Implications of a 125-GeV Higgs signal in SUSY extensions of the SM

Pietro Slavich

(LPTHE Paris)

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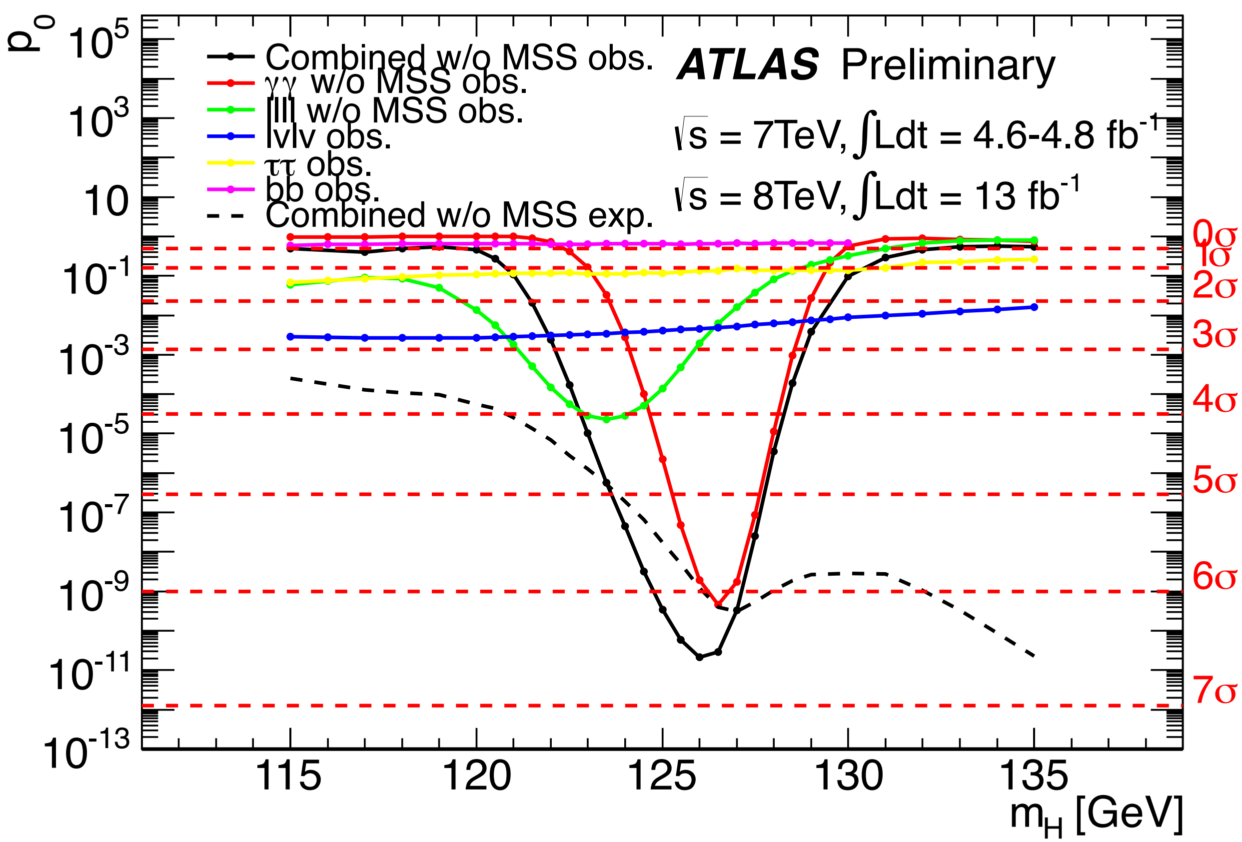
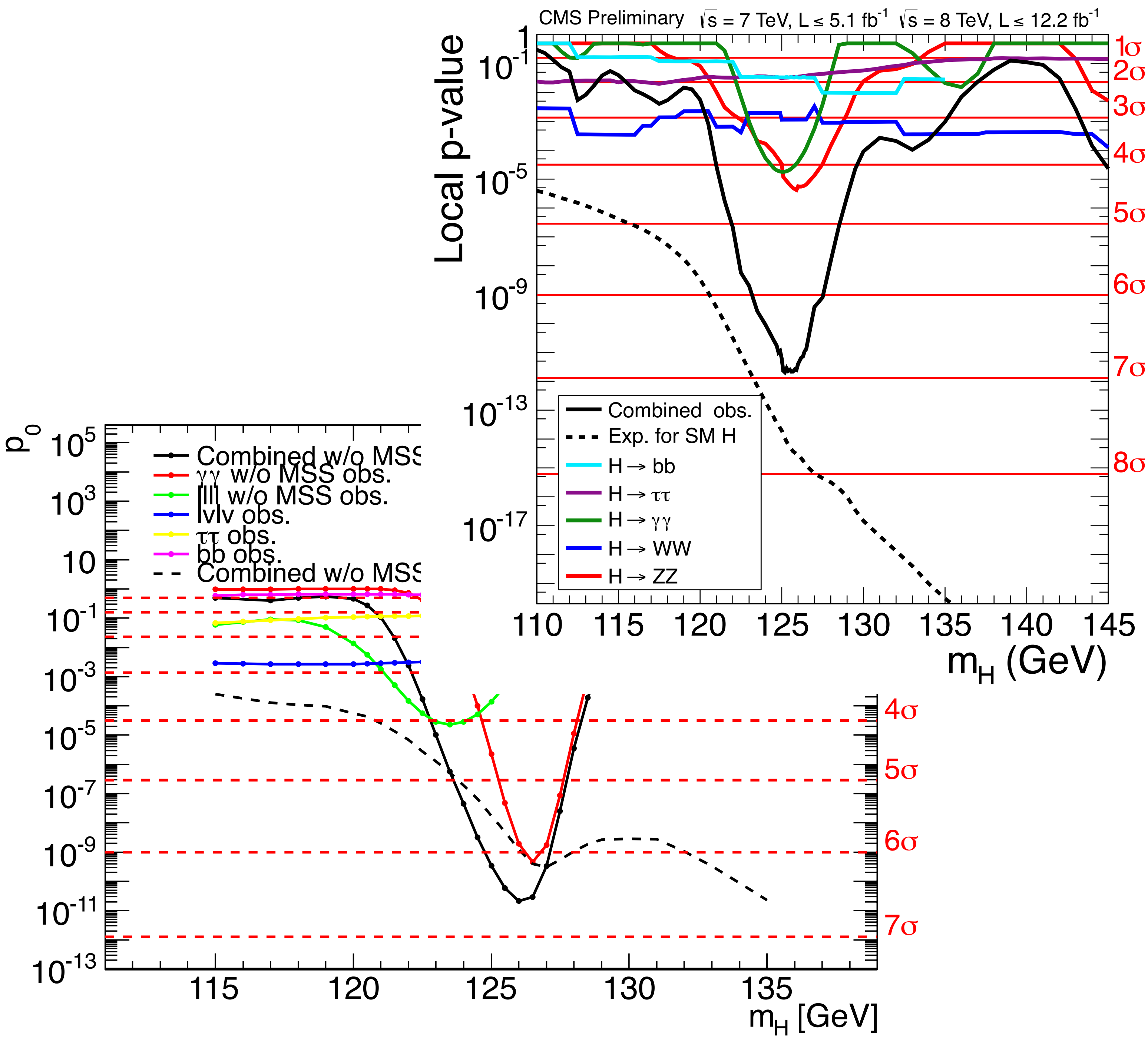
The Signal

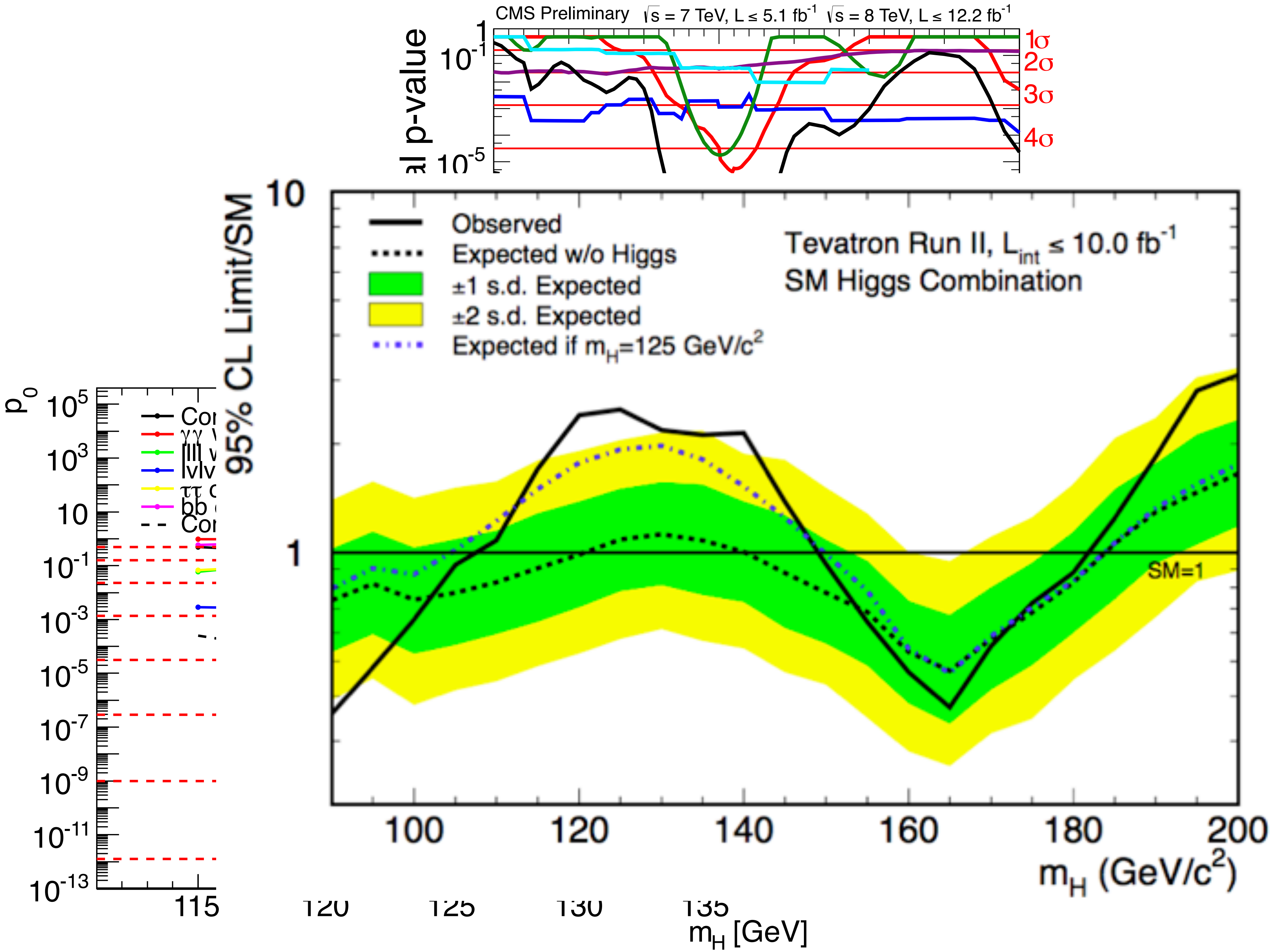
A Higgs boson!!!



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
p0
m_H [GeV]
0σ
1σ
2σ
3σ
4σ
5σ
6σ
7σ



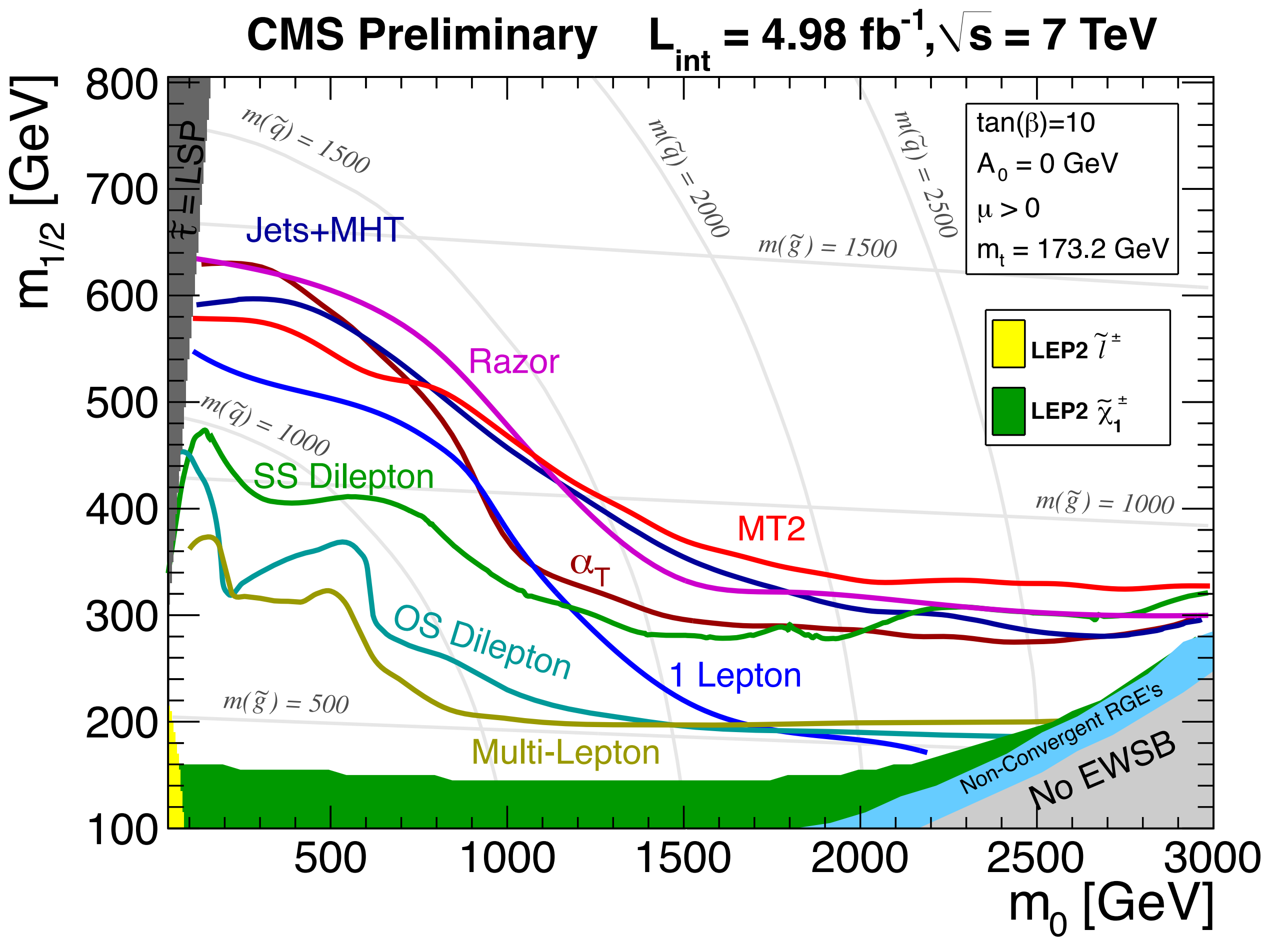
CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 12.2 fb-1
Local p-value
1σ
2σ
3σ
4σ
5σ
6σ
7σ
8σ
Combined obs.
Exp. for SM H
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
110 115 120 125 130 135 140 145
mH (GeV)
p0
Combined w/o MSS
γγ w/o MSS obs.
llll w/o MSS obs.
lvlv obs.
ττ obs.
bb obs.
Combined w/o MSS
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
al p-value
1σ
2σ
3σ
4σ
p0
115
120
125
130
135
mH [GeV]
95% CL Limit/SM
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
100
120
140
160
180
200
mH (GeV/c2)

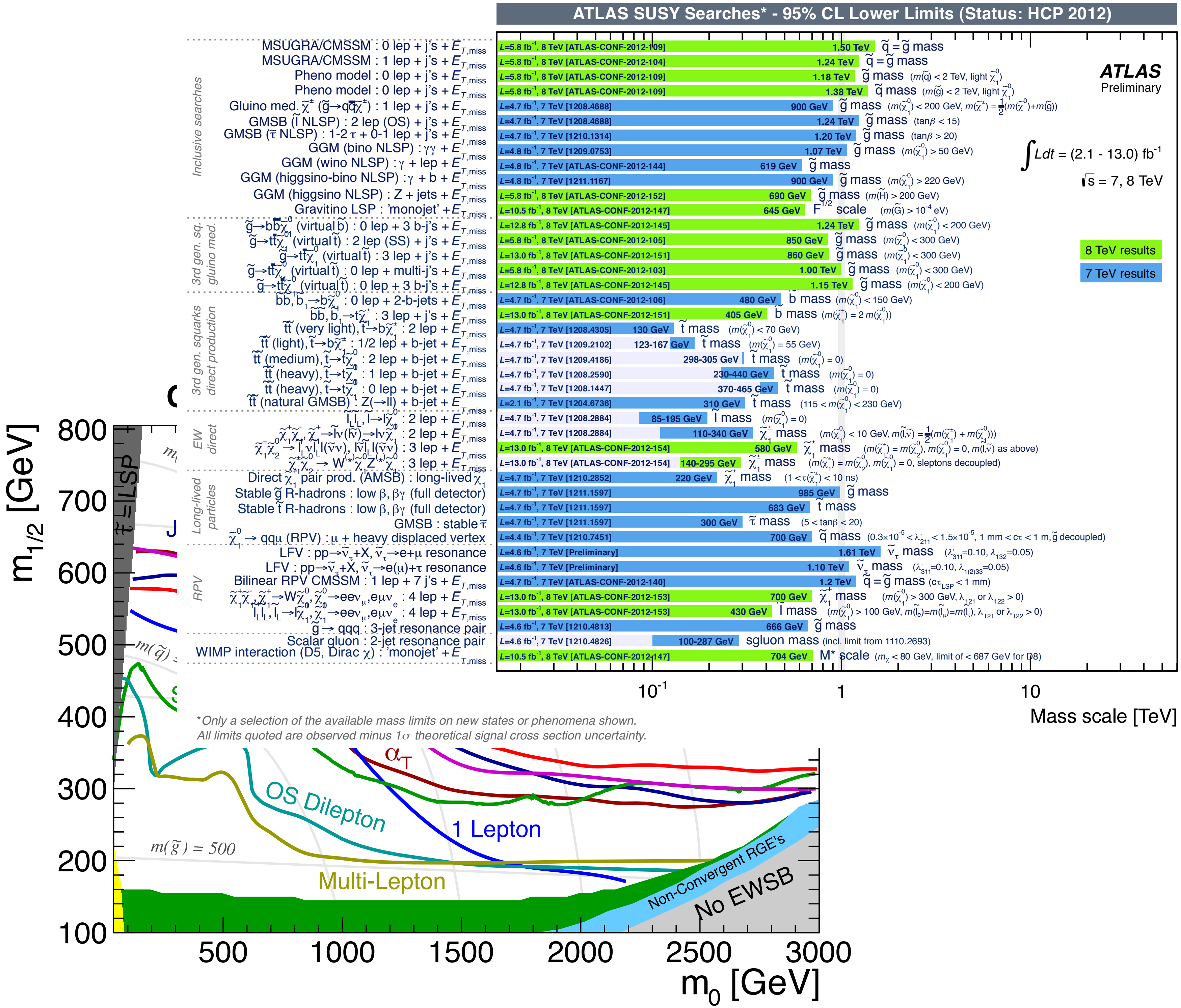
The Lack of Signal

New colored particles, more Higgs bosons, ...

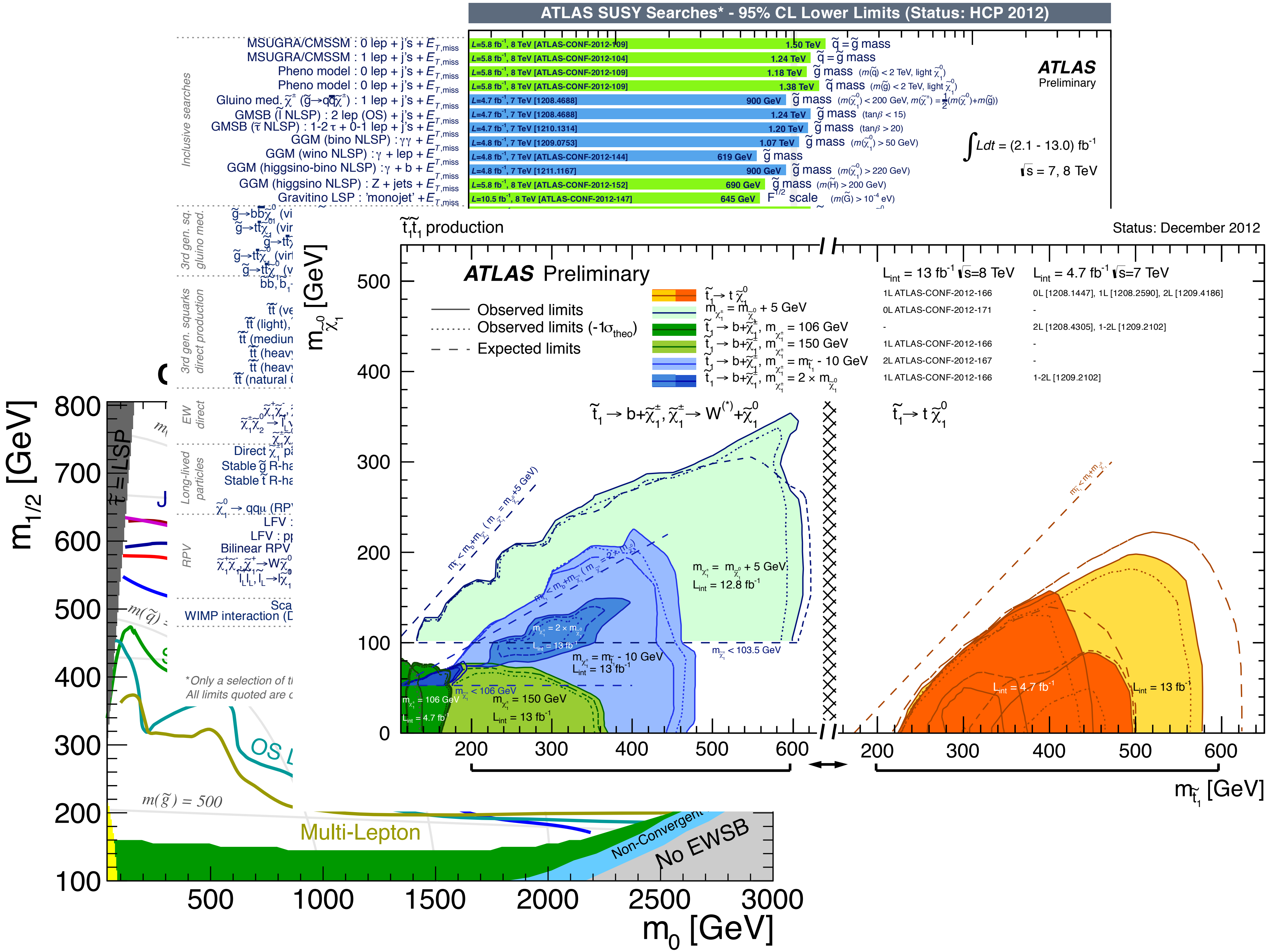


CMS Preliminary L_{int} = 4.98 fb^{-1}, $\sqrt{s}$ = 7 TeV
$m_{1/2}$ [GeV]
m_0 [GeV]
800
700
600
500
400
300
200
100
500
1000
1500
2000
2500
3000
tan(β)=10
A_0 = 0 GeV
μ > 0
m_t = 173.2 GeV
LEP2 $\tilde{l}^{\pm}$
LEP2 $\tilde{\chi}_1^{\pm}$
$\tilde{\tau}$ = LSP
$m(\tilde{q})$ = 1500
$m(\tilde{q})$ = 2000
$m(\tilde{q})$ = 2500
$m(\tilde{q})$ = 1000
$m(\tilde{g})$ = 1500
$m(\tilde{g})$ = 1000
$m(\tilde{g})$ = 500
Jets+MHT
Razor
SS Dilepton
MT2
α_T
OS Dilepton
1 Lepton
Multi-Lepton
Non-Convergent RGE's
No EWSB

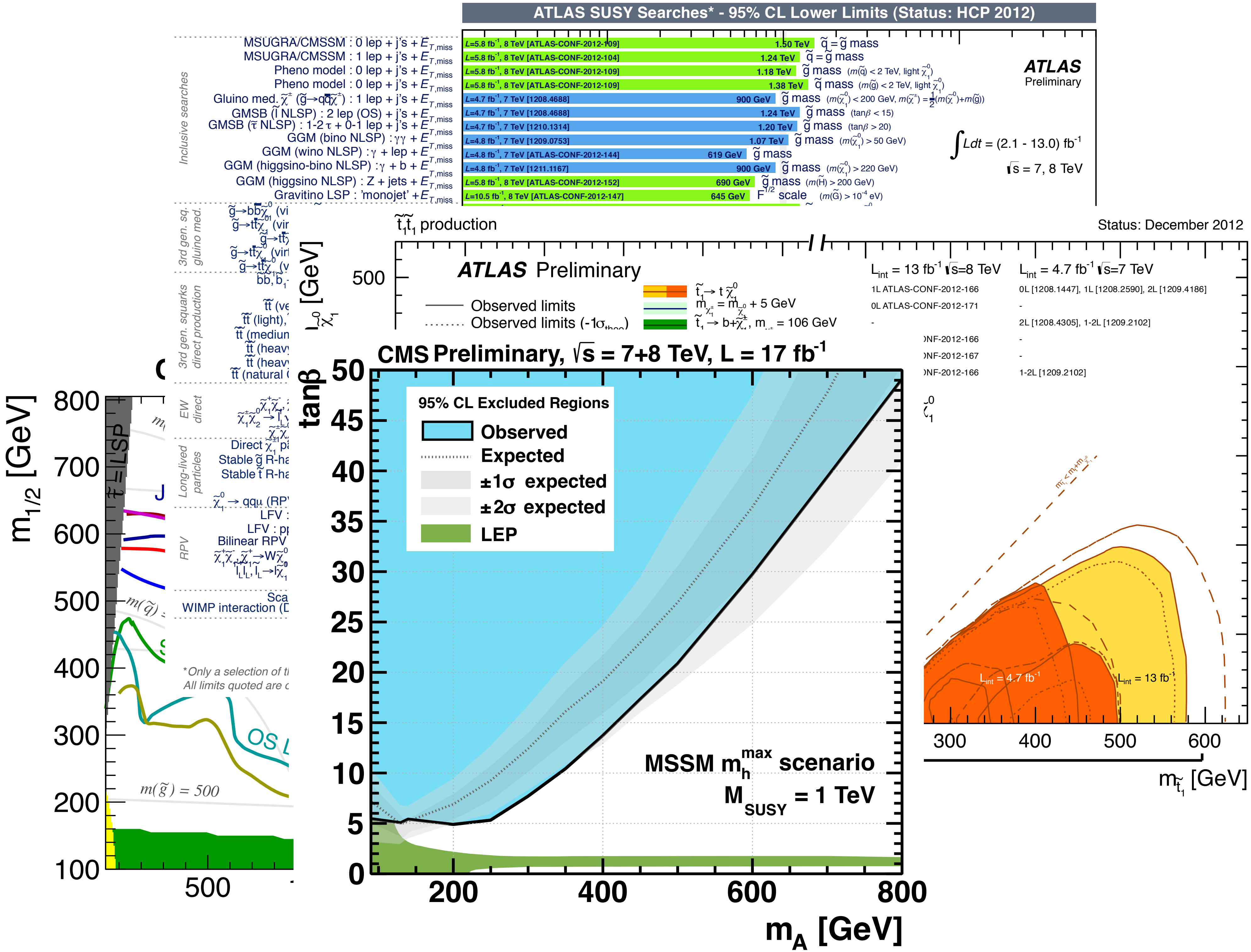
bosons, ...



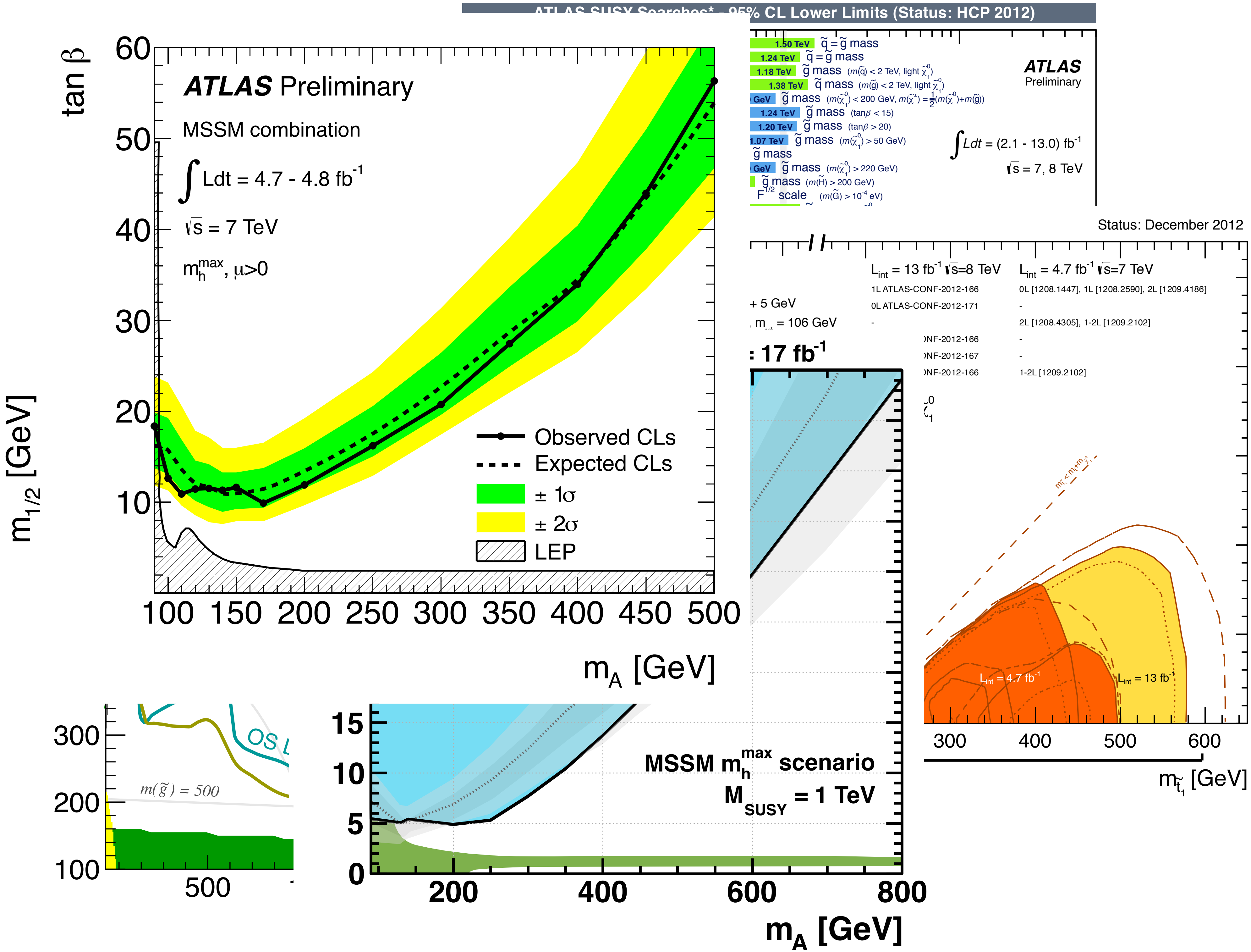
ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
ATLAS
Preliminary
∫Ldt = (2.1 - 13.0) fb^-1
√s = 7, 8 TeV
8 TeV results
7 TeV results
Inclusive searches
3rd gen. sq. gluino med.
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
MSUGRA/CMSSM : 0 lep + j's + E_T,miss
MSUGRA/CMSSM : 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
Gravitino LSP : 'monojet' + E_T,miss
Stable g̃ R-hadrons : low β, βγ (full detector)
Stable t̃ R-hadrons : low β, βγ (full detector)
GMSB : stable τ̃
Scalar gluon : 2-jet resonance pair
WIMP interaction (D5, Dirac χ) : 'monojet' + E_T,miss
1.50 TeV q̃ = g̃ mass
1.24 TeV q̃ = g̃ mass
1.18 TeV g̃ mass
1.38 TeV q̃ mass
985 GeV g̃ mass
683 GeV t̃ mass
300 GeV τ̃ mass
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]
800
700
600
500
400
300
200
100
500
1000
1500
2000
2500
3000
τ̃ = LSP
α_T
OS Dilepton
1 Lepton
Multi-Lepton
m(g̃) = 500
Non-Convergent RGE's
No EWSB

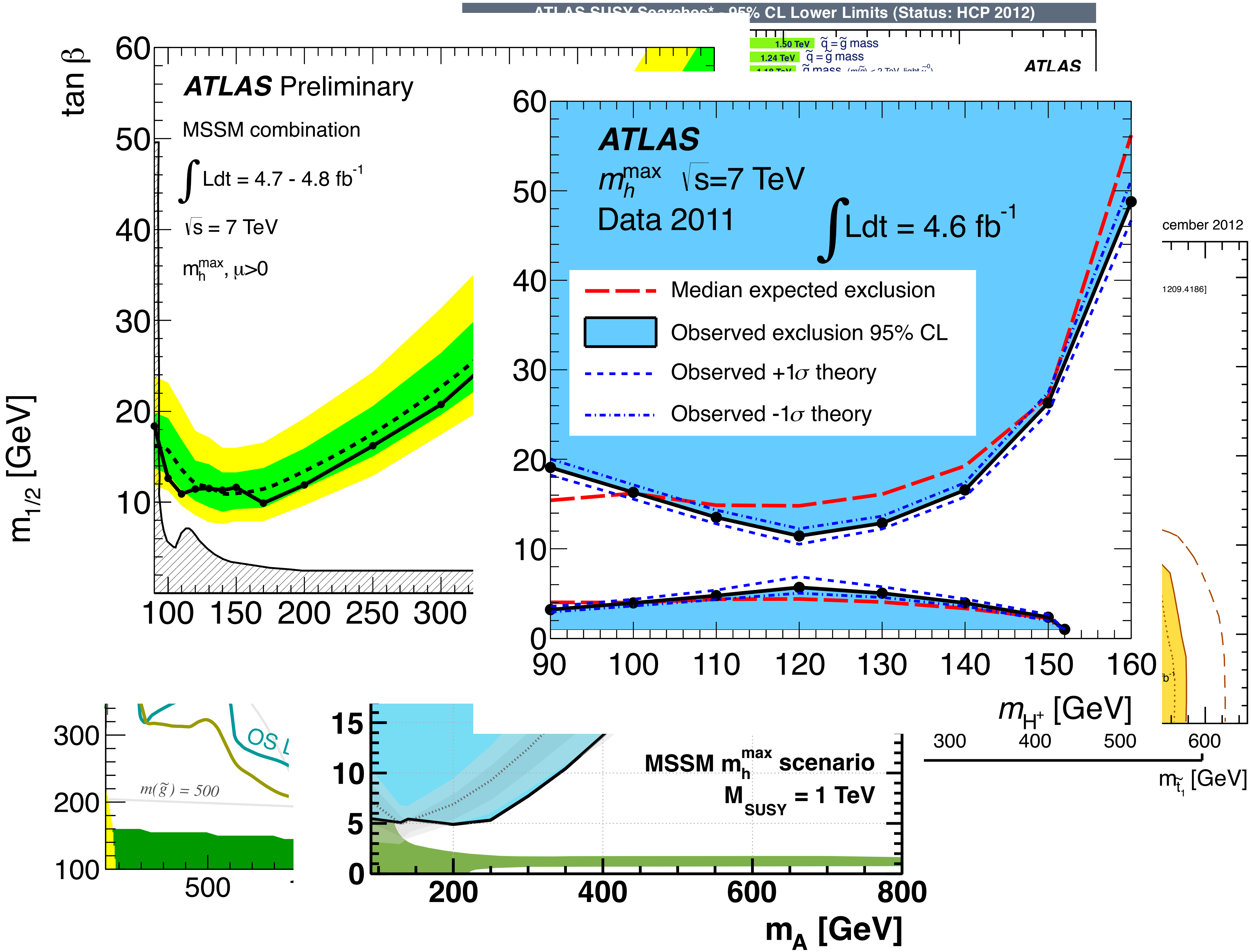


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
ATLAS
Preliminary
MSUGRA/CMSSM : 0 lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : 1 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
Pheno model : 0 lep + j's + $E_{T,miss}$
GGM (bino NLSP) : γγ + $E_{T,miss}$
GGM (higgsino NLSP) : Z + jets + $E_{T,miss}$
Gravitino LSP : 'monojet' + $E_{T,miss}$
Inclusive searches
1.50 TeV
1.24 TeV
1.18 TeV
1.38 TeV
900 GeV
1.24 TeV
1.20 TeV
1.07 TeV
619 GeV
900 GeV
690 GeV
645 GeV
$\int Ldt$ = (2.1 - 13.0) fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
$\tilde{t}_1\tilde{t}_1$ production
Status: December 2012
ATLAS Preliminary
Observed limits
Observed limits (-1σ_{theo})
Expected limits
L_{int} = 13 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
$\tilde{t}_1 \to b+\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_1 \to W^{(*)}+\tilde{\chi}^0_1$
$\tilde{t}_1 \to t\,\tilde{\chi}^0_1$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
$m_{1/2}$ [GeV]
m_0 [GeV]
Multi-Lepton
Non-Convergent
No EWSB
$m(\tilde{g}) = 500$
*Only a selection of t
All limits quoted are c



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)
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 + $E_{T,miss}$
GMSB ($\tilde{\tau}$ NLSP) : 1-2 τ + 0-1 lep + 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' + $E_{T,miss}$
L=5.8 fb^{-1}, 8 TeV [ATLAS-CONF-2012-109] 1.50 TeV $\tilde{q} = \tilde{g}$ mass
L=5.8 fb^{-1}, 8 TeV [ATLAS-CONF-2012-104] 1.24 TeV $\tilde{q} = \tilde{g}$ mass
L=5.8 fb^{-1}, 8 TeV [ATLAS-CONF-2012-109] 1.18 TeV $\tilde{g}$ mass
L=5.8 fb^{-1}, 8 TeV [ATLAS-CONF-2012-109] 1.38 TeV $\tilde{q}$ mass
L=4.7 fb^{-1}, 7 TeV [1208.4688] 900 GeV $\tilde{g}$ mass
L=4.7 fb^{-1}, 7 TeV [1208.4688] 1.24 TeV $\tilde{g}$ mass (tanβ < 15)
L=4.7 fb^{-1}, 7 TeV [1210.1314] 1.20 TeV $\tilde{g}$ mass (tanβ > 20)
L=4.8 fb^{-1}, 7 TeV [1209.0753] 1.07 TeV $\tilde{g}$ mass
L=4.8 fb^{-1}, 7 TeV [ATLAS-CONF-2012-144] 619 GeV $\tilde{g}$ mass
L=4.8 fb^{-1}, 7 TeV [1211.1167] 900 GeV $\tilde{g}$ mass
L=5.8 fb^{-1}, 8 TeV [ATLAS-CONF-2012-152] 690 GeV $\tilde{g}$ mass
L=10.5 fb^{-1}, 8 TeV [ATLAS-CONF-2012-147] 645 GeV $F^{1/2}$ scale
ATLAS Preliminary
$\int L dt$ = (2.1 - 13.0) fb^{-1}
$\sqrt{s}$ = 7, 8 TeV
$\tilde{t}_1\tilde{t}_1$ production
Status: December 2012
ATLAS Preliminary
Observed limits
Observed limits (-1σ_{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
0L [1208.1447], 1L [1208.2590], 2L [1209.4186]
2L [1208.4305], 1-2L [1209.2102]
L_{int} = 4.7 fb^{-1}
L_{int} = 13 fb^{-1}
$m_{\tilde{t}_1}$ [GeV]
CMS Preliminary, $\sqrt{s}$ = 7+8 TeV, L = 17 fb^{-1}
95% CL Excluded Regions
Observed
Expected
±1σ expected
±2σ expected
LEP
MSSM m_h^{max} scenario
M_{SUSY} = 1 TeV
tanβ
m_A [GeV]
$m_{1/2}$ [GeV]
$\tilde{\tau}$ = LSP
$m(\tilde{g})$ = 500
*Only a selection of t
All limits quoted are


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}, $\mu>0$
Observed CLs
Expected CLs
± 1σ
± 2σ
LEP
tan β
$m_{1/2}$ [GeV]
m_A [GeV]
$\int Ldt = (2.1 - 13.0)\ fb^{-1}$
$\sqrt{s} = 7, 8$ 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]
: 17 fb^{-1}
MSSM m_h^{max} scenario
M_{SUSY} = 1 TeV
m_A [GeV]
$m(\tilde{g}) = 500$
OS L
$L_{int} = 4.7\ fb^{-1}$
$L_{int} = 13\ fb^{-1}$
$m_{\tilde{t}_1}$ [GeV]


ATLAS Preliminary
MSSM combination
∫Ldt = 4.7 - 4.8 fb⁻¹
√s = 7 TeV
m_h^max, μ>0
tan β
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]
MSSM m_h^max scenario
M_SUSY = 1 TeV
m_A [GeV]
m(g̃) = 500
OS
1.50 TeV q̃ = g̃ mass
1.24 TeV q̃ = g̃ mass
cember 2012
1209.4186]
m_t̃1 [GeV]

The Minimal SUSY extension of the SM (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	$\tilde{b}$	$(1,\ 1,\ 0)$

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.: $H_i^0 = v_i + (S_i + i\,P_i)/\sqrt{2}$

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

$$m_Z^2 \;=\; \left(m_{H_2}^2\,\tan\beta - m_{H_1}^2\,\cot\beta\right)\,\tan 2\beta \;-\; 2\,|\mu|^2$$

(μ is a supersymmetric mass term for Higgs/higgsinos, $\tan\beta = v_2\,/\,v_1$)

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

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

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

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

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

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

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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)

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* : $\begin{cases} H \text{ is the SM-like boson} \\ (h, A, H^\pm) \text{ light exotic multiplet} \end{cases}$

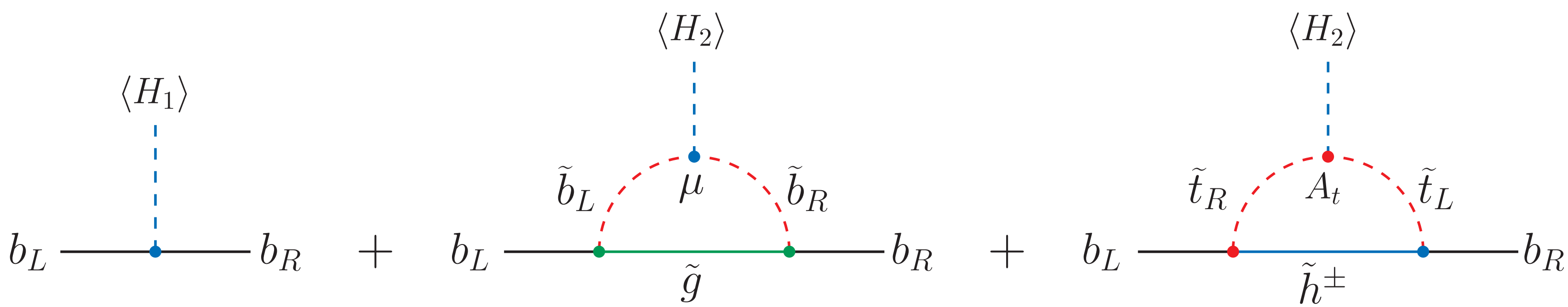
- The intermediate-coupling regime is for $m_A \gtrsim m_Z$ and moderate *tanβ*

  (neither scalar is SM-like)

tanβ-enhanced corrections to the Higgs-(s)bottom couplings

Already at tree level, the bottom Yukawa coupling is enhanced by *tanβ* : $\frac{h_b}{h_t} = \frac{m_b}{m_t} \tan\beta$

The relation between bottom mass and Yukawa coupling receives large 1-loop corrections



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

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

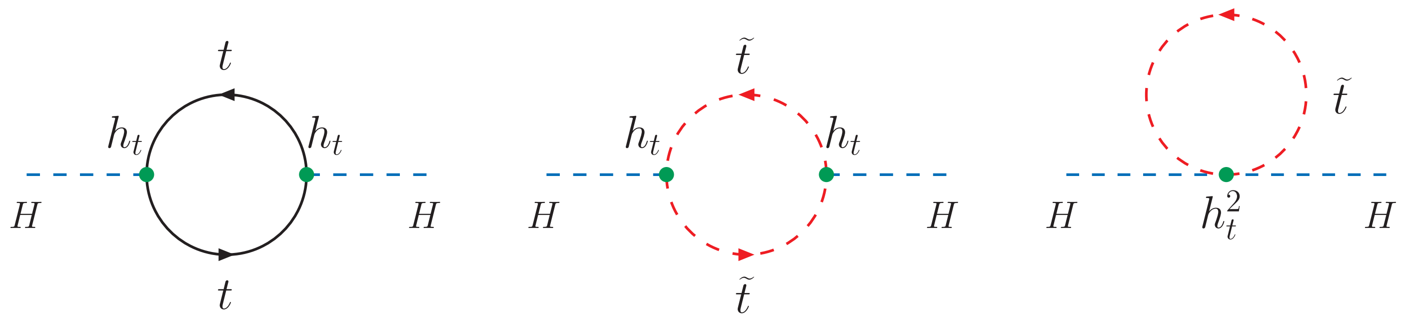
These corrections survive for heavy SUSY: $\epsilon_b \;\approx\; \frac{\alpha_s}{3\pi}\,\frac{\mu\, m_{\tilde{g}}}{m^2_{\tilde{b}}} \;+\; \frac{\alpha_t}{8\pi}\,\frac{\mu\, A_t}{m^2_{\tilde{t}}}$

However, they do decouple when the Higgs is SM-like: $g_{hbb} \;=\; g^{\rm tree}_{hbb}\,\frac{1 - \epsilon_b \cot\alpha}{1 + \epsilon_b \tan\beta}$

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

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



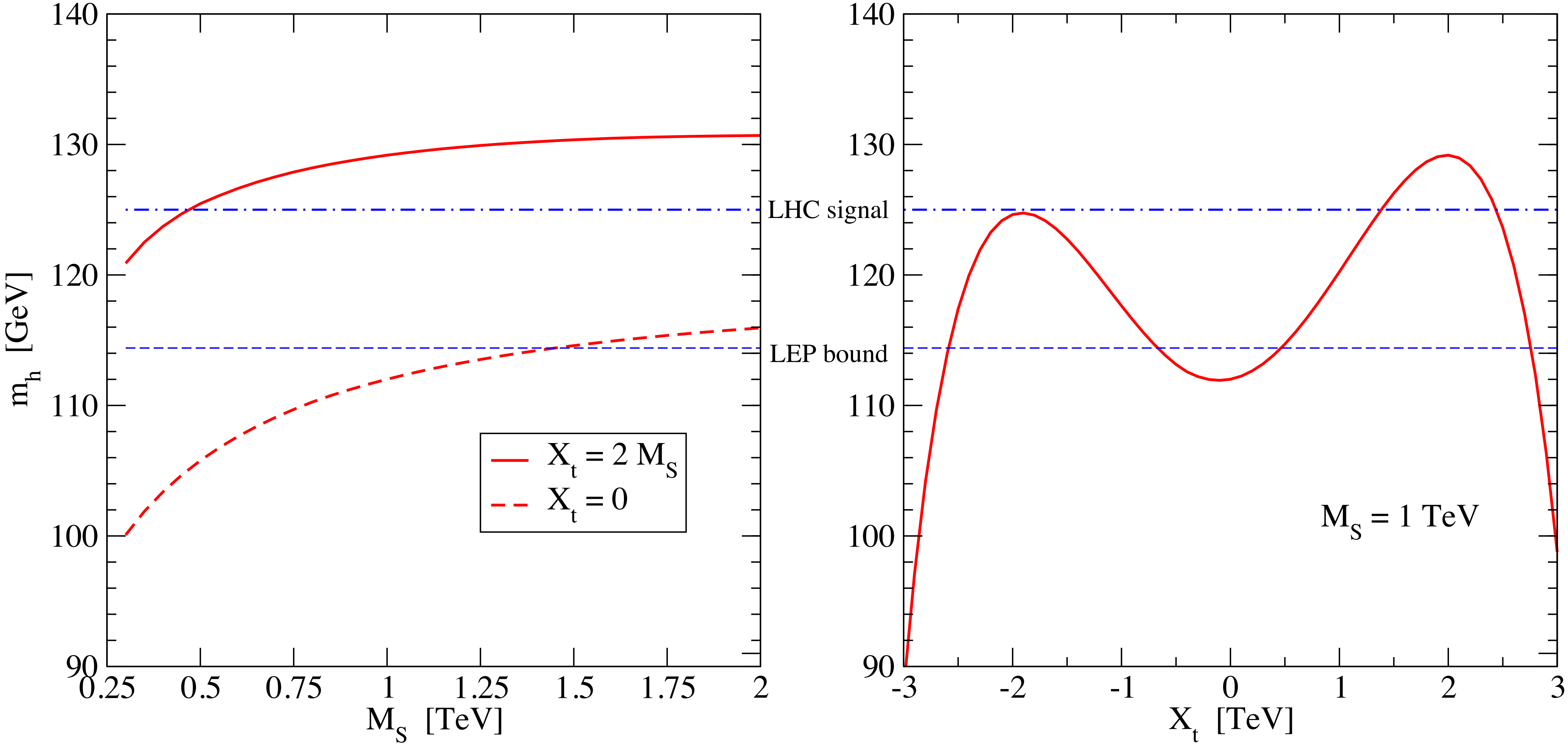
$$(\Delta m_h^2)^{1-\text{loop}} \simeq \frac{3\, m_t^4}{4\,\pi^2\, v^2} \left(\ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12\, M_S^4} \right) - \frac{h_b^4\, \mu^4\, v^2}{16\, \pi^2\, M_S^4}$$

(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

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

(plots produced with FeynHiggs)



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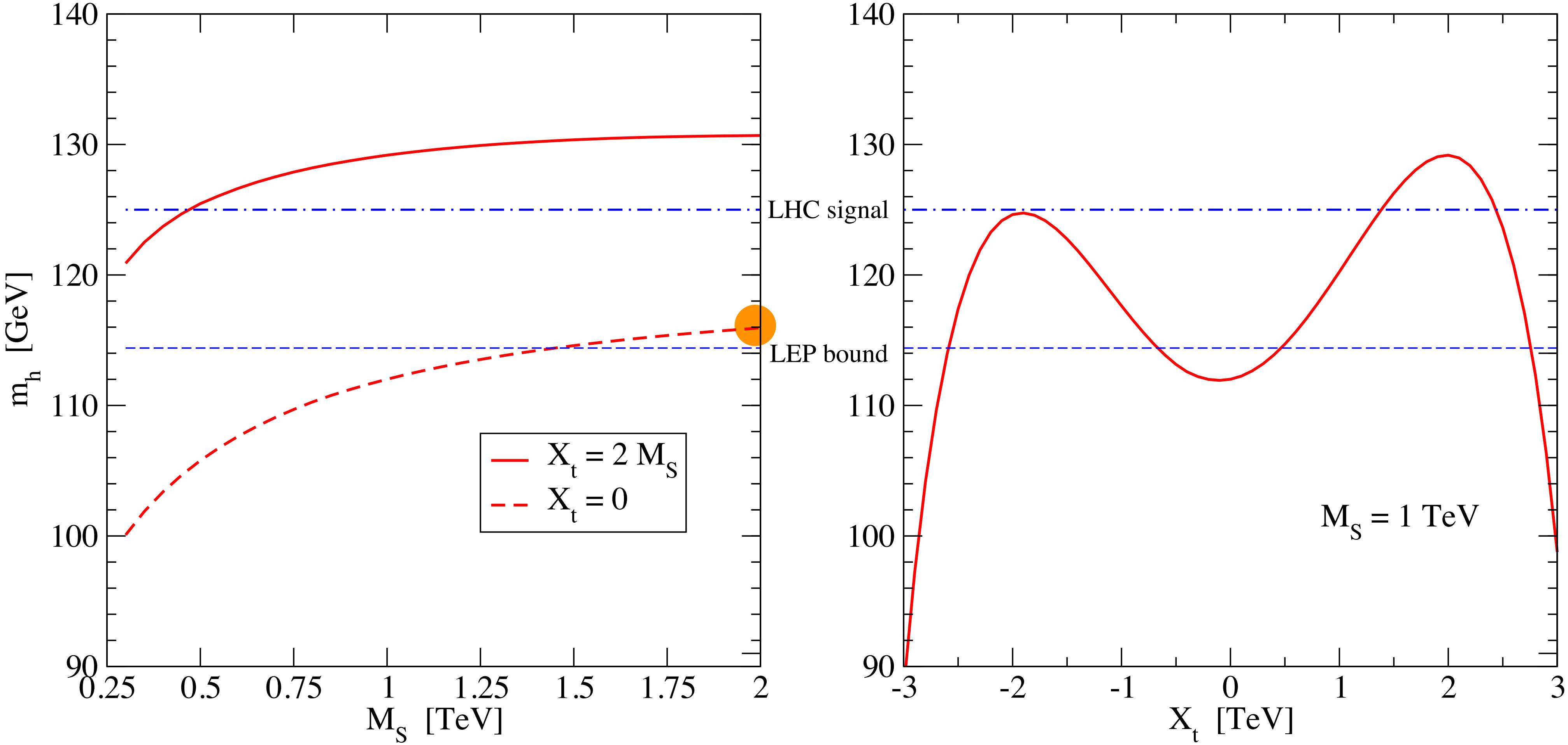

no-mixing scenario: $M_S = 2$ TeV, $X_t = 0$ TeV

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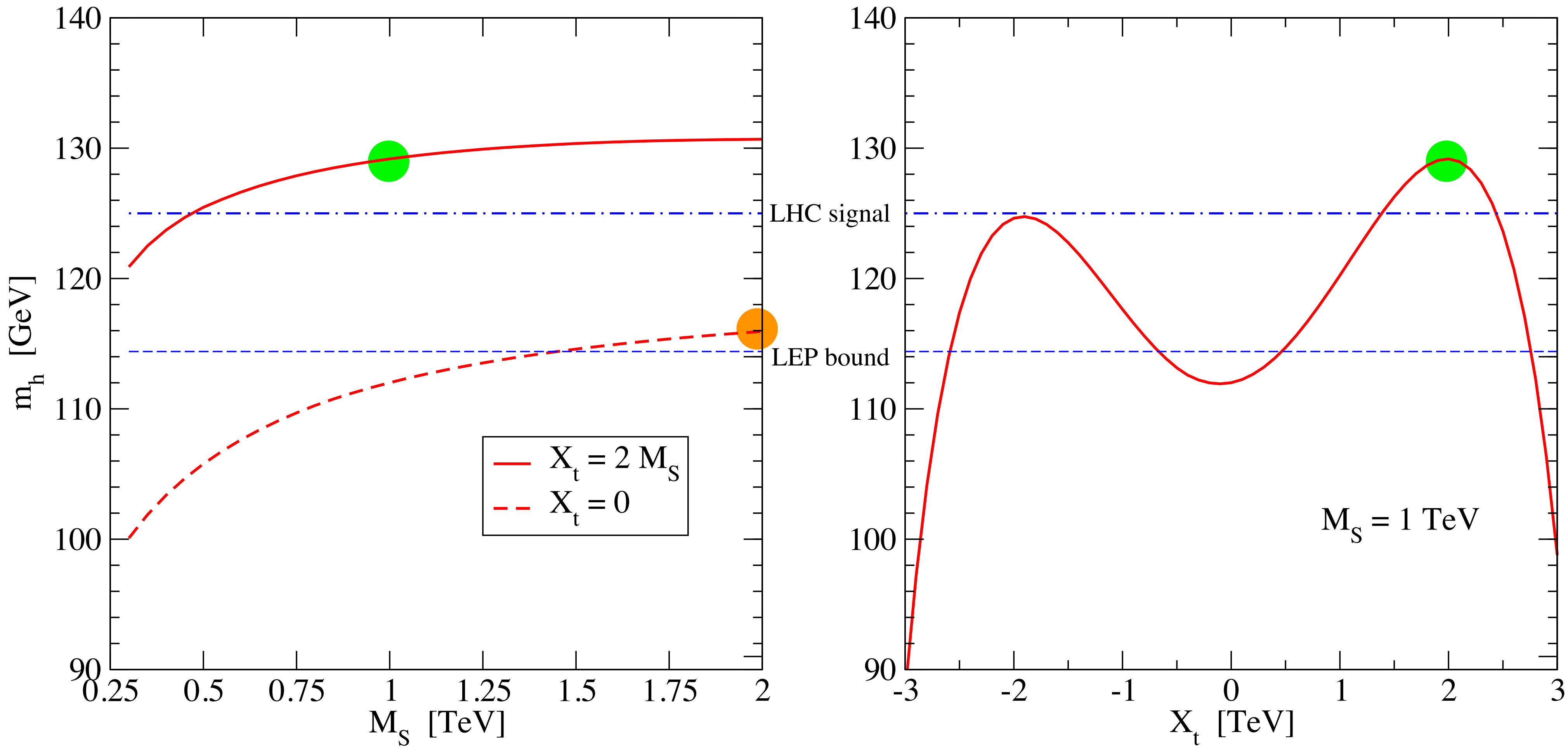

no-mixing scenario: $M_s = 2$ TeV, $X_t = 0$ TeV

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

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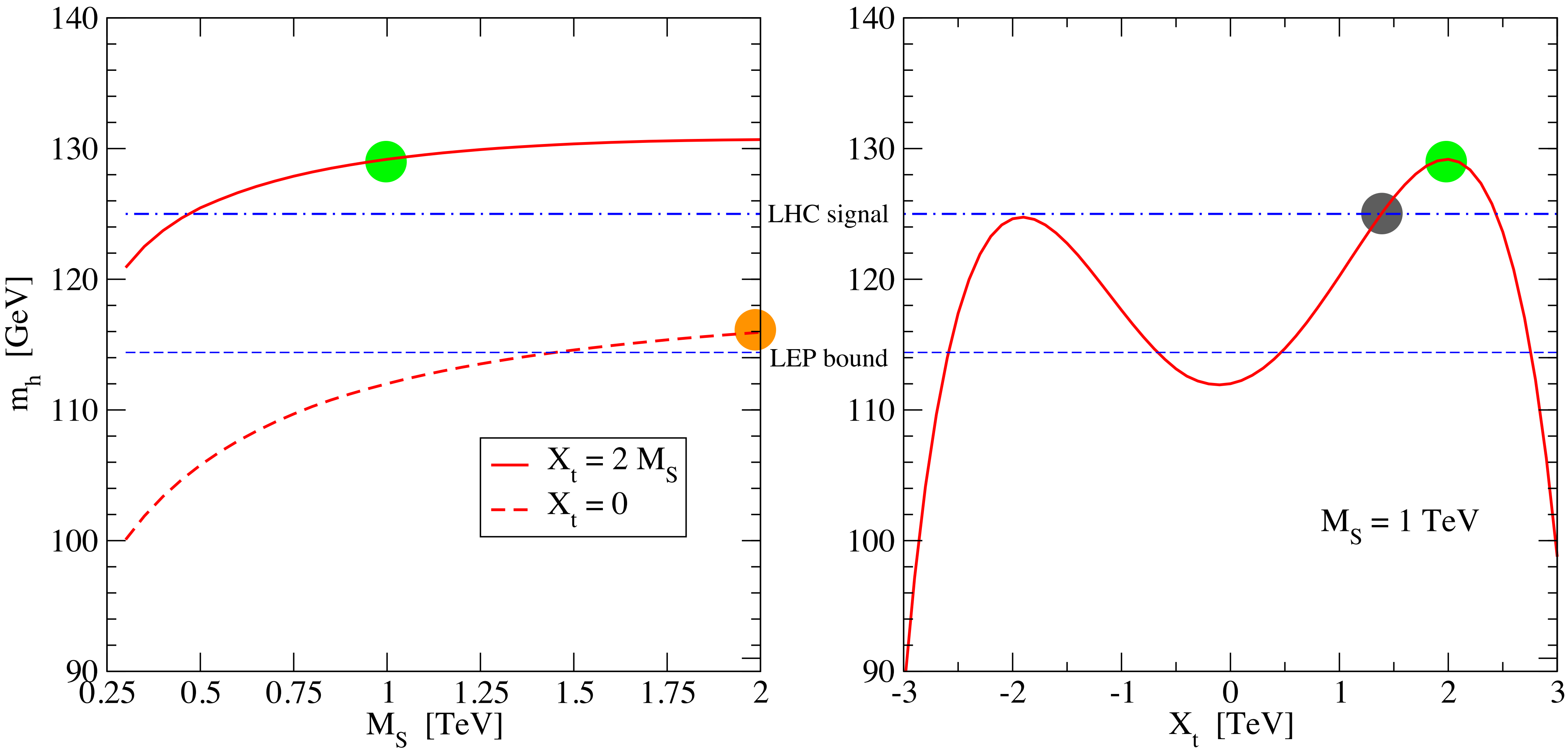

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modified m_h^{max} scenario: $M_S =$ 1 TeV, $X_t = 1.3$ TeV

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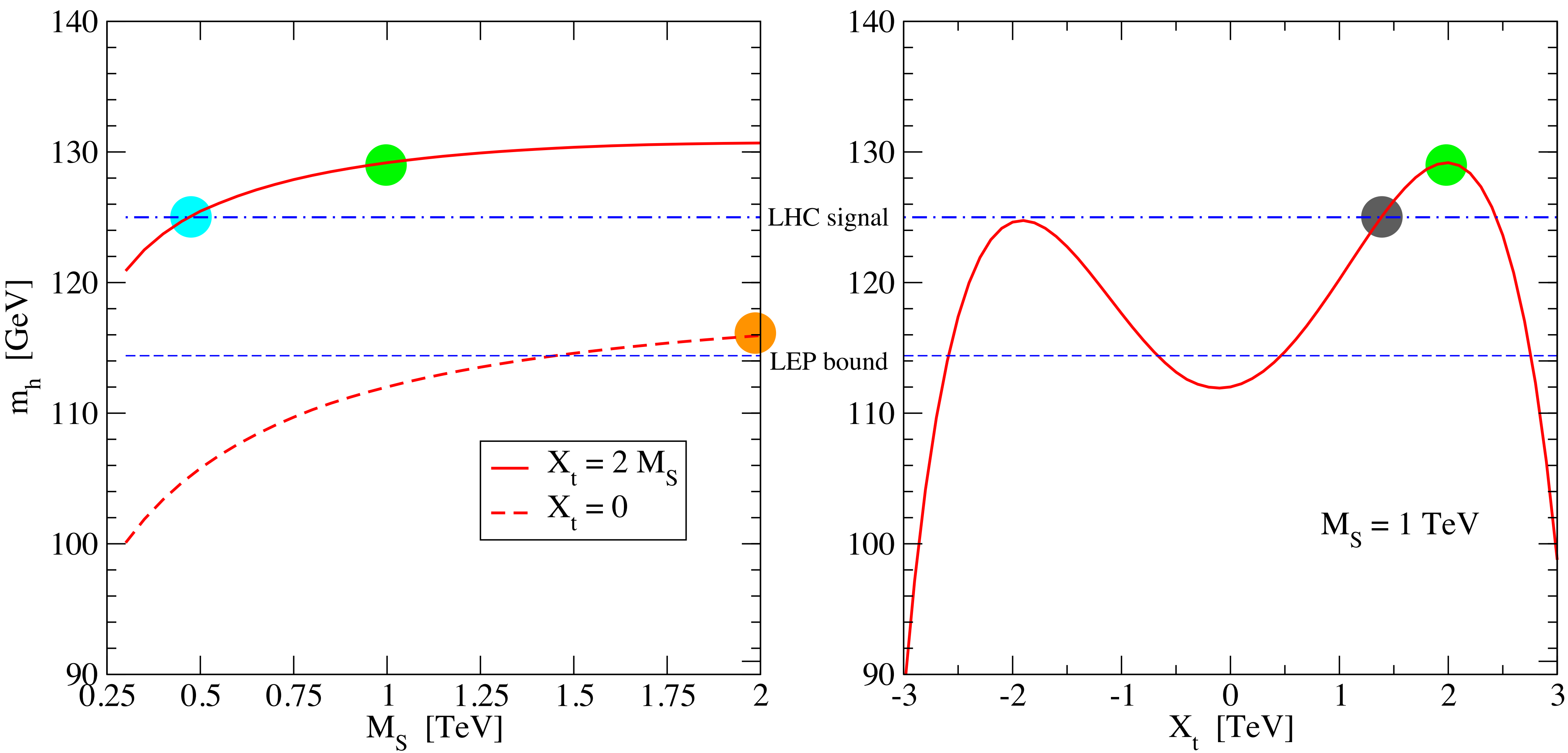

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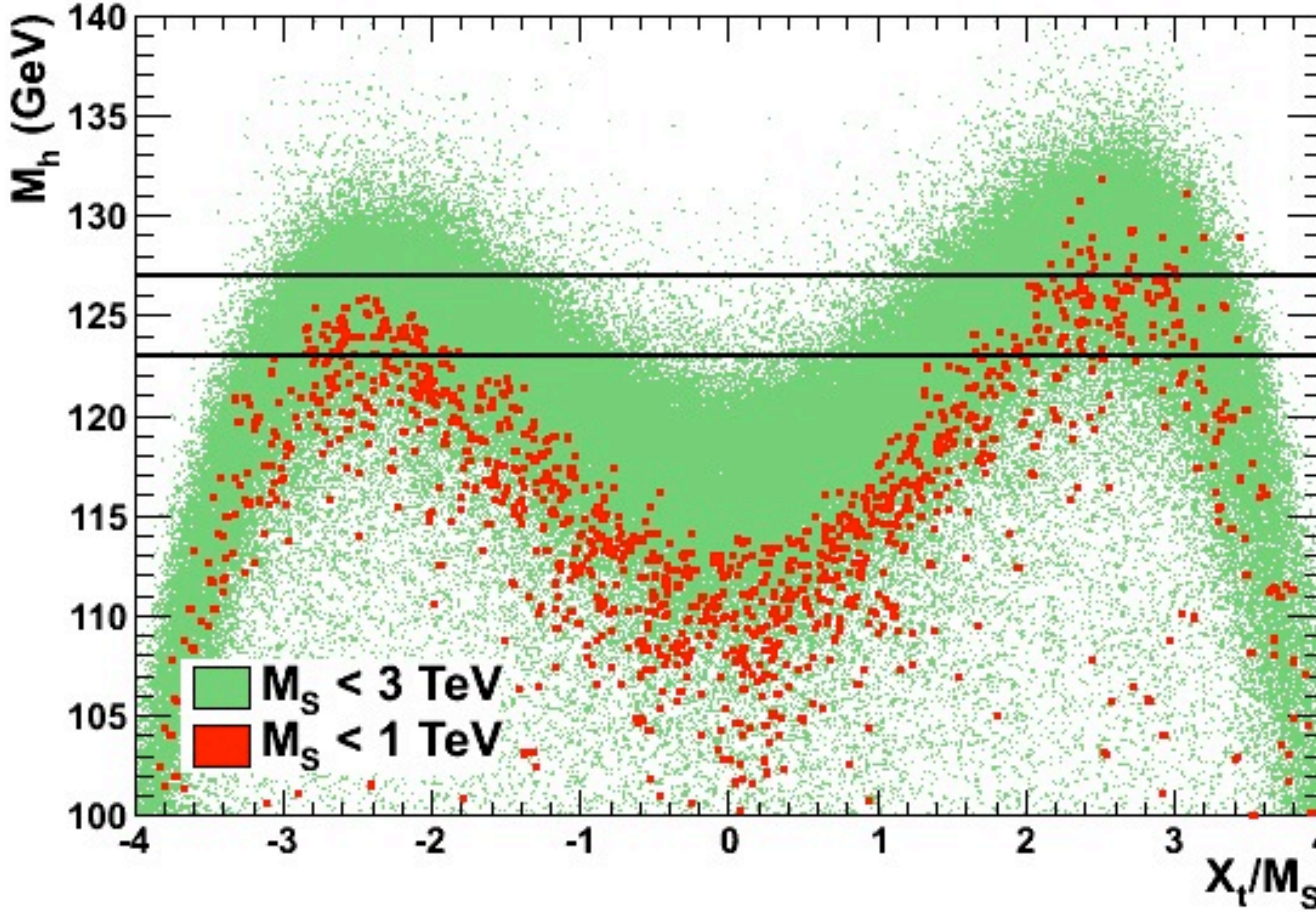
m_h^{max} scenario: M_s = 1 TeV, X_t = 2 TeV

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)

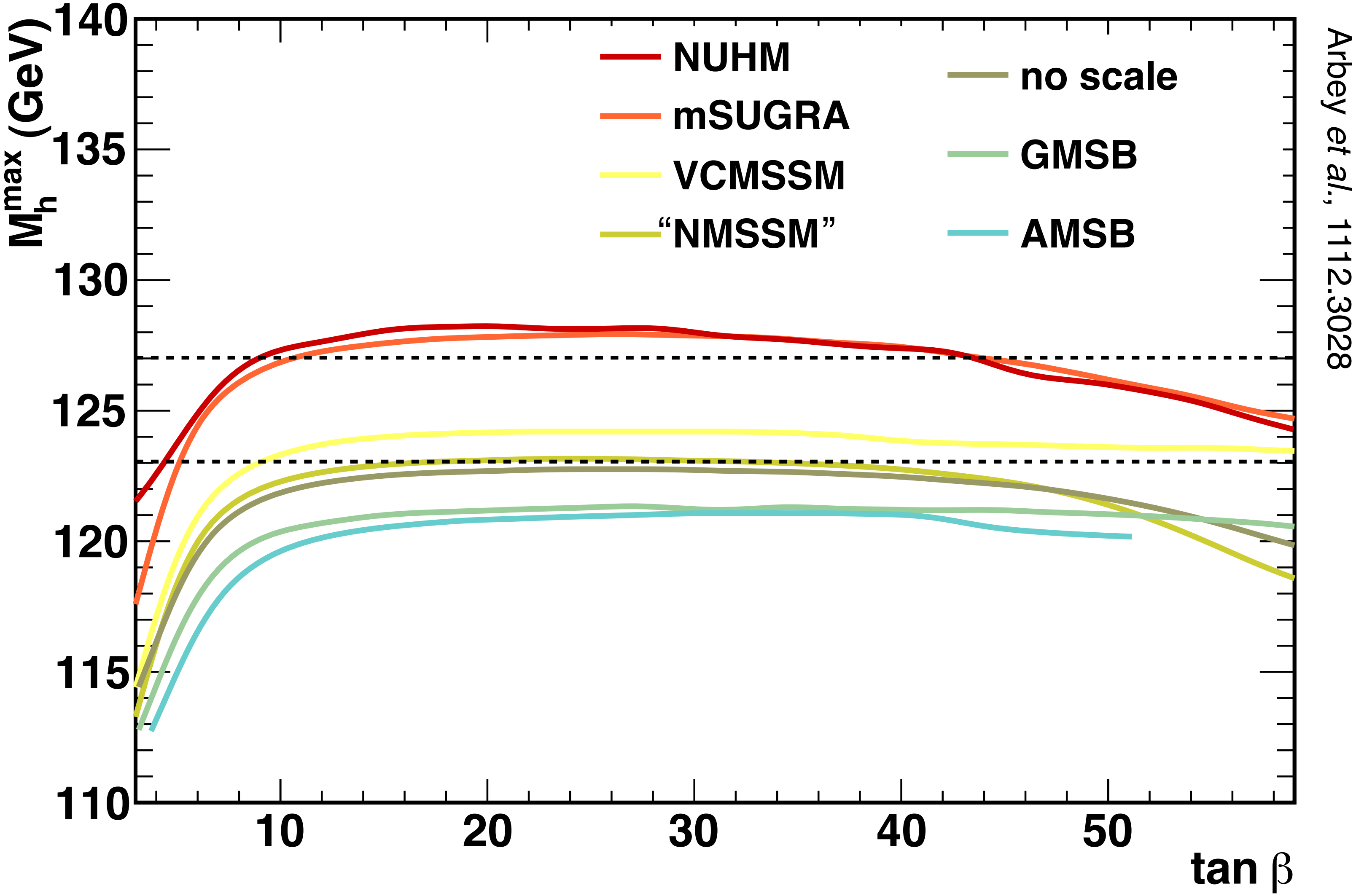
Implications of $m_h \approx 125$ GeV in the unconstrained MSSM



Arbey *et al.*, 1112.3028

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

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



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

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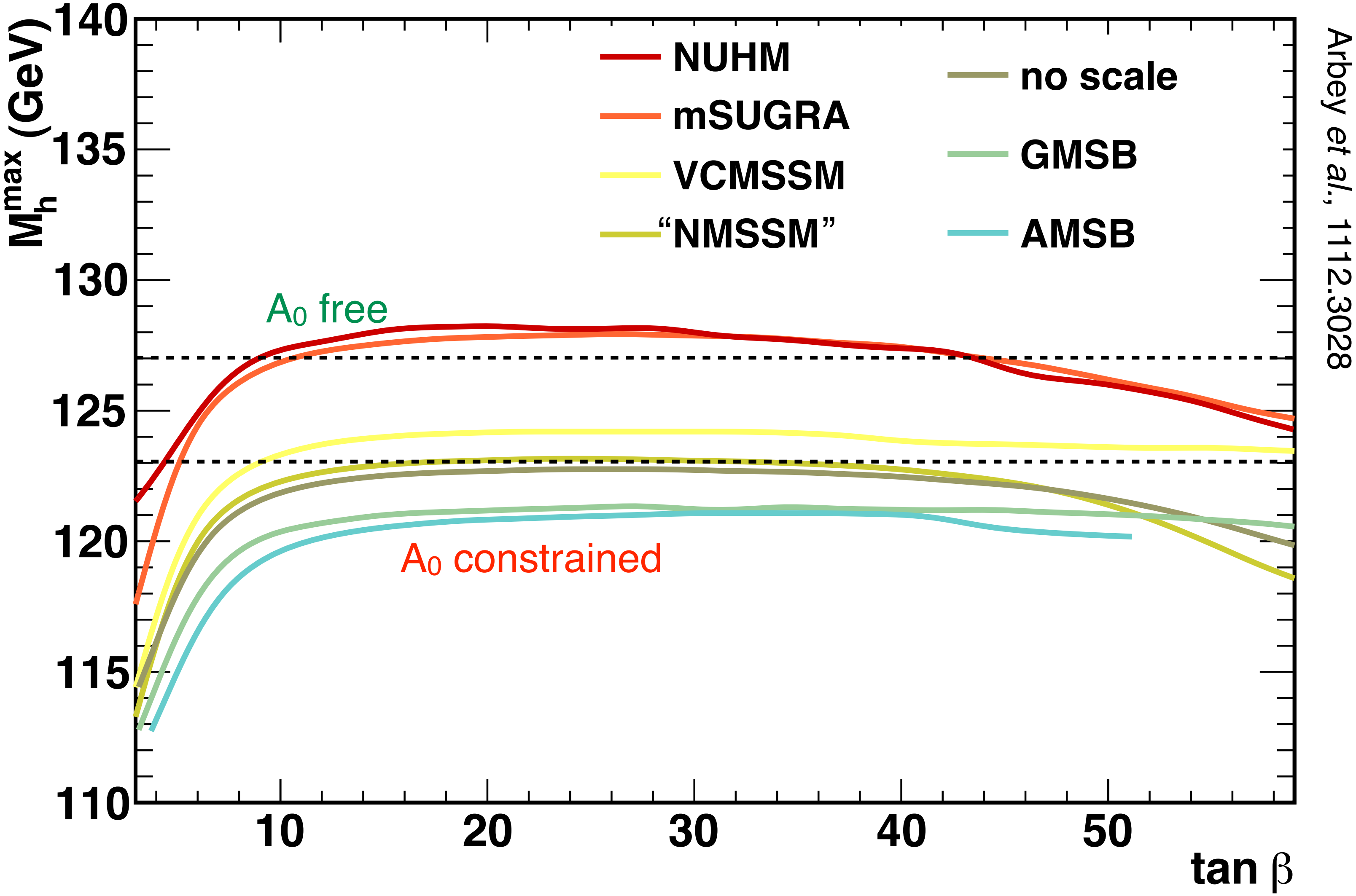

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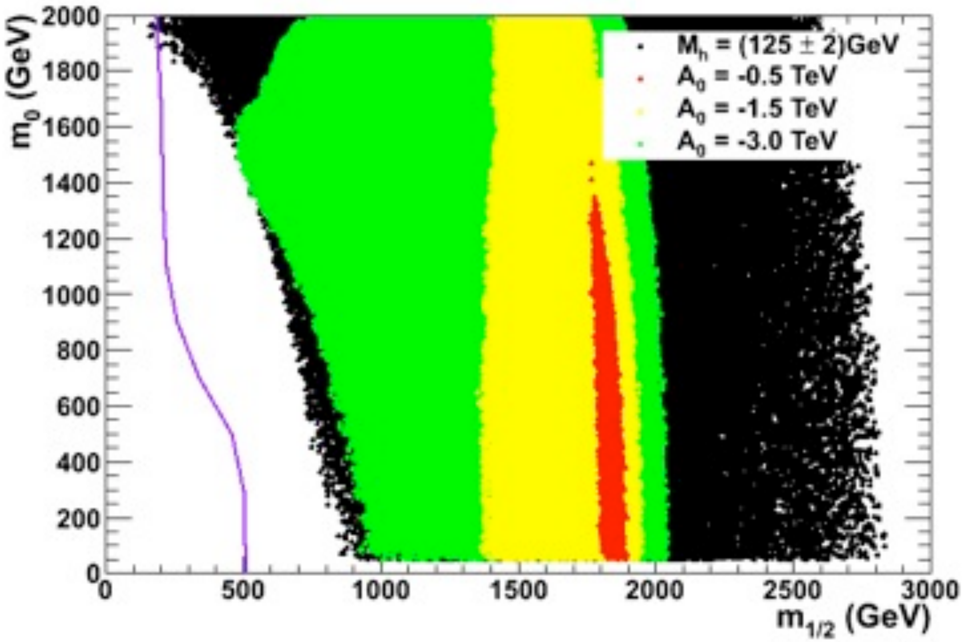
AMSB: $1 \text{ TeV} \le m_{3/2} \le 100 \text{ TeV}$, $50 \text{ GeV} \le m_0 \le 3 \text{ TeV}$.

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



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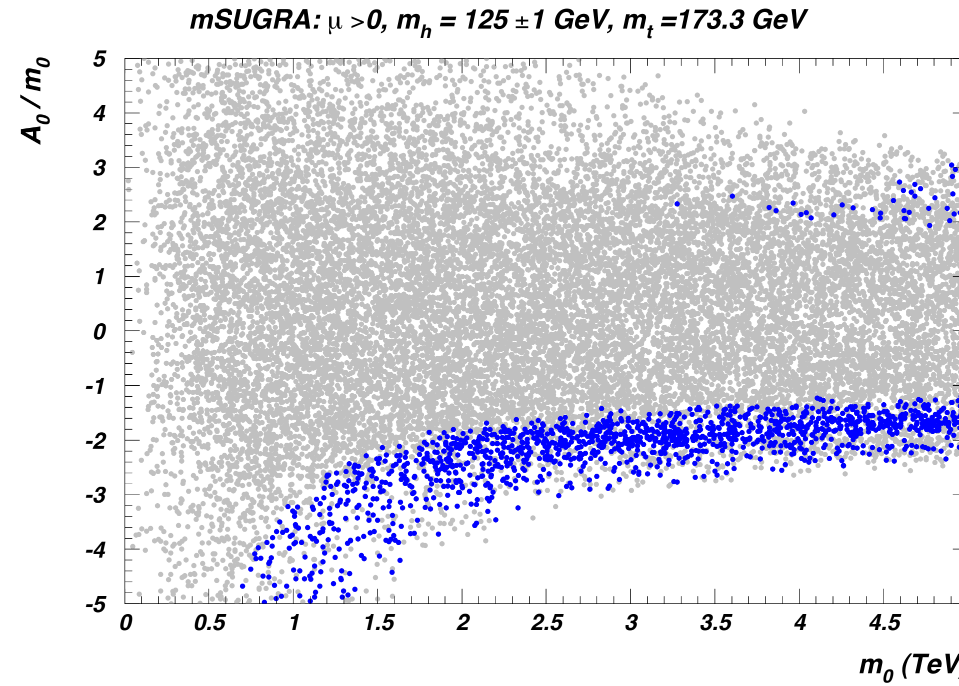

(Baer *et al.*, 1112.3017)

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

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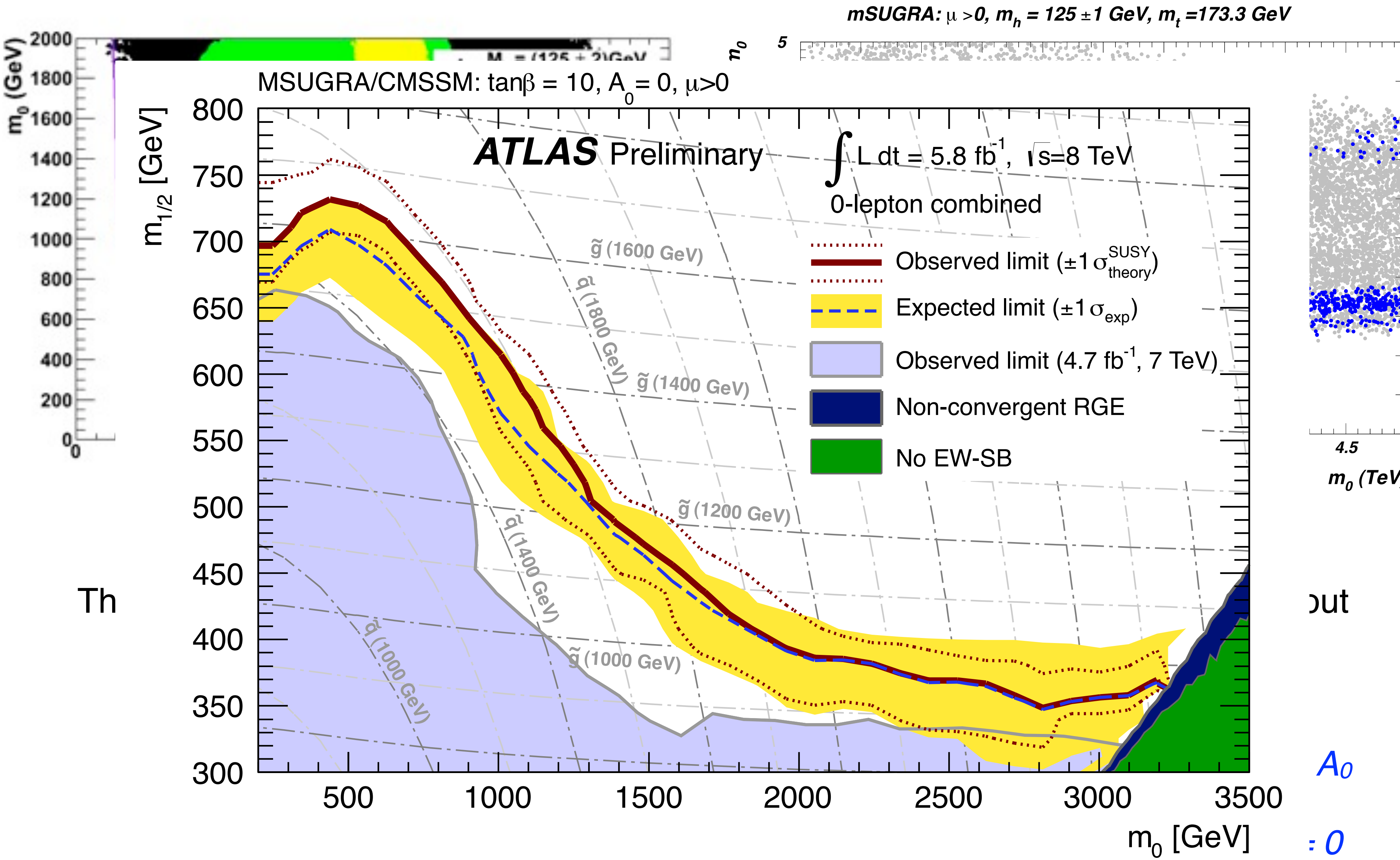

Th

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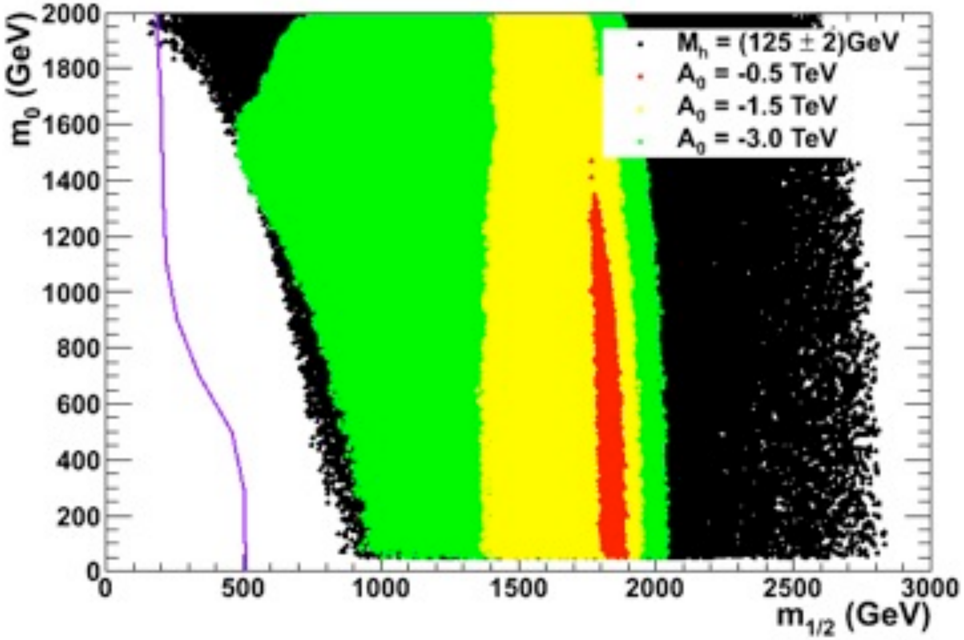

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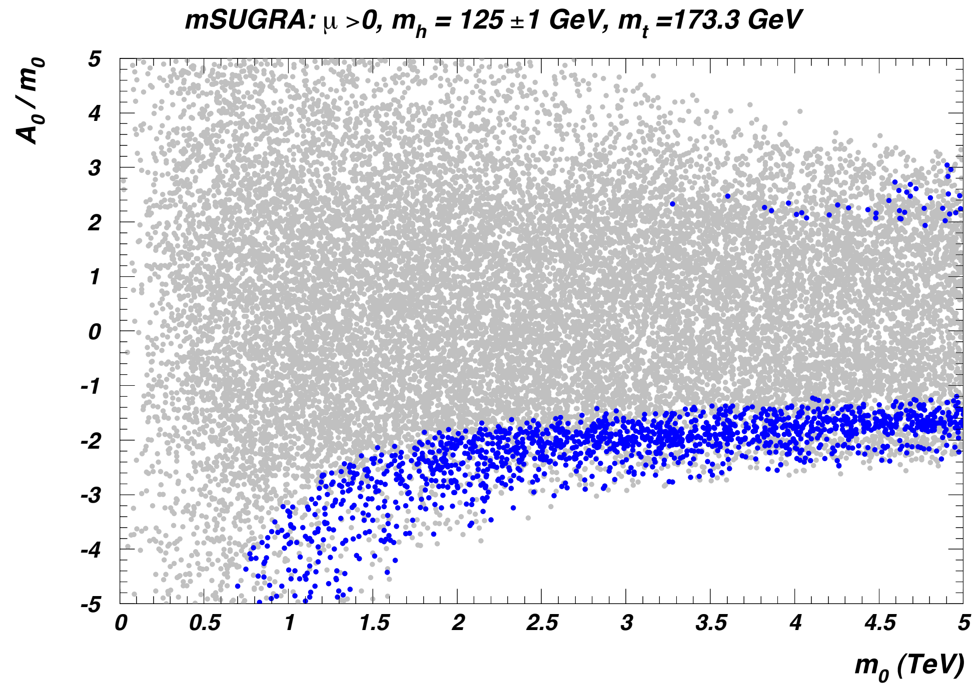

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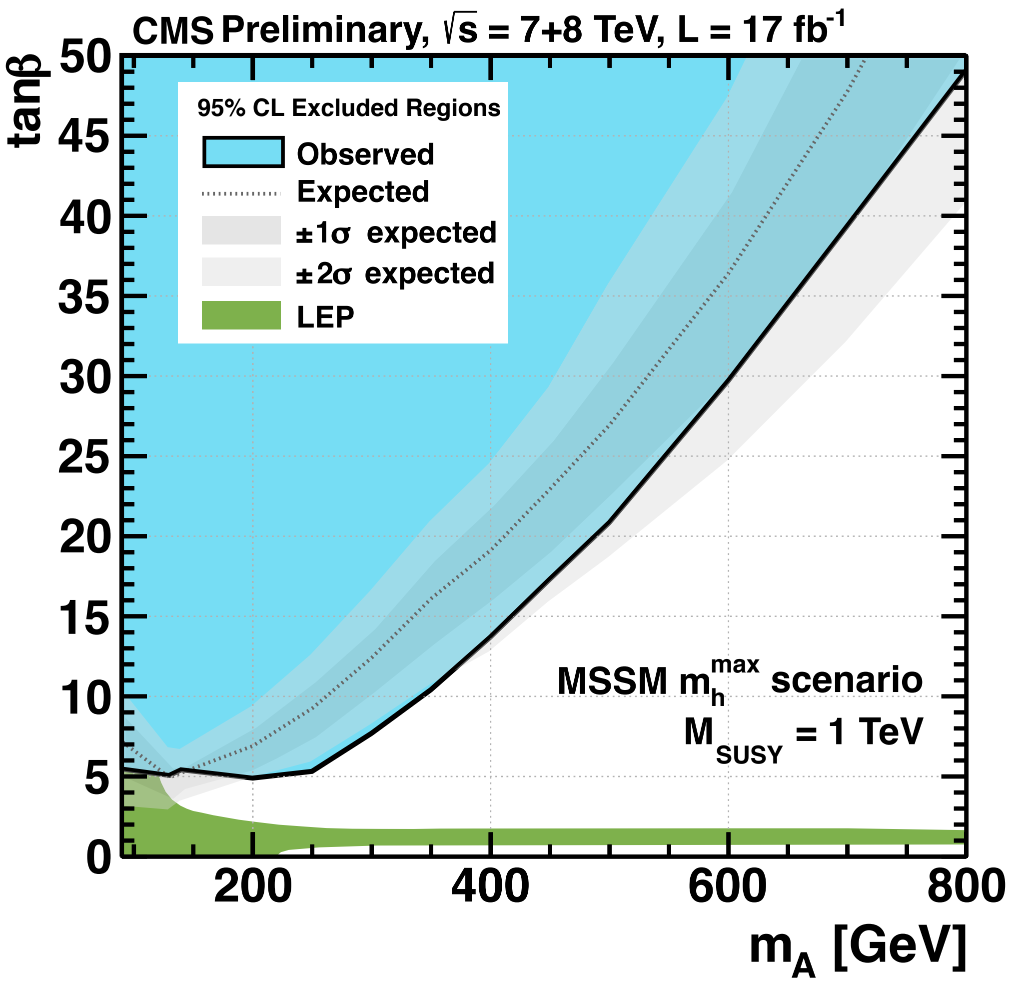
The m_h^{max} scenario used in the "MSSM Higgs" searches is also disfavored ($m_h \approx 129$ GeV)



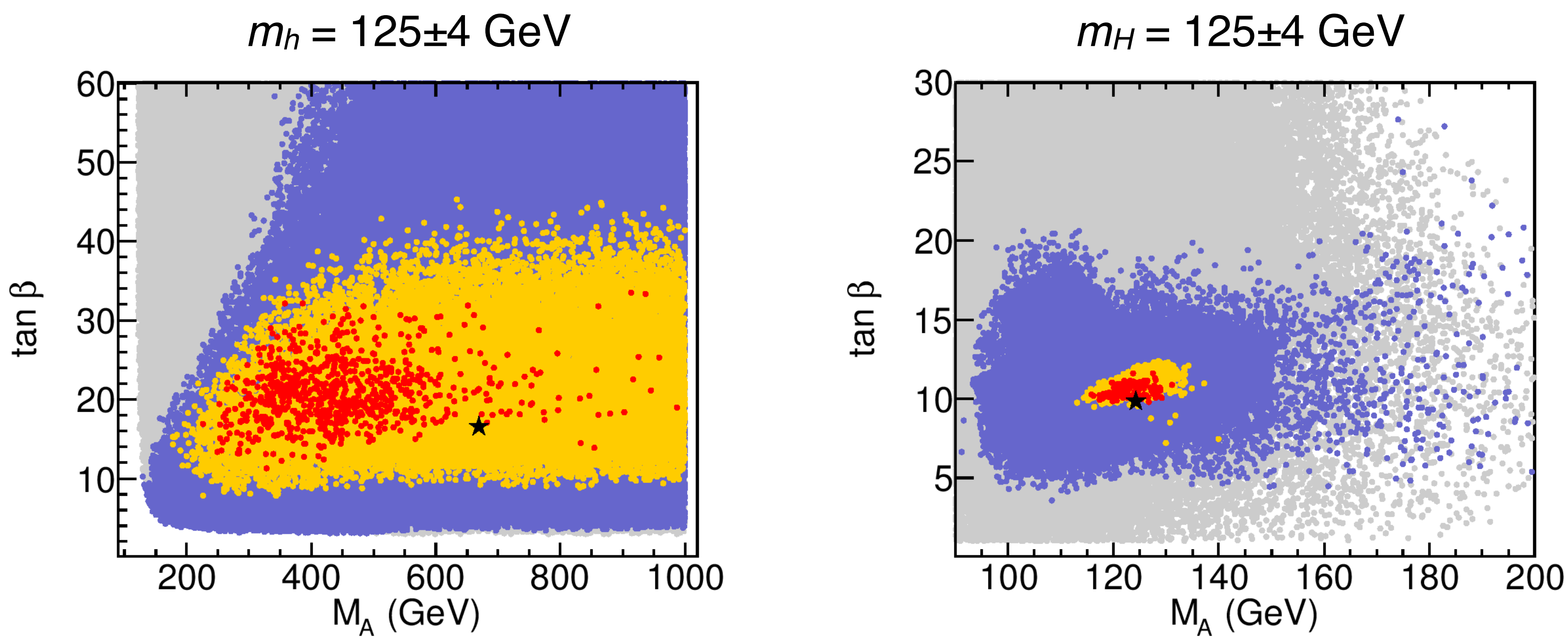
However, the tau tau searches mostly involve the "exotic" Higgses *(H, A)* with *tanβ*-enhanced couplings to *b* and tau (except for lower-left corner of the plot)

- 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 *$\tan\beta$* from LHC searches)
- h could explain the 2.3σ excess at 98 GeV seen by LEP [see also Drees, 1210.6507]
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m_h = 125±4 GeV

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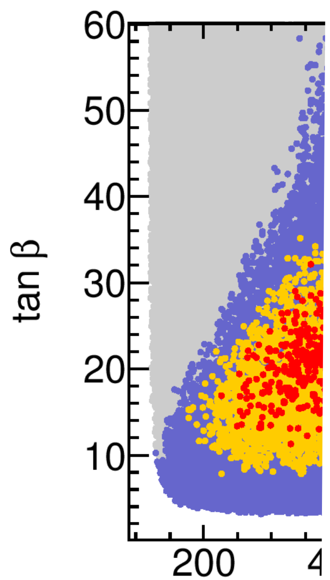

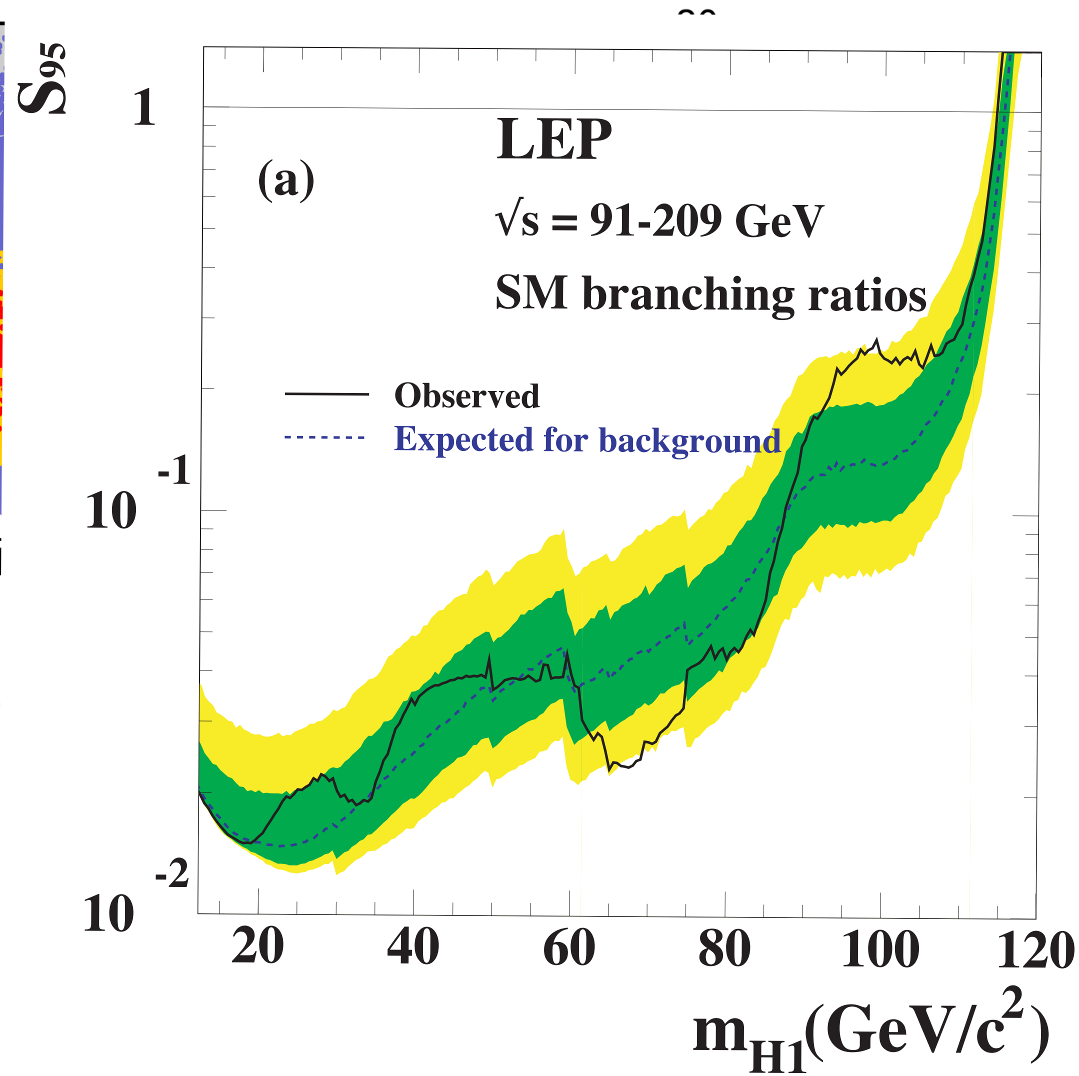

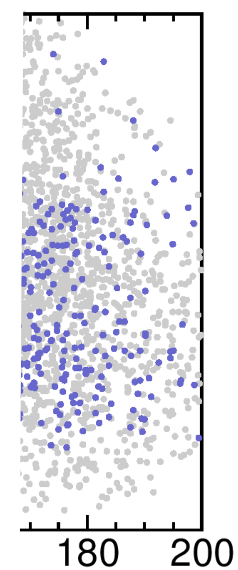

Bechtle *et al.*, 1211.1955

The scenar ... not ruled out:

- In this s...
- $H^{\pm}$ coul... searches)
- h could ... lso Drees, 1210.6507]

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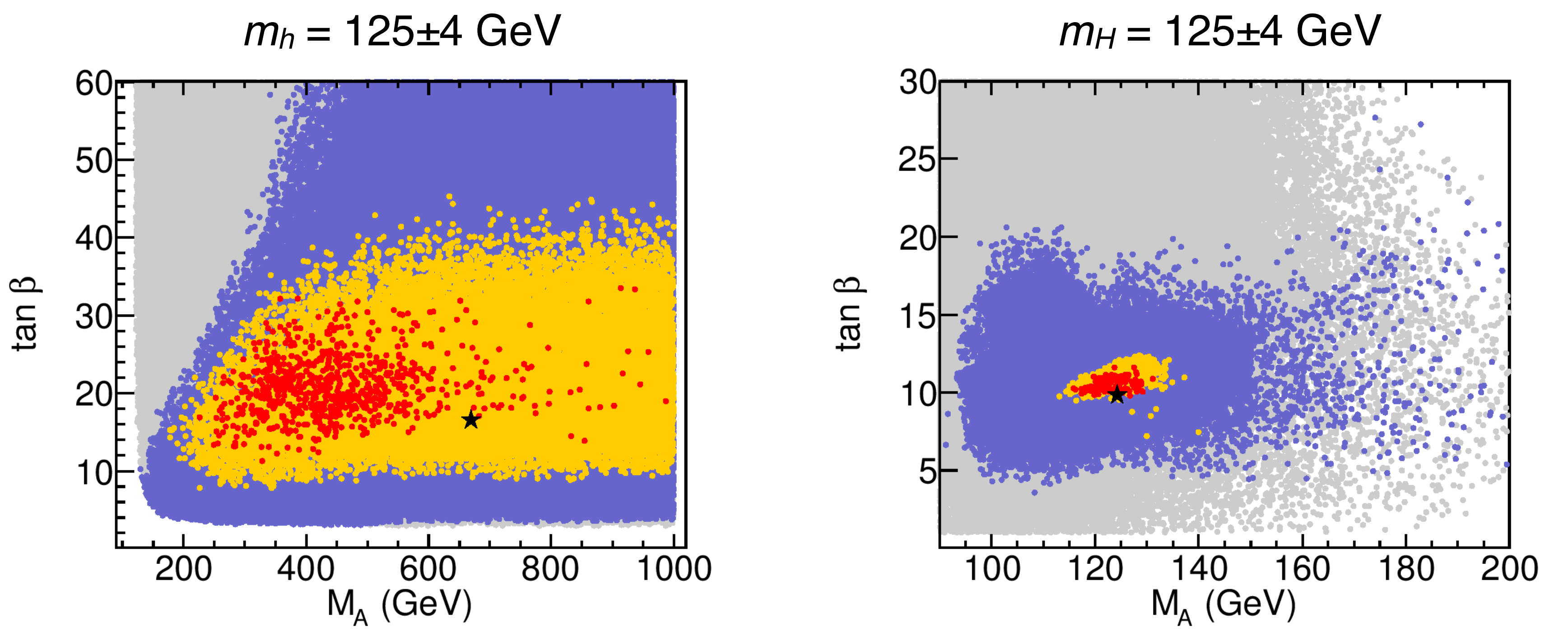

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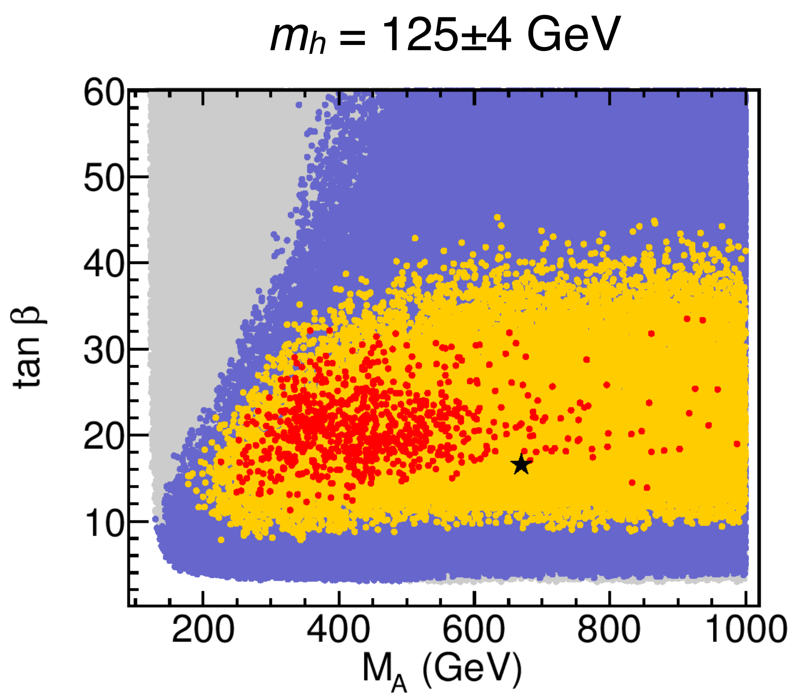

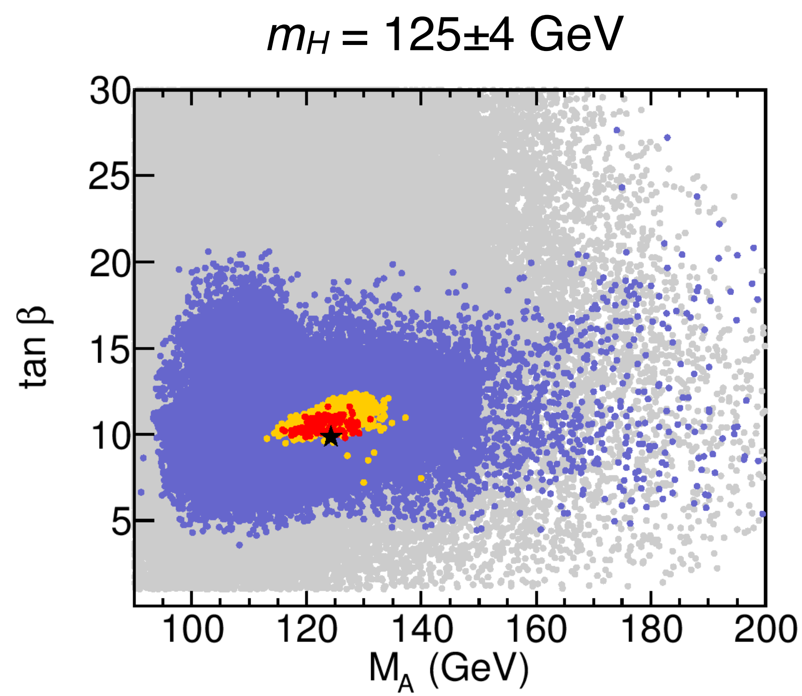

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(scenario excluded by new CMS results? see Arbey et al.,1211.4004)

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)

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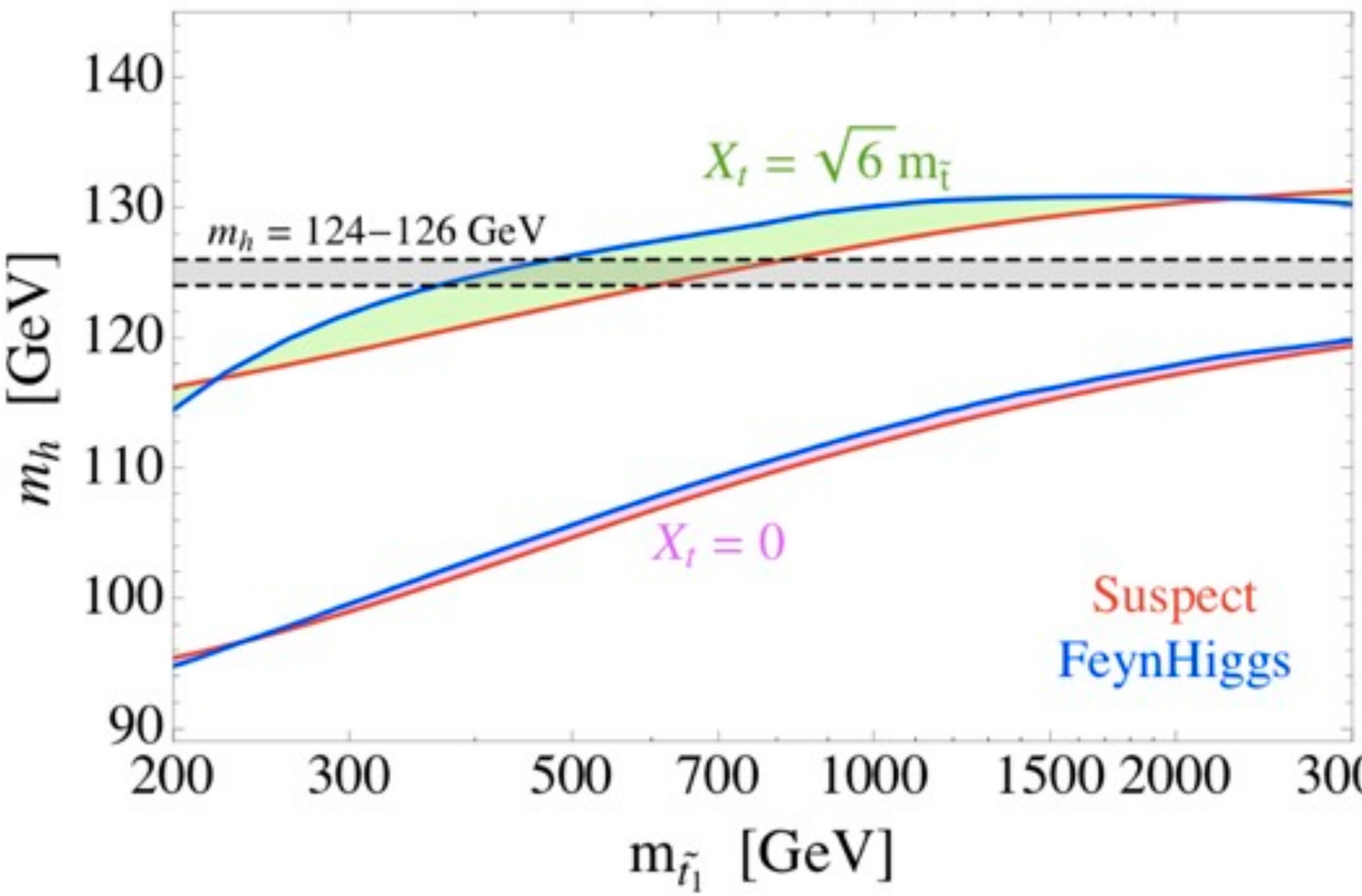

Hall *et al.*, 1112.2703

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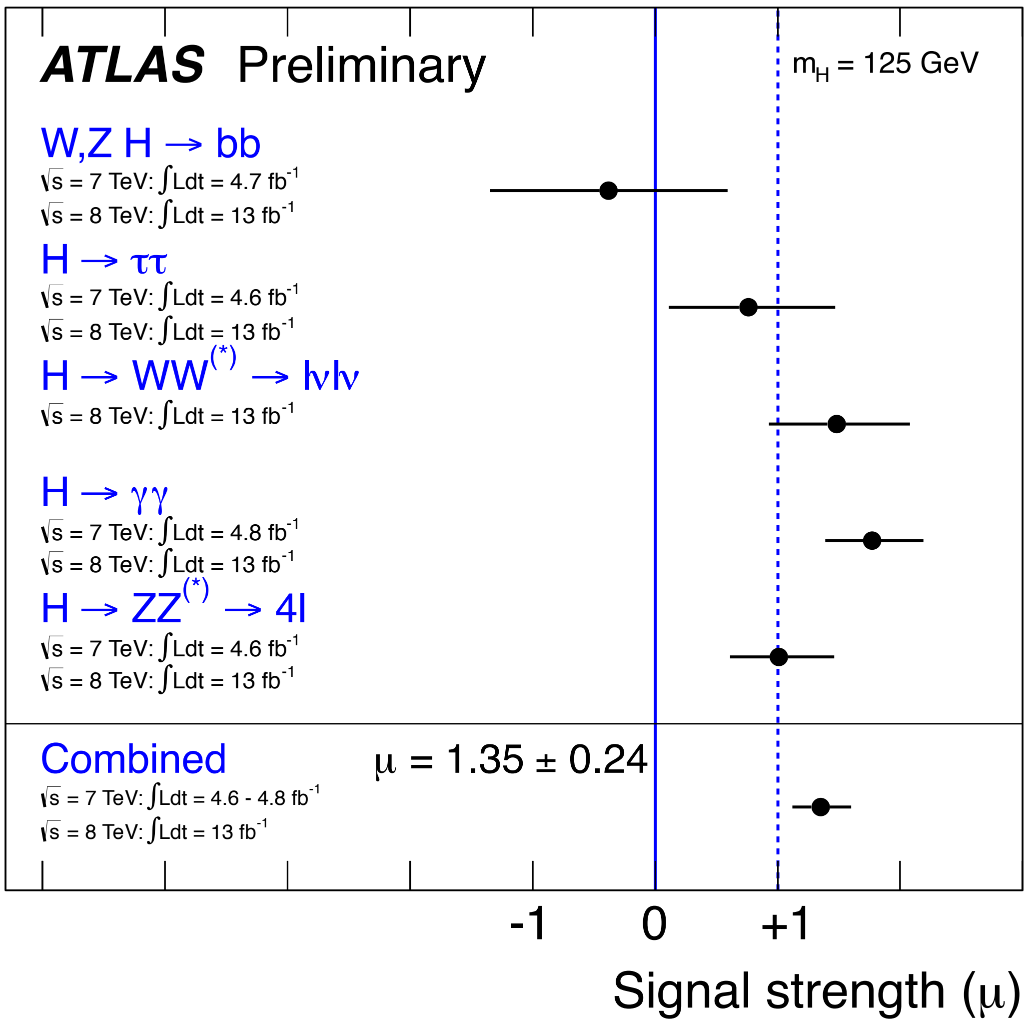
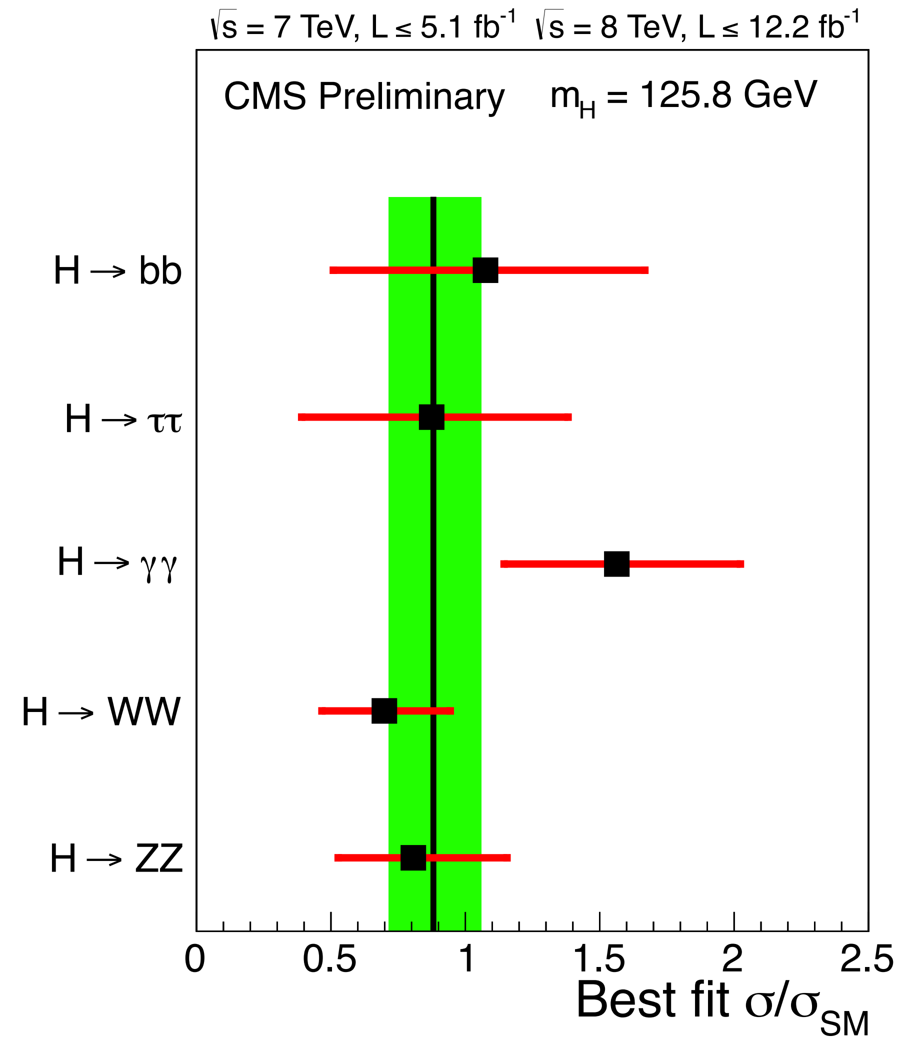
An exercise in wishful thinking: interpreting a diphoton excess





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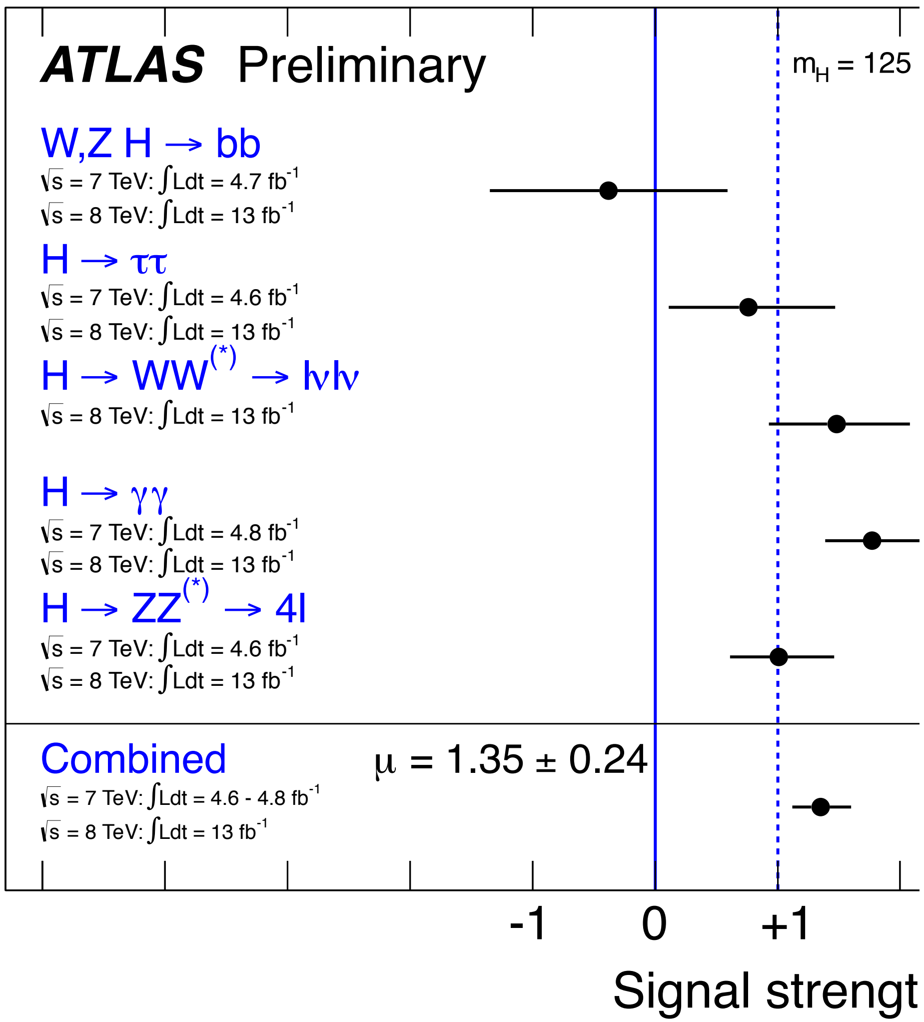
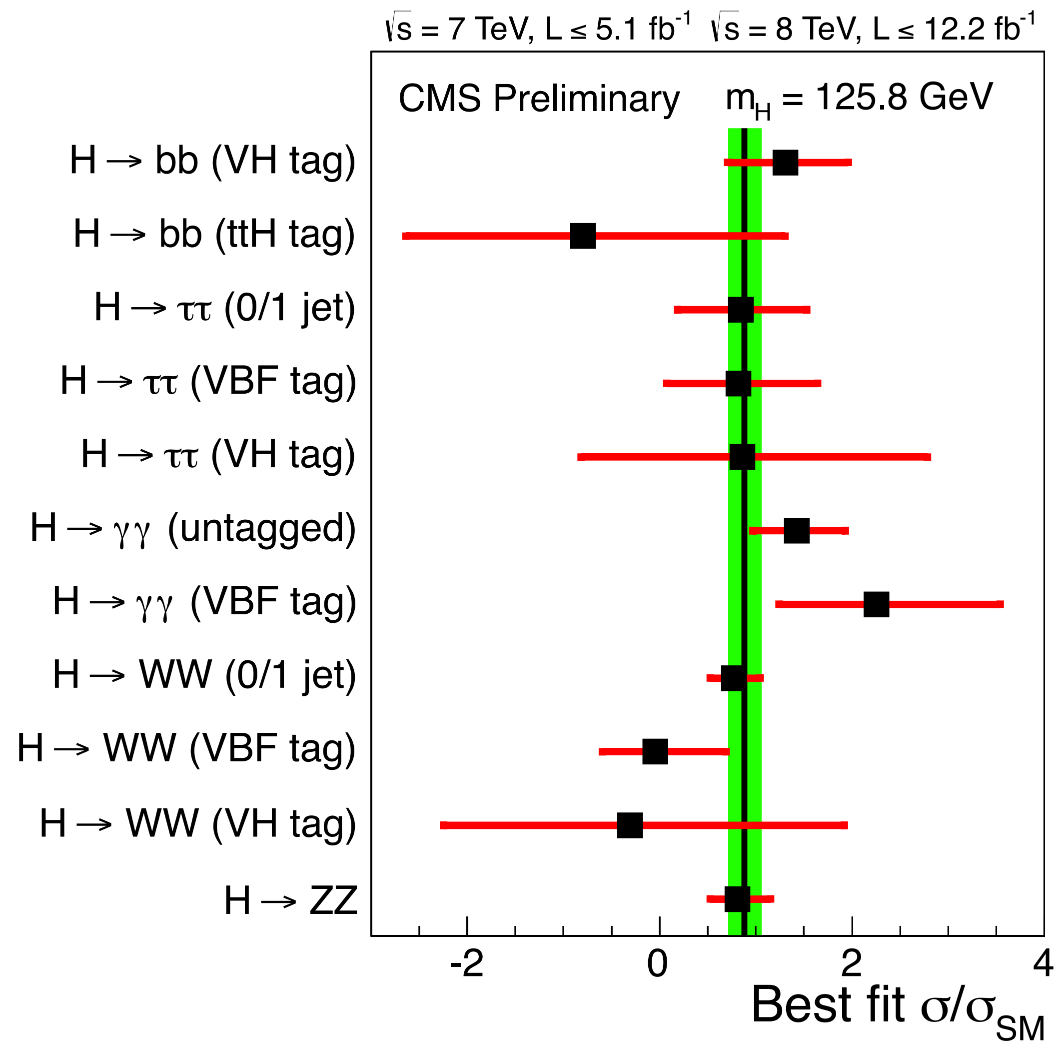
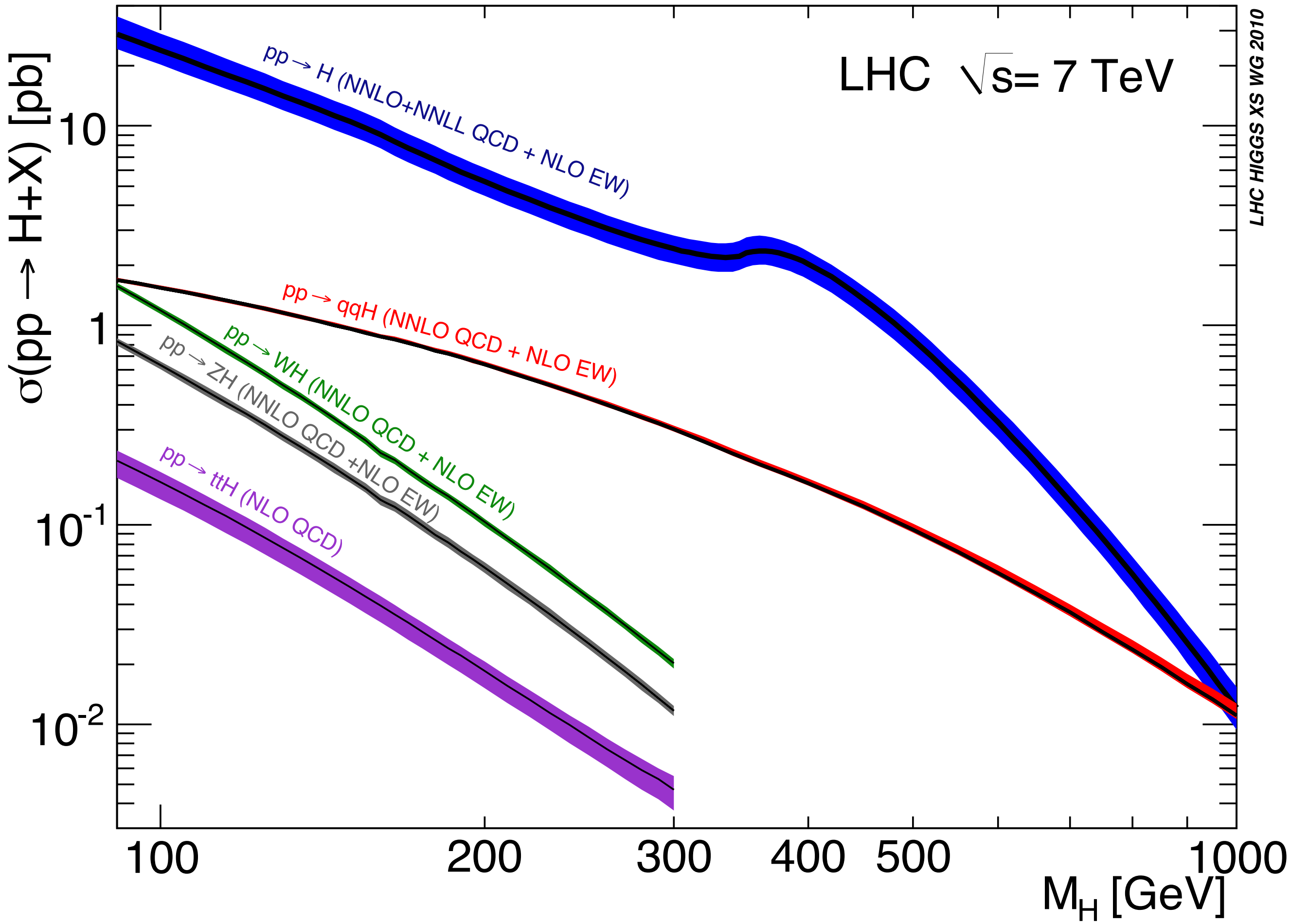
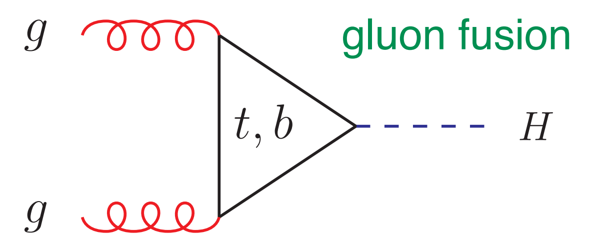




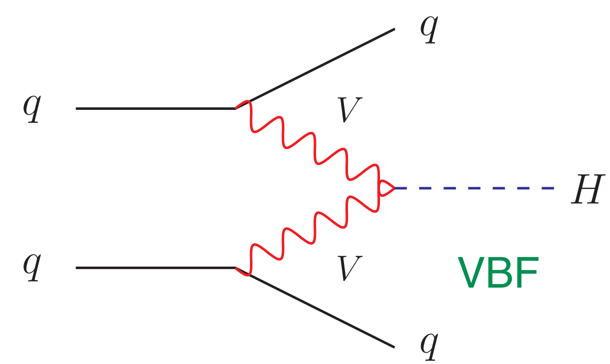
Higgs boson production at the LHC

SM predictions for the different channels:

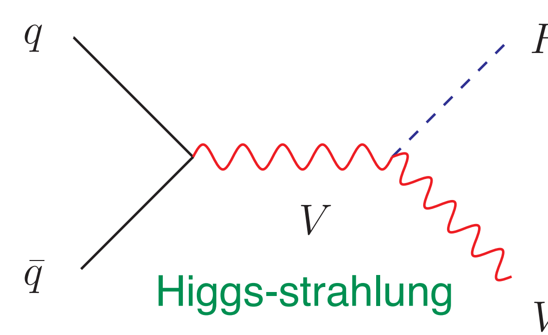




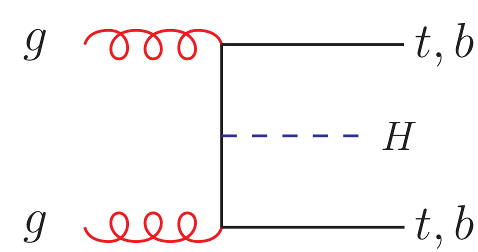
gluon fusion



VBF



Higgs-strahlung



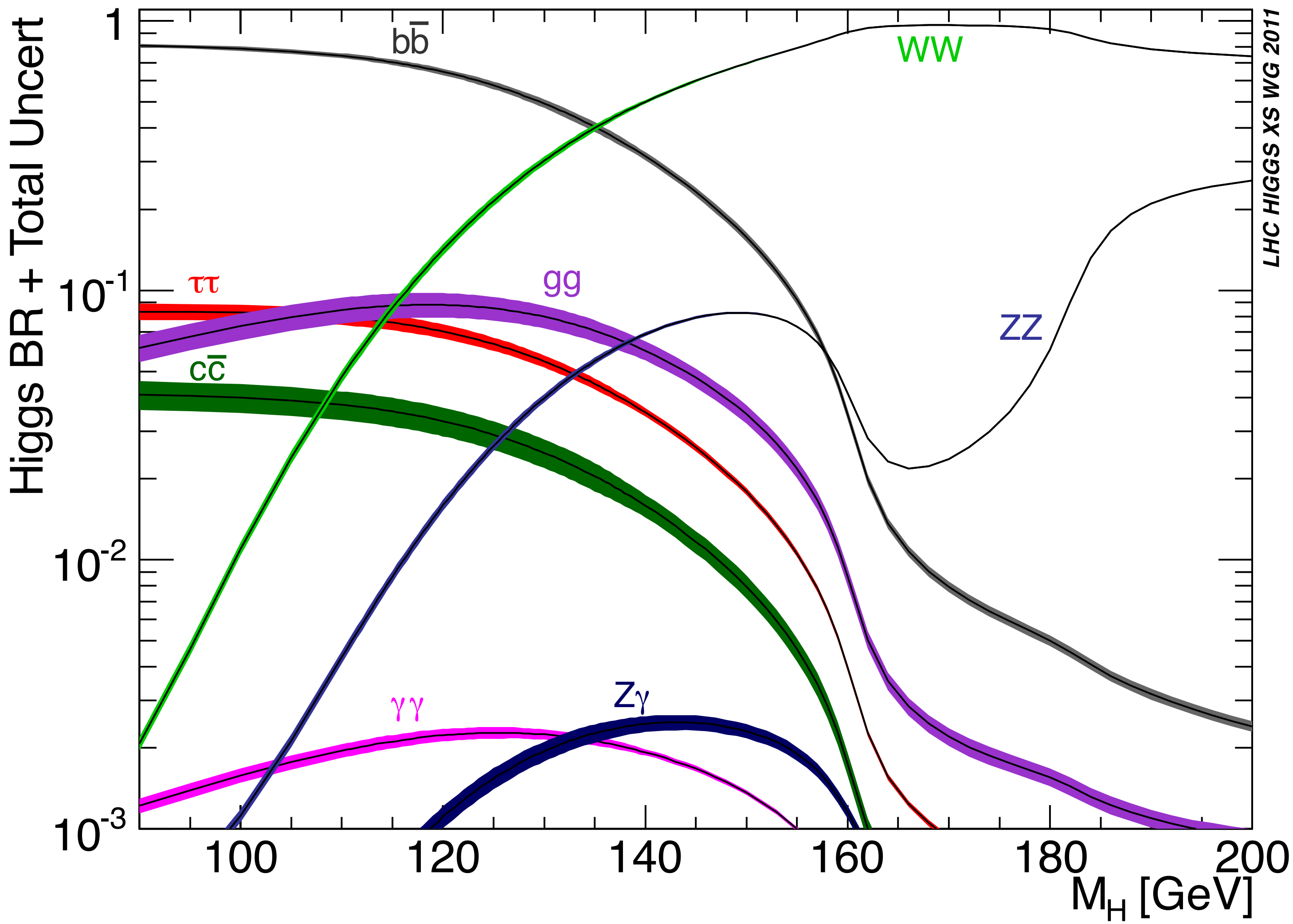
associated prod. with top/bottom

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

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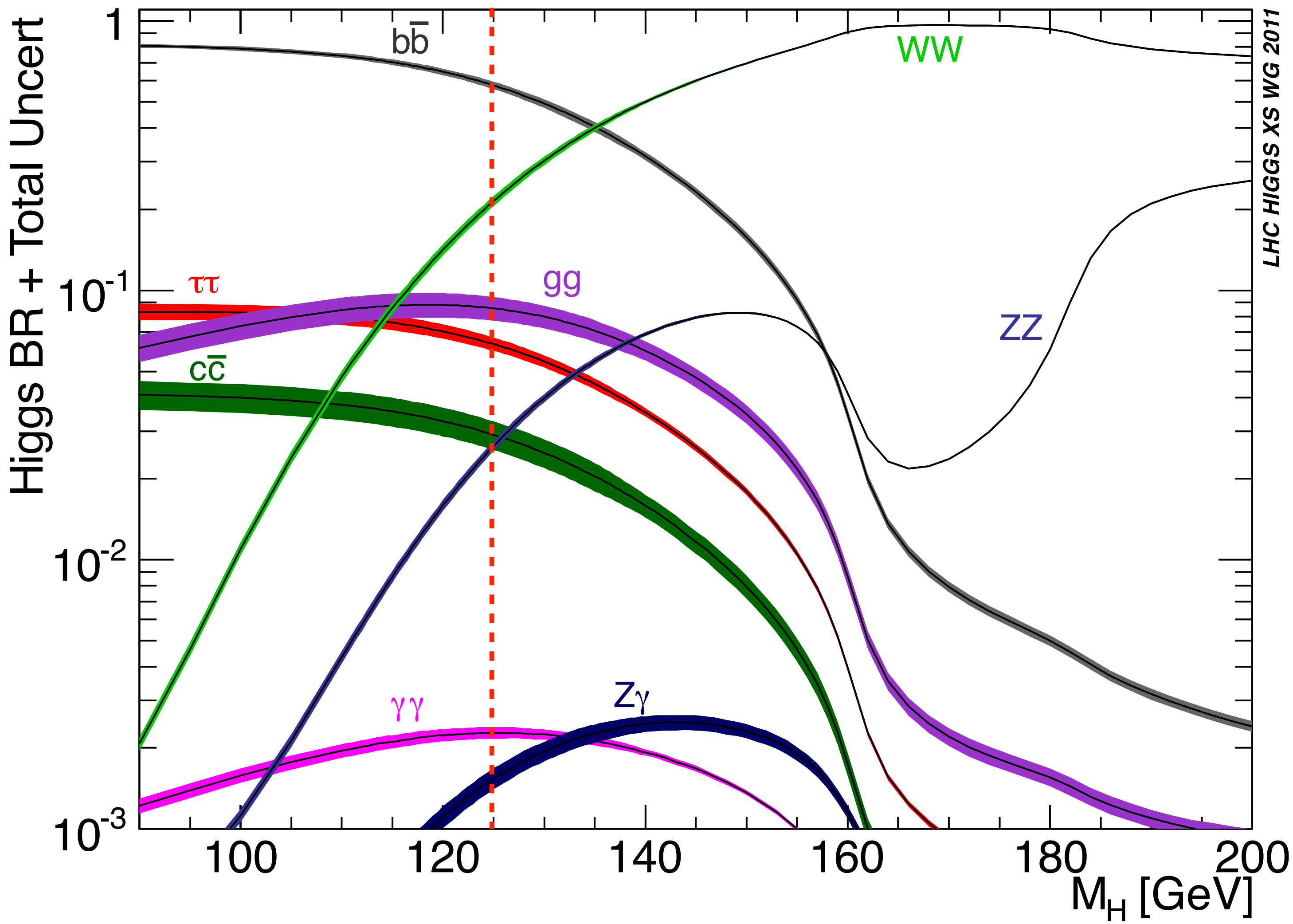

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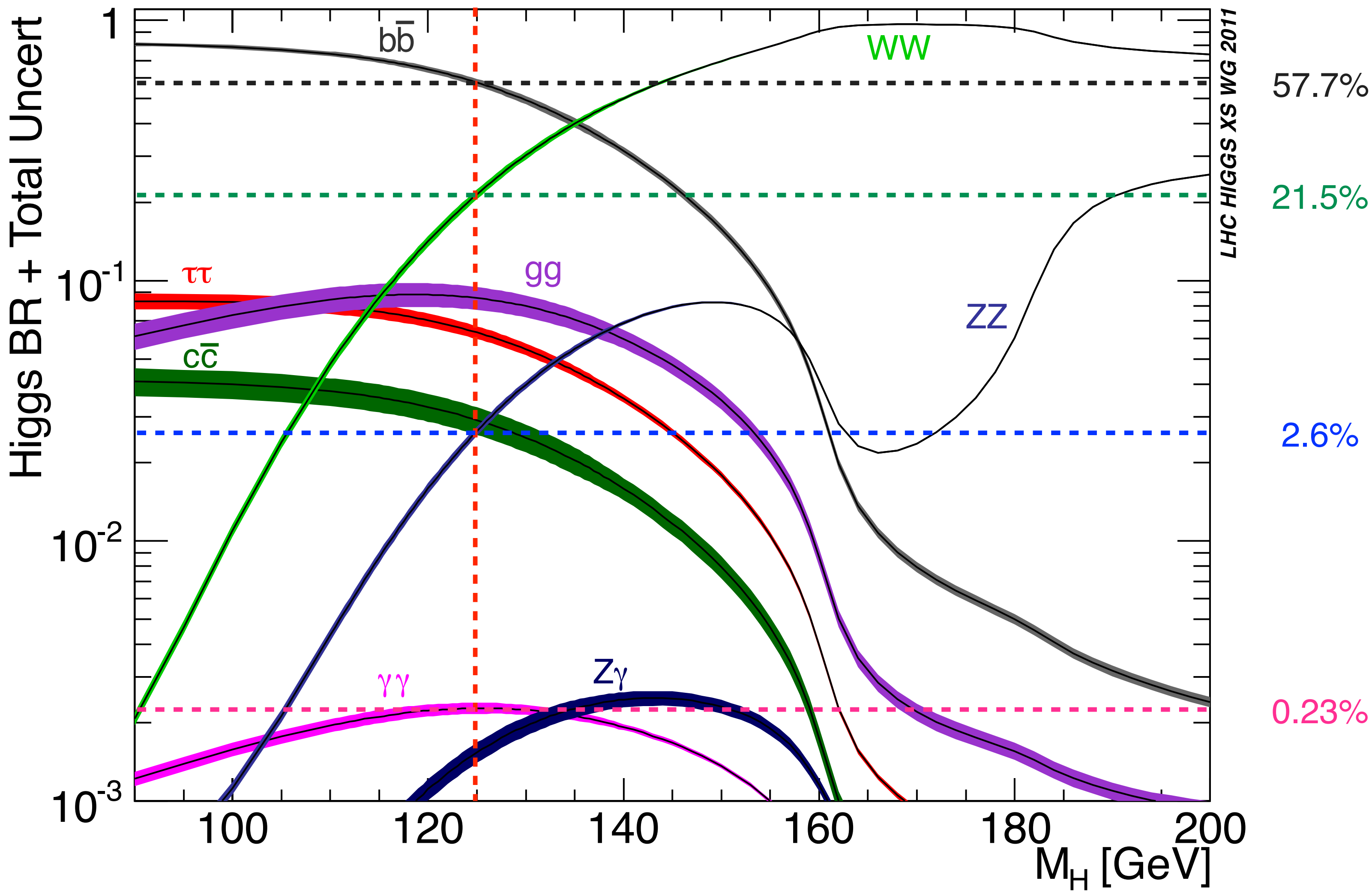

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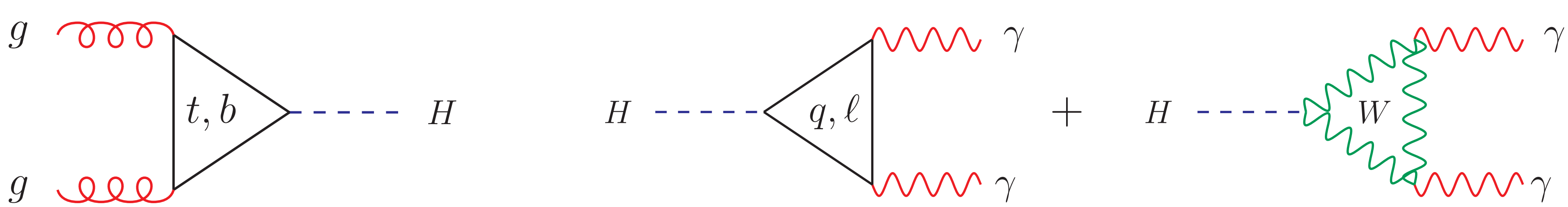
Various ways to increase the diphoton rate: $R_{gg}(\gamma\gamma) \equiv \frac{\sigma(gg \to H)\,\mathrm{BR}(H \to \gamma\gamma)}{\sigma(gg \to H)_{\mathrm{SM}}\,\mathrm{BR}(H \to \gamma\gamma)_{\mathrm{SM}}}$

- 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:



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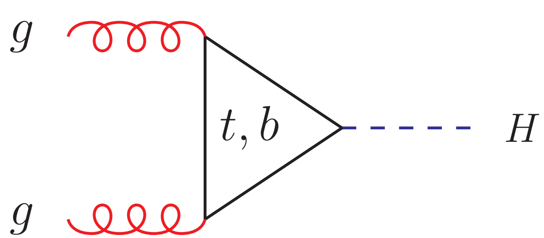
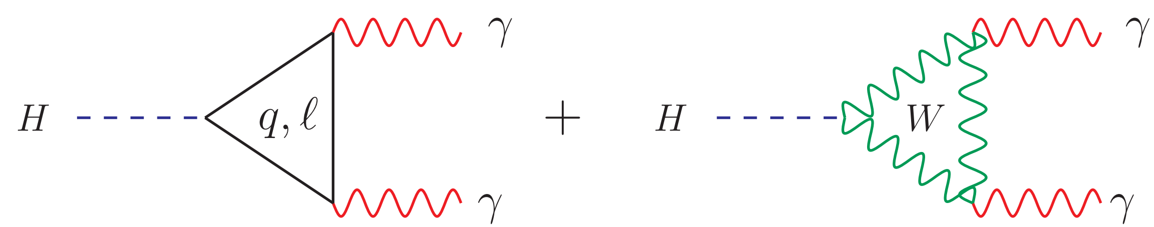




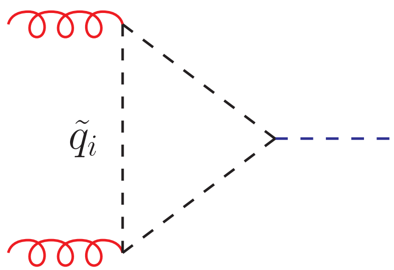
$+\ \tilde{q}$

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

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

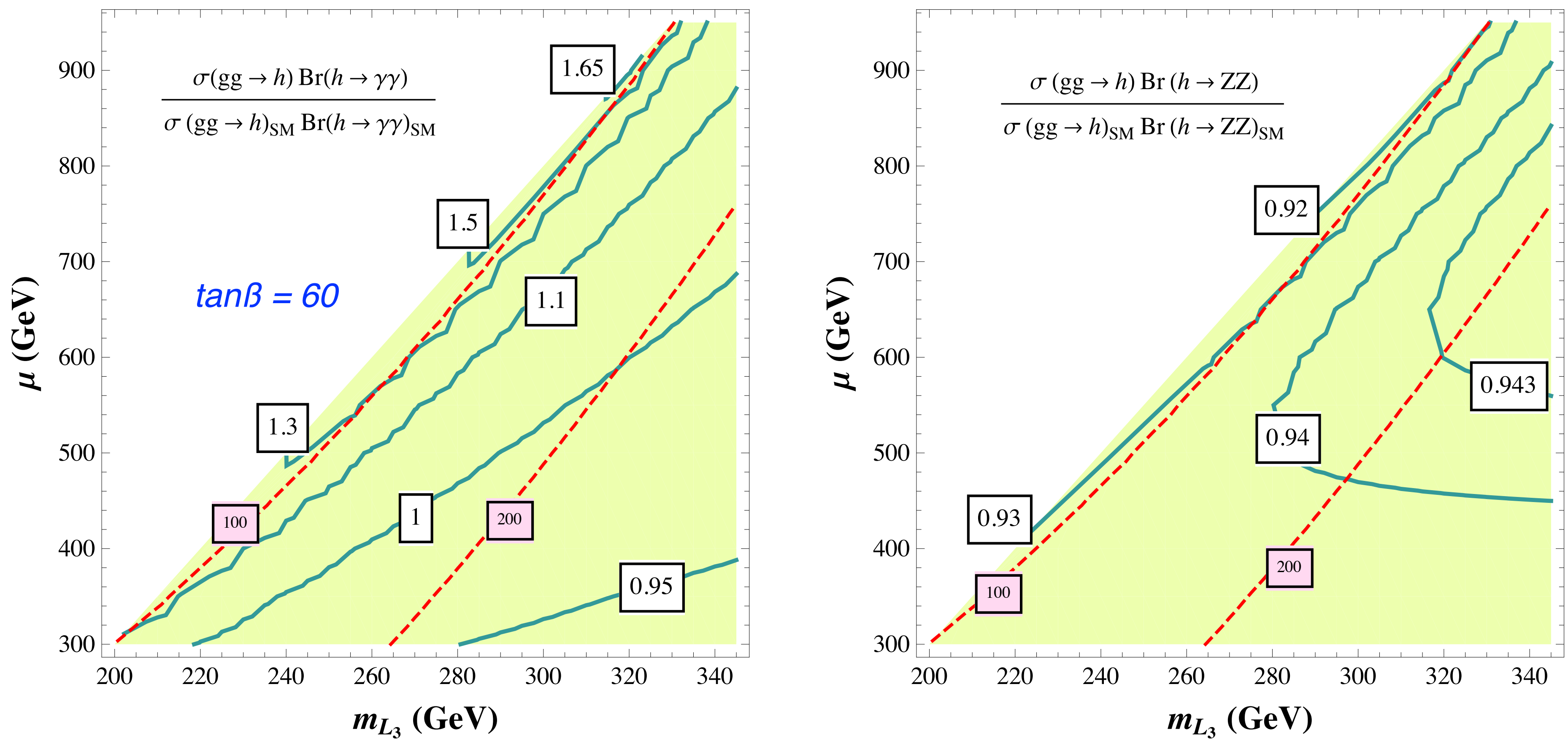
$$\Delta_{\tilde{t}} \;\approx\; \frac{m_t^2}{4}\left(\frac{1}{m^2_{\tilde{t}_1}}+\frac{1}{m^2_{\tilde{t}_2}}-\frac{X_t^2}{m^2_{\tilde{t}_1}\,m^2_{\tilde{t}_2}}\right)$$

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

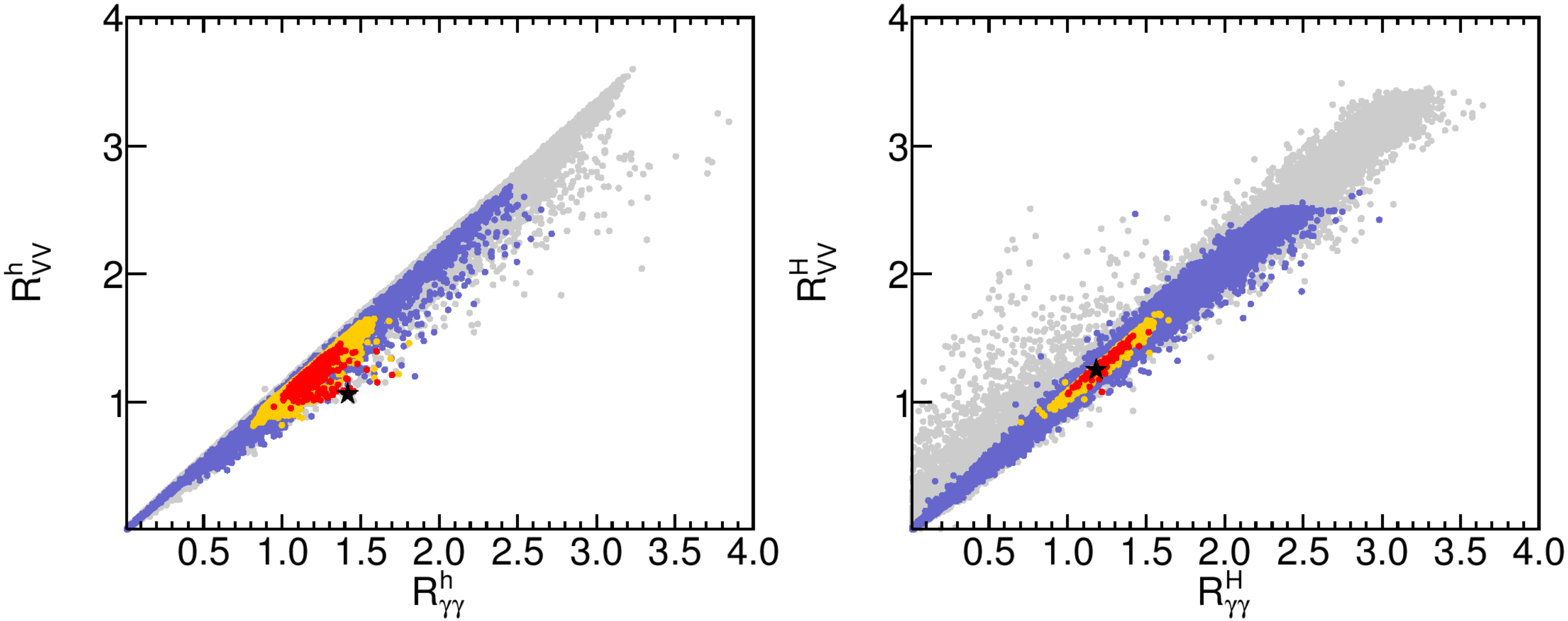
(NOTE: issues with vacuum stability. See Kitahara, 1208.4792 + Carena *et al.*, 1211.6136)

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

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

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

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

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R^S \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix}, \qquad \begin{pmatrix} G^0 \\ A_1 \\ A_2 \end{pmatrix} = R^P \begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix}, \qquad \begin{pmatrix} \chi^0_1 \\ \chi^0_2 \\ \chi^0_3 \\ \chi^0_4 \\ \chi^0_5 \end{pmatrix} = N \begin{pmatrix} -i\tilde{b} \\ -i\tilde{w}^0 \\ \tilde{h}^0_1 \\ \tilde{h}^0_2 \\ \tilde{s} \end{pmatrix}$$

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

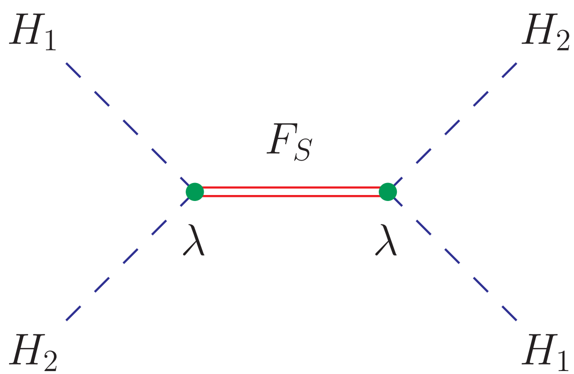
$$m_{A_1}^2 = \frac{2\,B_\mu}{\sin 2\beta} + \mathcal{O}(v^2)\,, \qquad m_{A_2}^2 = \frac{3\,\kappa^2}{w}\,v_s^2 + \mathcal{O}(v^2)$$

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

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

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:



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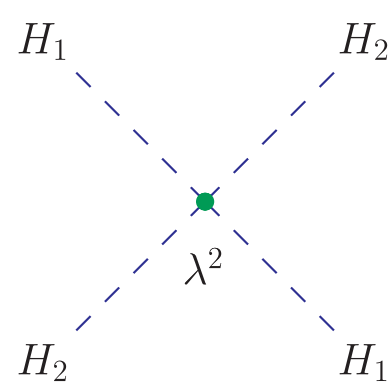

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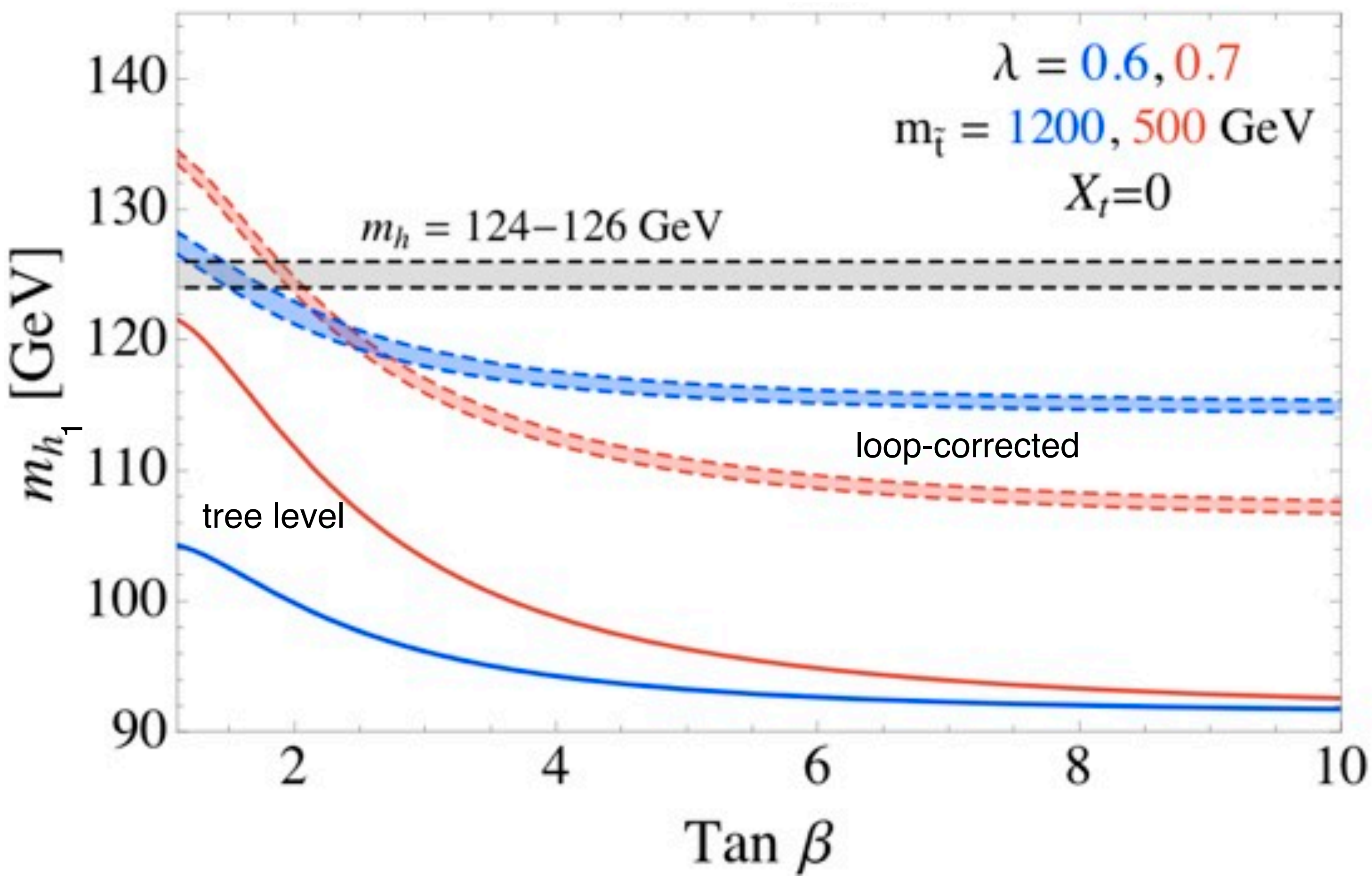
The additional contribution to the SM-like Higgs mass is maximized at low *tanβ*

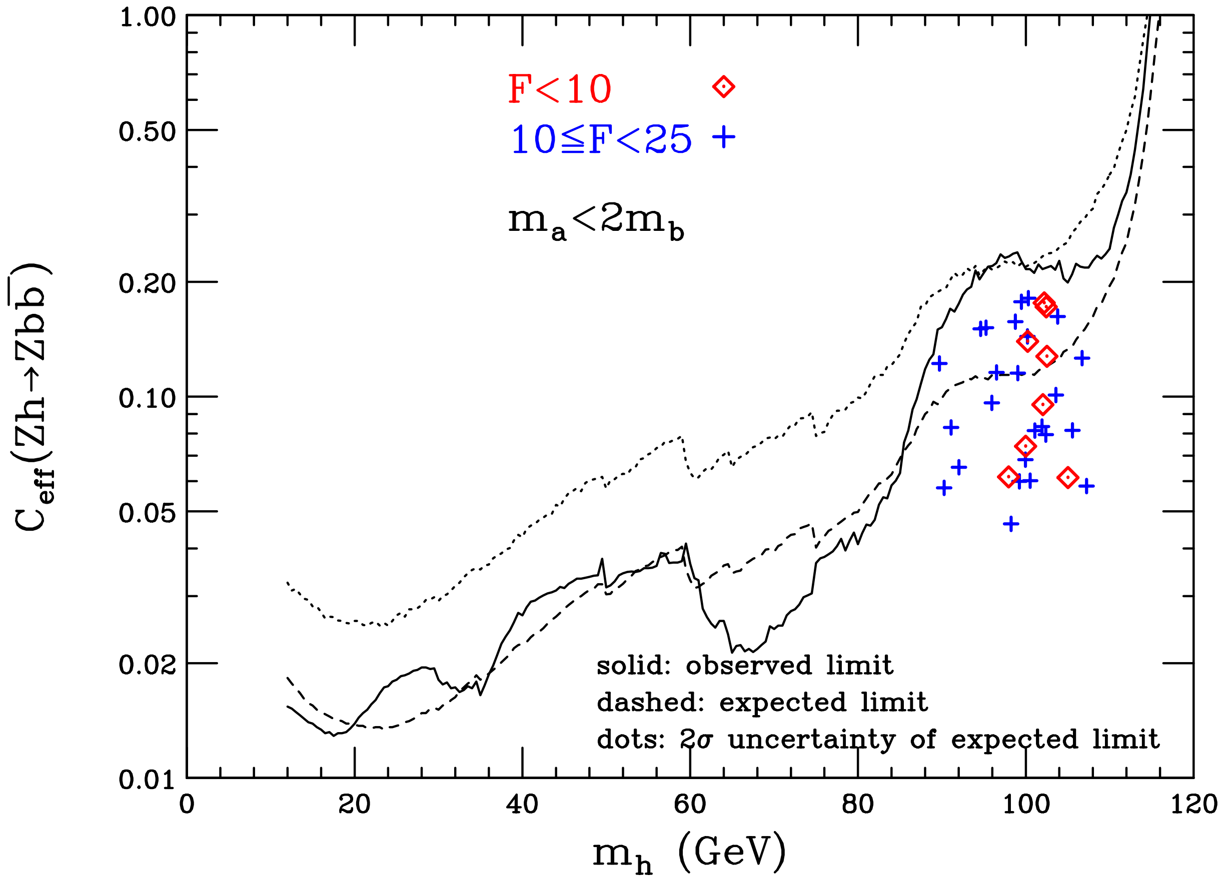


Hall *et al.*, 1112.2703

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 *h₁* 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)

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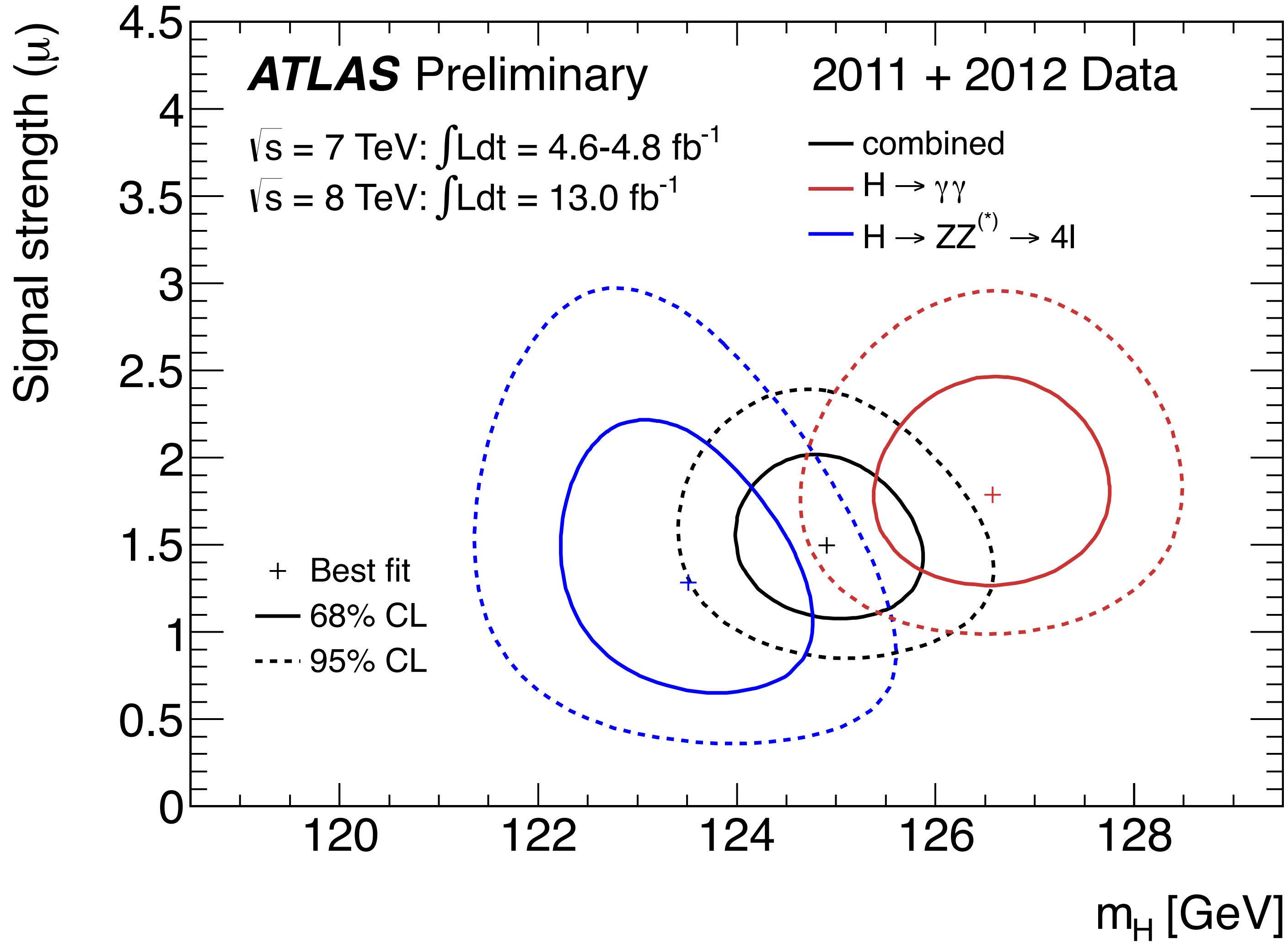

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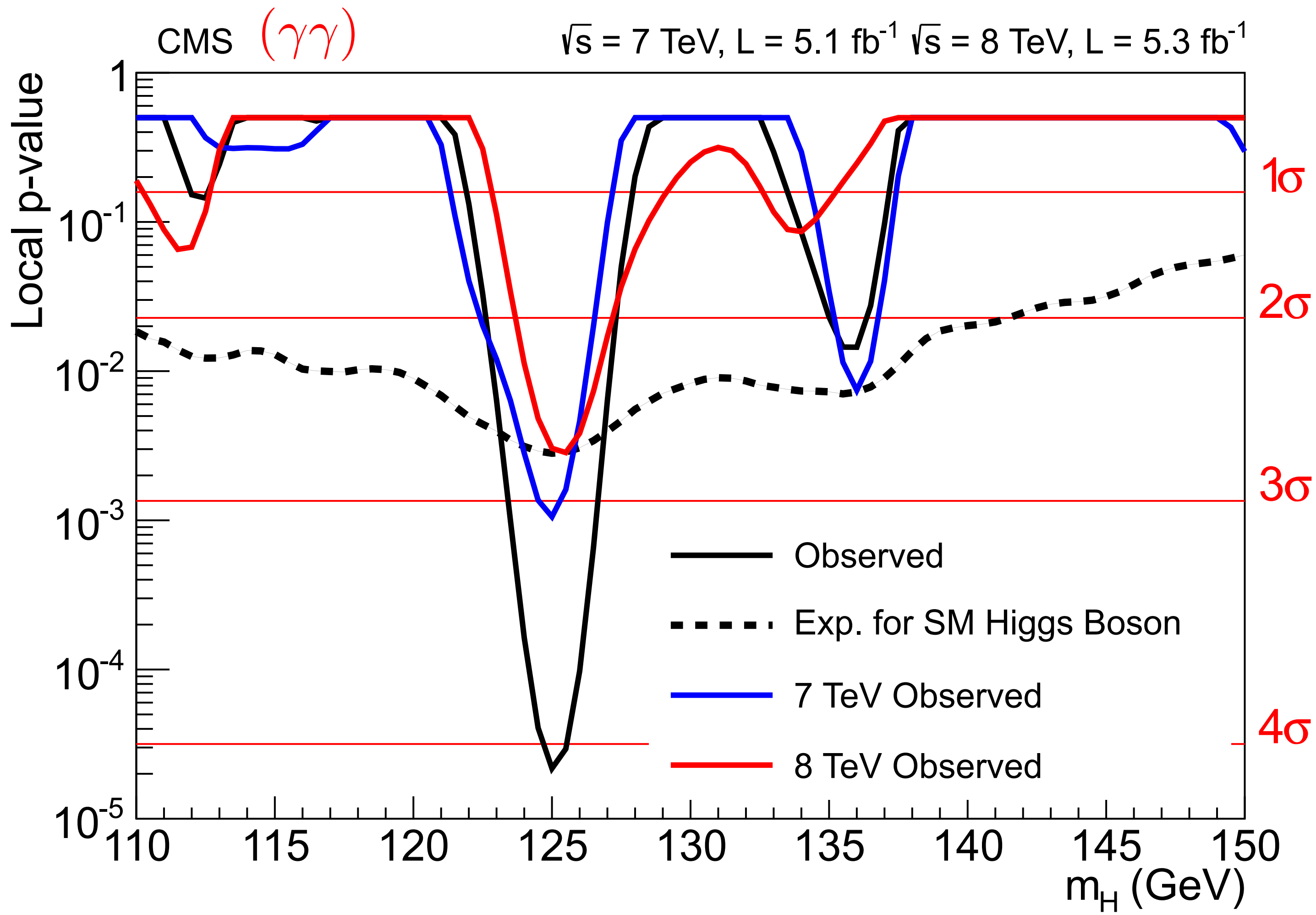

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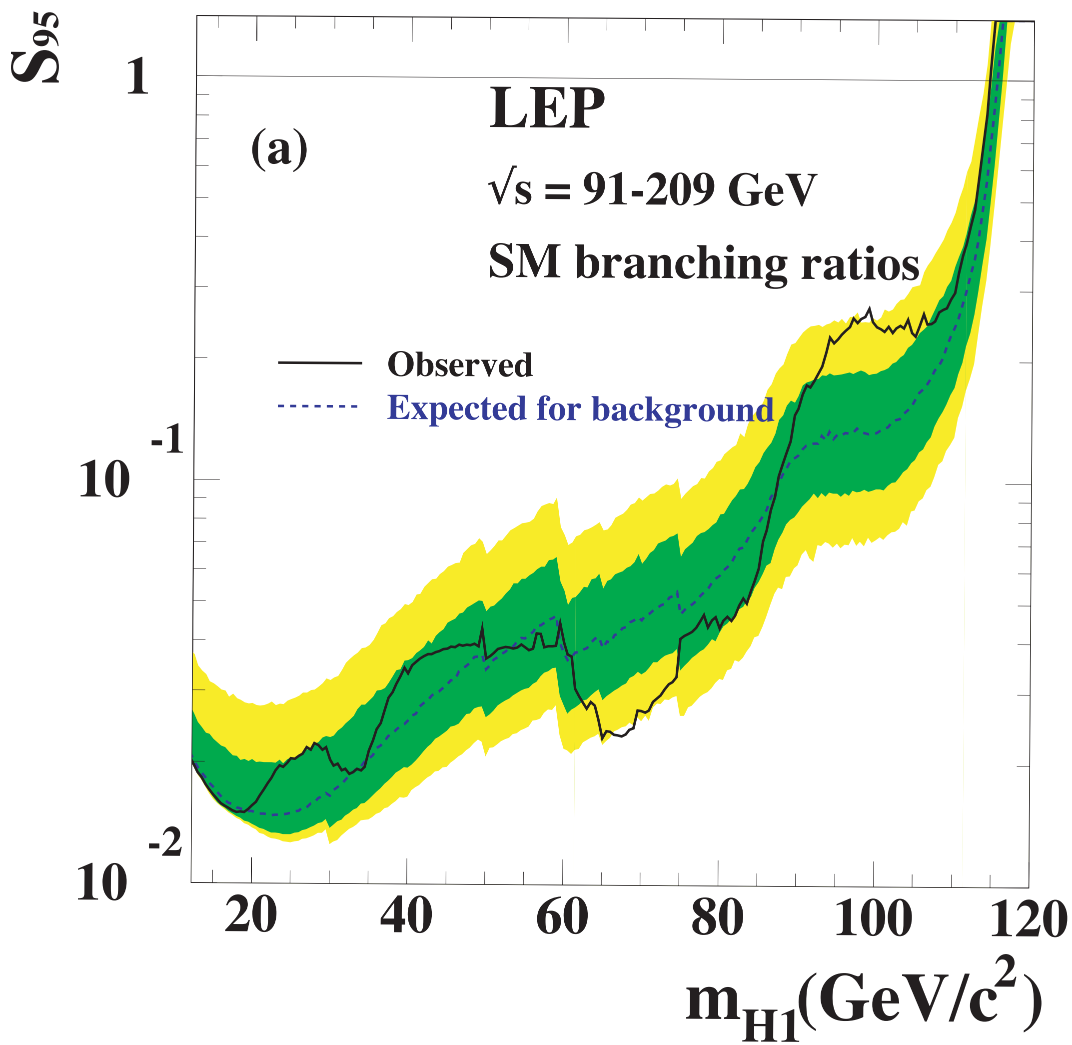

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A different approach: effective field theory Beyond the MSSM

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/M²* must be included in the analysis)

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

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and allows to accommodate several multi-Higgs scenarios
- Now the focus is on Higgs production and decay: do they deviate from SM?

Thank you!!!