The Higgs sector in SUSY extensions of the Standard Model

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(LPTHE Paris)

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The Higgs sector in SUSY extensions of the SM

- Extended Higgs sector: not just one SU(2) doublet
  - THDM, THDM+sneutrinos, THDM+singlet, THDM+sgauginos, (...)
  - Most extensions allow for a "Decoupling limit" with one SM-like Higgs

- Relations between the Higgs quartic coupling(s) and the EW gauge couplings
  - Predictions for the Higgs masses as function of M_Z (+ other parameters!)
  - Lightish tree-level mass of SM-like Higgs, maybe tension with $M_h \approx 125$ GeV

- Effects of superparticles on the properties of the Higgs boson(s)
  - Radiative corrections affect Higgs-mass predictions ($M_h \approx 125$ GeV feasible)
  - Indirect (=loop) effects from superparticles also on Higgs production / decay
  - New decay channels if superparticles (or new Higgses) are light enough

Our favorite playground: the MSSM

The Higgs sector of the MSSM

Two complex doublets H_1 and H_2, five physical states after EWSB: h , H , A , $H^\pm$

A SUSY peculiarity: the Higgs quartic couplings are not free parameters as in SM / THDM

$$V_{\rm SM} \supset \frac{\lambda}{2}|H|^4 , \qquad V_{\rm MSSM} \supset \frac{1}{8}(g^2+g'^2)\left(|H_1^0|^2-|H_2^0|^2\right)^2$$

At tree-level, the CP-even masses can be expressed in terms of M_A , M_Z and $\tan\beta = v_2/v_1$

$$M^2_{h,H} = \frac{1}{2}\left(M_A^2+M_Z^2 \mp \sqrt{(M_A^2+M_Z^2)^2 - 4\,M_Z^2\,M_A^2\,\cos^2 2\beta}\right)$$

For $M_A >> M_Z$ *(decoupling limit)* the lightest scalar h has SM-like couplings to fermions and gauge bosons; the other Higgses are mass-degenerate, decoupled from gauge-boson pairs, and their couplings to up-type (down-type) SM fermions are suppressed (enhanced) by $\tan\beta$

(in)famous upper bound on the tree-level mass: $M_h^{\rm tree} < M_Z\,|\cos 2\beta|$

Large radiative corrections to obtain $M_h \approx 125$ GeV : $$(125~{\rm GeV})^2 = (M_h^{\rm tree})^2 + \Delta M_h^2 \approx 2\times(M_h^{\rm tree})^2$$

Radiative corrections to the light-Higgs mass in the MSSM

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

$$(\Delta M_h^2)^{1-\mathrm{loop}} \simeq \frac{3\,M_t^4}{2\,\pi^2\,v^2}\left(\ln\frac{M_S^2}{M_t^2}+\frac{X_t^2}{M_S^2}-\frac{X_t^4}{12\,M_S^4}\right)-\frac{y_b^4\,\mu^4\tan^4\beta\,v^2}{32\,\pi^2\,M_S^4}$$

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

- "Maximal-mixing" scenarios ($X_t \approx \sqrt{6}\, M_S$) can work with stops around the TeV (but only if $\tan\beta$ and M_A are large enough that $M_h \approx M_Z$ at tree level)

- Small-mixing ($X_t \ll M_S$) or small $\tan\beta$ (or M_A) require multi-TeV stop masses

A quarter-century of calculations gave us full 1-loop, almost-full 2-loop and partial 3-loop results

Bagger Borowka Brignole Carena Casas Chankowski Dabelstein Dedes Degrassi DiVita Draper Ellis Espinosa Haber Hahn Harlander Heinemeyer Heinrich Hempfling Hoang Hollik Kant Lee Martin Matchev Mihaila Navarro Okada Pierce Pokorski Quiros Ridolfi Riotto Rosiek Rzehak Slavich Steinhauser Wagner Weiglein Yamaguchi Yanagida Zhang Zwirner

1991 – 2016

[Apologies if I forgot anybody – and this is just for radiative corrections in the (CP, R_p, flavor)-conserving MSSM !!!]

How well can we predict M_h in the MSSM with TeV-scale SUSY?

Simplified benchmark point: $\tan\beta = 20$, all SUSY masses = 1 TeV, X_t varied to maximize M_h

Public code	M_h [GeV]
SPheno 3.3.7	126.3
SuSpect 2.43	125.8
SoftSUSY 3.6.2	124.3
NMSSMTools 4.7.1	124.6
FeynHiggs 2.11.2	129.8

All of these codes include full 1-loop + dominant (strong+Yukawa) 2-loop corrections to M_h

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SPheno, SuSpect, SoftSUSY, NMSSMTools: *Same $\overline{DR}$ calculation of the Higgs mass, differences in determination of top Yukawa*

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(Slide from SUSY2015)

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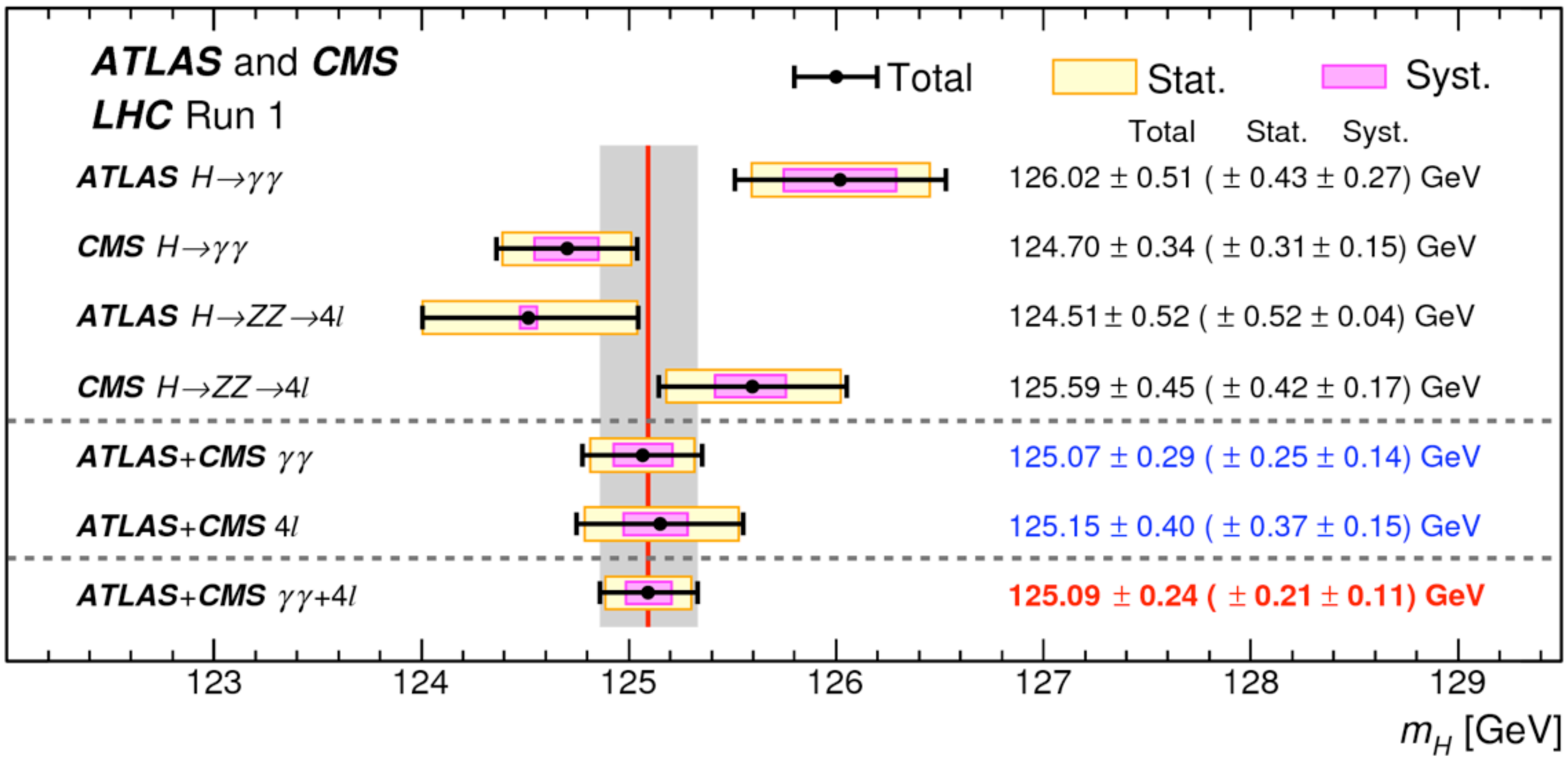
With great corrections comes great uncertainty!

A rather embarrassing comparison

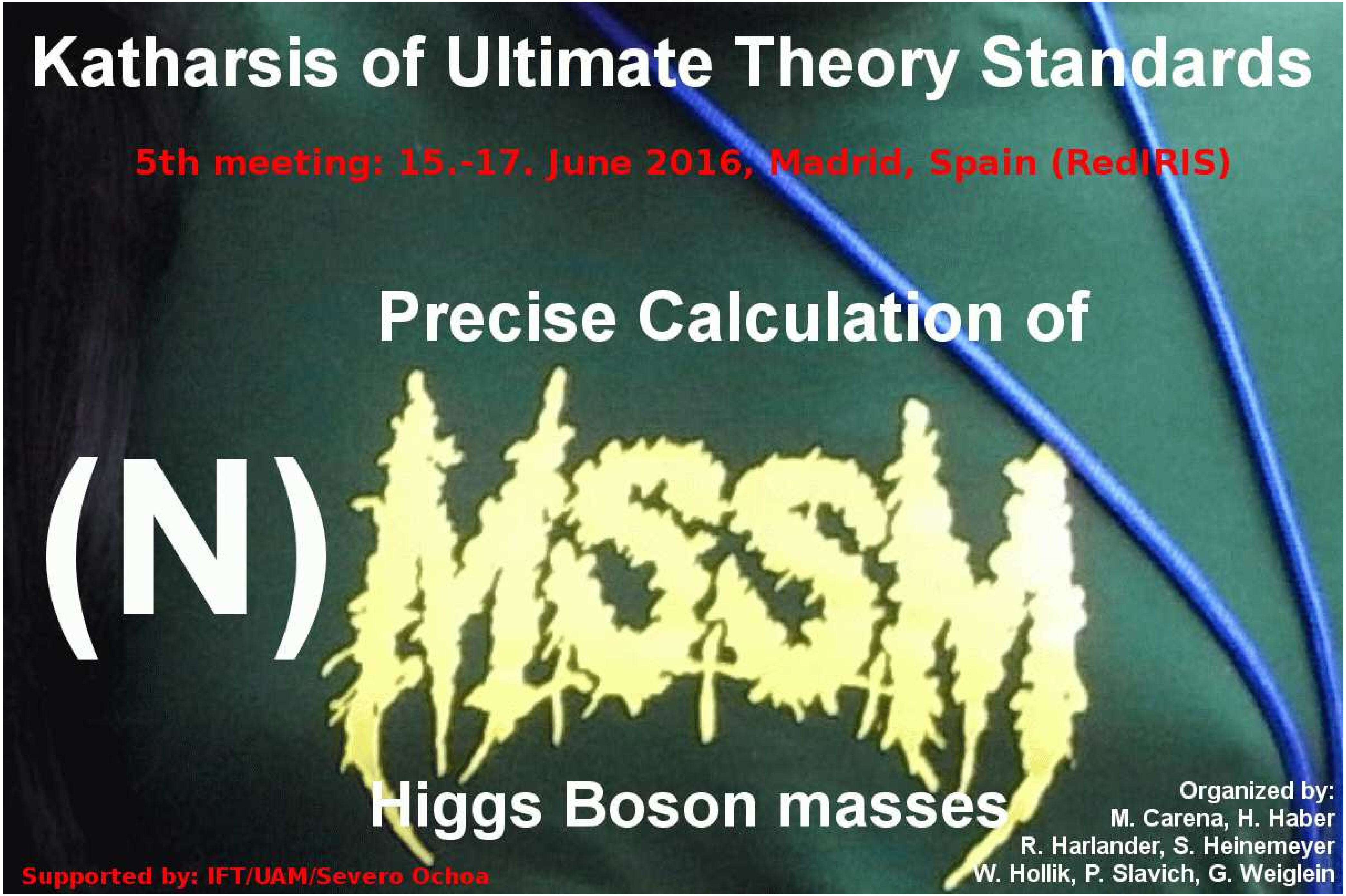
Theory uncertainty of the M_h prediction in the MSSM: “a few GeV”...

vs



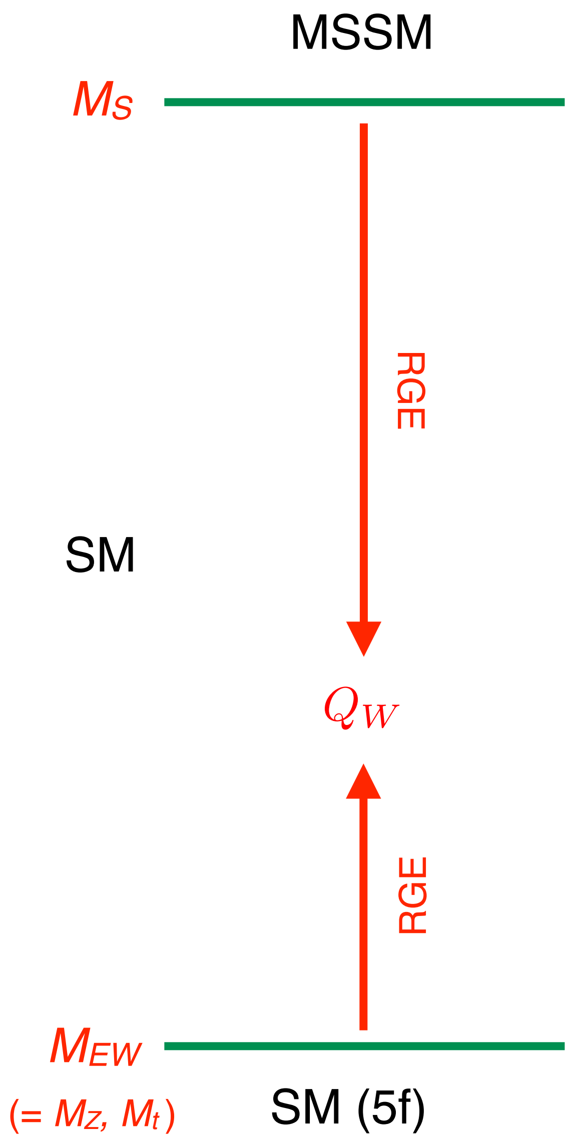
More work needed to:

1) *Estimate the theory uncertainty of M_h in SUSY models*
2) *Reduce it to a level comparable with experiment???*


Katharsis of Ultimate Theory Standards
5th meeting: 15.-17. June 2016, Madrid, Spain (RedIRIS)
Precise Calculation of
(N)
MSSM
Higgs Boson masses
Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein
Supported by: IFT/UAM/Severo Ochoa

Dealing with heavy SUSY particles

For multi-TeV SUSY masses, *log(M_S/M_EW)* terms must be resummed in an EFT approach



$$\lambda(M_S) = \frac{1}{8}\left(g^2 + g'^{\,2}\right)\cos^2 2\beta \; + \; \Delta\lambda$$

$$M_H^2 = \frac{\sqrt{2}\,\lambda(Q_W)}{G_F}\,(1+\delta_H)$$

$$g,\; g',\; g_s,\; y_t \;=\; (\ldots)$$

Resums large logarithms but neglects effects of $\mathcal{O}(v^2/M_S^2)$

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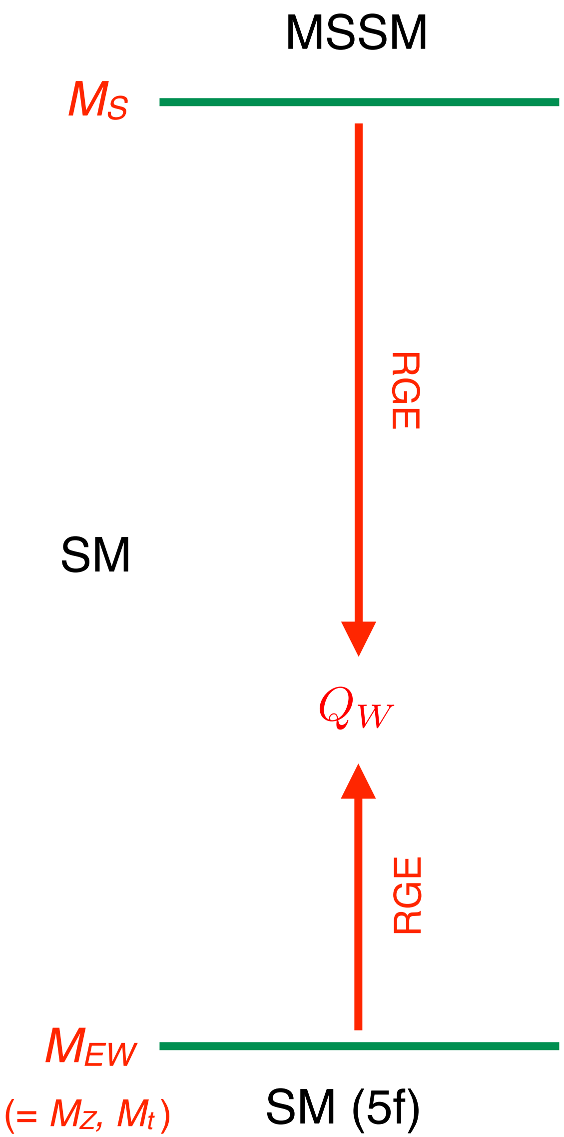

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(full 1-loop + dominant 2-loop SUSY threshold corrections)

(3-loop RGE for the SM)

$$M_H^2 = \frac{\sqrt{2}\,\lambda(Q_W)}{G_F}\,(1+\delta_H)$$

(2-loop "diagrammatic" calculations in the SM)

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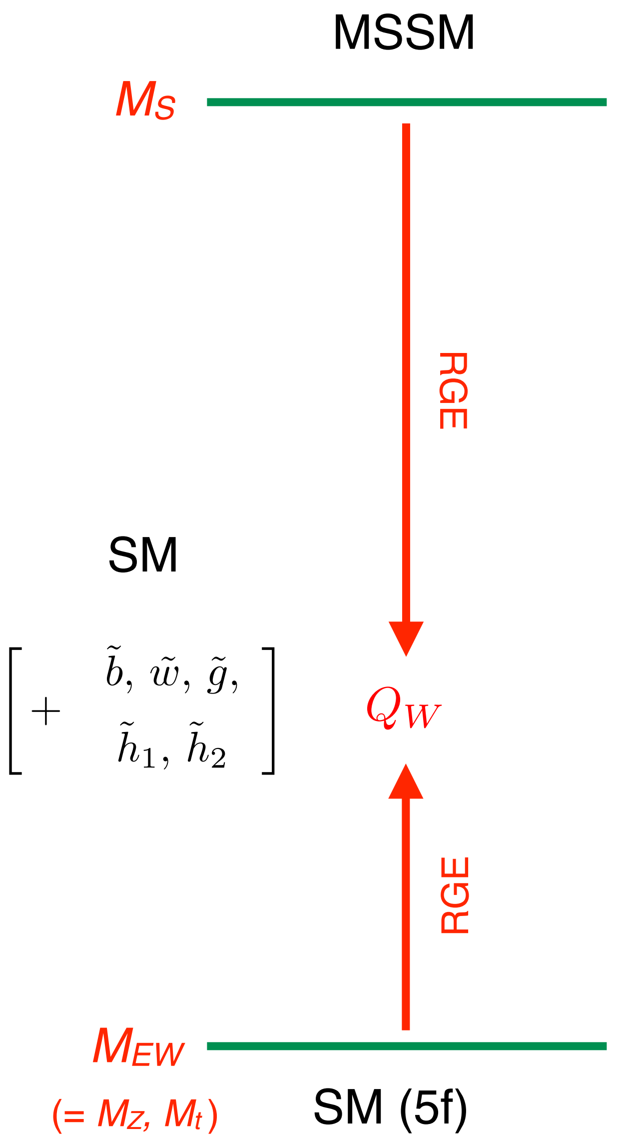


$$\lambda(M_S) = \frac{1}{8}\,\left(g^2 + g'^{\,2}\right)\,\cos^2 2\beta \;+\; \Delta\lambda$$

$$\left[\ \tilde{g}_u,\ \tilde{g}_d,\ \tilde{g}'_u,\ \tilde{g}'_d \;=\; (\ldots)\ \right]$$

(full 1-loop + dominant 2-loop SUSY threshold corrections)

(2-loop RGE for Split SUSY)

$$M_H^2 = \frac{\sqrt{2}\,\lambda(Q_W)}{G_F}\,(1+\delta_H)$$

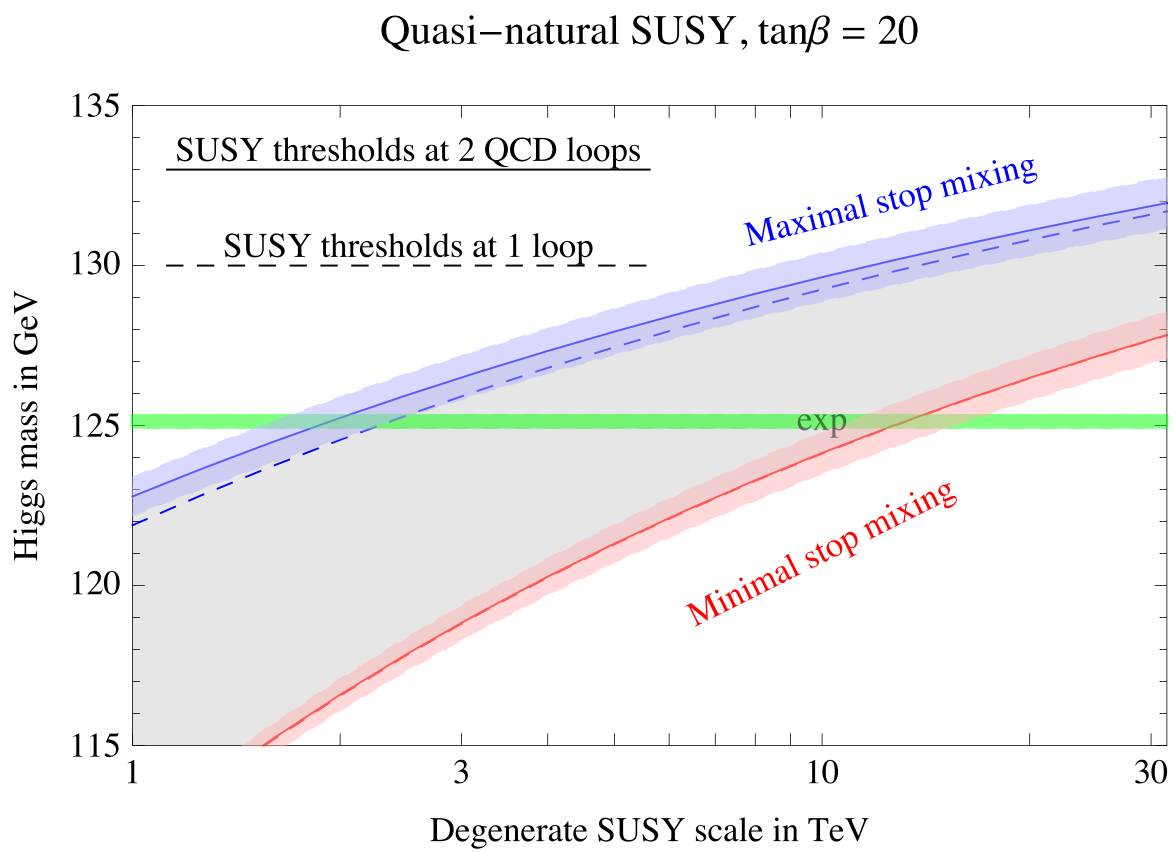
(2-loop "diagrammatic" calculations in the SM + leading -ino contributions)

$$g,\ g',\ g_s,\ y_t \;=\; (\ldots)$$

Resums large logarithms but neglects effects of $\mathcal{O}(v^2/M_S^2)$

Recent incarnations of the decades-old EFT approach:

Hahn *et al.* (FeynHiggs), 1312.4937; Draper *et al.*, 1312.5743;
Bagnaschi *et al.* (+P.S.), 1407.4081; PardoVega+Villadoro (SusyHD) 1504.05200



Bagnaschi *et al.*, 1407.4081

Simple test-point:

$M_S = 10$ TeV,

$X_t = 0$, $\tan\beta = 20$

Draper *et al* : $M_h = 123.2$ GeV

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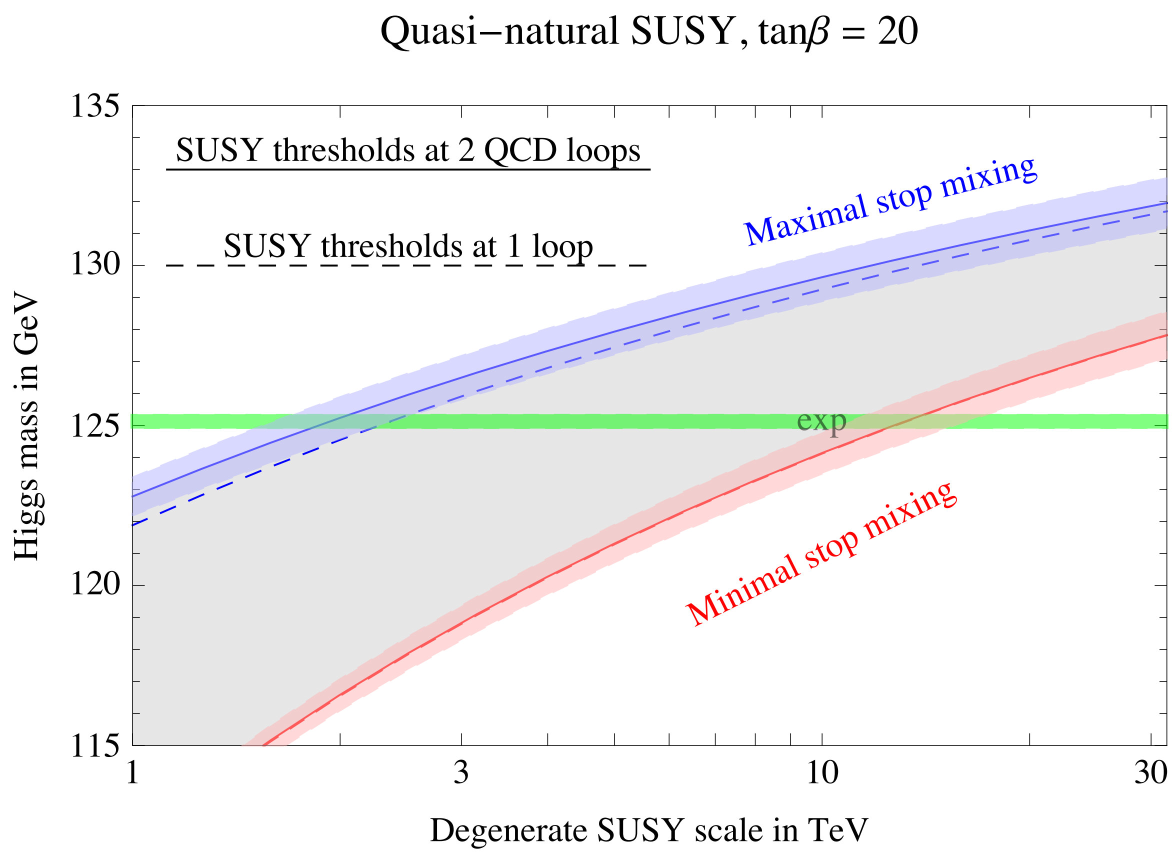

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"hybrid" calculation: 2-loop diagrammatic + partial resummation

Again, part of the discrepancy is related to the determination of y_t

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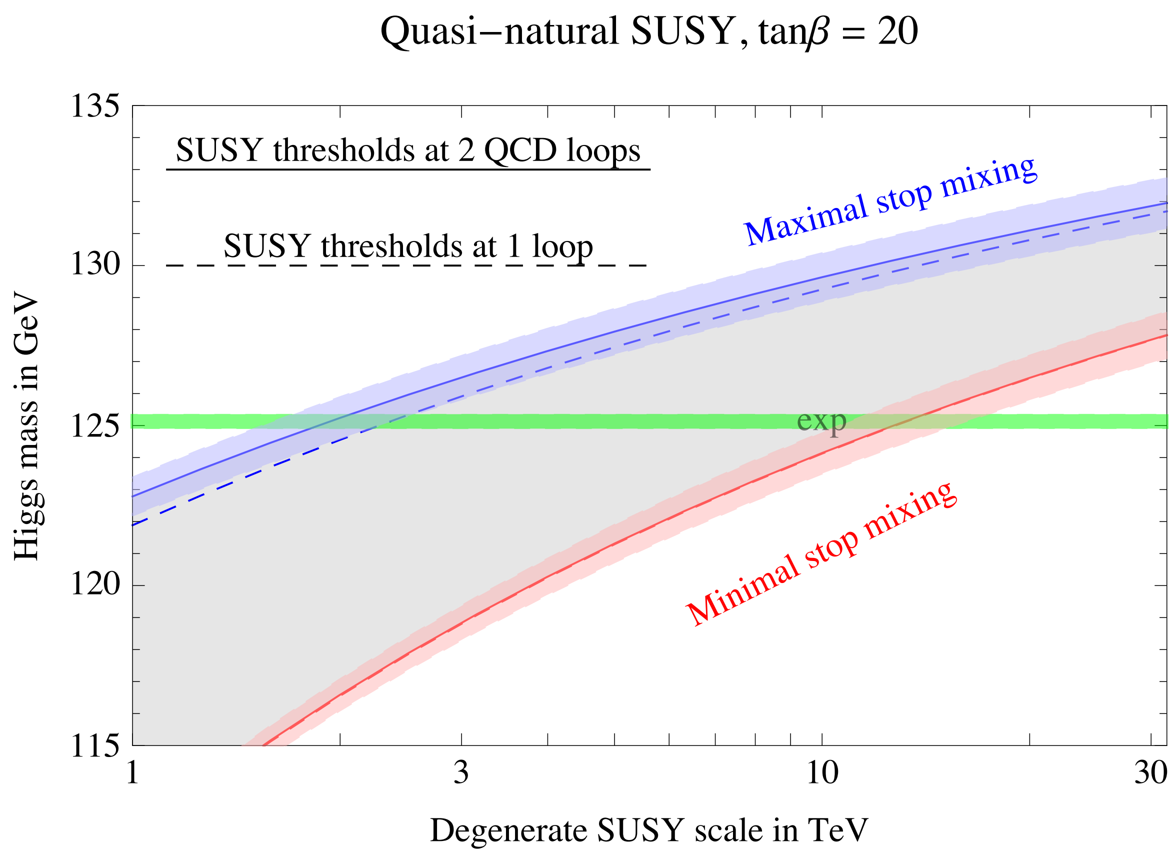

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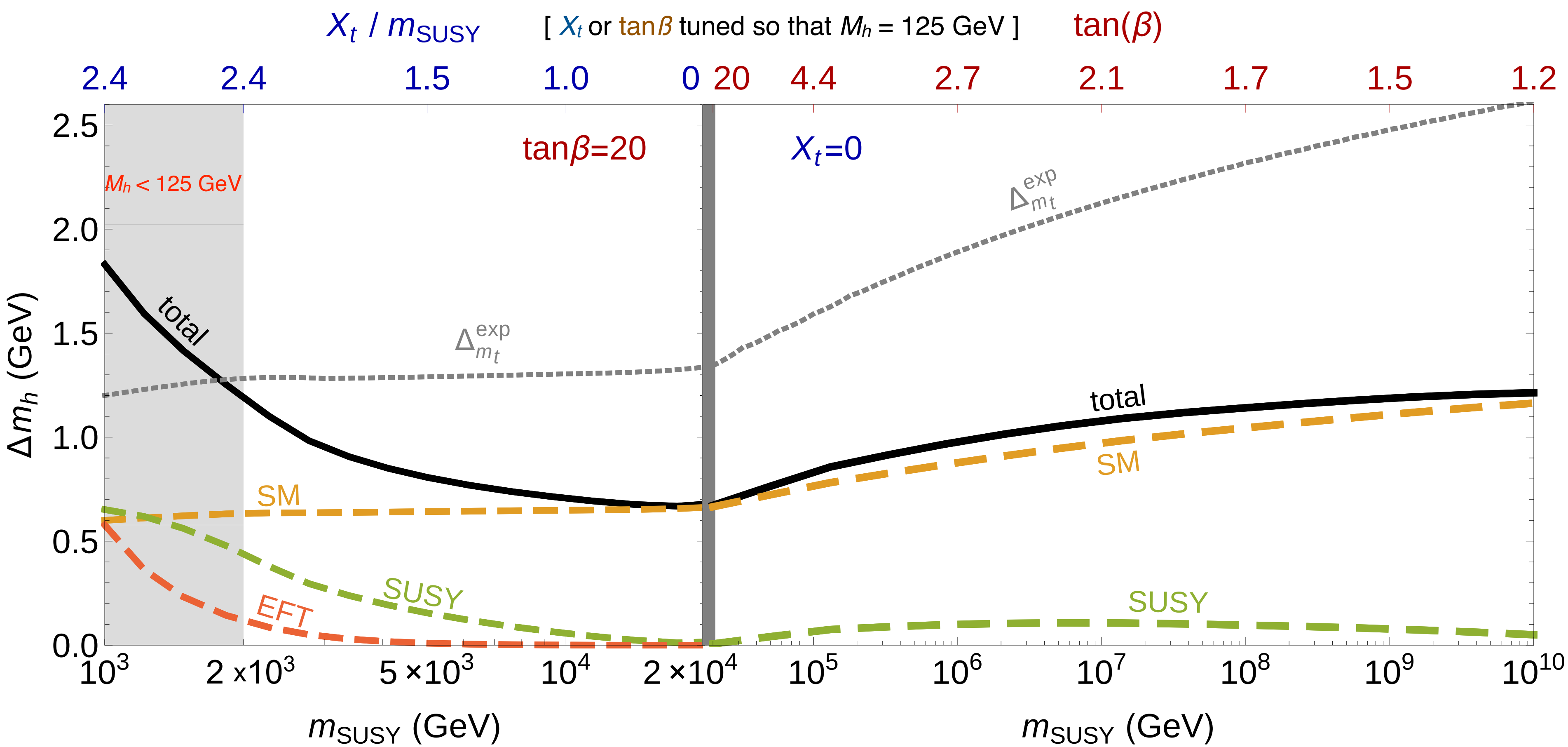
Uncertainties of the EFT calculation

[PardoVega+Villadoro (SusyHD) 1504.05200]



SM uncertainty: from the SM calculation (mostly from 3-loop QCD effects in y_t)

SUSY uncertainty: estimated varying the SUSY matching scale by a factor 1/2 or 2

EFT uncertainty: estimated replacing $\Delta\lambda \rightarrow \Delta\lambda\left(1+v^2/M_S^2\right)$ *(optimistic?)*

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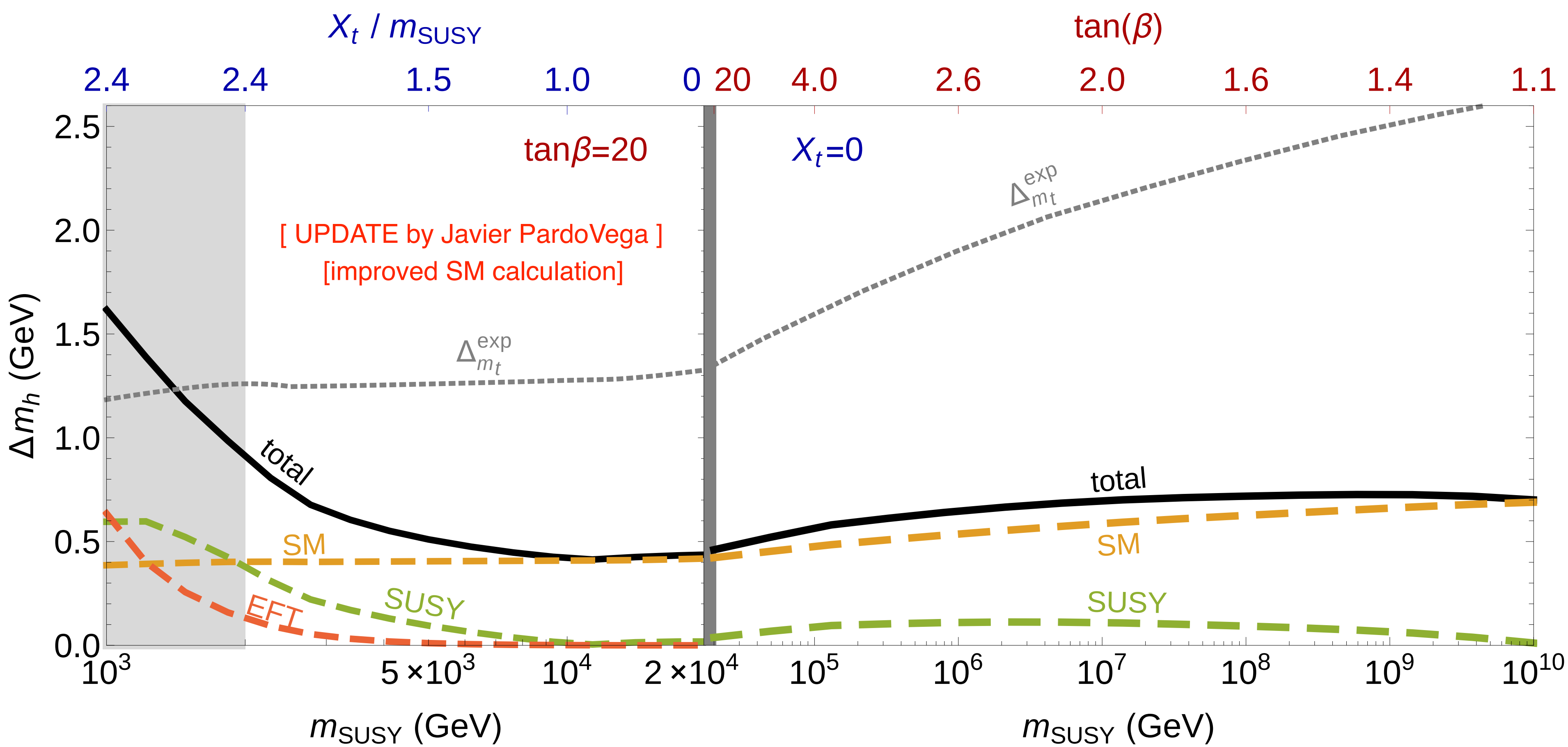

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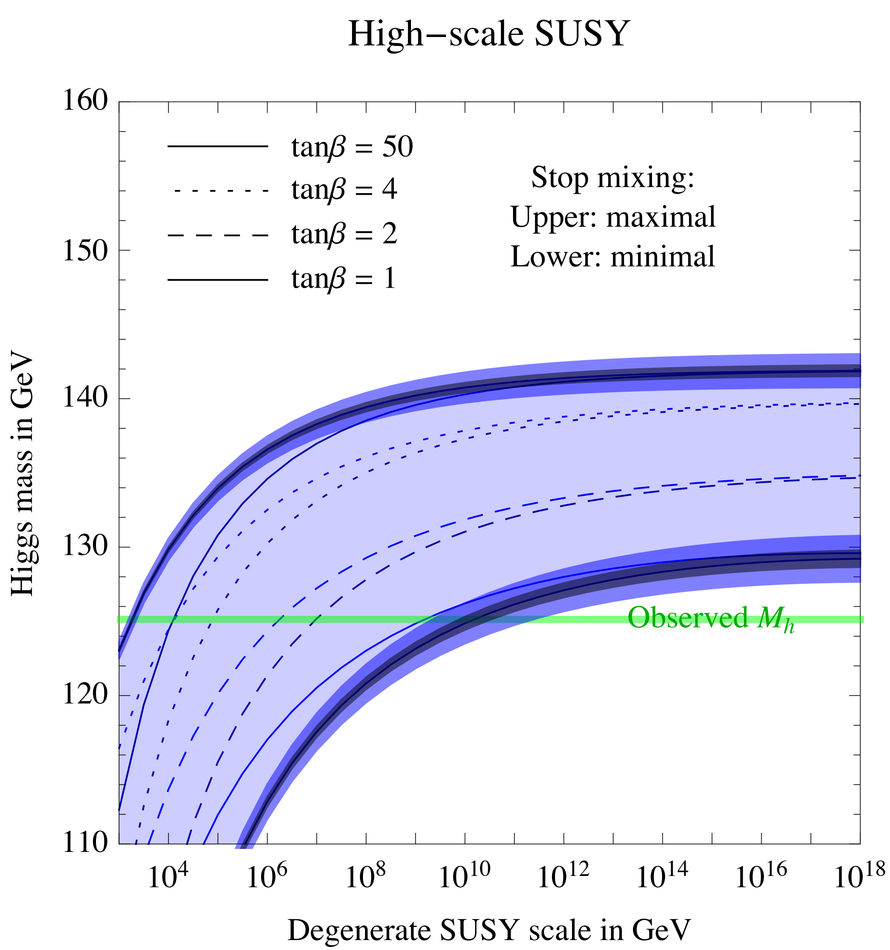
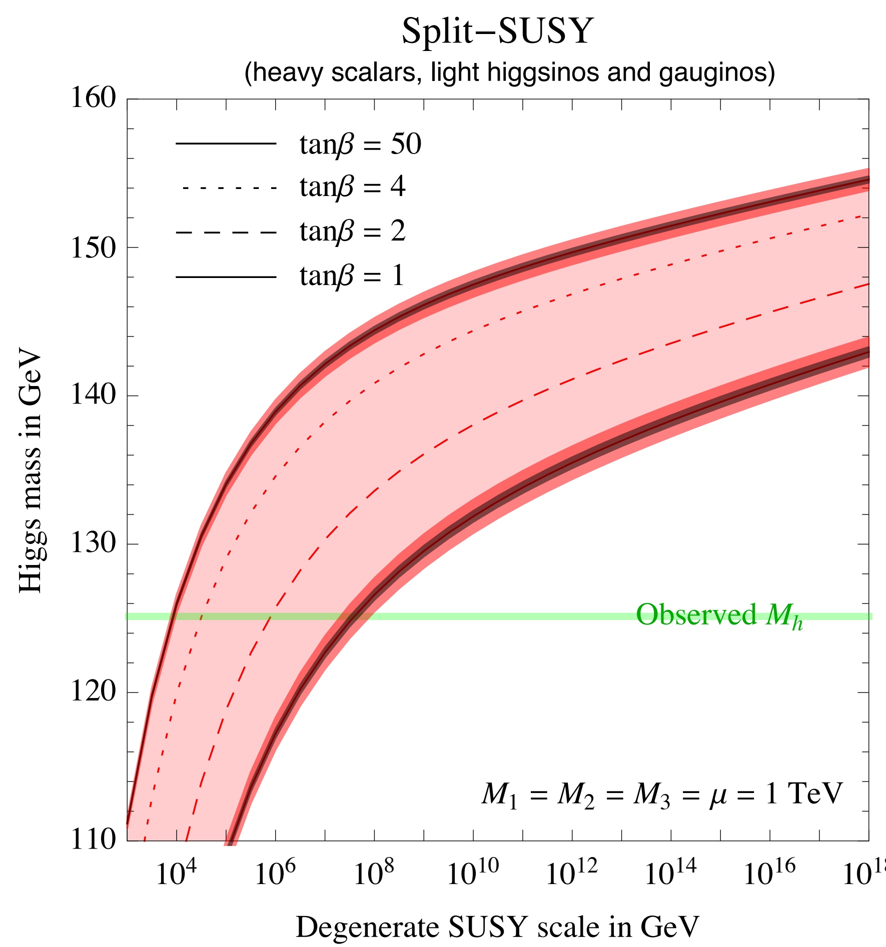
Pushing un-naturalness: High-scale SUSY and Split SUSY





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- The prediction depends on the high-scale parameter *tanβ* (and X_t in HSS)
- The observed M_h determines an upper bound on the SUSY-breaking scale

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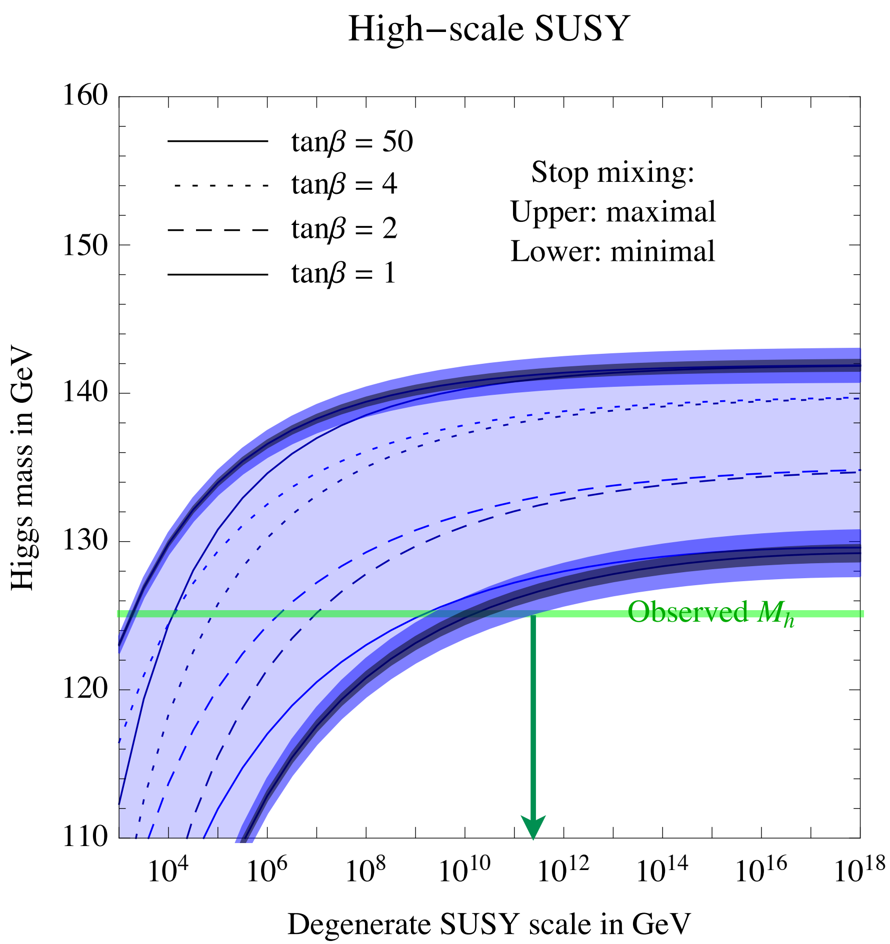

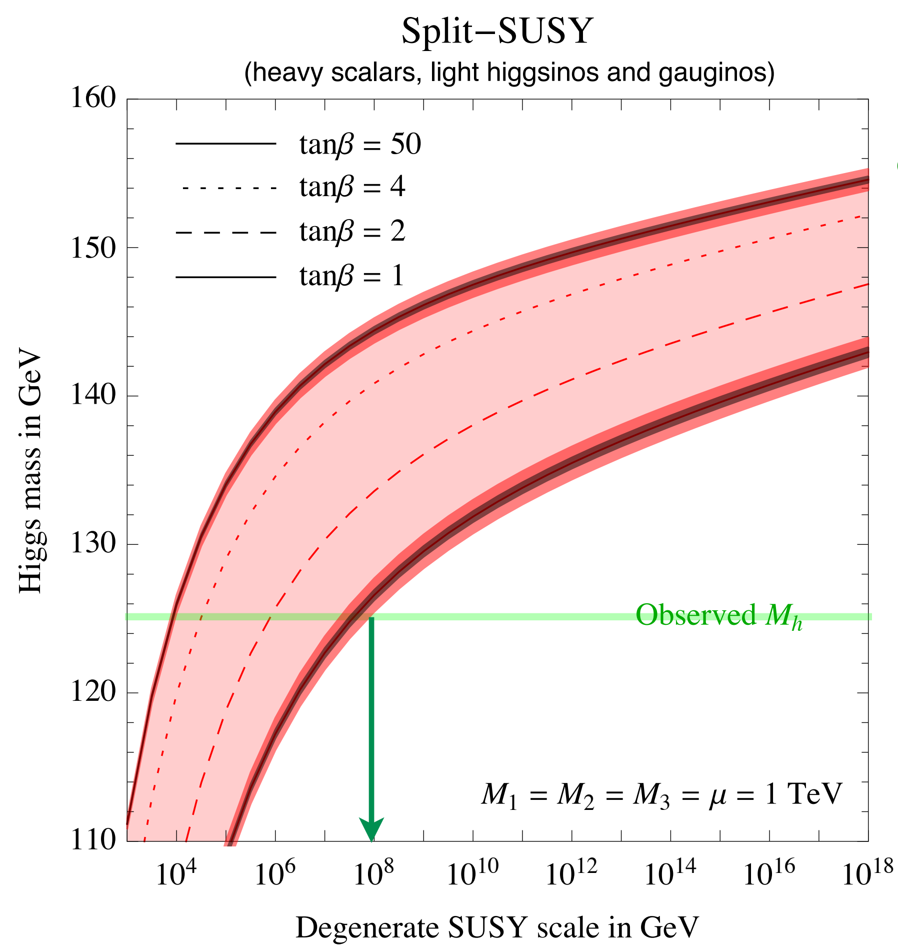

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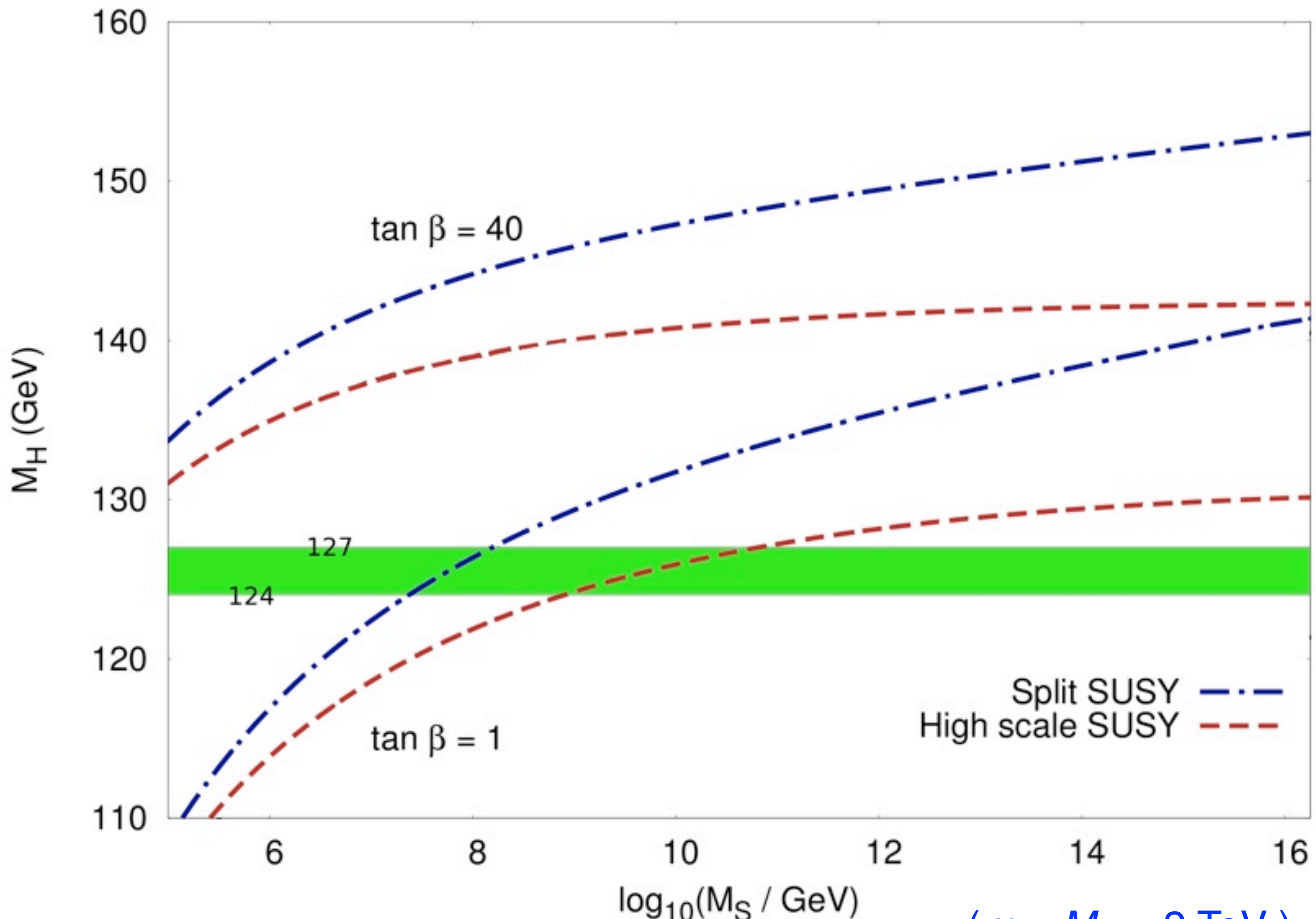
Self-promotion: the Fake Split-SUSY Model (FSSM)

[Benakli *et al.* (+P.S.), 1312.5220; also Benakli+Darme+Goodsell, 1508.02534]



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($\mu = M_{g'} = 2$ TeV)

Inspired by models with Dirac gauginos (see later): higgsinos and gauginos replaced by "fake" counterparts that do not couple to the SM-like Higgs boson

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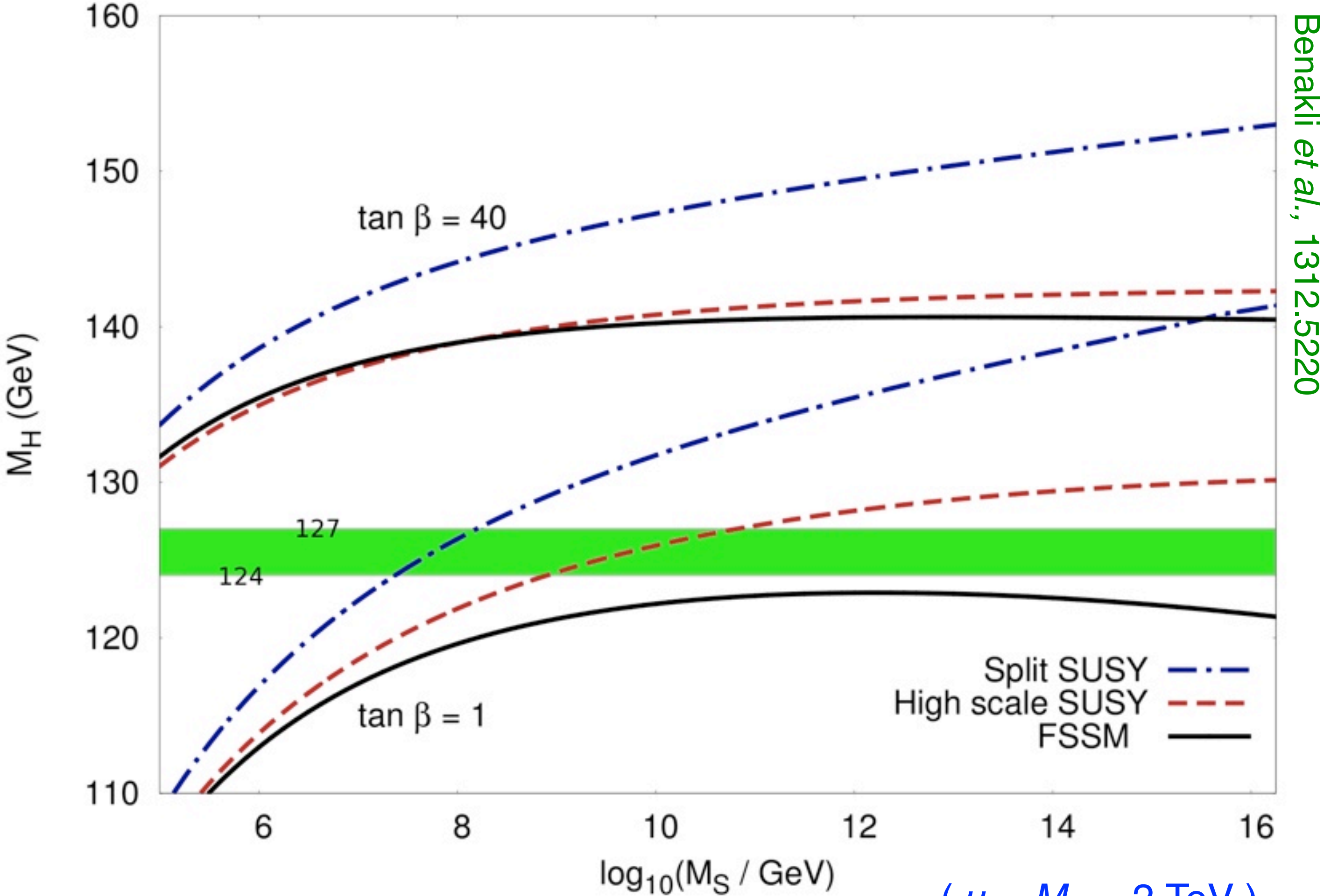

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In the FSSM there is no upper bound on the SUSY-breaking scale

Reopening the low (M_A, $\tan\beta$) window

[see e.g.: Arbey *et al.*, 1303.7450; Djouadi+Quevillon, 1304.1787]

Appeal of the low (M_A, $\tan\beta$) region:

- For low M_A, extended Higgs sector potentially accessible at the LHC
- For low $\tan\beta$, not yet ruled out by ATLAS+CMS searches for H, A, $H^\pm$
- Away from the decoupling limit, sizable couplings of H, A to gauge bosons and h

Interesting Higgs phenomenology: H —> hh, H —> WW, H —> ZZ, A —> Zh

However...

- At low $\tan\beta$, $M_h \approx 125$ GeV requires large stop masses M_S:
  - For $M_A \approx M_S$, $\tan\beta = 1$ implies $M_S \approx 10^8 - 10^{10}$ GeV

    At low M_A we might need an even larger M_S

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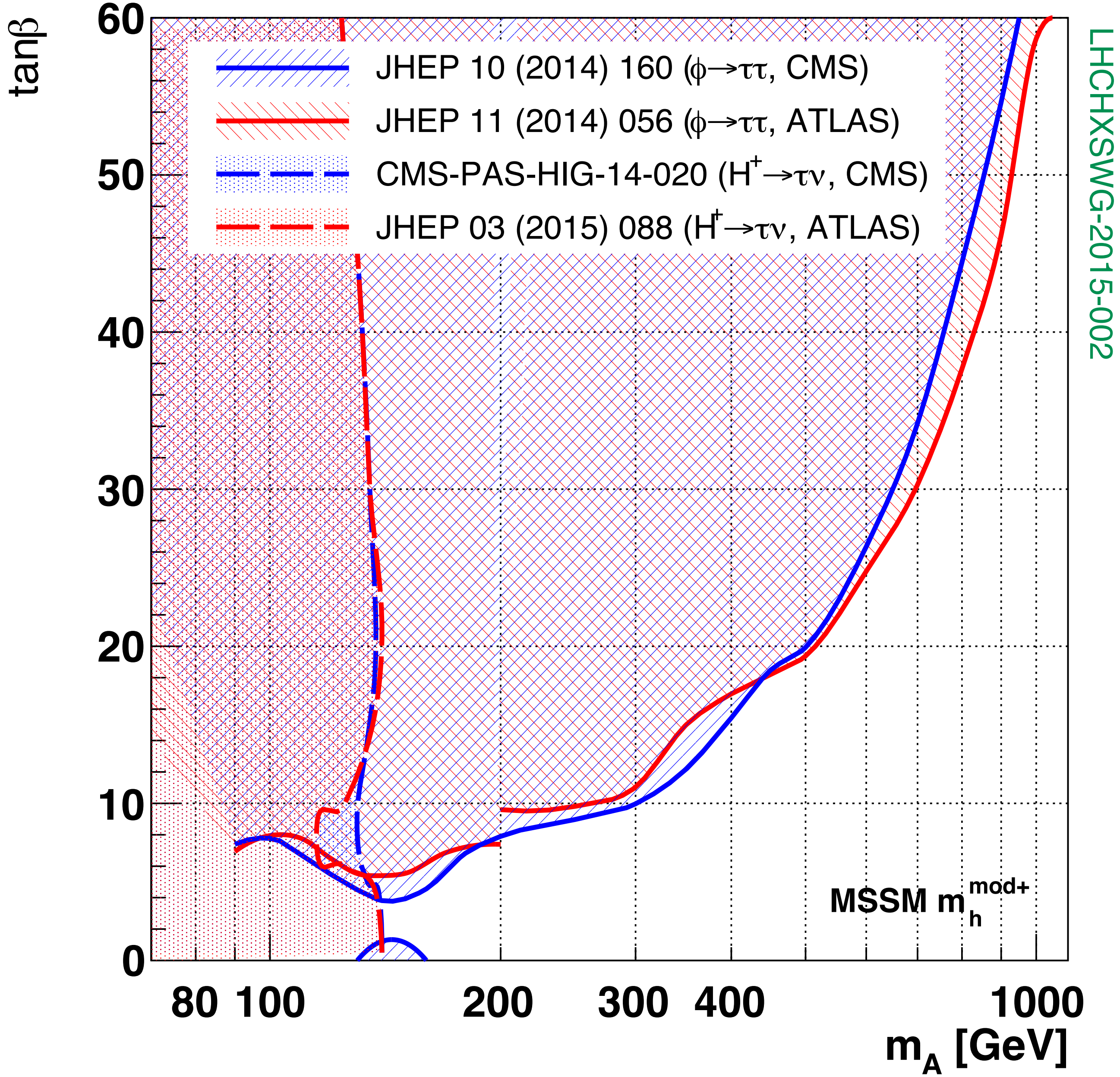

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Effective THDM with heavy SUSY

[Haber+Hempfling, early 90s, (...), Lee+Wagner, 1508.00576]

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

1) SUSY boundary conditions at the scale M_S :

$$
\lambda_1 \;=\; \lambda_2 \;=\; -(\lambda_3 + \lambda_4) \;=\; \frac{1}{4}(g^2 + g'^2)\,,
$$

$$
\lambda_4 \;=\; -\frac{g^2}{2}\,, \qquad \lambda_5 \;=\; \lambda_6 \;=\; \lambda_7 \;=\; 0
$$

(NOTE: loop corrections)

2) RG evolution of all seven lambdas from M_S to the weak scale;

3) scalar mass matrix in terms of the weak-scale lambdas:

$$
M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta\, c_\beta \\ -s_\beta\, c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}
$$

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

Effective THDM with heavy SUSY

[Haber+Hempfling, early 90s, (...), Lee+Wagner, 1508.00576]

$$\lambda_1 = \frac{1}{4}(g^2+g'^2) + \frac{2\,N_c}{(4\pi)^2}\left(y_b^4 \frac{A_b^2}{M_S^2}(1-\frac{A_b^2}{12M_S^2}) - y_t^4 \frac{\mu^4}{12M_S^4}\right)$$

$$\lambda_2 = \frac{1}{4}(g^2+g'^2) + \frac{2\,N_c}{(4\pi)^2}\left(y_t^4 \frac{A_t^2}{M_S^2}(1-\frac{A_t^2}{12M_S^2}) - y_b^4 \frac{\mu^4}{12M_S^4}\right)$$

$$\lambda_3 = \frac{1}{4}(g^2-g'^2) + \frac{2\,N_c}{(4\pi)^2}\left(y_b^2 y_t^2 \frac{A_{tb}}{2} + y_t^4(\frac{\mu^2}{4M_S^2} - \frac{\mu^2 A_t^2}{12M_S^4}) + y_b^4(\frac{\mu^2}{4M_S^2} - \frac{\mu^2 A_b^2}{12M_S^4})\right)$$

$$\lambda_4 = -\frac{1}{2}g^2 + \frac{2\,N_c}{(4\pi)^2}\left(-y_b^2 y_t^2 \frac{A_{tb}}{2} + y_t^4(\frac{\mu^2}{4M_S^2} - \frac{\mu^2 A_t^2}{12M_S^4}) + y_b^4(\frac{\mu^2}{4M_S^2} - \frac{\mu^2 A_b^2}{12M_S^4})\right)$$

$$\lambda_5 = -\frac{2\,N_c}{(4\pi)^2}\left(y_t^4 \frac{\mu^2 A_t^2}{12M_S^4} + y_b^4 \frac{\mu^2 A_b^2}{12M_S^4}\right),$$

$$\lambda_6 = \frac{2\,N_c}{(4\pi)^2}\left(y_b^4 \frac{\mu A_b}{M_S^2}(-\frac{1}{2} + \frac{A_b^2}{12M_S^2}) + y_t^4 \frac{\mu^3 A_t}{12M_S^4}\right),$$

$$\lambda_7 = \frac{2\,N_c}{(4\pi)^2}\left(y_t^4 \frac{\mu A_t}{M_S^2}(-\frac{1}{2} + \frac{A_t^2}{12M_S^2}) + y_b^4 \frac{\mu^3 A_b}{12M_S^4}\right),$$

$$M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta\, c_\beta \\ -s_\beta\, c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}$$

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

Effective THDM with heavy SUSY

[Haber+Hempfling, early 90s, (...), Lee+Wagner, 1508.00576]

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

1) SUSY boundary conditions at the scale M_S :

$$
\lambda_1 \;=\; \lambda_2 \;=\; -(\lambda_3 + \lambda_4) \;=\; \frac{1}{4} (g^2 + g'^2) \,,
$$

$$
\lambda_4 \;=\; -\frac{g^2}{2} \,, \qquad \lambda_5 \;=\; \lambda_6 \;=\; \lambda_7 \;=\; 0
$$

(NOTE: loop corrections)

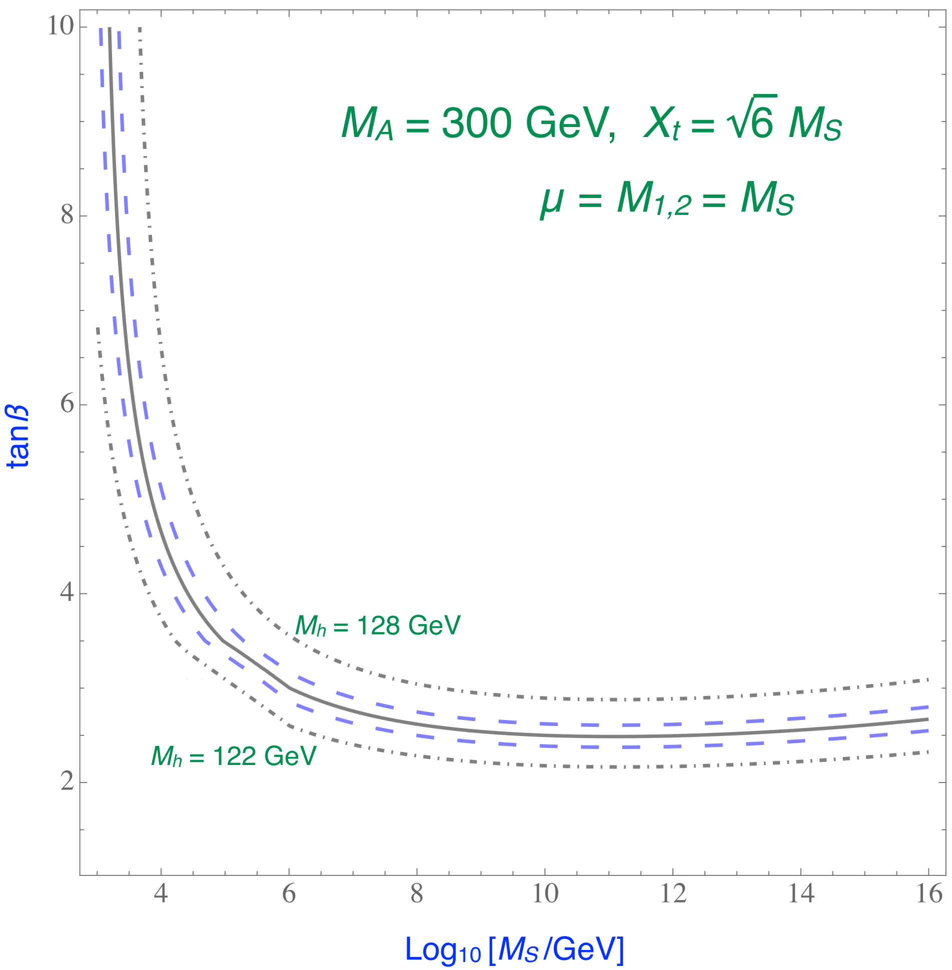
2) RG evolution of all seven lambdas from M_S to the weak scale;

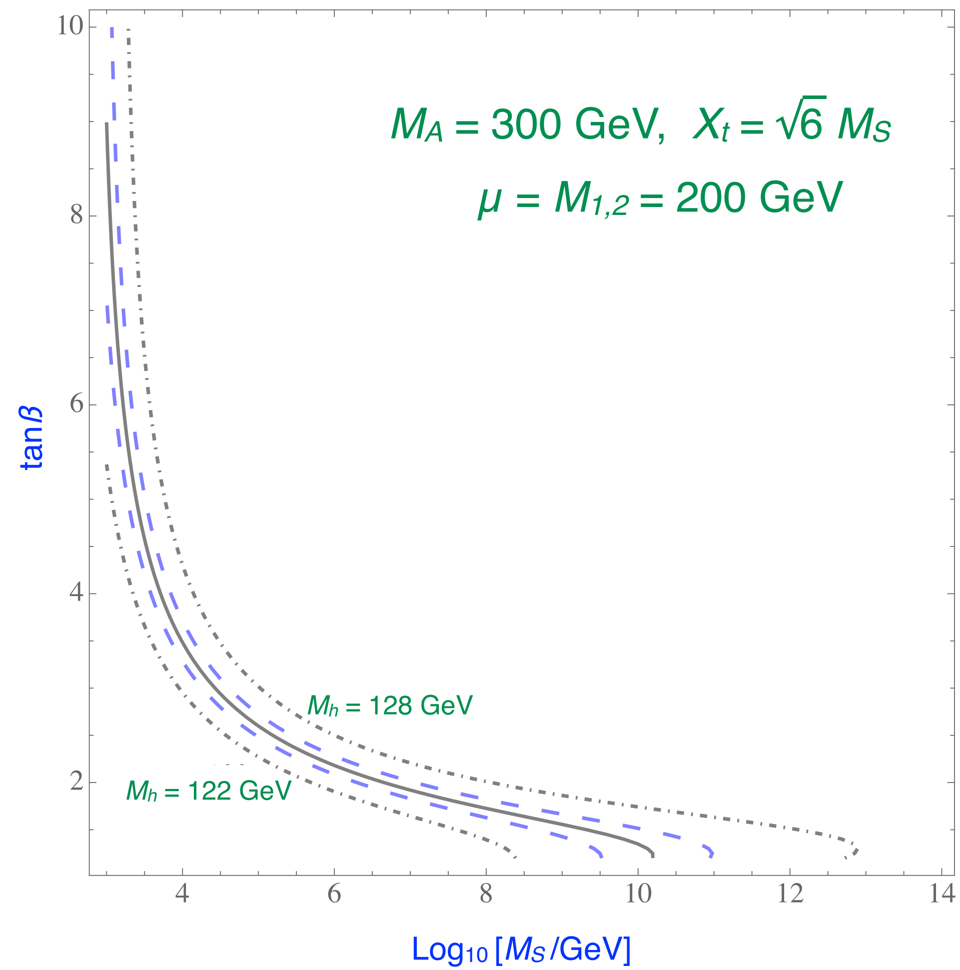
3) scalar mass matrix in terms of the weak-scale lambdas:

$$
M_A^2 \begin{pmatrix} s_\beta^2 & -s_\beta\, c_\beta \\ -s_\beta\, c_\beta & c_\beta^2 \end{pmatrix} + v^2 \begin{pmatrix} L_{11} & L_{12} \\ L_{12} & L_{22} \end{pmatrix}
$$

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

For very low M_A and $\tan\beta$, M_h = 125 GeV can only be reached with light EW-inos!





Lee+Wagner, 1508.00576

A public code for the EFT calculation of light THDM / heavy SUSY is being developed by Lee & Wagner

An alternative approach: the hMSSM

[Djouadi+Quevillon, 1304.1787; Maiani *et al.*, 1305.2172; Djouadi *et al.*, 1307.5205 and 1502.05653]

The dominant corrections affect mostly the (2,2) element of the scalar mass matrix. We can trade it for the known M_h, and get formulae for M_H and for the scalar mixing angle:

$$M_H^2 = \frac{\mathcal{M}_{11}^2(\mathcal{M}_{11}^2 - M_h^2) + (\mathcal{M}_{12}^2)^2}{\mathcal{M}_{11}^2 - M_h^2}\,, \qquad \tan\alpha = -\frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - M_h^2}$$

Setting the (1,1) and (1,2) elements to their tree-level values *(good approximation?)* we obtain formulae that depend only on M_h, M_Z, M_A and $\tan\beta$

$$M_H^2 = \frac{(M_Z^2 + M_A^2 - M_h^2)(M_Z^2 c_\beta^2 + M_A^2 s_\beta^2) - M_A^2 M_Z^2 c_{2\beta}^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

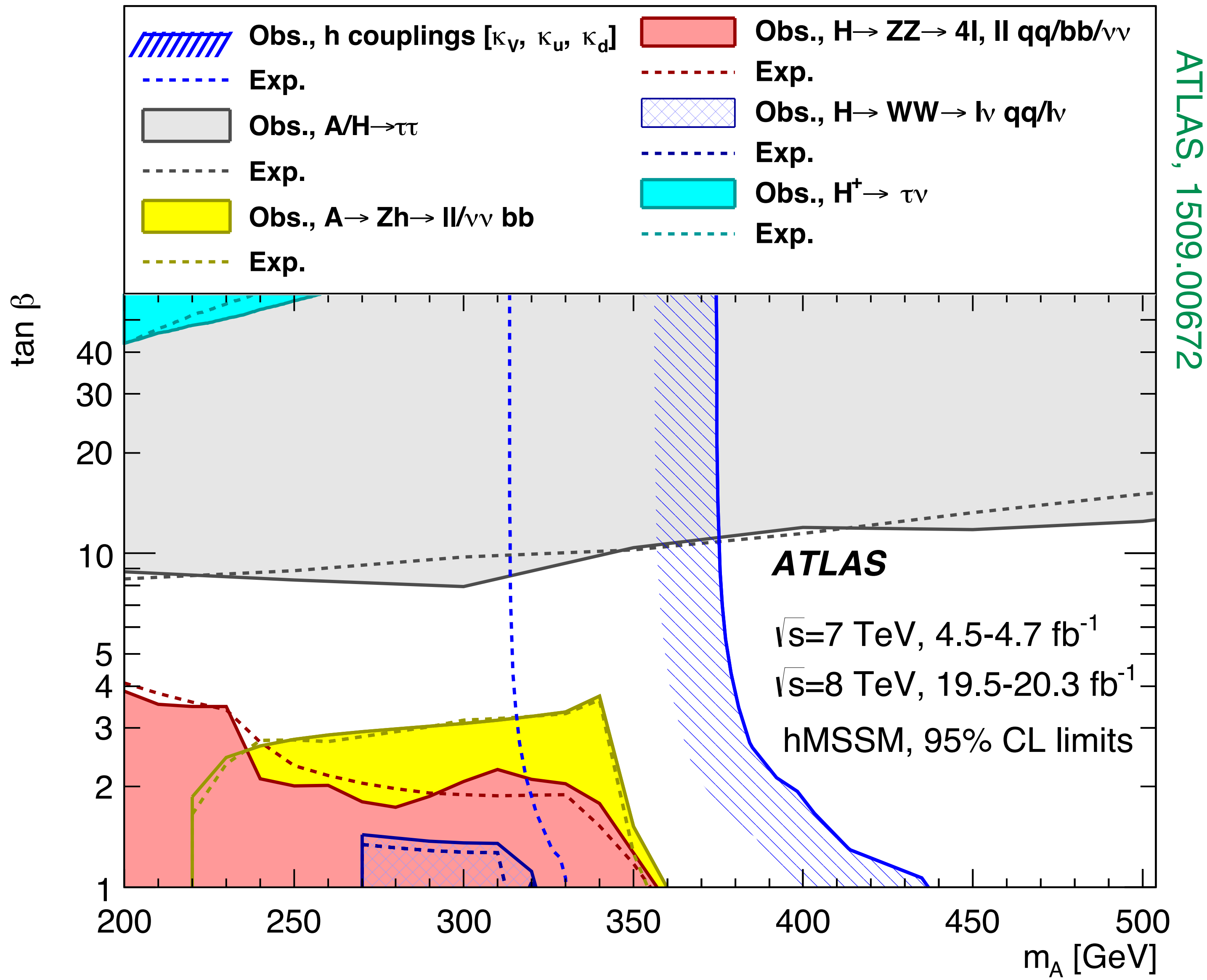
$$\tan\alpha = -\frac{(M_Z^2 + M_A^2) c_\beta s_\beta}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

This allows for a “model independent” analysis with only two input parameters *(assuming no direct corrections from SUSY particles to the Higgs couplings)*

EFT comparison:
[Lee+Wagner, 1508.00576]

Good agreement (few %) for M_H and mixing as long as the corrections to the (1,1) and (1,2) elements are suppressed (in particular, for $\mu X_t / M_S^2 \lesssim 1$)

ATLAS constraints on the hMSSM parameter space



LHCHXSWG-2015-002

August 1, 2015

LHC HIGGS CROSS SECTION WORKING GROUP

PUBLIC NOTE

Benchmark scenarios for low $\tan\beta$ in the MSSM

Emanuele Bagnaschi[1,a], Felix Frensch[2,b], Sven Heinemeyer[3,c],
Gabriel Lee[4,d], Stefan Liebler[1,e], Margarete Mühlleitner[2,f] Allison Mc Carn[5,g],
Jérémie Quevillon[6,h], Nikolaos Rompotis[7,i], Pietro Slavich[8,j], Michael Spira[9,k],
Carlos E.M. Wagner[10,11,l], and Roger Wolf[2,m]

Beyond the MSSM: adding singlets and/or doublets

NMSSM: raising the Higgs mass with a new coupling

The μ problem: If the Higgs/higgsino superpotential mass μ is allowed in the SUSY limit, why is it not of $O(M_P)$?

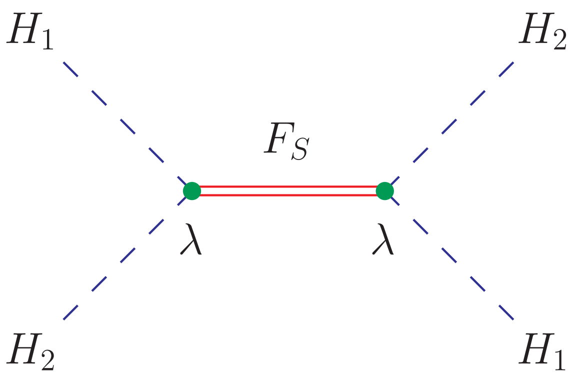
NMSSM solution: generate μ at the weak scale through the vev of a light singlet

$$W \supset -\lambda S H_1 H_2 + \frac{\kappa}{3} S^3 \longrightarrow \mu_{\rm eff} = \lambda \langle S \rangle$$

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

The singlets mix with their MSSM counterparts (3x3 Higgs mass matrices, 5x5 neutralino)

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



Modified tree-level bound on the lightest-scalar mass:

$$M_{h_1}^2 < M_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta$$

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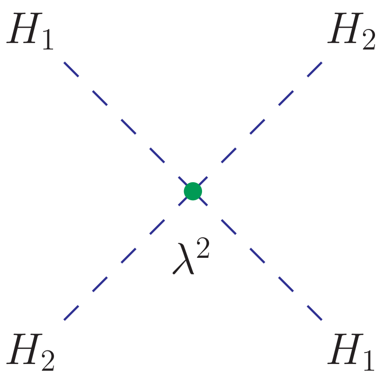

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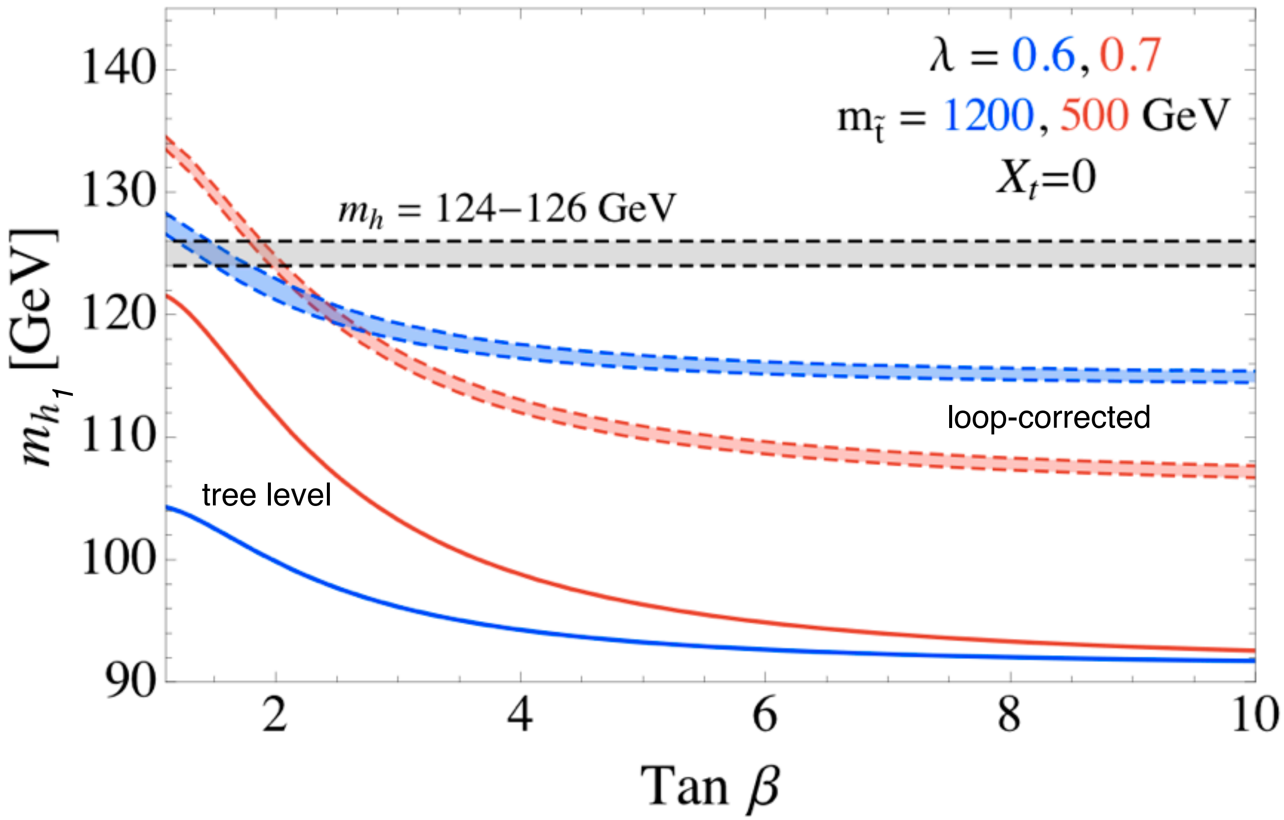
$$M_{h_1}^2 < M_Z^2 \cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin^2 2\beta$$

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



Hall *et al.*, 1112.2703

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

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

An extended Higgs sector also allows to accommodate additional “bumps” (see later)

Precise calculation of M_h in the NMSSM

The NMSSM calculation of the Higgs masses has almost caught up with the MSSM one

Full 1-loop: Degrassi+P.S. (2009), Staub *et al.* (2010), Muhlleitner *et al.* (2011-2012), Drechsel *et al.* (2016)

Dominant 2-loop (strong+Yukawa): Degrassi+P.S. (2009), Staub *et al.* (2014), Muhlleitner *et al.* (2014)

Public code	M_h [GeV]	
	MSSM-like point	NMSSM-specific point
SPheno + SARAH	124.8	126.8
SoftSUSY/ FlexibleSUSY	123.8	126.6
NMSSMTools	123.5	127.3
NMSSMCalc	120.3	124.9

Comparison of public codes from Staub *et al.* (+P.S.) 1507.05093

All $\overline{DR}$ calculations of the Higgs mass. Differences in the determination of the top Yukawa and in the 2-loop accuracy

An NMSSM version of FeynHiggs (based on the OS scheme) is currently being developed

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SPheno + SARAH: $\alpha_s\alpha_t + \alpha_s\alpha_b + \alpha_i\alpha_j \quad (i,j = t,b,\tau,\lambda,\kappa)$

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SUSY models with Dirac gaugino masses[†]

Majorana mass

$$\int d^2\theta \, \frac{X}{M} \, \mathrm{Tr}\,(W^\alpha W_\alpha)$$

vs

Dirac mass

$$\int d^2\theta \, 2\sqrt{2} \, \frac{W'_\alpha}{M} \, \mathrm{Tr}\,(W^\alpha \Sigma)$$

SUSY-breaking spurions:

$$X = \theta^2 F$$
$$W'_\alpha = \theta_\alpha D$$

Field-strength superfield:

$$W^\alpha = -i\,\lambda^\alpha + \ldots$$

Adjoint chiral superfield:

$$\Sigma = \sigma + \sqrt{2}\,\theta_\alpha \chi^\alpha + \ldots$$

$$\mathcal{L}^{\mathrm{MG}} \supset -\frac{F}{M}\,\lambda^\alpha \lambda_\alpha$$

$$\mathcal{L}^{\mathrm{DG}} \supset -\frac{D}{M}\,\lambda^\alpha \chi_\alpha$$

- Models with Dirac gauginos need extra fields, but have several attractive features:
  - ✓ Relax the LHC bounds on squarks (suppressed t-channel gluino exchange);
  - ✓ Suppress SUSY contributions to flavor- and CP-violating processes;
  - ✓ Only finite (“supersoft”) one-loop corrections to scalar masses;
  - ✓ They can be embedded in models with extended (N=2) supersymmetry.

[†] A favorite topic of my LPTHE colleagues K. Benakli and M. Goodsell

The Higgs sector in models with Dirac gauginos

The scalar components of the adjoint chiral partners of wino & bino mix with the Higgses

Minimal Dirac-gaugino SSM (MDGSSM)

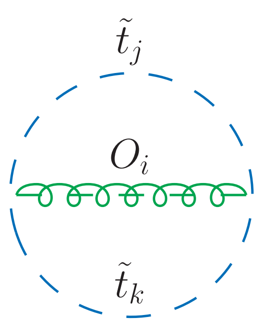
$$W \supset \; - (\mu + \lambda_S \, S) \, H_1 H_2 \; + \; \lambda_T \, H_1 T^a \, \sigma^a \, H_2 \; + \; W_\Sigma(S, \, T^a)$$

Minimal R-symmetric SSM (MRSSM) needs "inert" superfields $R_{1,2}$ to provide higgsino masses

$$\begin{aligned} W \;\; \supset & \;\; (\mu_1 + \lambda_{S_1} \, S) \, H_1 R_1 \; + \; \lambda_{T_1} \, H_1 T^a \, \sigma^a \, R_1 \\ + & \;\; (\mu_2 + \lambda_{S_2} \, S) \, R_2 H_2 \; + \; \lambda_{T_2} \, R_2 \, T^a \, \sigma^a \, H_2 \end{aligned}$$

The mass matrices for the neutral colorless scalars become (4x4) or even (6x6)

Diagrams with exchange of scalar octets ("sgluons", or "sgluinos"?) contribute to the 2-loop corrections to the Higgs masses at $\mathcal{O}(\alpha_s \alpha_q)$:



See: J. Braathen, M. Goodsell & P.S., *"Leading two-loop corrections to the Higgs-boson masses in SUSY models with Dirac gauginos"*, to appear soon.

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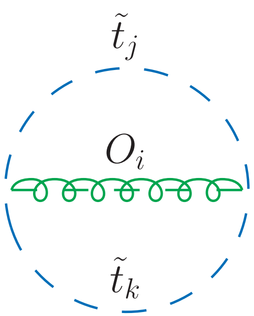

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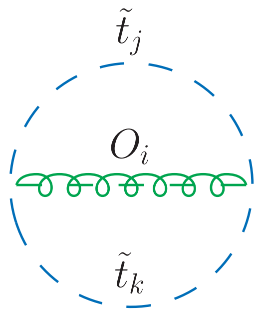

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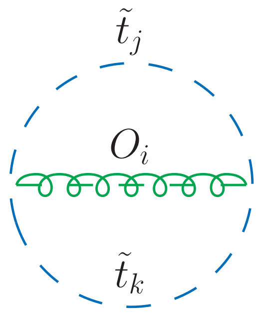

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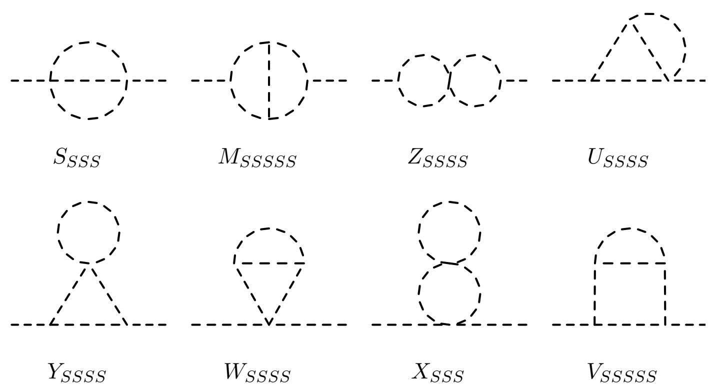
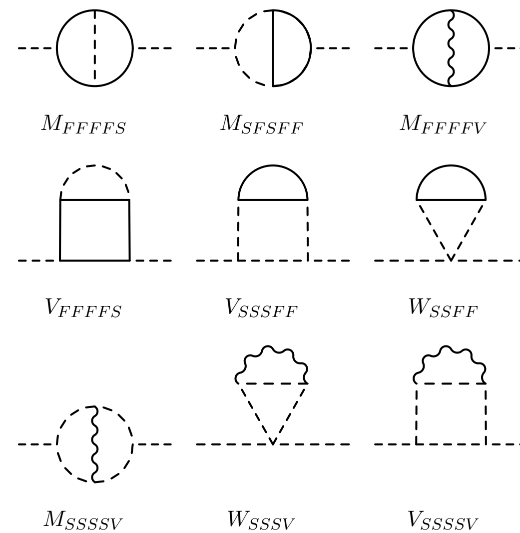
Automatizing 2-loop Higgs-mass calculations in SARAH

[M. Goodsell, K. Nickel & F. Staub, as described in 1411.0675 and 1503.03098]

General results for 2-loop, zero-momentum scalar self-energies in the “gaugeless limit”:





[Based on earlier work by S.P. Martin (2001-2005)]

For any SUSY model, just enter superfields, symmetries and superpotential in SARAH*; tell it which scalars get a vev and which fields mix when symmetries are broken; push a button, and generate a* SPheno *version with full-1-loop + leading-2-loop Higgs-mass calculation*

- $\overline{\text{DR}}$ scheme built in the calculation, translation to OS scheme not trivial
- Two-loop corrections to *Z* self-energy still missing (relevant to extract $v^{\overline{\text{DR}}}$)
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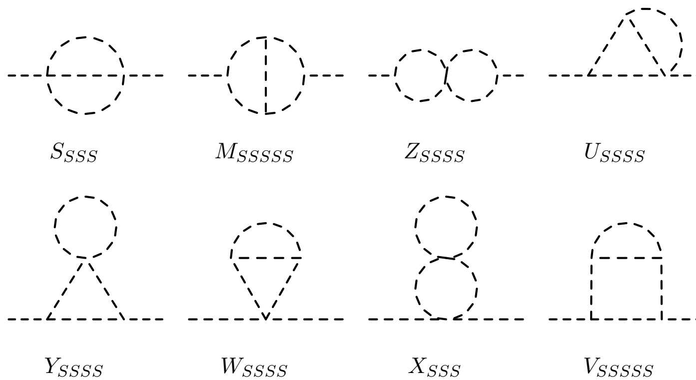

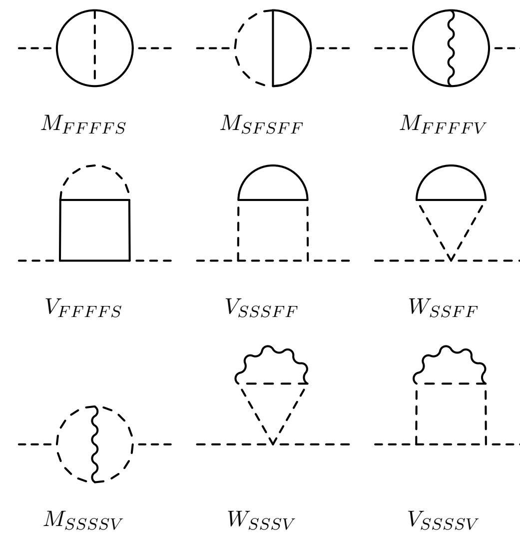

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Push another button and generate a publication... ;-)

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General results for 2-loop, zero-momentum scalar self-energies in the “gaugeless limit”:

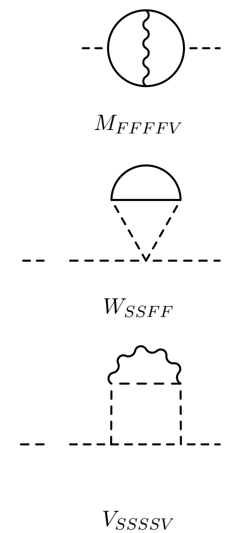
On the two–loop corrections to the Higgs mass in trilinear R–parity violation

Herbi K. Dreiner,[1,*] Kilian Nickel,[1,†] and Florian Staub[2,‡]

[1] *Bethe Center for Theoretical Physics & Physikalisches Institut der Universität Bonn, 53115 Bonn, Germany*

[2] *Theory Division, CERN, 1211 Geneva 23, Switzerland*

We study the impact of large trilinear R–parity violating couplings on the lightest CP–even Higgs boson mass in supersymmetric models. We use the publicly available computer codes **SARAH** and **SPheno** to compute the leading two–loop corrections. We use the effective potential approach. For not too heavy third generation squarks ($\tilde{m} \lesssim 1$ TeV) and couplings close to the unitarity bound we find positive corrections up to a few GeV in the Higgs mass.



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Automatizing 2-loop Higgs-mass calculations in SARAH

[M. Goodsell, K. Nickel & F. Staub, as described in 1411.0675 and 1503.03098]

General results for 2-loop,

PHYSICAL REVIEW D **91**, 035021 (2015)

Two-loop corrections to the Higgs masses in the NMSSM

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(Received 19 December 2014; published 19 February 2015)

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Herbi K. Dreiner,[1,*] K
[1] *Bethe Center for Theoretical Phys*
531
[2] *Theory Division, C*

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V_{SSSSV}

Push another button and generate a publication... ;-)

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- Two-loop corrections to Z self-energy still missing (relevant to extract $v^{\overline{\text{DR}}}$)
- Issues with the "Goldstone boson catastrophe" (massless states in loops)

Automatizing 2-loop Higgs-mass calculations in SARAH

[M. Goodsell, K. Nickel & F. Staub, as described in 1411.0675 and 1503.03098]

General results for 2-loop,

PHYSICAL REVIEW D **91**, 035021 (2015)

Two-loop corrections to the Higgs masses in the NMSSM

Mark D. Goodsell*

Sorbonne Universités, UPMC Univ Paris 06, UMR 7589, LPTHE, F-75005 Paris, France and CNRS, UMR 7589, LPTHE, F-75005 Paris, France

Kilian Nickel†

Bethe Center for Theoretical Physics & Physikalisches Institut der Universität Bonn,

On the two–loop corrections to t

Herbi K. Dreiner,[1,*] K

[1] *Bethe Center for Theoretical Phys*

[2] *Theory*

We study the impact of la
boson mass in supersymme
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find positive corrections up

Precise determination of the Higgs mass in supersymmetric models with vectorlike tops and the impact on naturalness in minimal GMSB

Kilian Nickel[a] **and Florian Staub**[b]

[a] *Bethe Center for Theoretical Physics & Physikalisches Institut der Universität Bonn, 53115 Bonn, Germany*

[b] *Theory Division, CERN, 1211 Geneva 23, Switzerland*

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Automatizing 2-loop Higgs-mass calculations in SARAH

The Higgs Mass in the MSSM at two-loop order beyond minimal flavour violation

Mark D. Goodsell[*]
1– Sorbonne Universités, UPMC Univ Paris 06, UMR 7589, LPTHE, F-75005, Paris, France
2– CNRS, UMR 7589, LPTHE, F-75005, Paris, France

Kilian Nickel[†]
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Florian Staub[‡]
Theory Division, CERN, 1211 Geneva 23, Switzerland

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V D **91**, 035021 (2015)

Higgs masses in the NMSSM

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, UMR 7589, LPTHE, F-75005 Paris, France
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15)

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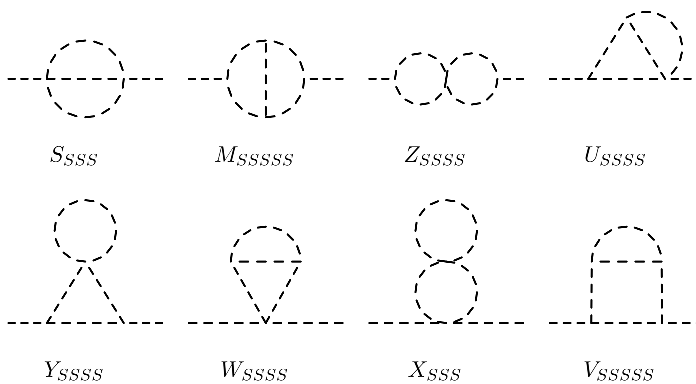
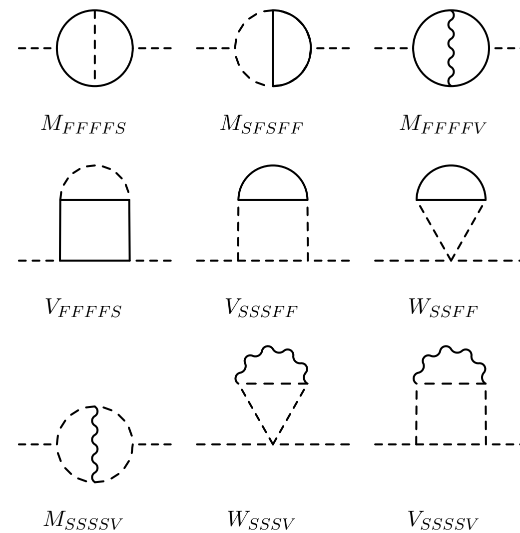
[M. Goodsell, K. Nickel & F. Staub, as described in 1411.0675 and 1503.03098]

General results for 2-loop, zero-momentum scalar self-energies in the “gaugeless limit”:





[Based on earlier work by S.P. Martin (2001-2005)]

For any SUSY model, just enter superfields, symmetries and superpotential in SARAH*; tell it which scalars get a vev and which fields mix when symmetries are broken; push a button, and generate a* SPheno *version with full-1-loop + leading-2-loop Higgs-mass calculation*

- $\overline{\text{DR}}$ scheme built in the calculation, translation to OS scheme not trivial
- Two-loop corrections to *Z* self-energy still missing (relevant to extract $v^{\overline{\text{DR}}}$)
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HOME ▪ JOBS ▪ RESULTS ▪ SEMINARS

HiggsAutomator

Tools for automatic calculations in general theories

HiggsAutomator is a *jeune chercheur* project funded by the Agence National de Recherche, which began on 1st October 2015.

The team is composed as follows:

- *Porteur du projet :* Mark Goodsell Follow @PitifulRed
- Karim Benakli
- Pietro Slavich

The team is part of the Particle Physics and Cosmology group at the LPTHE.

Latest news: jobs

We expect to recruit a postdoc starting autumn 2016, applications for which will be reviewed in December 2015.
Click here to apply
Deadline for applications: **30th November 2015**
Please address any enquiries by email to members of the team.

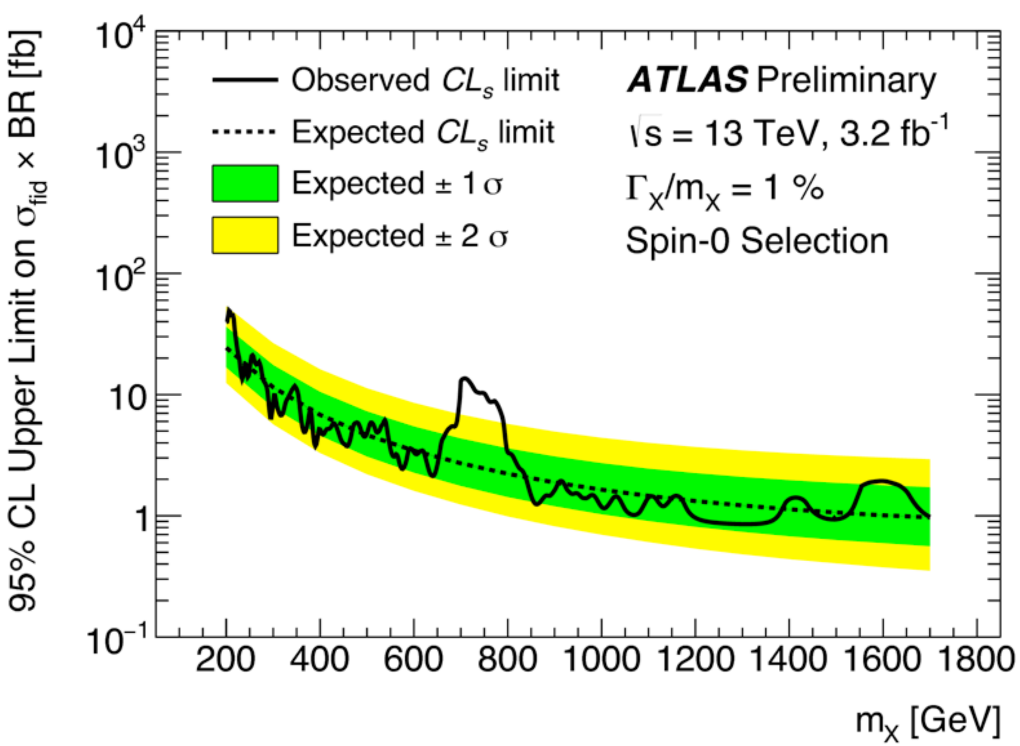
Project description

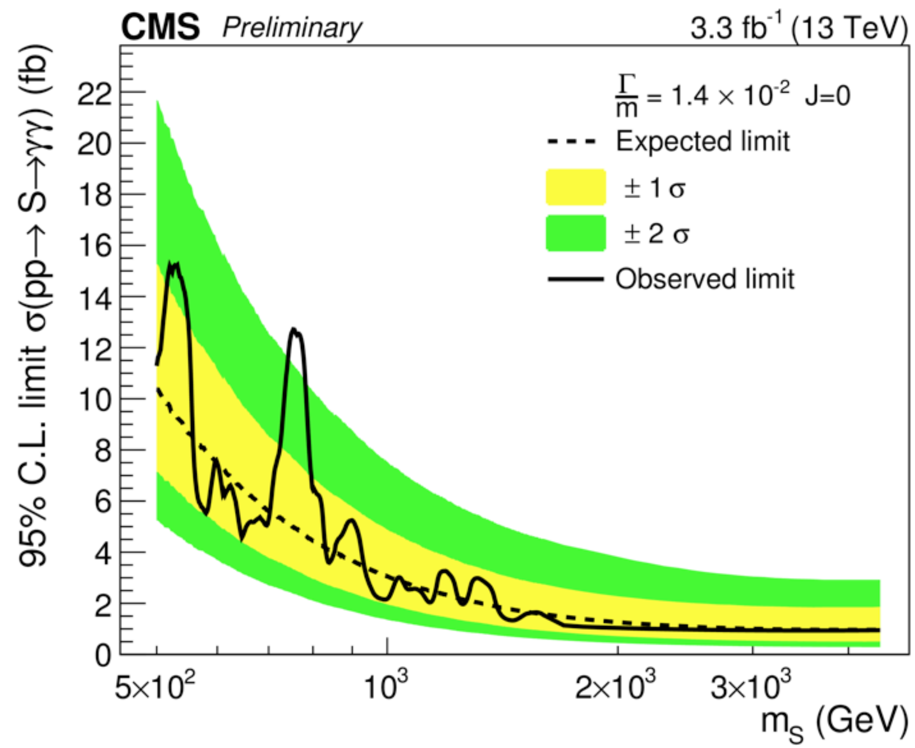
Although there are many indirect signs of new physics, it is certain that current bounds on new physics that can couple significantly to the Higgs boson present new challenges for understanding the mass of the Higgs, whatever new discoveries may or may not be made. The aim of this project is to develop theory and automatic tools to understand the implications for generic new physics of this quantity, taken in combination with the (new) information about the Higgs production and decays. The idea is to be able to use these experimentally well-determined quantities to automatically determine the viability of any new physics model. Specifically this will involve performing calculations and writing codes which will in turn write bespoke code for any given model to calculate the properties of the Higgs: mass, production and decays. This will give quantitative answers to questions such as: should we still be searching for superpartners at the LHC?

SUSY interpretations for a 750-GeV neutral scalar

SUSY interpretations for a 750-GeV neutral scalar

A new hope for BSM physics?





Some reassuring signs from Moriond:

- Adding more data (CMS) and refining the analysis (both) improves significance
- Tension between 8-TeV and 13-TeV data reduced w.r.t. December announcement

(see Aurelio's talk tomorrow)

Could it be the heavy Higgs(es) of the MSSM?

[see e.g. A. Angelescu, A. Djouadi & G. Moreau, 1512.04921]

ATLAS and CMS find: $\sigma(pp \to \Phi) \times \mathrm{BR}(\Phi \to \gamma\gamma) \approx \mathcal{O}(10\,\mathrm{fb})$

For comparison, if M_H = 750 GeV $\sigma(pp \to H_{\rm SM}) \times \mathrm{BR}(H_{\rm SM} \to \gamma\gamma) \approx \mathcal{O}(10^{-4}\,\mathrm{fb})$

Requires a large enhancement of cross section and/or BR!!!

Around 750 GeV, *H* and *A* are close in mass and decoupled from gauge-boson pairs

Enhanced (*H*, *A*) couplings to quarks?

→ *tanβ* >>1 enhances bottom coupling — Ruled out by $\Phi \longrightarrow \tau^+\tau^-$ searches!

→ *tanβ* <<1 enhances top coupling — Ruled out by $\Phi \longrightarrow t\bar{t}$ searches! (also, perturbativity)

Considering only top loops: $\sum_{\Phi=H,A} \sigma(gg \to \Phi) \times \mathrm{BR}(\Phi \to \gamma\gamma) \approx \mathcal{O}(10^{-2}\mathrm{fb}) / \tan^2\beta$

Loops of SUSY particles can alter the (production)x(decay) rates by at most factors of *O*(1)

(moreover, super-heavy stops needed for *tanβ* ≈ 1)

Could it be the heavy Higgs(es) of the MSSM? (NO)

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An exception: threshold enhancement

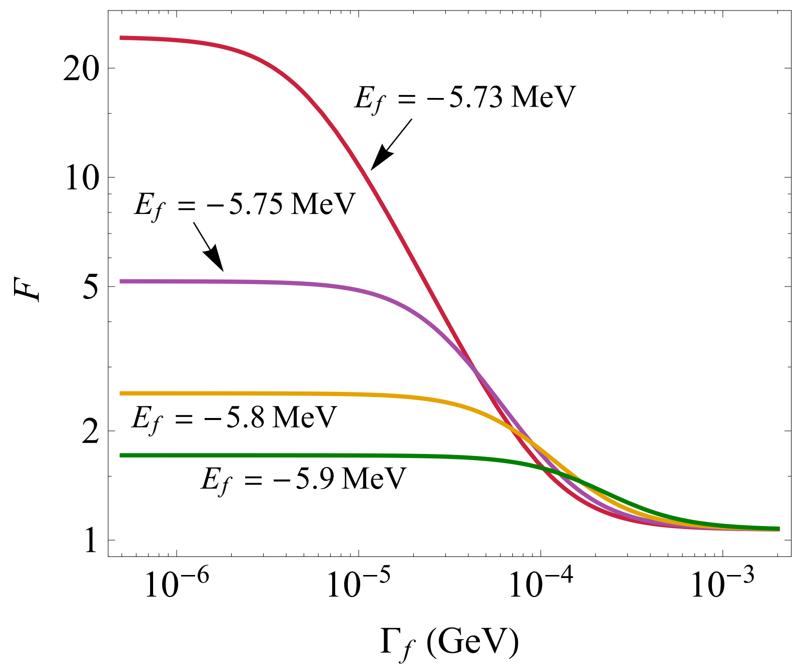
[A. Barucha, A. Djouadi & A. Goudelis, 1603.04464]

For particle masses just above threshold in the Φgg *and* $\Phi\gamma\gamma$ *loops, a Coulomb singularity develops, associated to quasi-bound states and regulated by the widths of the loop particles*

- The enhancement is more effective for the pseudoscalar couplings
- Better to enhance only the decay to avoid constraints from $A \to t\bar{t}$ (–> use chargino)
- Chargino width of *O*(keV) required for an *O*(20) enhancement of the amplitude; doable with three-body decay of the lightest chargino to neutralino+fermions via an off-shell *W*

The *"Achilles heel"*: insane fine-tuning!

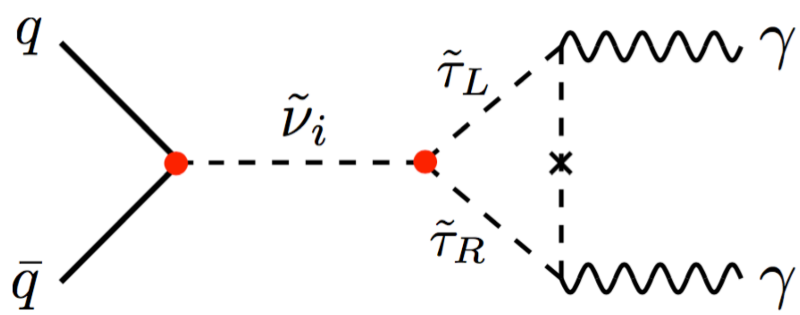
$$E_f = M_A - 2\,M_{\chi_1}$$



Resonant sneutrino in RPV MSSM: a saner variation?

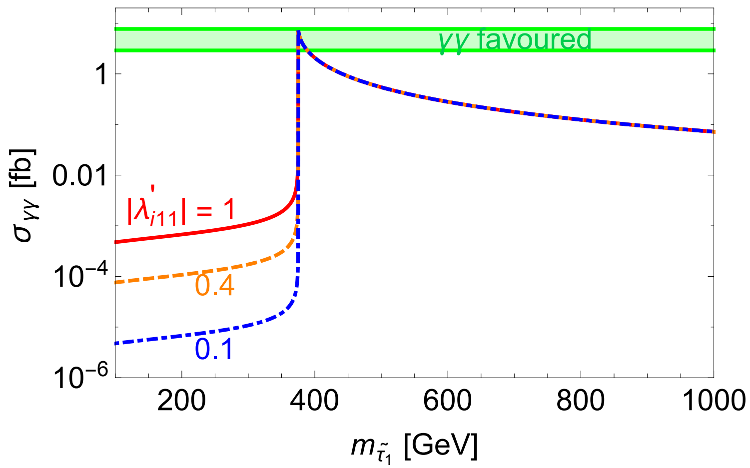
[see Ding *et al.*, 1512.06560 and Allanach *et al.*, 1512.07645*]

$W \supset \lambda'_{i11} L_i Q_1 \overline{D}_1$

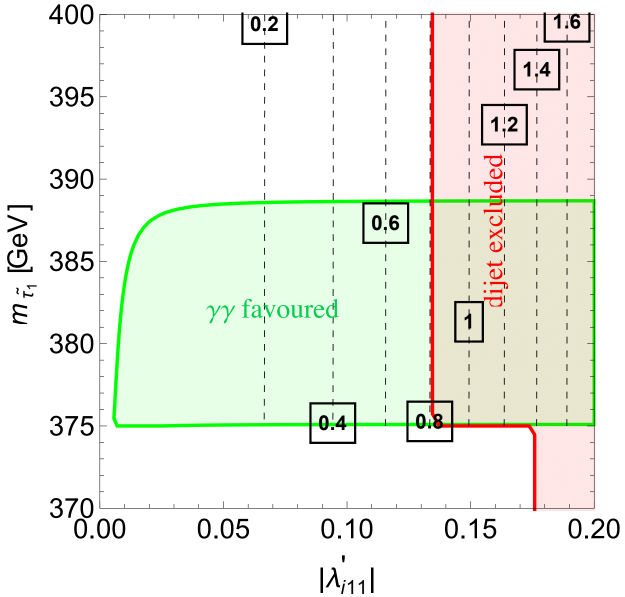


$\mathcal{L}^{\rm soft} \supset T_{i33}\, \tilde{\ell}_i \tilde{\ell}_3 \tilde{\tau}_R^+$

Decay enhanced by resonance for $M_{\tilde{\tau}_1} \approx M_{\tilde{\nu}_i}/2$:



Production bounded by di-jet searches:



* source of all plots in this slide

Interpreting the diphoton excess in the NMSSM

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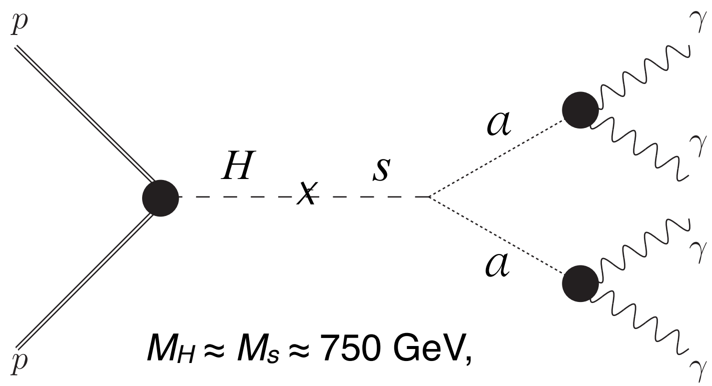
Two collimated photon pairs from heavy Higgses decaying to very light pseudoscalars?

[see Ellwanger+Hugonie, 1602.03344 and Domingo+Heinemeyer+Kim+Rolbiecki, 1602.07691]



$M_H \approx M_s \approx 750$ GeV,
$M_a \lesssim 0.5$ GeV

- Special values of M_a to beat e^+e^- decay

$$M_a \approx 2M_\mu, \quad M_a \approx M_\eta, \quad M_a \approx M_{\pi^0}$$

- Tuning needed to suppress *h*–*s* mixing (to avoid *h* —> *aa* decay)
- Constraints from hadronic/flavor physics

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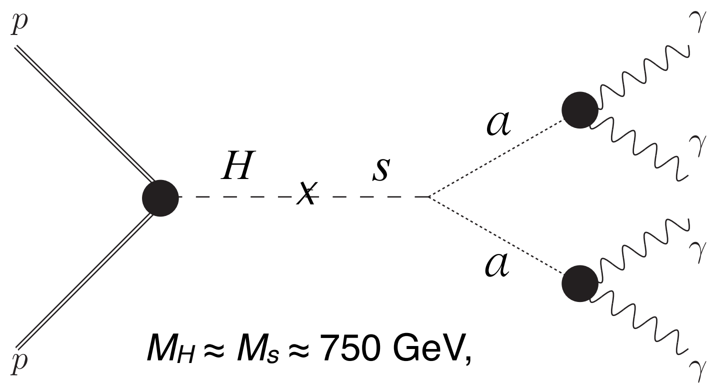

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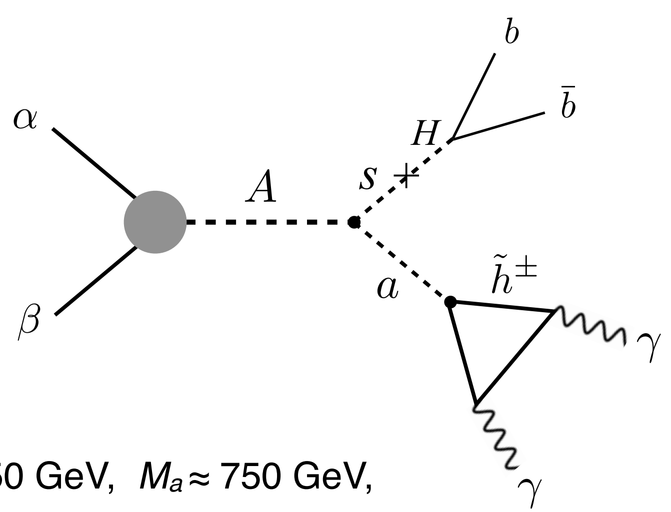
Cascade decay of the MSSM-like pseudoscalar to the singlet-like one?

[see Badziak+Olechowski+Pokorski+Sakurai, 1603.02203]



$M_A \approx 850$ GeV, $M_a \approx 750$ GeV,
$M_s \approx 65$ GeV

- Requires $\lambda\,\kappa > 1$ for sizeable *Aas* coupling
  - Landau pole around 100 TeV!
  - Large (uncomputed) radiative corrections
- $M_{\tilde{h}^\pm} \approx M_a/2$ to enhance di-photon decay
- Tuning to suppress both *h–s* and *A–a* mixing (to avoid *h* —> *aa* and *a* —> *ff* decays)

Interpreting the diphoton excess in the NMSSM

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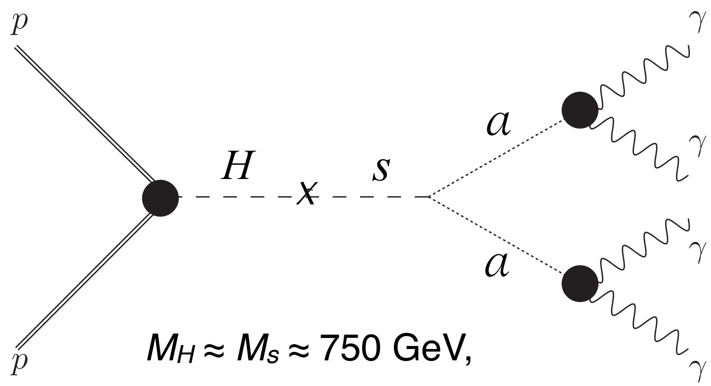

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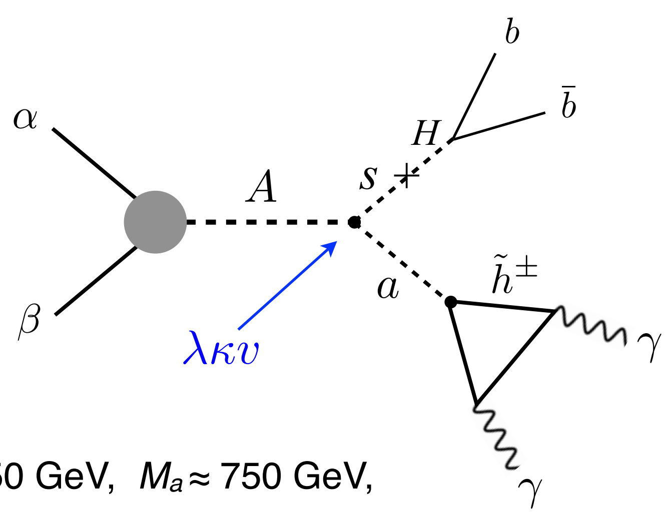

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Diphoton resonance in models with Dirac gauginos

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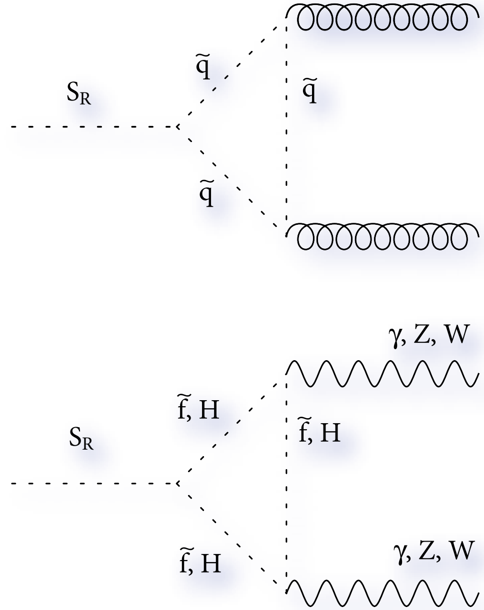
Could it be the sbino (or swino)?

[Carpenter *et al.*, 1512.06107]

$$\mathcal{L} \supset g' \, y_i \, m_D \, (S + S^*) \, \phi_i^\dagger \phi_i$$

Observed diphoton rates require m_D of *O*(10 TeV)

Problems: mixing with SM Higgs and stability of the potential



$\Gamma_{\gamma\gamma}/\Gamma_{gg}$ can be tuned to avoid dijet bounds by adjusting squark/slepton masses

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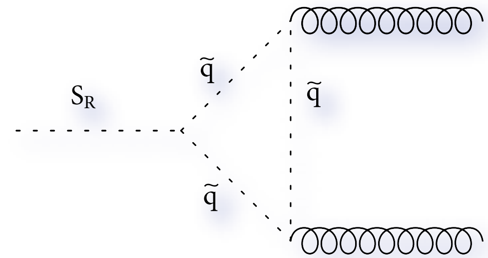
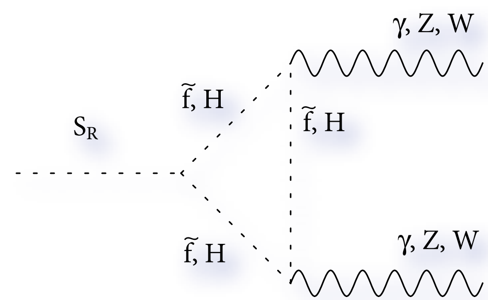




$\Gamma_{\gamma\gamma}/\Gamma_{gg}$ can be tuned to avoid dijet bounds by adjusting squark/slepton masses

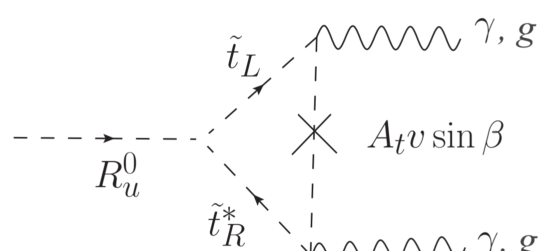
Could it be an "inert scalar" of MRSSM?

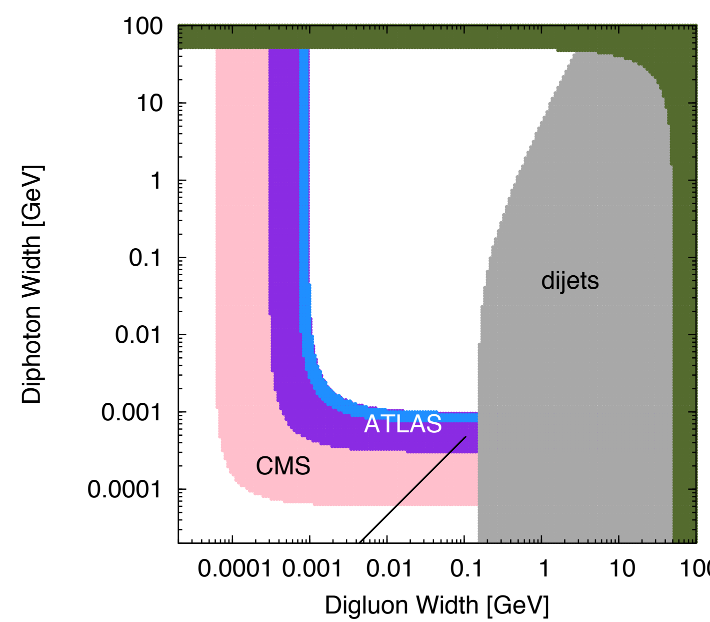
[Chakraborty *et al.*, 1512.07527]

$$\mathcal{L} \supset -\mu_2\, Y_t\, R_2^0\, \tilde{t}_L \tilde{t}_R^* + \text{h.c.}$$

Need to break R-symmetry to close the loop!!!

$$\mathcal{L}_{\not R} \supset A_t\, H_2^0\, \tilde{t}_L \tilde{t}_R^* + \text{h.c.}$$





More SUSY interpretations of the diphoton resonance

- NMSSM with additional vector-like matter (to mediate coupling of S to photons)
  [Dutta Gao Ghosh Gogoladze Hall Harigaya Li Nomura Shafi Tang Walker Wang Wu Yang Zhang Zhu...]

- SUSY models with extended gauge symmetry (additional 750-GeV candidates)
  [Chao Feng Jiang King Li Liu Ma Nevzorov Zhang Zhao...]

- Sgoldstino (complex scalar, direct couplings to gluons and photons $\sim M_i / F$)
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1602.05581: a systematic (187 pages!) survey of 40 models using SARAH & friends

Precision tools and models to narrow in on the 750 GeV diphoton resonance

Florian Staub,[a] Peter Athron,[b] Lorenzo Basso,[c] Mark D. Goodsell,[d] Dylan Harries,[e] Manuel E. Krauss,[f] Kilian Nickel,[f] Toby Opferkuch,[f] Lorenzo Ubaldi,[g] Avelino Vicente,[h] Alexander Voigt[i]

For each model check mass spectrum, branching ratios, Higgs properties, vacuum stability...

Summary

- Many SUSY models allow for an essentially SM-like Higgs, plus a rich variety of additional neutral+colorless scalars that mix and interact with it

- The predictions for the masses & mixing in the Higgs sector are affected by large radiative corrections, sensitive to the details of the superparticle spectrum
  - For the SM-like Higgs, accuracy of theory predictions still far from expt. one
  - An EFT approach might be needed in scenarios with multi-TeV sparticles
  - In general, calculations in BMSSM models are catching up with the MSSM

- The recent hints for a ~750-GeV resonance with rather large di-photon rate can be accommodated (with some effort... ;-) in SUSY extensions of the SM
  - Need to go beyond the MSSM to find suitable candidates
  - Some gymnastics to enhance diphoton over dilepton or dijets
  - Some tuning in the parameters to avoid mixing with SM-like Higgs

Thank you!!!