Status after the first LHC run

Looking for new directions in the physics landscape

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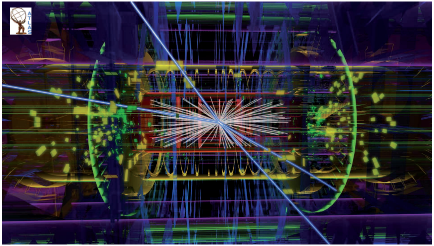
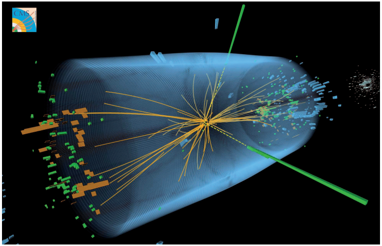
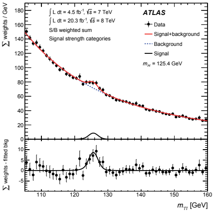
13th Pisa Meeting on Advanced Detectors, La Biodola, Isola d'Elba, 24–30 May 2015

A New Higgs-Like Boson





$H \to \gamma\gamma$



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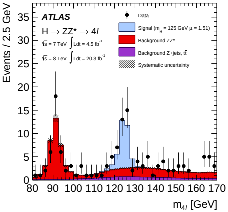

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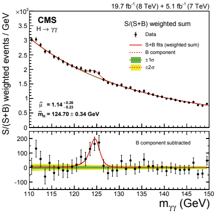

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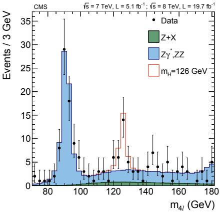
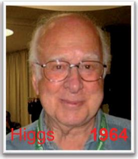
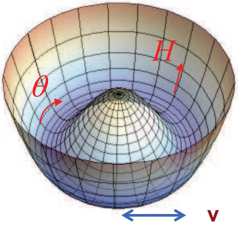


$$M_H = (125.09 \pm 0.21 \pm 0.11)\ \text{GeV}$$

Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism





Fundación
Príncipe de Asturias

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

v = 246 GeV

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

Beautiful Discovery

Boson, $J = 0$

Fermions = Matter ; Bosons = Forces

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

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- **Composite Boson:** **New underlying dynamics**

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 . . . ?

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

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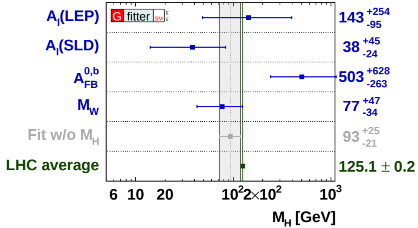

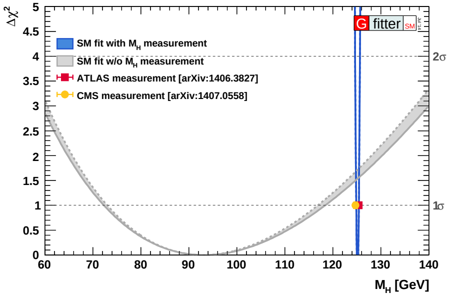

Favoured by

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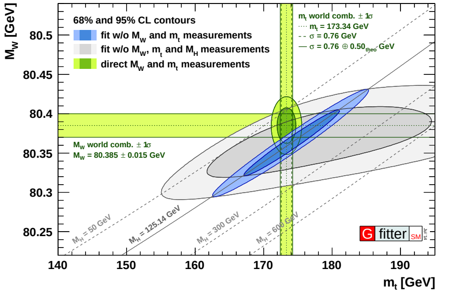


Top Mass

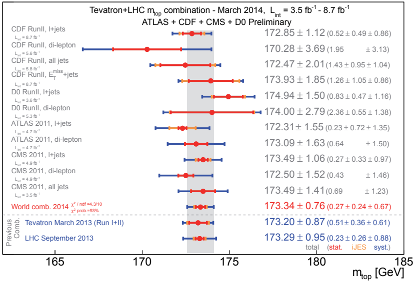
- **Monte Carlo mass:**

$$\mathbf{m_t^{MC} = (173.34 \pm 0.76)\ GeV}$$

Lacks a proper QCD definition

$$\Delta m_t^{\rm th} = |m_t^{\rm pole} - m_t^{\rm MC}| \approx \mathcal{O}(1\ {\rm GeV})$$

Hoang-Stewart 0808.0222



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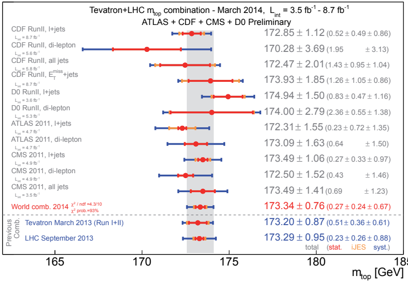
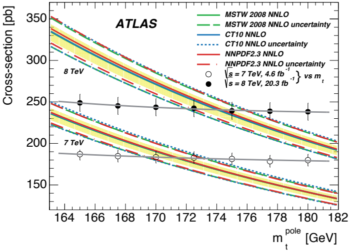
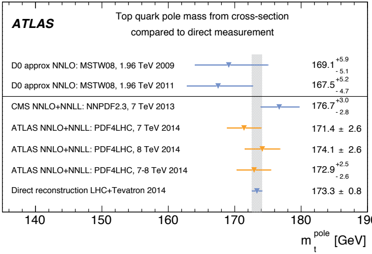
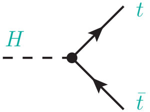


- **Well-defined mass:** $\sigma_{t\bar{t}}$ **NNLO + NNLL** Czakon et al., Bärnreuther et al., Cacciari et al.





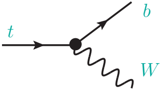
The Heaviest Mass Scale



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

The top quark:

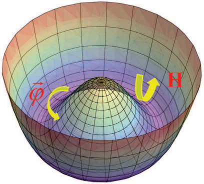
- **Sensitive probe of Electroweak Symmetry Breaking**
- **Non-perturbative (strong) dynamics?**
- **Very different from other quarks:** $y_b = 0.025\,,\; y_c = 0.007\;\ldots$
- **Is it really a SM quark?**



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

$$|\mathbf{V_{tb}}| > \mathbf{0.92} \qquad (95\%\ \mathrm{CL})$$

SM Higgs Potential



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

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

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

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

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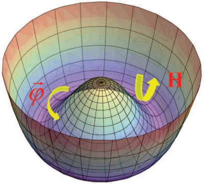

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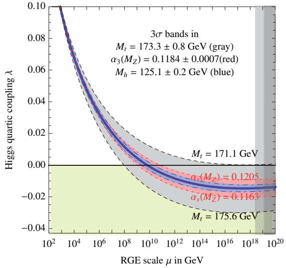
$$M_H = (125.09 \pm 0.24)\ \mathrm{GeV} \quad \Longrightarrow \quad \lambda \;=\; \frac{M_H^2}{2v^2} \;=\; 0.13$$

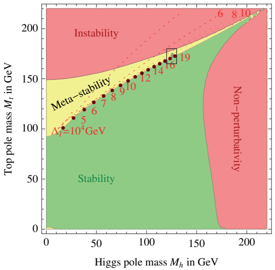
$$\frac{M_H^2}{2v^2} \;=\; \lambda(\mu) \;+\; \frac{2y_t^2}{(4\pi)^2} \left[\lambda + 3\left(y_t^2 - \lambda\right) \log\left(\mu/m_t\right)\right] + \cdots$$

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

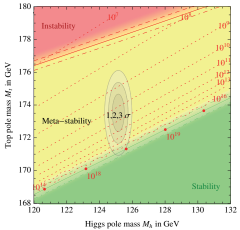
Vacuum Stability: $\lambda(\Lambda) \geq 0$

Degrassi et al, 1205.6497, 1307.3536
Buttazzo et al, 1307.3536





$\Lambda = M_{\text{Planck}}$ ➡ $M_H > (129.6 \pm 1.5)$ GeV



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

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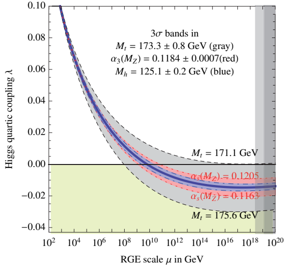

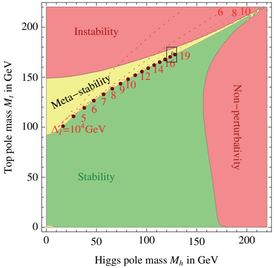

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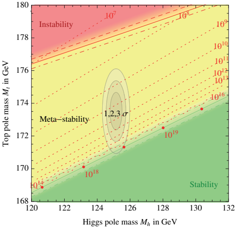
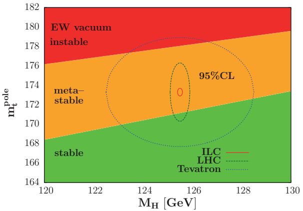


Alekhin et al, 1207.0980



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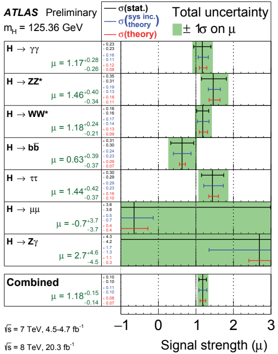
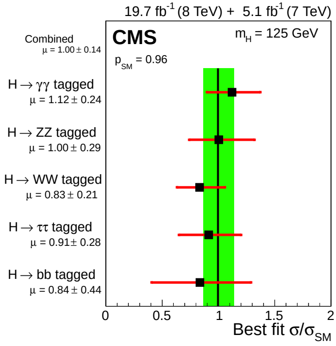
Signal Strengths

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



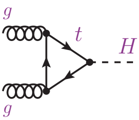


$$\langle \mu \rangle = 1.09 \pm 0.10$$

Decay Mode	ATLAS ($M_H = 125.36$ GeV)	CMS ($M_H = 125.0$ GeV)
$H \to bb$	$0.63^{+0.39}_{-0.37}$	0.84 ± 0.44
$H \to \tau\tau$	$1.44^{+0.42}_{-0.37}$	0.91 ± 0.28
$H \to \gamma\gamma$	$1.17^{+0.28}_{-0.26}$	1.12 ± 0.24
$H \to WW^*$	$1.18^{+0.24}_{-0.21}$	0.83 ± 0.21
$H \to ZZ^*$	$1.46^{+0.40}_{-0.34}$	1.00 ± 0.29
Combined	$\mathbf{1.18^{+0.15}_{-0.14}}$	$\mathbf{1.00 \pm 0.14}$

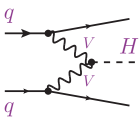
Production Channels

Gluon Fusion

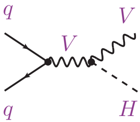


Vector Boson Fusion

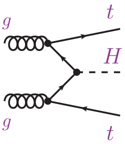
$(V = W^{\pm}, Z)$

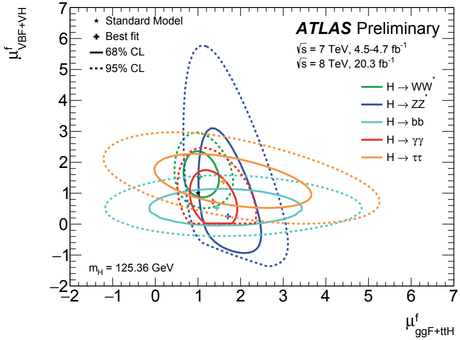


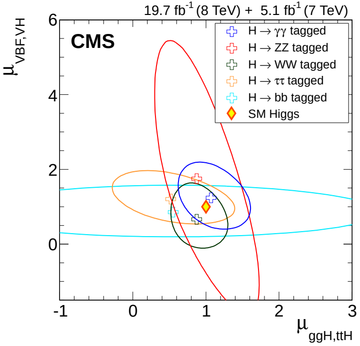
Ass. *VH* Production



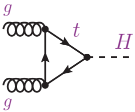
Ass. $t\bar{t}H$ Production



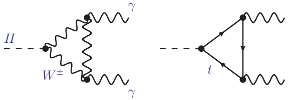




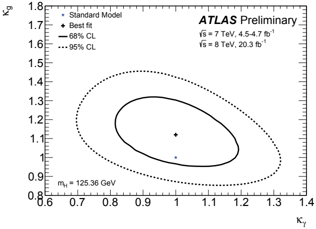
Strong (indirect) evidence for Higgs coupling to t

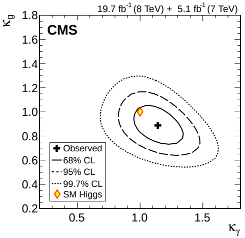


Dominant Production Mechanism



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

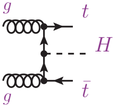




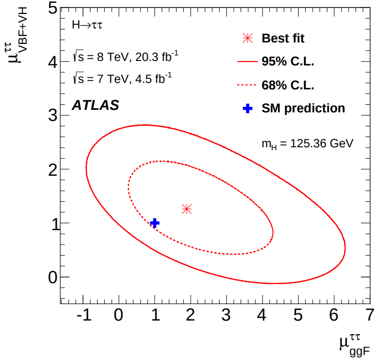
$\kappa_i \equiv g_i / g_i^{\mathrm{SM}}$

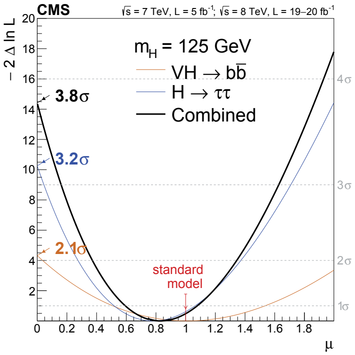
$H \to \gamma\gamma$	Signal Strength
ATLAS	$1.17^{+\,0.28}_{-\,0.26}$
CMS	1.12 ± 0.24

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



Strong evidence for Higgs coupling to τ and b





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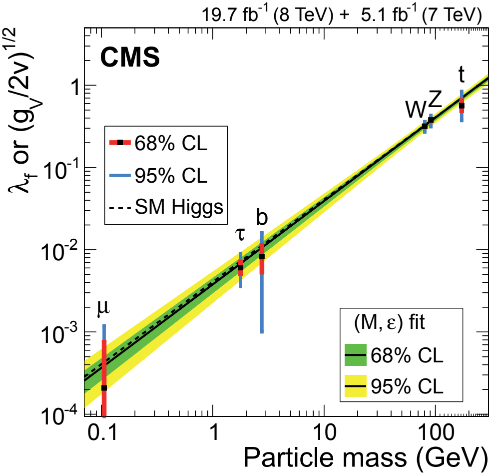
It is a Higgs Boson

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



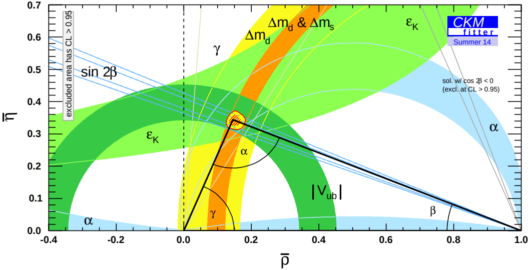
SM: $\epsilon = 0$, $M = v = 246$ GeV

CMS: (95% CL)

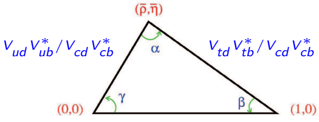
$\epsilon \in [-0.054, 0.100]$

$M \in [217, 279]$ GeV

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$_{fit}$

$$\bar\eta \equiv \eta\left(1-\tfrac{1}{2}\,\lambda^2\right) = 0.352 \pm 0.014$$

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

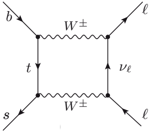
$$A = 0.821 \pm 0.012 \quad ; \quad \lambda = 0.2253 \pm 0.0007$$

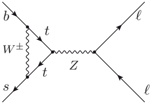
Successful CKM Mechanism (Tree / Loop / CP-c / CP-v)

Rare Decays

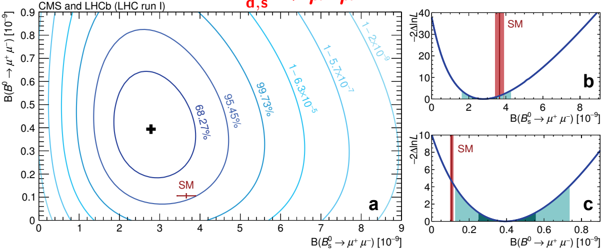
Loop & CKM suppression

→ **NP sensitivity**





$B^0_{d,s} \to \mu^+\mu^-$



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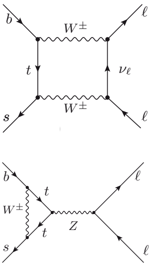
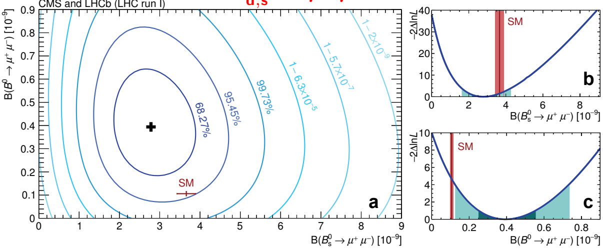
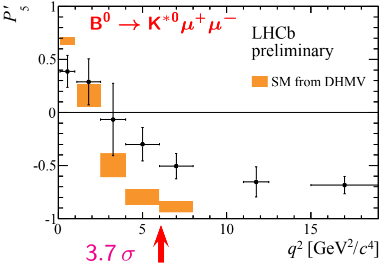


$B^0_{d,s} \to \mu^+\mu^-$





$3.7\,\sigma$

Flavour Anomalies

LHCb: $(q^2 \in [1, 6]\ \mathrm{GeV}^2)$

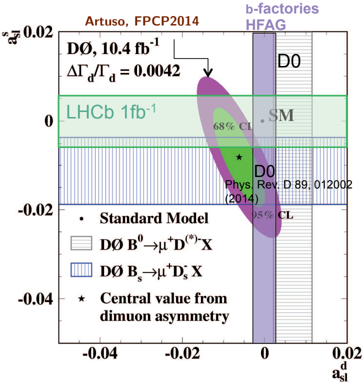
$$\frac{\mathrm{Br}(B^+ \to K^+\mu^+\mu^-)}{\mathrm{Br}(B^+ \to K^+e^+e^-)} = 0.745\,^{+\,0.090}_{-\,0.074} \pm 0.036$$

$2.6\,\sigma$ below the SM

$b \to \mu^\pm \mu^\pm X$ Asymmetry

$$A_{\rm sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

3.6 σ above SM



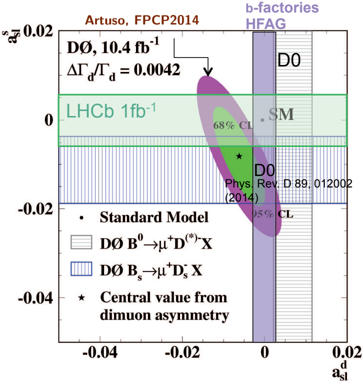
$$a_{\rm sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\bar{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

$$\phi_q \equiv \arg\left(-M_{12}^q / \Gamma_{12}^q\right) \sim m_c^2 / m_b^2$$

$b \to \mu^\pm \mu^\pm X$ Asymmetry

$$A_{\rm sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

3.6 σ above SM

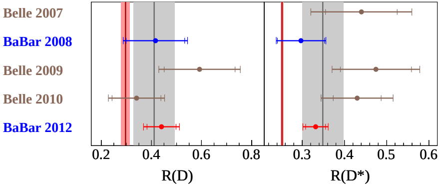


$$a_{\rm sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\bar{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

$$\phi_q \equiv \arg\left(-M_{12}^q/\Gamma_{12}^q\right) \sim m_c^2/m_b^2$$

$B \to D^{(*)} \tau \nu_\tau$

$$R(D^{(*)}) \equiv \frac{\mathrm{Br}(\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathrm{Br}(\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell)}$$



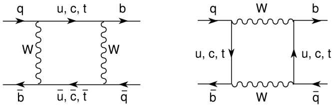
$R(D)$ 2.0 σ above SM

$R(D^*)$ 2.7 σ above SM

Combined significance 3.4 σ

New Belle & LHCb results presented today at FPCP2015

Bounds on New Flavour Physics



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

Isidori, 1302.0661

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Bounds on Λ in TeV ($c_{\rm NP}=1$) Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) 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 [$c_{\rm NP}$~O(1)] ruled out at the TeV scale**
- **$\Lambda_{\rm NP}$ ~ 1 TeV requires $c_{\rm NP}$ 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

Two-Higgs Doublets

$v^2 \equiv v_1^2 + v_2^2$, $\tan\beta \equiv v_2/v_1$

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

$$g_{hVV}^2 + g_{HVV}^2 + g_{AVV}^2 \; = \; \left(g_{hVV}^{\mathrm{SM}}\right)^2$$

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$$\mathcal{L}_Y = -\bar{Q}_L' \left(\Gamma_1\,\phi_1 + \Gamma_2\,\phi_2\right) d_R' \quad \longrightarrow \quad \mathcal{L}_Y = -\frac{\sqrt{2}}{v}\,\bar{Q}_L' \left(M_d'\,\Phi_1 + Y_d'\,\Phi_2\right) d_R'$$

$\mathbf{M_f'}$ & $\mathbf{Y_f'}$ unrelated (not simultaneously diagonal) $\longrightarrow$ **FCNCs**

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$\mathbf{M_f'}$ & $\mathbf{Y_f'}$ unrelated (not simultaneously diagonal) → **FCNCs**

Solutions: (same for u_R and ℓ_R Yukawas)

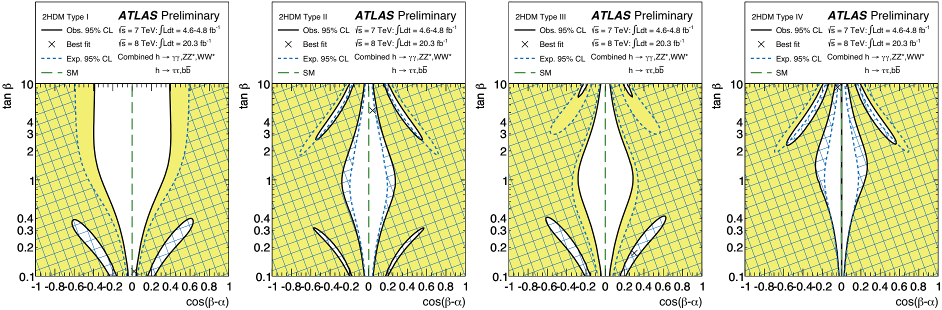
- **Natural Flavour Conservation:** $\Gamma_1 = 0$ or $\Gamma_2 = 0$ ($\mathcal{Z}_2$ models)

  Glashow-Weinberg, Paschos

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

  Pich-Tuzón, 0908.1554

LHC Fit within $\mathcal{Z}_2$ Models



$$g_{hVV} / g_{hVV}^{\rm SM} \; = \; \cos\tilde\alpha \; \equiv \; \sin\left(\beta - \alpha\right)$$

$$y_f^h \; = \; \cos\tilde\alpha + \varsigma_f \sin\tilde\alpha$$

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X (III)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y (IV)	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

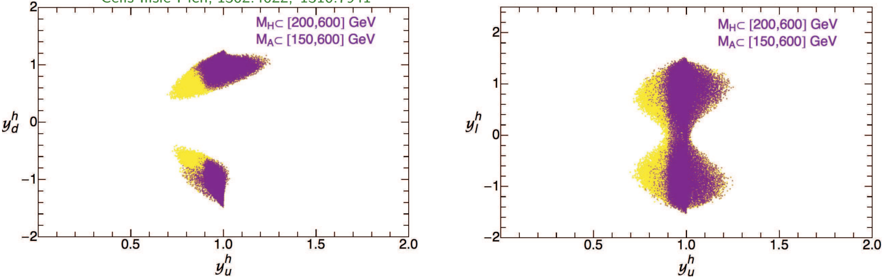
Flavour-Aligned 2HDM

Pich-Tuzón, 0908.1554

$$g_{hVV}/g_{hVV}^{\rm SM} = \cos\tilde{\alpha} \qquad , \qquad y_f^h = \cos\tilde{\alpha} + \varsigma_f \sin\tilde{\alpha} \qquad \text{(CP conserved)}$$

Fit to collider & flavour data: $|\cos\tilde{\alpha}| > 0.90$ (90% CL)

Celis-Ilisie-Pich, 1302.4022, 1310.7941



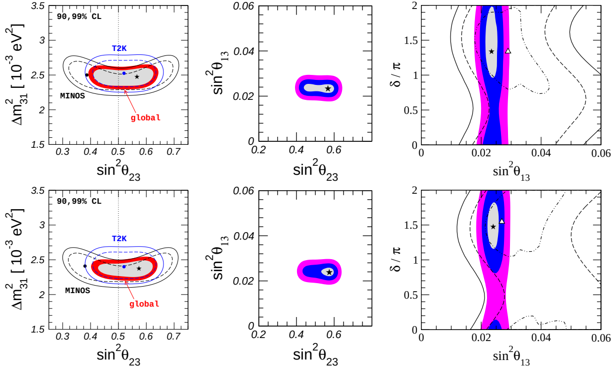
- **General setting without FCNCs & new sources of CP violation**
- **Rich phenomenology @ LHC**
- **Flavour & EDM constraints fulfilled**
- **Usual $\mathcal{Z}_2$ models recovered in particular (CP-conserving) limits**

Neutrino Oscillations

NH

Forero et al, 1405.7540

IH



$\sin^2 2\theta_{13} = 0.084 \pm 0.005$ Daya Bay, 1505.03456

González-García et al, 1409.5439

NuFIT 2.0 (2014)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

Flavour mixing is very different for quarks & leptons

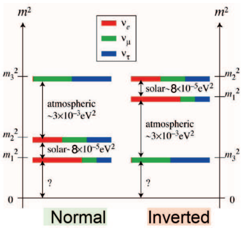
Cosmology: $\sum_i m_{\nu_i} < 0.23\ \mathrm{eV}$ Planck, 1502.01589

Open Questions in ν Physics

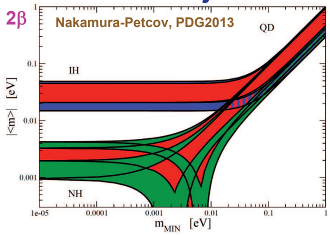
Lindner

Mass Hierarchy

Blennow



Dirac / Majorana



$$|\!<m>\!| = \left| m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2 \right|$$

Mass Scale

Sterile ν_R ?

CP Violation

Flavour Symmetries

Leptogenesis

Low-E Effective Theory:

$$L = L_{SM} + \sum_d \frac{c_d}{\Lambda^{d-4}} O_d$$

1 $SU(2)_L \otimes U(1)_Y$ invariant operator with d=5 — Weinberg

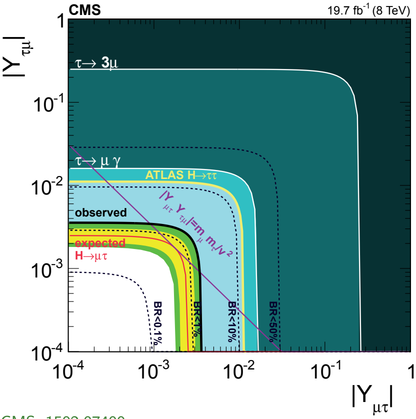
$$-\frac{c_{ij}}{\Lambda} \bar{L}_i \tilde{\phi} \tilde{\phi}^t L_j^c + \text{h.c.} \quad \xrightarrow{\text{SSB}} \quad -\frac{1}{2} \bar{\nu}_{iL} M_{ij} \nu_{jL}^c + \text{h.c.} \quad ; \quad M_{ij} \equiv \frac{c_{ij}}{\Lambda} v^2$$

Small Majorana Mass: $m_\nu > 0.05$ eV ➡ $\Lambda / c_{ij} < 10^{15}$ GeV

Flavour-Violating Higgs Couplings

$$\mathcal{L} = -H \, \{Y_{e\mu} \, \bar{e}_L \mu_R + Y_{e\tau} \, \bar{e}_L \tau_R + Y_{\mu\tau} \, \bar{\mu}_L \tau_R + \cdots \}$$

$\mathrm{Br}(H \to \mu^\pm \tau^\mp) < 1.51\%$ (95% CL)



CMS, 1502.07400

Flavour-Violating Higgs Couplings

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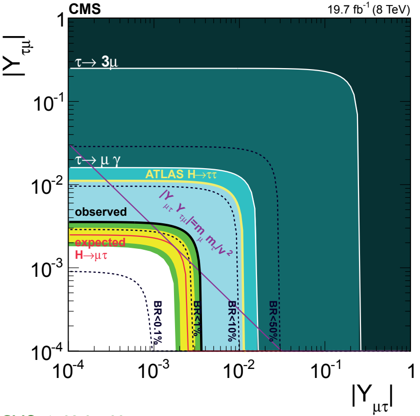
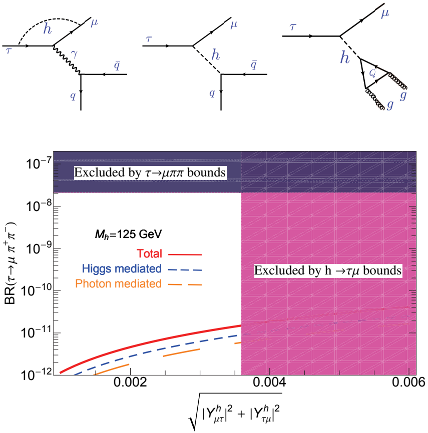
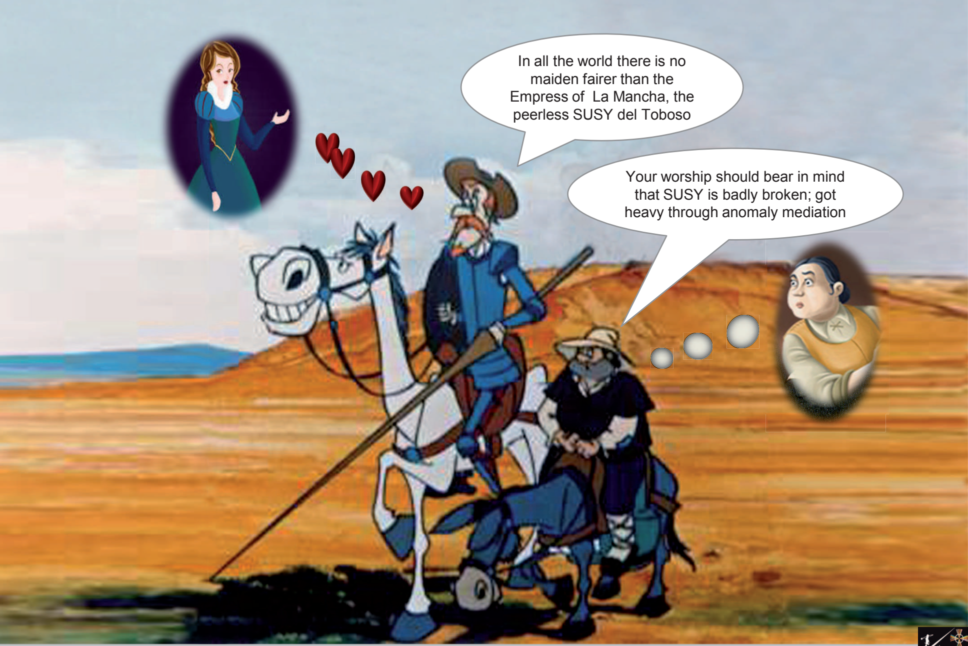


CMS, 1502.07400

$\tau\to\mu\,\pi^+\pi^-$ Celis et al., 1409.4439



Desperately Seeking SUSY (Dulcinea)



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

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

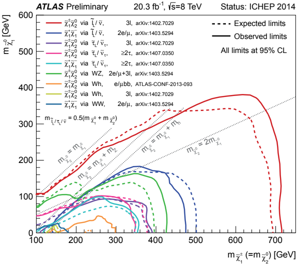
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde q, \tilde g$ 1.7 TeV	$m(\tilde q)=m(\tilde g)$	1405.7875
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi^0_1$	0	2-6 jets	Yes	20.3	$\tilde q$ 850 GeV	$m(\tilde\chi^0_1)$=0 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	1405.7875
	$\tilde q\tilde q\gamma$, $\tilde q\to q\tilde\chi^0_1$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde q$ 250 GeV	$m(\tilde q)-m(\tilde\chi^0_1) = m(c)$	1411.1559
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi^0_1$	0	2-6 jets	Yes	20.3	$\tilde g$ 1.33 TeV	$m(\tilde\chi^0_1)$=0 GeV	1405.7875
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi^\pm_1\to qqW^\pm\tilde\chi^0_1$	1 e,μ	3-6 jets	Yes	20	$\tilde g$ 1.2 TeV	$m(\tilde\chi^0_1)$<300 GeV, $m(\tilde\chi^\pm)=0.5(m(\tilde\chi^0_1)+m(\tilde g))$	1501.03555
	$\tilde g\tilde g$, $\tilde g\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde\chi^0_1$	2 e,μ	0-3 jets	-	20	$\tilde g$ 1.32 TeV	$m(\tilde\chi^0_1)$=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	$m(\tilde\chi^0_1)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 e,μ + γ	-	Yes	4.8	$\tilde g$ 619 GeV	$m(\tilde\chi^0_1)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde g$ 900 GeV	$m(\tilde\chi^0_1)$>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	$m(\tilde G)>1.8\times10^{-4}$ eV, $m(\tilde g)=m(\tilde q)$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde g$ med.	$\tilde g\to b\bar b\tilde\chi^0_1$	0	3 b	Yes	20.1	$\tilde g$ 1.25 TeV	$m(\tilde\chi^0_1)$<400 GeV	1407.0600
	$\tilde g\to t\bar t\tilde\chi^0_1$	0	7-10 jets	Yes	20.3	$\tilde g$ 1.1 TeV	$m(\tilde\chi^0_1)$ <350 GeV	1308.1841
	$\tilde g\to t\bar t\tilde\chi^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$ 1.34 TeV	$m(\tilde\chi^0_1)$<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	$m(\tilde\chi^0_1)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi^0_1$	0	2 b	Yes	20.1	$\tilde b_1$ 100-620 GeV	$m(\tilde\chi^0_1)$<90 GeV	1308.2631
	$\tilde b_1\tilde b_1$, $\tilde b_1\to t\tilde\chi^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde b_1$ 275-440 GeV	$m(\tilde\chi^\pm_1)=2\,m(\tilde\chi^0_1)$	1404.2500
	$\tilde t_1\tilde t_1$, $\tilde t_1\to b\tilde\chi^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde t_1$ 110-167 GeV, 230-460 GeV	$m(\tilde\chi^\pm_1) = 2m(\tilde\chi^0_1)$, $m(\tilde\chi^0_1)$=55 GeV	1209.2102, 1407.0583
	$\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi^0_1$ or $t\tilde\chi^0_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde t_1$ 90-191 GeV, 215-530 GeV	$m(\tilde\chi^0_1)$=1 GeV	1403.4853, 1412.4742
	$\tilde t_1\tilde t_1$, $\tilde t_1\to t\tilde\chi^0_1$	0-1 e,μ	1-2 b	Yes	20	$\tilde t_1$ 210-640 GeV	$m(\tilde\chi^0_1)$=1 GeV	1407.0583,1406.1122
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde t_1$ 90-240 GeV	$m(\tilde t_1)-m(\tilde\chi^0_1)$<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	$m(\tilde\chi^0_1)$>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	$m(\tilde\chi^0_1)$<200 GeV	1403.5222
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi^0_1$	2 e,μ	0	Yes	20.3	$\tilde\ell$ 90-325 GeV	$m(\tilde\chi^0_1)$=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	$\tilde\chi^\pm_1$ 140-465 GeV	$m(\tilde\chi^0_1)$=0 GeV, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi^\pm_1)+m(\tilde\chi^0_1))$	1403.5294
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to\tilde\tau\nu(\tau\tilde\nu)$	2 τ	-	Yes	20.3	$\tilde\chi^\pm_1$ 100-350 GeV	$m(\tilde\chi^0_1)$=0 GeV, $m(\tilde\tau,\tilde\nu)=0.5(m(\tilde\chi^\pm_1)+m(\tilde\chi^0_1))$	1407.0350
	$\tilde\chi^\pm_1\tilde\chi^0_2\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	20.3	$\tilde\chi^\pm_1,\tilde\chi^0_2$ 700 GeV	$m(\tilde\chi^\pm_1)=m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi^\pm_1)+m(\tilde\chi^0_1))$	1402.7029
	$\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1Z\tilde\chi^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde\chi^\pm_1,\tilde\chi^0_2$ 420 GeV	$m(\tilde\chi^\pm_1)=m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde\chi^\pm_1\tilde\chi^0_2\to W\tilde\chi^0_1h\tilde\chi^0_1$, $h\to b\bar b/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde\chi^\pm_1,\tilde\chi^0_2$ 250 GeV	$m(\tilde\chi^\pm_1)=m(\tilde\chi^0_2)$, $m(\tilde\chi^0_1)$=0, sleptons decoupled	1501.07110
	$\tilde\chi^0_2\tilde\chi^0_3$, $\tilde\chi^0_{2,3}\to\tilde\ell_R\ell$	4 e,μ	0	Yes	20.3	$\tilde\chi^0_{2,3}$ 620 GeV	$m(\tilde\chi^0_2)=m(\tilde\chi^0_3)$, $m(\tilde\chi^0_1)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi^0_2)+m(\tilde\chi^0_1))$	1405.5086
Long-lived particles	Direct $\tilde\chi^+_1\tilde\chi^-_1$ prod., long-lived $\tilde\chi^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde\chi^\pm_1$ 270 GeV	$m(\tilde\chi^\pm_1)-m(\tilde\chi^0_1)$=160 MeV, $\tau(\tilde\chi^\pm_1)$=0.2 ns	1310.3675
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde g$ 832 GeV	$m(\tilde\chi^0_1)$=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 $\tilde\tau$, $\tilde\chi^0_1\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde\chi^0_1$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde\chi^0_1\to\gamma\tilde G$, long-lived $\tilde\chi^0_1$	2 γ	-	Yes	20.3	$\tilde\chi^0_1$ 435 GeV	2<$\tau(\tilde\chi^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde q\tilde q$, $\tilde\chi^0_1\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde q$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde\chi^0_1)$=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 $e,\mu+\tau$	-	-	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
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to W\tilde\chi^0_1$, $\tilde\chi^0_1\to ee\tilde\nu_\mu, e\mu\tilde\nu_e$	4 e,μ	-	Yes	20.3	$\tilde\chi^\pm_1$ 750 GeV	$m(\tilde\chi^0_1)>0.2\times m(\tilde\chi^\pm_1)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde\chi^+_1\tilde\chi^-_1$, $\tilde\chi^+_1\to W\tilde\chi^0_1$, $\tilde\chi^0_1\to\tau\tau\tilde\nu_e, e\tau\tilde\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde\chi^\pm_1$ 450 GeV	$m(\tilde\chi^0_1)>0.2\times m(\tilde\chi^\pm_1)$, $\lambda_{133}\neq0$	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, $\tilde c\to c\tilde\chi^0_1$	0	2 c	Yes	20.3	$\tilde c$ 490 GeV	$m(\tilde\chi^0_1)$<200 GeV	1501.01325

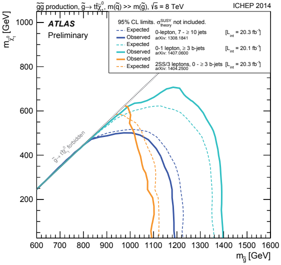
$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

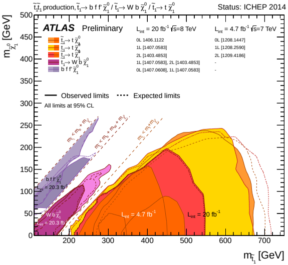
10^{-1} 1 **Mass scale [TeV]**

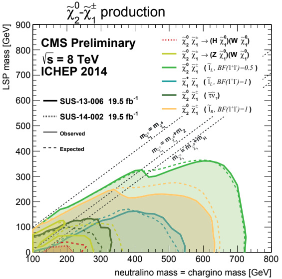
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

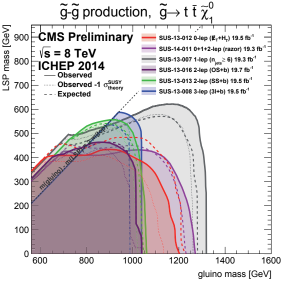
Strong limits on SUSY partners

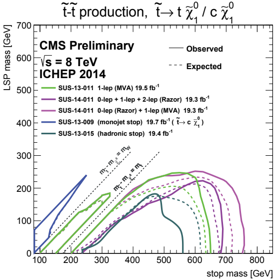












Tension with Higgs mass: $M_h^2 \leq M_Z^2 \cos^2(2\beta) + \epsilon$

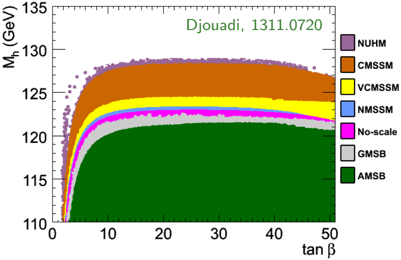
Large radiative corrections needed:

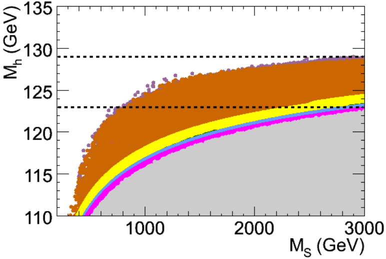
$M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$

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

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

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



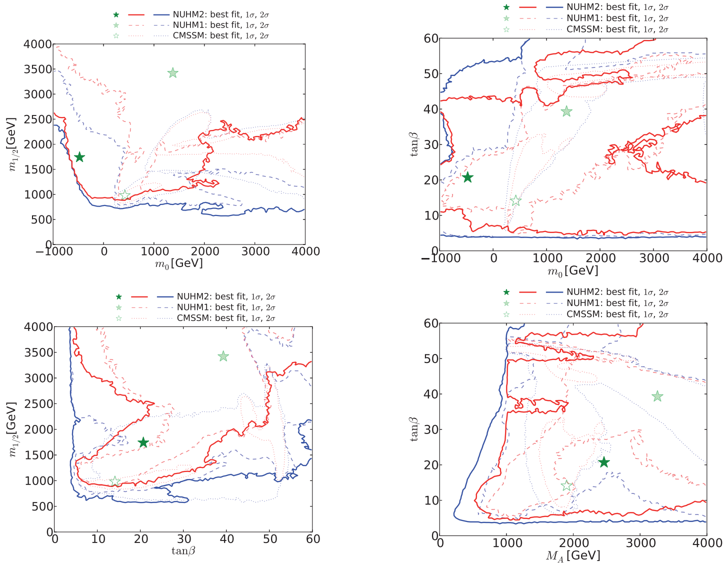


Improved higher-order calculations allow slightly larger values of M_h

Hahn et al, 1312.4937

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

Buchmueller et al, 1408.4060



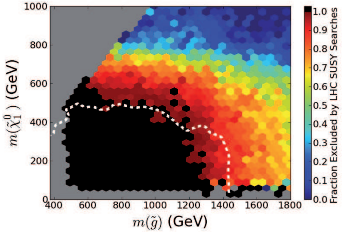
$(\mathbf{g}-\mathbf{2})_\mu$ cannot be explained (not included in the fit)

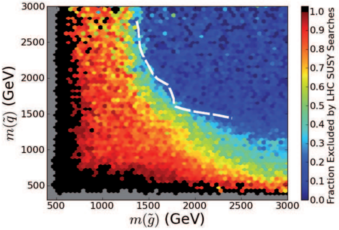
Which SUSY ?

- **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



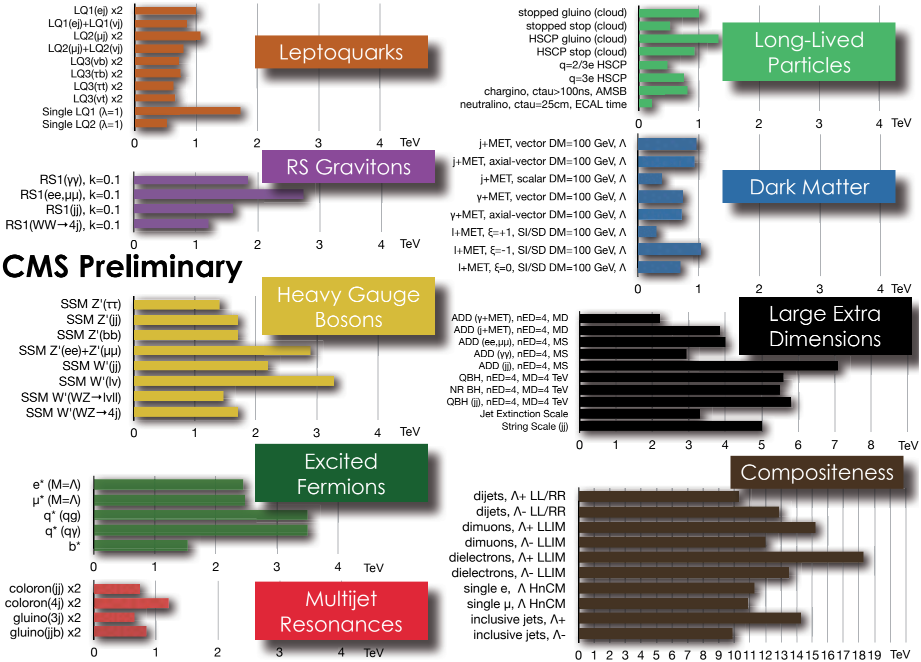


19–20 parameters

Data-driven search

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

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



CMS Exotica Physics Group Summary – Moriond, 2015

Don Quixote and the Windmills

Effective Field Theory

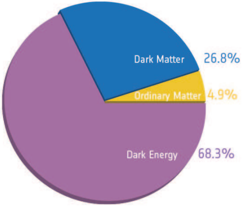
$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda_{\rm NP}^{D-4}} \mathcal{O}_i^{(D)}$$

- **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:**

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

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

The Dark Side of the Universe



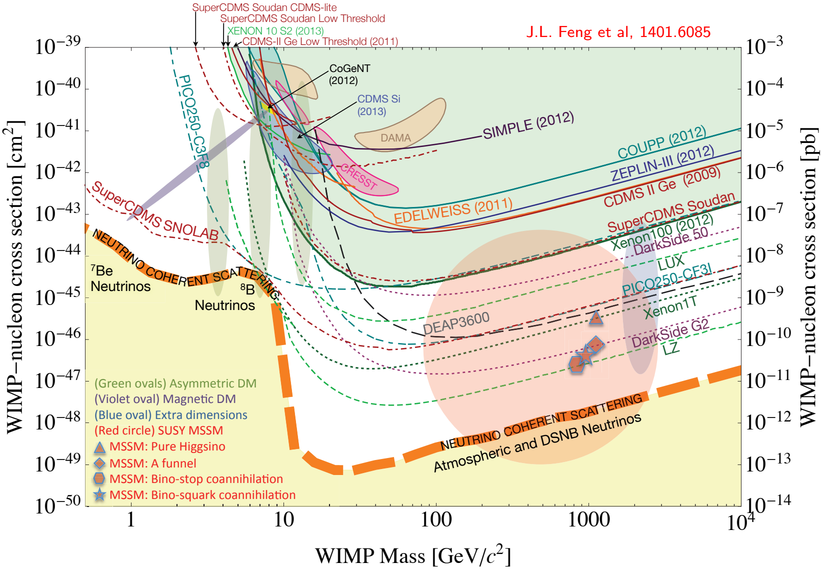
- **Dark Energy:** **?**
- **Dark Matter:**
  - Gravitational interactions
  - Weakly interacting?
  - Higgs-like interactions?

WIMP miracle: (DM relic density)

Right annihilation cross section after freeze-out

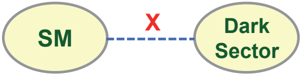
Viable DM candidates in many models

Mining for WIMPs



Hidden Portals

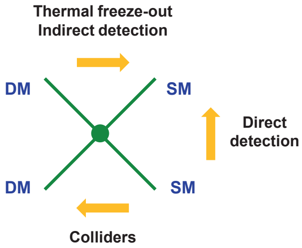
Coupling to a hidden Dark Sector
through new SM-singlet particles



- **Higgs Portal:** $\chi H^\dagger H \, , \; \chi^2 H^\dagger H$
- **Vector Portal:** $V_{\mu\nu} F^{\mu\nu}$
- **Neutrino Portal:** $\bar{L}_L H N_R$
- **Axion Portal:** $a \, \tilde{G}_{\mu\nu} G^{\mu\nu} \, , \; \partial^\mu a \, \bar{\psi}\gamma_\mu\gamma_5\psi$

DM candidates in many BSMs

Complementary experimental information



Status & Outlook

- The **SM** appears to be the **right theory at the EW scale**
- The **H**(**125**) behaves as the SM scalar boson
- The **CKM** mechanism works very well
- Neutrinos do have (tiny) masses. **Lepton flavour is violated**
- Different **flavour structure** for quarks & leptons
- **New physics needed** to explain many pending questions:
  Flavour, CP, baryogenesis, dark matter, cosmology. . .

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  Flavour, CP, baryogenesis, dark matter, cosmology. . .

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

Awaiting great discoveries @ LHC

Backup Slides

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

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

3×2 polarizations $= 6$

$+$

3 Goldstones $\varphi_i(x)$

SSB ⬇

Massive $W^\pm$, Z

3×3 polarizations $= 9$

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Gauge invariance

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3 × 2 polarizations = 6

+

3 Goldstones $\varphi_i(x)$

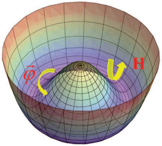
SSB ↓

Massive $W^\pm$, Z

3 × 3 polarizations = 9

Spontaneous Symmetry Breaking

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



$\mu^2 < 0$

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

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

Gauge invariance

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

3×2 polarizations $= 6$

$+$

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SSB ↓

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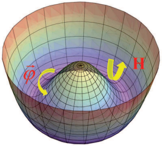

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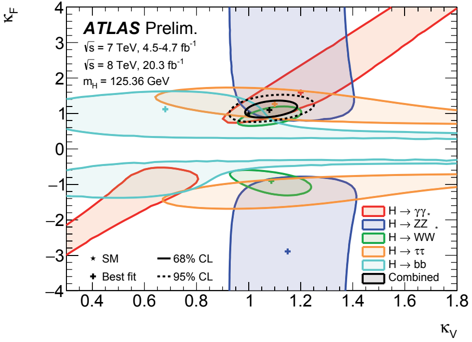
$$\Phi(x) = \exp\left\{ i\,\vec{\sigma}\cdot\frac{\vec{\varphi}(x)}{v}\right\} \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + H(x) \end{bmatrix}$$

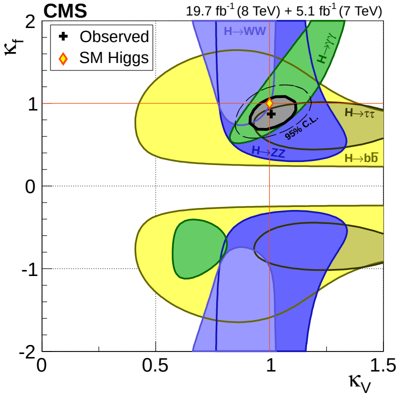
$D_\mu\Phi = (\partial_\mu + \frac{i}{2}\,g\,\vec{\sigma}\cdot\vec{W}_\mu + \frac{i}{2}\,g'\,B_\mu)\,\Phi \quad ; \quad v^2 = -\mu^2/\lambda$

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

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

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

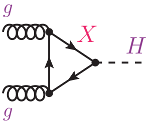




$$\sigma(i \to H) \cdot \mathrm{Br}(H \to f) \;=\; \sigma(i \to H) \cdot \Gamma(H \to f)/\Gamma_H \;\sim\; (\kappa_i \kappa_f / \kappa_H)^2$$

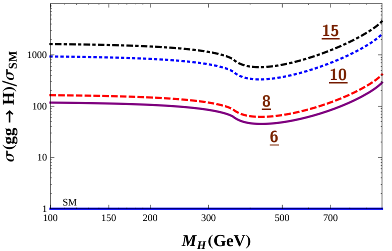
QCD Exotics

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



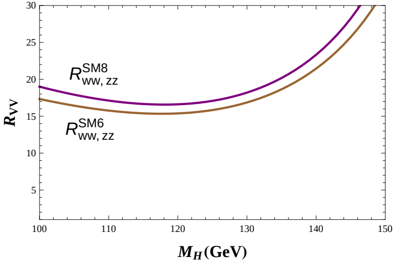
$$\sim \sum_{a=1}^{d_A} \mathrm{Tr}\left[t_R^a t_R^a\right] = C_R d_R$$

V. Ilisie - AP, 1202.3430



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

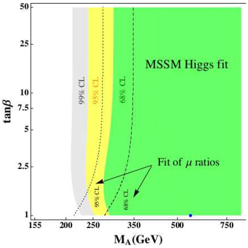
$R_{VV} = \mu_{VV}$



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)

Constraints from Higgs Decay



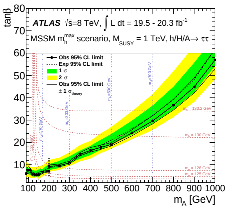
Djouadi, 1311.0720

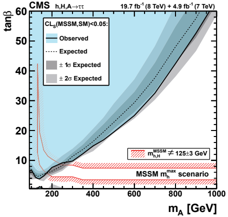
$$c_t \;\approx\; \frac{\cos\alpha}{\sin\beta}\left[1+\frac{m_t^2}{4m_{\tilde t_1}^2\, m_{\tilde t_2}^2}\left(m_{\tilde t_1}^2+m_{\tilde t_2}^2-X_t^2\right)\right]$$

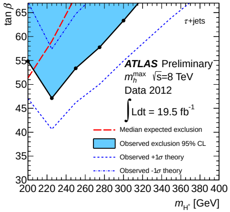
$$c_b \;\approx\; -\,\frac{\sin\alpha}{\cos\beta}\left[1-\frac{\Delta_b}{1+\Delta_b}\,\left(1+\cot\alpha\,\cot\beta\right)\right]$$

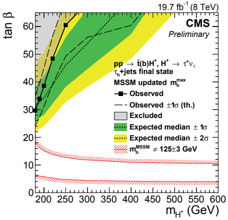
$$c_V \;=\; \sin\left(\beta-\alpha\right) \qquad , \qquad \Delta_b \;\approx\; \frac{2\alpha_s}{3\pi}\;\frac{\mu\, m_{\tilde g}\,\tan\beta}{\max\left(m_{\tilde g}^2,\, m_{\tilde b_1}^2,\, m_{\tilde b_2}^2\right)}$$

Heavy Higgs Searches









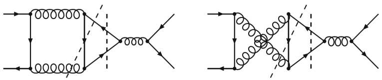
$t\bar{t}$ Production Asymmetries

Bernardi

Tevatron: $A_{FB} \equiv A_{t\bar{t}} = \dfrac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$

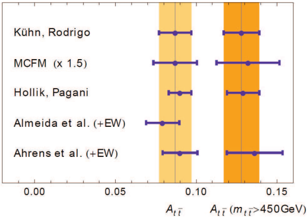
LHC: $A_C = \dfrac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$

$\Delta y = y_t - y_{\bar{t}} \qquad , \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$

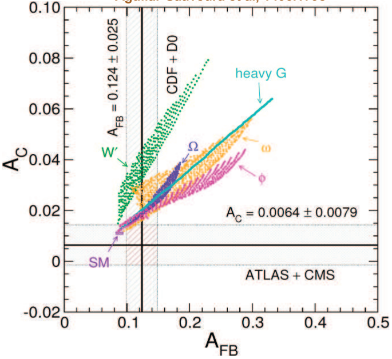


Rodrigo, 1207.0331

SM predictions



Aguilar-Saavedra et al, 1406.1798



Data is now consistent with the SM

(still 1.7 excess at CDF)

Models predicting larger asymmetries don't pass other phenomenological tests or are rather ad-hoc