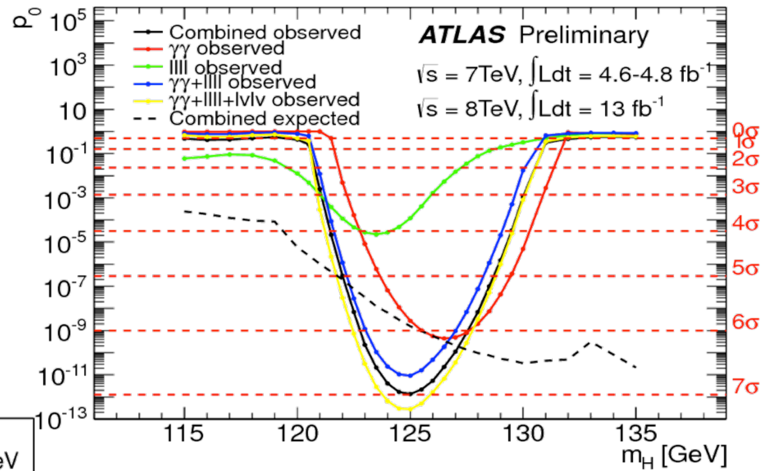
Beyond the SM and the LHC

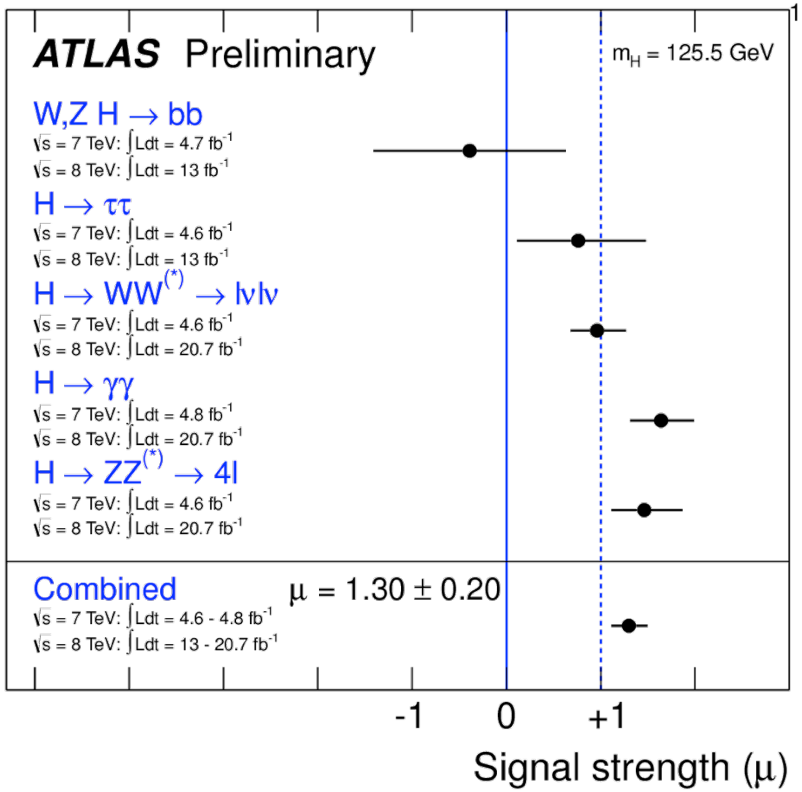
Corfu, September, 2013

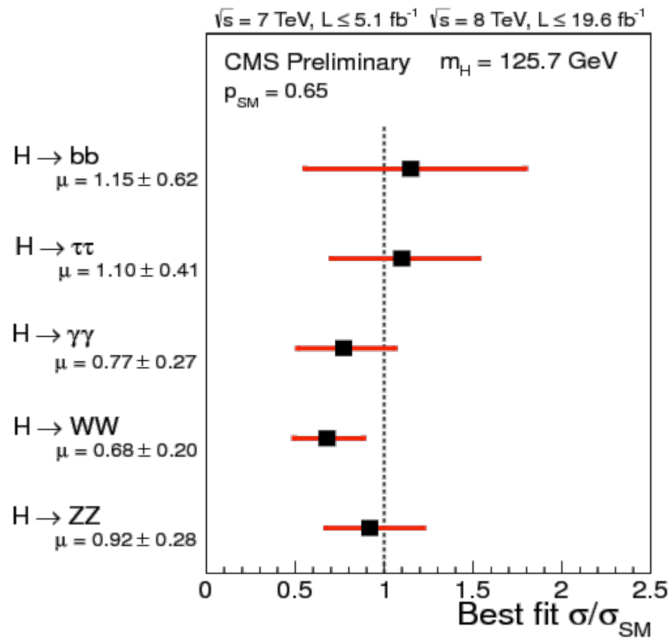
Graham Ross

Its been a great year:

Higgs(?) discovery!







Not the only new results

LHC

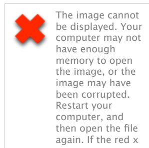
PLANCK

DARK MATTER

XENON, COGENT, CDMS, LUX...

AMS02, FERMI, PAMELA, ATIC, HESS...

NEUTRINOS



DAYA BAY, RENO, T2K, MINOS, DOUBLE CHOOZ

....

Where are we now?

- Is the Higgs the SM Higgs? $J^{PC} = 0^{++}$

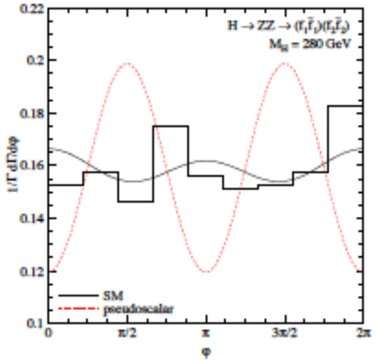
Butterworth, Djouadi

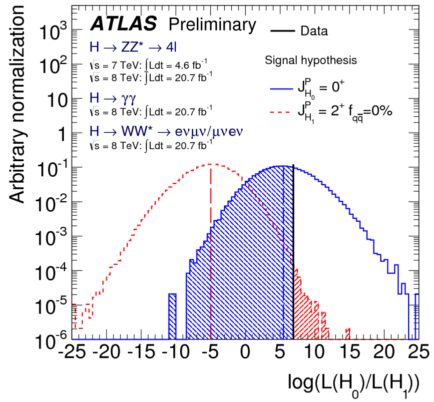
Spin?

$\gamma\gamma$ C+, J≠1 : Landau-Yang

J≠2 Angular dist.

J= 0 ✔





Pure spin 2 excluded at > 99.9%

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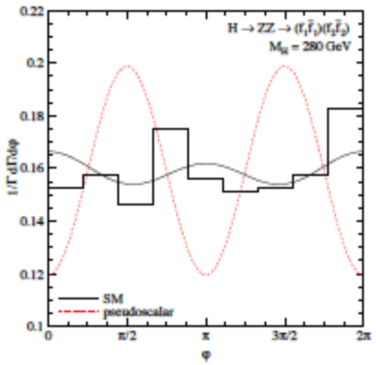
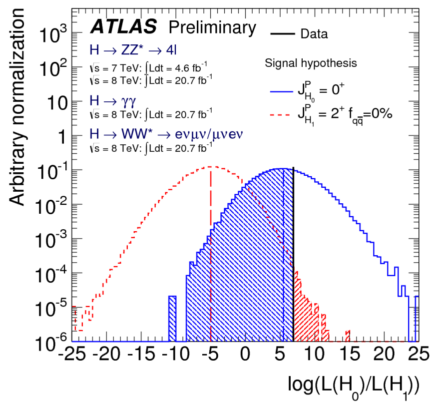




Pure spin 2 excluded at > 99.9%

CP even or CP odd?

$$\mathbf{HV_\mu V^\mu \text{ vs } H\epsilon^{\mu\nu\rho\sigma}Z_{\mu\nu}Z_{\rho\sigma}}$$

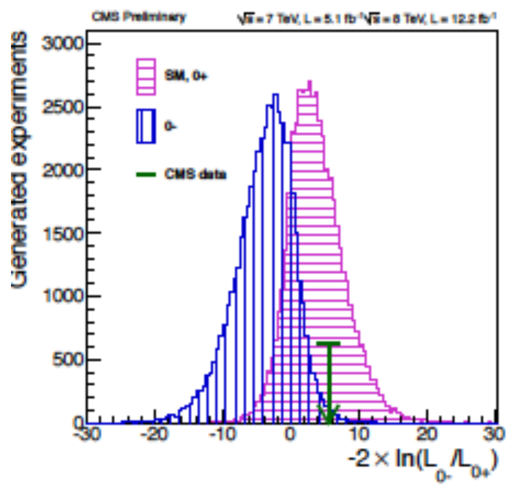
$$\Rightarrow \frac{d\Gamma(H\to ZZ^*)}{dM_*} \text{ and } \frac{d\Gamma(H\to ZZ)}{d\phi}$$

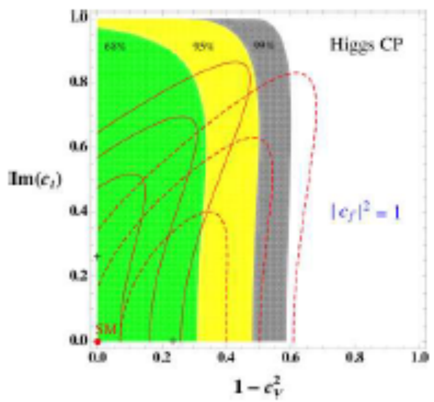
ATLAS/CMS: $\approx 3\sigma$ for CP-even.

Problem: if H is CP mixture, only 0^+ component is projected out! (or very large 0^-VV loop cplg).

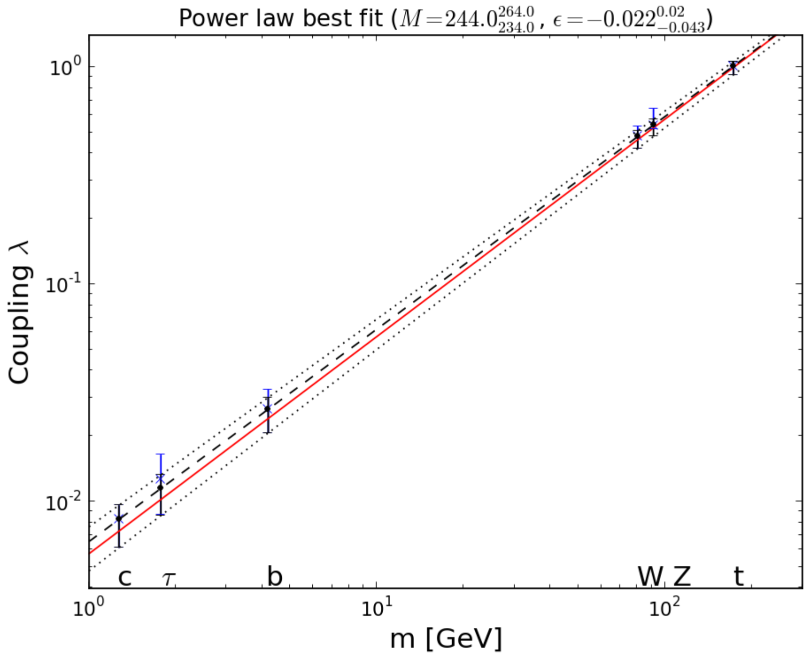
$\Rightarrow$ better probe: $\hat{\mu}_{ZZ} = 1.1 \pm 0.4$!

$$H = 0^{++} + \alpha 0^{--} + \beta 0^{+-} + \gamma 0^{-+}$$





● Is the Higgs the SM Higgs?



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

$$M = 244^{+20}_{-10}\ \text{GeV}, \quad \epsilon = -0.022^{+0.042}_{-0.021}$$

$$c.f. \quad M_{SM} = 246\ GeV, \quad \varepsilon_{SM} = 0$$

Ellis, You

Higgs couplings to elementary particles as predicted by Higgs mechanism

- **couplings to WW,ZZ,$\gamma\gamma$ roughly as expected for a CP-even Higgs**
- **couplings proportionial to masses as expected for the Higgs boson**

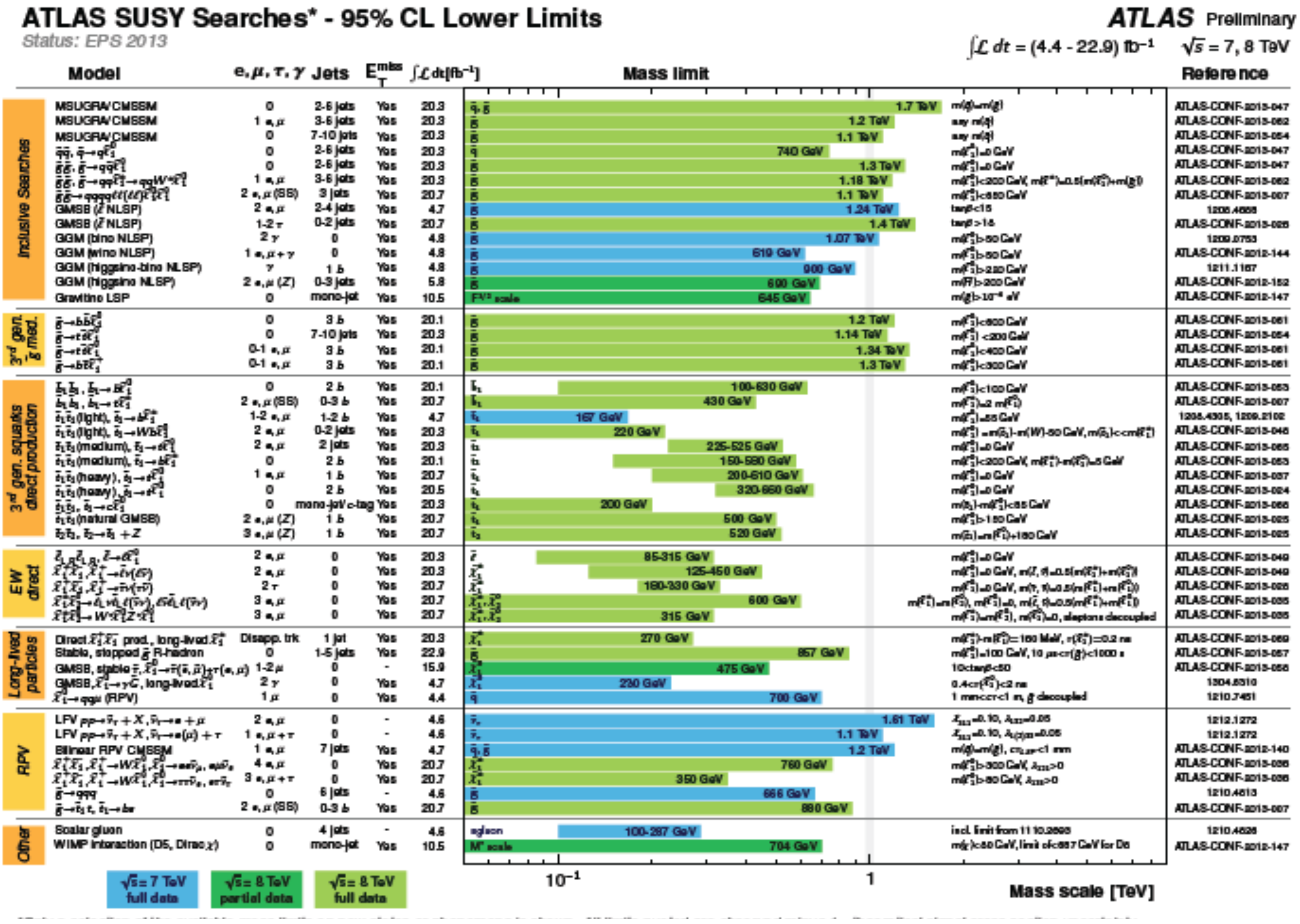
So, it is not only a "new particle", the "126 GeV boson", a "new state"...

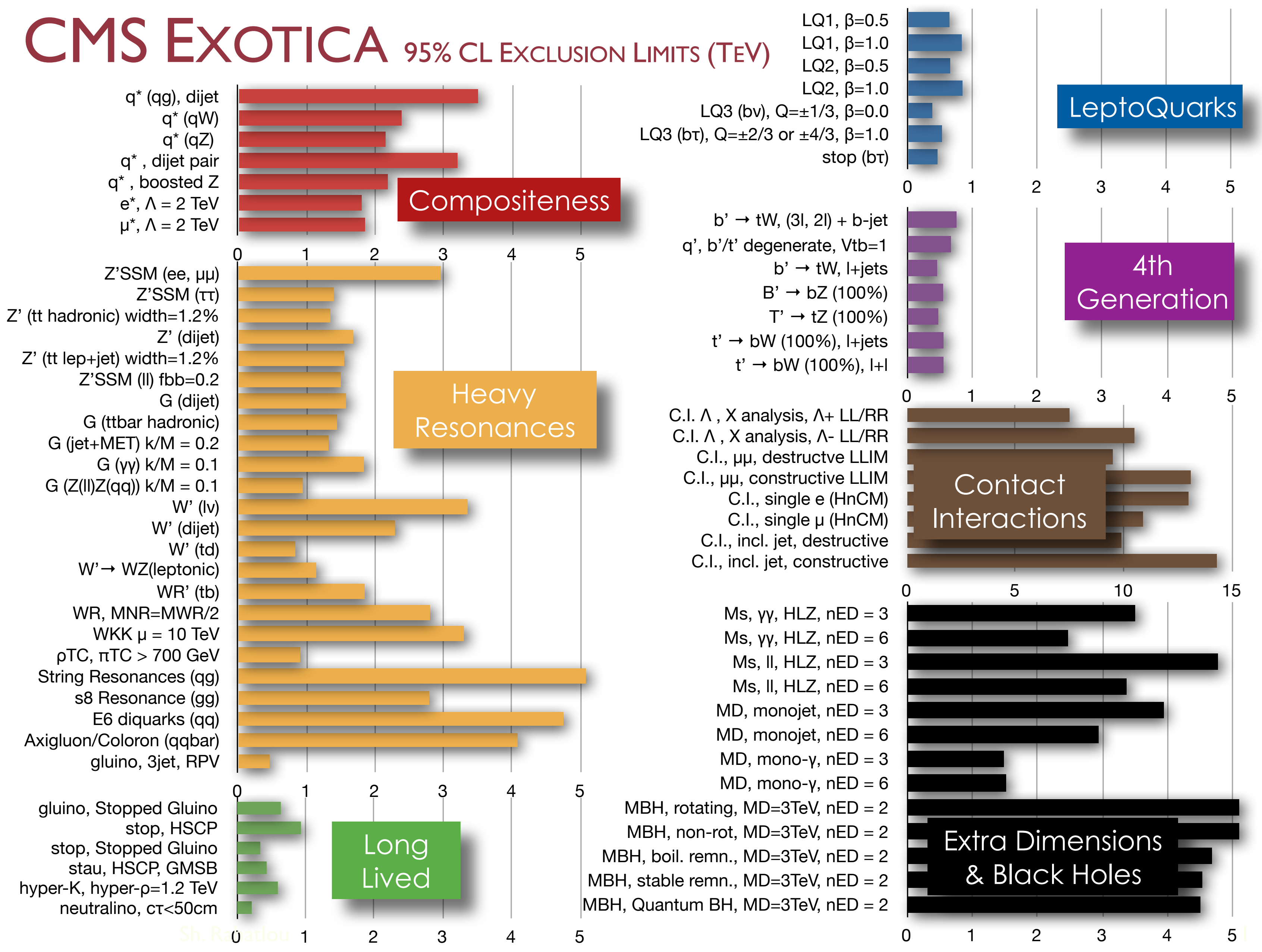
IT IS A HIGGS BOSON!

But is it THE SM Higgs boson or A Higgs boson from some extension?

BSM physics?

ATLAS Summary



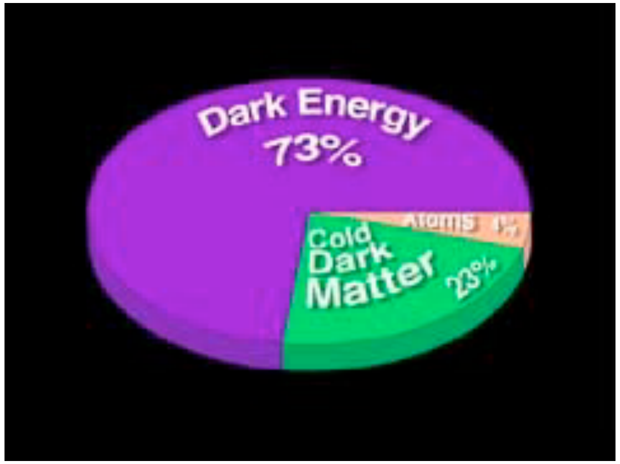

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0 1 2 3 4 5
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
0 1 2 3 4 5
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
0 1 2 3 4 5
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
0 1 2 3 4 5
4th Generation
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
0 1 2 3 4 5
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
0 5 10 15
Extra Dimensions & Black Holes
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
0 1 2 3 4 5

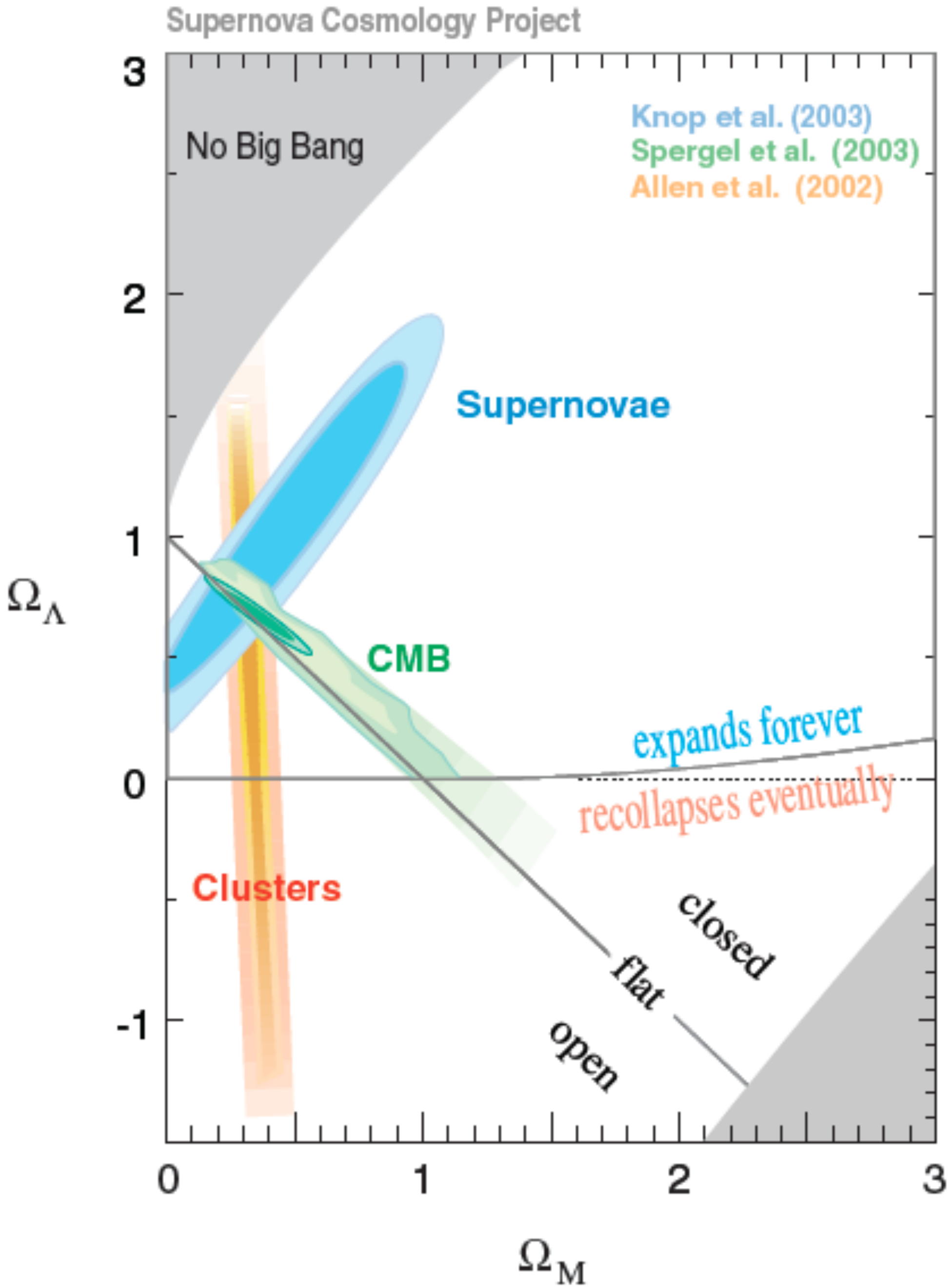
Planck

Consistent cosmological picture given in terms of only 6 parameters,

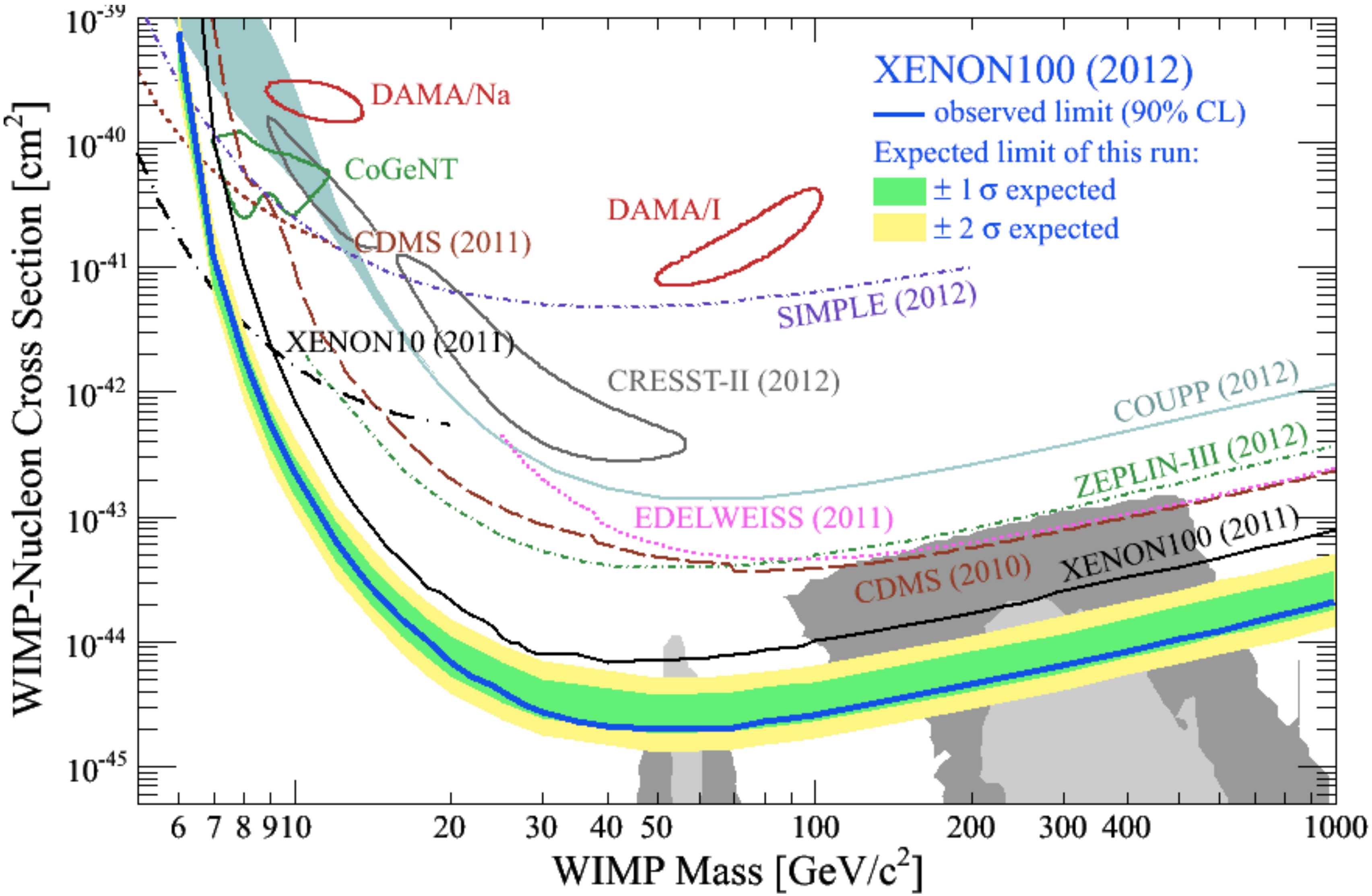
$$\Omega_M h^2, \Omega_b h^2, \ \tau, n_s, A_s$$

$$\theta_*(\Omega_k/\Omega_\Lambda, H_0)$$

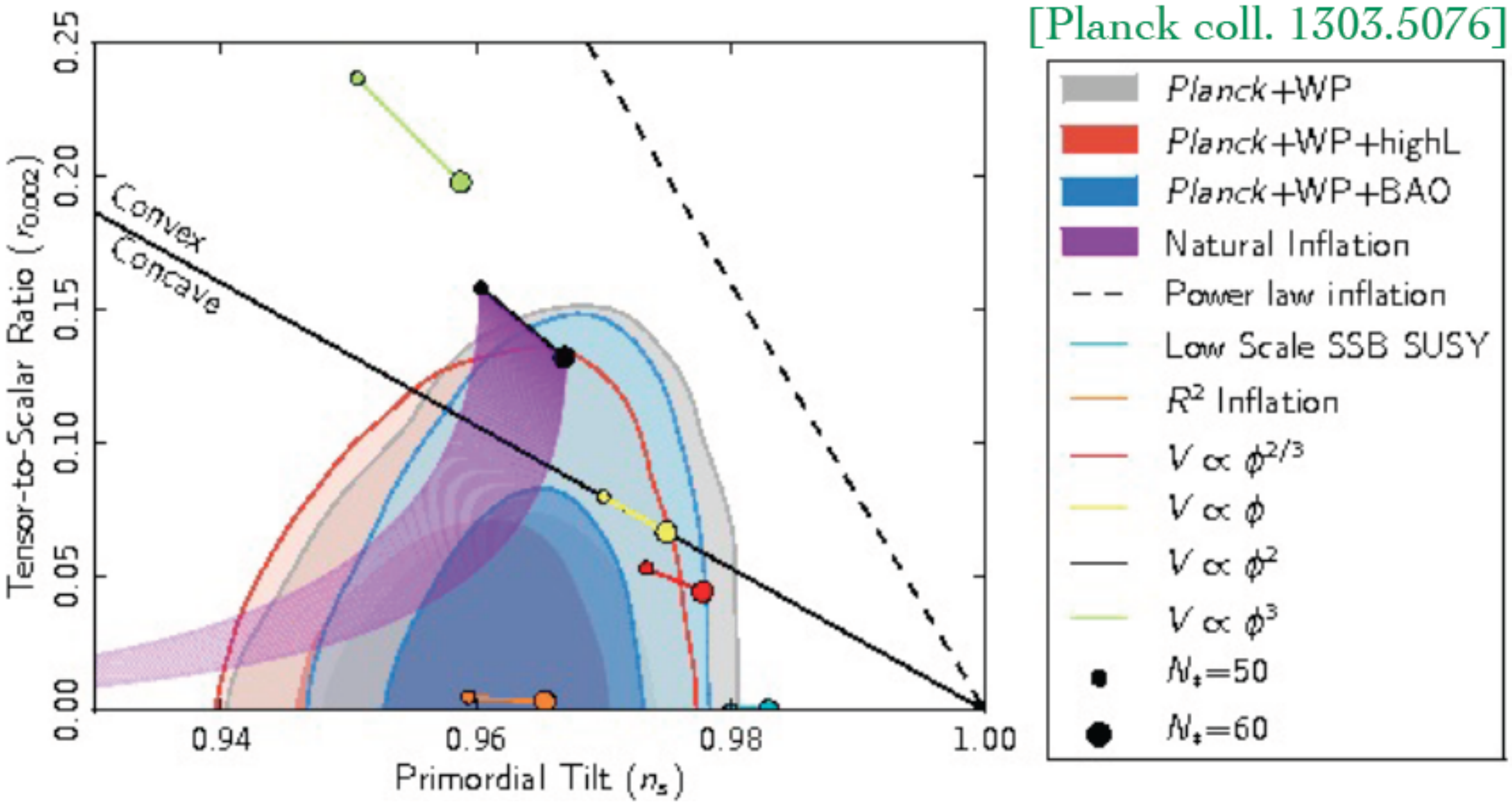




Dark matter searches



Inflation

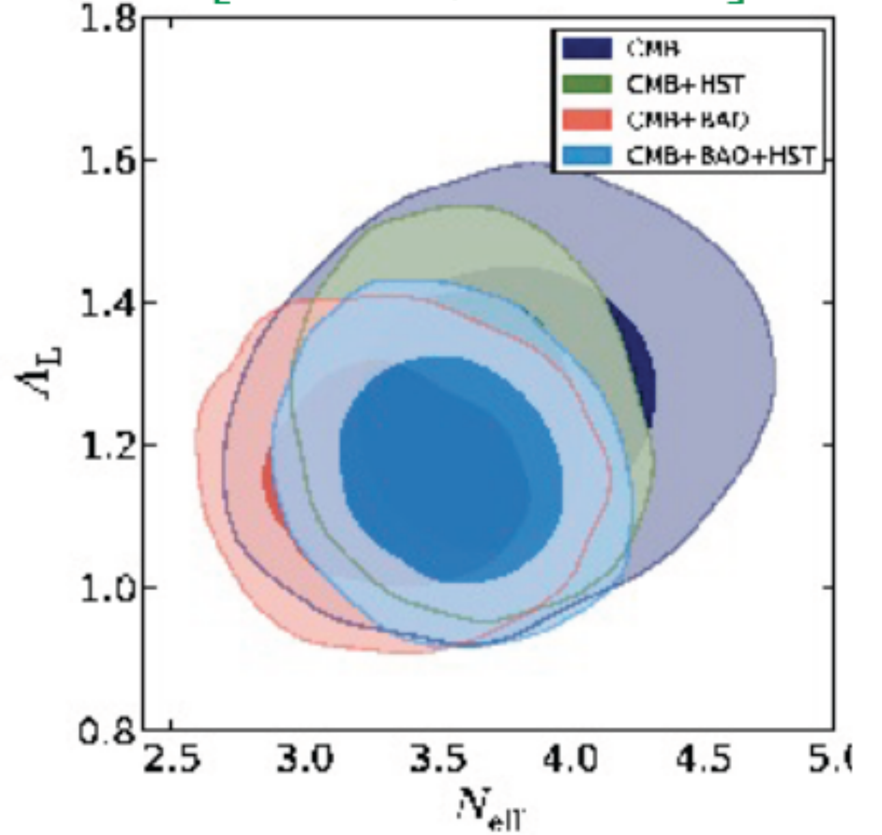


$$n_s = 0.959 \pm 0.007 \qquad r_{0.02} < 0.11 (95\% CL)$$

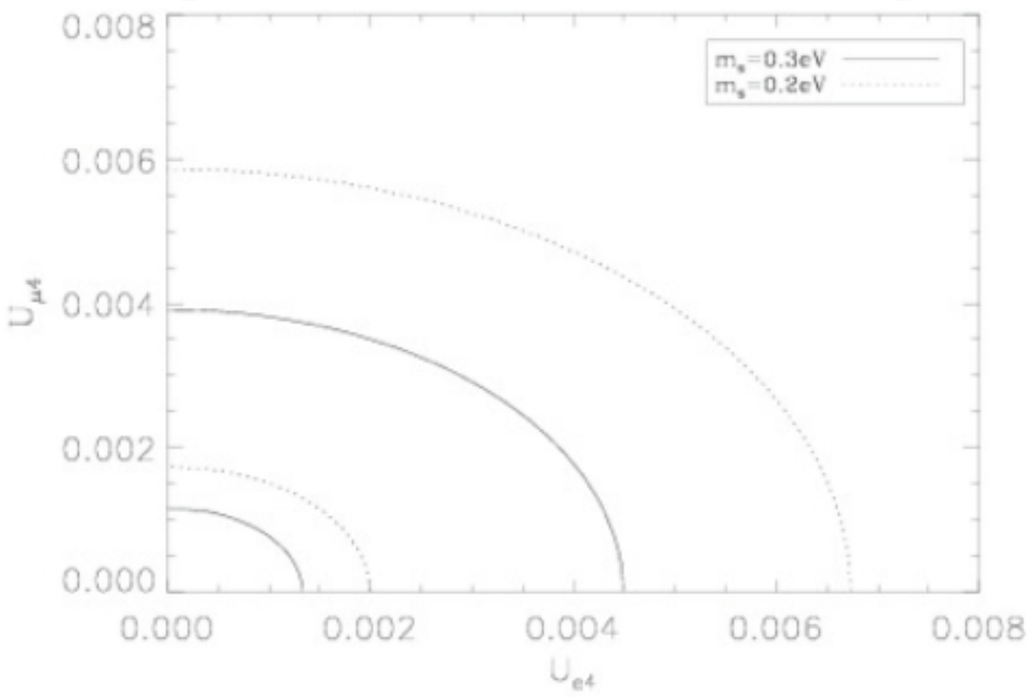
No evidence for running of n_s: $\frac{dn_s}{d\ln k} = -0.015 \pm 0.009$

STILL SOME ROOM FOR DARK RADIATION!

[Said et al, 1304.6217]



[Di Valentino et al, 1304.5981]



Larger ΔN_{eff} fitting with lensing amplitude

Sterile neutrino case, stills possible...

Implications ?

Part 1: Just the Standard Model

Implications of a 125 GeV Higgs

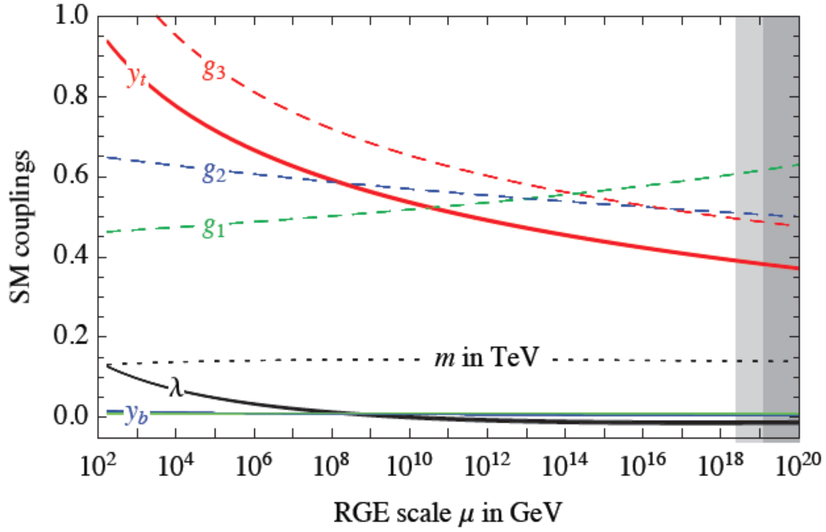
RG equations:

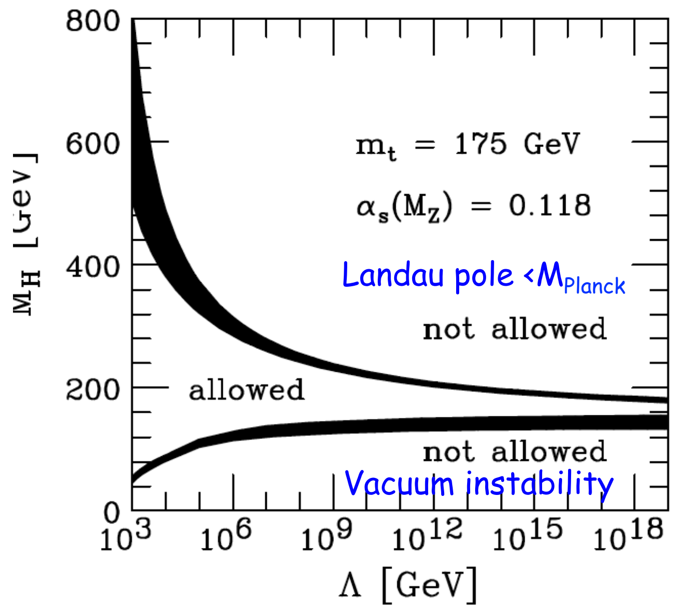
$$\beta_1^{\rm SM} = \frac{41}{96\pi^2} g_1^3\,, \quad \beta_2^{\rm SM} = -\frac{19}{96\pi^2} g_2^3\,, \quad \beta_3^{\rm SM} = -\frac{7}{16\pi^2} g_3^3$$

$$\beta_h^{\rm SM} = \frac{1}{16\pi^2}\left[\frac{9}{2}h^3 - 8g_3^2 h - \frac{9}{4}g_2^2 h - \frac{17}{12}g_1^2 h\right]$$

$$\beta_\lambda^{\rm SM} = \frac{1}{16\pi^2}\left[24\lambda^2 + 12\lambda h^2 - 9\lambda\,(g_2^2 + \frac{1}{3}g_1^2)\right.$$
$$\left. -6h^4 + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2 g_1^2\right]\,.$$

Implications of a 125 GeV Higgs





RGE - just the Standard Model

Higgs coupling small

Hambye, Riesselmann

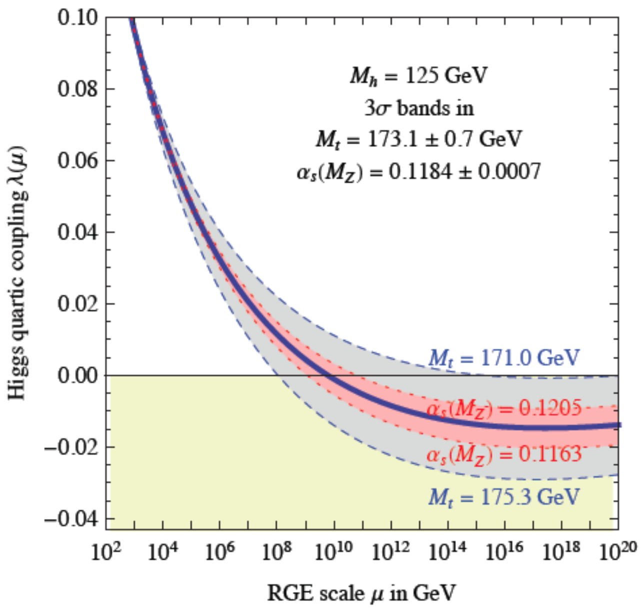
$$V_0 = -\frac{m_0^2}{2}|H_0|^2 + \lambda_0|H_0|^4$$

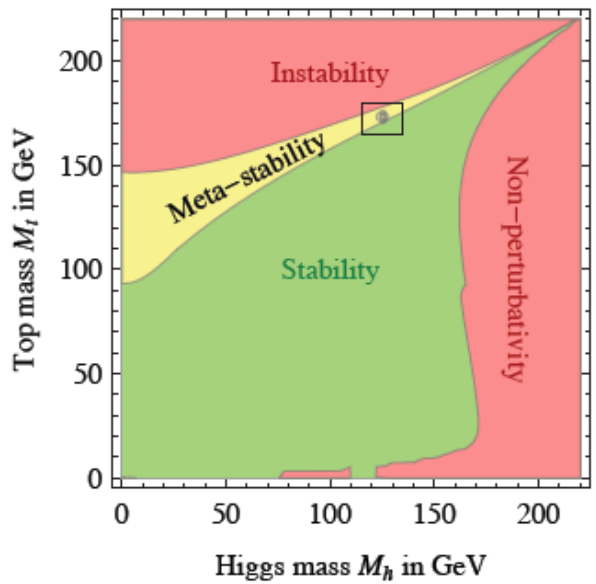
Implications of a 125 GeV Higgs - vacuum instability

$$V(H) = -\frac{1}{2} M_H^2 |H|^2 + \frac{\lambda}{4} |H|^4$$

Tunneling probability: $p = \max_R \frac{V_U}{R^4} \exp\left[-\frac{8\pi^2}{3\,|\lambda(\mu)|} - \Delta S\right]$

Isidori, Ridolfi, Strumia



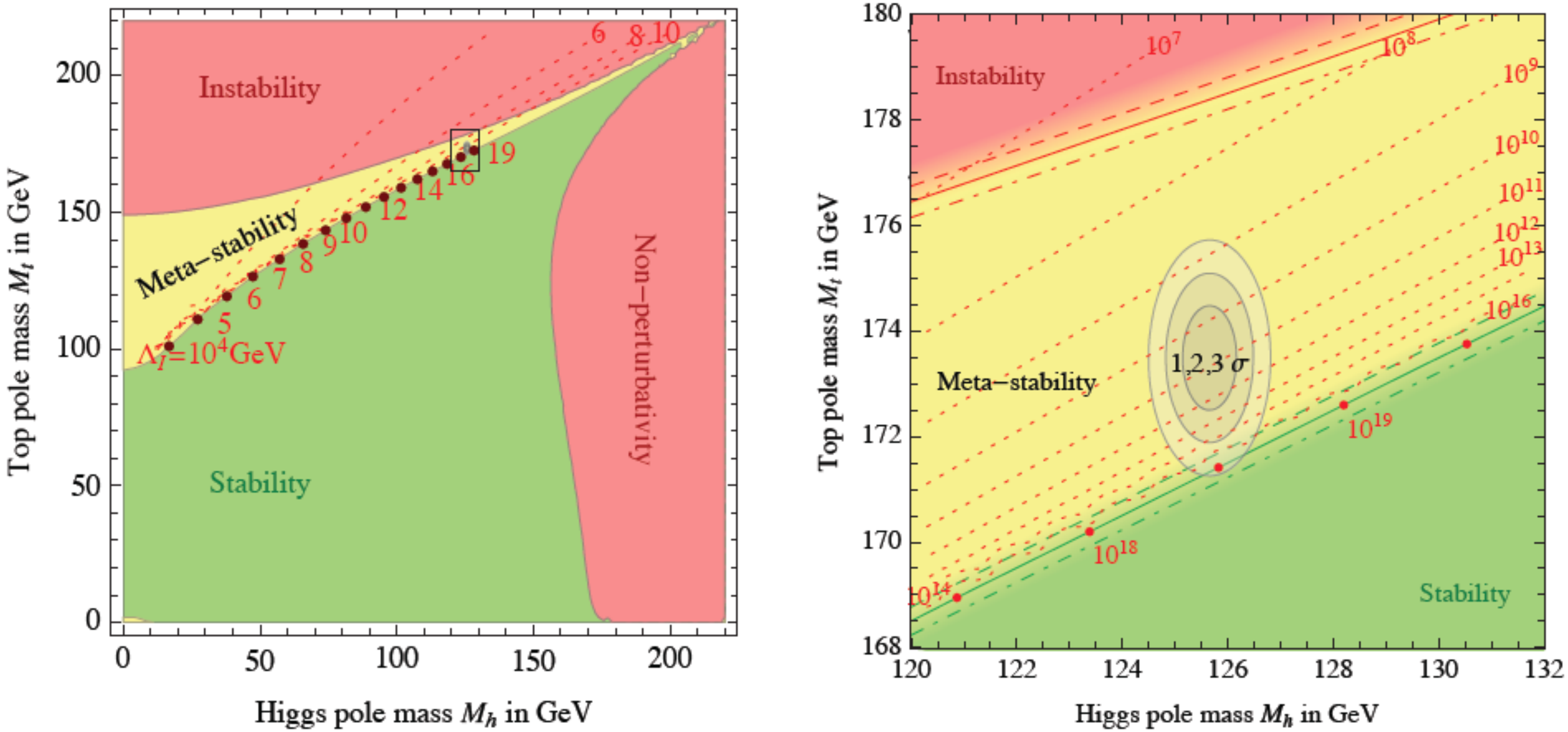


$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}$$

$$M_h > 129.4 \pm 1.8\ \text{GeV}$$

2σ away from stability

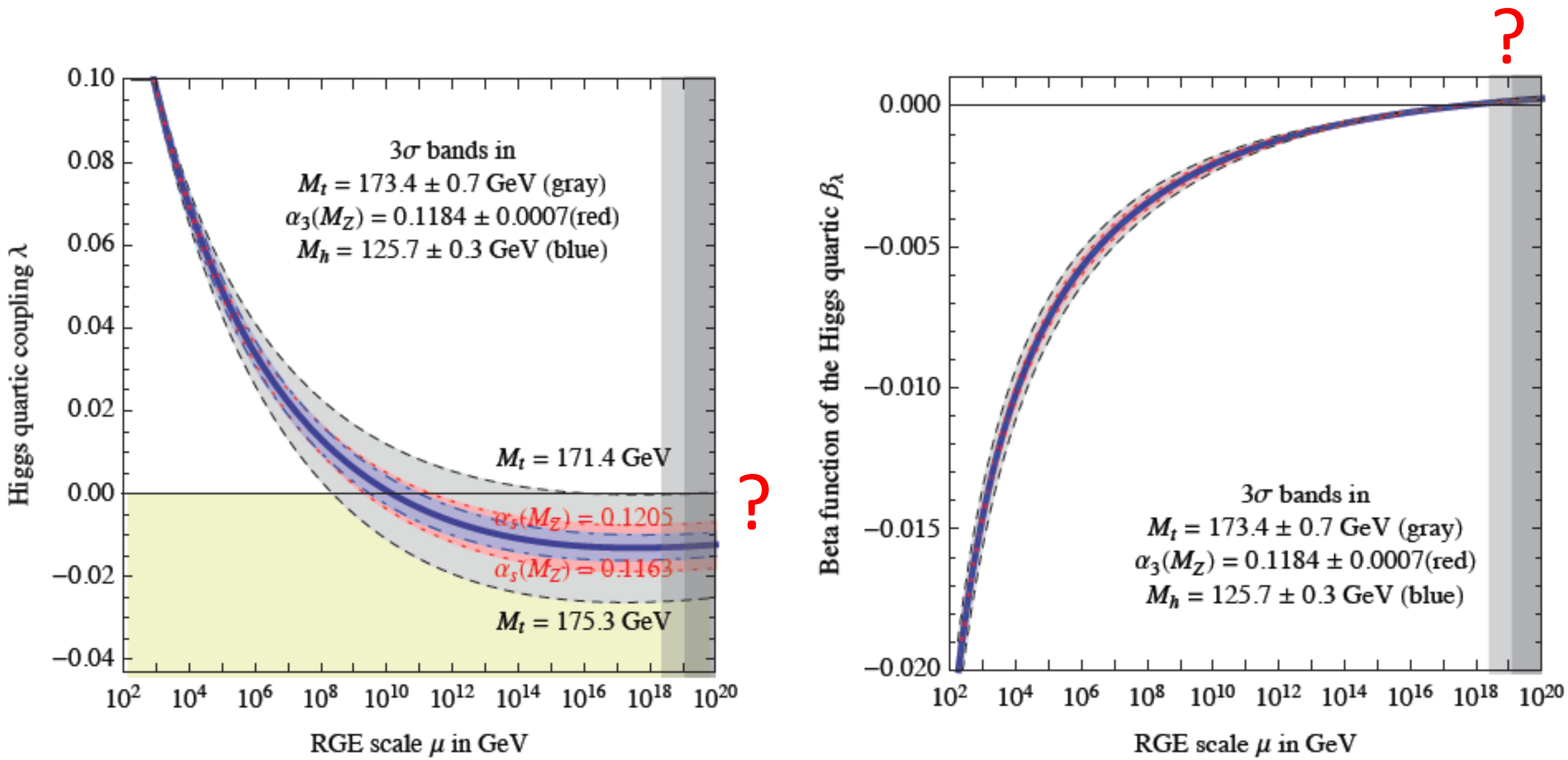
De Grassi et al



Instability
Meta−stability
Stability
Non−perturbativity
$\Lambda_I = 10^4$GeV
Top pole mass M_t in GeV
Higgs pole mass M_h in GeV
1,2,3 σ

Ideas: Is it Just the Standard Model?

$$V_0 = -\frac{m_0^2}{2}|H_0|^2 + \lambda_0 |H_0|^4$$



Just the Standard Model - boundary conditions

I. IR fixed point (M$_{Planck}$ is IR!)

$$k\frac{dx_j}{dk} = \beta_j^{SM} + \beta_j^{grav} \qquad \beta_j^{grav} = \frac{a_j}{8\pi}\frac{k^2}{M_p^2(k)}x_j$$

- $$\beta_\lambda \simeq \frac{a_\lambda}{8\pi}\frac{k^2}{\left(M_P^2 + 2\xi_0^2 k^2\right)}\lambda + \frac{1}{16\pi^2}\left(24\lambda^2 + 12\lambda h^2 - 6h^4 + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2 g_1^2\right)$$

$m_h \sim 125\, GeV!$

$a_\lambda > 0,\ \lambda(M_P) \simeq 0$, IRFP $\qquad (\xi_0 \sim 0.02)$

Shaposhnikov, Wetterich (2010)

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$(\xi_0 \sim 0.02)$

- $$\beta_h \simeq \frac{a_h}{8\pi}\frac{k^2}{\left(M_P^2+2\xi_0^2k^2\right)}h + \frac{1}{16\pi^2}\left[\frac{9}{2}h^3-8g_3^2h-\frac{9}{4}g_2^2h-\frac{17}{12}g_1^2h\right]$$

$$a_h < 0,\quad h_{UV}^2 = 0\ ,\ h_{IR}^2 = \frac{2\pi|a_h|}{9\xi_0}$$

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$$a_\lambda > 0,\ \lambda(M_P) \simeq 0,\ \text{IRFP} \qquad (\xi_0 \sim 0.02)$$

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$$a_h < 0, \quad h_{UV}^2 = 0\ ,\ h_{IR}^2 = \frac{2\pi|a_h|}{9\xi_0}$$

- Gauge couplings $a_1 = a_2 = a_3 = a_g$ - exercise

Summary

$\lambda \simeq 0$ ✔

h_t, g_i ?

$\beta_\lambda \approx 0$?

Remove by local field redefinition

$$\frac{b}{M_P^2}\int d^4x F_{\mu\nu}\Box F^{\mu\nu}$$

Ellis, Mavromatos

But…

$$\beta(g,E) = \frac{d\,g}{d\ln E} = \frac{b_0}{4\pi^2}\, g^3 - 3\frac{16\pi^2}{(4\pi)^2}\frac{E^2}{M_P^2}\, g$$

Summary

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- Another possibility – power law running in extra dimansions

But... N=2 sector only - $h = \sqrt{2}g$ ✗

II. Supersymmetry at M_{Planck}

$$\lambda(\tilde{m}) = \frac{1}{8}\left[g^2(\tilde{m}) + g'^2(\tilde{m})\right]\cos^2 2\beta$$

$$= 0$$

Shift symmetry

$$H_u \longrightarrow H_u + c, \qquad H_d \longrightarrow H_d - c^\dagger$$

$$\mathcal{L} \supset -m_1^2|H_u|^2 - m_2^2|H_d|^2 - m_3^2(H_uH_d + H_d^\dagger H_u^\dagger)$$

Massless state $H_0 = \frac{1}{\sqrt{2}}(H_u - H_d^\dagger)$ $\Rightarrow \tan\beta = 1$

Hebecker, Knochel, Weigand

II. Supersymmetry at M_X

$$\lambda(\tilde{m}) = \frac{1}{8}\left[g^2(\tilde{m}) + g'^2(\tilde{m})\right]\cos^2 2\beta$$

$= 0$

Shift symmetry

$$H_u \longrightarrow H_u + c, \qquad H_d \longrightarrow H_d - c^\dagger$$

$$\mathcal{L} \supset -m_1^2|H_u|^2 - m_2^2|H_d|^2 - m_3^2(H_u H_d + H_d^\dagger H_u^\dagger)$$

Massless state $H_0 = \frac{1}{\sqrt{2}}(H_u - H_d^\dagger)$ $\Rightarrow \tan\beta = 1$

Hebecker, Knochel, Weigand

or $m_{H_u}(M_P) = m_{H_d}(M_P)$ + minimal fine tuning

Ibanez, Valenzuela

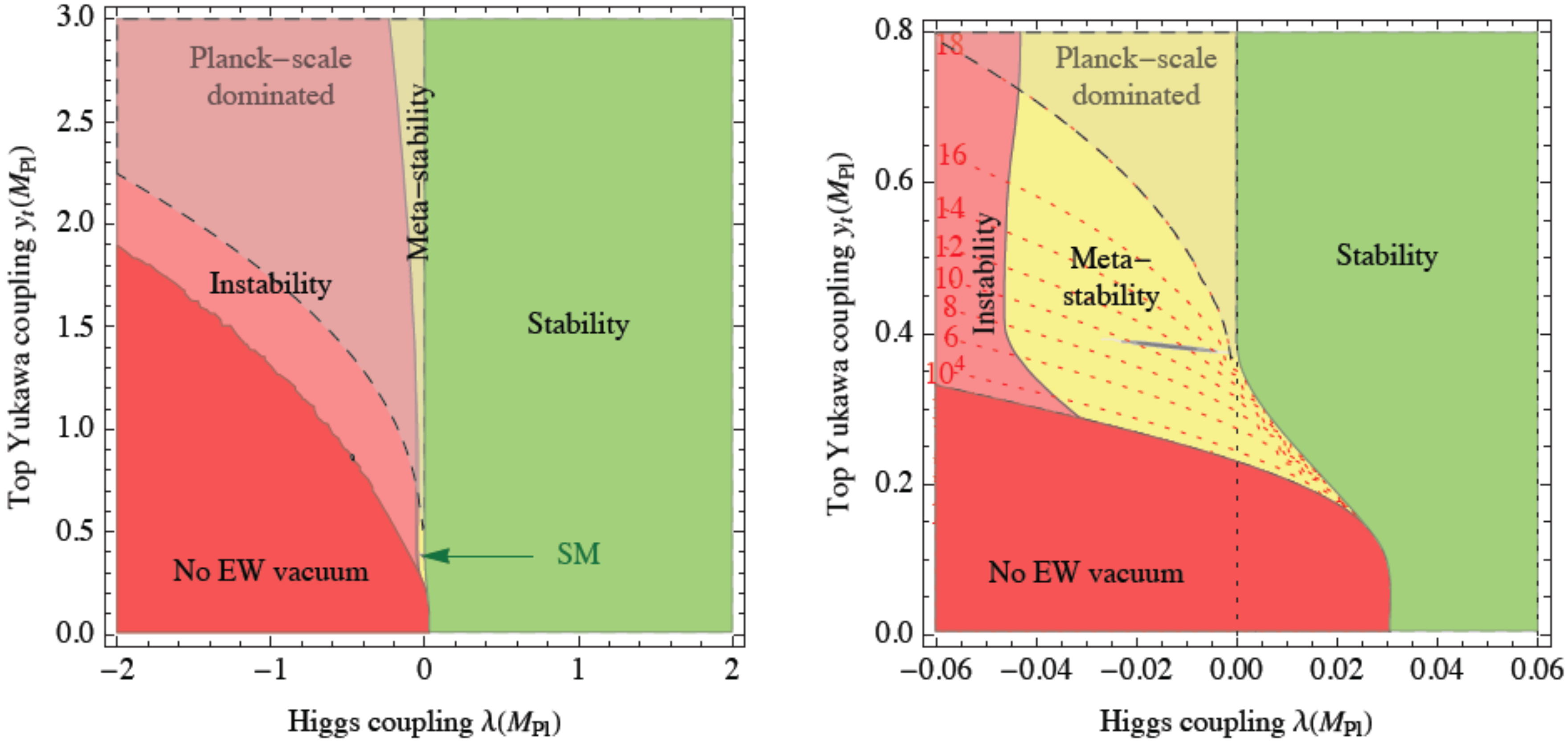
II. Supersymmetry at $M_{Planck,\ X}$

$$\lambda(\tilde{m}) = \frac{1}{8}\left[g^2(\tilde{m}) + g'^2(\tilde{m})\right]\cos^2 2\beta$$

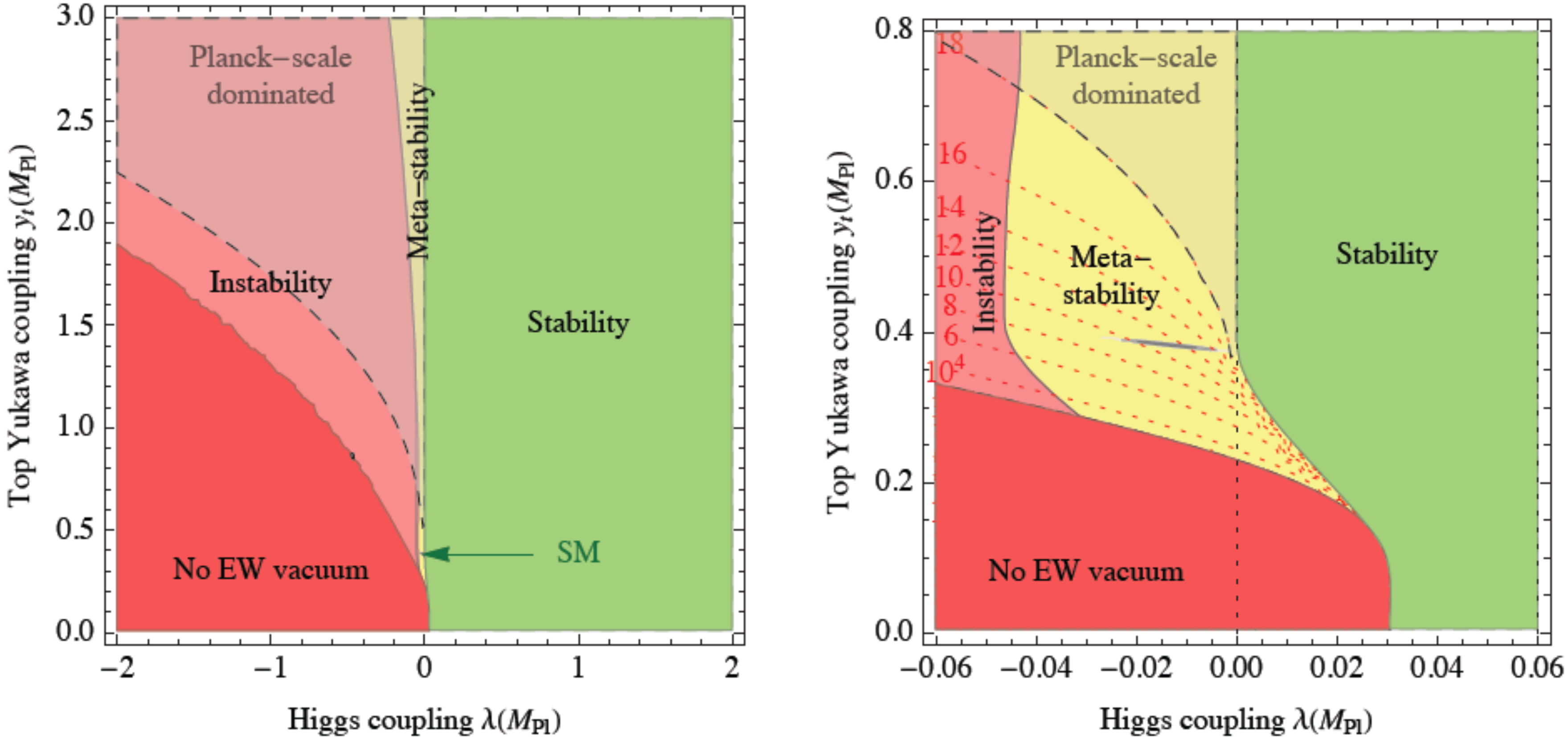
But…

Hierarchy problem introduced!

III. Environmental



III. Environmental



But...

larger m_t safe ??

Just beyond the SM - Origin of EW scale?

- natural (?)

If quadratic divergence in Higgs mass vanishes at one scale, vanishes at all scales

Scale invariance?

Bardeen

Just beyond the SM - Origin of EW scale?

e.g. Massless scalar QED $V_{\rm cl} = \frac{\lambda_\phi}{4!}|\phi|^4$ classically scale invariant

$$V(\phi) = V_{\rm cl} + \Delta V_{1-\rm loop} = \frac{\lambda_\phi}{4!}|\phi|^4 + \left(\frac{5\lambda_\phi^2}{1152\pi^2} + \frac{3e_\phi^4}{64\pi^2}\right)|\phi|^4\left[\log\left(\frac{|\phi|^2}{M^2}\right) - \frac{25}{6}\right]$$

Coleman Weinberg

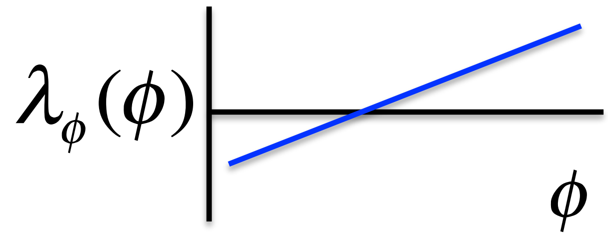
where $m^2 := V''(\phi)\Big|_{\phi=0} = 0$ is imposed

Potential has a minimum for $\langle\phi\rangle \neq 0$

Choosing $\quad M = \langle \phi \rangle, \quad V(\phi) = \frac{\lambda_\phi}{4!}|\phi|^4 + \frac{3e_\phi^4}{64\pi^2}|\phi|^4 \left[\log\left(\frac{|\phi|^2}{\langle|\phi|^2\rangle}\right) - \frac{25}{6}\right]$

$$\lambda_\phi(\langle|\phi|\rangle) = \frac{33}{8\pi^2} e_\phi^4(\langle|\phi|\rangle)$$

$$V(\phi) = \frac{3e_\phi^4}{64\pi^2}|\phi|^4 \left[\log\left(\frac{|\phi|^2}{\langle|\phi|^2\rangle}\right) - \frac{1}{2}\right]$$



RGE $\quad \frac{de_\phi}{dt} = \frac{e_\phi^3}{48\pi^2}, \quad$ where $\quad t = \log(M/\Lambda_{UV})$

$$\langle|\phi|\rangle = \Lambda_{UV} \exp\left[-24\pi^2 \left(\frac{1}{e_\phi^2(\langle|\phi|\rangle)} - \frac{1}{e_\phi^2(\Lambda_{UV})}\right)\right] \simeq \Lambda_{UV} \exp\left[\frac{-24\pi^2}{e_\phi^2(\langle|\phi|\rangle)}\right]$$

- dimensional transmutation!

Exponentially large separation natural!

Choosing $M = \langle\phi\rangle$, $V(\phi) = \frac{\lambda_\phi}{4!}|\phi|^4 + \frac{3e_\phi^4}{64\pi^2}|\phi|^4\left[\log\left(\frac{|\phi|^2}{\langle|\phi|^2\rangle}\right) - \frac{25}{6}\right]$

$$\lambda_\phi(\langle|\phi|\rangle) = \frac{33}{8\pi^2}e_\phi^4(\langle|\phi|\rangle)$$

$$V(\phi) = \frac{3e_\phi^4}{64\pi^2}|\phi|^4\left[\log\left(\frac{|\phi|^2}{\langle|\phi|^2\rangle}\right) - \frac{1}{2}\right]$$

Can Φ be the Higgs?

$$m_\phi^2 = \frac{3e_\phi^4}{8\pi^2}\langle|\phi|^2\rangle = \frac{3e_\phi^2}{8\pi^2}m_X^2 \ll m_X^2$$ ✗

- Coleman Weinberg with a Higgs portal:

$\phi, U(1)$ "hidden sector"

$$V(\phi, H) = \frac{\lambda_\phi}{4!}|\phi|^4 + \frac{3e_\phi^4}{64\pi^2}|\phi|^4 \left[\log\left(\frac{|\phi|^2}{\langle|\phi|^2\rangle}\right) - \frac{25}{6}\right] - \lambda_{\rm P}(H^\dagger H)|\phi|^2 + \frac{\lambda_{\rm H}}{2}(H^\dagger H)^2$$

$$\sqrt{\frac{\lambda_{\rm H}}{\lambda_{\rm P}}}\langle H\rangle = \langle\phi\rangle \simeq \Lambda_{UV}\exp\left[\frac{-24\pi^2}{e_\phi^2(\langle|\phi|\rangle)}\right] \ll \Lambda_{UV}$$

Englert, Jaeckel,Khoze, Spannowsky

$\langle\phi\rangle > \mathrm{v};\ \lambda_H \uparrow$

Bonus: Vacuum stability $\quad \Delta\beta_{\lambda_{\rm H}} \sim +\lambda_{\rm P}^2$ + threshold corrections

LHC phenomenology: 2 Higgs:

$$H^T(x) = \frac{1}{\sqrt{2}}(0, v + h(x)) \qquad \phi = \langle\phi\rangle + \varphi$$

$$m^2 = \begin{pmatrix} m_h^2 + \Delta m_{h,\mathrm{SM}}^2 & -\kappa\, m_h^2 \\ -\kappa\, m_h^2 & m_\varphi^2 + \kappa^2 m_h^2 \end{pmatrix}$$

$$\kappa = \sqrt{\frac{2\lambda_\mathrm{P}}{\lambda_H}} \qquad m_h^2 = \lambda_\mathrm{H} v^2, \qquad m_\varphi^2 = \frac{3e_\phi^4}{8\pi^2}\langle\phi\rangle^2 = \frac{3e_\phi^2}{8\pi^2} m_X^2$$

One-loop corrections to Higgs masss

$$\Delta m_{h,\mathrm{SM}}^2 = \frac{1}{16\pi^2}\frac{1}{v^2}\left(6m_W^4 + 3m_Z^4 + m_h^2 - 24m_t^4\right) \approx -2200\,\mathrm{GeV}^2$$

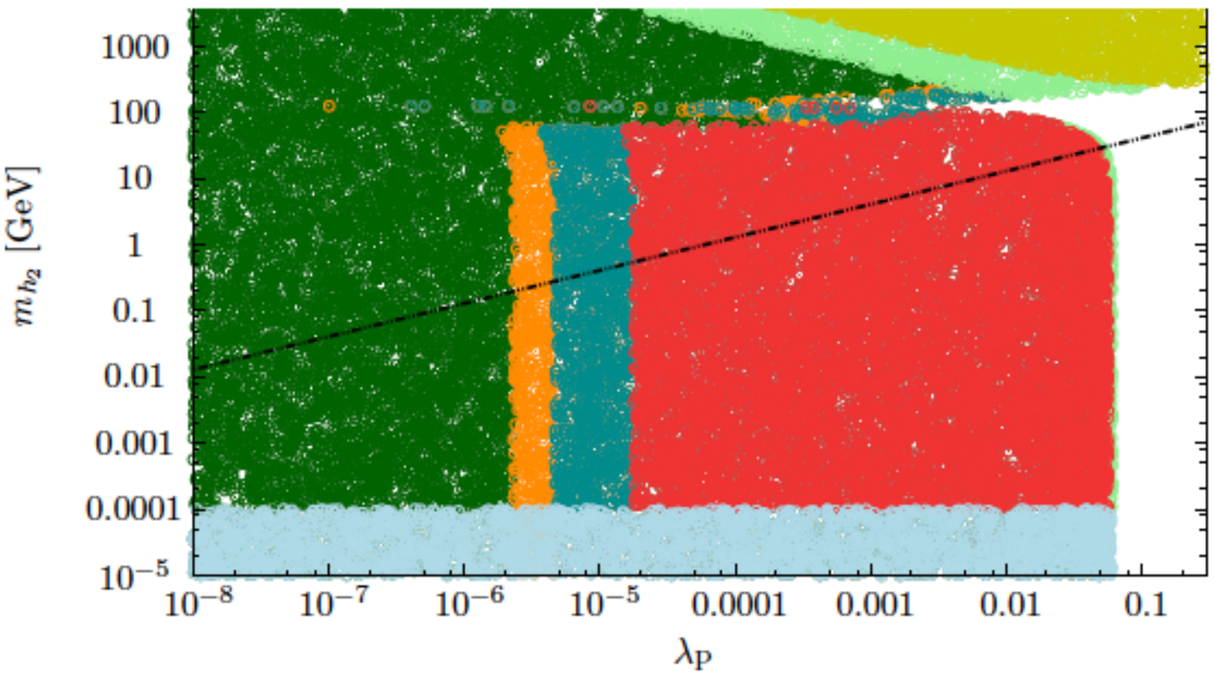
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} h \\ \varphi \end{pmatrix} \qquad \vartheta = O\left(\kappa \frac{m_h^2}{m_\varphi^2}\right) \ll 1$$

$$m_{h_1}^2 = (m_h^2 + \Delta m_{h,\mathrm{SM}}^2)(1 + \mathcal{O}(\vartheta^2)), \qquad m_{h_2}^2 = m_\varphi^2(1 + \mathcal{O}(\vartheta^2))$$

$$e.g. \quad m_{h_2} \ll m_{h_1} \qquad \Gamma_{h_1 \to h_2 h_2} = \frac{4\lambda_P^2 v^2}{16\pi} \frac{[m_{h_1}^2 - 4m_{h_2}^2]^{1/2}}{m_{h_1}^2}$$

$$\Gamma_{h_2 \to X X^c} = \sin^2\vartheta \, \Gamma^{SM}_{h \to X X^c}(m_h = m_{h_2}) \,,$$
$$\sigma(XY \to h_2) = \sin^2\vartheta \, \sigma^{SM}_{XY \to h}(m_h = m_{h_2}) \,.$$

extremely narrow resonance



LHC excluded

LHC high luminosity

+Linear Collider

Stellar evolution excluded

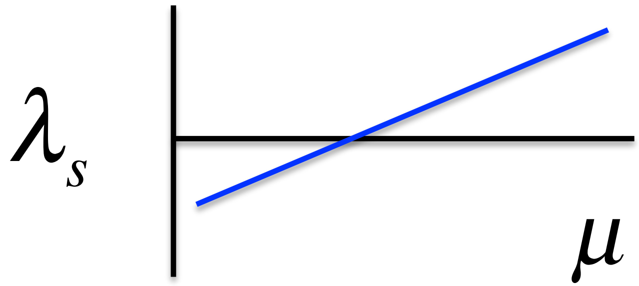
Another example:

$$\mathrm{U}(1)_Y \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_X$$

Hambye, Strumia

$$V = \lambda_H |H|^4 - \lambda_{HS}|HS|^2 + \lambda_S|S|^4$$

$$\beta_{\lambda_S} \equiv \frac{d\lambda_S}{d\ln\mu} = \frac{1}{(4\pi)^2}\left[\frac{9g_X^4}{8} - 9g_X^2\lambda_S + 2\lambda_{HS}^2 + 24\lambda_S^2\right]$$



$$\langle H \rangle \approx \langle S \rangle \sqrt{\frac{\lambda_{HS}}{2\lambda_H}}$$

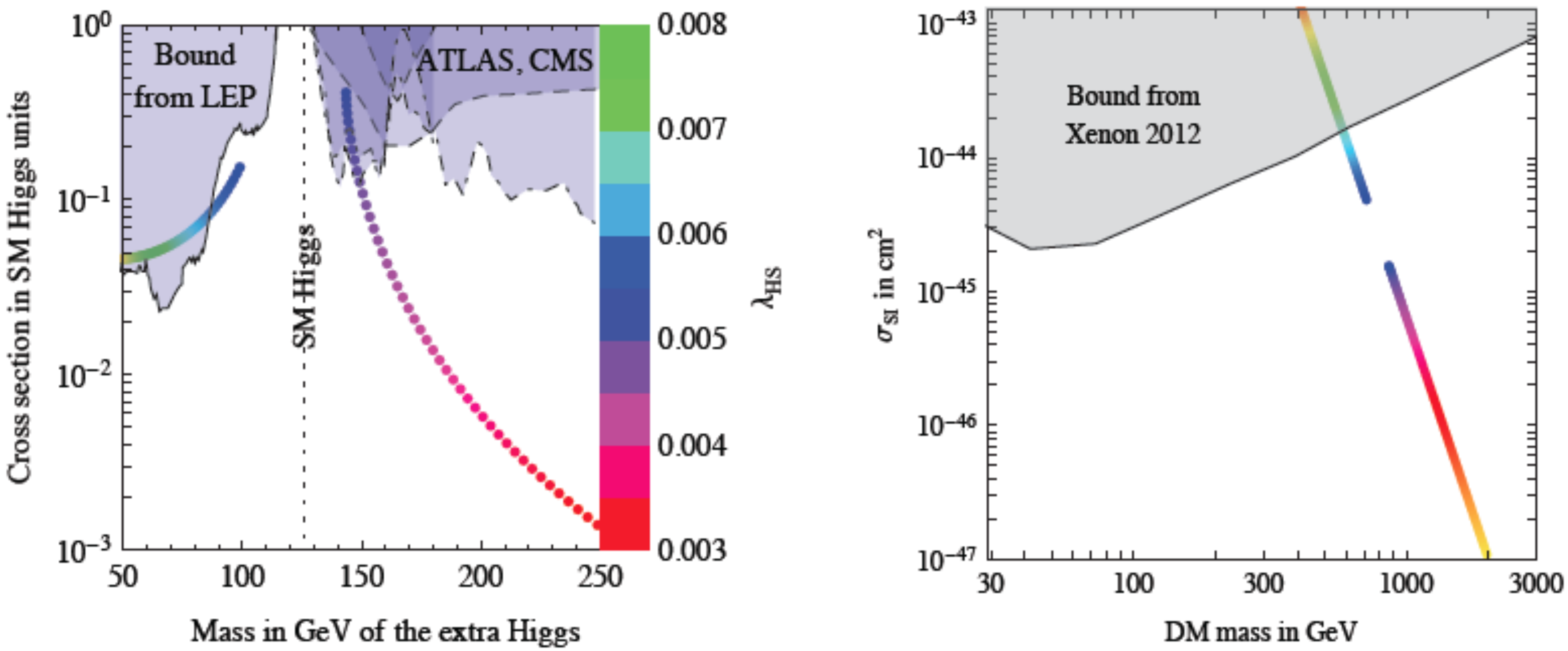


Figure 1: *Predicted cross sections for the extra scalar boson (left) and for DM direct detection (right) as function of the only free parameter of the model λ_{HS}, varied as shown in the colour legend.*

Natural light higgs - no hierarchy of scales possible???

- Baryon asymmetry $M_X \sim M_{GUT}$?? Baryo- Lepto- genesis,

Baryon asymmetry

$M_\nu \sim 10 GeV$

- In the νMSM, baryogenesis proceeds via leptogenesis; sterile neutrino oscillations produce a lepton asymmetry above T_{EW} that is converted into a baryon asymmetry by sphalerons
- More specifically,
  - N_I are produced by Yukawa interactions in a CP-invariant state ($\Delta N_I = 0$)
  - N_I then oscillate and second-order Yukawa interactions produce asymmetries in each flavour L_α but no total asymmetry ($\Delta L = \sum_\alpha \Delta L_\alpha = 0$)
  - Third-order Yukawa interactions then convert the flavour asymmetries in L_α into a total asymmetry $\Delta N \neq 0$ and hence a total asymmetry $\Delta L = -\Delta N$
  - Sphalerons convert the asymmetry ΔL into a baryon asymmetry ΔB until sphalerons freeze-out at T_{EW}

Natural light higgs - no hierarchy of scales possible???

- Baryon asymmetry

- Inflation and dark matter

Z_2

S dark matter

e.g. $$V_{\rm cl}(H,\phi,s) = \frac{\lambda_{hs}}{2}|H|^2 s^2 + \frac{\lambda_{\phi s}}{4}|\phi|^2 s^2 + \frac{\lambda_s}{4} s^4 + V_{\rm cl}(H,\phi)$$

Khoze

$$\mathcal{L}_J = \sqrt{-g_J}\Big(-\frac{M^2}{2} - \frac{\xi_s}{2}s^2 R + \frac{1}{2}g_J^{\mu\nu}\,\partial_\mu s\,\partial_\nu s + g_J^{\mu\nu}(D_\mu H)^\dagger D_\nu H + \frac{1}{2}g_J^{\mu\nu}(D_\mu\phi)^\dagger D_\nu\phi$$
$$-\frac{\lambda_s}{4}s^4 - \frac{\lambda_{hs}}{2}|H|^2 s^2 - \frac{\lambda_{\phi s}}{4}|\phi|^2 s^2 - V(H,\phi) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \text{Fermions} + \text{Yukawas}\Big)\,.$$

Non-minimally coupled to gravity – S inflaton

c.f. Higgs inflaton

Higgs inflation

$$L_{\rm tot} = L_{\rm SM} - \frac{M^2}{2} R - \xi H^\dagger H R$$

$$S_J = \int d^4x \sqrt{-g} \left\{ - \frac{M^2 + \xi h^2}{2} R + \frac{\partial_\mu h \partial^\mu h}{2} - \frac{\lambda}{4} \left(h^2 - v^2\right)^2 \right\}$$

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \ , \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

+ redefine scalar:
$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2 / M_P^2}{\Omega^4}}$$

$$S_E = \int d^4x \sqrt{-\hat{g}} \left\{ - \frac{M_P^2}{2} \hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - U(\chi) \right\}$$

$$U(\chi) = \frac{1}{\Omega(\chi)^4} \frac{\lambda}{4} \left(h(\chi)^2 - v^2\right)^2$$

Higgs inflation

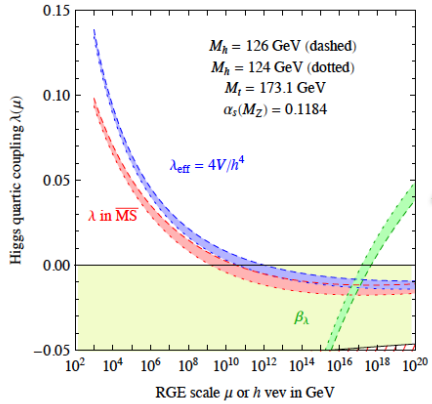
Flattens potential above $M_{Planck}/\sqrt{\xi}$

(i) $\xi|H|^2 R \quad \xi \approx 5 \times 10^4 \sqrt{\lambda}.$

Bezrukov, Shaposhnikov

$\lambda(M_P) \geq 0 \quad (2\sigma \text{ off})$

Perturbative unitarity?



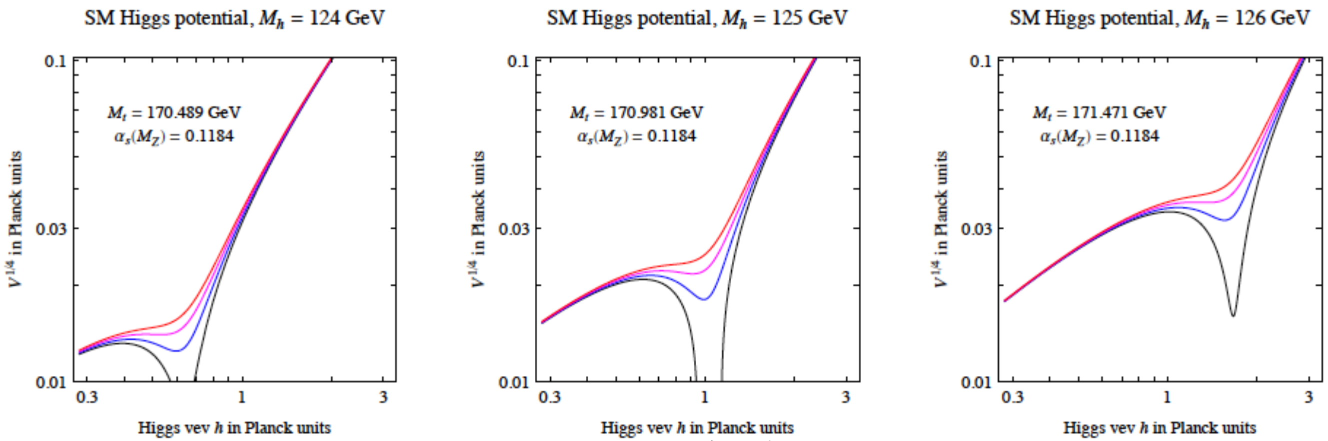
$$\beta_\lambda = \frac{d}{d\ln\mu}\lambda(\mu)$$

(ii) "Conventional"

$$V = \Delta^4 + m^2|H|^2 + \ldots, \quad m \ll H = \Delta^2 / M_P$$

$$\frac{dV}{dh} = \left(\lambda_{\rm eff} + \frac{\beta_{\rm eff}}{4}\right) h^3$$

Isidori et al



Higgs vev in Planck units

Classical scale invariance?

$\Rightarrow$ Softly broken scale invariance
….scale invariance restored in UV

Classical scale invariance?

$\Longrightarrow$ Softly broken scale invariance
….scale invariance restored in UV

But…

Beta functions must change at some scale Λ
to approach UV CFT fixed point

$\Lambda \sim TeV$ to avoid hierarchy problem ✗

Tavares, Schmaltz, Skiba
Czaki, Skiba, Terning

Part 2: Intermediate scale models

e.g. Unified models

Supersymmetric models

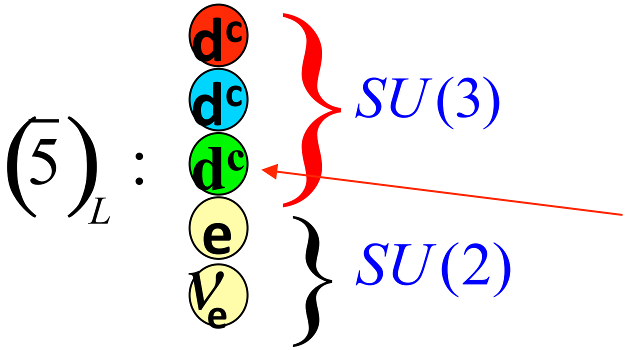
Composite models

Unification:

e.g. $SO(10) \supset SU(5) \supset SU(3) \otimes SU(2) \otimes U(1)$

$g_5 \quad g_3 \quad g_2 \quad g_1$

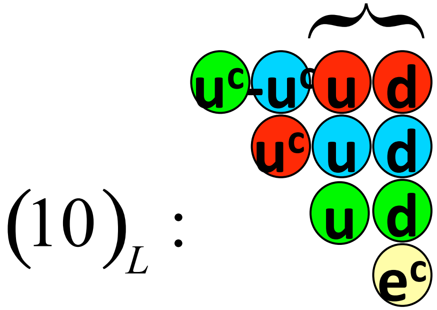
Georgi Glashow 1974



$3Q_? + Q_{e^-} = 0$

$Q_{d^c} = 1/3$

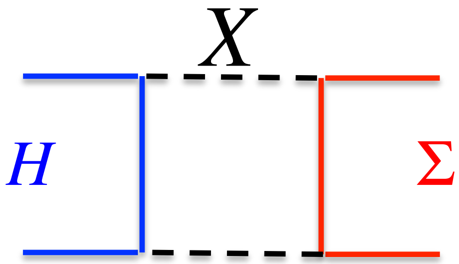
LH states SU(2) doublets



$$(16)_L = (10)_L + (\bar{5})_L + (1)_L$$

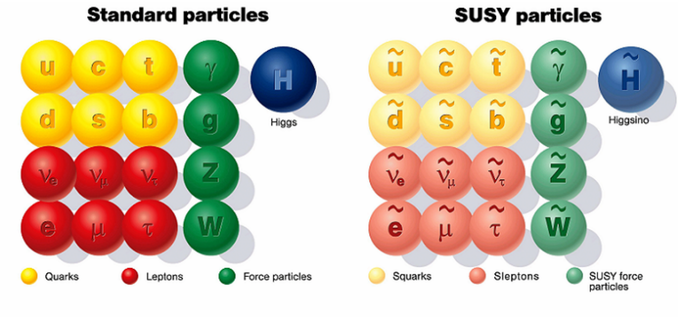
$\nu_{e,L}{}^c \equiv \nu_{e,R}$

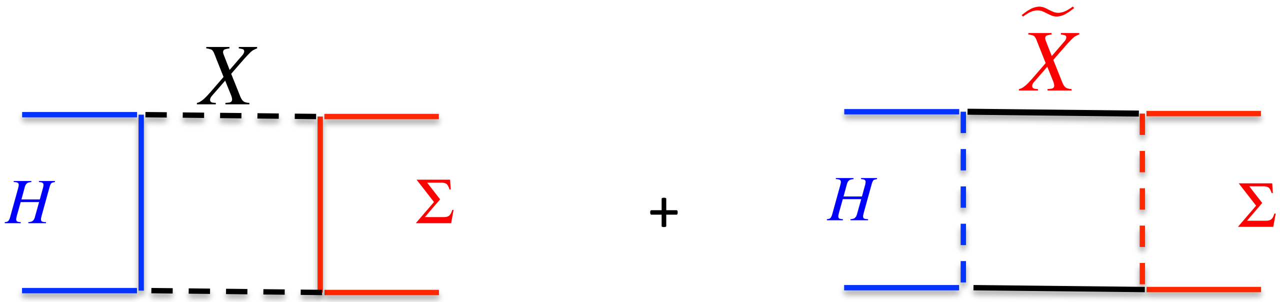
The hierarchy problem:



$$M_H \propto M_X$$ ✗

- The solution - Low scale SUSY $M_{SUSY} \sim TeV$





$$M_H \propto M_{SUSY}$$ ✔

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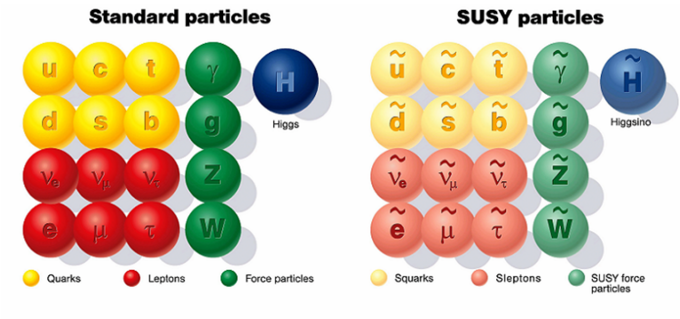
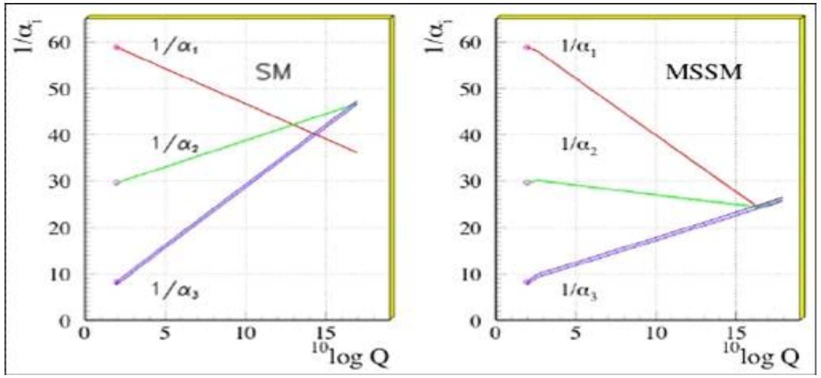


Unification:



✔

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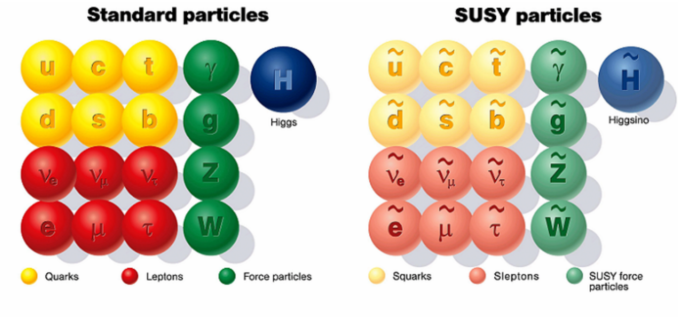
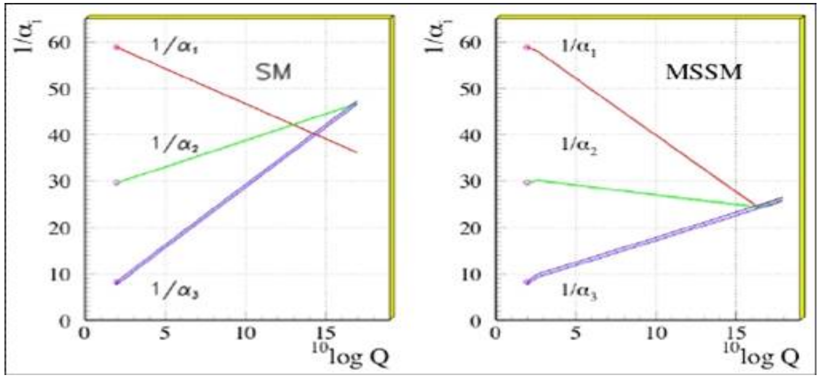


Unification:



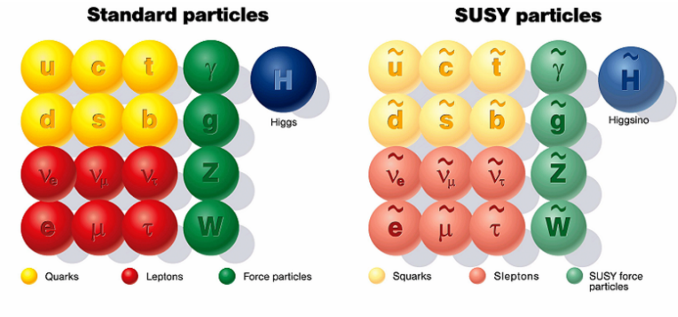
✔

The (SUSY) Standard Model as an EFT:

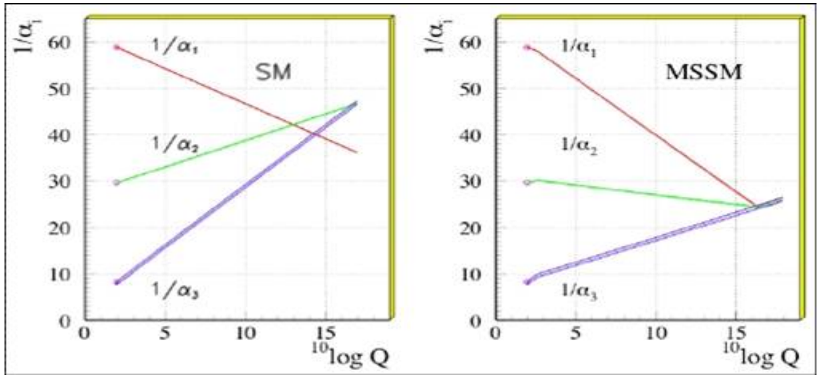
A_μ ✔, Ψ ✔ H ✔ ?

$M_{Higgs}, M_{W,Z} \ll M_{Planck}, M_{GUT}, ..$ ✔

- The solution - Low scale SUSY $M_{SUSY} \sim TeV$



Unification:



✔

The (SUSY) Standard Model as an EFT:

A_μ ✔, Ψ ✔ H ✔ ?

$M_{Higgs}, M_{W,Z} \ll M_{Planck}, M_{GUT}, ..$ ✔

$$\delta m_{H_u}^2 \simeq -\frac{3y_t^2}{4\pi^2}\left(m_{stop}^2 + \frac{g_s^2}{3\pi^2} m_{gluino}^2 \log\left(\frac{\Lambda}{m_{gluino}}\right)\right)\log\left(\frac{\Lambda}{m_{stop}}\right)$$

? Little hierarchy problem

Little hierarchy problem $\Rightarrow$ definite SUSY ^breaking structure

MSSM:

105 +(19) Parameters

$$M_Z^2 = \sum_{\tilde{q},\tilde{l}} a_i \widetilde{m}_i^2 + \sum_{\tilde{g},\widetilde{W},\widetilde{B}} b_i \widetilde{M}_i^2 + \ldots$$

$$m_{\tilde{q}} > 0.6 - 1 TeV \quad \Rightarrow \quad \Delta > a \frac{\widetilde{m}^2}{M_Z^2} \sim 100$$

(Unless light stop $m_{\tilde{t},LHC} > 250\ GeV$)

$\Rightarrow$ Correlations between SUSY breaking parameters and/or additional low-scale states

Little hierarchy problem $\Rightarrow$ definite SUSY ^breaking structure

MSSM: 105 +(19) Parameters

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(Unless light stop $m_{\tilde{t},LHC} > 250\ GeV$)

$\Rightarrow$ Correlations between SUSY breaking parameters and/or additional low-scale states

Fine Tuning measure:

$$\Delta(a_i) = \left| \frac{a_i}{M_Z} \frac{\partial M_Z}{\partial a_i} \right|,$$

$$\Delta_m = Max_{a_i} \Delta(a_i), \quad \Delta_q = \left(\sum \Delta_{\gamma_i}^2\right)^{1/2}$$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine tuning from a likelihood fit:

"Nuisance" variable

$$L\left(\text{data} \mid \gamma_i\right) \propto \int d\mathrm{v}\,\delta\left(m_Z - m_Z^0\right)\delta\left(\mathrm{v}-\left(-\frac{m^2}{\lambda}\right)^{1/2}\right)L\left(\text{data} \mid \gamma_i;\mathrm{v}\right)$$

$$= \frac{1}{\Delta_q}\delta\left(n_q(\ln\gamma_i - \ln\gamma_i^S)\right)L\left(\text{data} \mid \gamma_i;\mathrm{v}_0\right)$$

Fine tuning not optional!

Ghilencea, GGR
Casas et al

Probabilistic interpretation:

$$\chi^2_{new} = \chi^2_{old} + 2\ln\Delta_q$$

$$\Delta_q \ll 100$$

- The CMSSM

$$\gamma_i = \mu_0, m_0, m_{1/2}, A_0, B_0$$

assume correlation between SUSY breaking parameters

- # The CMSSM

$$\mu_0, m_0, m_{1/2}, A_0, B_0$$

$$\begin{aligned} V &= m_1^2\,|H_1|^2 + m_2^2\,|H_2|^2 - (m_3^2\,H_1\cdot H_2 + h.c.) \\ &+ \frac{1}{2}\lambda_1\,|H_1|^4 + \frac{1}{2}\lambda_2\,|H_2|^4 + \lambda_3\,|H_1|^2\,|H_2|^2 + \lambda_4\,|H_1\cdot H_2|^2 \\ &+ \left[\frac{1}{2}\lambda_5\,(H_1\cdot H_2)^2 + \lambda_6\,|H_1|^2\,(H_1\cdot H_2) + \lambda_7\,|H_2|^2\,(H_1\cdot H_2) + h.c.\right] \end{aligned}$$

Minimisation conditions:

$$v^2 = -m^2/\lambda, \qquad 2\lambda\frac{\partial m^2}{\partial\beta} = m^2\frac{\partial\lambda}{\partial\beta}$$

$$\begin{aligned} m^2 &= m_1^2\cos^2\beta + m_2^2\sin^2\beta - m_3^2\sin 2\beta \\ \lambda &= \frac{\lambda_1}{2}\cos^4\beta + \frac{\lambda_2}{2}\sin^4\beta + \frac{\lambda_{345}}{4}\sin^2 2\beta + \sin 2\beta\,(\lambda_6\cos^2\beta + \lambda_7\sin^2\beta) \end{aligned}$$

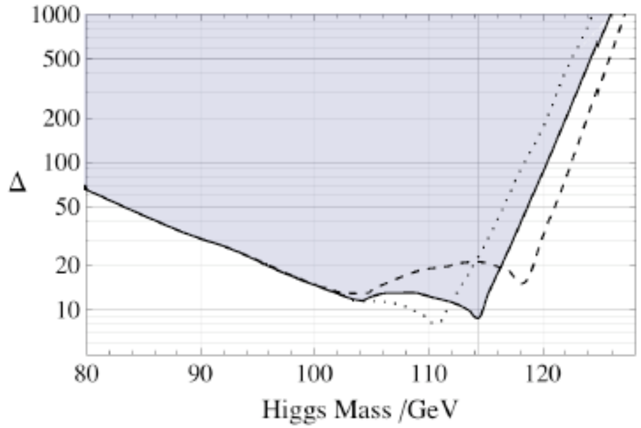
$$\Delta \equiv \max\left|\Delta_p\right|_{p=\{\mu_0^2, m_0^2, m_{1/2}^2, A_0^2, B_0^2\}}, \qquad \Delta_p \equiv \frac{\partial\ln v^2}{\partial\ln p}$$

Couplings and masses evaluated to two loop (leading log) order

…enhanced sensitivity due to small tree-level $\lambda = \frac{1}{8}\left(g_1^2 + g_2^2\right)\cos^2 2\beta$

Cassel, Ghilencea, GGR
c.f. earlier work : Dimopoulos, Giudice
Chankowski, Ellis, Olechowski, Pokorski

The CMSSM - before LHC



Constraints

SUSY particle masses

$3.20 < 10^4 \, \mathrm{Br}(b \to s\gamma) < 3.84$

$\mathrm{Br}(b \to \mu\mu) < 1.8 \times 10^{-8}$

$\delta a_\mu < 292 \times 10^{-11}$

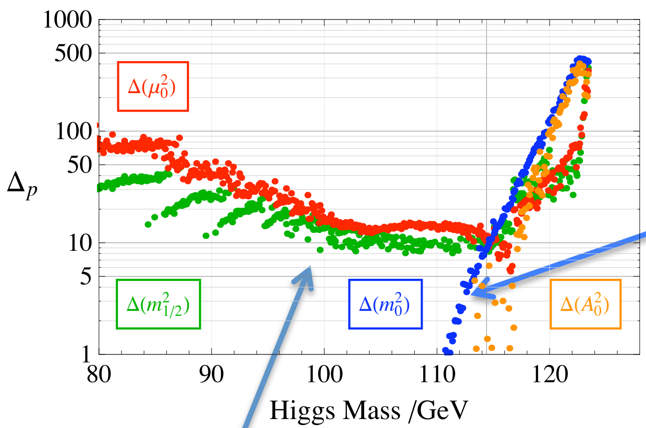
$-0.0007 < \delta\rho < 0.0012$

Radiative EW breaking

Relic density unrestricted

Guuge coupling unification

$$\Delta_i, \;\; i = \mu_0, m_0, m_{1/2}, A_0, B_0$$



Limit of focus point

λ increase with m_H

$$v^2 = -\frac{m^2}{\lambda}$$

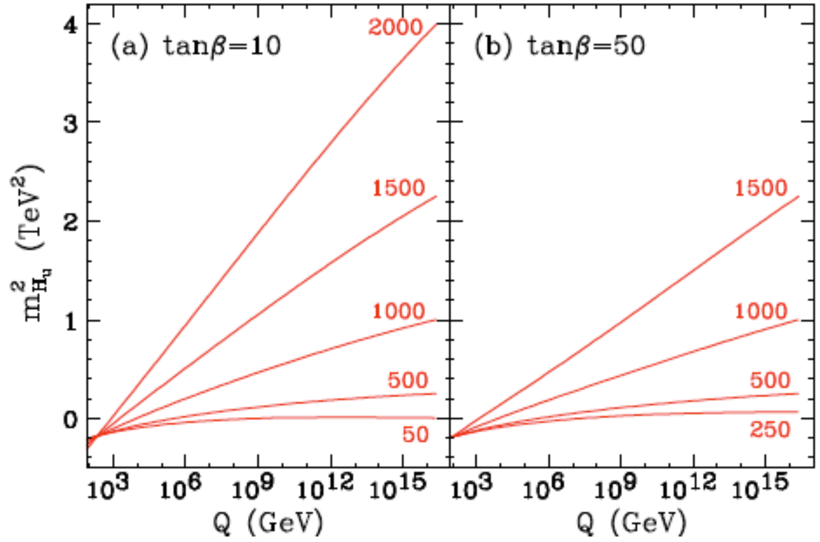
Focus Point

$$2|y_t|^2\,(m^2_{H_u}+m^2_{Q_3}+m^2_{\bar{u}3})+2|a_t|^2$$

$$16\pi^2\frac{d}{dt}m^2_{H_u}=3X_t-6g_2^2|M_2|^2-\frac{6}{5}g_1^2|M_1|^2$$

$$16\pi^2\frac{d}{dt}m^2_{Q_3}=X_t+X_b-\frac{32}{3}g_3^2|M_3|^2-6g_2^2|M_2|^2-\frac{2}{15}g_1^2|M_1|^2$$

$$16\pi^2\frac{d}{dt}m^2_{\bar{u}3}=2X_t-\frac{32}{3}g_3^2|M_3|^2-\frac{32}{15}g_1^2|M_1|^2$$



$$m^2_{H_u}(Q^2)=m^2_{H_u}(M_P^2)+\frac{1}{2}\left(m^2_{H_u}(M_P^2)+m^2_{Q_3}(M_P^2)+m^2_{\bar{u}3}(M_P^2)\right)\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}}-1\right]$$

m_0^2 $\quad$ $3m_0^2$ $\quad$ $\simeq -\frac{2}{3},\; Q^2\simeq M_Z^2$

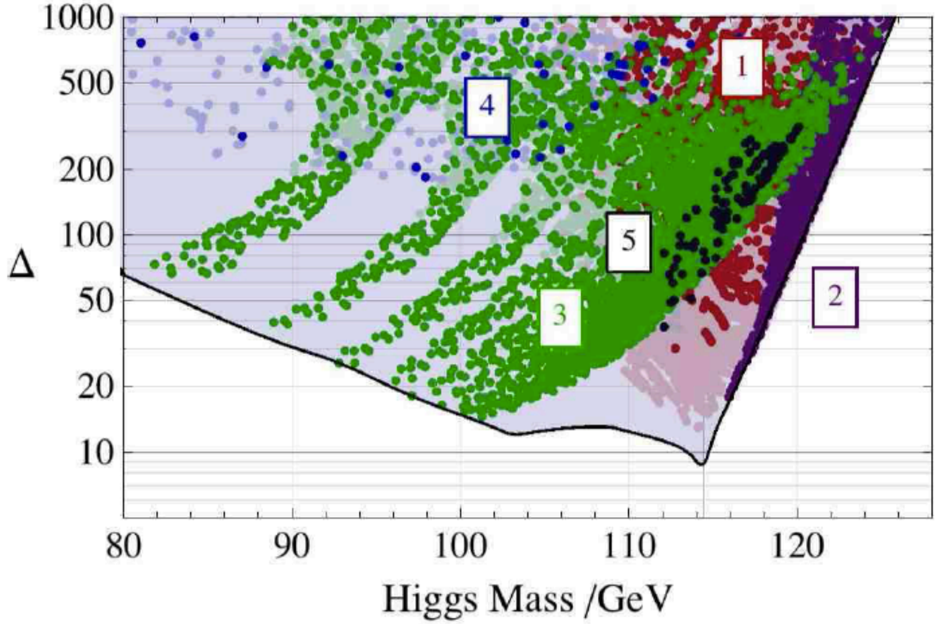
"Focus point": $m^2_{H_u}(0)=m^2_{Q_3}(0)=m^2_{\bar{u}3}(0)\equiv m^2$

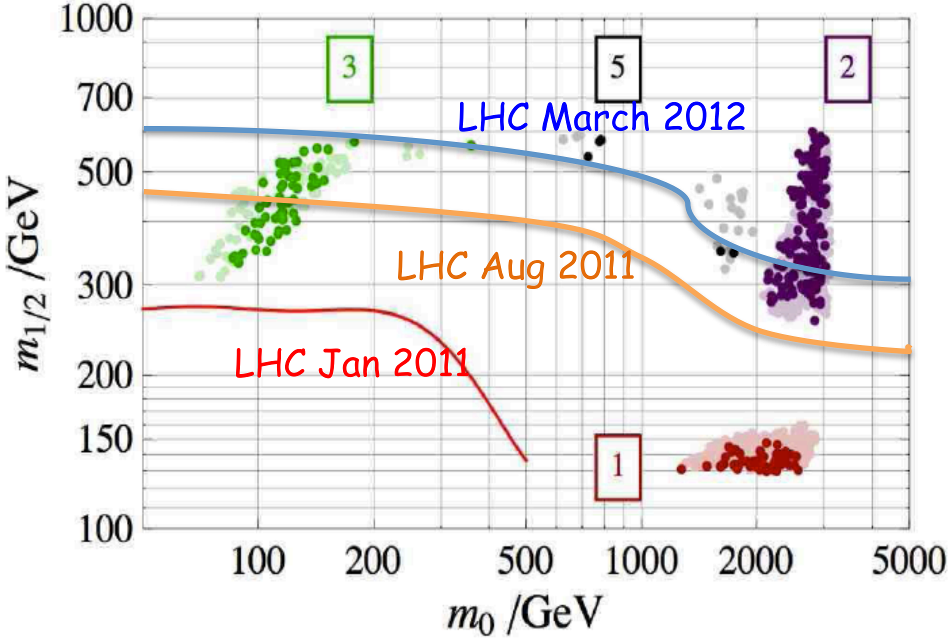
$$m^2_{H_u}(t_0)=a_0\,m^2+..,\; a_0\le 0.1$$

Natural choice

$i.e.\, m^3_{Q_3}, m^2_{\bar{u}3}\gg M_Z^2$ possible

Feng, Matchev, Moroi
Chan, Chattopadhay, Nath
Barbieri, Giudice
Feng, Sanford





Relic density restricted

1 h^0 resonant annihilation

2 $\tilde{h}$ t-channel exchange

3 $\tilde{\tau}$ co-annihilation

4 $\tilde{t}$ co-annihilation

• 5 A^0 / H^0 resonant annihilation

Within 3σ WMAP:

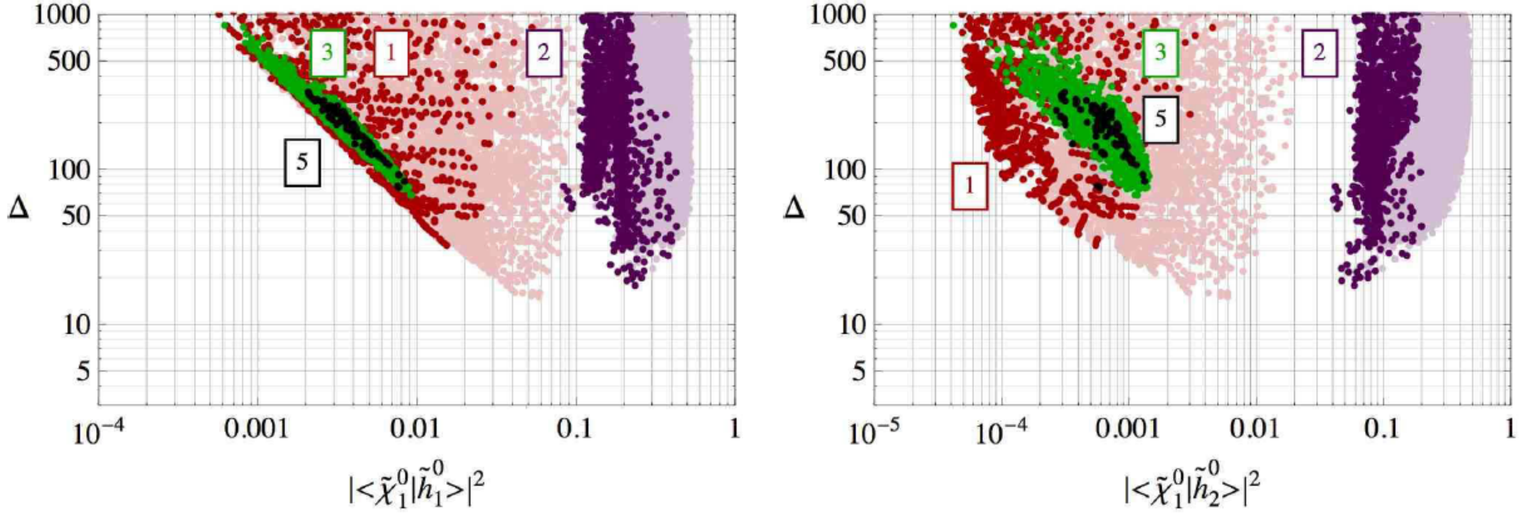
$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2 GeV$

< 3σ WMAP:

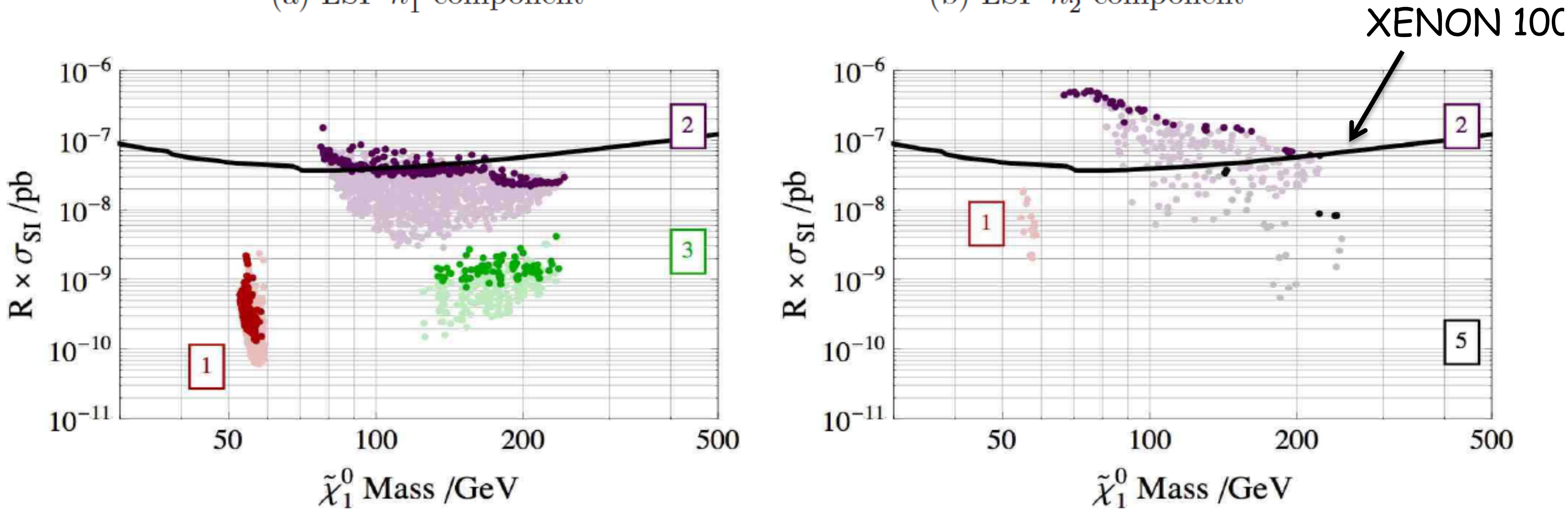
$\Delta_{Min} = 18, \quad m_h = 115.9 \pm 2 GeV$

Cassel, Ghilencea, GGR

DM - Scaled spin independent cross section for LSP-proton scattering:



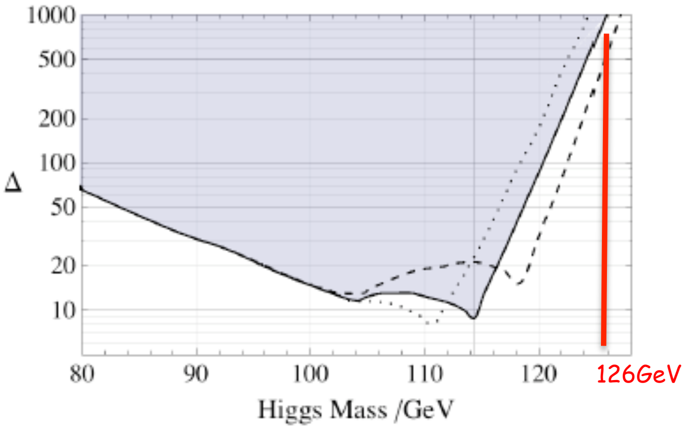
(a) LSP $\tilde{h}_1^0$ component (b) LSP $\tilde{h}_2^0$ component



(a) $\tan\beta \leq 45$ (b) $50 \leq \tan\beta \leq 55$

$\Delta < 100$ $\Delta < 100$

- The CMSSM - after Higgs discovery



$M_S^2 = m_{q_3} m_{U_3}$

$$M_{h^0}^2 = M_Z^2 \cos^2 2\beta + \frac{3M_t^2 h_t^2}{4\pi^2}\left(\ln(\frac{M_S^2}{M_t^2}) + \delta_t\right) + \cdots \qquad \simeq 126GeV$$

$$\Delta_{Min} > 350\,, \quad m_h = 125.6 \pm 3GeV$$

Reduced fine tuning (c.f. CMSSM)

- New focus points?

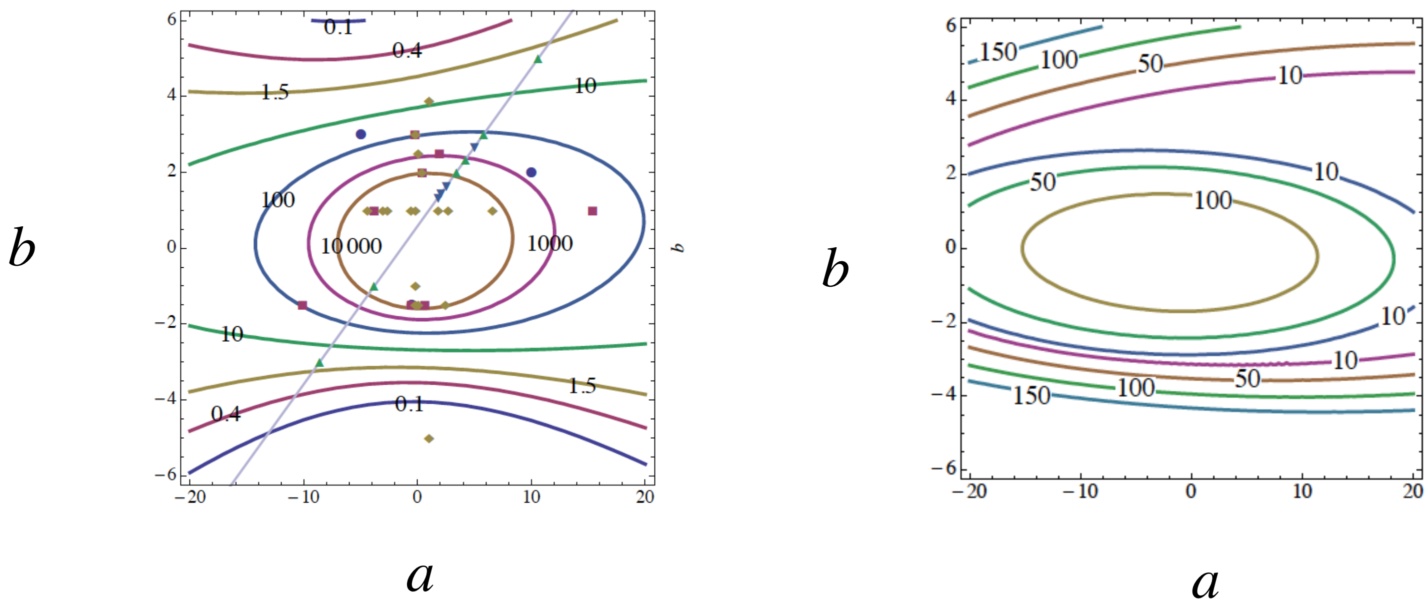
Gauginos: $M_{\tilde{g},\widetilde{W},\widetilde{B}}$ Non-universal gaugino correlations

- New degrees of freedom

I. Reduced fine tuning : nonuniversal gaugino masses

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2\,|y_t|^2\,(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2\,|a_t|^2\right) - 6g_2^2\,|M_2|^2 - \frac{6}{5} g_1^2\,|M_1|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}



$$M_3 : M_2 : M_1 = 1 : b : a$$

I. Reduced fine tuning : nonuniversal gaugino masses

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2\,|y_t|^2\,(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2\,|a_t|^2\right) - 6g_2^2\,|M_2|^2 - \frac{6}{5} g_1^2\,|M_1|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}

Natural ratios? e.g.:

GUT: $SU(5):\quad \Phi^N \subset (24\times 24)_{symm} = 1 + 24 + 75 + 200;\quad SO(10):\quad (45\times 45)_{symm} = 1 + 54 + 210 + 770$

$1:b:a$ $\qquad$ $2.7:b:0.5a$

Representation	$M_3 : M_2 : M_1$ at M_{GUT}	$M_3 : M_2 : M_1$ at M_{EWSB}
1	1:1:1	6:2:1
24	2:(-3):(-1)	12:(-6):(-1)
75	1:3:(-5)	6:6:(-5)
200	1:2:10	6:4:10

String: $(3+\delta_{GS}):(-1+\delta_{GS}):\left(-\frac{33}{5}+\delta_{GS}\right)$ (OII, also mixed moduli anomaly)

I. Reduced fine tuning : nonuniversal gaugino masses

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2\,|\,y_t\,|^2\,(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2\,|\,a_t\,|^2\right) - 6g_2^2\,|\,M_2\,|^2 - \frac{6}{5} g_1^2\,|\,M_1\,|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}

$$\Delta_{Min}^{CMSSM} = 60\ (500), \quad m_h = 125.6 \pm 3GeV$$

LHC8 SUSY bounds ✔

DM relic abundance ✔

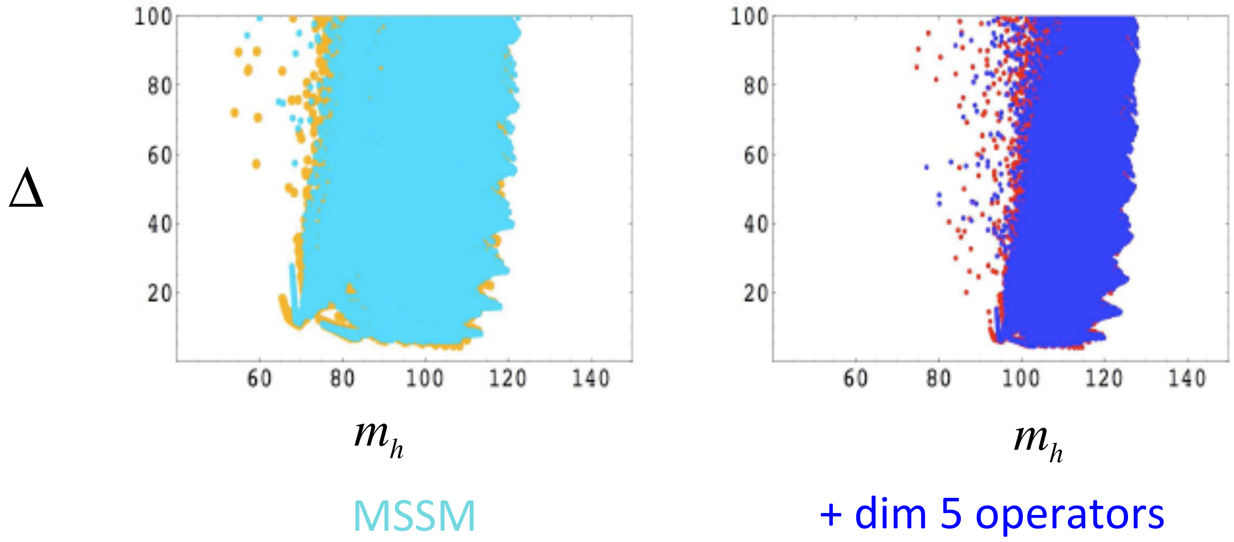
DM searches ✗

II. Reduced fine tuning : New heavy states – higher dimension operators

$$\delta L = \int d^2\theta \frac{1}{M_*}(\mu_0 + c_0 S)(H_u H_d)^2, \quad S = m_0\theta\theta$$

Dimension 5

$$\delta V = \varsigma_1\left(|h_u|^2 + |h_d|^2\right)h_u h_d + \varsigma_2 (h_u h_d)^2; \quad \varsigma_1 = \frac{\mu_0}{M_*}, \ \varsigma_2 = \frac{c_0 m_0}{M_*}$$



Cassel, Ghilencea, GGR
Casas, Espinosa, Hidalgo
Dine, Seiberg, Thomas
Batra, Delgardo, Tait
Kaplan,

Even for $M_*=65\ \mu_0$ a significant shift of m_h for constant Δ

…effect mainly comes from ς_1 term … origin?

II. Reduced fine tuning : New heavy states - higher dimension operators

$$\delta L = \int d^2\theta \frac{1}{M_*}(\mu_0 + c_0 S)(H_u H_d)^2, \quad S = m_0\theta\theta$$

Dimension 5

$$\delta V = \varsigma_1\left(|h_u|^2 + |h_d|^2\right)h_u h_d + \varsigma_2 (h_u h_d)^2; \quad \varsigma_1 = \frac{\mu_0}{M_*}, \ \varsigma_2 = \frac{c_0 m_0}{M_*}$$

Singlet extensions

$$W = W_{\text{Yukawa}} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

NMSSM

$$W = W_{\text{Yukawa}} + (\mu + \lambda S) H_u H_d + \frac{\mu_S}{2} S^2 + \frac{\kappa}{3} S^3 + \xi S$$

GNMSSM

$$\mu_S >> m_{3/2} : \quad W_{eff}^{GNMSSM} = (H_u H_d)^2 / \mu_s + \mu H_u H_d$$

$$\delta V = \frac{\mu}{\mu_S}\left(|H_u|^2 + |H_d|^2\right) H_u H_d$$

✔

II. Reduced fine tuning : New heavy states – higher dimension operators

$$\delta L = \int d^2\theta \frac{1}{M_*}(\mu_0 + c_0 S)(H_u H_d)^2 , \quad S = m_0 \theta\theta$$ Dimension 5

$$\delta V = \varsigma_1 \left(|h_u|^2 + |h_d|^2\right) h_u h_d + \varsigma_2 (h_u h_d)^2 ; \quad \varsigma_1 = \frac{\mu_0}{M_*}, \ \varsigma_2 = \frac{c_0 m_0}{M_*}$$

Singlet extensions

$$W = W_{\text{Yukawa}} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$ NMSSM

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$$\mu_S >> m_{3/2} : \quad W_{eff}^{GNMSSM} = (H_u H_d)^2 / \mu_s + \mu H_u H_d$$

$$\delta V = \frac{\mu}{\mu_S} \left(|H_u|^2 + |H_d|^2\right) H_u H_d$$ ✔

but are μ, μ_s naturally small?

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$

$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + LLH_u H_u \right)$$

R-parity: Z_2

$H_u, H_d \quad +1$

$L, \overline{E}, Q, \overline{D}, \overline{U}, \quad \theta \quad -1$

SUSY states odd

Weinberg, Sakai

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u + \mu_s H_d H_u$$
$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$
$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + L L H_u H_u \right)$$

R-parity: Z_2

Z_N^R R-symmetry

N=4,6,8,12,24

Discrete gauge symmetry
-anomaly free

Ibanez, GGR

N	q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}	q_S
4	1	1	0	0	2
8	1	5	0	4	6

$SU(5), SO(10)$
compatible

R-symmetry ensures singlets light

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u + \mu_s H_d H_u$$

$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + LLH_u H_u \right)$$

R-parity: Z_2

Z_N^R R-symmetry N=4,6,8,12,24

SUSY breaking:

Domain walls safe

$\langle W \rangle, \langle \lambda\lambda \rangle$ R=2, non=perturbative breaking

$Z_{4R} \rightarrow Z_2^R \quad R - parity$

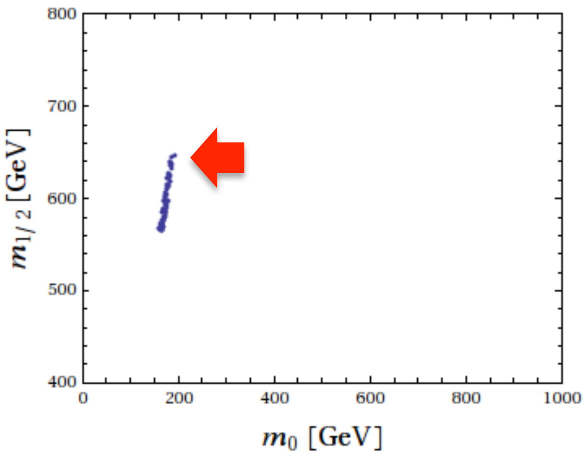
LSP stable

$\mu, \mu_s \sim m_{3/2}, \quad O(\frac{m_{3/2}}{M^2} QQQL)$

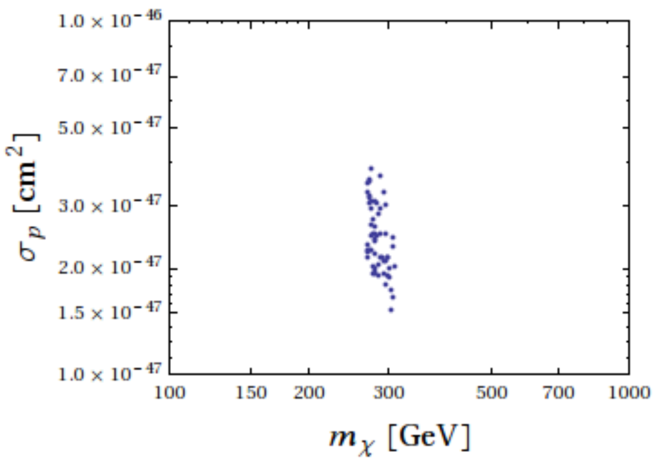
Fine tuning in the CGNMSSM $(\lambda \leq 0.7^{\dagger})$

$$\Delta_{Min} = 60\ (500), \quad m_h = 125.6 \pm 3 GeV$$

LHC8 SUSY bounds ✗
DM relic abundance ✔
DM searches ✔



Stau co-annihilation



DM searches insensitive

GGR, Schmidt-Hoberg , Staub

† c.f. Hall, Pinner, Ruderman

Fine tuning in the (C)GNMSSM $(\lambda \leq 0.7^{\dagger})$

Non-unversal gaugino masses

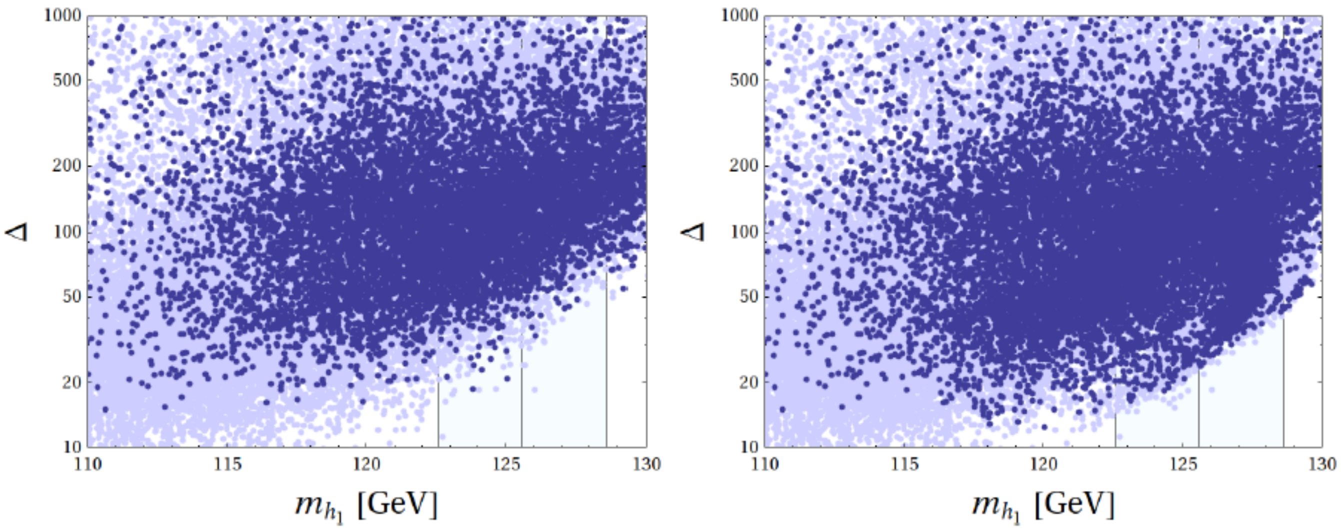
$$\Delta_{Min} = 20, \quad m_h = 125.6 \pm 3 GeV$$

LHC8 SUSY bounds ✔

DM relic abundance ✔

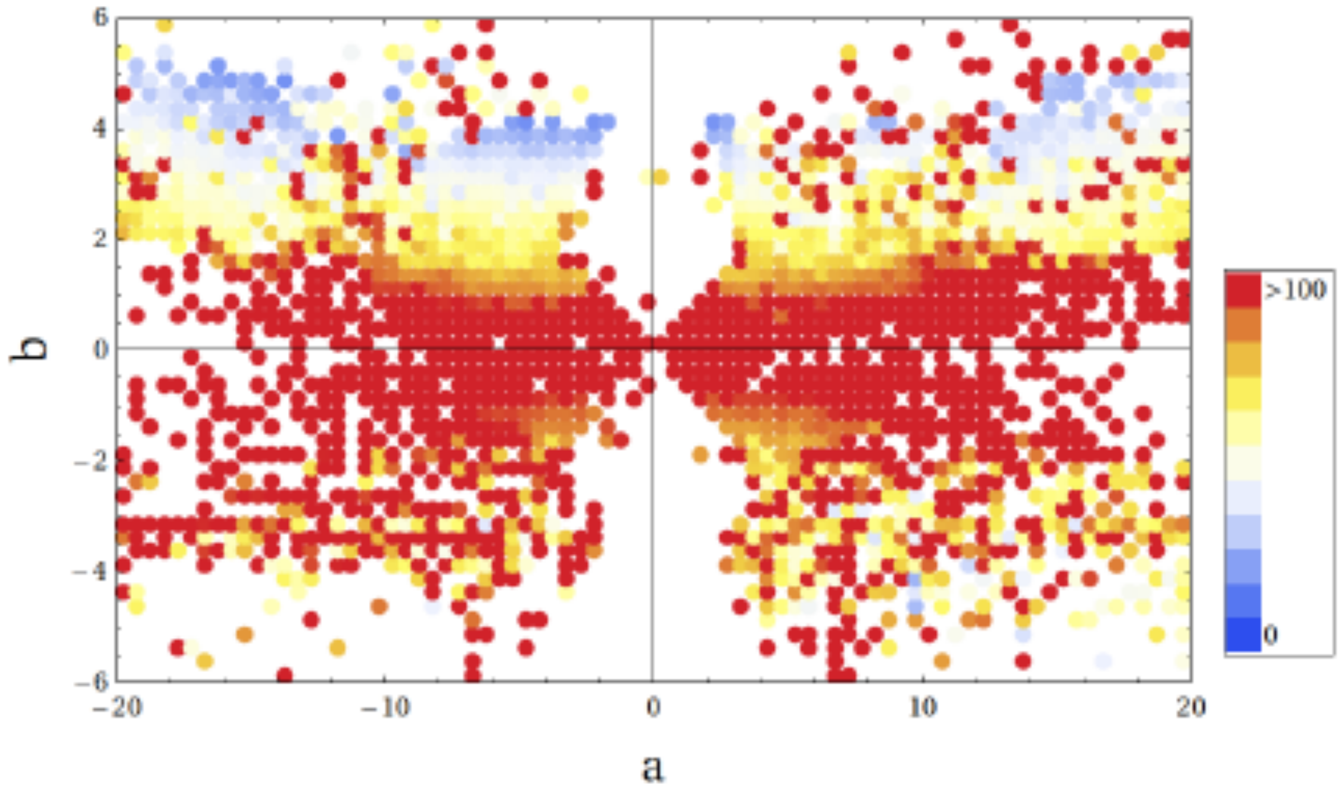
DM searches ✔

Δ



GGR, Kaminska, Schmidt-Hoberg

Fine tuning v/s gaugino mass ratios



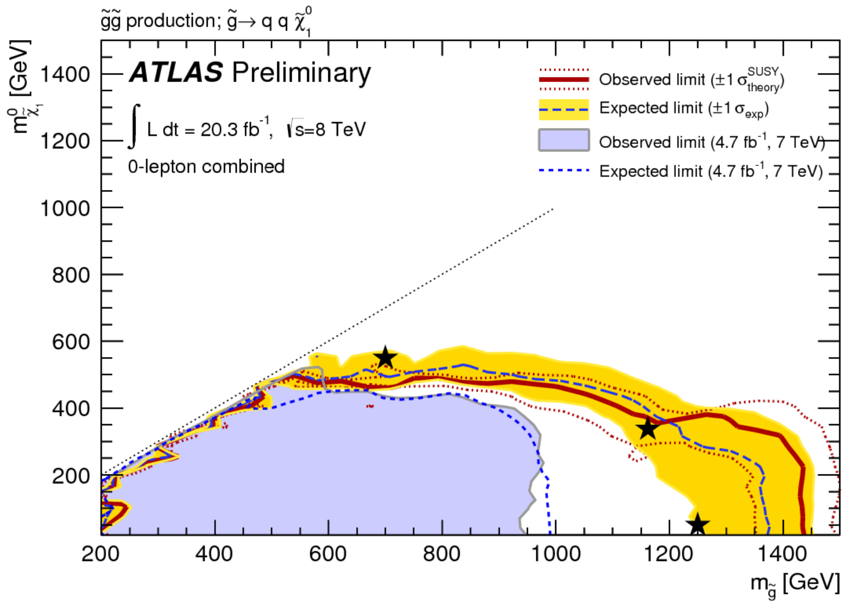
F.T.

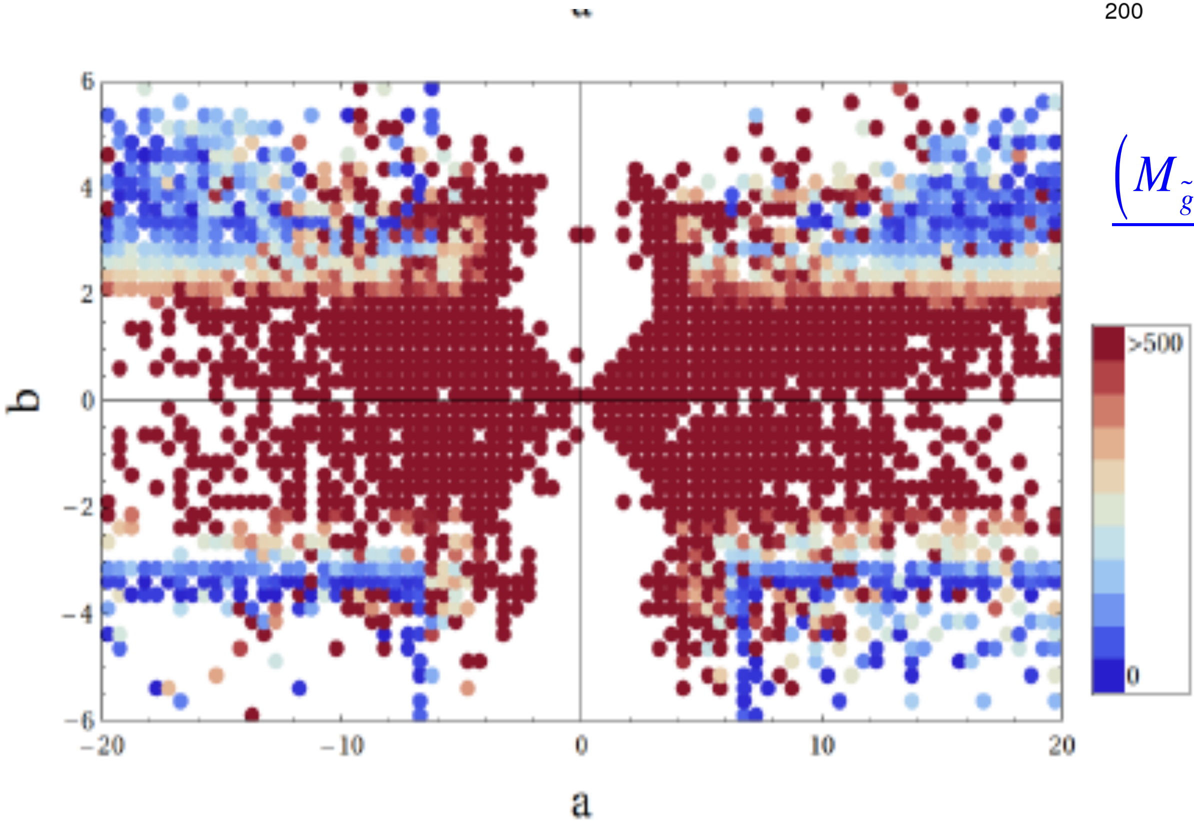
>100

0

$$M_3 = m_{1/2}, M_2 = b.m_{1/2}, M_1 = a.m_{1/2}$$

Compressed spectrum





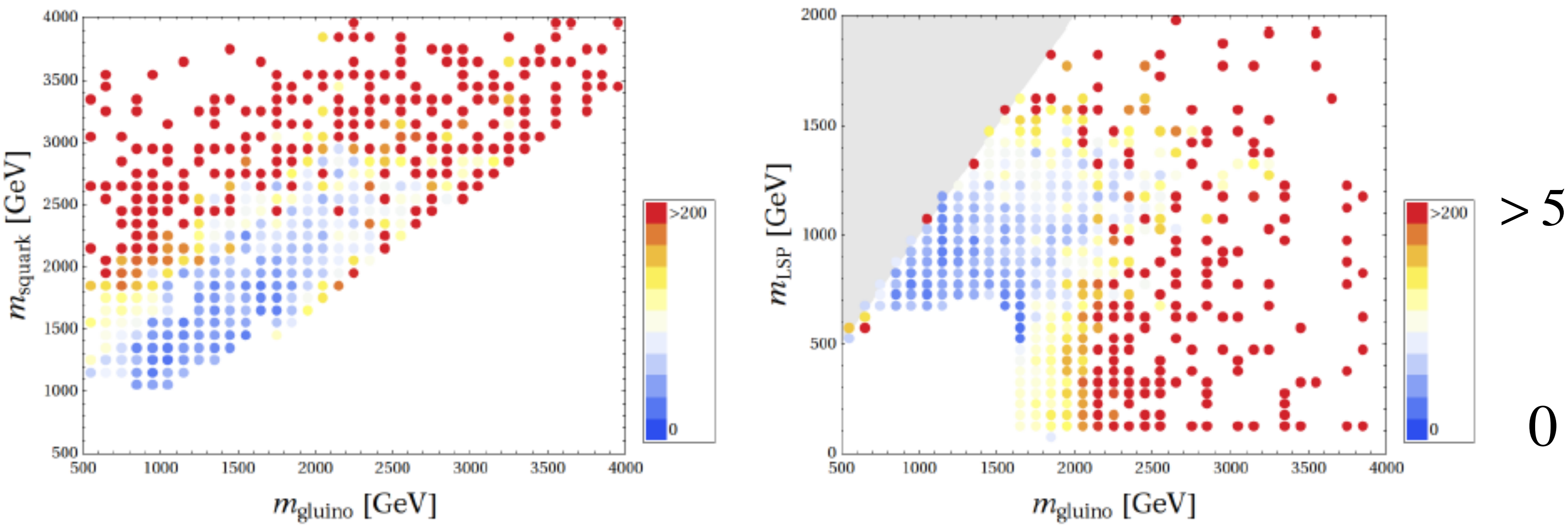
$$\frac{\left(M_{\tilde{g}} - M_{LSP}^{neutralino}\right)}{GeV}$$

> 500

0

Masses v/s fine tuning

m_{squark} m_{LSP}

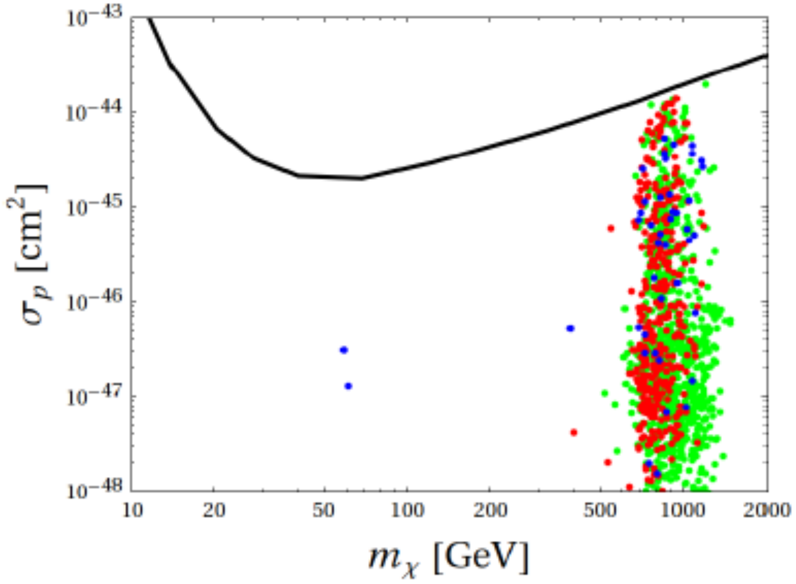


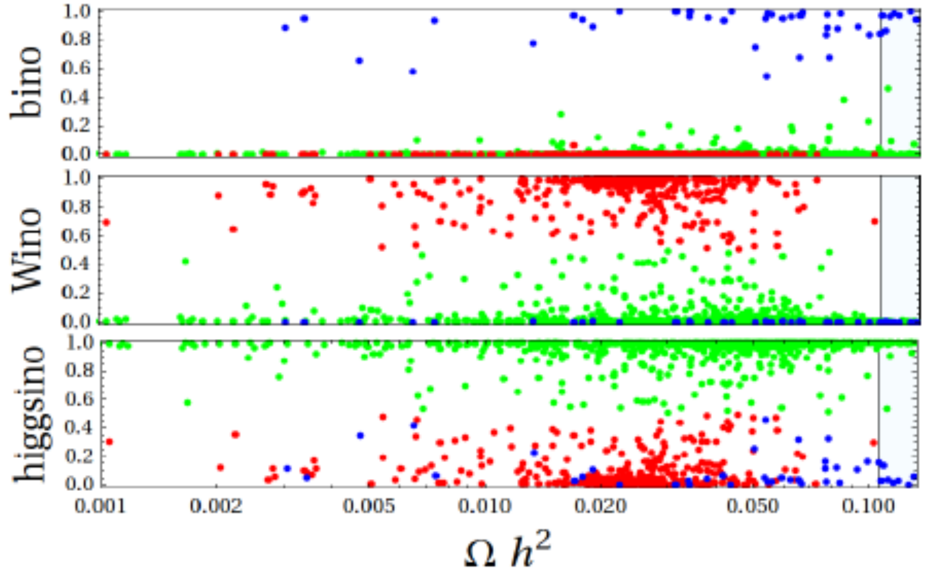
> 500

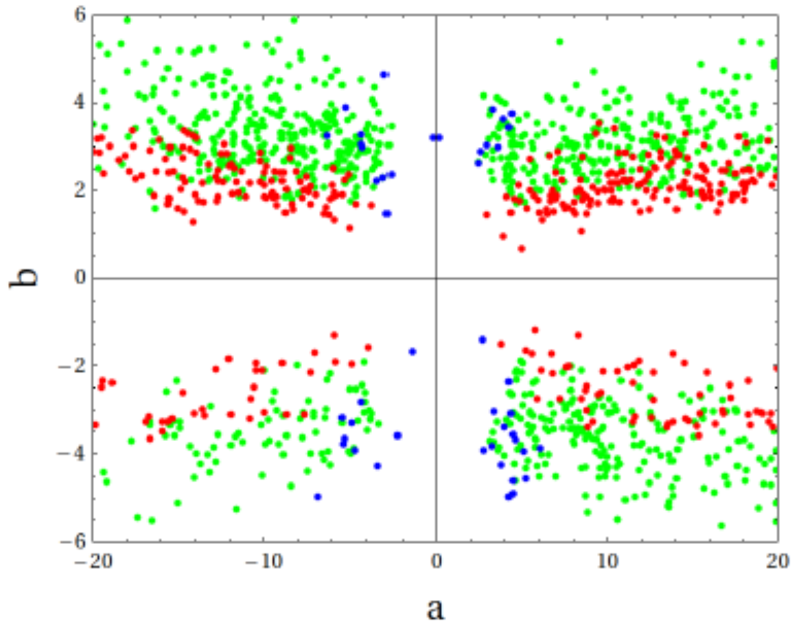
0

M_{gluino}

Dark matter


σ_p [cm^2]
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10
20
50
100
200
500
1000
2000
m_χ [GeV]


bino
Wino
higgsino
1.0
0.8
0.6
0.4
0.2
0.0
0.001
0.002
0.005
0.010
0.020
0.050
0.100
$\Omega\, h^2$


b
6
4
2
0
−2
−4
−6
−20
−10
0
10
20
a

Summary

- GUTs $\Longrightarrow$ SUSY-GUTS (hierarchy problem)
- Low fine tuning not optional
- Fine tuning sensitive to SUSY spectrum

  ...scalar and gaugino focus points

- $\Delta^{CMSSM} > 350$ ✗ $\Delta^{(C)MSSM} > 60$ ✗

  $\Delta^{CGMSSM} > 60$ ✗ $\Delta^{(C)GNMMS} > 20$ ✔

$$c.f.\quad \Delta^{CMSSM}_{Low\ scale} = (10-30), \quad m_{\tilde{t}} = (1-5)TeV$$

Barger et al

Summary

- GUTs $\Longrightarrow$ SUSY-GUTS (hierarchy problem)
- Low fine tuning not optional
- Fine tuning sensitive to SUSY spectrum

  ...scalar and gaugino focus points
- $\Delta^{CMSSM} > 350$ $\Delta^{(C)MSSM} > 60$

  $\Delta^{CGMSSM} > 60$ $\Delta^{(C)GNMMS} > 20$
- Well motivated SUSY models remain to be tested

  LHC14?

  Compressed spectra, TeV squarks and gluinos

Beyond the SM and the LHC

Part III: Dark matter

LHC tests of Dark Matter

For heavy SM-DM mediators interaction described by effective operators

e.g. χ DM Dirac fermion $\Lambda = M / \sqrt{g_\chi g_q}, M \gg q^2$

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}, \qquad \text{(vector, } s\text{-channel)}$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}, \qquad \text{(axial vector, } s\text{-channel)}$$

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R), \qquad \text{(scalar, } t\text{-channel)}$$

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3}. \qquad \text{(scalar, } s\text{-channel)}$$

$P_{R(L)} = (1 \pm \gamma_5)/2$

LHC tests of Dark Matter

For heavy SM-DM mediators interaction described by effective operators

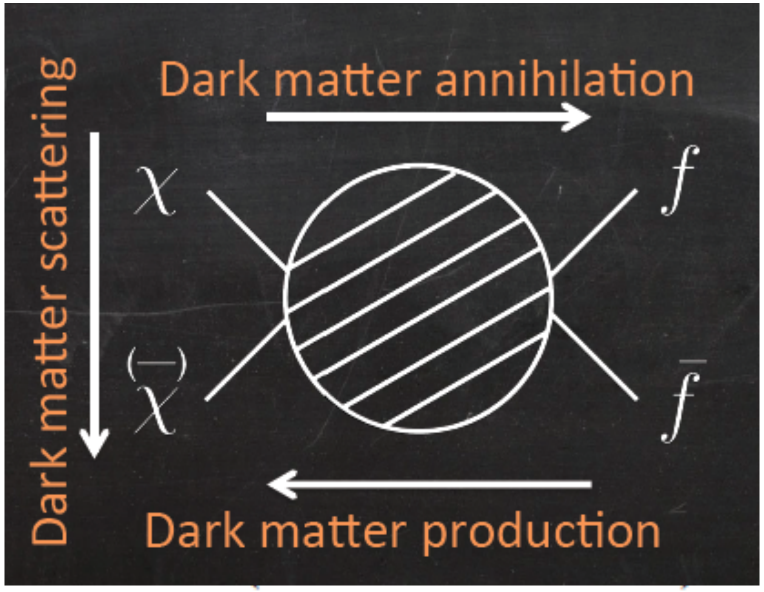
e.g.

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2},$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2},$$

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R),$$

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\left(G^a_{\mu\nu}G^{a\mu\nu}\right)}{\Lambda^3}.$$



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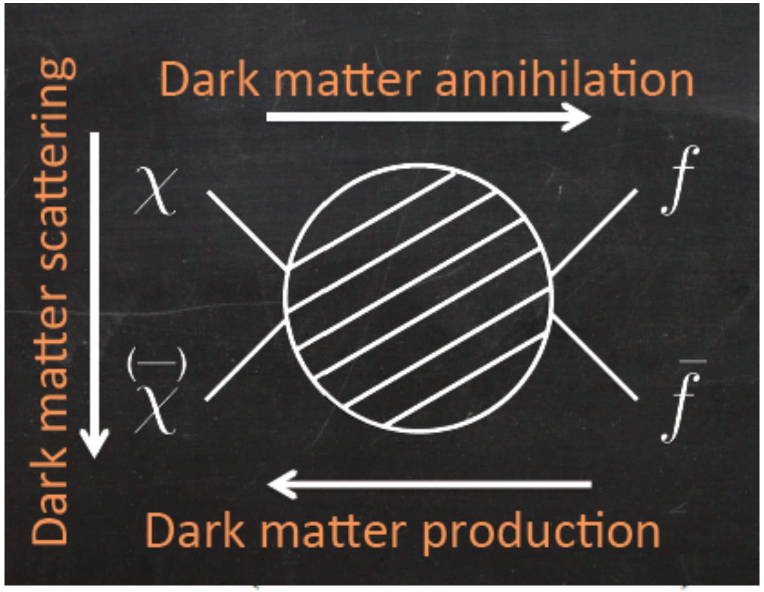
$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2},$$

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R),$$

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\left(G^a_{\mu\nu}G^{a\mu\nu}\right)}{\Lambda^3}.$$



To match to nucelon operators need these of the form $\mathcal{O}_{\rm SM}\mathcal{O}_\chi$

LHC tests of Dark Matter

For heavy SM-DM mediators interaction described by effective operators

e.g.

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2},$$

$$\mathcal{O}_A = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2},$$

$$\mathcal{O}_t = \frac{(\bar{\chi}P_R q)(\bar{q}P_L\chi)}{\Lambda^2} + (L \leftrightarrow R),$$

$$\mathcal{O}_g = \alpha_s \frac{(\bar{\chi}\chi)\,(G^a_{\mu\nu}G^{a\mu\nu})}{\Lambda^3}.$$

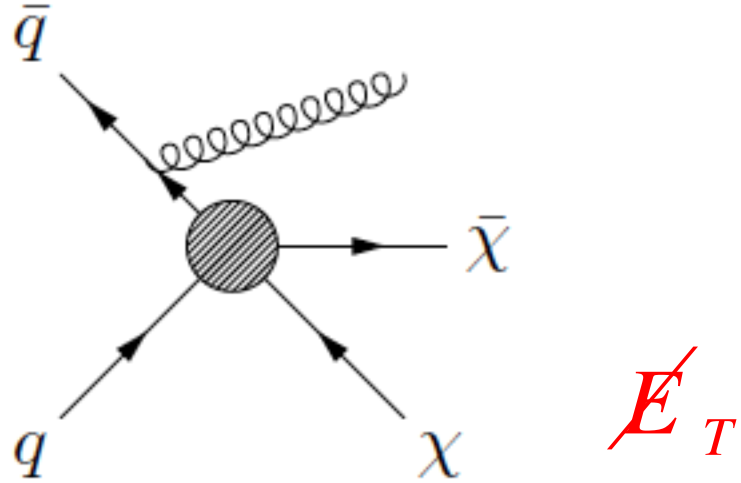
Spin independent cross section dominates $\propto O_V$

...vanishes for Majorana fermion

Fiertz identities: e.g.

$$\frac{1}{\Lambda^2}(\bar{\chi}P_R q)(\bar{q}P_L\chi) + (L \leftrightarrow R) = \frac{1}{4\Lambda^2}\left[(\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q) - (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)\right] = \frac{1}{4\Lambda^2}(\mathcal{O}_V - \mathcal{O}_A)$$

Monojets at the LHC

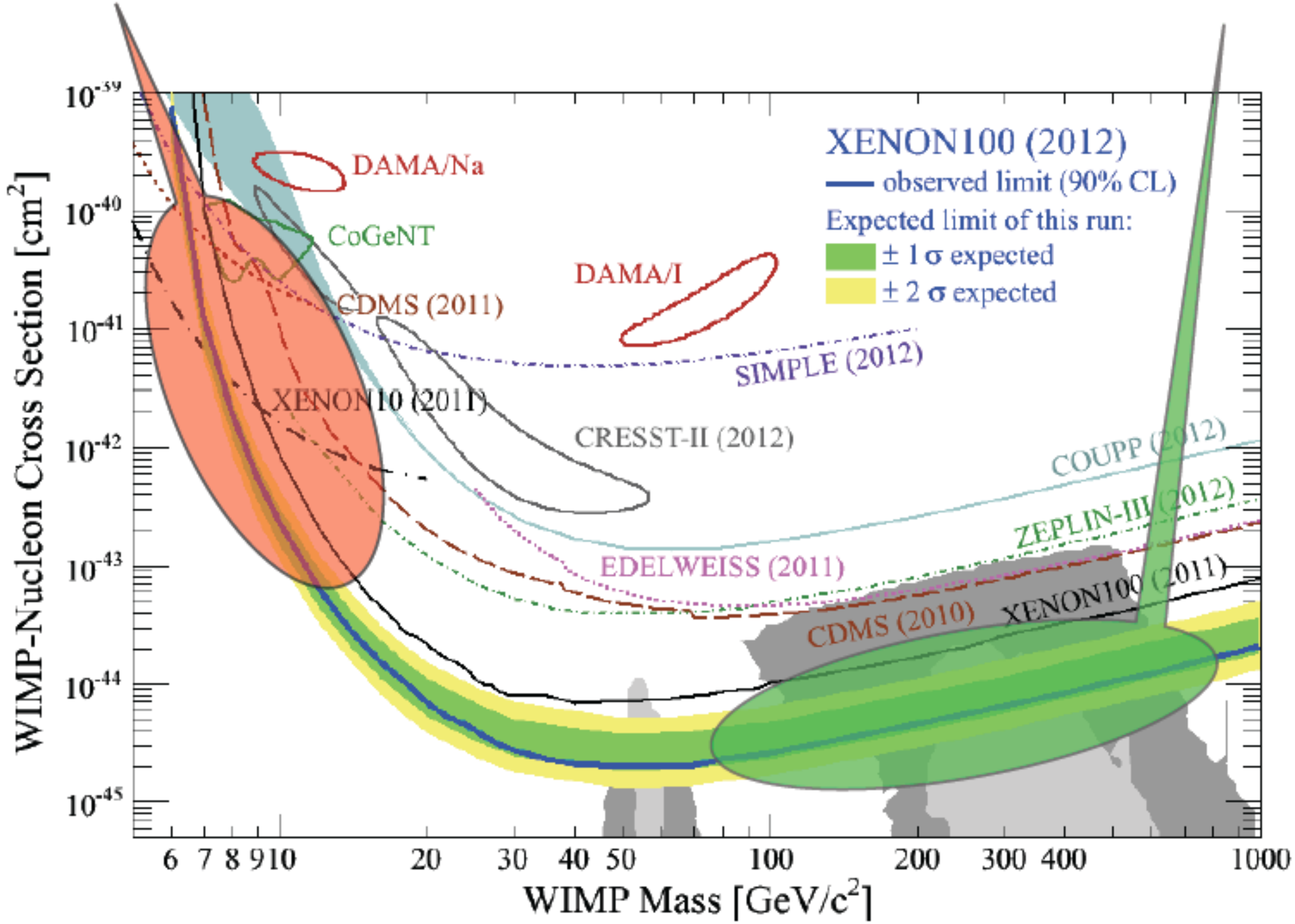


Look for excess over SM backgrounds:

$$(Z \to \nu\nu) + j \text{ and } (W \to \ell^{\text{inv}}\nu) + j$$

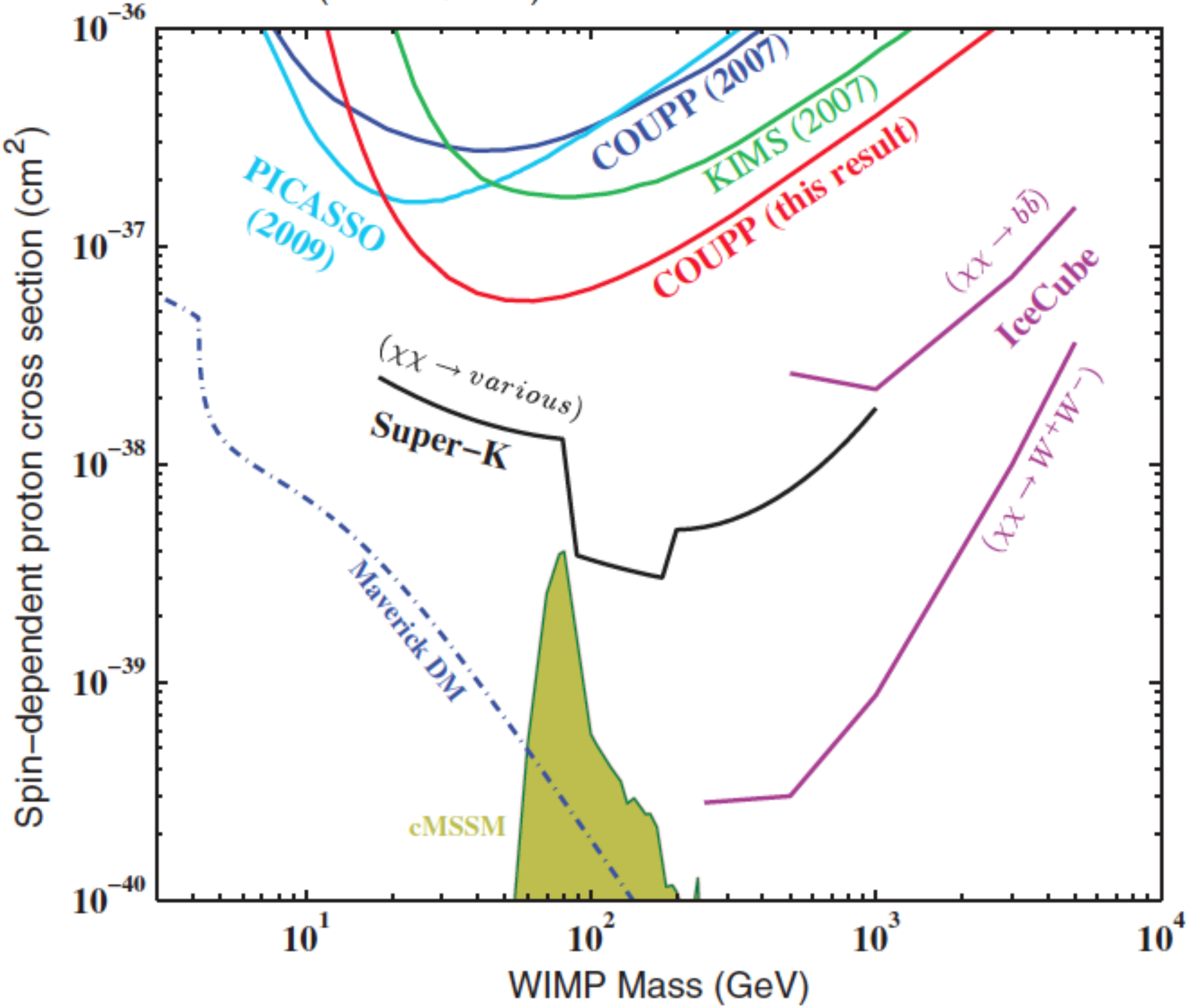
Threshold cuts off

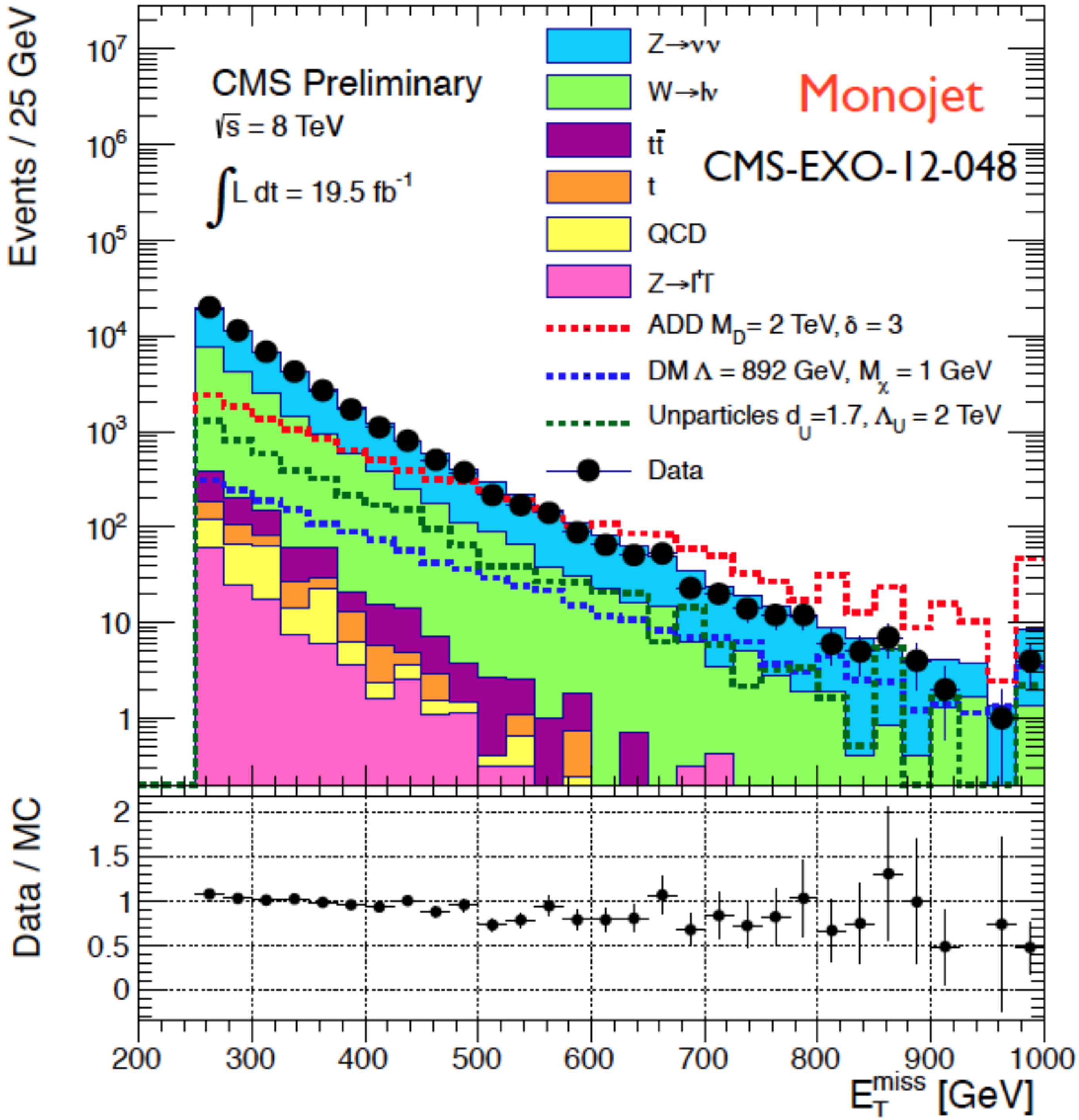
Rate ~1/m



(Assume local abundance is 0.3 GeV/cm^3)

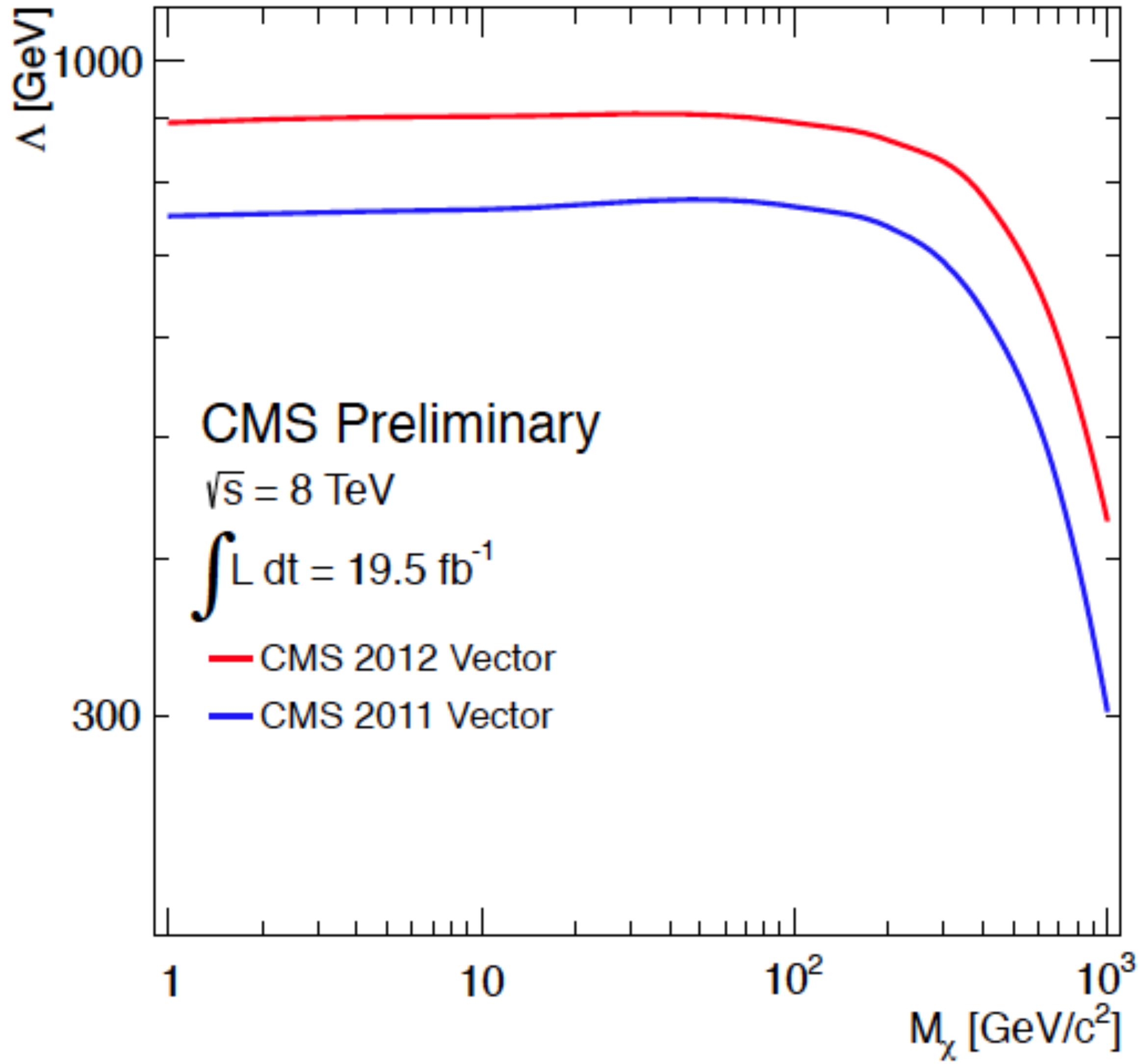
COUPP (PRL106, 2011)



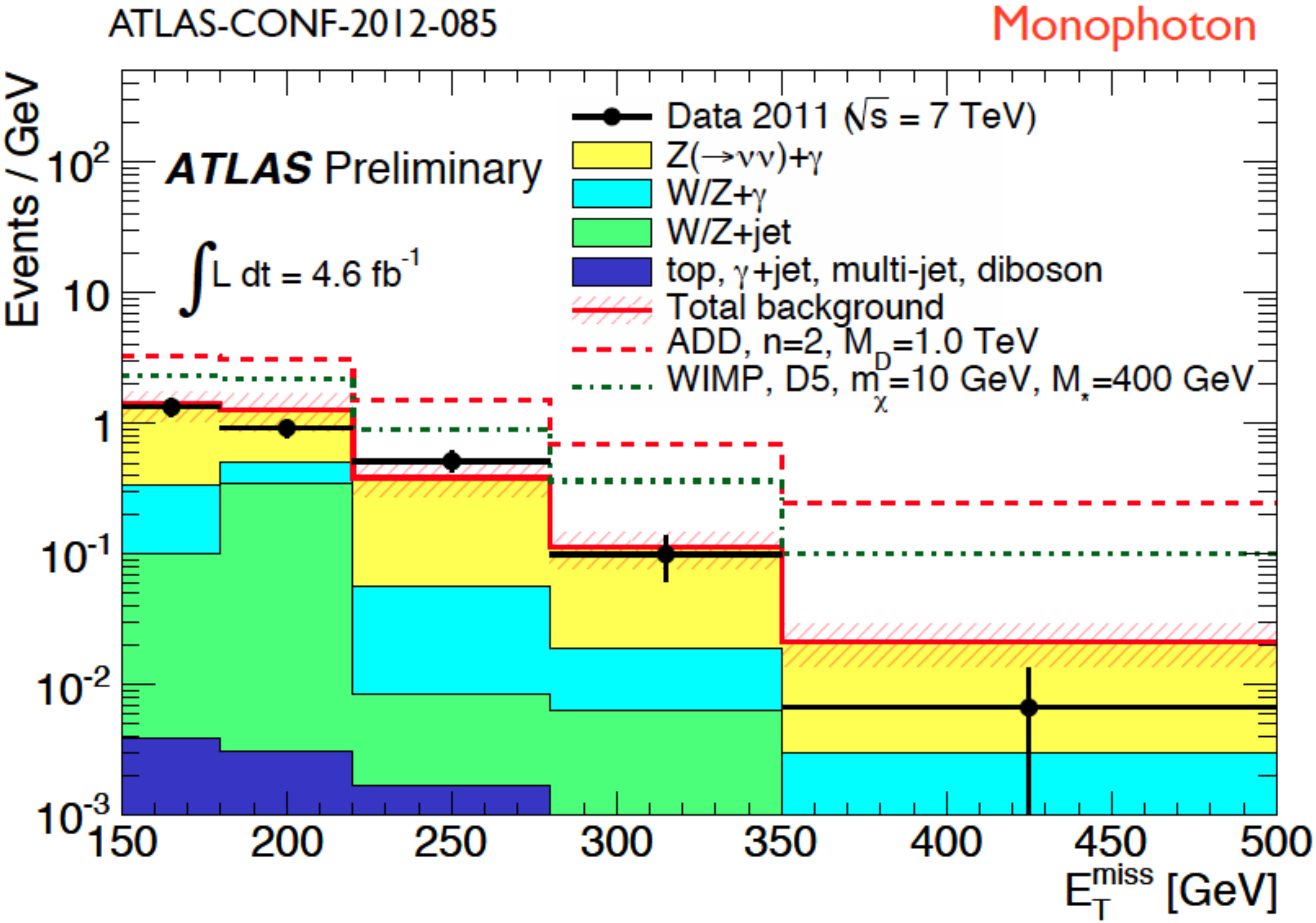


CMS Preliminary
√s = 8 TeV
∫L dt = 19.5 fb⁻¹
Monojet
CMS-EXO-12-048
Z→νν
W→lν
tt̄
t
QCD
Z→l⁺l⁻
ADD M_D = 2 TeV, δ = 3
DM Λ = 892 GeV, M_χ = 1 GeV
Unparticles d_U=1.7, Λ_U = 2 TeV
Data
Events / 25 GeV
Data / MC
E_T^miss [GeV]

Vector coupling



$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

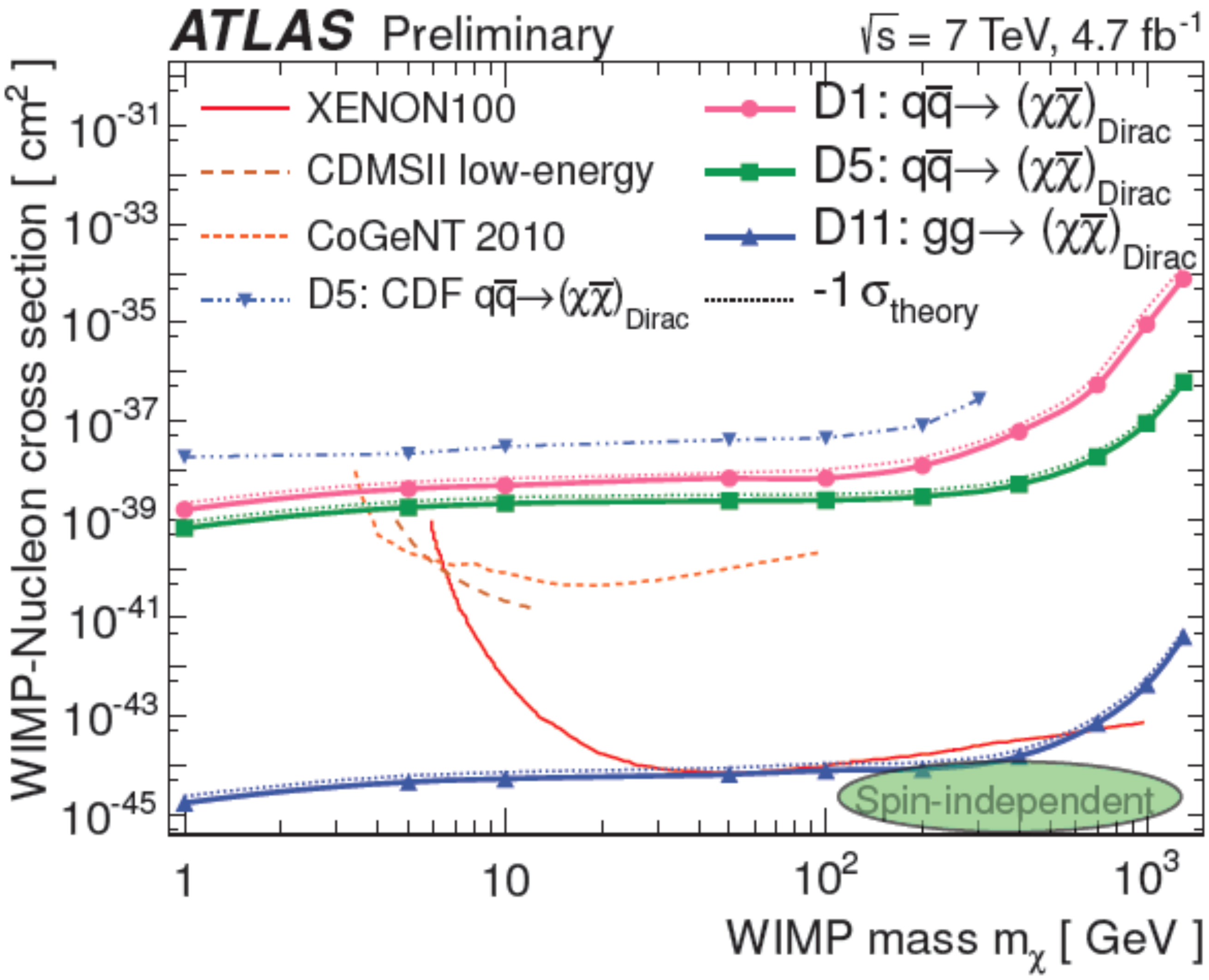

ATLAS-CONF-2012-085
Monophoton
ATLAS Preliminary
$\int L\,dt = 4.6\ fb^{-1}$
Data 2011 ($\sqrt{s}$ = 7 TeV)
$Z(\rightarrow\nu\nu)+\gamma$
$W/Z+\gamma$
W/Z+jet
top, γ+jet, multi-jet, diboson
Total background
ADD, n=2, M_D=1.0 TeV
WIMP, D5, m_χ=10 GeV, M_*=400 GeV
Events / GeV
E_T^{miss} [GeV]

Monojet

$$D1 = \bar{\chi}\chi\bar{q}q$$

$$D5 = \bar{\chi}\gamma^{\mu}\chi\gamma_{\mu}\bar{q}q$$

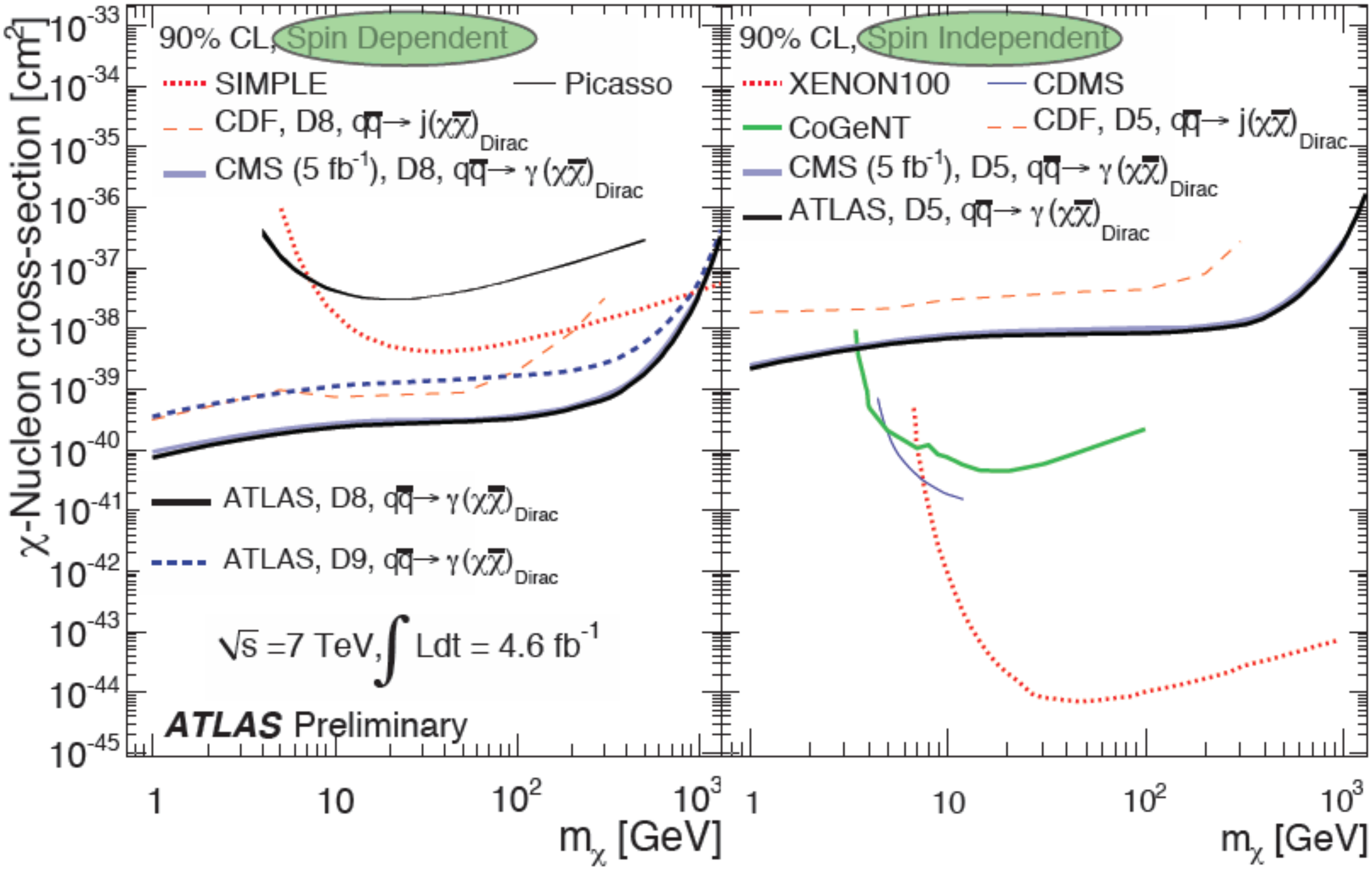
$$D11 = \bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$$



Monophoton

$$D8 = \bar{\chi}\gamma^{\mu}\gamma_5\chi\bar{q}\gamma^{\mu}\gamma_5 q$$

$$D5 = \bar{\chi}\gamma^{\mu}\chi\bar{q}\gamma^{\mu}q$$



Part IV: The Higgs Era

Tests for compositeness

Effective Field Theory description … nonlinear $SU(2)_L \times U(1)$

SM

$SO(4)/SO(3)$

$W^{\pm}_L$ & Z_L

$$\mathbf{H} = (H, \overline{H}) = \begin{pmatrix} h_1 + ih_2 & -h_3 + ih_4 \\ h_3 + ih_4 & h_1 - ih_2 \end{pmatrix}$$

$$= \frac{1}{\sqrt{2}}(h + \mathrm{v})\,\Sigma$$

$$V(H) = -\mu^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2$$

$$SO(4) \sim SU(2)_L \times SU(2)_R$$

$$\Sigma(x) \to U_L \Sigma(x) U_R^\dagger$$

"custodial" symm

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

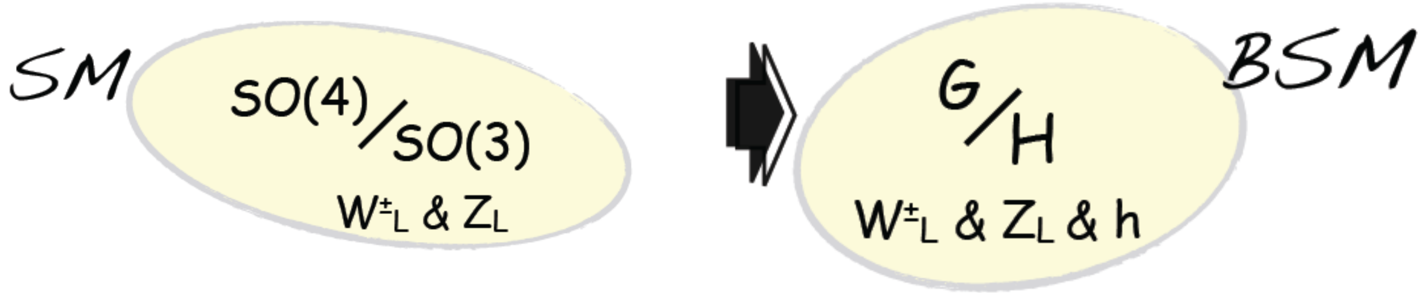
$$\Sigma(x) = e^{i\sigma_a \pi^a/\mathrm{v}}$$

$$SO(4) \xrightarrow{\mathrm{v}} SO(3)$$

$W_\mu^\pm, Z$

$\pi^a \subset SO(4)/SO(3)$ Goldstone bosons

Effective Field Theory description … nonlinear $SU(2)_L \times U(1)$



e.g.

$$SO(5)/SO(4): W, Z, h$$

$$SO(6)/SO(5): W, Z, h, a$$

…

Effective Field Theory description … nonlinear $SU(2)_L \times U(1)$

General parameterisation of composite models of Higgs:

$$\Sigma(x) = e^{i\sigma_a \pi^a / \mathrm{v}}, \quad h$$

$SM: \quad (h+\mathrm{v})^2$

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \cdots\right],$$
$$-\frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_j\frac{h}{v} + c_2\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u u_R^j \\ y_{ij}^d d_R^j \end{pmatrix} + h.c. \cdots,$$

(Reasonable) assumptions

- Spin-0 and CP-even
- Custodial symmetry
- No Higgs FCNC

SM

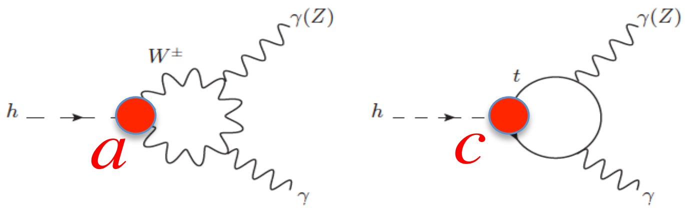
$a = b = (c_j = c) = 1$

$b_3 = c_2 = \ldots = 0$

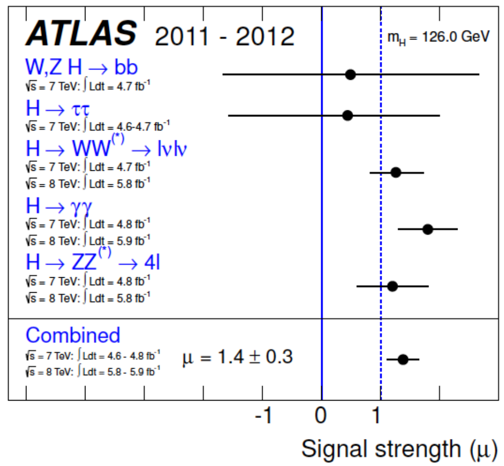
$$R = \sigma / \sigma_{SM}$$

$$R_{gg} = c^2 \quad , \quad R_{\rm VBF} = a^2 \quad , \quad R_{\rm ap} = a^2 \quad , \quad R_{\rm hs} = c^2$$

Higgs signal strength data



Interference term $\propto -a\,c$ c negative?

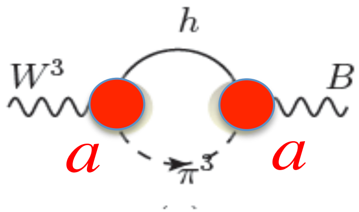


Electroweak precision tests

$$\Delta(\rho - 1) \simeq \frac{3(1-a^2)}{8\pi \cos^2\theta_W} \log\left(\frac{m_h}{\Lambda}\right)$$

$$\Delta S \approx \frac{-(1-a^2)}{6\,\pi} \log\left(\frac{m_h}{\Lambda}\right)$$

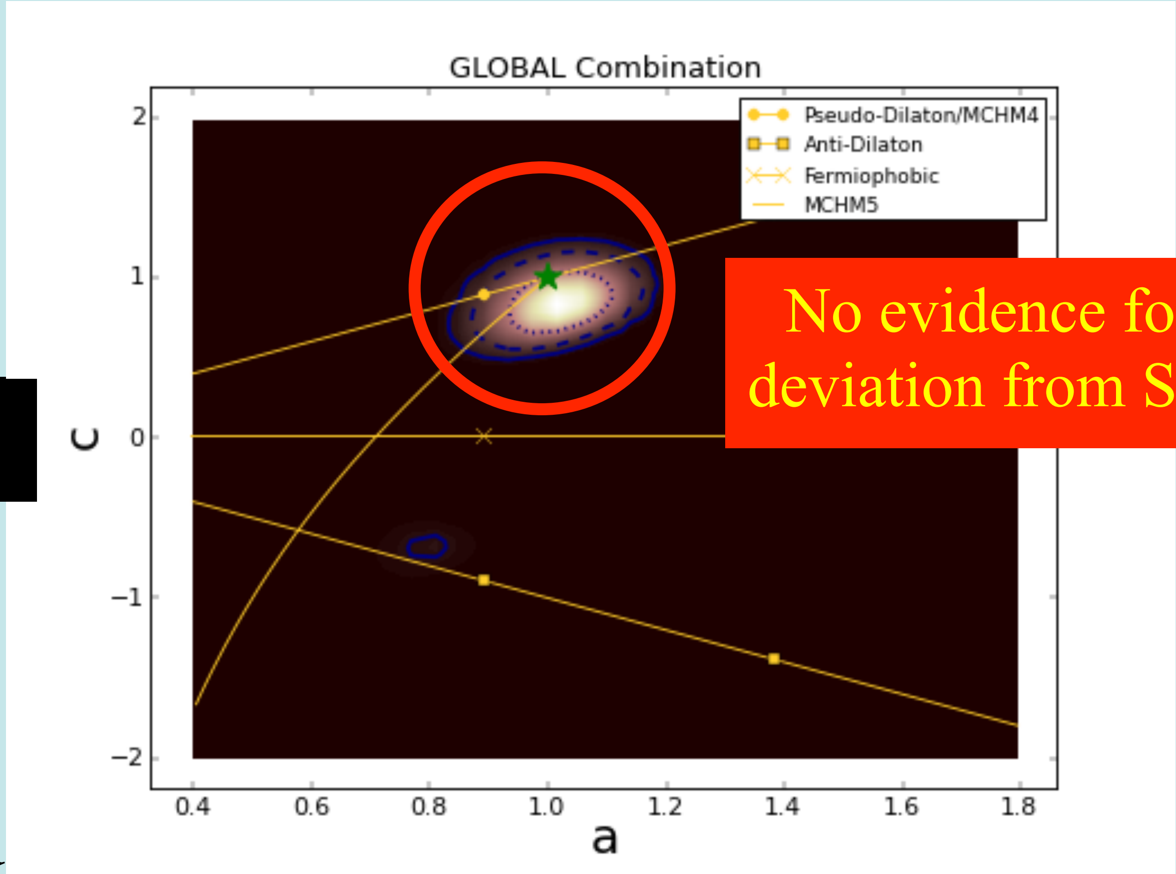
$$\alpha S \equiv -4e^2 \frac{d}{dq^2} \Delta_3(q^2)|_{q^2=0}$$



Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by *a*, to fermions by *c*

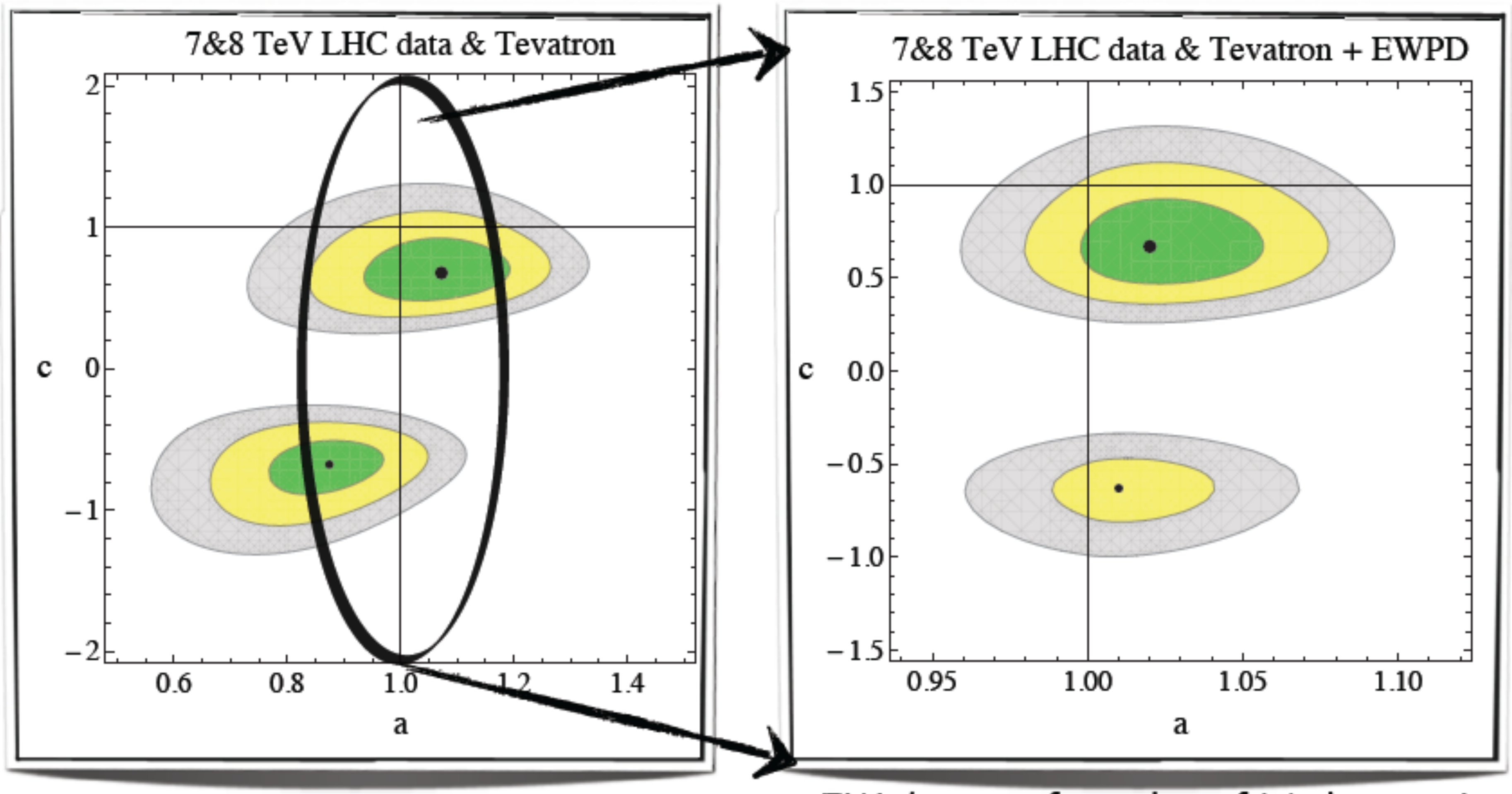
Global



No evidence for deviation from SM

- Stand

John Ellis & Tevong You, arXiv:1303.3



Espinosa, Grojean, Muhlleitner, Trott
Eboli et al
Falkowski, Evra, Urbano

EW data prefer value of ‘a’ close to 1

Standard Model

$$(a, c) = (1, 1) \text{ is } \sim 2\,\sigma \text{ (C.L. of 0.95)}$$

Bad news for the Higgs impostors

- dilaton with f~1TeV: a=v/f~0.25 will require new (light) dof to get back to the EW ellipses

Search for new physics

What else is there?

Slide from Ellis

- Higher-dimensional operators as relics of higher-energy physics?

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

- Operators constrained by SU(2) × U(1) symmetry:

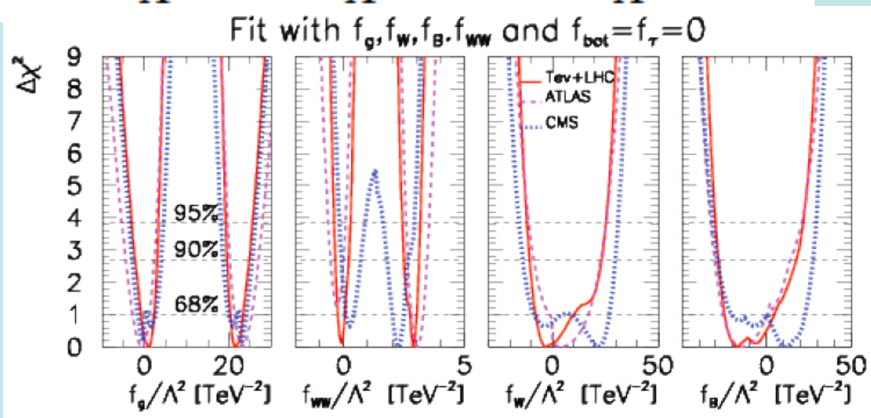
$$\mathcal{O}_{GG} = \Phi^\dagger \Phi \, G^a_{\mu\nu} G^{a\mu\nu} \;, \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \;, \qquad \mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \;,$$

$$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \;, \quad \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi) \;, \quad \mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \, \Phi \, \Phi^\dagger \, (D^\mu \Phi)$$

$$\mathcal{L}_{eff} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_{\text{bot}}}{\Lambda^2} \mathcal{O}_{d\Phi,33} + \frac{f_\tau}{\Lambda^2} \mathcal{O}_{e\Phi,33}$$

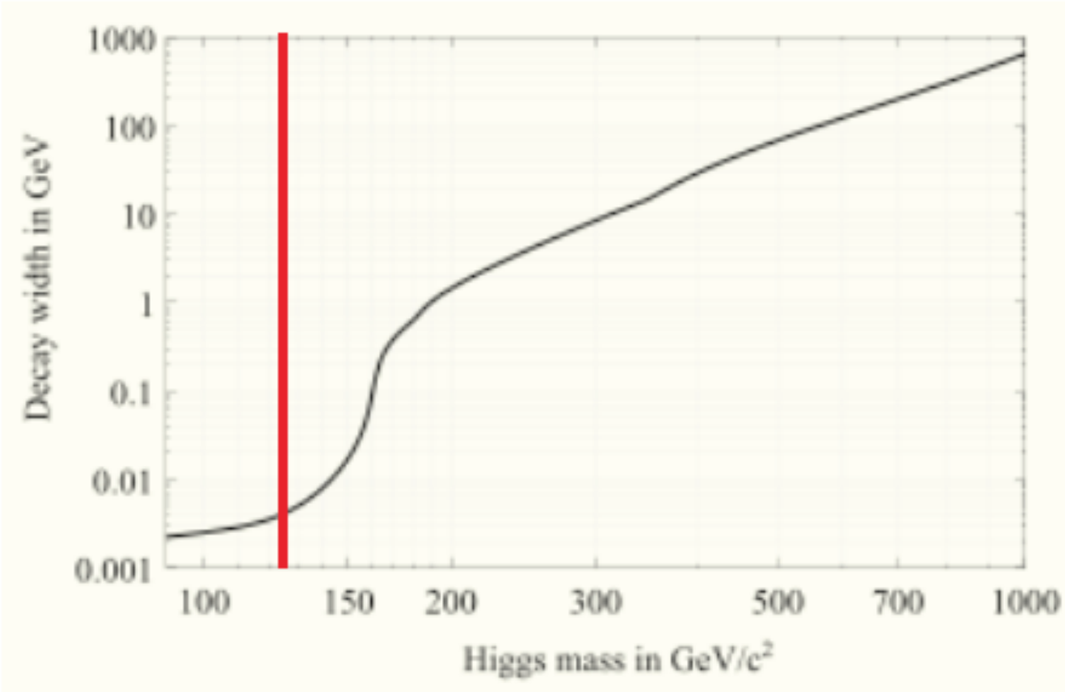
Corbett, Eboli & Gonzalez^2

- ng LHC + Tevatron Higgs measurements



Higgs Decay Width in the SM

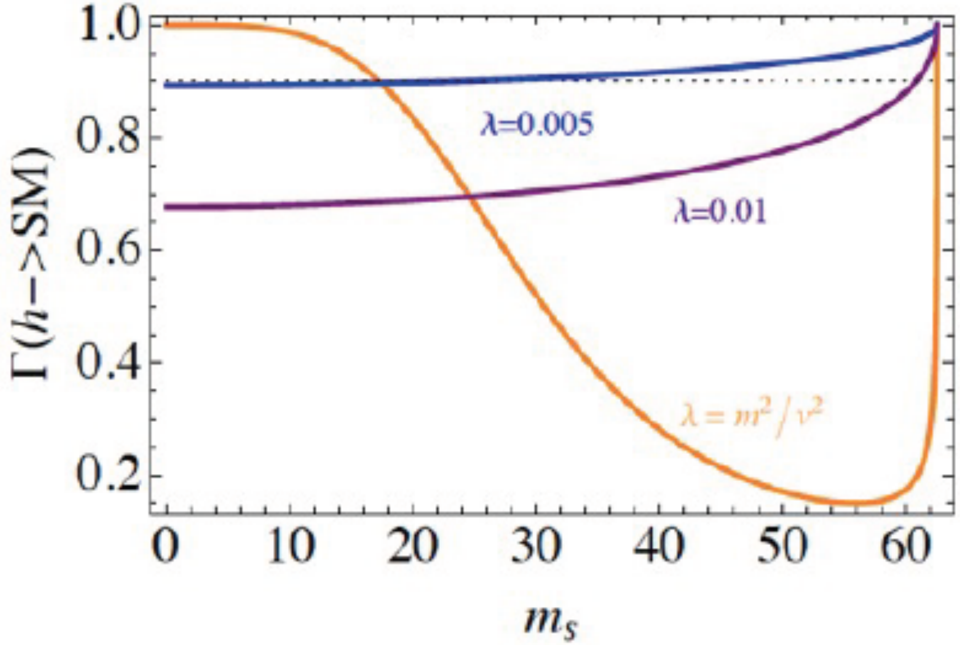
- The SM Higgs width is tiny for mh ~ 125 GeV
  - Its decays into gauge bosons are either off-shell (WW*, ZZ*), or at loop level (di-photon, di-gluon)
  - Its decays into fermions tend to be suppressed because of small Yukawa couplings (except tt*)
- About three orders smaller than the Z or W widths (~ 4MeV only) !



Exotic Higgs Decays

- A small non-standard Higgs coupling may lead to sizable effect.

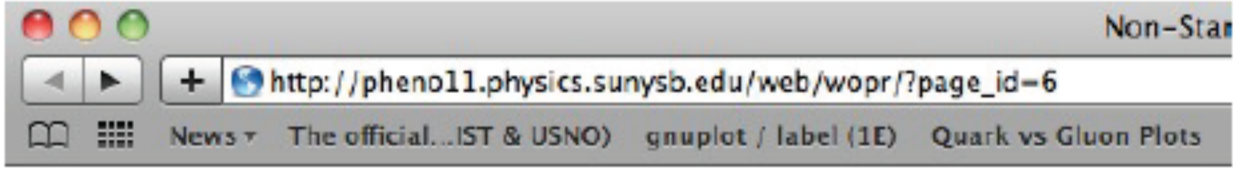
e.g., $\Delta\mathcal{L} = \lambda S^2 |H|^2$ (common building block in extended Higgs sectors)



$\lambda \sim 0.005$ and $m_S < \frac{m_H}{2}$ can give $\mathrm{Br}(H \to SS) \sim 10\%$

- So the exotic decays of the 125GeV Higgs are a natural and very efficient way for probing new physics

The Website of ``Exotic Higgs Decays''



Decays to Standard Objects Without Missing Energy

1. h → 2 → (2)+(1)
   - $\gamma + Z$
   - $\gamma + Z'$
2. h → 2 → (2)+(2)
   - *via Spin-0 Bosons (S)*
     - $(b\bar{b})(b\bar{b})$
     - $(b\bar{b})(\tau^+\tau^-)$
     - $(b\bar{b})(\mu^+\mu^-)$
     - $(\tau^+\tau^-)(\mu^+\mu^-)$
     - $(b\bar{b})(\gamma\gamma)$
     - $(\tau^+\tau^-)(\gamma\gamma)$
     - $(\gamma\gamma)(\gamma\gamma)$
     - $(\gamma\gamma)(gg)$
   - *via Spin-1 Bosons (Z')*
     - $(l^+l^-)(l^+l^-)$
     - $(l^+l^-)(q\bar{q})$
3. h → 2 → (3)+(3) or (2+1)(2+1)
   - *via Bosons*

Decays to Standard Objects With Missing Energy
(except for that from b's, c's, tau's)

1. h → 0
   - MET (Invisible decay)
2. h → 2 → 1+ 0
   - γ + MET
3. h → 2 → 2 + 0
   - *via Spin-0 Bosons (S)*
     - $(b\bar{b})$ + MET
     - $(\tau^+\tau^-)$ + MET
     - $(\mu^+\mu^-)$ + MET
     - $(\gamma\gamma)$ + MET
   - *via Spin-1 Bosons (Z')*
     - (l^+l^-) + MET
   - *via Spin-1/2 Fermions*
     - $\gamma\gamma$ + MET
     - $[\gamma\gamma]$ + MET
     - $[l^+l^-]$ + MET

Summary: Beyond the SM at the LHC

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