SM HH THEORY OVERVIEW

Michael Spira (PSI)

I Introduction

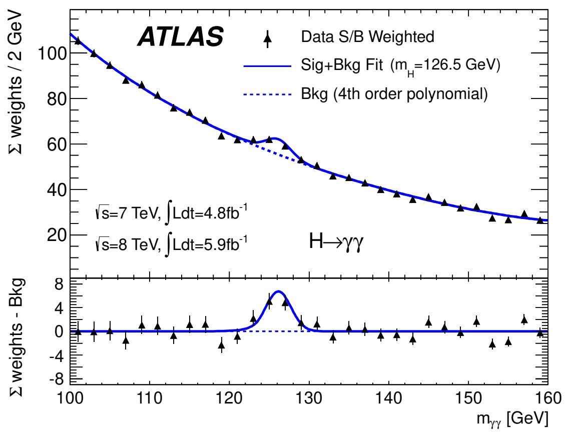
II Higgs Pair production

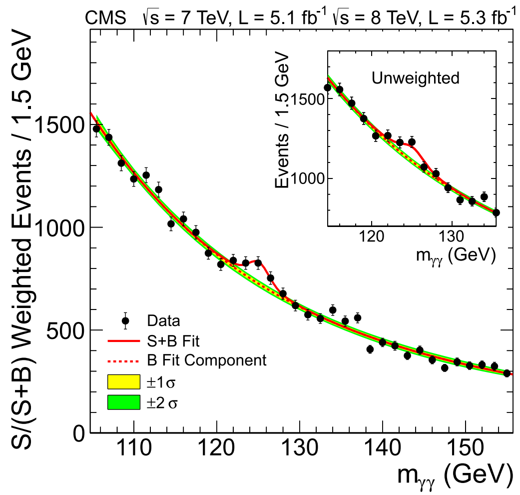
III Conclusions

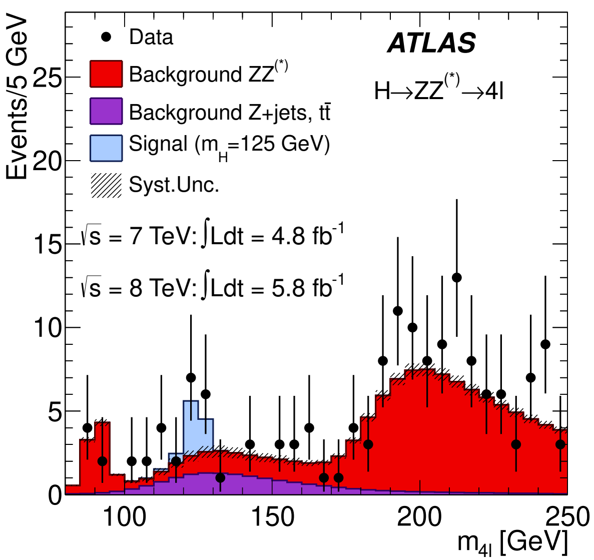
I INTRODUCTION

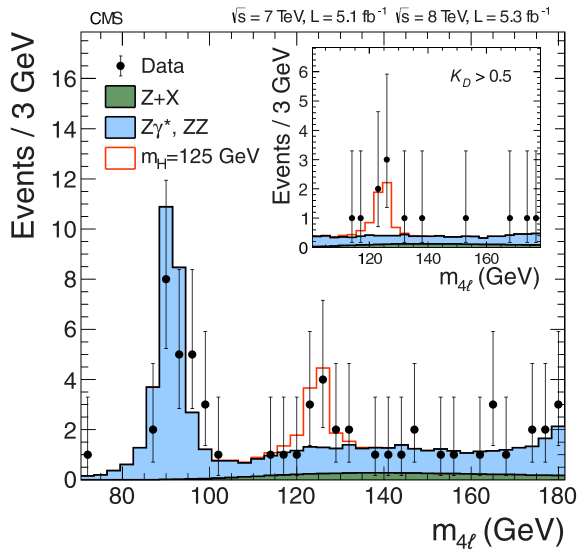
Standard Model

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

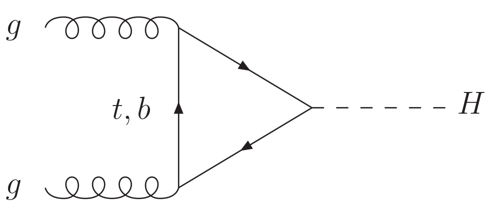


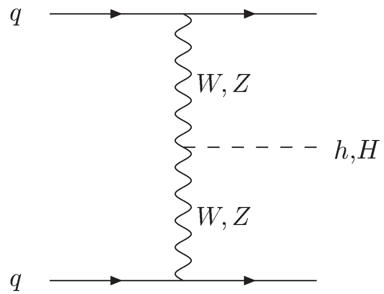


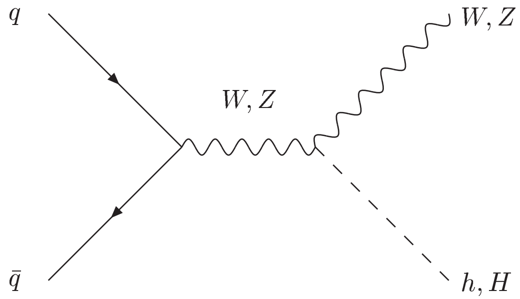


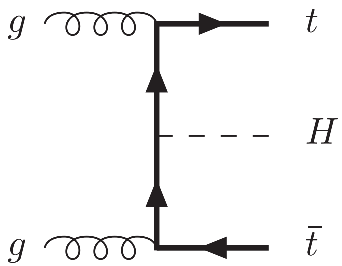


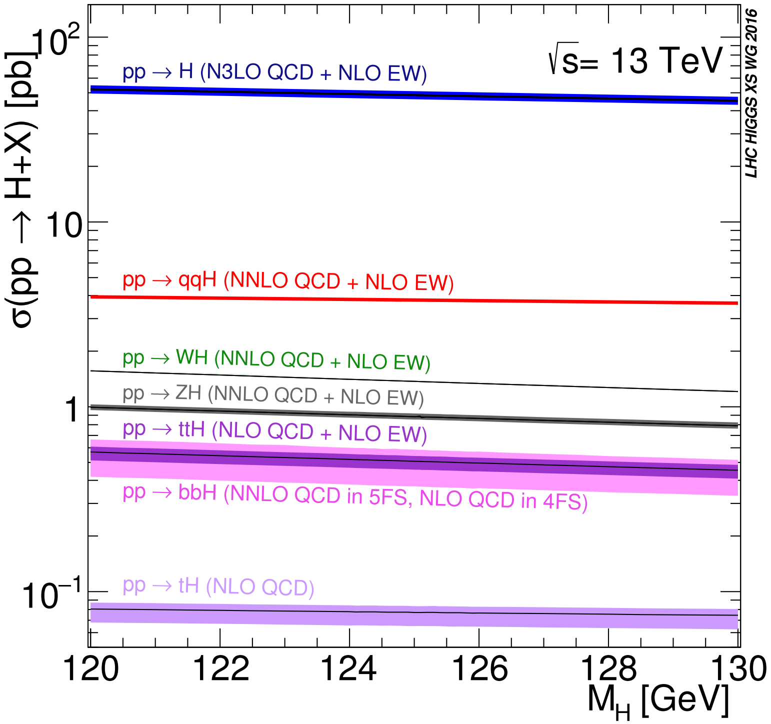
- Higgs Boson Production & Decay

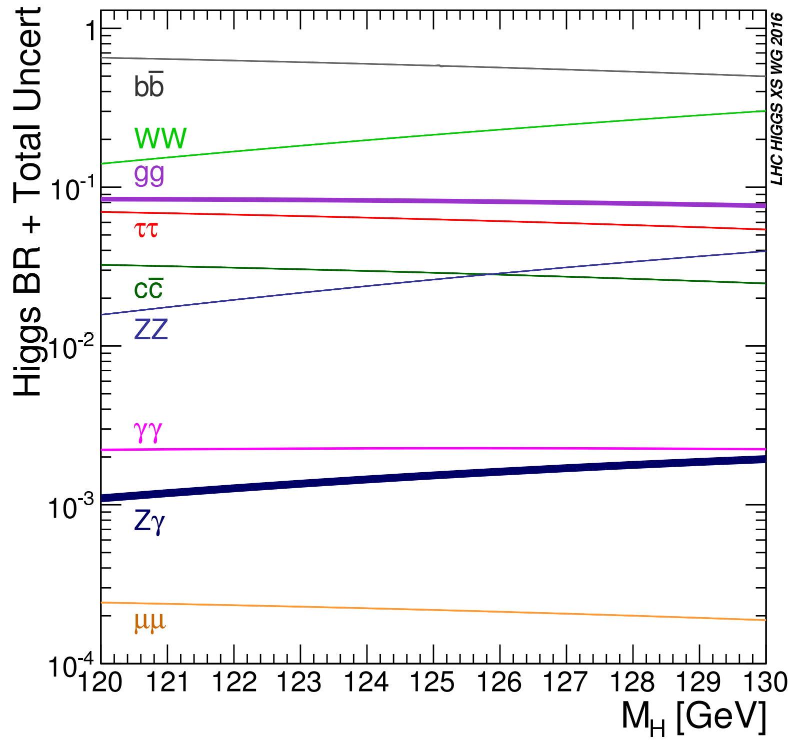






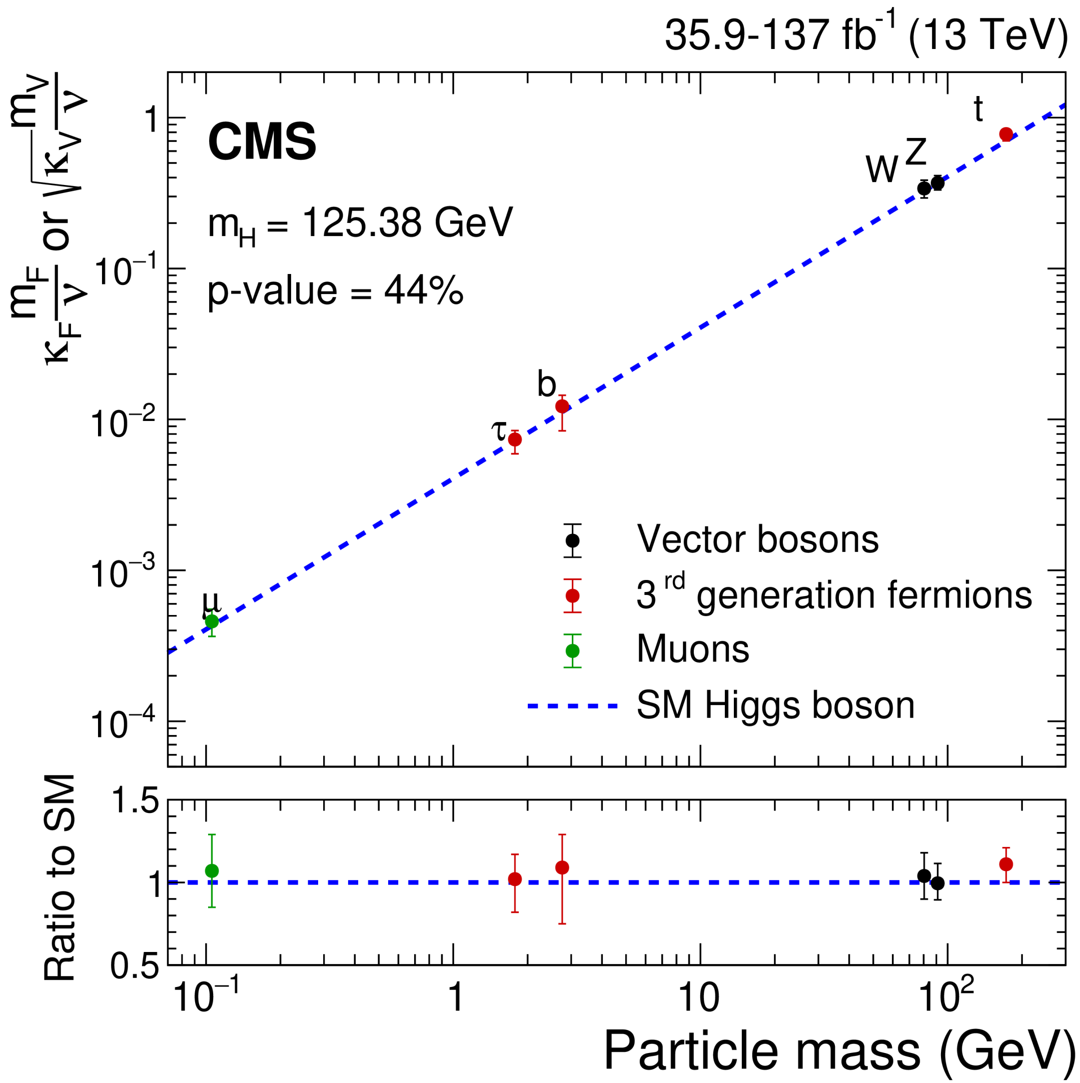




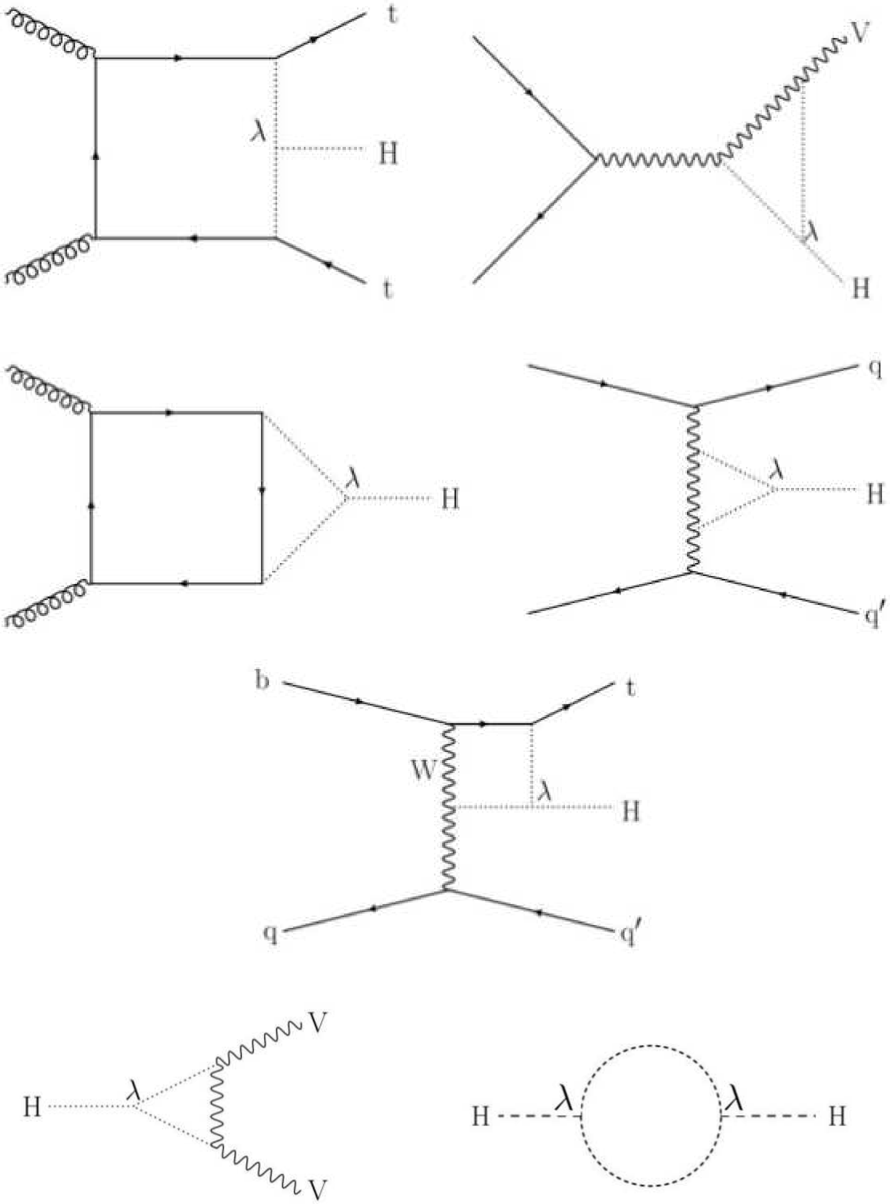


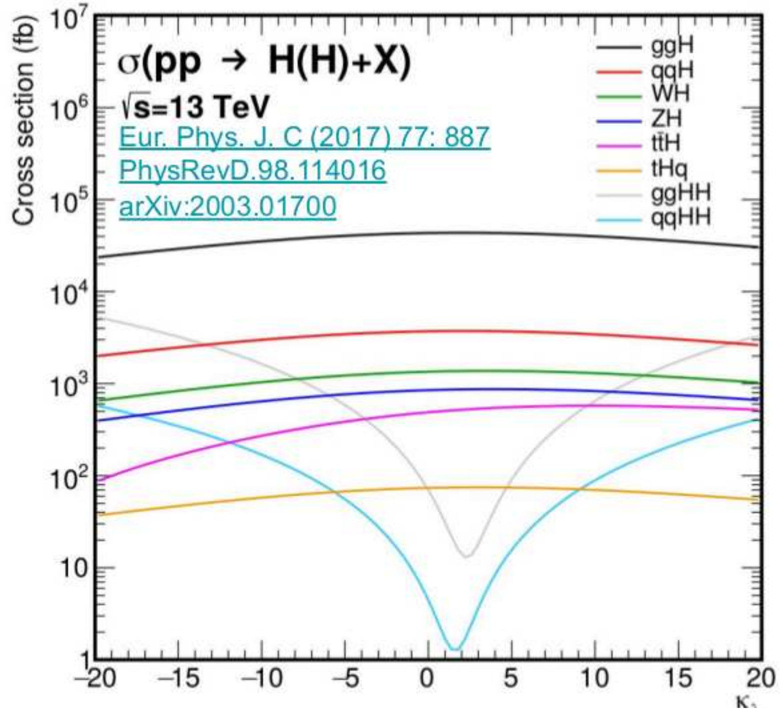
LHC Higgs XS WG

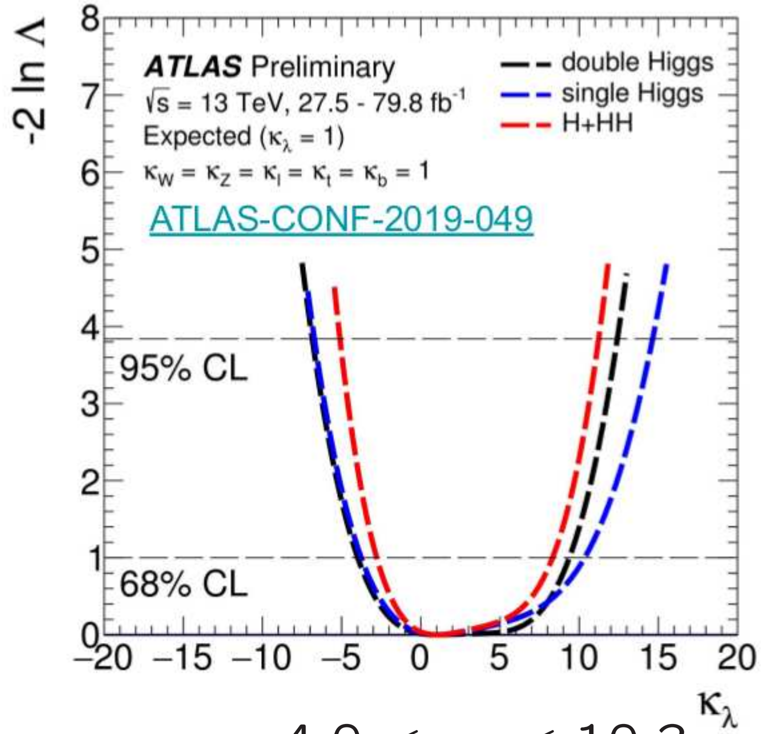
- Discovery: LHC [Tevatron]
  → Higgs mass
  couplings
  spin
  $\mathcal{CP}$
  λ ?



• indirect effects:



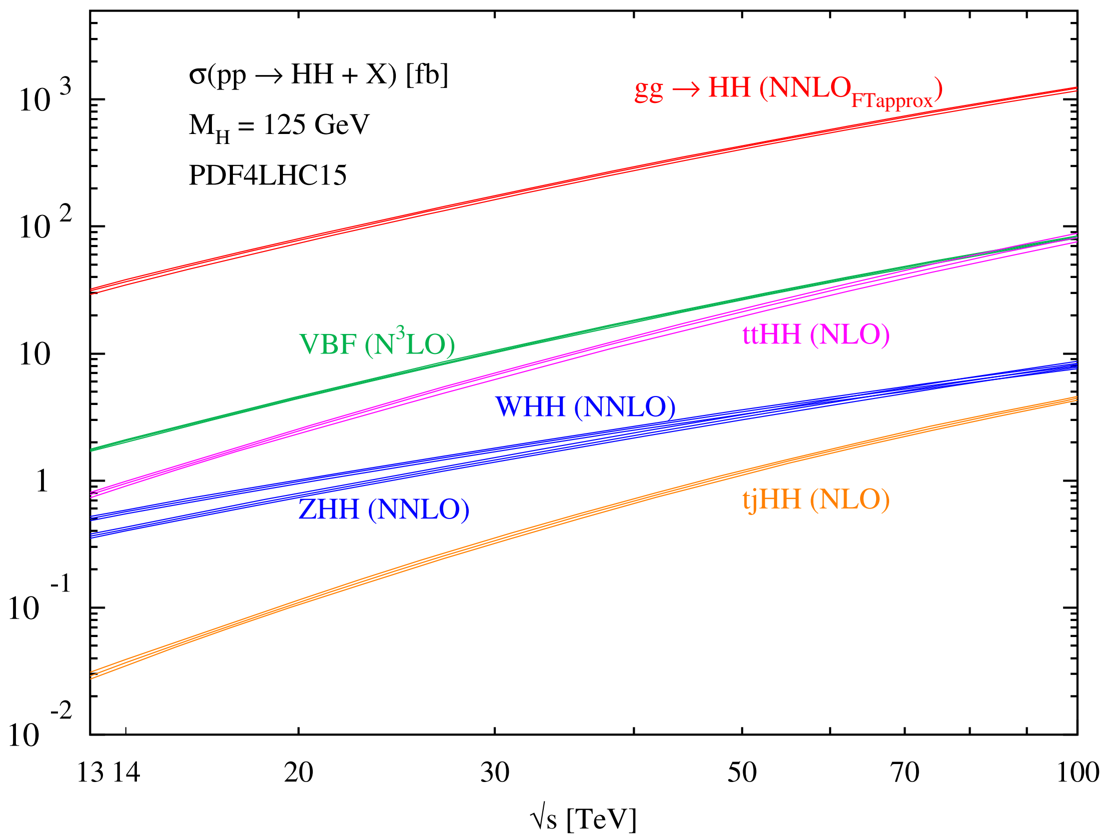


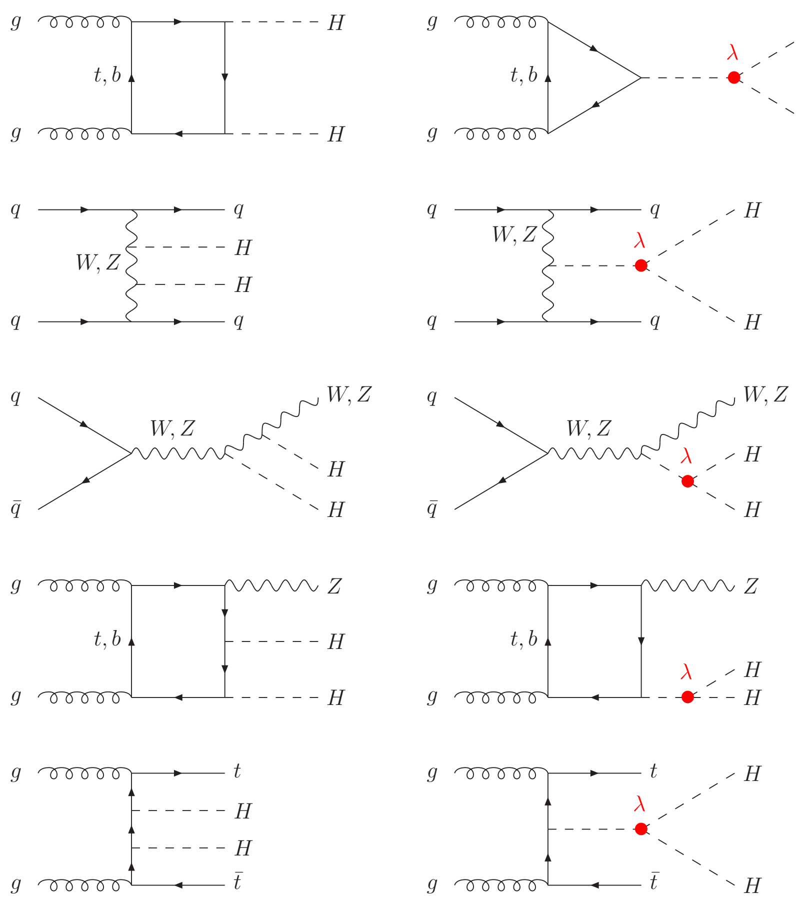


F. Monti (https://indico.cern.ch/event/1077767/)

$-4.0 < \kappa_\lambda < 10.3$

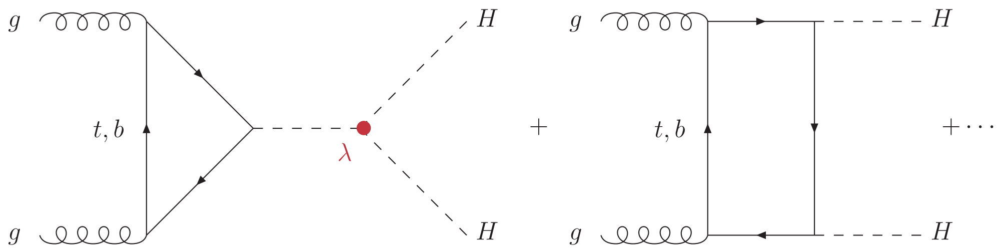
II HIGGS PAIR PRODUCTION



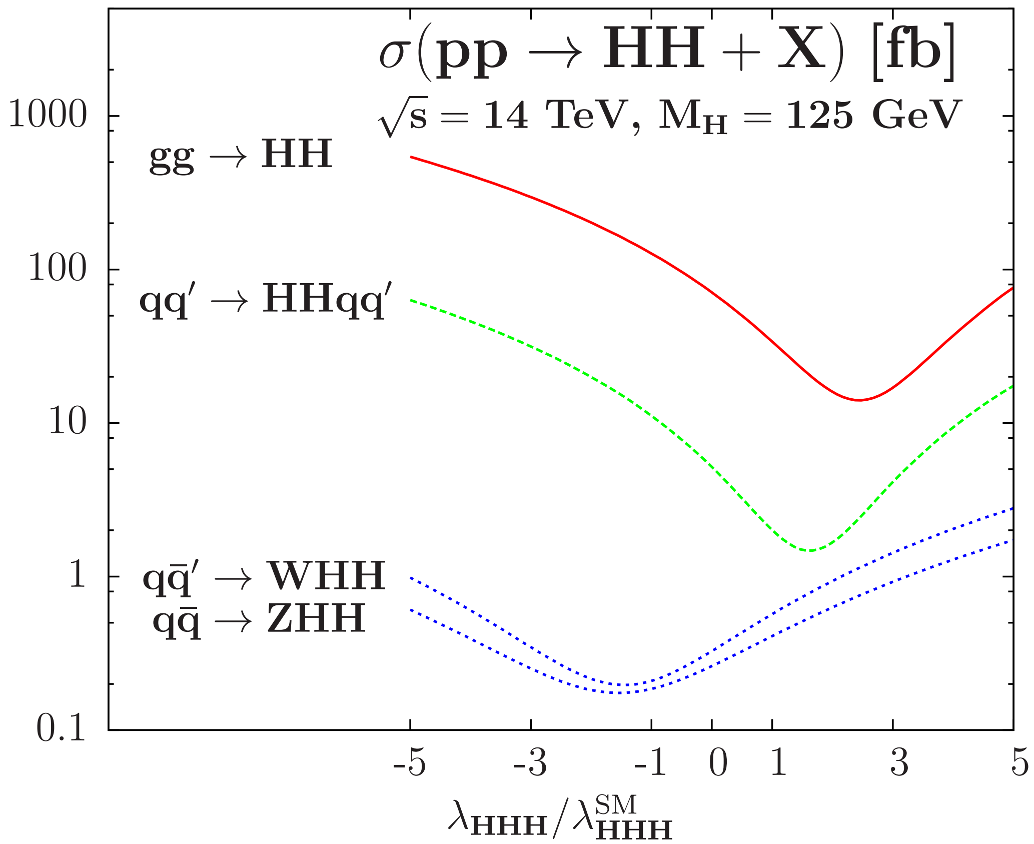


HH White Paper

(i) $gg \to HH$



- third generation dominant: $t\,(b)$



$gg \to HH$:

$$\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

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

- 2-loop QCD corr.: $\lesssim 70\%$ [HTL, $\mu = M_{HH}/2$]

  Dawson, Dittmaier, S.

- 2-loop QCD corr.: $\sigma = \sigma_0 + \frac{\sigma_1}{m_t^2} + \cdots + \frac{\sigma_4}{m_t^8}$
  [refinement: full LO at diff. level]

  Grigo, Hoff, Melnikov, Steinhauser

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

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

- NNLO QCD corrections: $\sim 20\%$ [HTL]

  de Florian, Mazzitelli
  Grigo, Melnikov, Steinhauser

- N^3LO QCD corrections: $\sim 5\%$ [HTL]

  Chen, Li, Shao, Wang

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

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

- NLO: matching to parton showers

Heinrich, Jones, Kerner, Luisoni, Vryonidou

- 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

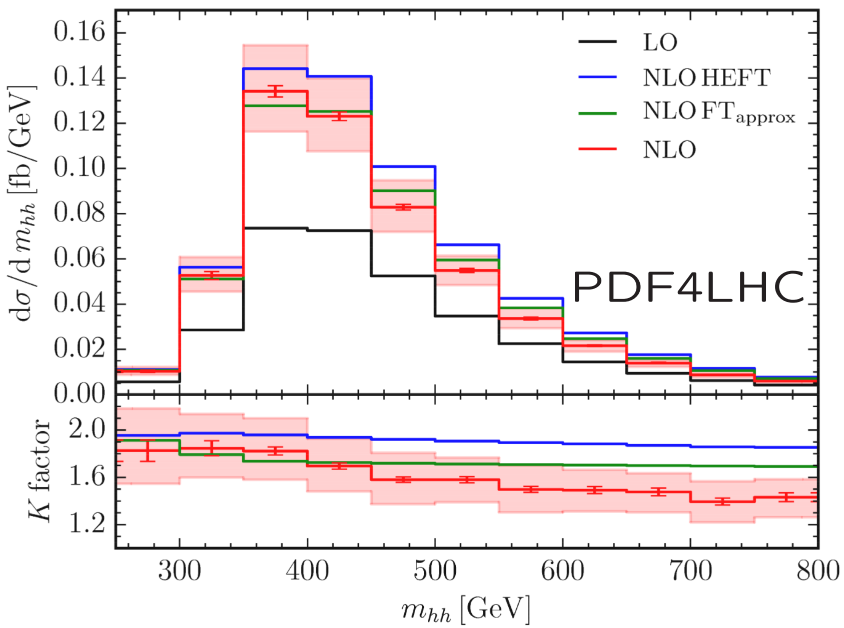
- combination of full NLO real and p_T^2/small-mass expansion inside Powheg $\rightarrow$ variation of M_H, m_t

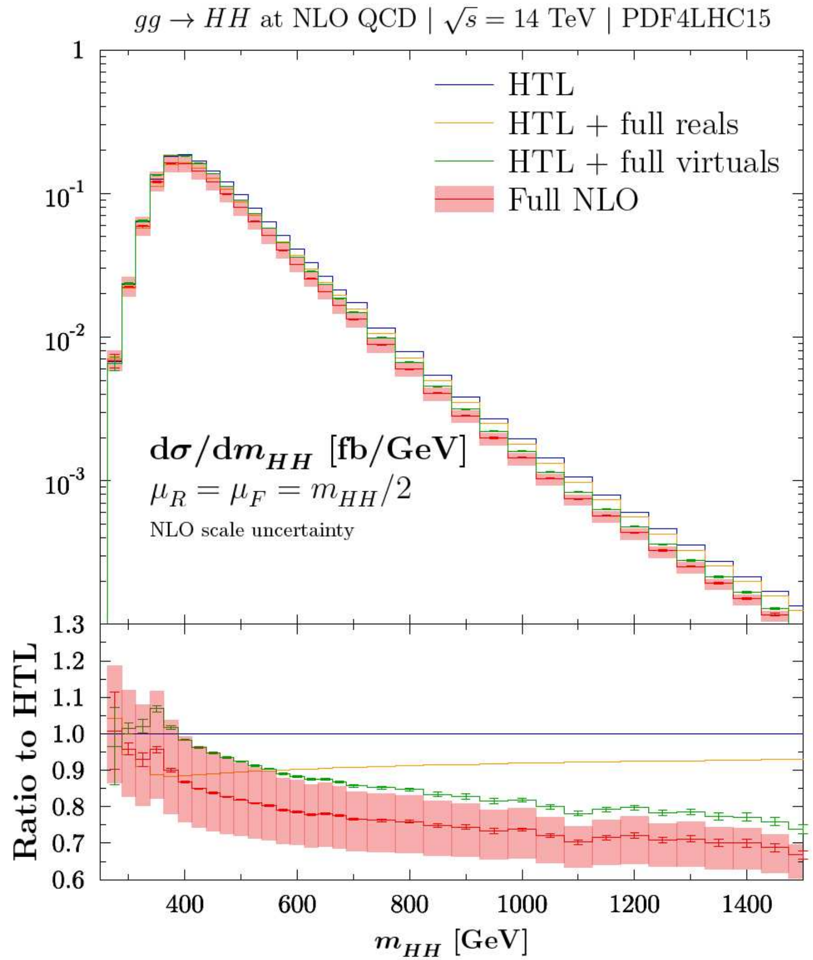
Bagnaschi, Degrassi, Gröber

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





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

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

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

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

uncertainties due to m_t

- 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:

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

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

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

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

- 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:

$\leftarrow$ Davies, Mishima, Steinhauser, Wellmann

pole mass m_t:

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

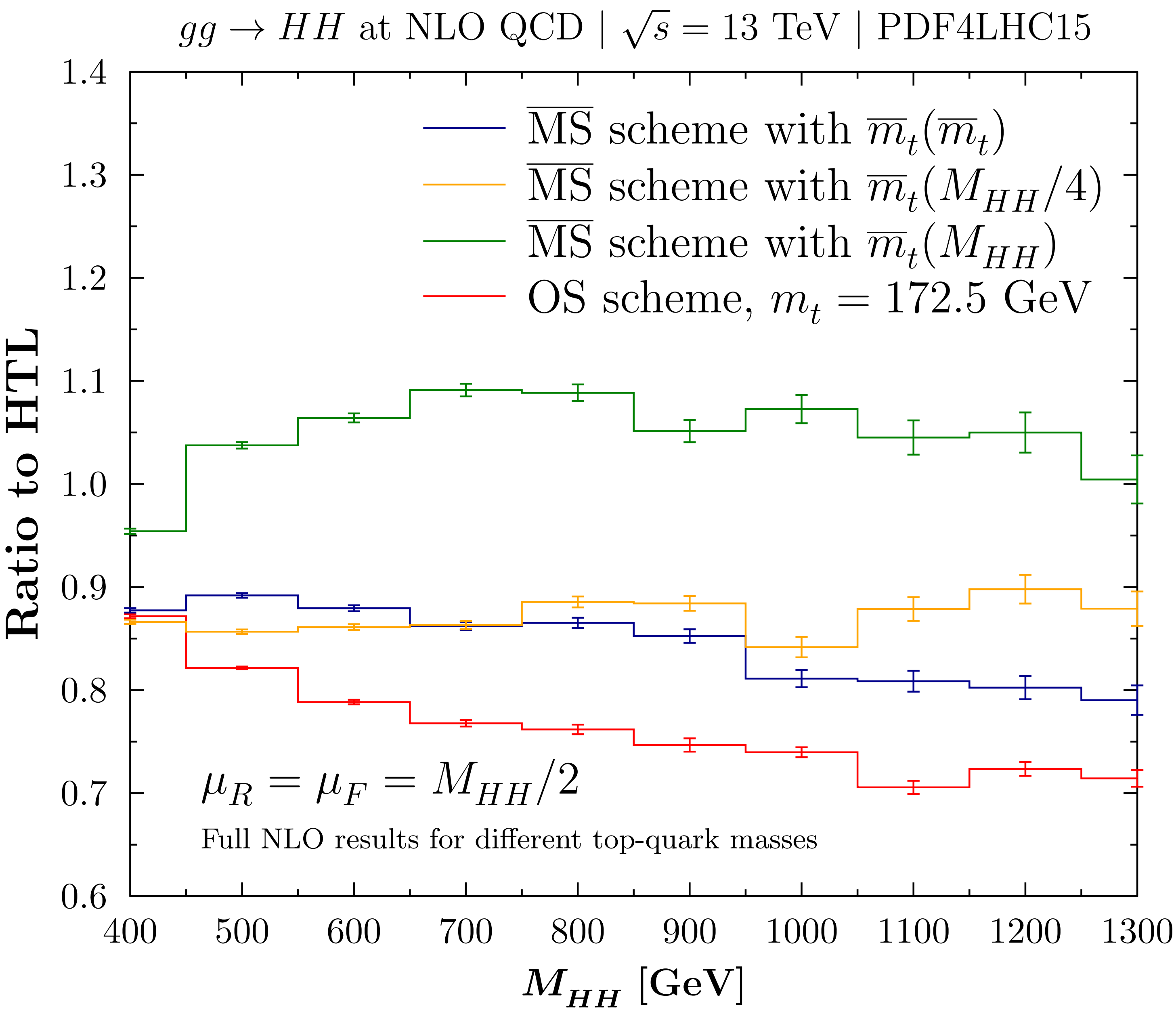
$$\Delta F_{2,mass} \rightarrow \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

$\overline{\text{MS}}$ 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 @ $\mathrm{NNLO}_{FTapprox}$:

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

- 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? $\to$ envelope $\to \sim$ linear sum (rel. err.)

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

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

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

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

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

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

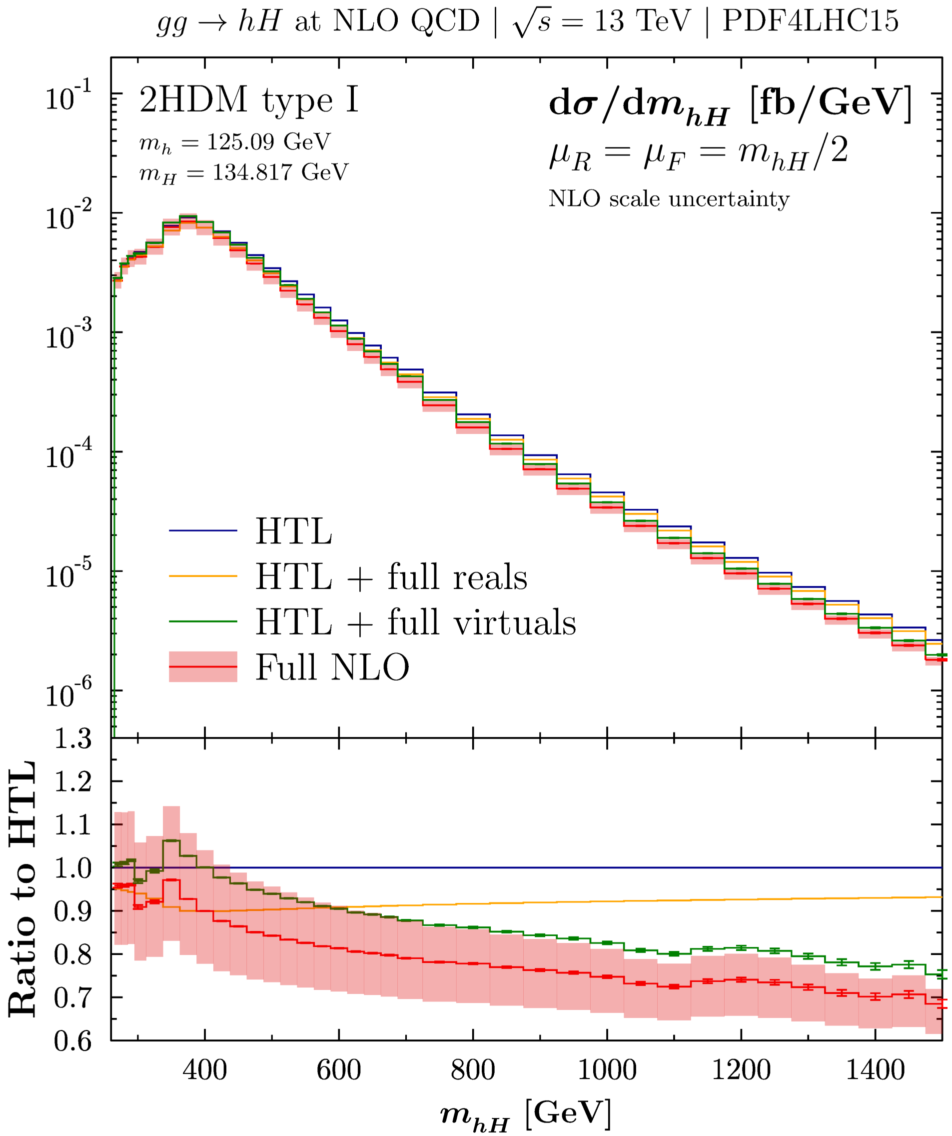
- combined uncertainties @ NNLO$_{FTapprox}$ $[\mu_R = \mu_F = M_{HH}/2]$:

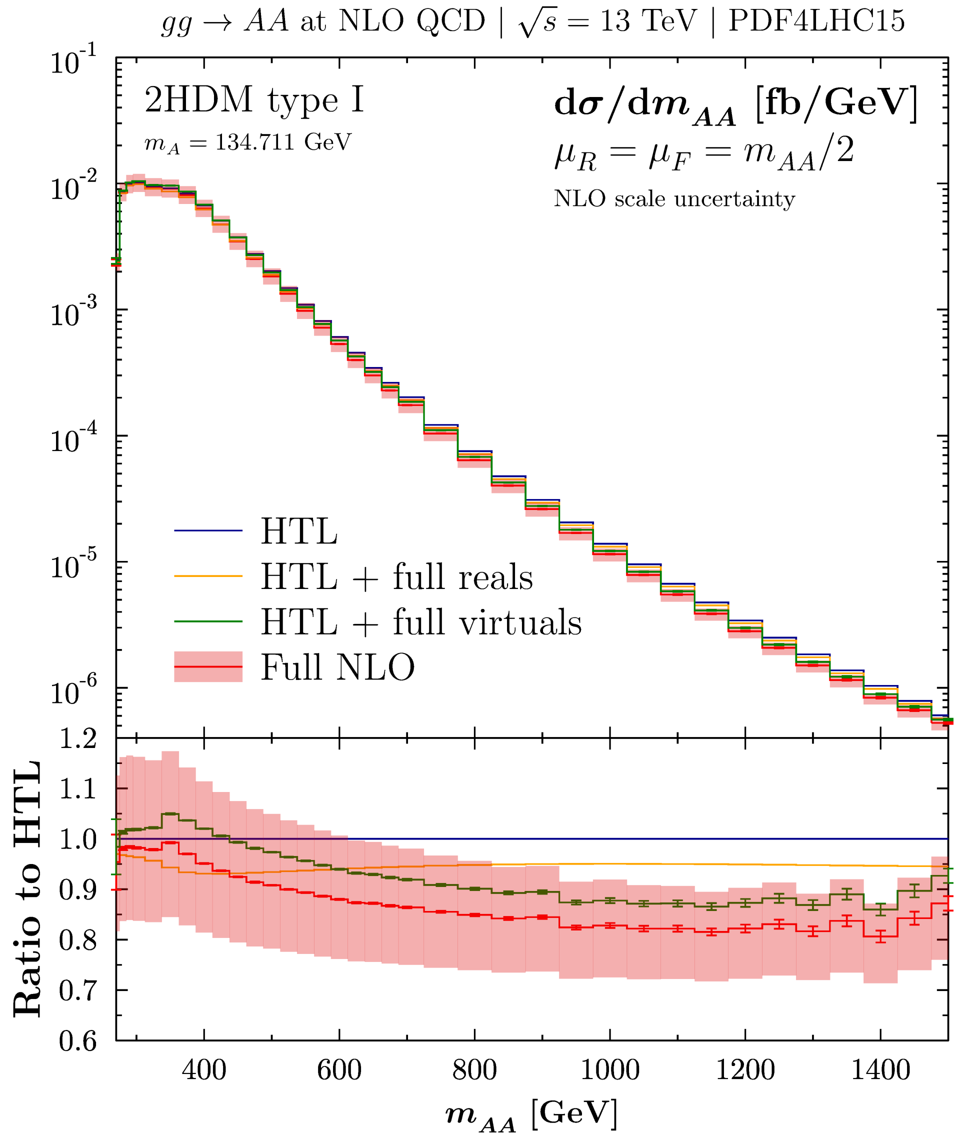
$$\kappa_\lambda = -10: \quad \sigma_{tot} = 1680^{+13\%}_{-14\%}\ \text{fb}$$
$$\kappa_\lambda = -5: \quad \sigma_{tot} = 598.9^{+13\%}_{-15\%}\ \text{fb}$$
$$\kappa_\lambda = -1: \quad \sigma_{tot} = 131.9^{+11\%}_{-16\%}\ \text{fb}$$
$$\kappa_\lambda = 0: \quad \sigma_{tot} = 70.38^{+8\%}_{-18\%}\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

2HDM [type I]

$M_h = 125.09$ GeV $\quad M_H = 134.817$ GeV $\quad M_A = 134.711$ GeV

$\mathrm{tg}\beta = 3.759 \quad \alpha = -0.102 \quad m_{12}^2 = 4305\ \mathrm{GeV}^2 \quad \Rightarrow \cos(\beta-\alpha) = 0.157$





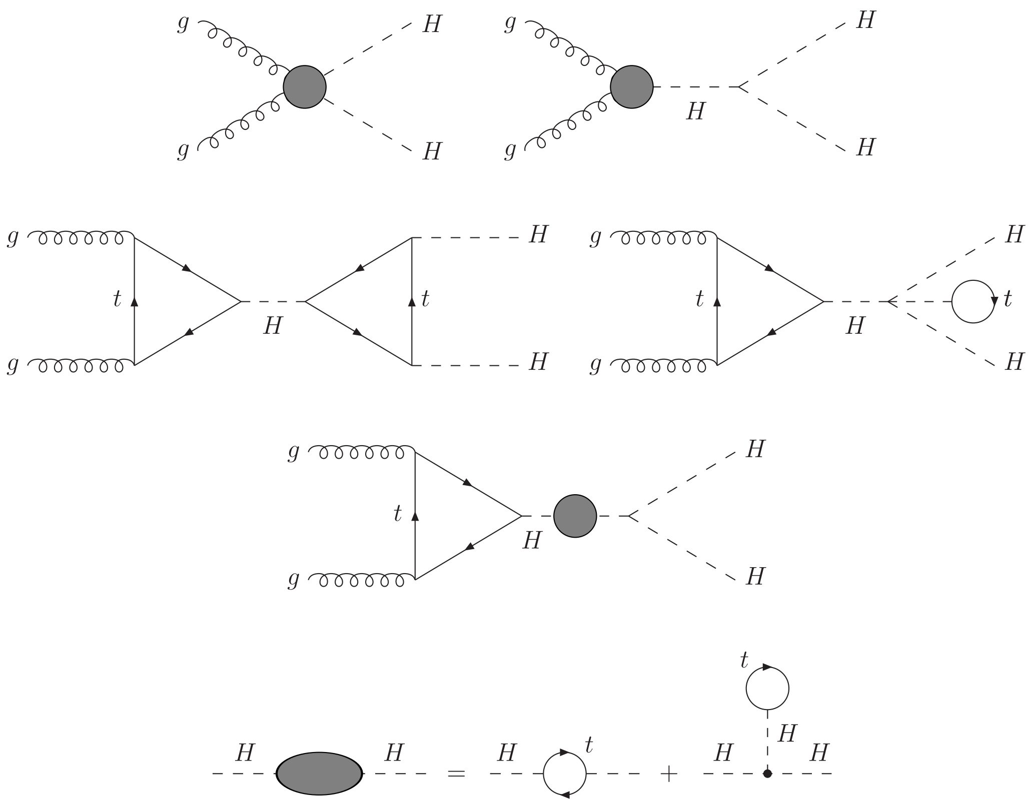
Baglio, Campanario, Glaus, Mühlleitner, Ronca, S.

Top-induced elw. corrections

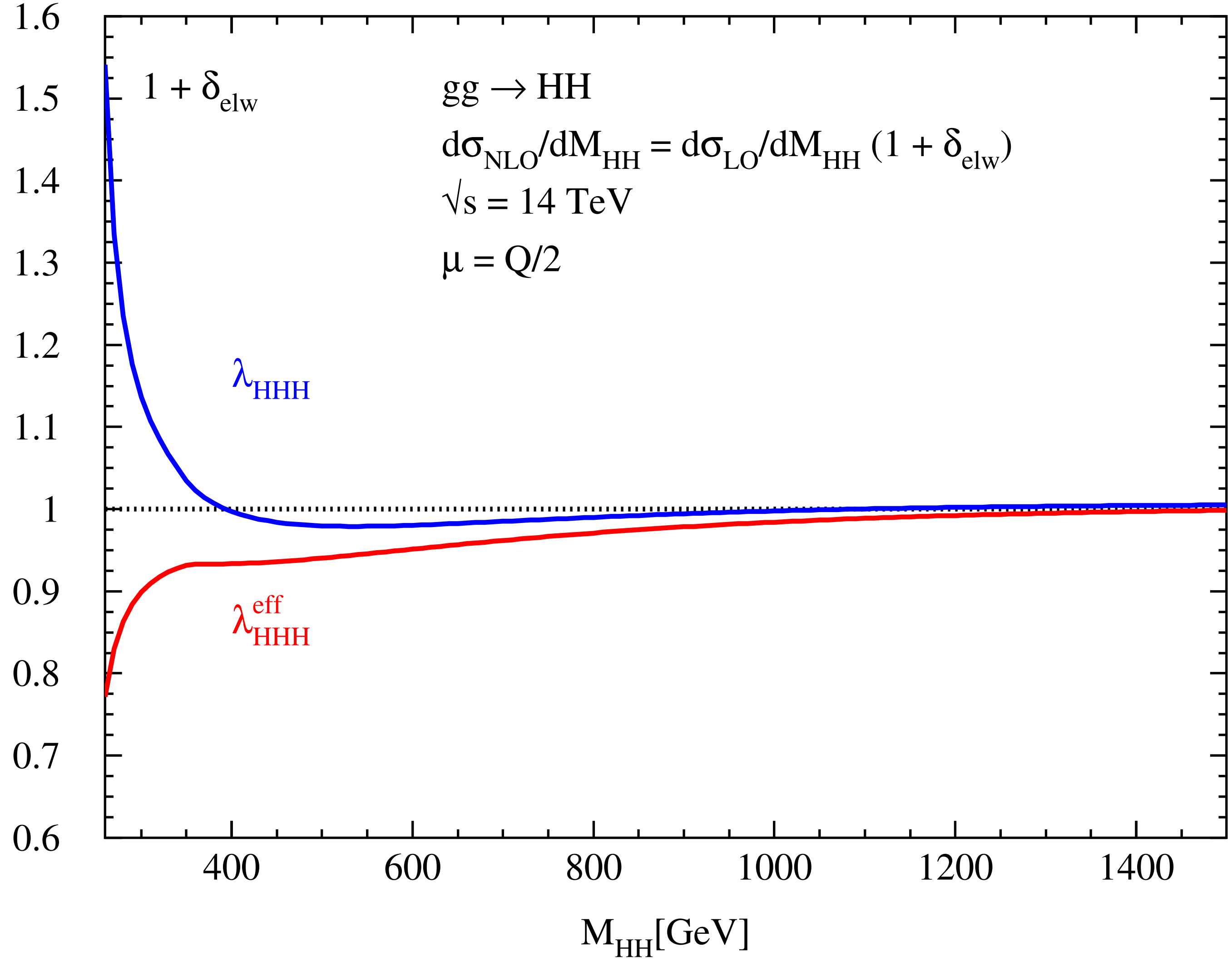
Mühlleitner, Schlenk, S.

$$HTL: \quad \mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \left\{ (1+\delta_1)\frac{H}{v} + (1+\eta_1)\frac{H^2}{2v^2} + \mathcal{O}(H^3) \right\}$$

$$\delta_1 = \frac{x_t}{2} + \mathcal{O}(x_t^2) \qquad \eta_1 = 4x_t + \mathcal{O}(x_t^2)$$



$$V_{eff}: \boxed{\lambda^{eff}_{HHH} = 3\frac{M_H^2}{v} - \frac{3m_t^4}{\pi^2 v^3} \approx 0.91 \times 3\frac{M_H^2}{v}}$$



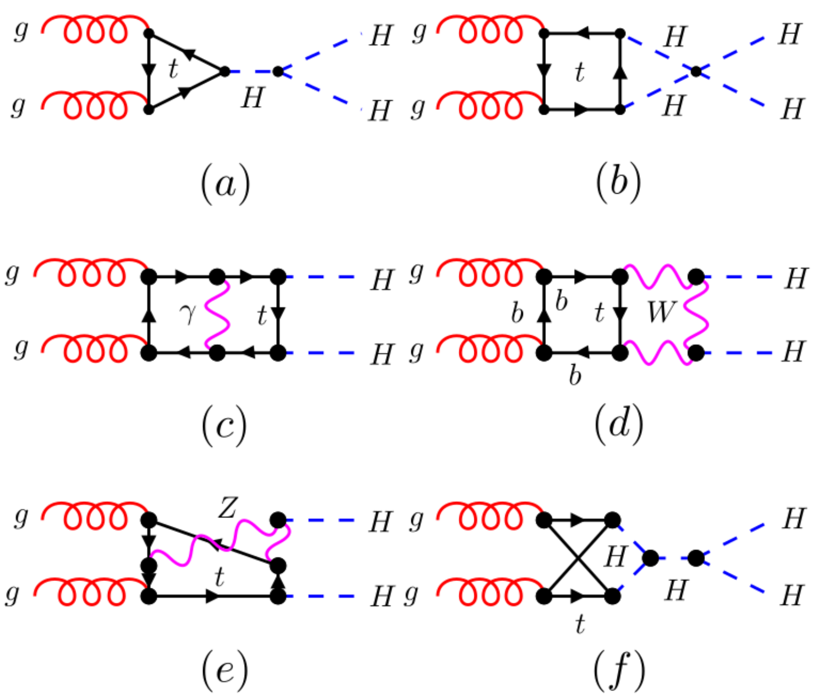
$$\sigma = 1.002 \times \sigma_{LO} \qquad (\lambda_{HHH})$$
$$\sigma = 0.938 \times \sigma_{LO} \qquad (\lambda_{HHH}^{eff})$$

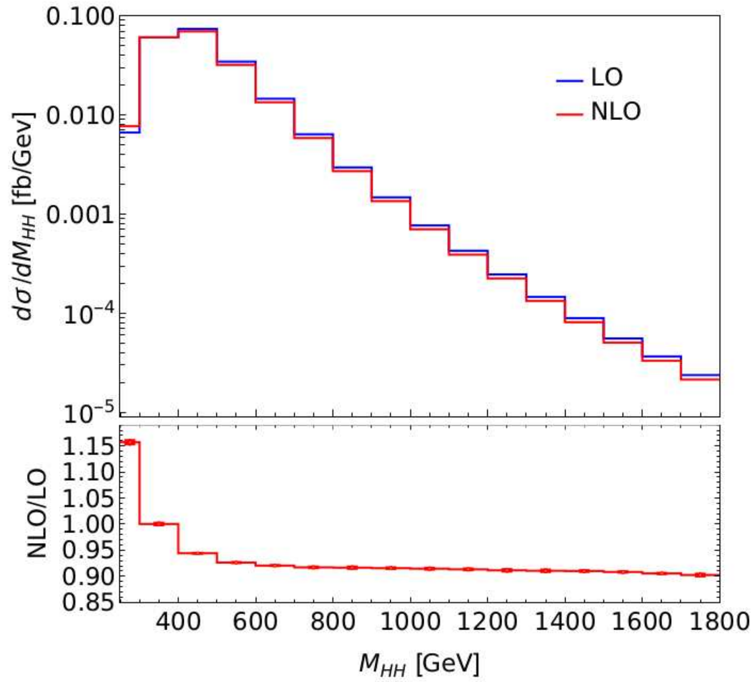
Mühlleitner, Schlenk, S.

- analytical results for $ggHH$ coupling in large top-mass exp. & HEL

Davies, Mishima, Schönwald, Steinhauser, Zhang

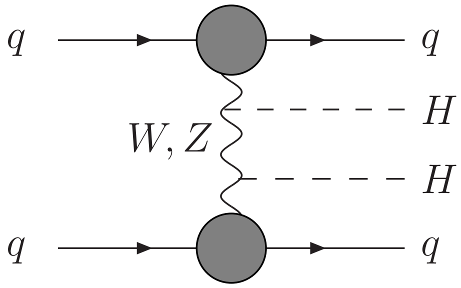
- full elw. corrections: Bi, Huang, Huang, Ma, Yu

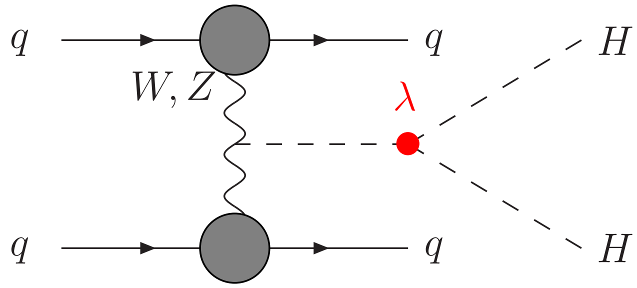




$$\frac{\delta\sigma}{\sigma} \sim -4\%$$

(ii) VBF





- QCD corrections ← DIS (STFU approach)

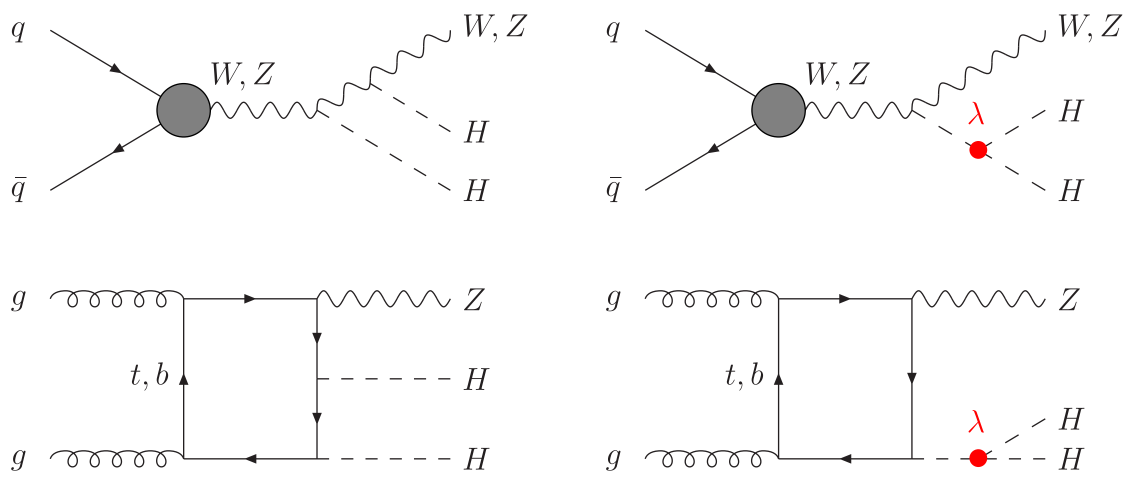
- NLO $\sim$ 10%, NNLO+N^{3}LO $\lesssim$ 1% $[\mu_R = \mu_F = \sqrt{-q^2_{1,2}}\,(\geq 1\ \mathrm{GeV})]$

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

- differential @ NNLO

Dreyer, Karlberg

(iii) Double Higgs-strahlung



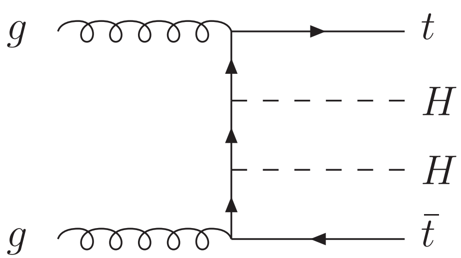
- QCD corrections ← DY
- $gg \to ZHH$: $\sim 30\%$ (LO → NNLO)
- NLO+NNLO $\sim 30\%$ $[\mu_R = \mu_F = M_{HHV}]$

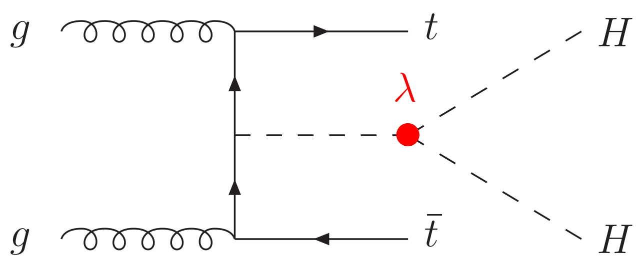
Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.
Li, Wang
Li, Li, Wang

- differential @ NNLO

Li, Wang
Li, Li, Wang

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





- QCD corrections: MG5_aMC@NLO
- $t\bar{t}HH$: $\sim -20\%$ moderate (← 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^3LO

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

• $gg \to HH$: 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

• top-Yukawa-induced electroweak corrections: small for total cxn, larger for distributions

• full elw. corrections $\sim -4\%$, larger for distributions

BACKUP SLIDES

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

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

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

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

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

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