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

$U = e^{i\alpha_0} \cdot e^{V}$ with V a member of SU(2)

You can show that V has unit det.

Gauge Group for EM and Weak Interactions

We will now select a gauge group for the em and weak interactions.

→ weak current for lepton ℓ:

$$J_\mu^+ = \bar{\ell}\,\gamma_\mu (1-\gamma_5)\,\nu = 2\,\bar{\ell}_L\,\gamma_\mu\,\nu_L$$

We introduce left-handed isospin doublet $(T = 1/2)$

$$L = \begin{pmatrix} \nu \\ \ell \end{pmatrix}_L = \begin{pmatrix} L\nu \\ L\ell \end{pmatrix} = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \quad \text{with } T_3 = \pm 1/2$$

Gauge Group for EM and Weak Interactions

We'll consider the neutrinos massless for now. So we'll accomodate the right-handed part of the charged lepton in a weak isospin singlet $(T=0)$

$$R\ell = \ell_R$$

The charged weak current can be written usi

$$J^i_\mu = \bar{L}\gamma_\mu \frac{\tau^i}{2} L$$

Explicitly:

$$J^1_\mu = \frac{1}{2}(\bar{\nu}_L\ \bar{\ell}_L)\gamma_\mu \begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}\begin{pmatrix}\nu_L\\ \ell_L\end{pmatrix} = \frac{1}{2}(\bar{\ell}_L\gamma_\mu\nu_L + \bar{\nu}_L\gamma_\mu\ell_L)$$

$$J^2_\mu = \frac{1}{2}(\bar{\nu}_L\ \bar{\ell}_L)\gamma_\mu \begin{pmatrix}0 & -i\\ i & 0\end{pmatrix}\begin{pmatrix}\nu_L\\ \ell_L\end{pmatrix} = \frac{i}{2}(\bar{\ell}_L\gamma_\mu\nu_L - \bar{\nu}_L\gamma_\mu\ell_L)$$

$$J^3_\mu = \frac{1}{2}(\bar{\nu}_L\ \bar{\ell}_L)\gamma_\mu \begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}\begin{pmatrix}\nu_L\\ \ell_L\end{pmatrix} = \frac{1}{2}(\bar{\nu}_L\gamma_\mu\nu_L - \bar{\ell}_L\gamma_\mu\ell_L)$$

Gauge Group for EM and Weak Interactions

Charged weak current can be written in terms of J^1 and J^2: $J^+_\mu = 2(J^1_\mu - iJ^2_\mu)$

$\rightarrow$ will couple to W^-_μ

J^3_μ will involve a neutral current. We define the hypercharge current:

$$J^Y_\mu \equiv -(\bar{L}\gamma_\mu L + 2\bar{R}\gamma_\mu R)$$

$$= -(\bar{\nu}_L\gamma_\mu\nu_L + \bar{\ell}_L\gamma_\mu\ell_L + 2\bar{\ell}_R\gamma_\mu\ell_R)$$

The em current is given by:

$$J^{em}_\mu = -\bar{\ell}\gamma_\mu\ell = -(\bar{\ell}_L\gamma_\mu\ell_L + \bar{\ell}_R\gamma_\mu\ell_R) = J^3_\mu + 1/2\, J^Y_\mu$$

Fermion-gauge coupling

We now introduce fermion-gauge coupling using the gauge-covariant derivative:

$$L : \partial_\mu + \frac{ig}{2} \tau^i W^i_\mu + \frac{ig'}{2} Y B_\mu$$

$$R = \partial_\mu + \frac{ig'}{2} Y B_\mu$$

$g \rightarrow SU(2)$, $Y_{Le} = -1$

$g' \longrightarrow U(1)$, $Y_{Re} = -2$

$$\mathcal{L}_{\text{lep.}} = \mathcal{L}_{\text{kep}} + \bar{L}\, i\gamma^\mu \left(\frac{ig}{2} \tau^i W^i_\mu + \frac{ig'}{2} Y B_\mu \right) L$$

$$+ \bar{R}\, i\gamma^\mu \left(\frac{ig'}{2} B_\mu \right) R$$

Fermion-gauge coupling

$$\mathcal{L}_{lep.} = \mathcal{L}_{Rep} + \bar{L}\, i\gamma^\mu \left(i\frac{g}{2}\tau^i W_\mu^i + i\frac{g'}{2} Y B_\mu \right) L + \bar{R}\, i\gamma^\mu \left(i\frac{g'}{2} B_\mu \right) R$$

expanding:

$$-g\bar{L}\gamma^\mu \left(\frac{\tau^1}{2} W_\mu^1 + \frac{\tau^2}{2} W_\mu^2 \right) L \qquad (1)$$

$$-g\bar{L}\gamma^\mu \frac{\tau^3}{2} L W_\mu^3 - \frac{g'}{2} Y \bar{L}\gamma^\mu L B_\mu \qquad (2)$$

We saw that Term (1) involves charged current. We can write it as:

$$-\frac{g}{2}\bar{L}\gamma^\mu \begin{pmatrix} 0 & W_\mu^1 - iW_\mu^2 \\ W_\mu^1 + iW_\mu^2 & 0 \end{pmatrix} L$$

We can define the charged bosons as: $W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2)$

Fermion-gauge coupling

Term ① becomes:

$$-\frac{g}{2\sqrt{2}}\left[\bar{\nu}\gamma^\mu(1-\gamma^5)\ell\, W_\mu^+ + \bar{\ell}\gamma^\mu(1-\gamma^5)\nu\, W_\mu^-\right]$$

note that $\frac{g}{2\sqrt{2}} = \left(\frac{M_W^2 G_F}{\sqrt{2}}\right)^{1/2}$

We now concentrate on the neutral current terms which involves both L and R components:

$$-g\bar{L}\gamma^\mu\frac{\tau^3}{2}LW_\mu^3 - \frac{g'}{2}(\bar{L}\gamma^\mu YL + \bar{R}\gamma^\mu YR)B_\mu$$

$$= -g\, J_3^\mu W_\mu^3 - \frac{g'}{2}J_Y^\mu B_\mu$$

$$J_3^\mu = \frac{1}{2}(\bar{\nu}_L\gamma^\mu\nu_L - \bar{\ell}\gamma^\mu\ell)$$

$$J_Y^\mu = -(\bar{\nu}_L\gamma^\mu\nu_L + \bar{\ell}_L\gamma^\mu\ell_L + 2\bar{\ell}_R\gamma^\mu\ell_R)$$

Physical Fields

Remember that $J_{em} = J_3 + \frac{1}{2} J_Y$

We want the right combination of fields that couple to J_{em}.

We can do this by rotating the fields:

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W^3_\mu \end{pmatrix}$$

$$W^3_\mu = \sin\theta_W A_\mu + \cos\theta_W Z_\mu$$

$$B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$$

with $\sin\theta_W = \dfrac{g'}{\sqrt{g^2+g'^2}}$ $\qquad$ $\cos\theta_W = \dfrac{g}{\sqrt{g^2+g'^2}}$

$\dfrac{g'}{g} = \tan\theta_W$, $\qquad g\sin\theta_W = g'\cos\theta_W$

Physics Fields

With the rotated fields, we get:

$$\left[-\left(g \sin\theta_W J_3^\mu + \tfrac{1}{2} g' \cos\theta_W J_Y^\mu\right) A_\mu\right]$$ correct form for em interaction

$$\left[+\left(-g\cos\theta_W J_3^\mu + \tfrac{1}{2} g' \sin\theta_W J_Y^\mu\right) Z_\mu\right]$$ something new...

first term

$$= -g \sin\theta_W \,(\bar{l}\gamma^\mu l)\, A_\mu$$

$\longrightarrow e = g\sin\theta_W$

second term: $\dfrac{-g}{2\cos\theta_W}\left(2\cos^2\theta_W J_3^\mu - \dfrac{g'}{g}\cos\theta_W \sin\theta_W J_Y^\mu\right) Z_\mu$

$$= \frac{-g}{2\cos\theta_W}\left(2\cos^2\theta_W J_3^\mu - \frac{g}{g}\sin^2\theta_W J_Y^\mu\right) Z_\mu$$

$$= \frac{-g}{2\cos\theta_W}\left(2(1-\sin^2\theta_W) J_3^\mu - \sin^2\theta_W J_Y^\mu\right) Z_\mu$$

$J_Y^\mu = -(\bar{\nu}_L \gamma_\mu \nu_L + \bar{l}_L \gamma_\mu l_L + 2\bar{l}_R \gamma_\mu l_R)$, $J_3^\mu = \frac{1}{2}(\bar{\nu}_L \gamma_\mu \nu_L - \bar{l}_L \gamma_\mu l_L)$

note that $\sin^2\theta_W$ terms cancel for neutrinos

Structure of Neutral Current

For electrons we have for $\sin^2\theta_W$ terms:

$$+\bar{l}_L\gamma^\mu l_L + \bar{l}_L\gamma^\mu l_L + 2\bar{l}_R\gamma^\mu l_R = 2(\bar{l}_L\gamma^\mu l_L + \bar{l}_R\gamma^\mu l_R)$$

other terms for neutrinos: $\bar{\nu}_L\gamma^\mu\nu_L$

" " " electrons: $-\bar{l}_L\gamma^\mu l_L$

Which can be summarized as:

$$-\frac{g}{2\cos\theta_W}\sum_{\psi_i=\nu,l}\bar{\psi}_i\gamma^\mu(g_V^i - g_A^i\gamma^5)\psi_i Z_\mu$$

$g_V^i \rightarrow T_3^i - 2Q_i\sin^2\theta_W$

$g_A^i \rightarrow T_3^i$

i	Q^i	g_A^i	g_V^i
$\nu_e\ \nu_\mu\ \nu_\tau$	0	1/2	1/2
$e\ \mu\ \tau$	−1	−1/2	$-1/2 + 2\sin^2\theta_W \simeq -0.03$
$u\ c\ t$	2/3	1/2	$1/2 - 4/3\sin^2\theta_W \simeq 0.19$
$d\ s\ b$	−1/3	−1/2	$-1/2 + 2/3\sin^2\theta_W \simeq -0.34$

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$g_A^i \to T_3^i$

$g_V^i \to T_3^i - 2Q_i\sin^2\theta_W$

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Tests with Z bosons

Many possible tests using the Z boson:

- Width
- Decay rates to up-type quarks, down-type quarks, charged leptons, neutrinos (invisible width)
  - Test coupling universality
- Production asymmetries: forward-backward (for various fermion types), left-right
- Measure Z mass precisely which will allow for self-consistency test of the SM

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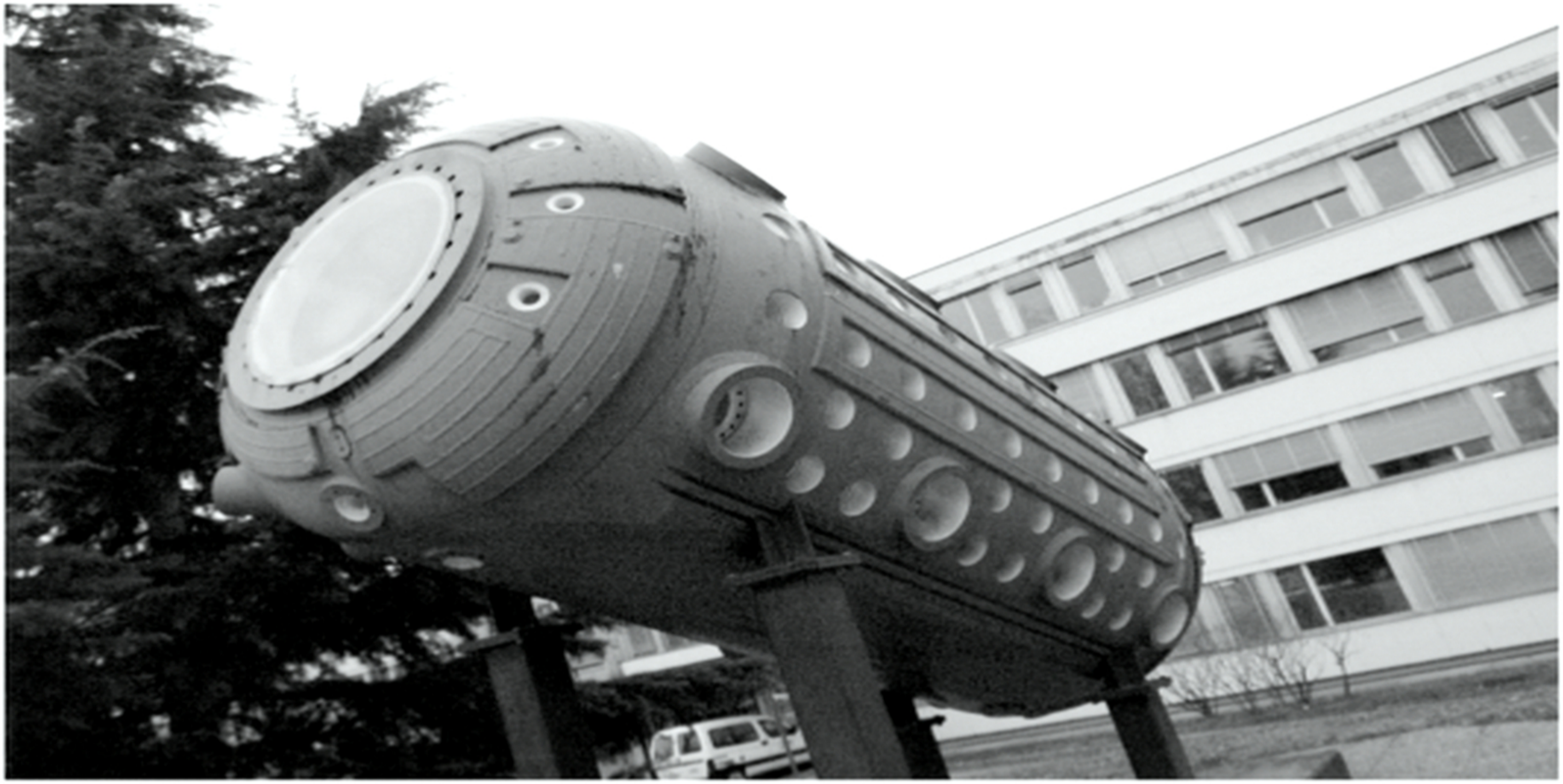
Observation of weak neutral currents

Gargamelle experiment:



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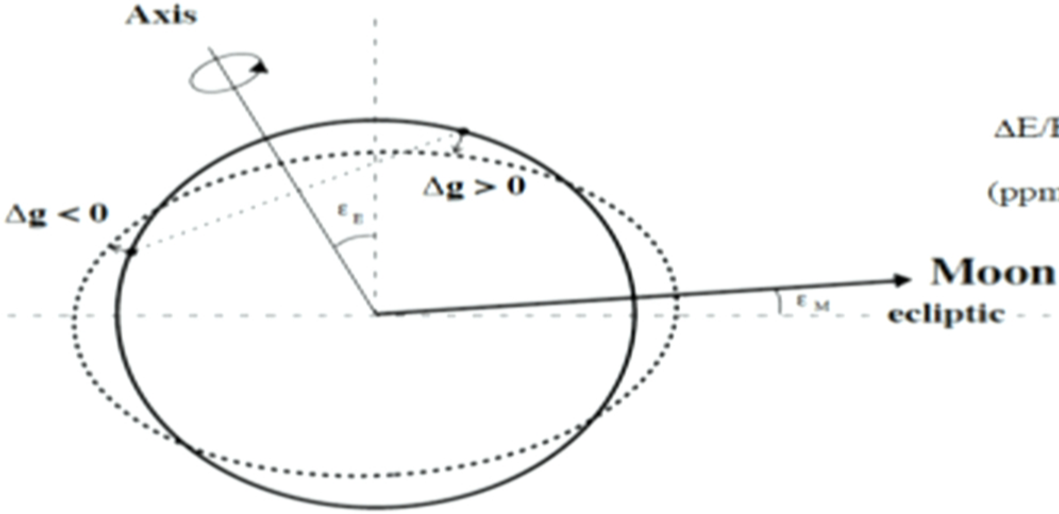
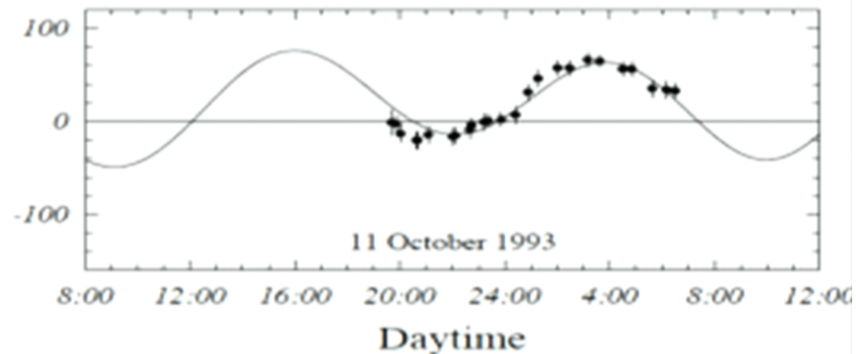
Mass of the Z Boson: $m_Z = 91.1875 \pm 0.0021\,\mathrm{GeV}$

From the Particle Data Group

Precise energy calibration was done outside normal data-taking using the resonant depolarization technique. Run-time energies were determined every 10 minutes by measuring the relevant machine parameters and using a model which takes into account all the known effects, including leakage currents produced by trains in the Geneva area and the tidal effects due to gravitational forces of the Sun and the Moon. The LEP





dependent gravity variation $\Delta g(t)$ is simpler to measure and to predict. Using estimates for the elastic properties of the Earth [10], the largest resulting strain is estimated to $\sim \pm 2 \cdot 10^{-8}$, which corresponds to a change of the 26.7 km LEP circumference of $\pm$ 0.5 mm. To a good 17

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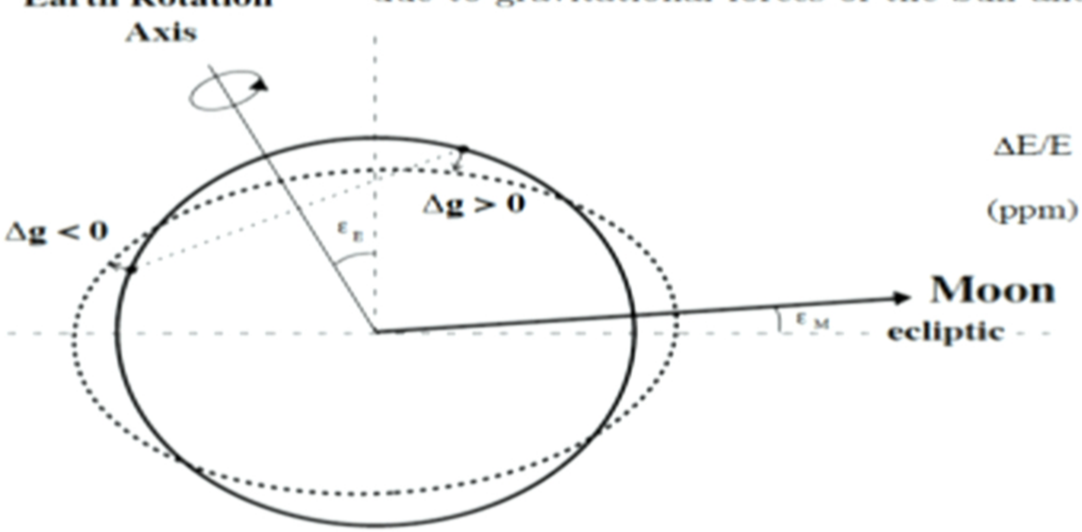

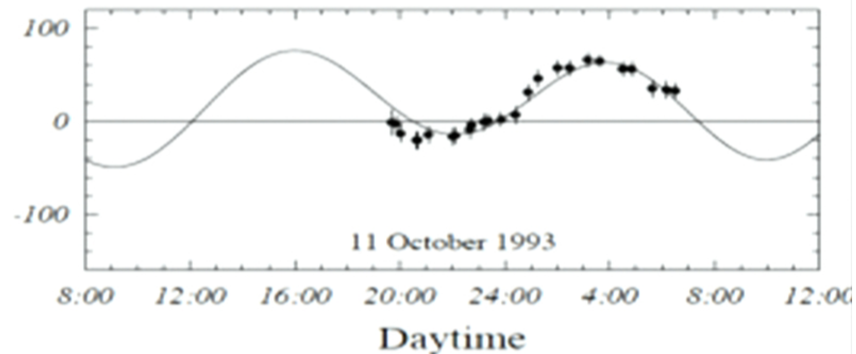

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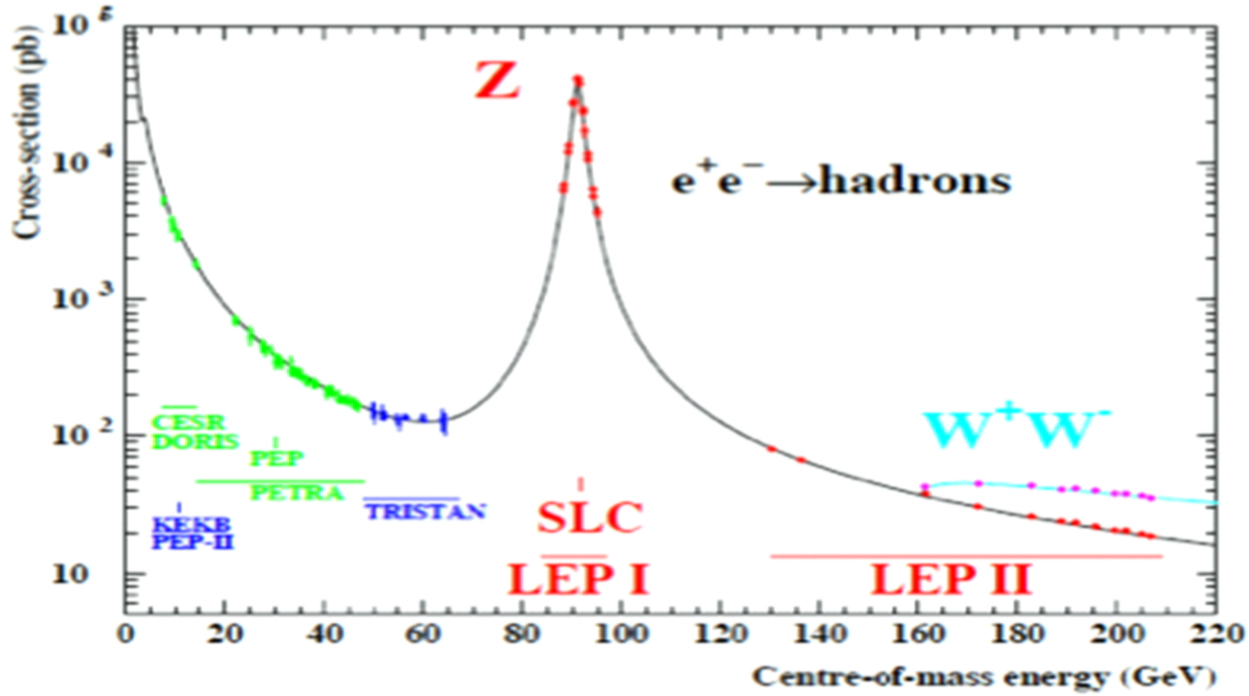
Z/γ* lineshape



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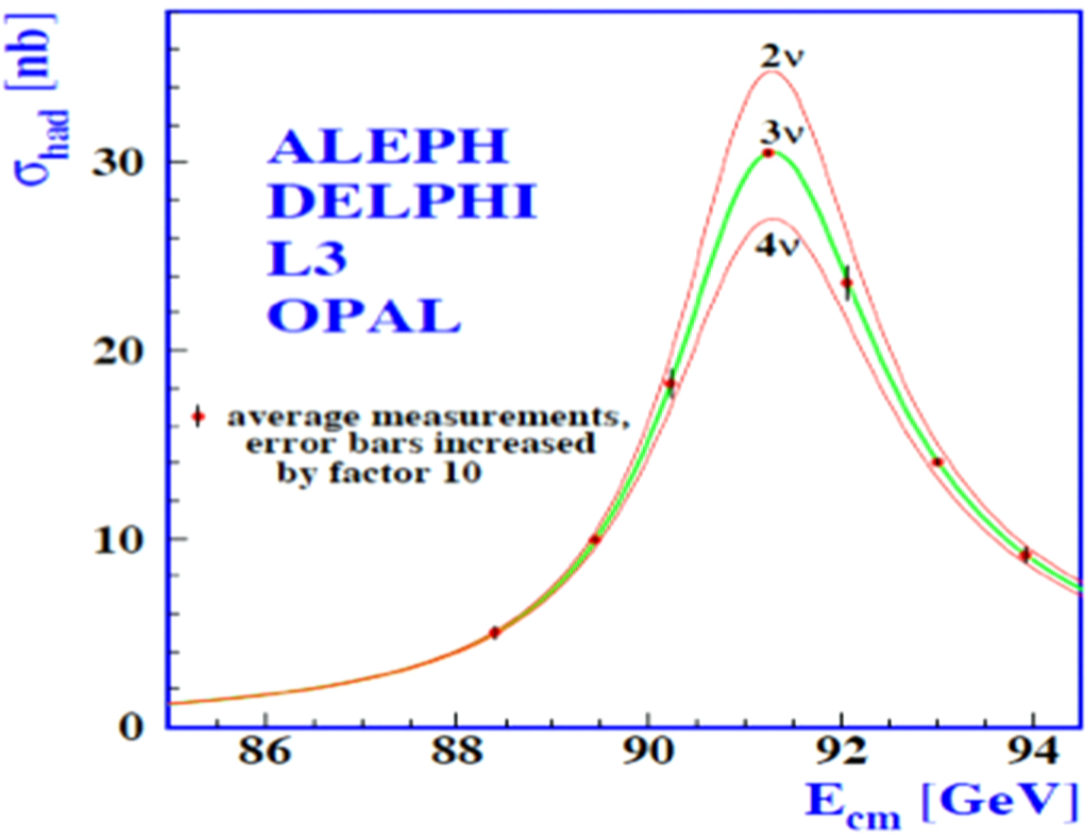
Neutrinos from Lineshape



$$N_\nu = 2.9840 \pm 0.0082$$

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\text{hadrons}} + \Gamma_{\nu_1\nu_1} + \Gamma_{\nu_2\nu_2} + \Gamma_{\nu_3\nu_3} + ?$$

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Z Partial Widths

Parameter $\Gamma_{f\bar{f}}$	Average [MeV]	Correlations						
Without Lepton Universality								
		Γ_{had}	Γ_{ee}	$\Gamma_{\mu\mu}$	$\Gamma_{\tau\tau}$	$\Gamma_{b\bar{b}}$	$\Gamma_{c\bar{c}}$	Γ_{inv}
Γ_{had}	1745.8 ± 2.7	1.00						
Γ_{ee}	83.92 ± 0.12	−0.29	1.00					
$\Gamma_{\mu\mu}$	83.99 ± 0.18	0.66	−0.20	1.00				
$\Gamma_{\tau\tau}$	84.08 ± 0.22	0.54	−0.17	0.39	1.00			
$\Gamma_{b\bar{b}}$	377.6 ± 1.3	0.45	−0.13	0.29	0.24	1.00		
$\Gamma_{c\bar{c}}$	300.5 ± 5.3	0.09	−0.02	0.06	0.05	−0.12	1.00	
Γ_{inv}	497.4 ± 2.5	−0.67	0.78	−0.45	−0.40	−0.30	−0.06	1.00
With Lepton Universality								
		Γ_{had}	$\Gamma_{\ell\ell}$	$\Gamma_{b\bar{b}}$	$\Gamma_{c\bar{c}}$	Γ_{inv}		
Γ_{had}	1744.4 ± 2.0	1.00						
$\Gamma_{\ell\ell}$	83.985 ± 0.086	0.39	1.00					
$\Gamma_{b\bar{b}}$	377.3 ± 1.2	0.35	0.13	1.00				
$\Gamma_{c\bar{c}}$	300.2 ± 5.2	0.06	0.03	−0.15	1.00			
Γ_{inv}	499.0 ± 1.5	−0.29	0.49	−0.10	−0.02	1.00		

Forward-Backward Asymmetries

Z differential cross section:

$$\langle|M_{fi}|\rangle^2 \propto [(c_L^e)^2+(c_R^e)^2][(c_L^\mu)^2+(c_R^\mu)^2](1+\cos^2\theta)+[(c_L^e)^2-(c_R^e)^2][(c_L^\mu)^2-(c_R^\mu)^2]\cos\theta$$

$$\tfrac{1}{2}(c_V-c_A\gamma^5) = \tfrac{1}{2}(c_L+c_R-(c_L-c_R)\gamma^5) = c_L\tfrac{1}{2}(1-\gamma^5)+c_R\tfrac{1}{2}(1+\gamma^5)$$

$$c_L=\tfrac{1}{2}(c_V+c_A),\quad c_R=\tfrac{1}{2}(c_V-c_A)$$

$$\frac{d\sigma}{d\Omega}=\kappa\times[A(1+\cos^2\theta)+B\cos\theta]$$

$$A=[(c_L^e)^2+(c_R^e)^2][(c_L^\mu)^2+(c_R^\mu)^2] \qquad B=[(c_L^e)^2-(c_R^e)^2][(c_L^\mu)^2-(c_R^\mu)^2]$$

$$\sigma_F\equiv\int_0^1\frac{d\sigma}{d\cos\theta}d\cos\theta \qquad \sigma_B\equiv\int_{-1}^0\frac{d\sigma}{d\cos\theta}d\cos\theta$$

$$A_{FB}=\frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B}$$

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Forward-Backward Asymmetries

Asymmetries in terms of left-right couplings:

$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{B}{(8/3)A} = \frac{3}{4}\left[\frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2}\right] \cdot \left[\frac{(c_L^\mu)^2 - (c_R^\mu)^2}{(c_L^\mu)^2 + (c_R^\mu)^2}\right]$$

$$A_{\mathrm{FB}} = \frac{3}{4} A_e A_\mu \qquad A_f \equiv \frac{2 c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2} = 2\frac{c_V/c_A}{1 + (c_V/c_A)^2}$$

$$A_{LR} = A_e$$

$$\boxed{A_e = 0.1514 \pm 0.0019}$$

$$\boxed{A_\mu = 0.1456 \pm 0.0091}$$

$$\boxed{A_\tau = 0.1449 \pm 0.0040}$$

$$\frac{c_V}{c_A} = \frac{I_W^3 - 2Q\sin^2\theta_W}{I_W^3} = 1 - \frac{2Q}{I_3}\sin^2\theta_W = 1 - 4|Q|\sin^2\theta_W$$

Use asymmetries to extract: $\sin^2\theta_W = 0.23154 \pm 0.00016$

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Left-Right Asymmetries

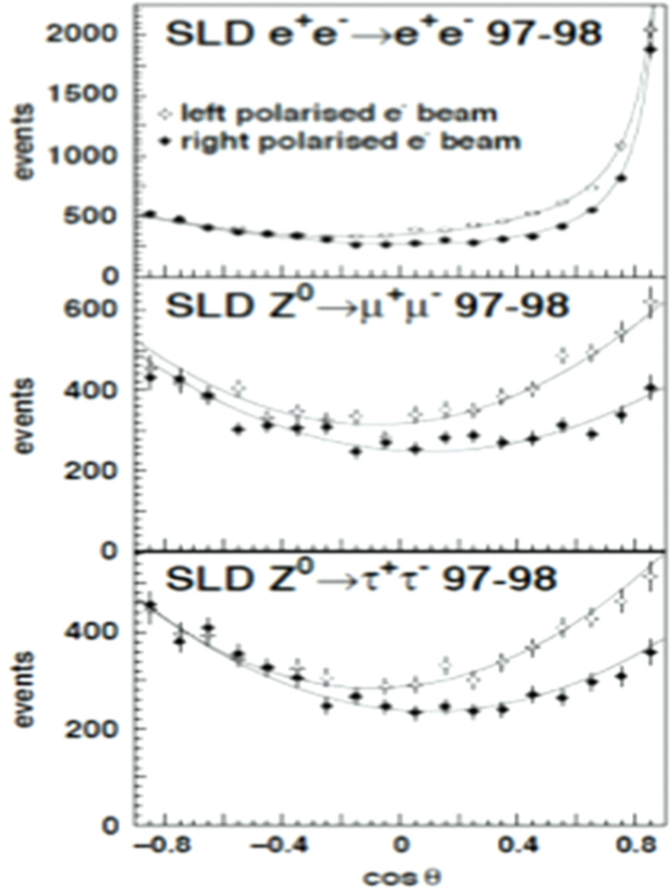
Stanford Linear Collider could produced polarized e beams

$$\sigma_L = \frac{1}{2}(\sigma_{LR} + \sigma_{LL})$$

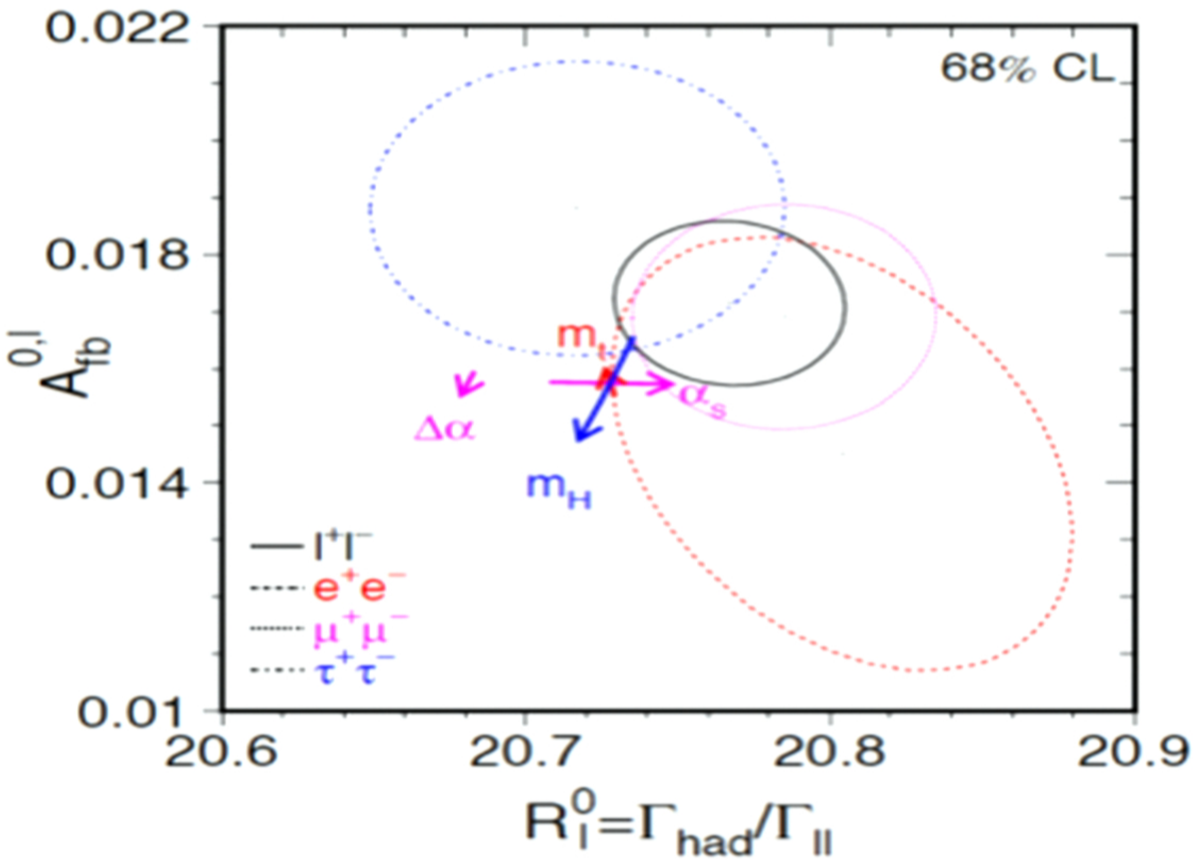
$$\sigma_R = \frac{1}{2}(\sigma_{RR} + \sigma_{RL})$$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

$$A_{LR} = \frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2} = A_e$$



LEP Results



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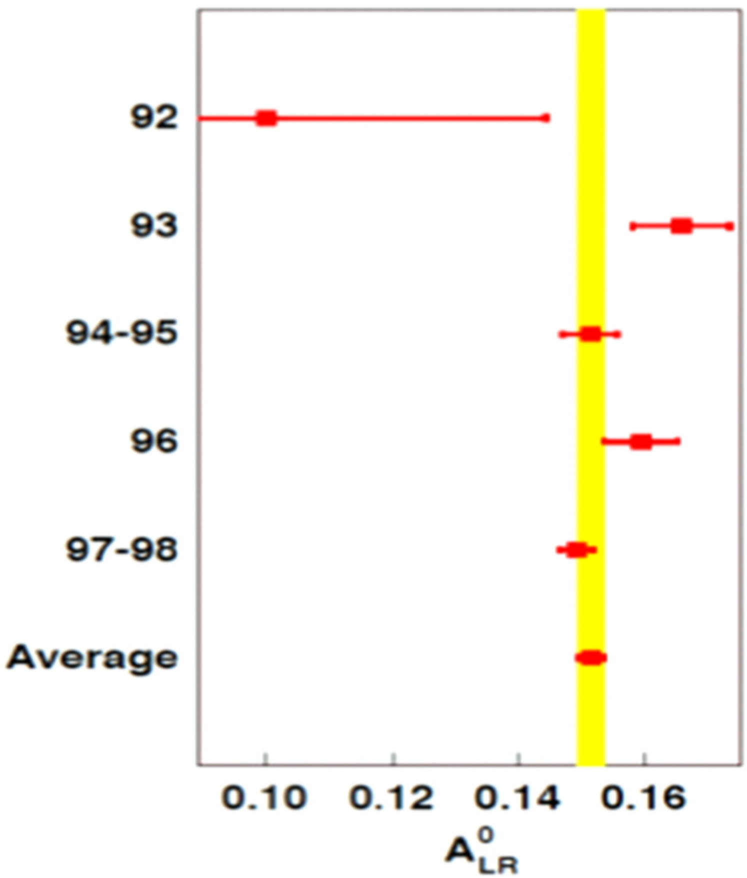
Left-Right Asymmetries



0.100	±	0.044	±	0.004
0.1656	±	0.0071	±	0.0028
0.1512	±	0.0042	±	0.0011
0.1593	±	0.0057	±	0.0010
0.1491	±	0.0024	±	0.0010
0.1514	±	0.0019	±	0.0011

χ^2/DOF=7.4/4 Prob.=11.4%

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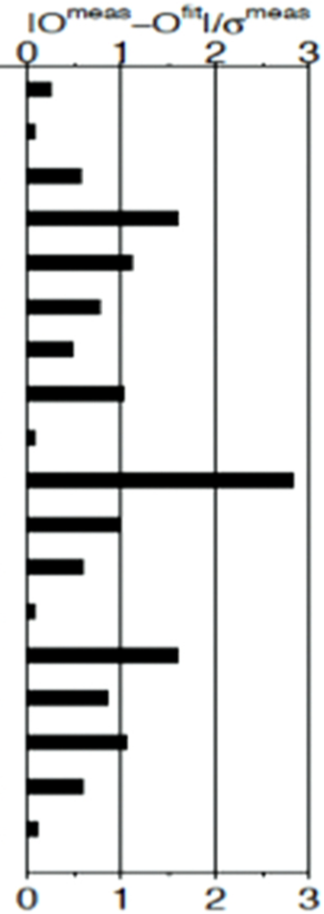
Z Measurements

	Measurement with Total Error	Systematic Error	Standard Model High-Q^2 Fit	Pull
$\Delta\alpha^{(5)}_{\rm had}(m_Z^2)$ [59]	0.02758 ± 0.00035	0.00034	0.02767 ± 0.00035	0.3
m_Z [GeV]	91.1875 ± 0.0021	[a]0.0017	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	[a]0.0012	2.4965 ± 0.0015	0.6
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	[a]0.028	41.481 ± 0.014	1.6
R^0_ℓ	20.767 ± 0.025	[a]0.007	20.739 ± 0.018	1.1
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	[a]0.0003	0.01642 ± 0.00024	0.8
+ correlation matrix Table 2.13				
$\mathcal{A}_\ell$ (P_τ)	0.1465 ± 0.0033	0.0015	0.1480 ± 0.0011	0.5
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.0011	0.1480 ± 0.0011	1.6
$R^0_{\rm b}$	0.21629 ± 0.00066	0.00050	0.21562 ± 0.00013	1.0
$R^0_{\rm c}$	0.1721 ± 0.0030	0.0019	0.1723 ± 0.0001	0.1
$A^{0,\rm b}_{\rm FB}$	0.0992 ± 0.0016	0.0007	0.1037 ± 0.0008	2.8
$A^{0,\rm c}_{\rm FB}$	0.0707 ± 0.0035	0.0017	0.0742 ± 0.0006	1.0
$\mathcal{A}_{\rm b}$	0.923 ± 0.020	0.013	0.9346 ± 0.0001	0.6
$\mathcal{A}_{\rm c}$	0.670 ± 0.027	0.015	0.6683 ± 0.0005	0.1
+ correlation matrix Table 5.11				
$\sin^2\theta^{\rm lept}_{\rm eff}$ ($Q^{\rm had}_{\rm FB}$)	0.2324 ± 0.0012	0.0010	0.23140 ± 0.00014	0.8

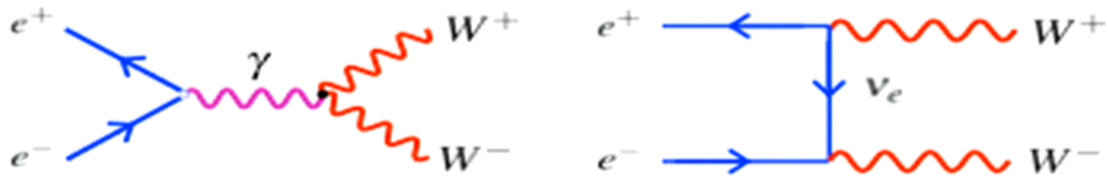
Compatibility with SM

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5

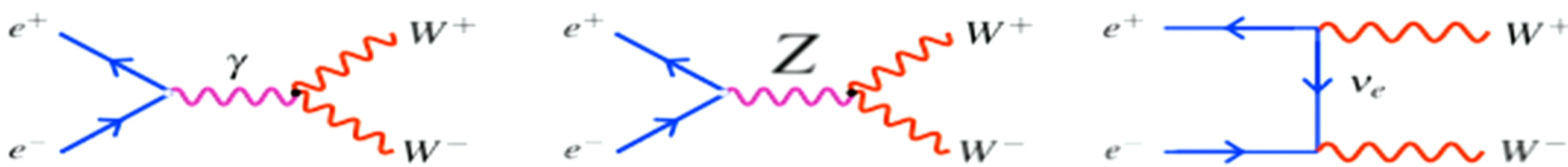


WW Production

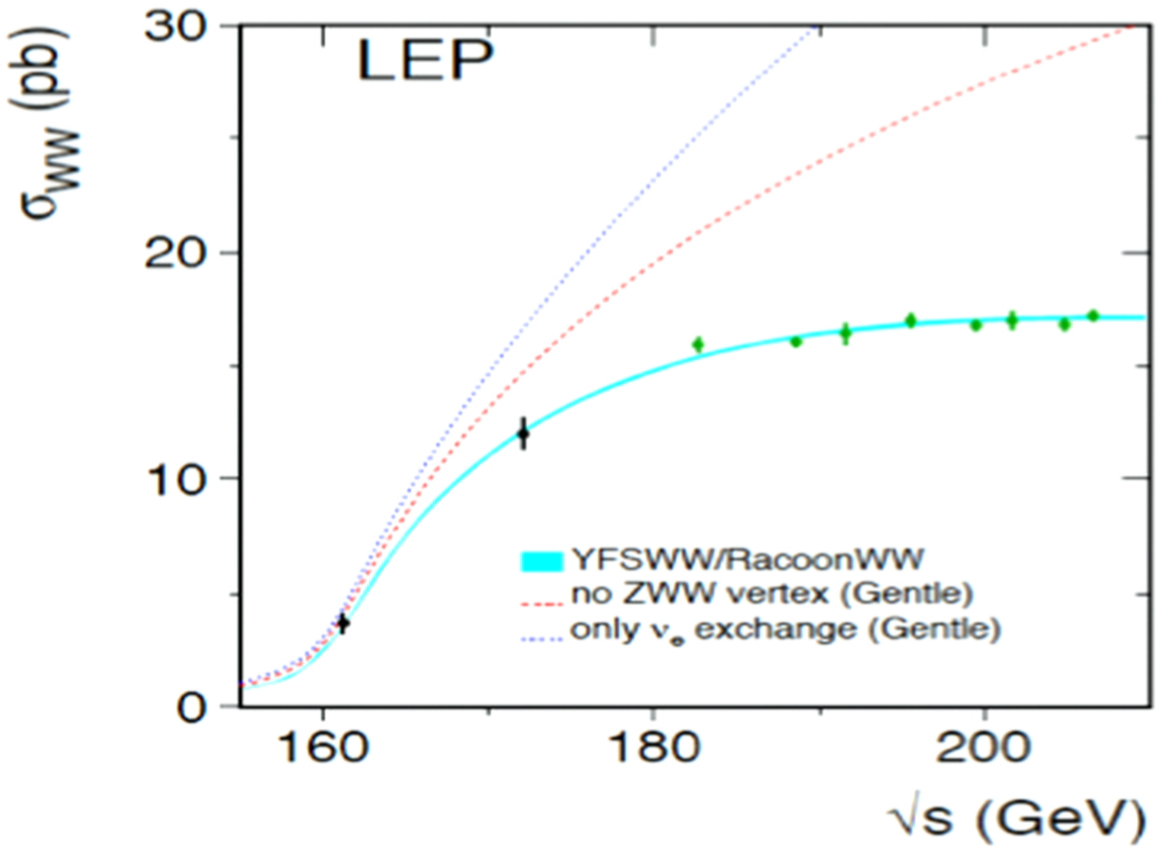
We need the Z boson... The cross section with the two diagrams below would violate unitarity



With the Z, cross section is well-behaved (but still need the Higgs at very high energies)



WW Cross section



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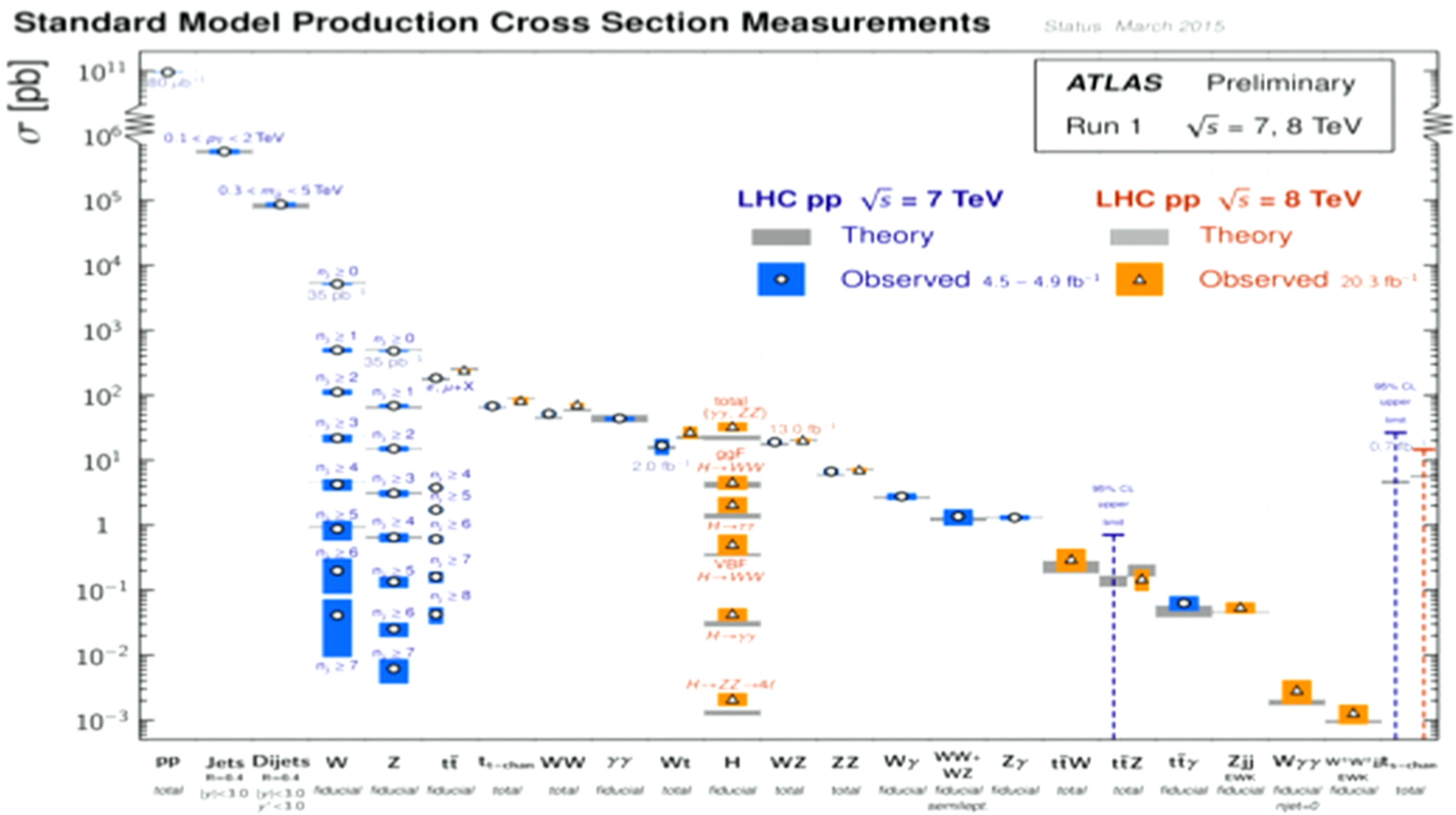
Triple gauge couplings at LEP

Start from most general Lorentz Invariant langranfian that describes triple-gauge couplings: 7 WWg couplings and 7 WWZ couplings. Assuming EM gauge invariance and C and P conservation, we have 5 left.

Measurments by LEP (with additional assumptions):

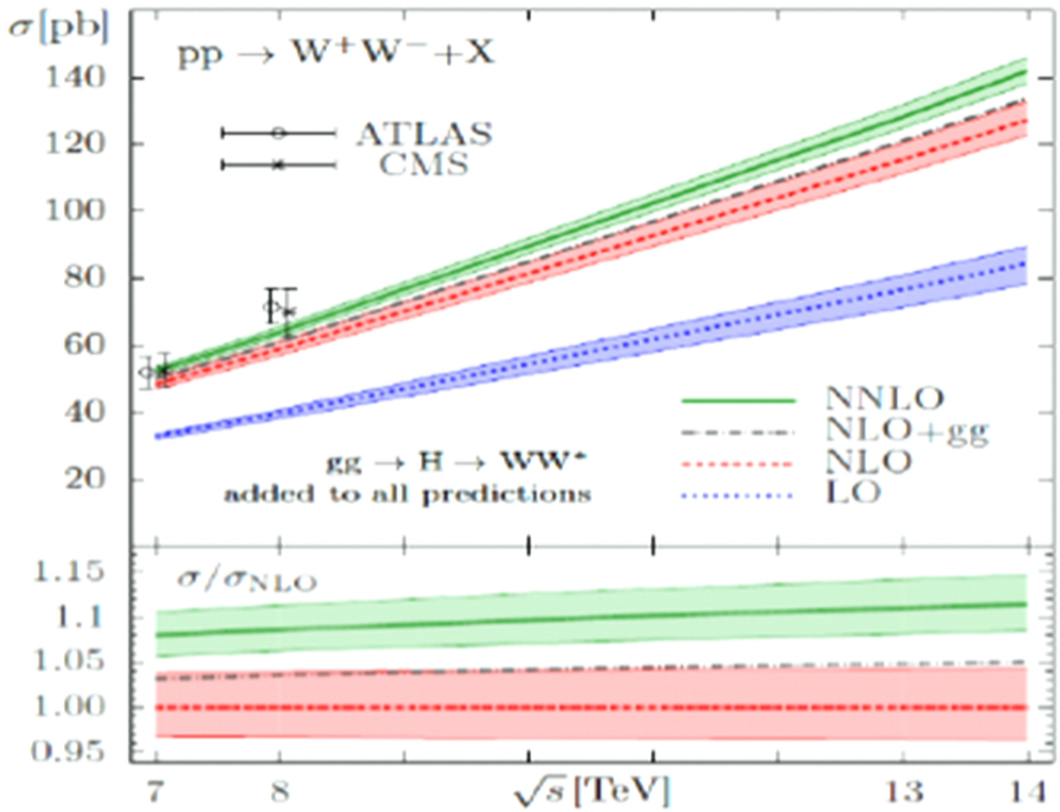
Parameter	ALEPH	DELPHI	L3	OPAL	SM
g_1^Z	$0.996^{+0.030}_{-0.028}$	$0.975^{+0.035}_{-0.032}$	$0.965^{+0.038}_{-0.037}$	$0.985^{+0.035}_{-0.034}$	1
κ_γ	$0.983^{+0.060}_{-0.060}$	$1.022^{+0.082}_{-0.084}$	$1.020^{+0.075}_{-0.069}$	$0.899^{+0.090}_{-0.084}$	1
λ_γ	$-0.014^{+0.029}_{-0.029}$	$0.001^{+0.036}_{-0.035}$	$-0.023^{+0.042}_{-0.039}$	$-0.061^{+0.037}_{-0.036}$	0

ATLAS Cross Section Measurements



WW Production at the LHC

[Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, D. R., Tancredi; 1408.5243]



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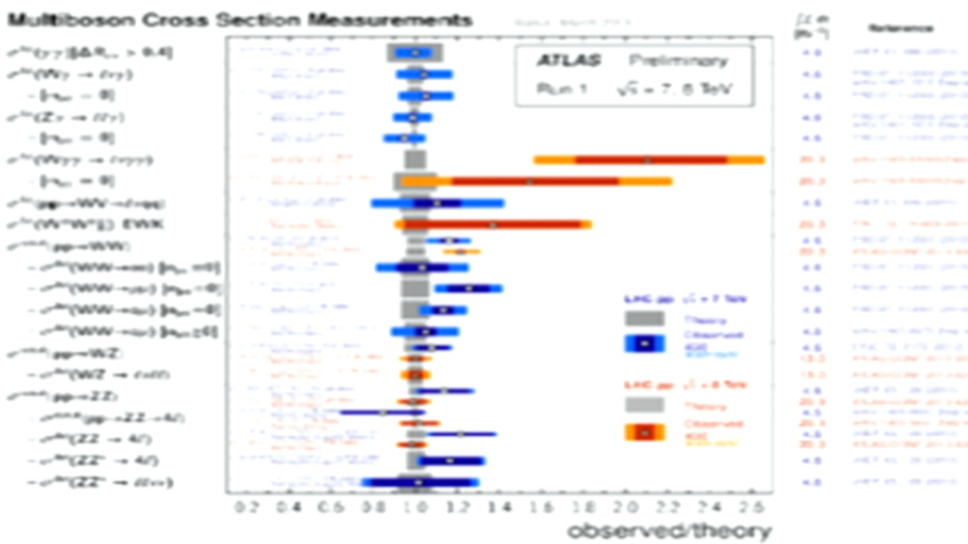
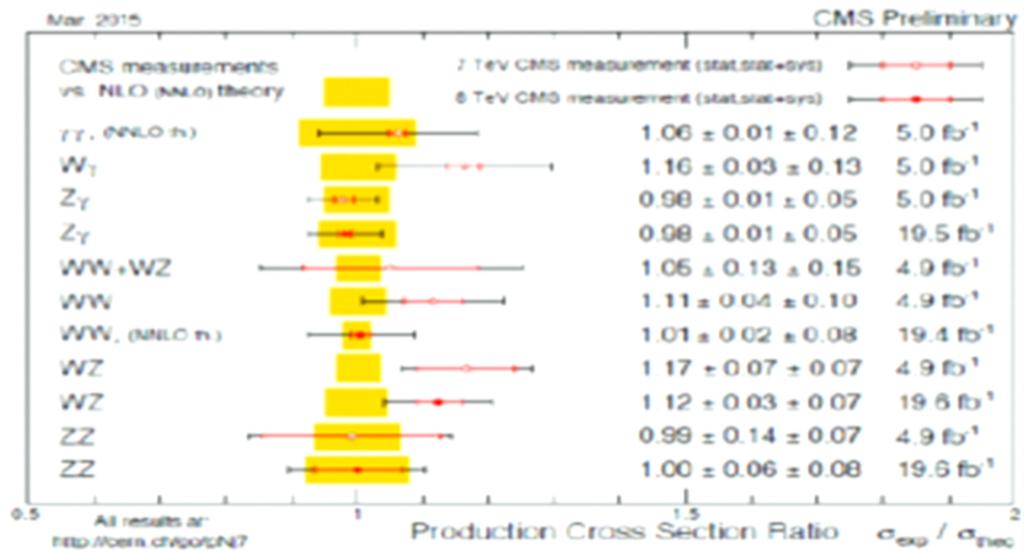
Multi-boson production at the LHC





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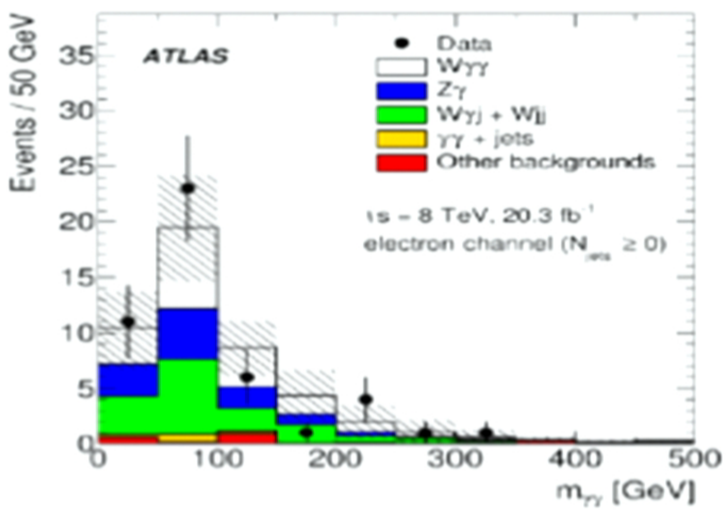
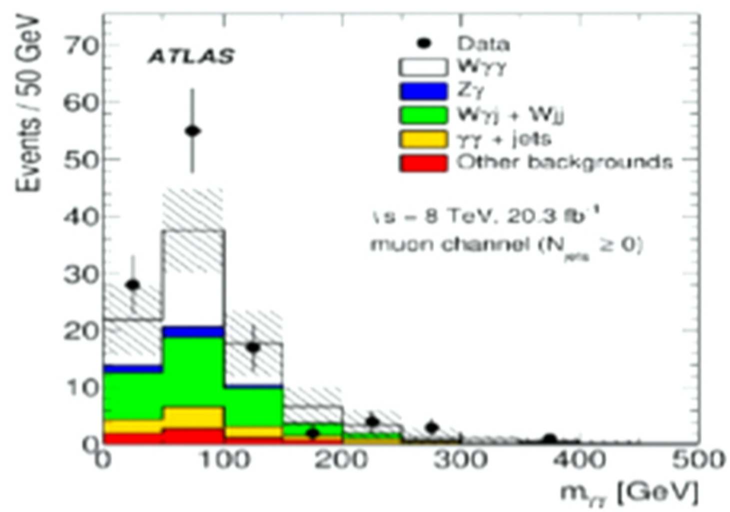
Triple Boson Production

Evidence of Wγγ production from ATLAS

	Electron channel	Muon channel
Wγj + Wjj	$15.3\pm4.8_{(stat)}\pm5.3_{(syst)}$	$30.5\pm7.7_{(stat)}\pm6.8_{(syst)}$
γγ+jets	$1.5\pm0.6_{(stat)}\pm1.0_{(syst)}$	$11.0\pm4.0_{(stat)}\pm4.9_{(syst)}$
Total Background	$30.2\pm5.0_{(stat)}\pm5.4_{(syst)}$	$52.1\pm8.9_{(stat)}\pm8.4_{(syst)}$
Data	47	110





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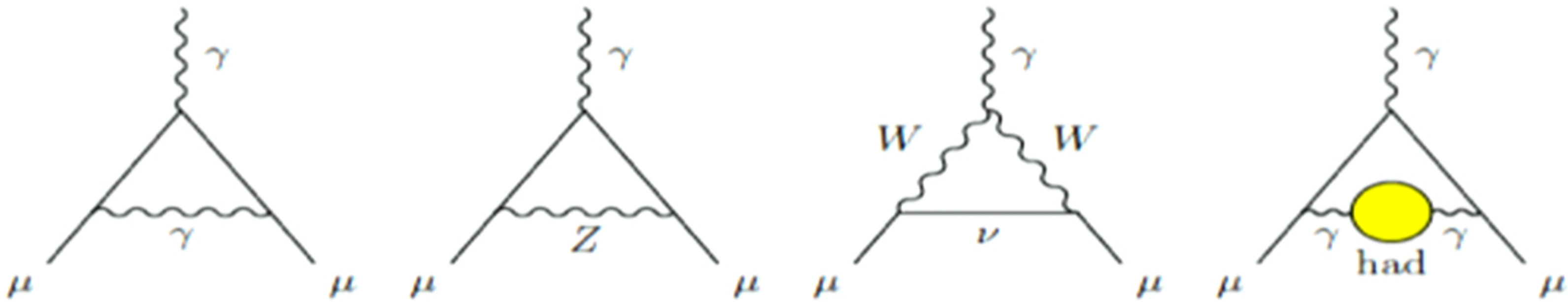
Anomalous Moment of the Muon

From the PDG:

$$\vec{M} = g_\mu \frac{e}{2m_u} \vec{S} \qquad a_\mu \equiv \frac{g_\mu - 2}{2}$$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Had}$$



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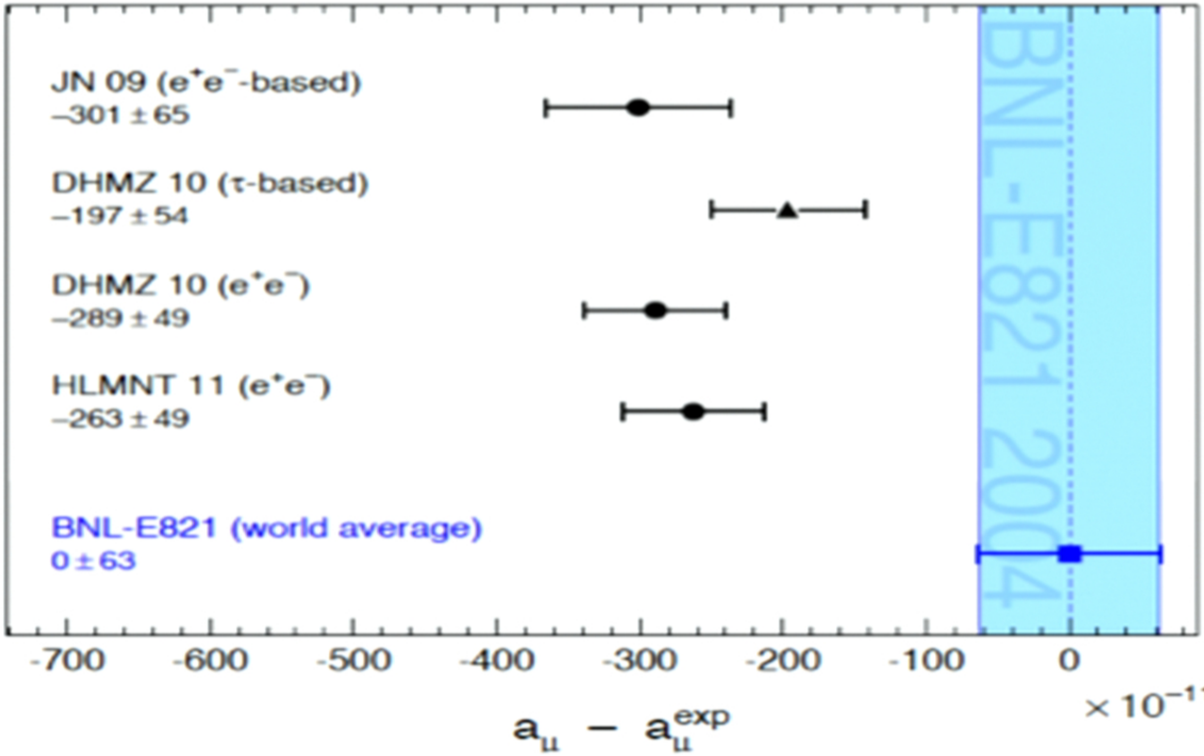
Anomalous Magnetic Moments

From the PDG:

Muon:



Electron:

$$g/2 = 1.001\ 159\ 652\ 180\ 73\ (28) \quad [0.28\ \text{ppt}]\ (\text{measured})$$
$$g(\alpha)/2 = 1.001\ 159\ 652\ 177\ 60\ (520) \quad [5.2\ \text{ppt}]\ (\text{predicted})$$