LHC Physics

Monday $15^{\underline{00}}$

15/02 , 01/03 , 15/03

22/03 , 29/03 , 26/04 , 17/05

24/05

LHC physics is rooted in the beauty and puzzles of the SM

- gauge symmetry and electroweak unification
- Higgs mechanism
- chiral fermions

Gauge invariance in QED has been "discovered" as the property of

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x)$$

$$A'_\mu(x) = A_\mu(x) + \partial_\mu \Theta(x)$$

leaves $F_{\mu\nu}(x)$ invariant

But one introduce gauge invariance starting with the matter fields (electron)

Free field theory of a Dirac particle

$$\mathcal{L} = \bar{\Psi}\, i\gamma^\mu \partial_\mu \Psi \;-\; \underbrace{m\bar{\Psi}\Psi}$$

$\mathcal{L}$ is invariant under $U(1)$ group of transformations

$$\Psi'(x) = e^{-iq\Theta}\,\Psi(x)$$

q is an eigenvalue of the generator Q of $U(1)$; invariance under (global) phase transformation implies conservation of the Noether current

$$j_\mu(x) = q\bar{\psi}\gamma_\mu\psi$$

Suppose we insist on invariance under local (gauge) transformation (more natural)

$$\psi'(x) = e^{-iq\theta(x)}\psi(x)$$

$\mathcal{L}$ is not invariant;

But

$$\partial_\mu \to D_\mu = \partial_\mu + iqeA_\mu(x)$$

and

$$\mathcal{L} = \bar{\psi} i\gamma_\mu D^\mu \psi - m\bar{\psi}\psi$$

is invariant provided

$$A'_\mu(x) = A_\mu(x) + \frac{1}{e}\partial_\mu \theta(x)$$

Interactions : $eA_\mu j^\mu$

The existence of the electromagnetic field (photon) follows from the assumption that the electron theory is invariant under local phase transformations!

- Electrons must then couple to photons;
- photons must be massless: $m^2 A_\mu A^\mu$ is not invariant;
- $m \bar{\psi} \psi$ is invariant

Weak interactions ($n \to p e \bar{\nu}$), now for quarks and leptons.

E.g. μ decay $\quad \mu^- \to e^- \bar{\nu}_e \nu_\mu$

$\quad$ d decay $\quad d \to u e \bar{\nu}_e$

Starting point: transitions between matter fields; we learned from experiment about their properties.

Fermi theory for β decays:

$$\mathcal{L}(x) = -2\sqrt{2}\, G_F\, J_\mu^-\, J^{\mu +}$$

$$G_F = 1.165 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

V − A:
$$J_\mu = \bar{\Psi}_L \gamma^\mu T^- \Psi_L$$

$$T^\pm \doteq \frac{1}{2}(\sigma^1 \pm \sigma^2)$$

$$\Psi_L = \frac{1}{2}(1-\gamma_5)\left\{ \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} u \\ d \end{pmatrix} \right\}$$

Chiral spinors

$$\psi_{\substack{L\\R}} = \frac{1}{2}(1 \mp \gamma^5)\psi$$

In the chiral representation

$$\gamma^5 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$ and,

if, $$\psi = \begin{pmatrix} \lambda_\alpha \\ \bar{\chi}^{\dot{\alpha}} \end{pmatrix}$$ then

$$\psi_L = \begin{pmatrix} \lambda_\alpha \\ 0 \end{pmatrix} \qquad \psi_R = \begin{pmatrix} 0 \\ \bar{\chi}^{\dot{\alpha}} \end{pmatrix}$$

Lorentz group = $SL(2,\mathbb{C})$

ψ_L & ψ_R are the smallest representations of the Lorentz group

For massless fermions (why massless - see later)

$$i\gamma^\mu \partial_\mu \psi_{L,R} = 0$$

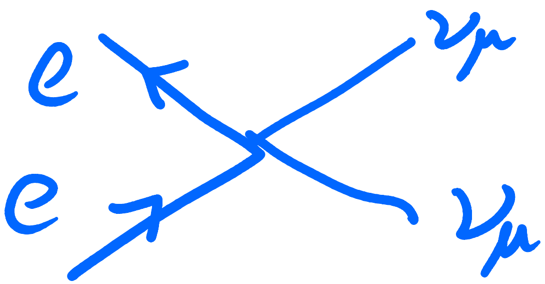
where $\gamma^5 \psi_{\substack{L\\R}} = \mp \psi_{\substack{L\\R}}$

One can check that for massless fermions chirality eigenstates are the same as helicity $\left(\sigma \cdot \frac{k}{|k|}\right)$ eigenstates (by writing the Dirac matrices and $\psi_{L,R}$ in the chiral representation)

Coming back to the Fermi currents for weak interactions: their structure suggest an extension to the full SU(2) group

$$[T^+, T^-] = 2T^3$$

i.e.



(Neutral currents).

But right handed fermions ψ_R carry no weak charges!

At the fundamental level right and left handed fermions are different physical objects

Go from global $SU_L(2)$ to local $SU_L(2) \Rightarrow$ gauge bosons

W^+, W^-, W^0 :

$$g\, j^i_\mu W^{\mu i}$$ where

$$j^i_\mu = \sum_f \bar{\Psi}^f_L \gamma_\mu T^i \psi^f_L$$

!

Immediate consequence of the <u>chiral</u> gauge symmetry:

$$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$ is

not invariant;

Electroweak unification:

include the electric charge Q in the most economical way into the set of generators.

We notice that for the left-handed doublets

$$Y = Q - T^3$$

commute with T^i (each doublet is an eigenvector of Y ($Y_{\nu_L} = Y_{e_L} = -1/2$)

If we include right handed fermions into our considerations by the prescription $Y = Q$ we arrive at $SU_L(2) \times U_Y(1)$

ψ_L, ψ_R carry different quantum numbers; chiral theory

Parity is not the symmetry of the universe

U(1) current

$$J_Y^\mu = \sum_f \bar{\psi}_L^f \gamma^\mu Y \psi_L^f + \sum_f \bar{\psi}_R \gamma^\mu Y \psi_R^f$$

Very important: charge Y <u>also</u> different for ψ_L and ψ_R

Using $Q = Y + T^3$ we can contract

$$J_{EM}^\mu = J_Y^\mu + \sum_f \bar{\psi}_f \gamma^\mu T^3 \psi_L^f$$

And on the other hand, we know from experiment that

$$J^{\mu}_{em} = \sum_{f} \bar{\psi}^{f} Q \gamma^{\mu} \psi^{f}$$

Dirac spinors !

How to achieve it in the presence of interactions

$$g J^{\alpha}_{\mu} W^{\alpha\mu} + g' J^{\mu}_{Y} B_{\mu}$$

Unification $\Rightarrow$ the photon A_μ must be a combination of W^3_μ, B_μ.

We want the photon couplings to fermions to be vector-like, with the strength given by the electric charge. We find

$$A_\mu = \frac{1}{(g^2+g'^2)^{1/2}}\left(g B_\mu + g' W^3_\mu\right) \equiv \cos\theta_W B_\mu + \sin\theta_W W^3_\mu$$

where

$$\sin^2\theta_W = \frac{g'^2}{g^2+g'^2}\,, \quad tg\,\theta_W = \frac{g'}{g}$$

$$e = \frac{g'g}{(g^2+g'^2)^{1/2}} = g\sin\theta_W$$

The orthogonal combination

$$Z^0_\mu = \frac{1}{(g^2+g'^2)^{1/2}}\left(g W^3_\mu - g' B_\mu\right) =$$

$$\cos\theta_W W^3_\mu - \sin\theta_W B_\mu$$

Its couplings to fermions

$$\frac{g}{\cos\theta_W} J_Z^{\mu} Z_\mu^0 = \frac{g}{\cos\theta_W}\left(J^{3\mu} - \sin^2\theta_W J^{\mu}_{EM}\right) * Z_\mu^0$$

Altogether

$$\mathcal{L} \supset -g J^{a\mu} W_\mu^a - g' J^\mu_Y B_\mu \equiv$$

$$- g J^+_\mu W^{+\mu} - g J^-_\mu W^{-\mu} - \frac{g}{\cos\theta_W} J^Z_\mu Z^\mu_0$$

$$- e J^\mu_{EM} A_\mu$$

The mixing angle θ_W measures the departure of the weak neutral current J_Z^μ from pure V–A structure

This is the main prediction of the electroweak unification (depends on the free parameter – $\sin^2\theta_W$);

The structure of currents has been tested in many experiments

Summary on couplings:

$$V_{\bar{\psi}\psi V} = g\, j^{\pm}_{\mu} W^{\mu}_{\mp} = \frac{1}{\sqrt{2}} g \bar{\psi} \gamma_{\mu} T^{\pm} \frac{1-\gamma_5}{2} \psi W^{-}_{\mu}$$

$$+ h c$$

$$V_{\bar{\psi}\psi Z} = \frac{g}{\cos\theta_W} \bar{\psi} \gamma_{\mu} \left[\frac{1-\gamma_5}{2} T^{3} - Q \sin^2\theta_W \right] \psi Z^{\mu}$$

One often defines vector and axial couplings for the neutral current

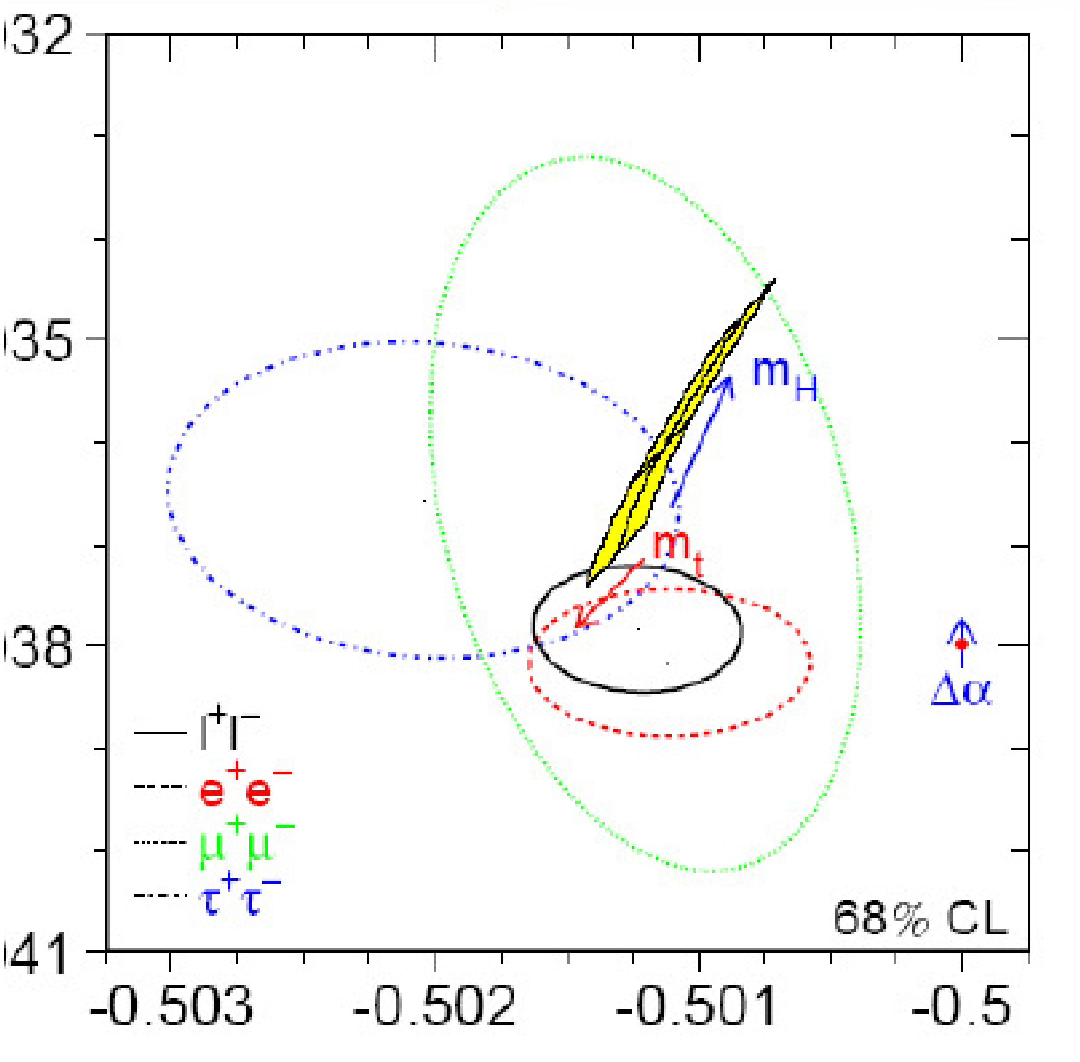
$$V_{\bar{\Psi}\Psi Z} = \frac{g}{2\cos\theta_W} \bar{\Psi} \gamma_\mu [g_V - g_A \gamma_5] \Psi Z^\mu$$

$$g_A = \pm 1/2$$

$$g_V / g_A = 1 - 4|Q| \sin^2\theta_W$$

Precision Tests of the Standard Model

epton couplings

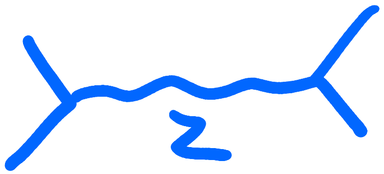


Pulls in global fit

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	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
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.410 ± 0.032	80.377
Γ_W [GeV]	2.123 ± 0.067	2.092
m_t [GeV]	172.7 ± 2.9	173.3

$$\rightarrow \quad \mathcal{L}_{eff}^{CC} = \frac{g^2}{8M_W^2}\left[\bar{\Psi}\gamma_\mu(1-\gamma_5)T^+\Psi\right]$$

$$* \left[\bar{\Psi}\gamma_\mu(1-\gamma_5)T^-\Psi\right]$$



$$\rightarrow \quad \mathcal{L}_{eff}^{NC} = 2\frac{g^2}{8M_W^2}\rho_0 \; *$$

$$* \; \bar{\Psi}\left[T^3(1-\gamma_5) - Q\sin^2\theta_W\right]\Psi\,\bar{\Psi}\left[\cdots\right]\Psi$$

$$\rho_0 = M_W^2/(M_Z^2\cos^2\theta_W)$$

The value of the Weinberg angle has a priori nothing to do with the vector boson masses.

The famous relation

$$\frac{M_W}{M_Z} = \cos\vartheta_W$$

$\rho_0 = 1$

could in principle not exist!

Two independent sectors of the electroweak theory

- fermion currents – depend on the symmetry structure
- gauge boson masses – depend on the choice of the vacuum