Precision calculations for BSM physics

KITP Conference

Stress Testing the Standard Model

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Precision calculations ‘beyond the Standard model’ required for

- Electroweak precision observables:
  - – indirect sensitivity to non-standard particles
  - – virtual effects of BSM physics
- precision studies of Higgs particles:
  - – sensitivity to electroweak symmetry breaking
  - – standard versus non-standard scenarios
- direct search for non-standard particles:
  - – verification of possible signals
  - – identify origin / theoretical frame if produced
  - – specific models: determine or constrain parameters

systematic calculations in renormalizable extensions of the Standard Model

Outline

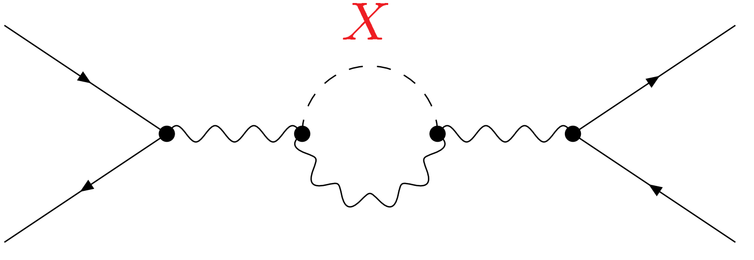
- EW precision observables with 2-doublet Higgs sector
  – general 2-doublet models
  – (minimal) supersymmetric standard model
- Higgs bosons in the MSSM
- SUSY particle production at the LHC
- Conclusions

- Electroweak precision observables have been a powerful tool since the days of LEP and SLC
- test compatibility of models with experimental precision data
- since LHC (2012): existence of a Higgs boson confirmed, mass M_H precisely measured
  - Standard Model precision observables uniquely determined
  - constraints on BSM model parameters more severe

electroweak precision observables

- μ lifetime: G_{F}
- Z observables: $M_Z, \Gamma_Z, \sin^2\theta_{\mathrm{eff}}, \ldots$
- LEP 2, Tevatron, LHC: $M_W, m_t \quad + \; M_H$
- low energy: $(g-2)_\mu$

exploit quantum structure



sensitivity to heavy internal particles (X)

X = Higgs boson(s), susy particles, . . .

$M_W - M_Z$ correlation (SM)

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)} \cdot (1 + \Delta r)$$

Δr : quantum correction

$$\Delta r = \Delta r(M_Z, M_W, m_t, M_H)$$

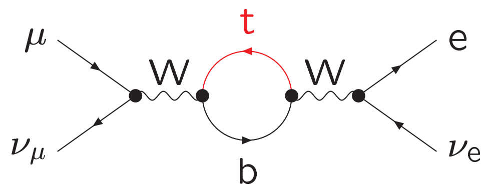
determines W mass

$$M_W = M_W(\alpha, G_F, M_Z, m_t, M_H)$$

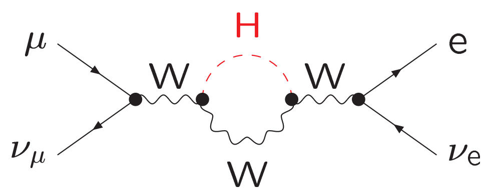
complete at 2-loop order α^2 and $\alpha\alpha_s$

1-loop SM examples

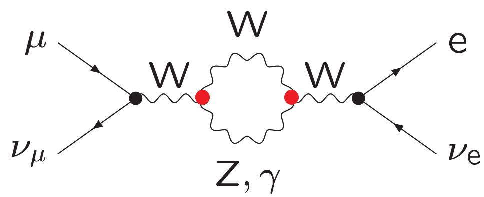
- top quark



- Higgs boson



- gauge-boson self-couplings



dominant contributions to Δr

$$\Delta r = \Delta\alpha - \frac{c_{\rm w}^2}{s_{\rm w}^2}\Delta\rho + \cdots$$

Large universal terms:

$$\Delta\alpha = \Pi^{\gamma}_{\rm ferm}(M_Z^2) - \Pi^{\gamma}_{\rm ferm}(0) = 0.05907 \pm 0.0001$$

$$\Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2} = 3\frac{G_F m_t^2}{8\pi^2\sqrt{2}} = 0.0094$$ *[one-loop]* $\sim \frac{m_t^2}{v^2} \sim \alpha_t$

beyond 2-loop order: $\Delta\rho^{(3)} + \Delta\rho^{(4)} \quad \sim \quad \alpha_s^2\alpha_t,\ \alpha_s\alpha_t^2,\ \alpha_t^3,\ \alpha_s^3\alpha_t$

reducible higher order terms from $\Delta\alpha$ and $\Delta\rho$ via

$$1 + \Delta r \quad \to \quad \frac{1}{\left(1-\Delta\alpha\right)\left(1+\frac{c_{\rm w}^2}{s_{\rm w}^2}\Delta\rho\right)+\cdots}$$

Consoli, WH, Jegerlehner

$O(\alpha\alpha_s)$ 2-loop calculations for Δr

Halzen, Kniehl

Djoaudi, Gambino

EW 2-loop calculations for Δr

Freitas, Hollik, Walter, Weiglein

Awramik, Czakon

Onishchenko, Veretin

Degrassi, Gambino, Giardino

universal terms at 3- and 4-loops (EW and QCD)

van der Bij, Chetyrkin, Faisst, Jikia, Seidensticker

Faisst, Kühn Seidensticker, Veretin

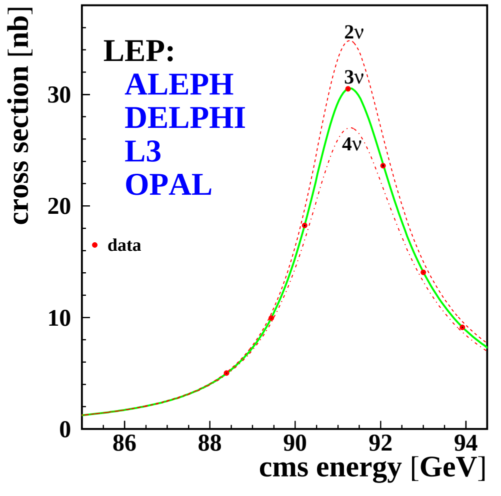
Boughezal, Tausk, van der Bij

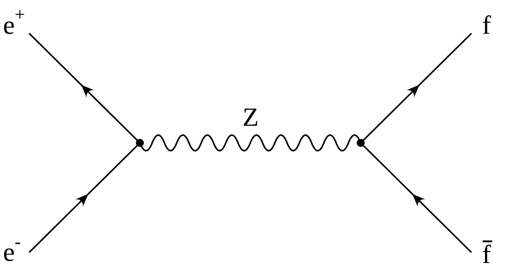
Schröder, Steinhauser

Chetyrkin, Faisst, Kühn *Chetyrkin, Faisst, Kühn, Maierhofer, Sturm*

Boughezal, Czakon

Z resonance





- effective Z boson couplings with higher-order $\Delta g_{V,A}$

$$g_V^f \to g_V^f + \Delta g_V^f, \qquad g_A^f \to g_A^f + \Delta g_A^f$$

- effective ew mixing angle (for $f = e$):

$$\sin^2\theta_{\text{eff}} = \frac{1}{4}\left(1 - \text{Re}\,\frac{g_V^e}{g_A^e}\right) = 1 - \frac{M_W^2}{M_Z^2} + \frac{M_W^2}{M_Z^2}\,\Delta\rho + \cdots$$

EW 2-loop calculations for $\sin^2\theta_{\rm eff}$

Awramik, Czakon, Freitas, Weiglein

Awramik, Czakon, Freitas

Hollik, Meier, Uccirati

$O(\alpha\alpha_s)$ 2-loop calculations (universal)

Halzen, Kniehl

Djoaudi, Gambino

universal terms at 3- and 4-loops (EW and QCD)

van der Bij, Chetyrkin, Faisst, Jikia, Seidensticker

Faisst, Kühn Seidensticker, Veretin

Boughezal, Tausk, van der Bij

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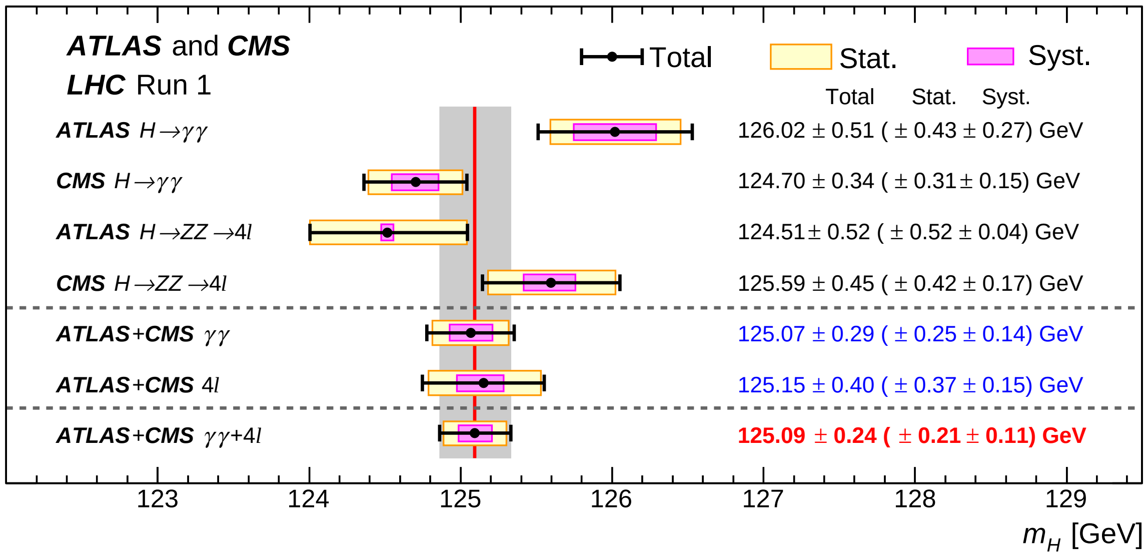


SM input completely determined $\Rightarrow$ precision observables uniquely predicted

	theo	exp
$\sin^2\theta_{\rm eff}$	$0.23152 \pm 0.00005 \pm 0.00005$	0.23153 ± 0.00016
M_W (GeV)	$80.361 \pm 0.006 \pm 0.004$	80.385 ± 0.015

Two-Doublet-Model Higgs Bosons

$$V(\Phi_1,\Phi_2) = \lambda_1(\Phi_1^+\Phi_1 - {v_1}^2)^2 + \lambda_2(\Phi_2^+\Phi_2 - {v_2}^2)^2 + \lambda_3[(\Phi_1^+\Phi_1 - {v_1}^2) + (\Phi_2^+\Phi_2 - {v_2}^2)]^2$$

$$+\lambda_4[(\Phi_1^+\Phi_1)(\Phi_2^+\Phi_2) - (\Phi_1^+\Phi_2)(\Phi_2^+\Phi_1)] + \lambda_5[Re(\Phi_1^+\Phi_2) - v_1 v_2]^2 + \lambda_6[Im(\Phi_1^+\Phi_2)]^2$$

mass eigenstates: $h^0, H^0, A^0, H^\pm$

free parameters: $m_h, m_H, m_A, m_{H^\pm},\quad \tan\beta = \frac{v_2}{v_1},\ \alpha \quad \lambda_5$

$$\lambda_1 = \frac{g^2}{16\cos^2\beta m_W^2}[m_H^2 + m_h^2 + (m_H^2 - m_h^2)\frac{\cos(2\alpha+\beta)}{\cos\beta}] + \lambda_3(-1+\tan^2\beta)$$

$$\lambda_2 = \frac{g^2}{16\sin^2\beta m_W^2}[m_H^2 + m_h^2 + (m_h^2 - m_H^2)\frac{\sin(2\alpha+\beta)}{\sin\beta}] + \lambda_3(-1+\cot^2\beta)$$

$$\lambda_4 = \frac{g^2 m_{H^\pm}^2}{2m_W^2} \quad , \quad \lambda_5 = \frac{g^2}{2m_W^2}\frac{\sin 2\alpha}{\sin 2\beta}(m_H^2 - m_h^2) - 4\lambda_3 \quad , \quad \lambda_6 = \frac{g^2 m_A^2}{2m_W^2}$$

vector-boson masses: $M_{W,Z} \sim v, \quad v = \sqrt{v_1^2 + v_2^2}$

coupling to vector bosons $V = W, Z$:

$$[h, H]VV = [\sin(\alpha - \beta), \cos(\alpha - \beta)] \cdot [\mathrm{SM}]$$

coupling to fermions, type I: $[h, H]ff = [\frac{\cos\alpha}{\sin\beta}, \frac{\sin\alpha}{\sin\beta}]\,[\mathrm{SM}]$

coupling to fermions, type II $(u \to \Phi_2,\ d \to \Phi_1)$:

$$[h, H]bb = [\frac{\sin\alpha}{\cos\beta}, \frac{\cos\alpha}{\cos\beta}][\mathrm{SM}], \quad [h, H]tt = [\frac{\cos\alpha}{\sin\beta}, \frac{\sin\alpha}{\sin\beta}][\mathrm{SM}]$$

$$A\,bb = \tan\beta\,[\mathrm{SM}] \qquad A\,tt = \cot\beta\,[\mathrm{SM}]$$

$\alpha = \beta - \frac{\pi}{2}$ $(\mathrm{or}\ \alpha = \beta)$: $h^0 (H^0)$ is SM-like

$H^0 (h^0), A^0$ with non-standard couplings

precision observables and two-Higgs doublet models – history

Bertolini 1986

WH 1986, 1988

Denner, Guth, WH, Kühn 1991

Chankowski, Krawczyk, Zochowski 1999

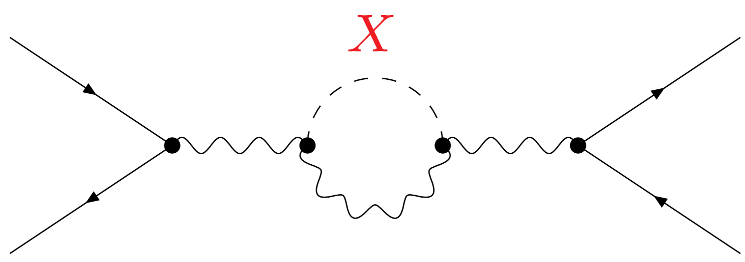
Solá, Lopez Val 2013

Stefan Hessenberger, Diploma Thesis, MPI and TUM,

ongoing PhD thesis

Hessenberger, WH arxiv:1606.xxxxx

precision observables with quantum loops



X = Higgs bosons

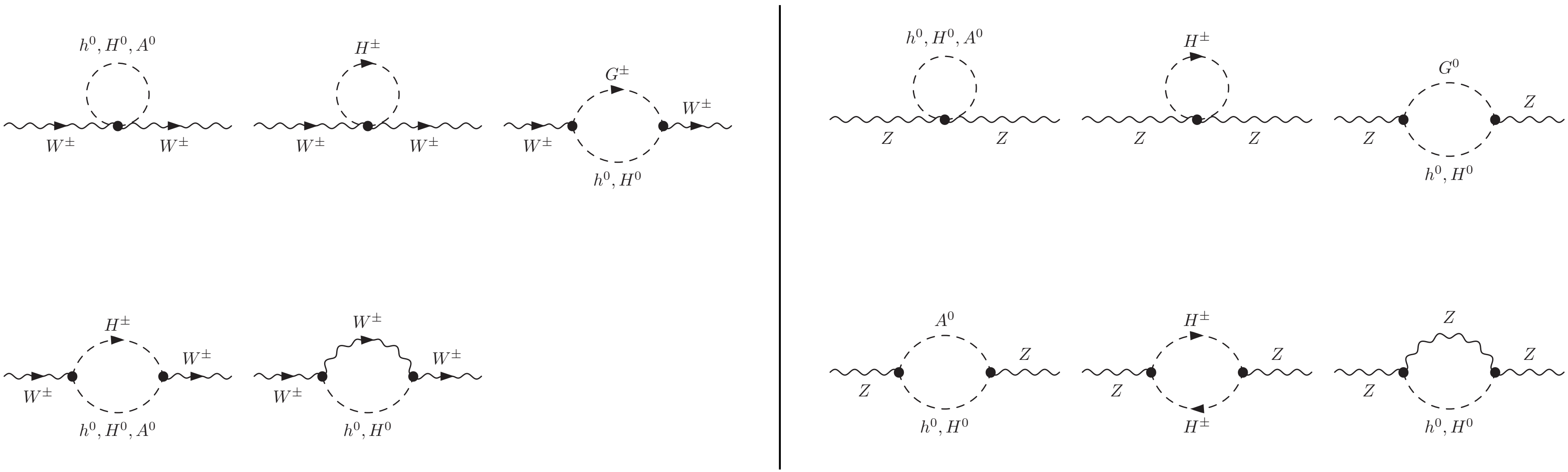
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)} \cdot [1 + \Delta r(m_t, X)]$$

determines W mass $M_W = M_W(\alpha, G_F, M_Z, m_t, X)$

similar: Z boson couplings $g_{V,A}(m_t, X)$, $\sin^2\theta_{\rm eff}(m_t, X)$

SM (full) + non-standard(1-loop + higher order terms)

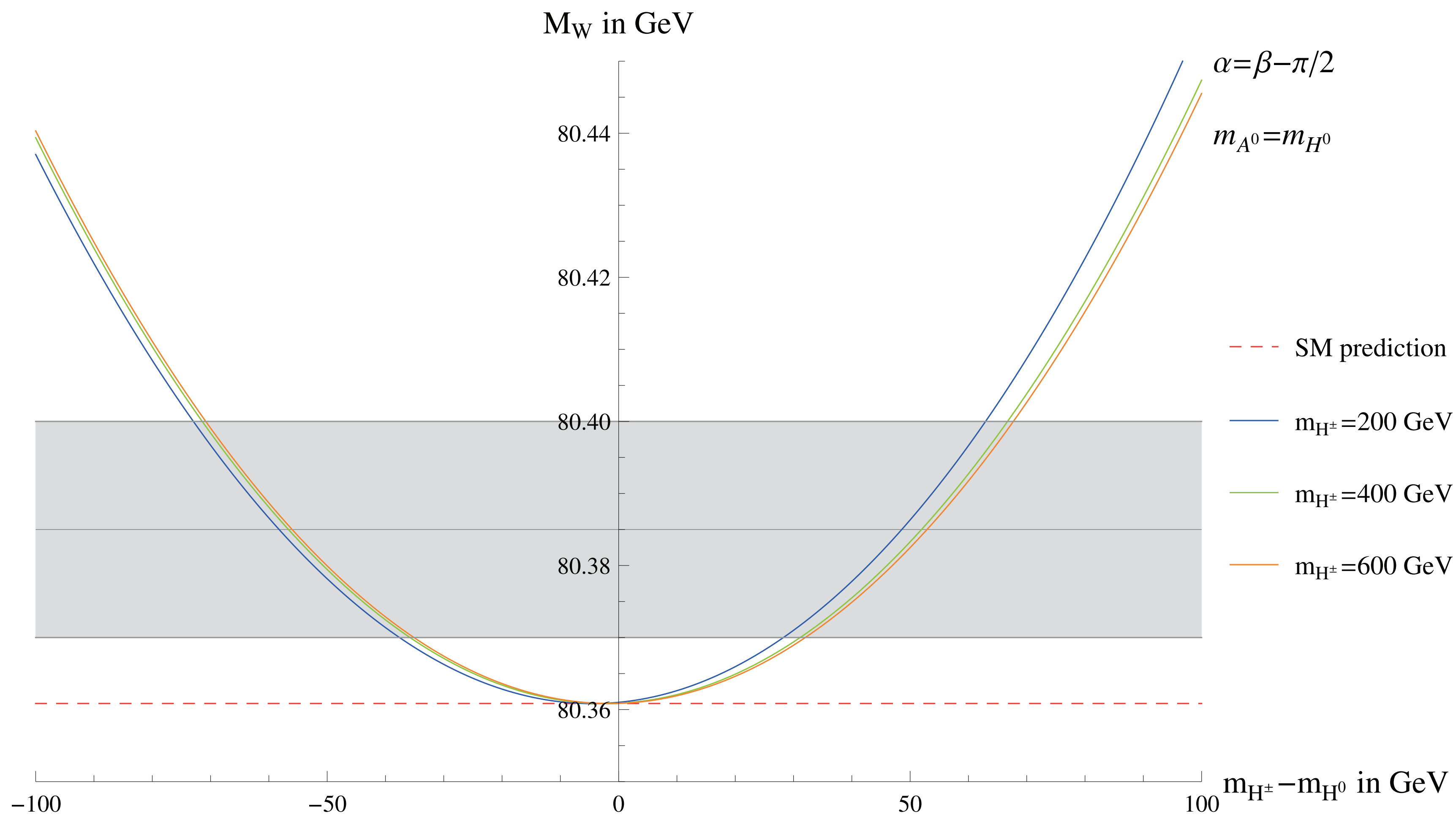
Higgs contributions to vector-boson self energies



alignment limit: $\alpha = \beta - \frac{\pi}{2}$

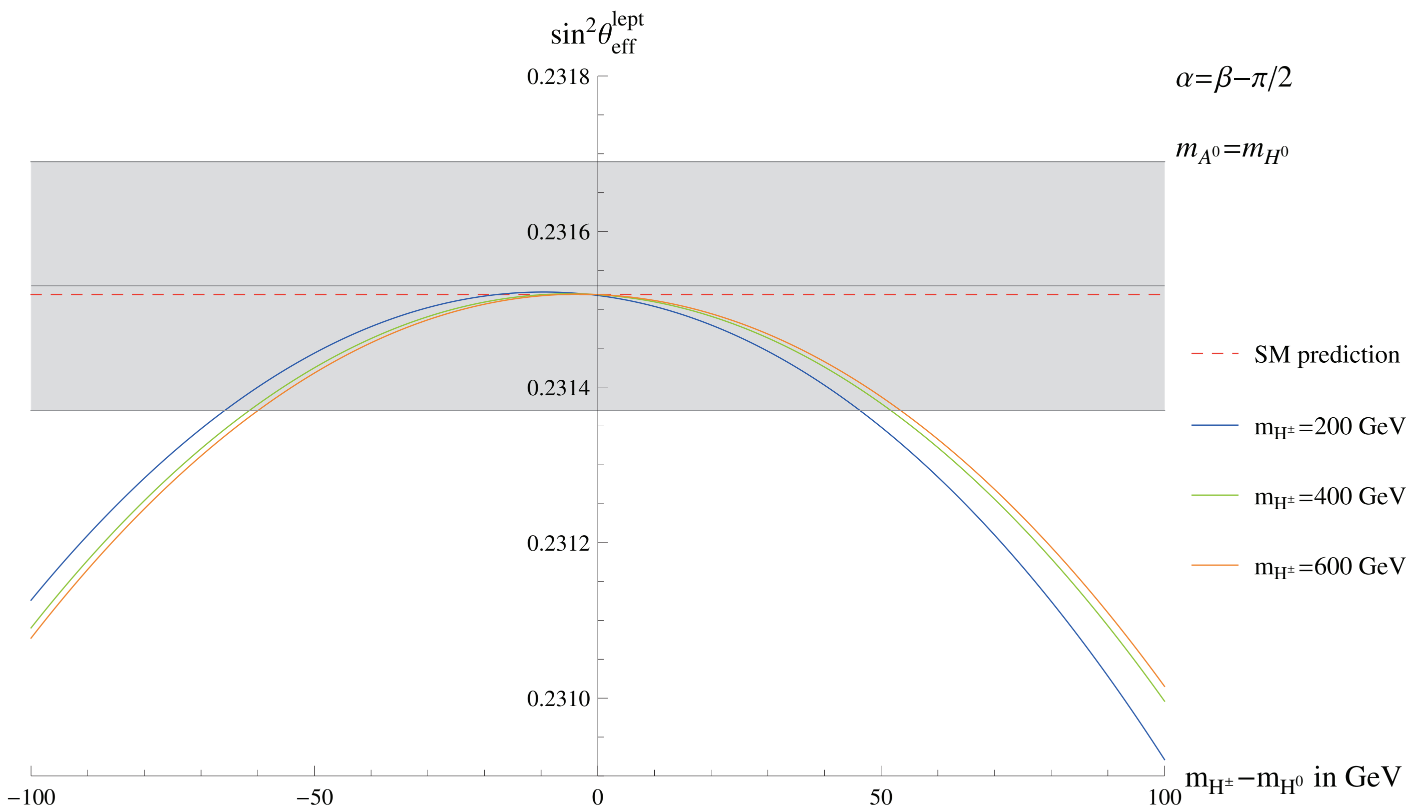
$$h^0 = H_{SM}, \quad m_{h^0} = 125\,\mathrm{GeV}$$

$H^0, A^0, H^\pm$ separated from SM part

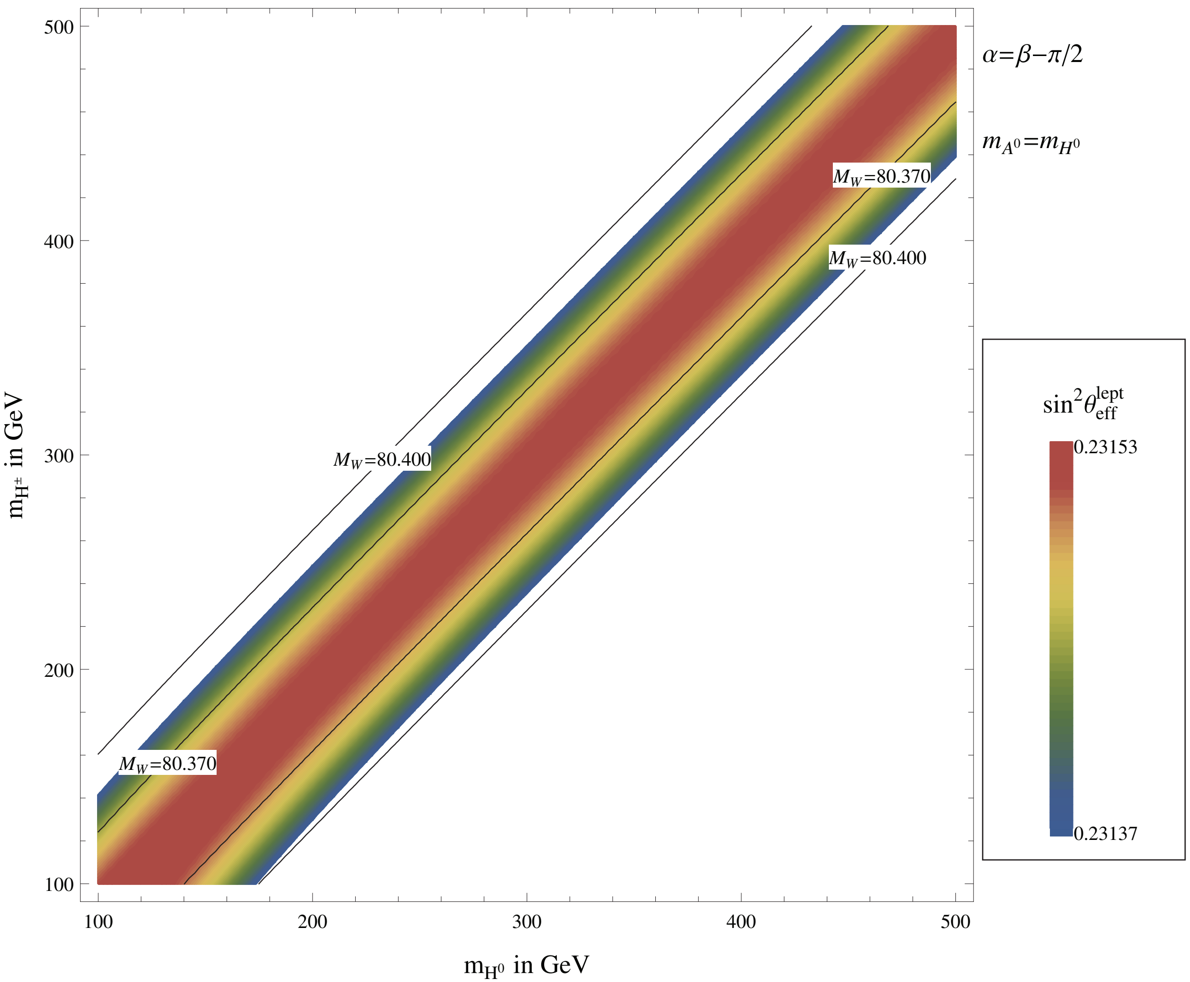


dominating term $\sim \Delta\rho$

$$\Delta r = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho + \cdots$$



$\sin^2\theta_{eff}^{lept}$
0.2318
0.2316
0.2314
0.2312
0.2310
$\alpha=\beta-\pi/2$
$m_{A^0}=m_{H^0}$
SM prediction
$m_{H^\pm}$=200 GeV
$m_{H^\pm}$=400 GeV
$m_{H^\pm}$=600 GeV
−100
−50
0
50
100
$m_{H^\pm}-m_{H^0}$ in GeV



$\alpha=\beta-\pi/2$
$m_{A^0}=m_{H^0}$
M_W=80.370
M_W=80.400
M_W=80.400
M_W=80.370
$\sin^2\theta_{\rm eff}^{\rm lept}$
0.23153
0.23137
$m_{H^\pm}$ in GeV
m_{H^0} in GeV
100
200
300
400
500

two-loop calculations for two-doublet models

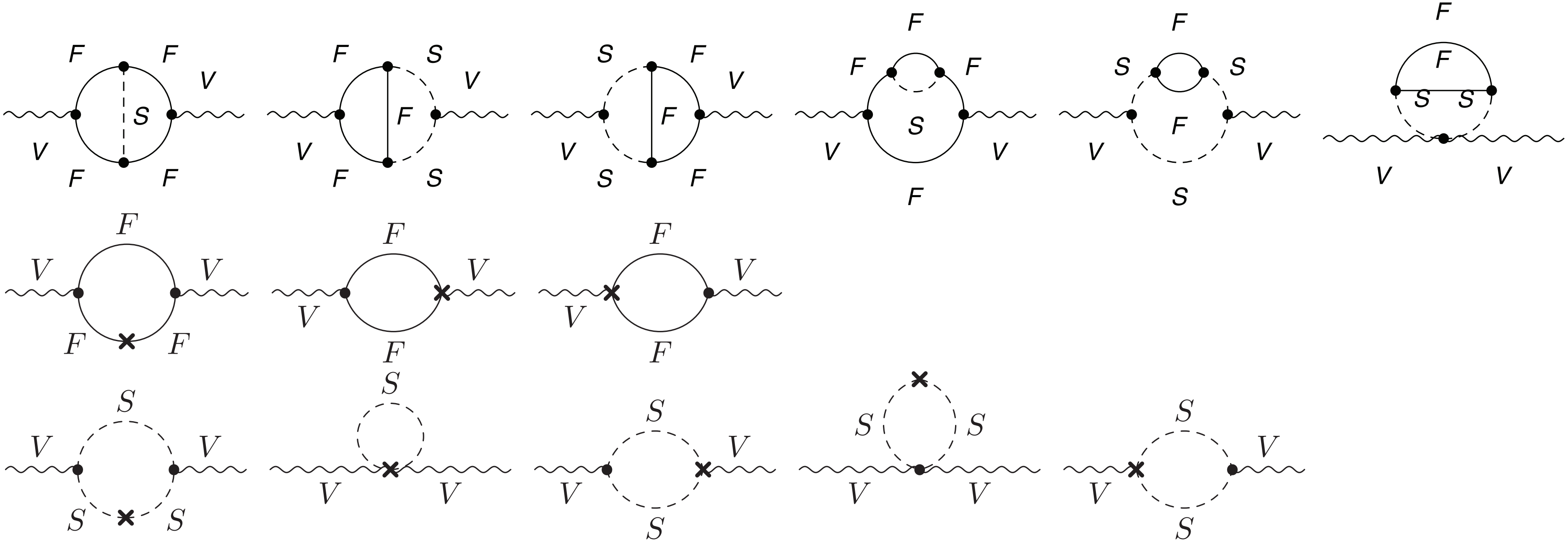
- dominating one-loop contributions from the ρ-parameter via $\Delta\rho$
  - ⋆ top-Yukawa contributions $\sim \alpha_t \sim \frac{m_t^2}{v^2}$
  - ⋆ Higgs-self-coupling contributions $\sim \frac{M_\phi^2}{v^2}\,, \quad \phi = H^0, A^0, H^\pm$
- most significant two-loop terms from the top-Yukawa and from the Higgs sector
- obtained in the "gaugeless limit"

$$g_1,\, g_2 \;\to\; 0$$
$$M_W \to 0, \quad M_Z \to 0, \quad \text{but} \quad c_\mathrm{w} = \frac{M_W}{M_Z} = \text{const}$$

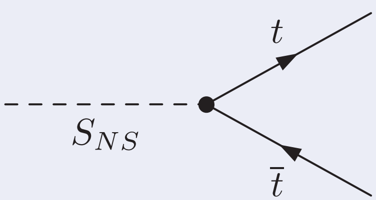
- new parameters $\tan\beta$ and λ_5 enter at the two-loop level
- NOTE: different from SUSY $m_{h^0} \neq 0$

  no gauge term, but independent Higgs-potential parameter

Top Yukawa contribution



Top Yukawa coupling

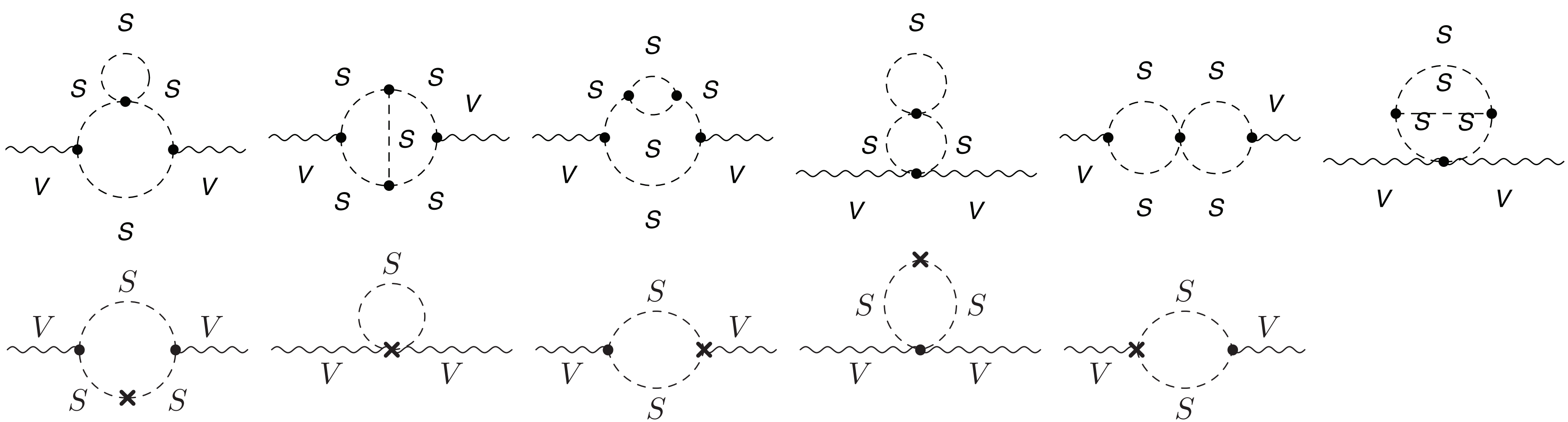


$$\propto \frac{m_t}{v t_\beta}$$

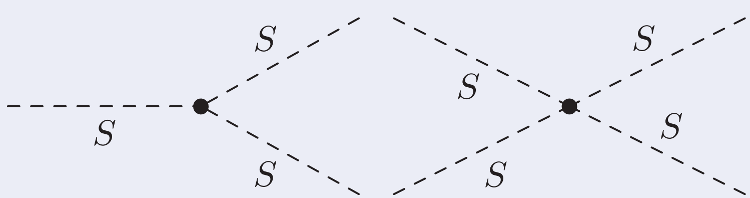
- neglect bottom quark mass: $m_b = 0$
- coupling proportional to large top mass
- coupling suppressed for large t_β
- $S_{NS} = H^0, A^0, H^\pm$

$\Rightarrow$ over 60 diagrams to calculate

Contribution from scalar self interaction



scalar self couplings



- contribution from the scalar self couplings $\Rightarrow$ contain t_β and λ_5
- $S = h^0, G^0, G^\pm, H^0, A^0, H^\pm$

$\Rightarrow$ over 200 diagrams to calculate

- **counterterms for 1-loop subrenormalization**

Vff / VSS couplings $$\delta s_{\rm w}^2 = c_{\rm w}^2\,\Delta\rho^{(1)}$$

top mass renormalization $$\delta m_t = \Sigma_t^{(1)}(\not{p} = m_t)$$

scalar mass renormalization $$\delta m_S^2 = \Sigma_S^{(1)}(m_S^2), \quad S = h, H, A, H^\pm$$

$$\delta m_G^2 = \frac{1}{v}\,\delta t_h^{(1)}, \quad G = G^0, G^\pm$$

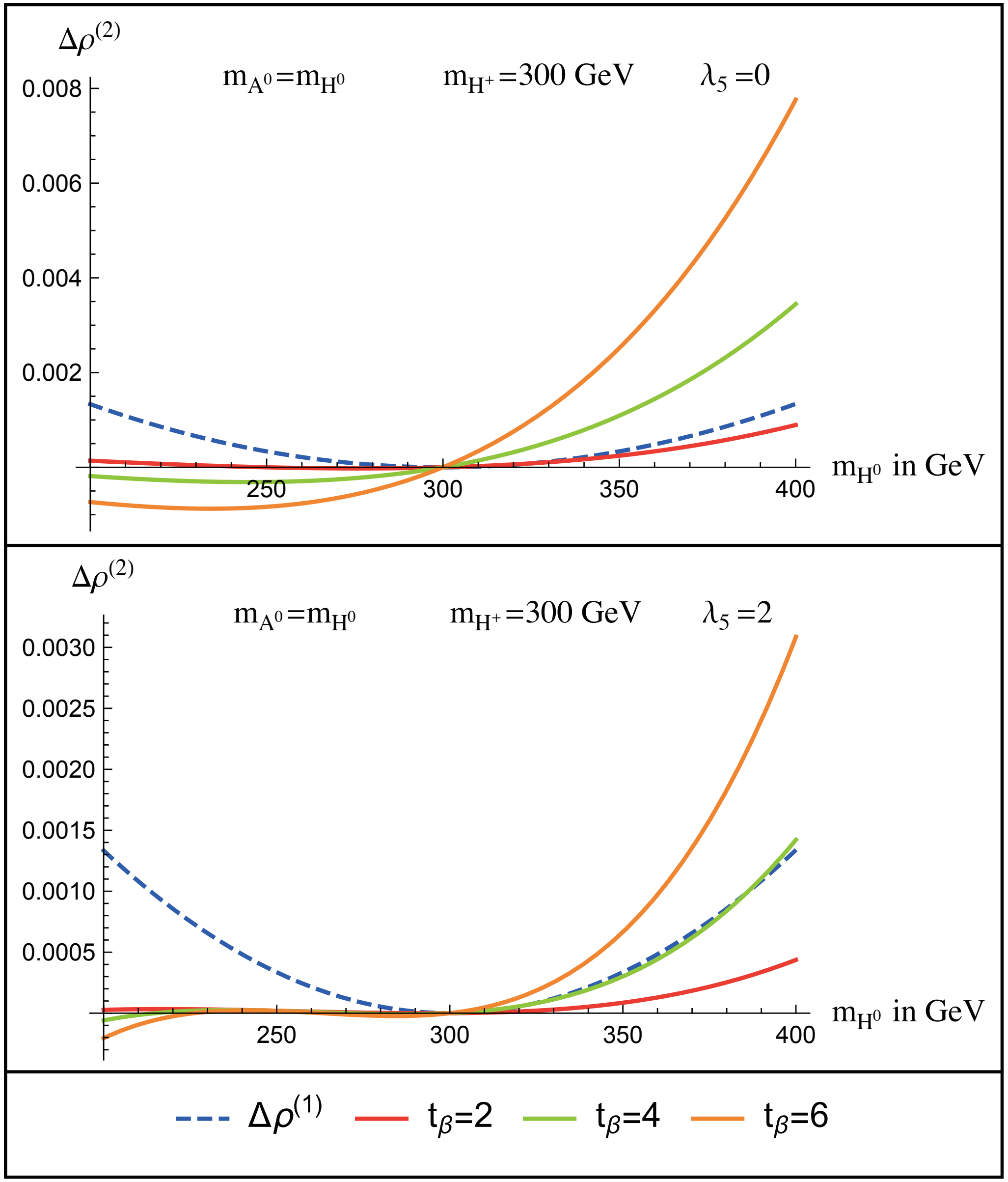
all with standard (t, h, G) and non-standard (H,A,$H^\pm$) contributions

- **Ward identity**

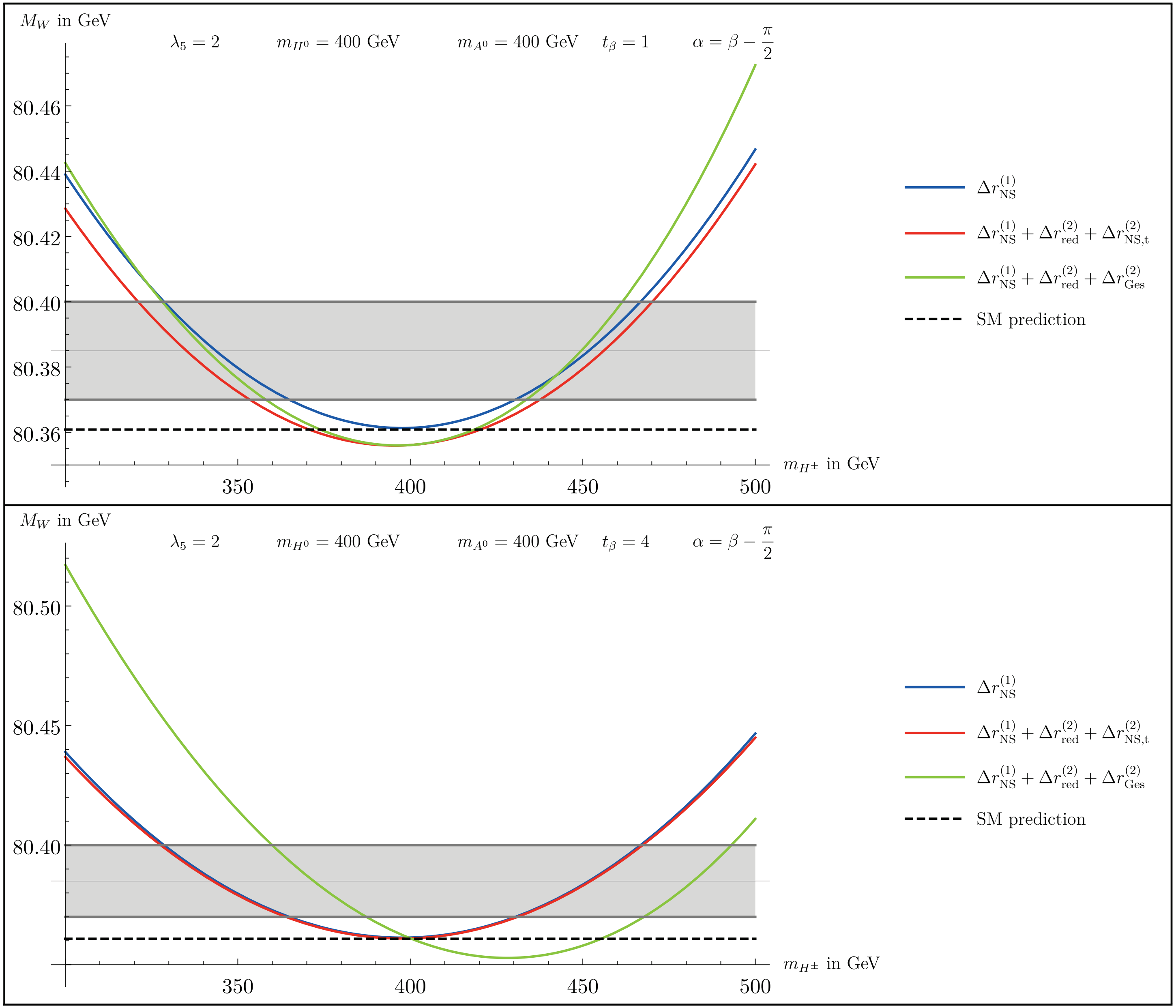
$$\Delta\rho = \Sigma'_{G^\pm}(0) - \Sigma'_{G^0}(0)$$

Barbieri et al. ’93 / Fleischer, Tarasov, Jegerlehner ’95

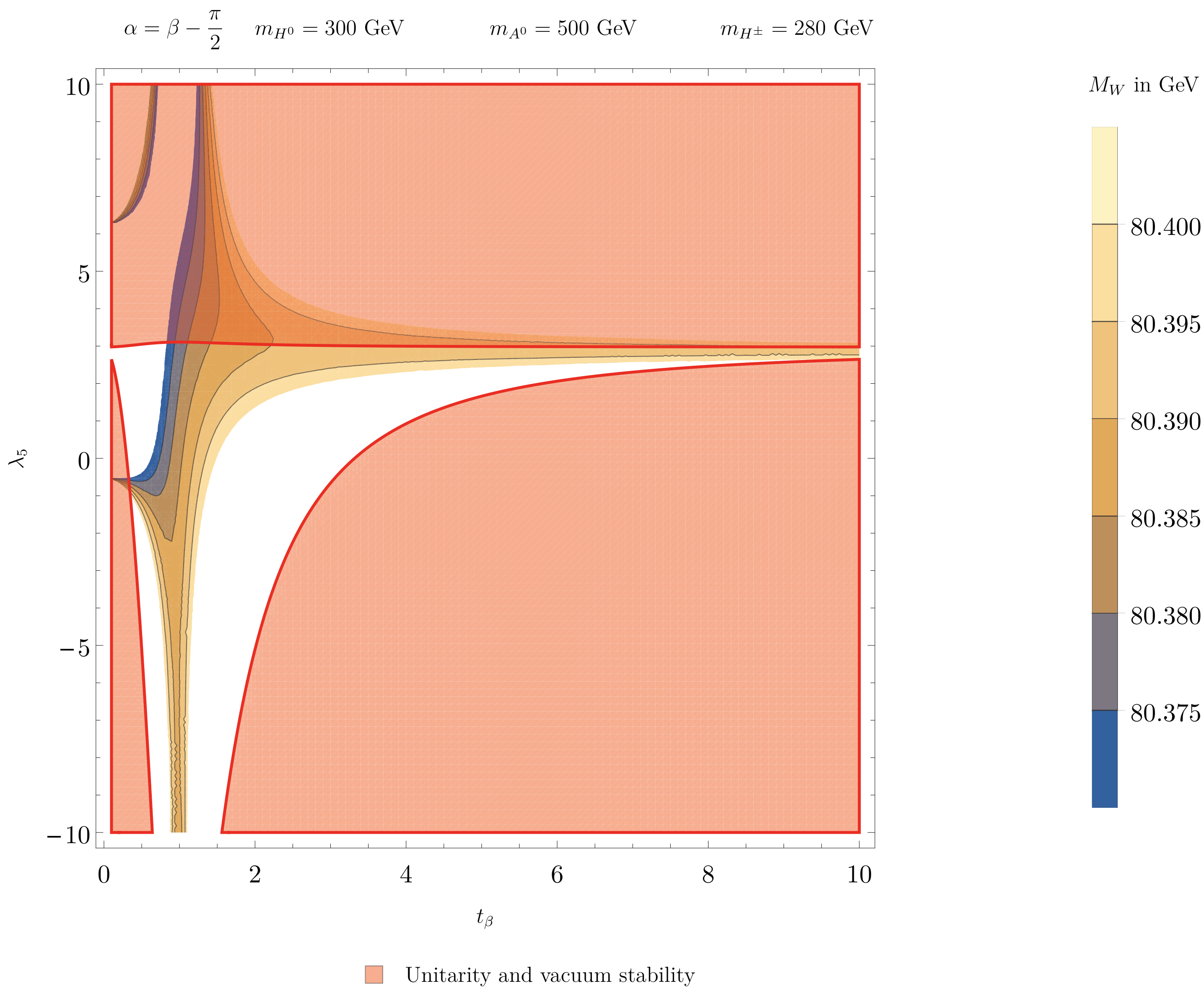
used for checking the results



$$\delta(\Delta\rho) = 10^{-4} \quad \Rightarrow \quad \delta M_W \simeq 6\,\text{MeV}$$

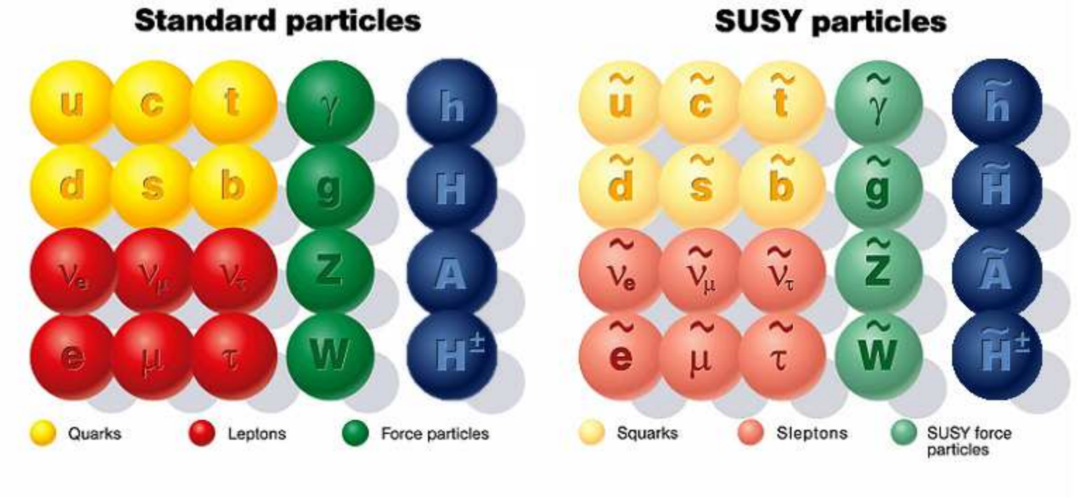


M_W in GeV
$\lambda_5 = 2$ $m_{H^0} = 400$ GeV $m_{A^0} = 400$ GeV $t_\beta = 1$ $\alpha = \beta - \frac{\pi}{2}$
80.46
80.44
80.42
80.40
80.38
80.36
350
400
450
500
$m_{H^\pm}$ in GeV
$\Delta r^{(1)}_{\text{NS}}$
$\Delta r^{(1)}_{\text{NS}} + \Delta r^{(2)}_{\text{red}} + \Delta r^{(2)}_{\text{NS,t}}$
$\Delta r^{(1)}_{\text{NS}} + \Delta r^{(2)}_{\text{red}} + \Delta r^{(2)}_{\text{Ges}}$
SM prediction
M_W in GeV
$\lambda_5 = 2$ $m_{H^0} = 400$ GeV $m_{A^0} = 400$ GeV $t_\beta = 4$ $\alpha = \beta - \frac{\pi}{2}$
80.50
80.45
80.40
350
400
450
500
$m_{H^\pm}$ in GeV
$\Delta r^{(1)}_{\text{NS}}$
$\Delta r^{(1)}_{\text{NS}} + \Delta r^{(2)}_{\text{red}} + \Delta r^{(2)}_{\text{NS,t}}$
$\Delta r^{(1)}_{\text{NS}} + \Delta r^{(2)}_{\text{red}} + \Delta r^{(2)}_{\text{Ges}}$
SM prediction



$\alpha = \beta - \frac{\pi}{2}$ $m_{H^0} = 300$ GeV $m_{A^0} = 500$ GeV $m_{H^\pm} = 280$ GeV
M_W in GeV
80.400
80.395
80.390
80.385
80.380
80.375
λ_5
t_β
10
5
0
−5
−10
0
2
4
6
8
10
Unitarity and vacuum stability

Supersymmetry



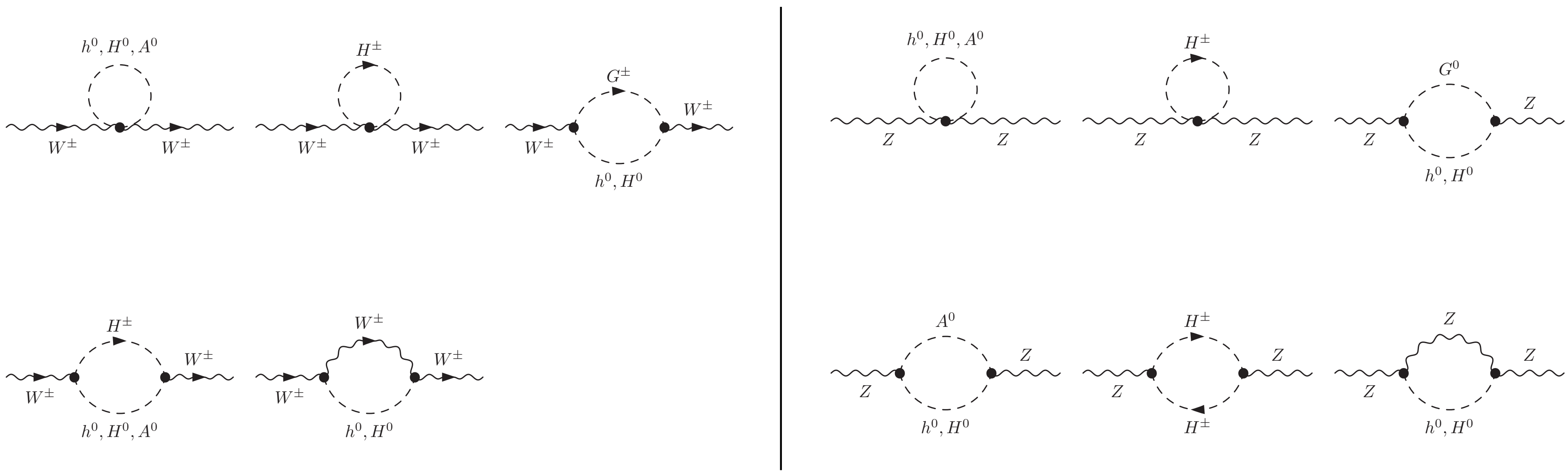
MSSM non-standard loop contributions from:

- charginos and neutralinos $\chi^{\pm}_{1,2}$, $\chi^{0}_{1,2,3,4}$
- sfermions $\tilde{f}_L,\ \tilde{f}_R\ \rightarrow\ \tilde{f}_1,\ \tilde{f}_2$
- Higgs bosons: $h^0,\ H^0,\ \ A^0,\ H^{\pm},$ input: $M_A, \tan\beta = \frac{v_2}{v_1}$

  constraint: $M_h\,(\text{or}\ M_H)\ =\ 125\,\text{GeV}$

vector-boson self energies:

Higgs contributions like THDM , but with constraints on masses and couplings



- Higgs masses from FEYNHIGGS
  (including higher-order contributions)

- Higgs couplings as effective couplings

- \+ loops with charginos, neutralinos, sleptons, squarks in
  self-energies, vertex corrections, box diagrams

long-standing activities in precision observables in SUSY

Grifols, Solá 1985

Chankowski, Dabelstein, WH, Moesle, Pokorski, Rosiek 1994

Garcia, Solá 1994

Pierce, Bagger, Matchev, Zhang 1997

Djouadi, Gambino, Heinemeyer, WH, Weiglein 1997, 1998

two-loop $\Delta\rho^{\rm susy} \sim \alpha_s \alpha_t$

Hastier, Heinemeyer, Stöckinger, Weiglein 2005

two-loop $\Delta\rho^{\rm susy} \sim \alpha_t^2, \alpha_t\alpha_b, \alpha_b^2$

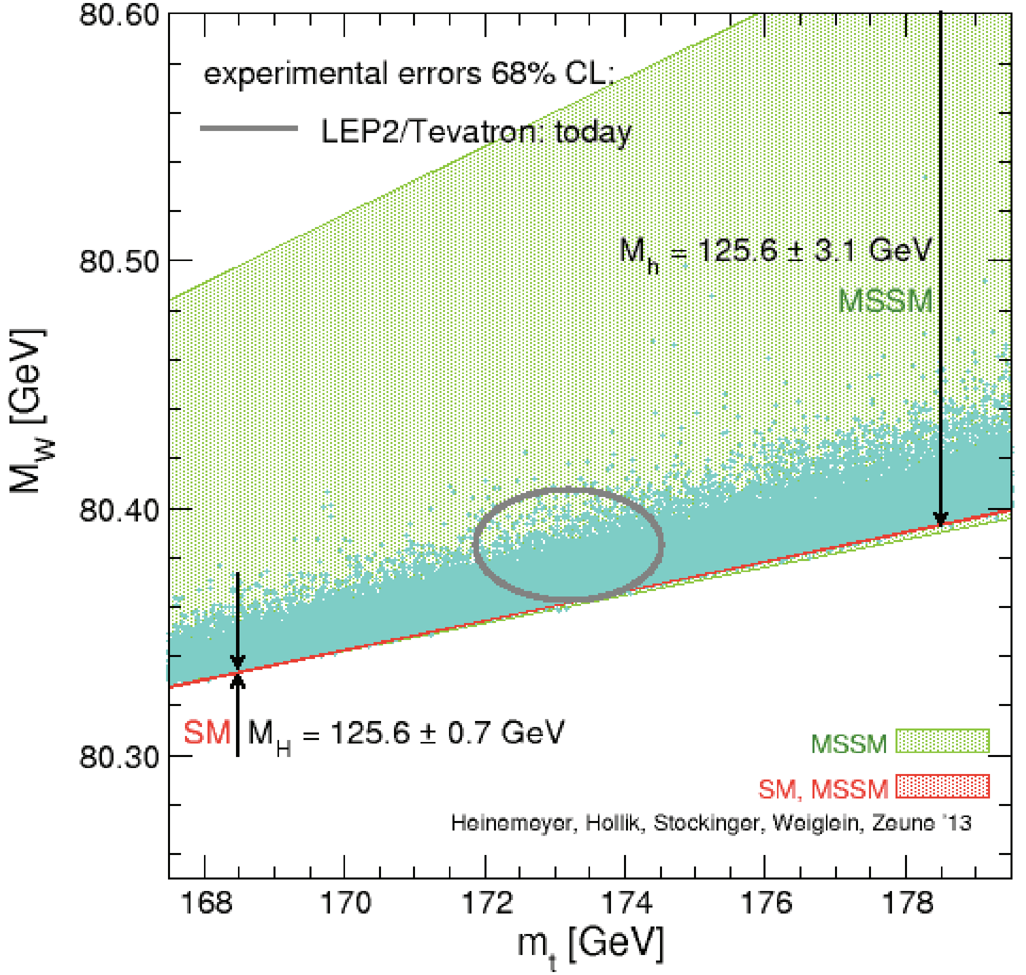
Heinemeyer, WH, Stöckinger, Weber, Weiglein 2006

Heinemeyer, WH, Weber, Weiglein 2008

Heinemeyer, WH, Weiglein, Zeune 2013

M_W *and* Δr *in view of LHC results*

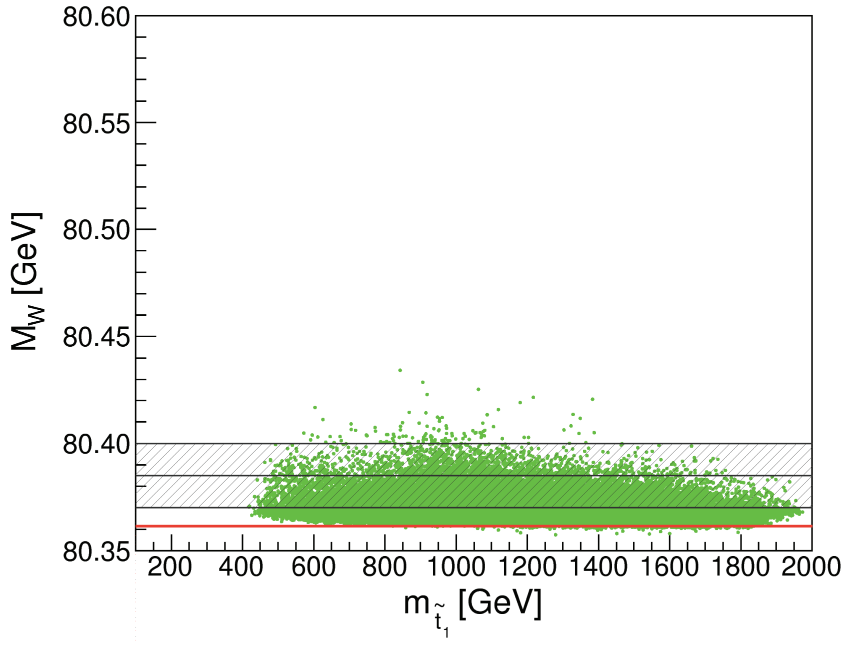
W mass with SUSY quantum loops

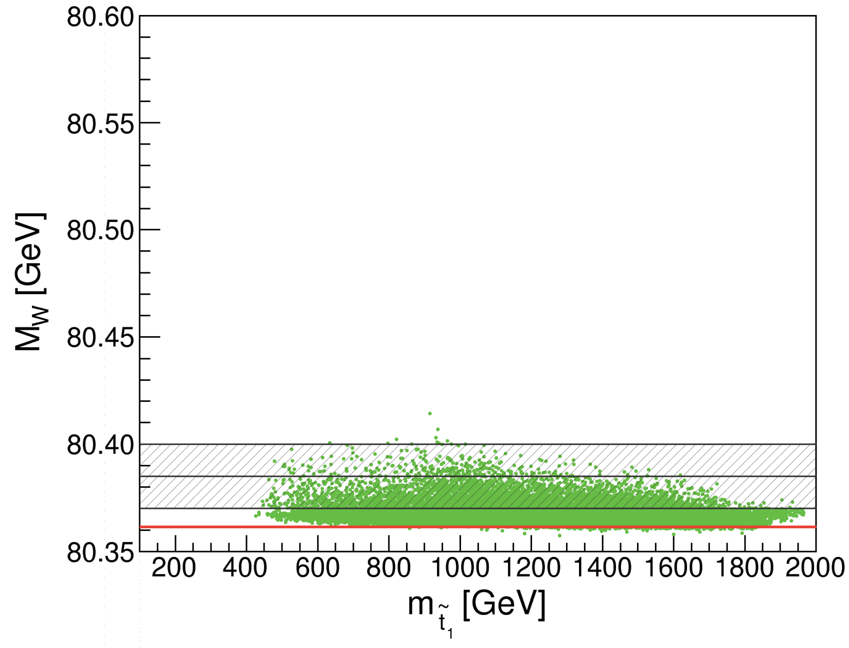


dark: $m_{\tilde{t}},\, m_{\tilde{b}} > 500\,\mathrm{GeV}$

$m_{\tilde{q}},\, m_{\tilde{g}} > 1200\,\mathrm{GeV}$

$$m_{\tilde{t}_1} < m_{\tilde{t}_2} < 2.5\, m_{\tilde{t}_1}$$



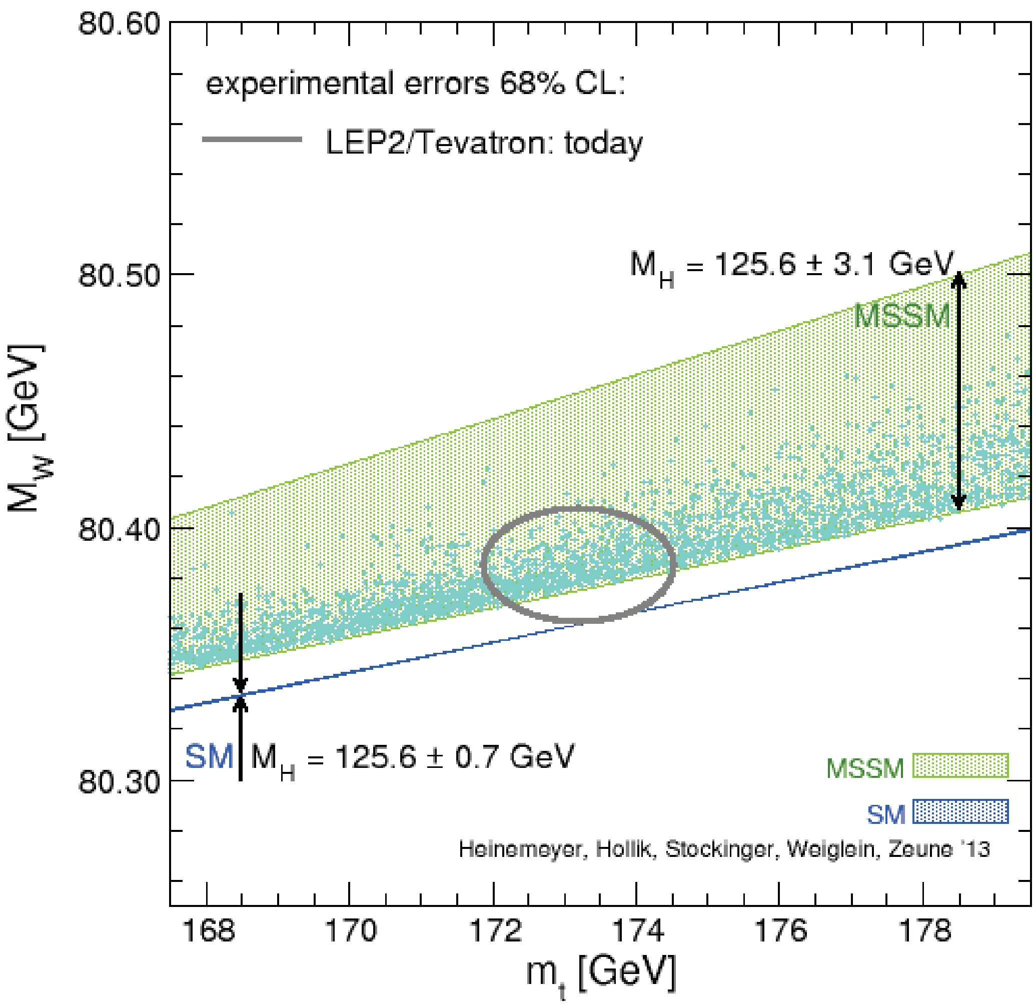


$$m_{\tilde{b}} > 1000\,\text{GeV}$$

$$(m_{\tilde{q}},\, m_{\tilde{g}} > 1200\,\text{GeV})$$

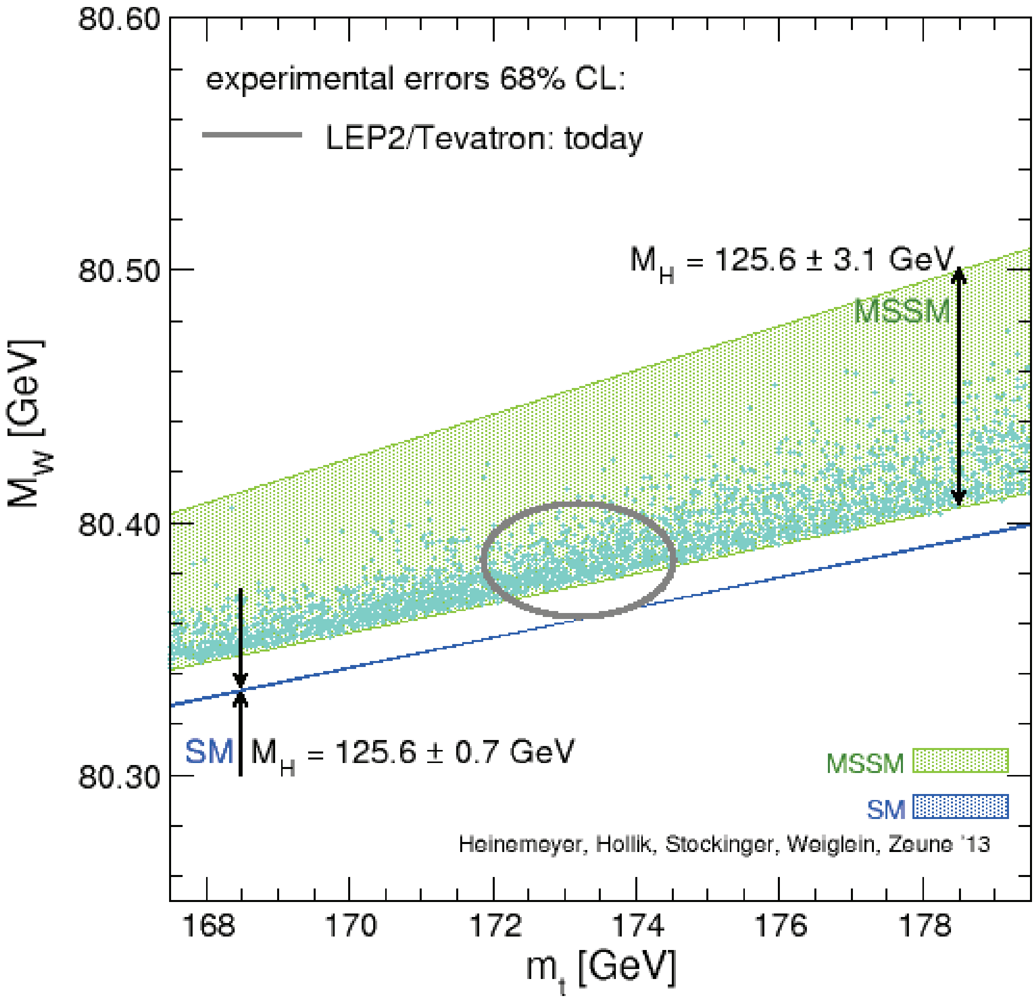
+ *charginos and sleptons above 500 GeV*

other interpretation: heavier H^0 = observed signal



dark: $m_{\tilde{t}}, m_{\tilde{b}} > 500\,\mathrm{GeV}, \quad m_{\tilde{q}}, m_{\tilde{g}} > 1200\,\mathrm{GeV}$

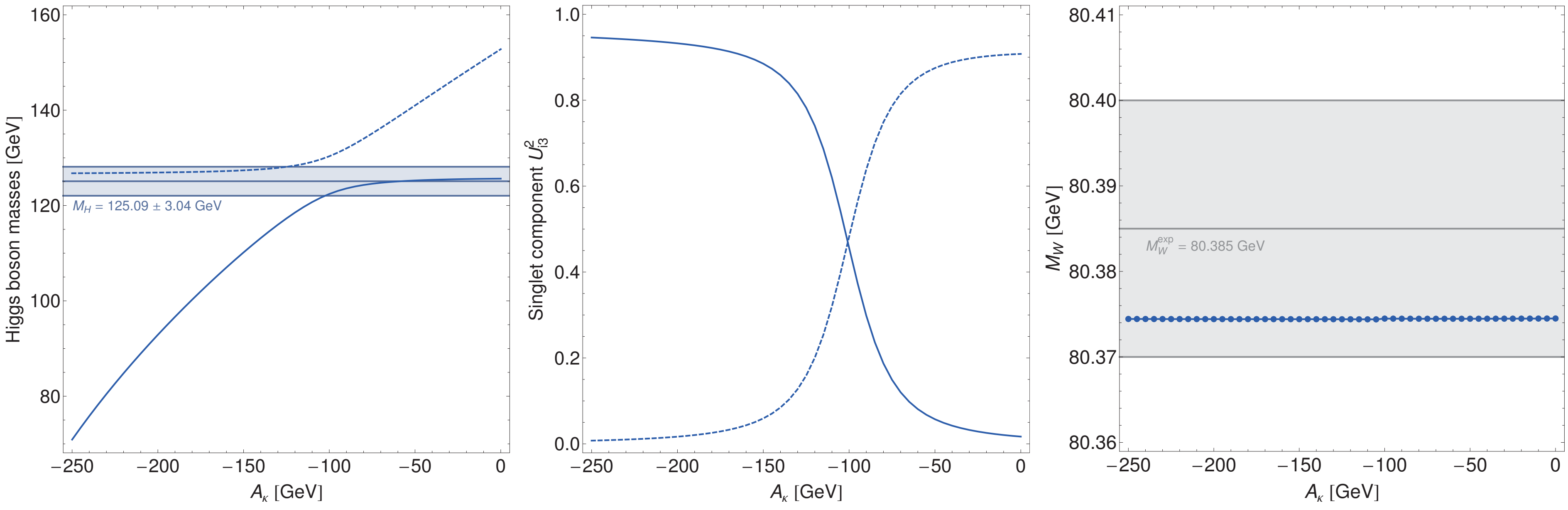
other interpretation: heavier H^0 = observed signal



dark: $m_{\tilde{t}}, m_{\tilde{b}} > 500\,\mathrm{GeV}, \quad m_{\tilde{q}}, m_{\tilde{g}} > 1200\,\mathrm{GeV}$

light $H^{\pm}$ needed – ruled out soon?

inverted hierarchy – NMSSM



Stal, Weiglein, Zeune, arxiv:1506.07465

MSSM Higgs bosons

Higgs potential: $V_H = V_H^{\rm susy} + V_H^{\rm soft}$

$$= (\mu^2 + m_1^2)\, H_1^\dagger H_1 + (\mu^2 + m_2^2)\, H_2^\dagger H_2 - m_3^2\, \varepsilon_{ij} \left(H_1^i\, H_2^j + h.c.\right)$$

$$+ \tfrac{g_1^2+g_2^2}{8} \left(H_1^\dagger H_1 - H_2^\dagger H_2\right)^2 + \tfrac{g_2^2}{2}\, |H_1^\dagger H_2|^2$$

SM particle masses:

$$M_{W,Z}^2 \sim v_1^2 + v_2^2 \equiv v^2, \quad m_d, m_e \sim v_1, \quad m_u \sim v_2$$

free parameters: $m_3^2,\ \tan\beta = \frac{v_2}{v_1}$

physical states: $h^0, H^0, A^0, H^\pm$

$$M_A^2 = m_3^2\,(\cot\beta + \tan\beta)$$

conventional input parameters: $M_A,\ \tan\beta$

- other masses predicted (tree-level):

$$m^2_{H^\pm} = M_A^2 + M_W^2$$

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

- substantial higher-order corrections:

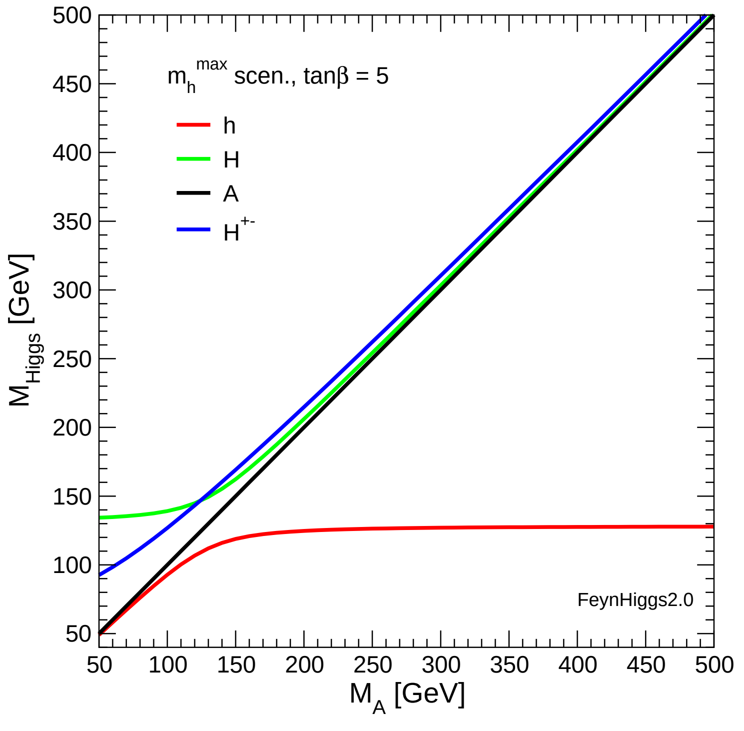
dominant one-loop term $\Delta m_h^2 \sim G_\mathrm{F}\, m_t^4\, \log(m_{\tilde{t}}^2/m_t^2)$
from the Yukawa sector $\sim \alpha_t\, m_t^2$

all other sectors also contribute

$m_h =$ observable sensitive to (still) unknown SUSY particles

testing MSSM requires precision calculations for Higgs boson masses (and mixing)

Higgs bosons in the MSSM: $h^0, H^0, A^0, H^\pm$



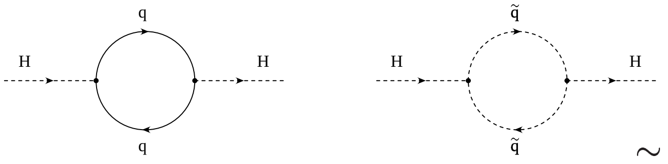
- *light Higgs boson h^0*

  $$m_h \leq m_Z |\cos(2\beta)| + \Delta m_{h^0}$$

- *for heavy $A^0, H^0, H^\pm$:*

  h^0 like Standard Model Higgs boson

m_h^0 strongly influenced by quantum effects, dominant from t, $\tilde{t}$



$\sim \alpha_t$

public tool: FeynHiggs *Hahn, WH, Heinemeyer, Rzehak, Weiglein*

other codes: *CPSuperH, SoftSusy, SPheno, Suspect, H3m, SusyHD, . . .*

neutral Higgs bosons: MSSM with real parameters

dressed $h,\ H$ propagators

$$(\Delta_{\rm Higgs})^{-1} = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_H(q^2) & \hat{\Sigma}_{hH}(q^2) \\ \hat{\Sigma}_{Hh}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_h(q^2) \end{pmatrix}$$

$\hat{\Sigma} = \Sigma + \text{counter terms}:$ renormalized self-energies

- det = 0 $\rightarrow$ $m_{h,H}^{\rm pole}$
- diagonalization $\rightarrow$ effective couplings, q^2-dep.

$\hat{\Sigma}(q^2) \rightarrow \hat{\Sigma}(0):$ rediagonalization with $\alpha_{\rm eff}$

$\alpha \rightarrow \alpha_{\rm eff}$ in tree-level couplings

self-energies: complete 1-loop + dominant 2-loop parts with α_t, α_s

importance of precise calculations of the mass M_h

Experiment:

ATLAS: $M_h^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18$ GeV

CMS: $M_h^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15$ GeV

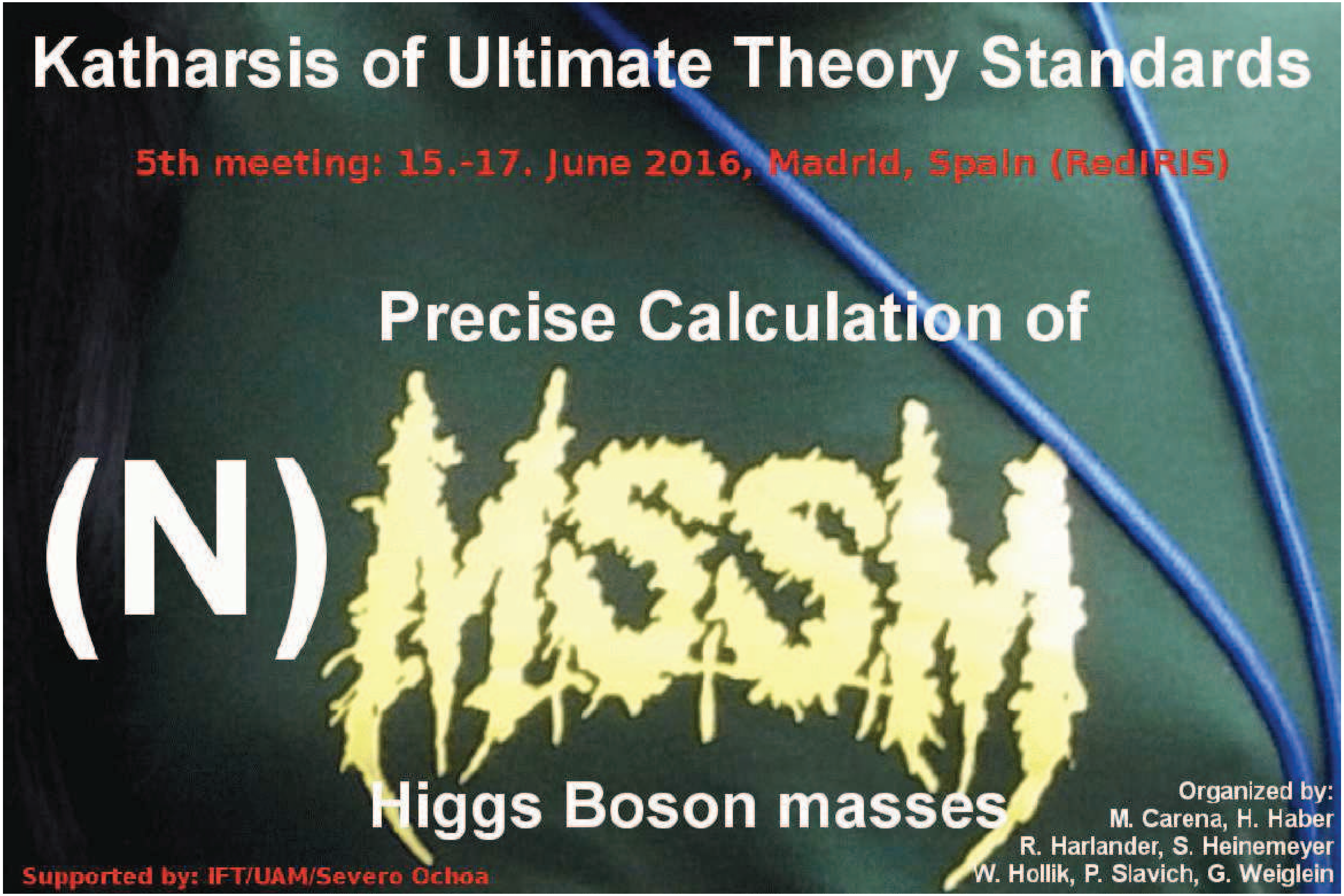
combined: $M_h^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11$ GeV

MSSM theory:

LHCHXSWG adopted FeynHiggs for the prediction of MSSM Higgs boson masses and mixings (considered to be the code containing the most complete implementation of higher-order corrections)

FeynHiggs: $\delta M_h^{\text{theo}} \sim 3$ GeV

Working group on M_h predictions: sites.google.com/site/kutsmh



recent progress in precision calculations:

- full momentum dependence of self-energies at 2-loop $O(\alpha_t\alpha_s)$

$$\Sigma(0) \;\; [\text{effective potential}] \;\rightarrow\; \Sigma(q^2)$$

  Borowka, Heinemeyer, Hahn, Heinrich, WH 2014, 2015

  Degrassi, Di Vita, Slavich 2014

- charged $H^{\pm}$ mass at 2-loop order $O(\alpha_t^2)$ *WH, Paßehr 2015*

- MSSM with complex parameters ($\rightarrow CP$-violation):
  contributions of 2-loop order $O(\alpha_t^2)$ with complex phases

  WH, Paßehr 2014; Hahn, Paßehr 2015

- resummation of large logarithms $\log(M_S/m_t)$ at LL and NLL
  for large SUSY mass scales M_S
  $\Rightarrow$ allows predictions also for high M_S $\rightarrow$ TeV scale

  Hahn, Heinemeyer, WH, Rzehak, Weiglein 2013; Bahl 2015

  Draper, Lee, Wagner 2013; Lee, Wagner 2015

  Bagnaschi, Giudice, Slavich, Strumia 2014

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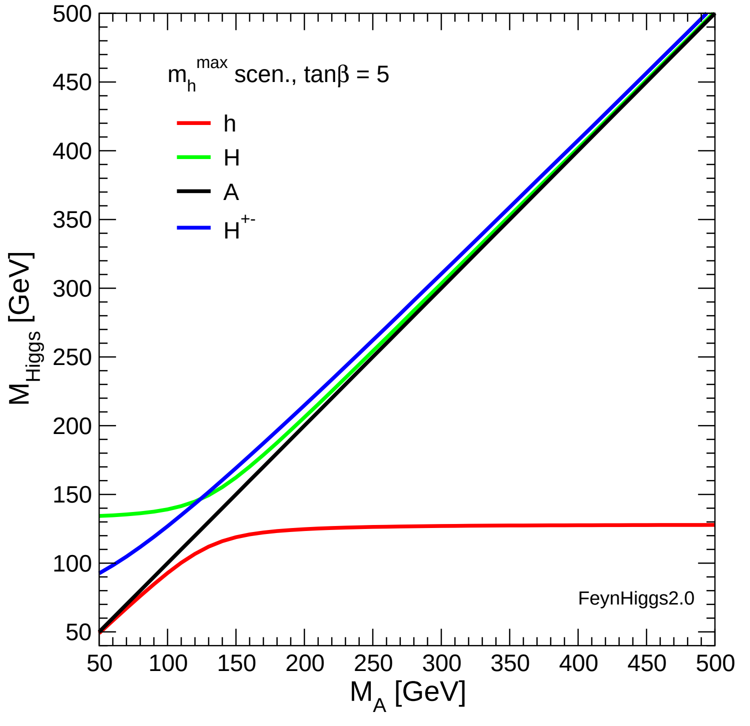
Higgs bosons in the MSSM: $h^0, H^0, A^0, H^\pm$



- *light Higgs boson* h^0

  $$m_h \le m_Z |\cos(2\beta)| + \Delta m_{h^0}$$

- *for heavy* $A^0, H^0, H^\pm$*:*

  h^0 *like Standard Model Higgs boson*

- Feynman-diagrammatic approach

  full mass spectrum from dressed propagators

- EFT approach (RGEs for SM Higgs below SUSY mass scale)

  mass of light h^0 : $\Delta m^2_{h^0} = \lambda(m_t)\, v$

- Feynman-diagrammatic calculations (fixed order)

  all contributions at fixed order taken into account

  also many different SUSY mass scales easily included

  control over self-energies, needed for other quantities

  (h.o. matrix elements for production and decay processes)

  disadvantage: *large logarithms not captured beyond fixed order*

- EFT approach (RGEs for SM Higgs below SUSY mass scale)

  large logarithms taken into account to all orders

  can easily be extended to very large SUSY scales

  disadvantage: *yields only M_h, no self-energies*

  not all contributions are captured, no momentum-dependence

  many different SUSY mass scales difficult to include

- Combining diagrammatic and EFT calculations

  best method for most precise prediction of M_h

- Feynman-diagrammatic calculations *basis of FeynHiggs*

1-loop: $\Delta M_h^2 \sim m_t^2 \, \alpha_t \left[L + L^0 \right], \quad L = \log \frac{M_S^2}{m_t^2}$

2-loop: $\Delta M_h^2 \sim m_t^2 \left\{ \alpha_t \alpha_s \left[L^2 + L + L^0 \right] + \alpha_t^2 \left[L^2 + L + L^0 \right] \right\}$

L^0 *only from explicit Feynman-diagrammatic calculation*

- Combining diagrammatic and EFT calculations in FeynHiggs

Hahn, Heinemeyer, WH, Rzehak, Weiglein 2013

resummation of large logarithms from α_t and α_s

on top of fixed-order 1- and 2-loop terms

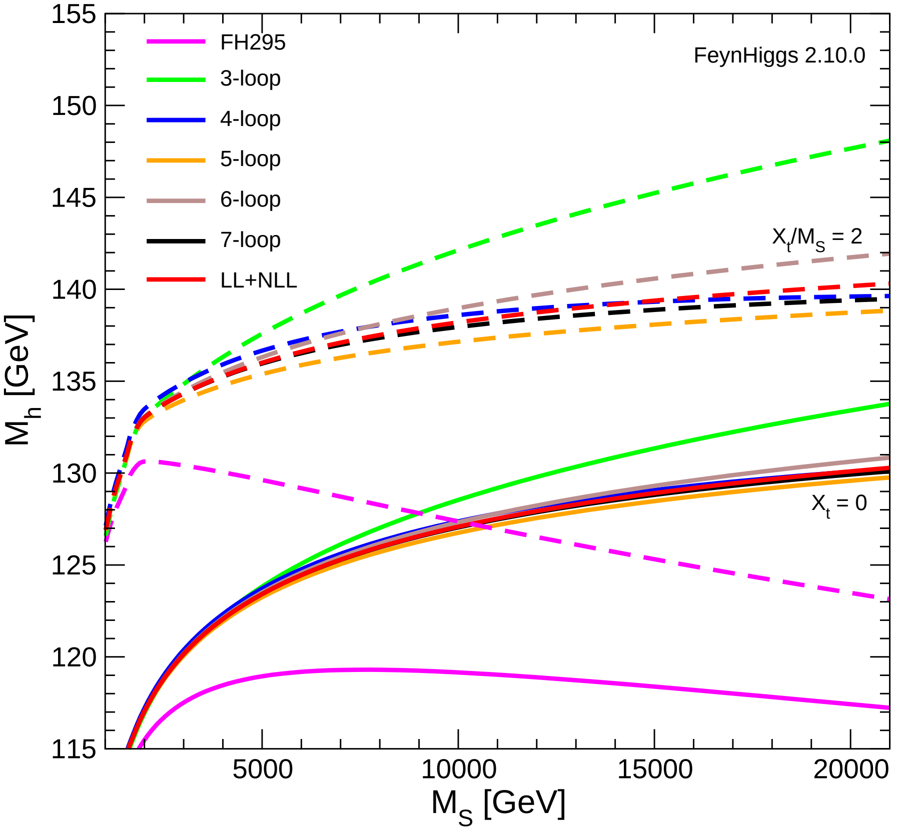
H. Bahl, Master Thesis, MPI/TUM 2015 / ongoing PhD work

resummation of large electroweak logarithms

additional independent mass scales ($M_{\tilde{t}}, M_{\tilde{g}}, M_\chi$)

avoid double-counting of logs: subtract logs from FH result

large log resummation from α_s, α_t *[Hahn et al.]*



– *fixed order*

– *full resummation of LL and NLL*

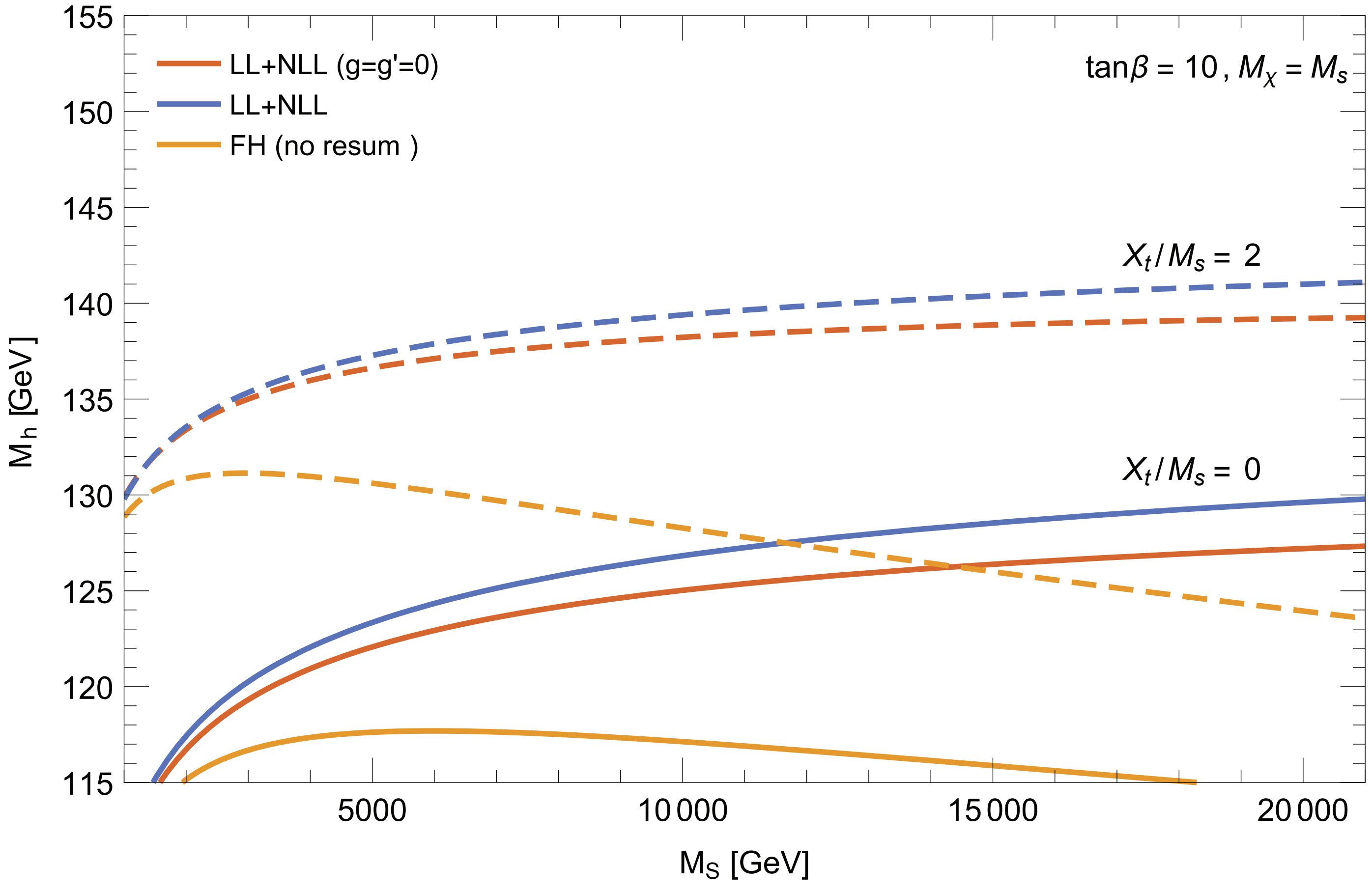
$\tilde{t}$*-squark mass matrix* $\mathcal{M}^2_{\tilde{t}} =$

$$\begin{pmatrix} M_S^2 + m_t^2 & m_t X_t \\ m_t X_t & M_S^2 + m_t^2 \end{pmatrix}$$

- sizeable upward shift for heavy top-squarks
- large impact for constraints from Higgs signal at 125 GeV

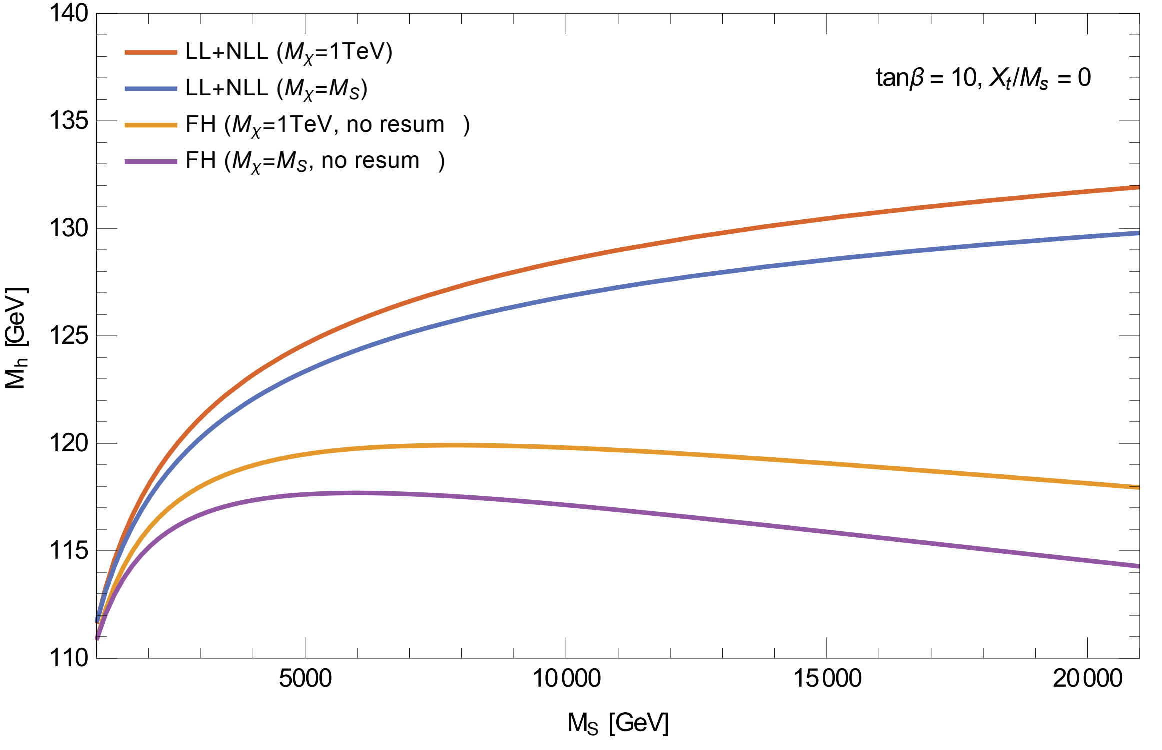
inclusion of EW resummed results at LL + NLL ($g, g' \neq 0$)

[H. Bahl, WH - preliminary]



inclusion of extra EWino mass scale M_χ

[H. Bahl, WH - preliminary]

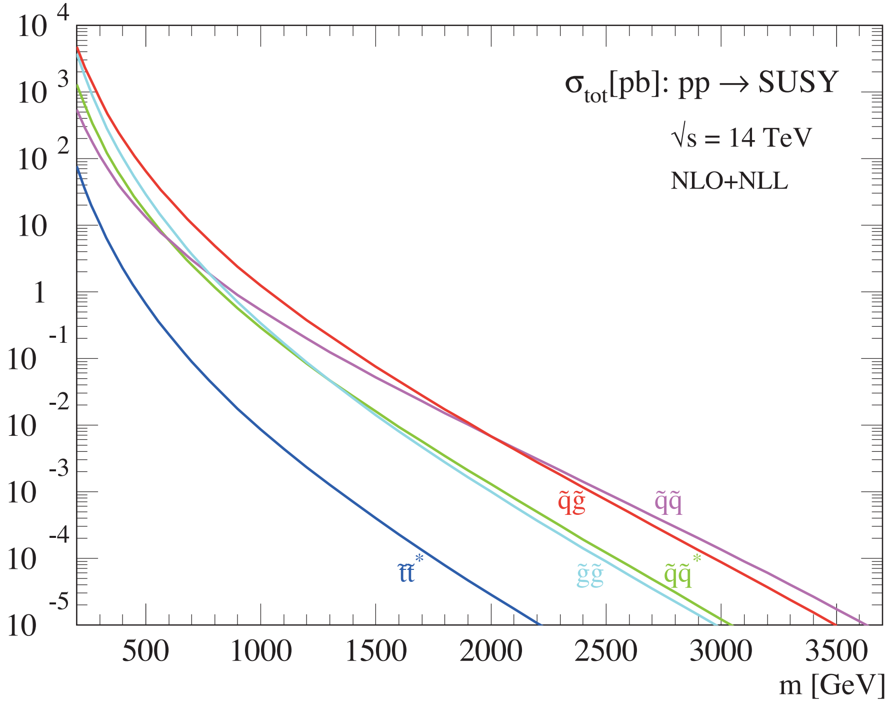


further improvements:

- going to NNLL, with 3-loop RGEs
- THDM as effective low-energy theory

SUSY particle production

LHC: predominantly colored SUSY particles produced



[Borschensky et al. arxiv:1407.5066]

NLO QCD → **PROSPINO**

Beenakker, Höpker, Spira, Zerwas 1994 – 1996

Beenakker, Krämer, Plehn, Spira, Zerwas 1998

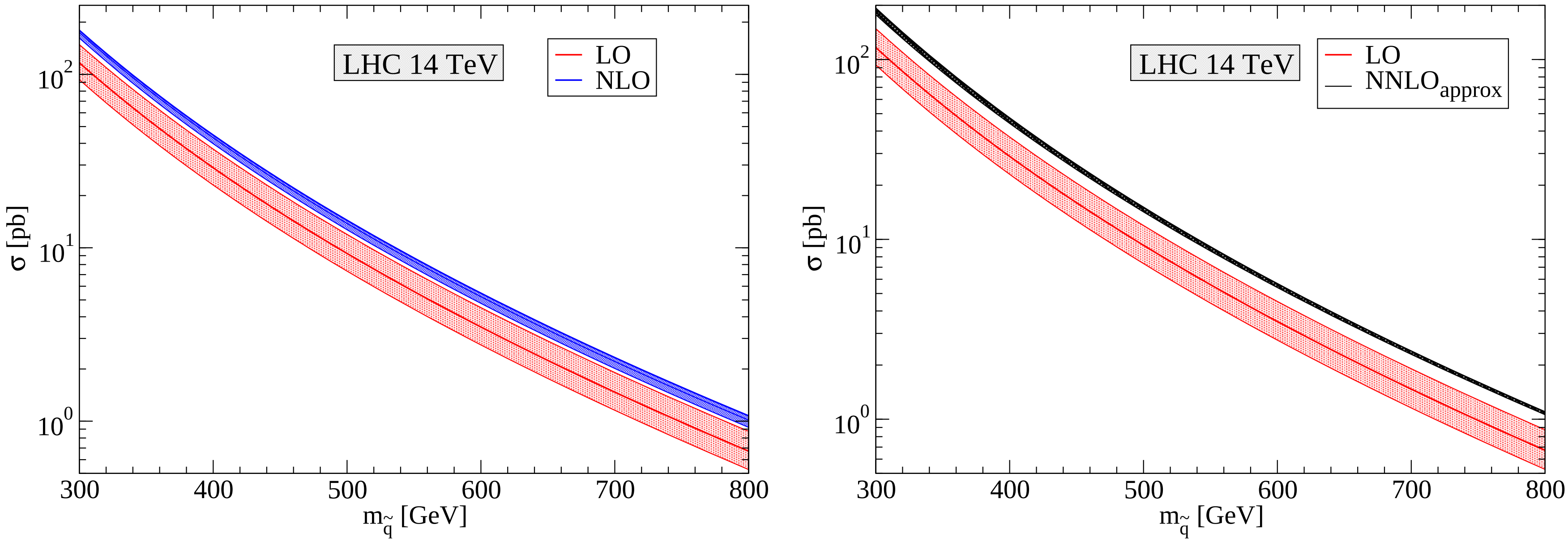
enhancement of cross sections by $30 - 50\,\%$

NNLO QCD contributions (dominant soft corrections)

Kulesza et al. 2008/09; Beenakker et al. 2009–2011, 2012–2014;

Langenfeld, Moch 2009; Langenfeld, Moch, Pfoh 2012; Broggio et al. 2013;

Beneke et al. 2009–2011,2013; Falgari, Schwinn, Wever 2012/13



squark pair production [from Langenfeld, Moch 2009]

– improved theoretical prediction

– reduction of scale uncertainty

NNLO QCD contributions $\sim$ electroweak contributions

$\bullet\mathcal{O}(\alpha_s^2\alpha)$: NLO EW contributions $(\tilde{t}\tilde{t}^*, \tilde{b}\tilde{b}^*, \tilde{q}\tilde{q}^*, \tilde{q}\tilde{q})$

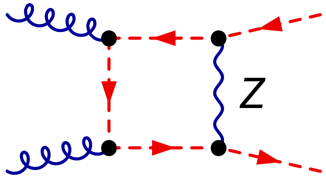
WH, Kollar, Mirabella, Trenkel 2007,2008

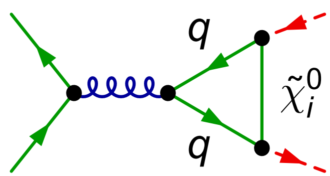
Germer, WH, Mirabella 2011

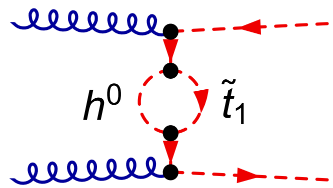
Germer, WH, Lindert, Mirabella 2014

WH, Lindert, Mirabella, Pagani 2015

QCD Born $\times$

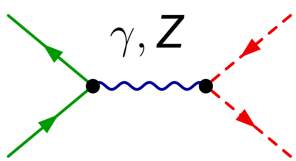




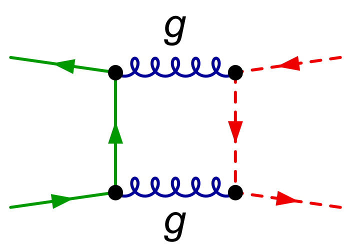


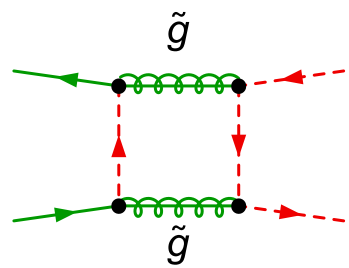
+ . . .

+ EW-QCD one-loop interferences



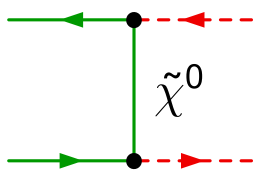
$\times$





$(\tilde{q} \neq \tilde{t})$

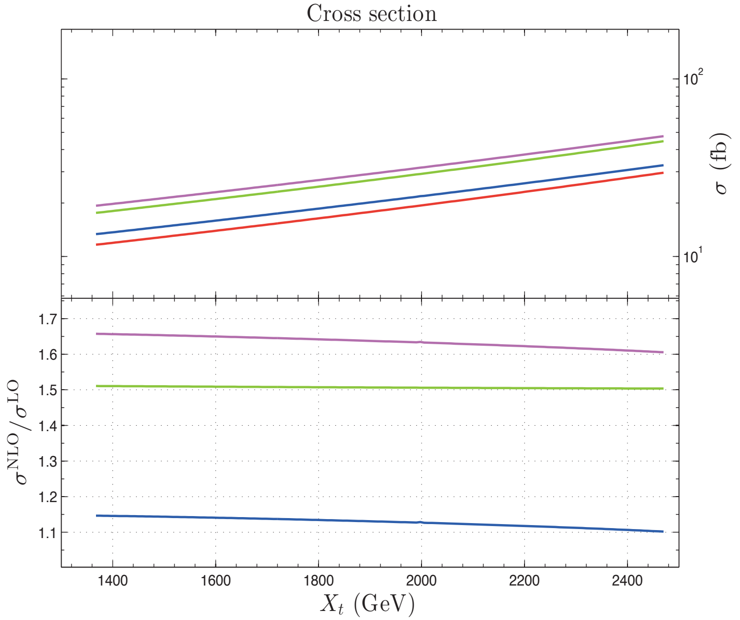
$+$



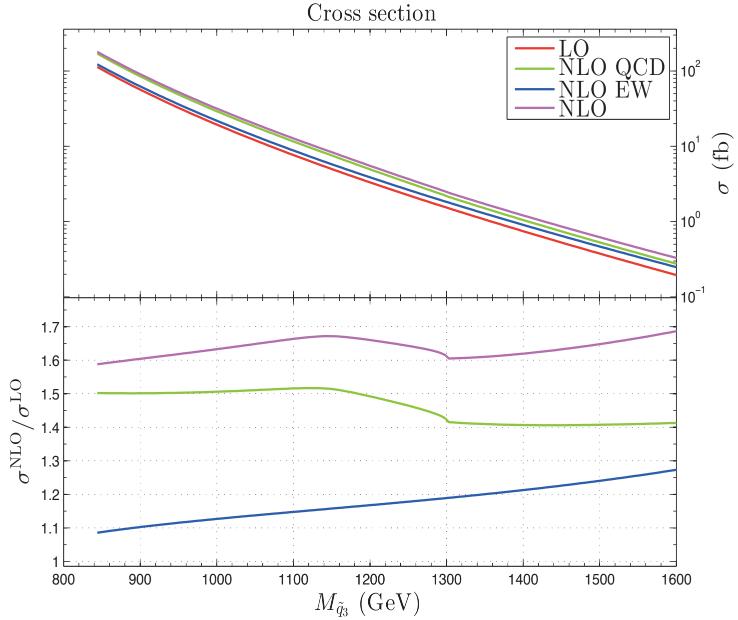
$\times$ full QCD 1-loop amplitude

+ real photon, gluon, and quark radiation

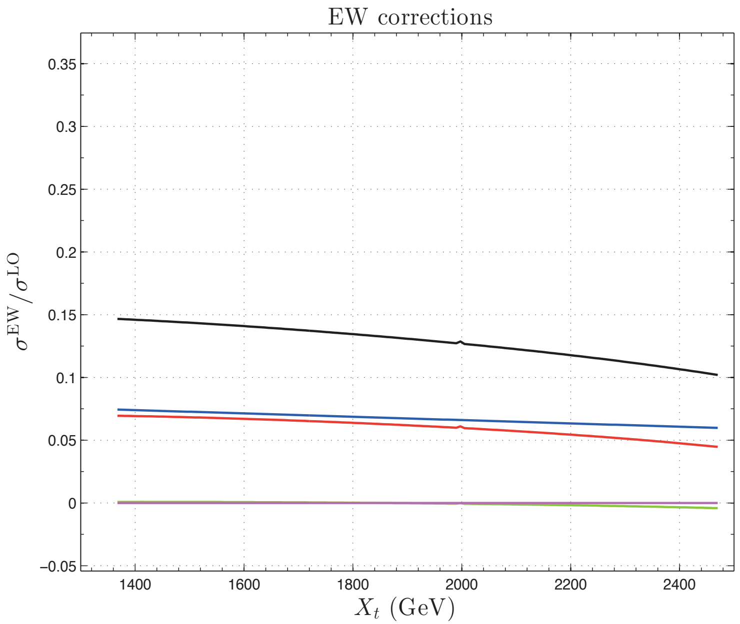
$\tilde{t}_1\tilde{t}_1^*$ production *[Germer, WH, Lindert, Mirabella 2015]*

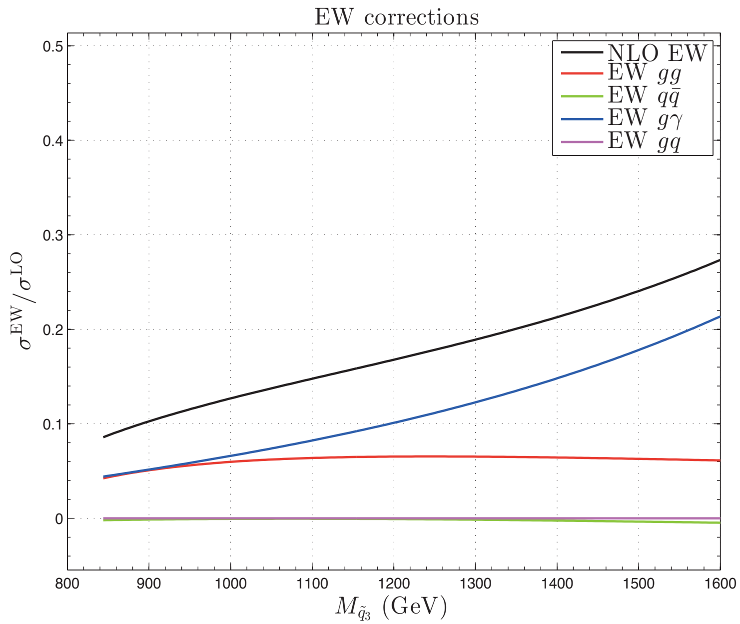


(a)



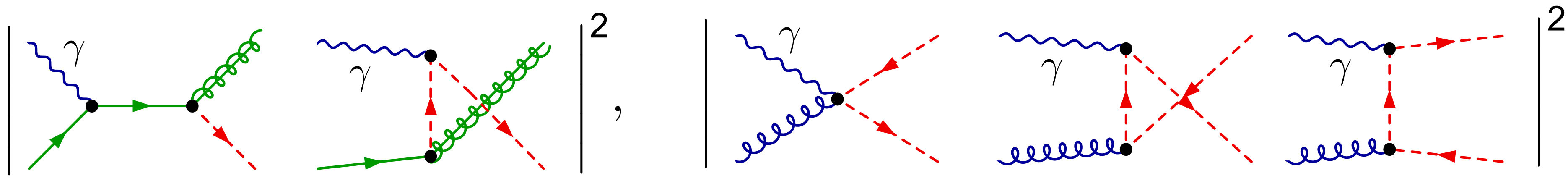
(b)

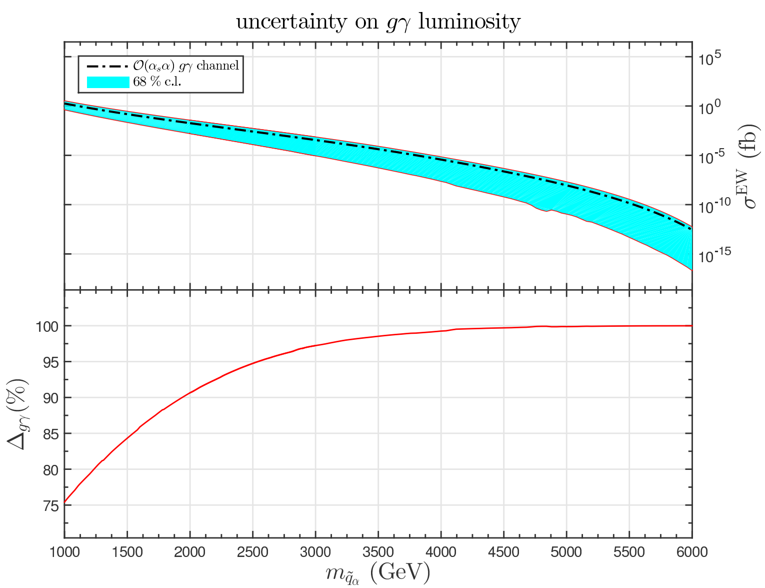




new production channel:

- $\mathcal{O}(\alpha_s \alpha)$: photon induced processes





example: squark pair production (inclusive)

REQUIRED:

PDFs with QED evolution

NNPDF2.3QED *[Ball et al. 2013]*

- yields large overall uncertainty of total EW contribution and thus of the predicted squark production cross section

Conclusions

- direct search for top and Higgs has been a convincing concept for the Standard Model, based on precision calculations versus precision measurements
- applicable also in the search for physics BSM, with the need of precision calulations
- precison observables yield important information on specific models, like THDM and supersymmetric models,
- decisive input now: $M_H = 125\,\mathrm{GeV}$, fits naturally in SUSY models, provides sensitive probe of others SUSY sectors
- complementary to direct searches, where precision calculations are required for identification and correct interpretation of experimental signatures