

# Weak interactions and Higgs Theory, 3 HCPSS lectures

(M. Schmaltz, Boston University)

1. SM Lagrangian, predictions
  2. Higgs Physics
  3. SM effective field theory
- (un)Naturalness

} see also TASI lectures 2013  
Heather Logan

The Standard Model is an  $SU(3)_{\text{color}} \times SU(2)_{\text{weak}} \times U(1)_{\text{Hypercharge}}$  gauge theory.

$$\mathcal{L}_{\text{gauge}} = \underbrace{-\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu}}_{\text{gluons}} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$W, Z, \gamma$

e.g.  $W_{\mu\nu}^a \equiv \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g \epsilon^{abc} W_\mu^b W_\nu^c$



Fermions:

QED: 4-component spinors  $\swarrow$  Lorentz group

Dirac

$$e = \begin{pmatrix} e_L \\ e_R \end{pmatrix} \quad e_L \equiv P_L e = \begin{pmatrix} e_L \\ 0 \end{pmatrix}$$

$$e_R \equiv P_R e = \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$

" $\gamma_0$ "

$$\mathcal{L}_e = \bar{e} (i \gamma^\mu D_\mu - m) e$$

$$D_\mu = \partial_\mu - ie A_\mu Q \quad \swarrow \text{charge } -1$$

$$\sim \begin{pmatrix} e_L^\dagger & e_R^\dagger \end{pmatrix} \begin{pmatrix} i \not{\partial} & -m \\ -m & i \not{\partial} \end{pmatrix} \begin{pmatrix} e_L \\ e_R \end{pmatrix}$$

$$= \underbrace{\bar{e}_L i \not{\partial} e_L + \bar{e}_R i \not{\partial} e_R}_{\text{independent kinetic terms, gauge couplings}} - \underbrace{m(\bar{e}_L e_R + \bar{e}_R e_L)}_{\text{breaks chiral symmetry}}$$

independent kinetic terms,  
gauge couplings

breaks chiral symmetry

$$e_L \rightarrow e^{i\alpha_L} e_L$$

$$e_R \rightarrow e^{i\alpha_R} e_R$$

the SM does NOT work this way!

SM field	$8\mathbf{N}(3)_c$	$SU(2)_w$	$U(1)_y$	$Q = T_3 + Y$
$e_R$	1	1	-1	Leptons
$L_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	1	2	$-\frac{1}{2}$	
$u_R$	3	1	$\frac{2}{3}$	Quarks
$d_R$	3	1	$-\frac{1}{3}$	
$Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	3	2	$\frac{1}{6}$	
$H$	1	2	$\frac{1}{2}$	Higgs
$\tilde{H} \equiv i\sigma_2 H^*$	1	2	$-\frac{1}{2}$	

Notation:  $e_R \equiv P_R e = \begin{pmatrix} 0 \\ e_R \end{pmatrix}$

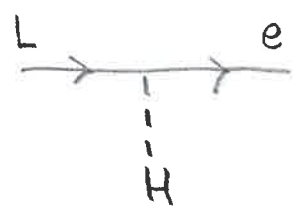
$e_L = \begin{pmatrix} e_L \\ 0 \end{pmatrix}$

2-component spinors in 4-component notation.

- $m \bar{e}_L e_R$  not gauge invariant
  - $m e_R^+ e_R$  not lorentz invariant ( $\bar{e}_R e_R = 0$ )
- } massless fermions!

But:

$\mathcal{L}_{\text{Yukawa}} = -y_e \bar{L}_L H e_R - y_d \bar{Q}_L H d_R - y_u \bar{Q}_L \tilde{H} u_R + \text{h.c.}$



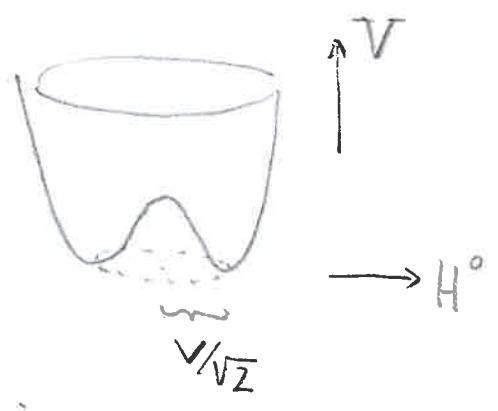
not a mass

Higgs doublet:

$$\mathcal{L}_H = D_\mu H^\dagger D^\mu H - \lambda \left( H^\dagger H - \frac{v^2}{2} \right)^2$$

$$H(x) = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \frac{1}{\sqrt{2}} e^{i\theta(x)} \begin{pmatrix} 0 \\ v+h(x) \end{pmatrix}$$

↑ complex
↑
↑ real



Remove from  $\mathcal{L}$  by gauge transformation

"unitary gauge"

$$V \rightarrow +\lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

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



hard to observe



impossible to see

# Higgs mechanism for $W^\pm, Z$ masses

$$D_\mu H = \left( \partial_\mu - ig' \frac{1}{2} B_\mu - ig \frac{\sigma^a}{2} W_\mu^a \right) H$$

$$\Rightarrow (D_\mu H)^\dagger D^\mu H \xrightarrow{H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}} \underbrace{\frac{g^2 v^2}{4}}_{m_W^2} W_\mu^+ W^{-\mu} + \underbrace{\frac{(g^2 + g'^2) v^2}{4}}_{m_Z^2} \frac{1}{2} Z_\mu Z^\mu$$

$$W^\pm = \frac{W_1 \mp i W_2}{\sqrt{2}} \quad \text{complex}$$

$$Z = c_W W_3 - s_W B \quad \text{real}, \quad A = s_W W_3 + c_W B \quad \text{massless}$$

$$s_W = \sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

$W^\pm, Z$  have "eaten"  $\theta^a$  Nambu-Goldstone-Bosons.

Fermion masses:

$$y_e \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix} e_R \rightarrow m_e = y_e \frac{\nu}{\sqrt{2}}$$

3 generations  $\rightarrow \frac{\nu}{\sqrt{2}} y_e^{ij} \bar{e}_L^i e_R^j$ , mass matrix  $m_e^{ij} = \frac{\nu}{\sqrt{2}} y_e^{ij}$

rotate fields:  $e_L \rightarrow U_{eL} e_L$  to diagonalize  $y_e/m_e \Rightarrow 3$  masses  
 $e_R \rightarrow U_{eR} e_R$

quarks:  $m_d = y_d \frac{\nu}{\sqrt{2}}$  diagonalize  $\Rightarrow 6$  masses

$$m_u = y_u \frac{\nu}{\sqrt{2}}$$

mismatch of bases:  $V_{CKM} = U_{uL}^\dagger U_{dL}$  3 angles, 1 phase

$W^\pm$  coupling:  $g (\overline{u c t})_L W^\pm V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L + h.c.$  flavor violating

Z:  $\frac{e}{c_w s_w} \bar{q}_i \not{=} (T_i^3 - s_w^2 Q_i) q_i$  } flavor preserving

photon:  $e \bar{q}_i \not{=} Q_i q_i$

Summary: •  $W^\pm, Z$ , fermion masses from Higgs VEV

$$V \approx 246 \text{ GeV} \quad (G_F \text{ in } \mu\text{-decay})$$

$$\frac{m_W}{m_Z} = \frac{g}{\sqrt{g^2 + g'^2}} = c_W \quad m_W = \frac{gV}{2}$$

$$m_f = y_f \frac{V}{\sqrt{2}} \quad m_h = \sqrt{2\lambda} V$$

• all gauge couplings determined by  $g, g' \Leftrightarrow e, \sin^2 \theta_W$

lecture 1.

Higgs couplings:  $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$

$\Rightarrow$  replace  $v \rightarrow v(1 + \frac{h}{v})$  in masses

e.g.  $m_W^2 W^+ W^- \rightarrow m_W^2 (1 + \frac{h}{v})^2 W^+ W^-$



$$m_b \bar{b}_L b_R \rightarrow m_b (1 + \frac{h}{v}) \bar{b}_L b_R$$

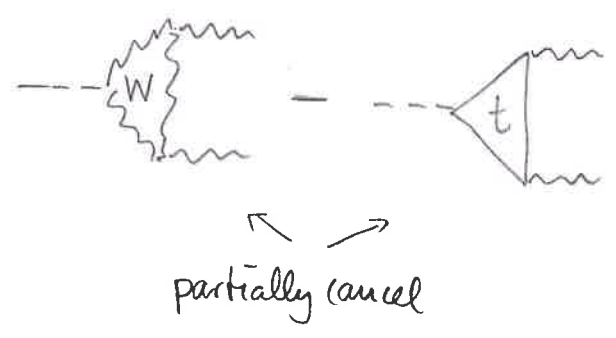


no new parameters  $\Rightarrow$  Higgs couplings predicted





•  $h \rightarrow \gamma\gamma$




$$\sim \frac{\alpha}{4\pi} \frac{1}{V}$$

### BR predictions (@125.5 GeV HXSWG)

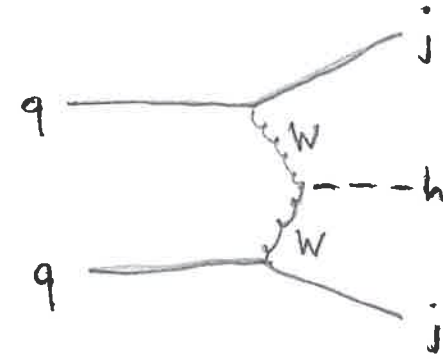
$b\bar{b}$	57%	$\sim 2\sigma$
$WW^*$	22%	$4\sigma$
$gg$	8.5%	
$\tau\tau$	6.2%	$1-2\sigma$
$c\bar{c}$	2.9%	
$ZZ^*$	2.8%	$>5\sigma$
$\gamma\gamma$	0.23%	$>5\sigma$
$\gamma Z$	0.16%	
$\mu^+\mu^-$	0.02%	

# Higgs production ( @ 125.5 GeV , 8 TeV HXSWG )

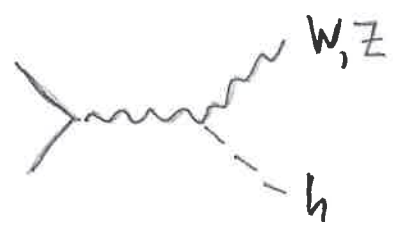
gg   $\sigma = 19 \text{ pb} \pm 10\%$

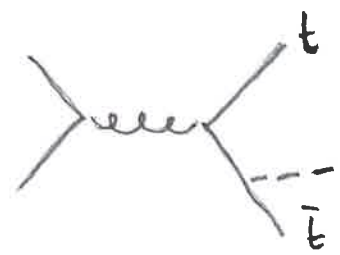
← pdfs, scale

most important

VBF   $\sigma = 1.6 \pm 3\%$

forward jet tags, "seen" in 88

Associated   $0.7 + 0.4 \text{ pb}$  Tevatron, LEP, LC

$t\bar{t}h$    $0.1 \text{ pb}$  measure  $t\bar{t}h$  coupling

Invisible decays? ( $h \rightarrow \text{dark matter}, \nu\text{'s}, aa \rightarrow 4j$ ) -11-

$$\text{visible rate}_i = \sigma \cdot \frac{\Gamma_i}{\Gamma_{\text{tot}}}$$

$$\Gamma_{\text{tot}} = \Gamma_{\text{SM}} + \Gamma_{\text{non-SM}}$$

$\Rightarrow$  uniform decrease of signal in all channels

1. current data allow  $\sim 20\%$   $\text{Br}_{\text{inv.}}$

2. flat direction:  $\text{Br}_{\text{inv.}} \uparrow \quad \sigma \uparrow$

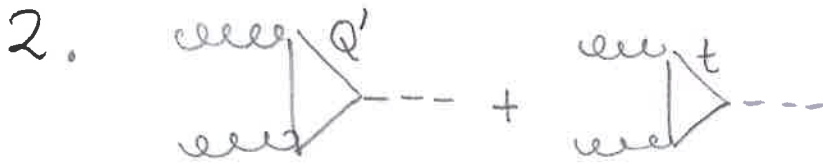
Q: reasonable?

1.  $\Gamma_{\text{SM}} \sim \Gamma_{b\bar{b}} \propto \lambda_b^2 \sim (10^{-2})^2$  very small

$\Rightarrow \Gamma_{\text{non-SM}} \sim \Gamma_{\text{SM}}$  easy

example:  $h \rightarrow \chi\chi$  "Higgs portal" DM

$\mathcal{L} \sim \frac{H^\dagger H}{M} \chi\chi \Rightarrow \lambda_\chi = \frac{v}{M}$  can probe  $M \sim 10 \text{ TeV}$



$$\sigma \sim \sigma_{SM} \left( 1 + \lambda_{Q'}^2 \frac{v^2}{m_{Q'}^2} \right)^2$$

20% easy ( $\lambda=1, m_Q \sim 750 \text{ GeV}$ )

does not enhance VBF  $\Rightarrow$  VBF already bounds  $\text{Br}_{inv} \lesssim 60\%$