

Title: Light sleptons, Higgs phenomenology and the vacuum

Date: Dec 07, 2012 01:00 PM

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Abstract: We analyze the implications for Susy theories of a Higgs to di-photon rate enhanced, if compared to the Standard Model prediction. We show how models predicting a sizable enhancement have generically an electroweak vacuum that is not absolutely stable. In particular we discuss the only viable scenario that can predict sizable new physics effects in the di-photon rate in the framework of the MSSM: a scenario with light and heavily mixed staus. We conclude with the phenomenology of this model and with the prospects of probing it at the LHC, through the direct production of light staus.

Outline

1. Introduction: the **discovery** of a new boson

2. Vacuum stability & Higgs to di-photon rate & Susy

- ♦ The Higgs gamma gamma rate in the MSSM (wino-Higgsino, **staus**)
- ♦ Constraints from vacuum stability

3. Phenomenology of the light stau model

- ♦ Constraints (EWPTs, DM abundance)
- ♦ (g-2)
- ♦ Direct production of light staus at the LHC

1. „A 125 GeV SM-like Higgs in the MSSM and the $\gamma\gamma$ rate“

Carena, Gori, Shah, Wagner arXiv: 1112.3336, JHEP 1203 (2012) 014

2. „Light Stau Phenomenology and the $\gamma\gamma$ Higgs Rate“

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3. „Vacuum Stability and Diphoton Decays of a MSSM Higgs boson“

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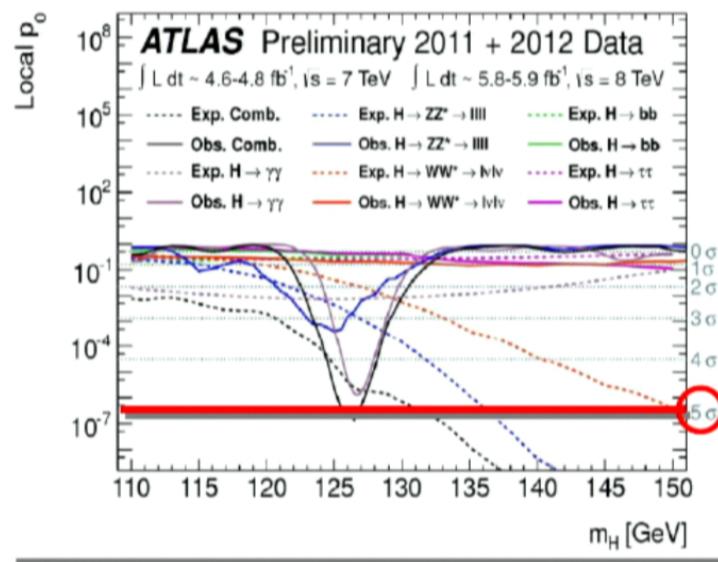
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We have a new boson!

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

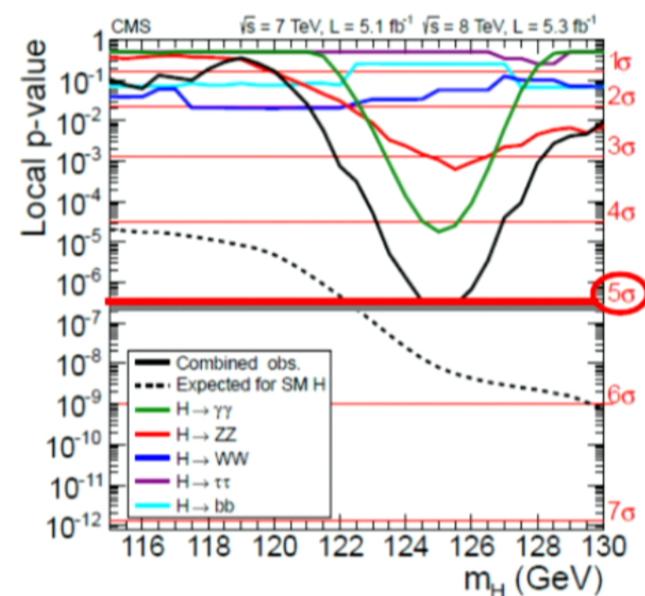
ATLAS

1207.7214



CMS

1207.7235



The nightmare scenario?

- ♦ Higgs at 125-126 GeV: most important result from the LHC so far
- ♦ No signs of low energy supersymmetry/exotic resonances yet
- ♦ 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!

$\text{BR}(h \rightarrow b\bar{b})$	=	58%, $\text{BR}(h \rightarrow ZZ^*)$ = 2.7%,
$\text{BR}(h \rightarrow WW^*)$	=	21.6%, $\text{BR}(h \rightarrow \tau\bar{\tau})$ = 6.4%,
$\text{BR}(h \rightarrow \gamma\gamma)$	=	0.22%, $\text{BR}(h \rightarrow \gamma Z)$ = 0.16%

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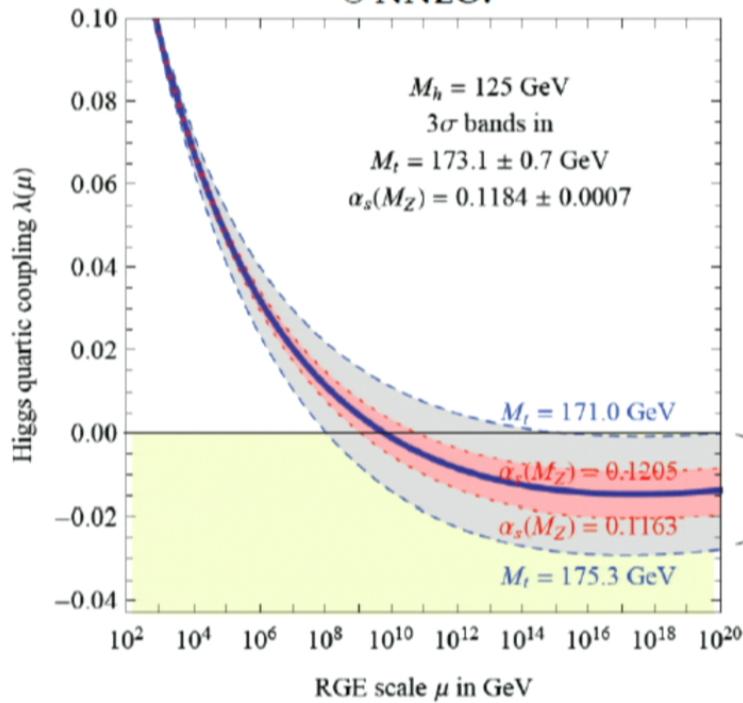
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Vacuum stability in the SM

@ NNLO:



Condition of absolute stability:

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

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

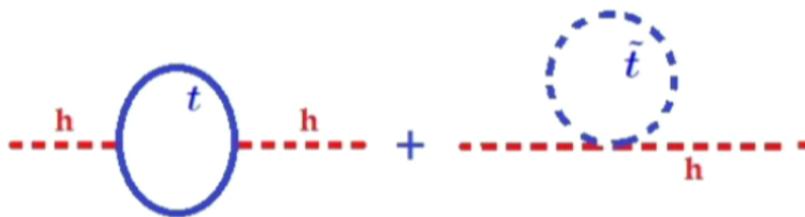
Variation by $\pm 3\sigma$

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

$M_h < 126 \text{ GeV}$ excluded at the 2σ level

Naturalness and the Higgs rates

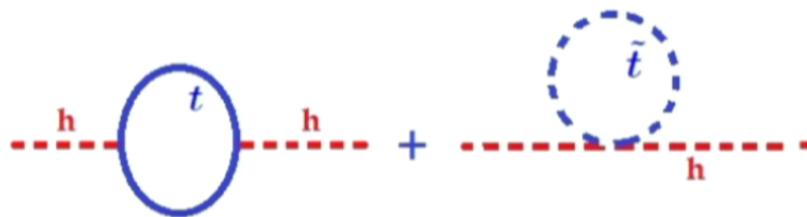
- ♦ New (light) particles introduced in models to address the **gauge hierarchy problem** also naturally enter in the gluon fusion Higgs production cross section and diphoton rate



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

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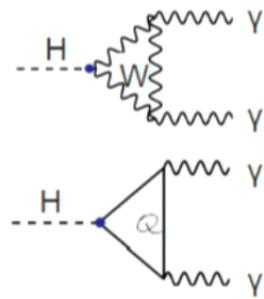


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Any connection with the vacuum?

In the SM the di-photon coupling

$\gamma\gamma$ coupling



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

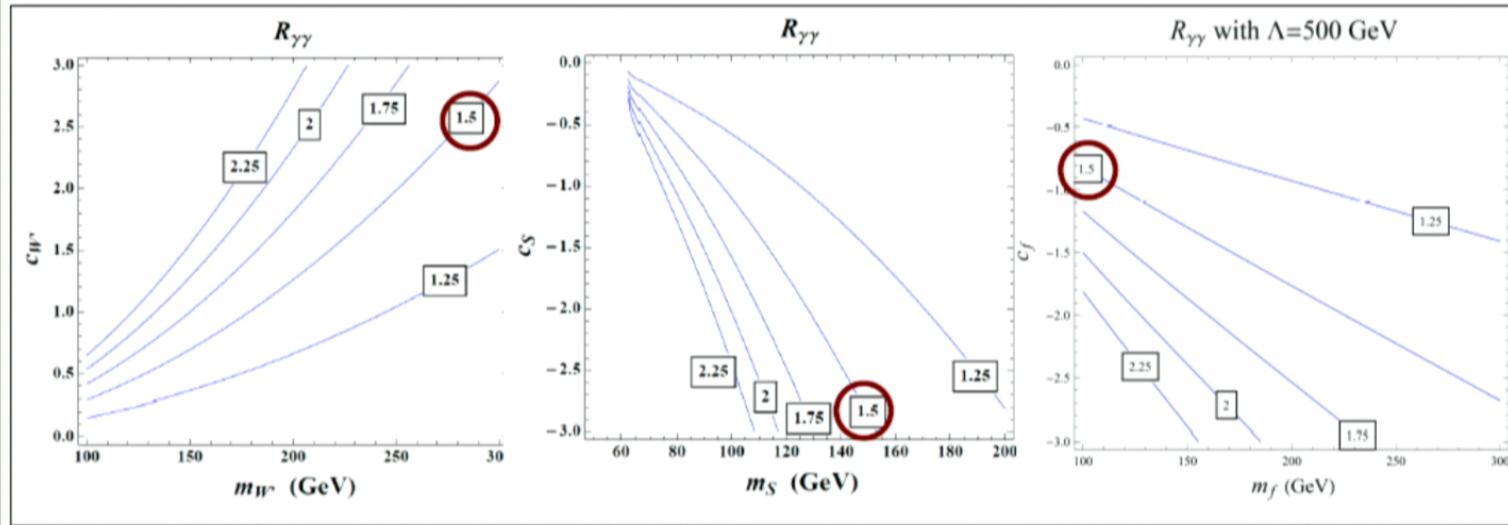
Standard Model:
Top contribution: $\Delta_t = \left(\frac{4}{3}\right)^2$
W contribution

W loop is the dominant contribution

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

New light electroweak particles

Carena, Low, Wagner, 1206.1082



New W boson

$$\frac{c_{W'}}{2} g^2 |H|^2 W'_\mu W^{\mu\nu}$$

New scalar

$$c_S |H|^2 |S|^2$$

New fermion

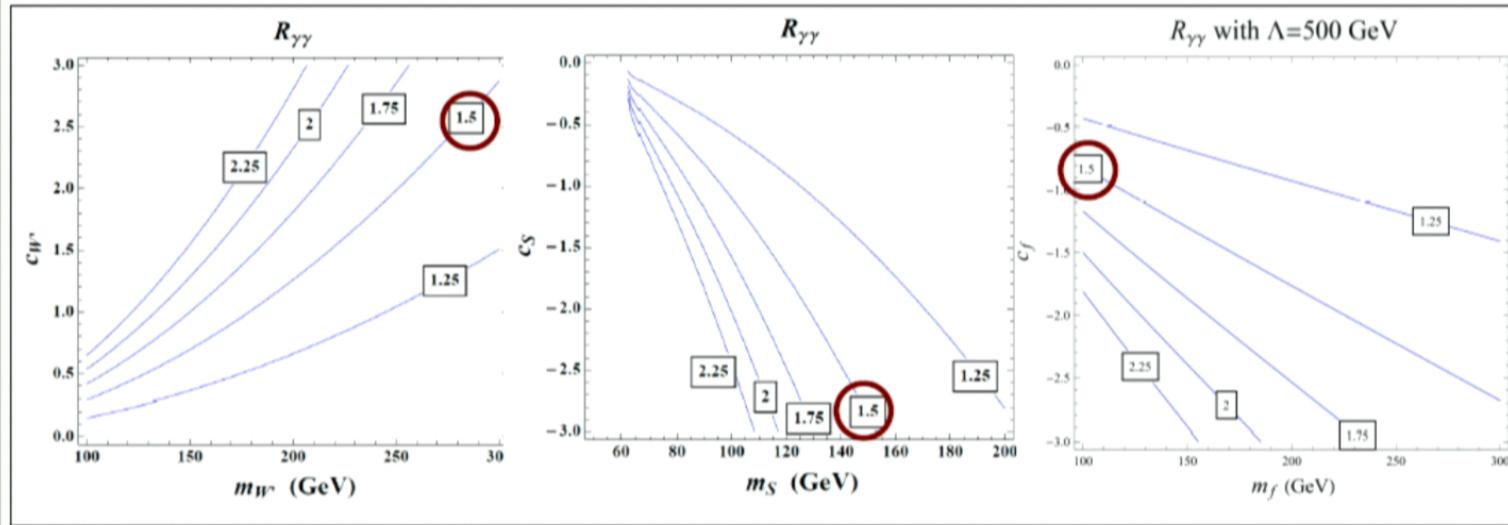
$$\frac{c_f}{\Lambda} |H|^2 \bar{f} f$$

See also Batell, SG, Wang, 1112.5180

The new particle has to be very light and sizably coupled with the Higgs

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Any good Susy candidate to enhance the di-photon rate?

1. Thinking to natural susy: light charginos
2. Other options? What about light scalars?

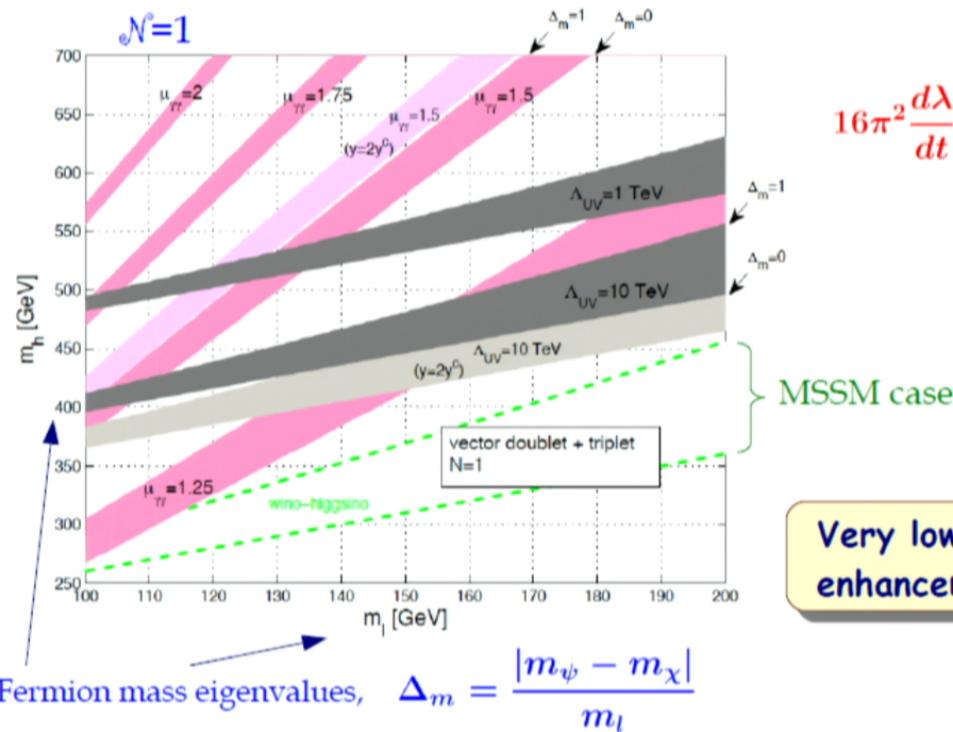
Split-like Susy models

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

Wino+Higgsino model:

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

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



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

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

See also Joglekar, Schwaller, Wagner, 1207.4235

S.Gori

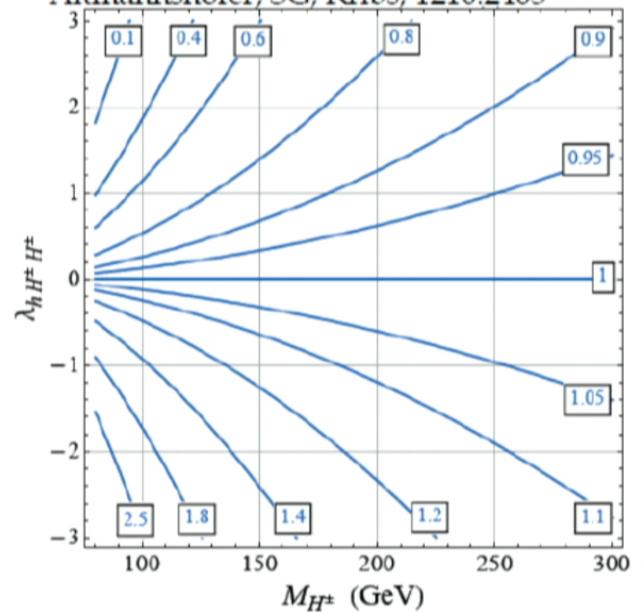
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Charged Higgs contributions

$$\Gamma(h \rightarrow \gamma\gamma) \sim \frac{\alpha^2 m_h^3}{1024\pi^3} \left| \frac{g_{hWW}}{m_W^2} A_1(x_W) - N_c Q_t^2 \frac{2g_{ht\bar{t}}}{m_t} A_{1/2}(x_t) + \frac{\lambda_{hH^\pm H^\pm} v}{m_{H^\pm}^2} A_0(x_{H^\pm}) \right|^2$$

Altmannshofer, SG, Kribs, 1210.2465



Maximized at
very small $\tan\beta$

$$|\lambda_{hH^\pm H^\pm}^{\text{MSSM}}| \lesssim \frac{g^2}{2} \sim 0.21$$

Quartic couplings in the MSSM
are dictated by the gauge couplings

And also, if very light charged Higgs:

- generically too large NP contributions to $b \rightarrow s\gamma$, $B \rightarrow \tau\nu$, ...
- mixing between the two Higgs scalars,
inducing dramatic change in the Higgs pheno

However see Schmidt, Staub, 1208.1683

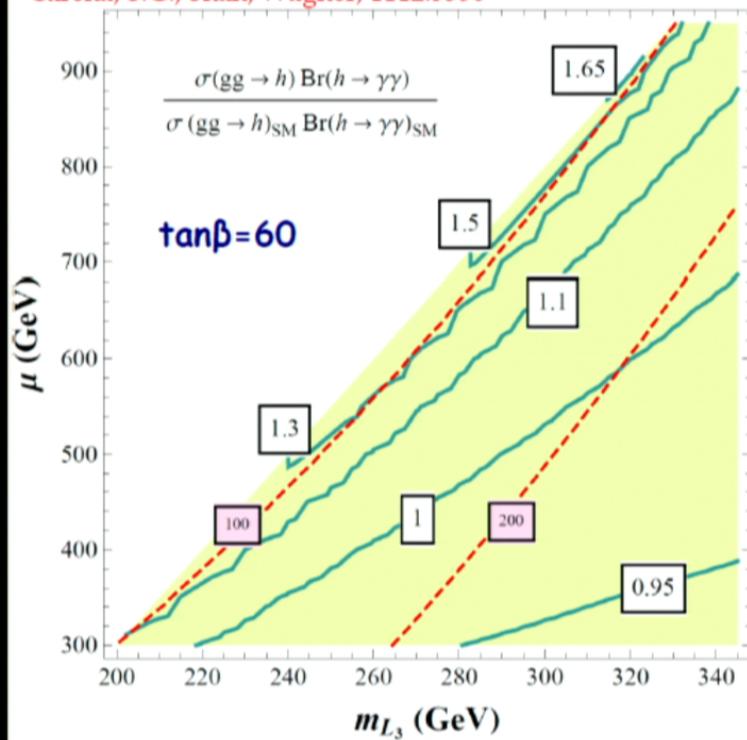
Very small NP effects coming from the MSSM charged Higgs

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



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

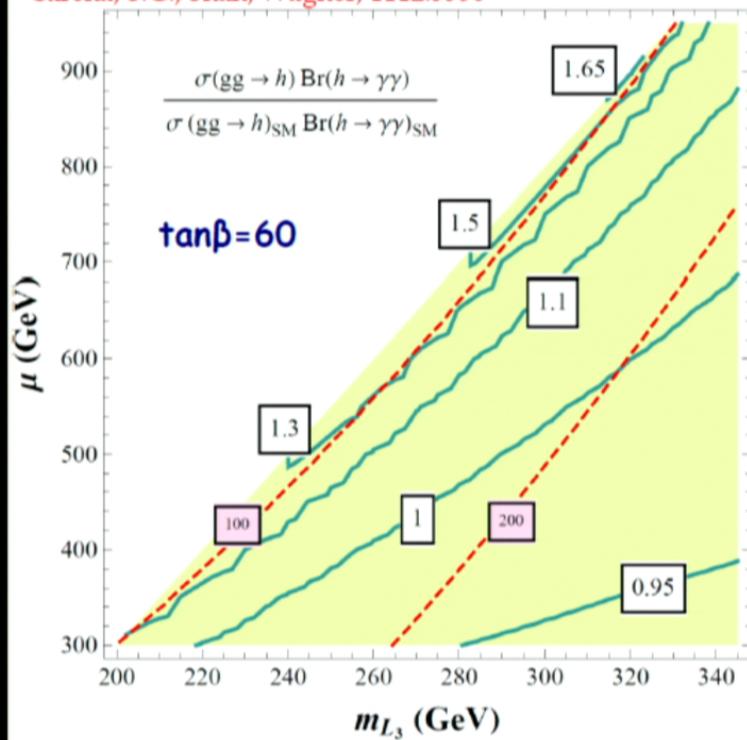
Heavily mixed light (LEP bound ~95GeV)
staus can lead to sizable effect in the $\gamma\gamma$ rate

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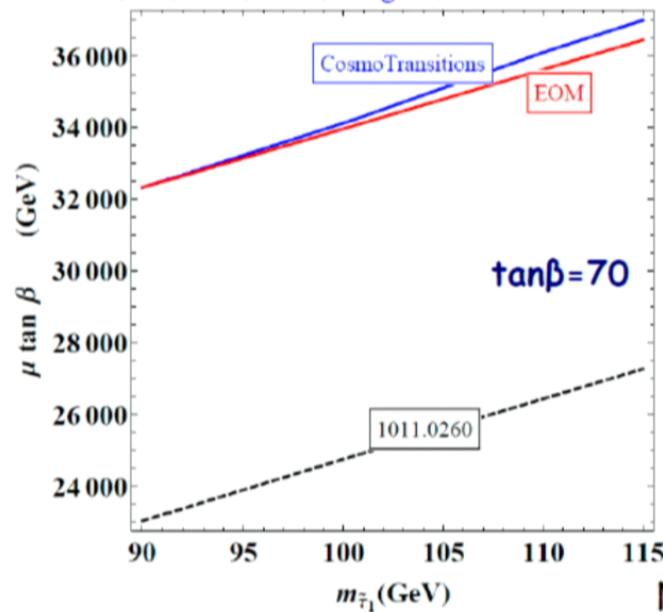
Vacuum stability in presence of light staus

Decoupling limit

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

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

Bound in Hisano, Sugiyama, 1011.0260

$$|\mu \tan \beta| < 76.9 \sqrt{m_{L_3} m_{E_3}} + \\ + 38.7(m_{L_3} + m_{E_3}) - 1.04 \times 10^4 \text{ GeV}$$

Kitahara, 1208.4752: with this bound enhancement of the $\gamma\gamma$ rate larger than $\sim 25\%$ are not possible

Note: we agree with the updated version of this paper

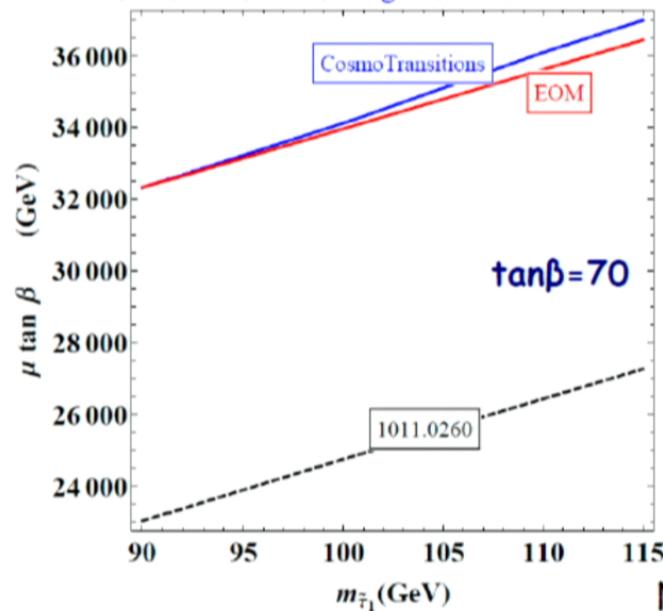
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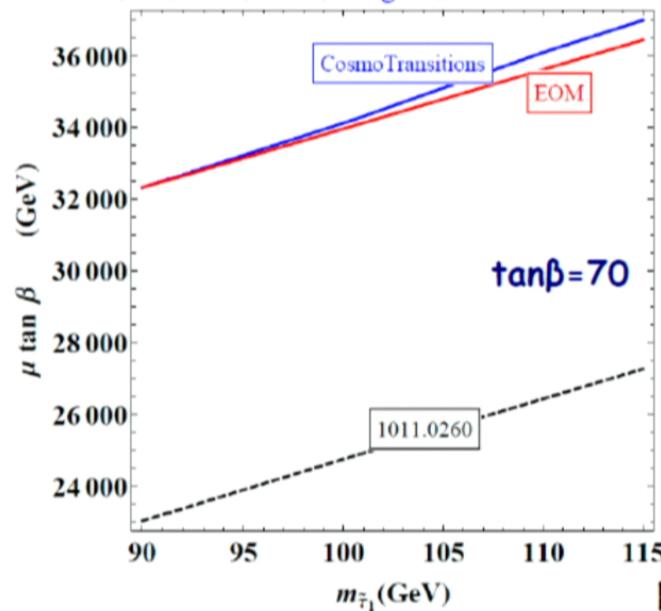
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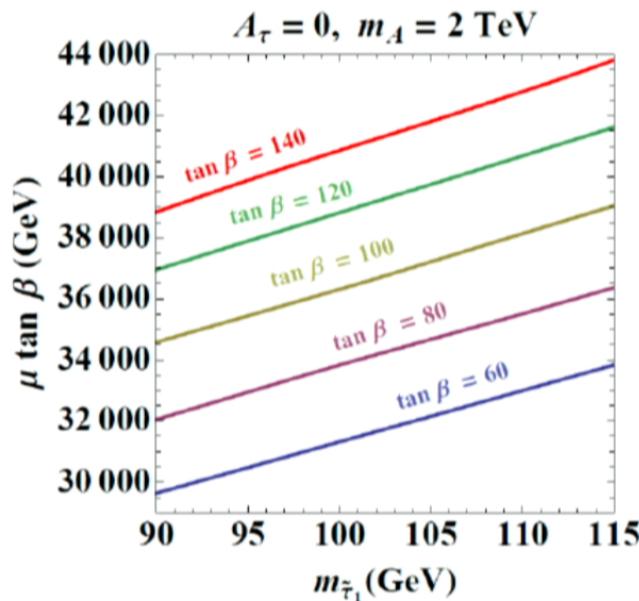
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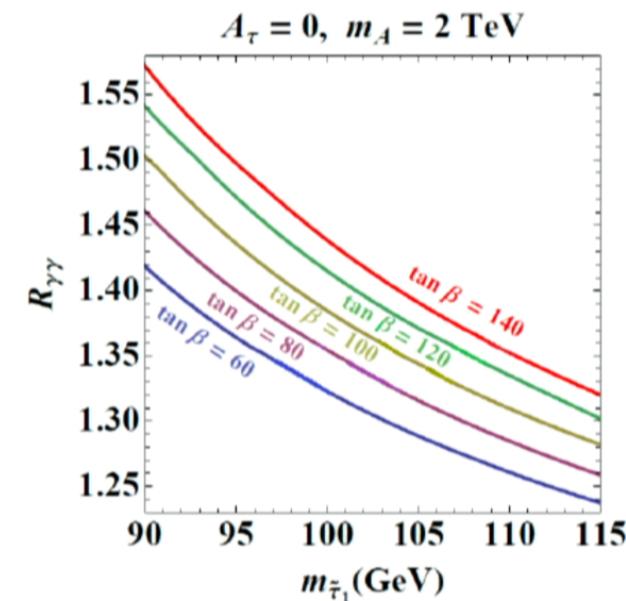
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Vacuum stability in presence of light staus

The $\tan\beta$ dependence of the bound is **not negligible**



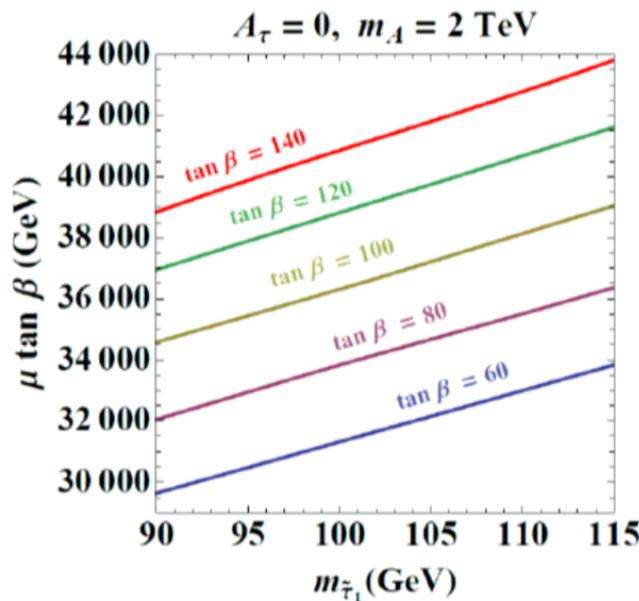
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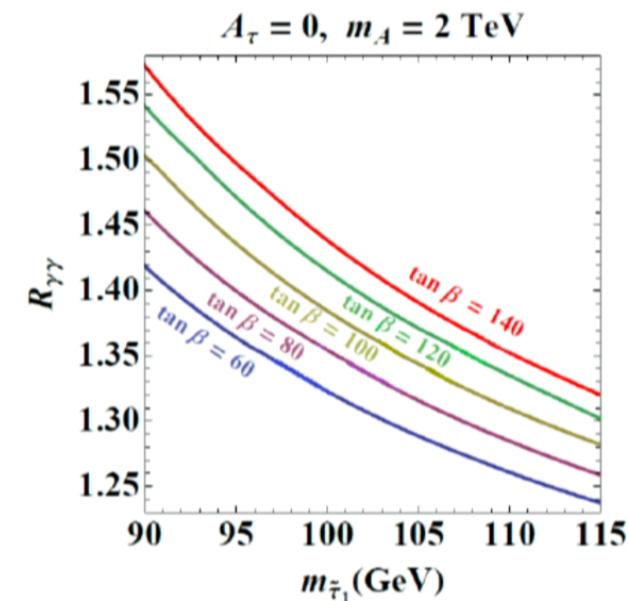
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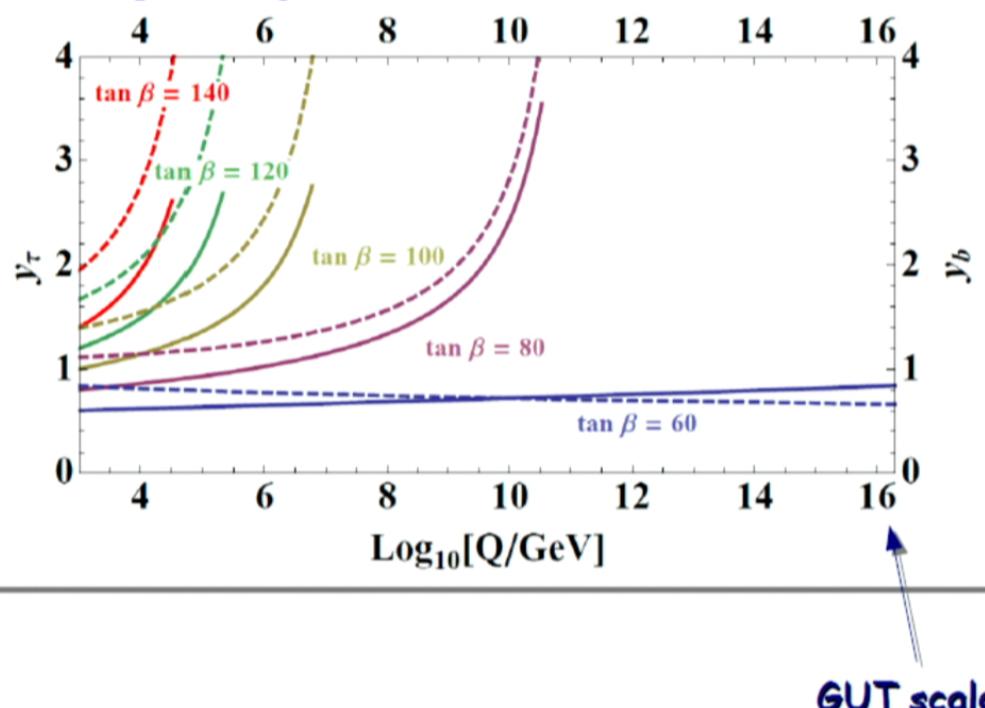
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Perturbativity bounds

- 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

Yukawa couplings

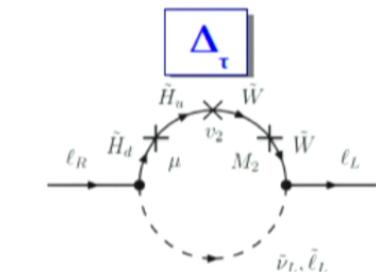
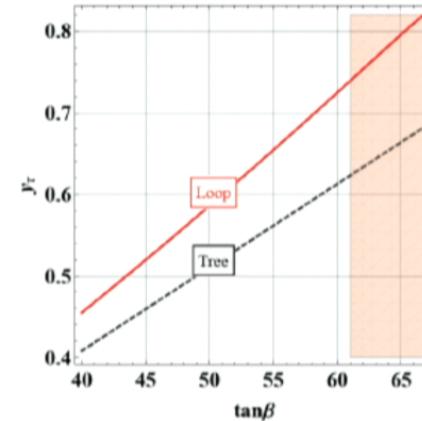
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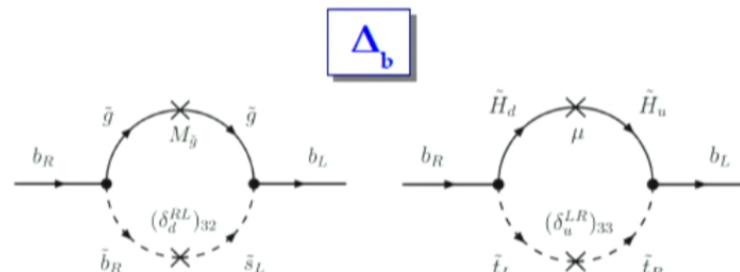
♦ Including loop corrections:

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

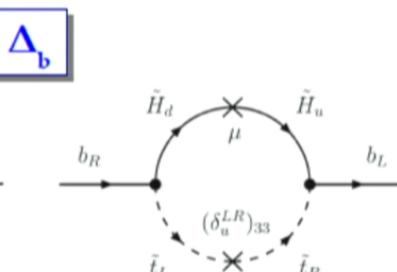
See for example Pierce et.al. 9606211
Carena et.al. 9808312



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



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



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

We can choose a scenario

with $\Delta_b = O(1) > 0$ and $\Delta_\tau = O(0.1) < 0$



$\tan \beta_{\tau \text{ eff}} > \tan \beta$, $\tan \beta_{b \text{ eff}} < \tan \beta$

Yukawa couplings

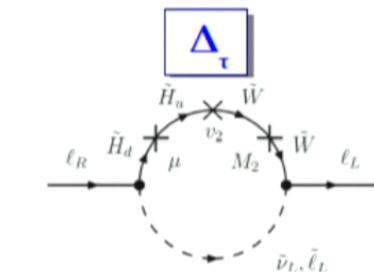
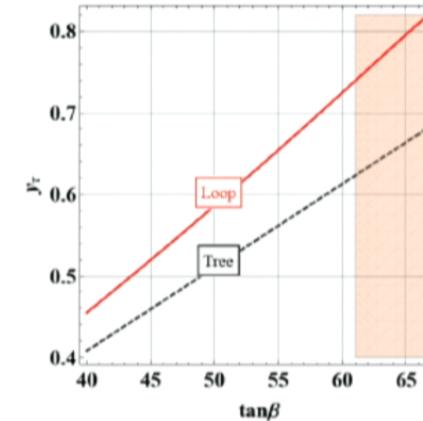
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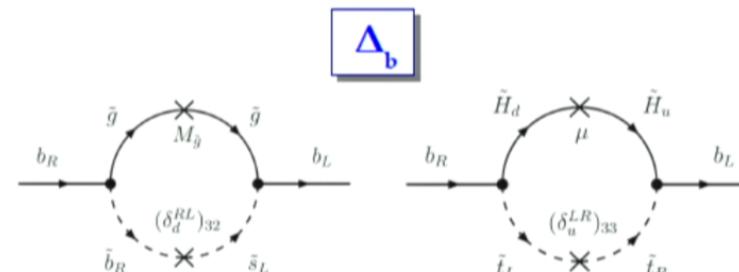
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We can choose a scenario

with $\Delta_b = \mathcal{O}(1) > 0$ and $\Delta_\tau = \mathcal{O}(0.1) < 0$



$\tan \beta_{\tau \text{ eff}} > \tan \beta$, $\tan \beta_{b \text{ eff}} < \tan \beta$

Other options...

Carena, SG, Shah, Wagner, Wang, 1205.5842

Almost decoupling limit

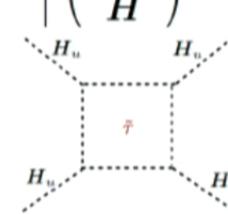
Maybe a possible di-photon enhancement is not just hinting towards the presence of new light charged particles but also of **additional Higgs bosons**...

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 bottom quarks

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

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

$$\begin{pmatrix} h & H \end{pmatrix} \begin{bmatrix} m_A^2 s_\beta^2 + M_Z^2 c_\beta^2 & -(m_A^2 + M_Z^2) s_\beta c_\beta + \text{Loop}_{12} \\ \star & m_A^2 c_\beta^2 + M_Z^2 s_\beta^2 \end{bmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$
$$\text{Loop}_{12} = \frac{m_\tau^4}{12\pi^2 v^2} \frac{\tan^4 \beta}{\sin^2 \beta} \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4} + \dots$$

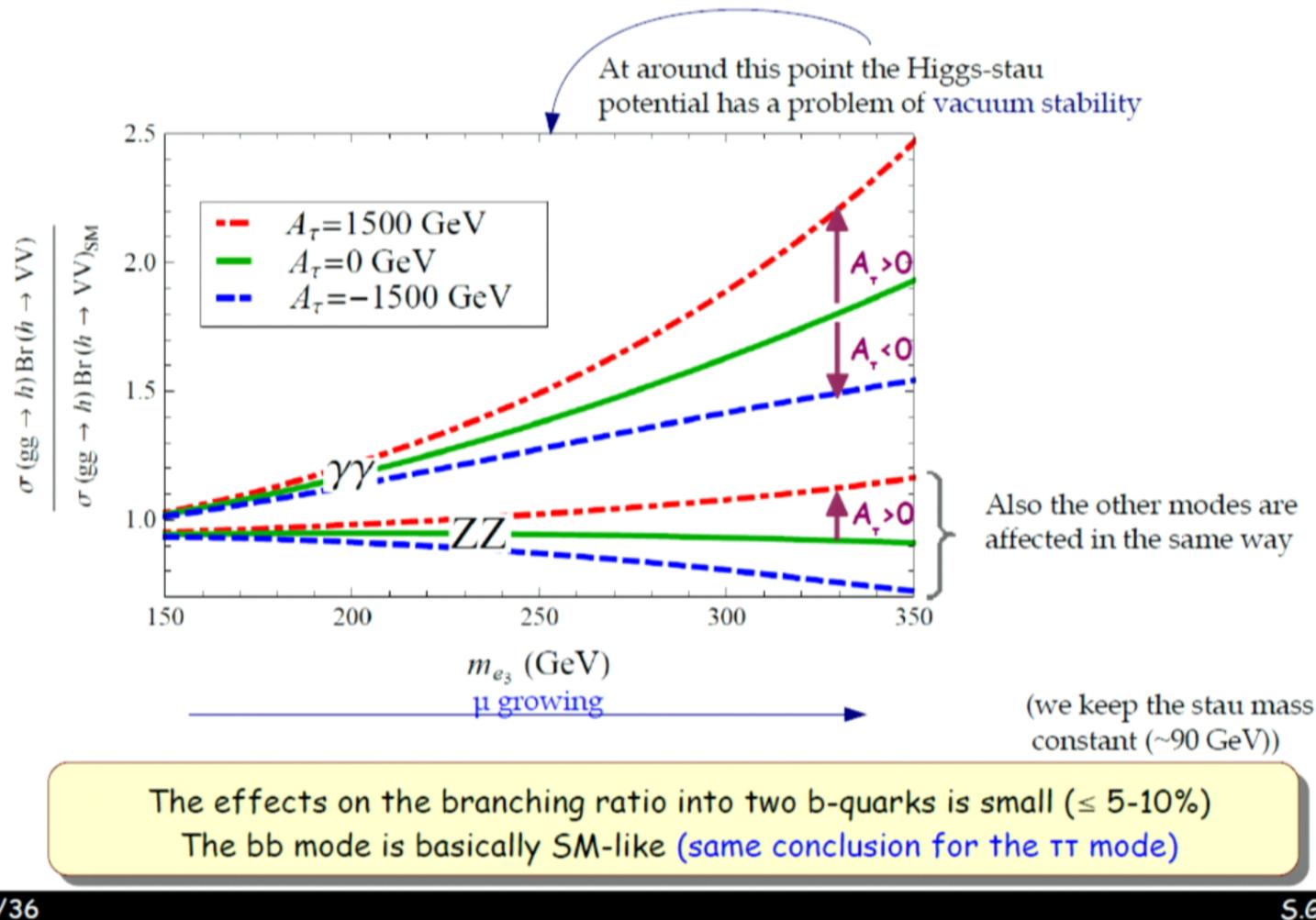


At large $\mu, A_\tau, \tan \beta$ we can have $|\xi_d^h| < 1$ (if $\text{Loop}_{12} > 0$) or $|\xi_d^h| > 1$ (if $\text{Loop}_{12} < 0$)

Γ_{bb} is suppressed

Γ_{bb} is enhanced

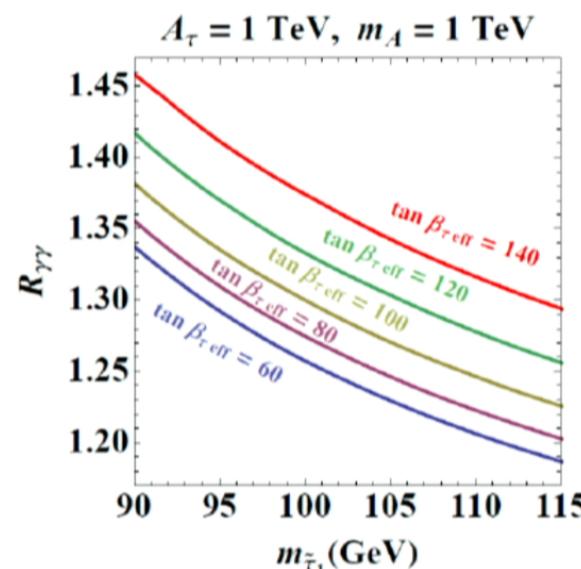
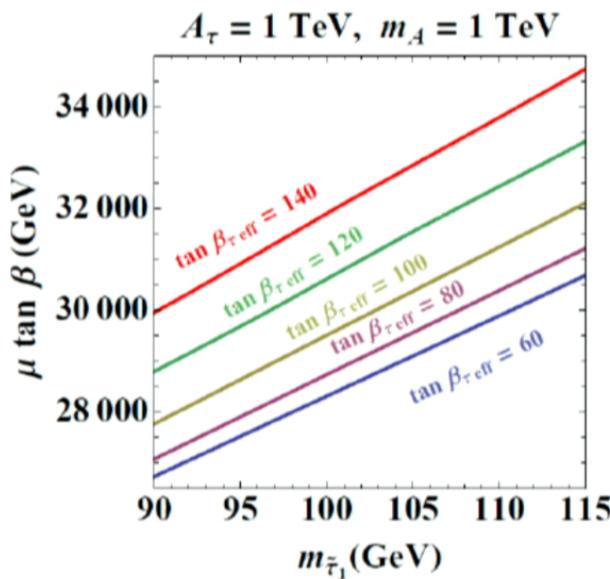
Higgs mixing effects



More stringent vacuum stability bounds

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

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



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**

Phenomenology of the light stau model

Based on

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

EWPTs
Dark matter constraints

} Constraints

$(g-2)_\mu$

} Predictions

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 electroweakinos
(sleptons, charginos) at ~ 100 GeV are still consistent with the data!

Electroweak Precision Tests

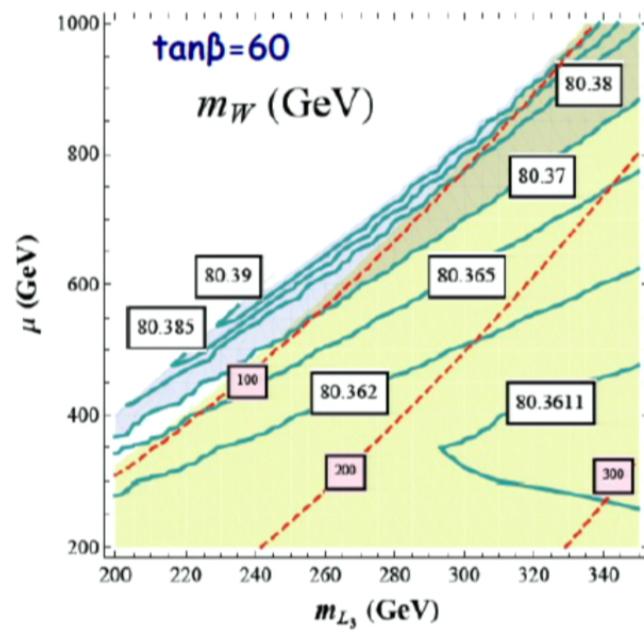
Staus: very light NP states charged under $SU(2) \times U(1)$

too large contribution to EWPTs?

New measurement of M_W :

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

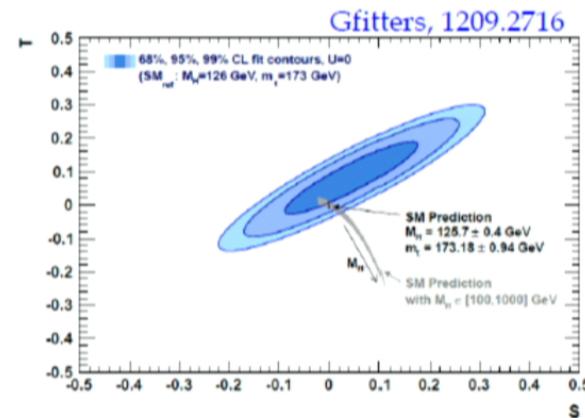
FERMILAB-TM-2532-E, 2012



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

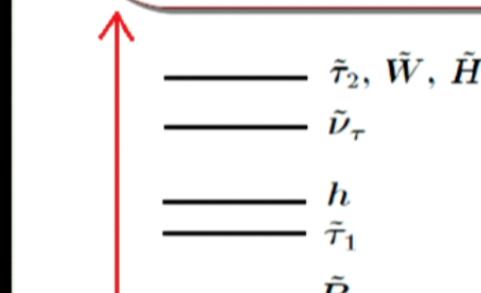
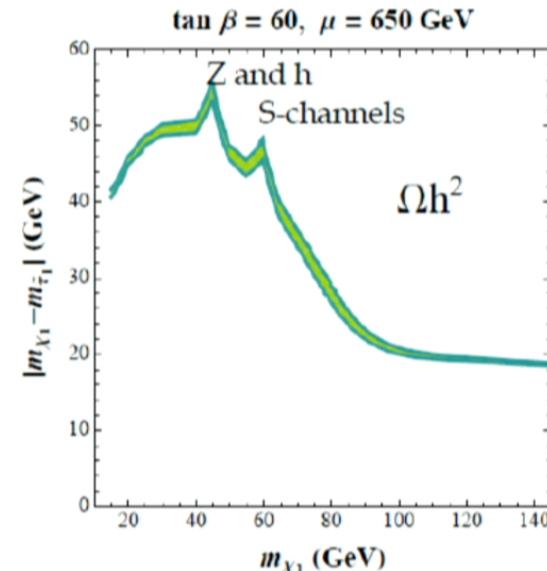
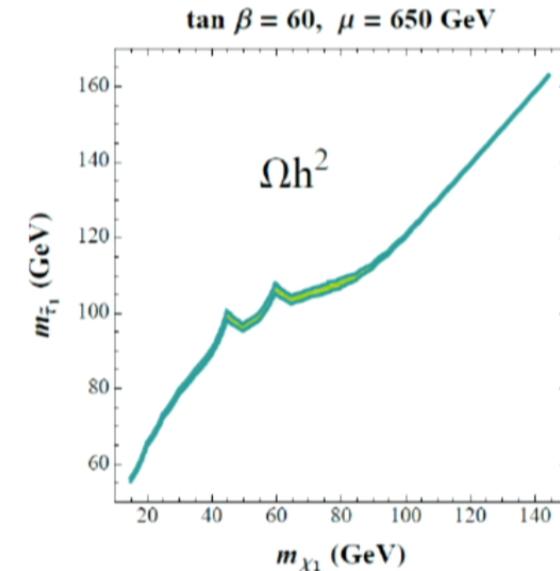


It corresponds to a contribution of (at most)

$$\Delta T \lesssim 0.1$$

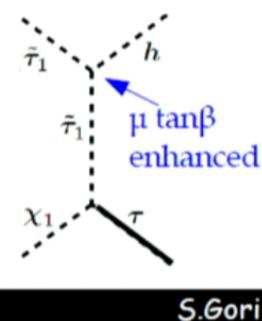
Some handle from Dark Matter?

Carena, SG, Shah, Wagner, Wang, 1205.5842



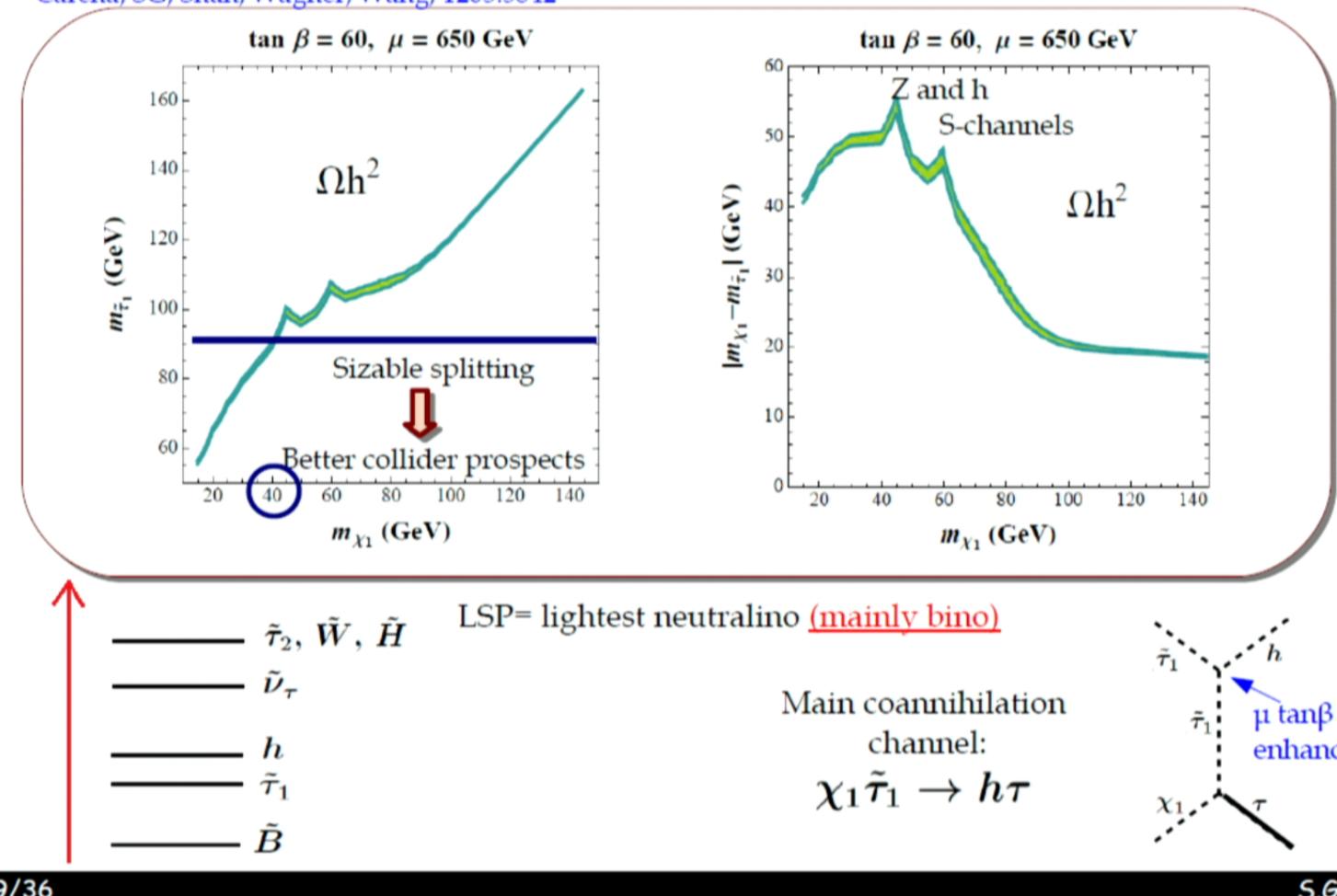
LSP= lightest neutralino (mainly bino)

Main coannihilation
channel:
 $\chi_1 \tilde{\tau}_1 \rightarrow h \tau$



Some handle from Dark Matter?

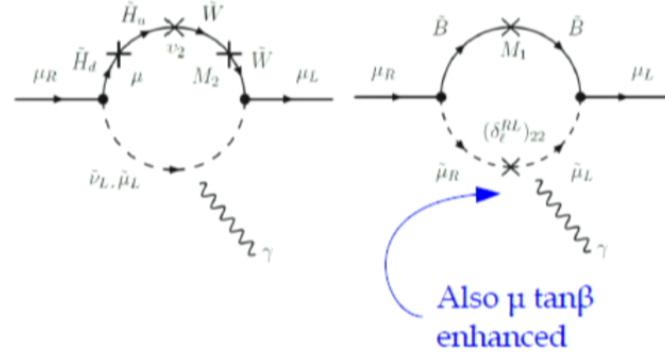
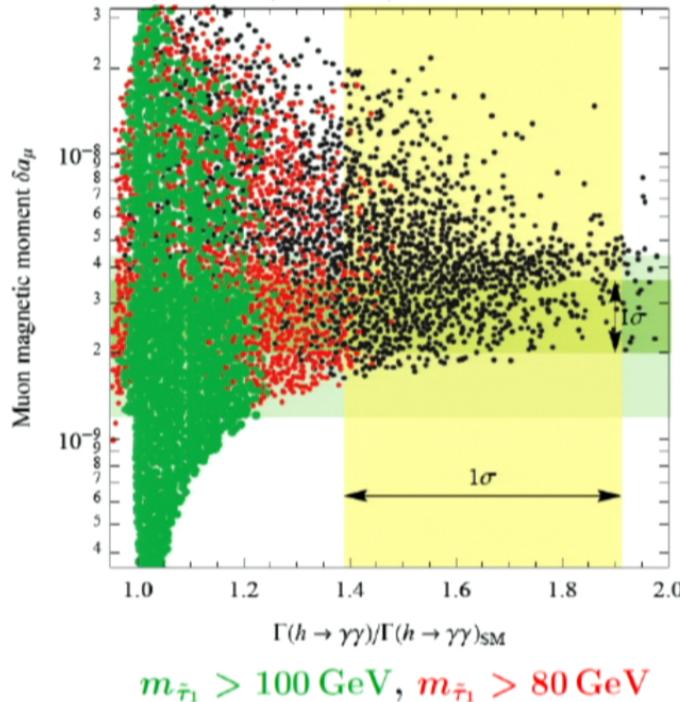
Carena, SG, Shah, Wagner, Wang, 1205.5842



$(g-2)_\mu$

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

Giudice, Paradisi, Strumia, 1207.6393



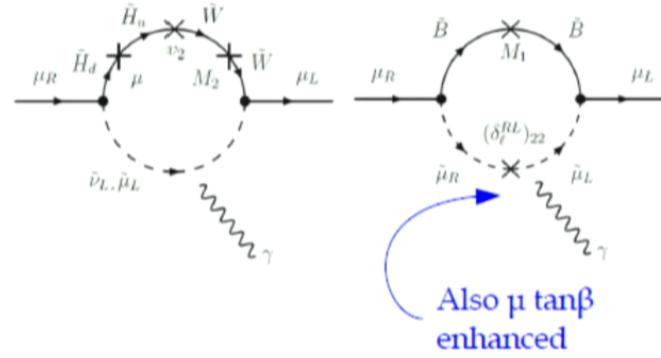
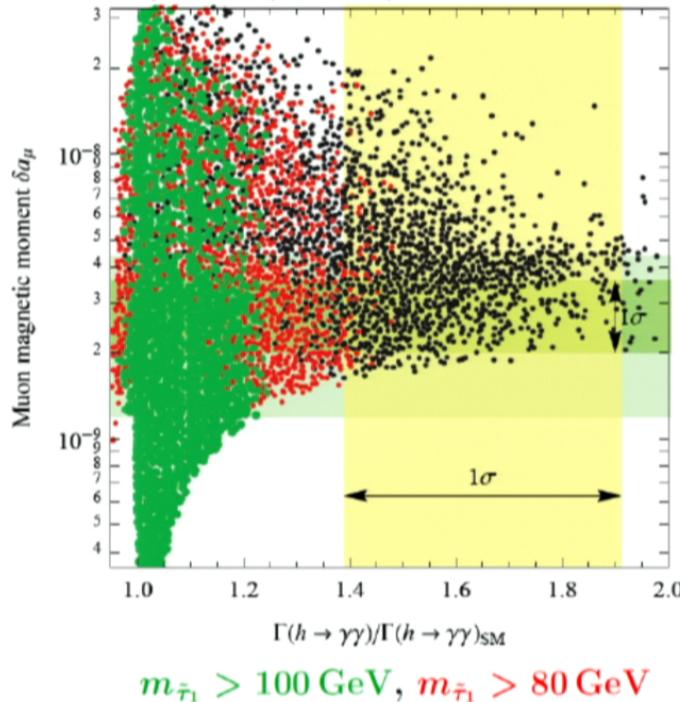
Correlation arising in the hypothesis of

- ♦ 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
- ♦ Slepion soft masses below the TeV

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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 promptly decaying

- ♦ 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

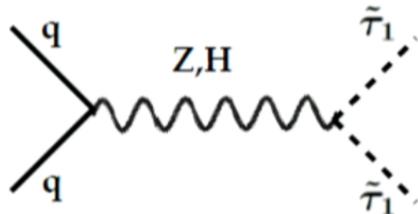
- ♦ CMS & ATLAS **multilepton searches** $\tilde{\chi}^\pm \rightarrow \tilde{\chi}^0 W, \ell\bar{\nu}, \ell\nu$, $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z, \ell\bar{\ell}$
3 or more leptons final states And also limits on sleptons produced in cascade decays
[CMS: SUS-12-022, SUS-12-026, SUS-12-027](#) (old @7TeV: 1204.5341)
[ATLAS: ATLAS-CONF-2012-154](#) (old @7TeV 1208.3144)

Improved strategies to look for our light staus?

Stau pair production

Carena, SG, Shah, Wagner, Wang, 1205.5842

1) $pp \rightarrow \tilde{\tau}_1 \tilde{\tau}_1 \rightarrow (\tau \text{ LSP})(\tau \text{ LSP})$



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

See also Lindert, D. Steffen, Trenkel, 1106.4005

Main backgrounds: ,,

$Z + Z/\gamma^*$: Veto on the invariant mass close to m_Z

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%)

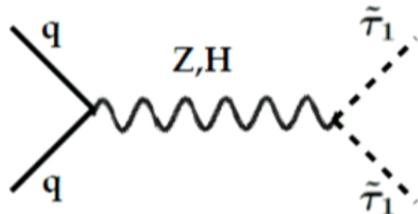
What about taus decaying leptonically?

Work in progress

Stau pair production

Carena, SG, Shah, Wagner, Wang, 1205.5842

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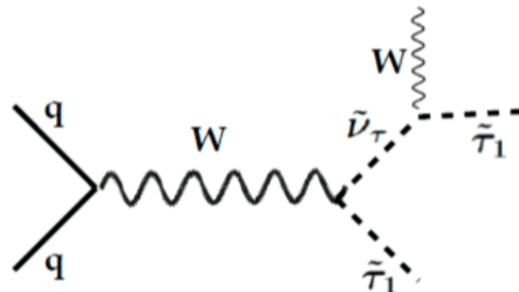
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Work in progress

Associated production

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

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:

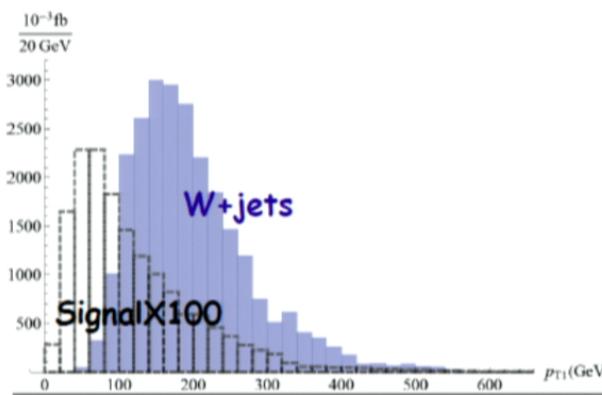
- ◆ $W + Z/\gamma^*$
- ◆ $W + \text{jets}$ (with jets faking taus)

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

Basic cuts for the 8TeV LHC:

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

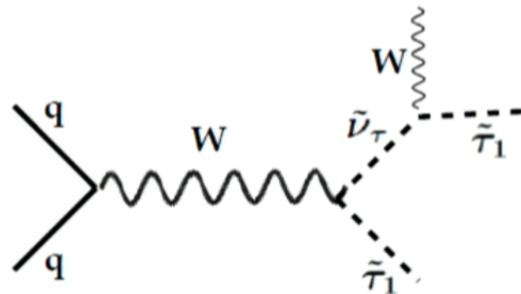
$$p_T^\ell > 70 \text{ GeV}, \not{E}_T > 70 \text{ GeV}$$



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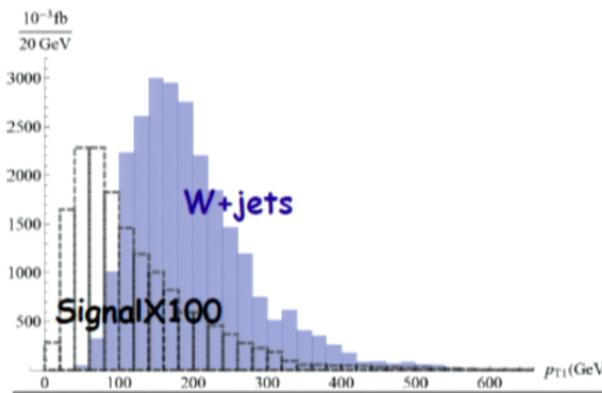
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$$p_T^\ell > 70 \text{ GeV}, \not{E}_T > 70 \text{ GeV}$$



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

Important connections with the vacuum of our universe