Status and New Developments in Higgs Phenomenology

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outline :

- Higgs bosons, SUSY and extended models
  - Spontaneous symmetry breakdown, Higgs mechanism
  - Standard Model and extensions
  - The minimal supersymmetric standard model (MSSM)
- Higgs production at future hadron colliders
  - How to produce a Higgs boson ?
  - Neutral Higgs production overview
  - The Higgs search programme (schematic)
- $H^{\pm}W^{\mp}$ production @ LHC: MSSM vs. THDM
  - Charged Higgs search at LHC/Tevatron
  - MSSM/THDM $H^{\pm}W^{\mp}$ production

• Higgs bosons, SUSY and extended models

– Spontaneous symmetry breakdown, Higgs mechanism

Theory: non-abelian gauge symmetry forbids explicit mass terms for gauge bosons.

Experiment: massive vector bosons compatible with non-abelian gauge symmetry have been observed (W, Z)

$\longrightarrow$ contradiction ? $\longleftarrow$

General solution: **spontaneous symmetry breakdown (SSB)**,
i.e. introduce gauge invariant dynamics,
which breaks gauge symmetry in ground state.

Thus, one major task in particle physics is:

> to unravel the nature of
> **electroweak symmetry breaking**.

different models realizing SSB

$\swarrow$ $\searrow$

introduce weakly interacting scalar gauge multiplets that acquire a VEV

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

$\downarrow$ consequences: $\downarrow$

$\longrightarrow$ existence of Higgs particle(s)

$\longrightarrow$ theory may be applicable up to very high energy ($\sim M_{\text{GUT}}$ or M_{Planck}).

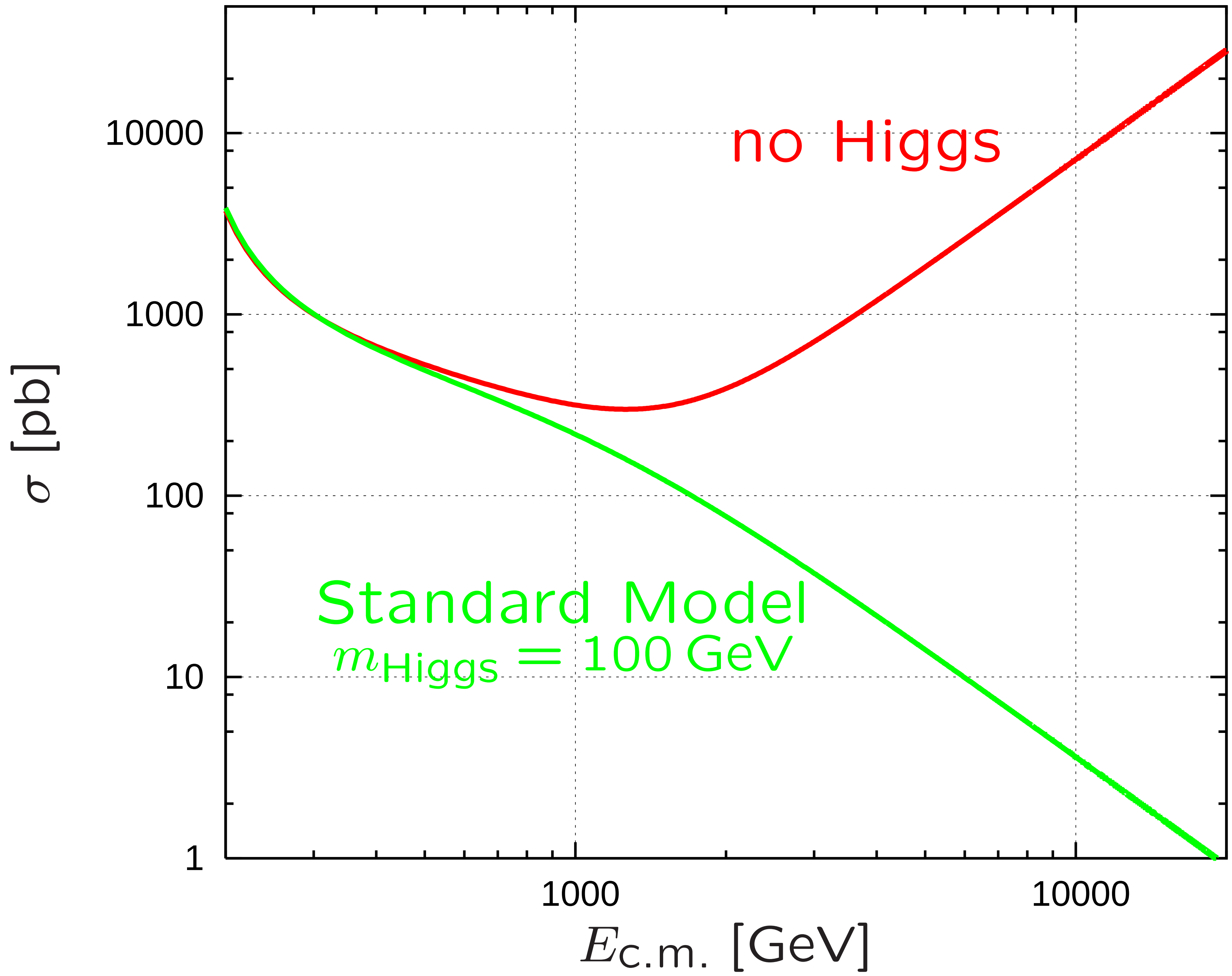
If so, then: Higgs is light, mass $m_H \lesssim 1\,\text{TeV}$

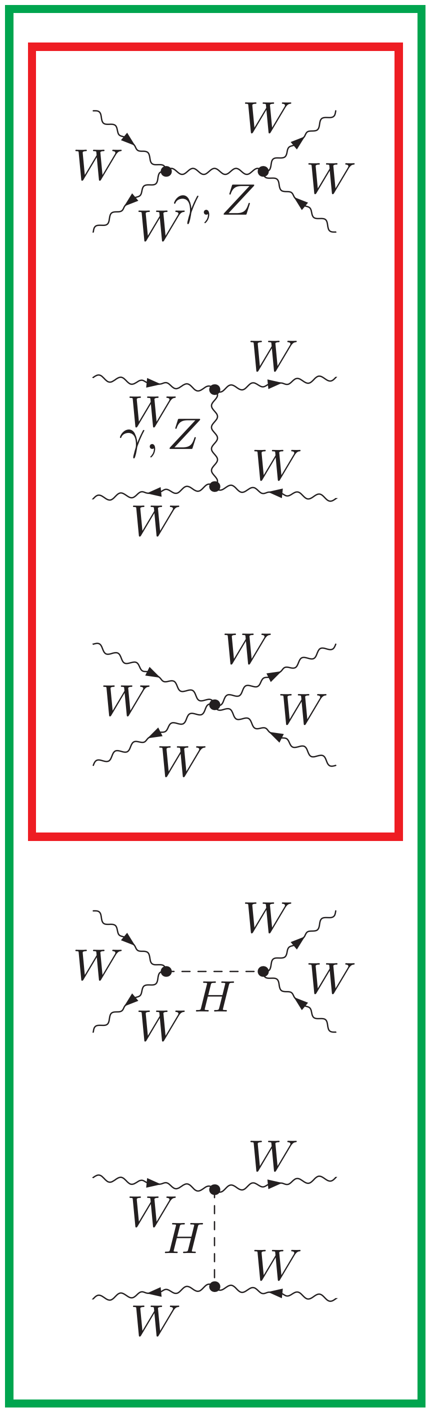
$\underbrace{\hphantom{\text{existence of Higgs particle(s), theory may be applicable}}}$

the Higgs mechanism

$\longrightarrow$ new effects of strong interaction at $\approx 1\,\text{TeV}$ (e.g. in WW-scattering)

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





– Standard Model and extensions

Experimental situation so far:

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

Theory:

- Many distinct possibilities to realize the Higgs mechanism.

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

$\longrightarrow$ models have to meet constraints, like

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

SM:

matter, gauge bosons + 1 Higgs doublet Φ

$\rightarrow$ 1 physical Higgs boson

$\swarrow$ $\searrow$

THDM:	MSSM:
(two Higgs doublet model)	(minimal supersym. 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

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

– The 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)

– The 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

MSSM Parameters (adding to the SM Parameters)

particles		parameters
gauginos/higgsinos $(\chi_i^{\pm}, \chi_i^0, \tilde{G})$	:	mass parameters $M_1, M_2, M_{\text{gluino}}, \mu$
sfermions $(\tilde{f})$	:	mass parameters $M_{\text{Sf.}}, A_f$
Higgs sector (H_1, H_2)	:	$m_{A^0}, \tan\beta = v_2/v_1$

usefull combination : mass mixing term in stop-sector:

$$X_t := A_t - \mu/\tan\beta$$

Consequences of SUSY for the MSSM Higgs sector

- The MSSM is *only* consistent with two Higgs doublets
- all Φ^4-interactions are determined by gauge couplings

$\longrightarrow$ mass spectrum and interactions determined (at tree-level) by two input parameters ($m_{A^0}, \tan\beta = v_2/v_1$)
[instead of seven ($m_{h^0}, m_{H^0}, m_{A^0}, m_{H^\pm}, \lambda_5, \alpha, \tan\beta$) in the THDM]

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

- There are large quantum corrections (esp. to m_{h^0})

$\longrightarrow$ Higgs properties depend on superpartners at the quantum level

$\longrightarrow$ even 3-loop corr. to m_{h^0} are significant for future comparison of LHC data with theory

$\longrightarrow$ m_{h^0} is a precision "observable"

present status: see [Degrassi, Heinemeyer, Hollik, Slavich, Weiglein '02]

• Higgs production at future hadron colliders

– How to produce a Higgs boson ?

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

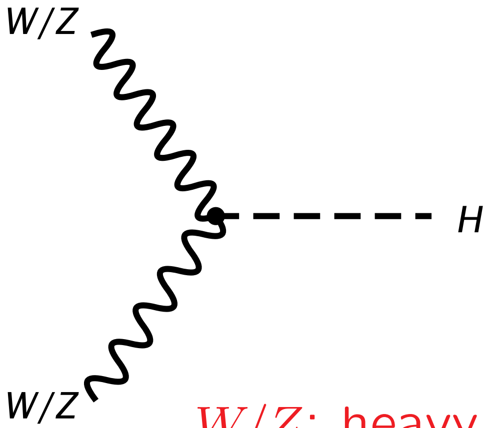
$\longrightarrow$ Problem: ordinary matter consists of

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

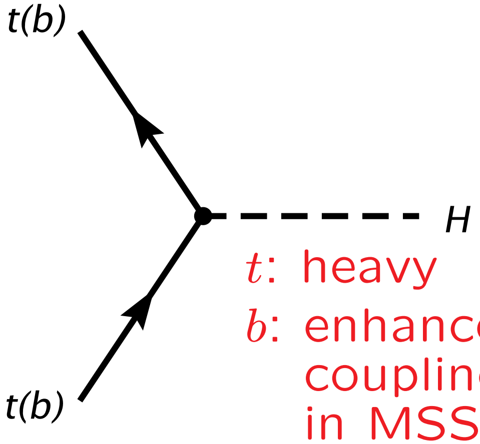
$\star$ with negligible couplings to the Higgs boson.

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

Therefore, most important couplings :

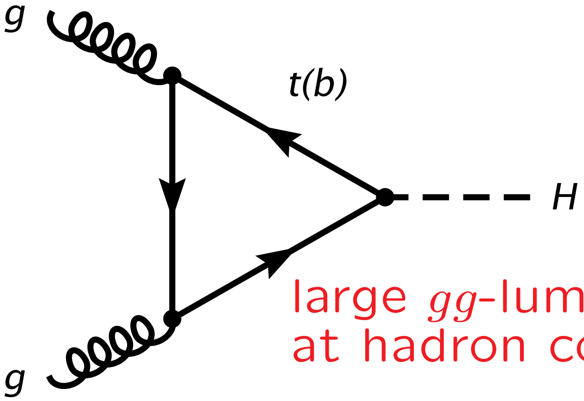


W/Z: heavy



t: heavy

b: enhanced coupling in MSSM



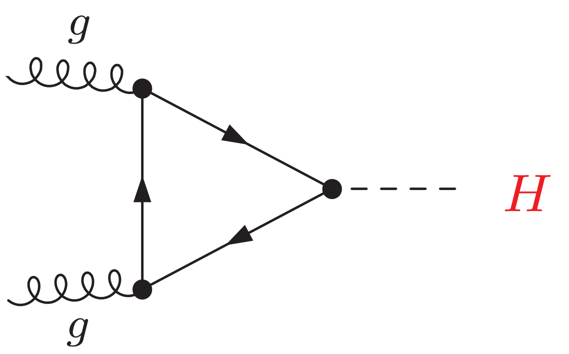
large gg-lumi at hadron colliders

very important property of *high* energy hadron colliders:

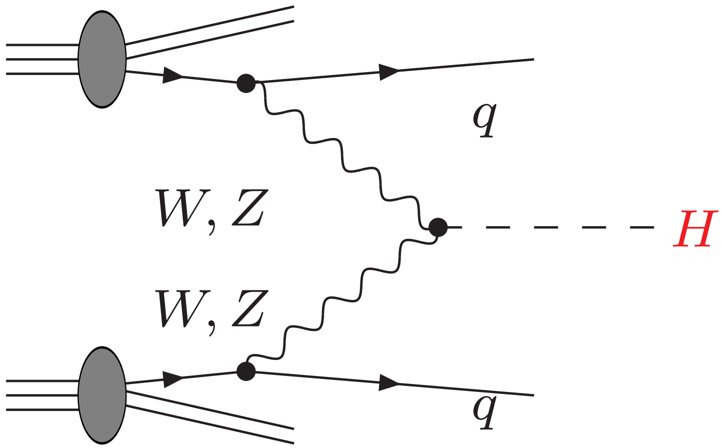
There is a huge number of gluons with small momentum fractions still having enough energy. to produce Higgs particles

– Neutral Higgs production overview

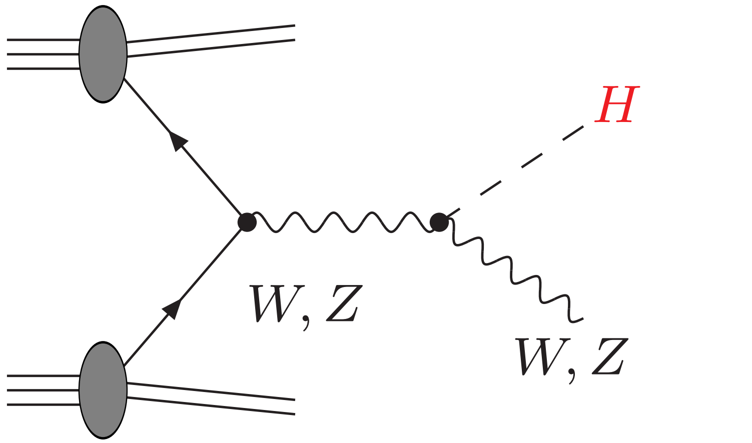
Important neutral Higgs Production Processes:



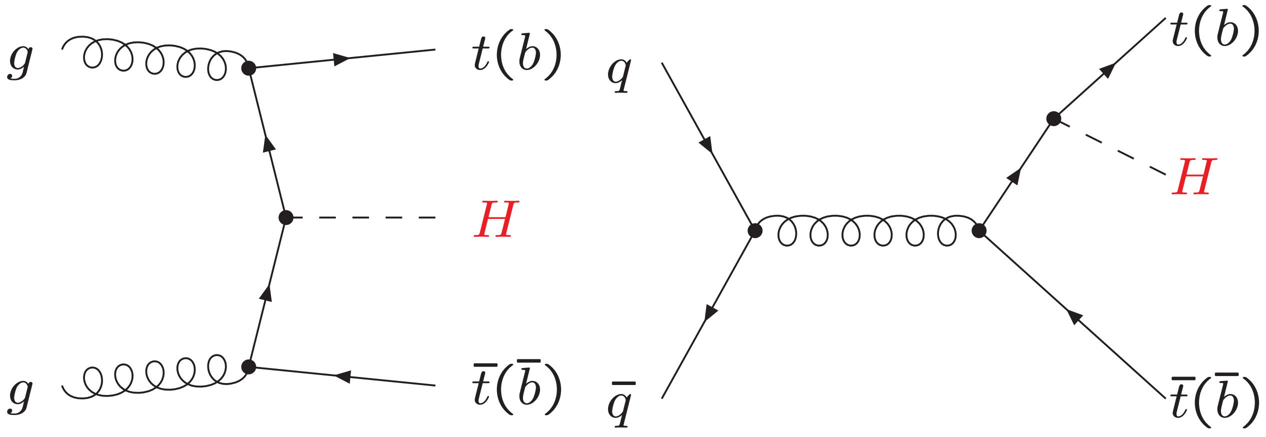
gluon fusion, $gg \to H$



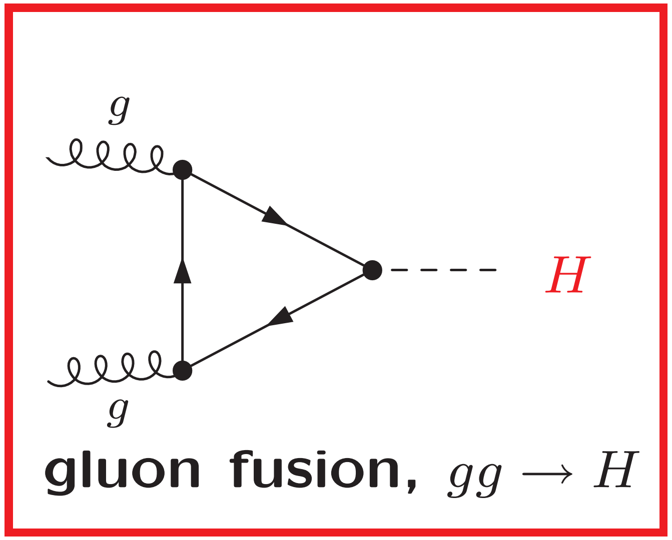
vector boson fusion, $qq \to qqH$

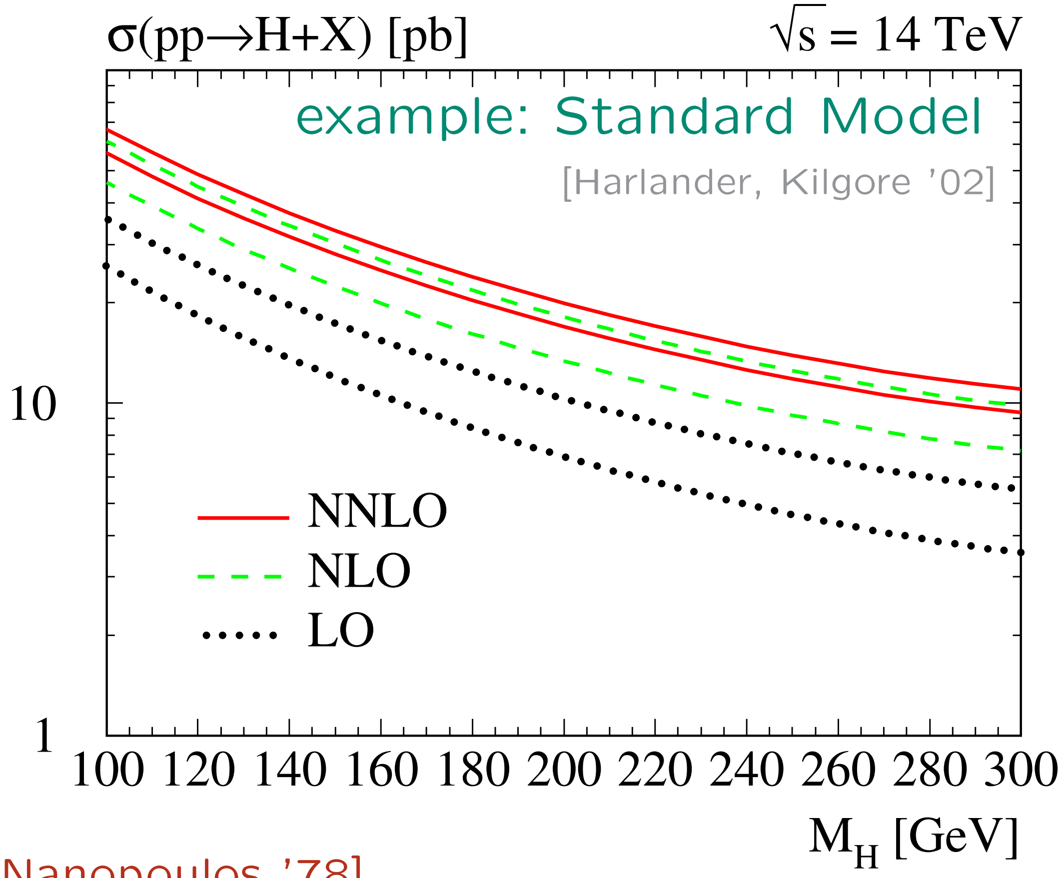


Higgs strahlung, $q\bar{q}' \to VH$



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





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

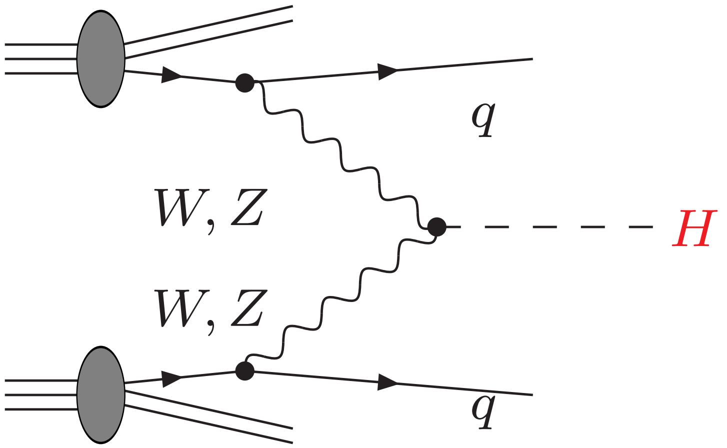
SM, NLO QCD [Dawson'91; Djouadi, Spira, Zerwas, Graudenz '91/'93]

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

SM, 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]

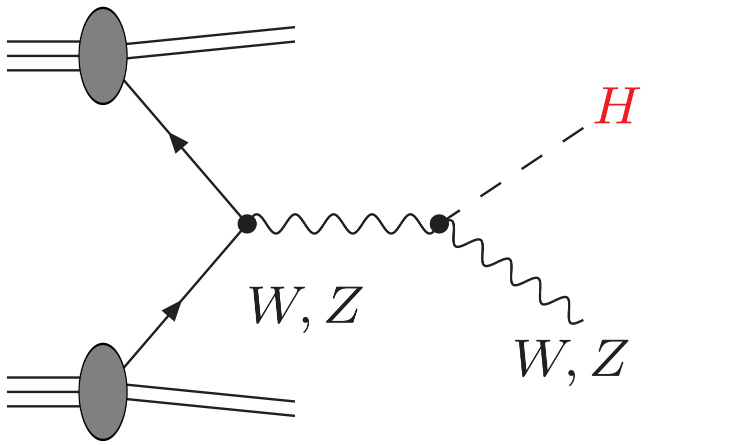


vector boson fusion, $qq \to qqH$

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

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

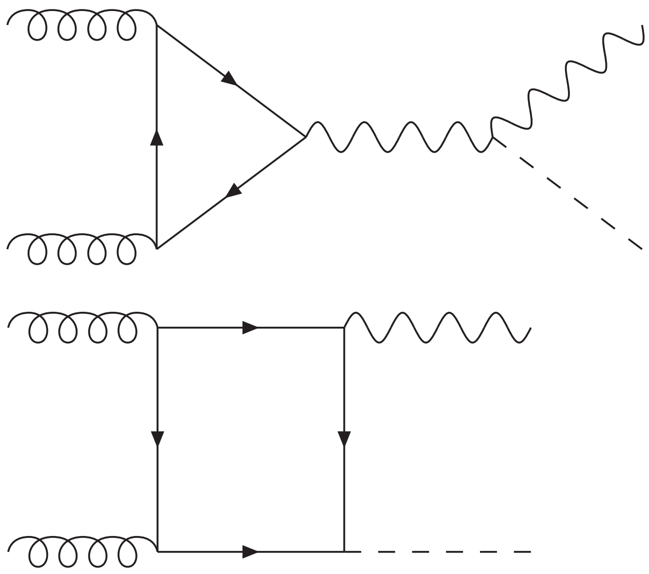
MSSM, NLO SUSY-QCD [Djouadi, Spira ’00]



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

note! : additional parton process @ NNLO

[Dicus, Kao '88; Kniehl '90]



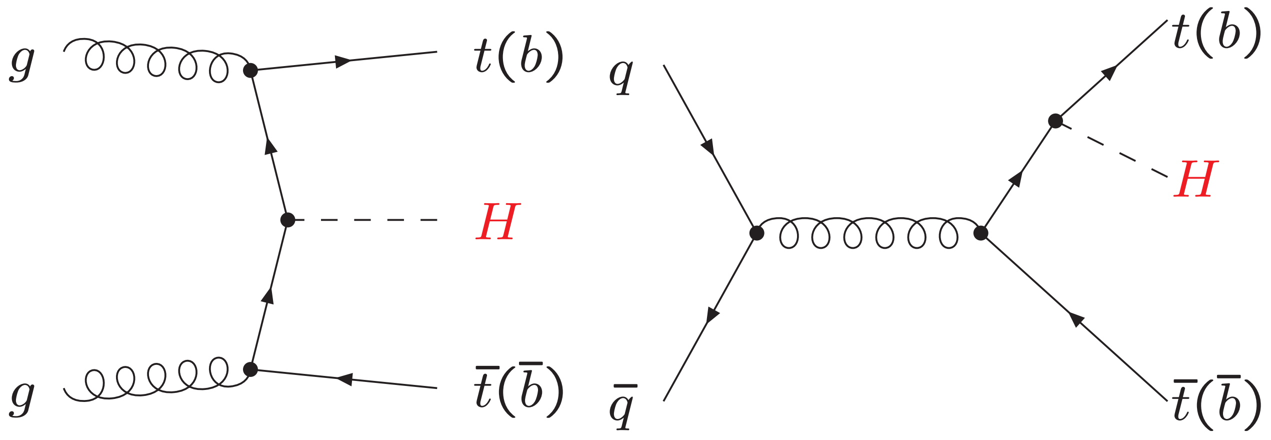
SM, LO [Glashow, Nanopoulos, Yildiz '78]

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 flavors]

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]

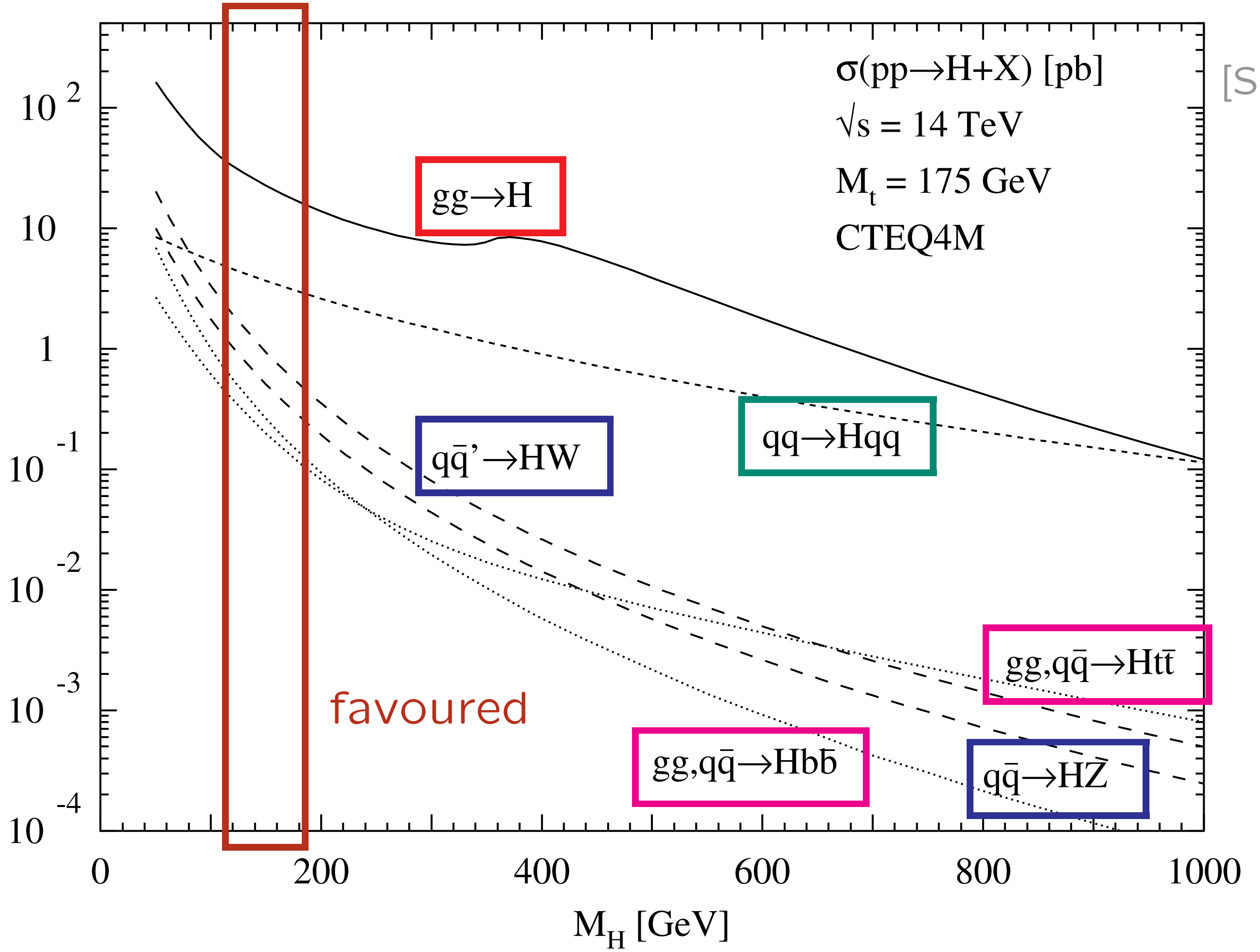
SM, NLO QCD ($b\bar{b}H$) [Dittmaier, Krämer, Spira '03; Dawson, Jackson, Reina, Wackeroth '03]

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]

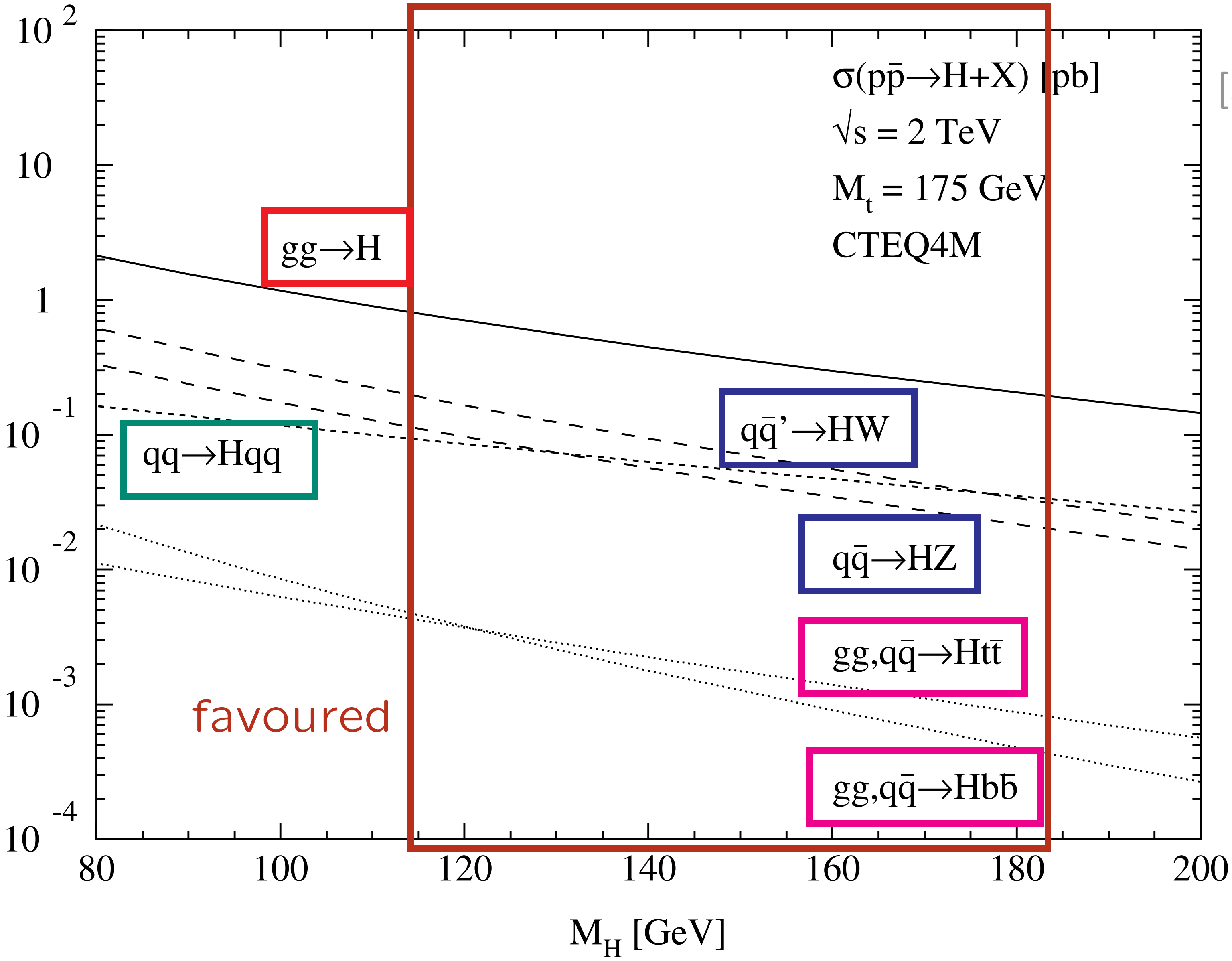
MSSM, NLO QCD, no superpartners [Dawson, Jackson, Reina, Wackeroth '03]

Predictions for Standard Model Higgs production processes @ LHC :



[Spira '98]

Predictions for Standard Model Higgs production processes @ Tevatron :



[Spira '98]

[Higgs production at hadron colliders, Neutral Higgs]

cross sections in the MSSM:

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 gaining importance
- $\sigma(gg \to h) \approx \sigma(gg, q\bar{q} \to hb\bar{b})$
- Higgs strahlung unimportant

– The Higgs search programme (schematic)

- finding the Higgs boson(s)

  production & decay $\longrightarrow$ rate & signatures

- measuring properties of the Higgs boson(s)

  angular distributions $\longrightarrow$ CP properties

  partial decay widths $\longrightarrow$ couplings

  pair production $\longrightarrow$ self-couplings

  (reconstruction of the Higgs potential)

- determine the underlying model

  information above

  observation of quantum effects

  $\longrightarrow$ information on particles too heavy to be directly observed

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

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

– Charged Higgs search at LHC/Tevatron

• $m_{H^{\pm}} < m_t$:

mainly via $t \longrightarrow H^{+}b$ and c.c. in $t\bar{t}$ events.

• $m_{H^{\pm}} > m_t$:

mainly via $gb \longrightarrow tH^{+}$, $gg \longrightarrow tbH^{+}$

[LO: Bawa, Kim, Martin '90; NLO QCD: Zhu '03; Plehn '03; Berger et al. '03]

other processes with (much) smaller c.s. :
$gg/b\bar{b} \longrightarrow H^{\pm}W^{\mp}$ [. . .] and $gg/q\bar{q} \longrightarrow H^{+}H^{-}$

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

most viable Signal:

excess of tau events

from the decays $H^{+} \longrightarrow \tau^{+}\nu_{\tau}$ and c.c.

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

Why study $H^{\pm}W^{\mp}$ production?

$\longrightarrow$ processes (partly) loop-induced

$\longrightarrow$ loop-induced processes are strongly dependent on virtual particles in the loop

$\longrightarrow$ the $W^{\pm}H^{\mp}$ production cross section is strongly model dependent

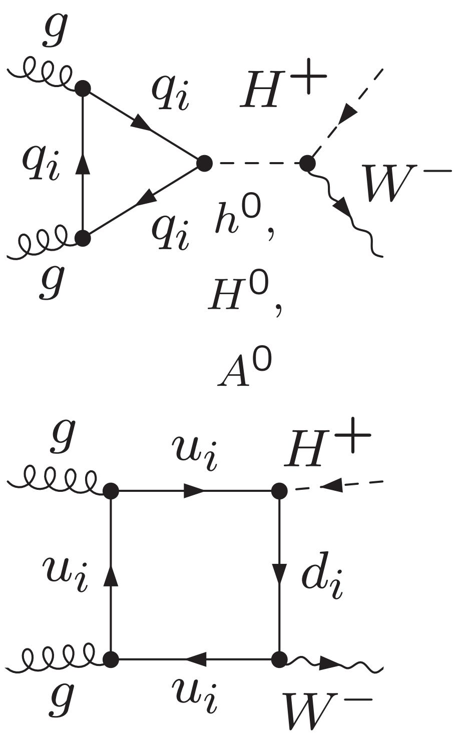
$\longrightarrow$ with a measurement of the cross section one would

gain information on the underlying model

(e.g. MSSM, THDM).

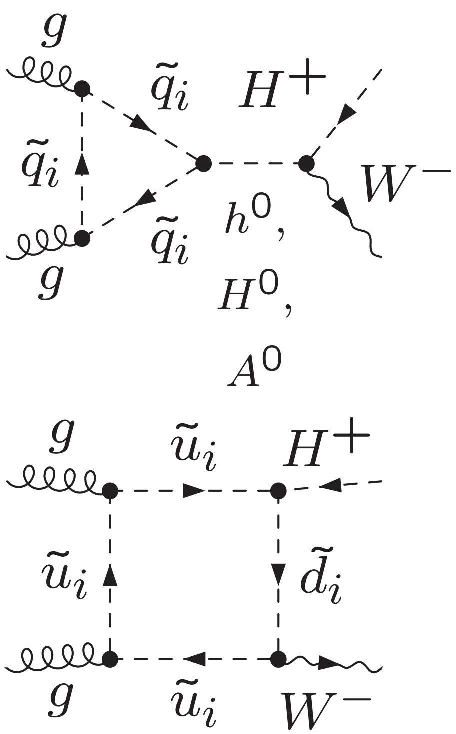
gluon fusion

THDM amplitude



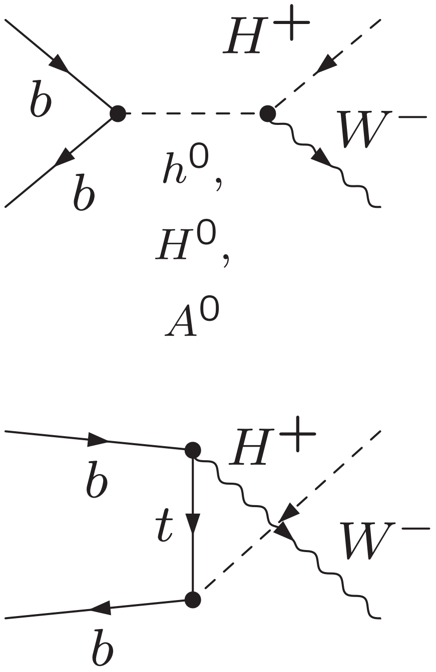
+ more

squark amplitude



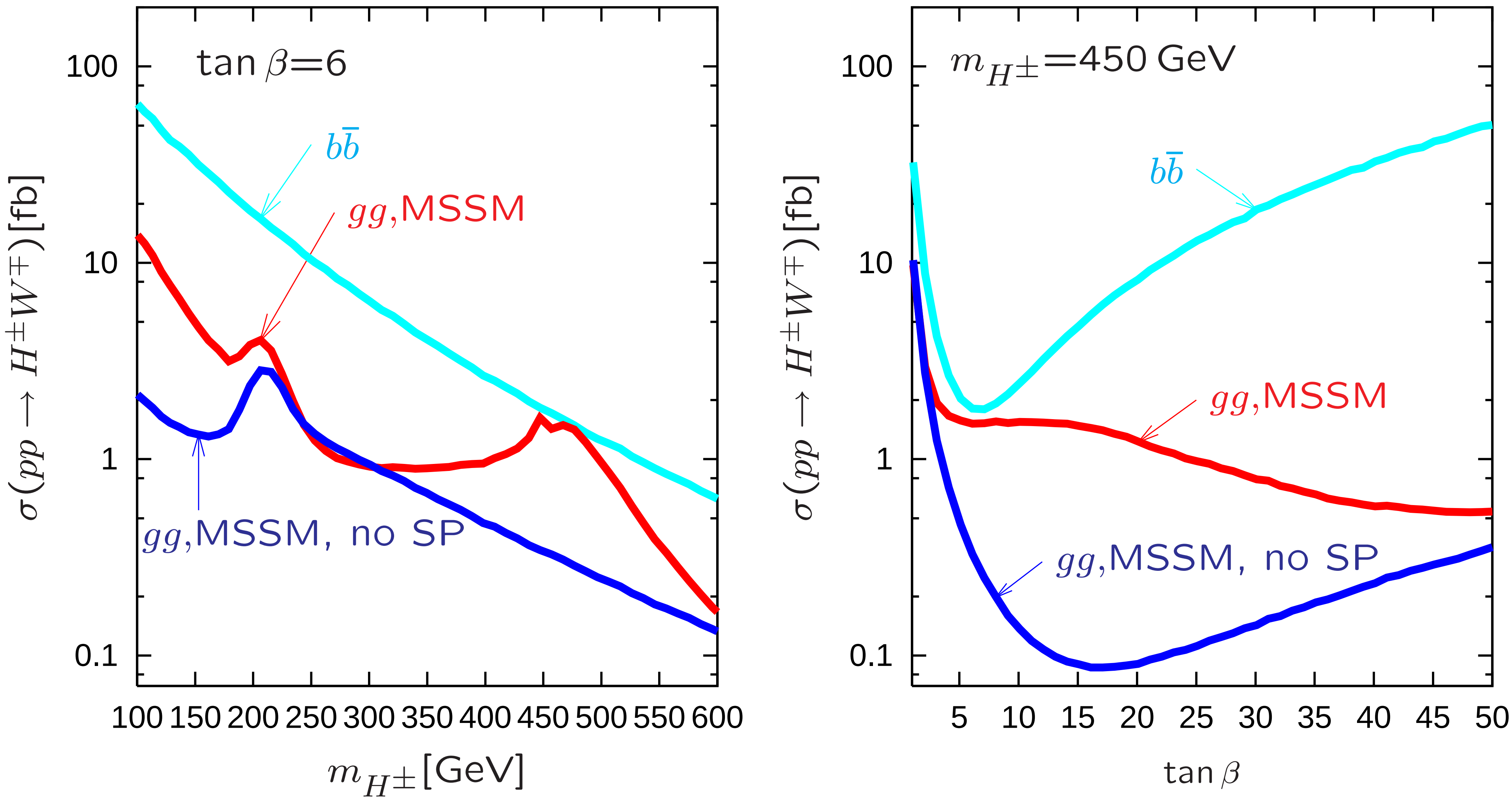
+ more

$b\bar{b}$ annihilation



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

inclusive $H^{\pm}W^{\mp}$ cross section at the LHC



MSSM versus general THDM

MSSM:

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

strong negative interference between $\Delta-$ and $\Box-$amplitudes,

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

reason: Higgs mass relations in the MSSM

$$m_{h^0} = \mathcal{O}(100\text{GeV}),\ m_{H^0} \approx m_{A^0} \approx m_{H^{\pm}}$$

$\longrightarrow$ $\Delta-$amplitudes cannot decouple from the process

$\longrightarrow$ no resonant s-channel Higgs exchange possible

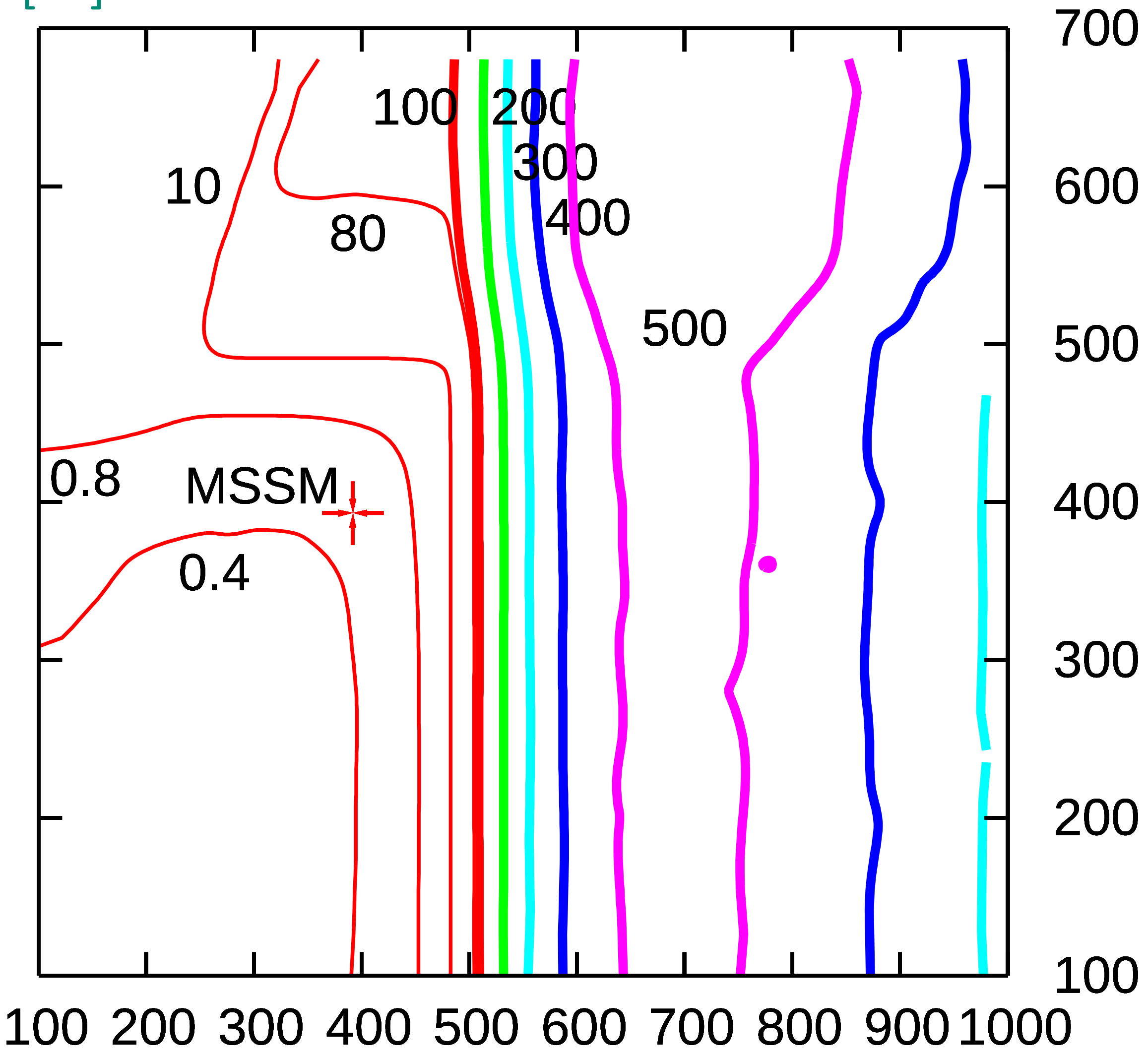
$\longrightarrow$ negative interference unavoidable

general THDM:

All this need not be true !

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

$\sigma(pp \to W^\pm H^\mp)$ [fb]

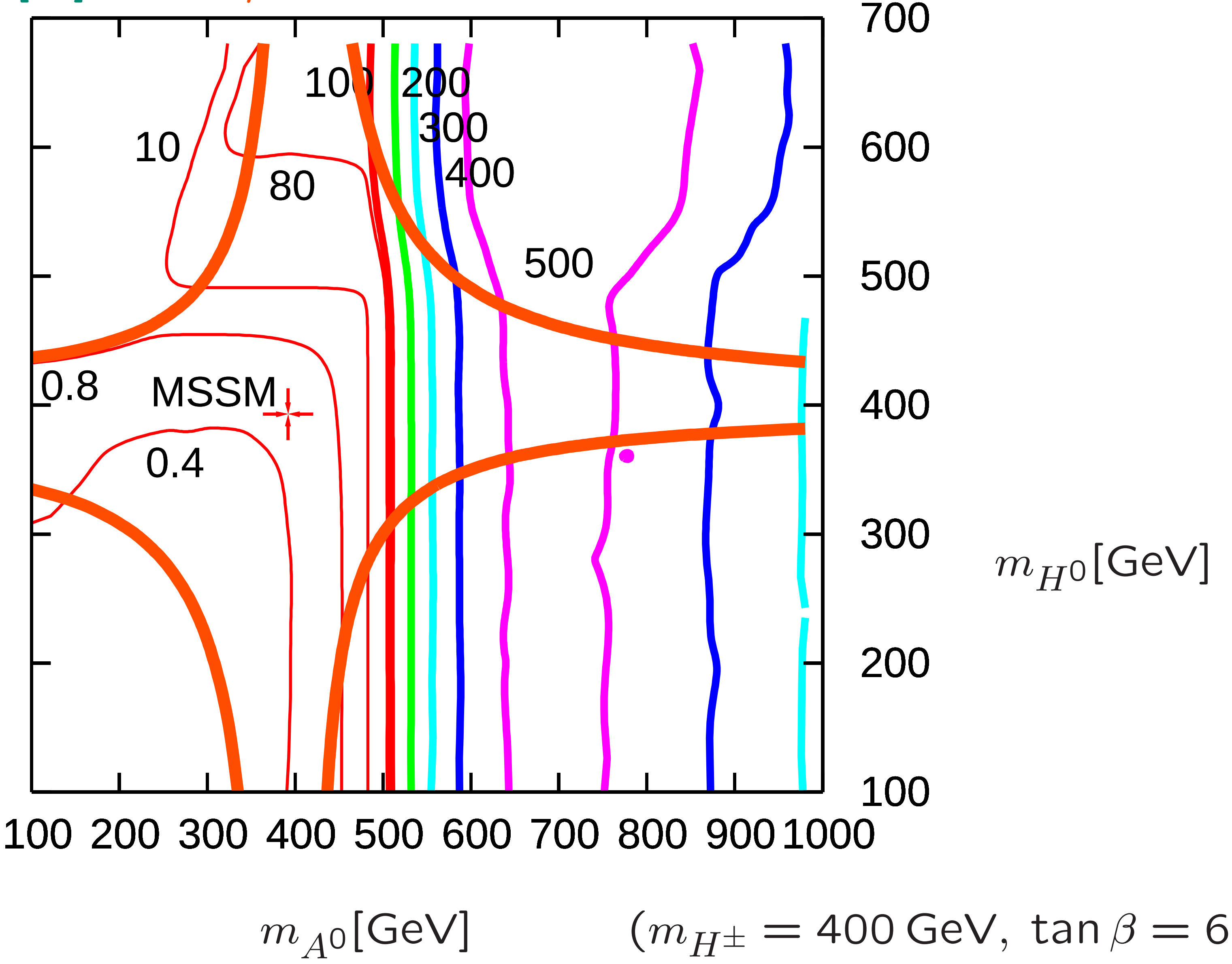


m_{H^0}[GeV]

m_{A^0}[GeV] $(m_{H^\pm} = 400\,\text{GeV},\ \tan\beta = 6)$

[Asakawa, OBr, Kanemura, work in progress]

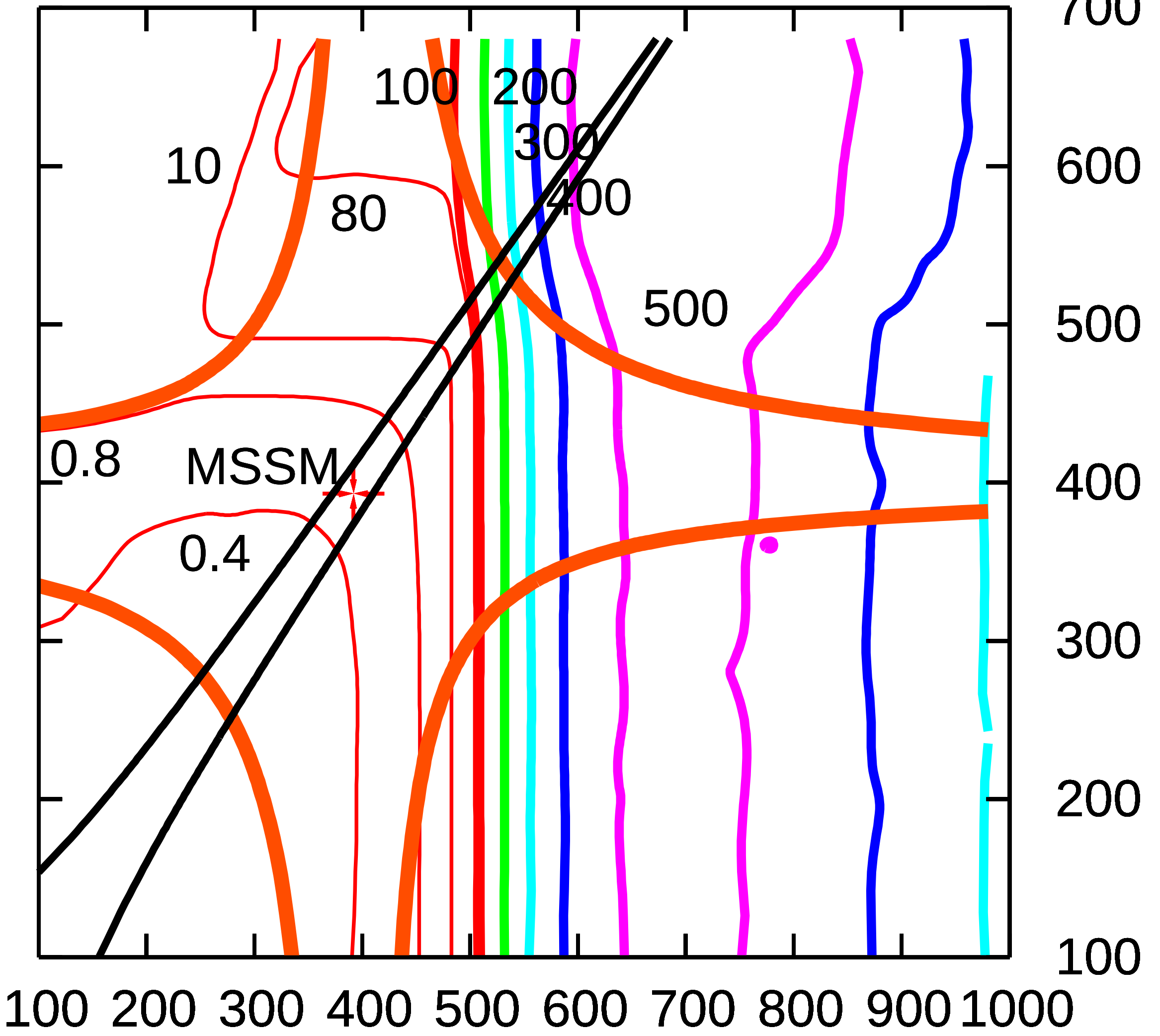
$\sigma(pp \to W^{\pm}H^{\mp})$ [fb] + $\Delta\rho$–bounds



$(m_{H^{\pm}} = 400\,\text{GeV},\ \tan\beta = 6)$

[Asakawa, OBr, Kanemura, work in progress]

$\sigma(pp \to W^{\pm}H^{\mp})$ [fb] $+$ $\Delta\rho$–bounds $+$ perturbative unitarity bounds



m_{A^0}[GeV] $(m_{H^{\pm}} = 400\,\text{GeV},\ \tan\beta = 6)$

[Asakawa, OBr, Kanemura, work in progress]

Summary

- The Higgs mechanism is an attractive theoretical description of massive vector bosons which is consistent up to very high energy.

- Extensions of the SM Higgs sector (and more) which are consistent with present data, like the MSSM or THDM, have to be taken seriously.

- The search for the Higgs boson(s) consists of
  * finding the Higgs,
  * measuring Higgs properties (e.g. self-couplings),
  * determining the underlying model.

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

- The $H^{\pm}W^{\mp}$ production cross section in the THDM can be much larger than in the MSSM