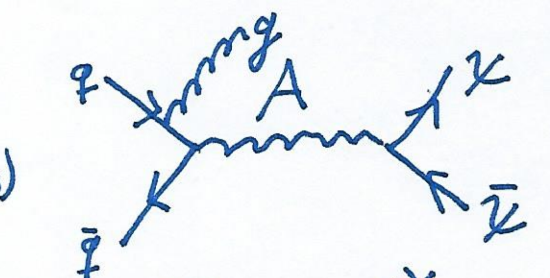
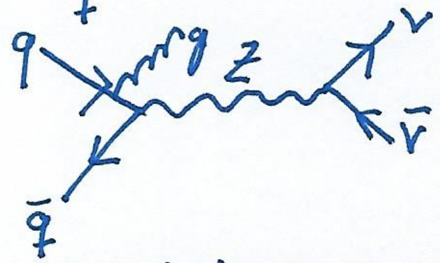
Transitioning from a Dark Matter search to a precision measurment at the LHC

Lecture 1: - electroweak precision measurments
- oblique parameters

Lecture 2: - LHC Dark matter searches
- 2 Higgs Doublet Models (2HDMs)



Lecture 3: - Γ_Z (invisible) measurment



Standard Model of particle physics has 18 (+1) free parameters:

- 9 fermion masses (quarks + charged leptons)
- 3 + 1 angles (CKM + 1 CP)
- g_s strong coupling constant
- (Θ_{QCD})

+ 4 electroweak parameters:

Electroweak symmetry breaking: $SU_2(L) \times U(1)_Y \rightarrow U(1)_{em}$

- $\mathcal{L}_{Higgs} = |D_\mu \phi|^2 - V(\phi)$ with $V(\phi) = -\mu\, \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$

$$D_\mu = i\partial_\mu + g\tfrac{1}{2}\tau^i W_\mu^i + g'\tfrac{Y}{2} B_\mu \Big] \quad \tau^i\text{: Pauli matrices}$$

SU(2) scalar $\phi = \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix} \xrightarrow{EWSB} \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h\end{pmatrix}$

$\Rightarrow$ defines: $W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp W_\mu^2)$

$$\left.\begin{aligned} Z_\mu &= \frac{-g' B_\mu + g W_\mu^3}{\sqrt{g^2+g'^2}} \equiv \sin\Theta_W B_\mu + \cos\Theta_W W_\mu^3 \\ A_\mu &= \frac{g B_\mu + g' W_\mu^3}{\sqrt{g^2+g'^2}} \equiv \cos\Theta_W B_\mu + \sin\Theta_W W_\mu^3 \end{aligned}\right\} \Rightarrow \sin\Theta_W = \frac{g'}{\sqrt{g^2+g'^2}}$$

gaug bosons aquire masses:

$m_W^2 = \frac{1}{4} g^2 v^2$; $m_Z^2 = \frac{1}{4}(g^2+g'^2)v^2$; $m_A^2 = 0$

vacuum expectation value v can be parametrised by G_F (determined from $\mu \to e \bar{\nu}_e \nu_\mu$):

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 m_W^2} = \frac{1}{2v^2} \Rightarrow v = 246 \text{ GeV}$$

$$m_h = 2v^2 \lambda$$

$\Rightarrow$ 4 fundamental parameters of EW sector: - couplings g, g'
- v, m_h

$\boxed{\text{EW part of SM is overconstraint} \Rightarrow \text{predictive} \Rightarrow \text{testable!}}$

Set with smallest exp uncertainties:

$m_Z = 91.1876 \pm 0.0021$ GeV (Z-line shape measurement @ LEP)

$G_F = 1.1663787(6) \times 10^{-5}$ GeV^{-2} (muon lifetime @ MuLan PSI)

$\alpha = 1/137.035999139(31)$ (g_e measurements combined by CODATA)

$m_h = 125.10 \pm 0.17$ GeV (LHC combination PDG)

examples of additional EW observables: m_W, $\sin^2\theta_W$

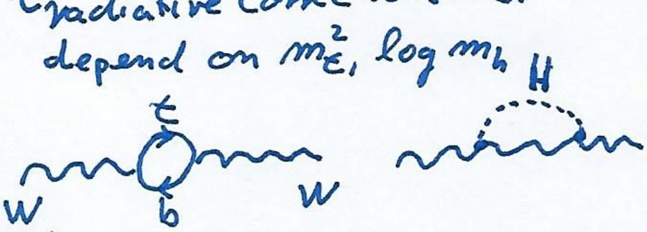
many results still from: - LEP (e^+e^- 209 GeV)
- SLC (e^+e^- 91 GeV)
- Tevatron (p^+p^- 1.8 TeV)

m_W measurement:

Motivation: SM predicts relations between m_W, m_h, m_t

$$m_W = \left(\frac{\pi\alpha}{\sqrt{2} G_F}\right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

radiative corrections ~3%
depend on m_t^2, $\log m_h$



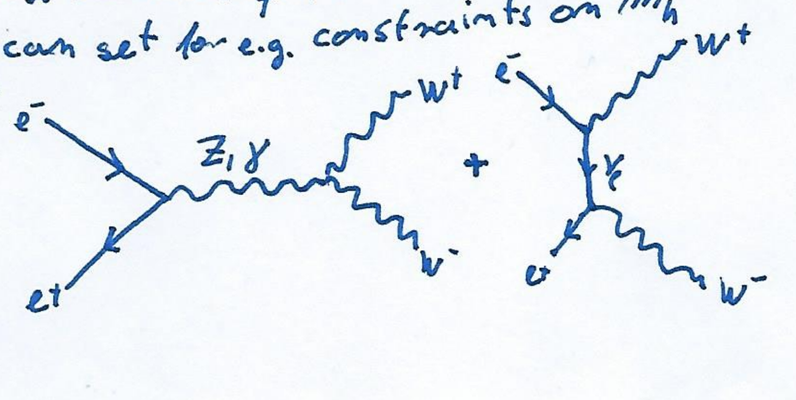
m_W (tree-level) = 79.829 GeV

m_W (exp) = 80.379 ± 0.012 GeV

$\Rightarrow$ consideration of radiative corrections necessary

$\hookrightarrow$ can set for e.g. constraints on m_h

Measurement @ LEP:



Oblique Parameters (Peskin, Takeuchi)

- Extensions to the Higgs sector can be constraint by EW observables
- oblique parameters are reparametrisations of radiative correction variables

$\Delta r, \Delta \kappa, \Delta\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} - 1$

1 loop self energy corrections to $\gamma, W^\pm, Z$:

$i[\Pi_{VV'}(q^2) g^{\mu\nu} - \Delta_{VV'}(q^2) q^\mu q^\nu]$ 2-point correlation functions

↑ vanishes for light quark limit

$\Rightarrow m_V^2 = m_V^2 + \Pi_{VV'}(q^2 = m_V^2)$

γ is massless $\rightarrow \Pi_{\gamma\gamma}(0) = 0 = \Pi_{\gamma Z}(0)$

$$\frac{\alpha S}{4 s_W^2 c_W^2} = \frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - \frac{c_W^2 - s_W^2}{c_W s_W} \frac{\Pi_{\gamma Z}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2}$$

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

$$\frac{\alpha U}{4 s_W^2} = \frac{\Pi_{WW}(m_Z^2) - \Pi_{WW}(0)}{m_W^2} - c_W^2 \frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - 2 c_W s_W \frac{\Pi_{\gamma Z}(m_Z^2)}{m_Z^2} - s_W \frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2}$$

T is sensitive to weak isospin violation & proportional to $\Delta\rho$

S, T, U constructed in such a way that they vanish in SM

Global EW fit yields: $S = -0.01 \pm 0.10$ (from M_Z)

$T = 0.03 \pm 0.12$ (from Γ_Z)

$U = 0.02 \pm 0.11$ (from M_Z)

e.g. extension of the SM Higgs sector by scalar S with $Y_S = 0$ & $\mathbb{Z}_2$: $S \to -S$:

$$V = -\mu^2 \phi^\dagger\phi - m^2 S^2 + \lambda(\phi^\dagger\phi)^2 + \frac{\lambda_{S\phi}}{2} S^2 \phi^\dagger\phi - \frac{\lambda_S}{4} S^4 \quad \text{with } \langle S \rangle = s$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \sqrt{2}\phi^0 - v \\ S - s \end{pmatrix}$$ with masses $m_h, m_H \gg m_W, m_Z$

SM Higgs couplings suppressed by $\cos\alpha$ via mixing

$\Delta S = \frac{1}{12\pi} \sin^2\alpha \log\left(\frac{m_H^2}{m_h^2}\right)$

$\Delta T = -\frac{3}{16\pi\cos^2\theta_W} \sin^2\alpha \log\left(\frac{m_H^2}{m_h^2}\right) \Rightarrow m_H$ restricts $\sin\alpha$!

$\Delta U = 0$