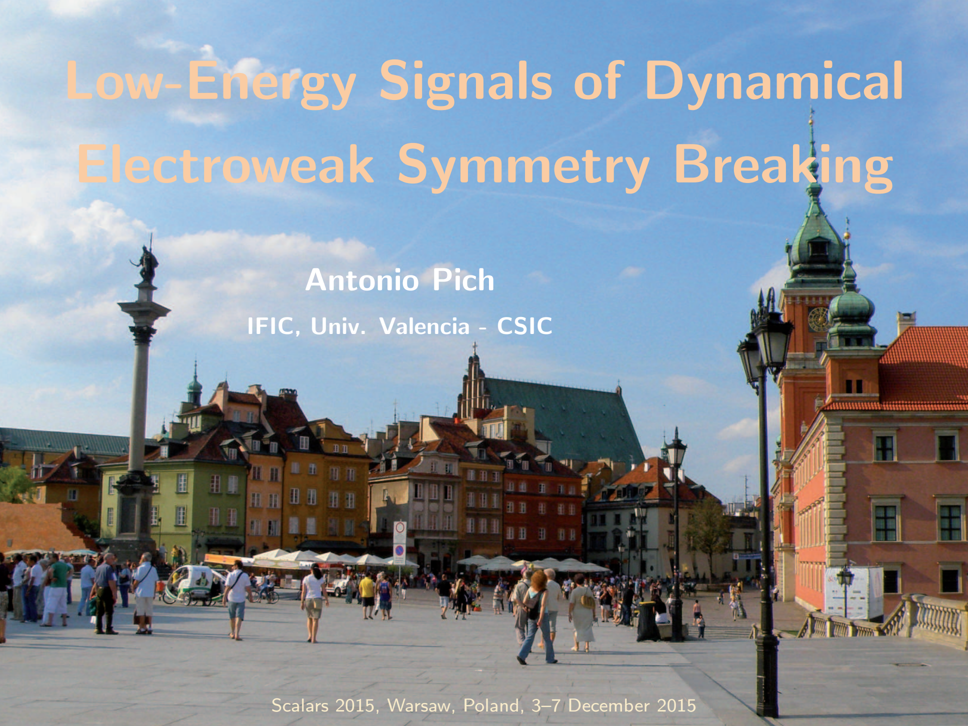
Low-Energy Signals of Dynamical Electroweak Symmetry Breaking

Antonio Pich

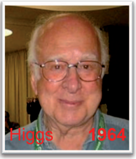
IFIC, Univ. Valencia - CSIC

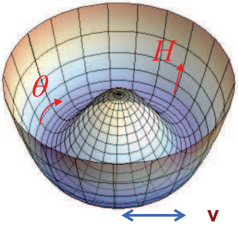


Scalars 2015, Warsaw, Poland, 3–7 December 2015

Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism





$$SU(2)_L \otimes U(1)_Y$$

v = 246 GeV

Fundación Príncipe de Asturias

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

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

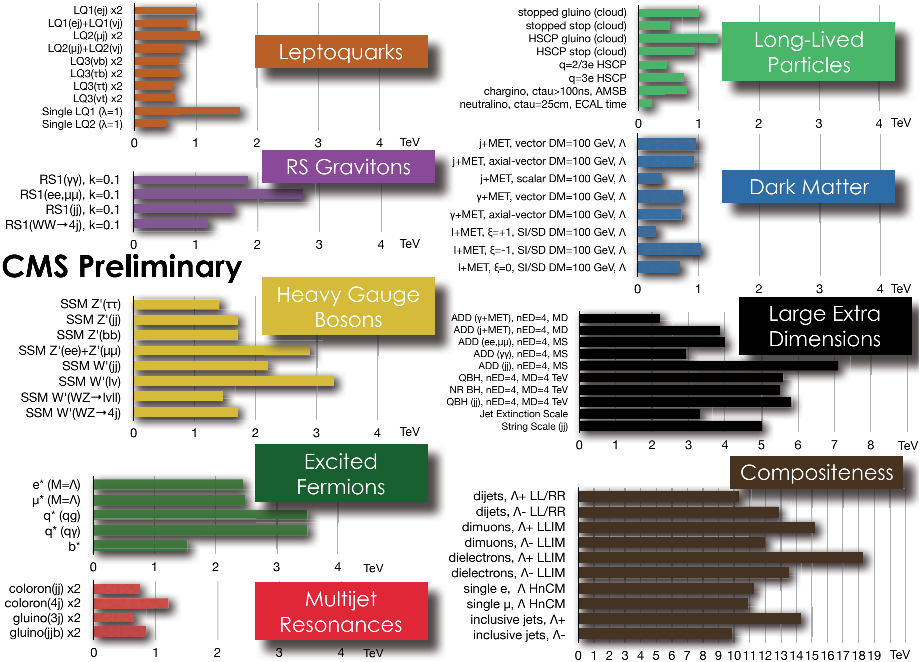
$\sqrt{s}$ = 7, 8 TeV

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

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	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
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$ 100-440 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<10 GeV	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 780 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$ 1.26 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1507.05525
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	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	$\tilde{g}$ 1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 850 GeV	m(NLSP)>430 GeV	1503.03290
	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.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	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	4.7/20.3	$\tilde{t}_1$ 110-167 GeV ($\sqrt{s}$ = 7 TeV), 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 $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 210-700 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	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
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$ 124-361 GeV	$c\tau$<1 mm	1507.05493
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
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 482 GeV	$m(\tilde{\chi}_1^{\pm})$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^{\pm})$<15 ns	1506.05332
	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
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$ 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	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
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 870 GeV	$m(\tilde{\chi}_1^0)$=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$ 100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
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

10^{-1} 1 **Mass scale [TeV]**

*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 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** -----	$\downarrow$	------------------------------------
M_W	H, W, Z, γ, g τ, μ, e, ν_i t, b, c, s, d, u	Standard Model

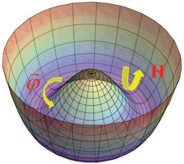
Effective Field Theory

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

- **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:**

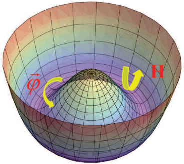
$$\mathcal{L}_{\rm NP} \doteq g_x \, (\bar{q}_L \gamma^\mu q_L) \, X_\mu \quad \longrightarrow \quad \frac{g_x^2}{M_X^2} \, (\bar{q}_L \gamma^\mu q_L) \, (\bar{q}_L \gamma_\mu q_L)$$

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



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

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix}$$

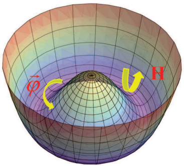


$$\mathcal{L}_\Phi = (D_\mu\Phi)^\dagger D^\mu\Phi - \lambda\left(|\Phi|^2 - \frac{v^2}{2}\right)^2$$

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

Custodial Symmetry

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix}$$



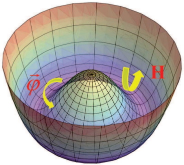
$$\begin{aligned} \mathcal{L}_\Phi &= (D_\mu\Phi)^\dagger D^\mu\Phi - \lambda\left(|\Phi|^2 - \frac{v^2}{2}\right)^2 \\ &= \frac{1}{2}\,\mathrm{Tr}\left[(D^\mu\Sigma)^\dagger D_\mu\Sigma\right] - \frac{\lambda}{4}\left(\mathrm{Tr}\left[\Sigma^\dagger\Sigma\right] - v^2\right)^2 \end{aligned}$$

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

Custodial Symmetry

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix} \equiv \frac{1}{\sqrt{2}} (v + H)\, U(\vec{\theta}\,)$$

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



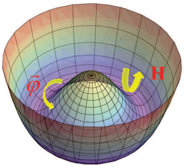
$$\boxed{\begin{aligned} \mathcal{L}_\Phi &= (D_\mu \Phi)^\dagger D^\mu \Phi - \lambda \left(|\Phi|^2 - \frac{v^2}{2} \right)^2 \\ &= \frac{1}{2} \mathrm{Tr}\left[(D^\mu \Sigma)^\dagger D_\mu \Sigma \right] - \frac{\lambda}{4} \left(\mathrm{Tr}\left[\Sigma^\dagger \Sigma \right] - v^2 \right)^2 \\ &=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

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

Custodial Symmetry

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \Phi^{0*} & \Phi^+ \\ -\Phi^- & \Phi^0 \end{pmatrix} \equiv \frac{1}{\sqrt{2}} (v + H)\; U(\vec{\theta}\,)$$

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



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

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

Same Goldstone Lagrangian as QCD pions:

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

Goldstone Electroweak Effective Theory

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

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

$$D^\mu U = \partial^\mu U - i\,\hat{W}^\mu U + i\,U\hat{B}^\mu \quad , \quad D^\mu U^\dagger = \partial^\mu U^\dagger + i\,U^\dagger \hat{W}^\mu - i\,\hat{B}^\mu U^\dagger \quad , \quad \langle A\rangle \equiv \mathrm{Tr}(A)$$

$$\hat{W}^{\mu\nu} = \partial^\mu \hat{W}^\nu - \partial^\nu \hat{W}^\mu - i\,[\hat{W}^\mu, \hat{W}^\nu] \quad , \quad \hat{B}^{\mu\nu} = \partial^\mu \hat{B}^\nu - \partial^\nu \hat{B}^\mu - i\,[\hat{B}^\mu, \hat{B}^\nu]$$

$SU(2)_L \otimes SU(2)_R \to SU(2)_{L+R}$ Symmetry: $\quad U(\varphi) \to g_L\, U(\varphi)\, g_R^\dagger$

$$\hat{W}^\mu \to g_L\,\hat{W}^\mu g_L^\dagger + i\,g_L\,\partial^\mu g_L^\dagger \quad , \quad \hat{B}^\mu \to g_R\,\hat{B}^\mu g_R^\dagger + i\,g_R\,\partial^\mu g_R^\dagger$$

SM Symmetry Breaking: $\quad \hat{W}^\mu = -\frac{g}{2}\,\vec{\sigma}\cdot\vec{W}^\mu \quad , \quad \hat{B}^\mu = -\frac{g'}{2}\,\sigma_3\, B^\mu$

Higher-Order Goldstone Interactions

$$\mathcal{L}_{\mathrm{EW}}^{(4)}\Big|_{\text{Bosonic}} = \sum_i \mathcal{F}_i(h/v)\, \mathcal{O}_i \qquad\qquad \mathcal{F}_i(h/v) = \sum_{n=0} \mathcal{F}_{i,n} \left(\frac{h}{v}\right)^n$$

Appelquist-Bernard, Longhitano, Buchalla et al, Alonso et al, Pich et al...

$\mathcal{O}(\mathbf{p}^4)$ $\mathcal{P}$-even bosonic operators

(A.P., Rosell, Santos, Sanz-Cillero)

$\mathcal{O}_1 = \frac{1}{4} \langle f_+^{\mu\nu} f^+_{\mu\nu} - f_-^{\mu\nu} f^-_{\mu\nu} \rangle$	$\mathcal{O}_6 = \frac{1}{v^2} (\partial_\mu h)(\partial^\mu h) \langle u_\nu u^\nu \rangle$
$\mathcal{O}_2 = \frac{1}{2} \langle f_+^{\mu\nu} f^+_{\mu\nu} + f_-^{\mu\nu} f^-_{\mu\nu} \rangle$	$\mathcal{O}_7 = \frac{1}{v^2} (\partial_\mu h)(\partial_\nu h) \langle u^\mu u^\nu \rangle$
$\mathcal{O}_3 = \frac{i}{2} \langle f_+^{\mu\nu} [u_\mu, u_\nu] \rangle$	$\mathcal{O}_8 = \frac{1}{v^4} (\partial_\mu h)(\partial^\mu h)(\partial_\nu h)(\partial^\nu h)$
$\mathcal{O}_4 = \langle u_\mu u_\nu \rangle \langle u^\mu u^\nu \rangle$	$\mathcal{O}_9 = \frac{1}{v} (\partial_\mu h) \langle f_-^{\mu\nu} u_\nu \rangle$
$\mathcal{O}_5 = \langle u_\mu u^\mu \rangle^2$	

$$U = u^2 = \exp\left\{\tfrac{i}{v}\, \vec{\sigma}\, \vec{\varphi}\right\} \quad , \quad u_\mu \equiv i\, u\, (D_\mu U)^\dagger u = u_\mu^\dagger \quad , \quad f_\pm^{\mu\nu} = u^\dagger \hat{W}^{\mu\nu} u \pm u\, \hat{B}^{\mu\nu} u^\dagger$$

Custodial symmetry assumed

EW Resonance Effective Theory

- Towers of heavy states are usually present in strongly-coupled models of EWSB: Technicolour, Walking TC...
- The low-energy constants (LECs) of the Goldstone Lagrangian contain information on the heavier states. The lightest states not included in the Lagrangian dominate

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1. Build $\mathcal{L}_{\mathrm{eff}}(\varphi_i, R_k)$ with the lightest R_k coupled to the φ_i
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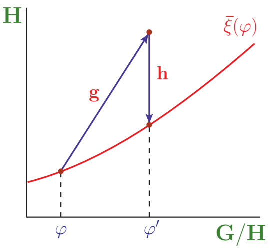
This program works in QCD: RχT **(Ecker–Gasser–Leutwyler–Pich–de Rafael)**

Good dynamical understanding at large N_C

Coset Space Coordinates: $G \equiv SU(2)_L \otimes SU(2)_R \;\to\; H \equiv SU(2)_V$



$$\bar\xi(\varphi) \;\equiv\; (\xi_L(\varphi), \xi_R(\varphi)) \;\in\; G$$

$$\xi_L(\varphi) \;\xrightarrow{G}\; g_L\, \xi_L(\varphi)\, h^\dagger(\varphi, g)$$

$$\xi_R(\varphi) \;\xrightarrow{G}\; g_R\, \xi_R(\varphi)\, h^\dagger(\varphi, g)$$

$$\mathbf{U}(\varphi) \;\equiv\; \xi_L(\varphi)\, \xi_R^\dagger(\varphi) \;\xrightarrow{G}\; g_L\, \mathbf{U}(\varphi)\, g_R^\dagger$$

Canonical choice: $\xi_L(\varphi) = \xi_R(\varphi)^\dagger \equiv \mathbf{u}(\varphi) \;\xrightarrow{G}\; g_L\, \mathbf{u}(\varphi)\, h^\dagger(\varphi, g) \;=\; h(\varphi, g)\, \mathbf{u}(\varphi)\, g_R^\dagger$

$$\mathbf{U}(\varphi) \;=\; \mathbf{u}(\varphi)^2 \;=\; \exp\left\{\frac{i}{v}\, \vec\sigma\, \vec\varphi\right\}$$

SU(2)$_V$ triplets: $\mathbf{X} \;\equiv\; \frac{1}{2}\, \sigma^a\, \mathbf{X}^a \;\xrightarrow{G}\; \mathbf{h}(\varphi, \mathbf{g})\; \mathbf{X}\; \mathbf{h}(\varphi, \mathbf{g})^\dagger$

$$\nabla_\mu X \;=\; \partial_\mu X + [\Gamma_\mu, X] \quad , \quad \Gamma_\mu \;=\; \frac{1}{2}\left\{u^\dagger(\partial_\mu - i\,\hat W_\mu)\, u \;+\; u\,(\partial_\mu - i\,\hat B_\mu) u^\dagger\right\}$$

$$u_\mu \;\equiv\; i\, u\, D_\mu U^\dagger\, u \;=\; u_\mu^\dagger \quad , \quad f_\pm^{\mu\nu} \;=\; u^\dagger\, \hat W^{\mu\nu}\, u \pm u \hat B^{\mu\nu}\, u^\dagger$$

LO Resonance EW Lagrangian:

Pich–Rosell–Santos–Sanz-Cillero

$$\mathcal{L}_{\rm eff} \;=\; \mathcal{L}_{\rm EWET} \;+\; \sum_R \mathcal{L}_R \;+\; \sum_{R,R'} \mathcal{L}_{RR'} \;+\; \cdots$$

Heavy Triplets: $\mathbf{V}(1^{--})\,,\ \mathbf{A}(1^{++})\,,\ \mathbf{P}(1^{++})$; **Heavy Singlet:** $\mathbf{S_1}(0^{++})$

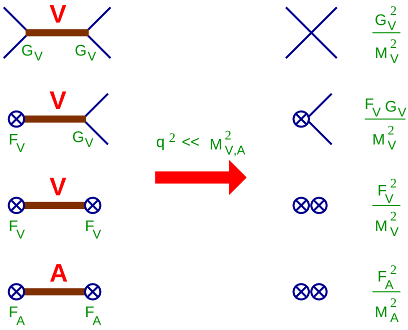
$$\boxed{\begin{aligned}\sum_R \mathcal{L}_R \;=\;& \frac{v}{2}\,\kappa_W\, h\,\langle u^\mu u_\mu\rangle \;+\; \frac{F_V}{2\sqrt{2}}\,\langle V_{\mu\nu}\, f_+^{\mu\nu}\rangle \;+\; \frac{i\,G_V}{2\sqrt{2}}\,\langle V_{\mu\nu}\,[u^\mu u^\nu]\rangle \\ &+\; \frac{F_A}{2\sqrt{2}}\,\langle A_{\mu\nu} f_-^{\mu\nu}\rangle \;+\; \sqrt{2}\,\lambda_1^{hA}\,\partial_\mu h\,\langle A^{\mu\nu} u_\nu\rangle \\ &+\; \frac{d_P}{v}\,\partial_\mu h\,\langle P\, u^\mu\rangle \;+\; \frac{c_d}{\sqrt{2}}\, S_1\,\langle u^\mu u_\mu\rangle \;+\; \lambda_{hS_1}\, v\, h^2\, S_1\end{aligned}}$$

$$U \;=\; u^2 \;=\; \exp\left\{\tfrac{i}{v}\,\vec{\sigma}\,\vec{\varphi}\right\} \quad,\quad u_\mu \;\equiv\; i\,u\,(D_\mu U)^\dagger u \;=\; u_\mu^\dagger \quad,\quad f_\pm^{\mu\nu} \;=\; u^\dagger\,\hat{W}^{\mu\nu}\,u \pm u\,\hat{B}^{\mu\nu}\,u^\dagger$$

Antisymmetric $V_{\mu\nu}$ and $A_{\mu\nu}$ fields **(better UV properties):**

$$\mathcal{L}_{\rm Kin} \;=\; -\frac{1}{2}\sum_{R=V,A}\langle \nabla^\lambda R_{\lambda\mu}\nabla_\nu R^{\nu\mu} - \frac{1}{2}\, M_R^2\, R_{\mu\nu} R^{\mu\nu}\rangle$$

Resonance Exchange



Pich, Rosell, Santos, Sanz-Cillero

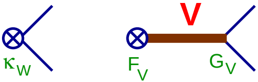
$$\mathcal{F}_1 = \frac{F_A^2}{4M_A^2} - \frac{F_V^2}{4M_V^2} \quad , \quad \mathcal{F}_2 = -\frac{F_A^2}{8M_A^2} - \frac{F_V^2}{8M_V^2} \quad , \quad \mathcal{F}_3 = -\frac{F_V G_V}{2M_V^2}$$

$$\mathcal{F}_4 = \frac{G_V^2}{4M_V^2} \quad , \quad \mathcal{F}_5 = \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} \quad , \quad \mathcal{F}_6 = -\frac{(\lambda_1^{hA})^2 v^2}{M_A^2}$$

$$\mathcal{F}_7 = \frac{d_P^2}{2M_P^2} + \frac{(\lambda_1^{hA})^2 v^2}{M_A^2} \quad , \quad \mathcal{F}_8 = 0 \quad , \quad \mathcal{F}_9 = -\frac{F_A \lambda_1^{hA} v}{M_A^2}$$

Short-Distance Constraints

- **Vector Form Factor:** $\langle \varphi(p_1)\varphi(p_2)| J_V^\mu |0\rangle \;=\; (p_1 - p_2)^\mu\, \mathcal{F}^V_{\varphi\varphi}(s)$



$$\mathcal{F}^V_{\varphi\varphi}(s) \;=\; 1 \;+\; \frac{F_V\, G_V}{v^2}\, \frac{s}{M_V^2 - s}$$

$$\lim_{s\to\infty} \mathcal{F}^V_{\varphi\varphi}(s) = 0 \qquad \longrightarrow \qquad \boxed{F_V\, G_V \;=\; v^2}$$

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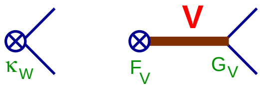

$$\mathcal{F}^V_{\varphi\varphi}(s) = 1 + \frac{F_V\, G_V}{v^2}\, \frac{s}{M_V^2 - s}$$

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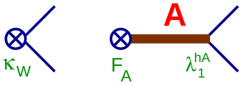
- **Axial Form Factor:** $\langle h(p_1)\varphi(p_2)| J^\mu_A |0\rangle = (p_1 - p_2)^\mu \, \mathcal{F}^A_{h\varphi}(s)$



$$\mathcal{F}^A_{h\varphi}(s) = \kappa_W \left(1 + \frac{F_A\, \lambda_1^{hA}}{\kappa_W\, v}\, \frac{s}{M_A^2 - s} \right)$$

$$\lim_{s\to\infty} \mathcal{F}^A_{h\varphi}(s) = 0 \quad \longrightarrow \quad \boxed{F_A\, \lambda_1^{hA} = \kappa_W\, v}$$

Weinberg Sum Rules

Chiral Symmetry:

$$\Pi^{\mu\nu}_{LR}(q) \,\equiv\, \int d^4x \; \mathrm{e}^{iqx} \; \langle 0| \, T\big(J^\mu_L(x)\, J^\nu_R(0)^\dagger\big)|0\rangle \;=\; \left(-g^{\mu\nu} q^2 + q^\mu q^\nu\right) \Pi_{LR}(q^2) \;=\; 0$$

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OPE: $\Pi_{LR}^{\mu\nu}(q) \neq 0$ only through **order parameters of EWSB**
(operators invariant under **H** but not under **G**)

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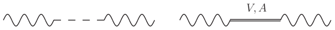
$$\rightarrow \quad \boxed{\begin{array}{ll} \dfrac{1}{\pi} \displaystyle\int_0^\infty \mathrm{d}s \, [\mathrm{Im}\Pi_{VV}(s) - \mathrm{Im}\Pi_{AA}(s)] = v^2 & (1^{\mathrm{st}} \text{ WSR}) \\[2ex] \dfrac{1}{\pi} \displaystyle\int_0^\infty \mathrm{d}s \, s \, [\mathrm{Im}\Pi_{VV}(s) - \mathrm{Im}\Pi_{AA}(s)] = 0 & (2^{\mathrm{nd}} \text{ WSR}) \end{array}}$$

• WSRs @ LO:

$$\Pi_{LR}(s) = \frac{v^2}{s} + \frac{F_V^2}{M_V^2 - s} - \frac{F_A^2}{M_A^2 - s}$$



$$\boxed{\begin{array}{ll} \bullet\ \textbf{1}^{\textbf{st}}\ \textbf{WSR:} & F_V^2 - F_A^2 = v^2 \\ \bullet\ \textbf{2}^{\textbf{nd}}\ \textbf{WSR:} & F_V^2\, M_V^2 - F_A^2\, M_A^2 = 0 \end{array}}$$

$$\Rightarrow \qquad F_V^2 = v^2\, \frac{M_A^2}{M_A^2 - M_V^2} \quad , \quad F_A^2 = v^2\, \frac{M_V^2}{M_A^2 - M_V^2} \quad , \quad M_A > M_V$$

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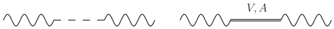

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$$\boxed{\kappa_W \equiv \frac{g_{hWW}}{g_{hWW}^{SM}} = \frac{M_V^2}{M_A^2}}$$

Pich–Rosell–Sanz-Cillero

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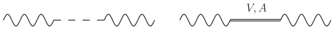

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Pich–Rosell–Sanz-Cillero

1^{st} WSR likely valid also in gauge theories with non-trivial UV fixed points

2^{nd} WSR questionable (not valid) in walking (conformal) TC scenarios

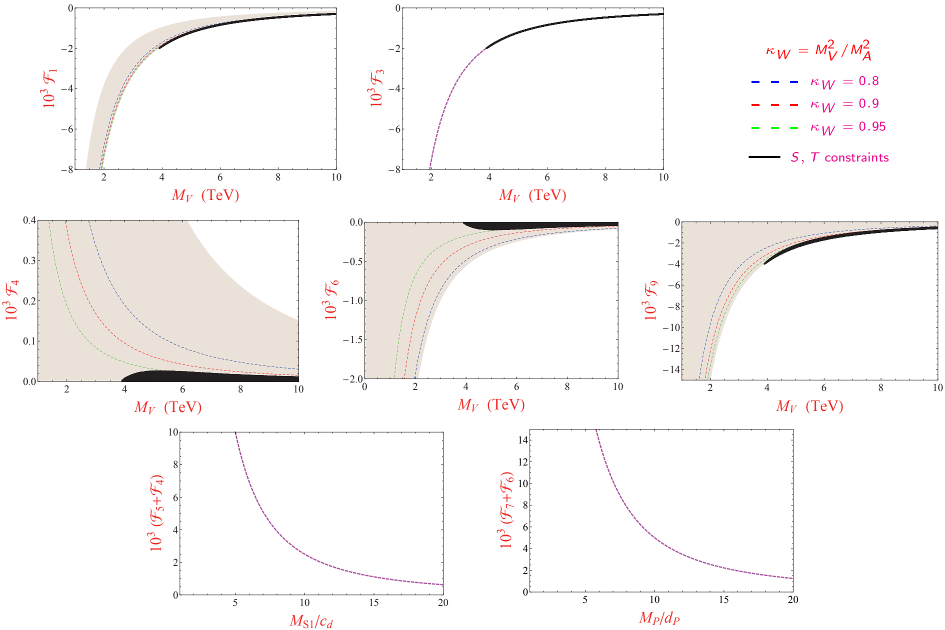
Appelquist–Sannino, Orgogozo–Rychkov

Short-distance constraints bring sharper predictions

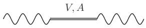
Pich, Rosell, Santos, Sanz-Cillero

$$
\begin{aligned}
\mathcal{F}_1 &= \frac{F_A^2}{4M_A^2} - \frac{F_V^2}{4M_V^2} &&= -\frac{v^2}{4}\left(\frac{1}{M_V^2} + \frac{1}{M_A^2}\right) \\
\mathcal{F}_2 &= -\frac{F_A^2}{8M_A^2} - \frac{F_V^2}{8M_V^2} &&= -\frac{v^2(M_V^4+M_A^4)}{8M_V^2 M_A^2(M_A^2-M_V^2)} \\
\mathcal{F}_3 &= -\frac{F_V G_V}{2M_V^2} &&= -\frac{v^2}{2M_V^2} \\
\mathcal{F}_4 &= \frac{G_V^2}{4M_V^2} &&= \frac{(M_A^2-M_V^2)v^2}{4M_V^2 M_A^2} \\
\mathcal{F}_5 &= \frac{c_d^2}{4M_{S_1}^2} - \frac{G_V^2}{4M_V^2} &&= \frac{c_d^2}{4M_{S_1}^2} - \frac{(M_A^2-M_V^2)v^2}{4M_V^2 M_A^2} \\
\mathcal{F}_6 &= -\frac{(\lambda_1^{hA})^2 v^2}{M_A^2} &&= -\frac{M_V^2(M_A^2-M_V^2)v^2}{M_A^6} \\
\mathcal{F}_7 &= \frac{d_P^2}{2M_P^2} + \frac{(\lambda_1^{hA})^2 v^2}{M_A^2} &&= \frac{d_P^2}{2M_P^2} + \frac{M_V^2(M_A^2-M_V^2)v^2}{M_A^6} \\
\mathcal{F}_8 &= 0 && \\
\mathcal{F}_9 &= -\frac{F_A \lambda_1^{hA} v}{M_A^2} &&= -\frac{M_V^2 v^2}{M_A^4}
\end{aligned}
$$

A.P., Rosell, Santos, Sanz-Cillero, arXiv:1510.03114

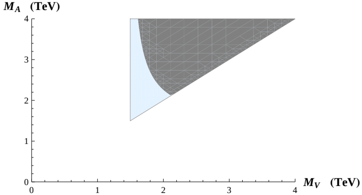


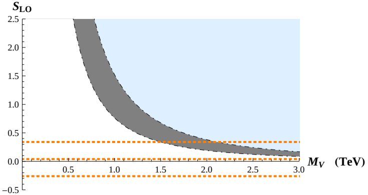
Gauge Boson Self-Energies @ LO



$$S_{\rm LO} = 4\pi \left(\frac{F_V^2}{M_V^2} - \frac{F_A^2}{M_A^2} \right) \qquad , \qquad T_{\rm LO} = 0$$

Sensitive to vector and axial states ➡ $\mathbf{M_A > M_V > 1.5\ TeV}$





$3\,\sigma$ bounds

AP–Rosell–Sanz-Cillero

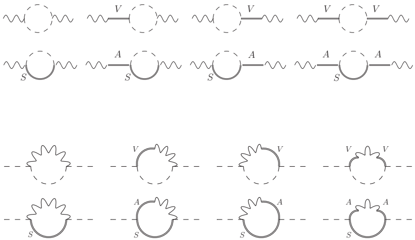
- **1st + 2nd WSR:** $$S_{\rm LO} = \frac{4\pi v^2}{M_V^2} \left(1 + \frac{M_V^2}{M_A^2} \right)$$

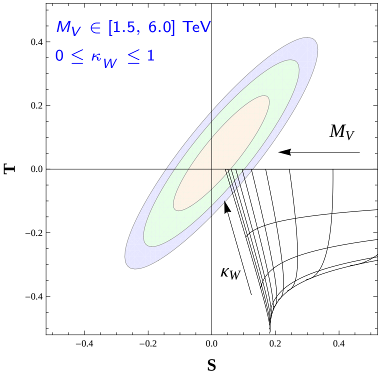
- **1st WSR ($M_A > M_V$):** $$S_{\rm LO} = 4\pi \left\{ \frac{v^2}{M_V^2} + F_A^2 \left(\frac{1}{M_V^2} - \frac{1}{M_A^2} \right) \right\} > \frac{4\pi v^2}{M_V^2} > \frac{4\pi v^2}{M_A^2}$$

Gauge Boson Self-Energies @ NLO

Sensitive to the light scalar h(125)

AP, Rosell, Sanz-Cillero



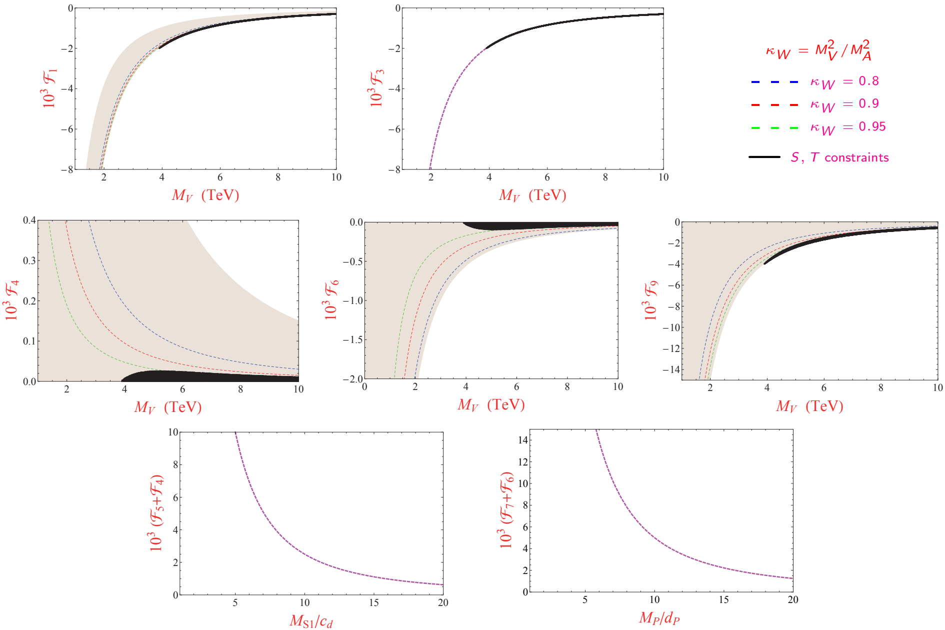


$$\kappa_W \equiv \frac{g_{SWW}}{g_{HWW}^{SM}} = \frac{M_V^2}{M_A^2} \in [0.94,\ 1]$$

$M_A \approx M_V > 4$ TeV (95% CL)

1st + 2nd WSRs

A.P., Rosell, Santos, Sanz-Cillero, arXiv:1510.03114



OUTLOOK

- **Effective Field Theory:** powerful low-energy tool
- **Mass Gap:** $E, m_{\text{light}} \ll \Lambda_{NP}$
- **Assumption:** relevant symmetries (breakings) & light fields
- Most general $\mathcal{L}_{\text{eff}}(\phi_{\text{light}})$ allowed by symmetry
- Short-distance dynamics encoded in LECs
- LECs constrained phenomenologically
- **Goal:** get hints on the underlying fundamental dynamics

$\Longrightarrow$ **New Physics**

Learning from QCD experience. EW problem more difficult

Fundamental Underlying Theory unknown

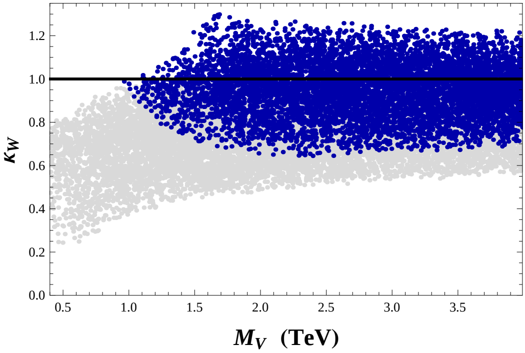
QCD	**?**
$\Downarrow$	$\Uparrow$
χ**PT**	**Standard Model**

Additional dynamical input (fresh ideas!) needed

Backup Slides

Gauge Boson Self-Energies @ NLO

Weaker assumptions: 1^{st} **WSR only** , $M_A > M_V > 0.4$ **TeV**



AP, Rosell, Sanz-Cillero

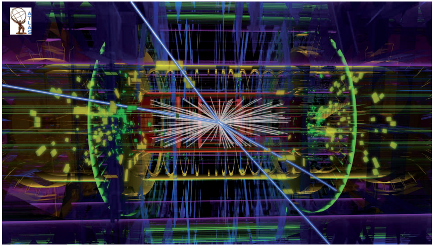
• $0.2 < \frac{M_V}{M_A} < 1$

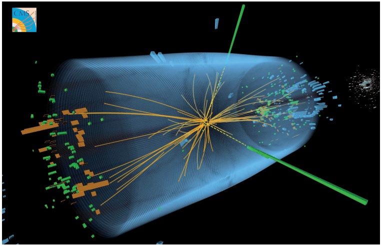
• $0.02 < \frac{M_V}{M_A} < 0.2$

$\kappa_W \equiv g_{SWW}/g^{SM}_{HWW}$ **very different from one**

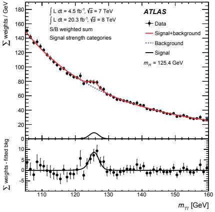
requires large (unnatural) mass splittings

A New Higgs-Like Boson

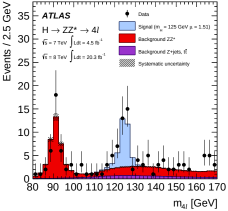




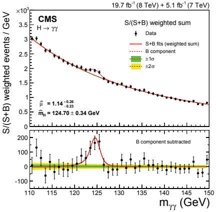
$H \to \gamma\gamma$



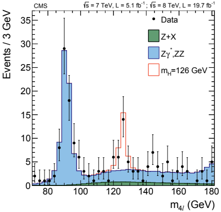
$H \to ZZ^* \to 4\ell$



$H \to \gamma\gamma$

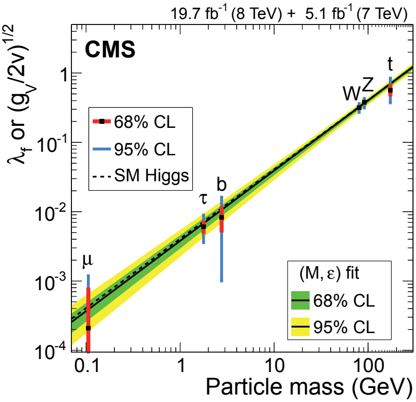


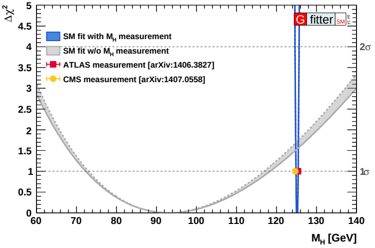
$H \to ZZ^* \to 4\ell$



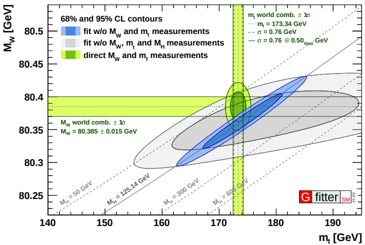
$$M_H = (125.09 \pm 0.21 \pm 0.11) \text{ GeV}$$

It is a Higgs Boson





SM Fit



$$\lambda_f = \left(\frac{m_f}{M}\right)^{1+\epsilon} \quad , \quad \left(\frac{g_V}{2v}\right)^{1/2} = \left(\frac{M_V}{M}\right)^{1+\epsilon}$$

(95% CL)

$$\epsilon \in [-0.054,\, 0.100] \quad , \quad M \in [217,\, 279]\ \text{GeV}$$

SM: $\epsilon = 0 \quad , \quad M = v = 246\ \text{GeV}$

Higgs Mechanism:

Gauge invariance

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

3×2 polarizations $= 6$

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

Gauge invariance

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$+$

3 Goldstones $\varphi_i(x)$

SSB $\Downarrow$

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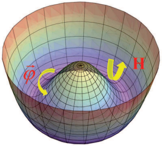
Spontaneous Symmetry Breaking

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



$\mu^2 < 0$

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

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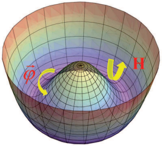

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$$D_\mu \Phi = \left(\partial_\mu + \tfrac{i}{2}\, g\, \vec{\sigma} \cdot \vec{W}_\mu + \tfrac{i}{2}\, g'\, B_\mu\right) \Phi \qquad ; \qquad v^2 = -\mu^2/\lambda$$

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

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

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Derivative Coupling

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Derivative Coupling

Goldstones become free at zero momenta

Electroweak Symmetry Breaking

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(explicit symmetry breaking)

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- **QCD pions also generate small W, Z masses:** $\delta_\pi M_W = \frac{1}{2}\, g\, f_\pi$

Higher-Order Goldstone Interactions

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

(Appelquist, Longhitano)

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

$\mathcal{O}_1 = \langle U \hat{B}_{\mu\nu} U^\dagger \hat{W}^{\mu\nu}\rangle$ $\qquad$ $\mathcal{O}_2 = i\,\langle U \hat{B}_{\mu\nu} U^\dagger [V^\mu, V^\nu]\rangle$

$\mathcal{O}_3 = i\,\langle \hat{W}_{\mu\nu} [V^\mu, V^\nu]\rangle$ $\qquad$ $\mathcal{O}_4 = \langle V_\mu V_\nu\rangle\, \langle V^\mu V^\nu\rangle$

$\mathcal{O}_5 = \langle V_\mu V^\mu\rangle^2$

$\mathcal{O}_{11} = \langle (D_\mu V^\mu)^2\rangle$

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

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

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$\mathcal{O}_7 = 4\, \langle V_\mu V^\mu\rangle\, \langle T_L V_\nu\rangle^2$

$\mathcal{O}_8 = \langle T_L \hat{W}_{\mu\nu}\rangle^2$

$\mathcal{O}_9 = -2\, \langle T_L \hat{W}_{\mu\nu}\rangle\, \langle T_L\, [V^\mu, V^\nu]\rangle$

$\mathcal{O}_{10} = 16\, \{\langle T_L V_\mu\rangle\, \langle T_L V_\nu\rangle\}^2$

$\mathcal{O}_{11} = \langle (D_\mu V^\mu)^2\rangle$

$\mathcal{O}_{12} = 4\, \langle T_L D_\mu D_\nu V^\nu\rangle\, \langle T_L V^\mu\rangle$

$\mathcal{O}_{13} = 2\, \langle T_L D_\mu V_\nu\rangle^2$

$\mathcal{O}_{14} = -2i\, \varepsilon^{\mu\nu\rho\sigma}\, \langle \hat{W}_{\mu\nu} V_\rho\rangle\, \langle T_L V_\sigma\rangle$

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Goldstone interactions are determined by the underlying symmetry

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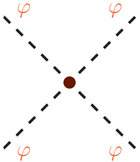

$$T\left(\varphi^+\varphi^- \to \varphi^+\varphi^-\right) = \frac{s+t}{v^2}$$

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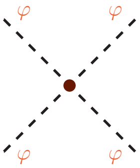
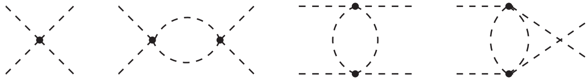


$$T\left(\varphi^+\varphi^- \to \varphi^+\varphi^-\right) \;=\; \frac{s+t}{v^2}$$

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

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



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

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

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

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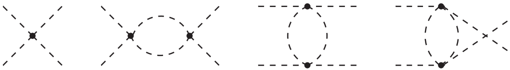

+ Higgs (tree + 1-loop) contributions

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

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

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

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

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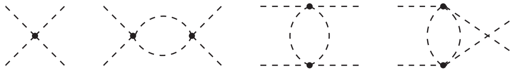

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SM: $a = b = 1$, $a_4 = a_5 = 0$ ➡ $A(s,t,u) \sim \mathcal{O}(M_H^2/v^2)$