Precision Observables and Higgs Bosons in the MSSM

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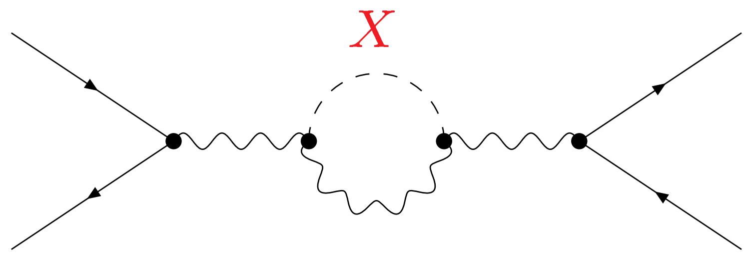
LOOPFEST 2009

MADISON, 7 - 9 MAY 2009

Outline

- Electroweak precision observables
- Higgs bosons in the real MSSM
- Higgs bosons in the complex MSSM
- Summary

electroweak precision tests through quantum loops



sensitivity to unknown particles (X)

X = Higgs [+ non-standard]

precision observables

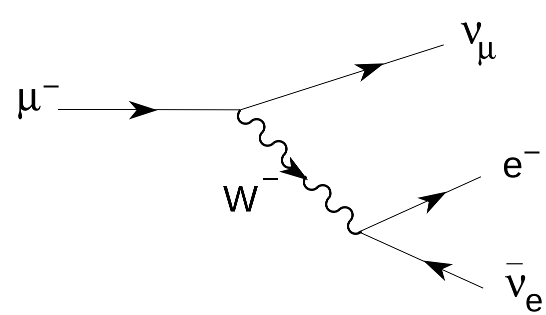
- μ lifetime: G_{F}
- Z observables: $M_Z, \Gamma_Z, g_V, g_A, \sin^2\theta_{\mathrm{eff}}, \ldots$
- LEP 2, Tevatron: M_W, m_t
- low energies: $(g-2)_\mu$

$M_W - M_Z$ correlation

Definition of Fermi constant G_F via muon lifetime:

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)(1 + \Delta q)$$

Δq: QED corrections in Fermi Model,



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

with loop contributions

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

$\Delta r :$ quantum correction

$\Delta r = \Delta r(m_t, M_H)$ SM

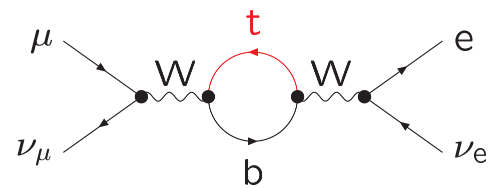
determines W mass

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

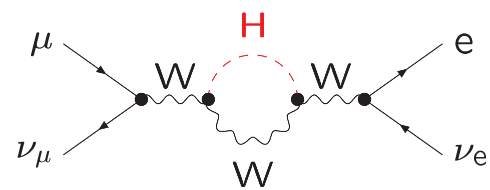
complete at 2-loop order

1-loop examples

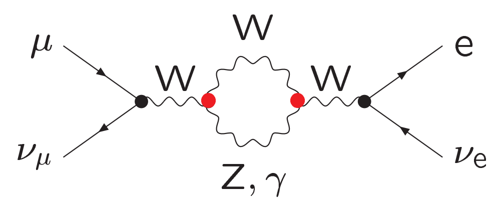
- top quark



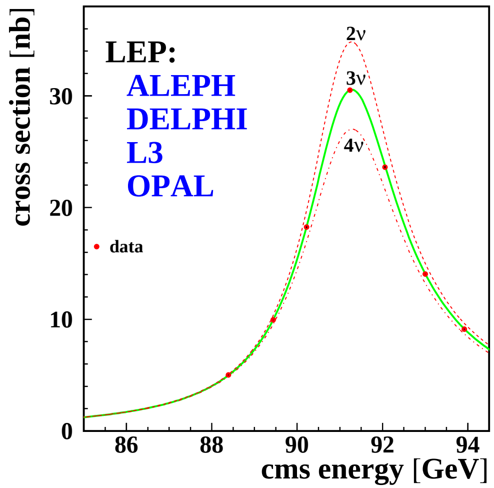
- Higgs boson

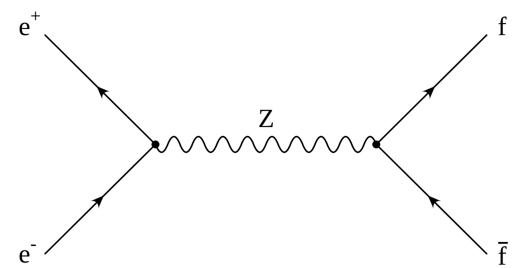


- gauge-boson self-couplings



Z resonance





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

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

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

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

EW 2-loop calculations for Δr

Freitas, Hollik, Walter, Weiglein

Awramik, Czakon

Onishchenko, Veretin

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

Awramik, Czakon, Freitas, Weiglein

Awramik, Czakon, Freitas

Hollik, Meier, Uccirati

universal terms beyond 2-loop order (EW and QCD)

van der Bij, Chetyrkin, Faisst, Jikia, Seidensticker

Faisst, Kühn Seidensticker, Veretin

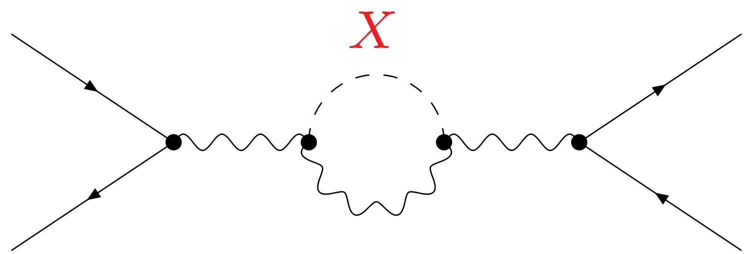
Boughezal, Tausk, van der Bij

Schröder, Steinhauser

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

Boughezal, Czakon

precision observables in the MSSM



X = Higgs bosons, SUSY particles

- μ lifetime: $M_W \leftrightarrow M_Z, G_{\rm F}$
- Z observables: $g_V, g_A, \sin^2\theta_{\rm eff}, \Gamma_Z, M_Z, \quad \ldots$

[Heinemeyer, WH, Weiglein, Phys. Rep. 425 (2006) 265]

2-loop improvements $\mathcal{O}(\alpha\alpha_s,\ \alpha_t^2,\ \alpha_b^2,\ \alpha_t\alpha_b)$
and complex parameters

[Heinemeyer, WH, Stöckinger, A. Weber, Weiglein 06]
[Heinemeyer, WH, A. Weber, Weiglein 07]

masses and mixing of SUSY particles

model parameters

- gaugino masses: M_1, M_2, M_3
- sfermion masses: $M_L, M_{\tilde{u}_R}, M_{\tilde{d}_R}$
  for each doublet of squarks and sleptons
- trilinear coupling: $A_{\tilde{f}}$ for each $\tilde{f}$
  $\longrightarrow$ L-R sfermion mixing
- supersymmetric Higgsino mass parameter: μ
- Higgs sector parameters: $M_A, \ \tan\beta = v_2/v_1$

Benchmark scenarios

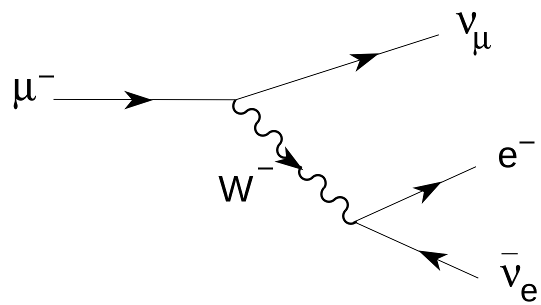
"Snowmass points and slopes" (SPS), hep-ph/0202233

examples (mSUGRA):

- SPS1a: $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A_0 = -100$, $\tan\beta = 10$, $\mu > 0$.

- SPS1b: $m_0 = 200$ GeV, $m_{1/2} = 400$ GeV, $A_0 = 0$, $\tan\beta = 30$, $\mu > 0$.

$M_W - M_Z$ correlation



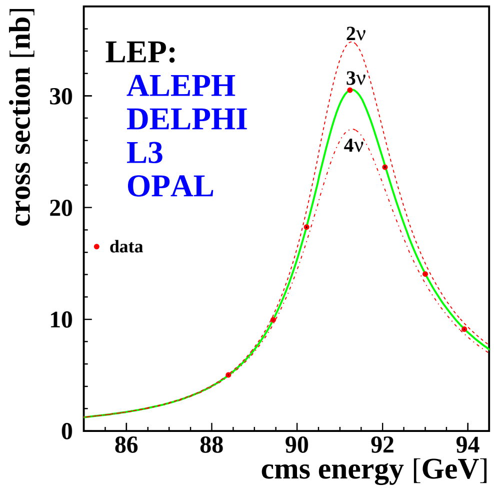
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}\left(1 + \Delta r\right)$$

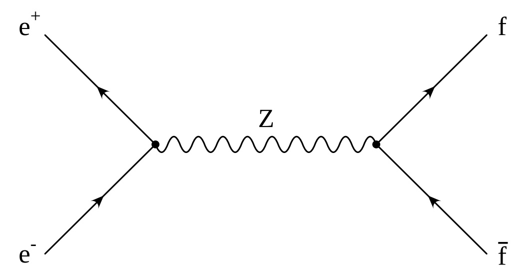
Δr : quantum correction, $\Delta r = \Delta r(m_t, X_{\rm SUSY})$

$\rightarrow \quad M_W = M_W(\alpha, G_F, M_Z, m_t, X_{\rm SUSY})$

$X_{\rm SUSY} =$ set of non-standard model parameters

Z resonance





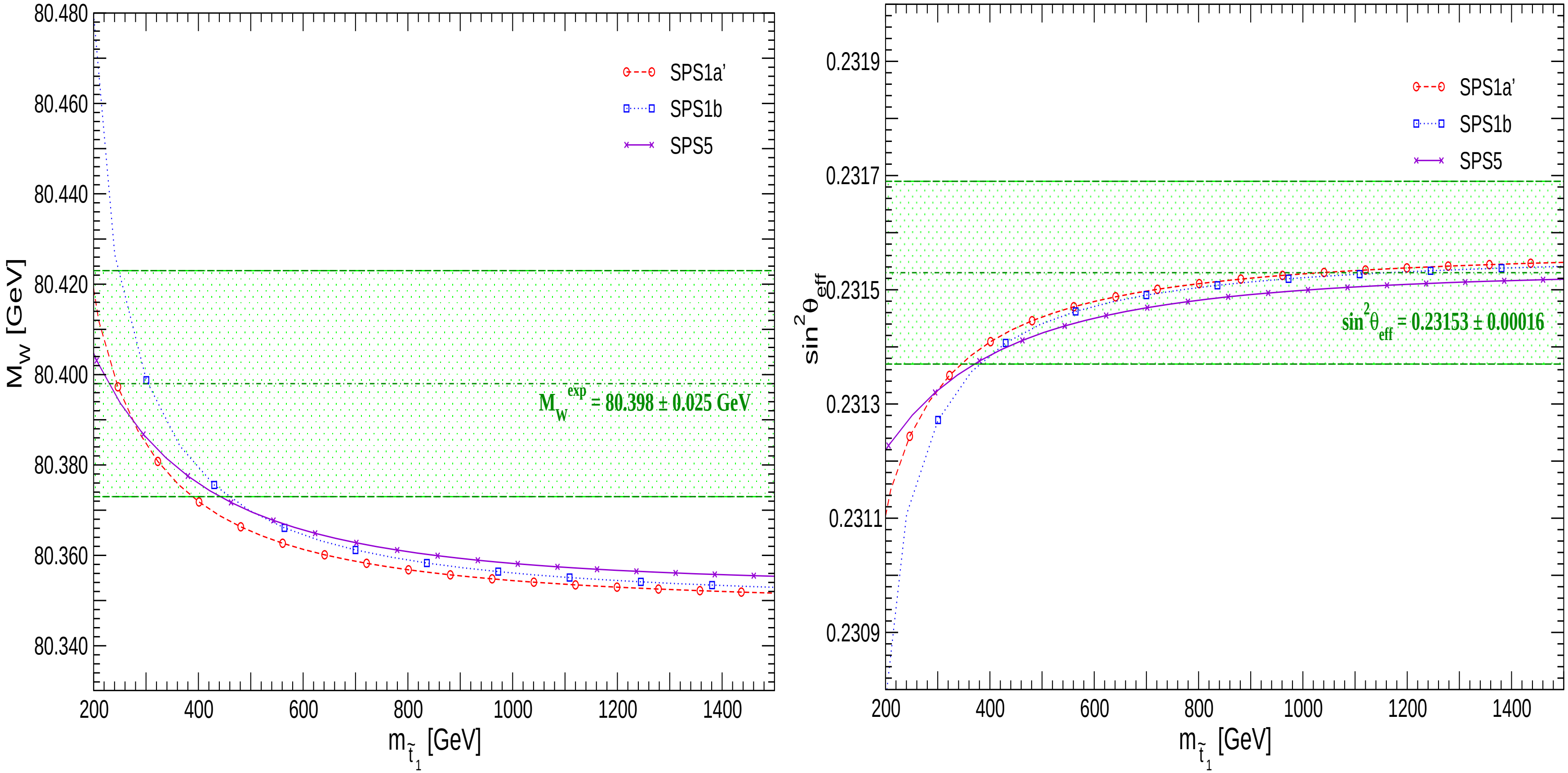
effective Z boson couplings

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

with higher order contributions $\Delta g_{V,A}^f \, (m_t, X_{\mathrm{SUSY}})$

$$\sin^2\theta_{\mathrm{eff}} = \frac{1}{4}\left(1 - \mathrm{Re}\,\frac{g_V^e}{g_A^e}\right) = \kappa \cdot \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

M_W and $\sin^2\theta_{\text{eff}}$ for varied SUSY-scale



Fortran Code SUSYPOPE *[A. Weber, PhD thesis, Munich 2008]*

also used in recent fits by *AbdusSalam, Allanach, Quevedo, Feroz, Hobson, arxiv:0904.2548*

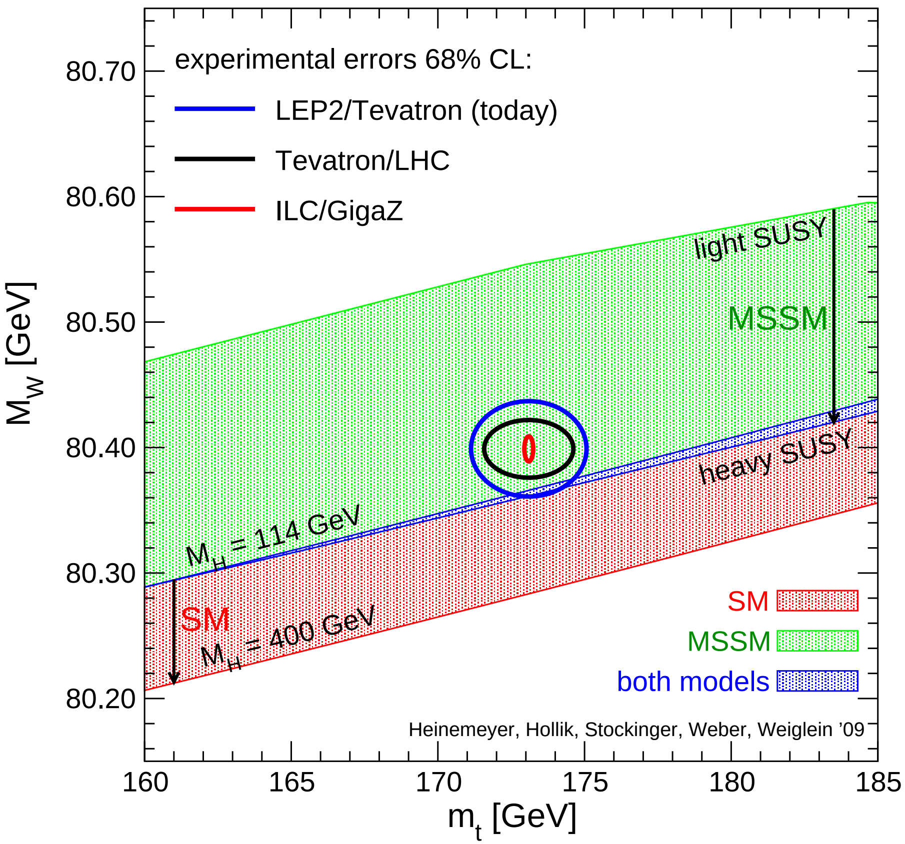
Scatter plots for M_W *&* $\sin^2\theta_{\rm eff}$

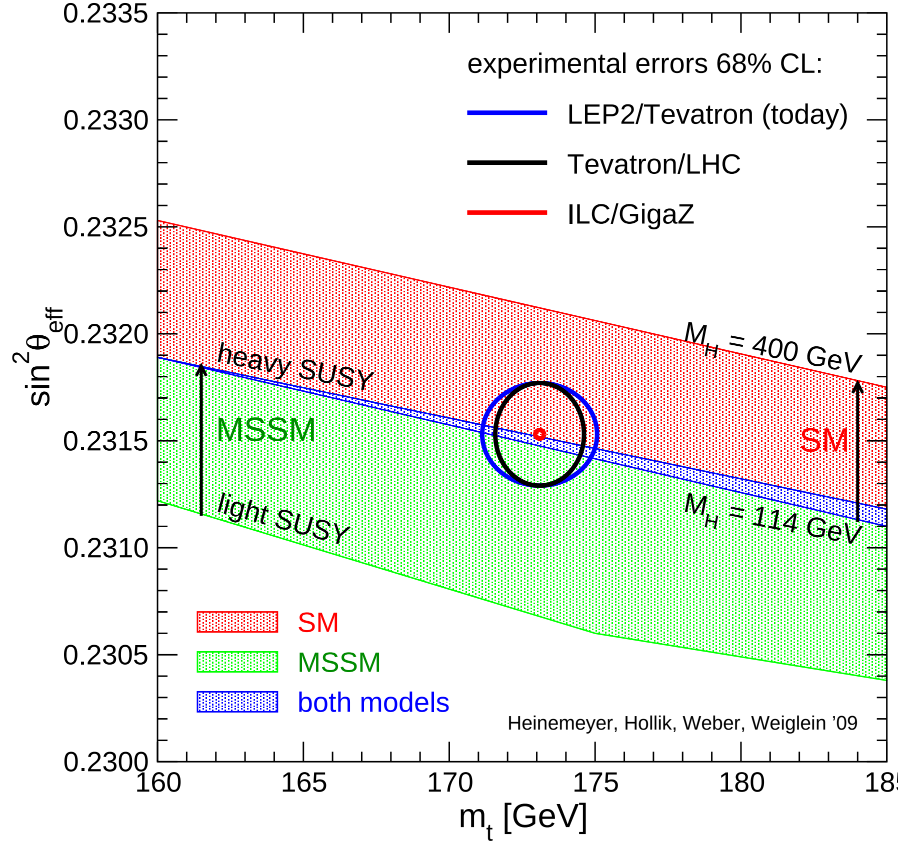
- SUSY parameters:

$$
\begin{aligned}
\text{sleptons} &: \quad M_{\tilde{F},\tilde{F}'} = 100 \ldots 2000 \text{ GeV} \\
\text{light squarks} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100 \ldots 2000 \text{ GeV} \\
\tilde{t}/\tilde{b} \text{ doublet} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100 \ldots 2000 \text{ GeV} \\
& \quad\;\; A_{t,b} = -2000 \ldots 2000 \text{ GeV} \\
\text{gauginos} &: \quad M_{1,2} = 100 \ldots 2000 \text{ GeV} \\
& \quad\;\; m_{\tilde{g}} = 195 \ldots 1500 \text{ GeV} \\
& \quad\;\; \mu = -2000 \ldots 2000 \text{ GeV} \\
\text{Higgs} &: \quad M_A = 90 - 1000 \text{ GeV} \\
& \quad\;\; \tan\beta = 1.1 \ldots 60
\end{aligned}
$$

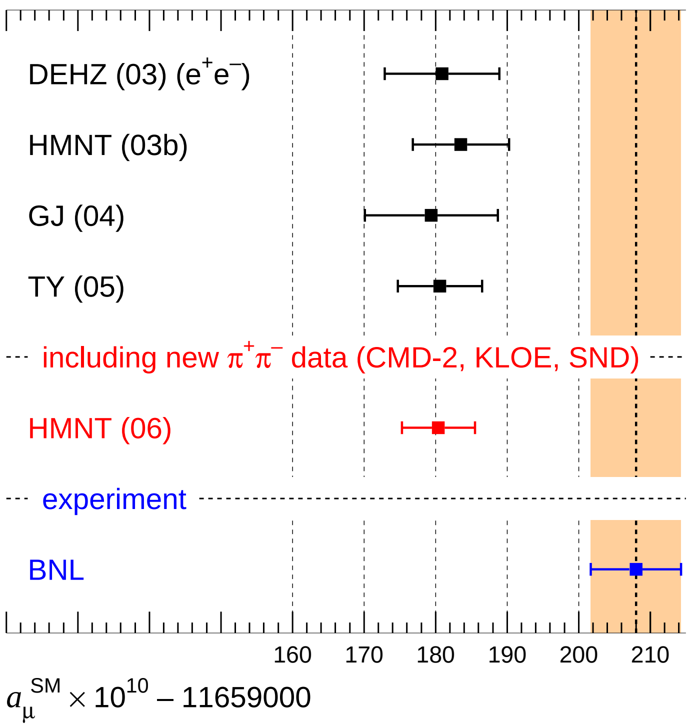
- Unconstrained scan, only Higgs mass required to be in agreement with LEP data.

[Heinemeyer, Hollik, Stöckinger, Weber, Weiglein]





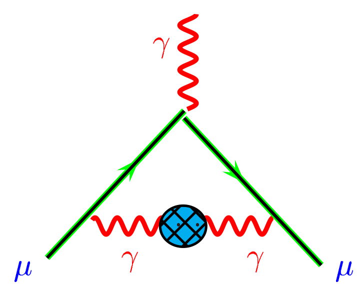
Anomalous g-factor of the muon



Hagiwara,Martin,Nomura,Teubner

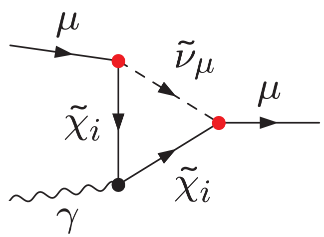
e^+e^- data based SM prediction: 3.4 σ below exp. value

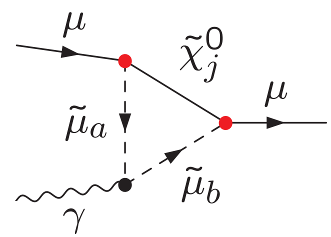
theory uncertainty from hadronic vacuum polarization



$g-2$ with supersymmetry

new contributions from virtual SUSY partners of $\mu,\ \nu_\mu$ and of $W^\pm,\ Z$





extra terms *[Czarnecki, Marciano]*

$$+ \quad \frac{\alpha}{\pi}\,\frac{m_\mu^2}{M_{\rm SUSY}^2}\cdot\frac{v_2}{v_1}$$

can provide missing contribution for

$$M_{\rm SUSY} = 200 - 600\,\mathrm{GeV}$$

2-loop calculation *[Heinemeyer, Stöckinger, ...]*

CMSSM

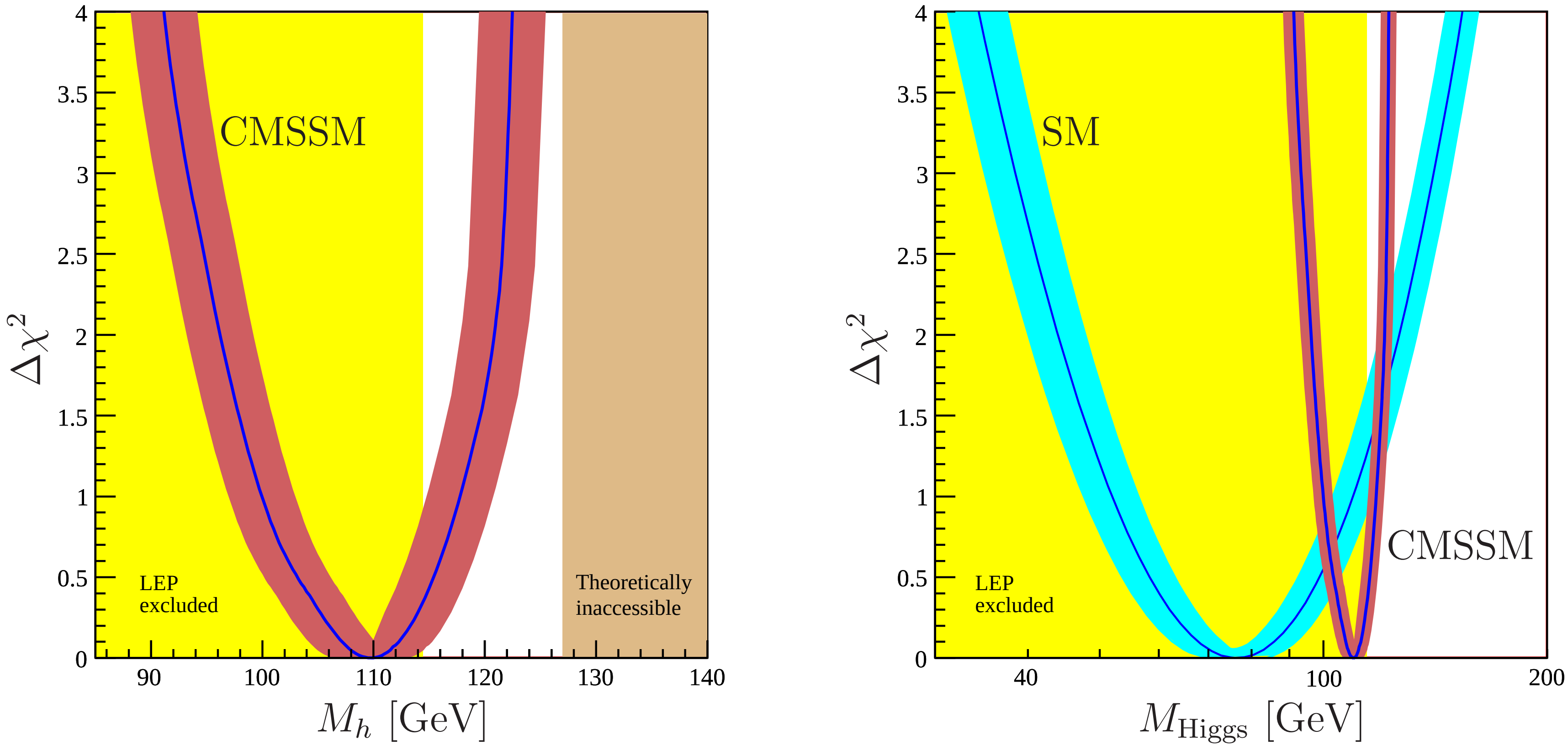
Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(M_Z)$	0.02758 ± 0.00035	0.02774	
M_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
σ^0_{had} [nb]	41.540 ± 0.037	41.486	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{FB}$	0.01714 ± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21613	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{FB}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
$A_l(SLD)$	0.1513 ± 0.0021	0.1479	
$\sin^2\theta^{l}_{eff}(Q_{FB})$	0.2324 ± 0.0012	0.2314	
M_W [GeV]	80.398 ± 0.025	80.382	
m_t [GeV]	170.9 ± 1.8	170.8	
$BR(b\to s\gamma)$	1.13 ± 0.12	1.12	
$BR(B_s\to\mu\mu)[\times10^{-8}]$	< 8.00	0.33	N/A (upper limit)
$\delta a_\mu[\times10^{-9}]$	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	

Standard Model

Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(M_Z)$	0.02758 ± 0.00035	0.02768	
M_Z [GeV]	91.1875 ± 0.0021	91.1875	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	
σ^0_{had} [nb]	41.540 ± 0.037	41.477	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{FB}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21586	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{FB}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
$A_l(SLD)$	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{l}_{eff}(Q_{FB})$	0.2324 ± 0.0012	0.2314	
M_W [GeV]	80.398 ± 0.025	80.374	
m_t [GeV]	170.9 ± 1.8	171.3	
Γ_W [GeV]	2.140 ± 0.060	2.091	

global fit in the constrained MSSM including data from $g-2$, B physics, and cosmic relic density

[O. Buchmüller, . . . , Weber, Weiglein]



$$M_h = 110^{+8}_{-10}\ \mathrm{GeV}$$

Higgs bosons in the MSSM

MSSM Higgs potential contains two Higgs doublets:

$$
\begin{aligned}
V &= m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
&\quad + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} \, |H_1 \bar{H}_2|^2
\end{aligned}
$$

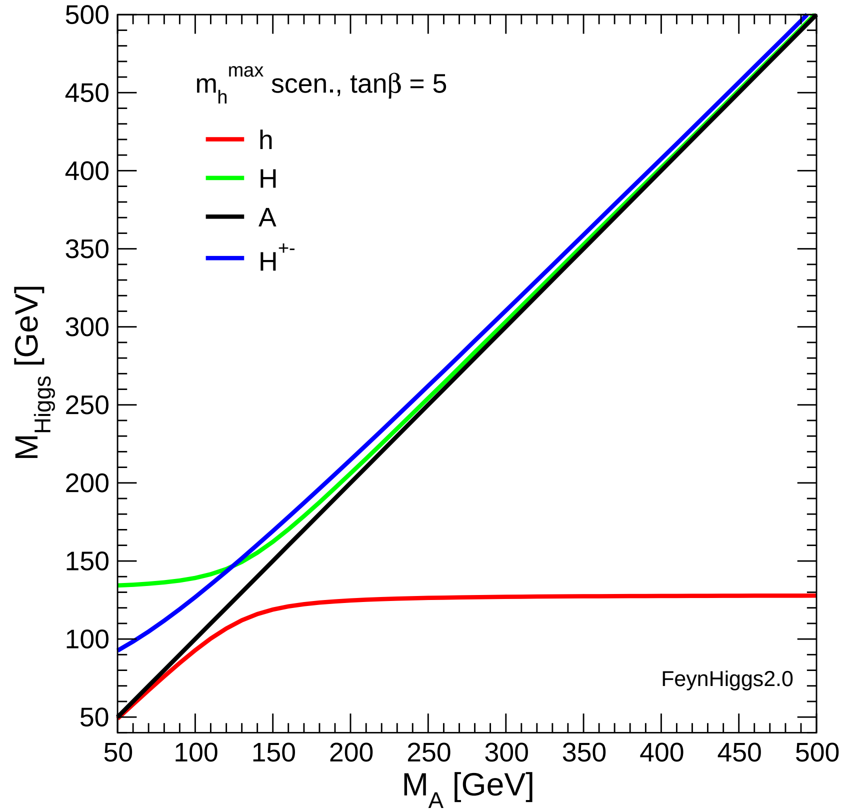
gauge couplings, in contrast to SM

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

Input parameters: $\tan\beta = \frac{v_2}{v_1}$, M_A

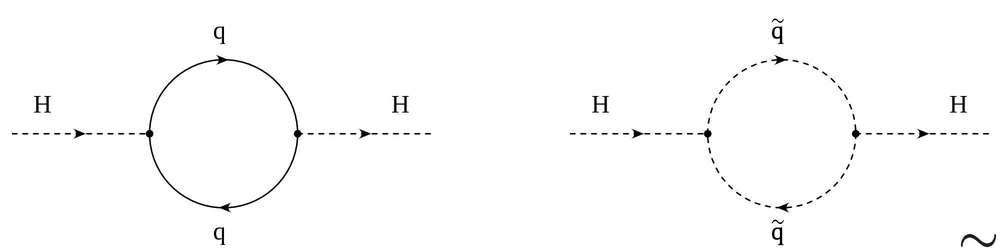
$\Rightarrow m_\text{h}$, m_H, mixing angle α, $m_{\text{H}^\pm}$: no free parameters

Spectrum of Higgs bosons in the MSSM (example)



large M_A: h^0 like SM Higgs boson $\sim$ decoupling regime

m_h^0 strongly influenced by quantum effects, *e.g.*



$\sim \alpha_t$

determination of masses and couplings at higher order

- physical states $h,\ H,\ A,\ H^\pm$
- conventional input: M_A, $\tan\beta = v_2/v_1$

dressed $h,\ H$ propagators, renormalized self-energies $\hat{\Sigma}$

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

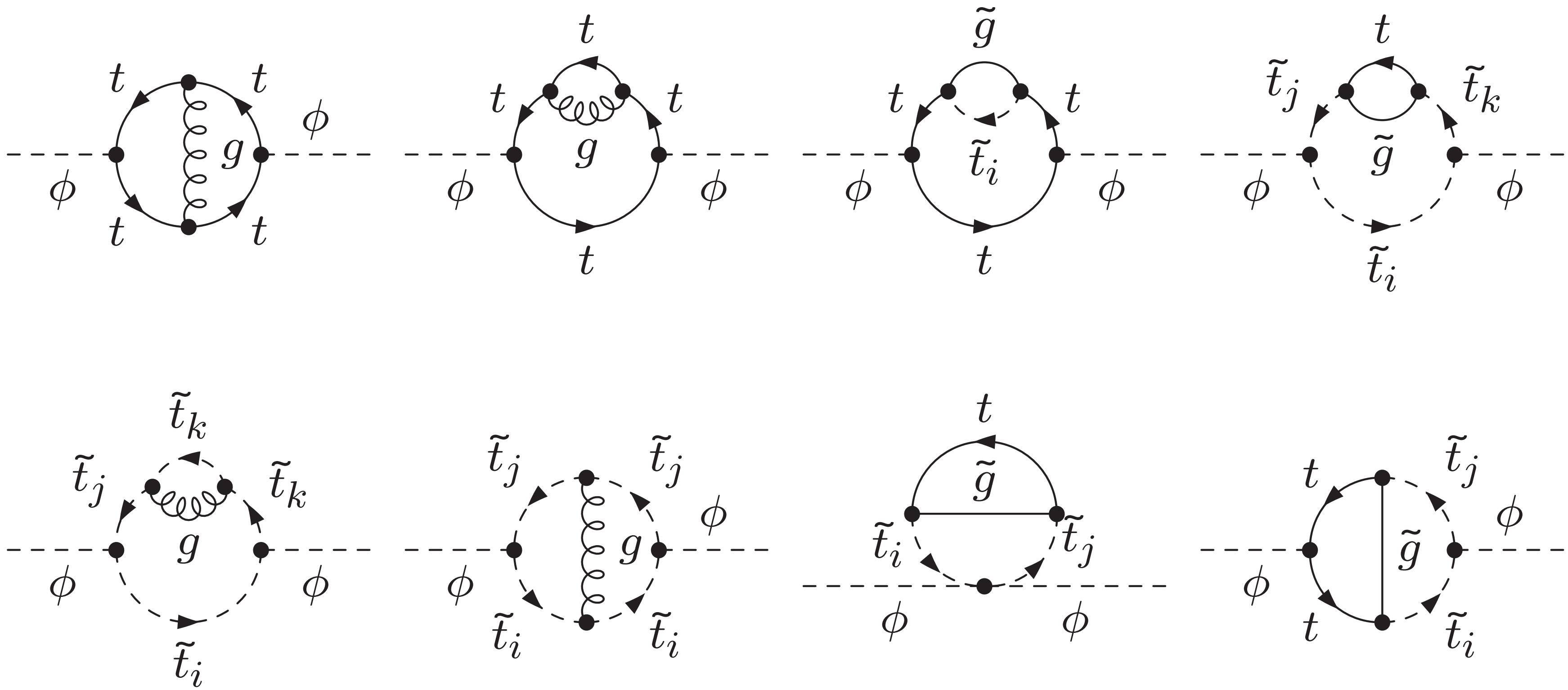
- det = 0 $\longrightarrow$ $m_{h,H}^{\rm pole}$

renormalized self energies:

$$\hat{\Sigma} = \Sigma + \text{counter terms}$$

Contributions to the 2-loop self-energy:

2-loop self-energy diagrams:



$\phi = h, H, A$

1-loop renormalization of t and of $\tilde{t}, \tilde{b}$ sector needed

- renormalization of M_A: $\delta M_A^2 = \Sigma_A(M_A^2)$
  on-shell conditon for pole mass

- renormalization of tadpoles:
  $T_h + \delta T_h = 0, \quad T_H + \delta T_H = 0$

- renormalization of $\tan\beta$:

$$\tan\beta = \frac{v_2}{v_1} \quad \to \quad \sqrt{\frac{Z_{H_2}}{Z_{H_1}}} \cdot \frac{v_2 + \delta v_2}{v_1 + \delta v_1}$$

$$= \quad \frac{v_2}{v_1}\left(1 + \delta Z_{H_2} - \delta Z_{H_1} + \frac{\delta v_2}{v_2} - \frac{\delta v_1}{v_1}\right)$$

$$\overline{DR} \qquad = 0$$

FeynHiggs $\longrightarrow$ *talk by H. Rzehak*

1-loop: complete

2-loop:

– QCD corrections $\sim \alpha_s \alpha_t,\ \alpha_s \alpha_b$

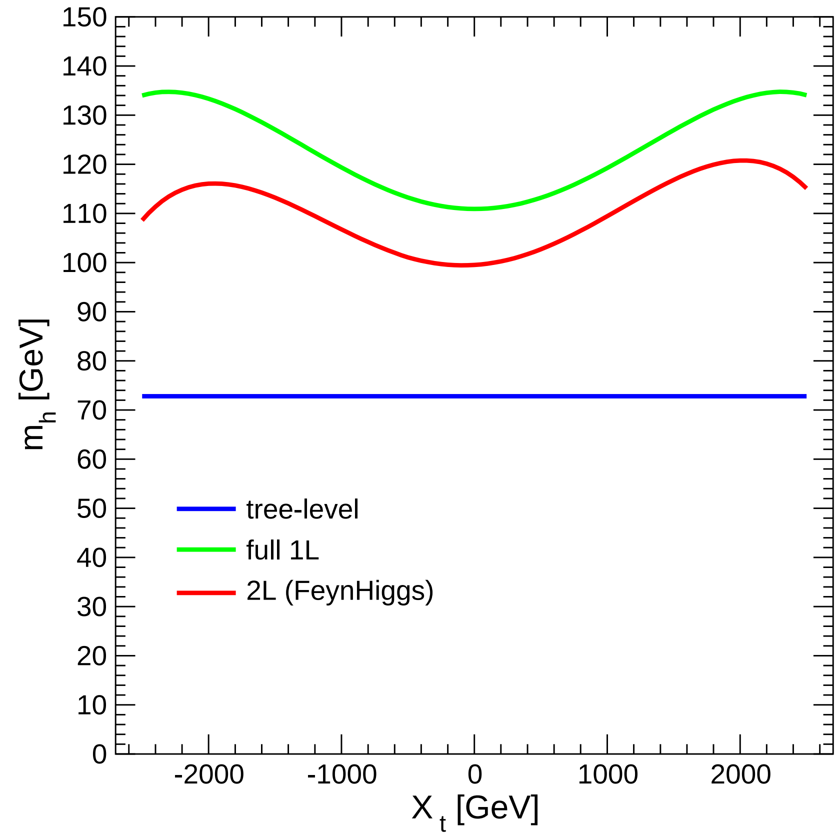
– Yukawa corrections $\sim \alpha_{t,b}^2$

theoretical uncertainty:

$\delta m_h \simeq$ 3-4 GeV

[Degrassi, Heinemeyer, WH, Slavich, Weiglein]

m_{h^0} prediction at different levels of accuracy:



$\tan\beta = 3$, $M_{\tilde{Q}} = M_A = 1$ TeV, $m_{\tilde{g}} = 800$ GeV

X_t : top-squark mixing parameter

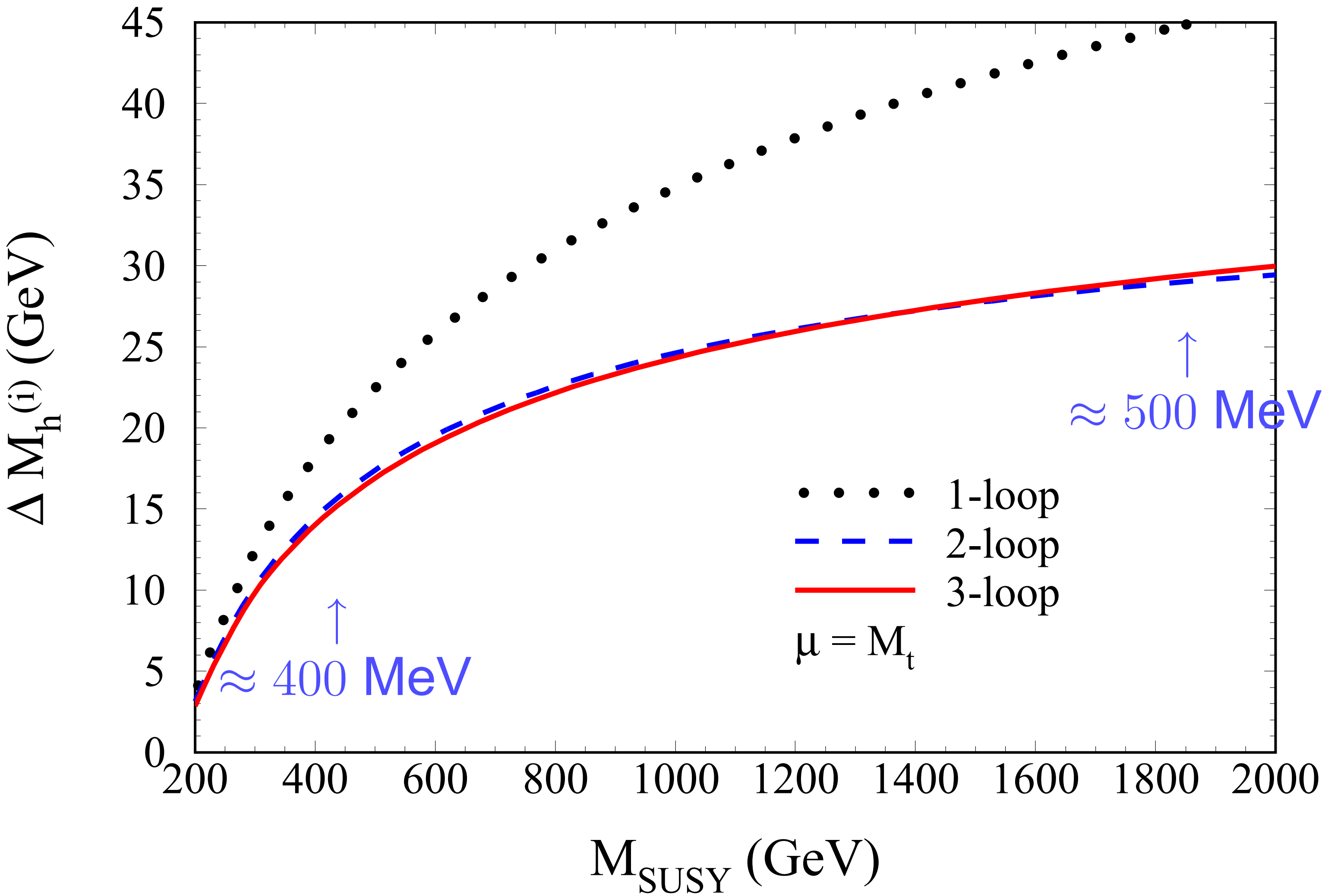
$$\mathrm{X_t} = \mathrm{A_t} - \mu \cot\beta$$

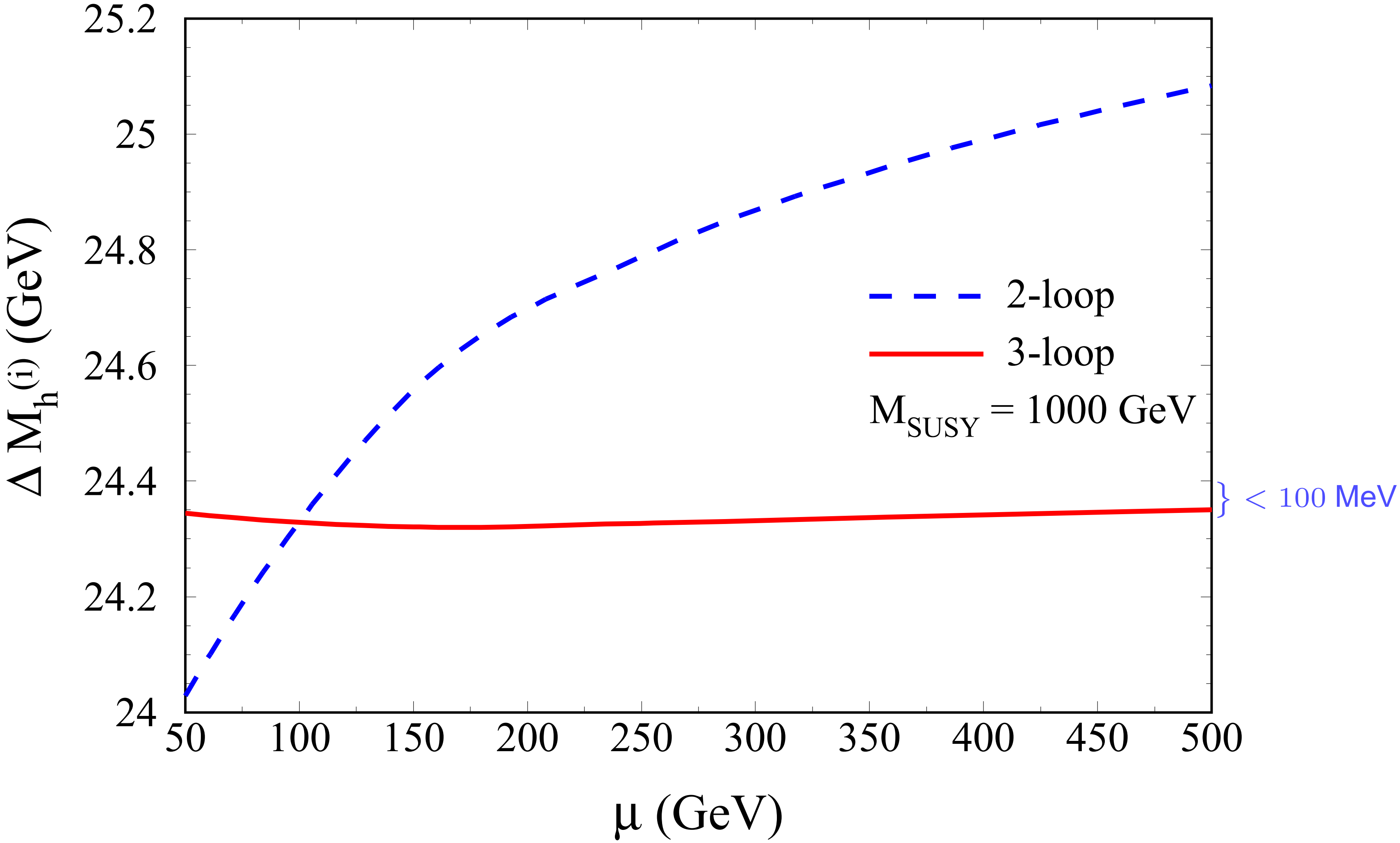
$X_\mathrm{t} = 0$: *no-mixing scenario*

at maximum: $m_h^{\max}$ *scenario*

3-loop contributions to $M_h \sim \alpha_s^2 \alpha_t$

[Harlander, Kant, Mihaila, Steinhauser]





25.2
25
24.8
24.6
24.4
24.2
24
50
100
150
200
250
300
350
400
450
500
$\Delta M_h^{(i)}$ (GeV)
μ (GeV)
2-loop
3-loop
M_{SUSY} = 1000 GeV
} < 100 MeV

couplings at higher order

dressed $h,\ H$ propagators

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

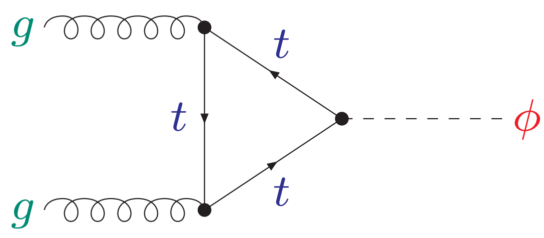
- det = 0 $\quad \longrightarrow \quad m_{h,H}^{\mathrm{pole}}$
- diagonalization $\quad \longrightarrow \quad$ effective couplings, q^2-dep.

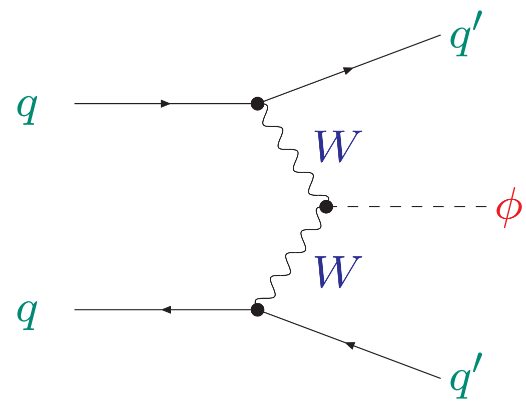
$\hat{\Sigma}(q^2) \to \hat{\Sigma}(0):$ rediagonalization with α_{eff}

$\alpha \to \alpha_{\mathrm{eff}}$ in tree-level couplings

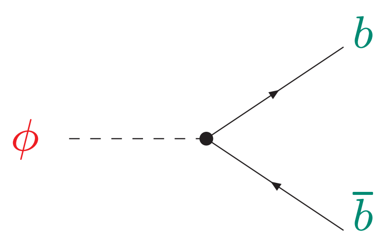
examples:

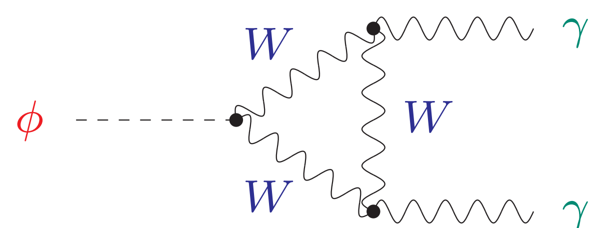
Higgs production:



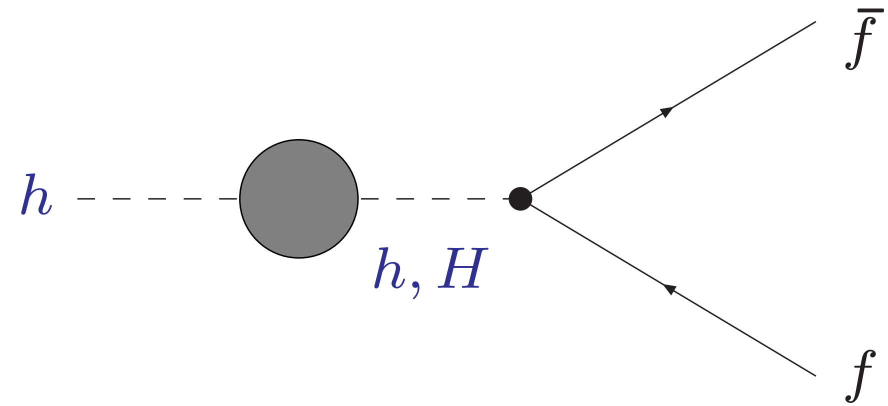


Higgs decays:





complete treatment:



h, H : loop-corrected (neutral $\mathcal{CP}$-even) Higgs bosons

Amplitude:

$$A(h \to f\bar{f}) = \sqrt{Z_h}\,(\Gamma_h + Z_{hH}\Gamma_H)$$

$\Gamma_{h,H}$: coupling of h, H to $f\bar{f}$

$$Z_i = \left[1 + \mathrm{Re}\,\hat{\Sigma}'_{ii}(p^2) - \mathrm{Re}\left(\frac{\left(\hat{\Sigma}_{ij}(p^2)\right)^2}{p^2 - m_j^2 + \hat{\Sigma}_{jj}(p^2)} \right)' \,\right]^{-1} \Bigg|_{p^2 = M_i^2}$$

$$Z_{ij} = -\frac{\hat{\Sigma}_{ij}(M_i^2)}{M_i^2 - m_j^2 + \hat{\Sigma}_{jj}(M_i^2)}$$

Z_i : residue at pole mass M_i, $i = h, H$

Z_{ij} : transition from i to j, $i, j = h, H$

$p^2 = 0$: equivalent to α_{eff}-approximation

Further theoretical progress:

1. Counterterms at two-loop order

   ST identities valid in dimensional reduction (DR)

   DR scheme consistent with symmetric counterterms

   [WH, Stöckinger]

2. $\mathcal{O}(\alpha_s\alpha_b)$ beyond $m_b^{\rm eff}$ approximation

   $m_b^{\rm eff} = \frac{m_b}{1-\Delta m_b} \quad \text{in} \quad \alpha_b$ Yukawa coupling

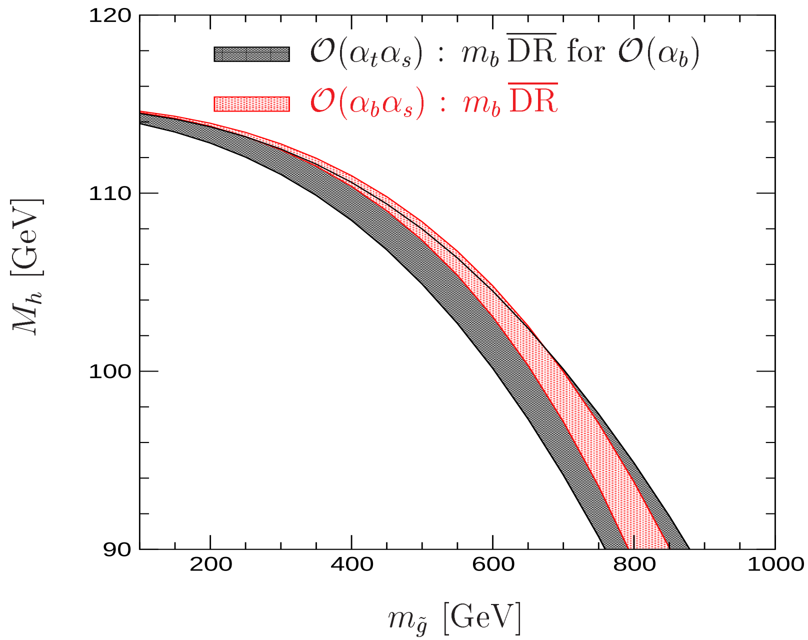
   $\Delta m_b =$ non-decoupling SUSY contribution $\sim \alpha_s \tan\beta$

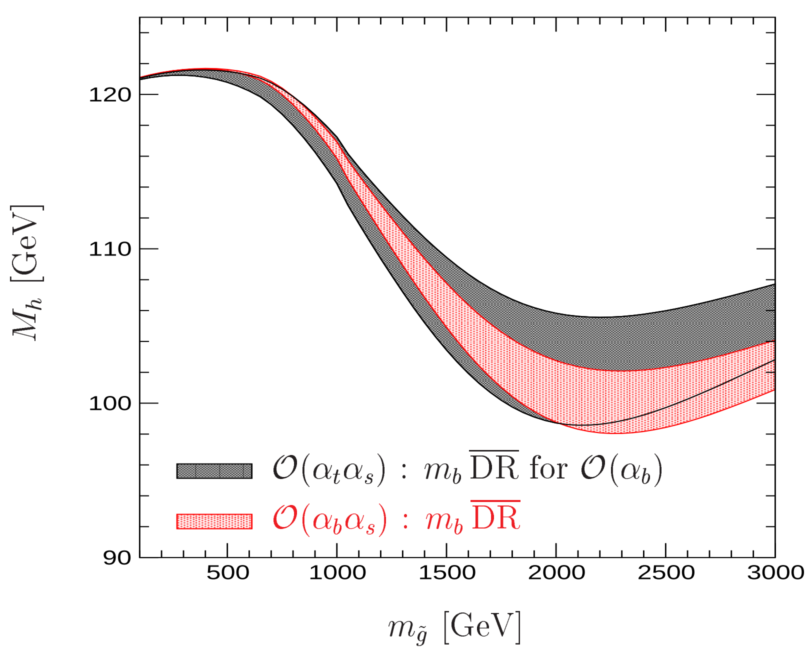
   [Heinemeyer, WH, Rzehak, Weiglein]

   small shifts $\sim$ few GeV, but stabilizes prediction

3. charged $H^\pm$ mass with two-loop terms $\sim \mathcal{O}(\alpha_s\alpha_t)$

   [Hahn, Heinemeyer, WH, Rzehak, Weiglein]





$$m_t/2 < \mu^{\overline{\mathrm{DR}}} < 2\,m_t$$

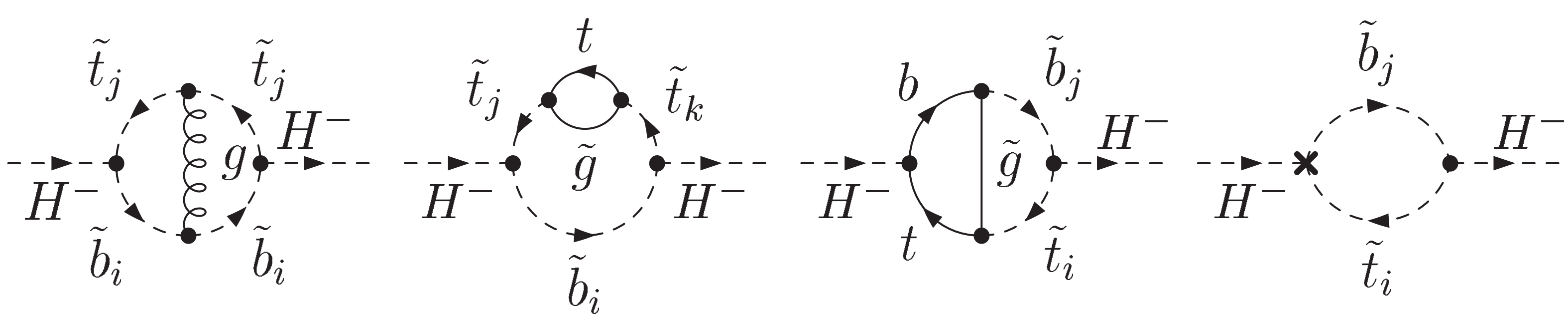
$$M_A = \begin{cases} 120\,\mathrm{GeV} \\ 700\,\mathrm{GeV} \end{cases}$$

charged Higgs boson mass

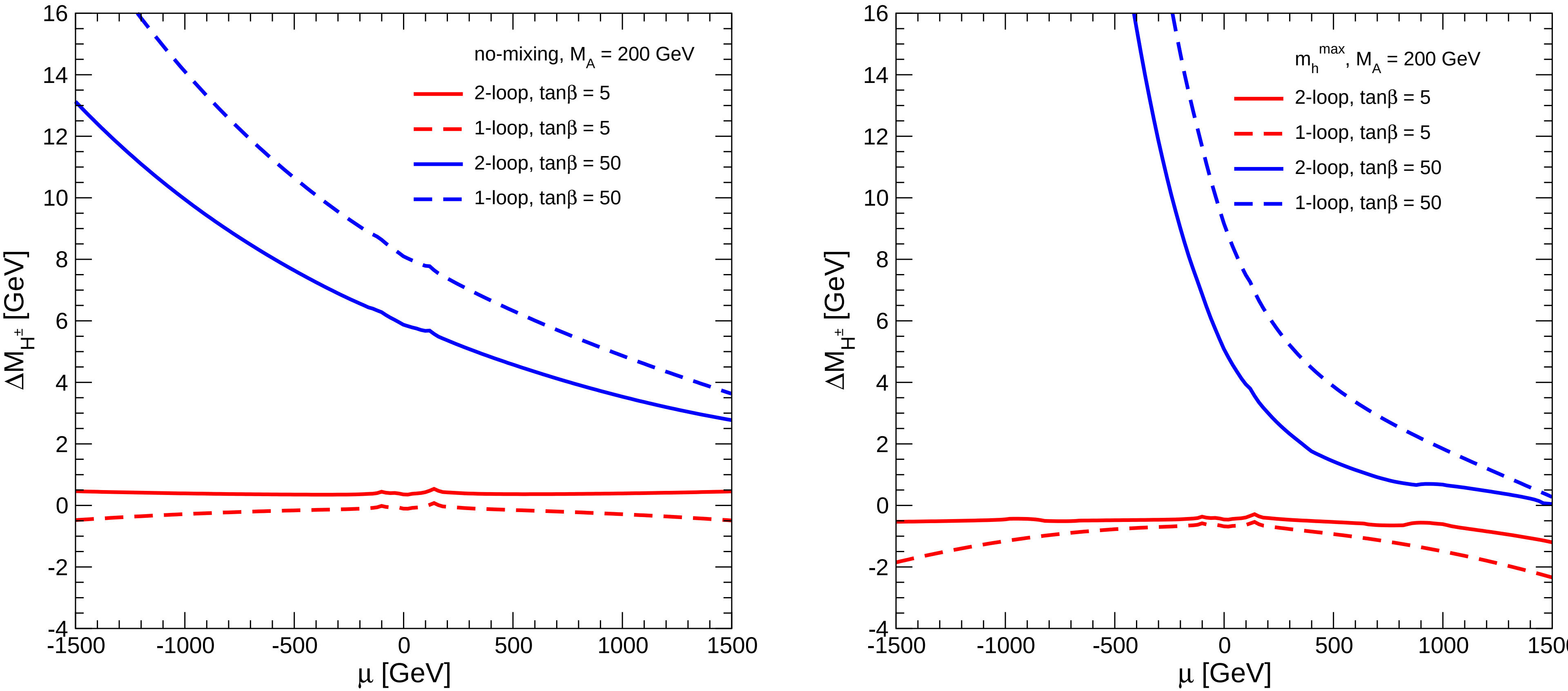
$$M_{H^\pm}^{(0)} = \sqrt{M_Z^2 + M_A^2}$$

$$M_{H^\pm} = M_{H^\pm}^{(0)} + \Delta M_{H^\pm}^{(1)} + \Delta M_{H^\pm}^{(2)}$$

two-loop contributions $\sim \mathcal{O}(\alpha_s \alpha_t)$ [examples]



charged Higgs boson mass shift



Higgs bosons in the complex MSSM

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^* \{\cot\beta, \tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– M_3 : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

renormalized self energies:

$$\hat{\Sigma} = \Sigma + \text{counter terms}$$

- renormalization of tadpoles:
  $T_h + \delta T_h = 0, \quad T_H + \delta T_H = 0, \quad T_A + \delta T_A = 0$

- renormalization of $M_{H^\pm}$: $\quad \delta M^2_{H^\pm} = \Sigma_{H^\pm}(M^2_{H^\pm})$
  on-shell conditon for pole mass

- renormalization of $\tan\beta$:

$$\tan\beta = \frac{v_2}{v_1} \quad \rightarrow \quad \sqrt{\frac{Z_{H_2}}{Z_{H_1}}} \cdot \frac{v_2 + \delta v_2}{v_1 + \delta v_1}$$

$$= \quad \frac{v_2}{v_1}\left(1 + \delta Z_{H_2} - \delta Z_{H_1} + \frac{\delta v_2}{v_2} - \frac{\delta v_1}{v_1}\right)$$

$$\overline{DR} \qquad\qquad = 0$$

propagator matrix Δ:

$$\boxed{\Delta^{-1}(q^2) = q^2\,\mathbf{1} - \mathbf{m}^2_{\text{tree}} + \hat{\mathbf{\Sigma}}(q^2)}$$

$$\begin{pmatrix} q^2 - M_A^2 + \hat{\Sigma}_{AA}(q^2) & \hat{\Sigma}_{AH}(q^2) & \hat{\Sigma}_{Ah}(q^2) \\ \hat{\Sigma}_{HA}(q^2) & q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ \hat{\Sigma}_{hA}(q^2) & \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H, A)$: renormalized Higgs self-energies

$\hat{\Sigma}_{Ah}, \hat{\Sigma}_{AH} \neq 0 \Rightarrow \mathcal{CP}$V, $\mathcal{CP}$-even and $\mathcal{CP}$-odd fields can mix

$\rightarrow$ sizeable effects on masses and couplings

present status:

effective potential approximation + RGE

[Carena, Ellis, Pilaftsis, Wagner]

complete at one-loop order

[Frank, Hahn, Heinemeyer, WH, Rzehak, Weiglein]

leading two-loop contributions of $\mathcal{O}(\alpha_s \alpha_t)$

[Heinemeyer, WH, Rzehak, Weiglein]

leading two-loop terms $\mathcal{O}(\alpha_t^2)$ by interpolation

$$\boxed{\hat{\Sigma}(q^2) = \hat{\Sigma}^{(1-\text{loop})}(q^2) + \hat{\Sigma}^{(2-\text{loop})}(0)}$$

stop and sbottom renormalization required at 1-loop level

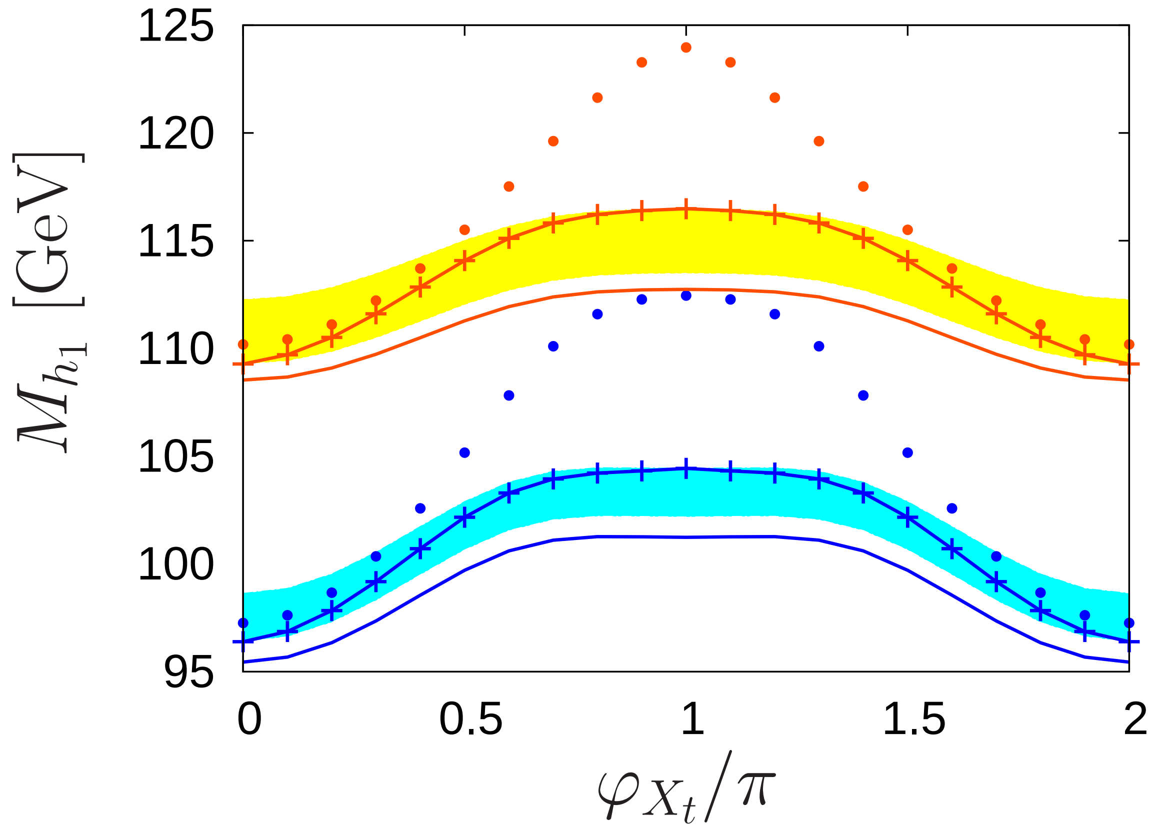
$$\mathbf{M}_{\tilde{q}} = \begin{pmatrix} M_L^2 + m_q^2 + M_Z^2 c_{2\beta}(T_q^3 - Q_q s_\mathrm{w}^2) & m_q X_q^* \\ m_q X_q & M_{\tilde{q}_R}^2 + m_q^2 + M_Z^2 c_{2\beta} Q_q s_\mathrm{w}^2 \end{pmatrix}$$

with

$$X_q = A_q - \mu^* \kappa \ , \qquad \kappa = \{\cot\beta, \tan\beta\} \quad \text{for} \quad q = t, b$$

$\Rightarrow$ Mass eigenvalues $m_{\tilde{q}_1}^2$, $m_{\tilde{q}_2}^2$, mixing angle $\theta_{\tilde{q}}$, phase $\varphi_{\tilde{q}}$

complex phases important at the two-loop level
$\rightarrow$ dependence on phases of $A_t\ (X_t)$, $m_{\tilde{g}}$



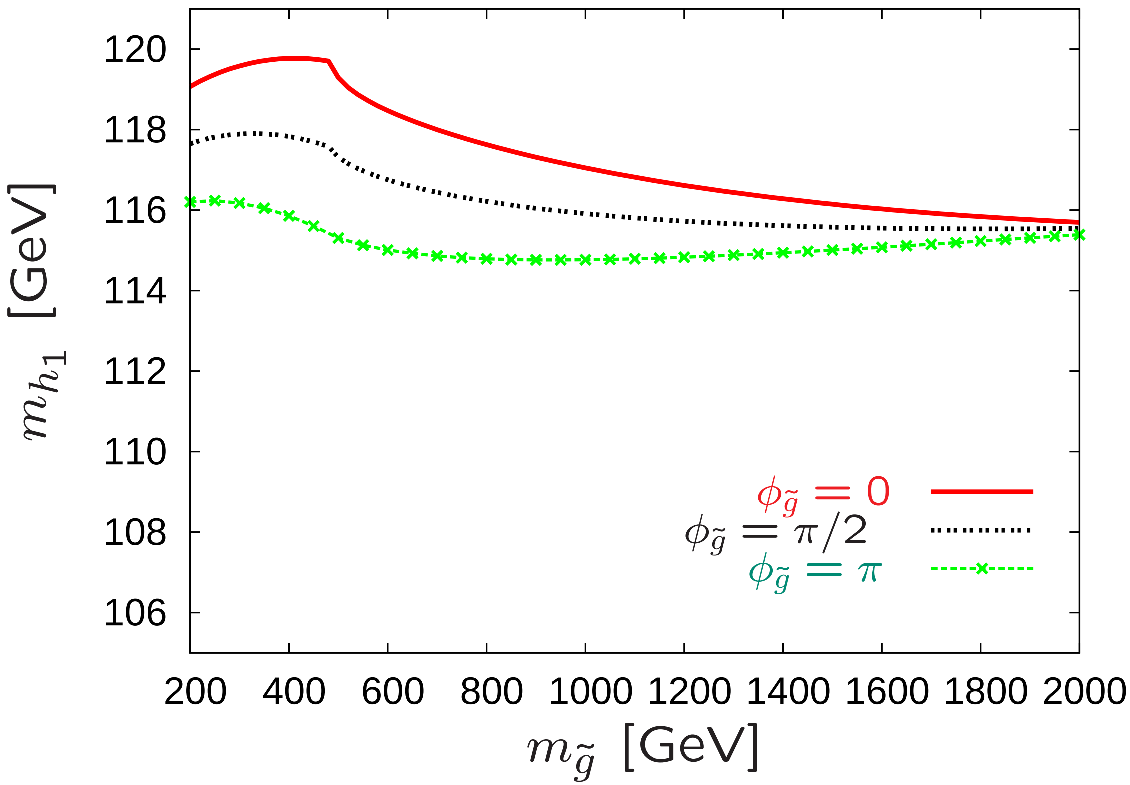
$\mathcal{O}(\alpha)$: $\tan\beta = 5$ ● ● $\tan\beta = 15$

$\mathcal{O}(\alpha + \alpha_t\alpha_s)$: $\tan\beta = 5$ $\tan\beta = 15$

$\mathcal{O}(\alpha + \alpha_t\alpha_s)$ + interpol. : $\tan\beta = 5$ (lower curves) $\tan\beta = 15$ (upper curves)

width of band: theoretical uncertainty

m_{h_1} as a function of $\phi_{\tilde{g}}$:



$M_{\text{SUSY}} = 500$ GeV
$A_t = 1000$ GeV
$\tan\beta = 10$
$M_{H^\pm} = 500$ GeV

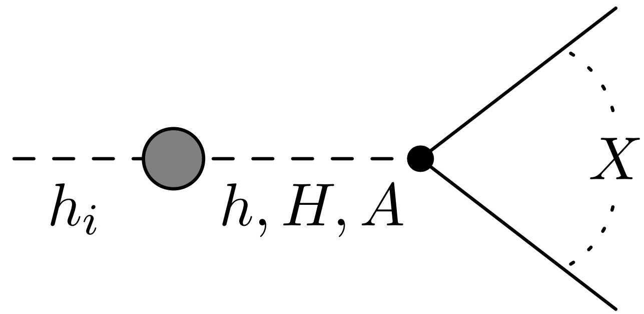
OS renormalization

$\Rightarrow$ threshold at $m_{\tilde{g}} = m_{\tilde{t}} + m_t$

$\Rightarrow$ large effects around threshold

$\Rightarrow$ phase dependence has to be taken into account

couplings at higher order



$$\Gamma_{h_1} = \sqrt{Z_h}\big(\Gamma_h + Z_{hH}\Gamma_H + Z_{hA}\Gamma_A\big)$$
$$\Gamma_{h_2} = \sqrt{Z_H}\big(Z_{Hh}\Gamma_h + \Gamma_H + Z_{HA}\Gamma_A\big)$$
$$\Gamma_{h_3} = \sqrt{Z_A}\big(Z_{Ah}\Gamma_h + Z_{AH}\Gamma_H + \Gamma_A\big)$$

approximation: $\hat{\Sigma}(0)$

[$\longrightarrow$ see talk by H. Rzehak]

$$\boxed{\;\boldsymbol{\Delta}^{-1}(p^2) \;\equiv\; \hat{\boldsymbol{\Gamma}}(p^2) \;=\; p^2\,\mathbf{1} - \mathbf{m}^2_{\text{tree}} + \hat{\boldsymbol{\Sigma}}(p^2)}$$

$$\Delta_{ii}(p^2) = \frac{i}{p^2 - m_i^2 + \hat{\Sigma}^{\text{eff}}_{ii}(p^2)},$$

$$\hat{\Sigma}^{\text{eff}}_{ii}(p^2) = \hat{\Sigma}_{ii}(p^2) - i\frac{2\hat{\Gamma}_{ij}(p^2)\hat{\Gamma}_{jk}(p^2)\hat{\Gamma}_{ki}(p^2) - \hat{\Gamma}^2_{ki}(p^2)\hat{\Gamma}_{jj}(p^2) - \hat{\Gamma}^2_{ij}(p^2)\hat{\Gamma}_{kk}(p^2)}{\hat{\Gamma}_{jj}(p^2)\hat{\Gamma}_{kk}(p^2) - \hat{\Gamma}^2_{jk}(p^2)}$$

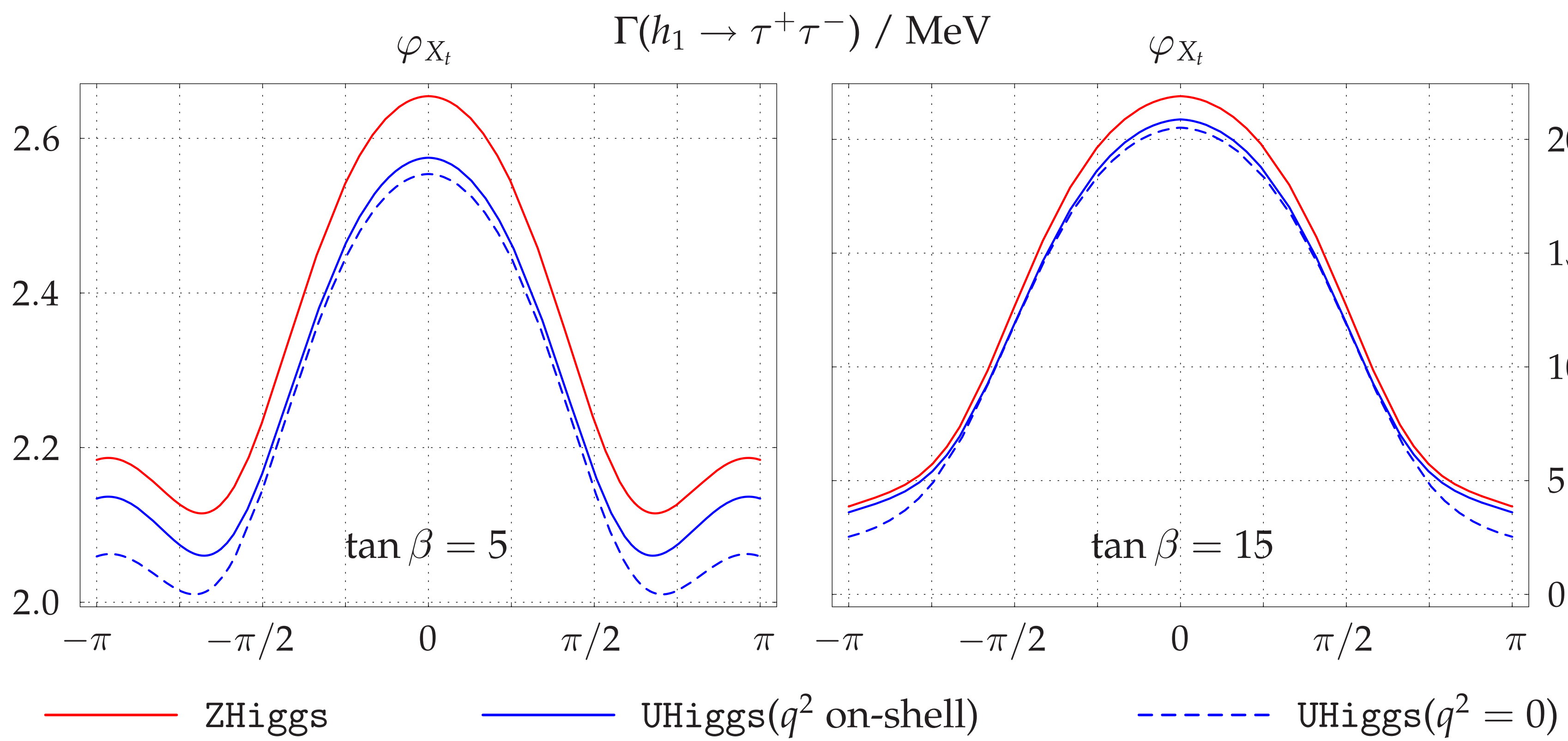
$$\Delta_{ij}(p^2) = \frac{\hat{\Gamma}_{ij}\hat{\Gamma}_{kk} - \hat{\Gamma}_{jk}\hat{\Gamma}_{ki}}{\hat{\Gamma}_{ii}\hat{\Gamma}_{jj}\hat{\Gamma}_{kk} + 2\hat{\Gamma}_{ij}\hat{\Gamma}_{jk}\hat{\Gamma}_{ki} - \hat{\Gamma}_{ii}\hat{\Gamma}^2_{jk} - \hat{\Gamma}_{jj}\hat{\Gamma}^2_{ki} - \hat{\Gamma}_{kk}\hat{\Gamma}^2_{ij}}$$

in amplitudes with a Higgs boson h_i:

$$\sqrt{\hat{Z}_i}\left(\Gamma_i \;+\; \hat{Z}_{ij}\Gamma_j \;+\; \hat{Z}_{ik}\Gamma_k \;+\; \cdots\right)$$

$$\hat{Z}_i = \frac{1}{1 + \left(\text{Re}\hat{\Sigma}^{\text{eff}}_{ii}\right)'(M_i^2)}$$

$$\hat{Z}_{ij} = \frac{\Delta_{ij}(p^2)}{\Delta_{ii}(p^2)}\Bigg|_{p^2 = M_i^2} = \frac{\hat{\Sigma}_{ij}(M_i^2)\left(M_i^2 - m_k^2 + \hat{\Sigma}_{kk}(M_i^2)\right) - \hat{\Sigma}_{jk}(M_i^2)\hat{\Sigma}_{ki}(M_i^2)}{\hat{\Sigma}^2_{jk}(M_i^2) - \left(M_i^2 - m_j^2 + \hat{\Sigma}_{jj}(M_i^2)\right)\left(M_i^2 - m_k^2 + \hat{\Sigma}_{kk}(M_i^2)\right)}$$

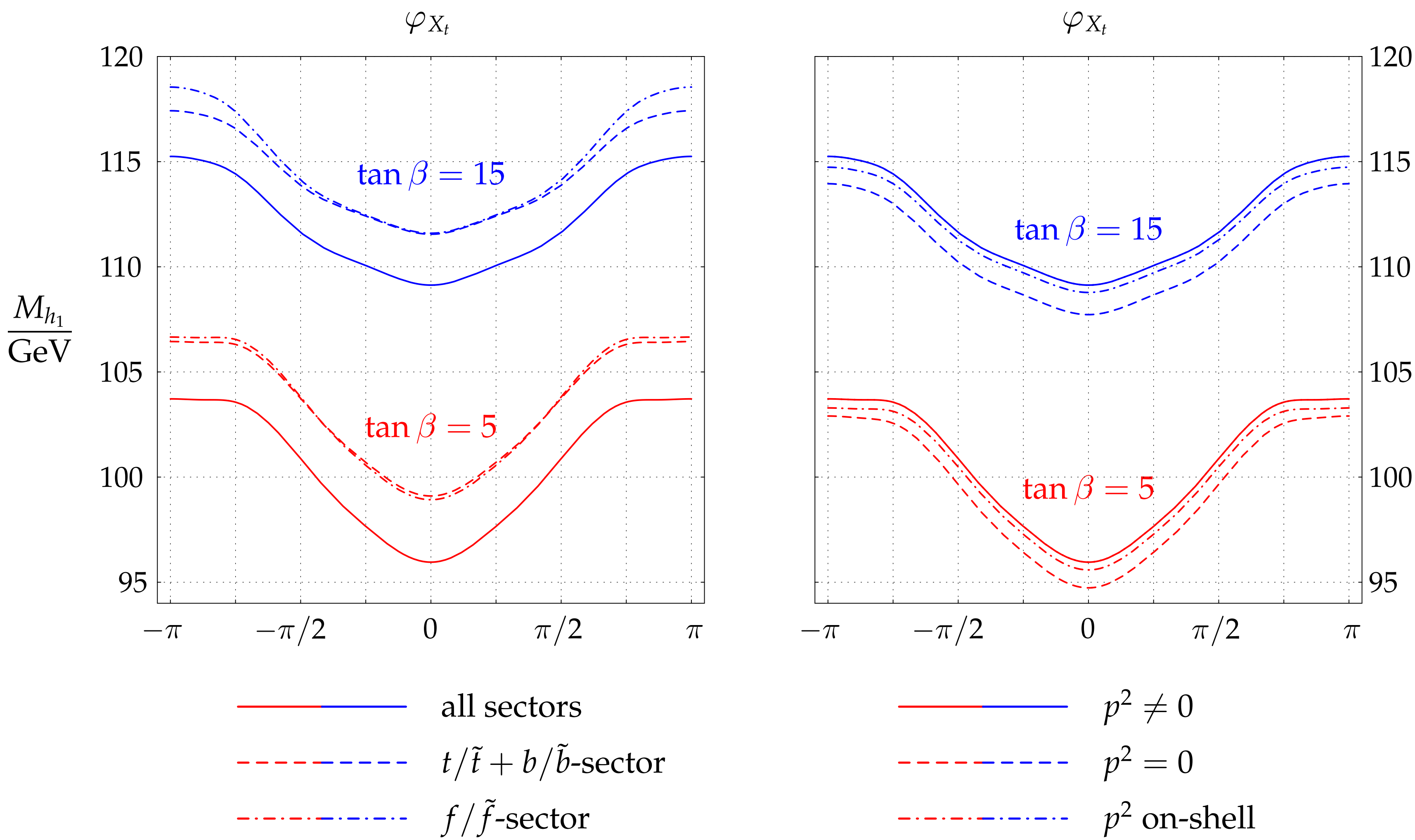


$\Gamma(h_1 \to \tau^+\tau^-)$ / MeV
φ_{X_t}
φ_{X_t}
2.6
2.4
2.2
2.0
20
15
10
5
0
$\tan\beta = 5$
$\tan\beta = 15$
$-\pi$
$-\pi/2$
0
$\pi/2$
π
$-\pi$
$-\pi/2$
0
$\pi/2$
π
ZHiggs
UHiggs(q^2 on-shell)
UHiggs($q^2 = 0$)

Summary

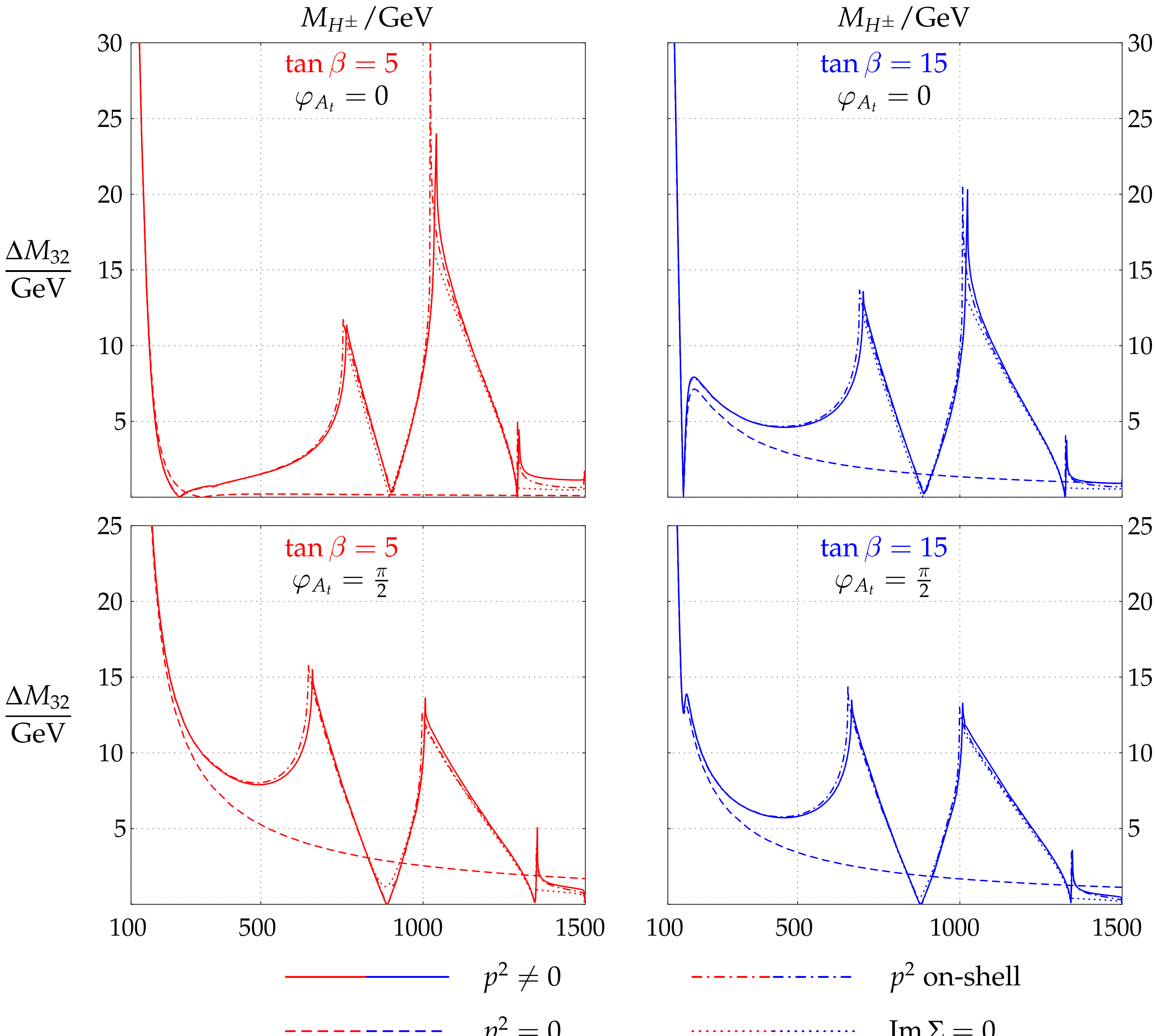
- Electroweak precision observables
  $\rightarrow$ sensitive to quantum structure
  $\rightarrow$ constraints on unknown parameters
- MSSM is competitive to the SM
  – global fits of similar quality (even better)
  – natural: light Higgs boson h^0
- mass of light h^0 is another precision observable
  – exp. accuracy $\sim \mathcal{O}(0.1\ \mathrm{GeV})$
  – theoretical uncertainty $\sim$ 3 GeV
- complex MSSM $\rightarrow$ CP-violating Higgs sector
  – mixing between h^0, H^0, and A^0
  – significant changes in masses and couplings

Backup pages

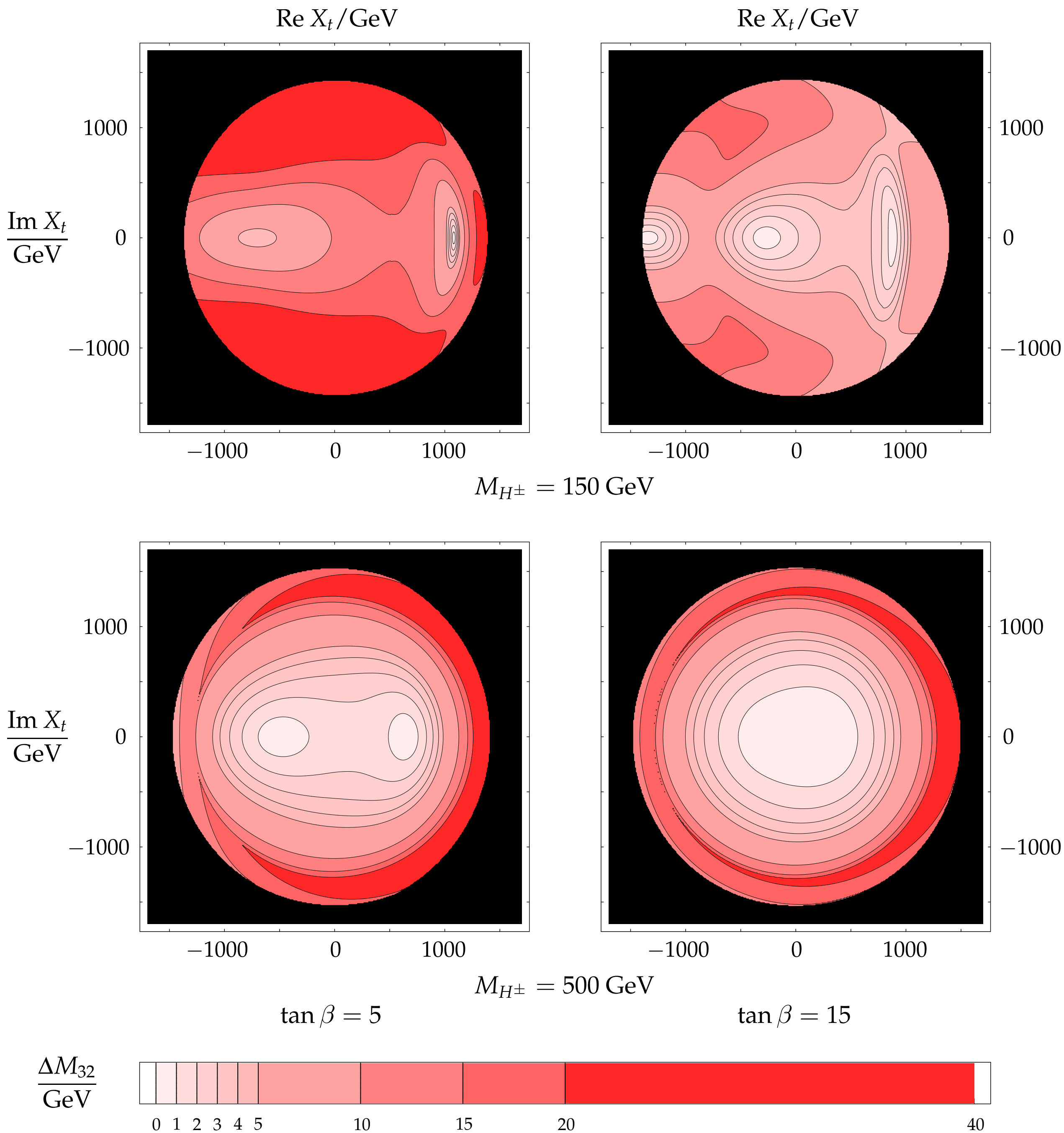


[Frank, Hahn, Heinemeyer, WH, Rzehak, Weiglein]

$$M_{\text{SUSY}} = 500,\ A_f = 1000,\ \mu = 1000,\ M_{H^\pm} = 150 \quad \text{GeV}$$



$M_{H^\pm}$ /GeV
$M_{H^\pm}$ /GeV
$\tan\beta = 5$
$\varphi_{A_t} = 0$
$\tan\beta = 15$
$\varphi_{A_t} = 0$
$\tan\beta = 5$
$\varphi_{A_t} = \frac{\pi}{2}$
$\tan\beta = 15$
$\varphi_{A_t} = \frac{\pi}{2}$
$\frac{\Delta M_{32}}{\mathrm{GeV}}$
$\frac{\Delta M_{32}}{\mathrm{GeV}}$
30
25
20
15
10
5
100
500
1000
1500
$p^2 \neq 0$
p^2 on-shell
$p^2 = 0$
$\mathrm{Im}\,\Sigma = 0$



Re X_t/GeV
Re X_t/GeV
Im X_t / GeV
1000
0
−1000
−1000
0
1000
$M_{H^\pm} = 150$ GeV
$M_{H^\pm} = 500$ GeV
tan $\beta = 5$
tan $\beta = 15$
ΔM_{32} / GeV
0 1 2 3 4 5 10 15 20 40