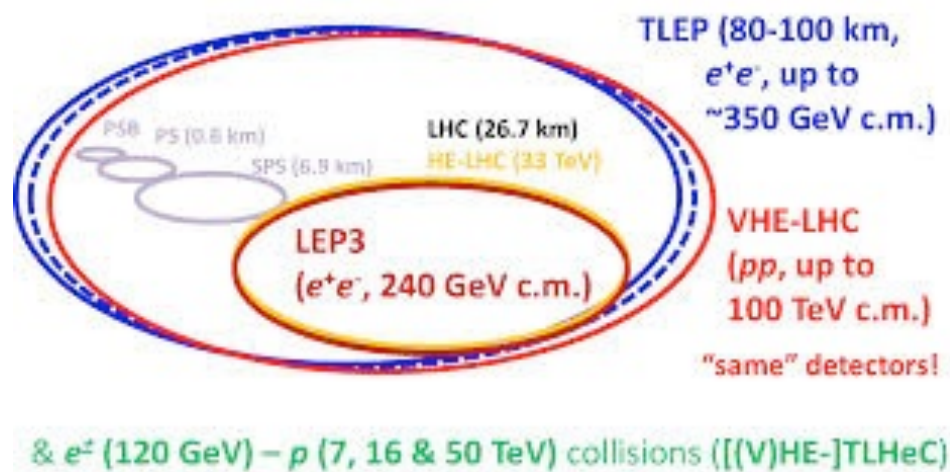


Interplay of TLEP and HL-LHC

$Z, W, \gamma, b, \tau, \mu$ $Z, W, \gamma, b, \tau, \mu$



H



g, Z, W, t | g, Z, W, t

Carlos E.M. Wagner
KICP and EFI, Univ. of Chicago
HEP Division Argonne National Lab



5th TLEP Workshop, Fermilab, 07.26.13

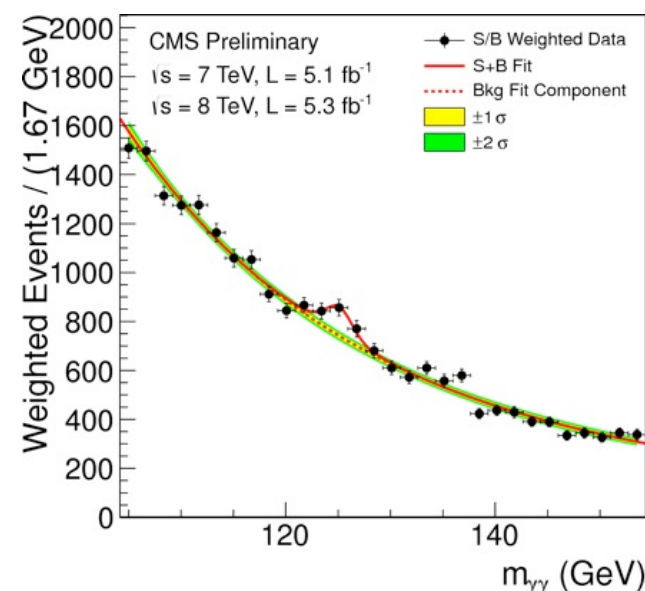
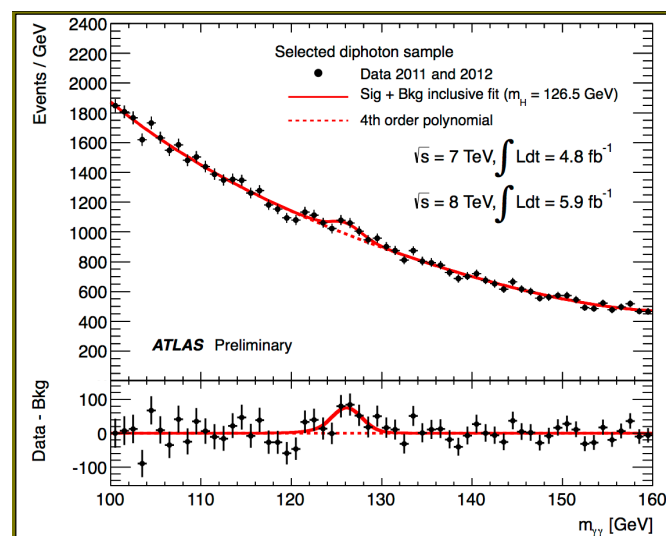
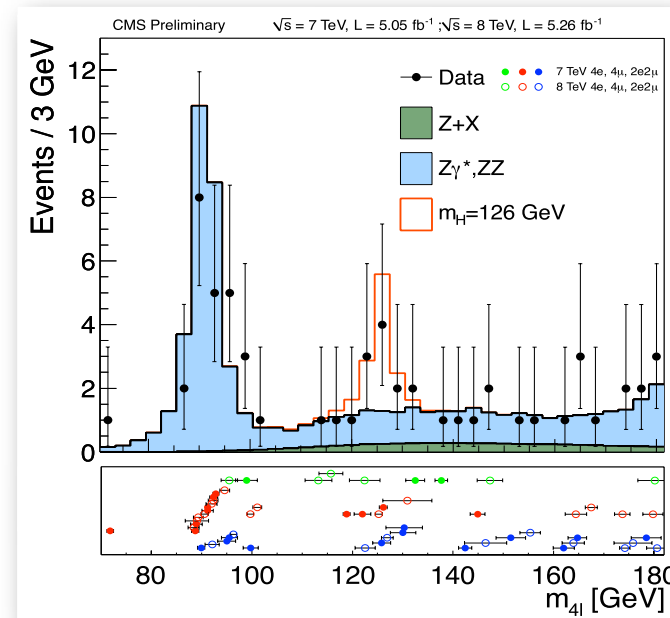
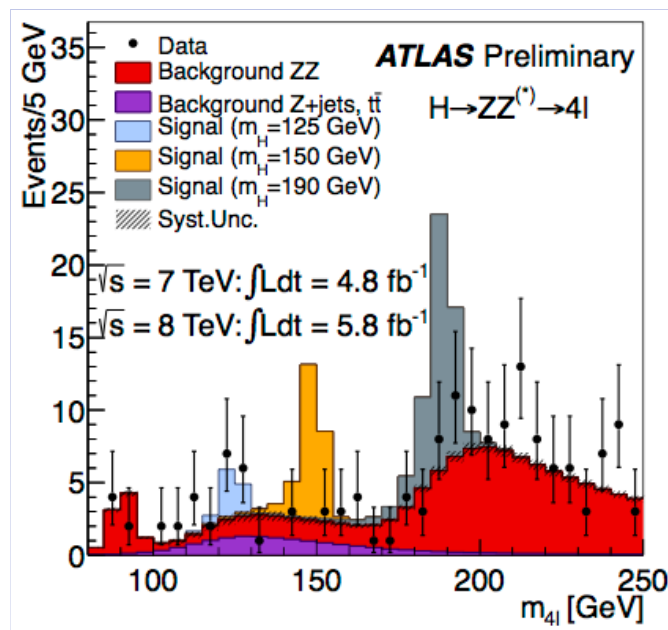


A Standard Model-like Higgs particle has been discovered by the ATLAS and CMS experiments at CERN

We see evidence of this particle in multiple channels.

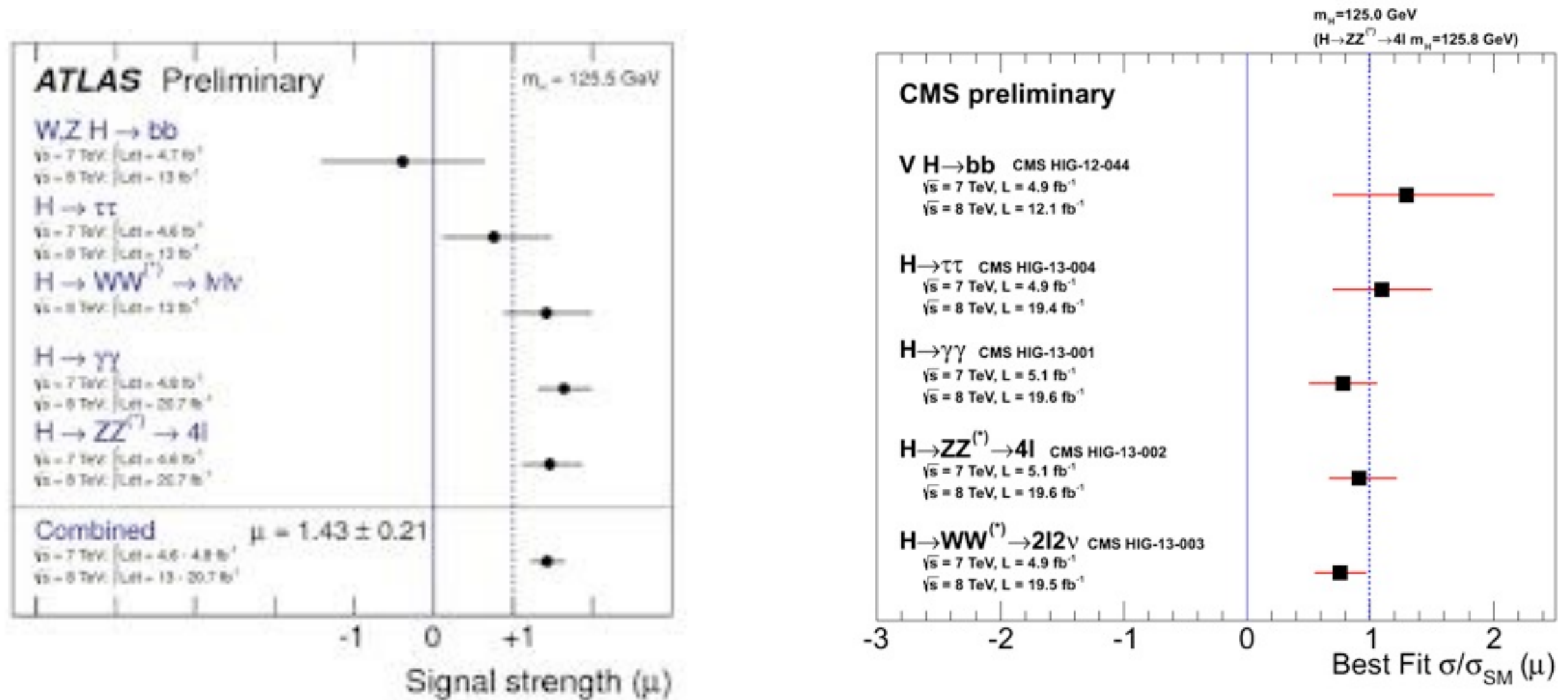
We can reconstruct its mass and we know that is about 125 GeV.

The rates are consistent with those expected in the Standard Model.



But we cannot determine the Higgs couplings very accurately

Large Variations of Higgs couplings are still possible



As these measurements become more precise, they constrain possible extensions of the SM, and they could lead to the evidence of new physics.

LHC :The Energy Frontier

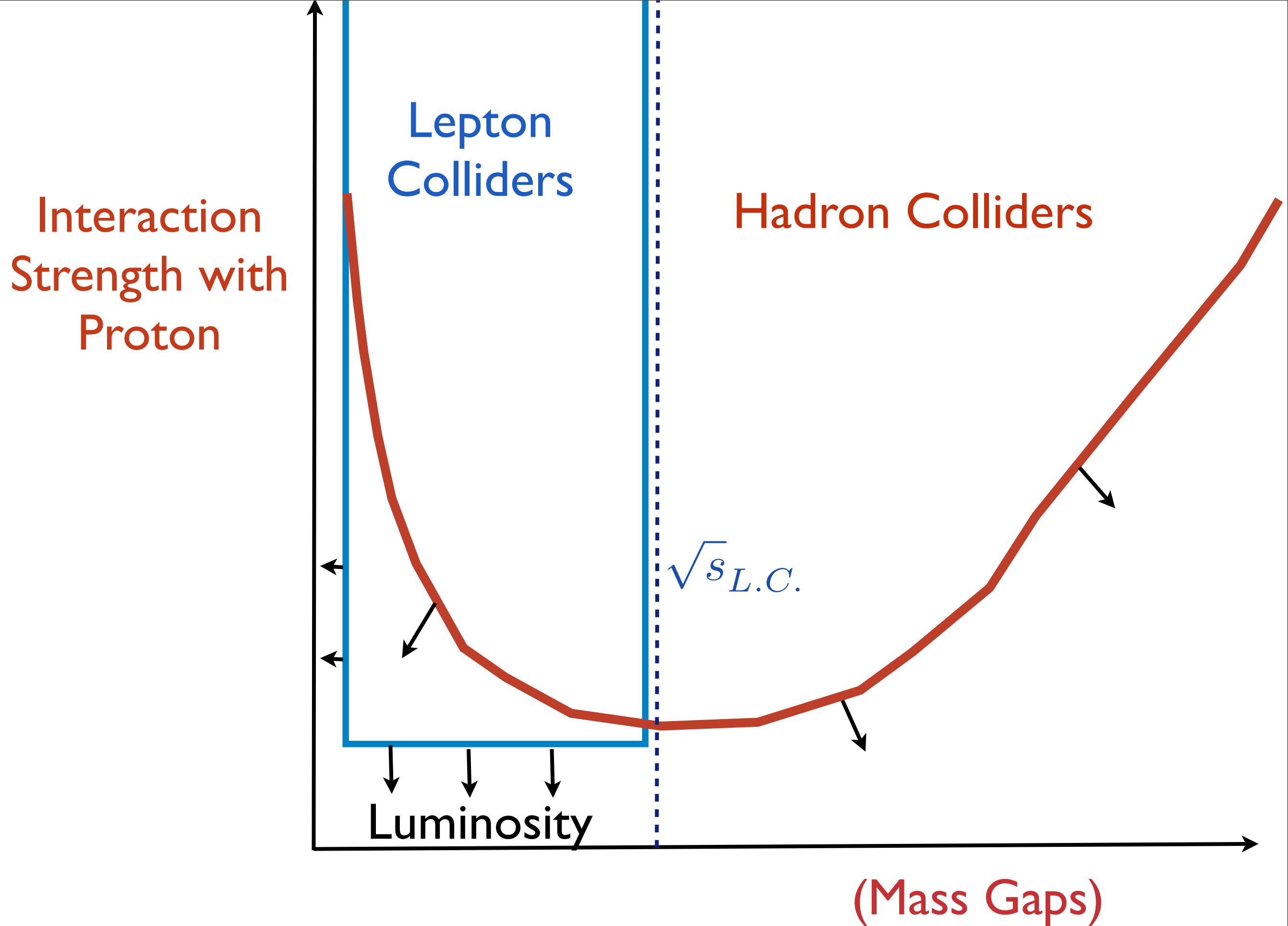
- The main mission of LHC is to explore the mechanism of electroweak symmetry breaking.
- First successful step : Find a SM -like Higgs
- Beyond the Higgs, LHC is sensitive to pair production of particles through QCD interactions, or resonances which couple to quarks and gluons.
- Bounds on Z' , KK gravitons, gluinos, squarks all of order of the TeV, although 3rd generation squarks are more difficult to test.

Theoretical Guidance : LHC and New Physics

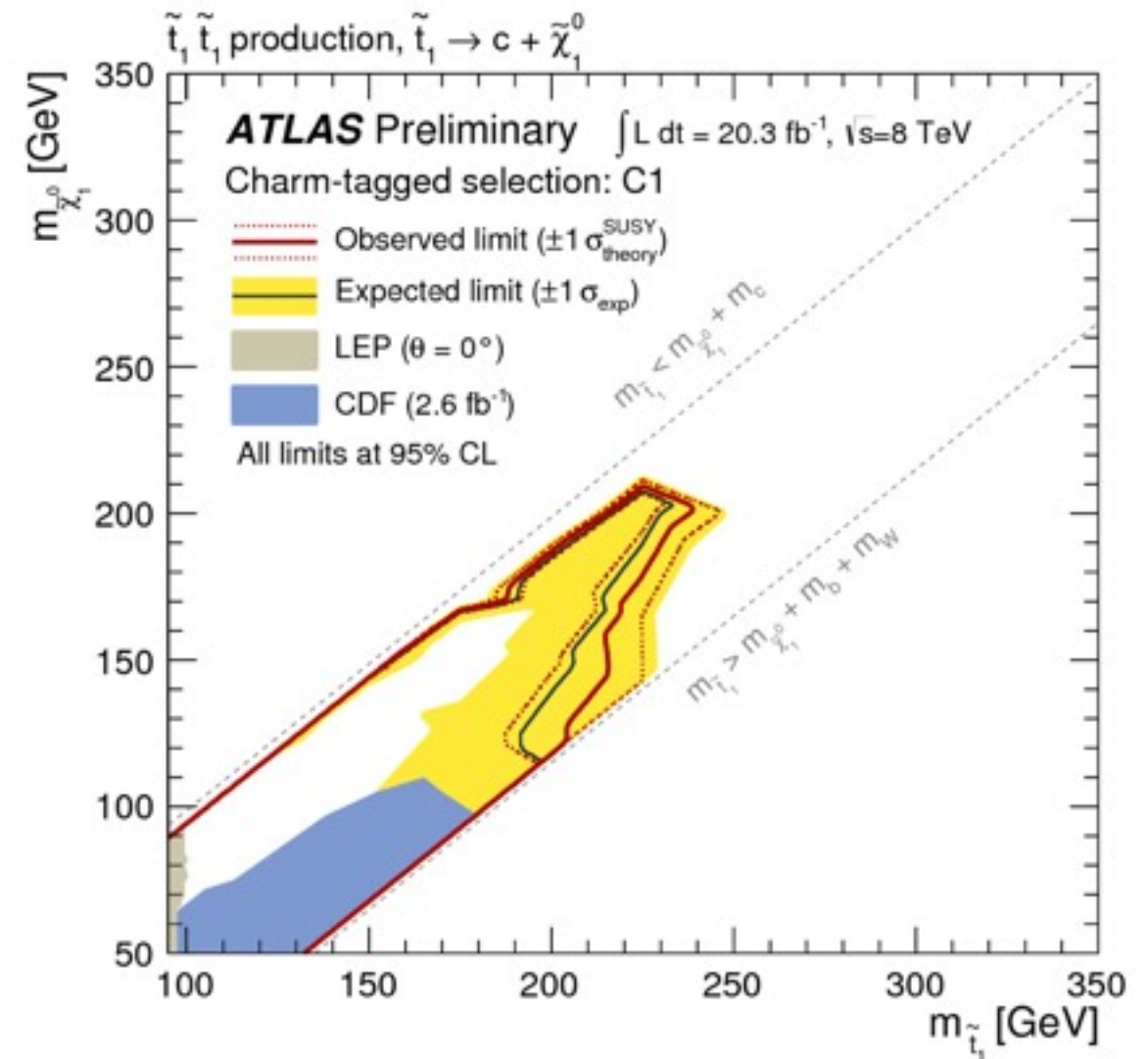
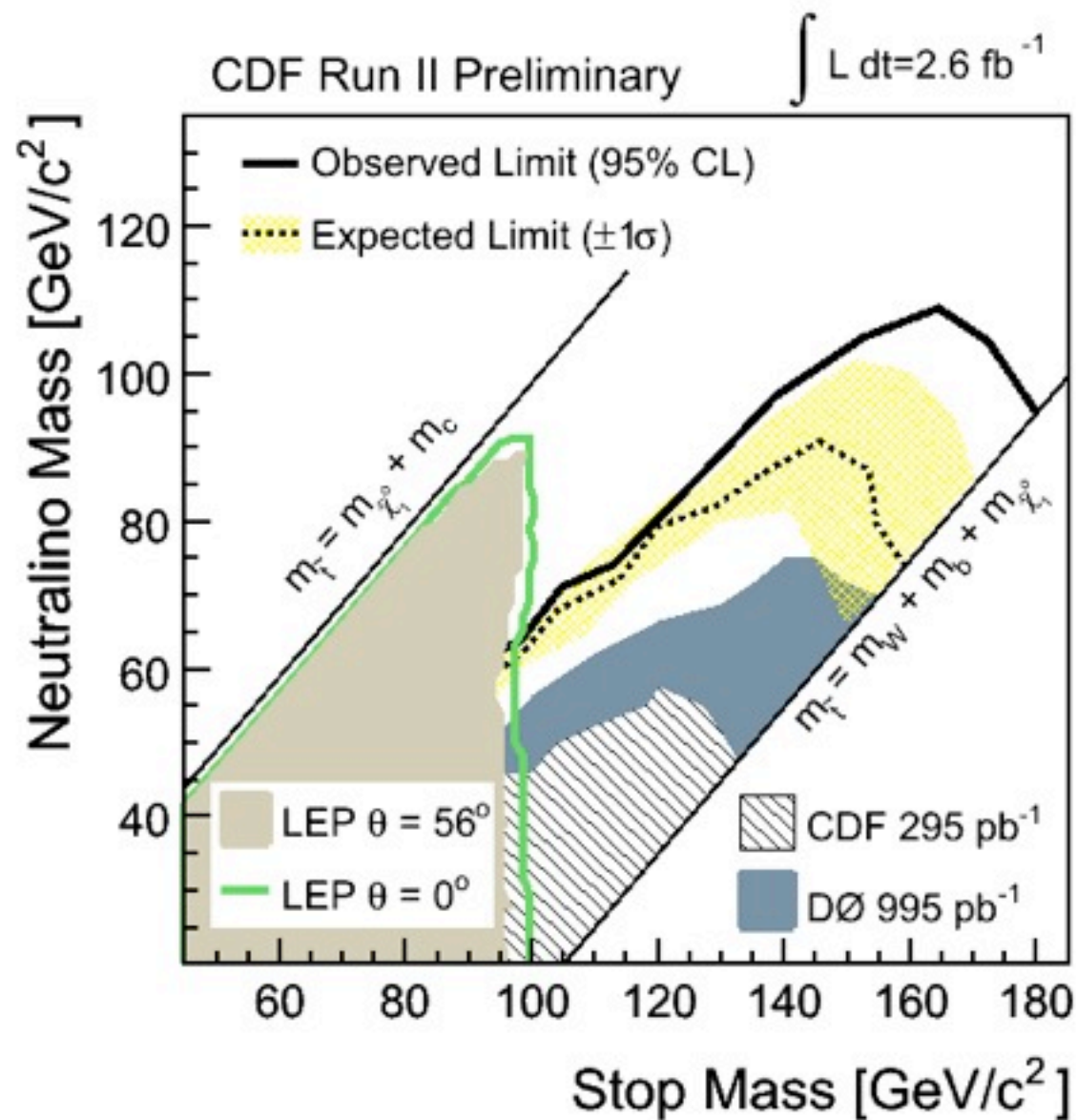
- **Colored particles** are part of most known mechanism to generate the weak scale in a natural way.
- Similarly, **gauge bosons and other resonances** also appear in scenarios of composite Higgs bosons, and in many gauge extensions.
- So, LHC is a great place to find the new physics connected to the weak scale !
- But there is no compelling physical argument that implies that, beyond a SM-like Higgs, new physics must be visible at the LHC.
- What if there are only weakly interacting particles at the weak scale ?

Weakly Interacting Particles at the LHC

- LHC is still sensitive to weakly interacting particles, if they proceed from decays of colored ones, or if there are light and there are large mass gaps between them.
- Weakly interacting particles heavier than a few hundred GeV, will be difficult to find at the LHC, particularly if they present a compressed spectra.
- Lepton colliders present an attractive alternative to search for these particles, even if the spectra is compressed.
- The higher the luminosity, the weaker the interactions that can be probed.
- In the search for new physics, lepton colliders are mostly limited by the maximum center of mass energy they can reach.



LHC can search for small mass gaps through monojet processes



See Carena, Freitas, C.W.'08

Are there Motivations for the Existence of Weak Scale Weakly Interacting Particles ?

- Dark Matter and its Relic Density
- Extensions of the Simple Higgs Mechanism
- The Muon Anomalous Magnetic Moment
- Modifications of Higgs couplings to photons
- Possible Direct or Indirect Dark Matter Signatures
- Neutrino Masses

See also talk by P. Fox

Muon Anomalous Magnetic Moment

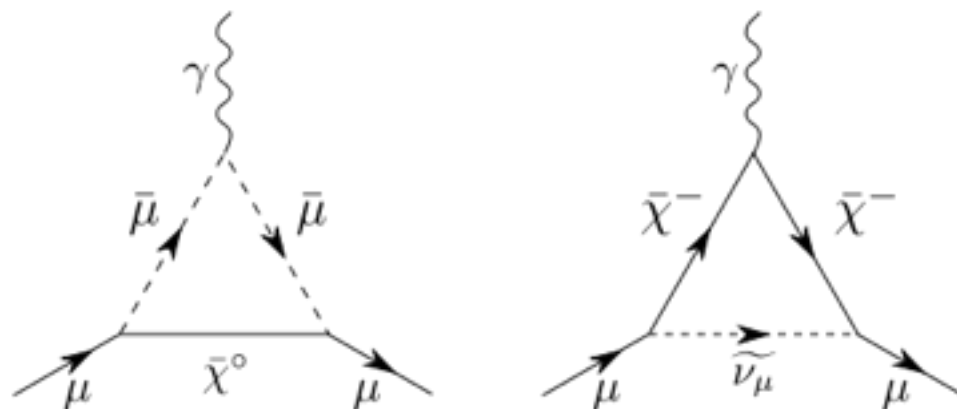
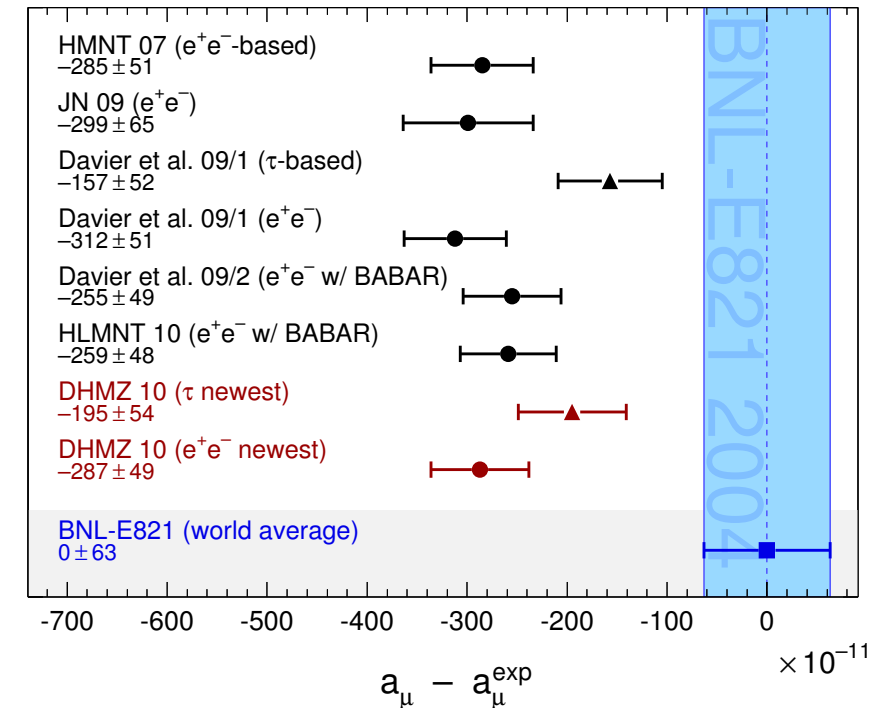
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 287 \pm (63)(49) \times 10^{-11}$$

3.6 σ Discrepancy

A. Hoecker'11

New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry



$$\delta a_\mu \simeq \frac{\alpha}{8\pi \sin^2 \theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan \beta \simeq 15 \times 10^{-10} \left(\frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \tan \beta$$

M. Carena, G. Giudice, C. E.M. Wagner '96

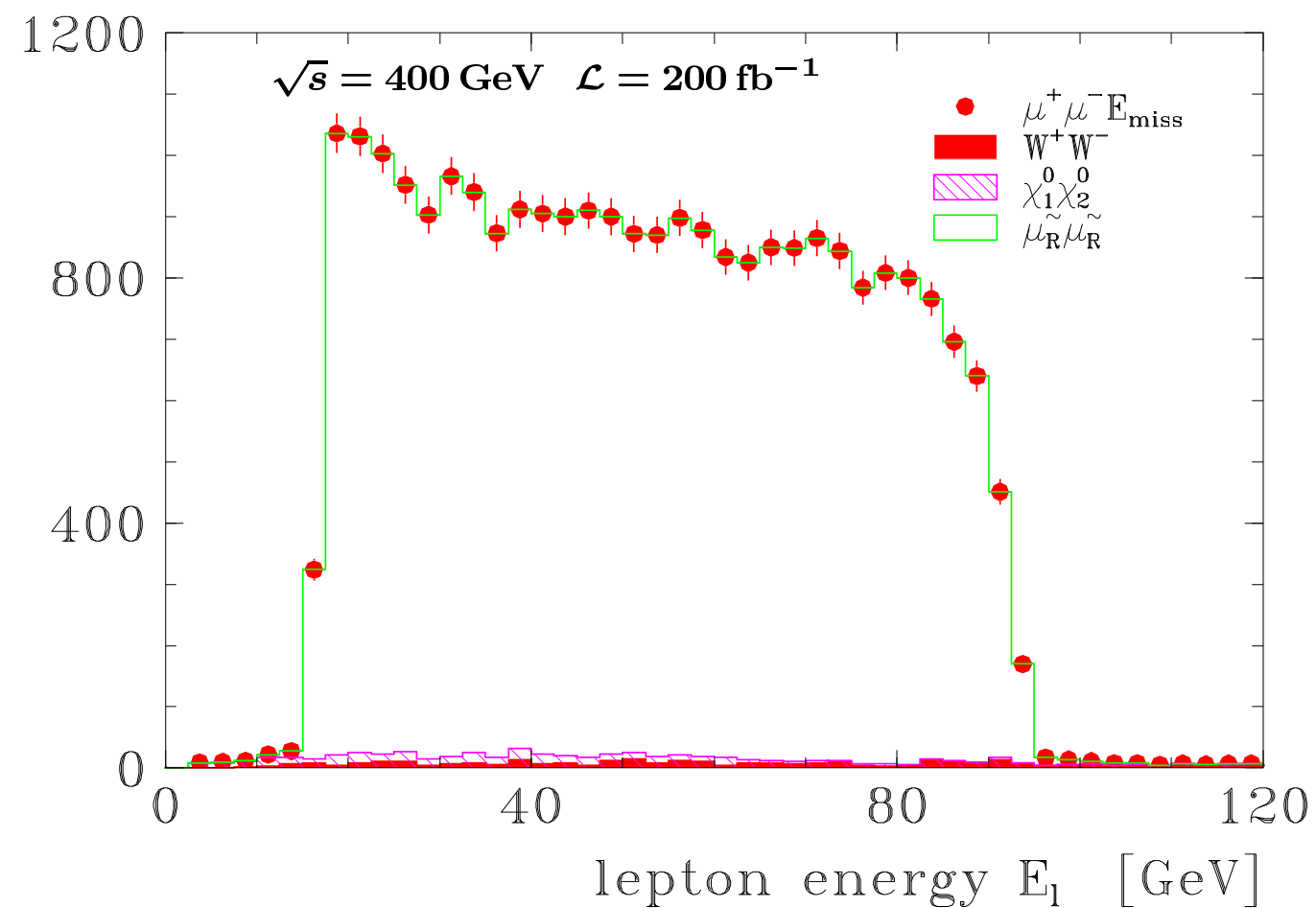
Here \tilde{m} represents the weakly interacting supersymmetric particle masses.

For $\tan \beta \simeq 10$ (50), values of $\tilde{m} \simeq 230$ (510) GeV would be preferred.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

Even Small masses for smaller couplings !

Mass measurement from lepton energy spectra

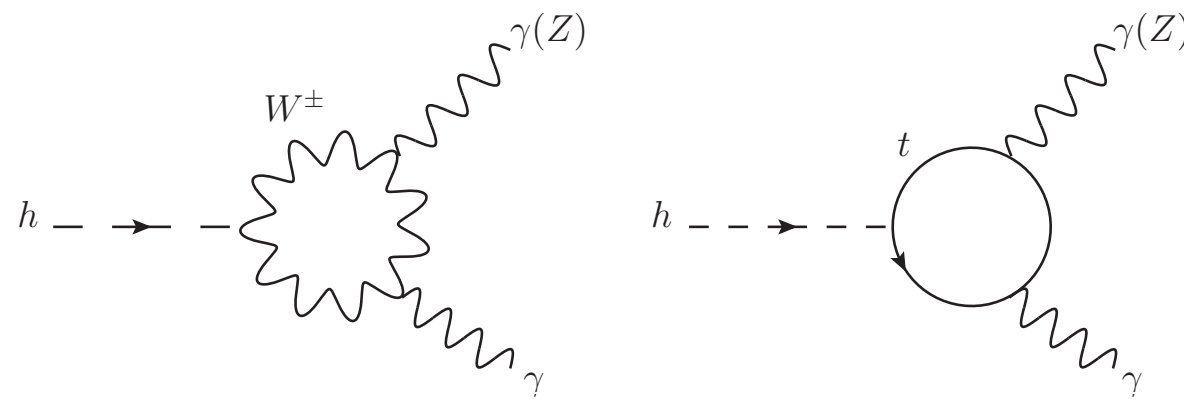


⇒ Mass determination at the per mille level

G.Weiglein, J.Wells'12

Loop Induced Higgs Couplings : Diphoton width

Dominant Contributions to the Diphoton Width in the Standard Model



Similar corrections appear from other scalar, fermion or vector particles. Clearly, similarly to the top quark, chiral fermions tend to reduce the vector boson contributions

Higgs Diphoton Decay Width in the SM

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128 \sqrt{2} \pi^3} \left| A_1(\tau_w) + N_c Q_t^2 A_{1/2}(\tau_t) \right|^2 \quad \tau_i \equiv 4m_i^2/m_h^2$$

A. Djouadi'05

For particles much heavier than the Higgs boson

$$A_1 \rightarrow -7, \quad N_c Q_t^2 A_{1/2} \rightarrow \frac{4}{3} N_c Q_t^2 \simeq 1.78, \quad \text{for } N_c = 3, Q_t = 2/3$$

In the SM, for a Higgs of mass about 125 GeV

$$m_h = 125 \text{ GeV} : A_1 = -8.32, \quad N_c Q_t^2 A_{1/2} = 1.84$$

Dominant contribution from W loops. Top particles suppress by 40 percent the W loop contribution. One can rewrite the above expression in terms of the couplings of the particles to the Higgs as :

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024 \pi^3} \left| \frac{g_{hWW}}{m_W^2} A_1(\tau_w) + \frac{2g_{ht\bar{t}}}{m_t} N_c Q_t^2 A_{1/2}(\tau_t) + N_c Q_s^2 \frac{g_{hSS}}{m_S^2} A_0(\tau_S) \right|^2$$

Inspection of the above expressions reveals that the contributions of particles heavier than the Higgs boson may be rewritten as

$$\mathcal{L}_{h\gamma\gamma} = -\frac{\alpha}{16\pi} \frac{h}{v} \left[\sum_i 2b_i \frac{\partial}{\partial \log v} \log m_i(v) \right] F_{\mu\nu} F^{\mu\nu} \quad \left\{ \begin{array}{ll} b = \frac{4}{3} N_c Q^2 & \text{for a Dirac fermion ,} \\ b = -7 & \text{for the } W \text{ boson ,} \\ b = \frac{1}{3} N_c Q_S^2 & \text{for a charged scalar .} \end{array} \right.$$

where in the Standard Model

$$\frac{g_{hWW}}{m_W^2} = \frac{\partial}{\partial v} \log m_W^2(v) , \quad \frac{2g_{ht\bar{t}}}{m_t} = \frac{\partial}{\partial v} \log m_t^2(v)$$

This generalizes for the case of fermions with contributions to their masses independent of the Higgs field. The couplings come from the vertex and the inverse dependence on the masses from the necessary chirality flip (for fermions) and the integral functions.

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi} \frac{h}{v} \left[\sum_i b_i \frac{\partial}{\partial \log v} \log \left(\det \mathcal{M}_{F,i}^\dagger \mathcal{M}_{F,i} \right) + \sum_i b_i \frac{\partial}{\partial \log v} \log \left(\det \mathcal{M}_{B,i}^2 \right) \right] F_{\mu\nu} F^{\mu\nu}$$

M. Carena, I. Low, C.W., arXiv:1206.1082, Ellis, Gaillard, Nanopoulos'76, Shifman, Vainshtein, Voloshin, Zakharov'79

Quite generally, large deviations of Higgs diphoton width associated with light charged particles, at the reach of TLEP

Two Scalars with Mixing

Similar to light stau scenario,

M. Carena, S. Gori, N. Shah, C.W., arXiv:1112.3336,

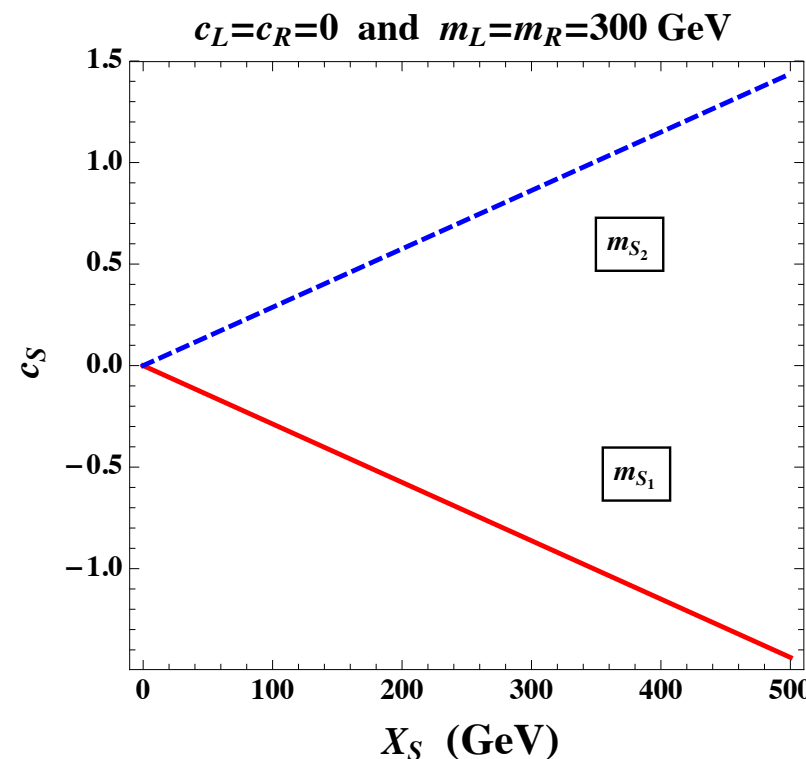
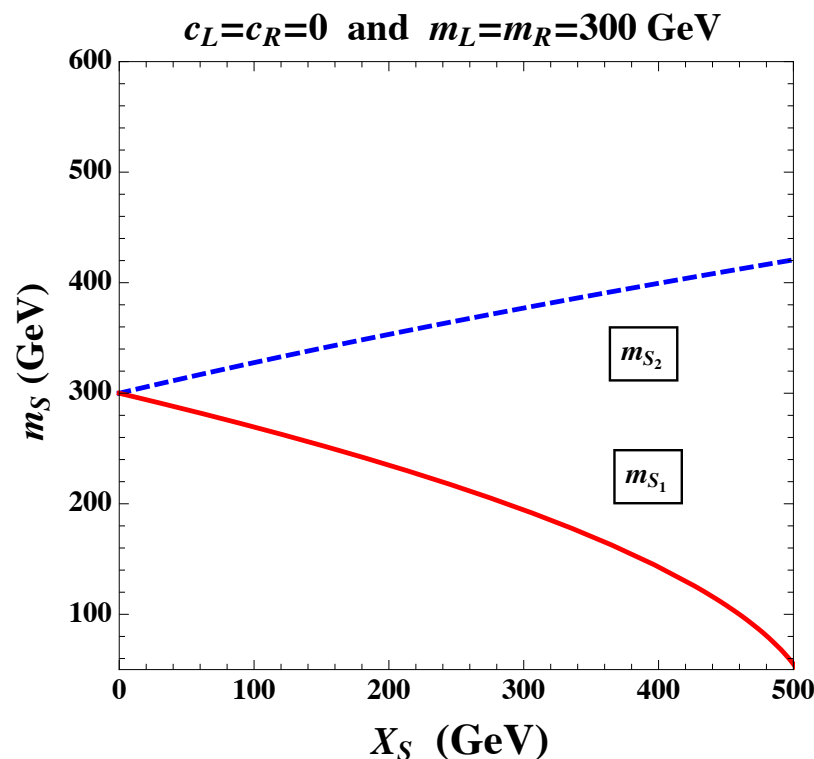
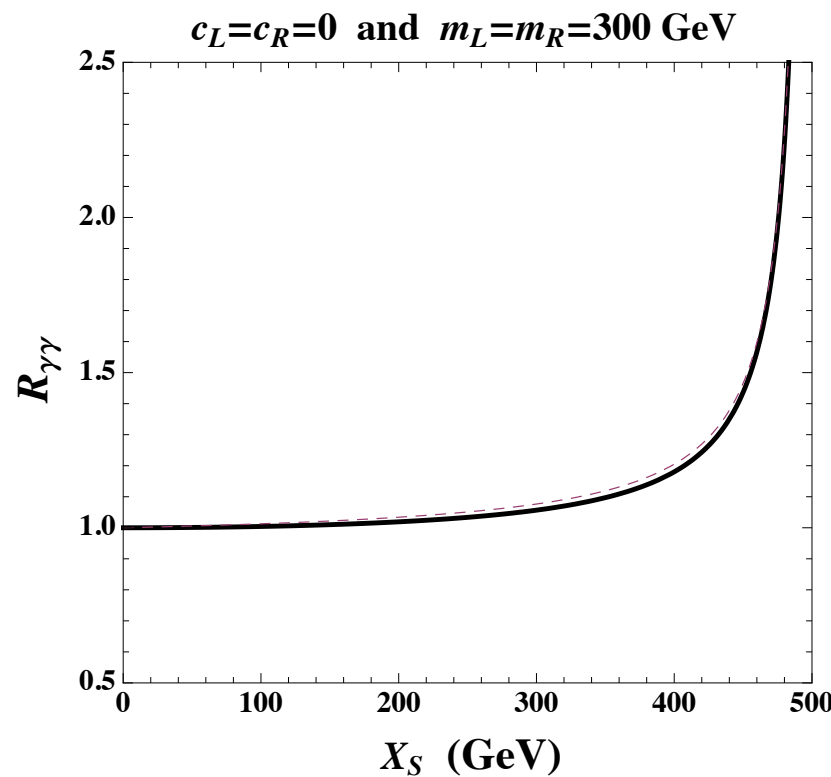
M. Carena, S. Gori, N. Shah, C.W., L.T. Wang, arXiv:1205.5842

$$\mathcal{M}_S^2 = \begin{pmatrix} \tilde{m}_L(v)^2 & \frac{1}{\sqrt{2}}vX_S \\ \frac{1}{\sqrt{2}}vX_S & \tilde{m}_R(v)^2 \end{pmatrix}$$

$$\frac{\partial \log(\text{Det} M_S^2)}{\partial v} \simeq - \frac{X_S^2 v}{m_{S_1}^2 m_{S_2}^2}$$

Negative Effective
Coupling of lightest
scalar

Large mixing and small value of the
lightest scalar mass leads to enhancement
of the diphoton amplitude



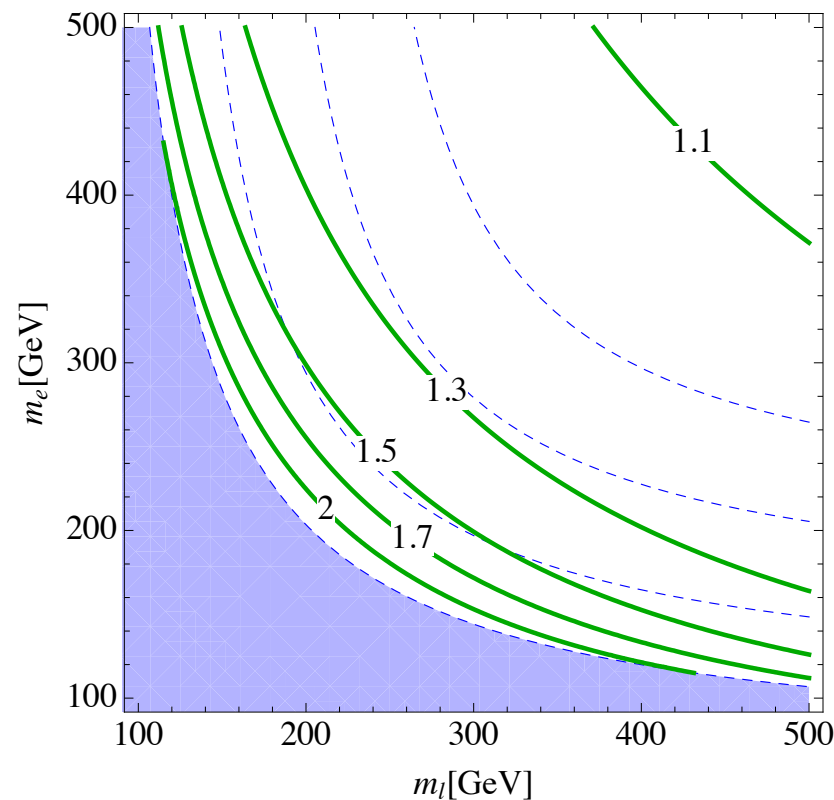
Lightest scalar, with
mass below 200 GeV
gives the dominant
contribution in this
case.

M. Carena, I. Low, C.W., arXiv:1206.1082

Model with a four generation leptons and their vector pairs.

Model can lead to the presence of Dark Matter and an enhanced diphoton rate

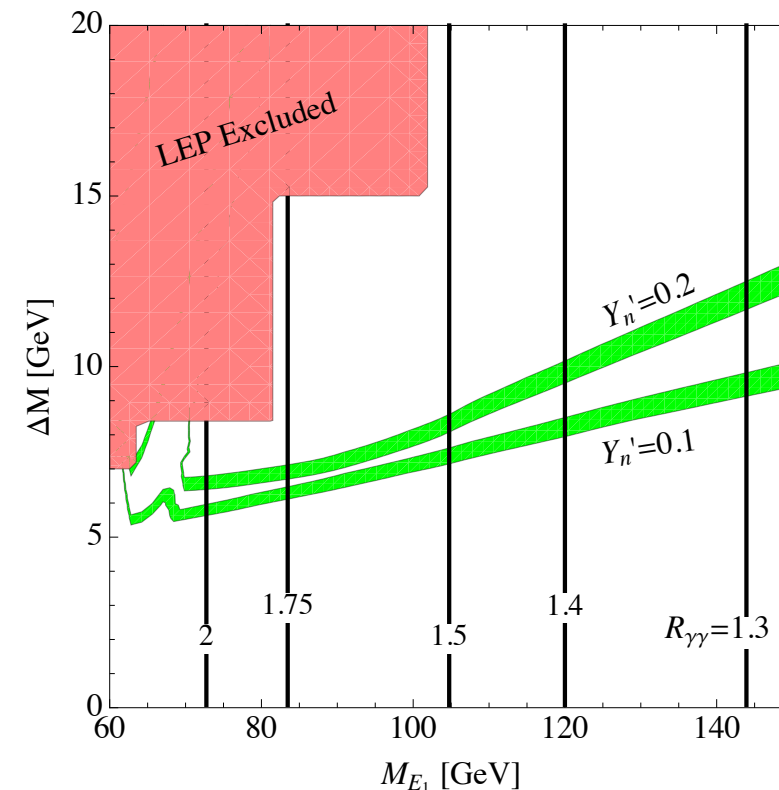
A. Joglekar, P. Schwaller, C.W.'12. See also Arkani Hamed, Blum, D'Agnolo and Fan'12



$$Y'_C = Y_C'' = 0.8$$

$$\mathcal{M} = \begin{pmatrix} Y'_C v & m_\ell \\ m_e & Y_C'' v \end{pmatrix}$$

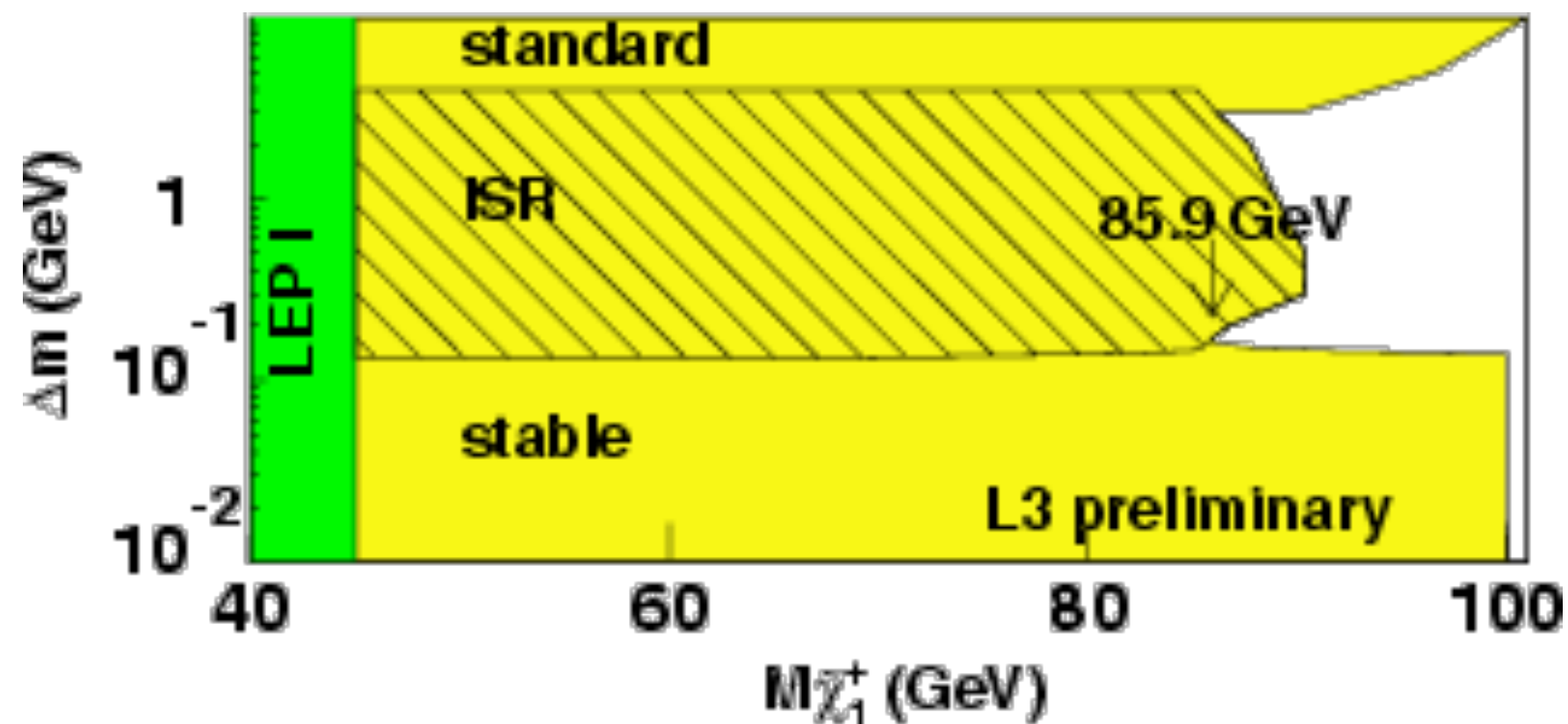
$$\frac{\partial \log(\text{Det} M_f)}{\partial v} \simeq -2 \frac{Y'_C Y_C'' v}{m_e m_\ell - Y'_C Y_C'' v^2}$$



Light, weakly interacting particles with small mass gap are present in this model

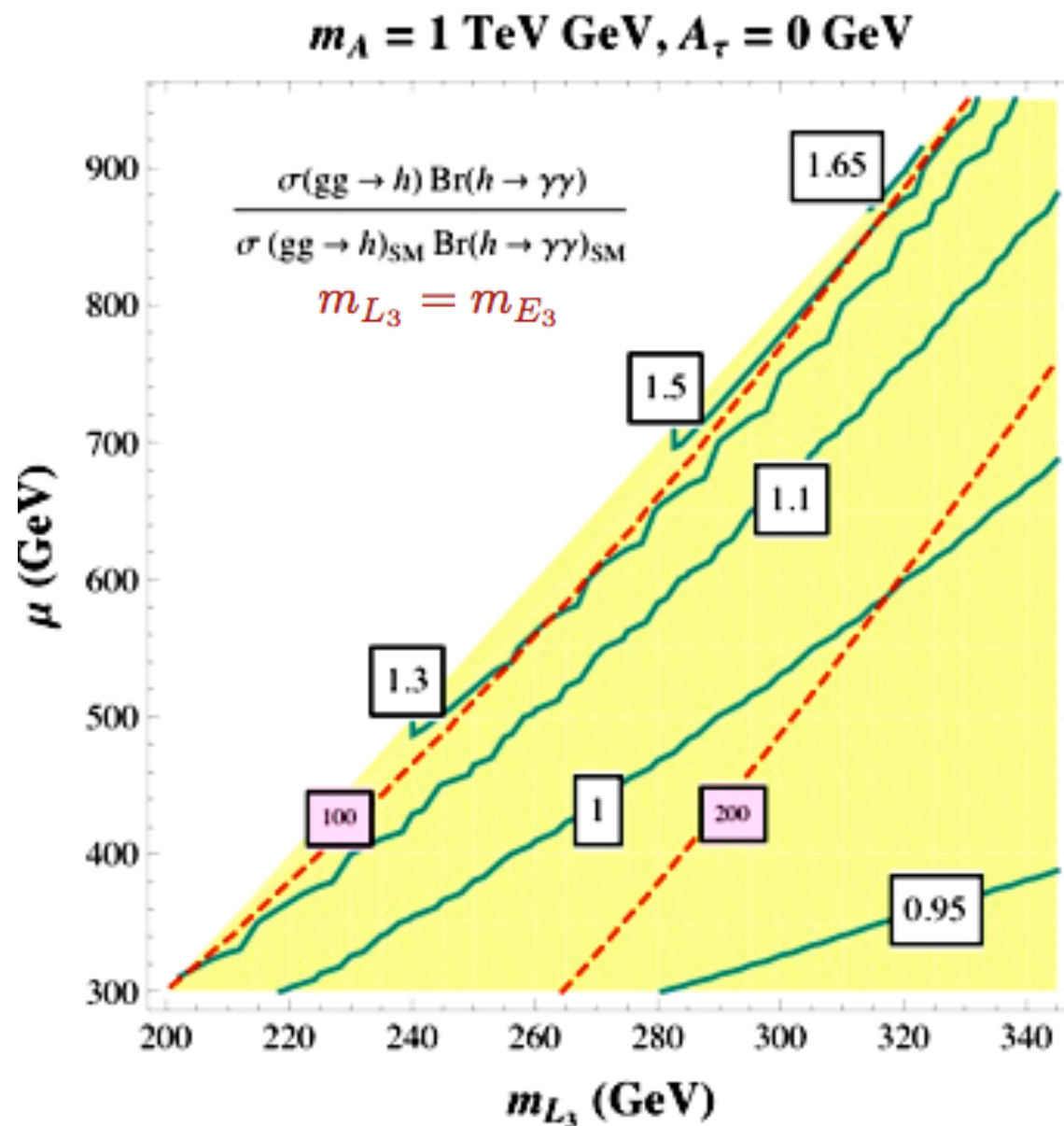
LEP put a strong constraint, of order 103.6 GeV on charginos decaying to W's and missing energy.

Bound significant even in the most difficult region of difference of mass between chargino and neutralinos.



Higgs Decay into two Photons in the MSSM

Charged scalar particles with no color charge can change di-photon rate without modification of the gluon production process



$$\mathcal{M}_{\tilde{\tau}}^2 \simeq \begin{bmatrix} m_{L_3}^2 + m_{\tilde{\tau}}^2 + D_L & h_\tau v (A_\tau \cos \beta - \mu \sin \beta) \\ h_\tau v (A_\tau \cos \beta - \mu \sin \beta) & m_{E_3}^2 + m_{\tilde{\tau}}^2 + D_R \end{bmatrix}$$

Light staus with large mixing

[sizeable μ and $\tan \beta$]:

**→ enhancement of the
Higgs to di-photon decay rate**

$$\delta \mathcal{A}_{h\gamma\gamma} / \mathcal{A}_{h\gamma\gamma}^{\text{SM}} \simeq -\frac{2 m_\tau^2}{39 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2} (m_{\tilde{\tau}_1}^2 + m_{\tilde{\tau}_2}^2 - X_\tau^2)$$

$$X_\tau = A_\tau - \mu \tan \beta$$

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842

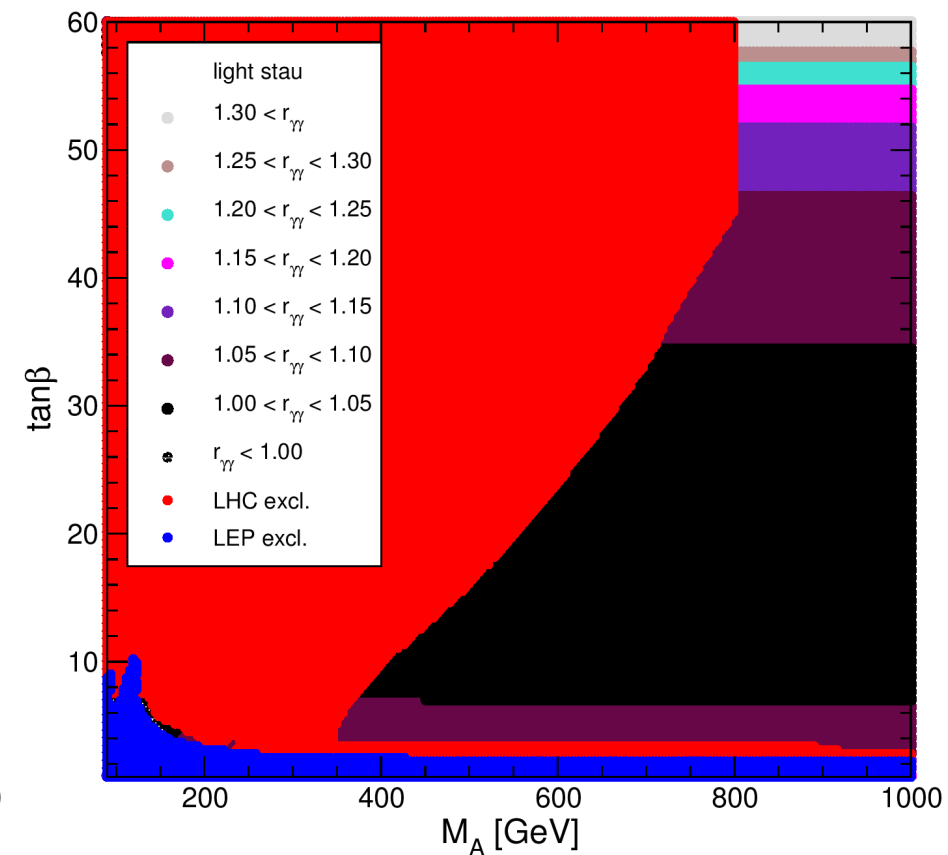
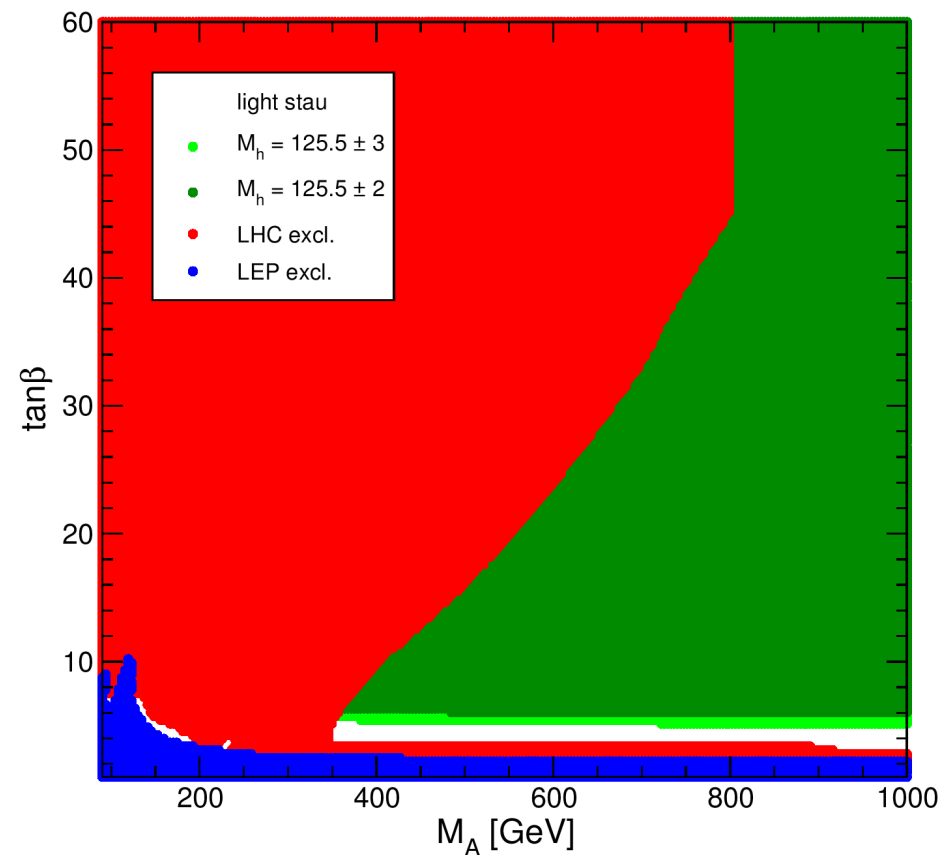
For a more generic discussion of modified diphoton width by new charged particles,
see M. Carena, I. Low and C. Wagner, arXiv:1206.1082

The Light Stau Scenario

Enhancement of diphoton decay rate at large values of $\tan(\beta)$.

$$\delta\mathcal{A}_{h\gamma\gamma}/\mathcal{A}_{h\gamma\gamma}^{\text{SM}} \simeq -\frac{2 m_\tau^2}{39 m_{\tilde{\tau}_1}^2 m_{\tilde{\tau}_2}^2} (m_{\tilde{\tau}_1}^2 + m_{\tilde{\tau}_2}^2 - X_\tau^2)$$

$$X_\tau = A_\tau - \mu \tan \beta$$



$$\begin{aligned} M_{\text{SUSY}} &= 1000 \text{ GeV}, \\ \mu &= 500 \text{ GeV}, \\ \mu &= 450 \text{ GeV } (\Delta_\tau \text{ calculation}), \\ M_2 &= 200 \text{ GeV}, \\ M_2 &= 400 \text{ GeV } (\Delta_\tau \text{ calculation}), \end{aligned}$$

$$\begin{aligned} X_t^{\text{OS}} &= 1.6 M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= 1.7 M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_t, \\ A_\tau &= 0, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \\ M_{\tilde{l}_3} &= 245 \text{ GeV}, \\ M_{\tilde{l}_3} &= 250 \text{ GeV } (\Delta_\tau \text{ calculation}). \end{aligned}$$

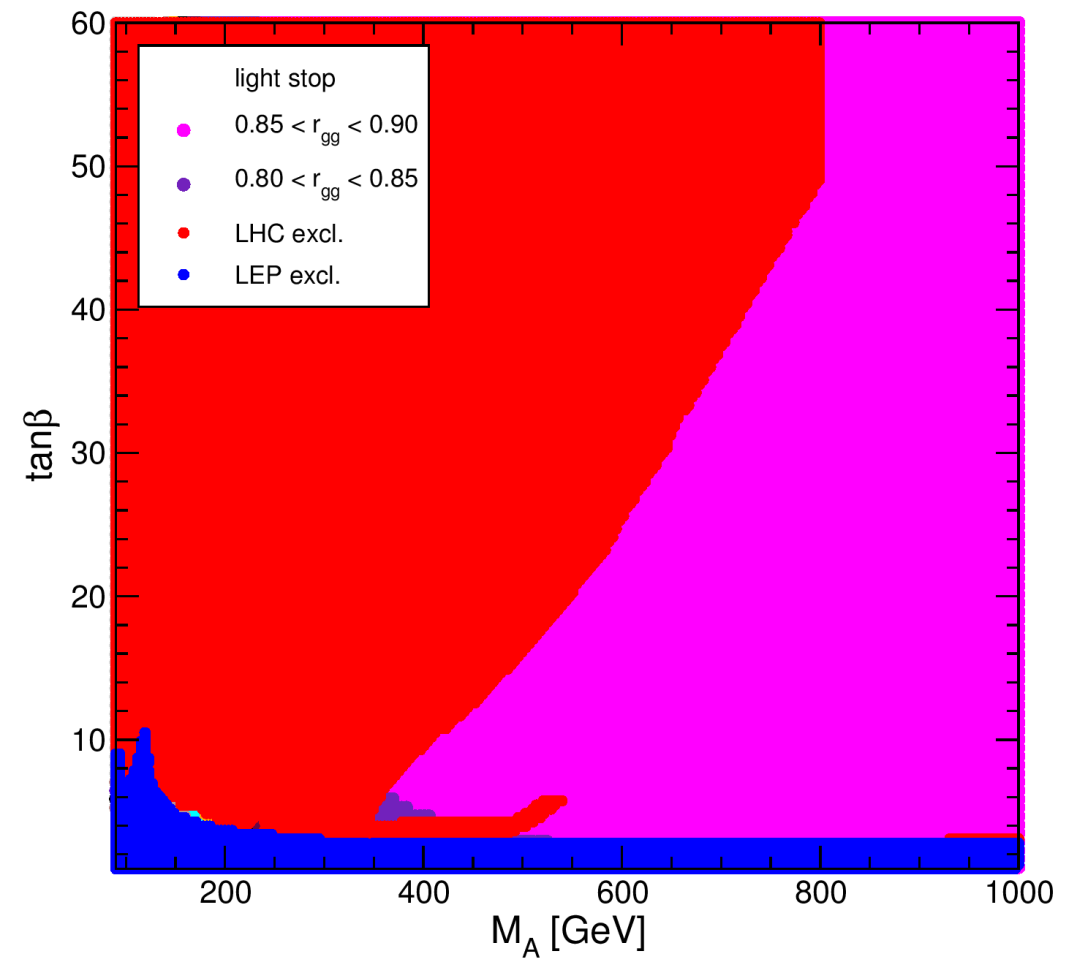
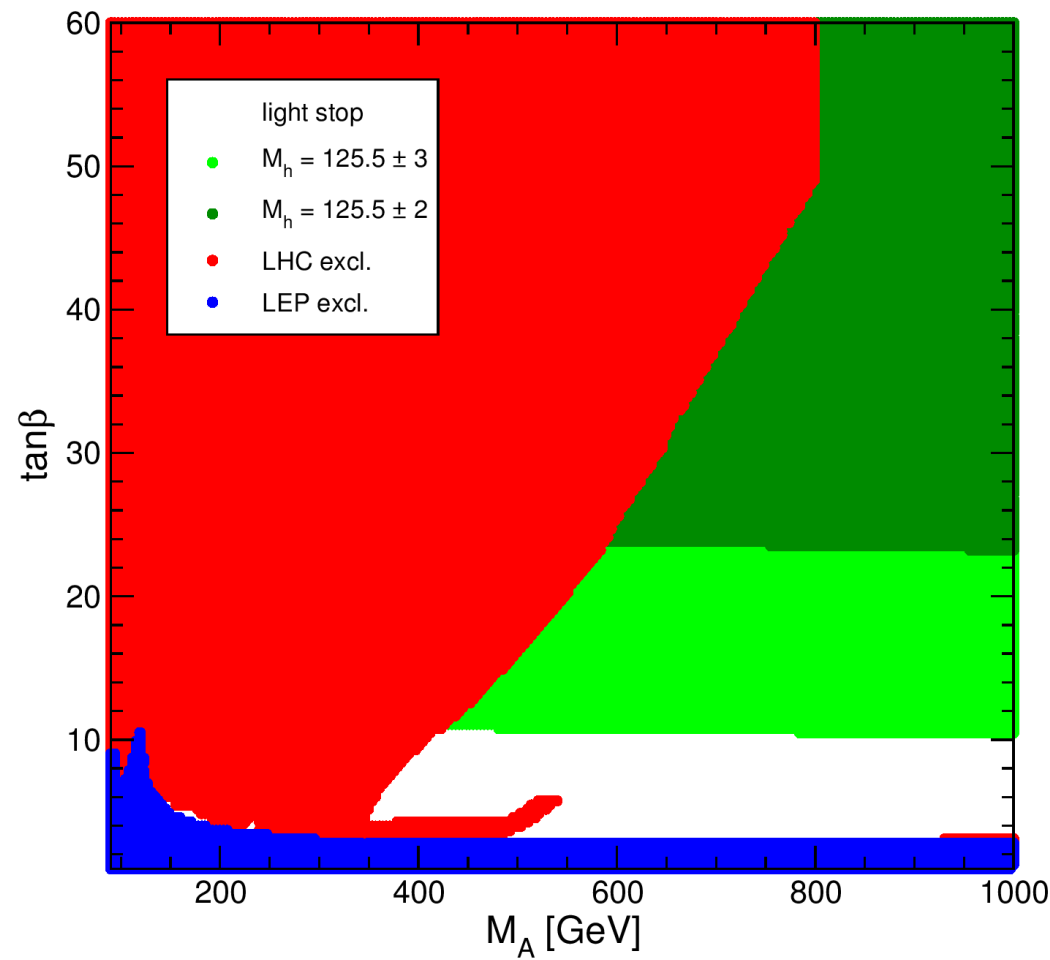
The Light Stop Scenario

Stop mixing large, lightest stop mass of order 320 GeV.

Heaviest stop mass of order 650 GeV.

Reduction of the gluon fusion process rate.

$$\delta\mathcal{A}_{hgg}/\mathcal{A}_{hgg}^{\text{SM}} \simeq \frac{m_t^2}{4m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} (m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2)$$



$$\begin{aligned} M_{\text{SUSY}} &= 500 \text{ GeV}, \\ \mu &= 350 \text{ GeV}, \\ M_2 &= 350 \text{ GeV}, \end{aligned}$$

$$\begin{aligned} X_t^{\text{OS}} &= 2.0 M_{\text{SUSY}} \text{ (FD calculation)}, \\ X_t^{\overline{\text{MS}}} &= 2.2 M_{\text{SUSY}} \text{ (RG calculation)}, \\ A_b &= A_t = A_\tau, \\ m_{\tilde{g}} &= 1500 \text{ GeV}, \end{aligned}$$

Light Stau Searches

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1205.5842

	Signature	8 TeV LHC (fb)	14 TeV LHC (fb)
$pp \rightarrow \tilde{\tau}_1 \tilde{\tau}_1$	$2\tau, \cancel{E}_T$	55.3	124.6
$pp \rightarrow \tilde{\tau}_1 \tilde{\tau}_2$	$2\tau, Z, \cancel{E}_T$	1.0	3.2
$pp \rightarrow \tilde{\tau}_2 \tilde{\tau}_2$	$2\tau, 2Z, \cancel{E}_T$	0.15	0.6
$pp \rightarrow \tilde{\tau}_1 \tilde{\nu}_\tau$	$2\tau, W, \cancel{E}_T$	14.3	38.8
$pp \rightarrow \tilde{\tau}_2 \tilde{\nu}_\tau$	$2\tau, W, Z, \cancel{E}_T$	0.9	3.1
$pp \rightarrow \tilde{\nu}_\tau \tilde{\nu}_\tau$	$2\tau, 2W, \cancel{E}_T$	1.6	5.3

$$\tilde{\tau}_1 \rightarrow \chi_1 \tau, \quad \text{or} \quad \tilde{\tau}_1 \rightarrow \tilde{G} \tau$$

Possible stau and sneutrino direct production channels with their signatures at the LHC. The cross sections shown are computed for $m_{L_3} = m_{e_3} = 280$ GeV, $\tan \beta = 60$, $\mu = 650$ GeV and $M_1 = 35$ GeV.

- Direct stau pair production leads to final states with two taus plus missing energy.
- Very large backgrounds coming from W plus jets, WW , ZZ^* (γ^*) production turn this channel difficult. In addition, tau tagging reduces the cross section from 55 to 7 fb. One can reduce the physical backgrounds but W plus jet seems difficult to overcome.
- We concentrated on the associated production of staus with sneutrinos.
- Production of stau pairs should be explored in more detail : Considering, for example, tau decays into leptons and possible tau polarization discrimination.

Stau plus Sneutrino Searches

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1205.5842

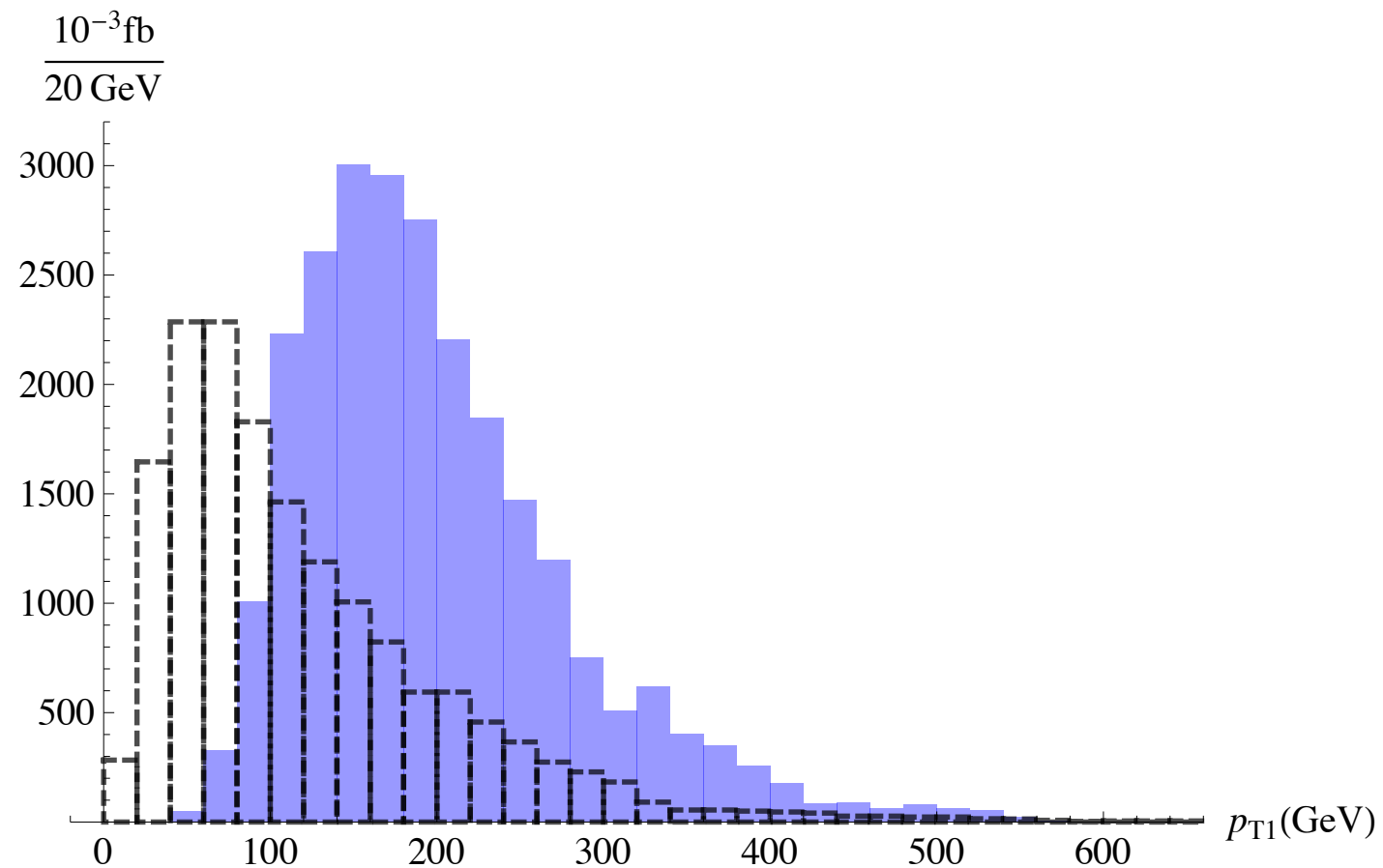
- We consider alternative searches for associated production of staus with sneutrinos. Since the staus have large mixing, the stau sneutrinos are relatively light, and of the order of the left-handed stau mass.

$$pp \rightarrow \tilde{\tau}_1 \tilde{\nu}_\tau \rightarrow \tilde{\tau}_1 (W \tilde{\tau}_1) \rightarrow \tau \chi_1 W \tau \chi_1$$

- W decaying leptonically. Main background :W + 2 jets. We impose two loose T tags.
- Lepton and neutrino from W in signal boosted :We required large lepton p_T and missing E_T larger than 70 GeV
- Then, jets from background tend to have large p_T . We required the largest jet p_T to be lower than 75 GeV
- We also avoid taus with invariant mass close to the Z mass, but improvement is insignificant after previous cuts.

Leading jet PT Distribution

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1205.5842



Signal (black histogram) and background (blue) p_T distributions.
Signal rescaled by a factor 100 for visibility

Results of Simulations

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, arXiv:1205.5842

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

- : Cross sections for the signal and the physical and fake backgrounds after τ -tags at the 8 TeV LHC: after imposing acceptance cuts $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^\ell > 70$ GeV and $\cancel{E}_T > 70$ (third column); imposing that the τ is not too boosted $p_T^\tau < 75$ GeV (fourth column).

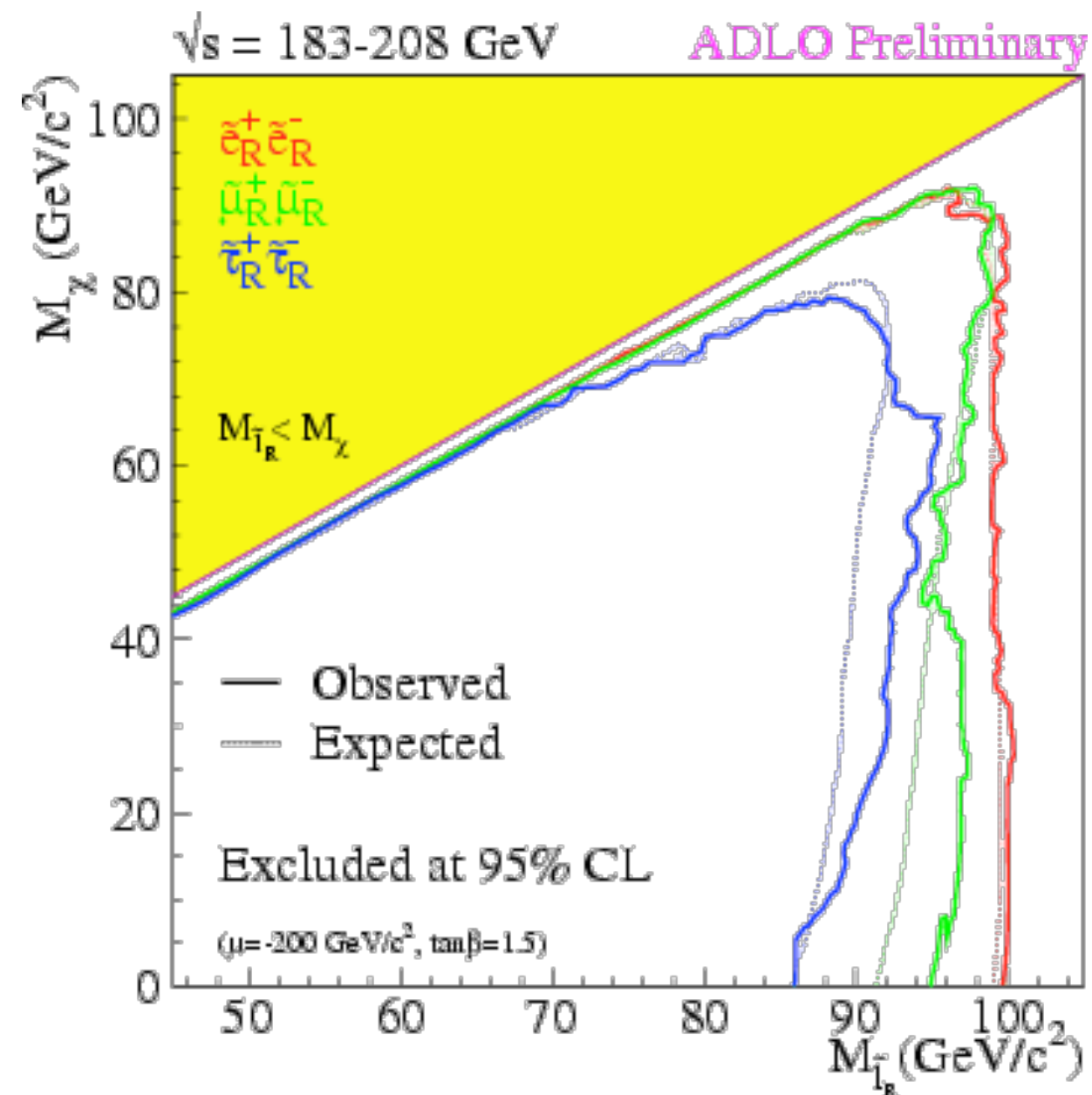
	Total (fb)	Basic (fb)	Hard Tau (fb)
Signal	1.6	0.26	0.11
Physical background, $W + Z/\gamma^*$	27	0.32	$\lesssim 10^{-3}$
$W + \text{jets}$ background	10^4	39	0.25

- : Cross sections for the signal and the physical and fake background after τ -tags at the 14 TeV LHC: after imposing $p_T^{\tau(j)} > 10$ GeV, $\Delta R > 0.4$ and $|\eta| < 2.5$ (second column); with the additional requirement $p_T^\ell > 85$ GeV and $\cancel{E}_T > 85$ (third column); imposing that the τ is not too boosted $p_T^\tau < 80$ GeV (fourth column).

**Very low statistics, but worth a dedicated analysis.
Prospects are better at the 14 TeV LHC.**

An electron positron collider presents also the opportunity of searching for these particles up to near the kinematic limit.

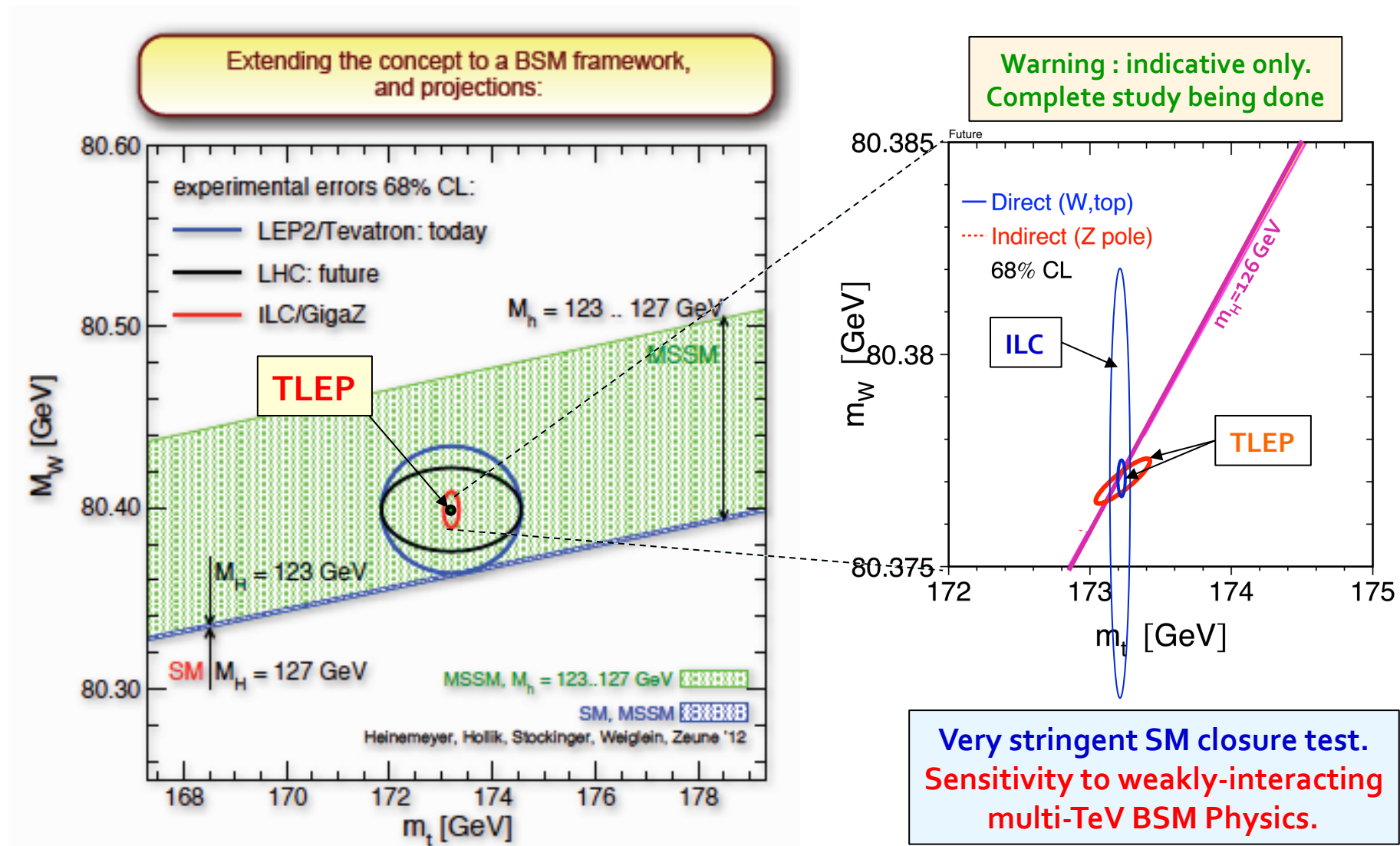
Light Slepton Searches at LEP



Precision Electroweak Data

- The **Tevatron + LHC** will allow a proper determination of 3 parameters which are essential for electroweak precision data : Higgs mass, W mass and top-quark mass. Precision data provided by LEP + SLC
- Not only will **TLEP** allow a more precise determination of these parameters, but running at high luminosity at the Z peak, can determine the precision Z observables at unprecedented level
- This will allow for a test of the SM which goes far beyond what can be observed by direct searches

Performance Comparison (11)



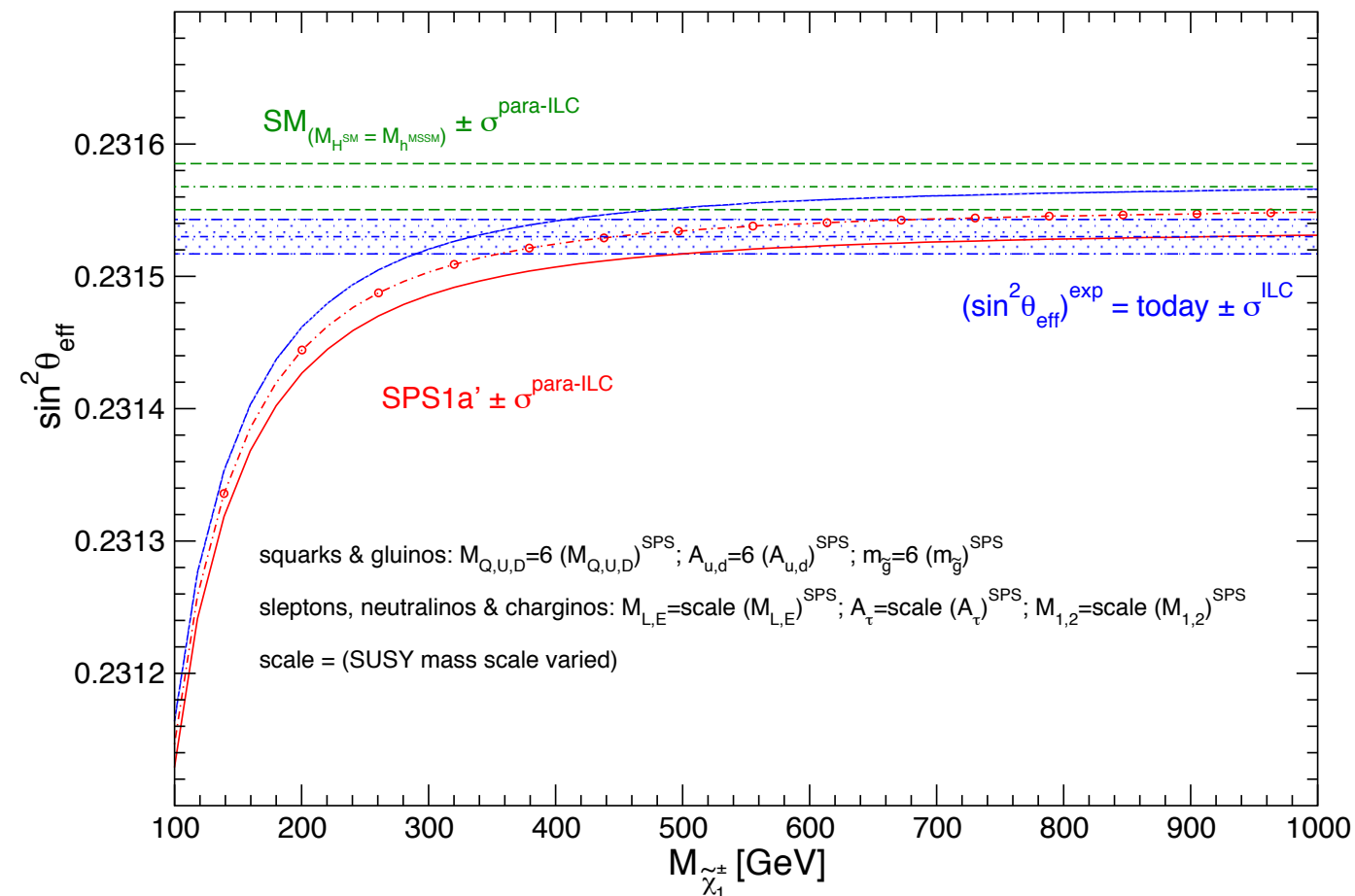
Patrick Janot

Paris, 14 Juin 2013
Séminaire LPNHE

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GigaZ: sensitivity to the scale of SUSY in a scenario where no SUSY particles are observed at the LHC

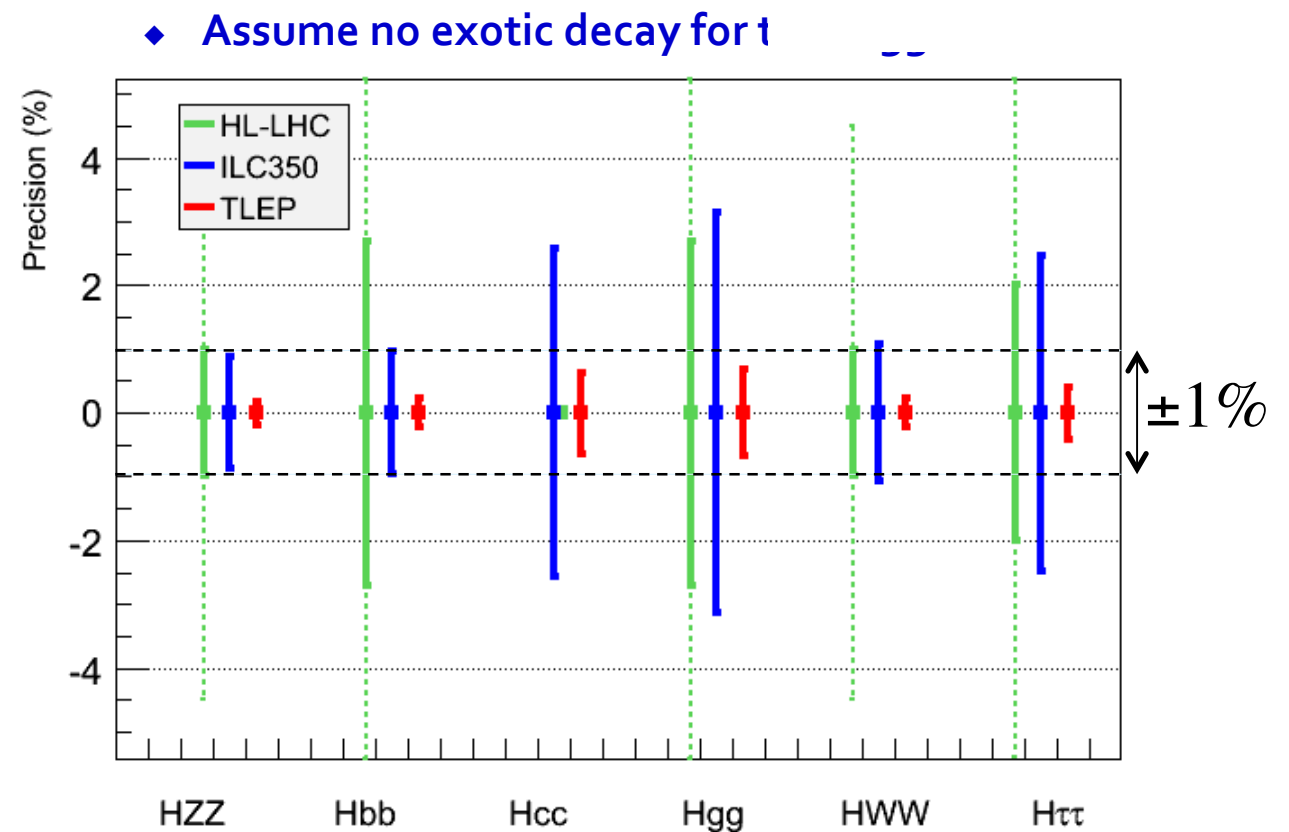
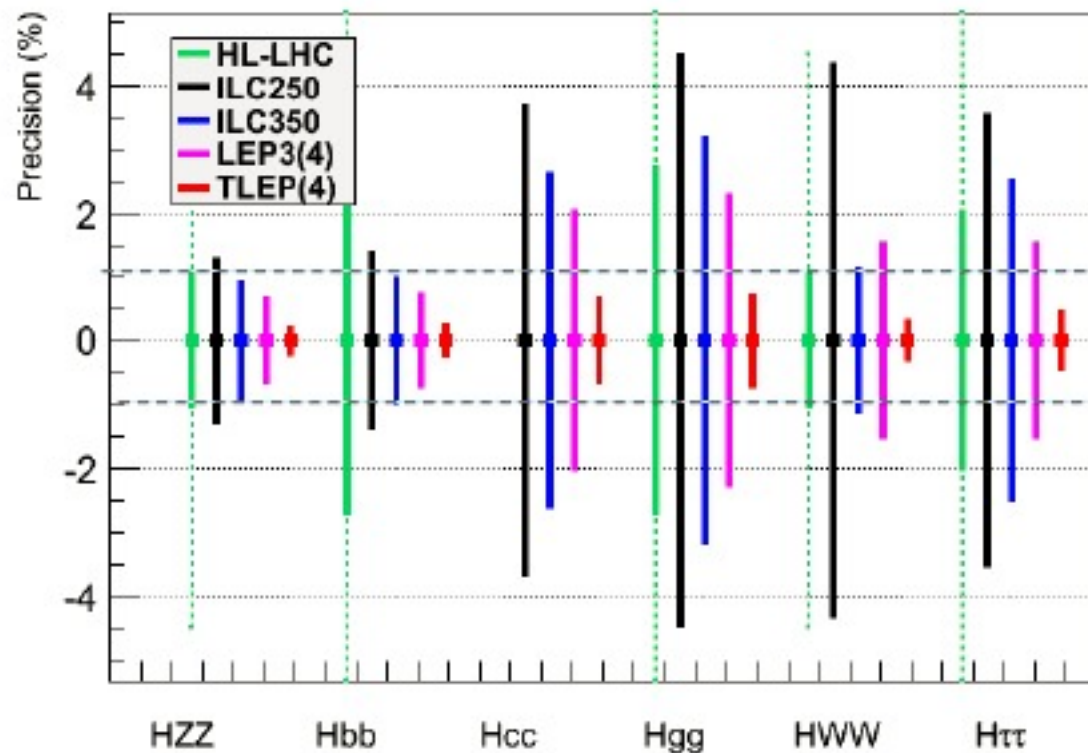
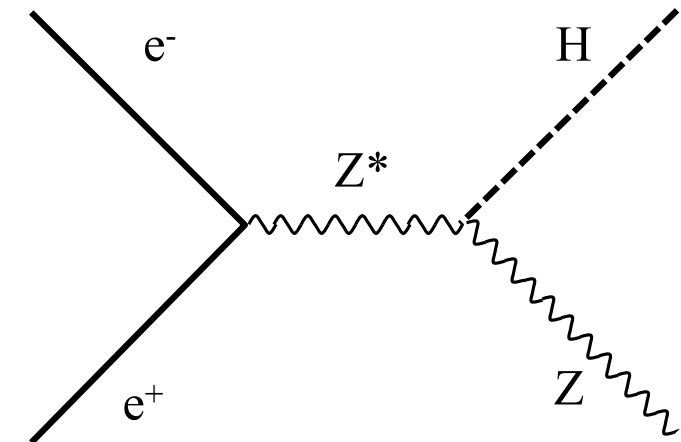
[S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '07]



⇒ GigaZ measurement provides sensitivity to SUSY scale,
extends the direct search reach of LC500

Precision Higgs Couplings

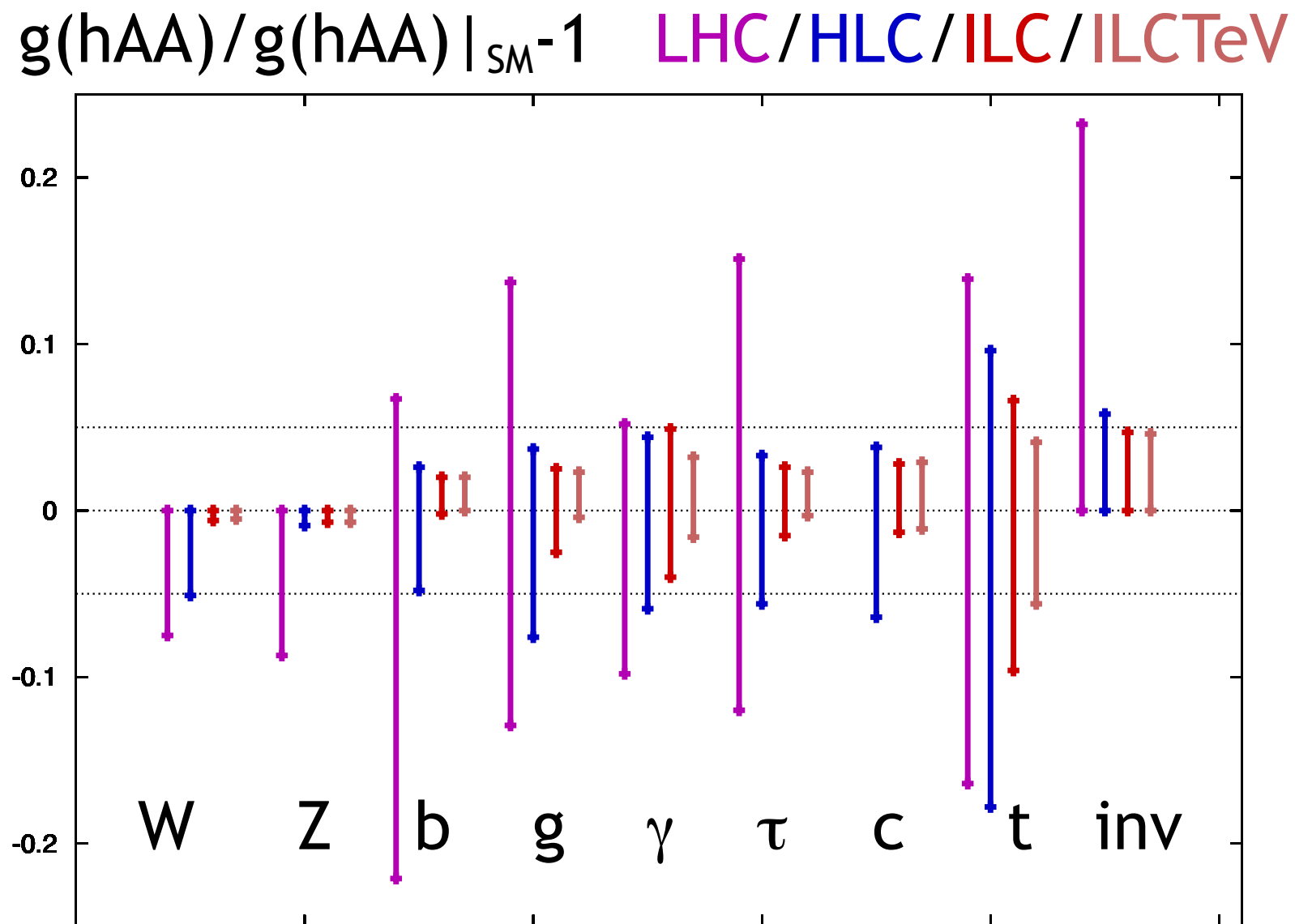
- Study of Higgs Couplings is perhaps our best window to Physics Beyond the Standard Model
- They will be study well at the LHC, in particular at high luminosity
- Lepton colliders allow to reach new precisions, particularly at high luminosities like the ones reachable at TLEP



● ILC complementary to HL-LHC (g_{Hcc} , Γ_H , Γ_{inv})

➤ TLEP reaches the sub-per-cent precision (>1 TeV BSM Physics)

Capabilities of different colliders to determine Higgs boson couplings



M. Peskin, arXiv:1207.2516

LHC at 14 TeV and 300 inv. fb, ILC at 250 GeV and 250 inv. fb,
500 GeV and 500 inv. fb and 1 TeV and 1000 inv. fb.

Typical Variation of Couplings in Different Models

- Two Higgs Doublet Models/MSSM

$$\frac{\Delta g_{hbb}}{(g_{hbb})_{SM}} \simeq \frac{\Delta g_{h\tau\tau}}{(g_{h\tau\tau})_{SM}} = \text{few percent} \times \left(\frac{1 \text{ TeV}}{m_A} \right)^2$$

But real deviations cannot always be parametrized this way (see later)

- Composite Models

$$\frac{\Delta g_{hff}}{(g_{hff})_{SM}} \simeq \frac{\Delta g_{hVV}}{(g_{hVV})_{SM}} = -\text{few percent} \times \left(\frac{1 \text{ TeV}}{m_R} \right)^2$$

- Extended Quark Sectors ($Y = O(1)$)

$$\frac{\Delta g_{hgg}}{(g_{hgg})_{SM}} \simeq -3 N_C Q_f^2 \frac{\Delta g_{h\gamma\gamma}}{(g_{h\gamma\gamma})_{SM}} = -\text{few percent} \times \left(\frac{1 \text{ TeV}}{m_Q} \right)^2$$

TLEP will probe new physics scales of a few TeV

Implications of Higgs Couplings Modifications in type II 2HDM

In supersymmetric theories, there is one Higgs doublet that behaves like the SM one.

$$H_{SM} = H_d \cos \beta + H_u \sin \beta, \quad \tan \beta = v_u/v_d$$

The orthogonal combination may be parametrized as

$$H = \begin{pmatrix} H + iA \\ H^\pm \end{pmatrix}$$

where H , H^\pm and A represent physical CP-even, charged and CP-odd scalars (non standard Higgs).

Strictly speaking, the CP-even Higgs modes mix and none behave exactly as the SM one.

$$h = -\sin \alpha \operatorname{Re}(H_d^0) + \cos \alpha \operatorname{Re}(H_u^0)$$

In the so-called decoupling limit, in which the non-standard Higgs bosons are heavy, $\sin \alpha = -\cos \beta$ and one recovers the SM as an effective theory.

Lightest SM-like Higgs mass strongly depends on:

* CP-odd Higgs mass m_A

* $\tan \beta$

* the top quark mass

* the stop masses and mixing

$$\mathbf{M}_{\tilde{t}}^2 = \begin{pmatrix} \mathbf{m}_Q^2 + \mathbf{m}_t^2 + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}_U^2 + \mathbf{m}_t^2 + \mathbf{D}_R \end{pmatrix}$$

M_h depends logarithmically on the averaged stop mass scale M_{SUSY} and has a quadratic and quartic dep. on the stop mixing parameter X_t . [and on sbottom/stau sectors for large $\tan\beta$]

For moderate to large values of $\tan \beta$ and large non-standard Higgs masses

$$m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[\frac{1}{2} \tilde{X}_t + t + \frac{1}{16\pi^2} \left(\frac{3}{2} \frac{m_t^2}{v^2} - 32\pi\alpha_3 \right) (\tilde{X}_t t + t^2) \right]$$

$$t = \log(M_{\text{SUSY}}^2 / m_t^2) \quad \tilde{X}_t = \frac{2X_t^2}{M_{\text{SUSY}}^2} \left(1 - \frac{X_t^2}{12M_{\text{SUSY}}^2} \right)$$

$$\underline{X_t = A_t - \mu / \tan \beta} \rightarrow \text{LR stop mixing}$$

M.Carena, J.R. Espinosa, M. Quiros, C.W.'95

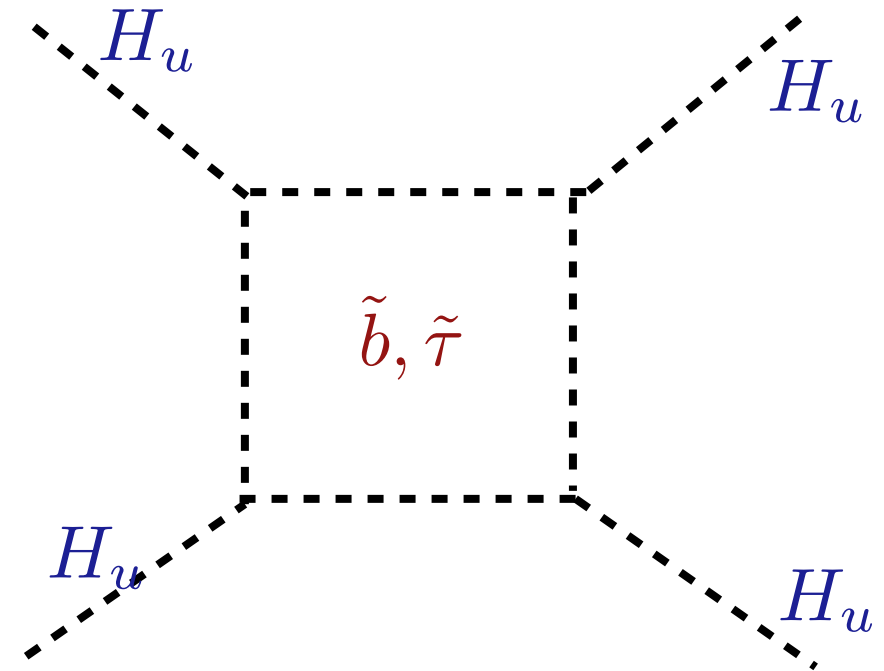
M. Carena, M. Quiros, C.W.'95

Analytic expression valid for $M_{\text{SUSY}} \sim m_Q \sim m_U$

Large $\tan \beta$ corrections

Corrections from the sbottom sector :
Negative contributions to the Higgs mass

$$\Delta m_h^2 \simeq -\frac{h_b^4 v^2}{16\pi^2} \frac{\mu^4}{M_{\text{SUSY}}^4}$$



$$h_b \simeq \frac{m_b}{v \cos \beta (1 + \tan \beta \Delta h_b)}$$

Similar negative corrections, often ignored,
appear from the stau sector

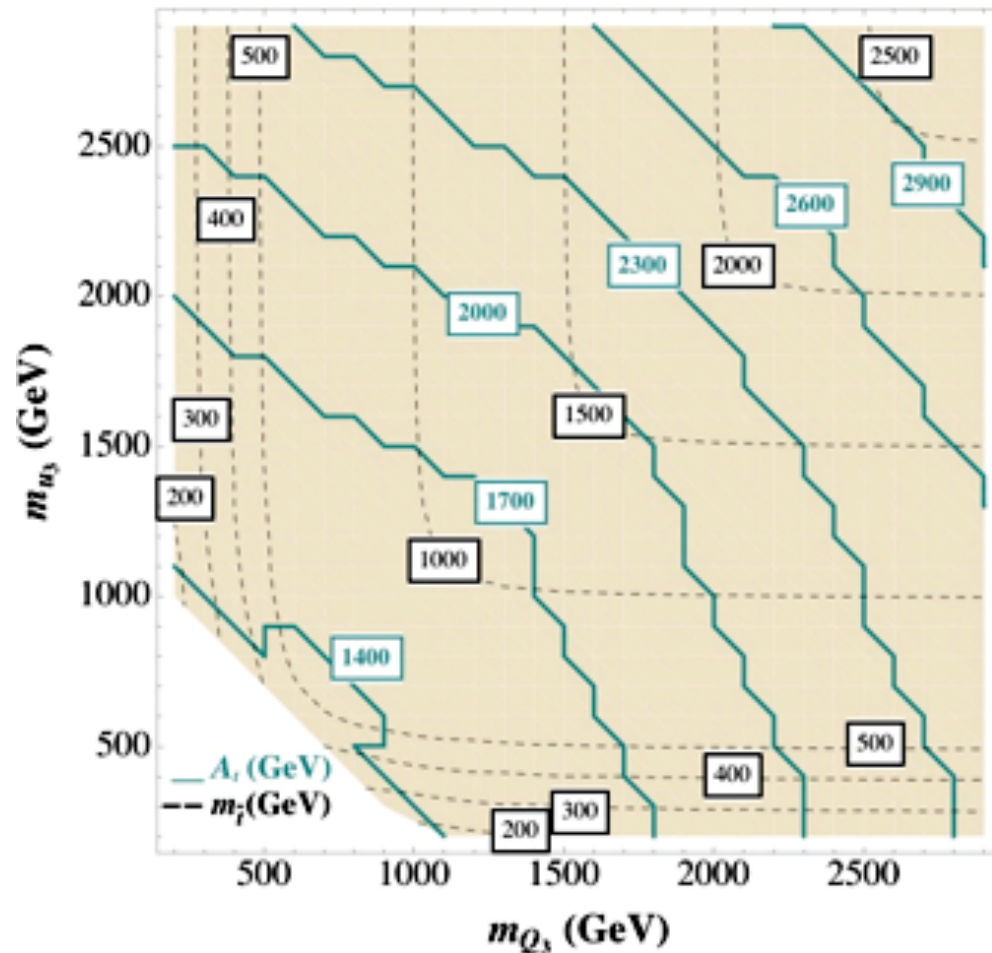
$$\Delta m_h^2 \simeq -\frac{h_\tau^4 v^2}{48\pi^2} \frac{\mu^4}{M_{\tilde{\tau}}^4},$$

$$h_\tau \simeq \frac{m_\tau}{v \cos \beta (1 + \tan \beta \Delta h_\tau)}$$

Soft supersymmetry Breaking Parameters

M. Carena, S. Gori, N. Shah, C. Wagner, arXiv:1112.336, +L.T.Wang, arXiv:1205.5842

A_t and $m_{\tilde{t}}$ for $124 \text{ GeV} < m_h < 126 \text{ GeV}$ and $\tan \beta = 10$



Large stop sector mixing

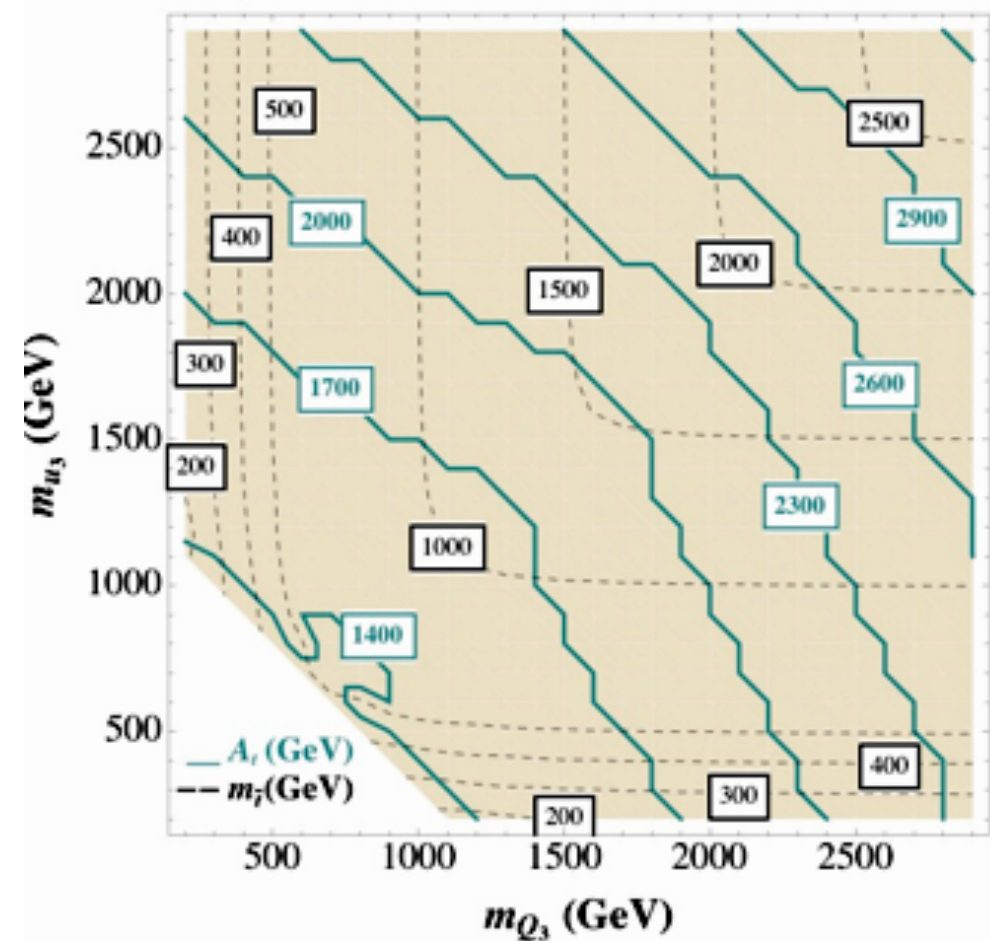
$$A_t > 1 \text{ TeV}$$

No lower bound on the lightest stop

One stop can be light and the other heavy
or

in the case of similar stop soft masses.
both stops can be below 1 TeV

A_t and $m_{\tilde{t}}$ for $124 \text{ GeV} < m_h < 126 \text{ GeV}$ and $\tan \beta = 60$



Intermediate values of tan beta lead to
the largest values of m_h for the same values
of stop mass parameters

At large tan beta, light staus/sbottoms can decrease
 m_h by several GeV's via Higgs mixing effects
and compensate tan beta enhancement

Impact of higher loops

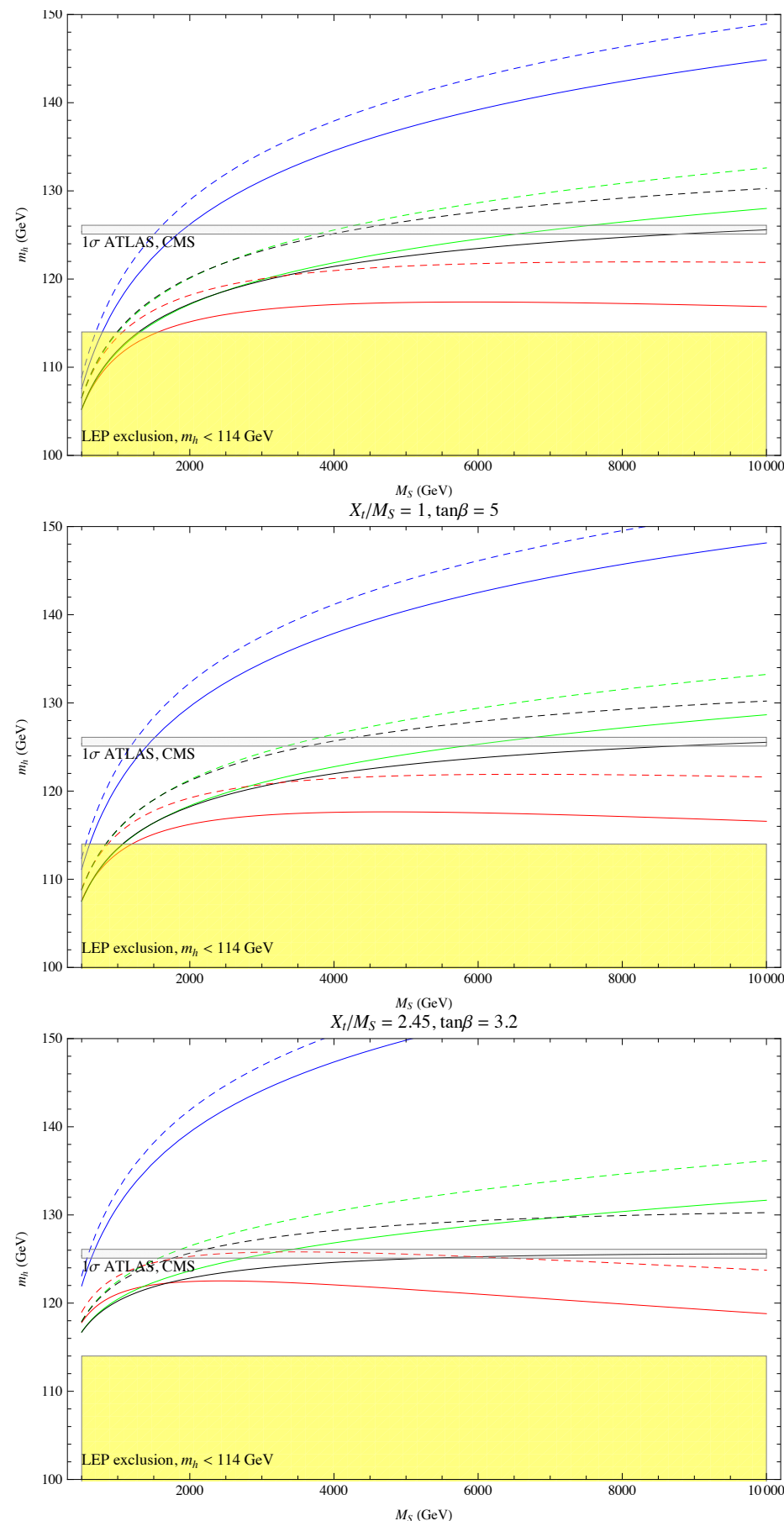
Recalculation of RG prediction including up to 4 loops in RG expansion

Agreement with S. Martin'07 and Espinosa and Zhang'00, Carena, Espinosa, Quiros, C.W.'00, Carena, Haber, Heinemeyer, Weiglein, Hollik and C.W.'00, in corresponding limits.

Two loops results agree w FeynHiggs and CPsuperH results

For moderate or large values of $\tan \beta$, the stop masses should be smaller than about 4 TeV for light inos and 10 TeV for heavy ones !

G. Lee, C.W.'13
(see also Feng et al.'13)



Higgs Boson Properties

The gauge boson masses still proceed from the kinetic terms

$$\mathcal{L} = (\mathcal{D}^\mu H_u)^\dagger \mathcal{D}_\mu H_u + (\mathcal{D}^\mu H_d)^\dagger \mathcal{D}_\mu H_d \rightarrow g^2 (H_u^\dagger W_\mu W^\mu H_u + H_d^\dagger W_\mu W^\mu H_d)$$

Therefore, the order parameter is $v = \sqrt{v_u^2 + v_d^2}$.

The fermion mass terms proceed from the Yukawa interactions

$$\mathcal{L} = -h_d \bar{D}_L H_d d_R - h_u \bar{U}_L H_u u_R + h.c.$$

Therefore, $m_d = h_d v \cos \beta$, and

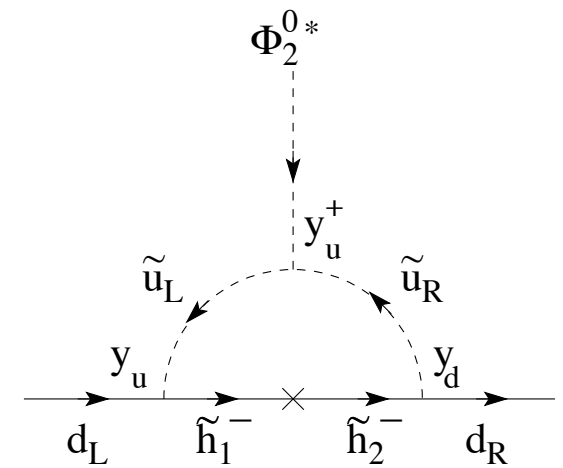
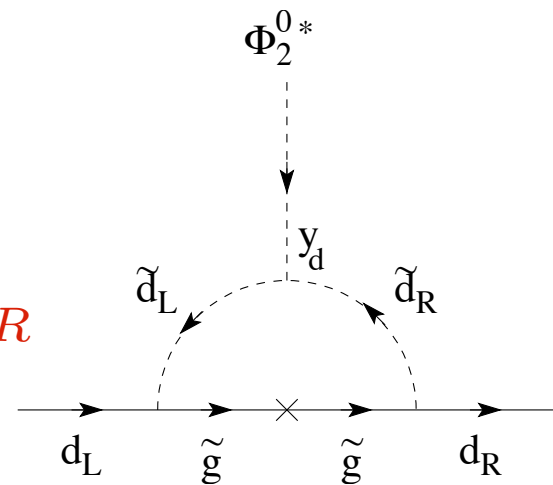
$$\mathcal{L} \rightarrow -\frac{m_d}{v} (h + \tan \beta H)$$

and the down sector has $\tan \beta$ enhanced couplings to the non-standard Higgs bosons.

Radiative Corrections to Flavor Conserving Higgs Couplings

- Couplings of down and up quark fermions to **both Higgs** fields arise after radiative corrections.

$$\mathcal{L} = \bar{d}_L (h_d H_1^0 + \Delta h_d H_2^0) d_R$$



- The radiatively induced coupling depends on ratios of supersymmetry breaking parameters

$$m_b = h_b v_1 \left(1 + \frac{\Delta h_b}{h_b} \tan \beta \right)$$

$$\tan \beta = \frac{v_2}{v_1}$$

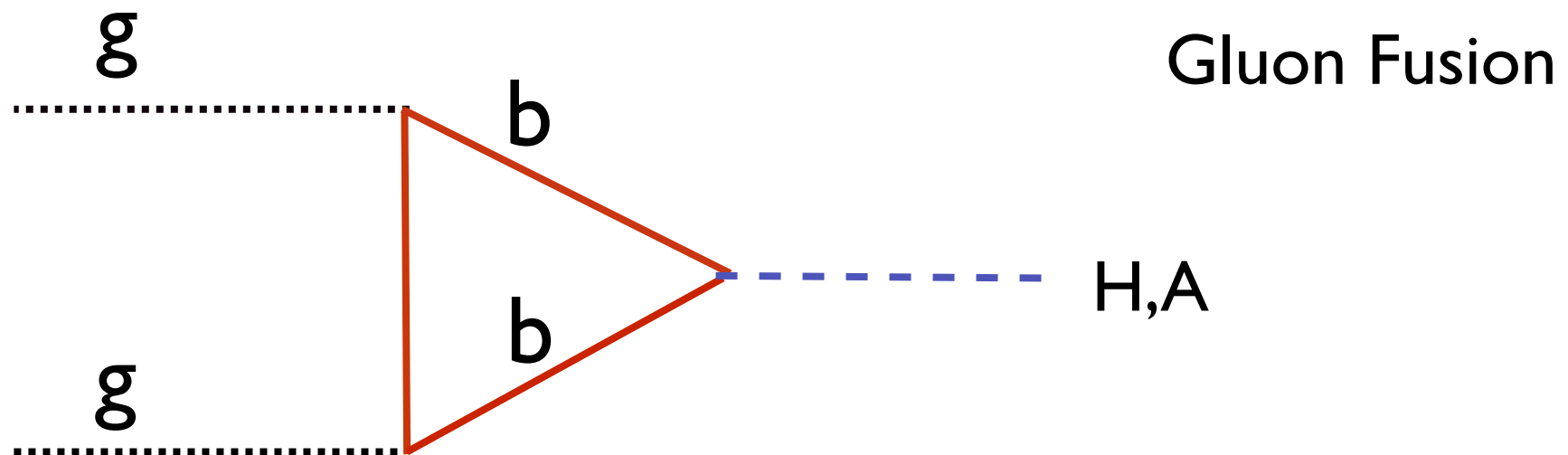
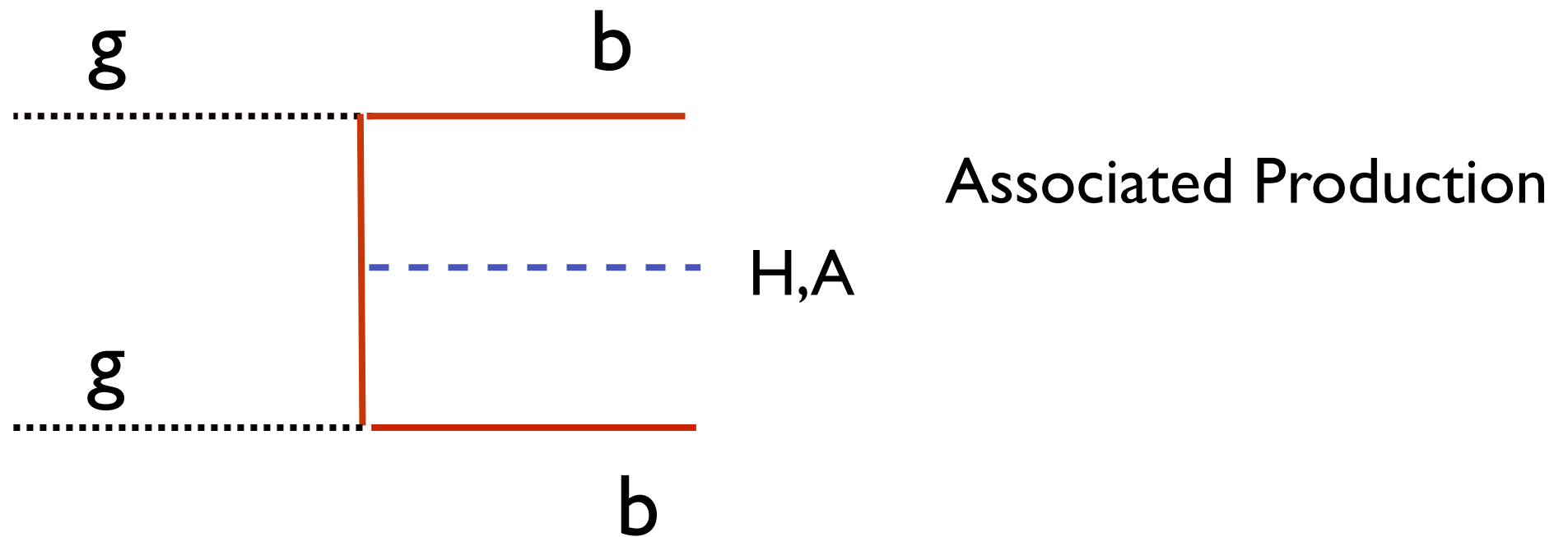
$$\frac{\Delta_b}{\tan \beta} = \frac{\Delta h_b}{h_b} \simeq \frac{2\alpha_s}{3\pi} \frac{\mu M_{\tilde{g}}}{\max(m_{\tilde{b}_i}^2, M_{\tilde{g}}^2)} + \frac{h_t^2}{16\pi^2} \frac{\mu A_t}{\max(m_{\tilde{t}_i}^2, \mu^2)}$$

$$X_t = A_t - \mu / \tan \beta \simeq A_t \quad \Delta_b = (E_g + E_t h_t^2) \tan \beta$$

Resummation : Carena, Garcia, Nierste, C.W.'00

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan \beta}{(1 + \Delta_b)v}, \quad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan \beta}{v}$$

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G. Weiglein, C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \rightarrow b\bar{b}) \simeq \sigma(b\bar{b}A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{9}{(1 + \Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \rightarrow A) \times BR(A \rightarrow \tau\tau) \simeq \sigma(b\bar{b}, gg \rightarrow A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2 + 9}$$

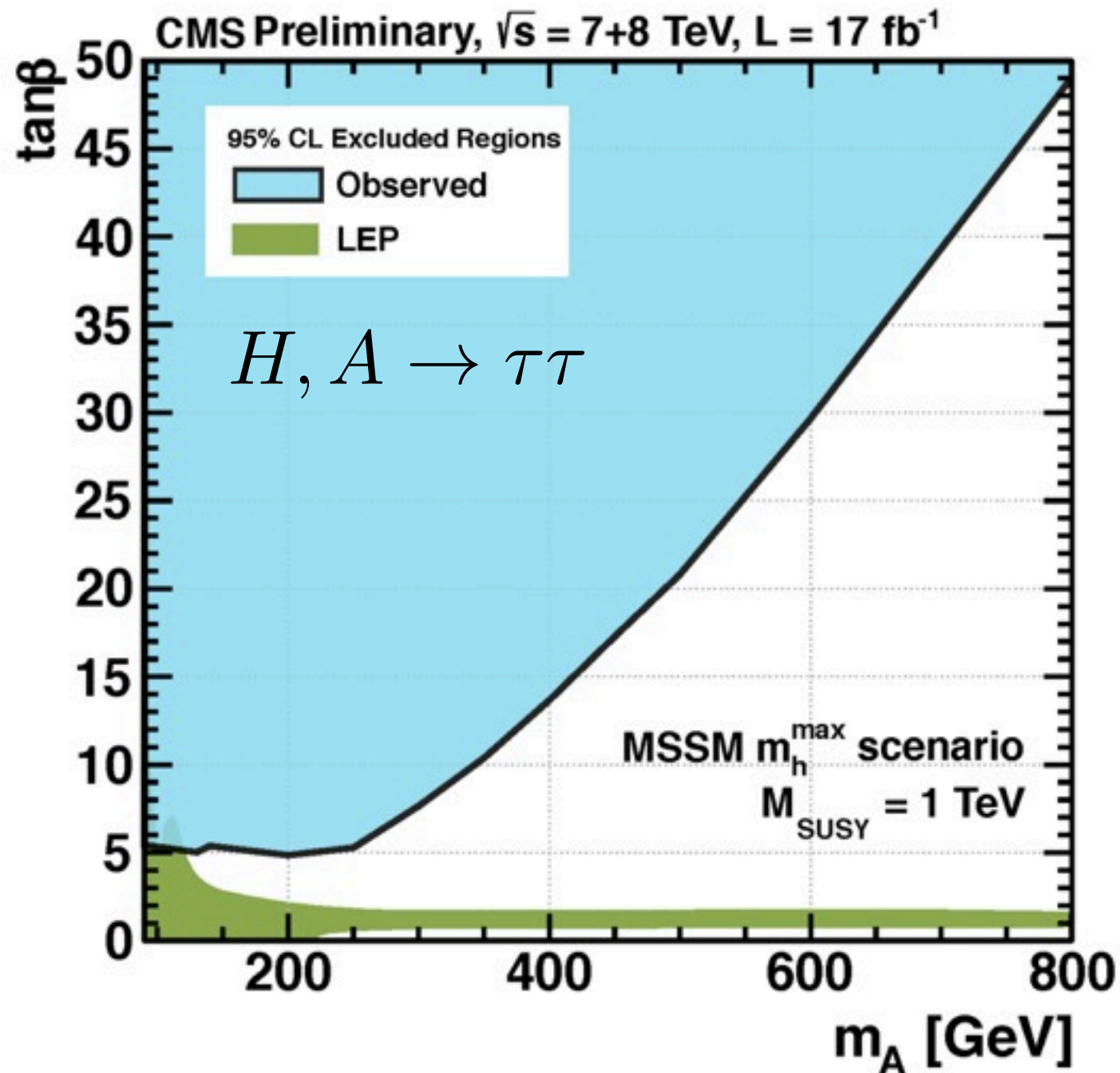
- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Validity of this approximation confirmed by NLO computation by D.

North and M. Spira, arXiv:0808.0087

Further work by Mhulleitner, Rzehak and Spira, 0812.3815

In the MSSM, non-standard Higgs may be produced via its large couplings to the bottom quark, and searched for in its decays into bottom quarks and tau leptons



How to test the region of low $\tan\beta$ and moderate m_A ?

Decays of non-standard Higgs bosons into pairs of standard ones, charginos and neutralinos may be a possibility.

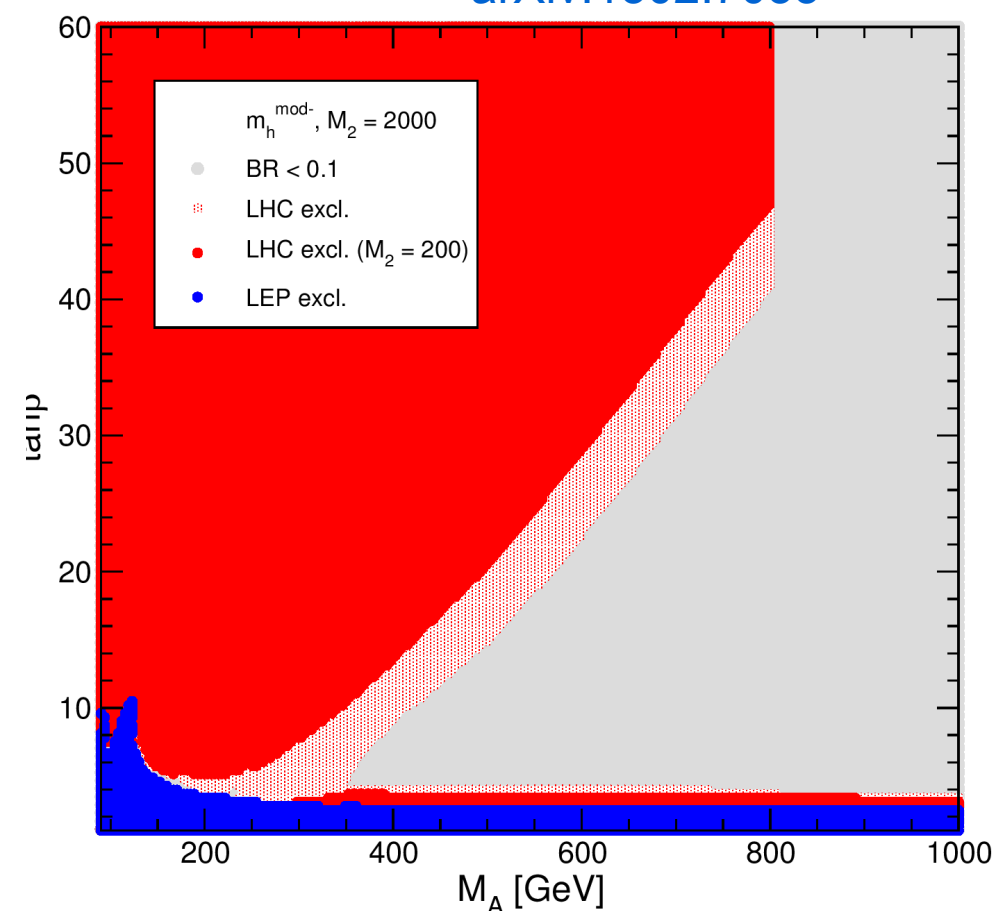
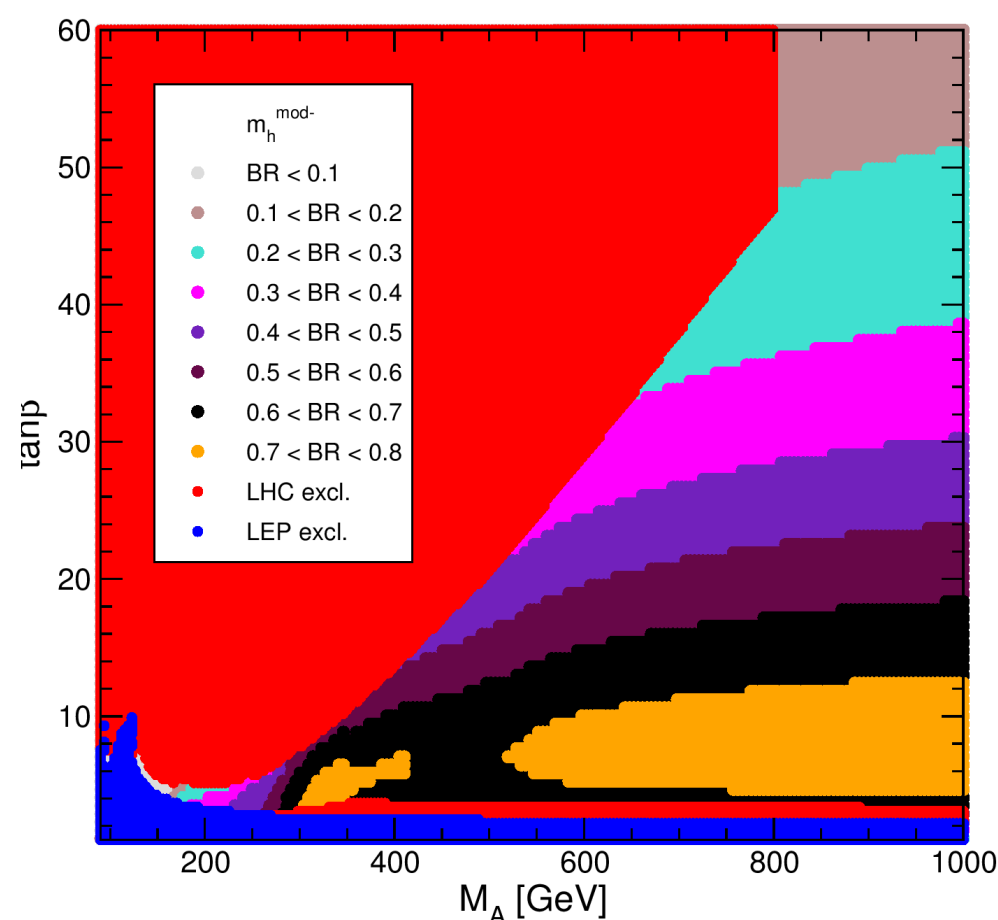
Can change in couplings help there?

It depends on radiative corrections

Decays of the non-standard Higgs bosons into EWKininos in the

m_h^{mod} scenario

[M. Carena](#), [S. Heinemeyer](#), [O. Stål](#),
[C.E.M. Wagner](#), [G. Weiglein](#),
[arXiv:1302.7033](#)



Reach of non-standard Higgs bosons in tau decays modified
Opportunity for dedicated search of these decays.

Also $BR(H \rightarrow hh)$ may become important
for small values of $\tan\beta$

Couplings of SM Higgs to Fermions and Gauge Bosons

Down-type Fermions

$$g_{hbb,h\tau\tau} = -h_{b,\tau} \sin \alpha + \Delta h_{b,\tau} \cos \alpha$$

$$g_{hbb,h\tau\tau} = -\frac{m_{b,\tau} \sin \alpha}{v \cos \beta (1 + \Delta_{b,\tau})} \left(1 - \frac{\Delta_{b,\tau}}{\tan \beta \tan \alpha} \right)$$

Up-type Fermions

$$g_{htt} = \frac{m_t \cos \alpha}{v \sin \beta}$$

Gauge Bosons

$$g_{hWW,hZZ} \simeq \sin(\alpha - \beta)$$

$$\frac{\cos \alpha}{\sin \beta} \simeq \sin(\beta - \alpha)$$

For moderate values of m_A and $\tan \beta$,
the top and W, Z couplings go fast to SM values

$$\cos(\alpha - \beta) \simeq \frac{M_h^2}{M_A^2 \tan \beta}$$

Effective Analysis of Behavior of Couplings in two Higgs Doublet Models

$$\begin{aligned}
 V = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
 & + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\
 & + \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\} ,
 \end{aligned}$$

In the MSSM, at tree-level, only the first four couplings are non-zero and are governed by D-terms in the scalar potential. At loop-level, all of them become non-zero via the trilinear and quartic interactions with third generation sfermions.

Haber, Hempfling'93

$$\begin{aligned}
 \lambda_1 &= \lambda_2 = \frac{1}{4} (g_1^2 + g_2^2) = \frac{m_Z^2}{v^2} , \\
 \lambda_3 &= \frac{1}{4} (g_1^2 - g_2^2) = -\frac{m_Z^2}{v^2} + \frac{1}{2} g_2^2 , \\
 \lambda_4 &= -\frac{1}{2} g_2^2 ,
 \end{aligned}$$

$$\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \equiv m_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta c_\beta \\ -s_\beta c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}$$

MSSM

$$\begin{aligned}
 v^2 L_{11} &= M_Z^2 \cos^2 \beta + v^2 \Delta L_{11} \\
 v^2 L_{12} &= -M_Z^2 \cos \beta \sin \beta + v^2 \Delta L_{12} \\
 v^2 L_{22} &= M_Z^2 \sin^2 \beta + \Delta L_{22}
 \end{aligned}$$

$$\begin{aligned}
 L_{11} &= \lambda_1 c_\beta^2 + 2\lambda_6 s_\beta c_\beta + \lambda_5 s_\beta^2 , \\
 L_{12} &= (\lambda_3 + \lambda_4) s_\beta c_\beta + \lambda_6 c_\beta^2 + \lambda_7 s_\beta^2 , \\
 L_{22} &= \lambda_2 s_\beta^2 + 2\lambda_7 s_\beta c_\beta + \lambda_5 c_\beta^2 .
 \end{aligned}$$

The mixing of the two CP-even Higgs bosons may be determined from the matrix elements

$$s_\alpha = \frac{\mathcal{M}_{12}^2}{\sqrt{(\mathcal{M}_{12}^2)^2 + (\mathcal{M}_{11}^2 - m_h^2)^2}}$$

In the MSSM,

$$s_\alpha = -\frac{(m_A^2 + M_Z^2)s_\beta c_\beta - v^2 \Delta L_{12}}{\sqrt{((m_A^2 + M_Z^2)s_\beta c_\beta - v^2 \Delta L_{12})^2 + (m_A^2 s_\beta^2 + M_Z^2 c_\beta^2 - m_h^2 + v^2 \Delta L_{11})^2}}$$

For $\tan \beta \geq 5$ and $m_A \geq 200$ GeV, if $\Delta L_{11,12}$ are small,

$$-\frac{s_\alpha}{c_\beta} \simeq \frac{m_A^2 + M_Z^2}{m_A^2 - m_h^2}.$$

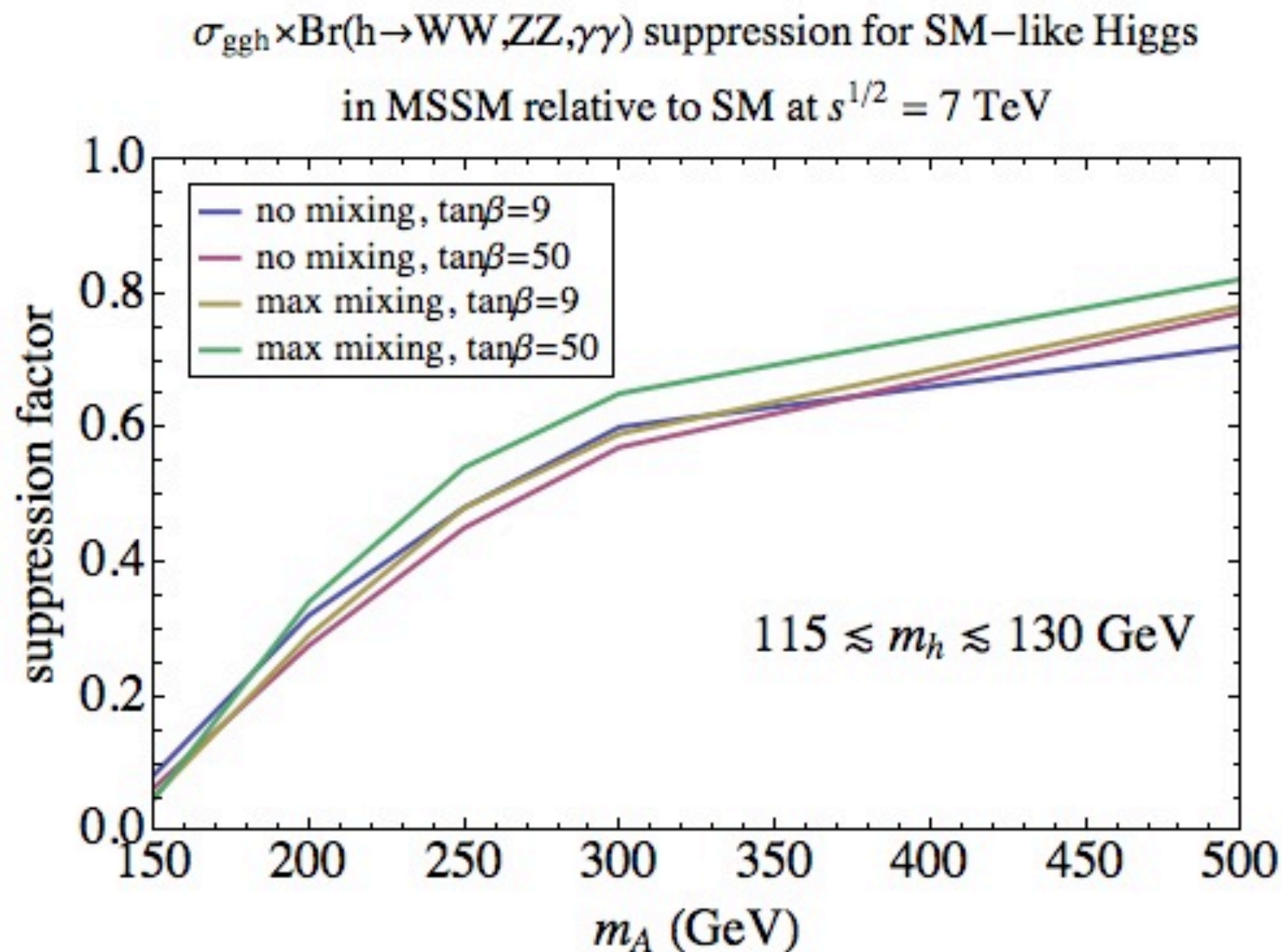
Deviations from SM behavior depend only on m_A and not on $\tan \beta$

M. Carena, I. Low, N. Shah, C.W.'13

Suppression Factors at the LHC

If loop corrections are small

[M. Carena, P. Draper, T. Liu, C. W., arXiv:1107.4354](#)



Loop Effects

It is easy to see that, if loop effects allow for

$$\tan \beta \mathcal{M}_{12}^2 = \mathcal{M}_{11}^2$$

one would obtain $\sin \alpha = -\cos \beta$ even if m_A is not large

In the MSSM this condition implies

$$m_h^2 = M_Z^2 c_{2\beta} + v^2 (\Delta L_{11} + t_\beta \Delta L_{12})$$

which is independent of the CP-odd mass !

Carena, Low, Shah, C.W.'13

This can be generalized to more general II Higgs Doublet Models.

See Haber and Gunion'03. for a similar demonstration in the physical basis.

$$v^2 \Delta L_{12} \simeq \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta} \frac{\mu \tilde{A}_t}{M_{\text{SUSY}}^2} \left[\frac{A_t \tilde{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4},$$

$$v^2 \Delta L_{11} \simeq -\frac{v^2}{96\pi^2} \left(\frac{3h_t^4 \mu^2 A_t^2}{M_{\text{SUSY}}^2} + \frac{3h_b^4 \mu^2 A_b^2}{M_{\text{SUSY}}^2} + \frac{h_\tau^4 \mu^2 A_\tau^2}{M_{\tilde{\tau}}^2} \right)$$

$$v^2 \Delta L_{ij} \simeq 200 \text{ GeV}^2 \times \mathcal{O} \left(\frac{\mu^m A_t^{4-m}}{M_{\text{SUSY}}^4} \right)$$

MSSM condition to obtain SM coupling to fermions (true for moderate or large tanbeta)

$$\tan \beta = \frac{m_h^2 + M_Z^2 - v^2 \Delta L_{11}}{v^2 \Delta L_{12}}$$

Observe that if ΔL_{12} is small, there is no solution for reasonable values of tanbeta.

ΔL_{12} has to be sizable. ΔL_{11} tends to be smaller than the radiative corrections to the Higgs mass and is negative in the region of parameters where ΔL_{12} is positive.

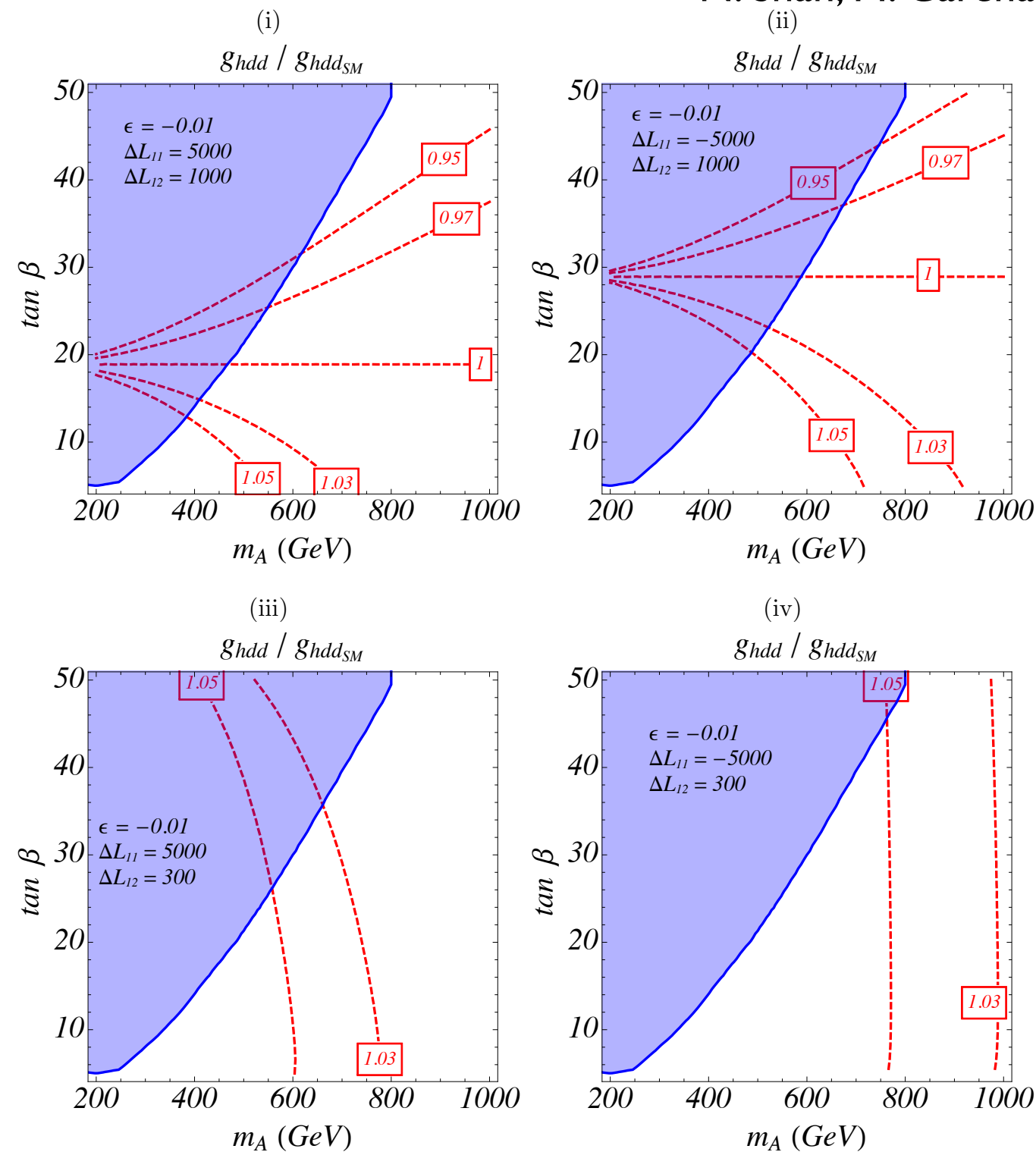
Large or small deviations in the wedge depend on if ΔL_{12} is positive or negative and on its magnitude.

For ΔL_{12} small, we should recover couplings that are approximately independent of tanbeta and larger than in the SM !

Here

$$\Delta_d = \epsilon \tan \beta$$

$$\Delta L_{ij} = [v^2 \Delta_{ij}] (GeV)$$



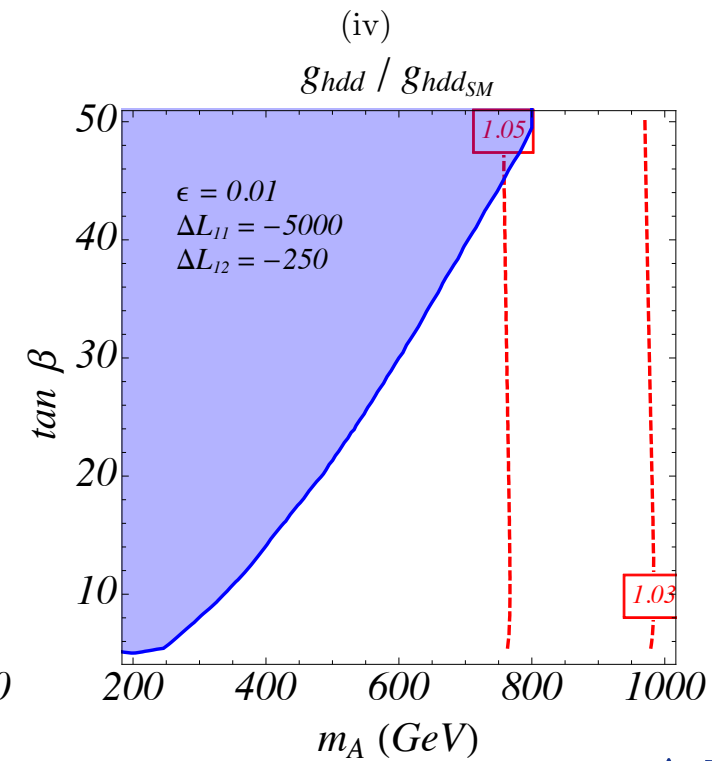
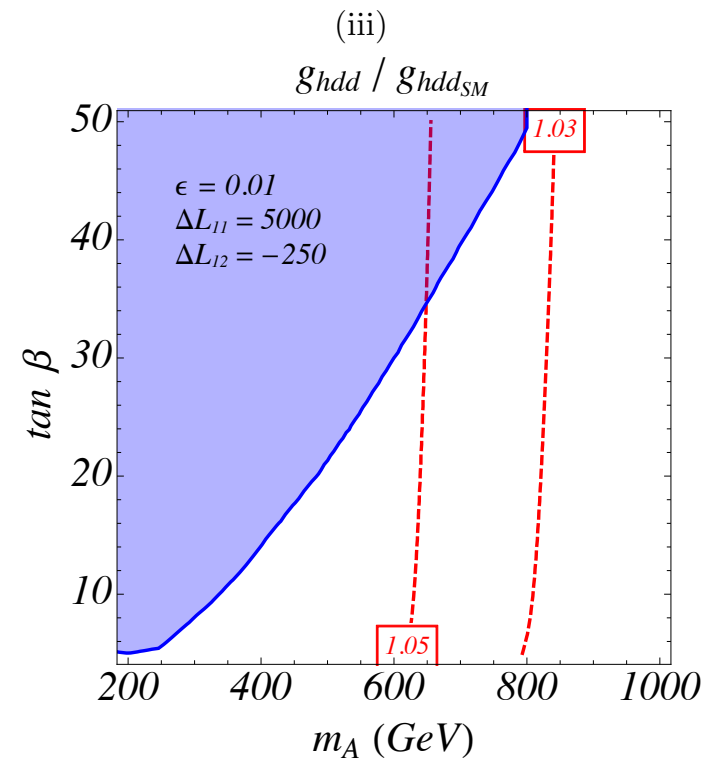
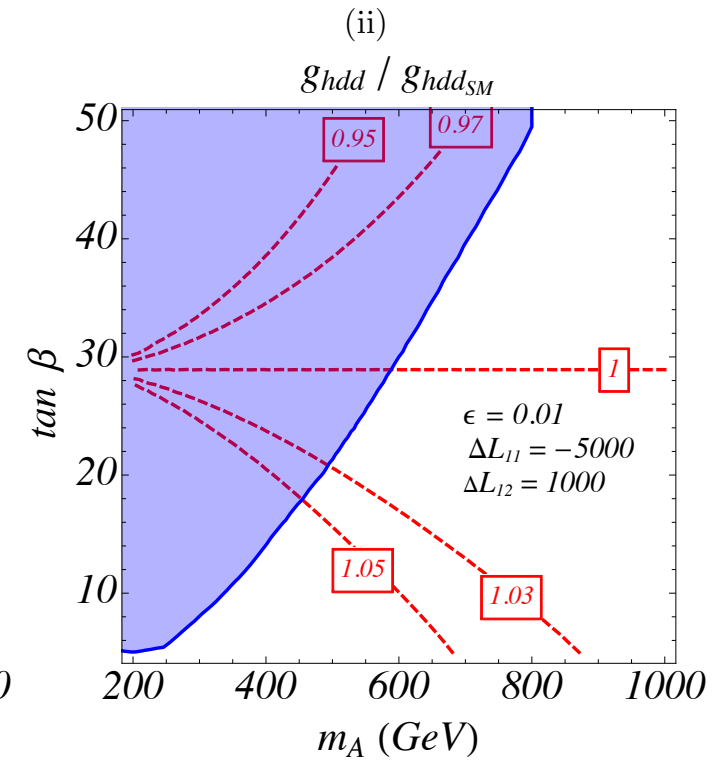
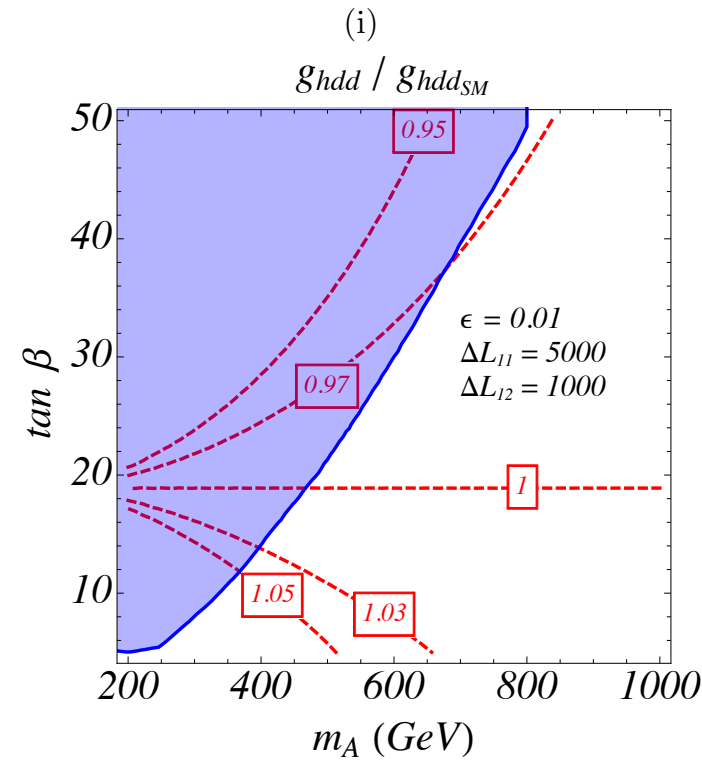
Decoupling condition is independent of ϵ

$$\tan \beta \simeq \frac{25000 - \Delta L_{11}}{\Delta L_{12}}$$

Here

$$\Delta_d = \epsilon \tan \beta$$

$$\Delta L_{ij} = [v^2 \Delta_{ij}](\text{GeV})$$

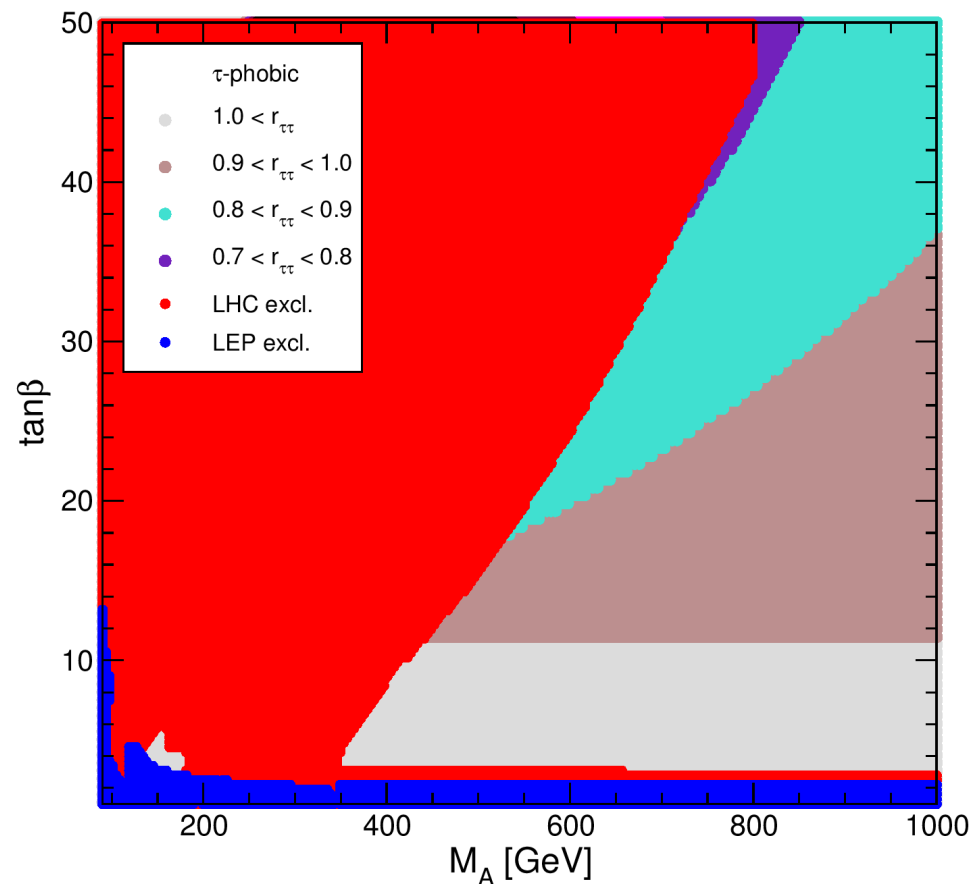
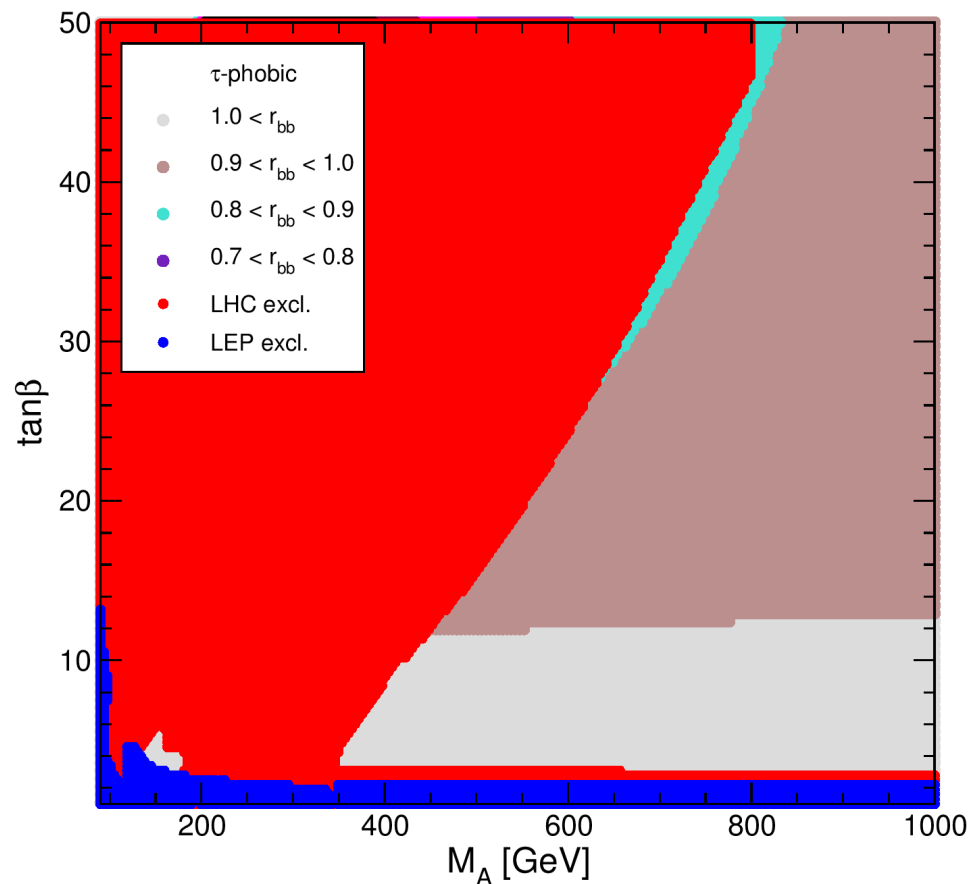


Decoupling condition is independent of ϵ

$$\tan \beta \simeq \frac{25000 - \Delta L_{11}}{\Delta L_{12}}$$

The τ -phobic Higgs scenario

Suppression of down-type fermion couplings to the Higgs due to Higgs mixing effects. Staus play a relevant role. Decays into staus relevant for heavy non-standard Higgs bosons.



$$\Delta L_{12} = 1500$$

$$\Delta L_{11} = -1500$$

$$M_{\text{SUSY}} = 1500 \text{ GeV},$$

$$\mu = 2000 \text{ GeV},$$

$$M_2 = 200 \text{ GeV},$$

$$X_t^{\text{OS}} = 2.45 M_{\text{SUSY}} \text{ (FD calculation),}$$

$$X_t^{\overline{\text{MS}}} = 2.9 M_{\text{SUSY}} \text{ (RG calculation),}$$

$$A_b = A_\tau = A_t,$$

$$m_{\tilde{g}} = 1500 \text{ GeV},$$

$$M_{\tilde{l}_3} = 500 \text{ GeV}.$$

[M. Carena](#), [S. Heinemeyer](#), [O. Stål](#),
[C.E.M. Wagner](#), [G. Weiglein](#),
[arXiv:1302.7033](#)

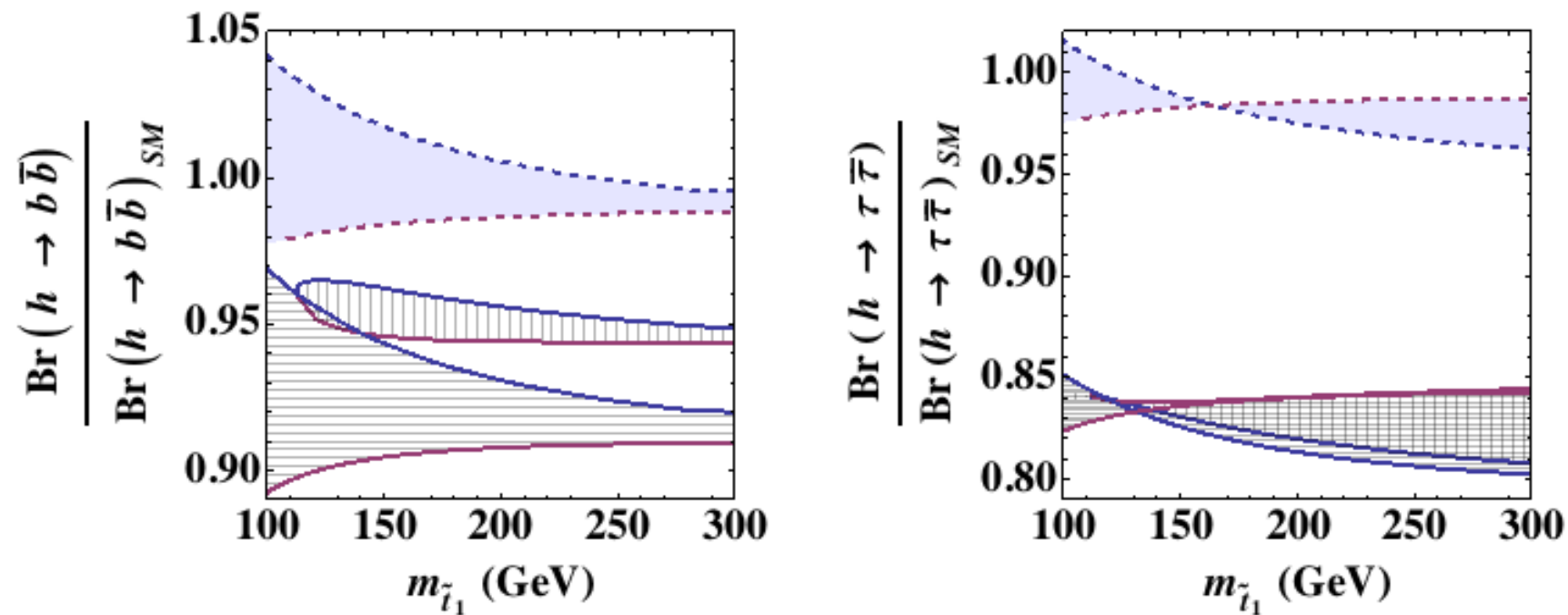
$$\text{Loop}_{12} = \frac{m_t^4}{16\pi^2 v^2 \sin^2 \beta} \frac{\mu \tilde{A}_t}{M_{\text{SUSY}}^2} \left[\frac{A_t \tilde{A}_t}{M_{\text{SUSY}}^2} - 6 \right] + \frac{h_b^4 v^2}{16\pi^2} \sin^2 \beta \frac{\mu^3 A_b}{M_{\text{SUSY}}^4} + \frac{h_\tau^4 v^2}{48\pi^2} \sin^2 \beta \frac{\mu^3 A_\tau}{M_{\tilde{\tau}}^4}$$

Conclusions

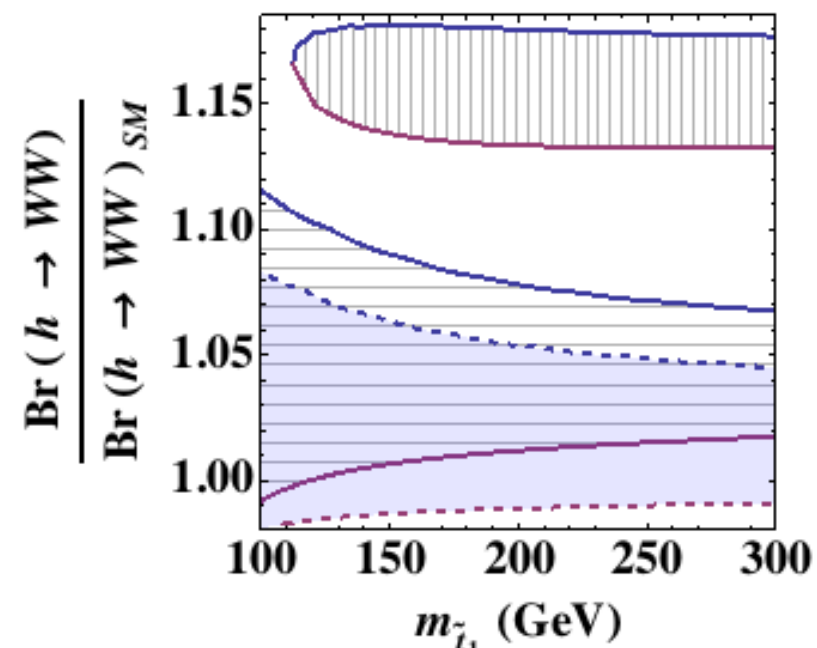
- After the Higgs Discovery at the LHC, it is important to define a coherent program in the search for new physics
- LHC will explore the TeV scale, while studying the properties of the newly discovered Higgs particle
- LHC is mostly sensitive to strongly interacting particles, or light weakly interacting particle with a large mass gap.
- TLEP can explore in a more efficient way, light, weakly interacting particles, particularly when the spectrum is compressed (or the interactions are weaker, for higher luminosity)
- TLEP can also provide significant improvements in precision electroweak data analysis, being sensitive indirectly to particles not visible at the LHC
- While the LHC will be sensitive to a few percent variation of the Higgs couplings and will be able to search for heavy non-standard Higgs particles, TLEP will be sensitive to smaller variations, implying indirectly higher scales. Some caveats to this conclusion were presented.
- Of course, TLEP presents another complementarity with LHC : It enables a VLHC, with energies up to 100 TeV in the center of mass !

Coupling to Fermions and Weak Gauge Bosons

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](https://arxiv.org/abs/1303.4414)



(iii)



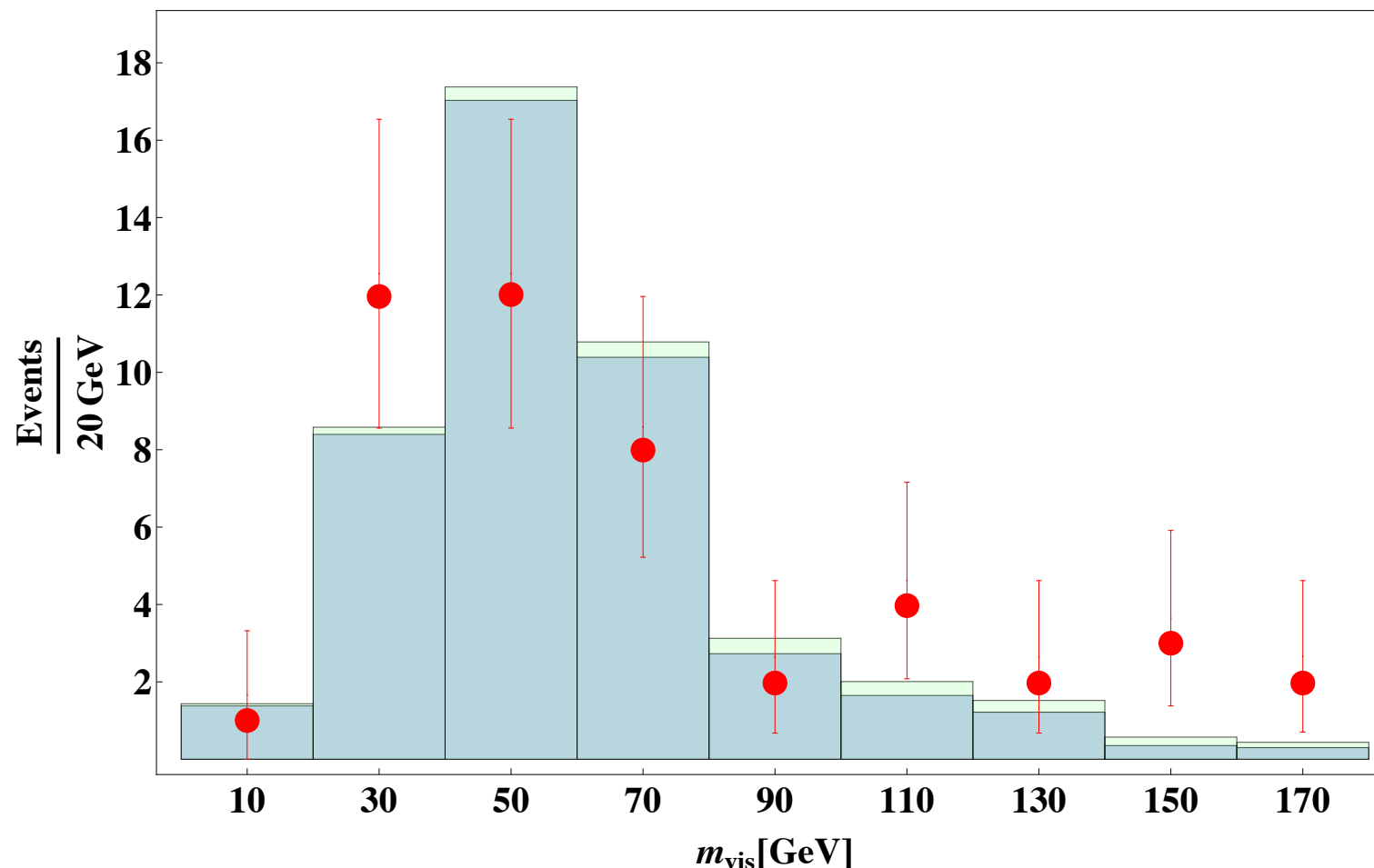
Searches for staus in associated production with sneutrinos.

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](https://arxiv.org/abs/1303.4414)

Final State in $pp \rightarrow Wh$, followed by $h \rightarrow \tau^+ \tau^-$ is similar to the one in

$pp \rightarrow \tilde{\tau} \tilde{\nu}_\tau$, followed by $\tilde{\nu}_\tau \rightarrow \tilde{\tau} + \chi_1^0$.

Look for leptonic decay of the W, and one hadronic and one leptonic tau decay. Same selection cuts as in the Higgs search analysis.



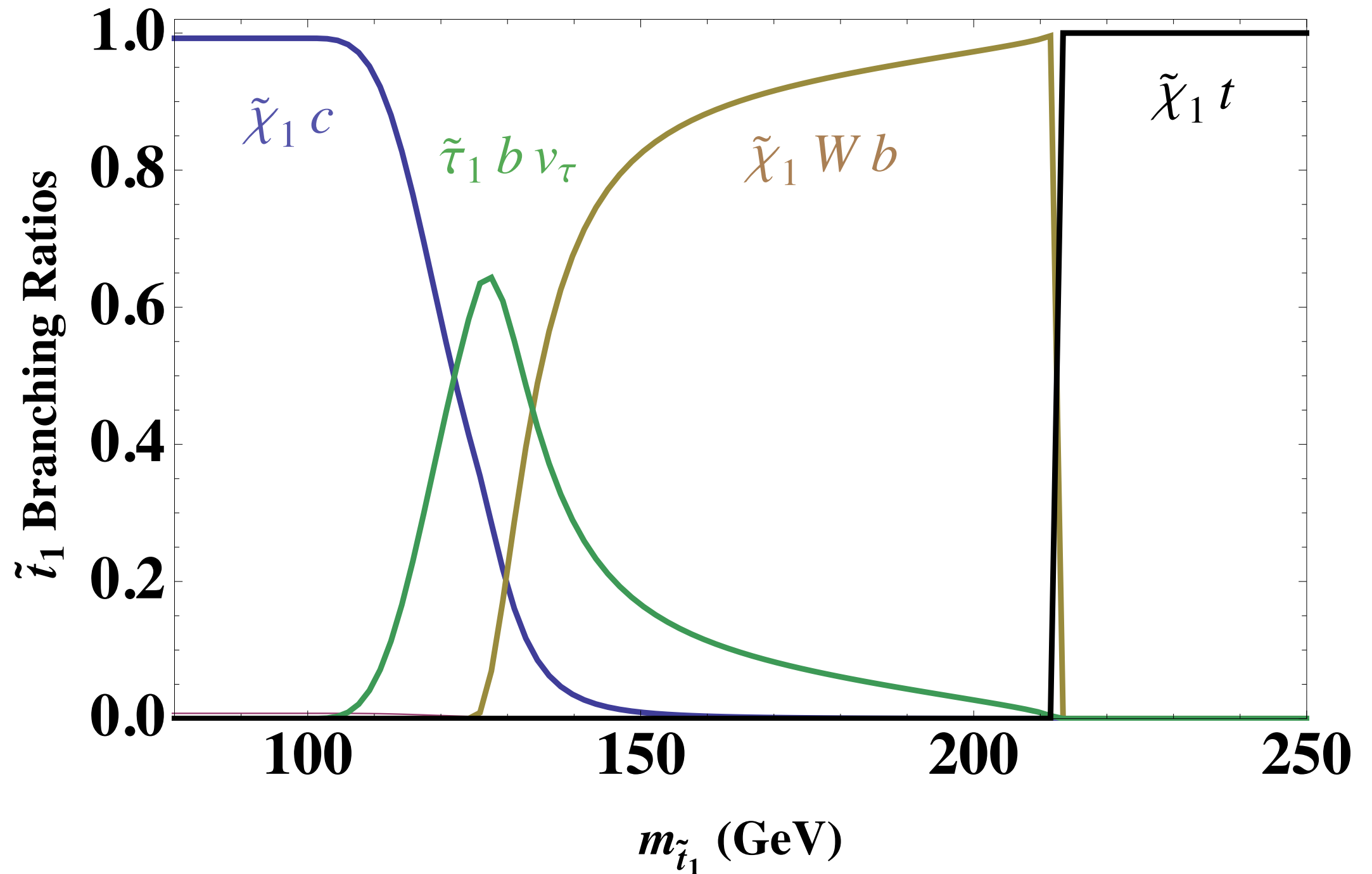
Cut in visible mass increase signal to background ratio, but very low statistics. Dedicated search with optimized selection cuts should be performed.

Light Stop Searches

- Light stops, mainly right handed, may be present without affecting the Higgs mass predictions and without affecting precision electroweak measurements.
- If present, they have an impact on both gluon fusion cross section as well as in $\gamma\gamma$ Higgs decay width. There are strong direct search constraints.
- Three body decay into staus may become the dominant stop decay mode, when three body decay into a neutralino, a W and a b is closed.
- For a neutralino mass of about 40 to 50 GeV, this happens for stop masses of about 130 GeV.

Stop Branching Ratios in Light Stau Scenario

M. Carena, S. Gori, N. Shah, C.W. and L.T.Wang, [arXiv:1303.4414](#)



Apart from region close to top neutralino decay threshold, decays of stops into staus open new possibilities

Vacuum stability

For large values of the μ parameter and the tau Yukawa coupling, one can generate new charge breaking minima deeper than the electroweak minimum

$$V = \left| \mu \frac{h_u}{\sqrt{2}} - y_\tau \tilde{\tau}_L \tilde{\tau}_R \right|^2 + \frac{g_2^2}{8} \left(|\tilde{\tau}_L|^2 + \frac{h_u^2}{2} \right)^2 + \frac{g_1^2}{8} \left(|\tilde{\tau}_L|^2 - 2|\tilde{\tau}_R|^2 - \frac{h_u^2}{2} \right)^2 \\ + m_{H_u}^2 \frac{h_u^2}{2} + m_{L_3}^2 |\tilde{\tau}_L|^2 + m_{E_3}^2 |\tilde{\tau}_R|^2 + \frac{g_1^2 + g_2^2}{8} \delta_H \frac{h_u^4}{4} ,$$

This occurs in this improved tree-level potential, but also occurs in the full one-loop effective potential we shall analyze

Vacuum Stability

Electroweak Minimum is in general metastable in this scenario

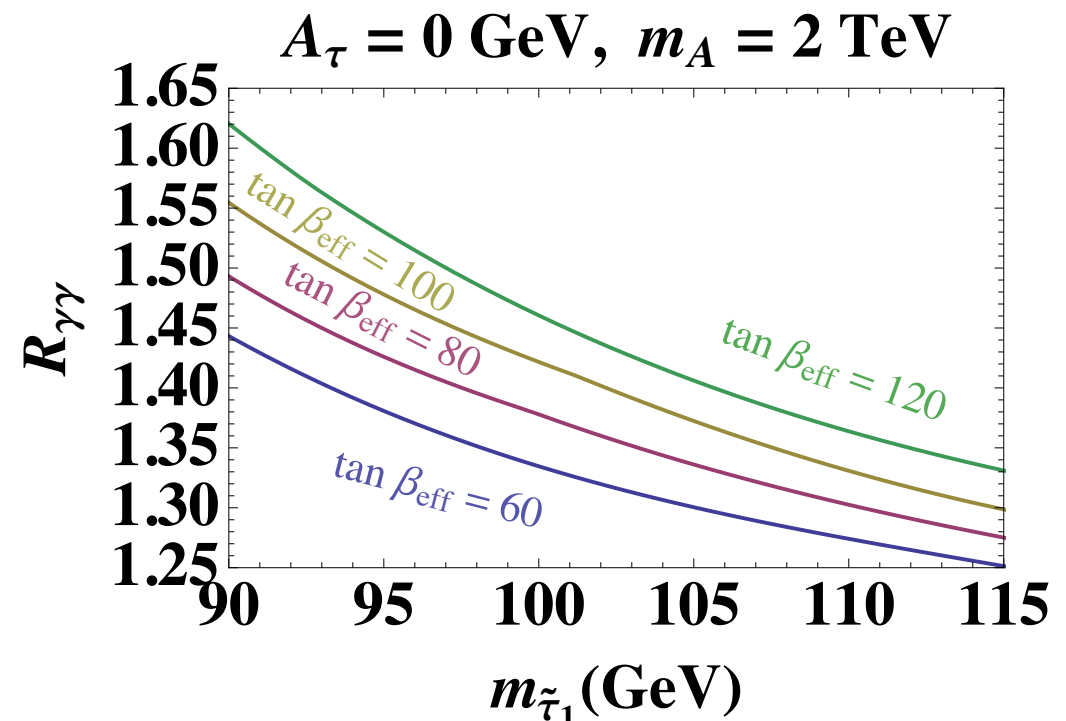
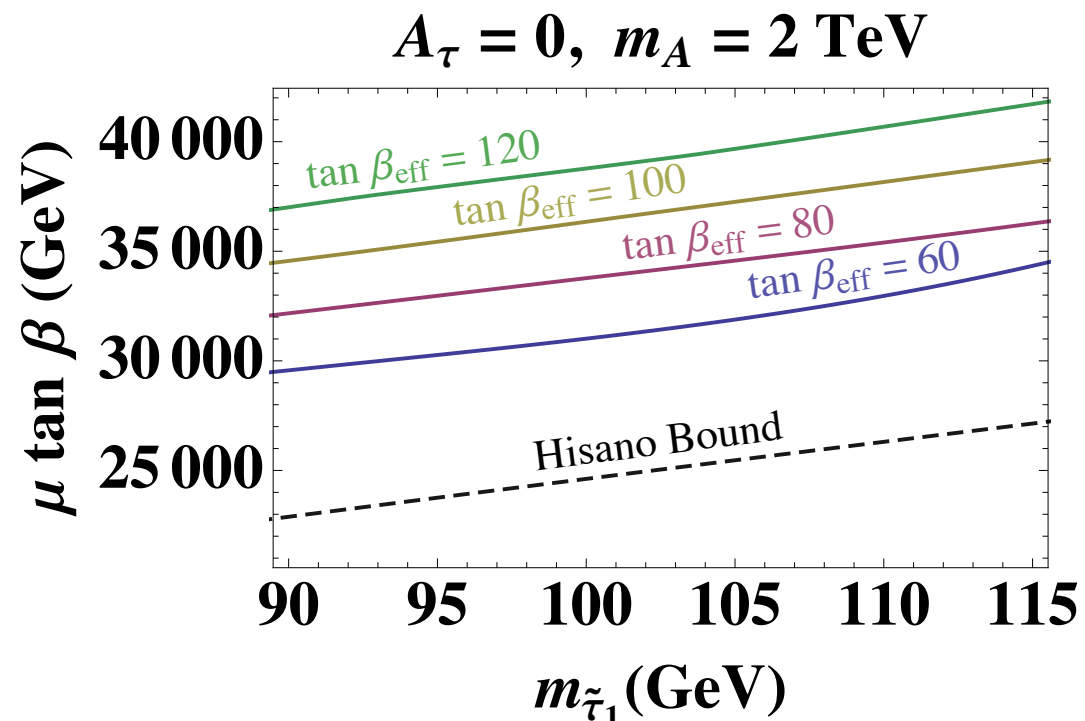
Hisano, Sugiyama'11

Metastability bound depends on $\tan(\beta)$

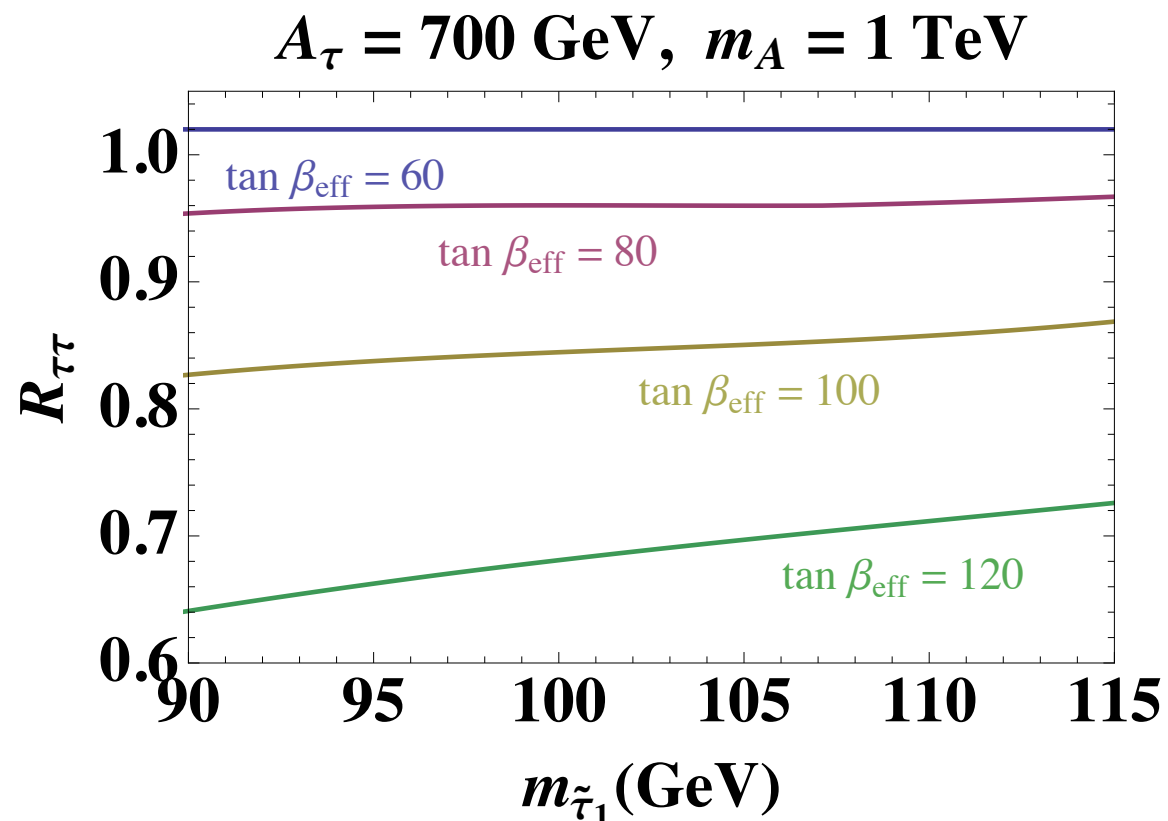
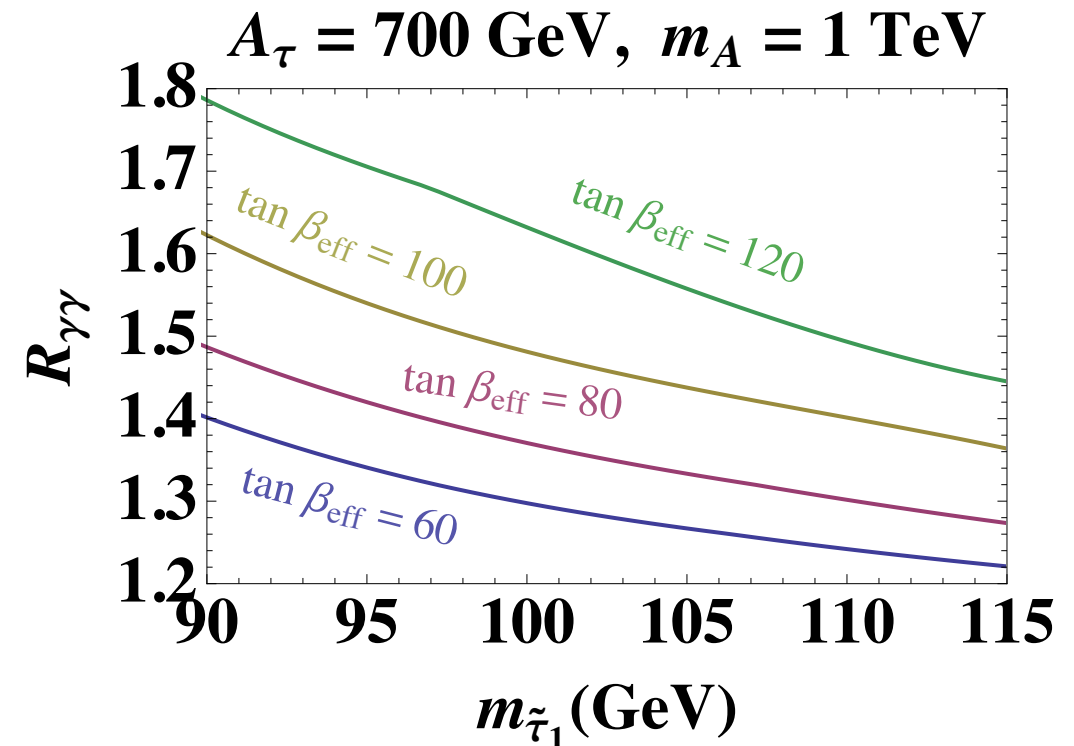
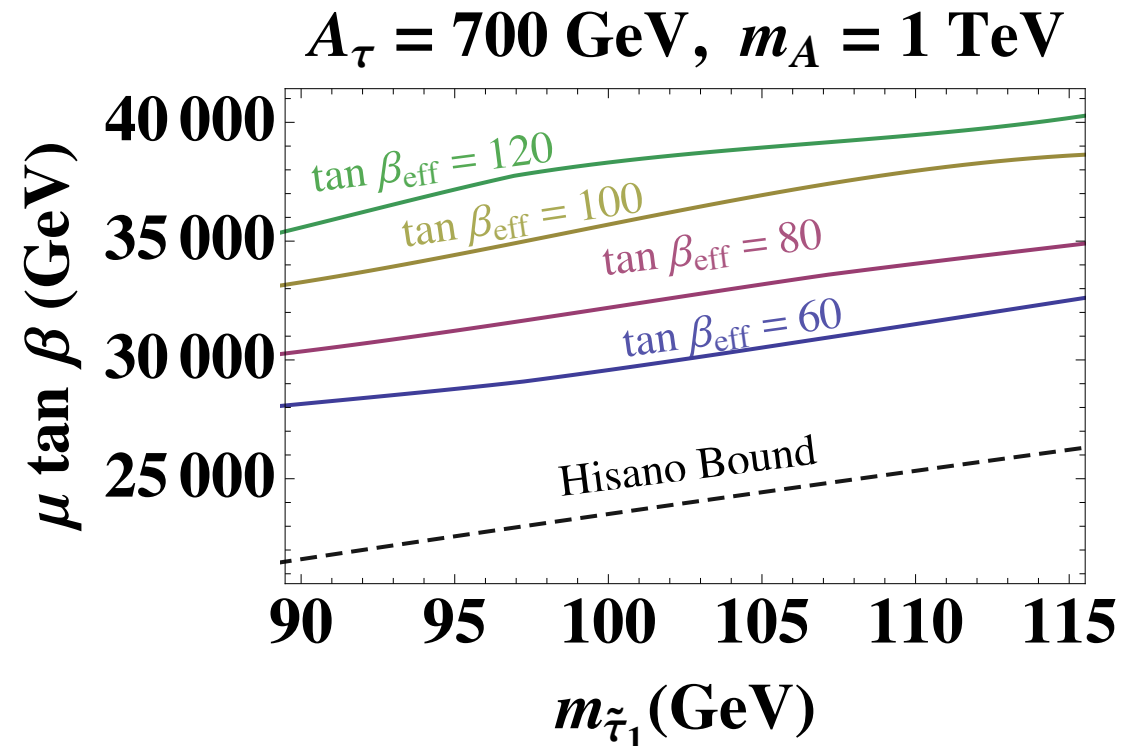
Effective values include one loop correction effects, and it is different for bottoms as for tau leptons. In the following, we refer to the tau one.

$$h_{b,\tau} \simeq \frac{m_b \tan \beta}{v(1 + \Delta_{b,\tau})}, \quad (\tan \beta_{\text{eff}})_{b,\tau} = \frac{\tan \beta}{(1 + \Delta_{b,\tau})}$$

S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W.'12



Inclusion of Mixing in the CP-even Higgs sector



[CPsuperH : arXiv:1208.2212](https://arxiv.org/abs/1208.2212)

S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W.'12

$$\frac{g_{hbb}}{g_{h\tau\tau}} = \frac{m_b(1 + \Delta_\tau)(1 - \Delta_b/(\tan \beta \tan \alpha))}{m_\tau(1 + \Delta_b)(1 - \Delta_\tau/(\tan \beta \tan \alpha))}.$$

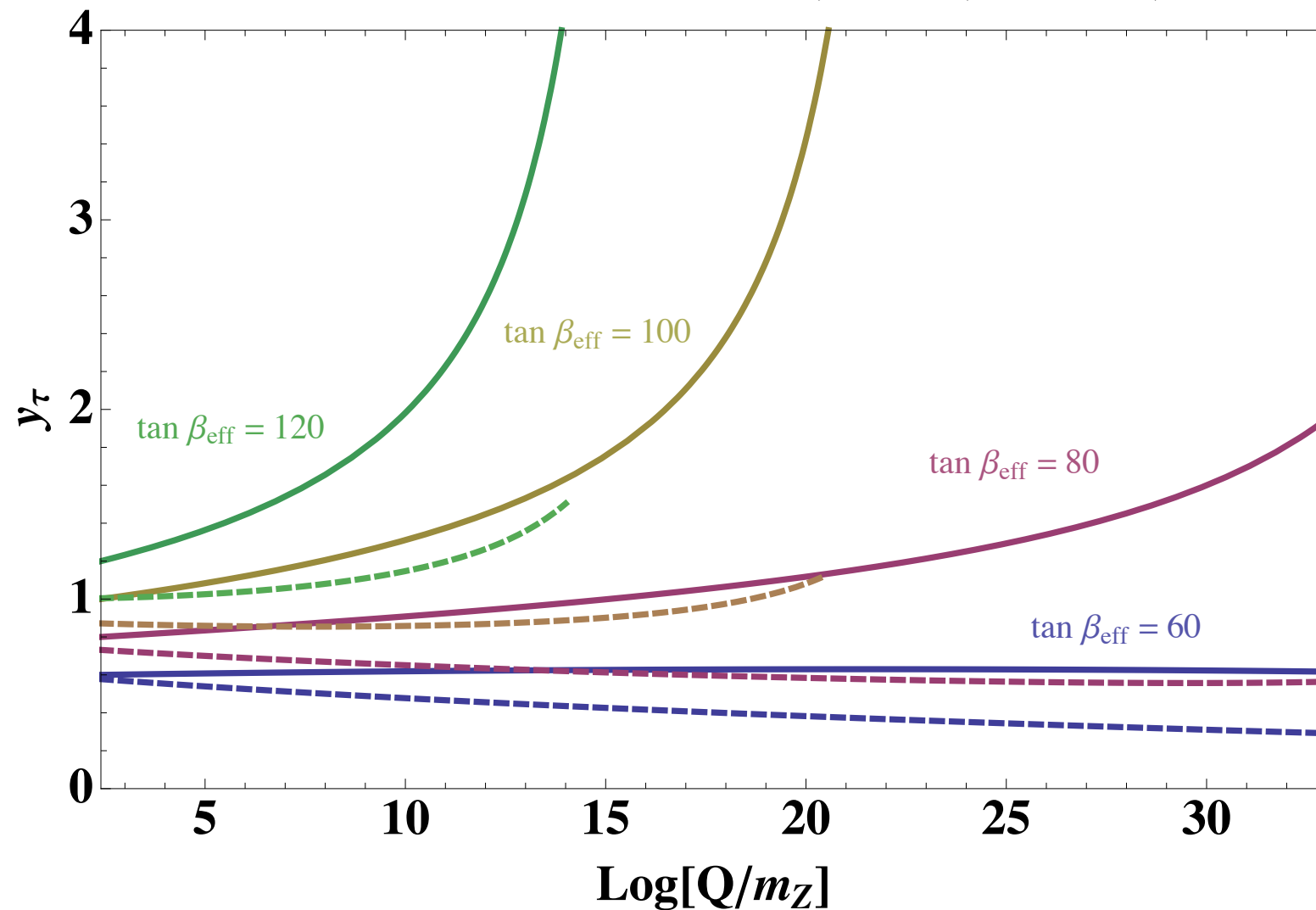
Branching ratio of decay into bottom quarks remain larger than 95 percent

Calculated with FeynHiggs (no Δ_τ but full one-loop corrections.)

New CPsuperH includes all Δ_f .
Leads to similar gamma gamma rates,
but slightly smaller τ suppressions.

Evolution of Yukawa Couplings

S. Gori, I. Low, N. Shah, M. Carena, C.E.M.W'12



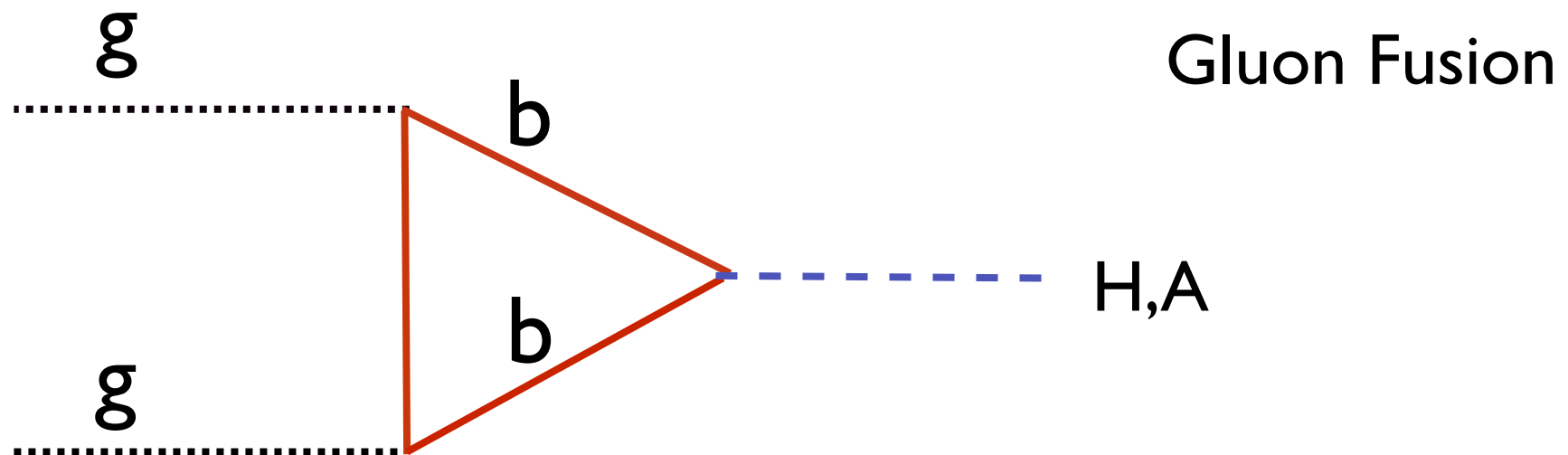
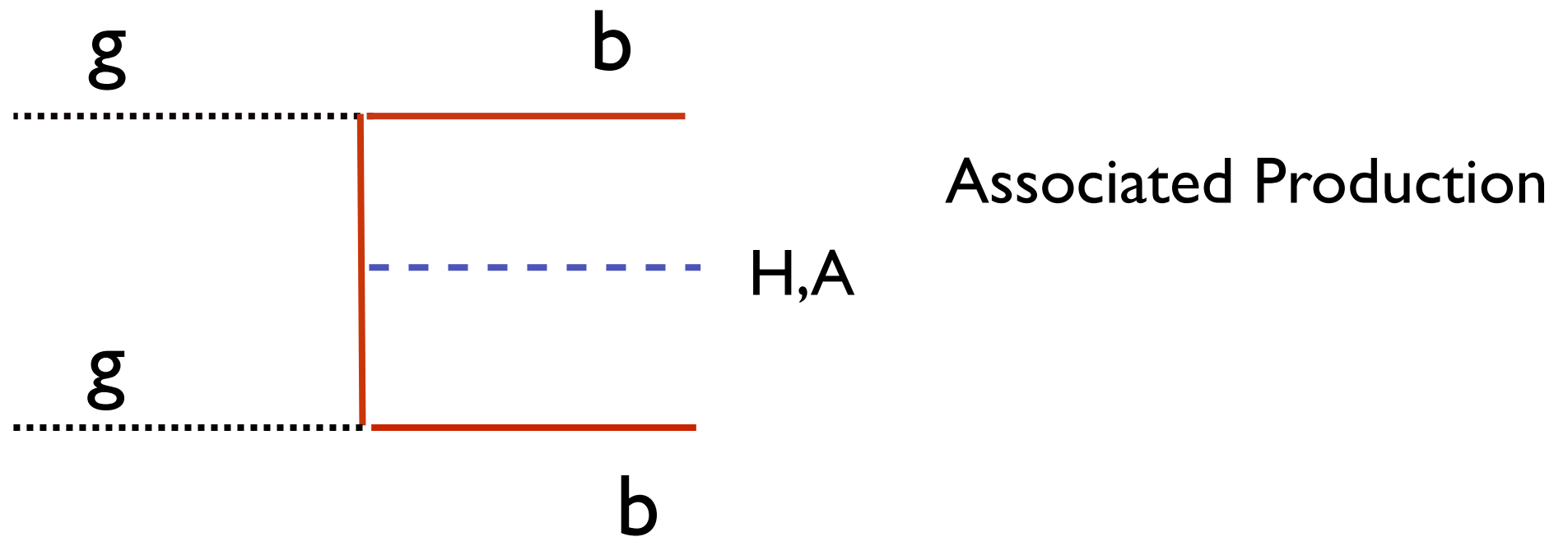
Large suppression of **Higgs decay into taus**, keeping metastability, may only be achieved at large values of the effective $\tan(\beta)$ of tau leptons.

Values of effective $\tan(\beta)$ larger than 90 imply the existence of a Landau pole before the GUT scale

An ultraviolet completion would be therefore necessary at high scales.

Non-Standard Higgs Production

QCD: S. Dawson, C.B. Jackson, L. Reina, D. Wackeroth, hep-ph/0603112



$$g_{Abb} \simeq g_{Hbb} \simeq \frac{m_b \tan \beta}{(1 + \Delta_b)v}, \quad g_{A\tau\tau} \simeq g_{H\tau\tau} \simeq \frac{m_\tau \tan \beta}{v}$$

Searches for non-standard Higgs bosons

M. Carena, S. Heinemeyer, G. Weiglein, C.W, EJPC'06

- Searches at the Tevatron and the LHC are induced by production channels associated with the large bottom Yukawa coupling.

$$\sigma(b\bar{b}A) \times BR(A \rightarrow b\bar{b}) \simeq \sigma(b\bar{b}A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{9}{(1 + \Delta_b)^2 + 9}$$

$$\sigma(b\bar{b}, gg \rightarrow A) \times BR(A \rightarrow \tau\tau) \simeq \sigma(b\bar{b}, gg \rightarrow A)_{\text{SM}} \frac{\tan^2 \beta}{(1 + \Delta_b)^2 + 9}$$

- There may be a strong dependence on the parameters in the bb search channel, which is strongly reduced in the tau tau mode.

Validity of this approximation confirmed by NLO computation by D.

North and M. Spira, arXiv:0808.0087

Further work by Mhulleitner, Rzehak and Spira, 0812.3815

