THEORY STATUS AFTER ICHEP 2014

Searching for New Physics at the Next LHC Run

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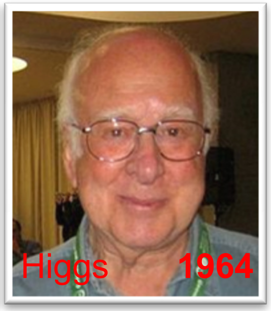
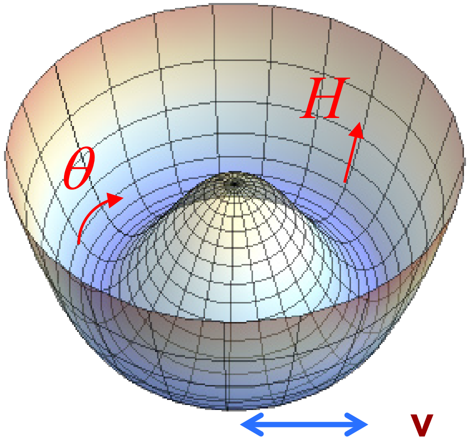
IFAE, Bellaterra, Spain, 24 November 2014

Great success of the Standard Model

BEGHHK (≡ Higgs) Mechanism



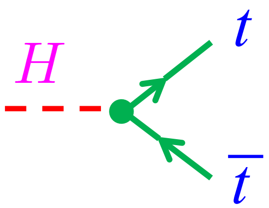


$SU(2)_L \otimes U(1)_Y$ v = 246 GeV

Fundación Príncipe de Asturias

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

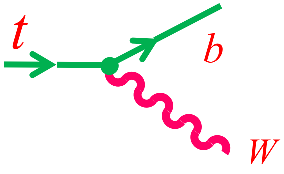
The Heaviest Mass Scale



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

The top quark:

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



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

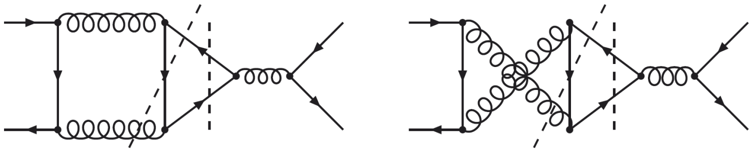
Single-top	$\lvert V_{tb}\rvert$
ATLAS ‘14	> 0.88 (95% CL)
CMS’14	> 0.92 (95% CL)
CDF’14	> 0.84 (95% CL)
D0 ‘13	> 0.92 (95% CL)

$t\bar{t}$ Production Asymmetries

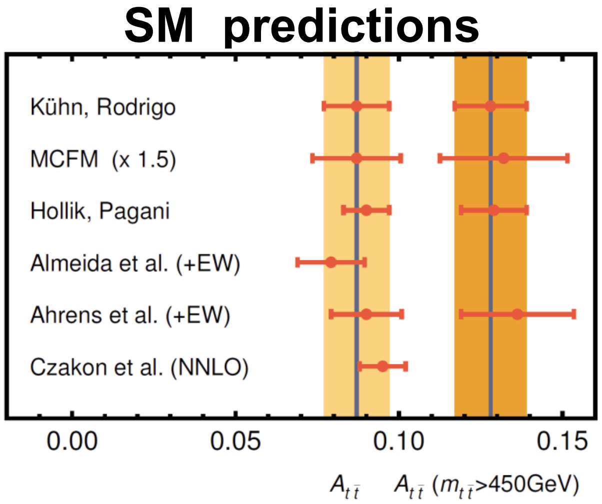
Tevatron: $$A_{FB} \equiv A_{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

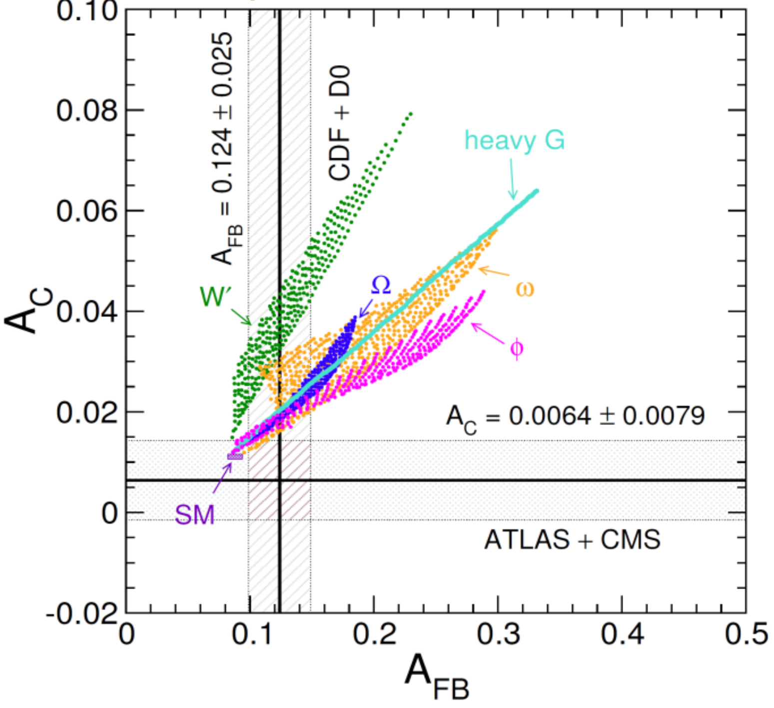
$$\Delta y = y_t - y_{\bar{t}} \qquad , \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$$



Kühn-Rodrigo, 1411.4675



Aguilar-Saavedra et al, 1406.1798

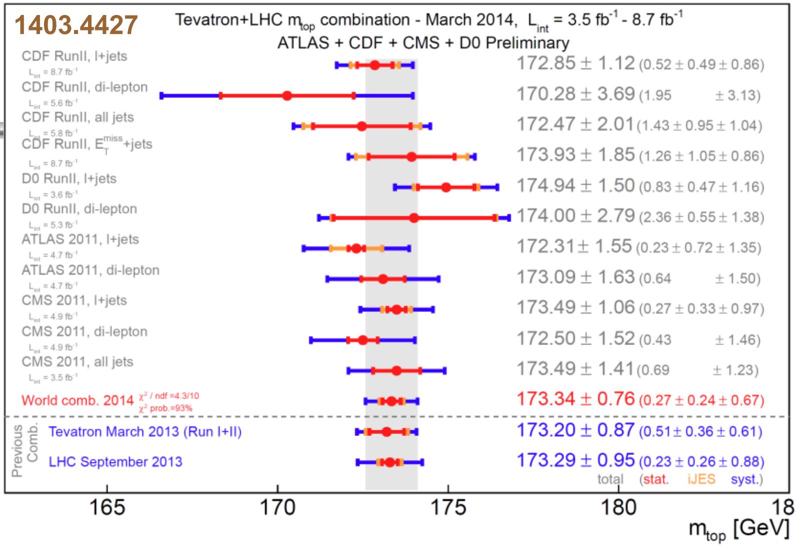


Data is now consistent with the SM

(still 1.7 excess at CDF)

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

TOP MASS



- **Monte Carlo mass:**

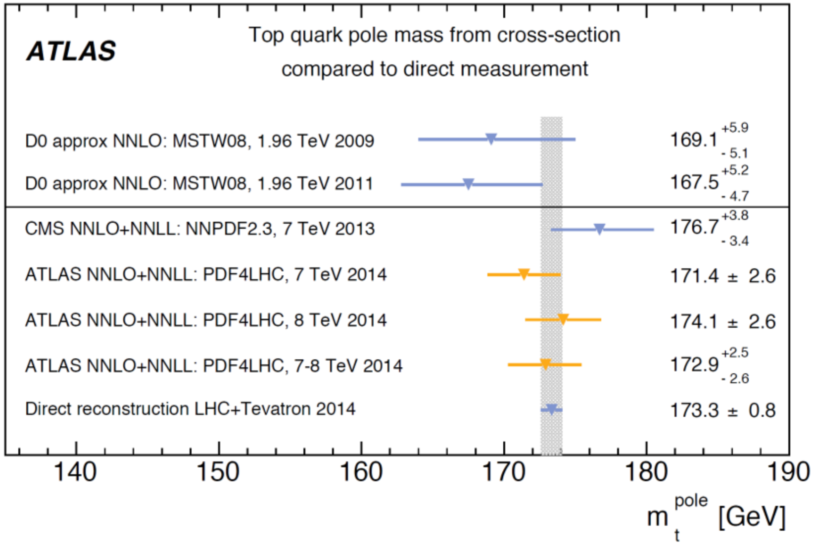
$$M_t^{\mathrm{MC}} = \left(173.34 \pm 0.76\right)\ \mathrm{GeV}$$

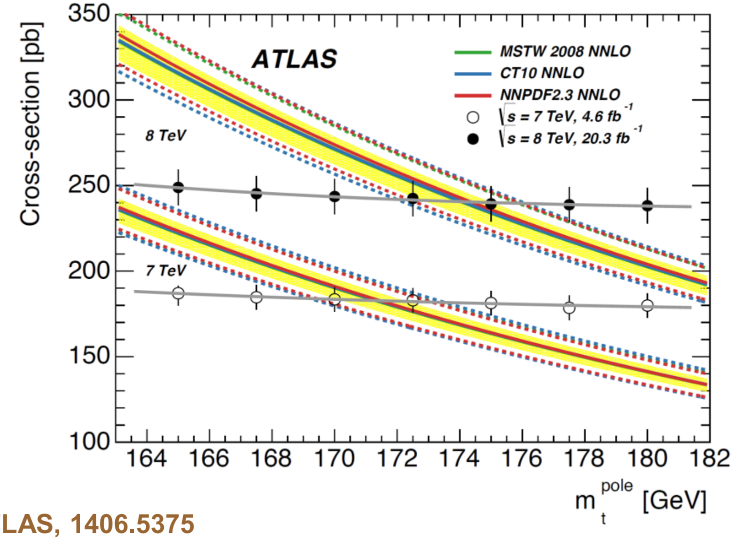
Lacks a proper QCD definition: $M_t^{\mathrm{pole}} = M_t^{\mathrm{MC}} + \Delta M_t^{\mathrm{th}}$

$\left|\Delta M_t^{\mathrm{th}}\right| \approx \mathrm{O}\left(1\ \mathrm{GeV}\right)$ **Hoang-Stewart, 0808.0222**

- **Cross section:** $\sigma_{t\bar{t}}$ **NNLO+NNLL** **Czakon et al, Bärnreuther et al, Cacciari et al**

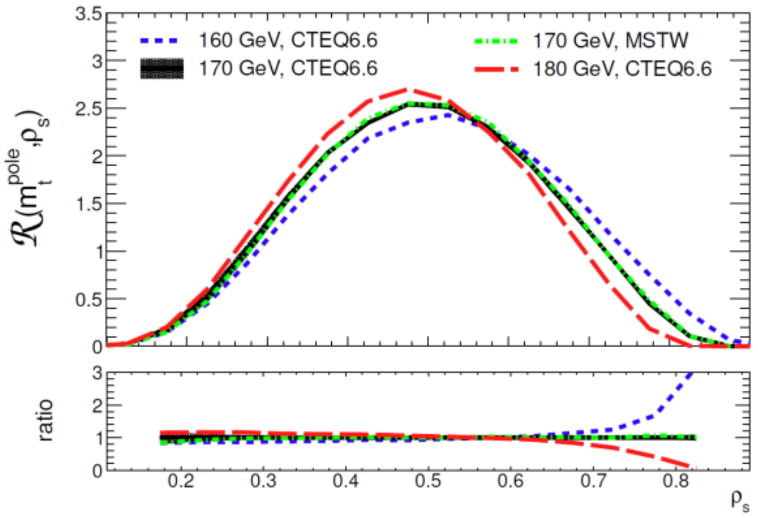
Well-defined mass





ATLAS, 1406.5375

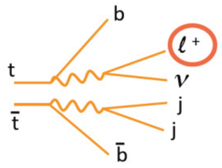
Possible Improvements:



- **Differential distribution in** $\rho_s = m_0 \Big/ \sqrt{s_{t\bar{t}+j}}$

Alioli et al, 1303.6415

$$R\left(m_t^{\text{pole}}, \rho_s\right) \equiv \frac{1}{\sigma_{t\bar{t}+1\,\text{jet}}} \frac{d\sigma_{t\bar{t}+1\,\text{jet}}}{d\rho_s}$$



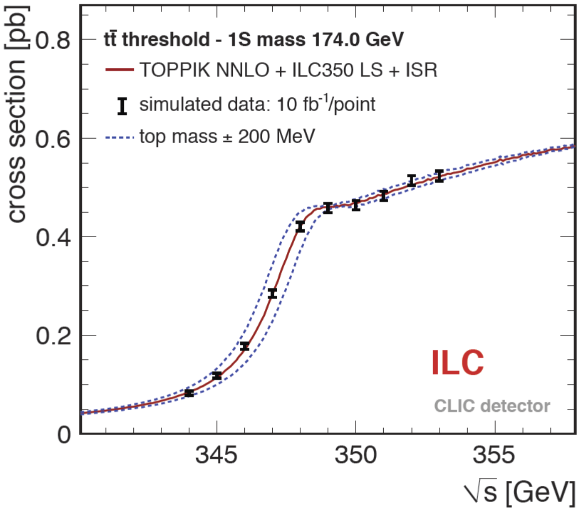
- **Weight function method:** Lepton energy distribution

Kawabata et al, 1405.2395

- $\sigma\left(e^+e^- \to t\,\bar{t}\right)_{\text{threshold}}$

Hoang et al, Beneke et al, Ruiz-Femenía, Martínez-Miquel

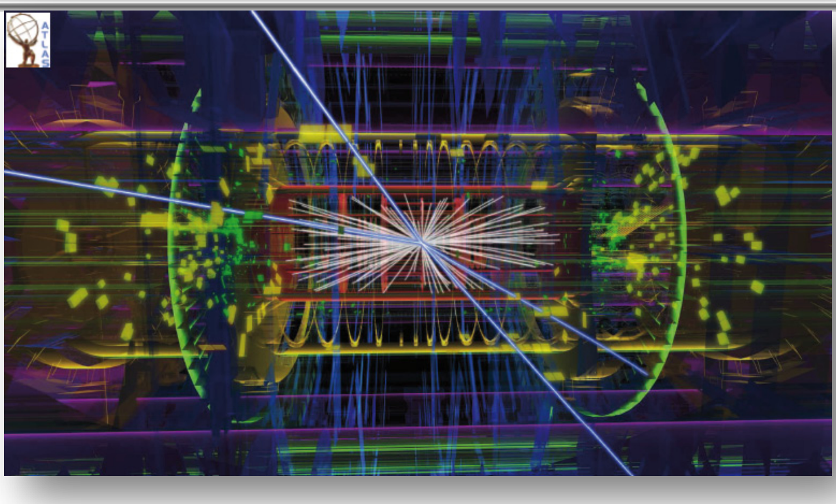
$\delta m_t < 100$ MeV

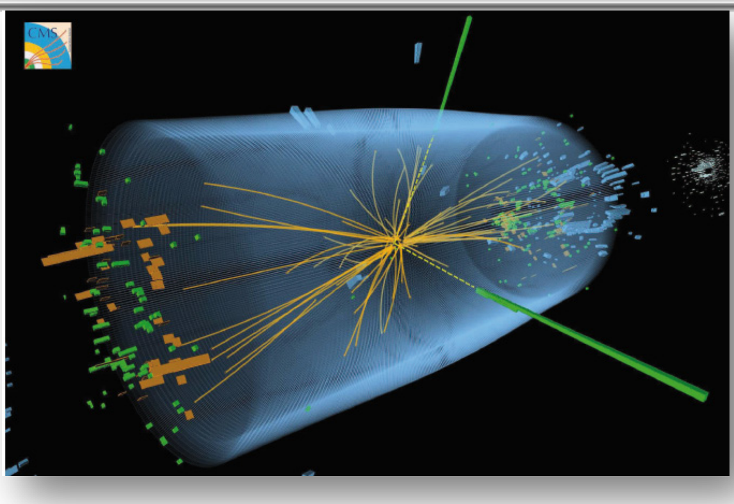


García-García

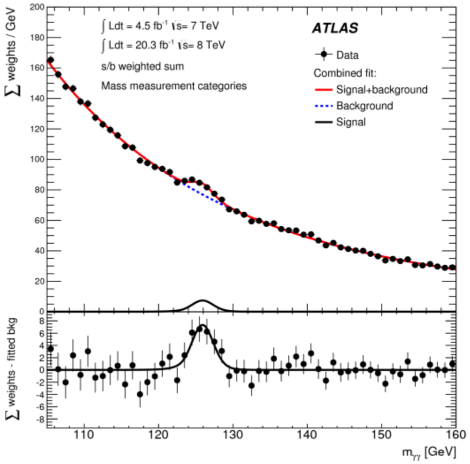
Precision measurement needed to test the EW theory

A New Higgs-like Boson

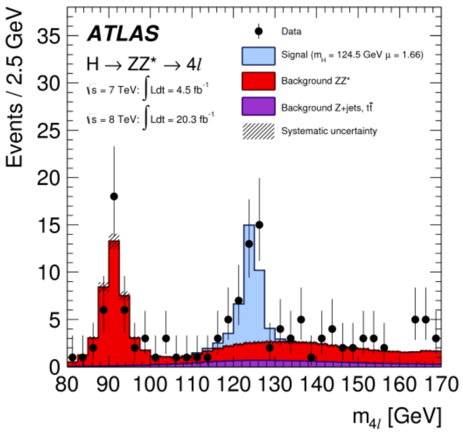




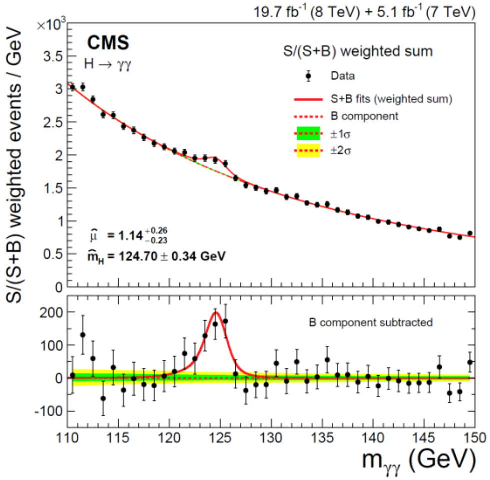
$H \to \gamma\gamma$



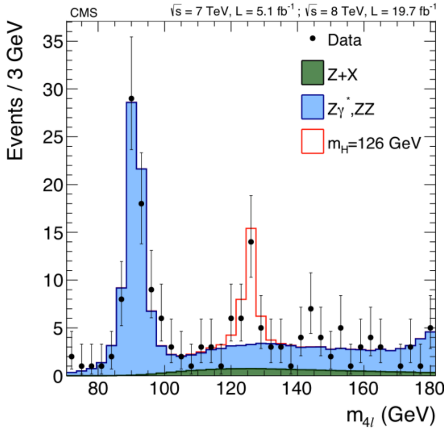
$H \to Z Z^* \to 4l$



$H \to \gamma\gamma$



$H \to Z Z^* \to 4l$



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

Beautiful Discovery

Boson (J = 0)

Fermions = Matter ; Bosons = Forces

- **Fundamental Boson:** **New interaction which is not gauge**
- **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 ... ?**

Symmetries & Mass Scales

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

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

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

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

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

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

Scalars: $\mathcal{L}_\phi \;=\; \tfrac{1}{2}\,\partial_\mu\phi\,\partial^\mu\phi - \tfrac{1}{2}\,m_\phi^2\,\phi^2$ **Any symmetry?**

No additional symmetry at $m_\phi = 0$ → $\delta m_\phi^2 \propto M^2$ ($M =$ any scale)

Symmetries & Mass Scales

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)

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

Pseudo-Goldstone Boson

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

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

Conformal Invariance. Dilaton

Possible Scenarios of EWSB

1. **SM scalar:** **Favoured by EW precision tests**

2. **Alternative perturbative EWSB:**

   Scalar Doublets and Singlets

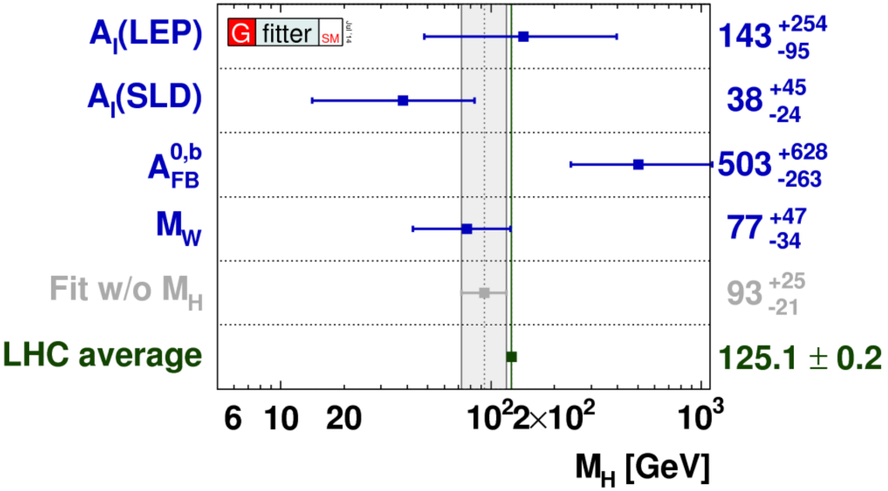
$$\rho_{\text{tree}} = \frac{M_W^2}{M_Z^2\, c_W^2} = \frac{\sum_k \mathrm{v}_k^2 \left[T_k \left(T_k + 1 \right) - Y_k^2 \right]}{2 \sum_k \mathrm{v}_k^2\, Y_k^2}$$

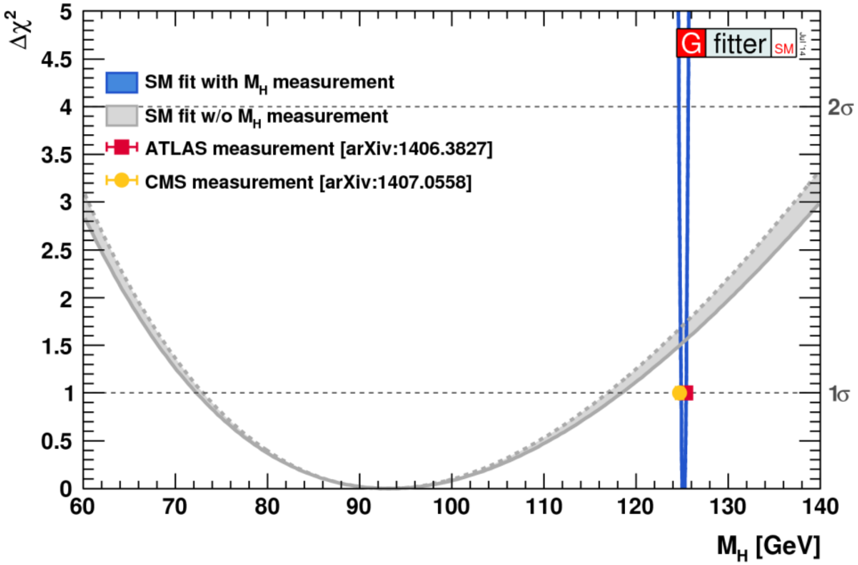
3. **Dynamical (non-perturbative) EWSB:**

   Pseudo-Goldstone Boson

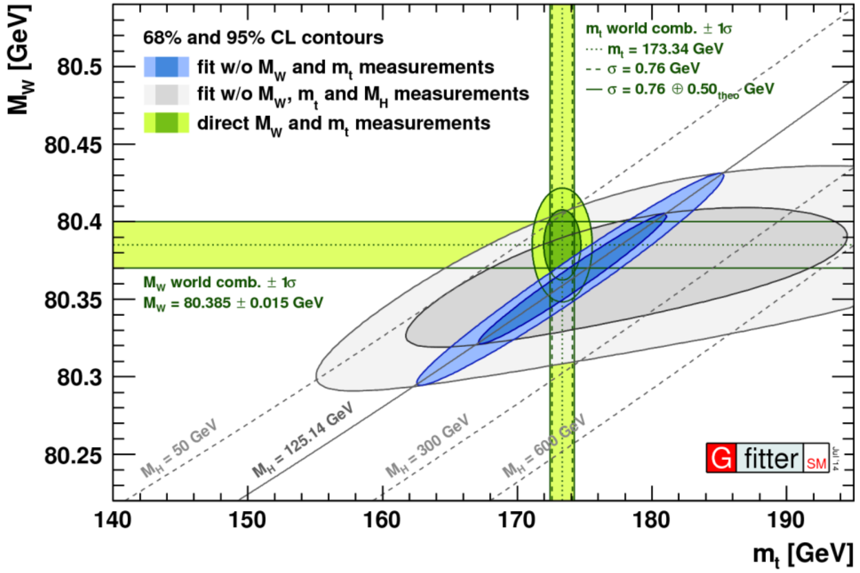
   Scalar Resonance

SM Higgs

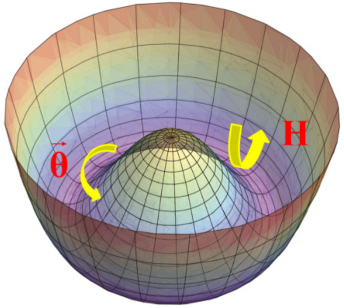




Favoured by
EW precision tests



SM Scalar Potential



$$V(\Phi) - V_0 = \lambda \left(|\Phi|^2 - \frac{v^2}{2} \right)^2 = \frac{1}{2} M_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2} \right)$$

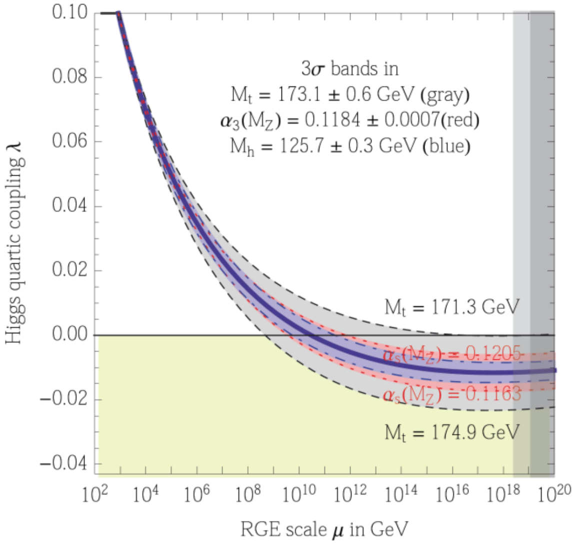
$$\boxed{M_H = 125.14 \pm 0.24 \qquad \Rightarrow \qquad \lambda = \frac{M_H^2}{2\,v^2} = 0.13}$$

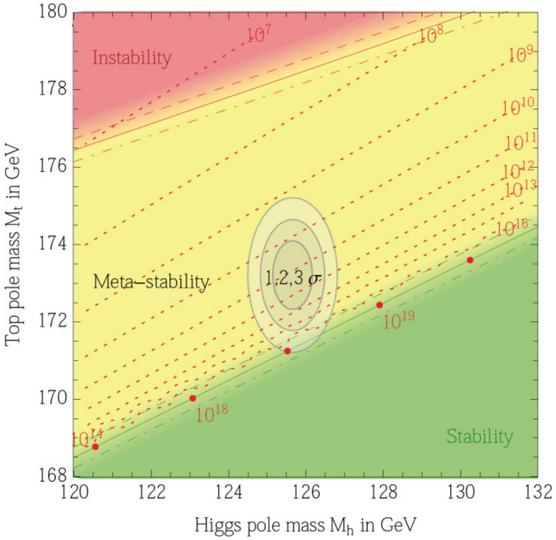
Loop corrections:

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

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

Meta-stable vacuum





$\Lambda = M_{Planck}$

⬇

$M_H > 129.1 \pm 1.5$ GeV

$M_t < 171.53 \pm 0.42$ GeV

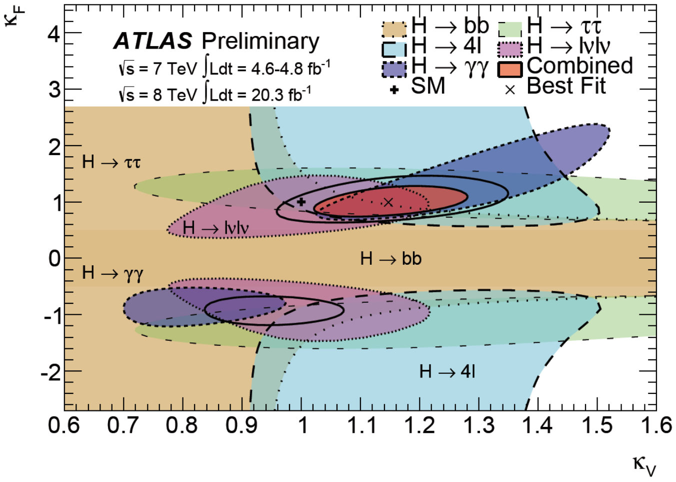
Buttazzo et al, 1307.3536

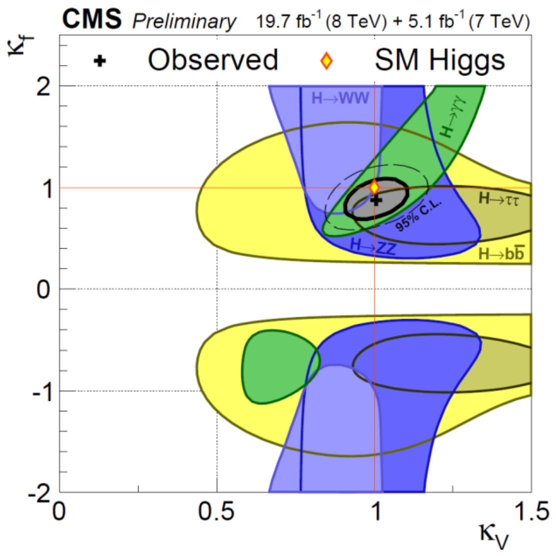
SM interactions only

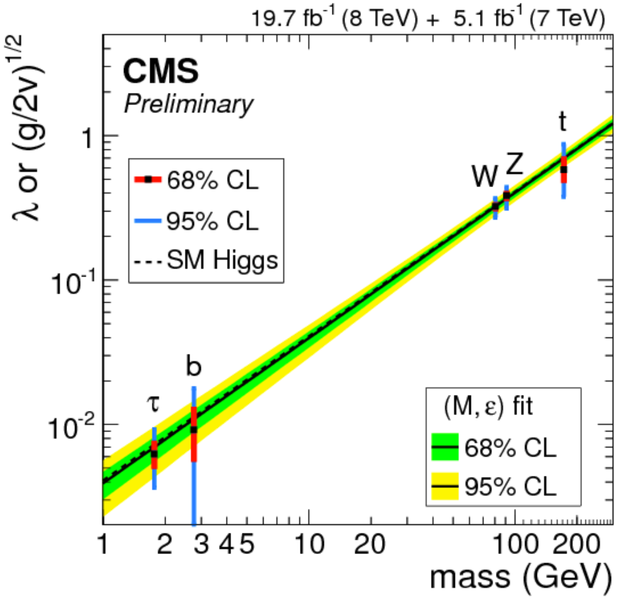
Strong sensitivity to New Physics

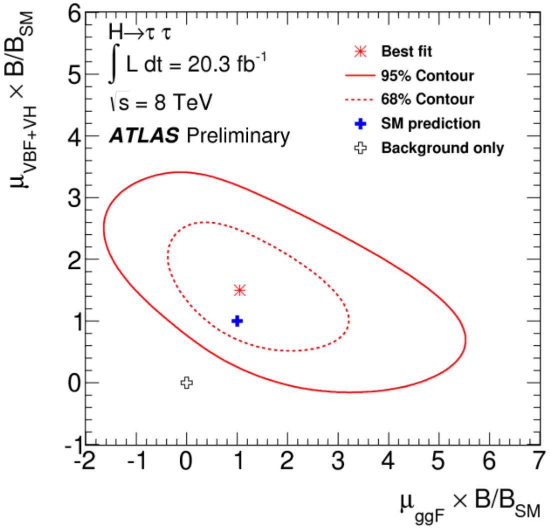
H(125) Couplings are SM-like

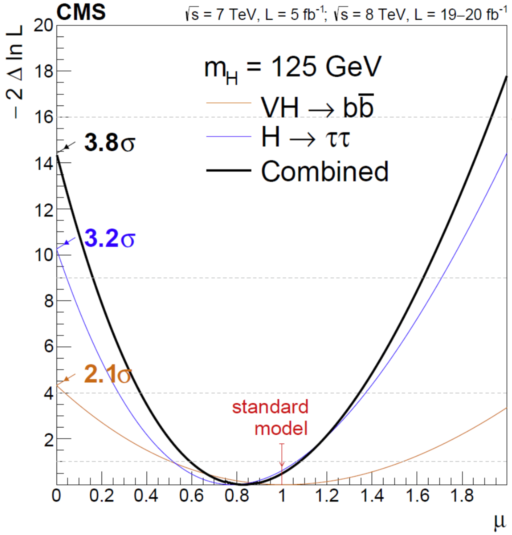
$\kappa_i \equiv g_i / g_i^{\mathrm{SM}}$





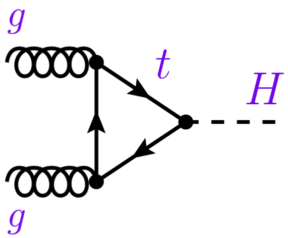




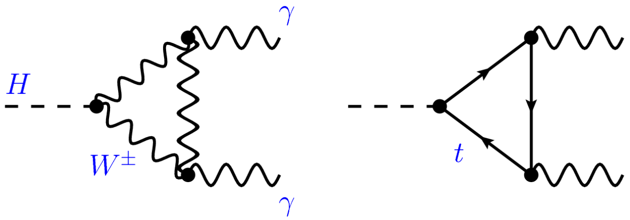


Strong evidence for H coupling to τ and b

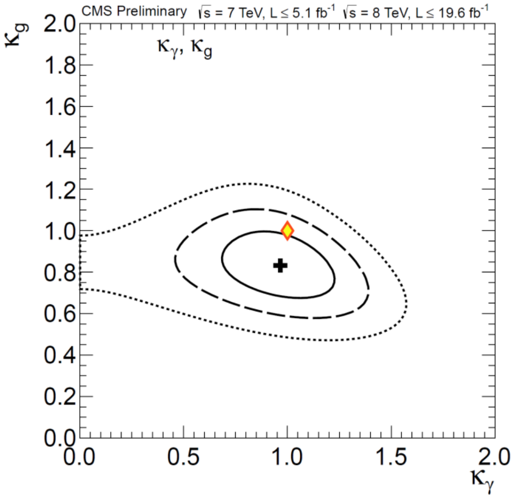
Strong (indirect) evidence for H coupling to t

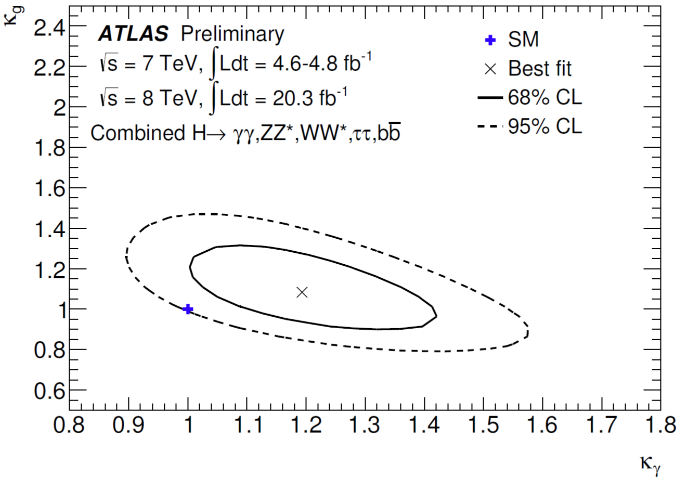


Dominant
Production Mechanism



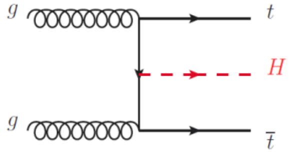
$$\Gamma \sim \left|1-0.21\right|^2$$





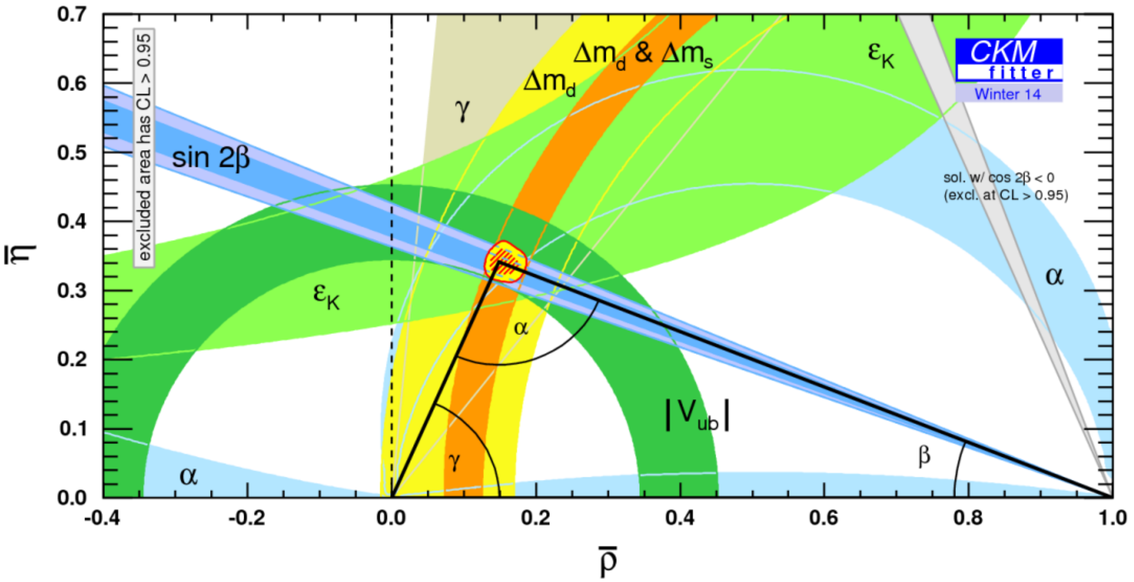
$H \to \gamma\gamma$	**Signal Strength**
ATLAS	1.17 ± 0.27
CMS	1.13 ± 0.24

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

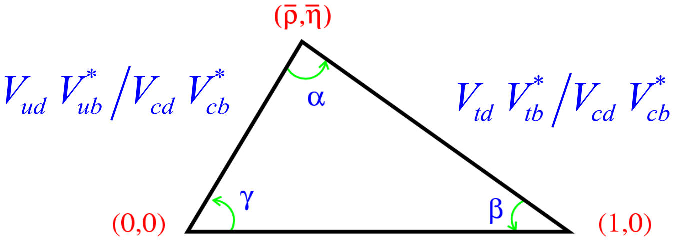


$\propto \kappa_t^2$

Quark Mixing



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



$V_{ud}\,V_{ub}^{*}/V_{cd}\,V_{cb}^{*}$

$V_{td}\,V_{tb}^{*}/V_{cd}\,V_{cb}^{*}$

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

UT*fit*

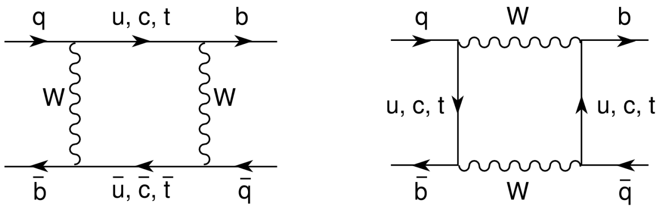
$$\bar\eta \equiv \eta\left(1-\frac{1}{2}\lambda^2\right) = 0.351\pm0.014$$

$$\bar\rho \equiv \rho\left(1-\frac{1}{2}\lambda^2\right) = 0.132\pm0.023$$

$$A=0.821\pm0.012 \quad ; \quad \lambda=0.2254\pm0.0006$$

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

Bounds on New Flavour Physics



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

Isidori, 1302.0661

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

- **Generic flavour structure [$c_{\rm NP}$~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**

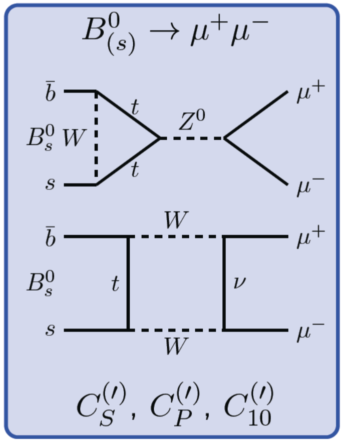
D'Ambrosio et al, Buras et al

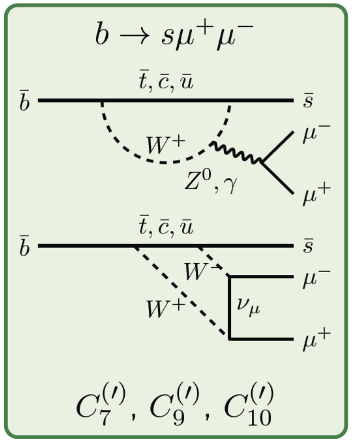
Rare Decays

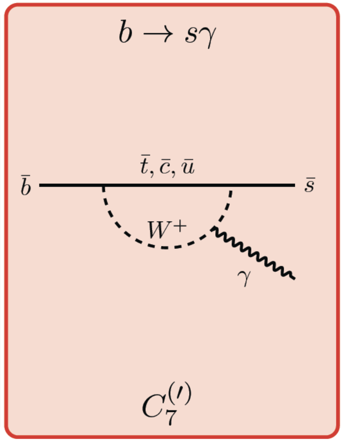
Albrecht

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \Big[\underbrace{C_i(\mu) O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu) O_i'(\mu)}_{\substack{\text{right-handed part} \\ \text{suppressed in SM}}} \Big]$$

$i = 1,2$	Tree
$i = 3-6,8$	Gluon penguin
$i = 7$	Photon penguin
$i = 9,10$	Electroweak penguin
$i = S$	Higgs (scalar) penguin
$i = P$	Pseudoscalar penguin

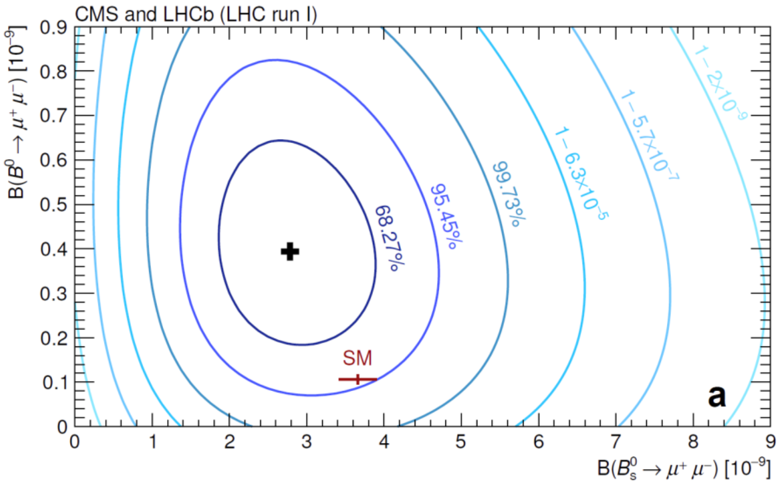






SM

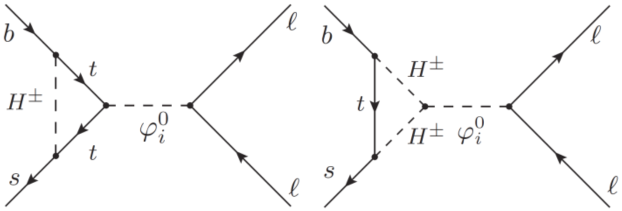
- **No tree-level contribution**
- **Strong CKM suppression**



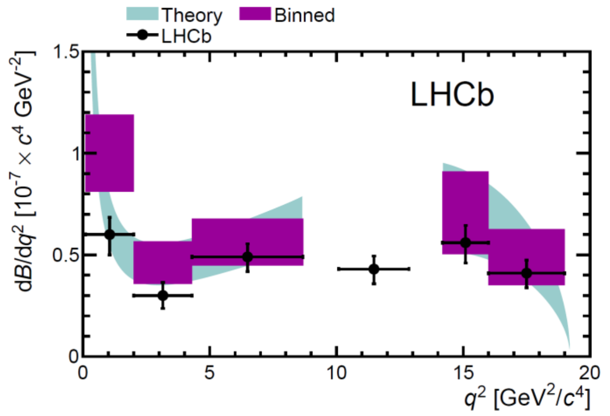
$B \to \mu^+\mu^-$ sensitive to (pseudo) scalar contributions

additional Higgs bosons

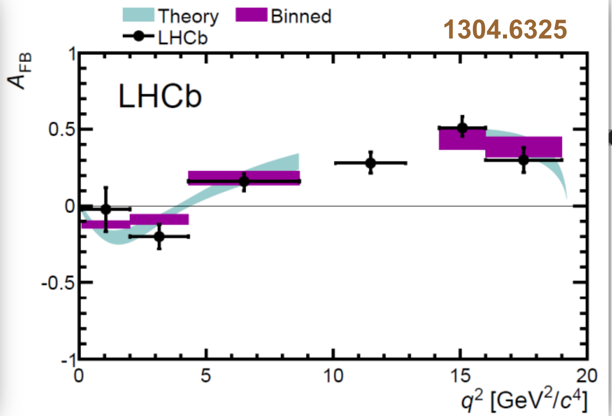
Li-Lu-A.P., 1404.5865



$B_d \to K^{*0}\mu^+\mu^-$



1304.6325



Phen. analysis with “clean observables”

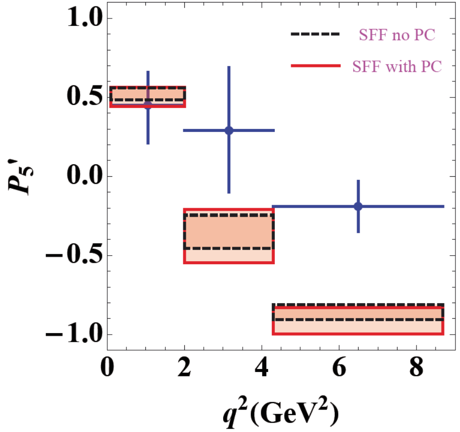
(FF independent)

Descotes-Genon et al

P’5 Anomaly

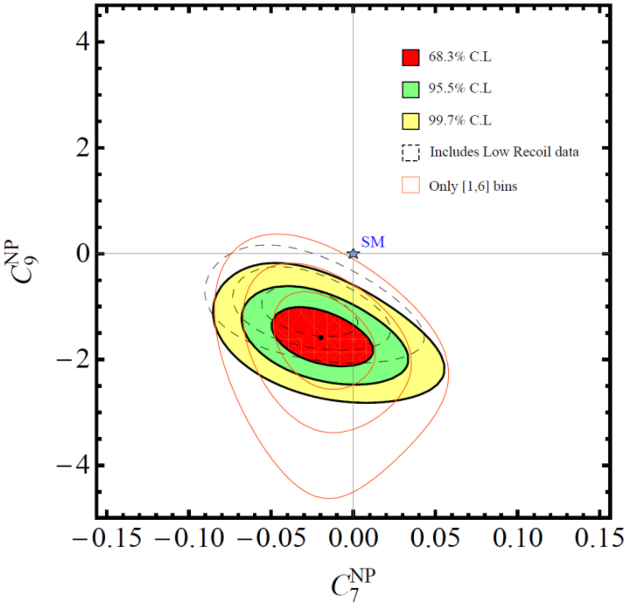
Observable	Experiment	SM prediction	Pull
$\langle P_2\rangle_{[0.1,2]}$	$0.03^{+0.14}_{-0.15}$	$0.172^{+0.020}_{-0.021}$	-1.0
$\langle P_2\rangle_{[2,4.3]}$	$0.50^{+0.00}_{-0.07}$	$0.234^{+0.060}_{-0.086}$	$+\mathbf{2.9}$
$\langle P_2\rangle_{[4.3,8.68]}$	$-0.25^{+0.07}_{-0.08}$	$-0.407^{+0.049}_{-0.037}$	$+\mathbf{1.7}$
$\langle P_2\rangle_{[1,6]}$	$0.33^{+0.11}_{-0.12}$	$0.084^{+0.060}_{-0.078}$	$+1.8$
$\langle P_5'\rangle_{[0.1,2]}$	$0.45^{+0.21}_{-0.24}$	$0.533^{+0.033}_{-0.041}$	-0.4
$\langle P_5'\rangle_{[2,4.3]}$	$0.29^{+0.40}_{-0.39}$	$-0.334^{+0.097}_{-0.113}$	$+\mathbf{1.6}$
$\langle P_5'\rangle_{[4.3,8.68]}$	$-0.19^{+0.16}_{-0.16}$	$-0.872^{+0.053}_{-0.041}$	$+\mathbf{4.0}$
$\langle P_5'\rangle_{[1,6]}$	$0.21^{+0.20}_{-0.21}$	$-0.349^{+0.088}_{-0.100}$	$+2.5$

preliminary **Hofer**



Fit with “New Physics” effective operators

Descotes-Genon et al, 1307.5683



$$O_7 = \frac{e}{(16\pi)^2}\, m_b \left(\bar{s}\,\sigma_{\mu\nu} P_R b\right) F^{\mu\nu}$$

$$O_9 = \frac{e^2}{(16\pi)^2}\, m_b \left(\bar{s}\,\gamma_\mu P_L b\right)\left(\bar{\ell}\,\gamma^\mu \ell\right)$$

New Physics?

Altmannshofer-Straub, Beaujean et al, Descotes-Genon et al, Horgan *et al.*

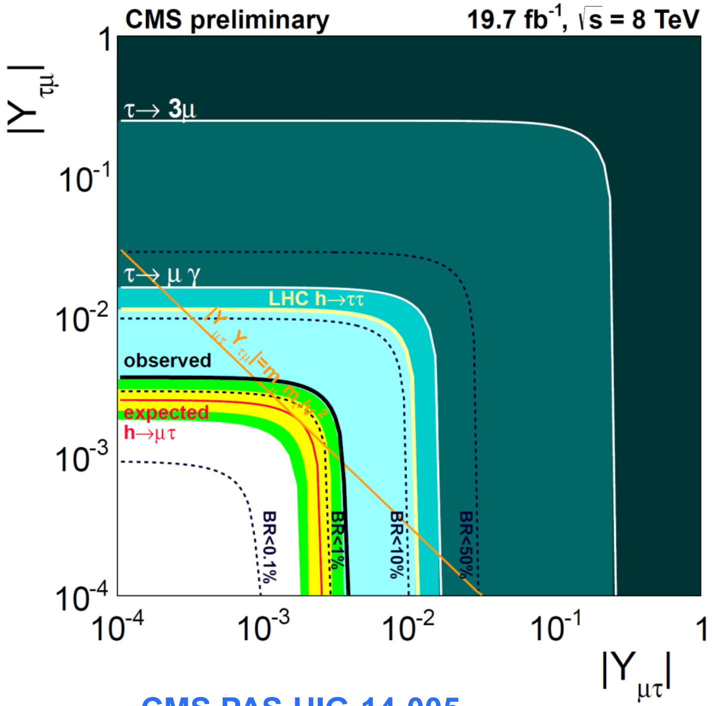
Hadronic uncertainties?

Jäger & Martín-Camalich, Zwicky et al

Flavour-Violating Higgs Couplings

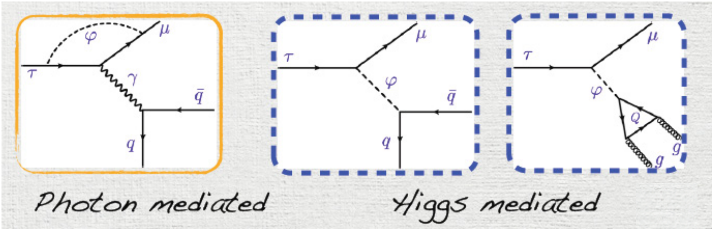
Blankenburg et al, Celis et al,
Harnik et al, Davidson-Verdier,
Kopp-Nardecchia

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

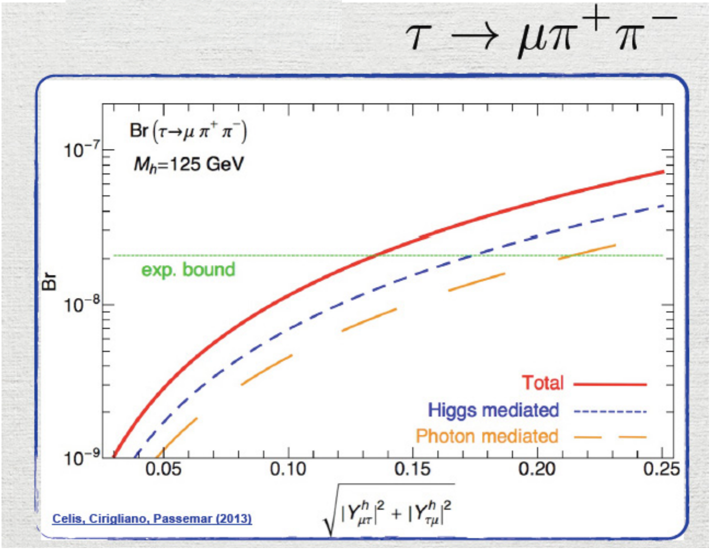


CMS PAS HIG-14-005

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



Celis



Two-Higgs Doublet Models

5 scalar fields: $H^\pm,\ \varphi_i^0 = (h, H, A)$ [3x3 mixing R_{ij}] $\qquad \mathrm{v} = \sqrt{\mathrm{v}_1^2+\mathrm{v}_2^2}\ ,\quad \tan\beta = \mathrm{v}_2/\mathrm{v}_1$

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

CP-conserving potential: $R = \begin{bmatrix} \cos\tilde\alpha & \sin\tilde\alpha & 0 \\ -\sin\tilde\alpha & \cos\tilde\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$ $\qquad g_{\varphi_i^0 VV}\big/ g_{\varphi_i^0 VV}^{\mathrm{SM}} = R_{i1} = \cos\tilde\alpha \equiv \sin(\beta-\alpha)$

Yukawas:

$$\mathcal{L}_Y = -\bar{Q}'_L\left(\Gamma_1\,\phi_1 + \Gamma_2\,\phi_2\right)d'_R + \cdots \quad \xrightarrow[\text{EWSB}]{} \quad \mathcal{L}_Y = -\frac{\sqrt{2}}{\mathrm{v}}\,\bar{Q}'_L\left(M'_d\,\Phi_1 + Y'_d\,\Phi_2\right)d'_R + \cdots$$

M'$_f$ & Y'$_f$ unrelated **(not simultaneously diagonal)** → **FCNCs**

Solutions: (same for u_R and ℓ_R Yukawas)

- **Natural Flavour Conservation:** $\Gamma_1 = 0$ or $\Gamma_2 = 0$ (Z_2 models) **Glashow-Weinberg...**
- **Alignment:** $\Gamma_1 \propto \Gamma_2$ → $Y_{d,l} = \varsigma_{d,l}\, M_{d,l}\ ,\quad Y_u = \varsigma_u^*\, M_u$ **AP-Tuzón**
- **BGL Models:** “controlled” FCNC (symmetries) **Branco et al**

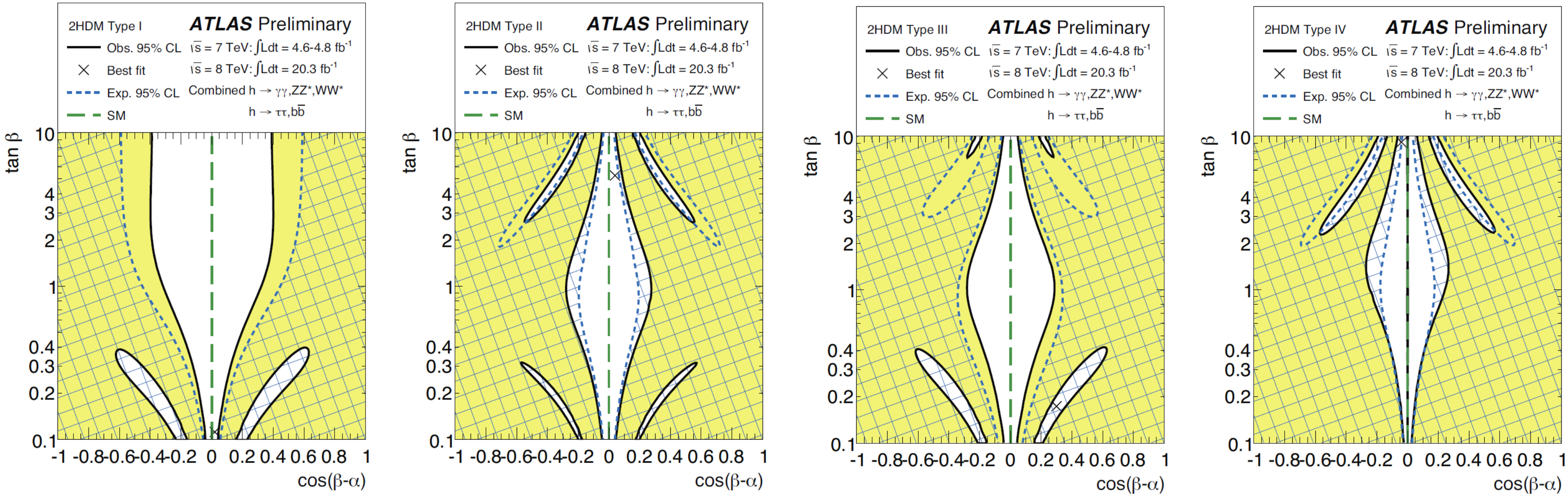
Z_2 2HDMs

5 scalar fields: $H^{\pm},\ \varphi_i^0 = (h, H, A)$ [3x3 mixing R_{ij}] $\mathrm{v} = \sqrt{\mathrm{v}_1^2 + \mathrm{v}_2^2}$, $\tan\beta = \mathrm{v}_2/\mathrm{v}_1$

CP-conserving potential:

$$R = \begin{bmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} & 0 \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$g_{VV\varphi_i^0} \big/ g^{\mathrm{SM}}_{VV\varphi_i^0} = R_{i1} = \cos\tilde{\alpha} \equiv \sin(\beta - \alpha)$$



Yukawas: (SM units)

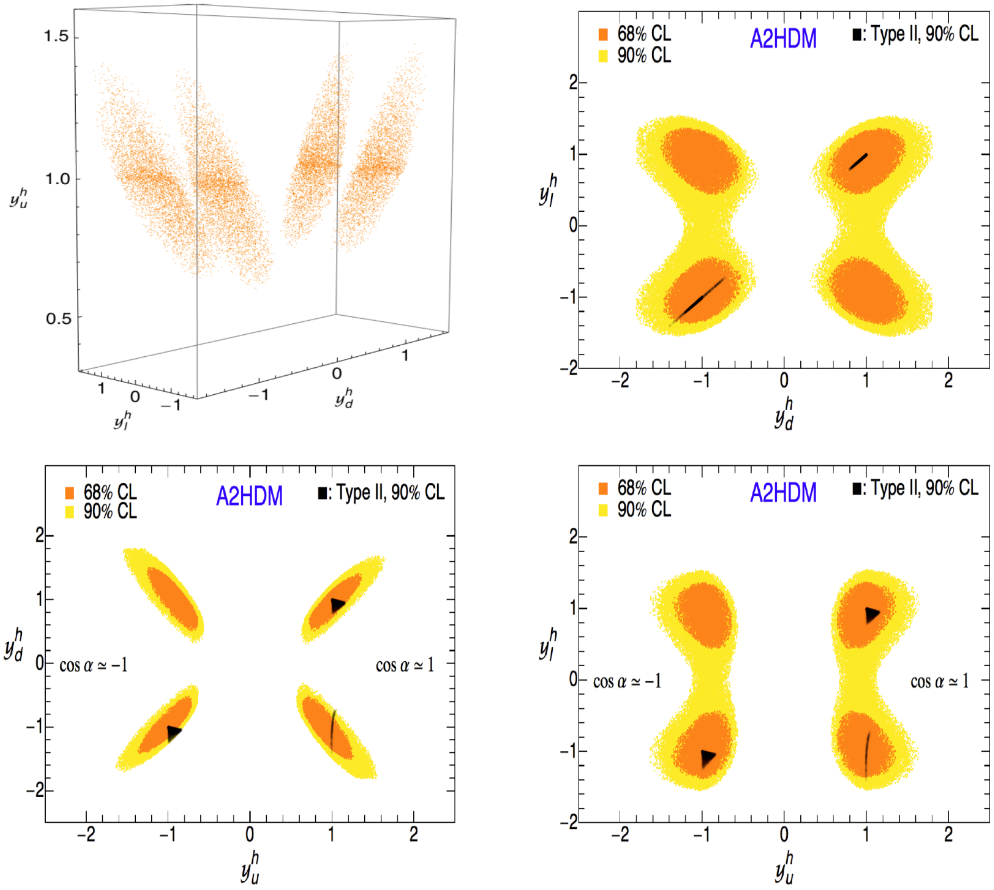
$$y_{d,l}^{\varphi_i^0} = R_{i1} + \left(R_{i2} + i\,R_{i3}\right)\varsigma_{d,l}$$

$$y_{u}^{\varphi_i^0} = R_{i1} + \left(R_{i2} - i\,R_{i3}\right)\varsigma_{u}^{*}$$

Type	ζ_d	ζ_u	ζ_l
I	$\cot\beta$	$\cot\beta$	$\cot\beta$
II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
X (III, lepton specific)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Y (IV, flipped)	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

Flavour Alignment (Aligned 2HDM)

Celis-Ilisie-AP, 1302.4022, 1310.7941



$$|\cos\tilde{\alpha}| > 0.80 \quad (90\%\ \text{CL})$$

General setting without FCNCs & new sources of CP violation

$$Y_{d,l} = \varsigma_{d,l}\, M_{d,l} \quad , \quad Y_u = \varsigma_u^*\, M_u$$

- **Rich phenomenology @ LHC**

  Altmannshofer et al, Barger et al, Celis et al, Cervero-Gerard, López-Val et al…

  Many allowed possibilities

  Search for light H±, H, A

  CP violation

- **Flavour constraints fulfilled**

  Celis et al, Jung et al, Li et al

- **EDMs**

  Jung-AP, 1308.6283

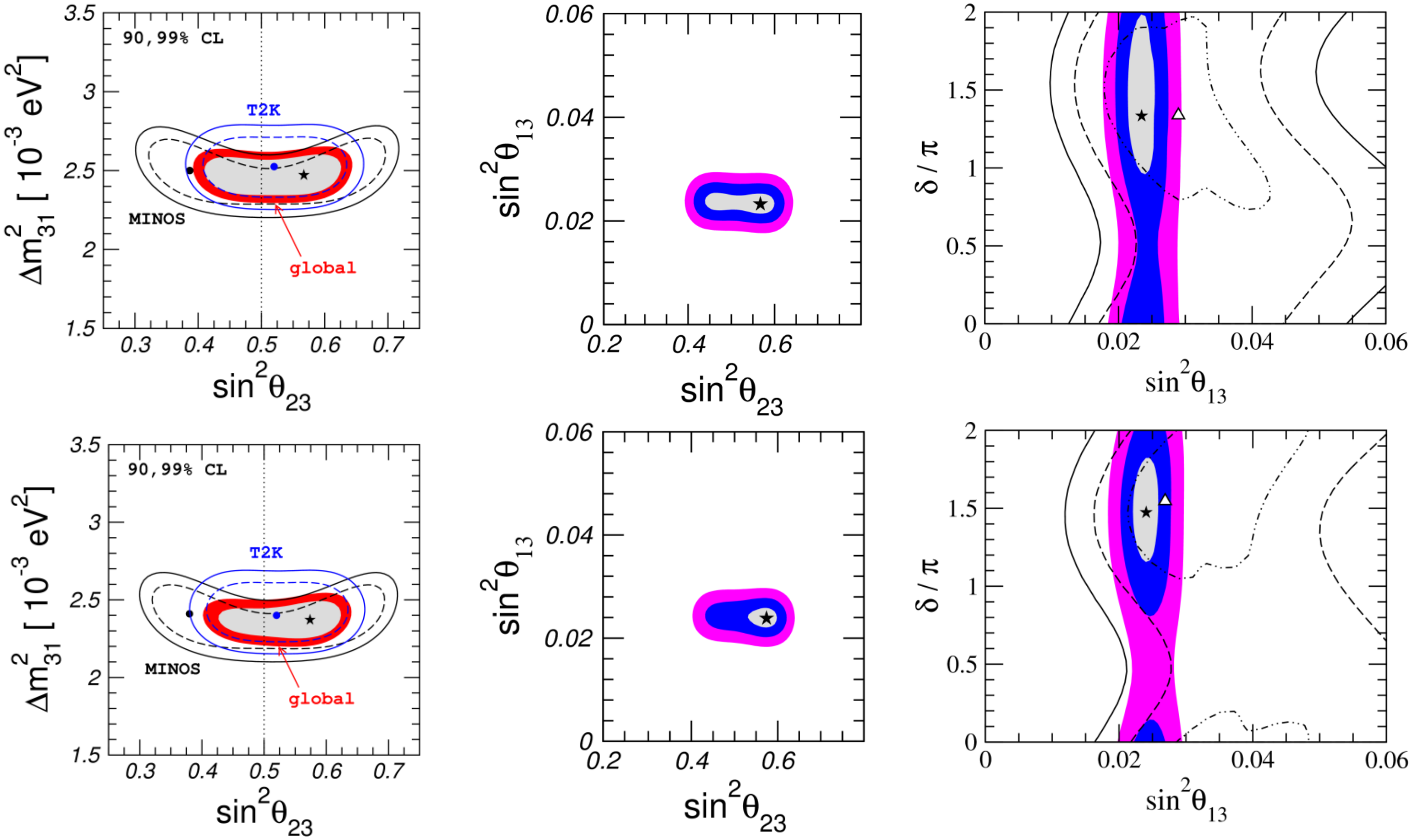
- **Usual Z_2 models recovered in particular (CP-conserving) limits**

ν Oscillations

Forero et al, 1405.7540

NH

IH



González-García et al

NuFIT 2.0 (2014)

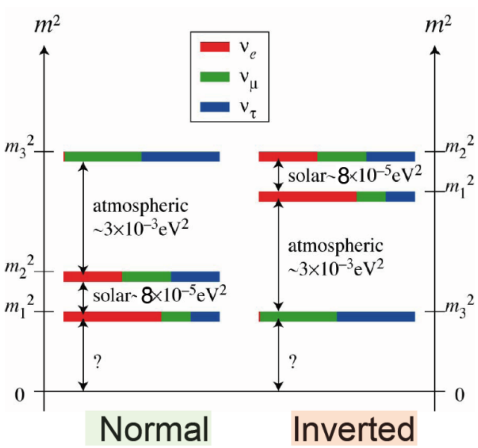
$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.514 \to 0.580 & 0.137 \to 0.158 \\ 0.225 \to 0.517 & 0.441 \to 0.699 & 0.614 \to 0.793 \\ 0.246 \to 0.529 & 0.464 \to 0.713 & 0.590 \to 0.776 \end{pmatrix}$$

Flavour mixing is very different for quarks & leptons

Open Questions in ν Physics

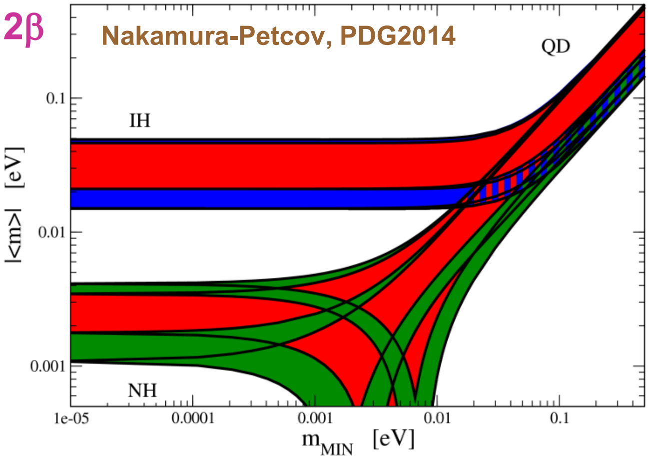
Mass Hierarchy

Blennow



Dirac / Majorana

2β


Nakamura-Petcov, PDG2014

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

Mass Scale

Sterile ν_R ?

CP Violation

Flavour Symmetries

Leptogenesis

Low-E Effective Theory:

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

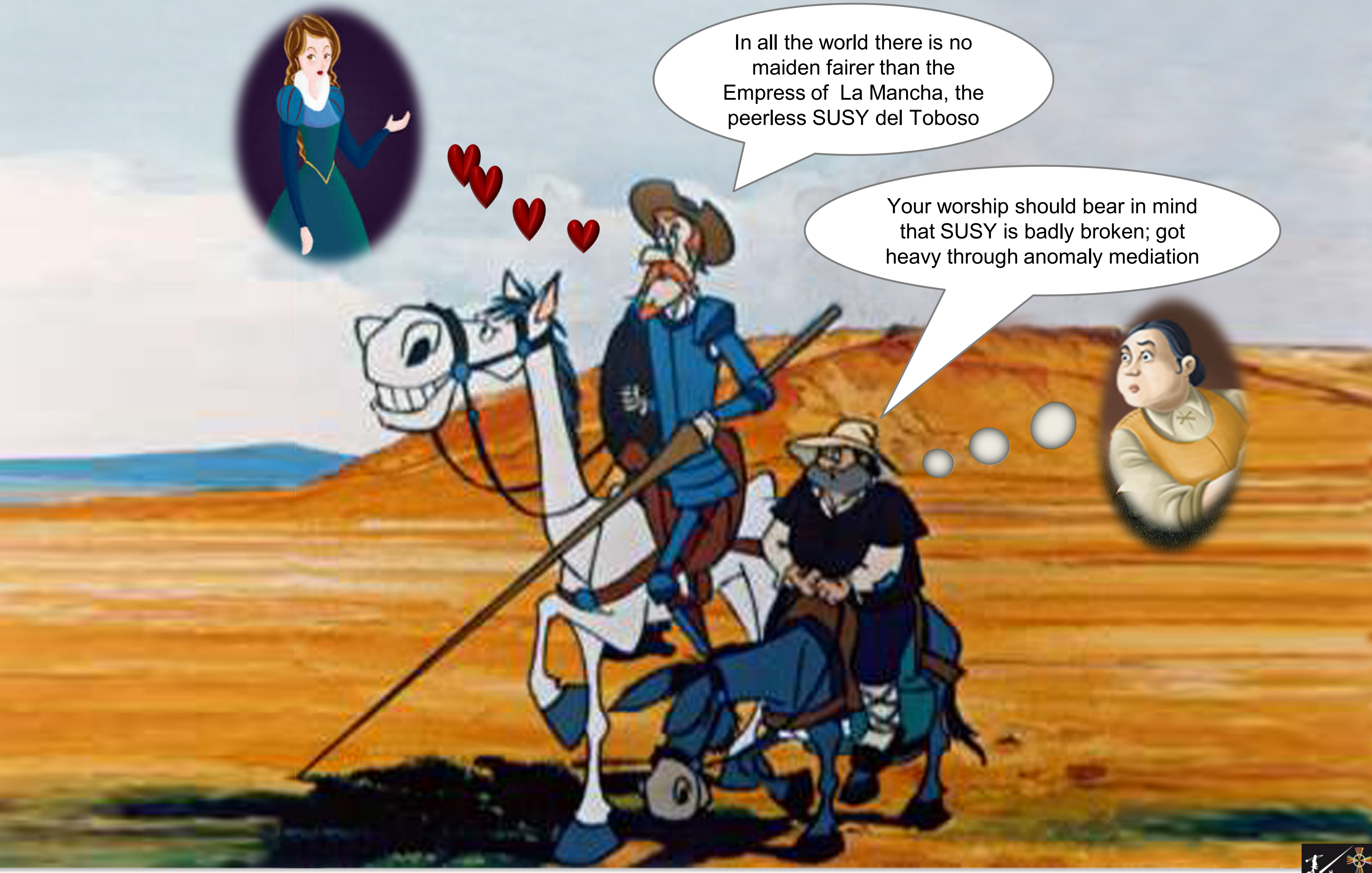
1 SU(2)$_L$ ⊗ U(1)$_Y$ invariant operator with d=5

Weinberg

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

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

Desperately Seeking SUSY (Dulcinea)



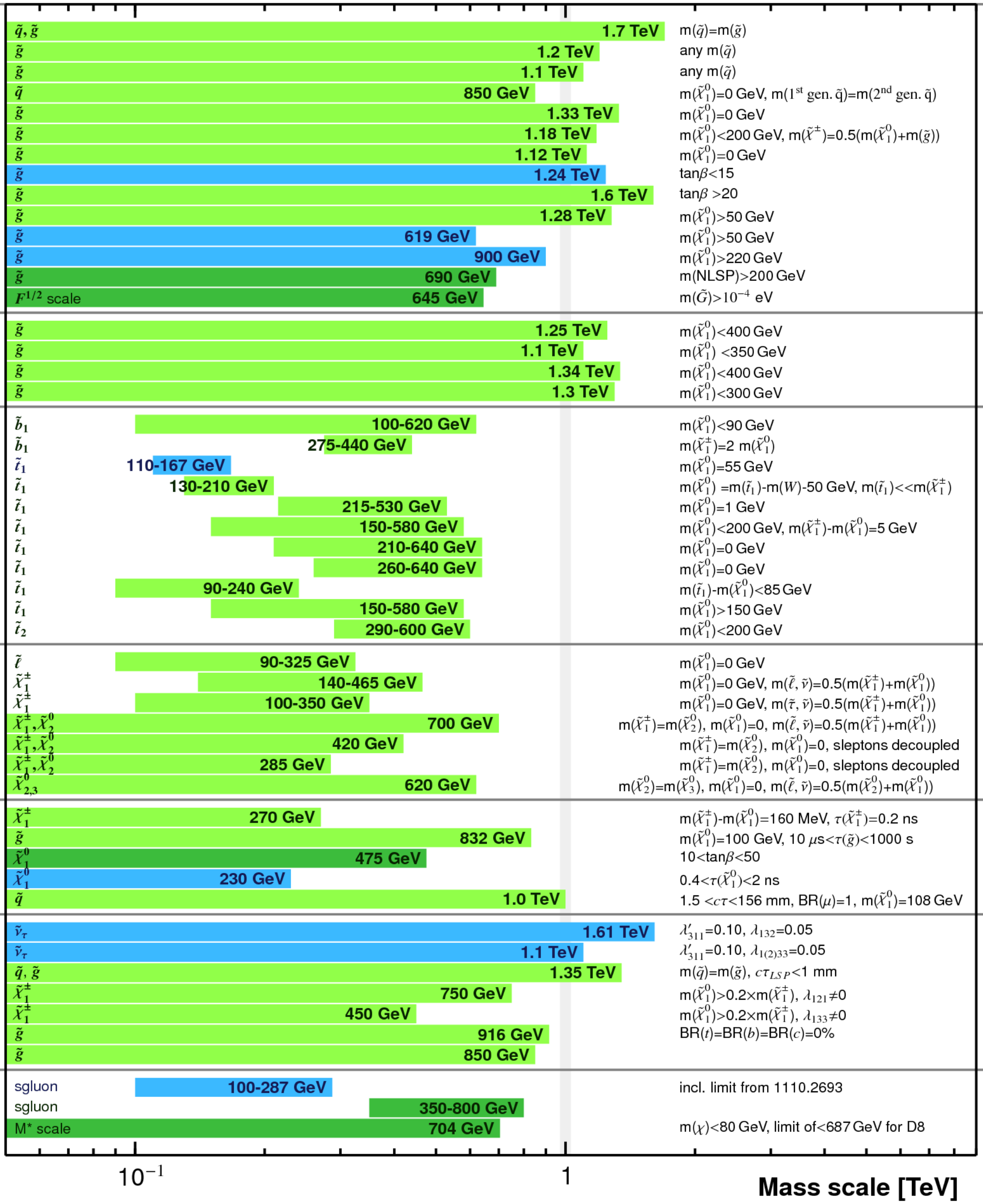
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

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

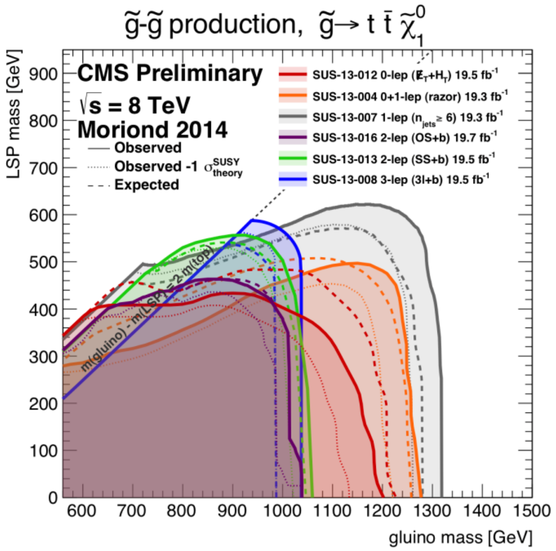
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	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
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	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	20.3	$\tilde{g}$ 1.18 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >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	10.5	$F^{1/2}$ scale 645 GeV	m($\tilde{G}$)>10^{-4} eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	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
3rd 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
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	m($\tilde{\chi}^0_1$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}^0_1$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	m($\tilde{\chi}^0_1$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}^\pm_1$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}^0_1$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	1 e, μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	m($\tilde{\chi}^0_1$)=0 GeV	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
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	2-3 e, μ	0	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
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 h\tilde{\chi}^0_1$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}^\pm_1, \tilde{\chi}^0_2$ 285 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	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, τ($\tilde{\chi}^\pm_1$)=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($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}^0_1$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	4.7	$\tilde{\chi}^0_1$ 230 GeV	0.4<τ($\tilde{\chi}^0_1$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}^0_1\to qq\mu$ (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, 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
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 750 GeV	m($\tilde{\chi}^0_1$)>0.2×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, μ + τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 450 GeV	m($\tilde{\chi}^0_1$)>0.2×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 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(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

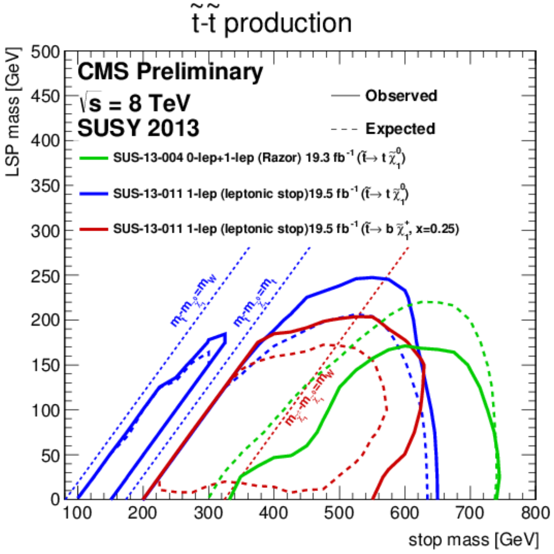


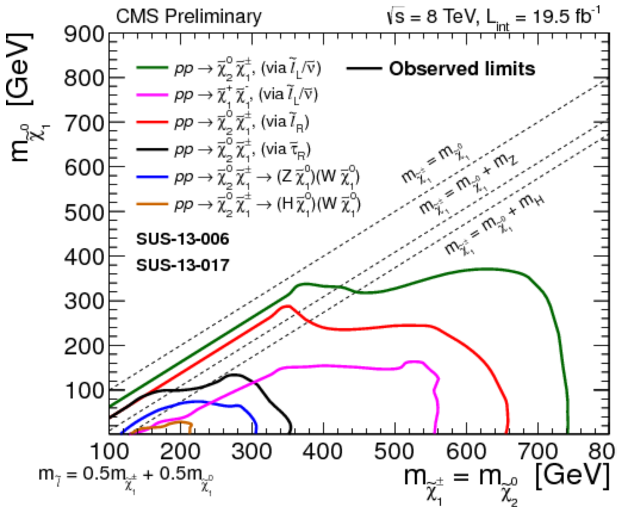
- 🟦 $\sqrt{s}$ = 7 TeV full data
- 🟩 $\sqrt{s}$ = 8 TeV partial data
- 🟩 $\sqrt{s}$ = 8 TeV full data

*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





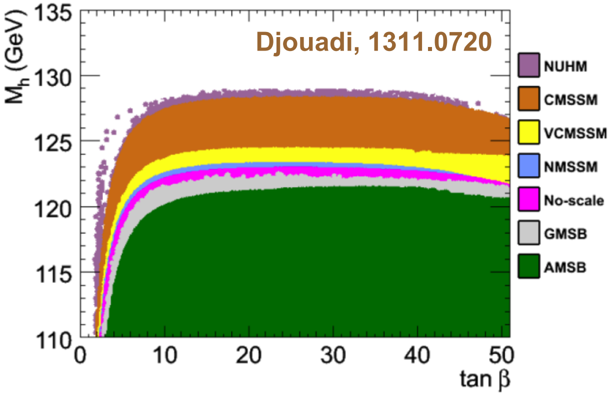


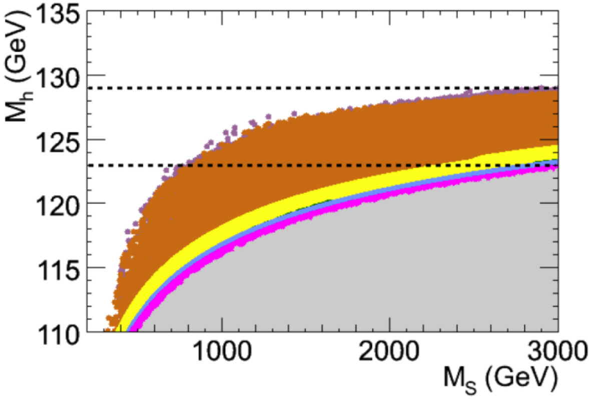
Tension with Higgs mass:

$$M_h^2 \leq M_Z^2 \cos^2(2\beta) + \varepsilon$$

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

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





Decoupling **($M_A \gg M_Z$)**

$\cos^2(2\beta) \to 1$

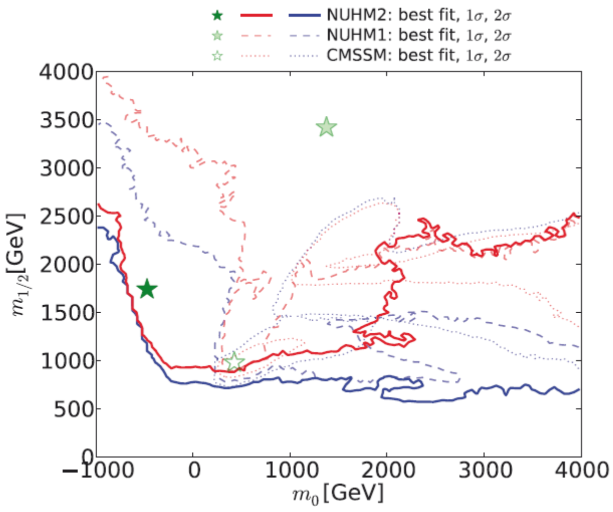
Maximal stop mixing X_t

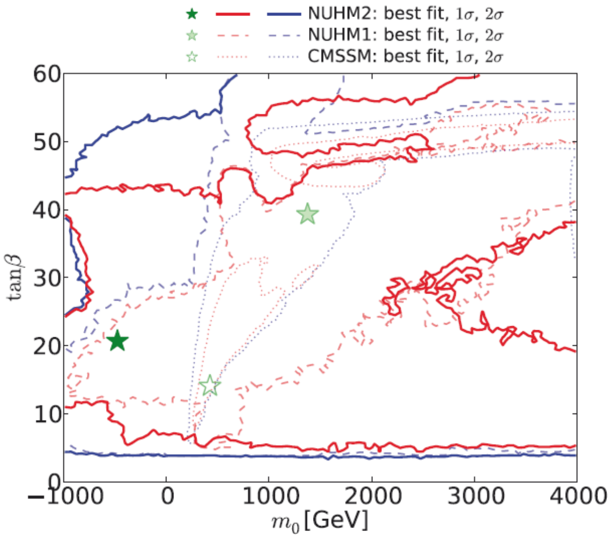
Improved higher-order calculations allow slightly larger values of M_h

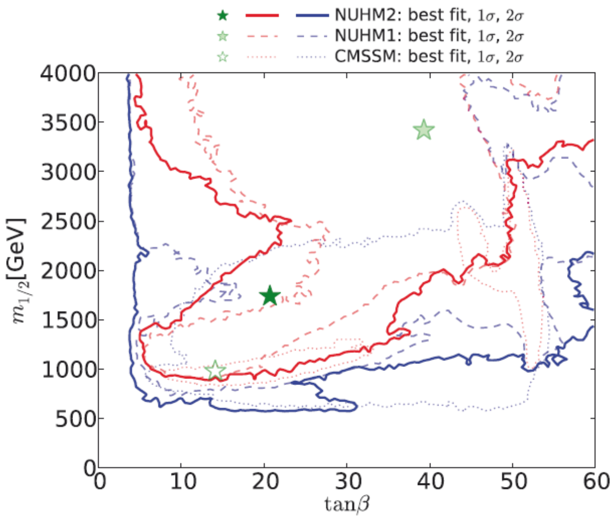
Heinemeyer et al

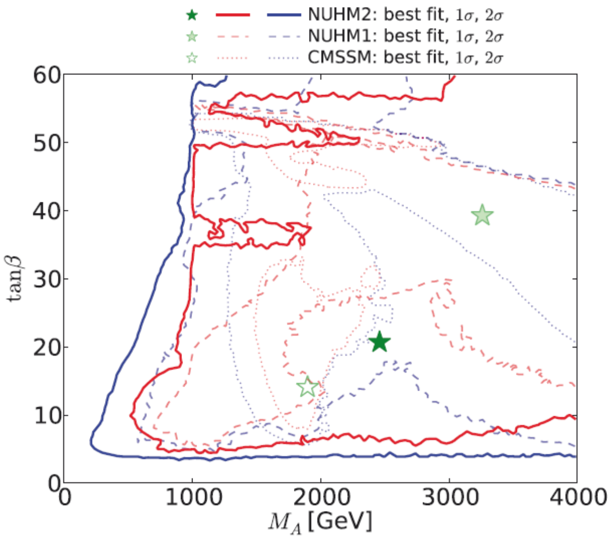
Global Fits (LHC, Flavour, DM. . .)

Buchmueller et al, 1408.4060







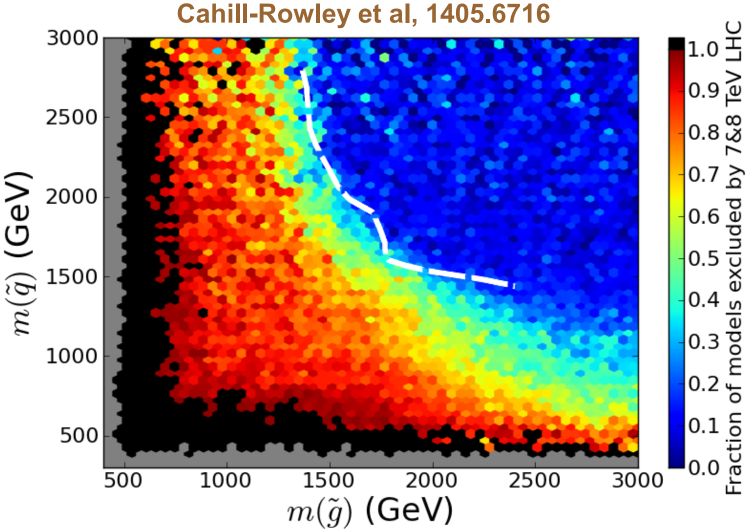


$(g-2)_\mu$ cannot be explained (not included in the fit)

Which SUSY?

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

Cahill-Rowley et al, 1405.6716



120 MSSM parameters reduced to 19-20

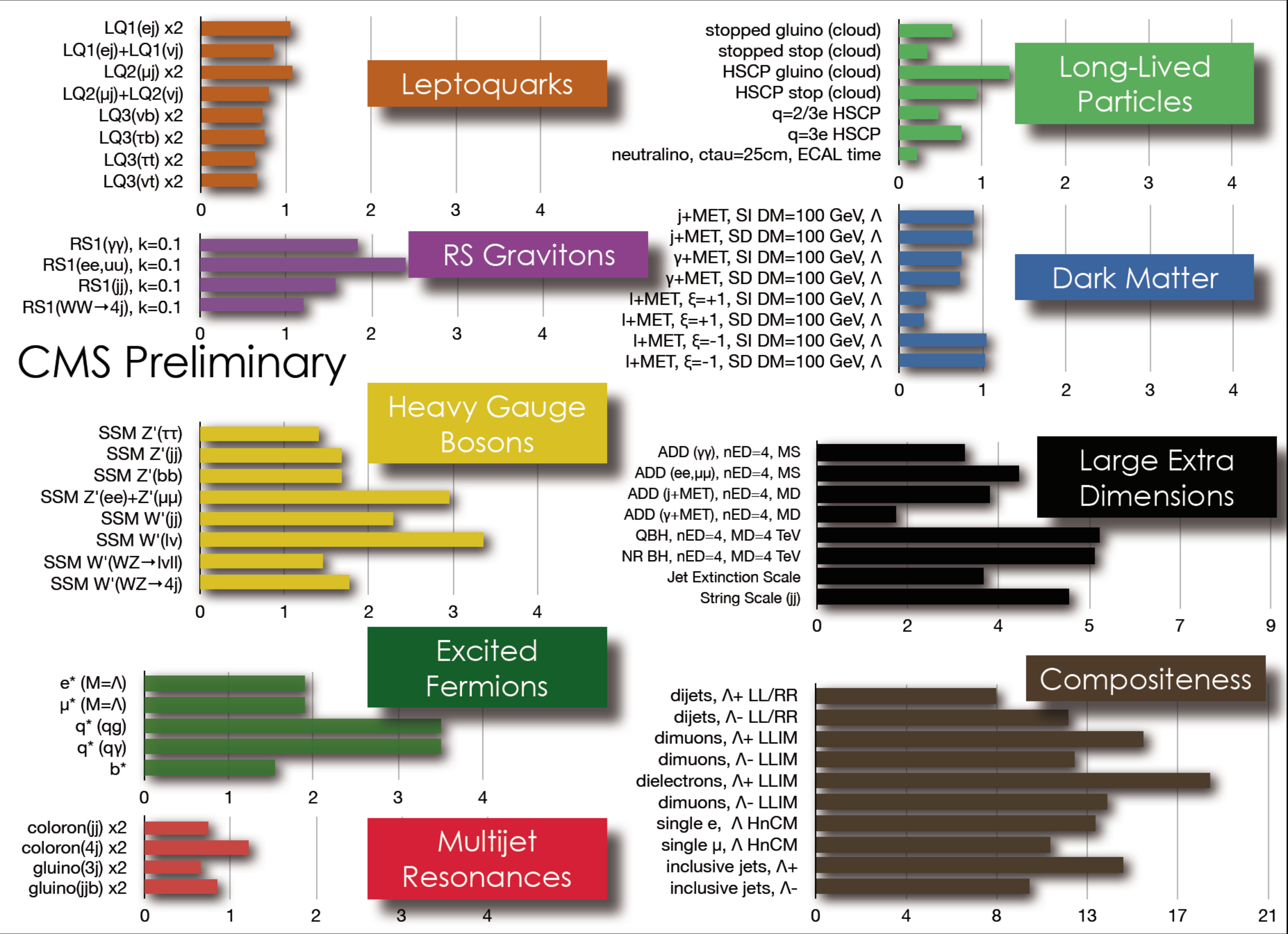
Many "models" consistent with data

Data-driven search

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

Naturalness?

$$\Delta M_h^2 \propto M_{\text{SUSY}}^2$$



CMS Exotica Physics Group Summary – ICHEP, 2014

Don Quixote and the Windmills

Effective Field Theory

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_{k} \frac{c_k^{(D)}}{\Lambda_{\text{NP}}^{D-4}} \, O_k^{(D)}$$

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

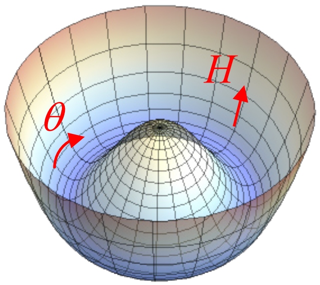
$$\mathcal{L}_{\text{NP}} \doteq g_X \left(\bar{q}_L \gamma^\mu q_L\right) X_\mu \quad \Rightarrow \quad \frac{g_X^2}{M_X^2} \left(\bar{q}_L \gamma^\mu q_L\right)\left(\bar{q}_L \gamma_\mu q_L\right)$$

- Options for H(126):

  - SU(2)$_L$ doublet (SM)
  - Scalar singlet
  - Additional light scalars

Custodial Symmetry

$$\boldsymbol{\Sigma} \equiv \left(\phi_C, \phi\right) = \begin{pmatrix} \phi^{(0)*} & \phi^{(+)} \\ -\phi^{(-)} & \phi^{(0)} \end{pmatrix} = \frac{1}{\sqrt{2}}\left[\mathrm{v} + H(x)\right] \mathbf{U}(\varphi) \quad , \quad \mathbf{U}(\varphi) = \exp\left\{\frac{i}{\mathrm{v}} \vec{\sigma}\vec{\varphi}\right\}$$



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

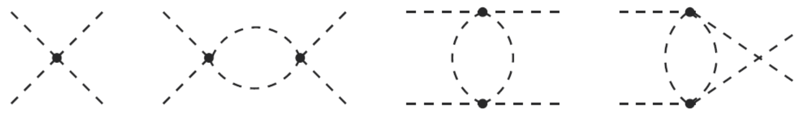
- **Invariant under global** **SU(2)$_L$ ⊗ SU(2)$_R$ ⊃ SU(2)$_L$ ⊗ U(1)$_Y$**

$$\boldsymbol{\Sigma} \to g_L \cdot \boldsymbol{\Sigma} \cdot g_R^\dagger \quad , \quad g_X \in SU(2)_X$$

- **Same Lagrangian than QCD pions:** $f_\pi \to \mathrm{v} \quad , \quad \pi^\pm, \pi^0 \to \varphi^\pm, \varphi^0 \to W_L^\pm, W_L^0$

Chiral Goldstone Bosons: SU(2)$_L$ ⊗ SU(2)$_R$ → SU(2)$_C$

$W_L\, W_L \rightarrow W_L\, W_L$



+ 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)

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

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

$$A\left(\gamma\gamma \to W_L^+ W_L^-\right)_{\text{NLO}} \sim \frac{(a^2-1)}{8\pi^2 v^2}$$

Delgado et al

Deviations of the SM gauge couplings imply bad UV behaviours

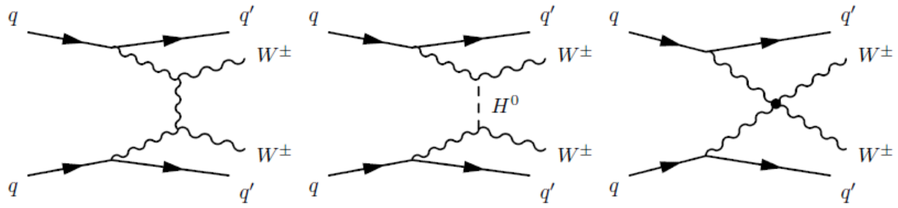
New states needed to restore unitarity

WW Scattering @ LHC

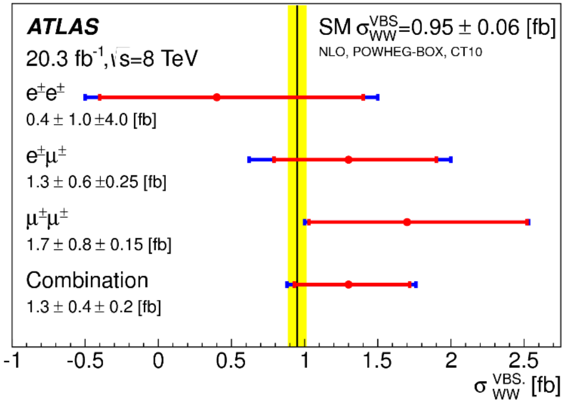
Berryhill

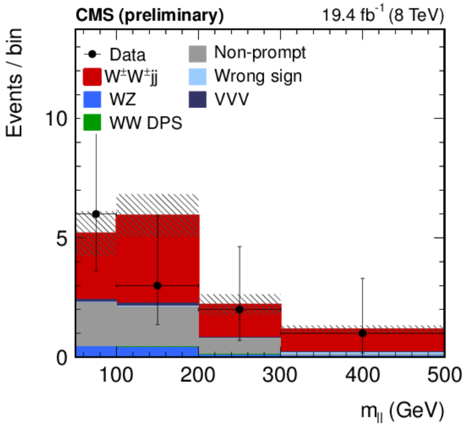
First evidence of $W^\pm W^\pm$ scattering

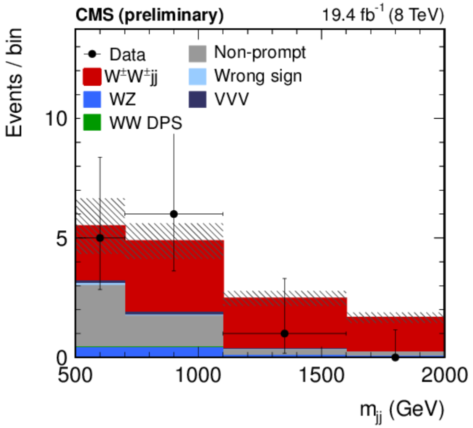
(3.6 σ)

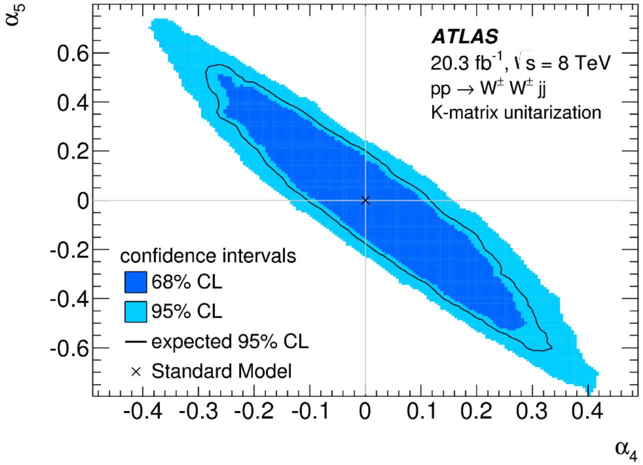


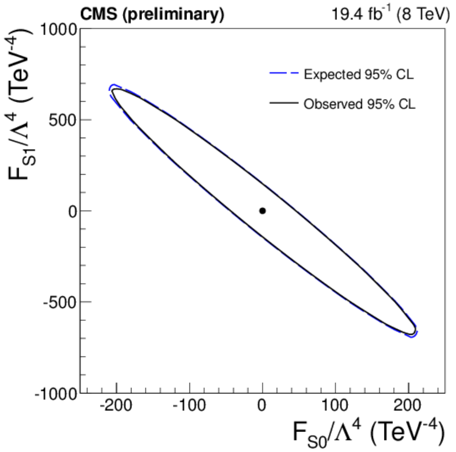
ATLAS, arxiv:1405.6241











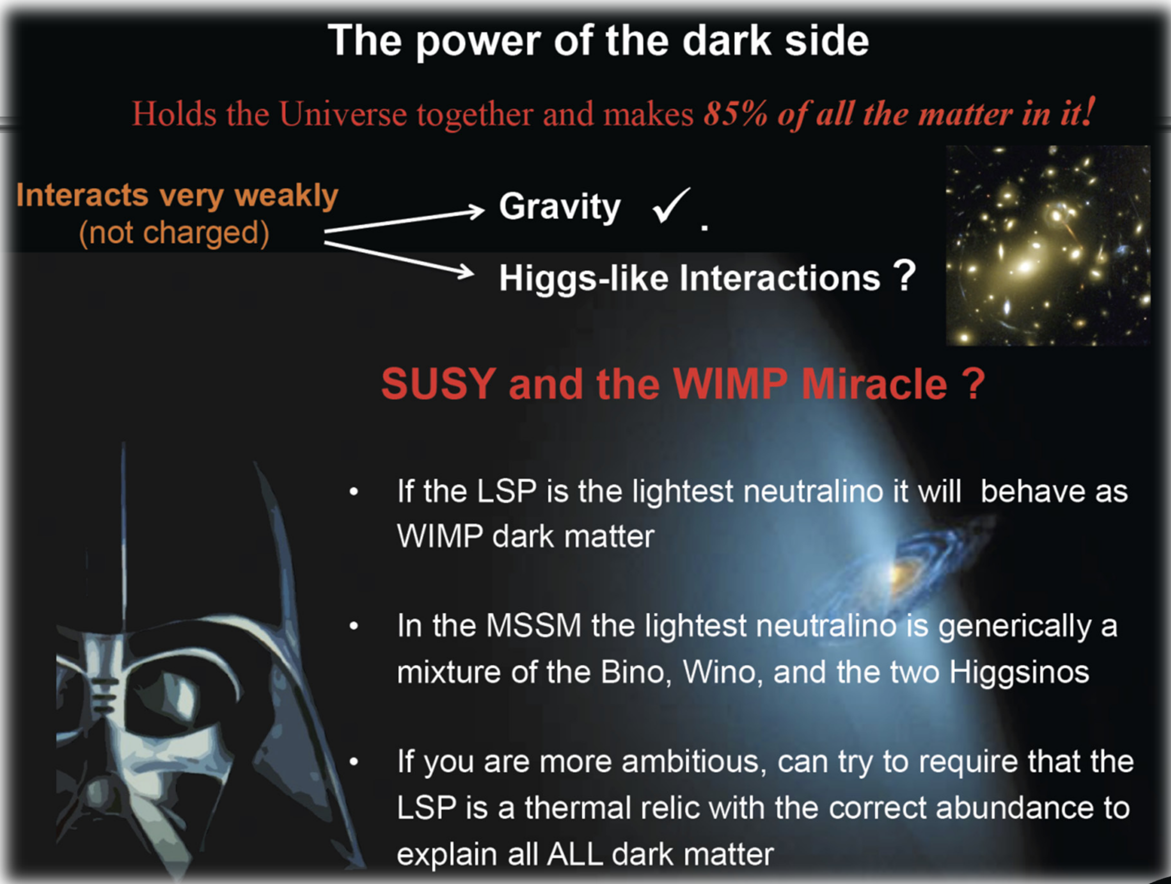
CMS-PAS-SMP-13-015

Strongly-Coupled Scenarios

- **Symmetry Breaking:** $SU(2)_L \otimes SU(2)_R \to SU(2)_C$
- **Goldstone Dynamics** ➡ **Electroweak Effective Theory**
- **Strong Electroweak Dynamics** ➡ **Heavy Resonances**
- **Many possibilities:** (Walking, Conformal) Technicolour, CFT, 5D …
- **Light Scalar Resonance H(125)**

➡ Pseudo-Goldstone (composite) Higgs, Dilaton ...

Dark Matter



The power of the dark side

Holds the Universe together and makes *85% of all the matter in it!*

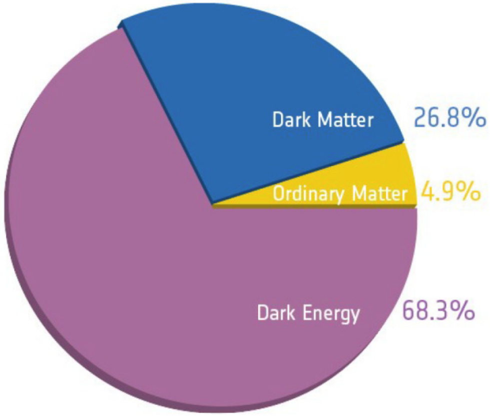
Interacts very weakly
(not charged)

→ Gravity ✓.

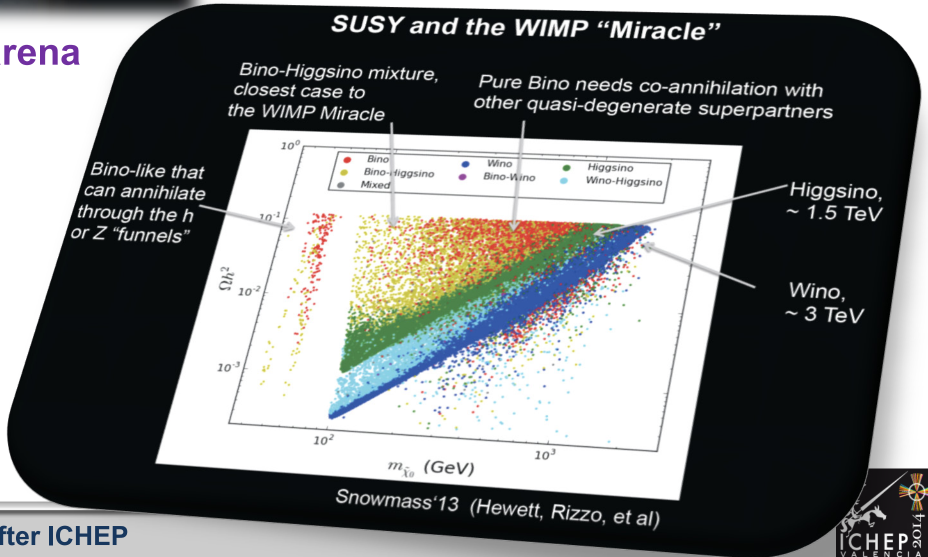
→ Higgs-like Interactions ?

SUSY and the WIMP Miracle ?

- If the LSP is the lightest neutralino it will behave as WIMP dark matter
- In the MSSM the lightest neutralino is generically a mixture of the Bino, Wino, and the two Higgsinos
- If you are more ambitious, can try to require that the LSP is a thermal relic with the correct abundance to explain all ALL dark matter



M. Carena



SUSY and the WIMP "Miracle"

Bino-Higgsino mixture, closest case to the WIMP Miracle

Pure Bino needs co-annihilation with other quasi-degenerate superpartners

Bino-like that can annihilate through the h or Z "funnels"

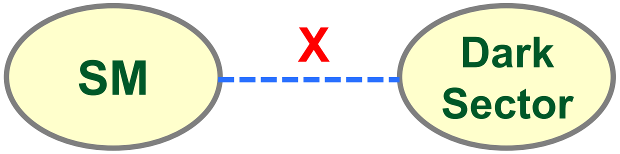
Higgsino, ~ 1.5 TeV

Wino, ~ 3 TeV

Snowmass'13 (Hewett, Rizzo, et al)

Hidden Portals

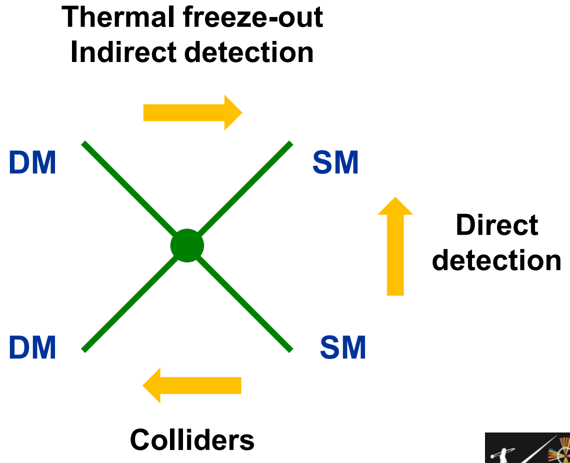
Coupling to a hidden Dark Sector through new SM-singlet particles



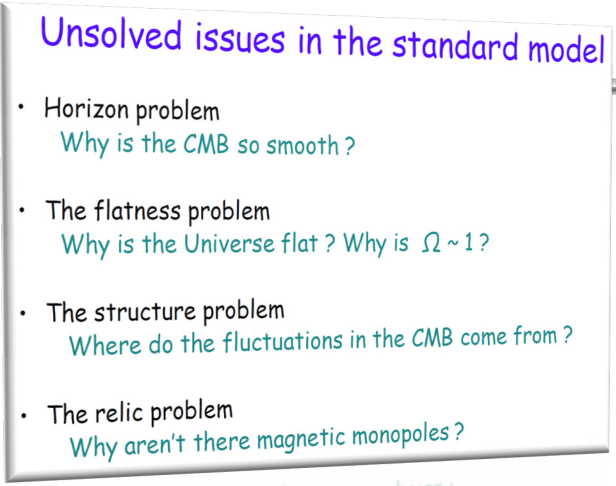
- **Higgs Portal:** $\chi\, H^\dagger H \quad , \quad \chi^2\, H^\dagger H$
- **Vector Portal:** $V_{\mu\nu} F^{\mu\nu}$
- **Neutrino Portal:** $\bar{L}_L\, H\, N_R$
- **Axion Portal:** $a\, \tilde{G}_{\mu\nu} G^{\mu\nu} \quad , \quad \partial^\mu a\;\; \bar{\psi}\, \gamma_\mu \gamma_5\, \psi$

DM candidates in many BSMs

Complementary experimental information



Barenboim



Unsolved issues in the standard model

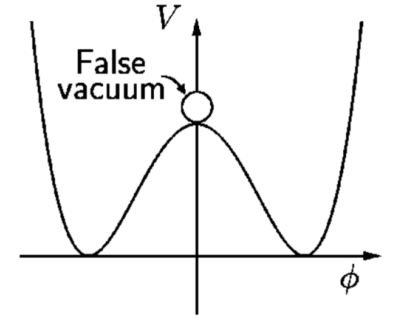
- Horizon problem
  Why is the CMB so smooth ?
- The flatness problem
  Why is the Universe flat ? Why is $\Omega \sim 1$?
- The structure problem
  Where do the fluctuations in the CMB come from ?
- The relic problem
  Why aren't there magnetic monopoles ?

Inflation Paradigm

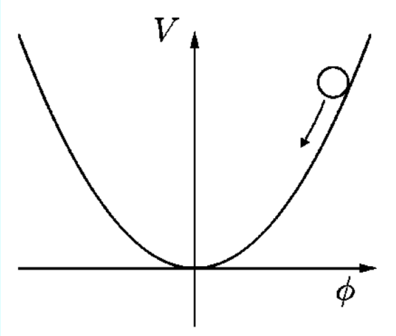
Guth

☆ **Negative Pressure $\Longrightarrow$ Repulsive Gravity.**

☆ State dominated by scalar field potential energy $\Longrightarrow$ Negative Pressure.



New (Small Field) Inflation
Linde; Albrecht & Steinhardt (1982)



Chaotic (Large Field) Inflation
Linde (1983)

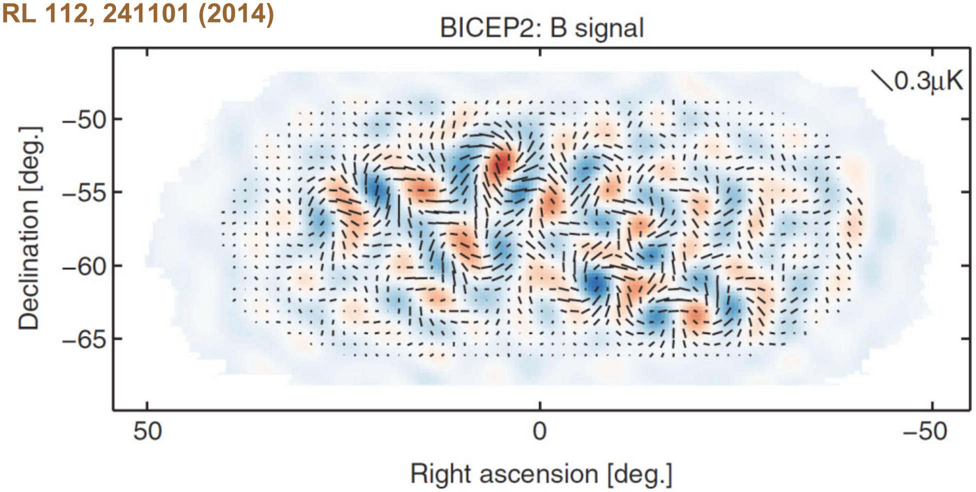
Planck ➡ $$\Omega = 1.0010 \pm 0.0065$$

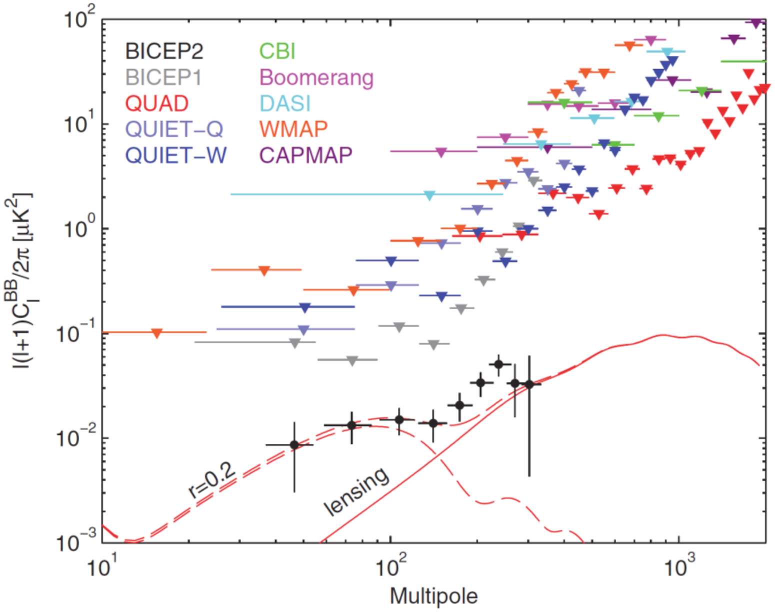
BICEP2 ➡ $$\rho_{\text{inf}}^{1/4} = 2.2 \times 10^{16}\ \text{GeV} \left(\frac{r}{0.2}\right)^{1/4}$$

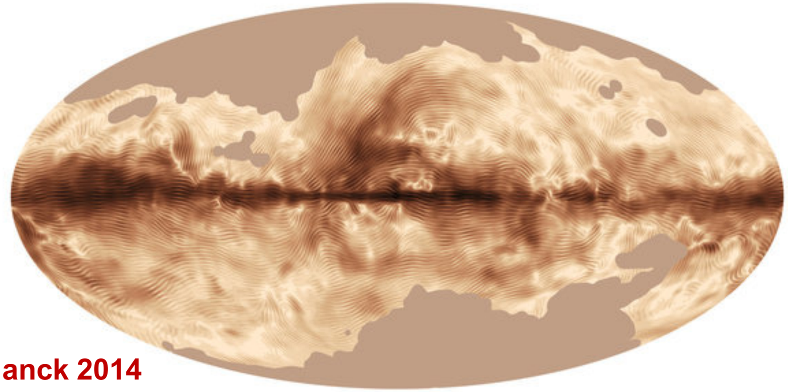
BICEP2 Data & Inflation Paradigm

$$r = 0.020\ ^{+\,0.07}_{-\,0.05} \qquad (\text{tensor / scalar})$$

PRL 112, 241101 (2014)







Planck 2014

Milky Way's (dust) magnetic fingerprint

- **Evidence of inflationary gravitational waves?**
- **Foreground polarized dust emission?**

Flauger et al 1405.7351, Mortonson-Seljak 1405.5857

Inflaton

- ☐ **Another scalar field?**

- ☐ **Could “Higgs Inflation” work?**

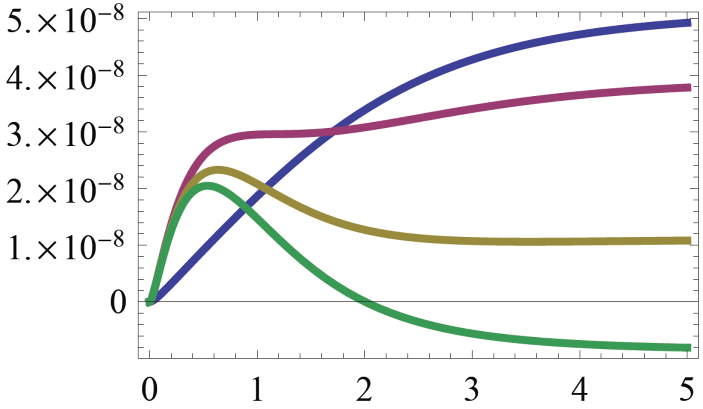
$$S_G = -\frac{1}{2}\int d^4x\,\sqrt{-g}\,\left\{M_{\rm Pl}^2\,R + \xi H^2 R\right\}$$

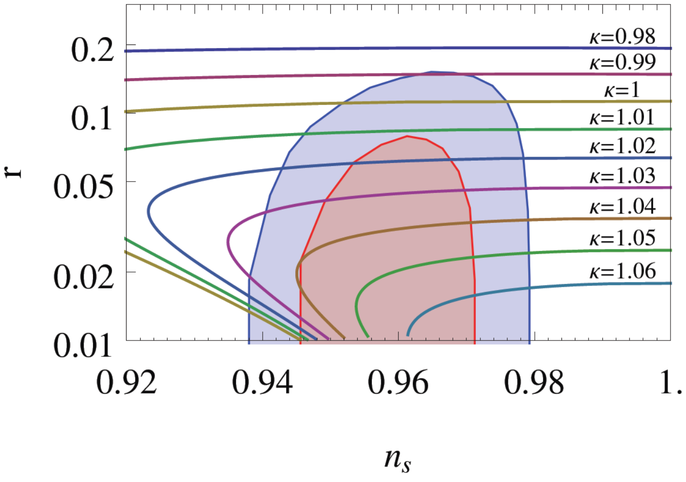
$$\xi \approx 47000\,\sqrt{\lambda} \quad (\mathbf{COBE}) \quad \Rightarrow \quad n_s \approx 0.97 \quad , \quad r \approx 0.003$$

Quantum effects: **$M_H > M_{crit} \sim 129.6$ GeV**

Bezrukov-Shaposhnikov, 1403.6078

Close to M_{crit} , n and r strongly depend on M_H and m_t





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...

- **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