Neutral & Charged Higgs Production

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outline :

- Intro: Higgs Production at the LHC
- Production of Neutral Higgs + Jet
- MC for Higgs + 3 jets via VBF at NLO QCD
- Charged Higgs Production: Refinements
- Minimal Phantom Higgs Sector

- Intro: Higgs Production at the LHC

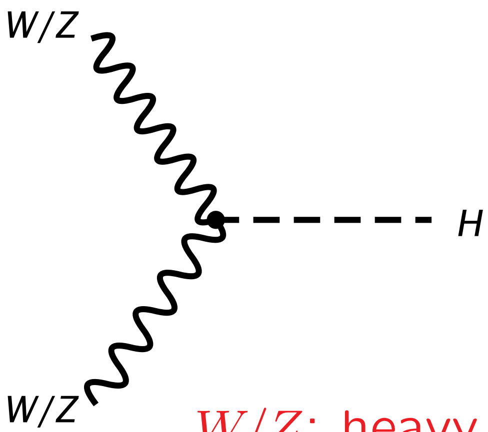
– How to produce a Higgs boson ?

Higgs mechanism $\longrightarrow$ Higgs couplings $\propto$ mass

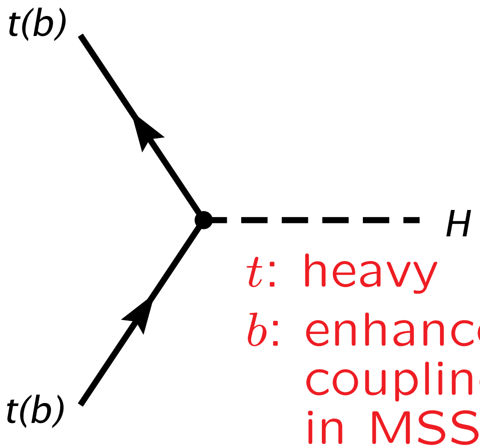
$\longrightarrow$ Problem: ordinary matter is very light !

$\longrightarrow$ Thus: At colliders the Higgs couples to heavy intermediate particles
with non-suppressed couplings to ordinary matter.

Therefore, most important couplings :

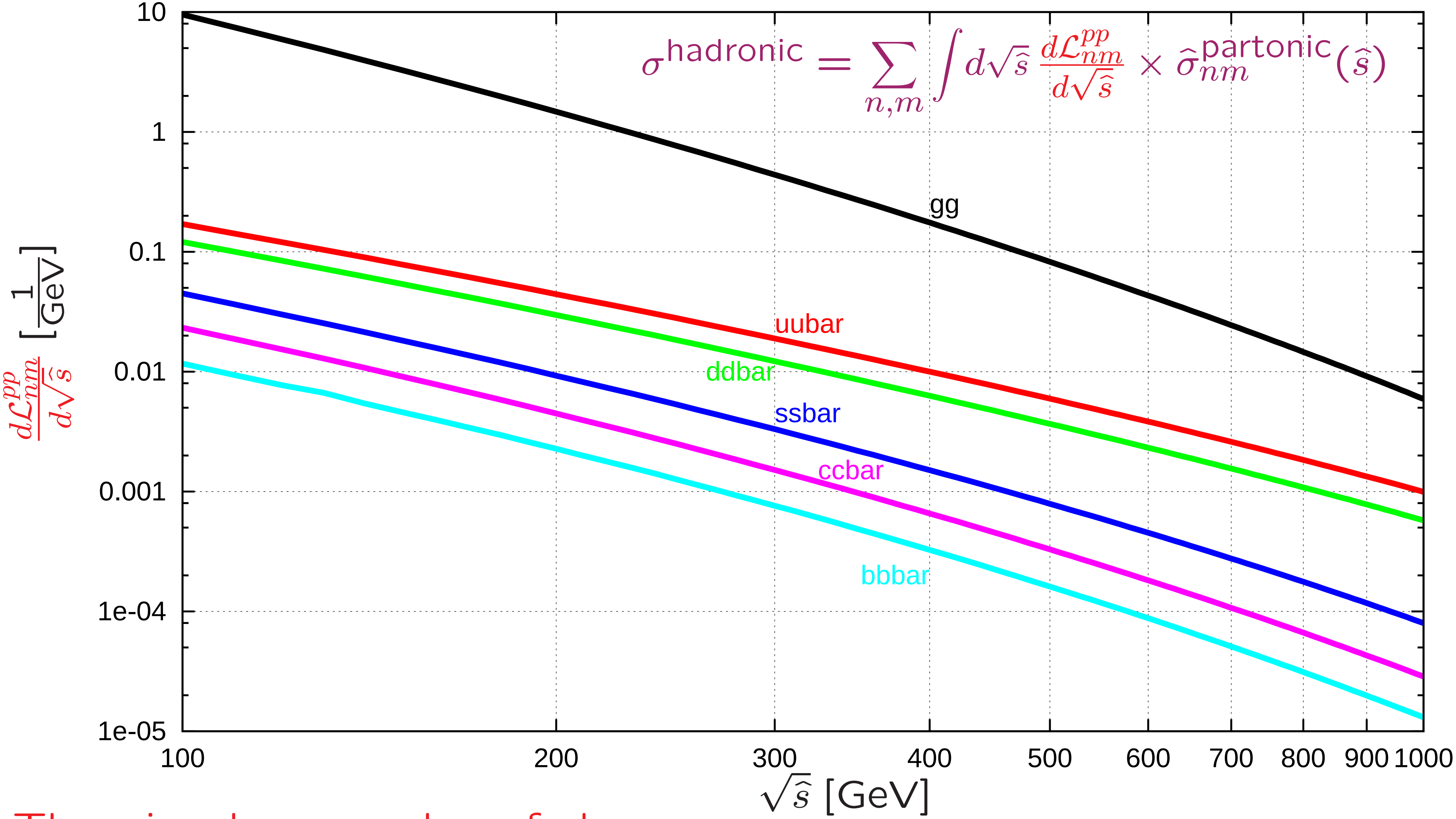


W/Z: heavy



t: heavy
b: enhanced coupling in MSSM

Parton luminosities $\frac{d\mathcal{L}^{pp}_{nm}}{d\sqrt{\hat{s}}}$ at the LHC:



There is a huge number of gluons
with small momentum fractions
still having enough energy to produce Higgs particles.

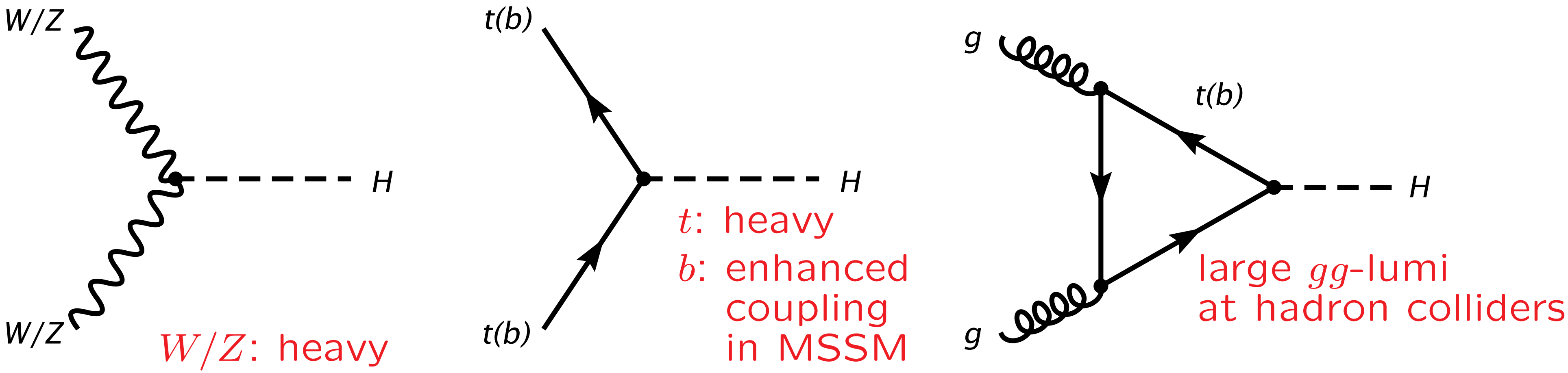
– How to produce a Higgs boson ?

Higgs mechanism $\longrightarrow$ Higgs couplings $\propto$ mass

$\longrightarrow$ Problem: ordinary matter is very light !

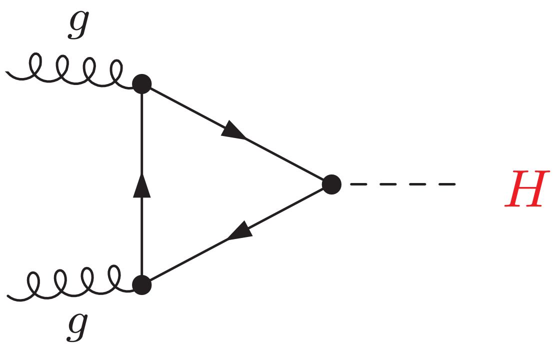
$\longrightarrow$ Thus: At colliders the Higgs couples to heavy intermediate particles with non-suppressed couplings to ordinary matter.

Therefore, most important couplings at high energy hadron colliders :



– Neutral Higgs Production Overview

Important neutral Higgs production processes:



gluon fusion, $gg \longrightarrow H$

– Neutral Higgs Production Overview

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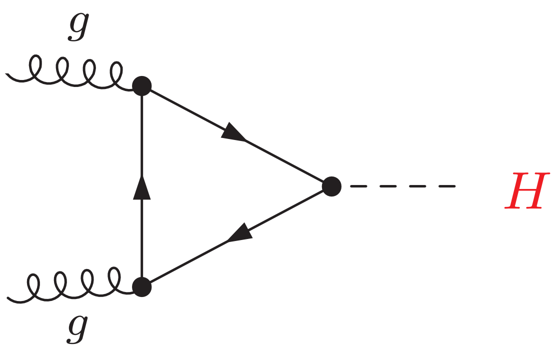
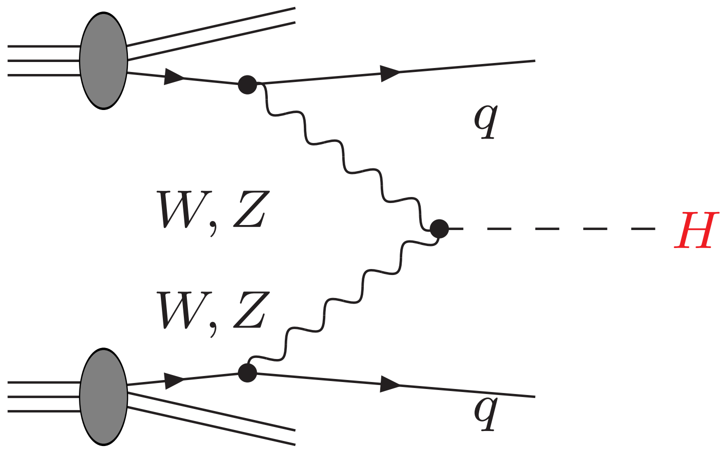


gluon fusion, $gg \to H$



vector boson fusion, $qq \to qqH$

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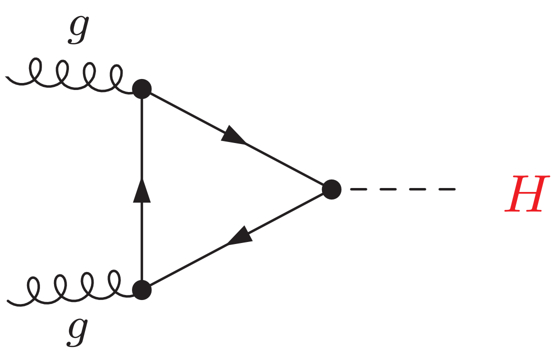

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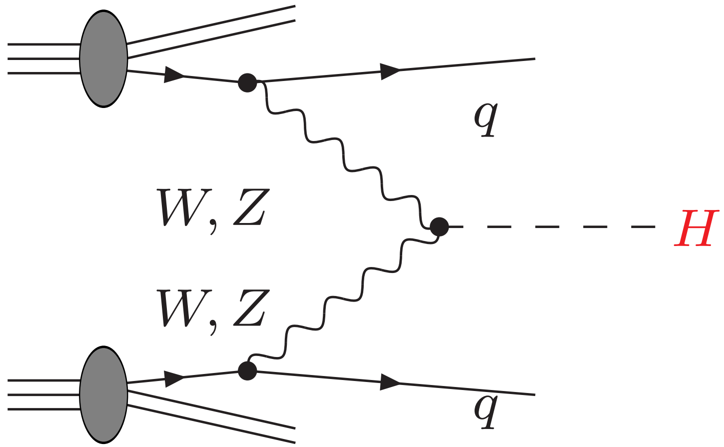
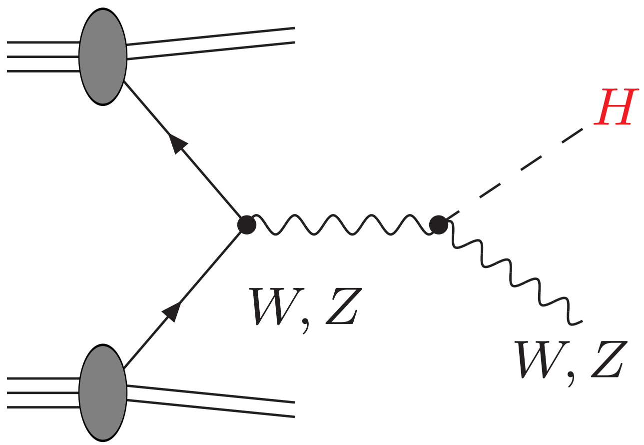


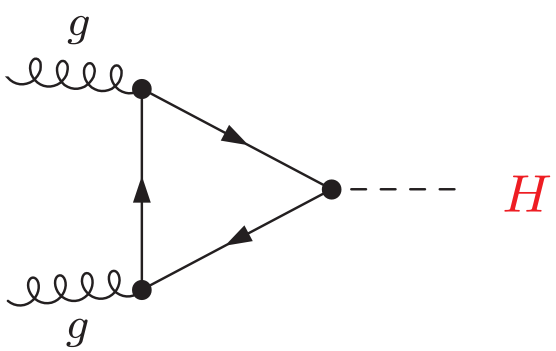
vector boson fusion, $qq \to qqH$



Higgs strahlung, $q\bar{q}' \to VH$

– Neutral Higgs Production Overview

Important neutral Higgs production processes:



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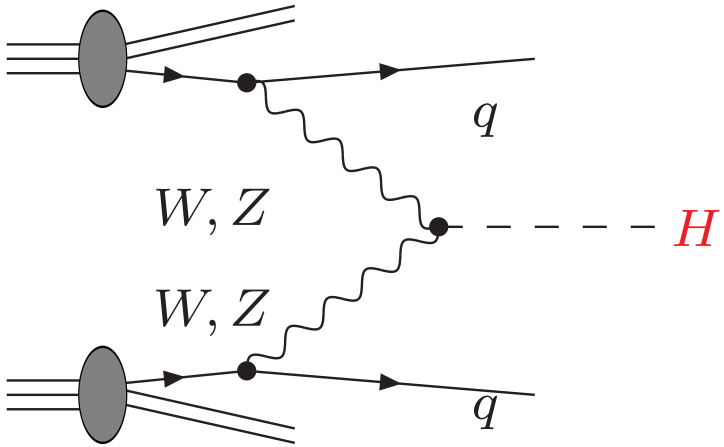
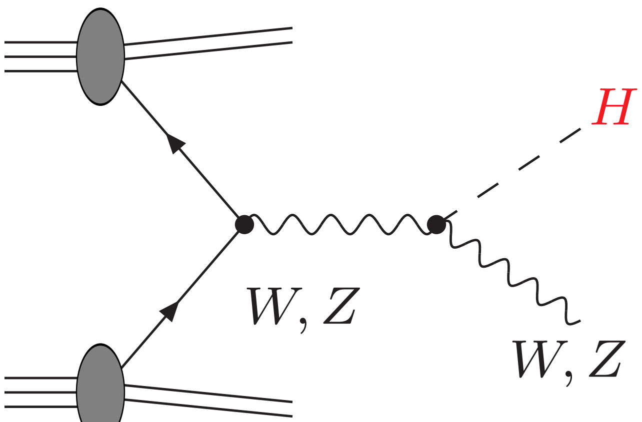
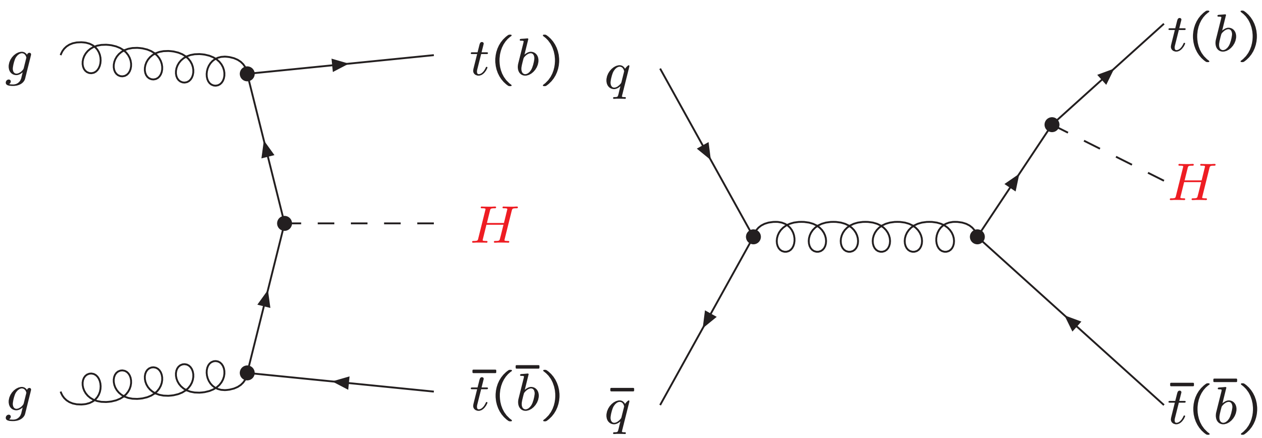


vector boson fusion, $qq \to qqH$

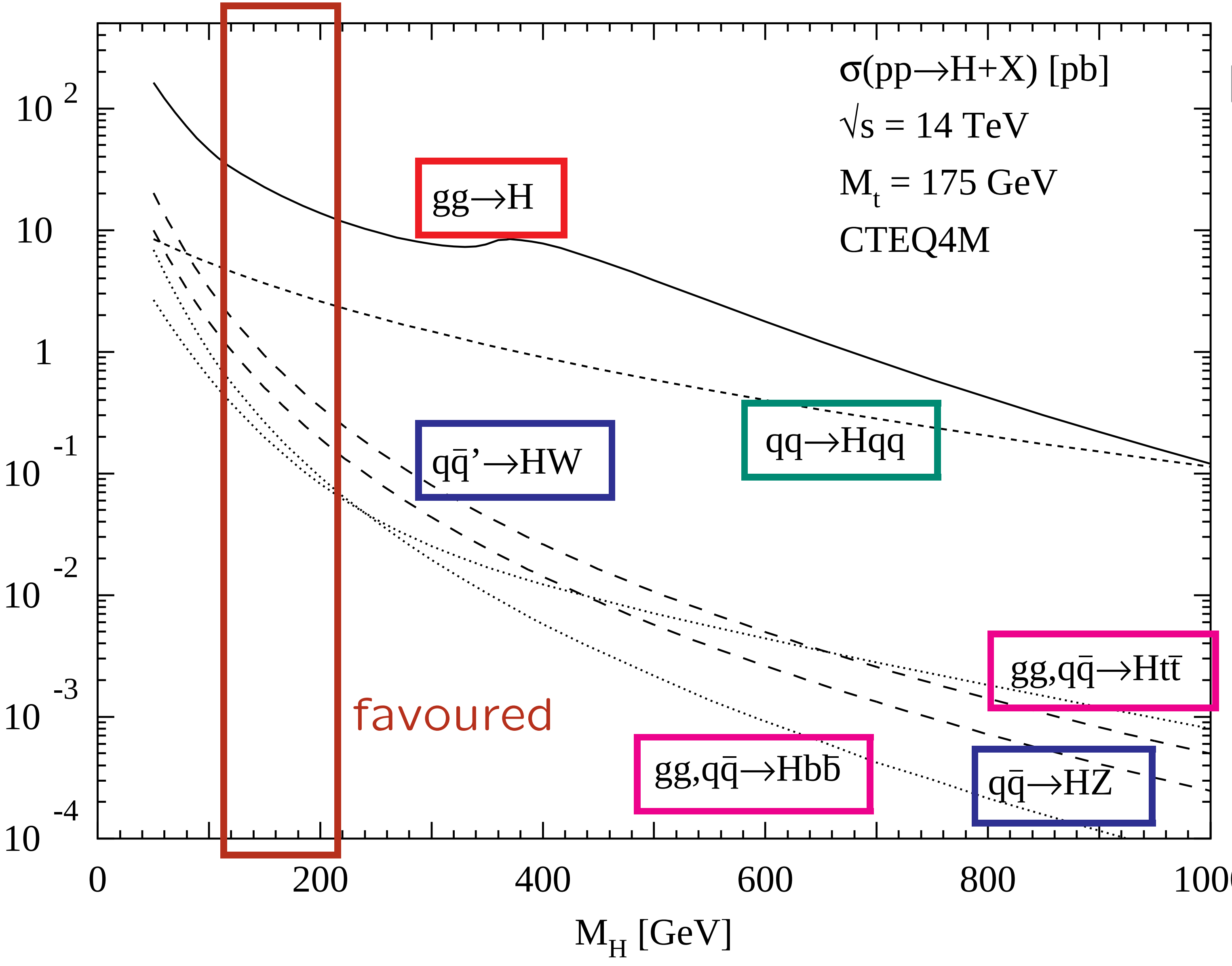


Higgs strahlung, $q\bar{q}' \to VH$



$t\bar{t}H$ **(**$b\bar{b}H$**) production [&** $b\bar{b} \to H$ **if 5 flavs]**

Predictions: SM Higgs production @ **LHC** :



[Spira '98]

cross sections in the MSSM:
(for the lightest neutral Higgs)

small $\tan\beta$ (say 3) :

- cross sections similar to SM
- gluon fusion, $\sigma(gg \to h)$, dominant

large $\tan\beta$ (say ≥ 30) :

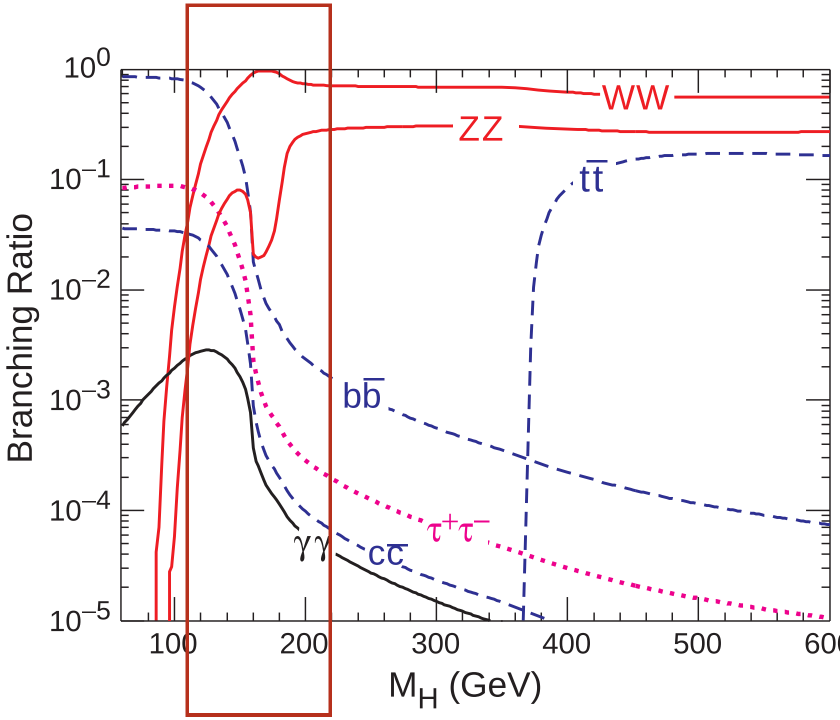
- gluon fusion cross section larger than in SM
- b-quark processes gain in importance
- $\sigma(gg \to h) \approx \sigma(gg, q\bar{q} \to hb\bar{b})$
- Higgs strahlung unimportant

SM Higgs branching ratios
and
signal significance @ LHC

note!

rate alone is not enough!

signals need to be silhouetted against **huge** QCD background



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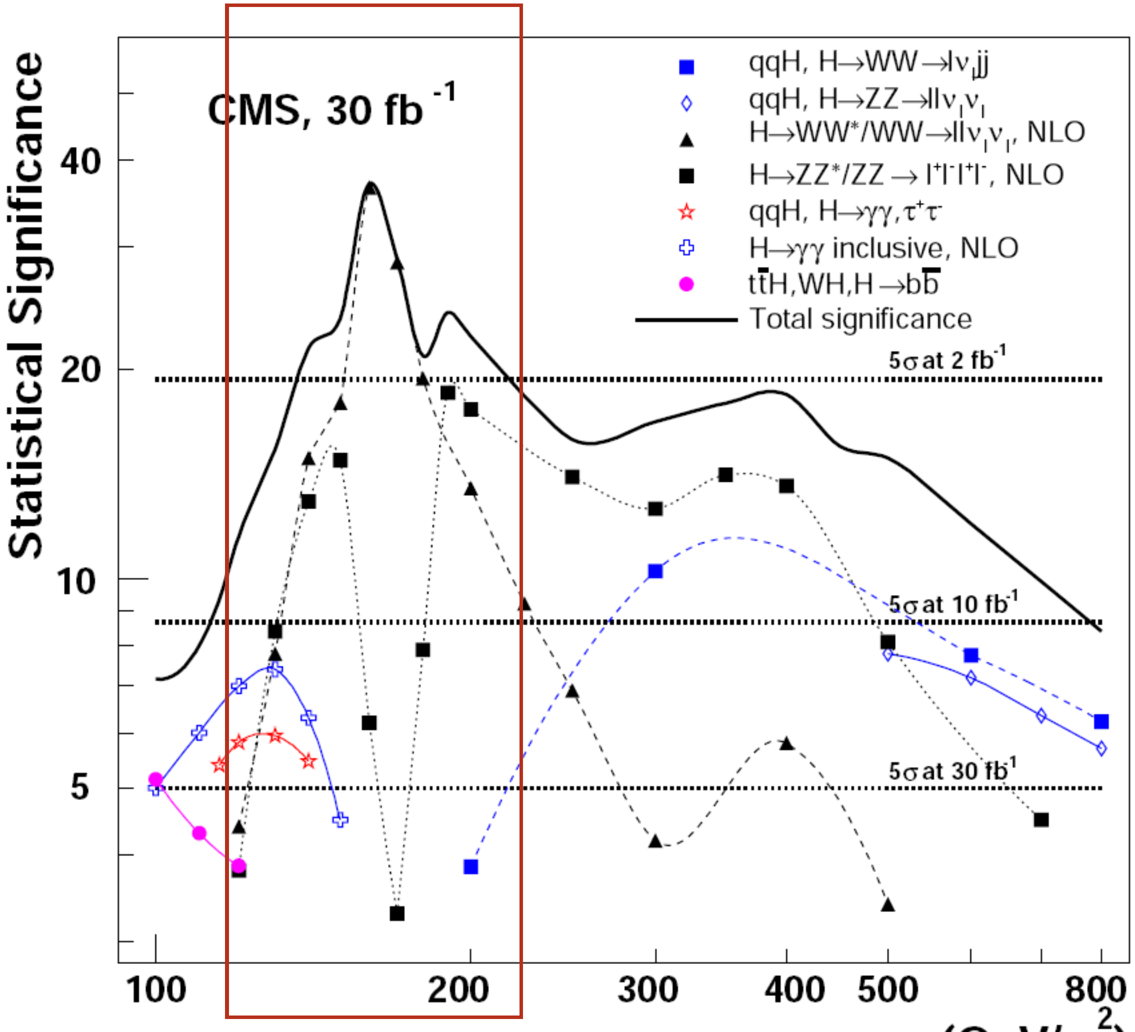

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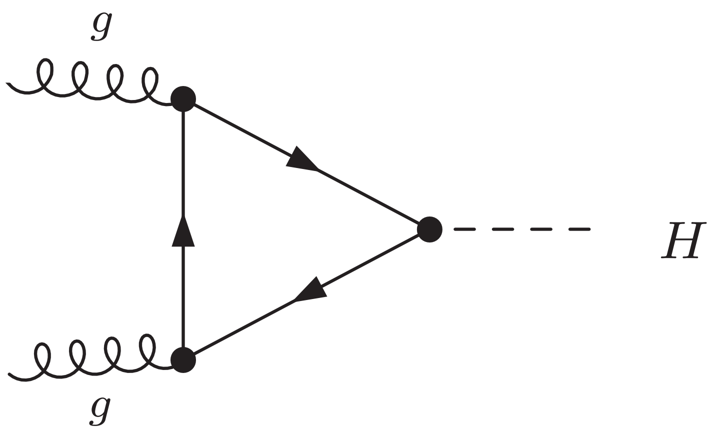
- Production of Neutral Higgs + Jet

• Production of Neutral Higgs + Jet

– Higgs + Jet in the Standard Model

SM Higgs production @ LHC mainly via gluon fusion:



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

→ difficult ! huge background

– Higgs + Jet in the Standard Model

suggestion: study Higgs events with a high-p_T hadronic jet

[R.K. Ellis et al. '87; Baur, Glover '89] (LO)

[de Florian, Grazzini, Kunszt '99] (NLO QCD)

advantage:

* richer kinematical structure compared to inclusive Higgs production.
  → allows for refined cuts
  → better S/B ratio

disadvantage:

* lower rate than inclusive Higgs production

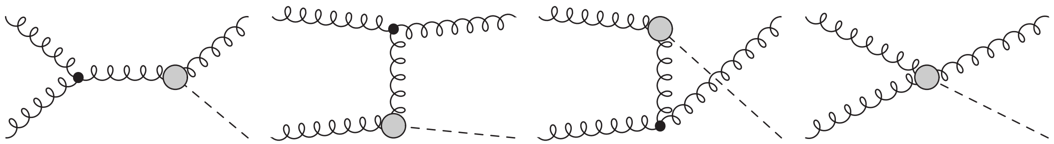
(*) NLO signal prediction has still sizable theoretical uncertainty ($\approx 20\%$)

(*) background only partly known at NLO accuracy

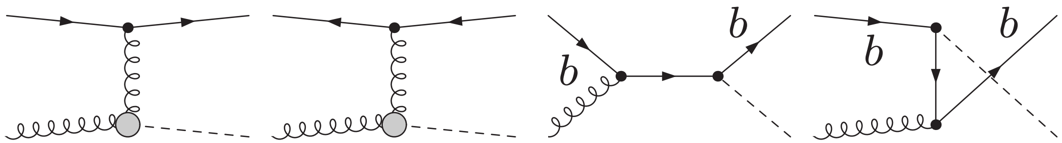
→ theoretical uncertainties larger than in the fully inclusive case (so far)

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

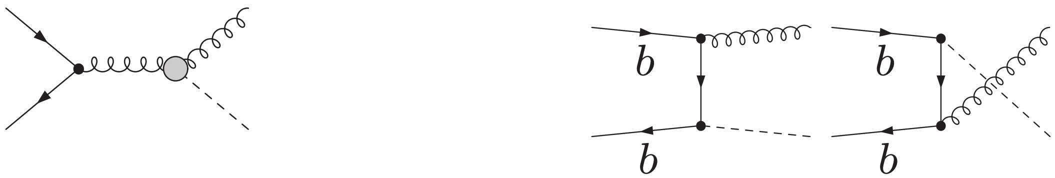
- $gg \longrightarrow Hg$ (≈ 50 - 70 % of total rate)



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



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



recently simulated: $pp \longrightarrow H + \text{jet}, H \longrightarrow \gamma\gamma$ [Abdullin et al. '98 & '02; Zmushko '02]

$pp \longrightarrow H + \text{jet}, H \longrightarrow \tau^+\tau^- \longrightarrow l^+l^-\not{p}_T$ [Mellado et al. '05]

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

− Higgs + Jet in the MSSM

[OBr, Hollik '03; '07] (full MSSM), [Field, Dawson, Smith '04] (MSSM, no superpartners),
[Langenegger et al. '06] (MSSM with soft-gluon resummation, no superpartners)

Motivation:

* promising simulation results in the SM case
* 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

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

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

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

→ change of overall rate

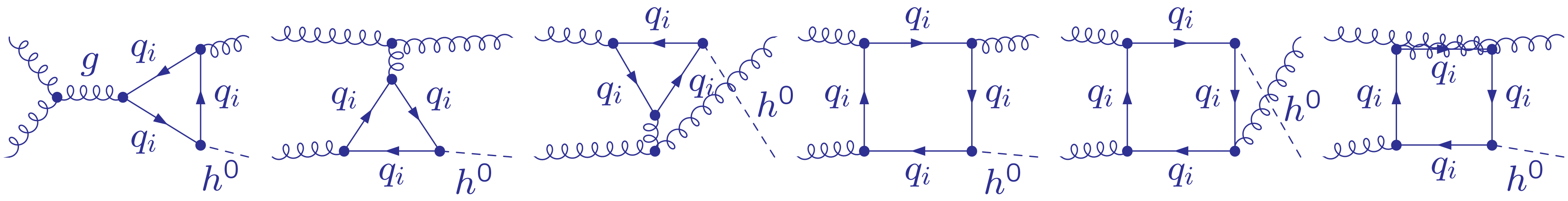
* additional superpartner-loops (even additional topologies)

→ also angular distribution changed

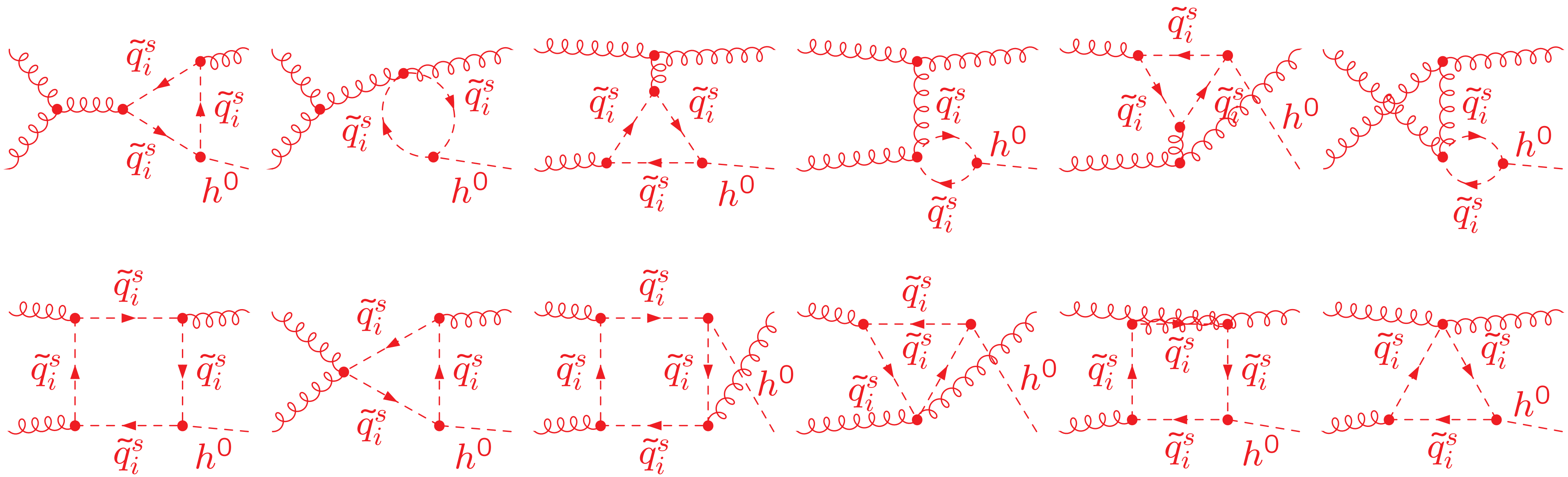
Feynman graphs :

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

quark loops

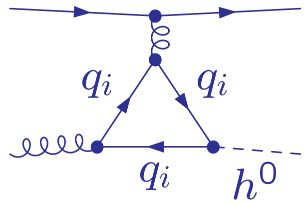


superpartner loops

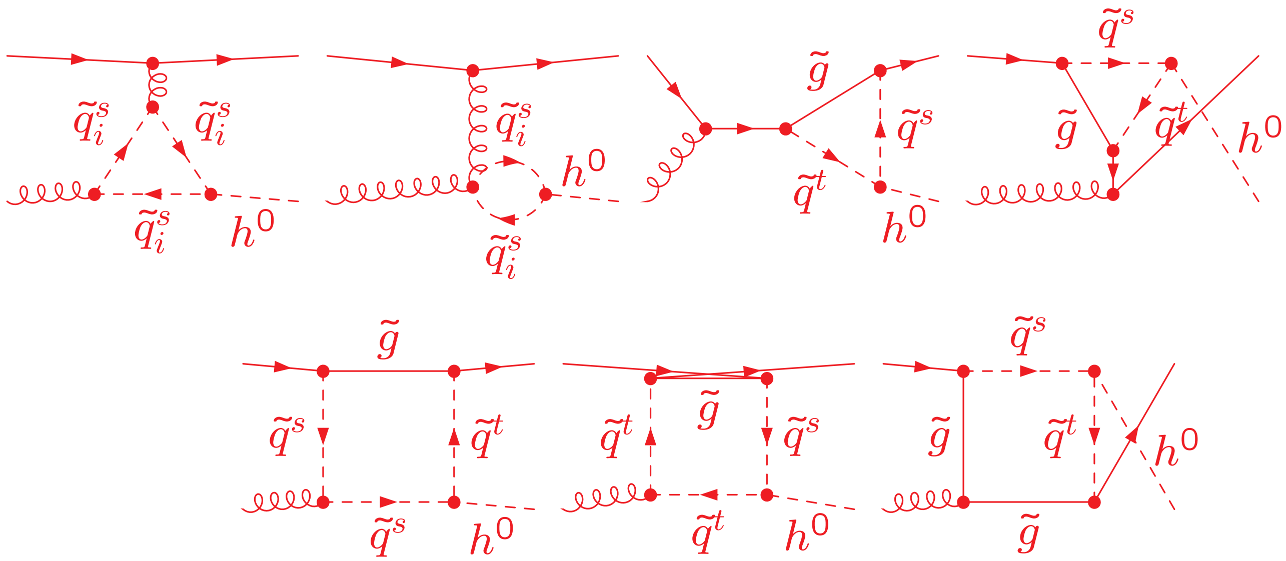


quark gluon scattering, $qg \to h^0 q$

quark loops

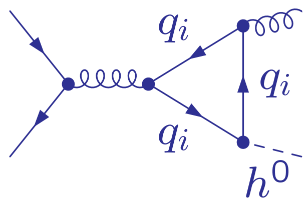


superpartner loops

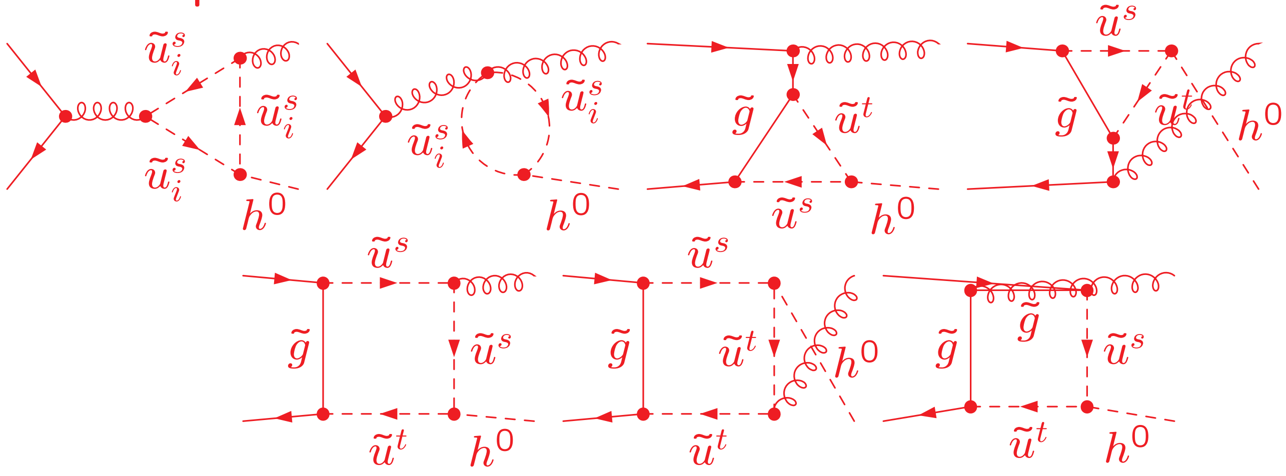


quark anti-quark annihilation, $q\bar{q} \to h^0 g$

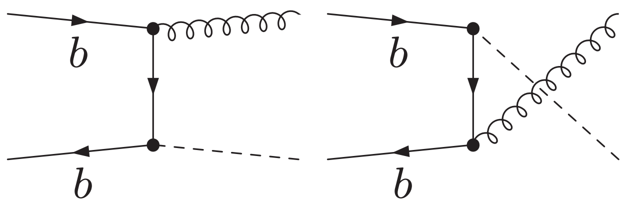
quark loops



superpartner loops



b-quark processes: bg scattering, $bg \to h^0 b$,
$b\bar{b}$ annihilation, $b\bar{b} \to h^0 g$



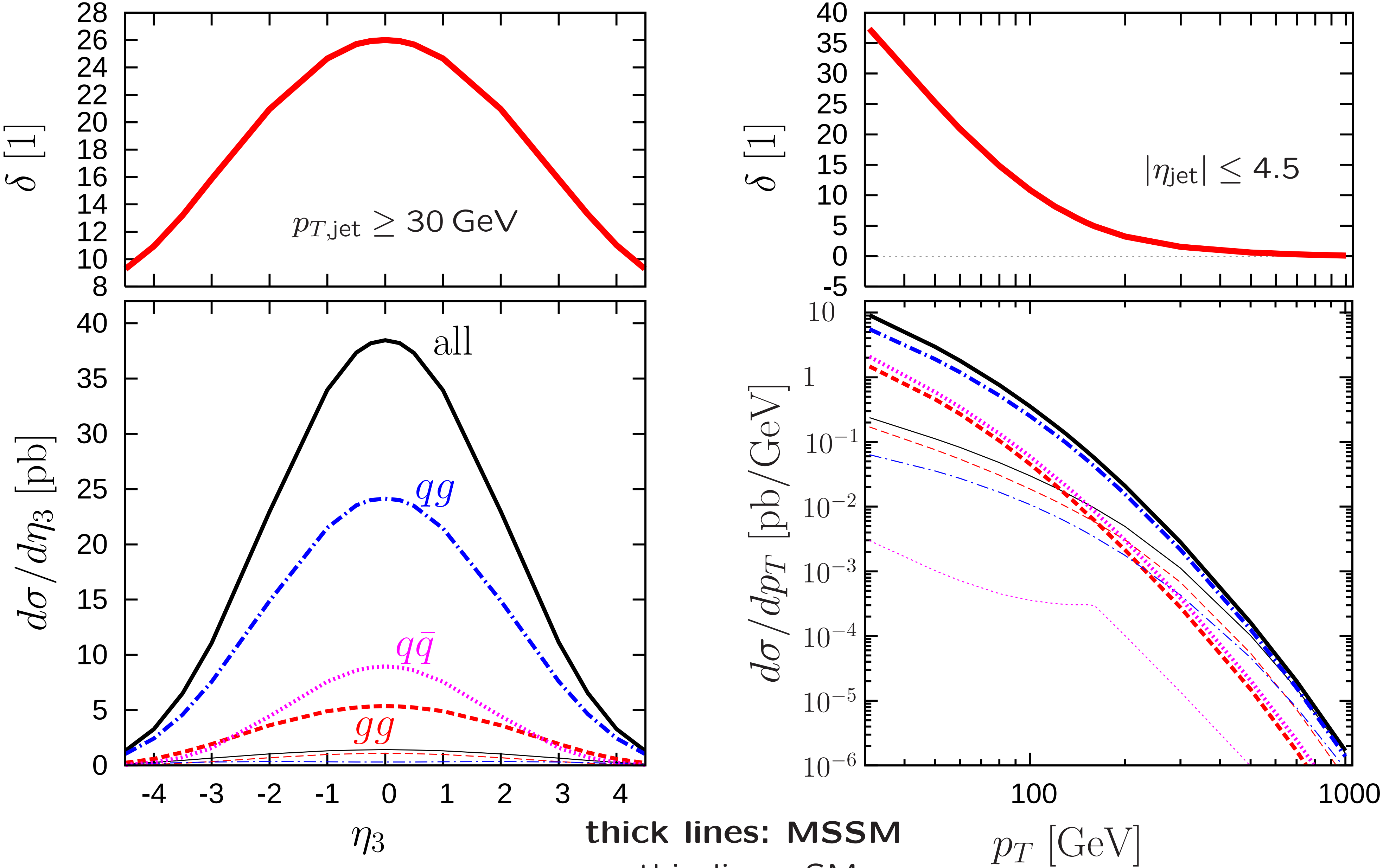
[partonic processes calculated using FeynArts/FormCalc, see : www.feynarts.de]

differential hadronic cross sections @ LHC

$$\frac{d\sigma(S,p_{T,\text{jet}})}{dp_{T,\text{jet}}},\ \frac{d\sigma(S,\eta_{\text{jet}})}{d\eta_{\text{jet}}},\ \frac{d^2\sigma(S,p_{T,\text{jet}},\eta_{\text{jet}})}{dp_{T,\text{jet}}\,d\eta_{\text{jet}}}$$

$p_{T,\text{jet}}$- and η_{jet}-dependence, low-m_A case

LHC, m_h**-max scenario**, $M_{\text{SUSY}} = 400$ **GeV**, $m_A = 110$ **GeV**, $\tan\beta = 30$

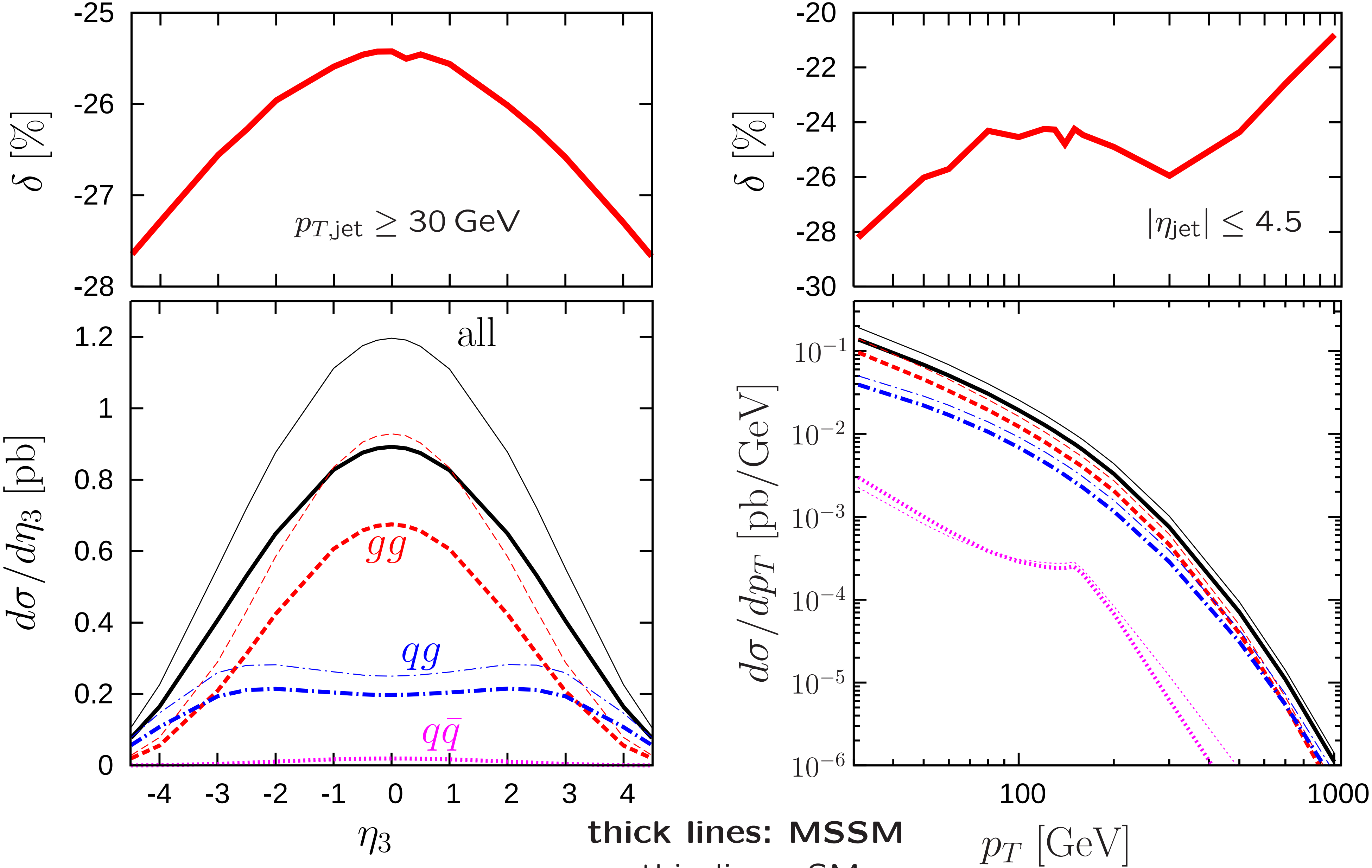


thick lines: MSSM

thin lines: SM

$p_{T,\text{jet}}$- and η_{jet}-dependence, high-m_A case

LHC, m_h-**max scenario**, $M_{\text{SUSY}} = 400$ **GeV**, $m_A = 400$ **GeV**, $\tan\beta = 30$



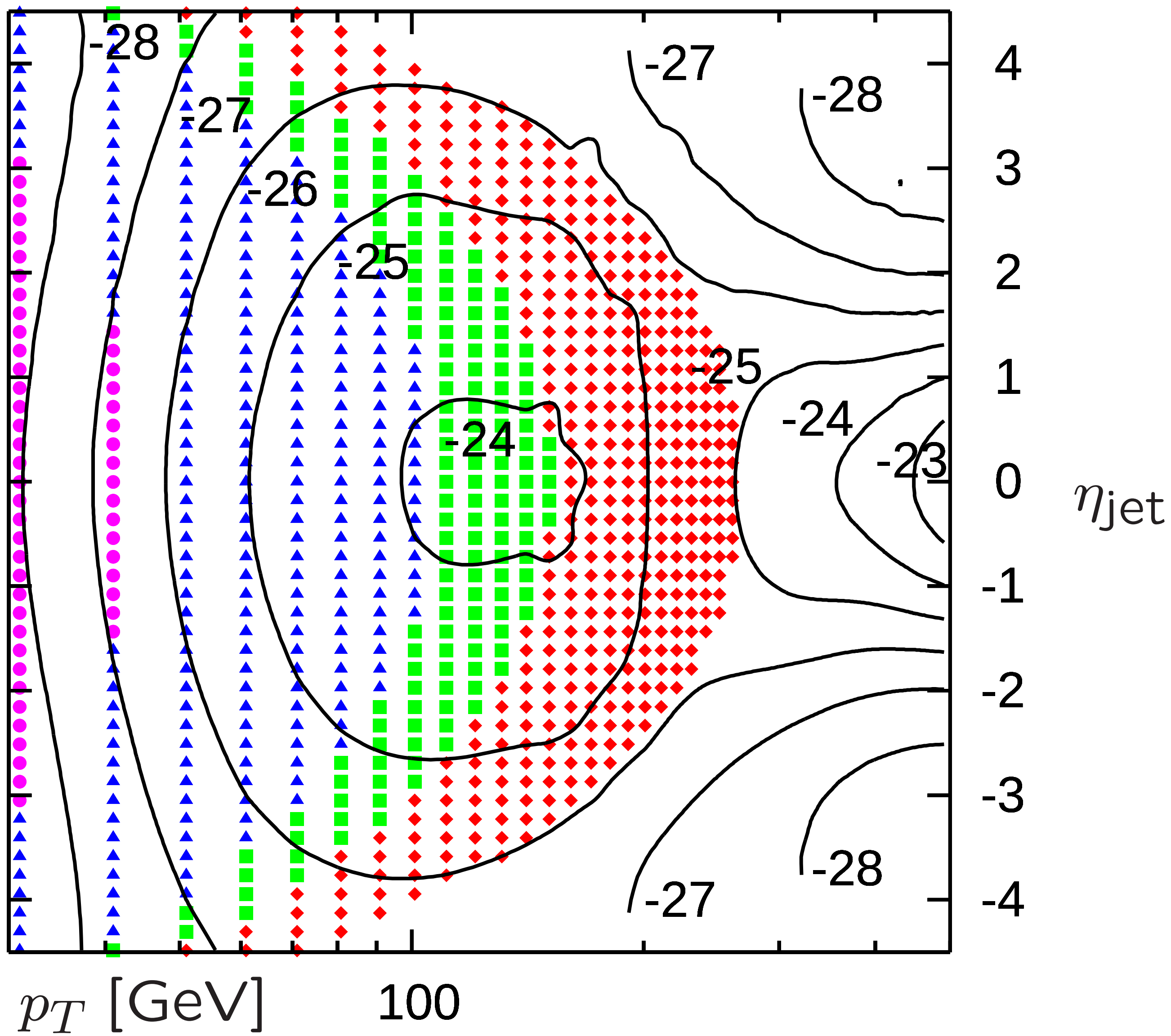
thick lines: MSSM

thin lines: SM

LHC, $\frac{d^2\sigma}{dp_{T,\text{jet}}d\eta_{\text{jet}}}$: MSSM − SM relative and absolute difference

relative difference in % :
contour lines ——

absolute difference :
● : 5 - 10 fb/GeV
▲ : 1 - 5 fb/GeV
■ : 0.5 - 1 fb/GeV
♦ : 0.1 - 0.5 fb/GeV



LHC, m_h-max scenario, $M_{\text{SUSY}} = 400\,\text{GeV}$, $m_A = 400\,\text{GeV}$, $\tan\beta = 30$

FORTRAN code HJET to calculate the MSSM (and SM) cross sections,

$$\sigma_{\text{hadronic}}^{\text{total}},$$

$$\frac{d\sigma_{\text{hadronic}}}{d\sqrt{\hat{s}}}, \quad \frac{d\sigma_{\text{hadronic}}}{dp_{T,\text{jet}}}, \quad \frac{d\sigma_{\text{hadronic}}}{d\eta_{\text{jet}}},$$

$$\frac{d^2\sigma_{\text{hadronic}}}{dp_{T,\text{jet}}\, d\eta_{\text{jet}}}$$

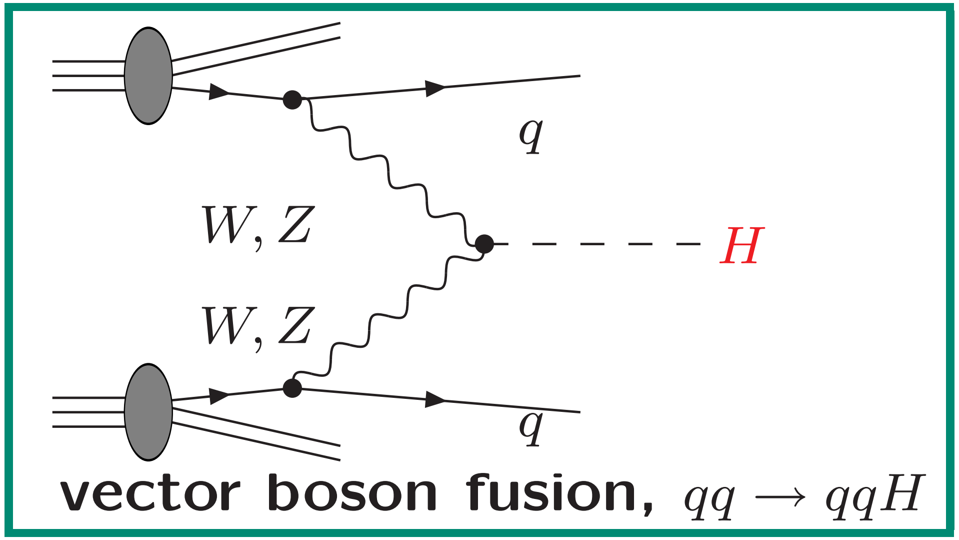
$$\hat{\sigma}_{\text{partonic}}^{\text{total}},$$

$$\frac{d\hat{\sigma}_{\text{partonic}}}{d\Omega}, \quad \frac{d\hat{\sigma}_{\text{partonic}}}{d\hat{t}}, \quad \frac{d\hat{\sigma}_{\text{partonic}}}{dy_{\text{jet}}}, \quad \frac{d\hat{\sigma}_{\text{partonic}}}{dp_{T,\text{jet}}},$$

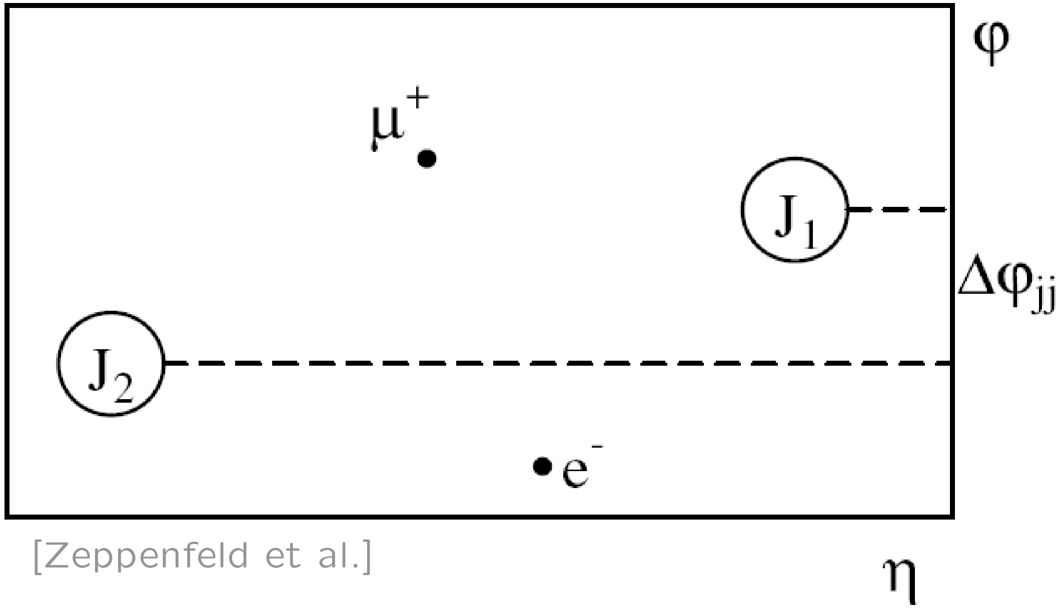
will be available on request → oliver.brein@durham.ac.uk

- MC for Higgs + 3 jets via VBF at NLO QCD

[Higgs + 3 jets at NLO QCD]



VBF signature ($H \to WW^{(\star)} \to \mu\nu_\mu e\nu_e$)



[Zeppenfeld et al.]

- Higgs + 3 Jets from gluon fusion & VBF populate the central rapidity region
- gluon fusion does so much more than VBF

$\to$ Central Jet Veto

Higgs + 3 Jets via VBF at NLO QCD

[Figy, Zeppenfeld]

Signal definition (for the following plots):

- k_T algorithm: require at least 3 hard jets with $P_{T,j} > 20\,\text{GeV}$, $|y_j| < 4.5$
- Tagging jets: 2 jets of $P_{T,j}^{\text{tag}} > 30\,\text{GeV}$, $|\eta_l| < 2.5$, $\Delta R_{jl} > 0.6$

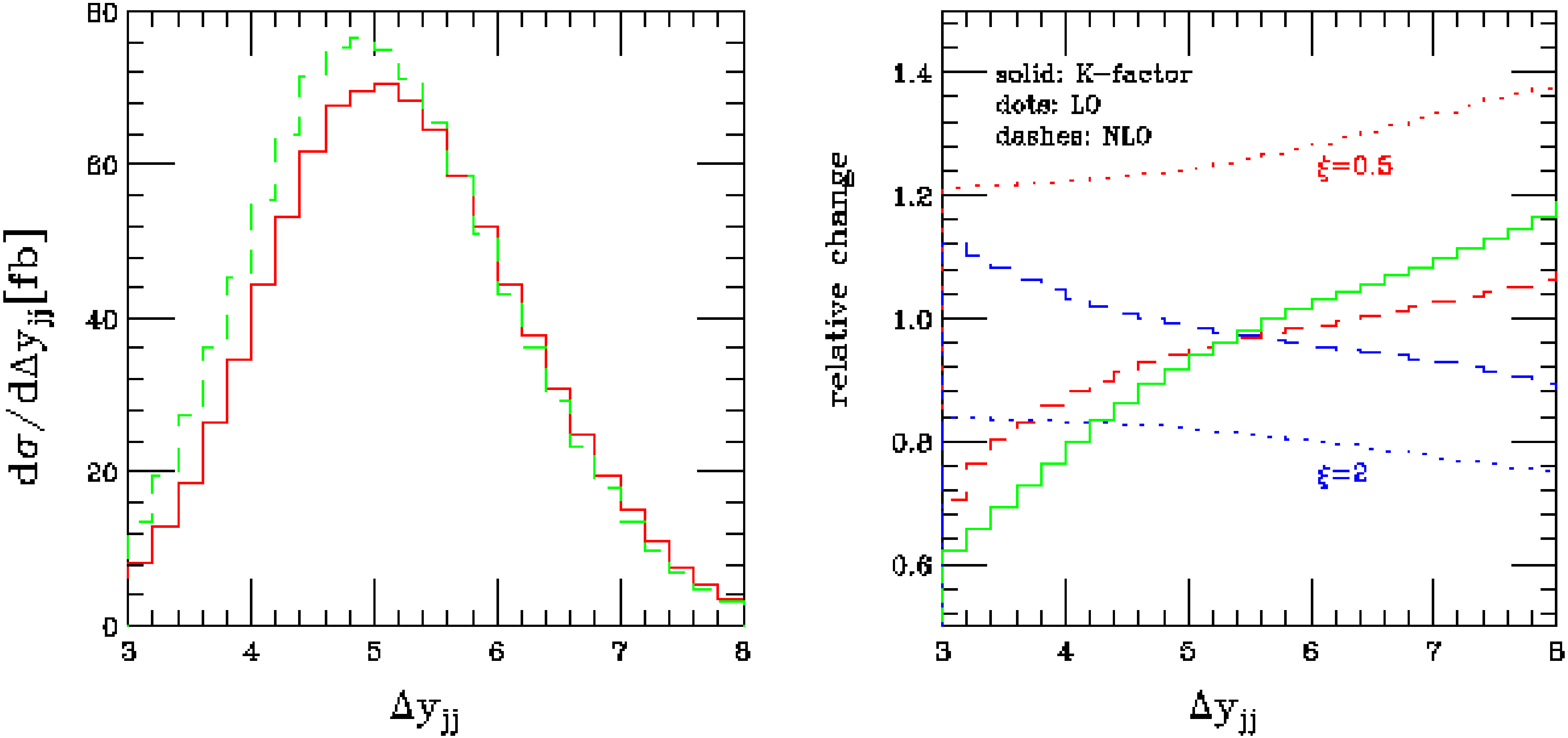
$$y_{j,\text{min}}^{\text{tag}} + 0.6 < \eta_{l_{1,2}} < y_{j,\text{max}}^{\text{tag}} - 0.6$$

- Rapidity gap and opposite detector hemispheres:

$$y_j^{\text{tag},1} \cdot y_j^{\text{tag},2} < 0$$
$$\Delta y_{jj} = |y_j^{\text{tag},1} - y_j^{\text{tag},2}| > 4$$

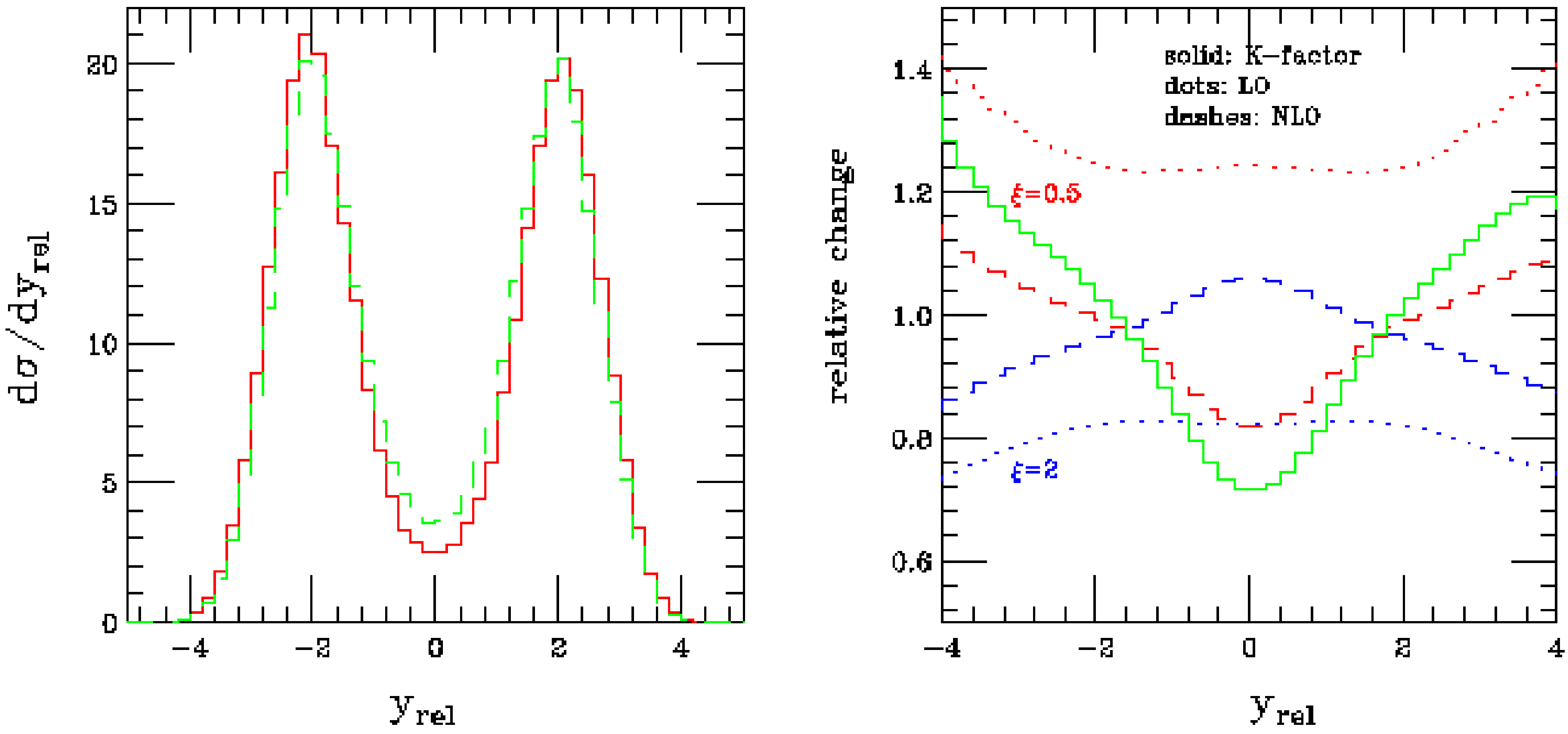
- Invariant mass of tagging jets: $m_{jj} > 600\,\text{GeV}$

tagging jet distributions: Δy_{jj}



dashes: LO, solid: NLO

veto jet distributions: $y_{\rm rel} = y_{\rm jet}^{\rm veto} - (y_j^{\rm tag,1} + y_j^{\rm tag,2})/2$



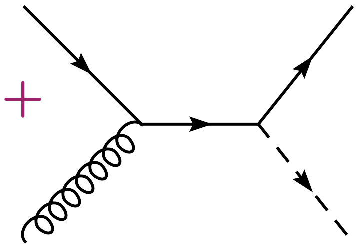
dashes: LO, solid: NLO

- Charged Higgs Production: Refinements

– Charged Higgs Search at the LHC

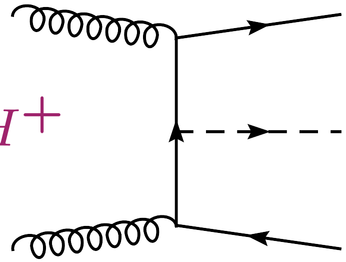
- $m_{H^{\pm}} < m_t$: mainly via $t \to H^+ b$ and c.c. in $t\bar{t}$ events. [Bawa et al.'90]
- $m_{H^{\pm}} > m_t$: mainly via

$gb \to tH^+$



,

$gg \to tbH^+$



[LO: Gunion et el. '87; NLO QCD: Zhu '03; Plehn '03; Berger et al. '03]

other processes with smaller c.s. :

$gg/b\bar{b} \to H^{\pm}W^{\mp}$

[gg: Dicus et al. '89; Barrientos, Kniehl '99-'00; OBr, Hollik, Kanemura '00;
$b\bar{b}$: MSSM, NLO QCD: Hollik, Zhu '01]

$gg/q\bar{q} \to H^+H^-$

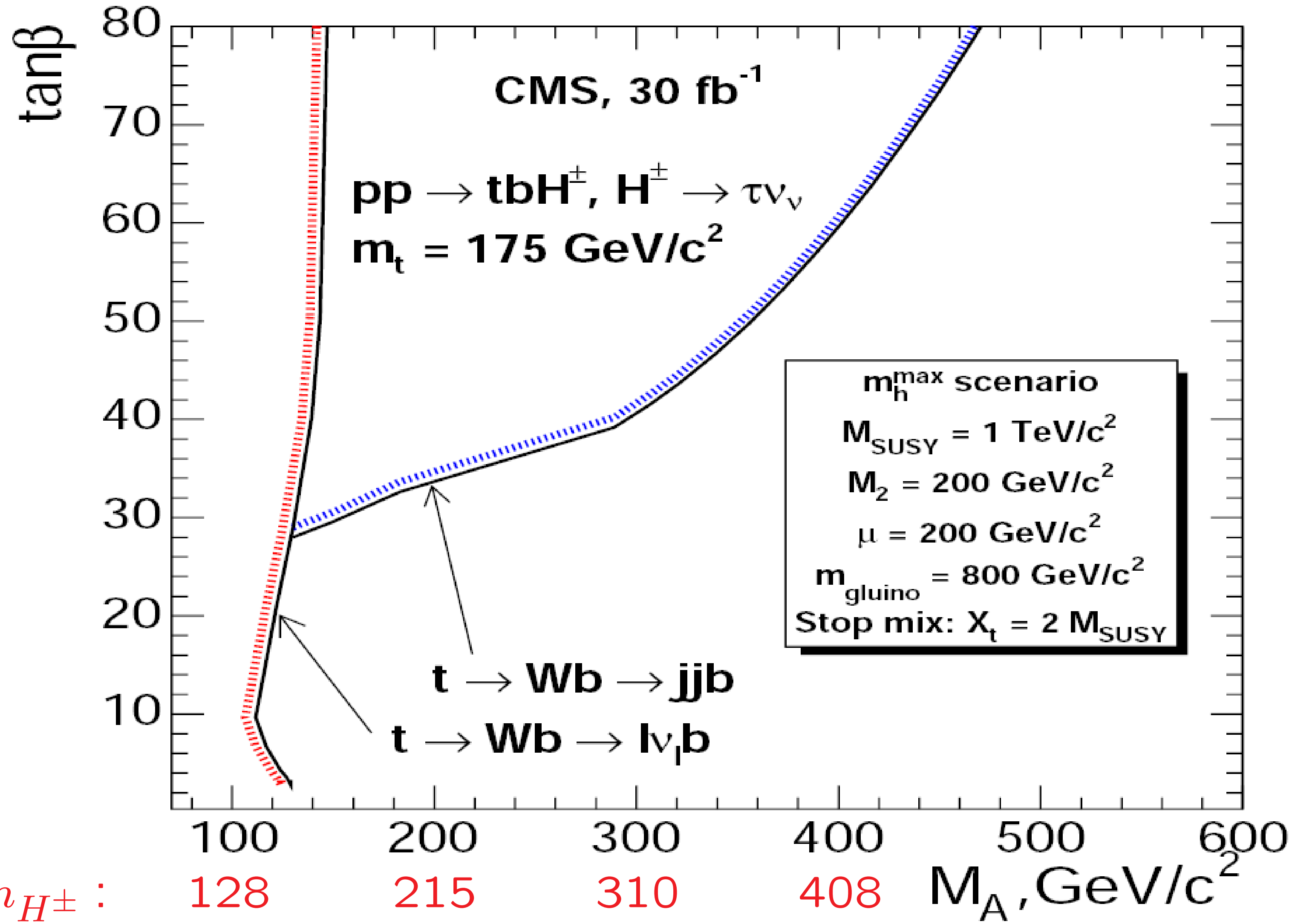
[Krause et al. '98; OBr, Hollik '99; Barrientos, Kniehl '99]

most viable signal: **excess of tau events**

from the decays $H^+ \to \tau^+\nu_\tau$ and c.c.

CMS charged Higgs discovery contour :

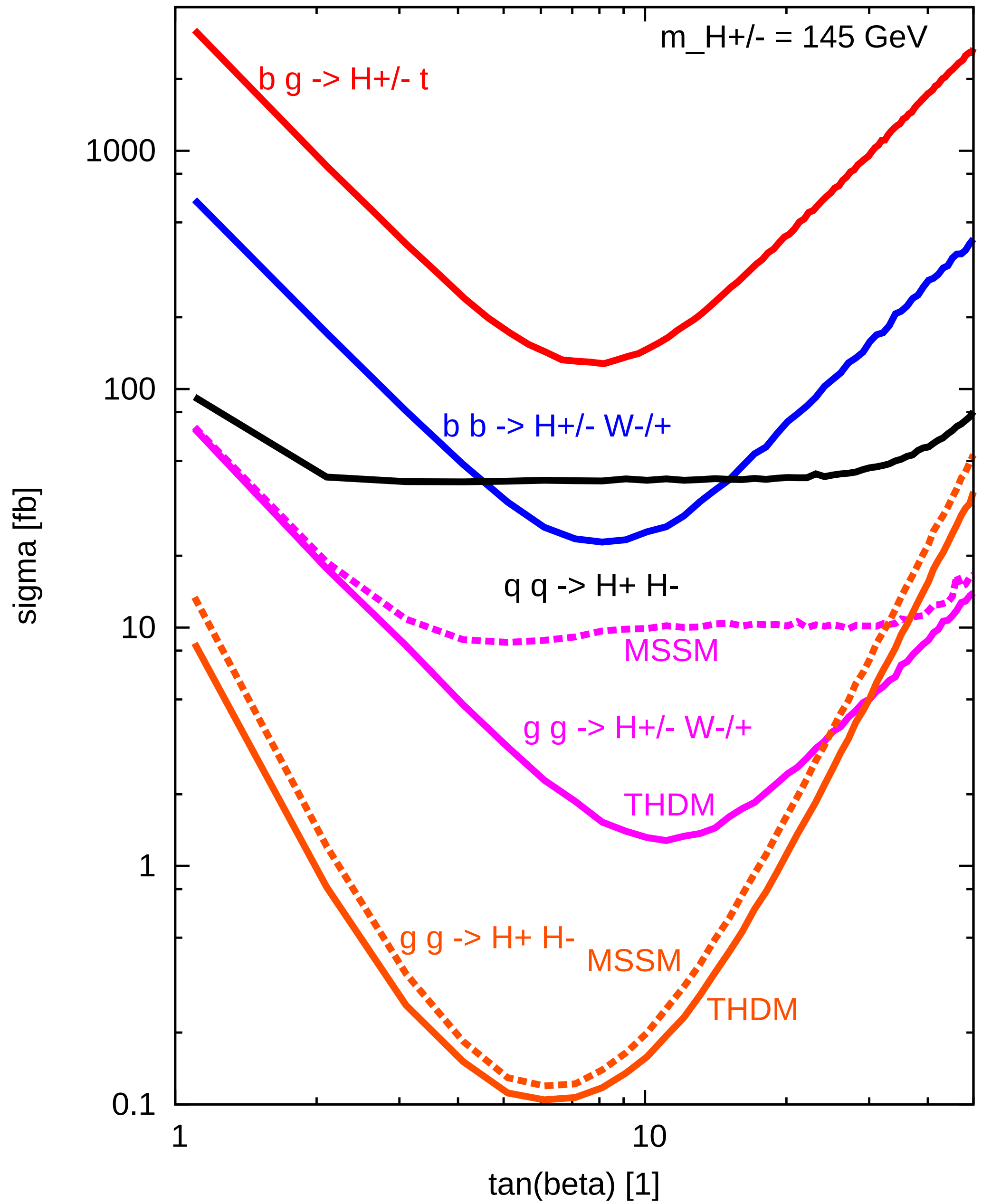
(with full simulation, including systematic uncertainties)

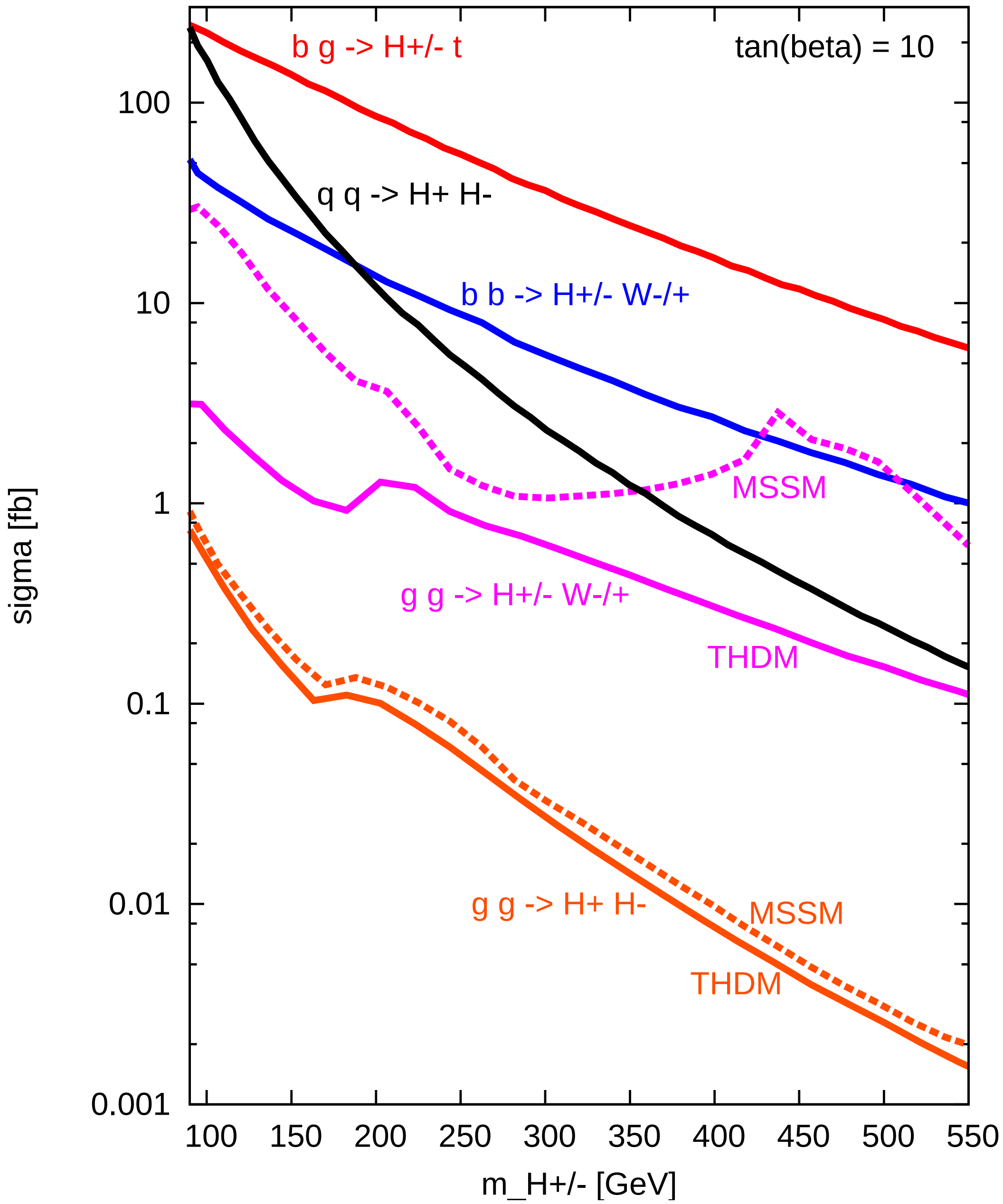


$m_{H^\pm}$: 128 215 310 408

[GeV]

cross sections at the LHC:





discovery processes beyond $bg \to H^\pm t$?

- $W^\pm H^\mp$ production
  - with $H^\pm \to tb$: not viable [Moretti, Odagiri '98]
  - with $H^\pm \to \tau\nu$: promising simulation [Eriksson, Hesselbach, Rathsman '06]
    $\to$ relevant supplementary discovery channel for large $\tan\beta$

- suggestion: H^+H^- production (with $H^\pm \to \tau\nu$)
  - could be relevant for low $m_{H^\pm}$ in wedge-region ($\tan\beta \approx 5 \ldots 25$)
  - main contribution is $\tan\beta$-independent

- Minimal Phantom Higgs Sector

– Simple Higgs Sector Extensions

• singlet extensions

motivation: the SM Higgs doublet Φ is the only multiplet which can have renormalizable interactions with a hidden, SM-singlet sector:

$$\mathcal{L}_{\text{Higgs-hidden sector int.}} \propto (\Phi^\dagger\Phi)(\phi^{(\dagger)}\phi)_{\text{hidden}}$$

Extension of the SM by ...

... a complex SU(2)-singlet scalar: Higgs sector: H_1^0, H_2^0, A_1^0

- hidden sector singlet:
  A_1^0 eaten by spontaneously broken $U(1)_{\text{hidden}} \rightarrow H_1^0, H_2^0$ remain
  [Schabinger, Wells '05,...]
- **minimal phantom sector** (contains extended neutrino sector):
  global $U(1)$ symmetry broken $\rightarrow H_1^0, H_2^0, A_1^0(= J$, massless Goldstone)
  [Cerdeño, Dedes, Underwood '06]

... a real SU(2)-singlet scalar: Higgs sector : H_1^0, H_2^0

[v.d. Bij '06; O'Connell et al. '06; Bahat-Treidel, et al.'06]

consequences for Higgs phenomenology

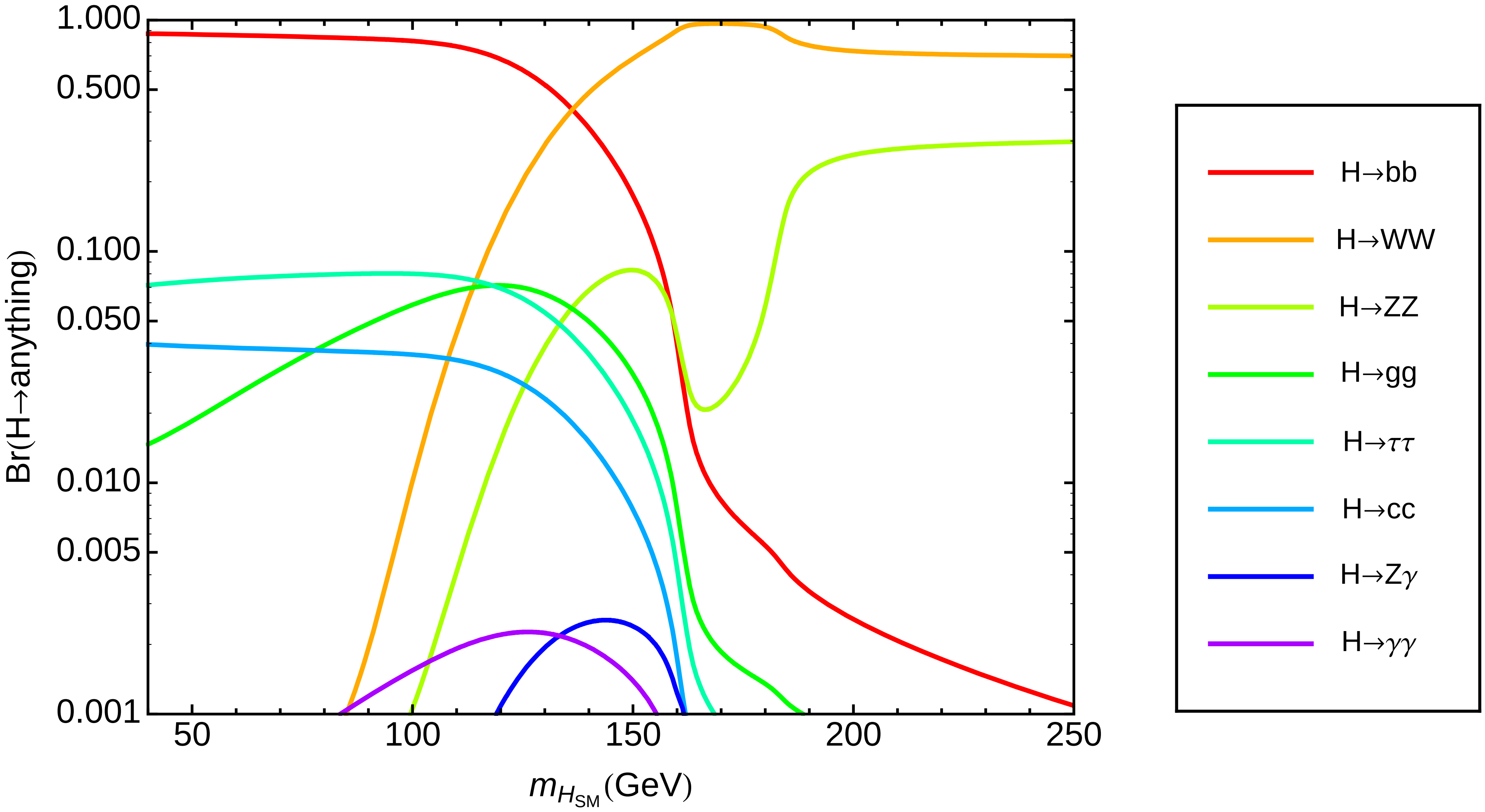
– mixing of new scalar(s) with ordinary Higgs d.o.f.

– couplings of scalars to SM particles reduced by mixing angles

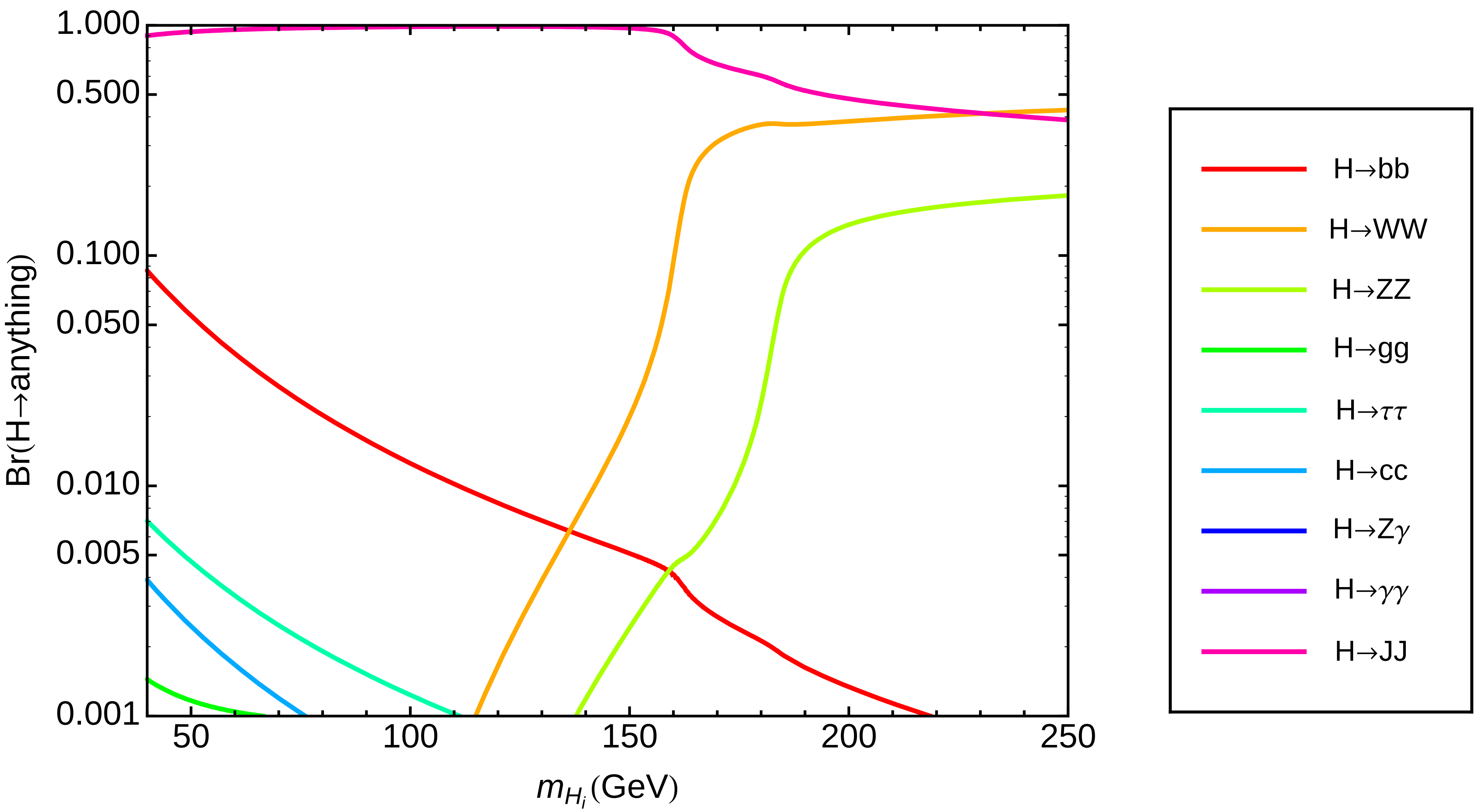
– potentially large BR(Higgs $\rightarrow$ invisible)

– Results for the Minimal Phantom Sector

SM branching ratios for Higgs decay:

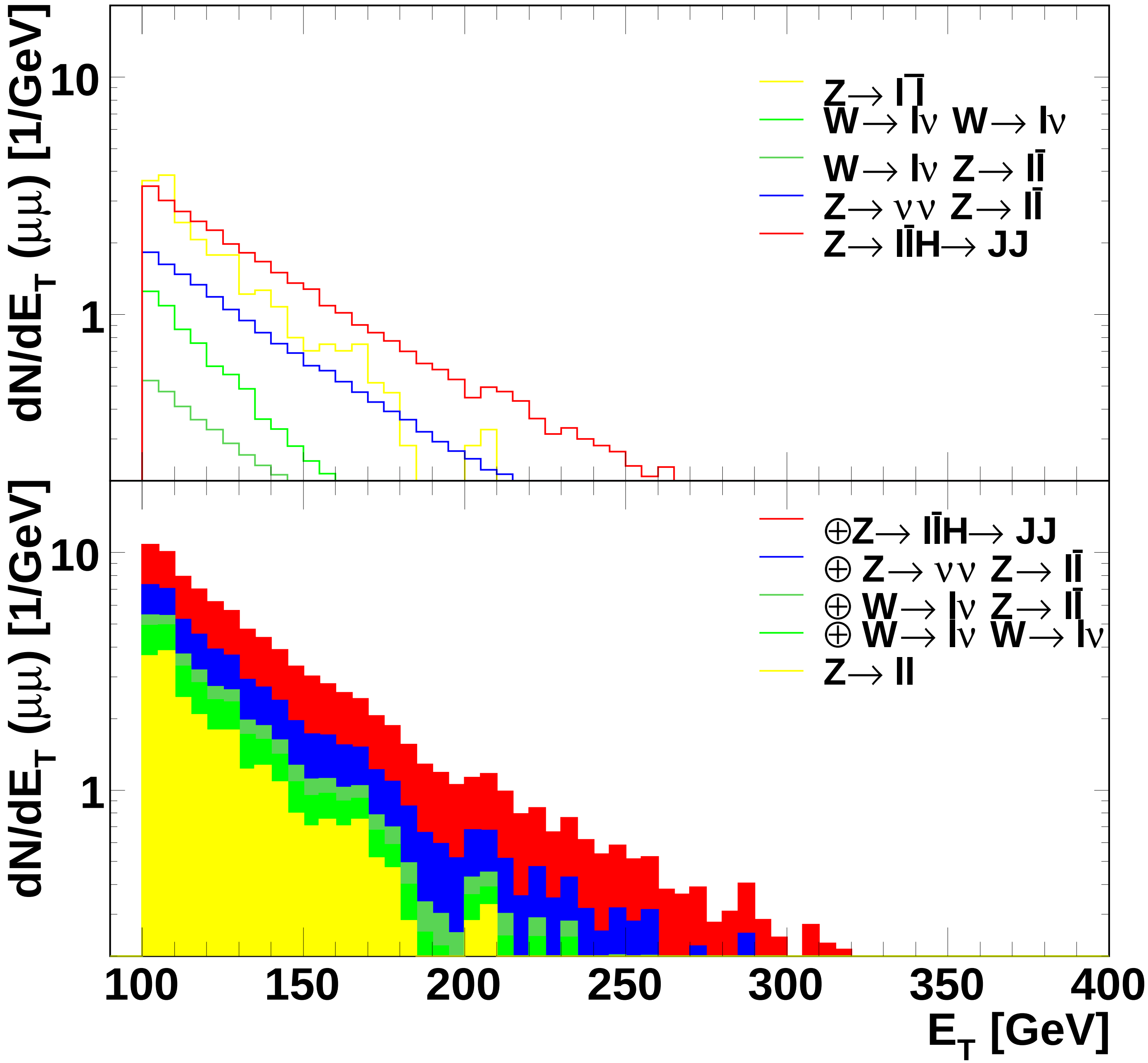


LEP-allowed example in the Minimal Phantom Sector:



Monte Carlo simulation with SHERPA: $pp \to q\bar{q} \to ZH, H \to$ invis., $Z \to l\bar{l}$

[Dedes, Figy, Krauss, Underwood '07, preliminary]



model parameters:

$m_{H_1} = 65$ GeV,

$m_{H_2} = 110$ GeV, ...

cuts :

$p_T^{l_1}, p_T^{l_2} > 15$ GeV

$\eta_{l_1}, \eta_{l_2} < 2.5$

81 GeV $< m_{ll} <$ 101 GeV

$E_{T,\text{miss}} > 100$ GeV

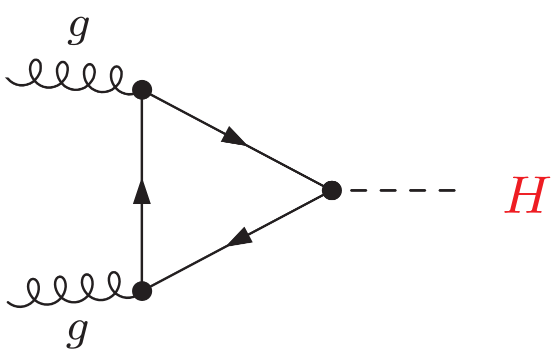
only l^+, l^- present

no jets within $|\eta| < 5$

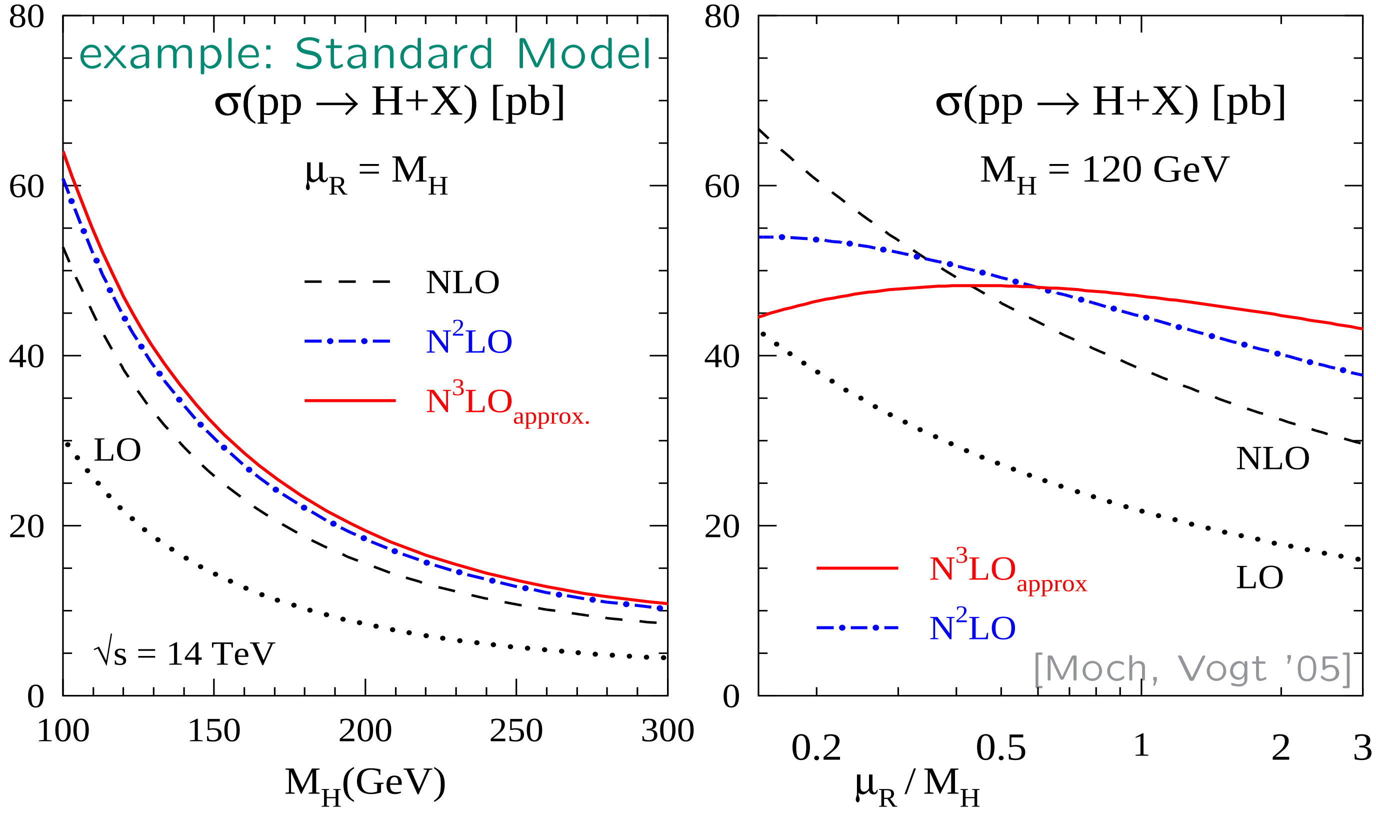
luminosity: 30fb^{-1}

a VBF study is in progress

Backup



gluon fusion, $gg \to H$



SM, LO [Georgi, Glashow, Machacek, Nanopoulos '78]

SM, NLO QCD [Dawson'91; Djouadi, Spira, Zerwas, Graudenz '91/'93]

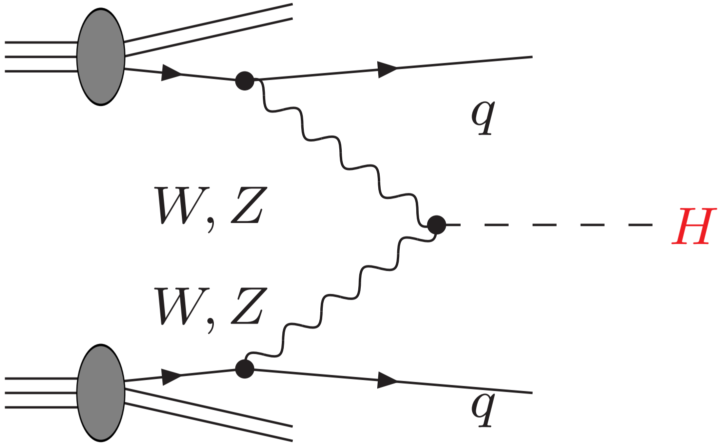
SM, NNLO QCD [Harlander '00; Catani, de Florian, Grazzini '01; Harlander, Kilgore '01 & '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03]

SM, NNNLO QCD, [Moch, Vogt '05]

SM, NLO EW [Djouadi, Gambino '94; Djouadi, Gambino, Kniehl '98; Aglietti, Bonciani, Degrassi, Vicini '04; Degrassi, Maltoni '04]

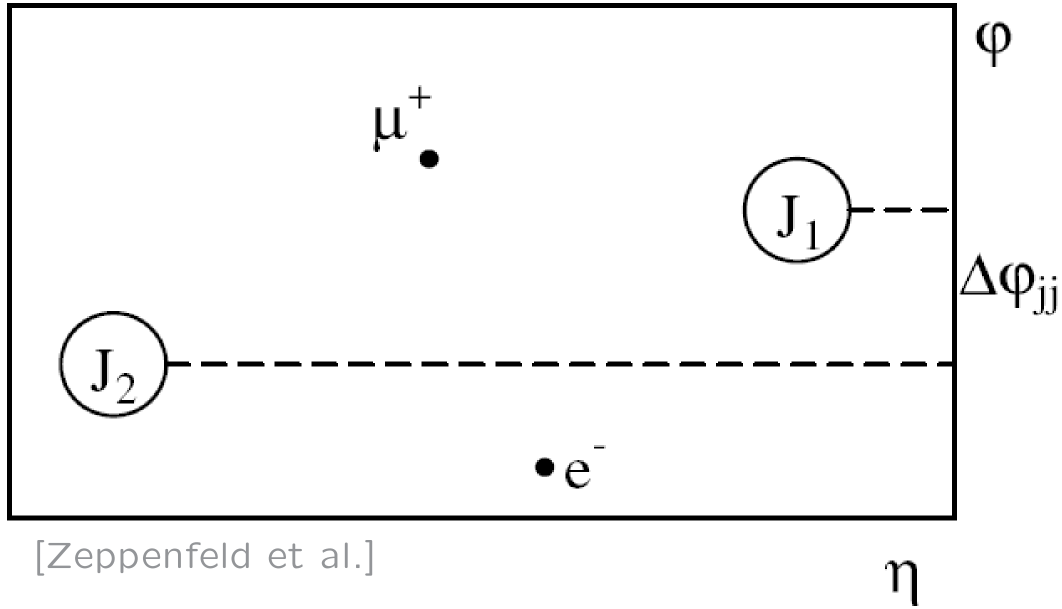
MSSM, NLO QCD, no superpartners [Djouadi, Spira, Zerwas, Graudenz '91/'93]

MSSM, NLO SUSY-QCD [Harlander, Steinhauser '04;Harlander, Hofmann '06; Mühlleitner, Spira '06]



vector boson fusion, $qq \to qqH$

VBF signature ($H \to WW^{(\star)} \to \mu\nu_\mu e\nu_e$)

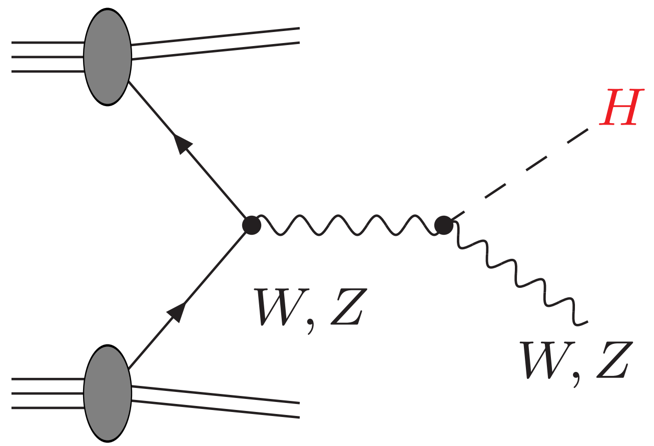


[Zeppenfeld et al.]

SM, LO [Cahn, Dawson '84; Kane, Repko, Rolnick '84]

SM, NLO QCD [Han, Valencia, Willenbrock ' 92; Figy, Oleari, Zeppenfeld' 03; Berger, Campbell '04]

MSSM, NLO SUSY-QCD [Djouadi, Spira '00]



Higgs strahlung, $q\bar{q}' \to VH$

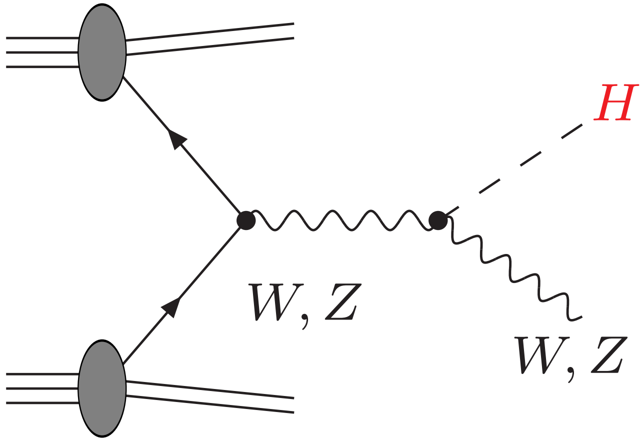
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

SM, NNLO QCD [OBr, Djouadi, Harlander '03]

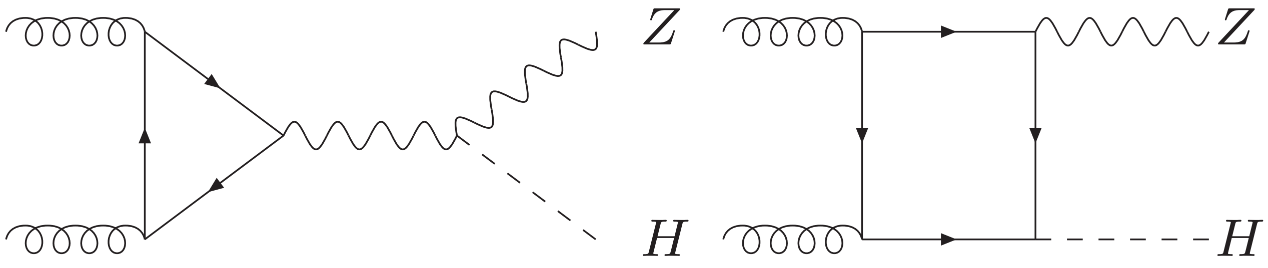
SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]

MSSM, NLO SUSY-QCD [Djouadi, Spira '00]

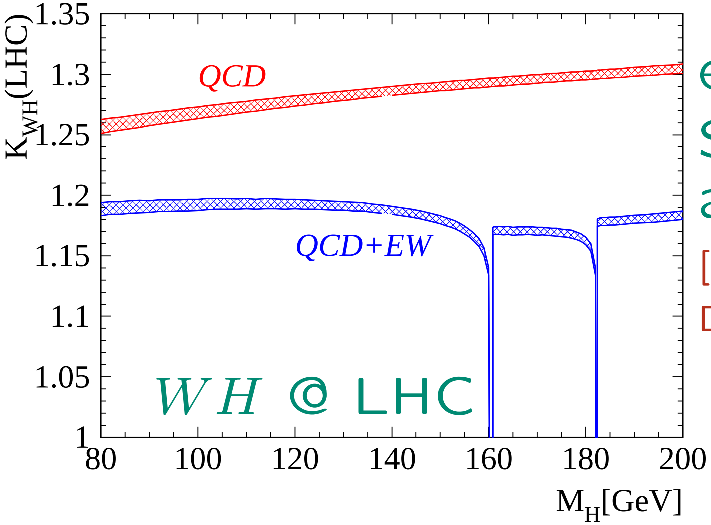


Higgs strahlung, $q\bar{q}' \to VH$

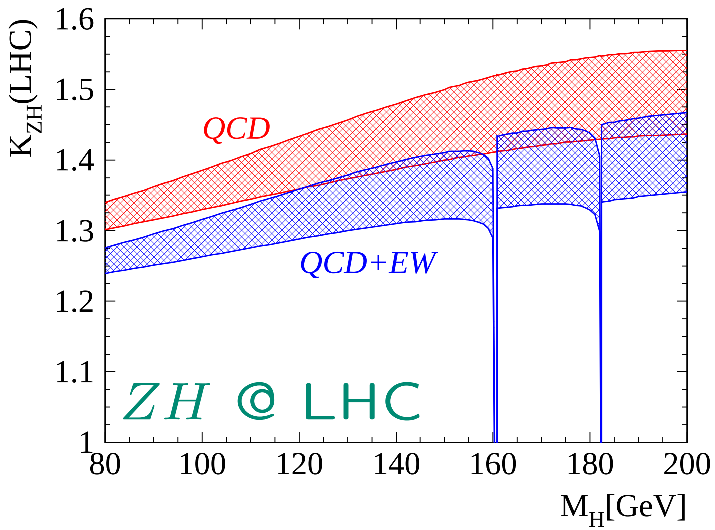
note! additional parton process for ZH @ NNLO



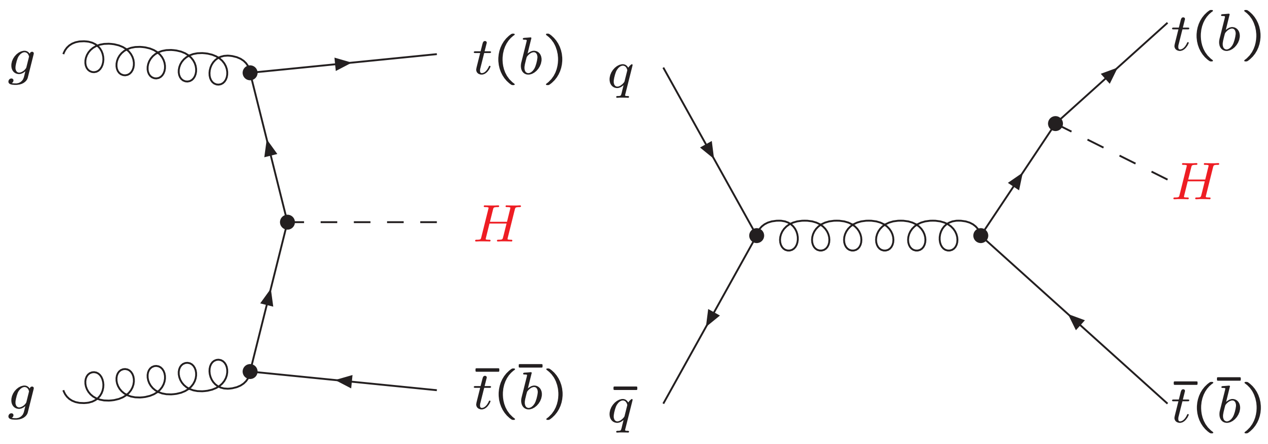
[Dicus, Kao '88; Kniehl '90]



example:
SM K-factors
and scale uncertainty
[OBr, Ciccolini, Dittmaier, Djouadi, Harlander, Krämer '04]



- SM, LO [Glashow, Nanopoulos, Yildiz '78]
- SM, NLO QCD [Han, Willenbrock ' 91]
- SM, NNLO QCD [OBr, Djouadi, Harlander '03]
- SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]
- MSSM, NLO SUSY-QCD [Djouadi, Spira '00]



$t\bar{t}H$ ($b\bar{b}H$) production [& $b\bar{b} \to H$ if 5 flavs]

SM, LO ($t\bar{t}H$) [Kunszt '84]

SM, NLO QCD ($t\bar{t}H$) [Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas '01; Dawson, Jackson, Orr, Reina, Wackeroth '01-'03]

SM, NLO QCD ($b\bar{b}H$) [Dittmaier, Krämer, Spira '03; Dawson, Jackson, Reina, Wackeroth '03]

SM, NNLO QCD ($b\bar{b} \to H$) [Harlander, Kilgore '03]

MSSM, LO, $Q\bar{Q} \to H, gg \to Q\bar{Q}H$ ($Q = t, b$) [Dicus, Willenbrock '89]

MSSM, NLO QCD, no superpartners [Dawson, Jackson, Reina, Wackeroth '03]

MSSM, NLO SUSY-QCD ($b\bar{b} \to H$)

MSSM, NLO EW ($b\bar{b} \to H$) [Dittmaier, Krämer, Mück, Schlüter '06]

available codes for Higgs + Jet in the SM:

- Higgsjet [de Florian, Grazzini, Kunszt '99]
  NLO QCD cross section for $pp \to H +$ jet
  also: soft gluon resummation [de Florian, Kulesza, Vogelsang '05]

- HqT [Bozzi, Catani, de Florian, Grazzini '03 & '06]
  p_T-distribution for $pp \to H + X$
  at $NLL + LO$ and $NNLL + NLO$ QCD accuracy
  (large effects at small p_T resummed)

- MC@NLO [Frixione, Webber '02; Frixione, Nason, Webber '05]
  contains $pp \to H + X$ event generation at NLO QCD accuracy

- FEHiP [Anastasiou, Melnikov, Petriello '05]
  NNLO QCD differential cross section for $pp \to H + X$

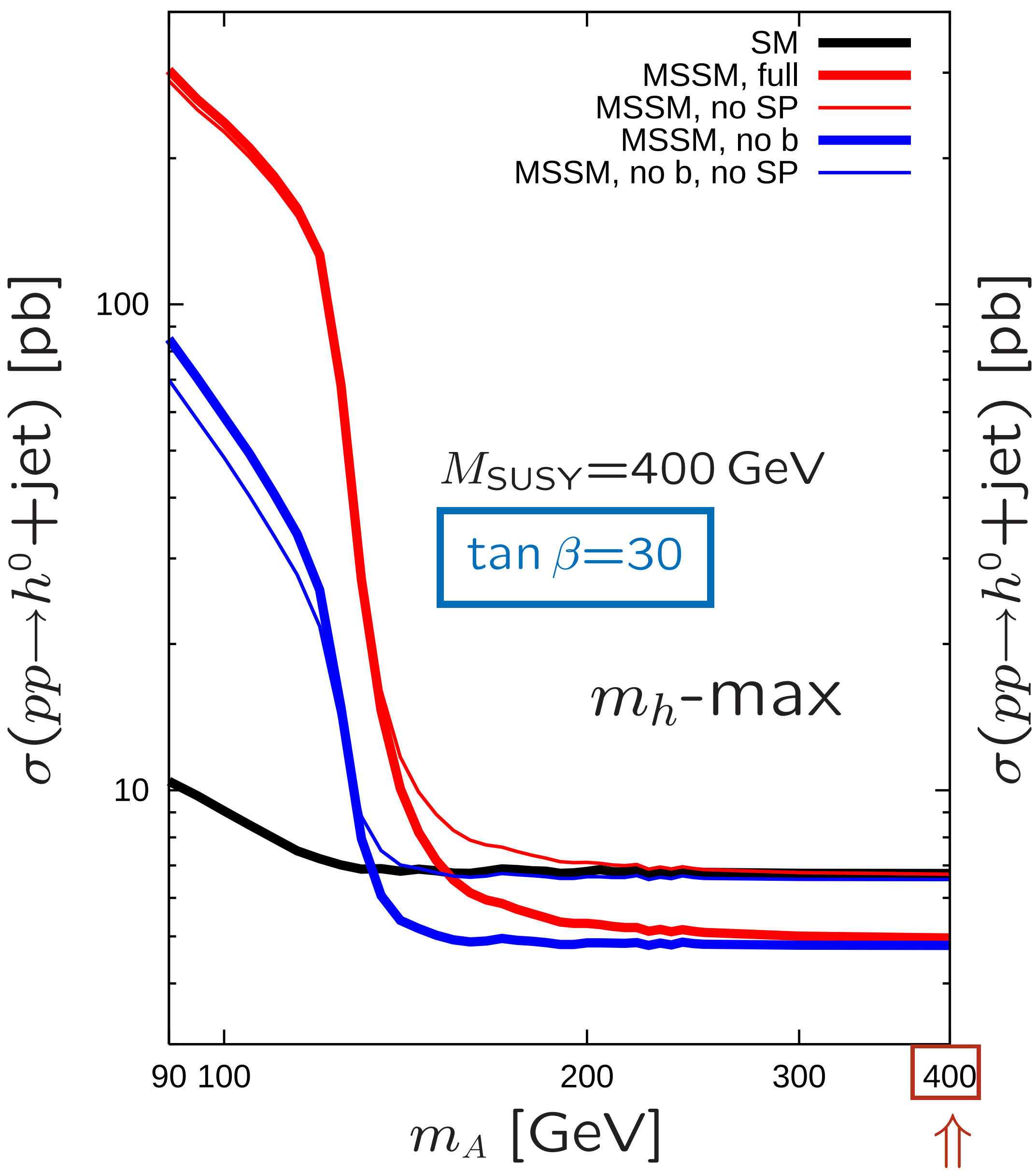
total hadronic cross section @ LHC (MSSM)

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

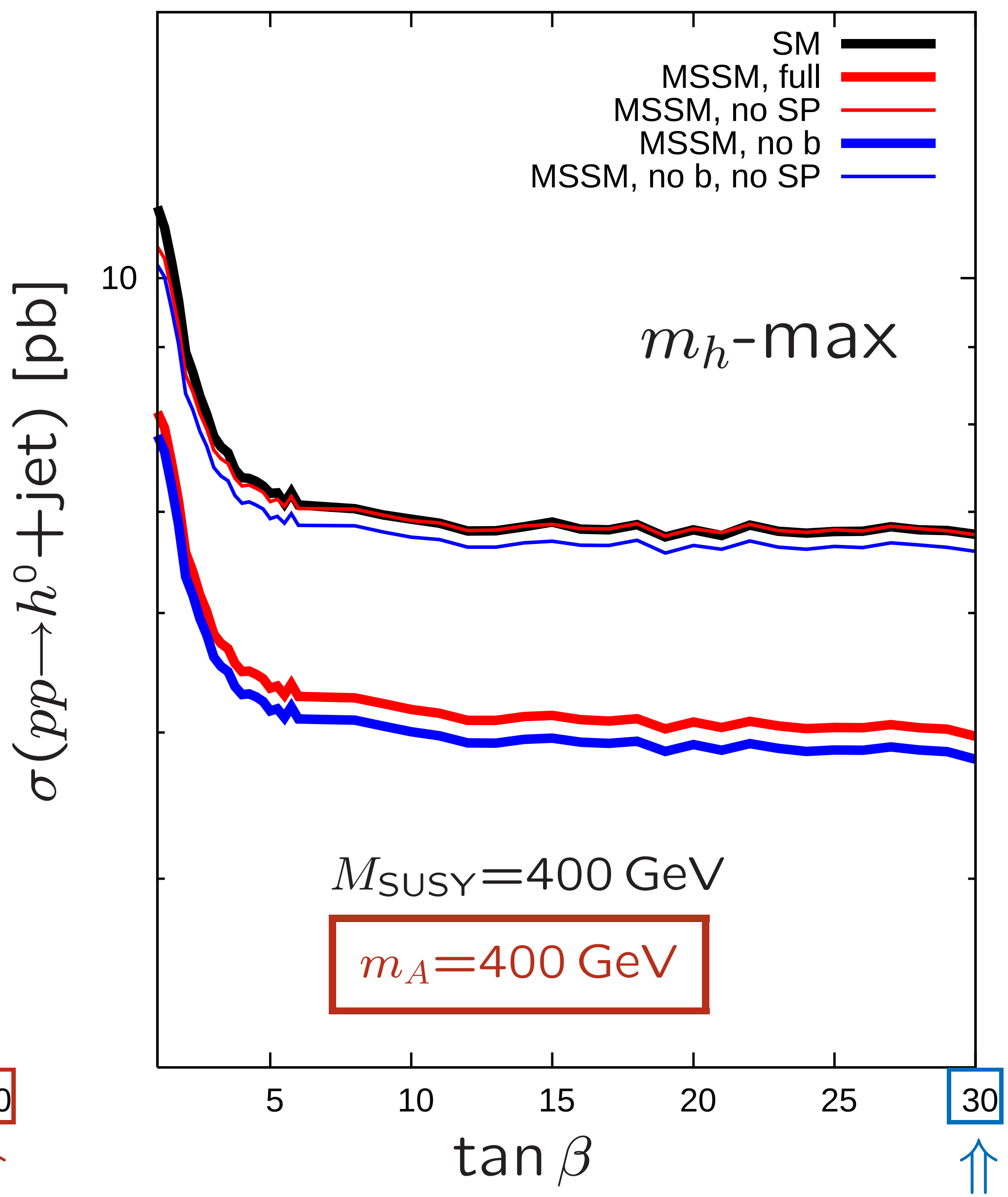
applying the cuts

$p_{T,\text{jet}} \geq 30\,\text{GeV}$ and $|\eta_{\text{jet}}| \leq 4.5$

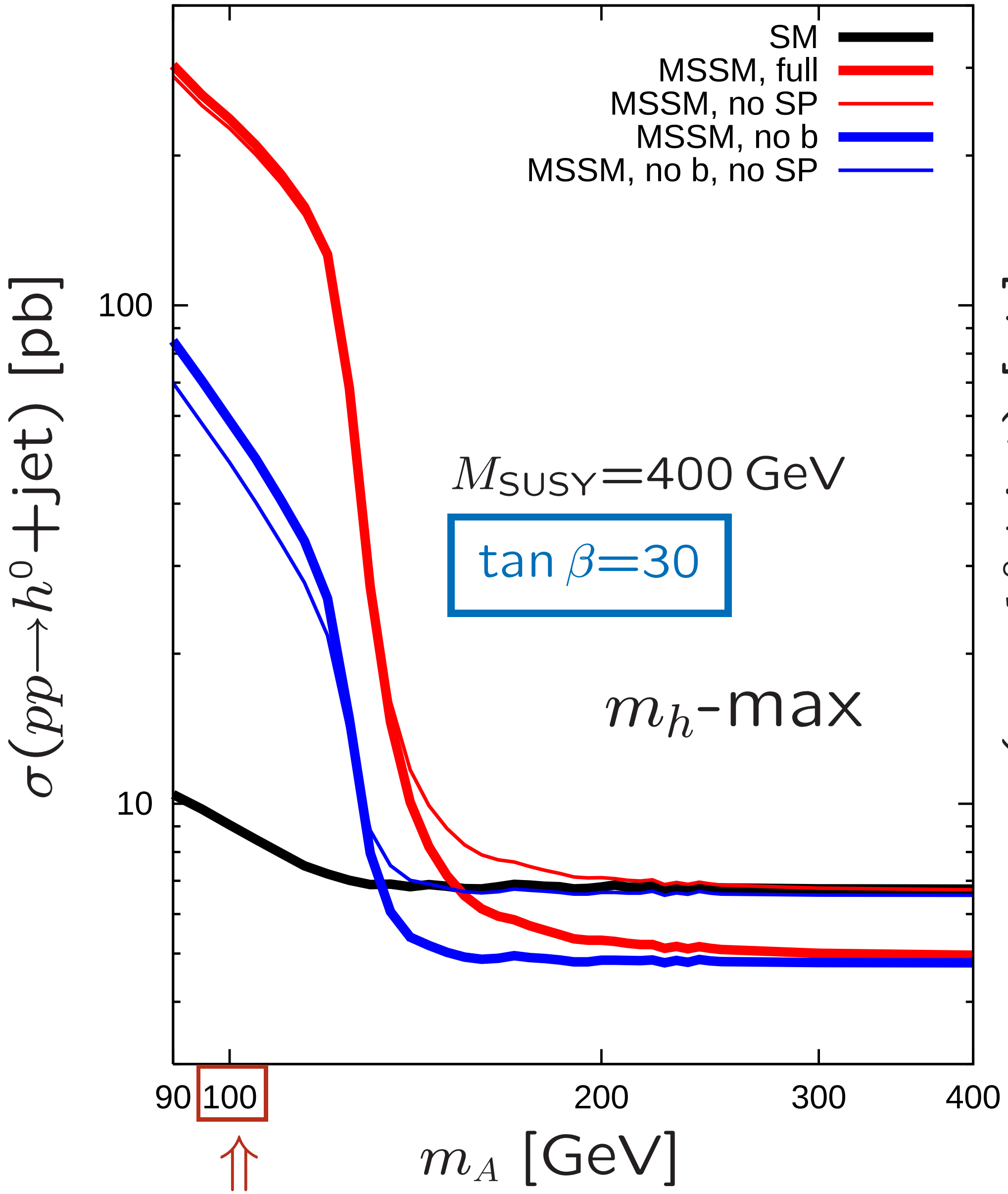
m_A- and $\tan\beta$-dependence :



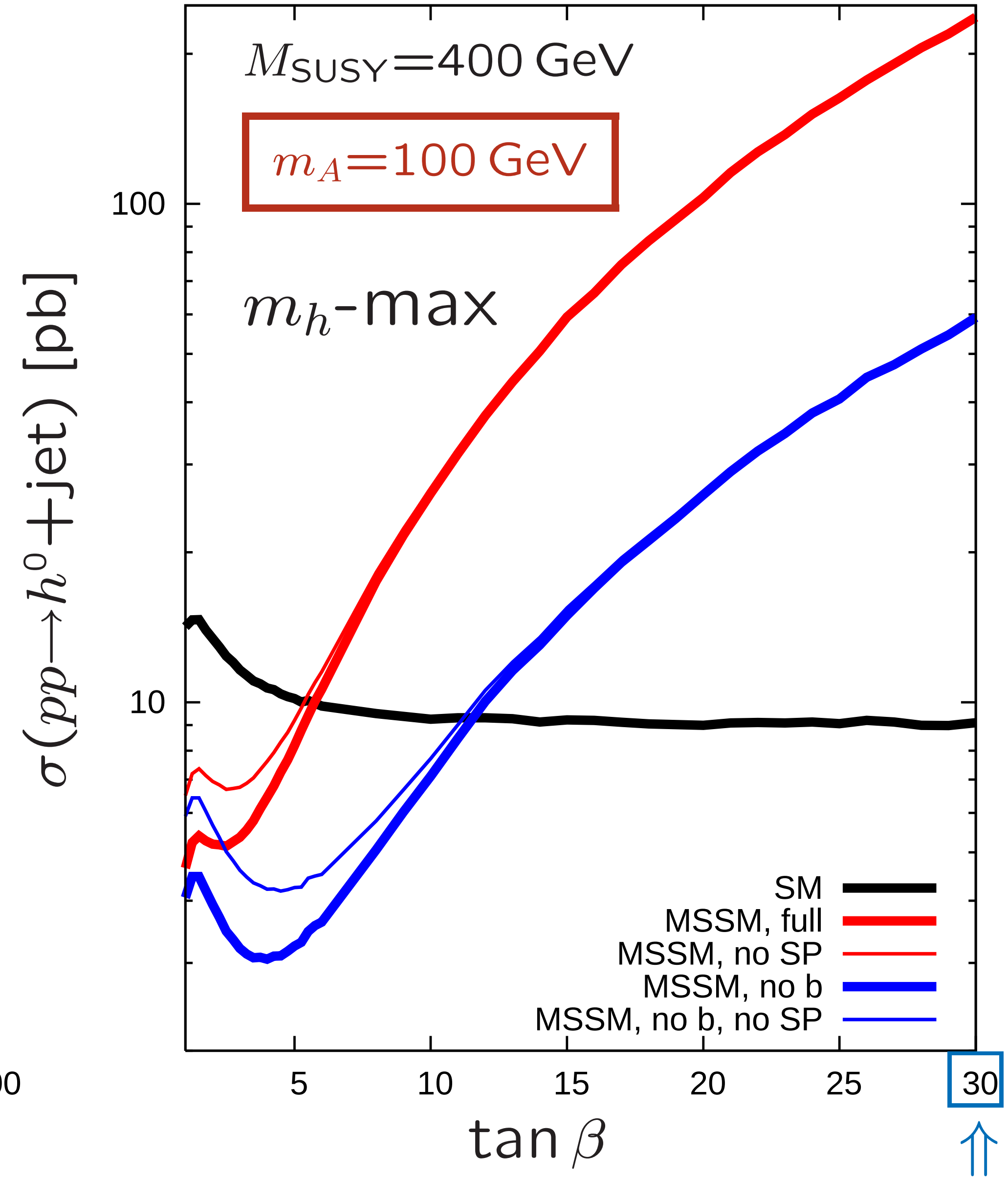
high m_A



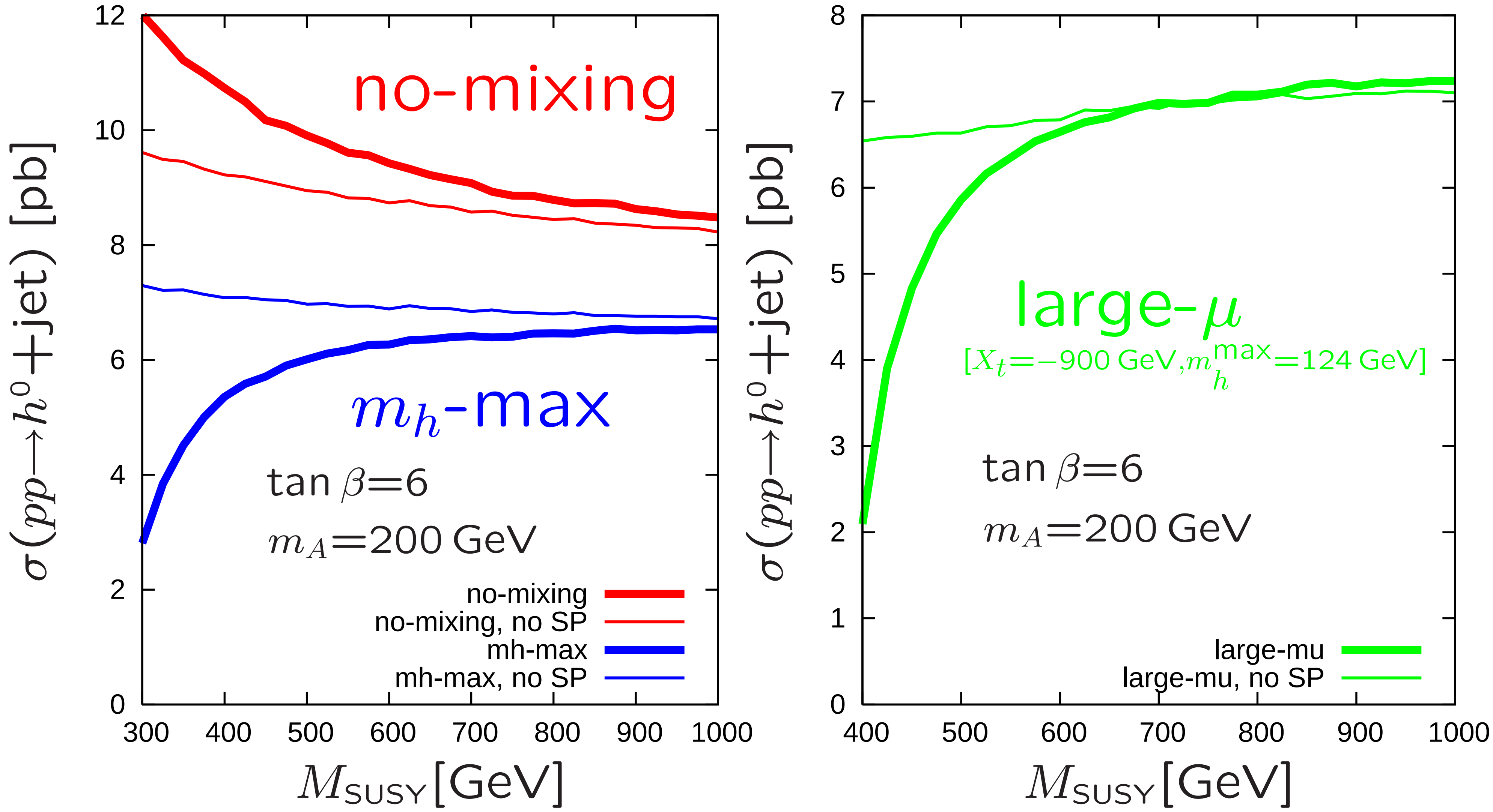
m_A- and $\tan\beta$-dependence :



low m_A

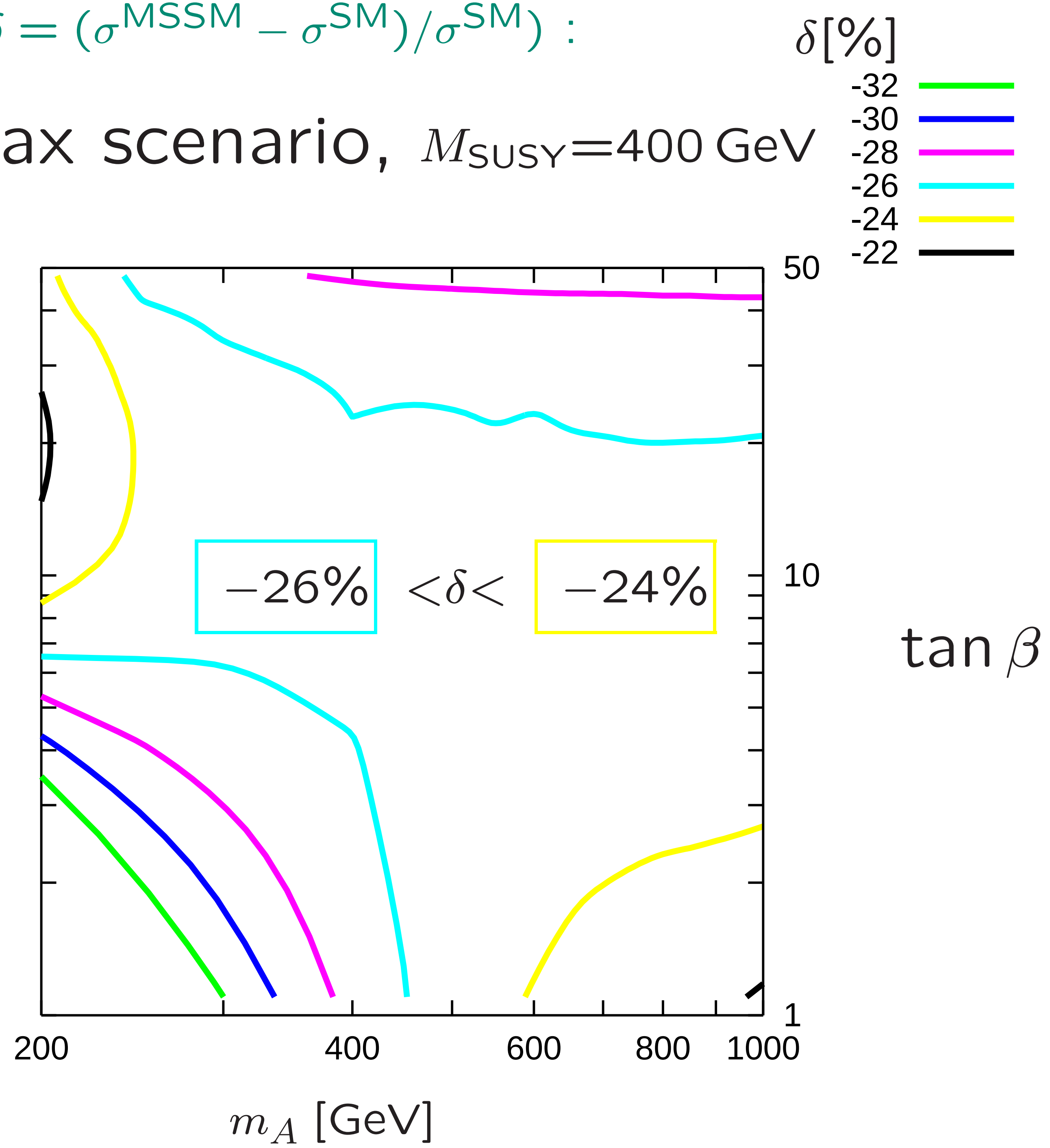


M_{SUSY} -dependence :



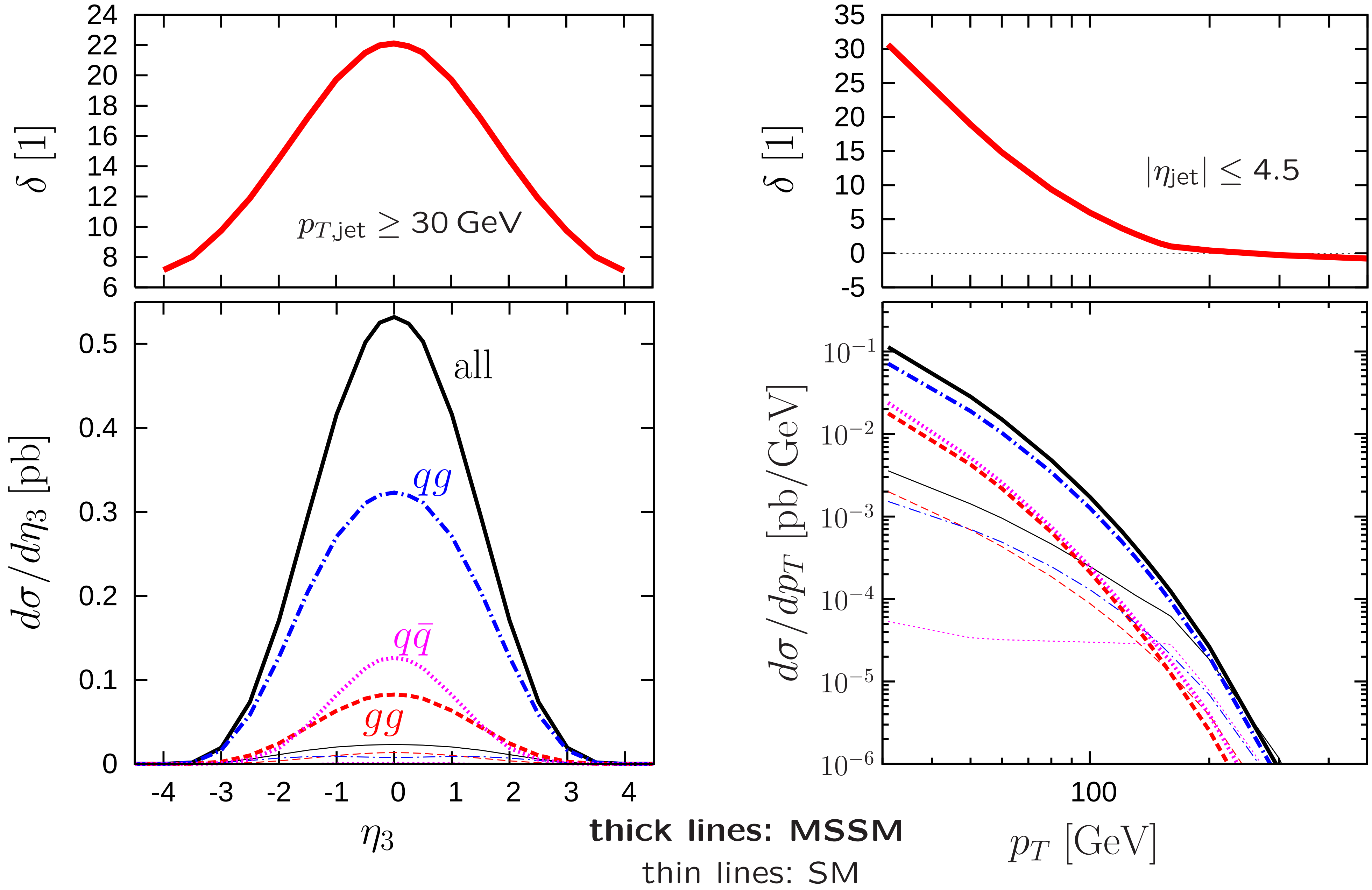
relative difference $\delta = (\sigma^{\mathrm{MSSM}} - \sigma^{\mathrm{SM}})/\sigma^{\mathrm{SM}}$:

m_h-max scenario, M_{SUSY}=400 GeV



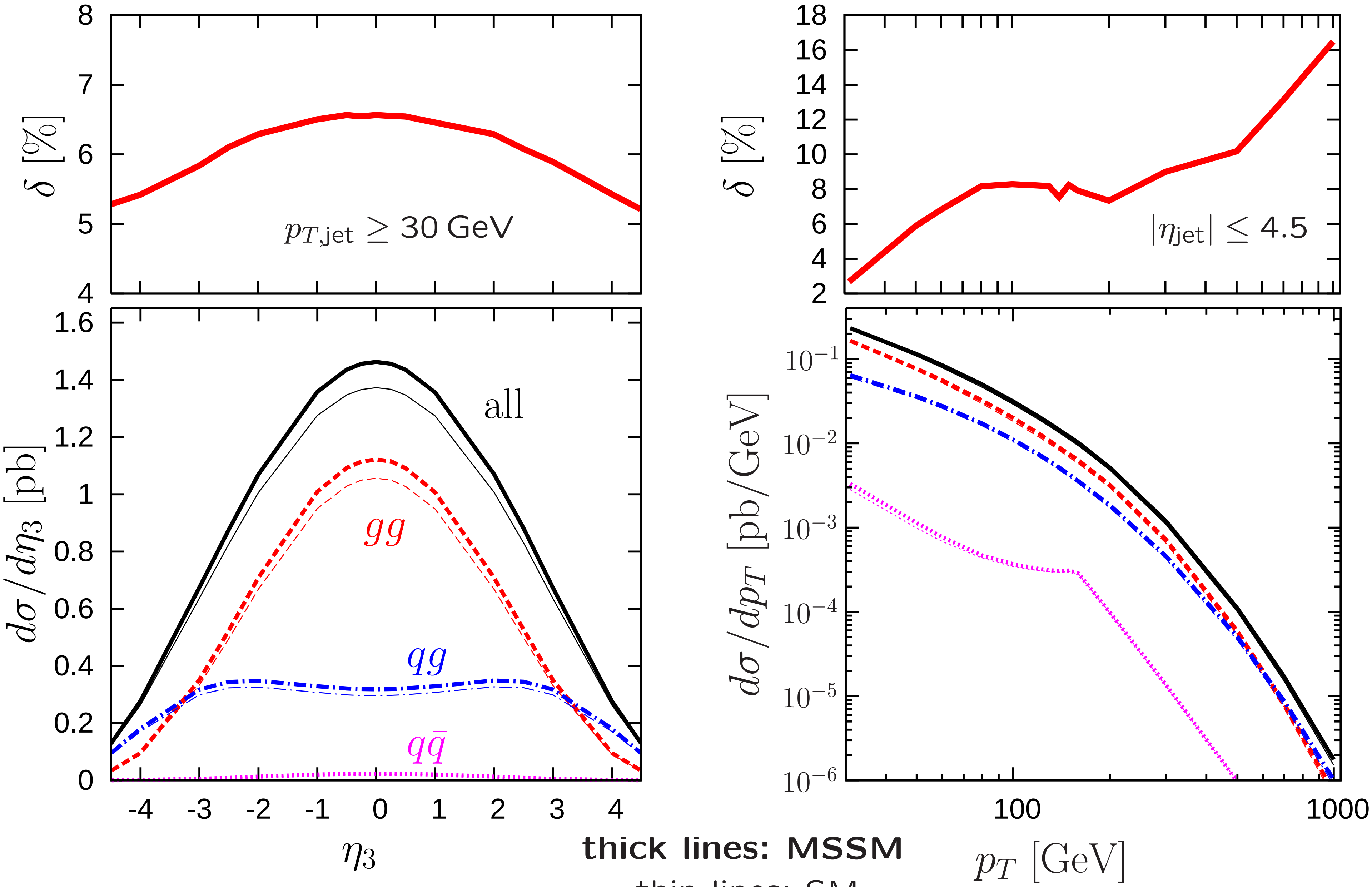
$p_{T,\text{jet}}$- and η_{jet}-dependence, low-m_A case

Tevatron, **m_h-max scenario**, $M_{\textbf{SUSY}} = 400\,\textbf{GeV}$, $m_A = 110\,\textbf{GeV}$, $\tan\beta = 30$



$p_{T,\text{jet}}$- and η_{jet}-dependence, high-m_A case

LHC, **no-mixing(700) scenario**, $M_{\text{SUSY}} = 700\,\text{GeV}$, $m_A = 500\,\text{GeV}$, $\tan\beta = 35$

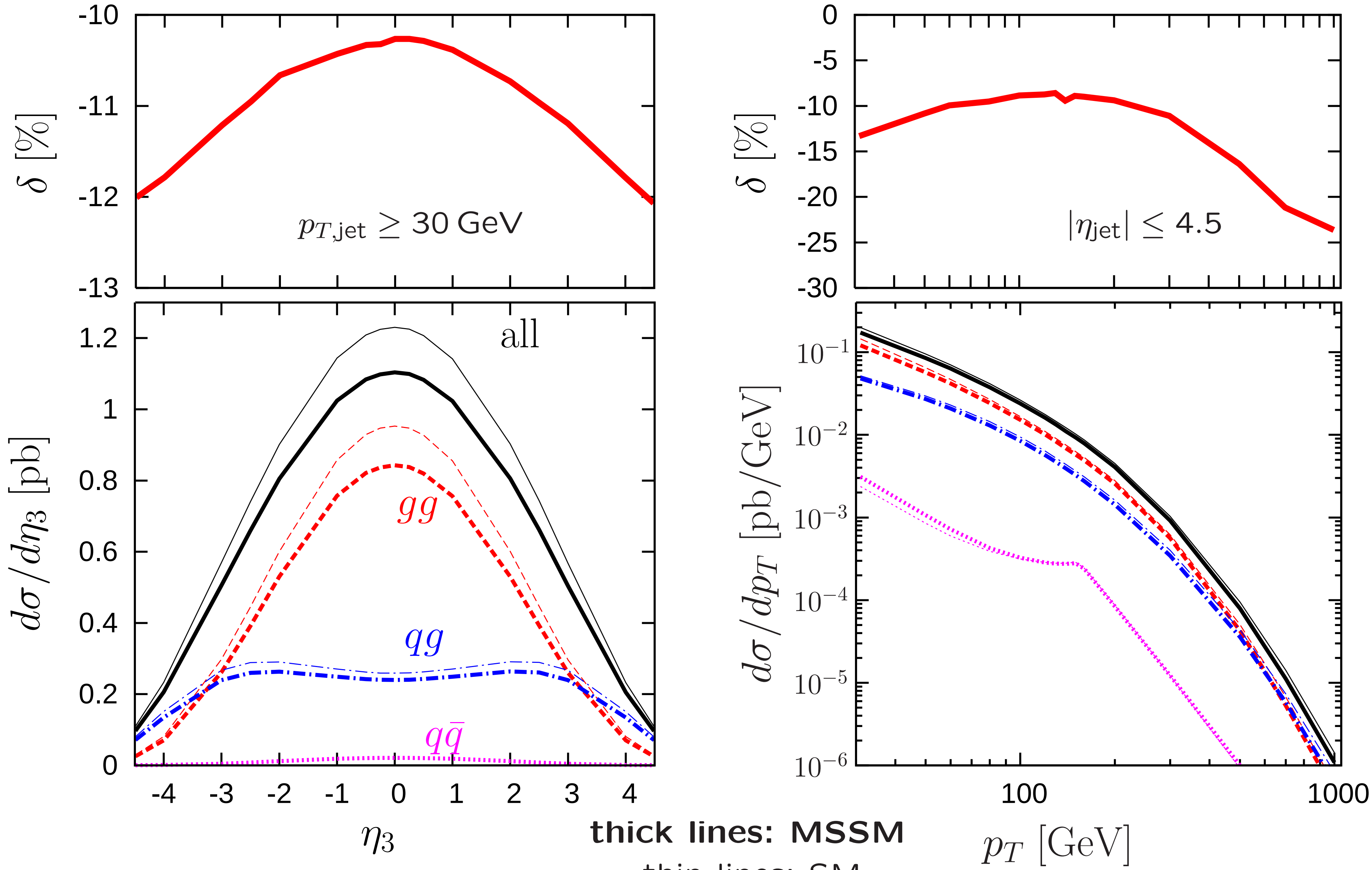


thick lines: MSSM

thin lines: SM

$p_{T,\text{jet}}$- and η_{jet}-dependence, high-m_A case

LHC, **small-α_{eff} scenario**, $m_A = 400$ **GeV**, $\tan\beta = 30$



thick lines: MSSM

thin lines: SM

[Minimal Phantom Higgs Sector, Results]

LHC, $\frac{d^2\sigma}{dp_{T,\mathrm{jet}}d\eta_{\mathrm{jet}}}$: MSSM − SM relative and absolute difference

relative difference in % :

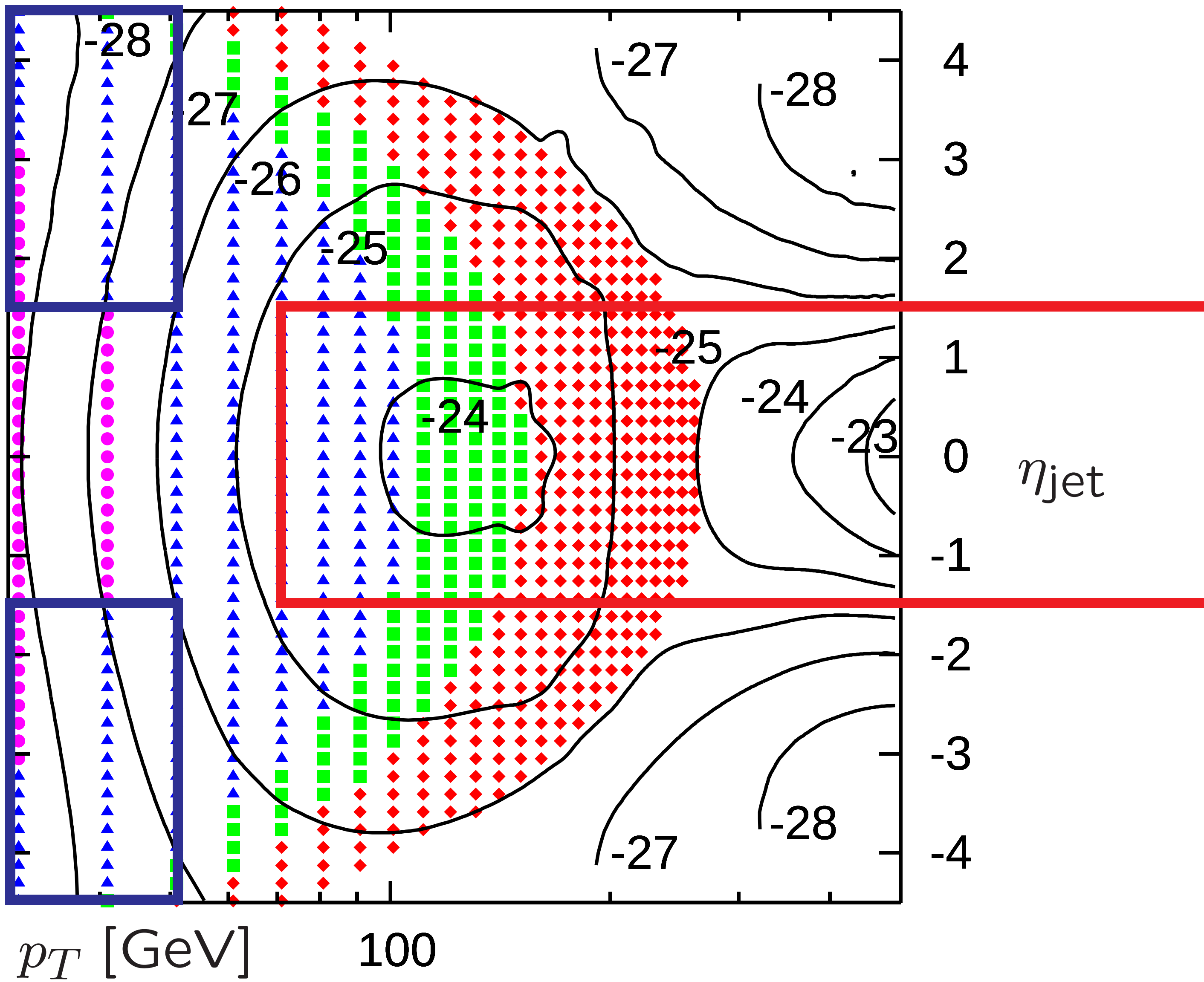
contour lines ——

absolute difference :

- ● : 5 - 10 fb/GeV
- ▲ : 1 - 5 fb/GeV
- ■ : 0.5 - 1 fb/GeV
- ♦ : 0.1 - 0.5 fb/GeV

→ consider ratio :

$$R = \frac{\sigma\left(\begin{array}{c} p_T > 70\ \mathrm{GeV} \\ |\eta| < 1.5 \end{array}\right)}{\sigma\left(\begin{array}{c} p_T \in [30, 50]\ \mathrm{GeV} \\ |\eta| > 1.5 \end{array}\right)}$$



LHC, m_h-max scenario, $M_{\mathrm{SUSY}} = 400$ GeV, $m_A = 400$ GeV, $\tan\beta = 30$

example: ratio $R = \dfrac{\sigma\left(\boxed{|\eta| < 1.5,\ p_T > 70\ \text{GeV}}\right)}{\sigma\left(\boxed{|\eta| > 1.5,\ p_T \in [30,50]\ \text{GeV}}\right)}$

for the above m_h-max scenario at the LHC ($m_A = 400\,\text{GeV}$, $\tan\beta = 30$):

quantity	SM	MSSM
$\sigma\left(\boxed{|\eta| < 1.5, p_T > 70\ \text{GeV}}\right)$	1.448 pb	1.096 pb
$\sigma\left(\boxed{|\eta| > 1.5, p_T \in [30,50]\ \text{GeV}}\right)$	1.419 pb	1.031 pb
R	1.020	1.063

$$\rightarrow \Delta = \frac{R_{\text{MSSM}} - R_{\text{SM}}}{R_{\text{SM}}} = 4.2\%$$