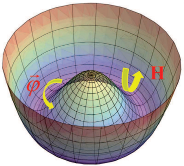
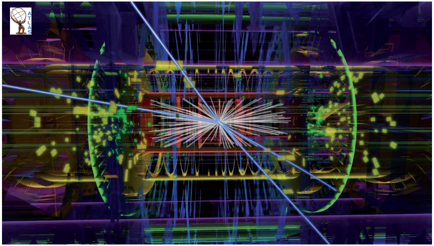
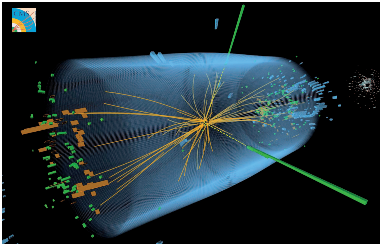
3. Electroweak Effective Theory



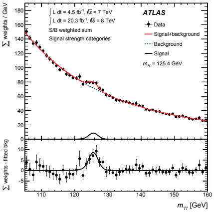
- **Higgs Mechanism**
- **Custodial Symmetry**
- **Equivalence Theorem**
- **EW Effective Theory**
- **Linear Realization**

A New Higgs-Like Boson

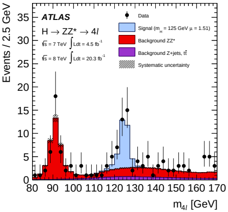




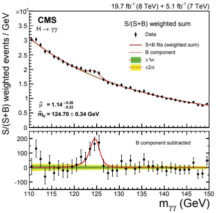
$H \to \gamma\gamma$



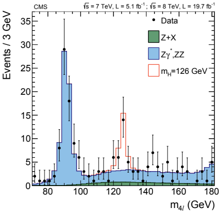
$H \to ZZ^* \to 4\ell$



$H \to \gamma\gamma$



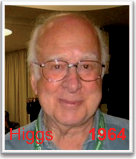
$H \to ZZ^* \to 4\ell$

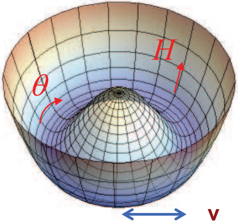


$$M_H = (125.09 \pm 0.21 \pm 0.11)\ \text{GeV}$$

Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism





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

Fundación Príncipe de Asturias

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

Beautiful Discovery

Boson, $J \neq 1$

Fermions = Matter ; Bosons = Forces

- **Fundamental Boson:** **New interaction which is not gauge**
- **Composite Boson:** **New underlying dynamics**

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If New Physics exists at Λ_{NP}

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

Which symmetry keeps M_H away from Λ_{NP}?

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

Symmetries & Mass Scales

Fermions: $\psi_{L,R} \longrightarrow e^{i\alpha_{L,R}}\, \psi_{L,R}$ **Chiral symmetry**

$$\mathcal{L}_\psi = \bar\psi\,(i\not\partial - m_\psi)\,\psi = \bar\psi_L i\not\partial\psi_L + \bar\psi_R i\not\partial\psi_R - m_\psi\,\left(\bar\psi_L\psi_R + \bar\psi_R\psi_L\right)$$

Symmetry recovered at $m_\psi = 0$ ➡ $\delta m_\psi \propto m_\psi$

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Vectors: $A_\mu \longrightarrow A_\mu + \partial_\mu\theta$ **Gauge symmetry**

$$\mathcal{L}_A = -\frac{1}{4}\,F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\,m_A^2\,A_\mu A^\mu$$

Symmetry recovered at $m_A = 0$ ➡ $\delta m_A^2 \propto m_A^2$

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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 $m_\phi = 0$ ➡ $\delta m_\phi^2 \propto M^2$ $(M =$ any scale$)$

Symmetries & Mass Scales

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- **Shift symmetry:** $\phi \;\longrightarrow\; \phi + c$

Pseudo-Goldstone Boson

Symmetries & Mass Scales

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 $m_\phi = 0$ $\Longrightarrow$ $\delta m_\phi^2 \propto M^2$ $(M = \text{any scale})$

- **Shift symmetry:** $\phi \;\longrightarrow\; \phi + c$

Pseudo-Goldstone Boson

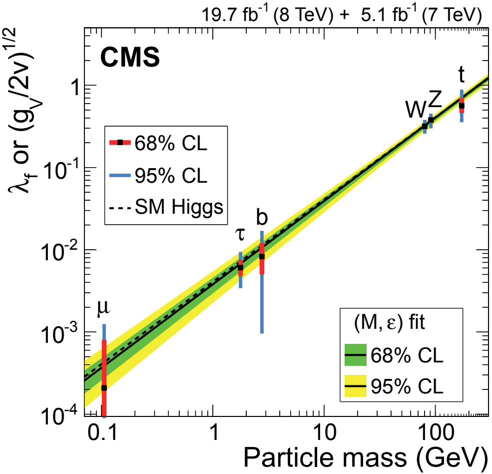
- **Scale symmetry:** $x \;\longrightarrow\; x/\lambda \quad , \quad \phi(x) \;\longrightarrow\; \lambda\,\phi(x/\lambda)$

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

Conformal Invariance. Dilaton

It is a Higgs Boson

$\lambda_f = (m_f/M)^{1+\epsilon}$, $(g_V/2v)^{1/2} = (M_V/M)^{1+\epsilon}$ Ellis-You, 1303.3879



SM: $\epsilon = 0$, $M = v = 246$ GeV

CMS: (95% CL)

$\epsilon \in [-0.054, 0.100]$

$M \in [217, 279]$ GeV

Possible Scenarios of EWSB

❶ **SM Higgs:** Favoured by EW precision tests

❷ **Alternative perturbative EWSB:**

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

❸ **Dynamical (non-perturbative) EWSB:**

Pseudo-Goldstone Higgs

Scalar Resonance

Possible Scenarios of EWSB

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

❸ **Dynamical (non-perturbative) EWSB:**

Pseudo-Goldstone Higgs

Scalar Resonance

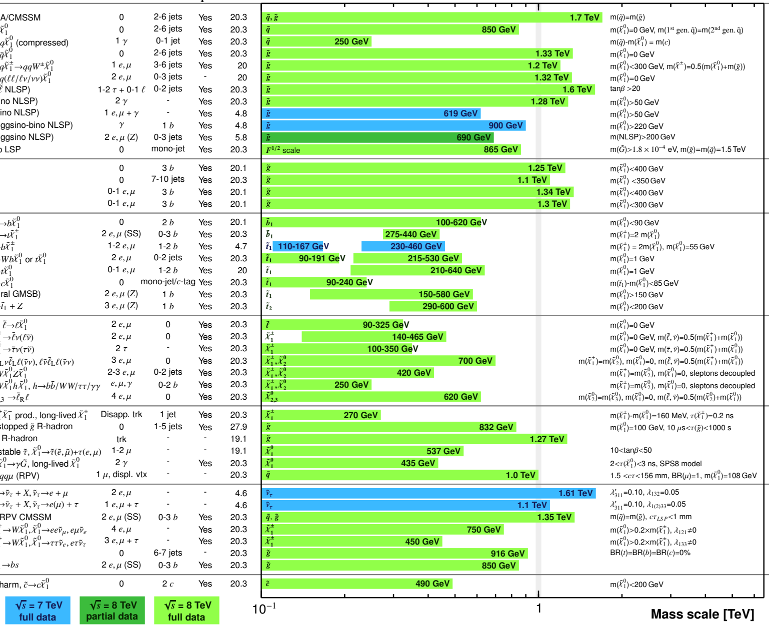
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

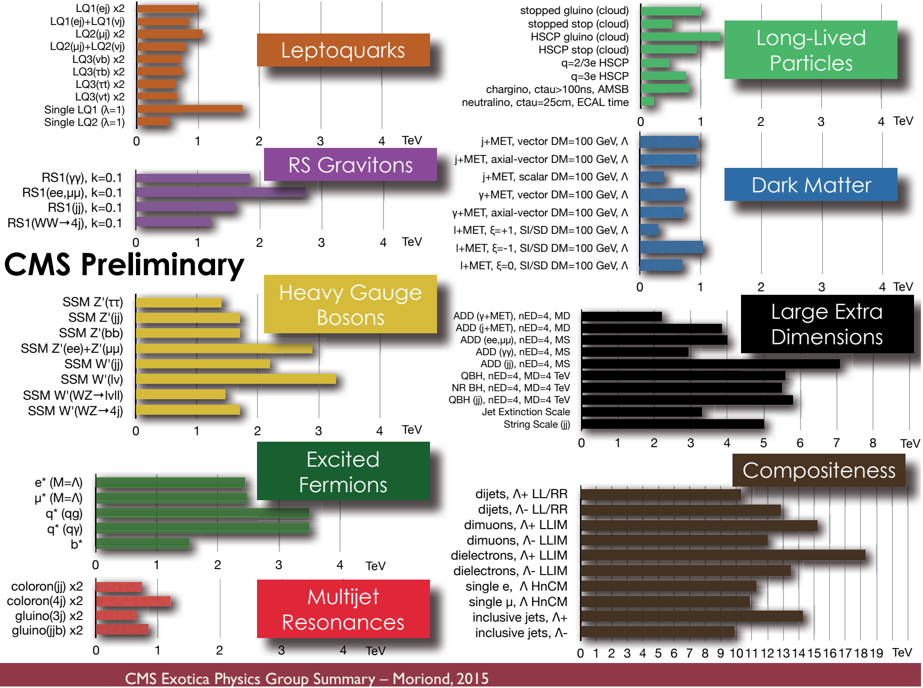
ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$m(\tilde{q})$=$m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$ = $m(c)$	1411.1559
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})$>1.8 × 10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV, 230-460 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^{\pm})$+$m(\tilde{\chi}_1^0)$)	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 GeV	$m(\tilde{\chi}_1^{\pm})$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})$+$\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 e,μ + τ	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325



*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.


CMS Preliminary
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(ττ) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
chargino, ctau>100ns, AMSB
neutralino, ctau=25cm, ECAL time
Dark Matter
j+MET, vector DM=100 GeV, Λ
j+MET, axial-vector DM=100 GeV, Λ
j+MET, scalar DM=100 GeV, Λ
γ+MET, vector DM=100 GeV, Λ
γ+MET, axial-vector DM=100 GeV, Λ
l+MET, ξ=+1, SI/SD DM=100 GeV, Λ
l+MET, ξ=-1, SI/SD DM=100 GeV, Λ
l+MET, ξ=0, SI/SD DM=100 GeV, Λ
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
TeV
CMS Exotica Physics Group Summary – Moriond, 2015

Energy Scale	Fields	Effective Theory
$\Lambda_{NP} \sim$ TeV	S_n, P_n, V_n, A_n, F_n H, W, Z, γ, g τ, μ, e, ν_i t, b, c, s, d, u	Underlying Dynamics

Energy Gap

M_W	H, W, Z, γ, g τ, μ, e, ν_i t, b, c, s, d, u	Standard Model

Effective Field Theory

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}}\, \mathcal{O}_i^{(D)}$$

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

$$\mathcal{L}_{\rm NP} \doteq g_X\, (\bar q_L \gamma^\mu q_L)\, X_\mu \quad \longrightarrow \quad \frac{g_X^2}{M_X^2}\, (\bar q_L \gamma^\mu q_L)\, (\bar q_L \gamma_\mu q_L)$$

- **Options for H(126):**
  - **$\mathbf{SU(2)_L}$ doublet (SM)**
  - **Scalar singlet**
  - **Additional light scalars**

Higgs Mechanism:

Gauge invariance

Massless $W^{\pm}$, Z (spin 1)

3×2 polarizations $= 6$

Higgs Mechanism: 3 additional degrees of freedom $\varphi_i(x)$

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Massless $W^{\pm}$, Z (spin 1)

3×2 polarizations $= 6$

$+$

3 Goldstones $\varphi_i(x)$

SSB $\Downarrow$

Massive $W^{\pm}$, Z

3×3 polarizations $= 9$

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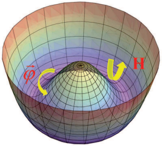
Spontaneous Symmetry Breaking

$$\mathcal{L}_\Phi = (D_\mu\Phi)^\dagger D^\mu\Phi - \mu^2\Phi^\dagger\Phi - \lambda\,(\Phi^\dagger\Phi)^2$$



$\mu^2 < 0$

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

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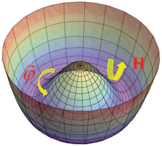

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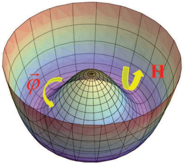
$D_\mu \Phi = (\partial_\mu + \frac{i}{2}\, g\, \vec{\sigma} \cdot \vec{W}_\mu + \frac{i}{2}\, g'\, B_\mu)\, \Phi \quad ; \quad v^2 = -\mu^2/\lambda$

$$(D_\mu \Phi)^\dagger D^\mu \Phi \;\to\; M_W^2\, W_\mu^\dagger W^\mu + \frac{M_Z^2}{2}\, Z_\mu Z^\mu$$

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



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

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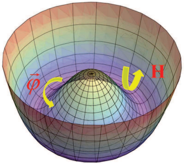

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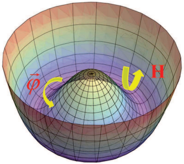

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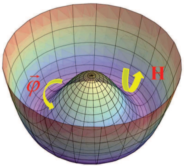

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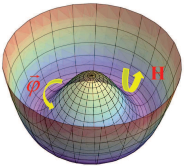

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Same Goldstone Lagrangian as QCD pions:

$$f_\pi \to v \qquad , \qquad \vec\pi \to \vec\varphi \to W_L^\pm, Z_L$$

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

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Parity $\longrightarrow$ even dimension ; $U\,U^\dagger = 1$ $\longrightarrow$ $2n \geq 2$

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$$\boxed{\mathcal{L}_2 \;=\; \frac{f^2}{4}\,\mathrm{Tr}\left(\partial_\mu U^\dagger\,\partial^\mu U\right)}$$

Derivative Coupling

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Derivative Coupling

Goldstones become free at zero momenta

Goldstone Electroweak Effective Theory

$$\boxed{\mathcal{L}_{\mathrm{EW}}^{(2)} \;=\; -\frac{1}{2g^2}\,\langle \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\rangle \;-\; \frac{1}{2g'^{\,2}}\,\langle \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\rangle + \frac{v^2}{4}\,\langle D^\mu U^\dagger D_\mu U\rangle}$$

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

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Electroweak Symmetry Breaking

$$\mathcal{L}_2 = \frac{v^2}{4}\,\mathrm{Tr}\left(D_\mu U^\dagger D^\mu U\right) \quad \xrightarrow{U=1} \quad \mathcal{L}_2 = M_W^2\, W_\mu^\dagger W^\mu + \frac{1}{2} M_Z^2\, Z_\mu Z^\mu$$

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- **EW Goldstones are responsible for $M_{W,Z}$ (not the Higgs!)**
- **QCD pions also generate small W, Z masses:** $\delta_\pi M_W = \frac{1}{2}\, g\, f_\pi$

Goldstone interactions are determined by the underlying symmetry

$$
\begin{aligned}
\frac{v^2}{4}\,\langle \partial_\mu U^\dagger \partial^\mu U \rangle \quad &= \quad \partial_\mu \varphi^- \partial^\mu \varphi^+ + \frac{1}{2}\,\partial_\mu \varphi^0 \partial^\mu \varphi^0 \\
&+ \quad \frac{1}{6v^2}\,\left\{ \left(\varphi^+ \overleftrightarrow{\partial}_\mu \, \varphi^- \right) \left(\varphi^+ \overleftrightarrow{\partial}^\mu \varphi^- \right) + 2 \left(\varphi^0 \overleftrightarrow{\partial}_\mu \, \varphi^+ \right) \left(\varphi^- \overleftrightarrow{\partial}^\mu \varphi^0 \right) \right\} \\
&+ \quad O\left(\varphi^6 / v^4 \right)
\end{aligned}
$$

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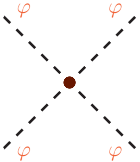

$$T\left(\varphi^+\varphi^- \to \varphi^+\varphi^-\right) \;=\; \frac{s+t}{v^2}$$

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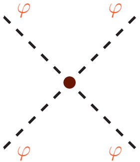

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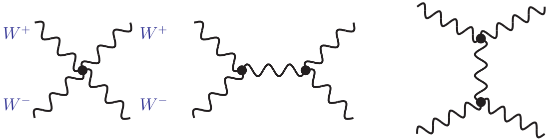
Non-Linear Lagrangian: $2\varphi\to 2\varphi,\ 4\varphi\ \cdots$ related

Equivalence Theorem



Cornwall–Levin–Tiktopoulos

Vayonakis

Lee–Quigg–Thacker

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

The scattering amplitude grows with energy

Goldstone dynamics $\Longleftrightarrow$ **derivative interactions**

Tree-level violation of unitarity

Longitudinal Polarizations

$$k^\mu = \left(k^0, 0, 0, |\vec{k}|\right) \quad \longrightarrow \quad \epsilon_L^\mu(\vec{k}) = \frac{1}{M_W}\,\left(|\vec{k}|, 0, 0, k^0\right) \;=\; \frac{k^\mu}{M_W} + O\left(\frac{M_W}{|\vec{k}|}\right)$$

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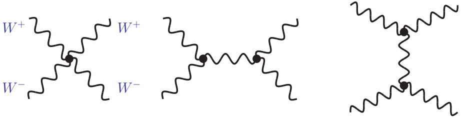
$$k^\mu = \left(k^0, 0, 0, |\vec{k}|\right) \quad \longrightarrow \quad \epsilon_L^\mu(\vec{k}) = \frac{1}{M_W}\,\left(|\vec{k}|, 0, 0, k^0\right) \; = \; \frac{k^\mu}{M_W} + O\left(\frac{M_W}{|\vec{k}|}\right)$$

One naively expects $\quad T(W_L^+ W_L^- \to W_L^+ W_L^-) \;\sim\; g^2\, \frac{|\vec{k}|^4}{M_W^4}$

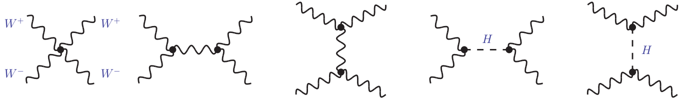


Gauge Cancelation

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

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

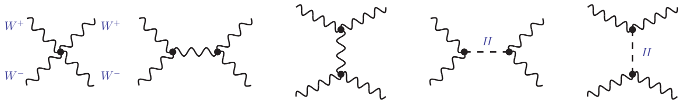
$W_L^+ W_L^- \to W_L^+ W_L^-$:



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

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

$W_L^+ W_L^- \to W_L^+ W_L^-$:



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

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

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

Unitarity:

Lee–Quigg–Thacker

$$|a_0| \leq 1 \quad \Longrightarrow \quad \mathbf{M_H} < \sqrt{8\pi}\,\mathbf{v} \; \underbrace{\sqrt{2/3}}_{\mathbf{W^+W^-,\, ZZ,\, HH}} \approx \mathbf{1\ TeV}$$

What happens in QCD?

- QCD satisfies unitarity (it is a renormalizable theory)
- Pion scattering unitarized by exchanges of resonances (composite objects):
  - P-wave $(J = 1)$ unitarized by ρ exchange
  - S-wave $(J = 0)$ unitarized by σ exchange
- The σ meson is the QCD equivalent of the SM Higgs
- **BUT**, the σ is an 'effective' object generated through π rescattering (summation of pion loops)

Does not seem to work this way in the EW case, but ...

Higher-Order Goldstone Interactions

$$\mathcal{L}_{\mathrm{EW}}^{(4)}\Big|_{\mathrm{CP-even}} = \sum_{i=0}^{14} a_i\, \mathcal{O}_i$$

(Appelquist, Longhitano)

$$\mathcal{O}_0 = v^2 \langle T_L V_\mu \rangle^2$$

$\mathcal{O}_1 = \langle U \hat{B}_{\mu\nu} U^\dagger \hat{W}^{\mu\nu} \rangle$	$\mathcal{O}_2 = i \langle U \hat{B}_{\mu\nu} U^\dagger [V^\mu, V^\nu] \rangle$
$\mathcal{O}_3 = i \langle \hat{W}_{\mu\nu} [V^\mu, V^\nu] \rangle$	$\mathcal{O}_4 = \langle V_\mu V_\nu \rangle \langle V^\mu V^\nu \rangle$
$\mathcal{O}_5 = \langle V_\mu V^\mu \rangle^2$	$\mathcal{O}_6 = 4 \langle V_\mu V_\nu \rangle \langle T_L V^\mu \rangle \langle T_L V^\nu \rangle$
$\mathcal{O}_7 = 4 \langle V_\mu V^\mu \rangle \langle T_L V_\nu \rangle^2$	$\mathcal{O}_8 = \langle T_L \hat{W}_{\mu\nu} \rangle^2$
$\mathcal{O}_9 = -2 \langle T_L \hat{W}_{\mu\nu} \rangle \langle T_L [V^\mu, V^\nu] \rangle$	$\mathcal{O}_{10} = 16 \{\langle T_L V_\mu \rangle \langle T_L V_\nu \rangle\}^2$
$\mathcal{O}_{11} = \langle (D_\mu V^\mu)^2 \rangle$	$\mathcal{O}_{12} = 4 \langle T_L D_\mu D_\nu V^\nu \rangle \langle T_L V^\mu \rangle$
$\mathcal{O}_{13} = 2 \langle T_L D_\mu V_\nu \rangle^2$	$\mathcal{O}_{14} = -2i\, \varepsilon^{\mu\nu\rho\sigma} \langle \hat{W}_{\mu\nu} V_\rho \rangle \langle T_L V_\sigma \rangle$

$$V_\mu \equiv D_\mu U\, U^\dagger \quad , \quad D_\mu V_\nu \equiv \partial_\mu V_\nu - i [\hat{W}_\mu, V_\nu] \quad , \quad (V_\mu, D_\mu V_\nu, T_L) \to g_L\, (V_\mu, D_\mu V_\nu, T_L)\, g_L^\dagger$$

Symmetry breaking: $\quad T_L \equiv U \frac{\sigma_3}{2} U^\dagger \quad , \quad \hat{B}_{\mu\nu} \equiv -g' \frac{\sigma_3}{2} B_{\mu\nu}$

Low-Energy Effective Theory → Power Counting

- **Momentum expansion:** $\Lambda \sim 4\pi v\,,\, M_X$

$$\mathcal{A} = \sum_n \mathcal{A}_n \left(\frac{p}{\Lambda}\right)^n$$

- $U \sim O(p^0) \quad , \quad D_\mu U,\, \hat{W}_\mu,\, \hat{B}_\mu \sim O(p^1) \quad , \quad \hat{W}_{\mu\nu},\, \hat{B}_{\mu\nu} \sim O(p^2)$

- **A general connected diagram with N_d vertices of $O(p^d)$ and L Goldstone loops has a power dimension:**

$$D = 2L + 2 + \sum_d N_d\,(d-2)$$

→ **Finite number of divergences / counterterms**

NLO Predictions

- $\mathcal{L}_{\mathbf{EW}}^{(2)}$ **at one loop:** **Unitarity**

  Non-local (logarithmic) dependences unambiguously predicted

- $\mathcal{L}_{\mathbf{EW}}^{(4)}$ **at tree level:** **Local (polynomic) amplitude**

  Short-distance information encoded in the a_i couplings

  Loop divergences reabsorbed through renormalized a_i

$$a_i \;=\; a_i^r(\mu) + \frac{\gamma_i}{16\pi^2}\,\left[\frac{2\,\mu^{D-4}}{4-D} + \log\left(4\pi\right) - \gamma_E\right]$$

$\hat{a}_i \equiv a_i/(16\pi)^2$ for different limits of the SM

	$M_H \to \infty$	$M_{t',b'} \to \infty$	$M_t \to \infty$
$\hat{a}_0$	$-\frac{3}{4} g'^2 \left[\log\left(M_H/\mu\right) - \frac{5}{12}\right]$	0	$\frac{3}{2}\frac{M_t^2}{v^2}$
$\hat{a}_1$	$-\frac{1}{6}\log\left(M_H/\mu\right) + \frac{5}{72}$	$-\frac{1}{2}$	$\frac{1}{3}\log\left(M_t/\mu\right) - \frac{1}{4}$
$\hat{a}_2$	$-\frac{1}{12}\log\left(M_H/\mu\right) + \frac{17}{144}$	$-\frac{1}{2}$	$\frac{1}{3}\log\left(M_t/\mu\right) - \frac{3}{4}$
$\hat{a}_3$	$\frac{1}{12}\log\left(M_H/\mu\right) - \frac{17}{144}$	$\frac{1}{2}$	$\frac{3}{8}$
$\hat{a}_4$	$\frac{1}{6}\log\left(M_H/\mu\right) - \frac{17}{72}$	$\frac{1}{4}$	$\log\left(M_t/\mu\right) - \frac{5}{6}$
$\hat{a}_5$	$\frac{2\pi^2 v^2}{M_H^2} + \frac{1}{12}\log\left(M_H/\mu\right) - \frac{79}{72} + \frac{9\pi}{16\sqrt{3}}$	$-\frac{1}{8}$	$-\log\left(M_t/\mu\right) + \frac{23}{24}$
$\hat{a}_6$	0	0	$-\log\left(M_t/\mu\right) + \frac{23}{24}$
$\hat{a}_7$	0	0	$\log\left(M_t/\mu\right) - \frac{23}{24}$
$\hat{a}_8$	0	0	$\log\left(M_t/\mu\right) - \frac{7}{12}$
$\hat{a}_9$	0	0	$\log\left(M_t/\mu\right) - \frac{23}{24}$
$\hat{a}_{10}$	0	0	$-\frac{1}{64}$
$\hat{a}_{11}$	—	$-\frac{1}{2}$	$-\frac{1}{2}$
$\hat{a}_{12}$	—	0	$-\frac{1}{8}$
$\hat{a}_{13}$	—	0	$-\frac{1}{4}$
$\hat{a}_{14}$	0	0	$\frac{3}{8}$

Decoupling:

Appelquist–Carazzone

The low-energy effects of heavy particles are either suppressed by inverse powers of the heavy masses, or they get absorbed into renormalizations of the couplings and fields of the EFT obtained by removing the heavy particles

SM: $\mathbf{M_W = M_Z \cos\theta_W = \frac{1}{2}\, g\, v} \quad , \quad \mathbf{M_H = \sqrt{2\lambda}\, v} \quad , \quad \mathbf{M_f = \frac{1}{\sqrt{2}}\, y_f\, v}$

- **Decoupling occurs when $\mathbf{v \to \infty}$, keeping the couplings fixed**

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2} \longrightarrow 0$$

- **There is no decoupling if some $\mathbf{M_i \to \infty}$, keeping $\mathbf{v = 246\ GeV}$ $(\mathbf{g}, \lambda, \mathbf{y_f} \to \infty)$**

Equations of Motion $\longrightarrow$ Redundant Operators

Equivalent to field redefinitions which only affect higher-order terms

For massless fermions: $\partial_\mu \langle T_L V^\mu \rangle = 0 \quad , \quad D_\mu V^\mu = 0$

$$\longrightarrow \left\{ \begin{array}{c} \mathcal{O}_{11} = \mathcal{O}_{12} = 0 \\ \\ \mathcal{O}_{13} = -\frac{g'^2}{4} B_{\mu\nu} B^{\mu\nu} + \mathcal{O}_1 - \mathcal{O}_4 + \mathcal{O}_5 - \mathcal{O}_6 + \mathcal{O}_7 + \mathcal{O}_8 \end{array} \right.$$

Equations of Motion $\longrightarrow$ Redundant Operators

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Heavy top: $\quad \mathcal{O}_{11} \doteq \frac{g^4}{8 M_W^4} \, m_t^2 \left\{ (\bar{t} \gamma_5 t)^2 - 4 \sum_{i,j} (\bar{d}_{iL} t_R) (\bar{t}_R d_{jL}) \, V_{tj} V_{ti}^* \right\}$

Unitary Gauge: $\mathbf{U = 1}$

All invariants reduce to polynomials of gauge fields

- **Bilinear terms:** $\mathcal{O}_0,\ \mathcal{O}_1,\ \mathcal{O}_8,\ \mathcal{O}_{11},\ \mathcal{O}_{12},\ \mathcal{O}_{13}$

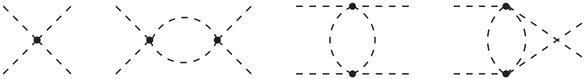
  $\longrightarrow$ **Oblique corrections** $(\Delta r,\ \Delta\rho,\ \Delta k \longleftrightarrow S,\ T,\ U)$

- **Trilinear terms:** $\mathcal{O}_2,\ \mathcal{O}_3,\ \mathcal{O}_9,\ \mathcal{O}_{14}$

- **Quartic terms:** $\mathcal{O}_4,\ \mathcal{O}_5,\ \mathcal{O}_6,\ \mathcal{O}_7,\ \mathcal{O}_{10}$

- $\mathcal{O}_{11} \sim m_t^2\, (\bar\psi\psi)(\bar\psi\psi)$**:** $Z\bar{b}b,\ B^0\text{–}\bar{B}^0,\ \varepsilon_K \ldots$

$\varphi^a\varphi^b \to \varphi^c\varphi^d$:

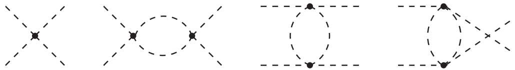


$$\mathcal{A}(\varphi^a\varphi^b \to \varphi^c\varphi^d) \;=\; A(s,t,u)\,\delta_{ab}\,\delta_{cd} + A(t,s,u)\,\delta_{ac}\,\delta_{bd} + A(u,t,s)\,\delta_{ad}\,\delta_{bc}$$

$$\boxed{\begin{aligned} A(s,t,u) \;=\;& \frac{s}{v^2} + \frac{4}{v^2}\left[a_4^r(\mu)\,(t^2+u^2) + 2\,a_5^r(\mu)\,s^2\right] \\ &+ \frac{1}{16\pi^2 v^2}\left\{\frac{5}{9}\,s^2 + \frac{13}{18}\,(t^2+u^2) + \frac{1}{12}\,(s^2-3t^2-u^2)\,\log\left(\frac{-t}{\mu^2}\right)\right. \\ &\left. + \frac{1}{12}\,(s^2-t^2-3u^2)\,\log\left(\frac{-u}{\mu^2}\right) - \frac{1}{2}\,s^2\,\log\left(\frac{-s}{\mu^2}\right)\right\} \end{aligned}}$$

$$a_i \;=\; a_i^r(\mu) + \frac{\gamma_i}{16\pi^2}\left[\frac{2\,\mu^{D-4}}{4-D} + \log\,(4\pi) - \gamma_E\right] \quad , \quad \gamma_4 \;=\; -\frac{1}{12} \quad , \quad \gamma_5 \;=\; -\frac{1}{24}$$

$$\varphi^a \varphi^b \to \varphi^c \varphi^d$$



+ Higgs (tree + 1-loop) contributions

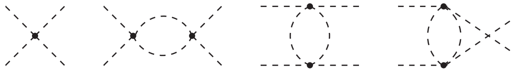
$$\mathcal{L} = \frac{v^2}{4} \langle D^\mu U^\dagger D_\mu U \rangle \left[1 + 2\, a\, \frac{H}{v} + b\, \frac{H^2}{v^2} \right]$$

Espriu–Mescia–Yencho, Delgado–Dobado–Llanes-Estrada

$$\begin{aligned} A(s,t,u) \;=\; & \frac{s}{v^2}\,(1-a^2) + \frac{4}{v^2}\left[a_4^r(\mu)\,(t^2+u^2) + 2\, a_5^r(\mu)\, s^2 \right] \\ & + \frac{1}{16\pi^2 v^2} \left\{ \frac{1}{9}\,(14\, a^4 - 10\, a^2 - 18\, a^2 b + 9\, b^2 + 5)\, s^2 + \frac{13}{18}\,(1-a^2)^2\,(t^2+u^2) \right. \\ & \qquad - \frac{1}{2}\,(2\, a^4 - 2\, a^2 - 2\, a^2 b + b^2 + 1)\, s^2 \,\log\left(\frac{-s}{\mu^2}\right) \\ & \qquad \left. + \frac{1}{12}\,(1-a^2)^2 \left[(s^2 - 3t^2 - u^2)\,\log\left(\frac{-t}{\mu^2}\right) + (s^2 - t^2 - 3u^2)\,\log\left(\frac{-u}{\mu^2}\right) \right] \right\} \end{aligned}$$

$$\gamma_4 = -\tfrac{1}{12}\,(1-a^2)^2 \qquad , \qquad \gamma_5 = -\tfrac{1}{48}\,(2 + 5\, a^4 - 4\, a^2 - 6\, a^2 b + 3\, b^2)$$

$$\varphi^a \varphi^b \to \varphi^c \varphi^d$$



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Espriu–Mescia–Yencho, Delgado–Dobado–Llanes-Estrada

$$\begin{aligned}
A(s,t,u) \;=\;& \frac{s}{v^2}\,(1-a^2) + \frac{4}{v^2}\,\left[a_4^r(\mu)\,(t^2+u^2) + 2\,a_5^r(\mu)\,s^2\right] \\
&+ \frac{1}{16\pi^2 v^2}\,\left\{\frac{1}{9}\,(14\,a^4 - 10\,a^2 - 18\,a^2 b + 9\,b^2 + 5)\,s^2 + \frac{13}{18}\,(1-a^2)^2\,(t^2+u^2)\right. \\
&\qquad - \frac{1}{2}\,(2\,a^4 - 2\,a^2 - 2\,a^2 b + b^2 + 1)\,s^2\,\log\left(\frac{-s}{\mu^2}\right) \\
&\qquad \left. + \frac{1}{12}\,(1-a^2)^2\,\left[(s^2 - 3t^2 - u^2)\,\log\left(\frac{-t}{\mu^2}\right) + (s^2 - t^2 - 3u^2)\,\log\left(\frac{-u}{\mu^2}\right)\right]\right\}
\end{aligned}$$

$$\gamma_4 \;=\; -\tfrac{1}{12}\,(1-a^2)^2 \qquad , \qquad \gamma_5 \;=\; -\tfrac{1}{48}\,(2 + 5\,a^4 - 4\,a^2 - 6\,a^2 b + 3\,b^2)$$

SM: $a = b = 1 \quad , \quad a_4 = a_5 = 0 \quad \Longrightarrow \quad A(s,t,u) \sim \mathcal{O}(M_H^2/v^2)$

Yukawa Couplings

$$\boxed{\mathcal{L}_Y \;=\; -v\, \left\{ \bar{Q}_L\, U(\varphi) \left[\hat{\mathbf{Y}}_{\mathbf{u}}\, \mathcal{P}_+ + \hat{\mathbf{Y}}_{\mathbf{d}}\, \mathcal{P}_- \right] Q_R \;+\; \bar{L}_L\, U(\varphi)\, \hat{\mathbf{Y}}_{\boldsymbol{\ell}}\, \mathcal{P}_+\, L_R \;+\; \text{h.c.} \right\}}$$

$$Q \;=\; \begin{pmatrix} u \\ d \end{pmatrix} \qquad , \qquad L \;=\; \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}$$

$$U(\varphi) \;\to\; g_L\, U(\varphi)\, g_R^\dagger \quad , \quad Q_L \;\to\; g_L\, Q_L \quad , \quad Q_R \;\to\; g_R\, Q_R \quad , \quad \mathcal{P}_\pm \;\to\; g_R\, \mathcal{P}_\pm\, g_R^\dagger$$

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Symmetry Breaking: $\qquad \mathcal{P}_\pm = \frac{1}{2}\left(\mathrm{I}_2 \pm \sigma_3\right)$

Yukawa Couplings

$$\boxed{\mathcal{L}_Y \;=\; -v\;\left\{\bar{Q}_L\, U(\varphi)\left[\hat{\mathbf{Y}}_{\mathbf{u}}\,\mathcal{P}_+ + \hat{\mathbf{Y}}_{\mathbf{d}}\,\mathcal{P}_-\right] Q_R \;+\; \bar{L}_L\, U(\varphi)\,\hat{\mathbf{Y}}_{\boldsymbol{\ell}}\,\mathcal{P}_+\, L_R \;+\; \mathrm{h.c.}\right\}}$$

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Symmetry Breaking: $\mathcal{P}_\pm \;=\; \frac{1}{2}\,(\mathrm{I}_2 \pm \sigma_3)$

Flavour Structure: $\hat{\mathbf{Y}}_{\mathbf{u},\mathbf{d},\boldsymbol{\ell}}$ **3×3 matrices in flavour space**

NLO Operators

Buchalla–Catá

$$\mathcal{O}_{\psi V1} = i\,\bar{Q}_L\gamma^\mu Q_L\ \langle V_\mu T_L\rangle \qquad \mathcal{O}_{\psi V2} = i\,\bar{Q}_L\gamma^\mu T_L Q_L\ \langle V_\mu T_L\rangle \qquad \mathcal{O}_{\psi V3} = i\,\bar{Q}_L\gamma^\mu \tilde{P}_{12} Q_L\ \langle V_\mu \tilde{P}_{21}\rangle$$

$$\mathcal{O}_{\psi V4} = i\,\bar{u}_R\gamma^\mu u_R\ \langle V_\mu T_L\rangle \qquad \mathcal{O}_{\psi V5} = i\,\bar{d}_R\gamma^\mu d_R\ \langle V_\mu T_L\rangle \qquad \mathcal{O}_{\psi V6} = i\,\bar{u}_R\gamma^\mu d_R\ \langle V_\mu \tilde{P}_{21}\rangle$$

$$\mathcal{O}_{\psi V7} = i\,\bar{L}_L\gamma^\mu L_L\ \langle V_\mu T_L\rangle \qquad \mathcal{O}_{\psi V8} = i\,\bar{L}_L\gamma^\mu T_L L_L\ \langle V_\mu T_L\rangle \qquad \mathcal{O}_{\psi V9} = \bar{L}_L\gamma^\mu \tilde{P}_{12} L_L\ \langle V_\mu \tilde{P}_{21}\rangle$$

$$\mathcal{O}_{\psi V10} = \bar{\ell}_R\gamma^\mu \ell_R\ \langle V_\mu T_L\rangle \qquad \mathcal{O}^\dagger_{\psi V3} \qquad \mathcal{O}^\dagger_{\psi V6}$$

$$\mathcal{O}_{\psi S1,2} = \bar{Q}_L\tilde{P}_\pm U Q_R\ \langle D_\mu U^\dagger D^\mu U\rangle \qquad \mathcal{O}_{\psi S3,4} = \bar{Q}_L\tilde{P}_\pm U Q_R\ \langle V_\mu T_L\rangle^2$$

$$\mathcal{O}_{\psi S5} = \bar{Q}_L\tilde{P}_{12} U Q_R\ \langle V_\mu \tilde{P}_{21}\rangle\,\langle V^\mu T_L\rangle \qquad \mathcal{O}_{\psi S6} = \bar{Q}_L\tilde{P}_{12} Q_R\ \langle V_\mu \tilde{P}_{12}\rangle\,\langle V^\mu T_L\rangle$$

$$\mathcal{O}_{\psi S7} = \bar{L}_L\tilde{P}_- U L_R\ \langle D_\mu U^\dagger D^\mu U\rangle \qquad \mathcal{O}_{\psi S8} = \bar{L}_L\tilde{P}_- U L_R\ \langle V^\mu T_L\rangle^2$$

$$\mathcal{O}_{\psi S9} = \bar{L}_L\tilde{P}_{12} U L_R\ \langle V_\mu \tilde{P}_{12}\rangle\,\langle V^\mu T_L\rangle$$

$$\mathcal{O}_{\psi T1} = \bar{Q}_L\sigma^{\mu\nu}\tilde{P}_{12} U Q_R\ \langle V_\mu \tilde{P}_{21}\rangle\,\langle V^\nu T_L\rangle \qquad \mathcal{O}_{\psi T2} = \bar{Q}_L\sigma^{\mu\nu}\tilde{P}_{21} U Q_R\ \langle V_\mu \tilde{P}_{12}\rangle\,\langle V^\nu T_L\rangle$$

$$\mathcal{O}_{\psi T3,4} = \bar{Q}_L\sigma^{\mu\nu}\tilde{P}_\pm U Q_R\ \langle V_\mu \tilde{P}_{12}\rangle\,\langle V_\nu \tilde{P}_{21}\rangle \qquad \mathcal{O}_{\psi T5} = \bar{L}_L\sigma^{\mu\nu}\tilde{P}_{12} U L_R\ \langle V_\mu \tilde{P}_{21}\rangle\,\langle V^\nu T_L\rangle$$

$$\mathcal{O}_{\psi T6} = \bar{L}_L\sigma^{\mu\nu}\tilde{P}_- U L_R\ \langle V_\mu \tilde{P}_{12}\rangle\,\langle V_\nu \tilde{P}_{21}\rangle$$

$$V_\mu = D_\mu U\,U^\dagger \quad , \quad T_L = U\,\frac{\sigma_3}{2}\,U^\dagger \quad , \quad \tilde{P}_{12} = U\,\frac{\sigma_{1+i2}}{2}\,U^\dagger \quad , \quad \tilde{P}_{21} = U\,\frac{\sigma_{1-i2}}{2}\,U^\dagger \quad , \quad \tilde{P}_\pm = U\,P_\pm\,U^\dagger$$

NLO Operators (cont.)

$\mathcal{O}_{LL6} = \bar{Q}_L\gamma^\mu T_L Q_L\ \bar{Q}_L\gamma_\mu T_L Q_L$ $\quad\mathcal{O}_{LL7} = \bar{Q}_L\gamma^\mu T_L Q_L\ \bar{Q}_L\gamma_\mu Q_L$ $\quad\mathcal{O}_{LL8} = \bar{q}_{L\alpha}\gamma^\mu T_L Q_{L\beta}\ \bar{Q}_{L\beta}\gamma_\mu T_L Q_{L\alpha}$

$\mathcal{O}_{LL10} = \bar{Q}_L\gamma^\mu T_L Q_L\ \bar{L}_L\gamma_\mu T_L L_L$ $\quad\mathcal{O}_{LL11} = \bar{Q}_L\gamma^\mu T_L Q_L\ \bar{L}_L\gamma_\mu L_L$ $\quad\mathcal{O}_{LL9} = \bar{Q}_{L\alpha}\gamma^\mu T_L Q_{L\beta}\ \bar{Q}_{L\beta}\gamma_\mu Q_{L\alpha}$

$\mathcal{O}_{LL12} = \bar{Q}_L\gamma^\mu Q_L\ \bar{L}_L\gamma_\mu T_L L_L$ $\quad\mathcal{O}_{LL13} = \bar{Q}_L\gamma^\mu T_L L_L\ \bar{L}_L\gamma_\mu T_L Q_L$ $\quad\mathcal{O}_{LL14} = \bar{Q}_L\gamma^\mu T_L L_L\ \bar{L}_L\gamma_\mu Q_L$

$\mathcal{O}_{LL15} = \bar{L}_L\gamma^\mu T_L L_L\ \bar{L}_L\gamma_\mu T_L L_L$ $\quad\mathcal{O}_{LL16} = \bar{L}_L\gamma^\mu T_L L_L\ \bar{L}_L\gamma_\mu L_L$

$\mathcal{O}_{LR10} = \bar{Q}_L\gamma^\mu T_L Q_L\ \bar{u}_R\gamma_\mu u_R$ $\quad\mathcal{O}_{LR12} = \bar{Q}_L\gamma^\mu T_L Q_L\ \bar{d}_R\gamma_\mu d_R$ $\quad\mathcal{O}_{LR11} = \bar{Q}_L\gamma^\mu t^a T_L Q_L\ \bar{u}_R\gamma_\mu t^a u_R$

$\mathcal{O}_{LR14} = \bar{u}_R\gamma^\mu u_R\ \bar{L}_L\gamma_\mu T_L L_L$ $\quad\mathcal{O}_{LR15} = \bar{d}_R\gamma^\mu d_R\ \bar{L}_L\gamma_\mu T_L L_L$ $\quad\mathcal{O}_{LR13} = \bar{Q}_L\gamma^\mu t^a T_L Q_L\ \bar{d}_R\gamma_\mu t^a d_R$

$\mathcal{O}_{LR16} = \bar{Q}_L\gamma^\mu T_L Q_L\ \bar{\ell}_R\gamma_\mu \ell_R$ $\quad\mathcal{O}_{LR17} = \bar{L}_L\gamma^\mu T_L L_L\ \bar{\ell}_R\gamma_\mu \ell_R$ $\quad\mathcal{O}_{LR18} = \bar{Q}_L\gamma^\mu T_L L_L\ \bar{\ell}_R\gamma_\mu d_R$

$\mathcal{O}_{ST5} = \bar{Q}_L\tilde{P}_+ UQ_R\ \bar{Q}_L\tilde{P}_- UQ_R$ $\quad\mathcal{O}_{ST6} = \bar{Q}_L\tilde{P}_{21} UQ_R\ \bar{Q}_L\tilde{P}_{12} UQ_R$ $\quad\mathcal{O}_{ST7} = \bar{Q}_L t^a\tilde{P}_+ UQ_R\ \bar{Q}_L t^a\tilde{P}_- UQ_R$

$\mathcal{O}_{ST9} = \bar{Q}_L\tilde{P}_+ UQ_R\ \bar{L}_L\tilde{P}_- UL_R$ $\quad\mathcal{O}_{ST10} = \bar{Q}_L\tilde{P}_{21} UQ_R\ \bar{L}_L\tilde{P}_{12} UL_R$ $\quad\mathcal{O}_{ST8} = \bar{Q}_L t^a\tilde{P}_{21} UQ_R\ \bar{Q}_L t^a\tilde{P}_{12} UQ_R$

$\mathcal{O}_{ST11} = \bar{Q}_L\sigma^{\mu\nu}\tilde{P}_+ UQ_R\ \bar{L}_L\sigma_{\mu\nu}\tilde{P}_- UL_R$ $\quad\mathcal{O}_{ST12} = \bar{Q}_L\sigma^{\mu\nu}\tilde{P}_{21} UQ_R\ \bar{L}_L\sigma_{\mu\nu}\tilde{P}_{12} UL_R$

$\mathcal{O}_{FY4} = \bar{Q}_L t^a\tilde{P}_- UQ_R\ \bar{Q}_L t^a\tilde{P}_- UQ_R$ $\quad\mathcal{O}_{FY8} = \bar{Q}_L\sigma^{\mu\nu}\tilde{P}_- UQ_R\ \bar{L}_L\sigma_{\mu\nu}\tilde{P}_- UL_R$

$\mathcal{O}_{FY1} = \bar{Q}_L\tilde{P}_+ UQ_R\ \bar{Q}_L\tilde{P}_+ UQ_R$ $\quad\mathcal{O}_{FY3} = \bar{Q}_L\tilde{P}_- UQ_R\ \bar{Q}_L\tilde{P}_- UQ_R$ $\quad\mathcal{O}_{FY2} = \bar{Q}_L t^a\tilde{P}_+ UQ_R\ \bar{Q}_L t^a\tilde{P}_+ UQ_R$

$\mathcal{O}_{FY5} = \bar{Q}_L\tilde{P}_- UQ_R\ \bar{Q}_R U^\dagger\tilde{P}_+ Q_L$ $\quad\mathcal{O}_{FY7} = \bar{Q}_L\tilde{P}_- UQ_R\ \bar{L}_L\tilde{P}_- UL_R$ $\quad\mathcal{O}_{FY6} = \bar{Q}_L t^a\tilde{P}_- UQ_R\ \bar{Q}_R t^a U^\dagger\tilde{P}_+ Q_L$

$\mathcal{O}_{FY9} = \bar{L}_L\tilde{P}_- UL_R\ \bar{Q}_R U^\dagger\tilde{P}_+ Q_R$ $\quad\mathcal{O}_{FY10} = \bar{L}_L\tilde{P}_- UL_R\ \bar{L}_L\tilde{P}_- UL_R$ $\quad\mathcal{O}_{FY11} = \bar{L}_L\tilde{P}_- UQ_R\ \bar{Q}_R U^\dagger\tilde{P}_+ L_L$

Including a Light (singlet) Higgs in the EWET

Let us assume that h(126) is an $\mathrm{SU}(2)_{\mathrm{L+R}}$ scalar singlet

All Higgsless operators can be multiplied by an arbitrary function of **h**:

$$\mathcal{O}_X \quad \longrightarrow \quad \tilde{\mathcal{O}}_X \equiv \mathcal{F}_X(h)\, \mathcal{O}_X$$

$$\mathcal{F}_X(h) = \sum_{n=0} c_X^{(n)} \left(\frac{h}{v}\right)^n$$

In addition, the LO Lagrangian should include the **scalar potential**:

$$V(h) = v^4 \sum_{n=2} c_V^{(n)} \left(\frac{h}{v}\right)^n$$

Plus operators with derivatives $(\partial_\mu \mathbf{h})$: $\quad F_X \equiv F_X(h)$

$$\mathcal{O}_{D7} = -\langle V_\mu V^\mu \rangle \frac{\partial_\nu h\, \partial^\nu h}{v^2} F_{D7} \qquad \mathcal{O}_{D8} = -\langle V_\mu V_\nu \rangle \frac{\partial^\mu h\, \partial^\nu h}{v^2} F_{D8} \qquad \mathcal{O}_{D11} = \frac{(\partial_\mu h\, \partial^\mu h)^2}{v^4} F_{D11}$$

$$\mathcal{O}_{D6} = -\langle T_L V_\mu V_\nu \rangle \langle T_L V^\mu \rangle \frac{\partial^\nu h}{v} F_{D6} \qquad \mathcal{O}_{D9} = -\langle T_L V_\mu \rangle \langle T_L V^\mu \rangle \frac{\partial_\nu h\, \partial^\nu h}{v^2} F_{D9}$$

$$\mathcal{O}_{D10} = -\langle T_L V_\mu \rangle \langle T_L V_\nu \rangle \frac{\partial^\mu h\, \partial^\nu h}{v^2} F_{D10} \qquad \mathcal{O}_{\psi S18} = \bar{L}_L \tilde{P}_- U L_R \frac{\partial_\mu h\, \partial^\mu h}{v^2} F_{\psi S18}$$

$$\mathcal{O}_{\psi S10} = -i\, \bar{Q}_L \tilde{P}_+ U Q_R \langle T_L V_\mu \rangle \frac{\partial^\mu h}{v} F_{\psi S10} \qquad \mathcal{O}_{\psi S11} = -i\, \bar{Q}_L \tilde{P}_- U Q_R \langle T_L V_\mu \rangle \frac{\partial^\mu h}{v} F_{\psi S11}$$

$$\mathcal{O}_{\psi S12} = -i\, \bar{Q}_L \tilde{P}_{12} U Q_R \langle \tilde{P}_{21} V_\mu \rangle \frac{\partial^\mu h}{v} F_{\psi S12} \qquad \mathcal{O}_{\psi S13} = -i\, \bar{Q}_L \tilde{P}_{21} U Q_R \langle \tilde{P}_{12} V_\mu \rangle \frac{\partial^\mu h}{v} F_{\psi S13}$$

$$\mathcal{O}_{\psi S14} = \bar{Q}_L \tilde{P}_+ U Q_R \frac{\partial_\mu h\, \partial^\mu h}{v^2} F_{\psi S14} \qquad \mathcal{O}_{\psi S15} = \bar{Q}_L \tilde{P}_- U Q_R \frac{\partial_\mu h\, \partial^\mu h}{v^2} F_{\psi S15}$$

$$\mathcal{O}_{\psi S16} = -i\, \bar{L}_L \tilde{P}_- U L_R \langle T_L V_\mu \rangle \frac{\partial^\mu h}{v} F_{\psi S16} \qquad \mathcal{O}_{\psi S17} = -i\, \bar{L}_L \tilde{P}_{12} U L_R \langle \tilde{P}_{21} V_\mu \rangle \frac{\partial^\mu h}{v} F_{\psi S17}$$

$$\mathcal{O}_{\psi T7} = -i\, \bar{Q}_L \sigma_{\mu\nu} \tilde{P}_+ U Q_R \langle T_L V^\mu \rangle \frac{\partial^\nu h}{v} F_{\psi T7} \qquad \mathcal{O}_{\psi T8} = -i\, \bar{Q}_L \sigma_{\mu\nu} \tilde{P}_- U Q_R \langle T_L V^\mu \rangle \frac{\partial^\nu h}{v} F_{\psi T8}$$

$$\mathcal{O}_{\psi T9} = -i\, \bar{Q}_L \sigma_{\mu\nu} \tilde{P}_{21} U Q_R \langle \tilde{P}_{12} V^\mu \rangle \frac{\partial^\nu h}{v} F_{\psi T9} \qquad \mathcal{O}_{\psi T10} = -i\, \bar{Q}_L \sigma_{\mu\nu} \tilde{P}_{12} U Q_R \langle \tilde{P}_{21} V^\mu \rangle \frac{\partial^\nu h}{v} F_{\psi T10}$$

$$\mathcal{O}_{\psi T11} = -i\, \bar{L}_L \sigma_{\mu\nu} \tilde{P}_- U L_R \langle T_L V^\mu \rangle \frac{\partial^\nu h}{v} F_{\psi T11} \qquad \mathcal{O}_{\psi T12} = -i\, \bar{L}_L \sigma_{\mu\nu} \tilde{P}_{12} U L_R \langle \tilde{P}_{21} V^\mu \rangle \frac{\partial^\nu h}{v} F_{\psi T12}$$

Buchalla–Catà–Krause

Linear Realization: $SU(2)_L \otimes U(1)_Y$

Assumes that H(126) and $\vec{\varphi}$ combine into an $SU(2)_L$ doublet:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{2}\,(v+H)\;U(\vec{\varphi})\,\begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

The SM Lagrangian is the low-energy effective theory with $D = 4$

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}}\,\mathcal{O}_i^{(D)}$$

- **1 operator with D = 5:** $\mathcal{O}^{(5)} = \bar{L}_L \tilde{\Phi} \tilde{\Phi}^T L_L^c$ **(violates L by 2 units)**

  Weinberg
- **59 independent $\mathcal{O}_i^{(6)}$ preserving B and L (for 1 generation)**

  Buchmuller–Wyler, Grzadkowski–Iskrzynski–Misiak–Rosiek
- **5 independent $\mathcal{O}_i^{(6)}$ violating B and L (for 1 generation)**

  Weinberg, Wilczek–Zee, Abbott–Wise,

$\mathbf{D = 6}$ Operators (other than 4-fermion ones)

Grzadkowski–Iskrzynski–Misiak–Rosiek

X^3		Φ^6 and $\Phi^4 D^2$		$\psi^2\Phi^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_\Phi$	$(\Phi^\dagger\Phi)^3$	$\mathcal{O}_{e\Phi}$	$(\Phi^\dagger\Phi)(\bar{l}_p e_r \Phi)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{\Phi\Box}$	$(\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{u\Phi}$	$(\Phi^\dagger\Phi)(\bar{q}_p u_r \widetilde{\Phi})$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{\Phi D}$	$(\Phi^\dagger D^\mu\Phi)^\star (\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{d\Phi}$	$(\Phi^\dagger\Phi)(\bar{q}_p d_r \Phi)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\Phi^2$		$\psi^2 X\Phi$		$\psi^2\Phi^2 D$	
$\mathcal{O}_{\Phi G}$	$\Phi^\dagger\Phi\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu} e_r)\,\tau^I\Phi\, W_{\mu\nu}^I$	$\mathcal{O}_{\Phi l}^{(1)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{\Phi\widetilde{G}}$	$\Phi^\dagger\Phi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu} e_r)\,\Phi\, B_{\mu\nu}$	$\mathcal{O}_{\Phi l}^{(3)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{\Phi W}$	$\Phi^\dagger\Phi\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu} T^A u_r)\,\widetilde{\Phi}\, G_{\mu\nu}^A$	$\mathcal{O}_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{\Phi\widetilde{W}}$	$\Phi^\dagger\Phi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu} u_r)\,\tau^I\widetilde{\Phi}\, W_{\mu\nu}^I$	$\mathcal{O}_{\Phi q}^{(1)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{\Phi B}$	$\Phi^\dagger\Phi\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu} u_r)\,\widetilde{\Phi}\, B_{\mu\nu}$	$\mathcal{O}_{\Phi q}^{(3)}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu^I\Phi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{\Phi\widetilde{B}}$	$\Phi^\dagger\Phi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu} T^A d_r)\,\Phi\, G_{\mu\nu}^A$	$\mathcal{O}_{\Phi u}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{\Phi WB}$	$\Phi^\dagger\tau^I\Phi\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu} d_r)\,\tau^I\Phi\, W_{\mu\nu}^I$	$\mathcal{O}_{\Phi d}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{\Phi\widetilde{W}B}$	$\Phi^\dagger\tau^I\Phi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu} d_r)\,\Phi\, B_{\mu\nu}$	$\mathcal{O}_{\Phi ud}$	$i(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{u}_p\gamma^\mu d_r)$

$q = q_L$, $l = l_L$, $u = u_R$, $d = d_R$, $e = e_R$, $\overleftrightarrow{D}_\mu^I \equiv \tau^I\overrightarrow{D}_\mu - \overleftarrow{D}_\mu\tau^I$, $p, r =$ generation indices

$D = 6$ Four-Fermion Operators

Grzadkowski–Iskrzynski–Misiak–Rosiek

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\,\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\,\varepsilon_{jk}\,(\bar{q}_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\,\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\,\varepsilon_{jk}\,(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\,\varepsilon_{jk}\,\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\,\varepsilon_{jk}\,(\bar{q}_s^k u_t)$	$\mathcal{O}_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}\,(\tau^I\varepsilon)_{jk}\,(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\,\varepsilon_{jk}\,(\bar{q}_s^k\sigma^{\mu\nu} u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

$q = q_L$, $l = l_L$, $u = u_R$, $d = d_R$, $e = e_R$, $p, r, s, t =$ generation indices

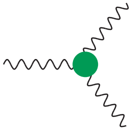
Equivalent Bases of CP-even Operators (EW bosons only)

Willenbrock–Zhang

BW	HISZ	GGPR
$\mathcal{O}_W = \epsilon^{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$	$\mathcal{O}_{WWW} = \mathrm{Tr}\,[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^{\mu}_{\rho}]$	$\mathcal{O}_{3W} = \frac{1}{3!}\, g\, \epsilon_{abc} W^{a\nu}_{\mu} W^{b}_{\nu\rho} W^{c\rho\mu}$
$\mathcal{O}_{\Phi W} = \Phi^\dagger\Phi\; W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$	—
$\mathcal{O}_{\Phi B} = \Phi^\dagger\Phi\; B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$	$\mathcal{O}_{BB} = g'^2\, \lvert H\rvert^2\, B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{\Phi WB} = \Phi^\dagger\sigma^I\Phi\; W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$	—
—	$\mathcal{O}_W = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi)$	$\mathcal{O}_{HW} = ig\,(D^\mu H)^\dagger\sigma^a(D^\nu H)\, W^a_{\mu\nu}$
—	$\mathcal{O}_B = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi)$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$
—	$\mathcal{O}_{DW} = \mathrm{Tr}\Big([D_\mu,\hat{W}_{\nu\rho}][D^\mu,\hat{W}^{\nu\rho}]\Big)$	$\mathcal{O}_{2W} = -\frac{1}{2}\,(D^\mu W^a_{\mu\nu})^2$
—	$\mathcal{O}_{DB} = -\frac{g'^2}{2}\,(\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho})$	$\mathcal{O}_{2B} = -\frac{1}{2}\,(\partial^\mu B_{\mu\nu})^2$
—	—	$\mathcal{O}_W = \frac{ig}{2}\,(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H)\, D^\nu W^a_{\mu\nu}$
—	—	$\mathcal{O}_B = \frac{ig'}{2}\,(H^\dagger \overleftrightarrow{D}^\mu H)\,\partial^\nu B_{\mu\nu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*\,(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D^\mu\Phi)$	$\mathcal{O}_T = \frac{1}{2}\,(H^\dagger \overleftrightarrow{D}^\mu H)^2$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\,\Box\,(\Phi^\dagger\Phi)$	$\mathcal{O}_{\Phi,2} = \frac{1}{2}\,\partial_\mu(\Phi^\dagger\Phi)\,\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}_H = \frac{1}{2}\,(\partial^\mu \lvert H\rvert^2)^2$
$\mathcal{O}_\Phi = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{\Phi,3} = \frac{1}{3}\,(\Phi^\dagger\Phi)^3$	$\mathcal{O}_6 = \lambda\,\lvert H\rvert^6$
—	$\mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger(D^\mu\Phi)\,(\Phi^\dagger\Phi)$	—

BW = Buchmuller–Wyler, Grzadkowski et al. **HISZ** = Hagiwara et al. **GGPR** = Giudice et al.

Anomalous Triple Gauge Couplings



$$\mathcal{L}_{WWV} = -i\, g_{WWV} \left\{ g_1^V \left(W^+_{\mu\nu} W^{-\mu} V^\nu - W^+_\mu W^{-\mu\nu} V_\nu \right) + \kappa_V\, W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}\, W^+_{\mu\nu} W^{-\nu\rho} V_\rho^{\;\mu} \right\}$$

$g_{WW\gamma} = e = g\,\cos\theta_W$, $g_{WWZ} = g\,\cos\theta_W$, $\kappa_V = 1 + \Delta\kappa_V$, $g_1^V = 1 + \Delta g_1^V$

Relevant operators: $\mathcal{O}_W,\, \mathcal{O}_{\Phi WB},\, \mathcal{O}^{(3)}_{\phi l}$ (BW)

$\mathcal{O}_{WWW},\, \mathcal{O}_W,\, \mathcal{O}_B,\, \mathcal{O}_{BW},\, \mathcal{O}_{DW}$ (HISZ)

$\mathcal{O}_{3W},\, \mathcal{O}_{HW},\, \mathcal{O}_{HB},\, \mathcal{O}_{2W},\, \mathcal{O}_W,\, \mathcal{O}_B$ (GGPR)

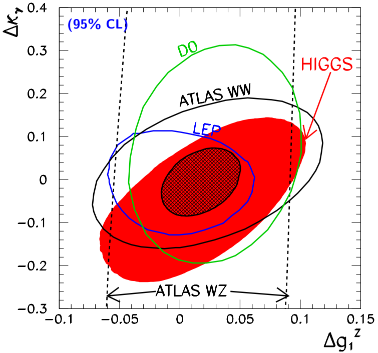
D = 6 Relations: $\lambda_\gamma = \lambda_Z$, $\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W\, \Delta\kappa_\gamma$

Anomalous Triple Gauge Couplings

HISZ basis: $$\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\,\mathcal{O}_n$$ Corbett–Eboli–González-Fraile–González-García

$$\lambda_\gamma = \lambda_Z = \frac{3g^2 M_W^2}{2\Lambda^2}\, f_{WWW} \quad , \qquad \Delta\kappa_\gamma = \frac{g^2 v^2}{8\Lambda^2}\, (f_W + f_B)$$

$$\Delta\kappa_Z = \frac{g^2 v^2}{8\Lambda^2}\left(f_W - \tan^2\theta_W\, f_B\right) \quad , \qquad \Delta g_1^Z = \frac{g^2 v^2}{8\cos^2\theta_W \Lambda^2}\, f_W$$



Higgs data: (90% CL)

$-0.047 \le \Delta g_1^Z \le 0.089$, $-0.19 \le \Delta\kappa_\gamma \le 0.099$

$\rightarrow$ $-0.019 \le \Delta\kappa_Z \le 0.083$

Combined: (90% CL)

$-0.005 \le \Delta g_1^Z \le 0.040$, $-0.058 \le \Delta\kappa_\gamma \le 0.047$

$\rightarrow$ $-0.004 \le \Delta\kappa_Z \le 0.040$

LEP, D0, ATLAS assume $\lambda_\gamma = \lambda_Z = 0$

Global Fit to $\mathcal{L}_{\text{eff}}^{(D=6)}$

Pomarol–Riva

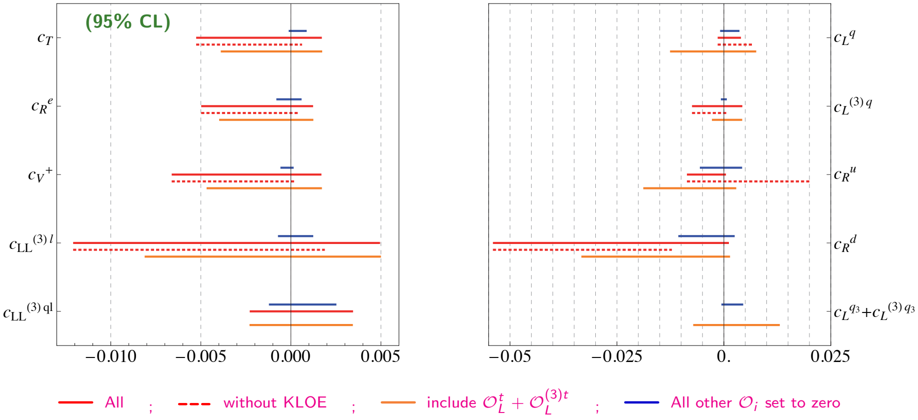
GGPR basis:

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$
$$\mathcal{O}_W = \tfrac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D_\nu W^{a\,\mu\nu}$$
$$\mathcal{O}_B = \tfrac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig (D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig' (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \tfrac{1}{3!} g\, \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R + \text{h.c.}$	$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R + \text{h.c.}$	$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R + \text{h.c.}$
$\mathcal{O}_R^u = i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = i(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_R^d = i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}_{LL}^{(3)\,ql} = (\bar{Q}_L \sigma^a \gamma_\mu Q_L)(\bar{L}_L \sigma^a \gamma^\mu L_L)$	$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$	

LEP-I + SLC + KLOE (CKM univ) + $pp \to l\bar{\nu}$ (LHC)

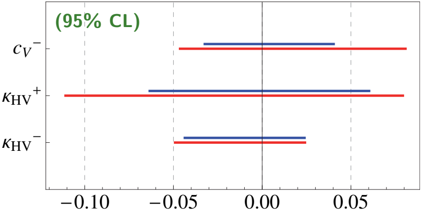


$$\Delta\mathcal{L} = \frac{c_T}{v^2}\,\mathcal{O}_T + \frac{c_V^+}{M_W^2}\,(\mathcal{O}_W + \mathcal{O}_B) + \frac{c_{LL}^{(3)\,l}}{v^2}\,\mathcal{O}_{LL}^{(3)\,l} + \frac{c_R^e}{v^2}\,\mathcal{O}_R^e$$

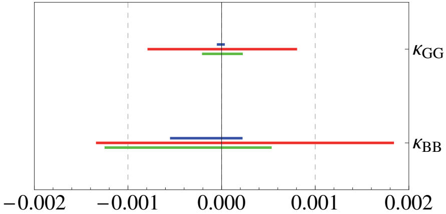
$$+ \frac{c_L^q}{v^2}\,\mathcal{O}_L^q + \frac{c_L^{(3)\,q}}{v^2}\,\mathcal{O}_L^{(3)\,q} + \frac{c_R^u}{v^2}\,\mathcal{O}_R^u + \frac{c_R^d}{v^2}\,\mathcal{O}_R^d + \frac{c_{LL}^{(3)\,ql}}{v^2}\,\mathcal{O}_{LL}^{(3)\,ql}$$

$$c_V^\pm = \tfrac{1}{2}(c_W \pm c_B)$$

LEP-II + $H \to Z\gamma$ (LHC)



$H \to VV, f\bar{f}$ (LHC)



All ; All other $\mathcal{O}_i$ set to zero ; c_H and c_{y_f} effects constrained to be below 50% of SM

$$\Delta\mathcal{L}_{\rm TGC} = \frac{\kappa_{HV}^+}{m_W^2}\,(\mathcal{O}_{HW} + \mathcal{O}_{HB}) + \frac{c_V^- + \kappa_{HV}^-}{2m_W^2}\,\mathcal{O}_+ + \frac{\kappa_{3W}}{m_W^2}\,\mathcal{O}_{3W}$$

$$\Delta\mathcal{L}_{\rm Higgs} = \frac{c_H}{v^2}\,\mathcal{O}_H + \sum_{f=t,b,\tau}\frac{c_{y_f}}{v^2}\,\mathcal{O}_{y_f} + \frac{c_6}{v^2}\,\mathcal{O}_6 + \frac{\kappa_{BB}}{M_W^2}\,\mathcal{O}_{BB} + \frac{\kappa_{GG}}{M_W^2}\,\mathcal{O}_{GG} + \frac{c_V^- - \kappa_{HV}^-}{2M_W^2}\,\mathcal{O}_-$$

$$\mathcal{O}_\pm \equiv (\mathcal{O}_W - \mathcal{O}_B) \pm (\mathcal{O}_{HW} - \mathcal{O}_{HB}) \quad , \quad \mathcal{O}_{WW} = 4\,\mathcal{O}_- + \mathcal{O}_{BB} \quad , \quad \kappa_{HV}^\pm = \tfrac{1}{2}(\kappa_{HW} \pm \kappa_{HB})$$

Backup Slides

Which symmetry keeps M_H away from Λ_{NP} ?

A. Pomarol

Quantum Stability

Vectors/fermions
protected by
gauge/chiral symmetries

SIMPLICITY

falls under quantum fluctuations!

stable	stable	unstable
"Vector" s=1	"fermion" s=1/2	"scalar" s=0

No spin, no "structure" to keep it light

Proposed Solutions

SUSY / Composite Higgs

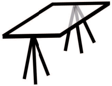
1) Keep the Higgs elementary, but protect it by symmetries: **Supersymmetry**

Higgs (boson) ⟷ Higgsino (fermion)

2) The Higgs is not elementary: **Composite Higgs**

Higgs made of fermions

(as a pion in strong interactions)



Spin, Mass & Degrees of Freedom

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

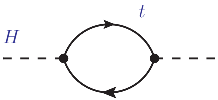
Vector $(2\neq 3)$ and fermion masses are safe $(2\neq 4)$

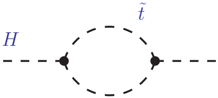
Scalar masses not protected (continuous $m\to 0$ limit)

Higgs Self-energy: **The top is the largest SM contribution**

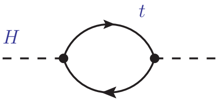
δM_H^2 stabilized through new-physics contributions

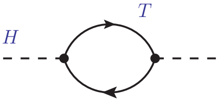
- **SUSY:** stop loops



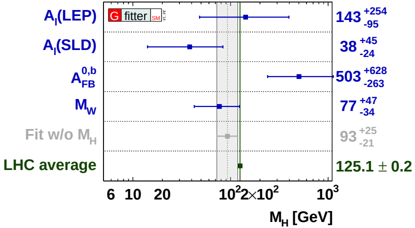


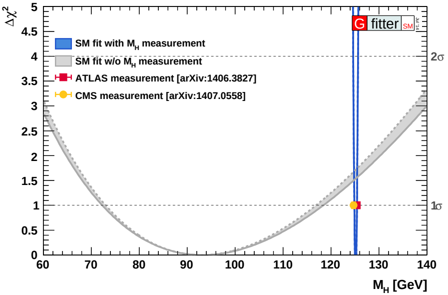
- **Composite Higgs:** fermionic top partners

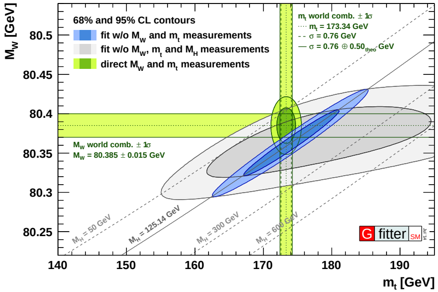




SM Higgs

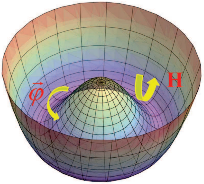






Favoured by EW precision tests

SM Higgs Potential

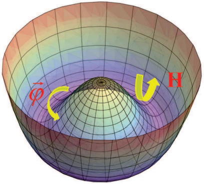


$$\Phi(x) \;=\; \exp\left\{\frac{i}{v}\,\vec{\sigma}\,\vec{\varphi}(x)\right\}\;\frac{1}{\sqrt{2}}\;\begin{bmatrix} 0 \\ v + H(x)\end{bmatrix}$$

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

$$\boxed{\begin{array}{c} v \;=\; \left(\sqrt{2}\,G_F\right)^{-1/2} \;=\; 246\ \mathrm{GeV} \\[1em] M_H = (125.09 \pm 0.24)\ \mathrm{GeV} \quad \Longrightarrow \quad \lambda \;=\; \dfrac{M_H^2}{2v^2} \;=\; 0.13 \end{array}}$$

SM Higgs Potential



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

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

$$v \; = \; \left(\sqrt{2}\, G_F \right)^{-1/2} \; = \; 246\ \mathrm{GeV}$$

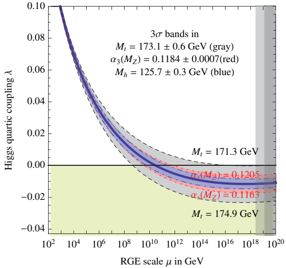
$$M_H = (125.09 \pm 0.24)\ \mathrm{GeV} \quad \Longrightarrow \quad \lambda \; = \; \frac{M_H^2}{2v^2} \; = \; 0.13$$

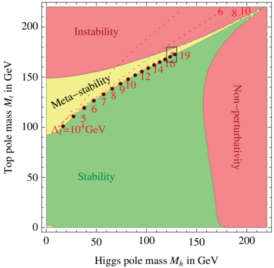
$$M_H^2 \; = \; 2v^2 \lambda(\mu) \; + \; \frac{2v^2 y_t^2}{(4\pi)^2} \; \left[2\lambda + 3 \left(\lambda - y_t^2 \right) \log\left(m_t^2/\mu^2 \right) \right] + \cdots$$

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

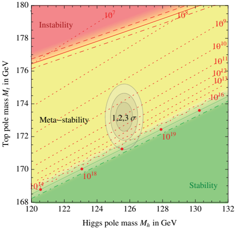
Vacuum Stability: $\lambda(\Lambda) \geq 0$

Degrassi et al, 1205.6497, 1307.3536





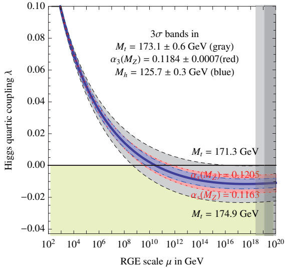
$\Lambda = M_{\mathrm{Planck}} \quad \Longrightarrow \quad M_H > (129.1 \pm 1.5)\ \mathrm{GeV}$

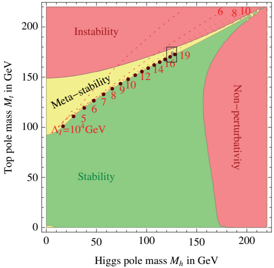


Assumes SM valid all the way up to $\Lambda \leq M_{\mathrm{Planck}}$

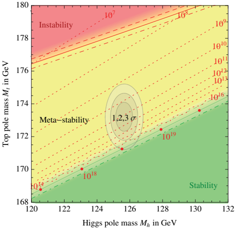
Vacuum Stability: $\lambda(\Lambda) \geq 0$

Degrassi et al, 1205.6497, 1307.3536

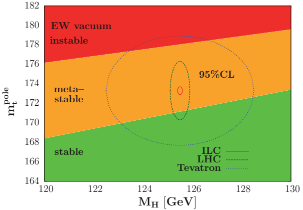




$\Lambda = M_{\mathrm{Planck}}$ ➡ $M_H > (129.1 \pm 1.5)$ GeV [129.8 ± 5.6]

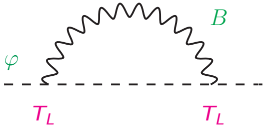


Alekhin et al, 1207.0980



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

Custodial Symmetry Breaking: $\hat{B}_\mu \equiv -g' \frac{\sigma_3}{2} B_\mu$



$$\longrightarrow \quad \langle V_\mu T_L V^\mu T_L \rangle$$

$$V_\mu \equiv D_\mu U U^\dagger = i \frac{\sqrt{2}}{v} D_\mu \Phi + \cdots \qquad , \qquad T_L \equiv U \frac{\sigma_3}{2} U^\dagger \qquad , \qquad T_L T_L = \frac{1}{4} I_2$$

$$\begin{aligned} \langle V_\mu T_L V^\mu T_L \rangle &= \langle V_\mu T_L \rangle \langle V^\mu T_L \rangle - \frac{1}{2} \langle V_\mu V^\mu \rangle \langle T_L T_L \rangle \\ &= \langle V_\mu T_L \rangle \langle V^\mu T_L \rangle - \frac{1}{4} \langle V_\mu V^\mu \rangle \end{aligned}$$

$$\longrightarrow \qquad \mathcal{O}_0 = v^2 \langle V_\mu T_L \rangle \langle V^\mu T_L \rangle$$

$\varphi^a \varphi^b \to \varphi^c \varphi^d$:

- **Isospin:**

$$\begin{aligned} A_0(s,t,u) &= 3\,A(s,t,u) + A(t,s,u) + A(u,t,s) \\ A_1(s,t,u) &= A(t,s,u) - A(u,t,s) \\ A_2(s,t,u) &= A(t,s,u) + A(u,t,s) \end{aligned}$$

- **Partial Waves:**

$$\begin{aligned} A_{IJ}(s) &= \frac{1}{64\pi} \int_{-1}^{+1} d\cos\theta \; P_J(\cos\theta)\; A_I(s,t,u) \\ \sigma(s) &= \frac{64\pi}{s} \sum_{I,J} (2I+1)\,(2J+1)\;|A_{IJ}|^2 \end{aligned}$$

$$\boxed{\begin{aligned} A_{00}(s) &= \frac{s}{16\pi v^2}\;\left\{1 + \frac{s}{16\pi^2 v^2}\;\left[\frac{101}{36} + \frac{64\pi^2}{3}\,(7\,a_4^r + 11\,a_5^r) - \frac{25}{18}\;\log\left(\frac{s}{\mu^2}\right) + i\,\pi\right] + \cdots\right\} \\ A_{11}(s) &= \frac{s}{96\pi v^2}\;\left\{1 + \frac{s}{16\pi^2 v^2}\;\left[\frac{1}{9} + 64\pi^2\,(a_4^r - 2\,a_5^r) + i\,\frac{\pi}{6}\right] + \cdots\right\} \\ A_{20}(s) &= \frac{-s}{32\pi v^2}\;\left\{1 + \frac{s}{16\pi^2 v^2}\;\left[-\frac{91}{36} - \frac{256\pi^2}{3}\,(2\,a_4^r + a_5^r) + \frac{10}{9}\;\log\left(\frac{s}{\mu^2}\right) - i\,\frac{\pi}{2}\right] + \cdots\right\} \end{aligned}}$$

Power Counting

- **Momentum expansion:** $\Lambda \sim 4\pi v\,,\ M_X$

$$T = \sum_n T_n \left(\frac{p}{\Lambda}\right)^n$$

Power Counting

- **Momentum expansion:** $\Lambda \sim 4\pi v\,,\ M_X$

$$\mathbf{T} = \sum_n \mathbf{T_n} \left(\frac{\mathbf{p}}{\Lambda}\right)^{\mathbf{n}}$$

- **Loop Expansion:** **A generic L-loop diagram $\mathcal{D}$ scales as**

$$\boxed{\begin{gathered}\mathcal{D} \sim \frac{(yv)^{\nu}(gv)^{m+2r+2x+u+z}}{v^{F_L+F_R-2-2\omega}}\,\frac{p^d}{\Lambda^{2L}}\;\bar\psi_L^{F_L^1}\psi_L^{F_L^2}\bar\psi_R^{F_R^1}\psi_R^{F_R^2}\left(\frac{X_{\mu\nu}}{v}\right)^V\left(\frac{\varphi}{v}\right)^B\left(\frac{h}{v}\right)^H \\[1em] d \equiv 2L+2-\tfrac{1}{2}(F_L+F_R)-V-\nu-m-2r-2x-u-z-2\omega\end{gathered}}$$

Buchalla–Catà–Krause

\# external fields: $F_L = F_L^1 + F_L^2$, $F_R = F_R^1 + F_R^2$, B , H , V (X_μ = gauge boson)

\# vertices: $m \equiv \sum_l m_l\ (X_\mu \varphi^l)$, $r \equiv \sum_s r_s\ (X_\mu^2 \varphi^s)$, $u\ (X_\mu^3)$, $x\ (X_\mu^4)$, $\omega \equiv \sum_q \omega_q\ (h^q)$

$\nu \equiv \sum_k \nu_k\ (\bar\psi\psi\varphi^k) + \sum_{t,b} \tau_{tb}\ (\bar\psi\psi\varphi^t h^b)$, $z \equiv z_L + z_R\ (\bar\psi_\lambda\psi_\lambda X_\mu\,,\ \lambda = L, R)$

Too many operators/couplings $\longrightarrow$ **Further input needed**

$$\mathcal{F}_X(h) \;=\; \sum_{n=0} c_X^{(n)} \,\left(\frac{h}{v}\right)^n \;=\; \sum_{n=0} \tilde{c}_X^{(n)} \,\left(\frac{g_h\, h}{\Lambda_{\mathrm{NP}}}\right)^n$$

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- **Weak coupling:** $g_h \ll 1$

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- **Weak coupling:** $g_h \ll 1$

- **Strong coupling:** $g_h \sim 4\pi = \Lambda_{\mathrm{NP}}/f$ $\longrightarrow$ $\mathcal{F}_X(h/f)$

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$$\mathcal{F}_X(h) \;=\; \sum_{n=0} c_X^{(n)} \left(\frac{h}{v}\right)^n \;=\; \sum_{n=0} \tilde{c}_X^{(n)} \left(\frac{g_h\, h}{\Lambda_{\mathrm{NP}}}\right)^n$$

- **Weak coupling:** $g_h \ll 1$
- **Strong coupling:** $g_h \sim 4\pi = \Lambda_{\mathrm{NP}}/f$ $\longrightarrow$ $\mathcal{F}_X(h/f)$
- **v $\ll$ f** $\longrightarrow$ $\xi \equiv \frac{v^2}{f^2}$, $c_X^{(n)} \;=\; \tilde{c}_X^{(n)}\, \xi^{n/2}$

Shifts of SM parameters:

$$\mathcal{L}_{\mathrm{eff}}^{(D=6)} = \sum_i \frac{C_i}{\Lambda^2}\, \mathcal{O}_i$$

$$V(H) = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2}\right)^2 - \frac{C_\Phi}{\Lambda^2} \left(\Phi^\dagger \Phi\right)^3 \qquad \Longrightarrow \qquad v_{_T} = \left(1 + \frac{3C_\Phi}{8\lambda}\,\frac{v^2}{\Lambda^2}\right) v$$

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Canonical Normalization: $H \to c_H^{\mathrm{kin}}\, H \quad , \quad c_H^{\mathrm{kin}} = \left(C_{\Phi\Box} - \frac{1}{4}\, C_{\Phi D}\right) \frac{v^2}{\Lambda^2}$

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Canonical Normalization: $H \to c_H^{\text{kin}}\, H \quad , \quad c_H^{\text{kin}} = \left(C_{\Phi\Box} - \frac{1}{4}\,C_{\Phi D}\right)\frac{v^2}{\Lambda^2}$

$$\longrightarrow \quad M_H^2 = 2\lambda\, v_T^2\left(1 - \frac{3C_\Phi}{2\lambda}\,\frac{v^2}{\Lambda^2} + 2\, c_H^{\text{kin}}\right)$$

Shifts of SM parameters:

$$\mathcal{L}_{\mathrm{eff}}^{(D=6)} = \sum_i \frac{C_i}{\Lambda^2}\, \mathcal{O}_i$$

$$V(H) = \lambda \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2 - \frac{C_\Phi}{\Lambda^2} \left(\Phi^\dagger\Phi\right)^3 \quad \longrightarrow \quad v_T = \left(1 + \frac{3C_\Phi}{8\lambda}\,\frac{v^2}{\Lambda^2}\right) v$$

Canonical Normalization: $H \to c_H^{\mathrm{kin}}\, H \quad , \quad c_H^{\mathrm{kin}} = \left(C_{\Phi\Box} - \frac{1}{4}\, C_{\Phi D}\right) \frac{v^2}{\Lambda^2}$

$$\longrightarrow \quad M_H^2 = 2\lambda\, v_T^2 \left(1 - \frac{3C_\Phi}{2\lambda}\,\frac{v^2}{\Lambda^2} + 2\, c_H^{\mathrm{kin}}\right)$$

Flavour: $\mathcal{Y}_f \not\propto M_f$

$$\mathcal{L} = -\bar{Q}_L^r \left[Y_d\right]_{rs} \Phi\, d_R^s + \cdots \quad \longrightarrow$$

$$[M_f]_{rs} = \frac{v_T}{\sqrt{2}} \left([Y_\psi]_{rs} - \frac{v^2}{2\Lambda^2}\, [C_{f\Phi}]_{rs}\right)$$

$$[\mathcal{Y}_f]_{rs} = \frac{1}{v_T}\, [M_f]_{rs} \left(1 + c_H^{\mathrm{kin}}\right) - \frac{v^2}{\Lambda^2}\, [C_{f\Phi}]_{rs}$$

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$$\longrightarrow \quad M_H^2 = 2\lambda\, v_T^2\left(1 - \frac{3C_\Phi}{2\lambda}\,\frac{v^2}{\Lambda^2} + 2\, c_H^{\rm kin}\right)$$

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$$\frac{4\,G_F}{\sqrt{2}} = \frac{2}{v_T^2} + \frac{1}{\Lambda^2}\left(2\left[C_{\Phi l}^{(3)}\right]_{ee} + 2\left[C_{\Phi l}^{(3)}\right]_{\mu\mu} - \left[C_{ll}\right]_{\mu e, e\mu} - \left[C_{ll}\right]_{e\mu,\mu e}\right)$$

Gauge Fields:

$$\mathcal{L}_{\text{eff}}^{(D=6)} = \sum_i \frac{C_i}{\Lambda^2}\,\mathcal{O}_i$$

Alonso et al

$$\bar{g}' = g'\left(1 + C_{\Phi B}\,\frac{v_T^2}{\Lambda^2}\right) \quad , \quad \bar{g} = g\left(1 + C_{\Phi W}\,\frac{v_T^2}{\Lambda^2}\right) \quad , \quad \bar{g}_s = g_s\left(1 + C_{\Phi G}\,\frac{v_T^2}{\Lambda^2}\right)$$

$$\tan\bar{\theta}_W = \frac{\bar{g}'}{\bar{g}} + \frac{v_T^2}{2\Lambda^2}\left(1 - \frac{\bar{g}'^2}{\bar{g}^2}\right) C_{\Phi WB}$$

$$M_W^2 = \frac{v_T^2}{4}\,\bar{g}^2 \quad , \quad M_Z^2 = \frac{v_T^2}{4}\left(\bar{g}^2 + \bar{g}'^2\right) + \frac{\bar{v}_T^4}{8\Lambda^2}\left\{\left(\bar{g}^2 + \bar{g}'^2\right) C_{\Phi D} + 4\,\bar{g}\,\bar{g}'\;C_{\Phi WB}\right\}$$

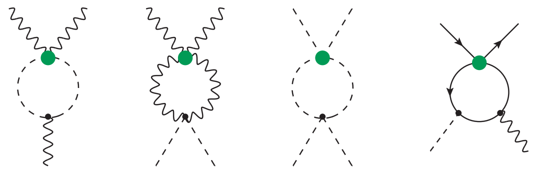
$$\bar{e} = \bar{g}\,\sin\bar{\theta}_W\left\{1 - \cot\bar{\theta}_W\,\frac{\bar{v}_T^2}{2\Lambda^2}\,C_{\Phi WB}\right\} \quad , \quad \bar{g}_Z = \frac{\bar{e}}{\sin\bar{\theta}_W\cos\bar{\theta}_W}\left\{1 + \frac{\bar{g}^2 + \bar{g}'^2}{2\bar{g}\bar{g}'}\,\frac{\bar{v}_T^2}{\Lambda^2}\,C_{\Phi WB}\right\}$$

$$\rho \equiv \frac{\bar{g}^2 M_Z^2}{\bar{g}_Z^2 M_W^2} = 1 + \frac{\bar{v}_T^2}{2\Lambda^2}\,C_{\Phi D}$$

Renormalization Group Equations

$$\mathcal{L}_{\mathrm{eff}}^{(D=6)} = \sum_i \frac{C_i(\mu)}{\Lambda^2}\, \mathcal{O}_i(\mu)$$

Loop Corrections



$$\boxed{\mu\, \frac{\mathrm{d}C_i}{\mathrm{d}\mu} = \sum_j \frac{\gamma_{ij}}{16\pi^2}\, C_j \quad \Longrightarrow \quad C_i(\mu) = C_i(\Lambda) - \sum_j \frac{\gamma_{ij}}{16\pi^2}\, C_j(\Lambda)\, \log\left(\frac{\Lambda}{\mu}\right)}$$

Anomalous Dimensions: γ_{ij}

Anomalous Dimensions γ_{ij}

Complete 59×59 matrix computed in the BW basis: Jenkins et al.

$$\gamma \sim O\left(1, g^2, \lambda, y^2, g^4, g^2\lambda, g^2 y^2, \lambda^2, \lambda y^2, y^4, g^6, g^4\lambda, g^6\lambda\right)$$

	g^3X^3	H^6	H^4D^2	$g^2X^2H^2$	$y\psi^2H^3$	$gy\psi^2XH$	ψ^2H^2D	ψ^4
g^3X^3	g^2	0	0	1	0	0	0	0
H^6	$g^6\lambda$	λ, g^2, y^2	$g^4, g^2\lambda, \lambda^2$	$g^6, g^4\lambda$	$\lambda y^2, y^4$	0	$\lambda y^2, y^4$	0
H^4D^2	g^6	0	g^2, λ, y^2	g^4	y^2	g^2y^2	g^2, y^2	0
$g^2X^2H^2$	g^4	0	1	g^2, λ, y^2	0	y^2	1	0
$y\psi^2H^3$	g^6	0	g^2, λ, y^2	g^4	g^2, λ, y^2	$g^2\lambda, g^4, g^2y^2$	g^2, λ, y^2	λ, y^2
$gy\psi^2XH$	g^4	0	0	g^2	1	g^2, y^2	1	1
ψ^2H^2D	g^6	0	g^2, y^2	g^4	y^2	g^2y^2	g^2, λ, y^2	y^2
ψ^4	g^6	0	0	0	0	g^2y^2	g^2, y^2	g^2, y^2

(X^2H^2, X^2H^2) **submatrix computed in the HISZ basis** Chen–Dawson–Zhang

A submatrix computed in the GGPR basis J. Elias-Miro et al.

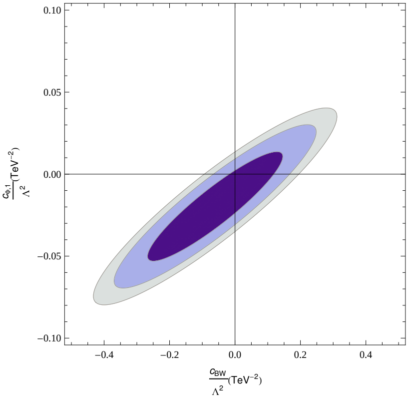
Oblique Corrections (NLO)

$$\frac{g^2}{16\pi}\, S \;\approx\; -\frac{M_W^2}{\Lambda^2}\left\{ C_{BW}(\mu) + \frac{g^2}{32\pi^2}\left[C_{WW} + \tan^2\theta_W\, C_{BB}\right]\left[1 - 2\,\log\left(\frac{M_H^2}{\mu^2}\right)\right]\right\}$$

$$\frac{g^2 \sin^2\theta_W}{4\pi}\, T \;\approx\; -\frac{v^2}{2\Lambda^2}\, C_{\Phi,1}$$

(HISZ basis)

Mebane et al., Chen–Dawson–Zhang



Tree-level Bounds