SUSY Phenomenology –

Precise predictions from the MSSM for colliders

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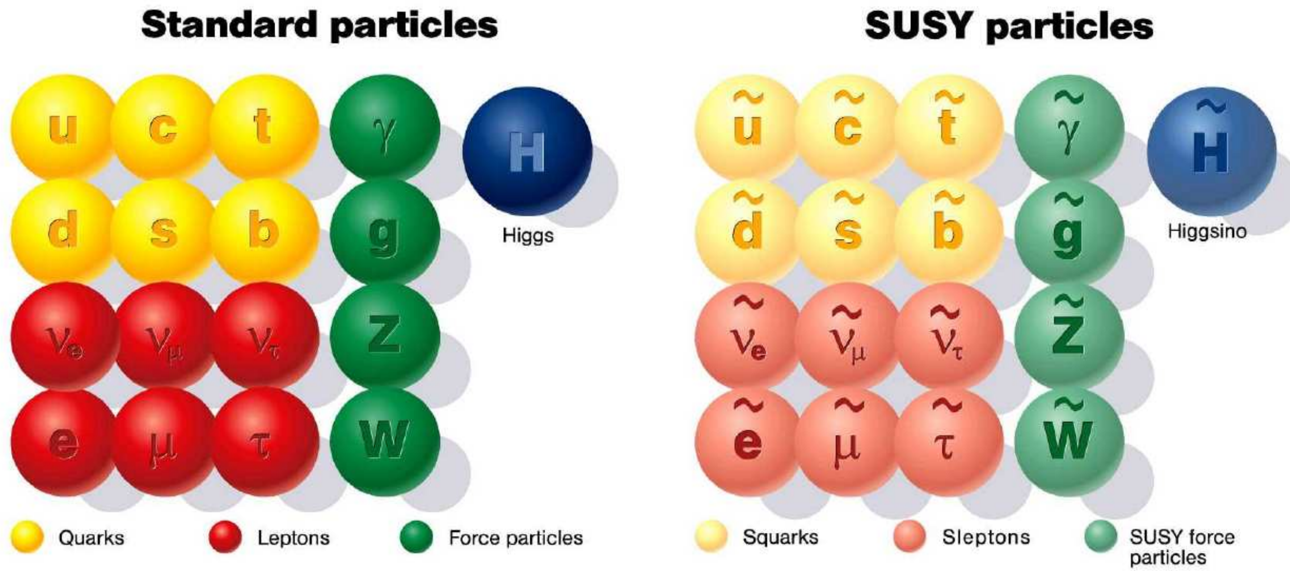
Outline

- Indirect SUSY search through precision observables
- Implications on Higgs bosons
- Direct study of SUSY particles
- Summary



- gauge coupling unification
- stabilization of the electroweak scale
- dark matter candidate (lightest SUSY particle)
- lightest Higgs boson h^0 < 135 GeV
  physical Higgs bosons: $h^0,\ H^0,\ A^0,\ H^\pm$

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \quad \tilde{\chi}_{1,2}^{\pm} \quad \tilde{\chi}_{1,2,3,4}^{0} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

masses and mixing of SUSY particles through soft-breaking

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 $\tilde{f}$
  $\rightarrow$ L-R sfermion mixing
- supersymmetric Higgsino mass parameter: μ
- Higgs sector parameters: $M_A,\ \tan\beta = v_2/v_1$

Precision analysis required for

- indirect tests of SUSY through
  $\rightarrow$ virtual SUSY effects in precision observables
- precision studies for SUSY particles
  $\rightarrow$ determination of masses & couplings
  $\rightarrow$ reconstruction of model parameters
- direct *versus* indirect tests
  $\rightarrow$ precision observables for precisely measured SUSY parameters
  $\rightarrow$ consistency check

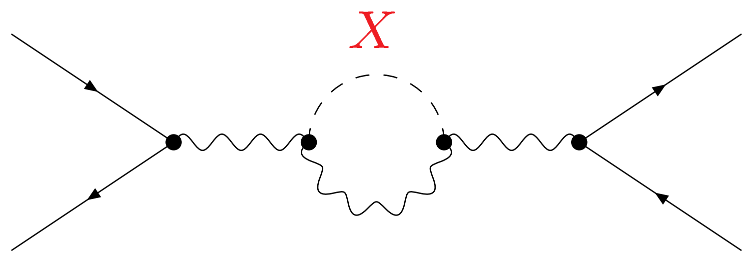
Processes with external

(i) standard particles

(ii) Higgs bosons, especially light Higgs h^0

(iii) SUSY particles

precision observables in the MSSM



X = Higgs bosons, SUSY particles

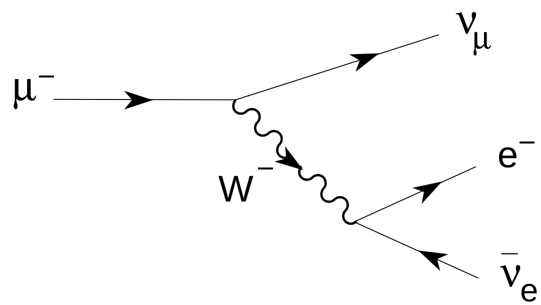
- μ lifetime: $M_W \leftrightarrow M_Z,\, G_\mathrm{F}$
- Z observables: $g_V,\, g_A,\, \sin^2\theta_\mathrm{eff},\, \Gamma_Z,\, M_Z,\, \ldots$

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

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

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

$M_W - M_Z$ correlation



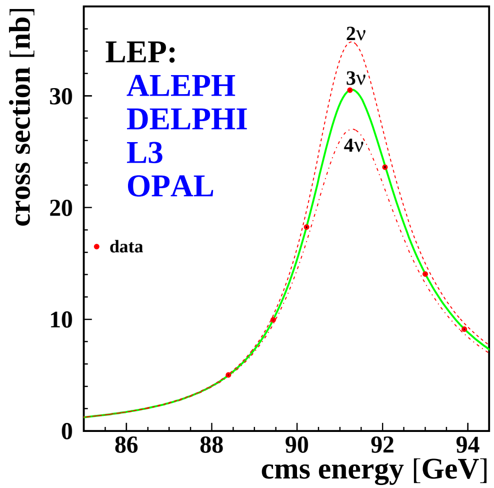
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{M_W^2\left(1 - M_W^2/M_Z^2\right)}\left(1 + \Delta r\right)$$

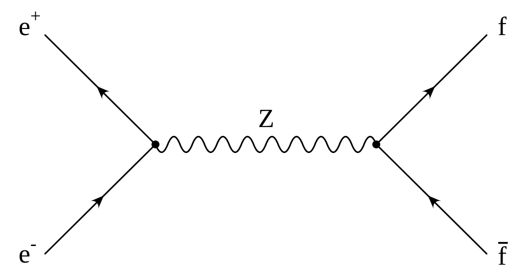
$\Delta r :$ quantum correction, $\Delta r = \Delta r(m_t, X_{\rm SUSY})$

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

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

Z resonance





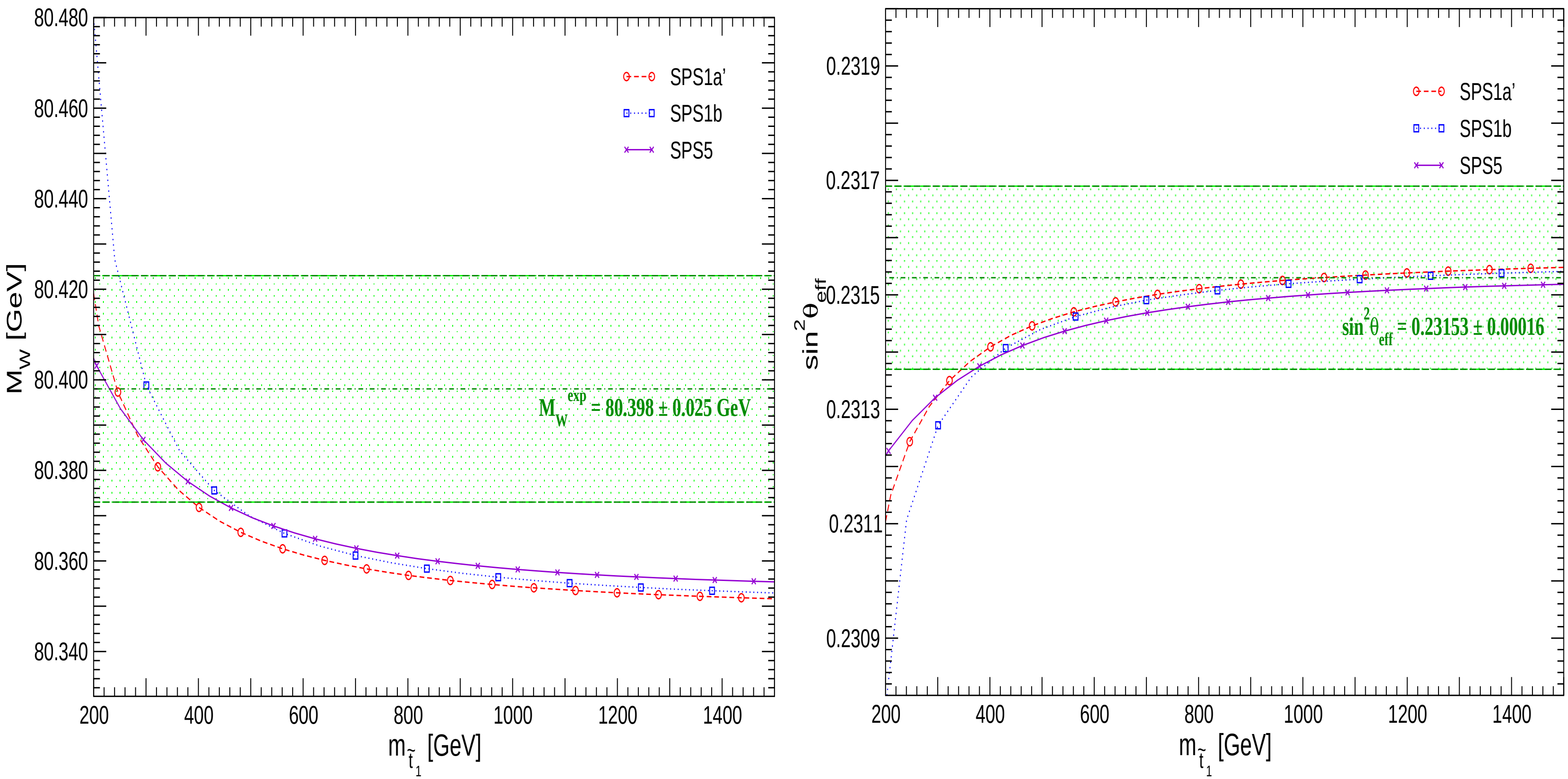
effective Z boson couplings

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

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

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

M_W and $\sin^2\theta_{\rm eff}$ 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*

Benchmark scenarios

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

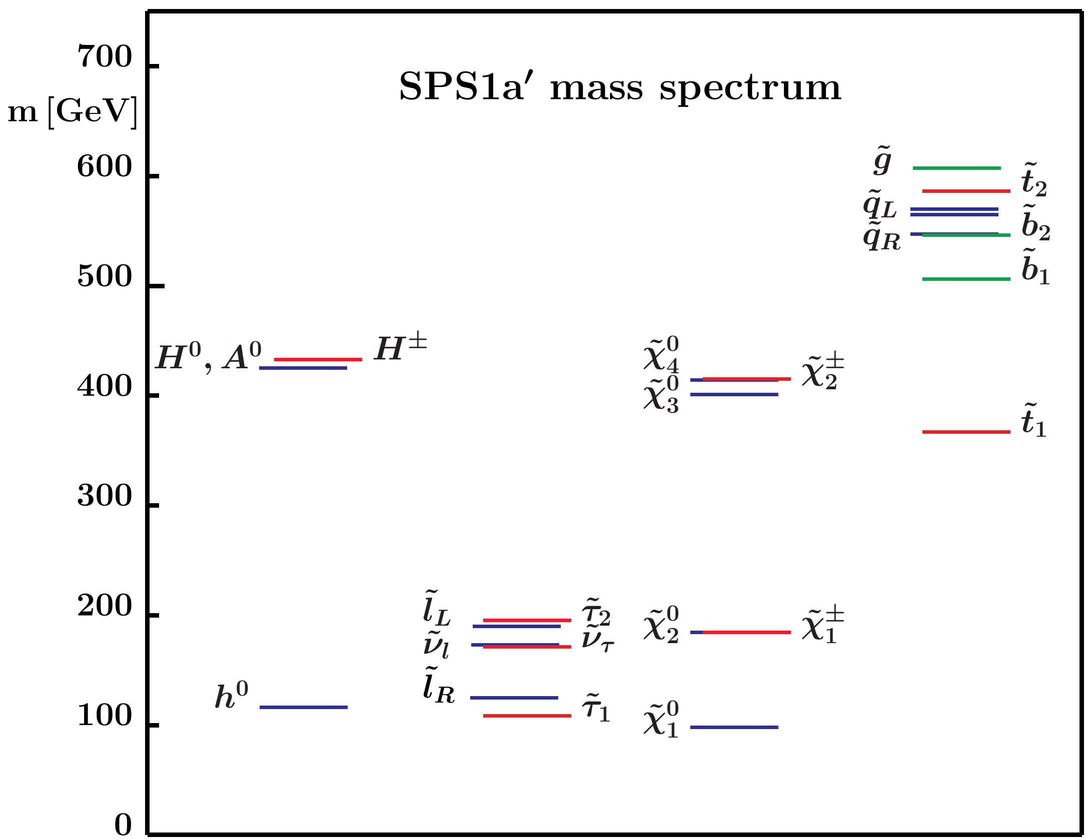
examples (mSUGRA):

- 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, $A_0 = 0$,
  $\tan\beta = 30$, $\mu > 0$.

SPS1a′ scenario *[SPA Report, hep-ph/0511344]*

$M_{1/2}$	$=$	250 GeV	sign(μ)	$=$	$+1$
M_0	$=$	70 GeV	$\tan\beta(\tilde{M})$	$=$	10
A_0	$=$	-300 GeV			

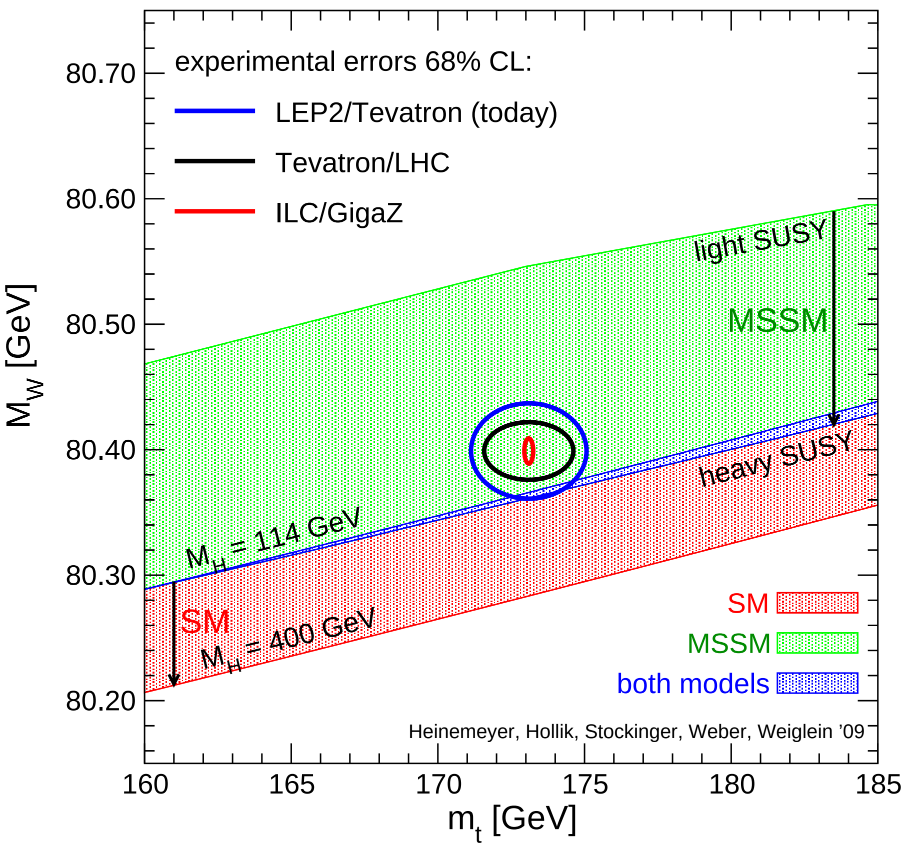


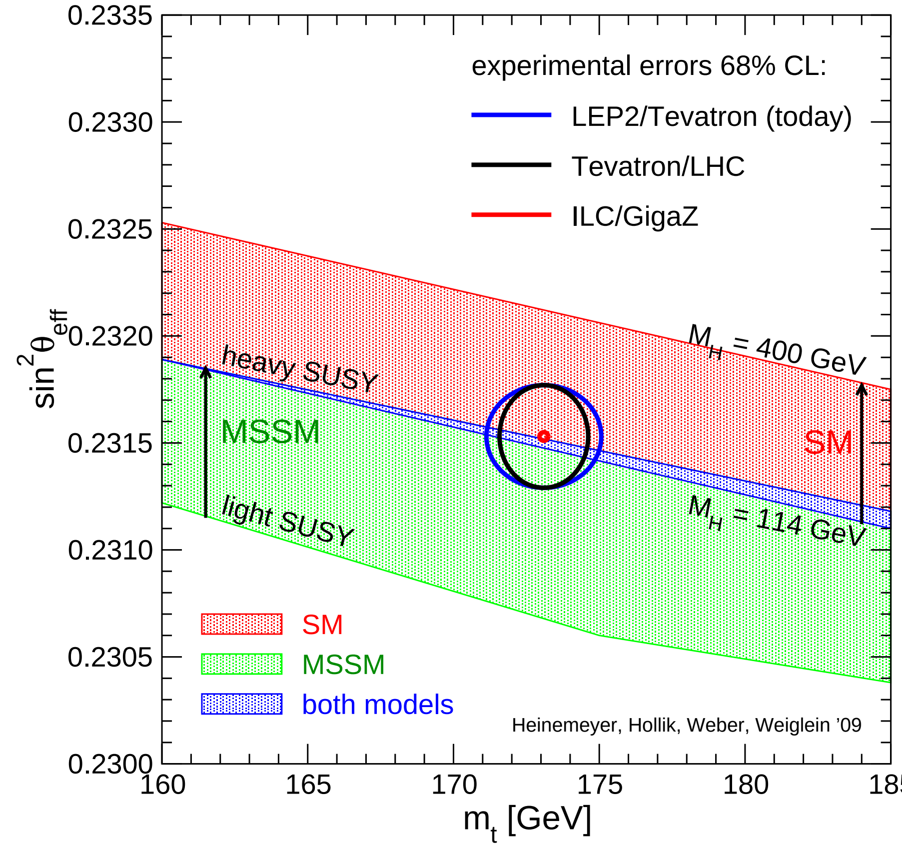
Scatter plots for M_W *&* $\sin^2\theta_{\rm eff}$

- SUSY parameters:

$$
\begin{aligned}
\text{sleptons} &: \quad M_{\tilde{F},\tilde{F}'} = 100\ldots2000\ \text{GeV} \\
\text{light squarks} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100\ldots2000\ \text{GeV} \\
\tilde{t}/\tilde{b}\ \text{doublet} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100\ldots2000\ \text{GeV} \\
& \quad\;\; A_{t,b} = -2000\ldots2000\ \text{GeV} \\
\text{gauginos} &: \quad M_{1,2} = 100\ldots2000\ \text{GeV} \\
& \quad\;\; m_{\tilde{g}} = 195\ldots1500\ \text{GeV} \\
& \quad\;\; \mu = -2000\ldots2000\ \text{GeV} \\
\text{Higgs} &: \quad M_A = 90-1000\ \text{GeV} \\
& \quad\;\; \tan\beta = 1.1\ldots60
\end{aligned}
$$

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


experimental errors 68% CL:
LEP2/Tevatron (today)
Tevatron/LHC
ILC/GigaZ
light SUSY
MSSM
heavy SUSY
M_H = 114 GeV
SM
M_H = 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '09
M_W [GeV]
m_t [GeV]
80.20
80.30
80.40
80.50
80.60
80.70
160
165
170
175
180
185


experimental errors 68% CL:
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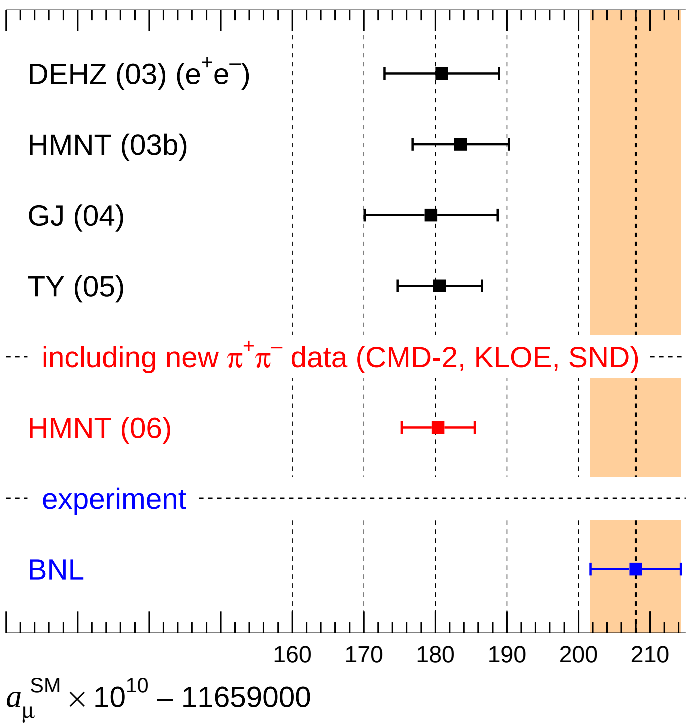
M_H = 400 GeV
heavy SUSY
MSSM
SM
light SUSY
M_H = 114 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Weber, Weiglein '09
sin²θ_eff
m_t [GeV]
0.2300
0.2305
0.2310
0.2315
0.2320
0.2325
0.2330
0.2335
160
165
170
175
180
185

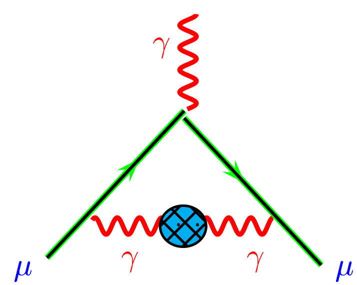
Anomalous g-factor of the muon



Hagiwara,Martin,Nomura,Teubner

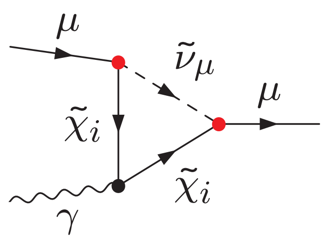
e^+e^- data based SM prediction: 3.4 σ below exp. value

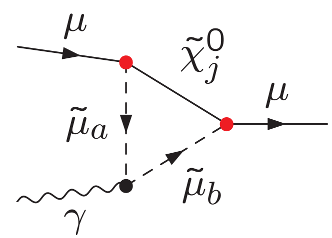
theory uncertainty from hadronic vacuum polarization



$g-2$ with supersymmetry

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





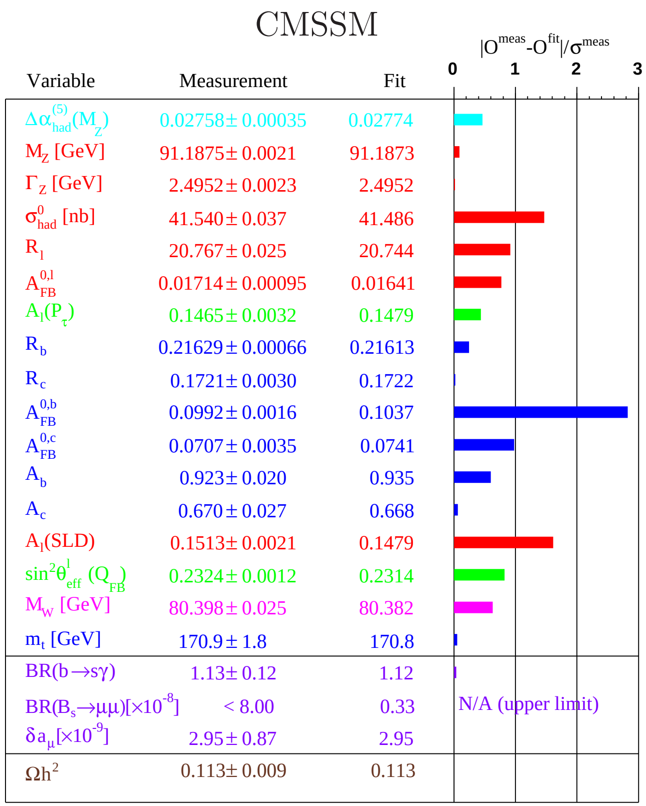
extra terms *[Czarnecki, Marciano]*

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

can provide missing contribution for

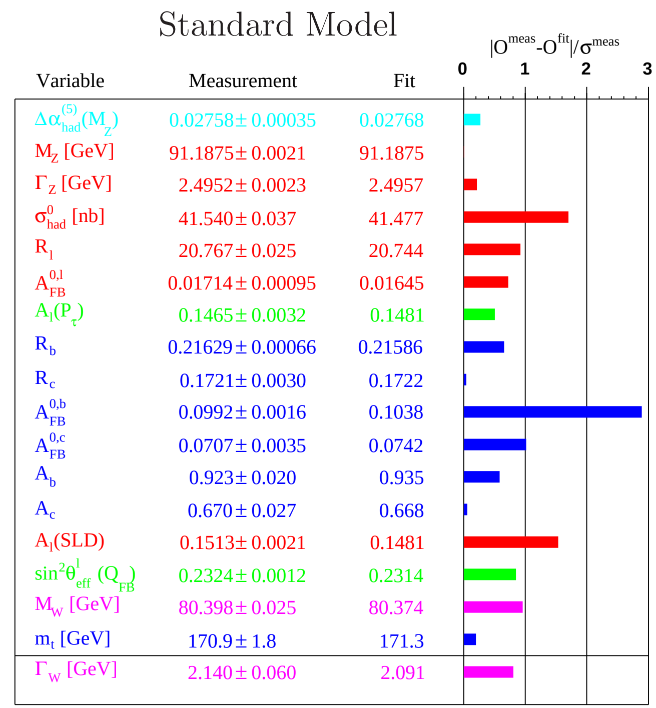
$$M_{\text{SUSY}} = 200 - 600\,\text{GeV}$$

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



CMSSM

Variable	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(M_Z)$	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_{had}^{0} [nb]	41.540 ± 0.037	41.486
R_l	20.767 ± 0.025	20.744
$A_{FB}^{0,l}$	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
$A_{FB}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{FB}^{0,c}$	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
$\sin^2\theta_{eff}^{l}(Q_{FB})$	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
$BR(B_s \to \mu\mu)[\times 10^{-8}]$	< 8.00	0.33
$\delta a_\mu [\times 10^{-9}]$	2.95 ± 0.87	2.95
Ωh^2	0.113 ± 0.009	0.113

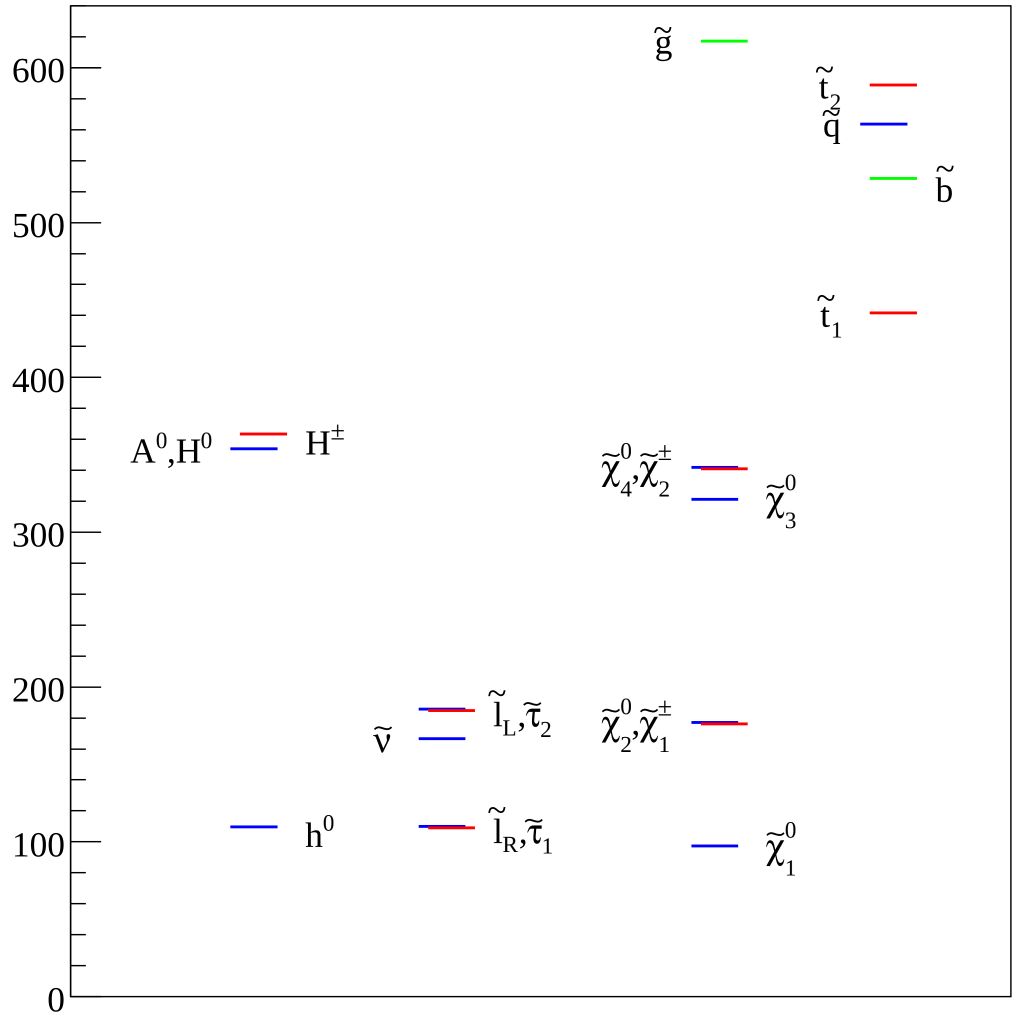


Standard Model

Variable	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(M_Z)$	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_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{FB}^{0,l}$	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
$A_{FB}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{FB}^{0,c}$	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
$\sin^2\theta_{eff}^{l}(Q_{FB})$	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

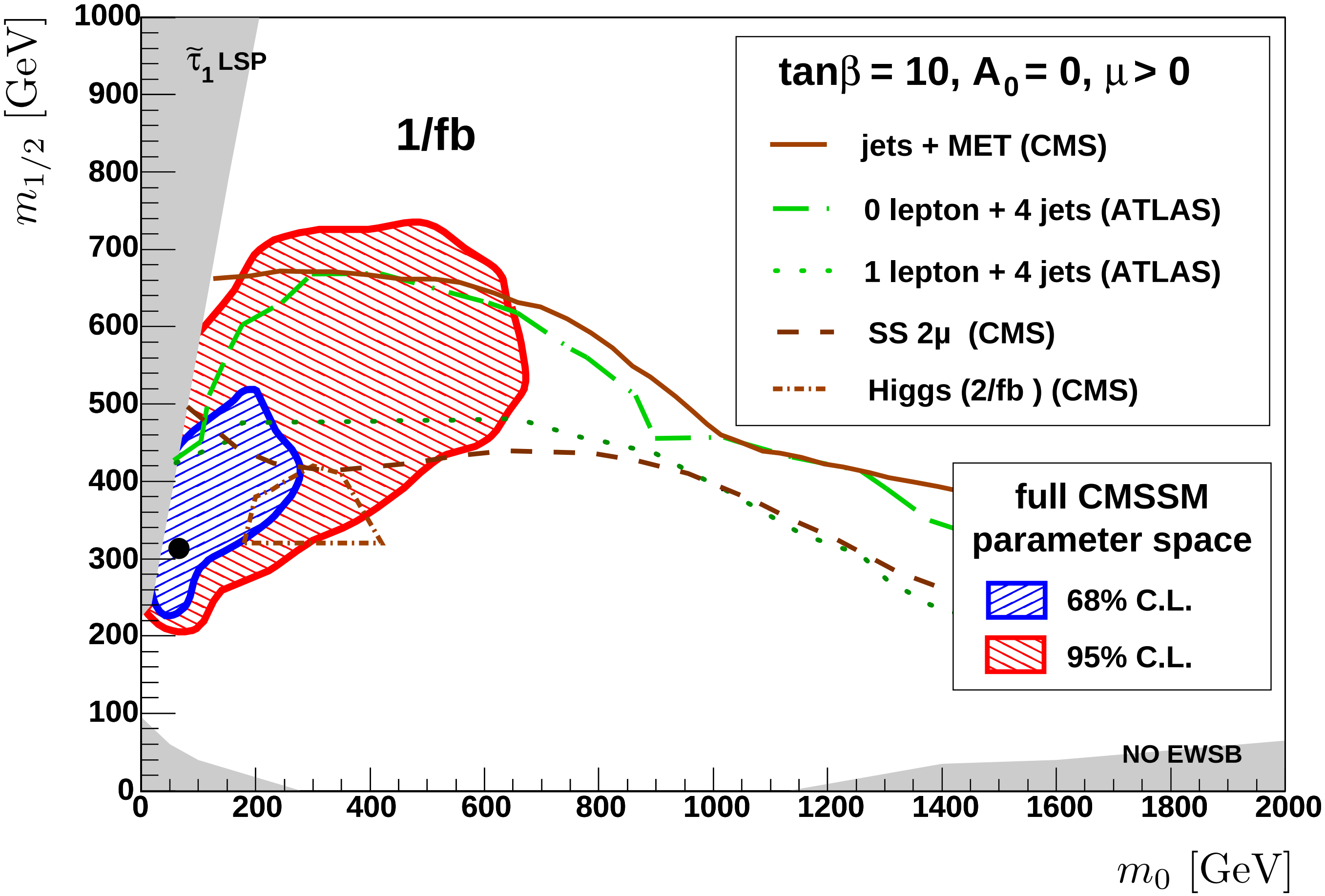
global fit in the constrained MSSM including data from $g-2$, B physics, and cosmic relic density

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

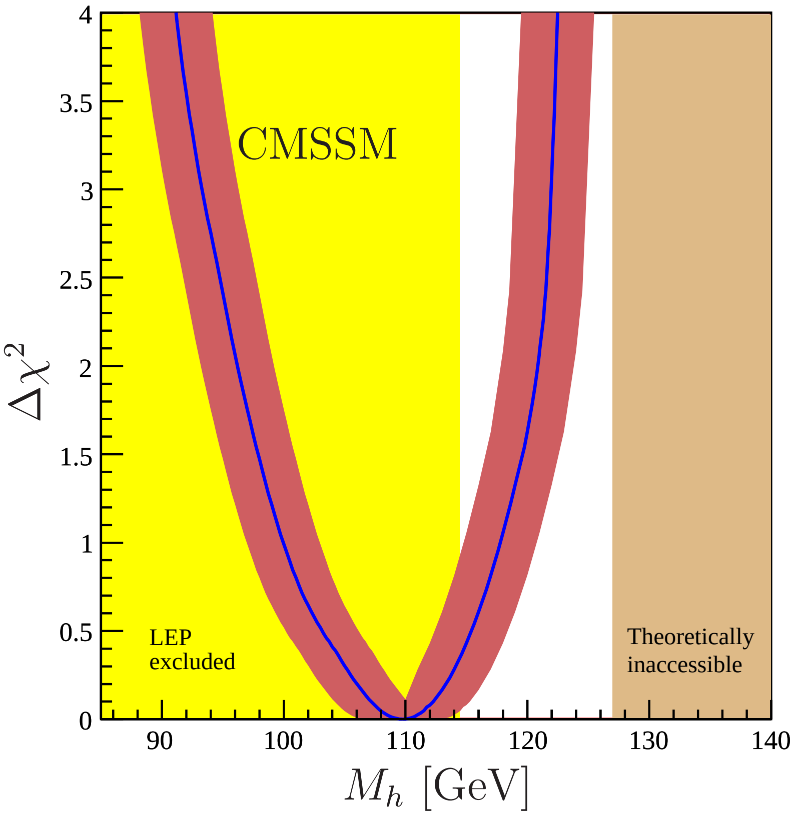


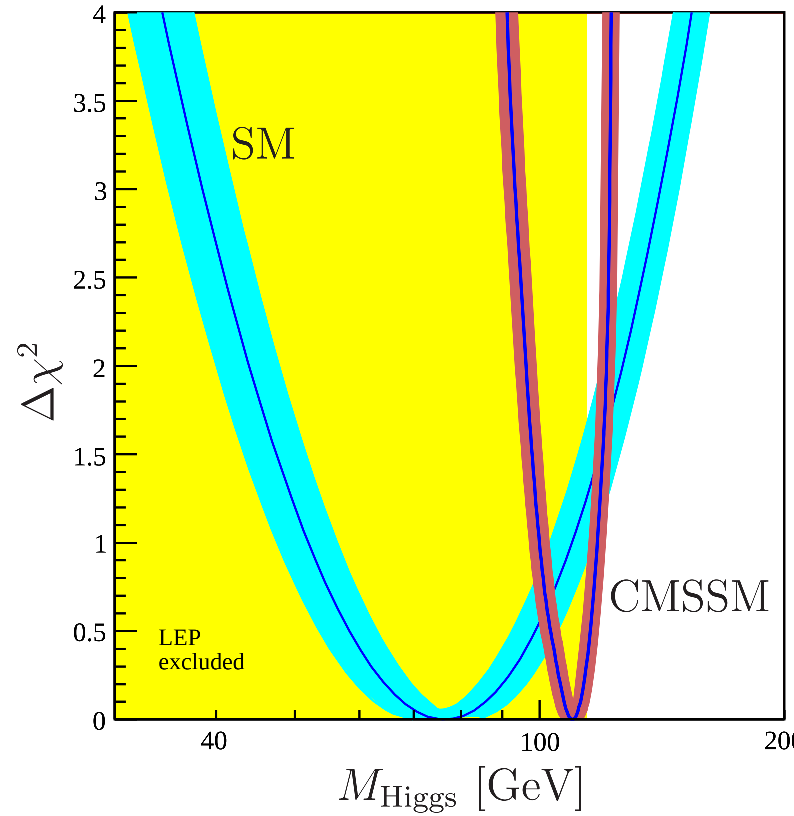
best fit particle spectrum

95% C.L. area in the $(m_{1/2}, m_0)$ plane to largest extend in the region that can be explored at the LHC with 1 fb^{-1}



[Buchmüller et al. 2008]





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

SM Higgs:

- $\lambda\, H^4$ term ad hoc
- Higgs boson mass: free parameter $\sim \sqrt{\lambda}$
- no a-priori reason for a light Higgs boson

SUSY Standard Model avoids these questions

$$H_2 = \begin{pmatrix} H_2^+ \\ v_2 + H_2^0 \end{pmatrix}, \qquad H_1 = \begin{pmatrix} v_1 + H_1^0 \\ H_1^- \end{pmatrix}$$

$$\text{couples to } u \qquad\qquad \text{couples to } d$$

- SUSY gauge interaction $\rightarrow$ H^4 terms
- self coupling remains weak

Higgs bosons

MSSM Higgs potential contains two Higgs doublets:

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

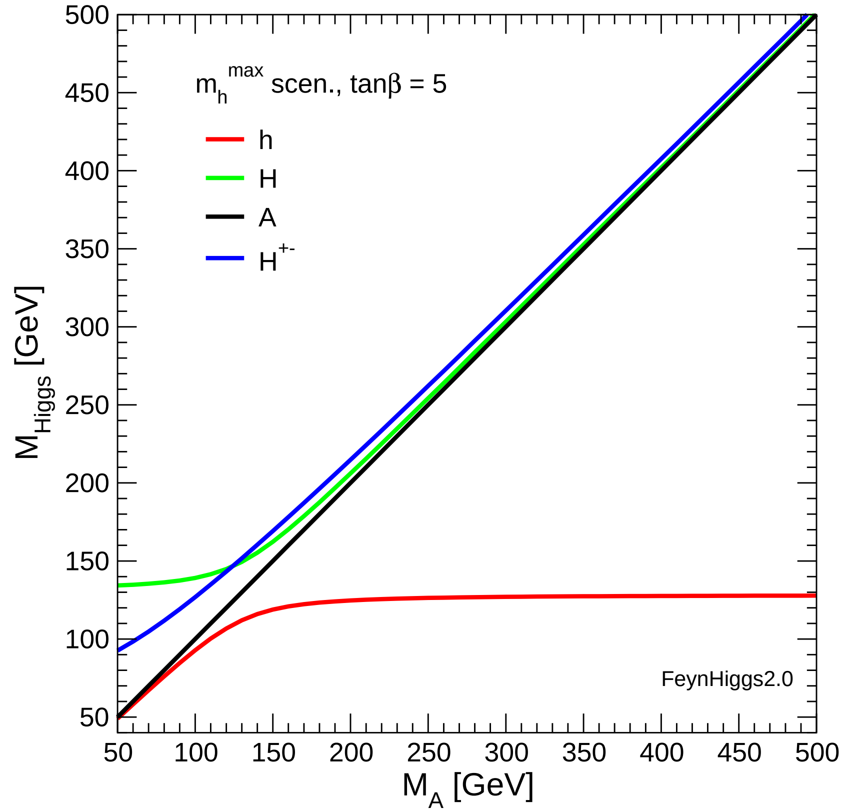
gauge couplings, in contrast to SM

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

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

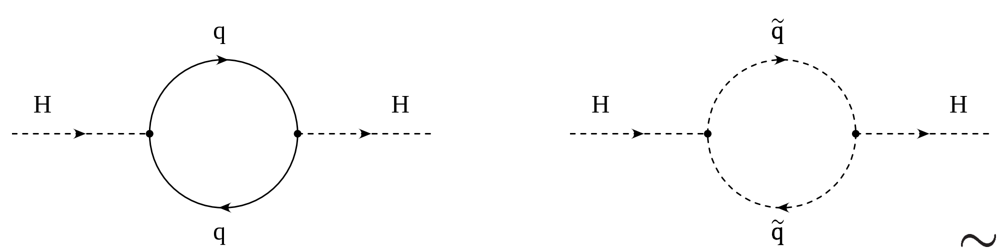
$\Rightarrow m_\mathrm{h}$, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters

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.*



$\sim \alpha_t$

masses and couplings at higher order

dressed $h,\ H$ propagators

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

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

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

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

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:

$\boldsymbol{\delta m_h} \simeq$ 3-4 GeV

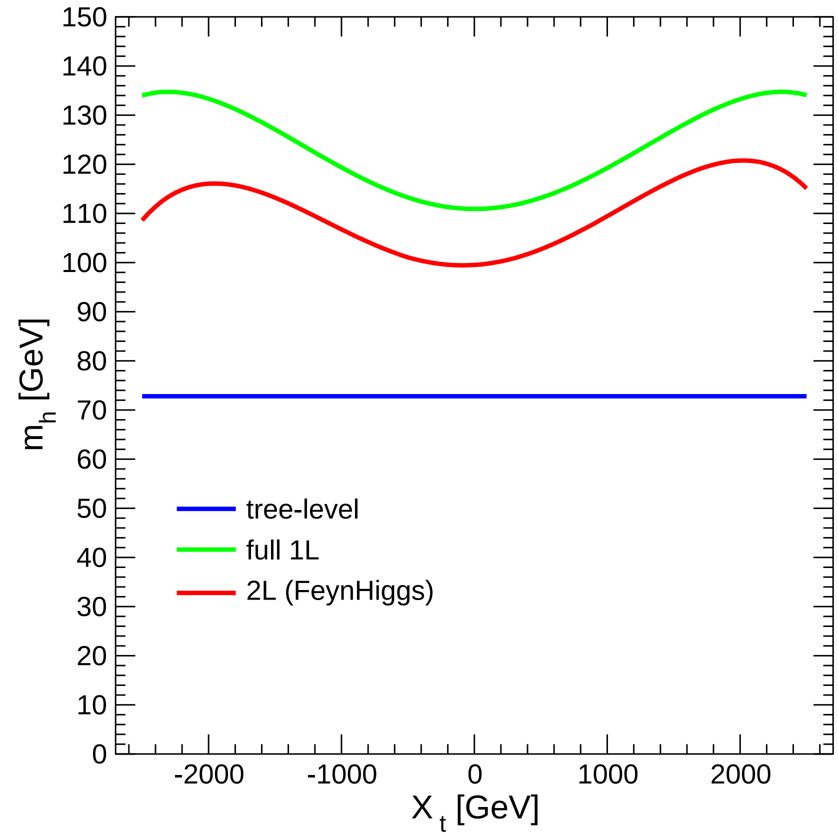
[Degrassi, Heinemeyer, WH, Slavich, Weiglein]

public code

`FeynHiggs2.6`

latest version *[arxiv:0710.4891]*

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



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

X_t : top-squark mixing parameter

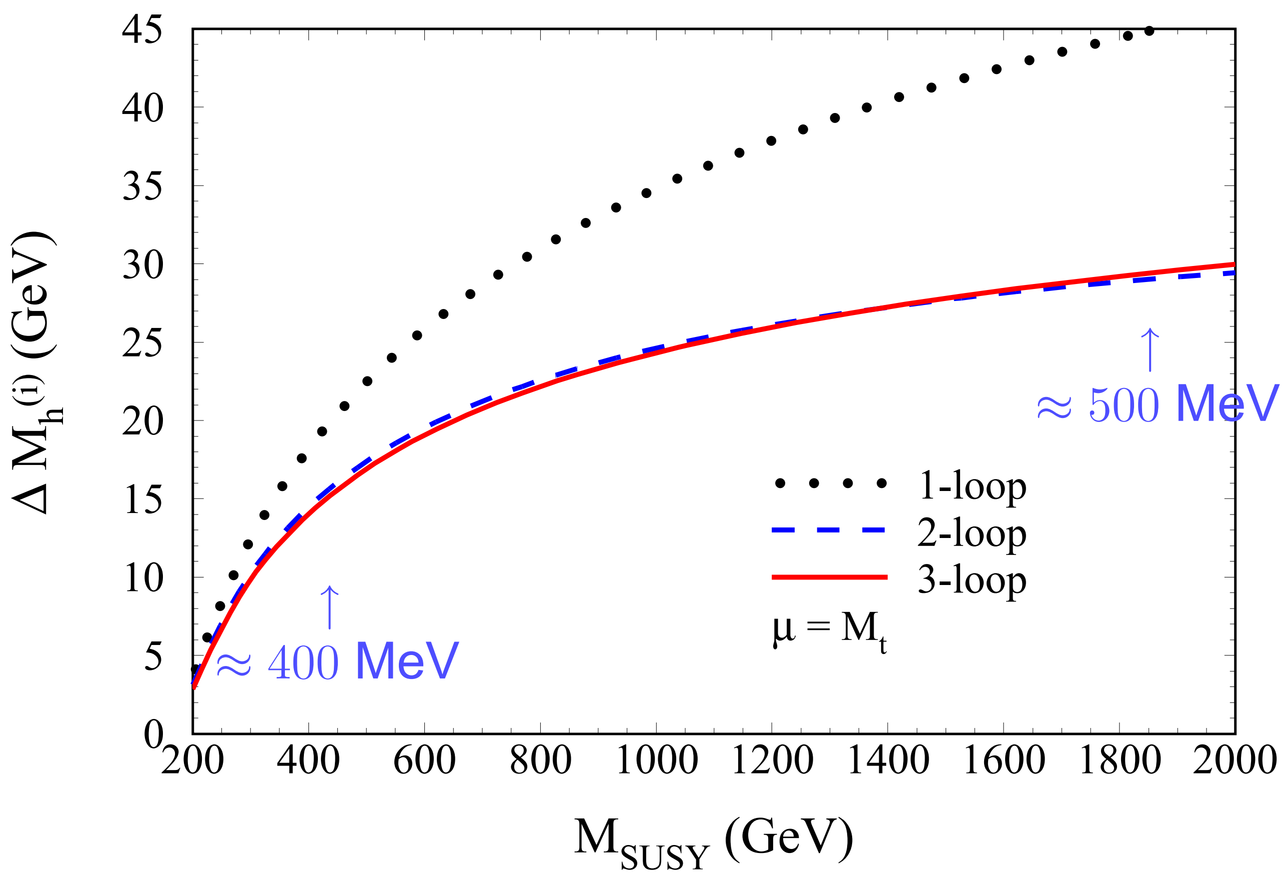
$$\mathrm{X_t} = \mathrm{A_t} - \mu \cot\beta$$

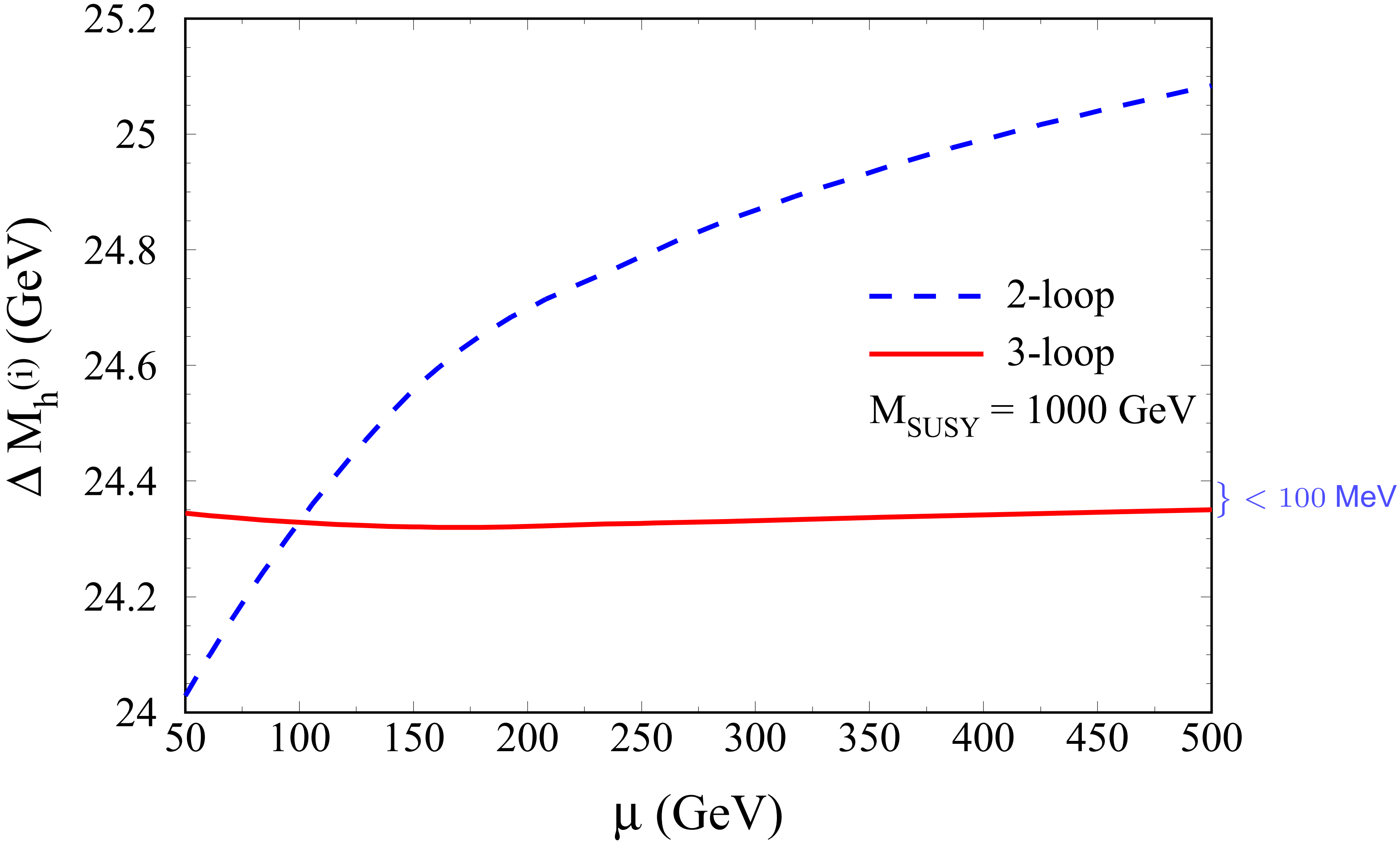
full 2-loop contribution, effective potential approximation

3-loop EPA, LL and NLL *[S. Martin]*

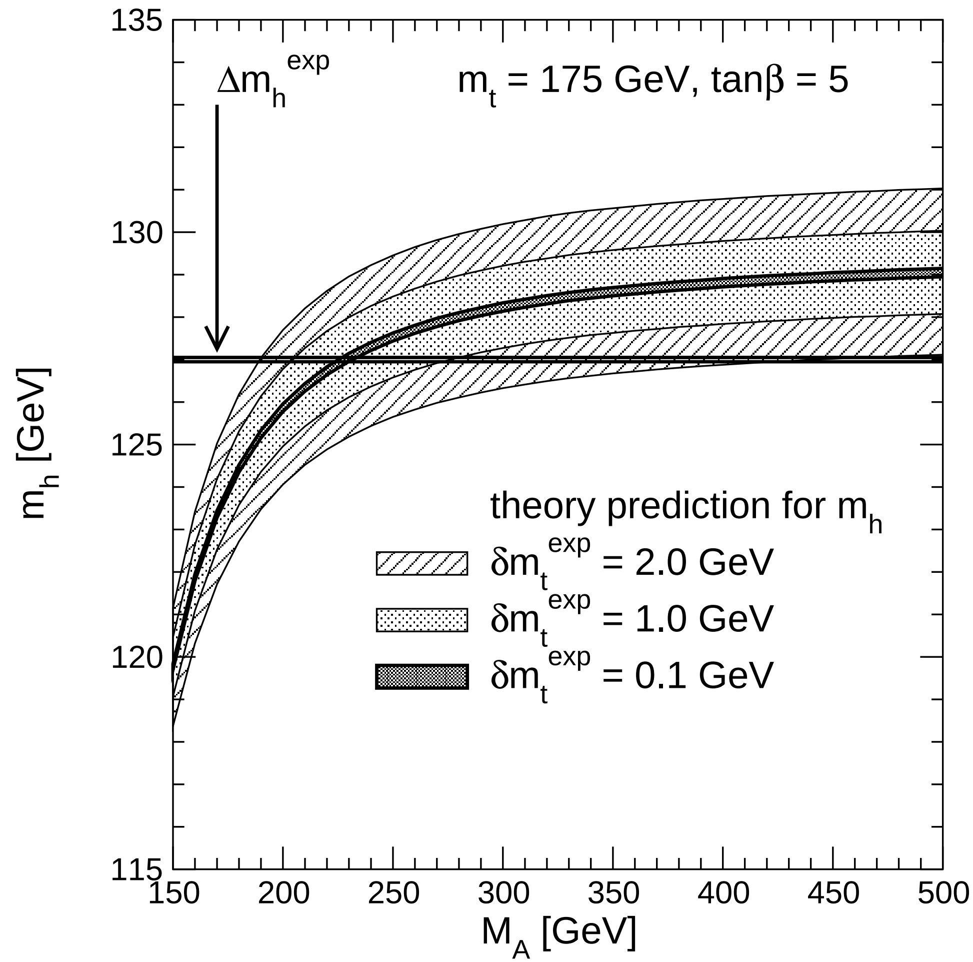
3-loop contributions $\sim \alpha_s^2\,\alpha_t$

[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
μ (GeV)
Δ M_h^(i) (GeV)
2-loop
3-loop
M_SUSY = 1000 GeV
} < 100 MeV



[Kraml et al.]

dependent on all SUSY particles and masses/mixings through Higgs self-energies

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

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

present status:

effective potential approximation + RGE

[Carena, Ellis, Pilaftsis, Wagner]

complete at one-loop order

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

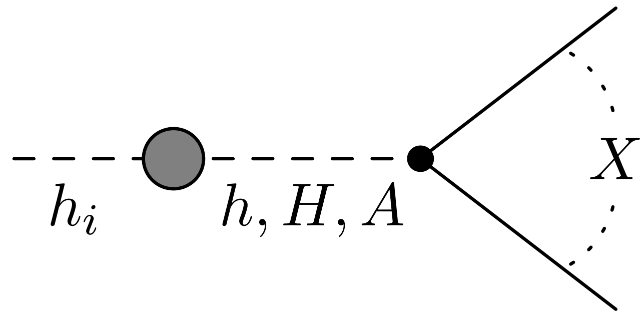
leading two-loop contributions of $\mathcal{O}(\alpha_s \alpha_t)$

[Heinemeyer, WH, Rzehak, Weiglein]

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

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

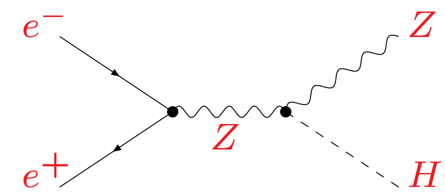
couplings at higher order

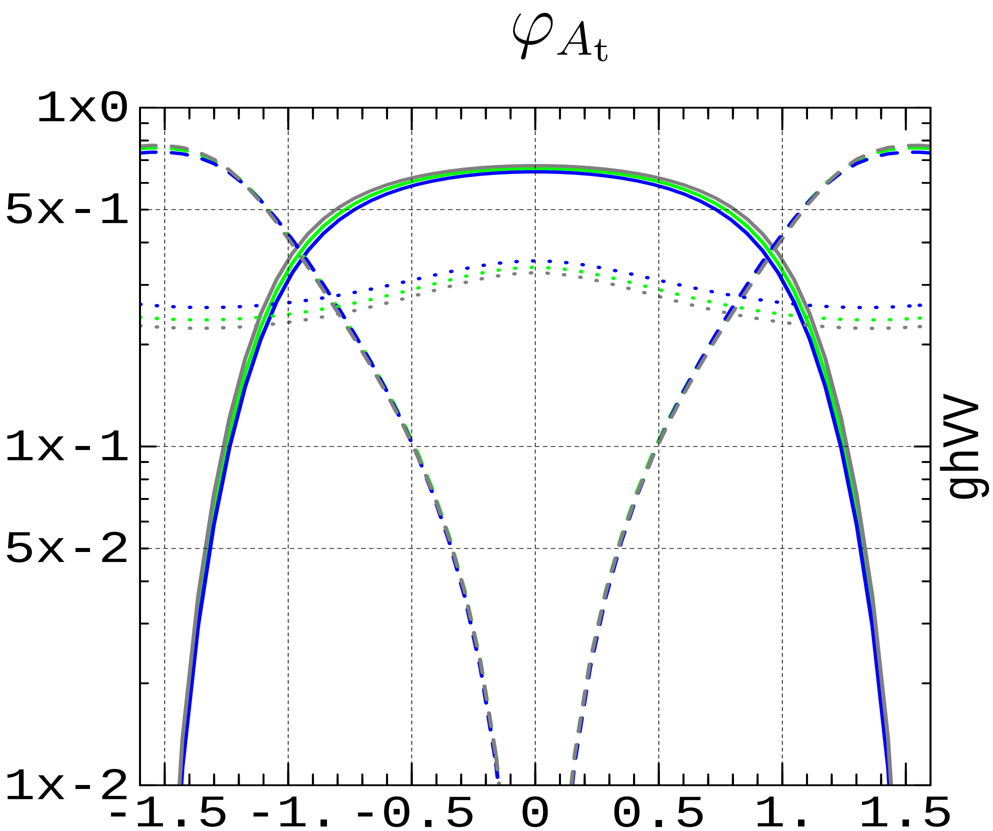


$$\Gamma_{h_1} = \sqrt{Z_h}\big(\Gamma_h + Z_{hH}\Gamma_H + Z_{hA}\Gamma_A\big)$$
$$\Gamma_{h_2} = \sqrt{Z_H}\big(Z_{Hh}\Gamma_h + \Gamma_H + Z_{HA}\Gamma_A\big)$$
$$\Gamma_{h_3} = \sqrt{Z_A}\big(Z_{Ah}\Gamma_h + Z_{AH}\Gamma_H + \Gamma_A\big)$$

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

couplings to vector bosons





full: h_1, dashed: h_2, dotted: h_3

Parameters:

$M_{\rm SUSY} = 500$ GeV,

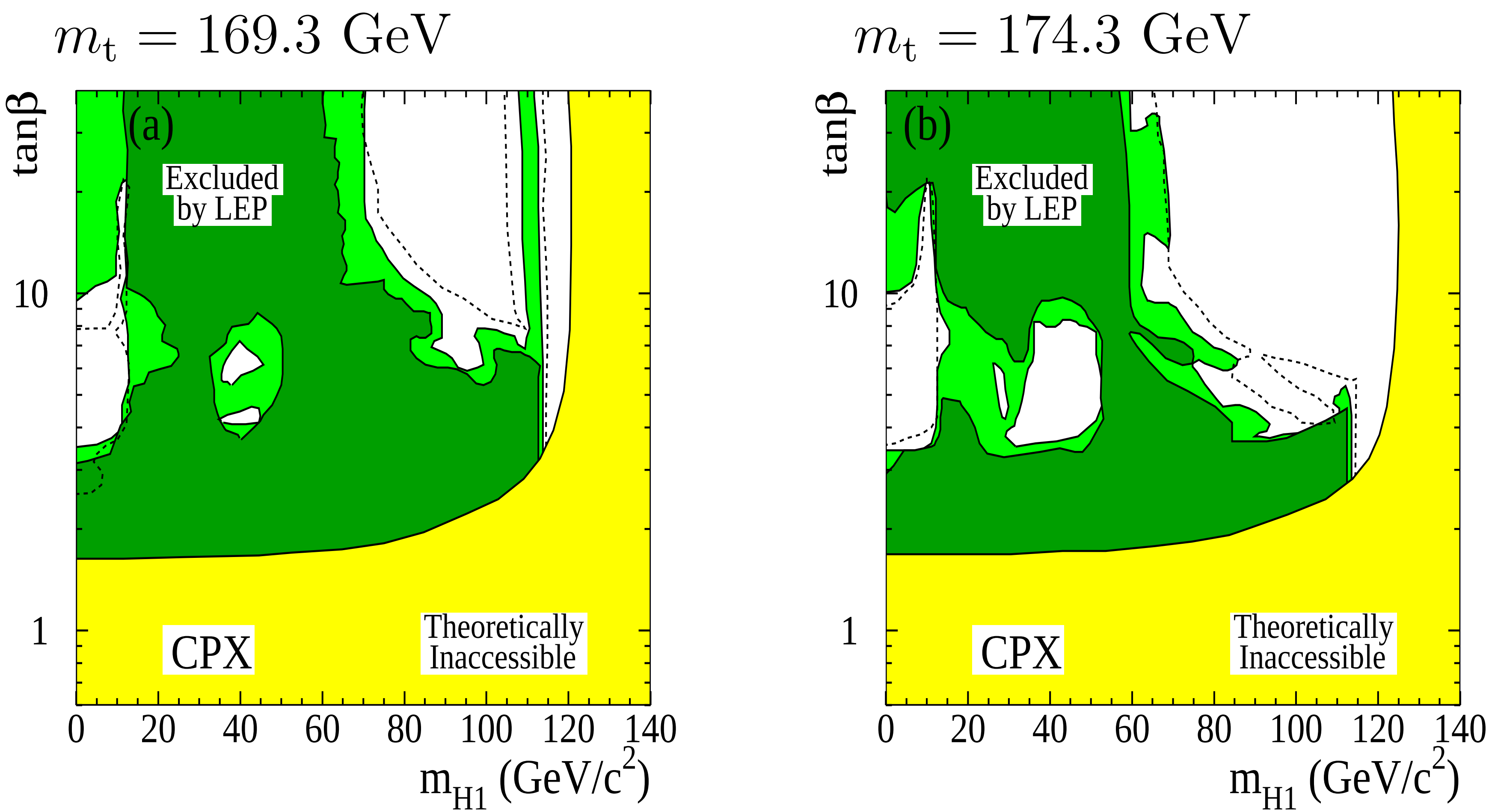
$M_2 = 500$ GeV,

$\mu = 2000$ GeV,

$|A_t| = 1000$ GeV,

$M_{H^\pm} = 150$ GeV, $\tan\beta = 5$

[*LEP Higgs Working Group ’06*]



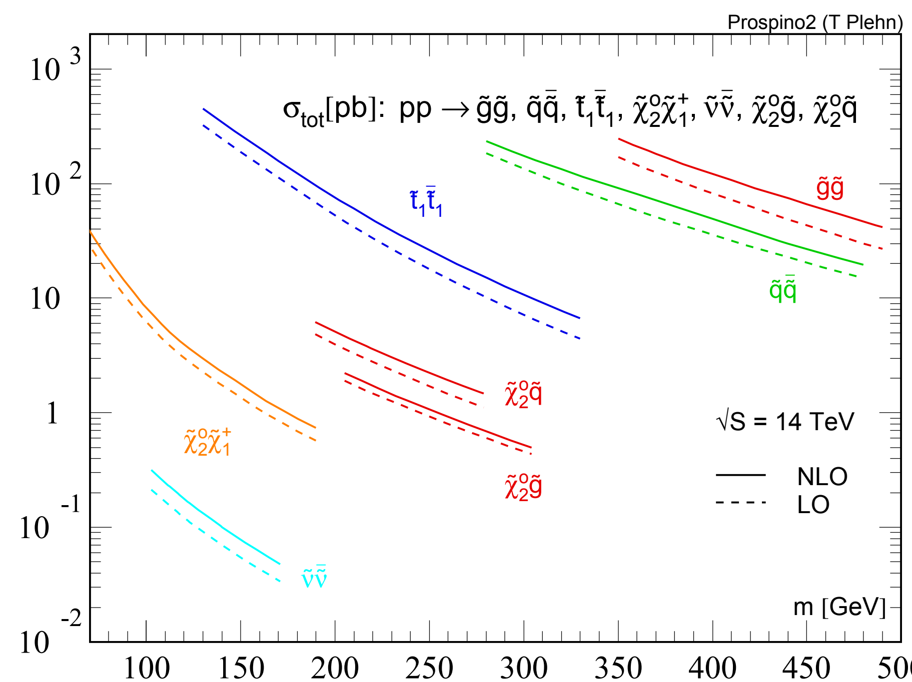
no lower limit on M_{h_1}: light SUSY Higgs not ruled out!

SUSY particle production

LHC: predominantly colored SUSY particles produced

- pair production of gluinos and squarks proceeds via **strong interaction**

  $\longrightarrow$ **large cross sections**



- large top-Yukawa coupling: **top-squark** $\tilde{t}_1$ candidate for **lightest squark**

  $\longrightarrow$ **high production rate**

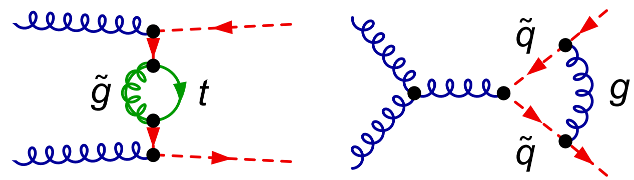
- **cross section depend** essentially **on final state masses**

Important **higher order effects** due to **QCD corrections**:

[Beenakker, Höpker, Spira, Zerwas ’95 & ’97] &
[Beenakker, Krämer, Plehn, Spira, Zerwas ’98]
$\longrightarrow$ PROSPINO, also for $\tilde{g}\tilde{q}$, $\tilde{g}\tilde{g}$

- $\mathcal{O}(\alpha_s^3)$: QCD NLO corrections

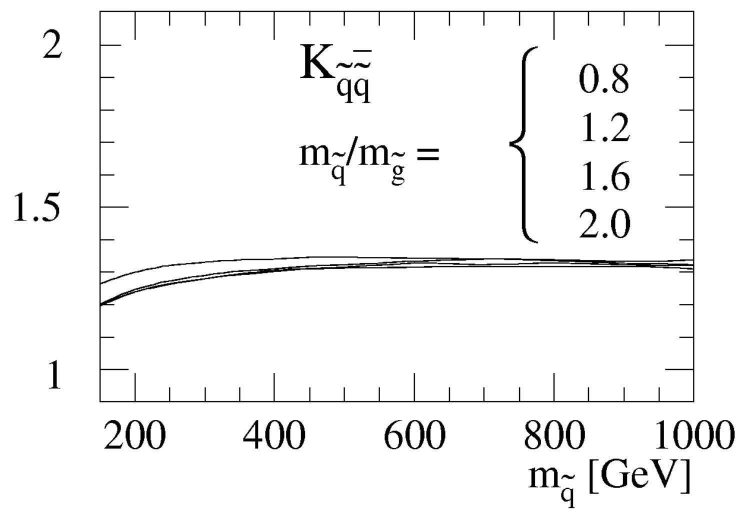
QCD Born $\times$

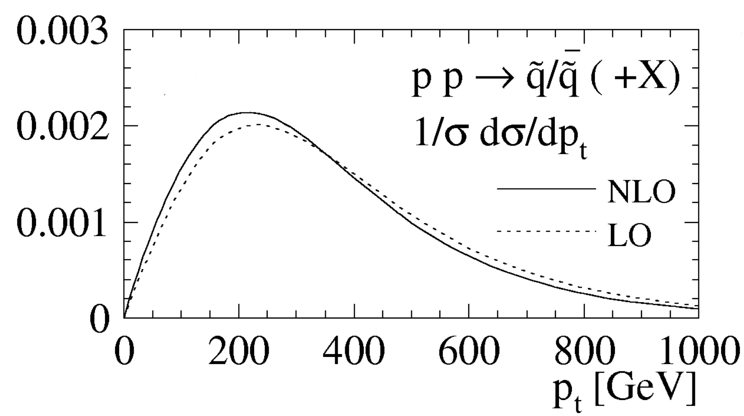


$+ \ldots$

+ real gluon & real quark radiation

[$\tilde{q}\tilde{q}^*$ production:]

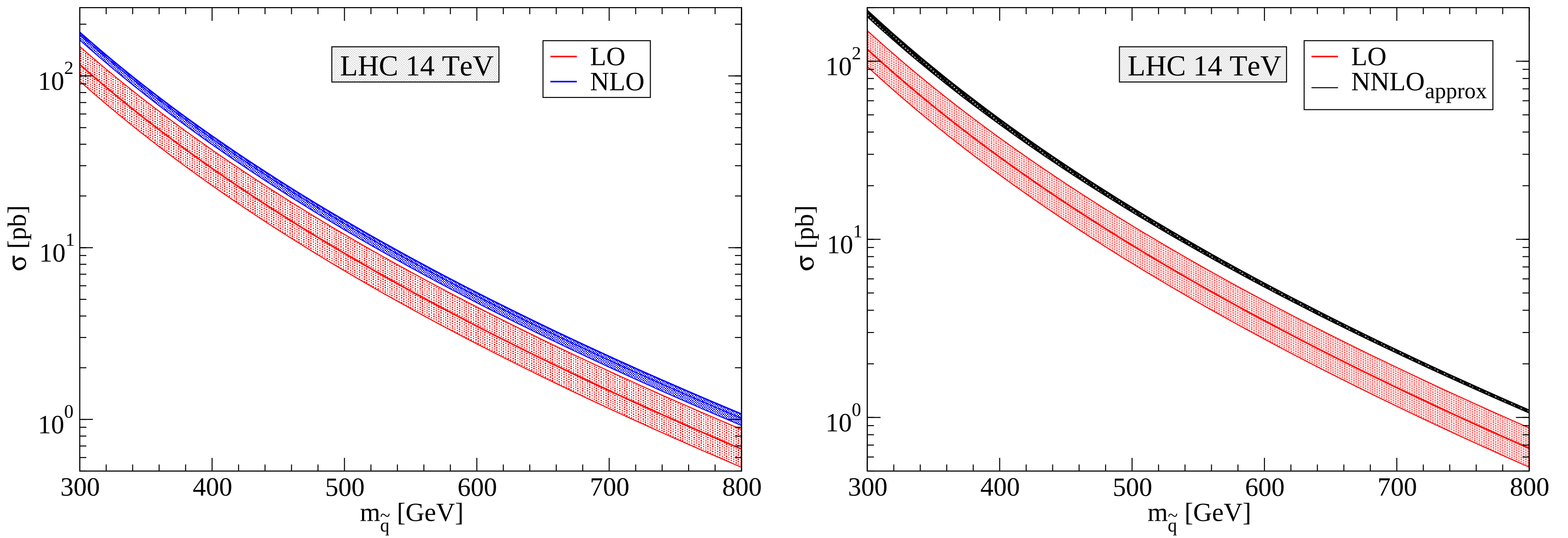




- large positive corrections
- reduced scale dependence
- negligible in normalized distributions

NNLO for squark production, dominant soft corrections

[Langenfeld, Moch 2009]



– improved theoretical prediction

– reduction of scale uncertainty

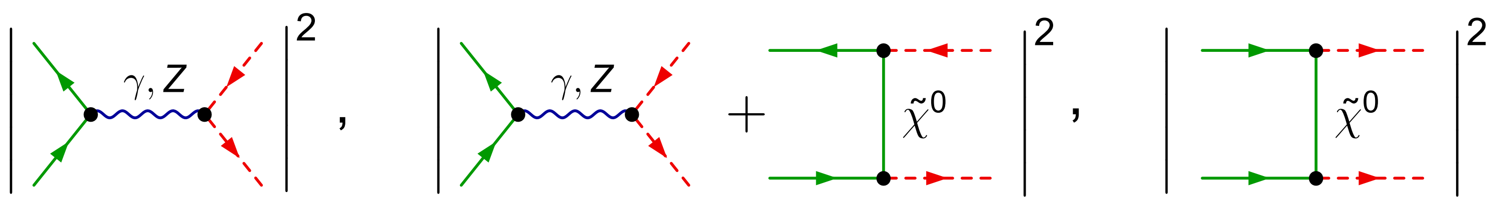
NNLO QCD contributions $\sim$ electroweak contributions

EW tree level contributions to squark pair production

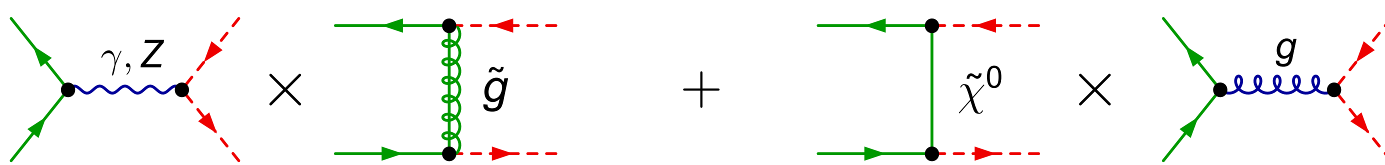
Bornhauser,Drees, Dreiner, Kim 2007

Bozzi, Fuks, Herrmann, Klasen 2007

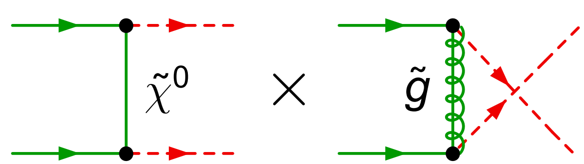
- $\mathcal{O}(\alpha^2)$: pure EW tree-level contributions ($\tilde{t}\tilde{t}^*$, $\tilde{q}\tilde{q}^*$, $\tilde{q}\tilde{q}$ prod.)



- $\mathcal{O}(\alpha_s\alpha)$: – EW-QCD tree-level interferences to $\tilde{q}\tilde{q}^*$ production



– EW-QCD tree-level interferences to $\tilde{q}\tilde{q}$ production

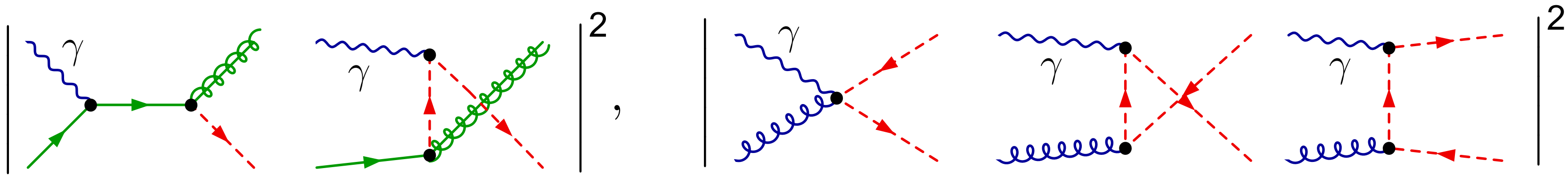


new production channel:

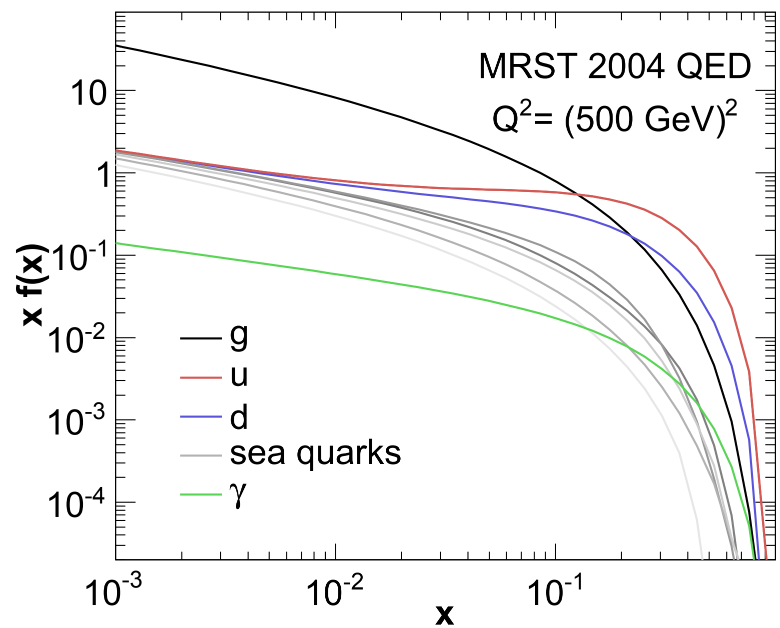
WH, Kollar, Trenkel 2007

WH, Mirabella 2008

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

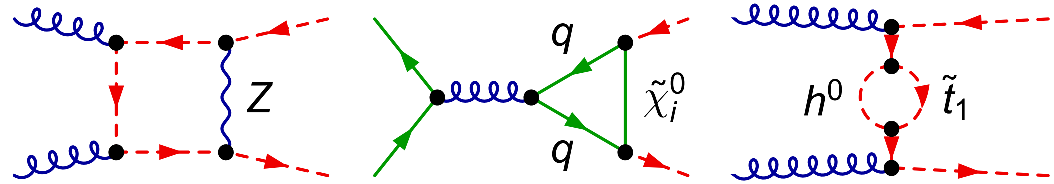


- not present at LO at the hadronic level
- **MRST 2004 QED**: inclusion of **NLO QED effects** in the evolution of PDFs
  - $\longrightarrow$ non-zero photon distribution
  - $\longrightarrow$ non-zero hadronic contributions



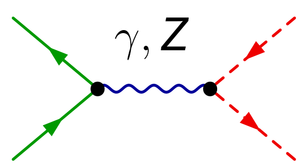
• $\mathcal{O}(\alpha_s^2 \alpha)$: NLO EW contributions

WH, Kollar, Mirabella, Trenkel 07,08

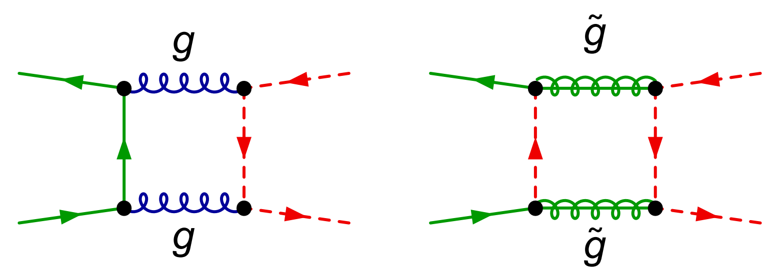
QCD Born $\times$ 

+ . . .

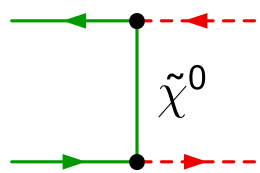
+ EW-QCD one-loop interferences



$\times$

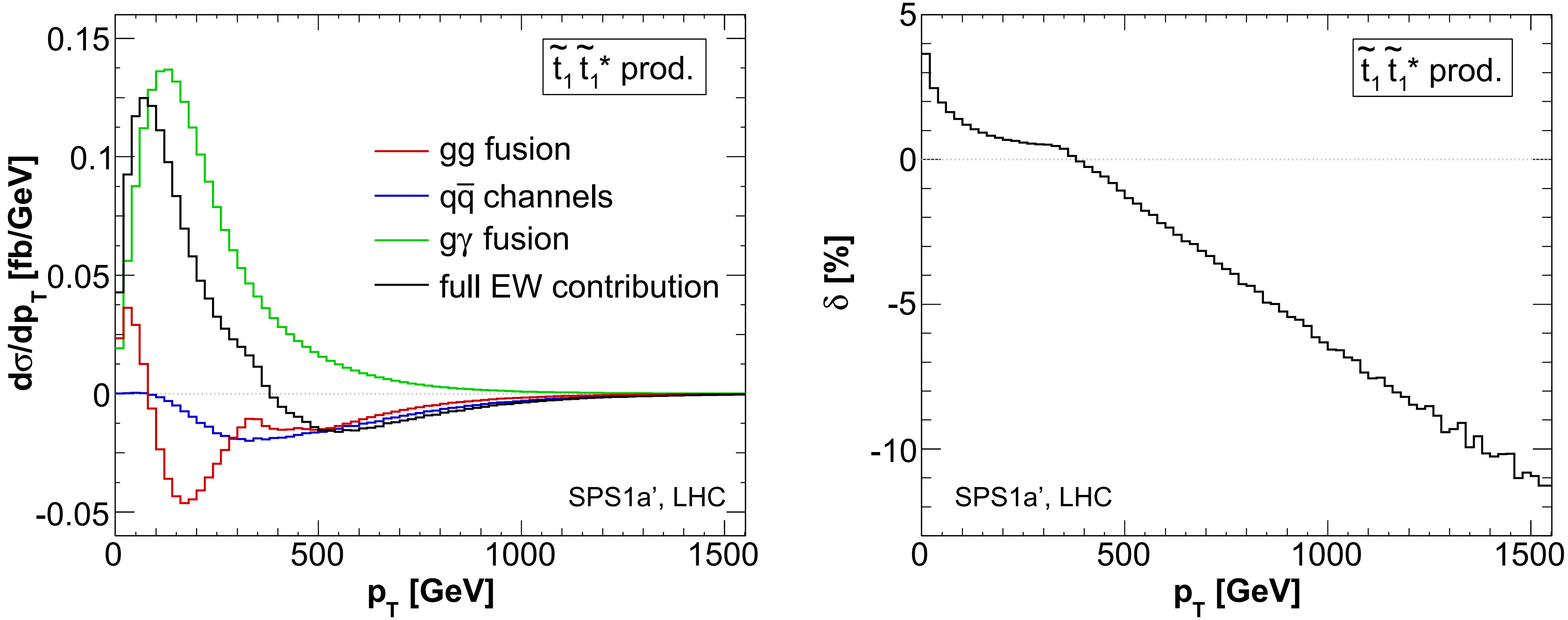


$(\tilde{q} \neq \tilde{t})$
$+$



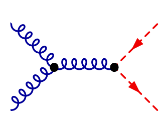
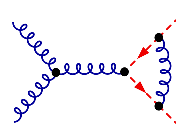
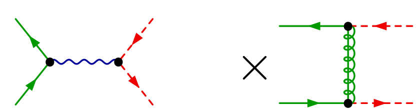
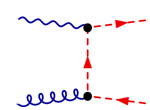
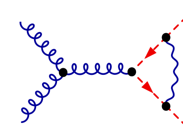
$\times$ full QCD 1-loop amplitude

+ real photon, gluon, and quark radiation



$\tilde{t}_1 \tilde{t}_1^*$ prod.
gg fusion
$q\bar{q}$ channels
$g\gamma$ fusion
full EW contribution
SPS1a', LHC
$d\sigma/dp_T$ [fb/GeV]
p_T [GeV]
$\tilde{t}_1 \tilde{t}_1^*$ prod.
SPS1a', LHC
δ [%]
p_T [GeV]

Overview: Squark and Gluino Production @ LHC

	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha_s\alpha)$	$\mathcal{O}(\alpha_s\alpha)$	$\mathcal{O}(\alpha_s^2\alpha)$
$\tilde{g}\tilde{g}$	+	+	−	−	−	+
$\tilde{g}\tilde{q}$	+	+	−	−	+	+
$\tilde{t}\tilde{t}^*$	+	+	+	−	+	+
$\tilde{q}\tilde{q}^*$	+	+	+	+	+	+
$\tilde{q}\tilde{q}$	+	+	+	+	−	+
						

EW contributions are chirality/flavour dependent

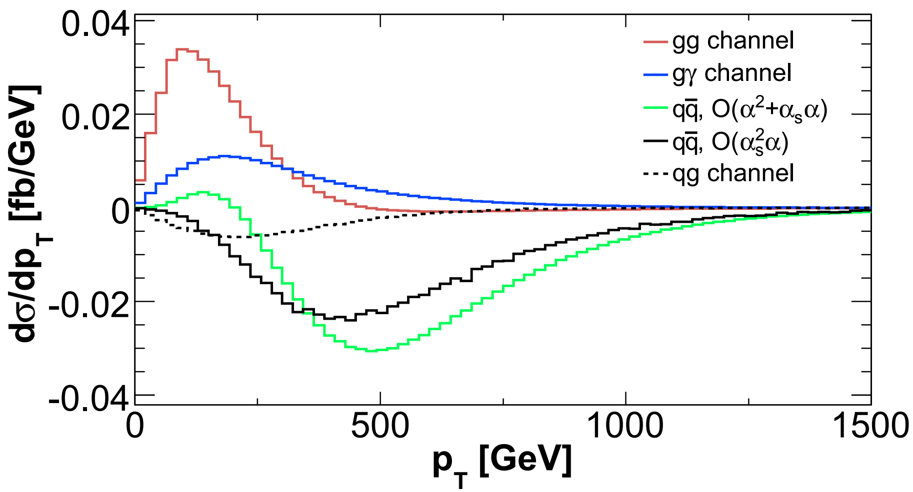
(xsection in pb, SPS1a$'$)

	$\tilde{u}^R\tilde{u}^{R*}$	$\tilde{u}^L\tilde{u}^{L*}$	$\tilde{d}^L\tilde{d}^{L*}$	$\tilde{c}^L\tilde{c}^{L*}$
$\mathcal{O}(\alpha_s^2)$	$(36.83 \pm 0.03) \cdot 10^{-2}$	$(31.31 \pm 0.01) \cdot 10^{-2}$	$(25.89 \pm 0.01) \cdot 10^{-2}$	$(22.65 \pm 0.01) \cdot 10^{-2}$
$\mathcal{O}(\alpha_s\alpha)$	$(-9.00 \pm 0.01) \cdot 10^{-3}$	$(-3.54 \pm 0.01) \cdot 10^{-2}$	$(-3.83 \pm 0.01) \cdot 10^{-2}$	$(\ 2.82 \pm 0.01) \cdot 10^{-3}$
$\mathcal{O}(\alpha^2)$	$(\ 2.42 \pm 0.01) \cdot 10^{-3}$	$(\ 2.39 \pm 0.01) \cdot 10^{-2}$	$(\ 3.20 \pm 0.01) \cdot 10^{-2}$	$(\ 2.11 \pm 0.01) \cdot 10^{-3}$
$\mathcal{O}(\alpha_s^2\alpha)$	$(-3.09 \pm 0.05) \cdot 10^{-3}$	$(-1.05 \pm 0.01) \cdot 10^{-2}$	$(-7.82 \pm 0.07) \cdot 10^{-3}$	$(\ 5.89 \pm 0.01) \cdot 10^{-3}$
$\delta(\%)$	-2.6	-7.0	-5.5	4.8

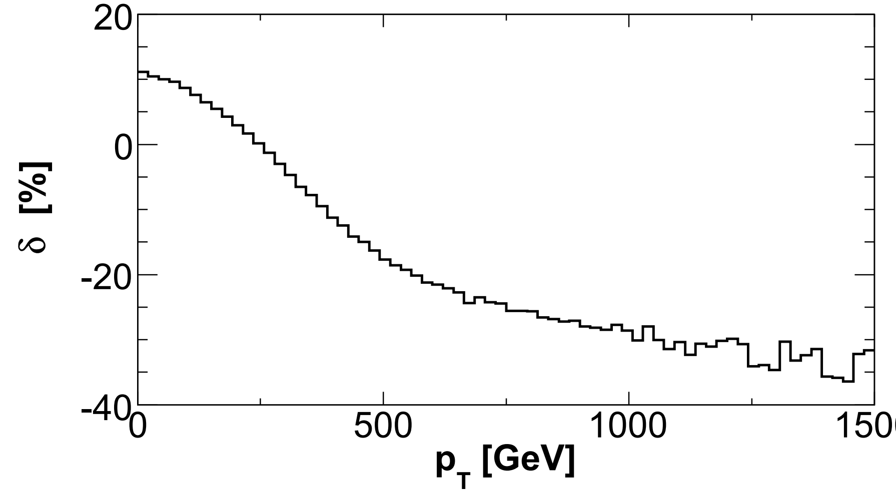
and fairly model dependent *[example: $u_L u_L^*$]*

	SPS5	SU1	SU4
$\mathcal{O}(\alpha_s^2)$	$(10.62 \pm 0.01) \cdot 10^{-2}$	$(51.77 \pm 0.02) \cdot 10^{-3}$	$(16.14 \pm 0.01) \cdot 10^{-1}$
$\mathcal{O}(\alpha_s\alpha)$	$(-1.37 \pm 0.01) \cdot 10^{-2}$	$(-7.22 \pm 0.01) \cdot 10^{-3}$	$(-1.45 \pm 0.01) \cdot 10^{-1}$
$\mathcal{O}(\alpha^2)$	$(\ 9.11 \pm 0.01) \cdot 10^{-3}$	$(\ 4.73 \pm 0.01) \cdot 10^{-3}$	$(\ 10.16 \pm 0.01) \cdot 10^{-2}$
$\mathcal{O}(\alpha_s^2\alpha)$	$(-4.83 \pm 0.03) \cdot 10^{-3}$	$(-2.75 \pm 0.02) \cdot 10^{-3}$	$(-2.61 \pm 0.01) \cdot 10^{-2}$
$\delta(\%)$	-8.9	-10.1	-4.3

$u_L u_L^*$, *SPS1a′*



0.04
0.02
0
-0.02
-0.04
dσ/dp_T [fb/GeV]
0
500
1000
1500
p_T [GeV]
gg channel
gγ channel
qq̄, O(α²+α_sα)
qq̄, O(α_s²α)
qg channel



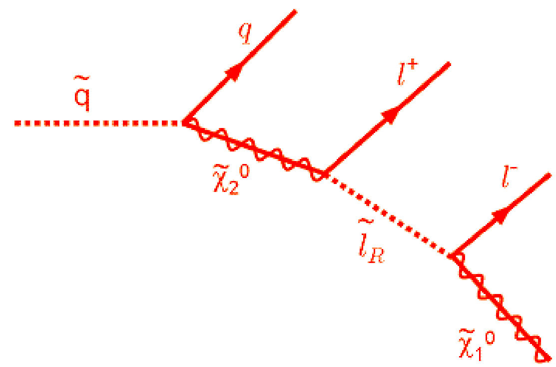
20
0
-20
-40
δ [%]
0
500
1000
1500
p_T [GeV]

measurements at colliders

- LHC

– direct production $pp \to \tilde{q}\tilde{q},\ \tilde{q}\tilde{g},\ \tilde{g}\tilde{g}$

– decay chains $\tilde{q} \to q\tilde{\chi}_2^0 \to q(\ell\ell)\tilde{\chi}_1^0$



- ILC/CLIC

– separate study for individual s-particles

$$e^+e^- \to \tilde{\chi}\tilde{\chi}$$
$$e^+e^- \to \tilde{\ell}\tilde{\ell}$$
$$e^+e^- \to \tilde{t}\tilde{t}$$

Accuracy of measurements

SPA Report, SPS1a$'$ scenario]

LHC/ILC Report [Weiglein et al.]

Parameter	SPS1a$'$value	Fit error [exp]
M_1	103.3	0.1
M_2	193.4	0.1
M_3	568.9	7.8
μ	400.4	1.1
$M_{\tilde{e}_L}$	181.3	0.2
$M_{\tilde{e}_R}$	115.6	0.4
$M_{\tilde{\tau}_L}$	179.5	1.2
$M_{\tilde{u}_L}$	523.2	5.2
$M_{\tilde{u}_R}$	503.9	17.3
$M_{\tilde{t}_L}$	467.7	4.9
m_{A}	374.9	0.8
A_{t}	-525.6	24.6
$\tan\beta$	10.0	0.3

High Scale Extrapolations

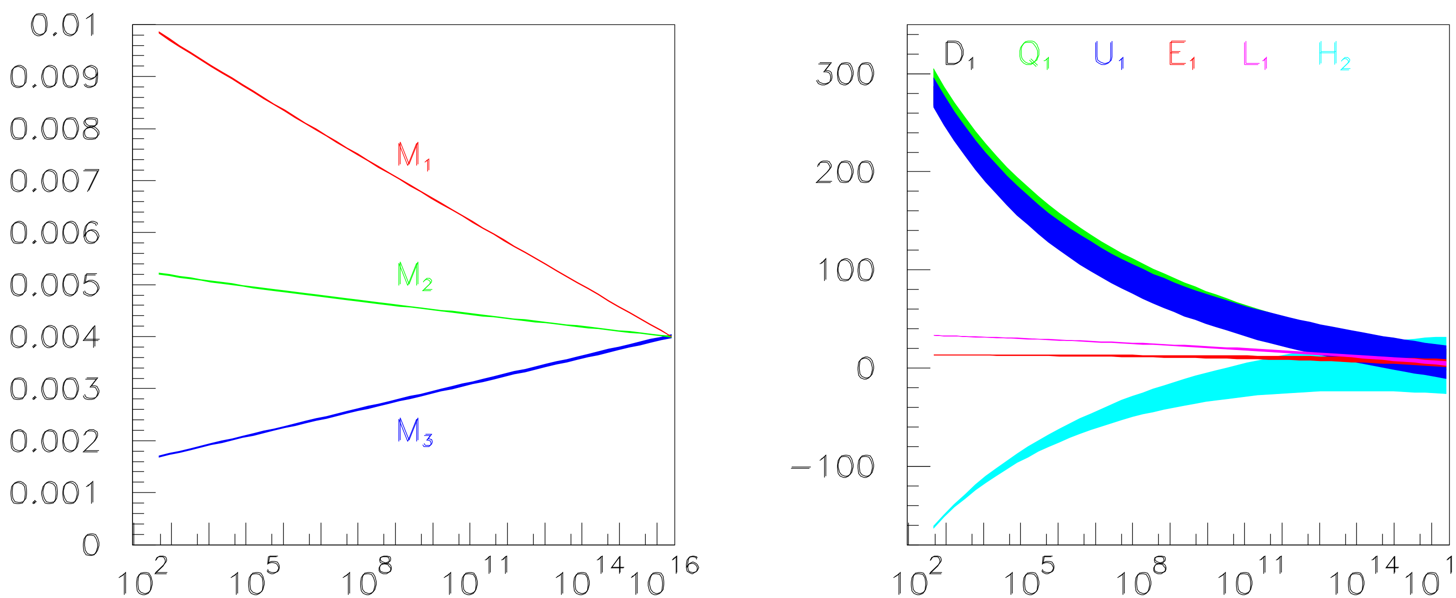


Fig. 1. *Running of the gaugino and scalar mass parameters in SPS1a′ [*SPheno 2.2.2 *]. Only experimental errors are taken into account; theoretical errors are assumed to be reduced to the same size in the future.*

SUSY particles

from experiment:

$\longrightarrow$ precision analyses of masses and couplings LHC$\oplus$ILC

from theory:

$\longrightarrow$ accurate theoretical predictions to match exp. data

$\longrightarrow$ loop contributions to Lagrangian param $\leftrightarrow$ observables

$\longrightarrow$ reconstruction of fundamental SUSY parameters and breaking mechanism

$\longrightarrow$ RGEs for extrapolation to high scales

Summary

- precise calculations for SUSY (MSSM) are well advanced
- electroweak precision observables with indirect sensitivity to SUSY parameters
  global fits of similar quality as in standard model indirect sensitivity to SUSY parameters
- m_{h^0} is another precision observable
  – dependent on all SUSY sectors
  – accurate theoretical evaluation available,
  but to be further improved
- progress for calculating SUSY processes at LHC and ILC, future precision will allow tests of breaking scenarios