The Higgs sector in SUSY extensions of the SM

Pietro Slavich

(LPTHE Paris)

YETI'13: Durham IPPP, 6-9 January 2013

Outline

- The MSSM and its Higgs sector
- Interpreting a 125-GeV scalar in the MSSM
- Extending the Higgs sector of the MSSM

The MSSM and its Higgs sector

Beyond the Standard Model

The Standard Model does an excellent job in describing physics at the weak scale.
Still, it is unlikely that it is valid all the way up to the scale of quantum gravity

Observational arguments for BSM physics

- The SM does not account for neutrino oscillations (this, however, can easily be fixed by adding heavy and sterile right-handed neutrinos to the theory)

- The SM does not include a suitable candidate for Dark Matter, and cannot justify the matter-antimatter asymmetry in the Universe

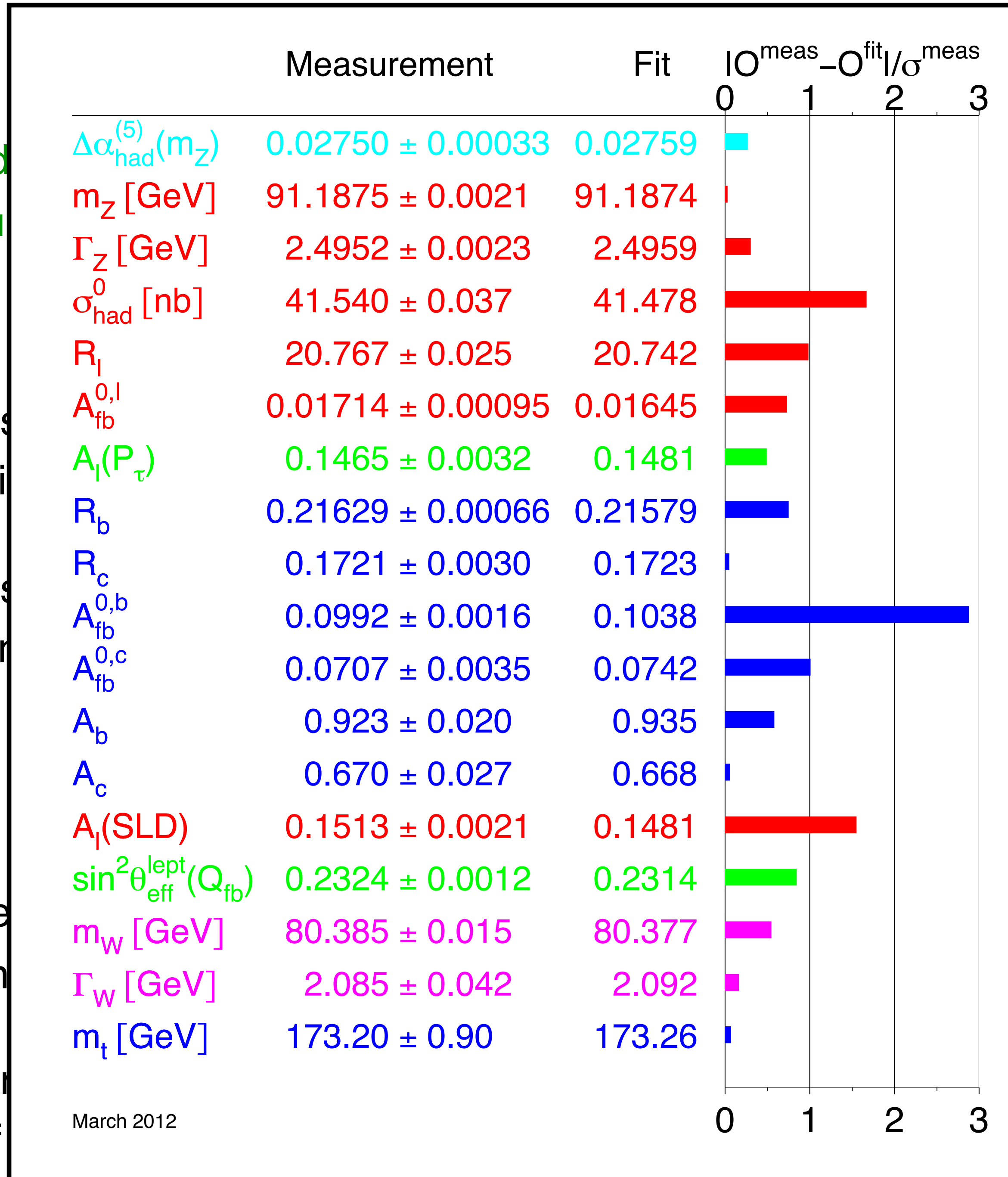
Theoretical arguments for BSM physics

- The SM has many (>20) arbitrary parameters, and a rather complicated structure ("odd" gauge group, generation mixing, large mass hierarchies among fermions). It would be nice to embed it in a simpler and more predictive theory (e.g., a GUT).

- Quantum corrections destabilize the Higgs mass inducing a quadratic dependence on the cutoff scale used to regularize the loop integrals *(the hierarchy problem)*

The Standard ... e weak scale.

Still, it is u ... um gravity

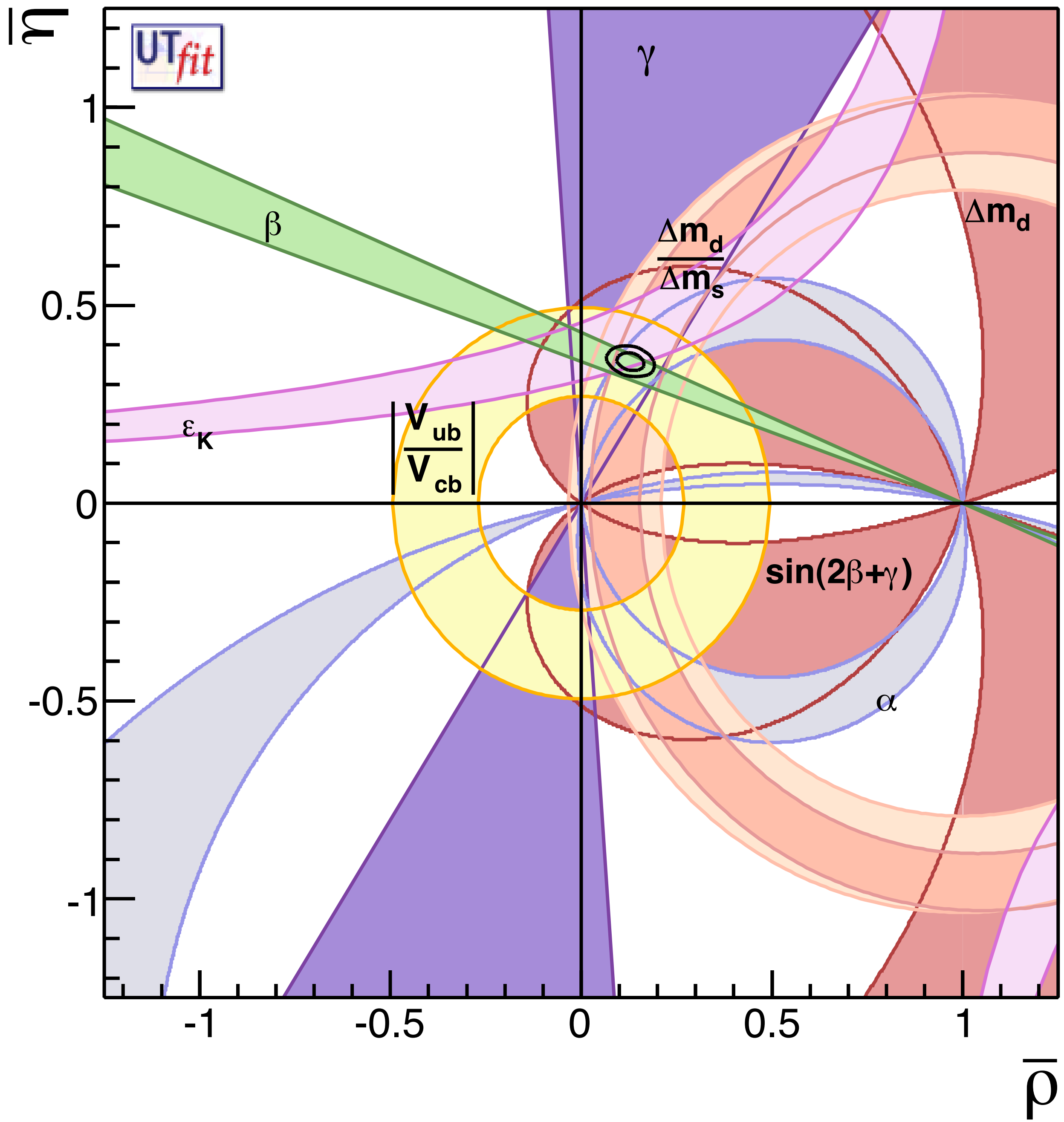


- The SM does ... n easily be fixed by addi ... y)
- The SM does ... annot justify the matter-ar ...
- The SM has ... ted structure ("odd" gauge ... ng fermions). It would be n ... (e.g., a GUT).
- Quantum co ... c dependence on the cutoff ... *y problem)*

The S … scale.

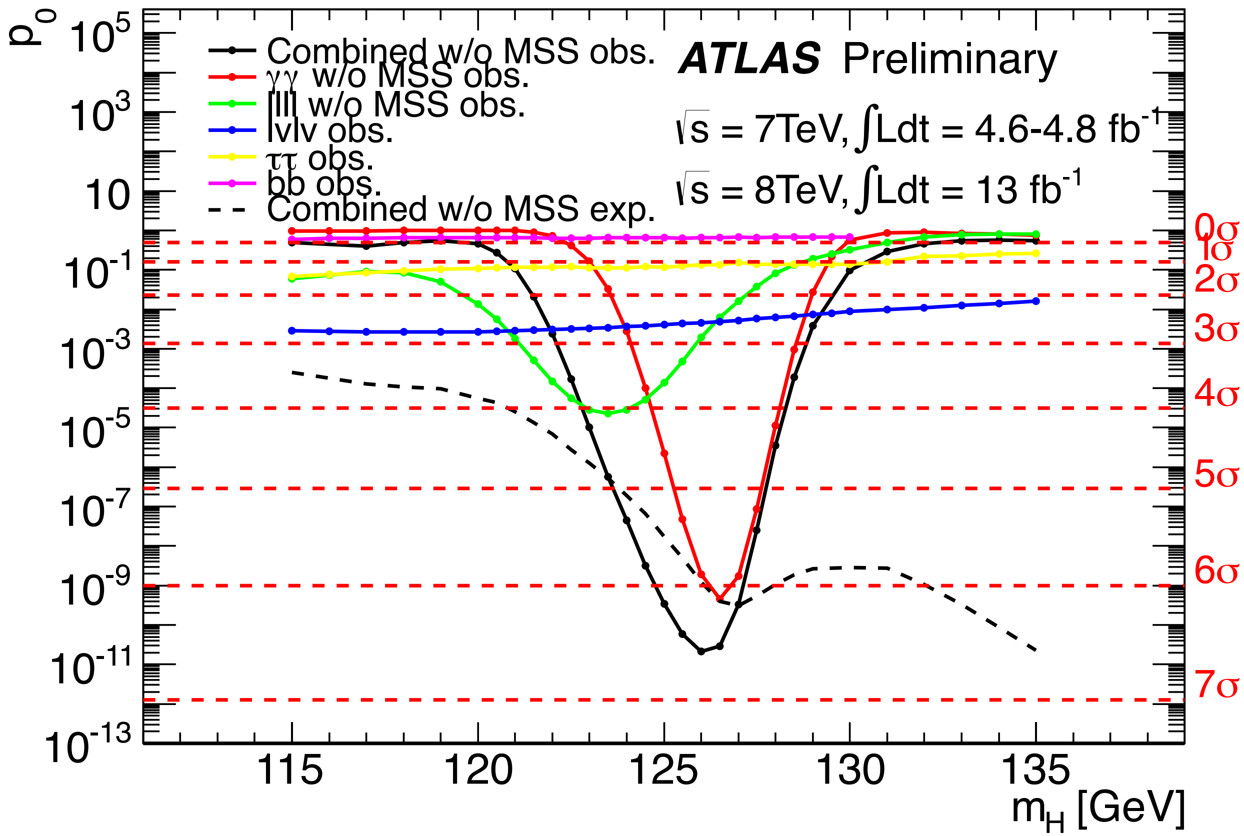
Sti … ity

- The … be
  fixed
- The … stify
  the n
- The … cture
  ("odc … ons).
  It wo … GUT).
- Quar … ndence
  on th … em)



Beyond the Standard Model

The Standard Model does an excellent job in describing physics at the weak scale.
Still, it is unlikely that it is valid all the way up to the scale of quantum gravity



- The SM ... sily be fixed by
- The SM ... ot justify the matt
- The SM ... structure ("odd" g ... rmions). It would ... a GUT).
- Quantum corrections destabilize the Higgs mass inducing a quadratic dependence on the cutoff scale used to regularize the loop integrals *(the hierarchy problem)*

Beyond the Standard Model

The Standard Model does an excellent job in describing physics at the weak scale. Still, it is unlikely that it is valid all the way up to the scale of quantum gravity

Observational arguments for BSM physics

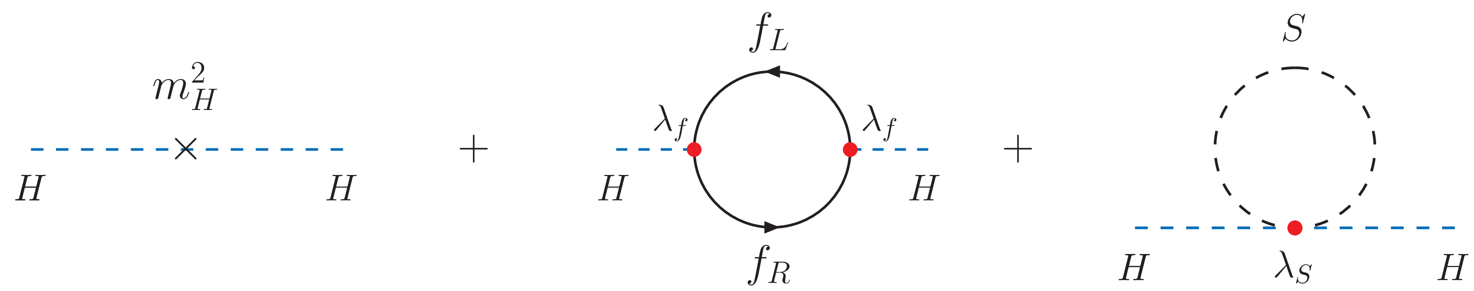
- The SM does not account for neutrino oscillations (this, however, can easily be fixed by adding heavy and sterile right-handed neutrinos to the theory)
- The SM does not include a suitable candidate for Dark Matter, and cannot justify the matter-antimatter asymmetry in the Universe

Theoretical arguments for BSM physics

- The SM has many (>20) arbitrary parameters, and a rather complicated structure (“odd” gauge group, generation mixing, large mass hierarchies among fermions). It would be nice to embed it in a simpler and more predictive theory (e.g., a GUT).
- Quantum corrections destabilize the Higgs mass inducing a quadratic dependence on the cutoff scale used to regularize the loop integrals *(the hierarchy problem)*

Supersymmetry and the hierarchy problem

Fermions and bosons enter the quantum corrections to the Higgs mass with opposite sign



In a supersymmetric theory, each fermion has a bosonic partner with the same mass and internal quantum numbers (their couplings to the Higgs are related, $\lambda_S = \lambda_f^2$). Their quadratically divergent contributions to the Higgs mass cancel each other

In the Minimal Supersymmetric Standard Model (MSSM) every SM particle is promoted to a *supermultiplet* (however, two Higgs supermultiplets are required)

The superpartners must be heavier than the ordinary SM particles → SUSY must be *broken* by explicit mass terms for the new particles

These SUSY-breaking masses M_S are *soft*, i.e. they do not reintroduce quadratic divergences:

$$\Delta m_H^2 \propto \frac{\lambda^2}{16\pi^2} M_S^2$$

Why does SUSY require an extended Higgs sector?

In the SM we can use Φ (Y=+1/2) and $\widetilde{\Phi} \equiv \epsilon\Phi^*$ (Y=−1/2) to give mass to up and down quarks

$$\mathcal{L}_{\rm SM} \supset -(Y_D)_{ij}\,\overline{q_L^i}\,\Phi\,d_R^j - (Y_U)_{ij}\,\overline{q_L^i}\,\widetilde{\Phi}\,u_R^j + \text{h.c.}$$

In SUSY the Yukawa interactions come from the *superpotential*, analytic in the *superfields*

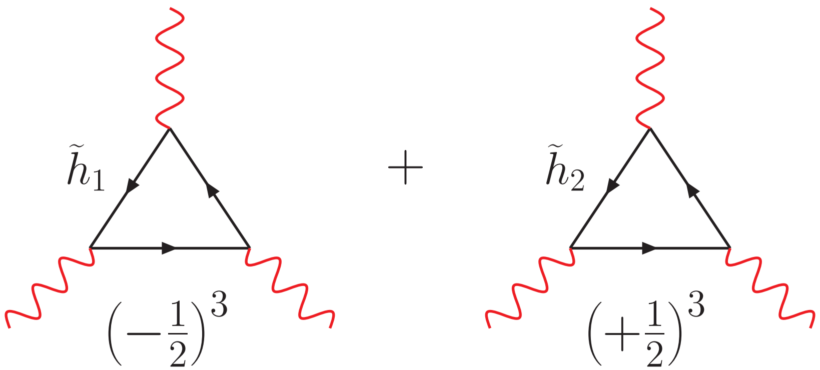
We need two Higgs superfields, H_1 (Y=−1/2) and H_2 (Y=+1/2)

$$W_{\rm MSSM} \supset h_d\,H_1\,Q\,D^c - h_u\,H_2\,Q\,U^c$$

The only possible SUSY mass term for Higgs and *Higgsinos* is

$$W_{\rm MSSM} \supset -\mu\,H_1\,H_2$$

Also, we need two Higgsinos of opposite hypercharge to cancel the Y^3 anomaly:



Superfield content of the MSSM

Chiral supermultiplets		spin 1/2	spin 0	SU(3)xSU(2)xU(1)
(s)quarks (3 families)	Q	$(u_L\,, d_L)$	$(\tilde{u}_L\,, \tilde{d}_L)$	$(3,\ 2,\ \frac{1}{6})$
	U^c	$u_R^\dagger$	$\tilde{u}_R^*$	$(\bar{3},\ 1,\ -\frac{2}{3})$
	D^c	$d_R^\dagger$	$\tilde{d}_R^*$	$(\bar{3},\ 1,\ \frac{1}{3})$
(s)leptons (3 families)	L	$(\nu\,, e_L)$	$(\tilde{\nu}\,, \tilde{e}_L)$	$(1,\ 2,\ -\frac{1}{2})$
	E^c	$e_R^\dagger$	$\tilde{e}_R^*$	$(1,\ 1,\ 1)$
Higgs(inos)	H_1	$(\tilde{h}_1^0\,, \tilde{h}_1^-)$	$(H_1^0\,, H_1^-)$	$(1,\ 2,\ -\frac{1}{2})$
	H_2	$(\tilde{h}_2^+\,, \tilde{h}_2^0)$	$(H_2^+\,, H_2^0)$	$(1,\ 2,\ +\frac{1}{2})$

Vector supermultiplets	spin 1	spin 1/2	SU(3)xSU(2)xU(1)
gluon, gluino	g	$\tilde{g}$	$(8,\ 1,\ 0)$
W bosons, winos	$W^\pm,\ W^0$	$\tilde{w}^\pm,\ \tilde{w}^0$	$(1,\ 3,\ 0)$
B boson, bino	B	$\tilde{b}$	$(1,\ 1,\ 0)$

Superfield content of the MSSM

Chiral supermultiplets		spin 1/2	spin 0	SU(3)xSU(2)xU(1)
(s)quarks (3 families)	Q	$(u_L\,, d_L)$	$(\tilde{u}_L\,, \tilde{d}_L)$	$(3,\ 2,\ \frac{1}{6})$
	U^c	$u_R^\dagger$	$\tilde{u}_R^*$	$(\bar{3},\ 1,\ -\frac{2}{3})$
	D^c	$d_R^\dagger$	$\tilde{d}_R^*$	$(\bar{3},\ 1,\ \frac{1}{3})$
(s)leptons (3 families)	L	$(\nu\,, e_L)$	$(\tilde{\nu}\,, \tilde{e}_L)$	$(1,\ 2,\ -\frac{1}{2})$
	E^c	$e_R^\dagger$	$\tilde{e}_R^*$	$(1,\ 1,\ 1)$
Higgs(inos)	H_1	$(\tilde{h}_1^0\,, \tilde{h}_1^-)$	$(H_1^0\,, H_1^-)$	$(1,\ 2,\ -\frac{1}{2})$
	H_2	$(\tilde{h}_2^+\,, \tilde{h}_2^0)$	$(H_2^+\,, H_2^0)$	$(1,\ 2,\ +\frac{1}{2})$

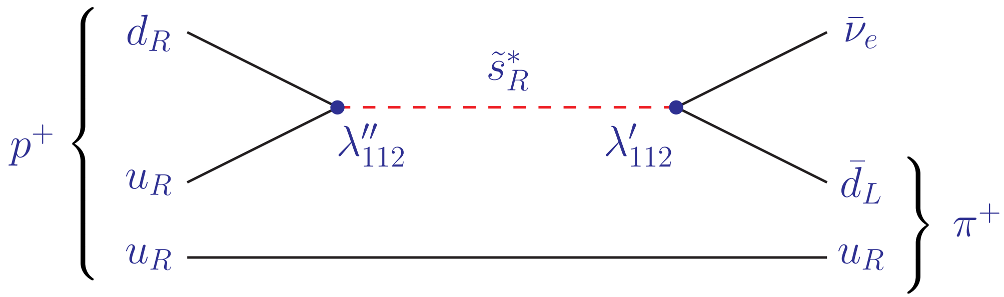
Vector supermultiplets	spin 1	spin 1/2	SU(3)xSU(2)xU(1)
gluon, gluino	g	$\tilde{g}$	$(8,\ 1,\ 0)$
W bosons, winos	$W^\pm,\ W^0$	$\tilde{w}^\pm,\ \tilde{w}^0$	$(1,\ 3,\ 0)$
B boson, bino	B	$\tilde{b}$	$(1,\ 1,\ 0)$

The most general superpotential compatible with the SM gauge group:

$$\begin{aligned} W \quad = \quad & -\mu\, H_1 H_2 + h_e\, H_1 L E^c + h_d\, H_1 Q D^c - h_u\, H_2 Q U^c \\ & -\mu'\, L\, H_2 + \ \lambda\, L\, L E^c \ \ + \lambda'\, L Q D^c \\ & + \lambda''\, U^c D^c D^c \end{aligned}$$

the terms in the second and third line violate Lepton and Baryon number, respectively.

If they are both present they can induce fast proton decay



we can postulate a new discrete symmetry, called R-parity: $P_R = (-1)^{3(B-L)+2S}$

It forbids both L-violating and B-violating terms in the superpotential

SM particles and the Higgs bosons have $P_R = +1$, superpartners have $P_R = -1$

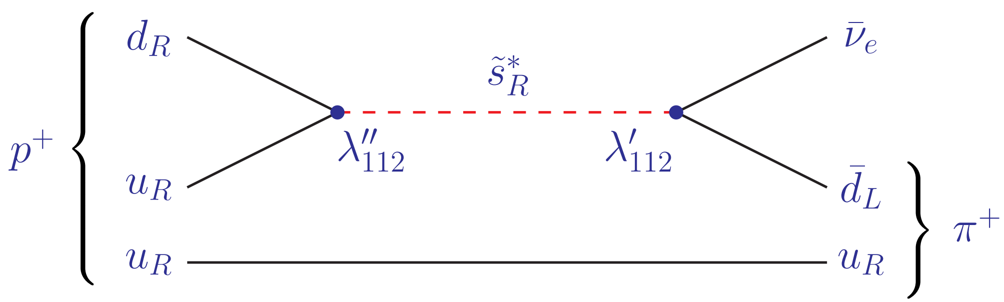
If R-parity is conserved, every interaction must contain an even number of superparticles

The most general superpotential compatible with the SM gauge group:

$$\begin{array}{rl} W \;= & -\mu\, H_1 H_2 + h_e\, H_1 L E^c + h_d\, H_1 Q D^c - h_u\, H_2 Q U^c \\ \text{L-violating} & -\mu'\, L\, H_2 + \lambda\, L\, L E^c + \lambda'\, L Q D^c \\ \text{B-violating} & +\lambda''\, U^c D^c D^c \end{array}$$

the terms in the second and third line violate Lepton and Baryon number, respectively.

If they are both present they can induce fast proton decay



we can postulate a new discrete symmetry, called R-parity: $P_R = (-1)^{3(B-L)+2S}$

It forbids both L-violating and B-violating terms in the superpotential

SM particles and the Higgs bosons have $P_R = +1$, superpartners have $P_R = -1$

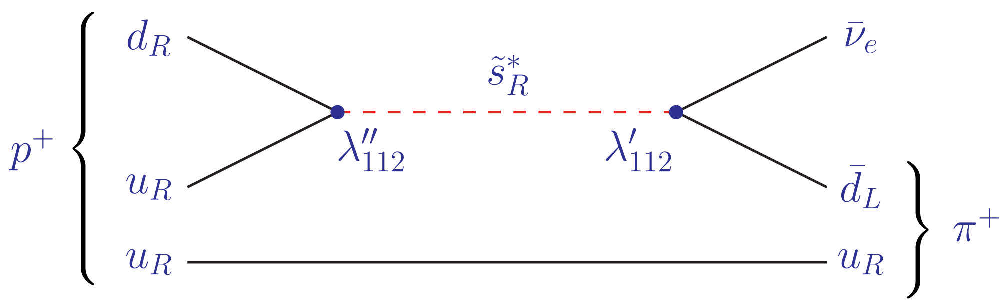
If R-parity is conserved, every interaction must contain an even number of superparticles

The most general superpotential compatible with the SM gauge group:

$$
\begin{aligned}
W \quad &= \quad -\mu\, H_1 H_2 + h_e\, H_1 L E^c + h_d\, H_1 Q D^c - h_u\, H_2 Q U^c \\
\text{L-violating} \quad & \quad \cancel{-\mu'\, L\, H_2 + \lambda\, L\, L E^c \;\; + \lambda'\, L Q D^c} \\
\text{B-violating} \quad & \quad \cancel{+\lambda''\, U^c D^c D^c}
\end{aligned}
$$

the terms in the second and third line violate Lepton and Baryon number, respectively.

If they are both present they can induce fast proton decay



we can postulate a new discrete symmetry, called R-parity: $P_R = (-1)^{3(B-L)+2S}$

It forbids both L-violating and B-violating terms in the superpotential

SM particles and the Higgs bosons have $P_R = +1$, superpartners have $P_R = -1$

If R-parity is conserved, every interaction must contain an even number of superparticles

The most general soft SUSY-breaking Lagrangian compatible with the SM gauge group and R-parity is (gauge and family indices are understood)

$$\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\;& -\frac{1}{2}\left(M_1\,\tilde{b}\tilde{b} + M_2\,\tilde{w}\tilde{w} + M_3\,\tilde{g}\tilde{g}\right) \;+\; \text{h.c.} \\
& -\tilde{q}^\dagger\, m_Q^2\,\tilde{q} - \tilde{\ell}^\dagger\, m_L^2\,\tilde{\ell} - \tilde{u}^{c\,\dagger}\, m_U^2\,\tilde{u}^c - \tilde{d}^{c\,\dagger}\, m_D^2\,\tilde{d}^c - \tilde{e}^{c\,\dagger}\, m_E^2\,\tilde{e}^c \\
& -m_{H_1}^2\, H_1^\dagger H_1 - m_{H_2}^2\, H_2^\dagger H_2 + (B_\mu\, H_1 H_2 \;+\; \text{h.c.}) \\
& +\tilde{e}^c\, T_e\,\tilde{\ell}\, H_1 + \tilde{d}^c\, T_d\,\tilde{q}\, H_1 - \tilde{u}^c\, T_u\,\tilde{q}\, H_2 \;+\; \text{h.c.}
\end{aligned}$$

To avoid excessive fine tuning the soft masses should be at most of the order of (a few) TeV

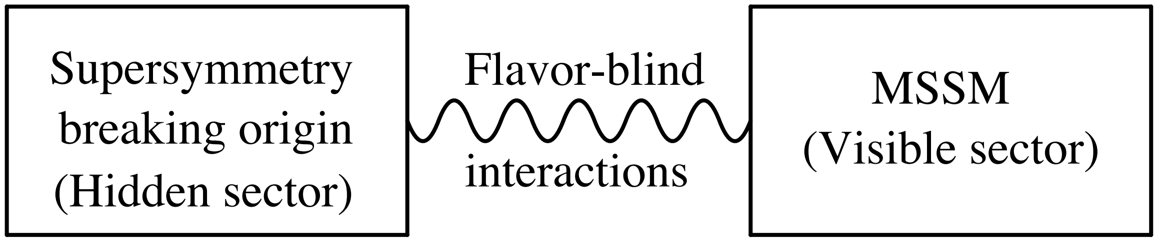
In the general case there are 105 new parameters in addition to the SM ones:

The squark and slepton masses $(m_Q^2,\, m_L^2,\, m_U^2,\, m_D^2,\, m_E^2)$ and the trilinear interaction terms $(T_e,\, T_d,\, T_u)$ are (3x3) matrices in family space. The amount of flavour mixing in the sfermion sector that they can induce is severely constrained by the experimental bounds on the FCNC processes *(flavour problem)*

The gaugino masses and the trilinear interaction terms (as well as the SUSY Higgs mass μ) are in general complex parameters. The amount of CP violation that they can induce is also constrained by the bounds on EDM *(CP problem)*

Models of supersymmetry breaking

It is not possible to break SUSY spontaneously within the MSSM. The breaking must occur in some *hidden sector* that does not couple directly to the MSSM superfields. Then it is transmitted to the *visible sector* by some interaction



If the interaction that mediates the breaking is flavour-blind, the soft SUSY-breaking terms of the MSSM will be as well, thus moderating the flavour problem

Two examples of mechanisms of supersymmetry breaking:

- gravity-mediated SUSY breaking
- gauge-mediated SUSY breaking

In models with gravity mediation *("mSUGRA")*, (super)gravitational interactions between hidden and visible sector induce non-renormalisable SUSY-breaking terms. One may assume that the mechanism is insensitive to flavor and gauge charges of the MSSM superfields

The soft terms will be proportional to the ratio $\frac{\langle F \rangle}{M_P}$

- $\langle F \rangle$ = v.e.v. of some hidden-sector superfield that breaks supersymmetry
- M_P = Planck mass (the scale that suppresses gravity interactions)

At the high boundary scale (e.g., GUT), only four *universal* soft SUSY-breaking parameters

- $m_{1/2}$ = common mass term for the gauginos
- m_0 = common mass term for the scalars
- A_0 = common trilinear interaction term for the scalars ($T_f = Y_f A_0$)
- B_0 = Higgs scalar mixing term

These soft SUSY-breaking terms are evolved from the GUT scale down to the weak scale with the RGE of the MSSM. This will generate some deviation from universality

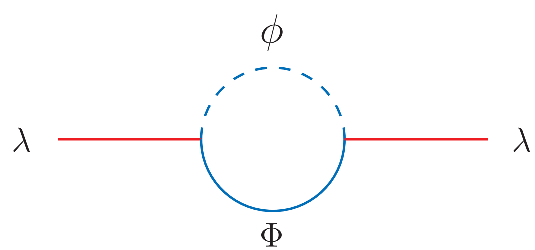
Models with gauge-mediated SUSY breaking *("GMSB")* have heavy chiral superfields, the *messengers* $(\Phi\,,\,\bar{\Phi})$, which couple directly to the SUSY-breaking sector, parameterised by $X \;=\; M + \theta\theta\, F$, but also share the MSSM gauge interactions

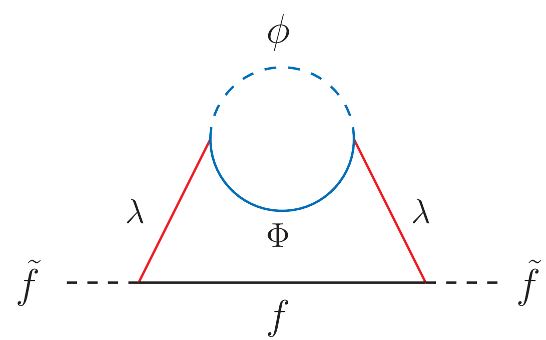
$$W_{\rm mess} = X\,\Phi\,\bar{\Phi}$$

The scalar components of the messenger superfields acquire SUSY-breaking masses

$$m^2_\Phi = M^2\,, \qquad\qquad m^2_\phi = M^2 \pm F$$

The SUSY-breaking is then transmitted to the MSSM gauginos through one-loop diagrams, and to the MSSM sfermions through two-loop diagrams





$$M_a = \frac{\alpha_a}{4\pi}\,\frac{F}{M} \qquad\qquad m^2_{\tilde{f}} = 2\sum_a C^\phi_a\,\left(\frac{\alpha_a}{4\pi}\right)^2\left(\frac{F}{M}\right)^2$$

These soft SUSY-breaking masses are RG-evolved from the messenger scale down to the weak scale. Trilinear terms are zero at the messenger scale.

The alternative is to take a pragmatic approach:

Forget the underlying model, fix the soft parameters "by hand" at the weak scale

A common choice *("phenomenological MSSM")*: neglect flavor mixing everywhere and assume common soft masses (and zero LR mixing) for the first-two-generation sfermions

$$m_{Q_3}\,,\ m_{U_3}\,,\ m_{D_3}\,,\ m_{L_3}\ \ m_{E_3}\,,\ m_Q\,,\ m_U\,,\ m_D\,,\ m_L\ \ m_E$$

$$T_t\,,\ T_b\,,\ T_\tau\,,\ M_1\,,\ M_2\,,\ M_3\,,\ B_\mu\,,\ \mu\,,\ \tan\beta$$

So far, the strongest bounds from LHC searches are on the masses of gluinos and first-two-generation squarks, $m_{\tilde g}, m_{\tilde q} > 1$ TeV, stops and sbottoms could be lighter

Electroweak Symmetry Breaking in the MSSM

The neutral components of both Higgs doublets participate in the EWSB.
Their contribution to the MSSM scalar potential is

$$
\begin{aligned}
V &= (m_{H_1}^2 + |\mu|^2)\,|H_1^0|^2 + (m_{H_2}^2 + |\mu|^2)\,|H_2^0|^2 - \left(B_\mu\, H_1^0 H_2^0 + \text{c.c.}\right) \\
&\quad + \frac{1}{8}\,(g^2 + g'^{\,2})\,\left(|H_1^0|^2 - |H_2^0|^2\right)^2
\end{aligned}
$$

NOTE: the quartic interaction is proportional to the electroweak gauge couplings.
Contrary to the SM case, the quartic Higgs coupling is not a free parameter

We can expand the Higgs fields around their v.e.v.: $H_i^0 = v_i + (S_i + i\,P_i)/\sqrt{2}$ $\quad \left(v \equiv \sqrt{v_1^2 + v_2^2}\right)$

EWSB imposes a tree-level relation involving μ, m_Z and the soft masses

$$
m_Z^2 = \left(m_{H_2}^2 \tan\beta - m_{H_1}^2 \cot\beta\right)\tan 2\beta - 2\,|\mu|^2 \qquad \left(\tan\beta \equiv \frac{v_2}{v_1}\right)
$$

Large contributions if stops are heavy: $\delta m_{H_2}^2 \approx -\frac{3\,h_t^2}{8\,\pi^2}\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\ln\frac{\Lambda_{\rm m}}{m_{\tilde t}}$ (fine tuning?)

Higgs mass spectrum: 2 Higgs doublets in the MSSM = 8 scalar degrees of freedom

(2 neutral, CP-even S_i + 2 neutral, CP-odd P_i + 4 charged $H_i^{\pm}$)

After the breaking of the electroweak symmetry we are left with 5 physical scalars (2 CP-even $h\,,H$, 1 CP-odd A, 2 charged $H^{\pm}$) and 3 would-be-Goldstone bosons ($G^0\,,G^{\pm}$)

$$m_A^2 \;=\; 2\,B_\mu/\sin 2\beta\;, \qquad\qquad m_{H^\pm}^2 \;=\; m_A^2 + m_W^2$$

At tree-level, the CP-even masses and mixing can be expressed in terms of m_A , m_Z and $\tan\beta$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix}, \qquad\qquad \tan 2\alpha = \left(\frac{m_A^2+m_Z^2}{m_A^2-m_Z^2}\right)\tan 2\beta$$

$$m_{h,H}^2 \;=\; \frac{1}{2}\left(m_A^2+m_Z^2 \mp \sqrt{(m_A^2+m_Z^2)^2 - 4\,m_Z^2\,m_A^2\,\cos^2 2\beta}\right)$$

There is an upper bound on the mass of the lightest CP-even Higgs boson

$$m_h \;<\; m_Z\,\cos 2\beta$$

Higgs mass spectrum:

2 Higgs doublets in the MSSM = 8 scalar degrees of freedom

(2 neutral, CP-even S_i + 2 neutral, CP-odd P_i + 4 charged $H_i^{\pm}$)

After the breaking of the electroweak symmetry we are left with 5 physical scalars (2 CP-even $h\,,H$, 1 CP-odd A, 2 charged $H^{\pm}$) and 3 would-be-Goldstone bosons ($G^0\,,G^{\pm}$)

$$m_A^2 \;=\; 2\,B_\mu/\sin 2\beta\ , \qquad\qquad m_{H^\pm}^2 \;=\; m_A^2 + m_W^2$$

At tree-level, the CP-even masses and mixing can be expressed in terms of m_A , m_Z and $\tan\beta$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix}, \qquad \tan 2\alpha = \left(\frac{m_A^2+m_Z^2}{m_A^2-m_Z^2}\right)\tan 2\beta$$

$$m_{h,H}^2 \;=\; \frac{1}{2}\left(m_A^2+m_Z^2 \mp \sqrt{(m_A^2+m_Z^2)^2 - 4\,m_Z^2\,m_A^2\,\cos^2 2\beta}\right)$$

There is an upper bound on the mass of the lightest CP-even Higgs boson

$$m_h \;<\; m_Z\,\cos 2\beta\;+\Delta$$

Luckily for the MSSM, radiative corrections can substantially relax the bound (details later)

After diagonalizing the various matrices of Yukawa couplings as in the SM, the quark and lepton masses are (e.g. for the third family)

$$m_\tau = h_\tau \, v_1 \,, \qquad m_b = h_b \, v_1 \,, \qquad m_t = h_t \, v_2$$

Since $v_1 = v \cos\beta$ and $v_2 = v \sin\beta$ the MSSM Yukawa couplings are rescaled w.r.t. their SM counterparts

$$h_\tau = \frac{h_\tau^{\rm SM}}{\cos\beta} \,, \qquad h_b = \frac{h_b^{\rm SM}}{\cos\beta} \,, \qquad h_t = \frac{h_t^{\rm SM}}{\sin\beta} \,,$$

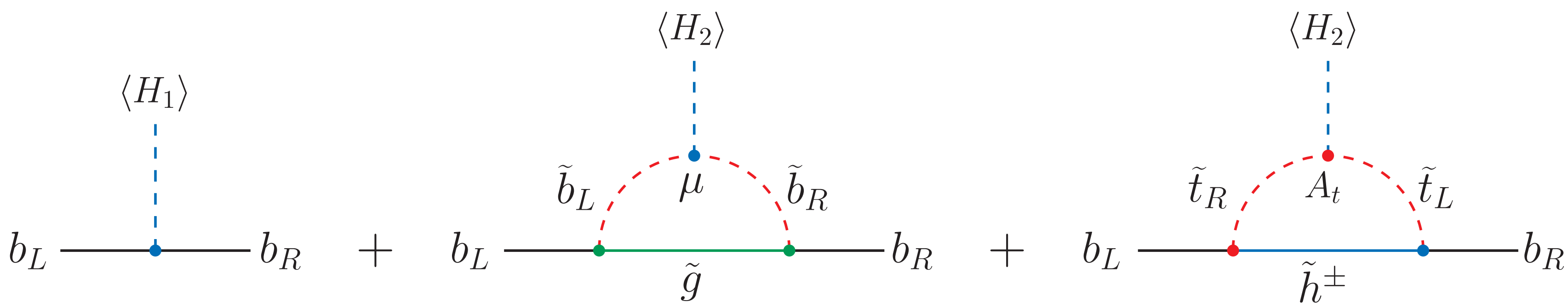
In particular, $\dfrac{h_b}{h_t} = \dfrac{m_b}{m_t} \tan\beta$, thus $h_b \simeq h_t$ for $\tan\beta \sim 40 - 50$

$\Rightarrow$ interactions involving the bottom Yukawa are enhanced at large $\tan\beta$

Requiring that the Yukawa couplings remain perturbative up to large scales provides a range of allowed values for $\tan\beta$:

$$1.5 \lesssim \tan\beta \lesssim 55$$

The relation between bottom mass and Yukawa coupling receives *tanβ*-enhanced corrections



$$m_b \;=\; h_b\, v_1 \;+\; \frac{2\,\alpha_s}{3\pi}\, m_{\tilde{g}}\, \mu\, h_b\, v_2\, I(m^2_{\tilde{q}_L}, m^2_{\tilde{b}_R}, m^2_{\tilde{g}}) \;+\; \frac{\alpha_t}{4\pi}\, A_t\, \mu\, h_b\, v_2\, I(m^2_{\tilde{q}_L}, m^2_{\tilde{t}_R}, |\mu|^2) \;+\; (\ldots)$$

$$\longrightarrow \qquad h_b \approx \frac{m_b}{v \cos\beta\,(1+\epsilon_b\,\tan\beta)}$$

These corrections survive for heavy SUSY: $\epsilon_b \;\approx\; \frac{\alpha_s}{3\pi}\,\frac{\mu\, m_{\tilde{g}}}{m^2_{\tilde{b}}} \;+\; \frac{\alpha_t}{8\pi}\,\frac{\mu\, A_t}{m^2_{\tilde{t}}}$

They depend on the sign and size of μ: bottom Yukawa suppressed (enhanced) for $\mu>0$ ($\mu<0$)

The couplings of the Higgs bosons to the SM particles depend on the Higgs mixing angles

$$g_{hVV} = \frac{\sqrt{2}\, m_V^2}{v}\, \sin(\beta-\alpha)\,, \qquad g_{HVV} = \frac{\sqrt{2}\, m_V^2}{v}\, \cos(\beta-\alpha) \qquad (V=W,Z)$$

$$g_{ht\bar{t}} = \frac{1}{\sqrt{2}} \frac{\cos\alpha}{\sin\beta}\, \frac{m_t}{v}\,, \qquad g_{hb\bar{b}} = -\frac{1}{\sqrt{2}} \frac{\sin\alpha}{\cos\beta}\, \frac{m_b}{v}\,, \qquad g_{h\tau^+\tau^-} = -\frac{1}{\sqrt{2}} \frac{\sin\alpha}{\cos\beta}\, \frac{m_\tau}{v}\,,$$

$$g_{Ht\bar{t}} = \frac{1}{\sqrt{2}} \frac{\sin\alpha}{\sin\beta}\, \frac{m_t}{v}\,, \qquad g_{Hb\bar{b}} = \frac{1}{\sqrt{2}} \frac{\cos\alpha}{\cos\beta}\, \frac{m_b}{v}\,, \qquad g_{H\tau^+\tau^-} = \frac{1}{\sqrt{2}} \frac{\cos\alpha}{\cos\beta}\, \frac{m_\tau}{v}\,,$$

$$g_{hAZ} = \frac{g\, \cos(\beta-\alpha)}{2\, \cos\theta_W}\, (p_h - p_A)\,, \qquad g_{HAZ} = \frac{-g\, \sin(\beta-\alpha)}{2\, \cos\theta_W}\, (p_H - p_A)$$

$$g_{At\bar{t}} = \frac{\gamma_5}{\sqrt{2}}\, \cot\beta\, \frac{m_t}{v}, \qquad g_{Ab\bar{b}} = \frac{\gamma_5}{\sqrt{2}}\, \tan\beta\, \frac{m_b}{v}, \qquad g_{A\tau^+\tau^-} = \frac{\gamma_5}{\sqrt{2}}\, \tan\beta\, \frac{m_\tau}{v},$$

$$g_{H^+t\bar{b}} = \frac{1}{\sqrt{2}v} \left[m_t\, \cot\beta\, P_R + m_b\, \tan\beta\, P_L\right]\,, \qquad g_{H^+\tau\nu_\tau} = \frac{1}{\sqrt{2}v} \left[m_\tau\, \tan\beta\, P_L\right]$$

- Interesting simplifications arise in the decoupling limit of the MSSM, i.e. for $m_A >> m_Z$

$$\cos(\beta-\alpha)\approx 0, \quad \sin(\beta-\alpha)\approx 1, \quad \cos\alpha \approx \sin\beta, \quad \sin\alpha\approx -\cos\beta$$

  - the lightest CP-even Higgs stays light, the others are heavy and close in mass

$$m_h^2 \approx m_Z^2 \cos^2 2\beta\,, \qquad m_H^2 \approx m_A^2 + m_Z^2 \sin^2 2\beta\,, \qquad m_{H^\pm}^2 = m_A^2 + m_W^2$$

  - the couplings of the lightest CP-even Higgs boson approach their SM limit

$$g_{hVV} \approx \frac{\sqrt{2}\, m_V^2}{v}\,, \qquad g_{hAZ}\approx 0\,, \qquad g_{hf\bar{f}} \approx \frac{m_f}{\sqrt{2}v}$$

  - The heavy Higgses are decoupled from the gauge bosons, and their couplings to up-type (down-type) SM fermions are suppressed (enhanced) by *tanβ*

We are left with a light, *SM-like* Higgs boson h plus a heavy exotic multiplet (*H, A,* $H^{\pm}$)

- The anti-decoupling limit is for $m_A \approx m_Z$ and large *tanβ* : $\begin{cases} H \text{ is the SM-like boson} \\ (h, A, H^{\pm}) \text{ light exotic multiplet} \end{cases}$

- The intermediate-coupling regime is for $m_A \lesssim m_Z$ and moderate *tanβ*

(neither scalar is SM-like)

The effect of EWSB on the superparticle masses

In the super-CKM basis, the quark mass matrices $m_{u,d}$ are diagonalised, and the squark fields are rotated parallel to the quark mass eigenstates

The breaking of the electroweak symmetry induces a mixing between the superpartners of left- and right-handed quarks. This results in 6x6 squark mass matrices

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} V_{\rm CKM}\,\hat{m}^2_Q\,V^\dagger_{\rm CKM} + m^2_u + D_{u_L} & v_2\,\hat{T}_U - \mu^*\,m_u\,\cot\beta \\ v_2\,\hat{T}^\dagger_U - \mu\,m_u\,\cot\beta & \hat{m}^2_U + m^2_u + D_{u_R} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{d}} = \begin{pmatrix} \hat{m}^2_Q + m^2_d + D_{d_L} & v_1\,\hat{T}_D - \mu^*\,m_d\,\tan\beta \\ v_1\,\hat{T}_D - \mu\,m_d\,\tan\beta & \hat{m}^2_D + m^2_d + D_{d_R} \end{pmatrix}$$

Flavor mixing can arise in the 3x3 soft SUSY-breaking mass matrices $\hat{m}^2_Q,\,\hat{m}^2_{U,D}$, and in the trilinear coupling matrices $\hat{T}_{U,D}$ (the hats denote the CKM rotation)

In the Minimal Flavour Violation (MFV) scenario those matrices are assumed to be flavor-diagonal, so that the only source of flavor mixing is the CKM matrix

The effect of EWSB on the superparticle masses

In the super-CKM basis, the quark mass matrices $m_{u,d}$ are diagonalised, and the squark fields are rotated parallel to the quark mass eigenstates

The breaking of the electroweak symmetry induces a mixing between the superpartners of left- and right-handed quarks. This results in 6x6 squark mass matrices

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} V_{\rm CKM}\, \hat{m}^2_Q\, V^\dagger_{\rm CKM} + m_u^2 + D_{u_L} & v_2\, \hat{T}_U - \mu^*\, m_u\, \cot\beta \\ v_2\, \hat{T}_U^\dagger - \mu\, m_u\, \cot\beta & \hat{m}^2_U + m_u^2 + D_{u_R} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{d}} = \begin{pmatrix} \hat{m}^2_Q + m_d^2 + D_{d_L} & v_1\, \hat{T}_D - \mu^*\, m_d\, \tan\beta \\ v_1\, \hat{T}_D - \mu\, m_d\, \tan\beta & \hat{m}^2_D + m_d^2 + D_{d_R} \end{pmatrix}$$

Flavor mixing can arise in the 3x3 soft SUSY-breaking mass matrices $\hat{m}^2_Q,\ \hat{m}^2_{U,D}$, and in the trilinear coupling matrices $\hat{T}_{U,D}$ (the hats denote the CKM rotation)

In the Minimal Flavour Violation (MFV) scenario those matrices are assumed to be flavor-diagonal, so that the only source of flavor mixing is the CKM matrix

If the MFV condition does not hold, the squark mass eigenstates will be linear combinations of the flavour eigenstates of the super-CKM basis

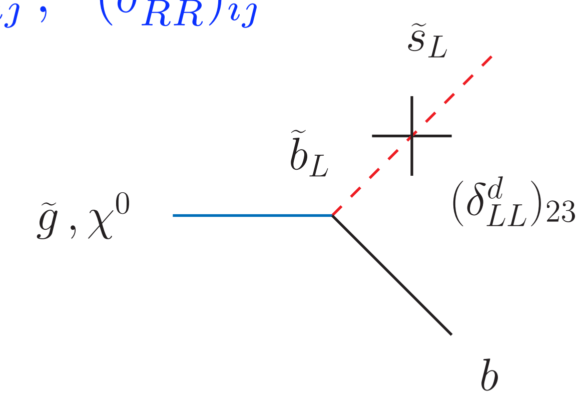
$$\begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix} = \mathbf{Z_D} \cdot \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix}, \qquad \begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix} = \mathbf{Z_U} \cdot \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$

($\mathbf{Z_D}$ and $\mathbf{Z_U}$ are 6x6 rotation matrices)

In the Mass Insertion Approximation we leave the squarks in the super-CKM basis and treat the off-diagonal entries of the mass matrices as flavour-changing mass insertions

$$(\delta^u_{LL})_{ij}\,, \quad (\delta^u_{LR})_{ij}\,, \quad (\delta^u_{RR})_{ij}\,, \quad (\delta^d_{LL})_{ij}\,, \quad (\delta^d_{LR})_{ij}\,, \quad (\delta^d_{RR})_{ij}$$

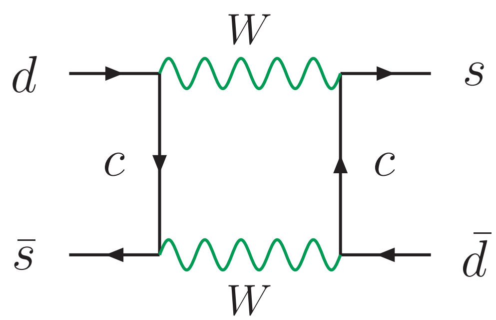
Such mass insertions will generate flavour-changing gluino and neutralino vertices, e.g.

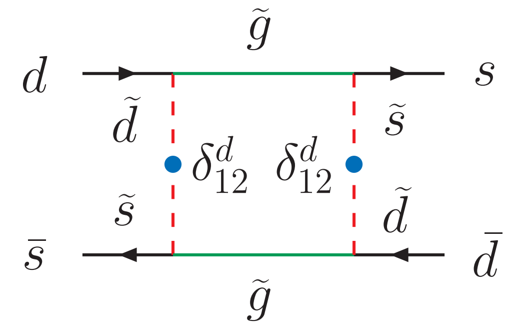


The MIA works fine as long as the flavour-changing insertions are much smaller than the flavour-diagonal mass terms (otherwise we need the full calculation)

The agreement between the SM predictions and the existing measurements of FCNC processes imposes strict bounds on the size of most flavour-changing mass insertions

(consider e.g. the SM and SUSY contributions to the $K^0 - \overline{K}^0$ mixing)





$$\sim \frac{\alpha^2\,\lambda_C^2}{16\pi^2\,m_W^2}\,\frac{m_c^2}{m_W^2} \qquad\qquad \sim \frac{\alpha_S^2}{16\pi^2\,m_{\tilde{q}}^2}\,\frac{(\delta^d_{12})^2}{m_{\tilde{q}}^4}$$

If there is any flavor violation in the squark mass matrix it must be quite small (or the squarks must be quite heavy)

We can take MFV as a reasonable approximation to the realistic case

Remember however that even in models where SUSY breaking is flavour-blind a small amount of flavour mixing in the squark masses is generated by RGE

If we neglect flavor mixing only the third-generation sfermions mix, due to their sizeable Yukawa interactions. It is customary to redefine the trilinear couplings

$$(\hat{T}_U)_{33} = h_t\, A_t\,, \qquad (\hat{T}_D)_{33} = h_b\, A_b\,, \qquad (\hat{T}_E)_{33} = h_\tau\, A_\tau$$

EWSB induces a (2x2) mixing between “L” and “R” squarks, e.g. for the stops

$$\begin{pmatrix} m^2_{Q_3} + m^2_t + D_{t_L} & m_t\,(A_t - \mu\cot\beta) \\ m_t\,(A_t - \mu\cot\beta) & m^2_{U_3} + m^2_t + D_{t_R} \end{pmatrix}$$

$$D_{t_L} = \frac{1}{6}\cos 2\beta\,(4\,m^2_W - m^2_Z)\,, \quad D_{t_R} = \frac{2}{3}\cos 2\beta\,(m^2_Z - m^2_W)$$

The mass matrix is diagonalised by a rotation with an angle $\theta_{\tilde{t}}$

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{t}} & \sin\theta_{\tilde{t}} \\ -\sin\theta_{\tilde{t}} & \cos\theta_{\tilde{t}} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

Same happens for the sbottoms (and staus). In that case however the L-R mixing term is $m_{b,\tau}\,(A_{b,\tau} - \mu\,\tan\beta)$, enhanced only for large values of $\tan\beta$

The breaking of the electroweak symmetry also induces a mixing among all the fermionic superparticles (gauginos, higgsinos) with the same charge and colour

Because of the SUSY interaction Higgs-higgsino-gaugino, when the Higgs bosons get a v.e.v. the two charged winos and the two charged higgsinos mix

$$\mathcal{L} \supset -\frac{1}{2} \begin{pmatrix} -i\tilde{w}^- & \tilde{h}_1^- \end{pmatrix} \begin{pmatrix} M_2 & g\,v_2 \\ g\,v_1 & \mu \end{pmatrix} \begin{pmatrix} -i\tilde{w}^+ \\ \tilde{h}_2^+ \end{pmatrix} + \text{c.c.}$$

the mass matrix is diagonalised by two unitary rotations U and V :

$$\begin{pmatrix} \chi_1^- \\ \chi_2^- \end{pmatrix} = U \begin{pmatrix} -i\tilde{w}^- \\ \tilde{h}_1^- \end{pmatrix} , \qquad \begin{pmatrix} \chi_1^+ \\ \chi_2^+ \end{pmatrix} = V \begin{pmatrix} -i\tilde{w}^+ \\ \tilde{h}_2^+ \end{pmatrix}$$

$$U^* \begin{pmatrix} M_2 & g\,v_2 \\ g\,v_1 & \mu \end{pmatrix} V^{-1} = \begin{pmatrix} m_{\chi_1} & 0 \\ 0 & m_{\chi_2} \end{pmatrix}$$

the two electrically charged mass eigenstates $(\chi_1^\pm \,, \chi_2^\pm)$ are called charginos

Similarly, the bino, the neutral wino and the two neutral higgsinos mix

$$\begin{pmatrix} -i\tilde{b} & -i\tilde{w}^0 & \tilde{h}_1^0 & \tilde{h}_2^0 \end{pmatrix} \begin{pmatrix} M_1 & 0 & -g'\,v_1/\sqrt{2} & g'\,v_2/\sqrt{2} \\ 0 & M_2 & g\,v_1/\sqrt{2} & -g\,v_2/\sqrt{2} \\ -g'\,v_1/\sqrt{2} & g\,v_1/\sqrt{2} & 0 & -\mu \\ g'\,v_2/\sqrt{2} & -g\,v_2/\sqrt{2} & -\mu & 0 \end{pmatrix} \begin{pmatrix} -i\tilde{b} \\ -i\tilde{w}^0 \\ \tilde{h}_1^0 \\ \tilde{h}_2^0 \end{pmatrix}$$

The mass matrix is diagonalised by a unitary matrix N. The four mass eigenstates $(\chi_1^0,\, \chi_2^0,\, \chi_3^0,\, \chi_4^0)$ are called neutralinos

Finally, the gluino is a colour octet thus it does not mix with any other fermion. At tree level the gluino mass coincides with the soft SUSY-breaking parameter M_3.

Digression: three bonus features of the MSSM

All searches for superparticles at LEP, Tevatron and LHC have been fruitless so far.
Until they are detected, some skepticism about SUSY is justified

However, besides providing a technical solution to the hierarchy problem,
the MSSM has a few more attractive features:

- Neutralino as a Dark Matter candidate (if R-parity is conserved)
- Gauge coupling unification
- Radiative breaking of EW symmetry

While none of these features can be invoked as a *proof* of the validity of the MSSM,
they look somehow too good to be false...

Gauge coupling unification

The gauge group of the SM, $SU(3)_C \times SU(2)_L \times U(1)_Y$, looks unnecessarily complicated

It is reasonable to suspect that this is just the low-energy relic of some greater (and simpler) symmetry that is manifest at higher energy scales

Examples of such *grand-unified* theories are based on the symmetry groups $SU(5)$ or $SO(10)$

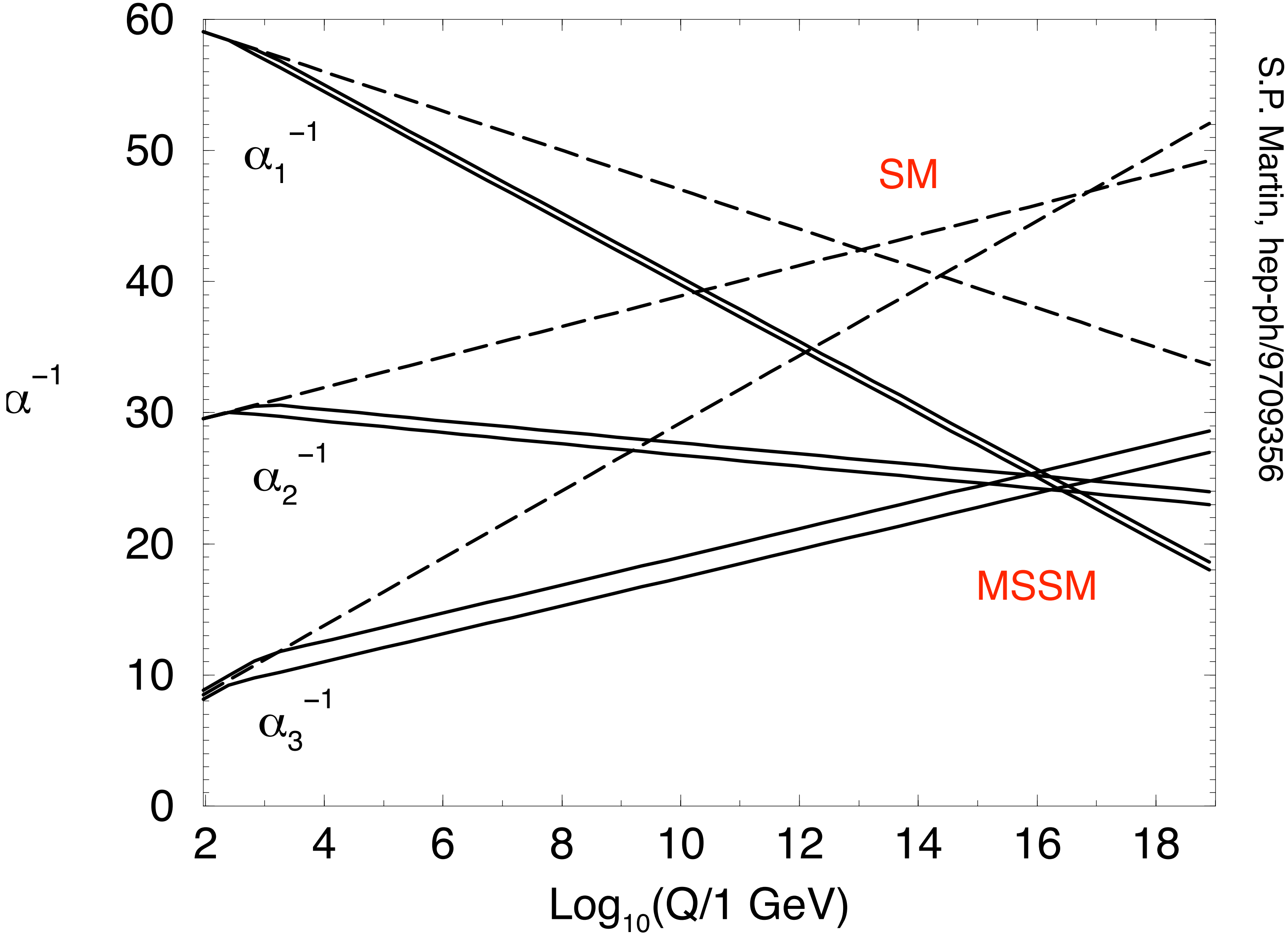
A key aspect of grand-unified theories is that, at some high energy scale, the three gauge couplings of the SM must unify

At one-loop order, the RGE for the gauge couplings are:

$$\frac{d\,\alpha_i}{d\log Q} = -\frac{b_i}{2\,\pi}\,\alpha_i^2 \qquad (i{=}1{,}2{,}3)$$

The coefficients b_i depend on the particle content of the theory:

$$b_i^{\rm SM} = \left(\frac{41}{10}\,,\,-\frac{19}{16}\,,\,-7\right), \qquad b_i^{\rm MSSM} = \left(\frac{33}{5}\,,\,1\,,\,-3\right)$$



The MSSM works much better! It is in agreement with unification at $M_{\rm GUT} \approx 2 \times 10^{16}$ GeV

Can this be just a coincidence?

Radiative EWSB

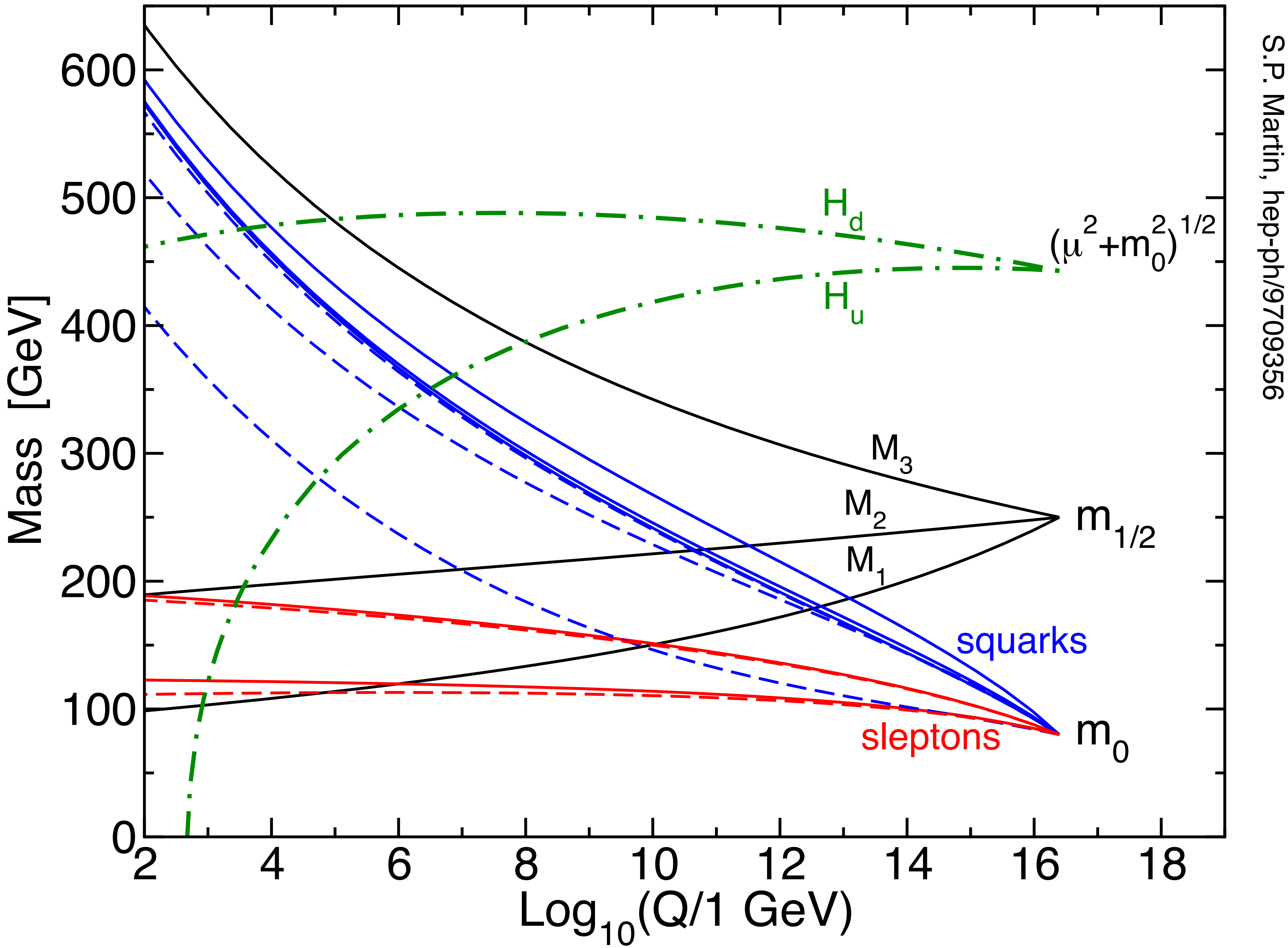
To ensure the spontaneous breaking of the electroweak symmetry,
the squared mass term in the Higgs potential must be negative

In the Standard Model the mass term is a free parameter of the Lagrangian.
The condition $m^2 < 0$ must be imposed "by hand"

In the MSSM, the Higgs mass terms are in the soft SUSY-breaking Lagrangian.
The RGE for $m^2_{H_2}$ has a large positive contribution from the top Yukawa coupling:

$$\frac{d\,m^2_{H_2}}{d\log Q} \;=\; \frac{h_t^2}{8\pi^2}\left(m^2_{H_2} + m^2_{Q_3} + m^2_{U_3} + A_t^2\right) \;+\; \mathrm{EW\ terms}$$

Therefore, even if $m^2_{H_2}$ starts positive at the high scale where SUSY is broken,
the radiative corrections make it negative at the weak scale, triggering EWSB

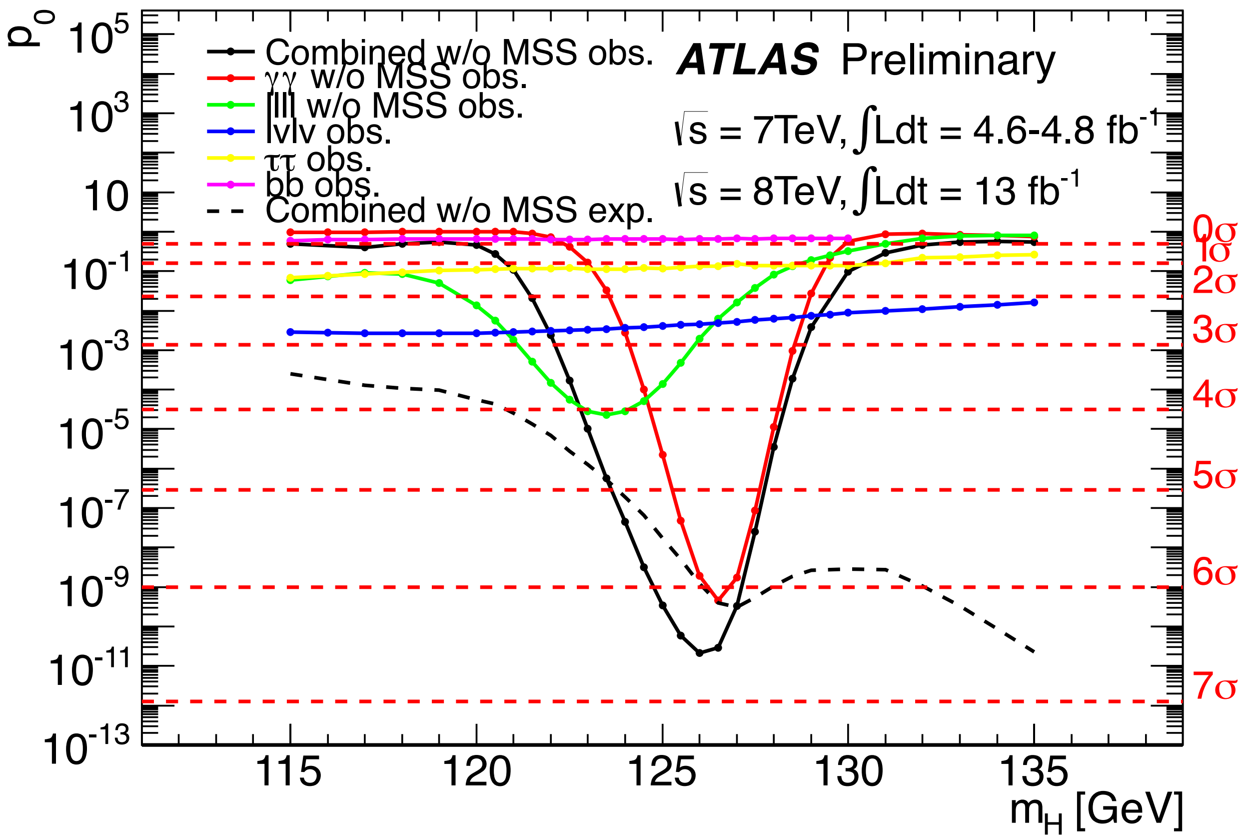


S.P. Martin, hep-ph/9709356
Mass [GeV]
Log$_{10}$(Q/1 GeV)
0
100
200
300
400
500
600
2
4
6
8
10
12
14
16
18
H_d
H_u
$(\mu^2+m_0^2)^{1/2}$
M_3
M_2
M_1
$m_{1/2}$
squarks
sleptons
m_0

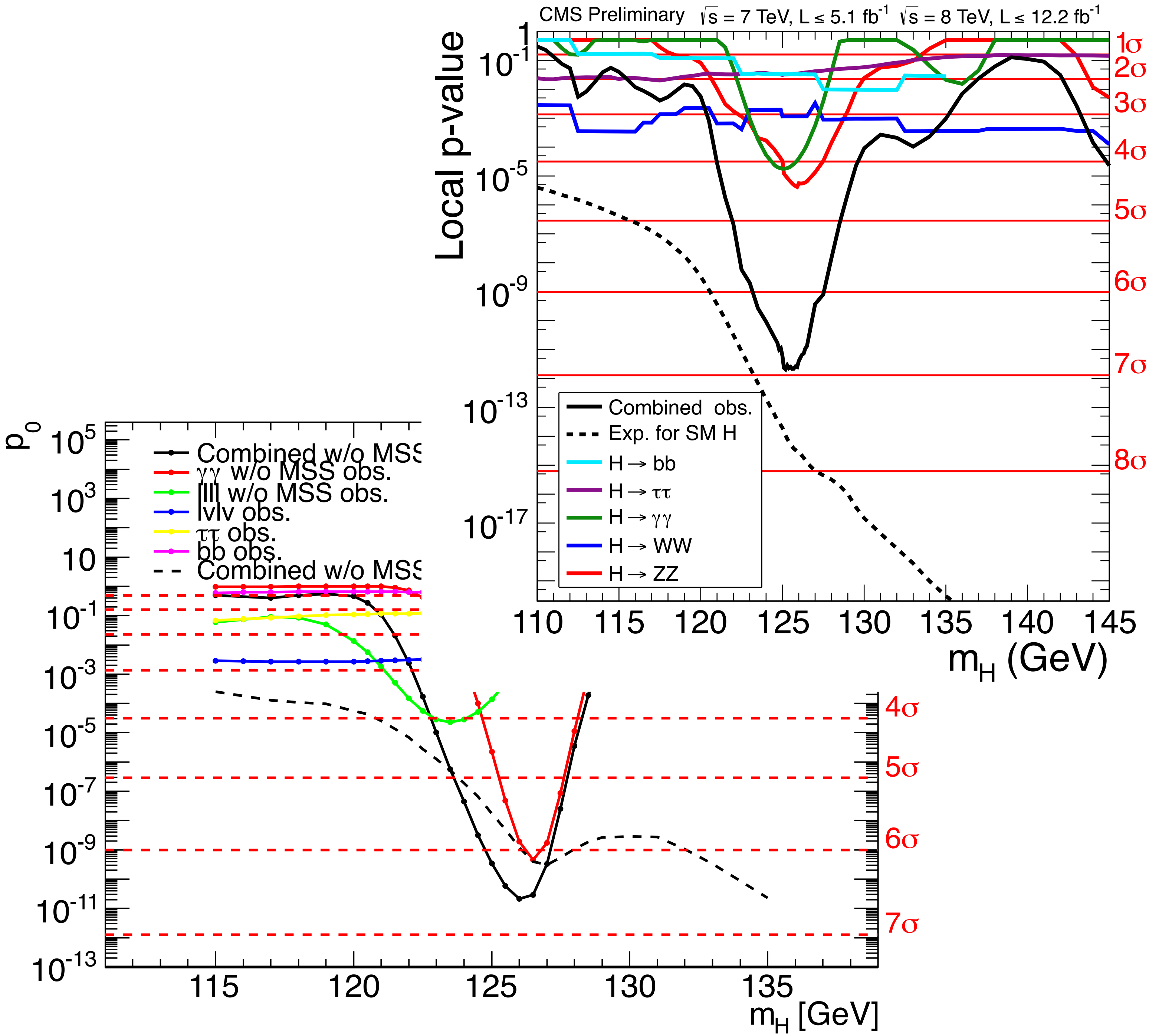
Interpreting a 125-GeV Higgs in the MSSM

The Signal

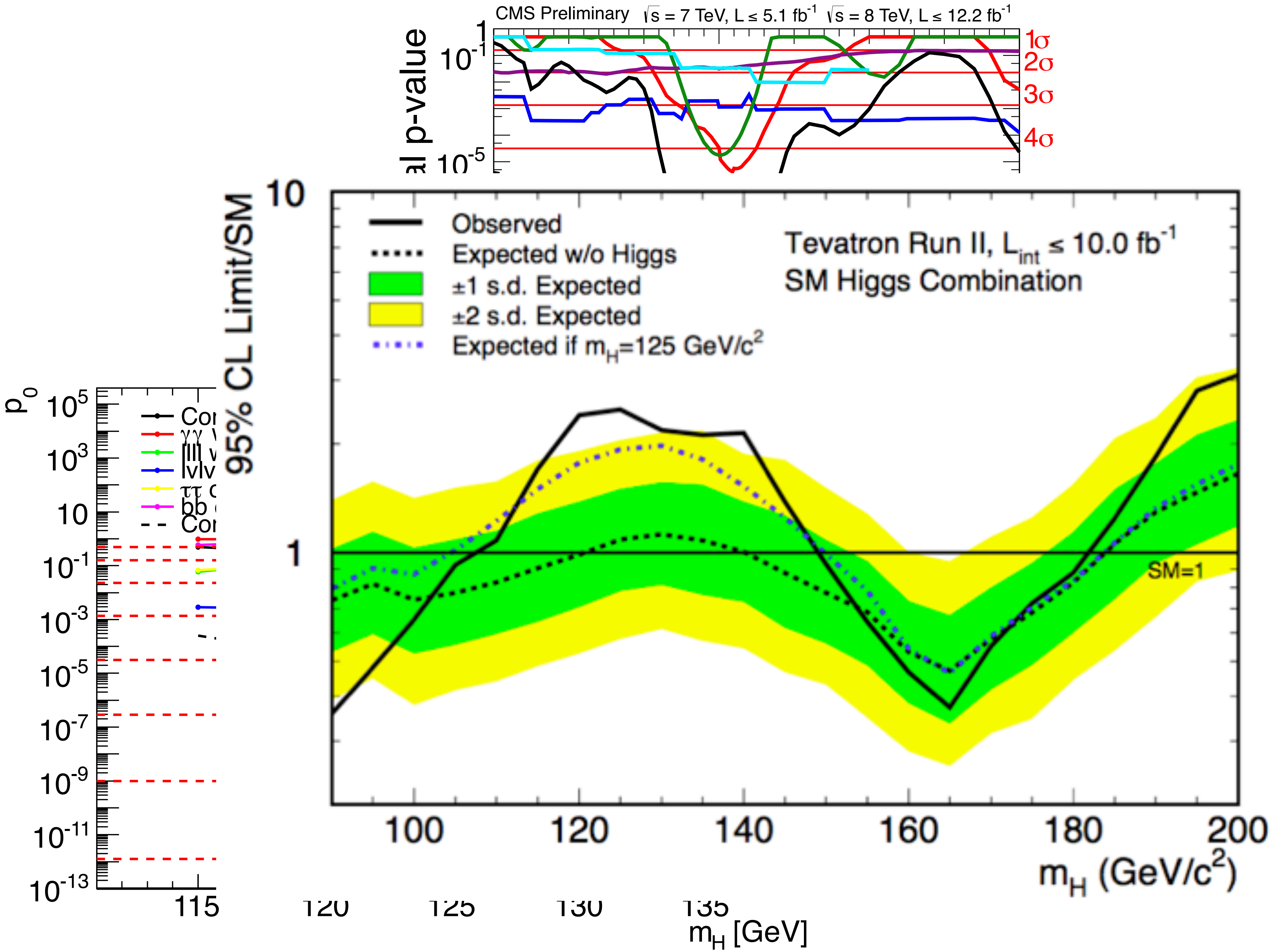
A Higgs boson!!!



p0
10^5
10^3
10
10^-1
10^-3
10^-5
10^-7
10^-9
10^-11
10^-13
Combined w/o MSS obs.
γγ w/o MSS obs.
llll w/o MSS obs.
lνlν obs.
ττ obs.
bb obs.
Combined w/o MSS exp.
ATLAS Preliminary
√s = 7TeV, ∫Ldt = 4.6-4.8 fb-1
√s = 8TeV, ∫Ldt = 13 fb-1
0σ
1σ
2σ
3σ
4σ
5σ
6σ
7σ
115
120
125
130
135
mH [GeV]

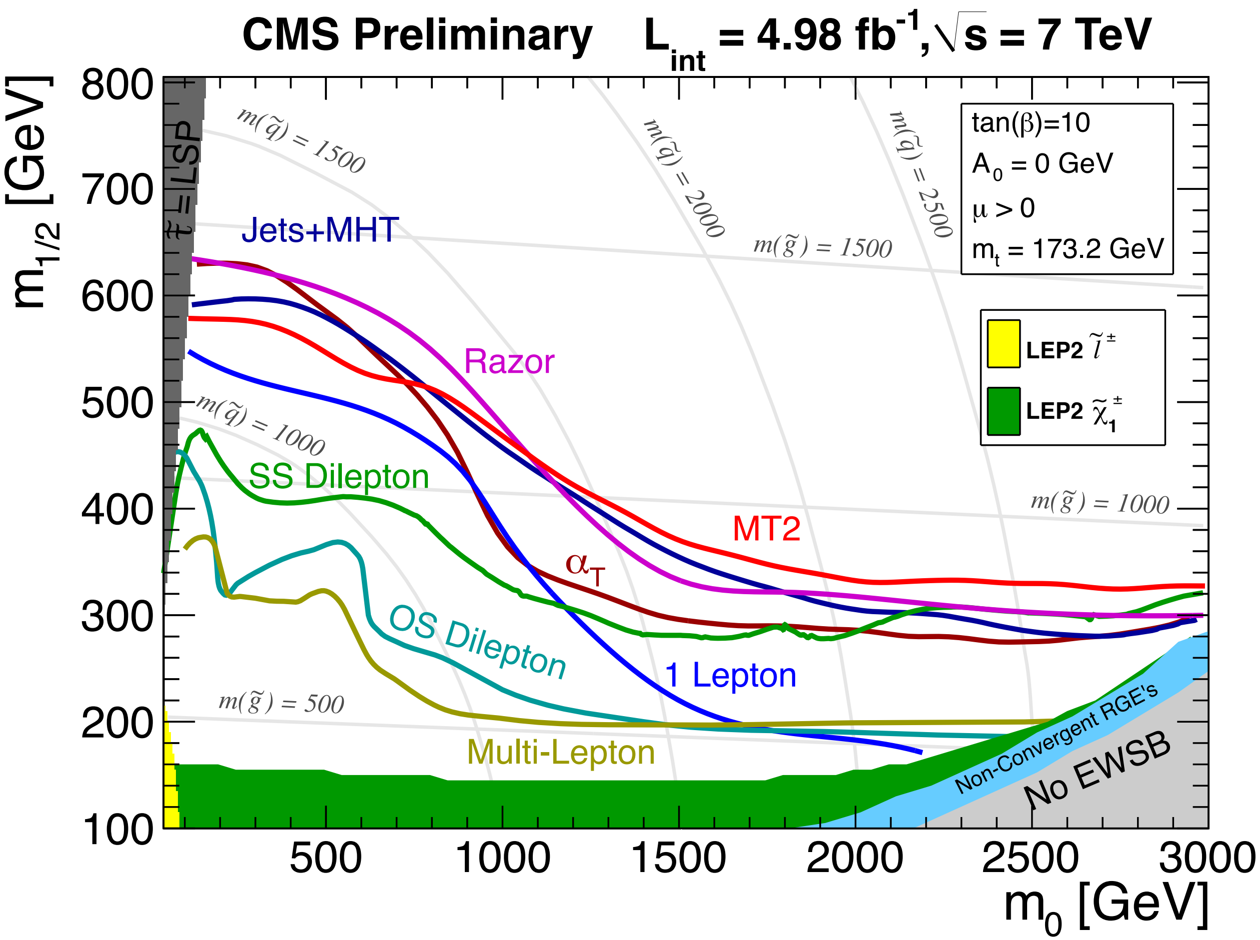


CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb⁻¹ √s = 8 TeV, L ≤ 12.2 fb⁻¹
Local p-value
m_H (GeV)
Combined obs.
Exp. for SM H
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
1σ
2σ
3σ
4σ
5σ
6σ
7σ
8σ
p_0
Combined w/o MSS
γγ w/o MSS obs.
llll w/o MSS obs.
lνlν obs.
ττ obs.
bb obs.
Combined w/o MSS
m_H [GeV]

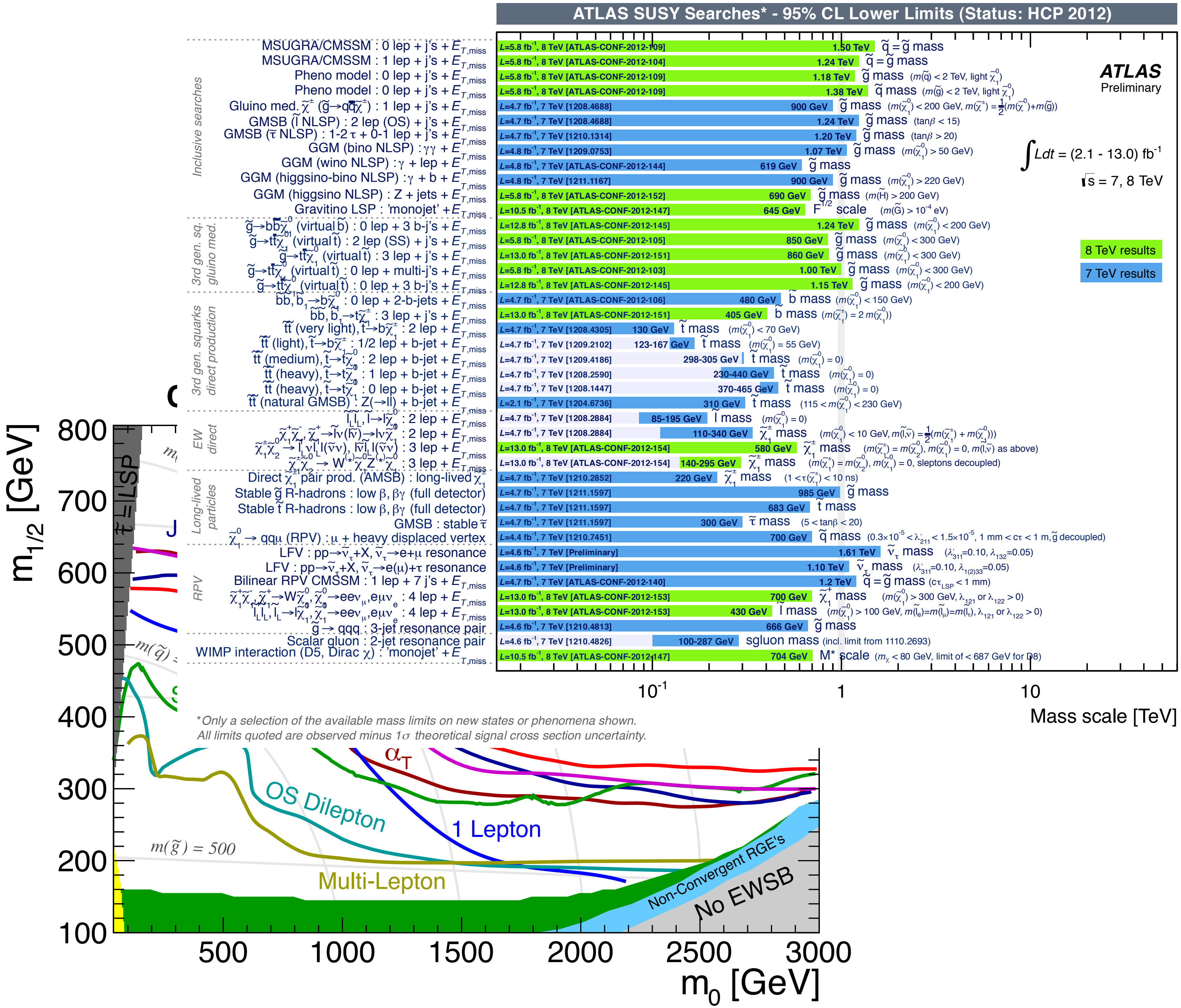

CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 12.2 fb-1
1σ
2σ
3σ
4σ
Observed
Expected w/o Higgs
±1 s.d. Expected
±2 s.d. Expected
Expected if mH=125 GeV/c2
Tevatron Run II, Lint ≤ 10.0 fb-1
SM Higgs Combination
SM=1
95% CL Limit/SM
mH (GeV/c2)
100
120
140
160
180
200
p0
115
120
125
130
135
mH [GeV]

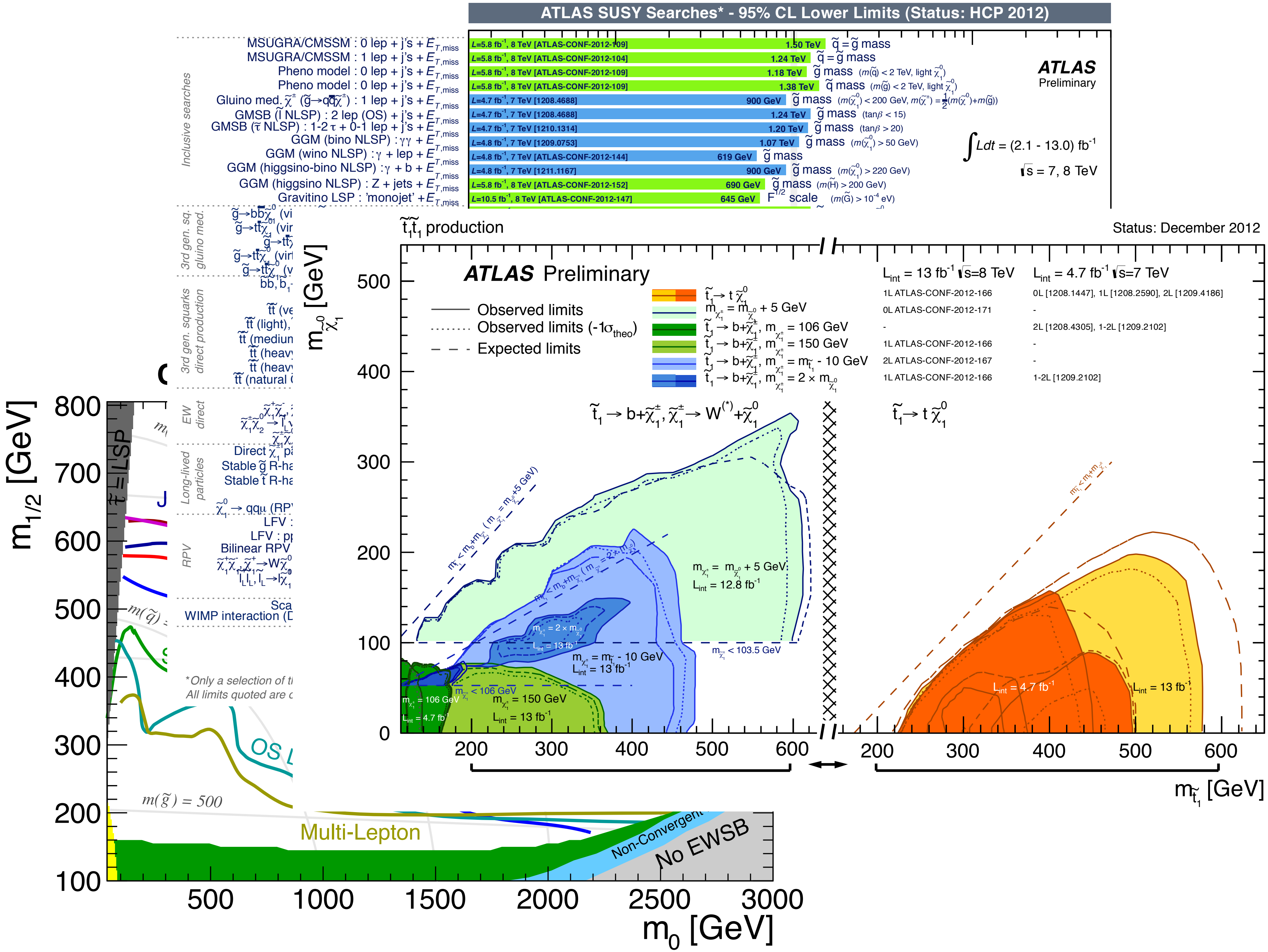
The Lack of Signal

New colored particles, more Higgs bosons, ...

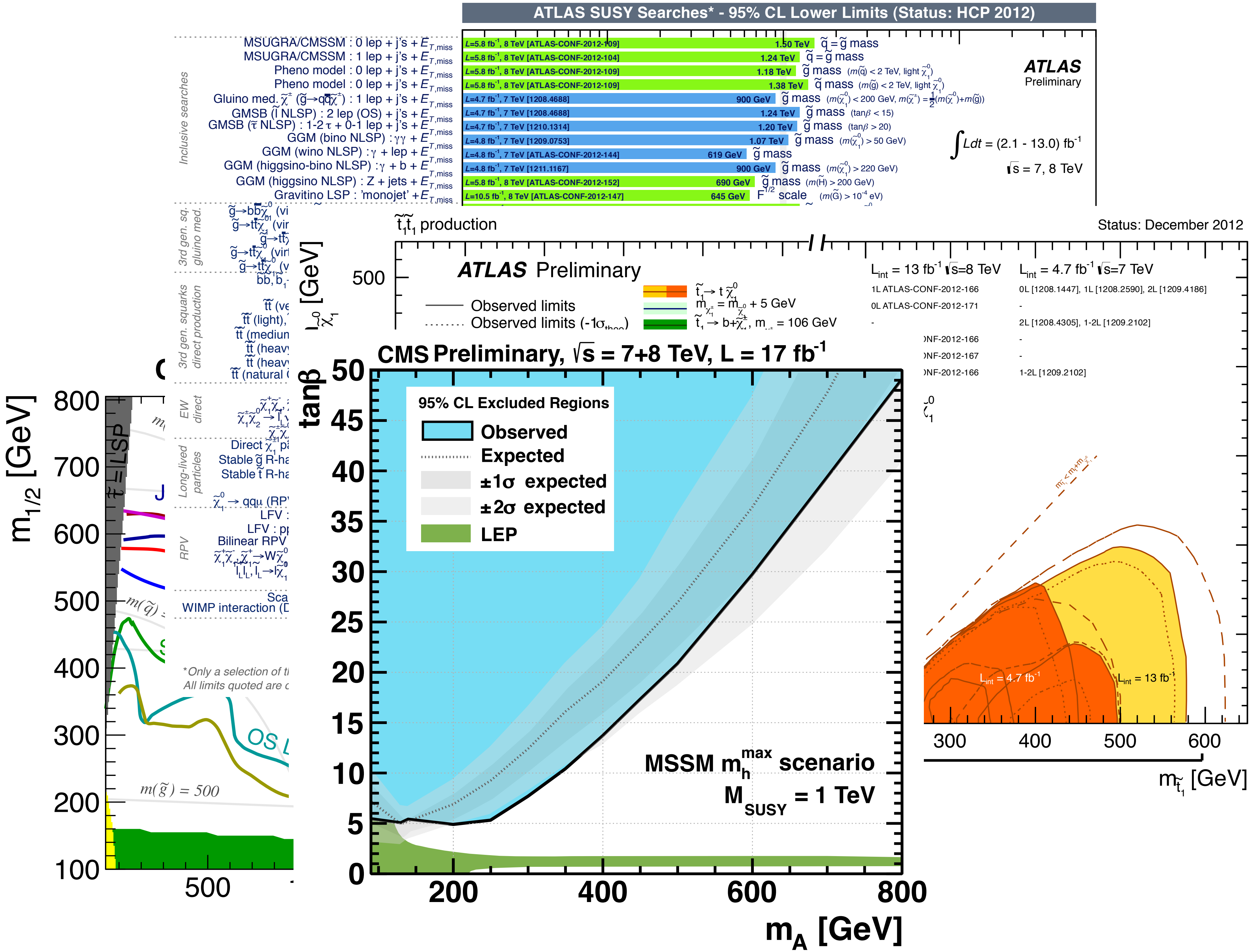

CMS Preliminary L_{int} = 4.98 fb^{-1}, $\sqrt{s}$ = 7 TeV
$m_{1/2}$ [GeV]
m_0 [GeV]
tan(β)=10
A_0 = 0 GeV
μ > 0
m_t = 173.2 GeV
LEP2 $\tilde{l}^{\pm}$
LEP2 $\tilde{\chi}_1^{\pm}$
$\tilde{\tau}$ = LSP
Jets+MHT
Razor
MT2
α_T
SS Dilepton
OS Dilepton
1 Lepton
Multi-Lepton
Non-Convergent RGE's
No EWSB
$m(\tilde{q})$ = 1500
$m(\tilde{q})$ = 2000
$m(\tilde{q})$ = 2500
$m(\tilde{q})$ = 1000
$m(\tilde{g})$ = 1500
$m(\tilde{g})$ = 1000
$m(\tilde{g})$ = 500

bosons, ...

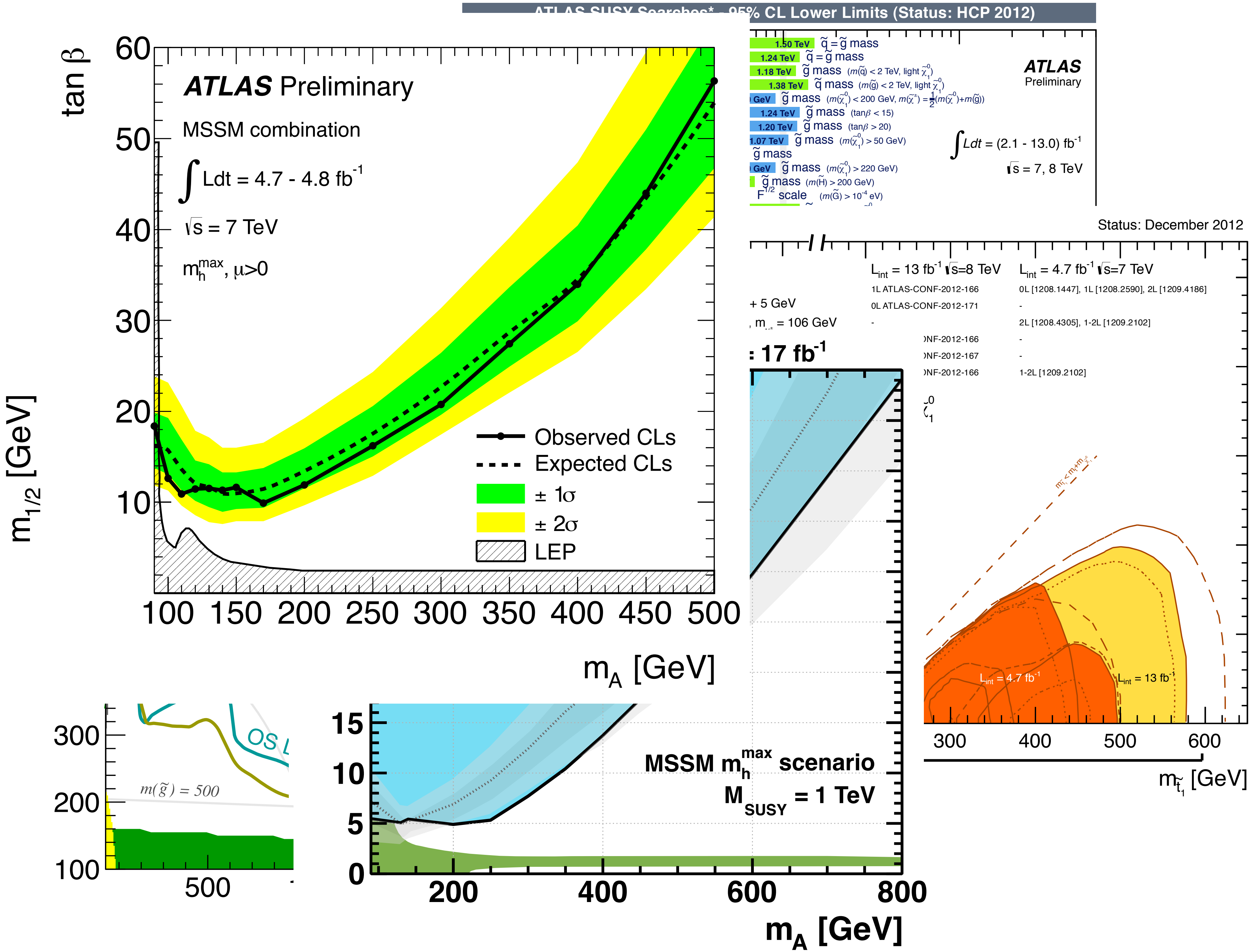

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
ATLAS
Preliminary
∫Ldt = (2.1 - 13.0) fb⁻¹
√s = 7, 8 TeV
8 TeV results
7 TeV results
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + E_T,miss
L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-109] 1.50 TeV q̃ = g̃ mass
MSUGRA/CMSSM : 1 lep + j's + E_T,miss
L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-104] 1.24 TeV q̃ = g̃ mass
Pheno model : 0 lep + j's + E_T,miss
L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-109] 1.18 TeV g̃ mass
Pheno model : 0 lep + j's + E_T,miss
L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-109] 1.38 TeV q̃ mass
L=4.7 fb⁻¹, 7 TeV [1208.4688] 900 GeV g̃ mass
L=4.7 fb⁻¹, 7 TeV [1208.4688] 1.24 TeV g̃ mass
L=4.7 fb⁻¹, 7 TeV [1210.1314] 1.20 TeV g̃ mass
L=4.8 fb⁻¹, 7 TeV [1209.0753] 1.07 TeV g̃ mass
L=4.8 fb⁻¹, 7 TeV [ATLAS-CONF-2012-144] 619 GeV g̃ mass
L=4.8 fb⁻¹, 7 TeV [1211.1167] 900 GeV g̃ mass
L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-152] 690 GeV g̃ mass
Gravitino LSP : 'monojet' + E_T,miss
L=10.5 fb⁻¹, 8 TeV [ATLAS-CONF-2012-147] 645 GeV F^1/2 scale
3rd gen. squ. gluino med.
L=12.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-145] 1.24 TeV g̃ mass
L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-105] 850 GeV g̃ mass
L=13.0 fb⁻¹, 8 TeV [ATLAS-CONF-2012-151] 860 GeV g̃ mass
L=5.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-103] 1.00 TeV g̃ mass
L=12.8 fb⁻¹, 8 TeV [ATLAS-CONF-2012-145] 1.15 TeV g̃ mass
3rd gen. squarks direct production
L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2012-106] 480 GeV b̃ mass
L=13.0 fb⁻¹, 8 TeV [ATLAS-CONF-2012-151] 405 GeV b̃ mass
L=4.7 fb⁻¹, 7 TeV [1208.4305] 130 GeV t̃ mass
L=4.7 fb⁻¹, 7 TeV [1209.2102] 123-167 GeV t̃ mass
L=4.7 fb⁻¹, 7 TeV [1209.4186] 298-305 GeV t̃ mass
L=4.7 fb⁻¹, 7 TeV [1208.2590] 230-440 GeV t̃ mass
L=4.7 fb⁻¹, 7 TeV [1208.1447] 370-465 GeV t̃ mass
L=2.1 fb⁻¹, 7 TeV [1204.6736] 310 GeV t̃ mass
EW direct
L=4.7 fb⁻¹, 7 TeV [1208.2884] 85-195 GeV l̃ mass
L=4.7 fb⁻¹, 7 TeV [1208.2884] 110-340 GeV χ̃₁± mass
L=13.0 fb⁻¹, 8 TeV [ATLAS-CONF-2012-154] 580 GeV χ̃₁± mass
L=13.0 fb⁻¹, 8 TeV [ATLAS-CONF-2012-154] 140-295 GeV χ̃₁± mass
Long-lived particles
Direct χ̃₁ pair prod. (AMSB) : long-lived χ̃₁
L=4.7 fb⁻¹, 7 TeV [1210.2852] 220 GeV χ̃₁± mass
Stable g̃ R-hadrons : low β, βγ (full detector)
L=4.7 fb⁻¹, 7 TeV [1211.1597] 985 GeV g̃ mass
Stable t̃ R-hadrons : low β, βγ (full detector)
L=4.7 fb⁻¹, 7 TeV [1211.1597] 683 GeV t̃ mass
GMSB : stable τ̃
L=4.7 fb⁻¹, 7 TeV [1211.1597] 300 GeV τ̃ mass
L=4.4 fb⁻¹, 7 TeV [1210.7451] 700 GeV q̃ mass
RPV
L=4.6 fb⁻¹, 7 TeV [Preliminary] 1.61 TeV ν̃_τ mass
L=4.6 fb⁻¹, 7 TeV [Preliminary] 1.10 TeV ν̃_τ mass
Bilinear RPV CMSSM : 1 lep + 7 j's + E_T,miss
L=4.7 fb⁻¹, 7 TeV [ATLAS-CONF-2012-140] 1.2 TeV q̃ = g̃ mass
L=13.0 fb⁻¹, 8 TeV [ATLAS-CONF-2012-153] 700 GeV χ̃₁± mass
L=13.0 fb⁻¹, 8 TeV [ATLAS-CONF-2012-153] 430 GeV l̃ mass
g̃ → qqq : 3-jet resonance pair
L=4.6 fb⁻¹, 7 TeV [1210.4813] 666 GeV g̃ mass
Scalar gluon : 2-jet resonance pair
L=4.6 fb⁻¹, 7 TeV [1210.4826] 100-287 GeV sgluon mass
WIMP interaction (D5, Dirac χ) : 'monojet' + E_T,miss
L=10.5 fb⁻¹, 8 TeV [ATLAS-CONF-2012-147] 704 GeV M* scale
10⁻¹
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.
m_1/2 [GeV]
m_0 [GeV]
τ̃ = LSP
α_T
OS Dilepton
1 Lepton
Multi-Lepton
m(g̃) = 500
Non-Convergent RGE's
No EWSB

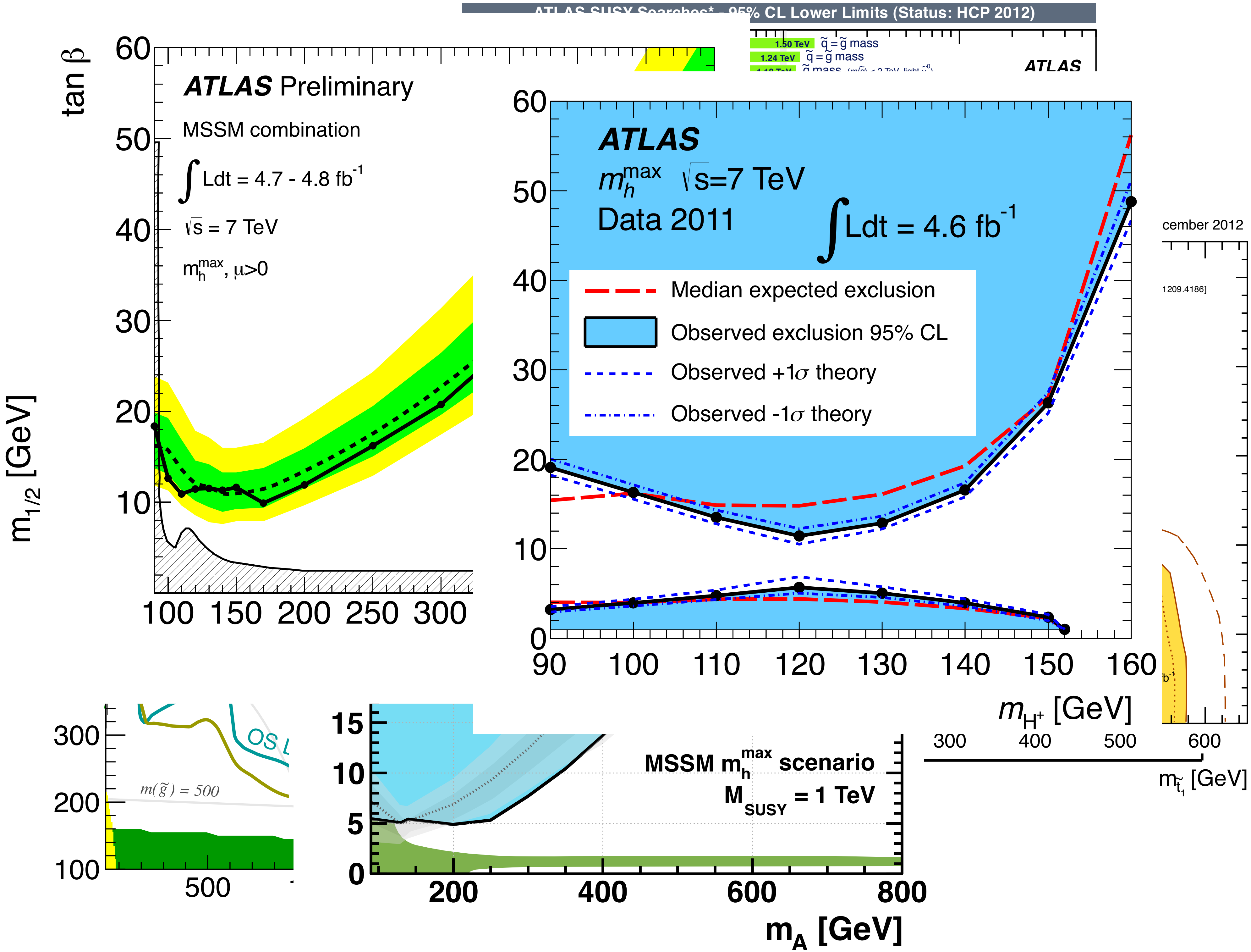


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
ATLAS
Preliminary
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
GMSB ($\tilde{l}$ NLSP) : 2 lep (OS) + j's + $E_{T,miss}$
GGM (bino NLSP) : $\gamma\gamma$ + $E_{T,miss}$
GGM (wino NLSP) : γ + lep + $E_{T,miss}$
GGM (higgsino-bino NLSP) : γ + b + $E_{T,miss}$
GGM (higgsino NLSP) : Z + jets + $E_{T,miss}$
Gravitino LSP : 'monojet' + $E_{T,miss}$
1.50 TeV $\tilde{q} = \tilde{g}$ mass
1.24 TeV $\tilde{q} = \tilde{g}$ mass
1.18 TeV $\tilde{g}$ mass
1.38 TeV $\tilde{q}$ mass
900 GeV $\tilde{g}$ mass
1.24 TeV $\tilde{g}$ mass
1.20 TeV $\tilde{g}$ mass
1.07 TeV $\tilde{g}$ mass
619 GeV $\tilde{g}$ mass
900 GeV $\tilde{g}$ mass
690 GeV $\tilde{g}$ mass
645 GeV $F^{1/2}$ scale
$\int Ldt = (2.1 - 13.0)$ fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
3rd gen. sq. gluino med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
WIMP interaction
*Only a selection of t
All limits quoted are
$\tilde{t}_1\tilde{t}_1$ production
Status: December 2012
ATLAS Preliminary
Observed limits
Observed limits ($-1\sigma_{theo}$)
Expected limits
L_{int} = 13 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
$\tilde{t}_1 \to t\tilde{\chi}_1^0$
$\tilde{t}_1 \to b+\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm} \to W^{(*)}+\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
$m_{1/2}$ [GeV]
m_0 [GeV]
$\tilde{\tau}$ = LSP
Multi-Lepton
Non-Convergent
No EWSB



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
ATLAS Preliminary
Inclusive searches
MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
GMSB ($\tilde{l}$ NLSP) : 2 lep (OS) + j's + $E_{T,miss}$
GGM (bino NLSP) : $\gamma\gamma$ + $E_{T,miss}$
GGM (wino NLSP) : γ + lep + $E_{T,miss}$
GGM (higgsino NLSP) : Z + jets + $E_{T,miss}$
Gravitino LSP : 'monojet' + $E_{T,miss}$
$\int Ldt$ = (2.1 - 13.0) fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
*Only a selection of t
All limits quoted are
$\tilde{t}_1\tilde{t}_1$ production
Status: December 2012
ATLAS Preliminary
Observed limits
Observed limits ($-1\sigma_{theo}$)
L_{int} = 13 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
1L ATLAS-CONF-2012-166
0L ATLAS-CONF-2012-171
L_{int} = 4.7 fb^{-1}
L_{int} = 13 fb^{-1}
$m_{\tilde{t}_1}$ [GeV]
$m_{1/2}$ [GeV]
$m(\tilde{g})$ = 500
CMS Preliminary, $\sqrt{s}$ = 7+8 TeV, L = 17 fb^{-1}
95% CL Excluded Regions
Observed
Expected
$\pm 1\sigma$ expected
$\pm 2\sigma$ expected
LEP
MSSM m_h^{max} scenario
M_{SUSY} = 1 TeV
tanβ
m_A [GeV]

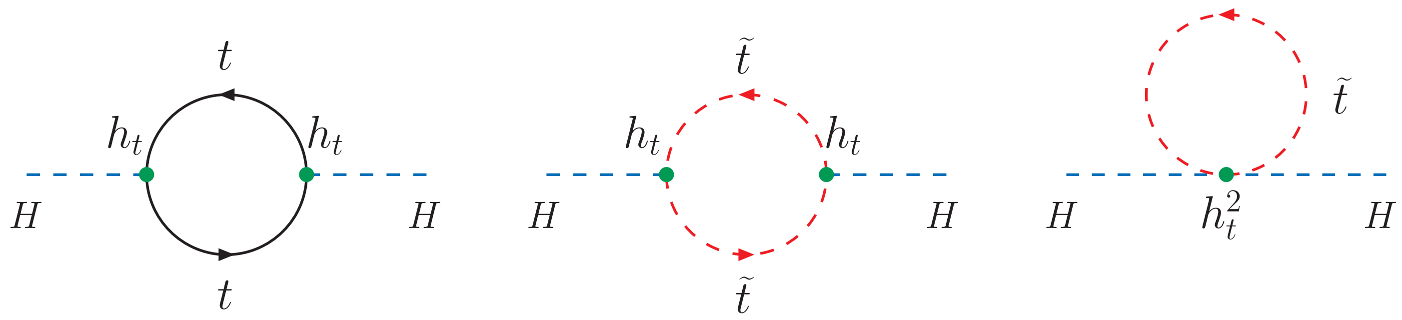

ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
ATLAS Preliminary
MSSM combination
$\int Ldt = 4.7 - 4.8\ fb^{-1}$
$\sqrt{s}$ = 7 TeV
m_h^{max}, μ>0
Observed CLs
Expected CLs
± 1σ
± 2σ
LEP
tan β
$m_{1/2}$ [GeV]
m_A [GeV]
ATLAS
Preliminary
$\int Ldt = (2.1 - 13.0)\ fb^{-1}$
$\sqrt{s}$ = 7, 8 TeV
Status: December 2012
L_{int} = 13 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
1L ATLAS-CONF-2012-166
0L ATLAS-CONF-2012-171
0L [1208.1447], 1L [1208.2590], 2L [1209.4186]
2L [1208.4305], 1-2L [1209.2102]
1-2L [1209.2102]
MSSM m_h^{max} scenario
M_{SUSY} = 1 TeV
m_A [GeV]
$m(\tilde{g})$ = 500
L_{int} = 4.7 fb^{-1}
L_{int} = 13 fb^{-1}
$m_{\tilde{t}_1}$ [GeV]



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
tan β
ATLAS Preliminary
MSSM combination
∫Ldt = 4.7 - 4.8 fb-1
√s = 7 TeV
m_h^max, μ>0
m_1/2 [GeV]
ATLAS
m_h^max √s=7 TeV
Data 2011
∫Ldt = 4.6 fb-1
Median expected exclusion
Observed exclusion 95% CL
Observed +1σ theory
Observed -1σ theory
m_H+ [GeV]
m(g̃) = 500
MSSM m_h^max scenario
M_SUSY = 1 TeV
m_A [GeV]
m_t̃1 [GeV]

Radiative corrections to the Higgs masses in the MSSM

The dominant one-loop corrections to the Higgs masses are due to the particles with the strongest couplings to the Higgs bosons: the top (and bottom) quarks and squarks



$$(\Delta m_h^2)^{1-\mathrm{loop}} \simeq \frac{3\, m_t^4}{4\,\pi^2\, v^2} \left(\ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12\, M_S^4} \right) - \frac{h_b^4\, \mu^4\, v^2}{16\,\pi^2\, M_S^4}$$

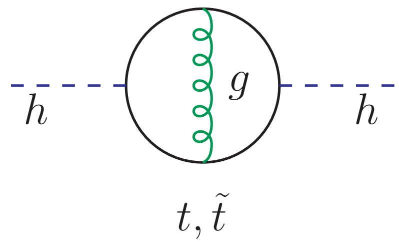
(decoupling limit, M_S = average stop mass, $X_t = A_t - \mu \cot\beta$ = L-R stop mixing)

- Δm_h^2 depends on the SUSY-breaking mismatch between top and stop mass
- It is maximised for large stop masses and large stop mixing ($X_t \simeq \sqrt{6}\, M_S$)
- The negative corrections controlled by h_b are relevant only for large *tanβ*
- Two-loop corrections are also important

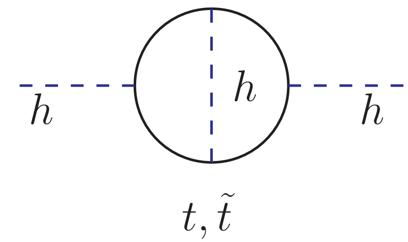
Two-loop corrections to the Higgs masses

- Top corrections (always important)

$\mathcal{O}(\alpha_t\alpha_s)$:

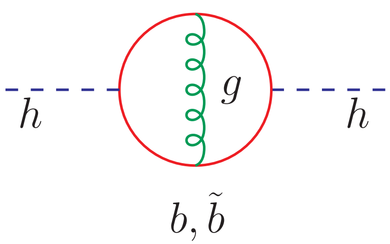


$\mathcal{O}(\alpha_t^2)$:

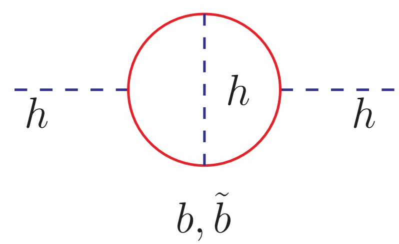


- Bottom corrections (relevant only for large $\tan\beta$)

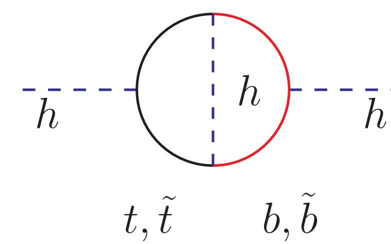
$\mathcal{O}(\alpha_b\alpha_s)$:



$\mathcal{O}(\alpha_b^2)$:

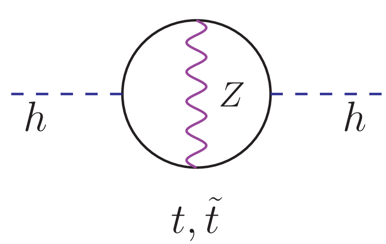


$\mathcal{O}(\alpha_t\alpha_b)$:

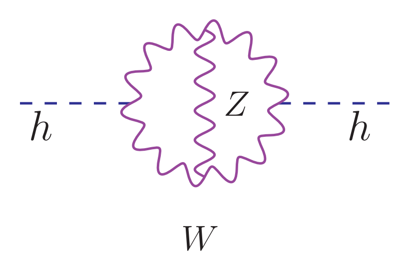


- Electroweak corrections (generally small)

$\mathcal{O}(\alpha_t\alpha)$:

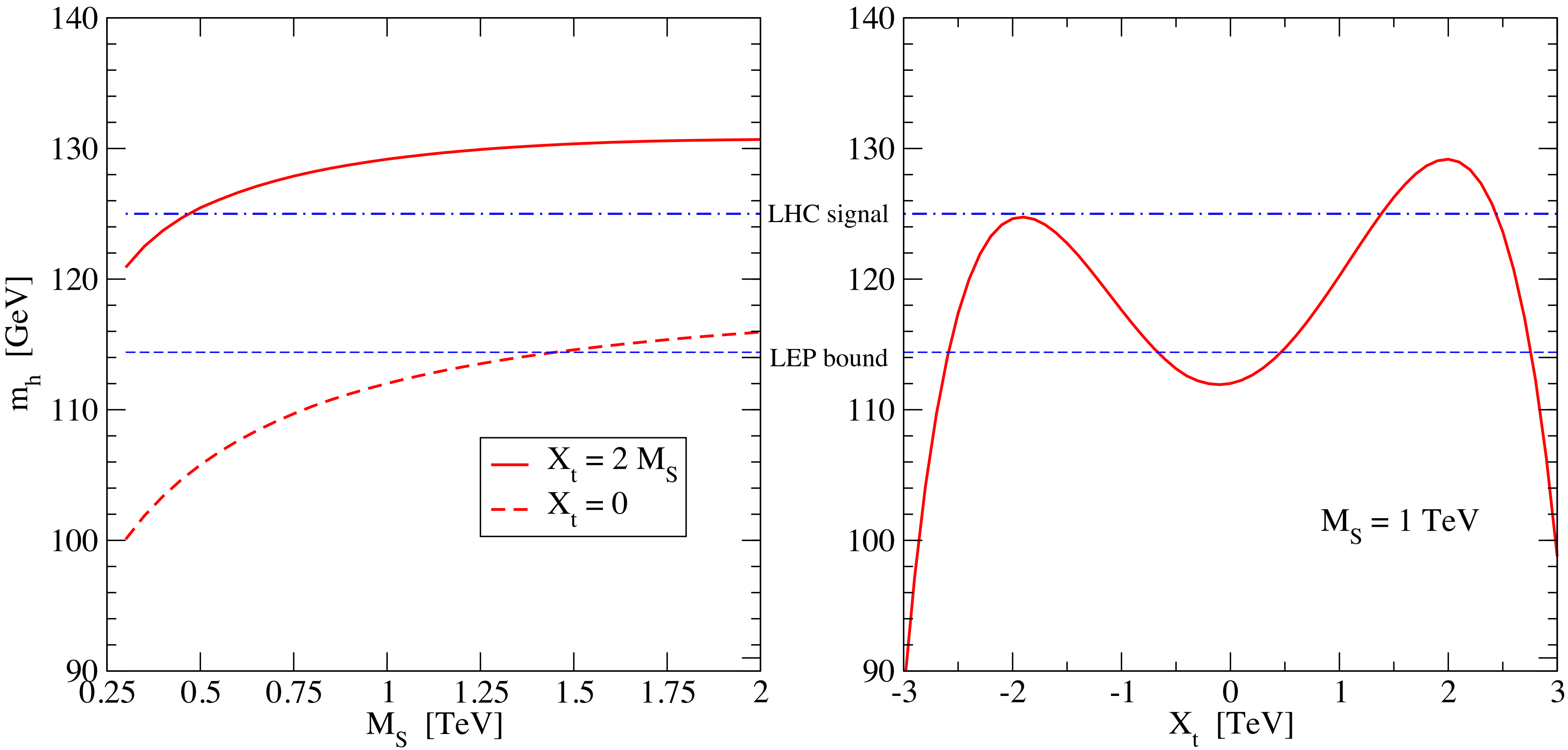


$\mathcal{O}(\alpha^2)$:



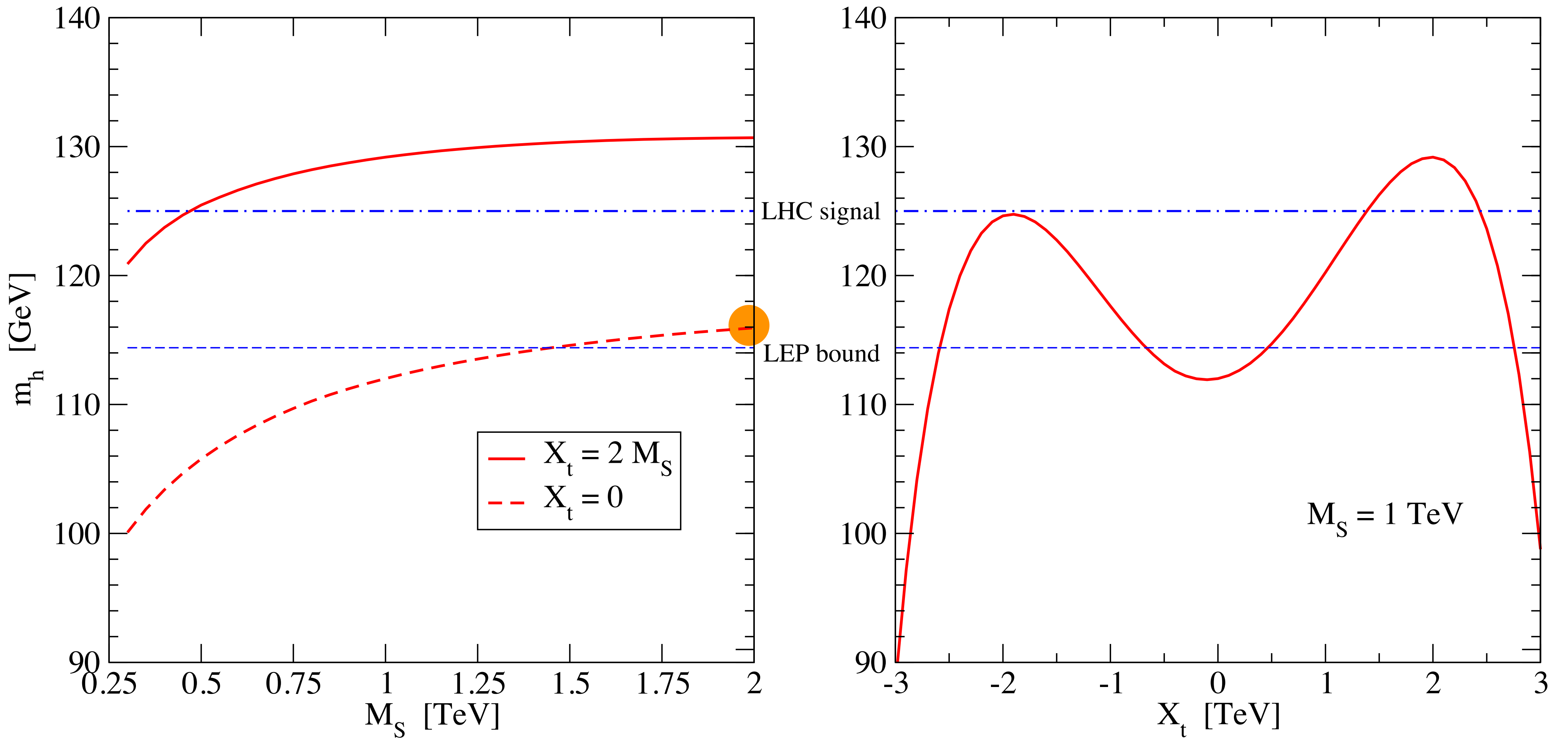
$\mu = M_2 = 200$ GeV, $\quad m_{\tilde{g}} = 0.8\, M_S$, $\quad m_A = 500$ GeV, $\quad \tan\beta = 10$

(plots produced with FeynHiggs)



$\mu = M_2 = 200$ GeV, $\quad m_{\tilde{g}} = 0.8\, M_S$, $\quad m_A = 500$ GeV, $\quad \tan\beta = 10$

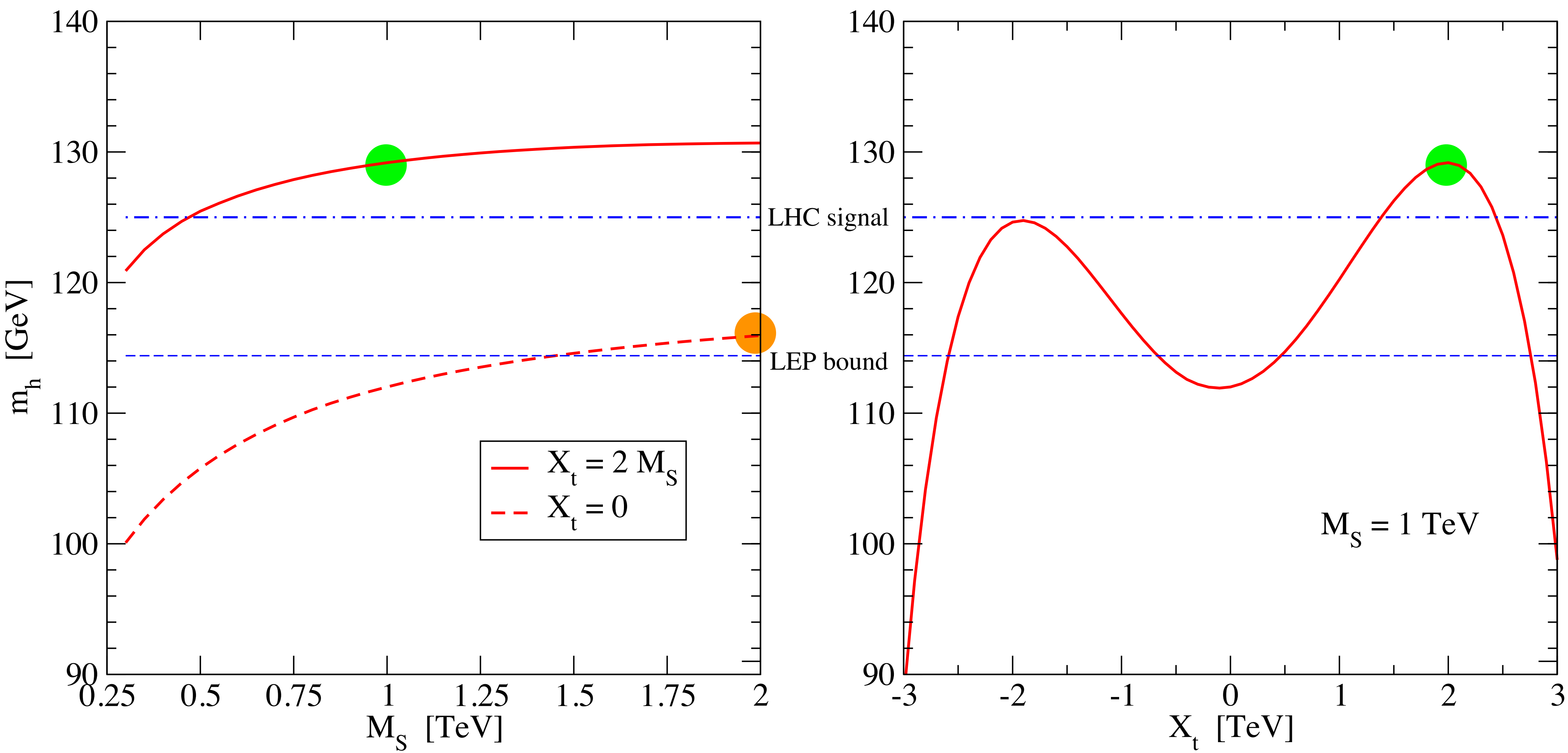
(plots produced with FeynHiggs)



no-mixing scenario: $M_s = 2$ TeV, $X_t = 0$ TeV

$\mu = M_2 = 200$ GeV, $m_{\tilde{g}} = 0.8\, M_S$, $m_A = 500$ GeV, $\tan\beta = 10$

(plots produced with FeynHiggs)

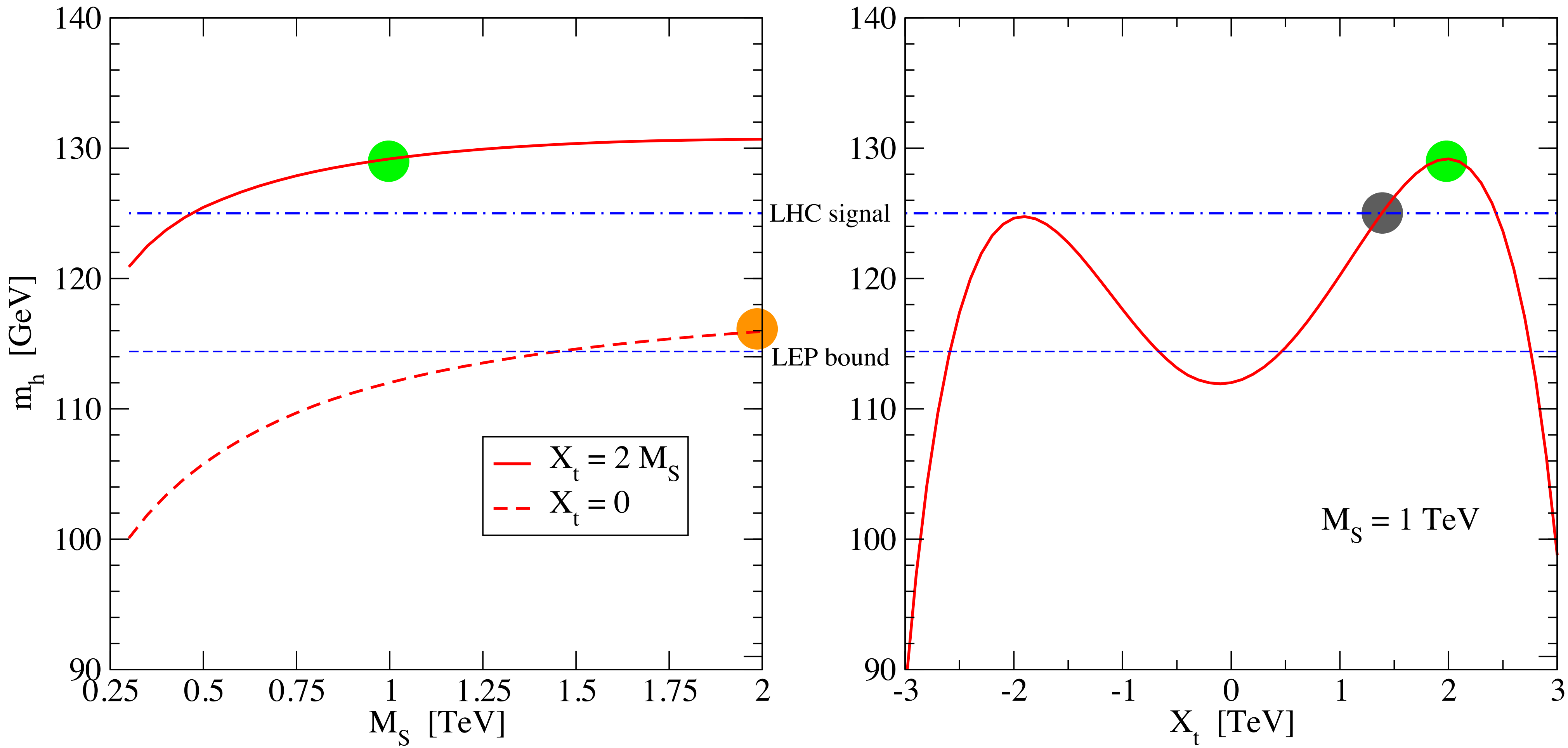


no-mixing scenario: $M_s = 2$ TeV, $X_t = 0$ TeV

m_h^{max} scenario: $M_s = 1$ TeV, $X_t = 2$ TeV

$\mu = M_2 = 200$ GeV, $\quad m_{\tilde{g}} = 0.8\, M_S$, $\quad m_A = 500$ GeV, $\quad \tan\beta = 10$

(plots produced with FeynHiggs)



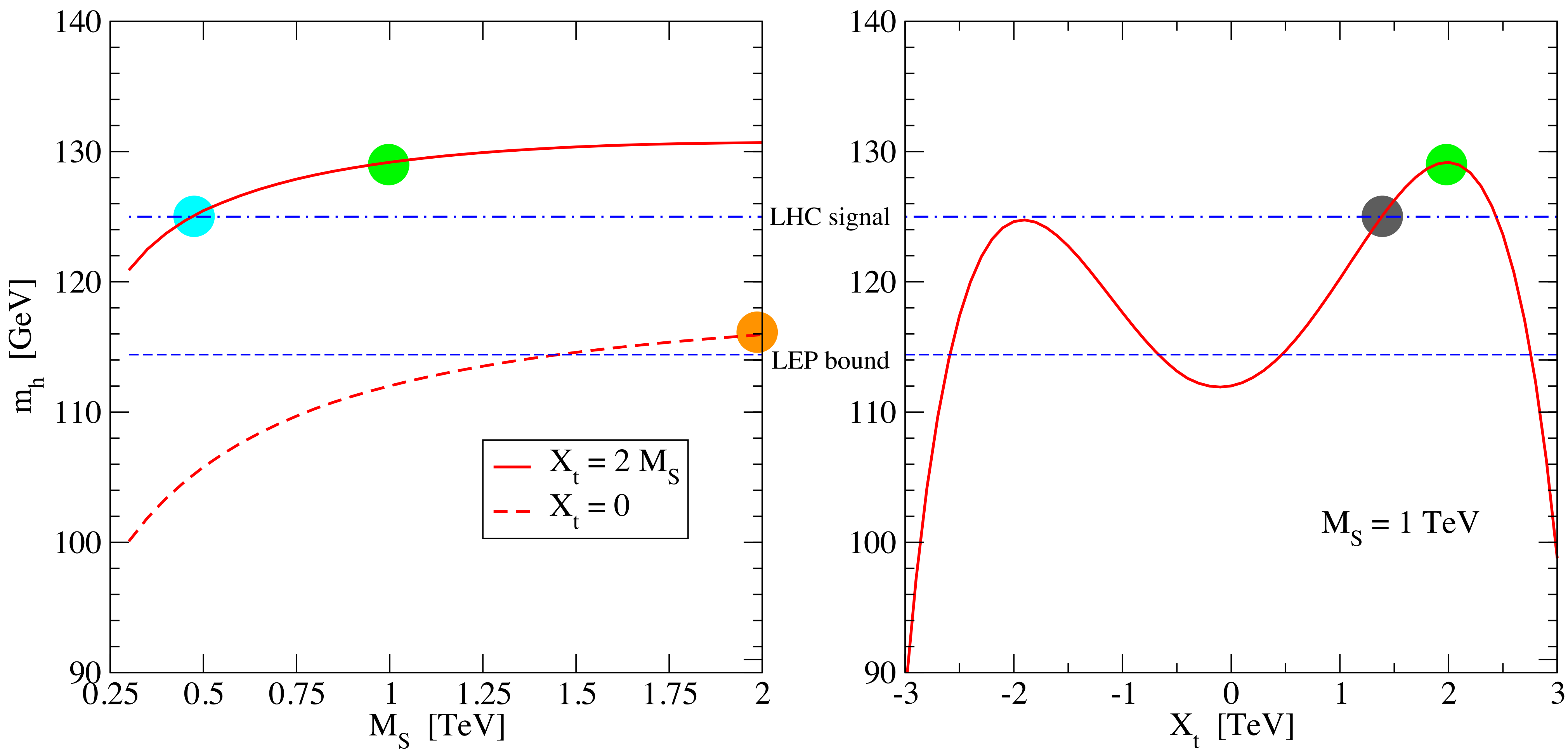
no-mixing scenario: $M_s = 2$ TeV, $X_t = 0$ TeV

m_h^{max} scenario: $M_s = 1$ TeV, $X_t = 2$ TeV

modified m_h^{max} scenario: $M_s = 1$ TeV, $X_t = 1.3$ TeV

$\mu = M_2 = 200$ GeV, $m_{\tilde{g}} = 0.8\, M_S$, $m_A = 500$ GeV, $\tan\beta = 10$

(plots produced with FeynHiggs)



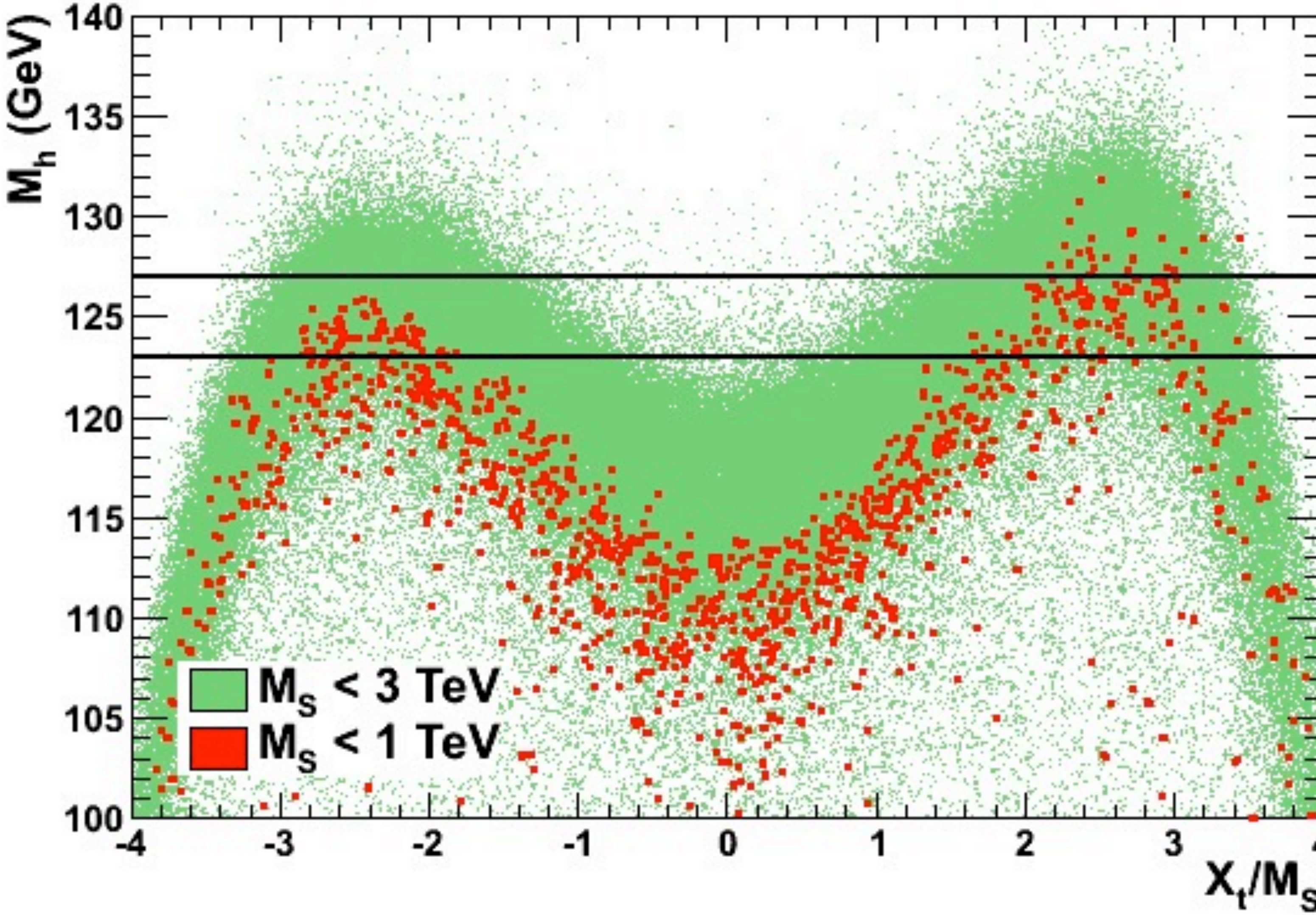
no-mixing scenario: $M_s = 2$ TeV, $X_t = 0$ TeV

m_h^{max} scenario: $M_s = 1$ TeV, $X_t = 2$ TeV

modified m_h^{max} scenario: $M_s = 1$ TeV, $X_t = 1.3$ TeV

light-stop scenario: $M_s \approx 500$ GeV, $X_t \approx 1$ TeV ($m_{\tilde{t}_1} \approx 320$ GeV, $m_{\tilde{t}_2} \approx 670$ GeV)

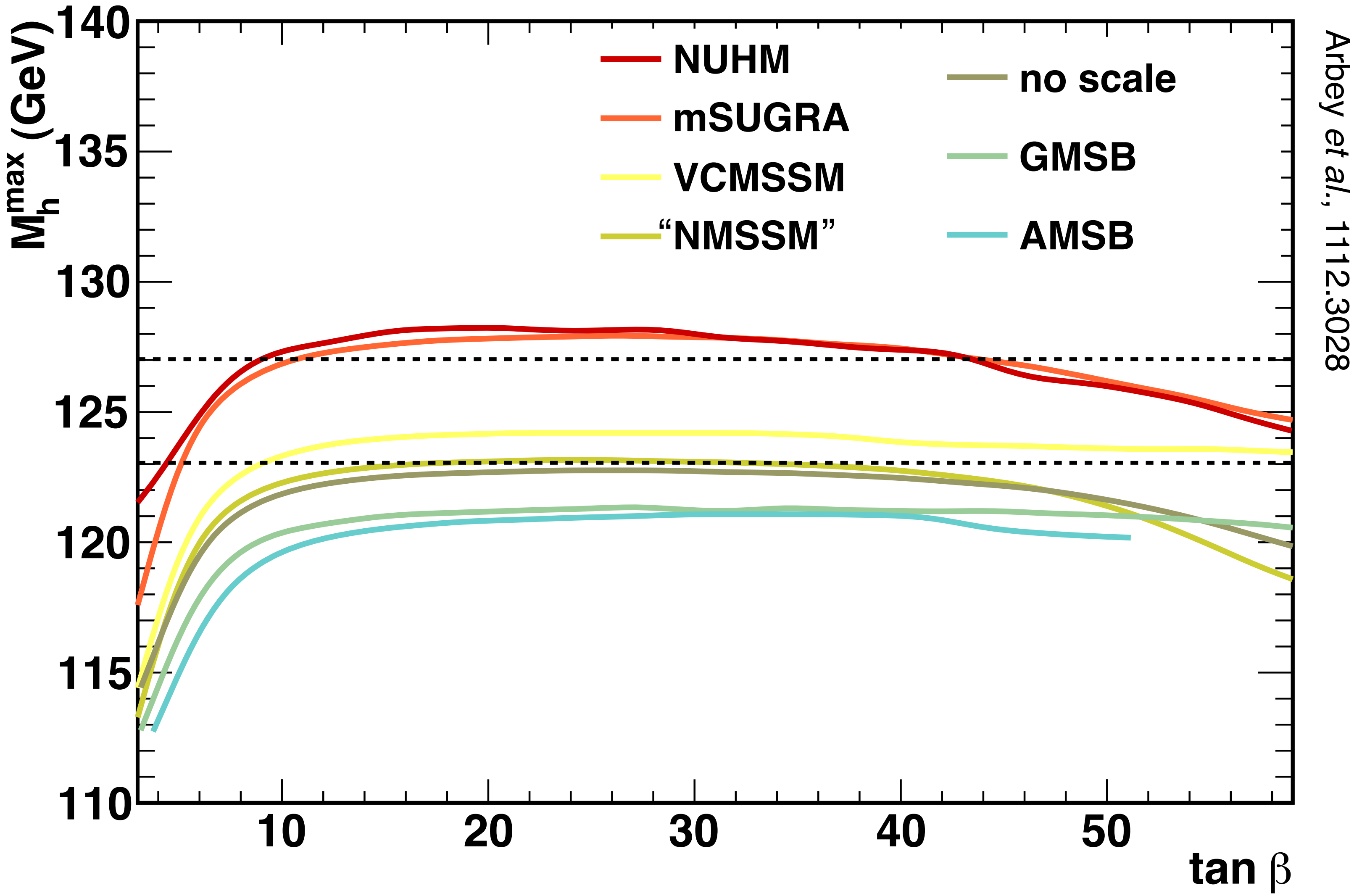
Implications of $m_h \approx 125$ GeV in the unconstrained MSSM



Arbey *et al.*, 1112.3028

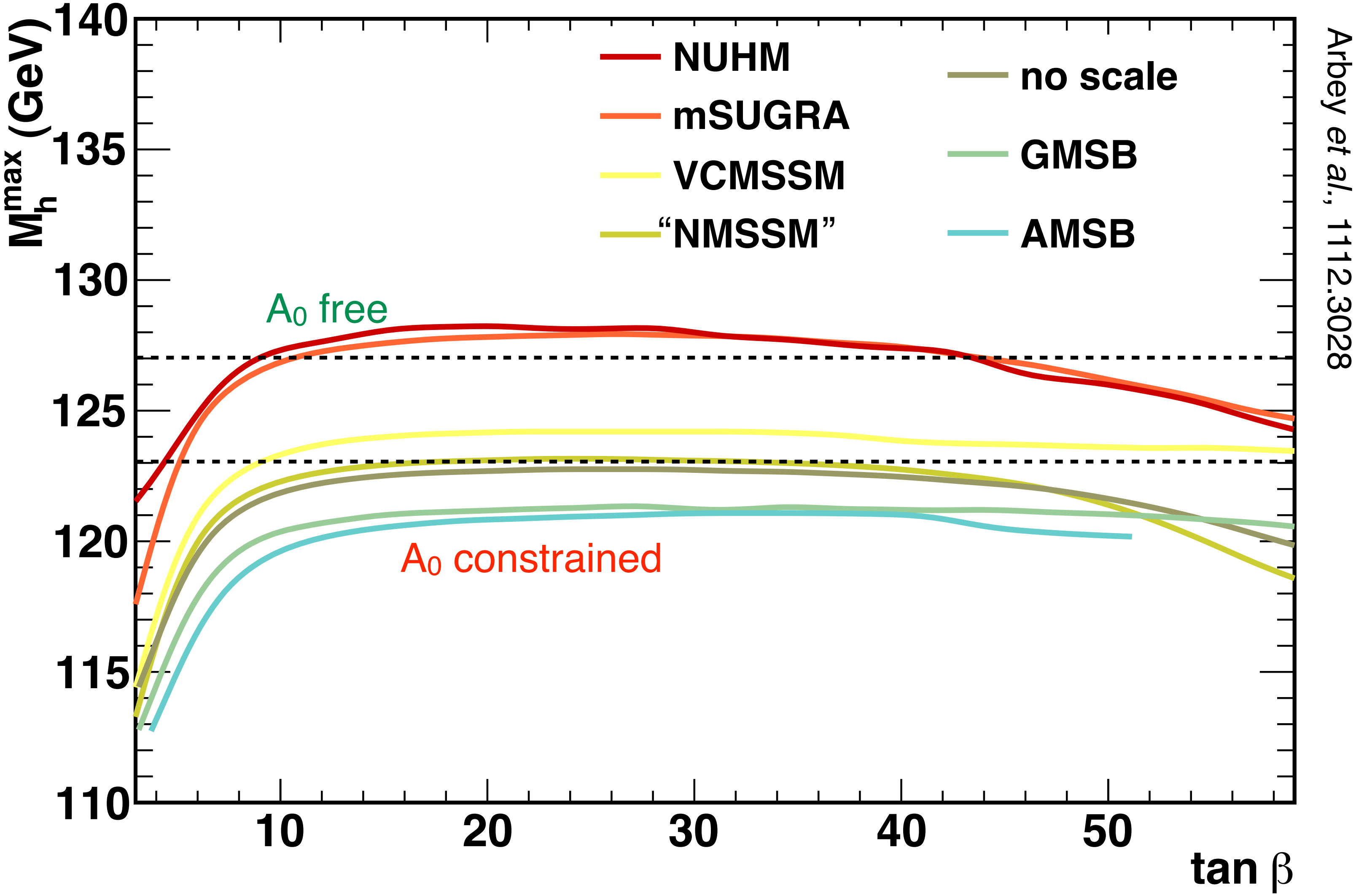
$$1 \le \tan\beta \le 60\,,\ 50\ \mathrm{GeV} \le M_A \le 3\ \mathrm{TeV}\,,\ -9\ \mathrm{TeV} \le A_f \le 9\ \mathrm{TeV}\,,$$
$$50\ \mathrm{GeV} \le m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \le 3\ \mathrm{TeV}\,,\ 50\ \mathrm{GeV} \le M_1, M_2, |\mu| \le 1.5\ \mathrm{TeV}.$$

$m_h \approx 125$ GeV in constrained SUSY-breaking scenarios



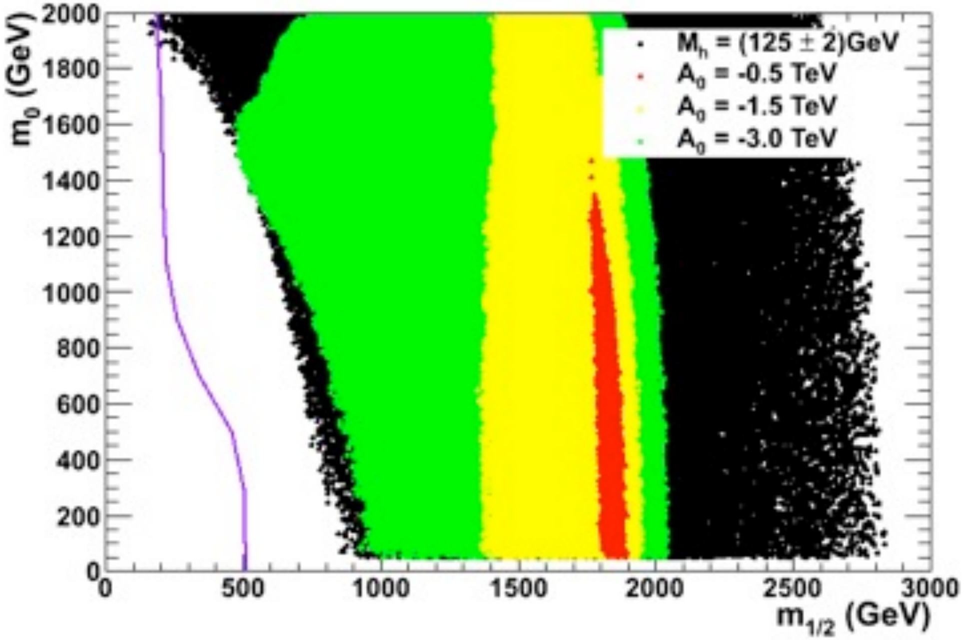
$$
\begin{aligned}
\text{mSUGRA:} &\quad 50\text{ GeV} \le m_0 \le 3\text{ TeV}, \quad 50\text{ GeV} \le m_{1/2} \le 3\text{ TeV}, \quad |A_0| \le 9\text{ TeV};\\
\text{GMSB:} &\quad 10\text{ TeV} \le \Lambda \le 1000\text{ TeV}, \quad 1 \le M_{\text{mess}}/\Lambda \le 10^{11}, \quad N_{\text{mess}} = 1;\\
\text{AMSB:} &\quad 1\text{ TeV} \le m_{3/2} \le 100\text{ TeV}, \quad 50\text{ GeV} \le m_0 \le 3\text{ TeV}.
\end{aligned}
$$

$m_h \approx 125$ GeV in constrained SUSY-breaking scenarios

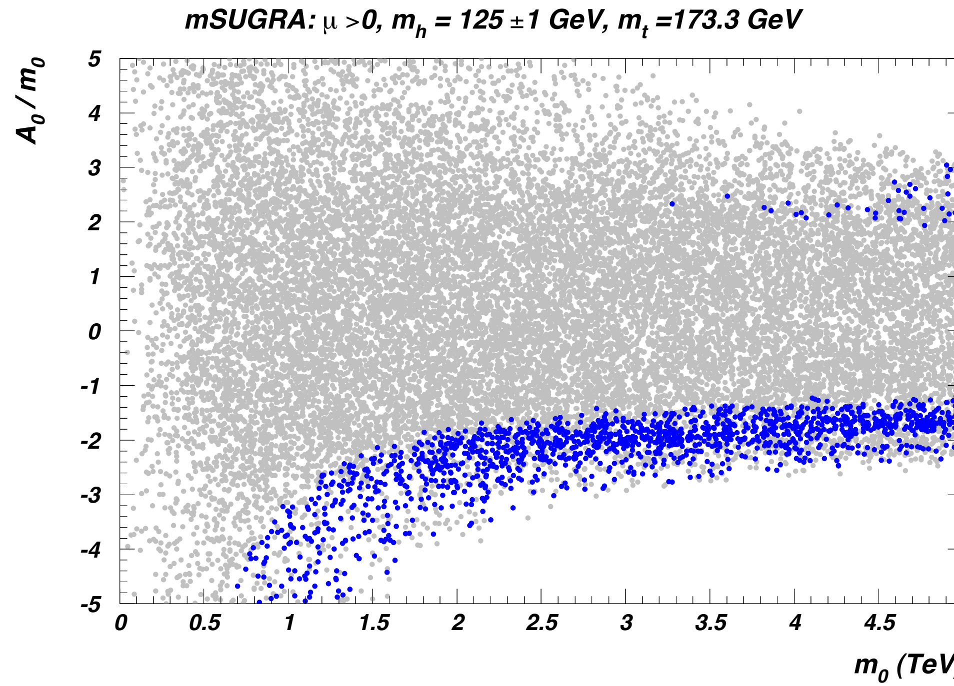


$$
\begin{array}{rlll}
\text{mSUGRA:} & 50\text{ GeV} \le m_0 \le 3\text{ TeV}, & 50\text{ GeV} \le m_{1/2} \le 3\text{ TeV}, & |A_0| \le 9\text{ TeV}; \\
\text{GMSB:} & 10\text{ TeV} \le \Lambda \le 1000\text{ TeV}, & 1 \le M_{\rm mess}/\Lambda \le 10^{11}, & N_{\rm mess} = 1; \\
\text{AMSB:} & 1\text{ TeV} \le m_{3/2} \le 100\text{ TeV}, & 50\text{ GeV} \le m_0 \le 3\text{ TeV}. &
\end{array}
$$

The Higgs mass cuts slices in the m_0-$m_{1/2}$ plane of mSUGRA (large and negative A_0 required)



(Arbey *et al.*, 1112.3028)



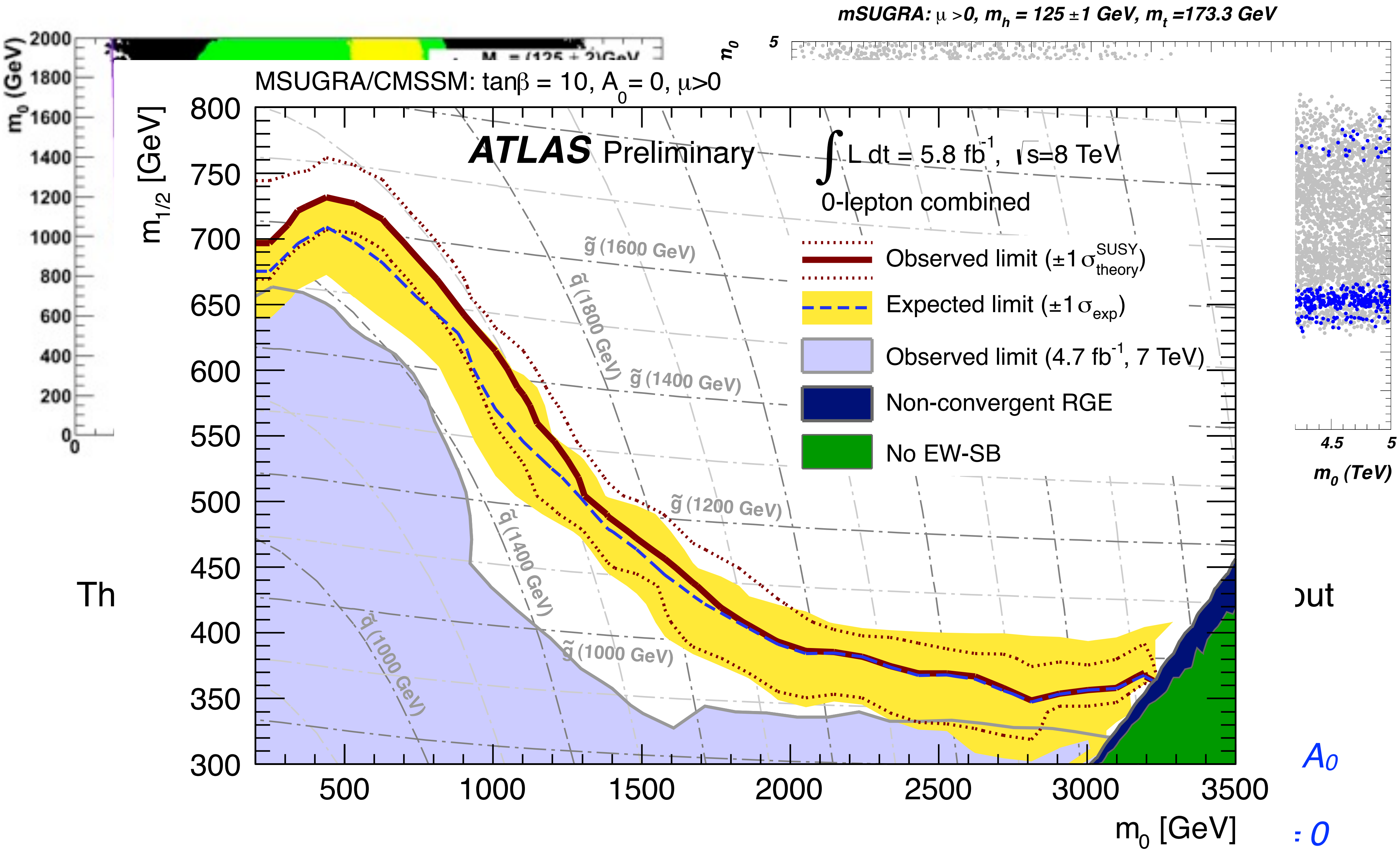
(Baer *et al.*, 1112.3017)

The parameter space in the usual mSUGRA exclusion plots with $A_0 = 0$ is ruled out

It's not a big deal...

- The masses of 1,2-gen. squarks and of gauginos depend very weakly on A_0
- Choose large A_0 and the plots will look very much the same as with $A_0 = 0$ (caveat: branching ratios of chargino/neutralino decays may be affected)
- Otherwise, stick to topology-based plots with particle masses on the axes

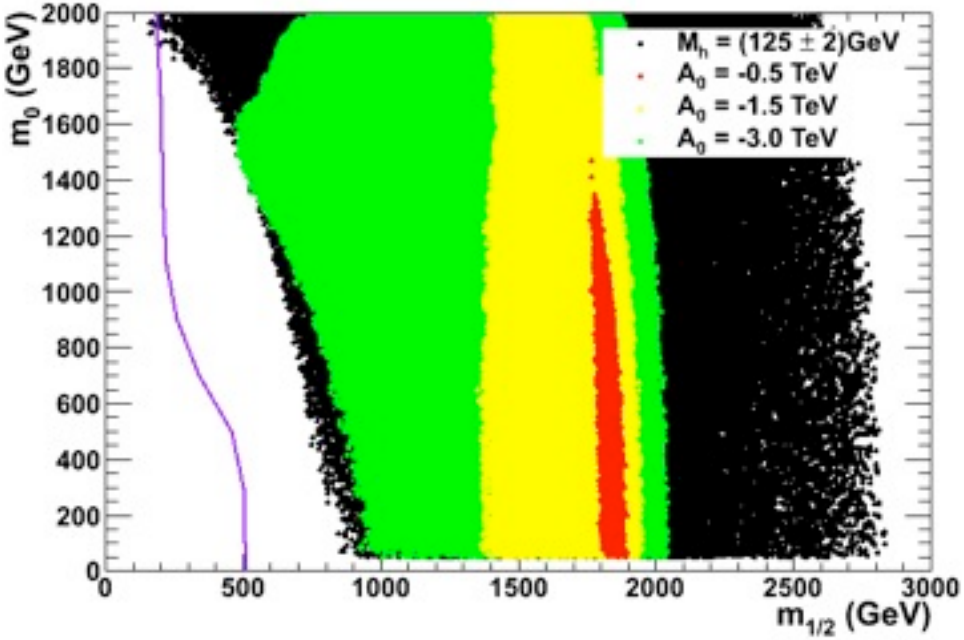
The Higgs mass cuts slices in the m_0-$m_{1/2}$ plane of mSUGRA (large and negative A_0 required)



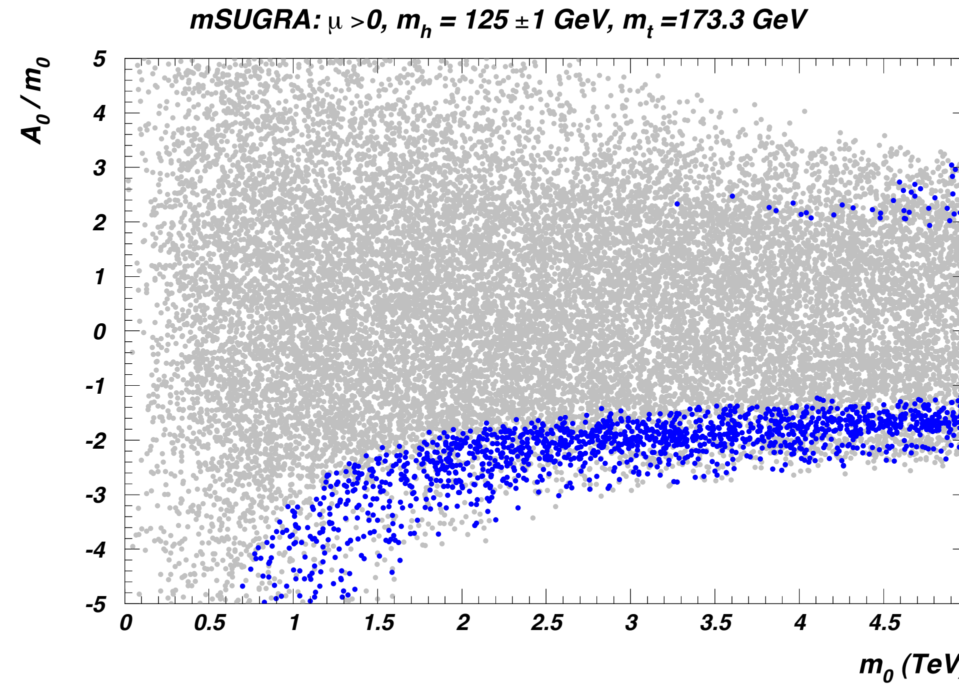
(caveat: branching ratios of chargino/neutralino decays may be affected)

- Otherwise, stick to topology-based plots with particle masses on the axes

The Higgs mass cuts slices in the m_0-$m_{1/2}$ plane of mSUGRA (large and negative A_0 required)



(Arbey *et al.*, 1112.3028)



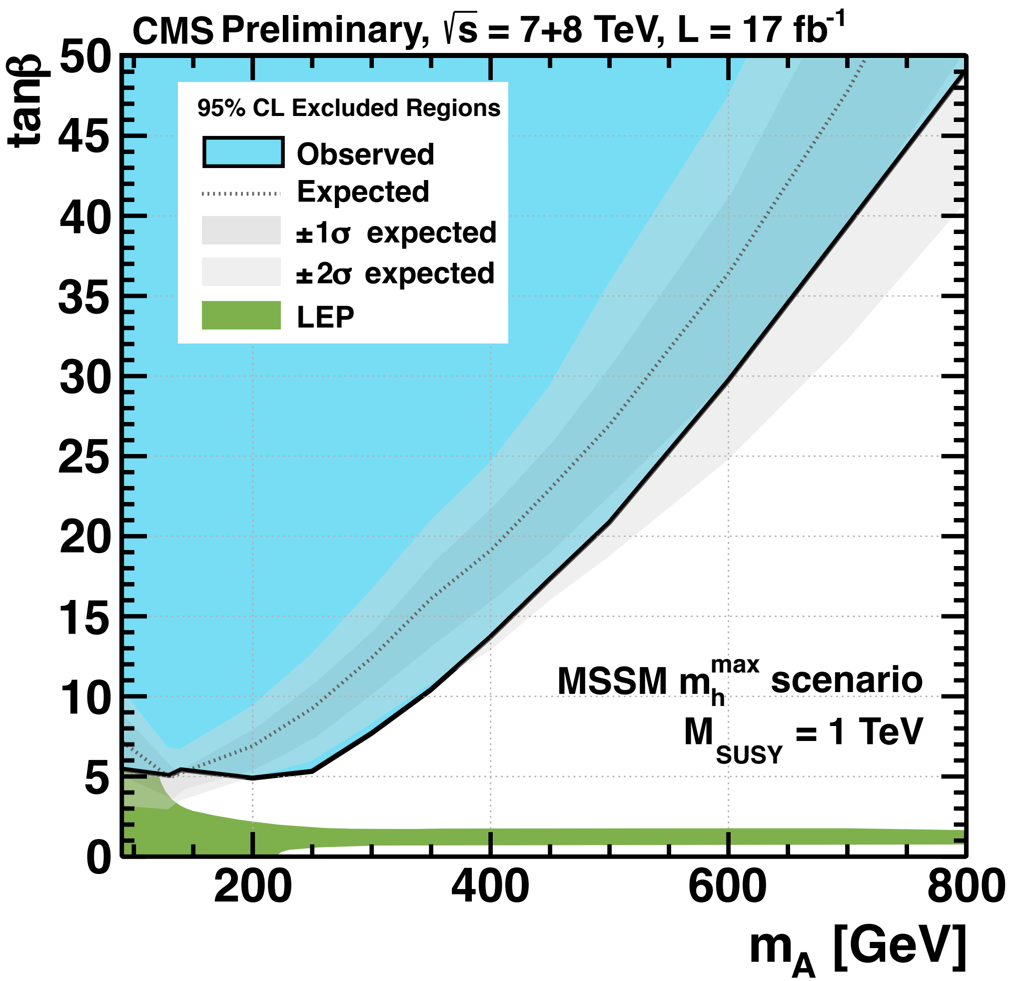
(Baer *et al.*, 1112.3017)

The parameter space in the usual mSUGRA exclusion plots with $A_0 = 0$ is ruled out

It's not a big deal...

- The masses of 1,2-gen. squarks and of gauginos depend very weakly on A_0
- Choose large A_0 and the plots will look very much the same as with $A_0 = 0$ (caveat: branching ratios of chargino/neutralino decays may be affected)
- Otherwise, stick to topology-based plots with particle masses on the axes

The m_h^{max} scenario used in the "MSSM Higgs" searches is also disfavored ($m_h \approx 129$ GeV)



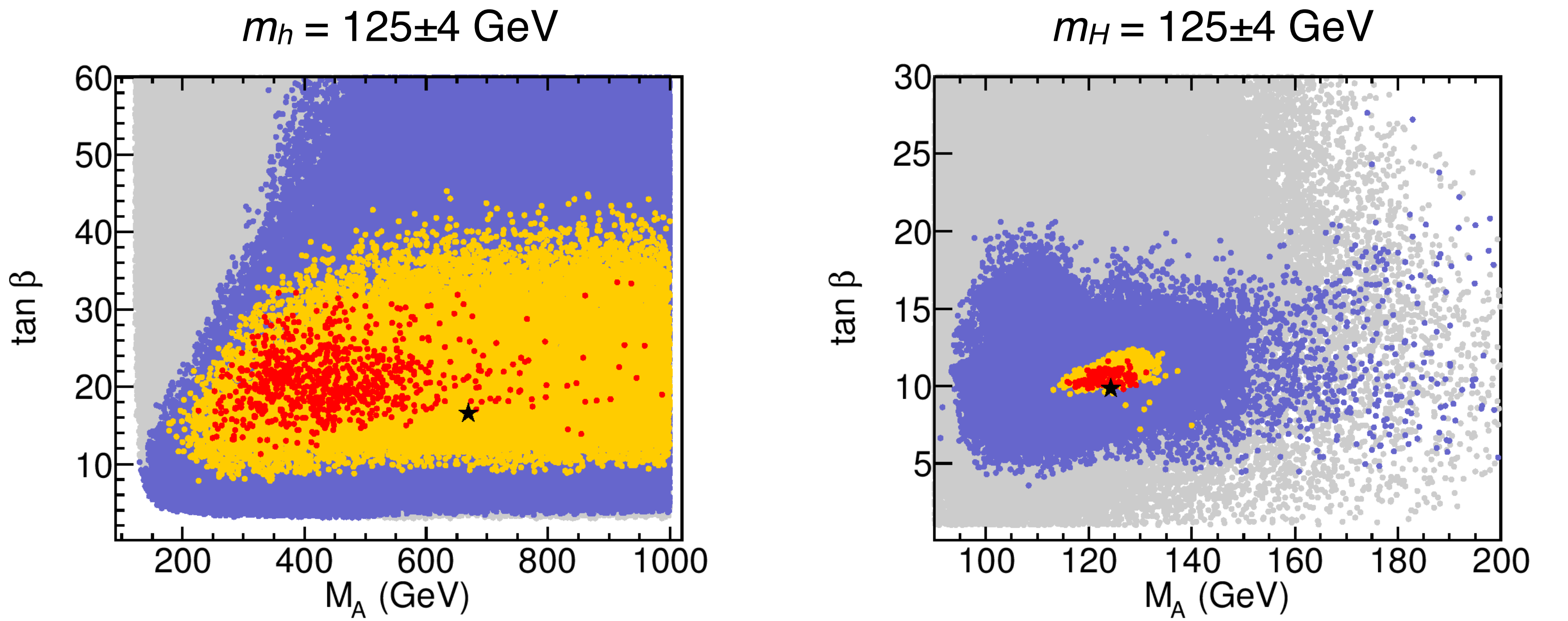
However, the tau tau searches mostly involve the "exotic" Higgses *(H, A)* with *tanβ*-enhanced couplings to *b* and tau (except for lower-left corner of the plot)

- masses and couplings of *H* and *A* mostly independent of stop params.
- the dependence on the corrections to bottom Yukawa cancels (partially) between cross section and BR

$$\sigma(b\bar{b}\phi) \times \mathrm{BR}(\phi \to \tau^+\tau^-) \;\propto\; \frac{\tan^2\beta}{(1+\epsilon_b \tan\beta)^2 + 9}$$

Adjusting the SUSY parameters to get the right m_h will not change the excluded area by much

Allowed and preferred regions in a scan over the MSSM parameters:



Bechtle *et al.*, 1211.1955

The scenario in which the heavy scalar *H* is the SM-like Higgs is not ruled out:

- In this scenario the other Higgses *(h, A, $H^\pm$)* would all be light

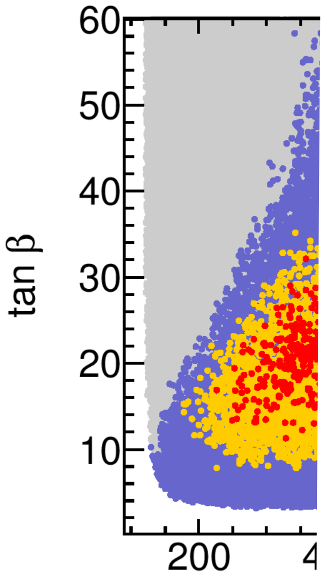
- *$H^\pm$* could be detected in top decays (bounds on *tanβ* from LHC searches)

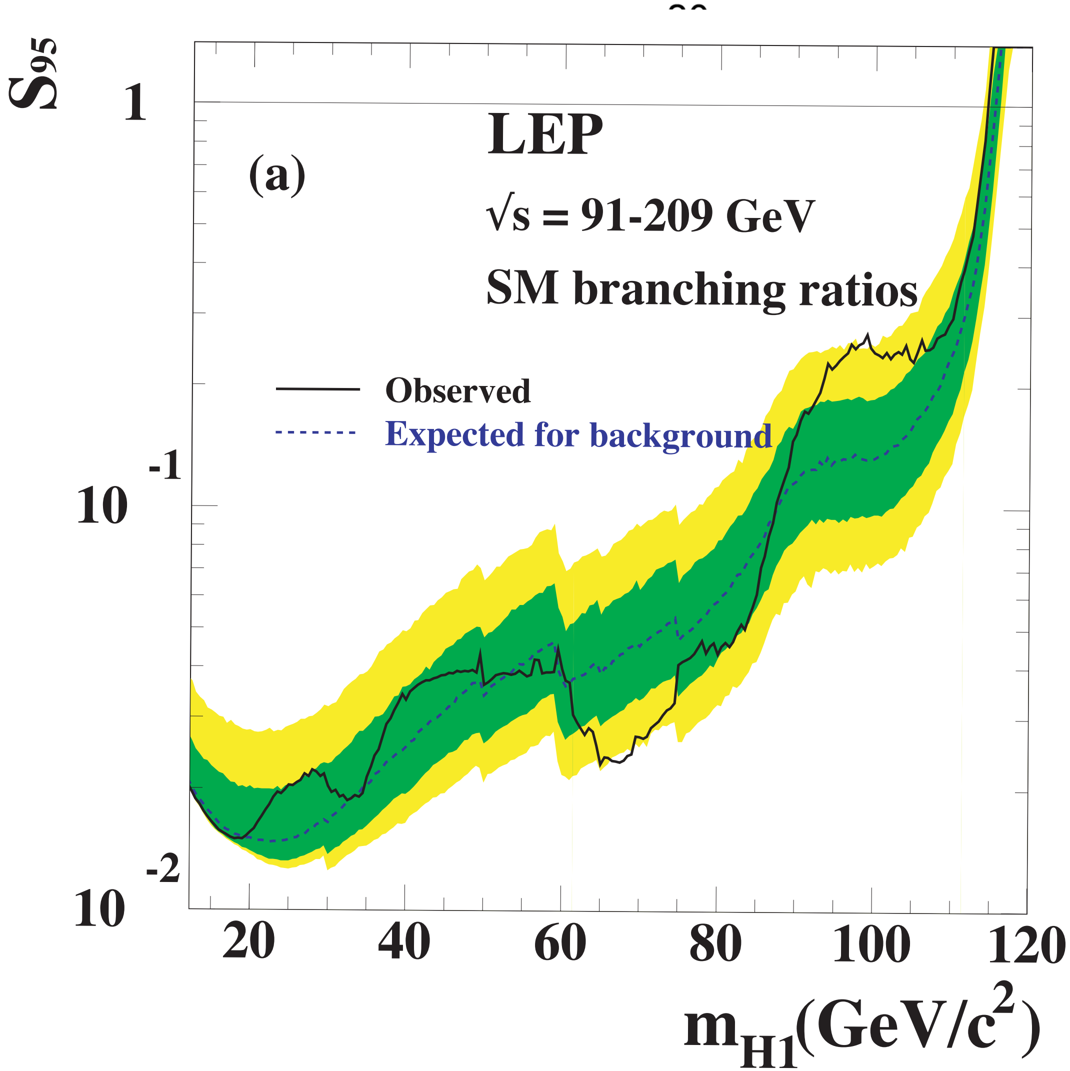
- *h* could explain the 2.3σ excess at 98 GeV seen by LEP [see also Drees, 1210.6507]
  However, difficult to see at LHC (small *VV* couplings, large background from *Z*)

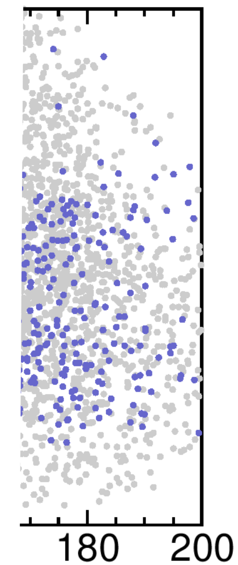
Allowed and preferred regions in a scan over the MSSM parameters:

m_h = 125±4 GeV

m_H = 125±4 GeV





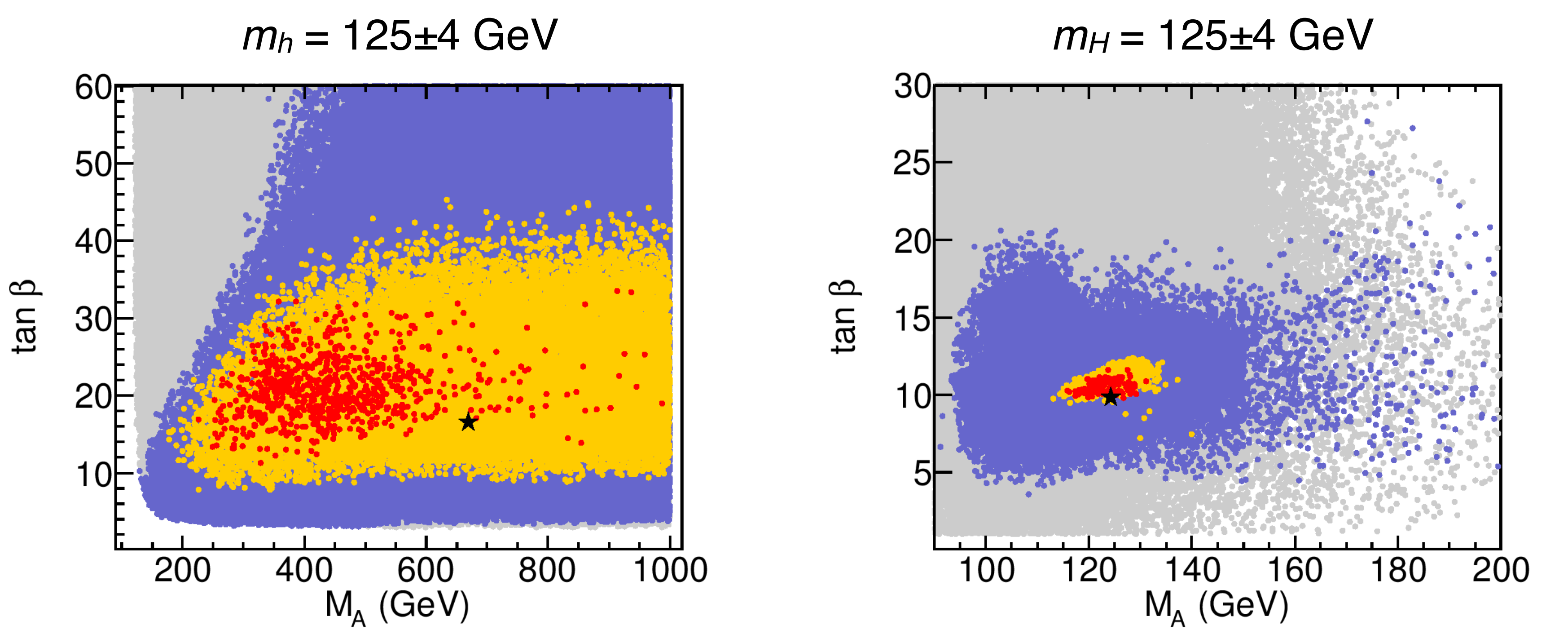


Bechtle *et al.*, 1211.1955

The scenar … iot ruled out:

- In this s…
- $H^\pm$ coul … searches)
- h could … lso Drees, 1210.6507]
  Howeve … kground from Z)

Allowed and preferred regions in a scan over the MSSM parameters:

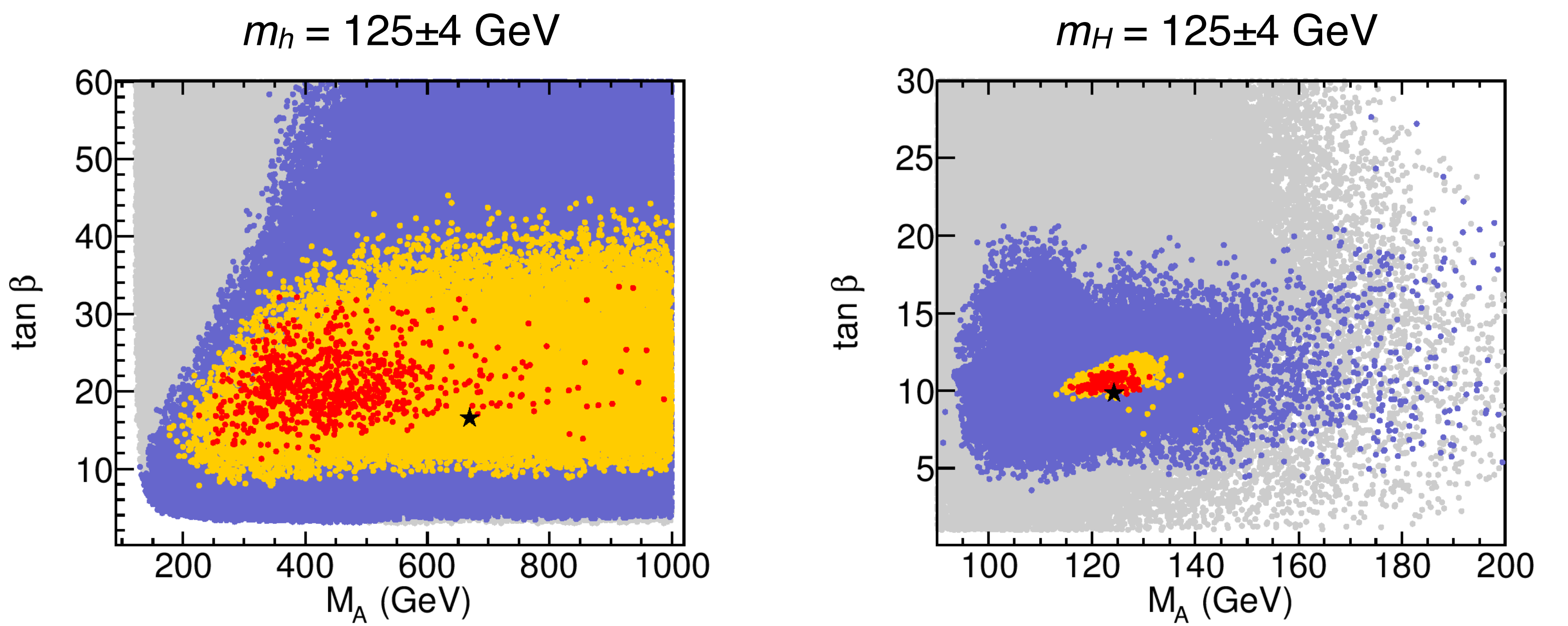


Bechtle *et al.*, 1211.1955

The scenario in which the heavy scalar H is the SM-like Higgs is not ruled out:

- In this scenario the other Higgses $(h, A, H^{\pm})$ would all be light
- $H^{\pm}$ could be detected in top decays (bounds on $\tan\beta$ from LHC searches)
- h could explain the 2.3σ excess at 98 GeV seen by LEP [see also Drees, 1210.6507]
  However, difficult to see at LHC (small VV couplings, large background from Z)

Allowed and preferred regions in a scan over the MSSM parameters:



Bechtle *et al.*, 1211.1955

The scenario in which the heavy scalar *H* is the SM-like Higgs is not ruled out:

- In this scenario the other Higgses *(h, A, $H^\pm$)* would all be light
- *$H^\pm$* could be detected in top decays (bounds on *tanβ* from LHC searches)
- *h* could explain the 2.3σ excess at 98 GeV seen by LEP [see also Drees, 1210.6507]
  However, difficult to see at LHC (small *VV* couplings, large background from *Z*)

(scenario excluded by new CMS results? see Arbey et al.,1211.4004)

NOTE: uncertainty in the MSSM prediction for the light Higgs mass

Public codes for the MSSM mass spectrum (e.g. `FeynHiggs, SuSpect, SoftSusy, SPheno`) currently include full 1-loop plus leading 2-loop top/stop and bottom/sbottom corrections (2-loop part by Heinemeyer *et al.* 98-07; P.S. *et al.* 01-04)

The estimated *theoretical* uncertainty is $\Delta^{th}\, m_h \approx 3$ GeV (especially at large stop mixing!!!)

A nearly-full 2-loop calculation including EW (Martin 02-04) and even the leading 3-loop terms (Martin 07; Harlander *et al.* 08-10) are now available. Uncertainty should go down to ≤ 1 GeV

Still largish w.r.t. the expected *experimental* accuracy at LHC: $\Delta^{exp}\, m_h \approx 100$ MeV (with 30 fb^{-1})

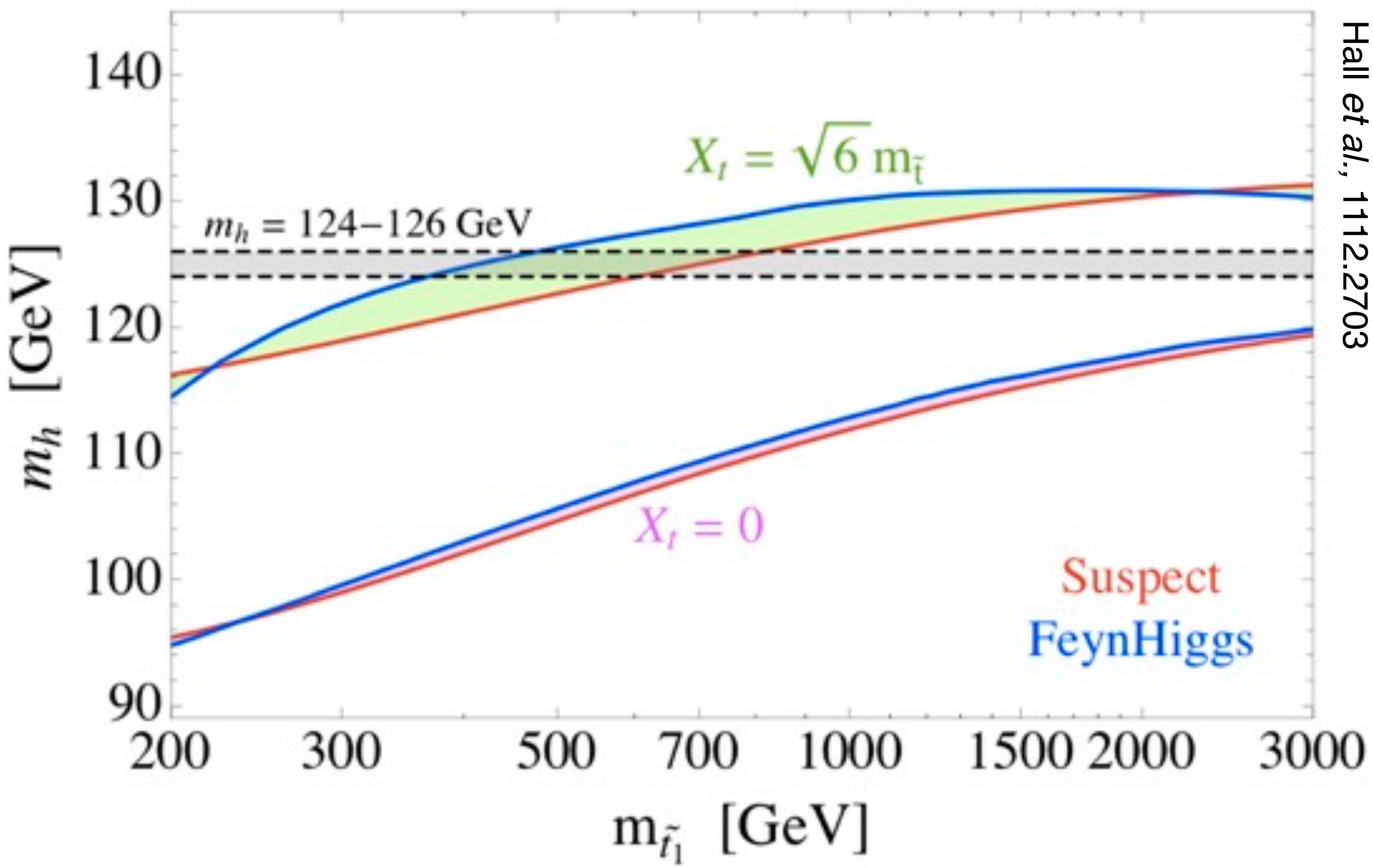
We must also consider the *parametric* uncertainty stemming from the experimental uncertainty of the SM parameters entering the corrections (especially m_t)

More work to do!!! However - if squarks are found - a precise determination of m_h will allow us to constrain parameters that the LHC can measure only poorly (e.g., X_t)

NOTE: uncertainty in the MSSM prediction for the light Higgs mass

Public c ... tSusy, SPheno)

curre ... m corrections



The es ... stop mixing!!!)

A nearly ... ing 3-loop terms

(Martin ... lown to ≤ 1 GeV

Still largi ... leV (with 30 fb^{-1})

W ... perimental

lly m_t)

More work to do!!! However - if squarks are found - a precise determination of m_h will allow us to constrain parameters that the LHC can measure only poorly (e.g., X_t)

NOTE: uncertainty in the MSSM prediction for the light Higgs mass

Public codes for the MSSM mass spectrum (e.g. `FeynHiggs, SuSpect, SoftSusy, SPheno`) currently include full 1-loop plus leading 2-loop top/stop and bottom/sbottom corrections (2-loop part by Heinemeyer *et al.* 98-07; P.S. *et al.* 01-04)

The estimated *theoretical* uncertainty is $\Delta^{th}\, m_h \approx 3$ GeV (especially at large stop mixing!!!)

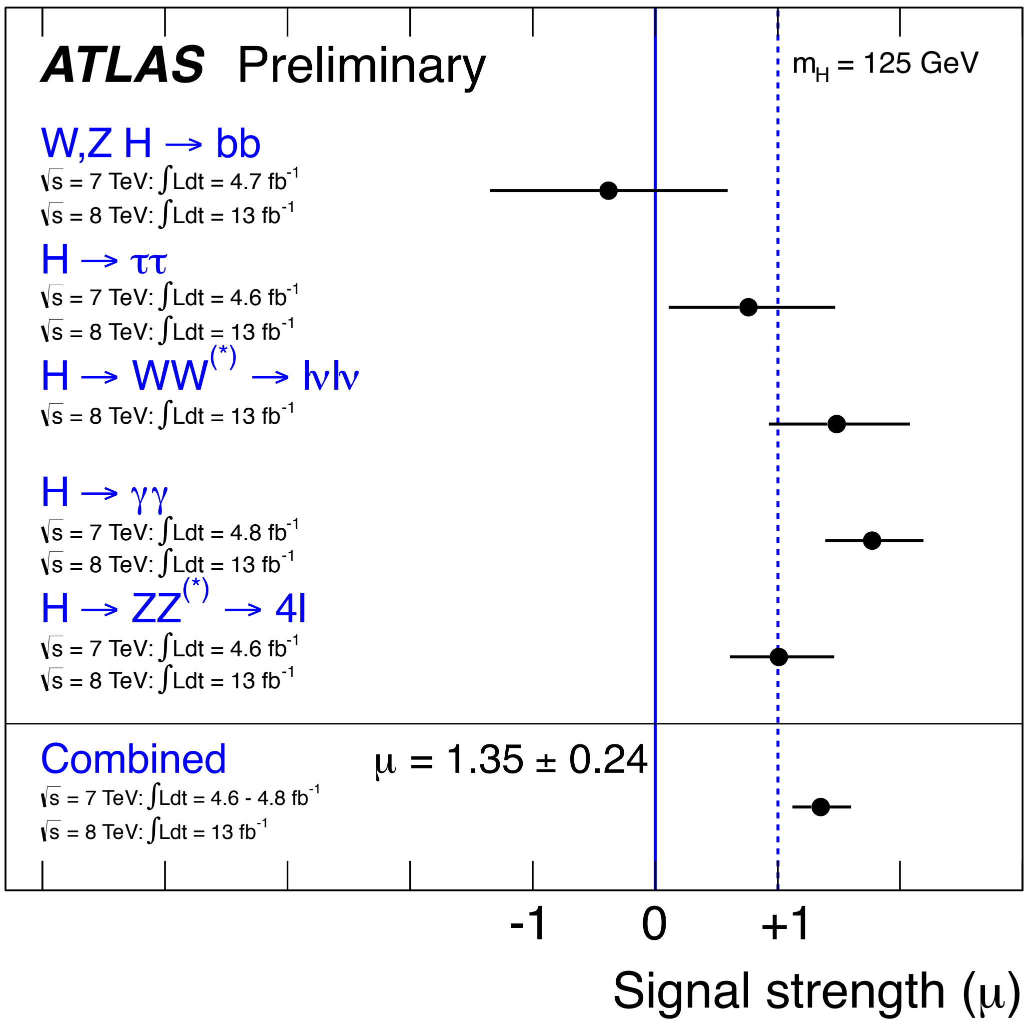
A nearly-full 2-loop calculation including EW (Martin 02-04) and even the leading 3-loop terms (Martin 07; Harlander *et al.* 08-10) are now available. Uncertainty should go down to ≤ 1 GeV

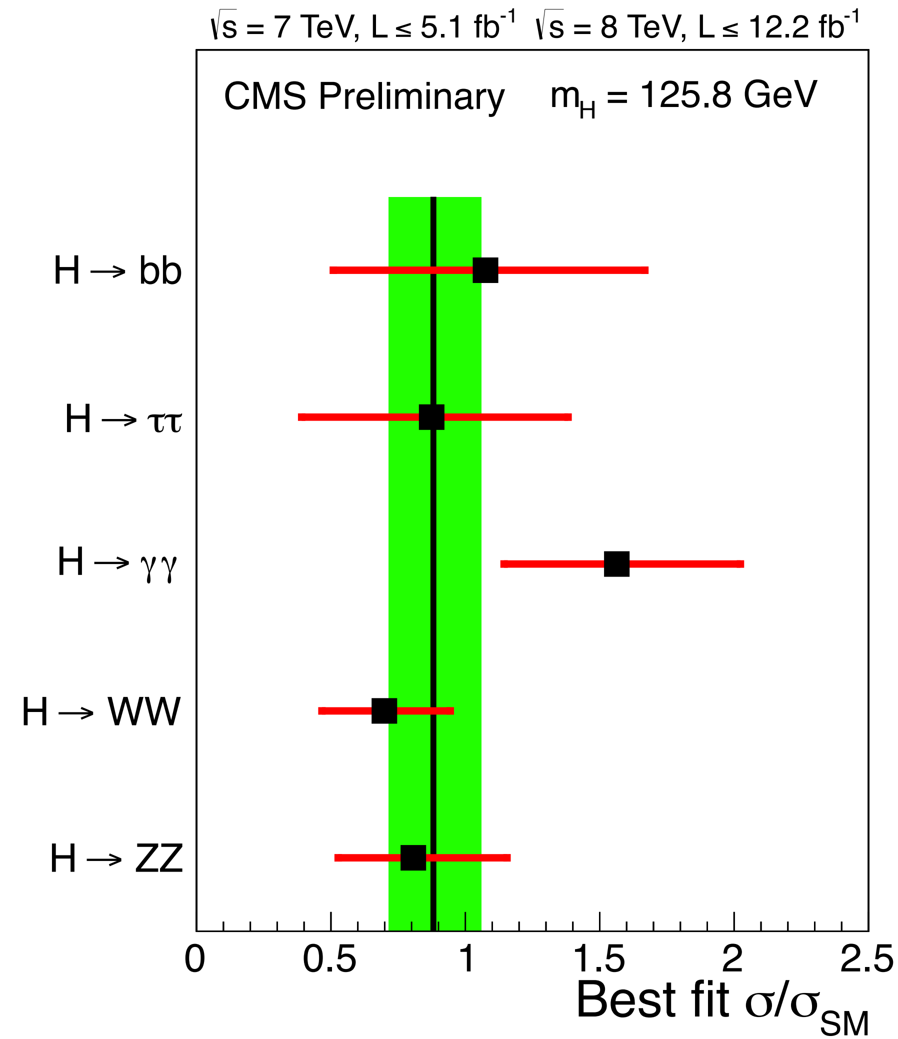
Still largish w.r.t. the expected *experimental* accuracy at LHC: $\Delta^{exp}\, m_h \approx 100$ MeV (with 30 fb^{-1})

We must also consider the *parametric* uncertainty stemming from the experimental uncertainty of the SM parameters entering the corrections (especially m_t)

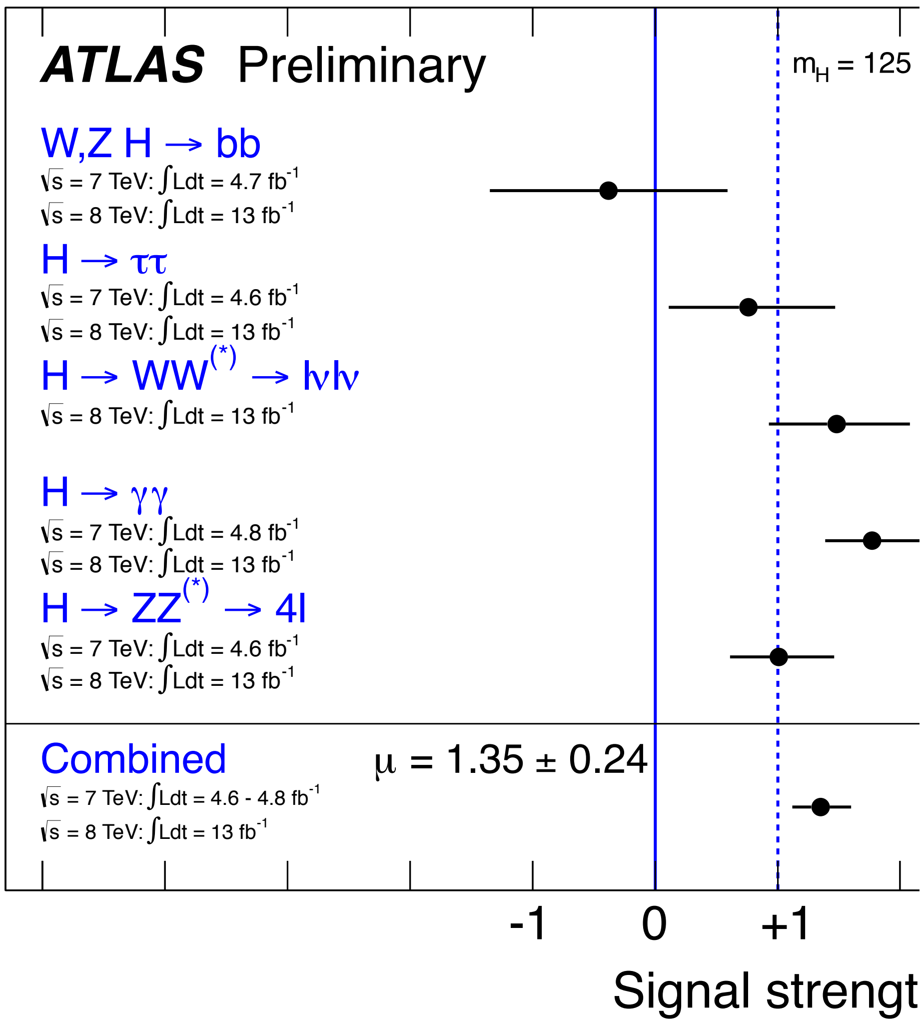
More work to do!!! However - if squarks are found - a precise determination of m_h will allow us to constrain parameters that the LHC can measure only poorly (e.g., X_t)

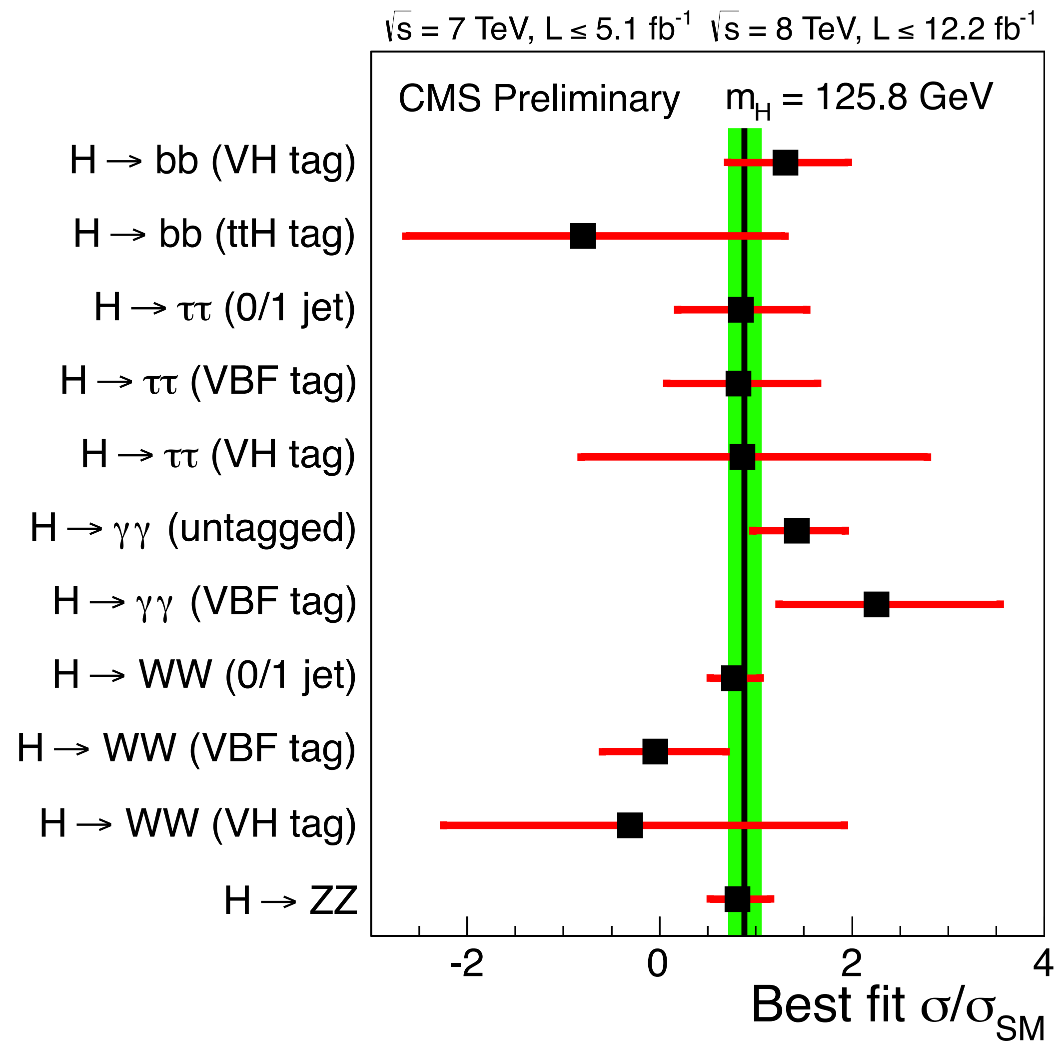
An exercise in wishful thinking: interpreting a diphoton excess





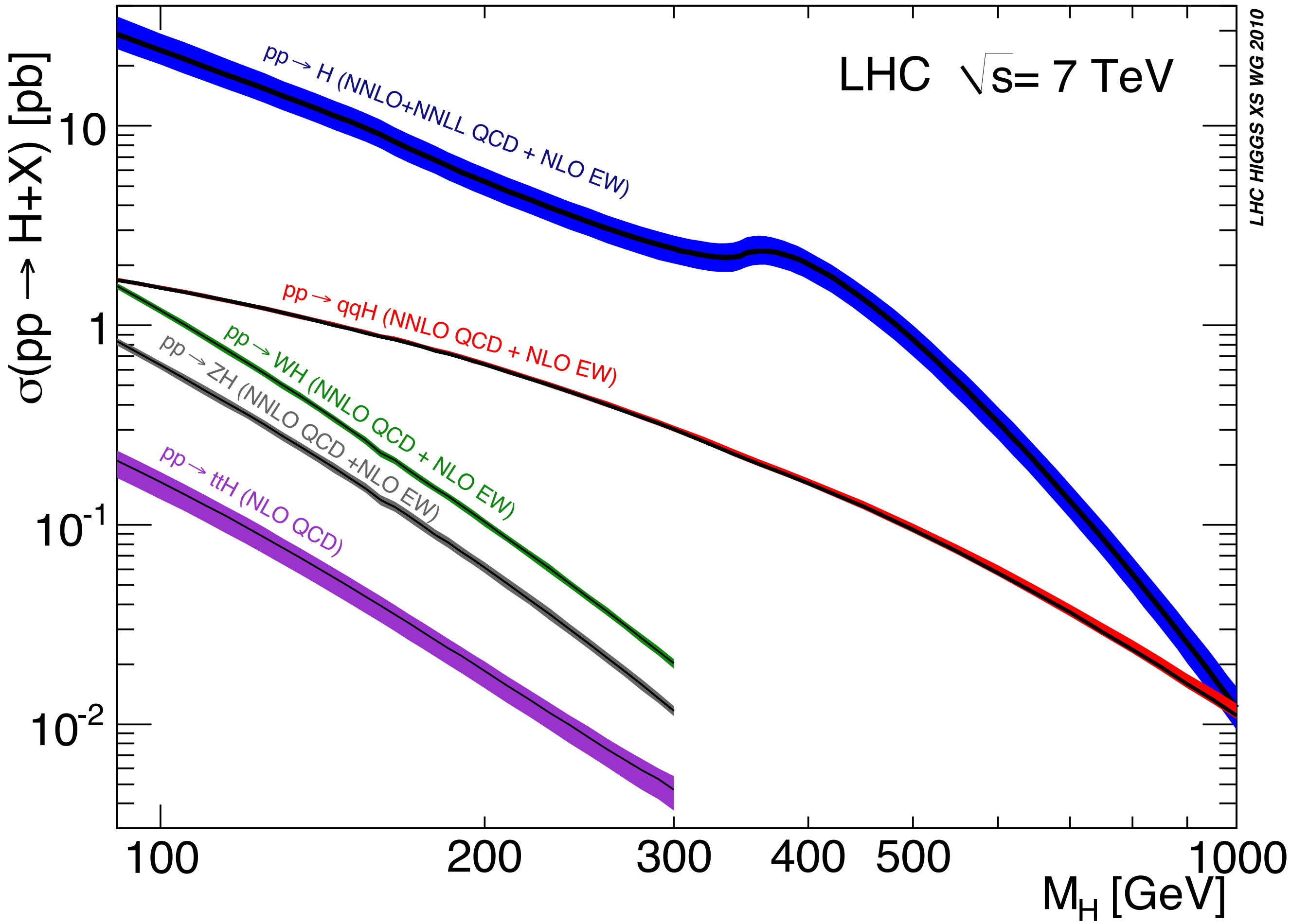
An exercise in wishful thinking: interpreting a diphoton excess

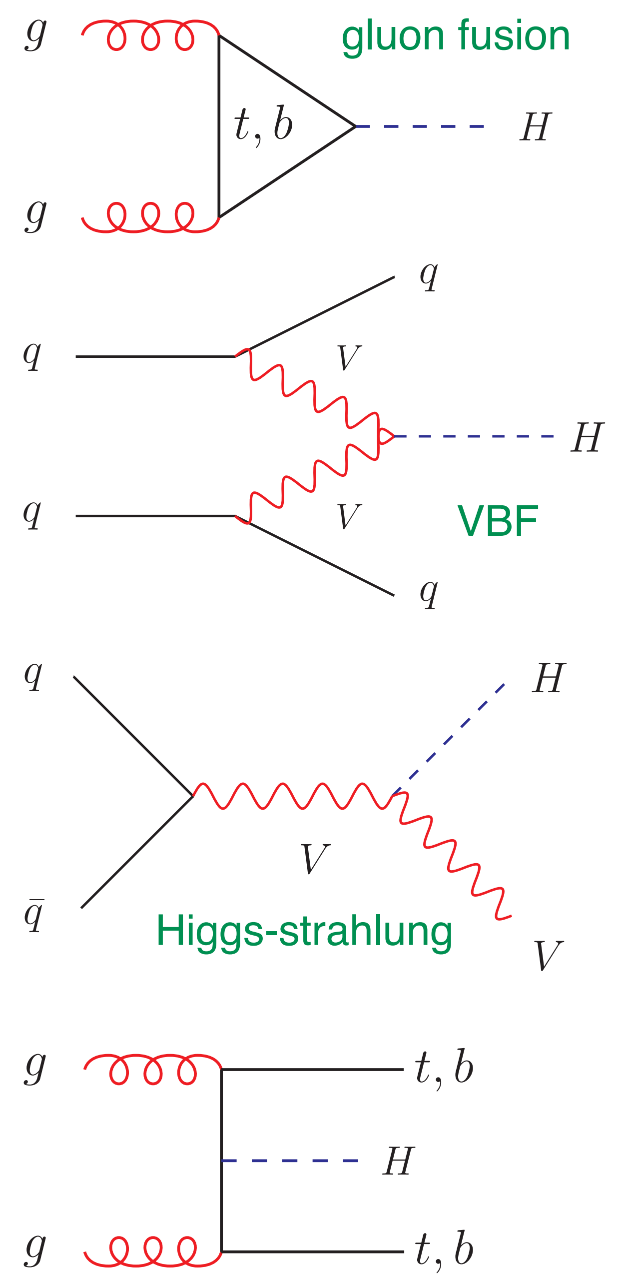




Higgs boson production at the LHC

SM predictions for the different channels:

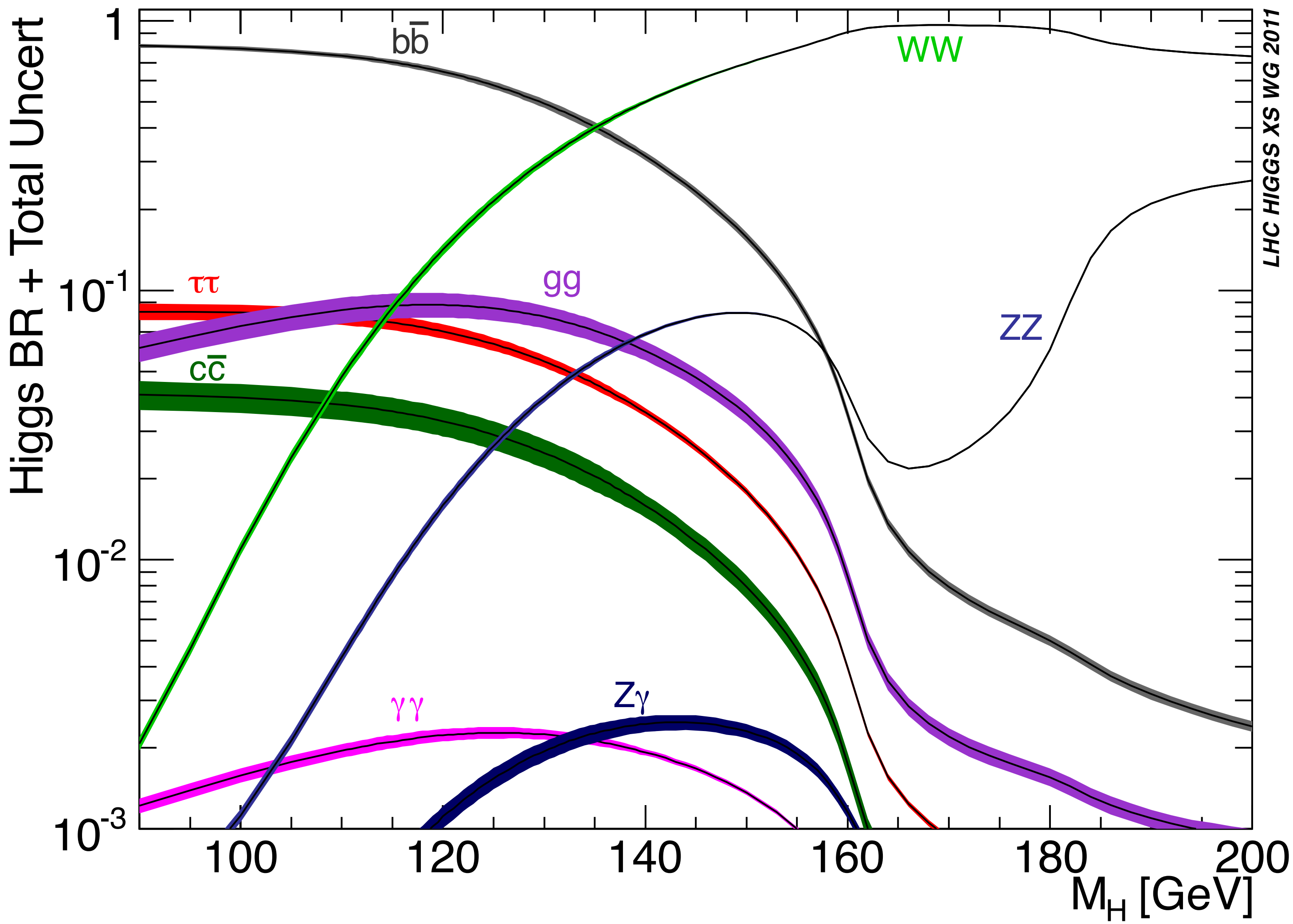




In the SM, gluon fusion is the dominant production channel
(in the MSSM, also associated production with bottom)

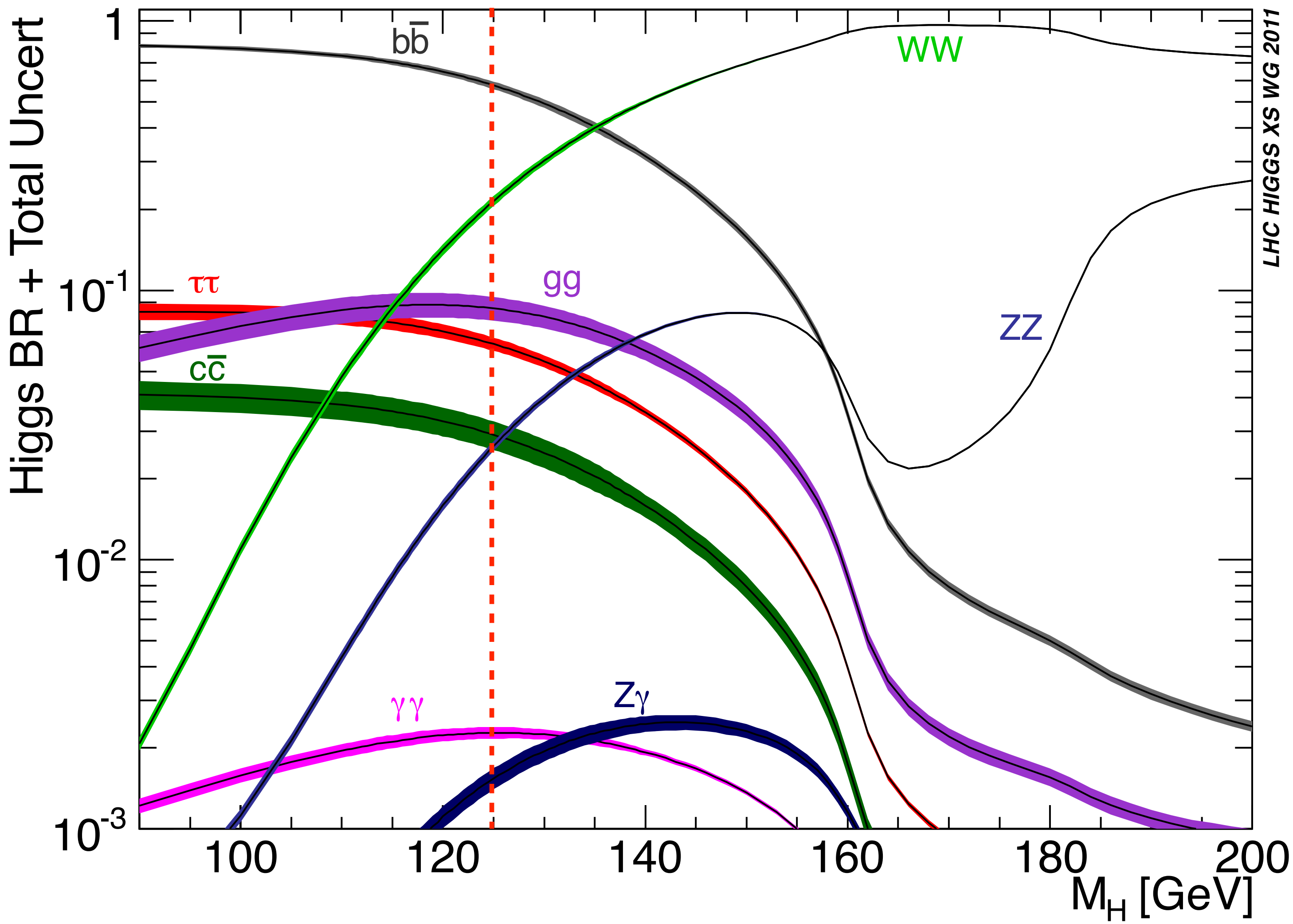
A precise computation of the cross sections is crucial to the interpretation of the Higgs searches

In the SM, a 125-GeV Higgs decays mostly into bottom quarks



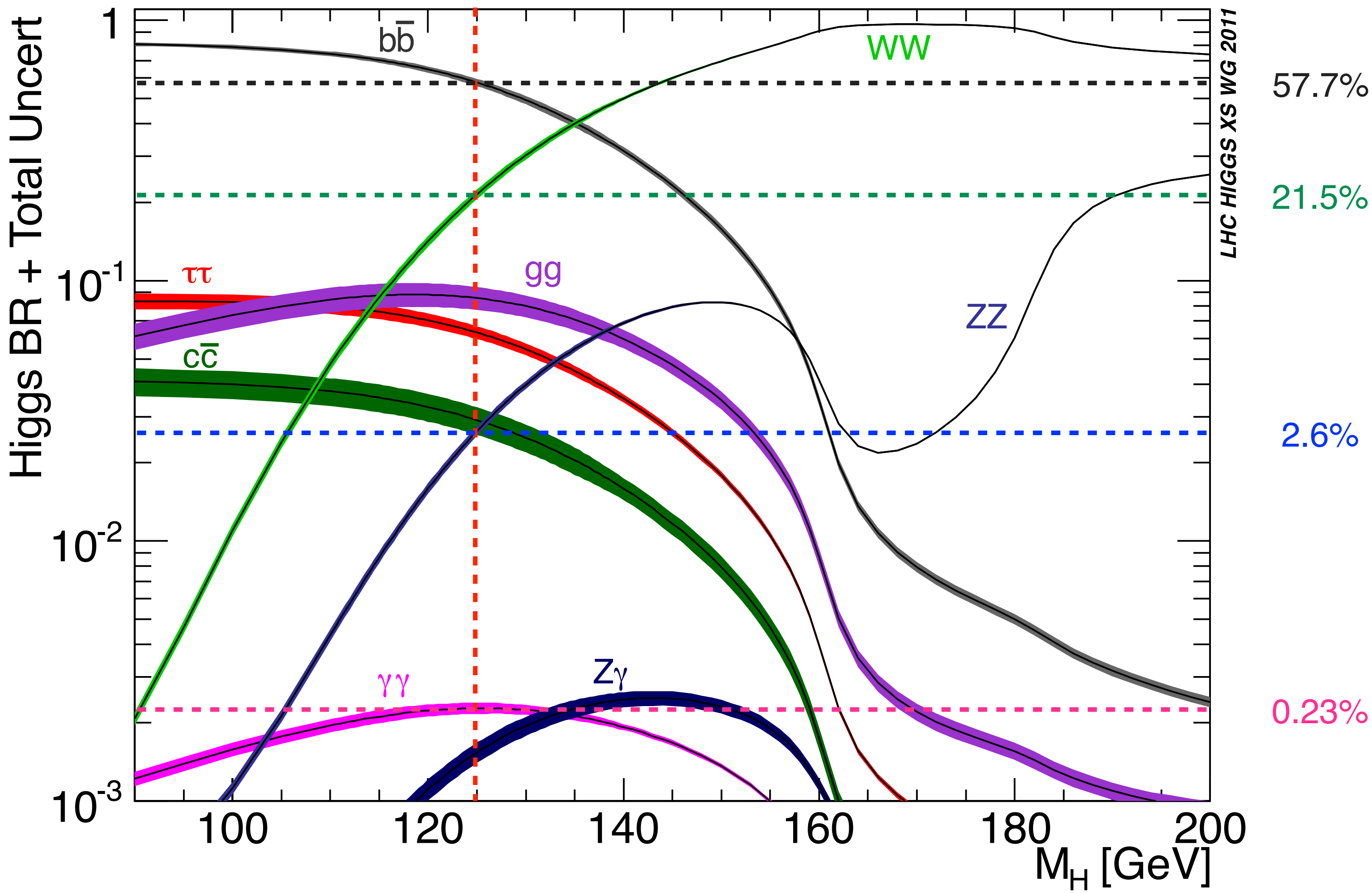
Decays to two photons are suppressed but easy to detect

In the SM, a 125-GeV Higgs decays mostly into bottom quarks



Decays to two photons are suppressed but easy to detect

In the SM, a 125-GeV Higgs decays mostly into bottom quarks

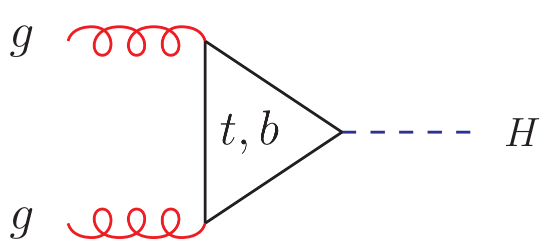


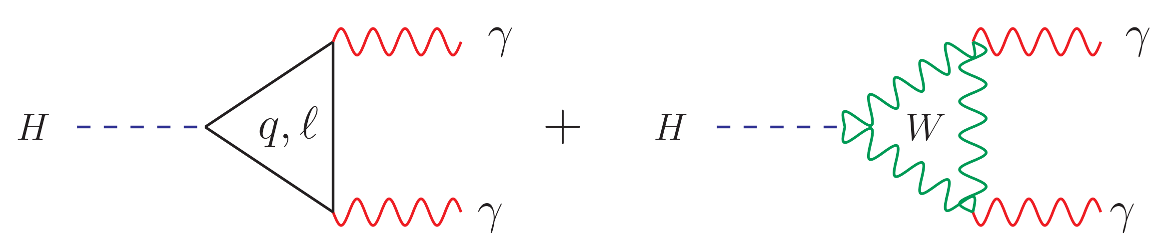
Decays to two photons are suppressed but easy to detect

Various ways to increase the diphoton rate: $R_{gg}(\gamma\gamma) \equiv \dfrac{\sigma(gg \to H)\,\mathrm{BR}(H \to \gamma\gamma)}{\sigma(gg \to H)_{\mathrm{SM}}\,\mathrm{BR}(H \to \gamma\gamma)_{\mathrm{SM}}}$

- Enhance the production cross section *(why no excess in other channels?)*
- Enhance the branching ratio into two photons:
  - by enhancing the two-photon width;
  - by suppressing the total width (especially bottom width).

Both the Higgs production in gluon fusion and the decay into photons are loop-mediated:

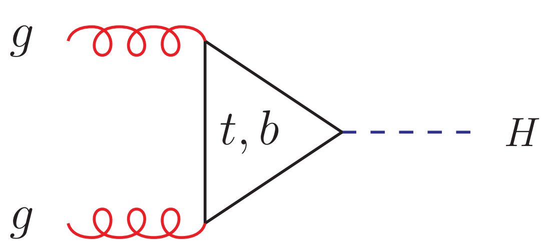




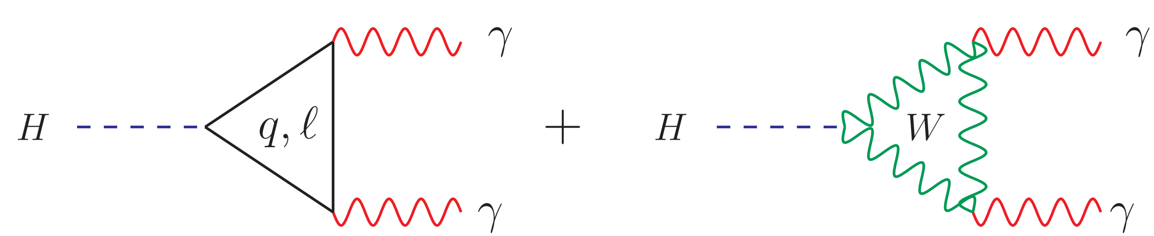
Various ways to increase the diphoton rate: $R_{gg}(\gamma\gamma) \equiv \dfrac{\sigma(gg \to H)\,\mathrm{BR}(H \to \gamma\gamma)}{\sigma(gg \to H)_{\mathrm{SM}}\,\mathrm{BR}(H \to \gamma\gamma)_{\mathrm{SM}}}$

- Enhance the production cross section *(why no excess in other channels?)*
- Enhance the branching ratio into two photons:
  - by enhancing the two-photon width;
  - by suppressing the total width (especially bottom width).

Both the Higgs production in gluon fusion and the decay into photons are loop-mediated:



$+\ \tilde{q}$

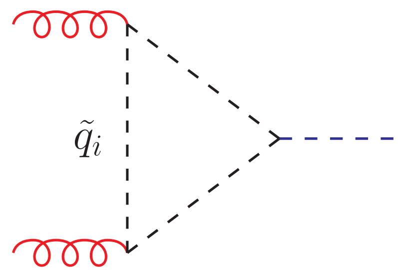


$+\ \tilde{q}\,,\ \tilde{\ell}\,,\ \chi^{\pm}\,,\ H^{\pm}$

Can superparticle contributions do the job?

Stop contribution to Higgs production in gluon fusion

At LO, one-loop squark contribution:



$(\tilde{q} = \tilde{t}, \tilde{b})$

The one-loop sbottom contribution is small (especially for a SM-like Higgs)

For a light Higgs much lighter than top and stops, we can consider an effective hgg vertex:

$$\mathcal{L}_{\rm eff} \;=\; \frac{\alpha_s}{12\,\pi\,v}\,h\,G^{a\,\mu\nu}G^a_{\mu\nu} \qquad \longrightarrow \qquad (1+\Delta_{\tilde t})\,\frac{\alpha_s}{12\,\pi\,v}\,h\,G^{a\,\mu\nu}G^a_{\mu\nu}$$

The stop contribution can enhance or suppress the cross section, depending on the mixing X_t

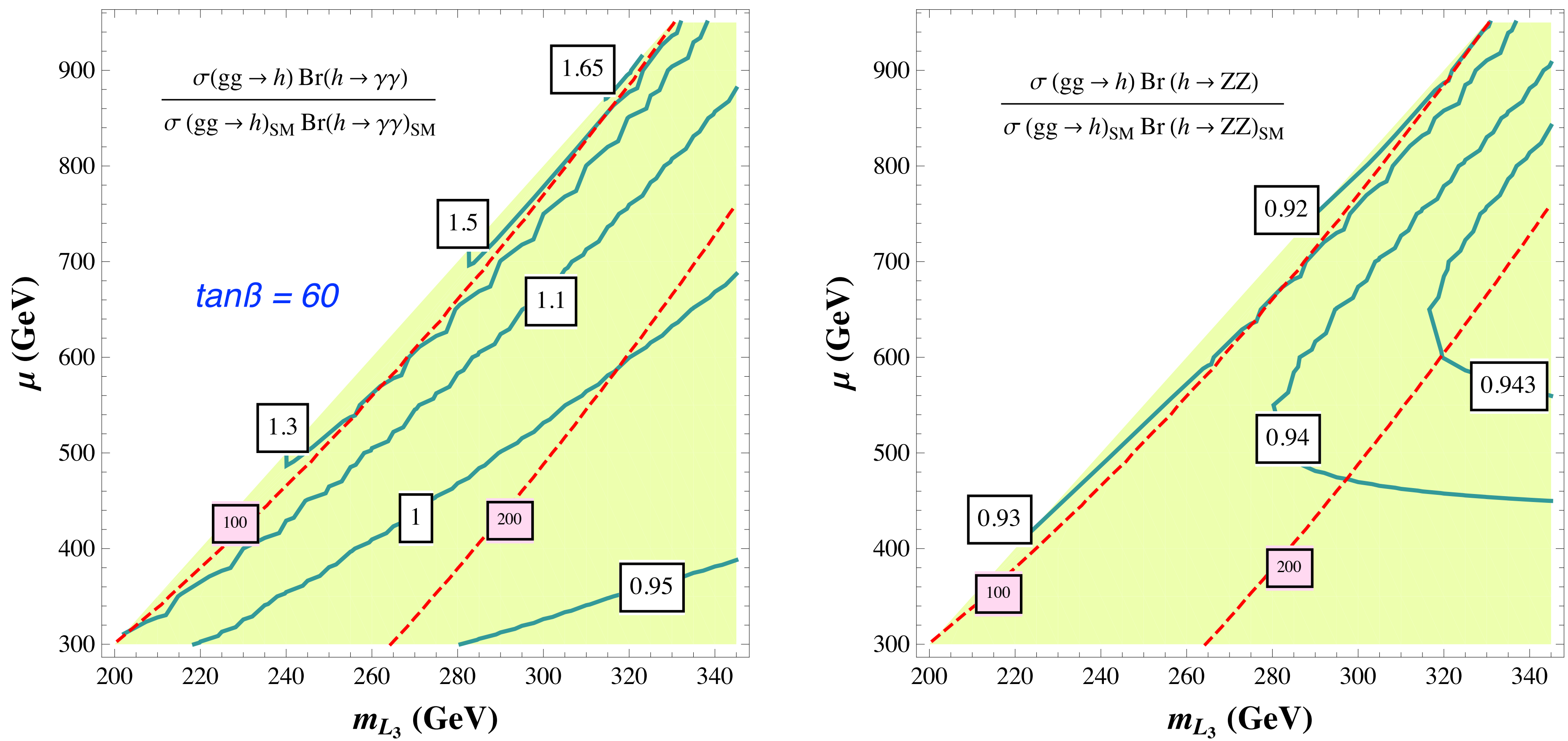
$$\Delta_{\tilde t} \;\approx\; \frac{m_t^2}{4}\left(\frac{1}{m^2_{\tilde t_1}} + \frac{1}{m^2_{\tilde t_2}} - \frac{X_t^2}{m^2_{\tilde t_1}\,m^2_{\tilde t_2}}\right)$$

The same rescaling occurs in the top contribution to the $h\gamma\gamma$ vertex.
However, that vertex is dominated by the W loop (opposite sign w.r.t. top loop)

For large stop mixing (favoured by Higgs mass) the diphoton rate is *suppressed*

Stau contribution to Higgs decay in two photons

For large stau mixing $X_\tau \approx \mu \tan\beta$, light staus can enhance the two-photon decay without affecting the gluon-fusion production mechanism



Carena *et al.,* 1205.5842

Light sleptons (however, smuons) and large *tanβ* might also fix the muon g-2

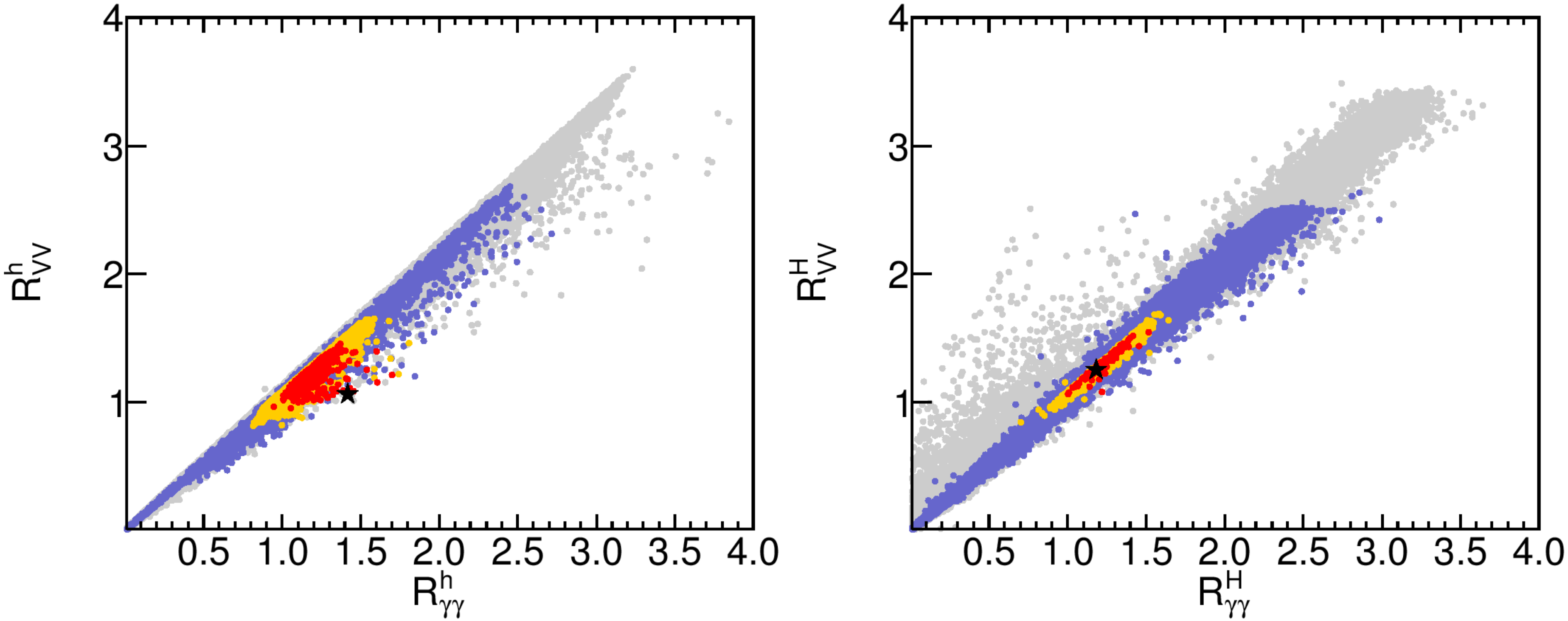
(NOTE: issues with vacuum stability. See Kitahara, 1208.4792 + Carena *et al.*, 1211.6136)

Raising the diphoton rate by suppressing the decay width to bottom

light-Higgs to bottom coupling can be suppressed
for small α and/or large and positive $\epsilon_b \tan\beta$
(only if away from the decoupling limit!)

$$g_{hbb}/g_{hbb}^{\rm SM} \;=\; -\,\frac{\sin\alpha}{\cos\beta}\,\frac{1-\epsilon_b\cot\alpha}{1+\epsilon_b\tan\beta}$$

However, the two-gauge-boson rate is enhanced together with the diphoton rate:



Bechtle *et al.*, 1211.1955

Acceptable points with enhanced diphoton rate exist for both *h* and *H*

Extending the Higgs sector of the MSSM

The μ problem of the MSSM and the Next-to-Minimal SSM

In the MSSM, the Higgs/higgsino mass is the only dimensionful parameter in the superpotential: $W \supset -\mu\, H_1\, H_2$

The μ problem: if μ is allowed in the SUSY limit, why is it not of $\mathcal{O}(M_P)$?

The *Giudice-Masiero* solution: (1988)

μ is forbidden in the SUSY limit, and is generated at the SUSY-breaking scale together with the soft parameters

NMSSM alternative: generate μ at the weak scale through the vev of a light singlet

$$W \supset -\lambda\, S\, H_1\, H_2 \quad \longrightarrow \quad \mu_{\rm eff} = \lambda\, \langle S \rangle$$

This brings along an extended Higgs sector (scalar & pseudoscalar singlet, singlino) and a whole new set of soft SUSY-breaking parameters

Half-empty glass: more complicated, less predictive than the MSSM

Half-full glass:

- extra particles, richer phenomenology at colliders
- no need for heavy stops to increase the Higgs mass

The Higgs sector of the NMSSM

Superpotential and soft SUSY-breaking terms: $W \supset -\lambda\, S H_1 H_2 + \frac{\kappa}{3} S^3$

$$V_{\rm soft} \supset m^2_{H_1} H_1^\dagger H_1 + m^2_{H_2} H_2^\dagger H_2 + m^2_S\, S^* S + \left(-\lambda\, A_\lambda\, S H_1 H_2 + \frac{\kappa}{3} A_\kappa\, S^3 \; + \; {\rm h.c.} \right)$$

The scalar, pseudoscalar and fermion components of S mix with their MSSM counterparts

$$H_i^0 \;=\; v_i + \frac{1}{\sqrt{2}} (S_i + i P_i) \quad (i = 1,2) \;, \qquad\qquad S \;=\; v_s + \frac{1}{\sqrt{2}} (S_3 + i P_3)$$

$$\left(\begin{array}{c} h_1 \\ h_2 \\ h_3 \end{array} \right) = R^S \left(\begin{array}{c} S_1 \\ S_2 \\ S_3 \end{array} \right) , \qquad \left(\begin{array}{c} G^0 \\ A_1 \\ A_2 \end{array} \right) = R^P \left(\begin{array}{c} P_1 \\ P_2 \\ P_3 \end{array} \right) , \qquad \left(\begin{array}{c} \chi_1^0 \\ \chi_2^0 \\ \chi_3^0 \\ \chi_4^0 \\ \chi_5^0 \end{array} \right) = N \left(\begin{array}{c} -i\tilde{b} \\ -i\tilde{w}^0 \\ \tilde{h}_1^0 \\ \tilde{h}_2^0 \\ \tilde{s} \end{array} \right)$$

The charged-Higgs and chargino sectors are the same as in the MSSM, once we identify

$$\mu \;\equiv\; \lambda\, v_s \,, \qquad B_\mu \;\equiv\; \lambda\, v_s \,(A_\lambda + \kappa v_s) - \lambda^2\, v_1 v_2 \;, \qquad \tan\beta \;\equiv\; \frac{v_2}{v_1}$$

In the limit $v_s^2 \gg v^2 \equiv v_1^2 + v_2^2$ the singlet decouples from the MSSM doublets

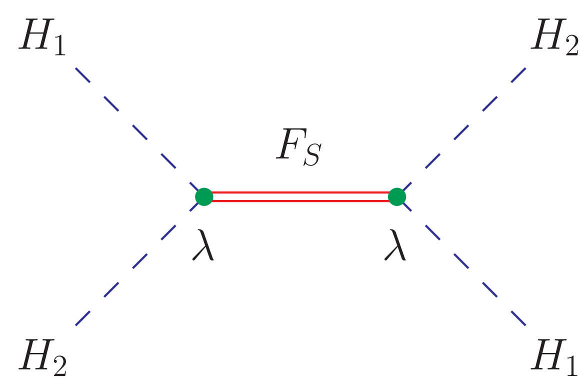
$$m_{A_1}^2 = \frac{2\,B_\mu}{\sin 2\beta} + \mathcal{O}(v^2)\,, \qquad m_{A_2}^2 = \frac{3\,\kappa^2}{w}\,v_s^2 + \mathcal{O}(v^2)$$

$$m_{h_2}^2 = m_{A_1}^2 + \mathcal{O}(v^2)\,, \qquad m_{h_3}^2 = \frac{4w-1}{3}\,m_{A_2}^2 + \mathcal{O}(v^2)$$

$$m_{h_1}^2 = M_Z^2\cos^2 2\beta + \lambda^2 v^2 \left\{ \sin^2 2\beta - \frac{\left[\frac{\lambda}{k} + \left(\frac{A_\lambda}{2wA_\kappa} - 1\right)\sin 2\beta\right]^2}{1 - \frac{1}{4w}} \right\} + \mathcal{O}(v^4)$$

where $w \equiv \frac{1}{4}\left(1 + \sqrt{1 - 8\,\frac{m_S^2}{A_\kappa^2}}\right) > \frac{1}{3}$

Additional, F-term induced contribution
to the MSSM Higgs quartic coupling:



If $\lambda \to 0$ with $\mu = \lambda v_s$ constant we recover the MSSM

In the limit $v_s^2 \gg v^2 \equiv v_1^2 + v_2^2$ the singlet decouples from the MSSM doublets

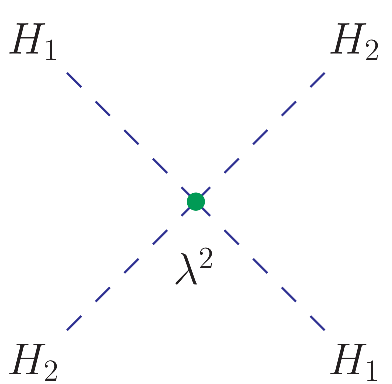
$$m_{A_1}^2 = \frac{2\,B_\mu}{\sin 2\beta} + \mathcal{O}(v^2)\,, \qquad m_{A_2}^2 = \frac{3\,\kappa^2}{w}\,v_s^2 + \mathcal{O}(v^2)$$

$$m_{h_2}^2 = m_{A_1}^2 + \mathcal{O}(v^2)\,, \qquad m_{h_3}^2 = \frac{4w-1}{3}\,m_{A_2}^2 + \mathcal{O}(v^2)$$

$$m_{h_1}^2 = M_Z^2\cos^2 2\beta + \lambda^2 v^2 \left\{ \sin^2 2\beta - \frac{\left[\frac{\lambda}{k} + \left(\frac{A_\lambda}{2wA_\kappa} - 1\right)\sin 2\beta\right]^2}{1 - \frac{1}{4w}} \right\} + \mathcal{O}(v^4)$$

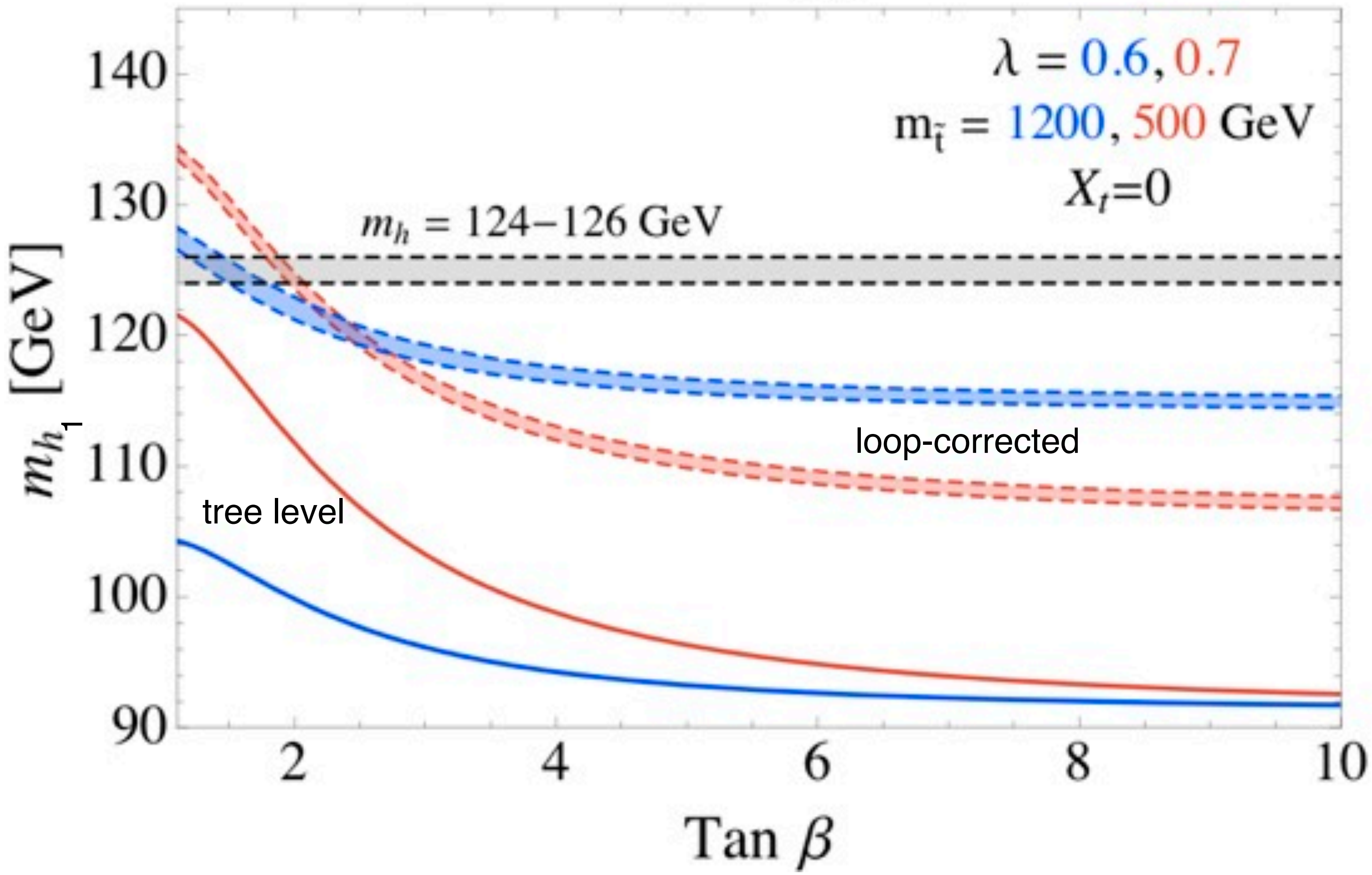
where $w \equiv \frac{1}{4}\left(1 + \sqrt{1 - 8\,\frac{m_S^2}{A_\kappa^2}}\right) > \frac{1}{3}$

Additional, F-term induced contribution
to the MSSM Higgs quartic coupling:



If $\lambda \to 0$ with $\mu = \lambda v_s$ constant we recover the MSSM

The additional contribution to the SM-like Higgs mass is maximized at low *tanβ*

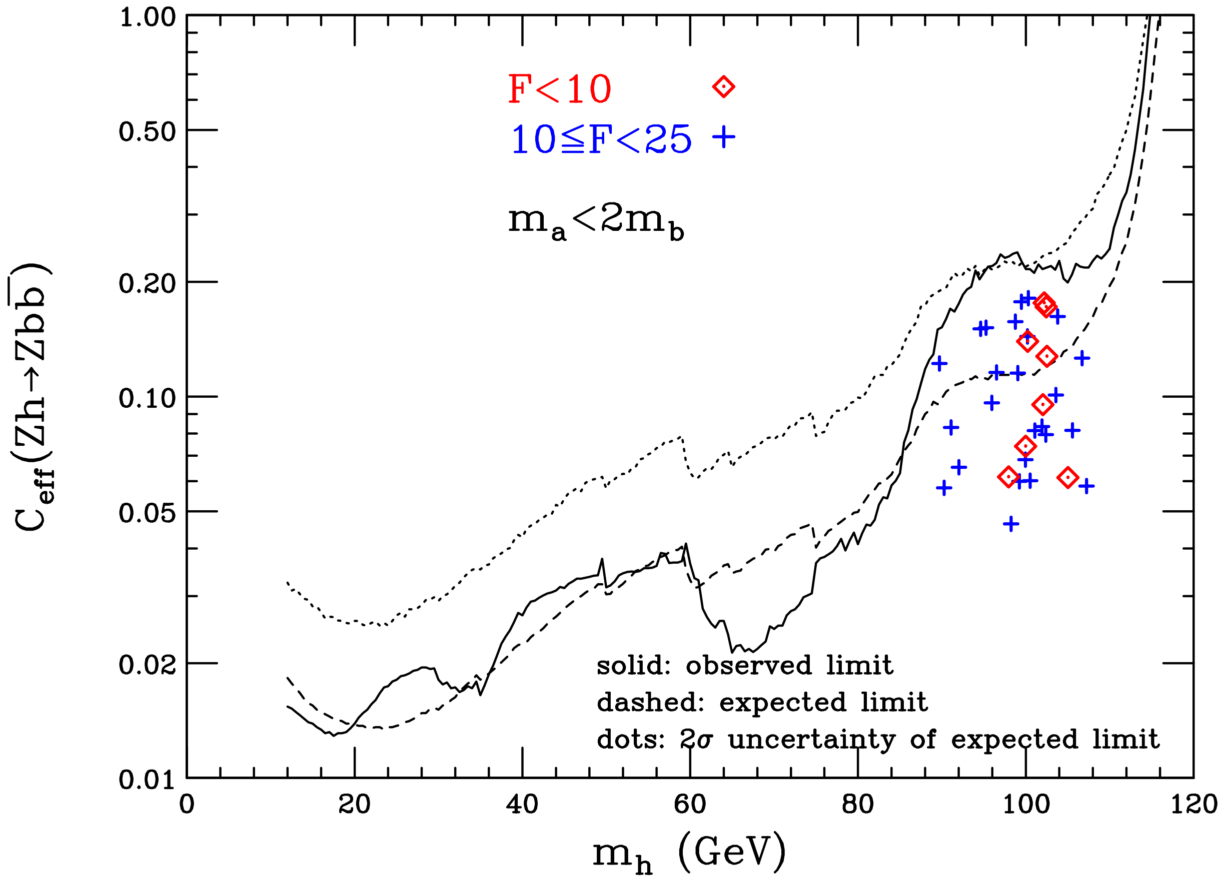


Hall *et al.*, 1112.2703

For large λ we can get $m_h \approx 125$ GeV even with zero mixing and relatively light stops

(fine-tuning reduced w.r.t. MSSM)

An interesting possibility: a light scalar might not be ruled out by LEP searches



(plot from Dermisek & Gunion, hep-ph/0510322)

$$F = \mathrm{Max}_p \left| \frac{d \log m_Z}{d \log p} \right|$$

$$C_{\rm eff} = [g^2_{ZZh_1} / g^2_{ZZh_{\rm SM}}] \, \mathrm{BR}(h_1 \to b\bar{b})$$

The coupling to the Z can be reduced if h_1 has a sizeable singlet component

The BR into bottom can be reduced if $h_1 \to 2\,A_1 \to 4\,\tau$ (with $m_{A_1} < 2\,m_b$)

The extended Higgs sector of the NMSSM allows to accommodate additional "bumps"

Some recently proposed multi-Higgs scenarios:

- Gunion *et al.*, 1207.1545: both h_1 and h_2 near 125 GeV
  (could explain $\gamma\gamma$ excess and a shift between measured masses in $\gamma\gamma$ and 4ℓ)

- Belanger *et al.*, 1208.4952: $m_{h1} \approx 125$ GeV, $m_{h2} \approx 136$ GeV
  (could explain the second peak in $\gamma\gamma$ seen by CMS)

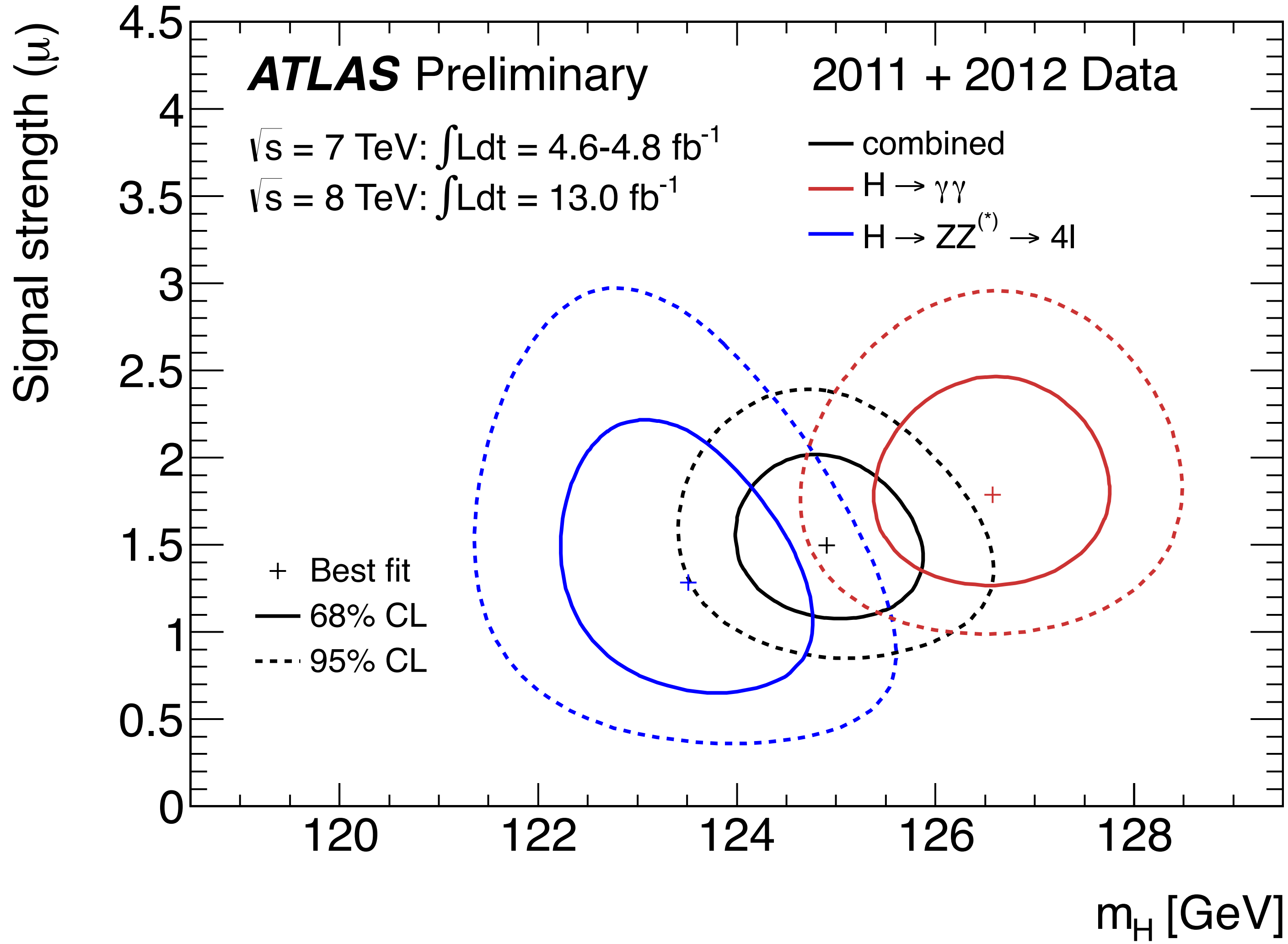
- Belanger *et al.*, 1210.1976: $m_{h1} \approx 98$ GeV, $m_{h2} \approx 125$ GeV
  (could explain the LEP excess, but h_1 only detectable at LHC-14)

(in all scenarios h_1 and h_2 are mixtures of singlet and doublets, h_3 is mostly MSSM-like)

Note: a sizeable singlet-doublet mixing can suppress the Higgs-bottom coupling
(thus enhancing the diphoton rate)

The ext bumps”

- G
  (c ıd 4ℓ)



- B
  (c

- B
  (c

(in all scenarios *h_1* and *h_2* are mixtures of singlet and doublets, *h_3* is mostly MSSM-like)

Note: a sizeable singlet-doublet mixing can suppress the Higgs-bottom coupling
(thus enhancing the diphoton rate)

The extended Higgs sector of the NMSSM allows to accommodate additional “bumps”

Some recently proposed multi-Higgs scenarios:

- Gunion *et al.*, 1207.1545: both h_1 and h_2 near 125 GeV
  (could explain $\gamma\gamma$ excess and a shift between measured masses in $\gamma\gamma$ and 4ℓ)

- Belanger *et al.*, 1208.4952: $m_{h1} \approx$ 125 GeV, $m_{h2} \approx$ 136 GeV
  (could explain the second peak in $\gamma\gamma$ seen by CMS)

- Belanger *et al.*, 1210.1976: $m_{h1} \approx$ 98 GeV, $m_{h2} \approx$ 125 GeV
  (could explain the LEP excess, but h_1 only detectable at LHC-14)

(in all scenarios h_1 and h_2 are mixtures of singlet and doublets, h_3 is mostly MSSM-like)

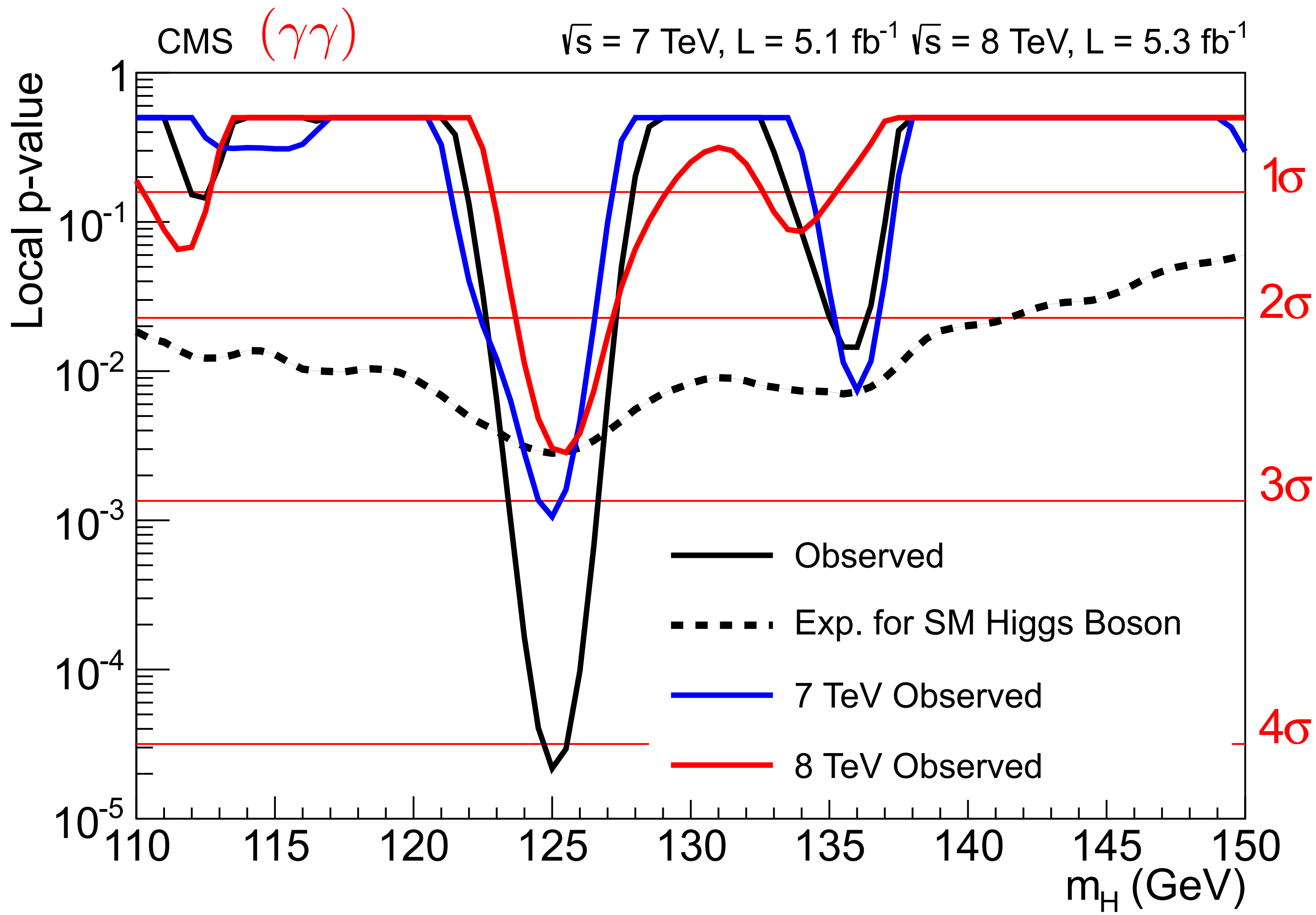
Note: a sizeable singlet-doublet mixing can suppress the Higgs-bottom coupling
(thus enhancing the diphoton rate)

The extended Higgs sector of the NMSSM allows to accommodate additional “bumps”

- Gu
(co ... ınd 4ℓ)

- Be
(co

- Be
(co



(in all sce ... SSM-like)

Note: a sizeable singlet-doublet mixing can suppress the Higgs-bottom coupling
(thus enhancing the diphoton rate)

The extended Higgs sector of the NMSSM allows to accommodate additional “bumps”

Some recently proposed multi-Higgs scenarios:

- Gunion *et al.*, 1207.1545: both h_1 and h_2 near 125 GeV
  (could explain $\gamma\gamma$ excess and a shift between measured masses in $\gamma\gamma$ and 4ℓ)

- Belanger *et al.*, 1208.4952: $m_{h1} \approx 125$ GeV, $m_{h2} \approx 136$ GeV
  (could explain the second peak in $\gamma\gamma$ seen by CMS)

- Belanger *et al.*, 1210.1976: $m_{h1} \approx 98$ GeV, $m_{h2} \approx 125$ GeV
  (could explain the LEP excess, but h_1 only detectable at LHC-14)

(in all scenarios h_1 and h_2 are mixtures of singlet and doublets, h_3 is mostly MSSM-like)

Note: a sizeable singlet-doublet mixing can suppress the Higgs-bottom coupling
(thus enhancing the diphoton rate)

The extended Higgs sector of the NMSSM allows to accommodate additional “bumps”

Some recently proposed multi-Higgs scenarios:

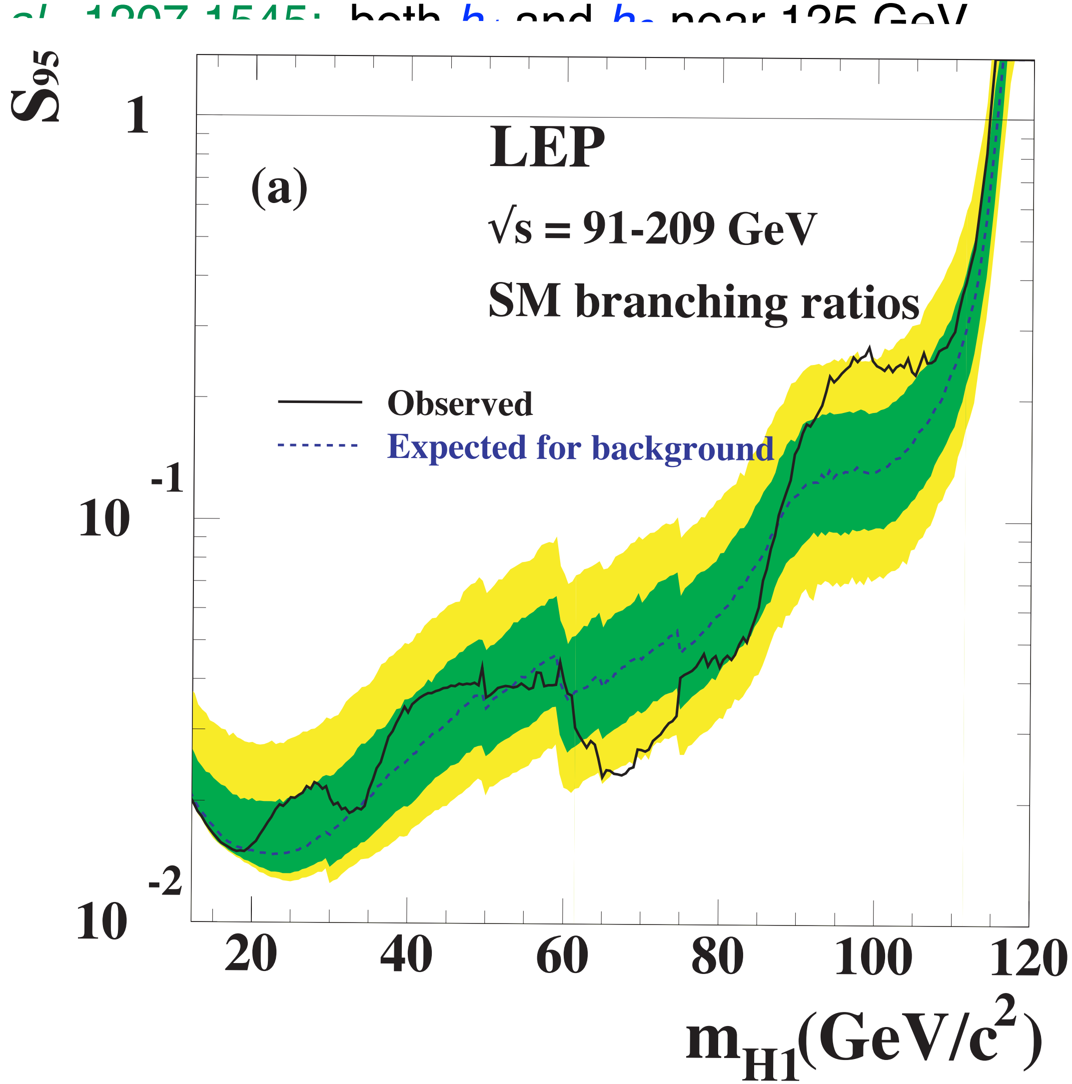
- Gunion *et al.* 1207.1545: both h_1 and h_2 near 125 GeV
  (could exp … n $\gamma\gamma$ and 4ℓ)

- Belanger …
  (could exp …

- Belanger …
  (could exp …)

(in all scenarios … ostly MSSM-like)

Note: a size … tom coupling



The extended Higgs sector of the NMSSM allows to accommodate additional “bumps”

Some recently proposed multi-Higgs scenarios:

- Gunion *et al.*, 1207.1545: both h_1 and h_2 near 125 GeV
  (could explain $\gamma\gamma$ excess and a shift between measured masses in $\gamma\gamma$ and 4ℓ)

- Belanger *et al.*, 1208.4952: $m_{h1} \approx 125$ GeV, $m_{h2} \approx 136$ GeV
  (could explain the second peak in $\gamma\gamma$ seen by CMS)

- Belanger *et al.*, 1210.1976: $m_{h1} \approx 98$ GeV, $m_{h2} \approx 125$ GeV
  (could explain the LEP excess, but h_1 only detectable at LHC-14)

(in all scenarios h_1 and h_2 are mixtures of singlet and doublets, h_3 is mostly MSSM-like)

Note: a sizeable singlet-doublet mixing can suppress the Higgs-bottom coupling
(thus enhancing the diphoton rate)

A different approach: effective field theory Beyond the MSSM

Suppose there is additional *(BMSSM)* physics in the Higgs sector, characterized by a *large* mass *M* (e.g. singlets, or SU(2) triplets, or additional gauge interactions)

At leading order in *1/M*, integrating out the heavy fields induces just one new operator in the superpotential:

$$\Delta W \;=\; \frac{\lambda}{M}\,(H_1 H_2)^2 \;+\; \mathcal{O}(M^{-2})$$

Together with a possible SUSY-breaking term, the new term affects the Higgs potential:

$$\Delta V \;=\; 2\,\frac{\mu\,\lambda}{M}\,(H_1 H_2)(H_1^\dagger H_1 + H_2^\dagger H_2) \;-\; \frac{m_{\cancel{\rm SUSY}}\,\lambda}{M}\,(H_1 H_2)^2 \;+\; {\rm h.c} \;+\; \mathcal{O}(M^{-2})$$

The effect on the Higgs masses (here in the decoupling limit $m_A >> m_Z$) is:

$$\Delta m_h^2 \;\approx\; 16\,v^2\,\cot\beta\,\frac{\mu\,\lambda}{M}\;, \qquad \Delta m_H^2 \;\approx\; 4\,v^2\,\frac{m_{\cancel{\rm SUSY}}\,\lambda}{M}\;, \qquad \Delta m_{H^\pm}^2 \;\approx\; 2\,v^2\,\frac{m_{\cancel{\rm SUSY}}\,\lambda}{M}$$

(for large *tanβ* the terms of order $1/M^2$ must be included in the analysis)

The BMSSM contributions can significantly raise the Higgs mass and enhance the diphoton rate

A final word of caution

A final word of caution

Constraining SUSY models through their predictions for the Higgs sector is instructive

A final word of caution

Constraining SUSY models through their predictions for the Higgs sector is instructive

However...

A final word of caution

Constraining SUSY models through their predictions for the Higgs sector is instructive

However...

...only the discovery of superpartners will convince us
that nature is supersymmetric at the weak scale!

Thank you!!!