Higgs Searches at the LHC

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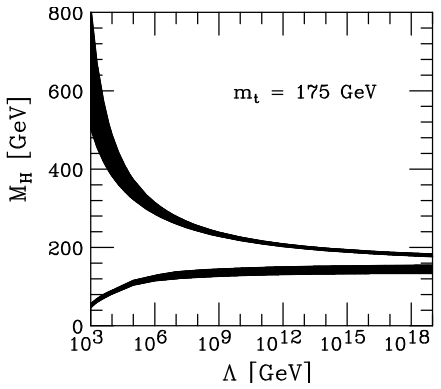
Outline

SM Higgs Sector - Mass Constraints

- Triviality $\rightarrow$ upper bound
  Vacuum stability $\rightarrow$ lower bound

Cabibbo,...;Sher; Lindner;Hasenfratz,...; Lüscher, Weisz; Hambye,...;...

Hambye,Riesselmann

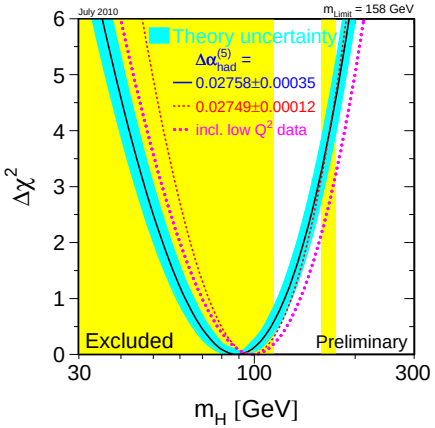


$\Lambda = 1$ TeV : 55 GeV $\lesssim M_H \lesssim$ 700 GeV

$\Lambda_{GUT} = 10^{16}$ GeV: 130 GeV $\lesssim M_H \lesssim$ 190 GeV

- Fits to electroweak precision data

EWWG



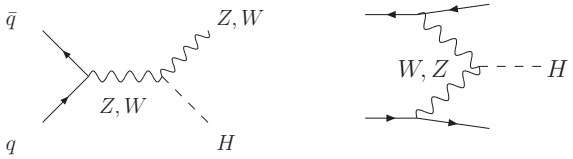
LEP Coll.

$M_H = 89^{+35}_{-26}$ GeV, $M_H \lesssim 185$ GeV @ 95% CL

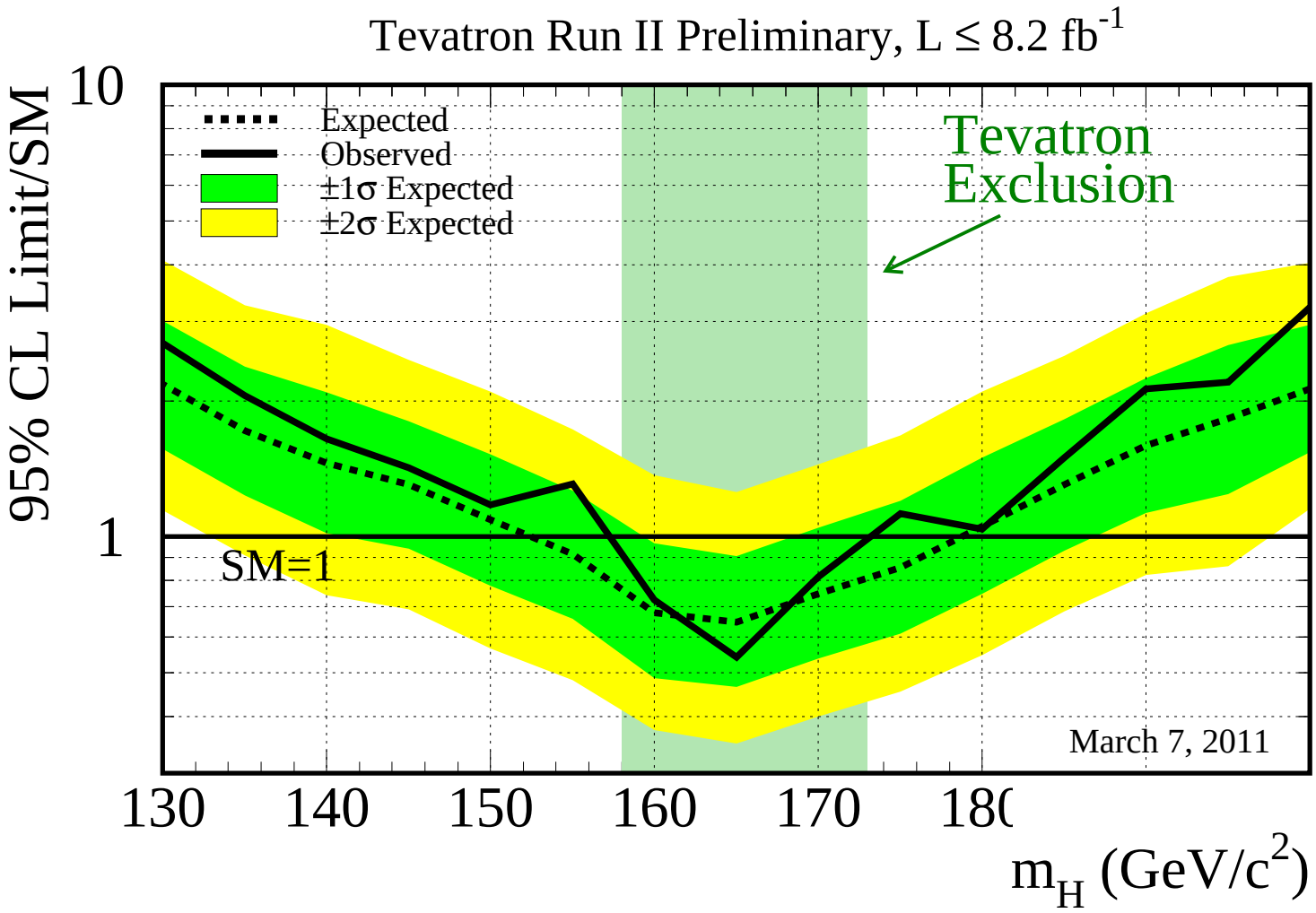
- Direct search @ LEP: $[M_H = 115.3$ GeV$]$

$M_H > 114.4$ GeV @ 95% CL

LEP Coll.



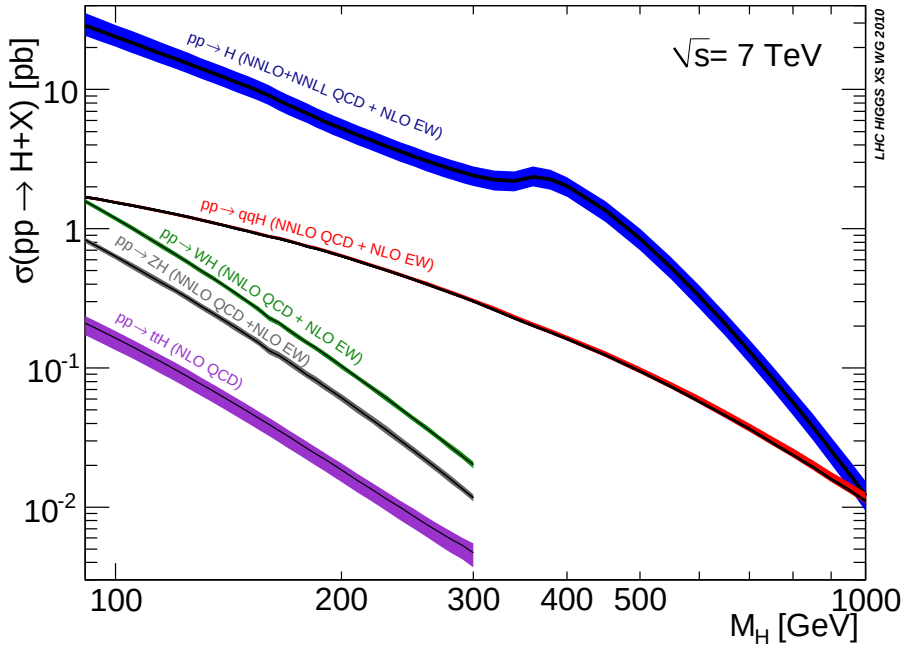
$\mathcal{T}$evatron $\mathcal{E}$xclusion

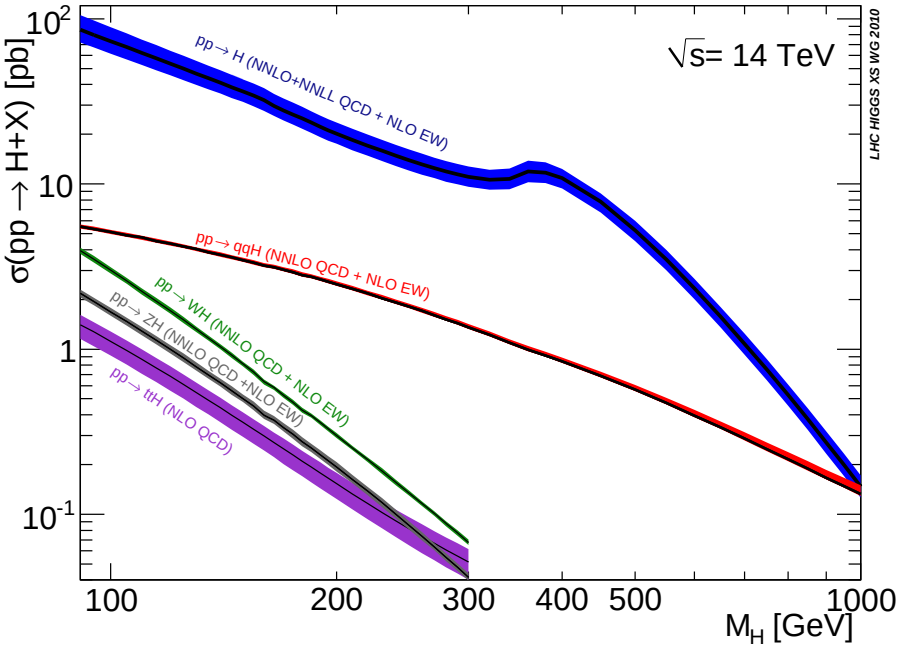


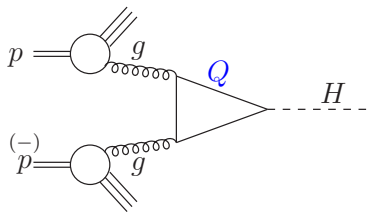
excluded: 158 GeV $\leq M_H \leq 173$ GeV at 95% C.L.

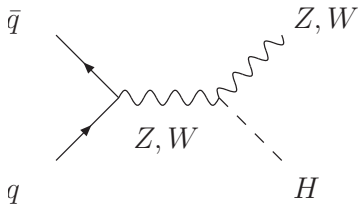
SM Higgs Boson Production at the LHC

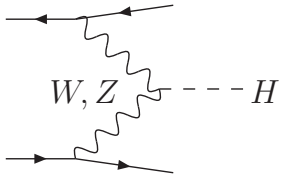
LHC Higgs XS WG, arXiv:1101.0593

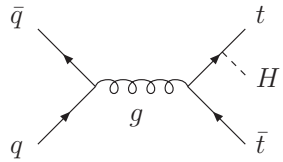












$\mathcal{LHC}$ $\mathcal{H}$iggs $\mathcal{C}$ross $\mathcal{S}$ection $\mathcal{W}$orking $\mathcal{G}$roup

- ◇ *"Handbook of LHC Higgs cross sections: 1. Inclusive observables."* arXiv:1101.0593
- ◇ provide best theory prediction for Higgs cross sections and branching ratios (SM and MSSM)
- ◇ provide theoretical uncertainties on these quantities
- ◇ give precise common inputs
- ◇ inclusive cross sections (effects of cuts on cxns and K factors $\rightarrow$ future publication)
- ◇ https://twiki.cern.ch/twiki/bin/view/LHCPhysics/Cross Sections

The MSSM Higgs Sector

MSSM Higgs sector – supersymmetry & anomaly free theory $\Rightarrow$ 2 complex Higgs doublets

$\overset{\text{EWSB}}{\rightarrow}$ neutral, CP-even h, H | neutral, CP-odd A | charged H^+, H^-

Higgs masses

$$M_h \lesssim 140 \text{ GeV}$$
$$M_{A,H,H^\pm} \sim \mathcal{O}(v)...1 \text{ TeV}$$

Ellis et al;Okada et al;Haber,Hempfling;
Hoang et al;Carena et al;Heinemeyer et al;
Zhang et al;Brignole et al;Harlander et al;...

Modified couplings with respect to the SM:

$$\tan\beta \uparrow \Rightarrow g_{\Phi uu} \downarrow$$
$$g_{\Phi dd} \uparrow$$
$$g^{MSSM}_{\Phi VV} \lesssim g^{SM}_{\Phi VV}$$

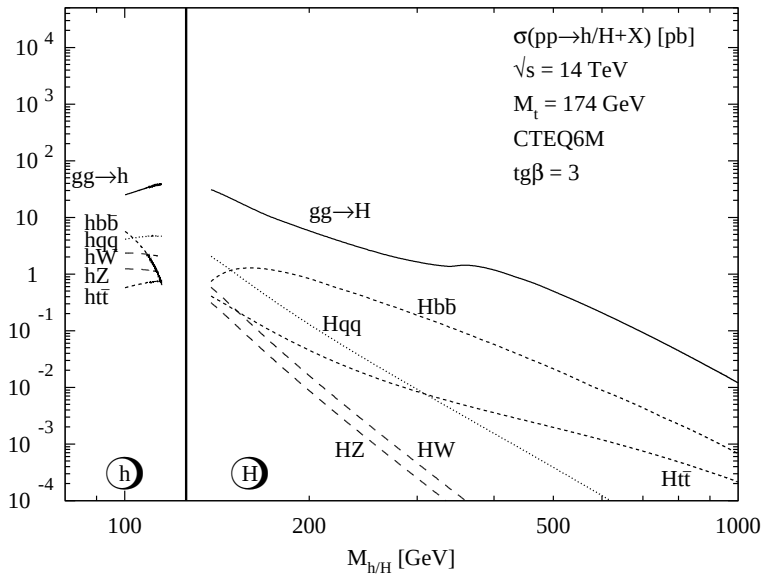
Direct search at LEP: $e^+e^- \rightarrow Z + h/H, A + h/H, \nu_e\bar{\nu}_e + h/H$

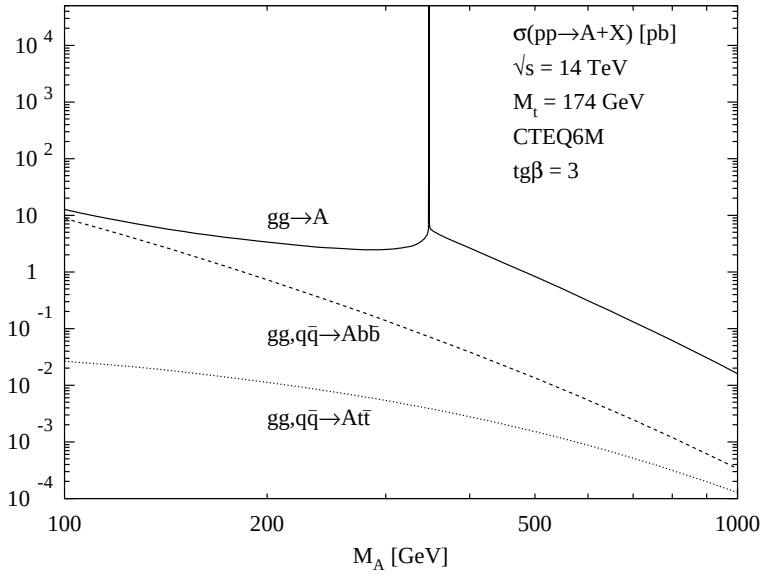
$M_{h,H} \gtrsim 92.6$ GeV, $M_A \gtrsim 93.4$ GeV, $M_{H^\pm} \gtrsim 78.6$ GeV,

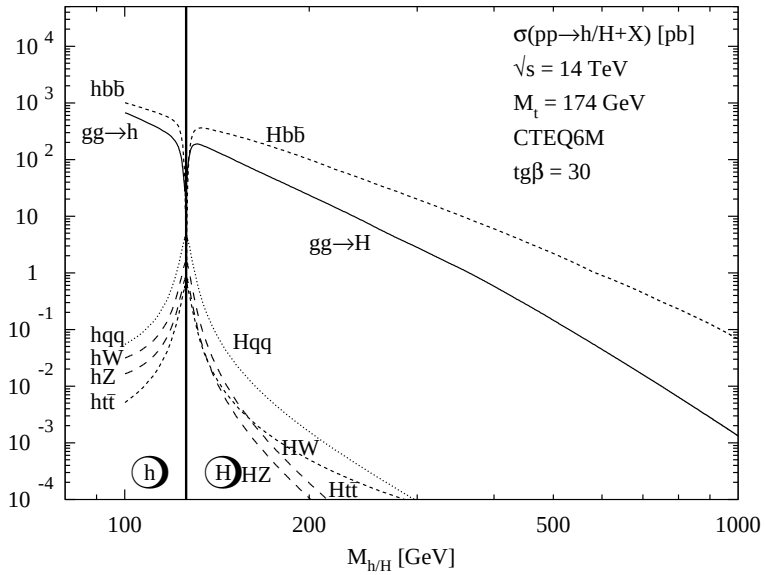
$0.6 < \tan\beta < 2.5$ excluded ($m_t = 174.3$ GeV)

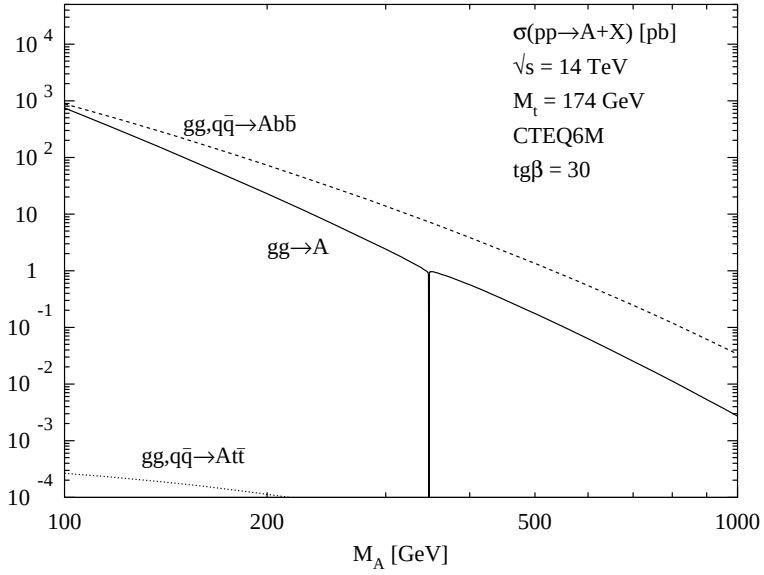
MSSM Higgs Boson Production at the LHC

Spira





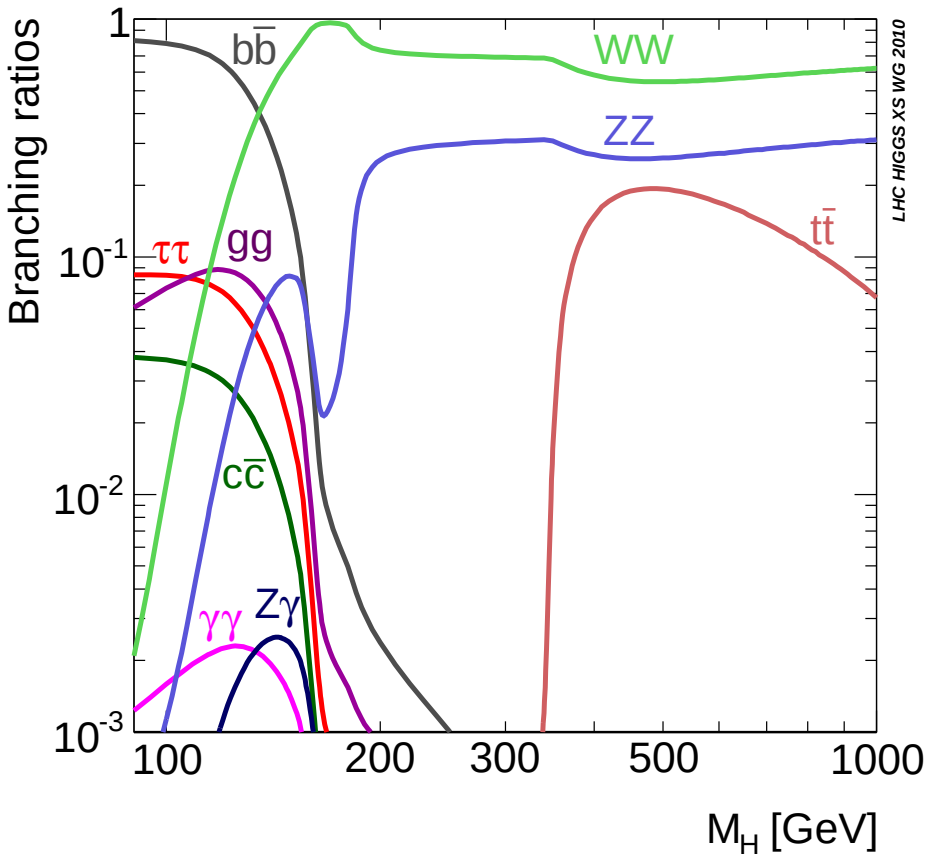


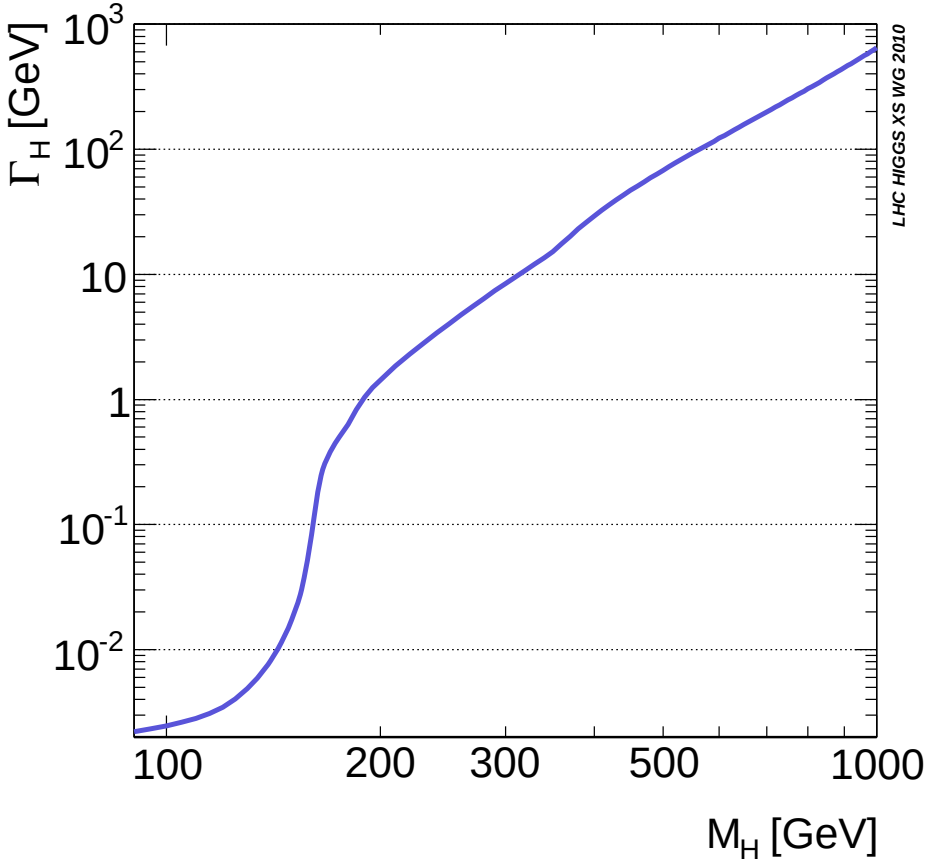


Decays

Branching Ratios

LHC Higgs XS WG





$\mathcal{B}$ranching $\mathcal{R}$atios

Created with HDECAY Djouadi,Kalinowski,MMM,Spira

PROPHECY4F Bredenstein,Denner,Dittmaier,Mück,Weber

⋆ HDECAY - upgrade '11

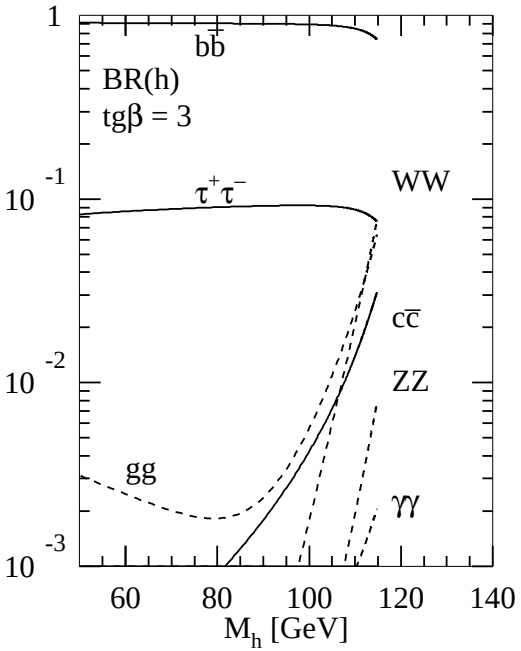
- SM 4th generation
- dominant EW corrs to $H \to WW, ZZ$ in fermiophobic and 4th generation SM
- 4-loop QCD to $H \to gg$ Baikov,Chetyrkin
- 3-loop QCD to $A \to gg$ Bardeen,Chetyrkin,Kniehl,Steinhauser
- NNLO running of α_s

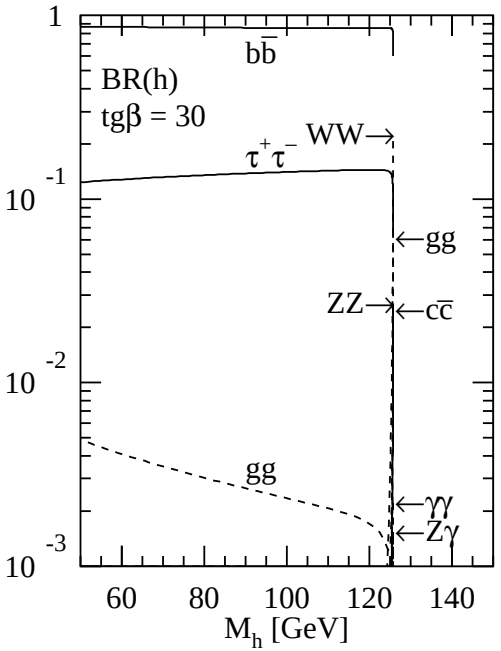
⋆ PROPHECY4F

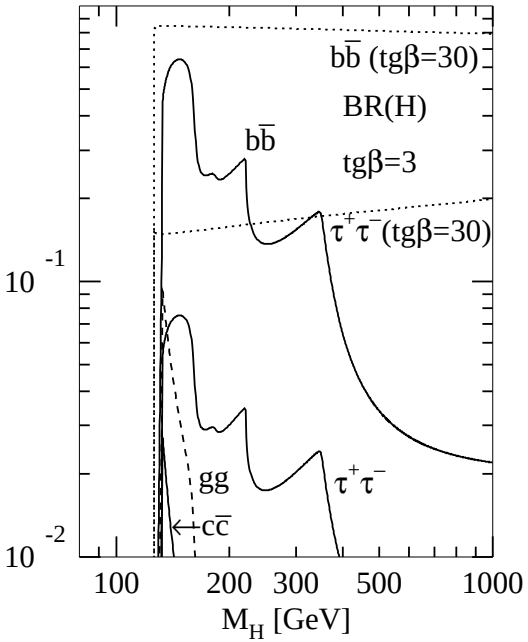
- $H \to WW/ZZ \to 4f$ complete NLO QCD and EW corrections w/ all interferences and leading 2-loop heavy Higgs corrections

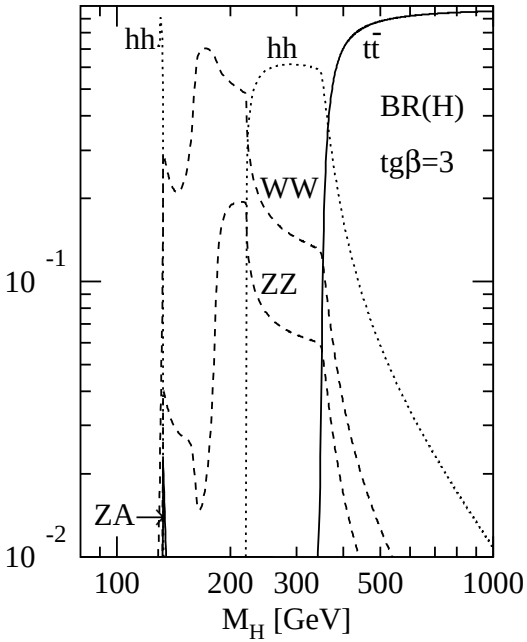
MSSM Branching Ratios

HDECAY



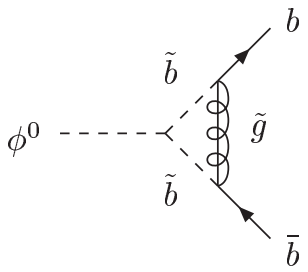






$\mathcal{SUSY}$ $\mathcal{D}$ecays - Further developments

- **Large SUSY-QCD corrections to $\phi^0 \to b\bar{b}$**



$+\ldots \qquad \sim \frac{\alpha_s}{\pi} \frac{m_{\tilde{g}} \mu \tan\beta}{m^2_{\tilde{b}}}$

Hall eal; Carena eal; Nierste eal; Guasch eal; ...

$\Rightarrow$ resummed Yukawa couplings

Carena, Garcia, Nierste, Wagner; Eberl eal; Guasch, Häfliger, Spira

$*$ NNLO to effective bottom Yukawa couplings: Δ_{th} at per cent level

Noth,Spira '08; Mihaila, Reißer '10

- **Full 1-loop corrections to $h_a \to h_b h_c$, $h_a \to f\bar{f}$ in complex MSSM**

Williams,Rzehak Weiglein '11

[tools for complex MSSM: FeynHiggs Hahn eal, CPsuperH Lee eal]

- **HFOLD:** Fortran package for MSSM Higgs 2-body decays and BRs at full one-loop level

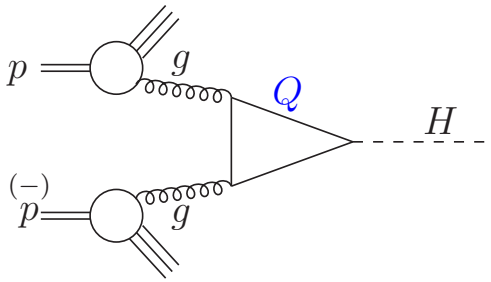
Frisch,Eberl,Hlucha '10

Production

$\mathcal{H}$iggs Boson Production in gluon fusion

(i) Dominant: Gluon Fusion $pp \to gg \to H^{SM}$ / h, H, A (small & moderate $\tan\beta$)

Georgi et al; Gamberini et al



QCD corrections to top & bottom loops

- ▷ NLO (SM, MSSM): increase σ by $\sim$ 10...100% [moderate for large $\tan\beta \leftarrow b$-loop] — Spira,Djouadi,Graudenz,Zerwas; Dawson;Kauffman,Schaffer
- ▷ SM; tg$\beta \lesssim 5$: limit $M_\Phi \ll m_t$ - approximation $\sim$ 20-30% — Krämer,Laenen,Spira
- ▷ NNLO @ $M_\Phi \ll m_t \Rightarrow$ further increase by 20-30% — Harlander,Kilgore; Anastasiou,Melnikov; Ravindran,Smith,van Neerven
- ▷ Estimate of NNNLO effects @ $M_\Phi \ll m_t \rightsquigarrow$ scale stabilisation; scale dependence: $\Delta \lesssim 10 - 15\%$ — Moch,Vogt; Ravindran
- ▷ NNLL resummation: $+ \sim 10\%$ — Catani,de Florian,Grazzini,Nason
- ▷ resummation of soft gluons @ N^{3}LL and of π^2 enhanced terms — Ahrens,Neubert,Becher,Yang

$\mathcal{H}$iggs Boson Production in gluon fusion

Corrections to top & bottom loops

- ▷ NNLO mass effects (t loops) — Harlander,Ozeren;Pak,Rogal,Steinhauser; Marzani et al.

  for $M_H \lesssim 300$ GeV $\Rightarrow \mathcal{O}(0.5\%)$
- ▷ NLO electroweak corrections $\sim -4\% - 6\%$ (SM) — Aglietti et al.;Degrassi,Maltoni; Actis et al
- ▷ mixed QCD and EW corrections — Anastasiou,Boughezal,Petriello

NLO corrections to squark loops

- ▷ in the heavy mass limit — Dawson,Djouadi,Spira
- ▷ full SUSY-QCD corrections in heavy mass limit — Harlander,Steinhauser;Harlander,Hofmann; Degrassi,Slavich '11
- ▷ bottom/sbottom contributions — Degrassi,Slavich '11; Harlander,Hofmann,Mantler '11

  asymptotic expansion in $\tilde{M} \gg m_b, M_\phi$

$m_{\tilde{Q}} \lesssim 400$ GeV:

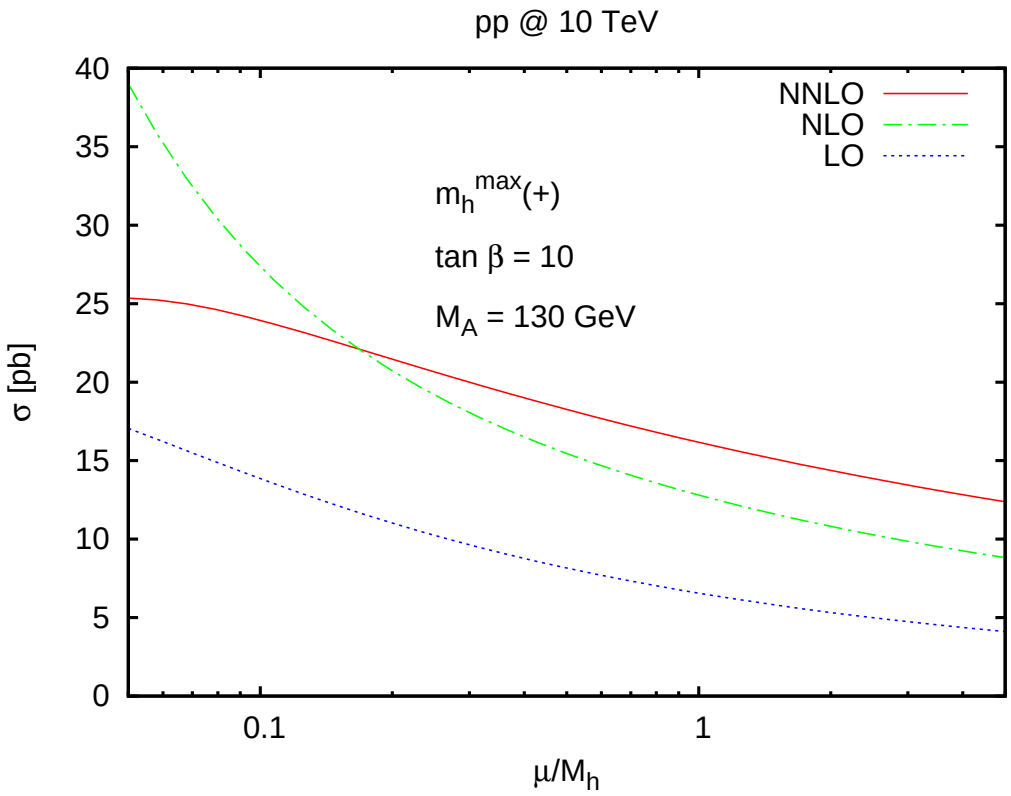
- ▷ NLO squark mass effects $\sim 15\%$ — MMM,Spira;Anastasiou,Beerli,Bucherer, Daleo,Kunszt;Aglietti,Bonciani,Degrassi,Vicini
- ▷ full NLO SUSY QCD calculation — Anastasiou,Beerli,Daleo; MMM,Rzehak,Spira

NNLO SUSY-QCD corrections from $t/\tilde{t}$ sector — Pak,Steinhauser,Zerf '10

MSSM Higgs production in gluon fusion

$$\sigma^{MSSM} = \sigma^{MSSM}_{NLO} + (g^h_t)^2 \left[(1+\delta_{EW})\sigma^{SM,t}_{NNLO} - \sigma^{SM,t}_{NLO} \right]$$

Harlander,Hofmann,Mantler '11

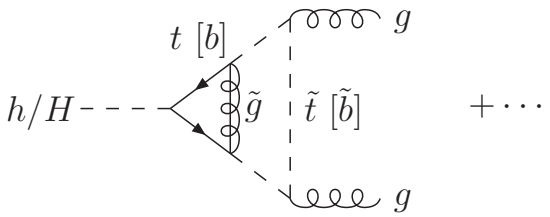


Mhmax: $\tan\beta = 10$, $M_{SUSY} = 1$ TeV, $\mu = 200$ GeV, $M_2 = 200$ GeV, $M_3 = 800$ GeV, $X_t = 2$ TeV
$m_{\tilde{t}_1} = 830$ GeV, $m_{\tilde{t}_2} = 1170$ GeV, $m_{\tilde{b}_1} \approx m_{\tilde{b}_2} \approx 1$ TeV, $m_{\tilde{g}} = 800$ GeV

Genuine SUSY-QCD corrections

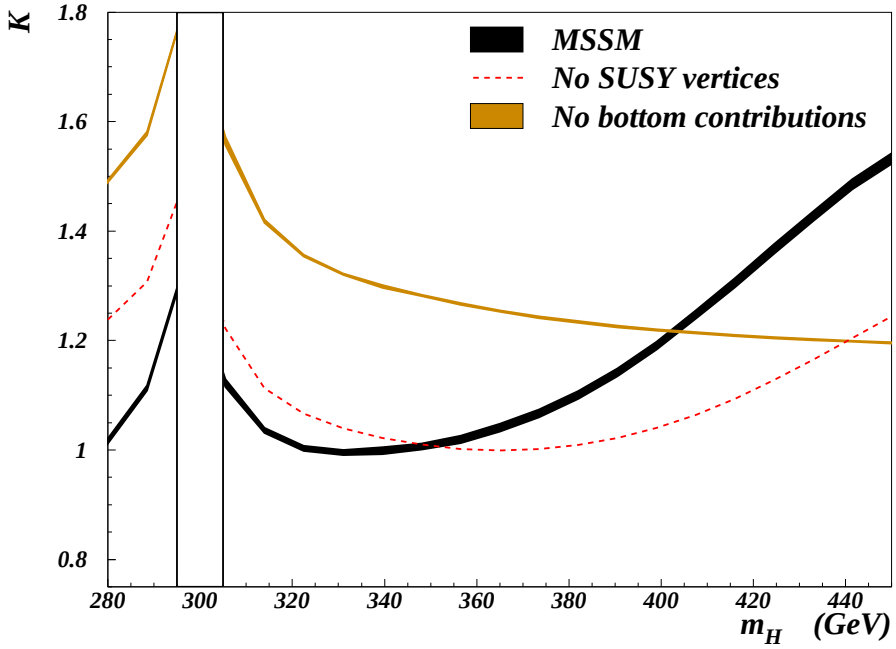
- **Limit heavy SUSY masses** $\rightarrow \mathcal{O}(10\ \%)$

Harlander,Steinhauser,Hofmann



Anastasiou,Beerli,Daleo
MMM,Rzehak,Spira

Anastasiou,Beerli,Daleo

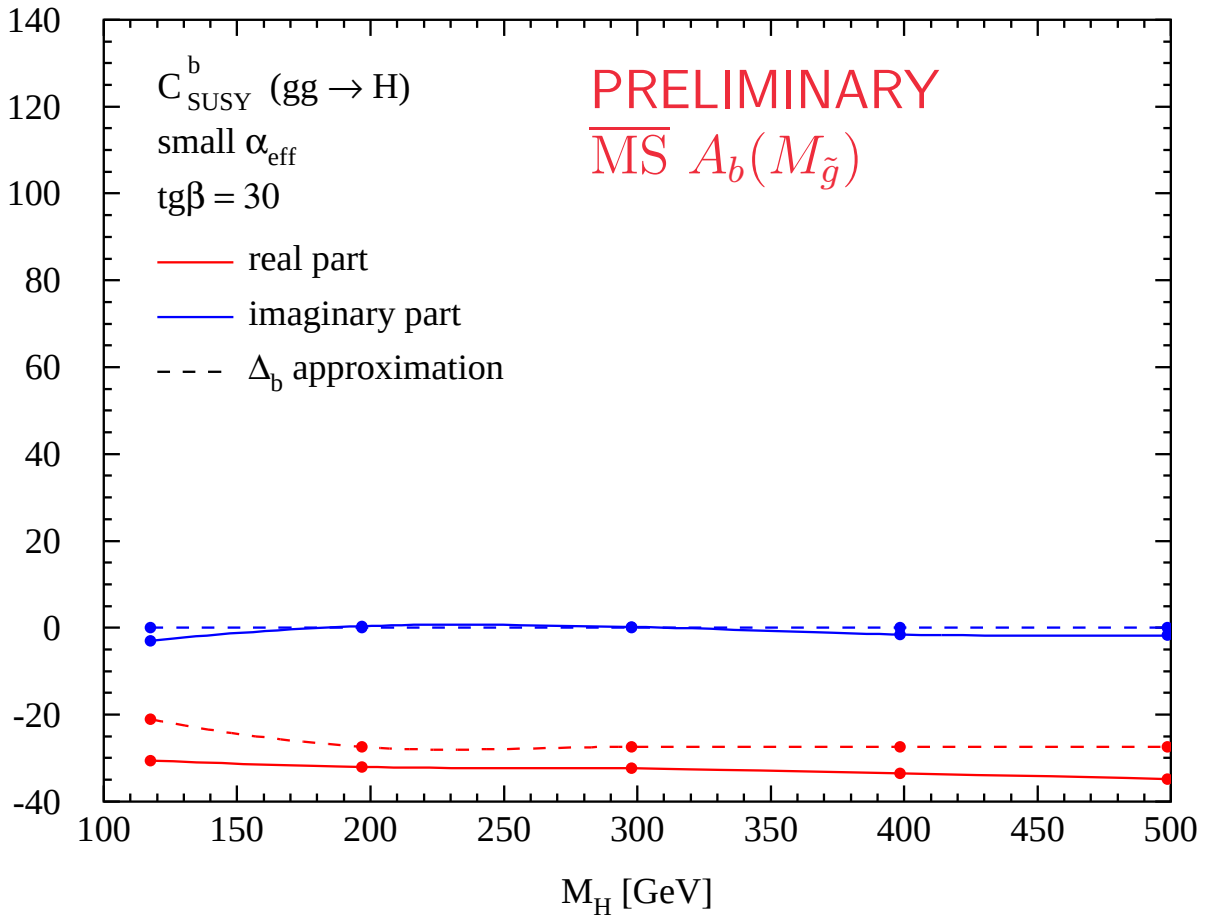


$\tan\beta = 20$, $\mu = 300$ GeV, $\alpha = 3°$, $\theta_t = \theta_b = 40°$, $m_{\tilde{g}} = 500$ GeV,
$m_{\tilde{t}_1} = 150$ GeV, $m_{\tilde{t}_2} = 350$ GeV, $m_{\tilde{b}_1} = 350$ GeV, $m_{\tilde{b}_2} = 370$ GeV

Genuine SUSY-QCD corrections

$$\sigma(pp \to \phi) = \sigma_0^{\phi} \tau_\phi \frac{d\mathcal{L}^{gg}}{d\tau_\phi}$$

$$\sigma^{h/H} = \frac{G_F \alpha_s^2}{288\sqrt{2}\pi} \left| \sum_Q g_Q^{h/H} A_Q^{h/H} \left[1 + C_{SUSY}^{Q} \frac{\alpha_s}{\pi} \right] + \sum_Q g_{\tilde{Q}}^{h/H} A_{\tilde{Q}}^{h/H}(\tau_{\tilde{Q}}) \right|^2$$



MMM, Rzehak, Spira

Further developments

- **Update of** `HIGLU: Version 3.01` Spira '11
  - NNLO QCD corrections and mixed EW/QCD corrections (fully factorized)
  - NNLO evolution of α_s
  - 4th generation SM4 with NNLO QCD (g_B, g_T, m_B, m_T)
  - inferface with LHAPDF library
- **Program** `iHixs` Anastasiou,Bühler,Herzog,Lazopoulos '11
  - gluon fusion & bottom quark fusion up to NNLO, mixed QCD/EW corrections, finite Γ_H effects
  - SM and modified w/ anomalous Yukawa couplings & EW interactions (4th generation, ...)
  - inferface with LHAPDF library

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  - SM and modified w/ anomalous Yukawa couplings & EW interactions (4th generation, ...)
  - inferface with LHAPDF library
- **Gluon fusion with four generations** Anastasiou et al '11
  - NLO QCD w/ full quark mass dependence, NNLO QCD in HQET, 3-loop EW/QCD corrections

    Cxn increased by factor 9 compared to SM Anastasiou eal '11; Ruan,Zhang '11

Further developments

- **Update of** `HIGLU: Version 3.01` Spira '11
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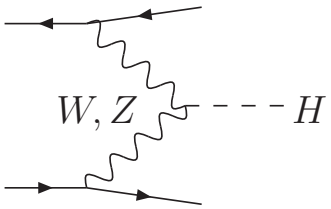
- **MadLoop** Hirschi et al. '11
  - complete automation of 1-loop QCD corrections
  - example $t\bar{t}H$ production

$\mathcal{H}$iggs Boson Production in W/Z boson fusion

(ii) W/Z boson fusion: $pp \to qq \to qq + WW/ZZ \to qq + H^{SM}/\ h, H$



Cahn, Dawson
Hikasa
Altarelli, Mele, Pitolli

- ▷ **NLO QCD corrections to total rate (SM/MSSM)** ~ 5 to 10% — Han, Valencia, Willenbrock
  distributions (SM/MSSM) ~ 20 % — Figy, Oleari, Zeppenfeld; Berger, Campbell
  dominant NLO QCD to H+3j — Figy, Hankele, Zeppenfeld
- ▷ **Full EW & QCD corrections** $\sim 5\%$ — Ciccolini, Denner, Dittmaier — HAWK — $(\Delta^{\text{theor}} \sim 5\ \%)$
- ▷ **SUSY QCD corrections small** — Djouadi, Spira
- ▷ **SUSY EW+QCD corrections small** — Hollik, Plehn, Rauch, Rzehak; Figy, Palmer, Weiglein '10

W/Z boson fusion - further higher order corrections

- ▷ **One-loop interference effects in H+jj** — Andersen,Binoth,Heinrich,Smillie; Bredenstein,Hagiwara,Jäger

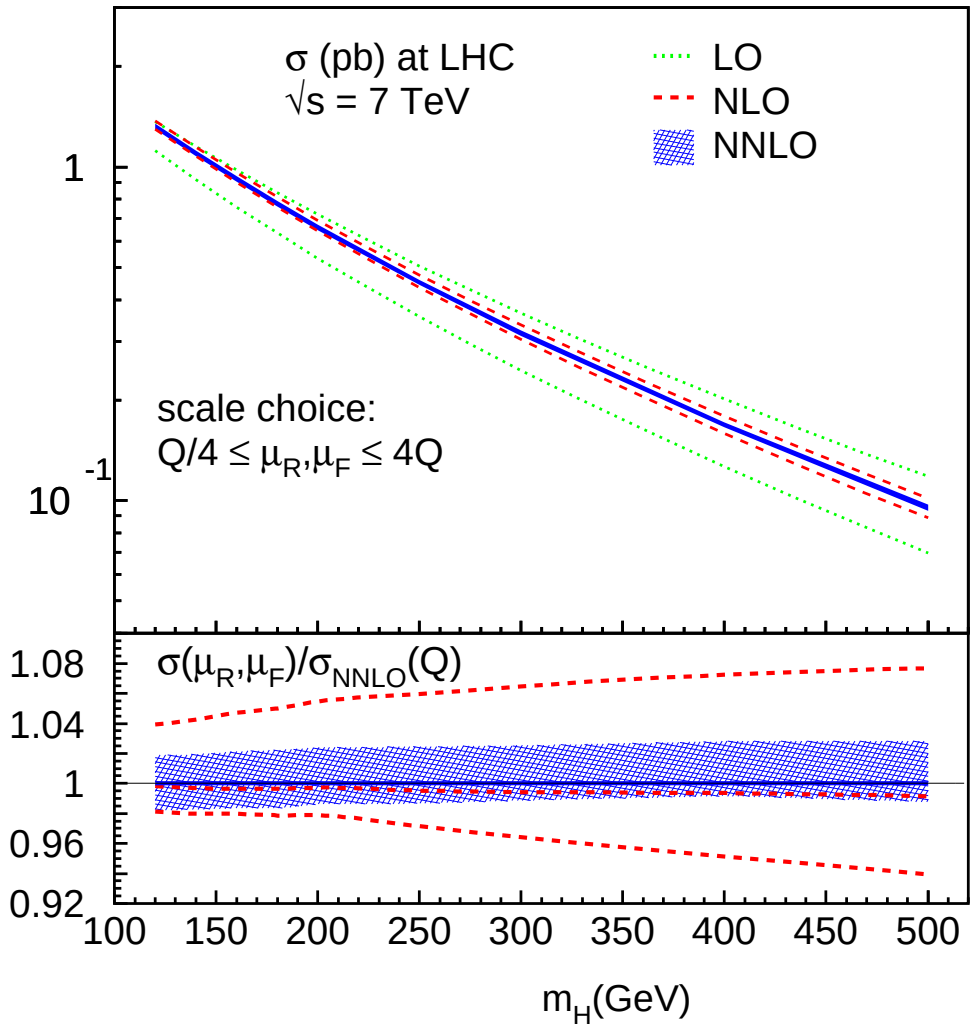
  between gg fusion and WBF at $\mathcal{O}(\alpha^2\alpha_s^3)$ — below percent level

  implemented in `VBFNLO` — Bredenstein,Hagiwara,Jäger

- ▷ **NNLO QCD effects $\mathcal{O}(\alpha^3\alpha_s^2)$** — $\Delta_{th} \sim 2\%$ — Harlander,Vollinga,Weber; Bolzoni,Maltoni,Moch,Zaro '10

W/Z boson fusion NNLO QCD corrections

Bolzoni,Maltoni,Moch,Zaro '10

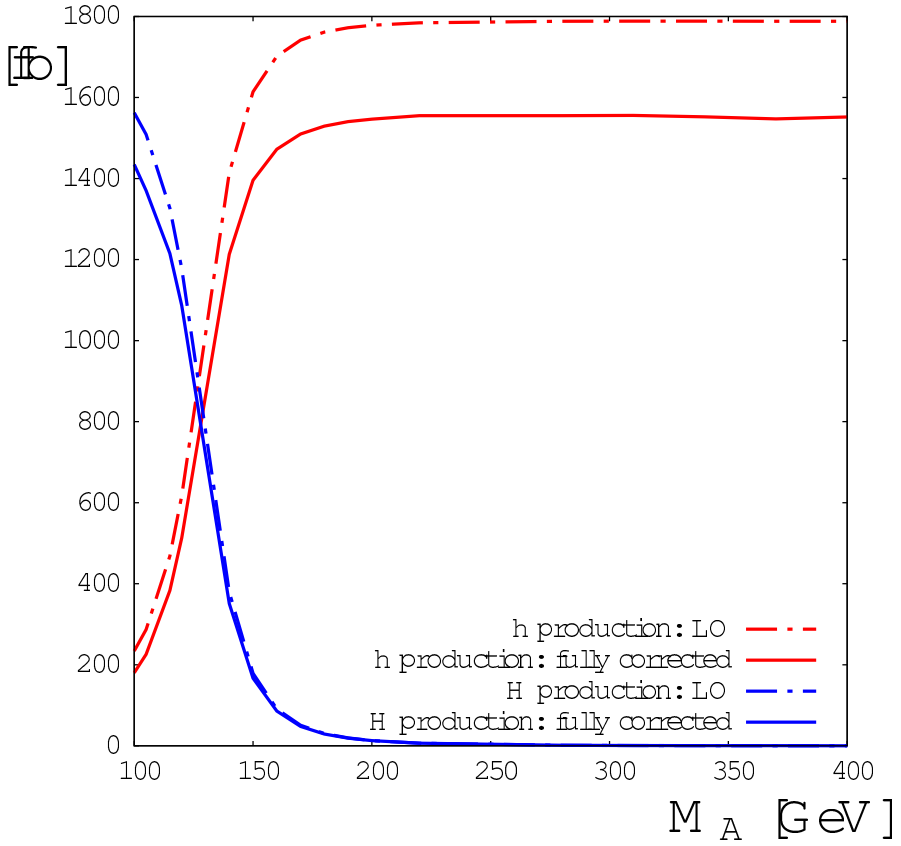


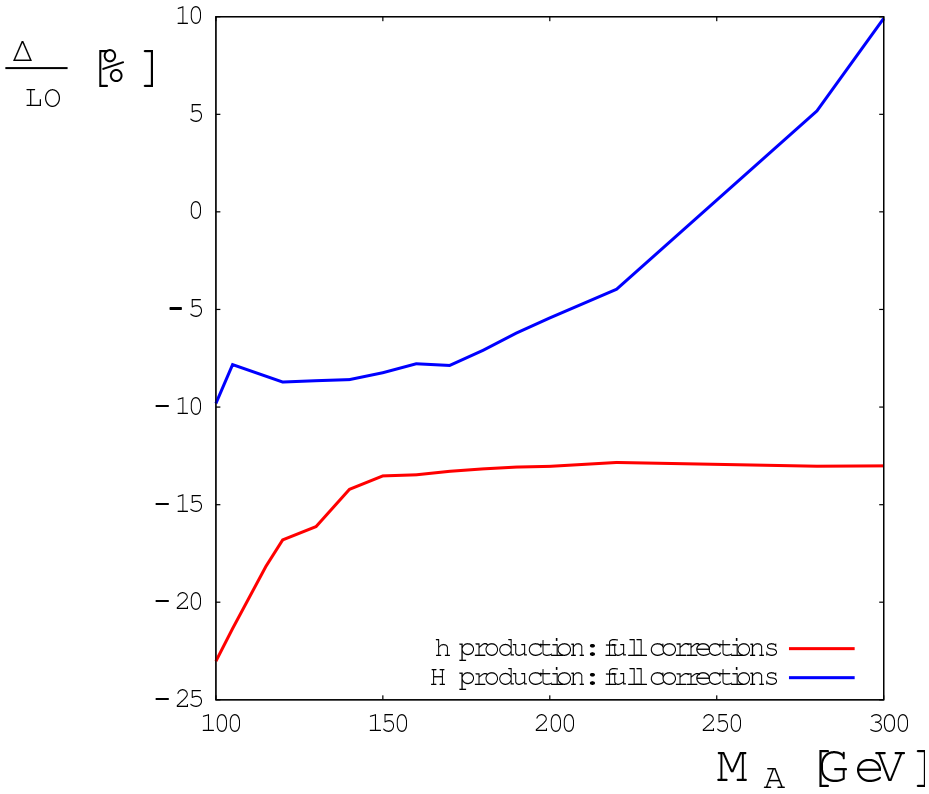
W/Z boson fusion in the SM and MSSM

SM: Full 1-loop

Figy,Palmer,Weiglein '10

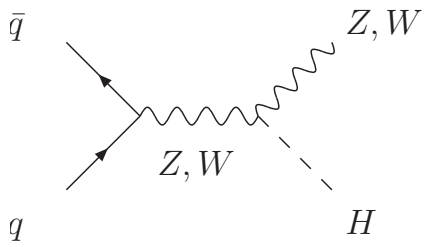
MSSM: dominant SUSY 1-loop combined w/ full 1-loop SM type corrections; complex phases





$\mathcal{H}$iggs-strahlung

(iii) $pp \to q\bar{q} \to Z^*/W^* \to Z/W + H^{SM}/\ h, H$



Glashow et al.
Kunszt et al.

Contribution to $\Phi \to \gamma\gamma$ discovery contour

- **NLO QCD corrections (SM/MSSM)** $\sim +30\%$ (Drell-Yan) — Han,Willenbrock

  NNLO QCD corrections (SM/MSSM) $\sim +5$-10% — Harlander,Kilgore; Hamberg,Van Neerven,Matsuura; Brein,Djouadi,Harlander

  $\Delta_{\text{theor}} \sim 5\ \%$

- **SUSY QCD corrections** $\lesssim$ few per cent — Djouadi,Spira

- **Full EW corrections (SM)** ~ -5-10% — Ciccolini,Dittmaier,Krämer

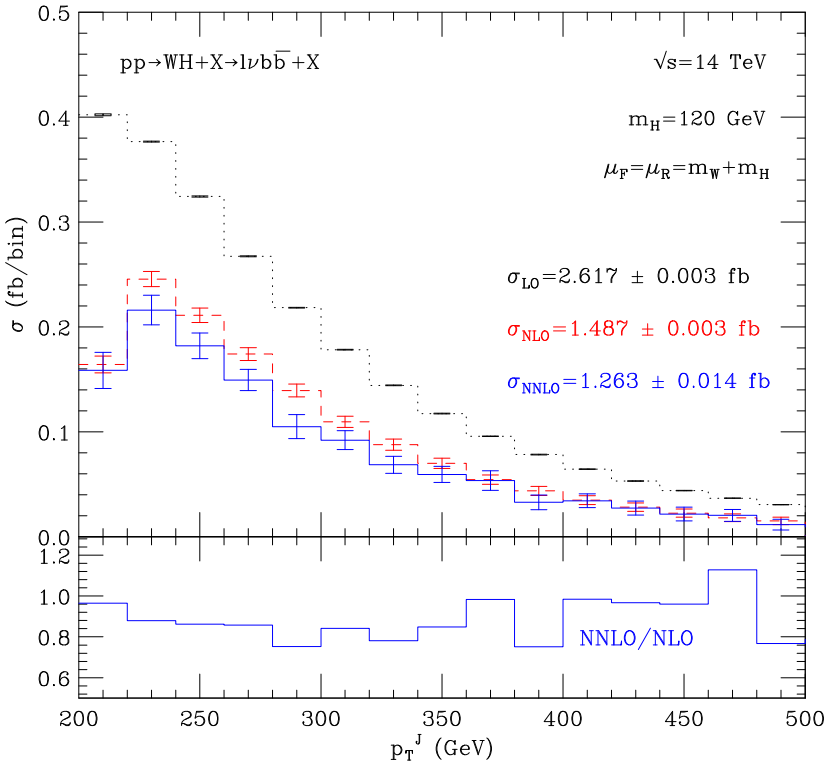
WH: Fully exclusive at NNLO QCD

WH: fully exclusive at NNLO QCD

Ferrera, Grazzini, Tramontano '11

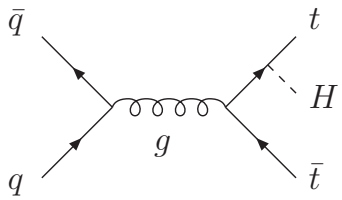
- finite width effects
- W boson leptonic decay w/ spin correlations
- Higgs decay into $b\bar{b}$

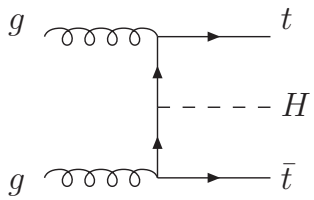
scale dep $\pm 13\%$ (NLO) $\rightarrow$ $\pm 6\%$ (NNLO)



Associated production with a $t\bar{t}$ pair

(iv) Higgs $t\bar{t}$ production: $pp \to q\bar{q}/gg \to t\bar{t} + H^{SM}/\ h(H, A)$





dominant

Kunszt;Gunion;
Marciano,Paige

Significant role: $M_H^{SM} \lesssim 150$ GeV; light scalar MSSM Higgs

- **$t\bar{t}H \to t\bar{t}\gamma\gamma$ important contr. to $H \to \gamma\gamma$ discovery**
- **$t\bar{t}H \to t\bar{t}b\bar{b}$ important at LHC $\rightsquigarrow$ top Yukawa coupling**

  Gunion et al.;
  Drollinger et al.

- **NLO bkg $t\bar{t}b\bar{b}$, $t\bar{t}jj$***

  Bredenstein,Denner,Dittmaier,Pozzorini;
  Bevilacqua,Czakon,Papadopoulos,Pittau,Worek
  *Bevilacqua et al. `HELAC-NLO`

- **NLO QCD corrections (SM,MSSM): $\sim +20$ %**
  $\Delta^{\text{theor}} \sim 15$ %

  Beenakker et al.;
  Dawson et al.

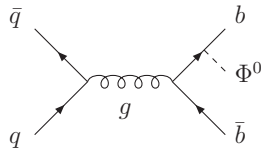
- **SUSY QCD corrections: $\pm(10 - 30)$ %**

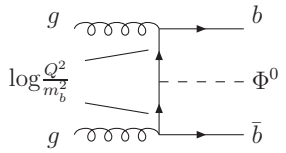
  Peng et al.
  Dittmaier,Häfliger,Krämer,Spira,Walser

Associated production with a $b\bar{b}$ pair

(v) Higgs $b\bar{b}$ production: dominant MSSM Higgs production mechanism for $\tan\beta \gtrsim 7$
measurement of $\tan\beta$

- Four-flavour scheme 4FS: LO cxn $gg \to b\bar{b}\Phi^0$





dominant

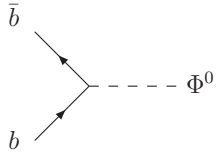
NLO with 0,1,2 high-transverse momentum b jets

Dittmaier,Krämer,Spira;
Dawson,Jackson,Reina,Wackeroth

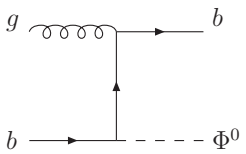
exact $g \to b\bar{b}$ splitting & mass/off-shell effects

large logs from phase space integration $\rightsquigarrow$ absorbed in bottom PDF $\Rightarrow$

- Five-flavour scheme 5FS: LO cxn $b\bar{b} \to \Phi^0$



NNLO



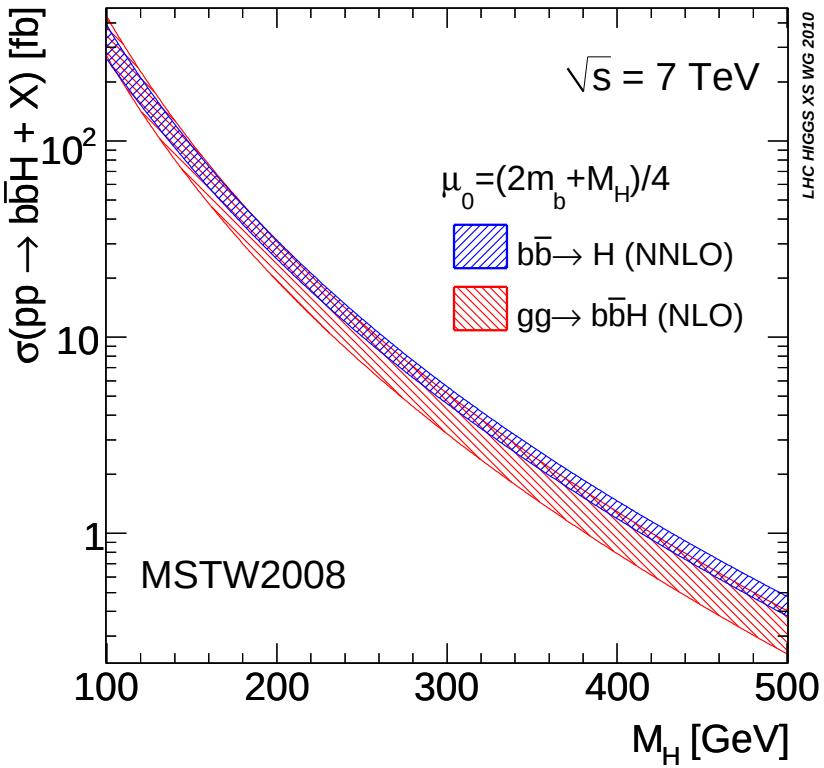
NLO

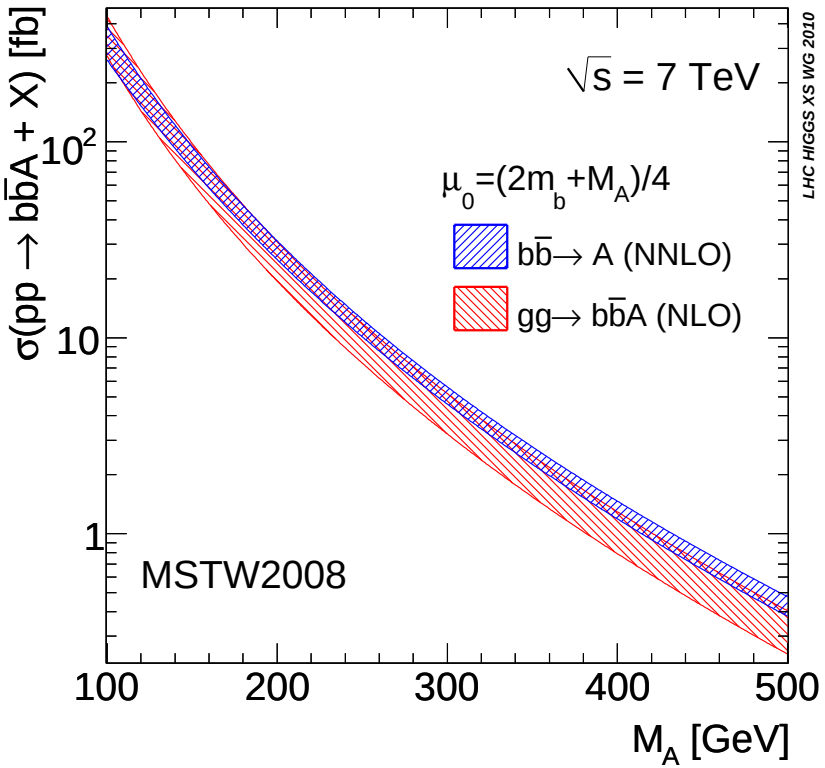
Dicus,Willenbrock
Stelzer et al.;Balazs et al.
Campbell et al.
Harlander,Kilgore
Kidonakis

massless/on-shell b's, no p_{Tb}, resummation of $\log M_H^2/m_b^2$ terms

Associated production with a $b\bar{b}$ pair

LHC Higgs XS WG





blue bands: combined scale and 68% CL PDF+α_s uncertainties of the 5FS

red bands: scale uncertainties of the 4FS

Associated production with a $b\bar{b}$ pair

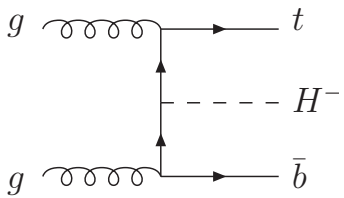
- **Further corrections:**

◦ EW and QCD corrections to $b\bar{b} \to \Phi^0$:	few % ($\sim \Delta_b$)	Dittmaier,Krämer, Mück,Schlüter
◦ dominant t contr. to "NNLO" $b\bar{b}h$:	few % $M_H \lesssim 120$ GeV several 10 % above	Boudjema, Ninh
◦ SUSY QCD to $gg \to b\bar{b}h$		Gao et al.; Hollik,Rauch
◦ SUSY QCD to $b\bar{b} \to \Phi^0, bg \to b\Phi^0$:	few % ($\sim \Delta_b$)	Dawson, Jackson
◦ EW to $bg \to bH^{\text{SM}}$		Dawson, Jaiswal '10
◦ Complete EW to $bg \to b\Phi^0$		Beccaria, et al. '10

Charged Higgs Production

(vi) Dominant: $pp \to q\bar{q}, gg \to t\bar{b}H^- + X$ (4FS), $bg \to H^- t$ (5FS)

- Four-flavour scheme 4FS: LO cxn $pp \to q\bar{q}, gg \to t\bar{b}H^-$



Bawa eal;
Borzumati eal;
Belyaev eal

NLO QCD & SUSY QCD corrections

Peng et al.
Dittmaier et al.

scale dependence reduced: $\Delta \lesssim 25\ \%$

exact $g \to b\bar{b}$ splitting & mass/off-shell effects
no resummation of $\log M_H^2/m_b^2$ terms $\Rightarrow$

- Five-flavour scheme 5FS: LO cxn $gb \to H^- t$

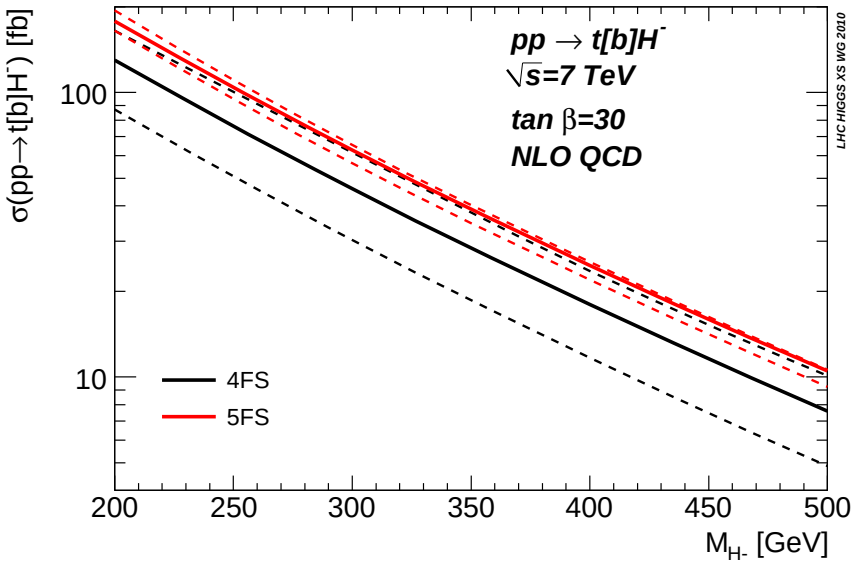
NLO SUSY QCD corrs.: significant

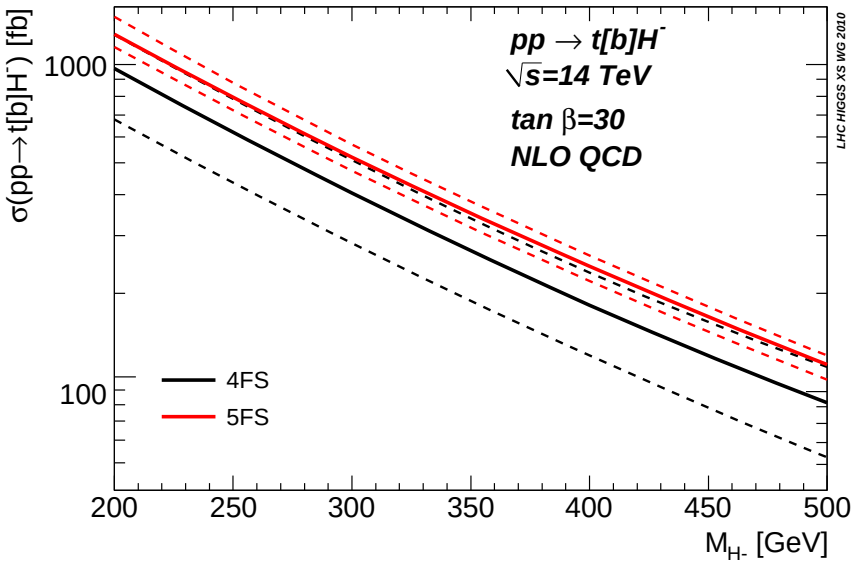
Zhu; Plehn; Berger eal;
Gao et al.;Kidonakis

massless/on-shell b's, no p_{Tb},
resummation of $\log M_H^2/m_b^2$ terms

Charged Higgs Production

LHC Higgs XS WG





error bands: $\mu_0/3 \leq \mu_R, \mu_F \leq 3\mu_0$

5FS: $\mu_0 = (m_t + M_{H^-})/4$

4FS: $\mu_0 = (m_t + m_b + M_{H^-})/3$

$\mathcal{C}$harged Higgs Production

- **Further corrections:**
  - EW and strong corrections to in 4FS and 5FS — Jin et al.; Belyaev et al
  - Complete NLO MSSM EW corrections to $bg \to tH^-$ can be sizeable — Beccaria et al.

Higgs Physics - Beyond

UnHiggs

Private Higgs

Little Higgs

Gaugephobic Higgs

Intermediate Higgs

Littlest Higgs

Slim Higgs

Composite Higgs

Fat Higgs

Higgsless

Portal Higgs

Gauge Higgs

Twin Higgs

Lone Higgs

Simplest Higgs

Phantom Higgs

Composite Higgs Boson - Introduction

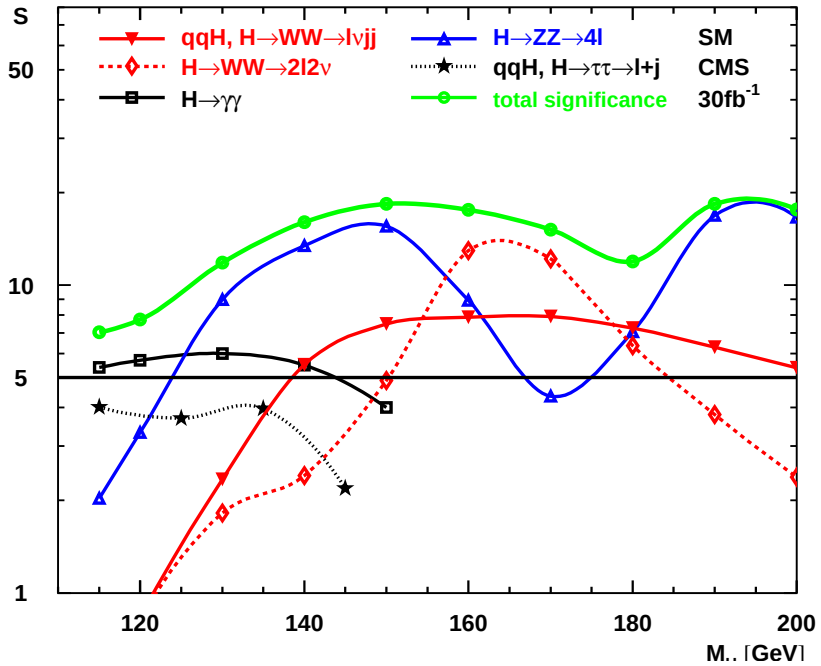
- **Higgs: bound state from a strongly interacting sector** Kaplan,Georgi;Dimopoulos eal;Dugan eal
- **SILH** effective low energy description, Higgs couplings modified by $\xi = \frac{v^2}{f^2}$ Giudice,Grojean Pomarol,Rattazzi
- **Fermion couplings** depend on embedding into representations of the bulk symmetry Contino eal; Agashe eal

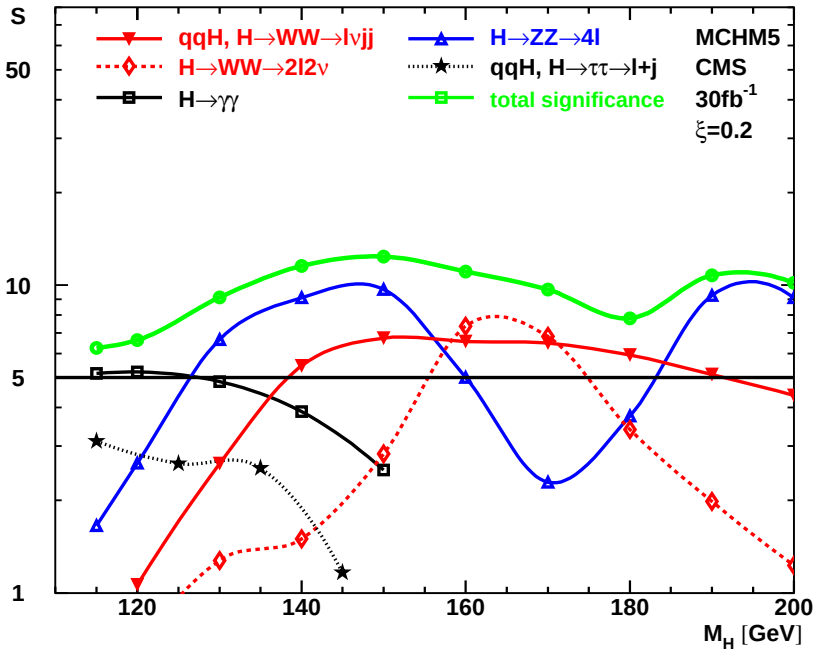
spinorial representations of $SO(5)$	fundamental representations of $SO(5)$
MCHM4	MCHM5

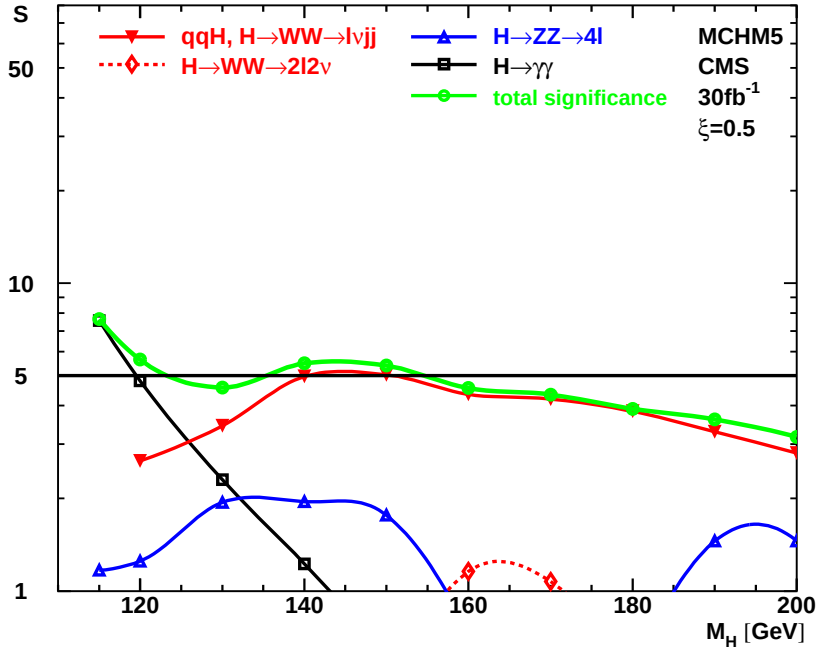
MCHM4	**MCHM5**
$g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi}$ $g_{Hff} = g^{SM}_{Hff}\sqrt{1-\xi}$	$g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi}$ $g_{Hff} = g^{SM}_{Hff}\frac{(1-2\xi)}{\sqrt{1-\xi}}$
universal factor $\rightsquigarrow$ BRs unchanged	g_{Hff} coupling vanishes for $\xi = 0.5$

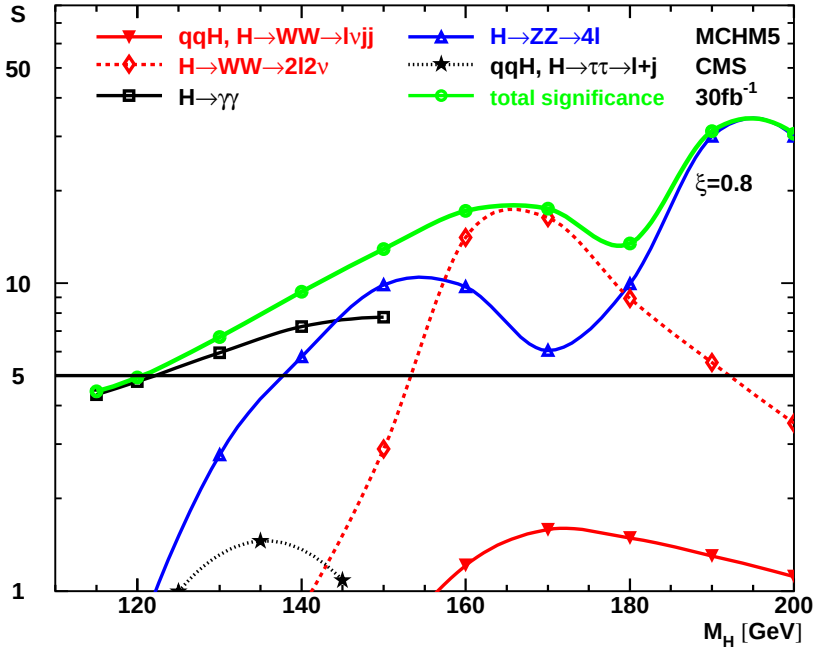
- **Impact on** BR's, Γ_{tot}, production cross sections, Higgs searches at the LHC Espinosa,Grojean,MMM
  (gg fusion at NNLO Furlan '11)

• Significances MCHM5









Summary

⋆ **Higgs discovery**	one of the major LHC goals
⋆ **Discovery prospects at LHC**	SM Higgs boson, at least one MSSM Higgs boson (light h)
⋆ **Higher order corrections**	most (SUSY-)QCD and EW corrections are known remaining theoretical uncertainties: $\sim 100\% \to \lesssim 15\%$
⋆ **LHC Higgs XS WG:**	close collaboration between experimentalists and theorists
⋆ **New Physics extensions**	Example: Composite Higgs discovery prospects significantly changed