Higgs Physics Phenomenology

Oliver Brein

Institute of Particle Physics Phenomenology,
University of Durham

e-mail: Oliver.Brein@durham.ac.uk

outline :

- Higgs bosons, SUSY and extended models
  - Electroweak symmetry breaking, Higgs mechanism
  - Standard Model and extensions
  - Minimal supersymmetric standard model (MSSM)
- Higgs production at future hadron colliders
  - Higgs search programme (schematic)
  - How to produce a Higgs boson ?
  - Neutral Higgs production overview
- Production of Neutral Higgs + Jet
  - Higgs + jet in the Standard Model
  - Higgs + jet in the MSSM
  - MSSM results

• Higgs bosons, SUSY and extended models

– Electroweak symmetry breaking, Higgs mechanism

Theory:		Experiment:
non-Abelian gauge symmetry	→ problem ←	massive gauge bosons exist
forbids $M^2 A_\mu A^\mu$-terms		($W^\pm$,Z)

solution: **spontaneous symmetry breaking (SSB)**,

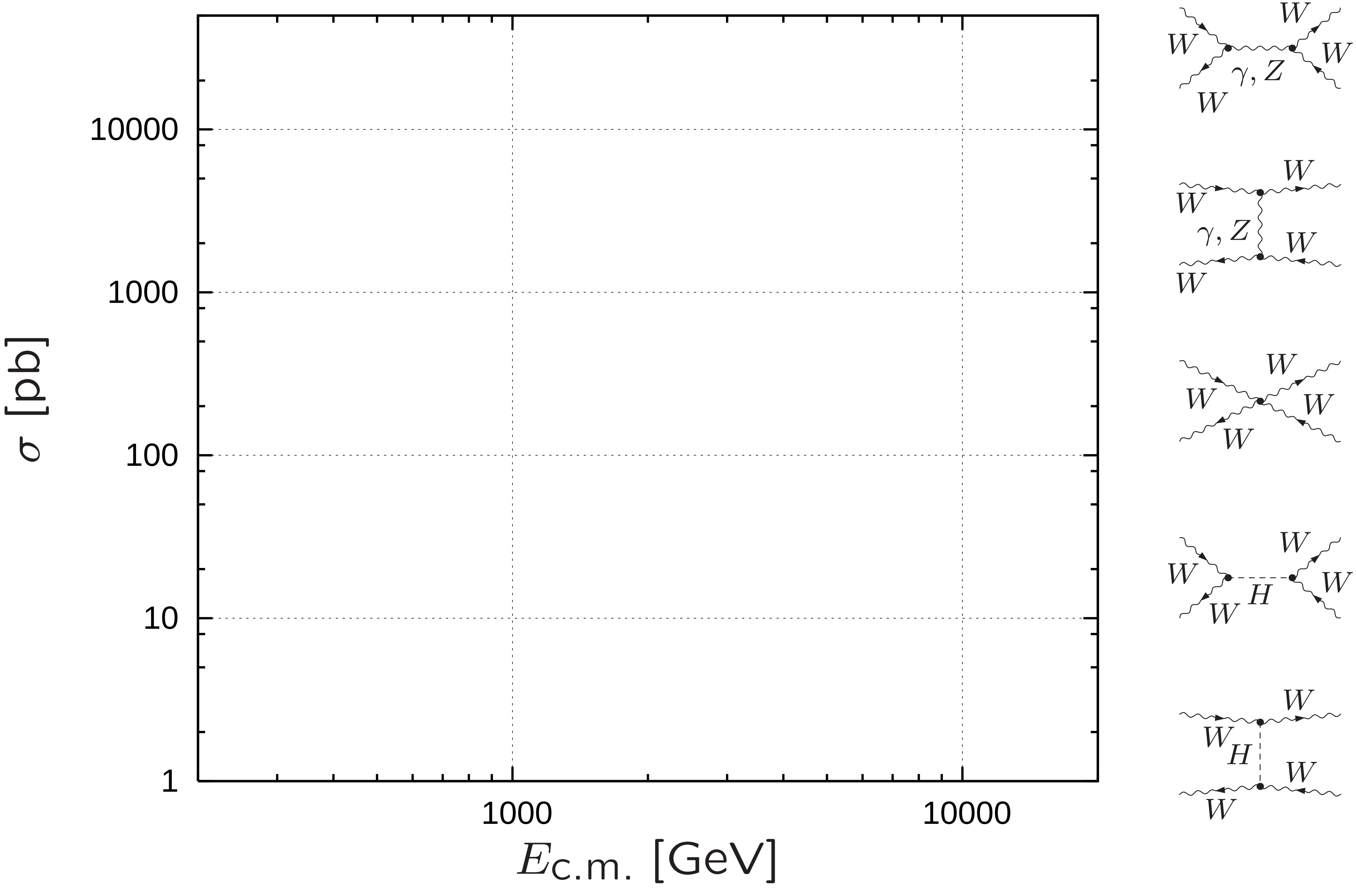
i.e. introduce gauge invariant dynamics, which breaks gauge symmetry in the ground state.

SSB can be realised by

• weakly interacting scalar gauge multiplets that acquire a VEV
→ Higgs mechanism

• strongly interacting dynamics, e.g. particles that form scalar condensates with a VEV

$\sigma(W_L W_L \to W_L W_L)$ at tree-level



[Higgs bosons, SUSY and extended models, SSB]

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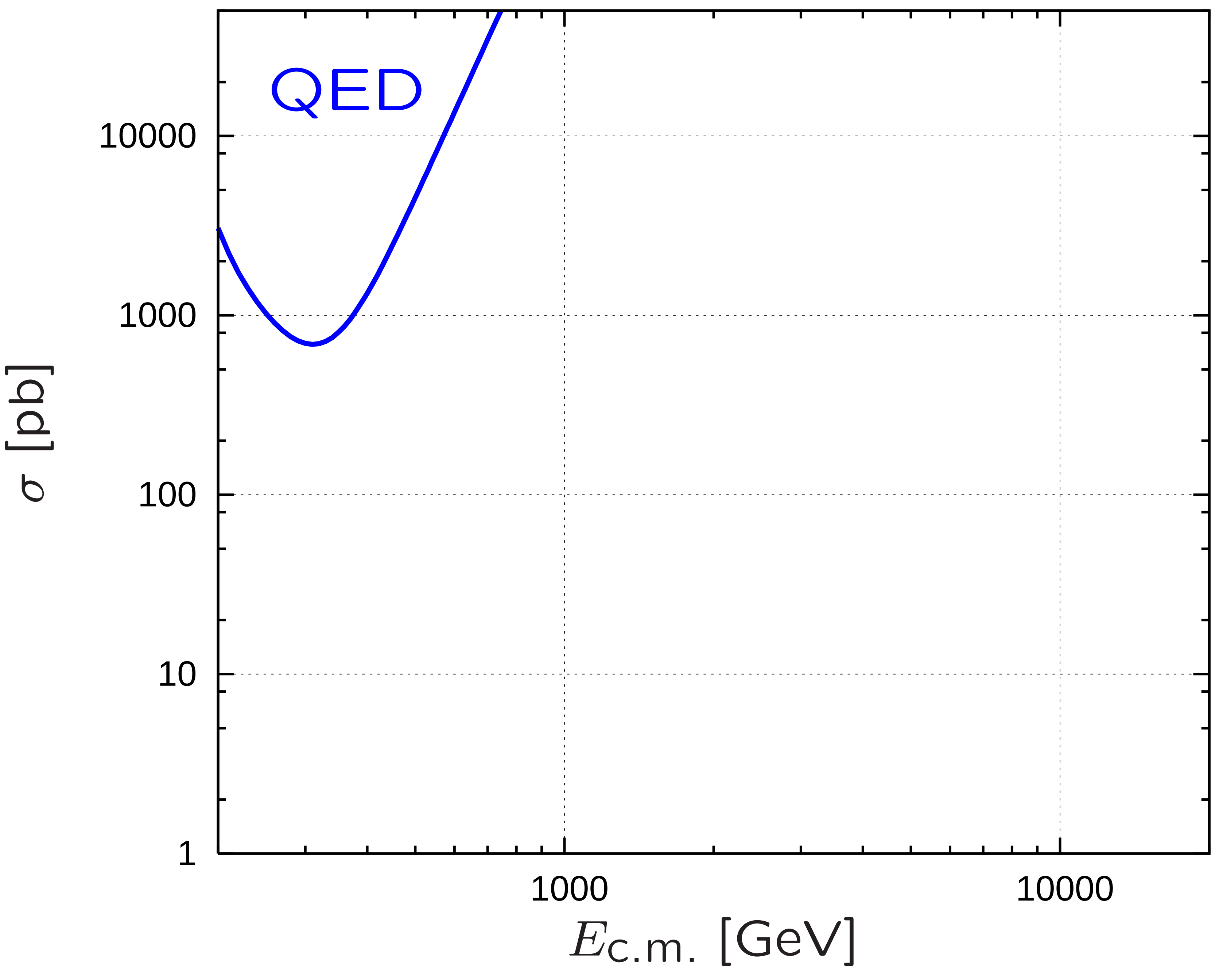

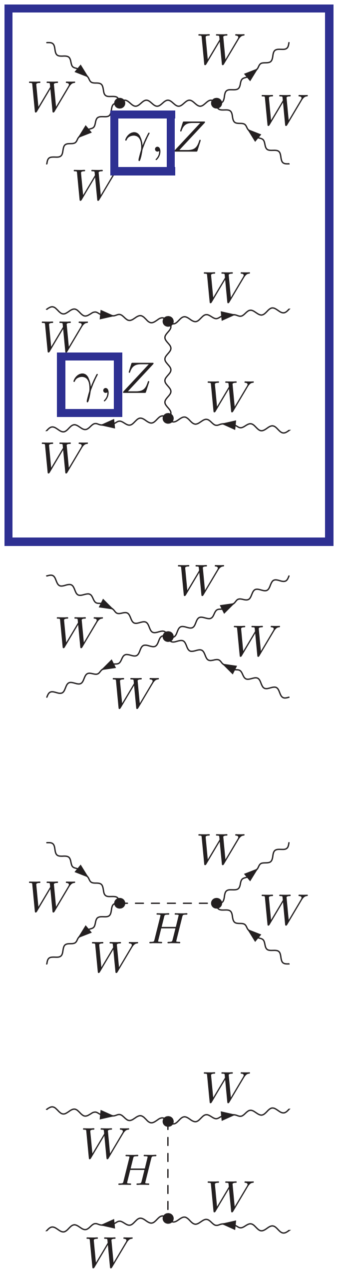

[Higgs bosons, SUSY and extended models, SSB]

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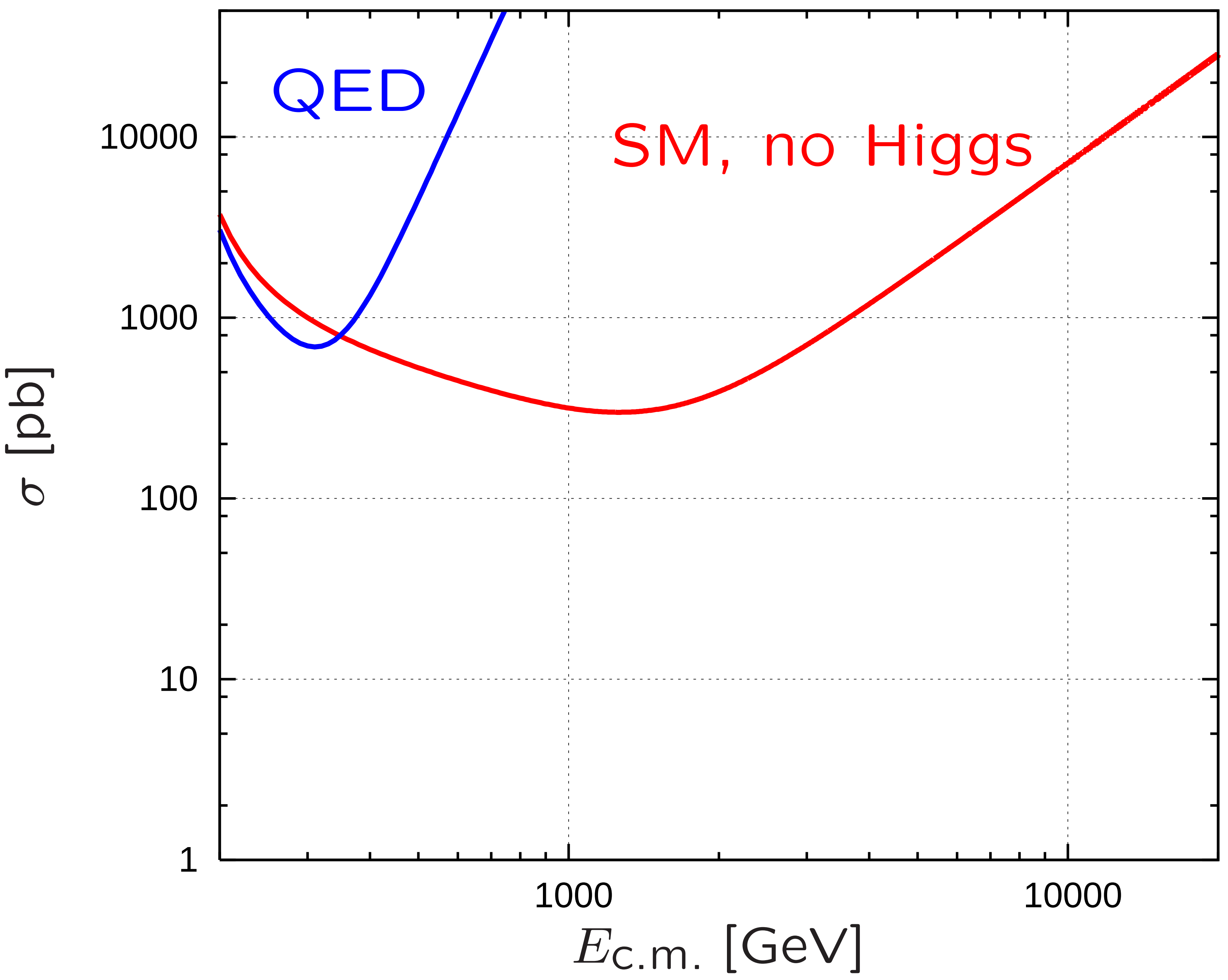

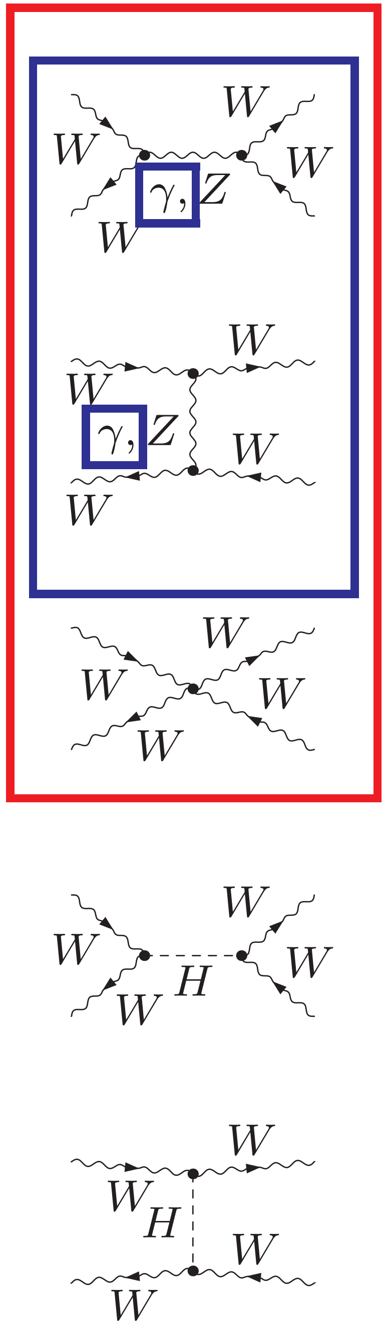

[Higgs bosons, SUSY and extended models, SSB]

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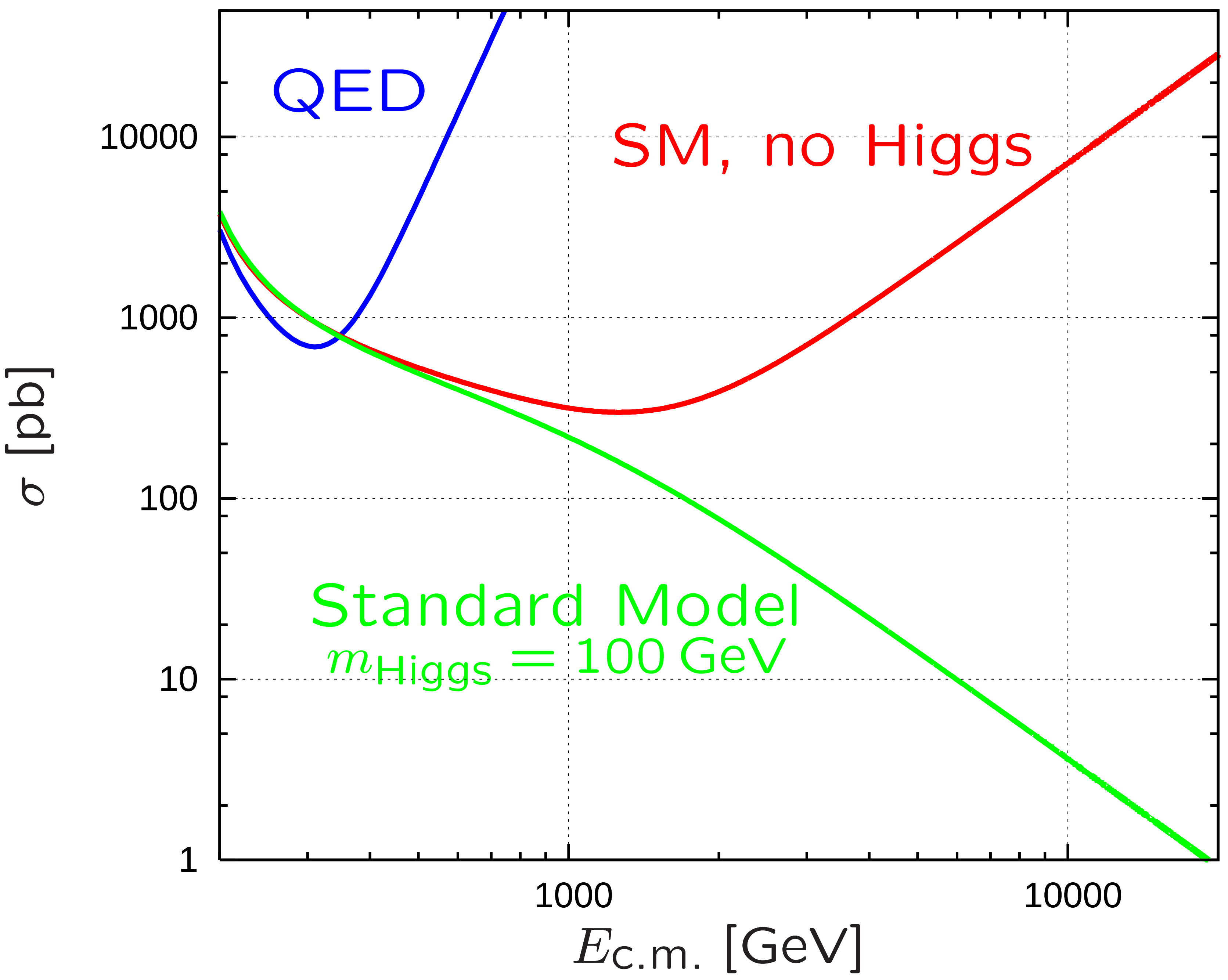
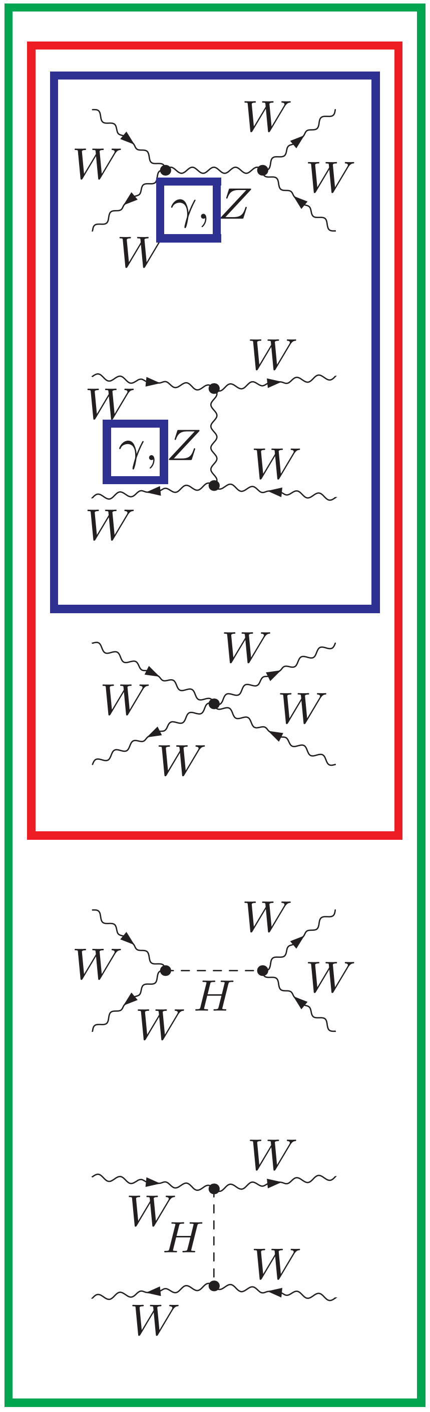




– Standard Model and extensions

Experimental situation so far:

- no Higgs signal.
- no significant deviation from SM.

Theory:

- many distinct possibilities to realise the Higgs mechanism

  which meet major constraints, like

  - the electroweak rho-parameter
    $\rho_{\text{exp.}} = \frac{m_W}{\cos\theta_W m_Z} \approx 1$ up to a few per mille
  - absence of flavour changing neutral currents (FCNC).

$\longrightarrow$ take extensions of the SM (Higgs sector) seriously

SM:

matter, gauge bosons + 1 Higgs doublet Φ

$\rightarrow$ 1 physical Higgs boson

$\swarrow$ $\searrow$

THDM:

(two Higgs doublet model)

SM matter, SM gauge bosons

+ 2 Higgs doublets Φ_1, Φ_2

MSSM:

(minimal supersym. standard model)

SM matter, SM gauge bosons

+ 2 Higgs doublets Φ_1, Φ_2

+ Superpartners

$\rightarrow$ 5 physical Higgs bosons: h^0, H^0, A^0, H^+, H^-

note! : charged Higgs bosons cannot appear with *one* Higgs doublet

$\rightarrow$ $\boxed{\text{discovery of } H^\pm \text{ : unambiguous sign of an extended Higgs sector}}$

– Minimal supersymmetric standard model (MSSM)

Supersymmetry . . .

. . . is *the* extension of the Poincaré-symmetry of space-time

. . . leads to a symmetry between Fermions & Bosons

gauge theory with minimal SUSY :

- same # of fermionic & bosonic d. o. f.
  $\longrightarrow$ a superpartner of different spin exists for each particle

- couplings are correlated
  $\longrightarrow$ e.g. scalar 4-point int. $\longleftrightarrow$ gauge couplings

- superpartners have the same mass
  $\longrightarrow$ SUSY must be broken at the electroweak scale

gauge theory with broken SUSY :

- superpartner masses enter as additional free parameters (essentially)

– Minimal supersymmetric standard model (MSSM)

gauge group : $SU(3)_{\text{colour}} \times SU(2)_{\text{isospin}} \times U(1)_{\text{hypercharge}}$

particle content :

regular particles		spin	superpartners		spin
fermions	quarks u, d, s, c, b, t leptons $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$	$\frac{1}{2}$	sfermions	squarks $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$ sleptons $\tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau$	0
gauge bosons	$G, W^\pm, Z, \gamma$	1	gauginos	$\tilde{G}, \tilde{W}^\pm, \tilde{Z}, \tilde{\gamma}$	$\frac{1}{2}$
Higgs bosons	H_1, H_2	0	Higgsinos	$\tilde{H}_1, \tilde{H}_2$	$\frac{1}{2}$

$\tilde{W}^\pm, \tilde{Z}, \tilde{\gamma}$ and $\tilde{H}_1, \tilde{H}_2$ mix to charginos $\chi_1^\pm, \chi_2^\pm$ and neutralinos $\chi_1^0, \ldots, \chi_4^0$

R-parity : discrete, multiplicative quantum number

$$R(\text{regular particles}) = +1$$
$$R(\text{superpartners}) = -1$$

$\rightarrow$ designed to avoid large Flavour Canging Neutral Currents (FCNC)

consequences of R-parity conservation:

- all interactions involve an *even* number of superpartners
  $\rightarrow$ superpartners can only be pair-produced

- the lightest superpartner (LSP) is stable
  $\rightarrow$ the LSP is a candidate for dark matter

Consequences of SUSY for the MSSM Higgs sector

- MSSM *only* consistent with two Higgs doublets

- all Φ^4-interactions determined by gauge couplings

  $\longrightarrow$ only two Higgs sector input parameters:

  $$m_{A^0} \text{ (mass of } A^0\text{)}, \tan\beta \; (= v_2/v_1, \text{ ratio of VEVs})$$

  instead of seven in the THDM:

  $$m_{A^0}, \tan\beta \quad + \quad \underbrace{m_{h^0}, m_{H^0}, m_{H^\pm}, \alpha, M^2 (= v^2\lambda_5)}_{\text{in the MSSM functions of } m_{A^0},\, \tan\beta}$$

  $\longrightarrow$ bound on lightest neutral Higgs mass ($m_{h^0} \lesssim 135\,\text{GeV}$)

- large quantum corrections to Higgs masses (esp. to m_{h^0})

  present status: see [Heinemeyer, Hollik, Weiglein '06]

• Higgs production at future hadron colliders

– Higgs search programme (schematic)

1. finding the Higgs boson(s) $\rightarrow$ establish a signal
   production & decay $\longrightarrow$ rate & signatures

2. measuring properties of the Higgs boson(s) $\rightarrow$ make sure it's a Higgs
   angular distributions $\longrightarrow$ spin, parity, CP properties
   partial decay widths $\longrightarrow$ couplings to other particles
   pair production $\longrightarrow$ self-couplings
   ("reconstruction" of the Higgs potential)

3. detailed probe of the Higgs sector $\rightarrow$ determine the underlying model
   precision measurements
   observation of quantum effects
   $\longrightarrow$ information on particles too heavy to be directly observed

Step 3: performance of the LHC limited, ideal task for the ILC.

– How to produce a Higgs boson ?

Higgs mechanism $\longrightarrow$ Higgs couplings to all other particles $\propto$ mass

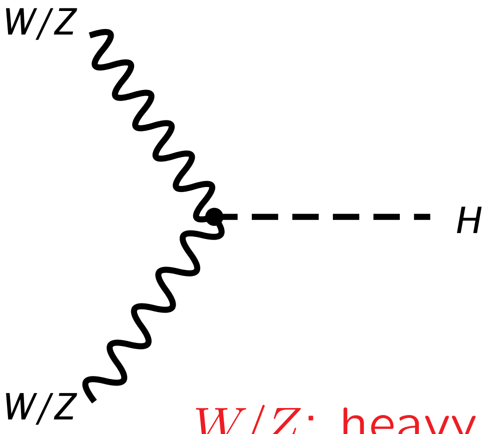
$\longrightarrow$ Problem: ordinary matter consists of

$\star$ e^-,u-, d-quarks, gluons : very light

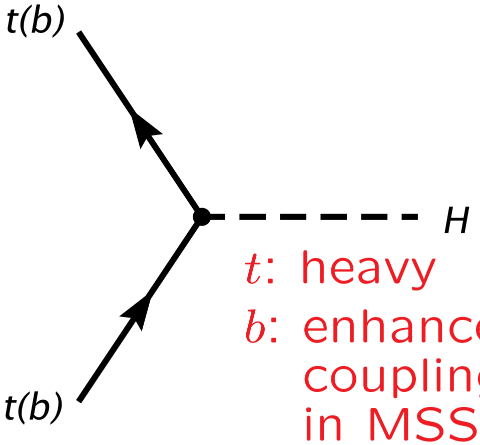
$\star$ with negligible couplings to the Higgs boson.

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

Therefore, most important couplings :



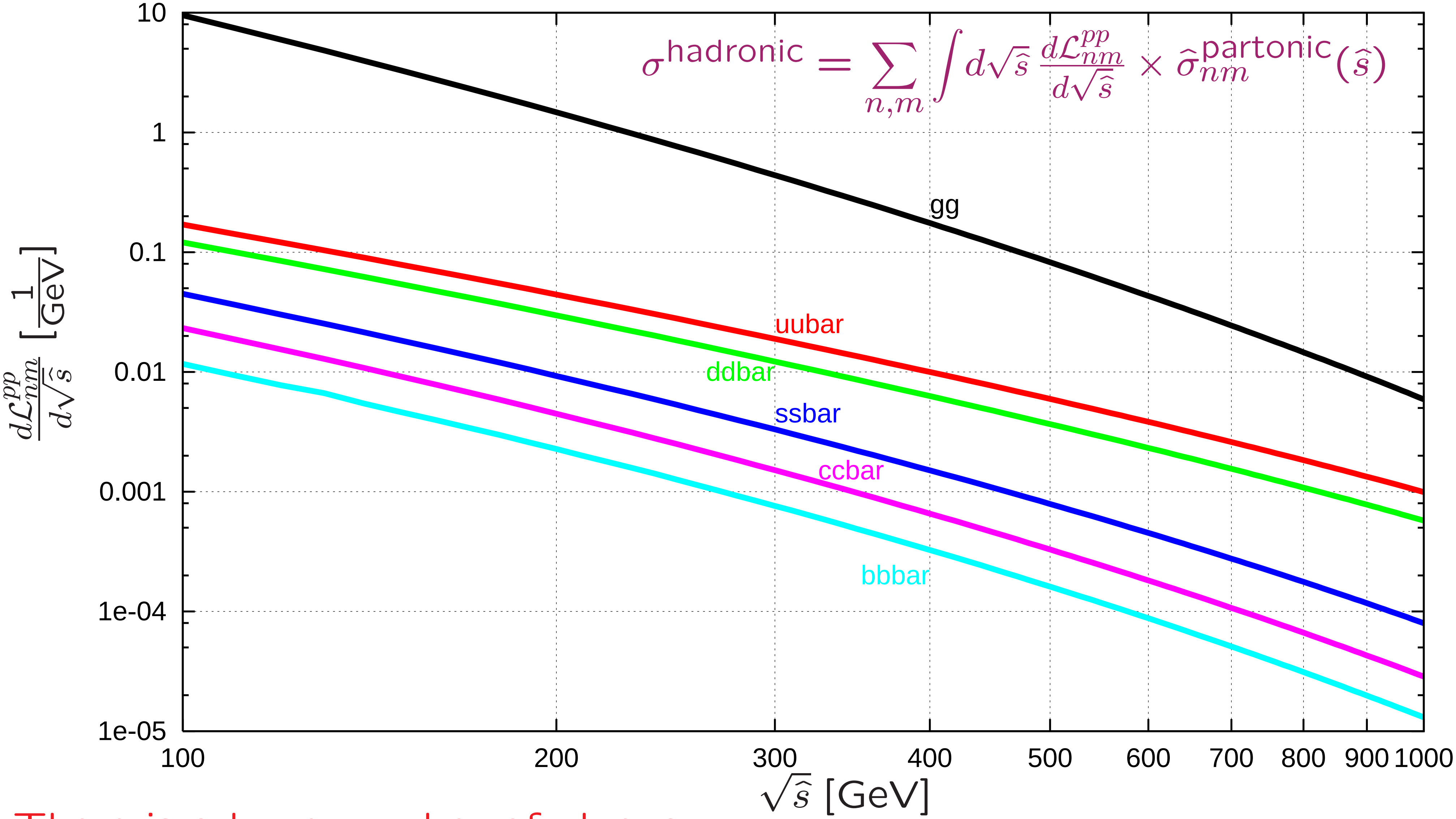
W/Z: heavy



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 ?

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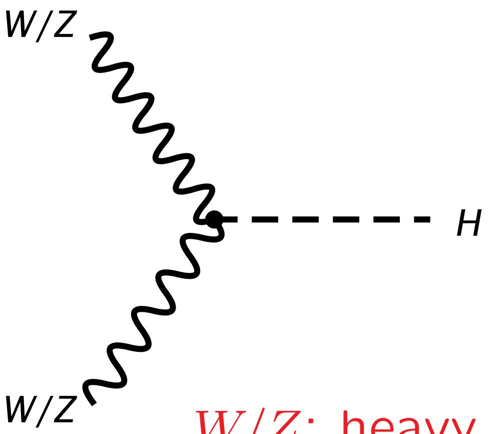

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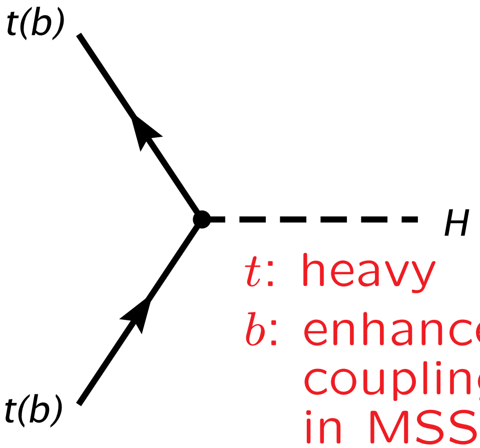

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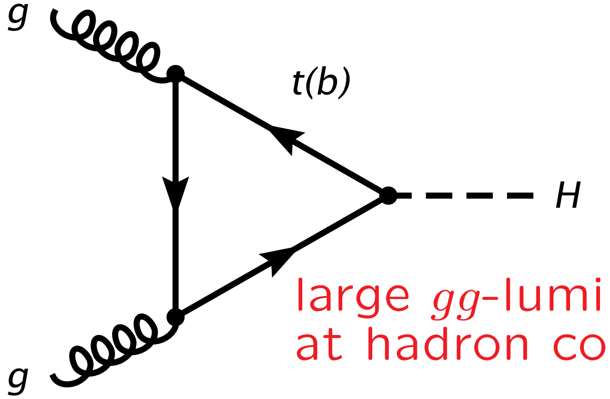
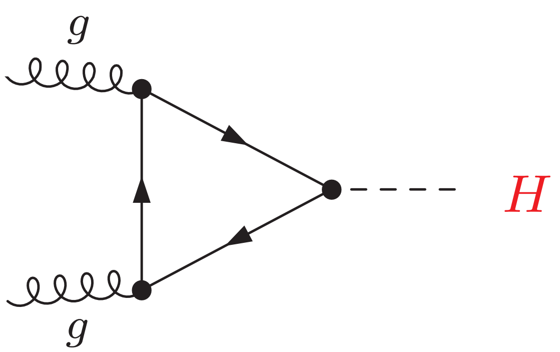


large gg-lumi at hadron colliders

– Neutral Higgs production overview

Important neutral Higgs production processes:



gluon fusion, $gg \longrightarrow H$

– Neutral Higgs production overview

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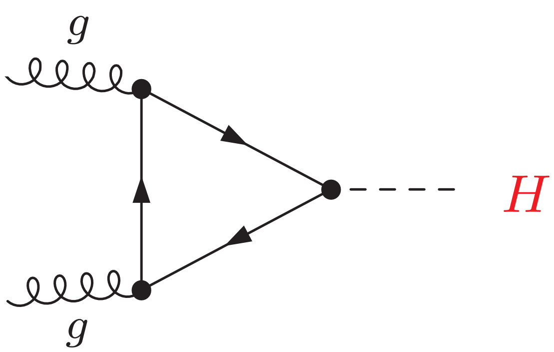
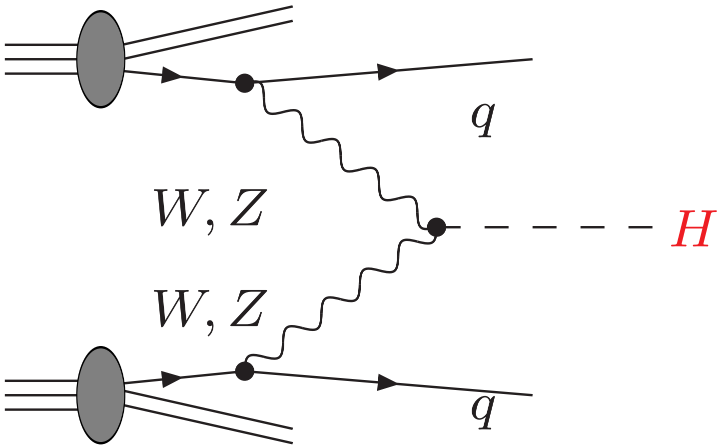


gluon fusion, $gg \to H$



vector boson fusion, $qq \to qqH$

– Neutral Higgs production overview

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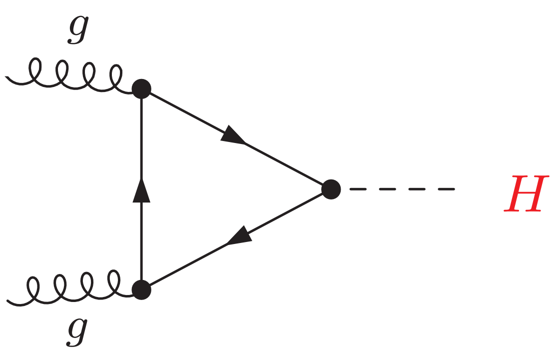

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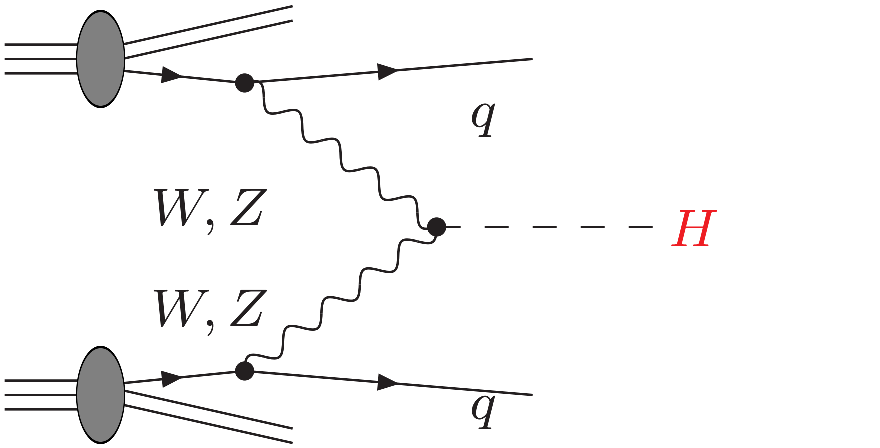

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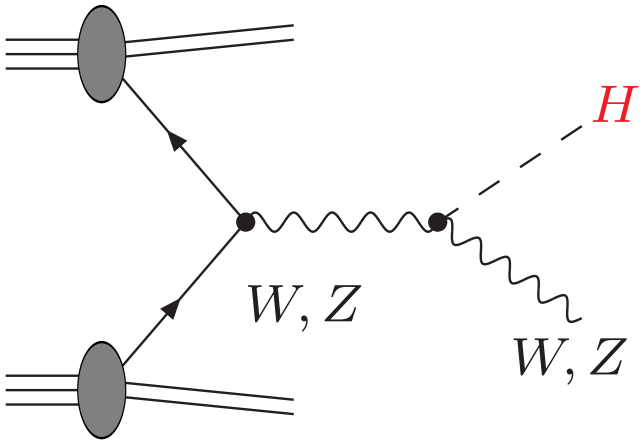

Higgs strahlung, $q\bar{q}' \to VH$

– Neutral Higgs production overview

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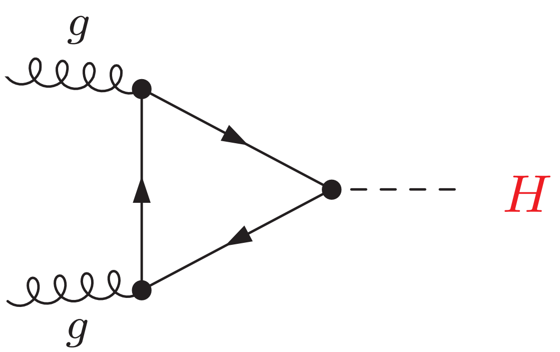

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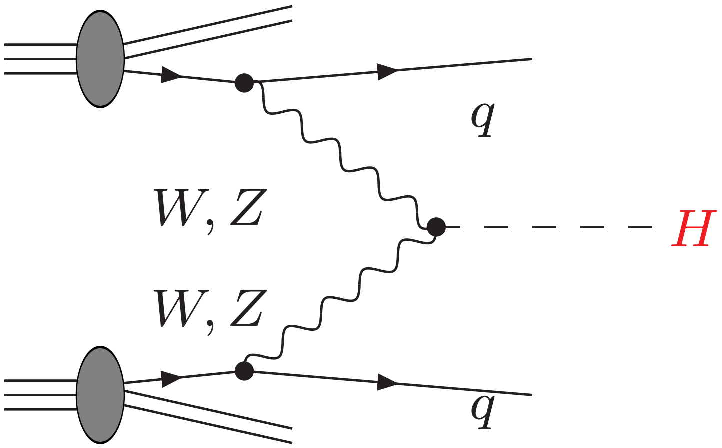

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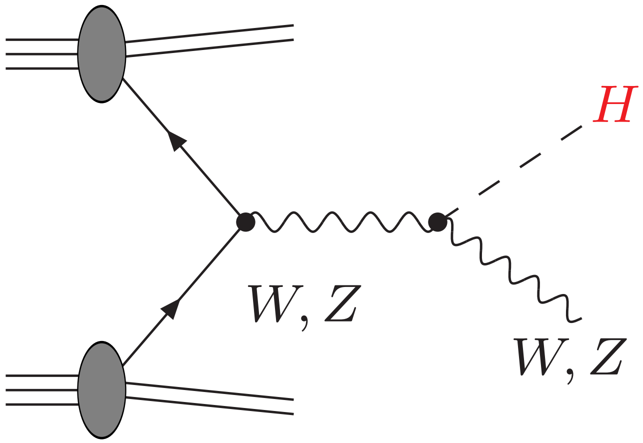

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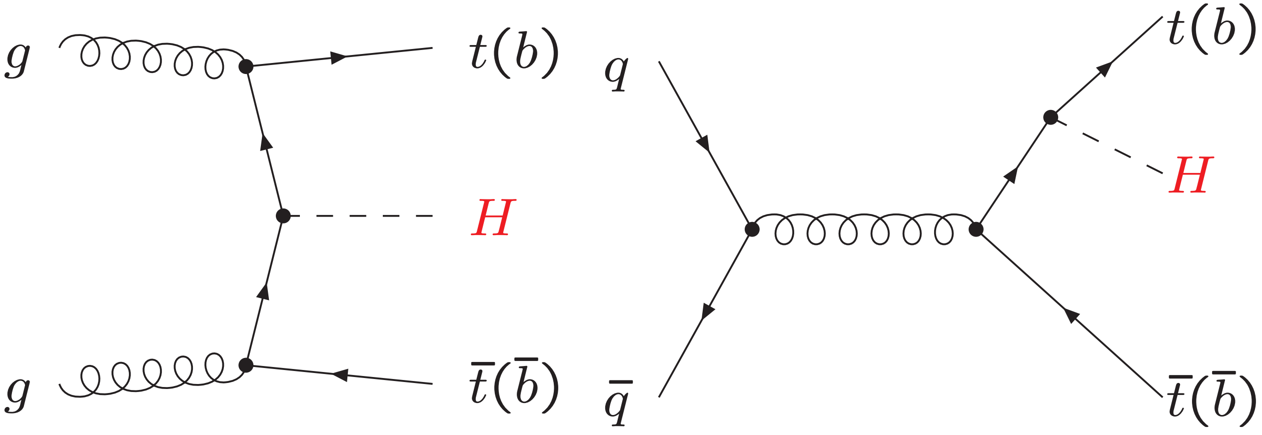
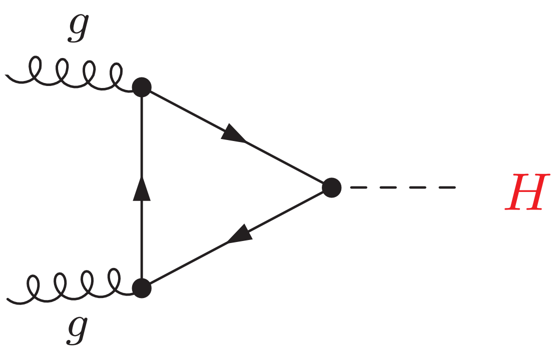
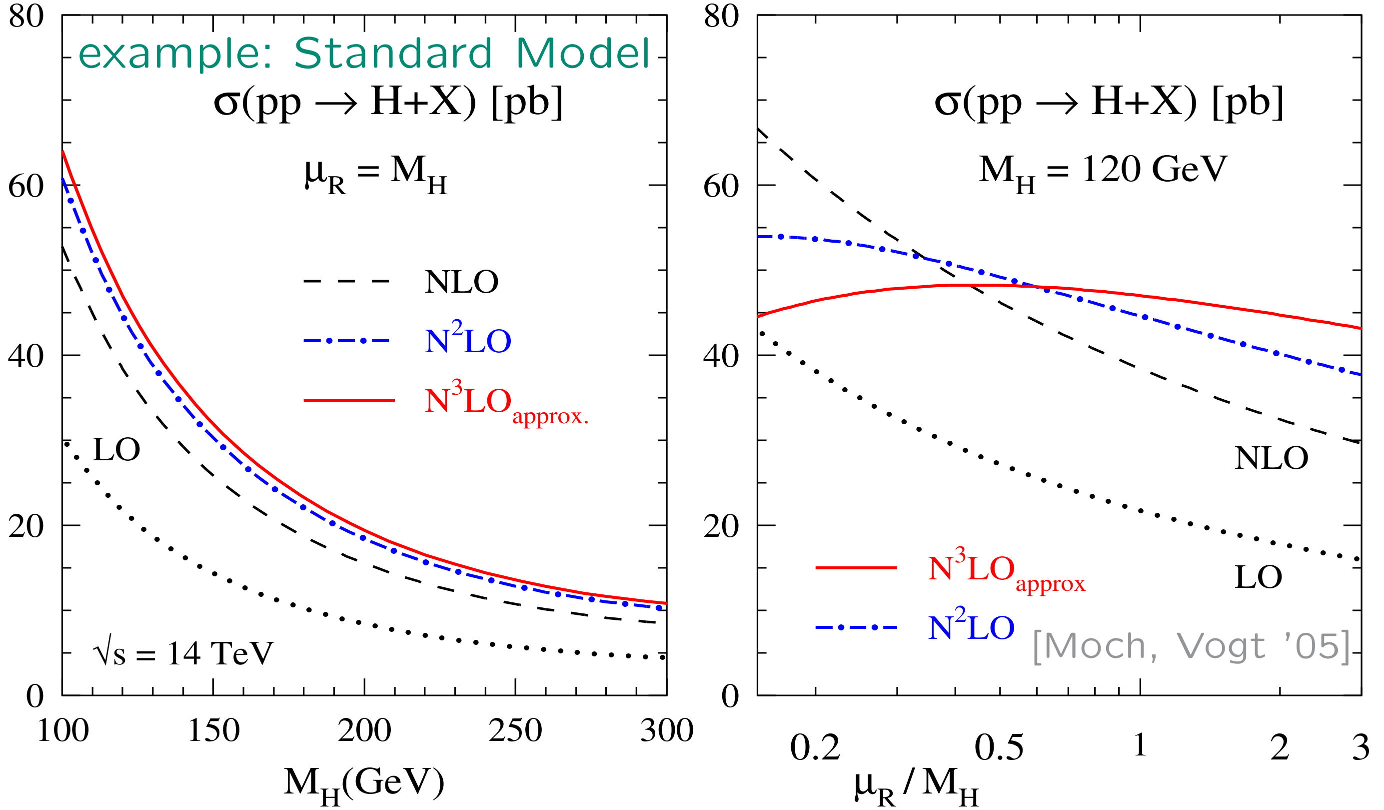


$t\bar{t}H$ **(**$b\bar{b}H$**) production [&** $b\bar{b} \to$ H **if 5 flavs]**



gluon fusion, $gg \to H$



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

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

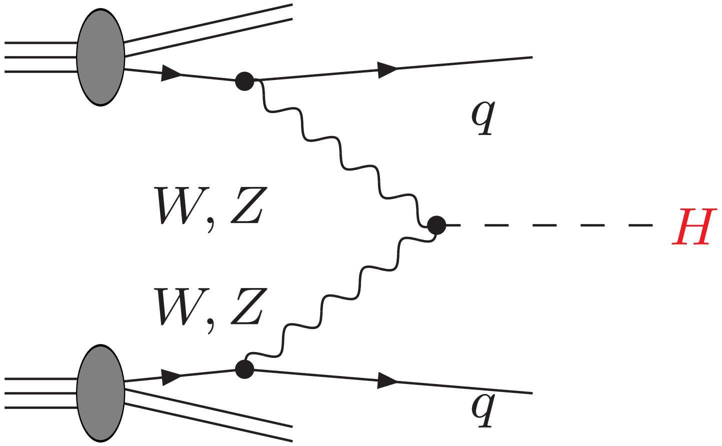
SM, NNLO QCD [Harlander '00; Catani, de Florian, Grazzini '01; Harlander, Kilgore '01 & '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03]

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]

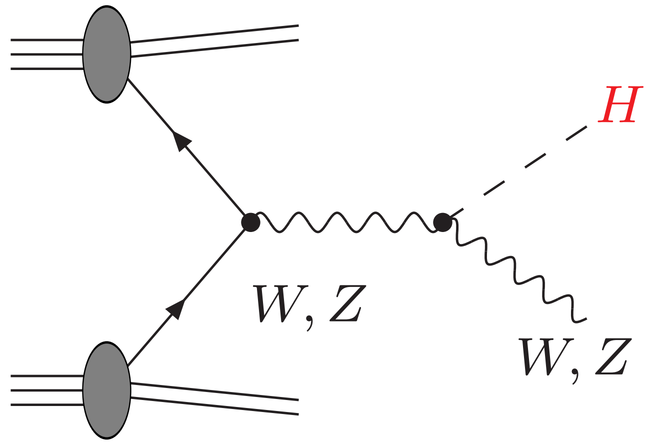


vector boson fusion, $qq \to qqH$

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

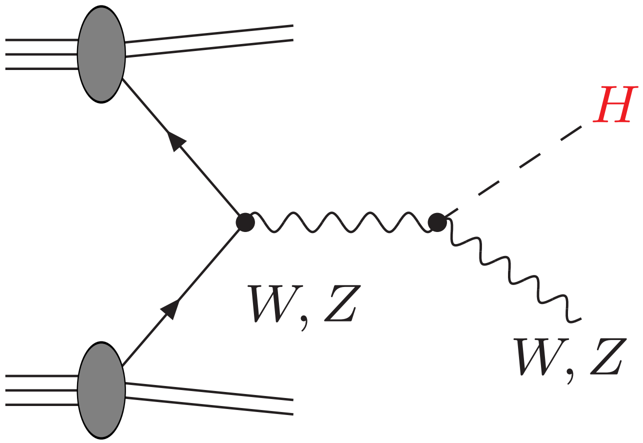
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

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

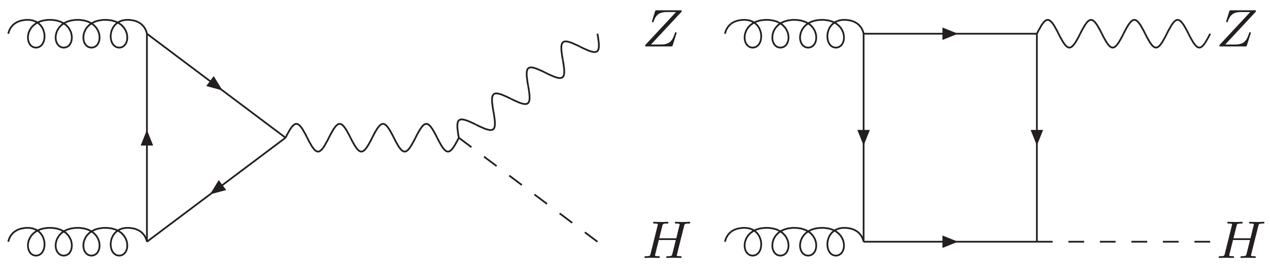
SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]

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

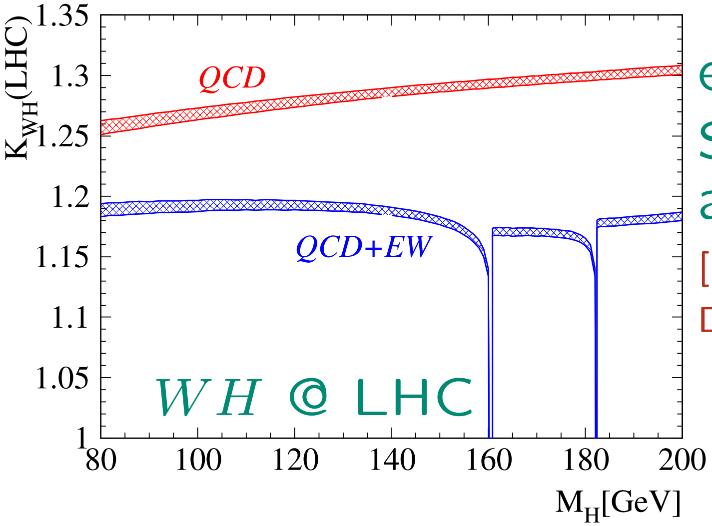


Higgs strahlung, $q\bar{q}' \to VH$

note! additional parton process for ZH @ NNLO

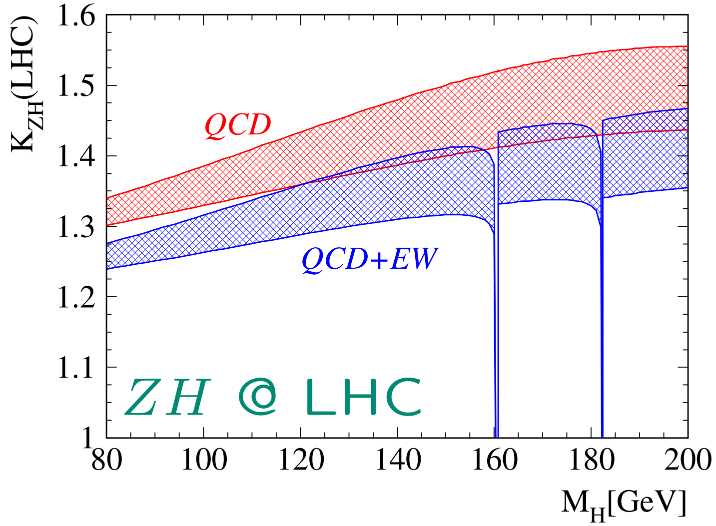


[Dicus, Kao '88; Kniehl '90]



example:
SM K-factors
and scale uncertainty

[OBr, Ciccolini, Dittmaier, Djouadi, Harlander, Krämer '04]



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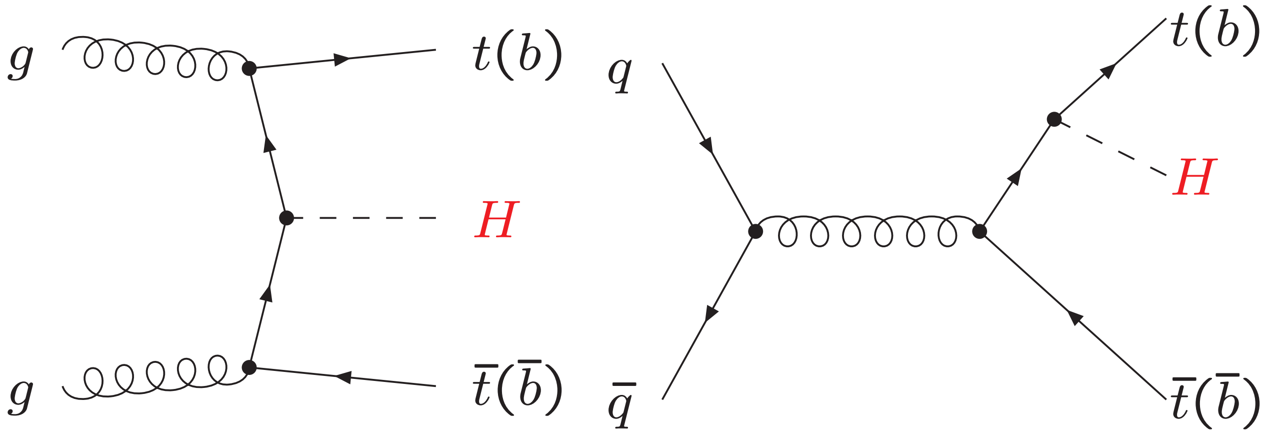


$t\bar{t}H$ ($b\bar{b}H$) **production [&** $b\bar{b} \to H$ **if 5 flavs]**

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]

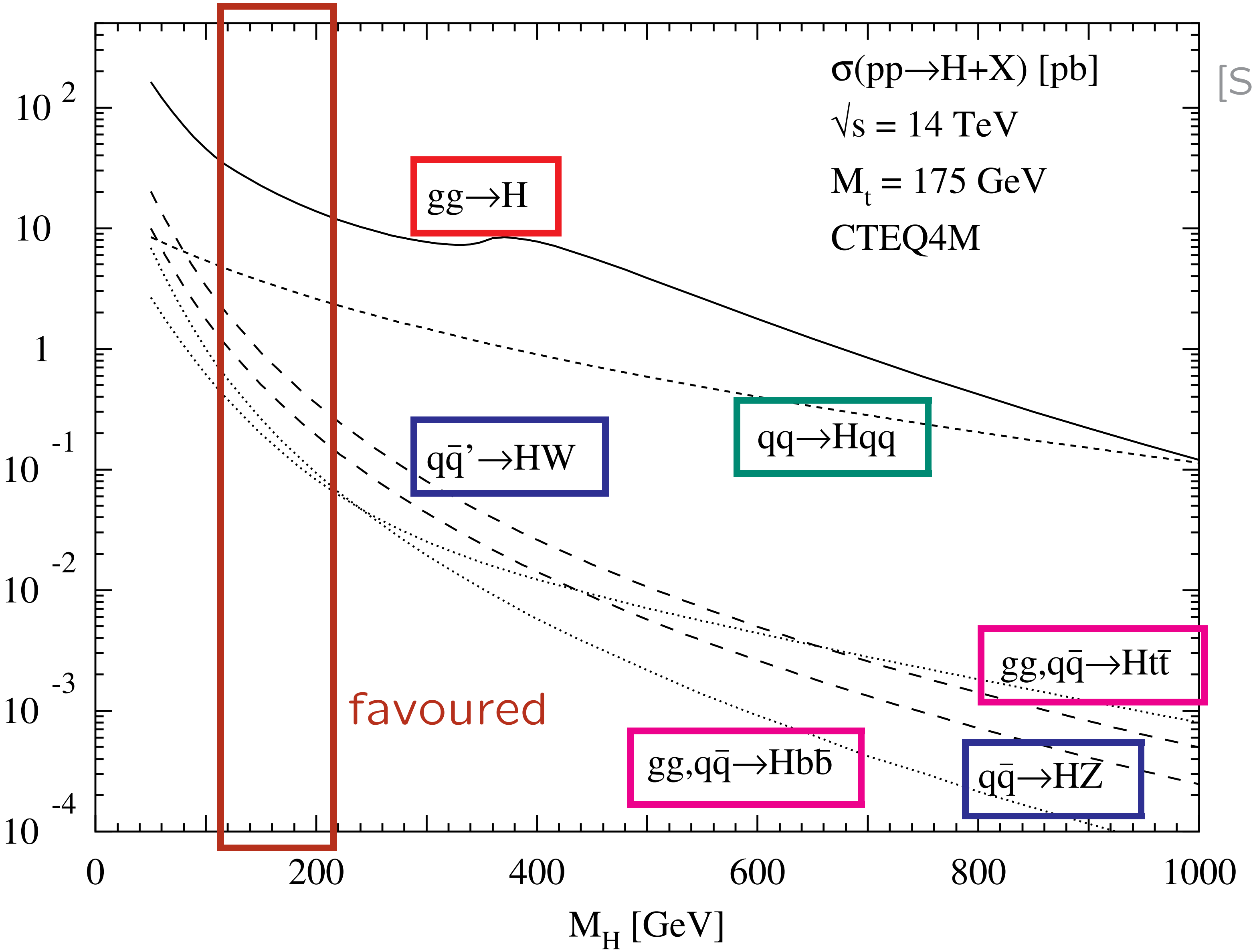
SM, NLO QCD ($b\bar{b}H$) [Dittmaier, Krämer, Spira '03; Dawson, Jackson, Reina, Wackeroth '03]

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]

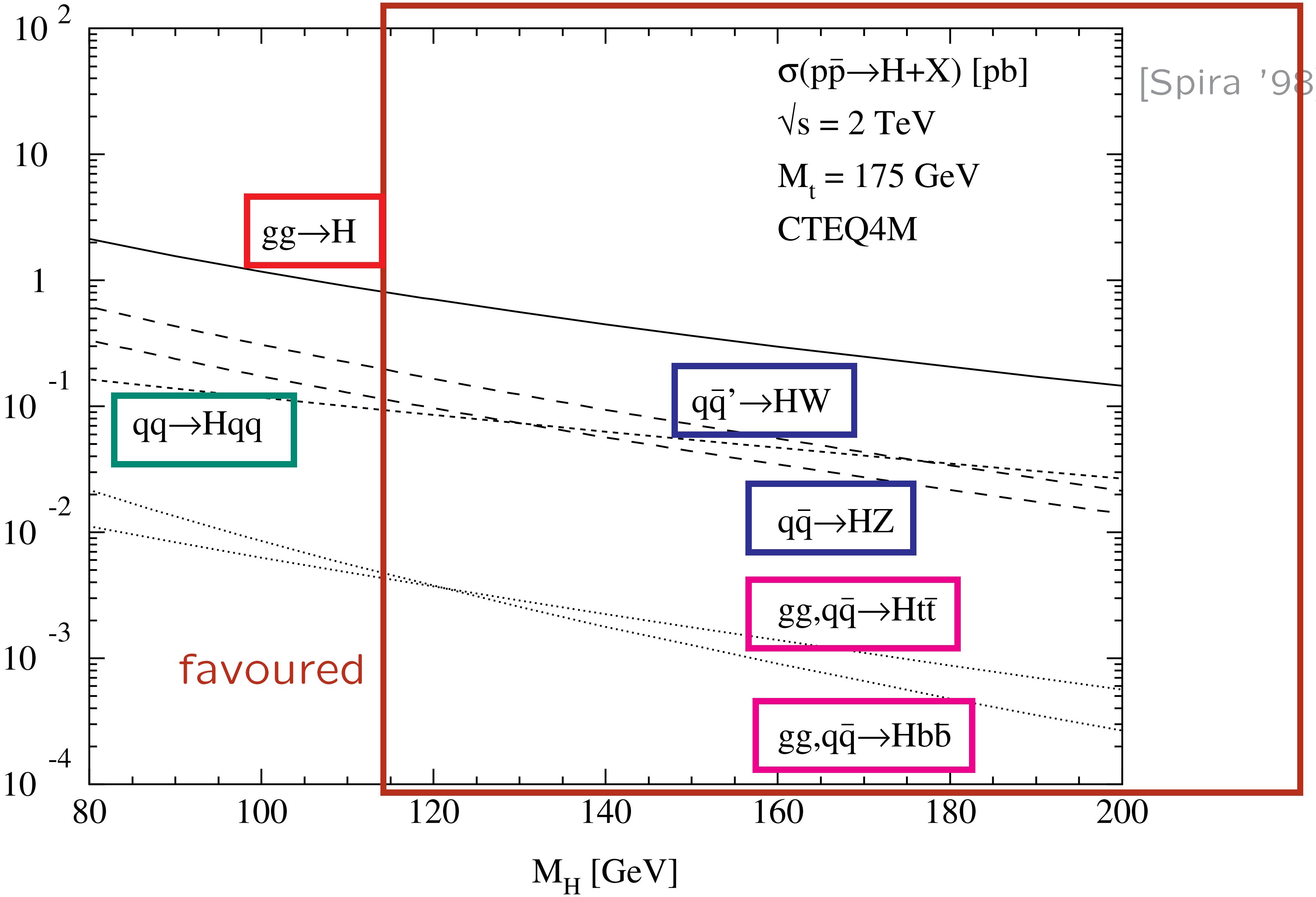
MSSM, NLO QCD, no superpartners [Dawson, Jackson, Reina, Wackeroth '03]

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



[Spira '98]

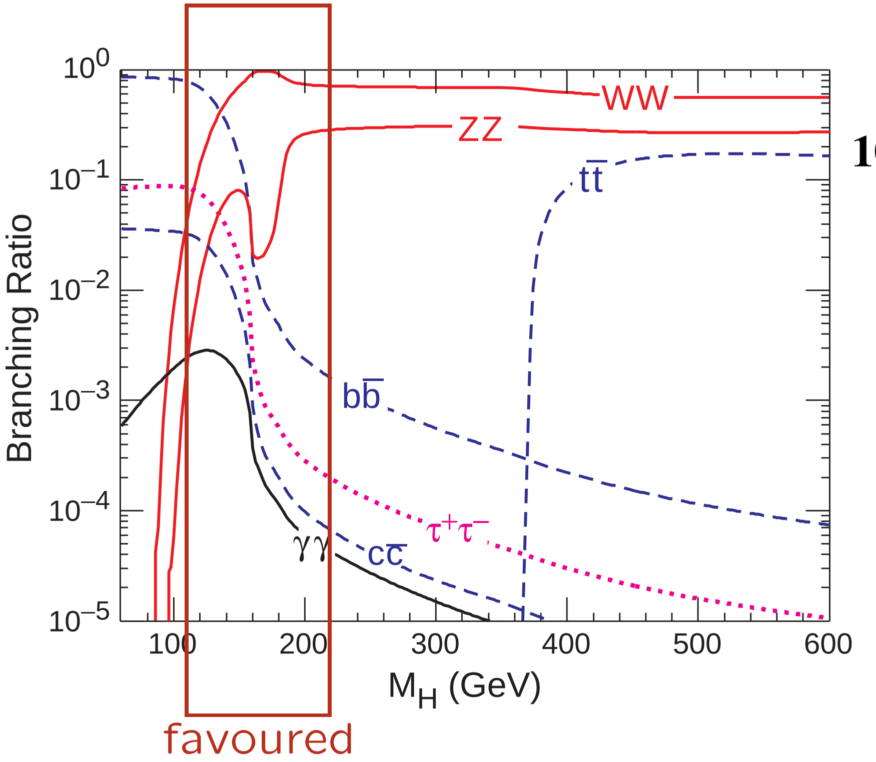
Predictions: SM Higgs production @ **Tevatron** :

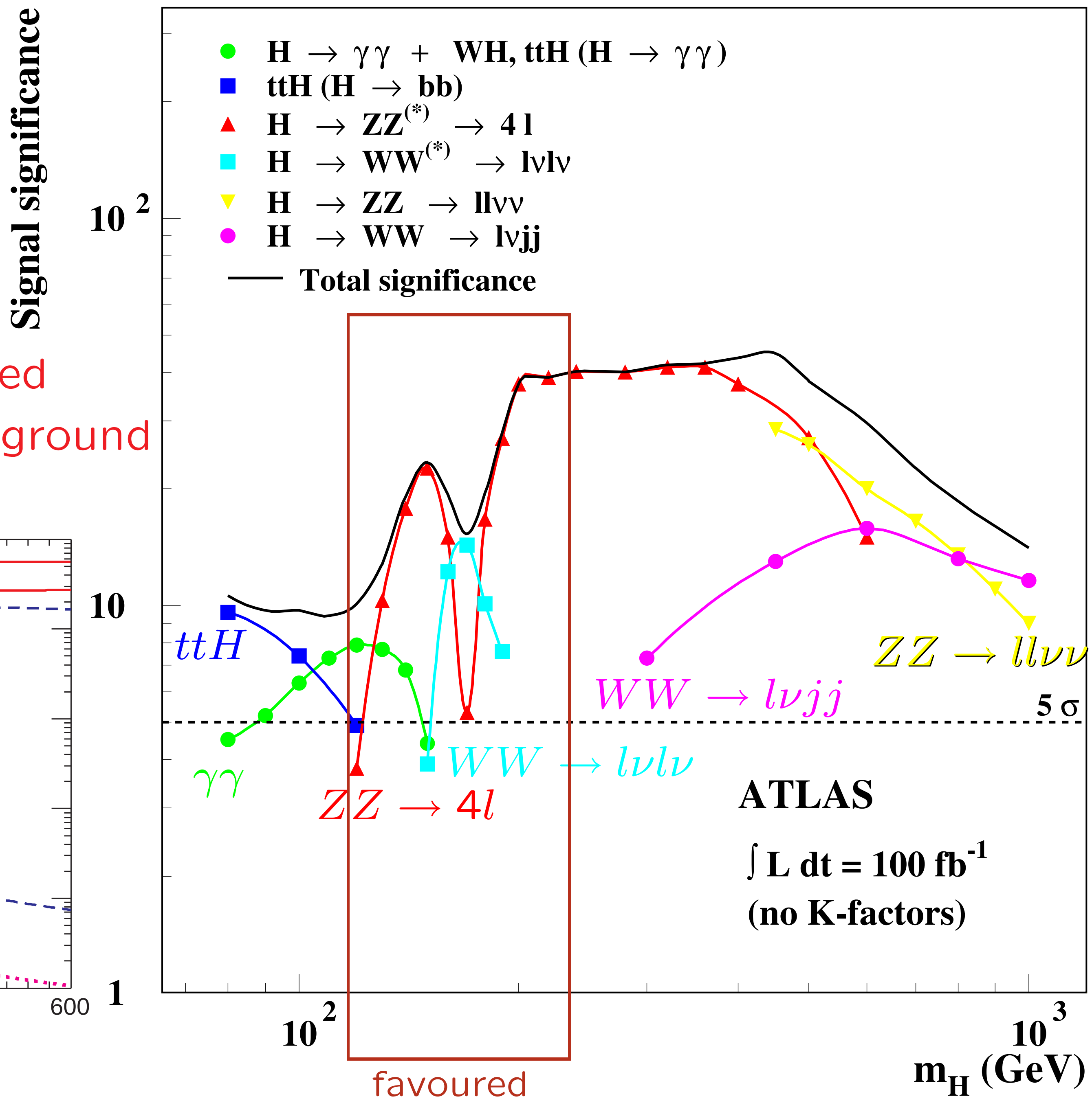


[Spira '98]

SM Higgs branching ratios
and
signal significance @ LHC

note!
rate alone is not enough!
signals need to be silhouetted
against **huge** QCD background





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

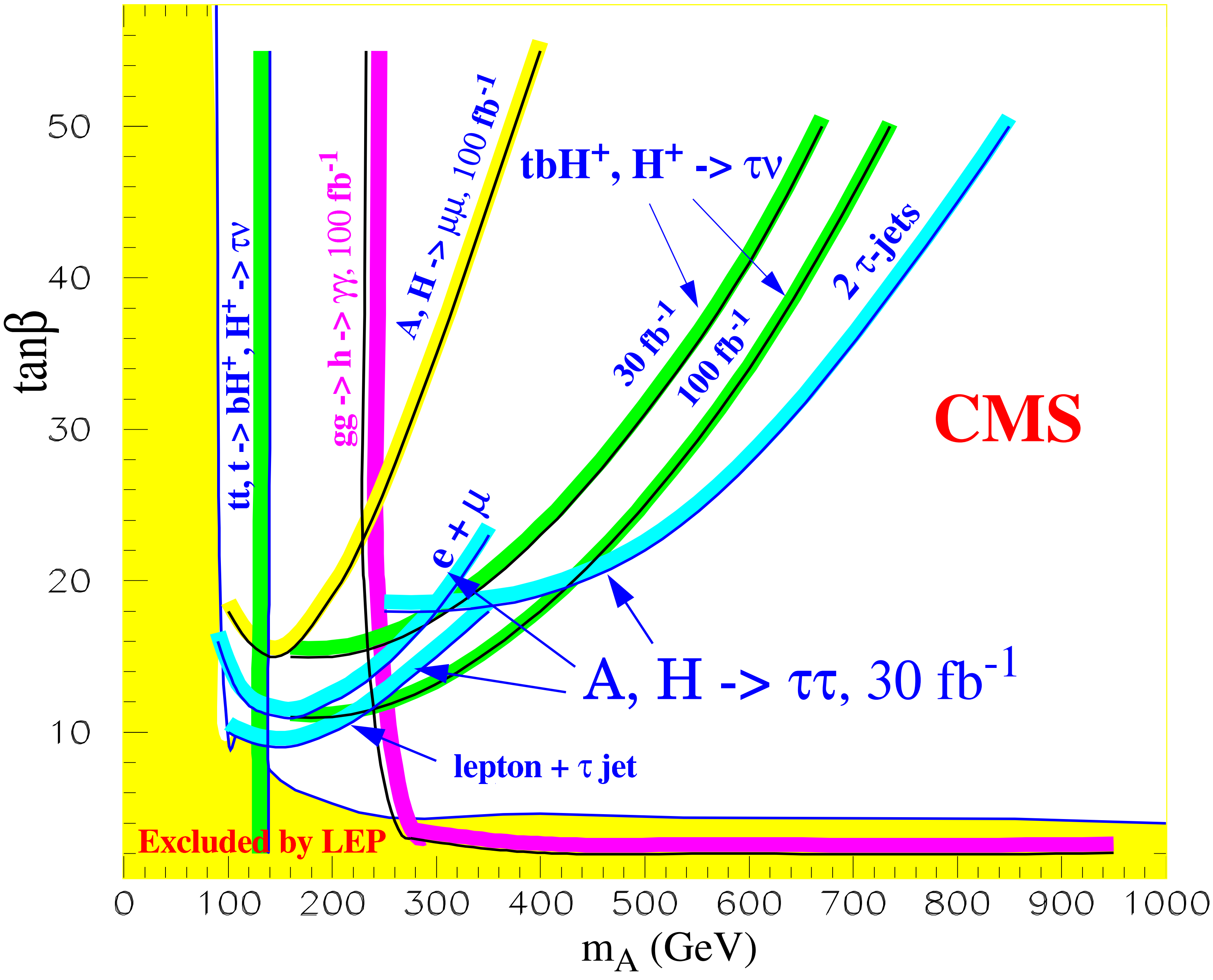
small $\tan\beta$ (say 3) :

- 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

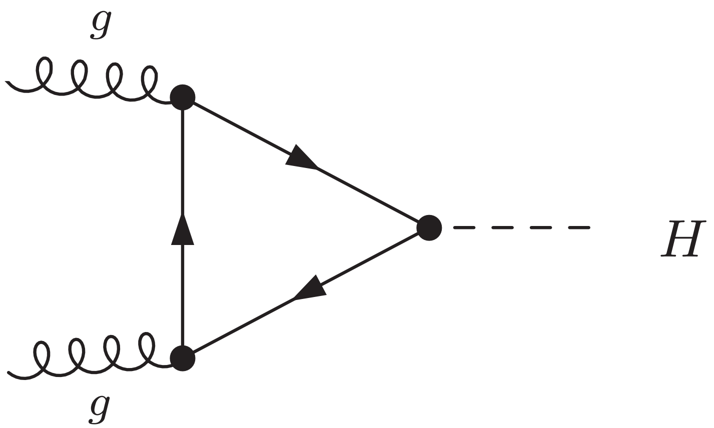
LHC/CMS 5σ discovery contours for the MSSM Higgs bosons



• 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 $H \to \gamma\gamma$.

$\longrightarrow$ difficult ! huge background 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.
  $\longrightarrow$ better S/B ratio
  $\longrightarrow$ allows for refined cuts

disadvantage:

* lower rate than inclusive Higgs production

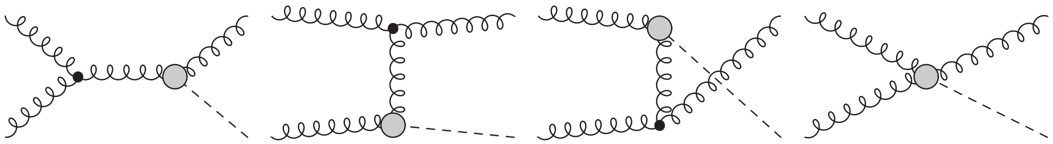
(*) NLO signal prediction has still sizable theoretical uncertainty ($\approx$ 20%)

(*) background only partly known at NLO accuracy

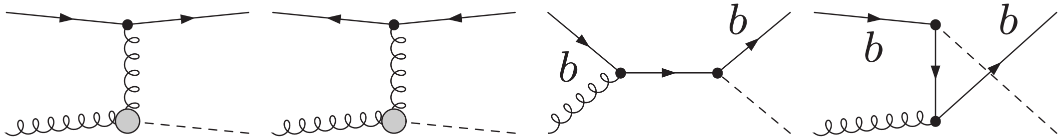
$\longrightarrow$ theoretical uncertainties larger than in the fully inclusive case (so far)

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

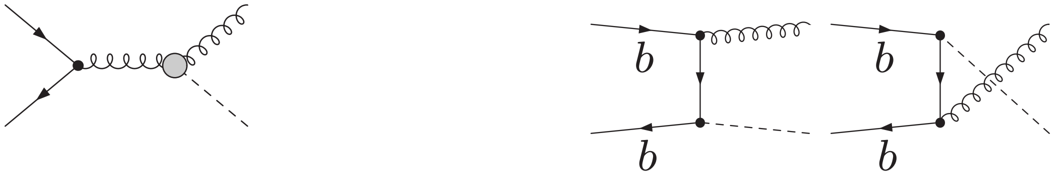
- $gg \longrightarrow Hg$ ($\approx$ 50 - 70 % of total rate)



- $qg \longrightarrow Hq, \bar{q}g \longrightarrow H\bar{q}$ ($\approx$ 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]

$pp \longrightarrow H + \text{jet}, H \longrightarrow \tau^+\tau^- \longrightarrow l^+l^-\not{p}_T$ [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 $m_H \approx 100 - 140\text{GeV}$.

available codes:

- Higgsjet [de Florian, Grazzini, Kunszt '99]
  NLO QCD cross section for $pp \to H + \text{jet}$
  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 $pp \to H + X$

but the LHC calls for further improvement of the theoretical predictions

– Higgs + jet in the MSSM [OBr, Hollik '03]

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

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

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

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

→ change of overall rate

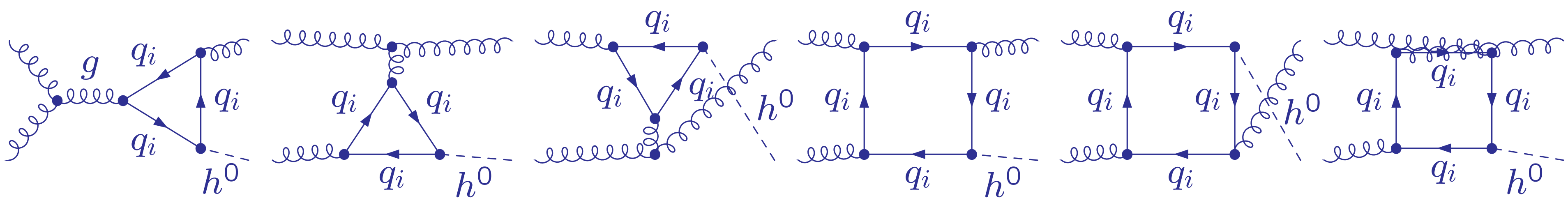
* additional superpartner-loops (even additional topologies)

→ also angular distribution changed

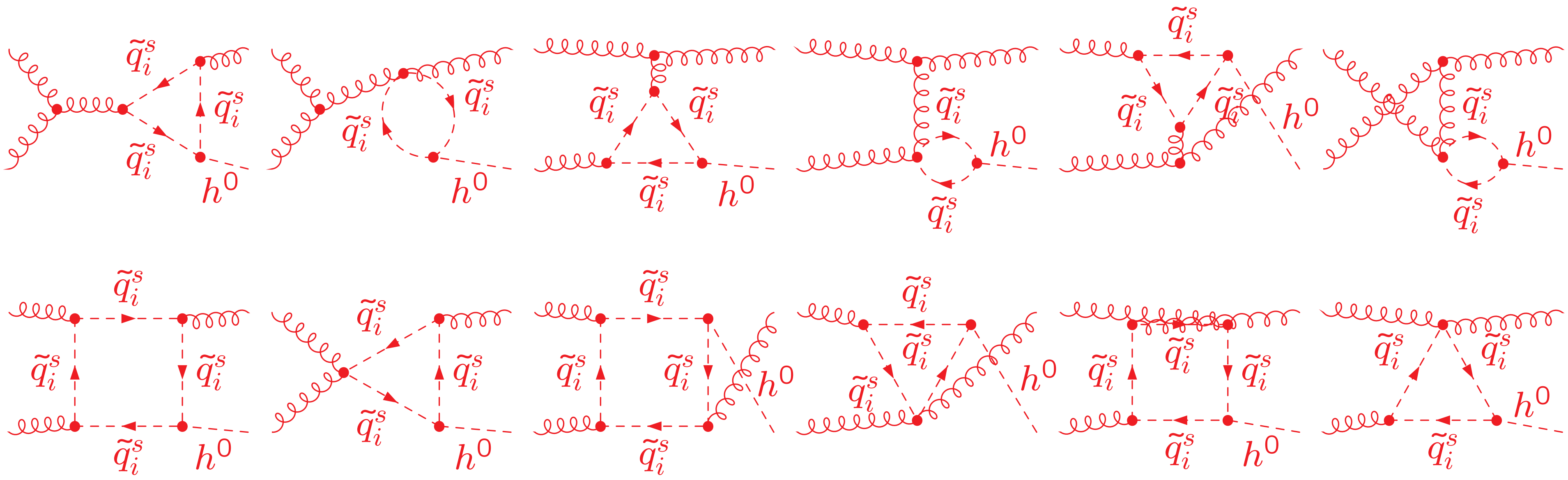
Feynman graphs :

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

quark loops

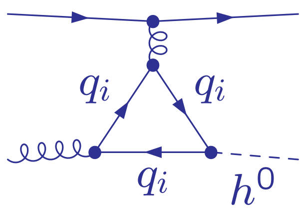


superpartner loops

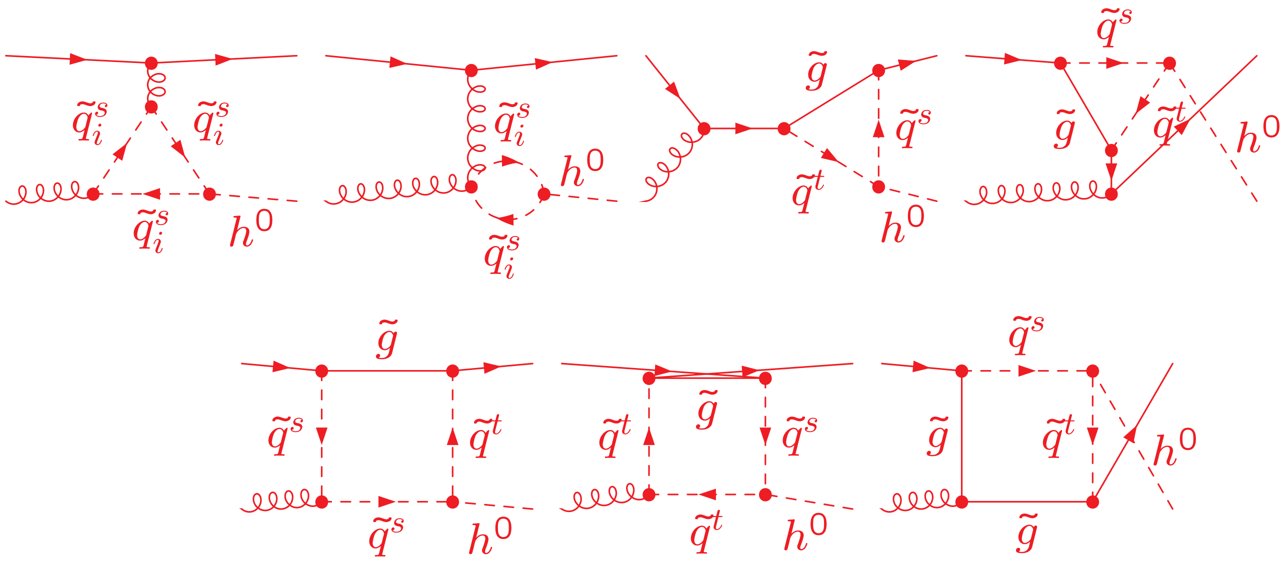


quark-gluon scattering, $qg \to h^0 q$

quark loops

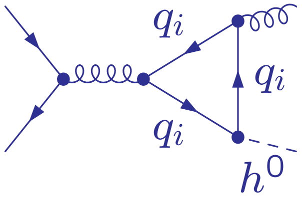


superpartner loops

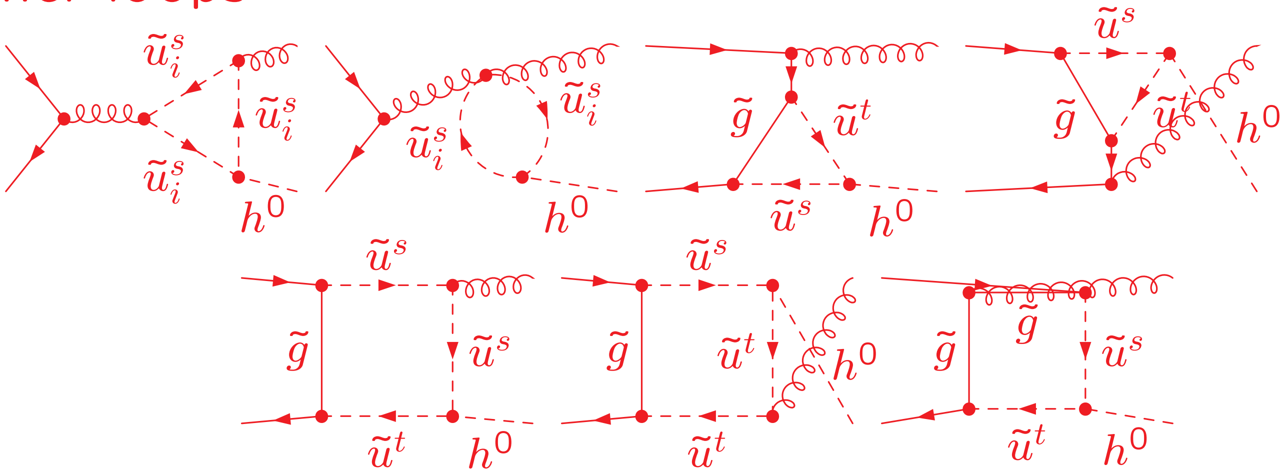


quark-antiquark annihilation, $q\bar{q} \to h^0 g$

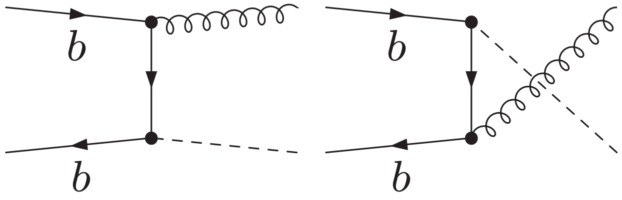
quark loops



superpartner loops



$b\bar{b}$ annihilation, $b\bar{b} \to h^0 g$



– MSSM results

hadronic cross section @ LHC ($\sqrt{S} = 14\,\text{TeV}$):

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

$$\int_{\tau_0}^{1} d\tau \left(\frac{d\mathcal{L}^{pp}_{gg}}{d\tau}\, \hat{\sigma}_{gg\to gh^0}(\hat{s}) + \sum_q \frac{d\mathcal{L}^{pp}_{qg}}{d\tau}\, \hat{\sigma}_{qg\to qh^0}(\hat{s}) + \sum_q \frac{d\mathcal{L}^{pp}_{q\bar{q}}}{d\tau}\, \hat{\sigma}_{q\bar{q}\to gh^0}(\hat{s}) \right)\Bigg|_{\hat{s}=\tau S}$$

with the parton luminosity

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

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.

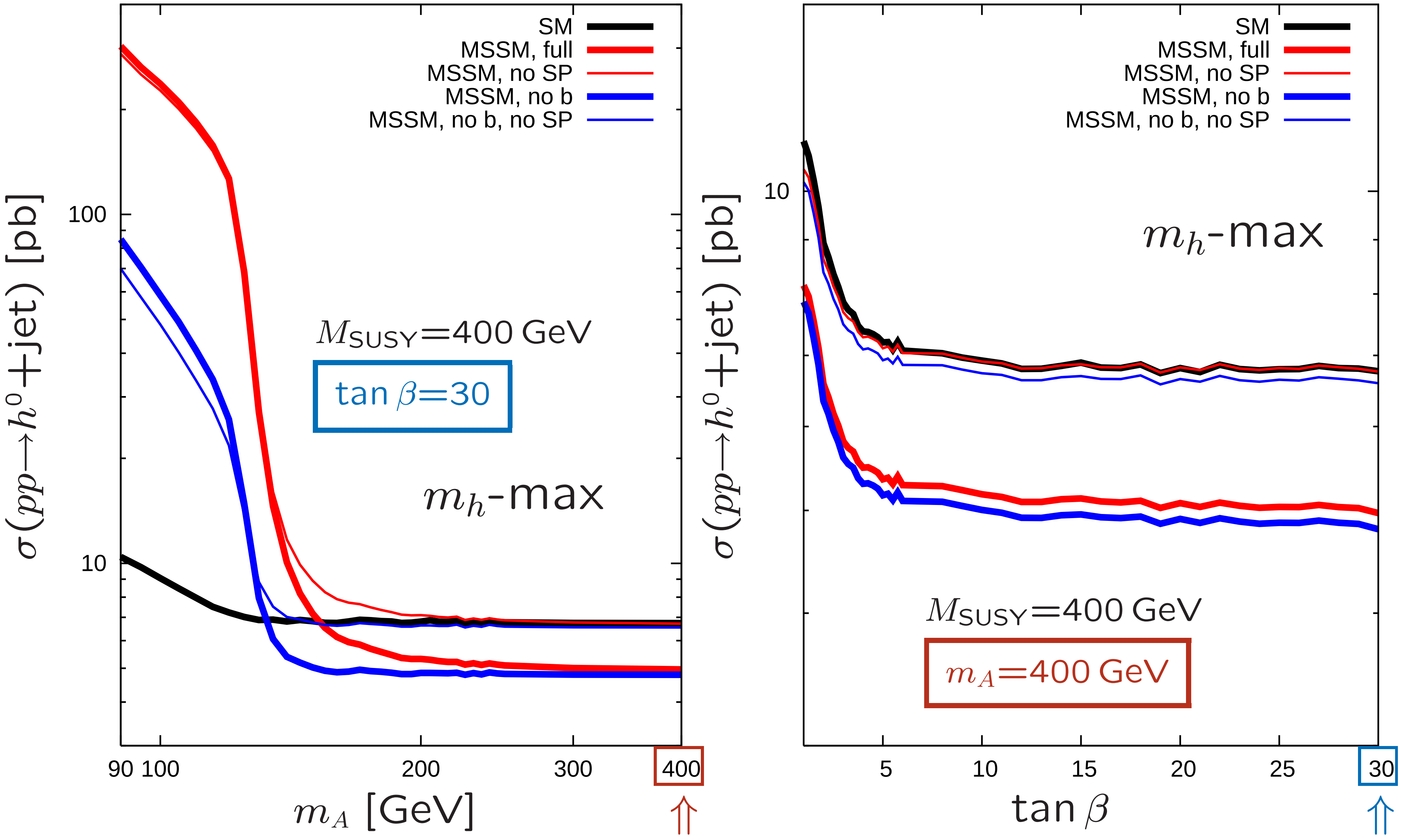
The results shown are for the MSSM m_h^{max} benchmark scenario with common squark mass scale M_{SUSY}.

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

[Higgs + Jet, MSSM results]

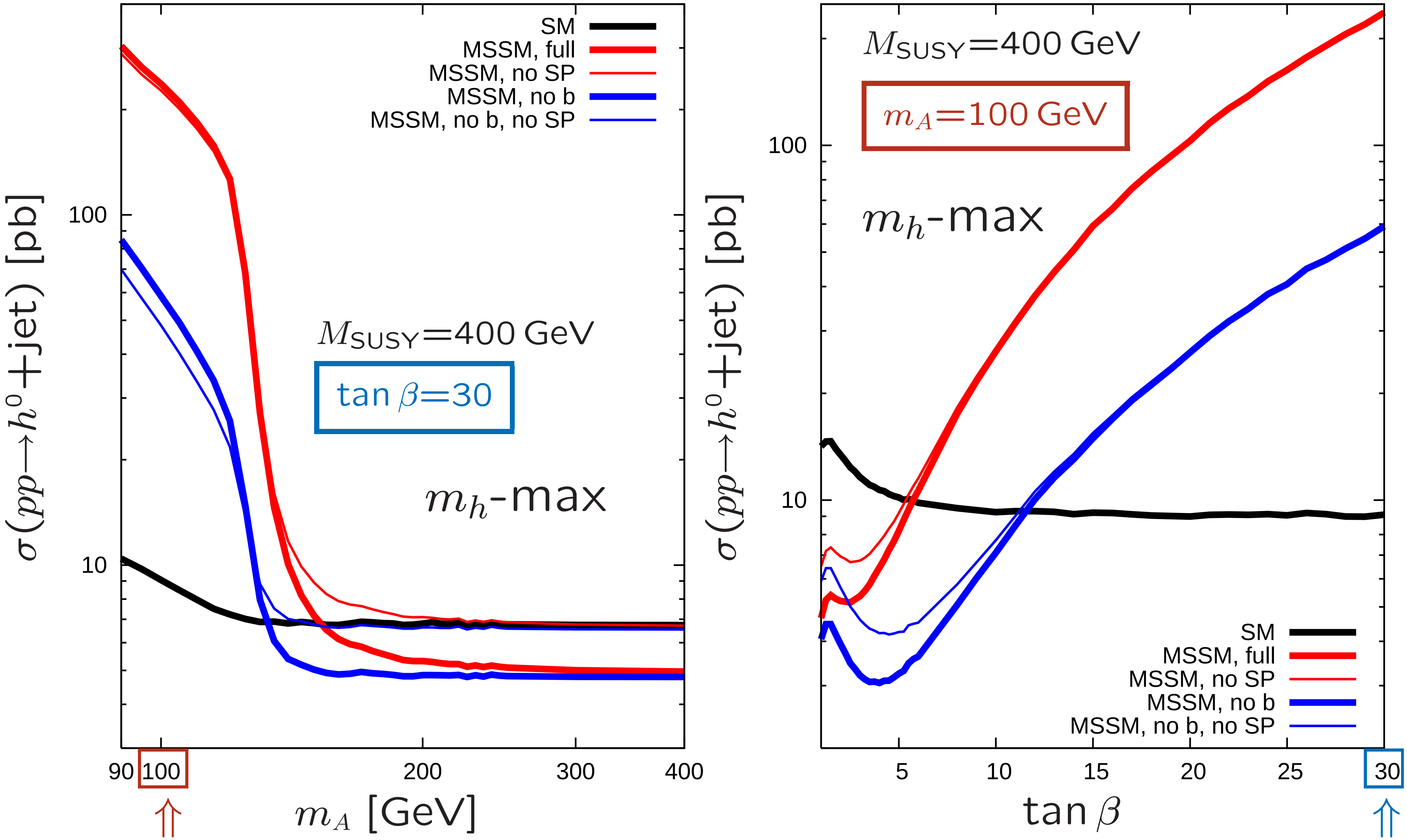
m_A- and $\tan\beta$-dependence :

(cuts: $p_{T,\mathrm{jet}} \geq 30$ GeV , $|\eta_{\mathrm{jet}}| \leq 4.5$)

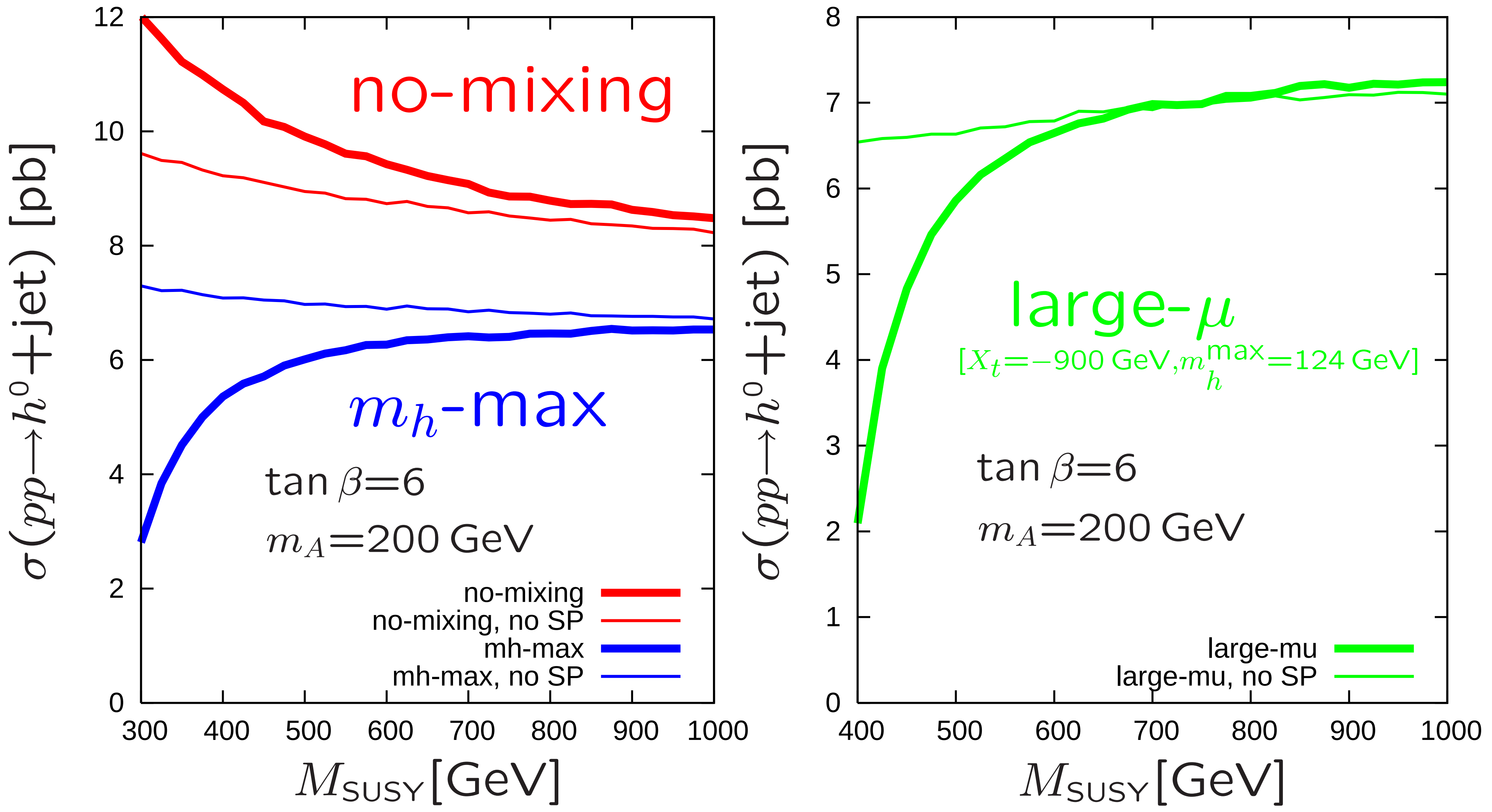


m_A- and $\tan\beta$-dependence :

(cuts: $p_{T,\text{jet}} \geq 30$ GeV , $|\eta_{\text{jet}}| \leq 4.5$)

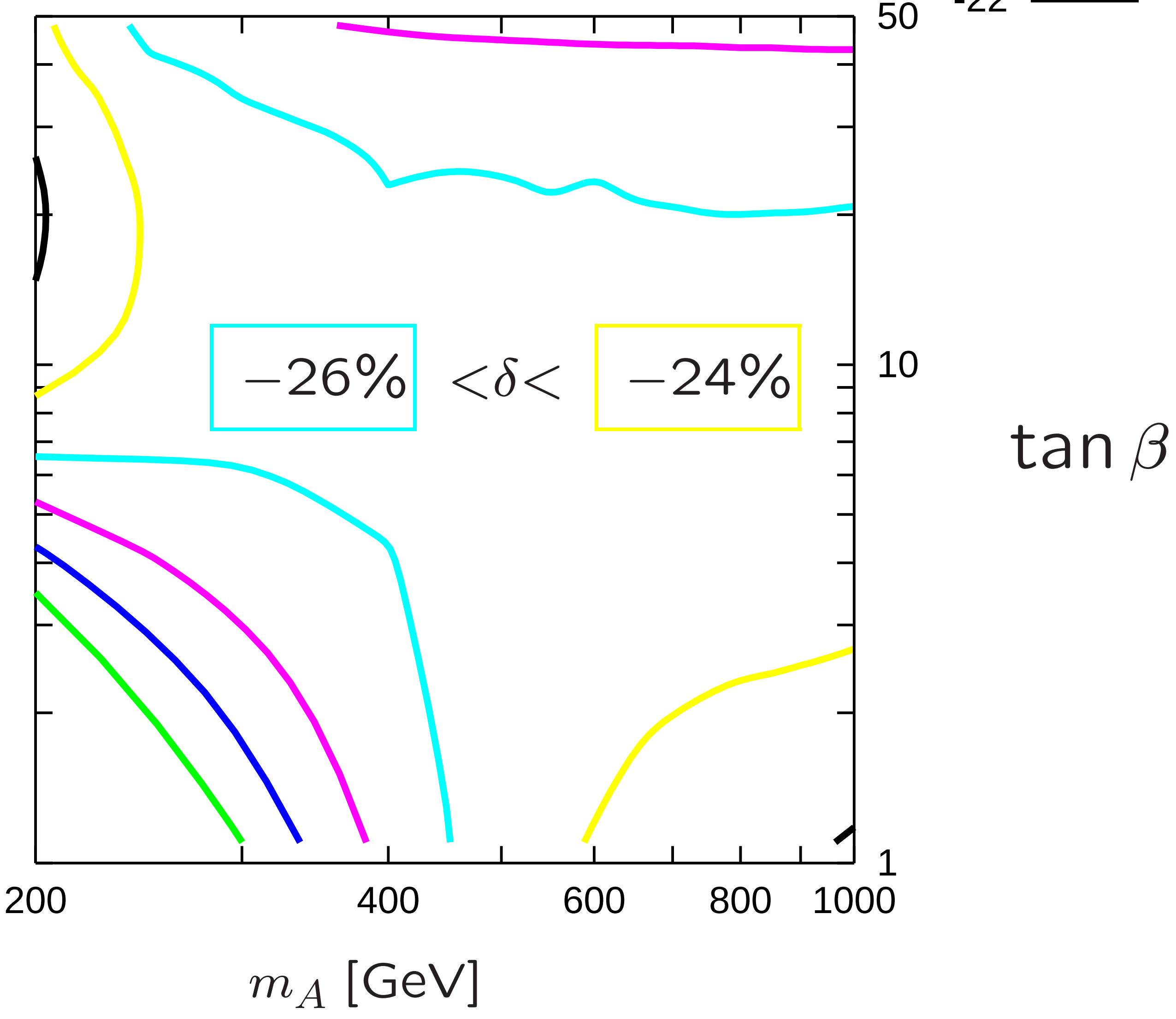


M_{SUSY} -dependence : (cuts: $p_{T,\text{jet}} \geq 30$ GeV , $|\eta_{\text{jet}}| \leq 4.5$)



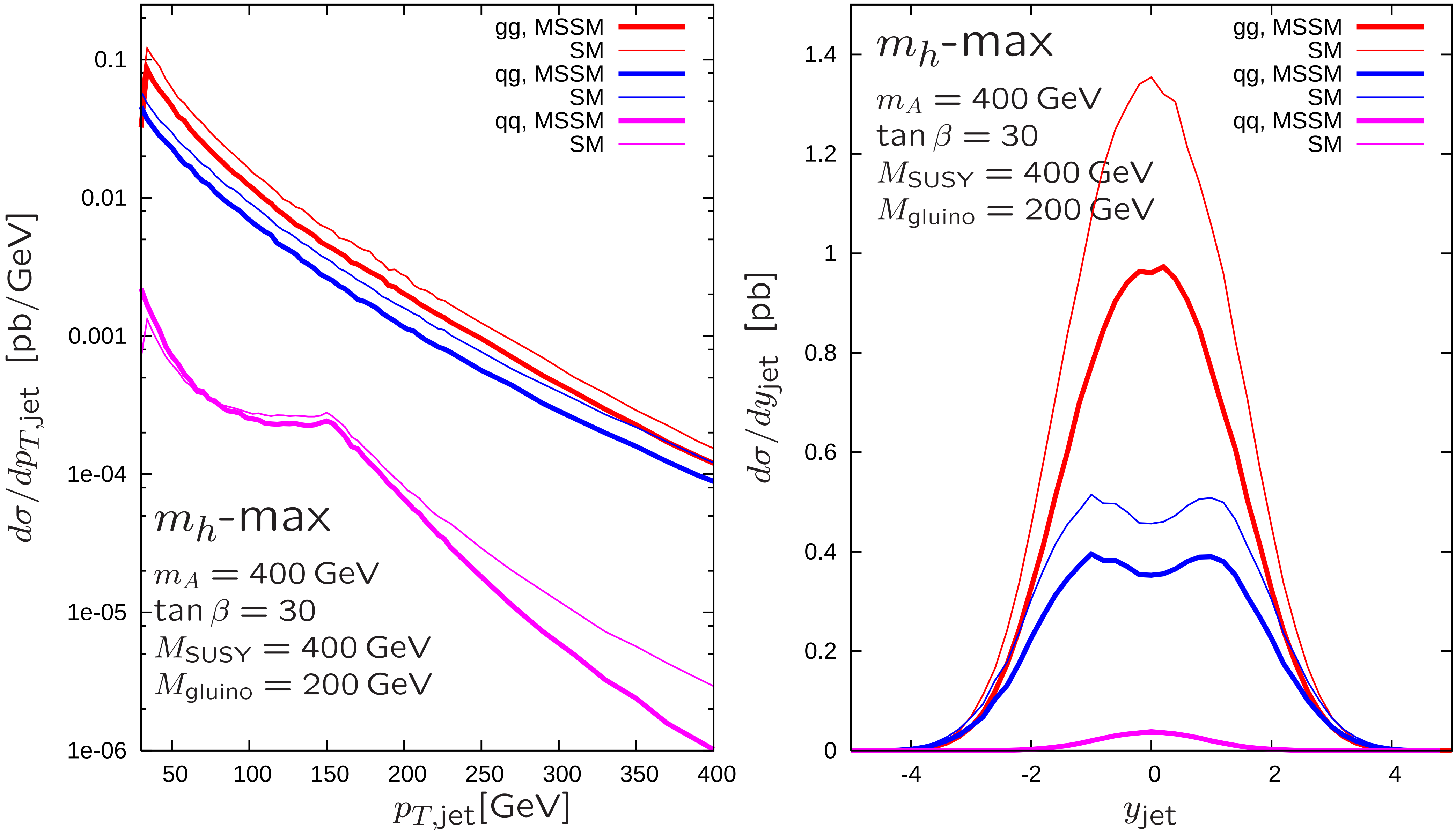
relative difference $\delta = (\sigma^{\mathrm{MSSM}} - \sigma^{\mathrm{SM}})/\sigma^{\mathrm{SM}})$:

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



[Higgs + Jet, MSSM results]

$p_{T,\text{jet}}$- and y_{jet}-dependence : (cuts: $p_{T,\text{jet}} \geq 30$ GeV , $|\eta_{\text{jet}}| \leq 4.5$)



Summary

- We are sure to observe electroweak symmetry breaking in nature. However, up to now, we have no clue how it is realised. The Higgs mechanism allows to describe EWSB consistently up to very high energy.

- The search for the Higgs boson(s) proceeds in 3 steps: 1. establish a signal / 2. make sure it's a Higgs / 3. determine the underlying model.

- SM simulations show: Higgs + high-p_T jet production is a promising alternative to the inclusive production.

- LO MSSM prediction shows large effects due to virtual squarks. (processes loop-induced)
  – sizeable differences between SM and MSSM
  – angular distributions are changed at the $\approx 5\%$ level

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

$$\sigma^{\text{total}}_{\text{hadronic}},$$

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

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

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

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

is available on request $\longrightarrow$ oliver.brein@durham.ac.uk