HUGS 2018
Jefferson Lab, Newport News, VA
May 29- June 15 2018

Fundamental Symmetries - 2

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Los Alamos National Laboratory

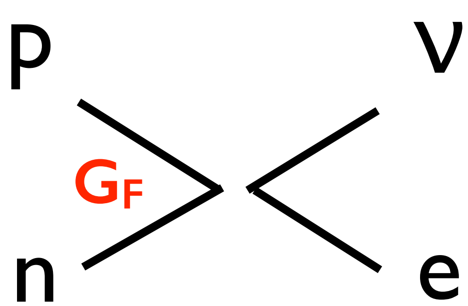
Plan of the lectures

- Review symmetry and symmetry breaking
- Introduce the Standard Model and its symmetries
- Beyond the SM:
  - hints from current discrepancies?
  - effective theory perspective
- Discuss a number of "worked examples"
  - Precision measurements: charged current (beta decays); neutral current (Parity Violating Electron Scattering).
  - Symmetry tests: CP (T) violation and EDMs; Lepton Number violation and neutrino-less double beta decay.

The making of the Standard Model

(theory-centric, simplified perspective)

Fermi, 1934



Current-current, parity conserving

Fermi scale: $\Lambda = G_F^{-1/2} \sim 250$ GeV

Fermi's theory of beta decays ($n \to p\, e\, \bar{\nu}_e$):

Postulate local interaction in terms of "light" degrees of freedom (n,p,e,ν)

Coupling constant $G_F \equiv 1/\Lambda^2$ determined by fitting the "slow" beta decay rates ⇒

point to mass scale $\Lambda >> m_n \sim$ GeV

(Note: this is an effective theory "ante litteram")

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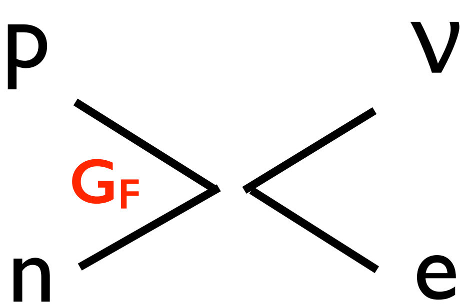

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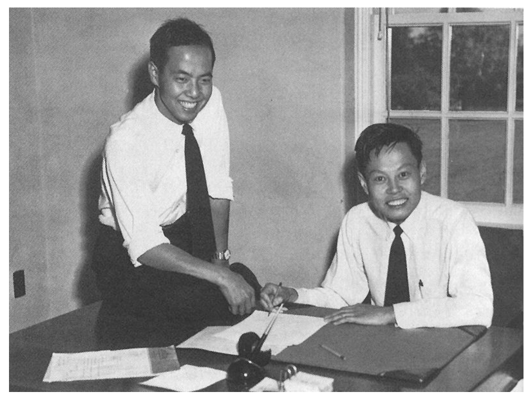

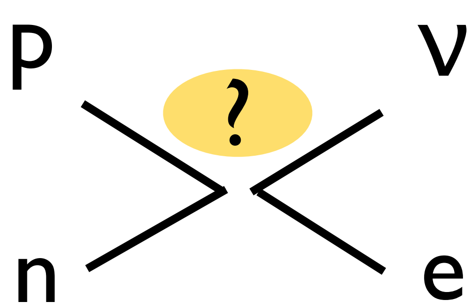

Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Lee and Yang:
use most general Lorentz-invariant interaction

The making of the Standard Model

(theory-centric, simplified perspective)

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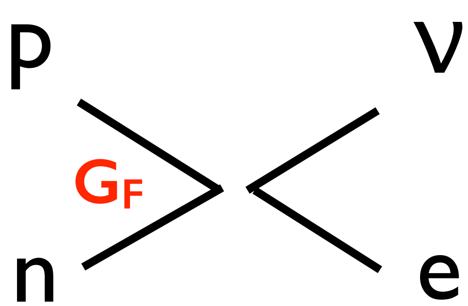

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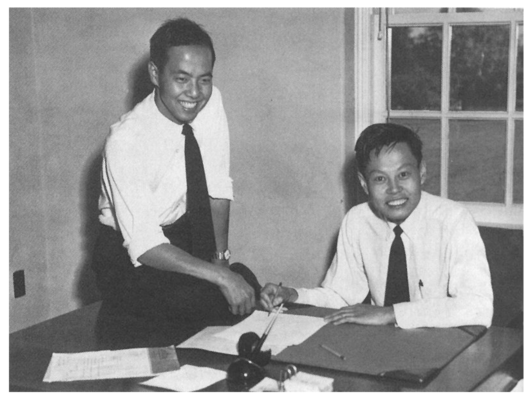

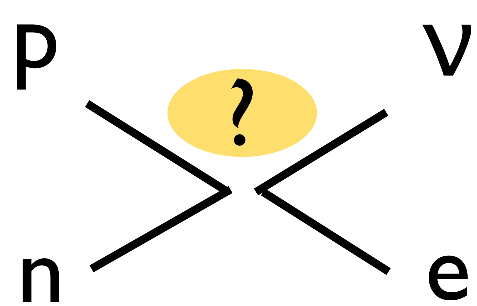

Parity conserving: VV, AA, SS, TT ...

Parity violating: VA, SP, ...

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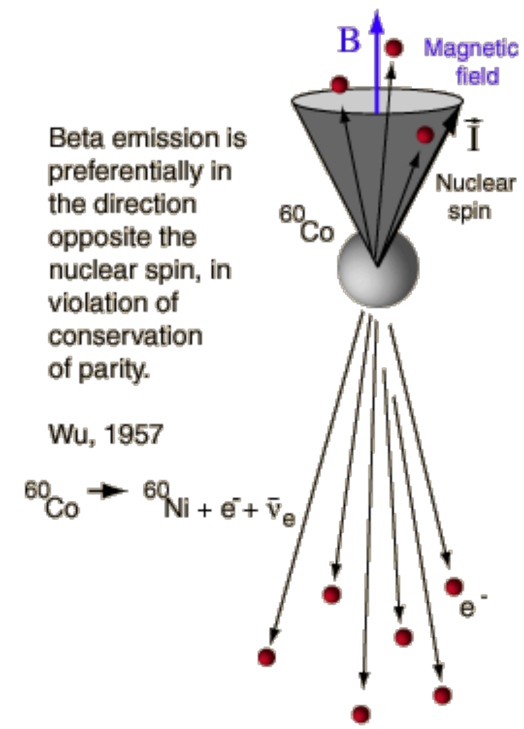

C-S Wu

Experiment:

$d\Gamma \sim A\ \mathbf{J}\cdot\mathbf{p}_e$

parity is violated!
(but could be VA, SP, ...)

The making of the Standard Model

(theory-centric, simplified perspective)

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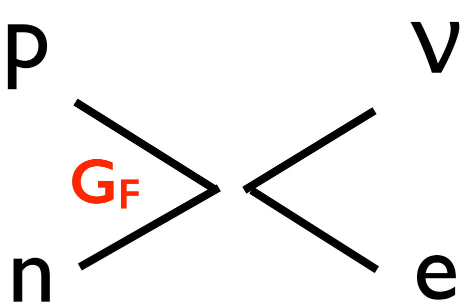

Current-current, parity conserving

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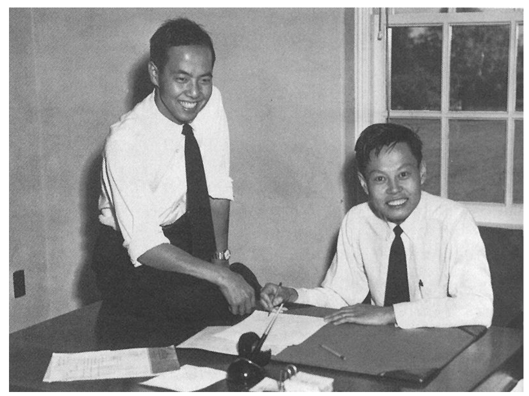

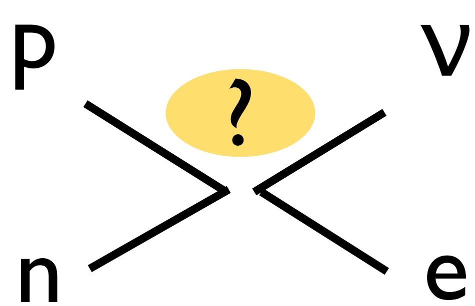

Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Fermi scale:
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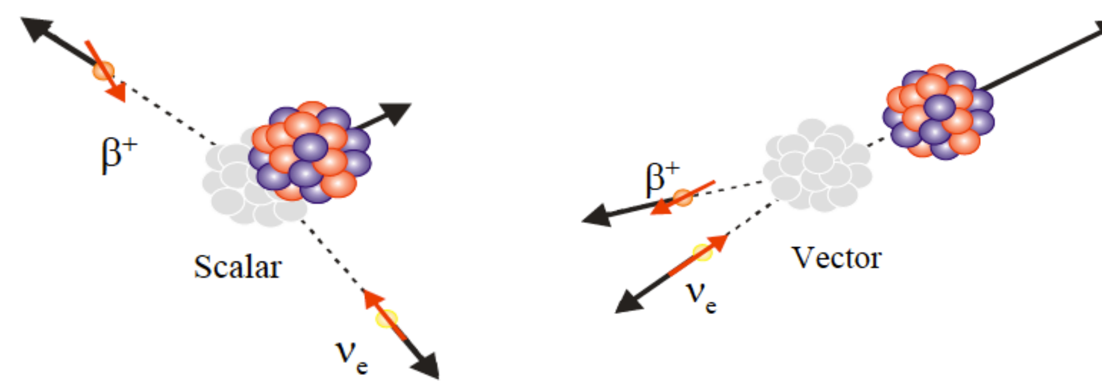
Differential decay distributions depend on operator structure



Model diagnosing!

The making of the Standard Model

(theory-centric, simplified perspective)

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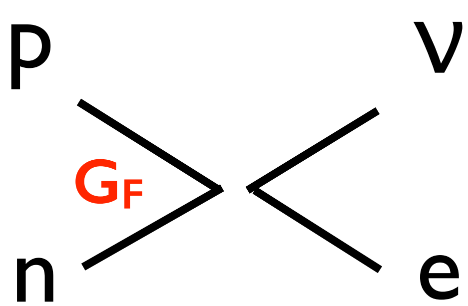

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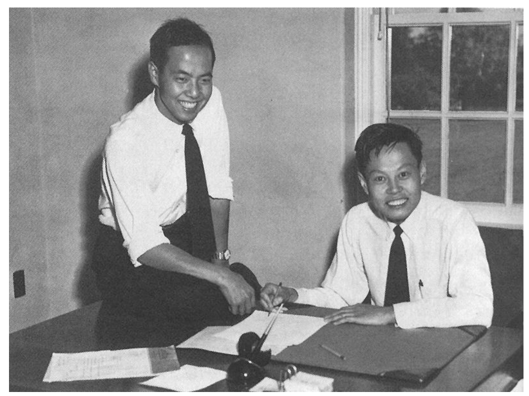

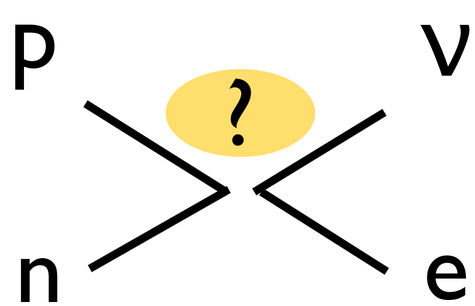

Parity conserving:
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Marshak & Sudarshan,
Feynman & Gell-Mann 1958

It's (V-A)*(V-A) !!

"V-A was the key"
S. Weinberg

The making of the Standard Model

(theory-centric, simplified perspective)

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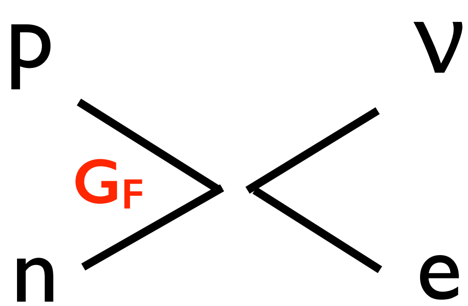

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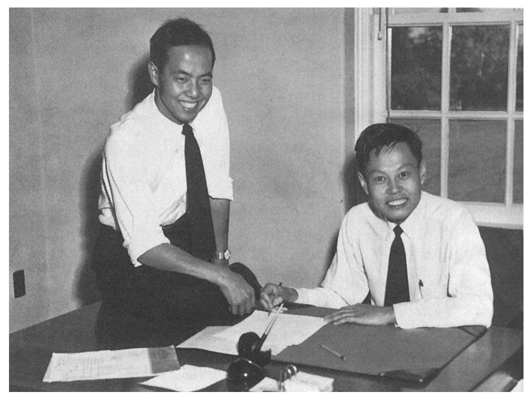

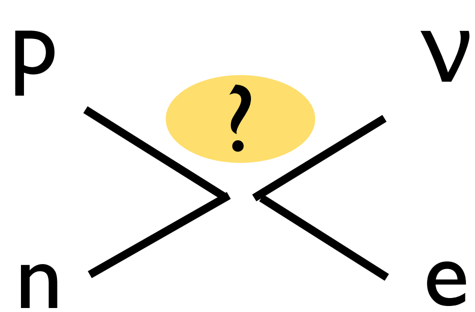

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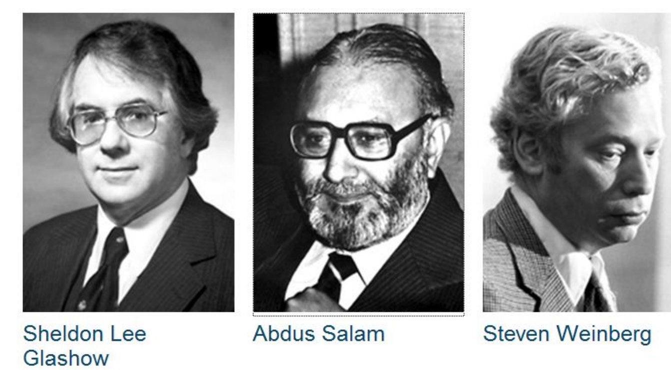
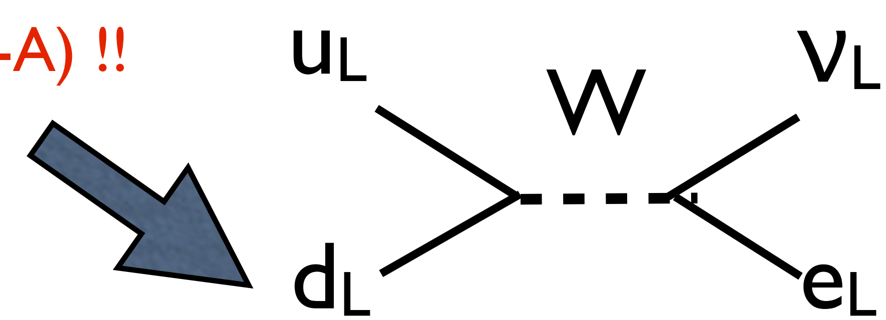
Glashow,
Salam,
Weinberg





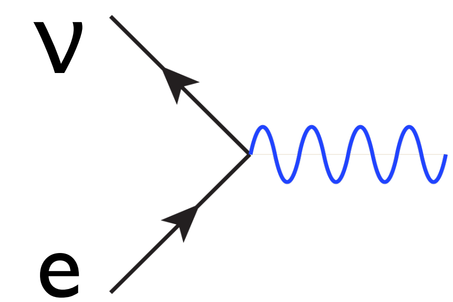
Embed in non-abelian chiral gauge theory, predict neutral currents

The making of the Standard Model

- Features of underlying (gauge) theory emerging from phenomenology

$$J^{\mu,a} = \bar{\psi}\gamma^{\mu}T^{a}\psi$$

1. It involves non-abelian gauge group under which (n,p) [or (u,d)] and (e,ν) transform in same representation



$$\bar{\nu}\ e = (\bar{\nu}, \bar{e}) \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \nu \\ e \end{pmatrix}$$

The making of the Standard Model

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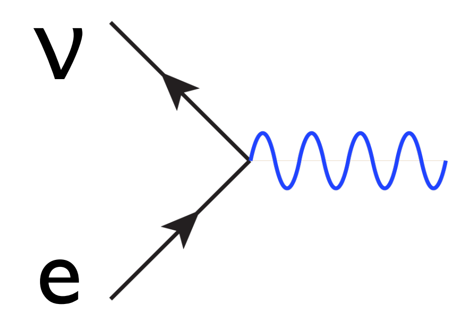


$$\bar{\nu}\ e = (\bar{\nu}, \bar{e}) \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \nu \\ e \end{pmatrix}$$

2. It involves chiral fermions (V-A structure)

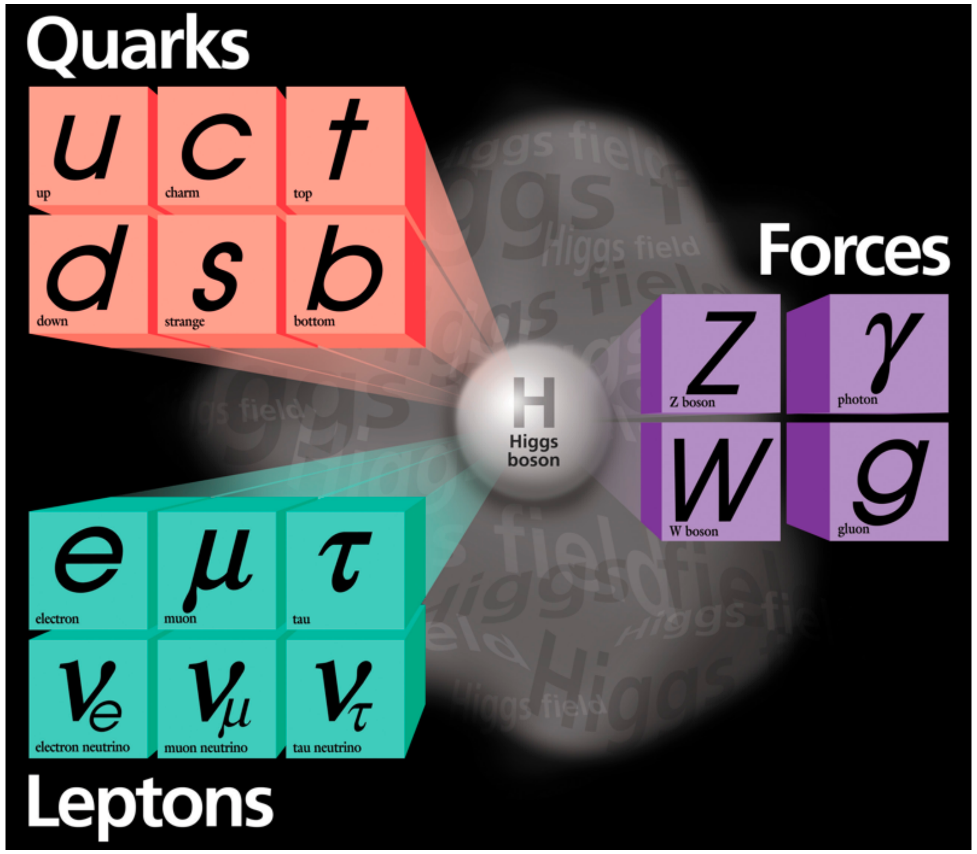
$$\psi_{L,R} = \frac{1 \mp \gamma_5}{2} \psi$$

$\Psi_{L,R}$: chiral fields. For m=0,

Ψ_L : L-handed (h=-1) particles, R-handed anti-particles (h=+1)

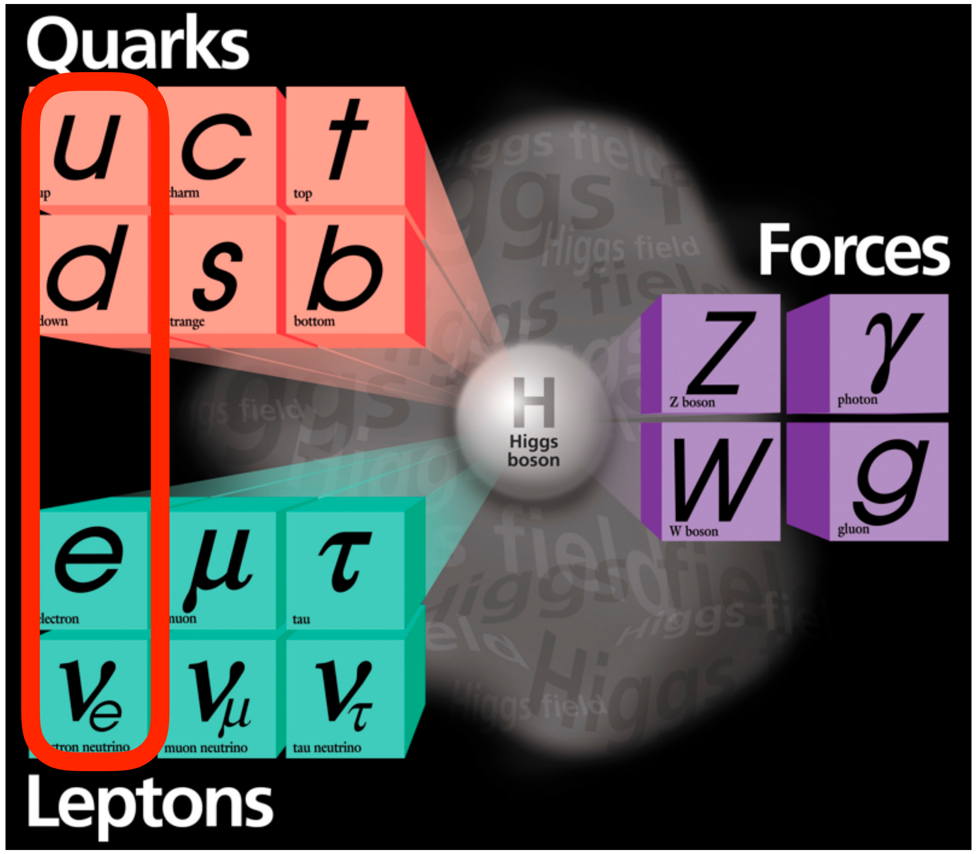
Ψ_R : R-handed (h=+1) particles, L-handed anti-particles (h=-1)

The Standard Model in pictures



The Standard Model in pictures

Spin 1/2:
ordinary matter
+ 2 heavier
generations



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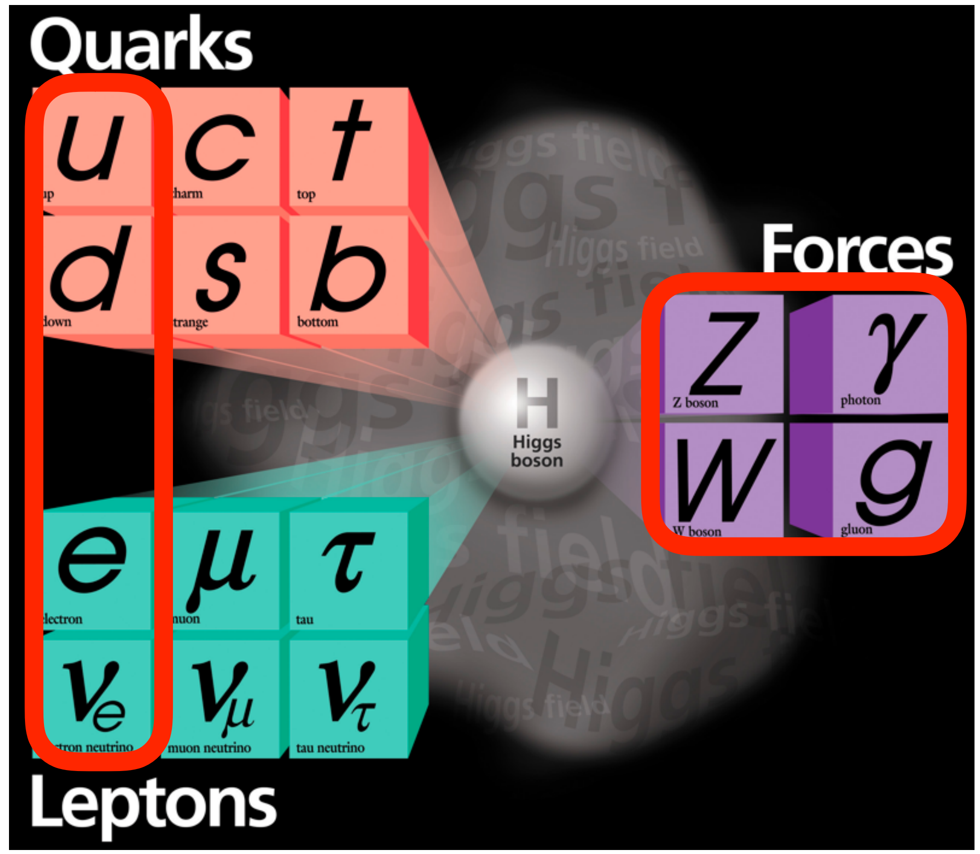
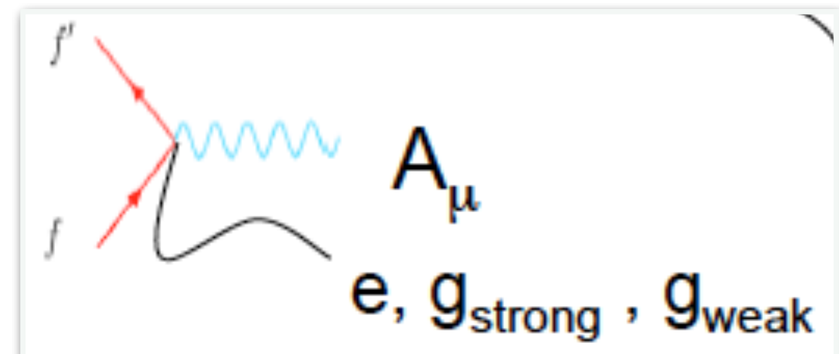


Spin 1: force carriers

Interactions governed by gauge symmetry principle

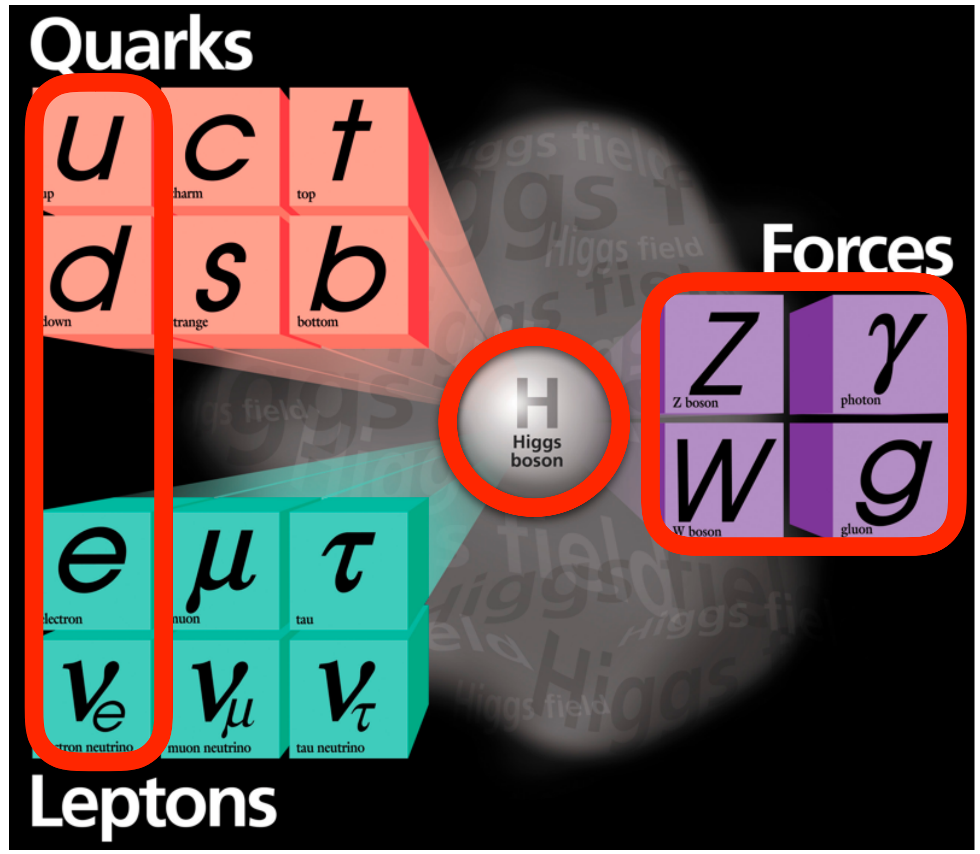
$SU(3)_c \times SU(2)_W \times U(1)_Y$



$$\mathcal{L}_I(x) \sim J_\mu(x)\, A^\mu(x)$$

The Standard Model in pictures

Spin 0: Higgs boson



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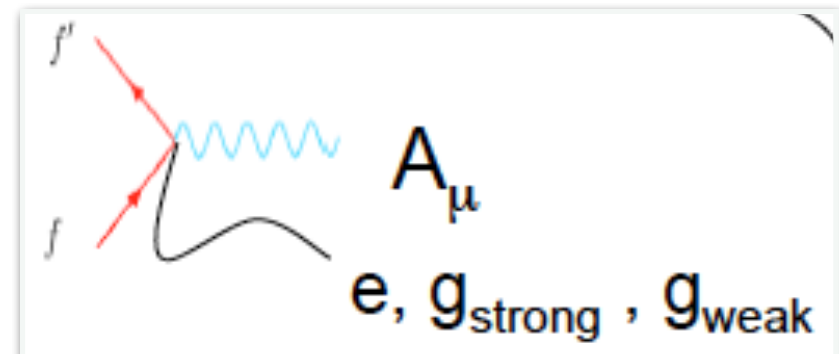

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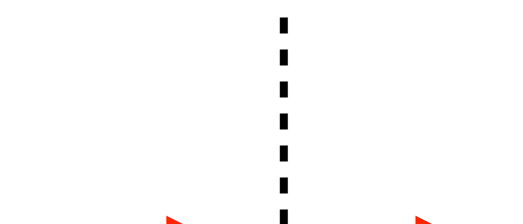

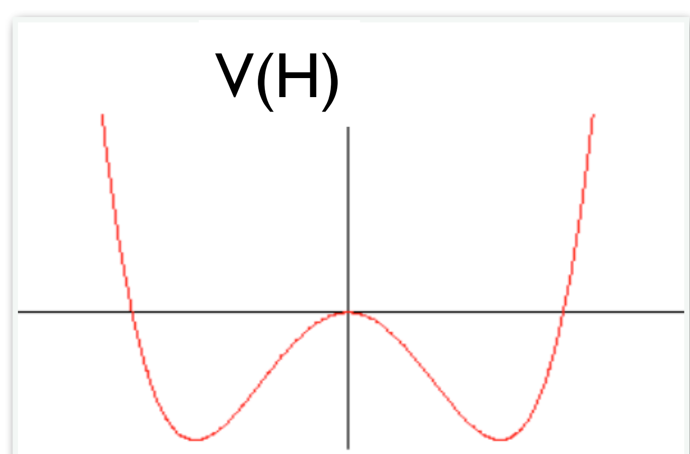

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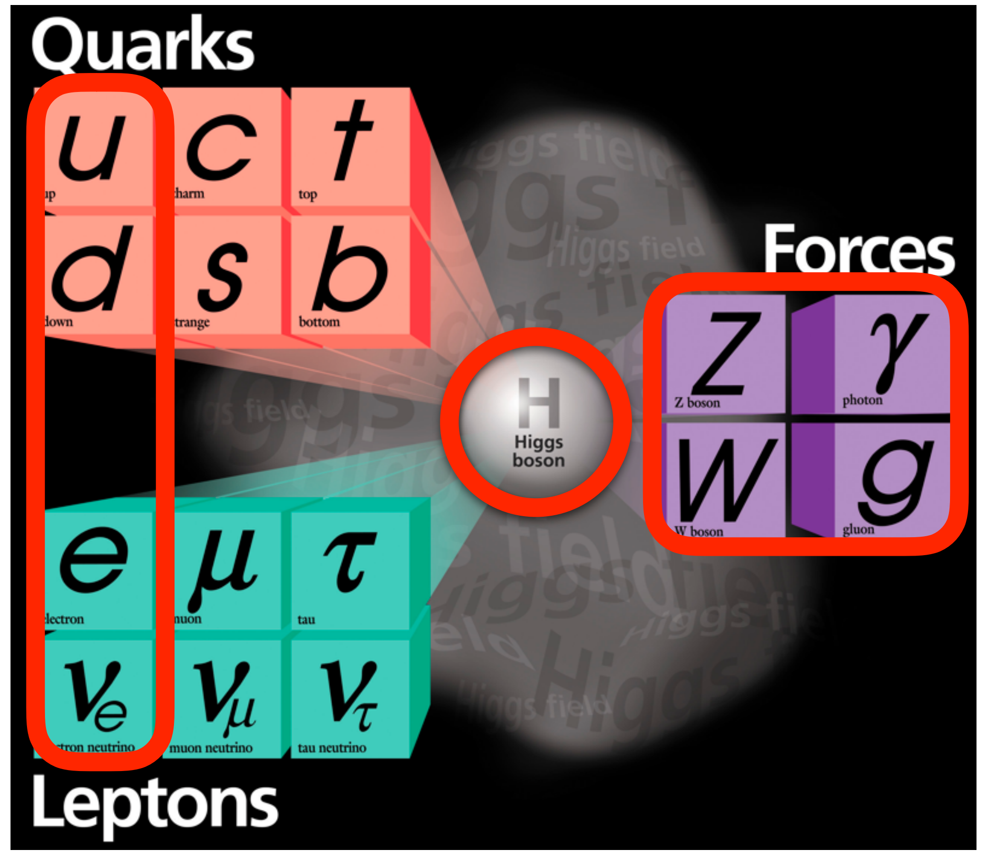

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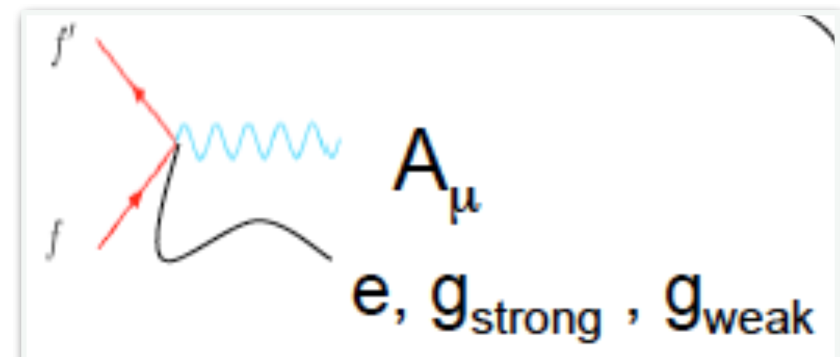

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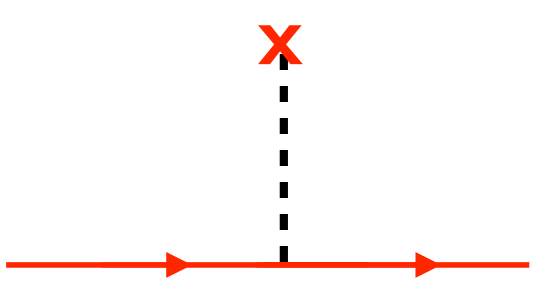
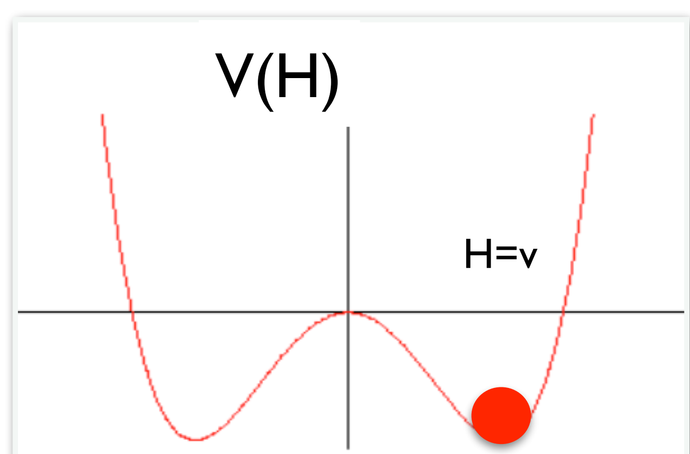
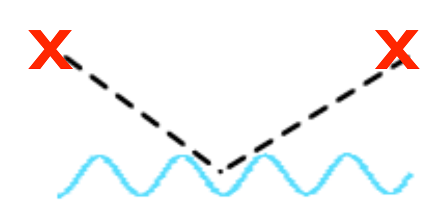


Massive quarks
and leptons

Higgs mechanism





Massive EW gauge bosons
(short range weak force)

The Standard Model

- Gauge group:

$$SU(3)_c \times SU(2)_W \times U(1)_Y$$

$$\psi'(x) = e^{ig_s \alpha_A(x) \frac{\lambda_A}{2}} \psi(x)$$

$$\psi'(x) = e^{ig' \gamma(x) Y} \psi(x)$$

$$\psi'(x) = e^{ig \beta_a(x) \frac{\sigma_a}{2}} \psi(x)$$

Fundamental representation (color triplets and weak doublets)

The Standard Model

	SU(3)c x SU(2)W x U(1)Y representation: (dim[SU(3)c], dim[SU(2)W], Y)	SU(2)W transformation
$l = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	(1,2,-1/2)	$l \to V_{SU(2)}\, l$
$e = e_R$	(1,1,-1)	
$q^i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix}$	(3,2,1/6)	$q \to V_{SU(2)}\, q$
$u^i = u^i_R$	(3,1,2/3)	
$d^i = d^i_R$	(3,1,-1/3)	
$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$	(1,2,1/2)	$\varphi \to V_{SU(2)}\, \varphi$

		SU(3)c x SU(2)W x U(1)Y representation
gluons:	$G^A_\mu\,, \quad A = 1\cdots 8\,,$ $G^A_{\mu\nu} = \partial_\mu G^A_\nu - \partial_\nu G^A_\mu + g_s f_{ABC} G^B_\mu G^C_\nu$	(8,1,0)
W bosons:	$W^I_\mu\,, \quad I = 1\cdots 3\,,$ $W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK} W^J_\mu W^K_\nu$	(1,3,0)
B boson:	$B_\mu\,,$ $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu\,.$	(1,1,0)

Gauge transformation:

$$W^I_{\mu\nu}\frac{\sigma^I}{2} \longrightarrow V(x)\left[W^I_{\mu\nu}\frac{\sigma^I}{2}\right]V^\dagger(x)$$

$$V(x) = e^{ig\beta_a(x)\frac{\sigma_a}{2}}$$

$Q = T_3 + Y$

The Standard Model

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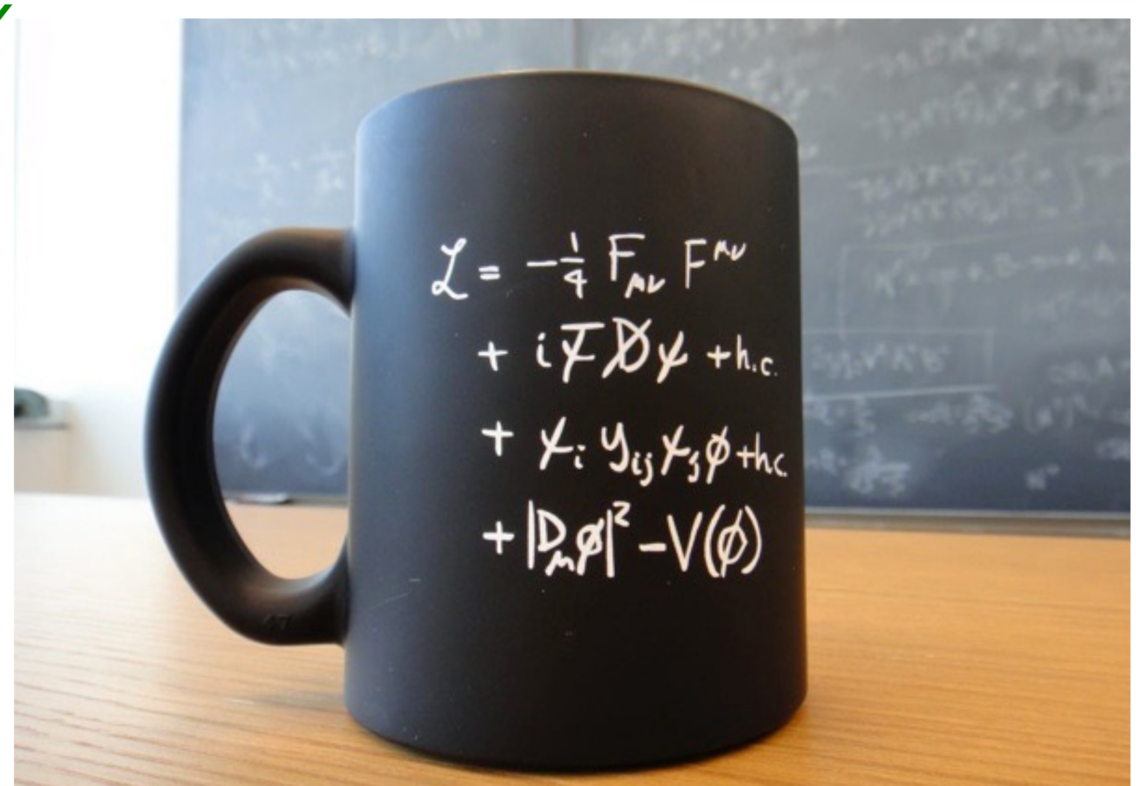
$Q = T_3 + Y$



$$\psi = \begin{pmatrix} q \\ \ell \\ u \\ d \\ e \end{pmatrix}$$

The Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$D_\mu = I\,\partial_\mu - ig_s \frac{\lambda^A}{2} G^A_\mu - ig \frac{\sigma^a}{2} W^a_\mu - ig' Y B_\mu$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ \sum_{i=1,2,3} \left(i\bar{\ell}_i \not{D} \ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i \right)$$

- $U(3)^5$ symmetry: no notion of "flavor" (three identical copies)

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$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4}G_{\mu\nu}^A G^{A\mu\nu} - \frac{1}{4}W_{\mu\nu}^I W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+ \sum_{i=1,2,3}\left(i\bar{\ell}_i \not{D}\ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i\right)$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\varphi)^\dagger(D^\mu\varphi) - \lambda(\varphi^\dagger\varphi - v^2)^2$$

EWSB →

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

$$\langle\tilde{\varphi}\rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$\tilde{\varphi} = \epsilon\,\varphi^*$$

$$\varphi = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$$

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$$+ \sum_{i=1,2,3}\left(i\bar{\ell}_i \not{D}\ell_i \;+\; i\bar{e}_i\not{D}e_i \;+\; i\bar{q}_i\not{D}q_i \;+\; i\bar{u}_i\not{D}u_i \;+\; i\bar{d}_i\not{D}d_i\right)$$

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EWSB →

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$$\langle\tilde{\varphi}\rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$\tilde{\varphi} = \epsilon\,\varphi^*$$

$$[m_W^2 W^+_\mu W^-_\mu + \frac{1}{2}m_Z^2 Z_\mu Z_\mu](1 + \frac{1}{\sqrt{2}v}h)^2$$

Higgs h couples to $W^\pm$ Z proportionally to their mass squared

The Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$D_\mu = I\,\partial_\mu - ig_s \frac{\lambda^A}{2} G^A_\mu - ig \frac{\sigma^a}{2} W^a_\mu - ig' Y B_\mu$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ \sum_{i=1,2,3} \left(i\bar{\ell}_i \not{D} \ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i \right)$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \varphi)^\dagger (D^\mu \varphi) - \lambda (\varphi^\dagger \varphi - v^2)^2$$

EWSB →

$$\langle \varphi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \langle \tilde{\varphi} \rangle = \begin{pmatrix} v \\ 0 \end{pmatrix} \qquad \tilde{\varphi} = \epsilon\, \varphi^*$$

$$\mathcal{L}_{\text{Yukawa}} = \bar{\ell}\, Y_e\, e \varphi + \bar{q}\, Y_d\, d \varphi + \bar{q}\, Y_u\, u \tilde{\varphi} + \text{h.c.}$$

- $Y_{e,u,d}$ are the only couplings that distinguish the three families!

Fermion-Higgs couplings

$$\mathcal{L}_{\text{Yukawa}} = \bar{e}_L Y_e e_R \left(v + \frac{h}{\sqrt{2}}\right) + \bar{d}_L Y_d d_R \left(v + \frac{h}{\sqrt{2}}\right) + \bar{u}_L Y_u u_R \left(v + \frac{h}{\sqrt{2}}\right) + \text{h.c.}$$

$$\varphi = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$$

- Fermion mass matrices diagonalized by bi-unitary transformation

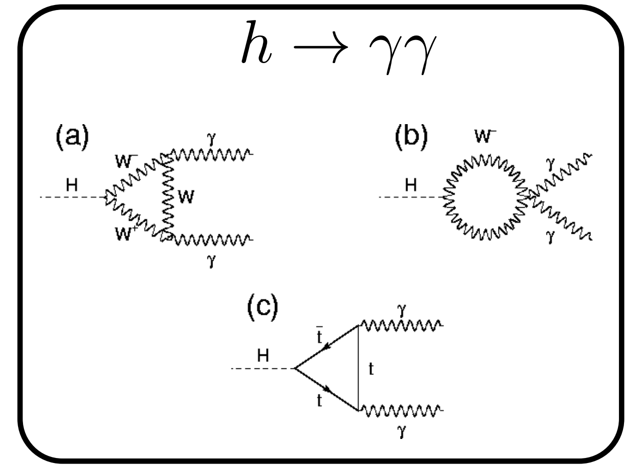
$$Y_f = V_{f_L}^{\dagger} Y_f^{\text{diag}} V_{f_R} \qquad f = e, d, u \longrightarrow m_{f,i} = v \left(Y_f^{\text{diag}}\right)_{ii}$$

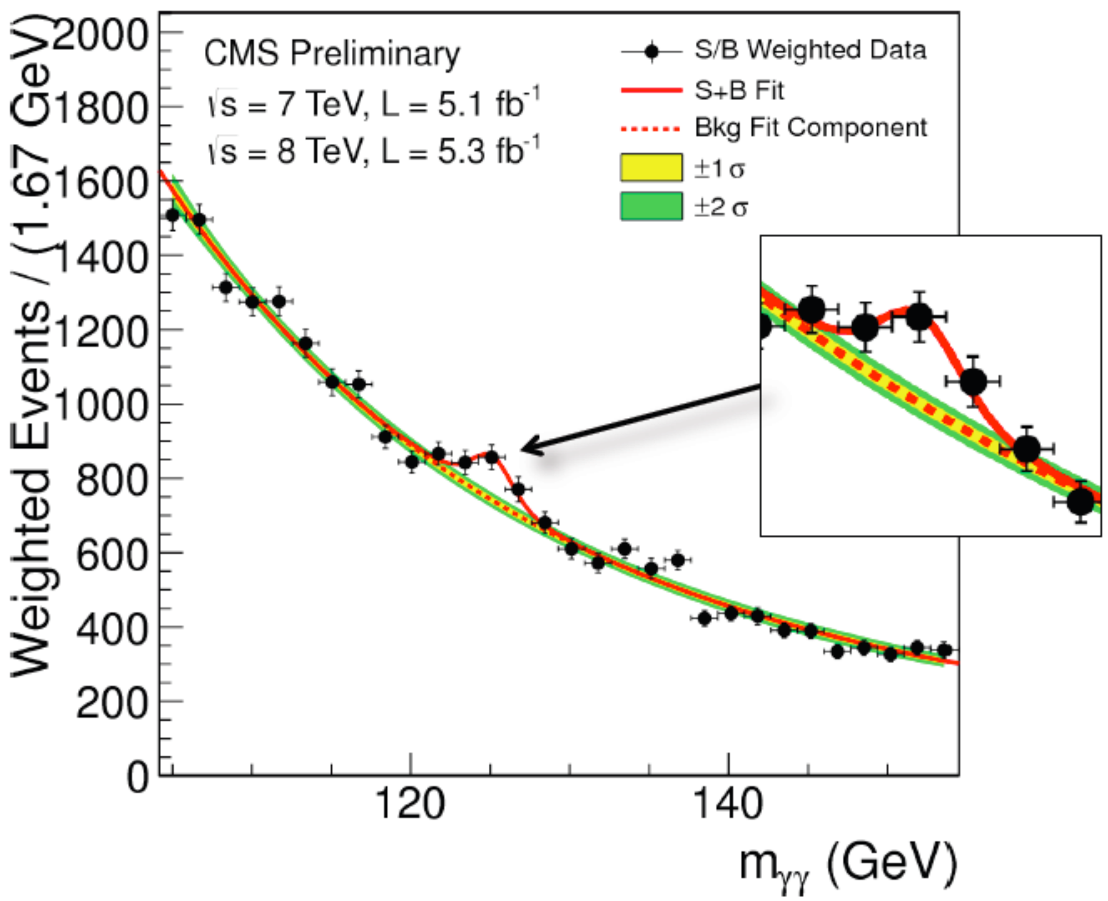
- Higgs coupling to fermions is flavor-diagonal and proportional to mass

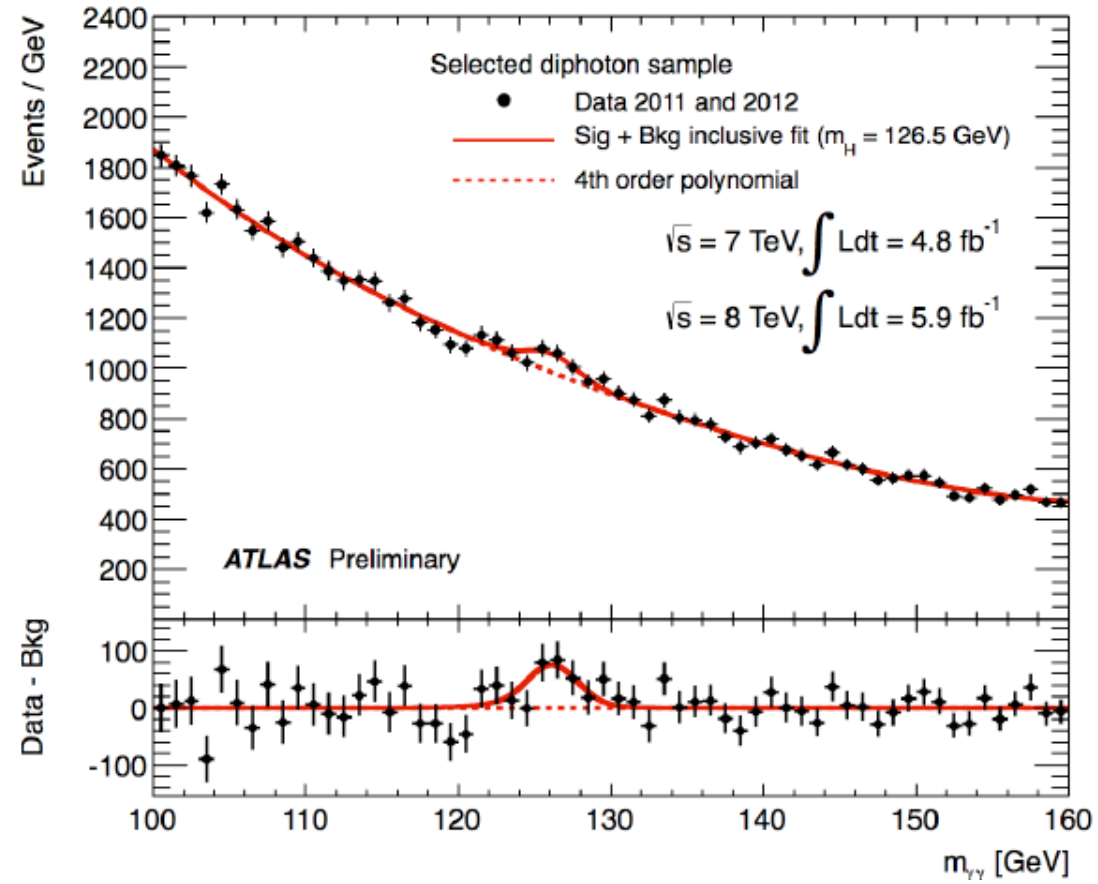
$$\mathcal{L}_{\text{Yukawa}} = \sum_{f=e,d,u} m_f \bar{f} f \left(1 + \frac{h}{\sqrt{2}v}\right) \qquad f = f_L + f_R$$

Does nature agree?

- Higgs boson: discovered in H →γγ mode

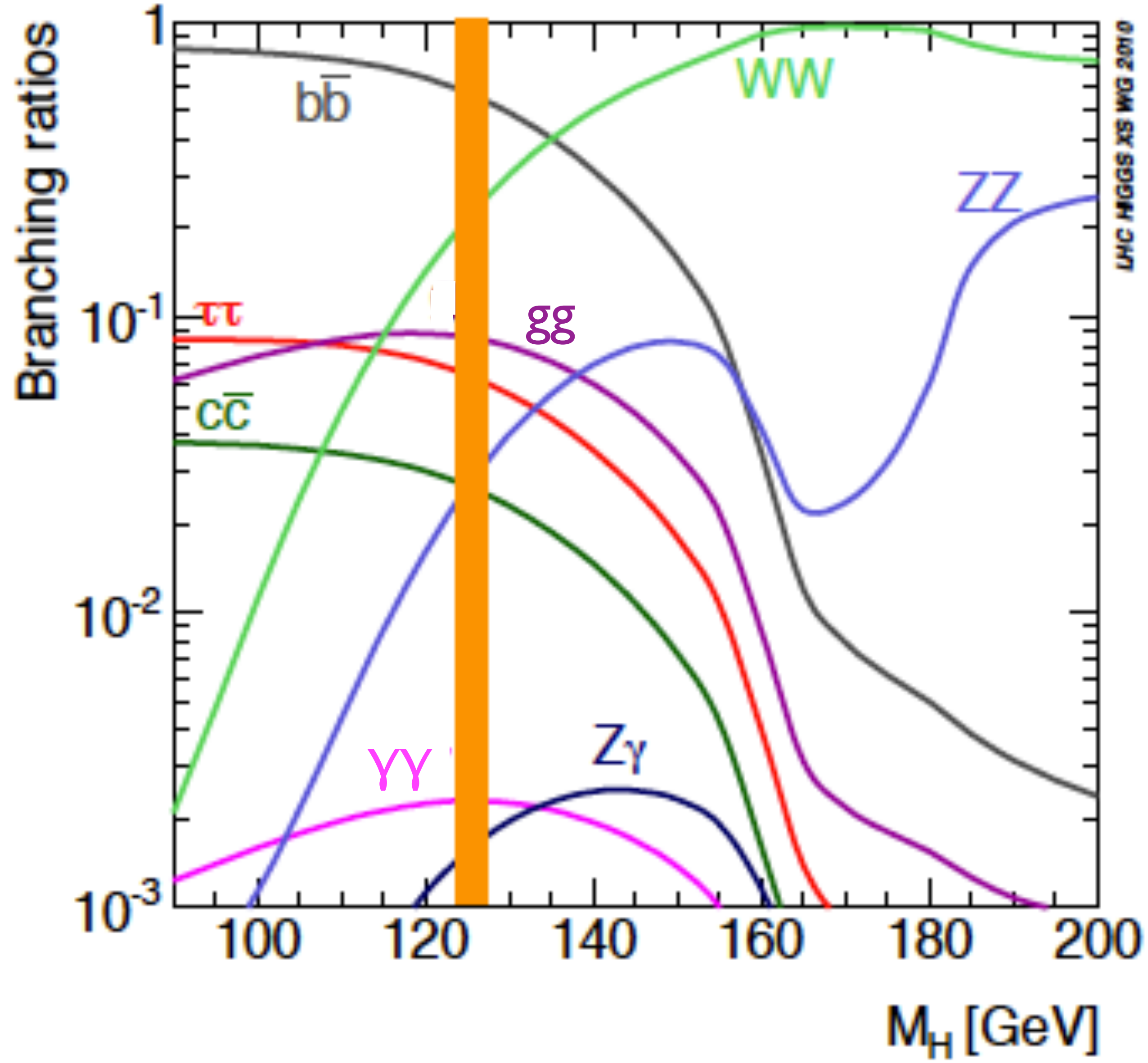






Does nature agree?

- Many decay modes accessible: can test Standard Model BR pattern



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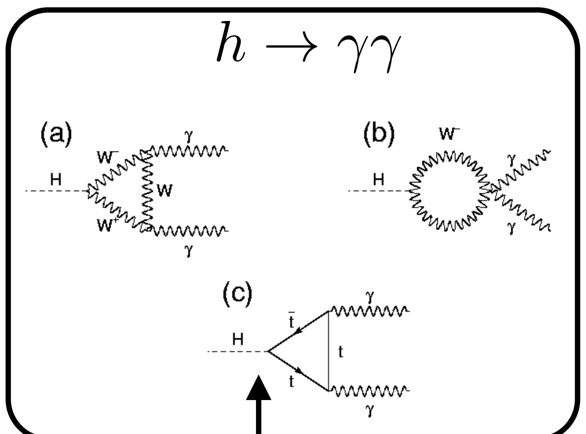
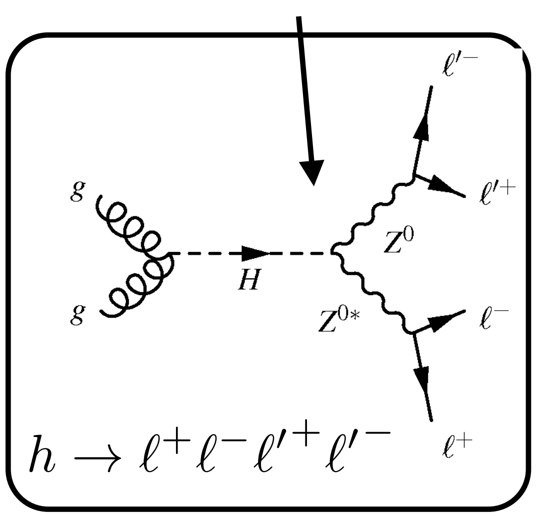
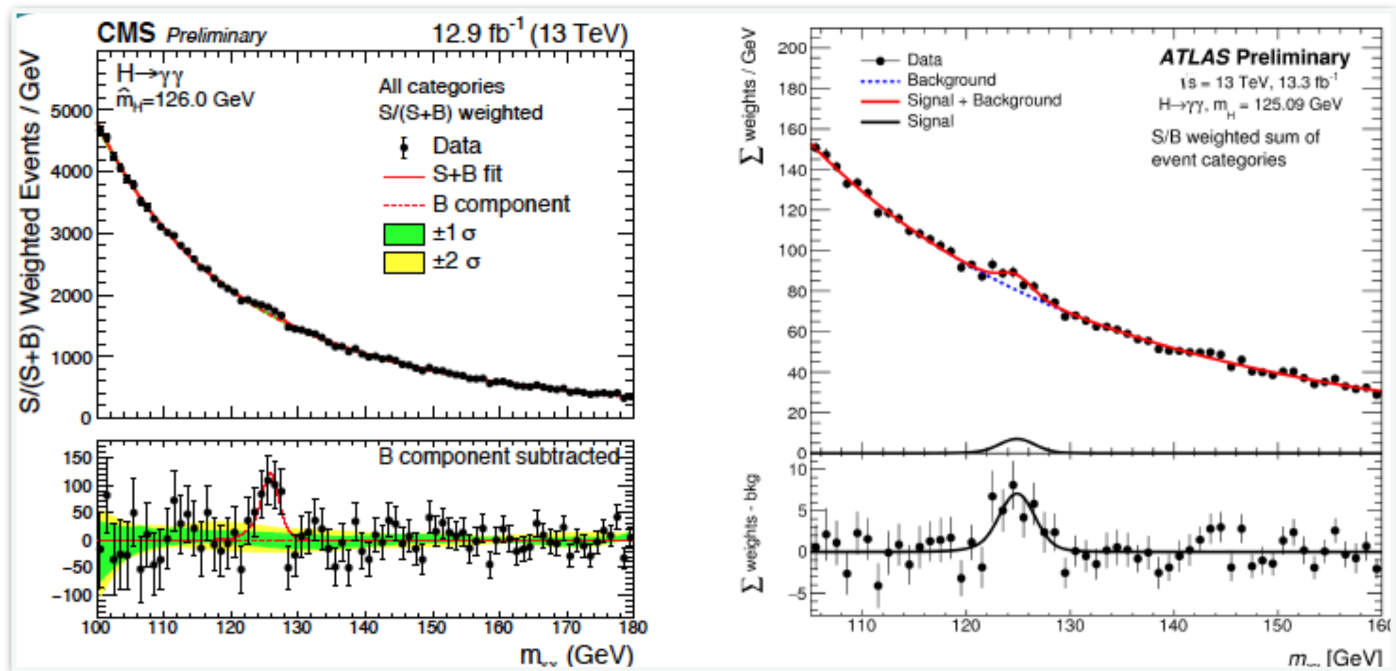
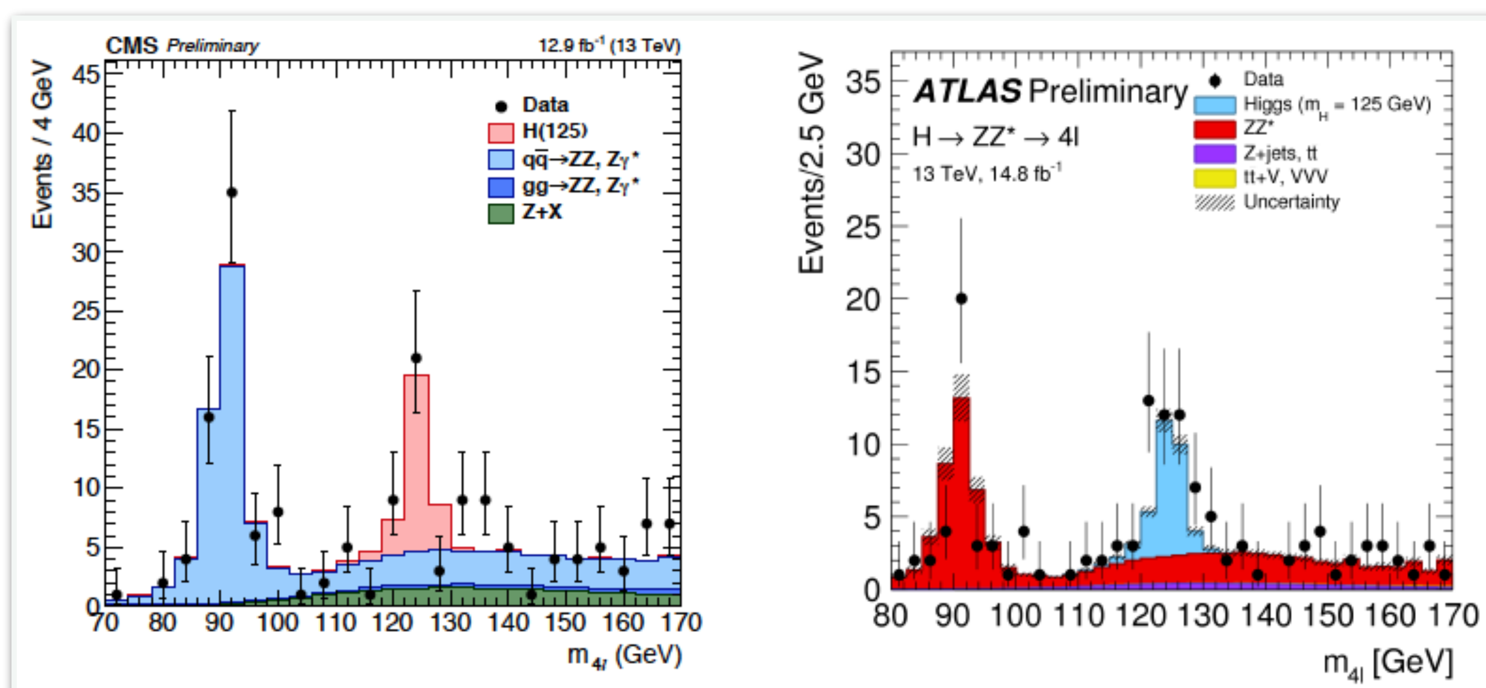


Access to
Higgs couplings



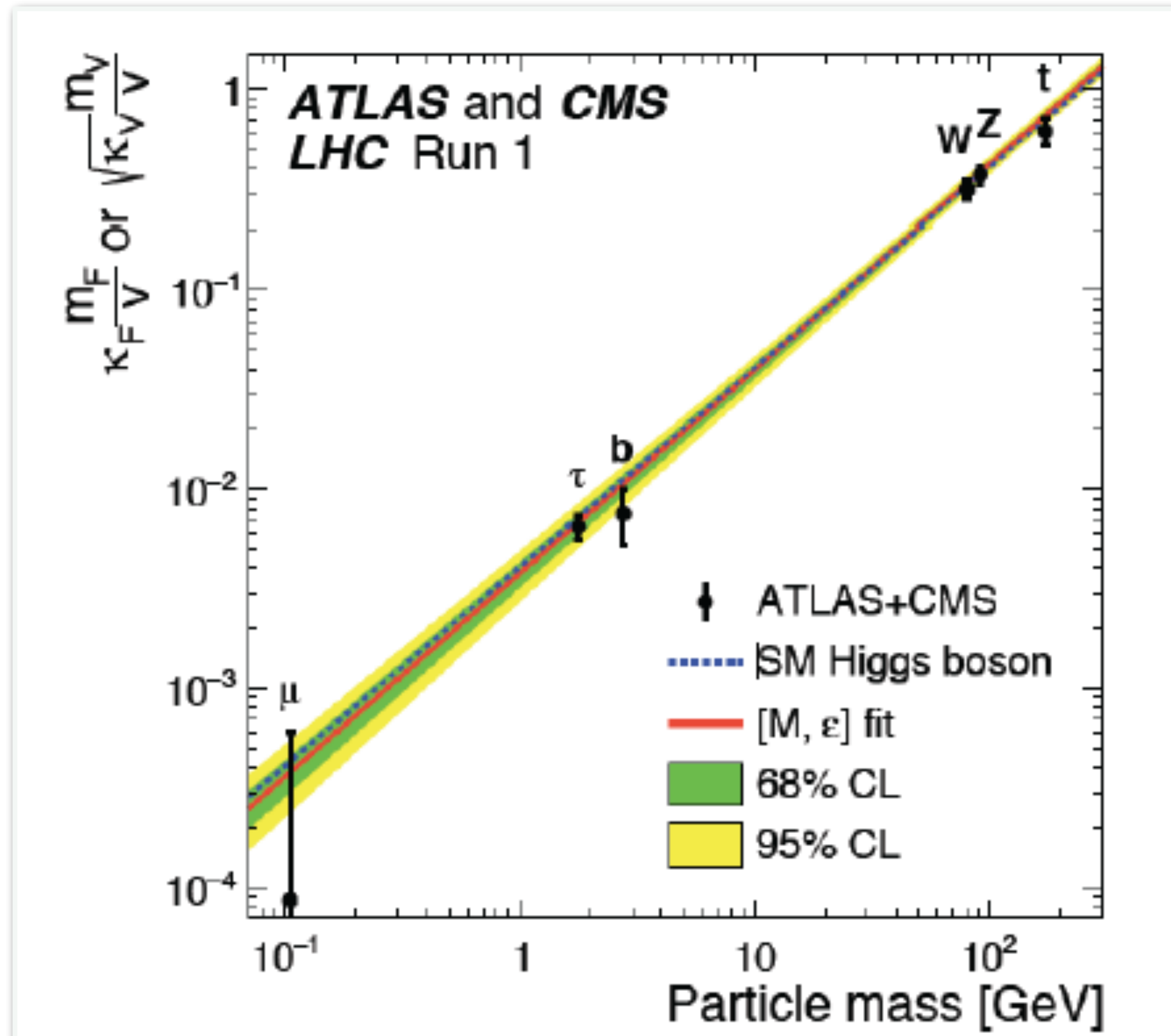




Does nature agree?

- Many decay modes accessible: can test Standard Model BR pattern

- Higgs couplings to heavy particles consistent with SM prediction (~10-20% level)
- Room for surprises in:
  - coupling to light particles
  - SM forbidden decays: $h \rightarrow \tau\mu, \ldots$
- Major area of activity for Run 2 and opportunity for Precision / Intensity frontier



Fermion-gauge boson couplings

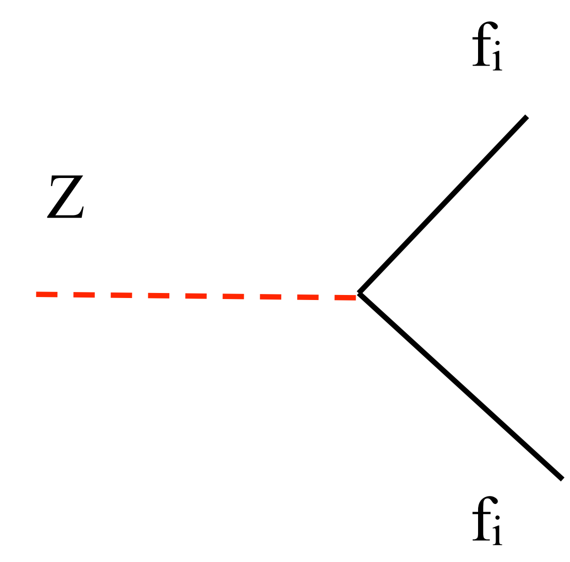
- Neutral current

$$\mathcal{L}_{\rm int} = -\frac{g}{2\cos\theta}\, Z^\mu\, \bar{\psi}_f \left(g_V^{(f)} \gamma_\mu - g_A^{(f)} \gamma_\mu \gamma_5 \right) \psi_f$$

$$\theta = \arctan \frac{g'}{g}$$

$$e = g \sin\theta,$$

$$g_V^{(f)} = T_3^{(f)} - 2\sin^2\theta\, Q^{(f)} \qquad g_A^{(f)} = T_3^{(f)}$$

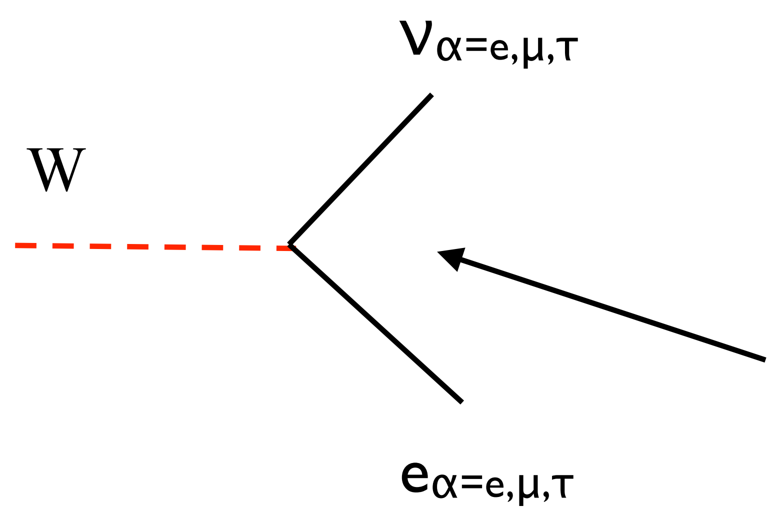


- Flavor diagonal
- Both V and A: expect P-violation!

Fermion-gauge boson couplings

- Charged current: leptons

$$\frac{g}{\sqrt{2}} W_\mu^- \, \bar{e}_L^\alpha \gamma^\mu \nu_L^\alpha$$



Unitary transformation of e_L needed to diagonalize charged lepton mass matrix can be reabsorbed by a redefinition of ν_L (this will change for massive neutrinos)

- Flavor diagonal: ⇒ individual lepton family numbers $L_{e,\mu\tau}$ conserved

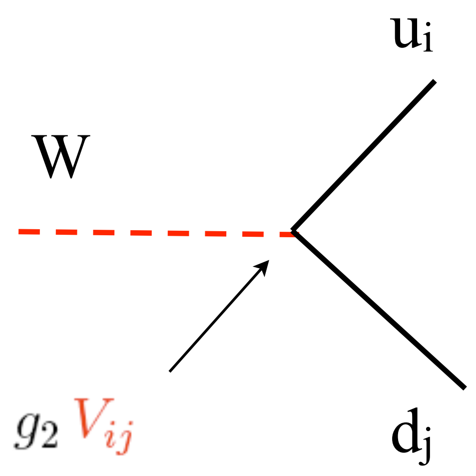
Fermion-gauge boson couplings

- Charged current: quarks

$$\frac{g}{\sqrt{2}} W^+ \, \bar{u}_L \gamma_\mu d_L \;\rightarrow\; \frac{g}{\sqrt{2}} W^+ \, \bar{u}'_L \, V_{\rm CKM} \, \gamma_\mu \, d'_L$$

$$V_{\rm CKM} = V_{u_L} V^\dagger_{d_L}$$

Unitary matrix encoding the physically observable mismatch in the transformation of u_L and d_L needed to diagonalize quark masses



$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maksawa matrix

- CKM matrix is unitary:
    - 9 real parameters, but redefinition of quark phases reduces physical parameters to 4: 3 mixing angles and 1 phase

$$V_{ij} \;\rightarrow\; V_{ij}\; e^{i((\phi_d)_j-(\phi_u)_i)}$$

5 independent parameters (phase differences)

- Irreducible phase implies CP violation:

$$g_2 V_{ij}\, W^+_\mu\, \bar{u}^i_L \gamma^\mu d^j_L \;+\; g_2 V^*_{ij}\, W^-_\mu\, \bar{d}^j_L \gamma^\mu u^i_L$$

$$\Big\downarrow \quad \text{CP transformation}$$

$$g_2 V_{ij}\, W^-_\mu\, \bar{d}^j_L \gamma^\mu u^i_L \;+\; g_2 V^*_{ij}\, W^+_\mu\, \bar{u}^i_L \gamma^\mu d^j_L$$

- CKM matrix and m_q govern the pattern of flavor and CPV in the SM

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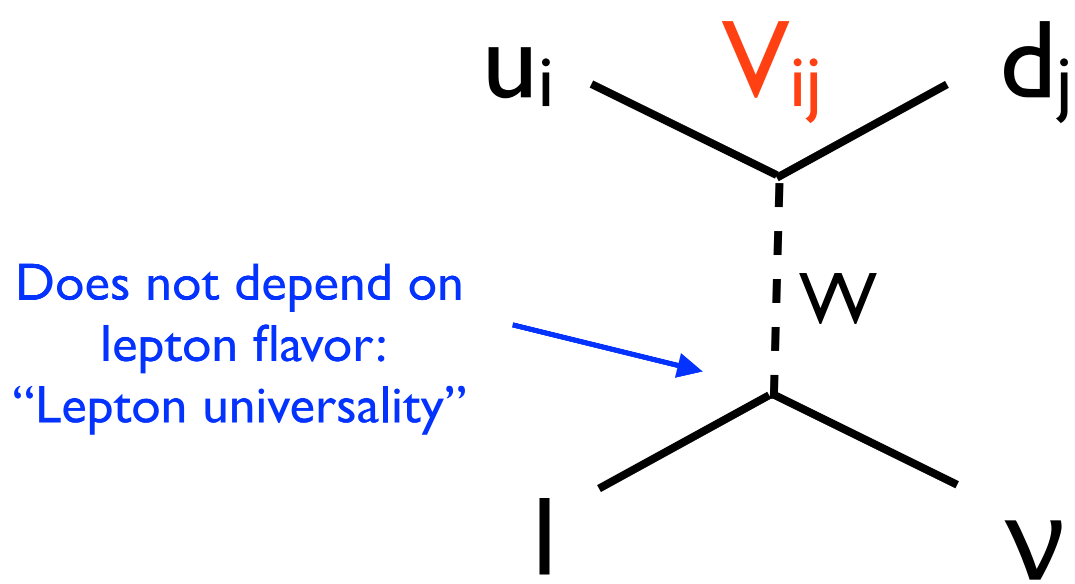
- CKM matrix and m_q govern the pattern of flavor and CPV in the SM

Flavor and CP violation: quarks

- Tree-level flavor changing charged-current processes (semi-leptonic decays can be studied to extract all $|V_{ij}|$, except for V_{td} and V_{ts})



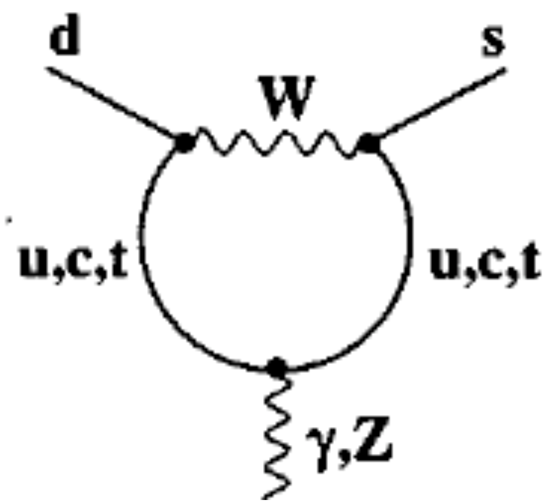
⟷ Data indicates hierarchical structure of mixing matrix

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Make explicit the hierarchical structure revealed by experiment:
expand in $\lambda \approx V_{us} \approx 0.225$, with $\rho, \eta, A \sim O(1)$ (Wolfenstein 1983)

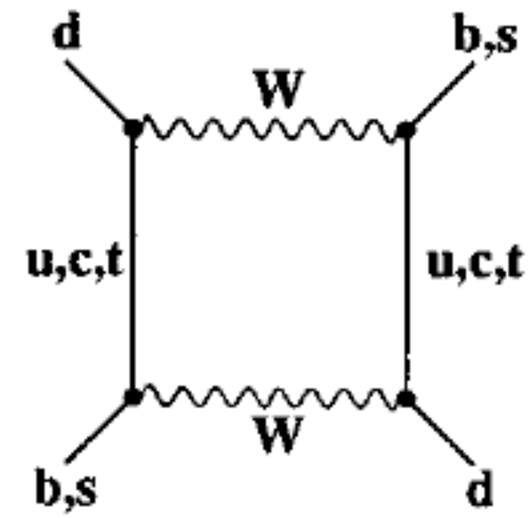
- By connecting flavor-changing charged-current vertices obtain flavor-changing neutral currents (FCNC) at loop level: penguins and boxes

$\Delta F=1$



Sensitive to $|V_{td,ts}|$ and phases of V_{ij}

$\Delta F=2$



Rare K and B decays

$$K \to \pi\nu\bar{\nu},\ K \to \pi\ell^+\ell^-, \ldots$$

$$B \to X_s\gamma,\ B \to X_s\ell^+\ell^-, \ldots$$

Neutral meson mixing (Δm, CPV in mixing)

$$K^0 - \bar{K}^0 \quad B^0_{d,s} - \bar{B}^0_{d,s}$$

- Important Example: CP violation in neutral kaon mixing

$$|K^0\rangle = |d\bar{s}\rangle$$
$$|\overline{K^0}\rangle = |\bar{d}s\rangle$$
$$\downarrow$$
$$K_L = K_{\text{heavy}}$$
$$K_S = K_{\text{light}}$$

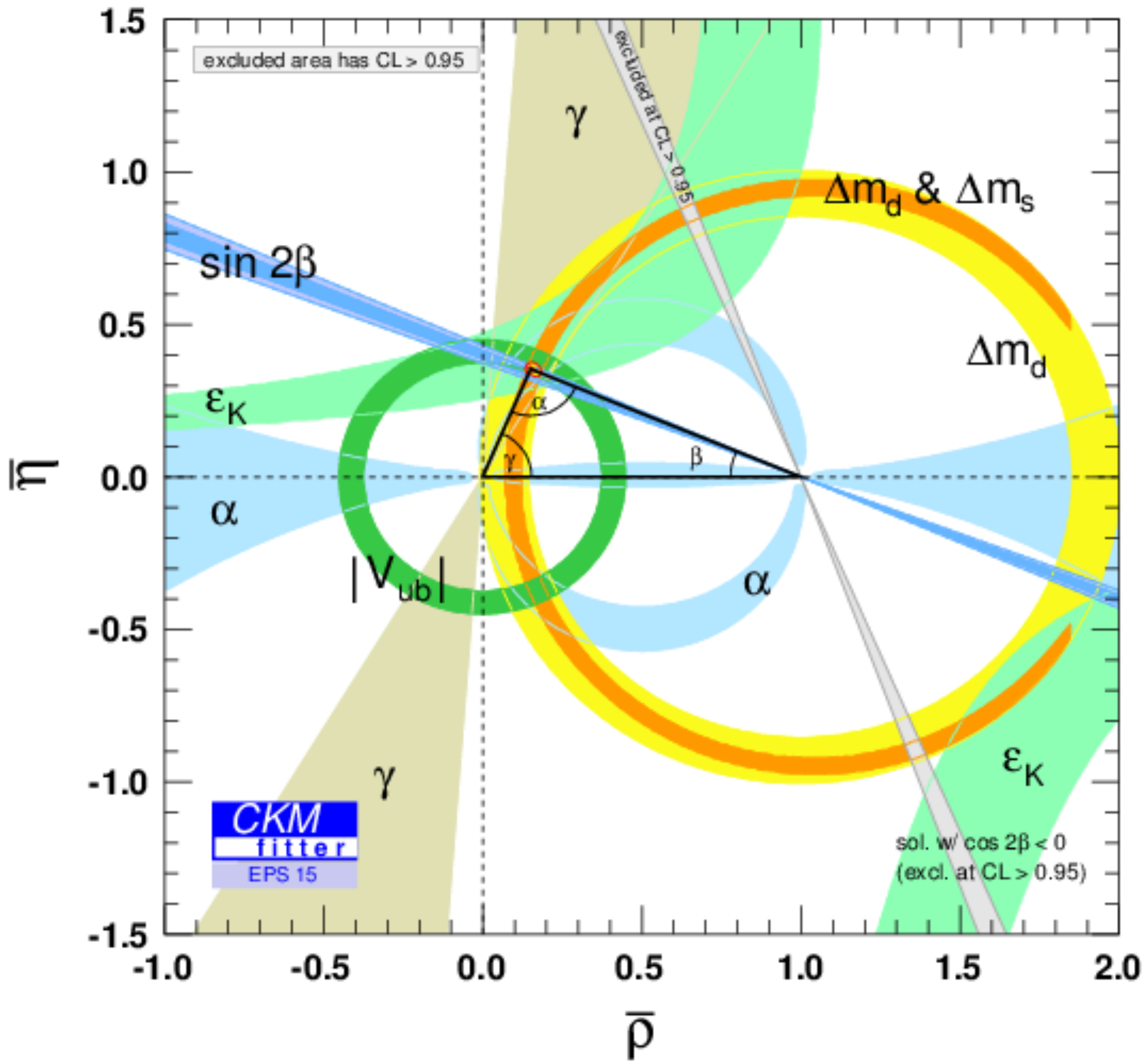
$$i\,\frac{d}{dt}\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix} = \left(M - i\,\frac{\Gamma}{2}\right)\begin{pmatrix} K^0 \\ \overline{K}^0 \end{pmatrix}$$

- $K_{L,S}$ not eigenstates of CP: non-zero asymmetries

$$\delta_L = \frac{\Gamma(K_L \to \pi^-\ell^+\nu) - \Gamma(K_L \to \pi^+\ell^-\bar{\nu})}{\Gamma(K_L \to \pi^-\ell^+\nu) + \Gamma(K_L \to \pi^+\ell^-\bar{\nu})} = \boxed{(3.32 \pm 0.06) \times 10^{-3}}$$

- CP violation in B-meson decays fully consistent with CKM paradigm!

- Status of the CKM matrix: quark flavor physics (including CPV) is well described by 3 mixing angles and a phase!



$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\bar{\rho} = \rho\ \left(1 - \frac{\lambda^2}{2}\right)$$

$$\bar{\eta} = \eta\ \left(1 - \frac{\lambda^2}{2}\right)$$

Symmetries of the Standard Model

- Gauge symmetry is hidden (Higgs mechanism)
- Flavor symmetry:
  - $U(3)^5$ explicitly broken only by Yukawa couplings: specific pattern of FCNC — falsifiable!
  - U(1) associated with B, L, and $L_{\alpha=e,\mu,\tau}$ survive
  - Anomaly: only B-L is conserved
- P, C maximally violated by weak interactions
- CP (and T) violated by CKM (and QCD theta term*): specific pattern of CPV in flavor transitions and EDMs

$$* \quad \mathcal{L}_\theta^{CPV} = \theta \, \frac{g_s^2}{64\pi^2} \, \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}$$

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(Approximate) symmetries and symmetries broken in a very specific way offer great opportunity to probe non-standard physics at the Intensity Frontier

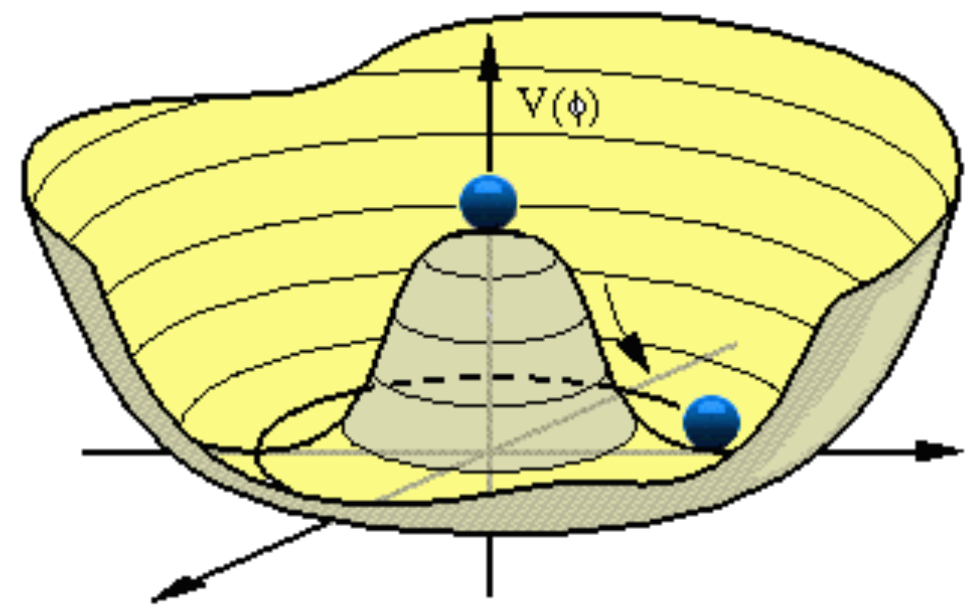
Additional material

$SU(2)_W \times U(1)_Y \rightarrow U(1)_{EM}$

- Expand around the minimum of the potential

$$\mathcal{L}_{\text{Higgs}} = (D_\mu\varphi)^\dagger(D^\mu\varphi) - \lambda(\varphi^\dagger\varphi - v^2)^2$$

$$\phi(x) = e^{i\pi_i(x)\sigma_i/v}\begin{pmatrix} 0 \\ v + \frac{h(x)}{\sqrt{2}} \end{pmatrix}$$



- Generalization of the abelian Higgs model discussed in detail earlier on

- $Q = T_3 + Y$ annihilates the vacuum → unbroken $U(1)_{EM}$. Photon remains massless, other gauge bosons ($W^\pm$, Z) acquire mass

$SU(2)_W \times U(1)_Y \rightarrow U(1)_{EM}$

- Expand around the minimum of the potential

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \varphi)^\dagger (D^\mu \varphi) - \lambda(\varphi^\dagger \varphi - v^2)^2$$

$$\phi(x) = e^{i\pi_i(x)\sigma_i/v} \begin{pmatrix} 0 \\ v + \frac{h(x)}{\sqrt{2}} \end{pmatrix}$$

$$[m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2} m_Z^2 Z_\mu Z_\mu](1 + \frac{1}{\sqrt{2}v} h)^2$$

Neutral scalar h couples to $W^\pm$ Z proportionally to their mass squared

Weak mixing angle

$$\theta = \arctan \frac{g'}{g}$$

$$e = g \sin\theta$$

$$W_\mu^\pm = 1/\sqrt{2}(W_\mu^1 \pm W_\mu^2)$$

$$Z_\mu = \cos\theta W_\mu^3 - \sin\theta B_\mu$$

$$A_\mu = \sin\theta W_\mu^3 + \cos\theta B_\mu$$

$$m_W = gv/\sqrt{2}$$

$$m_Z = \frac{\sqrt{g^2 + g'^2}}{2} v$$

$$m_W = m_Z \cos\theta$$

SU(2)$_W$ x U(1)$_Y$ → U(1)$_{EM}$

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$$[m_W^2 W_\mu^+ W_\mu^- + \frac{1}{2}m_Z^2 Z_\mu Z_\mu](1 + \frac{1}{\sqrt{2}v}h)^2$$

$$\frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - \sqrt{\frac{\lambda}{2}}\, m_h h^3 - \frac{\lambda}{4}h^4$$

$$m_h = 2\sqrt{\lambda}v$$

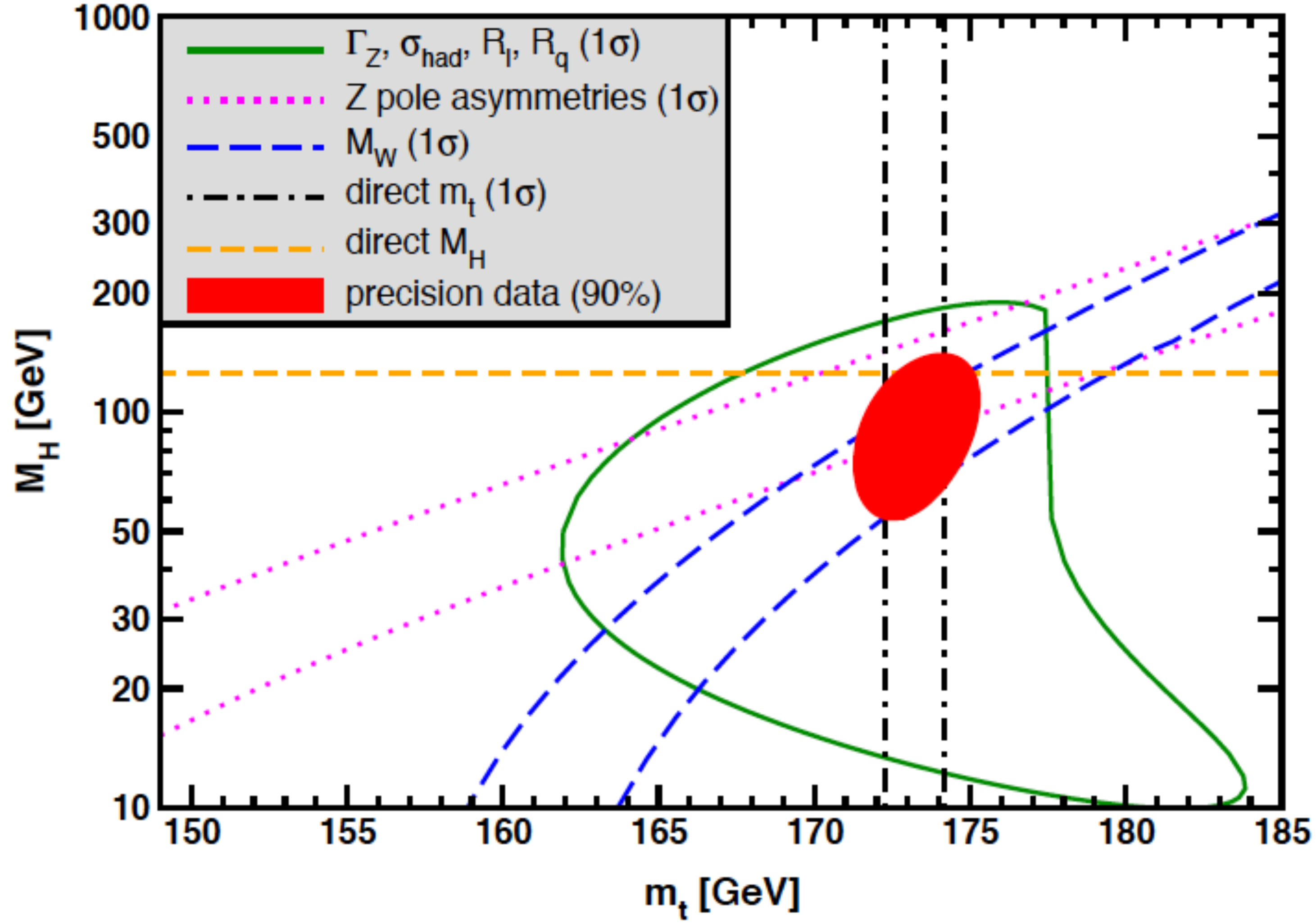
Higgs mass controlled by v and Higgs self-coupling

$$G_F^{-1} = 2\sqrt{2}v^2$$

Status of the Standard Model

- Standard Model tested at the quantum (loop) level in both electroweak and flavor sector

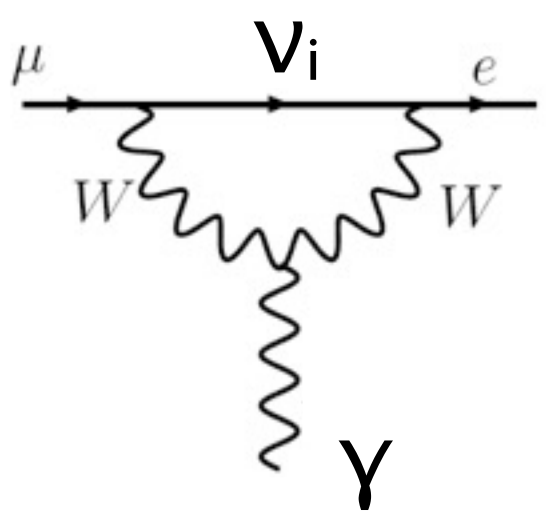
- Precision EW tests are at the 0.1% level. Example:



- A few “tensions” and “anomalies”, such as muon g-2

Symmetry breaking in the νSM

- CC vertex & mass terms: individual flavors not conserved (ν osc.)
- Loop-level charged lepton FCNC: GIM at work → tiny effects!



Current limit on BR ~ 10^{-13}

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$$

Petcov '77, Marciano-Sanda '77 ....

- $L_{\alpha=e,\mu,\tau}$ broken: but unobservable effects in charged lepton sector. Extremely clean probe of BνSM dynamics: no background!
- L broken by Majorana mass — specific expectations in 0νββ