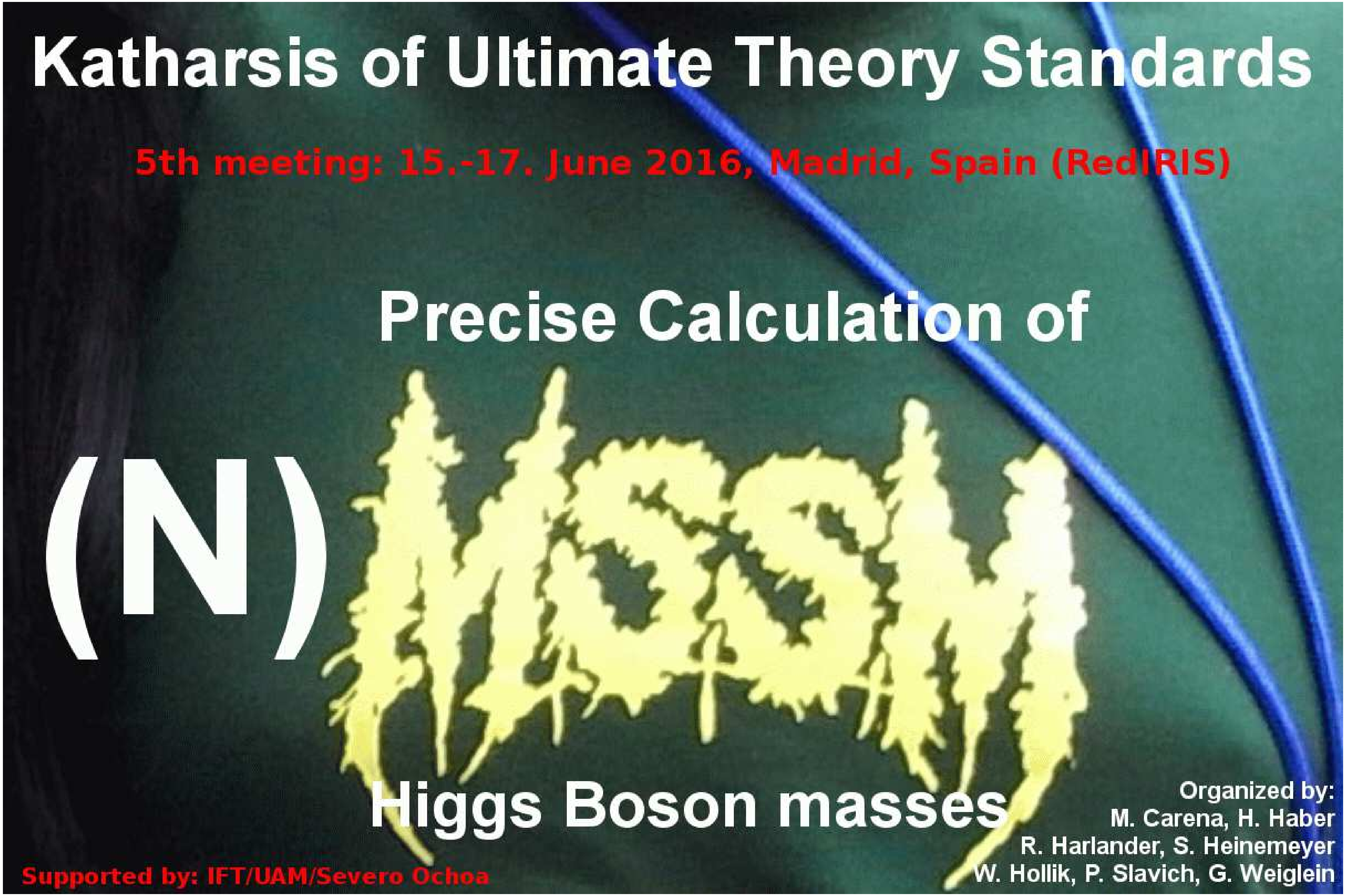
Status of the Higgs-mass calculation in SUSY models

Pietro Slavich

LPTHE
LABORATOIRE DE PHYSIQUE
THEORIQUE ET HAUTES ENERGIES

Higgs Days at Santander 2016 – 19-23 September

Sven’s order: A KUTS summary


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

Five KUTS meetings so far: can we spot any trends?

Talks	2014 / 4 Munich	2014 / 10 Hamburg	2015 / 5 Paris	2016 / 1 Heidelberg	2016 / 6 Madrid	2017 / 1 Aachen
(Participants)	20	19	22	25	17	?
MSSM 2-loop (p^2, CPV, FLV)	3	3	1	2	2	?
MSSM 3-loop	1	1	1	—	—	?
NMSSM	1	2	3	1	2	?
Heavy SUSY	3	1	3	6	4	?
Code Updates (except HS)	5	2	2	1	—	?
Others	3	2	2	—	1	?
Diphoton	—	—	—	1	1	—

(Disclaimer: for several talks the classification is somewhat arbitrary)

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In 2016, 10/21 talks on heavy SUSY

(Disclaimer: for several talks the classification is somewhat arbitrary)

Starting point: 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 ($X_t << M_S$) or small $\tan\beta$ (or M_A) require multi-TeV stop masses –> resummation of large logarithms

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(SuSpect, SPheno/SARAH, SoftSUSY/FlexibleSUSY, FeynHiggs, H3m, ...)

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(SusyHD, MhEFT*, HSSUSY*)

(* = *new in 2016*)

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"hybrid" codes
(FeynHiggs $\geqslant$ 2.10, FlexibleEFTHiggs*)

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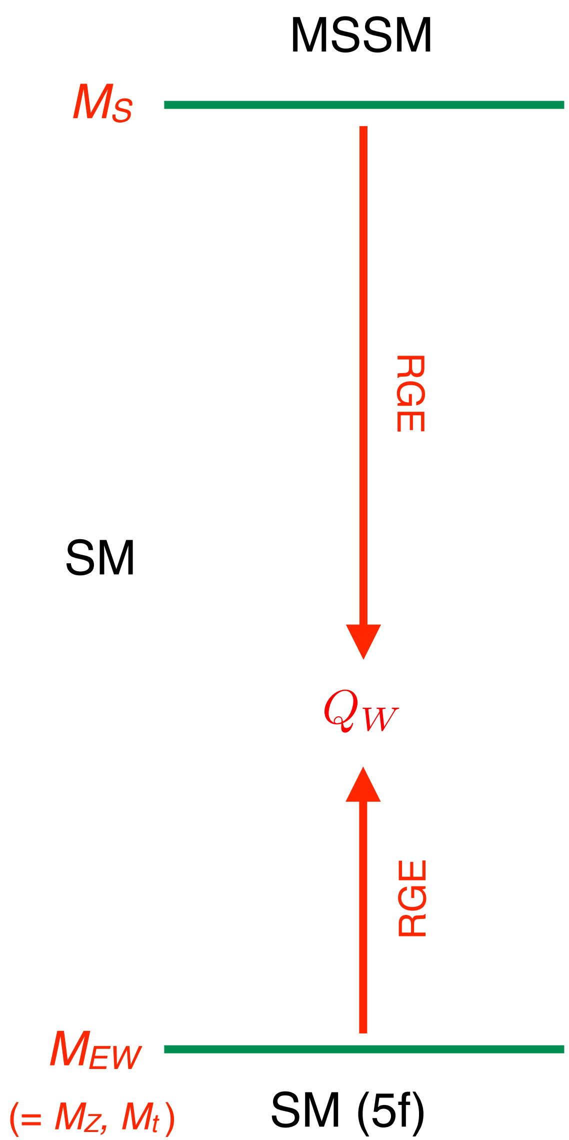
Dealing with heavy SUSY particles

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



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

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

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

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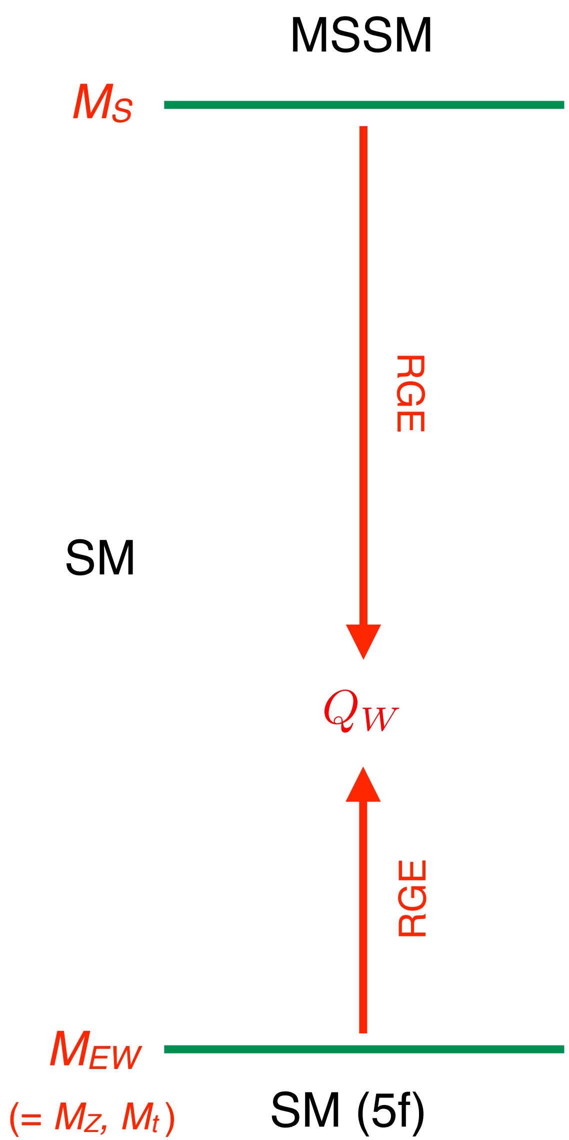

$$\lambda(M_S) = \frac{1}{8}\left(g^2 + g'^2\right)\cos^2 2\beta \;+\; \Delta\lambda$$

(unbroken EW symmetry)

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

(EWSB)

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

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

State-of-the-art EFT calculations

Recent studies: Draper *et al.*, 1312.5743; Bagnaschi *et al.* (+P.S.), 1407.4081; PardoVega+Villadoro (SusyHD) 1504.05200

- SUSY-scale boundary conditions: 1-loop + 2-loop $O(g_t^4\, g_s^2)$ and $O(g_t^6)$

- Evolution between the SUSY and EW scales: 3-loop full RGE of the SM

- EW-scale boundary conditions: full 2-loop + 3-loop QCD for g_t

This setup allows for a full NLL and partial NNLL resummation of large logs

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  degenerate M_S
  [see 1312.5743, 1504.05200]

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  [*interpolating formulae* from 1307.3536v4]

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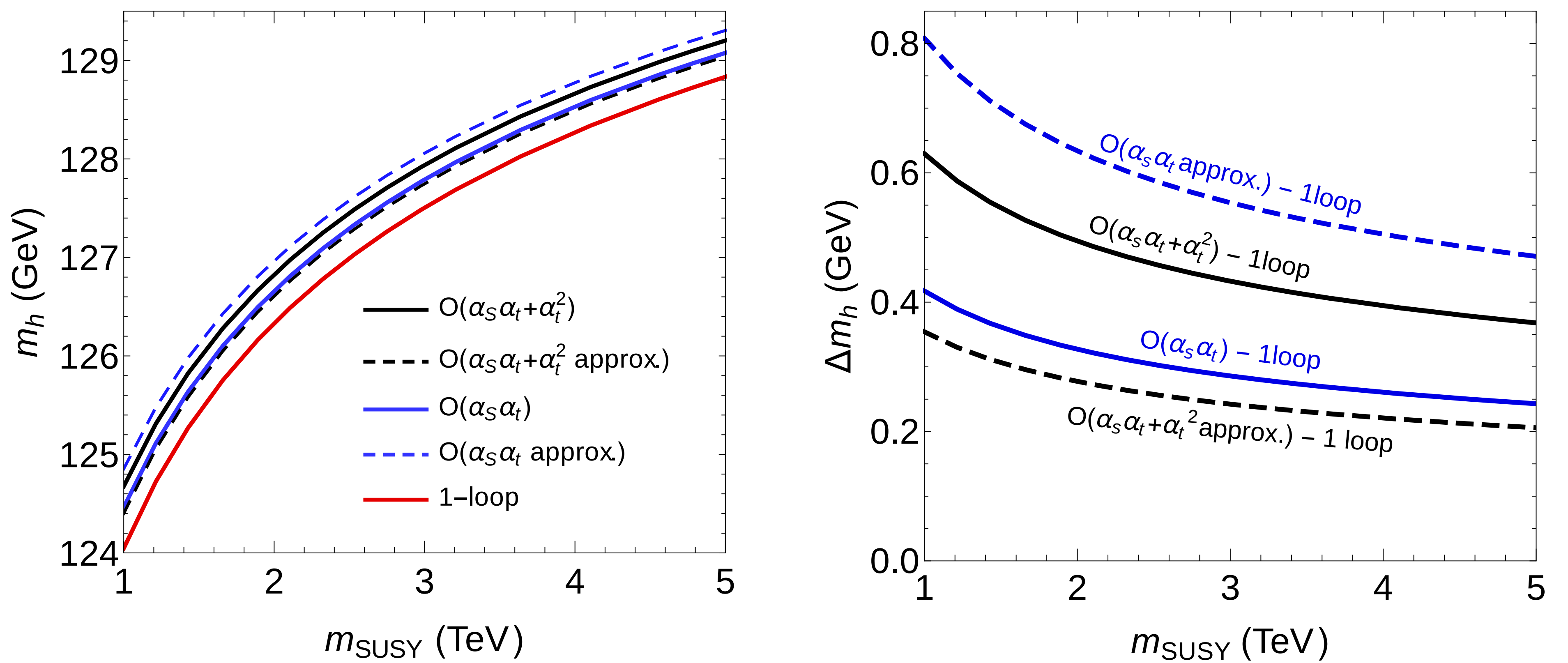
Coming soon: $O(g_t^6)$ corrections for general SUSY parameters

[E. Bagnaschi, P.S. and J. Pardo-Vega]

All scalar masses degenerate to m_{SUSY} except $m_{Q_3} = 3m_{SUSY}$,
$X_t = \sqrt{6 m_{Q_3} m_{U_3}}$, $\tan\beta = 20$, $A_b = A_t$, $\mu = 4m_{SUSY}$

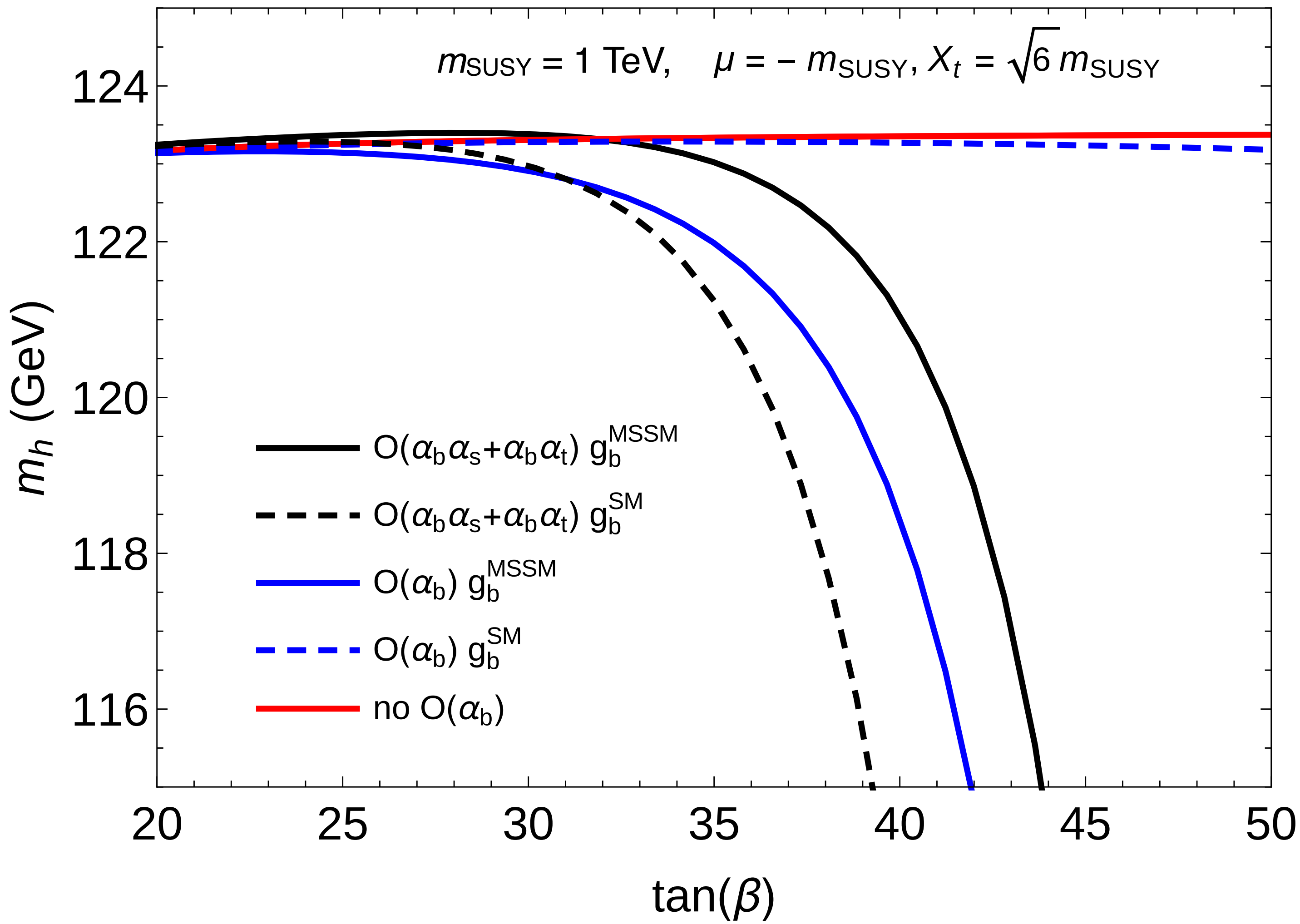


[Plots from J. Pardo-Vega's talk at KUTS5]

approx. : all scalar masses degenerate to $M_S = \sqrt{m_{Q_3}\, m_{U_3}}$

Coming soon: effect of the two-loop bottom (& tau) corrections

[E. Bagnaschi, P.S. and J. Pardo-Vega]



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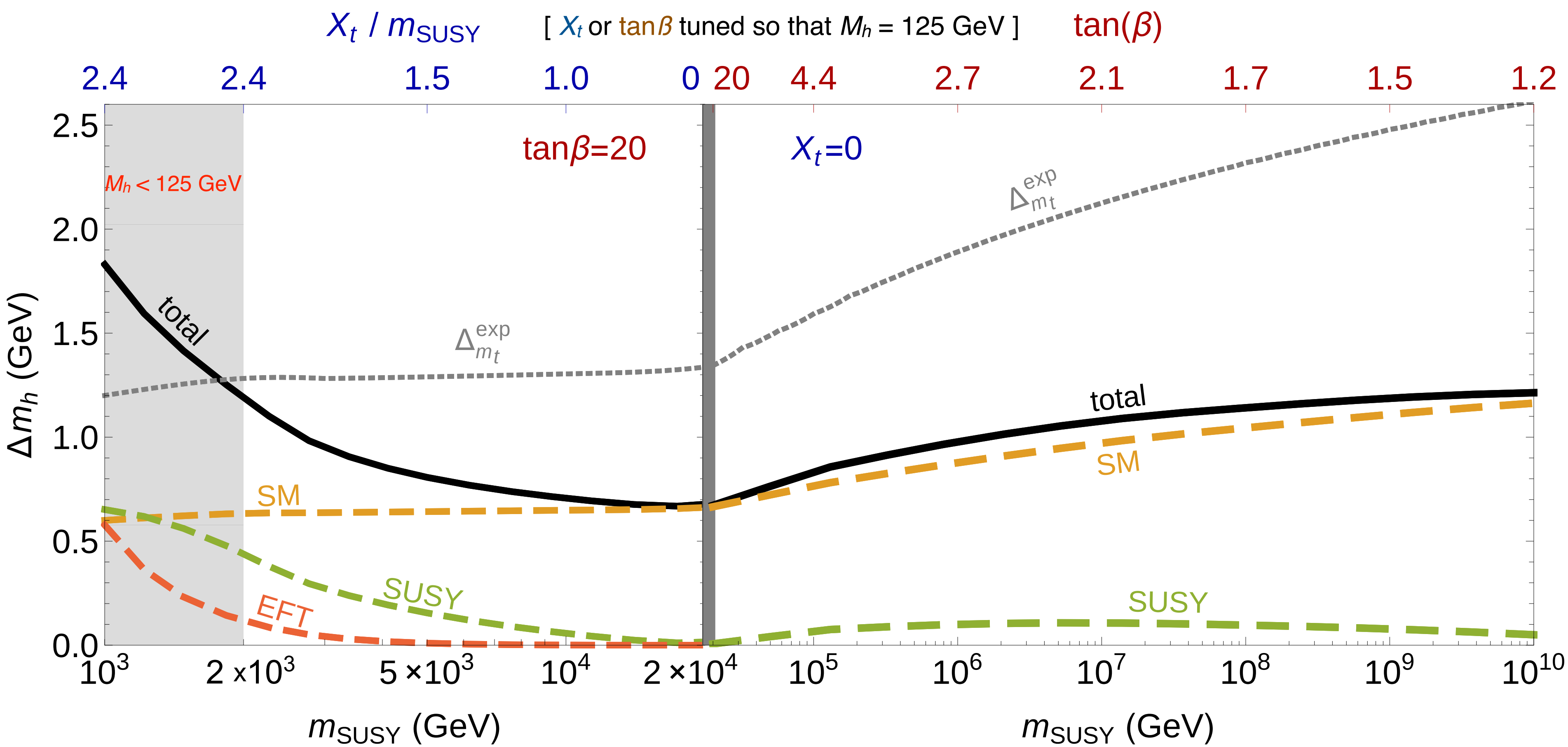
Uncertainties of the EFT calculation

[PardoVega+Villadoro (SusyHD) 1504.05200]



SM uncertainty: from the SM calculation (mostly from higher-order QCD effects)

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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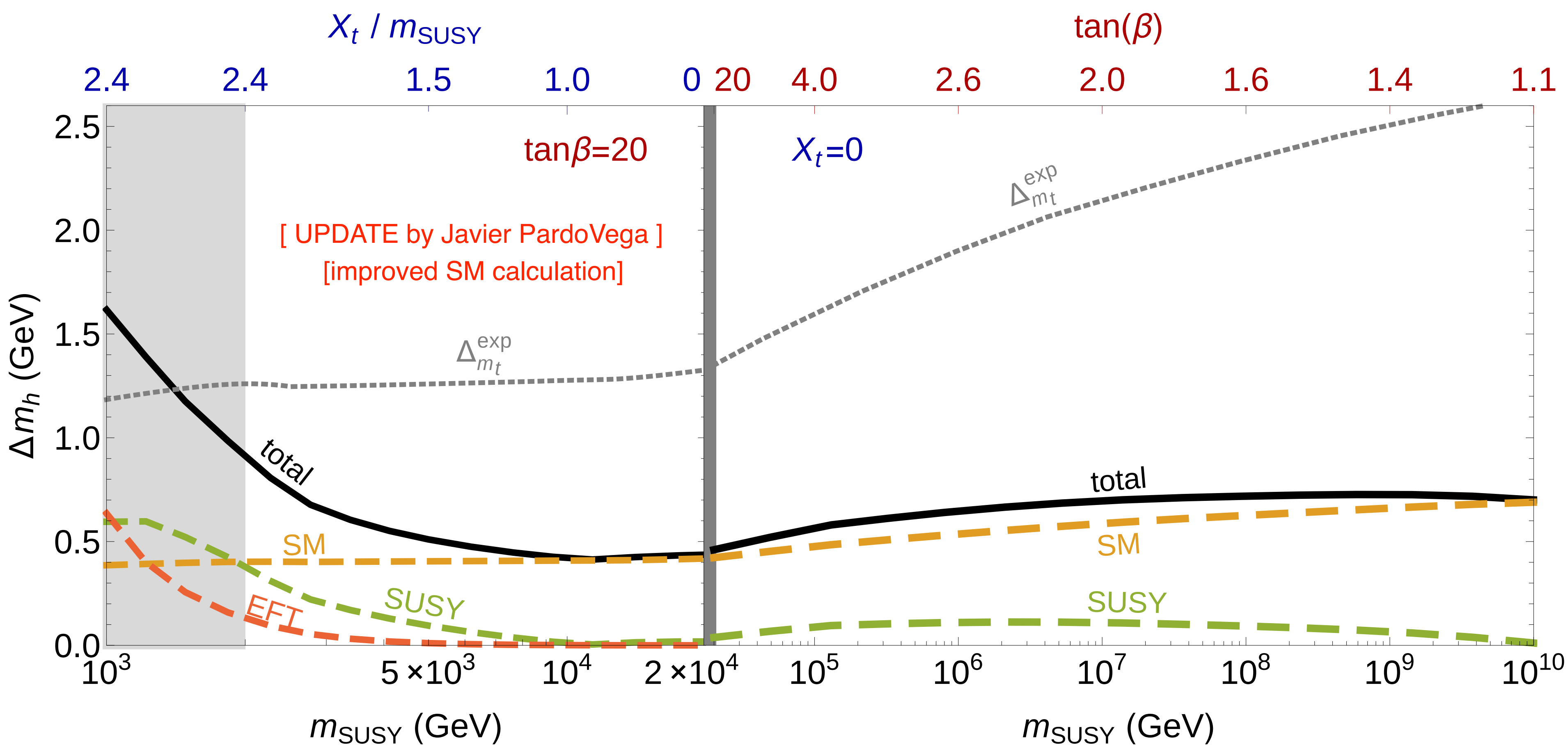

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Coming soon: effects of dim-6 operators in the EFT calculation

[E. Bagnaschi, P.S. and J. Pardo-Vega]

We focus on the operators that induce the dominant $O(m_t^2/M_S^2)$ effects at one and two loops:

$$\mathcal{L}_{\rm eff} \;=\; \mathcal{L}_{\rm SM} \;+\; c_6\,|H|^6 \;+\; \left(c_t\,g_t\,|H|^2\,\overline{q_L}\,H\,t_R \;+\; {\rm h.c.}\right) \;+\; \ldots$$

$$\left(c_6, c_t \;\propto\; \frac{1}{M_S^2}\right)$$

- Compute 1- and 2-loop matching conditions on c_6 and c_t at the SUSY scale
- Include effects of c_6 and c_t in the RG evolution between SUSY and EW scales
- Include effects of c_6 and c_t in the calculation of M_h and g_t at the EW scale

This will allow us to improve the EFT determination of M_h when $M_S \approx 1$–2 TeV, and provide a more-realistic estimate of the remaining $O(v^2/M_S^2)$ effects

“hybrid” calculations: combining fixed-order and EFT

- FeynHiggs $\geqslant 2.10$ [Hahn *et al.*, 1312.4937 + Bahl & Hollik, 1608.01880]

$$M_h^2 \;=\; (M_h^2)^{\rm FH} \;+\; \left[(M_h^2)^{\rm EFT} \;-\; (\Delta M_h^2)^{\rm dblcount}\right]$$

- FlexibleEFTHiggs [Athron *et al.*, 1609.00371]

$$\lambda(M_S) \;=\; \frac{1}{v^2}\,\left[(M_h^2)^{\rm MSSM} \;-\; (\Delta M_h^2)^{\rm SM}_{Q=M_S}\;\right]$$

+ standard EFT calculation below M_S

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+ standard EFT calculation below M_S

$(M_h^2)^{\rm MSSM}$ and $(\Delta M_h^2)^{\rm SM}_{Q=M_S}$ → fixed-order (SoftSUSY-style) full 1-loop

standard EFT calculation below M_S → NLL resummation of large logarithms

Comparing calculations in a simple test point: $M_S(M_S)$ = 10 TeV, $X_t(M_S)$ = 0, $\tan\beta$ = 20

Calculation	M_h [GeV]
Bagnaschi *et al.* [1407.4081]	123.6
SusyHD [1504.05200]	123.6
MhEFT [1508.00576]	123.8
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Partial 1-loop [QCD + $O(y_t^2)$]

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Partial 1-loop [QCD + $O(y_t^2)$]

Full 1-loop + 2-loop QCD

[Wait for Henning's talk!!!]

NOTE: the updates in FeynHiggs affect also the “standard” scenarios

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

Public code	M_h [GeV]
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NMSSMTools 4.7.1	124.6
FeynHiggs 2.11.2	129.8

(*Slide from SUSY2015*)

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

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

OS calculation of Higgs mass (using running m_t at NLO in loops) (FeynHiggs)

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OS calculation of Higgs mass (using running m_t at NNLO in loops) (FeynHiggs 2.11.3)

Including resummation plus EW effects in m_t (FeynHiggs 2.12.0)

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Same $\overline{DR}$ calculation of the Higgs mass, differences in determination of top Yukawa

ΔM_h estimated by FH 2.11.2 *to* 1.5 GeV ...

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

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: $H \to hh$, $H \to WW$, $H \to ZZ$, $A \to Zh$

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

This calls for the resummation of large logarithms in the EFT approach

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* :

$$\begin{aligned} \lambda_1 &= \lambda_2 = -(\lambda_3 + \lambda_4) = \frac{1}{4}(g^2 + g'^2) , \\ \lambda_4 &= -\frac{g^2}{2} , \quad \lambda_5 = \lambda_6 = \lambda_7 = 0 \end{aligned}$$

(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:

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

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

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

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

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

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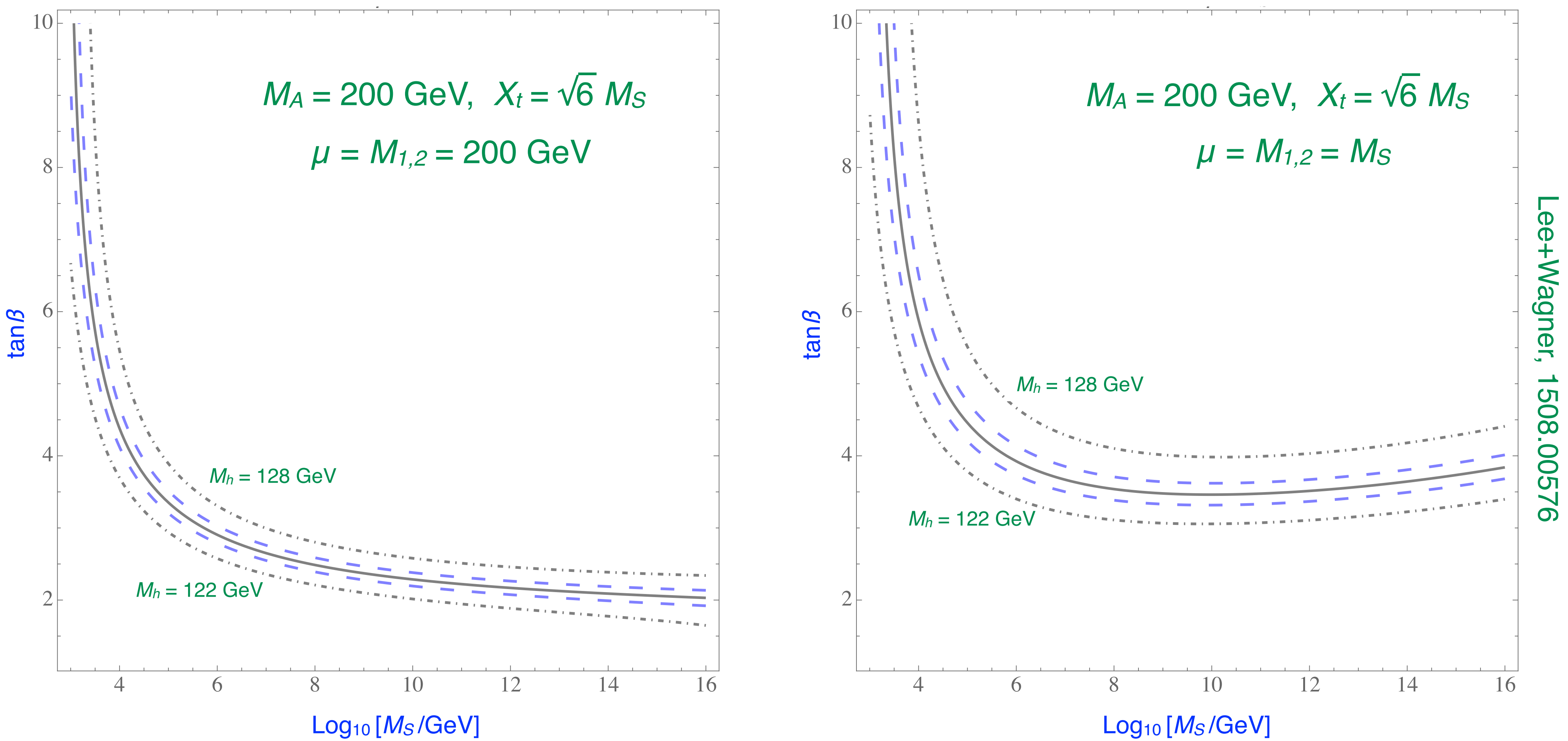
NEW from Lee & Wagner: MhEFT, a code for scenarios with light THDM / heavy SUSY

http://gabrlee.com/code/

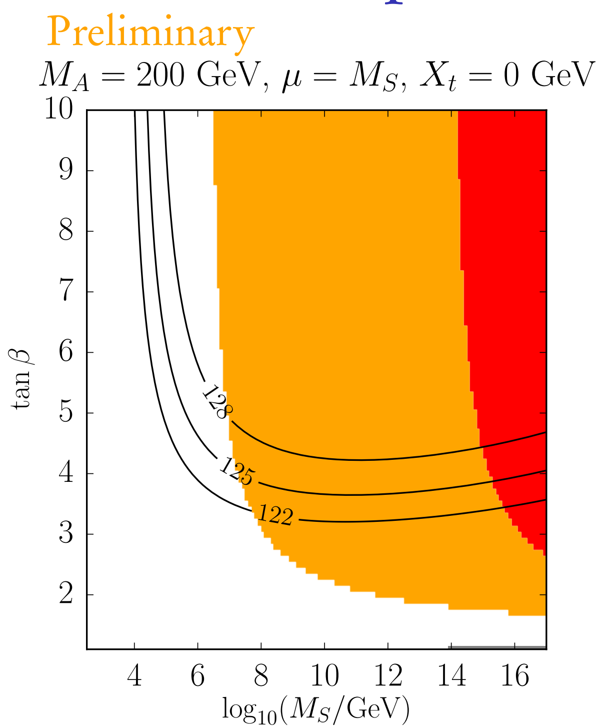
[Partial 1- / 2-loop thresholds at M_S ; 2-loop RGE for THDM (+EWinos); usual SM calculation below $Q = M_A$]

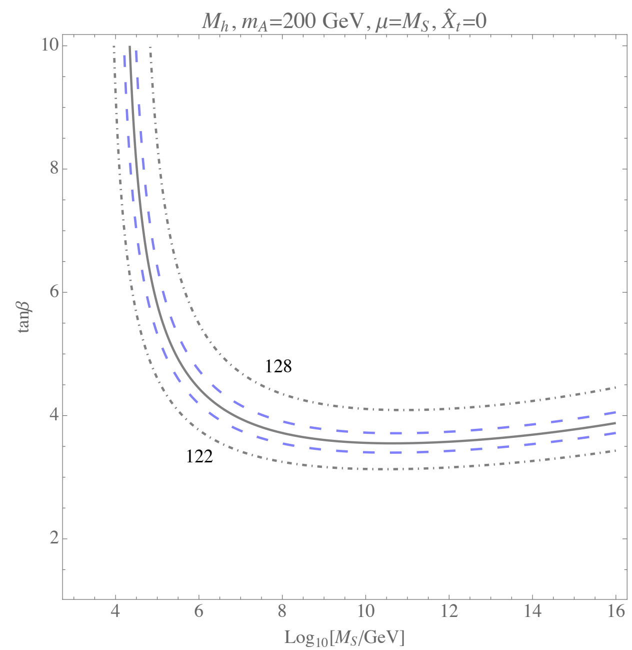


NOTE: M_h = 125 GeV cannot be reached at all for very low M_A and tanβ !

Light THDM / heavy SUSY also implemented in FlexibleSUSY

Comparison with Wagner et al





- Good qualitative agreement for the THDM. Looking forward for a more thorough comparison of the implementations.

[Slide from E. Bagnaschi's talk at KUTS4]

Used in [Bagnaschi *et al.*, 1512.07761] to study the vacuum stability of this scenario

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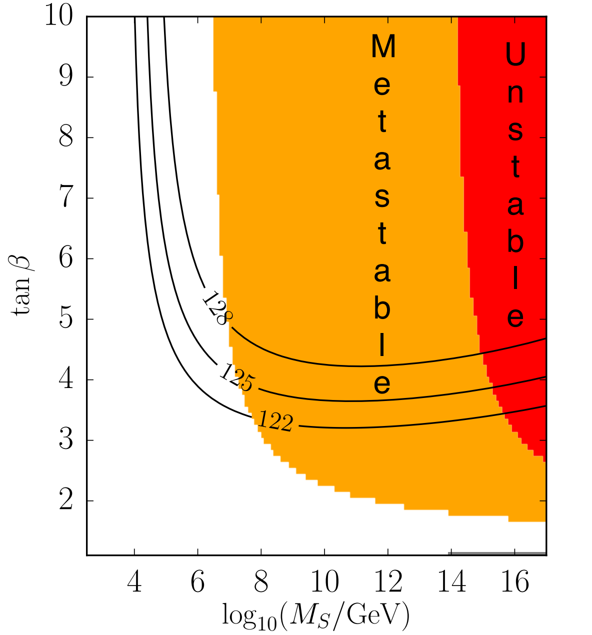

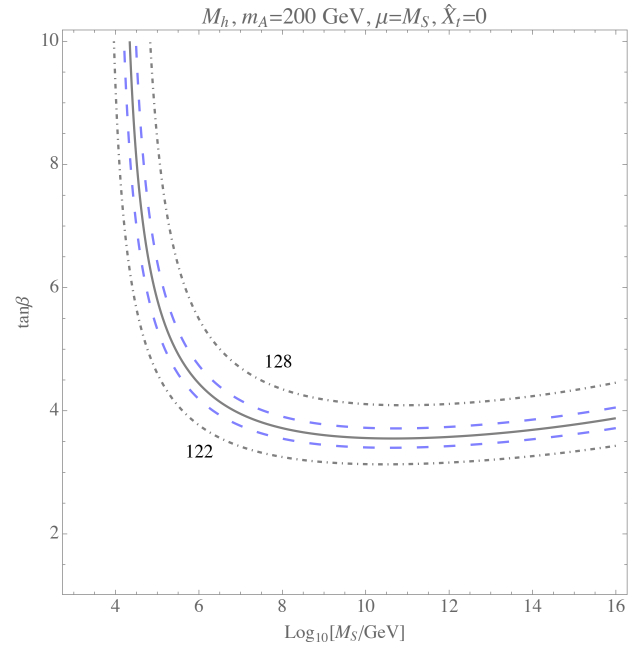

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Thoughts for the LHCHXSWG

- Proper EFT codes for light THDM / heavy SUSY now available, superseding the "low-tb-high" scenario (where M_h was computed by FeynHiggs with $M_A \approx M_S$) and showing the limitations of the "hMSSM" ($M_h = 125$ GeV not always possible)

- Even for $M_S \approx$ TeV, the predictions of FeynHiggs for M_h are a few GeV lower than when the MSSM benchmarks of [Carena et al., 1302.7033] were devised

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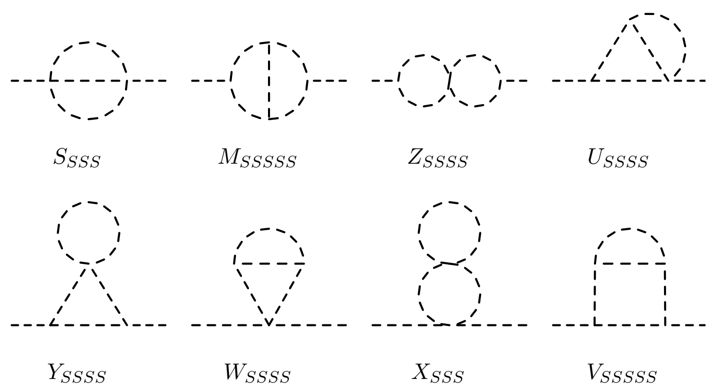
⟶ Time to update our benchmarks for the MSSM?

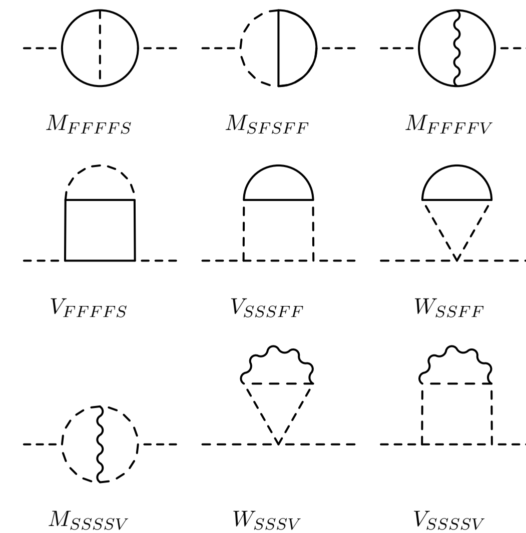
Beyond the MSSM

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":





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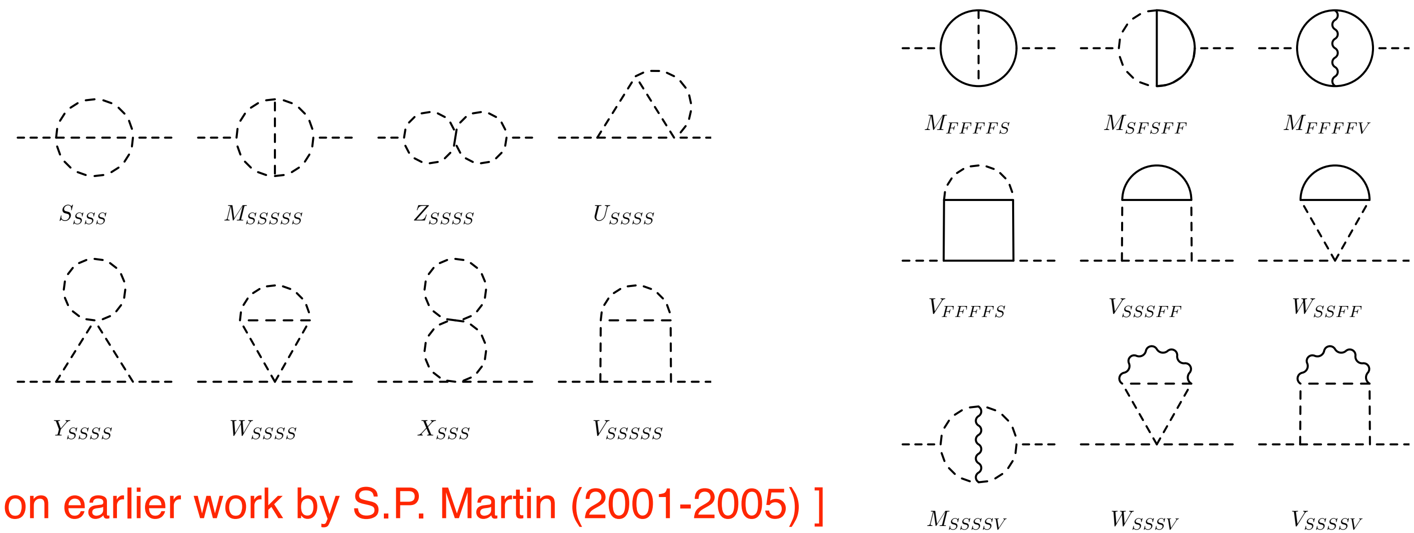

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Push another button and generate a publication... ;-)

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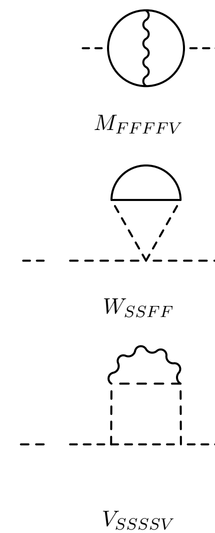
On the two–loop corrections to the Higgs mass in trilinear R–parity violation

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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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†
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(Received 19 December 2014; published 19 February 2015)

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Herbi K. Dreiner,[1,*] K
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531
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V_{SSSSV}

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

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575 and 1503.03098]

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The Higgs mass in the CP violating MSSM, NMSSM, and beyond

Mark D. Goodsell [1]**, Florian Staub** [2]

[1] Sorbonne Universités, UPMC Univ Paris 06, UMR 7589, LPTHE, F-75005, Paris, & CNRS, UMR 7589, LPTHE, F-75005, Paris, France
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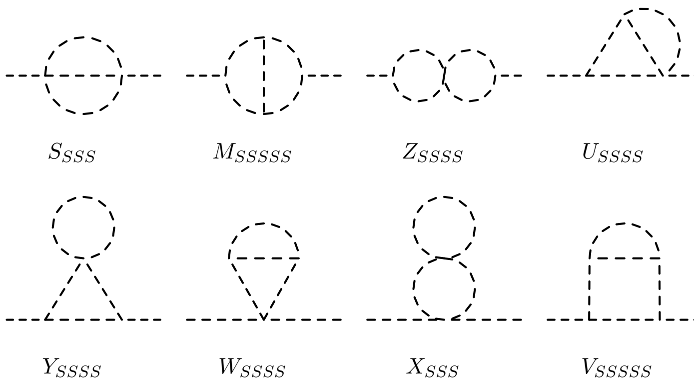

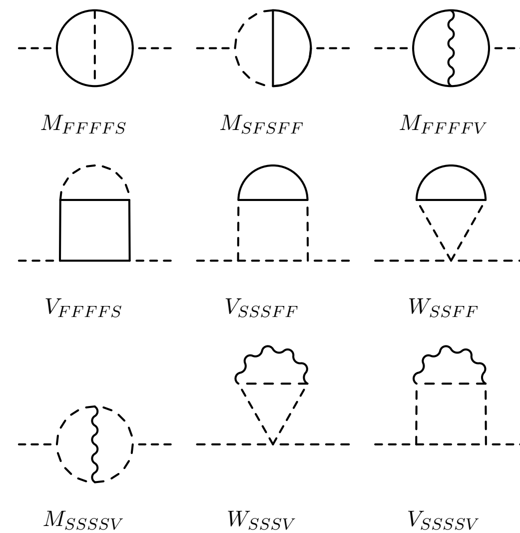

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The NMSSM calculation of the Higgs masses has almost caught up with the MSSM one

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Public code	M_h [GeV]	
	MSSM-like point	NMSSM-specific point
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SoftSUSY/ FlexibleSUSY	123.8	126.6
NMSSMTools	123.5	127.3
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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

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"MSSM approximation" : correct only (2,2) submatrix taking $\lambda, \kappa \to 0, \quad \lambda\langle S\rangle \to \mu$.

Extending FeynHiggs to the NMSSM

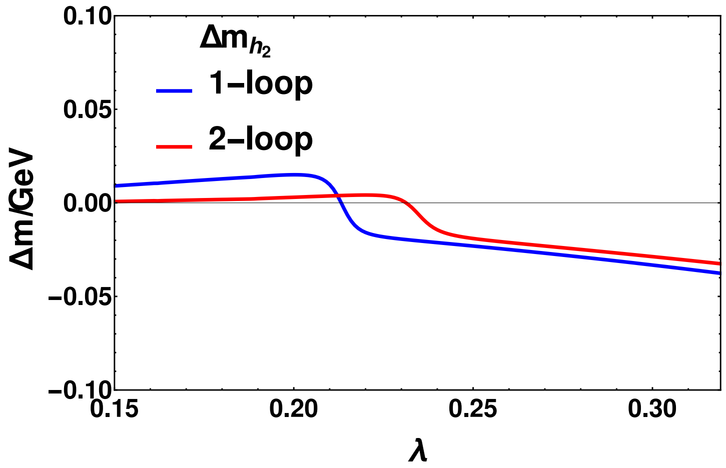
[P. Drechsel *et al.*, 1601.08100]

Full 1-loop NMSSM calculation + dominant 2-loop (OS, FH-style) in the MSSM approximation

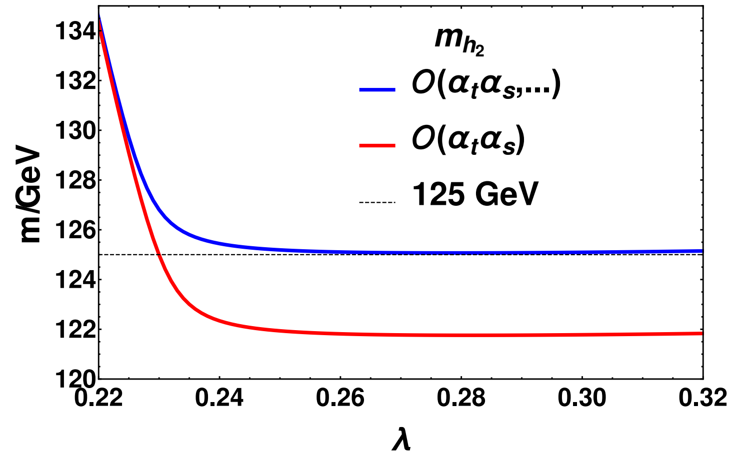
$(\alpha_i \alpha_s + \alpha_i \alpha_j)_{\text{MSSM}} \quad (i, j = t, b)$

Comparison with the OS calculation of NMSSMCalc [= full 1-loop + $\mathcal{O}(\alpha_t \alpha_s)$]

Good agreement including only $\mathcal{O}(\alpha_t \alpha_s)$ in both codes



~ 3 GeV discrepancy including also $\mathcal{O}(\alpha_t^2 + \ldots)$ in FeynHiggs



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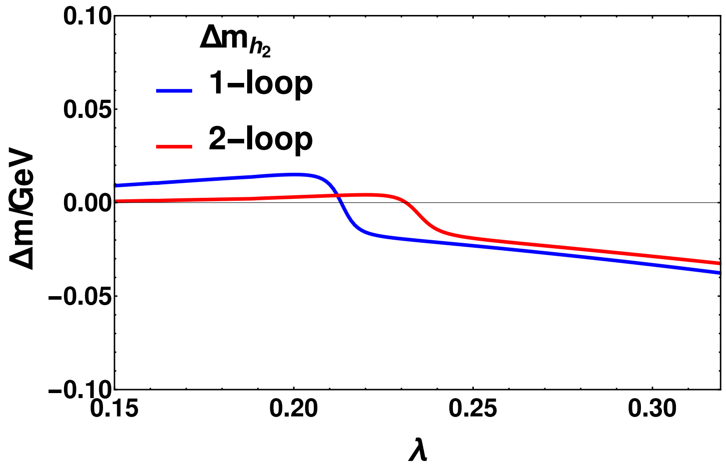
→ The MSSM approx. works fine for "perturbative" scenarios

$\lambda^2 + \kappa^2 \lesssim 0.5$



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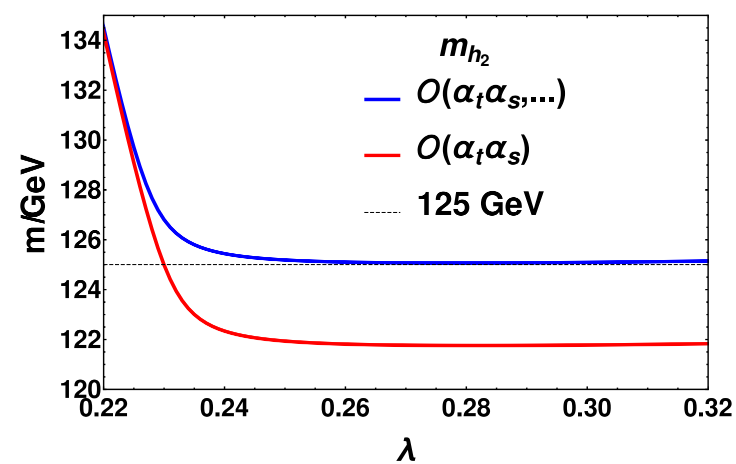

Thoughts for the LHCHXSWG (II)

- Tools for NMSSM Higgs mass spectrum, production and decays are maturing (see also Stefan's talk on SusHi ?)

- The NMSSM section of the YR4 lists a number of benchmark scenarios from different papers, each obtained with a different suite of codes

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→ How far are we from developing "official" ROOT files as for the MSSM?

Summary

- Scope of precise Higgs-mass calculations widened beyond “vanilla” MSSM
  - Effects of CP and Flavor violation
  - Heavy-SUSY scenarios (with or without light THDM)
  - NMSSM (now almost on par with MSSM)
  - Models beyond (N)MSSM – both automated and “old-fashioned” calculations

    [e.g. Dirac-gaugino models in J. Braathen, M. Goodsell & P.S., 1606.09213]

- Still a largish spread (–> theoretical uncertainty) in the predictions for the Higgs mass in the LHC-friendly scenario with stop masses ≈ 1 TeV and large mixing (however, the discrepancy between FeynHiggs and other codes is shrinking)
  - Work is under way to improve the EFT calculation in this “difficult” region

- Old codes have been updated and new ones have come to the market.
  Is it time to rethink the LHCHXSWG benchmark scenarios for the (N)MSSM?

Thank you!!!

Backup Material

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 $O(M_P)$?

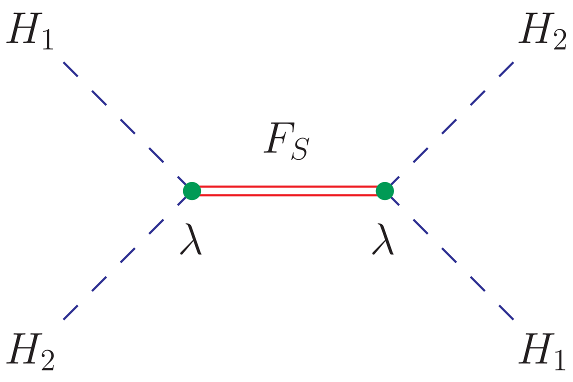
NMSSM solution: generate μ at the weak scale through the vev of a light singlet

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

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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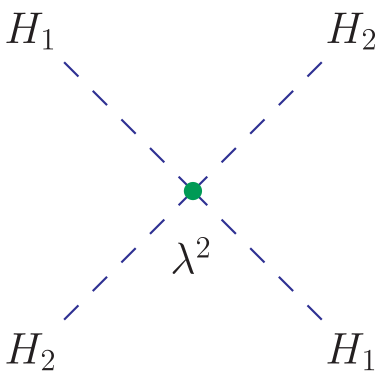

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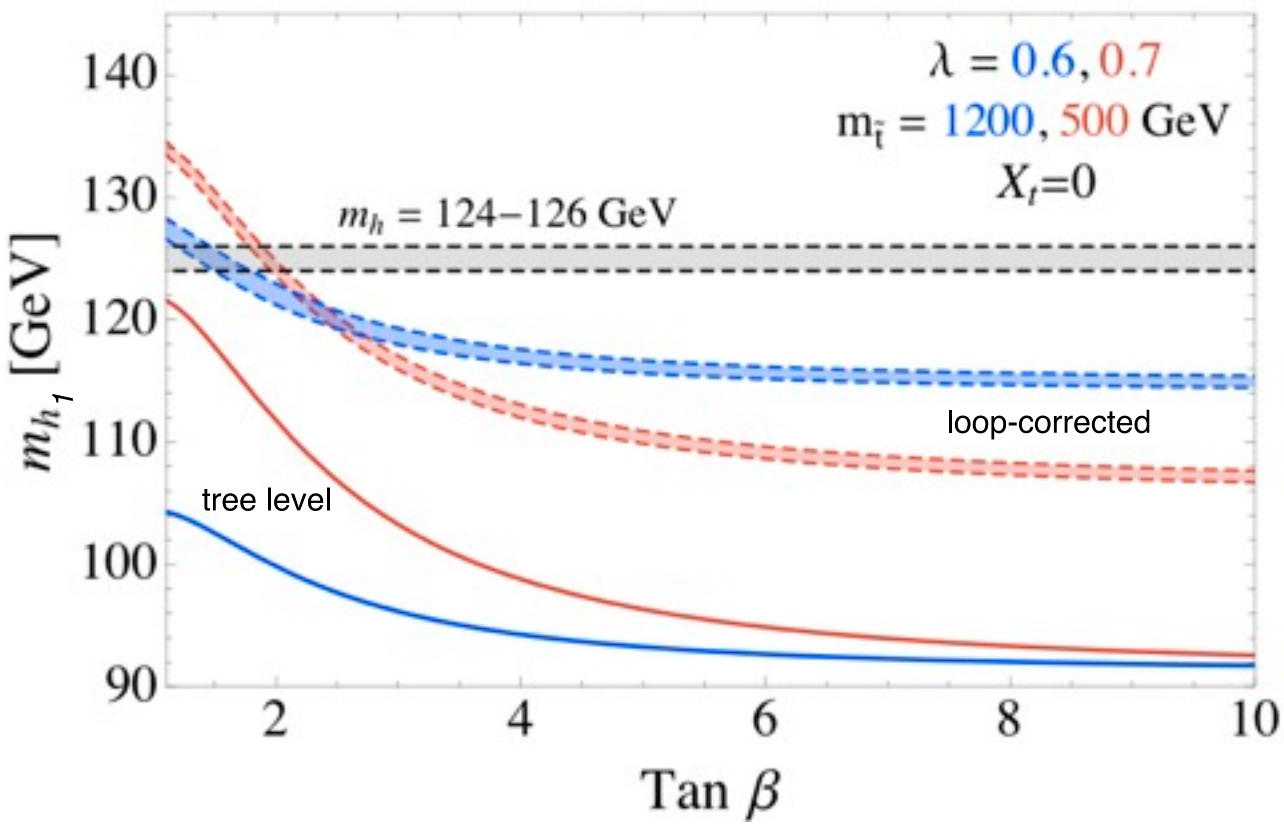
$$M_{h_1}^2 < M_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta$$

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”

[e.g., diphoton interpretations: Ellwanger+Hugonie, 1602.03344; Domingo *et al.*, 1602.07691; Badziak *et al.*, 1603.02203]

The "low-tb-high" scenario

[Sven Heinemeyer for the LHC-HXSWG]

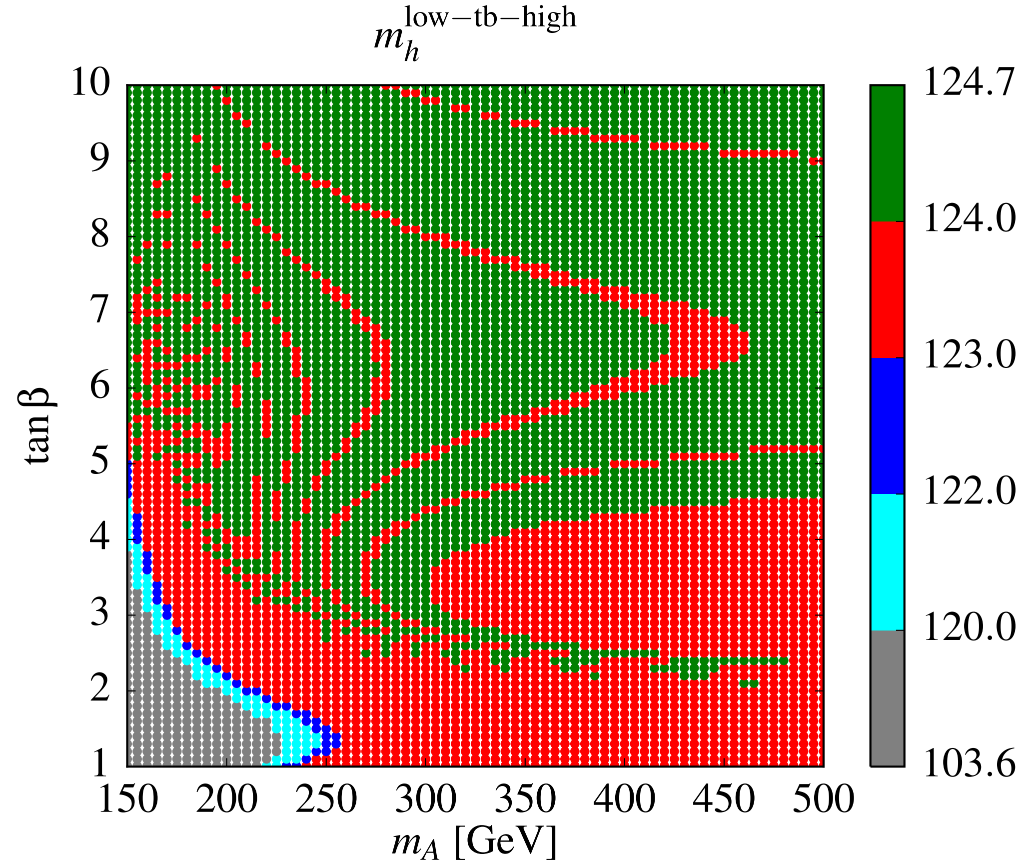
FeynHiggs > 2.10.0 includes a (simplified) NLL resummation

Low (m_A, *tanβ*) scenario with heavy sfermions & gluino, TeV-scale EW-inos:

$$m_{\tilde{f}} = M_3 = M_S, \quad 0 \leq X_t/M_S \leq 2,$$

$$M_2 = 2 \text{ TeV}, \quad \mu = 1.5 \text{ TeV}$$

M_S and X_t adjusted to get $m_h > 122$ GeV (allowing for a 3-GeV th. uncertainty)



NOTE: the resummation procedure in FeynHiggs does not account for low μ, $M_{1,2}$ and m_A

EFT comparison: The EFT calculation finds in general smaller m_h than FeynHiggs. Discrepancies about 3 GeV for *tanβ* > 5, even larger at lower *tanβ* (e.g., more than 10 GeV for *tanβ* < 2.5)

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 $\tan\beta$

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

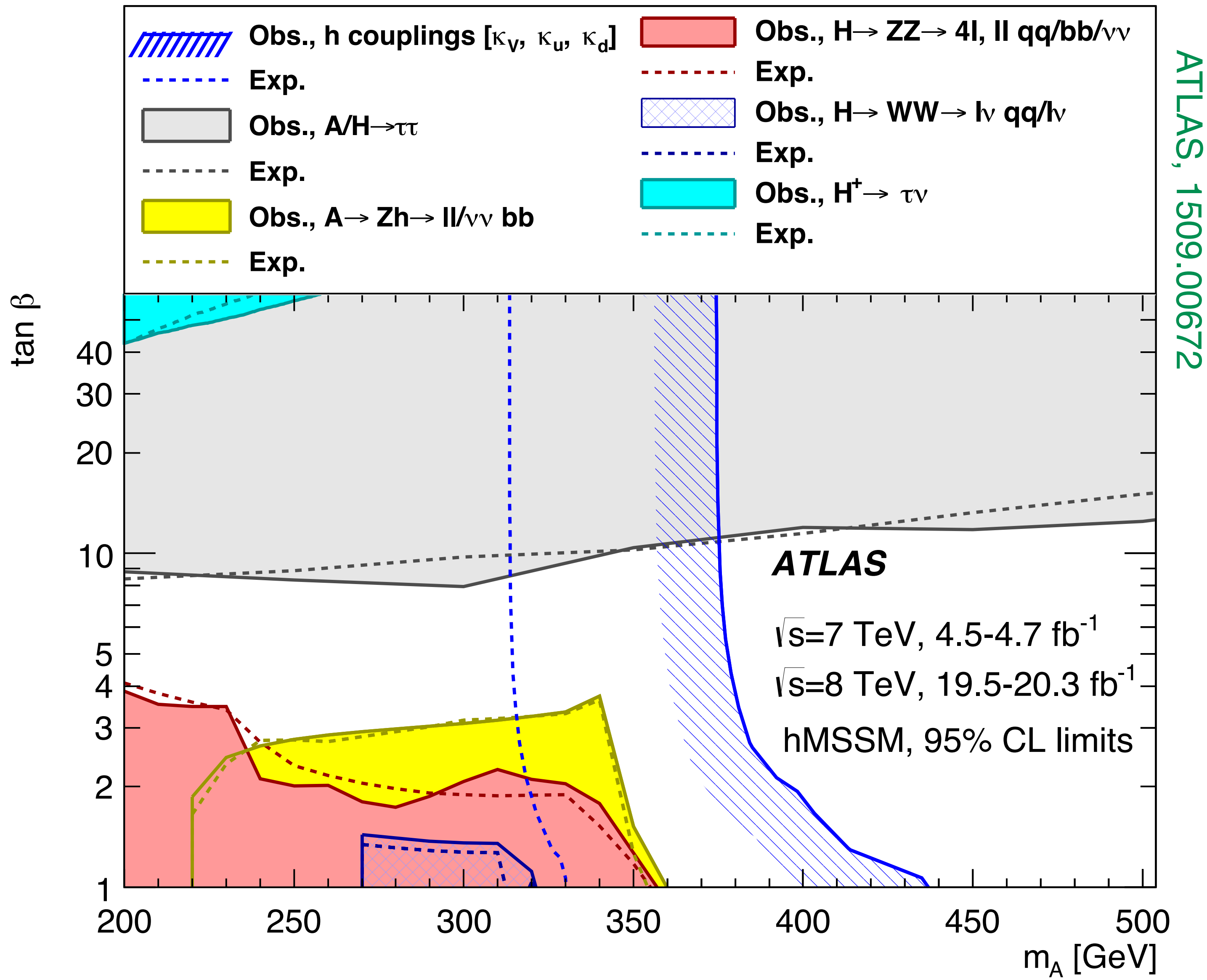
$$\tan\alpha \;=\; -\frac{(M_Z^2 + M_A^2) c_\beta s_\beta}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}$$

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



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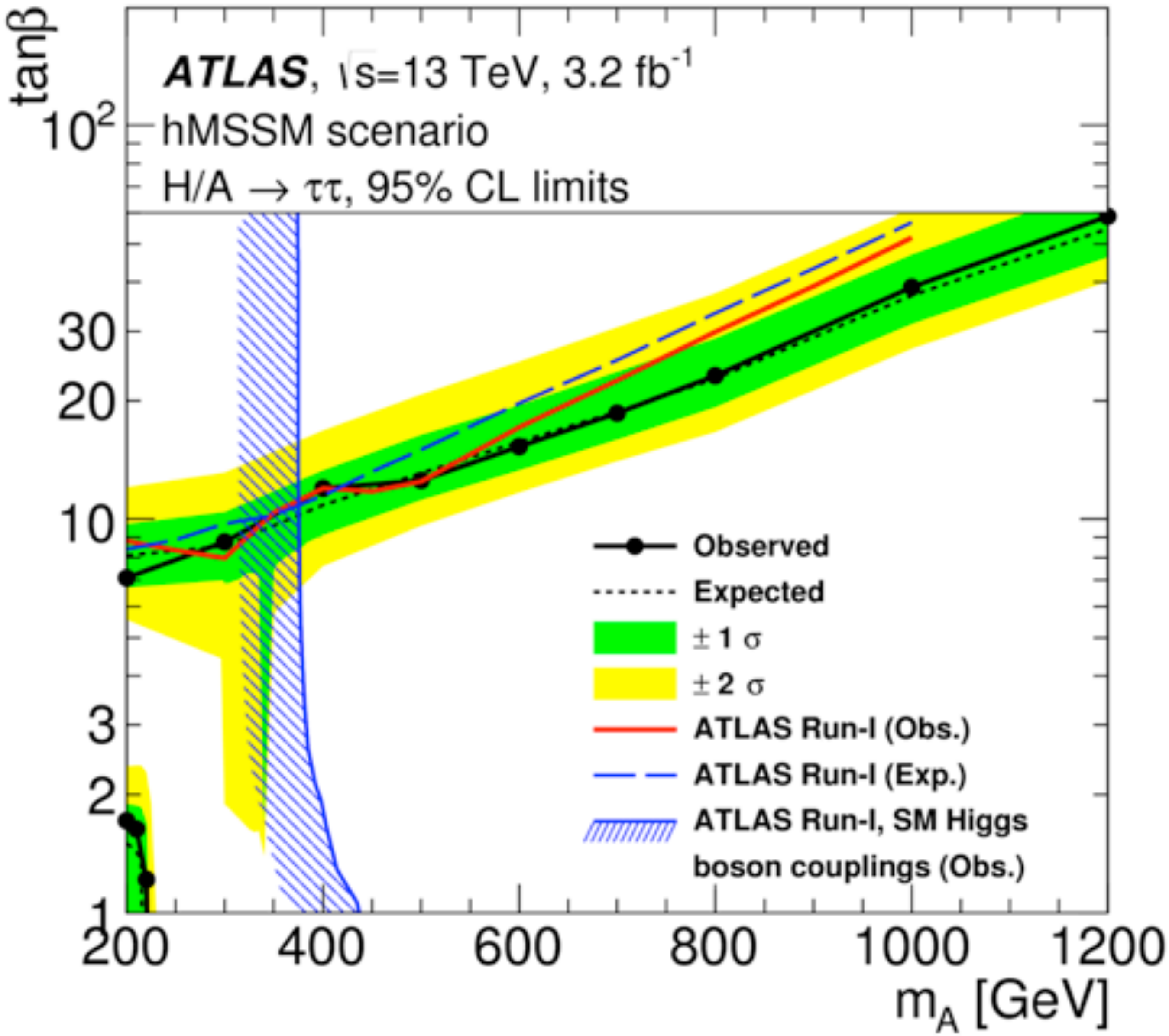

ATLAS, 1608.00890