Higgs Boson Production at the LHC

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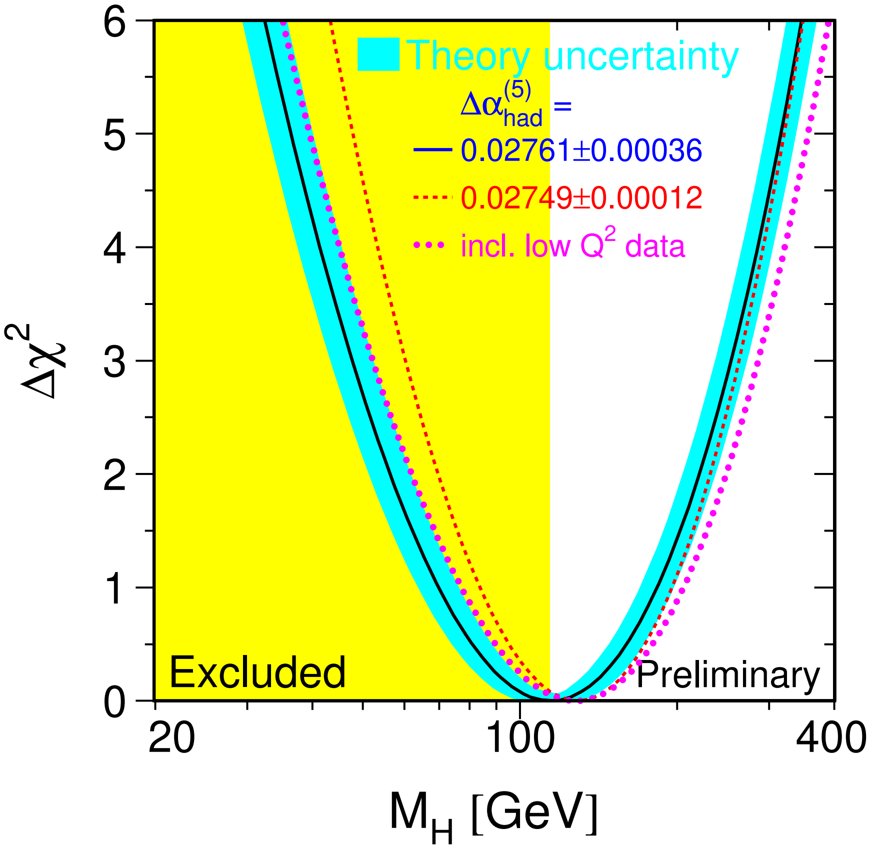
2004 LHC Days in Split
5 - 9 October 2004

- Higgs bosons in the SM and MSSM
- SM Higgs production
- Higgs+Jet in the Standard Model
- Higgs+Jet in the MSSM
- Conclusions

Standard Model Higgs bound from precision data

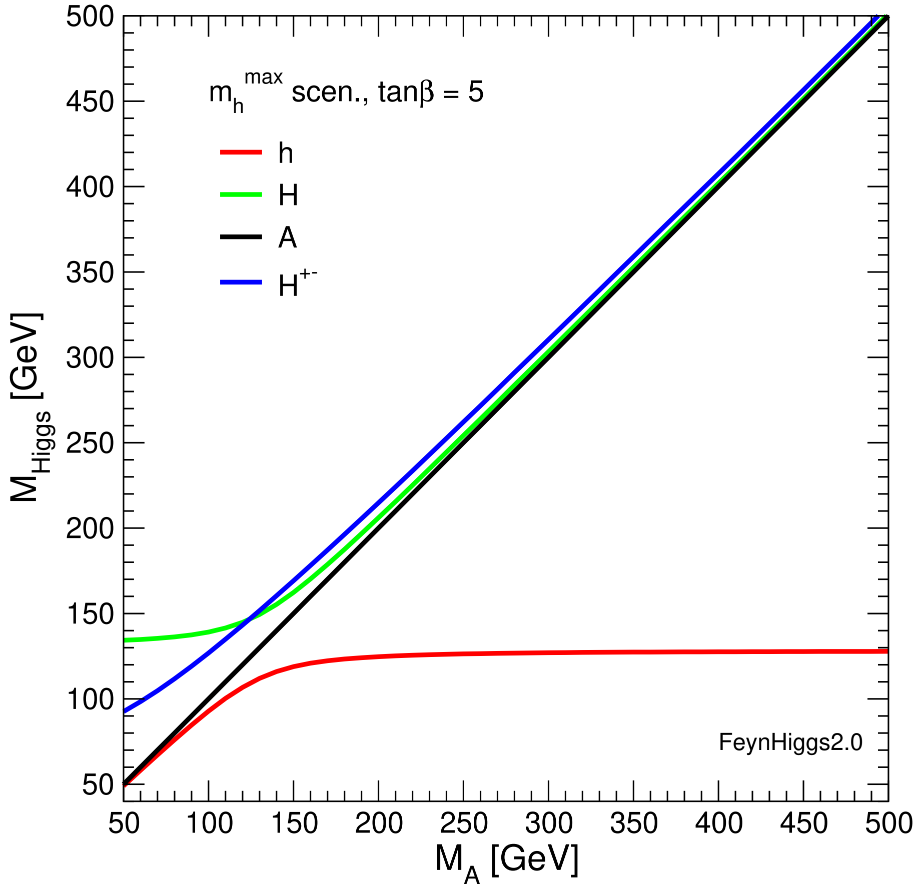
[LEP-EWWG]



$M_{\rm H} < 260$ GeV at 95% C.L.

Spectrum of Higgs bosons in the MSSM

(example)



Possible scenarios

- a single light Higgs boson
  - SM Higgs boson?
  - SUSY light Higgs boson?
    with H, A, $H^\pm$ heavy (decoupling scenario)
    $h \sim H_{\rm SM}$
- a light Higgs boson + more $(H, A, H^\pm)$
  - SUSY Higgs?
  - non-SUSY 2-Higgs-Doublet model?
- a single heavy Higgs boson ($\gg 200$ GeV)
  - SUSY ruled out
  - SM + (?)   strong interaction?
- no Higgs boson
  - strongly interacting weak interaction
    new strong force $\sim$ TeV scale

Production mechanisms

- gluon-gluon fusion:

$$gg \to H$$

NNLO QCD [Harlander, Kilgore]
NL EW [Degrassi, Maltoni]

- WW (ZZ) fusion:

$$qq \to Hq'q'$$

NLO QCD [Figy, Oleari, Zeppenfeld]

- Higgs-strahlung processes:

$$qq' \to WH$$
$$q\bar{q} \to ZH$$

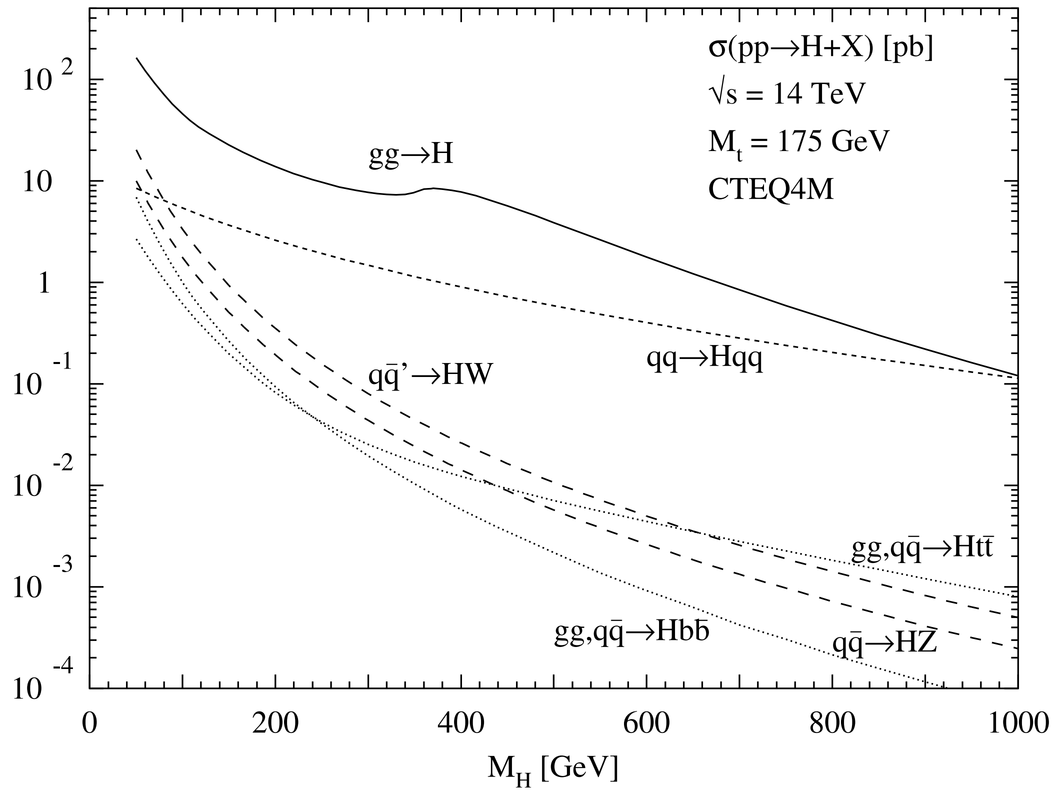
NNLO QCD + NLO EW [Brein et al.]

- radiation from heavy quarks:

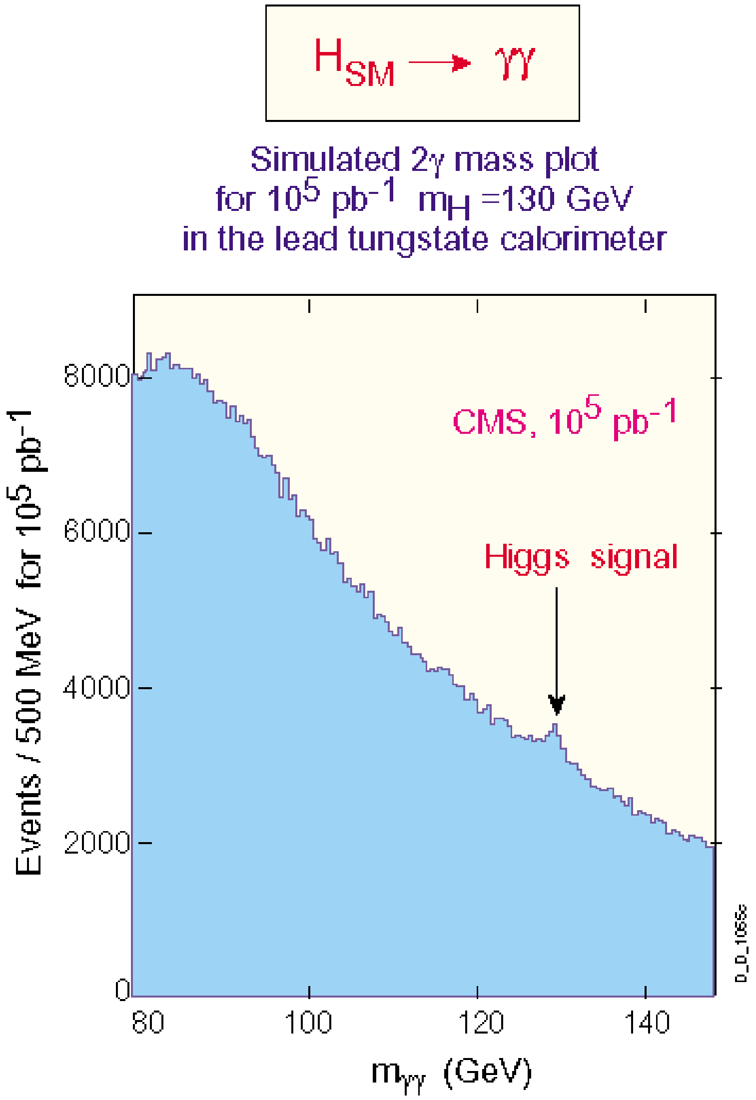
$$gg,\ q\bar{q} \to t\bar{t}H\ (b\bar{b}H$$

NLO QCD [Beenakker et al., Dawson et al.]
NLO EW [Denner et al.]

Size of various SM Higgs production cross sections



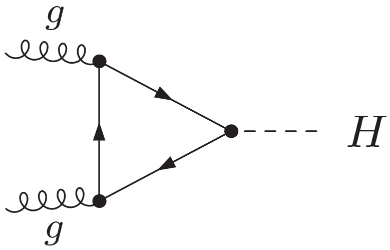
[Spira]



H_SM → γγ
Simulated 2γ mass plot
for 10^5 pb^-1 m_H =130 GeV
in the lead tungstate calorimeter
CMS, 10^5 pb^-1
Higgs signal
Events / 500 MeV for 10^5 pb^-1
8000
6000
4000
2000
0
80
100
120
140
m_γγ (GeV)
D_D_1055c

• Higgs + Jet in the Standard Model

Higgs production @ LHC mainly via gluon fusion:



Detection ($m_H \approx 100 - 140$GeV): mainly via the rare decay $H \to \gamma\gamma$.
$\to$ difficult ! huge background

– Higgs + Jet [R.K. Ellis et al. '87; Baur, Glover '89]

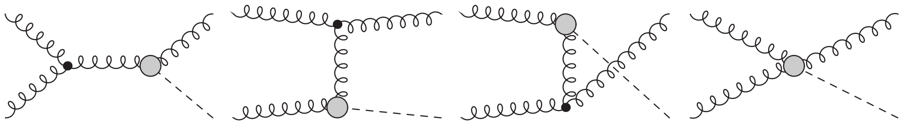
idea: study events with a high-p_T hadronic jet.

advantage:
* richer kinematical structure compared to inclusive Higgs production.
$\to$ better S/B ratio
$\to$ allows for refined cuts

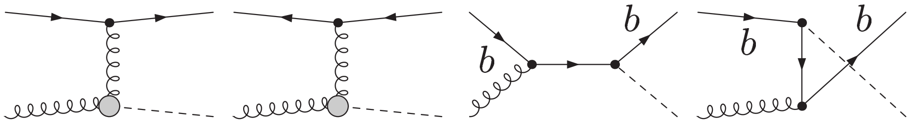
disadvantage:
* lower rate than inclusive Higgs production

H+jet, partonic processes (mostly loop-induced):

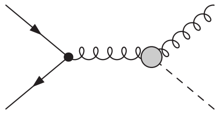
- $gg \to Hg$ (≈ 50 - 70 % of total rate)

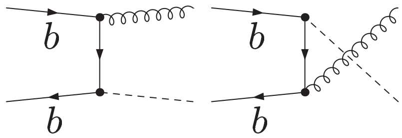


- $qg \to Hq, \bar{q}g \to H\bar{q}$ (≈ 30 - 50 % of total rate)



- $q\bar{q} \to Hg$ (rate small)





Recently simulated: $pp \to H + \text{jet}, H \to \gamma\gamma$

[Abdullin et al. '98 & '02]

Result: H+jet production (with $p_{T,\text{jet}} \geq 30$ GeV, $|\eta_{\text{jet}}| \leq 4.5$) is a promising alternative (supplement) to the inclusive SM Higgs production for $m_H \approx 100 - 140$GeV,

NNLO QCD + soft gluon resummation: Catani et al.

• Higgs + Jet in the MSSM

Motivation:

* promising simulation results in the SM case
* MSSM prediction for h^0 + jet not known yet
* process loop-induced: potentially large effects from virtual particles

– partonic processes

similar to the SM:

gluon fusion	$gg \to h^0 g$,
quark-gluon scattering	$q(\bar{q})g \to h^0 q(\bar{q})$,
$q\bar{q}$ annihilation	$q\bar{q} \to h^0 g$

but:

* different Higgs Yukawa-couplings

$$g^{\text{SM}}_{q\bar{q}H} = \frac{e}{2s_W}\frac{m_q}{m_W} \longrightarrow g^{\text{MSSM}}_{q\bar{q}h^0} = \frac{e}{2s_W}\frac{m_q}{m_W} f_q(\alpha,\beta),$$

$$f_{u_I}(\alpha,\beta) = \cos\alpha / \sin\beta$$

$$f_{d_I}(\alpha,\beta) = -\sin\alpha / \cos\beta$$

$\to$ mainly change of overall rate

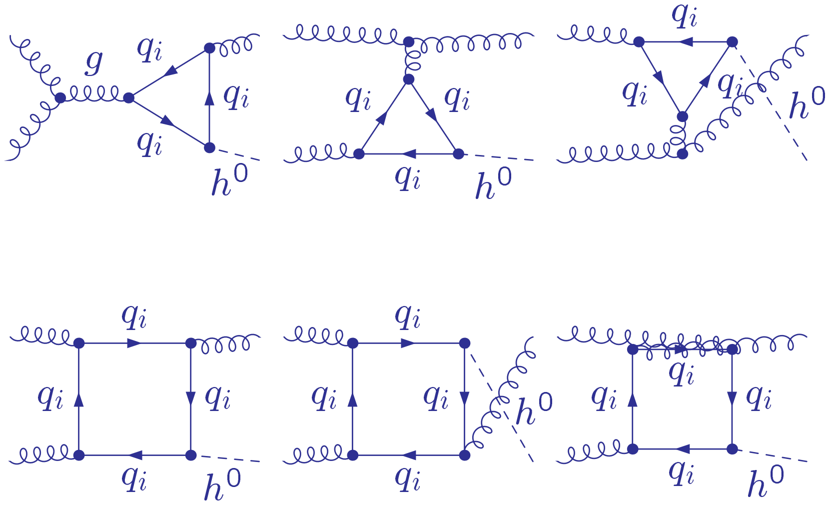
* additional superpartner-loops (even additional topologies)

$\to$ angular distribution changed

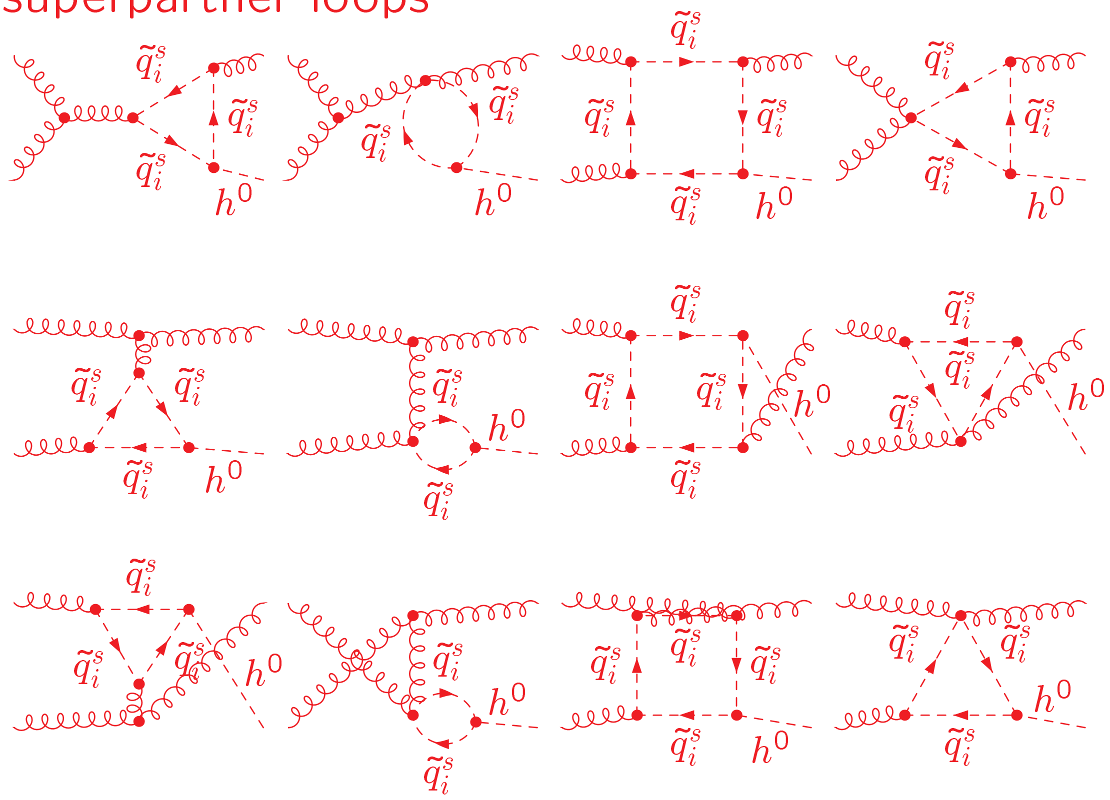
[work with O. Brein, hep-ph/0305321]

gluon fusion, $gg \to h^0 g$

quark loops

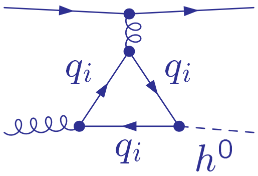


superpartner loops

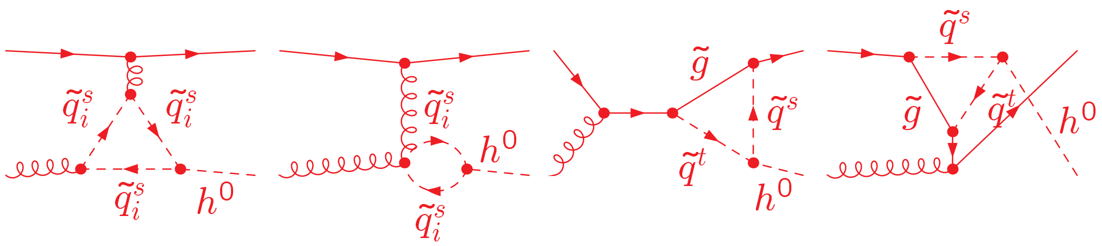


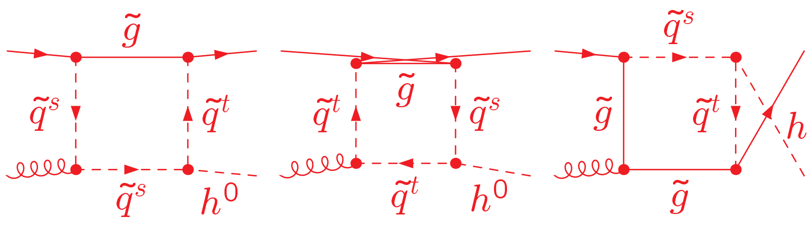
quark-gluon scattering, $qg \to h^0 q$

quark loops



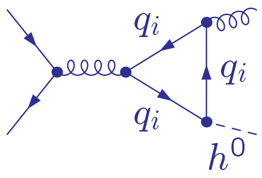
superpartner loops



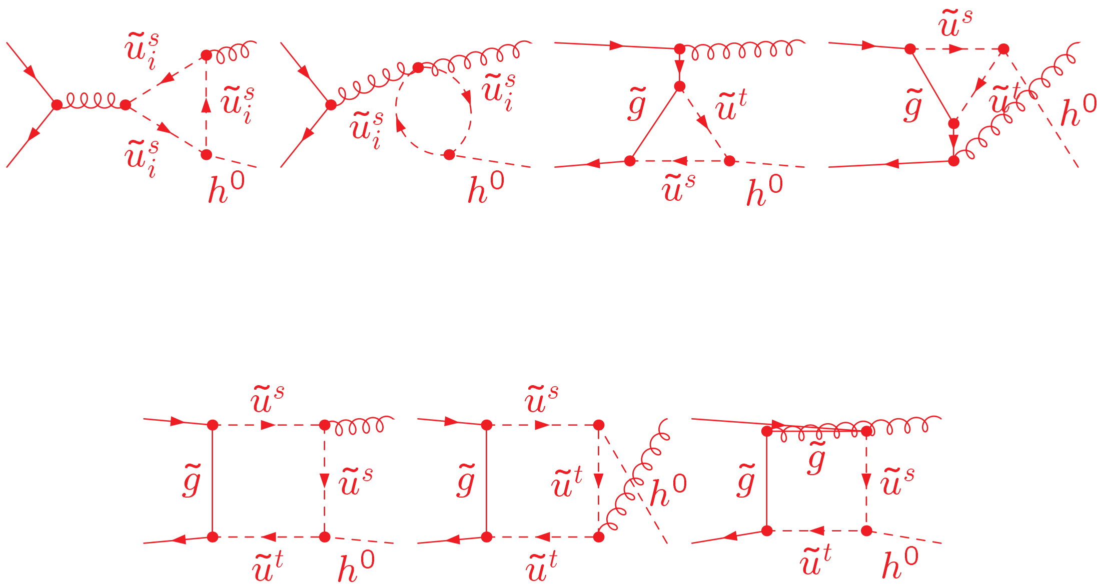


quark-antiquark annihilation, $q\bar{q} \to h^0 g$

quark loops



superpartner loops



• Results

– Hadronic cross section @ LHC ($\sqrt{S} = 14$ TeV)

$$\sigma(pp \to h^0 + \text{jet} + X) =$$

$$\int_{\tau_0}^{1} d\tau \Bigg(\frac{d\mathcal{L}_{gg}^{pp}}{d\tau}\, \sigma_{gg\to gh^0}(\tau S) + \sum_q \frac{d\mathcal{L}_{qg}^{pp}}{d\tau}\, \sigma_{qg\to qh^0}(\tau S) + \sum_q \frac{d\mathcal{L}_{q\bar{q}}^{pp}}{d\tau}\, \sigma_{q\bar{q}\to gh^0}(\tau S) \Bigg)$$

with the parton luminosity

$$\frac{d\mathcal{L}_{nm}^{AB}}{d\tau} = \int_{\tau}^{1} \tfrac{dx}{x} \tfrac{1}{1+\delta_{nm}} \Big[f_{n/A}(x) f_{m/B}(\frac{\tau}{x}) + f_{m/A}(x) f_{n/B}(\frac{\tau}{x}) \Big] .$$

The cuts $p_{T,\text{jet}} \geq 30\,\text{GeV}$ and $|\eta_{\text{jet}}| \leq 4.5$ determine τ_0 and the angular integration limits.

The results shown are for the MSSM m_h^{max} benchmark scenario with common squark mass scale M_{SUSY}.

[partonic processes calculated using FeynArts/FormCalc, see : www.feynarts.de]

Scenarios

- no-mixing scenario:

  unmixed $\tilde{t}$-squarks

$$\tilde{t}_{1,2} = \tilde{t}_{L,R} \qquad (X_t = 0)$$
$$m_{\tilde{g}} = 800\mathrm{GeV}$$

- maximal-m_h scenario:

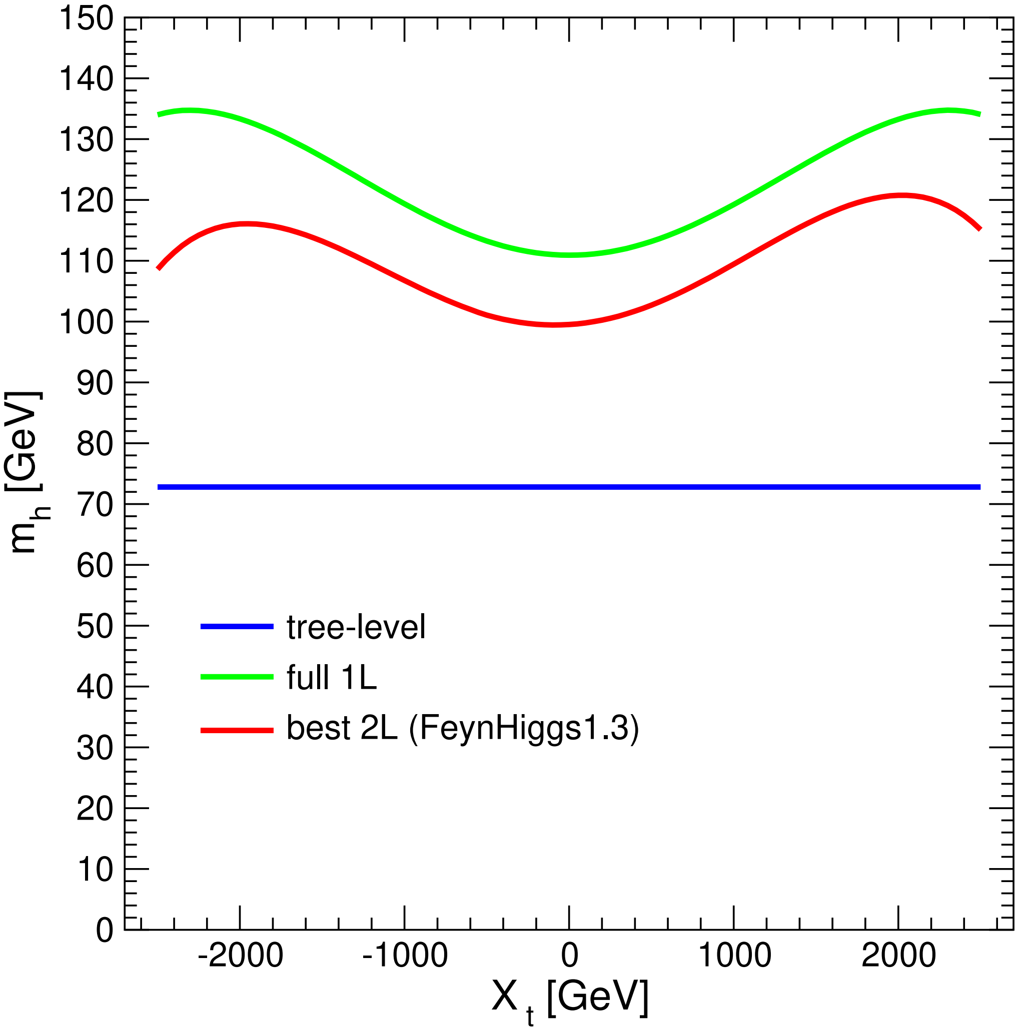
  yields max. value for m_h (see next figure)

$$X_t = 2M_{\tilde{Q}} \equiv M_{\mathrm{SUSY}}$$

- large-μ scenario:

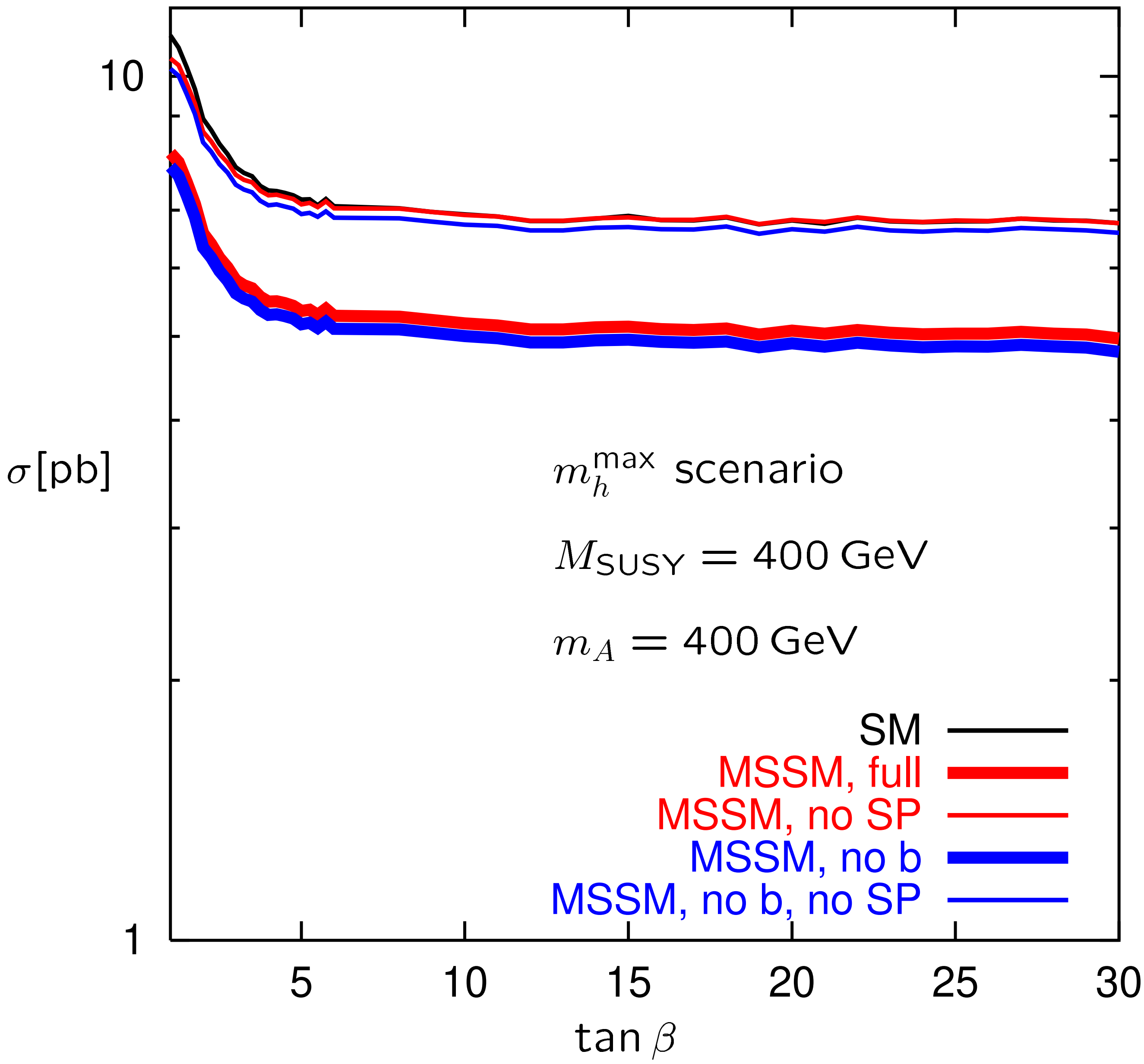
$$\mu = 1\ \mathrm{TeV}$$
$$X_t = -900\ \mathrm{GeV}$$
$$m_{\tilde{g}} = 400\mathrm{GeV}$$

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

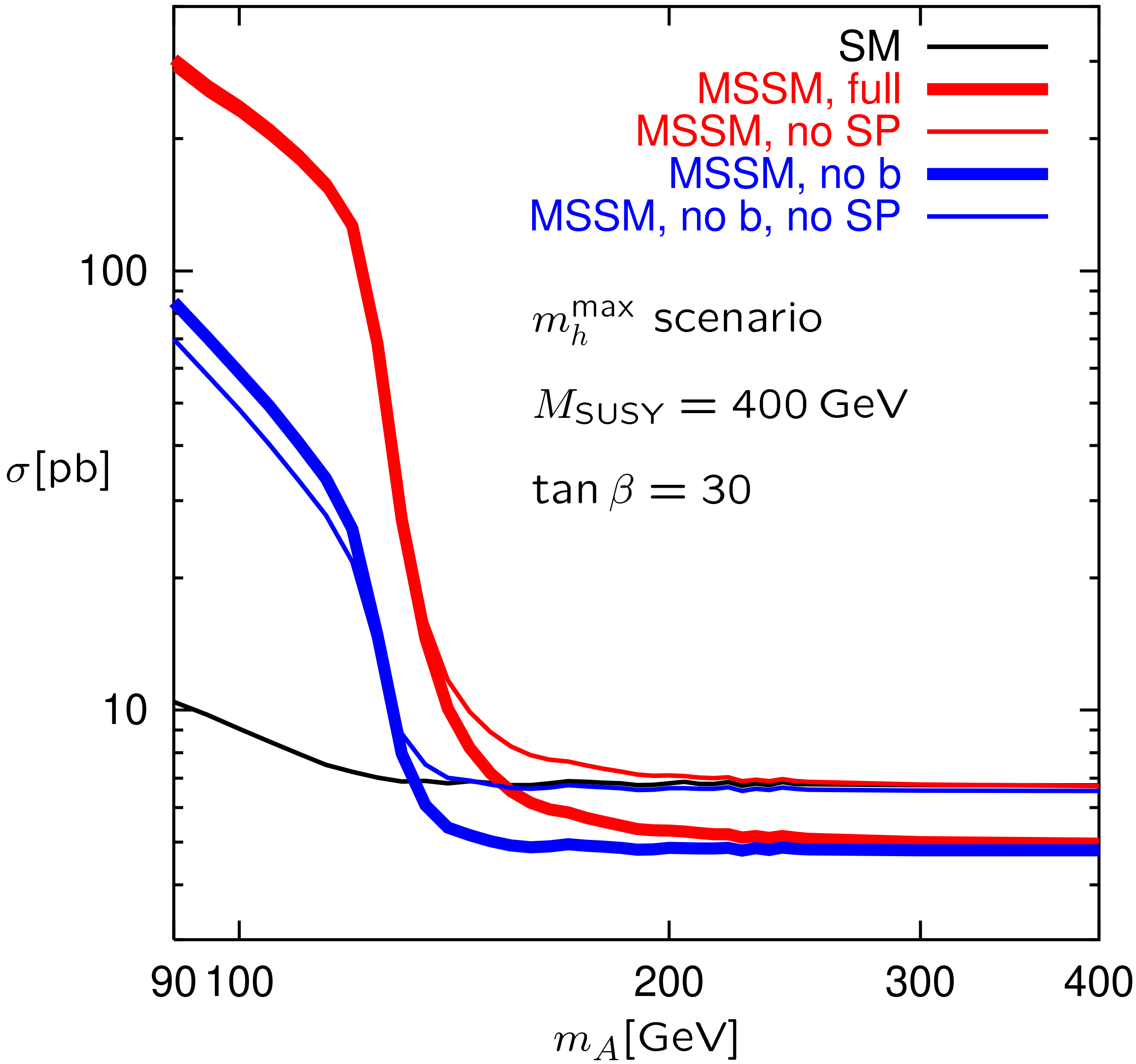


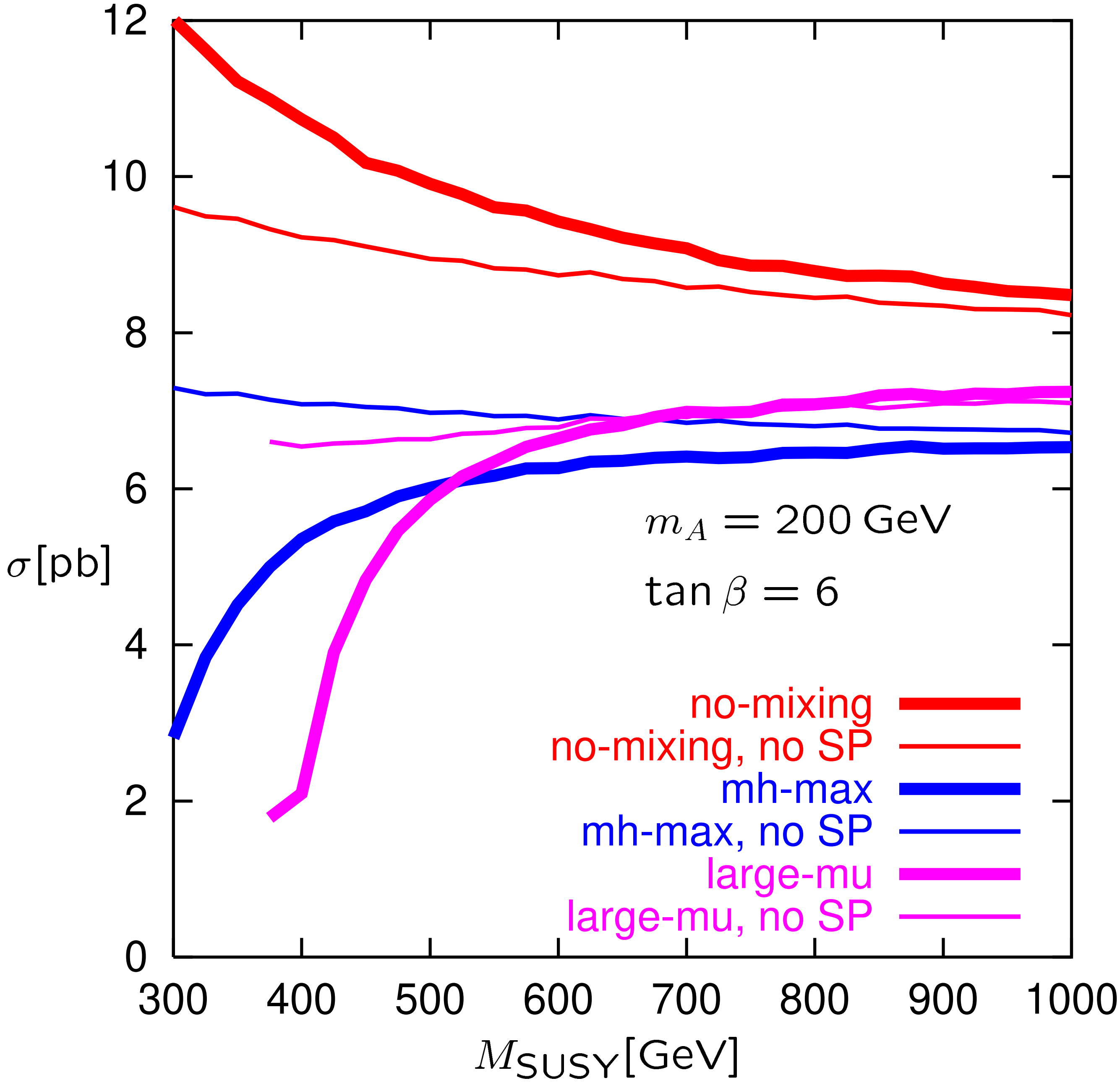
$\tan\beta = 3, \quad M_{\tilde{Q}} = M_A = 1$ TeV, $\quad m_{\tilde{g}} = 800$ GeV

X_t : top-squark mixing parameter

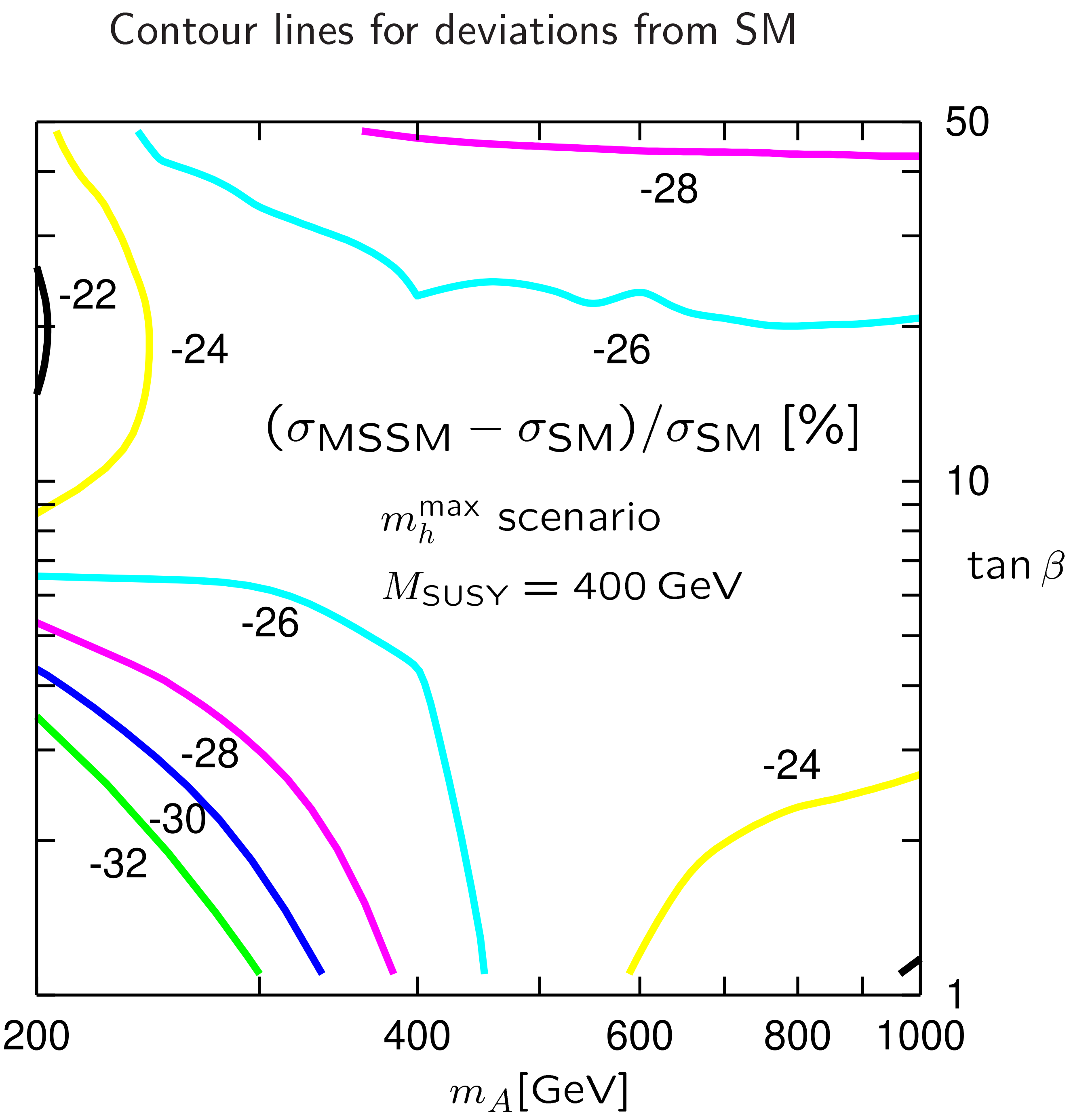


10
1
5
10
15
20
25
30
$\tan\beta$
σ[pb]
$m_h^{\rm max}$ scenario
$M_{\rm SUSY} = 400$ GeV
$m_A = 400$ GeV
SM
MSSM, full
MSSM, no SP
MSSM, no b
MSSM, no b, no SP


SM
MSSM, full
MSSM, no SP
MSSM, no b
MSSM, no b, no SP
$m_h^{\rm max}$ scenario
$M_{\rm SUSY} = 400$ GeV
$\tan\beta = 30$
100
10
σ[pb]
90
100
200
300
400
m_A[GeV]



12
10
8
6
4
2
0
σ[pb]
300
400
500
600
700
800
900
1000
$M_{\rm SUSY}$[GeV]
$m_A = 200$ GeV
$\tan\beta = 6$
no-mixing
no-mixing, no SP
mh-max
mh-max, no SP
large-mu
large-mu, no SP


Contour lines for deviations from SM
-22
-24
-28
-26
$(\sigma_{\mathrm{MSSM}} - \sigma_{\mathrm{SM}})/\sigma_{\mathrm{SM}}$ [%]
m_h^{max} scenario
$M_{\mathrm{SUSY}} = 400$ GeV
-26
-28
-30
-32
-24
50
10
1
tan β
200
400
600
800
1000
m_A[GeV]

Summary

- Higgs+jet production is a promising alternative to inclusive Higgs production
- Main production channel@LHC is gluon fusion (loop-induced)
- Differences for MSSM h^0 and $H_{\rm SM}$ sizeable

  Large effects from virtual squarks
- Large tree-level contributions from b quarks for $M_A < 150$ GeV
- NLO calculation required