PAUL SCHERRER INSTITUT PSI

HH XS UPDATE

Michael Spira (PSI)

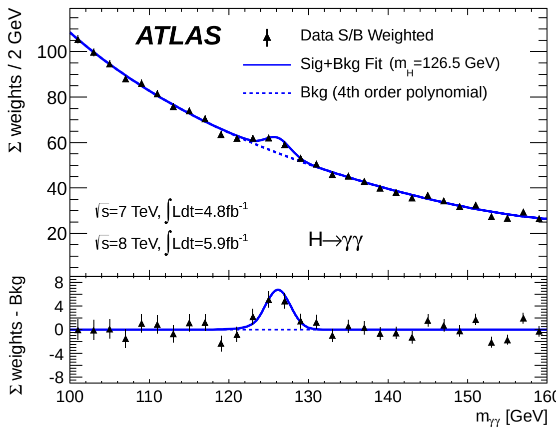
I Introduction

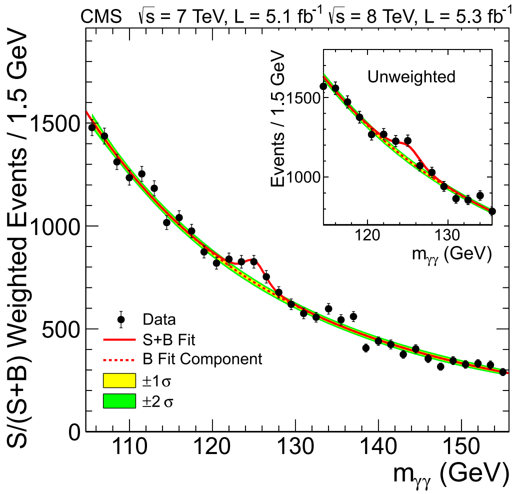
II Higgs Boson Pair Production

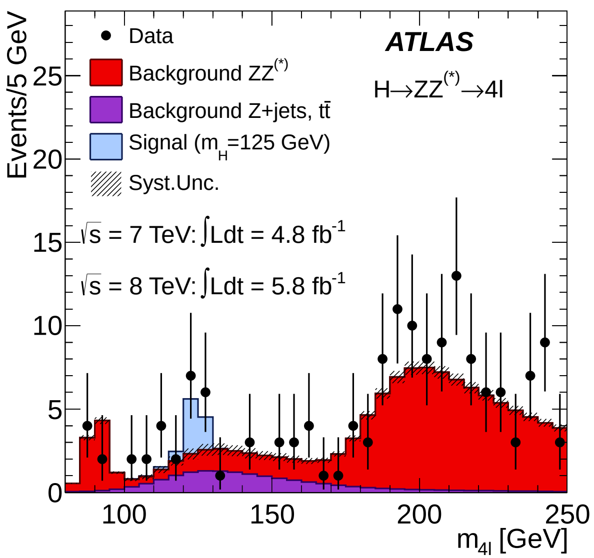
I INTRODUCTION

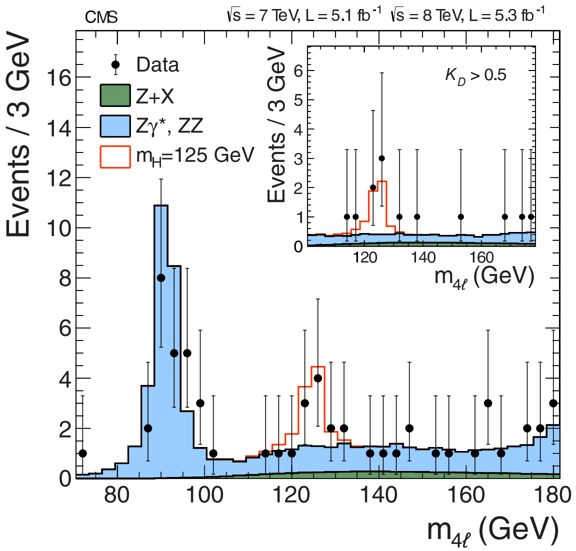
(i) Standard Model

- we have found the Higgs: $M_H \sim 125$ GeV
- $gg \to H$ dominant

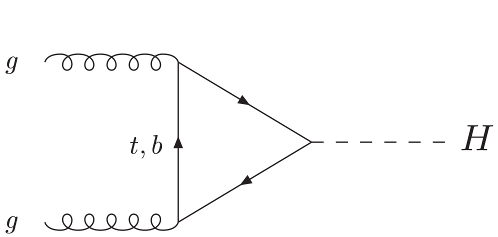


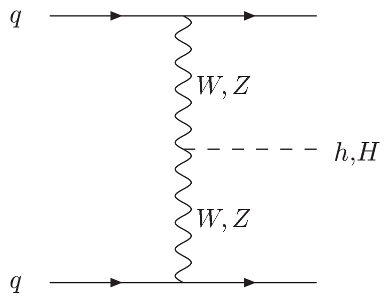


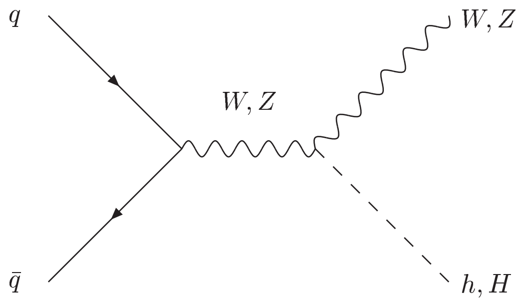


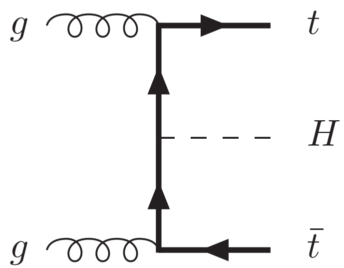


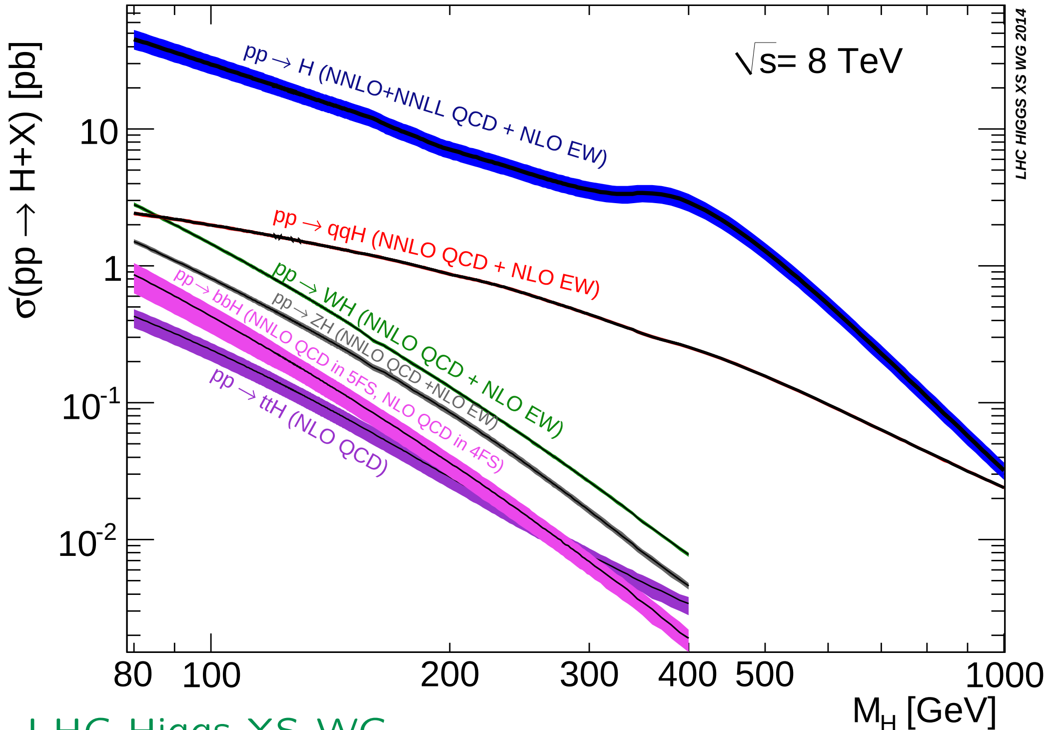
- Higgs Boson Production

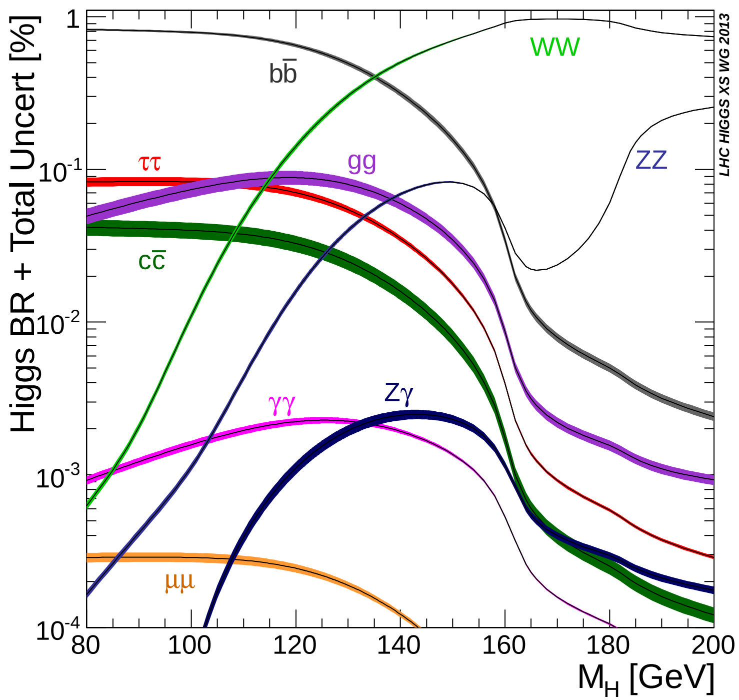












LHC Higgs XS WG

- Discovery: LHC [Tevatron]

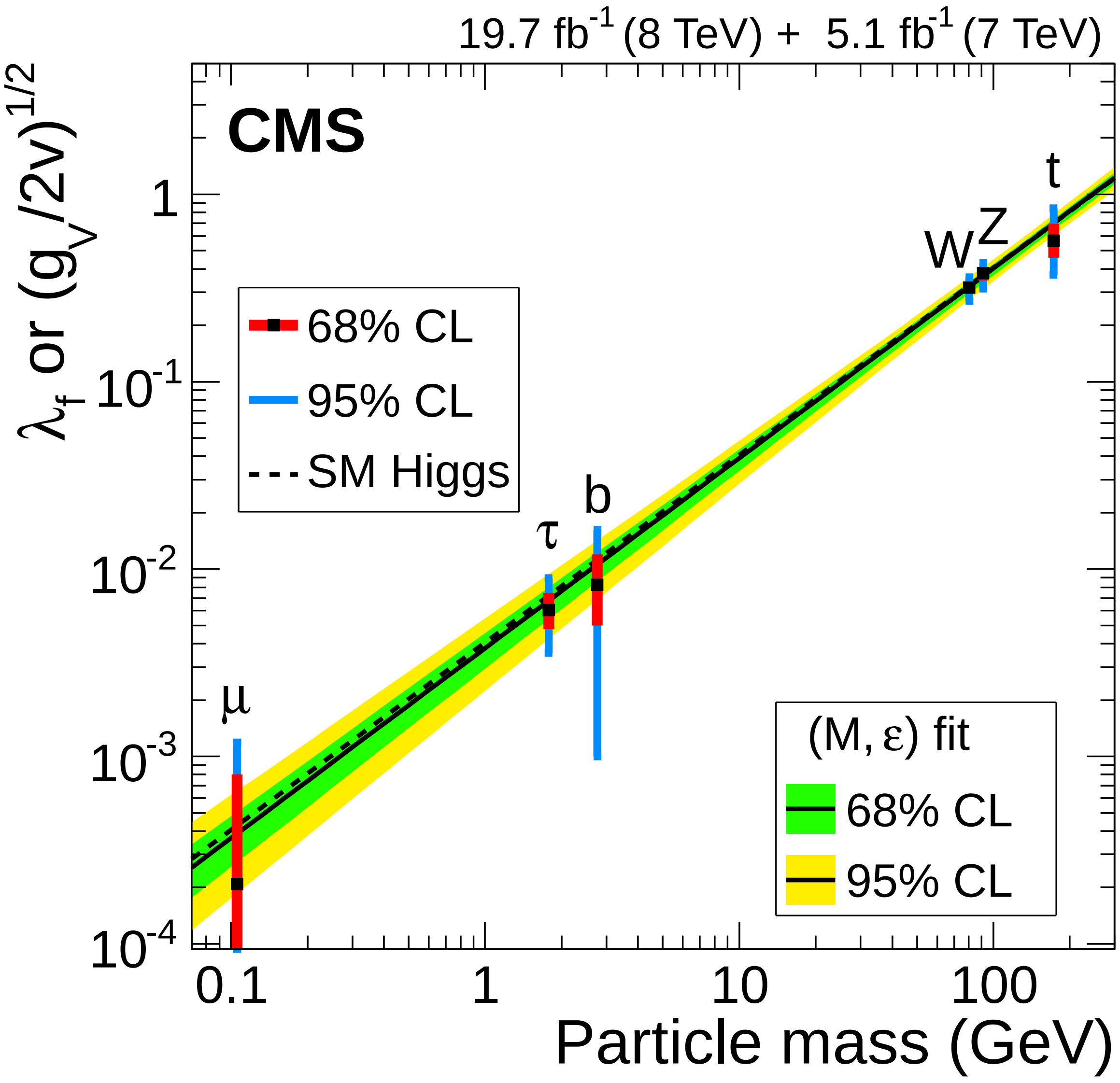
  → Higgs mass

  couplings

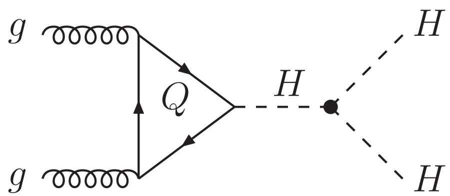
  spin

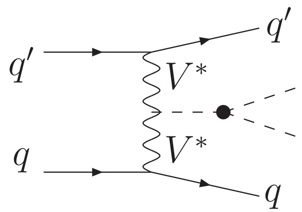
  $\mathcal{CP}$

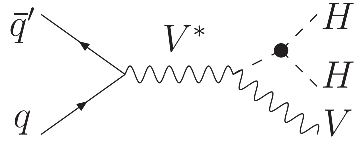
  λ ?

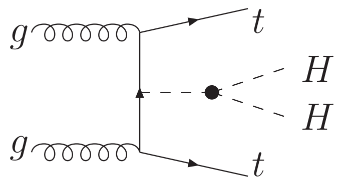


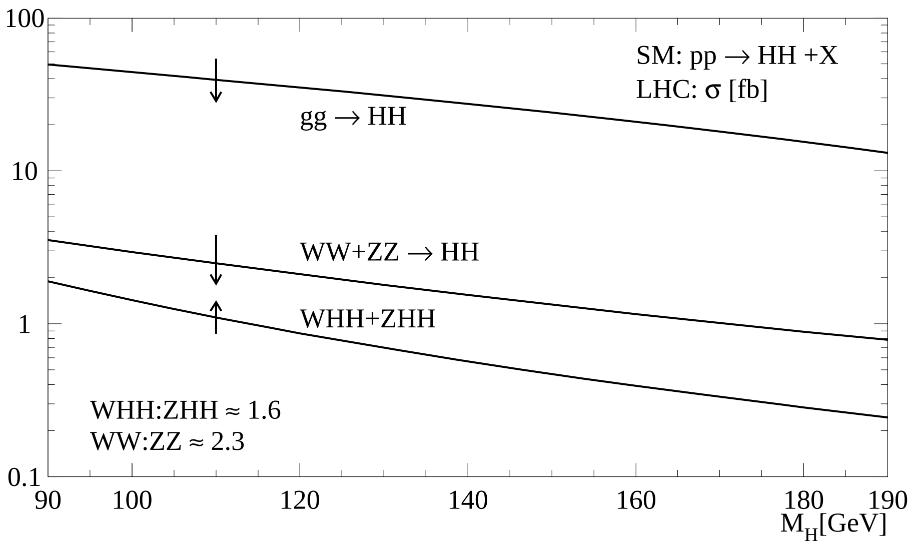
- Higgs boson pair production cross sections:

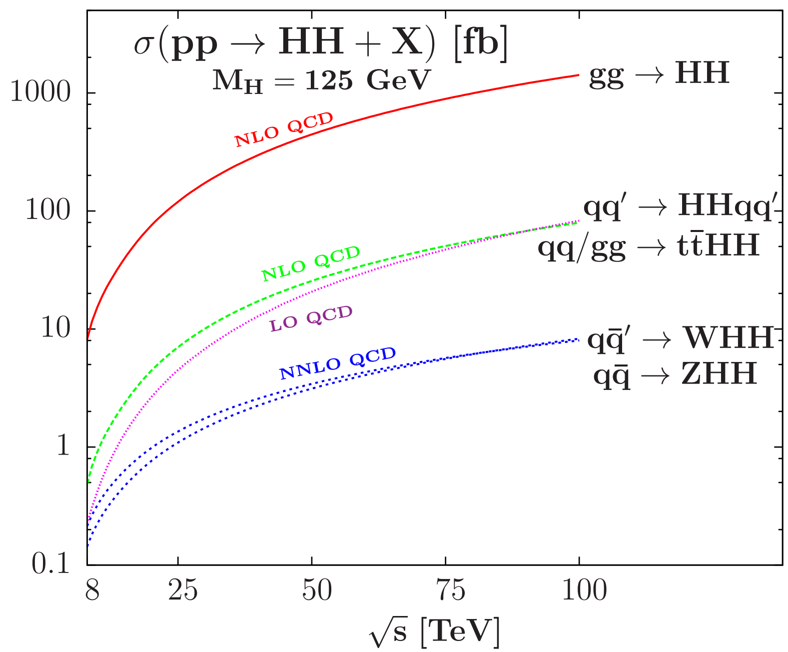












Djouadi, Kilian, Mühlleitner, Zerwas

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

(ii) MSSM

- 2 Higgs doubletts $\stackrel{\text{ESB}}{\rightarrow}$ 5 Higgs bosons: $h, H, A, H^{\pm}$

- LO: 2 input parameters: $M_A, \text{tg}\beta = \frac{v_2}{v_1}$

- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\rightarrow$ $\boxed{M_h \lesssim 135 \text{ GeV}}$

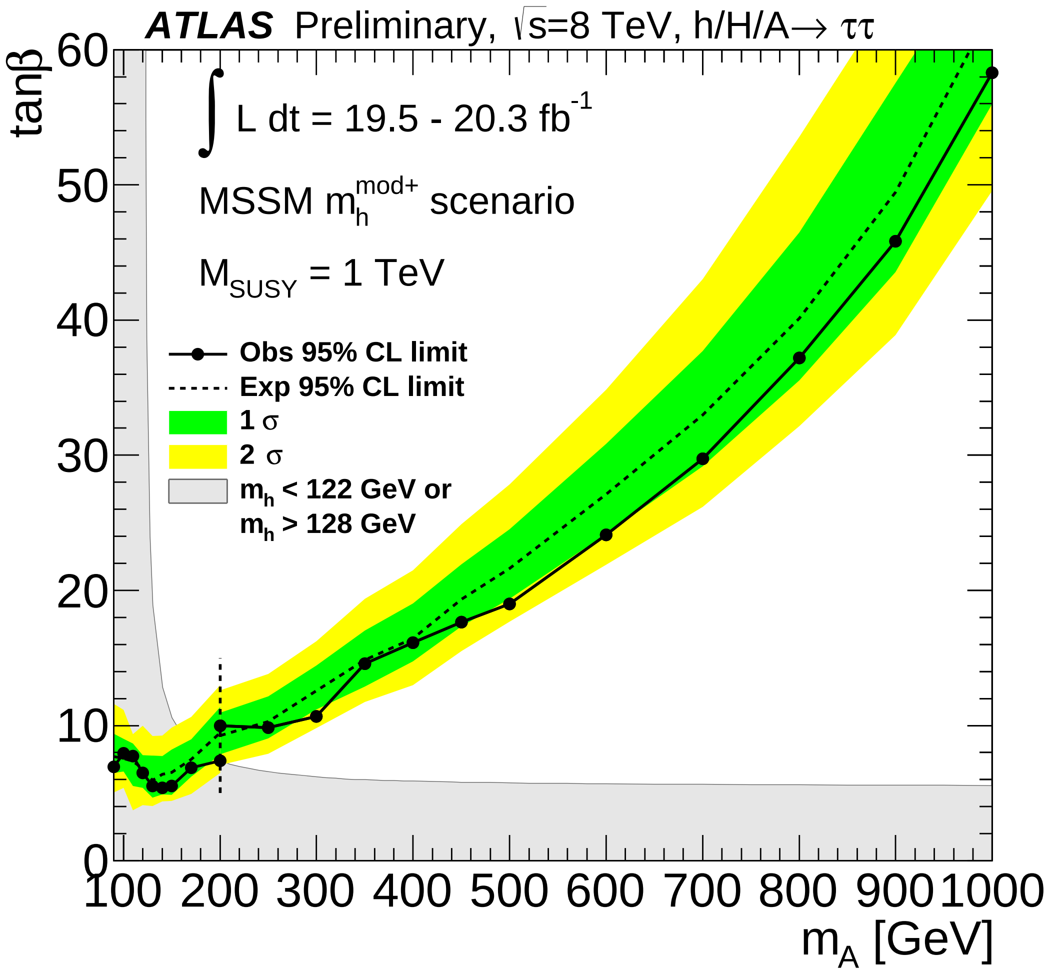
Haber
Carena,...
Heinemeyer,...
Zhang
Slavich,...
...

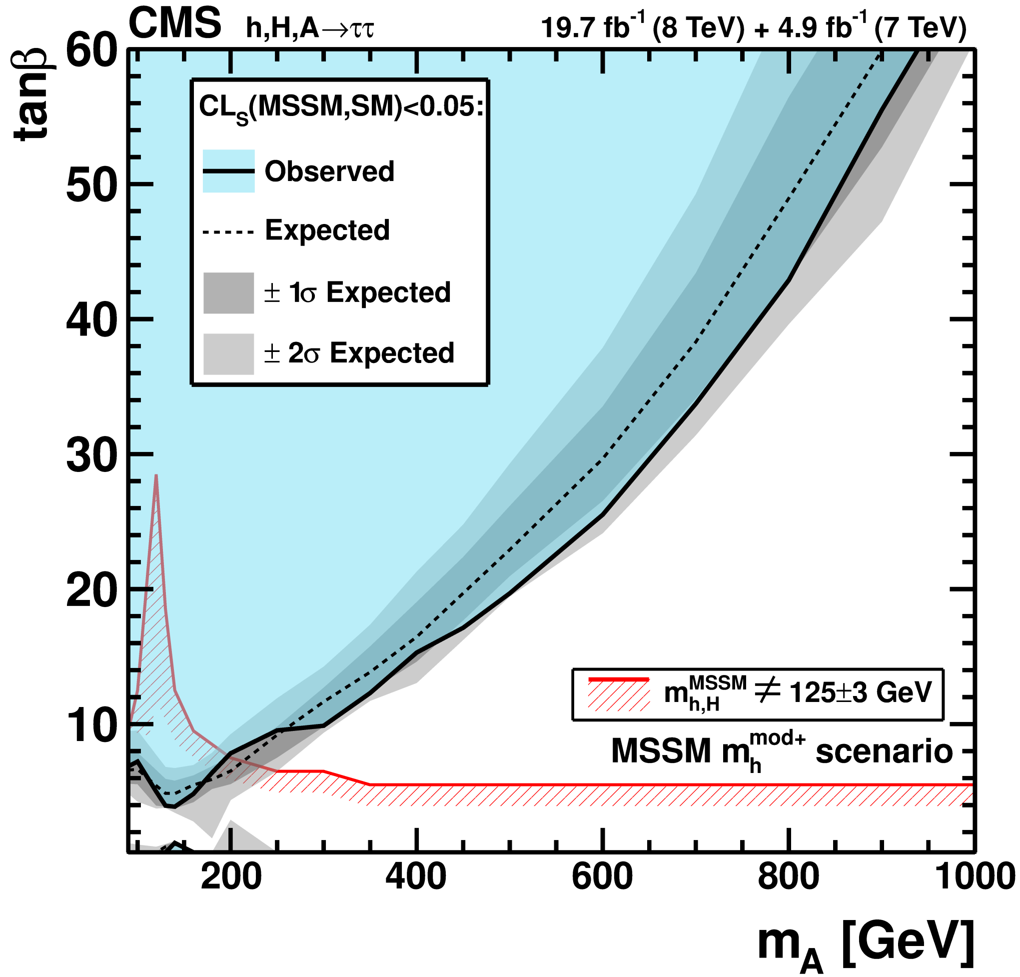
- Yukawa couplings: $\text{tg}\beta\uparrow \quad \Rightarrow \quad g_u^\phi\downarrow \quad g_d^\phi\uparrow \quad g_V^\phi\downarrow$

- LHC: $gg \rightarrow \phi$ dominant for $\text{tg}\beta \lesssim 10$
  $gg \rightarrow \phi b\bar{b}$ dominant for $\text{tg}\beta \gtrsim 10$

$$gg \to b\bar{b}\phi^0, \;\; gg \to \phi^0 \qquad \phi^0 \to \tau^+\tau^-$$

↓ ↓

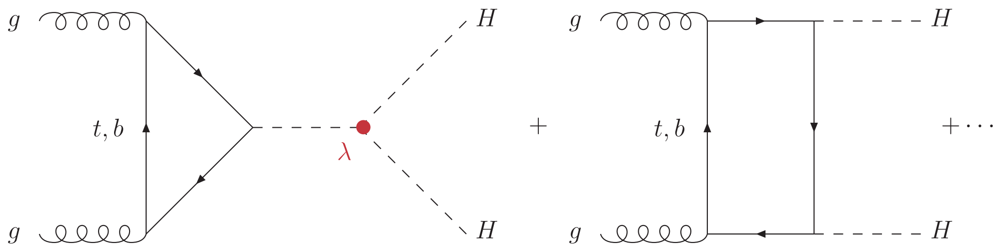




II *HIGGS BOSON PAIR PRODUCTION*

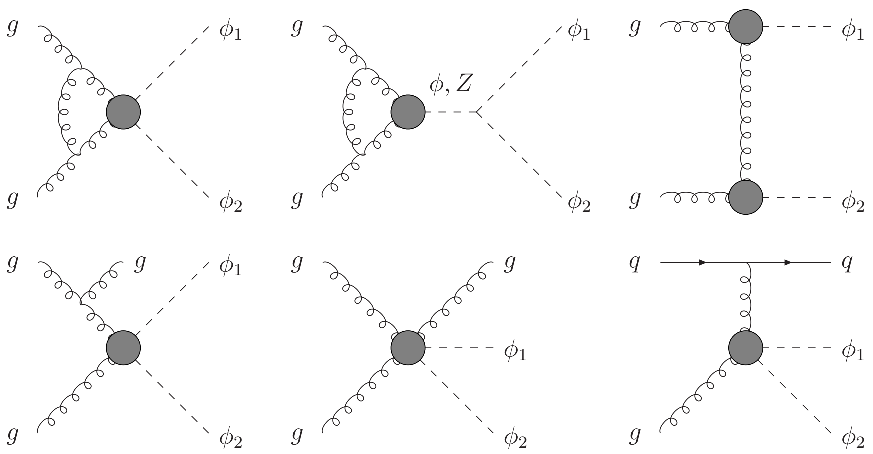
$gg \to HH$

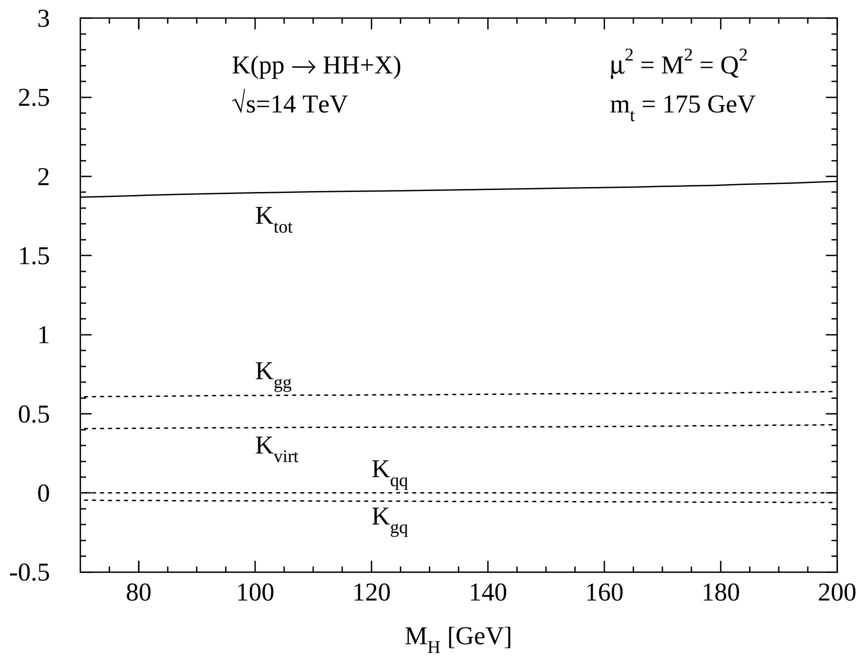
SM



- third generation dominant $\to t, b$

- 2-loop QCD corrections: $\sim 90 - 100\%$
  $[M_H^2 \ll 4m_t^2, \qquad \mu = M_{HH}]$

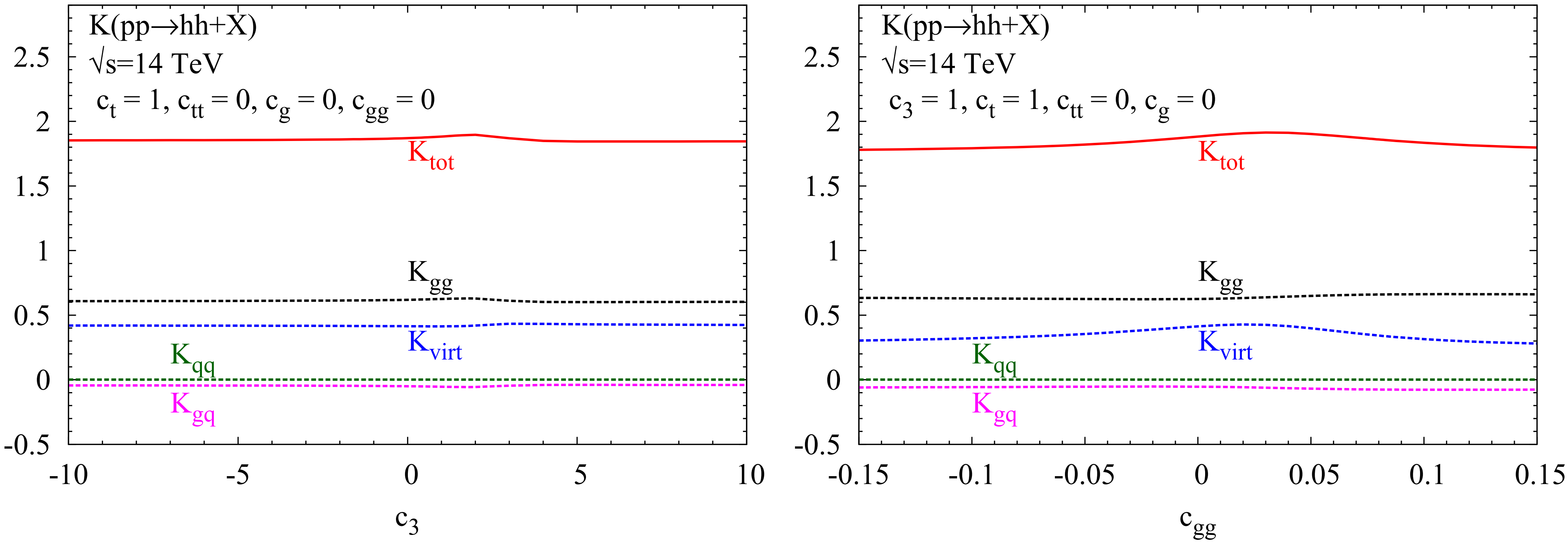




Dawson, Dittmaier, S.

- extended to dim6 → large impact on cxn [factor $\lesssim 10$]
  small impact on K-factor

$$\mathcal{L}_{eff} = -m_t \bar{t} t \left(c_t \frac{h}{v} + c_{tt} \frac{h^2}{2v^2} \right) - c_3 \frac{1}{6} \left(\frac{3M_h^2}{v} \right) h^3 + \frac{\alpha_s}{\pi} G^{a\,\mu\nu} G^a_{\mu\nu} \left(c_g \frac{h}{v} + c_{gg} \frac{h^2}{2v^2} \right)$$



Gröber, Mühlleitner, S., Streicher

$$\sigma_{\mathsf{NLO}}(pp \to HH + X) = \sigma_{\mathsf{LO}} + \Delta\sigma_{\mathsf{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}},$$

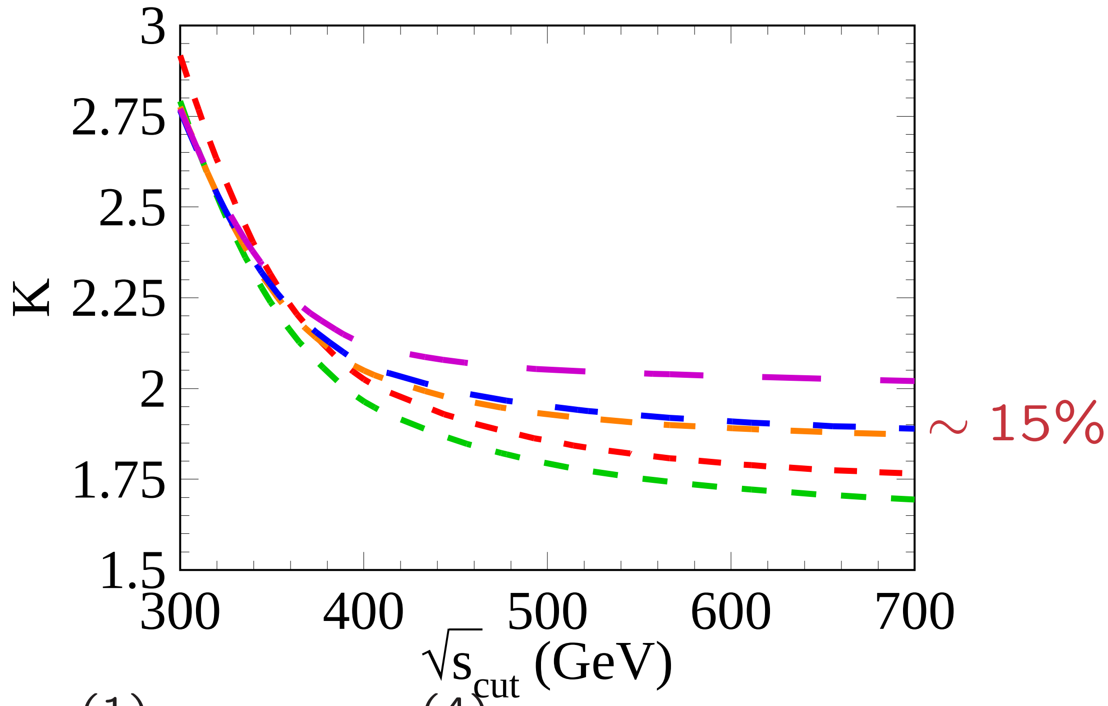
$$\begin{aligned}
\sigma_{\mathsf{LO}} &= \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\mathsf{LO}}(Q^2 = \tau s) \\
\Delta\sigma_{\mathsf{virt}} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\mathsf{LO}}(Q^2 = \tau s) \; C \\
\Delta\sigma_{gg} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathsf{LO}}(Q^2 = z\tau s) \left\{ -zP_{gg}(z) \log \frac{M^2}{\tau s} \right. \\
&\qquad \left. + d_{gg}(z) + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\} \\
\Delta\sigma_{gq} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathsf{LO}}(Q^2 = z\tau s) \left\{ -\frac{z}{2} P_{gq}(z) \log \frac{M^2}{\tau s (1-z)^2} \right. \\
&\qquad \left. + d_{gq}(z) \right\} \\
\Delta\sigma_{q\bar{q}} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathsf{LO}}(Q^2 = z\tau s) \; d_{q\bar{q}}(z)
\end{aligned}$$

$$C \to \pi^2 + \frac{11}{2} + C_{\triangle\triangle}, \qquad d_{gg} \to -\frac{11}{2}(1-z)^3, \qquad d_{gq} \to \frac{2}{3}z^2 - (1-z)^2, \qquad d_{q\bar{q}} \to \frac{32}{27}(1-z)^3$$

• 2-loop QCD corrections:

$$\sigma = \sigma_0 + \frac{\sigma_1}{m_t^2} + \cdots + \frac{\sigma_4}{m_t^8}$$

Grigo, Hoff, Melnikov, Steinhauser



$$C = C^{(0)} + \frac{C^{(1)}}{m_t^2} + \cdots + \frac{C^{(4)}}{m_t^8}$$

$$d_{ij} = d_{ij}^{(0)} + \frac{d_{ij}^{(1)}}{m_t^2} + \cdots + \frac{d_{ij}^{(4)}}{m_t^8}$$

keep LO mass dependence locally $\Rightarrow \pm 10\%$ Grigo, Hoff, Steinhauser

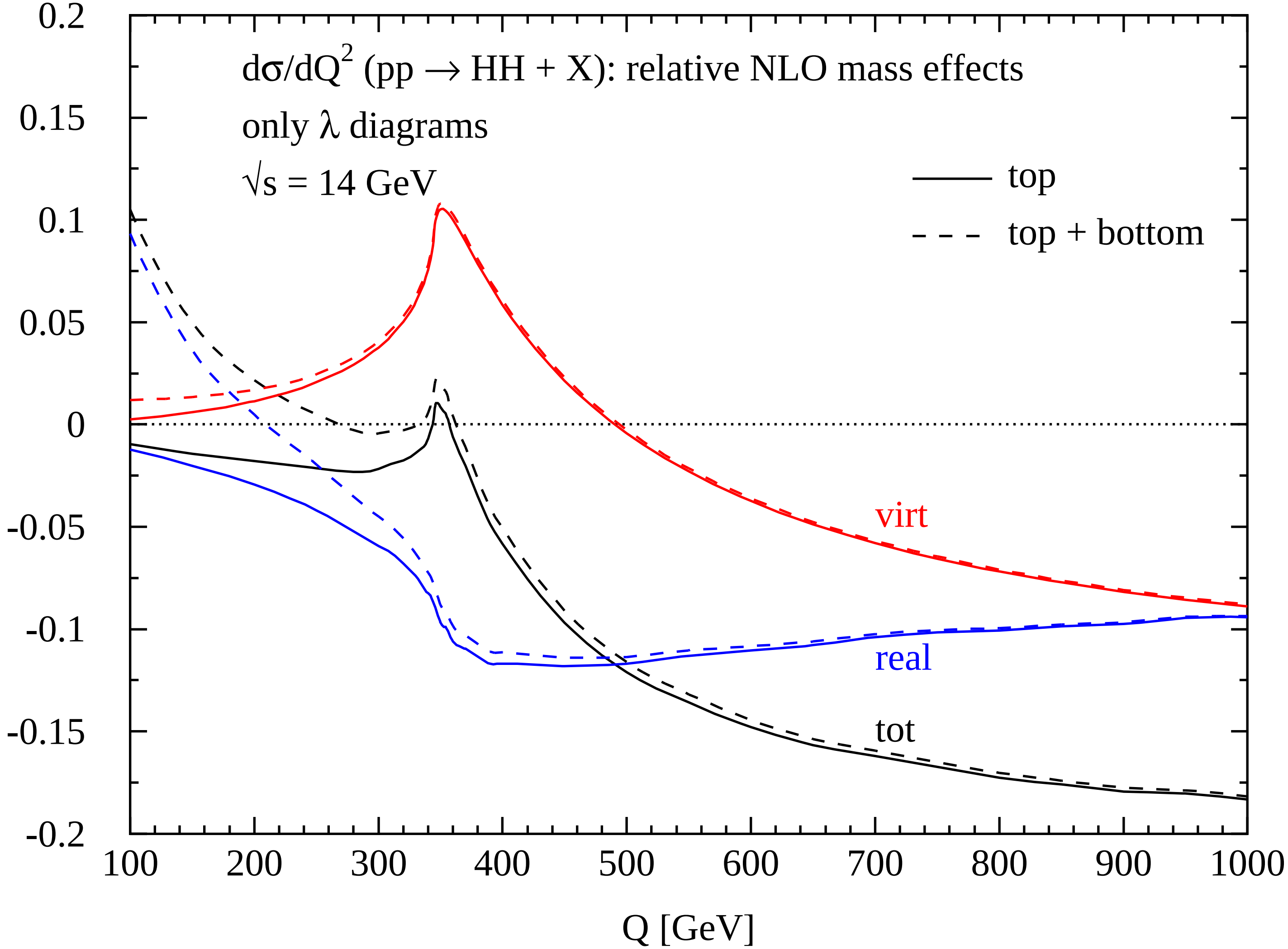
$$C = C^{(0)}, \qquad d_{ij} \quad \text{exact}$$

keep LO mass dependence locally $\Rightarrow -10\%$

Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro

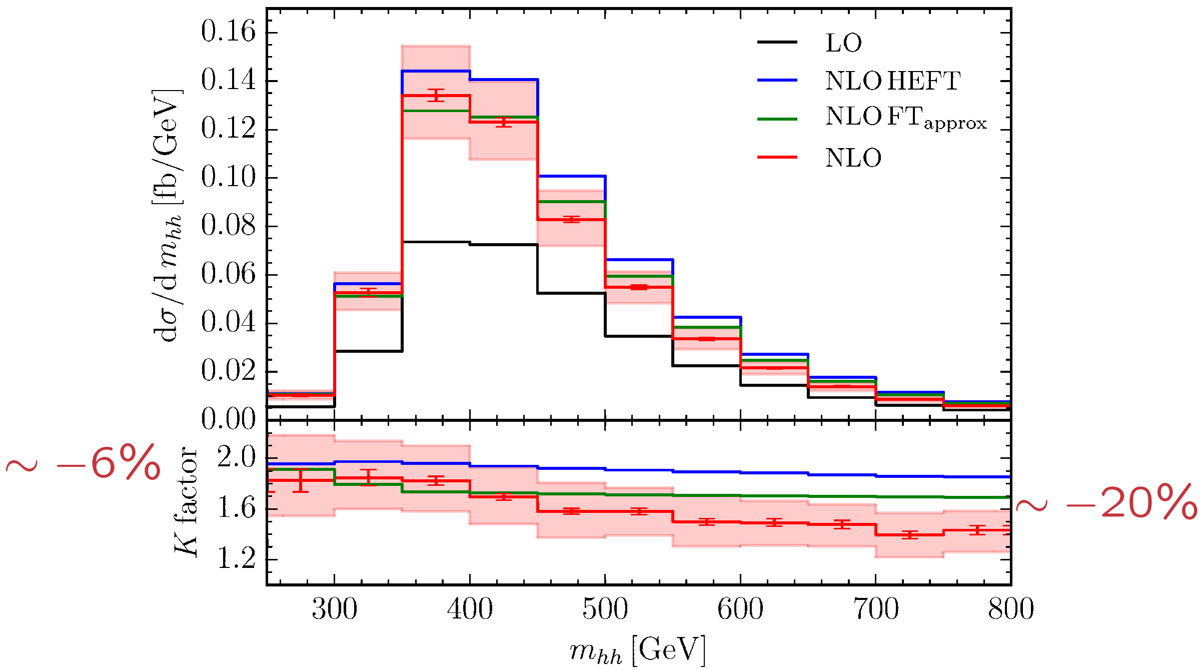
exact result for double-blob diagrams [%-effect] Degrassi, Giardino, Gröber

Diagrams with λ only: $$\frac{d\sigma_m^{NLO} - d\sigma_\infty^{NLO}}{d\sigma_\infty^{NLO}}$$



Full NLO calculation: top only

Numerical integration, sector decomposition, contour deformation



Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke

Baglio, Campanario, Glaus, Mühlleitner, S., Streicher (in preparation)

- 13 TeV:

$$\sigma_{NLO} = 27.80(8)^{+13.8\%}_{-12.8\%}\ fb$$

$$\sigma^{HEFT}_{NLO} = 32.22^{+18\%}_{-15\%}\ fb$$

⇒ -13.7% mass effects

- NNLO QCD corrections:
  mainly obtained from NNLO single Higgs $\rightarrow \frac{d\sigma}{dQ^2}$
  NLO corrections to double blob diagrams de Florian, Mazzitelli
  NNLO corrections to effective $HHgg$ coupling:

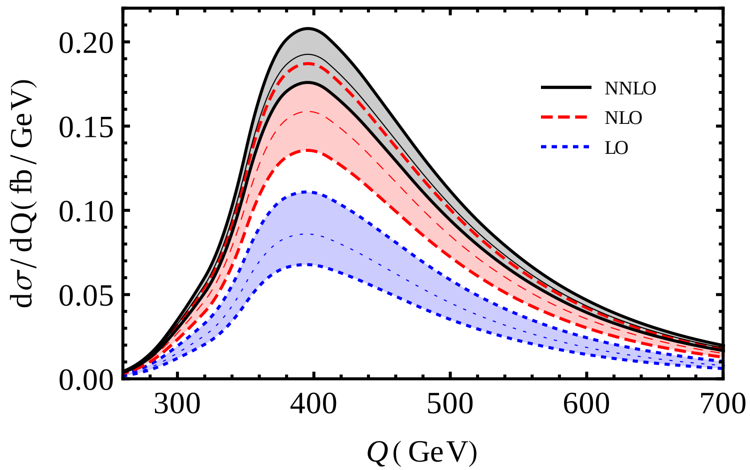
$$C_{HH}^{NNLO} = C_H^{NNLO} + \frac{35 + 16N_F}{12}\left(\frac{\alpha_s}{\pi}\right)^2$$

obtained from explicit diagrammatic calculation

Grigo, Hoff, Melnikov, Steinhauser

- NNLO corrections: $\sim 20\%$
  $[M_H^2 \ll 4m_t^2]$ de Florian, Mazzitelli
  Grigo, Melnikov, Steinhauser
- mass corrections: $\sim 5\%$ Grigo, Hoff, Steinhauser
- soft gluon resummation: $\sim 10\%$
  $[M_H^2 \ll 4m_t^2]$

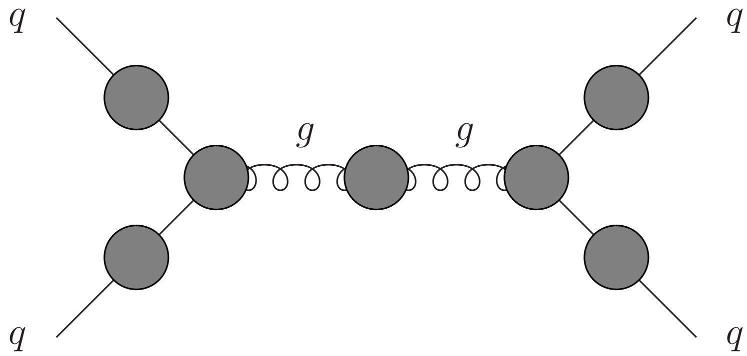
de Florian, Mazzitelli
Shao, Li, Li, Wang



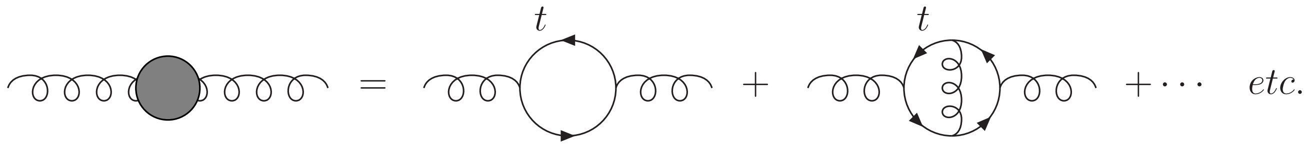
- uncertainties: $\sim 15 - 20\%$

Is there an easier way to obtain C_{HH}^{NNLO}?

Yes…



$$\rightarrow \frac{\zeta_3^0 {\zeta_2^0}^2}{{\zeta_1^0}^2} = \frac{1}{\zeta_{\alpha_s}^0} \rightarrow \frac{1}{\zeta_{\alpha_s}} \qquad [\overline{\text{MS}}]$$



$$\begin{aligned} \mathcal{L}_g &= -\frac{1}{4\zeta_{\alpha_s}} \widehat{G}^{a\mu\nu}\widehat{G}^a_{\mu\nu} = -\frac{1-\Pi_t}{4}\widehat{G}^{a\mu\nu}\widehat{G}^a_{\mu\nu} \qquad [\leftarrow (N_F+1)] \\ \alpha_s^{(N_F)}(\mu_R^2) &= \zeta_{\alpha_s}\ \alpha_s^{(N_F+1)}(\mu_R^2) \\ \Pi_t &= 1 - \frac{1}{\zeta_{\alpha_s}} = \sum_n C_n \left(\frac{\alpha_s^{(N_F+1)}}{\pi}\right)^n \end{aligned}$$

- $L_t = \log(\mu_R^2/\overline{m_t}^2(\mu_R^2))$

$$\begin{aligned} C_1 &= -\frac{1}{6}L_t \\ C_2 &= \frac{11}{72} - \frac{11}{24}L_t \\ C_3 &= \frac{564731}{124416} - \frac{82043}{27648}\zeta_3 - \frac{2633}{31104}N_F - \frac{2777-201N_F}{1728}L_t - \frac{35+16N_F}{576}L_t^2 \end{aligned}$$

Bernreuther, Wetzel
Chetyrkin, Kniehl, Steinhauser

- shift the $\overline{\text{MS}}$ top mass

$$\begin{aligned}\overline{m_t}(\mu_R^2) &\to \overline{m_t}(\mu_R^2)\left(1+\frac{H}{v}\right)\\ L_t &\to \bar{L}_t = L_t - 2\log\left(1+\frac{H}{v}\right)\end{aligned}$$

- keep only H-dependent terms

- reexpress $(N_F+1)-$ by N_F-flavour quantities

$$\begin{aligned}\hat{G}^{a\mu\nu}\hat{G}^{a}_{\mu\nu} &= \zeta_{\alpha_s} G^{a\mu\nu}G^{a}_{\mu\nu}\\ \alpha_s^{(N_F+1)}(\mu_R^2) &= \alpha_s^{(N_F)}(\mu_R^2)\left\{1+\frac{\alpha_s^{(N_F)}(\mu_R^2)}{\pi}\frac{L_t}{6}+\left(\frac{\alpha_s^{(N_F)}(\mu_R^2)}{\pi}\right)^2\left[-\frac{11}{72}+\frac{11}{24}L_t+\frac{L_t^2}{36}\right]\right\}\end{aligned}$$

Bernreuther, Wetzel
Chetyrkin, Kniehl, Steinhauser

$$
\begin{aligned}
\mathcal{L}_{eff} &= \frac{\alpha_s}{12\pi}\left\{(1+\delta)\log\left(1+\frac{H}{v}\right) - \frac{\eta}{2}\log^2\left(1+\frac{H}{v}\right)\right. \\
&\qquad \left. +\frac{\rho}{3}\log^3\left(1+\frac{H}{v}\right) - \frac{\sigma}{4}\log^4\left(1+\frac{H}{v}\right)\right\} G^{a\mu\nu}G^a_{\mu\nu} \\
\delta &= \delta_1\frac{\alpha_s}{\pi} + \delta_2\left(\frac{\alpha_s}{\pi}\right)^2 + \delta_3\left(\frac{\alpha_s}{\pi}\right)^3 + \delta_4\left(\frac{\alpha_s}{\pi}\right)^4 + \mathcal{O}(\alpha_s^5) \\
\eta &= \eta_2\left(\frac{\alpha_s}{\pi}\right)^2 + \eta_3\left(\frac{\alpha_s}{\pi}\right)^3 + \eta_4\left(\frac{\alpha_s}{\pi}\right)^4 + \mathcal{O}(\alpha_s^5) \\
\rho &= \rho_3\left(\frac{\alpha_s}{\pi}\right)^3 + \rho_4\left(\frac{\alpha_s}{\pi}\right)^4 + \mathcal{O}(\alpha_s^5) \\
\sigma &= \sigma_4\left(\frac{\alpha_s}{\pi}\right)^4 + \mathcal{O}(\alpha_s^5)
\end{aligned}
$$

$$
\begin{aligned}
\delta_1 &= \frac{11}{4} \\
\delta_2 &= \frac{2777}{288} + \frac{19}{16}L_t + N_F\left(\frac{L_t}{3} - \frac{67}{96}\right) \\
\eta_2 &= \frac{35+16N_F}{24}
\end{aligned}
$$

$$\begin{aligned}
\mathcal{L}_{eff} &= \frac{\alpha_s}{12\pi}\left\{(1+\delta)\log\left(1+\frac{H}{v}\right)-\frac{\eta}{2}\log^2\left(1+\frac{H}{v}\right)\right. \\
&\qquad \left. +\frac{\rho}{3}\log^3\left(1+\frac{H}{v}\right)-\frac{\sigma}{4}\log^4\left(1+\frac{H}{v}\right)\right\} G^{a\mu\nu}G^a_{\mu\nu} \\
\delta &= \delta_1\frac{\alpha_s}{\pi}+\delta_2\left(\frac{\alpha_s}{\pi}\right)^2+\delta_3\left(\frac{\alpha_s}{\pi}\right)^3+\delta_4\left(\frac{\alpha_s}{\pi}\right)^4+\mathcal{O}(\alpha_s^5) \\
\eta &= \eta_2\left(\frac{\alpha_s}{\pi}\right)^2+\eta_3\left(\frac{\alpha_s}{\pi}\right)^3+\eta_4\left(\frac{\alpha_s}{\pi}\right)^4+\mathcal{O}(\alpha_s^5) \\
\rho &= \rho_3\left(\frac{\alpha_s}{\pi}\right)^3+\rho_4\left(\frac{\alpha_s}{\pi}\right)^4+\mathcal{O}(\alpha_s^5) \\
\sigma &= \sigma_4\left(\frac{\alpha_s}{\pi}\right)^4+\mathcal{O}(\alpha_s^5)
\end{aligned}$$

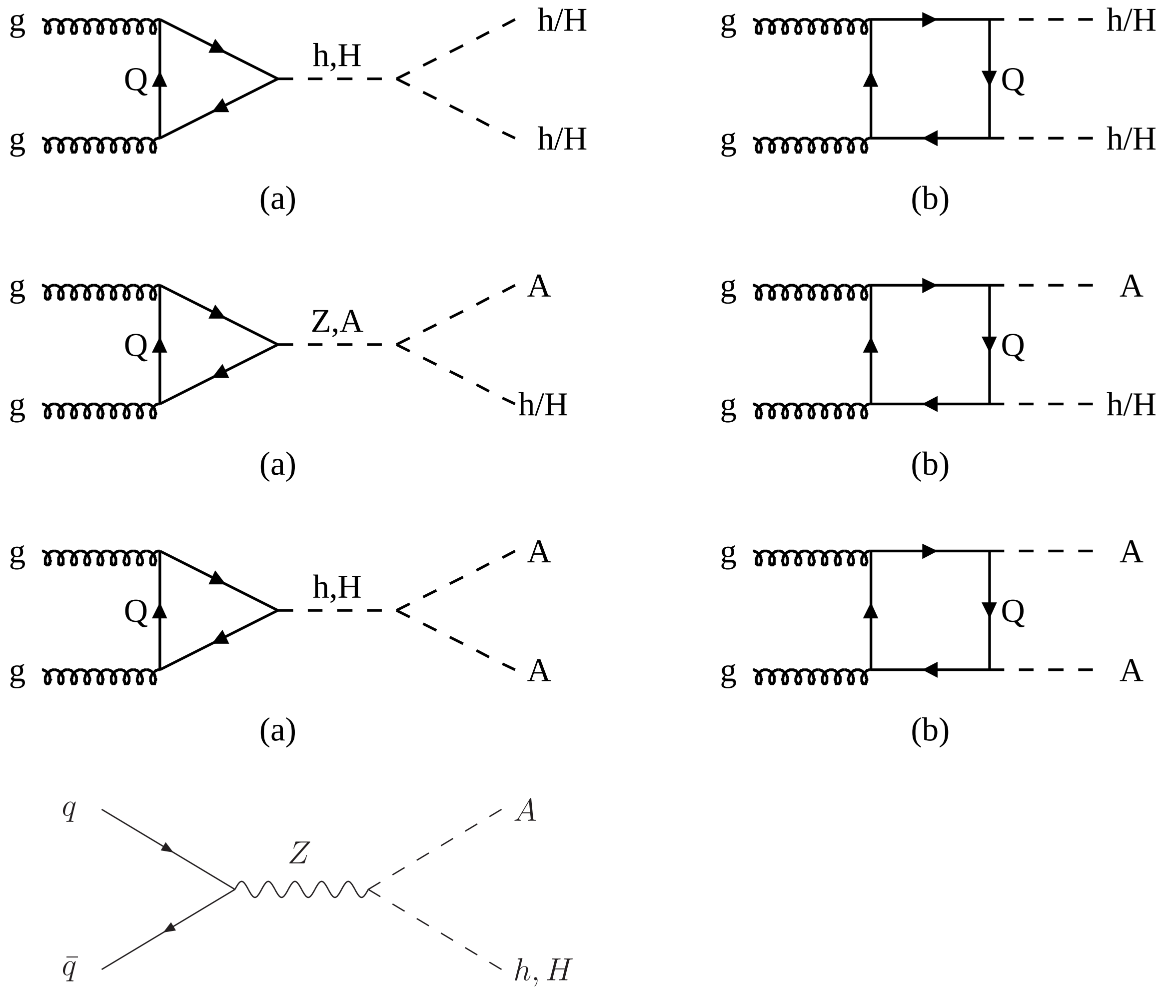
$$\begin{aligned}
\delta_1 &= \frac{11}{4} \\
\delta_2 &= \frac{2777}{288}+\frac{19}{16}L_t+N_F\left(\frac{L_t}{3}-\frac{67}{96}\right) \\
\eta_2 &= \frac{35+16N_F}{24}
\end{aligned}$$

- known now up to N^4LO:

$$
\begin{aligned}
\delta_3 &= \frac{897943}{9216}\zeta_3 - \frac{2892659}{41472} + \frac{209}{64}L_t^2 + \frac{1733}{288}L_t \\
&+ N_F\left(\frac{40291}{20736} - \frac{110779}{13824}\zeta_3 + \frac{23}{32}L_t^2 + \frac{55}{54}L_t\right) + N_F^2\left(-\frac{L_t^2}{18} + \frac{77}{1728}L_t - \frac{6865}{31104}\right) \\
\delta_4 &= -\frac{121}{1440}N_F\log^5 2 + \frac{3751}{2880}\log^5 2 + \frac{685}{41472}N_F^2\log^4 2 + \frac{11679301}{1741824}N_F\log^4 2 \\
&- \frac{93970579}{870912}\log^4 2 + \frac{121}{144}N_F\zeta_2\log^3 2 - \frac{3751}{288}\zeta_2\log^3 2 - \frac{685}{6912}N_F^2\zeta_2\log^2 2 \\
&- \frac{11679301}{290304}N_F\zeta_2\log^2 2 + \frac{93970579}{145152}\zeta_2\log^2 2 + \frac{2057}{192}N_F\zeta_4\log 2 - \frac{63767}{384}\zeta_4\log 2 \\
&+ \frac{685}{1728}N_F^2 a_4 + \frac{11679301}{72576}N_F a_4 - \frac{93970579}{36288}a_4 + \frac{121}{12}N_F a_5 - \frac{3751}{24}a_5 + \frac{211}{1728}N_F^3\zeta_3 \\
&- \frac{270407}{1492992}N_F^3 + \frac{4091305}{331776}N_F^2\zeta_3 - \frac{576757}{55296}N_F^2\zeta_4 - \frac{115}{384}N_F^2\zeta_5 - \frac{48073}{27648}N_F^2 \\
&- \frac{151369}{725760}N_F X_0 - \frac{12171659669}{38707200}N_F\zeta_3 + \frac{608462731}{11612160}N_F\zeta_4 + \frac{313489}{6912}N_F\zeta_5 \\
&+ \frac{76094378783}{522547200}N_F + \frac{4692439}{1451520}X_0 + \frac{28121193841}{19353600}\zeta_3 + \frac{4674213853}{2903040}\zeta_4 - \frac{807193}{1728}\zeta_5 \\
&- \frac{854201072999}{522547200} + \left(\frac{481}{5184}N_F^3 + \frac{28297}{9216}N_F^2\zeta_3 - \frac{21139}{3456}N_F^2 - \frac{32257}{288}N_F\zeta_3\right. \\
&\left. + \frac{5160073}{41472}N_F + \frac{9364157}{12288}\zeta_3 - \frac{49187545}{55296}\right)L_t + \left(-\frac{77}{6912}N_F^3 - \frac{1267}{13824}N_F^2 + \frac{4139}{2304}N_F\right. \\
&\left. + \frac{8401}{384}\right)L_t^2 + \left(\frac{1}{108}N_F^3 - \frac{157}{576}N_F^2 + \frac{275}{192}N_F + \frac{2299}{256}\right)L_t^3
\end{aligned}
$$

$$
\begin{aligned}
\eta_3 &= \frac{1333}{432} + \frac{589}{48} L_t + N_F \left(\frac{1081}{432} + \frac{191}{72} L_t \right) + N_F^2 \left(\frac{77}{864} - \frac{2}{9} L_t \right) \\
\eta_4 &= \frac{481}{2592} N_F^3 + N_F^2 \left(\frac{28297}{4608} \zeta_3 - \frac{373637}{31104} \right) + N_F \left(\frac{429965}{1728} - \frac{2985893}{13824} \zeta_3 \right) \\
&+ \frac{26296585}{18432} \zeta_3 - \frac{143976701}{82944} + \left(-\frac{77}{1728} N_F^3 - \frac{1421}{3456} N_F^2 + \frac{9073}{1728} N_F + \frac{45059}{576} \right) L_t \\
&+ \left(\frac{N_F^3}{18} - \frac{455}{288} N_F^2 + \frac{63}{8} N_F + \frac{6479}{128} \right) L_t^2 \\
\rho_3 &= \frac{1697}{144} + \frac{175}{72} N_F - \frac{2}{9} N_F^2 \\
\rho_4 &= \frac{130201}{1728} + \frac{18259}{192} L_t + N_F \left(\frac{5855}{1728} + \frac{2077}{144} L_t \right) - N_F^2 \left(\frac{175}{384} + \frac{439}{144} L_t \right) \\
&+ N_F^3 \left(\frac{L_t}{9} - \frac{77}{1728} \right) \\
\sigma_4 &= \frac{51383}{864} + \frac{317}{36} N_F - \frac{47}{24} N_F^2 + \frac{2}{27} N_F^3
\end{aligned}
$$

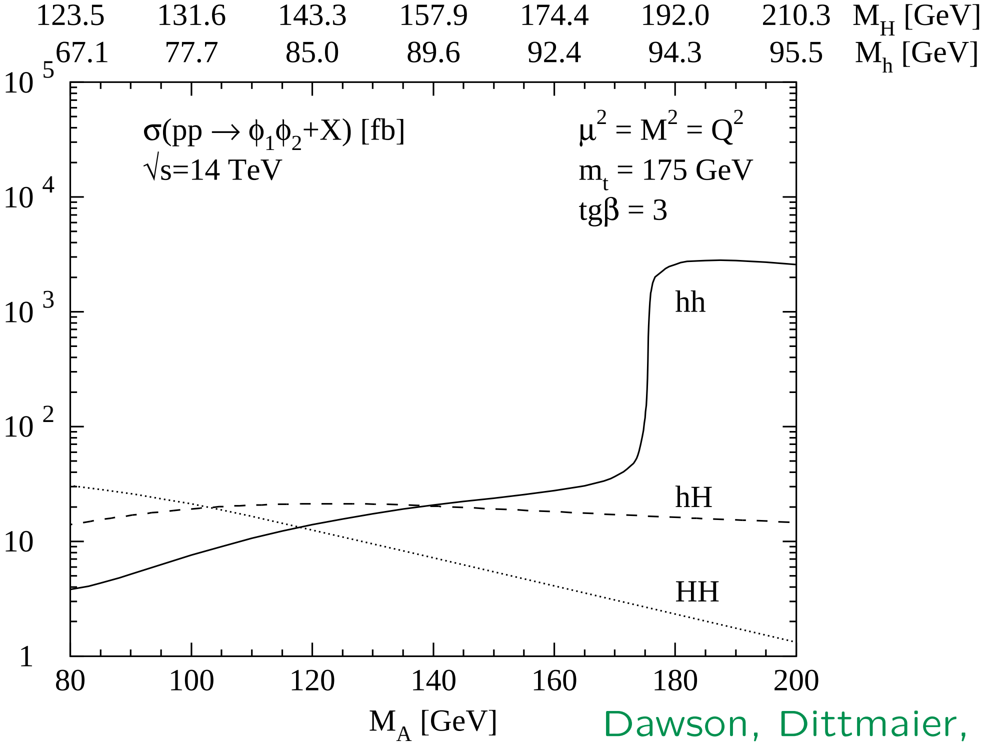
MSSM $gg \to hh, hH, HH, hA, HA, AA$ and $q\bar{q} \to hA, HA$

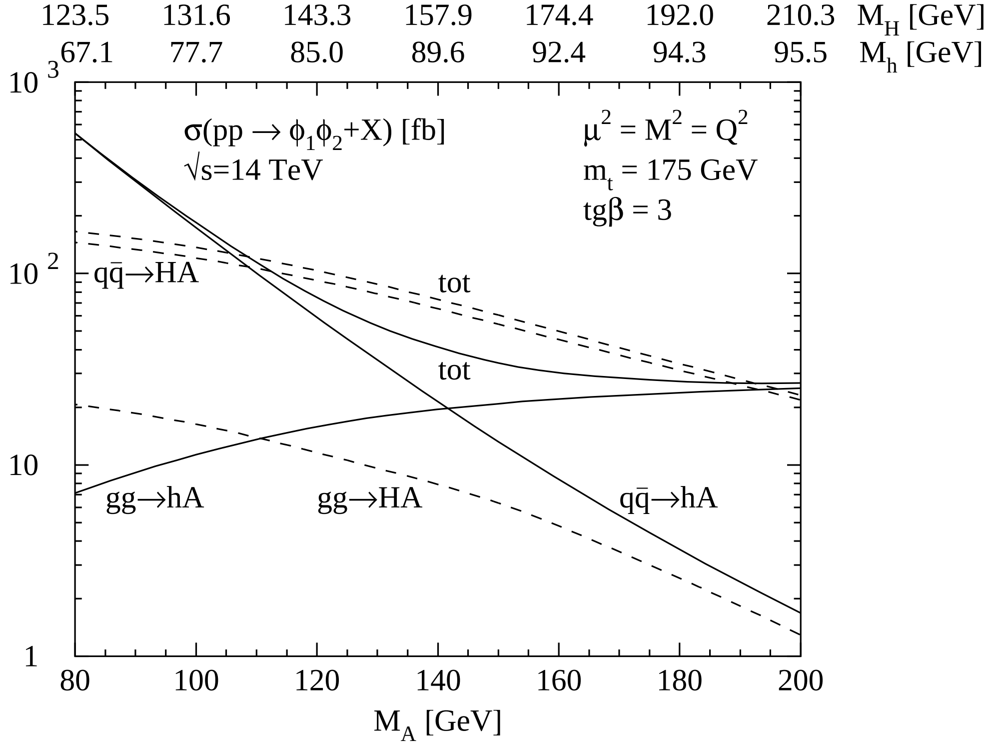


- resonant contributions: $H \to hh, AA$
- QCD corrections: $\lesssim 100\%$ [$m_t^2 \gg Q^2 \Rightarrow$ small tgβ]
- partial SUSY–QCD corrections: $\lesssim 100\%$ [heavy SUSY particles]

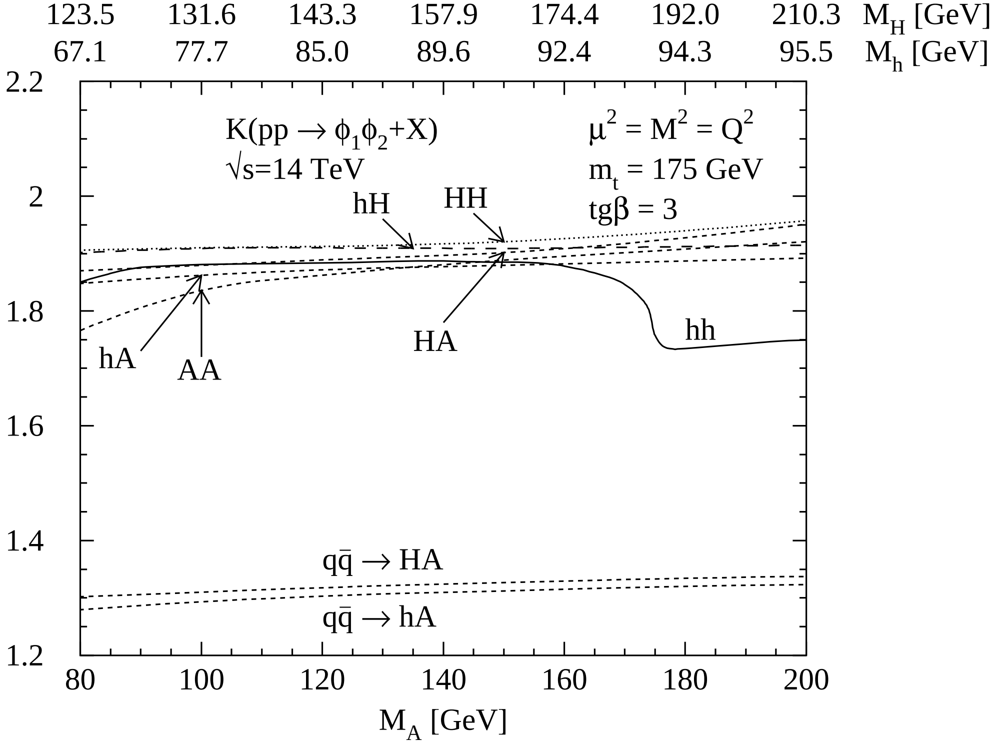
Agostini, Degrassi, Gröber, Slavich

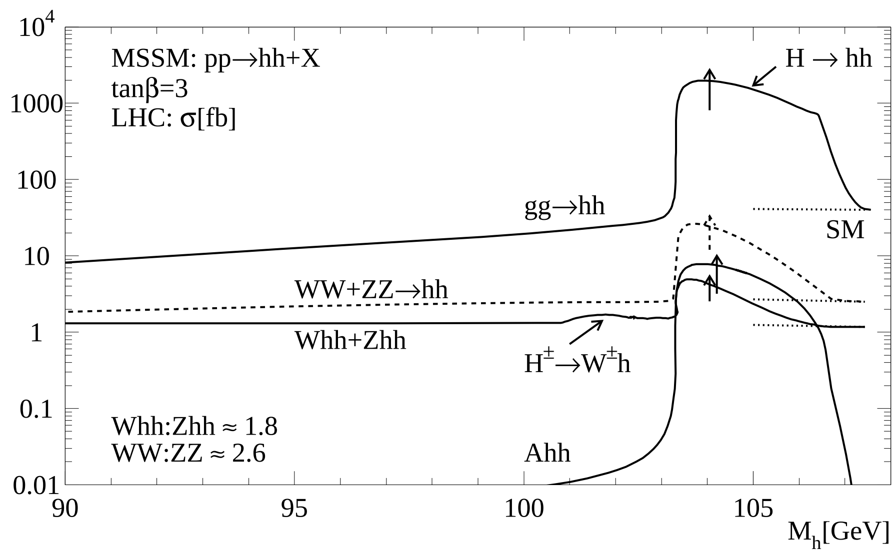
MSSM $gg \to hh, hH, HH, hA, HA, AA$ and $q\bar{q} \to hA, HA$





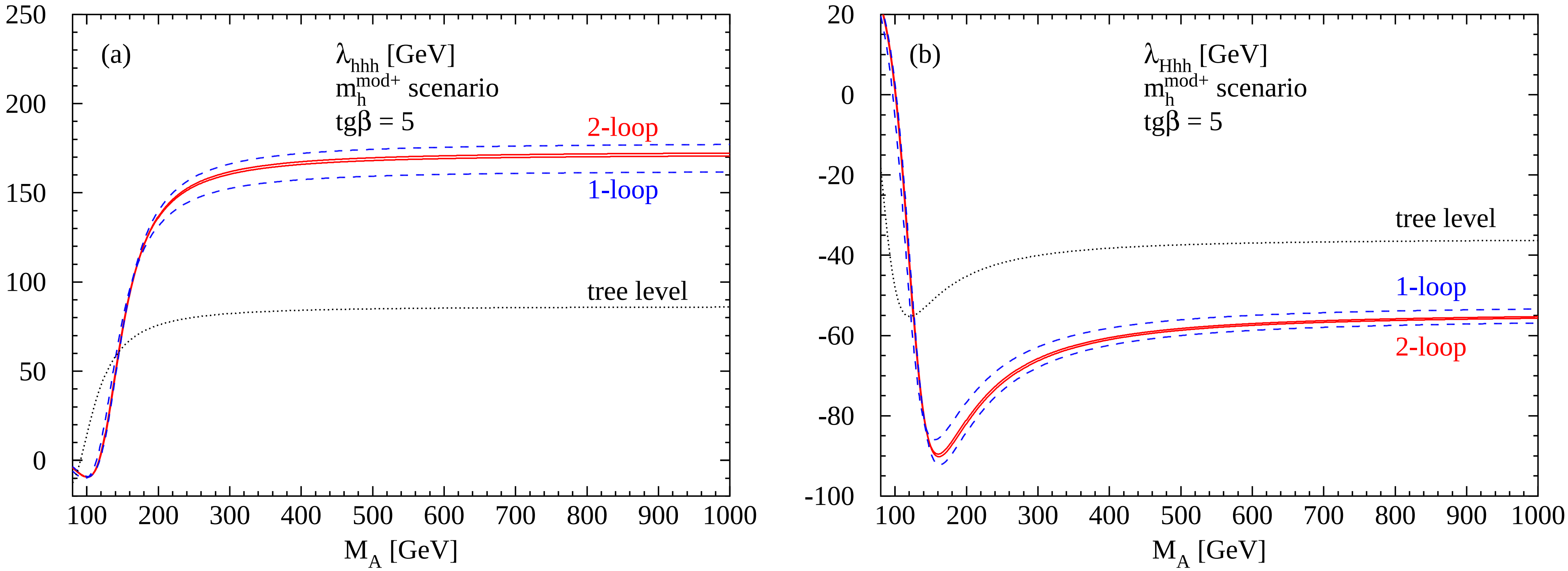
Dawson, Dittmaier, S.





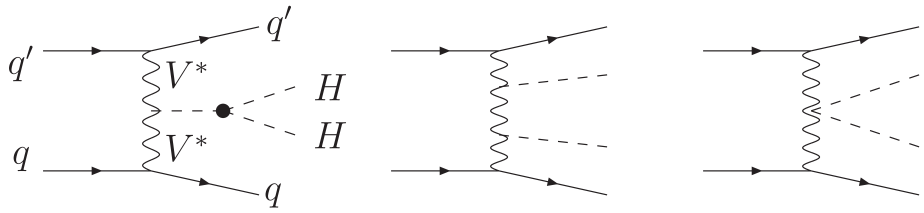
Djouadi, Kilian, Mühlleitner, Zerwas

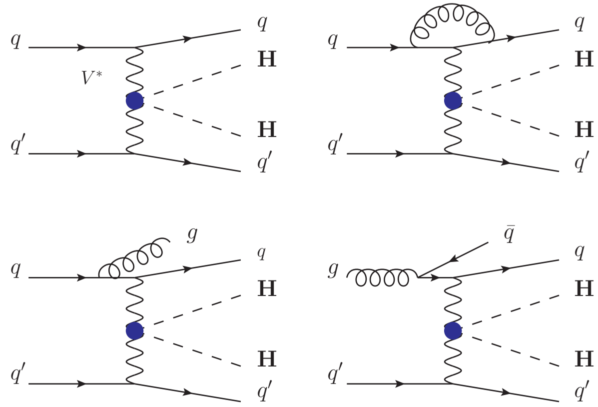
MSSM trilinear couplings up to $\mathcal{O}(\alpha_t \alpha_s)$



Brucherseifer, Gavin, S.

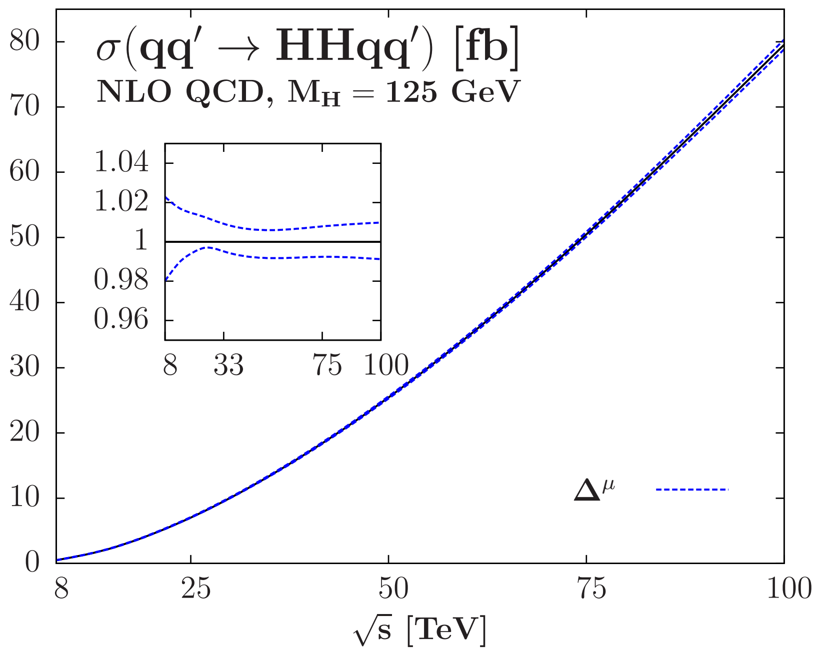
(ii) $VV \to HH$

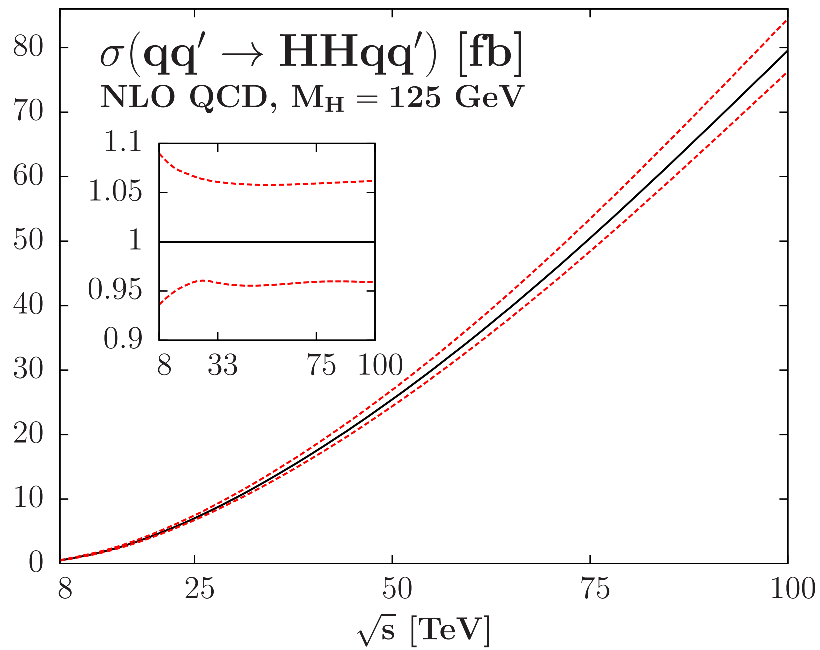




- NLO QCD corrections [← DIS]: $\sim 10\%$
  $[\mu = Q_{V*}]$
- NNLO QCD corrections [← DIS]: $\lesssim 1\%$

Sheng, Ren-You, Wen-Gan, Lei, Wei-Hua, Xiao-Zhou

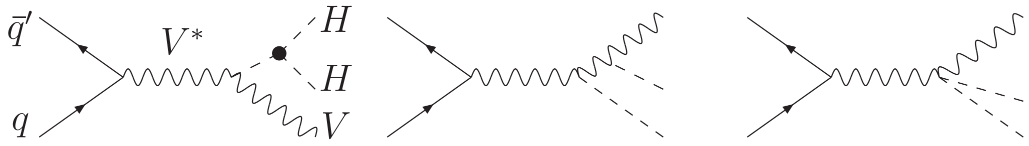


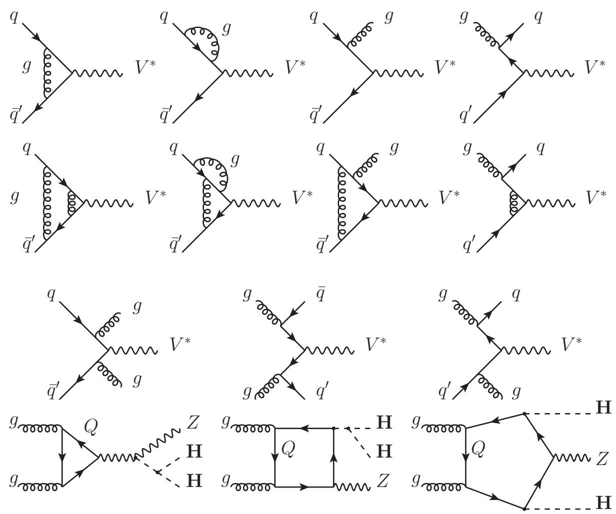


- uncertainties: $\sim 5 - 7\%$

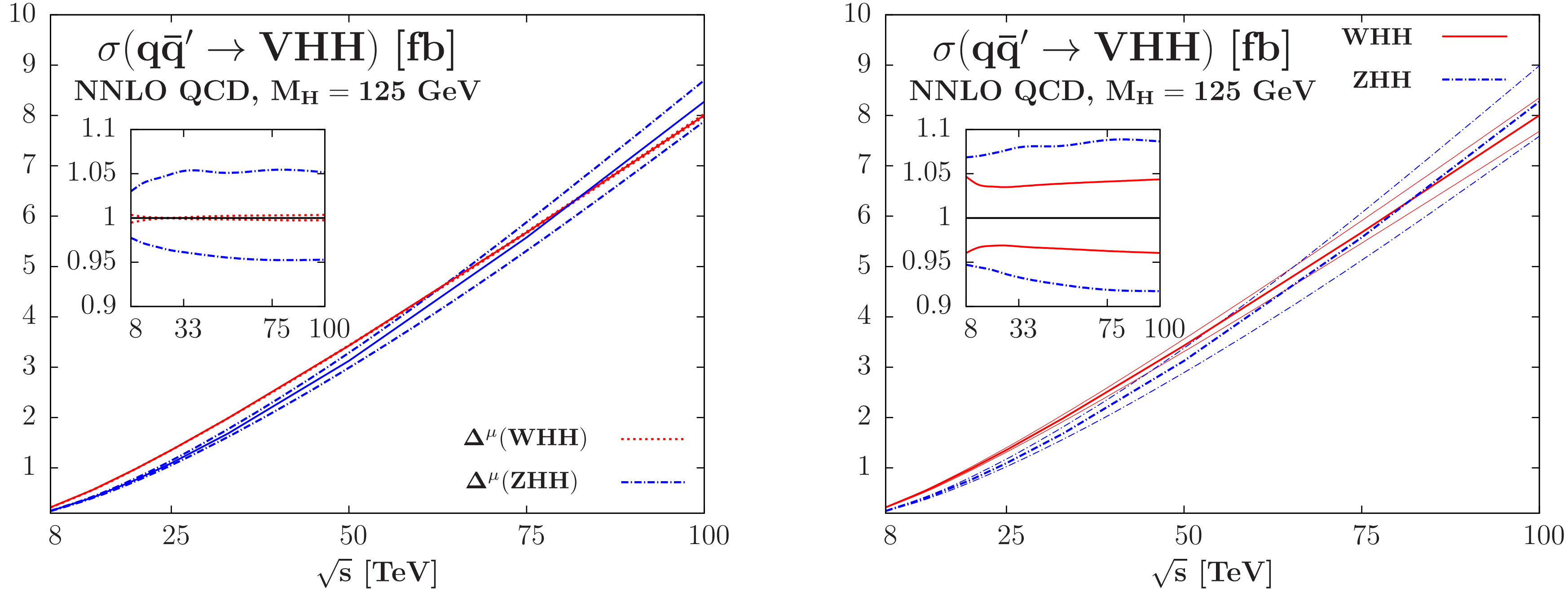
Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

$(iii)\ q\bar{q} \to VHH$





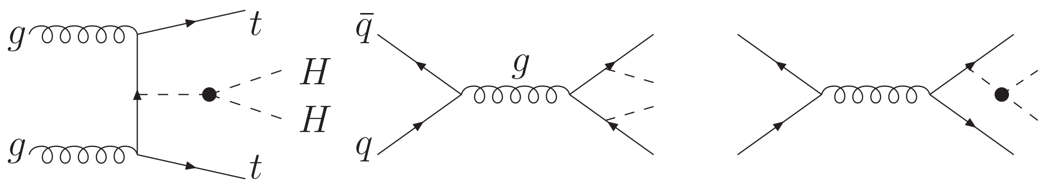
- NNLO QCD corrections [← DIS]: $\sim 30\%$
  $[\mu = M_{VHH}]$ $[gg \to ZHH : 20-30\%]$



- uncertainties: $\sim 2-6\%$

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

$(iv)\ q\bar{q} \to t\bar{t}HH$



- NLO QCD corrections moderate $\sim 20\%$

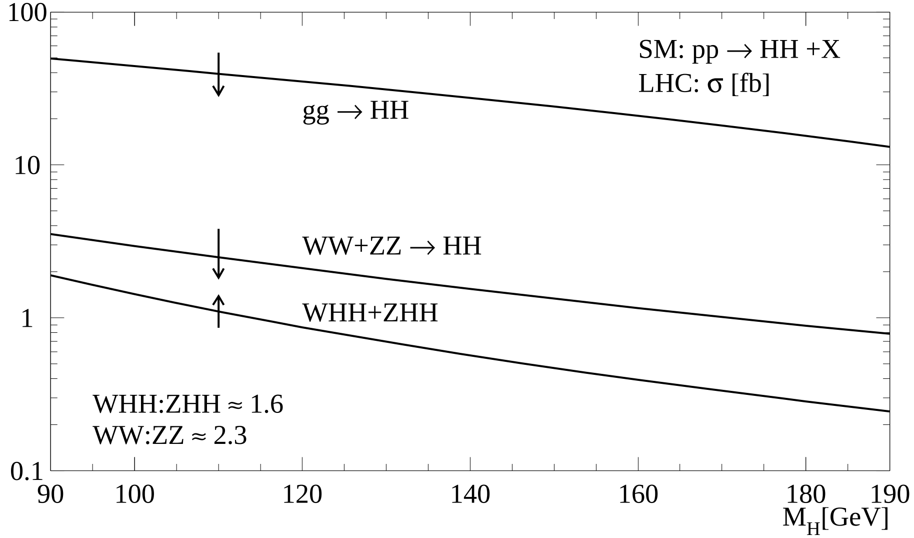
Frederix, Frixione, Hirschi, Maltoni, Mattelaer,Torrielli, Vryonidou, Zaro

- uncertainties: $\sim 10 - 15\%$

$\leftarrow$ very difficult channel

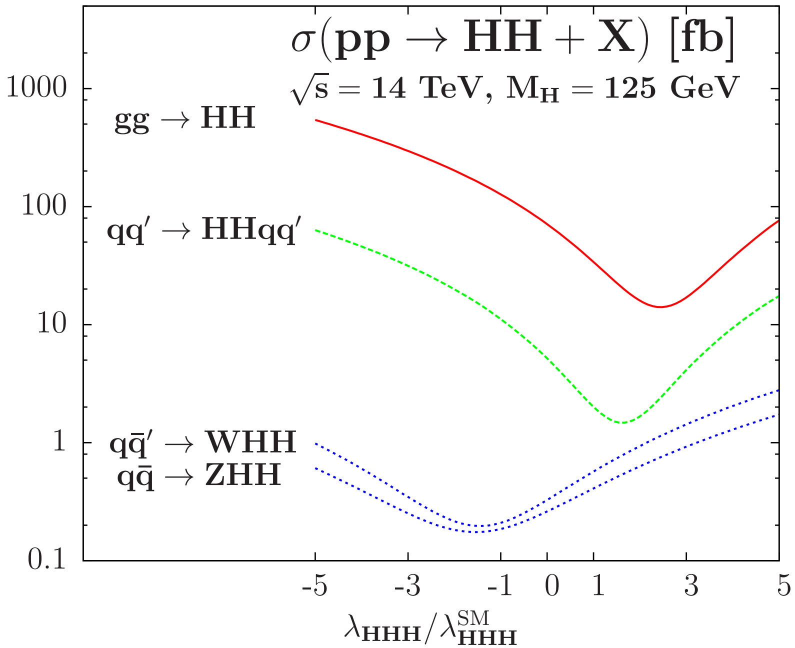
SENSITIVITY TO TRILINEAR COUPLING

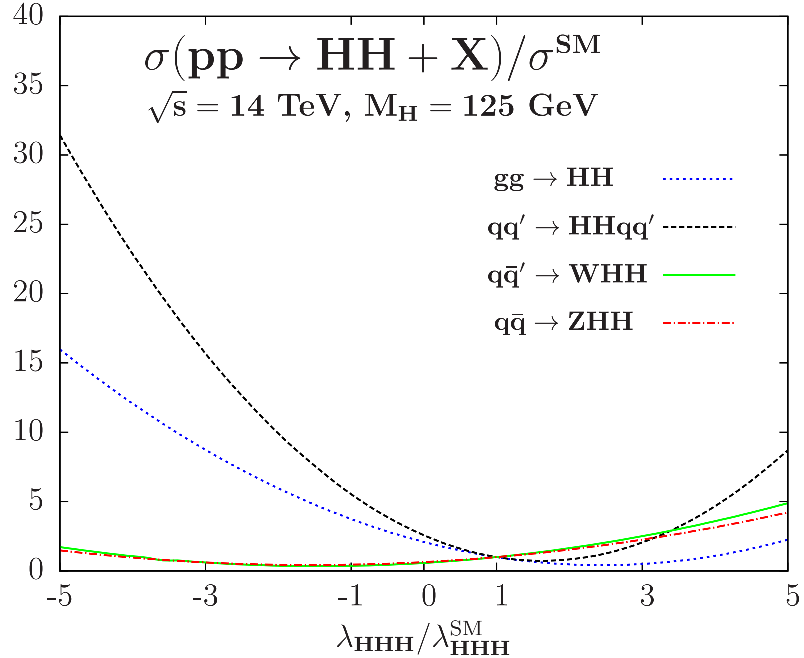
SM



Djouadi, Kilian, Mühlleitner, Zerwas

$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$





Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

Channels: need 3 ab^{-1}

$HH \to b\bar{b}\gamma\gamma$: low signal rate, most promising?
$HH \to b\bar{b}\tau^+\tau^-$: mass reconstruction difficult
$HH \to b\bar{b}W^*W^{(*)}$: hopeless?

- $b\bar{b}\gamma\gamma$: ${}^{+160\%}_{-190\%}$ @ 600 fb^{-1}

  ${}^{+74\%}_{-62\%}$ @ 6 ab^{-1}

  Baur, Plehn, Rainwater

- boosted kinematics: less sensitive to λ — Dolan, Englert, Spannowsky

- $HH + jet \to b\bar{b}b\bar{b}j, b\bar{b}\tau^+\tau^-j$ promising? — Dolan, Englert, Spannowsky

- reduction of THUs by ratio $\dfrac{\sigma(gg \to HH)}{\sigma(gg \to H)} \to \dfrac{\delta\lambda}{\lambda} \sim 30\%$?

  [different Q^2!]

  Goertz, Papaefstathiou, Yang, Zurita