Higgs and light sleptons

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Outline

1. Introduction: the discovery of a new boson

2. Implications for Susy (MSSM)

- The mass of the Higgs and natural theories
- The Higgs rates: an enhancement of the di-photon rate?

3. Phenomenology of the light stau scenario

- Constraints (EWPTs, DM abundance, ...)
- Phenomenology of the heavy scalars and of the stops
- Direct production of light staus at the LHC

1. „A 125 GeV SM-like Higgs in the MSSM and the γγ rate "
Carena, Gori, Shah, Wagner **arXiv: 1112.3336, JHEP 1203 (2012) 014**

2. „Light Stau Phenomenology and the γγ Higgs Rate"
Carena, Gori, Shah, Wagner, Wang, **arXiv: 1205.5842, JHEP 1207 (2012) 175**

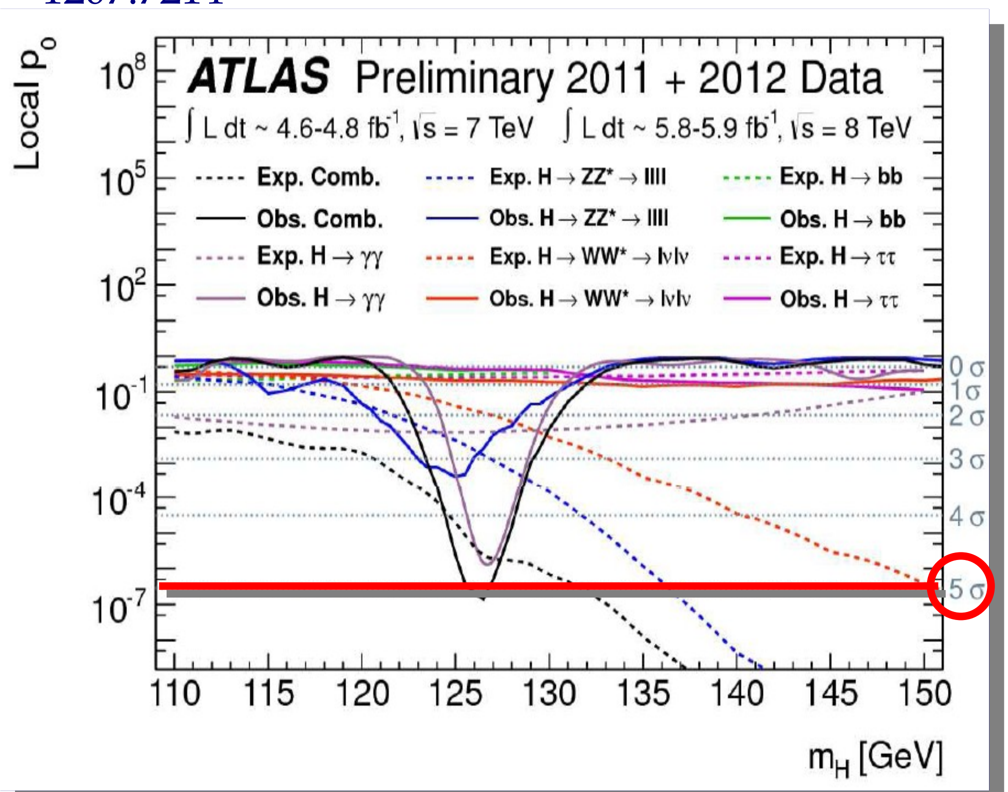
3. „Vacuum Stability and Diphoton Decays of a MSSM Higgs boson"
Carena, Gori, Low, Shah, Wagner **arXiv: 1211.6136**

We have a new boson!

July 4th, 2012: Both ATLAS and CMS: „We have observed a new boson“

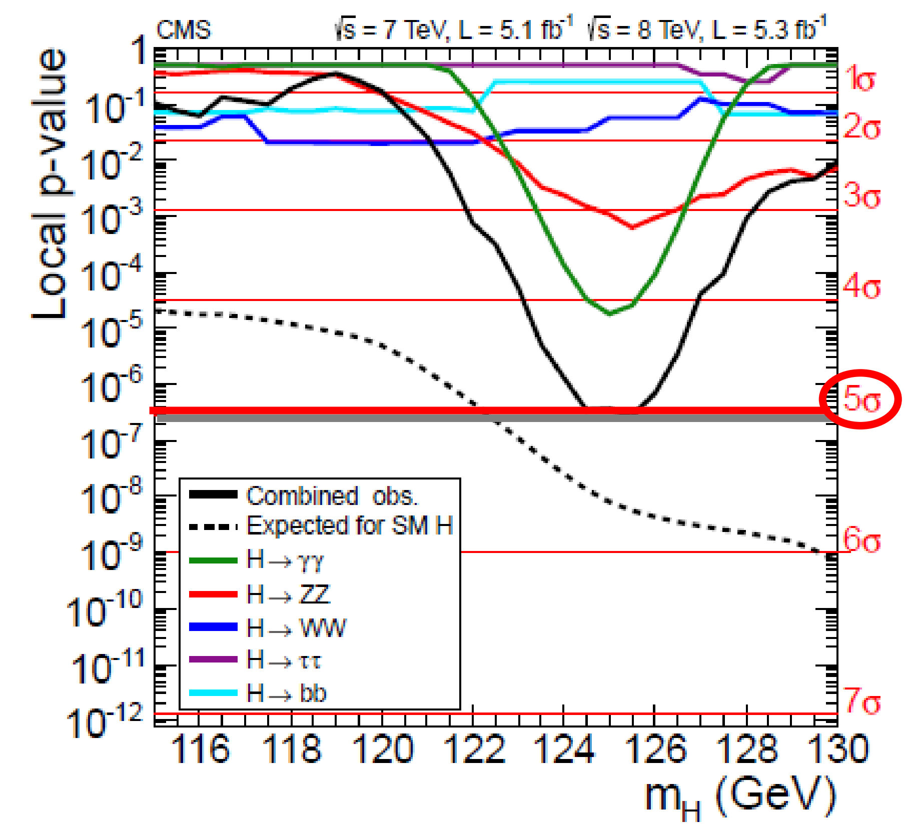
ATLAS

1207.7214



CMS

1207.7235

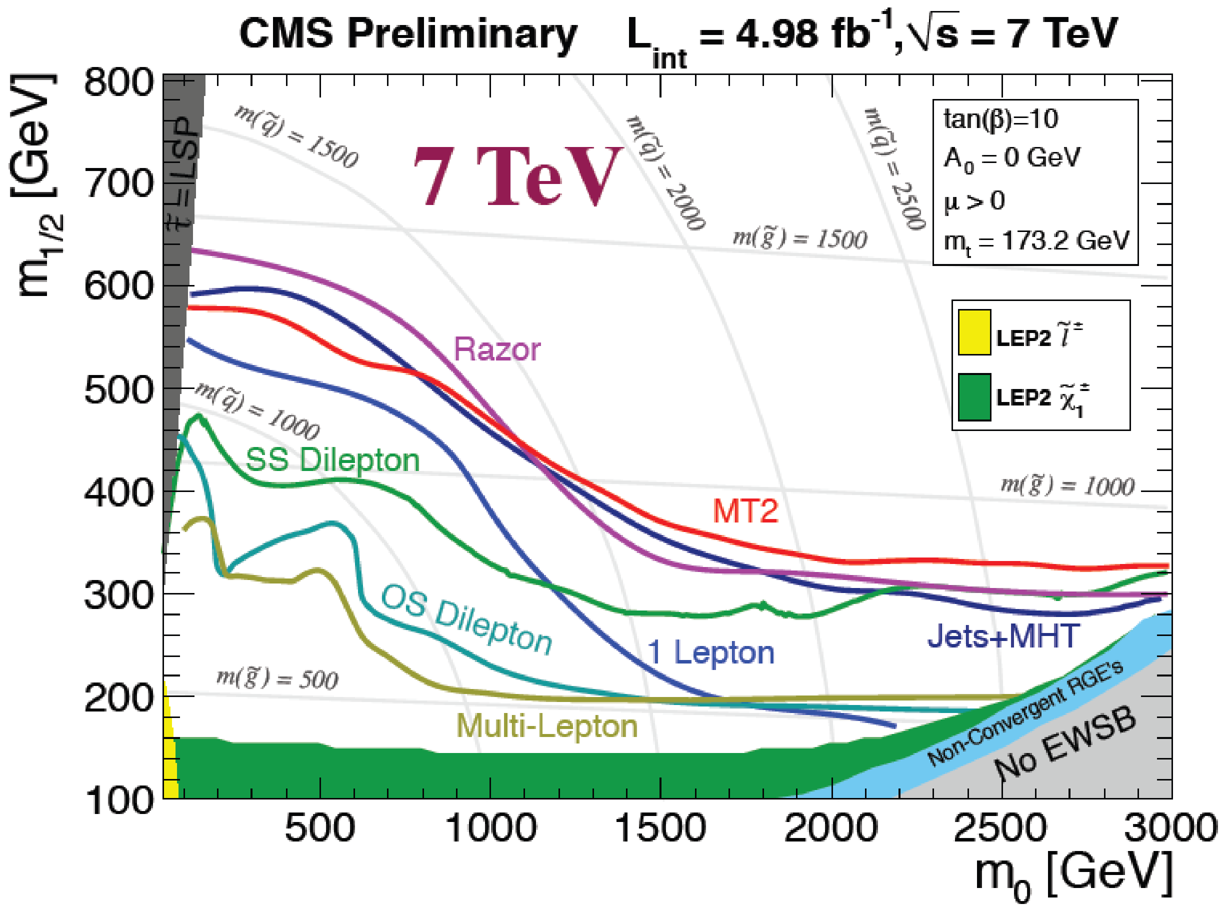


Now: with ~5 fb^{-1} at 7 TeV and ~12 fb^{-1} at 8 TeV → ~7σ of significance each experiment

The LHC so far

- Higgs at 125-126 GeV: most important result from the LHC so far

- No signs of low energy supersymmetry/exotic resonances yet



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- What can we learn?

    1. Mass of Higgs
    2. Higgs rates

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~125 GeV: a good mass for experimentalists

Several decay modes will be measured at the LHC!

$$\begin{aligned} \mathrm{BR}(h \to b\bar{b}) &= 58\%,\ \mathrm{BR}(h \to ZZ^*) = 2.7\%, \\ \mathrm{BR}(h \to WW^*) &= 21.6\%,\ \mathrm{BR}(h \to \tau\bar{\tau}) = 6.4\%, \\ \mathrm{BR}(h \to \gamma\gamma) &= 0.22\%,\ \mathrm{BR}(h \to \gamma Z) = 0.16\% \end{aligned}$$

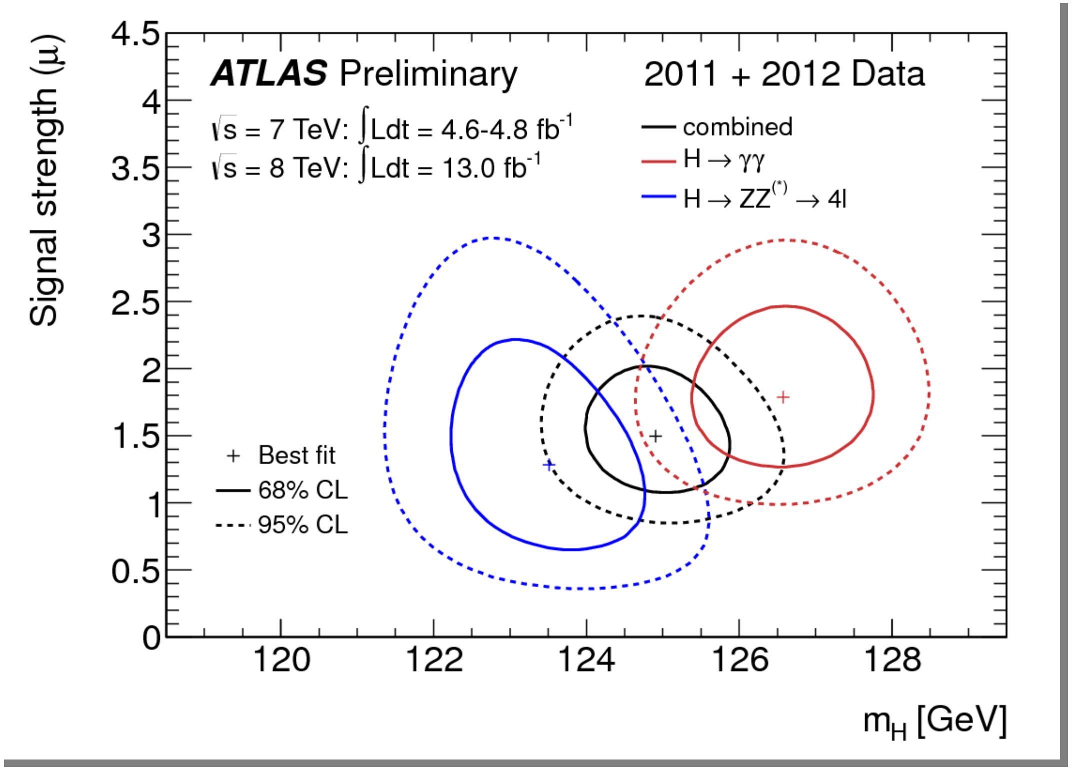
(for a SM Higgs)

The mass of the new boson

How well is the
mass determined?

ATLAS

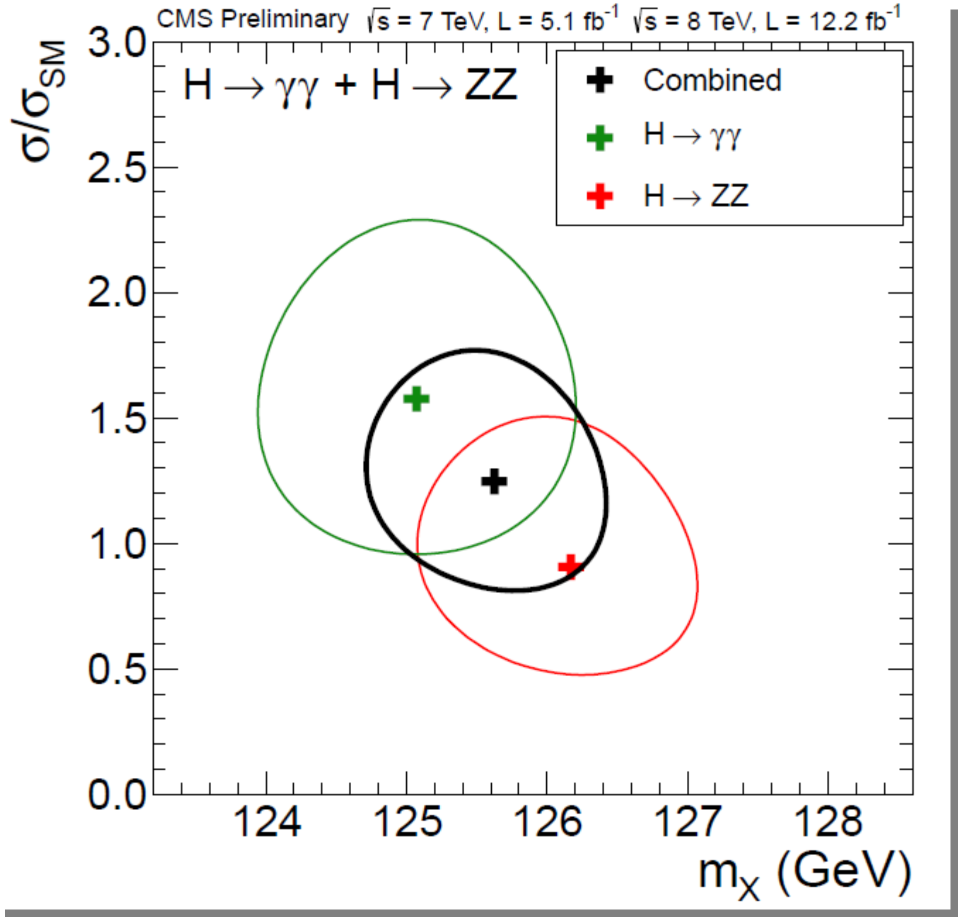
ATLAS-CONF-2012-170



$M_h = (125.2 \pm 0.3\ (stat) \pm 0.6\ (syst))$ GeV

CMS

CMS PAS HIG-12-045

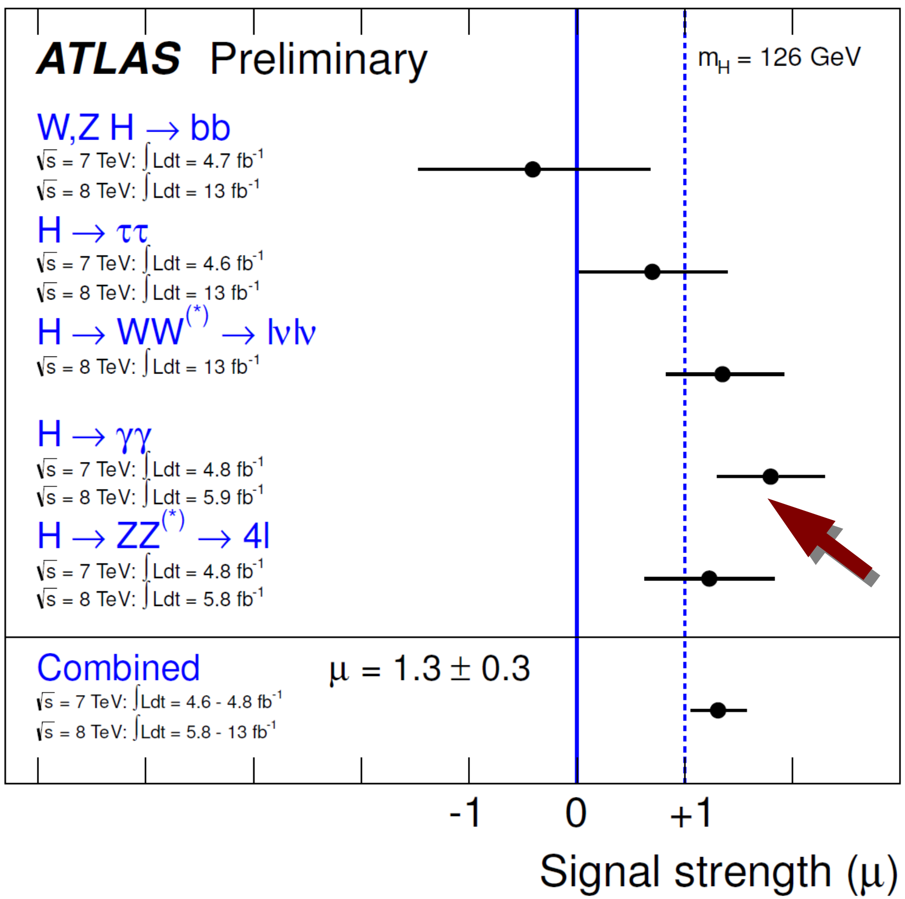


$M_h = (125.8 \pm 0.4\ (stat) \pm 0.4\ (syst))$ GeV

SM-like?

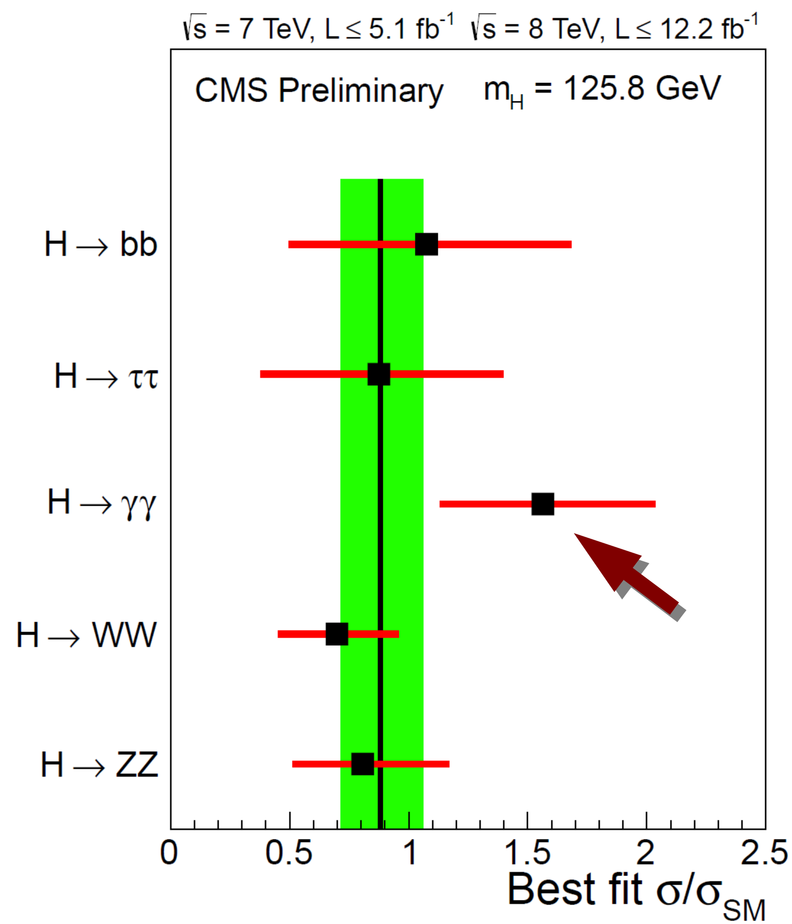
ATLAS

ATLAS-CONF-2012-162



CMS

CMS-PAS-HIG-12-045



SM-like but still large room for **surprises**

Interesting to speculate...

SM-like?

ATLAS

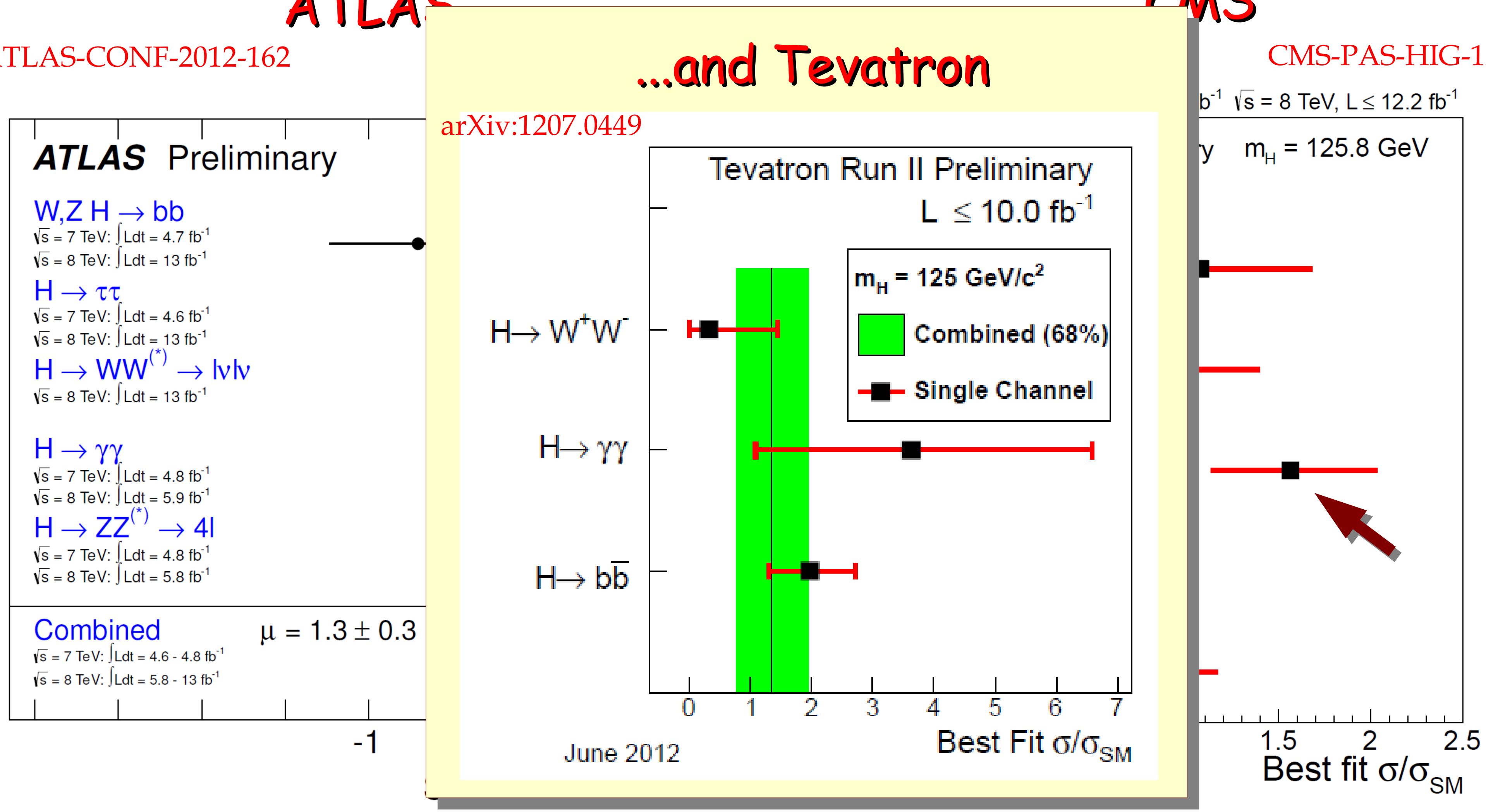
ATLAS-CONF-2012-162

CMS

CMS-PAS-HIG-12-045

...and Tevatron

arXiv:1207.0449



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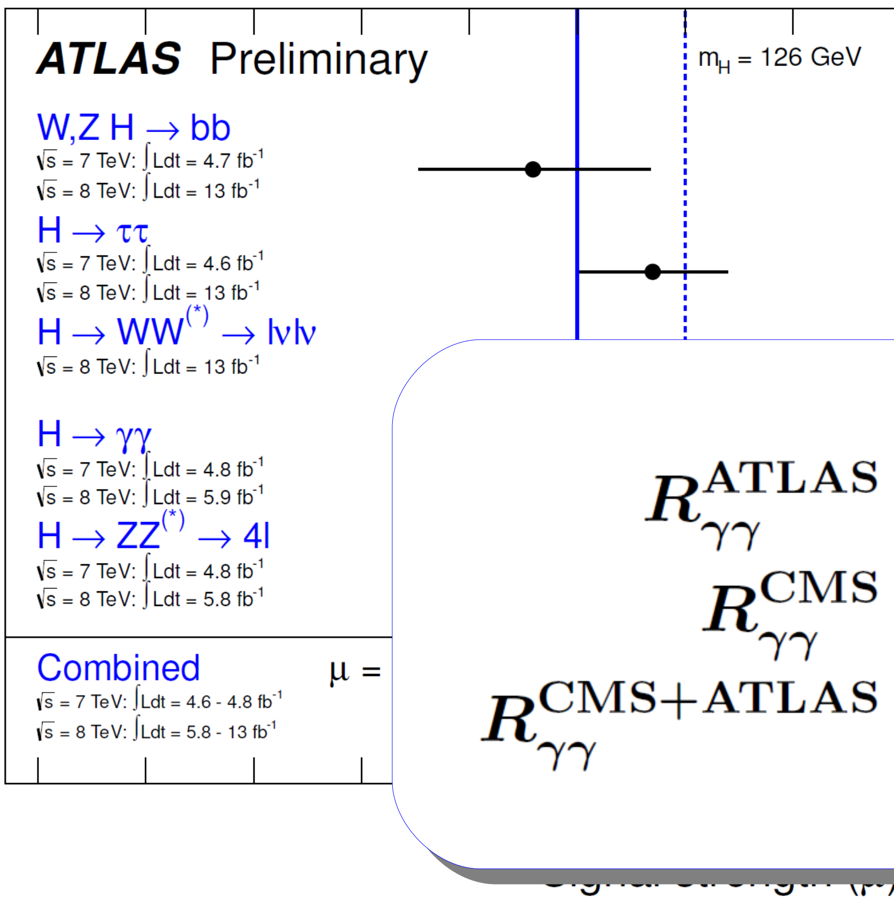
ATLAS-CONF-2012-162



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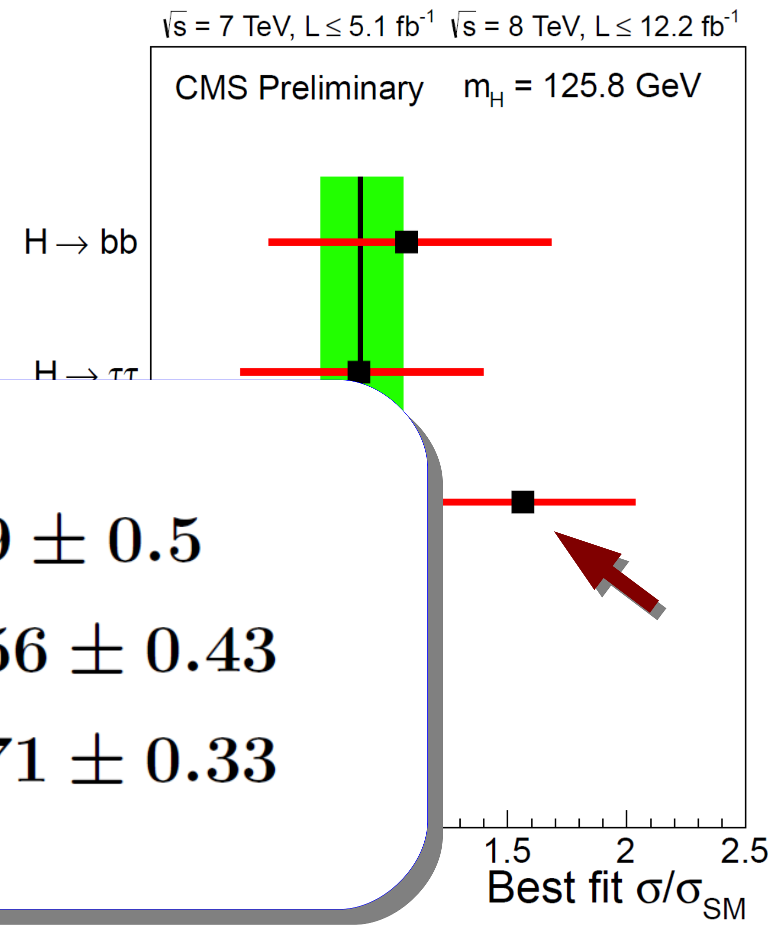


$$R_{\gamma\gamma}^{\rm ATLAS} = 1.9 \pm 0.5$$

$$R_{\gamma\gamma}^{\rm CMS} = 1.56 \pm 0.43$$

$$R_{\gamma\gamma}^{\rm CMS+ATLAS} = 1.71 \pm 0.33$$

SM-like but still large room for surprises

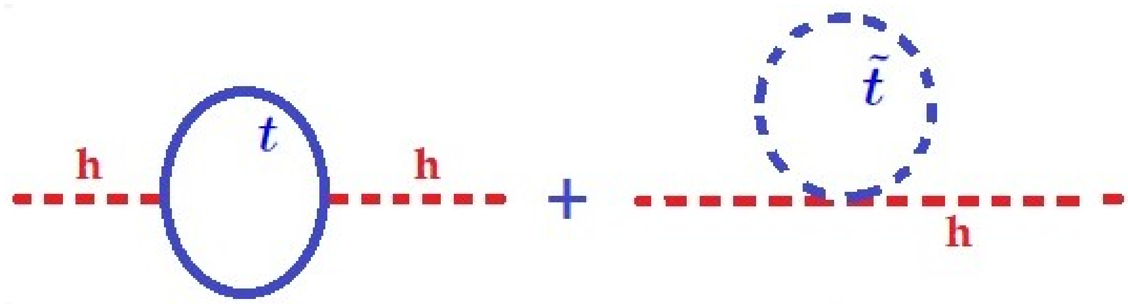
Interesting to speculate...

Naturalness and the Higgs rates

- New (light) particles introduced in models to address the **gauge hierarchy problem**

<u>Example:</u>

In the SM | **Supersymmetric contribution**



$$m_h^2 = m_{h0}^2 + c\Lambda^2,$$
$$\Lambda = M_{\text{Planck}}$$

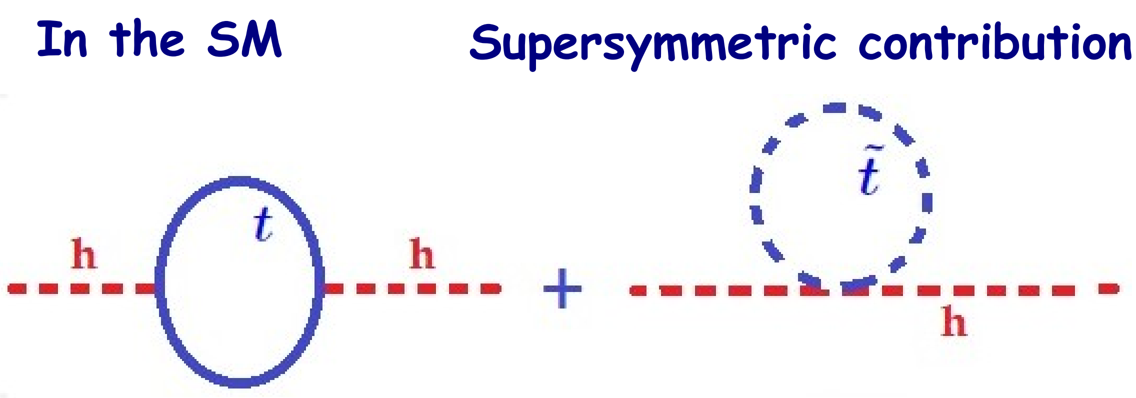
Quadratic corrections cancelled

also naturally enter in the Higgs phenomenology: Higgs rates at the LHC

Naturalness and the Higgs rates

- New (light) particles introduced in models to address the gauge hierarchy problem

Example:



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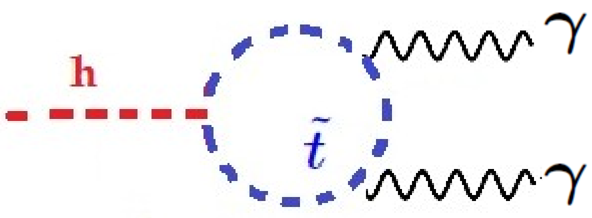

Naturalness and the Higgs rates

- New (light) particles introduced in models to address the **gauge hierarchy problem**

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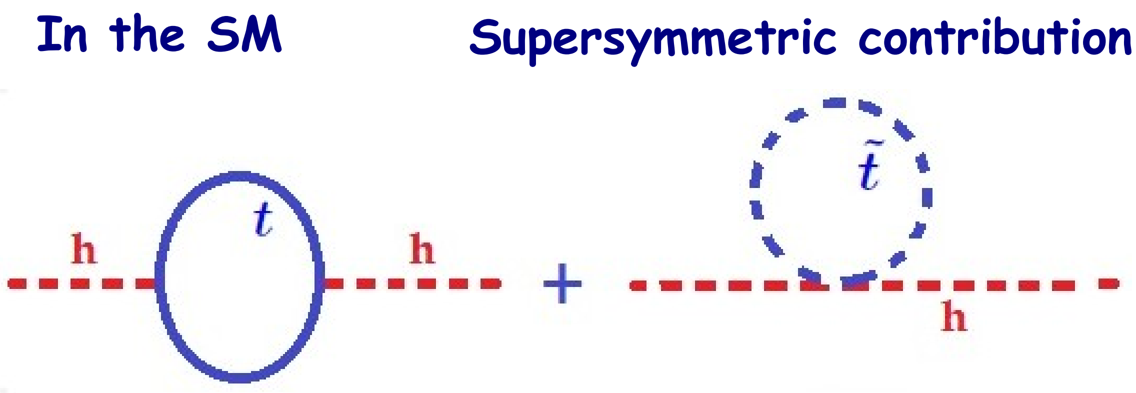

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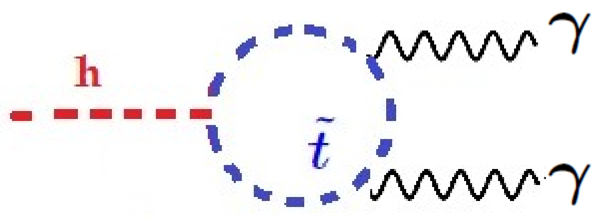

- Higgs rates may be **one of the best route to new physics**

Susy

Still a convincing candidate for New Physics for many...

Let´s take the minimal model...

MSSM

Higgs mass in the MSSM

Tree level contribution

$$m_h^2 \sim m_Z^2 \cos^2(2\beta) + \underbrace{\frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left(\frac{\tilde{X}_t}{2} + \log\frac{M_{\text{Susy}}^2}{m_t^2}\right)}$$

Stop loop contributions

Valid in the approximation $m_{Q3} \sim m_{u3}$

They have to lift the mass of the Higgs by ~ **35 GeV!**

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$$\begin{cases} \tilde{X}_t = \dfrac{2X_t^2}{M_{\text{Susy}}^2}\left(1 - \dfrac{X_t^2}{12M_{\text{Susy}}^2}\right) \\ X_t = A_t - \dfrac{\mu}{\tan\beta} \end{cases}$$

They have to lift the mass of the Higgs by ~ **35 GeV!**

$$\mathcal{M}_{stop}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_{u_3}^2 + m_t^2 + D_R \end{pmatrix}$$

Higgs mass in the MSSM

Tree level contribution

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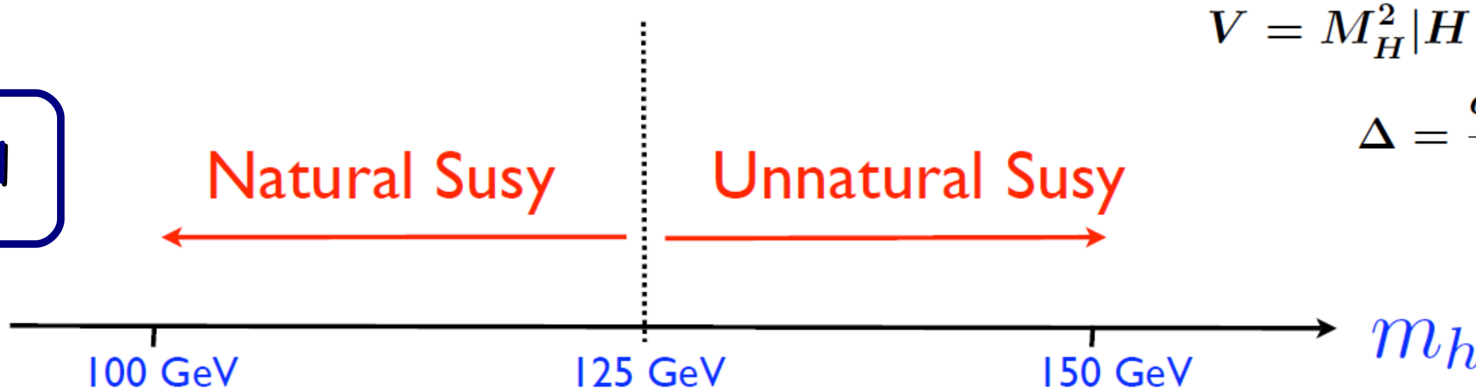
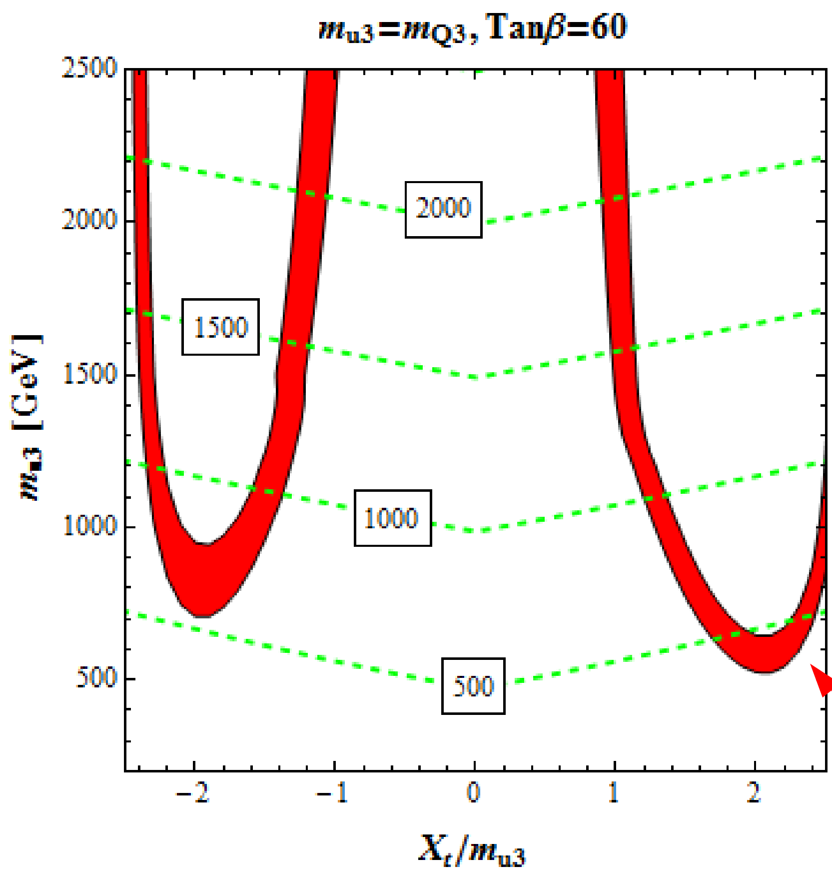
L. Hall

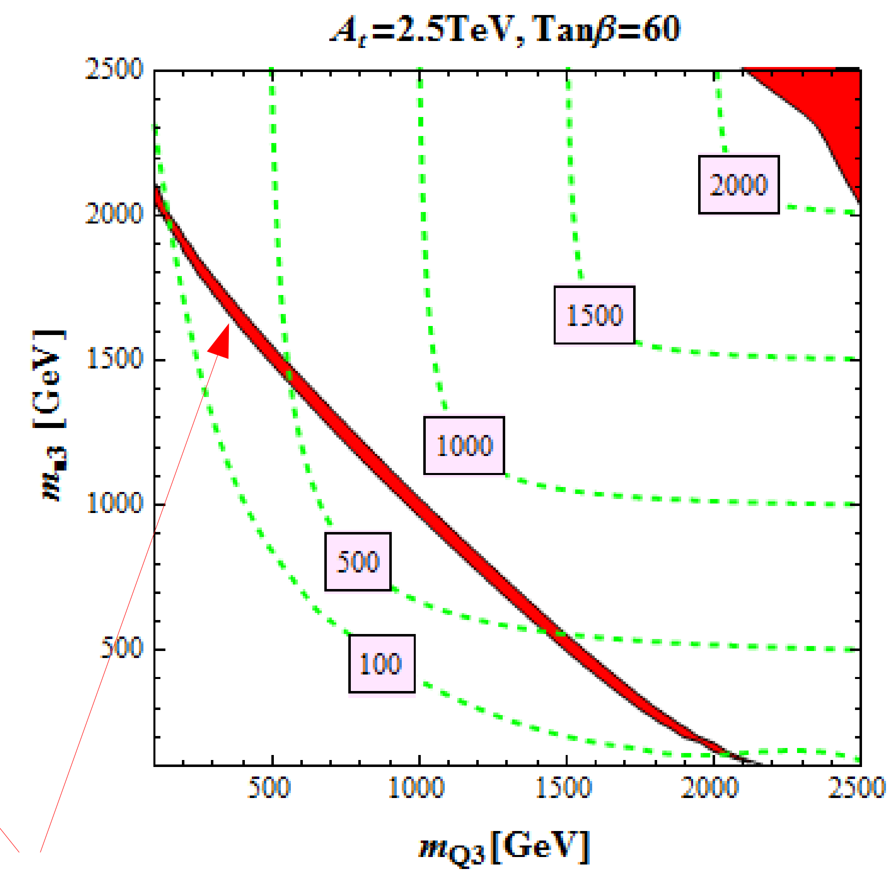


$$V = M_H^2|H|^2 + \lambda|H|^4$$

$$\Delta = \frac{\delta M_H^2}{m_h^2}$$

Higgs mass: some info on the stop spectrum





Carena, SG, Shah, Wagner, 1112.3336

Higgs mass between 124 and 126 GeV

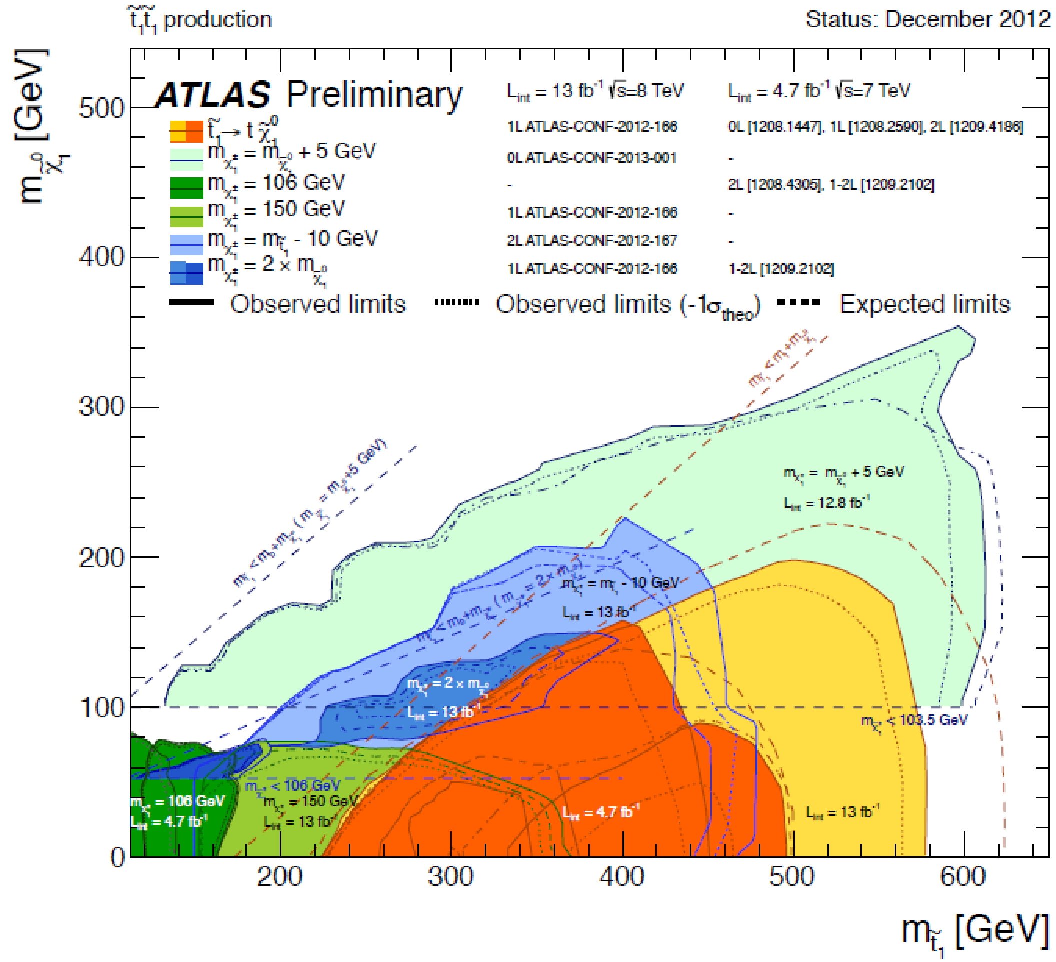
See also Draper et.al., 1112.3068
Arbey et. al., 1112.3028
Cahill-Rowley et.al., 1206.5800

Two possibilities:

1) Small mixing parameter ⇒ both stops in the multiTeV range

2) Sizable mixing parameter ⇒
- Two stops close in mass, in the several hundred GeV scale
- Very large splitting between the two stops: one is very light (100-200 GeV)

LHC is starting to probe natural stops



Several scenarios are already excluded

But still room for natural theories...

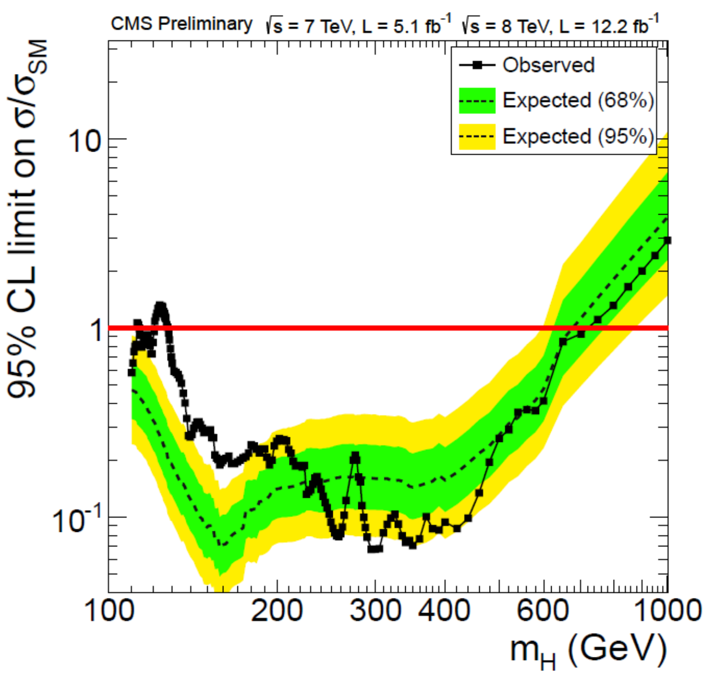
A multi-Higgs model

$$\begin{pmatrix} H_u \\ H_d \end{pmatrix} = \begin{pmatrix} v\sin\beta \\ v\cos\beta \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h \\ H \end{pmatrix} + \frac{i}{\sqrt{2}} R_\beta \begin{pmatrix} G \\ A \end{pmatrix}$$

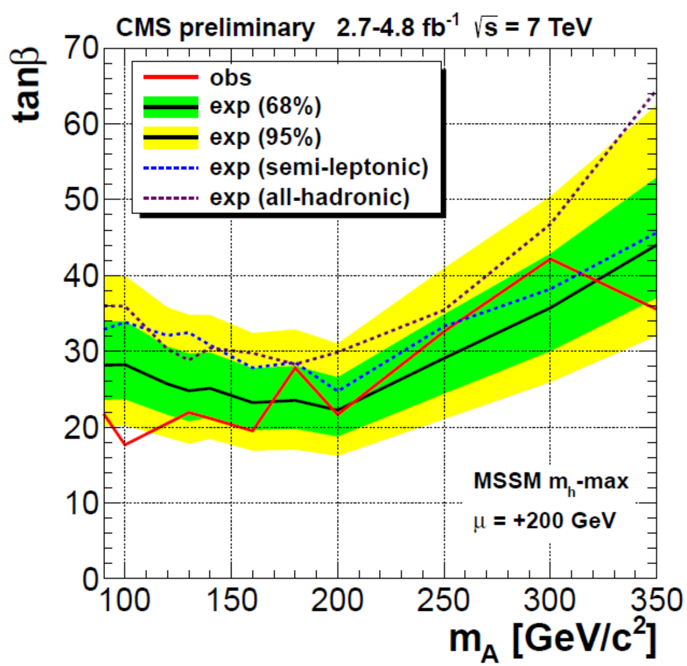
$$R_\alpha = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}, \; R_\beta = \begin{pmatrix} \sin\beta & \cos\beta \\ -\cos\beta & \sin\beta \end{pmatrix}$$

Very many searches for heavy scalars at the LHC

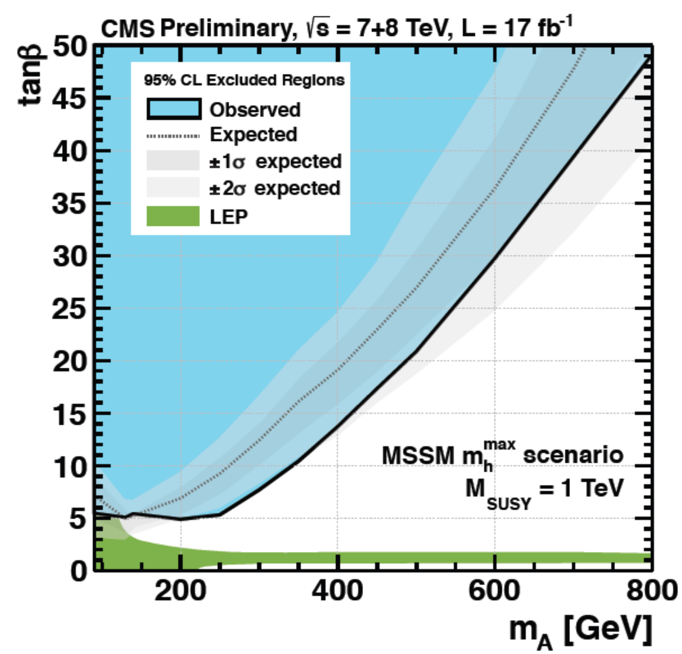
CMS-PAS-HIG-12-045



CMS-PAS-HIG-12-033



CMS-PAS-HIG-12-050

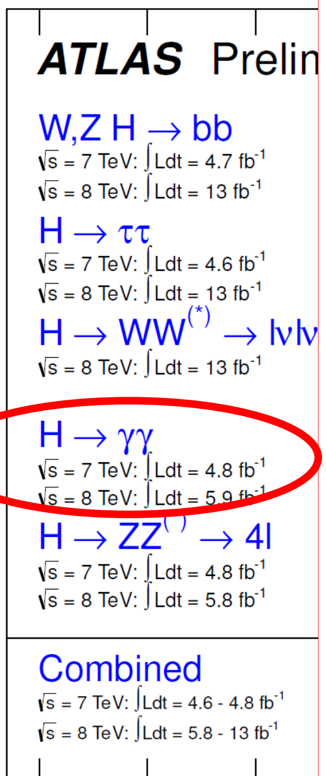


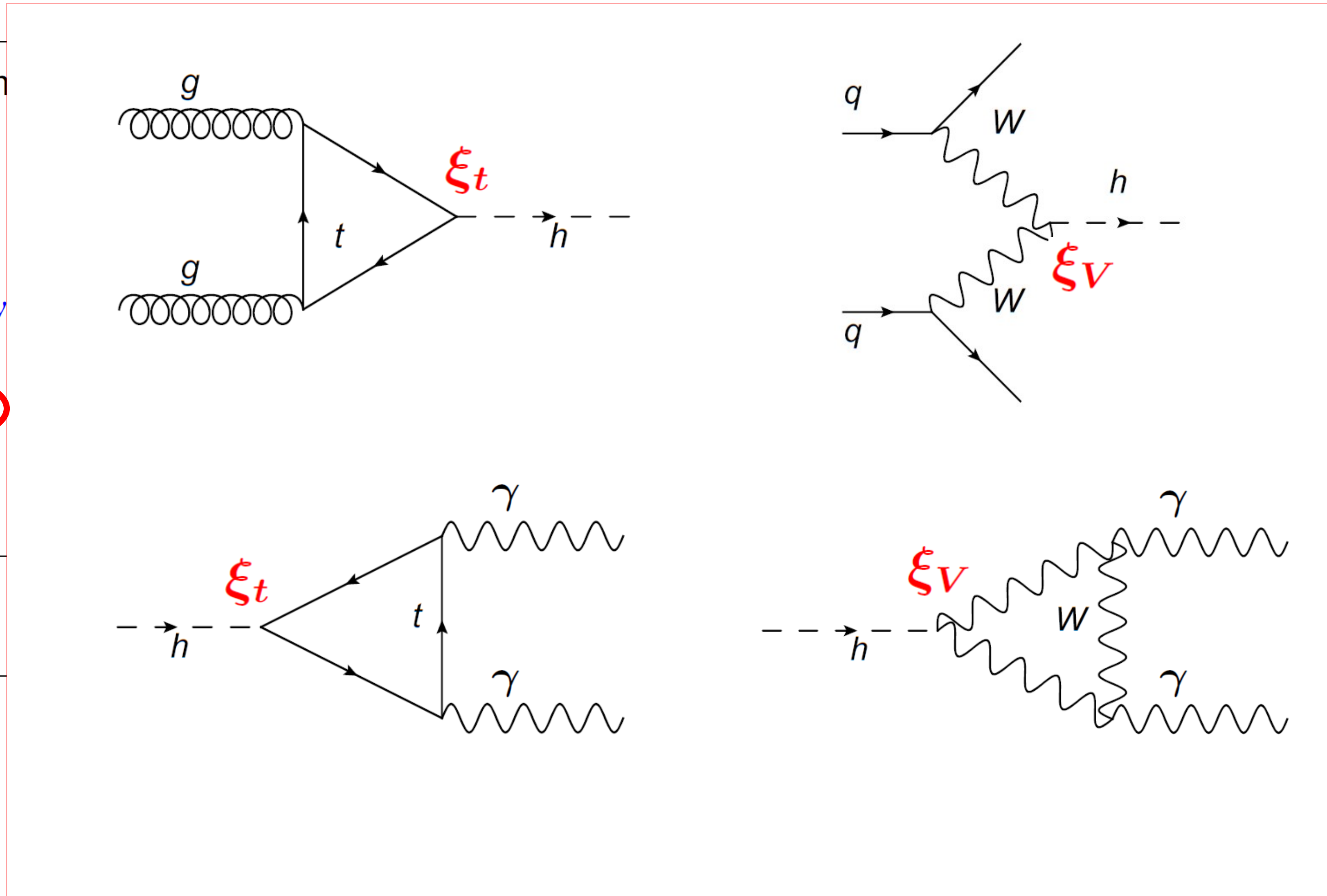
If the A,H Higgs bosons are there and tanβ is large → rather heavy H, A

 S.Gori

Fit of the Higgs couplings

$$\xi_b,\ \xi_t,\ \xi_\tau,\ \xi_V$$

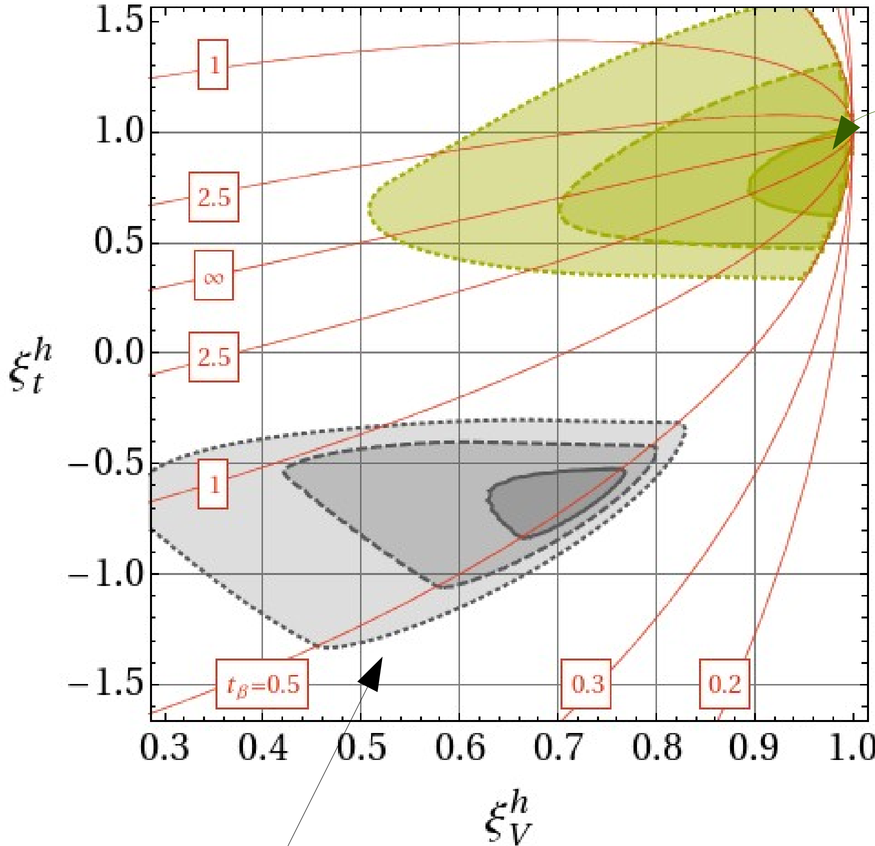




First info from Higgs data

First results in measuring the Higgs couplings

Altmannshofer, SG, Kribs, 1210.2465



This solution is excluded by heavy Higgs searches

A (very incomplete list):
Batell, SG, Wang, 1112.5180
Azatov, Contino, Galloway,1202.3415
Carmi, Falkowski, Kuflik, Volansky, 1202.3144
Giardino, Kannike, Raidal, Strumia, 1203.4254
Rauch, 1203.6826, ...

„Quasi decoupling limit“

$$\xi_t^h = \frac{\cos\alpha}{\sin\beta} \qquad \xi_V^h = s_{\beta-\alpha}$$

<u>In the decoupling limit</u>

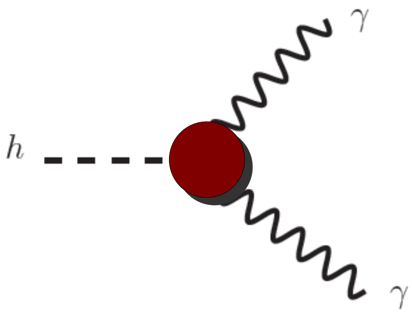
$$\alpha \sim \beta - \pi/2$$

$$\Rightarrow \xi_t^h \sim \xi_V^h \sim 1$$

Data seems to hint

$$m_A \gg m_h$$

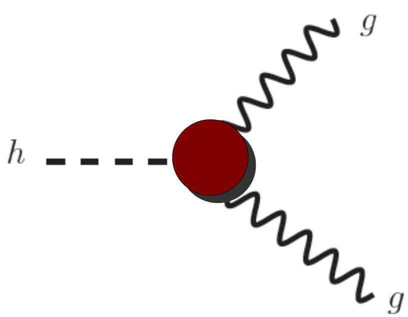
Non SM-like properties in the dec. limit



Low energy Higgs theorem:

hgg and hγγ couplings are related to beta function coefficients

Ellis, Gaillard, Nanopoulos, 1976
Shifman, Vainshtein, Voloshin, Zakharov, 1979

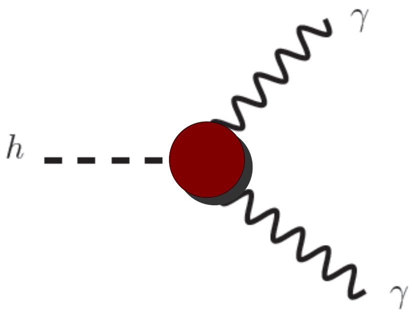


Given a new (heavy) charged particle with mass M(v) and contribution to the QED beta function Δ

$$\sim \frac{\Delta}{(4\pi)^2}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}\frac{\partial \log M(v)}{\partial \log v}$$

Any heavy matter with mass proportional to the Higgs VEV contribute with the same sign, whether it is a fermion or a scalar.
Low energy Higgs theorem captures the leading log correction from the new heavy mass threshold (there are finite mass corrections, which are small)

Non SM-like properties in the dec. limit

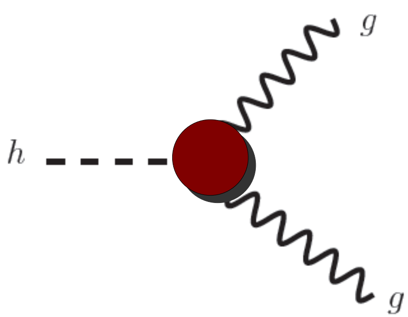


Low energy Higgs theorem:

hgg and hγγ couplings are related to beta function coefficients

Let´s focus on this

Ellis, Gaillard, Nanopoulos, 1976
Shifman, Vainshtein, Voloshin, Zakharov, 1979



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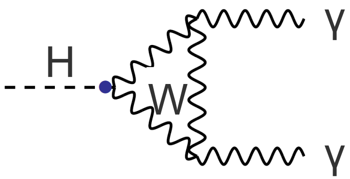
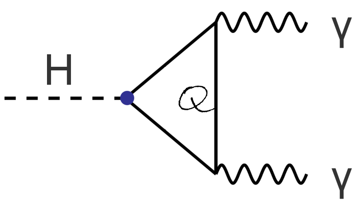
In the SM the di-photon coupling

γγ coupling





$$\left\{\begin{aligned} \Delta_{1/2} &= \frac{4}{3} N_c Q_f^2 \\ \Delta_1 &= -7 \\ \Delta_0 &= \frac{1}{3} N_c Q_S^2 \end{aligned}\right.$$

Standard Model:

Top contribution: $\Delta_t = \left(\frac{4}{3}\right)^2$

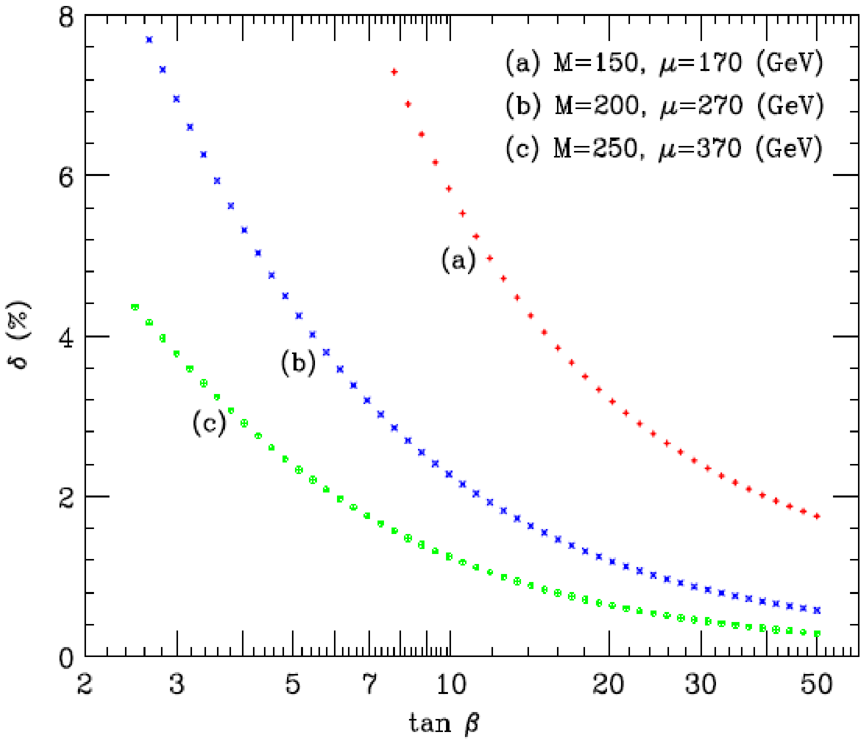
W contribution

W loop is the dominant contribution

$$\sim \frac{\Delta}{(4\pi)^2} \frac{h}{v} F_{\mu\nu} F^{\mu\nu} \frac{\partial \log M(v)}{\partial \log v}$$

Candidates in the MSSM

Diaz, Perez, 0412066



Charginos

$$\Delta A_{\gamma\gamma} \propto -\frac{m_W^2 s_\beta c_\beta}{M_2 \mu}$$

Corrections to the γγ rate are smaller than ~20% and arise only at very small tanβ

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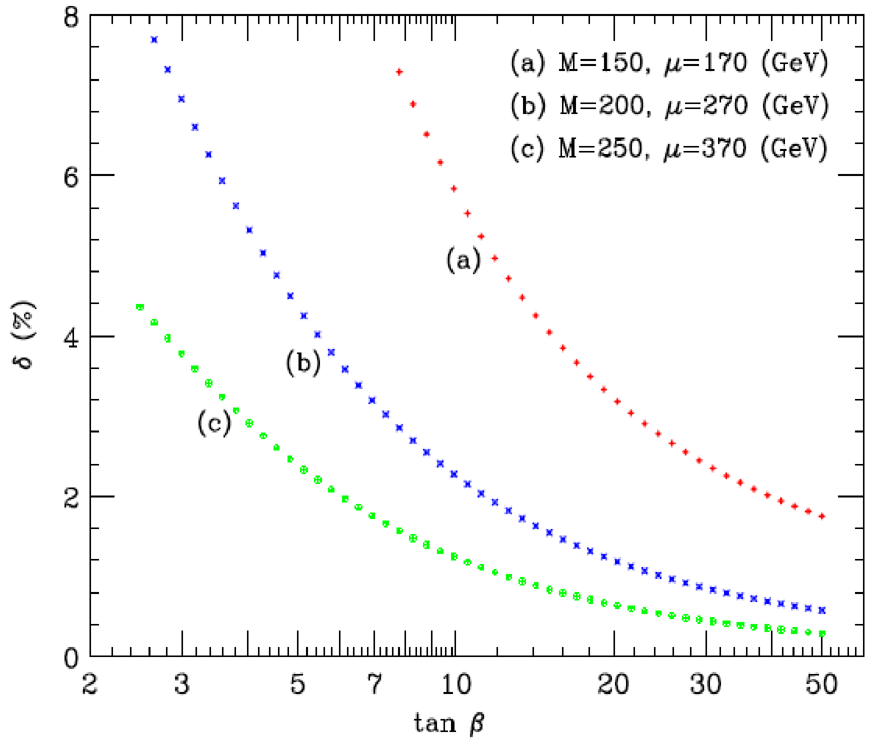
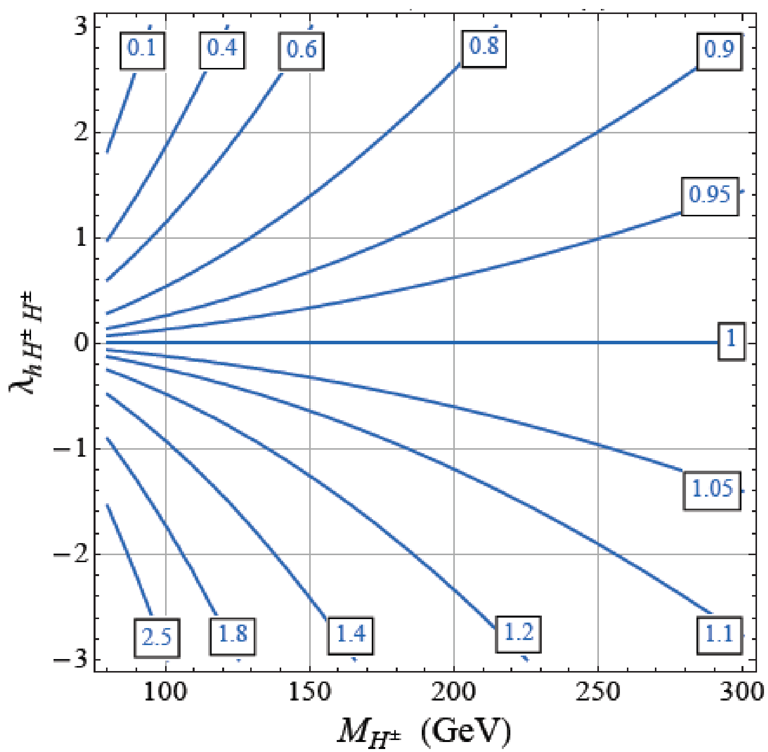


Altmannshofer, SG, Kribs, 1210.2465



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Charged Higgs

$$|\lambda^{\rm MSSM}_{hH^\pm H^\pm}| \lesssim \frac{g^2}{2} \sim 0.21$$

Only very small contribution

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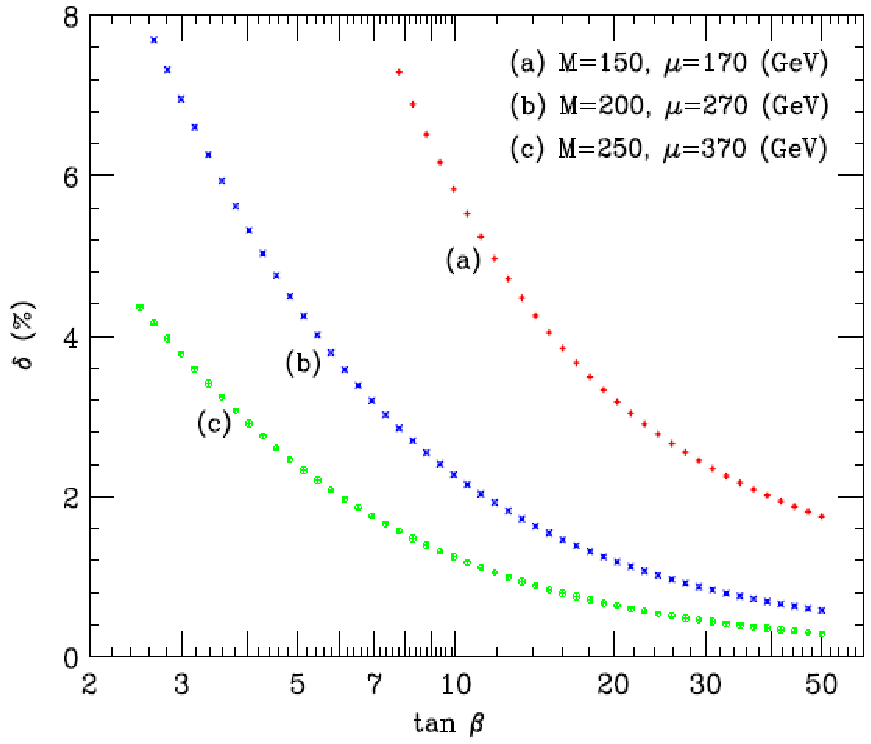

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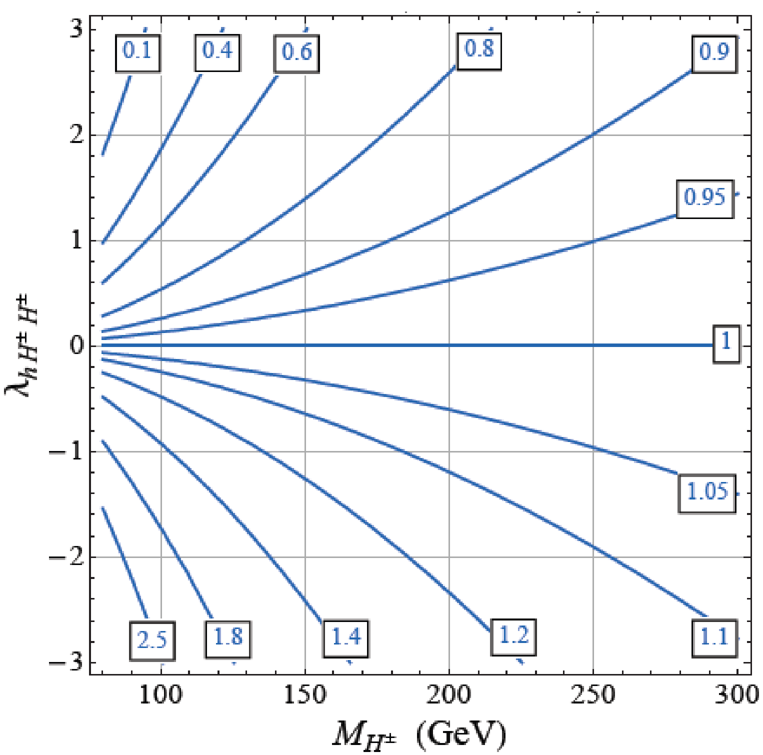

L A R G E ?

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Charged Higgs

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Only very small contribution

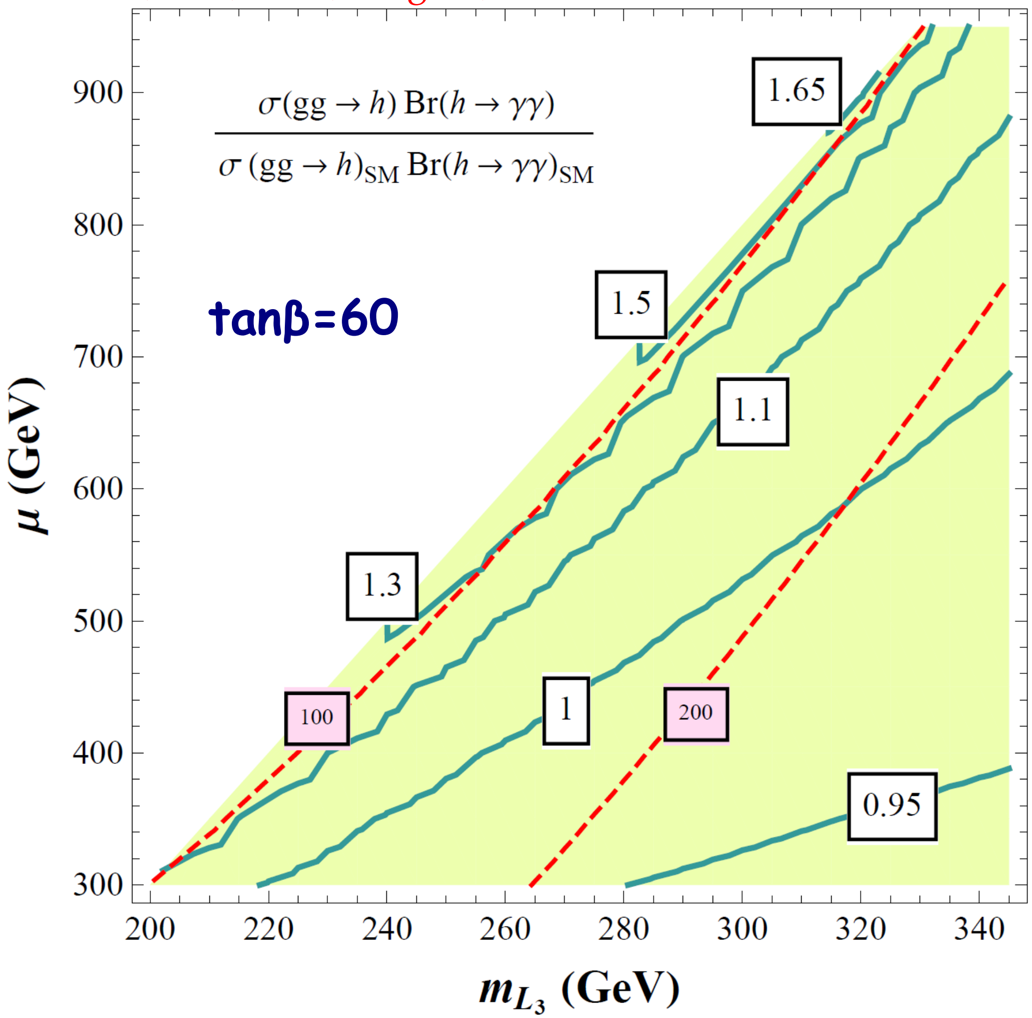
3rd generation sleptons

Light sleptons contributions

$$\Delta A_{\gamma\gamma} \propto -\frac{(\mu\tan\beta)^2 m_\tau^2}{m_{L3}^2 m_{e3}^2 - m_\tau^2(\mu\tan\beta)^2} \sim -\frac{m_{\tilde{\tau}_2}^2}{m_{\tilde{\tau}_1}^2}\left(1-\frac{m_{\tilde{\tau}_1}^2}{m_{\tilde{\tau}_2}^2}\right)^2$$

For degenerate stau soft masses

Carena, S.G., Shah, Wagner, 1112.3336



$$\mathcal{M}_{\tilde{\tau}}^2 \simeq \begin{pmatrix} m_{L_3}^2 + m_\tau^2 + D_L^\tau & m_\tau(A_\tau - \mu\tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & m_{E_3}^2 + m_\tau^2 + D_R^\tau \end{pmatrix}$$

Heavily mixed light (LEP bound ~95GeV) staus can lead to sizable effect in the γγ rate

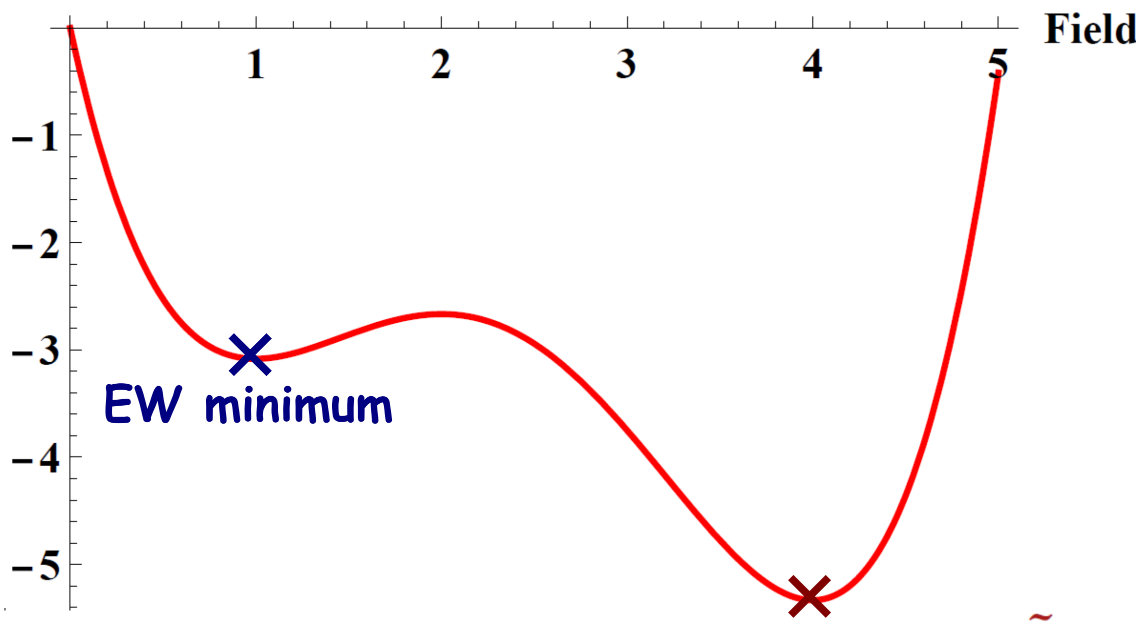
Vacuum stability in presence of light staus

Decoupling limit

$$V \supset -2 y_\tau \mu \tilde{L} \tilde{\tau} \phi_u + \tilde{L}^2 \tilde{\tau}^2 \left(y_\tau^2 - \frac{g_1^2}{2} \right)$$

At the tree level: $y_\tau \mu = \sqrt{2} \frac{m_\tau}{v \cos\beta} \mu \sim \sqrt{2} \frac{m_\tau}{v} \mu \tan\beta$

Charge breaking minima can arise



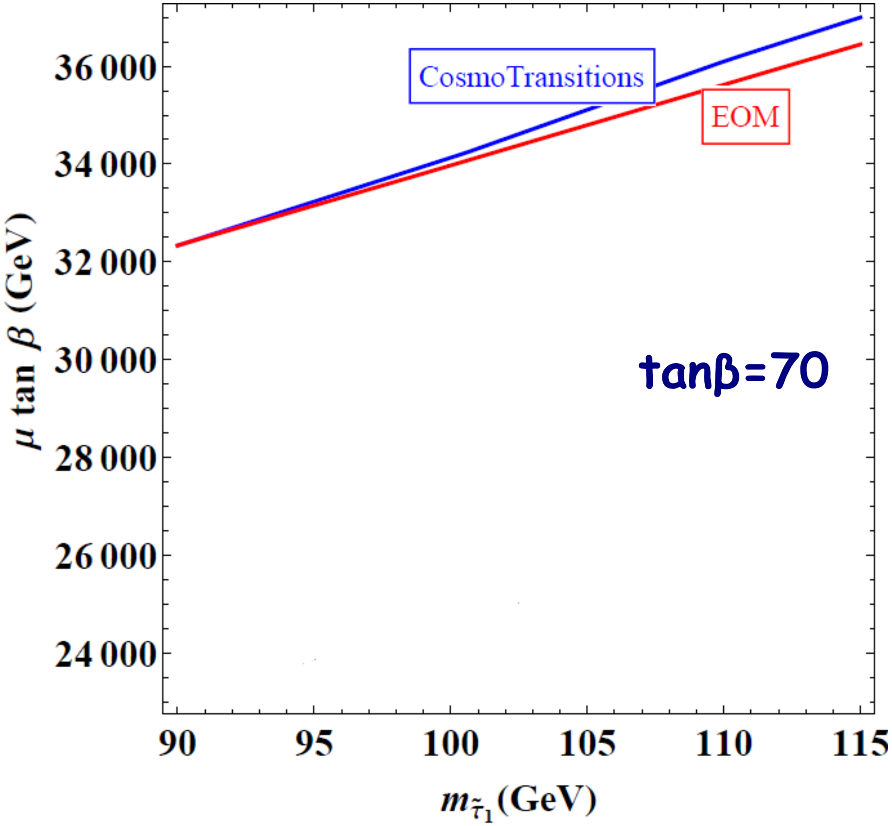
Additional minimum with $\tilde{L}, \tilde{\tau} \neq 0$

Decoupling limit

$$V \supset -2 y_\tau \mu \tilde{L} \tilde{\tau} \phi_u + \tilde{L}^2 \tilde{\tau}^2 \left(y_\tau^2 - \frac{g_1^2}{2} \right)$$

At the tree level: $y_\tau \mu = \sqrt{2}\frac{m_\tau}{v \cos\beta}\mu \sim \sqrt{2}\frac{m_\tau}{v}\mu \tan\beta$

Carena, SG, Low, Shah, Wagner, 1211.6136



Charge breaking minima can arise

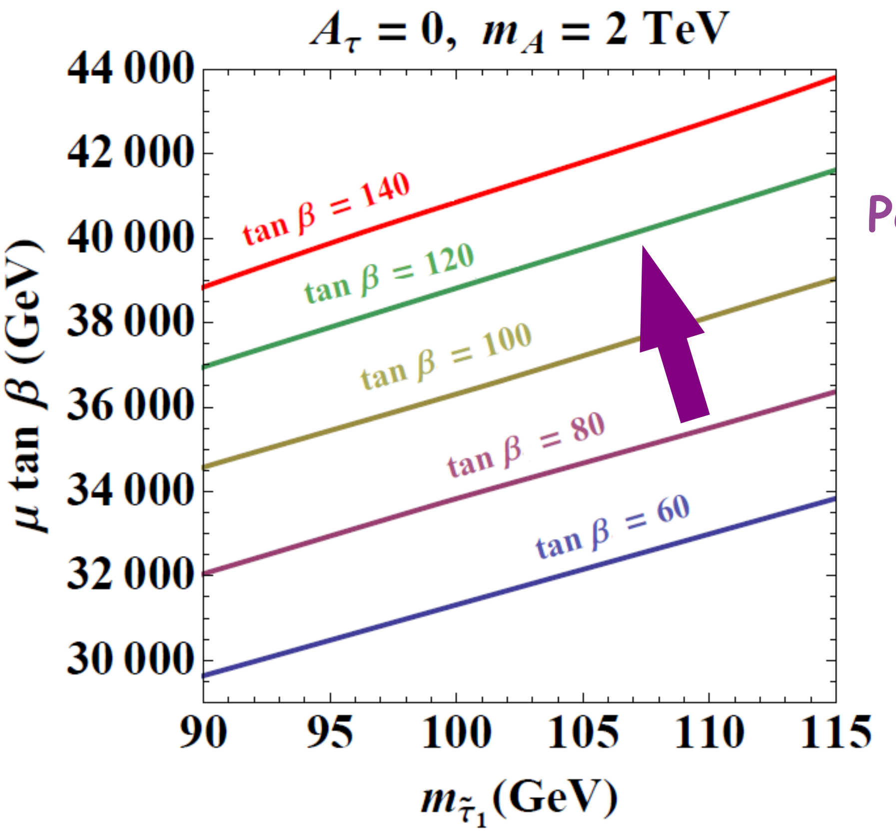
Agreement with the updated bound in
Hisano, Sugiyama, 1011.0260

$$|\mu \tan\beta| < 213.5\sqrt{m_{L_3} m_{E_3}} - 17.0(m_{L_3} + m_{E_3}) + 4.52 \times 10^{-2}\ \mathrm{GeV}^{-1}(m_{L_3} - m_{E_3})^2 - 1.3 \times 10^4 \mathrm{GeV}$$

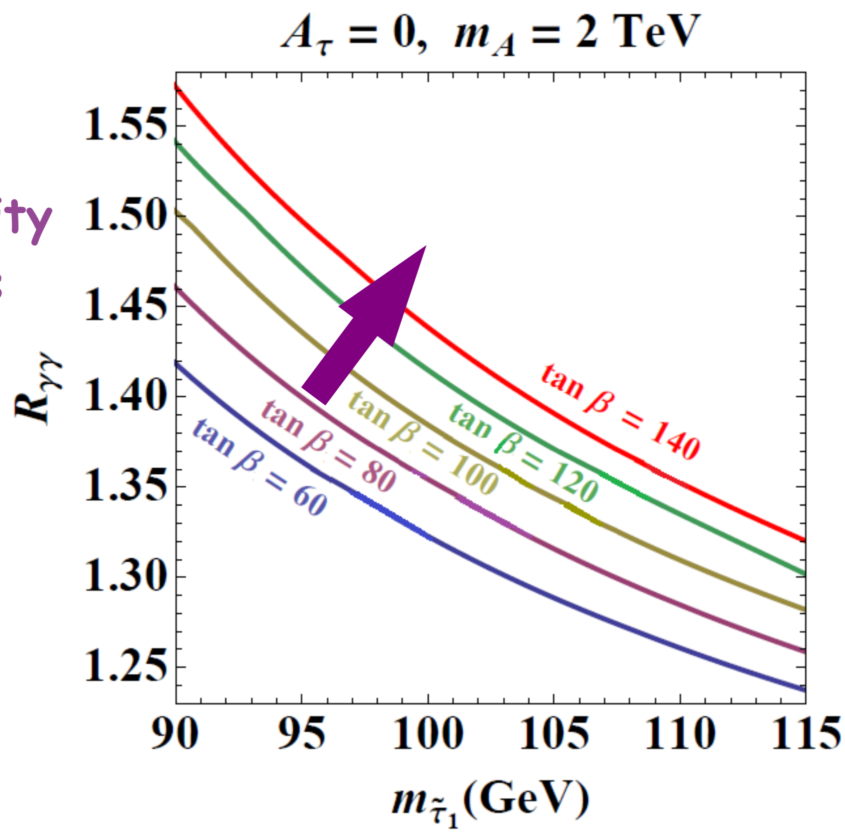
See also Ratz, Schmidt-Hoberg, Winkler, 0808.0829

Vacuum stability in presence of light staus

The tanβ dependence of the bound is not negligible



Perturbativity problems



Carena, SG, Low, Shah, Wagner, 1211.6136

Phenomenology of the light stau model

Based on

Carena, SG, Shah, Wagner, Wang, 1205.5842
Giudice, Paradisi, Strumia, 1207.6393 ($(g-2)_\mu$)
Carena, SG, Shah, Wagner, Wang, appearing soon

EWPTs
Dark matter constraints } Constraints

$(g-2)_\mu$ } Predictions

Phenomenology of stops and of the heavy Higgs bosons New

How to look for these light staus: direct searches

It is noteworthy that in spite LHC is pushing higher and higher the bound on the mass of gluinos and squarks of the first two generations, particular models with staus at ~ 100 GeV are still consistent with the data!

Electroweak Precision Tests

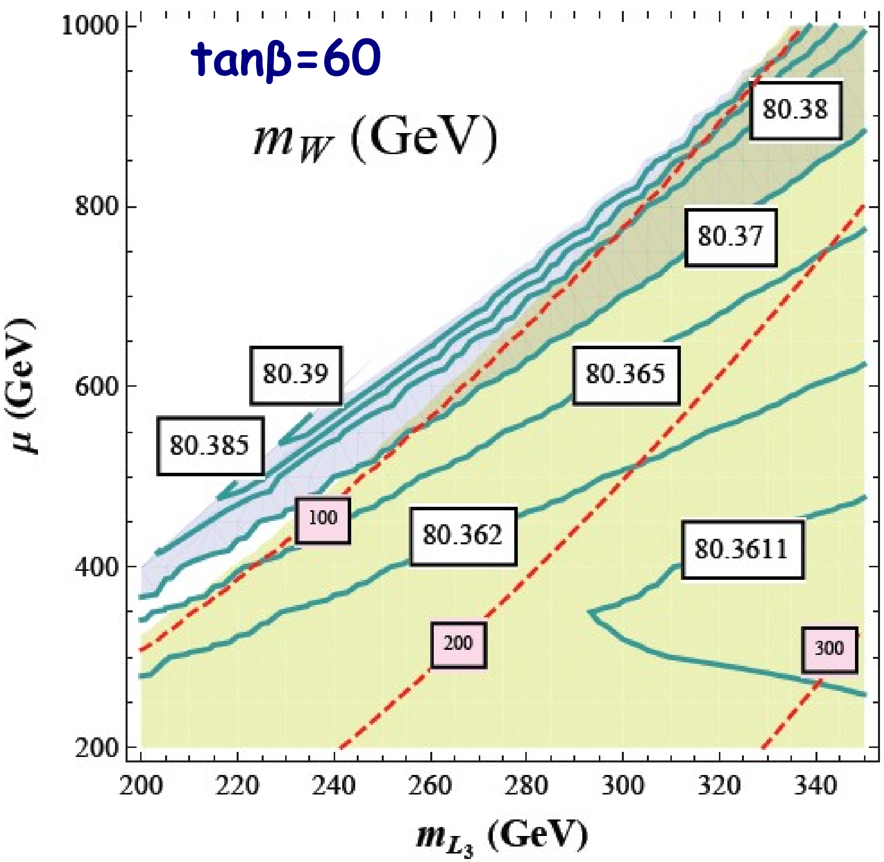
Staus: very light NP states charged under SU(2) x U(1)

too large contribution to EWPTs?

New measurement of M_W:

$$(80.385 \pm 0.015)\mathrm{MeV}$$

FERMILAB-TM-2532-E, 2012

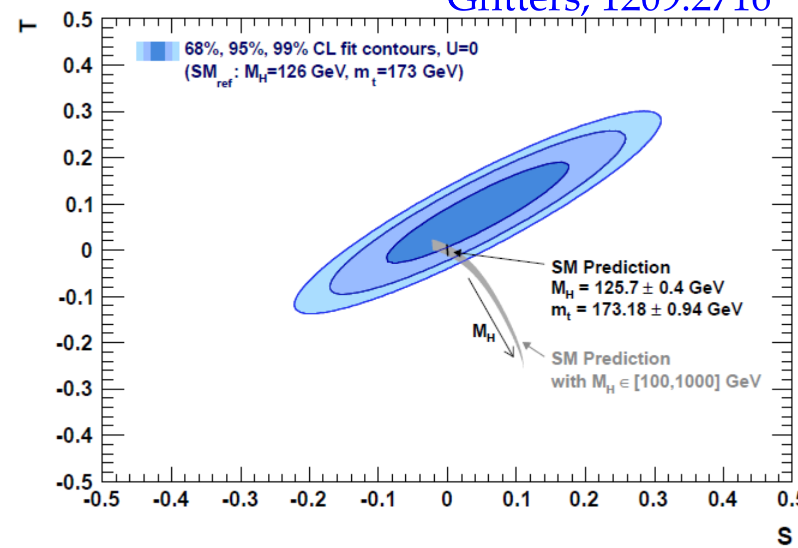


Carena, SG, Shah, Wagner, Wang, 1205.5842

$$\Delta M_W \simeq \frac{M_W}{2}\frac{\cos^2\theta_W}{\cos^2\theta_W - \sin^2\theta_W}\alpha\,\Delta T$$

Heinemeyer, Hollik, Weiglein, 0412214

Gfitters, 1209.2716

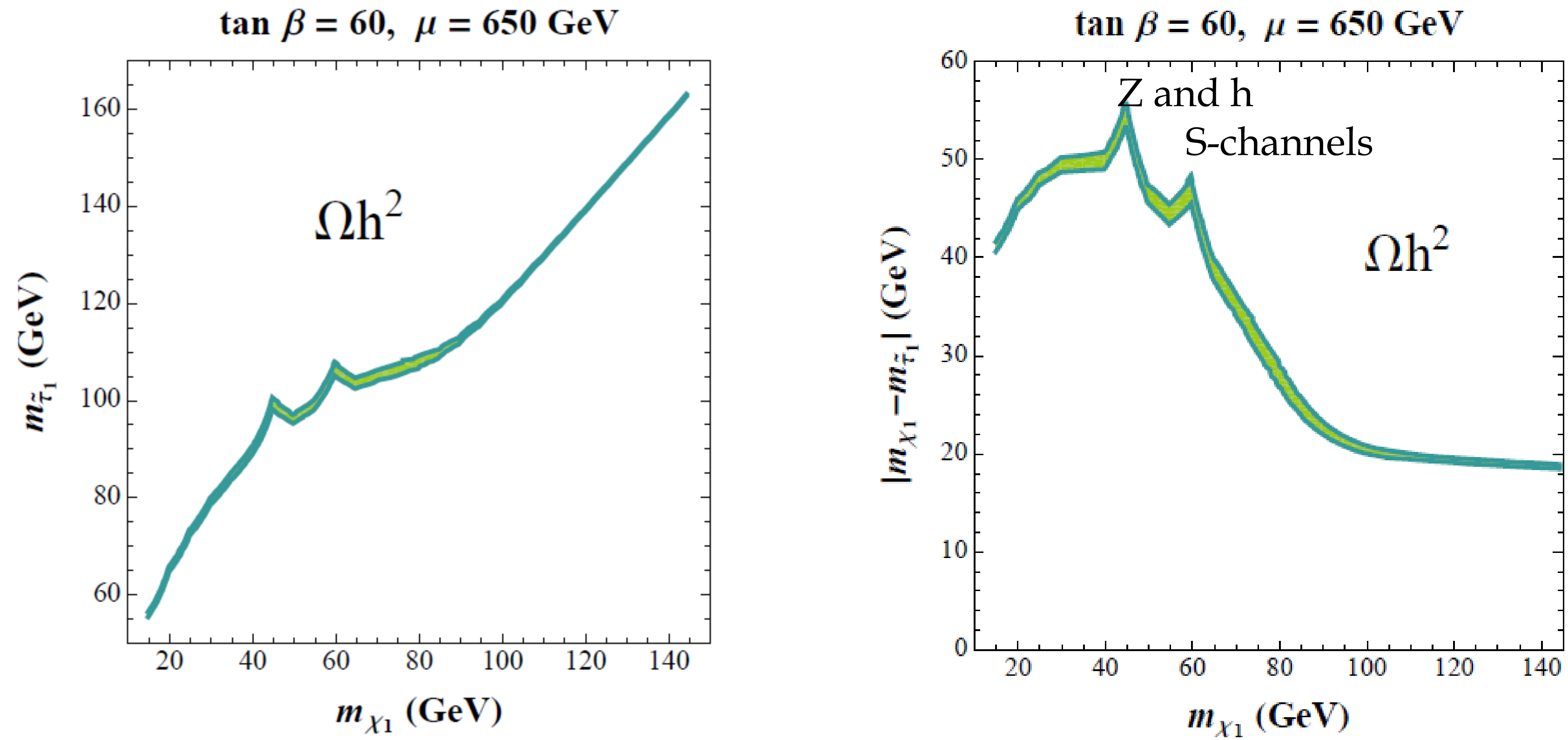


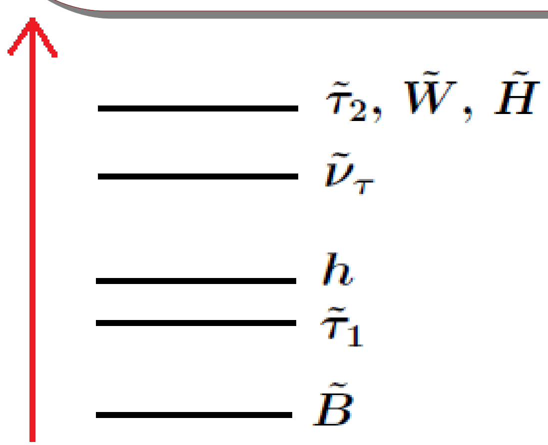
It corresponds to a contribution of (at most)

$$\Delta T \lesssim 0.1$$

Some handle from Dark Matter?

Carena, SG, Shah, Wagner, Wang, 1205.5842

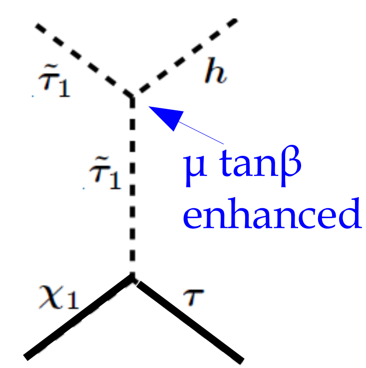




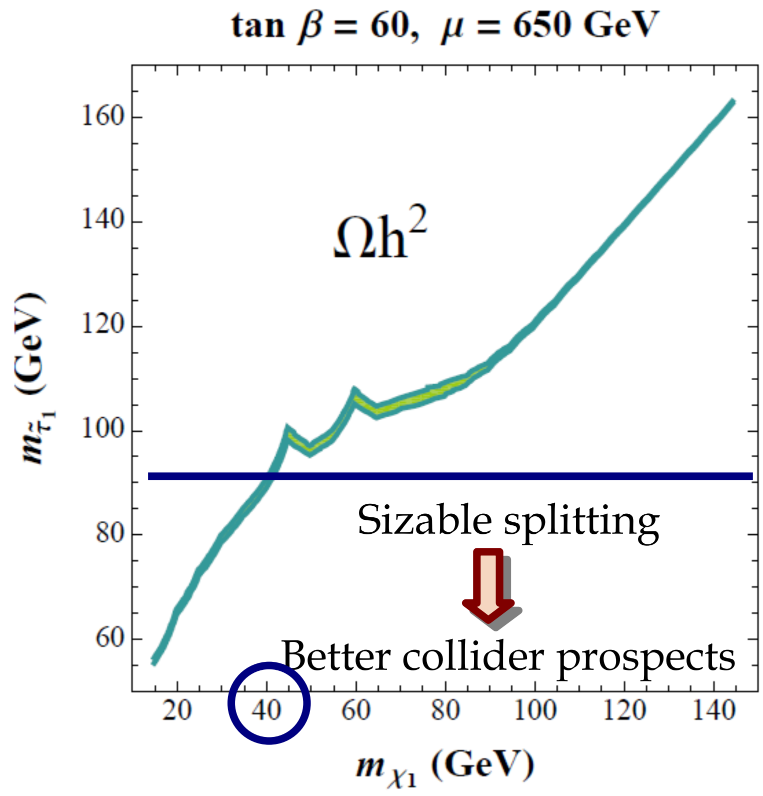
LSP= lightest neutralino (mainly bino)

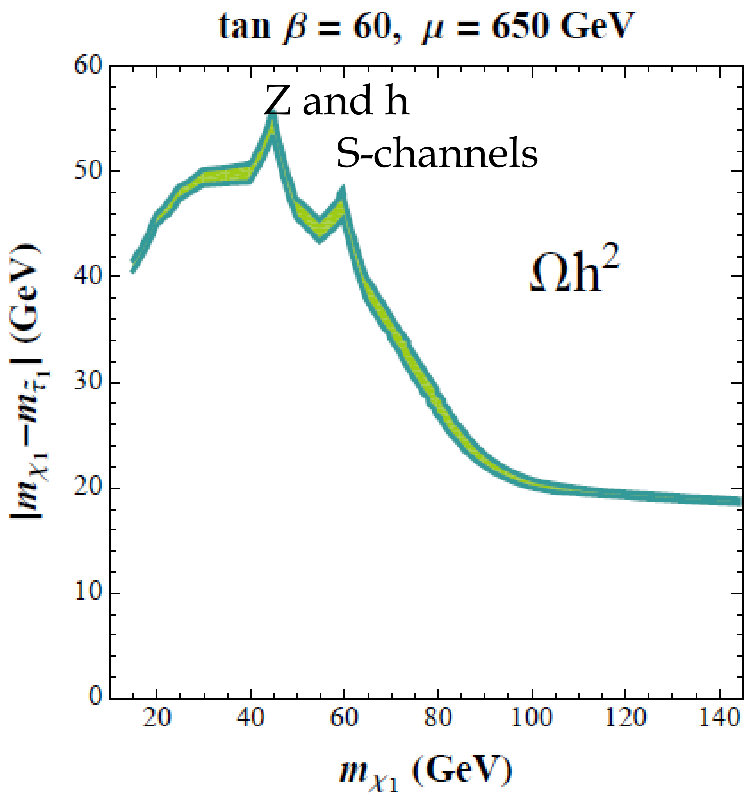
Main coannihilation channel:

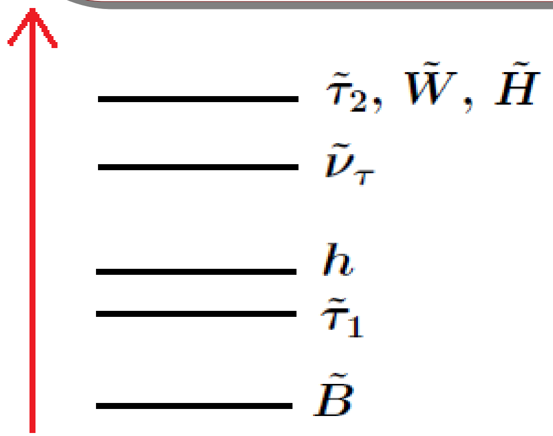
$$\chi_1 \tilde{\tau}_1 \rightarrow h\tau$$



Carena, SG, Shah, Wagner, Wang, 1205.5842







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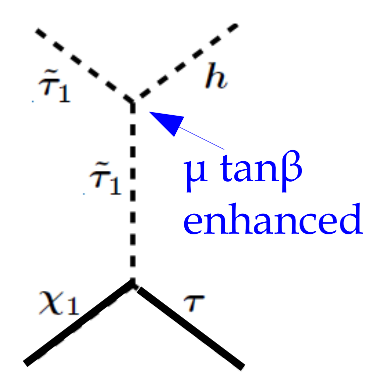
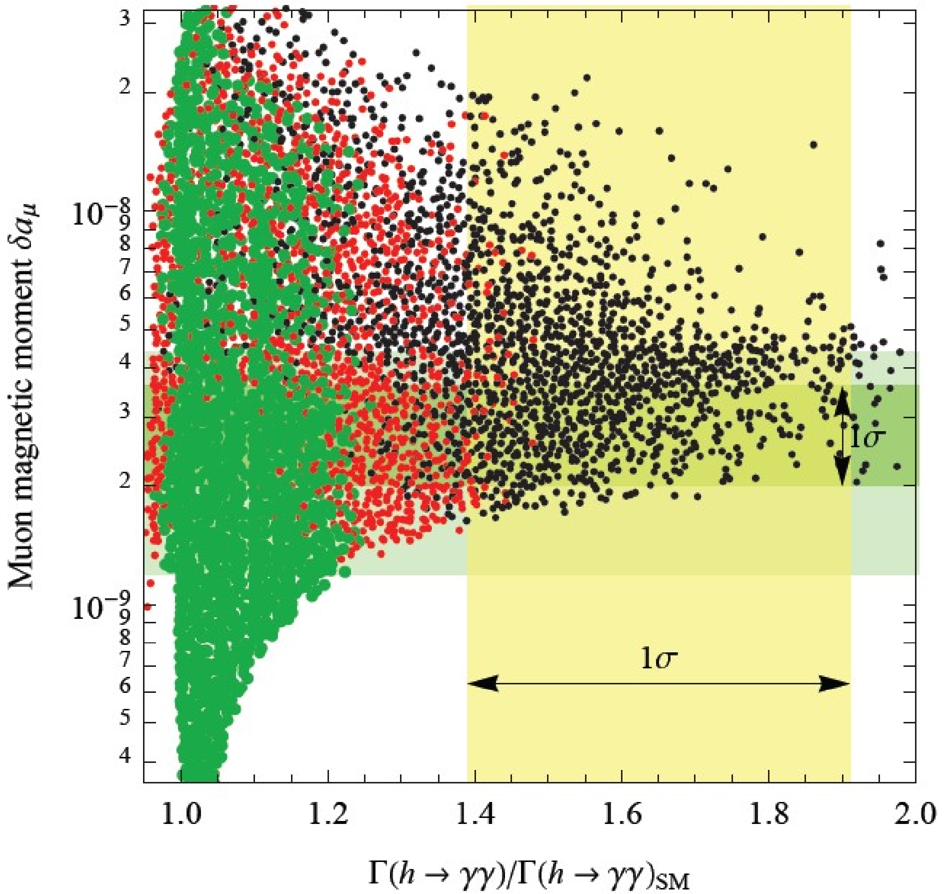
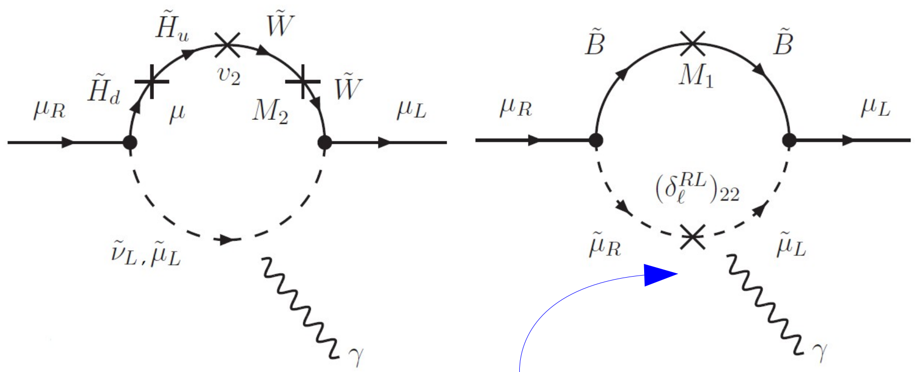


$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (2.8 \pm 0.8)10^{-9}$$

Giudice, Paradisi, Strumia, 1207.6393



$m_{\tilde\tau_1} > 100$ GeV, $m_{\tilde\tau_1} > 80$ GeV



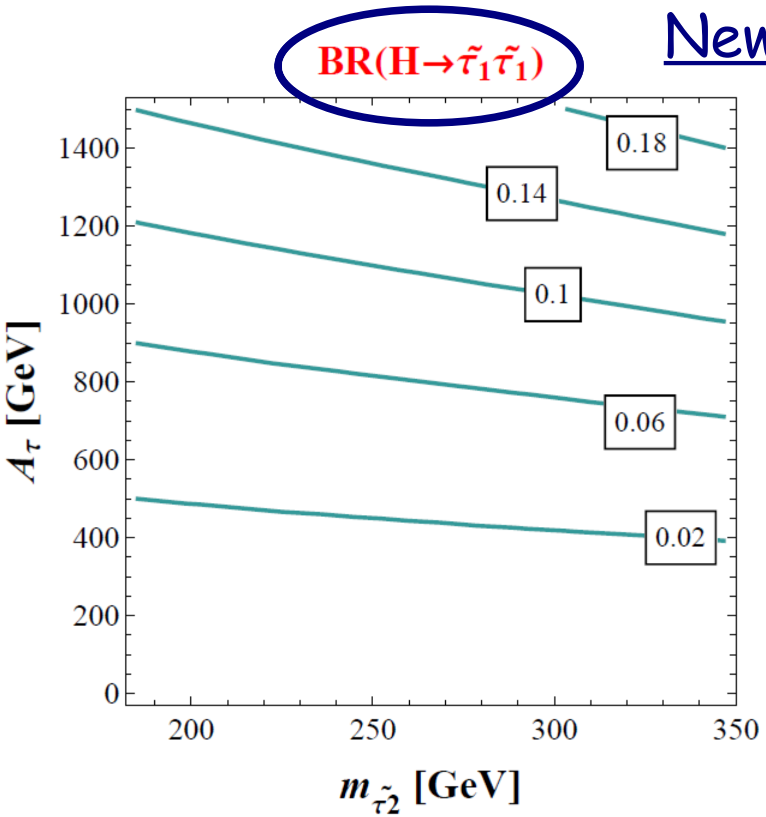
Also μ tanβ enhanced

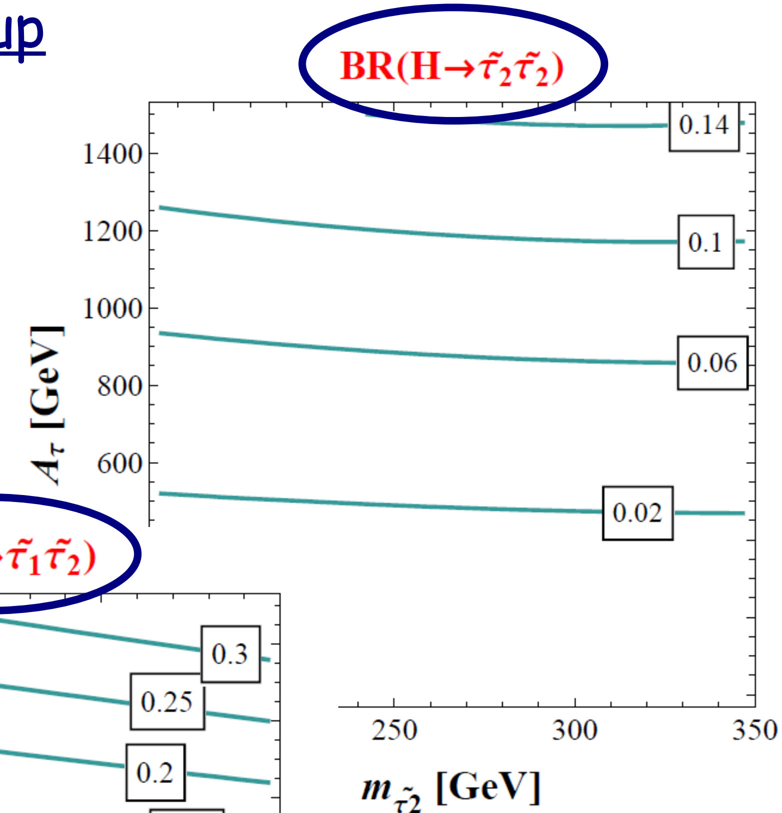
Correlation arising in the hypothesis of

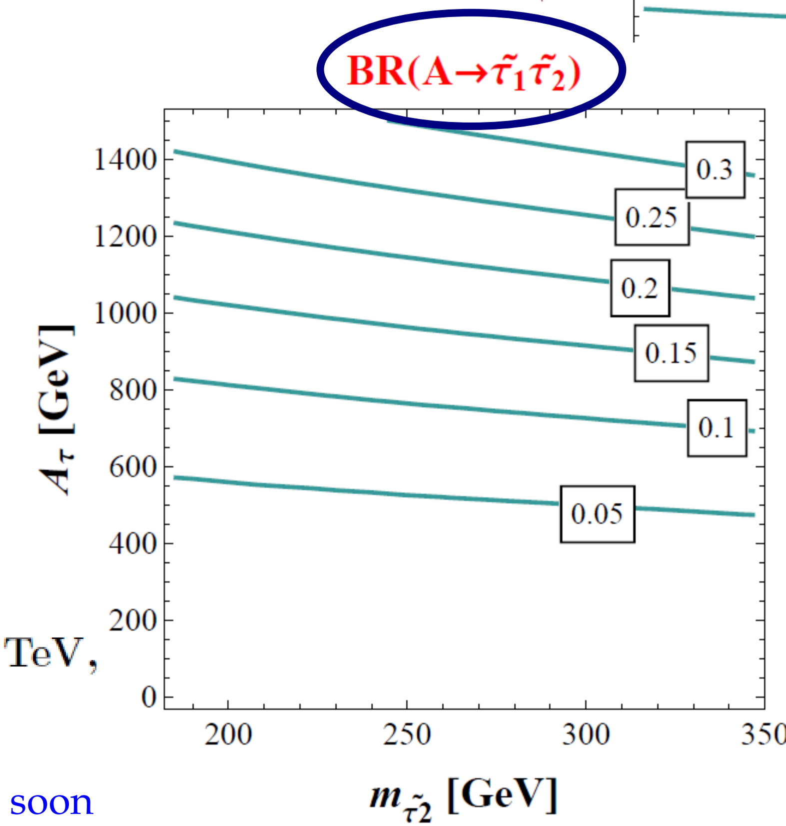
- degenerate slepton soft masses at the EW scale
- M1 scanned in such a way that the LSP is neutral and the stau is the NLSP
- Slepton soft masses below the TeV

Heavy Higgs Phenomenology (1)

New decay modes open up







Example scenario

$$m_{Q3} = m_{U3} = m_{D3} = 1\,\text{TeV},$$
$$A_t = 1.8\,\text{TeV},\ m_A = 1\,\text{TeV},$$
$$M_1 = 40\,\text{GeV},\ M_2 = 300\,\text{GeV},\ M_3 = 1.2\,\text{TeV},$$
$$m_{\tilde\tau_1} = 95\,\text{GeV},\ \tan\beta = 70$$

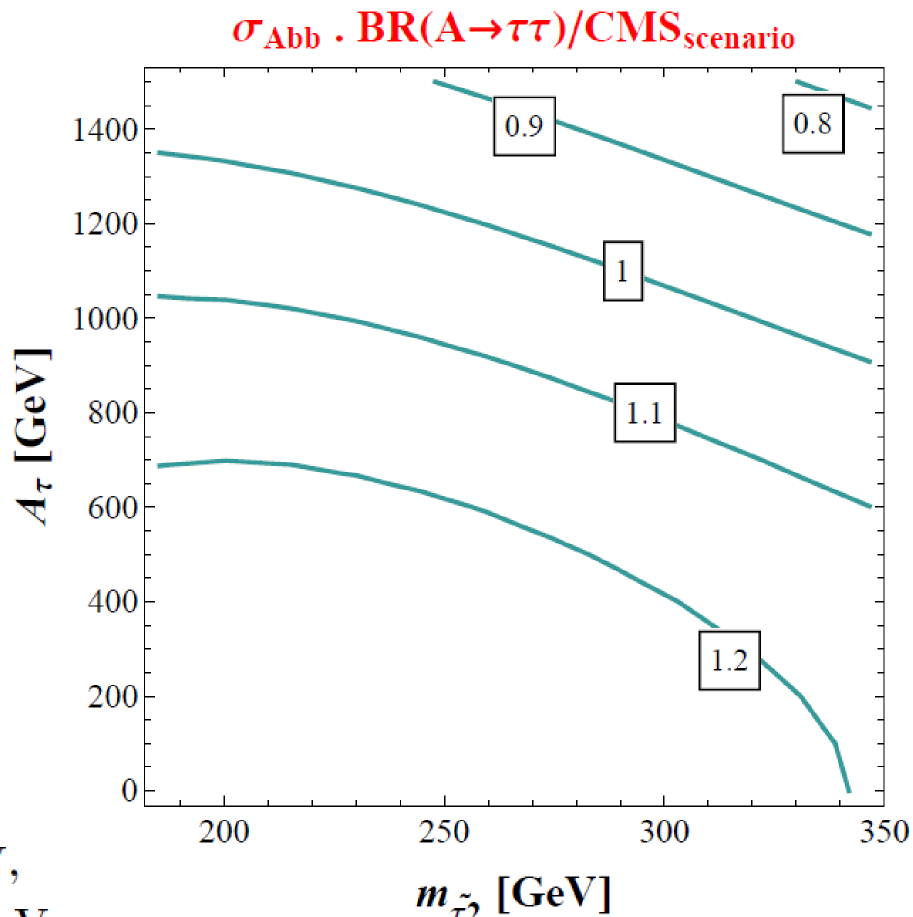
Carena, SG, Shah, Wagner, Wang, appearing soon

Depleting the „old ones"...

Heavy Higgs Phenomenology (2)

$$\sigma(pp \to H \to \tau^+\tau^-) \propto \frac{m_b^2 \tan^2\beta}{\left[\left(3\frac{m_b^2}{m_\tau^2} + \frac{M_W^2(1+\Delta_b)^2}{m_\tau^2 \tan^2\beta}\right)(1+\Delta_\tau)^2 + (1+\Delta_b)^2\left(1+\frac{A_\tau^2}{m_A^2}\right)\right]}$$

Depleting the „old ones"...



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$m_{\tilde{\tau}_1} = 95\,\mathrm{GeV},\ \tan\beta = 70$

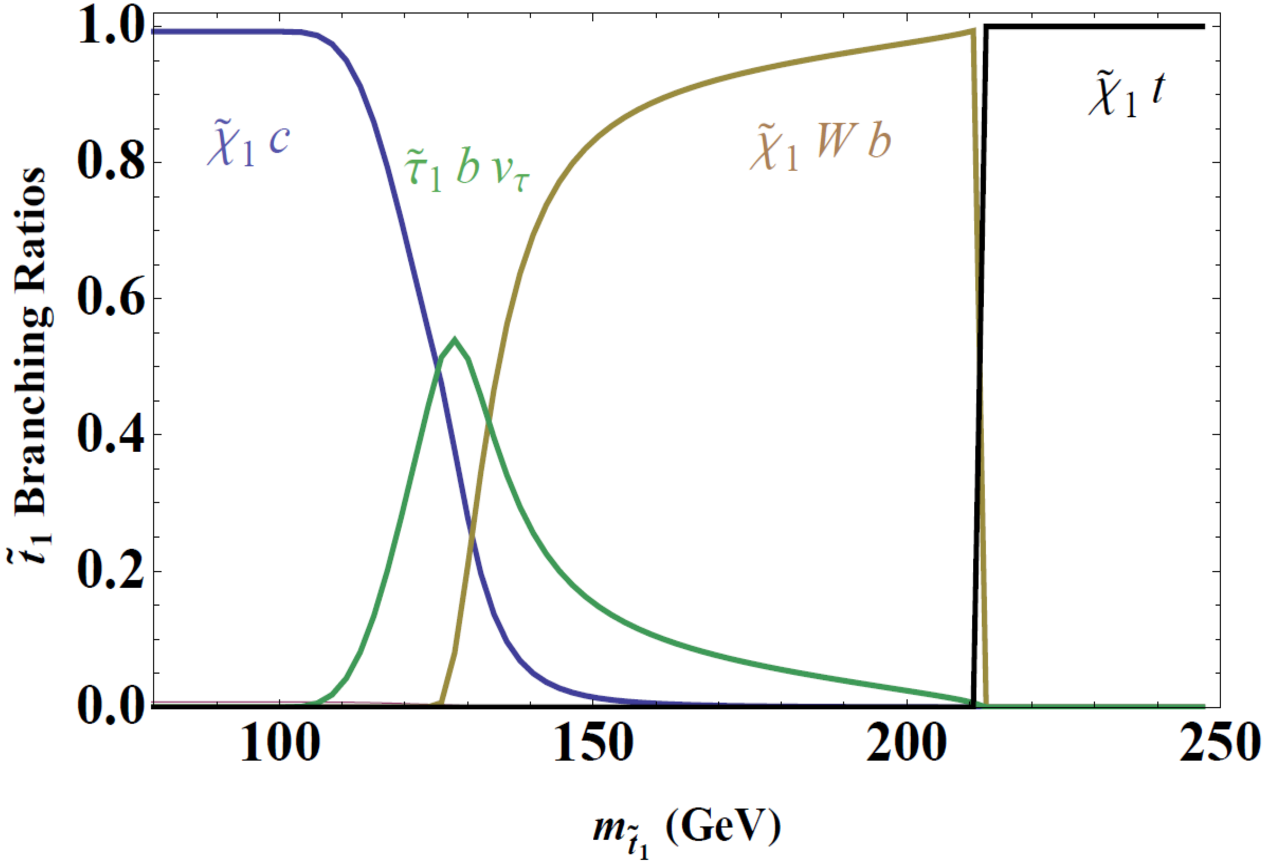
CMS scenario

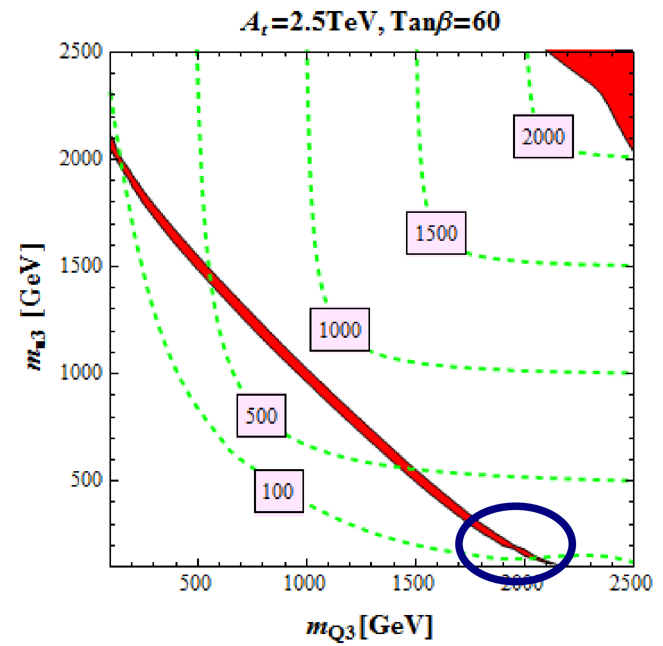
$m_{Q3} = m_{U3} = m_{D3} = 1\,\mathrm{TeV}$,
$A_t = 2\,\mathrm{TeV}$,
$m_{L3} = m_{E3} = 1\,\mathrm{TeV}$,
$M_1 = 100\,\mathrm{GeV},\ M_2 = 200\,\mathrm{GeV},\ M_3 = 800\,\mathrm{GeV}$

Carena, SG, Shah, Wagner, Wang, appearing soon

Stop Phenomenology

More interesting if they are <u>light</u>!





<u>Reminder</u>

<u>Work in progress</u>

A new decay mode opens up $\tilde{t}_1 \rightarrow \tilde{\tau}_1 b \nu_\tau$

It starts to be probed by tt cross section measurements (leptonic modes)

Carena, SG, Shah, Wagner, Wang, appearing soon

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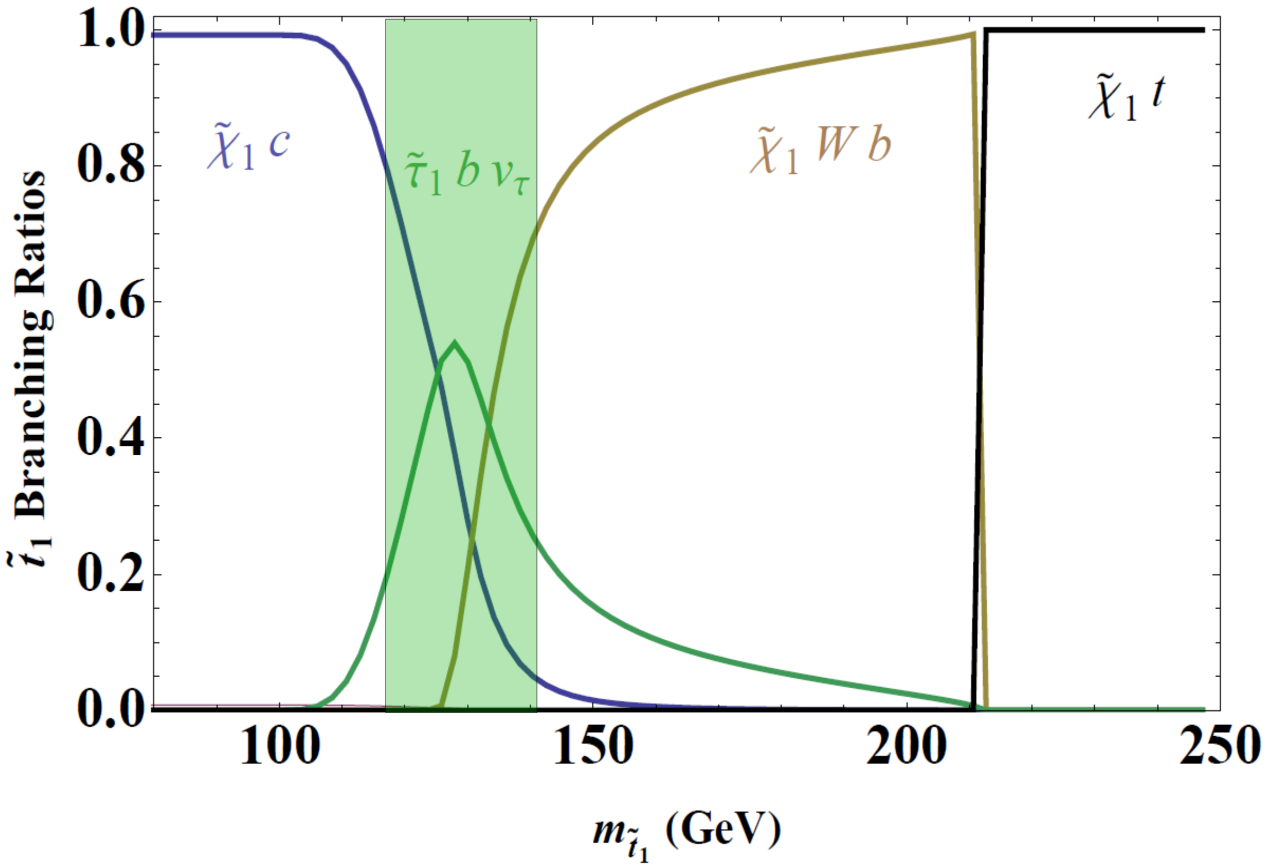

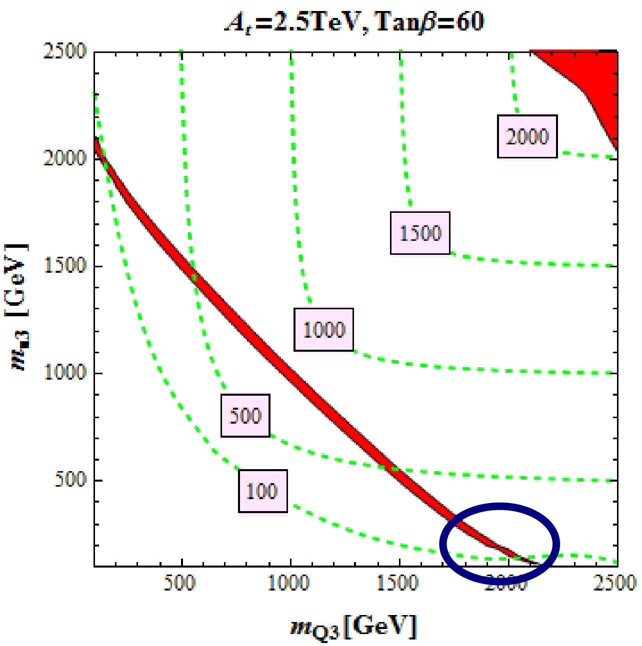

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Signals at the LHC

Ex. $m_{\tilde{\tau}_1} \sim 95\,\mathrm{GeV},\ m_{\tilde{\tau}_2} \sim 390\,\mathrm{GeV},\ m_{\tilde{\nu}_\tau} \sim 270\,\mathrm{GeV},\ m_{\chi_0} \sim 35\,\mathrm{GeV}$

	Signature	8 TeV LHC (fb)	14 TeV LHC (fb)
$pp \to \tilde{\tau}_1\tilde{\tau}_1$	$2\tau, \not{E}_T$	55.3	124.6
$pp \to \tilde{\tau}_1\tilde{\tau}_2$	$2\tau, Z, \not{E}_T$	1.0	3.2
$pp \to \tilde{\tau}_2\tilde{\tau}_2$	$2\tau, 2Z, \not{E}_T$	0.15	0.6
$pp \to \tilde{\tau}_1\tilde{\nu}_\tau$	$2\tau, W, \not{E}_T$	14.3	38.8
$pp \to \tilde{\tau}_2\tilde{\nu}_\tau$	$2\tau, W, Z, \not{E}_T$	0.9	3.1
$pp \to \tilde{\nu}_\tau\tilde{\nu}_\tau$	$2\tau, 2W, \not{E}_T$	1.6	5.3

Signature: multileptons+missing energy

Signals at the LHC

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Possible!

Maybe

Signature: multileptons+missing energy

CMS & ATLAS multilepton searches
3 or more leptons final states

$\tilde{\chi}^{\pm} \to \tilde{\chi}^0 W, \ell\tilde{\nu}, \tilde{\ell}\nu, \quad \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z, \ell\tilde{\ell}$

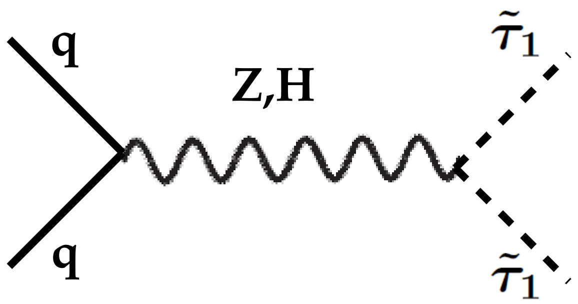
And also limits on sleptons produced in cascade decays

CMS: SUS-12-022, SUS-12-026, SUS-12-027 (old @7TeV: 1204.5341)
ATLAS: ATLAS-CONF-2012-154 (old @7TeV 1208.3144)

Stau pair production

Carena, SG, Shah, Wagner, Wang, 1205.5842

1) $pp \to \tilde{\tau}_1\tilde{\tau}_1 \to (\tau\,\mathrm{LSP})(\tau\,\mathrm{LSP})$



Production cross section for staus at ~ 95 GeV:
~55 fb (8TeV), ~130 fb (14TeV)

See also Lindert, D. Steffen, Trenkel, 1106.4005

Main backgrounds: ,,

Z+ Z/γ*: Veto on the invariant mass close to mZ

WW: Cut on the p_T of the taus > $m_W/2$

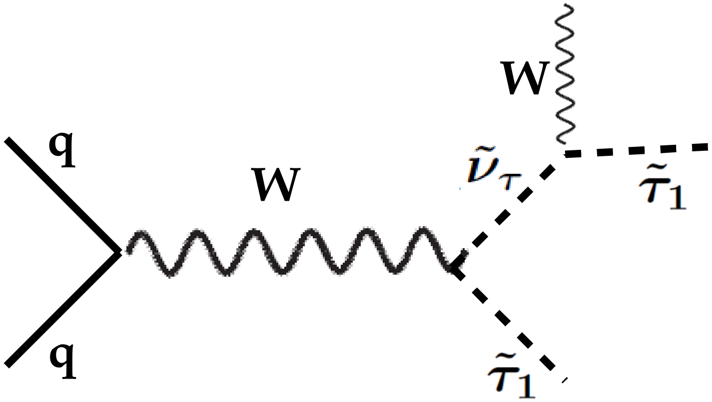
W+jets: Difficult to reduce reasonably:
jet rejection factor 20-50 for loose hadronic taus (id~60%)

What about taus decaying leptonically? **Work in progress**

Associated production

2) $pp \to \tilde{\tau}_1[\tilde{\nu}_\tau(\to W\tilde{\tau}_1)] \to \ell\tau\bar{\tau} + \mathrm{MET}$

Carena, SG, Shah, Wagner, Wang, 1205.5842



Production cross section for staus at ~ 95 GeV, sneutrino ~ 270 GeV:
~15 fb (8TeV), ~40 fb (14TeV)

Main backgrounds:

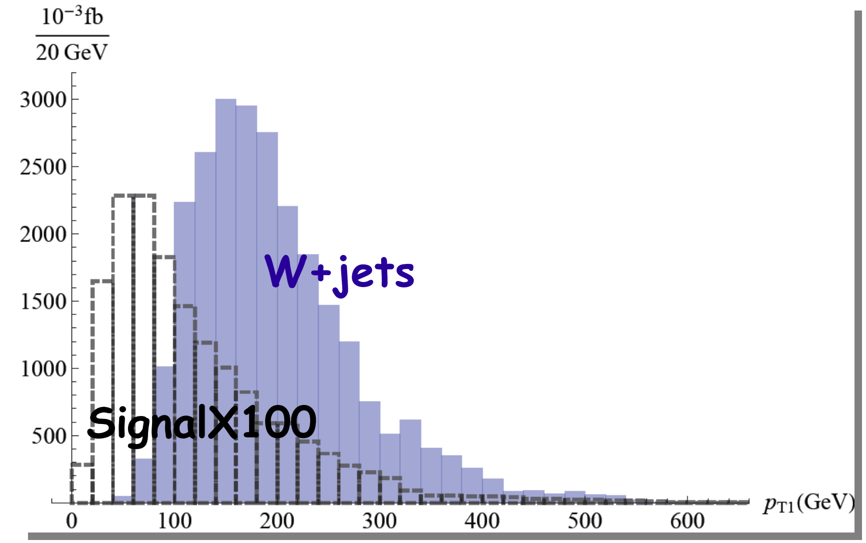
- W+ Z/γ*
- W+jets (with jets faking taus)

jet rejection factor 20-50 for loose hadronic taus (id~60%)

Basic cuts for the 8TeV LHC:

$$p_T^{\tau\,(j)} > 10\,\mathrm{GeV},\ \Delta R > 0.4,\ |\eta| < 2.5$$

$$p_T^{\ell} > 70\,\mathrm{GeV},\ \not{E}_T > 70\,\mathrm{GeV}$$



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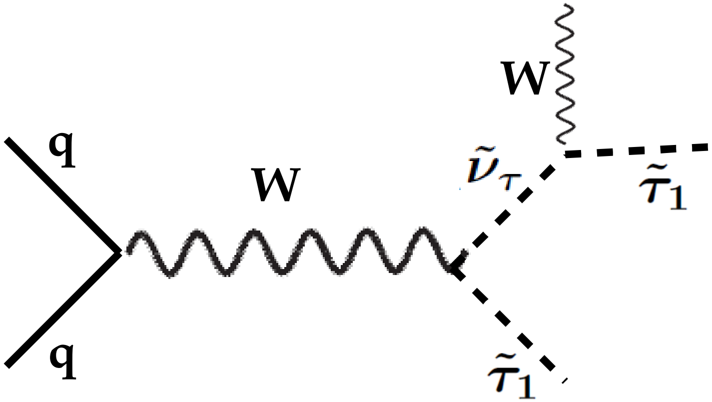
Carena, SG, Shah, Wagner, Wang, 1205.5842



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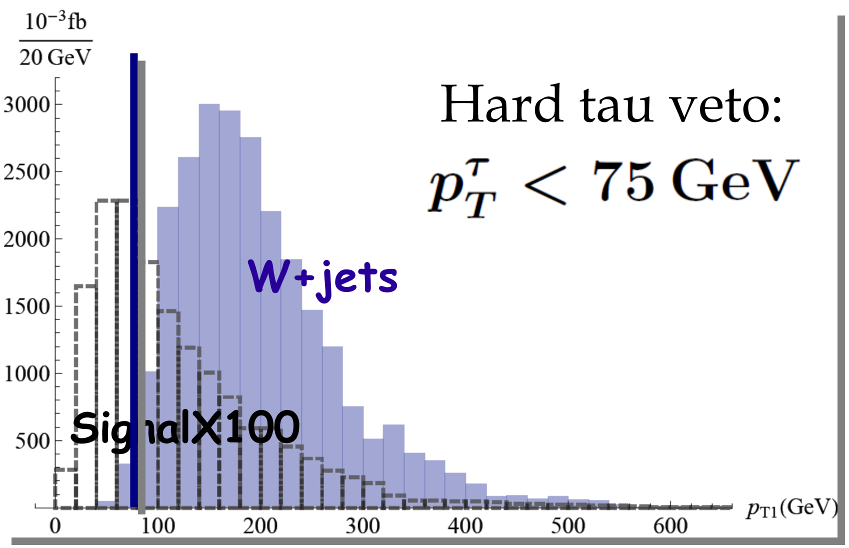


LHC reach

Carena, SG, Shah, Wagner, Wang, 1205.5842

LHC 8TeV

	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	0.6	0.16	0.07
Physical background, $W + Z/\gamma^*$	15	0.25	$\lesssim 10^{-3}$
$W+$ jets background	4×10^3	26	0.3

LHC 14TeV

	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	1.6	0.26	0.11
Physical background, $W + Z/\gamma^*$	27	0.32	$\lesssim 10^{-3}$
$W+$ jets background	10^4	39	0.25

(similar cuts applied)

Existing Higgs searches (1)

CMS PAS HIG-12-051

$$pp \to (Z, W)H,\ H \to \tau\tau$$

- Same final state of the electroweak production

$$pp \to \tilde{\tau}_1[\tilde{\nu}_\tau(\to W\tilde{\tau}_1)] \to \ell\tau\bar{\tau} + \mathrm{MET}$$

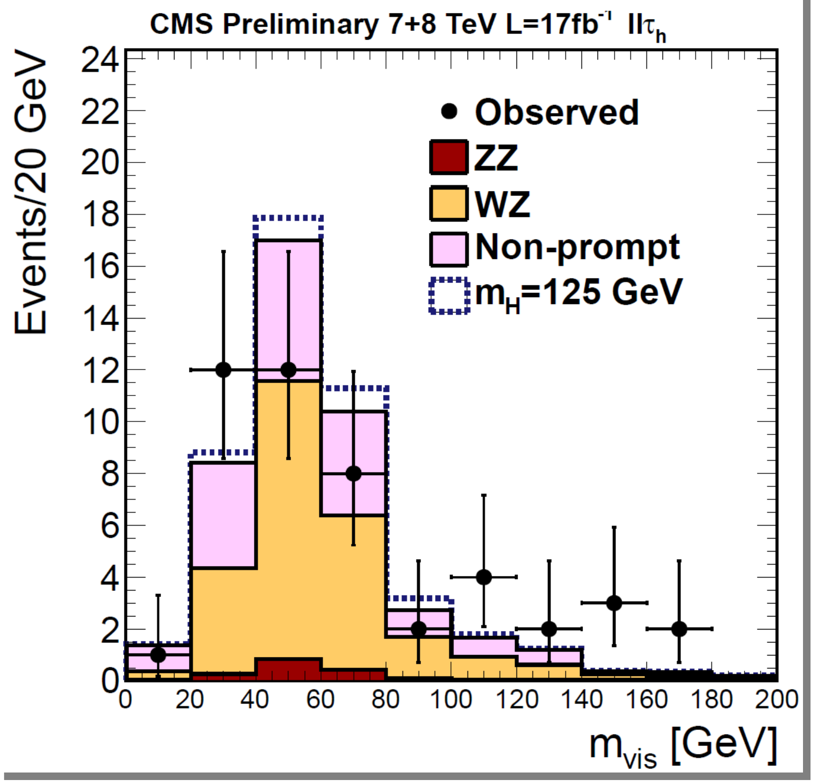
- $\ell\ell\tau_h$ channel

Basic cuts: $p_T^{\ell_1} > 20\,\mathrm{GeV},\ p_T^{\ell_2} > 10\,\mathrm{GeV},\ p_T^{\tau_h} > 20\,\mathrm{GeV}$

$$|\eta^{\tau_h}| < 2.3,\ |\eta^{\mu}| < 2.4,\ |\eta^{e}| < 2.5,$$

$$L_T > 80\,\mathrm{GeV}$$

Background is much smaller,
even if we pay the price of a leptonic decay of a tau



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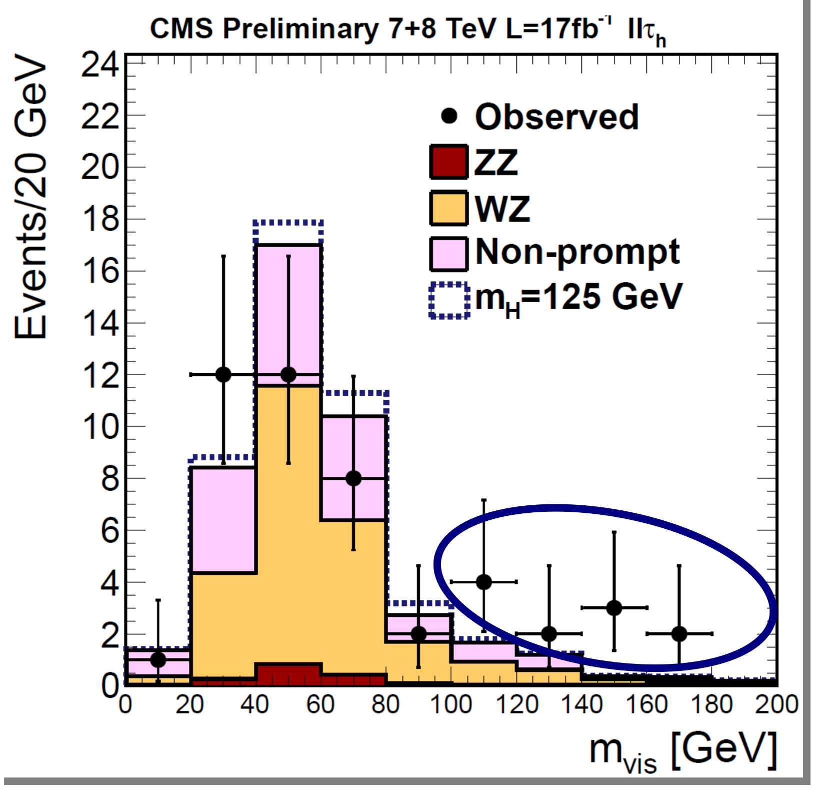
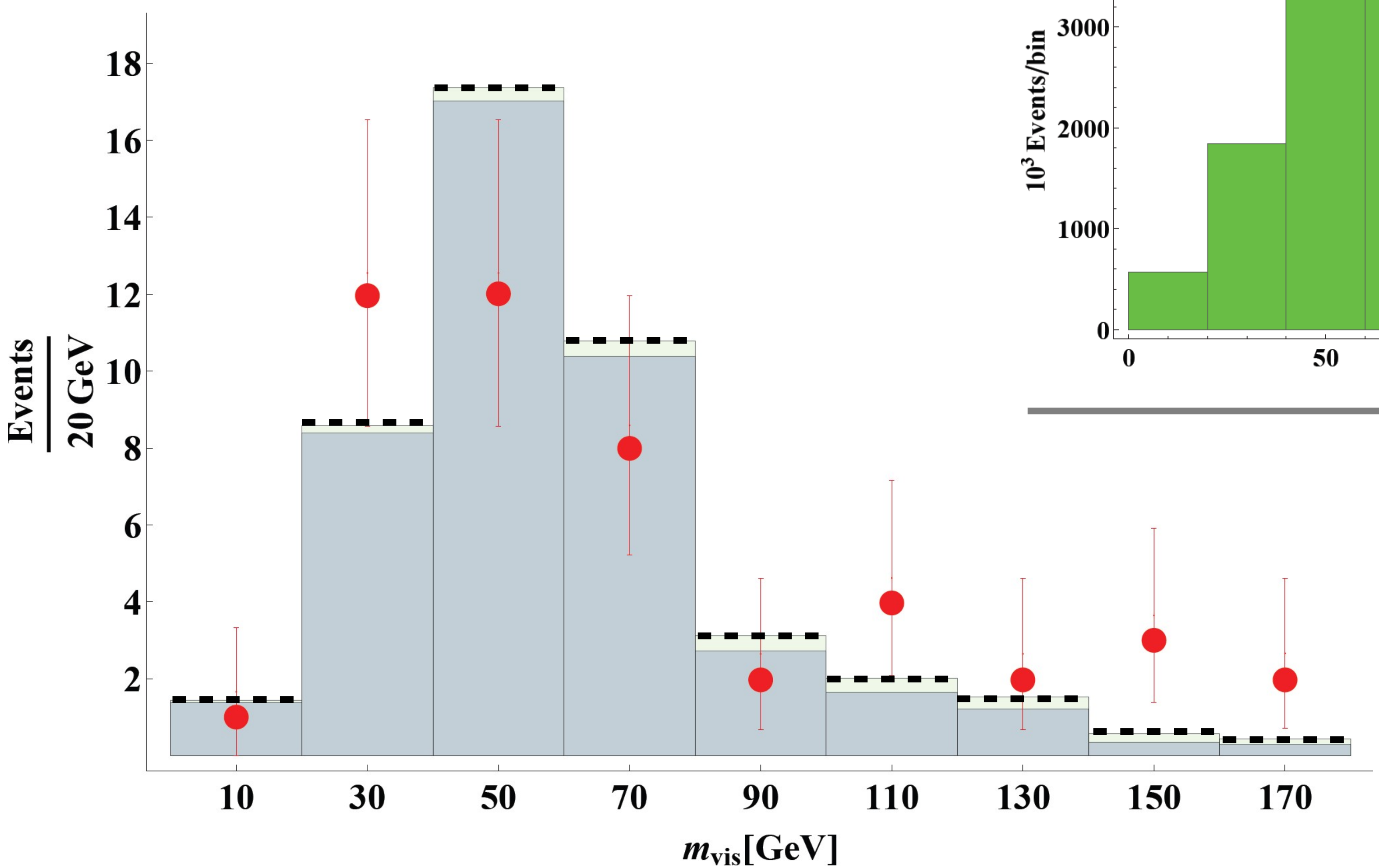
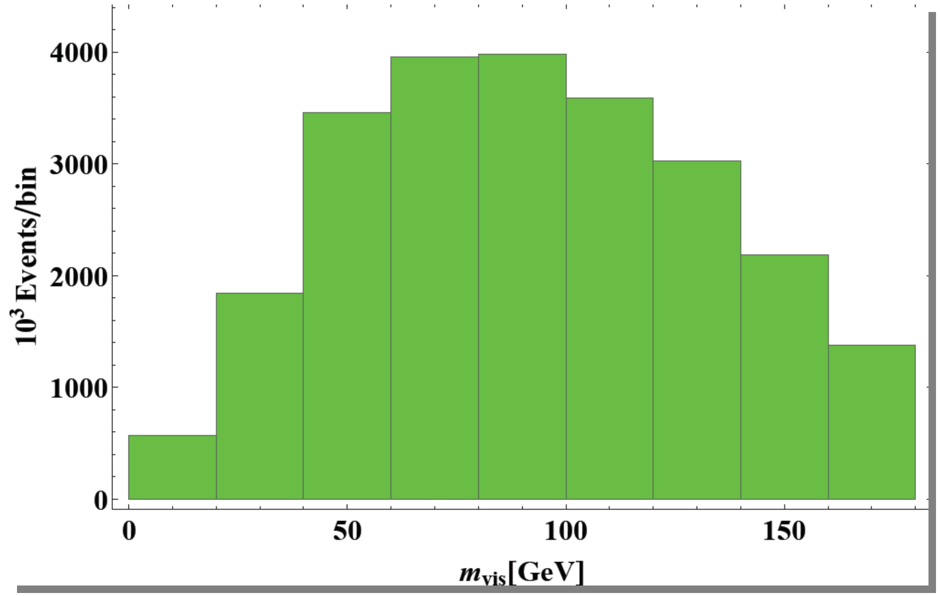


Existing Higgs searches (2)





5 fb^{-1} at 7TeV + 12 fb^{-1} at 8 TeV

S/B ~ 0.3 for $m_{vis} \geq$ 80GeV

Carena, SG, Shah, Wagner, Wang, appearing soon

Conclusions

If LHC will find a Higgs (at ~125 GeV) with enhanced $\gamma\gamma$ rate (and the other rates SM like)

→ Light staus with large mixing provide a good candidate to look for

- Only possible scenario in the framework of the MSSM

- Interesting prospects for the LHC:
  good LHC reach for the associated production
  of a stau and a sneutrino

Interesting new phenomenology of the model

Yukawa couplings

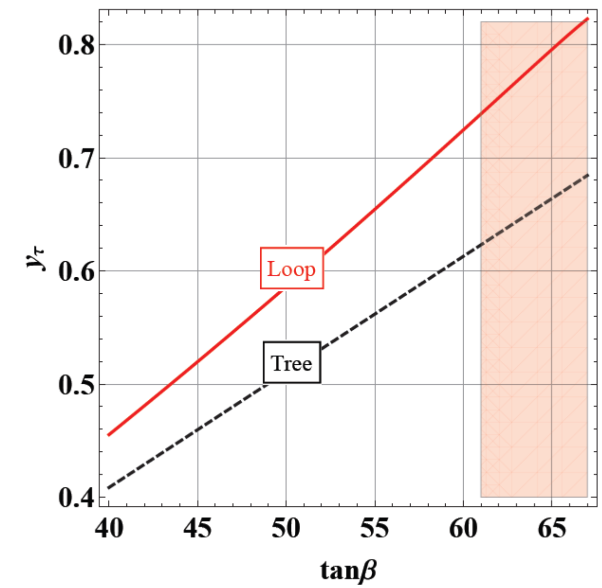
- At the tree level:

$$y_{\tau,b} = \sqrt{2}\frac{m_{\tau,b}}{v\cos\beta} \sim \sqrt{2}\frac{m_{\tau,b}}{v}\tan\beta$$

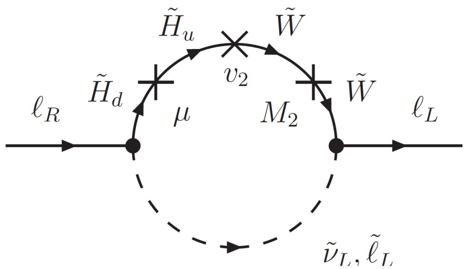
- Including loop corrections:

$$y_{\tau,b} \sim \sqrt{2}\frac{m_{\tau,b}}{v}\frac{\tan\beta}{(1+\Delta_{\tau,b})} \equiv \sqrt{2}\frac{m_{\tau,b}}{v}\tan\beta_{\tau,b\,\mathrm{eff}}$$

See for example Pierce et.al. 9606211
Carena et.al. 9808312

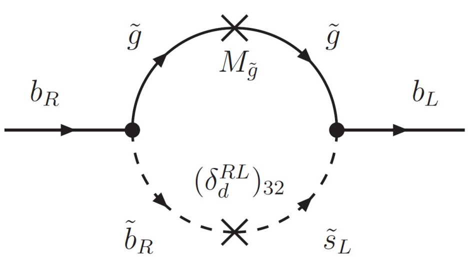


Δ_τ

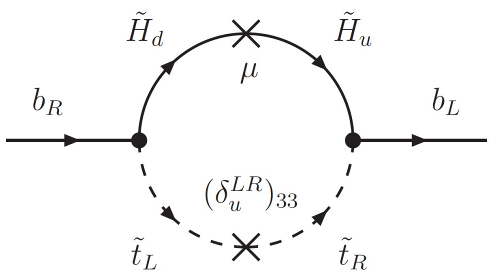


$$-3\frac{\alpha_2}{8\pi}\frac{\mu M_2}{\tilde{m}^2}f_2\left(\frac{M_2^2}{\tilde{m}^2},\frac{\mu^2}{\tilde{m}^2}\right)\tan\beta$$

Δ_b



$$2\frac{\alpha_s}{3\pi}\frac{\mu M_{\tilde{g}}}{\tilde{m}^2}f_1\left(\frac{M_{\tilde{g}}^2}{\tilde{m}^2}\right)\tan\beta$$



$$\frac{\alpha_2}{8\pi}\frac{m_t^2}{m_W^2}\frac{\mu A_t}{\tilde{m}^2}f_1\left(\frac{\mu^2}{\tilde{m}^2}\right)\tan\beta$$

We can choose a scenario with Δ_b = O(1)>0 and Δ_τ = O(0.1)<0 $\Rightarrow$ $\tan\beta_{\tau\,\mathrm{eff}} > \tan\beta,\ \tan\beta_{b\,\mathrm{eff}} < \tan\beta$

Staus direct searches

- LEP bound on the stau mass: Aleph, 0112011
  90 GeV in the case of no degeneracy with the lightest neutralino

- CMS bound on long lived staus: 223 GeV
  1205.0272

Not applicable to our model since our staus are proptly decaying

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- ATLAS: searches for staus NLSP produced from gluino & squark cascade decays.
  Up to 4 leptons, jets and missing energy signature. 1210.1314

  The limits are model dependent and not applicable if squarks and gluinos are heavy

- CMS & ATLAS multilepton searches
  3 or more leptons final states

  $$\tilde{\chi}^{\pm} \to \tilde{\chi}^{0} W, \ell\tilde{\nu}, \tilde{\ell}\nu, \quad \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z, \ell\tilde{\ell}$$

  And also limits on sleptons produced in cascade decays

  CMS: SUS-12-022, SUS-12-026, SUS-12-027 (old @7TeV: 1204.5341)
  ATLAS: ATLAS-CONF-2012-154 (old @7TeV 1208.3144)

Improved strategies to look for our light staus?

Split-like Susy models

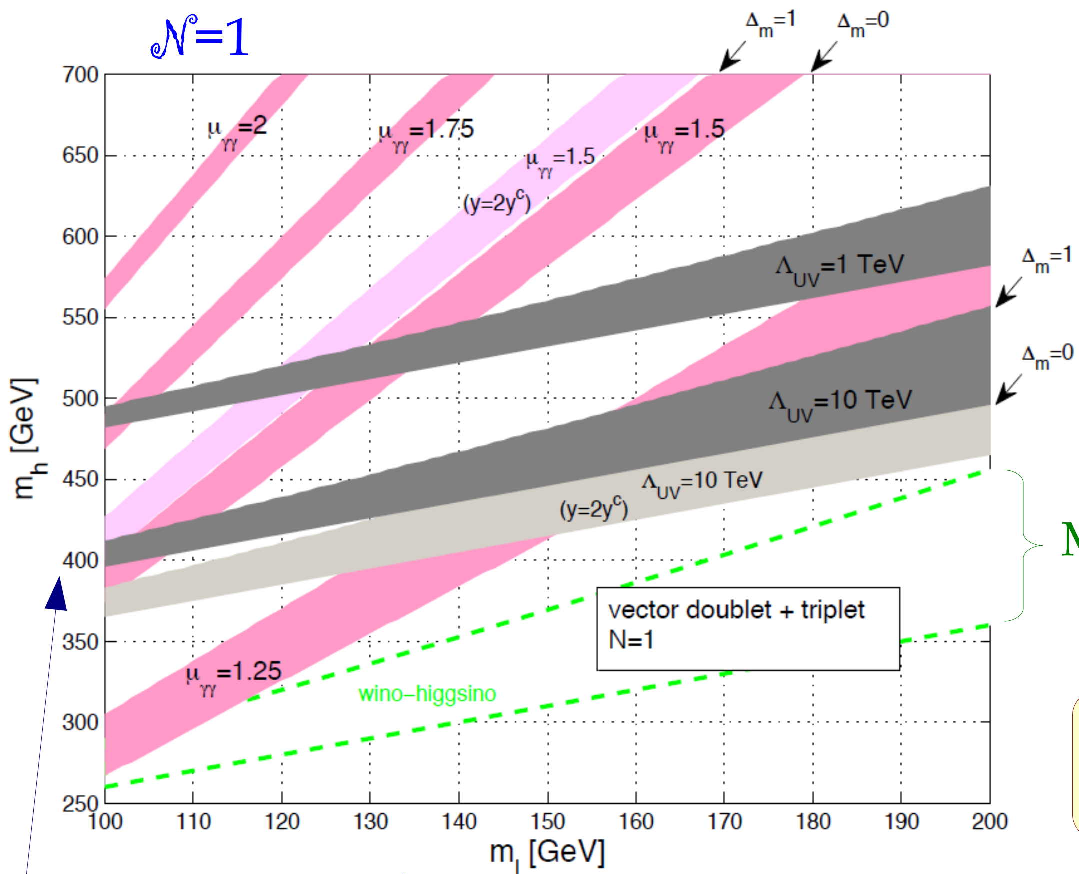
Arkani-Hamed, Blum, D´Agnolo, Fan, 1207.4482

Wino+Higgsino model:

$$V = m_\psi \psi\psi^c + \frac{1}{2} m_\chi \chi\chi + \sqrt{2} y H \psi\chi + \sqrt{2} y^c H^\dagger \psi^c \chi + cc.$$

$$\psi,\ \psi^c \sim (1,2)_{\pm 1/2},\ \chi \sim (1,3)_0$$

$\mathcal{N}$=1



MSSM case

$$16\pi^2 \frac{d\lambda}{dt} \supset -\frac{\mathcal{N}}{2}(5y^4 + 5y^{c4} + 2y^2 y^{c2})$$

Very low cut-off scale for a sizable enhancement of the di-photon rate

Fermion mass eigenvalues, $\Delta_m = \dfrac{|m_\psi - m_\chi|}{m_l}$

See also Joglekar, Schwaller, Wagner, 1207.4235

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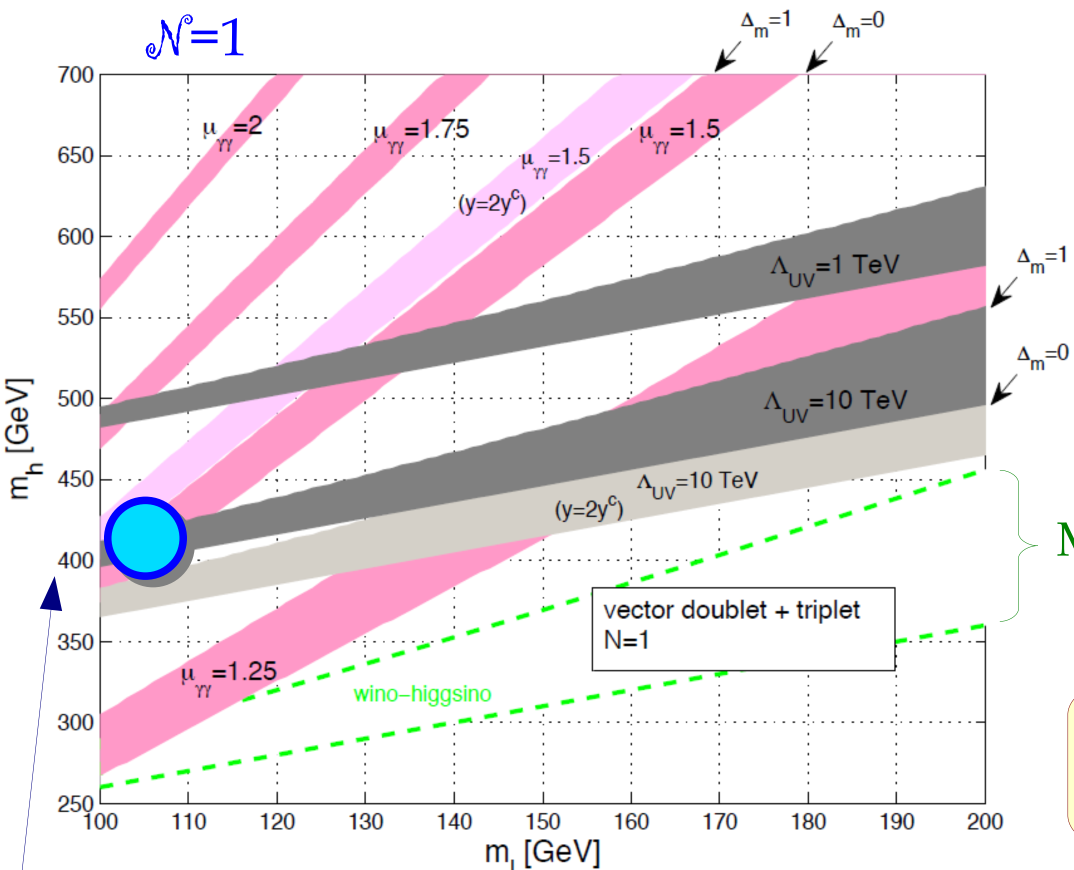

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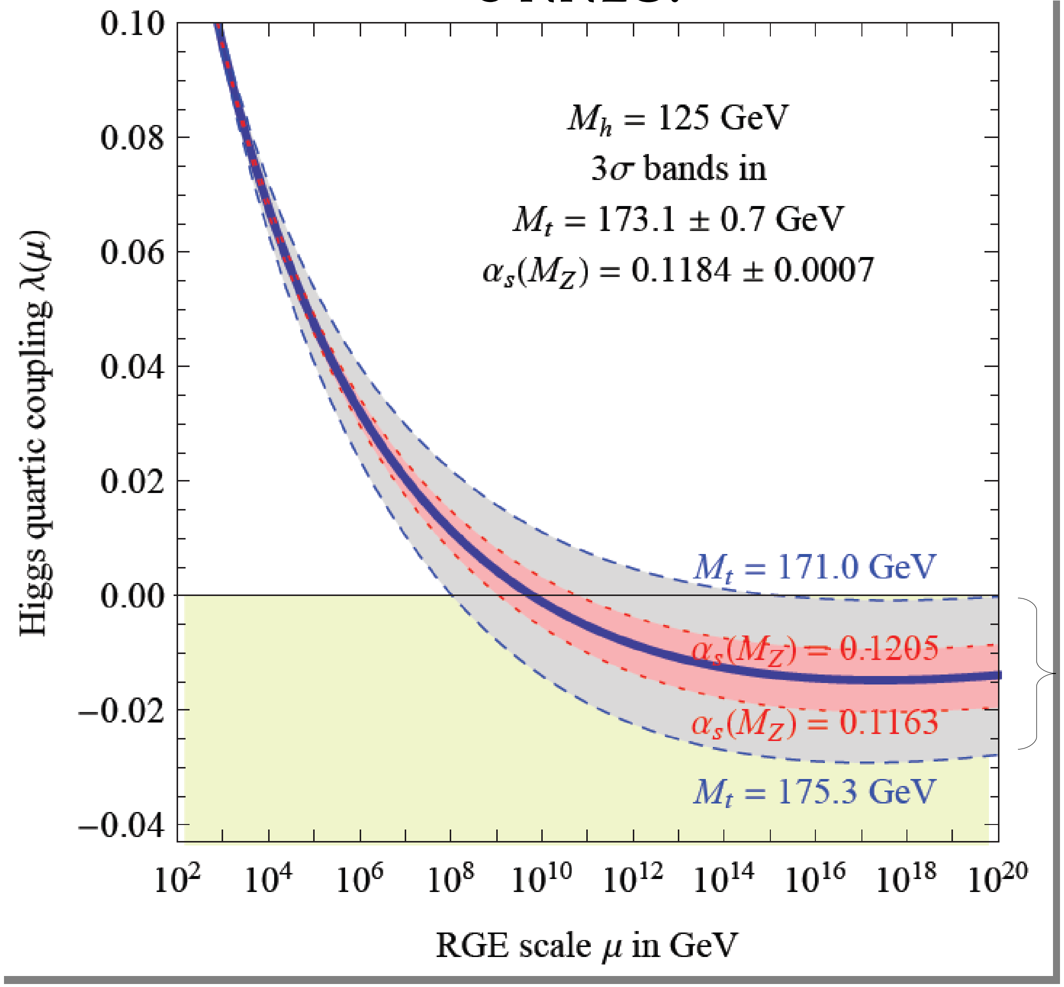
Vacuum stability in the SM

@ NNLO:



Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice,Isidori, Strumia,1205.6497

Very slow running at high scales

$$\lambda \sim 0, \ \beta_\lambda \sim 0$$

It may hide some information about Planckian physics

Variation by ± 3σ

Sizable uncertainty still coming from threshold corrections to λ and from non-perturbative uncertainties on the pole top mass Hoang and I. W. Stewart, 0808.0222

M_h<126 GeV excluded at the 2σ level

Condition of absolute stability:

$$m_h\,(\mathrm{GeV}) > 129.4 + 1.4\left(\frac{\mathrm{M_t}\,(\mathrm{GeV}) - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_\mathrm{s}(\mathrm{M_Z}) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$

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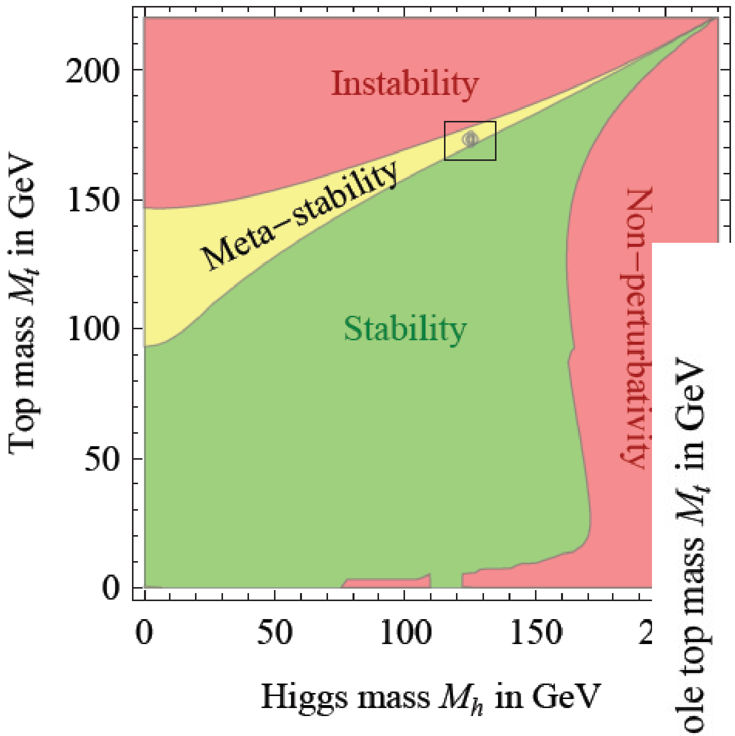
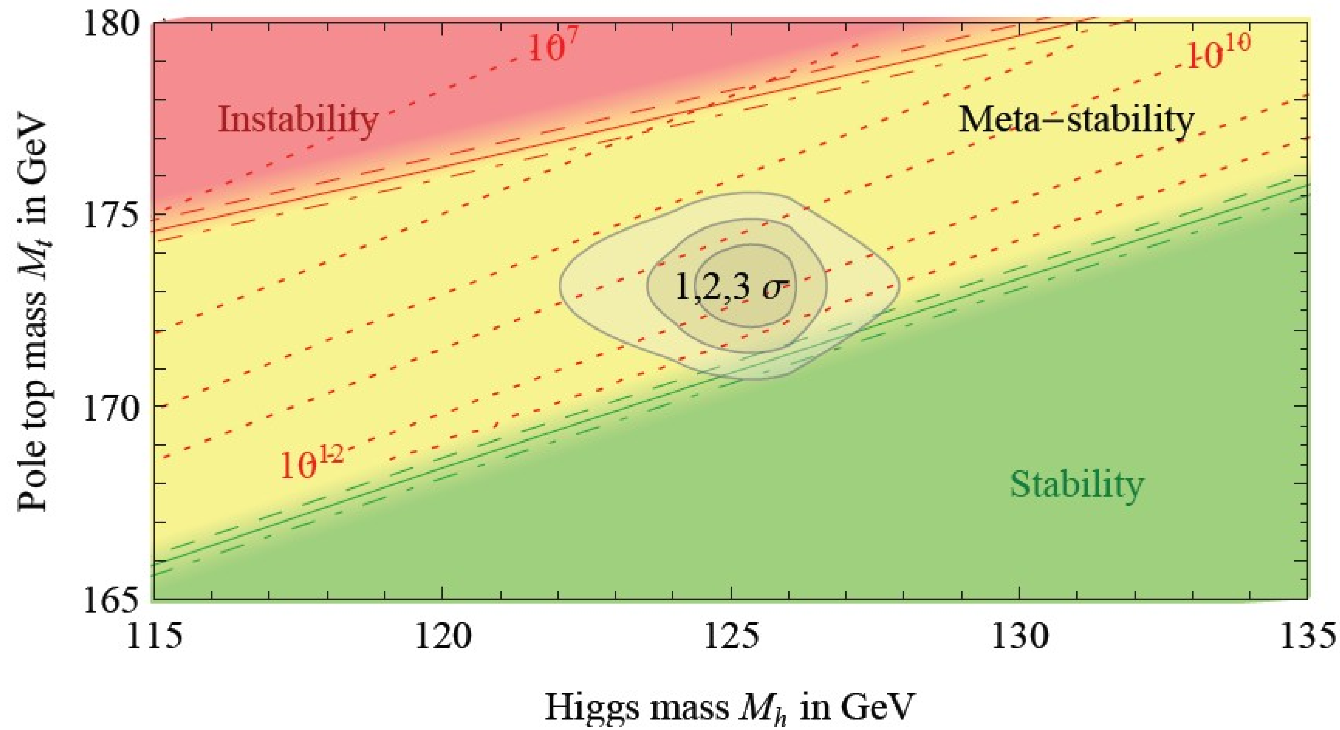
Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice,Isidori, Strumia,1205.6497





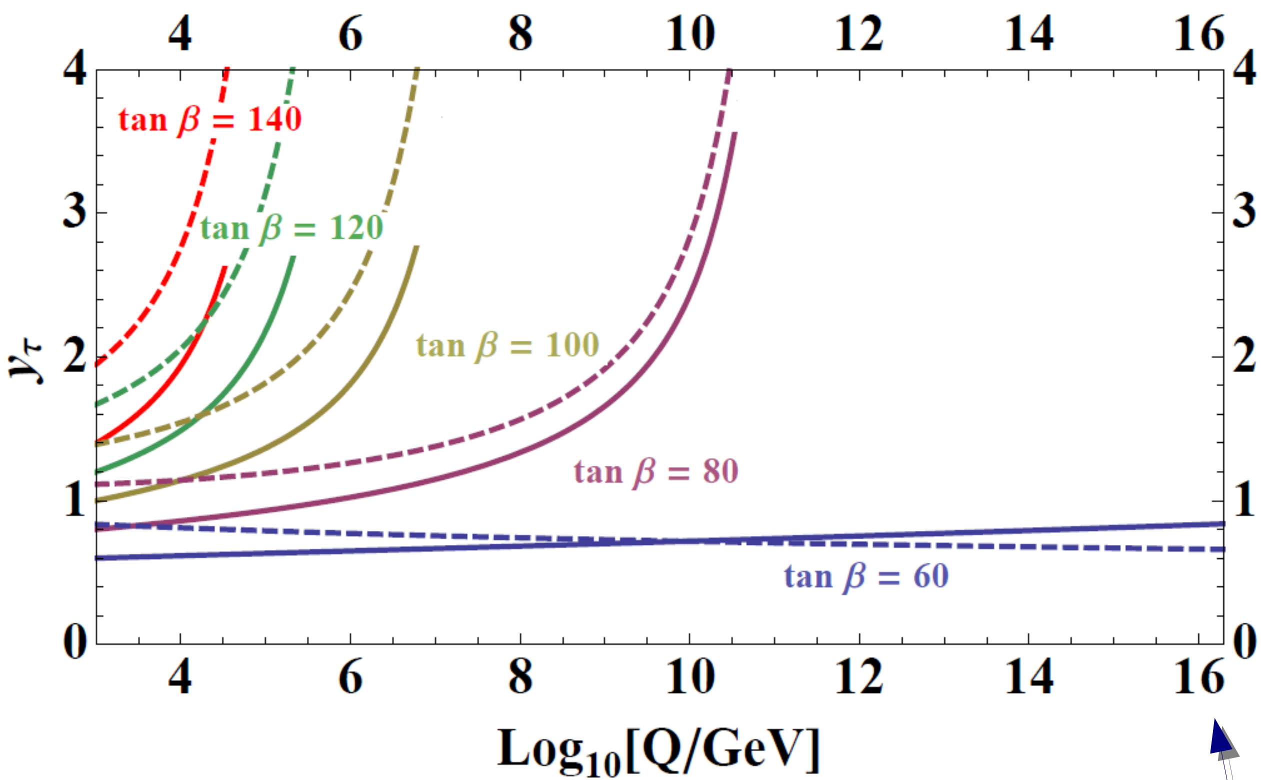
We live in a metastable minimum

Perturbativity bounds

- At the tree level:

$$y_{\tau,b} = \sqrt{2}\frac{m_{\tau,b}}{v\cos\beta} \sim \sqrt{2}\frac{m_{\tau,b}}{v}\tan\beta$$

2-loop running



$\tan\beta \lesssim 70$ allowed by the requirement of perturbativity until the GUT scale

GUT scale

Other options...

Almost decoupling limit

Carena, SG, Shah, Wagner, Wang, 1205.5842

Maybe a possible di-photon enhancement is not just hinting towards the presence of new light charged particles but also of additional Higgs bosons...

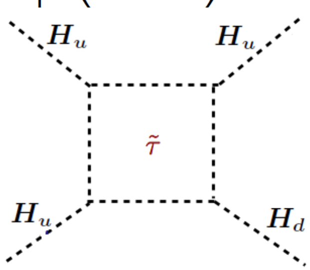
The mixing between the Higgs of the SM and an additional Higgs can induce a modification of the SM Higgs width, because of the modification of its coupling with botton quarks

In a 2HDM: $\xi_d^h = \xi_\ell^h = -\frac{\sin\alpha}{\cos\beta}$

In particular in the MSSM (for $m_A \gg M_Z$)

$$\begin{pmatrix} h & H \end{pmatrix} \begin{bmatrix} m_A^2 s_\beta^2 + M_Z^2 c_\beta^2 & -(m_A^2 + M_Z^2) s_\beta c_\beta + \mathrm{Loop}_{12} \\ \star & m_A^2 c_\beta^2 + M_Z^2 s_\beta^2 \end{bmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

$$\mathrm{Loop}_{12} = \frac{m_\tau^4}{12\pi^2 v^2} \frac{\tan^4\beta}{\sin^2\beta} \frac{\mu^3 A_\tau}{M_{\tilde\tau}^4} + \cdots$$



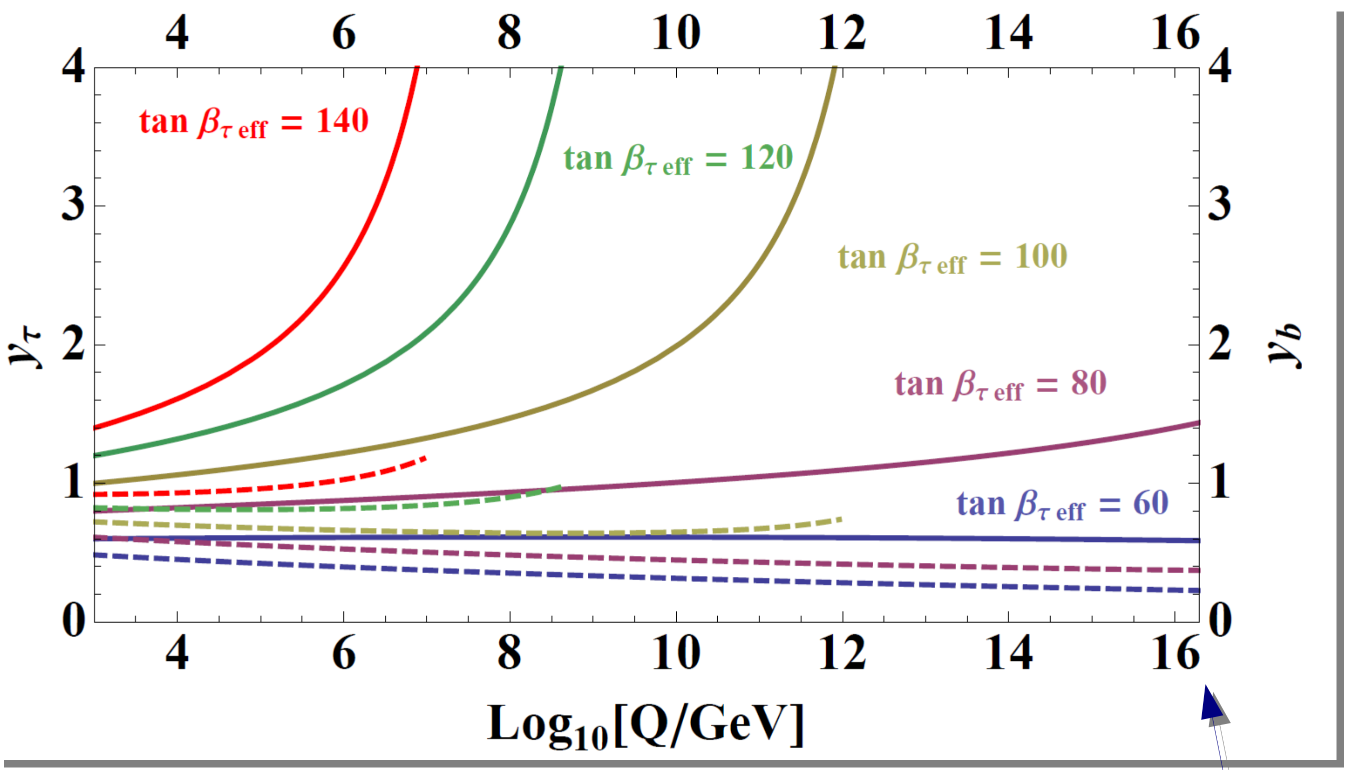
At large μ, A_τ, tanβ we can have $|\xi_d^h| < 1$ (if Loop_{12}>0) or $|\xi_d^h| > 1$ (if Loop_{12}<0)

Γ_{bb} is suppressed Γ_{bb} is enhanced

Perturbativity of the Yukawa couplings

Very high di-photon rates would univocally point towards
the existence of a NP scale of the physics beyond the MSSM

2-loop running



$$\tan\beta_{\tau\,\mathrm{eff}} \lesssim 90$$

$$\tan\beta \lesssim 70$$

GUT scale

Carena, SG, Low, Shah, Wagner, 1211.6136

Perturbativity of the Yukawa couplings

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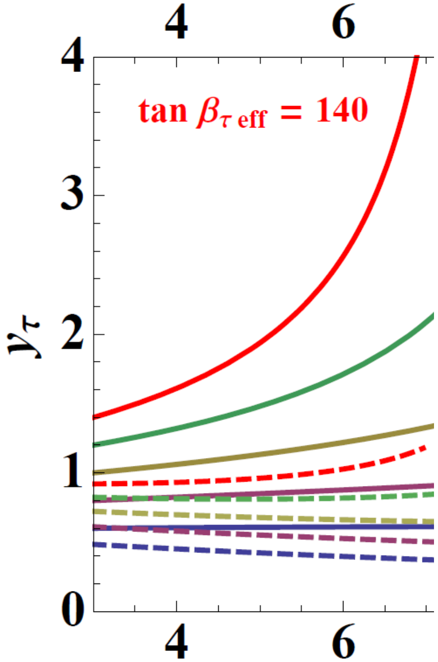
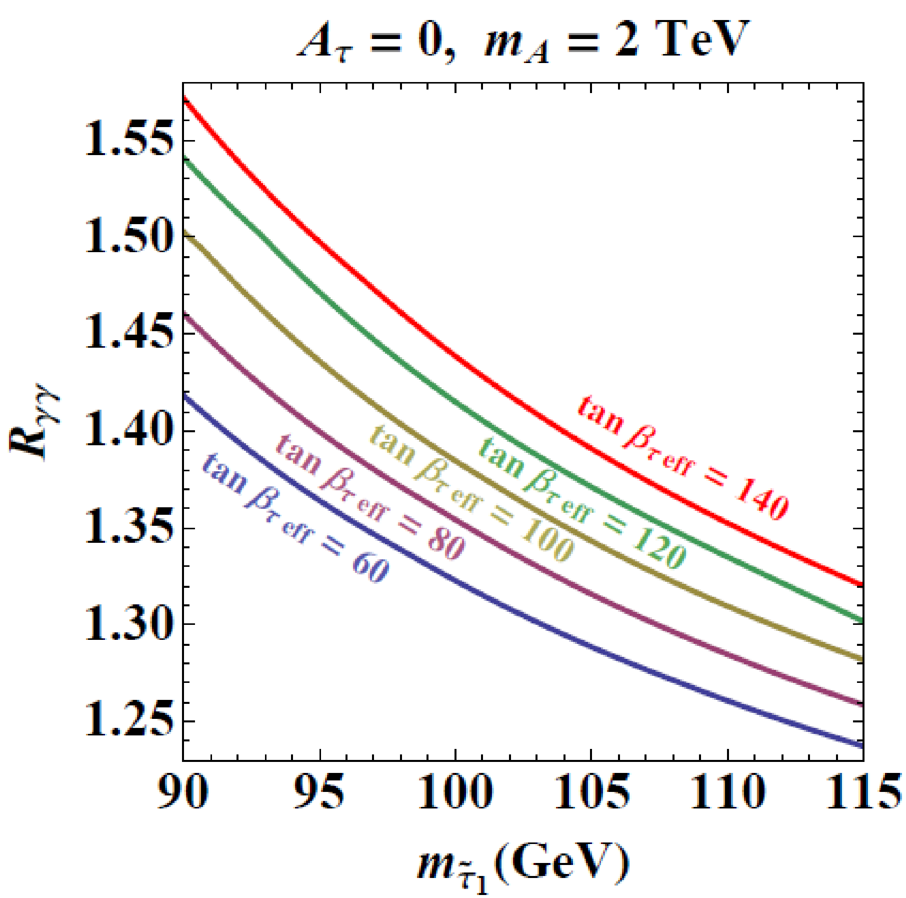




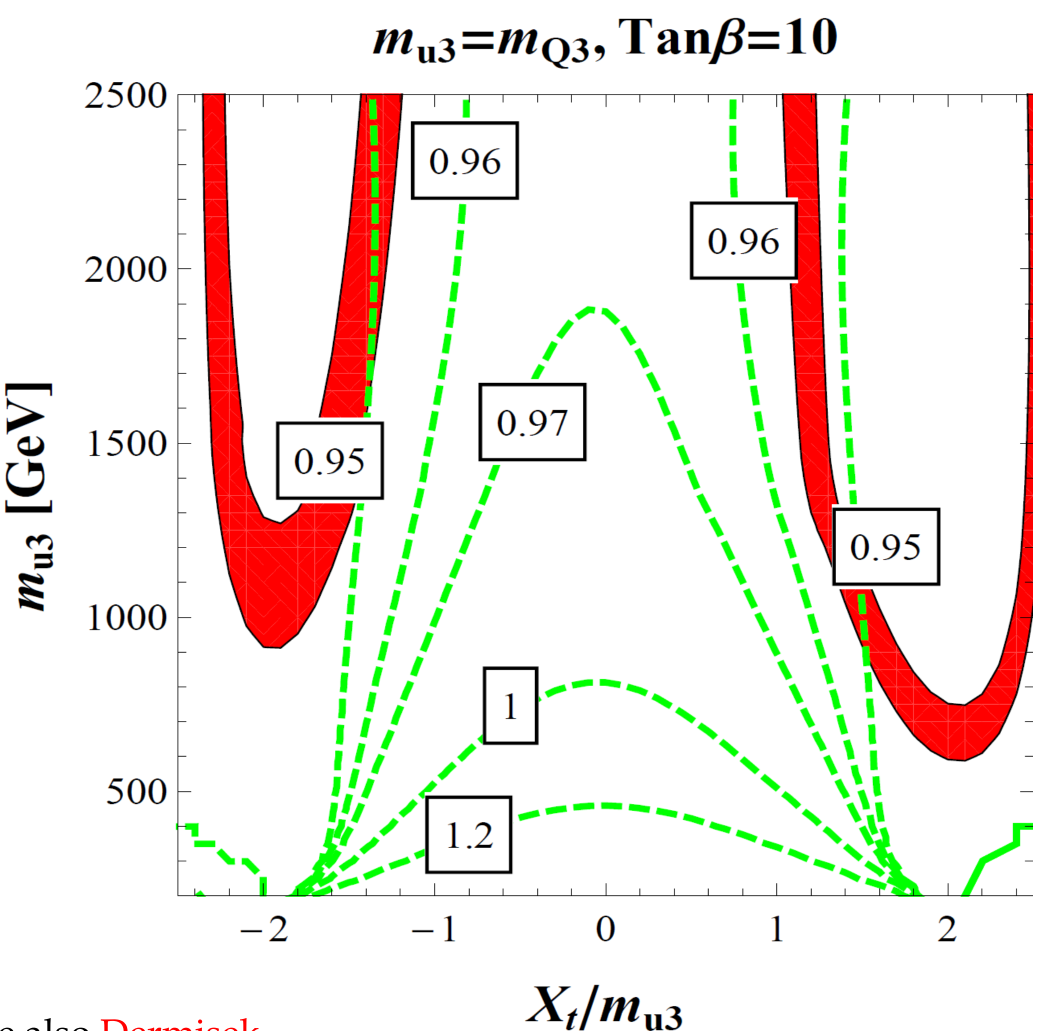
Using light staus, „only" 50% enhancements of the di-photon rate are feasable if the MSSM is perturbative until the GUT scale

GUT scale

Carena, SG, Low, Shah, Wagner, 1211.6136

Stop contributions

First case: large mixing and comparable stop masses



$$\sigma(pp \to h \to \gamma\gamma) = \sigma(pp \to h)\frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{tot}}$$

- Competing effects in gg fusion and in the γγ partial width
- Both effects are rather small in the region reproducing the correct Higgs mass
- Overall **small suppression** of the γγ rate coming from stops in this region

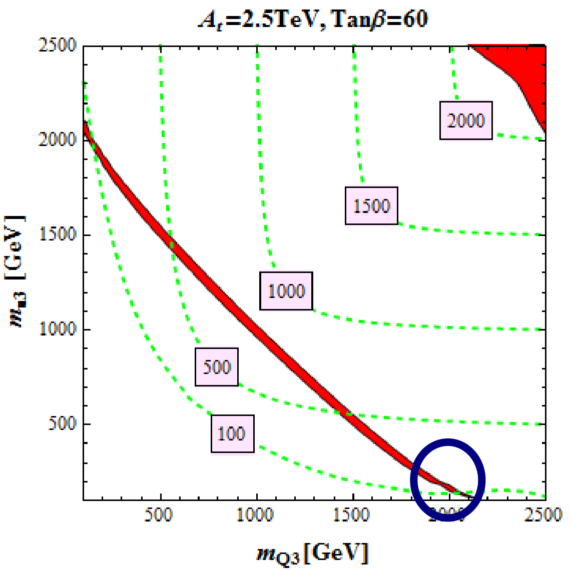
$$\mathcal{M}^2_{stop} = \begin{pmatrix} m^2_{Q_3} + m_t^2 + D_L & m_t X_t \\ m_t X_t & m^2_{u_3} + m_t^2 + D_R \end{pmatrix}$$

See also Dermisek, Low, 0701235

Stop contributions

Second case: very large splitting between the two stops

Reminder:

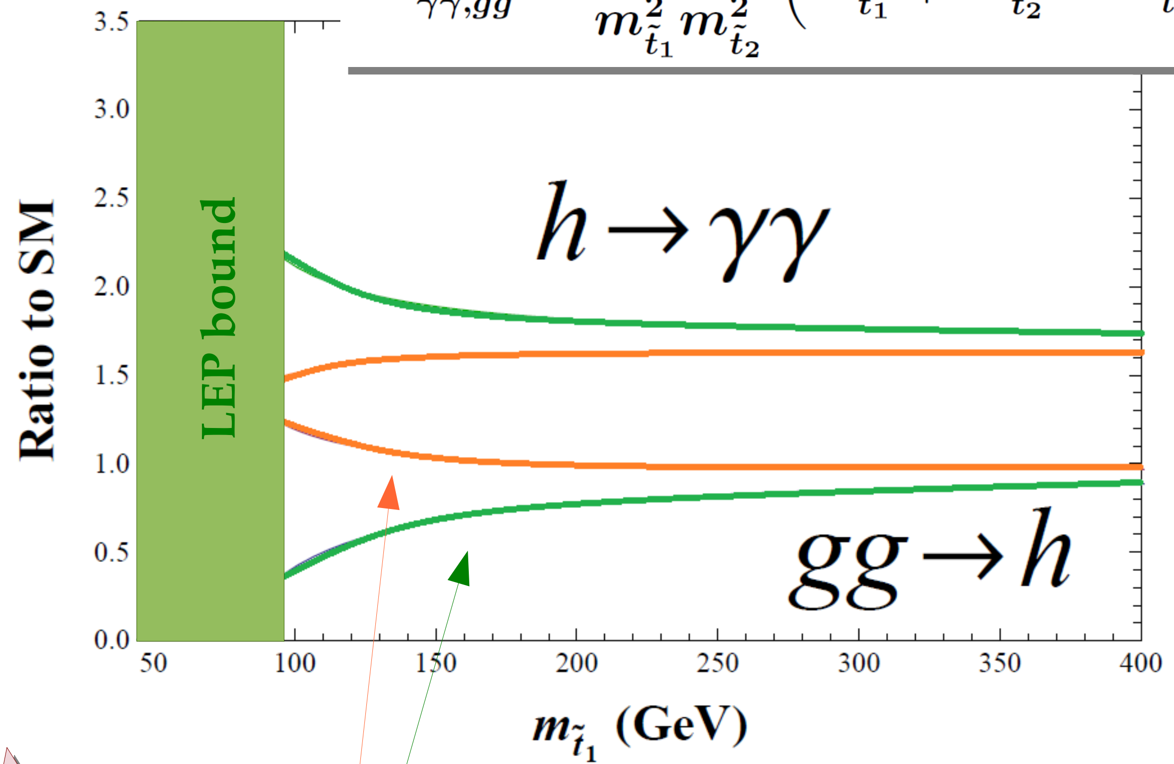


$$m_h^2 \sim m_Z^2 \cos^2(2\beta) + \frac{3}{8\pi^2}\frac{m_t^4}{v^2}\tilde{X}_t$$

$$\tilde{X}_t = \frac{2X_t^2}{M_{\rm Susy}^2}\left(1 - \frac{X_t^2}{12M_{\rm Susy}^2}\right)$$

valid for $m_{Q3} >> m_{u3}$

$$\delta A^{\tilde{t}}_{\gamma\gamma,gg} \propto \frac{m_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2\right)$$



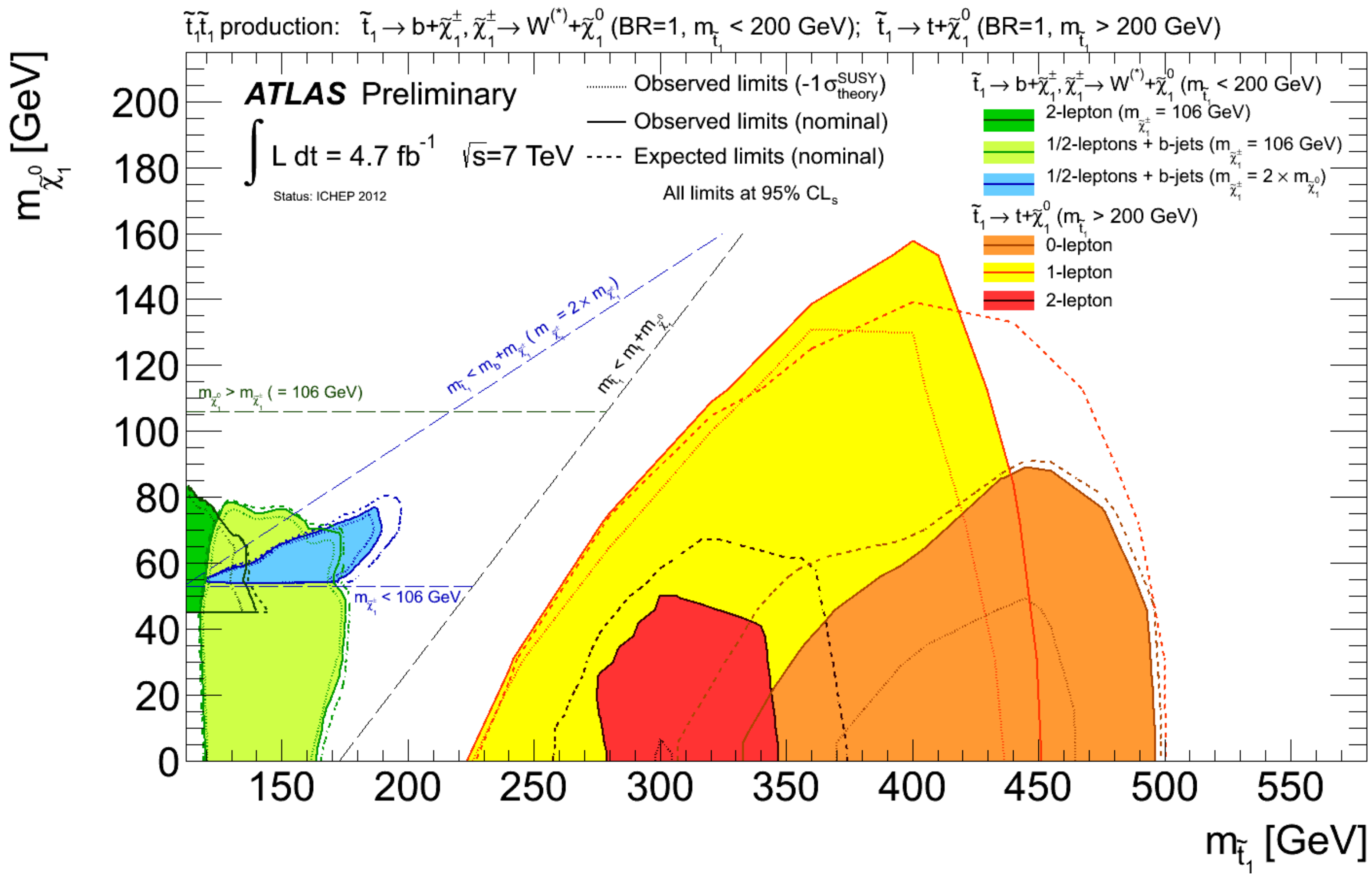
Two solutions for X_t leading to the same Higgs mass

LHC searches for light stops

We have already spoken about the possibility of changing the Higgs production cross section through loops of very light (right handed) stops

Only recently LHC started to probe directly produced stops

Crucial searches if gluinos are heavy ($\gtrsim$ 2TeV)



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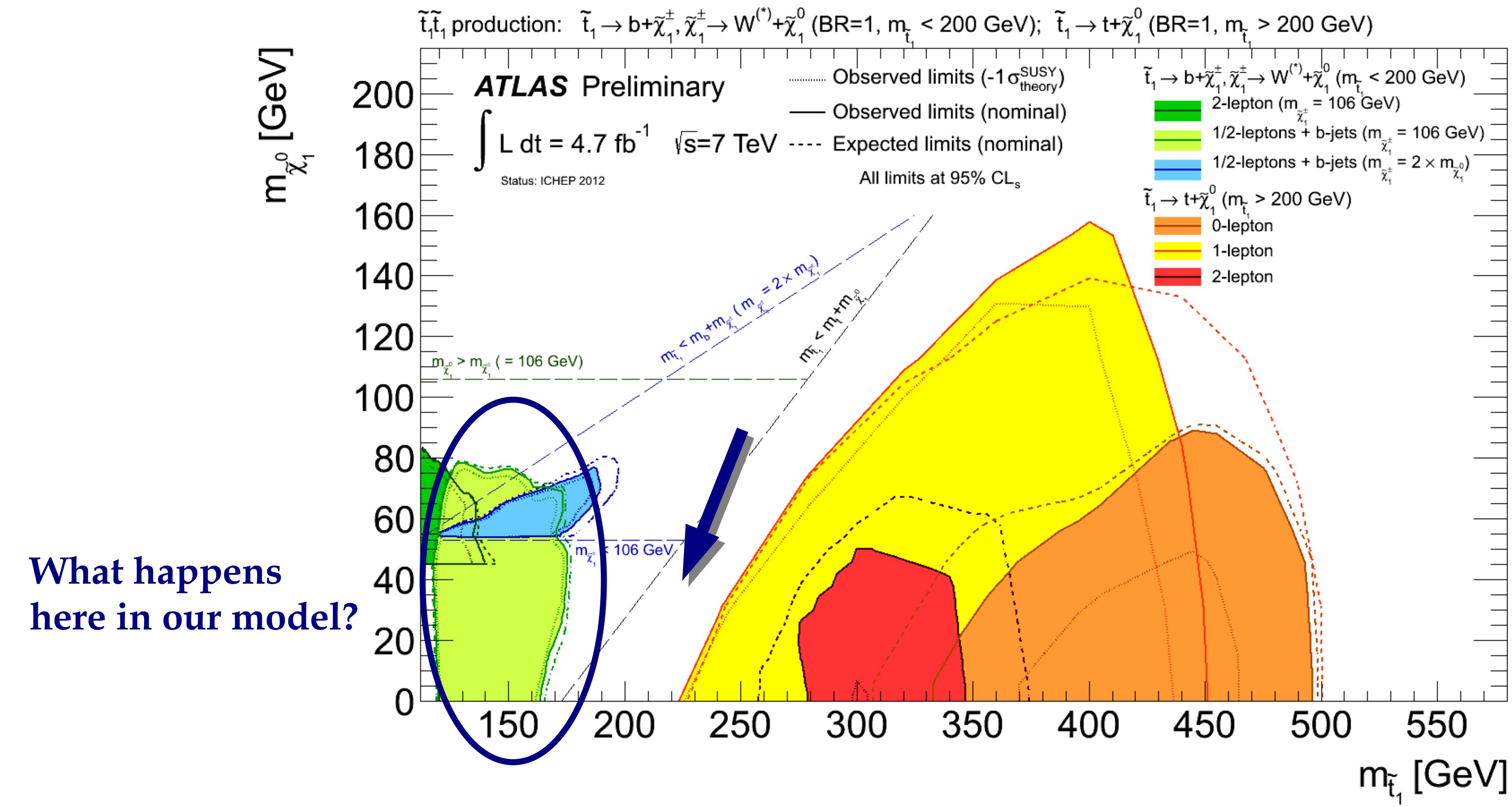

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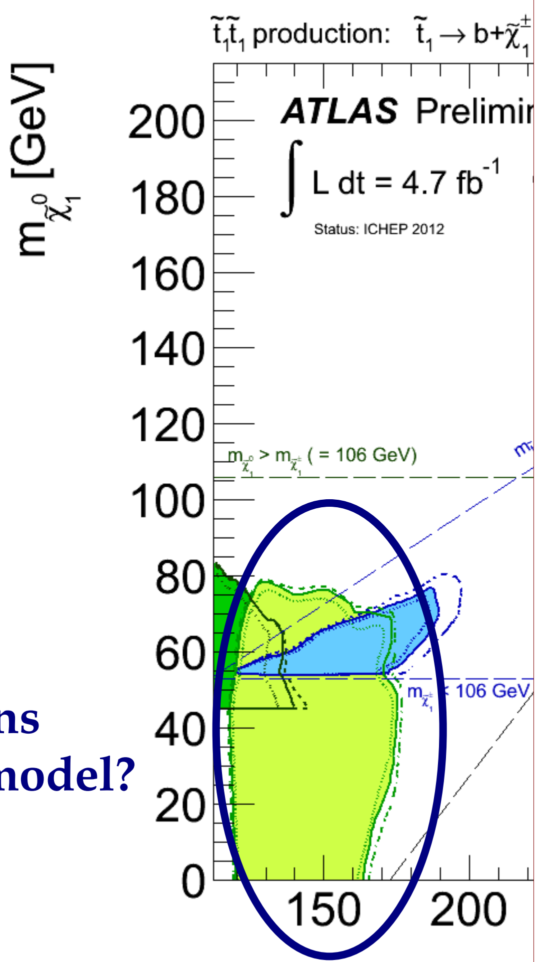


What happens here in our model?

Carena, SG, Shah, Wagner, Wang, work in progress

The decay $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm},\ \tilde{\chi}_1^{\pm} \to W\tilde{\chi}_1^0$ is usually suppressed

thanks to the opening up of new decay modes

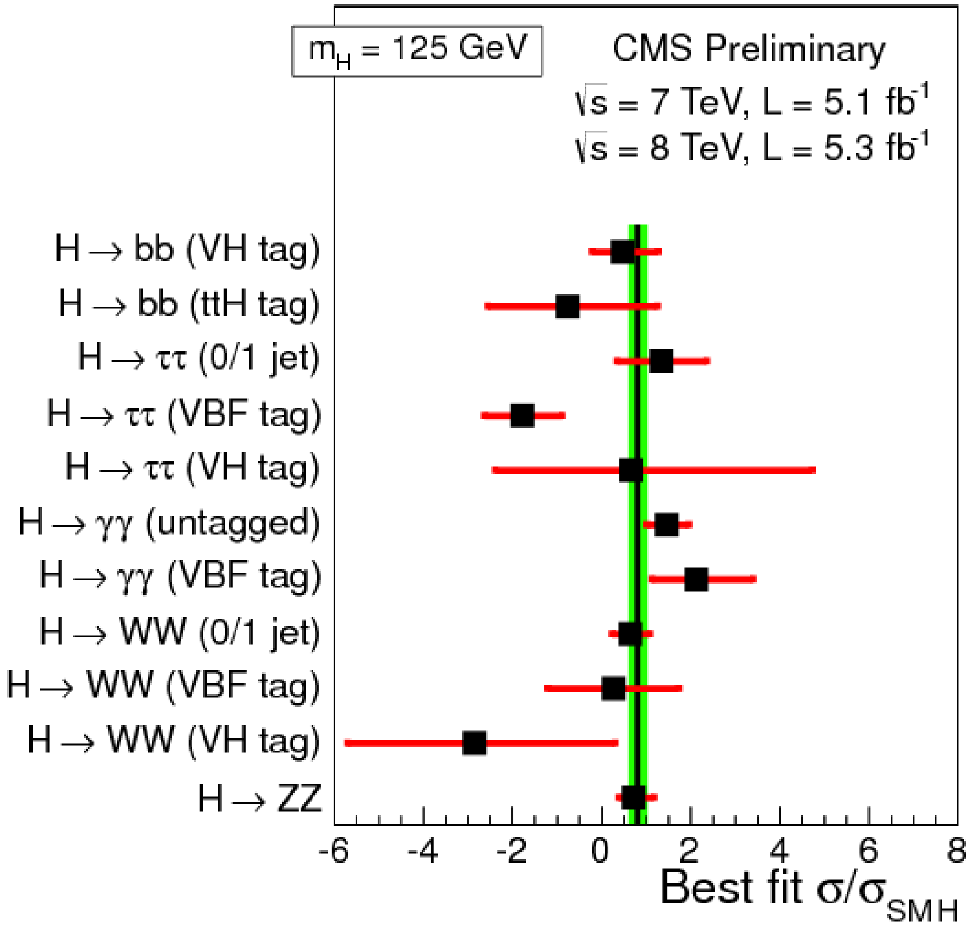
$$\tilde{t}_1 \to \tilde{\tau}_1 b \nu_\tau$$

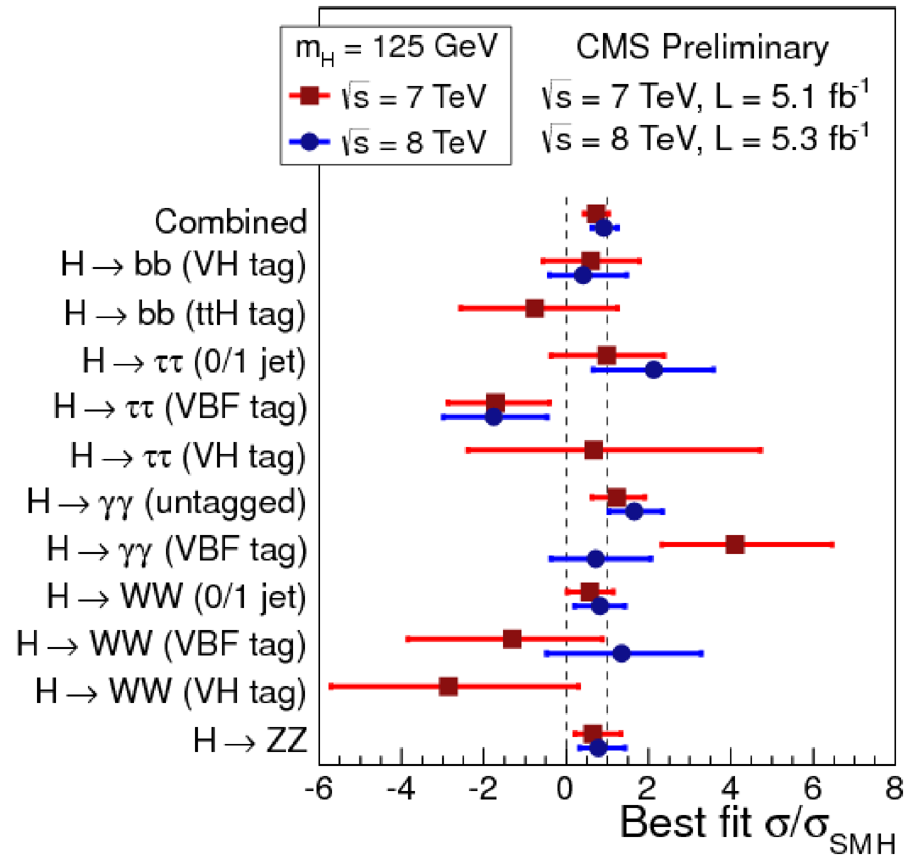
To recast multilepton searches

$$\tilde{t}_1 \to \tilde{\chi}_1^0 c$$

CDF bound: m_{stop}>120 GeV if 100% decaying in this final state and neutralino mass ~30-40 GeV
0707.2567

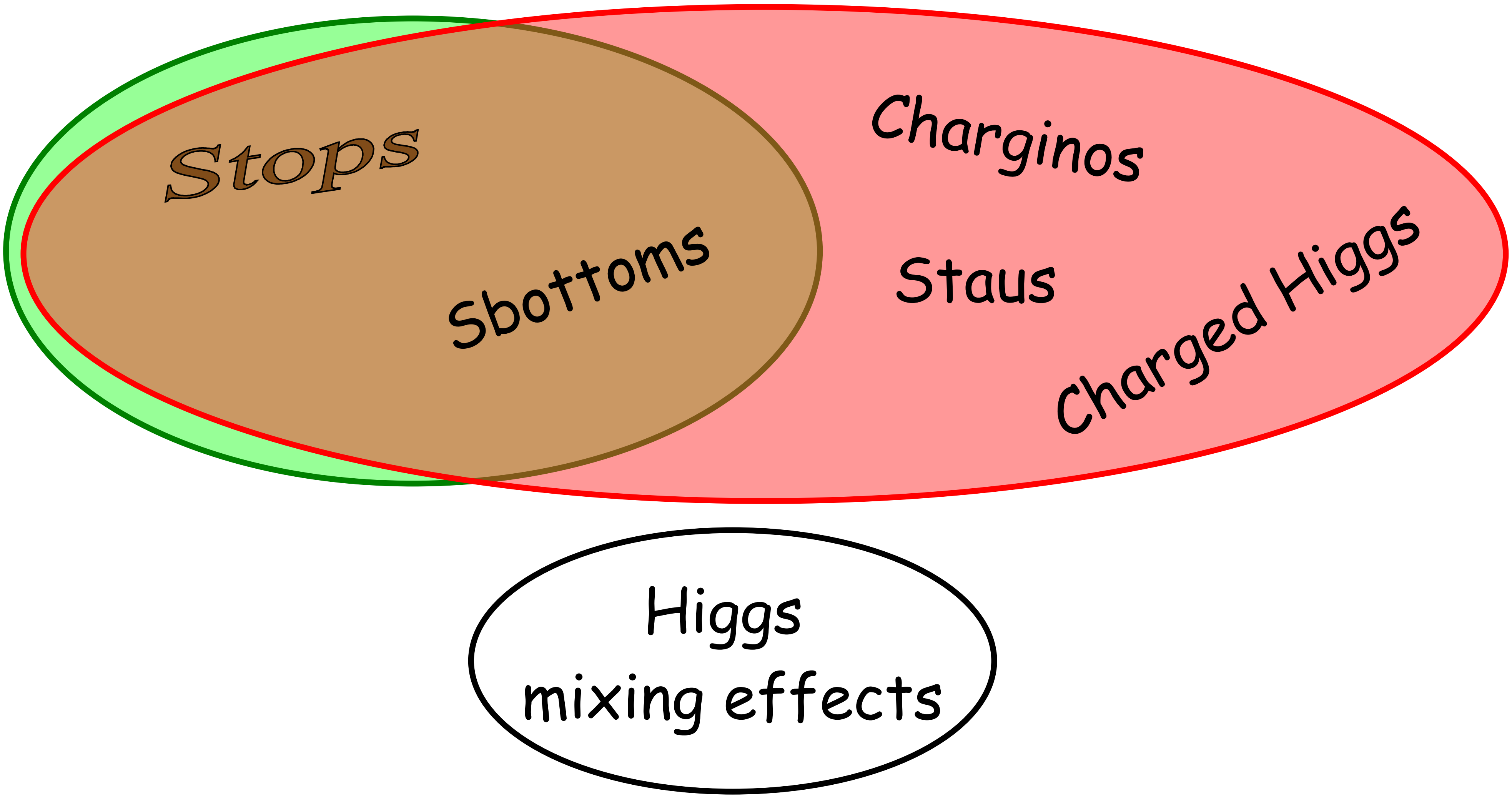
CMS Higgs results, more detail





MSSM NP effects in the γγ rate

$$\sigma(pp \to h \to \gamma\gamma) = \sigma(pp \to h)\frac{\Gamma(h \to \gamma\gamma)}{\Gamma_{\rm tot}}$$



Higgs to di-photon rate beyond the MSSM

An (incomplete) list of references:

1112.2703, Hall, Pinner, Ruderman
λsusy, enhancement of the di-photon rate through the suppression of the bb width
(sizable mixing between the two Higgs doublets)

1112.3548, Ellwanger
1203.3446, Vasquez, Belanger, Böhm, Da Silva, Richardson, Wymant
1203.5048, Ellwanger
1210.1976, Belanger, Ellwanger, Gunion, Jiang, Kraml
NMSSM with h ~ H2, enhancement of the di-photon rate through the suppression of the bb width
(sizable singlet component of the Higgs)

1207.1545: Gunion, Jiang, Kraml
NMSSM: enhancement of the di-photon rate since coming from two degenerate Higgs bosons

1207.2473: An, Liu, Wang
MSSM+ gauged U(1) symmetry: enhancement of the di-photon rate through loops of the fermions curing the gauge anomaly

1207.6596, Delgado, Nardini, Quiros
MSSM+Higgs triplet of SU(2): enhancement of the di-photon rate through chargino loops

1208.1683: Schmidt, Staub
NMSSM+R-symmetry: enhancement of the di-photon rate through chargino, charged Higgs loops

. . .

Higgs mixing effects

$$\begin{pmatrix} h & H \end{pmatrix} \begin{bmatrix} m_A^2 s_\beta^2 + M_Z^2 c_\beta^2 & -(m_A^2 + M_Z^2) s_\beta c_\beta + \text{Loop}_{12} \\ \star & m_A^2 c_\beta^2 + M_Z^2 s_\beta^2 \end{bmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

- In the decoupling limit: $m_A \gg M_Z$

  The lightest Higgs couplings are SM-like

- Introducing some mixing between the two Higgs bosons:

$$\begin{cases} \xi_d^h = \xi_\ell^h = -\dfrac{\sin\alpha}{\cos\beta} \\ \xi_u^h = \dfrac{\cos\alpha}{\sin\beta} \\ \xi_V^h = \sin(\beta - \alpha) \end{cases}$$

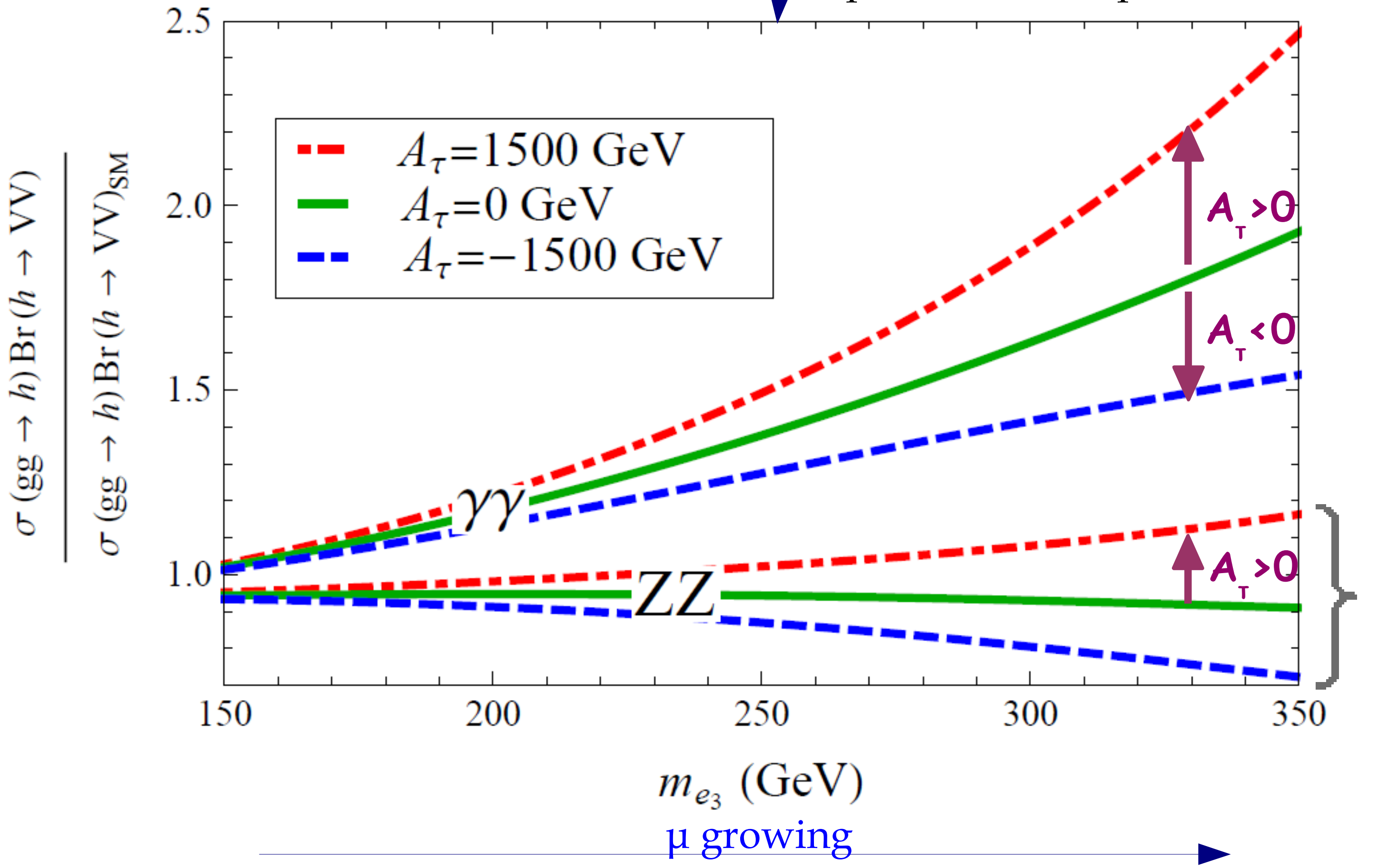
For generic mixings, the coupling with bottom quarks would be highly non-SM-like

The Higgs width would be very different from the one of the SM

It does not seem to be hinted by the data
(still it is a viable possibility)

Higgs mixing effects

At around this point the Higgs-stau potential has a problem of vacuum stability



Also the other modes are affected in the same way

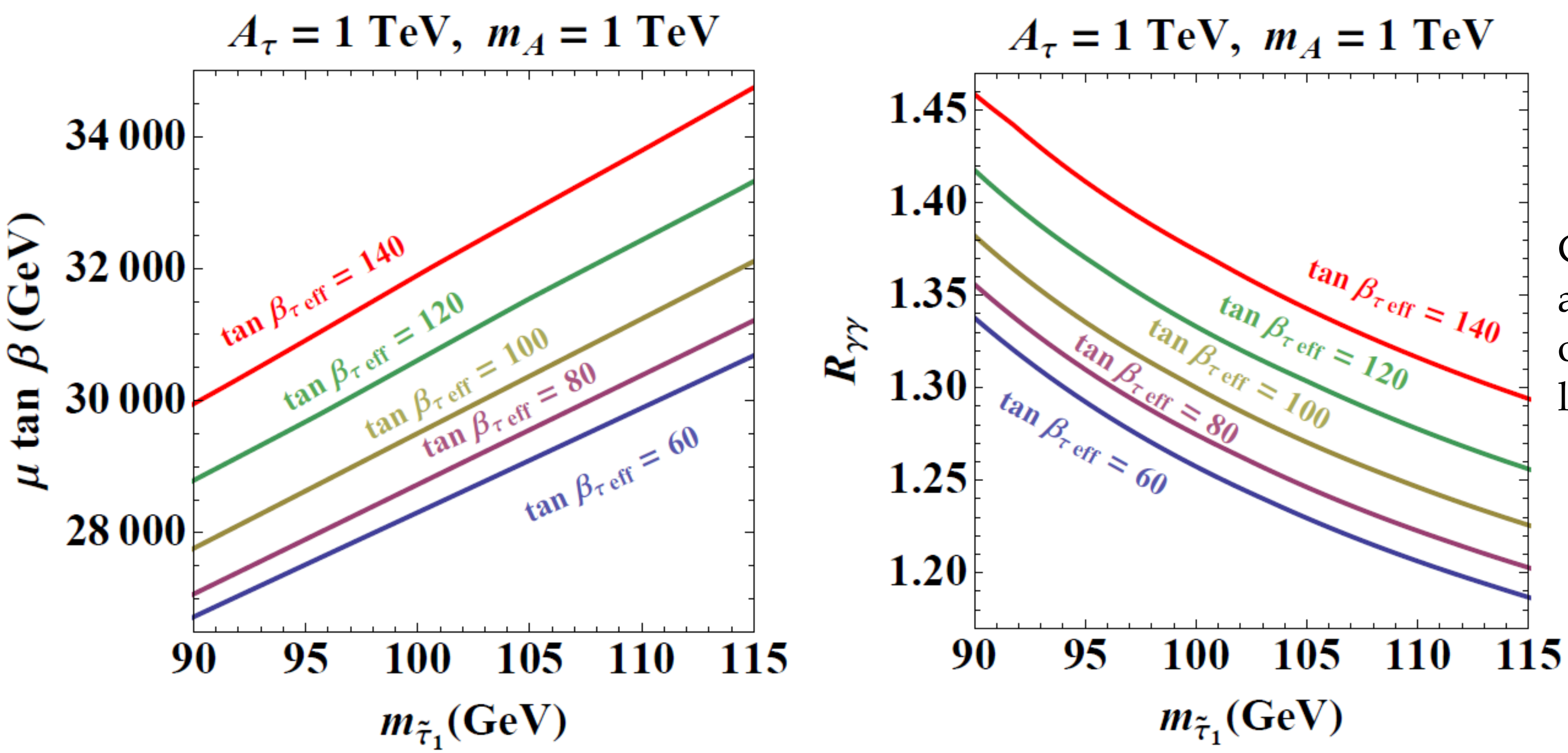
(we keep the stau mass constant (~90 GeV))

The effects on the branching ratio into two b-quarks is small (≤ 5-10%)
The bb mode is basically SM-like (same conclusion for the ττ mode)

More stringent vacuum stability bounds

In this limit one cannot neglect the scalar field ϕ_d anymore:

$$V \supset -2 y_\tau \mu \tilde{L} \tilde{\tau} \phi_u + \tilde{L}^2 \tilde{\tau}^2 \left(y_\tau^2 - \frac{g_1^2}{2} \right) \underbrace{- 2 \frac{m_A^2}{\tan\beta} \phi_d \phi_u + 2 y_\tau A_\tau \tilde{L} \tilde{\tau} \phi_d}$$



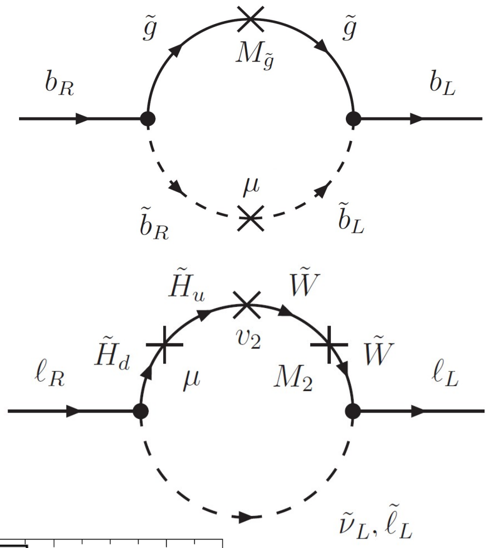
Corresponding to a suppression of the bb rate by less than 10%

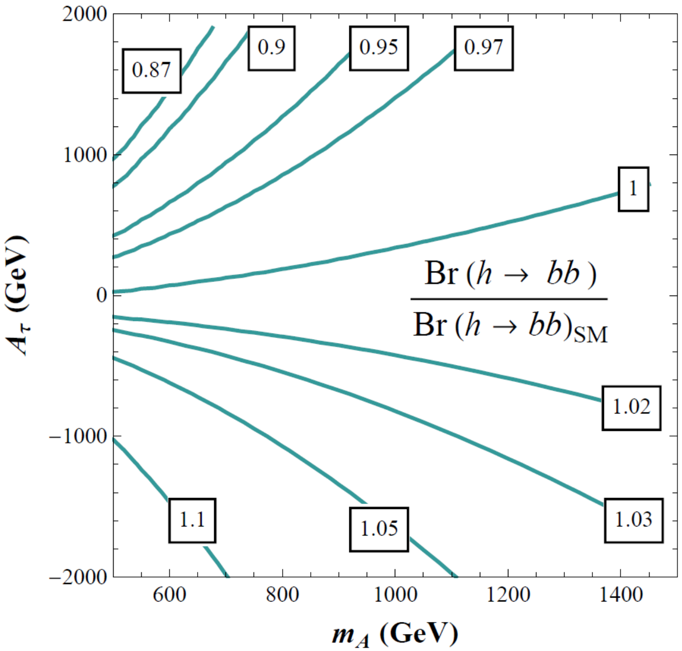
Only a precision measurement of the Higgs couplings can tell which is the right scenario

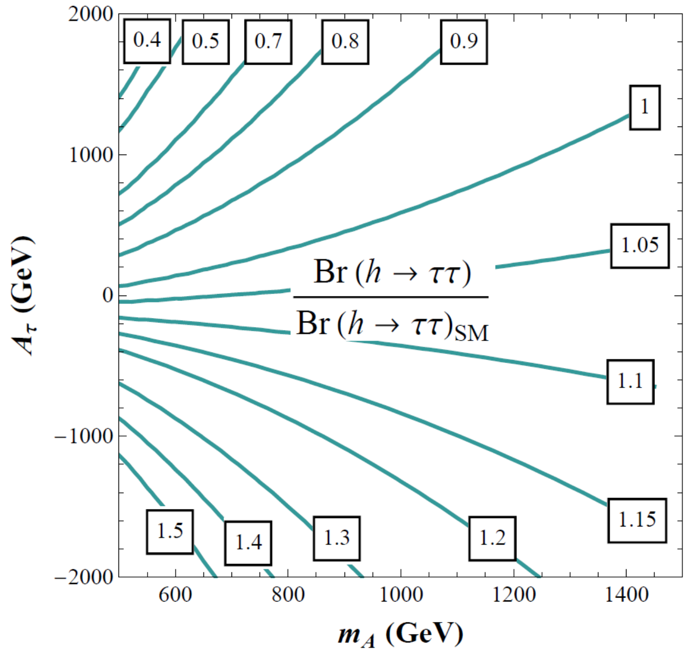
bb and ττ modes

Carena, SG, Shah, Wagner, Wang, work in progress

$$\begin{cases} g_{hbb,h\tau\tau} = -h_{b,\tau}\sin\alpha + \Delta h_{b,\tau}\cos\alpha \\ g_{hbb,h\tau\tau} = -\dfrac{m_{b,\tau}\sin\alpha}{v\cos\beta(1+\Delta_{b,\tau})}\left[1 - \dfrac{\Delta_{b,\tau}}{\tan\beta\tan\alpha}\right] \\ \dfrac{g_{hbb}}{g_{h\tau\tau}} = \dfrac{m_b(1+\Delta_\tau)\,(1-\Delta_b/(\tan\beta\tan\alpha))}{m_\tau(1+\Delta_b)\,(1-\Delta_\tau/(\tan\beta\tan\alpha))} \end{cases}$$







$A_t = 2\text{TeV},\ m_{Q_3} = 1.65\text{TeV},\ m_{u_3} = 200\text{GeV},\ m_{L_3} = m_{e_3} = 280\text{GeV},\ \tan\beta = 60$

MSSM Higgs properties

<u>At the tree level</u>

Higgs mixing angle

$$\begin{cases} \xi_u^h = \dfrac{\cos\alpha}{\sin\beta} \\ \xi_d^h = \xi_\ell^h = -\dfrac{\sin\alpha}{\cos\beta} \\ \xi_V^h = \sin(\beta-\alpha) \end{cases}$$

Couplings normalized to the SM value

+

Couplings with sparticles and additional Higgs bosons

Giving the effective couplings

$\xi_\gamma^h,\ \xi_g^h$

$$\sigma(pp \to h \to X_{\rm SM}) = \sigma(pp \to h)\frac{\Gamma(h \to X_{\rm SM})}{\Gamma_{\rm tot}}$$

Main contribution coming from gluon gluon fusion,

Dominated by Γ_{bb}

Is this the Higgs boson?

New program: Higgs Identification

What makes a Higgs a Higgs?

1) **Spin 0 boson**
- **Spin 1 is excluded, but spin 2 is hard to exclude**

2) **CP even**
- **Pure CP odd should be ruled out or in this year**

3) **Taking a vev and breaking SU(2)×U(1)**

An (incomplete) list

Chivukula et. al.1207.0450
Coleppa et. al. 1208.2692
Bellazzini et. al, 1209.3299
Chacko et. al. 1209.3259, ...

Well motivated „Higgs imposter"

Dilaton (conformal strong dynamics)

Radion (warped extra dimensional models)

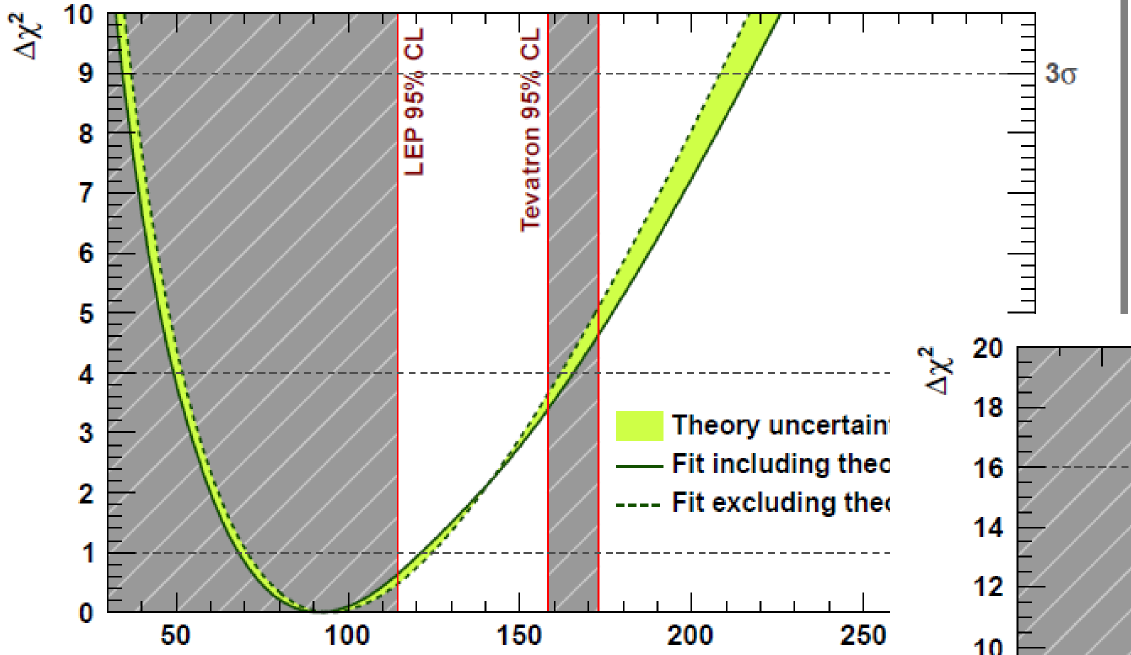
Plain singlets & triplets (extended Higgs sectors)

Low, Lykken, Shaughnessy 1207.1093

Let me call the new boson the Higgs boson

The mass of the Higgs

A mass that one could have expected?



Gfitters, 1107.0975