Title: Standard Model Lecture

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Collection: Standard Model 2023/24

Date: January 16, 2024 - 9:00 AM

URL: https://pirsa.org/24010043

Today

- mass eigenstate couplings
- Custodial Symmetry in S.M.
- Constraints on Physics beyond S.M due to 2-p.t. functions
- Electroweak Precision data (EWPD)
- Higgs production & decay

$$\gamma_\mu d \, W_\mu^+ \frac{g_2}{\sqrt{2}} \rightarrow \bar{u}' \gamma_\mu d' \, W_\mu^+ \frac{g_2}{\sqrt{2}} V_{CKM}$$

mass eigenstate fermion

Similarly

$$\bar{d} \gamma_\mu u \, W_\mu^- \frac{g_2}{\sqrt{2}} V_{CKM}^+$$

$$S_0 \quad (\bar{u} \ \bar{d}) \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \to \bar{u} \gamma_\mu d \, W_\mu^+ \frac{g_2}{\sqrt{2}}$$

+1)

$$\frac{g_2^2 v^2}{8}\left(W_\mu^1 W_\mu^1 + W_\mu^2 W_\mu^2\right) + \frac{(\cancel{g_1^2} + g_2^2)v^2}{8}\left(\frac{g_2}{\sqrt{\cancel{g_1^2}+g_2^2}} W_3^\mu - \cancel{\frac{g_1 B_\mu}{\sqrt{g_1^2+g_2^2}}}\right)^2$$

<u>W triplet</u> $\begin{pmatrix} W_1 \\ W_2 \\ W_3 \end{pmatrix}$

$g_1 \to 0 \Rightarrow$ partial symmetry

$Y_e \to 0$ only <u>some</u> terms in <u>$\mathcal{L}_{SM}$</u> preserve

$Y_D \to 0$ $Y_{u\,\text{term}} \to 0$

$Y_u \to 0$

Custodial Symmetry

$(D^\mu H)^\dagger (D_\mu H)$

masses

$$\frac{g_2^2 v^2}{8}\left(W^1_\mu W^1_\mu + W^2_\mu W^2_\mu\right) + \frac{\cancel{g_1^2} + g_2^2}{8}$$

W triplet $\begin{pmatrix} W_1 \\ W_2 \\ W_3 \end{pmatrix}$

$g_1 \to 0$

$Y_e \to 0$

$\cancel{Y_D} \to 0$

$Y_u \to 0$

$$V(H^\dagger H) = \frac{\lambda}{4}\left(H^\dagger H - v^2/2\right)^2 \leftarrow SO(4) \quad \begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\\ \phi_4\end{pmatrix}$$

$$(D_\mu H)^\dagger (D_\mu H)\Big|_{g_1 \to 0} \qquad H = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2\\ \phi_3 + i\phi_4\end{pmatrix}$$

$$H^\dagger H = \frac{1}{2}\left(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right)$$

$$V(H^\dagger H) = \frac{\lambda}{4}\left(H^\dagger H - v^2/2\right)^2 \quad \leftarrow \underline{SO(4)}$$

$$\to \mathrm{Tr}(\Phi^\dagger \Phi)$$

$$\begin{pmatrix}\phi_1\\ \phi_2\\ \phi_3\\ \phi_4\end{pmatrix} \to O \begin{pmatrix}\phi_1'\\ \phi_2'\\ \phi_3'\\ \phi_4'\end{pmatrix}$$

$$(D_\mu H)^\dagger (D_\mu H)\Big|_{g_1 \to 0}$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2\\ \phi_3 + i\phi_4\end{pmatrix}$$

$$H^\dagger H = \frac{1}{2}\left(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right)$$

$$\to O \begin{pmatrix} \phi_1' \\ \phi_2' \\ \phi_3' \\ \phi_4' \end{pmatrix}$$

$$SO(4) \overset{\text{isomorphic}}{\simeq} SU(2)_L \times SU(2)_R \overset{\text{vev } \langle \Phi \rangle}{\Longrightarrow} \underset{\text{vectorial}}{SU(2)} \qquad SU(2)_L = SU(2)_R$$

bi-doublet Higgs field $\Phi = \left(i\sigma_2^{IJ} H_I^{*} , H_K \right)$ $\quad \begin{pmatrix} \times & \times \\ \times & \times \end{pmatrix}$

$$|H\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \quad \text{vev} \quad \langle \Phi \rangle = \begin{pmatrix} v/\sqrt{2} & 0 \\ 0 & v/\sqrt{2} \end{pmatrix}$$

$$\Phi \to L \Phi R^{+}$$

<u>Masses</u> affected by g_1, doublet splittings $m_u \neq m_d$

$m_t \neq m_b$

Experimental $m_W \simeq 80$ GeV

$m_Z \simeq 92$ GeV

$$\bar{u}\gamma_\mu d W_\mu^+ \frac{g_2}{\sqrt{2}} \xrightarrow[\text{fermion}]{\substack{\text{mass}\\ \text{eigenstate}}} \bar{u}'\gamma_\mu d' W_\mu^+ \frac{g_2}{\sqrt{2}} V_{CKM}$$

$$V_{CKM} = U^\dagger(u,L)\, U(d,L)$$

Similarly $\quad \bar{d}\gamma_\mu u W_\mu^- \frac{g_2}{\sqrt{2}} V_{CKM}^\dagger$

$$= \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

$$S_6 \quad (\bar{u}\ \bar{d}) \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \rightarrow \bar{u} \gamma_\mu d W_\mu^+ \frac{g_2}{\sqrt{2}} \rightarrow$$

mass

eigenstate

fermion

Similarity

$$= -\frac{11}{48\pi^2}\frac{m_Z^2}{v^2}\sin^2\theta \log\left[\frac{m_h^2}{m_Z^2}\right]$$

Measure m_Z, m_W ← includes Quantum corrections

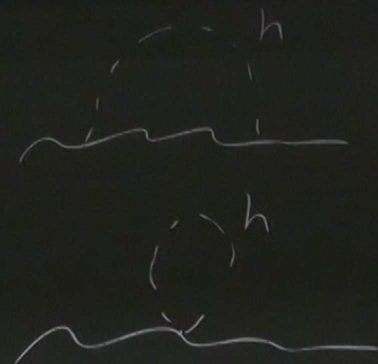
90's LEP large electron positron
CERN

2000's Tevatron → Chicago

$m_h \simeq 100$'s GeV

$(D^\mu H)(D^\mu H) \to$ tree level contribution

m_Z



$\Delta \rho_{g_1 \text{ loop}} = -\frac{11}{48\pi^2}\frac{m_Z}{v}$

Use mass eigenstates in D^μ: $D^\mu = \partial_\mu + i g_3 A_\mu^A T^A + i \frac{g_2}{\sqrt{2}} (W_\mu^+ T^+ + W_\mu^-$

(for $\bar{\Psi} i \not{D} \Psi$ & $D^\mu H$)

<u>Ex</u>: $\bar{Q}_L i \not{D} Q_L \to \frac{g_2}{\sqrt{2}} W^+ (\bar{u}, \bar{d}) T^+ \gamma_\mu ($

$T^\pm = T^1 \pm i T^2$ $T^+ = \frac{1}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + \frac{1}{2}($

$$g_3 A_\mu^A T^A + i\frac{g_2}{\sqrt{2}}\left(W_\mu^+ T^+ + W_\mu^- T^-\right) + i\underbrace{\sqrt{g_1^2+g_2^2}}_{g_Z}\left(T_3^{\psi} - \sin^2\theta\, Q_\psi\right) Z_\mu + i\underbrace{g_2 \sin\theta}_{e}\, Q_\psi A_\mu$$

$$\to \frac{g_2}{\sqrt{2}} W^+ (\bar{u}, \bar{d})\, T^+ \gamma_\mu \begin{pmatrix} u \\ d \end{pmatrix}$$

$$iT^2 \qquad T^+ = \frac{1}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + \frac{1}{2}\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \qquad T^- = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$\tilde{\rho} = 1 + \bigcirc g + \bigcirc g$$

doublet 1 loop

hypercharge

$$\frac{\rho_{exp}}{\tilde{\rho}} = \rho_{exp} - \text{Quantum corrections}$$

$$\overset{exp}{\equiv} 1$$

Experimen

$\mathcal{L}_{SM}$

tions

<u>Experiment</u> $\rho_{\text{corrected}} = 1.00039 \pm 0.00019$

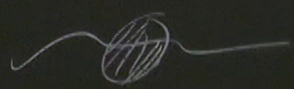
$\underline{2\sigma}$ <u>consistent with SM</u>

So long as $m_h \sim 125$ <u>GeV</u>

$$\mathcal{L}_{SM} + \mathcal{L}_{BSM} \Rightarrow \Pi_{WW} \quad \Pi_{ZZ}$$

Define how 2 point functions : 2 key parameters $\alpha_{ew}(m_Z)\,T$

shifted in general



$$\frac{\alpha_{ew}(m_Z)}{4\sin^2\theta\cos^2\theta}\,S =$$

$$(m_Z)\, T = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}$$

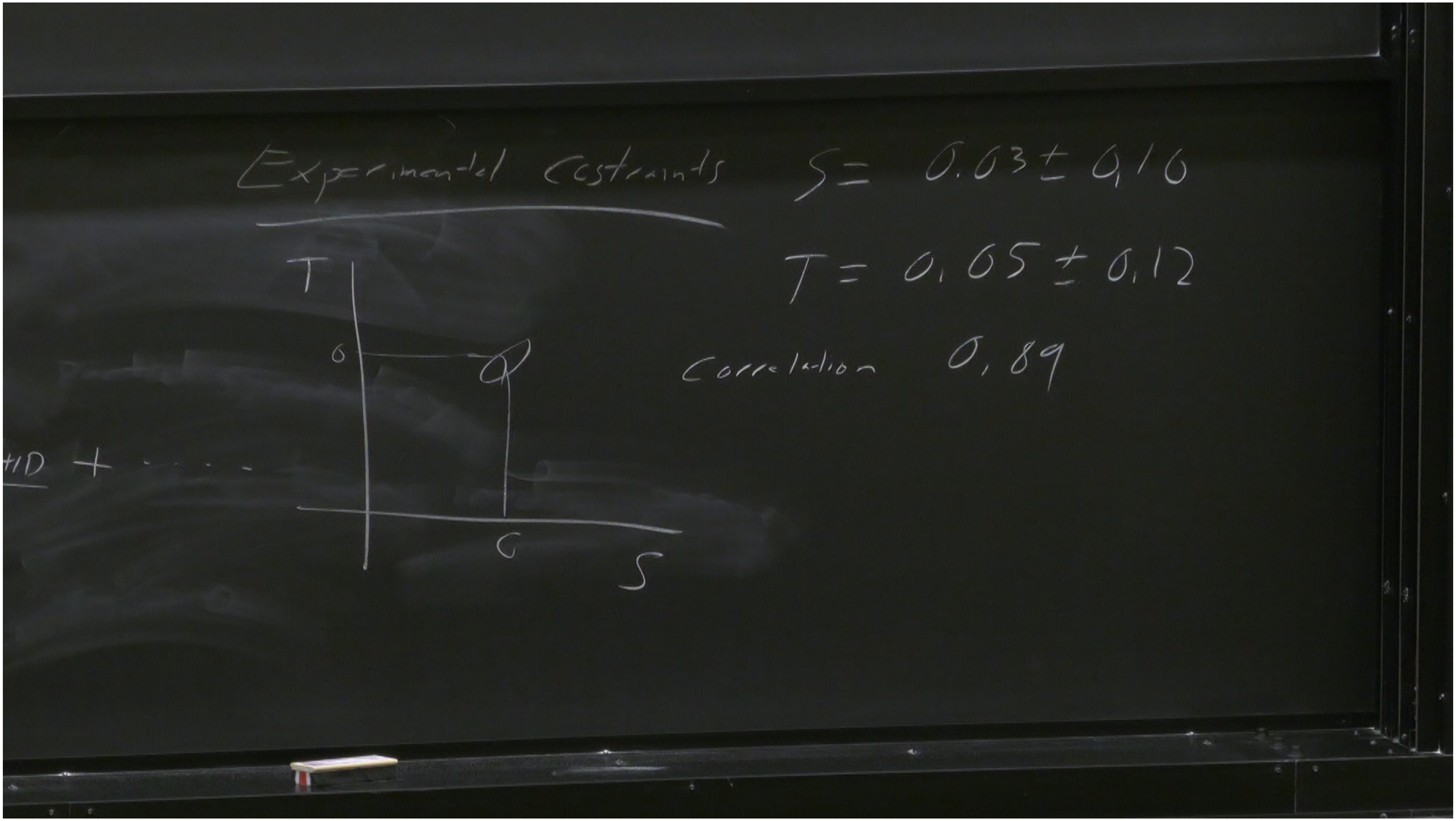
$$S = \frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - \frac{\cos^2\theta - \sin^2\theta}{\cos\theta \sin\theta} \frac{\Pi_{Z\gamma}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2}$$

$$S \equiv \frac{16\pi^2 v^2}{g_1 g_2} C_{HWB} \qquad T = -2\pi v^2 \left(\frac{1}{g_1^2} + \frac{1}{g_2^2}\right) C_{HD}$$

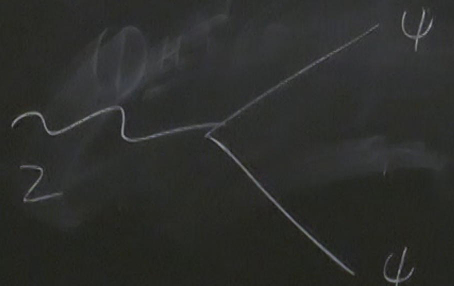
$$Q_{HWB} = H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{L}_{SM} + \frac{C_{HWB} Q_{HWB}}{\Lambda^2} + \frac{C_{HD} Q_{HD}}{\Lambda^2} + \ldots$$

$$Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$$


Experimental Constraints
S = 0.03 ± 0.10
T = 0.05 ± 0.12
Correlation 0.89
T
S
0
0

Electroweak precision

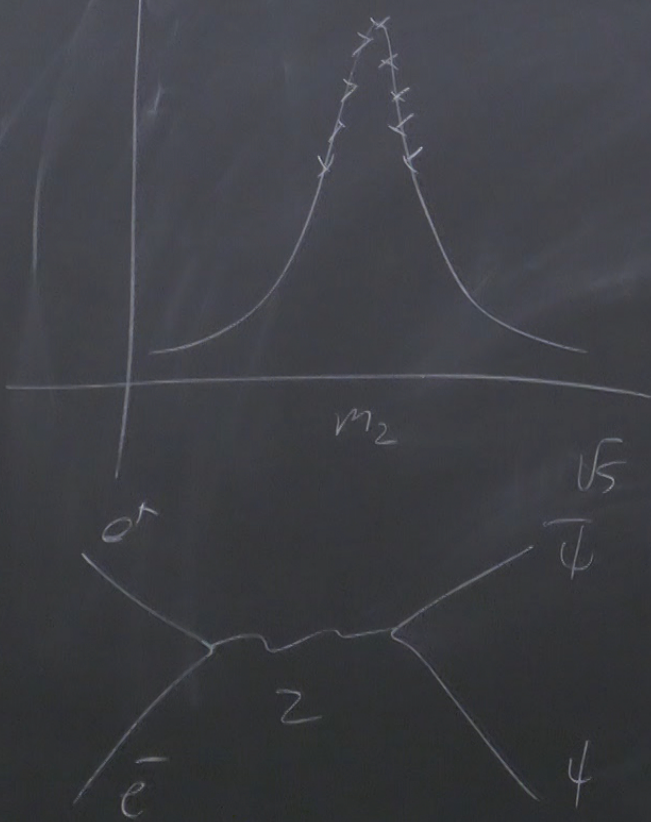


$$\bar{\psi}\, i \not{\partial} \psi \;\rightarrow\; -\bar{\psi}\left(T_3^{\psi} - \sin\theta\, Q^{\psi}\right) Z_\mu \gamma_\mu \psi \sqrt{g_1^2+g_2^2}$$

$$T_3^{\psi} = \frac{1}{2}(1,1,-1,-1) \qquad \psi = (u,\nu,d,e)$$

$$\Gamma_{i=\psi}$$

e)



$$\sigma_{\bar{\psi}\psi}(s) = \sigma_{\bar{\psi}\psi}^{\text{peak}} \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

$$\Rightarrow m_Z,\ \Gamma_Z,\ \sigma_{\bar{\psi}\psi}$$

$$\bar{R}_\ell = \frac{\bar{\Gamma}_{had}}{\bar{\Gamma}_\ell}$$

$$\bar{\sigma}^{\,0}_{had} = \frac{12\pi}{m_Z^2}\,\frac{\bar{\Gamma}_e\,\bar{\Gamma}_{had}}{\bar{\Gamma}_Z^{\,2}}$$

$$\bar{A}_{FB}^{0,q} = \frac{3}{4}\,\bar{A}_\ell\,\bar{A}_q$$

$$\bar{A}_i = \frac{\left(g_{eff}^{Z,L} - g_{eff}^{ZR}\right)\left(g_{eff}^{Z,L} + g_{eff}^{Z,R}\right)}{\left(g_{eff}^{Z,L}\right)^2 + \left(g_{eff}^{ZR}\right)^2}$$

$$\bar{R}_{c,b} = \frac{\bar{\Gamma}_{c,b}}{\bar{\Gamma}_{had}}$$

$$\bar{\Gamma}_{had} = \sum_{\substack{all \\ quarks}}$$

$$\bar{R}_{\ell} = \frac{\bar{\Gamma}_{had}}{\bar{\Gamma}_{\ell}}$$