Higgs Physics Phenomenology

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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
- $H^{\pm}W^{\mp}$ production @ LHC: MSSM vs. THDM
  - Charged Higgs search at LHC/Tevatron
  - MSSM/THDM $H^{\pm}W^{\mp}$ production

• Higgs bosons, SUSY and extended models

– Electroweak symmetry breaking, Higgs mechanism

Theory:		Experiment:
non-Abelian gauge symmetry	$\longrightarrow$ problem $\longleftarrow$	massive gauge bosons exist
forbids $M^2 A_\mu A^\mu$-terms		

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

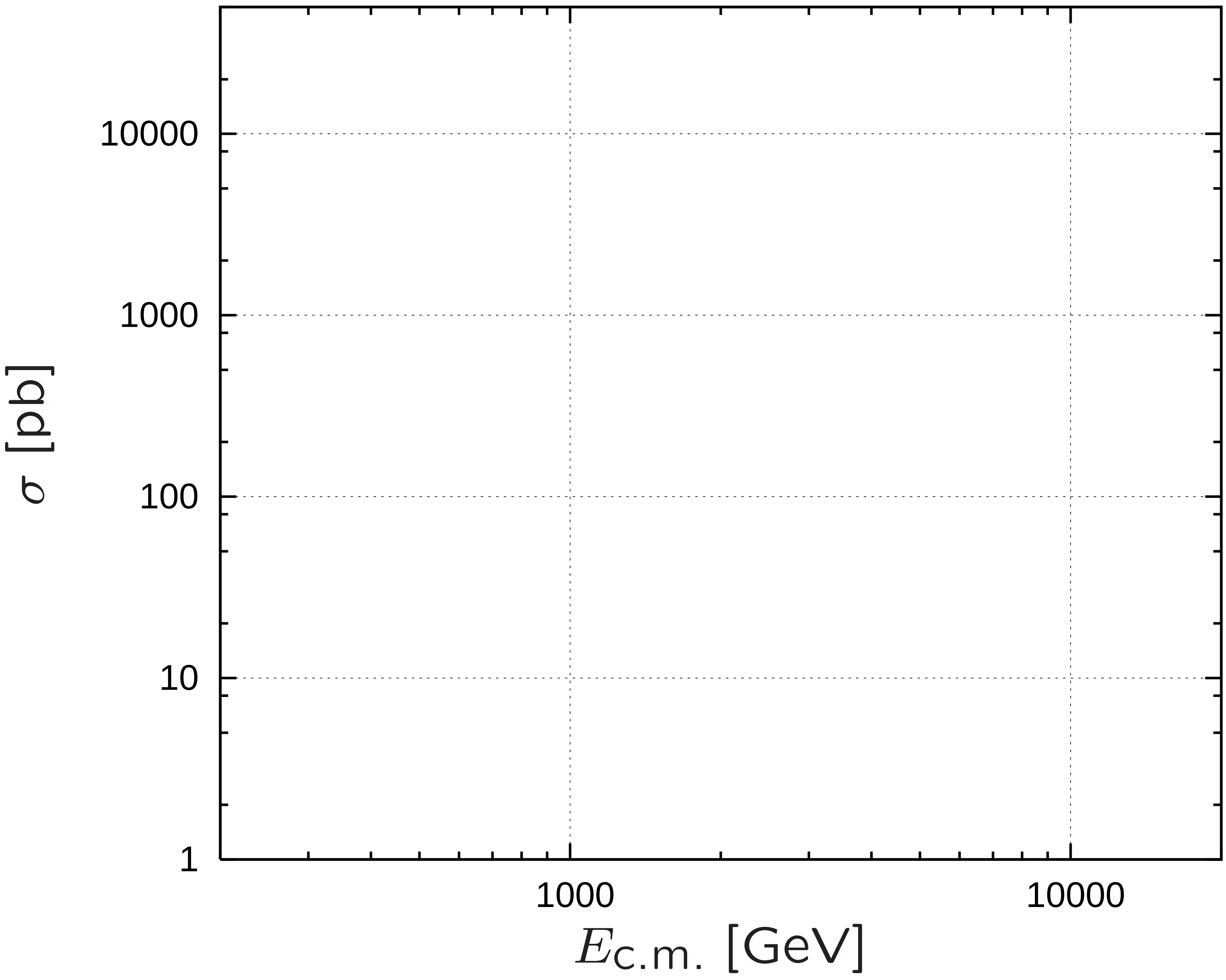
i.e. introduce gauge invariant dynamics, which breaks gauge symmetry in the ground state.

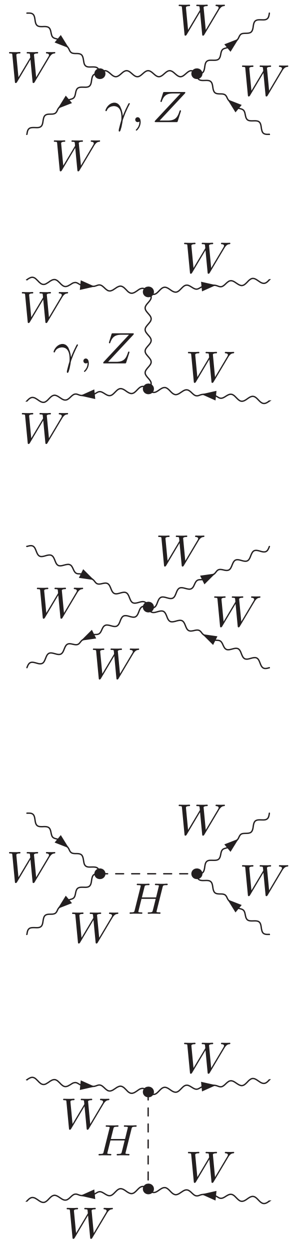
SSB can be realised by

- weakly interacting scalar gauge multiplets that acquire a VEV
$\longrightarrow$ 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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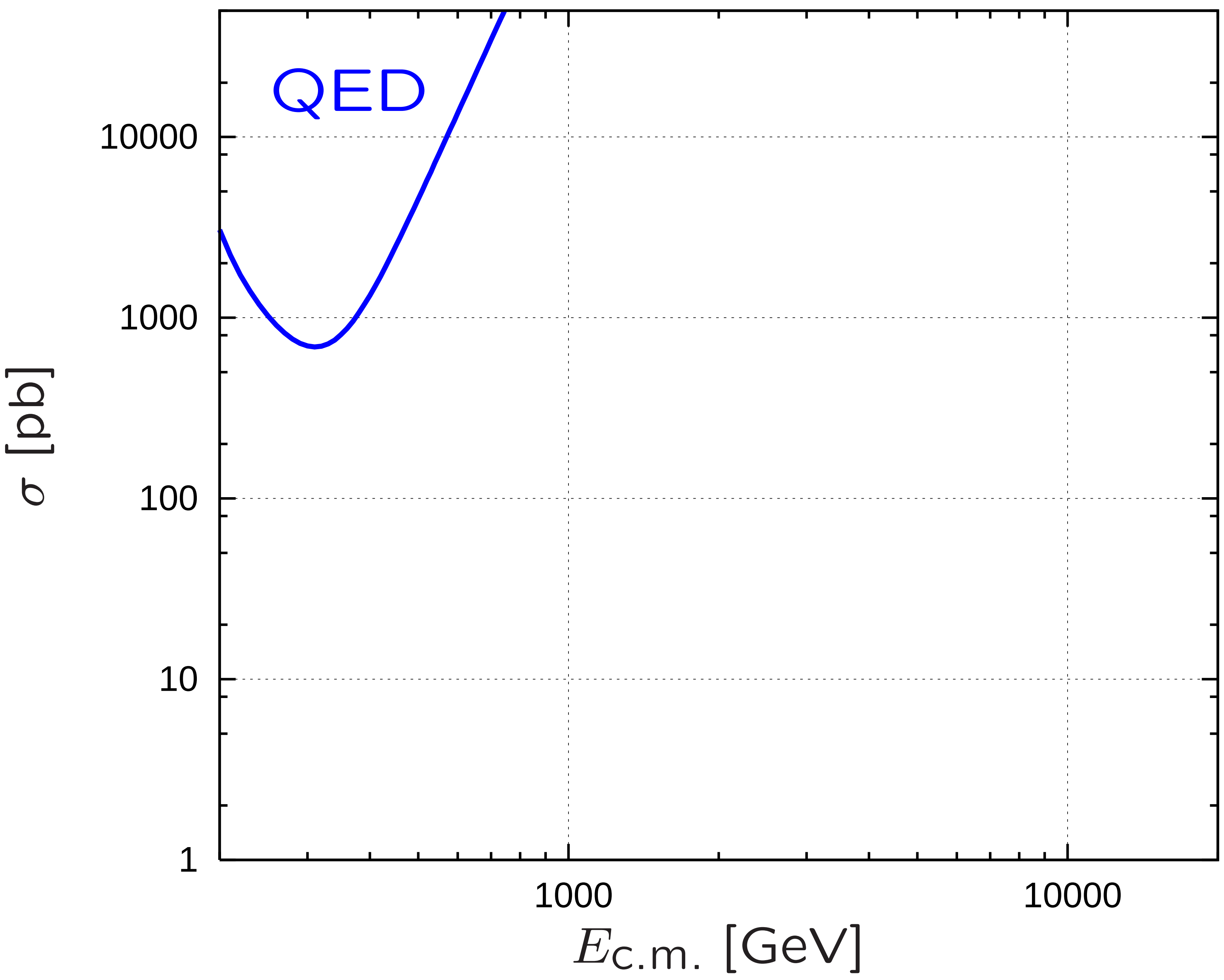

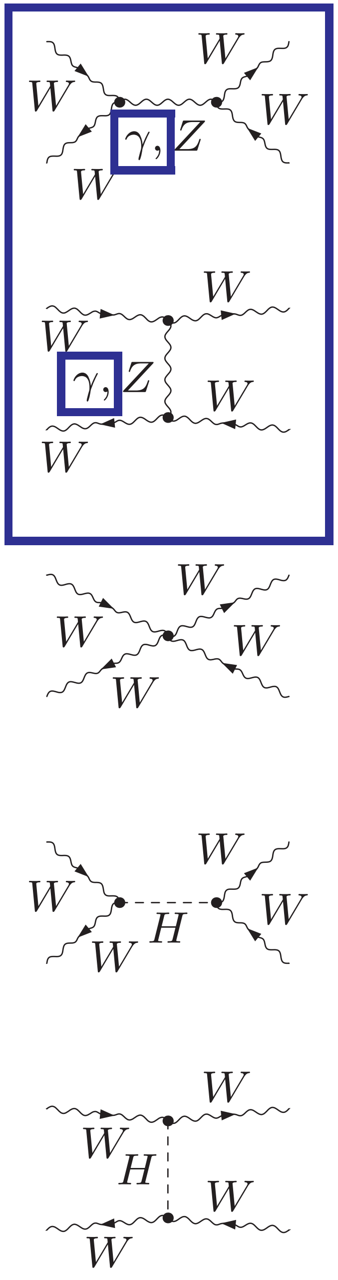

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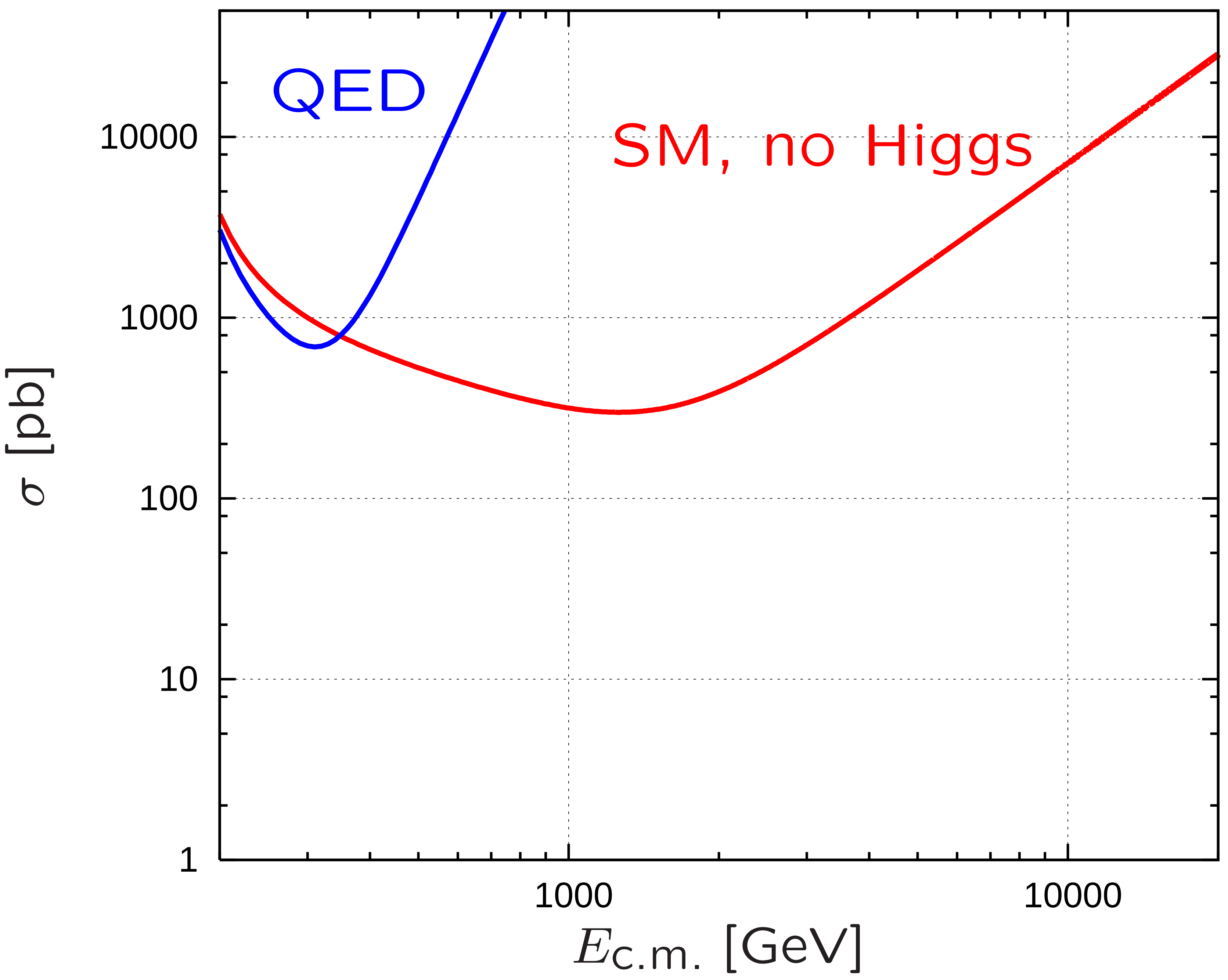
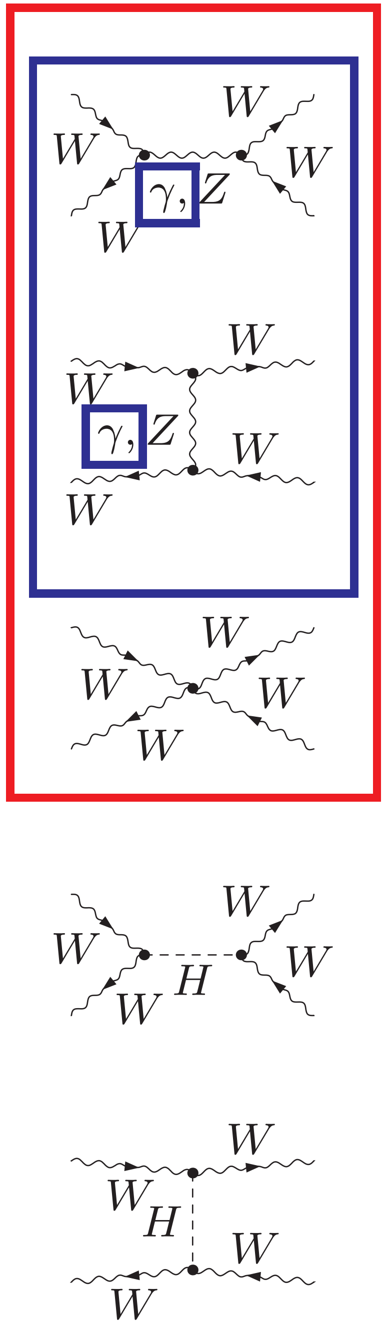
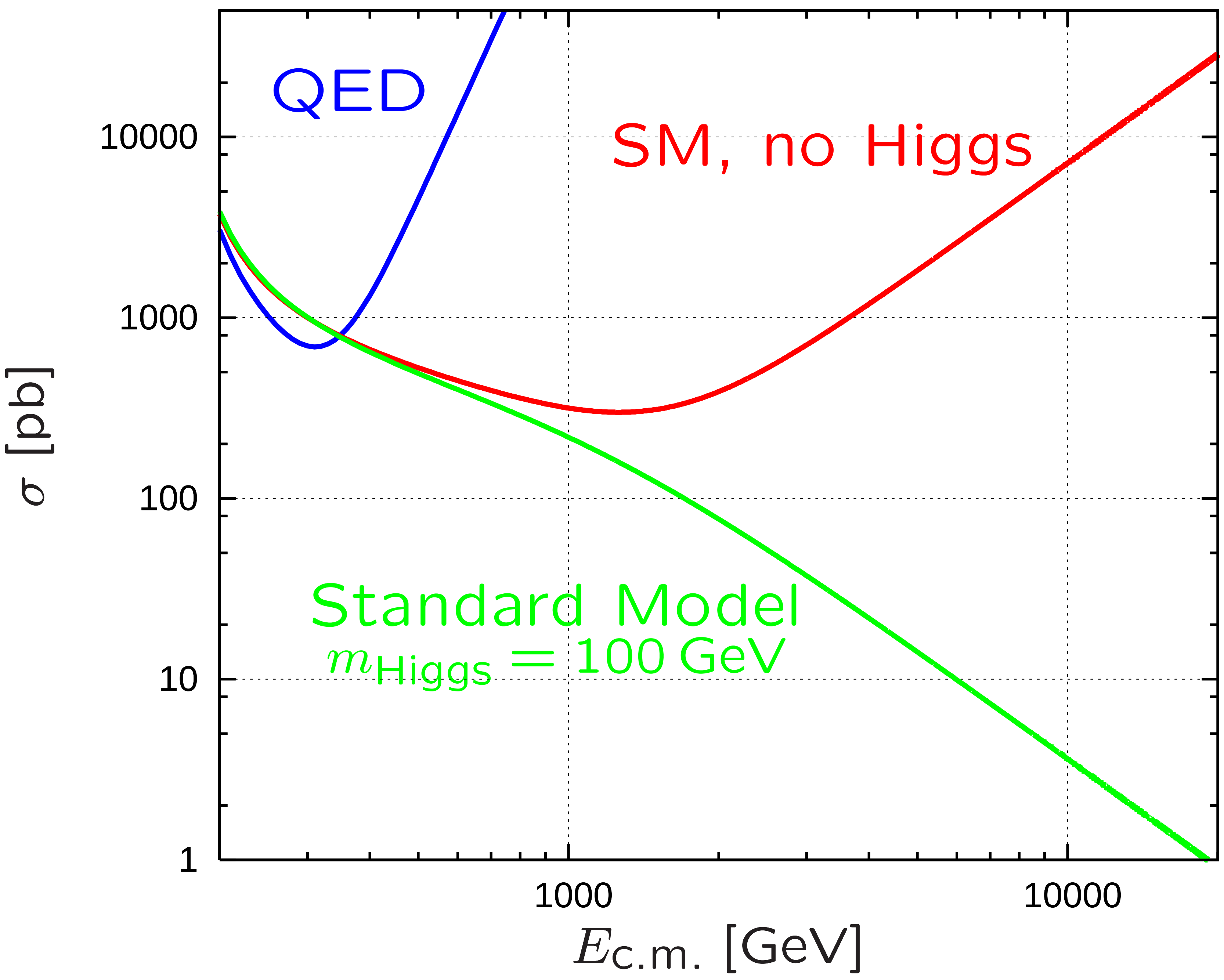
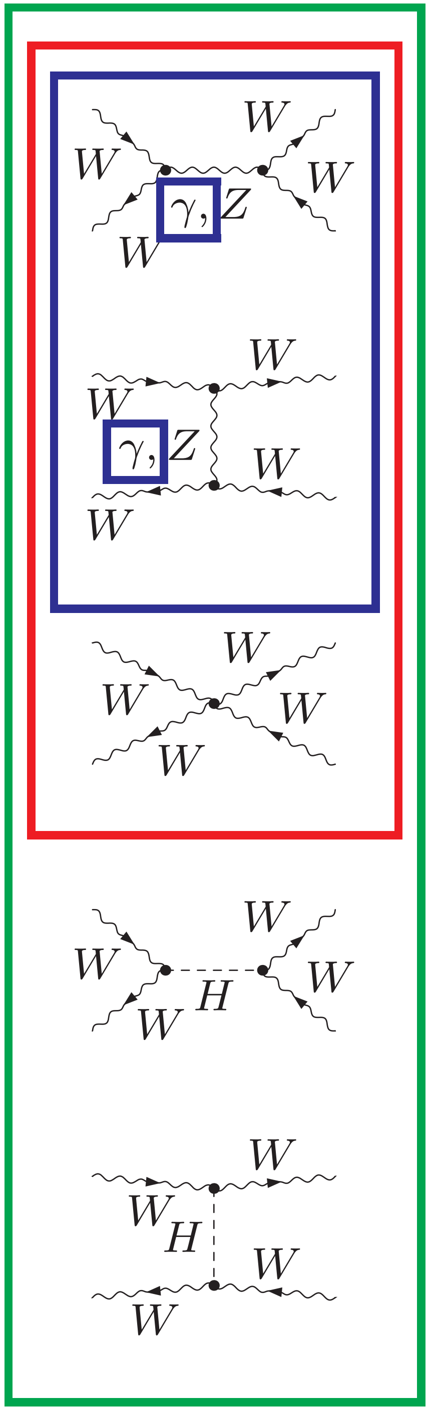




[Higgs bosons, SUSY and extended models, SSB]

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





– 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. $\leftrightarrow$ 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} (mass of A^0), $\tan\beta$ ($= v_2/v_1$, ratio of VEVs)

  instead of seven in the THDM:

  $$m_{A^0}, \tan\beta \quad + \quad \underbrace{m_{h^0}, m_{H^0}, m_{H^\pm}, \alpha, M^2 (= v^2 \lambda_5)}$$

  in the MSSM functions of m_{A^0}, $\tan\beta$
  at tree-level, e.g. $M^2 = m_{A^0}^2$

  $\longrightarrow$ 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 [Degrassi, Heinemeyer, Hollik, Slavich, Weiglein '02]

• Higgs production at future hadron colliders

– Higgs search programme (schematic)

1. finding the Higgs boson(s) $\longrightarrow$ establish a signal

   production & decay $\longrightarrow$ rate & signatures

2. measuring properties of the Higgs boson(s) $\longrightarrow$ 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 $\longrightarrow$ 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

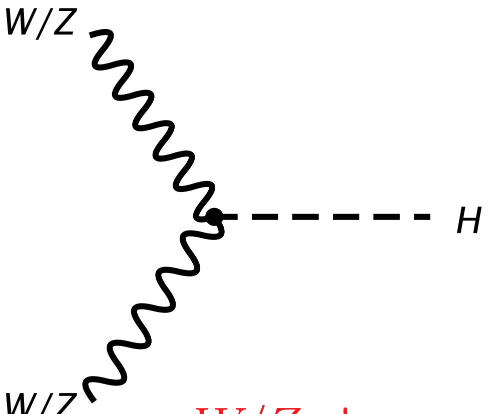
$\longrightarrow$ Problem: ordinary matter consists of

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

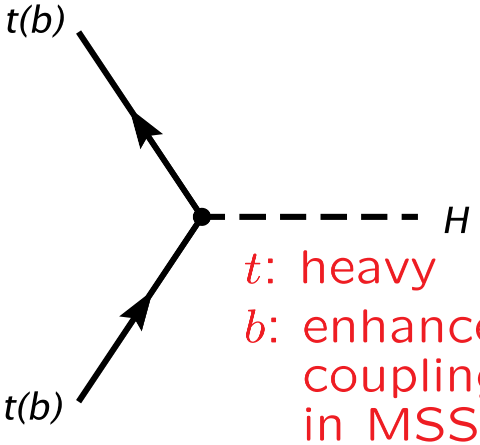
$\star$ with negligible couplings to the Higgs boson.

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

Therefore, most important couplings :



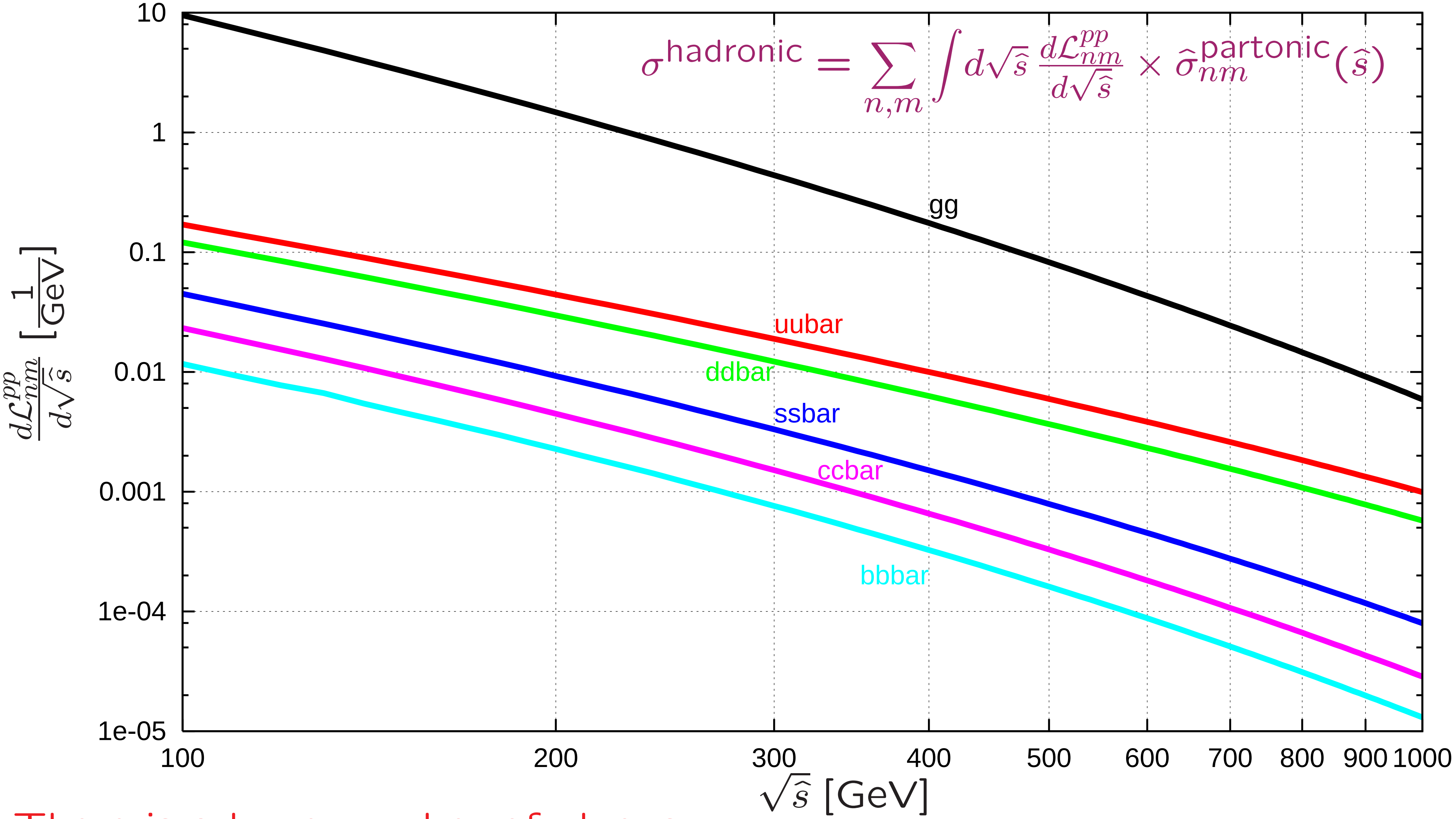
W/Z: heavy



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 ?

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
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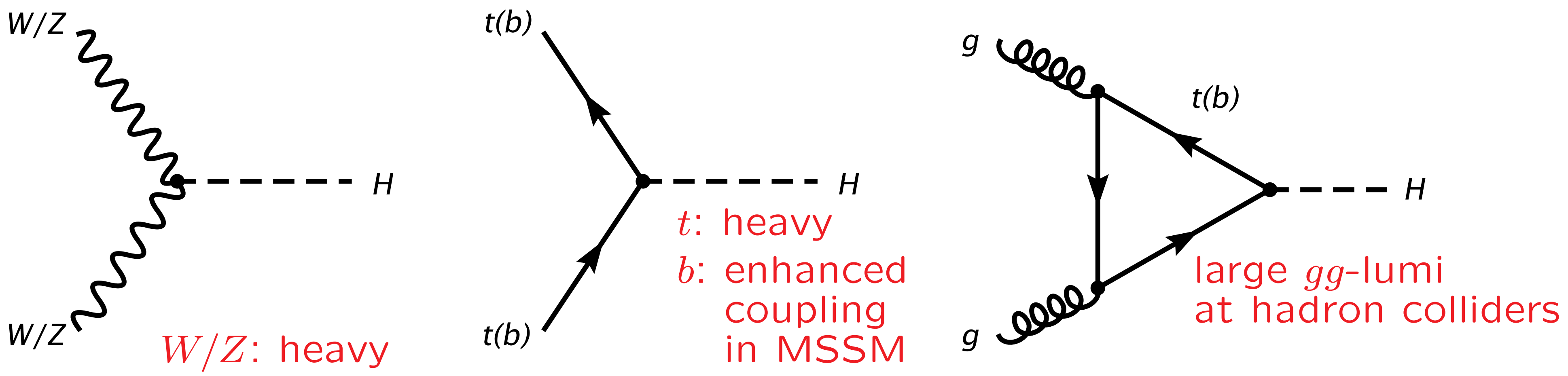
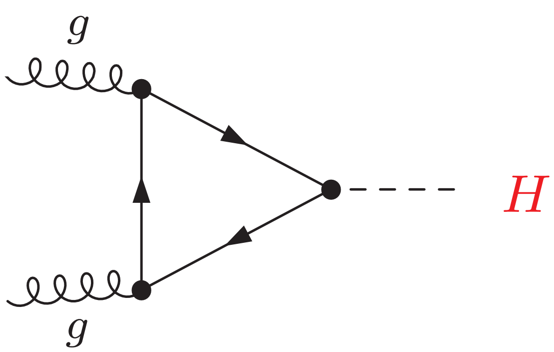


– Neutral Higgs production overview

Important neutral Higgs production processes:



gluon fusion, $gg \longrightarrow H$

– Neutral Higgs production overview

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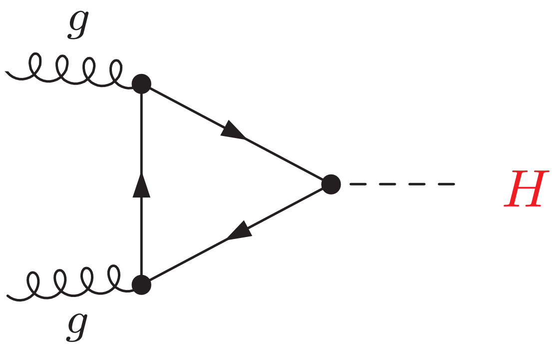

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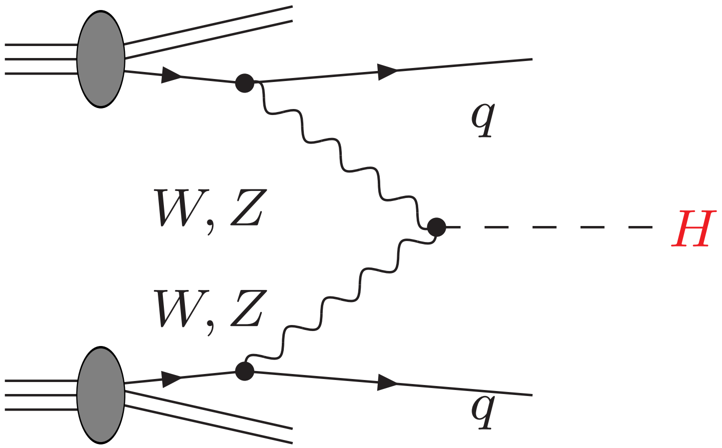
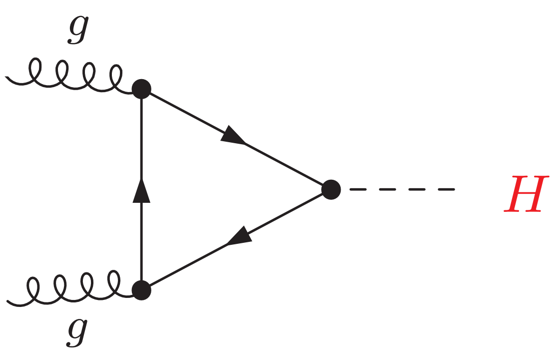


vector boson fusion, $qq \to qqH$

– Neutral Higgs production overview

Important neutral Higgs production processes:



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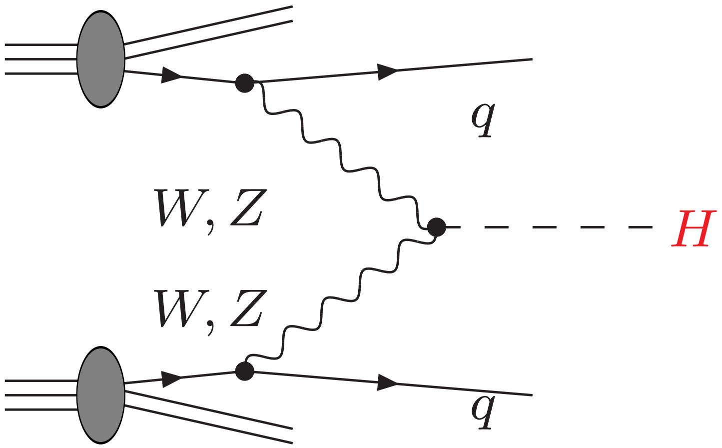

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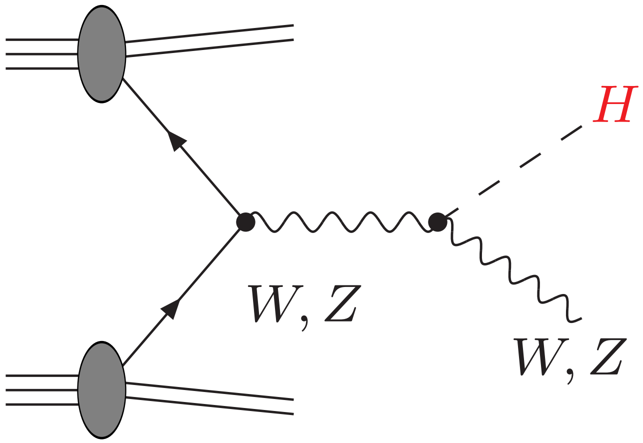
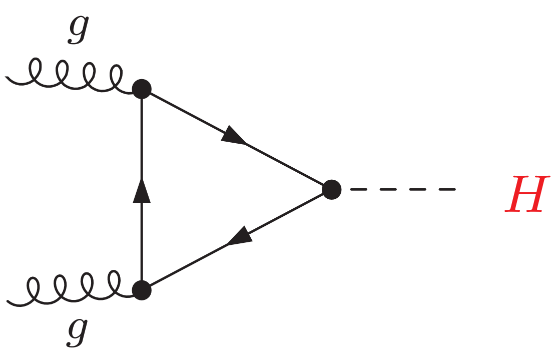


Higgs strahlung, $q\overline{q}' \to VH$

– Neutral Higgs production overview

Important neutral Higgs production processes:



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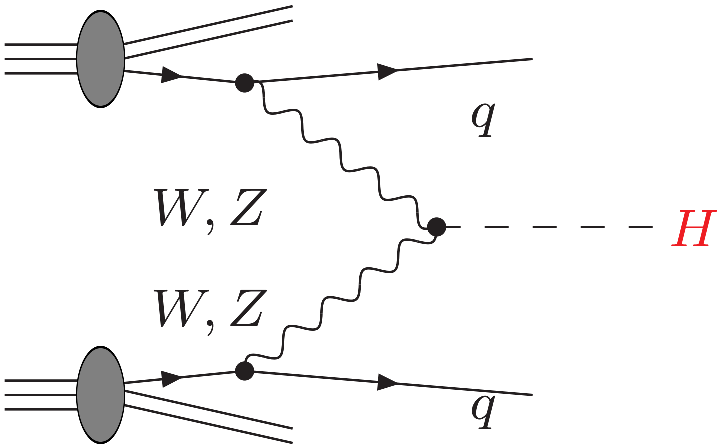

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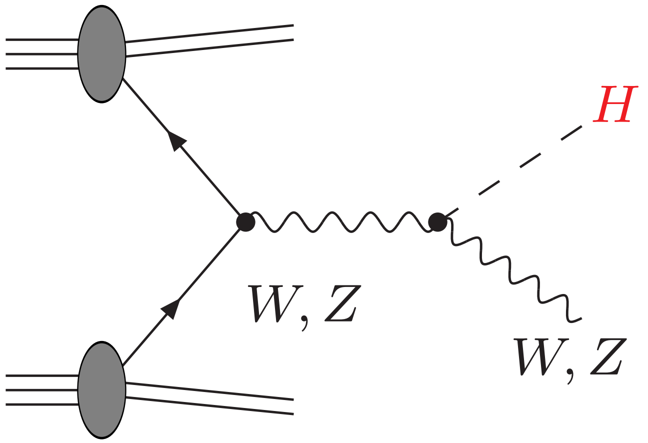
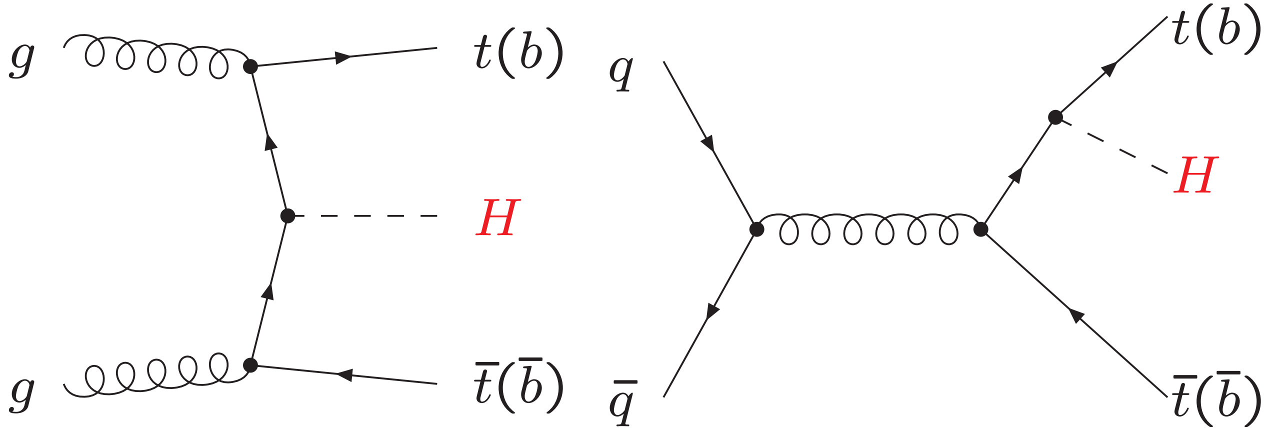
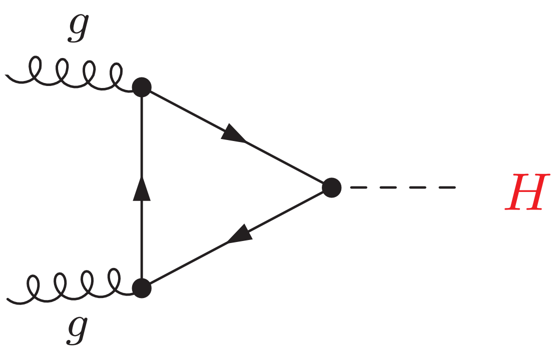


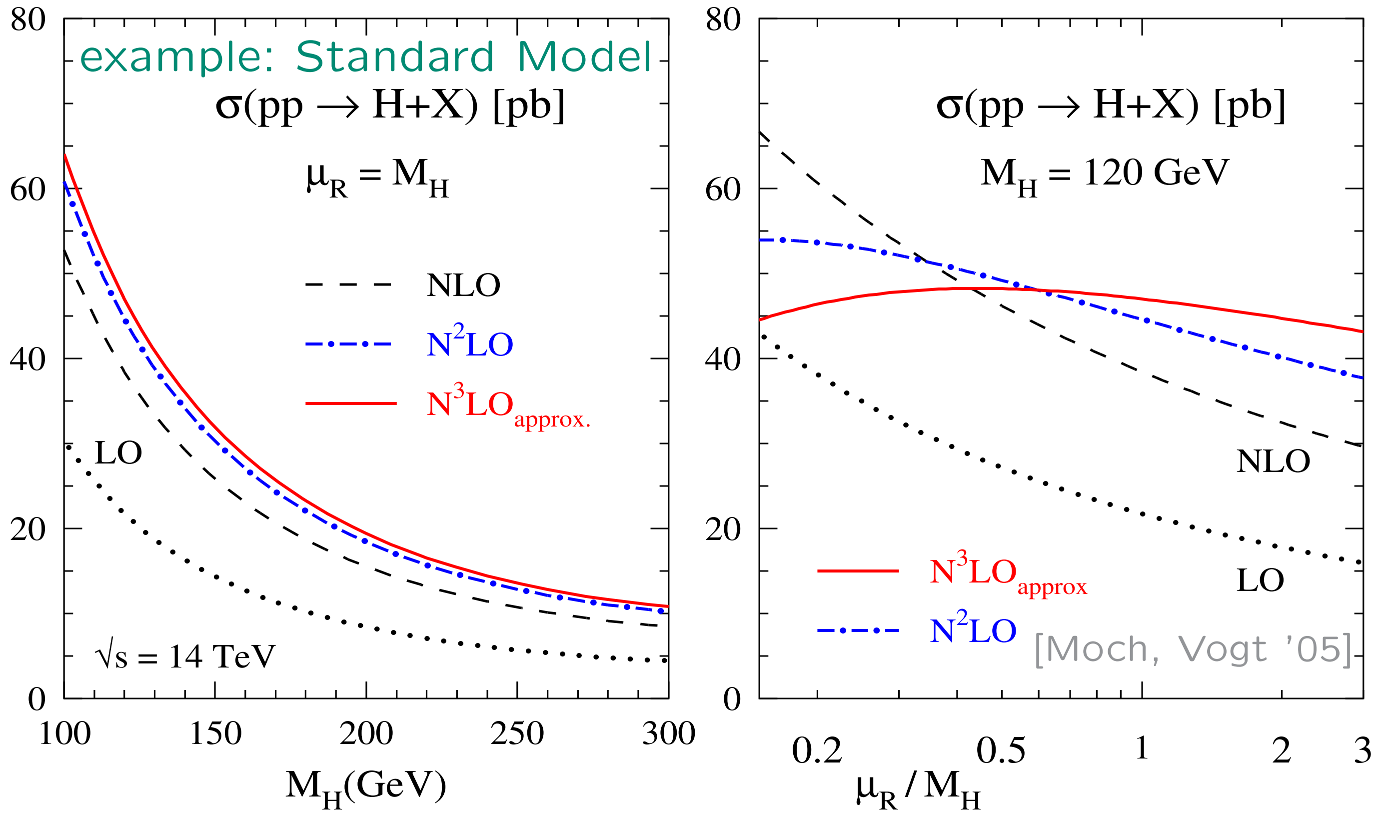
Higgs strahlung, $q\bar{q}' \to VH$



$t\bar{t}H$ **(**$b\bar{b}H$**) 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]

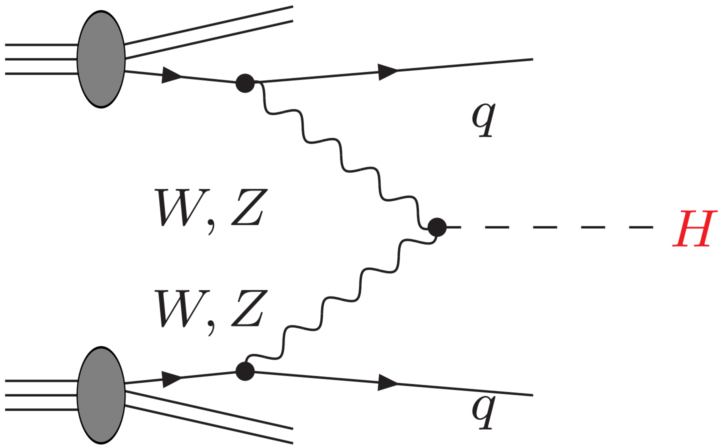
SM, NNLO QCD [Harlander '00; Catani, de Florian, Grazzini '01; Harlander, Kilgore '01 & '02; Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03]

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]

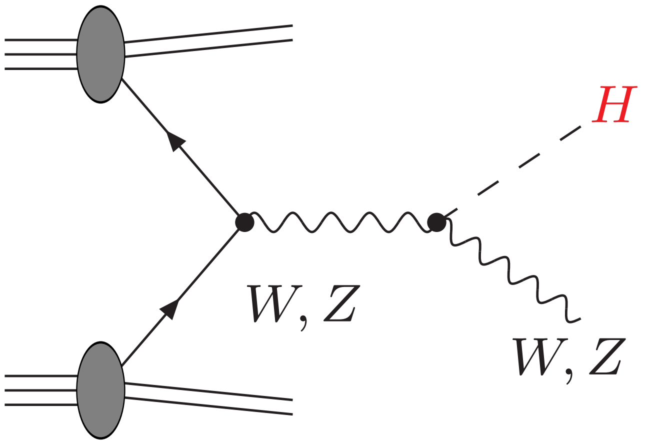


vector boson fusion, $qq \to qqH$

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

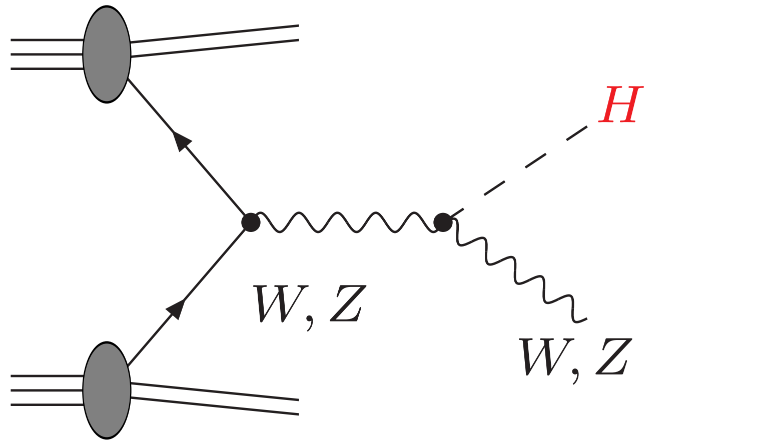
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

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

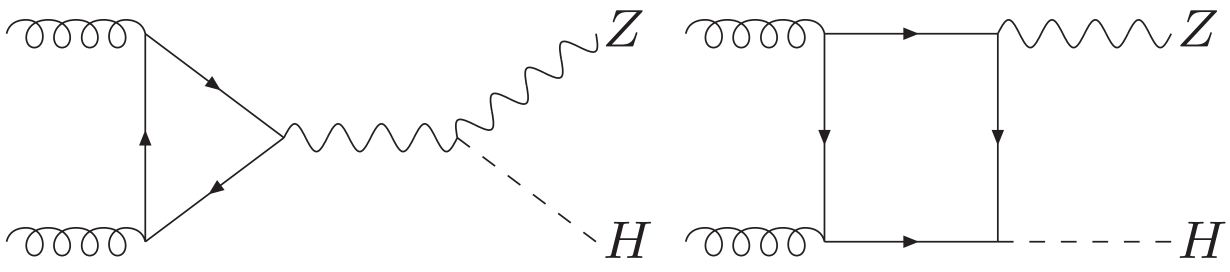
SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]

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

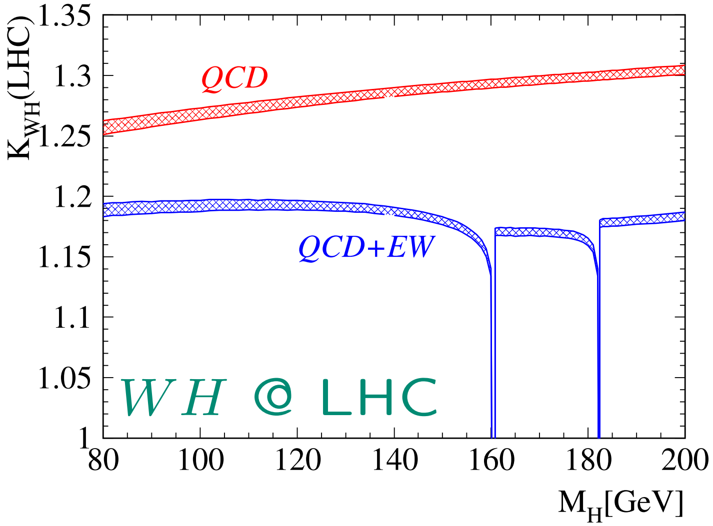


Higgs strahlung, $q\bar{q}' \to VH$

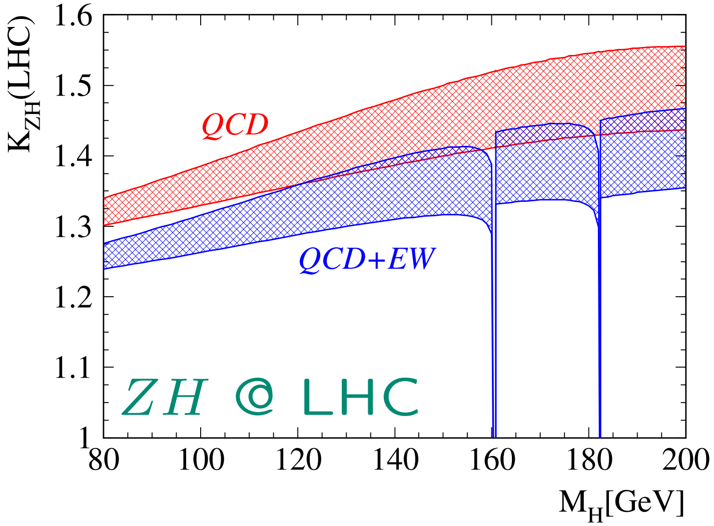
note! additional parton process for ZH @ NNLO



[Dicus, Kao '88; Kniehl '90]



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



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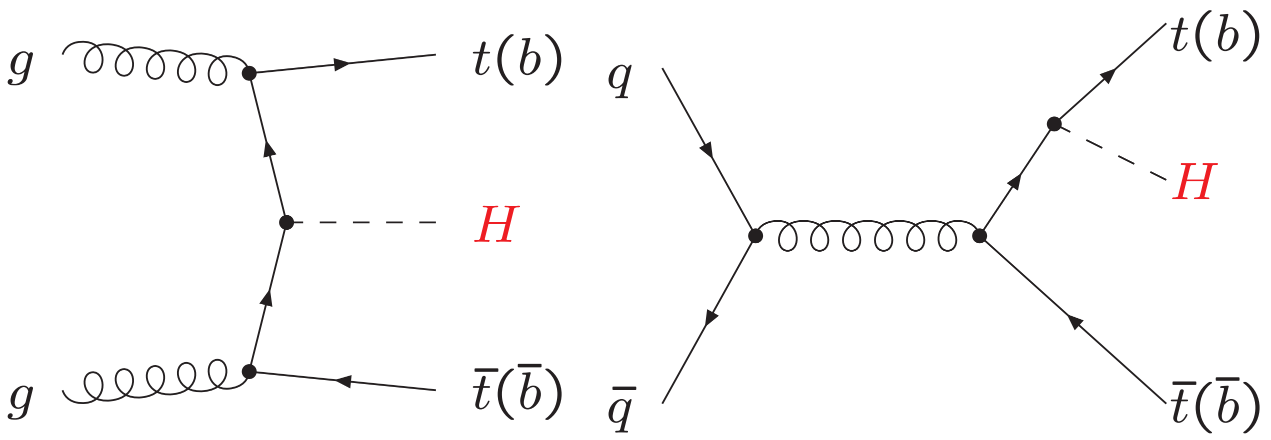
MSSM, NLO SUSY-QCD [Djouadi, Spira '00]



$t\bar{t}H$ ($b\bar{b}H$) 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]

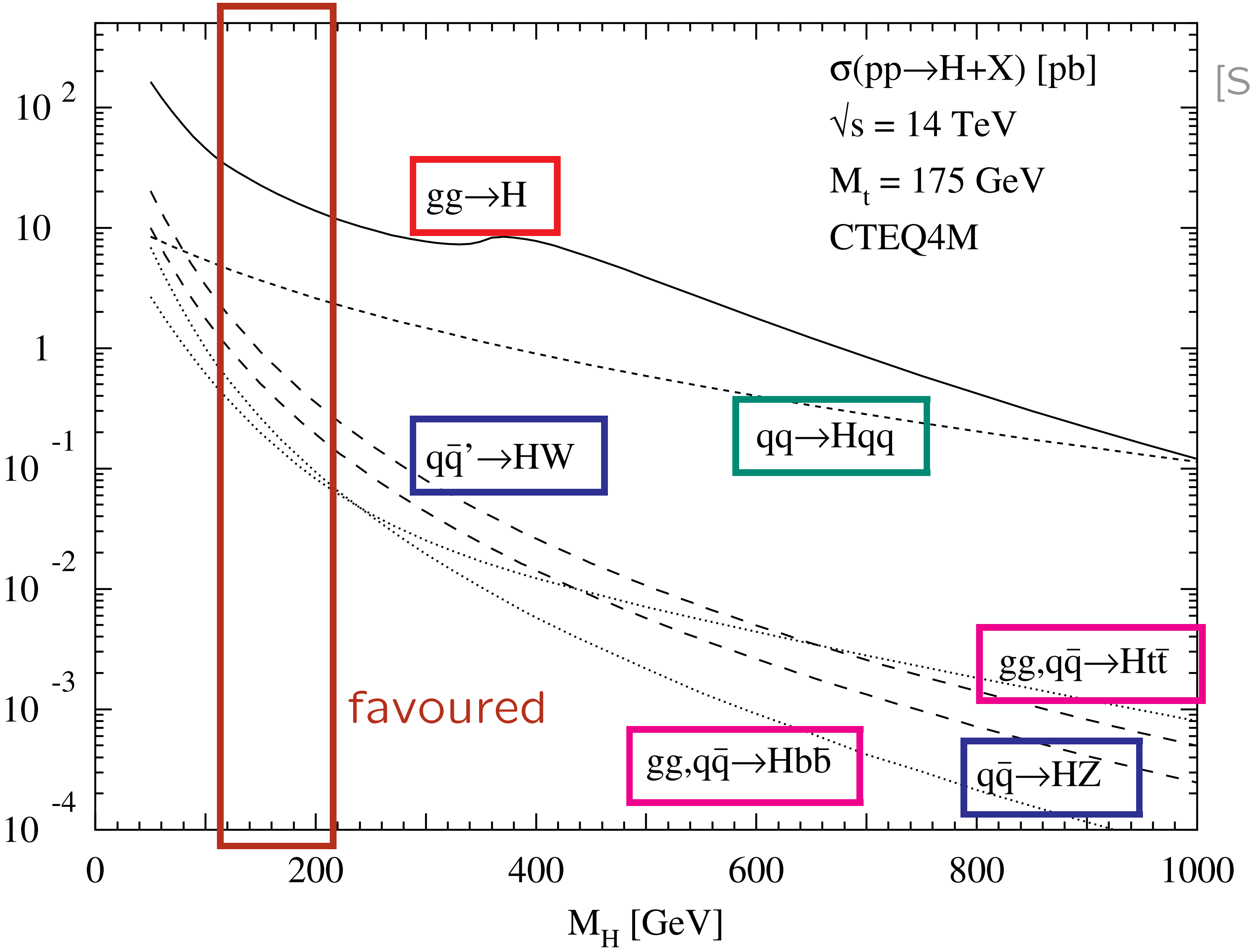
SM, NLO QCD ($b\bar{b}H$) [Dittmaier, Krämer, Spira '03; Dawson, Jackson, Reina, Wackeroth '03]

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]

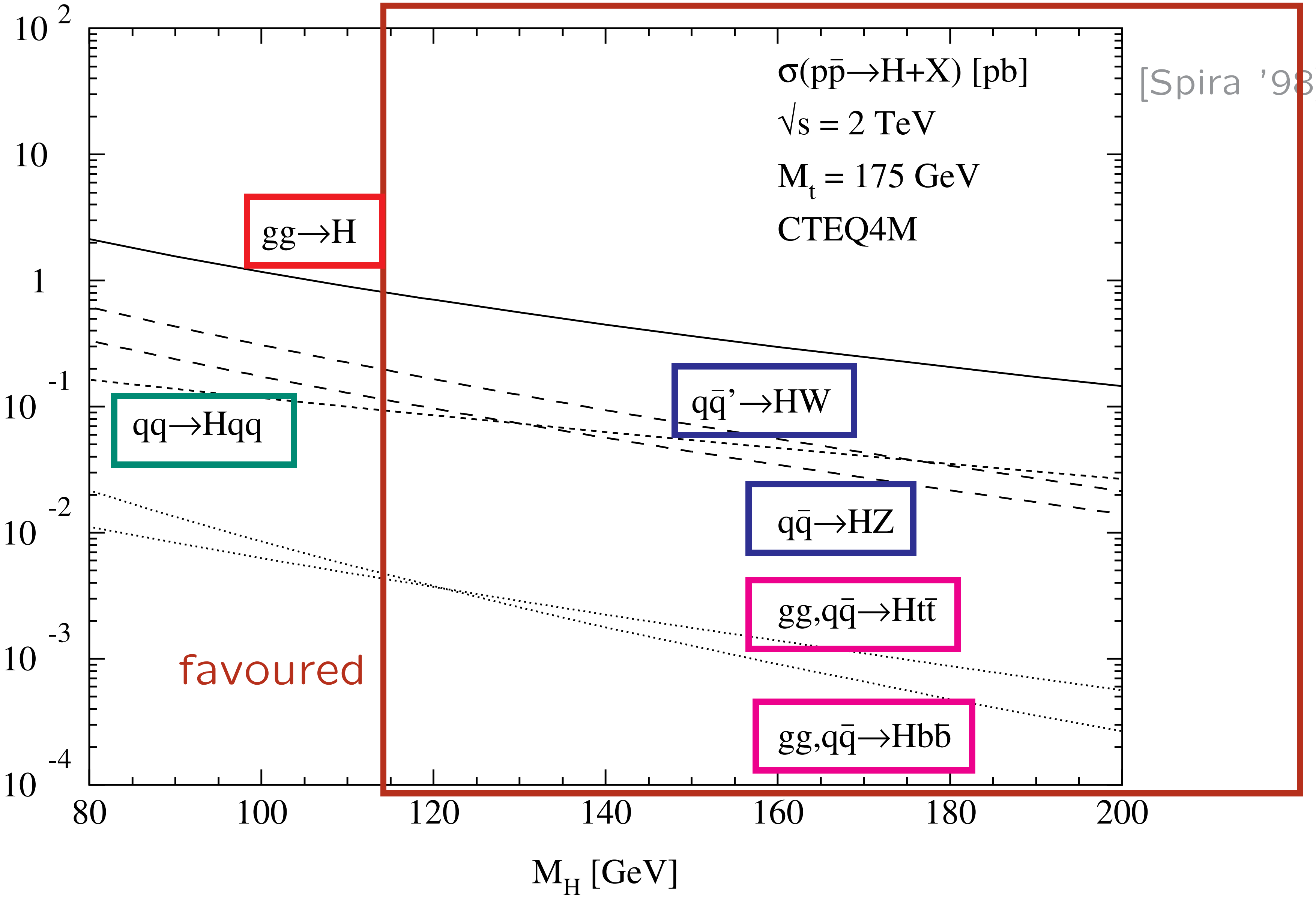
MSSM, NLO QCD, no superpartners [Dawson, Jackson, Reina, Wackeroth '03]

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



[Spira '98]

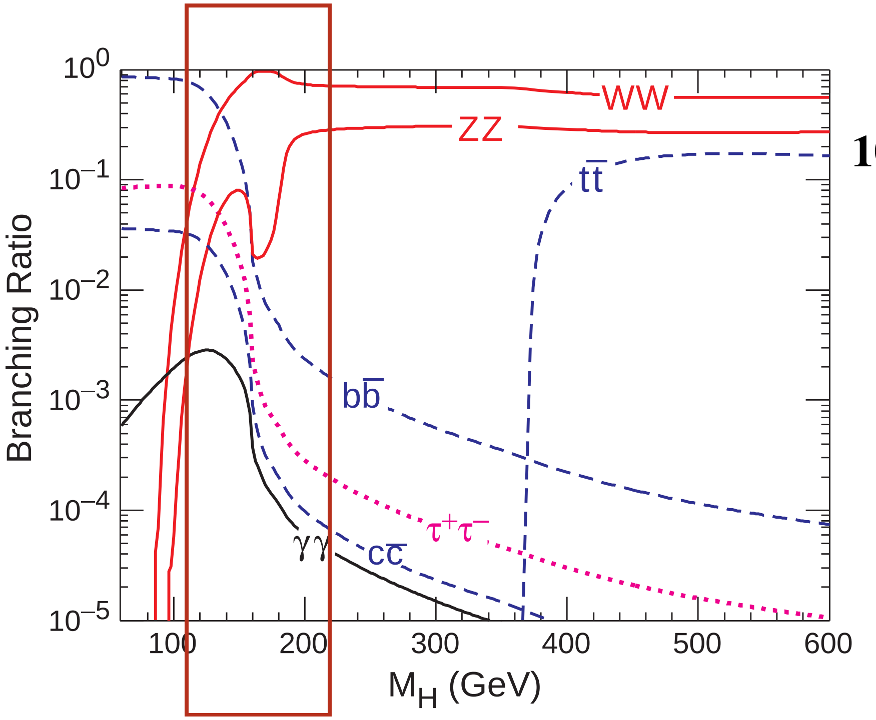
Predictions: SM Higgs production @ **Tevatron** :



[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



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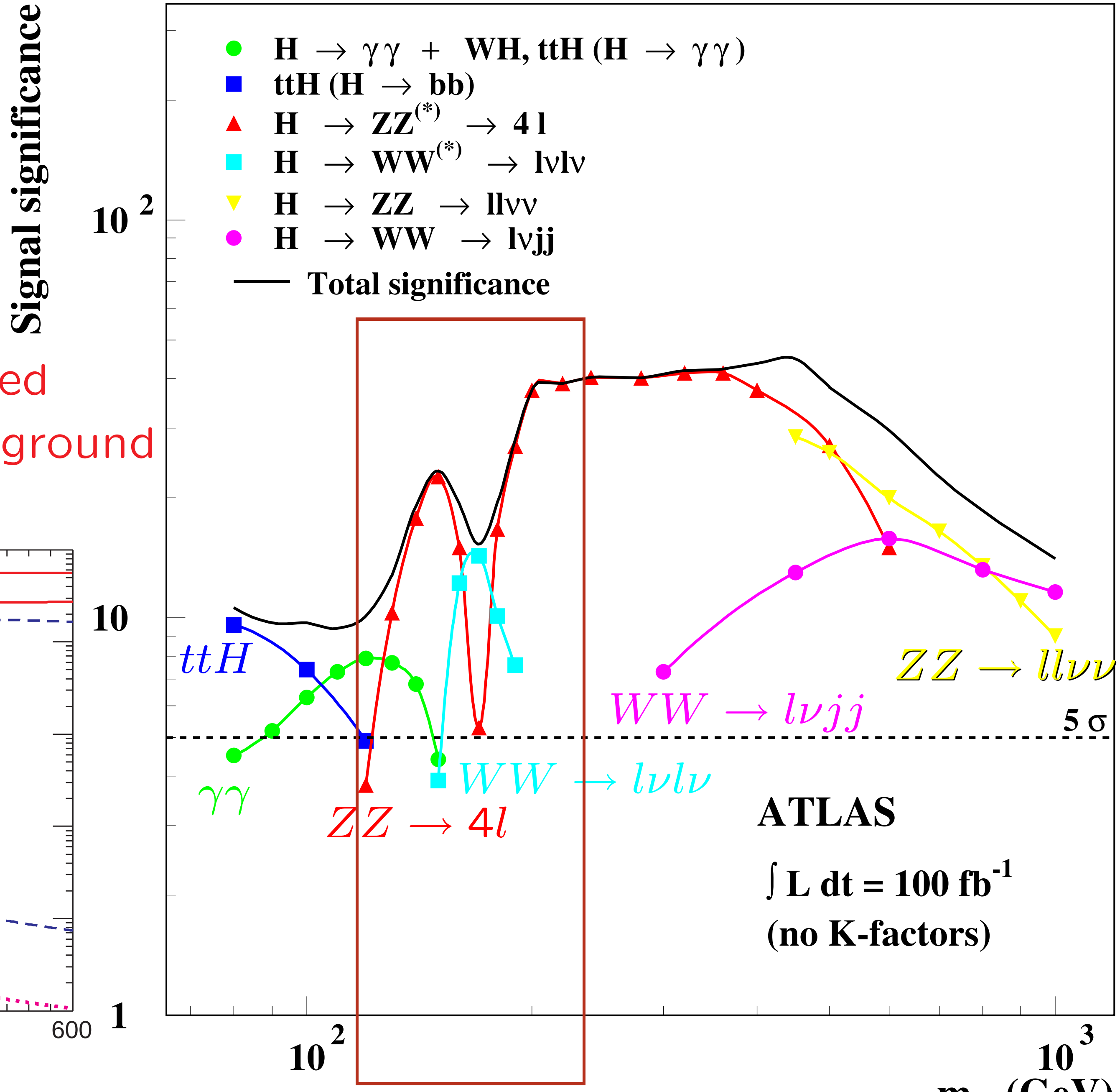


favoured

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

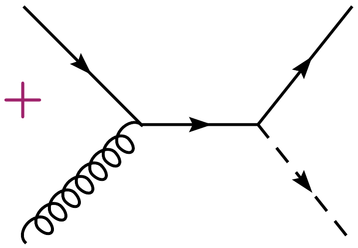
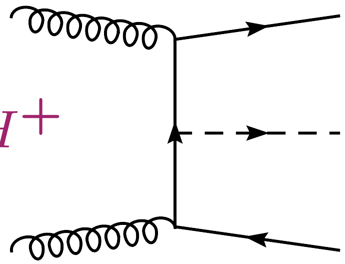
– $\sigma(gg \to h) \approx \sigma(gg, q\bar{q} \to hb\bar{b})$

– Higgs strahlung unimportant

• $H^{\pm}W^{\mp}$ production @ LHC: MSSM vs. THDM

– Charged Higgs search at LHC/Tevatron

- $m_{H^{\pm}} < m_t$: 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 (much) 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]

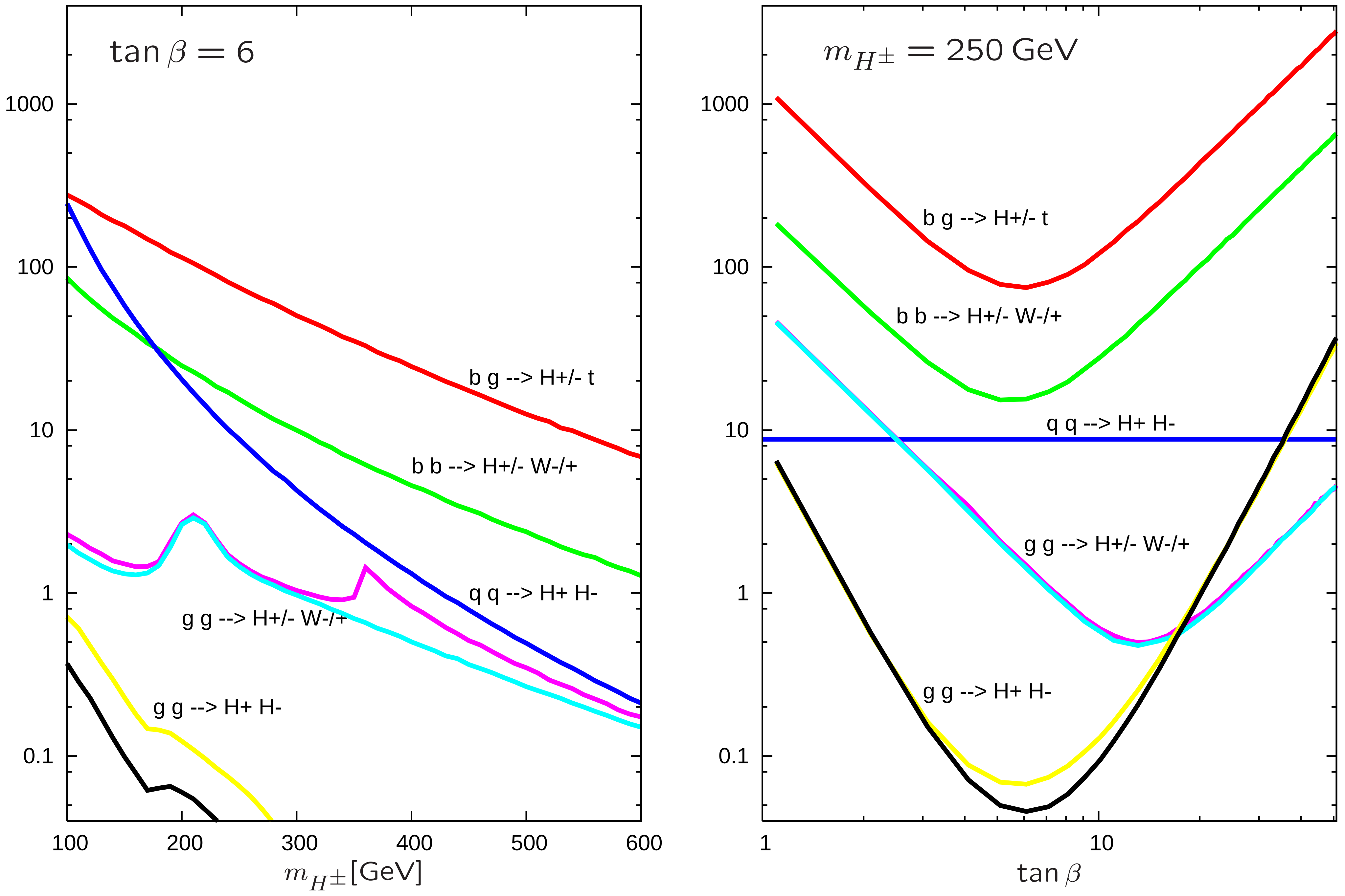
$gg/q\bar{q} \to H^{+}H^{-}$

[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.

[$H^{\pm}W^{\mp}$ @ LHC, $H^{\pm}$ search at LHC/Tevatron]

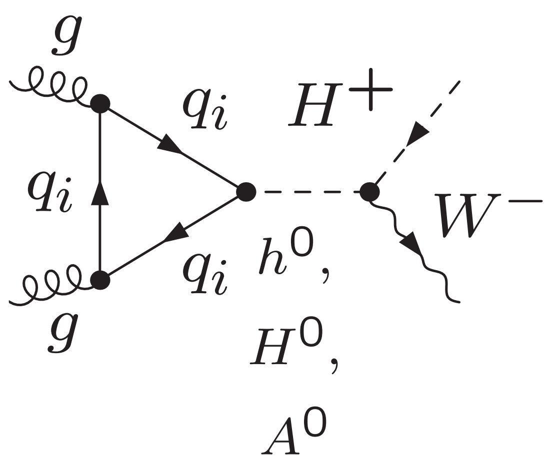
MSSM Charged Higgs production cross sections @ LHC in fb

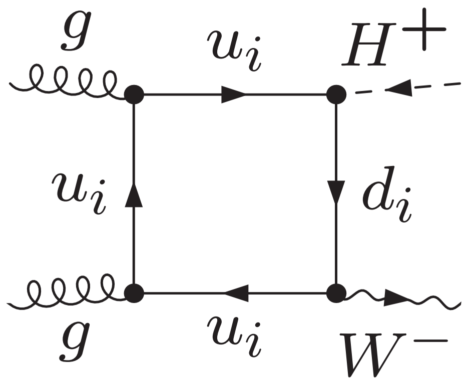


– MSSM/THDM $H^{\pm}W^{\mp}$ production

gluon fusion

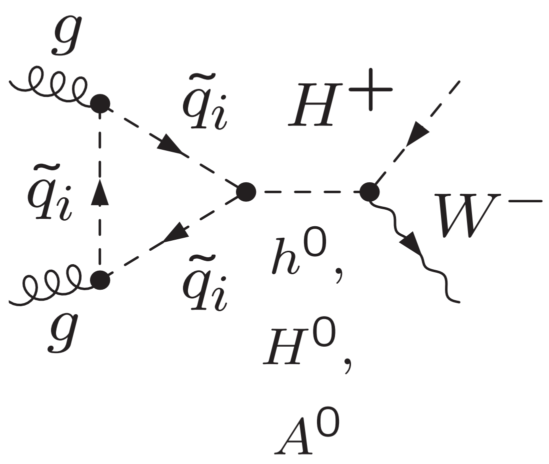
THDM amplitude

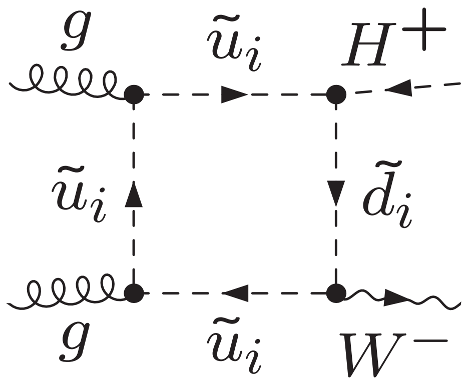




+ more

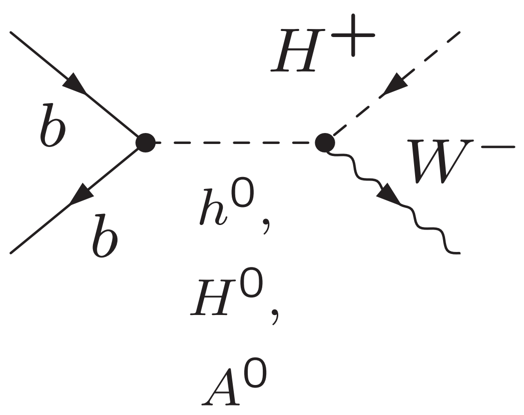
squark amplitude

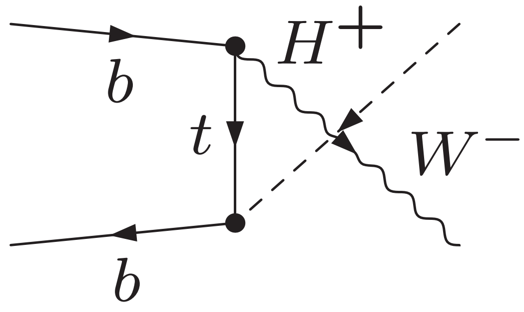




+ more

$b\bar{b}$ annihilation





MSSM versus general THDM

MSSM: interesting feature of $gg \to H^{\pm}W^{\mp}$:

strong negative interference between Δ– and $\Box$–amplitudes,

i.e. $|\Delta|^2 \approx |\Box|^2 \approx (10 - 100) \cdot |\Delta + \Box|^2$

general THDM: all this need not be true !

$\to$ cross section may be much larger than in the MSSM

note! a S/B analysis showed:

MSSM cross section (probably) too low to be seen @ LHC

[Moretti, Odagiri'98]

– Numerical results

calculation: inclusive hadronic cross section @ LHC ($S = 14\,$TeV)

$$\sigma_{pp\to W^-H^+} = \sum_{n,m} \int_{\tau_0}^{1} d\tau \frac{d\mathcal{L}_{nm}^{pp}}{d\tau}\, \hat{\sigma}_{nm\to W^-H^+}(\tau S)$$

with parton luminosity

$$\frac{d\mathcal{L}_{nm}^{pp}}{d\tau} = \int_{\tau}^{1} \frac{dx}{x} \frac{1}{1+\delta_{nm}} \left[f_{n/p}(x,\mu_F) f_{m/p}(\frac{\tau}{x},\mu_F) + f_{m/p}(x,\mu_F) f_{n/p}(\frac{\tau}{x},\mu_F) \right]$$

parameters:

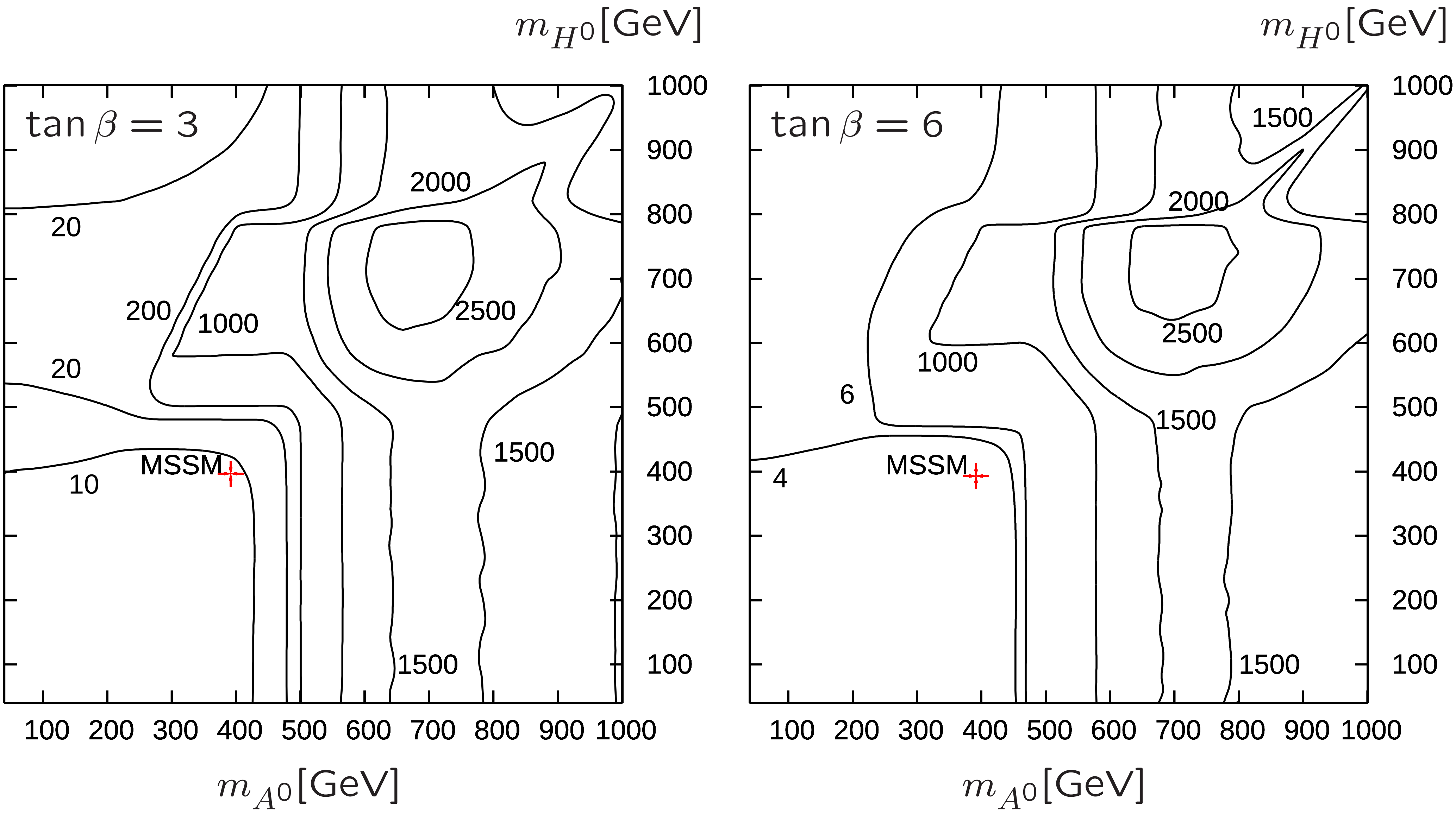
MSSM: we choose one reference scenario with $m_{H^\pm} = 400\,$GeV.

This leads to: ($m_{H^0,A^0} \approx 400\,$GeV, $\cdots$)

$\tan\beta = 3$: $\sigma^{\text{MSSM}}_{pp\to W^\pm H^\mp} = 9.5\,$fb, $\tan\beta = 6$: $\sigma^{\text{MSSM}}_{pp\to W^\pm H^\mp} = 3\,$fb.

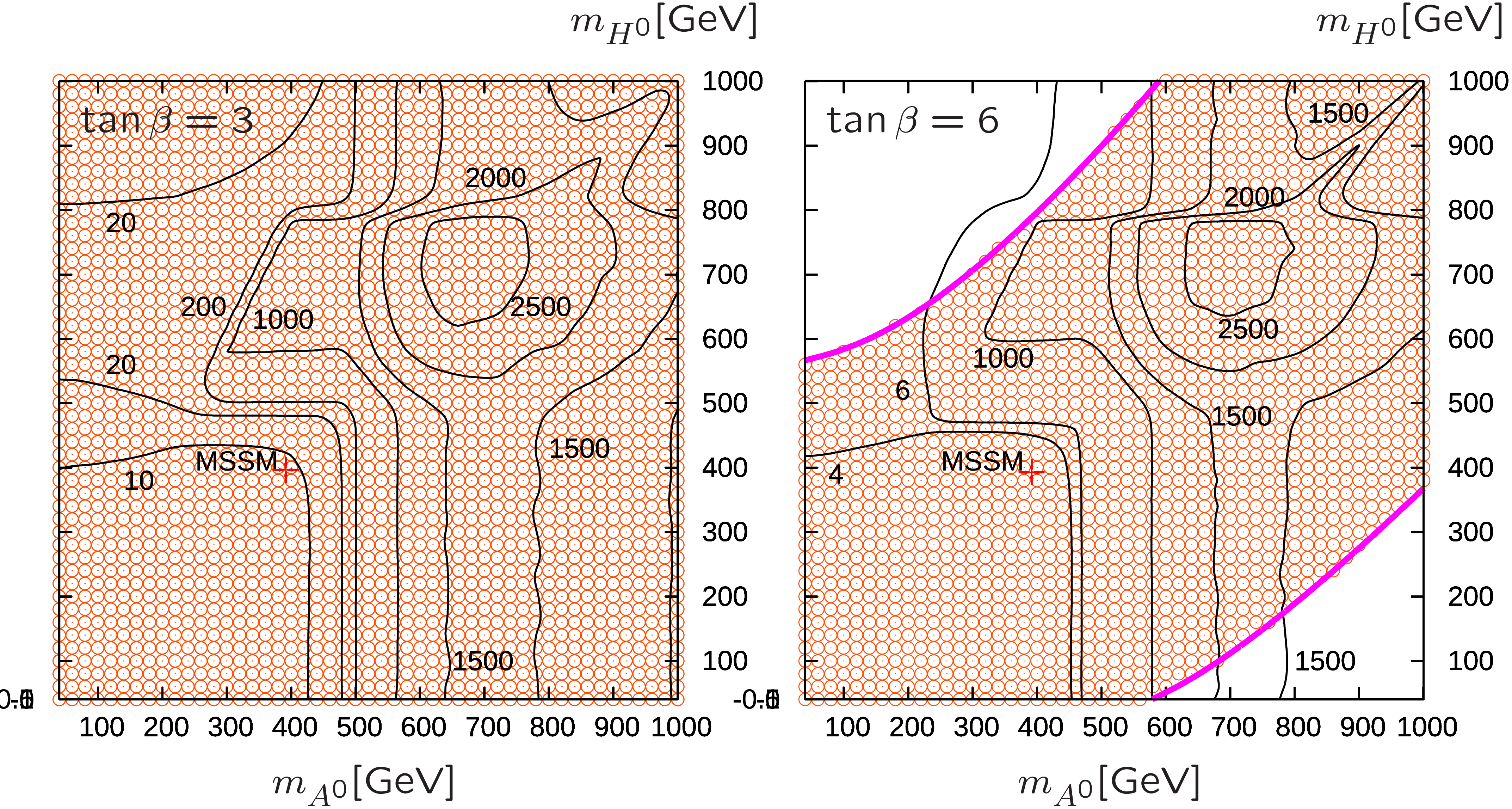
THDM: we vary the masses m_{H^0,A^0} and keep MSSM values for all other THDM parameters (e.g. $M^2 = m^2_{A^0}$).

inclusive hadronic cross section $\sigma^{\text{THDM}}_{pp\to W^{\pm}H^{\mp}}$ in fb for $M^2 = m^2_{A^0}$



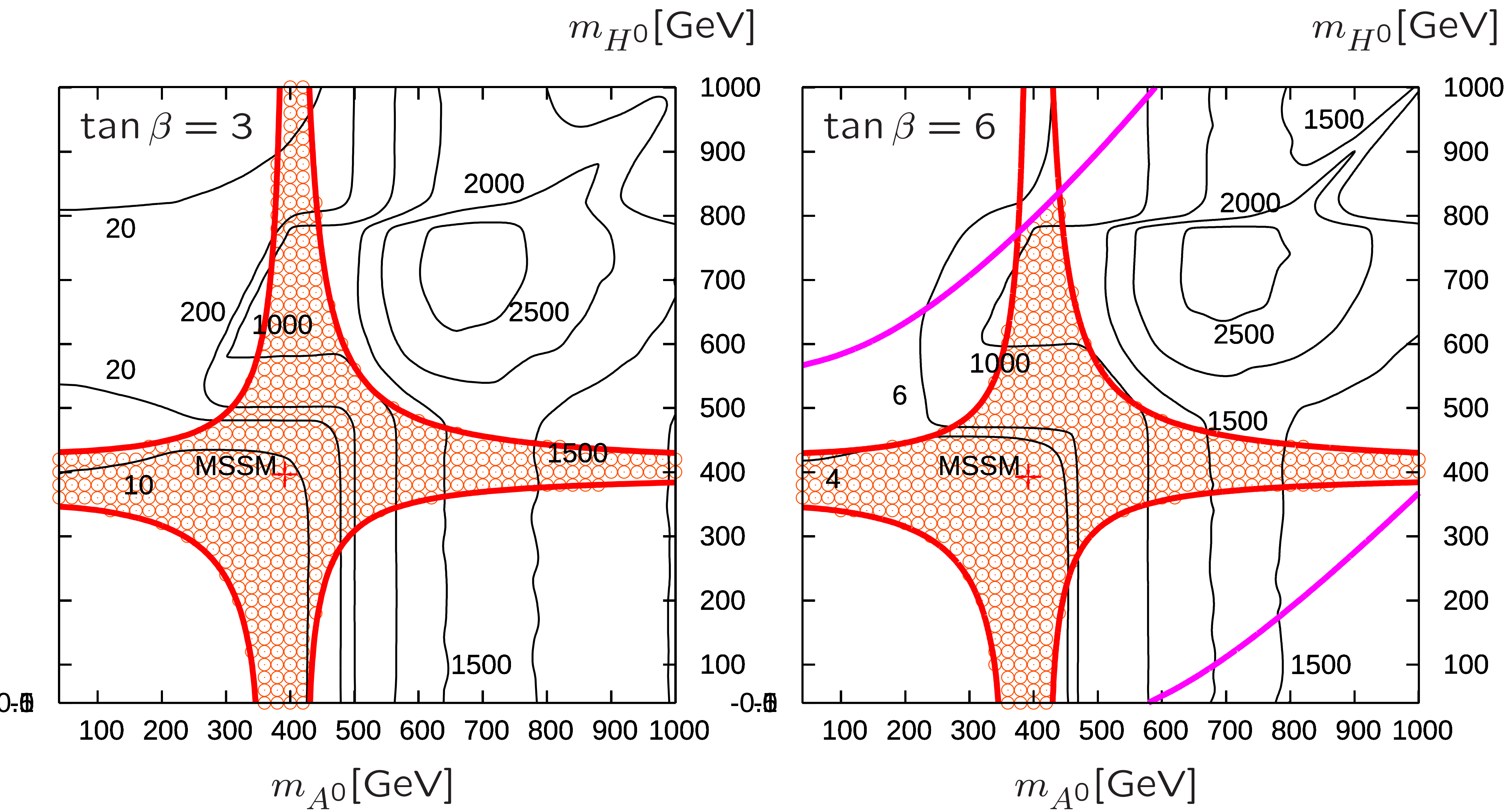
no constraints

inclusive hadronic cross section $\sigma^{\text{THDM}}_{pp\to W^{\pm}H^{\mp}}$ in fb for $M^2 = m^2_{A^0}$



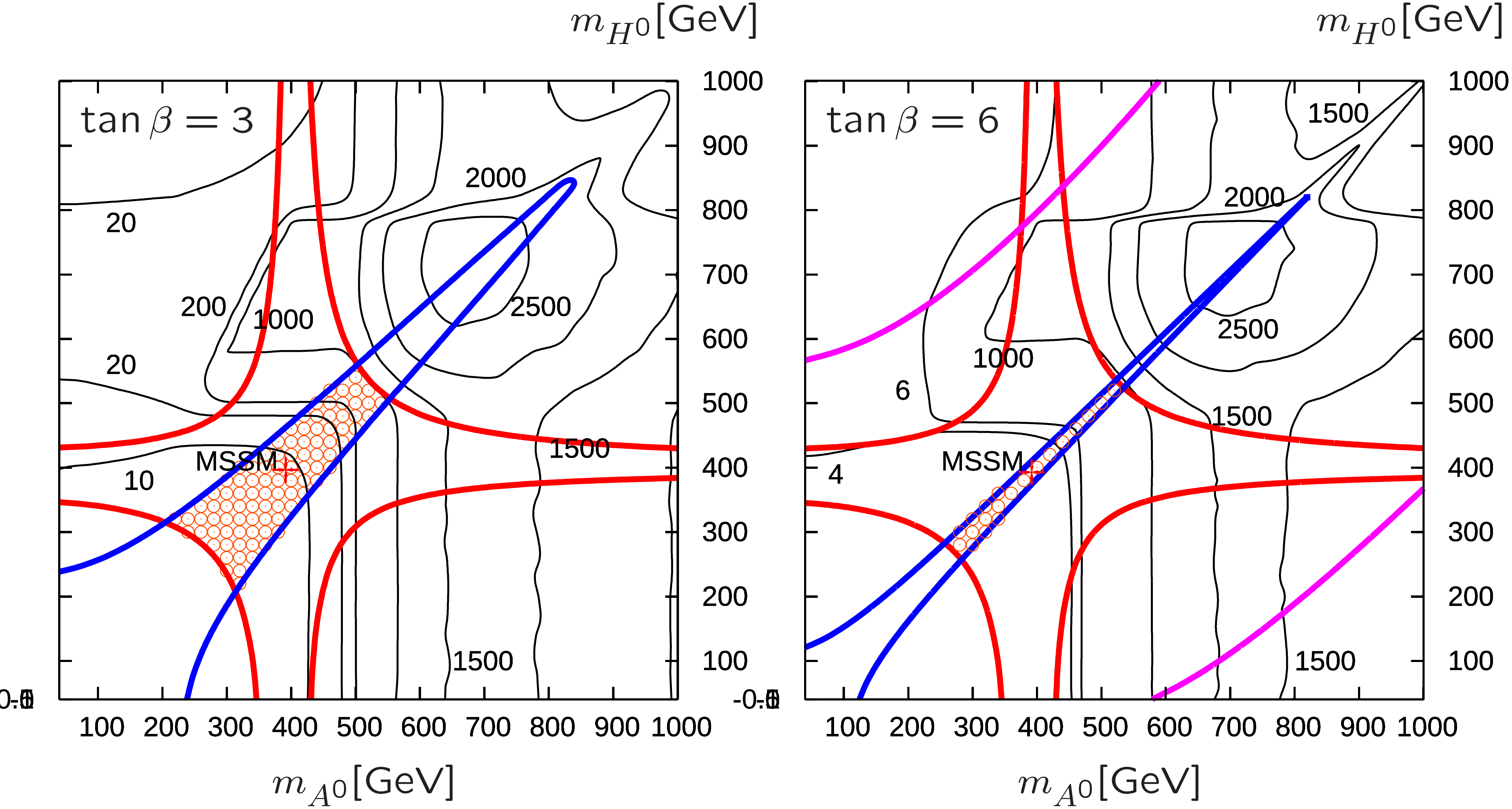
constraints: magn. moment a_μ

inclusive hadronic cross section $\sigma^{\text{THDM}}_{pp\to W^{\pm}H^{\mp}}$ in fb for $M^2 = m^2_{A^0}$

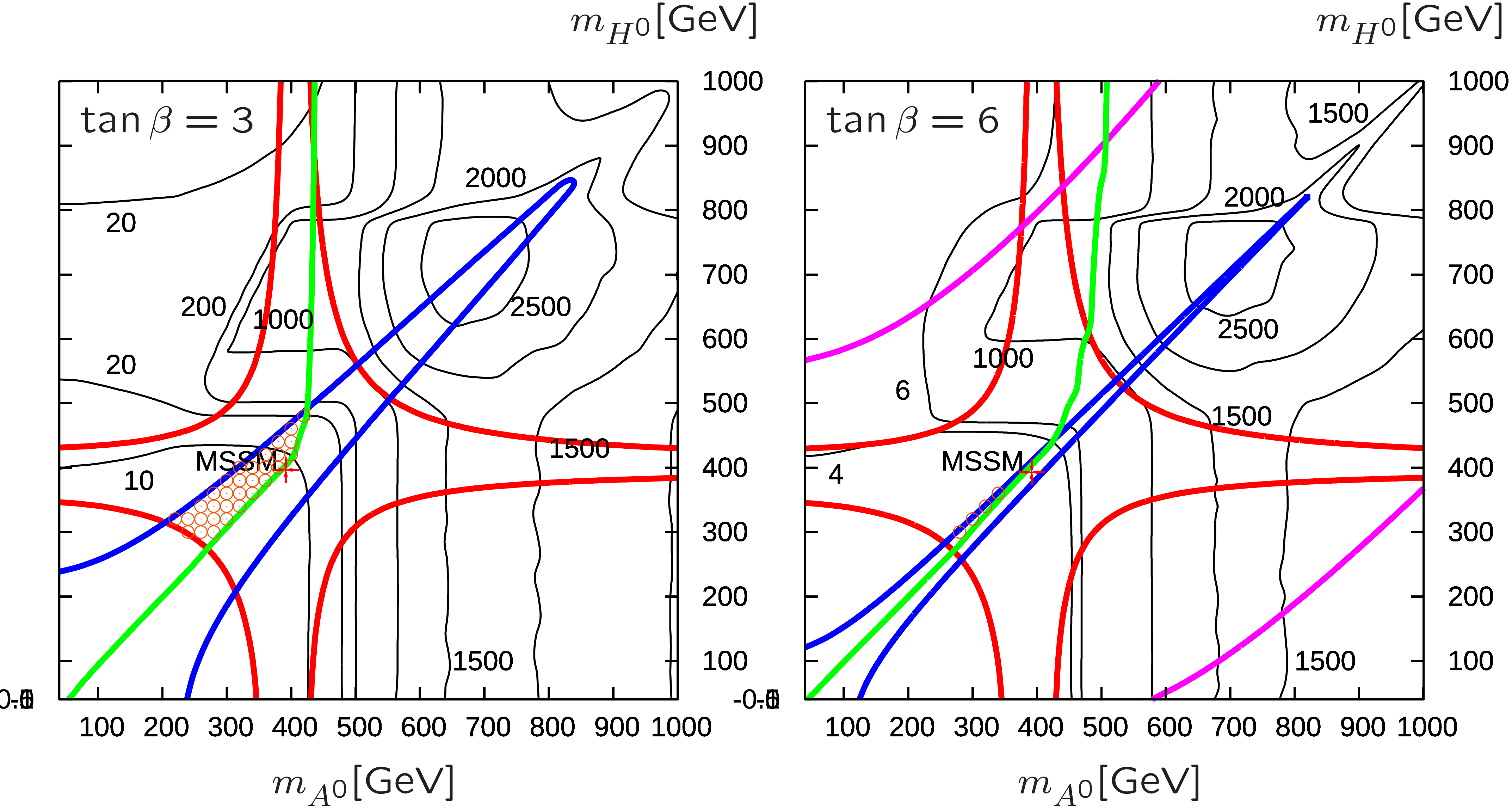


constraints: magn. moment a_μ $+\rho$-parameter

inclusive hadronic cross section $\sigma^{\text{THDM}}_{pp\to W^{\pm}H^{\mp}}$ in fb for $M^2 = m^2_{A^0}$

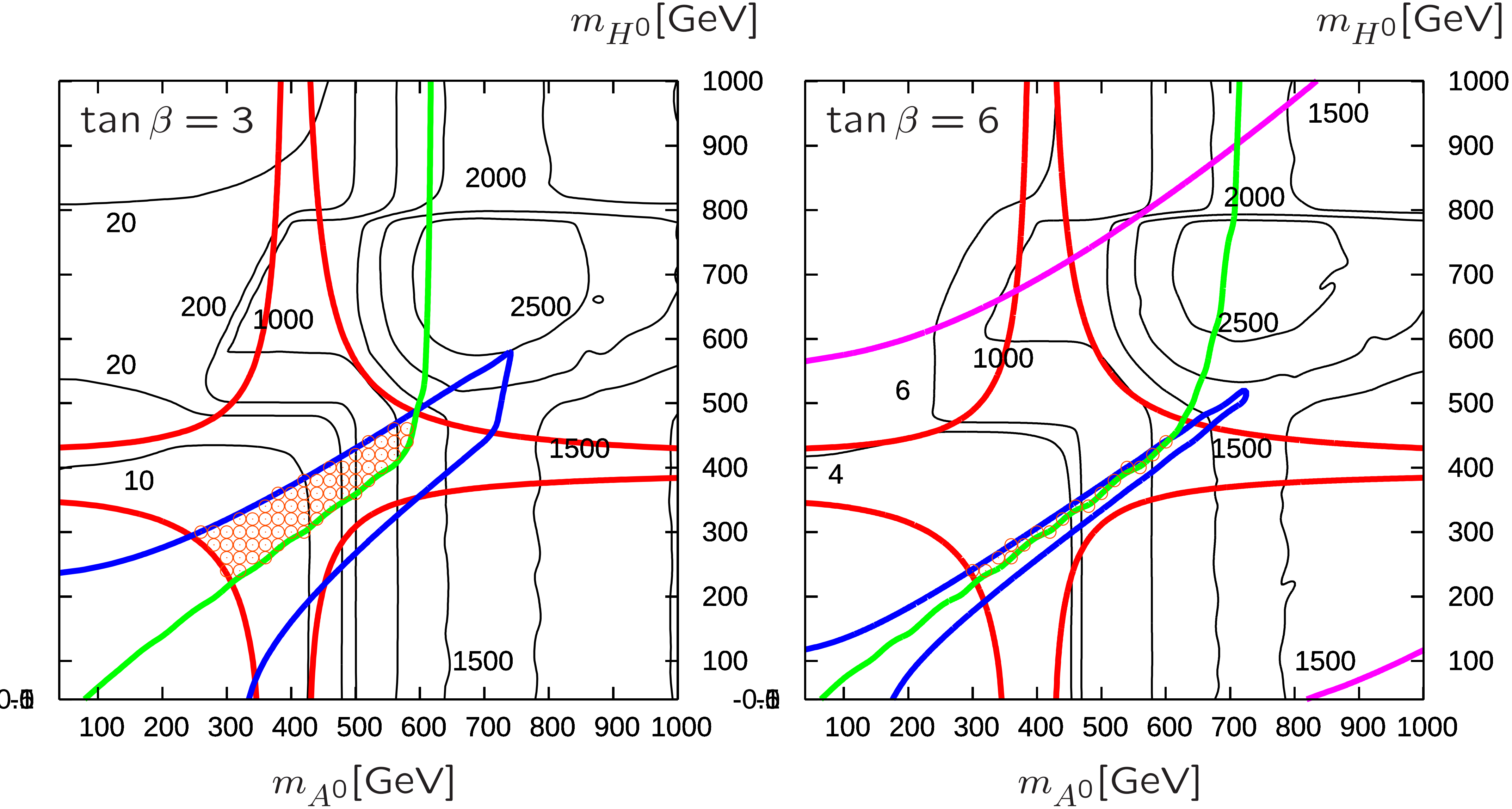


constraints: magn. moment a_μ + ρ-parameter + pert. unitarity inclusive hadronic cross section $\sigma^{\text{THDM}}_{pp\to W^\pm H^\mp}$ in fb for $M^2 = m^2_{A^0}$



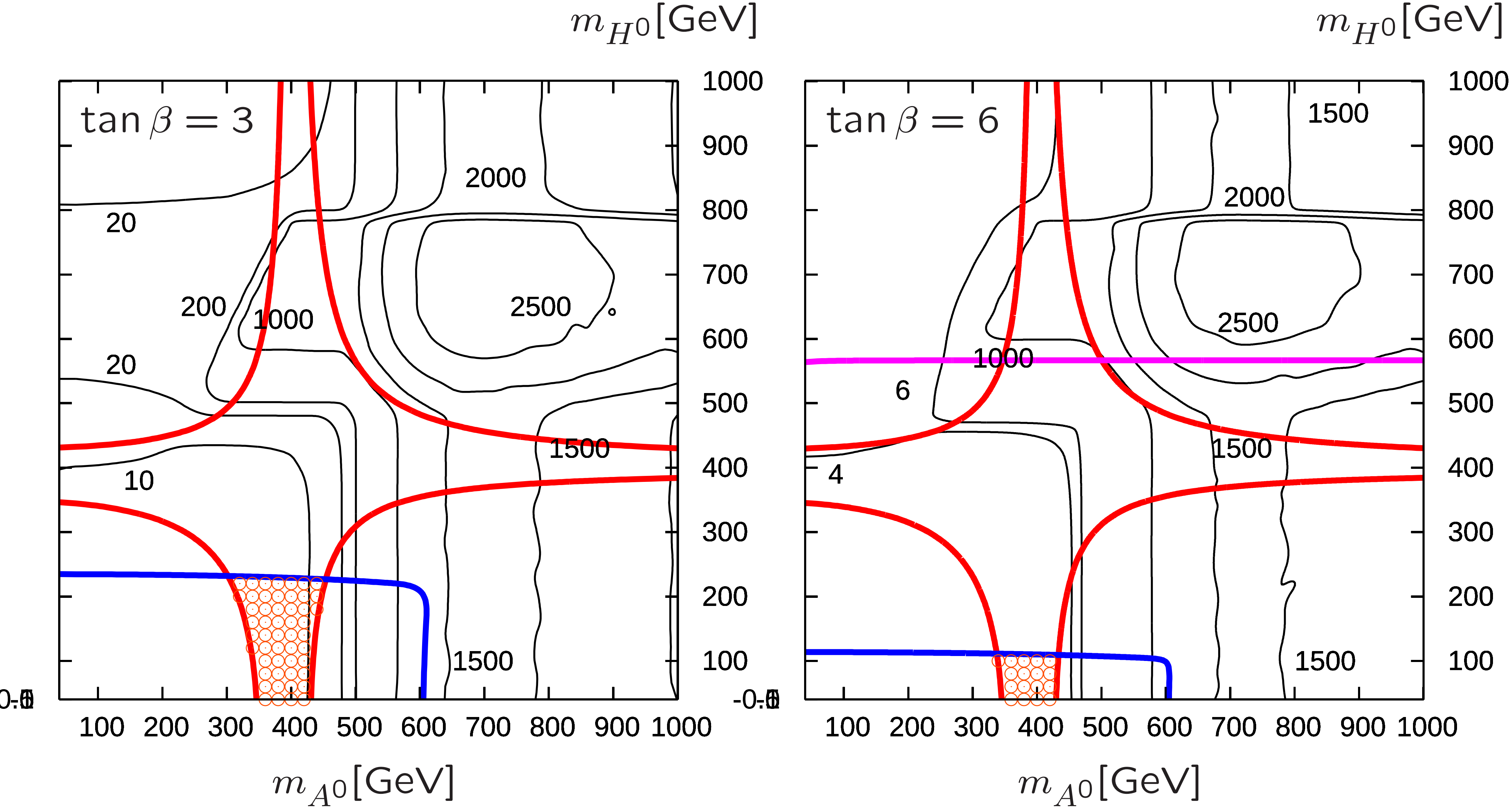
constraints: magn. moment a_μ+ρ-parameter +pert. unitarity+vac. stability

inclusive hadronic cross section $\sigma^{\mathrm{THDM}}_{pp\to W^{\pm}H^{\mp}}$ in fb for $M^2 = m^2_{A^0}/2$



constraints: magn. moment a_μ+ρ-parameter +pert. unitarity+vac. stability

inclusive hadronic cross section $\sigma^{\mathrm{THDM}}_{pp\to W^{\pm}H^{\mp}}$ in fb for $M^2 = 0$



constraints: magn. moment a_μ+ρ-parameter +pert. unitarity+vac. stability

Summary

- We are sure to observe electroweak symmetry breaking in nature. However, up to now, we have no clue how it is realised.

- Theoretically many different ways, consistent with present data, exist and have to be taken seriously.
  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.

- Studying $H^{\pm}W^{\mp}$ production at the LHC may help to gain information about the underlying model.