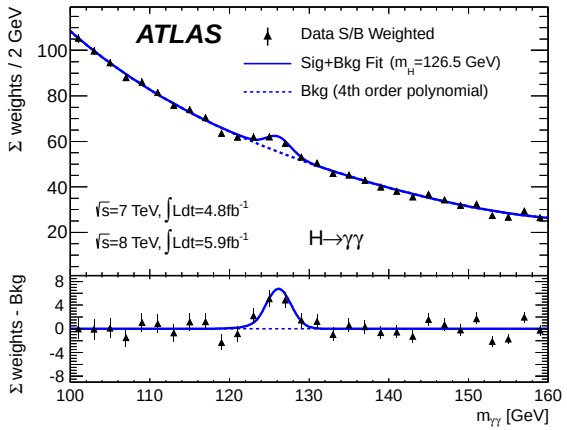
PAUL SCHERRER INSTITUT

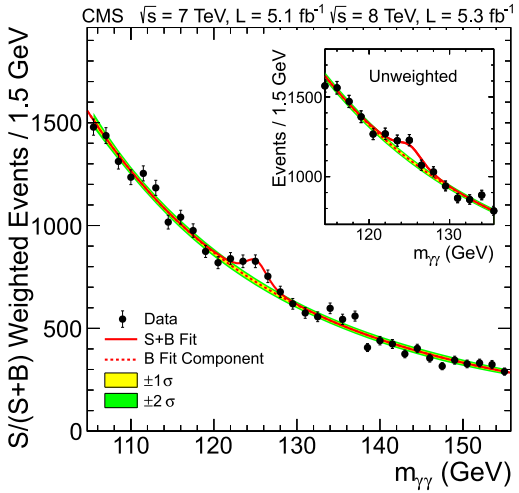
SM HH THEORY OVERVIEW

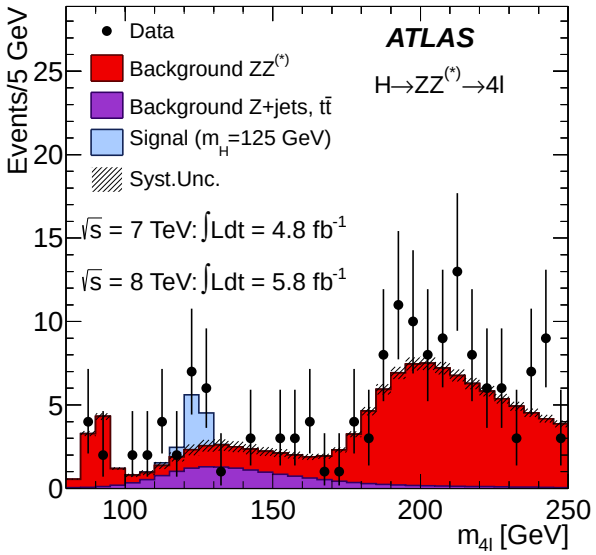
Michael Spira (PSI)

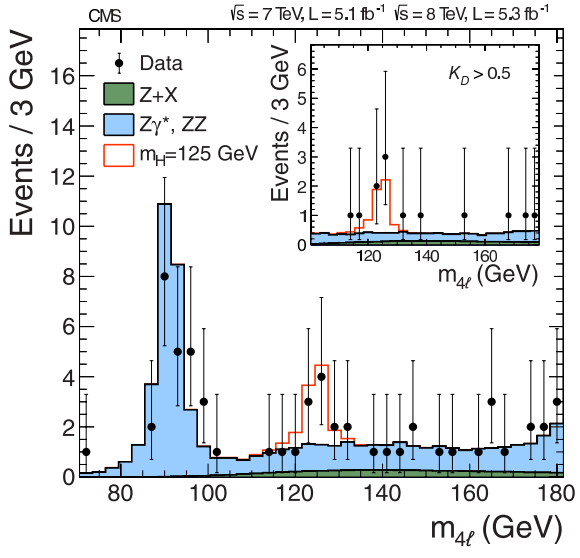
Standard Model

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

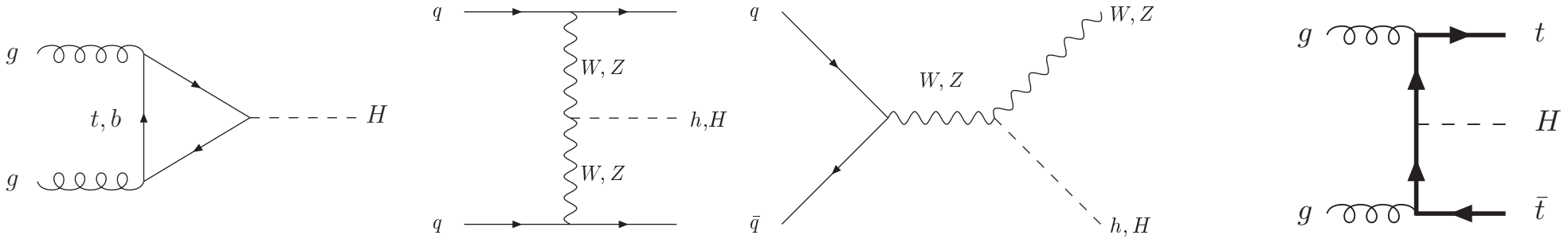


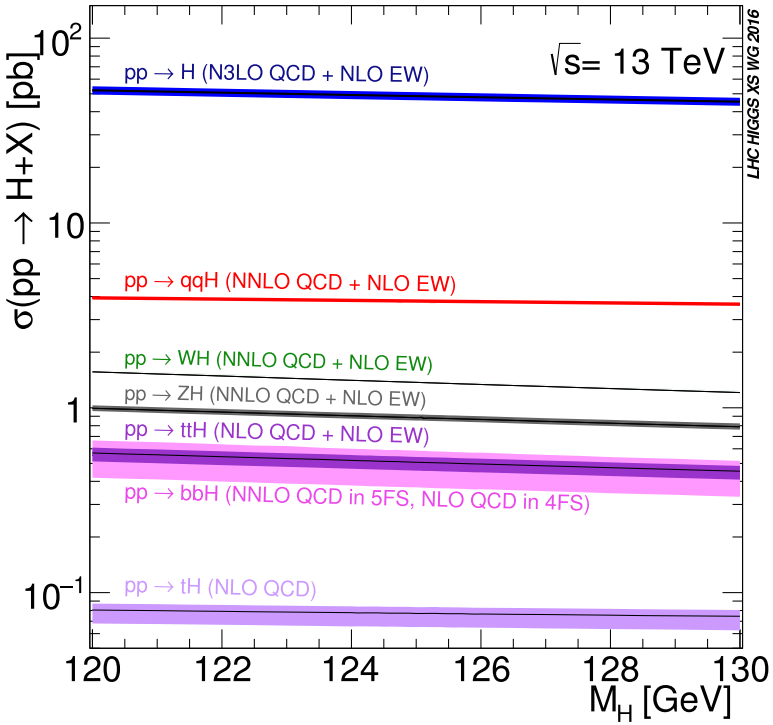


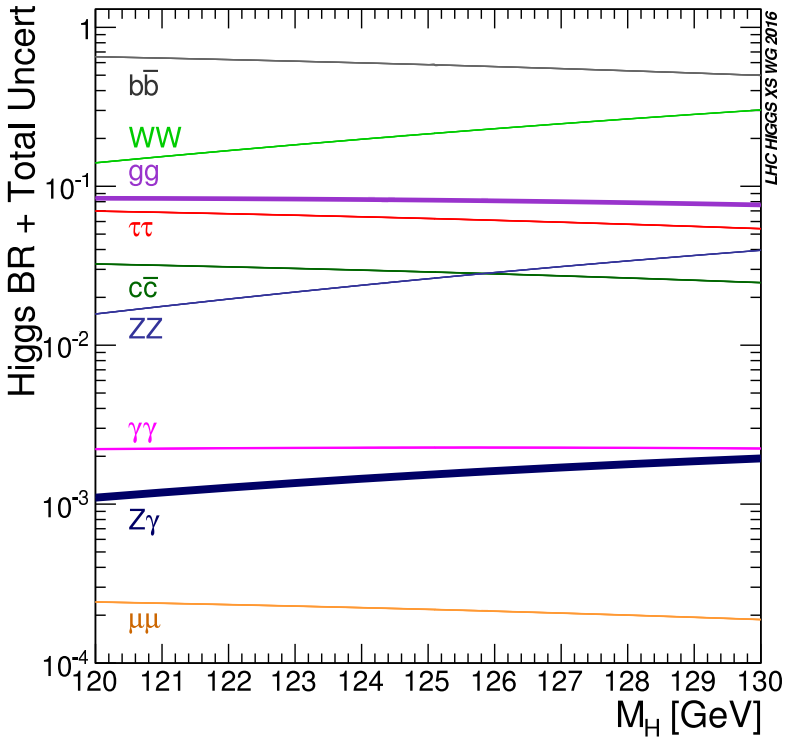




- Higgs Boson Production & Decay

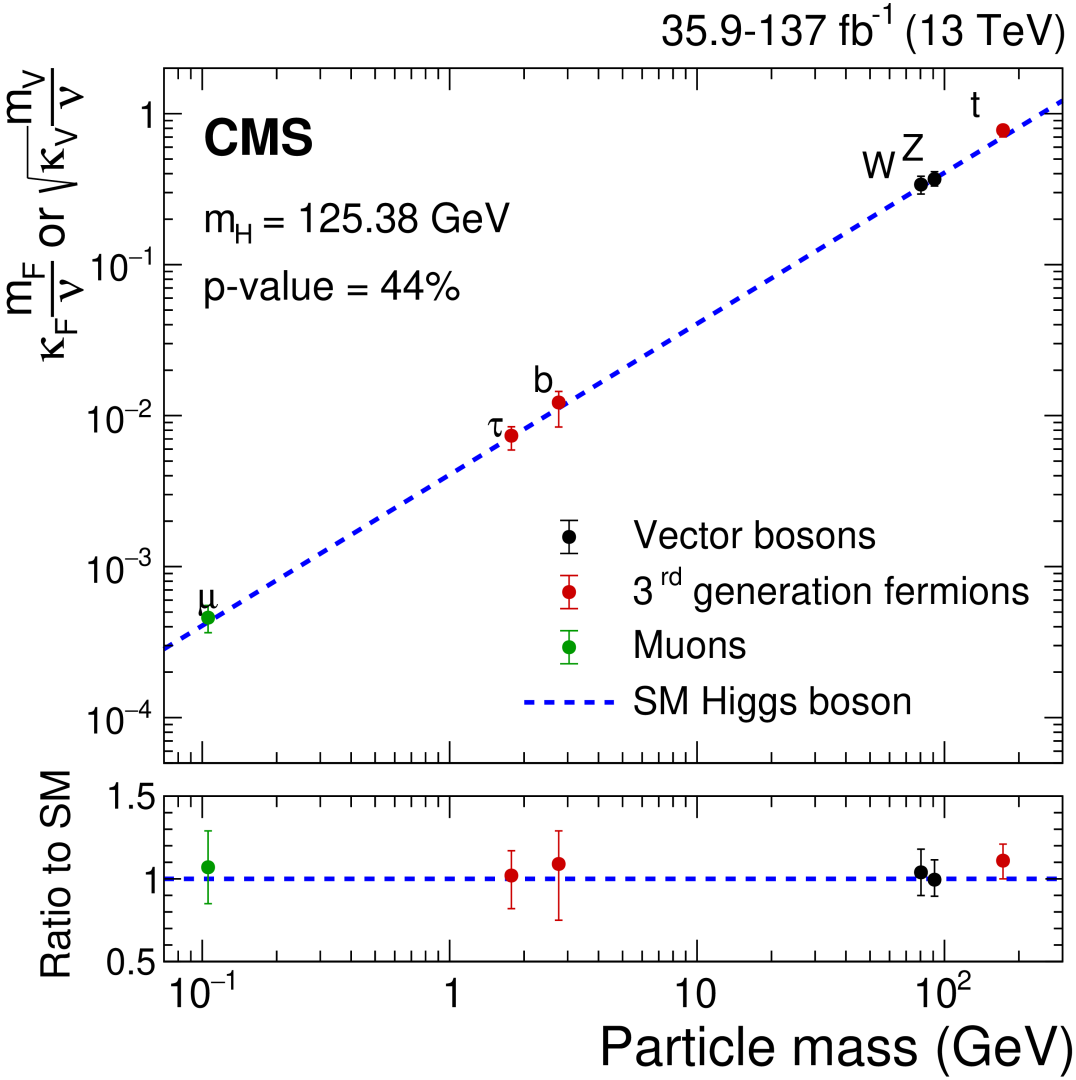




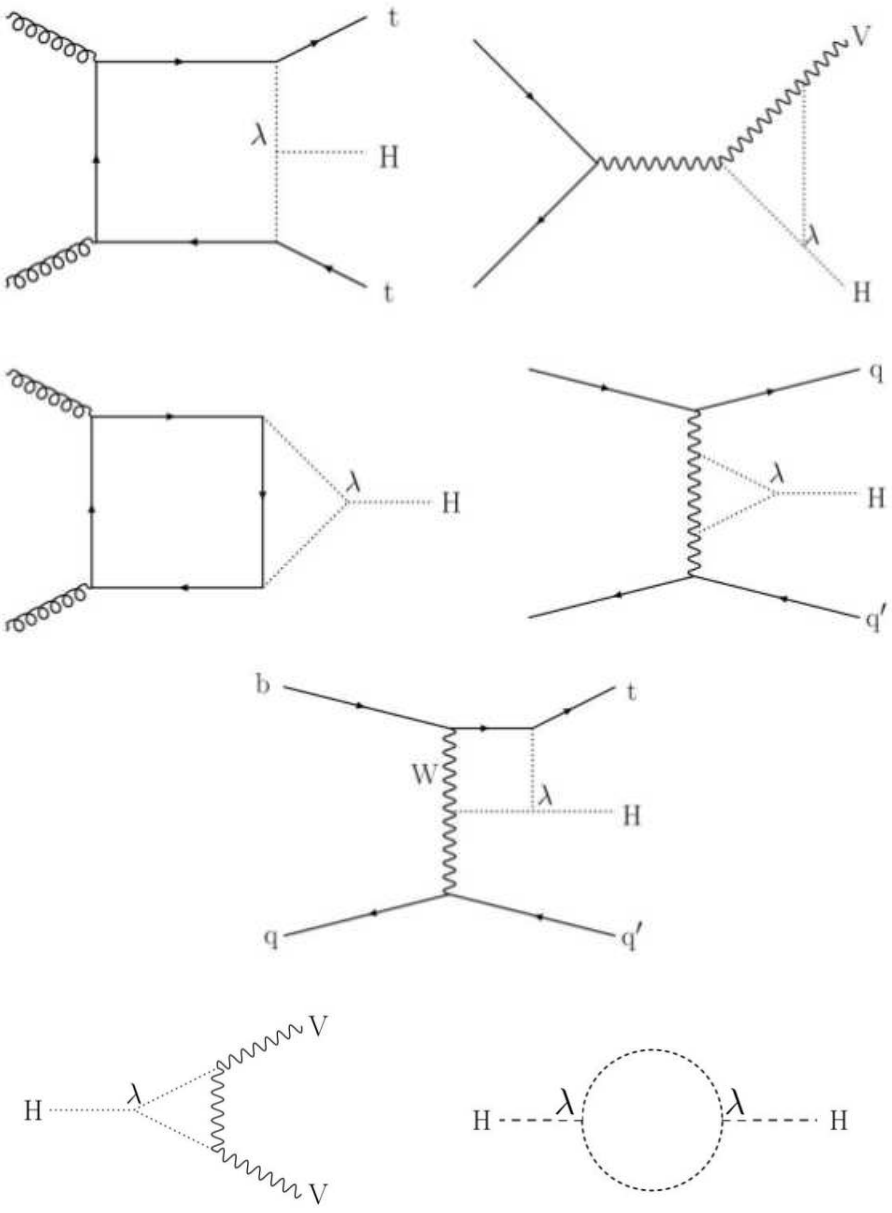


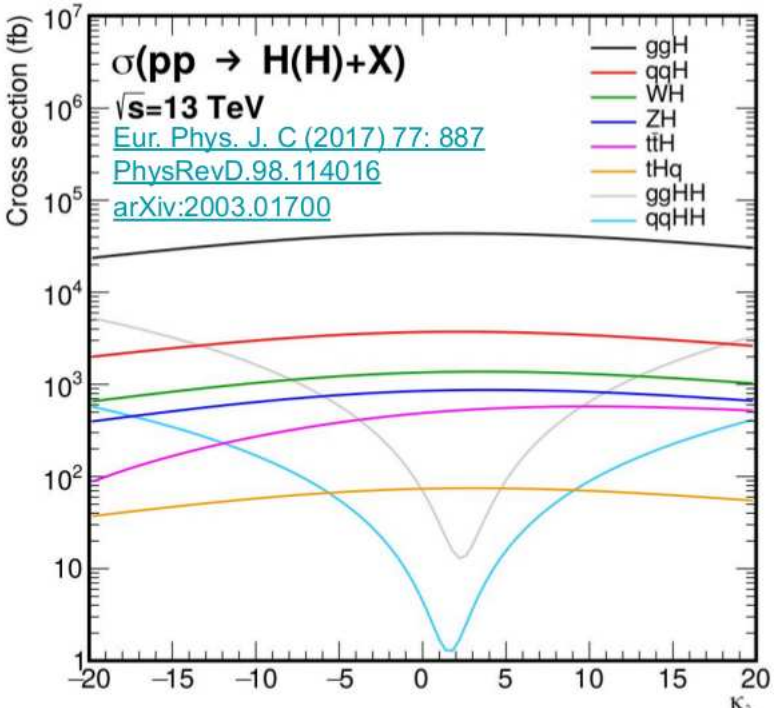
LHC Higgs XS WG

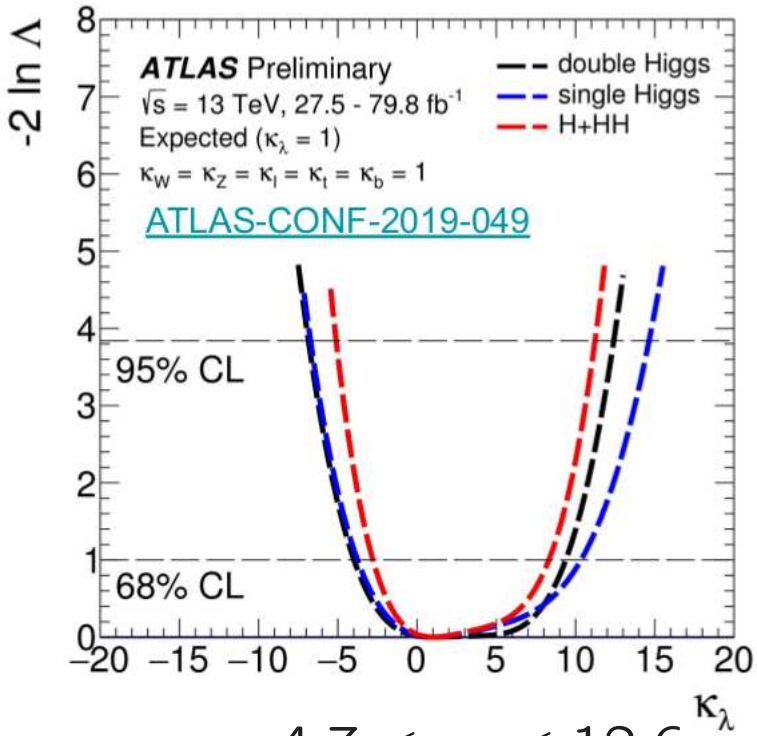
- Discovery: LHC [Tevatron]
  → Higgs mass
  couplings
  spin
  $\mathcal{CP}$
  λ ?



- indirect effects:

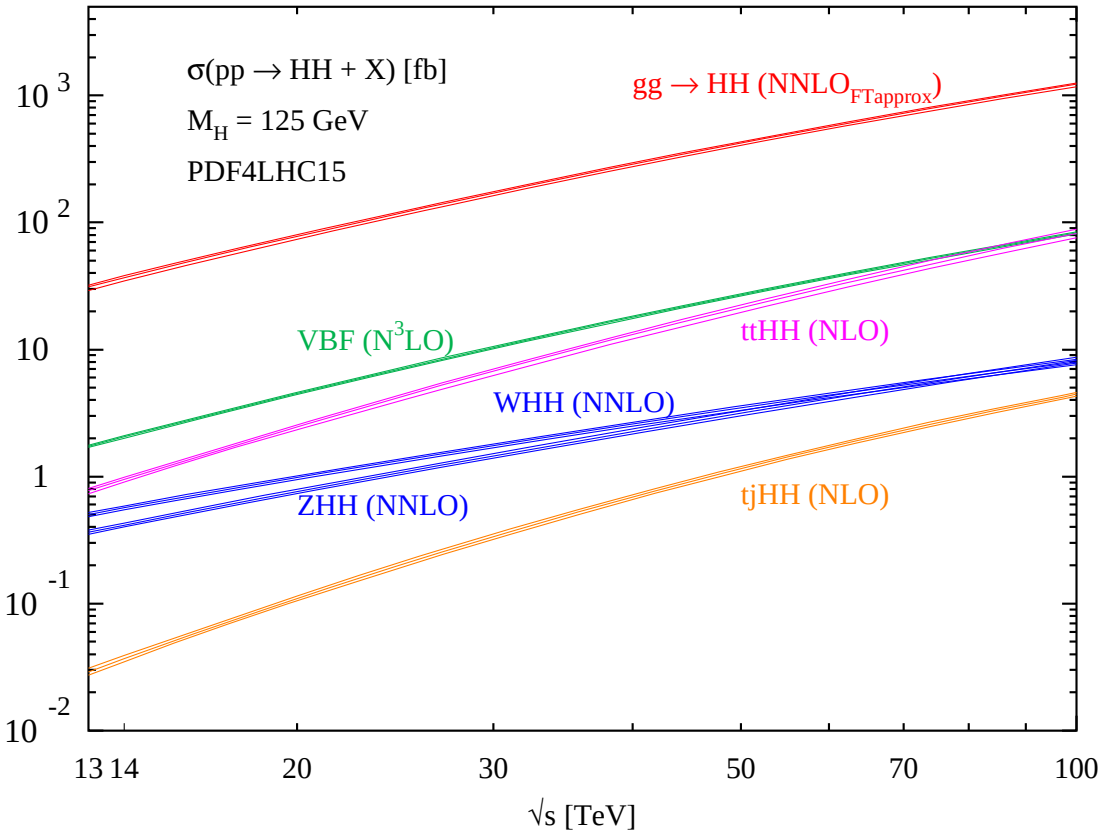


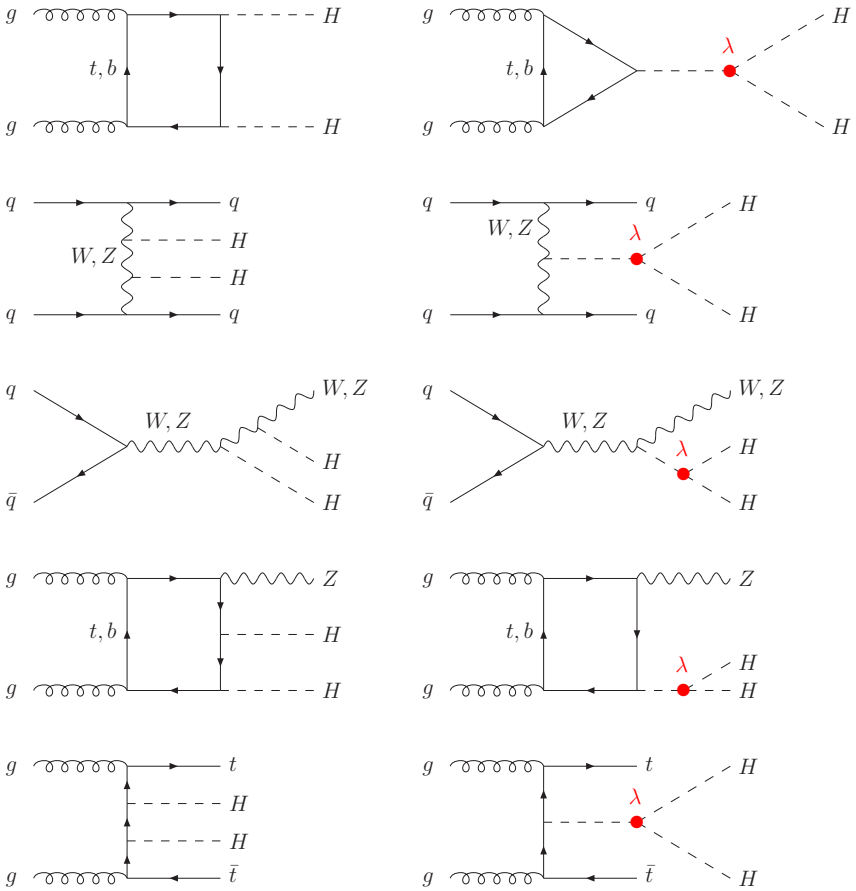




$-4.7 < \kappa_\lambda < 12.6$

II HIGGS PAIR PRODUCTION

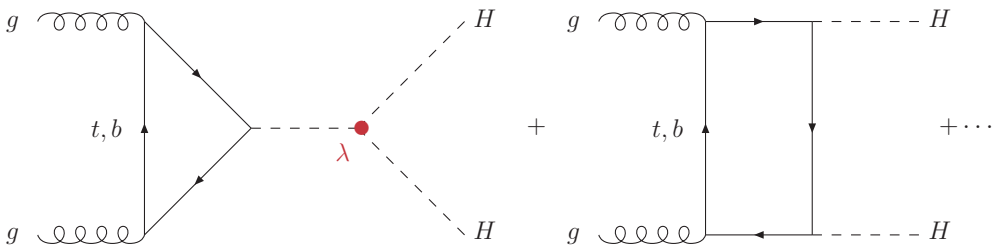




HH White Paper

(i) $gg \to HH$

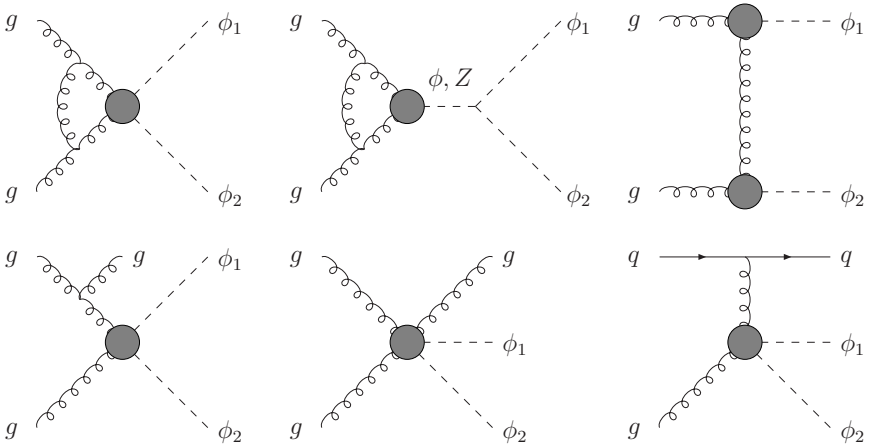
SM

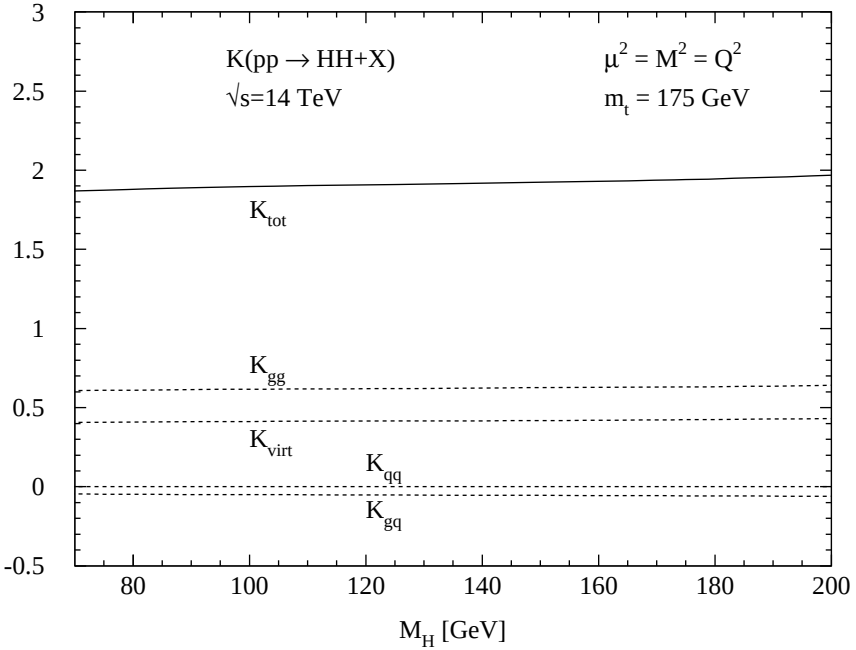


- third generation dominant $\longrightarrow t, b$

- 2-loop QCD corrections: $\sim 90 - 100\%$

  $[M_H^2 \ll 4m_t^2, \qquad \mu = M_{HH}]$





Dawson, Dittmaier, S.

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

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

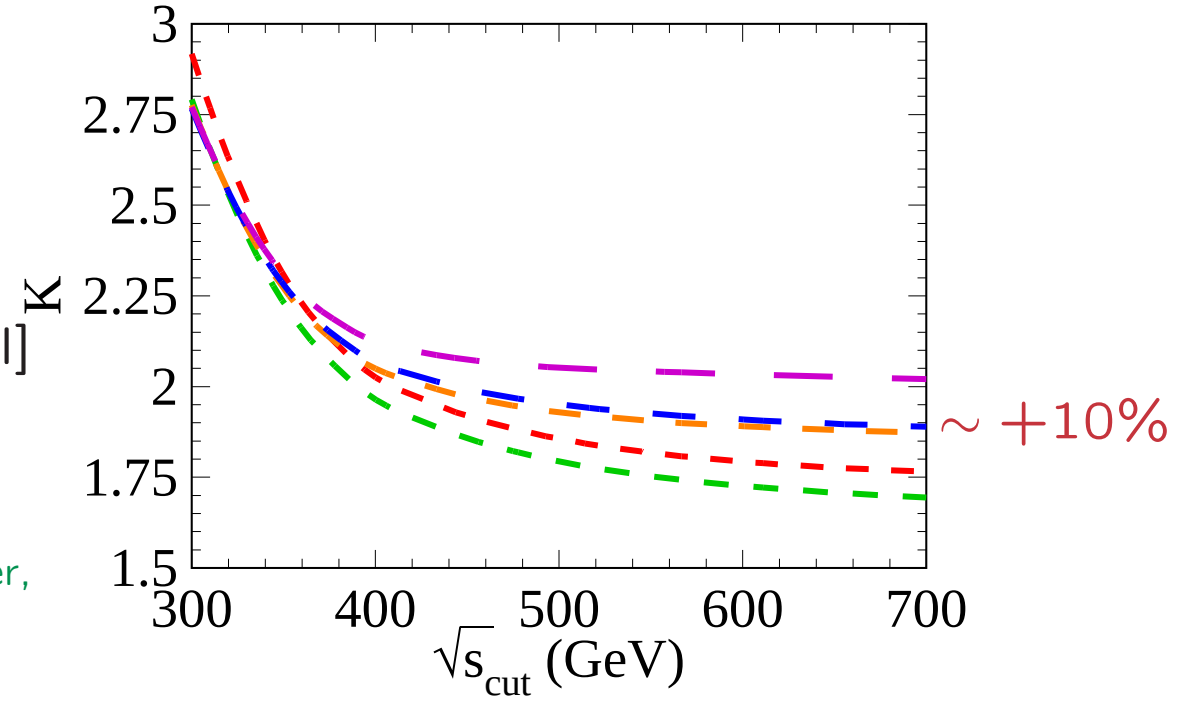
$$C \to \pi^2 + \frac{11}{2} + C_{\triangle\triangle}, \quad d_{gg} \to -\frac{11}{2}(1-z)^3, \quad d_{gq} \to \frac{2}{3}z^2 - (1-z)^2, \quad d_{q\bar{q}} \to \frac{32}{27}(1-z)^3$$

- 2-loop QCD corrections:

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

Grigo, Hoff, Melnikov, Steinhauser

[refinement: full LO at diff. level]



- mass effects @ NLO in

  real corrections: $\sim -10\%$

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

  $\longrightarrow$ 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: $\sim 10\%$

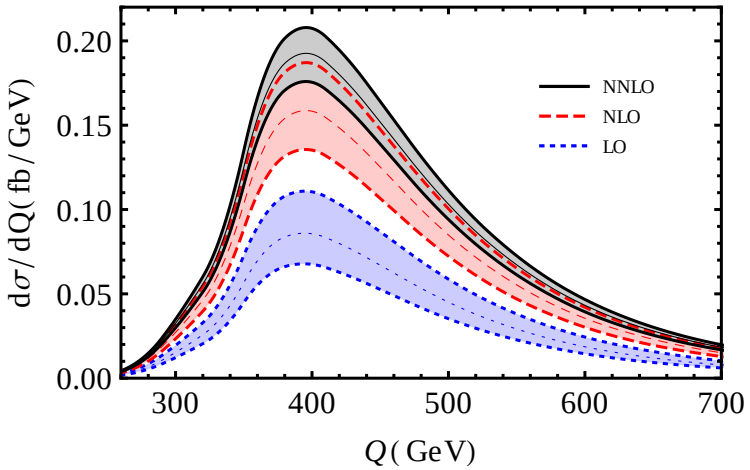
  $[M_H^2 \ll 4m_t^2]$ Shao, Li, Li, Wang; de Florian, Mazzitelli

- N^{3}LO QCD corrections: $\lesssim 3\%$

  $[M_H^2 \ll 4m_t^2]$ Chen, Li, Shao, Wang

- NLO: small quark mass expansion

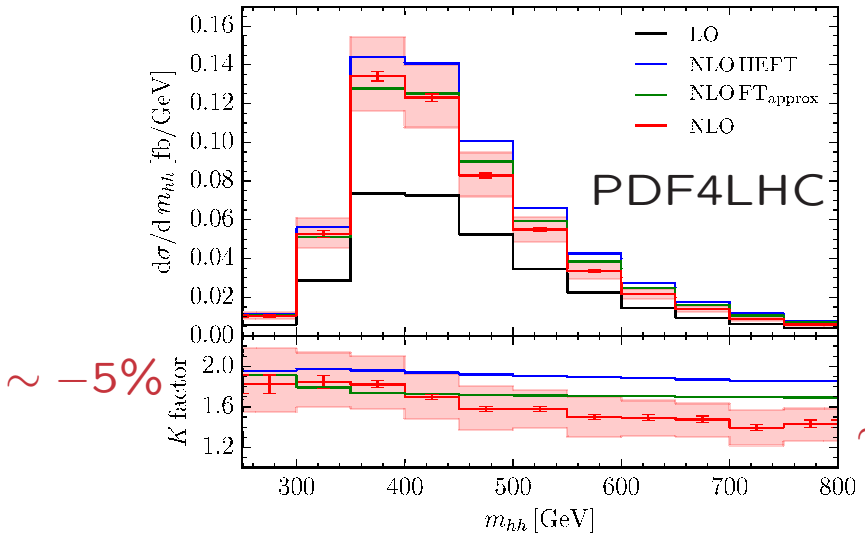
  $[Q^2 \gg m_t^2]$



Davies, Mishima, Steinhauser, Wellmann

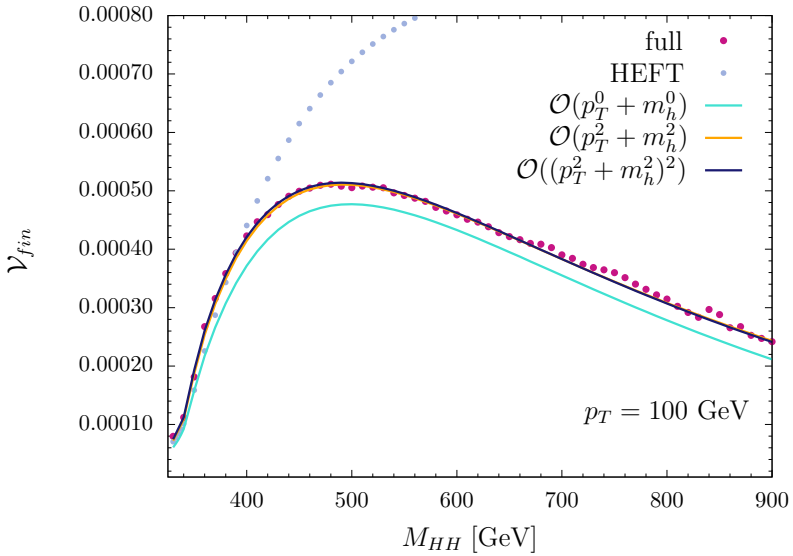
Full NLO calculation: top only $[\mu_R = \mu_F = M_{HH}/2]$

Numerical integration, sector decomposition, tensor reduction, contour deformation



$\sim -5\%$ $\sim -20\%$

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



Bonciani, Degrassi, Giardino, Gröber

- 14 TeV: $(m_t = 173$ GeV$)$ $\sigma_{NLO} = 32.91(10)^{+13.8\%}_{-12.8\%}\ fb$

$\sigma^{HTL}_{NLO} = 38.75^{+18\%}_{-15\%}\ fb$ ($\leftarrow$ HPAIR)

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

- new expansion/extrapolation methods:

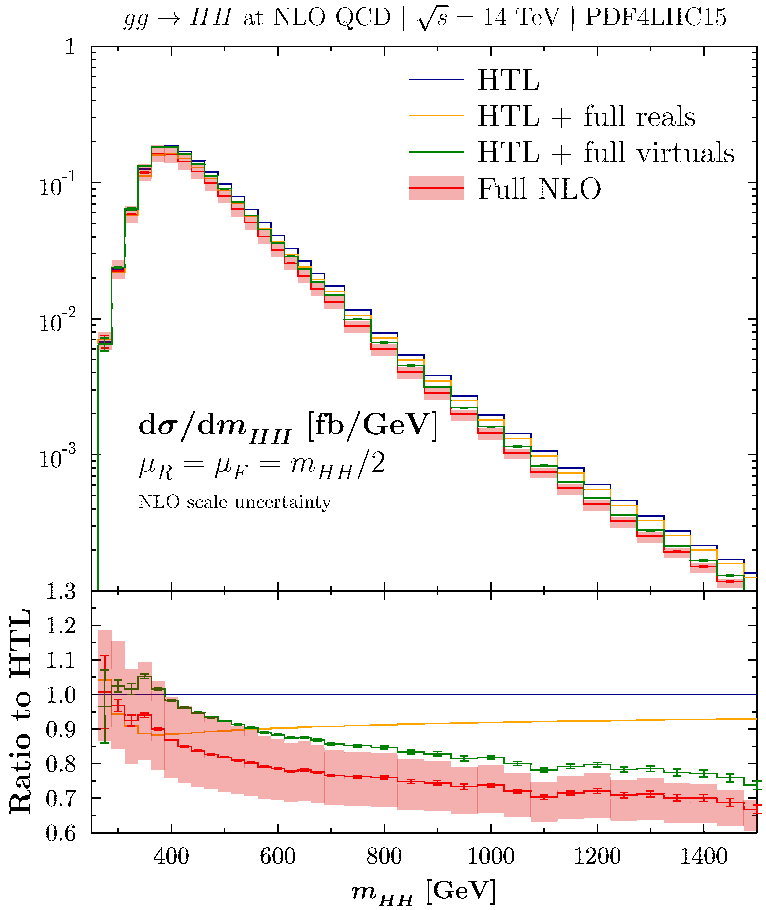
(i) $1/m_t^2$ + thresh. expansion + conformal mapping + Padé approx.

Gröber, Maier, Rauh

(ii) M_T^2 expansion

Bonciani, Degrassi, Giardino, Gröber

Full NLO calculation: top only $[\mu_R = \mu_F = M_{HH}/2]$
Numerical integration, IR subtraction, no tensor reduction, Richardson extrapolation



$\sim -5\%$

$\sim -30\%$

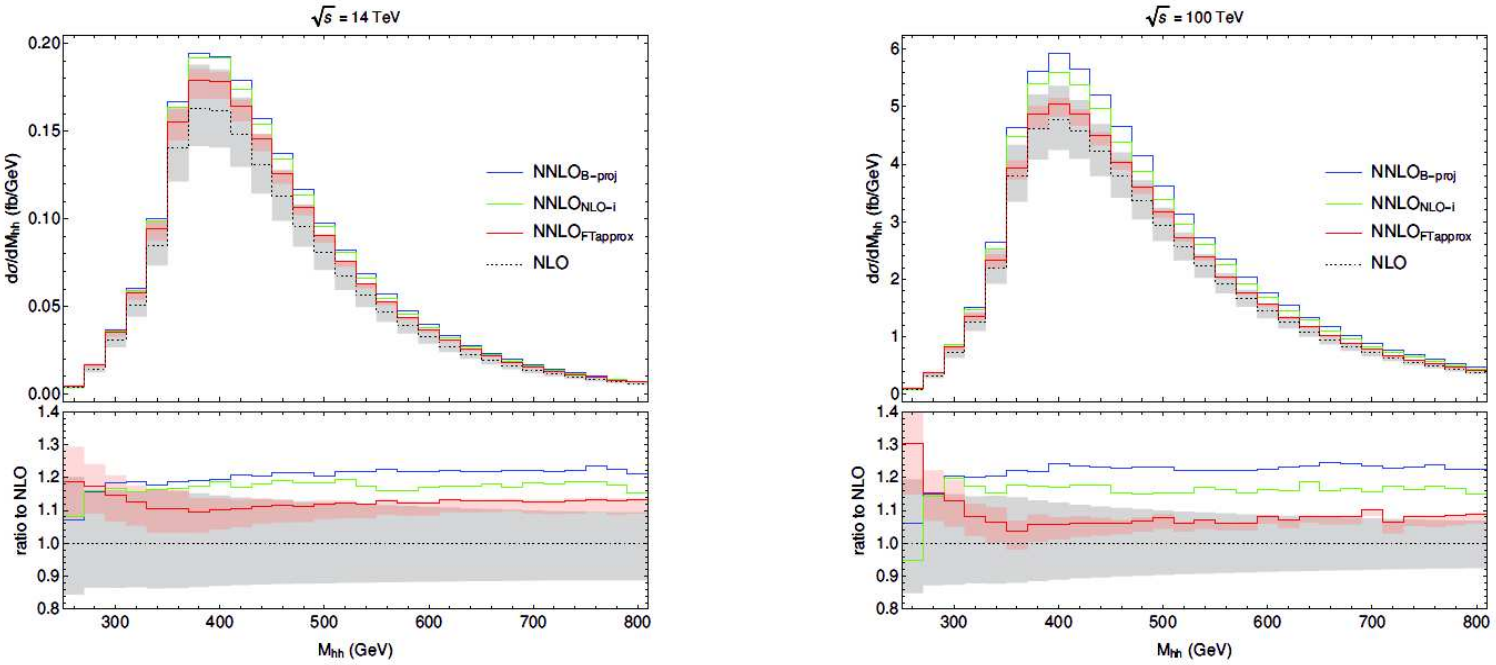
Baglio, Campanario, Glaus, Mühlleitner, S., Streicher

- 14 TeV: $(m_t = 172.5$ GeV$)$ $\sigma_{NLO} = 32.81(7)^{+13.5\%}_{-12.5\%}\ fb$

$\sigma^{HTL}_{NLO} = 38.66^{+18\%}_{-15\%}\ fb$ ($\leftarrow$ HPAIR)

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

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



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

$\Rightarrow$ 20% effects beyond NLO

- NLO: matching to parton showers Heinrich, Jones, Kerner, Luisoni, Vryonidou

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

uncertainties due to m_t

- transform $m_t \to \overline{m}_t(\mu)$ ($\overline{\text{MS}}$)

  $\to$ modification of mass CT

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

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

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

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

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

- bin-by-bin interpolation:

$$\sigma(gg \to HH) = 32.81(7)^{+4\%}_{-18\%}\ \text{fb}$$

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

← Davies, Mishima, Steinhauser, Wellmann

pole mass m_t:

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

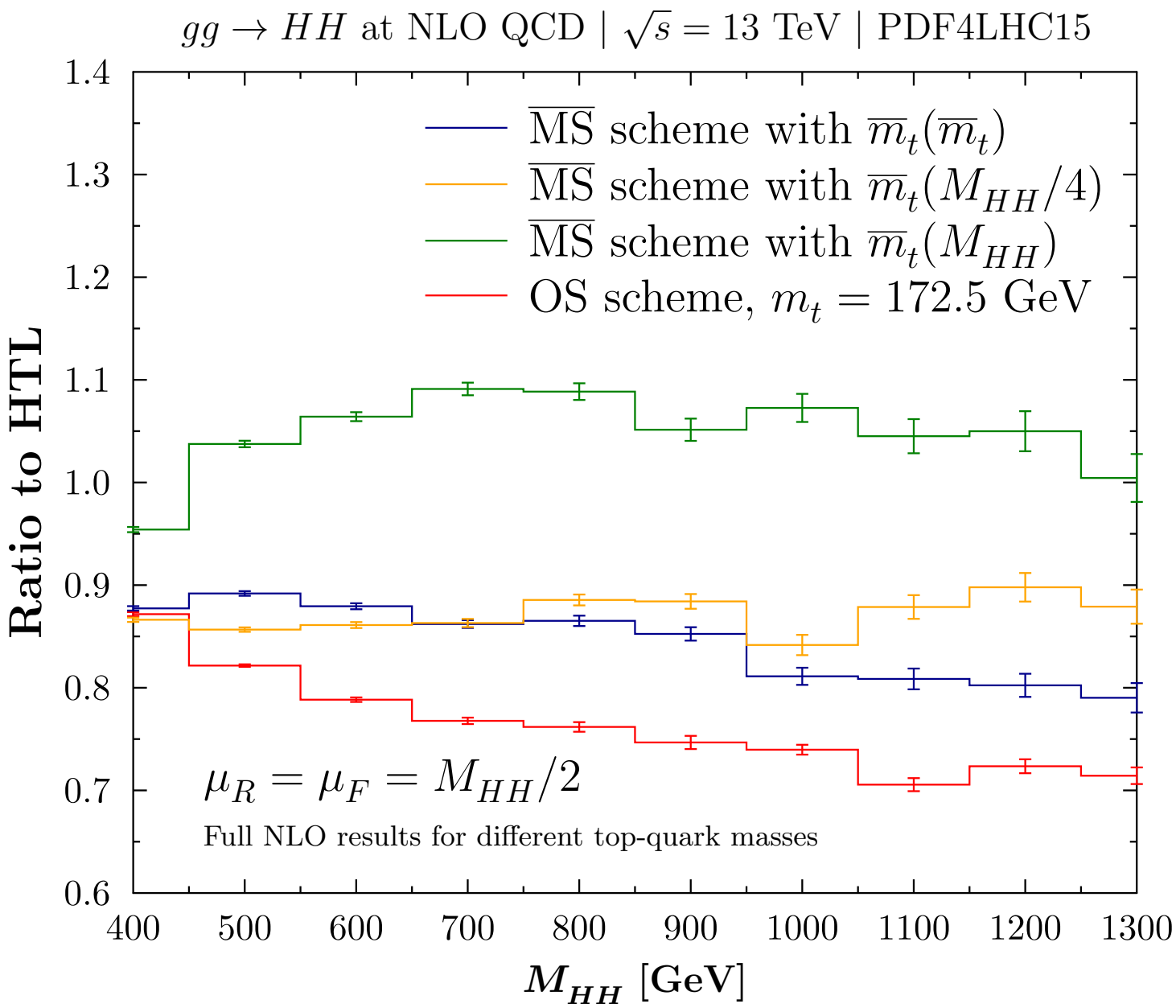
$$\Delta F_{2,mass} \rightarrow \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

$\overline{\text{MS}}$ mass $\overline{m}_t(\mu_t)$:

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

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

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



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

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

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

- 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 $\rightarrow \sim$ linear sum (rel. err.)

• combined ren./fac. scale and m_t scale/scheme unc. @ NNLO$_{FTapprox}$:

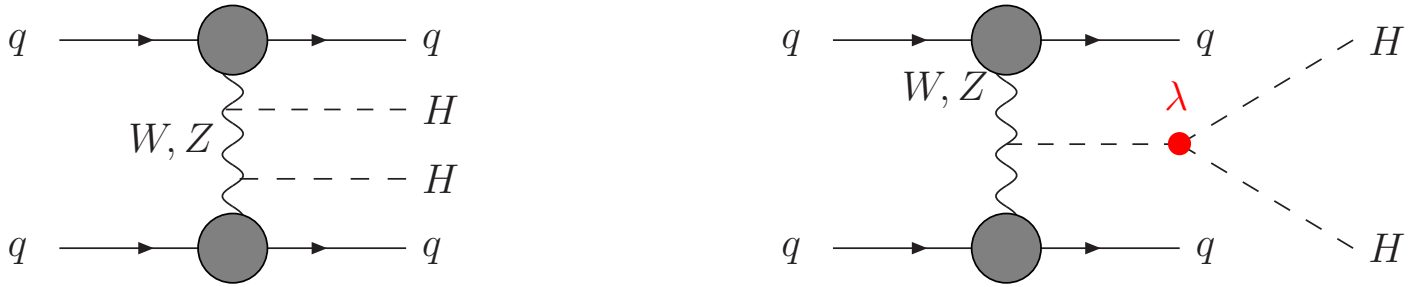
$$\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} &= 31.05^{+6\%}_{-23\%} \text{ fb} \\
\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} &= 36.69^{+6\%}_{-23\%} \text{ fb} \\
\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} &= 139.9^{+5\%}_{-22\%} \text{ fb} \\
\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} &= 1224^{+4\%}_{-21\%} \text{ fb}
\end{aligned}$$

$[\mu_R = \mu_F = M_{HH}/2]$

- combined uncertainties @ NNLO$_{FTapprox}$ [$\mu_R = \mu_F = M_{HH}/2$]:

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

(ii) VBF



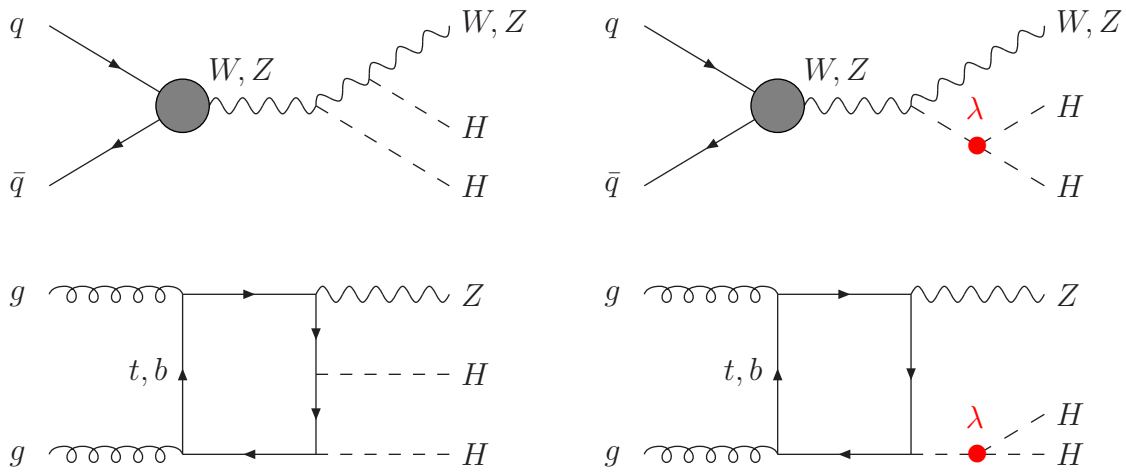
- QCD corrections ← DIS (STFU approach)
- NLO $\sim 10\%$, NNLO+N^{3}LO $\lesssim 1\%$ $[\mu_R = \mu_F = \sqrt{-q^2_{1,2}}\,(\geq 1\ \text{GeV})]$

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S. Ling, Zhang, Ma, Guo, Li, Li
Dreyer, Karlberg

- differential @ NNLO

Dreyer, Karlberg

(iii) Double Higgs-strahlung



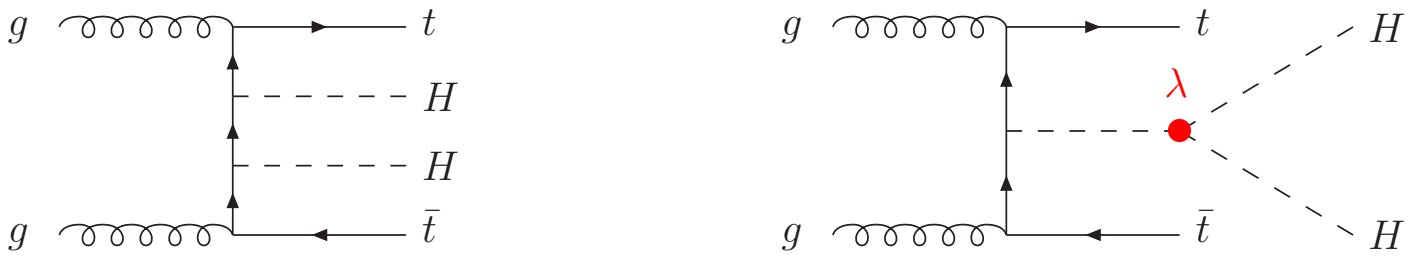
- QCD corrections ← DY
- $gg \to ZHH$: $\sim 30\%$ (LO $\to$ NNLO)
- NLO+NNLO $\sim 30\%$ $[\mu_R = \mu_F = M_{HHV}]$

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

- differential @ NNLO

  Li, Wang
  Li, Li, Wang

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



- QCD corrections: MG5_aMC@NLO
- $t\bar{t}HH$: $\sim -20\%$ moderate ($\leftarrow$ single H) $[\mu_R = \mu_F = M_{t\bar{t}}/2]$
- $tjHH$: $\sim +20\%$ moderate $[\mu_R = \mu_F = M_{HH}/2]$

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

III *CONCLUSIONS*

- Higgs pair production at full NLO... N^{3}LO

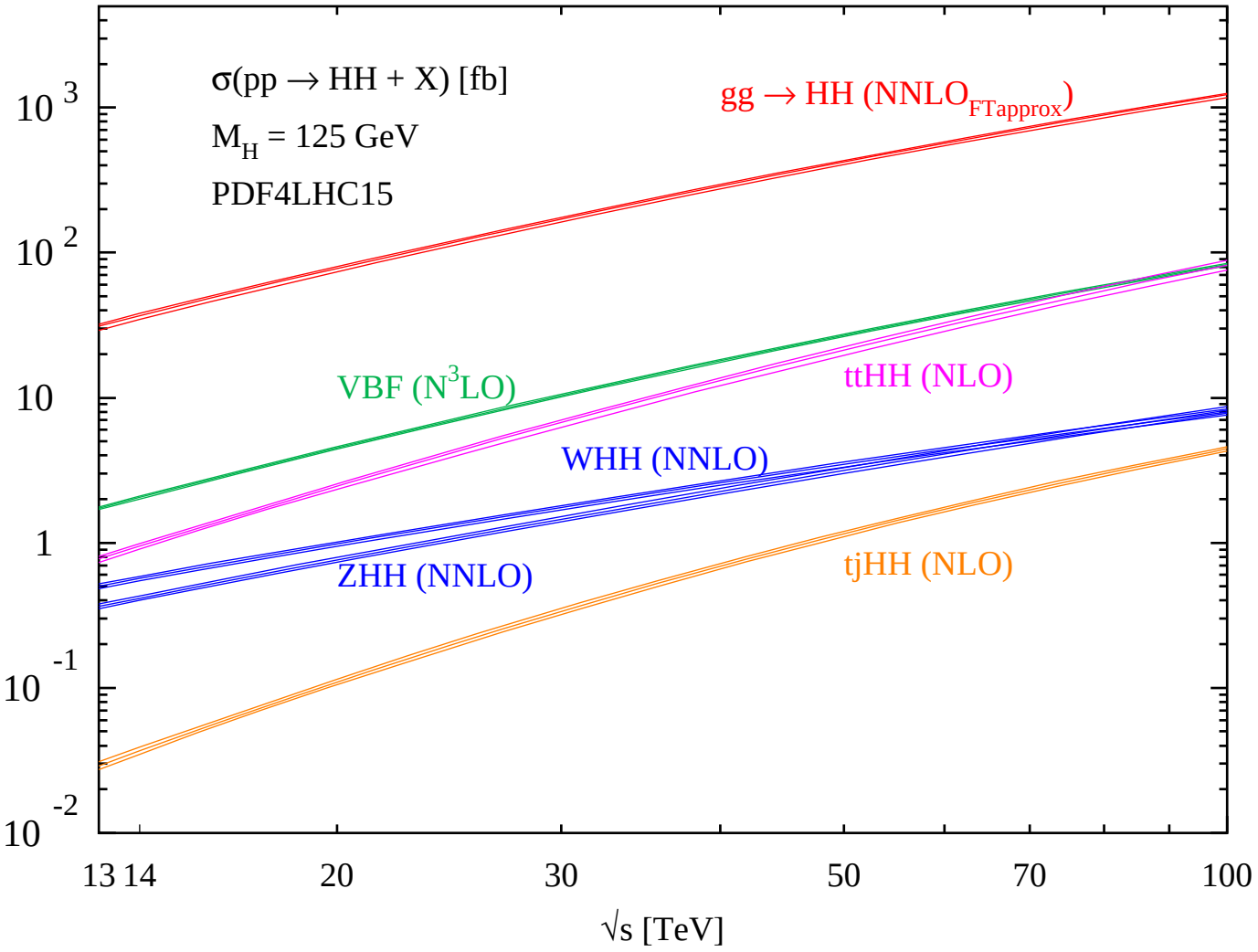
  $\Rightarrow$ THU $\lesssim$ 25...1%

- $gg \to HH$: NLO top mass effects on top of LO sizeable

  factorization/renormalization scale uncertainties $\sim$ 15%

  uncertainties due to scale/scheme choice of m_t sizeable $\lesssim$ 30%

  recommended scheme to comb. fac./ren. scale and m_t uncertainties



HH White Paper

BACKUP SLIDES

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

$$\overline{m}_t(M_t) = \frac{M_t}{1 + \frac{4}{3}\frac{\alpha_s(M_t)}{\pi} + 10.9\left(\frac{\alpha_s(M_t)}{\pi}\right)^2}$$

$$\overline{m}_t(\mu) \;=\; \overline{m}_t(M_t)\,\frac{c\left[\alpha_s(\mu)/\pi\right]}{c\left[\alpha_s(M_t)/\pi\right]}$$

$$c(x) = \left(\frac{7}{2}x\right)^{\frac{4}{7}}\left[1 + 1.398x + 1.793\,x^2 - 0.6834\,x^3\right]$$

$$M_t \;=\; 172.5 \text{ GeV}$$

$$\overline{m}_t(\overline{m}_t) \;=\; 163.0 \text{ GeV}$$