

3. Aspects of EWSB

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Great success of the Standard Model

BEGHHK (= Higgs) Mechanism









 ${SU(2)}_L \otimes {U(1)}_Y$ v = 246 GeV

$$M_Z \cos \theta_W = M_W = \frac{1}{2} \mathrm{v} \mathrm{g}$$



3





Theory Highlights & Outlook



Beautiful Discovery Boson, J = 0Fermions = Matter : Bosons = Forces

- Fundamental Boson: New interaction which is not gauge
- Composite Boson: N

New underlying dynamics



Beautiful Discovery Boson, J = 0Fermions = Matter : Bosons = Forces

- Fundamental Boson: New interaction which is not gauge
- Composite Boson: New underlying dynamics
 - If New Physics exists at $\Lambda_{\rm NP}$

$$\delta M_H^2 \sim \frac{g^2}{(4\pi)^2} \Lambda_{\rm NP}^2 \log\left(\frac{\Lambda_{\rm NP}^2}{M_H^2}\right)$$

Which symmetry keeps M_H away from Λ_{NP} ?

- Fermions: Chiral Symmetry
- Gauge Bosons: Gauge Symmetry
- Scalar Bosons: Supersymmetry, Scale/Conformal Symmetry ...?



Fermions: $\psi_{L,R} \longrightarrow e^{i\alpha_{L,R}} \psi_{L,R}$	Chiral symmetry						
$\mathcal{L}_{\psi} = \bar{\psi} \left(i\partial \!\!\!/ - m_{\psi} \right) \psi = \bar{\psi}_{L} i\partial \!\!\!/ \psi_{L} + \bar{\psi}_{R} i\partial \!\!\!/ \psi_{R} - m_{\psi} \left(\bar{\psi}_{L} \psi_{R} + \bar{\psi}_{R} \psi_{L} \right)$							
Symmetry recovered at $m_\psi=0$	$\delta m_\psi \propto m_\psi$						
Vectors: $A_{\mu} \longrightarrow A_{\mu} + \partial_{\mu} \theta$	Gauge symmetry						
$\mathcal{L}_{A} \;=\; -rac{1}{4} F_{\mu u}F^{\mu u} + rac{1}{2} m_{A}^{2} A_{\mu}A^{\mu}$							
Symmetry recovered at $m_A = 0$ \longrightarrow	$\delta m_A^2 \propto m_A^2$						

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Symmetry recovered at $m_\psi=0$	$\delta m_\psi \propto m_\psi$						
Vectors: $A_{\mu} \longrightarrow A_{\mu} + \partial_{\mu} \theta$	Gauge symmetry						
${\cal L}_A \;=\; -rac{1}{4} {\cal F}_{\mu u}{\cal F}^{\mu u} + rac{1}{2} m_A^2 {\cal A}_\mu {\cal A}^\mu$							
Symmetry recovered at $m_A = 0$	$\delta m_A^2 \propto m_A^2$						
Scalars: $\mathcal{L}_{\phi} = \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} m_{\phi}^2 \phi^2$	Any symmetry?						
No additional symmetry at $m_{\phi}=0$ \longrightarrow δm_{ϕ}^2	$\propto M^2$ (<i>M</i> = any scale)						

Scalars: $\mathcal{L}_{\phi} = \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} m_{\phi}^{2} \phi^{2}$ Any symmetry?No additional symmetry at $m_{\phi} = 0$ \checkmark $\delta m_{\phi}^{2} \propto M^{2}$ (M = any scale)

• Shift symmetry: $\phi \longrightarrow \phi + c$

Pseudo-Goldstone Boson

Scalars: $\mathcal{L}_{\phi} = \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - \frac{1}{2} m_{\phi}^{2} \phi^{2}$ Any symmetry?No additional symmetry at $m_{\phi} = 0$ \checkmark $\delta m_{\phi}^{2} \propto M^{2}$ (M = any scale)

• Shift symmetry: $\phi \longrightarrow \phi + c$

Pseudo-Goldstone Boson

• Scale symmetry: $x \longrightarrow x/\lambda$, $\phi(x) \longrightarrow \lambda \phi(x/\lambda)$

$$\mathbf{M} = \mathbf{0}$$
 , $\forall \mathbf{M}$

Conformal Invariance. Dilaton

Which symmetry keeps M_H away from Λ_{NP} ?

Quantum Stability: Vectors/fermions protected by gauge/chiral symmetries

	J = 1	$J = \frac{1}{2}$	$\mathbf{J} = 0$
	2 d.o.f.	2 d.o.f.	1 d.o.f.
$ \mathbf{M} = 0$	Trans. Pol.	ψ_L	
	3 d.o.f.	4 d.o.f.	1 d.o.f.
$M \neq 0$	Trans & Long.	ψ_L , ψ_R	

Spin, Mass & Degrees of Freedom

Vector (2 \neq 3) and fermion (2 \neq 4) masses are safe Scalar masses not protected (continuous m \rightarrow 0 limit)

Proposed Solutions:

- SUSY.- Symmetry relates bosons to fermions
- Composite Higss.- Higgs made of fermion constituents
- Pseudo-Goldstone Higgs.-

ATLAS SUSY Searches* - 95% CL Lower Limits

A	TLAS SUSY Sea	rches*	- 95%	6 CI	L Lov	ver Limits			ATLAS Preliminary $\sqrt{s} = 7, 8, 13 \text{ TeV}$
	Model	e, μ, τ, γ	Jets	E_{T}^{miss}	∫£ dt[fb	-1] Mass limit	$\sqrt{s} = 7,3$	B TeV $\sqrt{s} = 13 \text{ TeV}$	Reference
Inclusive Searches	$ \begin{split} & MSUGRA/CMSSM \\ & \varphi_i, \delta \rightarrow \varphi_i^T (\text{compressed}) \\ & \varphi_i, \delta \rightarrow \varphi_i^T (\text{compressed}) \\ & \varphi_i, \delta \rightarrow \varphi_i^T (\text{compressed}) \\ & \varphi_i, \delta \rightarrow \varphi_i^T (- \varphi_i) \\ & \varphi_i, \delta \rightarrow \varphi_i \\ & \varphi_i, \varphi_i \\ $	$\begin{array}{c} 0.3 \ e, \mu/1 \cdot 2 \ \tau \\ 0 \\ mono-jet \\ 0 \\ 3 \ e, \mu \\ 0 \\ 1 \cdot 2 \ \tau + 0 \cdot 1 \\ 2 \ \gamma \\ \gamma \\ 2 \ e, \mu \left(Z \right) \\ 0 \end{array}$	2-10 jets/3 <i>b</i> 2-6 jets 1-3 jets 2-6 jets 2-6 jets 2-6 jets 4 jets 7-11 jets <i>v</i> 0-2 jets 2 jets 2 jets mono-jet	Yes Yes Yes Yes Yes Yes Yes Yes Yes	20.3 36.1 36.1 36.1 36.1 36.1 36.1 36.2 3.2 20.3 13.3 20.3 20.3	8.8 9 9 9 8 8 8 8 8 8 8 8 8 8 8 8 8	1.85 TeV 1.57 TeV 2.01 TeV 1.825 TeV 1.8 TeV 2.0 TeV 1.85 TeV 1.85 TeV 1.85 TeV 1.8 TeV	$\begin{split} m_{ij}^{(2)},m_{ij}^{(2)} & = 0.00 \text{GeV}, m_{i}^{(1)} \text{ goss } ij) + m_{i}^{(2)} \text{ goss } ij) \\ m_{ij}^{(2)},m_{ij}^{(2)},\text{GSeV} & m_{i}^{(2)},\text{GSOGeV} & m_{i}^{(2)},\text{GSOEV} & m_{i}^{(2)},\text{GSOEV} & m_{i}^{(2)},\text{GSOEV} & m_{i}^{(2)},\text$	1507 0825 ATLAS-COLF-0317 022 1604.07773 ATLAS-COLF-0317 022 ATLAS-COLF-0317 020 ATLAS-COLF-0317 030 ATLAS-COLF-0316 0350 1037 05490 ATLAS-COLF-0316 066 1030.02506 1030.02506 1030.02506
3' ^d gen ğ med.	$\begin{array}{c} & gg, g \rightarrow bb \tilde{\chi}_1^0 \\ & gg, g \rightarrow t t \tilde{\chi}_1^0 \\ & gg, g \rightarrow t t \tilde{\chi}_1^- \end{array}$	0 0-1 e,μ 0-1 e,μ	3 b 3 b 3 b	Yes Yes Yes	36.1 36.1 20.1	90 70	1.92 TeV 1.97 TeV 1.37 TeV	$m(\tilde{r}_{1}^{0}) < 600 \text{ GeV}$ $m(\tilde{r}_{1}^{0}) < 200 \text{ GeV}$ $m(\tilde{r}_{1}^{0}) < 300 \text{ GeV}$	ATLAS-CONF-2017-021 ATLAS-CONF-2017-021 1407.0500
3 ^{nl} gen. squarks direct production	$\begin{array}{l} b_1b_1, b_1 \rightarrow b\xi_1^0\\ b_1b_1, b_2 \rightarrow \xi_1^0\\ \tilde{t}_1^1, \tilde{t}_1 \rightarrow b\xi_1^0\\ \tilde{t}_1^2, \tilde{t}_1 \rightarrow b\xi_1^0\\ \tilde{t}_1^1, \tilde{t}_1 \rightarrow b\xi_1^0\\ \tilde{t}_1^1, \tilde{t}_1 \rightarrow b\xi_1^0\\ \tilde{t}_1^1, \tilde{t}_1 \rightarrow b\xi_1^0\\ \tilde{t}_1^1, \tilde{t}_1^1 \rightarrow b\xi_1^0\\ \tilde{t}_1^1, \tilde{t}_2^1 \rightarrow \xi_1^1\\ \tilde{t}_2^1, \tilde{t}_2^1 \rightarrow \xi_1^1\\ \tilde{t}_2^1, \tilde{t}_2^1 \rightarrow \xi_1^1 + L \end{array}$	$\begin{array}{c} 0 \\ 2 \ e, \mu \ (\text{SS}) \\ 0.2 \ e, \mu \\ 0.2 \ e, \mu \\ 0 \\ 2 \ e, \mu \ (Z) \\ 3 \ e, \mu \ (Z) \\ 1.2 \ e, \mu \end{array}$	2 b 1 b 1-2 b 0-2 jets/1-2 b mono-jet 1 b 1 b 4 b	Yes Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 4.7/13.3 20.3/36.1 3.2 20.3 36.1 36.1 36.1	Image: Second		$\begin{split} m(\tilde{r}_1^2) &< 420 \text{GeV} \\ m(\tilde{r}_1^2) &> 2200 \text{GeV}, m(\tilde{r}_1^2) = m(\tilde{r}_1^2) + 100 \text{GeV} \\ m(\tilde{r}_1^2) &= m(\tilde{r}_1^2), m(\tilde{r}_1^2) = 25 \text{GeV} \\ m(\tilde{r}_1^2) + 1 \text{GeV} \\ m(\tilde{r}_1^2) + 1 \text{GeV} \\ m(\tilde{r}_1^2) - 10 \text{GeV} \\ m(\tilde{r}_1^2) - 0 \text{GeV} \\ m(\tilde{r}_1^2) - 0 \text{GeV} \end{split}$	ATLAS.CONF-2017-038 ATLAS.CONF-2017-030 1202:120_ATLAS.CONF-2017-020 1506.08516,ATLAS.CONF-2017-020 1604.07773 1403.5222 ATLAS.CONF-2017-019 ATLAS.CONF-2017-019
EW direct	$ \begin{array}{l} \tilde{\ell}_{1,k}\tilde{\ell}_{1,k}, \tilde{\ell} \rightarrow \ell \ell_1^0 \\ \tilde{\ell}_1\tilde{\ell}_1, \tilde{\ell}_1 \rightarrow \tilde{\ell}_1\ell \ell_1^0 \\ \tilde{\ell}_1\tilde{\ell}_1^-\tilde{\ell}_1^-\tilde{\ell}_1^-\tilde{\ell}_1\ell \ell_1^0 \\ \tilde{\ell}_1^+\tilde{\ell}_1^-\tilde{\ell}_1^-\tilde{\ell}_1^-\ell_1(\tilde{\ell}_1), \tilde{\ell}_1^+\tilde{\ell}_1(\tilde{\ell}_1) \\ \tilde{\ell}_1^+\tilde{\ell}_2^-\rightarrow \tilde{\ell}_1^-\tilde{\ell}_1^-\ell_1(\tilde{\ell}_1), \tilde{\ell}_1^+\tilde{\ell}_1(\tilde{\ell}_1) \\ \tilde{\ell}_1\tilde{\ell}_2^W \tilde{\ell}_1^-\ell$	$2 e, \mu$ $2 e, \mu$ 2τ $3 e, \mu$ $2 \cdot 3 e, \mu$ e, μ, γ $4 e, \mu$ γG $1 e, \mu + \gamma$ γG 2γ	0 0 0-2 jets 0-2 b 0 -	Yes Yes Yes Yes Yes Yes Yes Yes	36.1 36.1 36.1 36.1 20.3 20.3 20.3 20.3	2 90-440 GeV 2 90-440 GeV 2 710 GeV 2 710 GeV 4 71 2 770 GeV 4 74 2 780 GeV 580 GeV 0 115-370 GeV 9 115-370 GeV 580 GeV	TeV $m(\tilde{t}_{2}^{*}) = m(\tilde{t}_{2}^{0})$	$\begin{split} m(\tilde{t}_{1}^{n}) &= 0 \\ m(\tilde{t}_{1}^{n}) &= 0, m(\tilde{t}_{1}^{n}) &= 0, m(\tilde{t}_{1}^{n}) &= 0, m(\tilde{t}_{1}^{n}) &= m(\tilde{t}_{1}^{n}) \\ m(\tilde{t}_{1}^{n}) &= 0, m(\tilde{t}, \tilde{t}) &= 0, m(\tilde{t}_{1}^{n}) &= m(\tilde{t}_{1}^{n}), m(\tilde{t}_{1}^{n}) &= m(\tilde{t}_{1}^{n}), m(\tilde{t}_{1}^{n}) &= 0, m(\tilde{t}_{1}^{$	ATLAS-CONF-2017-639 ATLAS-CONF-2017-639 ATLAS-CONF-2017-639 ATLAS-CONF-2017-639 ATLAS-CONF-2017-639 1501.07110 1403.5066 1507.56493
Long-lived particles	Direct $\hat{k}_1^+\hat{k}_1^-$ prod., long-lived \hat{k}_1^+ Direct $\hat{k}_1^+\hat{k}_1^-$ prod., long-lived \hat{k}_1^+ Stable, stopped \hat{g} R-hadron Stable \hat{g} R-hadron GMSB, stable $\hat{\tau}_1, \hat{k}_1^0 \rightarrow \tau(x, \hat{\mu}) + \tau(x, \mu)$ GMSB, $\hat{k}_1^0 \rightarrow \gamma \hat{G}_1$ long-lived \hat{k}_1^0 $\hat{g}_3, \hat{k}_1^0 \rightarrow x \hat{g}_1 \rightarrow x \hat{G}_2$ GGM $\hat{g}_3, \hat{k}_1^0 \rightarrow X \hat{G}_2$	Disapp. trk dE/dx trk 0 trk dE/dx trk 1-2 µ 2 y displ. ce/cµ/µ displ. vtx + je	1 jet 1-5 jets - - - - - - - - - - - - - - - - - - -	Yes Yes · · · Yes ·	36.1 18.4 27.9 3.2 19.1 20.3 20.3 20.3	। 430 GeV 2 495 GeV 2 80 GeV 2 495 GeV 4 50 GeV 4 51 GeV 5 40 GeV 5 40 GeV 5 1 0 TeV 5 10 TeV 5 1	1.58 TeV 1.57 TeV	$\begin{split} m(\tilde{t}_1^*), m(\tilde{t}_1^*) & \sim 160 \ \text{MeV}, \tau(\tilde{t}_2^*) & = 0.2 \ \text{ns} \\ m(\tilde{t}_1^*), m(\tilde{t}_1^*) & = 160 \ \text{MeV}, \tau(\tilde{t}_1^*) & \leq 15 \ \text{ns} \\ m(\tilde{t}_1^*) & = 100 \ \text{GeV}, 10 \ \mu \text{s} & \tau(\tilde{g}) < 1000 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{s} \\ 10 \ \text{ctarg}, \tau(\tilde{g}) & < 100 \ \text{ctarg}, \tau(\tilde{g}$	ATLAS-CONF-017-017 1066.0532 110.6584 1606.05129 1604.04520 1411.8795 1409.5542 1504.05162 1504.05162
RPV	$ \begin{array}{l} LFV pp {\rightarrow} \psi_r + X, \psi_r {\rightarrow} e\mu/e\tau/\mu\tau \\ Biinear RPV CMSSM \\ K^*_r(x_r^2, \forall {\rightarrow} W^{n_r}_r \mathcal{K}^*_r - exer, \mu\mur \\ \mathcal{K}^*_r(x_r^2, \forall {\rightarrow} W^{n_r}_r \mathcal{K}^*_r - exer, \mu\mur \\ \mathcal{K}^*_r(x_r^2, \forall {\rightarrow} W^{n_r}_r \mathcal{K}^*_r - exer, \\ \mathcal{B}^*_r = aqq \\ \mathcal{B}^*_r = aqq \\ \mathcal{B}^*_r = aqq \\ \mathcal{B}^*_r = aqq \\ \mathcal{B}^*_r = adt_r \mathcal{K}^*_r - qaq \\ \mathcal{B}^*_r = adt_r \mathcal{B}^*_r \mathcal{B}^*_r = adt_$	$e\mu, e\tau, \mu\tau$ $2 e, \mu$ (SS) $4 e, \mu$ $3 e, \mu + \tau$ 0 - 4 $1 e, \mu = 8$ $1 e, \mu = 6$ 0 $2 e, \mu$	- 0-3 b - 1-5 large-R je 1-5 large-R je 3-10 jets/0-4 3-10 jets/0-4 2 jets + 2 b 2 b	- Yes Yes ts - ts - b - b - - -	3.2 20.3 13.3 20.3 14.8 14.8 36.1 36.1 15.4 36.1	57 88 11 11 11 11 11 11 11 11 11	1.9 TeV 1.45 TeV TeV 1.55 TeV 2.1 TeV 1.65 TeV 4-1.45 TeV	$\begin{split} \lambda_{111}^{\prime}=&0.11,\lambda_{122(11),223}=&0.07\\ m(\beta)^{-}=&(\beta)^{-},\alpha_{122}^{\prime}<1m\\ m(\gamma)^{-}=&(0,0,1),\alpha_{122}^{\prime}=&(1-2)\\ m(\gamma)^{-}=&0.02,\alpha_{122}^{\prime}=&(1-2)\\ m(\gamma)^{-}=&10.02,\alpha_{122}^{\prime}=&(1-2)\\ m(\gamma)^{-}=&10.02,\alpha_{122}^{\prime}=&0\\ m(\gamma)$	1607.08079 1404.2500 ATLAS-CONF-2016.075 1405.5068 ATLAS-CONF-2016.067 ATLAS-CONF-2016.067 ATLAS-CONF-2017.013 ATLAS-CONF-2017.013 ATLAS-CONF-2017.015 ATLAS-CONF-2017.035
Other	Scalar charm, $\tilde{c} \rightarrow c \tilde{\ell}_1^0$	0	2 c	Yes	20.3	2 510 GeV		m($\tilde{\chi}_1^0)$ <200 GeV	1501.01325
Only pher	a selection of the available ma omena is shown. Many of the	ss limits on limits are ba	new state: ised on	s or	1	D ⁻¹	1	Mass scale [TeV]	

phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

A. Pich

EW & Higgs Physics

Desperately Seeking SUSY (Dulcinea)

In all the world there is no maiden fairer than the Empress of La Mancha, the peerless SUSY del Toboso

> Your worship should bear in mind that SUSY is badly broken; got heavy through anomaly mediation



coloron(jj) x2

coloron(4i) x2

gluino(3j) x2

aluino(iib) x2

ADD (y+MET), nED=4, MD

QBH, nED=6, MD=4 TeV

ADD (jj), nED=4, MS

13 TeV





CMS Preliminary



NR BH, nED=6, MD=4 TeV String Scale (ii) QBH (jj), nED=4, MD=4 TeV ADD (j+MET), nED=4, MD ADD (ee,µµ), nED=4, MS ADD (yy), nED=4, MS Jet Extinction Scale dijets. A+ LL/RR diiets. A- LL/RR







CMS Exotica Physics Group Summary - ICHEP, 2016

EW & Higgs Physics

Don Quixote and the Windmills

Look, your worship, it's just the spectrum of the Standard Model

Massive & dark SUSY states show up through a hidden portal from a warped dimension





The Heaviest Mass Scale



The top quark:

- Sensitive probe of Electroweak Symmetry Breaking
- Non-perturbative (strong) dynamics?
- Very different from other quarks: $y_b = 0.025$, $y_c = 0.007$...
- Is it really a SM quark?



So far, we only know the decay $~t\to W^+b$ $|V_{tb}|>0.92~(95\%~\text{CL})$

EW & Higgs Physics

Top Mass

• Monte Carlo mass:

 $m_t^{_{MC}} = (173.34 \pm 0.76) \; \text{GeV}$

Lacks a proper QCD definition

 $\Delta m_t^{
m th} = |m_t^{
m pole} - m_t^{
m MC}| pprox \mathcal{O}(1~{
m GeV})$

Hoang-Stewart 0808.0222



Top Mass

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 $m_t^{_{MC}} = (173.34 \pm 0.76) \; \text{GeV}$

Lacks a proper QCD definition $\Delta m_t^{
m th} = |m_t^{
m pole} - m_t^{
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m GeV})$

Hoang-Stewart 0808.0222





Well-defined mass:

 $\sigma_{t\bar{t}}$ (NNLO + NNLL)

Czakon et al., Bärnreuther et al., Cacciari et al.

$t \overline{t} + j \ shape$

Alioli et al

EW & Higgs Physics





$$\Phi(x) = \exp\left\{\frac{i}{v}\vec{\sigma}\vec{\varphi}(x)\right\} \frac{1}{\sqrt{2}} \begin{bmatrix} 0\\ v+H(x) \end{bmatrix}$$

$$V(\Phi) + \frac{\lambda}{4} v^4 = \lambda \left(|\Phi|^2 - \frac{v^2}{2} \right)^2 = \frac{1}{2} M_H^2 H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

$$v = (\sqrt{2} G_F)^{-1/2} = 246 \text{ GeV}$$

 $M_H = (125.09 \pm 0.24) \text{ GeV} \longrightarrow \lambda = \frac{M_H^2}{2v^2} = 0.13$





$$\Phi(x) = \exp\left\{\frac{i}{v}\vec{\sigma}\vec{\varphi}(x)\right\} \frac{1}{\sqrt{2}} \begin{bmatrix} 0\\ v + H(x) \end{bmatrix}$$

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$$v = (\sqrt{2} G_F)^{-1/2} = 246 \text{ GeV}$$

 $M_H = (125.09 \pm 0.24) \text{ GeV} \longrightarrow \lambda = \frac{M_H^2}{2v^2} = 0.13$

$$\frac{M_{H}^{2}}{2v^{2}} = \lambda(\mu) + \frac{2y_{t}^{2}}{(4\pi)^{2}} \left[\lambda + 3\left(y_{t}^{2} - \lambda\right) \log\left(\mu/m_{t}\right)\right] + \cdots$$

 $y_t = \sqrt{2} m_t / v \approx 1$







 $\Lambda = M_{\rm Planck} \quad \Longrightarrow \quad M_H > (129.6 \pm 1.5) \, {\rm GeV}$



Assumes SM valid all the way up to $\Lambda \leq M_{\text{Planck}}$

EW & Higgs Physics







 $\Lambda = M_{\text{Planck}} \longrightarrow M_H > (129.6 \pm 1.5) \text{ GeV}$ [129.8 ± 5.6]



Alekhin et al, 1207.0980



Assumes SM valid all the way up to $\Lambda \leq M_{\text{Planck}}$

EW & Higgs Physics



$$\mathcal{L}_{\Phi} = (D_{\mu}\Phi)^{\dagger}D^{\mu}\Phi - \lambda \left(|\Phi|^2 - rac{v^2}{2}
ight)^2$$

$$\Sigma \equiv (\Phi^{c}, \Phi) = \left(egin{array}{cc} \Phi^{0*} & \Phi^{+} \ -\Phi^{-} & \Phi^{0} \end{array}
ight)$$

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

$$= \frac{1}{2}\operatorname{Tr}\left[(D^{\mu}\Sigma)^{\dagger}D_{\mu}\Sigma\right] - \frac{\lambda}{4}\left(\operatorname{Tr}\left[\Sigma^{\dagger}\Sigma\right] - v^{2}\right)^{2}$$



$\label{eq:stodial} \begin{array}{ll} \Sigma \equiv (\Phi^c, \Phi) = \left(\begin{array}{c} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{array} \right) \\ Symmetry \end{array}$



$$\begin{aligned} \mathcal{L}_{\Phi} &= (D_{\mu}\Phi)^{\dagger}D^{\mu}\Phi - \lambda \left(|\Phi|^2 - \frac{v^2}{2}\right)^2 \\ &= \frac{1}{2}\operatorname{Tr}\left[(D^{\mu}\Sigma)^{\dagger}D_{\mu}\Sigma\right] - \frac{\lambda}{4}\left(\operatorname{Tr}\left[\Sigma^{\dagger}\Sigma\right] - v^2\right)^2 \end{aligned}$$

$SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_{L+R}$ Symmetry: $\Sigma \rightarrow g_L \Sigma g_R^{\dagger}$

Custodial Symmetry

$$\Sigma \equiv (\Phi^{c}, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^{+} \\ -\Phi^{-} & \Phi^{0} \end{pmatrix} \equiv \frac{1}{\sqrt{2}} (v + H) U(\vec{\varphi})$$
$$U(\vec{\varphi}) \equiv \exp\left\{i\vec{\sigma} \cdot \frac{\vec{\varphi}}{v}\right\}$$

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

$$= \frac{1}{2}\operatorname{Tr}\left[(D^{\mu}\Sigma)^{\dagger}D_{\mu}\Sigma\right] - \frac{\lambda}{4}\left(\operatorname{Tr}\left[\Sigma^{\dagger}\Sigma\right] - v^{2}\right)^{2}$$

$$= \frac{v^{2}}{4}\operatorname{Tr}\left[(D^{\mu}U)^{\dagger}D_{\mu}U\right] + O(H/v)$$

 $SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_{L+R}$ Symmetry: $\Sigma \rightarrow g_L \Sigma g_R^{\dagger}$

Custodial Symmetry

$$\Sigma \equiv (\Phi^{c}, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^{+} \\ -\Phi^{-} & \Phi^{0} \end{pmatrix} \equiv \frac{1}{\sqrt{2}} (v + H) U(\vec{\varphi})$$
$$U(\vec{\varphi}) \equiv \exp\left\{i\vec{\sigma} \cdot \frac{\vec{\varphi}}{v}\right\}$$

$$\begin{aligned} \mathcal{L}_{\Phi} &= (D_{\mu}\Phi)^{\dagger}D^{\mu}\Phi - \lambda \left(|\Phi|^{2} - \frac{v^{2}}{2}\right)^{2} \\ &= \frac{1}{2}\operatorname{Tr}\left[(D^{\mu}\Sigma)^{\dagger}D_{\mu}\Sigma\right] - \frac{\lambda}{4}\left(\operatorname{Tr}\left[\Sigma^{\dagger}\Sigma\right] - v^{2}\right)^{2} \\ &= \frac{v^{2}}{4}\operatorname{Tr}\left[(D^{\mu}U)^{\dagger}D_{\mu}U\right] + O(H/v) \end{aligned}$$

 $SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_{L+R}$ Symmetry: $\Sigma \rightarrow g_L \Sigma g_R^{\dagger}$

Same Goldstone Lagrangian as QCD pions:

$$f_{\pi} \rightarrow v$$
 , $\vec{\pi} \rightarrow \vec{\varphi} \rightarrow W_L^{\pm}, Z_L$

EW & Higgs Physics

Electroweak Symmetry Breaking

$$\mathcal{L}_{2} = \frac{v^{2}}{4} \operatorname{Tr} \left(D_{\mu} U^{\dagger} D^{\mu} U \right) \xrightarrow{U=1} \mathcal{L}_{2} = \mathcal{M}_{W}^{2} \mathcal{W}_{\mu}^{\dagger} \mathcal{W}^{\mu} + \frac{1}{2} \mathcal{M}_{Z}^{2} \mathcal{Z}_{\mu} \mathcal{Z}^{\mu}$$
$$\mathbf{M}_{W} = \mathbf{M}_{Z} \cos \theta_{W} = \frac{1}{2} \mathbf{g} \mathbf{v}$$

$$D^{\mu}U = \partial^{\mu}U - i\,\hat{W}^{\mu}U + i\,U\,\hat{B}^{\mu} \qquad , \qquad D^{\mu}U^{\dagger} = \partial^{\mu}U^{\dagger} + i\,U^{\dagger}\hat{W}^{\mu} - i\,\hat{B}^{\mu}U^{\dagger}$$

 $\hat{W}^{\mu} = -\frac{g}{2} \vec{\sigma} \cdot \vec{W}^{\mu}$, $\hat{B}^{\mu} = -\frac{g'}{2} \sigma_3 B^{\mu}$ (explicit symmetry breaking)

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- EW Goldstones are responsible for M_{W,Z} (not the Higgs!)
- QCD pions also generate small W, Z masses:

$$\delta_{\pi}\mathsf{M}_{\mathsf{W}}=rac{1}{2}\,\mathsf{g}\,\mathsf{f}_{\pi}$$

Goldstone interactions are determined by the underlying symmetry

$$\frac{v^{2}}{4} \operatorname{Tr} \left(\partial_{\mu} \mathcal{U}^{\dagger} \partial^{\mu} \mathcal{U} \right) = \partial_{\mu} \varphi^{-} \partial^{\mu} \varphi^{+} + \frac{1}{2} \partial_{\mu} \varphi^{0} \partial^{\mu} \varphi^{0} \\ + \frac{1}{6v^{2}} \left\{ \left(\varphi^{+} \overset{\leftrightarrow}{\partial}_{\mu} \varphi^{-} \right) \left(\varphi^{+} \overset{\leftrightarrow}{\partial}^{\mu} \varphi^{-} \right) + 2 \left(\varphi^{0} \overset{\leftrightarrow}{\partial}_{\mu} \varphi^{+} \right) \left(\varphi^{-} \overset{\leftrightarrow}{\partial}^{\mu} \varphi^{0} \right) \right\} \\ + O \left(\varphi^{6} / v^{4} \right)$$



$$T\left(\varphi^+\varphi^- \to \varphi^+\varphi^-\right) = rac{s+t}{v^2}$$

Non-Linear Lagrangian:

$$2\varphi \rightarrow 2\varphi, 4\varphi, \cdots$$
 related

A. Pich

EW & Higgs Physics

 $U(\vec{\varphi}) \equiv \exp\left\{i \vec{\sigma} \cdot \frac{\vec{\varphi}}{v}\right\}$

Equivalence Theorem





Cornwall–Levin–Tiktopoulos Vayonakis Lee–Quigg–Thacker

$$T(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{s+t}{v^2} + O\left(\frac{M_W}{\sqrt{s}}\right)$$
$$= T(\varphi^+ \varphi^- \to \varphi^+ \varphi^-) + O\left(\frac{M_W}{\sqrt{s}}\right)$$

The scattering amplitude grows with energy

Goldstone dynamics \iff derivative interactions

Tree-level violation of unitarity

EW & Higgs Physics

Longitudinal Polarizations

$$k^{\mu} = \left(k^{0}, 0, 0, |\vec{k}|\right) \quad \Longrightarrow \quad \epsilon^{\mu}_{L}(\vec{k}) = \frac{1}{M_{W}} \left(|\vec{k}|, 0, 0, k^{0}\right) = \frac{k^{\mu}}{M_{W}} + O\left(\frac{M_{W}}{|\vec{k}|}\right)$$

1

1

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$$\begin{bmatrix} w^{*} \mathcal{N}_{V} \mathcal{N}_{W}^{-} \mathcal{N}_{V} \mathcal{N}_{W}^{-} \mathcal{N}_{V} \mathcal{N}_{W}^{-} \mathcal{N}_{W}^{-$$

 $W_I^+W_I^- \rightarrow W_I^+W_I^-$:



$$T_{\rm SM} = \frac{1}{v^2} \left\{ s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2} \right\} = -\frac{M_H^2}{v^2} \left\{ \frac{s}{s - M_H^2} + \frac{t}{t - M_H^2} \right\}$$

Higgs-exchange exactly cancels the O(s,t) terms in the SM

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Higgs-exchange exactly cancels the O(s,t) terms in the SM

When
$$s \gg M_H^2$$
, $T_{\rm SM} \approx -\frac{2M_H^2}{v^2}$, $a_0 \equiv \frac{1}{32\pi} \int_{-1}^1 d\cos\theta \ T_{\rm SM} \approx -\frac{M_H^2}{8\pi v^2}$

Unitarity:

Lee-Quigg-Thacker

$$|a_0| \leq 1$$
 \longrightarrow $M_H < \sqrt{8\pi}v \sqrt{2/3} \approx 1 \text{ TeV}$
 w^+w^-, zz, HH

Status & Outlook

- The SM appears to be the right theory at the EW scale
- The H(125) behaves as the SM scalar boson
- The CKM mechanism works very well (but flavour not understood)
- Neutrinos do have (tiny) masses. Lepton flavour is violated
- Different flavour structure for quarks & leptons
- New physics needed to explain many pending questions: Flavour, CP, baryogenesis, dark matter, cosmology...

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- How far is the Scale of New-Physics Λ_{NP} ?
- Which symmetry keeps M_H away from Λ_{NP}? Supersymmetry, scale/conformal symmetry...
- Which kind of New Physics?

Awaiting great discoveries @ LHC

This, no doubt, Sancho, will be a most mighty and perilous adventure, in which it will be needful for me to put forth all my valour and resolution

Let your worship be calm, senor. Maybe it's all enchantment, like the phantoms last night







Backup Slides

2017 CERN – Fermilab Hadron Collider Physics Summer School CERN, 28 August – 6 September 2017:

EFFECTIVE LAGRANGIAN:



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• Goldstone Bosons

 $\langle 0| \, \bar{q}^{i}_{L} q^{i}_{R} | 0 \rangle$ (QCD), Φ (SM) \longrightarrow $U_{ij}(\phi) = \{ \exp\left(i\vec{\sigma} \cdot \vec{\varphi}/f\right) \}_{ij}$

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 $\mathcal{L}(U) = \sum_n \mathcal{L}_{2n}$

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Parity \longrightarrow even dimension ; $U U^{\dagger} = 1 \implies 2n \ge 2$

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 $U \implies g_L U g_R^{\dagger}$; $g_{L,R} \in SU(2)_{L,R}$

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Derivative
Coupling

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$$\begin{array}{c} \text{Derivative} \\ \text{Coupling} \end{array}$$

Goldstones become free at zero momenta



Possible Scenarios of EWSB

1 SM Higgs: Favoured by EW precision tests

2 Alternative perturbative EWSB:

Scalar Doublets and singlets

$$\rho_{\text{tree}} = \frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i v_i^2 [T_i(T_i + 1) - Y_i^2]}{2 \sum_i v_i^2 Y_i^2}$$

3 Dynamical (non-perturbative) EWSB:

Pseudo-Goldstone Higgs

Scalar Resonance



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Pseudo-Goldstone Higgs

Scalar Resonance





143 +254

 $\Delta \chi^2$

4.5

3.5

3 2.5 2 1.5

1

M fit with M. measuremen

CMS measurement [arXiv:1407.0558]

SM fit w/o M_H measurement ATLAS measurement [arXiv:1406.3827]

SM Higgs

A,(LEP) C fitter

EW & Higgs Physics

G fitter

2σ

1σ

Evidence of Gauge Self-interactions







No evidence of γZZ or ZZZ couplings

EW & Higgs Physics

Flavour Dynamics:

$N_G = 3$ Fermion Families

$$\Phi = \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix} , \qquad \Phi \equiv i\tau_2 \Phi^* = \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} \longrightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} v+H \\ 0 \end{pmatrix}$$
$$\mathcal{L}_{Y} = -\sum_{jk} \left\{ (\bar{u}'_{j}, \bar{d}'_{j})_{L} \begin{bmatrix} c^{(d)}_{jk} \Phi d'_{kR} + c^{(u)}_{jk} \tilde{\Phi} u'_{kR} \end{bmatrix} - (\bar{\nu}'_{j}, \bar{\ell}'_{j})_{L} \frac{c^{(\ell)}_{jk} \Phi \ell'_{kR}}{\ell_{jk}} \right\} + \text{h.c.}$$
$$\bigvee SSB$$
$$\mathcal{L}_{Y} = -\left(1 + \frac{H}{v}\right) \left\{ \bar{d}'_{L} \cdot M'_{d} \cdot d'_{R} + u'_{L} \cdot M'_{u} \cdot u'_{R} + \ell'_{L} \cdot M'_{\ell} \cdot \ell'_{R} + \text{h.c.} \right\}$$

Non-Diagonal Complex Mass Matrices:

 $(M'_f)_{jk} = c_{jk}^{(f)} \frac{v}{2}$

Flavour Dynamics:

$N_G = 3$ Fermion Families

Non-Diagonal Complex Mass Matrices:

 $(M'_f)_{jk} = c_{jk}^{(f)} \frac{v}{2}$

Diagonalization \rightarrow $\begin{cases}
GIM \text{ Mechanism} \\
g_{Hff} = m_f/v & f \\
f = f \\
f$

No Flavour-Changing Neutral Currents

Quark Mixing



Successful CKM Mechanism

EW & Higgs Physics

Bounds on New Flavour Physics



$$L_{\rm eff} = L_{\rm SM} + \sum_{D>4} \sum_{k} \frac{C_k^{(D)}}{\Lambda_{\rm NP}^{D-4}} O_k^{(D)}$$

Isidori. 1302.0661

Operator	Bounds on Λ	in TeV ($c_{\rm NP} = 1$)	Bounds on $c_{\rm NP}$ ($\Lambda = 1 \text{ TeV}$)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^{2}	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K; \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^{3}	2.9×10^{3}	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D; q/p , \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	$1.5 imes 10^4$	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D; q/p , \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^{2}	9.3×10^{2}	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	$3.9 imes 10^{-7}$	1.9×10^{-7}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^{2}	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s}; S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s}; S_{\psi\phi}$

- Generic flavour structure [C_{NP}~O(1)] ruled out at the TeV scale
- $\Lambda_{NP} \sim 1$ TeV requires c_{NP} to inherit the strong SM suppressions (GIM)

Minimal Flavour Violation: The up and down Yukawa matrices are the only source of quark-flavour symmetry breaking D'Ambrosio et al, Buras et al





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Two-Higgs Doublets $v^2 \equiv v_1^2 + v_2^2$, $\tan \beta \equiv v_2/v_1$

5 scalar fields: H^{\pm} , $\varphi_i^0 = (h, H, A)$ [3 × 3 mixing matrix \mathcal{R}_{ij}]

$$g_{_{HVV}}^2 + g_{_{HVV}}^2 + g_{_{AVV}}^2 = (g_{_{HVV}}^{\rm SM})^2$$

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$$\mathsf{M}'_{f} \& \mathsf{Y}'_{f} \text{ unrelated (not simultaneously diagonal)} \implies \mathsf{FCNCs}$$

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Solutions: (same for u_R and ℓ_R Yukawas)

• Natural Flavour Conservation: $\Gamma_1 = 0$ or $\Gamma_2 = 0$ (\mathcal{Z}_2 models)

Glashow-Weinberg, Paschos

• Alignment:
$$\Gamma_2 \propto \Gamma_1 \implies Y_{d,\ell} = \varsigma_{d,\ell} M_{d,\ell}$$
, $Y_u = \varsigma_u^* M_u$

Pich-Tuzón, 0908.1554

A. Pich

EW & Higgs Physics

Effective Field Theory

$$\mathcal{L}_{ ext{eff}} \; = \; \mathcal{L}^{(4)} \; + \; \sum_{D>4} \sum_{i} \; rac{c_{i}^{(D)}}{\Lambda_{ ext{NP}}^{D-4}} \; \mathcal{O}_{i}^{(D)}$$

- Most general Lagrangian with the SM gauge symmetries
- Light (m $\ll \Lambda_{NP}$) fields only
- The SM Lagrangian corresponds to D = 4
- $c_i^{(D)}$ contain information on the underlying dynamics:

$$\mathcal{L}_{\rm NP} \doteq g_{\chi} \left(\bar{q}_L \gamma^{\mu} q_L \right) X_{\mu} \quad \Longrightarrow \quad \frac{g_{\chi}^2}{M_{\chi}^2} \left(\bar{q}_L \gamma^{\mu} q_L \right) \left(\bar{q}_L \gamma_{\mu} q_L \right)$$

2

- Options for H(125):
 - SU(2)_L doublet (SM)
 - Scalar singlet
 - Additional light scalars