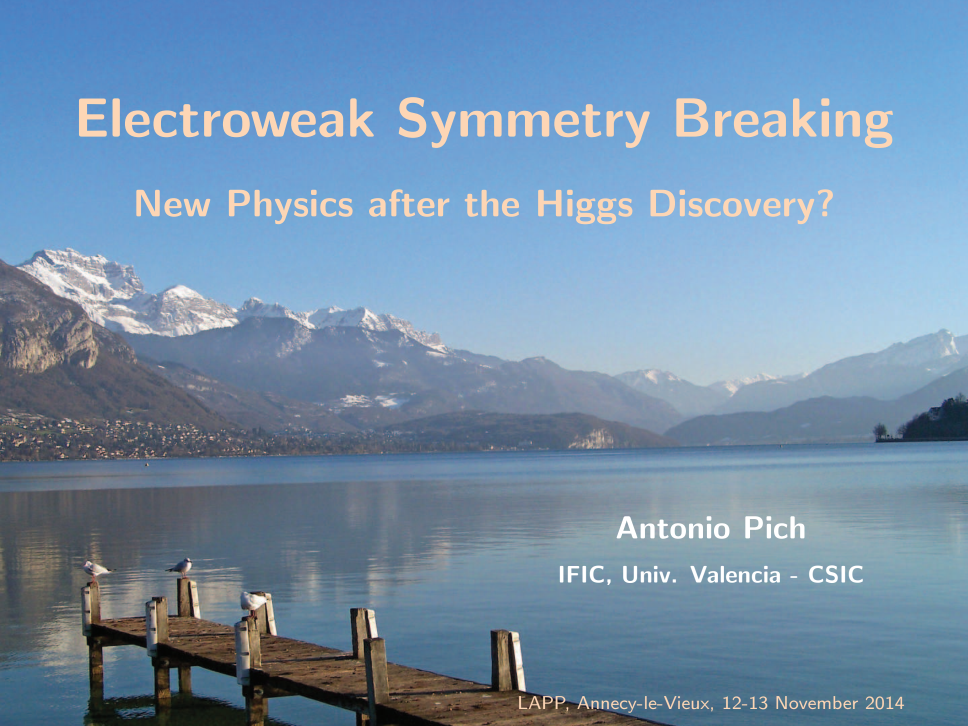


Electroweak Symmetry Breaking

New Physics after the Higgs Discovery?

Antonio Pich

IFIC, Univ. Valencia - CSIC

LAPP, Annecy-le-Vieux, 12-13 November 2014

Outline

1) Higgs Physics

- Hierarchy problem. Naturalness
- Top: the heaviest mass scale
- Standard Model Higgs
- Supersymmetry
- Flavour Dynamics

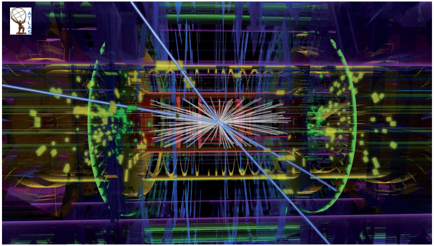
2) Two Higgs Doublets

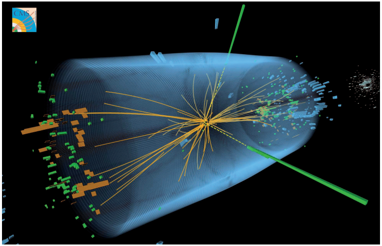
- FCNCs
- Flavour alignment
- Flavour & LHC constraints
- EDMs

3) Electroweak Effective Theory

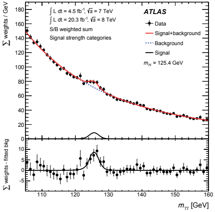
- Custodial Symmetry
- Equivalence Theorem
- Strong Coupling

A New Higgs-Like Boson

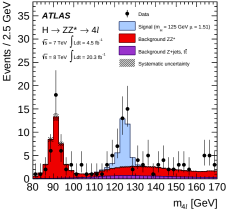




$H \to \gamma\gamma$



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



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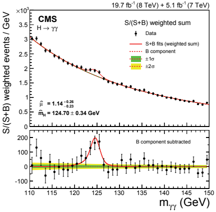

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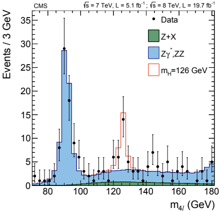
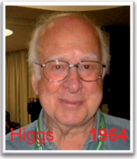
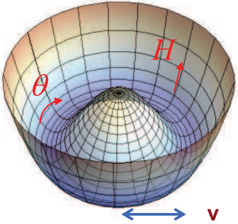


$$M_H^{ATLAS} = (125.36 \pm 0.37 \pm 0.18)\ \text{GeV} \quad ; \quad M_H^{CMS} = (125.03\, {}^{+0.26}_{-0.27}\, {}^{+0.13}_{-0.15})\ \text{GeV}$$

Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism





Fundación Príncipe de Asturias

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

v = 246 GeV

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

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 $\Lambda_{\rm NP}$

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

Which symmetry keeps M_H away from $\Lambda_{\rm NP}$?

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

Symmetries & Mass Scales

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

$$\mathcal{L}_\psi \;=\; \bar\psi\,(i\partial\!\!\!/ - m_\psi)\,\psi \;=\; \bar\psi_L i\partial\!\!\!/\psi_L + \bar\psi_R i\partial\!\!\!/\psi_R - m_\psi\,\left(\bar\psi_L\psi_R + \bar\psi_R\psi_L\right)$$

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

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

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

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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)

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Pseudo-Goldstone Boson

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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

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

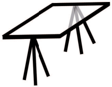
1) Keep the Higgs elementary, but protect it by symmetries: **Supersymmetry**

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. $\psi_L,\ \psi_R$	1 d.o.f.

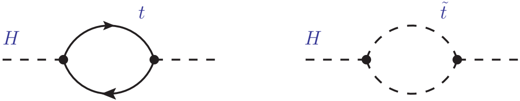
Vector $(2 \neq 3)$ and fermion masses are safe $(2 \neq 4)$

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

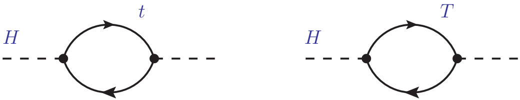
Higgs Self-energy: **The top is the largest SM contribution**

δM_H^2 stabilized through new-physics contributions

- **SUSY:** stop loops



- **Composite Higgs:** fermionic top partners



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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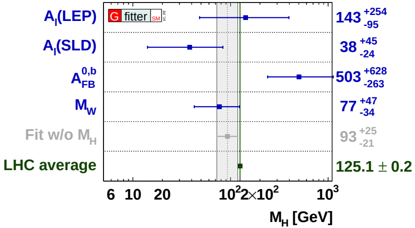
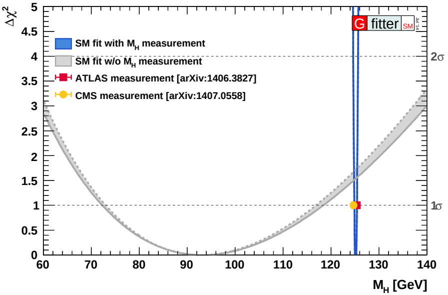
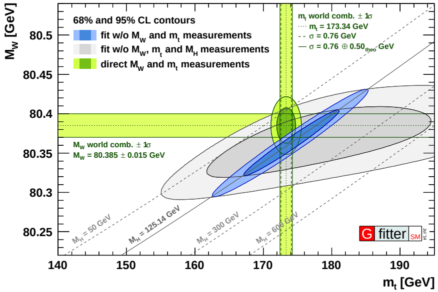




Favoured by EW precision tests



TOP MASS

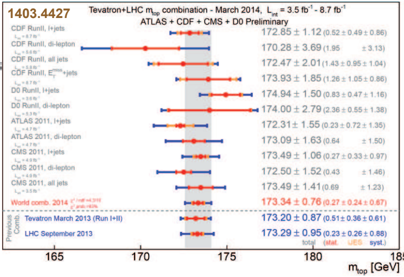
- **Monte Carlo mass:**

$$M_t^{\mathrm{MC}} = (173.34 \pm 0.76)\ \mathrm{GeV}$$

Lacks a proper QCD definition: $M_t^{\mathrm{pole}} = M_t^{\mathrm{MC}} + \Delta M_t^{\mathrm{th}}$

$$\left|\Delta M_t^{\mathrm{th}}\right| \approx O(1\ \mathrm{GeV})$$

Hoang-Stewart, 0808.0222

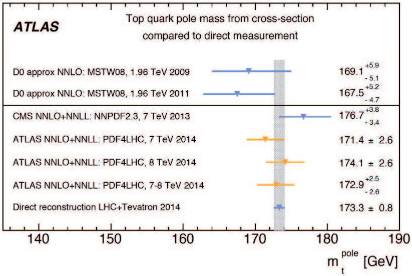


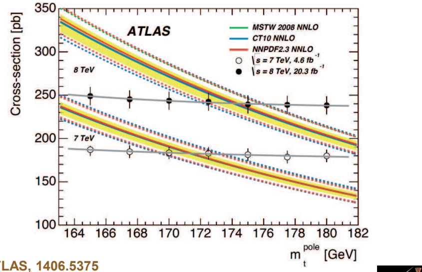
Aldaya, Bernardi, Carli

- **Cross section:** $\sigma_{t\bar{t}}$ **NNLO+NNLL**

Czakon et al, Bärnreuther et al, Cacciari et al

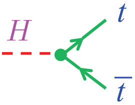
Well-defined mass





ATLAS, 1406.5375

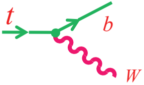
The Heaviest Mass Scale



$$y_t = \frac{\sqrt{2}}{v}\, m_t = 2^{3/4}\, G_F^{1/2}\, m_t = 1 \qquad (0.995)$$

The top quark:

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



So far, we only know the decay $t \to b\, W^+$

Single-top	$\|V_{tb}\|$
ATLAS '14	> 0.88 (95% CL)
CMS'14	> 0.92 (95% CL)
CDF'14	> 0.84 (95% CL)
D0 '13	> 0.92 (95% CL)

Higgs Mechanism:

Gauge invariance

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

3×2 polarizations $=$ 6

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

Gauge invariance

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

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$+$

3 Goldstones $\theta_i(x)$

SSB $\downarrow$

Massive $W^\pm$, Z

3×3 polarizations $= 9$

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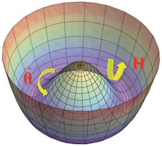
Spontaneous Symmetry Breaking

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



$\mu^2 < 0$

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

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

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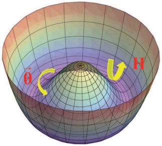

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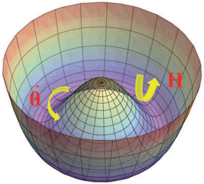
$$\Phi(x) = \exp\left\{ i\,\frac{\vec{\sigma}}{2}\cdot\vec{\theta}(x)\right\} \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + H(x) \end{bmatrix}$$

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

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

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

SM Higgs Potential



$$\Phi(x) \;=\; \exp\left\{\frac{i}{2}\,\vec{\sigma}\,\vec{\theta}(x)\right\}\;\frac{1}{\sqrt{2}}\left[\begin{array}{c} 0 \\ v+H(x)\end{array}\right]$$

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

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

$$M_H = (125.14 \pm 0.24)\ \mathrm{GeV} \quad \longrightarrow \quad \lambda \;=\; \frac{M_H^2}{2v^2} \;=\; 0.13$$

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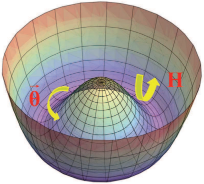

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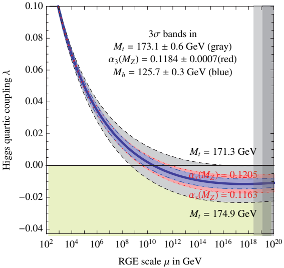
$M_H = (125.14 \pm 0.24)$ GeV ➡ $\lambda \;=\; \frac{M_H^2}{2v^2} \;=\; 0.13$

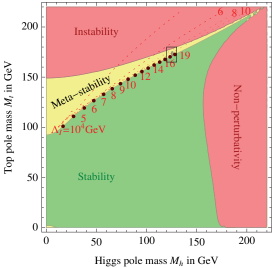
$$M_H^2 \;=\; 2v^2\lambda(\mu) + \frac{2v^2 y_t^2}{(4\pi)^2}\left[2\lambda + 3\left(\lambda - y_t^2\right)\,\log\left(m_t^2/\mu^2\right)\right] + \cdots$$

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

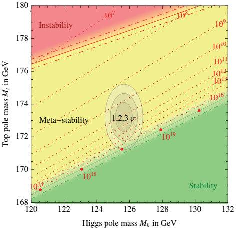
Vacuum Stability: $\lambda(\Lambda) \geq 0$

Degrassi et al, 1205.6497, 1307.3536





$\Lambda = M_{\rm Planck}$ ➡ $M_H > (129.1 \pm 1.5)$ GeV



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

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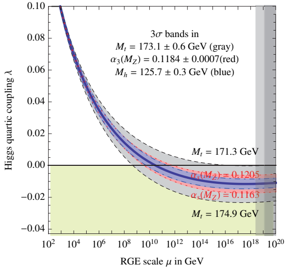
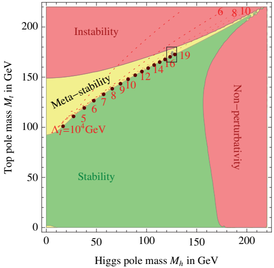
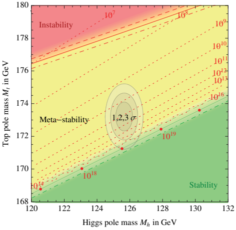
Degrassi et al, 1205.6497, 1307.3536

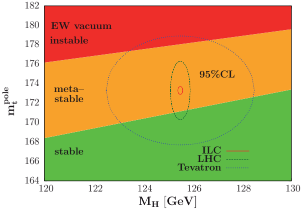




$\Lambda = M_{\text{Planck}}$ ➡ $M_H > (129.1 \pm 1.5)$ GeV [129.8 ± 5.6]



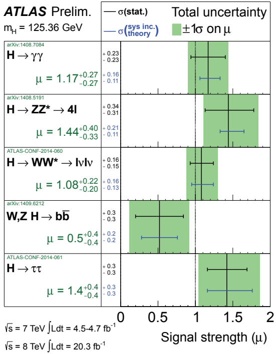
Alekhin et al, 1207.0980

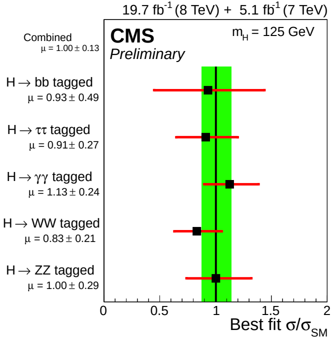


Assumes SM valid all the way up to $\Lambda \leq M_{\text{Planck}}$

Signal Strengths

$$\mu \equiv \sigma \cdot \mathrm{Br} / (\sigma \cdot \mathrm{Br})_{\mathrm{SM}}$$

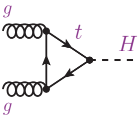




Decay Mode	ATLAS ($M_H = 125.4$ GeV)	CMS ($M_H = 125.0$ GeV)
$V H \to bb$	0.5 ± 0.4	0.93 ± 0.49
$H \to \tau\tau$	1.4 ± 0.4	0.91 ± 0.27
$H \to \gamma\gamma$	1.17 ± 0.27	1.13 ± 0.24
$H \to WW^*$	$1.08\,^{+\,0.22}_{-\,0.20}$	0.83 ± 0.21
$H \to ZZ^*$	$1.44\,^{+\,0.40}_{-\,0.33}$	1.00 ± 0.29
Combined		$\mathbf{1.00 \pm 0.13}$

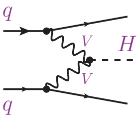
Production Channels

Gluon Fusion

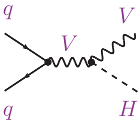


Vector Boson Fusion

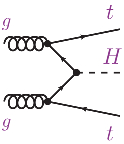
$(V = W^{\pm}, Z)$

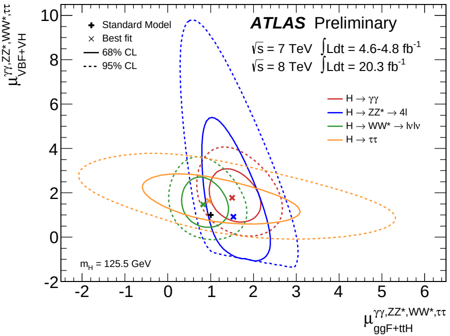


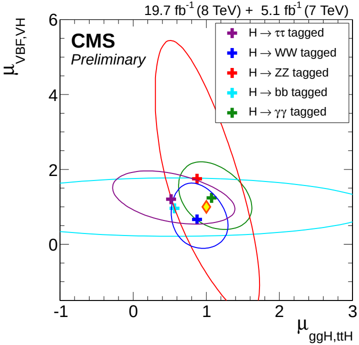
Ass. *VH* Production



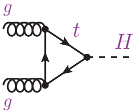
Ass. $t\bar{t}H$ Production



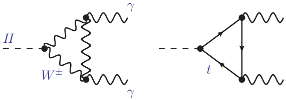




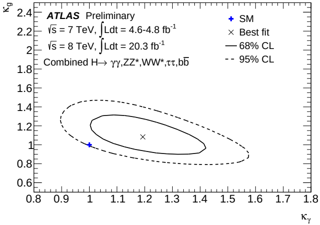
Strong (indirect) evidence for Higgs coupling to t

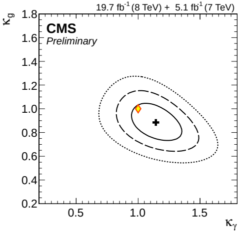


Dominant Production Mechanism



$\Gamma \sim |1 - 0.21|^2$

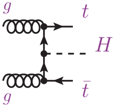




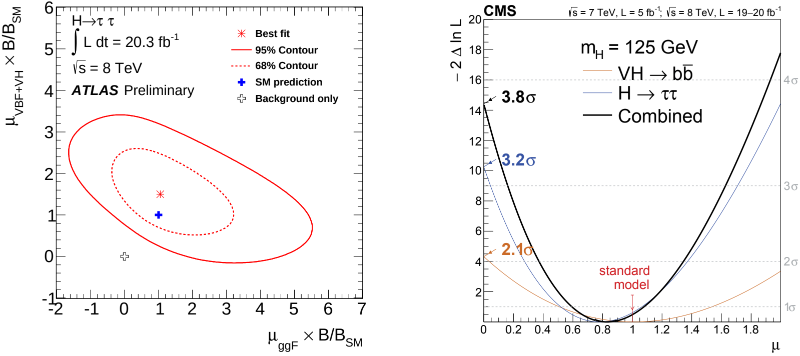
$\kappa_i \equiv g_i / g_i^{\mathrm{SM}}$

$H \to \gamma\gamma$	Signal Strength
ATLAS	1.17 ± 0.27
CMS	1.13 ± 0.24

Direct (tree-level) sensitivity through $t\bar{t}H$

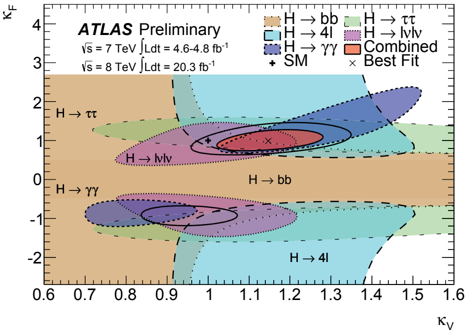


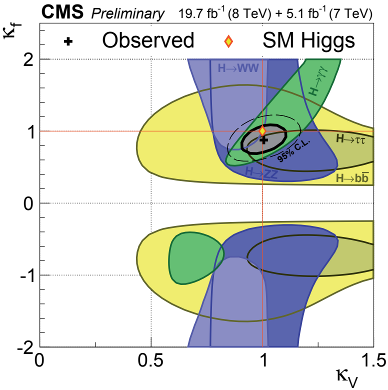
Strong evidence for Higgs coupling to τ and b



Signal Strength	ATLAS ($M_H = 125.4$ GeV)	CMS ($M_H = 125.0$ GeV)
$VH \to bb$	0.5 ± 0.4	0.93 ± 0.49
$H \to \tau\tau$	1.4 ± 0.4	0.91 ± 0.27

Effective Couplings $\quad \kappa_i \equiv g_i / g_i^{\mathrm{SM}}$

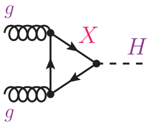




$$\sigma(i \to H) \cdot \mathrm{Br}(H \to f) \;=\; \sigma(i \to H) \cdot \Gamma(H \to f)/\Gamma_H \;\sim\; (\kappa_i \kappa_f / \kappa_H)^2$$

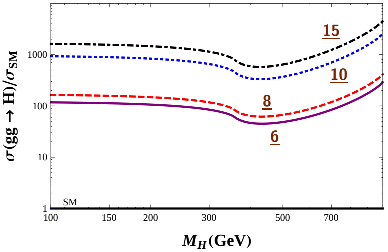
QCD Exotics

$X \in SU(3)_C$ representation $\underline{R}$



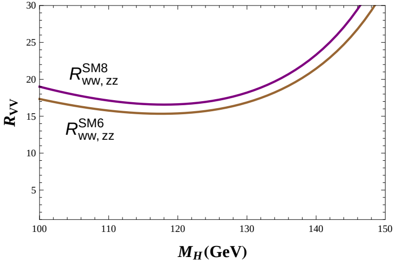
$$\sim \sum_{a=1}^{d_A} \mathrm{Tr}\,[t_R^a t_R^a] = C_R d_R$$

V. Ilisie - AP, 1202.3430



Non decoupling: $\mathcal{L} = -\frac{M_X}{v}\,(\bar{X}X)\,H$

$R_{VV} = \mu_{VV}$

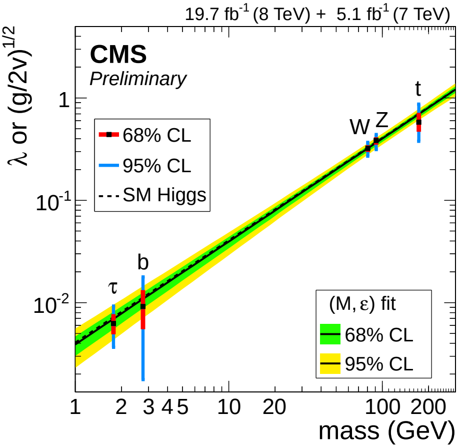


Exotic fermions in higher-colour representations could only exist provided their masses are not generated by the SM Higgs

(or fine-tuned cancelations with scalar loops)

It is a Higgs Boson

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



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

$\epsilon = 0.00 \pm 0.03$

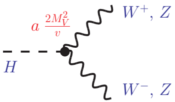
$M/v = 0.97 \pm 0.06$

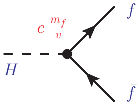
SM rates:

$M_H = (125.0 \pm 1.8)$ GeV

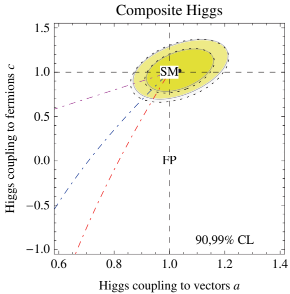
Giardino et al, 1303.3570v4

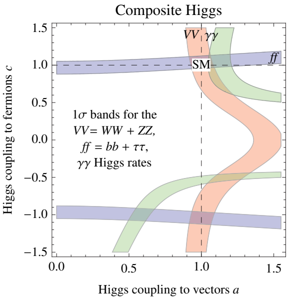
2-Parameter Fit

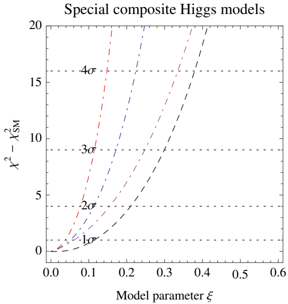




Giardino et al, 1303.3570v4





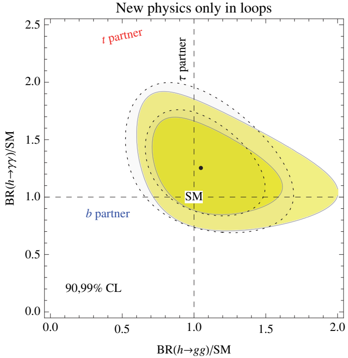


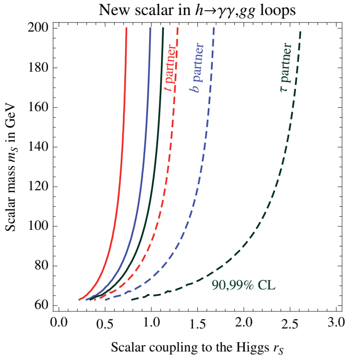
	a	c	
----	$\sqrt{1-\xi}$	a	MCHM4 (Agashe et al)
----	$\sqrt{1-\xi}$	$(1-2\xi)/a$	MCHM5 (Contino et al)
----	$\sqrt{1-\xi}$	$(1-3\xi)/a$	
----	1	$1-\xi$	

$\xi = v^2/F^2$

New Physics Only in Loops

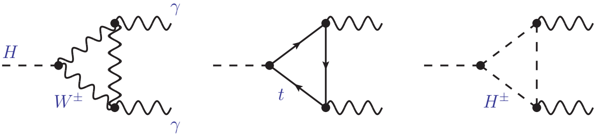
Giardino et al, 1303.3570v4





$$\mathcal{L}_S^{\rm NP} = r_S \, \frac{2m_S^2}{v} \, H \, S^2$$

$H \to \gamma\gamma$



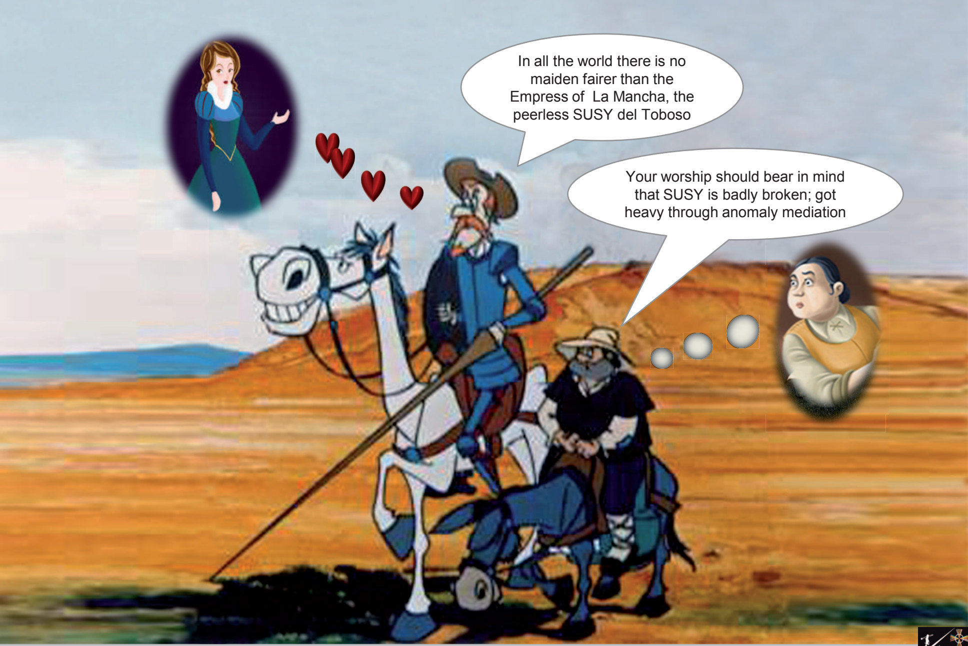
$$\Gamma \;\propto\; \left|-8.4\,\kappa_W + 1.8\,\kappa_t + \mathcal{C}_{\mathrm{NP}}\right|^2$$

SM: $\kappa_W = \kappa_t = 1 \quad , \quad \mathcal{C}_{\mathrm{NP}} = 0$ **Destructive interference**

Enhanced rate if:

- $\kappa_W\,\kappa_t < 0$
- $\mathcal{C}_{\mathrm{NP}} < 0$

Desperately Seeking SUSY (Dulcinea)



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

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

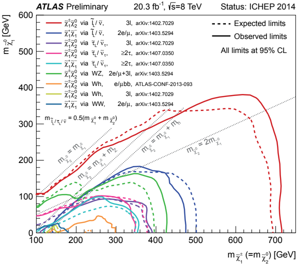
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	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
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	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	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	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	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
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
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^{\pm})$	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	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	ATLAS-CONF-2013-069
	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
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (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	$m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	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	$m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	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
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

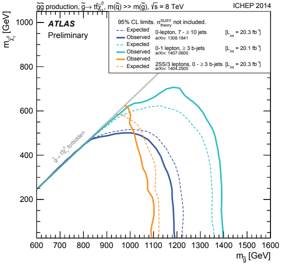
$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

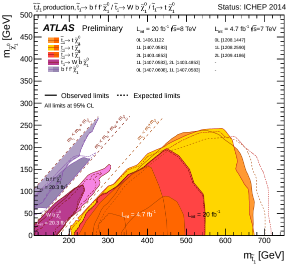
10^{-1} — 1 — Mass scale [TeV]

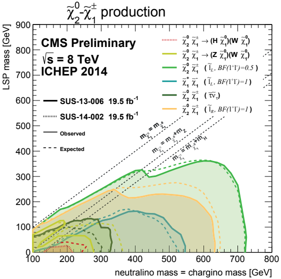
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

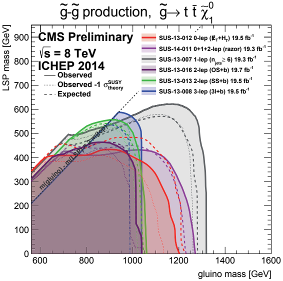
Strong limits on SUSY partners

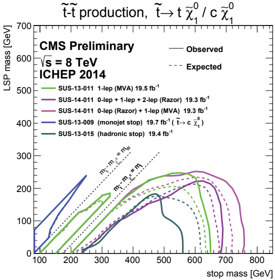












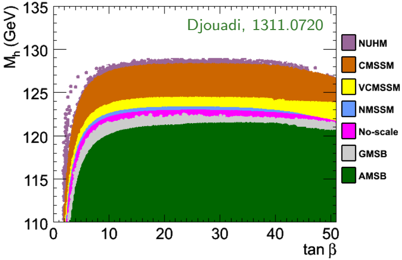
Tension with Higgs mass: $M_h^2 \leq M_Z^2 \cos^2(2\beta) + \epsilon$

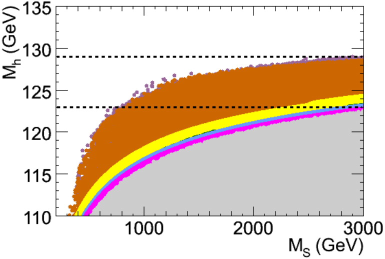
Large radiative corrections needed: $M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$

$$\epsilon \approx \frac{3m_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

→ Decoupling limit $(M_A \gg M_Z)$, $\cos^2(2\beta) \to 1$

Maximal stop mixing $X_t = A_t - \mu \cot\beta$

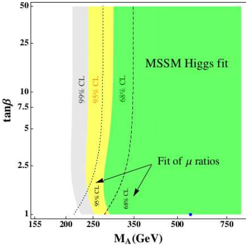




Improved higher-order calculations allow slightly larger values of M_h

Hahn et al, 1312.4937

Constraints from Higgs Decay



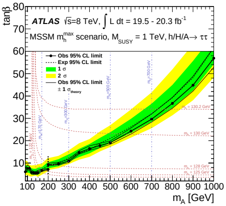
Djouadi, 1311.0720

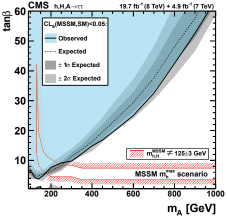
$$c_t \;\approx\; \frac{\cos\alpha}{\sin\beta}\left[1 + \frac{m_t^2}{4 m_{\tilde t_1}^2\, m_{\tilde t_2}^2}\left(m_{\tilde t_1}^2 + m_{\tilde t_2}^2 - X_t^2\right)\right]$$

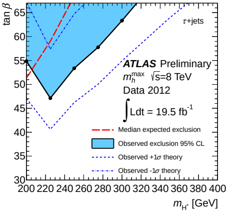
$$c_b \;\approx\; -\,\frac{\sin\alpha}{\cos\beta}\left[1 - \frac{\Delta_b}{1+\Delta_b}\,\left(1 + \cot\alpha\,\cot\beta\right)\right]$$

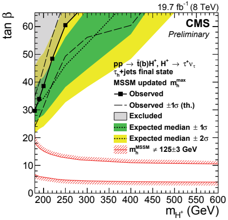
$$c_V \;=\; \sin\left(\beta-\alpha\right) \qquad , \qquad \Delta_b \;\approx\; \frac{2\alpha_s}{3\pi}\;\frac{\mu\, m_{\tilde g}\,\tan\beta}{\max\left(m_{\tilde g}^2,\, m_{\tilde b_1}^2,\, m_{\tilde b_2}^2\right)}$$

Heavy Higgs Searches



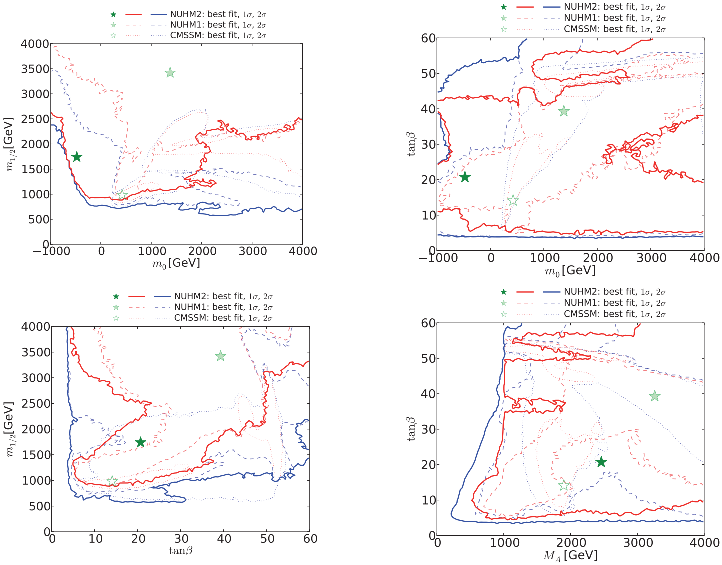






Global Fits (LHC, Flavour, DM. . .)

Buchmueller et al, 1408.4060



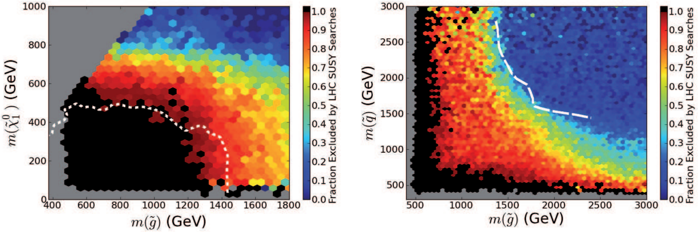
$(g-2)_\mu$ cannot be explained (not included in the fit)

Which SUSY ?

- **Looks bad in CMSSM** (120 MSSM parameters reduced to 4 + 1 sign)

- **More freedom in the Phenomenological MSSM**

Many “models” consistent with data Cahill-Rowley et al, 1407.4130



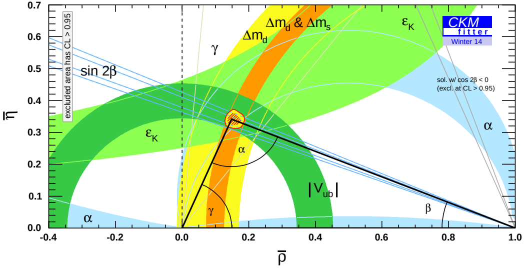
19–20 parameters

Data-driven search

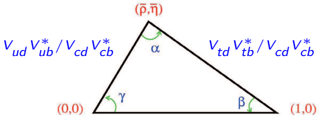
- **Many SUSY variants: NMSSM, Split, High-Scale, Stealth, 5D, Natural, Folded, Twin. . .**

Naturalness? $\Delta M_h^2 \propto M_{\mathrm{SUSY}}^2$

Quark Mixing



$$V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* \;=\; 0$$



$$\mathbf{V} \;=\; \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + \mathcal{O}\left(\lambda^4\right)$$

UT$_{fit}$

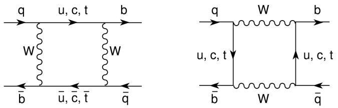
$$\bar\eta \equiv \eta\,\left(1-\tfrac{1}{2}\,\lambda^2\right) \;=\; 0.351 \pm 0.014$$

$$\bar\rho \equiv \rho\,\left(1-\tfrac{1}{2}\,\lambda^2\right) \;=\; 0.132 \pm 0.023$$

$$A = 0.821 \pm 0.012 \quad ; \quad \lambda = 0.2254 \pm 0.0006$$

Successful CKM Mechanism (Tree / Loop / CP-c / CP-v)

Bounds on New Flavour Physics



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

Isidori, 1302.0661

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

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

Minimal Flavour Violation: **The up and down Yukawa matrices are the only source of quark-flavour symmetry breaking**

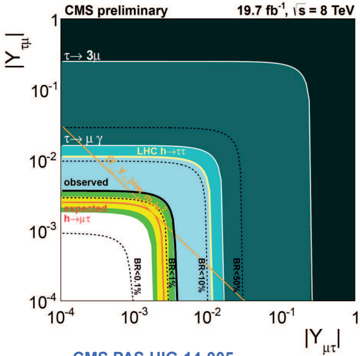
D'Ambrosio et al, Buras et al

Flavour-Violating Higgs Couplings

Isidori

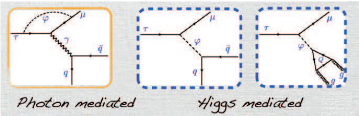
Blankenburg et al, Celis et al, Harnik et al, Davidson-Verdier, Kopp-Nardecchia

$$L = -h\,\left\{Y_{e\mu}\,\overline{e}_L\,\mu_R + Y_{e\tau}\,\overline{e}_L\,\tau_R + Y_{\mu\tau}\,\overline{\mu}_L\,\tau_R + \cdots\right\}$$



CMS PAS HIG-14-005

$\mathrm{Br}\left(H \to \mu\tau\right) < 1.57\%$ (95% CL)



Celis