3

STANDARD MODEL

3!

$2! = 2 \times 1$

ELECTROWEAK INTERACTIONS

S. WEINBERG (Phys. Rev. Lett. 1967):

"LEPTONS INTERACT ONLY WITH PHOTONS AND WITH THE INTERMEDIATE BOSONS WHICH PRESUMABLY MEDIATE THE WEAK INTERACTIONS. WHAT CAN BE MORE NATURAL THAN LINKING THOSE SPIN BOSONS IN A MULTIPLATE OF GAUGE FIELDS?"

SALAM - WEINBERG - GLASHOW MODEL

NEED TO SOLVE SEVERAL DIFFICULTIES :

$$\left.\begin{array}{lll} - \gamma & : & m_\gamma = 0 \\ - W & : & m_W \neq 0 \end{array}\right\} \leftarrow \text{LATENT SYMMETRY}$$

- e VERY DIFFERENT FROM G_F

$\downarrow$

HIERARCHY THROUGH A MIXING ANGLE

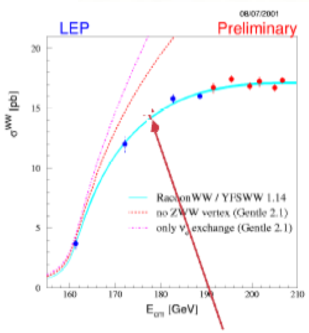
ELECTION OF THE GAUGE GROUP G

THE MODEL MUST INCLUDE :

- CHARGED WEAK CURRENT $J_\mu^\pm$
- ELECTROMAGNETIC INTERACTION

  $\Downarrow$

  $U(1)_{em}$ UNBROKEN $\Rightarrow m_\gamma = 0$



ZWW vertex exists!

- NEUTRAL WEAK CURRENT J_μ^0

  (CANCELLATION MECHANISM)

$\Downarrow$

— G HAS TO BE A 4 PARAMETER GROUP —

PROPOSAL:

$$\boxed{G \equiv SU(2)_L \times U(1)_Y}$$

$2! = 2 \times 1$

- L: LEFT
- Y: HYPERCHARGE

FERMION FIELDS: (LEFT AND RIGHT COMPONENTS)

$$\psi_{L,R} = \frac{1 \mp \gamma_5}{2} \psi$$

$SU(2)_L \Rightarrow$ ψ_L BEHAVES DIFFERENT FROM ψ_R

THE MODEL 2! IS A CHIRAL THEORY

→ DISTINGUISHES BETWEEN LEFT AND RIGHT

CHARGED WEAK CURRENT

MUST HAVE (V − A) STRUCTURE

ONLY ψ_L APPEARS $\psi_L = \frac{1-\gamma_5}{2}\psi$

EX:

$$J_\mu^- = \bar{\nu}_e \gamma_\mu (1-\gamma_5) e^- = 2 \bar{\nu}_{e_L} \gamma_\mu e_L^-$$

- MATTER UNDER $SU(2)_L \times U(1)_Y$:

IN EACH GENERATION OF q AND ℓ :

$SU(2)_L \times U(1)_Y$ QUANTUM NUMBERS ARE REPEATED

EX 1st. GENERATION (e, ν_e, u, d) :

- $(\nu_e, e)_L$ AND $(u, d)_L$: DOUBLETS OF $SU(2)$

(ONLY THE LEFT PARTS CARRY CONTENT OF SU(2))

$\Downarrow$

(V-A) IS GUARANTEED -

L IN $SU(2)_L$ IS UNDERSTOOD

QCD

– QUANTUM CHROMODYNAMICS –

STRONG INTERACTION AMONG QUARKS AND GLUONS

$SU(3)_{COLOR}$

HEIR(ESS) OF :

- PARTON MODEL

  SCALE INVARIANCE OF DIS (QUARKS AND GLUONS)

- QUARK MODEL

  HADRONIC SPECTROSCOPY ($SU(3)_{flavor}$)

- COLOR HYPOTHESIS

  EXTRA DEGREE OF FREEDOM (STATISTIC)

- GAUGE THEORY

  SYMMETRY

COLOR

- FERMI-DIRAC STATISTIC

$\Delta^{++} = |u\uparrow\ u\uparrow\ u\uparrow\rangle$ $\qquad$ $\Omega^{-} = |s\uparrow\ s\uparrow\ s\uparrow\rangle$

ANTISYMMETRY:

$$|\mathrm{BARYON}\rangle = \frac{1}{\sqrt{6}} \sum_{i,j,k}^{3} \varepsilon_{ijk}\, |q_i\, q_j\, q_k\rangle$$

$$|\mathrm{MESON}\rangle = \frac{1}{\sqrt{3}} \sum_{i=1}^{3} |q_i\, \bar{q}_i\rangle$$

- EXPERIMENTAL DATA :

  - $R = \frac{\sigma(e^+e^- \to \text{hadrones})}{\sigma(e^+e^- \to \mu^+\mu^-)} \simeq 3 \sum_q Q_q^2$

  - $\Gamma(\pi^0 \to 2\gamma) = \frac{m_\pi^2}{64\pi}\left[\frac{2\alpha}{\pi f_\pi} \, 3 \sum_q (I_3)_q Q_q^2\right]^2$

- RENORMALIZABILITY OF 2!

ANOMALY $\equiv 0$ IF $T_r\, Q_{f,r}^{\dagger} = T_r(Q_{Lep} + 3\,Q_q) = 0$

WHY SU(3)?

REQUIREMENTS

* LIE GROUP SIMPLE
  (NO DIRECT PRODUCT)
* LIE GROUP COMPACT
  (FINITE UNITARY REPRESENTATIONS)

CONDITIONS

* 3 DEGREES OF FREEDOM
* $\bar{q} \neq q$ (COMPLEX REPRESENTATION)
* MESONS AND BARYONS "WHITE" (SINGLETS)

COMPACT LIE GROUPS

- A_N (= $SU(N+1)$)
- B_N (= $SO(2N+1)$)
- C_N (= $Sp(N)$)
- D_N (= $SO(2N)$)
- E_6, E_7, E_8, F_4, G_2

$N = 1, 2, 3, \ldots$ (PARA D_N, $N > 2$)

E_i, F, G : EXCEPCIONALES

WITH REPRESENTATIONS OF $D = 3$

- $SU(2)$, $SU(3)$, $SO(3)$, $Sp(1)$

3 ISOMORPHIC $SO(3) \simeq SU(2) \simeq Sp(1)$

[$SO(3)$ REPRESENTATIVE]

$SO(3)$, $SU(3)$ CANDIDATES

TRIPLET REPRESENTATION OF SO(3) : REAL

$(q \equiv \bar{q})$

↓

SU(3)

THE CANDIDATE !

* ALL CONDITIONS FULFILLED !

THEORETICAL IMPUTS OF THE S.M.

- ALL INTERACTIONS ARE LOCAL
- QUANTUM MECHANICS IS CORRECT (UP TO ~ 1 TeV)
- POINCARÉ INVARIANCE IS VALID

$\Uparrow$

* RELATIVISTIC QUANTUM FIELD THEORY *

- GAUGE FORCES (VIA GAUGE BOSONS)
- LOCAL GAUGE SYMMETRY $SU(3)_c \times SU(2)_L \times U(1)_Y$

  (3!)
- GRAVITY IGNORED
- FUNDAMENTAL MATTER $\equiv$ WEYL FERMIONS
- THREE FAMILIES (GENERATIONS)
- 3! SPONTANEOUSLY BROKEN TO $SU(3)_c \times U(1)_{em}$
- HIGGS SCALAR YUKAWA COUPLED TO FERMIONS
- MATRICES FOR YUKAWA NEITHER REAL NOR DIAGONAL
- ONLY OPERATORS UP TO DIMENSION FOUR

  (RENORMALIZABILITY)

SHORT RANGE OF W.I $\rightarrow$ SYMMETRY SPONTANEOUSLY BROKEN

$U(1)_{em}$ MUST PERSIST $\Rightarrow$

$$SU(2)_L \times U(1)_Y \supset U(1)_{em}$$

GENERATOR OF $U(1)_{em}$ $[Q]$ MUST BE THE SUM OF THE GENERATOR OF $U(1)_Y$ AND OF THE DIAGONAL GENERATOR OF $SU(2)_L$

$$Q = T_3 + Y$$

GELL MANN - NISHIJIMA RELATION VALID ALSO FOR LEPTONS

BUILDING THE LAGRANGIAN

MATTER

LEFT HANDED COMPONENTS OF EACH GENERATION (FAMILY) ASSIGNED INTO DOUBLETS OF THE FUNDAMENTAL REPRESENTATION OF $SU(2)_L$

COUNTING FERMIONS

$\underline{1}$: $\underbrace{\overbrace{u_L^R, u_L^B, u_L^G}^{SU(3)_c}, \overbrace{d_L^R, d_L^B, d_L^G}^{SU(3)_c}}_{SU(2)_L}$

$\underline{1}$: $\overbrace{u_R^R, u_R^B, u_R^G}^{SU(3)_c}$

$\underline{1}$: $\overbrace{d_R^R, d_R^B, d_R^G}^{SU(3)_c}$

$\underline{1}$: $\underbrace{\nu_{e_L}, e_L}_{SU(2)_L}$

$\underline{1}$: e_R

$\underline{1}$: ν_{e_R}

---

6 $\times$ 3 FAMILIES

- $\underline{6 \times 3}$: FERMION MULTIPLETS

* PARTICLES RELATED BY GAUGE SYMMETRY
<u>NOT</u> TRULY INDEPENDENT ENTITIES

$$* \; L_\alpha(x) = \frac{(1-\gamma_5)}{2} \begin{pmatrix} i_\alpha(x) \\ j_\alpha(x) \end{pmatrix}$$

- $i_\alpha(x) \equiv \nu_e(x) \,;\, \nu_\mu(x) \,;\, \nu_\tau(x)$

  $\equiv u(x) \,;\, c(x) \,;\, t(x)$ $\qquad q_\uparrow$

- $j_\alpha(x) \equiv e(x) \,;\, \mu(x) \,;\, \tau(x)$

  $\equiv d(x) \,;\, s(x) \,;\, b(x)$ $\qquad q_\downarrow$

RIGHT HANDED COMPONENTS : SINGLETS of $SU(2)_L$

$$R_\alpha(x) = \frac{(1+\gamma_5)}{2}\, k_\alpha(x)$$

ALL CARRY WEAK HYPERCHARGE OF $U(1)_Y$

TO REPRODUCE THE DESIRED ELECTRIC CHARGE OF FERMIONS

$$* \quad Q = I_3^W + \frac{Y_W}{2}$$

GOOD ASSIGNEMENTS OF $T_3|_\ell$ AND $Y|_\ell$

EX FIRST GENERATION

	$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	e_R	$\begin{pmatrix}u\\ d\end{pmatrix}_L$	u_R	d_R
$SU(2)_L$	2	1	2	1	1
$U(1)_Y$	$-\frac{1}{2}$	-1	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$

GAUGE VECTOR BOSONS

* WEAK ISOSPIN: $\vec{I}_W \rightarrow 3$
    - $W_\mu^{(1)}(x),\ W_\mu^{(2)}(x),\ W_\mu^{(3)}(x)$

* WEAK HYPERCHARGE: $Y_W \rightarrow 1$
    - $B_\mu(x)$

* COLOR: $T_{\text{color}}^{(a)}$ $[a=1,2,\ldots,8] \rightarrow 8$
    - $G_\mu^{(a)}(x)$ $[a=1,2,\ldots,8]$

COUPLINGS 3

(VIA COVARIANT DERIVATIVES)

- $SU(3)_C$: g_s
- $SU(2)_L$: g
- $U(1)_Y$: g'

$$\mathcal{L}(x)_{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y} =$$

$$- \frac{1}{4} \sum_a G^{(a)}_{\mu\nu}(x) \, G^{(a)\mu\nu}(x) - \frac{1}{4} \vec{F}_{\mu\nu}(x) \vec{F}^{\mu\nu}(x) - \frac{1}{4} B_{\mu\nu}(x) B^{\mu\nu}(x)$$

$$+ i \sum_{l = e, \mu, \tau} \bar{L}_l(x) \not{D} L_l(x) + i \sum_l \bar{R}_l(x) \not{D} R_l(x)$$

$$+ i \sum_{q_\uparrow = u, c, t} \bar{L}_{q_\uparrow}(x) \not{D} L_{q_\uparrow}(x) + i \sum_{q_\uparrow} \bar{R}_{q_\uparrow}(x) \not{D} R_{q_\uparrow}(x)$$

$$+ i \sum_{q_\downarrow = d, s, b} \bar{R}_{q_\downarrow}(x) \not{D} R_{q_\downarrow}(x)$$

* YANG-MILLS STRENGTH TENSORS:

- $G^{(a)}_{\mu\nu}(x) = \partial_\mu G^{(a)}_\nu(x) - \partial_\nu G^{(a)}_\mu(x) + g_s f_{abc} G^{(b)}_\mu(x) G^{(c)}_\nu(x)$

- $\vec{F}_{\mu\nu}(x) = \partial_\mu \vec{W}_\nu(x) - \partial_\nu \vec{W}_\mu(x) + g \vec{W}_\mu(x) \wedge \vec{W}_\nu(x)$

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

- $\not{D} = \gamma^\mu D_\mu$ FIXED BY GAUGE INVARIANCE !

LEPTONS

- $D_\mu \equiv \partial_\mu + i g \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu(x) - i \frac{1}{2} g' B_\mu(x)$ $[L_\ell(x)]$
- $D_\mu \equiv \partial_\mu - i g' B_\mu(x)$ $[R_\ell(x)]$

QUARKS

- $D_\mu \equiv \left(\partial_\mu + i g \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu(x) + i \frac{1}{6} g' B_\mu(x)\right) \delta_{\alpha\beta}$

$$- i g_s \frac{\lambda^{(a)}_{\alpha\beta}}{2} G^{(a)}_\mu(x) \qquad [L_{q_\uparrow}(x)]$$

- $D_\mu \equiv \left(\partial_\mu \qquad + i \frac{2}{3} g' B_\mu(x)\right) \delta_{\alpha\beta}$

$$- i g_s \frac{\lambda^{(a)}_{\alpha\beta}}{2} G^{(a)}_\mu(x) \qquad [R_{q_\uparrow}(x)]$$

- $D_\mu \equiv \left(\partial_\mu \qquad - i \frac{1}{3} g' B_\mu(x)\right) \delta_{\alpha\beta}$

$$- i g_s \frac{\lambda^{(a)}_{\alpha\beta}}{2} G^{(a)}_\mu(x) \qquad [R_{q_\downarrow}(x)]$$

- α, β : COLOR INDICES
- $\lambda^{(a)}_{\alpha\beta}$: 8 SU(3) GELL-MANN MATRICES
- SUM OVER $a = 1, 2, \ldots, 8$

BUILDING THE $\mathcal{L}$ LAGRANGIAN

GAUGE FIELDS:

$SU(2)_L \Rightarrow W_i^\mu \quad (i=1,2,3)$

$U(1)_Y \Rightarrow Y^\mu$

$\Downarrow$

COVARIANT DERIVATIVES:

$g_1 \leftarrow U(1)_Y$

$g_2 \leftarrow SU(2)_L$

- $D_\mu \begin{pmatrix} u \\ d \end{pmatrix}_L = \left[\partial_\mu - i g_1 \frac{1}{6} Y_\mu - i g_2 \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu \right] \begin{pmatrix} u \\ d \end{pmatrix}_L$

- $D_\mu \; u_R = \left[\partial_\mu - i g_1 \frac{2}{3} Y_\mu \right] u_R$

- $D_\mu \; d_R = \left[\partial_\mu - i g_1 \frac{1}{2} Y_\mu \right] d_R$

- $D_\mu \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L = \left[\partial_\mu - i g_1 \frac{1}{2} Y_\mu - i g_2 \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu \right] \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$

- $D_\mu \; e_R = \left[\partial_\mu - i g_1 Y_\mu \right] e_R$

2! LAGRANGIAN (FIRST GENERATION)

$$\mathcal{L} = -\frac{1}{2}(\bar{u}\ \bar{d})_L \gamma^\mu D_\mu \begin{pmatrix} u \\ d \end{pmatrix}_L - \frac{1}{2}\bar{u}_R \gamma^\mu D_\mu u_R$$

$$-\frac{1}{2}\bar{d}_R \gamma^\mu D_\mu d_R - \frac{1}{2}(\bar{\nu}_e\ \bar{e})_L \gamma^\mu D_\mu \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

$$-\frac{1}{2}\bar{e}_R \gamma^\mu D_\mu e_R - \frac{1}{4}\vec{W}^{\mu\nu}\cdot\vec{W}_{\mu\nu} - \frac{1}{4}Y^{\mu\nu}Y_{\mu\nu}$$

- $W_i^{\mu\nu} = \partial^\mu W_i^\nu - \partial^\nu W_i^\mu + g_2\,\varepsilon_{ijk} W_j^\mu W_k^\nu$
- $Y^{\mu\nu} = \partial^\mu Y^\nu - \partial^\nu Y^\mu$

- SOME INTERACTIONS PRESENT:

$$\mathcal{L}_{INT} = g_1 J_Y^\mu Y_\mu + g_2 \vec{J}^\mu \cdot \vec{W}_\mu$$

- $$J_Y^\mu = \frac{1}{6} (\bar{u}\ \bar{d})_L \gamma^\mu \begin{pmatrix} u \\ d \end{pmatrix}_L + \frac{2}{3} \bar{u}_R \gamma^\mu u_R - \frac{1}{3} \bar{d}_R \gamma^\mu d_R - \frac{1}{2} (\bar{\nu}_e\ \bar{e})_L \gamma^\mu \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L - \bar{e}_R \gamma^\mu e_R$$

- $$J_i^\mu = (\bar{u}\ \bar{d})_L \gamma^\mu \frac{\tau_i}{2} \begin{pmatrix} u \\ d \end{pmatrix}_L - (\bar{\nu}_e\ \bar{e})_L \gamma^\mu \frac{\tau_i}{2} \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

- SELFINTERACTIONS
- GAUGE - GAUGE INTERACTIONS

MASS OF (MASSIVE) FERMIONS

- PROPOSAL 1 : TYPICAL ~~DIRAC~~ MASS :

$$\mathcal{L} = -m\bar{\psi}\psi = -m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right)$$

UNACCEPTABLE !

ψ_L : $SU(2)_L$ DOUBLET

ψ_R : $SU(2)_L$ SINGLET

- PROPOSAL$_2$ (THE PROPOSAL): LATENT SYMMETRY

$\Downarrow$ MASSIVE GAUGE FIELDS

CAUTION: ONE MASSLESS PHOTON NEEDED

$\Downarrow$

$$\boxed{SU(2)_L \times U(1)_Y \longrightarrow U(1)_{em}}$$

4 MASSLESS $(W_1^\mu, W_2^\mu, W_3^\mu, Y^\mu)$ $\rightarrow$ 3 MASSIVE
1 MASSLESS (γ)

PHOTON : A_μ : COMBINATION OF W_3^μ AND Y^μ

NEUTRALS

NEUTRAL BOSON : Z_μ : ORTHOGONAL TO A_μ

MASSIVE

WEINBERG ANGLE:

GOOD COMBINATIONS:

- $A_\mu = \sin\theta_W \, W_{\mu 3} + \cos\theta_W \, Y_\mu$
- $Z_\mu = \cos\theta_W \, W_{\mu 3} - \sin\theta_W \, Y_\mu$

θ_W : MIXING ANGLE (WEINBERG ANGLE)

CHARGED FIELDS:

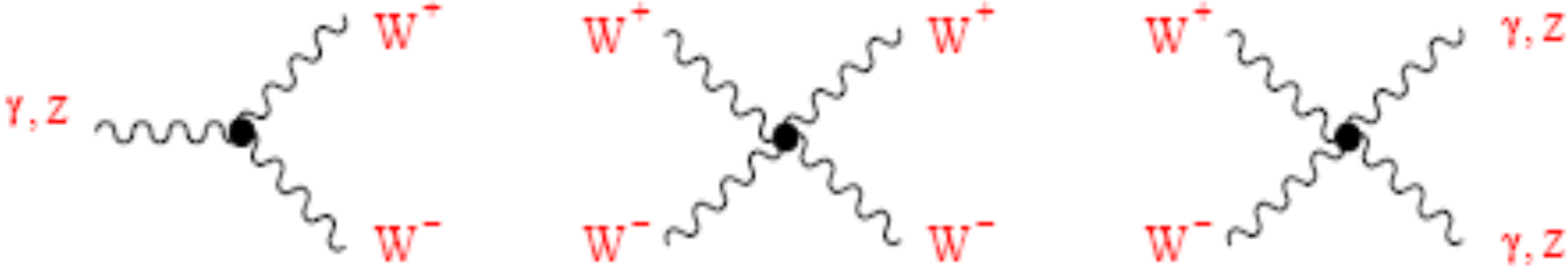
$$W^\mu_\pm = \frac{1}{\sqrt{2}} \left(W^\mu_1 \mp i W^\mu_2 \right)$$

θ_W : MIXING ANGLE $\Rightarrow$

$$\mathcal{L}_G = -\frac{1}{4}\vec{W}^{\mu\nu}\cdot\vec{W}_{\mu\nu} - \frac{1}{4}Y^{\mu\nu}Y_{\mu\nu}$$

- $W_i^{\mu\nu} = \partial^\mu W_i^\nu - \partial^\nu W_i^\mu + g_2\,\varepsilon_{ijk}W_j^\mu W_k^\nu$
- $Y^{\mu\nu} = \partial^\mu Y^\nu - \partial^\nu Y^\mu$

$\Downarrow$



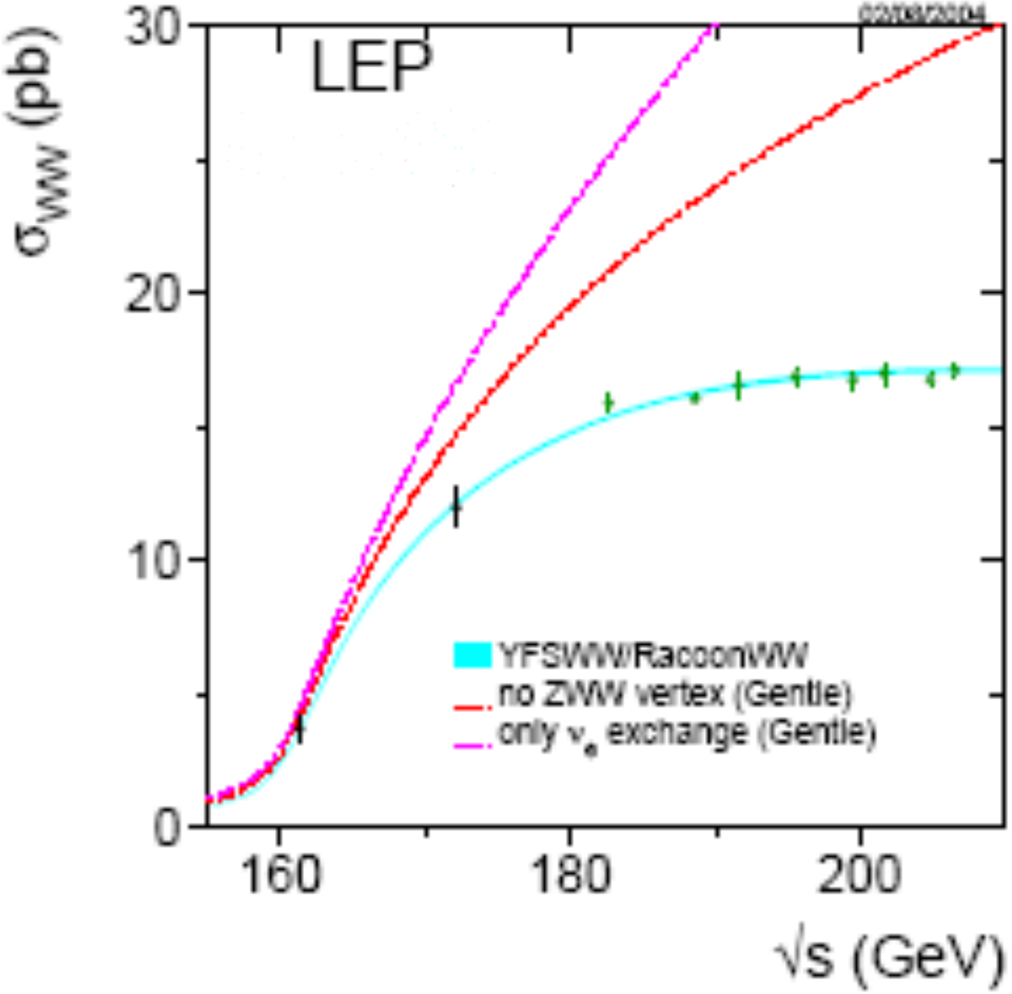
$$\mathcal{L}_3 = -ie\cot\theta_W\left\{\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right)W^\dagger_\mu Z_\nu - \left(\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}\right)W_\mu Z_\nu + W_\mu W^\dagger_\nu\left(\partial^\mu Z^\nu - \partial^\nu Z^\mu\right)\right\}$$

$$-\, ie\left\{\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right)W^\dagger_\mu A_\nu - \left(\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}\right)W_\mu A_\nu + W_\mu W^\dagger_\nu\left(\partial^\mu A^\nu - \partial^\nu A^\mu\right)\right\};$$

$$\mathcal{L}_4 = -\frac{e^2}{2\sin^2\theta_W}\left\{\left(W^\dagger_\mu W^\mu\right)^2 - W^\dagger_\mu W^{\mu\dagger} W_\nu W^\nu\right\} - e^2\cot^2\theta_W\left\{W^\dagger_\mu W^\mu Z_\nu Z^\nu - W^\dagger_\mu Z^\mu W_\nu Z^\nu\right\}$$

$$-\, e^2\cot\theta_W\left\{2W^\dagger_\mu W^\mu Z_\nu A^\nu - W^\dagger_\mu Z^\mu W_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu Z^\nu\right\}$$

$$-\, e^2\left\{W^\dagger_\mu W^\mu A_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu A^\nu\right\}.$$



LEP
σ_{WW} (pb)
$\sqrt{s}$ (GeV)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only ν_e exchange (Gentle)

$$\mathcal{L}_{INT} = \frac{1}{2\sqrt{2}} \left[J_-^{\mu} W_{\mu +} + J_+^{\mu} W_{\mu -} \right]$$

$$+ \left[(g_2 \cos\theta_W + g_1 \sin\theta_W) J_3 - g_1 \sin\theta_W J^{\mu}_{em} \right] Z_\mu$$

$$\underbrace{+ \left[(g_1 \cos\theta_W J^{\mu}_{em} + (g_1 \cos\theta_W - g_2 \sin\theta_W) J_3^{\mu}) \right] A_\mu}_{\mathcal{L}^{em}_{INT}}$$

$$\underline{J_\pm^{\mu} = 2 \left(J_1^{\mu} \mp i J_2^{\mu} \right)}$$

$$\underline{J^{\mu}_{em} = J_3^{\mu} + J_Y^{\mu}}$$

$$\mathcal{L}^{em}_{INT} = e\, J^{\mu}_{em} A_{\mu}$$

$$\downarrow$$

$$\boxed{e = g_1 \cos\theta_W = g_2 \sin\theta_W}$$

$$\boxed{\begin{aligned}\mathcal{L}_{INT} &= \frac{e}{2\sqrt{2}\sin\theta_W}\left(W^{\mu}_{+} J_{\mu -} + W^{\mu}_{-} J_{\mu +}\right) \\ &+ \frac{e}{2\cos\theta_W \sin\theta_W} Z^{\mu} J_{\mu NC} + e A^{\mu} J_{\mu\, em}\end{aligned}}$$

$$J^{\mu}_{NC} = 2\left(J^{\mu}_{3} - \sin^2\theta_W J^{\mu}_{em}\right)$$

$\mathcal{L}_{INT}$ →

- ELECTROMAGNETIC INTERACTIONS

$$\left[e \right]$$

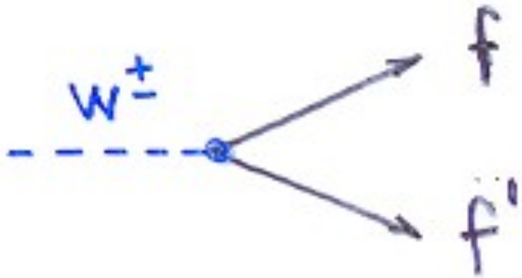
- CHARGED WEAK INTERACTIONS

$$\left[\frac{e}{2\sqrt{2}\sin\theta_W} \right]$$

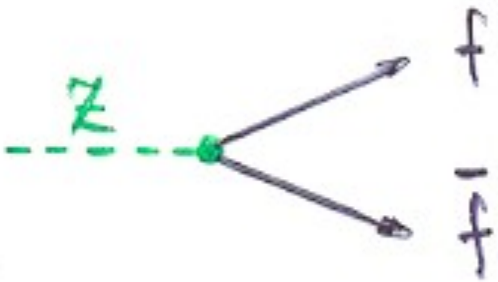
- NEUTRAL WEAK INTERACTIONS

$$\left[\frac{e}{2\cos\theta_W \sin\theta_W} \right]$$

NEUTRAL AND CHARGED PROCESSES (FERMIONS)

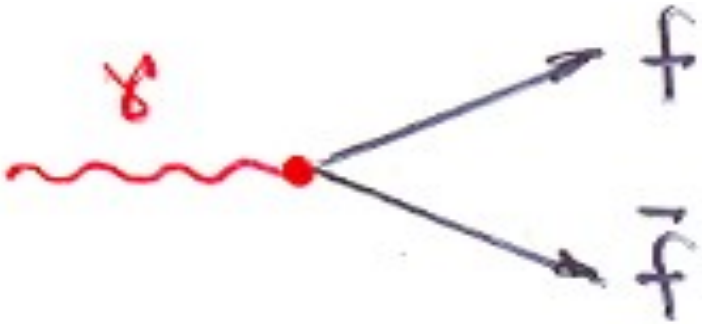


$$= i\, e\, \gamma_\mu (1-\gamma_5)\, \frac{1}{2\sqrt{2}\,\sin\theta_W}$$



$$= i\, e\, \gamma_\mu \,(v_f - a_f \gamma_5)$$

- $v_f = \dfrac{I_3^f - 2Q_f \sin^2\theta_W}{2\sin\theta_W \cos\theta_W}$
- $a_f = \dfrac{I_3^f}{2\sin\theta_W \cos\theta_W}$



$$= -i\, e\, Q_f\, \gamma_\mu$$

$$= -\, i\,\frac{g_{\mu\nu}}{k^2}$$

(F. G.)

$$= i\,\frac{-g_{\mu\nu} + k_\mu k_\nu / M^2_{W/Z}}{k^2 - M^2_{W/Z}}$$

↓

CROSS SECTIONS, RATES . . .

MASSES : HIGGS MECHANISM

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{e.m.}$$

LATENT

$$\Downarrow$$

TO INTRODUCE SCALAR FIELDS

(SU(2)$_L$ × U(1)$_Y$ NON TRIVIAL)

- SIMPLEST ELECTION: SU(2)$_L$ DOUBLET

$$\Phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$$

- ϕ^0, ϕ^- COMPLEX -

$$Y_\Phi = -\frac{1}{2}$$

- LATENT SYMMETRY $\Rightarrow$

$$V(\Phi^\dagger \Phi) = \lambda\left(\Phi^\dagger \Phi - v^2\right)^2$$

$$\Downarrow$$

$$\langle 0 | \Phi | 0 \rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$$

IT GUARANTEES $U(1)_{em}$

TEST OF COHERENCE OF LATENT SYMMETRY

$SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$

WITH $\langle 0|\Phi|0\rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$

i) $SU(2)_L$:

$$G_1 \langle 0|\Phi|0\rangle = \frac{\tau_1}{2}\langle 0|\Phi|0\rangle = \frac{1}{2}\begin{pmatrix} 0 \\ v \end{pmatrix} \neq 0$$

$$G_2 \langle 0|\Phi|0\rangle = \frac{\tau_2}{2}\langle 0|\Phi|0\rangle = \frac{1}{2}\begin{pmatrix} 0 \\ i v \end{pmatrix} \neq 0$$

$$G_3 \langle 0|\Phi|0\rangle = \frac{\tau_3}{2}\langle 0|\Phi|0\rangle = \frac{1}{2}\begin{pmatrix} v \\ 0 \end{pmatrix} \neq 0$$

ii) $U(1)_Y$:

$$G_Y \langle 0|\Phi|0\rangle = -\frac{1}{2}\begin{pmatrix} v \\ 0 \end{pmatrix} \neq 0$$

NONE OF THE GENERATORS OF $SU(2)_L \times U(1)_Y$ ANNIHILATES THE VACUUM

BUT: $(Q \equiv Q_{em})$

$$Q \langle 0 | \Phi | 0 \rangle = (I_3 + Y) \langle 0 | \Phi | 0 \rangle = 0$$

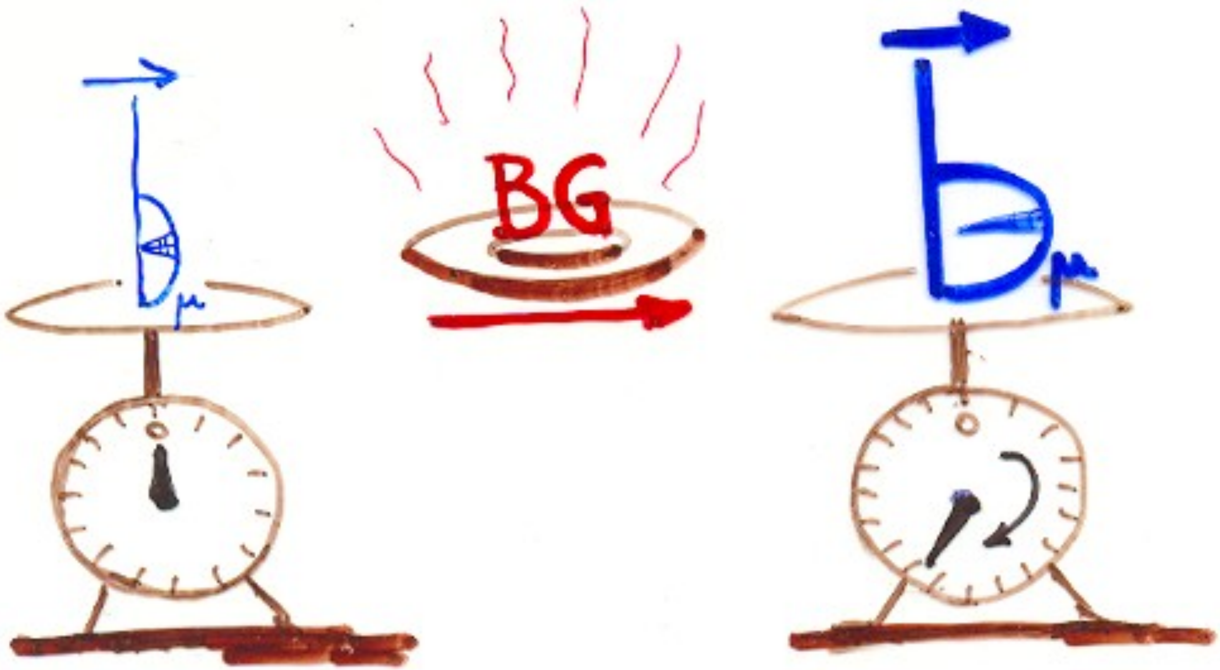
$\Downarrow$

Q LEAVES THE VACUUM INVARIANT

$\Downarrow$

$U(1)_{em}$ REALIZED À LA WIGNER-WEYL $(m_\gamma = 0)$

THE GOLDSTONE BOSONS DEGREES OF FREEDOM ARE TRANSFERED TO CREATE THE LONGITUDINAL POLARIZATION OF (MASSIVE) GAUGE BOSONS.



$$\mathcal{L}_H = -(D_\mu \Phi)^\dagger D^\mu \Phi - V(\Phi^\dagger \Phi)$$

$$D_\mu \Phi = \left(\partial_\mu + i\frac{g_1}{2} Y_\mu - i g_2 \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu\right) \Phi$$

$$\Phi = H + v$$

SHIFT TO: $H(x)$ $\langle 0 | H(x) | 0 \rangle = 0$

$$m_H^2 = 2\lambda v^2$$

?

$$V(\Phi^\dagger \Phi) = \lambda\left(\Phi^\dagger \Phi - v^2\right)^2$$

$\Downarrow$ (FROM THE COVARIANT DERIVATIVES)

$$\mathcal{L}_{G-H} = \left[\left(g_2 \frac{\vec{\tau}}{2}\cdot\vec{W}^\mu - g_1 \frac{1}{2} Y^\mu\right)\Phi\right]^\dagger \cdot \left(g_2 \frac{\vec{\tau}}{2}\cdot\vec{W}^\mu - g_1 \frac{1}{2} Y^\mu\right)\Phi$$

$\Phi = H + v$

$\downarrow$

$$\mathcal{L}_{GM} = -\frac{1}{2}\left(g_2 v\right)^2 W^\mu_+ W_{\mu -} - \frac{1}{2}\left(\frac{g_2 v}{\cos\theta_W}\right)^2 Z^\mu Z_\mu$$

$$M_W^2 = \frac{g_2^2 v^2}{4}$$

$$M_Z^2 = \frac{g_2^2 v^2}{4\cos^2\theta_W} = \frac{M_W^2}{\cos^2\theta_W}$$

THREE MASSIVE GAUGE BOSONS

- $\sin^2\theta_W = 1 - \dfrac{M_W^2}{M_Z^2}$

- $\sin^2\theta_W = 0.2231$ (ON SHELL)

• LOW ENERGY W.I. PHENOMENOLOGY: * FERMI O.K. !

MATRIX ELEMENTS

$q^2 \ll M_W$ NEEDS $\dfrac{g_2^2}{8 M_W^2} \to \dfrac{G_F}{\sqrt{2}}$

μ-LIFETIME $\to$ $G_F = 1.16637\ 10^{-5}\ \mathrm{GeV}^{-2}$

• $v = \dfrac{2 M_W}{g_2} \simeq (\sqrt{2}\, G_F)^{-1/2} \simeq 246\ \mathrm{GeV}$

LEPTON MASSES

VIA YUKAWA TYPE COUPLING: (WITH HIGGS DOUBLET)

$$* \quad \mathcal{L}_Y(x) = \sum_{\ell = e,\mu,\tau} - h_\ell \, \overline{R}_\ell(x) \, \Phi^\dagger(x) \, L_\ell(x) + h.c.$$

FROM THE V.E.V. : $\frac{v}{\sqrt{2}}$ → MASS LIKE COUPLING:

$$\sum_{\ell = e,\mu,\tau} - h_\ell \frac{v}{\sqrt{2}} \, \overline{\psi}_\ell(x) \, \psi_\ell(x)$$

$$* \quad m_\ell = h_\ell \frac{v}{\sqrt{2}} \quad ; \quad \ell = e,\mu,\tau$$

– h_ℓ: NOT FIXED BY ANY PRINCIPLE IN 3!

QUARK MASSES

VIA YUKAWA : TWO POSSIBLE ISOSCALARS

* $\sum_{i,j} h_{ij} \bar{L}_{q_i^\uparrow}(x)\, \Phi(x)\, R_{q_j^\downarrow}(x) + \tilde{h}_{ij} \bar{L}_{q_i^\uparrow}(x)\, \tilde{\Phi}(x)\, R_{q_j^\downarrow}(x) + h.c.$

Y_W: $\left(-\frac{1}{3}\right)$ (1) $\left(-\frac{2}{3}\right)$ $\left(-\frac{1}{3}\right)$ (-1) $\left(\frac{4}{3}\right)$

- $$\tilde{\Phi}(x) = i\tau_2\, \Phi^*(x) = \begin{pmatrix} \Phi^0(x) \\ -\Phi^+(x) \end{pmatrix}^*$$

FROM THE V.E.V. OF $\Phi^0(x)$:

$$* \quad \mathcal{L}_{MASSES}(x) = \bar{q}^{\uparrow}_{L}(x)\, \mathcal{M}\left(\tfrac{2}{3}\right) q^{\uparrow}_{R}(x) + \bar{q}^{\downarrow}_{L}\, \mathcal{M}\left(-\tfrac{1}{3}\right) q^{\downarrow}_{R} + h.c.$$

- $q^{\uparrow}_{L,R}(x) \equiv \frac{1}{2}(1 \mp \gamma_5)\begin{pmatrix} u(x) \\ c(x) \\ t(x) \end{pmatrix}$
- $q^{\downarrow}_{L,R}(x) \equiv \frac{1}{2}(1 \mp \gamma_5)\begin{pmatrix} d(x) \\ s(x) \\ b(x) \end{pmatrix}$

- $\mathcal{M}\left(\frac{2}{3}\right) \equiv \tilde{h}_{ij}\,\frac{v}{\sqrt{2}}$ $\qquad i,j = u,c,t \qquad u,c,t$
- $\mathcal{M}\left(-\frac{1}{3}\right) \equiv h_{ij}\,\frac{v}{\sqrt{2}}$ $\qquad i,j = d,s,b \qquad d,s,b$

(3 x 3 MATRICES)

* $\mathcal{M}(\frac{2}{3})$ AND $\mathcal{M}(-\frac{1}{3})$ CAN BE DIAGONALIZED

- $\mathcal{U}_L(Q)\,\mathcal{M}(Q)\,\mathcal{U}_R(Q) = \hat{M}(Q)$ (DIAGONAL) $\quad (Q = \frac{2}{3}, -\frac{1}{3})$

$$\Downarrow$$

$$\mathcal{L}_{\text{MASSES}}(x) = \bar{\psi}^{\uparrow}_L(x)\,\hat{M}(\tfrac{2}{3})\,\psi^{\uparrow}_R(x) + \bar{\psi}^{\downarrow}_L(x)\,\hat{M}(-\tfrac{1}{3})\,\psi^{\downarrow}_R(x)$$

EIGENSTATES OF MASS

$$\begin{cases} \psi^{\uparrow}_{L,R}(x) = \mathcal{U}_{L,R}(\tfrac{2}{3})\, q^{\uparrow}_{L,R}(x) \\ \psi^{\downarrow}_{L,R}(x) = \mathcal{U}_{L,R}(-\tfrac{1}{3})\, q^{\downarrow}_{L,R}(x) \end{cases}$$

$\Downarrow$ <u>FLAVOR MIXING</u> (IN THE CHARGED CURRENT SECTOR)

$$\bar{q}^{\uparrow}_{L}(x)\,\gamma^{\mu}\,q^{\downarrow}_{L}(x)\,W^{+}_{\mu}(x) + \text{h.c.}$$

$\Big\downarrow$ AFTER "ROTATION"

- $$\bar{\psi}^{\uparrow}_{L}(x)\,\gamma^{\mu}\,\underbrace{U_{L}\left(\tfrac{2}{3}\right)U^{+}_{L}\left(-\tfrac{1}{3}\right)}\,\psi^{\downarrow}_{L}(x)\,W^{+}_{\mu}(x) + \text{h.c.}$$

$*\quad V \equiv U_{L}\left(\tfrac{2}{3}\right)U^{+}_{L}\left(-\tfrac{1}{3}\right)\quad *$

* CABIBBO - KOBAYASHI - MASKAWA MATRIX *

$$* \quad V \equiv U_L\left(\tfrac{2}{3}\right) U_L^{\dagger}\left(-\tfrac{1}{3}\right) \quad *$$

- UNITARY MATRIX
- ACTS OF FLAVOR DEGREES OF FREEDOM OF CHARGE $-\frac{1}{3}$ QUARKS $(\downarrow)$
- GENERALIZES CABIBBO MATRIX

* CABIBBO - KOBAYASHI - MASKAWA MATRIX *

$$V_q = \begin{pmatrix} u_{ud} & u_{us} & u_{ub} \\ u_{cd} & u_{cs} & u_{cb} \\ u_{td} & u_{ts} & u_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \sin\theta_c$$

$$\Uparrow$$

— PHENOMENOLOGY —

W INTERACTION TO FERMIONS:

$$\mathcal{L} = -\frac{g_2}{2\sqrt{2}}\left(J_W^{\mu} W_{\mu}^{-} + J_W^{\mu +} W_{\mu}^{+}\right)$$

WITH

$$J_W^{\mu +} = (\bar{\nu}_e \bar{\nu}_\mu \bar{\nu}_\tau)\, \gamma^\mu (1-\gamma^5)\, V_\ell \begin{pmatrix} e^- \\ \mu^- \\ \tau^- \end{pmatrix}$$

$$+ (\bar{u}\, \bar{c}\, \bar{t})\, \gamma^\mu (1-\gamma^5)\, V_q \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

— PHENOMENOLOGY —

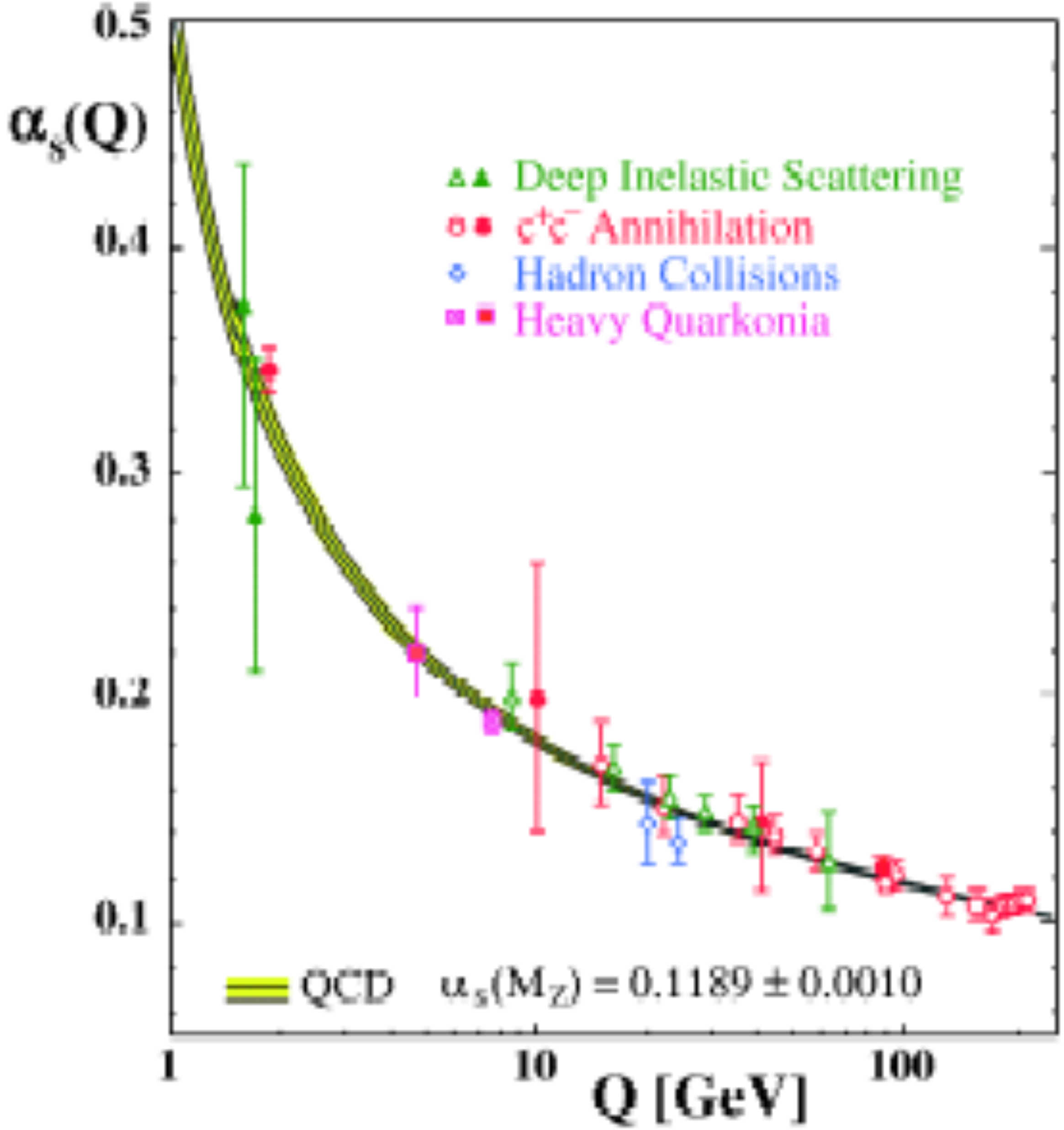
QCD

$$\mathcal{L}_{QCD} = -\frac{1}{4}\sum_{A=1}^{8} F^{A}_{\mu\nu} F^{A\mu\nu} + \sum_{j=1}^{f} \bar{q}_j (i \not{D} - m_j) q_j$$

$$F^{A}_{\mu\nu} = \partial_\mu g^{A}_\nu - \partial_\nu g^{A}_\mu - g_s C^{ABC} g^{B}_\mu g^{C}_\nu$$

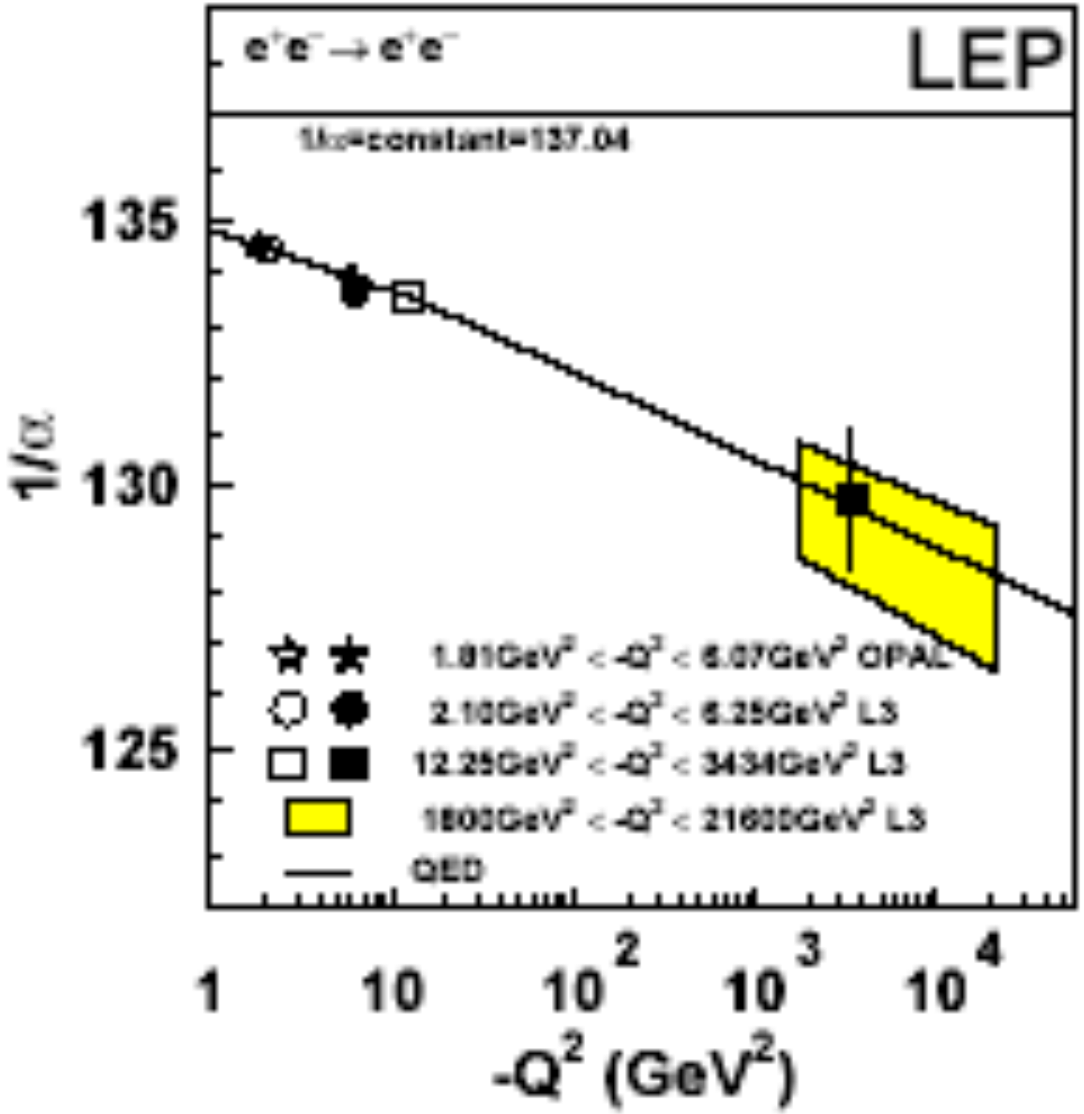
$$D_\mu = \partial_\mu + i g_s \sum_{A=1}^{8} t^{A} g^{A}_\mu$$

COUPLING $\quad \alpha_s = \dfrac{g_s^2}{4\pi}$



ASYMPTOTIC FREEDOM

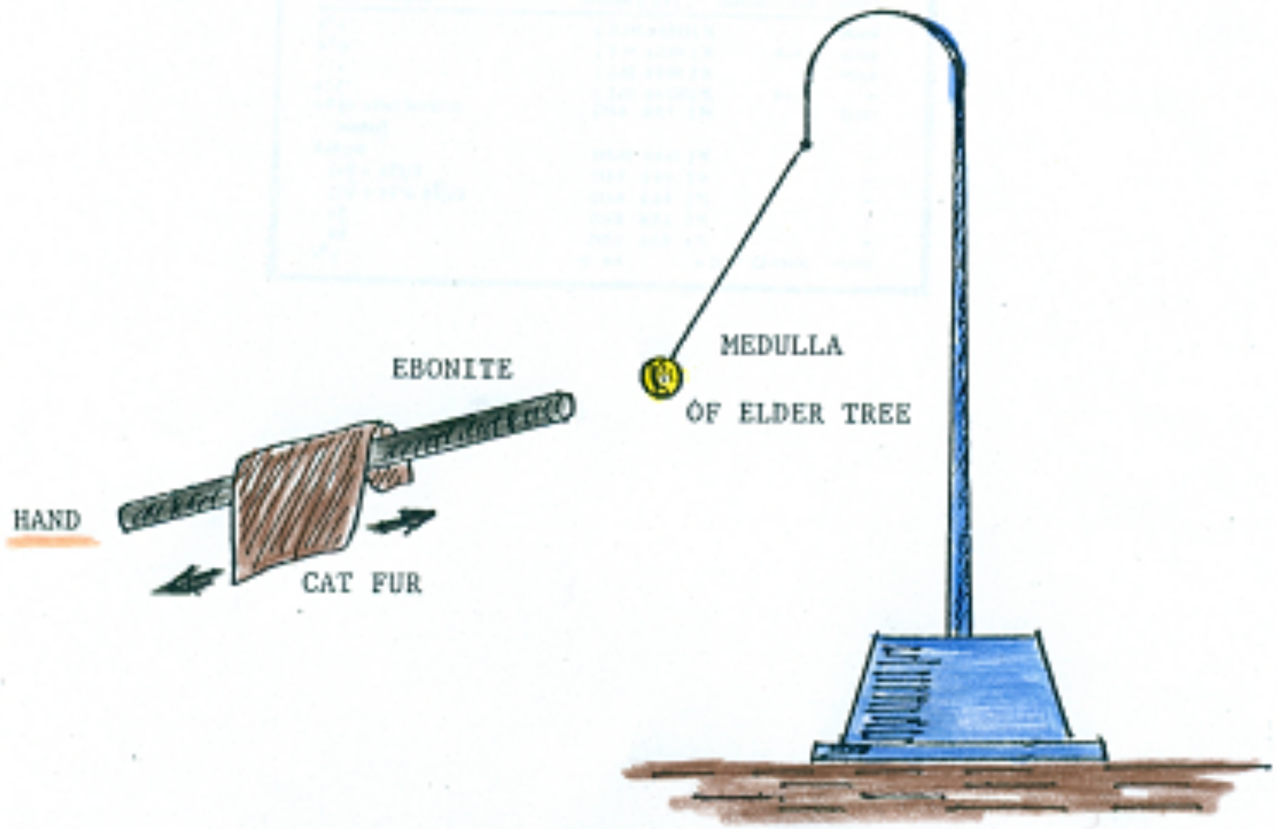
α e.m.



e⁺e⁻ → e⁺e⁻
LEP
1/α=constant=137.04
135
130
125
1/α
1.81GeV² < -Q² < 6.07GeV² OPAL
2.10GeV² < -Q² < 6.25GeV² L3
12.25GeV² < -Q² < 3434GeV² L3
1800GeV² < -Q² < 21600GeV² L3
QED
1
10
10²
10³
10⁴
-Q² (GeV²)

- PREDICTIVE POWER OF 3! AND SUCCESSES

* FIRST EXPERIMENTAL TEST OF 3!



A, B, C, . . . , Z COLLABORATION

i) ELECTROMAGNETIC INTERACTION ≡ QED

ii) WEAK INTERACTIONS OF CHARGED CURRENTS (FERMI)

iii) NEUTRAL WEAK CURRENTS ($Z^0 \Rightarrow$ CANCELLATIONS)

iv) ABSENCE OF FLAVOR CHANGING NEUTRAL CURRENTS (GIM)

v) ELIMINATES ANOMALIES ($\mathrm{Tr}\, Q = 0$)

(SEPARATELY FOR EACH GENERATION (~~$\ell(1+0) + c(3)$~~

$$\underbrace{(-1+0)}_{\text{LEPTONS}} + \underbrace{(3)}_{\text{COLOR}} \times \underbrace{\left(\frac{2}{3} + \left(-\frac{1}{3}\right)\right)}_{\text{QUARKS}} = 0$$

[NEW LEPTON $\Rightarrow$ TWO NEW FLAVORS OF QUARKS]

vi) ASYMPTOTIC FREEDOM OF QCD (DIS PERTURBATIVE)

⋮

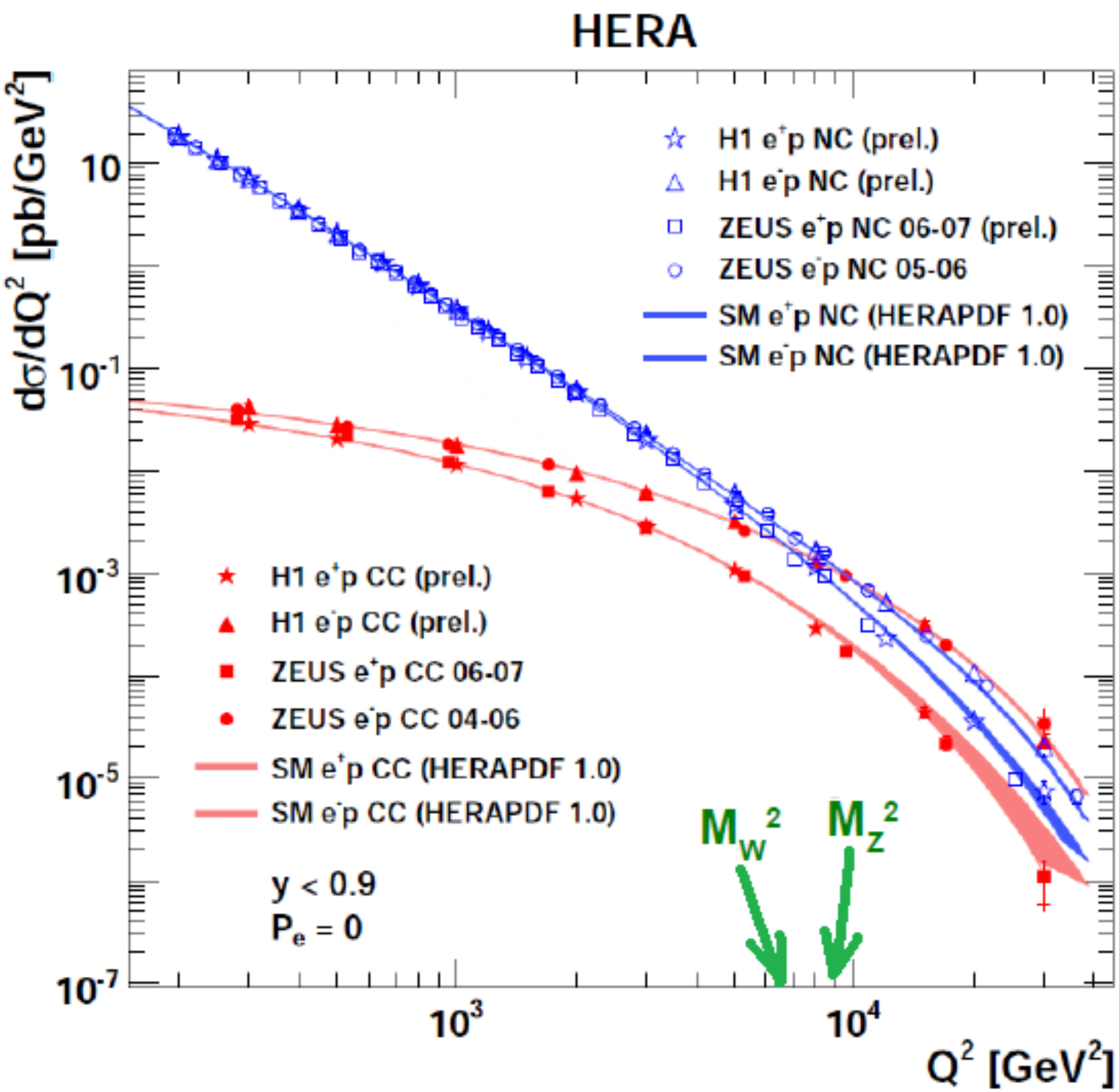
• ELECTROWEAK PHYSICS •

(WITH CONSTRAINTS TO "NEW" PHYSICS)

http://pdg.lbl.gov/2012/reviews/rpp2012-rev-standard-model.pdf

“UNIFICATION” OF E.M AND WEAK FORCES

PHOTON
+ HEAVY W



Unpolarized neutral and charged currents single differential cross section
for combined HERA-I & HERA-II, e-p and e+p data measured by H1 and ZEUS

* A WAY TOWARDS THE HIGGS: • $p + p \to H \to \gamma + \gamma$ •

• ALL 3! IN ACTION

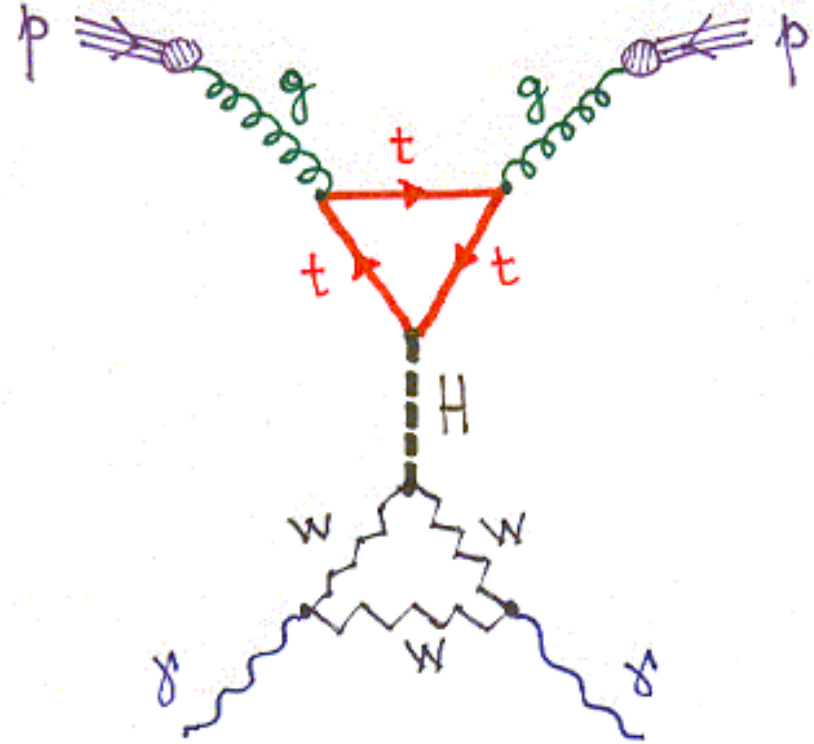
• GLUONS IN THE PROTON

• $\alpha_s(Q^2)$ COUPLING

• HIGGS COUPLING ($\sim m$)

• GAUGE VERTEX $WW\gamma$

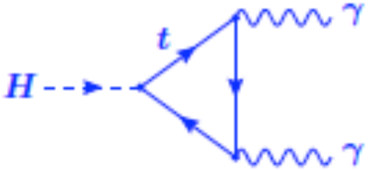
• QUANTUM LOOPS

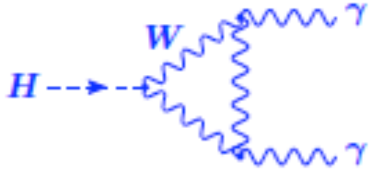


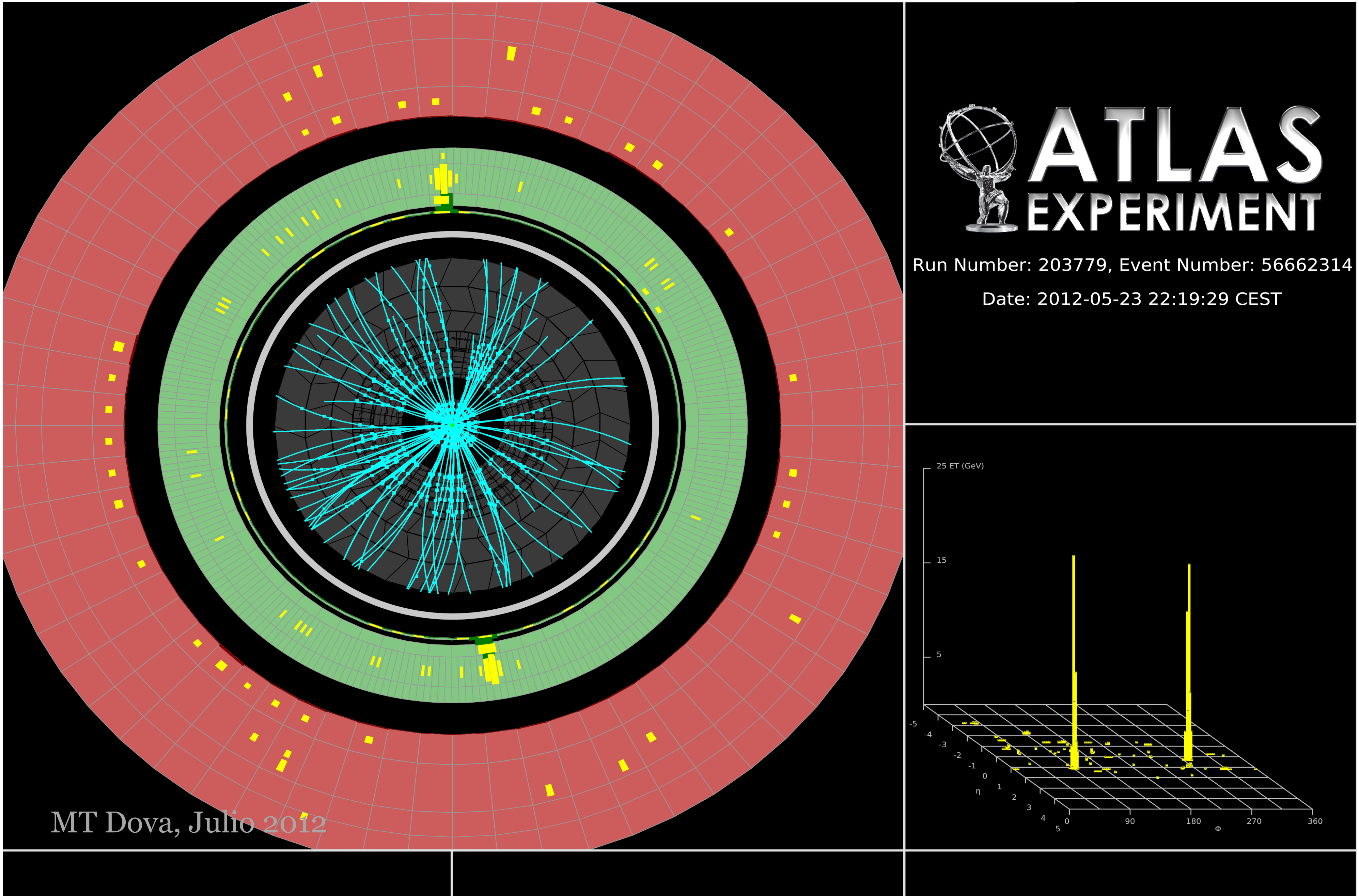
WILCZEK

* IT CAN BE COMPUTED! *

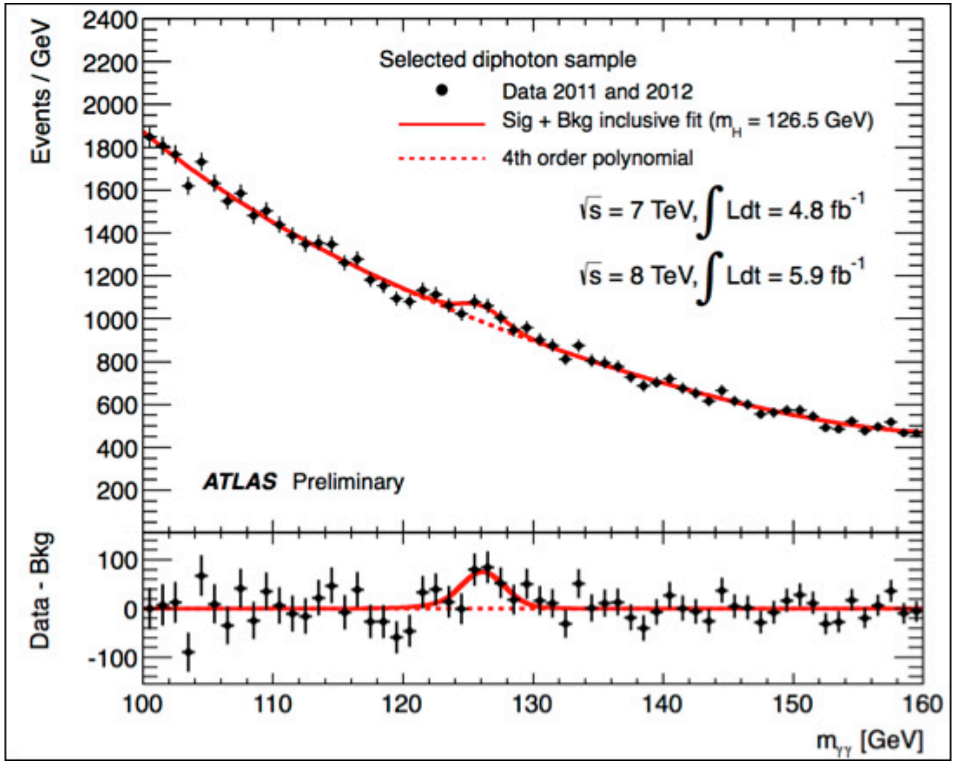
(DO IT!)

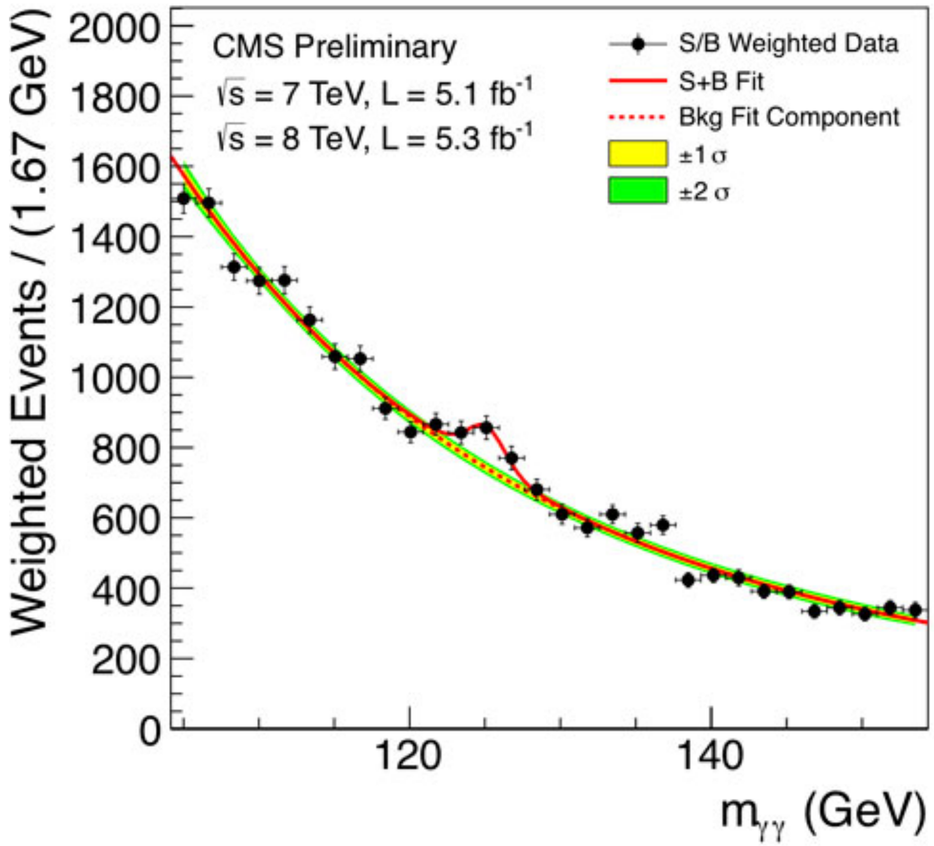

H
t
γ
γ

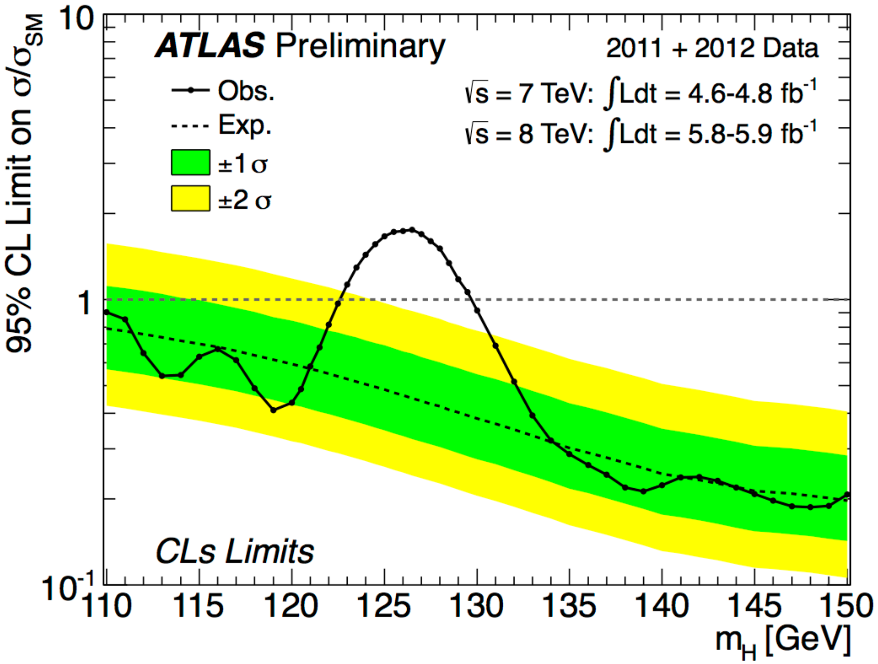

H
W
γ
γ

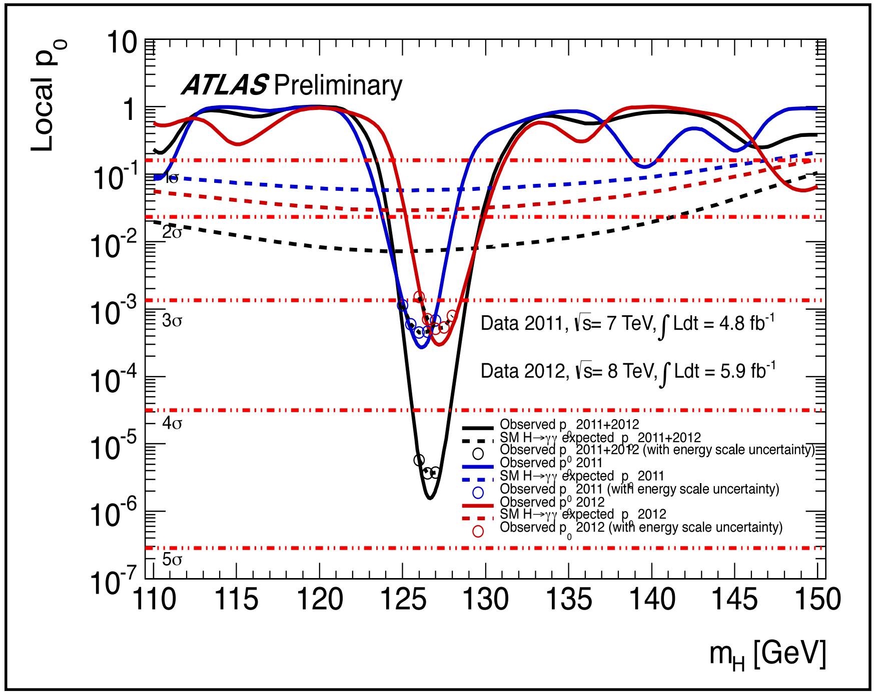

ATLAS
EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST
25 ET (GeV)
15
5
η
Φ
0
90
180
270
360
MT Dova, Julio 2012

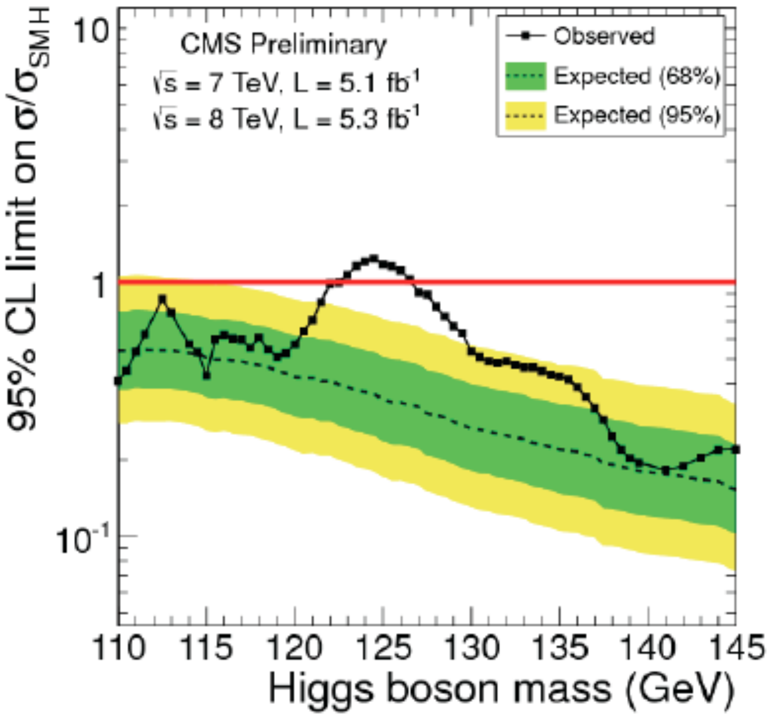
4th JULY 2012

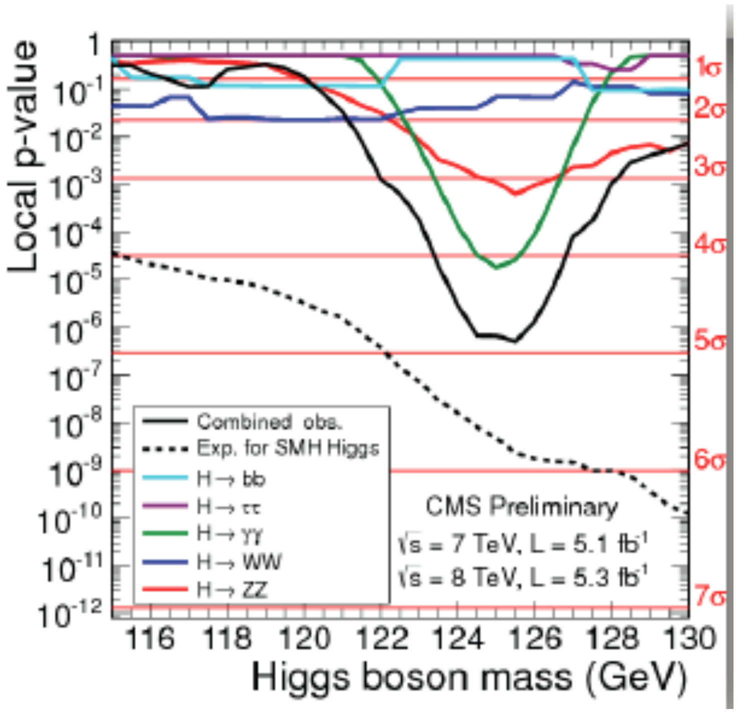


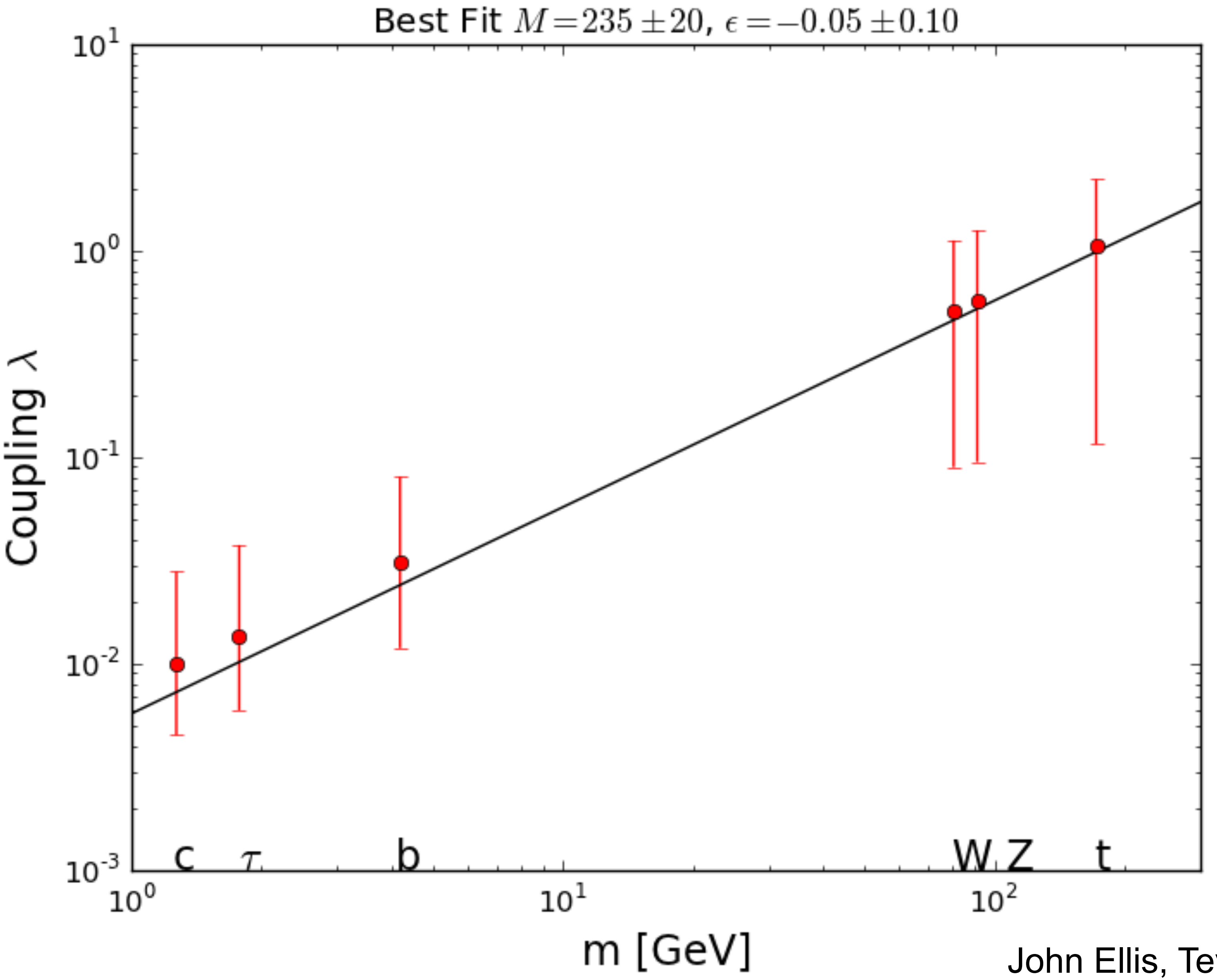



ATLAS Preliminary
2011 + 2012 Data
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
Obs.
Exp.
±1 σ
±2 σ
CLs Limits
95% CL Limit on σ/σSM
mH [GeV]


ATLAS Preliminary
Local p0
Data 2011, √s= 7 TeV, ∫Ldt = 4.8 fb-1
Data 2012, √s= 8 TeV, ∫Ldt = 5.9 fb-1
1σ
2σ
3σ
4σ
5σ
mH [GeV]


CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σSMH
Higgs boson mass (GeV)


Combined obs.
Exp. for SM H Higgs
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
1σ
2σ
3σ
4σ
5σ
6σ
7σ
Local p-value
Higgs boson mass (GeV)



John Ellis, Tevong You

Figure 5: The mass dependence of the h couplings found in our (;M) t. The vertical error bars correspond to the uncertainties shown in Fig. 4. The Standard Model prediction that Higgs couplings should be proportional to the masses of other particles, shown by the diagonal solid line, is completely consistent with the data.

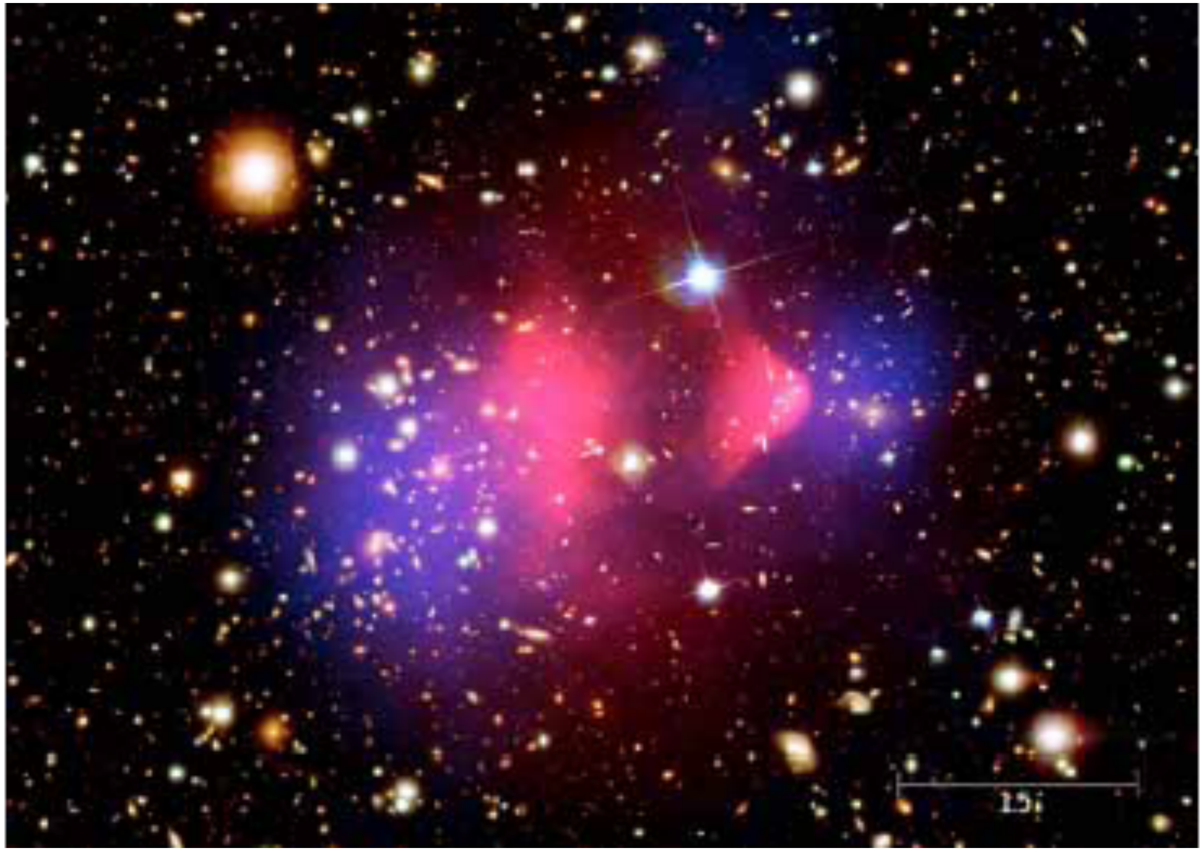
Brout-Englert-Guralnik-Hagen-Higgs-Kibble

IS NOT FINISHED!!!

- GALAXY CLUSTER – GALAXY CLUSTER COLLISION

* HUBBLE + CHANDRA + LENSING *

DATA



– ORDINARY MATTER : ⇒ → X RAYS (CHANDRA)

– DARK MATTER : (ALMOST NO INTERACTION) → LENSING

- DARK MATTER 25%
- DARK ENERGY 70%
- US 5%

* TODAY'S UNIVERSE $\neq$ UNIVERSE OF 2000!

* HARD TO BE ANTHROPIC!

THANKS!

cgarciacanal@fisica.unlp.edu.ar