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
  - Supersymmetry
- Higgs Production at Future Colliders
  - LHC/Tevatron
  - e^+e^- Collider
- Some New Results
  - SM Higgs Strahlung: NNLO QCD + NLO electroweak
  - MSSM Higgs + high-p_T Jet
  - $H^\pm W^\mp$ Production at the LHC: MSSM versus THDM

• 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:

$\boxed{\text{to unravel the nature of } \textbf{electroweak symmetry breaking}.}$

different models realizing SSB

$\swarrow$ $\searrow$

introduce *weakly* interacting scalar gauge multiplets that acquire a VEV

introduce *strongly* interacting 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}).

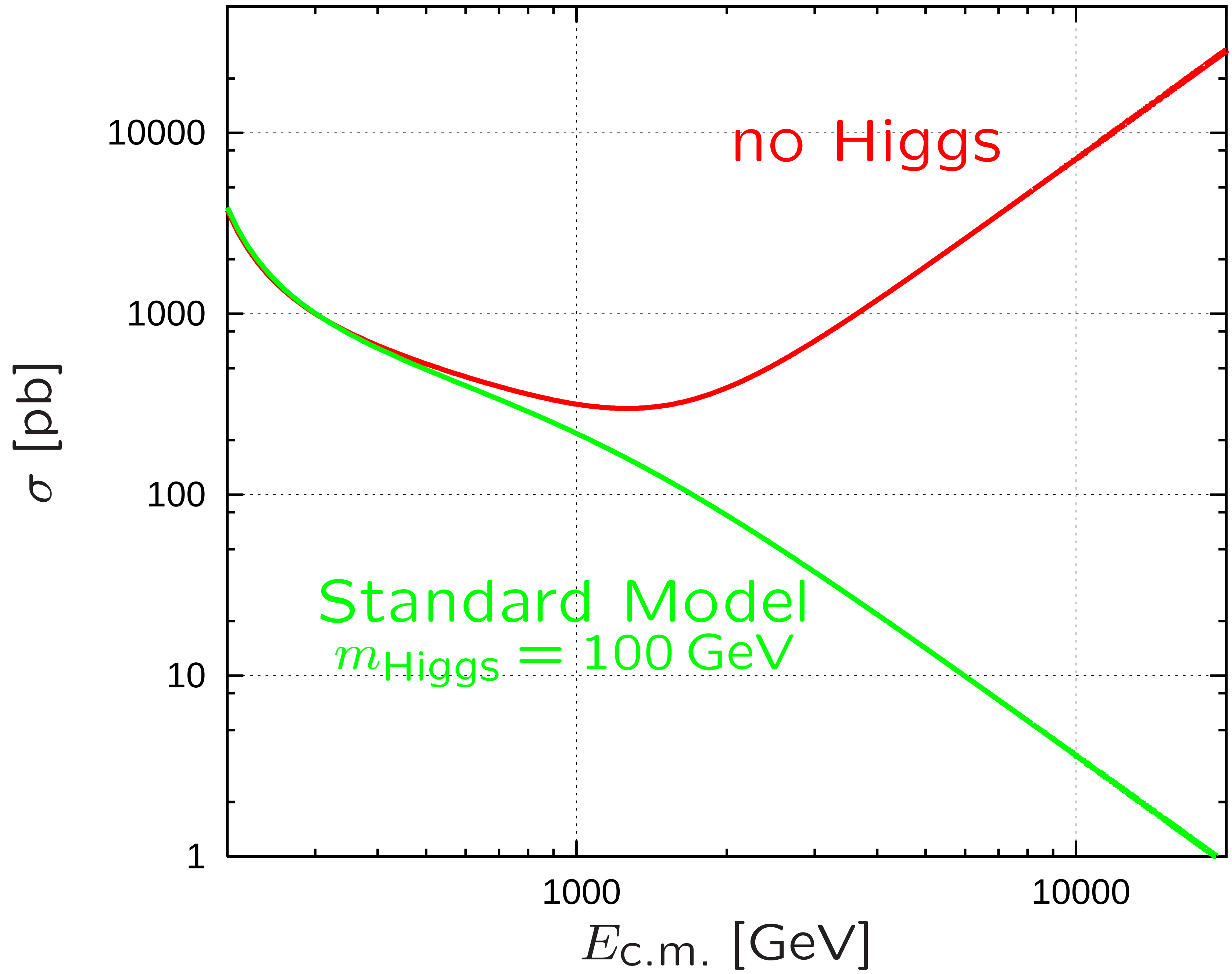
If so, then: Higgs is light, mass $m_H < 1\,\text{TeV}$

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

$\boxed{\text{the Higgs mechanism}}$

$\longrightarrow$ 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

SM:

matter, gauge bosons + 1 Higgs doublet Φ

$\rightarrow$ 1 physical Higgs boson

$\swarrow$ $\searrow$

THDM:

SM matter, SM gauge bosons

+ 2 Higgs doublets Φ_1, Φ_2

MSSM:

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

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

Experimental situation so far:

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

$\longrightarrow$ 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).

– Supersymmetry . . .

. . . is an 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. $\rightarrow$ a superpartner of different Spin exists for each particle
- couplings are correlated, e.g. scalar 4-point int. $\leftrightarrow$ gauge couplings
- superpartners have the same mass. $\rightarrow$ SUSY must be broken at the electroweak scale

gauge theory with broken SUSY :

- superpartner masses enter as additional free parameters (essentially)

consequences of SUSY for the MSSM Higgs sector

- all scalar 4-point interactions in the MSSM 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})

- 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 Colliders

How to produce a Higgs boson ?

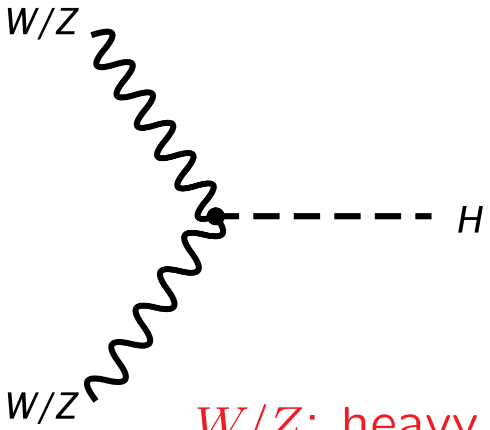
Higgs mechanism $\longrightarrow$ Higgs couplings to all other particles $\propto$ mass

$\longrightarrow$ Problem: ordinary matter consists of

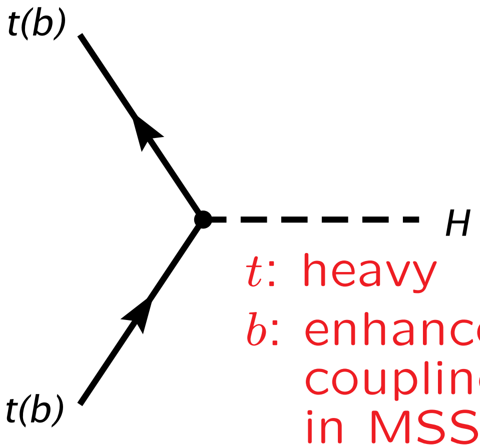
- $\star$ e^-,u-, d-quarks : very light
- $\star$ with negligible couplings to the Higgs boson.

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

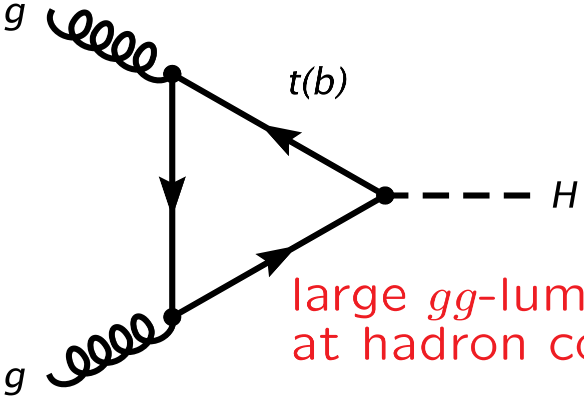
Therefore, most important couplings :



W/Z: heavy



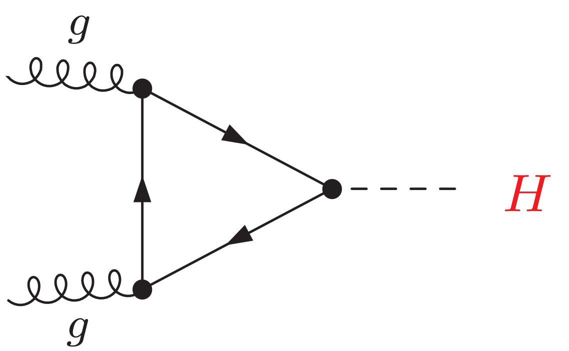
t: heavy
b: enhanced coupling in MSSM



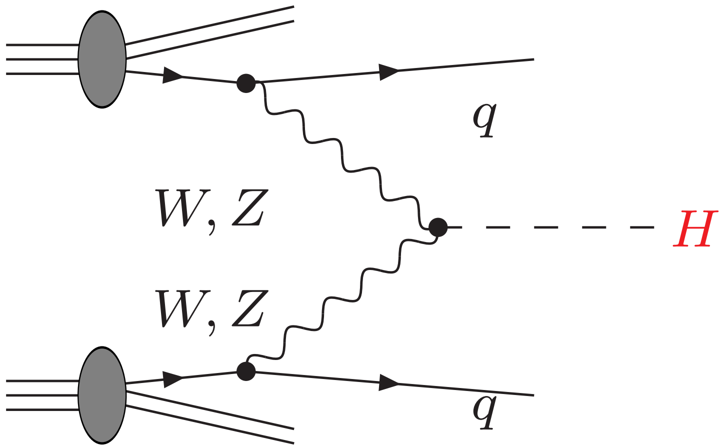
large gg-lumi at hadron colliders

– LHC/Tevatron

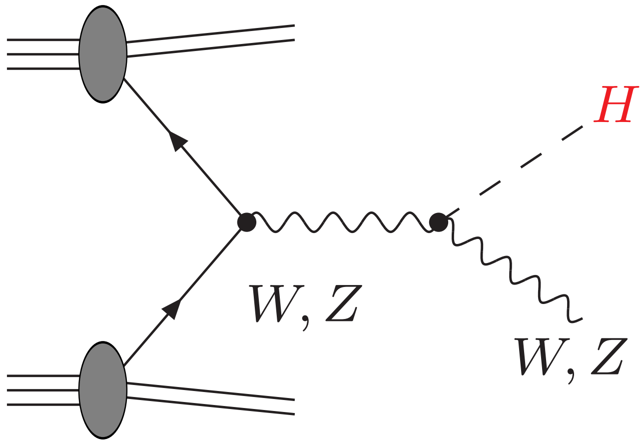
Important neutral Higgs Production Processes:



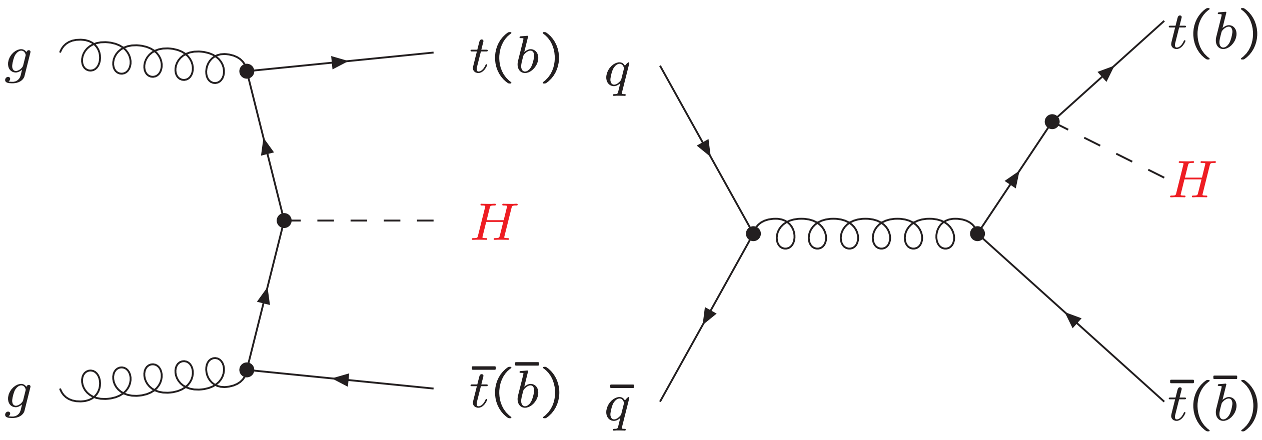
gluon fusion, $gg \to H$



vector boson fusion, $qq \to qqH$

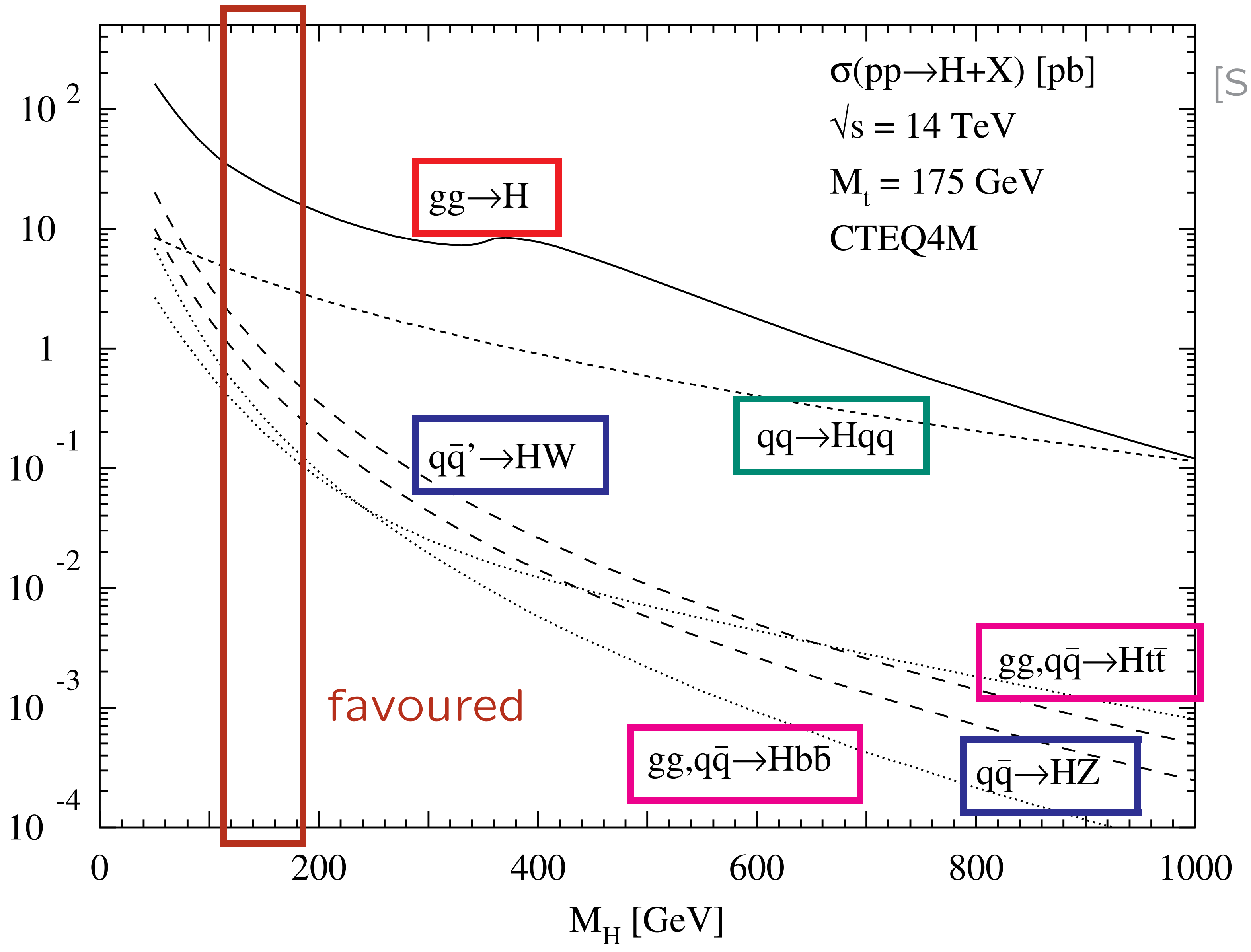


Higgs strahlung, $q\bar{q}' \to VH$



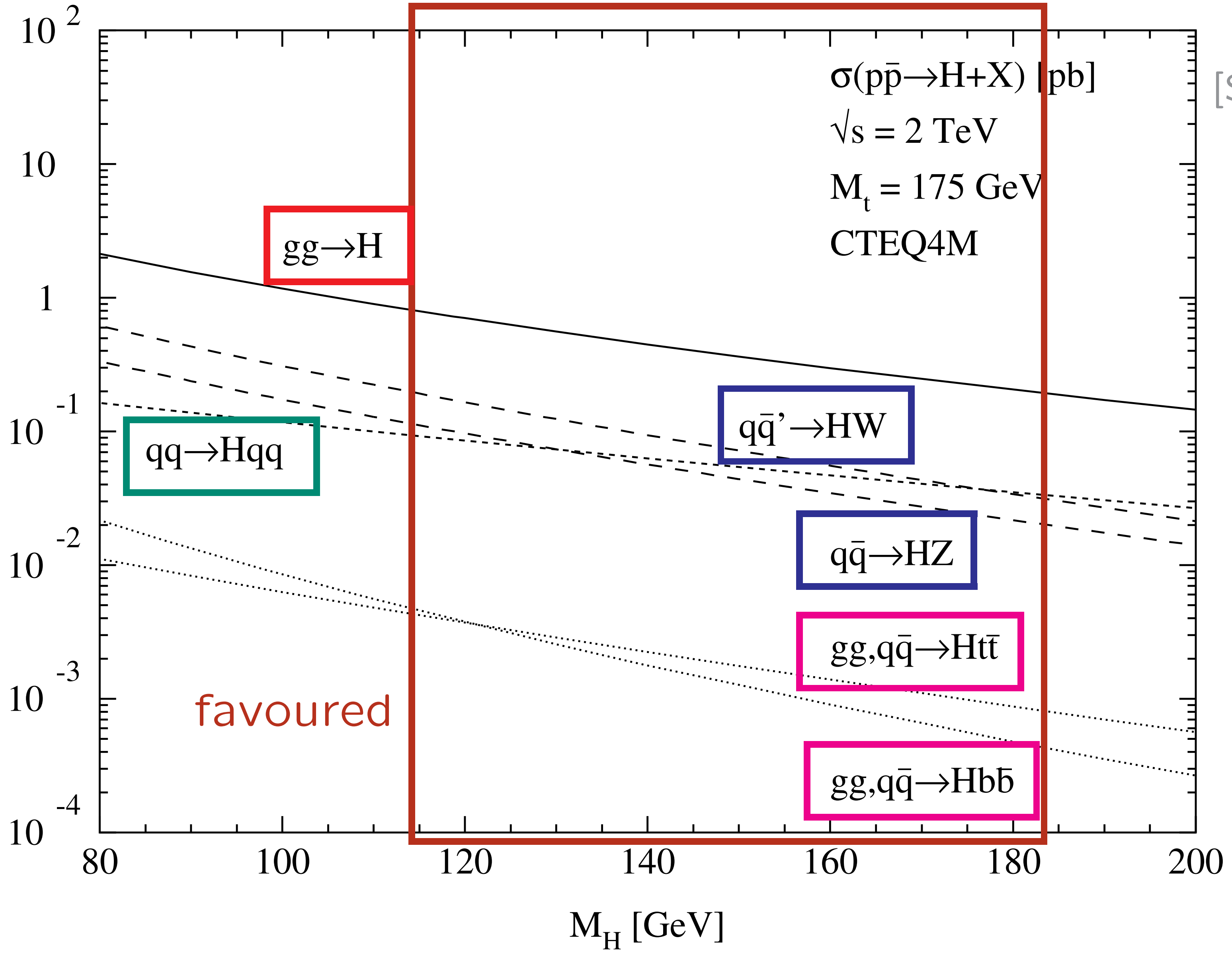
$t\bar{t}H$ ($b\bar{b}H$) **production [&** $b\bar{b} \to H$ **if 5 flavors]**

Predictions for Standard Model Higgs production processes @ LHC :



[Spira '98]

Predictions for Standard Model Higgs production processes @ Tevatron :



[Spira '98]

cross sections in the MSSM:

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

– cross sections similar to SM

– gluon fusion, $\sigma(gg \to h)$, dominant

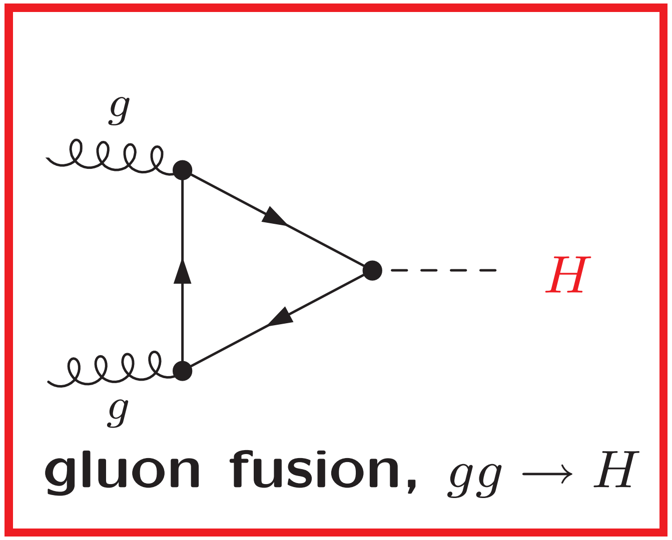
large $\tan\beta$ (say ≥ 30) :

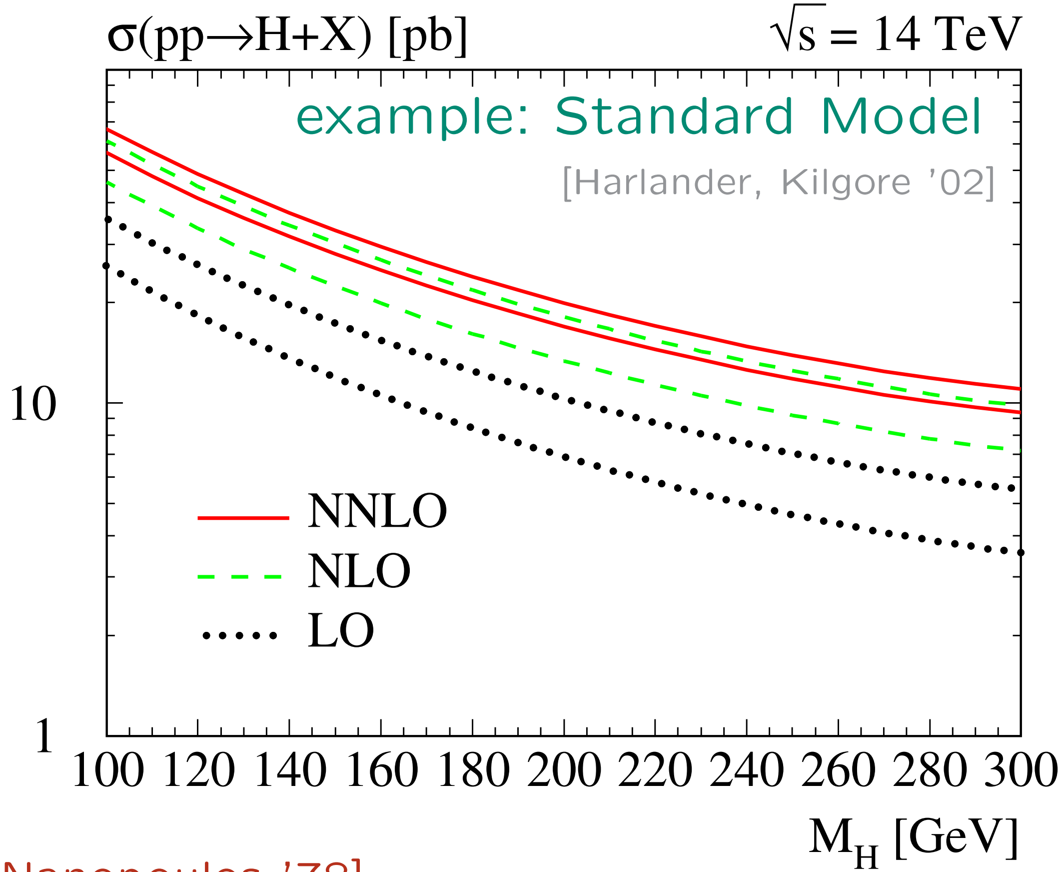
– gluon fusion cross section larger than in SM

– b-quark processes gaining importance

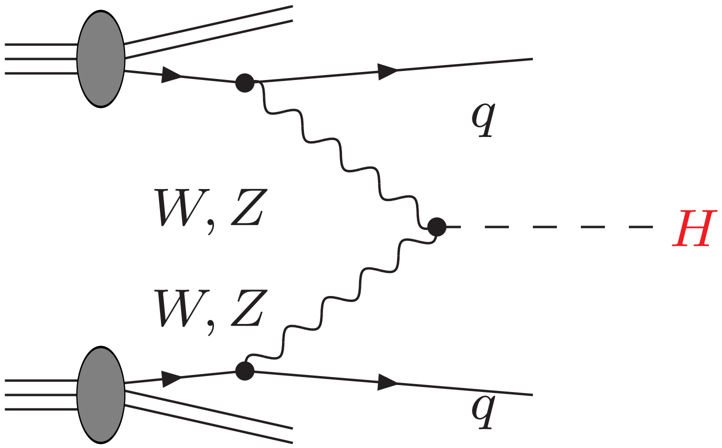
– $\sigma(gg \to h) \approx \sigma(gg, q\bar{q} \to hb\bar{b})$

– Higgs strahlung unimportant





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]

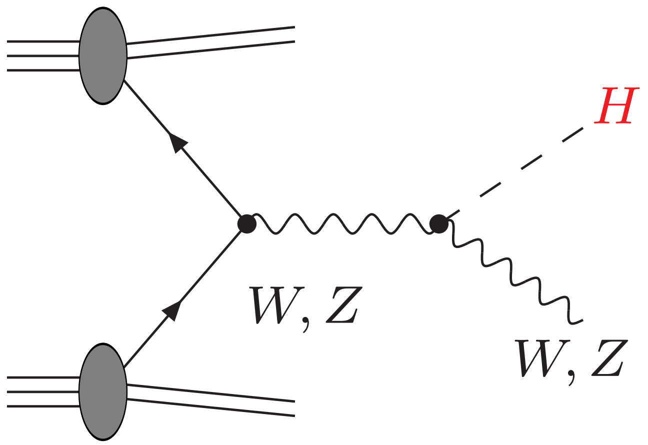


vector boson fusion, $qq \to qqH$

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

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

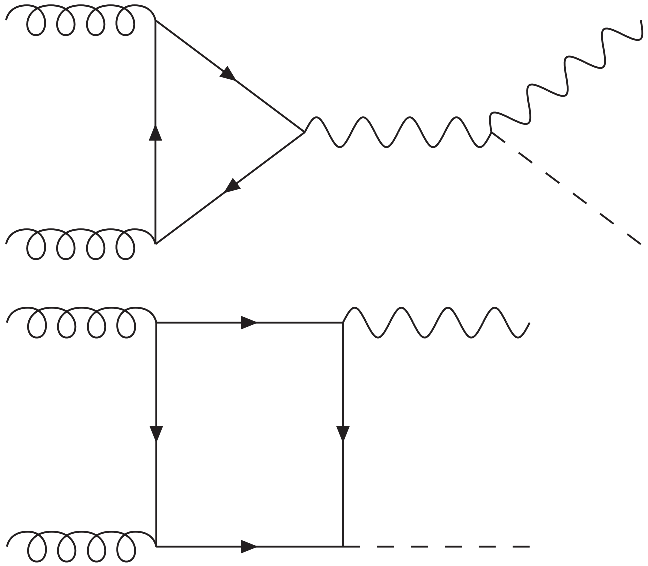
MSSM, NLO SUSY-QCD [Djouadi, Spira '00]



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

note! : additional parton process @ NNLO

[Dicus, Kao '88; Kniehl '90]



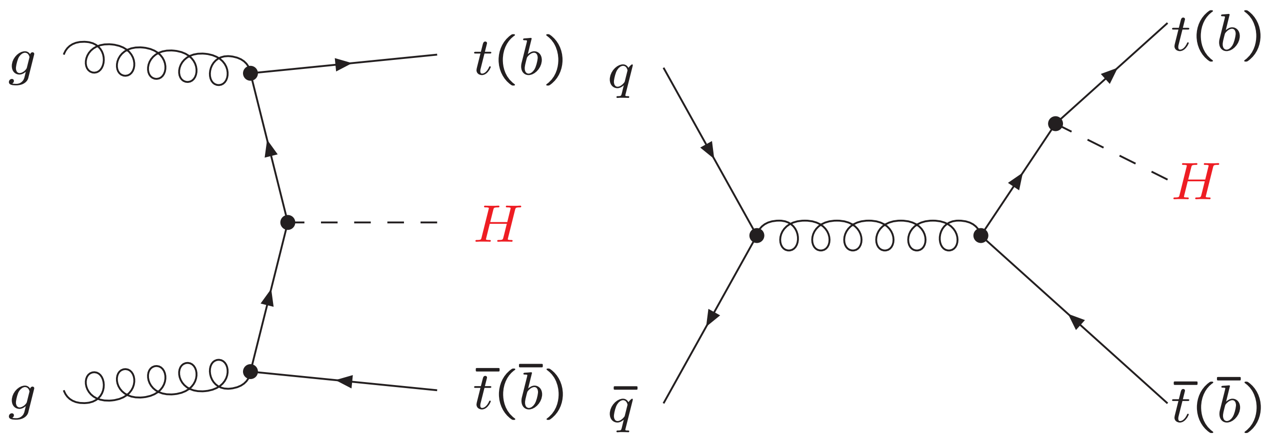
SM, LO [Glashow, Nanopoulos, Yildiz '78]

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]

• Some New Results

– SM Higgs Strahlung: NNLO QCD + NLO electroweak

– MSSM Higgs + high-p_T Jet

– $H^{\pm}W^{\mp}$ Production at the LHC: MSSM versus THDM

– SM Higgs Strahlung: NNLO QCD + NLO electroweak

Observation 1: In LO/NLO QCD the cross section factorizes

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

Observation 2: The complete NNLO QCD corr. to $\sigma(q\bar{q} \to V^\star)$ are known [Hamberg, van Neerven, Matsuura '91; Harlander, Kilgore '02].

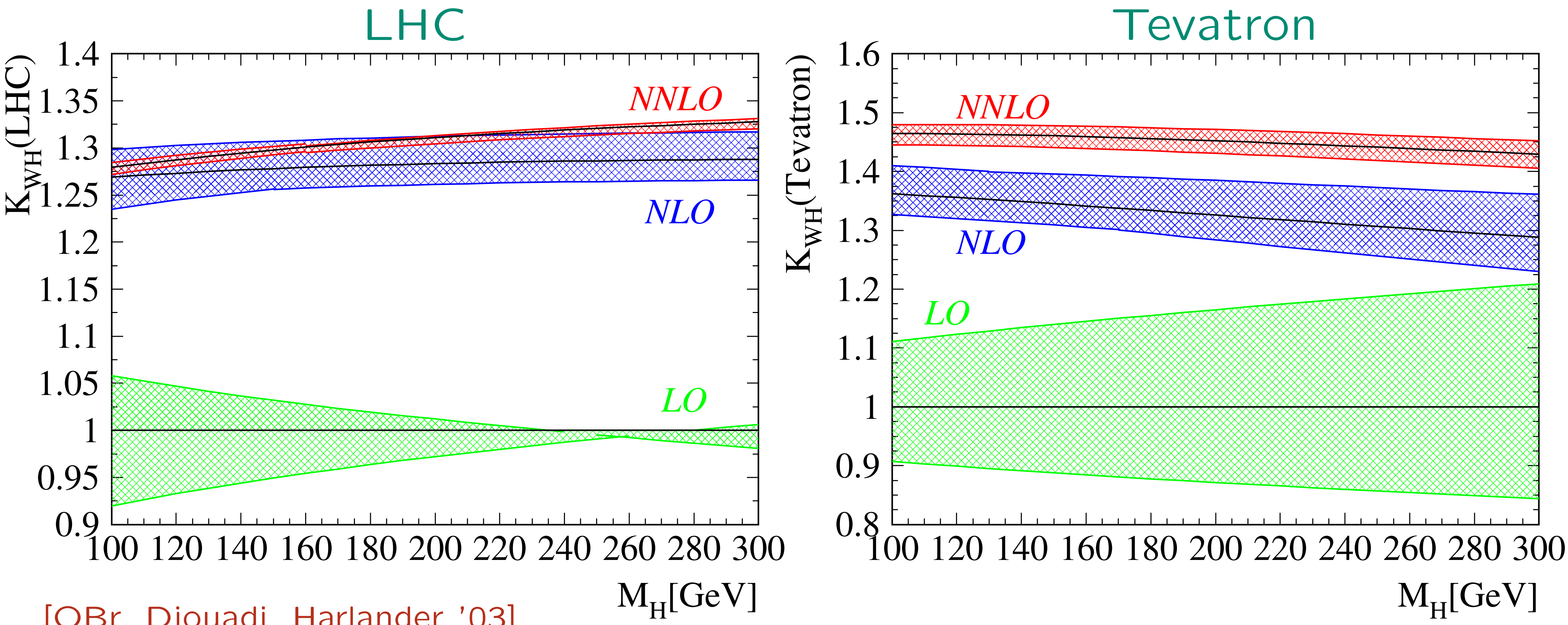
$\longrightarrow$ Idea : Use $\sigma_{\text{NNLO}}(q\bar{q} \to V^\star)$ to evaluate $\sigma(pp \to HV)$.

Our calculation: SM Higgs strahlung at $\mathcal{O}(\alpha_S^2)$

- use $\sigma_{\text{NNLO}}(q\bar{q} \to V^\star)$-results to obtain $\sigma(pp/p\bar{p} \to q\bar{q} \to HV)$ at NLO QCD + NNLO QCD corr. to DY-type process.
- add $\sigma(pp/p\bar{p} \to gg \to HZ)$ (LO=$\mathcal{O}(\alpha_S^2)$) [Dicus, Kao '88; Kniehl '90], recalculated '03
- use (approximate) NNLO parton distribution functions [MRST '02].
- missing NNLO piece: $(q\bar{q} \to HV)$ 2-loop contributions *not* of DY-type (gauge invariant subset, small at LHC).

K-factors for WH production and scale variation at LO, NLO, NNLO QCD

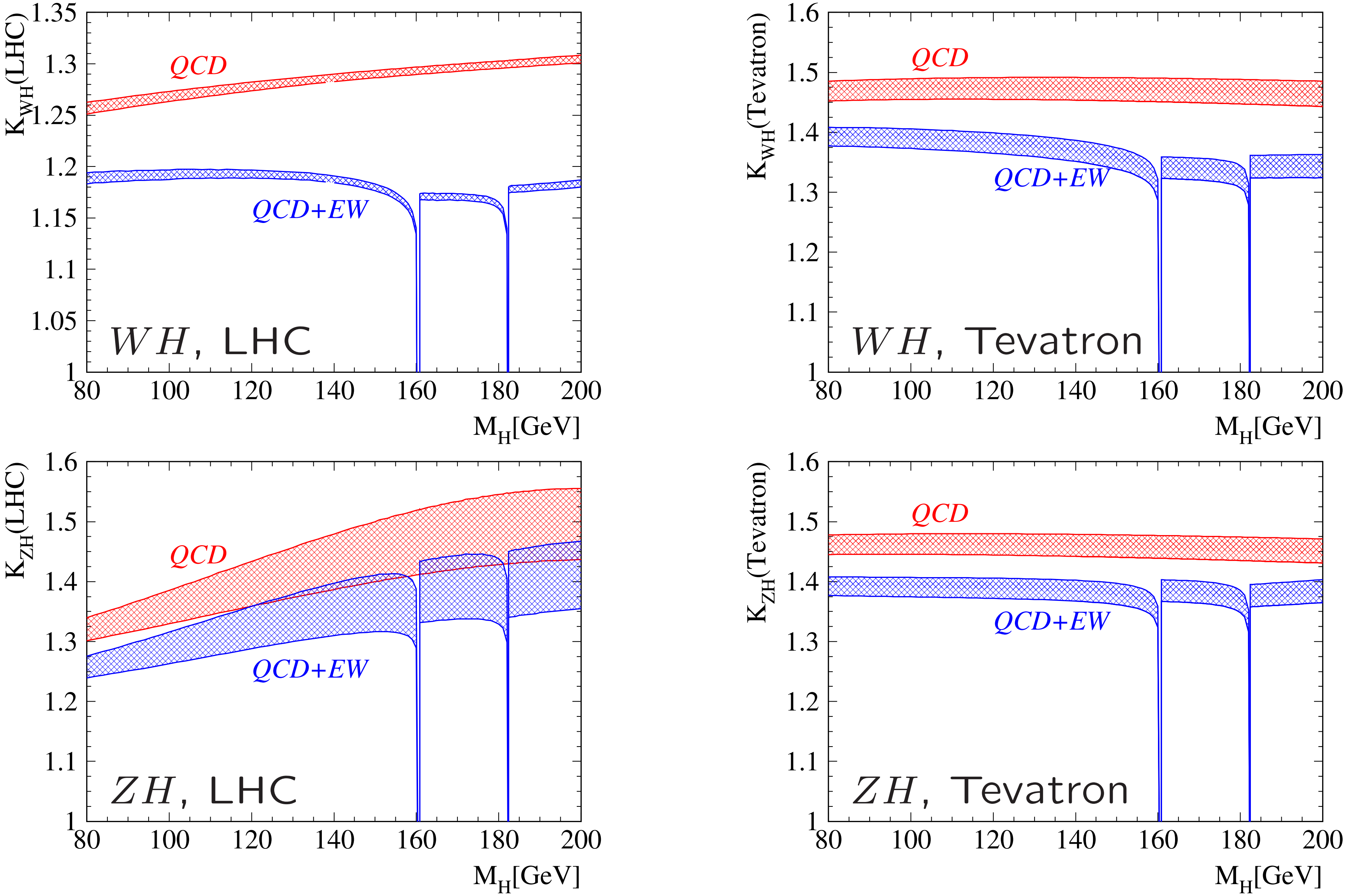
$$K_{VH} = \sigma_{\mathrm{HO}}(pp/p\bar{p} \to HV)/\sigma_{\mathrm{LO}}(pp/p\bar{p} \to HV) \quad (V = W, Z)$$



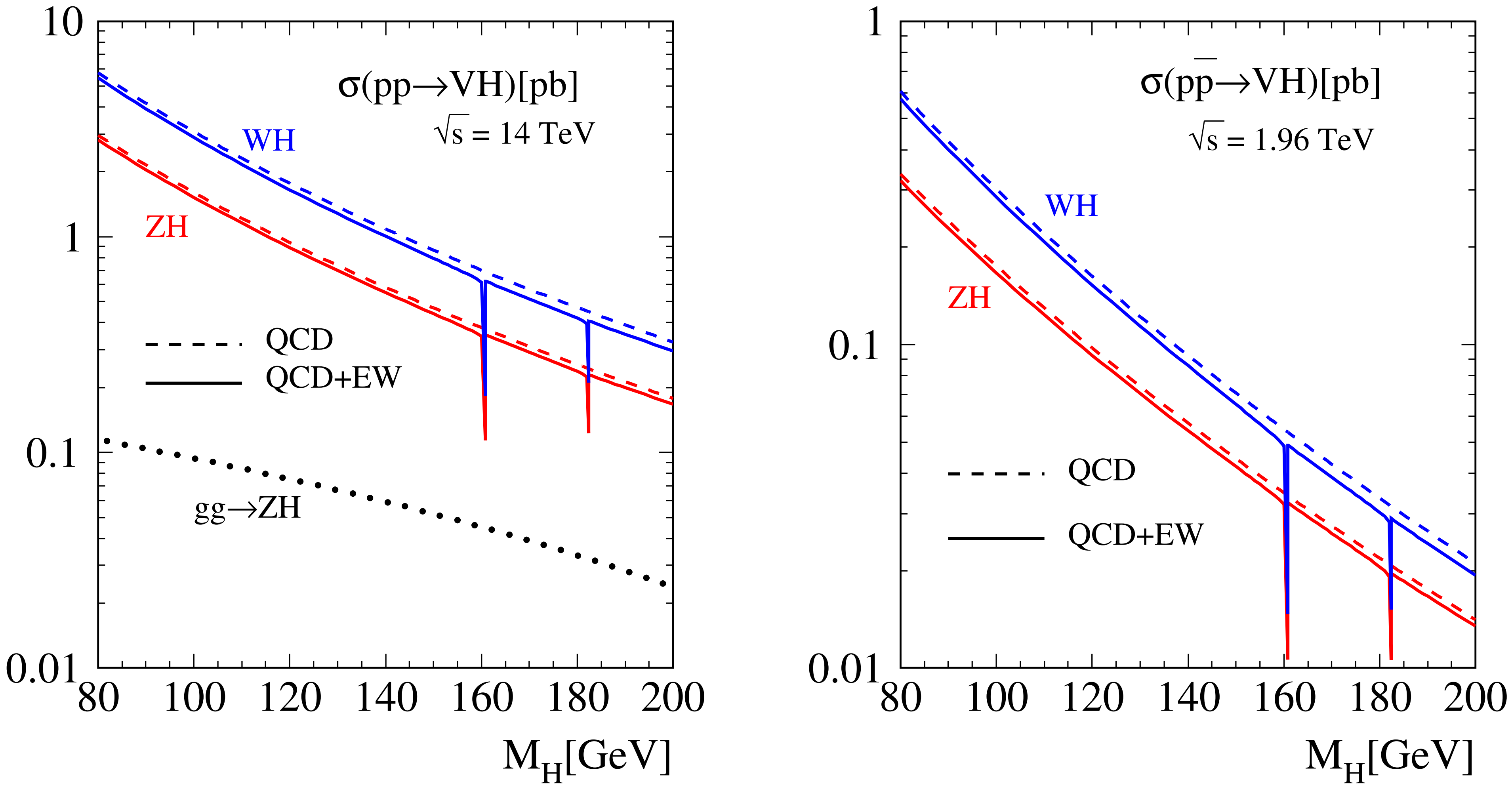
[OBr, Djouadi, Harlander '03]

K-factors for WH and ZH production at NNLO QCD + NLO EW

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



Hadronic cross section for HW/HZ production at LHC/Tevatron



Summary [SM Higgs Strahlung]

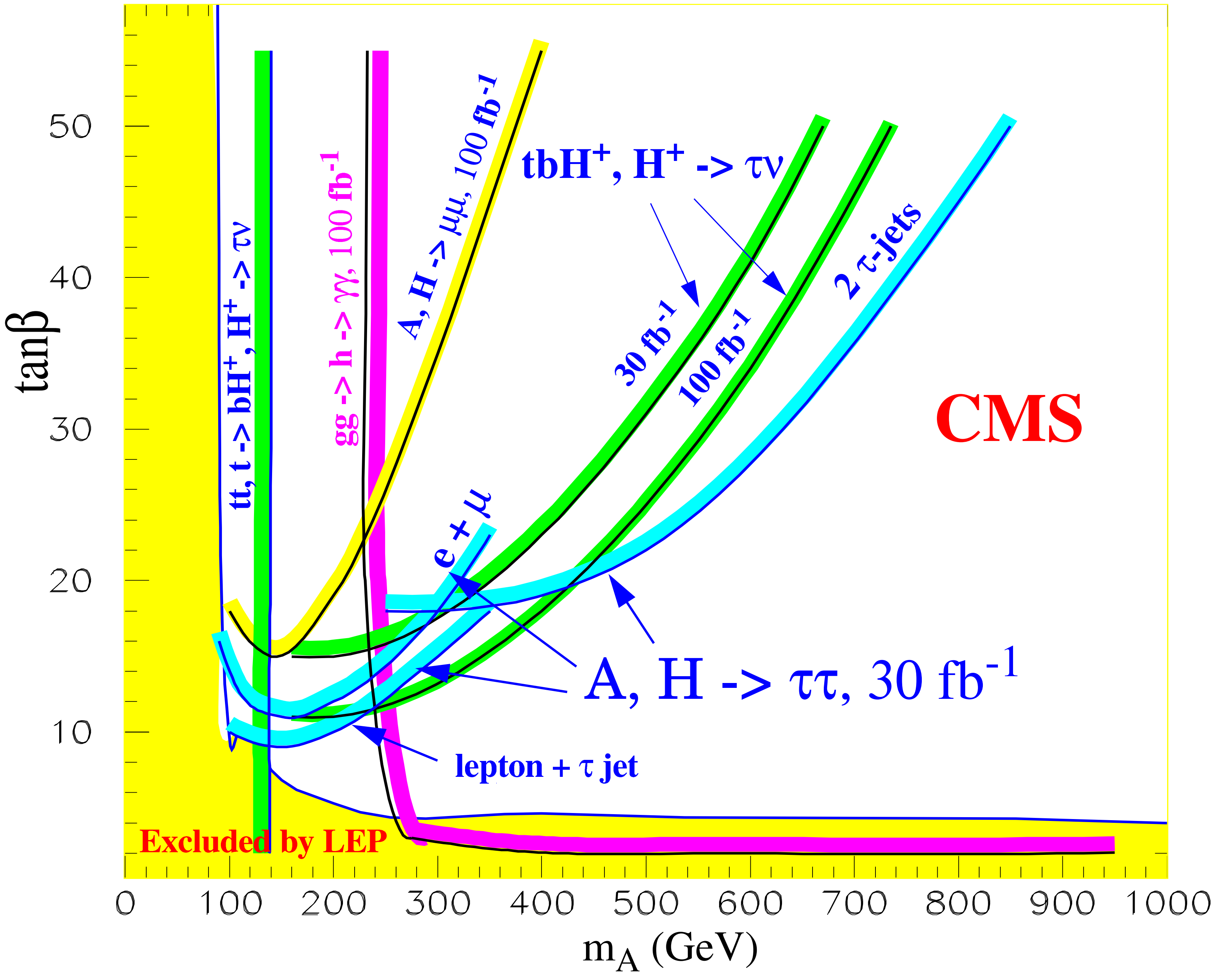
- Including NNLO QCD + NLO EW corrections the theoretical uncertainties drop significantly (Especially for the HW process at the LHC).

- At the LHC the HZ uncertainty is dominated by the uncertainty in the gluon fusion cross section.

- Still missing: the non-DY type NNLO corrections. ($\rightarrow$ work in progress)

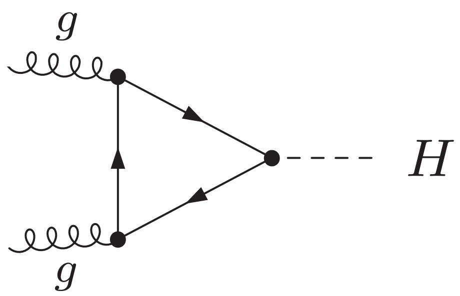
Intermezzo

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



– MSSM Higgs + high-p_T Jet

SM Higgs production @ LHC mainly via gluon fusion:



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

suggestion: study Higgs events with a high-p_T hadronic jet
[R.K. Ellis et al. '87; Baur, Glover '89]

advantage:

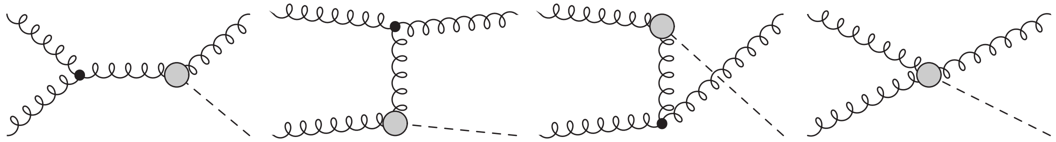
* richer kinematical structure compared to inclusive Higgs production.
  - $\to$ better S/B ratio
  - $\to$ allows for refined cuts

disadvantage:

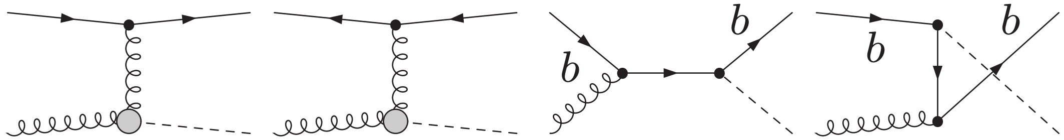
* lower rate than inclusive Higgs production
* signal and background only known in LO
  - $\to$ large theoretical uncertainties (so far)

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

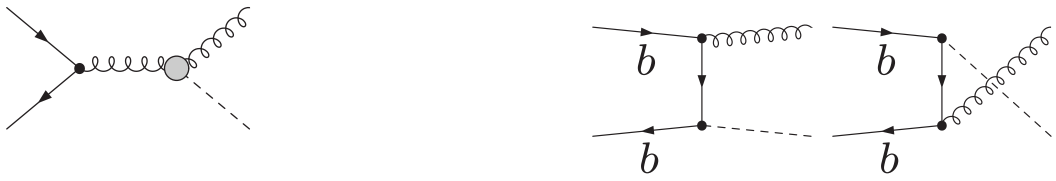
- $gg \to Hg$ (≈ 50 - 70 % of total rate)



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



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



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

result: H+jet production (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 $m_H \approx 100 - 140\text{GeV}$,

but theoretical predictions need improvement.

[Abdullin et al., ATLAS TDR '99]

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

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

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

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

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

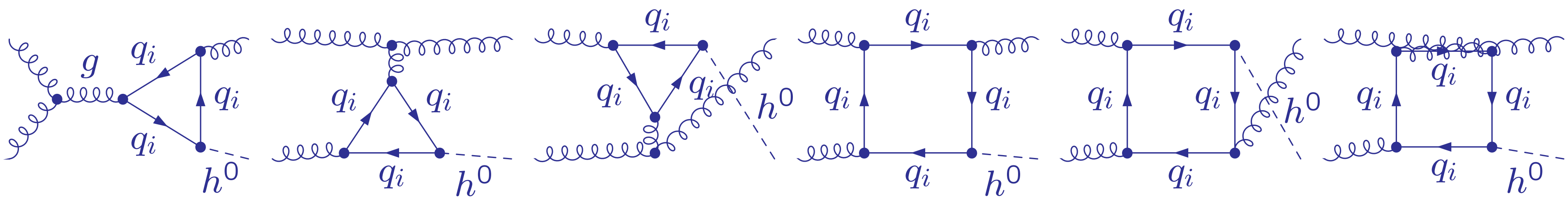
$\longrightarrow$ mainly change of overall rate

* additional superpartner-loops (even additional topologies)

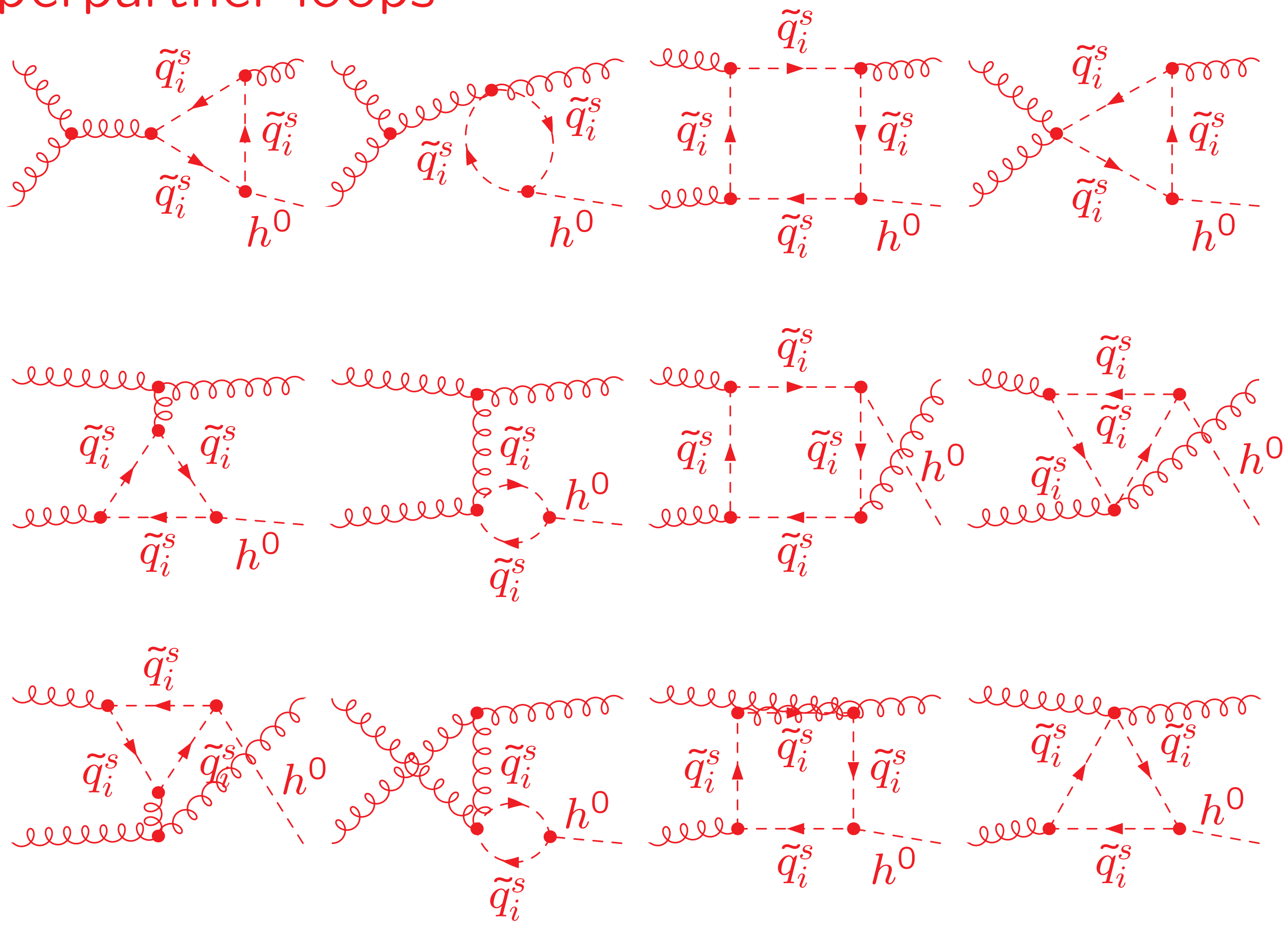
$\longrightarrow$ angular distribution changed

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

quark loops

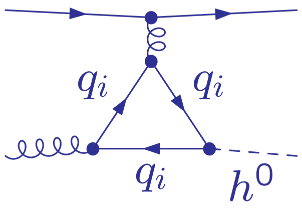


superpartner loops

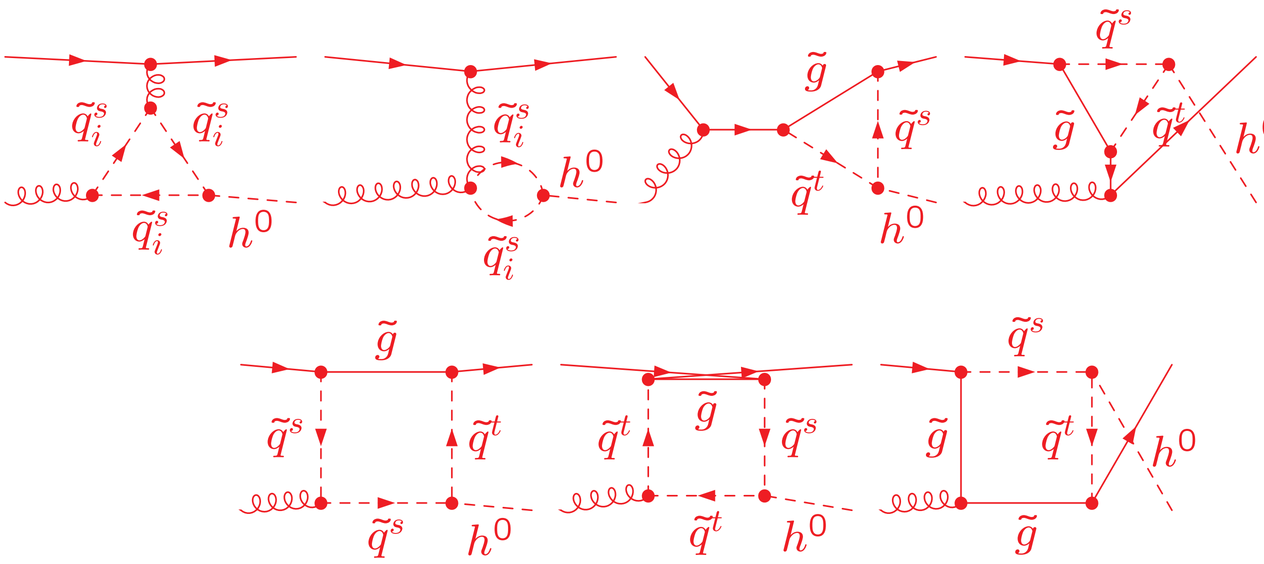


quark-gluon scattering, $qg \rightarrow h^0 q$

quark loops

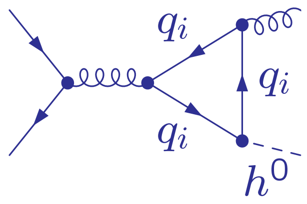


superpartner loops

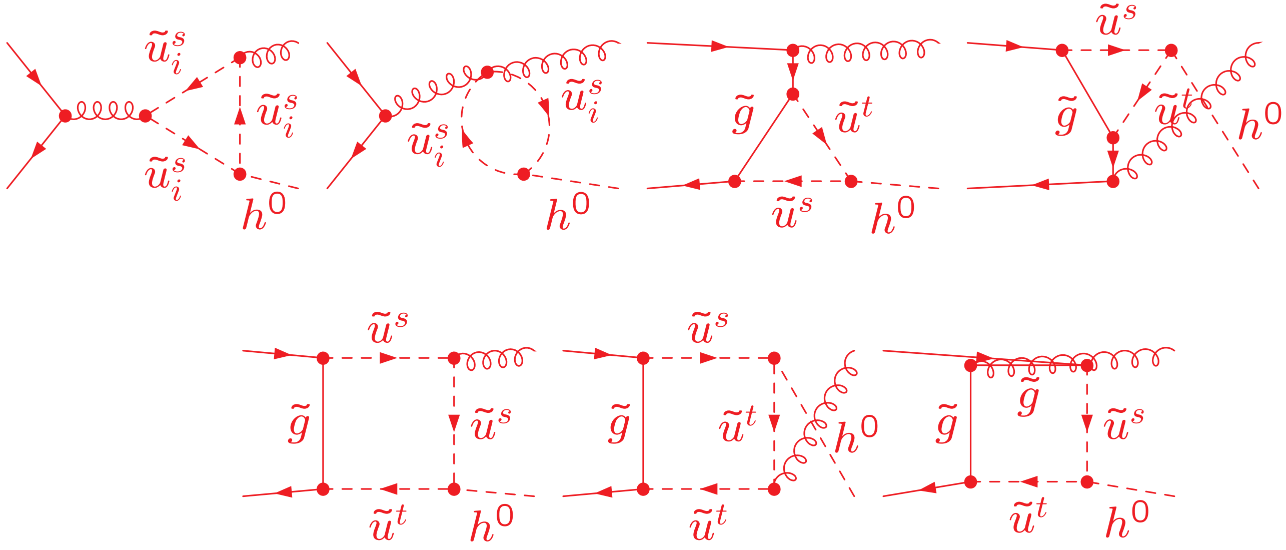


quark-antiquark annihilation, $q\bar{q} \to h^0 g$

quark loops



superpartner loops



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

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

with the parton luminosity

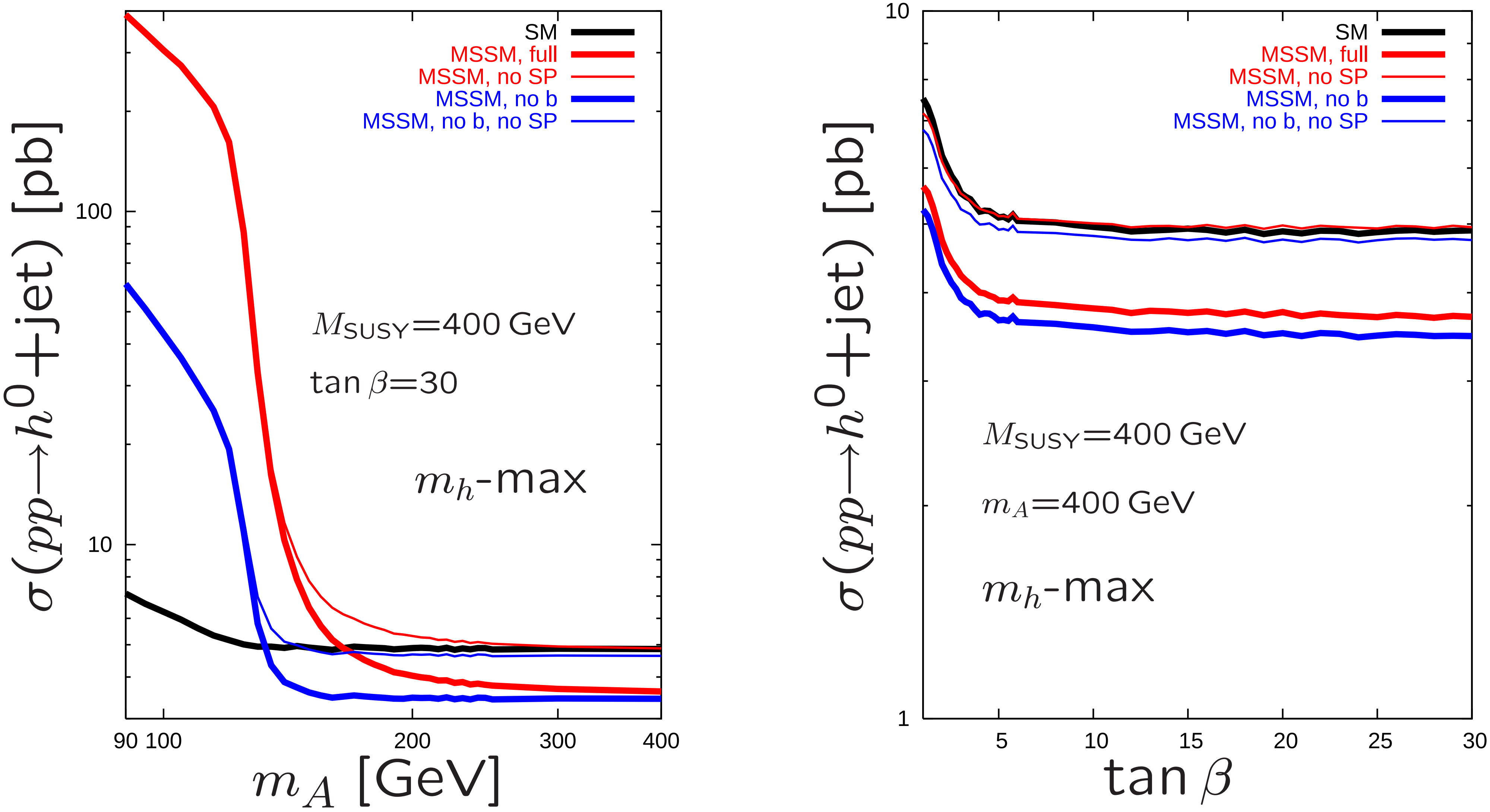
$$\frac{d\mathcal{L}^{AB}_{nm}}{d\tau} = \int_{\tau}^{1} \frac{dx}{x} \frac{1}{1+\delta_{nm}} \left[f_{n/A}(x) f_{m/B}\left(\frac{\tau}{x}\right) + f_{m/A}(x) f_{n/B}\left(\frac{\tau}{x}\right) \right].$$

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.

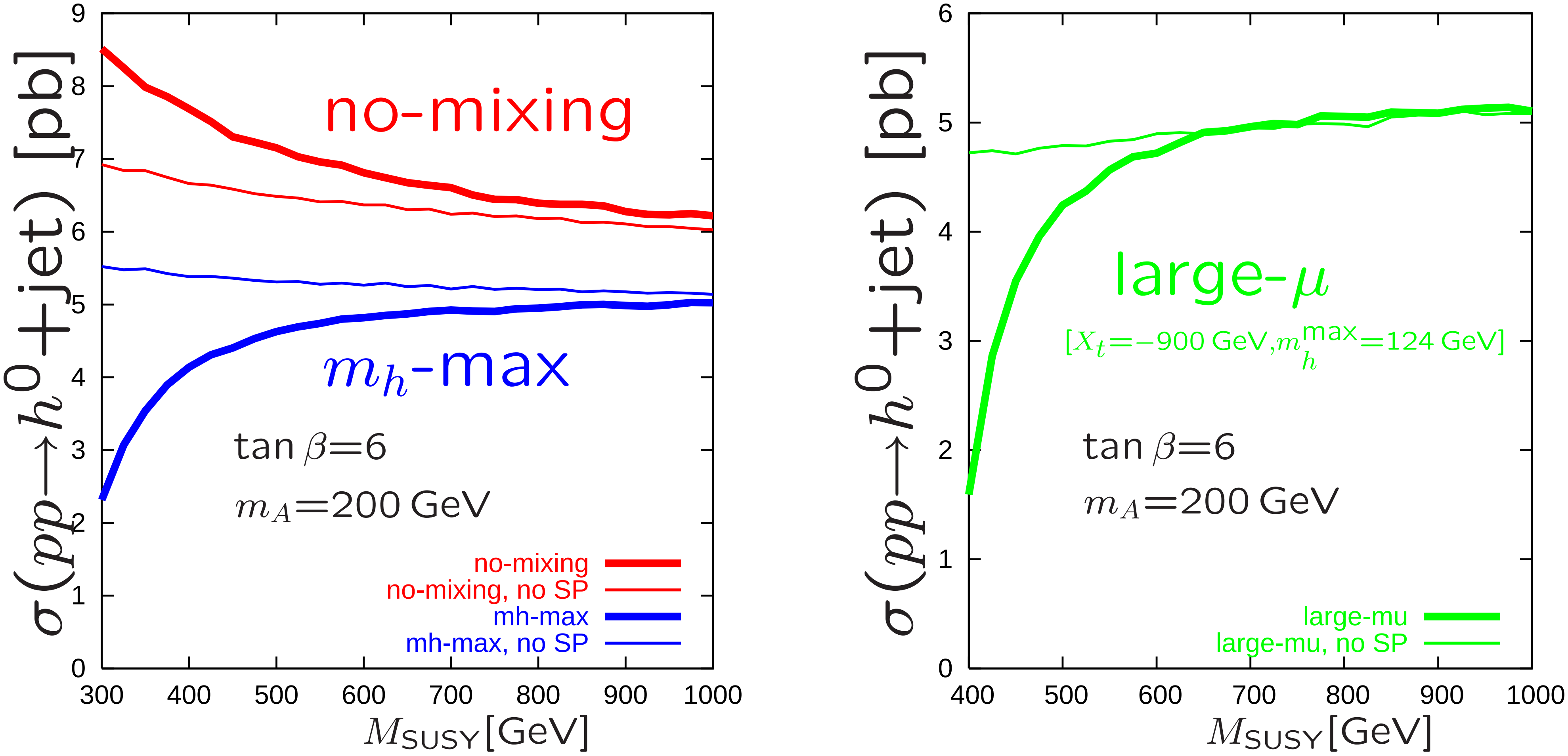
The results shown are for the MSSM m_h^{max} benchmark scenario with common squark mass scale M_{SUSY}.

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

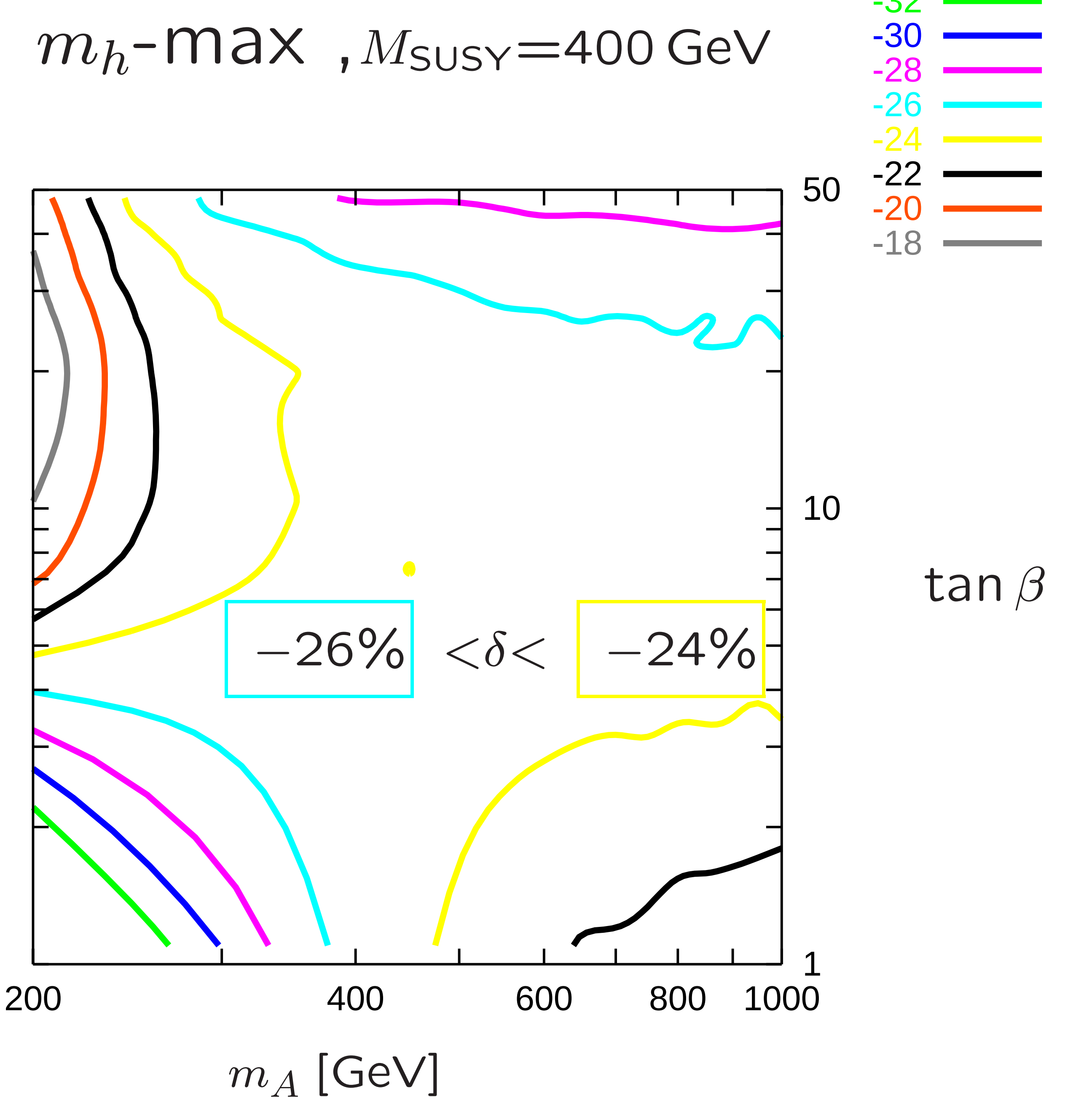
m_A- and $\tan\beta$-dependence (cuts: $p_{T,\mathrm{jet}} \geq 30$ GeV , $|\eta_{\mathrm{jet}}| \leq 4.5$)



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



Relative Difference $\delta = (\sigma^{\mathrm{MSSM}} - \sigma^{\mathrm{SM}})/\sigma^{\mathrm{SM}})$



Summary [MSSM Higgs + high-p_T Jet]

- 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 expectations can occur.

- NLO predictions for signal *and* background are needed in order to be useful for experimental analyses.

FORTRAN code HJET to calculate the SM and MSSM cross sections is available on request $\longrightarrow$ brein@physik.rwth-aachen.de

– $H^{\pm}W^{\mp}$ Production at the LHC: MSSM versus THDM

charged Higgs search ...

discovery of a charged Higgs boson $\rightarrow$ sign of an extended Higgs sector

Tevatron/LHC, $H^{\pm}$ production

- $m_{H^{\pm}} < m_t$:

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

- $m_{H^{\pm}} > m_t$:

  mainly via $gb \rightarrow tH^+$, $gg \rightarrow tbH^+$

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

  other processes with (much) smaller c.s. :

  $gg/b\bar{b} \rightarrow H^{\pm}W^{\mp}$ [. . .] and $gg/q\bar{q} \rightarrow H^+H^-$

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

most viable Signal:

excess of tau events

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

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

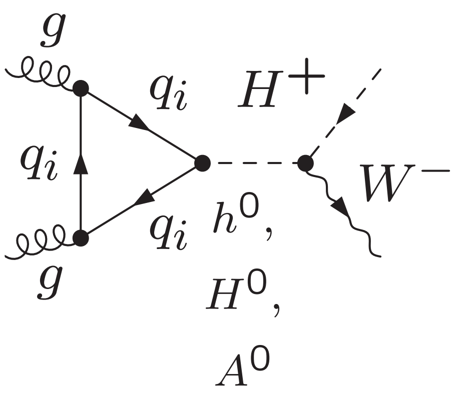
$\longrightarrow$ with a measurement of the cross section one would

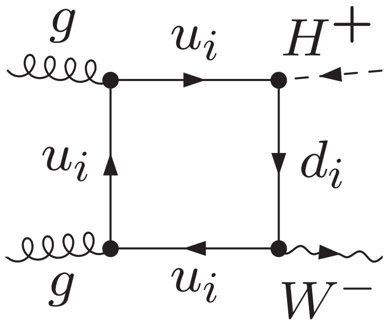
gain information on the underlying model

(e.g. MSSM, THDM).

gluon fusion

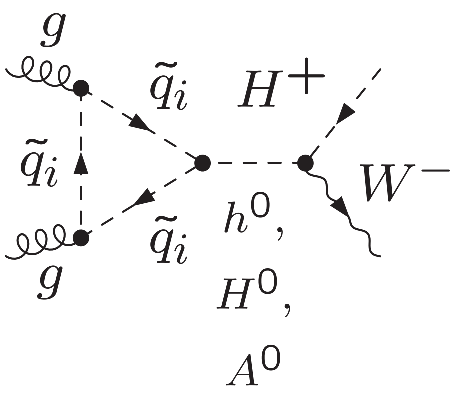
THDM amplitude

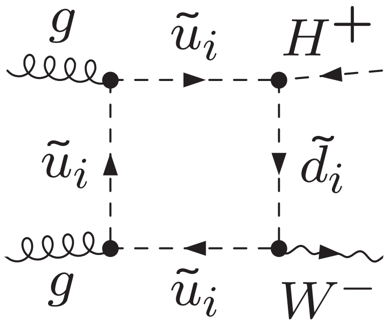




+ more

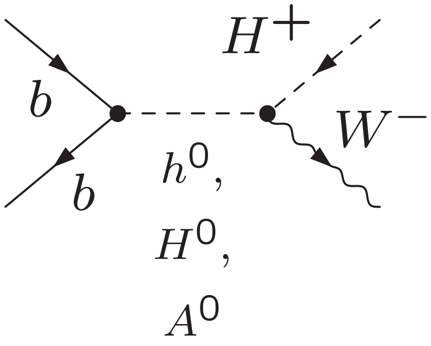
squark amplitude

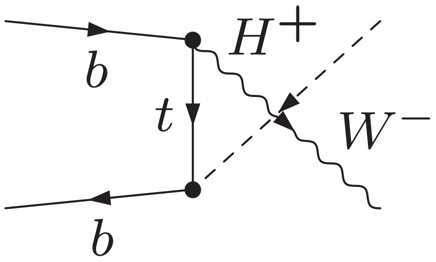




+ more

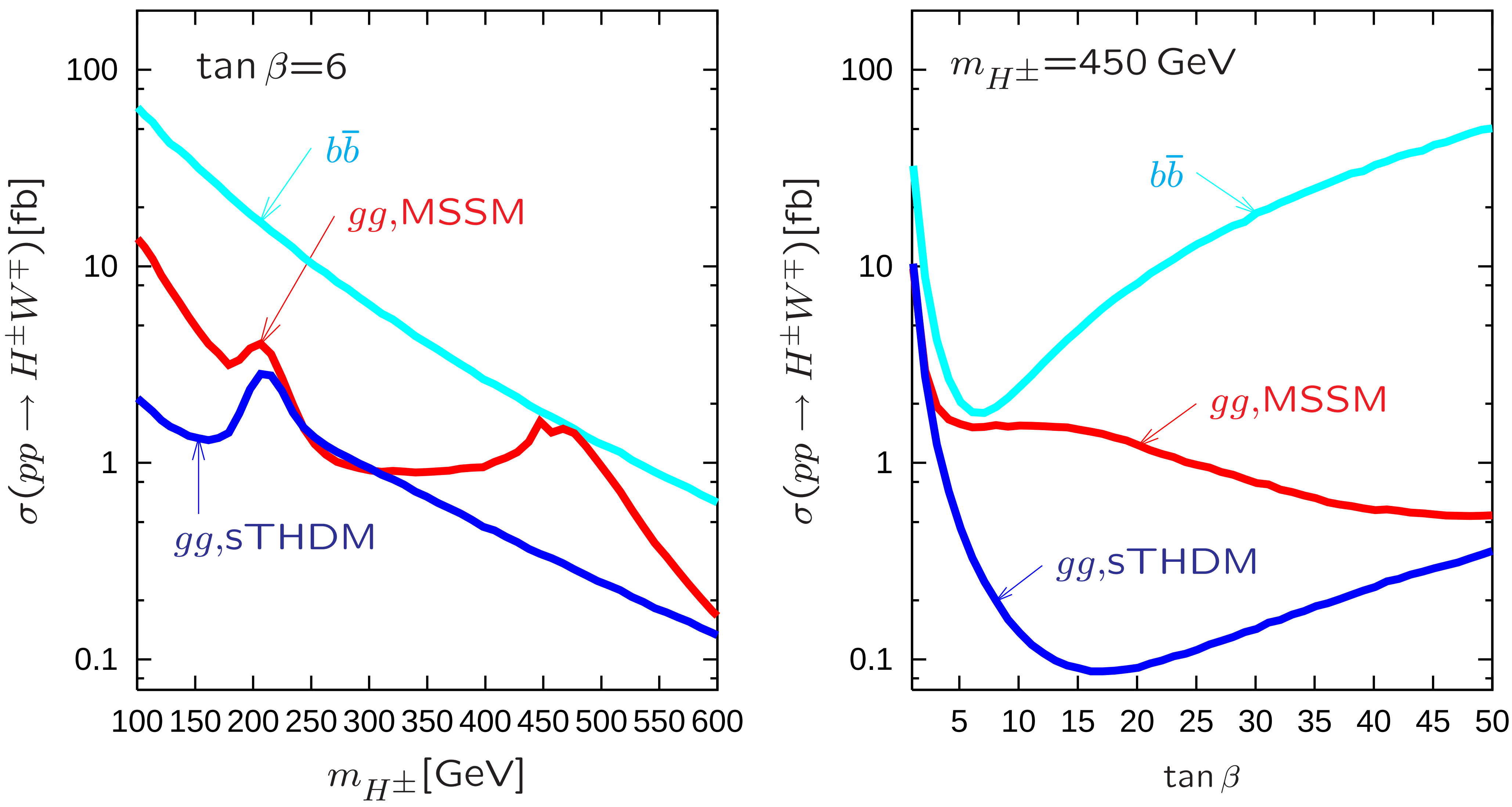
$b\bar{b}$ annihilation





[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 THDM

MSSM:

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

strong negative interference between Δ− 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

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

$\to$ Δ−amplitudes cannot decouple from the process

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

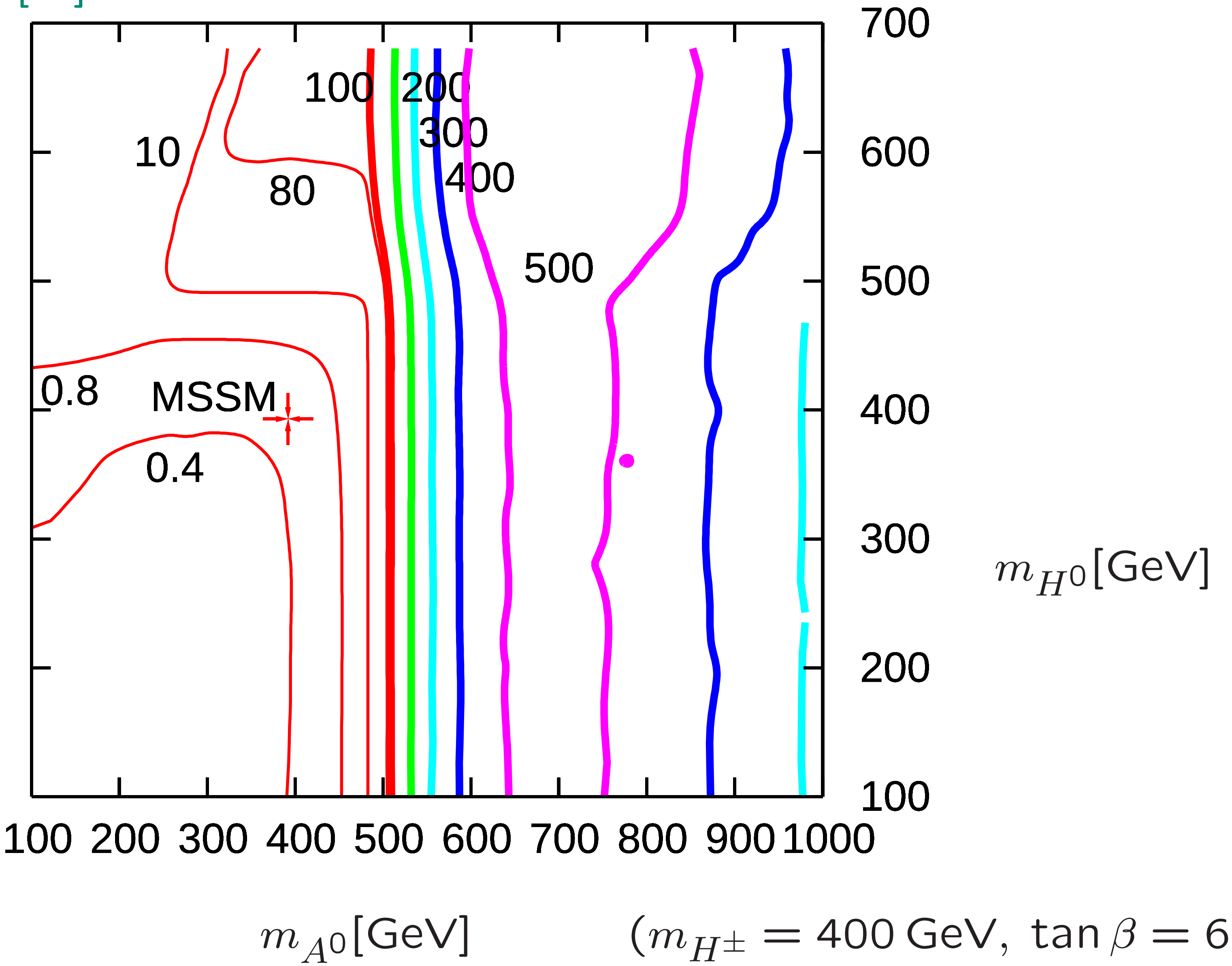
$\to$ negative interference unavoidable

THDM:

All this need not be true !

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

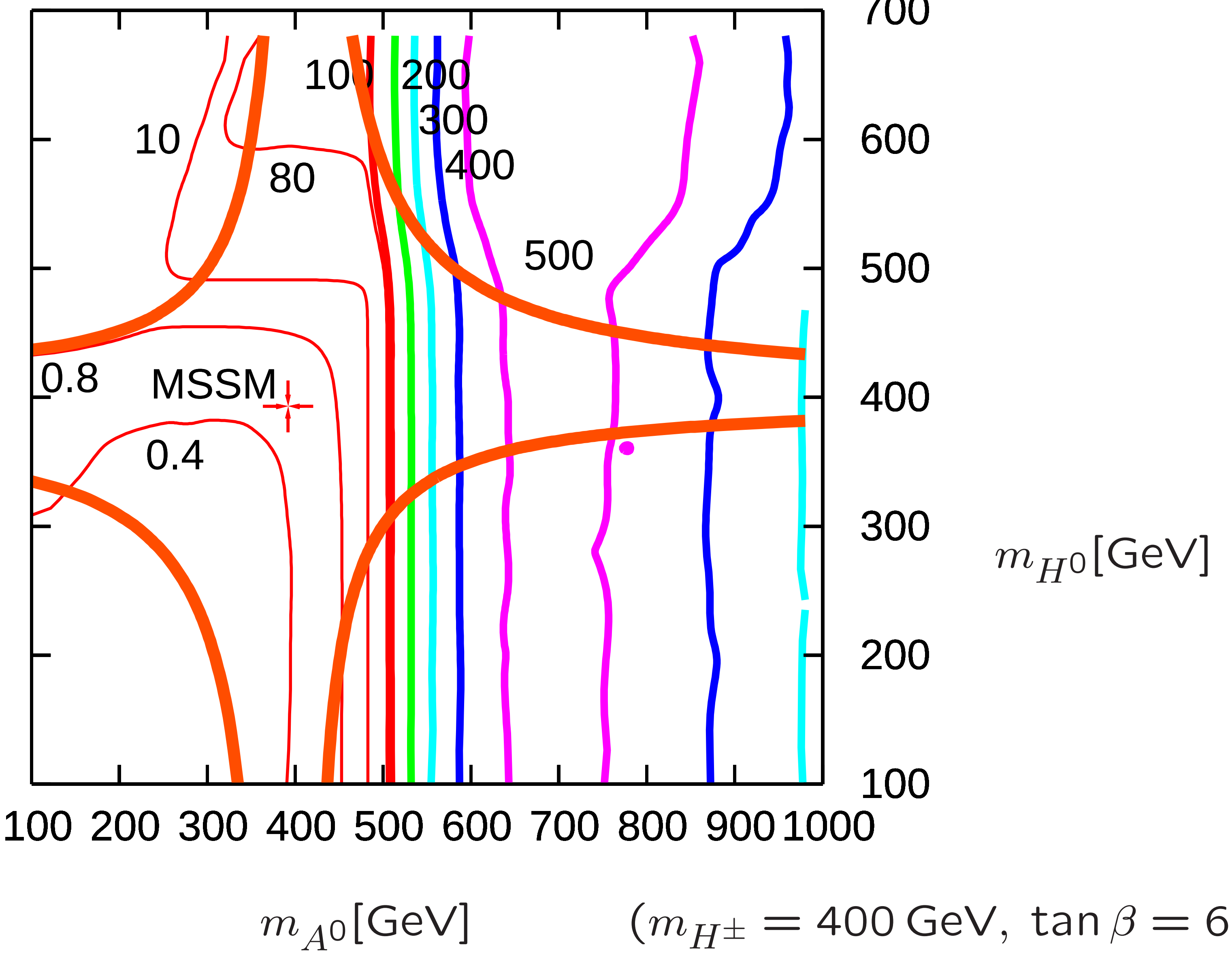
$\sigma(pp \to W^{\pm}H^{\mp})$ [fb]



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

[Asakawa, OBr, Kanemura, work in progress]

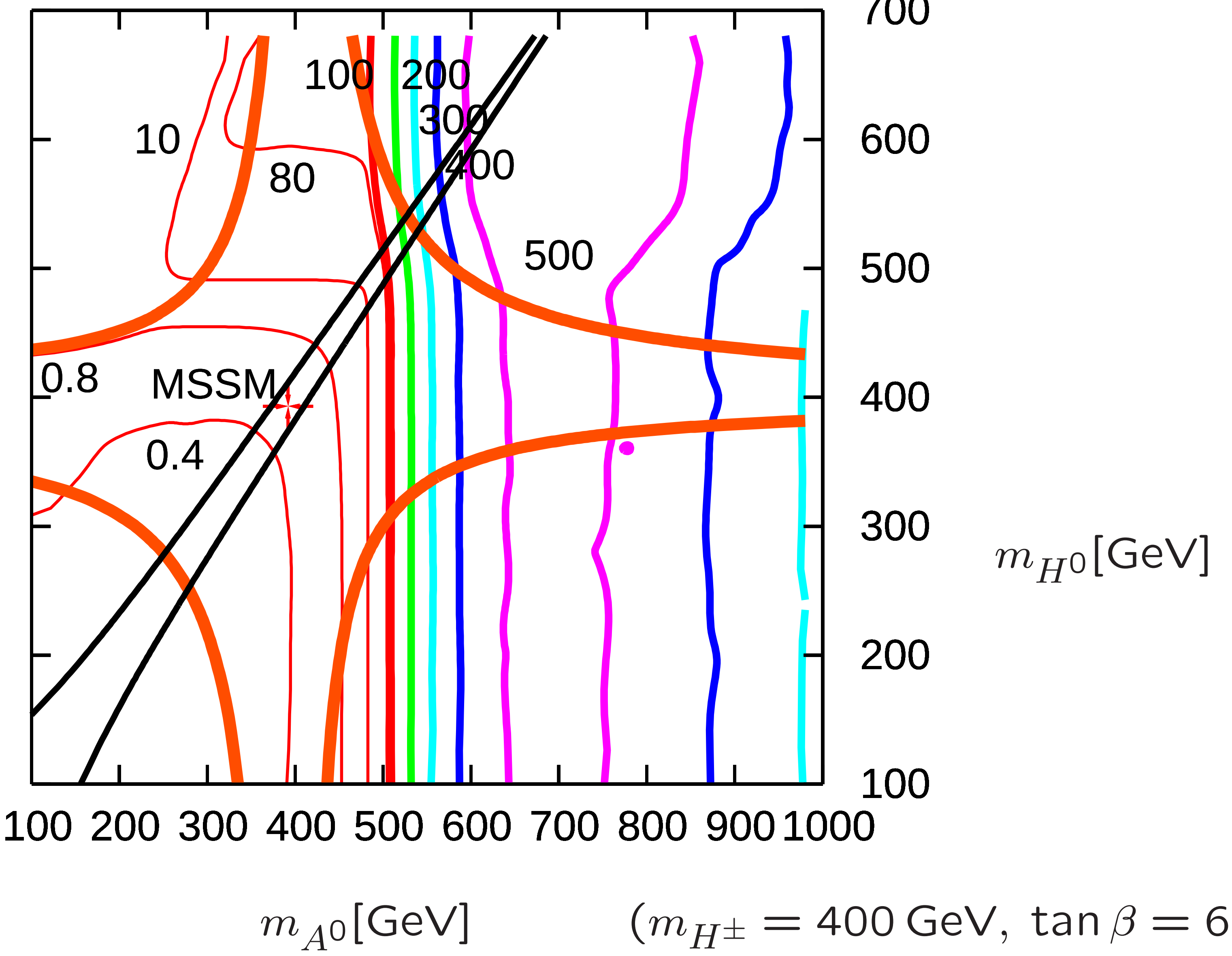
$\sigma(pp \to W^\pm H^\mp)$ [fb] $+$ $\Delta\rho$–bounds



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

[Asakawa, OBr, Kanemura, work in progress]

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



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

[Asakawa, OBr, Kanemura, work in progress]

Summary [$H^{\pm}W^{\mp}$ Production at the LHC: MSSM versus THDM]

- $H^{\pm}W^{\mp}$ production is no discovery process at the LHC

- 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