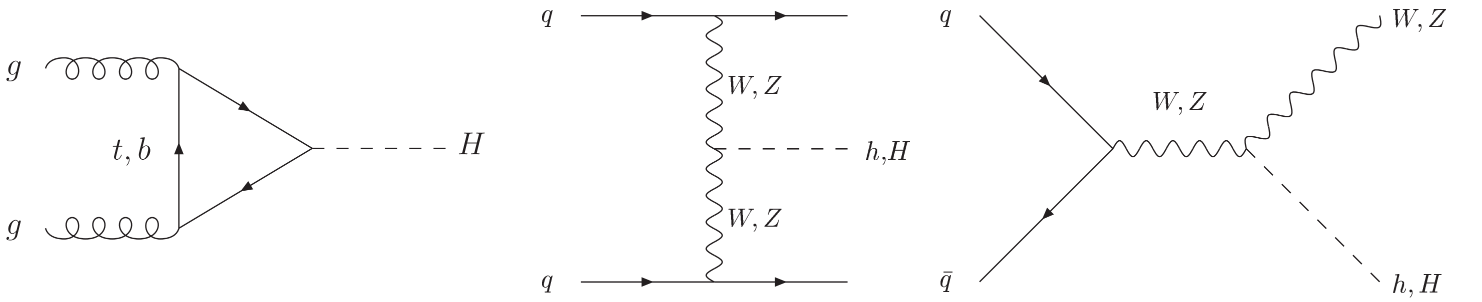
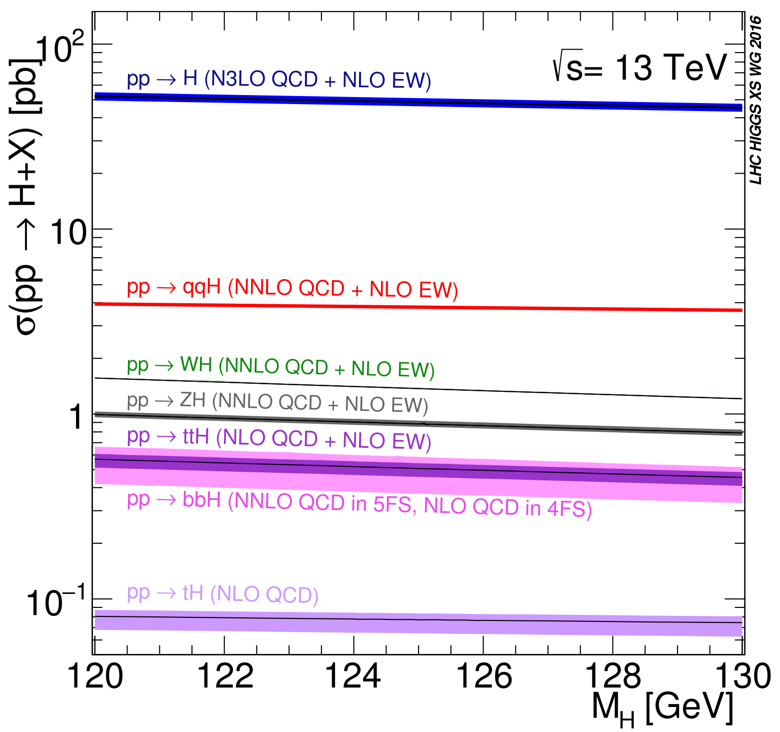
HIGGS BOSON PRODUCTION AT HADRON COLLIDERS

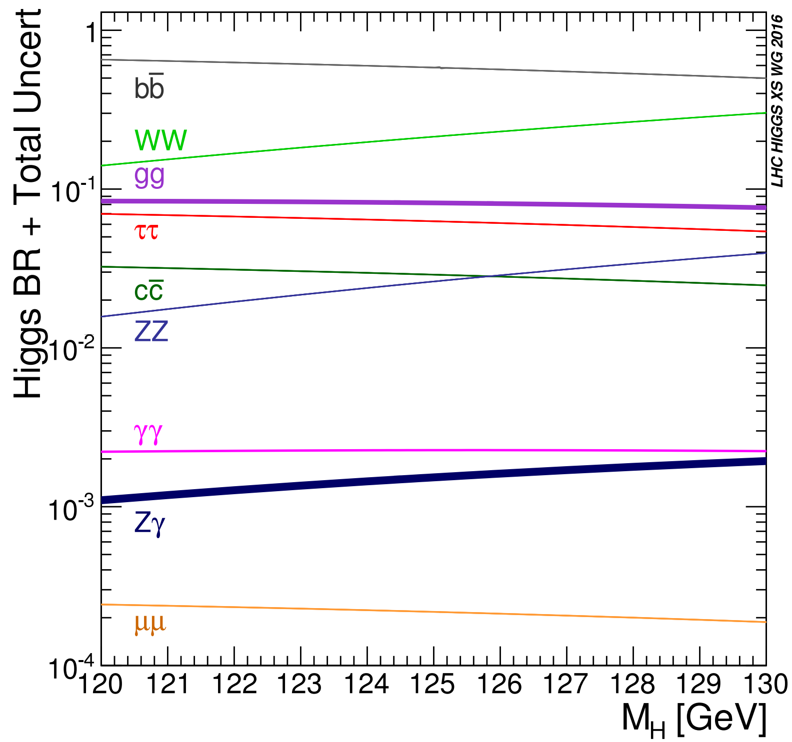
Michael Spira (PSI)

I INTRODUCTION

- Higgs Boson Production







LHC Higgs XS WG

- Discovery: LHC [Tevatron]

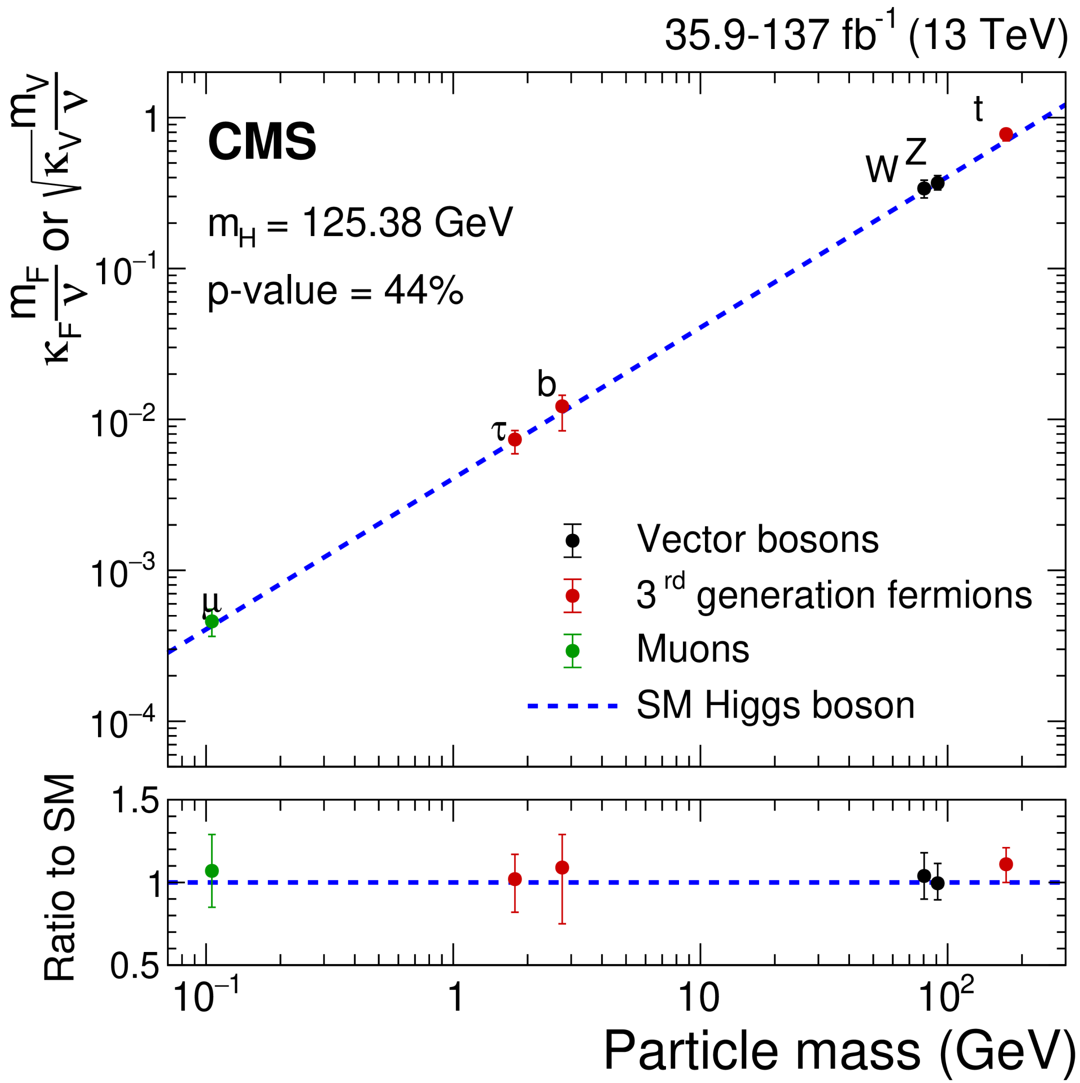
  → Higgs mass

  couplings

  spin

  $\mathcal{CP}$

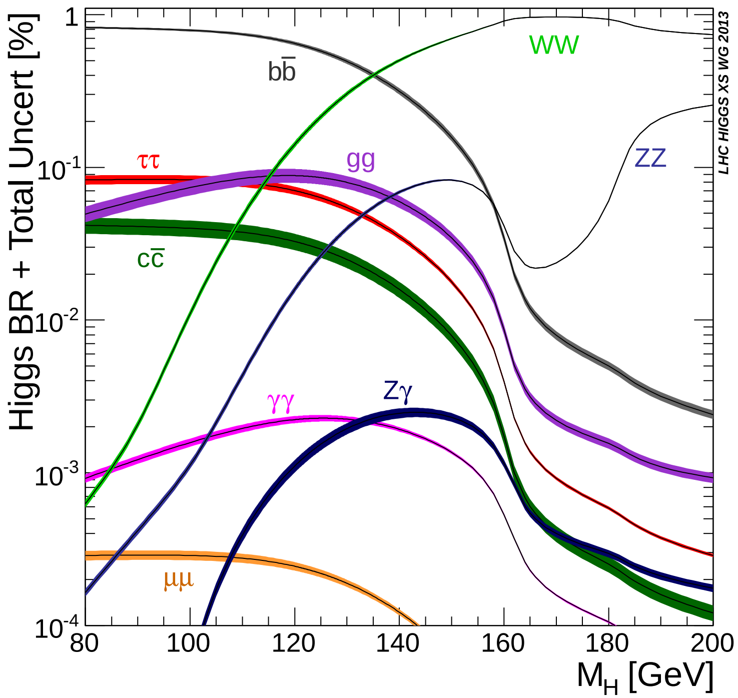
  λ ?



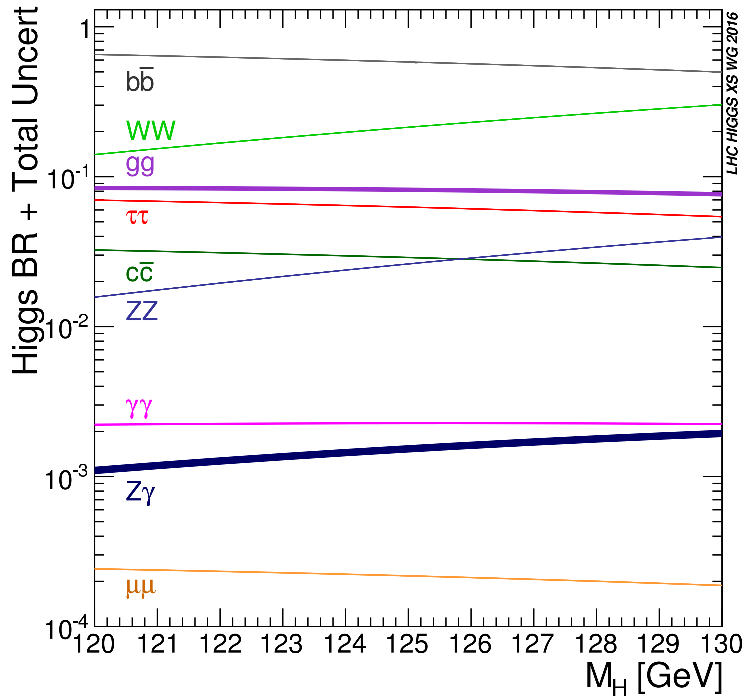
II *HIGGS BOSON DECAYS*

YR3 HDECAY & Prophecy4f YR4

∼ 10% →
∼ 10% →



⟶

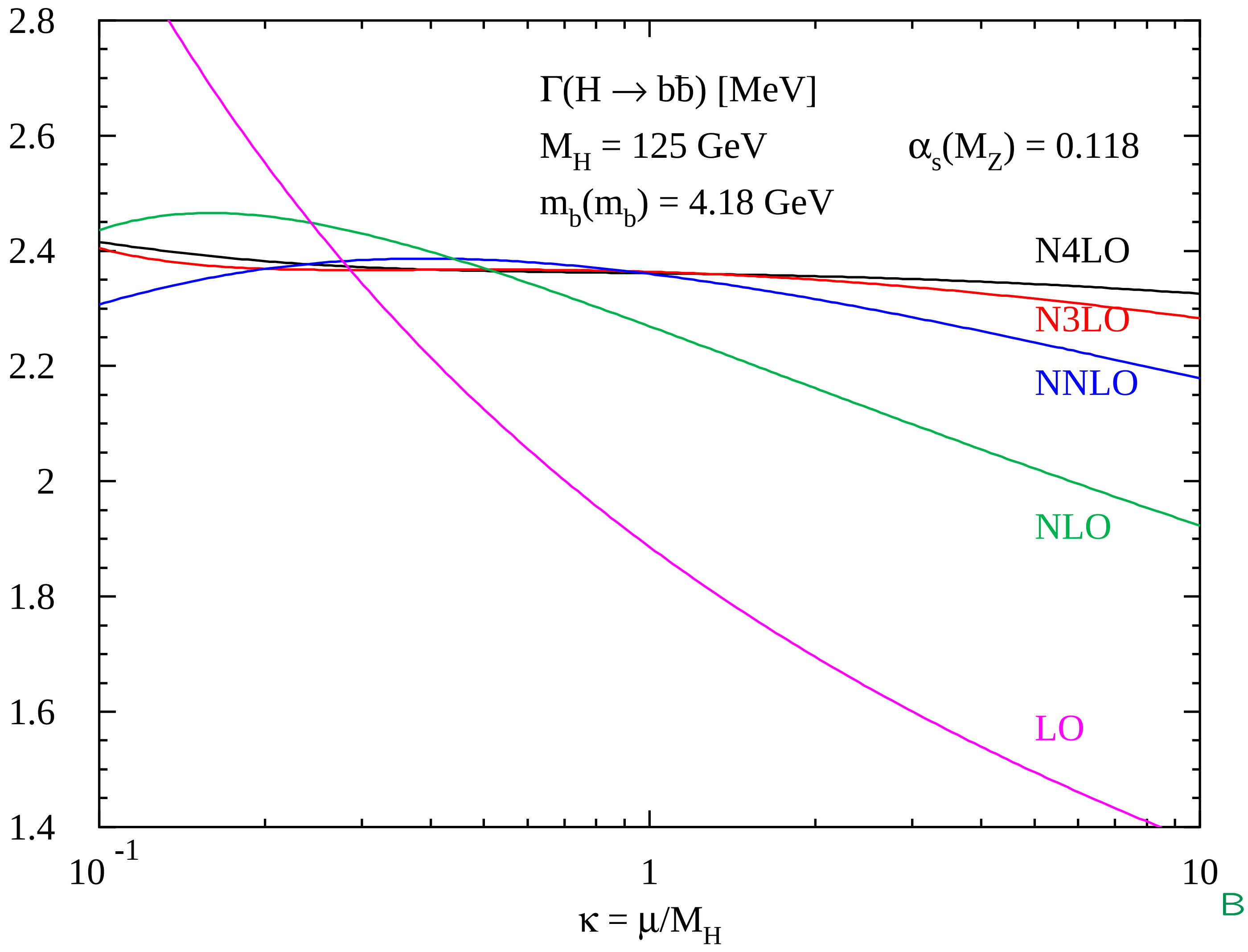


Denner, Heinemeyer, Puljak, Rebuzzi, S.

$$\Gamma[H \to b\bar{b}] = \frac{3 G_F M_H}{4\sqrt{2}\pi} \, \overline{m}_b^2(M_H) \, \Delta_{\rm QCD}$$

↑

log resummation → ∼ factor 1/2
(larger than BSM effects!)



Braaten, Leveille
Drees, Hikasa
Kataev,. . .
Chetyrkin,. . .
etc.

→ HDECAY

Djouadi, Kalinowski, Mühlleitner, S.

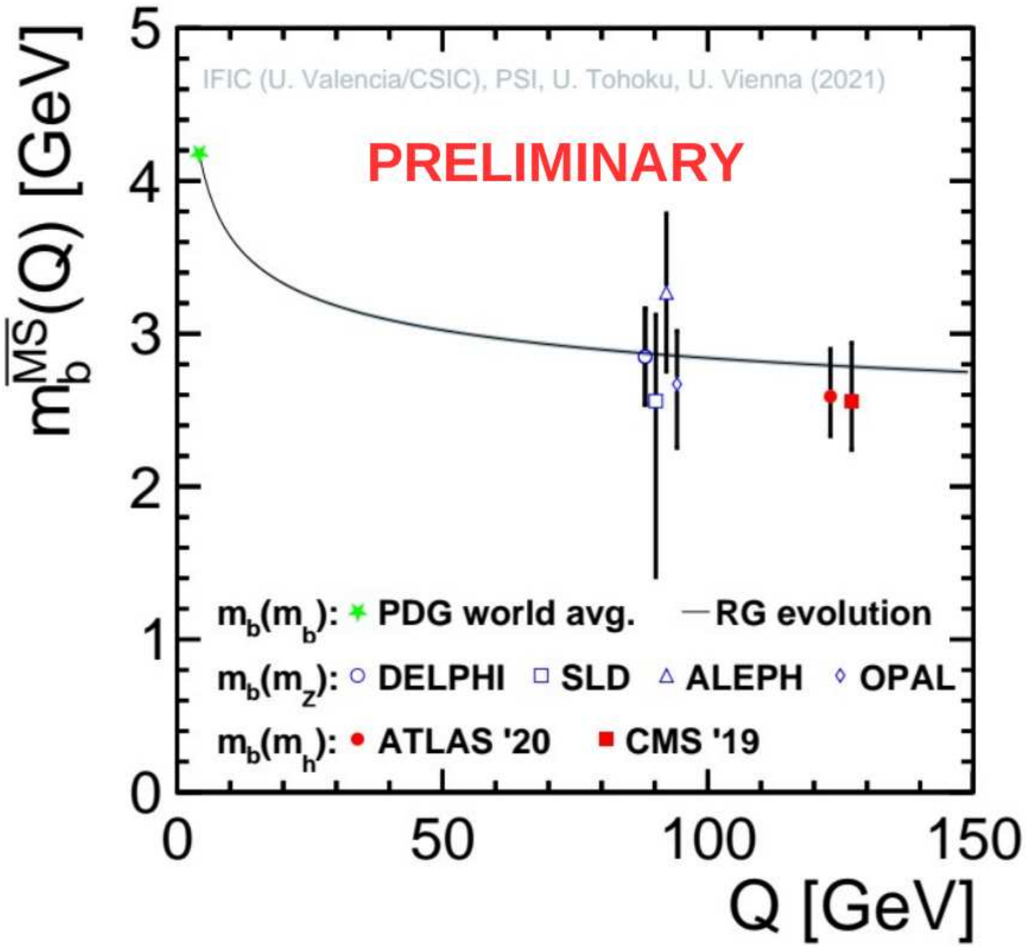
- ATLAS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.87^{+0.28}_{-0.21}$
  $\to \overline{m}_b(M_H) = 2.59^{+0.31}_{-0.26}\text{(stat)}^{+0.26}_{-0.18}\text{(syst) GeV}$

- CMS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.84^{+0.37}_{-0.27}$
  $\to \overline{m}_b(M_H) = 2.55^{+0.38}_{-0.32}\text{(stat)}^{+0.37}_{-0.26}\text{(syst) GeV}$

$\Rightarrow \overline{m}_b(M_H) = 2.58^{+0.35}_{-0.27}$ GeV
(BLUE) Nisius

RG-evolution: REvolver

Hoang, Lepenik, Mateu



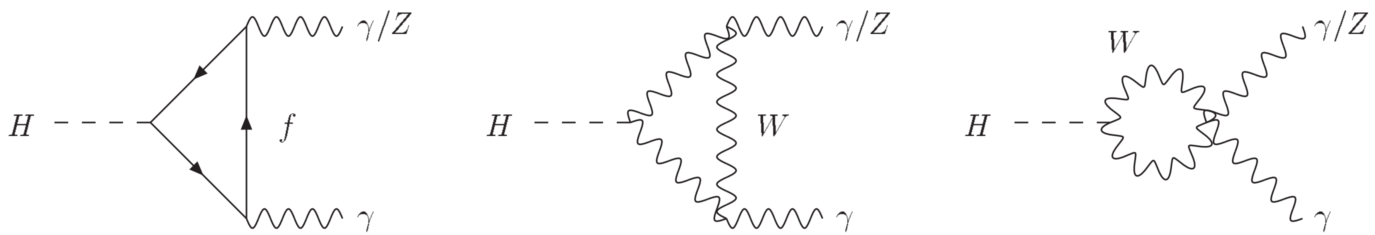
Aparisi, Fuster, Irles, Rodrigo, Vos, Yamamoto, Hoang, Lepenik, S., Tarafune, Yonamine

- off-shell Higgs production: $gg \to H^* \to X$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma_H}{dQ^2} + \frac{d\sigma_{int}}{dQ^2} + \frac{d\sigma_{cont}}{dQ^2}$$

$$\frac{d\sigma_H}{dQ^2} = \frac{Q}{\pi} \frac{\sigma(gg \to H^*) \times \Gamma(H^* \to X)}{(Q^2 - M_H^2)^2 + M_H^2 \Gamma_H^2} \qquad \rightsquigarrow \qquad \Gamma_H$$

$H^* \to \gamma\gamma$



$$BR(H \to \gamma\gamma) \lesssim 2 \times 10^{-3}$$

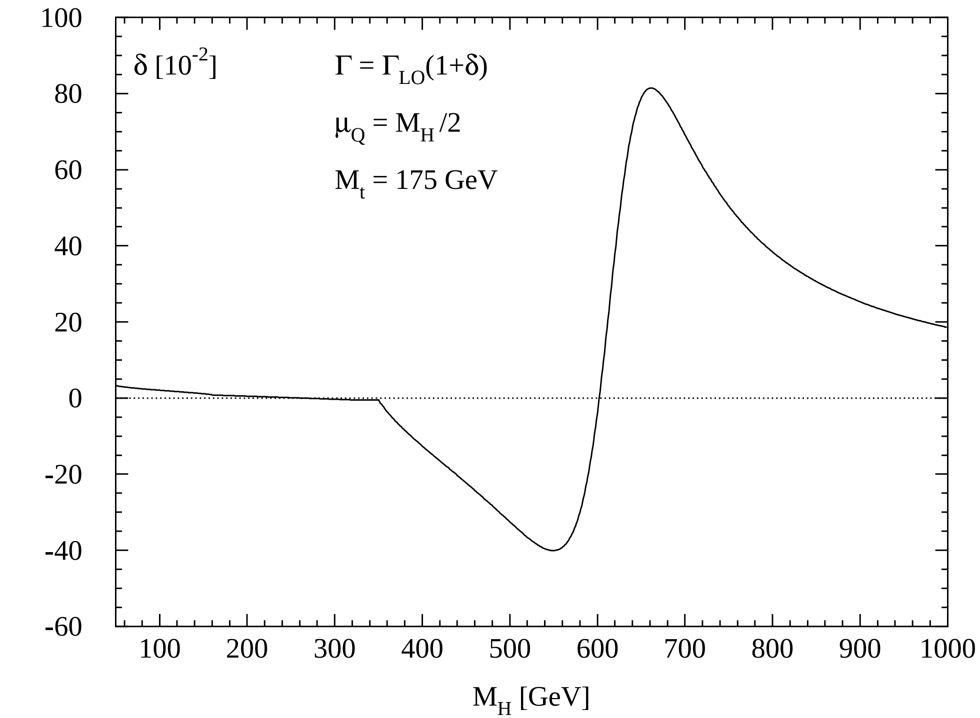
- $W - t$ destructive interference
- QCD corrections: $\lesssim 3\%$ in intermediate mass range

Zheng, Wu
Djouadi, S., Zerwas
Melnikov, Yakovlev
Inoue,. . .

- elw. corr.: $\lesssim \mathcal{O}(10\%)$

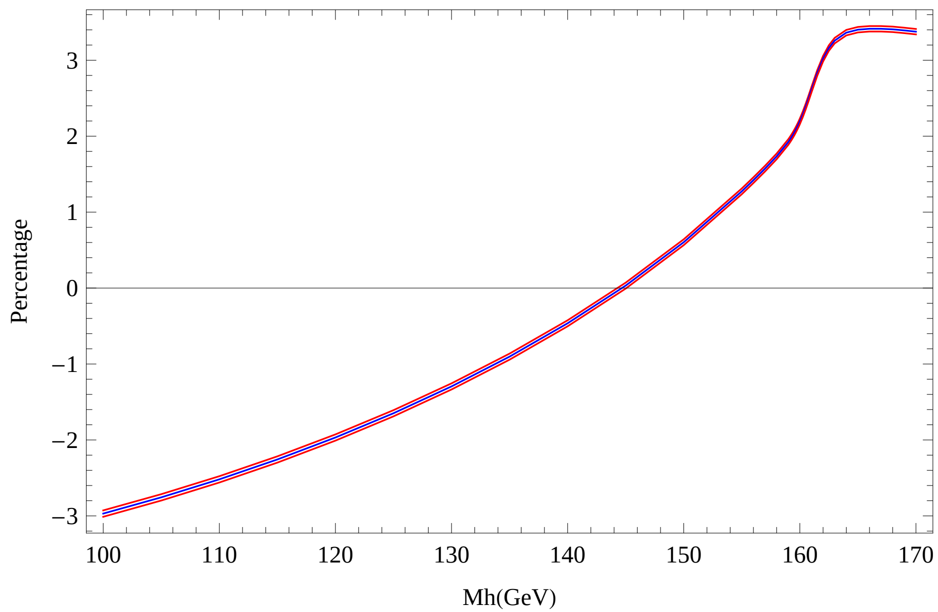
Aglietti, Bonciani, Degrassi, Vicini
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

$H \rightarrow \gamma\gamma$



QCD (running mass)

S., Djoaudi, Zerwas



elw

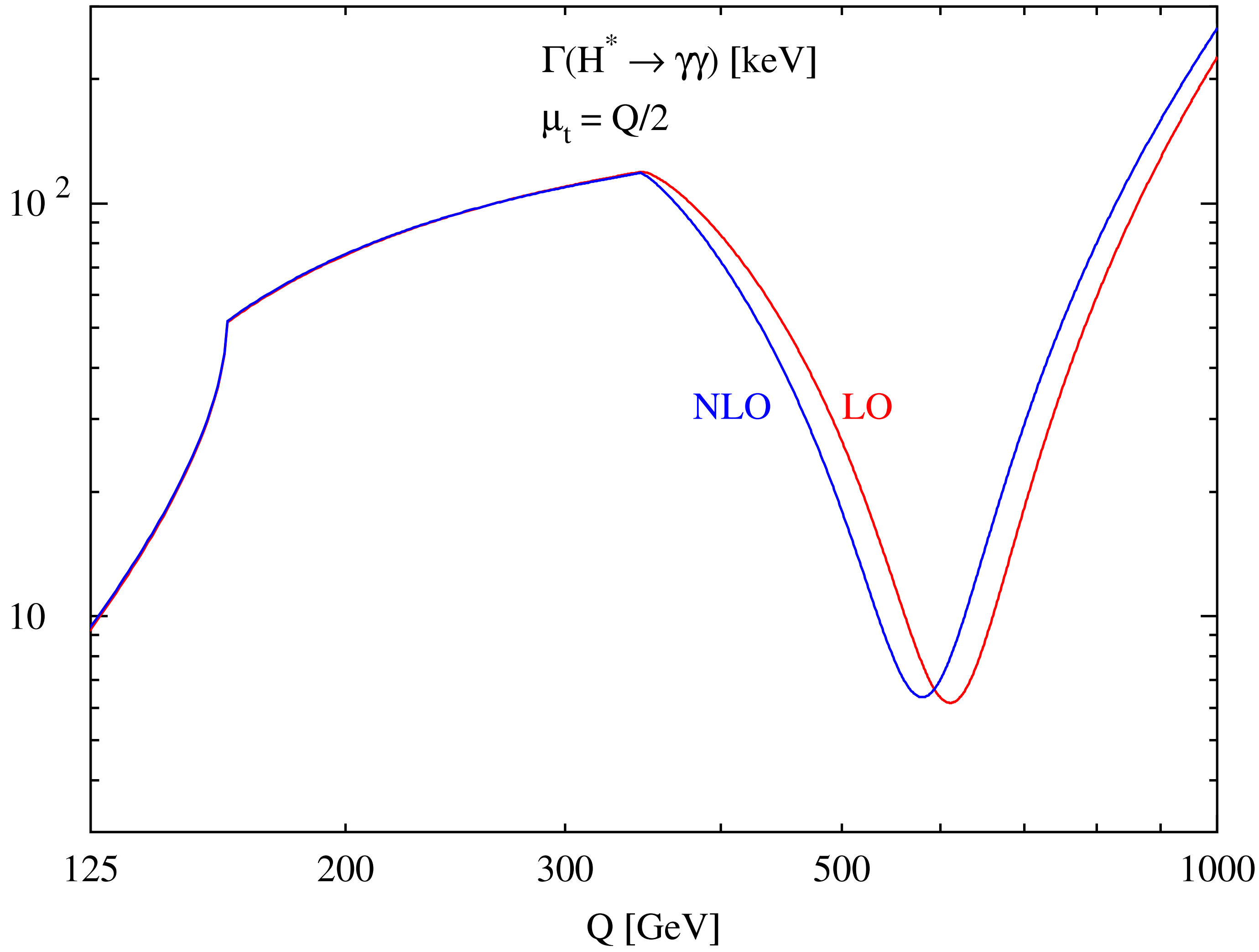
Actis, Passarino, Sturm, Uccirati

• pole mass $\leftrightarrow$ $\overline{\text{MS}}$ mass:

$$\begin{aligned}
\overline{m}_t(m_t) &= \frac{m_t}{\kappa(m_t)} \\
\kappa(m_t) &= 1 + \frac{4}{3}\frac{\alpha_s(m_t)}{\pi} + 10.9\left(\frac{\alpha_s(m_t)}{\pi}\right)^2 + 107.1\left(\frac{\alpha_s(m_t)}{\pi}\right)^3 \\
\overline{m}_t(\mu_t) &= \overline{m}_t(m_t)\,\frac{c\left[\alpha_s(\mu_t)/\pi\right]}{c\left[\alpha_s(m_t)/\pi\right]} \\
c(x) &= \left(\frac{7}{2}x\right)^{\frac{4}{7}}\left[1 + 1.398x + 1.793\,x^2 - 0.6834\,x^3\right]
\end{aligned}$$

$m_t = 172.5$ GeV $\qquad \overline{m}_t(\overline{m}_t) = 163.0$ GeV $\qquad M_H/4 < \mu_t < M_H$

- running mass: $m_t(\mu_t) = \kappa(m_t)\overline{m}_t(\mu_t) \leftarrow$ HDECAY



- $\mu_t = Q/4 \ldots Q$ @ NLO:

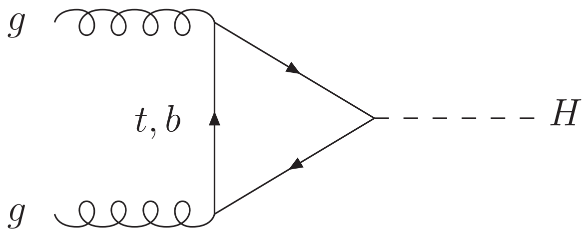
$$\Gamma(H^* \to \gamma\gamma)|_{Q=125\ \mathrm{GeV}} = 9.43^{+0.1\%}_{-0.4\%}\,\mathrm{keV}, \quad \Gamma(H^* \to \gamma\gamma)|_{Q=300\ \mathrm{GeV}} = 109.4^{+0.5\%}_{-2.2\%}\,\mathrm{keV}$$

$$\Gamma(H^* \to \gamma\gamma)|_{Q=400\ \mathrm{GeV}} = 72.3^{+9.9\%}_{-35\%}\,\mathrm{keV}, \quad \Gamma(H^* \to \gamma\gamma)|_{Q=600\ \mathrm{GeV}} = 7.03^{+156\%}_{-35\%}\,\mathrm{keV}$$

$$\Gamma(H^* \to \gamma\gamma)|_{Q=900\ \mathrm{GeV}} = 158.7^{+16\%}_{-1.5\%}\,\mathrm{keV}, \quad \Gamma(H^* \to \gamma\gamma)|_{Q=1200\ \mathrm{GeV}} = 572.3^{+3.4\%}_{-0\%}\,\mathrm{keV}$$

III *HIGGS BOSON PRODUCTION*

(i) $gg \to H$



Georgi, . . .

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman

- NLO QCD corrections: $\sim 100\%$

- NNLO calculated for $m_t \gg M_\phi \Rightarrow$ further increase by 20–30%
  [top mass effects small in SM]

Harlander, Kilgore
Anastasiou, Melnikov
Ravindran, Smith, van Neerven

Marzani, Ball, Del Duca, Forte, Vicini
Harlander, Ozeren
Pak, Rogal, Steinhauser

- N^{3}LO for $m_t \gg M_\phi \quad \Rightarrow$ scale stabilization

scale dependence: $\Delta \lesssim 5\%$

Moch, Vogt
Ravindran
de Florian, Mazzitelli, Moch, Vogt
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger
Ball, Bonvini, Forte, Marzani, Ridolfi

- N^{3}LL soft gluon resummation: $\lesssim 1\%$

Catani, de Florian, Grazzini, Nason
Ravindran
Ahrens, Becher, Neubert, Yang
Ball, Bonvini, Forte, Marzani, Ridolfi
Bonvini, Marzani
Schmidt, S.

- impl. of $gg \to \phi$ in POWHEG including mass effects @ NLO
  (QCD also valid for 2HDM and other Higgs extensions)

Bagnaschi, Degrassi, Slavich, Vicini

- elw. corrections: $\sim 5\%$

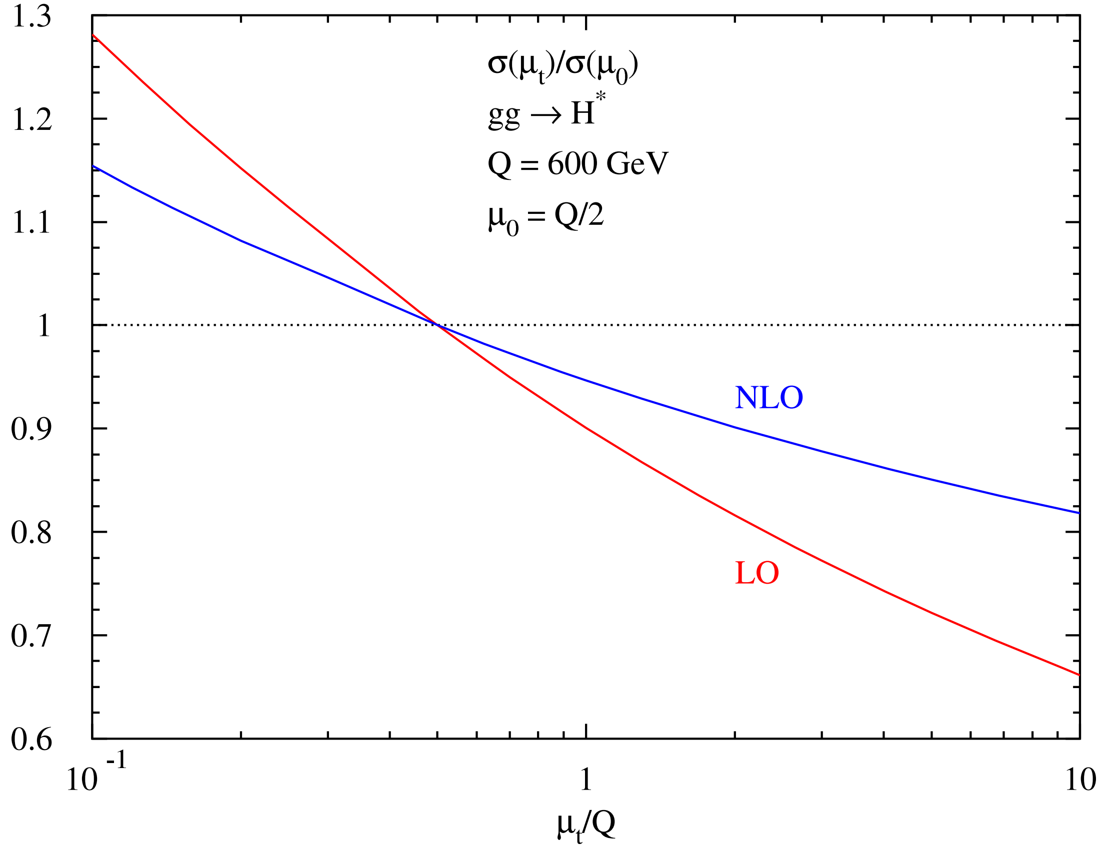
Aglietti,...
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

- $\sigma(gg \to H) = \left(54.72^{+4.3\%}_{-6.5\%}(TH) \pm 3.2\%(PDF, \alpha_s)\right)\ pb$ @ $\sqrt{s} = 14$ TeV

Anastasiou,...

- uncertainties: PDF+α_s, renormalization/factorization scale
  top/bottom masses: $\sim \pm 0.8\% \leftarrow$ scale/scheme dependence

$$\sigma(gg \to H)_{LO} = 18.43^{+0.8\%}_{-1.1\%}\ \text{pb} \qquad \sigma(gg \to H)^{QCD}_{NLO} = 42.17^{+0.4\%}_{-0.5\%}\ \text{pb}$$



Jones, S.

m_t scheme/scale uncertainties only:

- LO:

$$\sigma(gg \to H^*)|_{Q=125\ \text{GeV}} = 18.43^{+0.8\%}_{-1.1\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=300\ \text{GeV}} = 4.88^{+23.1\%}_{-1.1\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=400\ \text{GeV}} = 4.94^{+1.2\%}_{-1.8\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=600\ \text{GeV}} = 1.13^{+0.0\%}_{-26.2\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=900\ \text{GeV}} = 0.139^{+0.0\%}_{-36.0\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=1200\ \text{GeV}} = 0.0249^{+0.0\%}_{-41.1\%}\ \text{pb}$$

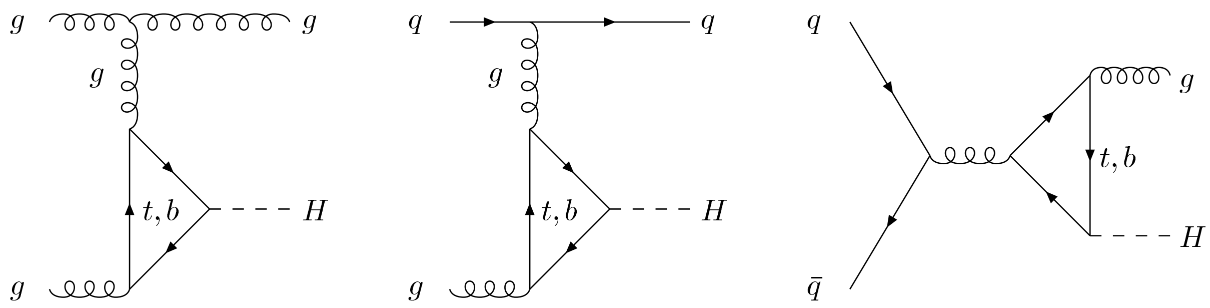
- NLO QCD:

$$\sigma(gg \to H^*)|_{Q=125\ \text{GeV}} = 42.17^{+0.4\%}_{-0.5\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=300\ \text{GeV}} = 9.85^{+7.5\%}_{-0.3\%}\ \text{pb}$$

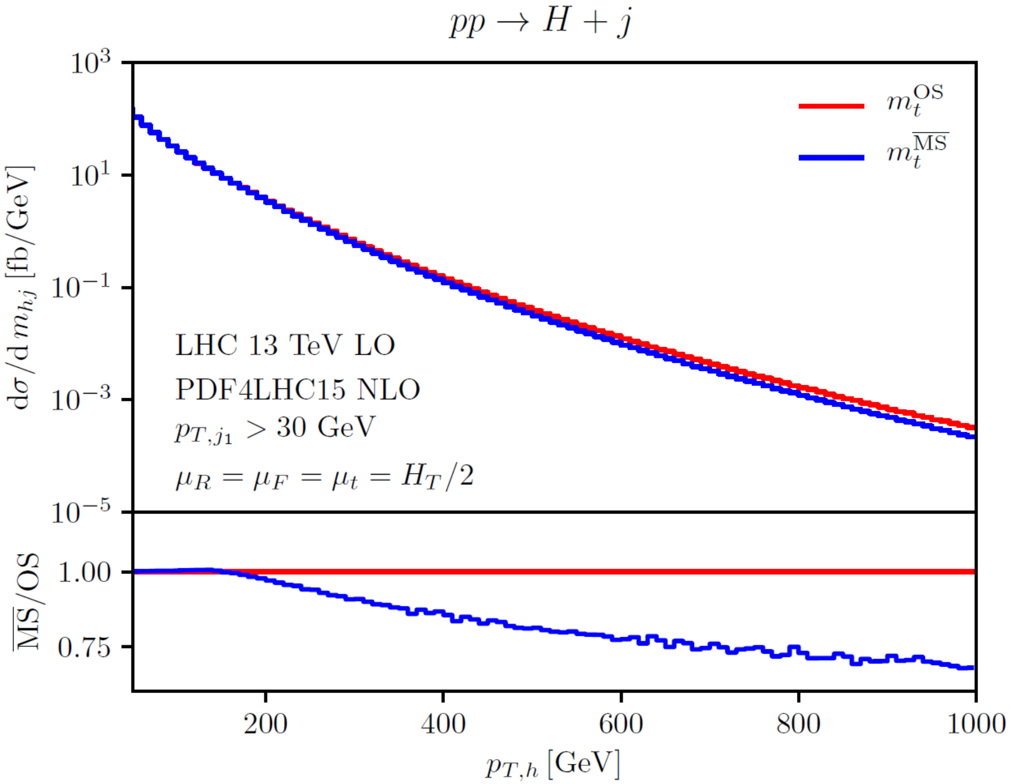
$$\sigma(gg \to H^*)|_{Q=400\ \text{GeV}} = 9.43^{+0.1\%}_{-0.9\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=600\ \text{GeV}} = 1.97^{+0.0\%}_{-15.9\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=900\ \text{GeV}} = 0.230^{+0.0\%}_{-22.3\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=1200\ \text{GeV}} = 0.0402^{+0.0\%}_{-26.0\%}\ \text{pb}$$

- Higgs + jet production: $gg \to H + j$



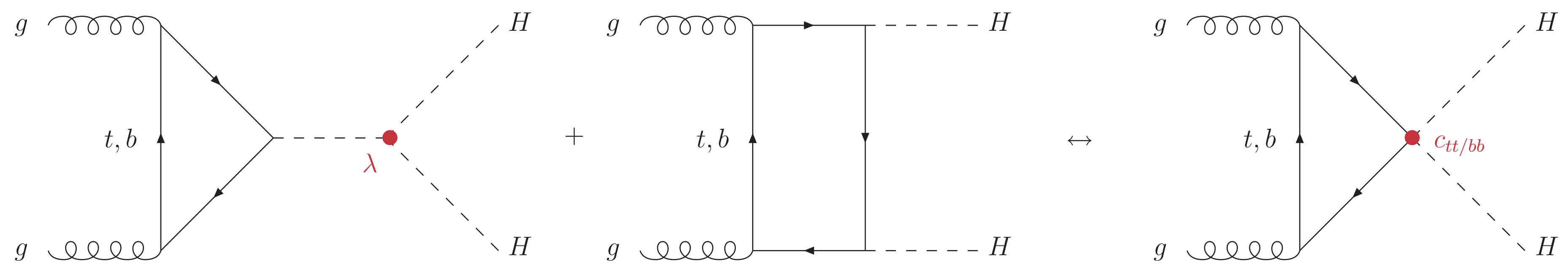
LO: $\mu_t = H_T/2 = (\sqrt{M_H^2 + p_T^2} + p_{Tj})/2$



Jones, S.

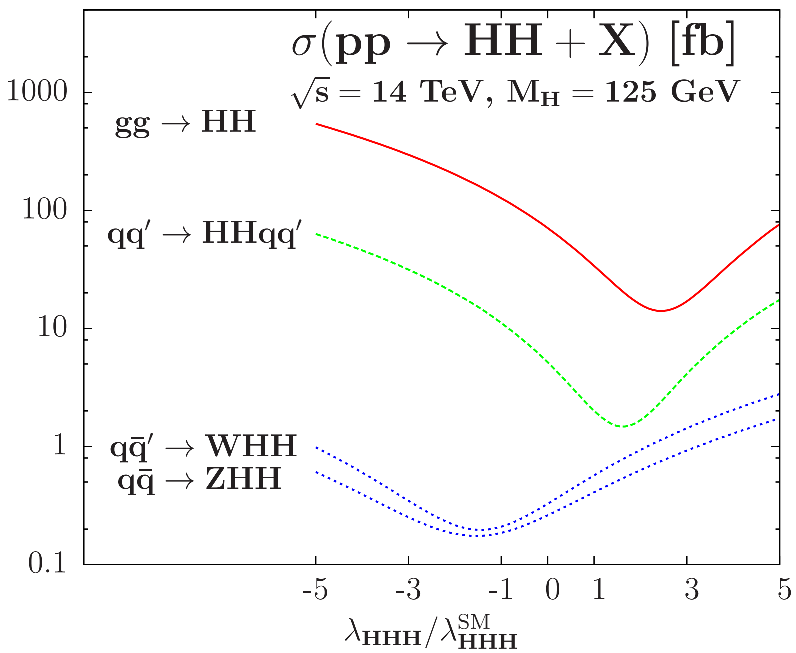
→ NLO? Jones, Kerner, Luisoni

(ii) $gg \to HH$



- threshold region: sensitive to λ

  large M_{HH}: sensitive to $c_{tt/bb}$ [e.g. boosted Higgs pairs]

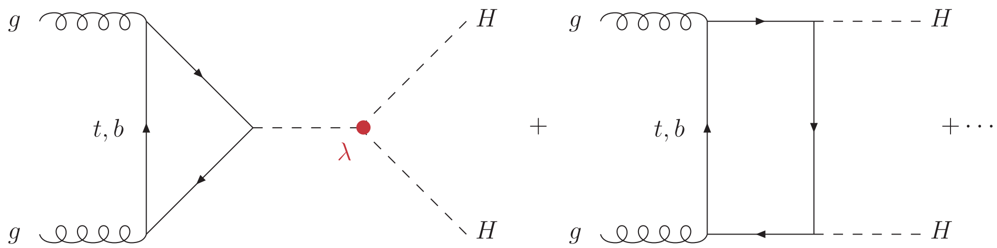


$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

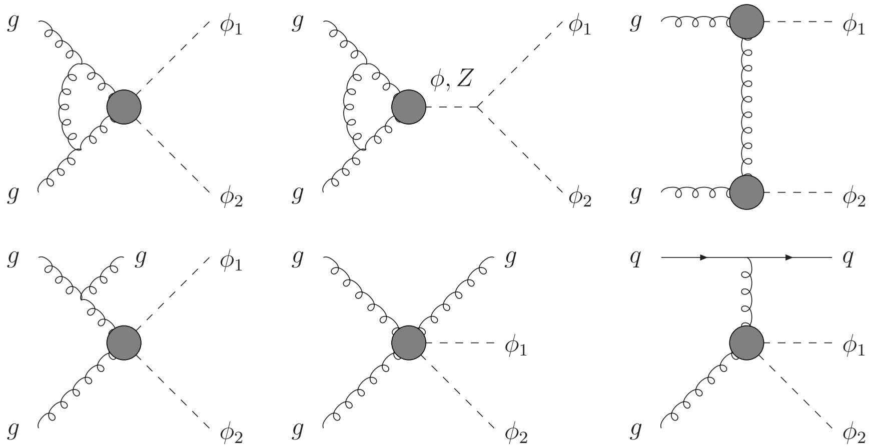
Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

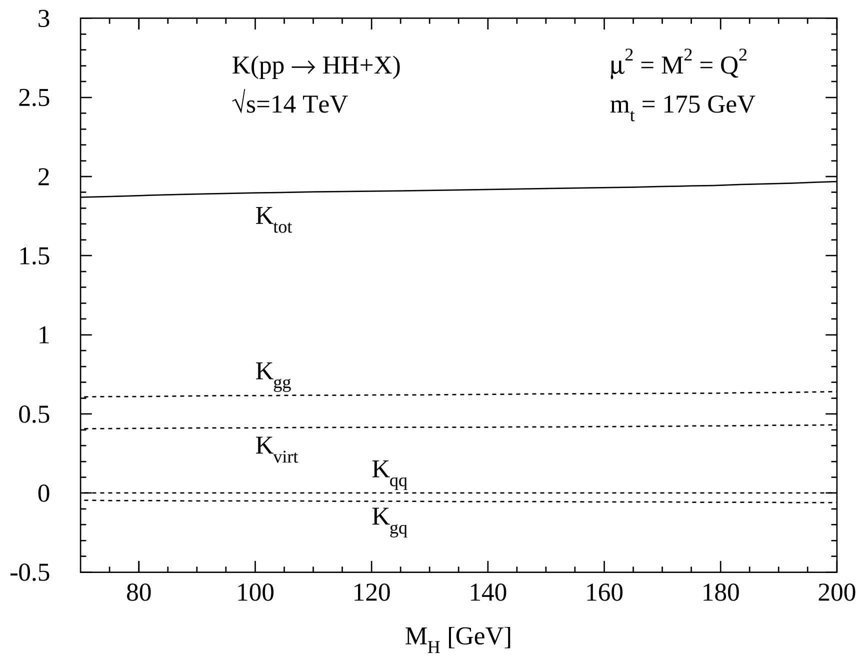
SM



- third generation dominant $\rightarrow t, b$

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





Dawson, Dittmaier, S.

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

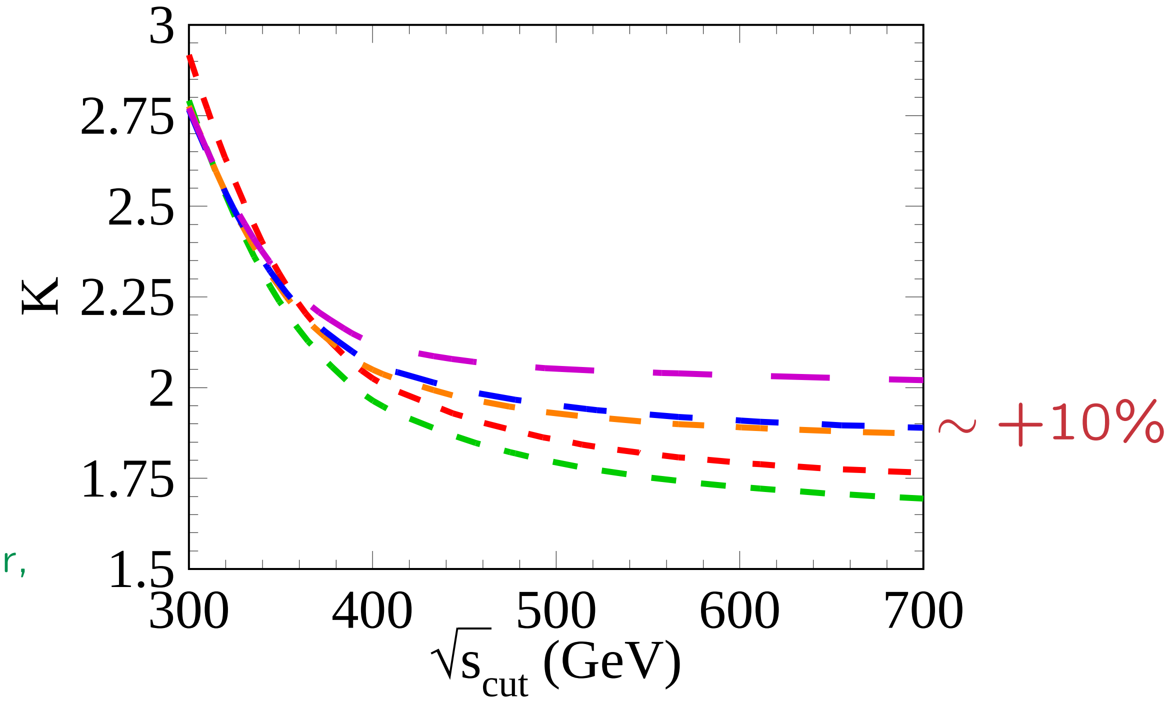
$$\begin{aligned}
\sigma_{\mathsf{LO}} &= \int_{\tau_0}^{1} d\tau\, \frac{d\mathcal{L}^{gg}}{d\tau}\, \hat{\sigma}_{\mathsf{LO}}(Q^2 = \tau s) \\
\Delta\sigma_{\mathsf{virt}} &= \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau\, \frac{d\mathcal{L}^{gg}}{d\tau}\, \hat{\sigma}_{\mathsf{LO}}(Q^2 = \tau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

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

• 2-loop QCD corrections:

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

Grigo, Hoff, Melnikov, Steinhauser



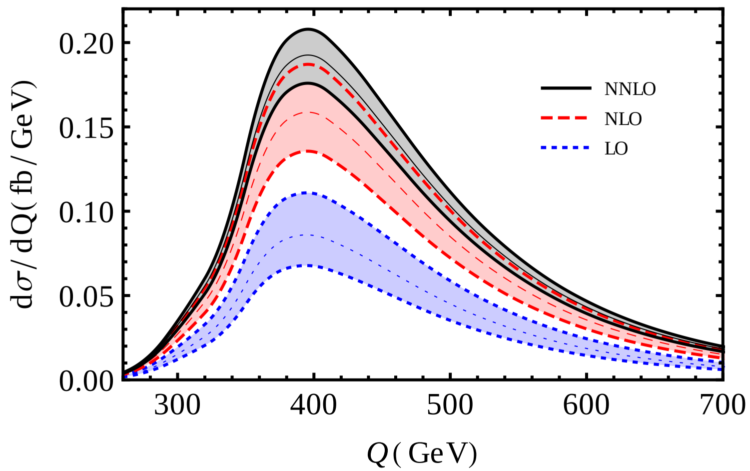
• NLO mass effects @ NLO in real corrections: $\sim -10\%$

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

→ sizeable virtual mass effects

• NNLO QCD corrections: $\sim 20\%$ $[M_H^2 \ll 4m_t^2]$

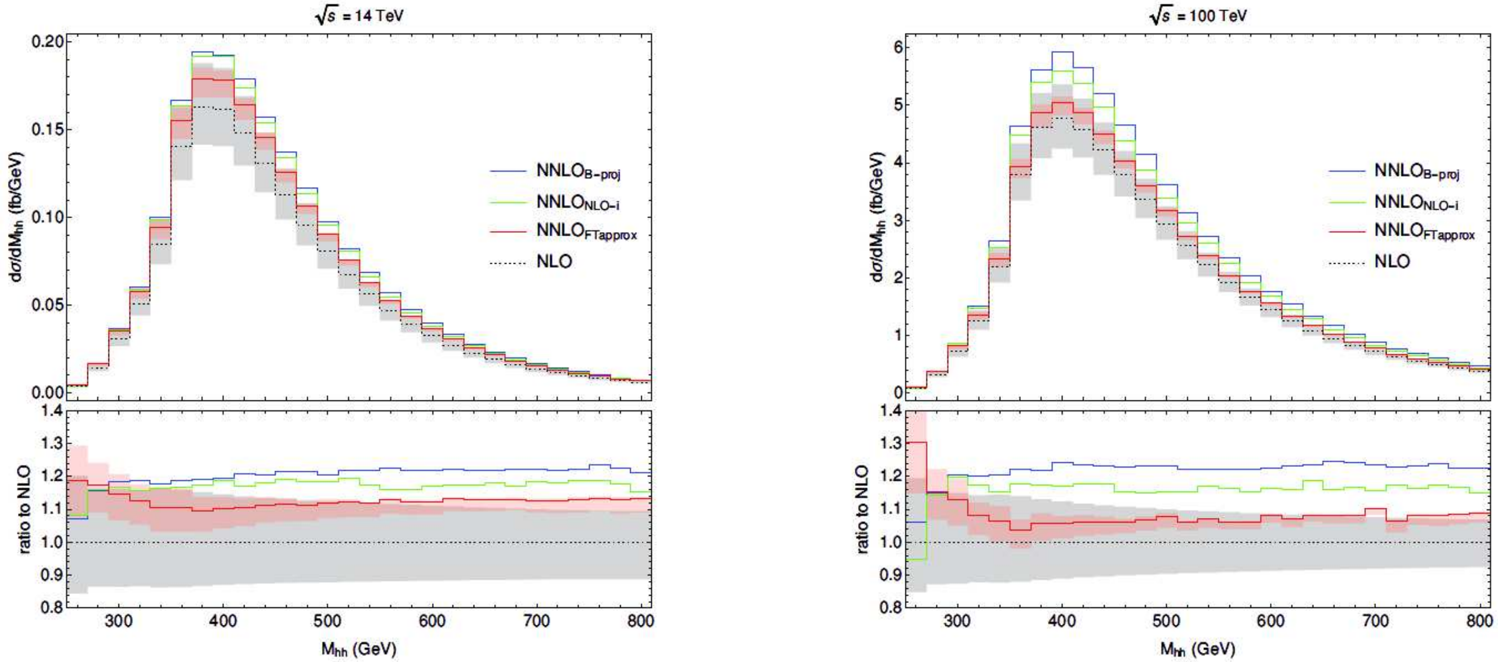
de Florian, Mazzitelli
Grigo, Melnikov, Steinhauser



• soft gluon resummation: $\sim 10\%$ $[M_H^2 \ll 4m_t^2]$

Shao, Li, Li, Wang
de Florian, Mazzitelli

NNLO Monte Carlo: inclusion of full top-mass effects @ NLO [partly @ NNLO]



Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli

- 20% effects beyond NLO
- NLO: matching to parton showers

Heinrich, Jones, Kerner, Luisoni, Vryonidou

Full NLO calculation: top only, numerical integration

Borowka *et al.*	Baglio *et al.*
tensor reduction	no tensor reduction
sector decomposition	IR, end-point subtraction
contour deformation	IBP, Richardson extrapolation
$m_t = 173$ GeV	$m_t = 172.5$ GeV

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke
Baglio, Campanario, Glaus, Mühlleitner, Ronca, S., Streicher

- new expansion/extrapolation methods:

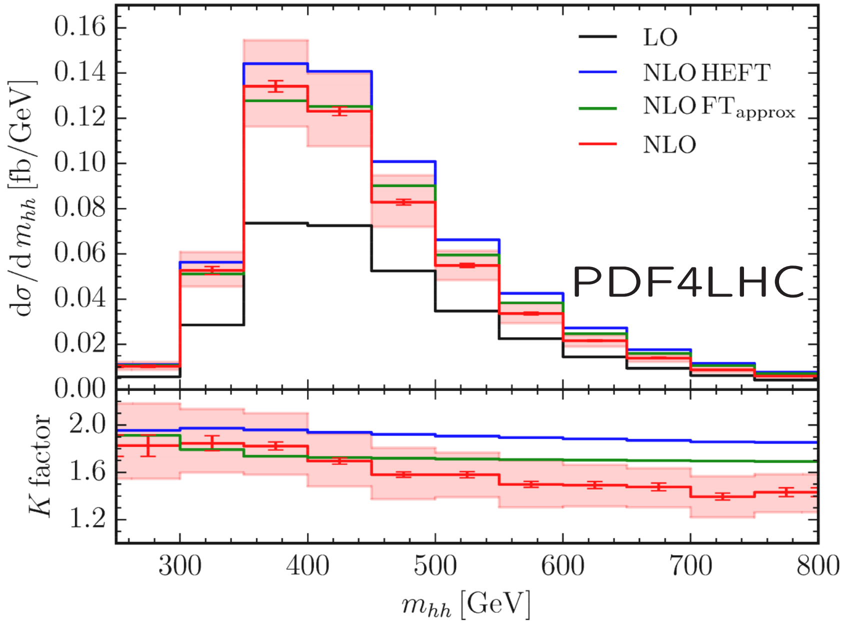
(i) $1/m_t^2$ expansion + conformal mapping + Padé approximants
Gröber, Maier, Rauh

(ii) p_T^2 expansion
Bonciani, Degrassi, Giardino, Gröber

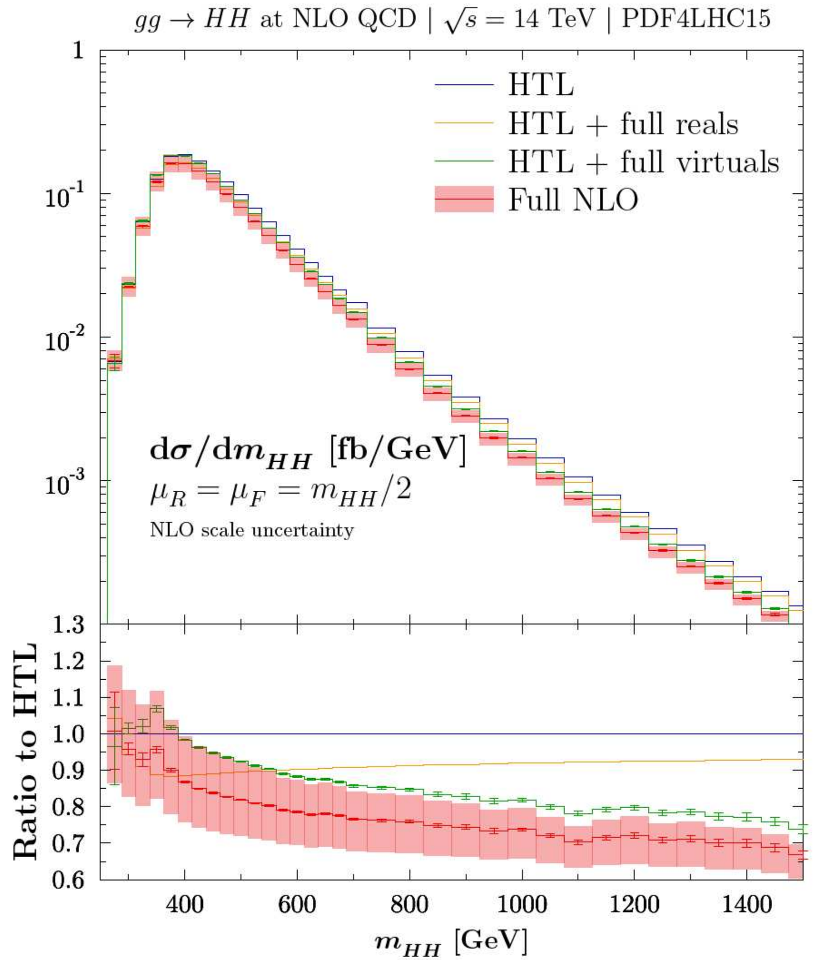
- NLO: small mass exp. $[Q^2 \gg m_t^2]$
Davies, Mishima, Steinhauser, Wellmann

- combination of full NLO and small mass expansion
Davies, Heinrich, Jones, Kerner, Mishima, Steinhauser, Wellmann

Full NLO results:



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



Baglio, Campanario, Glaus,
Mühlleitner, Ronca, S., Streicher

$\sigma_{NLO} =$	$32.91(10)^{+13.8\%}_{-12.8\%}\ fb$	$32.81(7)^{+13.5\%}_{-12.5\%}\ fb$
$\sigma^{HTL}_{NLO} =$	$38.75^{+18\%}_{-15\%}\ fb$	$38.66^{+18\%}_{-15\%}\ fb$
$m_t =$	173 GeV	172.5 GeV

$\Rightarrow$ -15% mass effects on top of LO

uncertainties due to m_t

- use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$ → uncertainty = envelope:

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=300\ \mathrm{GeV}} = 0.02978(7)^{+6\%}_{-34\%}\ \mathrm{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=400\ \mathrm{GeV}} = 0.1609(4)^{+0\%}_{-13\%}\ \mathrm{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=600\ \mathrm{GeV}} = 0.03204(9)^{+0\%}_{-30\%}\ \mathrm{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=1200\ \mathrm{GeV}} = 0.000435(4)^{+0\%}_{-35\%}\ \mathrm{fb/GeV}$$

- bin-by-bin interpolation:

$$\sigma(gg \to HH) = 32.81^{+4\%}_{-18\%}\ \mathrm{fb}$$

- why a dynamical scale $\sim Q$?
  large momentum expansion ($\hat{s} = Q^2 \gg m_t^2$), two FF:

← Davies, Mishima, Steinhauser, Wellmann

<u>pole mass m_t:</u>

$$\Delta F_{1,mass} \;\to\; \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_1(\hat{s},\hat{t})\right\} ,$$

$$\Delta F_{2,mass} \;\to\; \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

<u>$\overline{\text{MS}}$ mass $\overline{m}_t(\mu_t)$:</u>

$$\Delta F_{1,mass} \;\to\; \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_1(\hat{s},\hat{t})\right\} ,$$

$$\Delta F_{2,mass} \;\to\; \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

$\Rightarrow$ scale $\mu_t \sim Q$ preferred at large Q

- renormalization/factorization scale uncertainties @ NLO:

$$
\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} &= 27.73(7)^{+13.8\%}_{-12.8\%} \text{ fb} \\
\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} &= 32.81(7)^{+13.5\%}_{-12.5\%} \text{ fb} \\
\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} &= 127.0(2)^{+11.7\%}_{-10.7\%} \text{ fb} \\
\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} &= 1140(2)^{+10.7\%}_{-10.0\%} \text{ fb}
\end{aligned}
$$

- m_t scale/scheme uncertainties @ NLO:

$$
\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} &= 27.73(7)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} &= 32.81(7)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} &= 127.8(2)^{+4\%}_{-18\%} \text{ fb} \\
\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} &= 1140(2)^{+3\%}_{-18\%} \text{ fb}
\end{aligned}
$$

- how to combine them? $\rightarrow$ envelope $\sim$ linear sum (rel. err.)

• renormalization/factorization scale uncertainties @ NNLO$_{FTapprox}$:

$$\begin{aligned}
\sqrt{s} = 13\ \text{TeV}: \quad \sigma_{tot} &= 31.05^{+2.2\%}_{-5.0\%}\ \text{fb} \\
\sqrt{s} = 14\ \text{TeV}: \quad \sigma_{tot} &= 36.69^{+2.1\%}_{-4.9\%}\ \text{fb} \\
\sqrt{s} = 27\ \text{TeV}: \quad \sigma_{tot} &= 139.9^{+1.3\%}_{-3.9\%}\ \text{fb} \\
\sqrt{s} = 100\ \text{TeV}: \quad \sigma_{tot} &= 1224^{+0.9\%}_{-3.2\%}\ \text{fb}
\end{aligned}$$

• HO corrections: dominated by universal S+V+C corrections

$\Rightarrow \sim$ rescaling of rel. m_t scale/scheme uncertainties final combined ren./fac. scale and m_t scale/scheme unc. @ NNLO$_{FTapprox}$:

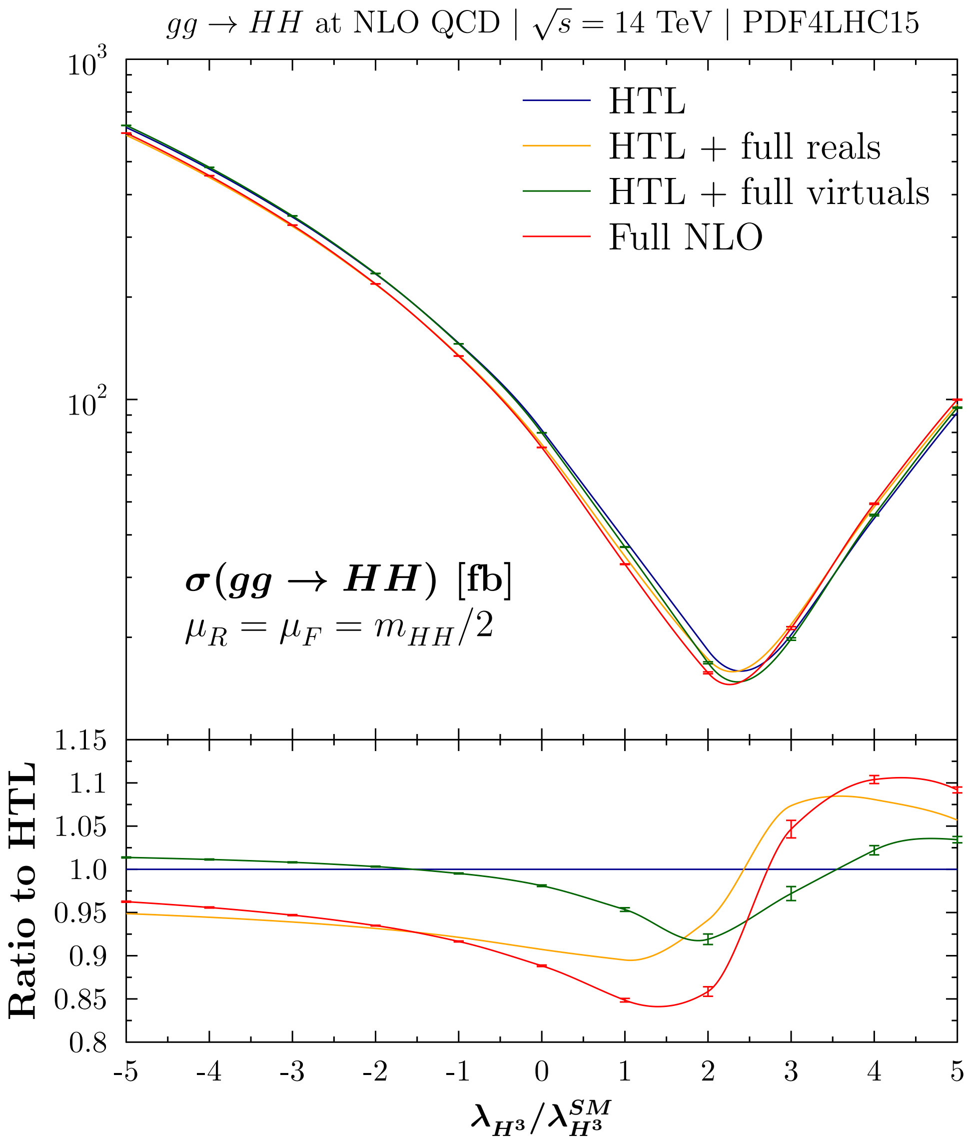
$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%} \text{ fb}$$

$$\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} = 36.69^{+6\%}_{-23\%} \text{ fb}$$

$$\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} = 139.9^{+5\%}_{-22\%} \text{ fb}$$

$$\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} = 1224^{+4\%}_{-21\%} \text{ fb}$$

λ dependence



Baglio, Campanario, Glaus, Mühlleitner, Ronca, S.

- final combined uncertainties @ $\text{NNLO}_{FTapprox}$ ($\sqrt{s} = 14$ TeV):

$$
\begin{aligned}
\kappa_\lambda = -10: &\quad \sigma_{tot} = 1680^{+13\%}_{-14\%}\ \text{fb} \\
\kappa_\lambda = -5: &\quad \sigma_{tot} = 598.9^{+13\%}_{-15\%}\ \text{fb} \\
\kappa_\lambda = -1: &\quad \sigma_{tot} = 131.9^{+11\%}_{-16\%}\ \text{fb} \\
\kappa_\lambda = 0: &\quad \sigma_{tot} = 70.38^{+8\%}_{-18\%}\ \text{fb} \\
\kappa_\lambda = 1: &\quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}\ \text{fb} \\
\kappa_\lambda = 2: &\quad \sigma_{tot} = 13.81^{+3\%}_{-28\%}\ \text{fb} \\
\kappa_\lambda = 2.4: &\quad \sigma_{tot} = 13.10^{+6\%}_{-27\%}\ \text{fb} \\
\kappa_\lambda = 3: &\quad \sigma_{tot} = 18.67^{+12\%}_{-22\%}\ \text{fb} \\
\kappa_\lambda = 5: &\quad \sigma_{tot} = 94.82^{+18\%}_{-13\%}\ \text{fb} \\
\kappa_\lambda = 10: &\quad \sigma_{tot} = 672.2^{+16\%}_{-13\%}\ \text{fb}
\end{aligned}
$$

IV CONCLUSIONS

- Higgs boson searches/studies at LHC belong to major endeavours
- important to develop NLO event generators [$\leftarrow$ backgrounds]
- scale and scheme uncertainties due to m_t relevant for large momenta
- significant uncertainties for Higgs production @ large p_T
- significant uncertainties for off-shell Higgs production and decays (heavy BSM Higgs bosons)
- Higgs pair production: m_t effects on top of LO $\sim -15\%$ for σ_{tot} [larger for distributions]
- factorization/renormalization scale uncertainties @NNLO$_{FTapprox}$ $\lesssim 5\%$
- uncertainties due to m_t scale/scheme choice sizeable $\lesssim 20\%$
  $\rightarrow$ linear combination of rel. uncertainties
- analogous issues in $gg \rightarrow H + 2jet, ZH, ZZ$ etc.

BACKUP SLIDES

- m_t scale/scheme uncertainties @ NLO:

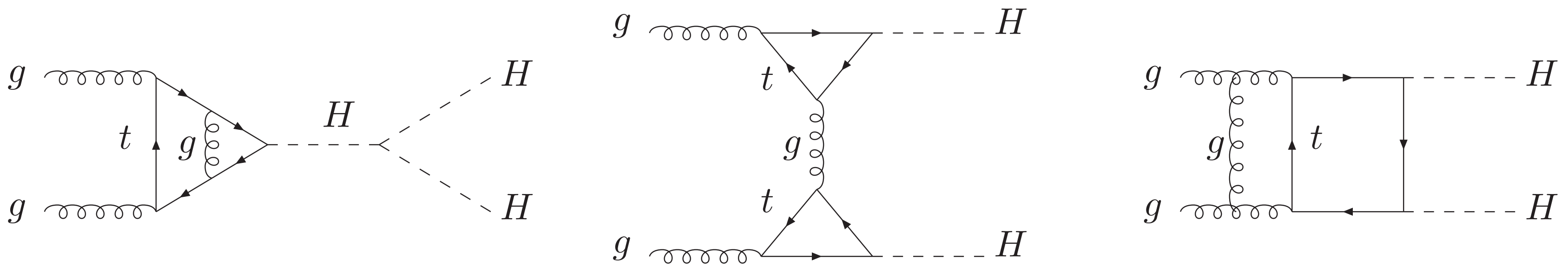
$$
\begin{aligned}
\kappa_\lambda = -10: &\quad \sigma_{tot} &= 1438(1)^{+10\%}_{-6\%} \text{ fb} \\
\kappa_\lambda = -5: &\quad \sigma_{tot} &= 512.8(3)^{+10\%}_{-7\%} \text{ fb} \\
\kappa_\lambda = -1: &\quad \sigma_{tot} &= 113.66(7)^{+8\%}_{-9\%} \text{ fb} \\
\kappa_\lambda = 0: &\quad \sigma_{tot} &= 61.22(6)^{+6\%}_{-12\%} \text{ fb} \\
\kappa_\lambda = 1: &\quad \sigma_{tot} &= 27.73(7)^{+4\%}_{-18\%} \text{ fb} \\
\kappa_\lambda = 2: &\quad \sigma_{tot} &= 13.2(1)^{+1\%}_{-23\%} \text{ fb} \\
\kappa_\lambda = 2.4: &\quad \sigma_{tot} &= 12.7(1)^{+4\%}_{-22\%} \text{ fb} \\
\kappa_\lambda = 3: &\quad \sigma_{tot} &= 17.6(1)^{+9\%}_{-15\%} \text{ fb} \\
\kappa_\lambda = 5: &\quad \sigma_{tot} &= 83.2(3)^{+13\%}_{-4\%} \text{ fb} \\
\kappa_\lambda = 10: &\quad \sigma_{tot} &= 579(1)^{+12\%}_{-4\%} \text{ fb}
\end{aligned}
$$

- renormalization/factorization scale uncertainties @ NNLO$_{FTapprox}$:

$$
\begin{aligned}
\kappa_\lambda = -10: \quad & \sigma_{tot} = 1680^{+3.0\%}_{-7.7\%} \text{ fb} \\
\kappa_\lambda = -5: \quad & \sigma_{tot} = 598.9^{+2.7\%}_{-7.5\%} \text{ fb} \\
\kappa_\lambda = -1: \quad & \sigma_{tot} = 131.9^{+2.5\%}_{-6.7\%} \text{ fb} \\
\kappa_\lambda = 0: \quad & \sigma_{tot} = 70.38^{+2.4\%}_{-6.1\%} \text{ fb} \\
\kappa_\lambda = 1: \quad & \sigma_{tot} = 31.05^{+2.2\%}_{-5.0\%} \text{ fb} \\
\kappa_\lambda = 2: \quad & \sigma_{tot} = 13.81^{+2.1\%}_{-4.9\%} \text{ fb} \\
\kappa_\lambda = 2.4: \quad & \sigma_{tot} = 13.10^{+2.3\%}_{-5.1\%} \text{ fb} \\
\kappa_\lambda = 3: \quad & \sigma_{tot} = 18.67^{+2.7\%}_{-7.3\%} \text{ fb} \\
\kappa_\lambda = 5: \quad & \sigma_{tot} = 94.82^{+4.9\%}_{-8.8\%} \text{ fb} \\
\kappa_\lambda = 10: \quad & \sigma_{tot} = 672.2^{+4.2\%}_{-8.5\%} \text{ fb}
\end{aligned}
$$

(i) virtual corrections

47 gen. box diags, 8 triangle diags ($\leftarrow$ single Higgs), 1PR ($\leftarrow H \to Z\gamma$)



- full diagram w/o tensor reduction $\to$ 6-dim. Feynman integral (2 FF)
- UV-singularities: end-point subtractions

$$\int_0^1 dx\, \frac{f(x)}{(1-x)^{1-\epsilon}} = \int_0^1 dx\, \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx\, \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx\, \frac{f(x)-f(1)}{1-x} + \mathcal{O}(\epsilon)$$

- IR-sing.: IR-subtraction (based on struc. of integr. and rel. to HTL)
- thresholds: $Q^2 \geq 0, 4m_t^2 \to$ IBP $\to$ reduction of power of denominator $[m_t^2 \to m_t^2(1-ih)]$

$$\int_0^1 dx\, \frac{f(x)}{(a+bx)^3} = \frac{f(0)}{2a^2b} - \frac{f(1)}{2b(a+b)^2} + \int_0^1 dx \frac{f'(x)}{2b(a+bx)^2}$$

- renormalization: α_s: $\overline{\text{MS}}$, 5 flavours
  m_t: on-shell

- PS-integration $\to$ 7-dim. integrals for $d\sigma/dQ^2$

- subtraction of HTL $\to$ IR-finite mass effects [adding back HTL results $\leftarrow$ HPAIR]

- extrapolation to NWA ($h \to 0$): Richardson extrapolation

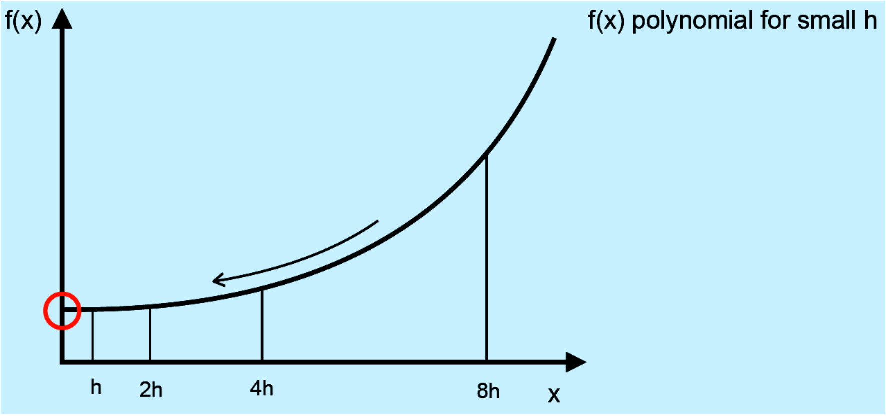
$M_2 = 2f(h) - f(2h) = f(0) + \mathcal{O}(h^2)$

$M_4 = \{8f(h) - 6f(2h) + f(4h)\}/3 = f(0) + \mathcal{O}(h^3)$

$M_8 = \{64f(h) - 56f(2h) + 14f(4h) - f(8h)\}/21 = f(0) + \mathcal{O}(h^4)$

etc.

[$h \geq 0.05$]



(ii) real corrections

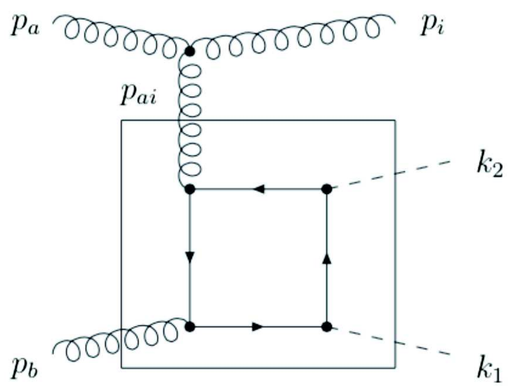
- full matrix elements generated with FeynArts and FormCalc

- matrix elements in HTL involving full LO sub-matrix elements subtracted → IR-, COLL-finite [adding back HTL results ← HPAIR]

$$\sum \overline{|\mathcal{M}_{gg}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{24\pi^2}{Q^4}\frac{\alpha_s}{\pi}\left\{\frac{s^4+t^4+u^4+Q^8}{stu} - 4\frac{\epsilon}{1-\epsilon}Q^2\right\}$$

$$\sum \overline{|\mathcal{M}_{gq}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{32\pi^2}{3Q^4}\frac{\alpha_s}{\pi}\left\{\frac{s^2+u^2}{-t} + \epsilon\frac{(s+u)^2}{t}\right\}$$

$$\sum \overline{\left|\mathcal{M}_{q\bar{q}}\right|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{256\pi^2}{9Q^4}\frac{\alpha_s}{\pi}(1-\epsilon)\left\{\frac{t^2+u^2}{s} - \epsilon\frac{(t+u)^2}{s}\right\}$$



$$\begin{aligned} F_i &= F_{i,LO} + \Delta F_i \\ \Delta F_i &= \Delta F_{i,HTL} + \Delta F_{i,mass} \end{aligned}$$

- pole mass:

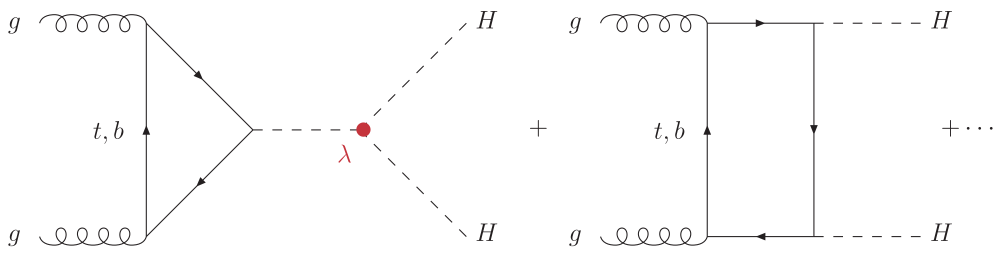
$$\begin{aligned} F_{1,LO} &\to 4\frac{m_t^2}{\hat{s}} \\ F_{2,LO} &\to -\frac{m_t^2}{\hat{s}\hat{t}(\hat{s}+\hat{t})}\{(\hat{s}+\hat{t})^2 L_{1ts}^2 + \hat{t}^2 L_{ts}^2 + \pi^2[(\hat{s}+\hat{t})^2 + \hat{t}^2]\} \end{aligned}$$

- $\overline{\text{MS}}$ mass:

$$\begin{aligned} F_{1,LO} &\to 4\frac{\overline{m}_t^2(\mu_t)}{\hat{s}} \\ F_{2,LO} &\to -\frac{\overline{m}_t^2(\mu_t)}{\hat{s}\hat{t}(\hat{s}+\hat{t})}\{(\hat{s}+\hat{t})^2 L_{1ts}^2 + \hat{t}^2 L_{ts}^2 + \pi^2[(\hat{s}+\hat{t})^2 + \hat{t}^2]\} \end{aligned}$$

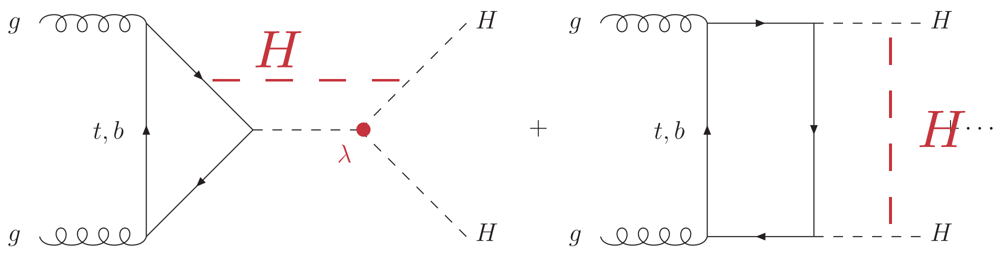
- different scales for y_t in triangle (Q) and box (M_H) diagrams?

$\longrightarrow$ has to hold at all orders



• different scales for y_t in triangle (Q) and box (M_H) diagrams?

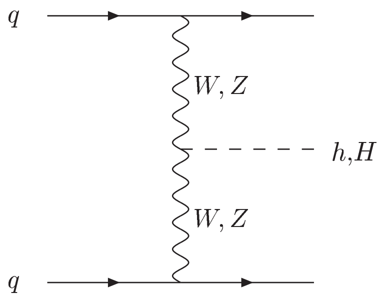
$\longrightarrow$ has to hold at all orders



elw. corrections

$\Rightarrow$ same scales in all diagrams

(ii) W/Z fusion: $pp \to W^*W^*/Z^*Z^* \to h/H$



Cahn, Dawson
Hikasa
Atarelli, Mele, Pitolli

Han, Valencia, Willenbrock
Figy, Oleari, Zeppenfeld
Berger, Campbell

- QCD corrections $\leftarrow$ DIS: $\sim 10\%$

[approx] 2–loop: $\lesssim 1\%$ — Bolzano, Maltoni, Moch, Zaro; Cacciari, Dreyer, Karlberg, Salam, Zanderighi

[approx] 3–loop: $\lesssim 0.3\%$ — Dreyer, Karlberg

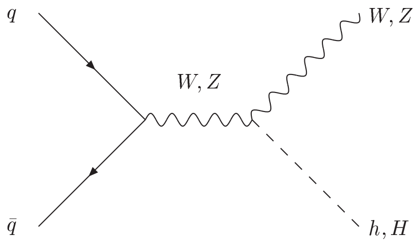
- elw. corrections: $\sim 10\%$ — Ciccolini, Denner, Dittmaier

- genuine SUSY-QCD corrections small — Djouadi, S.

- genuine SUSY-elw. corrections: $\lesssim 5\%$ — Hollik, Rzehak, Plehn, Rauch; Figy, Palmer, Weiglein

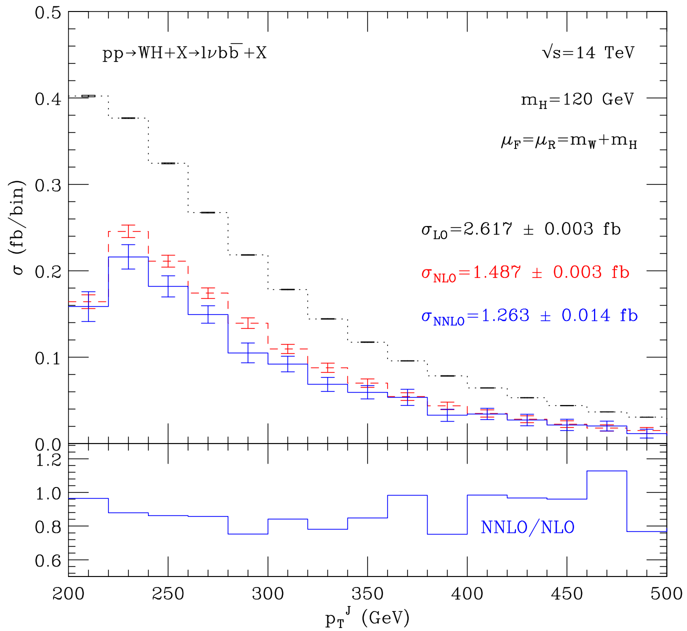
  [implemented in VBFNLO]

(iii) Higgs–strahlung: $pp \to W^*/Z^* \to W/Z + h/H$

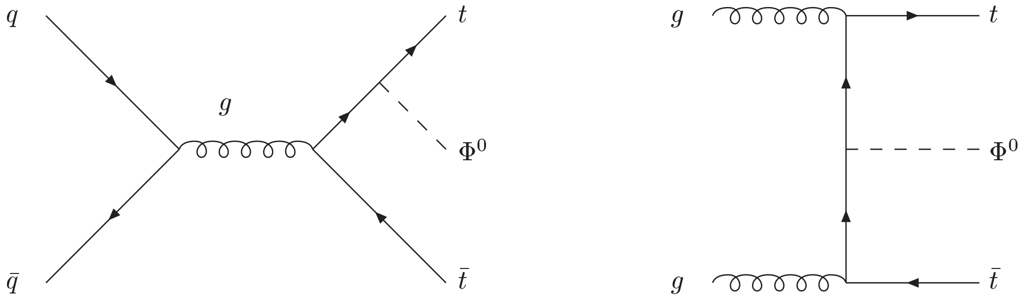


Glashow,. . .
Kunszt,. . .

- QCD corrections ← DY: $\sim 30\%$ — Han, Willenbrock
  2–loop: $\lesssim 5\%$ — Brein, Djouadi, Harlander
- SUSY-QCD corrections small — Djouadi, S.
- electroweak corrections: $\sim -10\%$ — Ciccolini, Dittmaier, Krämer
- $W/Z + H$: fully exclusive @ NNLO QCD — Ferrera, Grazzini, Tramantano



(iv) Bremsstrahlung: $pp \to t\bar{t} + h/H/A$



Kunszt
Gunion
Marciano, Paige

dominant

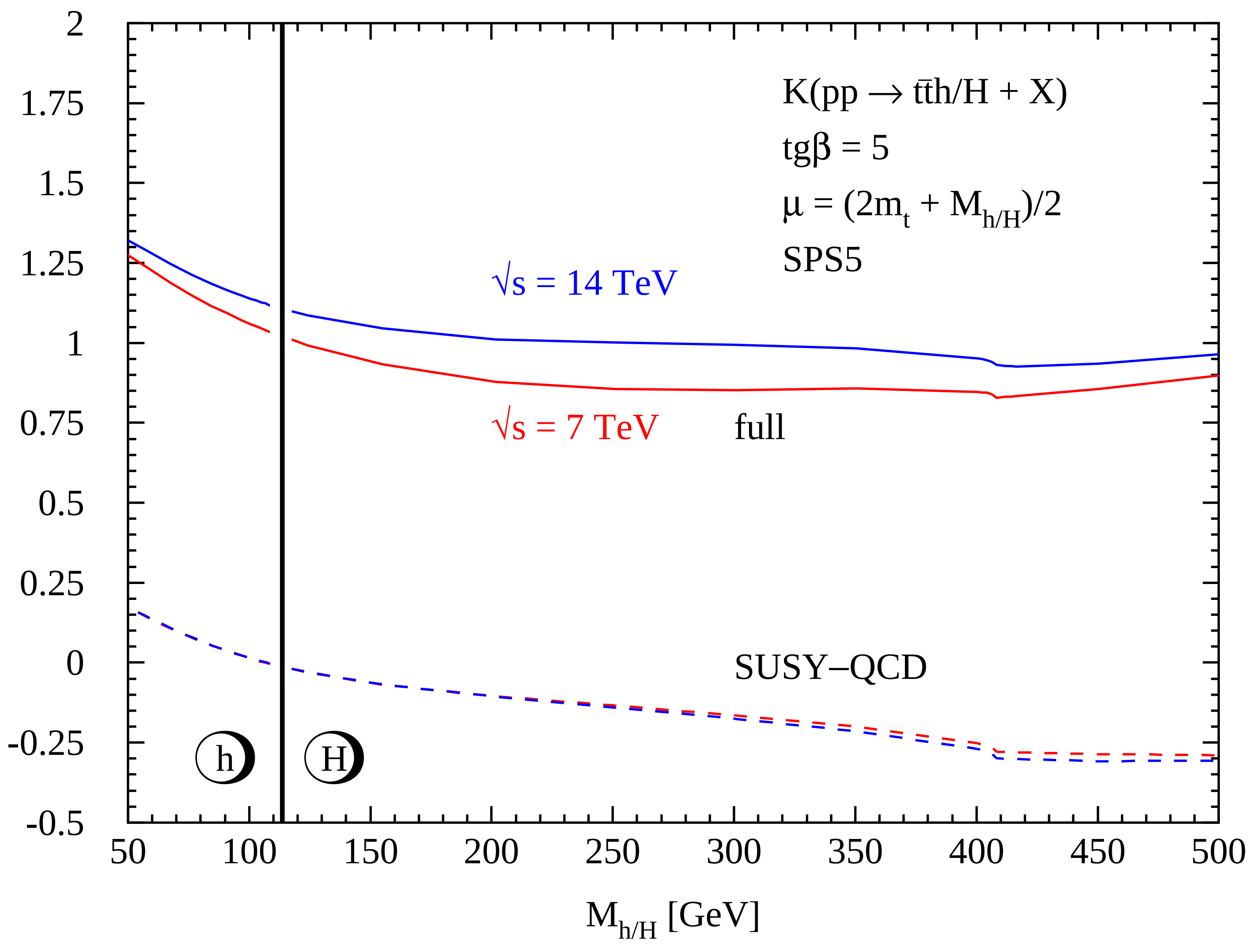
- $t\bar{t}h \to t\bar{t}b\bar{b}$ important @ LHC $\to$ top Yukawa cplg.

- QCD corrections [SM]: $\sim 20\%$ [threshold suppressed: $\sigma_{LO} \sim \beta^4$]
  Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas
  Dawson, Orr, Reina, Wackeroth
  Broggio, Ferroglia, Pecjak, Signer, Yang

- SUSY-QCD corrections: moderate
  Dittmaier, Häfliger, Krämer, S., Walser

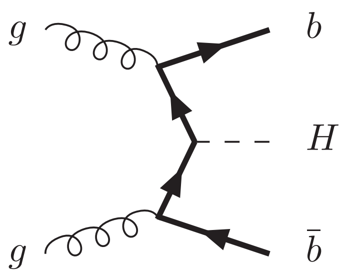
- link to parton showers: aMC@NLO, PowHel
  Frederix et al.
  Garzelli, Kardos, Papadopoulos, Trócsányi

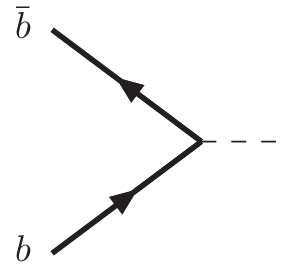
- important work on backgrounds $t\bar{t}b\bar{b}, t\bar{t}jj$, etc.
  Bredenstein, Denner, Dittmaier, Pozzorini
  Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
  Cascioli, Maierhofer, Pozzorini



Dittmaier, Häfliger, Krämer, S., Walser

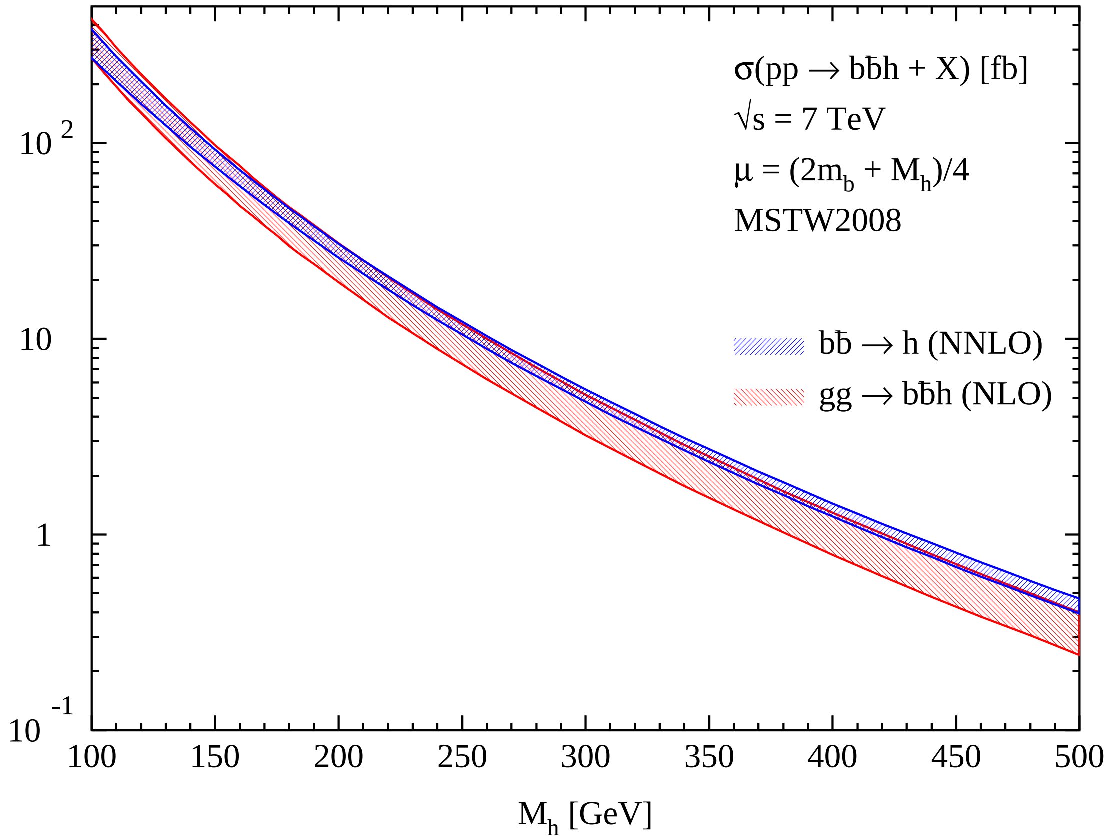
(v) $b\bar{b}$+Higgs production





$[\leftarrow \Delta_b]$

NLO	NNLO
exact $g \to b\bar{b}$ splitting & mass/off-shell effects	massless/on-shell b's, no p_{Tb}
no resummation of $\log M_H^2/m_b^2$ terms	resummation of $\log M_H^2/m_b^2$ terms



Santander matching:

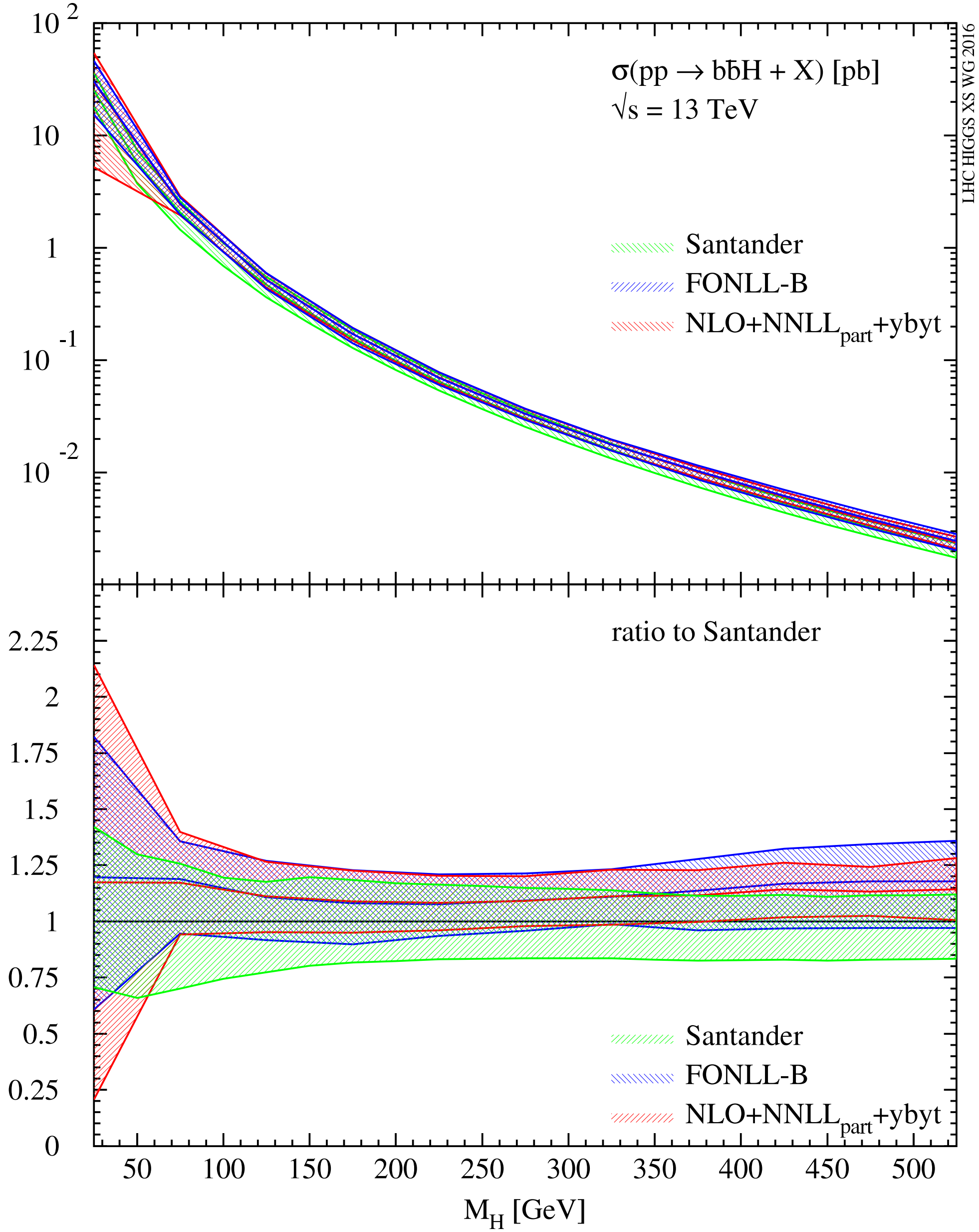
$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1 + w}$$

$$w = \log \frac{M_H}{m_b} - 2$$

Harlander, Krämer, Schumacher

Dittmaier, Krämer, S.
Dawson, Jackson, Reina, Wackeroth
Harlander, Kilgore

matching



Bonvini, Papanastasiou, Tackmann

Forte, Napoletano, Ubiali