Phenomenology of Higgs Bosons

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outline :

- Higgs Bosons: why and what to expect ?
  - Electroweak Symmetry Breaking, Higgs mechanism
  - Restrictions on Higgs Sectors
  - Higgs in the Standard Model and Extensions
- How to find Higgs Bosons ?
  - Higgs Search Programme
  - Higgs Production and Decay
- Selected Higgs Physics Projects
  - SM Higgsstrahlung
  - MSSM Higgs + high-p_T Jet
  - HiggsBounds

- Higgs Bosons: why and what to expect ?

– 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		$(W^\pm, Z)$

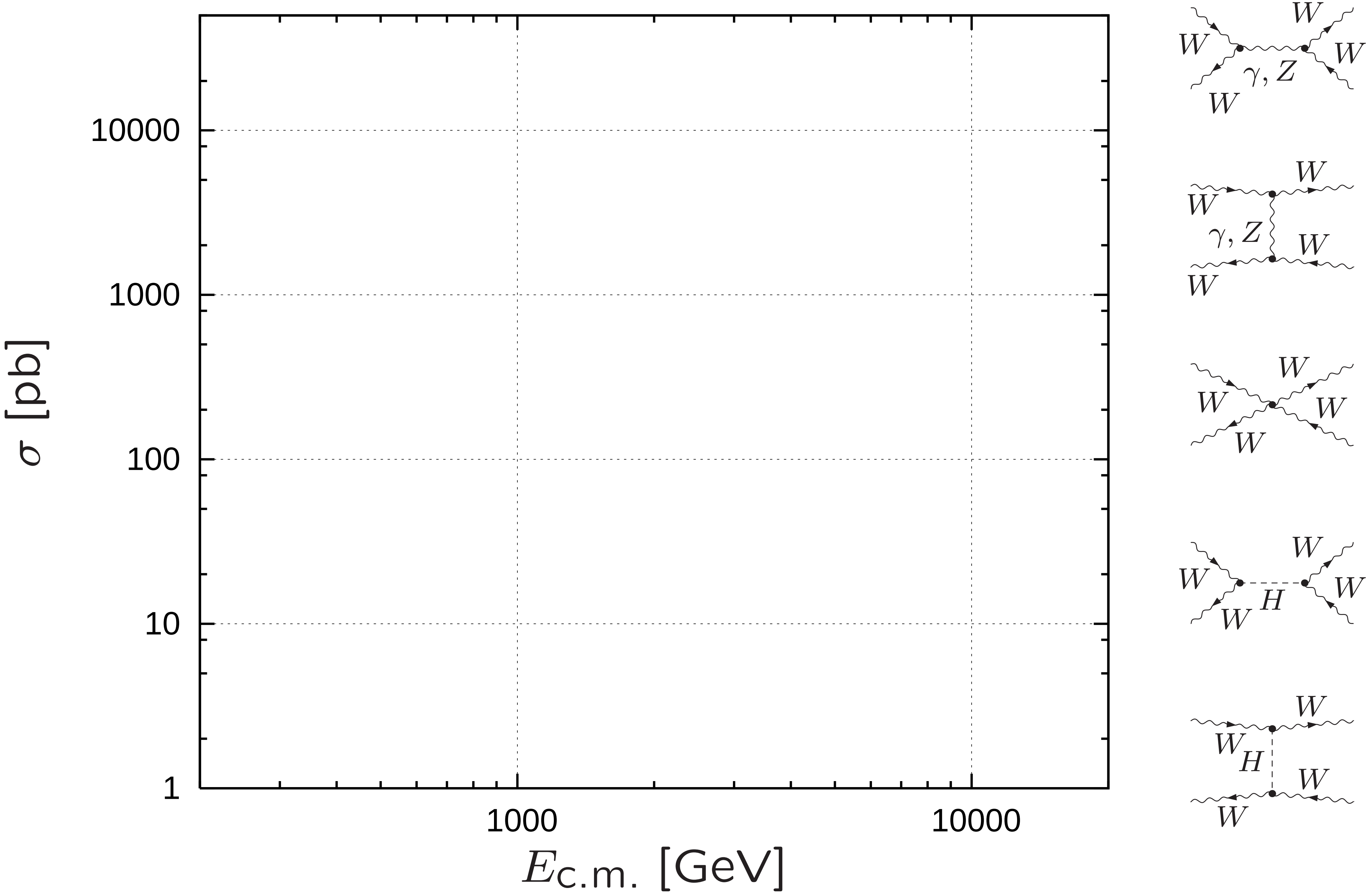
solution: **spontaneous symmetry breaking (SSB)**,

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 $\longrightarrow$ 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



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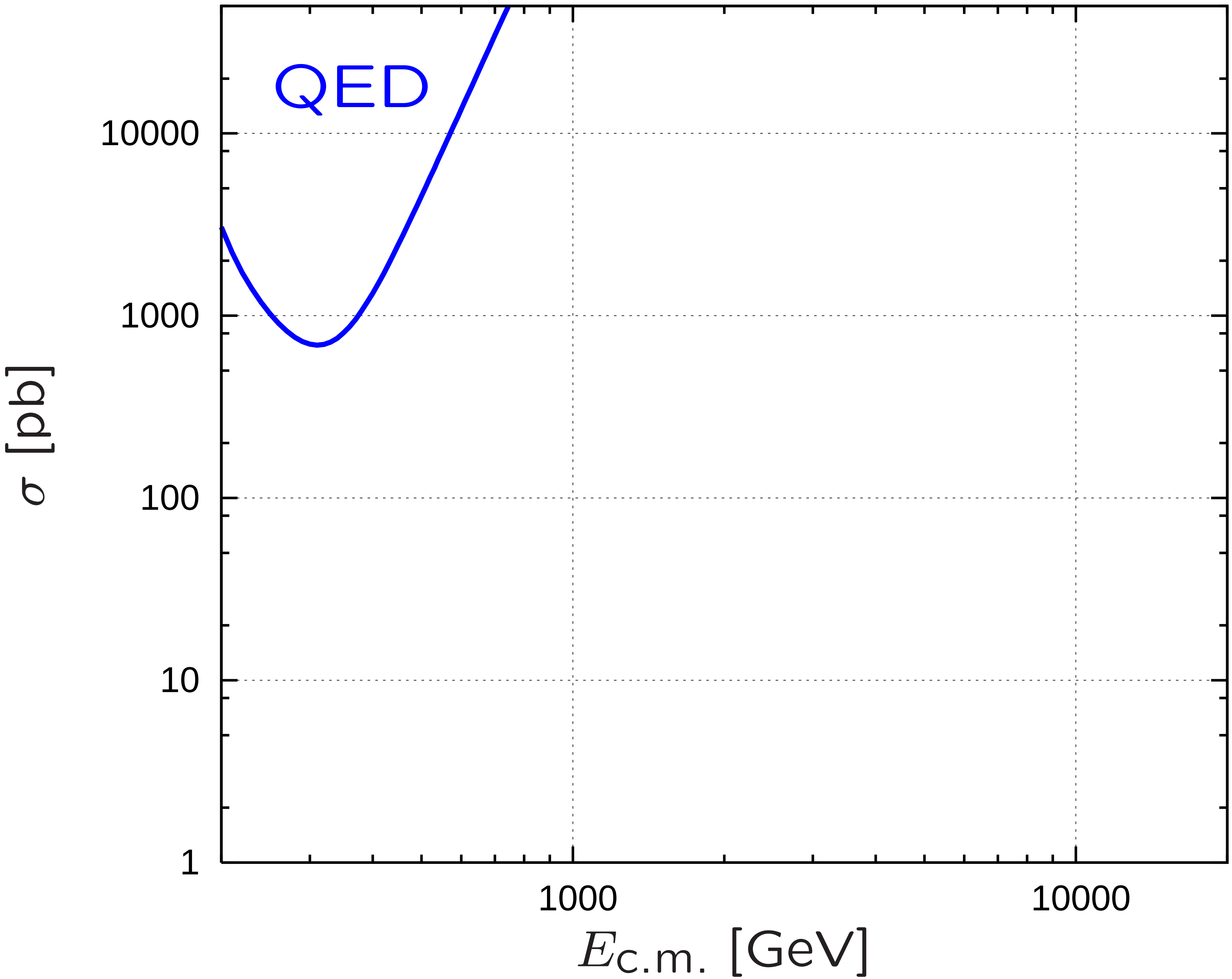

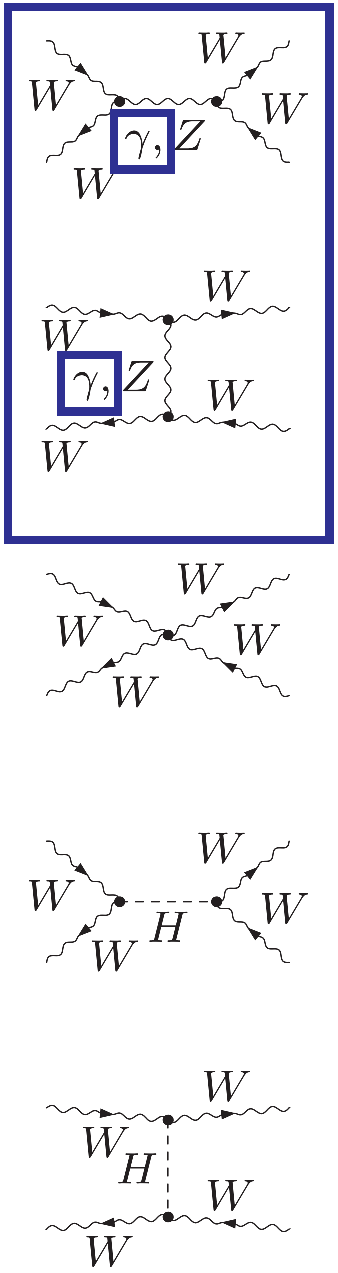

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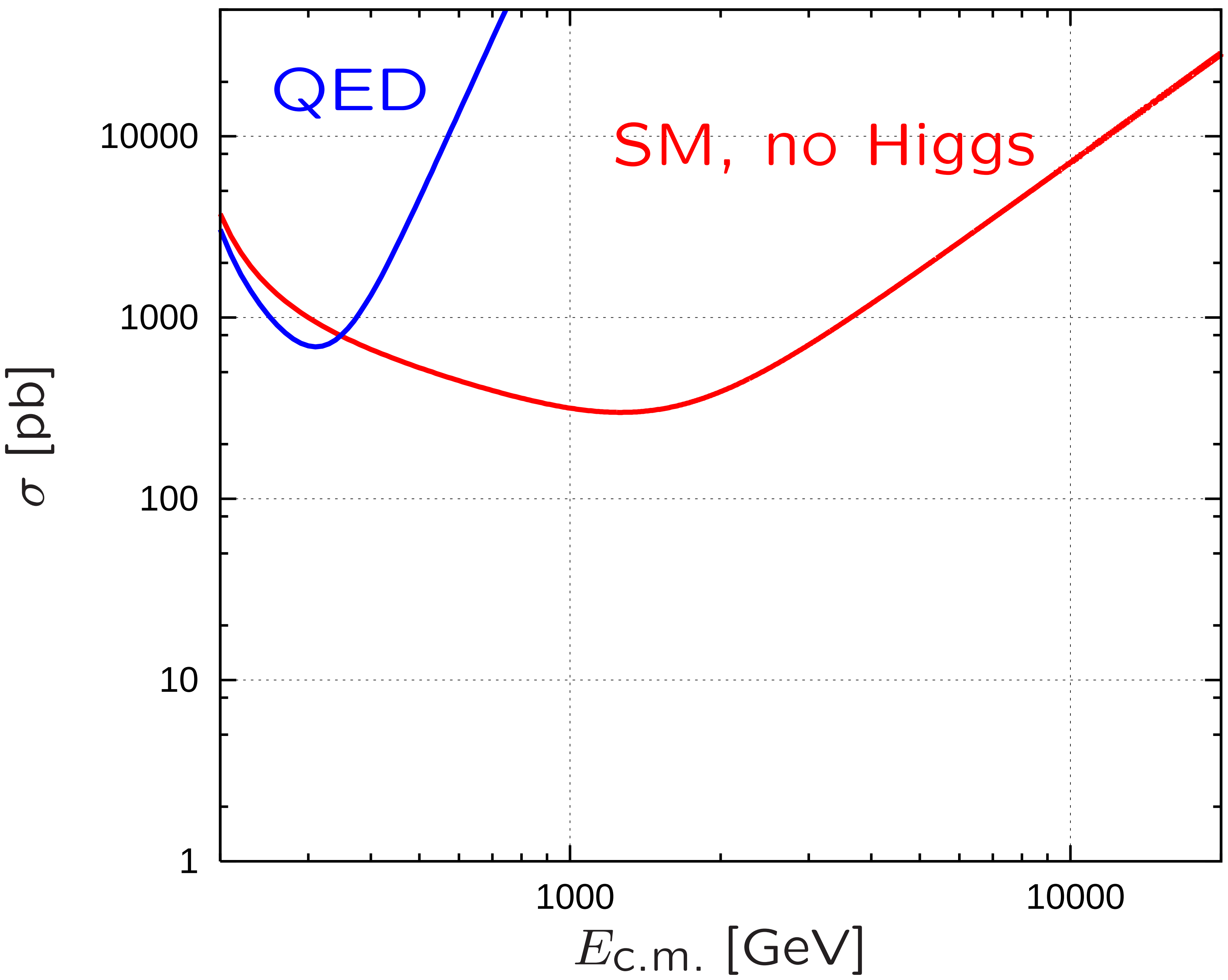

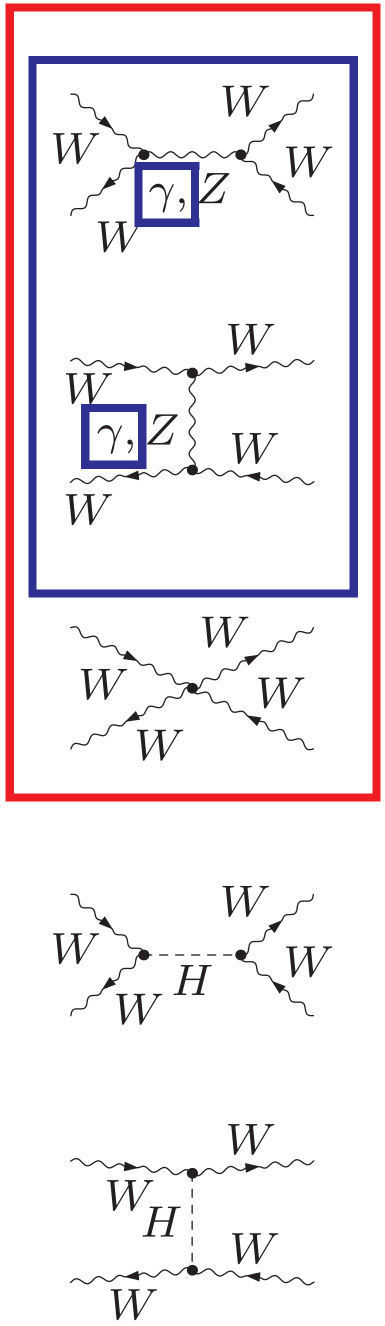

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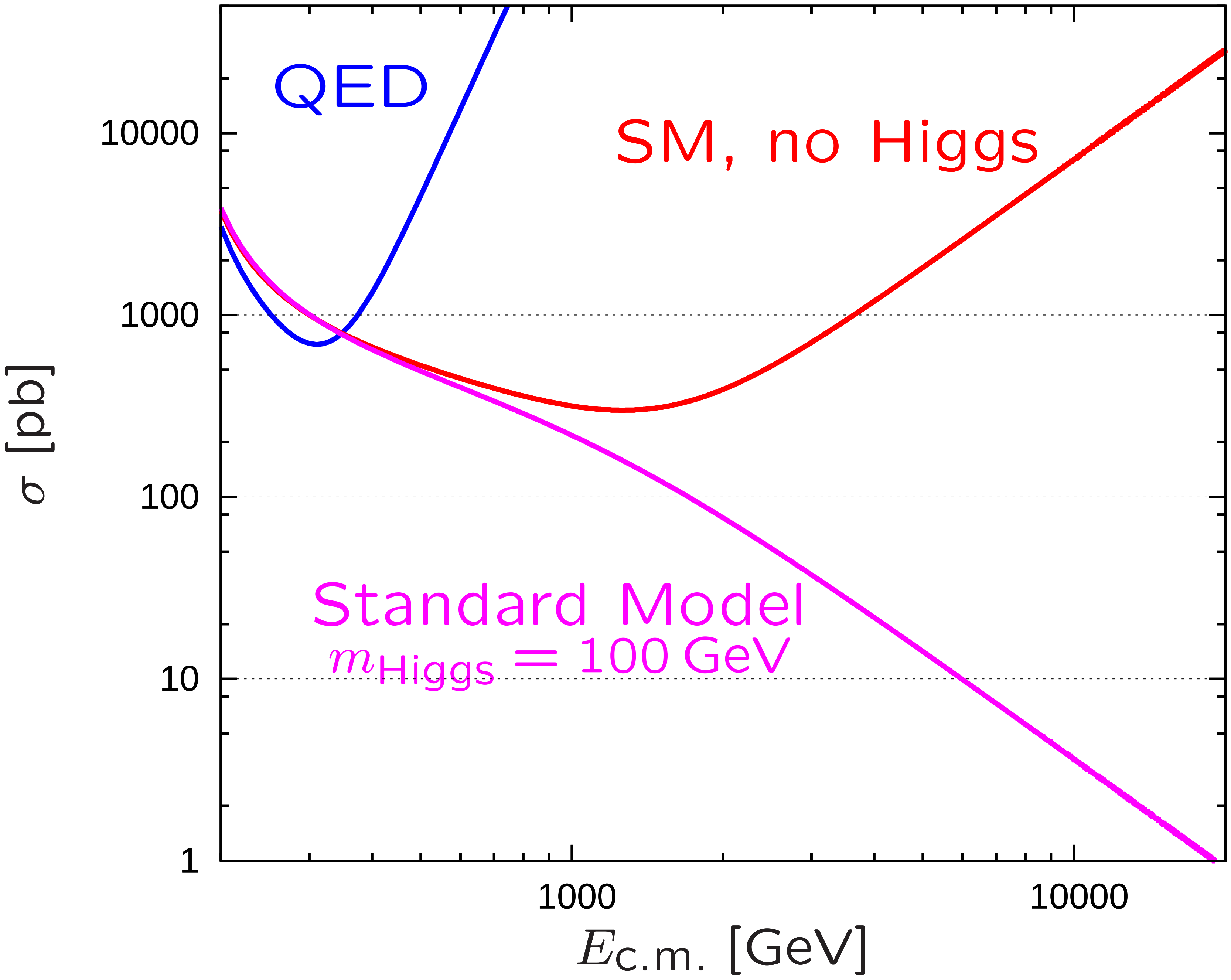
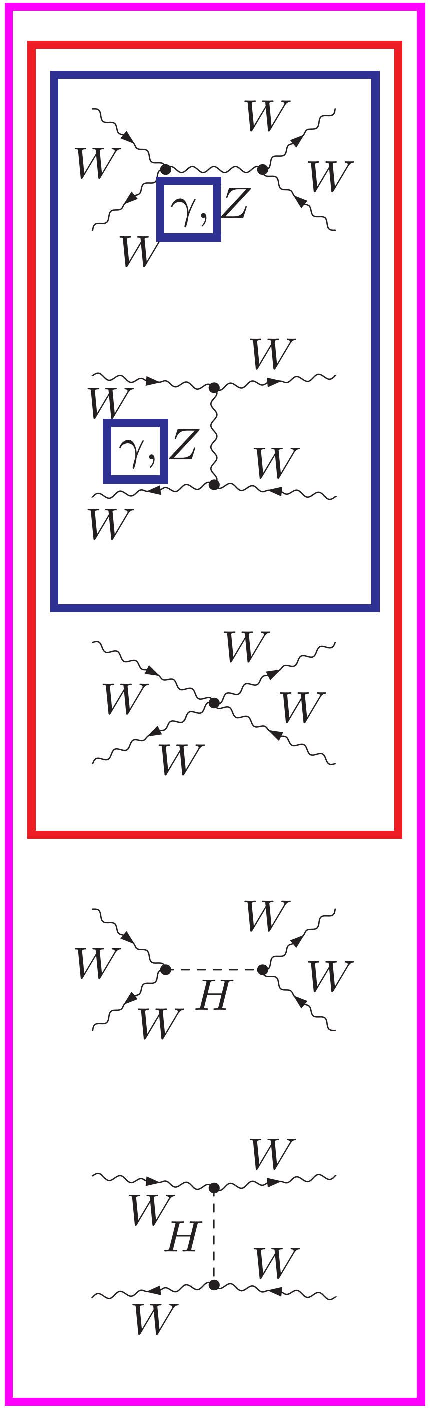




– Restrictions on Higgs Sectors

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
  $\rho_{\mathrm{exp.}} = \frac{m_W}{\cos\theta_W m_Z} \approx 1$ up to a few per mille

- absence of flavour changing neutral currents (FCNC).

- upper bounds on production cross sections
  from negative direct search results (LEP, Tevatron)

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

– Higgs in the Standard Model and Extensions

SM:

matter, gauge bosons + 1 Higgs doublet Φ

$\rightarrow$ 1 physical Higgs boson

$\swarrow$ $\searrow$

THDM:	MSSM:
(two Higgs doublet model)	(minimal supersymmetric standard model)
SM matter, SM gauge bosons	SM matter, SM gauge bosons
+ 2 Higgs doublets Φ_1, Φ_2	+ 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

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

Consequences of Supersymmetry 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:

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

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

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

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

- How to find Higgs Bosons ?

– Higgs Production and Decay

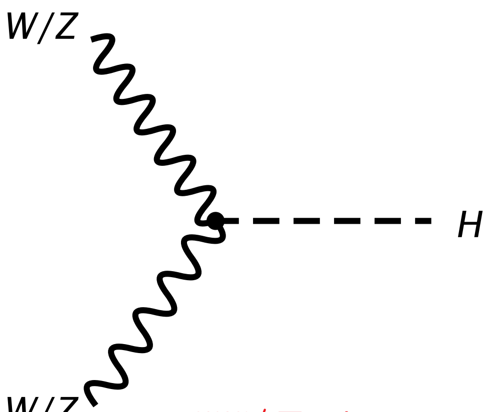
$\boxed{\text{Higgs mechanism} \longrightarrow \text{Higgs couplings} \propto \text{mass}}$

$\longrightarrow$ Problem: ordinary matter is made of very light particles:

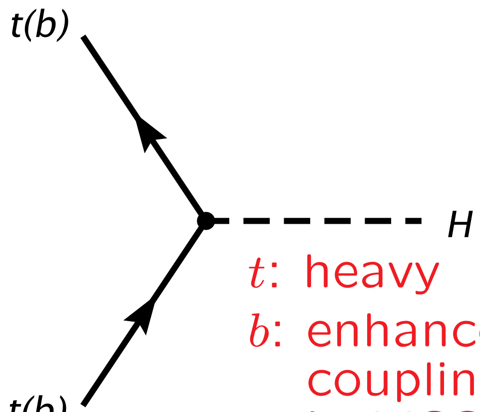
e^-, u-, d-quarks, gluons $\longrightarrow$ (essentially) no coupling to the Higgs

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

$\longrightarrow$ most important couplings:



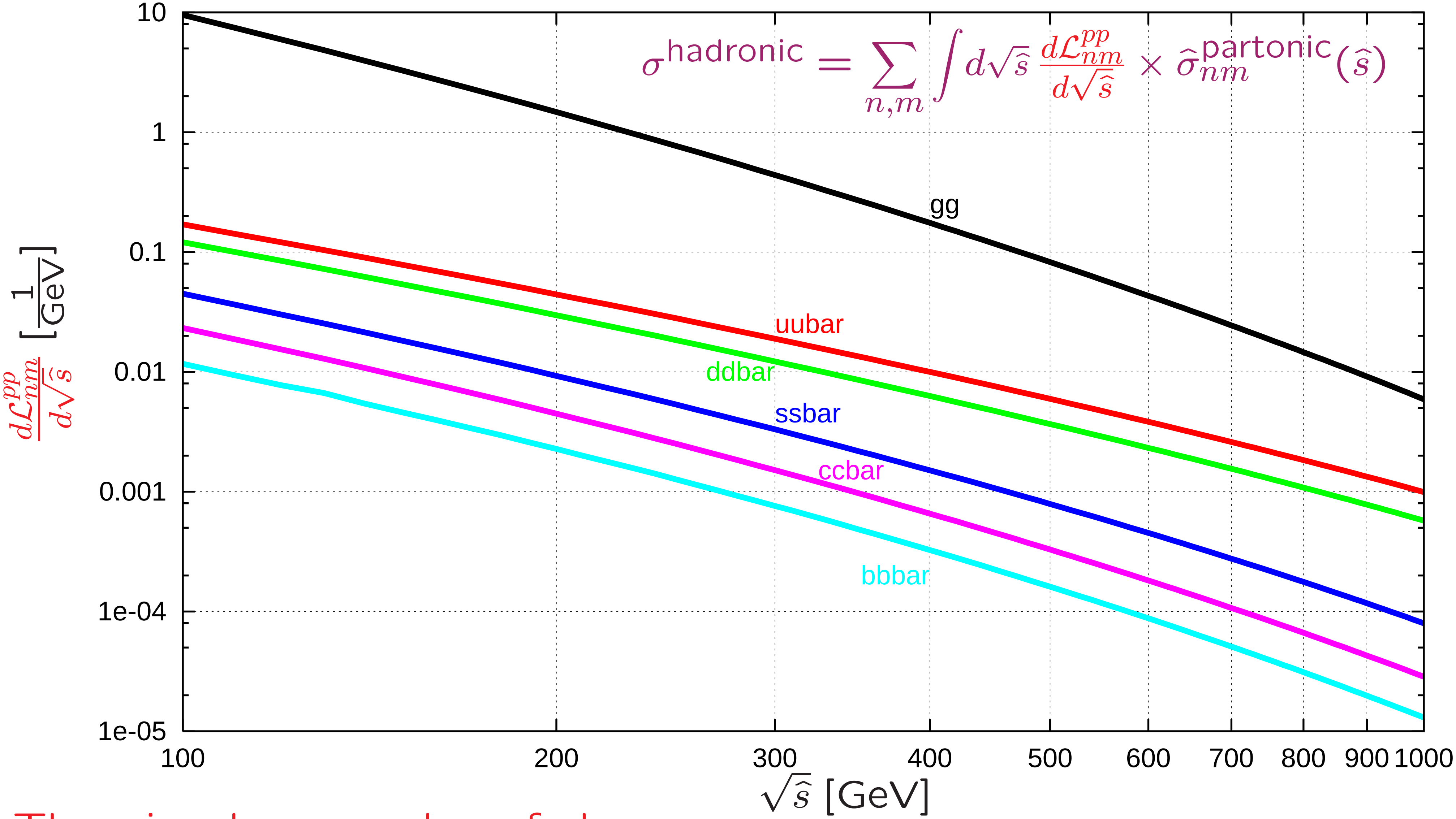
W/Z: heavy



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.

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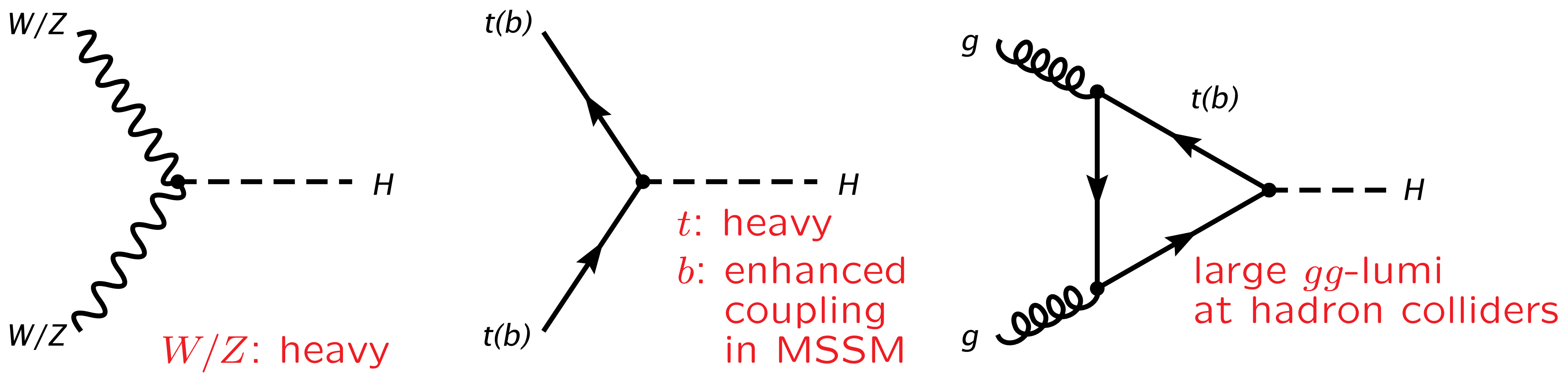
$\longrightarrow$ most important couplings at high energy hadron colliders:



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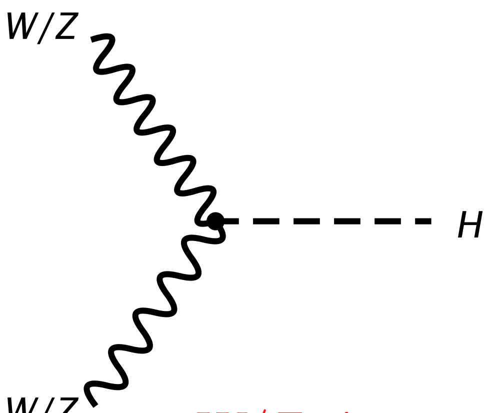

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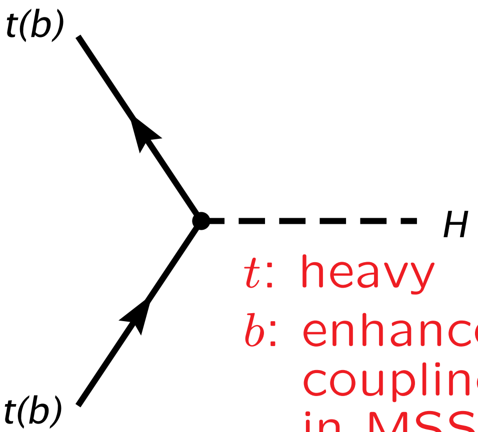

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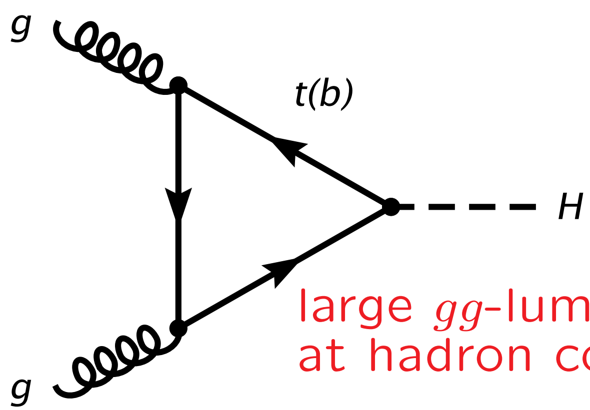

large gg-lumi at hadron colliders

Therefore, most important couplings at high energy hadron colliders

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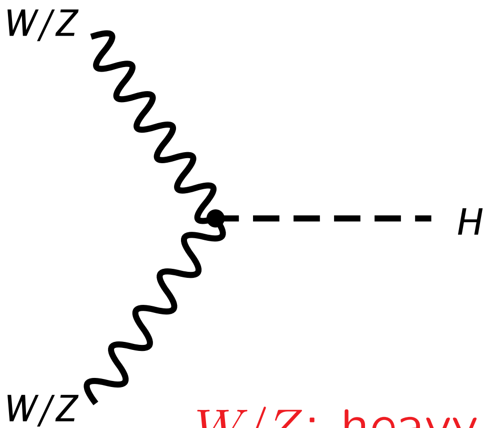

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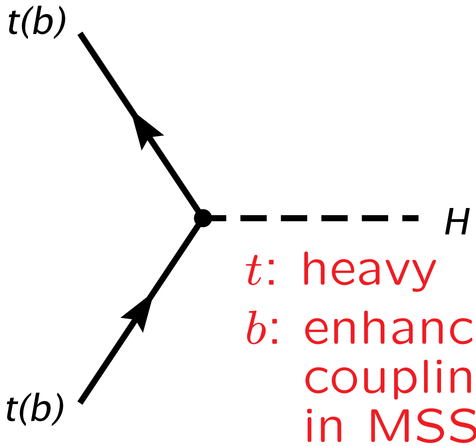

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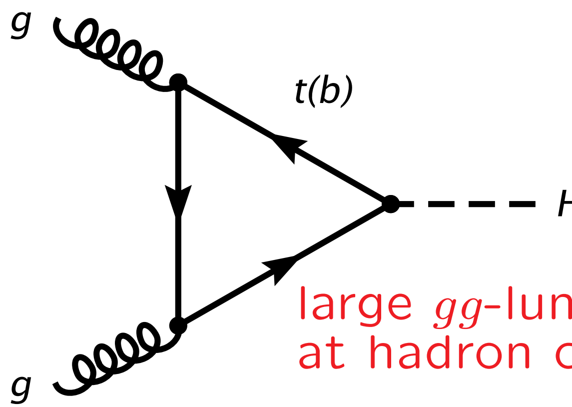

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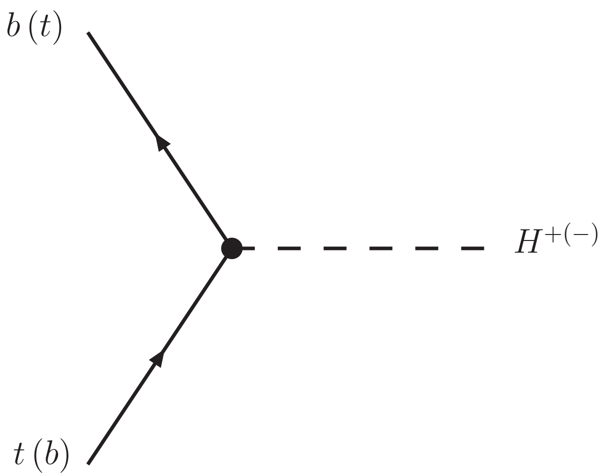
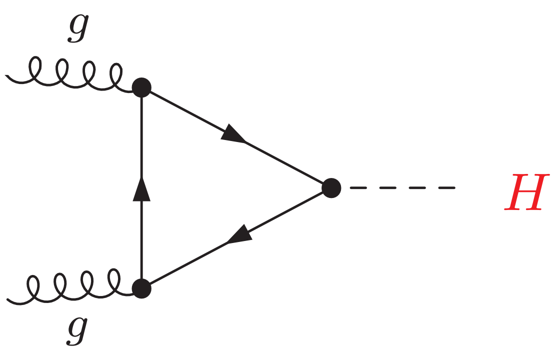
… for charged Higgs production:



Important neutral Higgs production processes:



gluon fusion, $gg \longrightarrow H$

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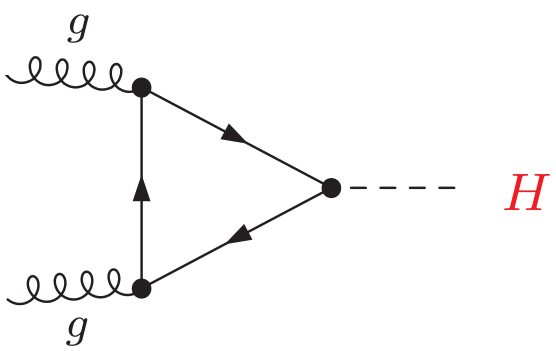

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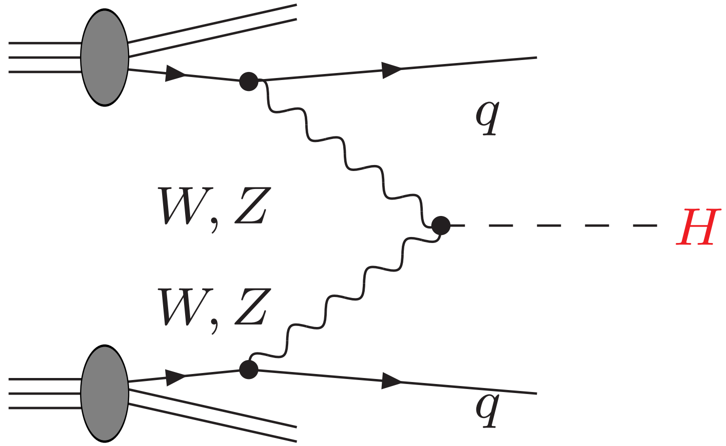

vector boson fusion, $qq \longrightarrow qqH$

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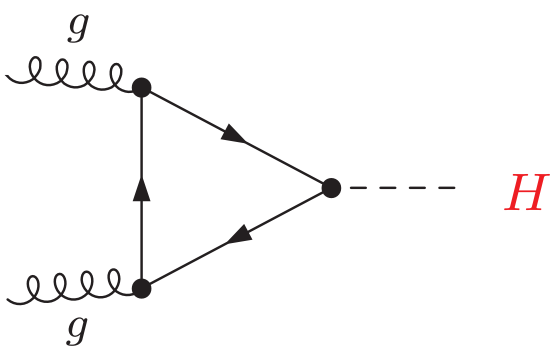

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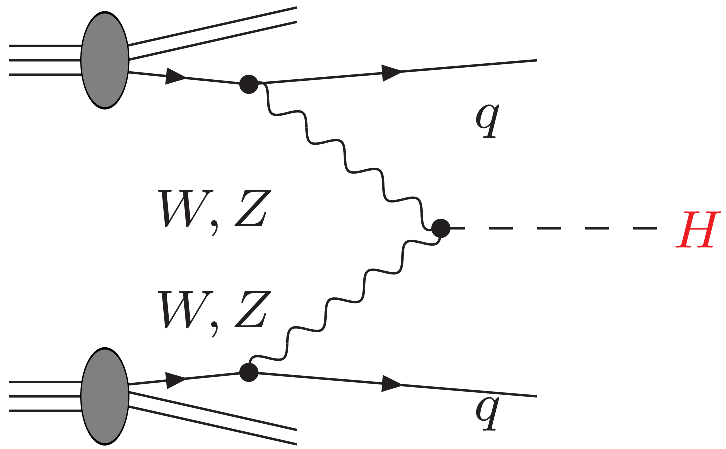

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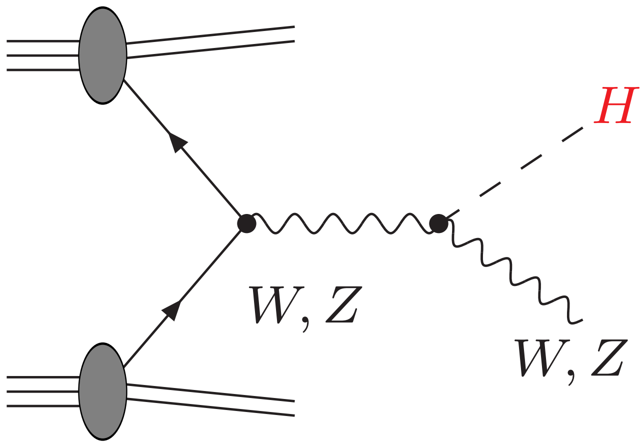

Higgs strahlung, $q\overline{q}' \longrightarrow VH$

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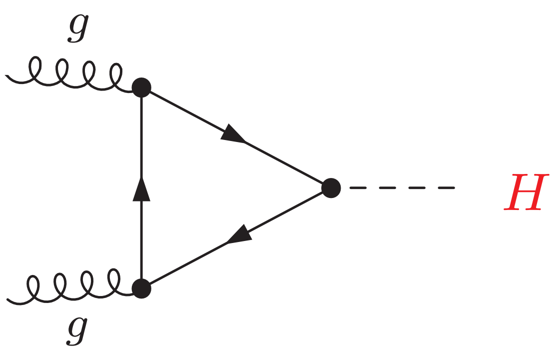
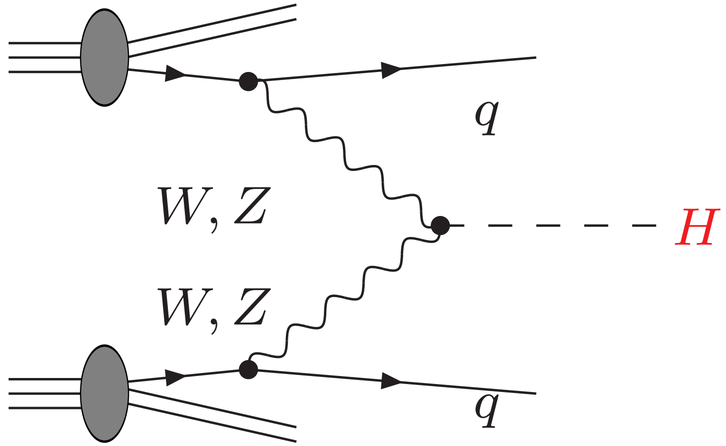


gluon fusion, $gg \to H$



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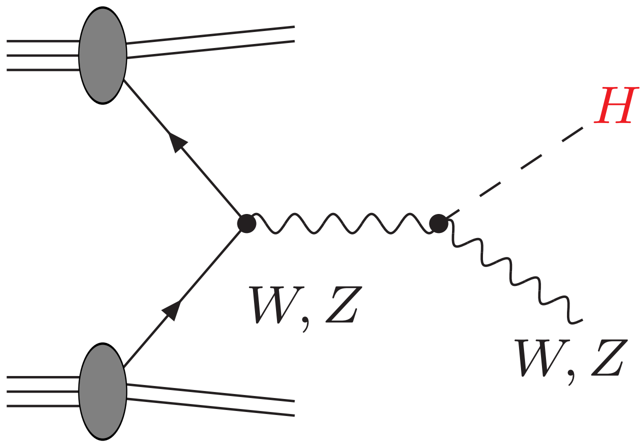

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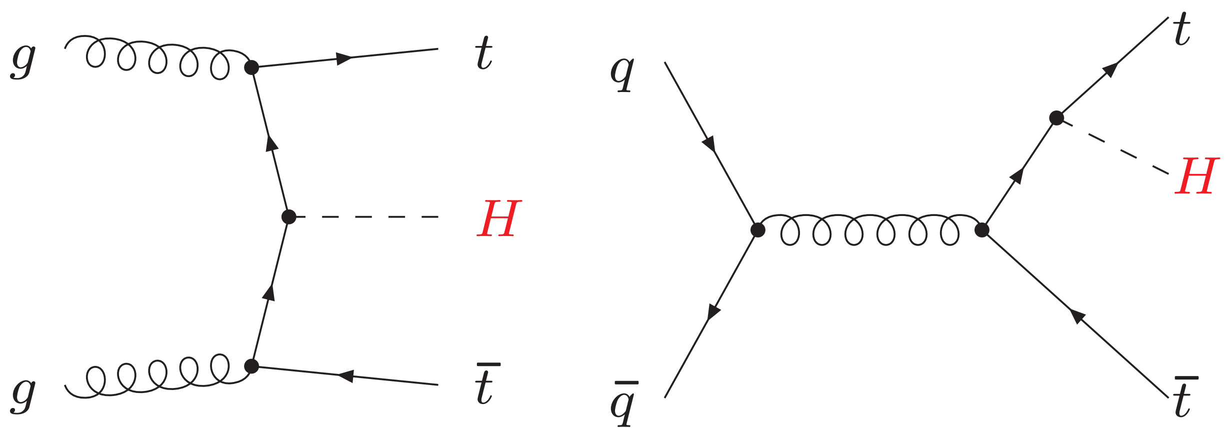

$t\bar{t}H$ **production**

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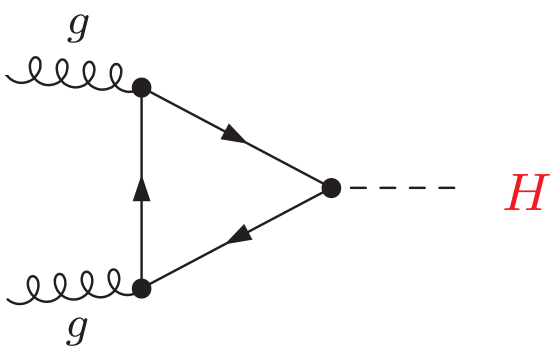

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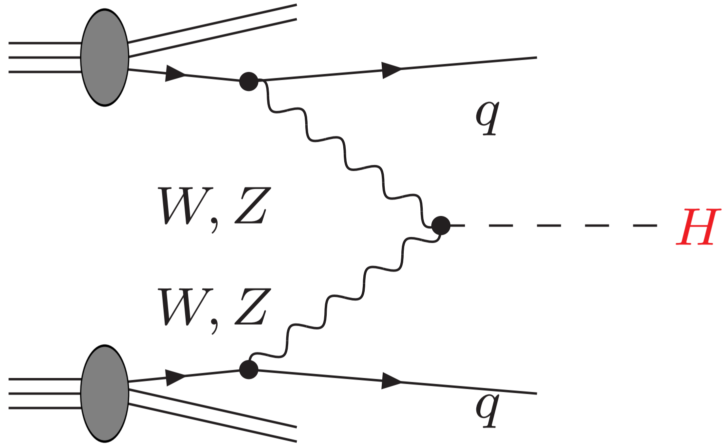

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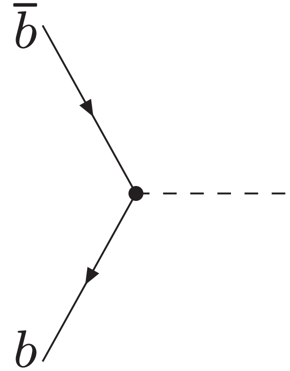
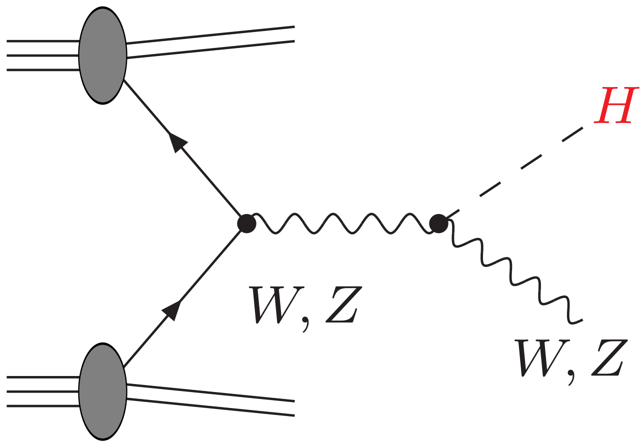


$b\bar{b} \to H$



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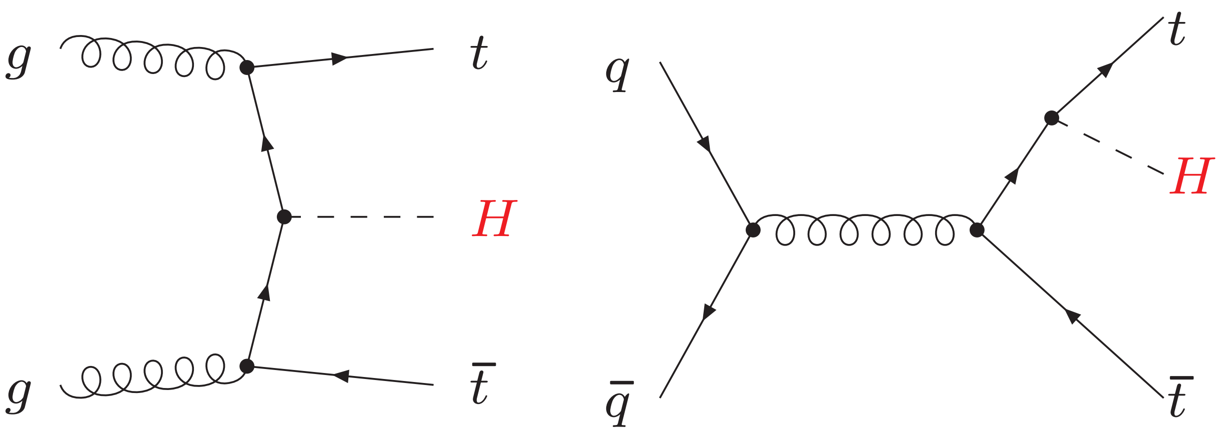
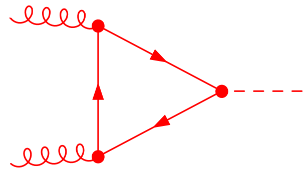
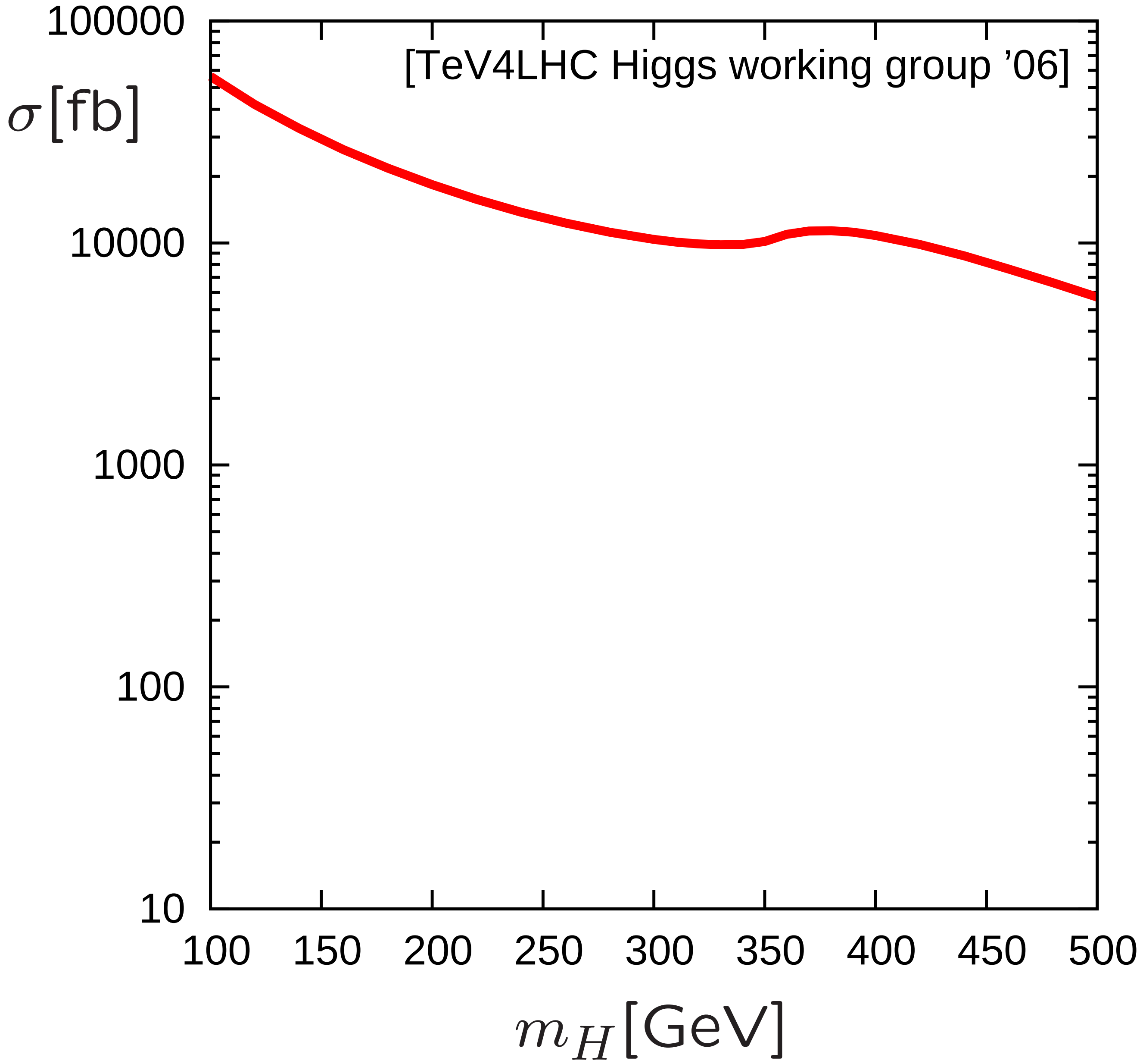


$t\bar{t}H$ **production**

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





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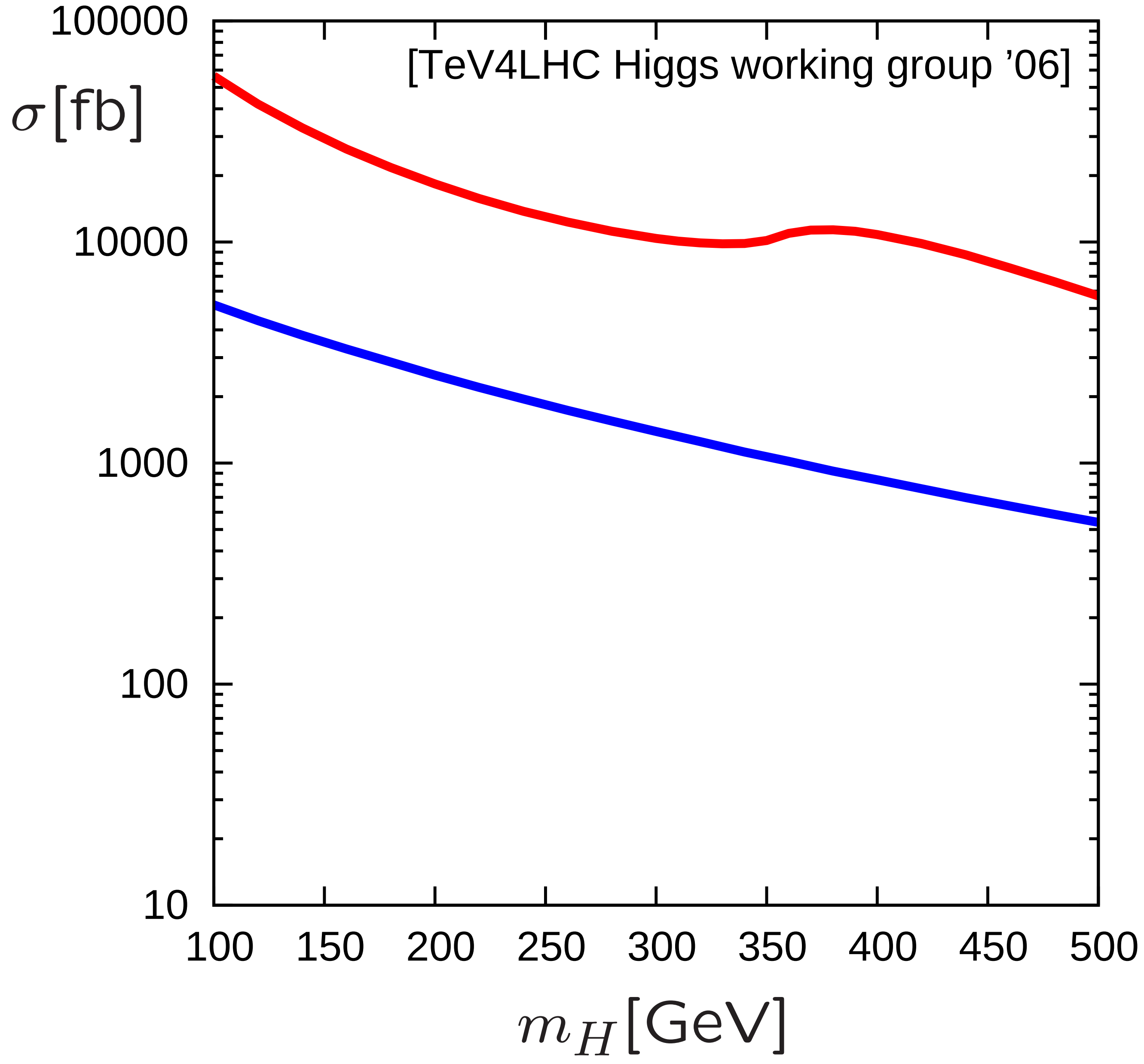

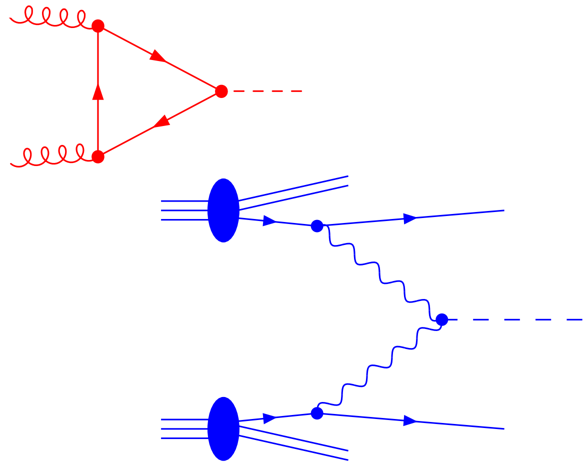

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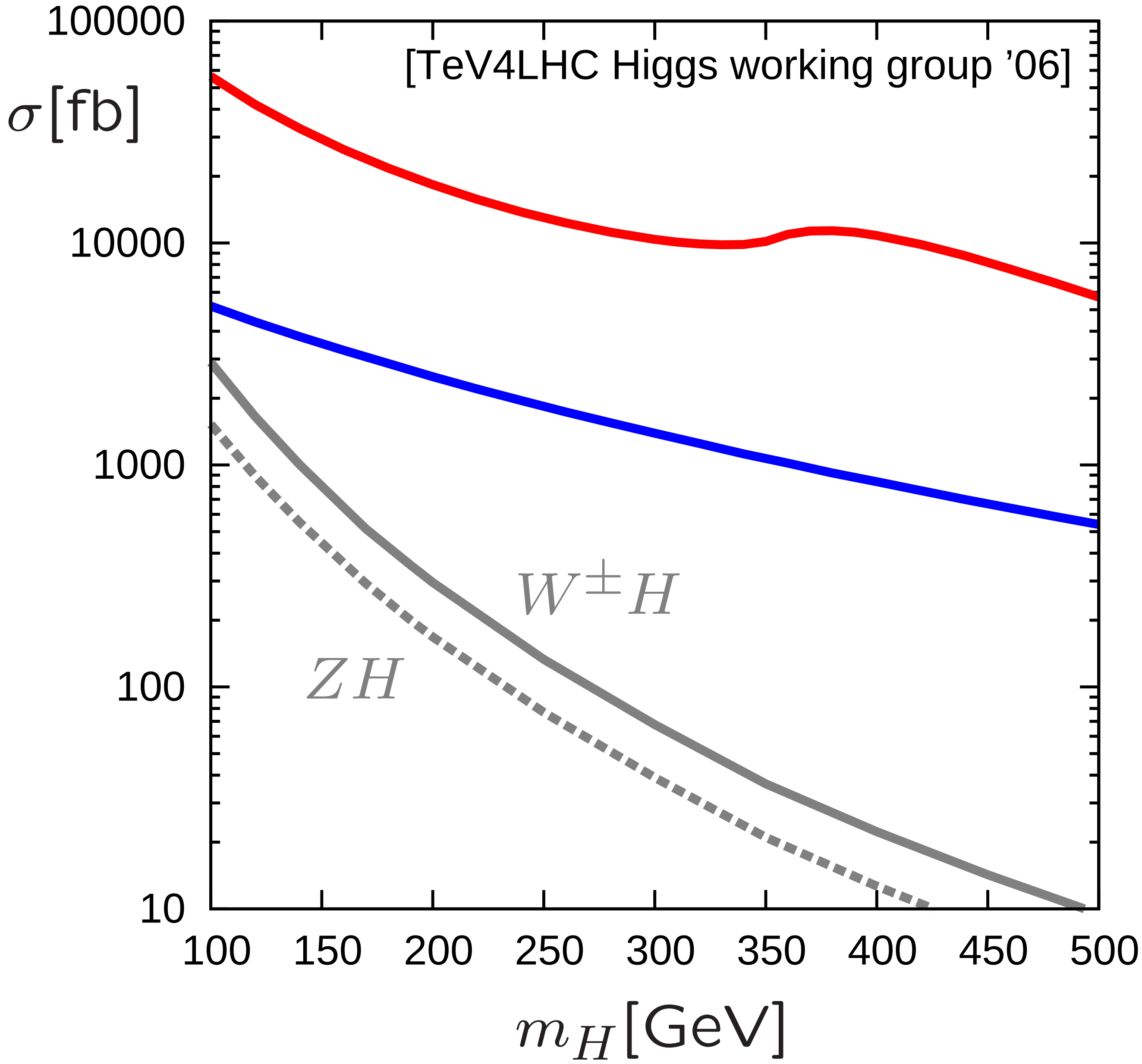

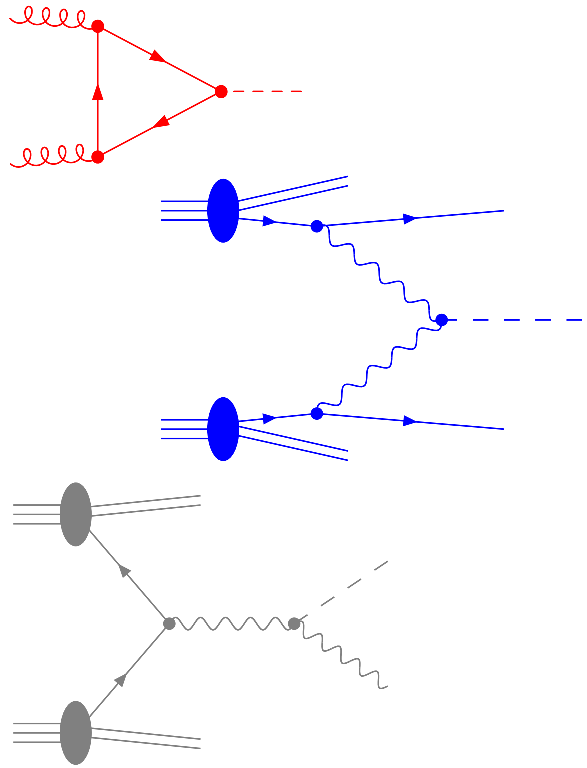

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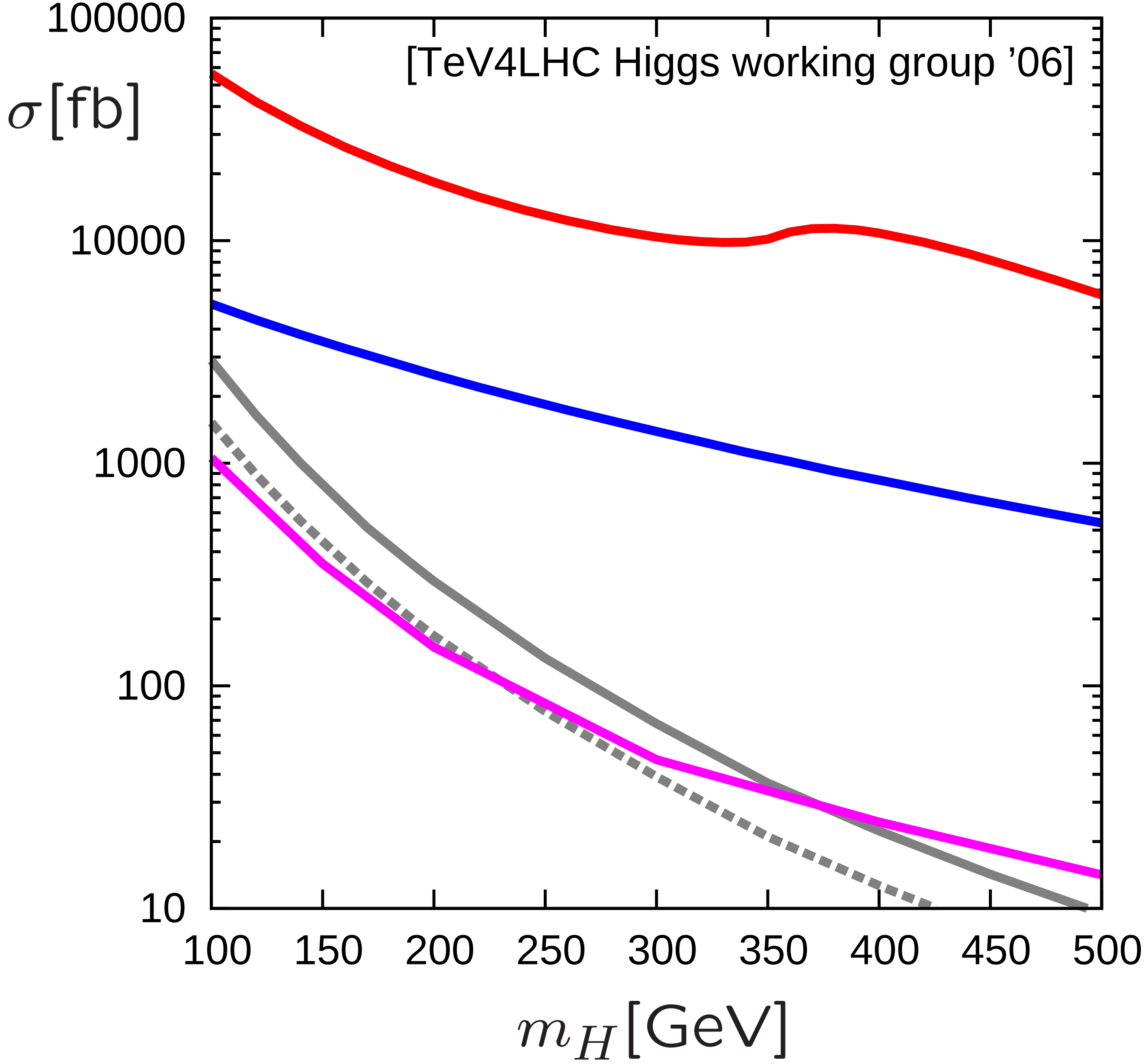

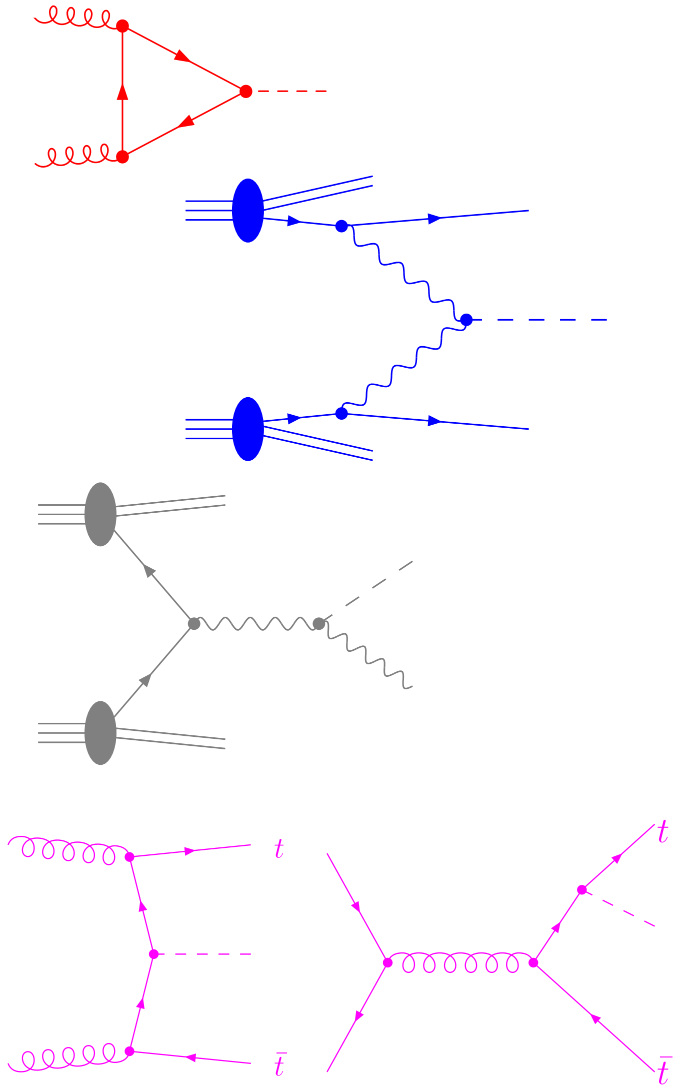

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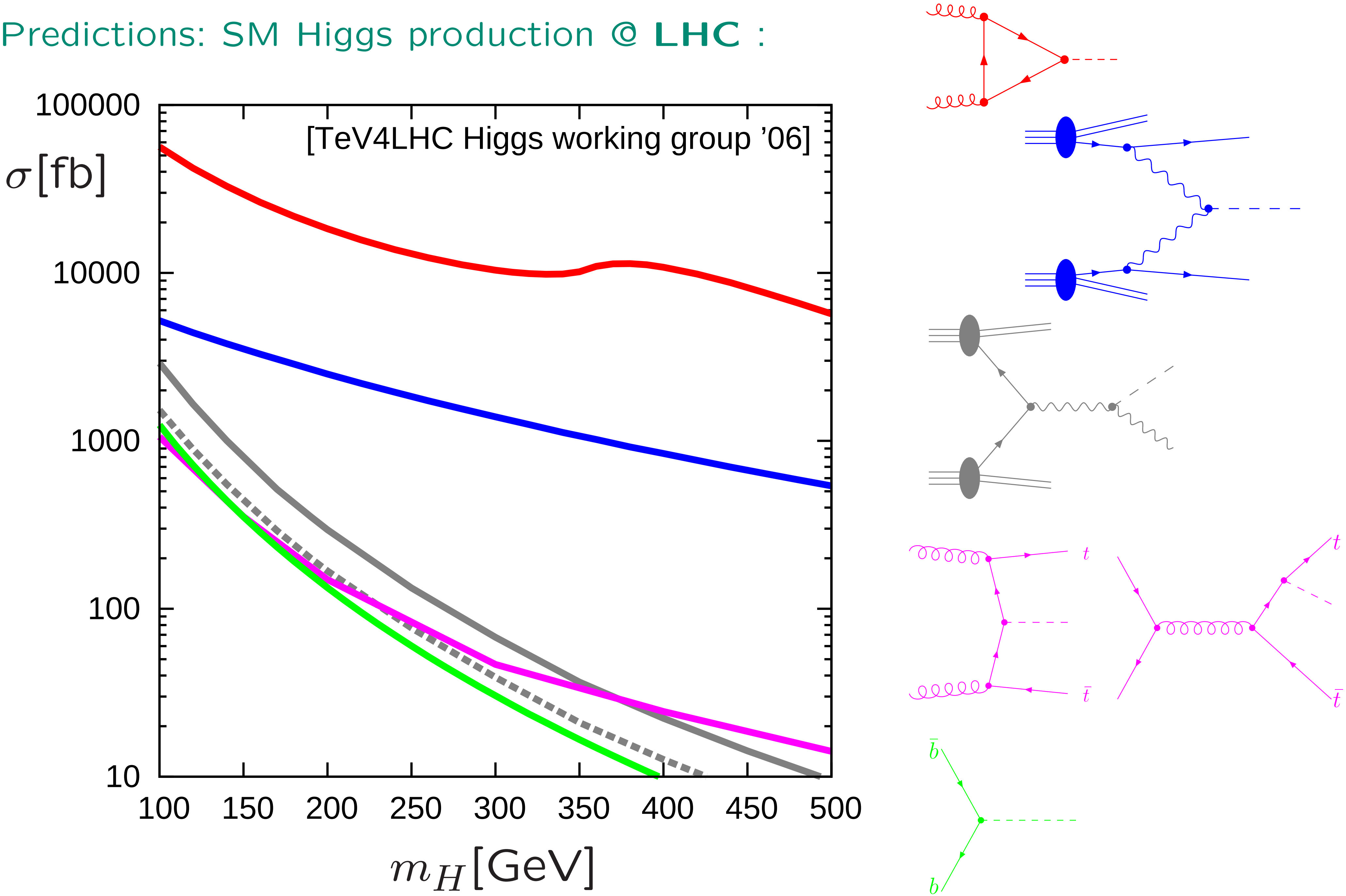
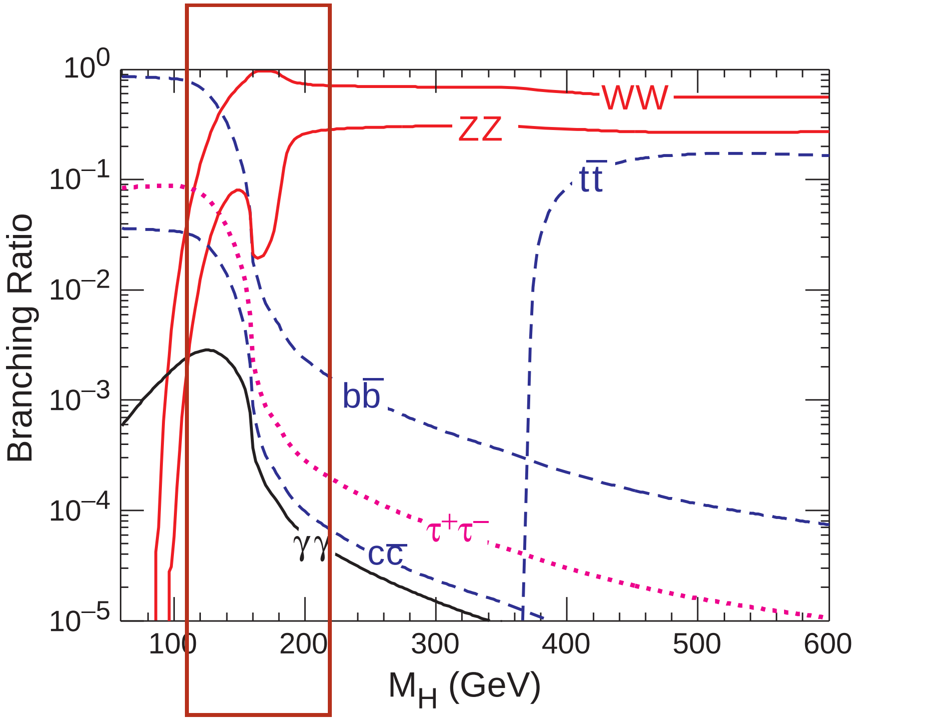


SM Higgs branching ratios
and
signal significance @ LHC

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



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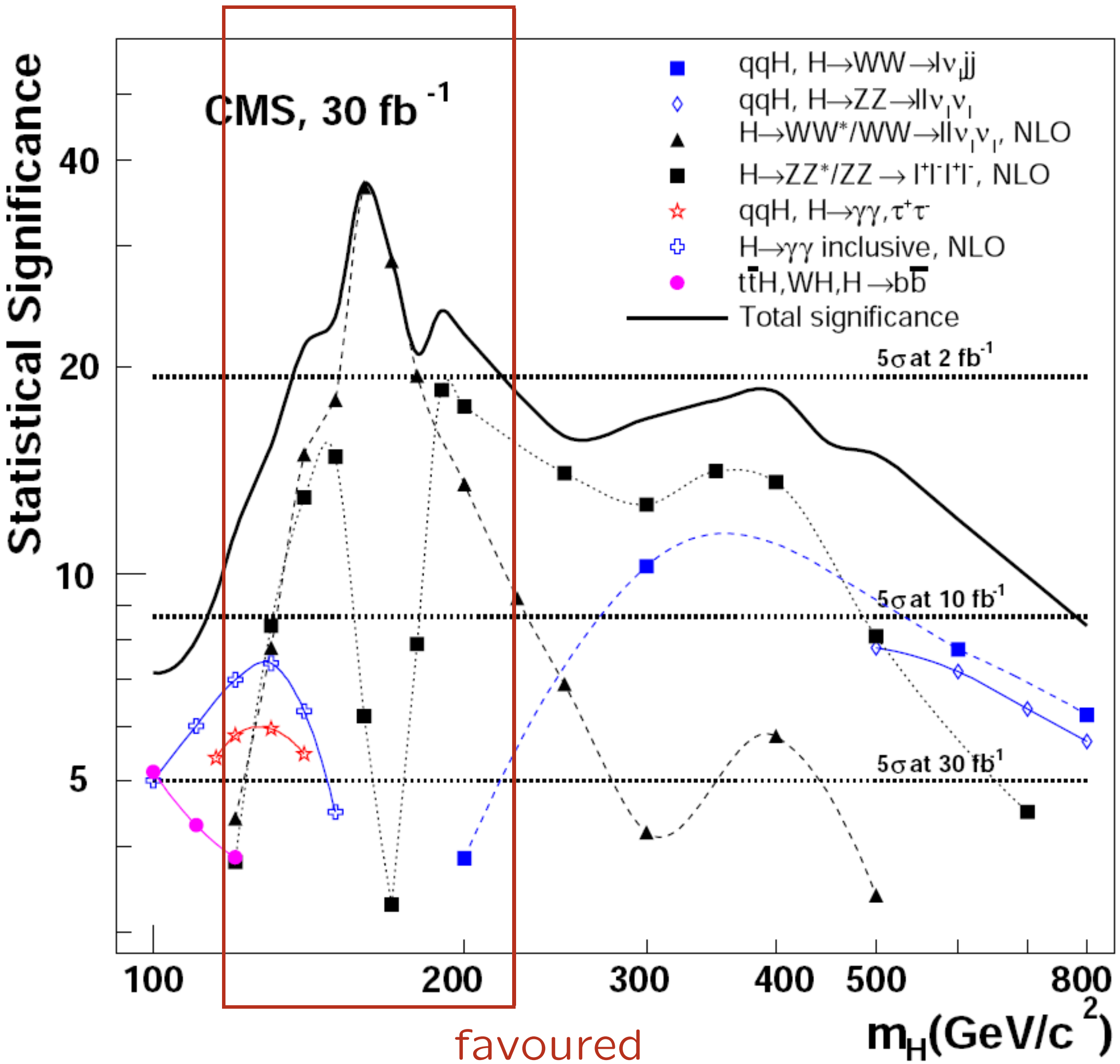

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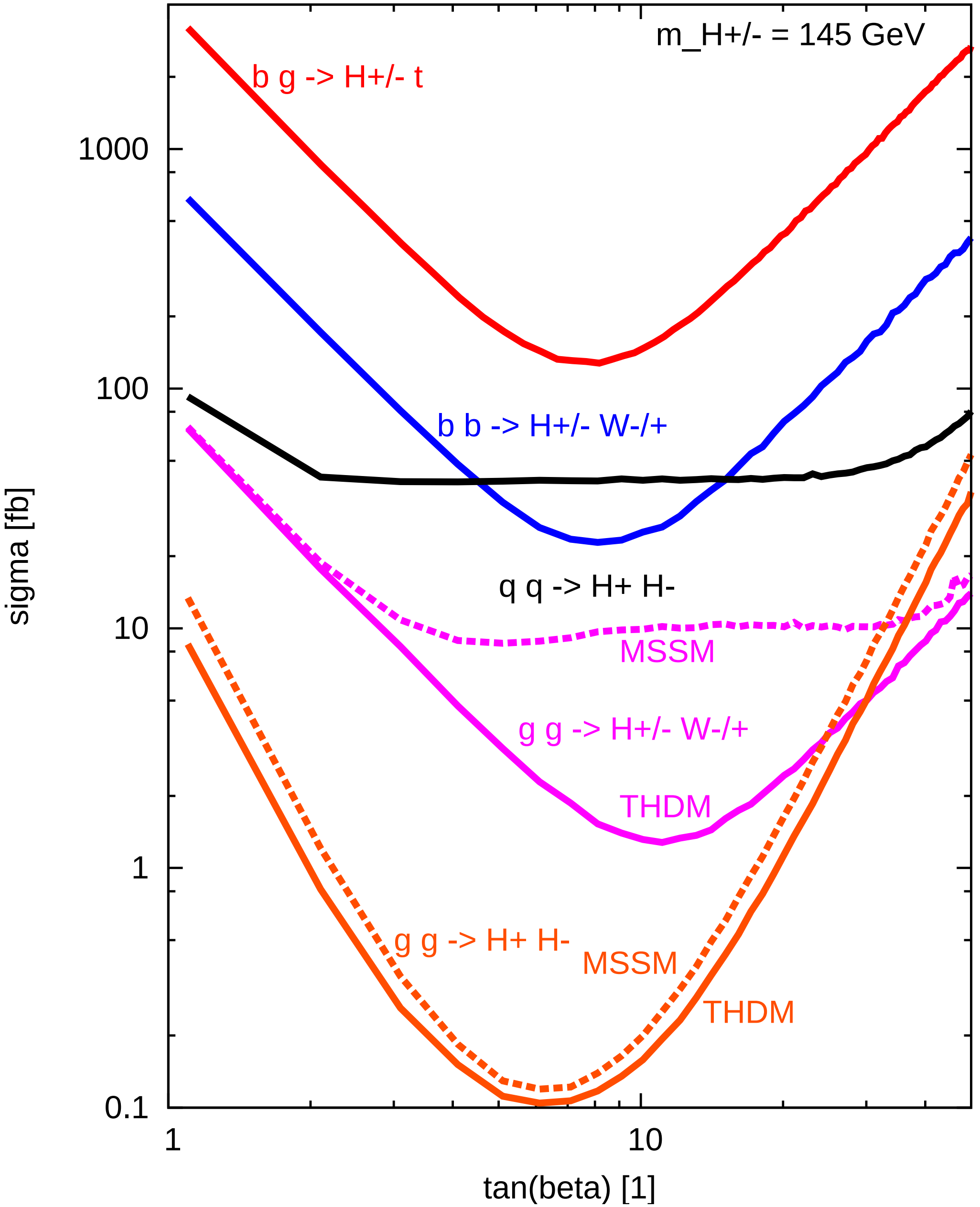
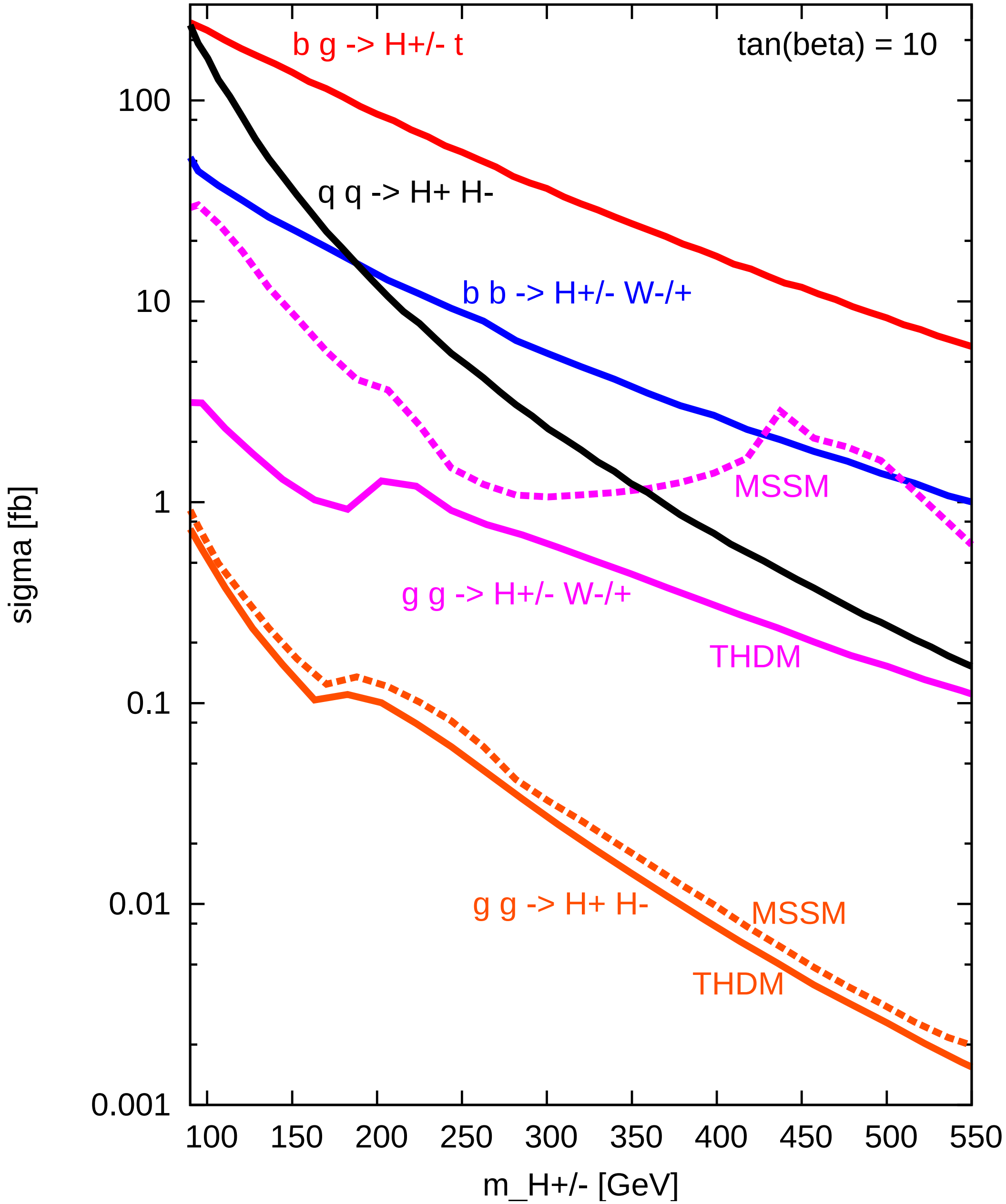
Predictions: charged Higgs cross sections @ **LHC**:





- Selected Higgs Physics Projects

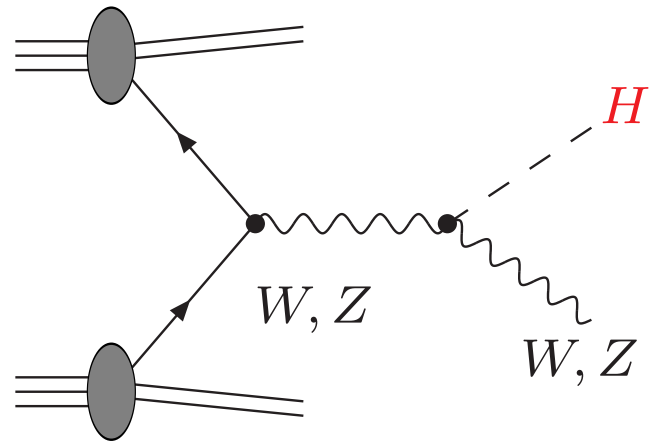
outline of the following:

– SM Higgsstrahlung

– MSSM Higgs + high-p_T Jet

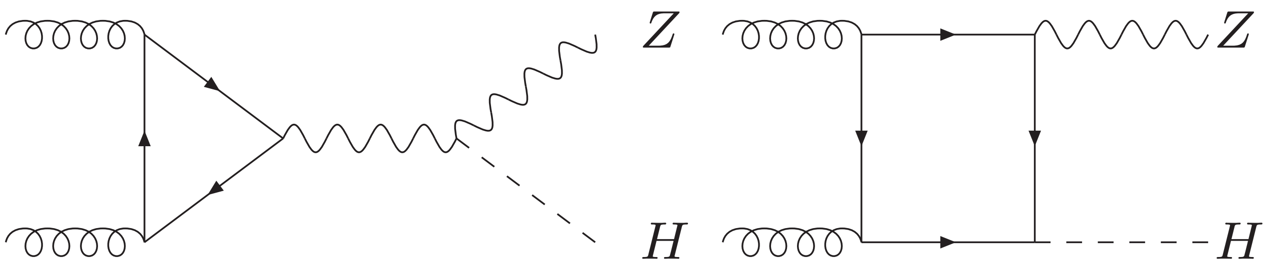
– HiggsBounds

– SM Higgsstrahlung

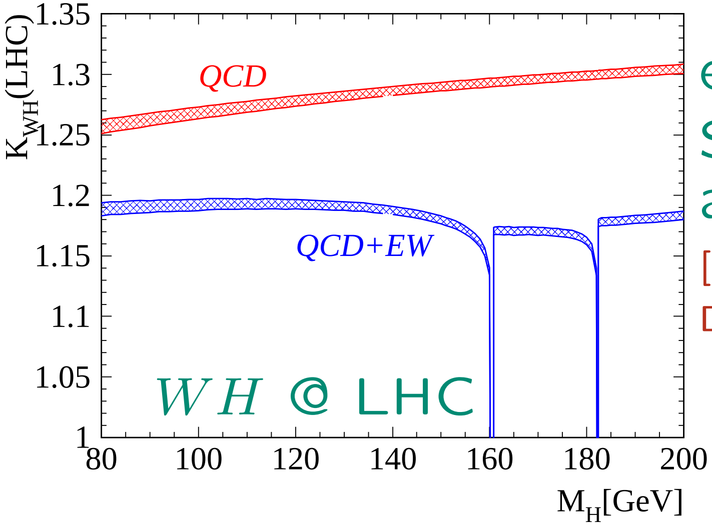


Higgs strahlung, $q\bar{q}' \to VH$

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]

status of theory predictions:

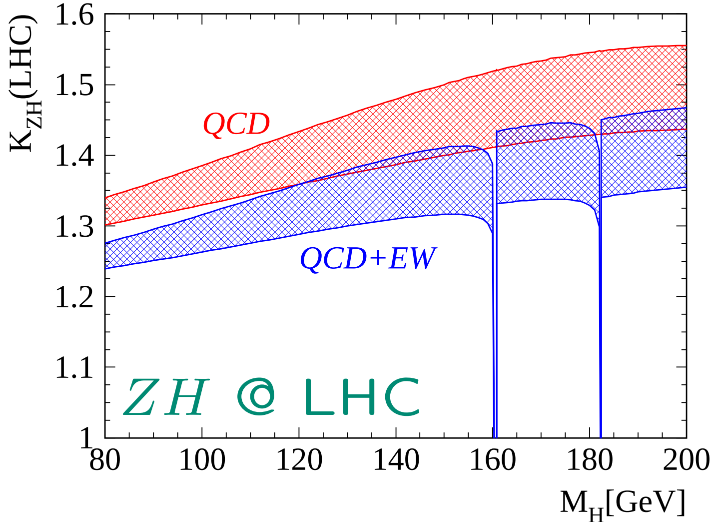
SM, LO [Glashow, Nanopoulos, Yildiz '78]

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]



– MSSM Higgs + high-p_T Jet

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[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:

* richer kinematical structure compared to inclusive Higgs production
* promising simulation results in the SM case

[Abdullin et al. '98 & '02; Zmushko '02; Mellado et al. '05]

* process loop-induced $\rightarrow$ potentially large effects from virtual particles

partonic processes similar to the SM:

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

but: * different Higgs Yukawa-couplings : $g_{q\bar{q}h^0}^{\text{MSSM}} = g_{q\bar{q}H}^{\text{SM}} \times f_q(\alpha, \beta)$

$\rightarrow$ mainly change of overall rate

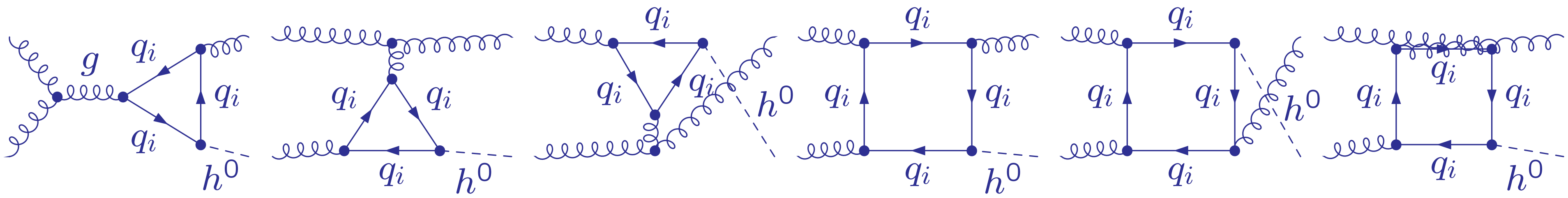
* additional superpartner-loops (even additional topologies)

$\rightarrow$ also angular distribution changed

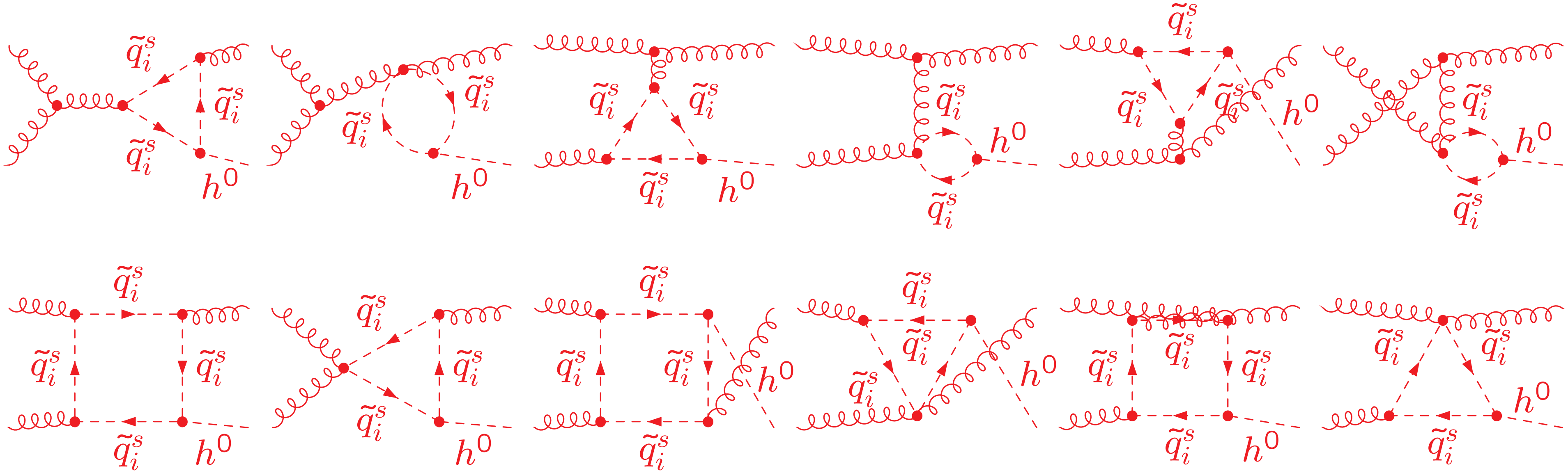
Feynman graphs :

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

quark loops

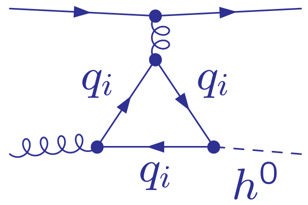


superpartner loops

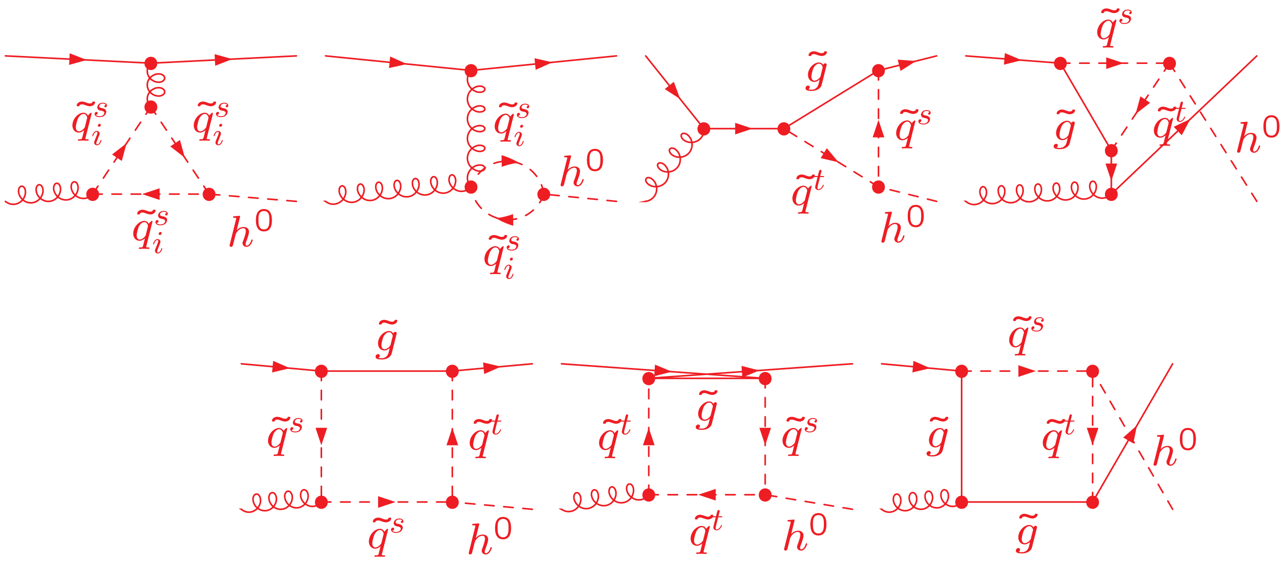


quark gluon scattering, $qg \to h^0 q$

quark loops

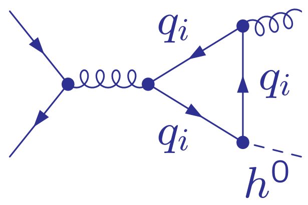


superpartner loops

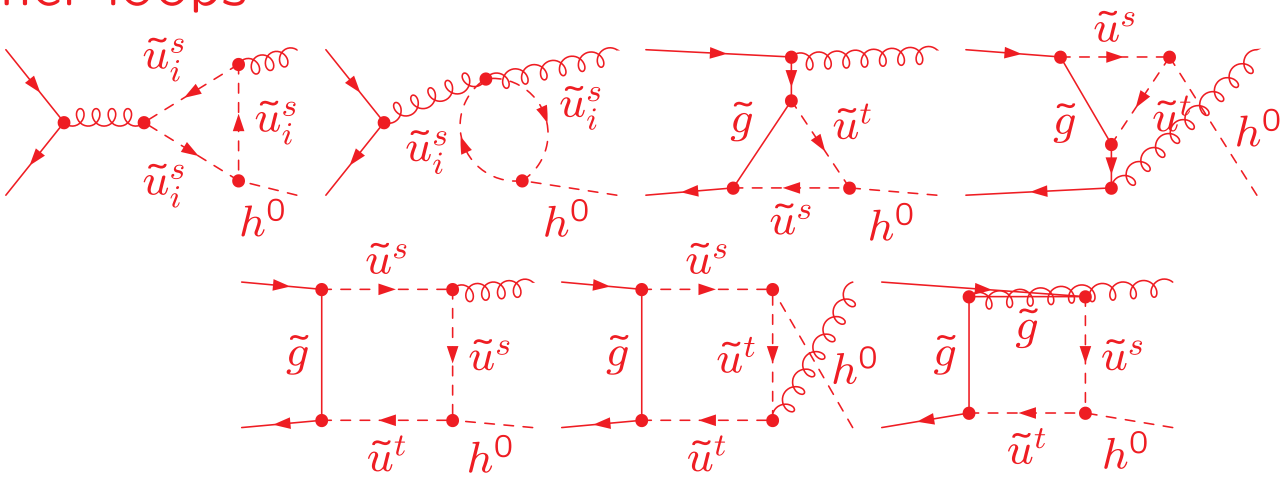


quark anti-quark annihilation, $q\bar{q} \longrightarrow h^0 g$

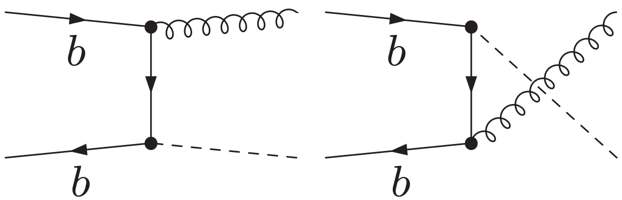
quark loops



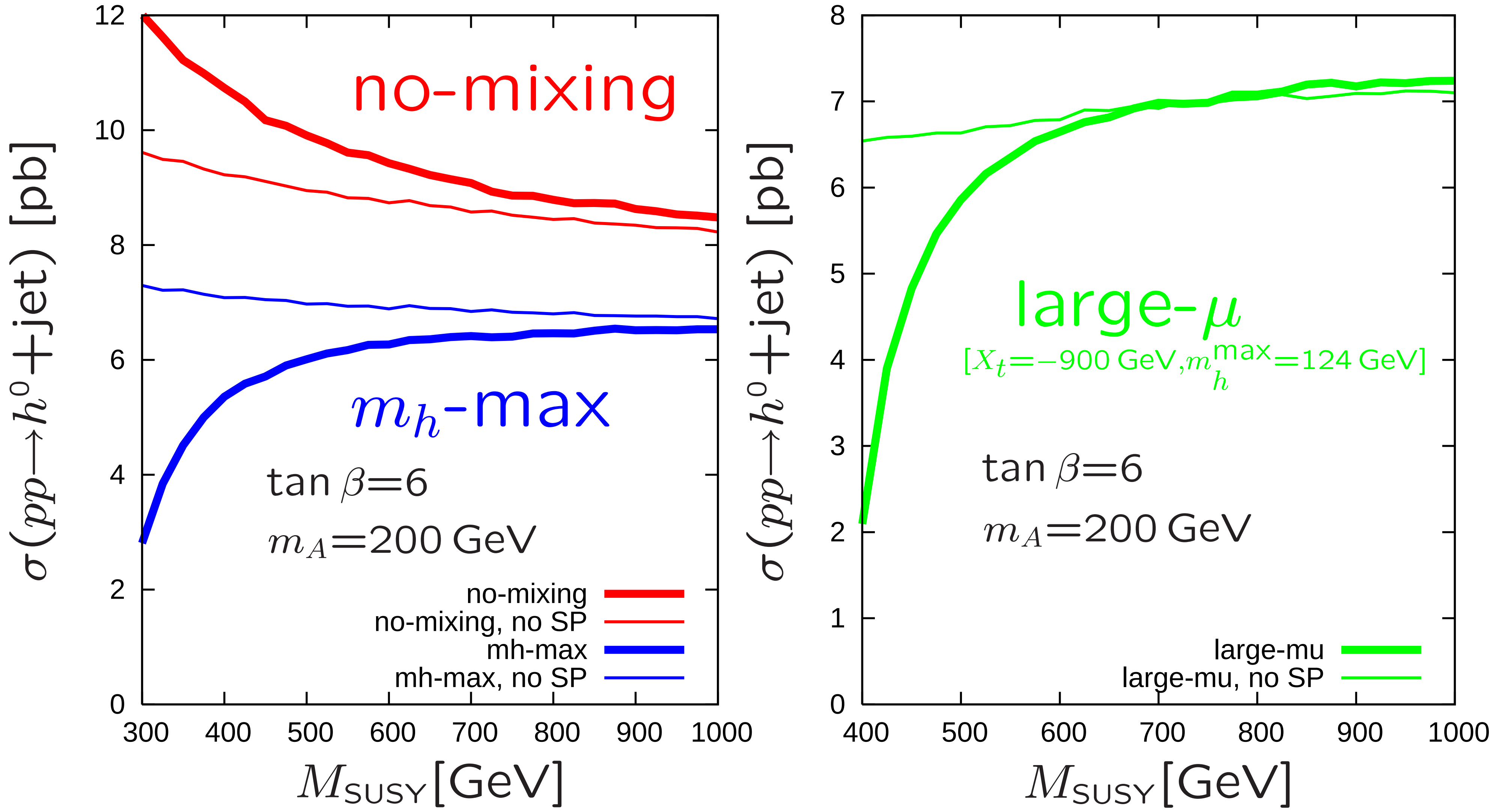
superpartner loops



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

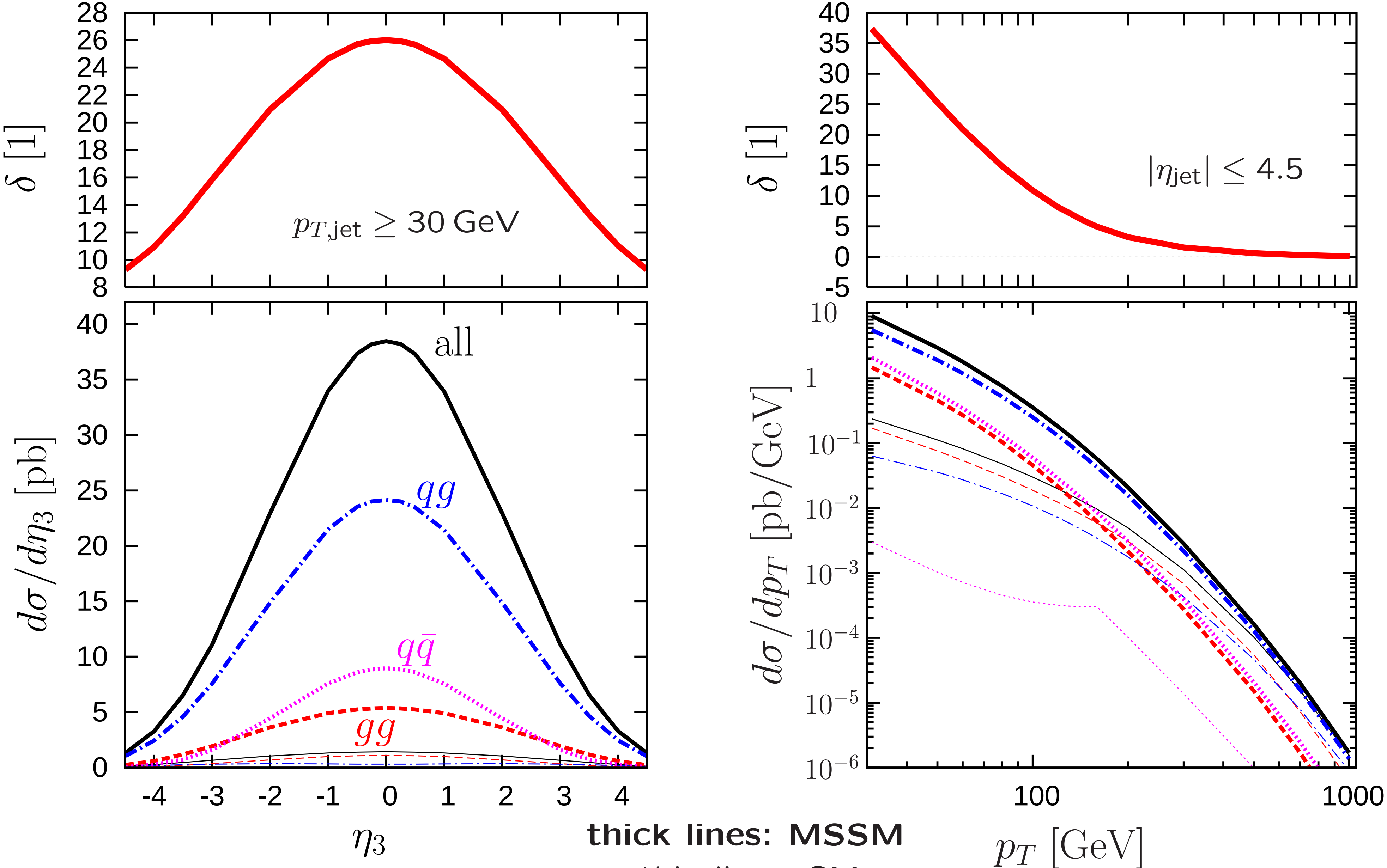


M_{SUSY} -dependence :



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

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

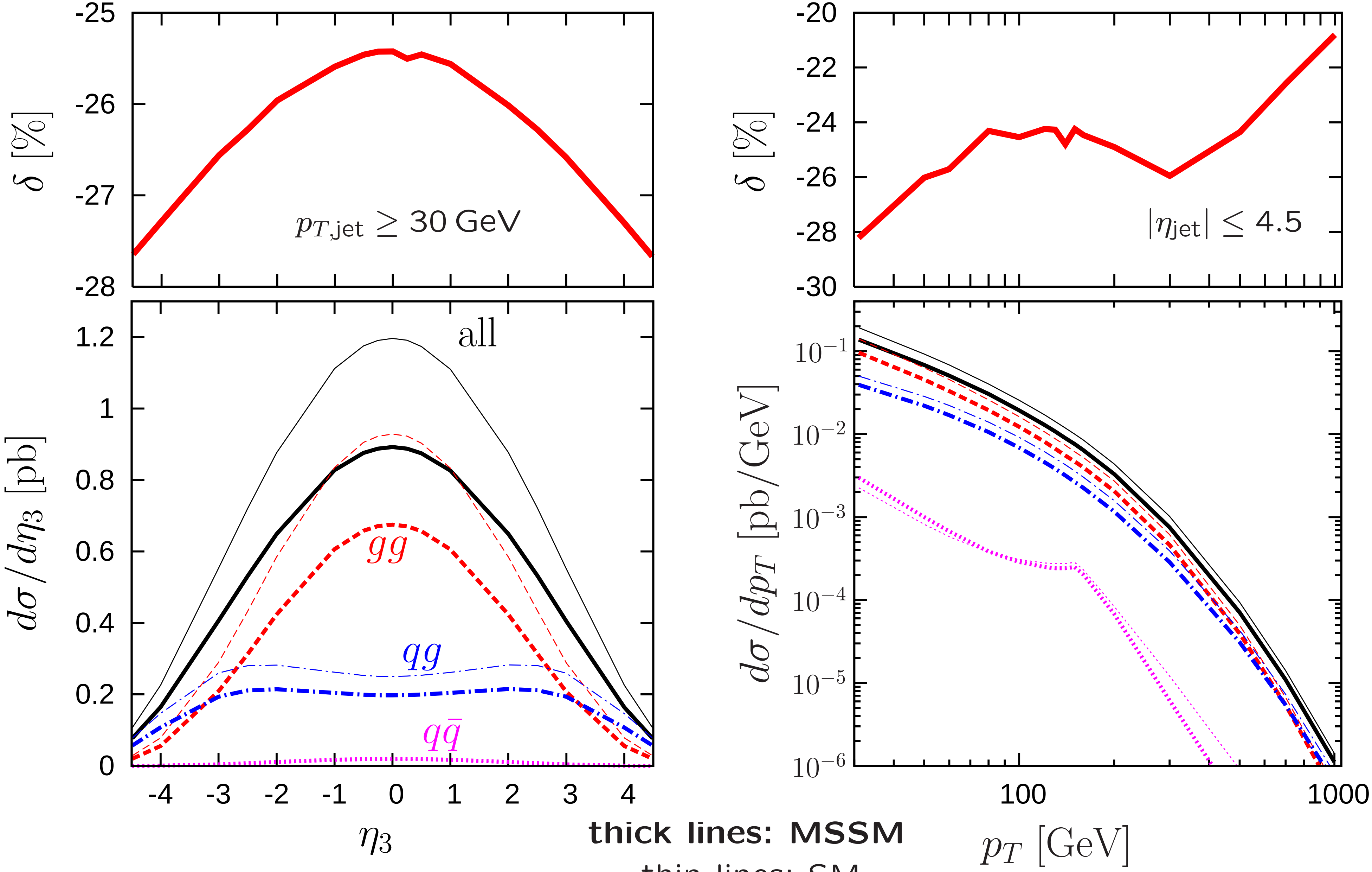


thick lines: MSSM

thin lines: SM

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

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



thick lines: MSSM

thin lines: SM

– HiggsBounds

– HiggsBounds: [Bechtle, Brein, Heinemeyer, Weiglein, Williams '08]

Decide for models with an arbitrary number of neutral Higgs bosons, whether a scenario is excluded at the 95% C.L. by LEP or Tevatron.

- Higgs search @ LEP/Tevatron:

  → limits on cross sections of signal topologies (individual & combined).

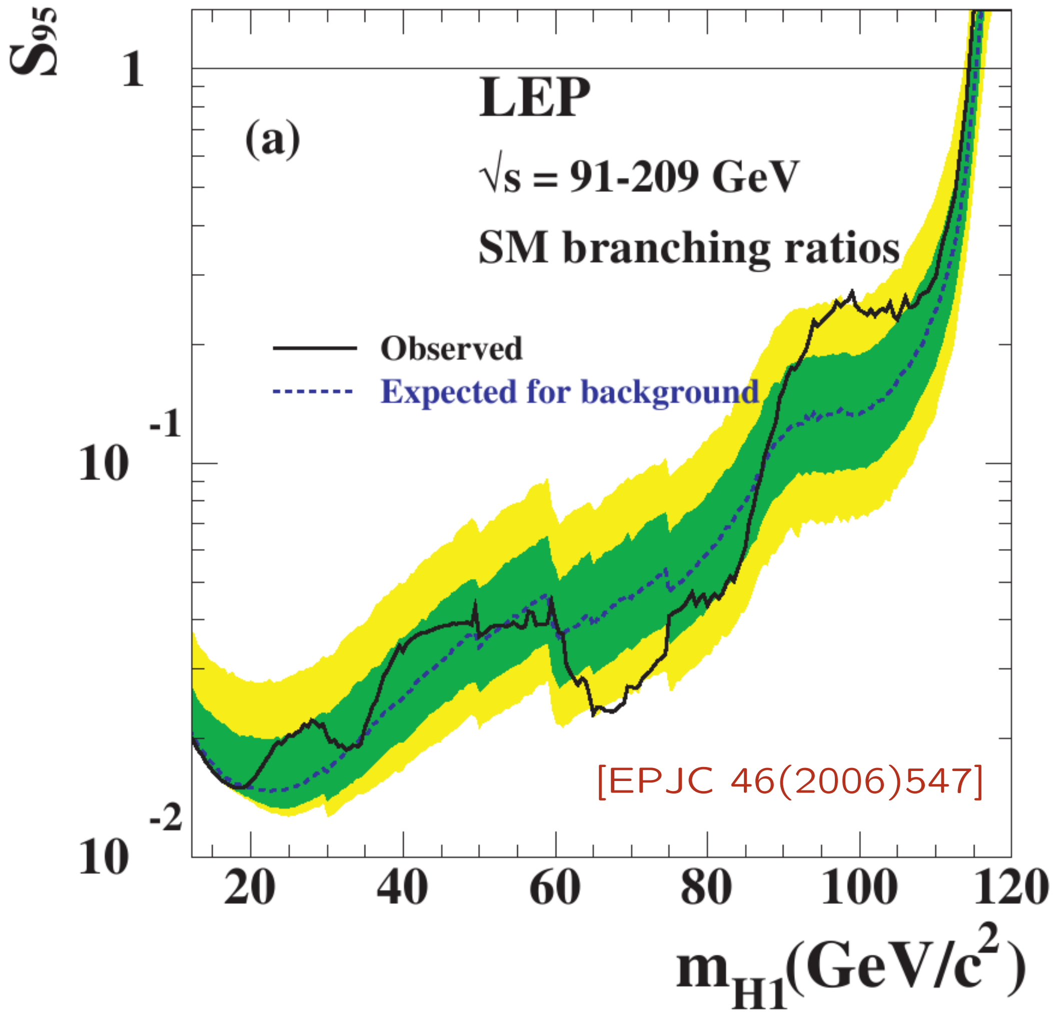
  → individual publications, not convenient to use *all* of them

- HiggsBounds:

  → offers easy access to a wealth of published limits in form of a FORTRAN program and a web page (`www.ippp.dur.ac.uk/HiggsBounds/`).

  → model-independent tool which offers a flexible range of input formats for the necessary model predictions (including the number of neutral Higgs bosons).

example 1: LEP SM combined limit



$$S_{95}(m_{H1}) := \frac{\sigma_{\text{max}}}{\sigma_{\text{SM}}}(m_{H1})$$

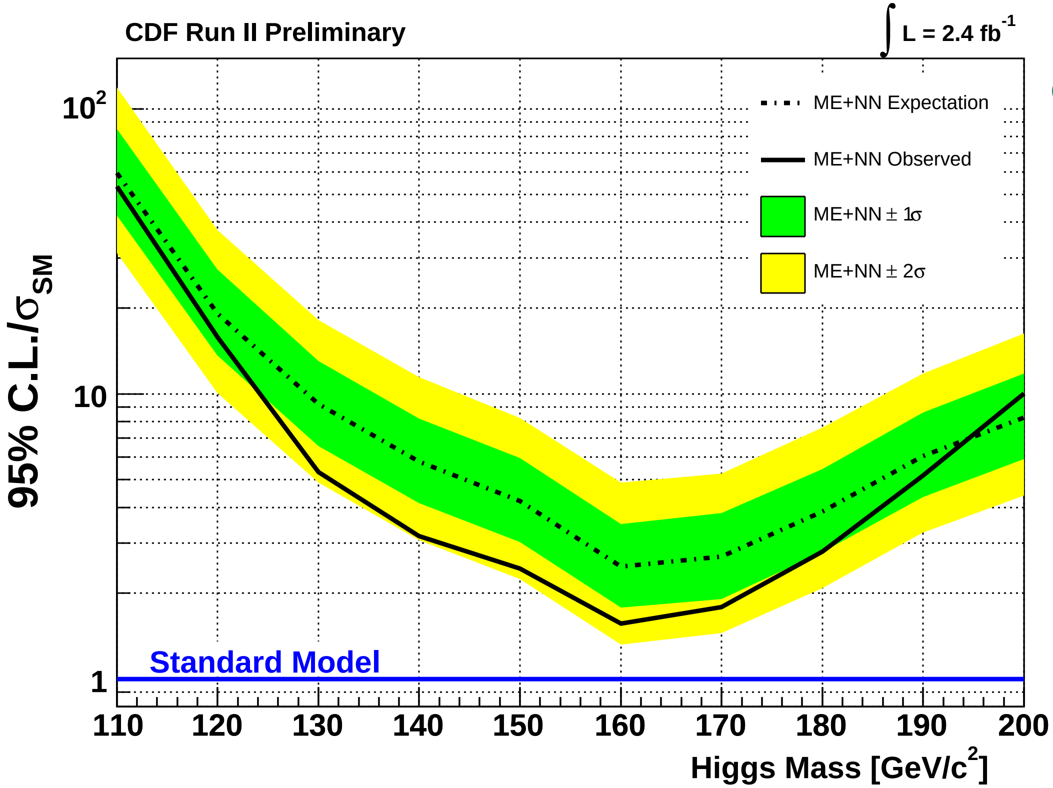
where $\sigma_{\text{max}}(m_{H1})$ is the maximal Higgs production cross section compatible with the background-only hypothesis at 95% C.L.

A SM-like model with

$$\sigma_{\text{model}}(m_{H1}) > \sigma_{\text{max}}(m_{H1})$$

or $\frac{\sigma_{\text{model}}(m_{H1})}{\sigma_{\text{max}}(m_{H1})} > 1$

is said to be excluded at the 95% C.L.



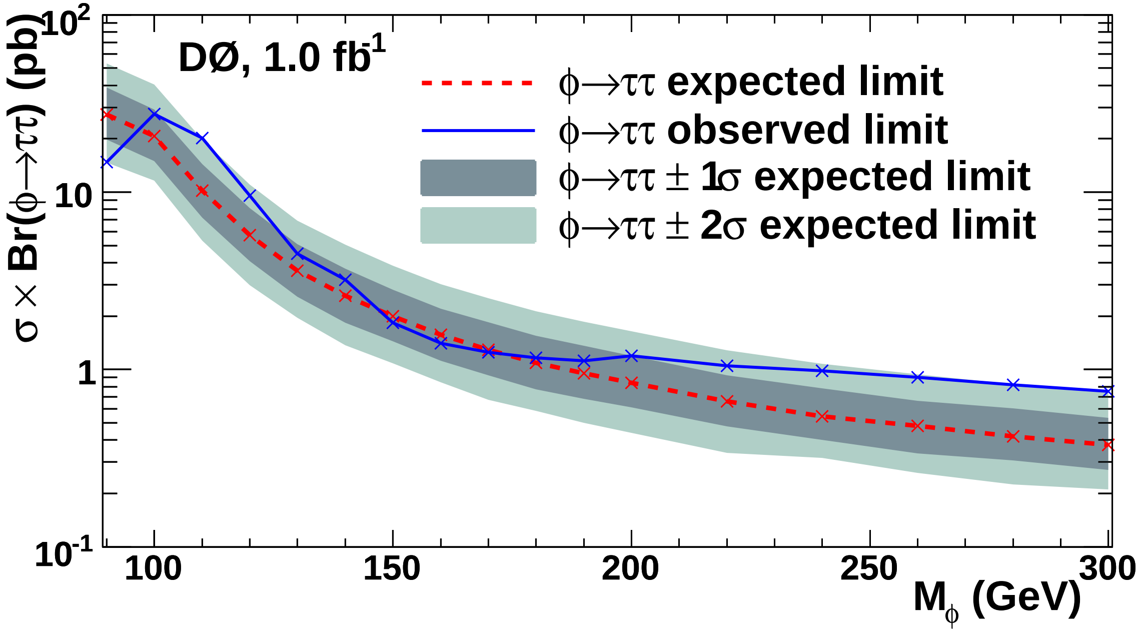
example 2: Tevatron single topology limits

a) $p\bar{p} \to H \to WW^\star$ using 1.9 fb^{-1} [CDF note 8958]

cross section ratio limit

b) $p\bar{p} \to H \to \tau^+\tau^-$ using 1 fb^{-1} [DØ hep-ex/0805.2491]

absolute cross section limit



LEP search topologies

Currently, we include predicted and observed S_{95} values for the following search topologies [EPJC 46(2006)547]

1. $e^+e^- \to (h_k)Z \to (b\bar{b})Z$,
2. $e^+e^- \to (h_k)Z \to (\tau^+\tau^-)Z$,
3. $e^+e^- \to (h_k \to h_ih_i)Z \to (b\bar{b}b\bar{b})Z$,
4. $e^+e^- \to (h_k \to h_ih_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$,
5. $e^+e^- \to (h_kh_i)Z \to (b\bar{b}b\bar{b})Z$,
6. $e^+e^- \to (h_kh_i)Z \to (\tau^+\tau^-\tau^+\tau^-)Z$,
7. $e^+e^- \to (h_k \to h_ih_i)h_i \to (b\bar{b}b\bar{b})b\bar{b}$,
8. $e^+e^- \to (h_k \to h_ih_i)h_i \to (\tau^+\tau^-\tau^+\tau^-)\tau^+\tau^-$,
9. $e^+e^- \to (h_k \to h_ih_i)Z \to (b\bar{b})(\tau^+\tau^-)Z$,
10. $e^+e^- \to (h_k \to b\bar{b})(h_i \to \tau^+\tau^-)$,
11. $e^+e^- \to (h_k \to \tau^+\tau^-)(h_i \to b\bar{b})$,

Inclusion of additional channels, e.g. with $h_k \to$ invisible, is work in progress.

Tevatron search topologies

Currently, we include predicted and observed S_{95} values of 28 analyses of CDF, DØ and combinations of both experiments, using the following topologies:

$$p\bar{p} \to H \to \begin{cases} W^+W^- \to l^\pm \nu l^\mp \nu \\ \tau^+\tau^- \\ \gamma\gamma \end{cases}$$

$$p\bar{p} \to W^\pm H \to \begin{cases} l\nu b\bar{b} \\ W^\pm W^+ W^- \\ \gamma\gamma \end{cases}$$

$$p\bar{p} \to ZH \to \begin{cases} l^+ l^- b\bar{b} \\ \gamma\gamma \end{cases}$$

$$p\bar{p} \to W^\pm H/ZH \to b\bar{b} + E_T^{\text{miss.}}$$

$$p\bar{p} \to Hb \to 3\ b\text{-jets}$$

$$p\bar{p} \to H \text{ via VBF}, H \to \gamma\gamma$$

How to preserve the 95% C.L. limit:

- Determine for each search topology X the experimental predicted limit $[\sigma \times \mathrm{BR}]_{\text{predicted}}(X)$.

- Determine the topology X_0 with the highest sensitivity for the signal, i.e. of all topologies X find the topology X_0 where

$$\frac{[\sigma \times \mathrm{BR}]_{\text{model}}(X)}{[\sigma \times \mathrm{BR}]_{\text{predicted}}(X)}$$

  is maximal.

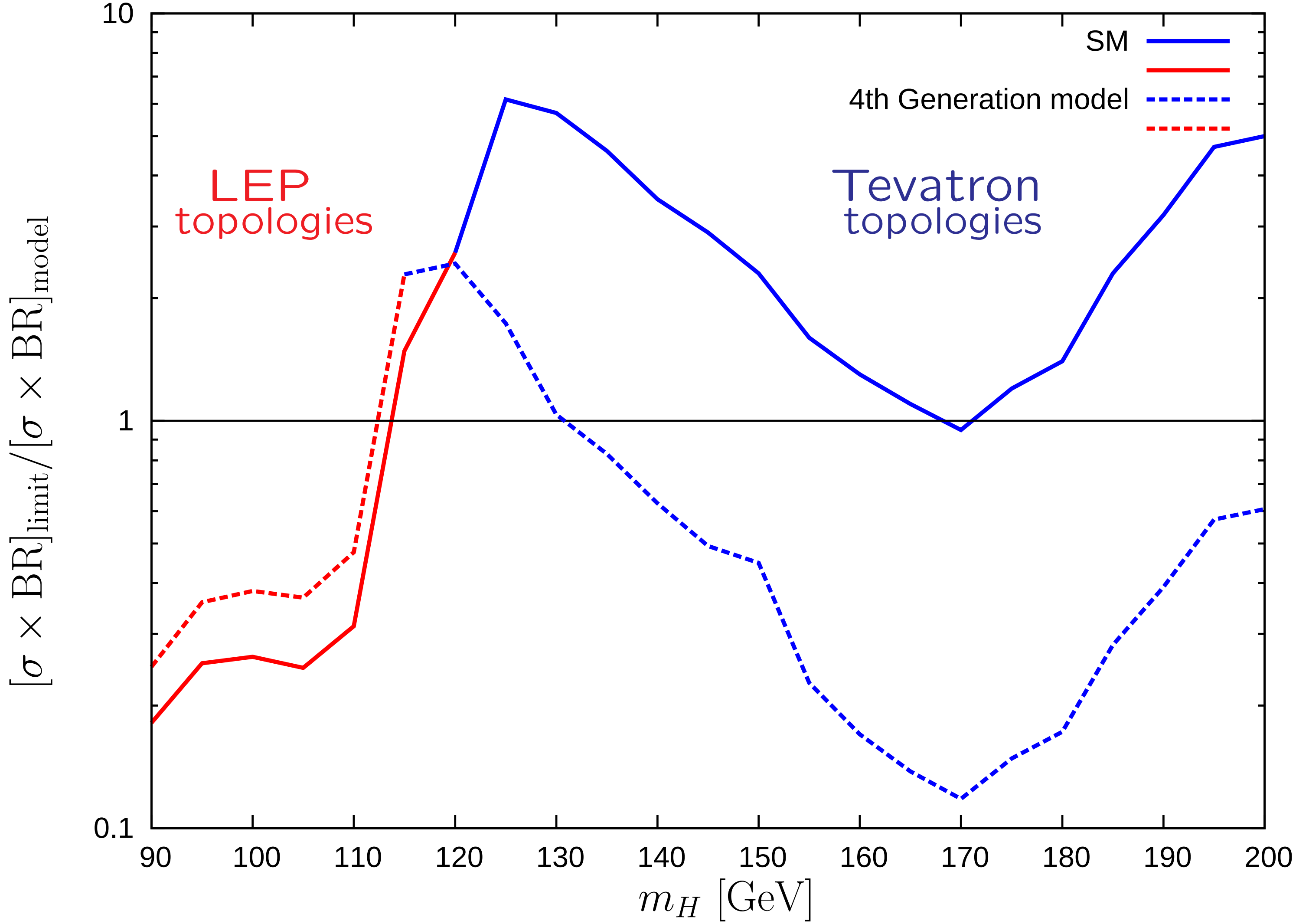
- If for this topology

$$\frac{[\sigma \times \mathrm{BR}]_{\text{model}}(X_0)}{[\sigma \times \mathrm{BR}]_{\text{observed}}(X_0)} > 1\,,$$

  then the model is excluded at 95% C.L. by the corresponding experimental analysis for the search topology X_0

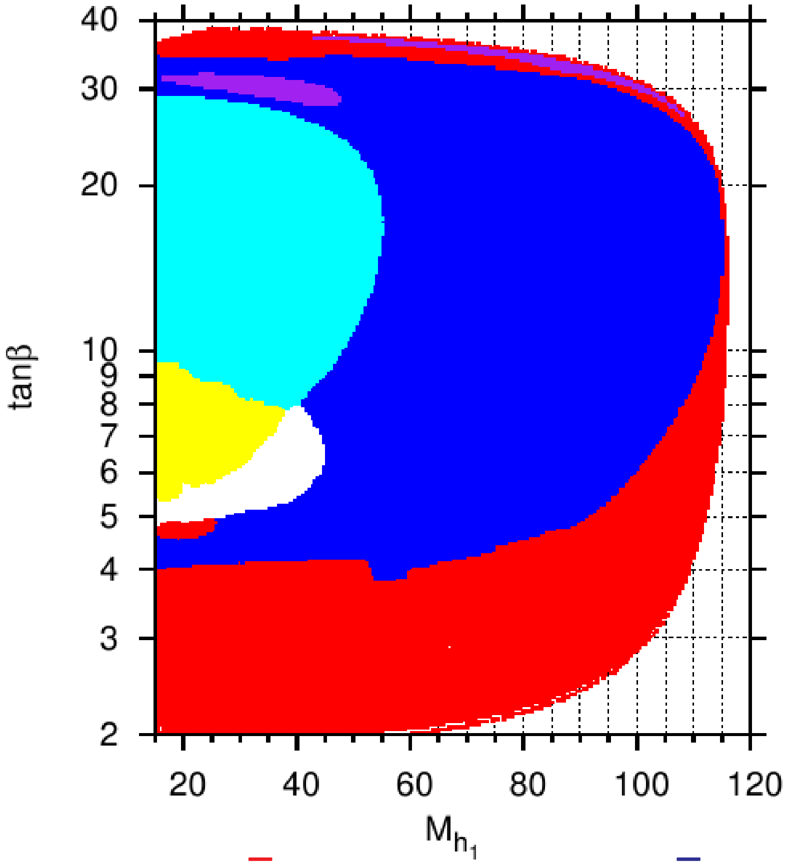
Application 1 : Exclusion range of SM vs. 4th Generation Model

$$\Gamma(H \to gg)_{\mathsf{model}} = 9 \times \Gamma(H \to gg)_{\mathsf{SM}}$$

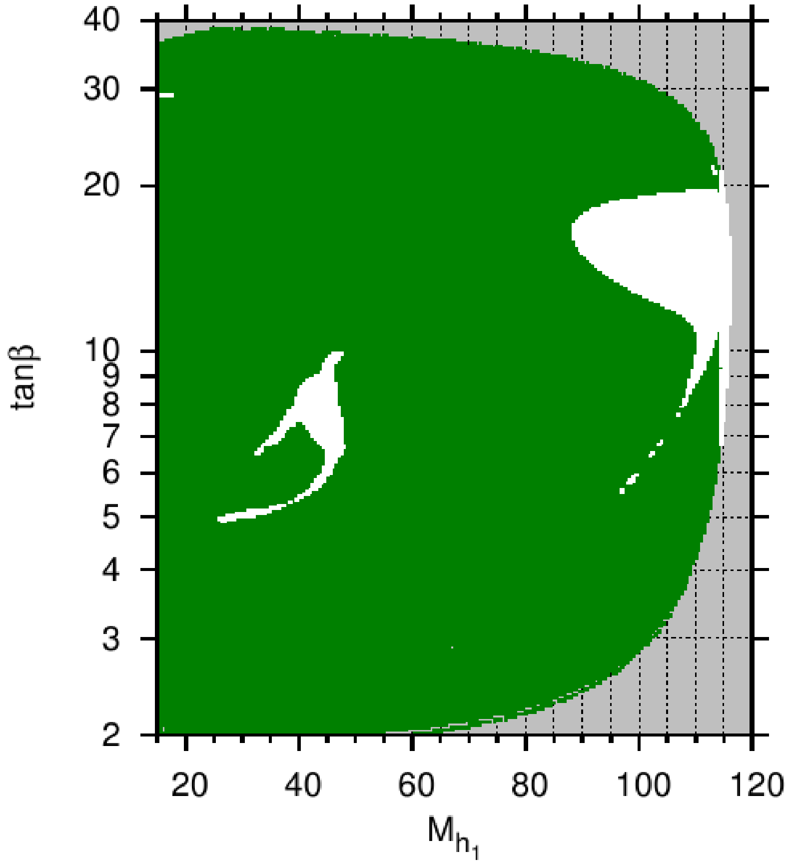


Application 2: LEP exclusion of the MSSM in the CPX scenario

channel with highest sensitivity



excluded region



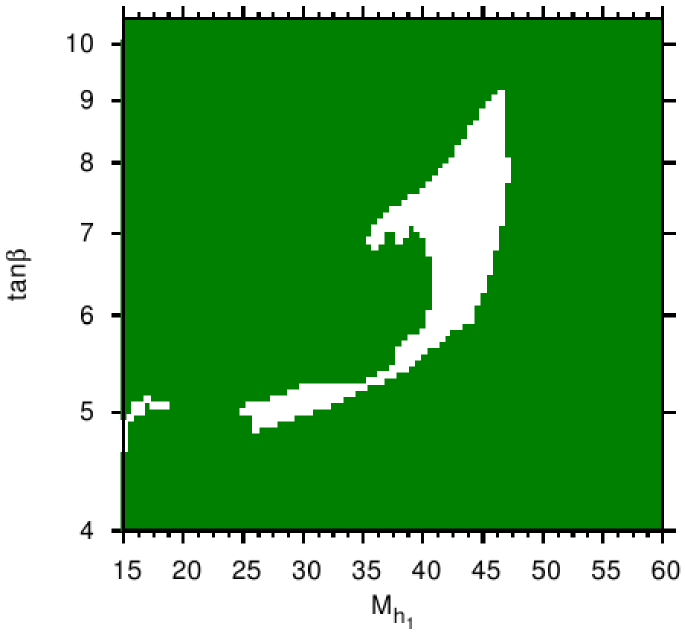
- $h_1 Z \to b\bar{b}Z$
- $h_2 Z \to b\bar{b}Z$
- $h_2 Z \to h_1 h_1 Z \to b\bar{b}b\bar{b}Z$
- $h_2 h_1 \to b\bar{b}b\bar{b}$
- $h_2 h_1 \to h_1 h_1 h_1 \to b\bar{b}b\bar{b}b\bar{b}$
- other channels

[Weiglein, Williams '08]

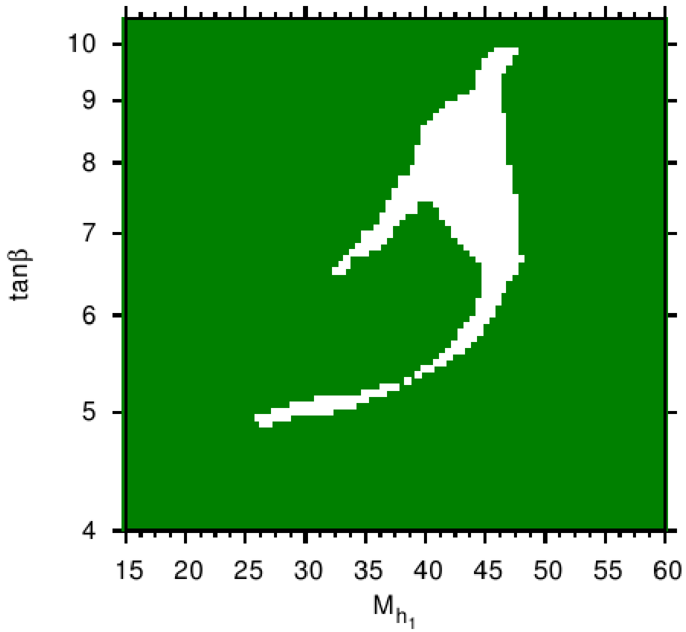
Application 2: LEP exclusion of the MSSM in the CPX scenario

top mass dependence of the “CPX hole”

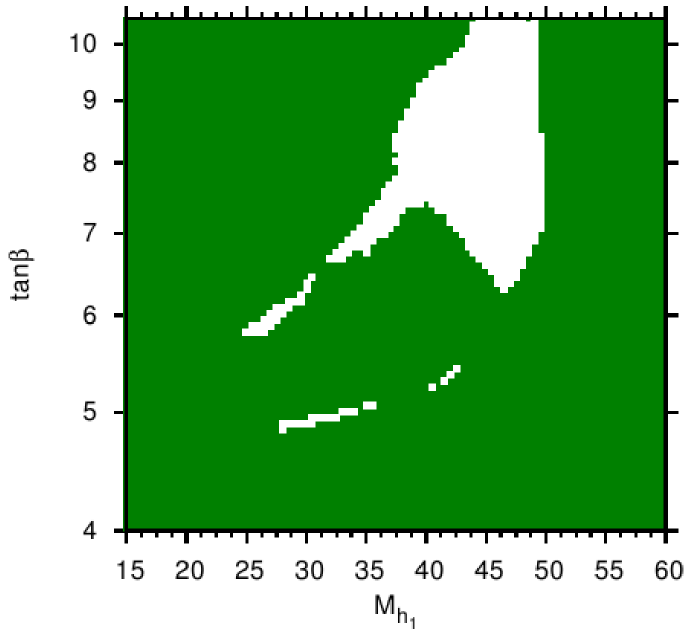
m_t=170.9 GeV



m_t=172.6 GeV



m_t=174.3 GeV



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.

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

- SM simulations show: Higgs + high-p_T jet is a promising alternative to the inclusive production. Differences between MSSM and SM also extend to shapes of differential distributions.

- HiggsBounds: powerful tool for constraining Higgs sectors of new physics models systematically. (soon available)

- Backup

– 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

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

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

consequences of R-parity conservation:

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

- the lightest superpartner (LSP) is stable
  $\longrightarrow$ 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:

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

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

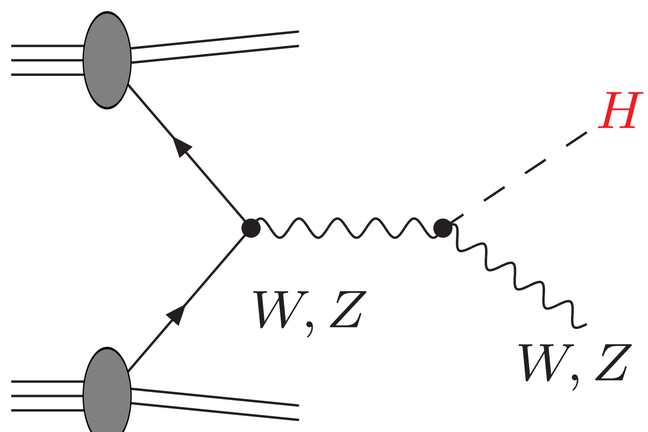
- large quantum corrections to Higgs masses (esp. to m_{h^0})

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

– SM Higgsstrahlung

[Backup]

– SM Higgsstrahlung



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

Our calculation: [OBr, Djouadi, Harlander '03]

Observation 1:

In LO/NLO QCD the cross section factorises ($V = W, Z$):

$$\frac{d\sigma}{dk^2}(q\bar{q} \to HV) = \sigma(q\bar{q} \to V^\star(k)) \cdot \frac{d\Gamma}{dk^2}(V^\star(k) \to HV)\,.$$

Observation 2:

Complete NNLO QCD corr. to $\sigma(q\bar{q} \to V^\star)$ are known

[Hamberg, van Neerven, Matsuura '91; Harlander, Kilgore '02].

$\longrightarrow$ Idea : Use $\sigma_{\rm NNLO}(q\bar{q} \to V^\star)$ to evaluate $\sigma(pp \to HV)$.

status of theory predictions:

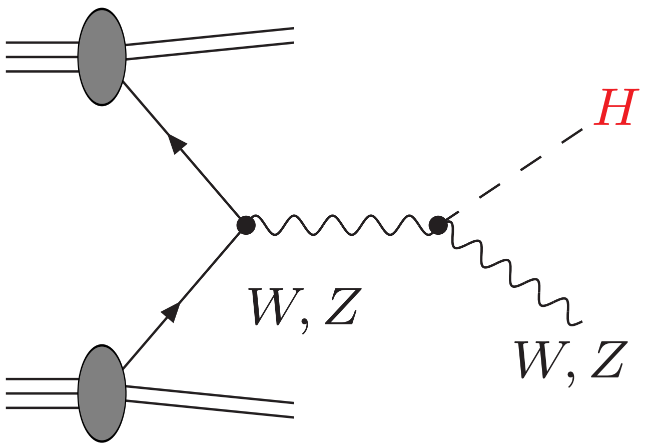
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

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

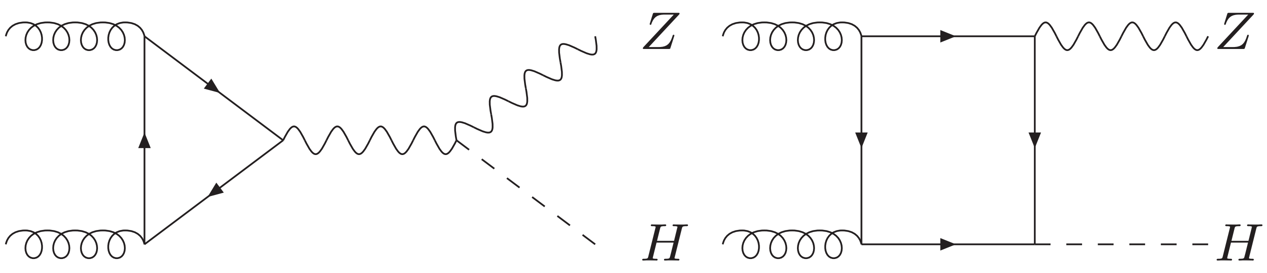
SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]

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

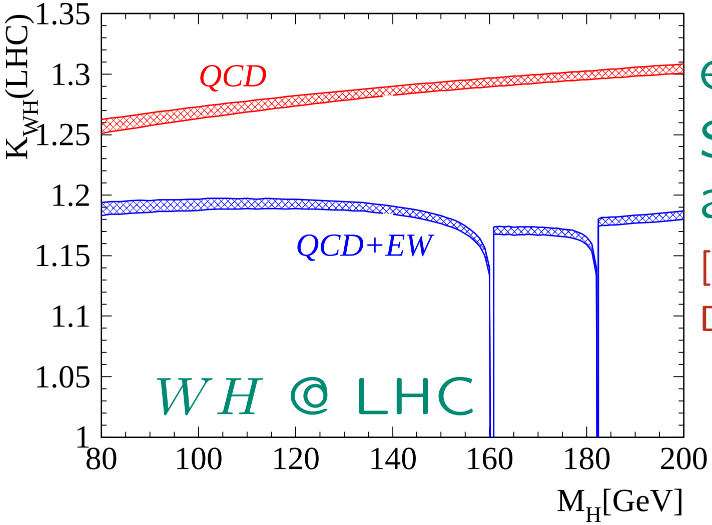


Higgs strahlung, $q\bar{q}' \to VH$

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]

status of theory predictions:

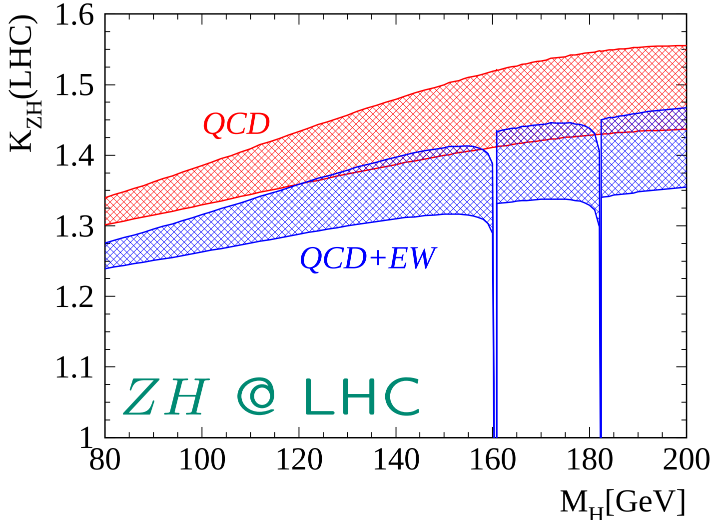
SM, LO [Glashow, Nanopoulos, Yildiz '78]

SM, NLO QCD [Han, Willenbrock ' 91]

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

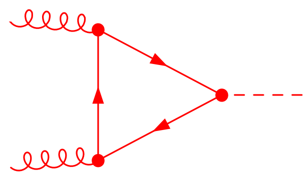
SM, NLO EW [Ciccolini, Dittmaier, Krämer '03]

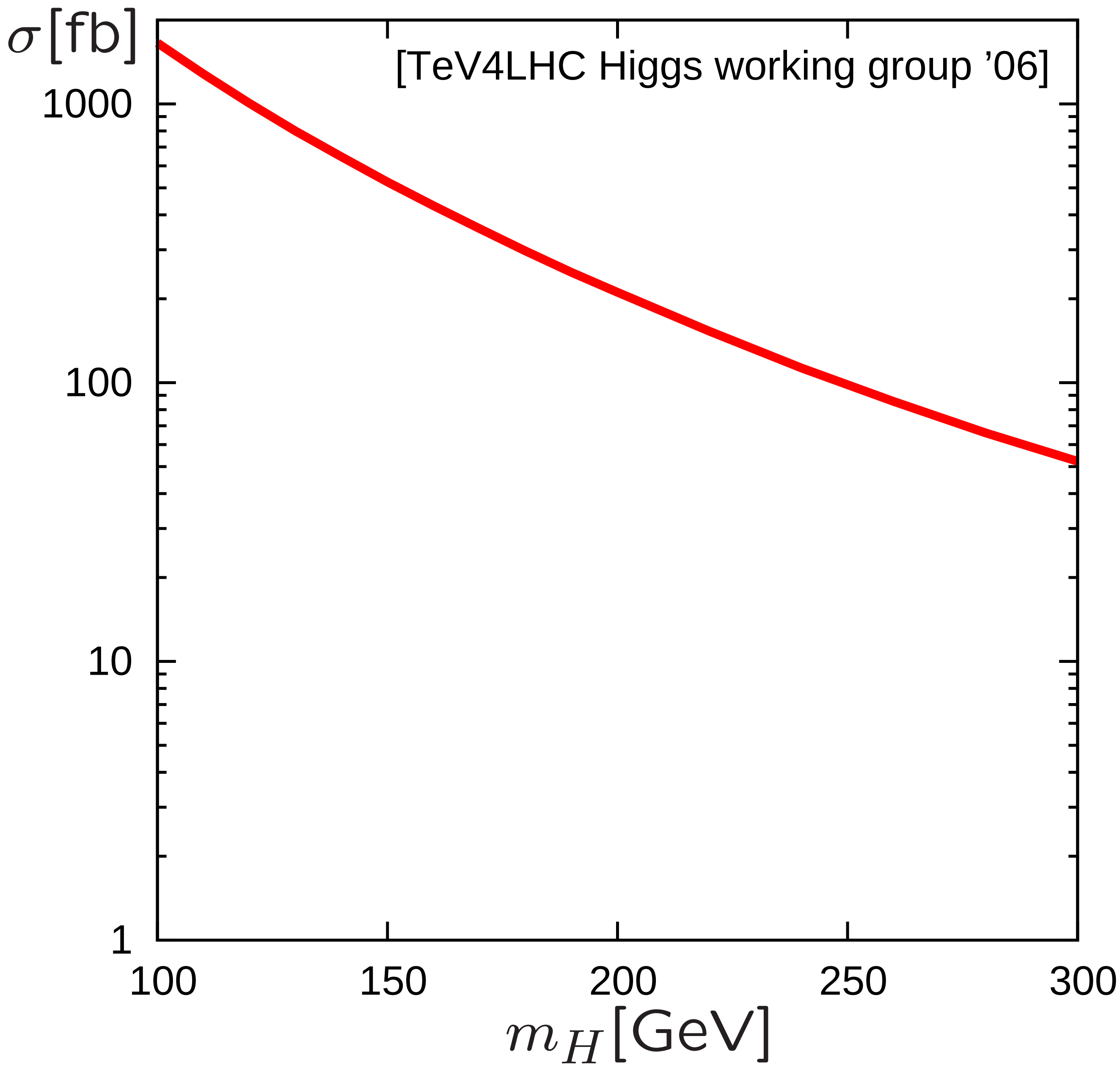
MSSM, NLO SUSY-QCD [Djouadi, Spira '00]

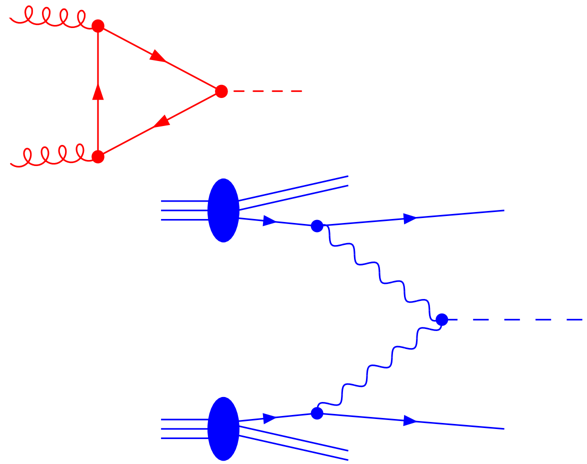


– SM Higgs Production at the Tevatron

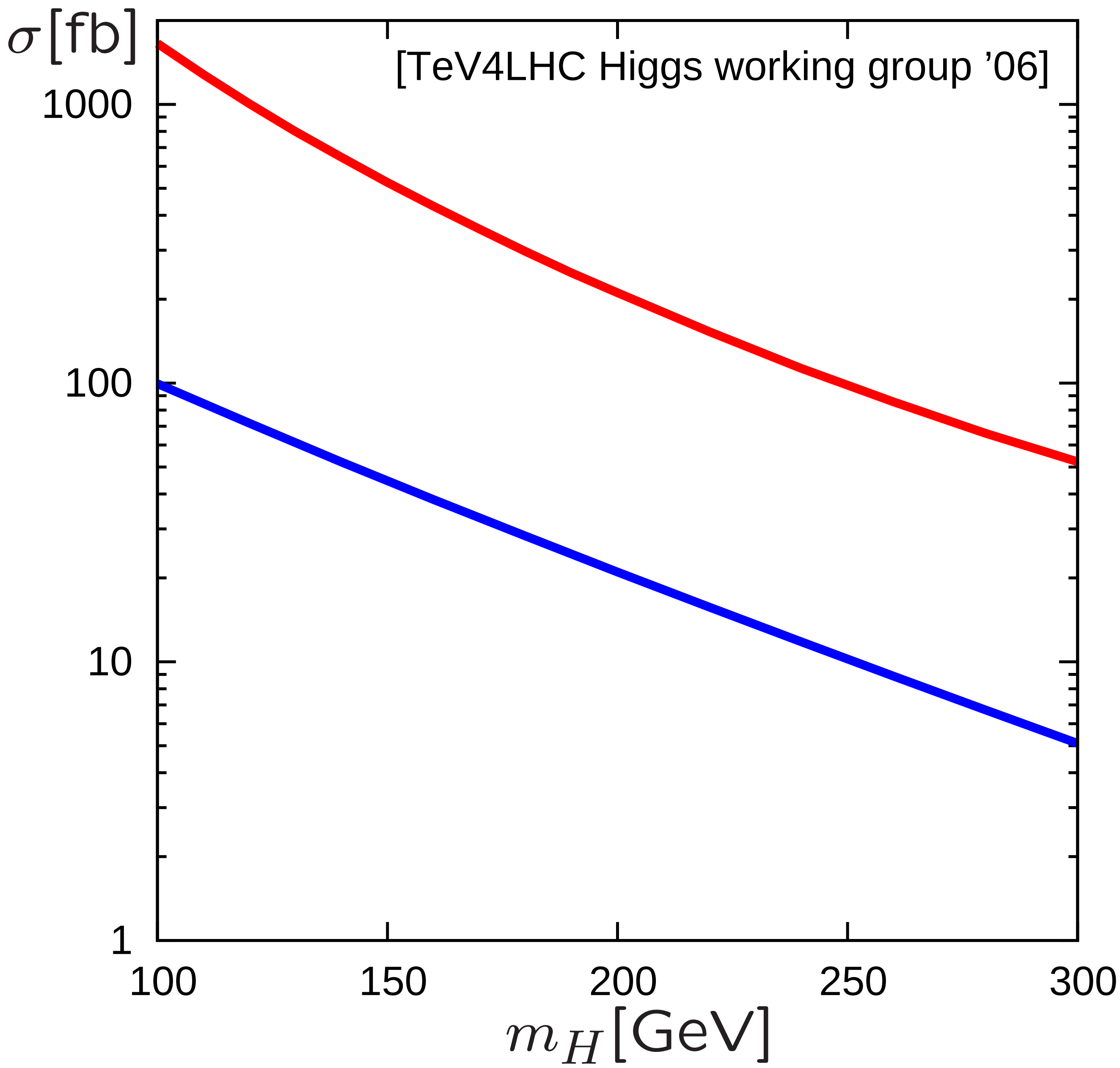
Predictions: SM Higgs production @ **Tevatron** :



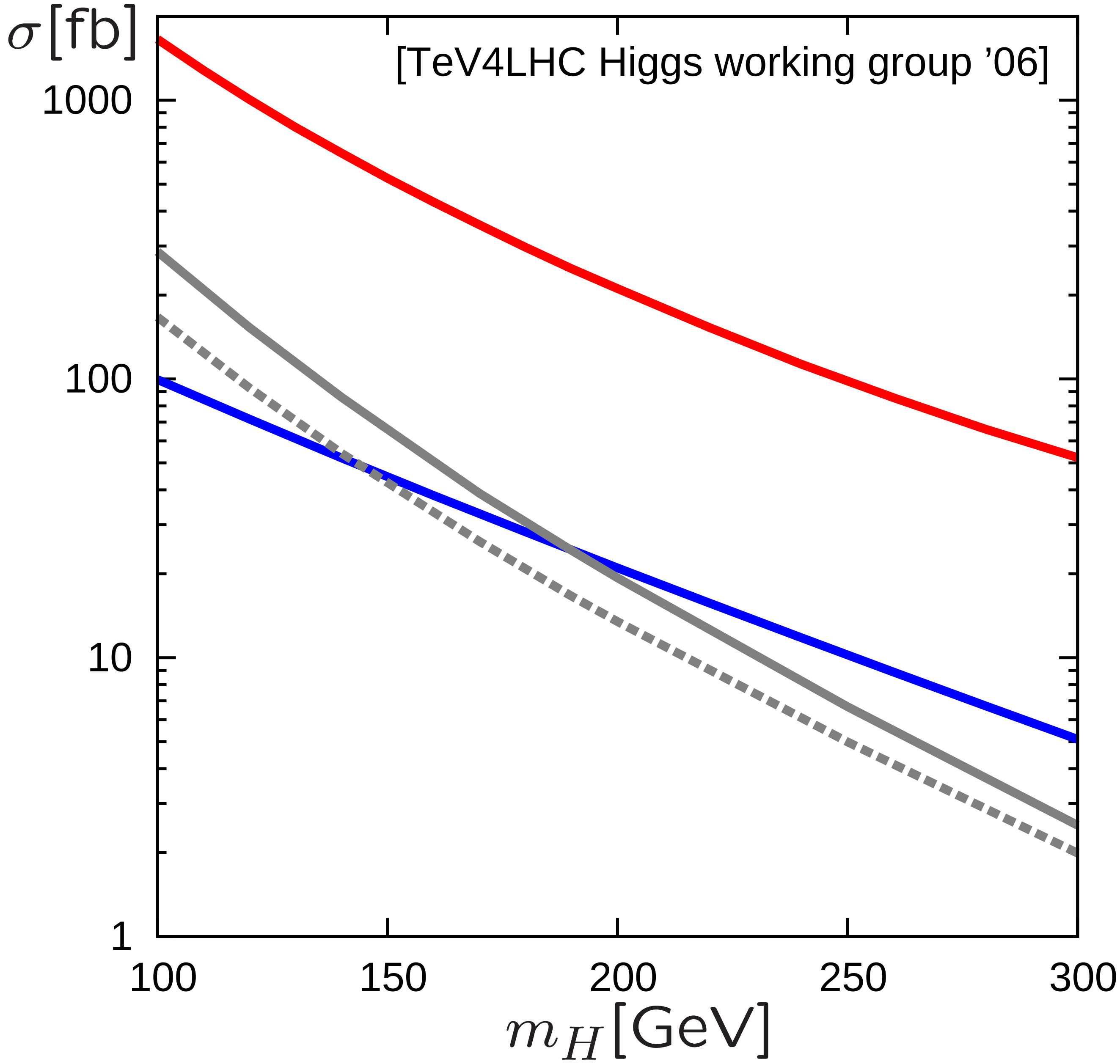


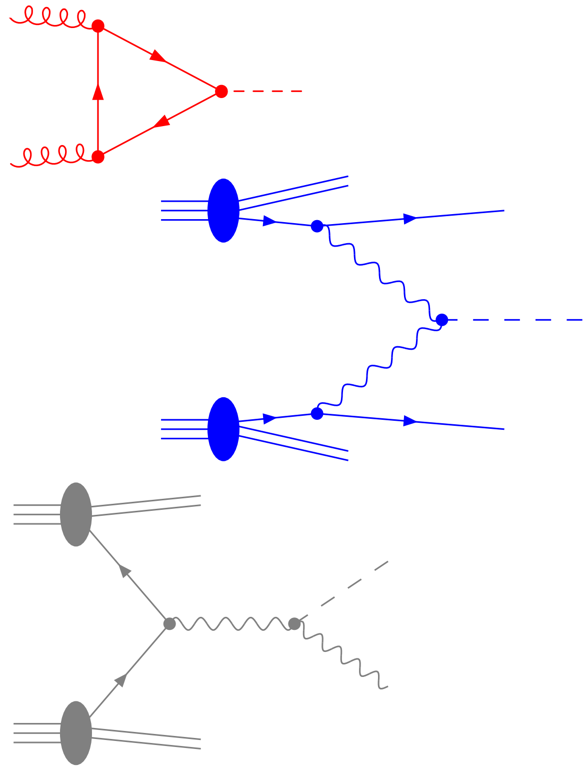


Predictions: SM Higgs production @ **Tevatron** :

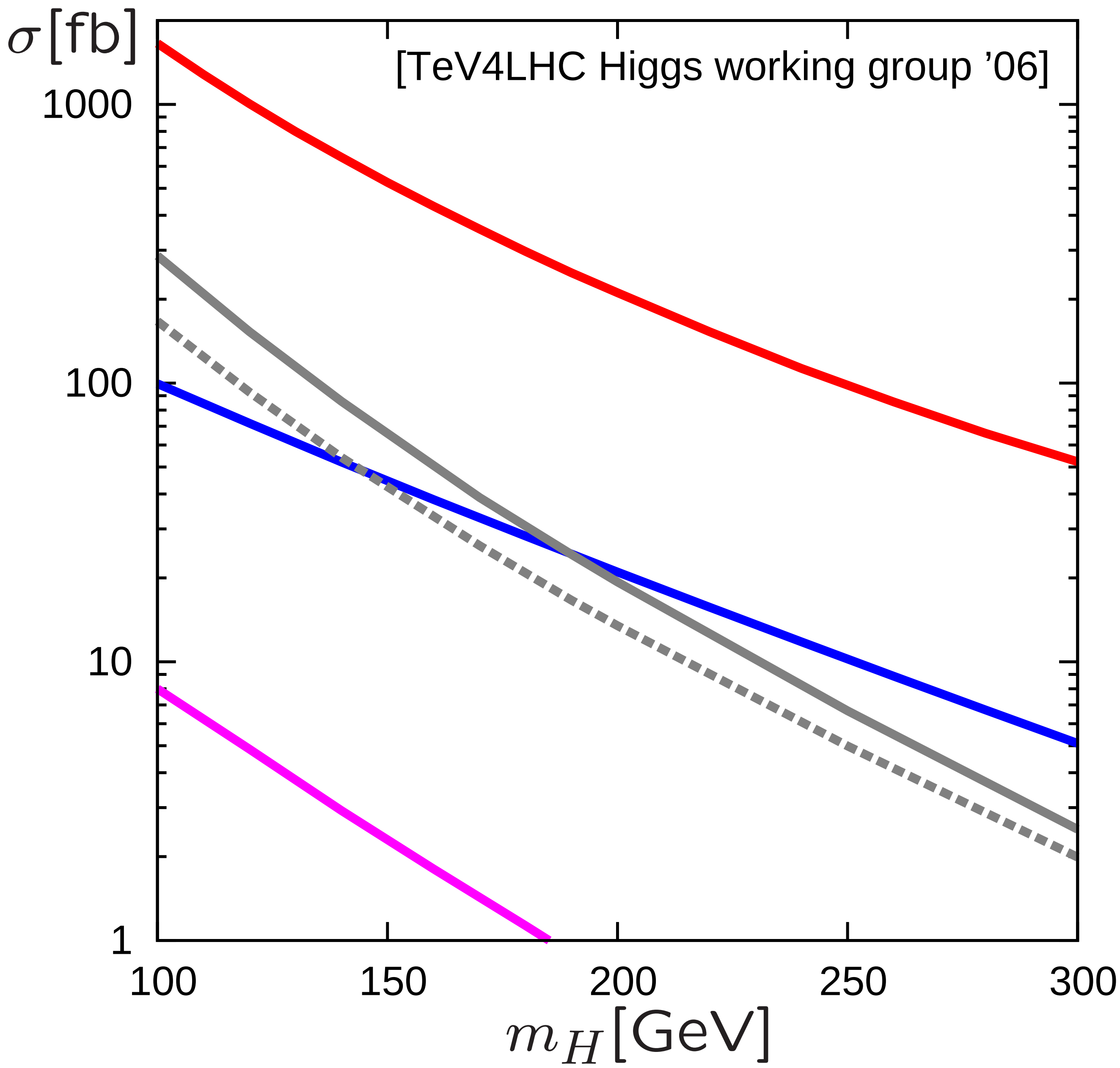


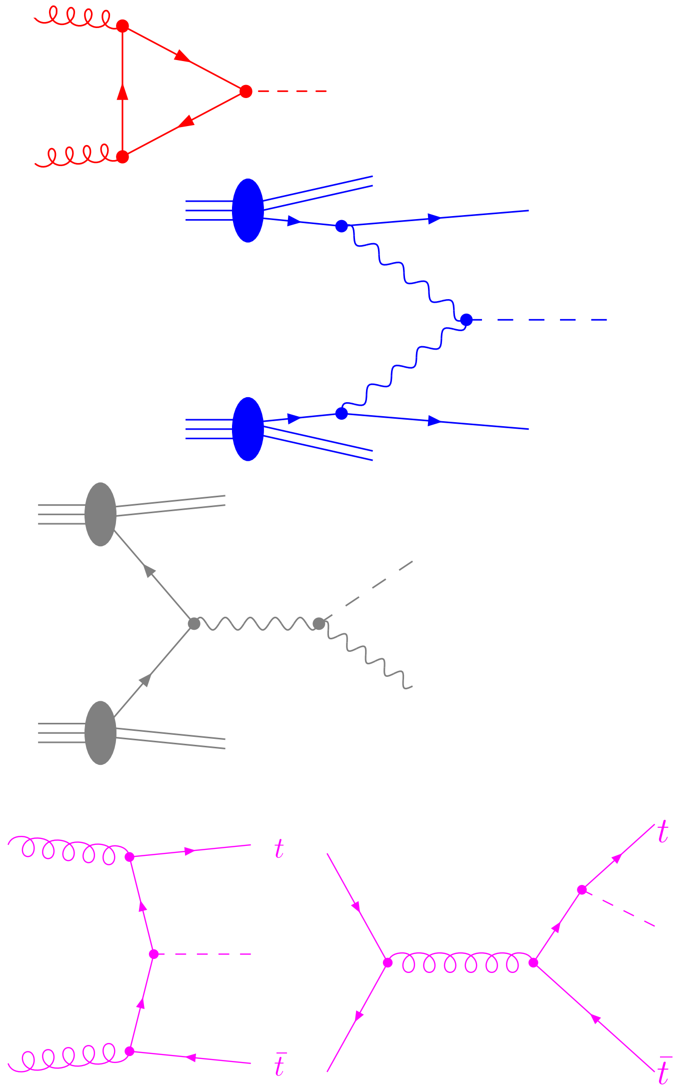
Predictions: SM Higgs production @ **Tevatron** :



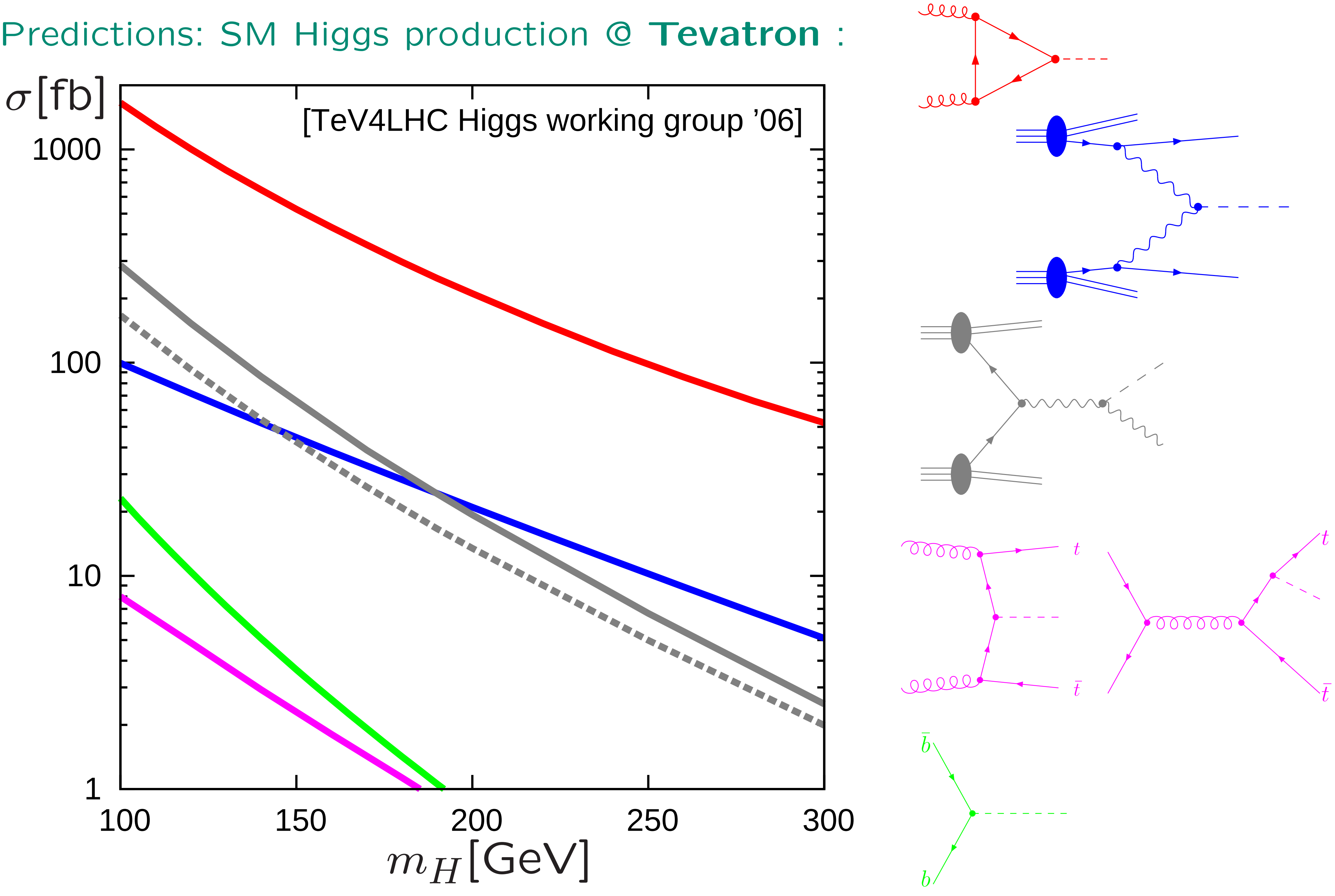


Predictions: SM Higgs production @ **Tevatron** :





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



– SM extensions

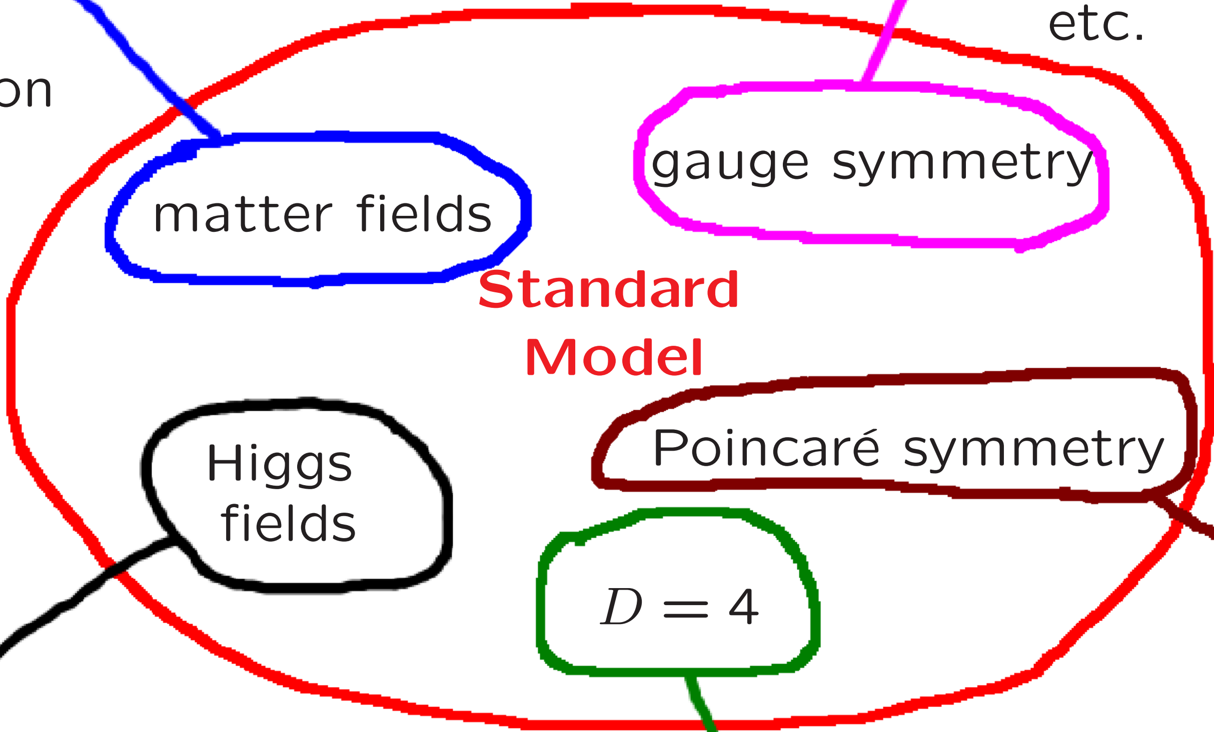
SM extensions: what is anticipated ?

extra matter fields
- ⋆ SUSY
- ⋆ Little Higgs
- ⋆ 4th generation

etc.

extra gauge groups
- ⋆ GUT
- ⋆ Technicolor
- ⋆ Little Higgs models
- ⋆ Z' models

etc.



supersymmetry
- ⋆ MSSM
- ⋆ NMSSM,...

etc.

change/extra multiplets
- ⋆ SUSY
- ⋆ Little Higgs
- ⋆ Higgs triplet models

etc.

extra dimensions
- ⋆ universal ED
- ⋆ Randall-Sundrum

etc.