PAUL SCHERRER INSTITUT PSI

HIGGS PAIR PRODUCTION AT NLO QCD

Michael Spira (PSI)

I Introduction

II Higgs Boson Pair Production

III Calculation

IV Conclusions

I *INTRODUCTION*

- SM very successful $\longleftarrow$ precision data [LEP, Tevatron, LHC]

- open problems: – mechanism of electroweak symmetry breaking
  – unification of forces
  – space-time structure @ short distances

- LHC: fundamental discoveries: Higgs boson(s?)
  Supersymmetry ?
  Extra space dimensions ?

- electroweak symmetry breaking: two classes of realization:
  – standard Higgs mechanism [SM, SUSY,. . .]
  – strong elw. symmetry breaking [TC, LH, Higgsless, ED,. . .]

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  – standard Higgs mechanism [SM, SUSY,. . .]
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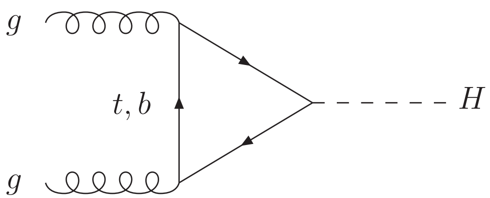
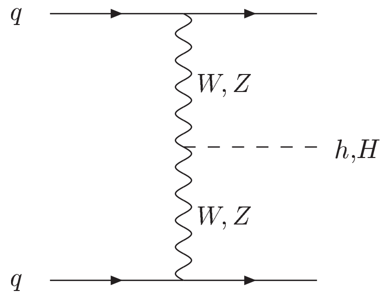
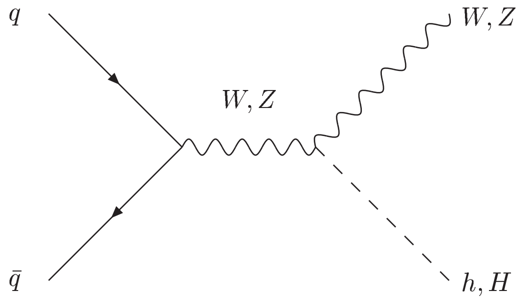
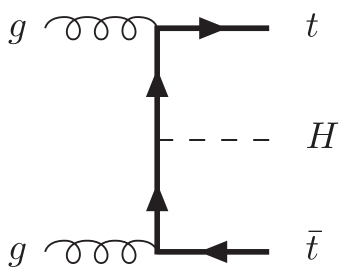
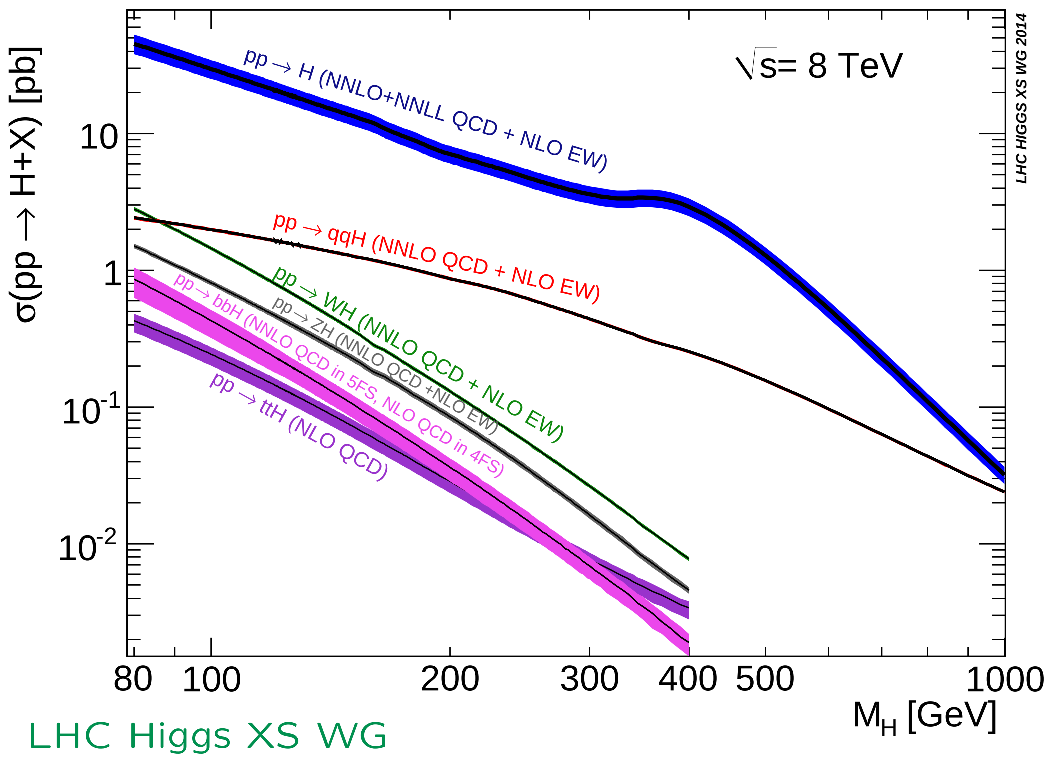
- Higgs Boson Production



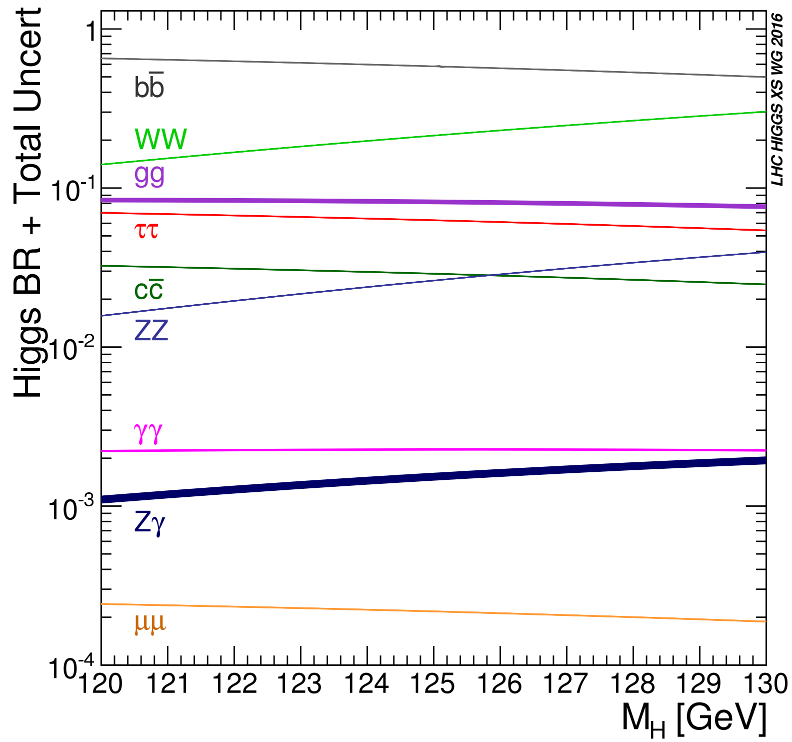








LHC Higgs XS WG



- Discovery: LHC [Tevatron]

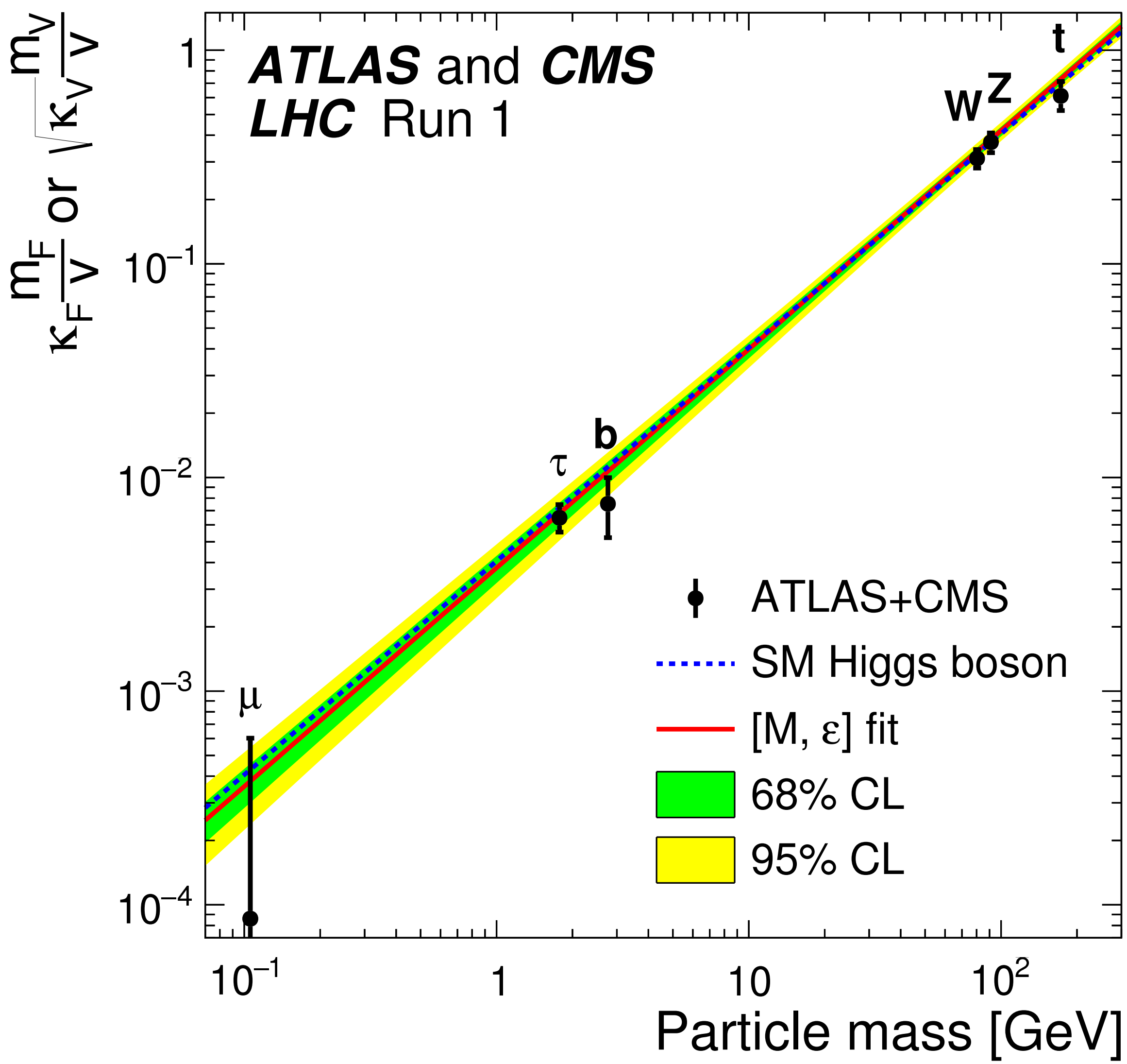
  $\rightarrow$ Higgs mass

  couplings

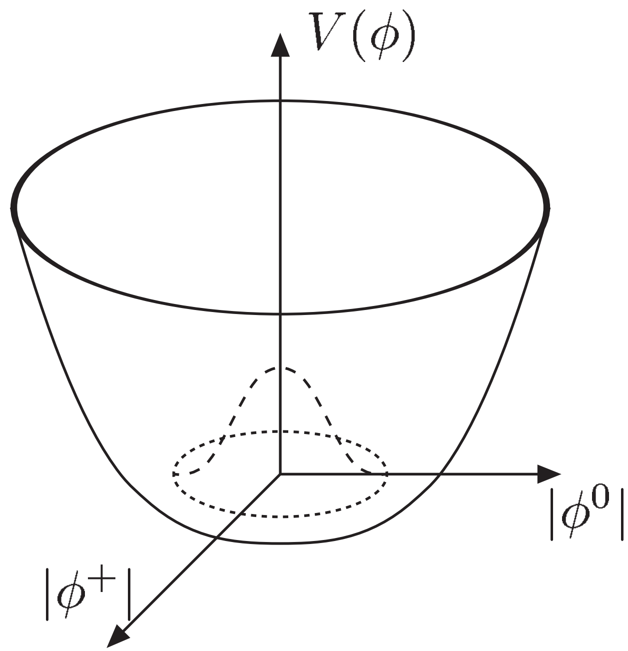
  spin

  $\mathcal{CP}$

  λ ?



• Higgs potential:



$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \underbrace{\exp\left[i\vec{\Theta}\frac{\vec{\tau}}{2}\right]}_{\Rightarrow W^\pm, Z} \begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix}$$

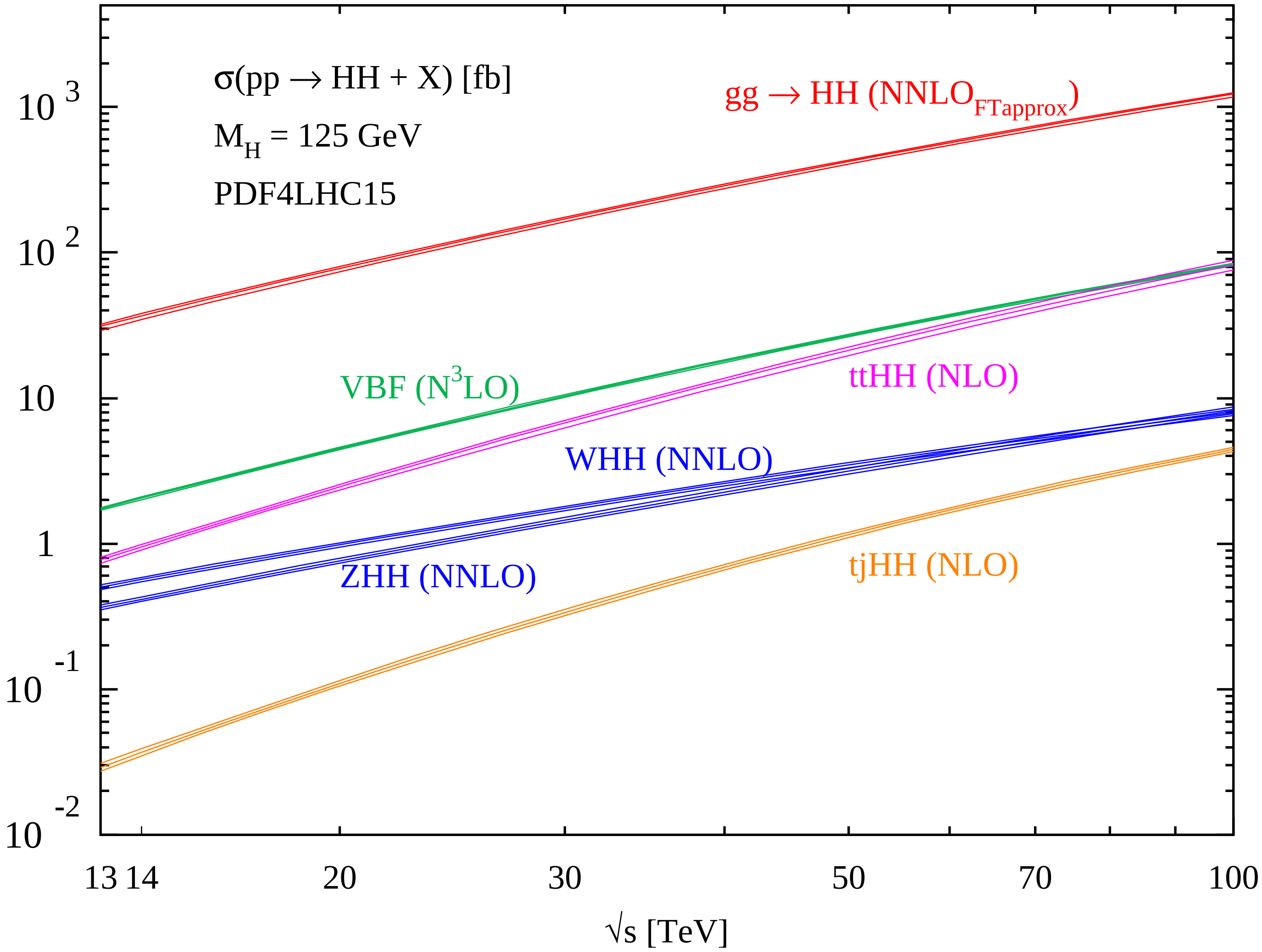
Higgs
Englert, Brout
Guralnik, Hagen, Kibble

$$V(\phi) = \frac{\lambda}{2}\left[|\phi|^2 - \frac{v^2}{2}\right]^2 = \frac{M_H^2}{2}H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^2}{8v^2}H^4$$

$\Rightarrow$ one scalar Higgs boson

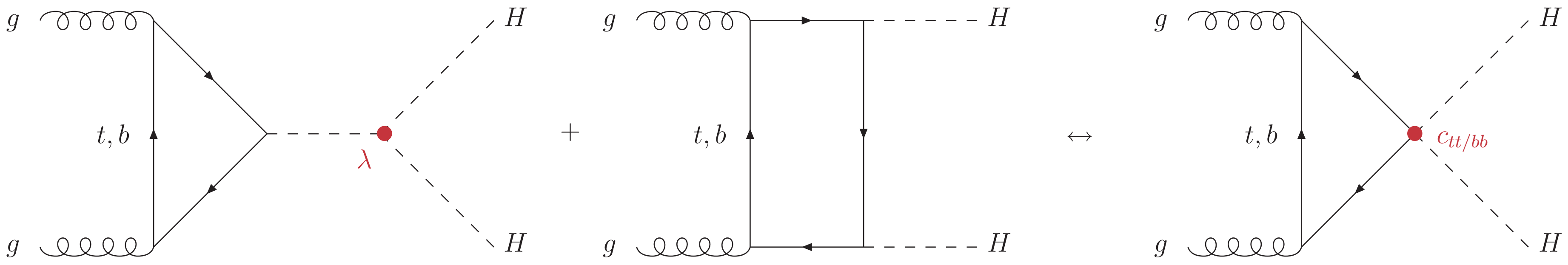
$$v = 1/\sqrt{\sqrt{2}G_F} \approx 246 \text{ GeV}$$

II HIGGS PAIR PRODUCTION

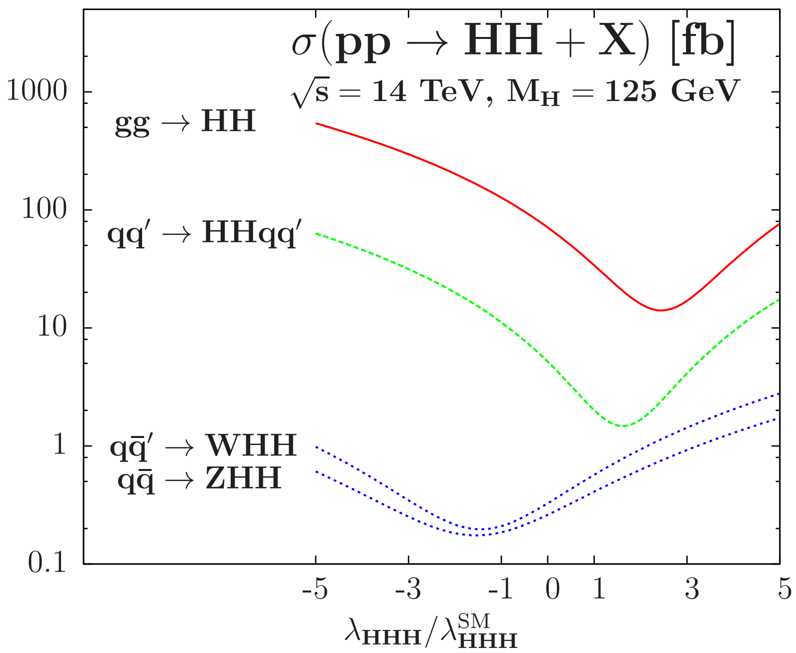


HH White Paper

$gg \to HH$



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



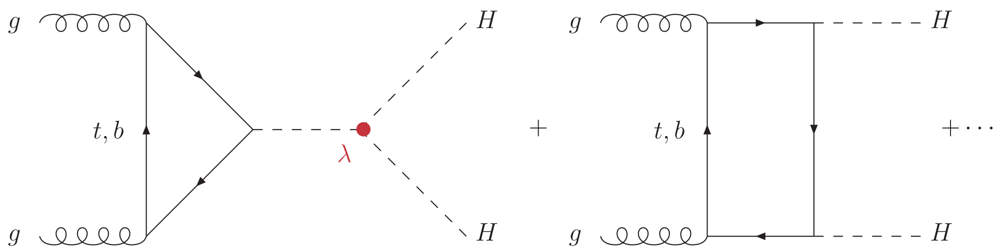
$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

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

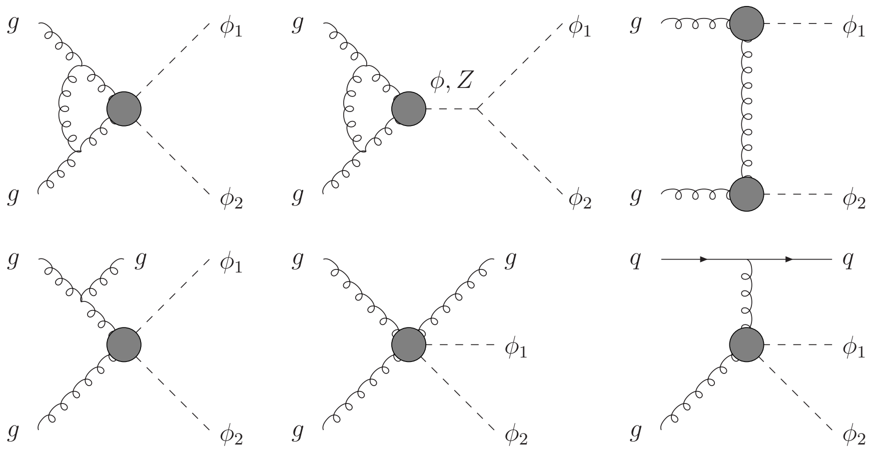
$gg \to HH$

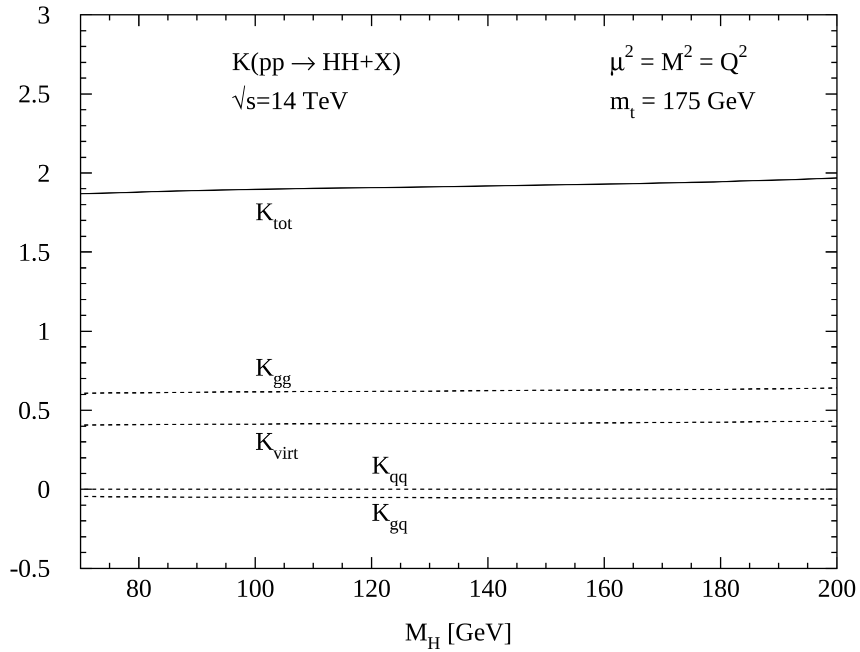
SM



- third generation dominant $\to t, b$

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





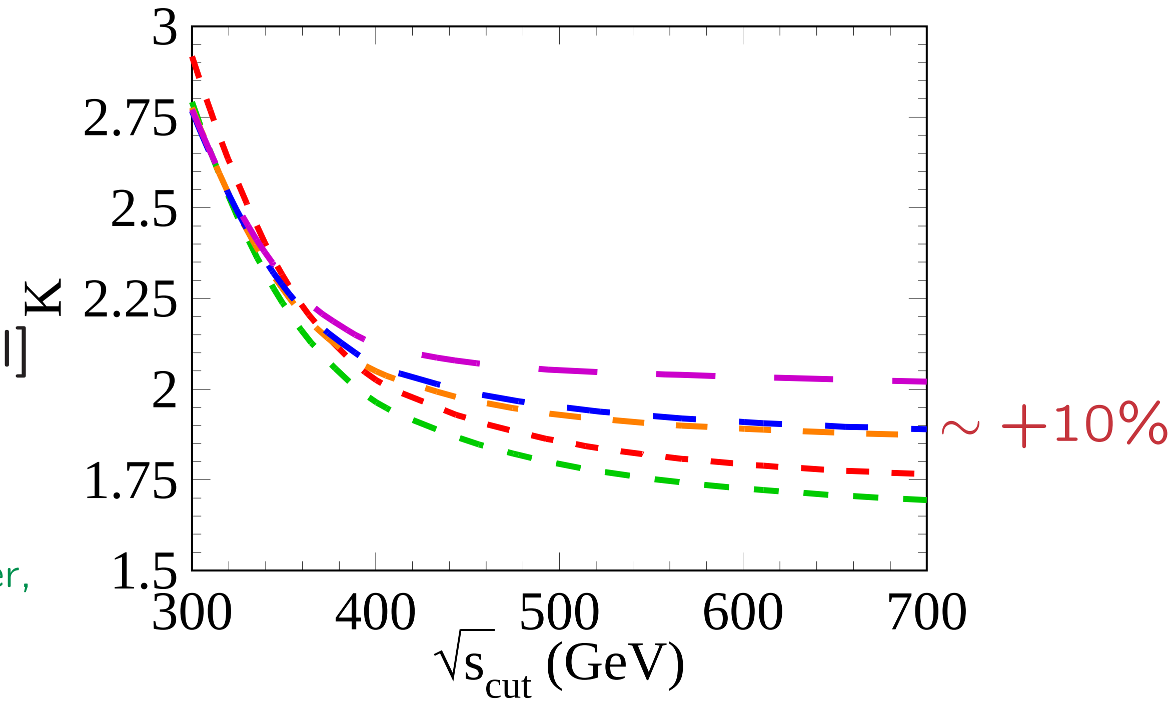
Dawson, Dittmaier, S.

- 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]



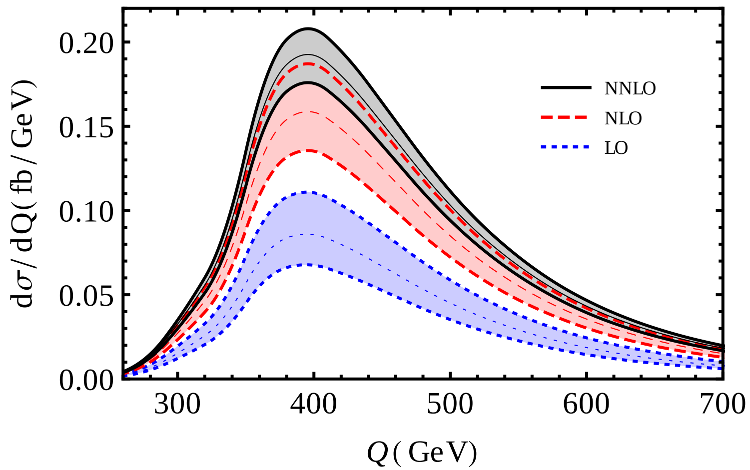
- NLO mass effects @ NLO in real corrections: $\sim -10\%$

  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



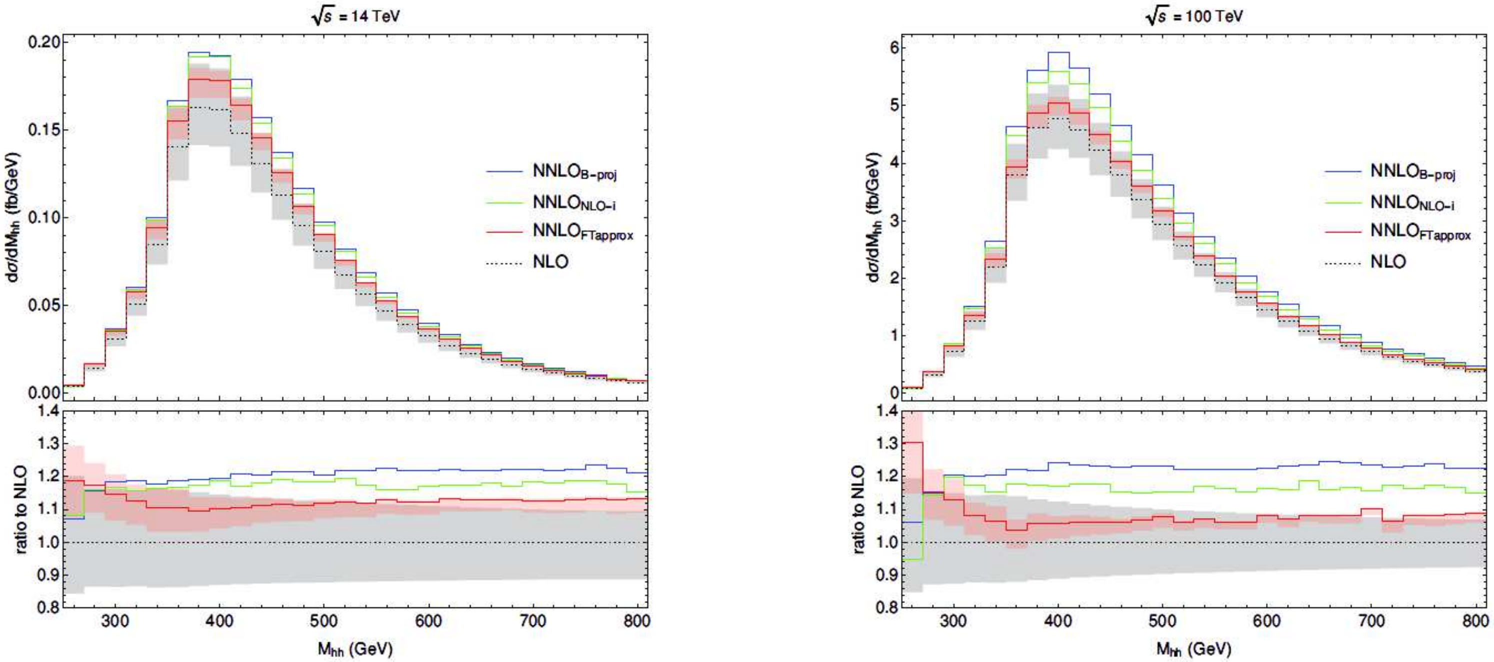
- soft gluon resummation: $\sim 10\%$
  $[M_H^2 \ll 4m_t^2]$

  Shao, Li, Li, Wang
  de Florian, Mazzitelli

- NLO: small quark mass expansion
  $[Q^2 \gg m_t^2]$

  Davies, Mishima, Steinhauser, Wellmann

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



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

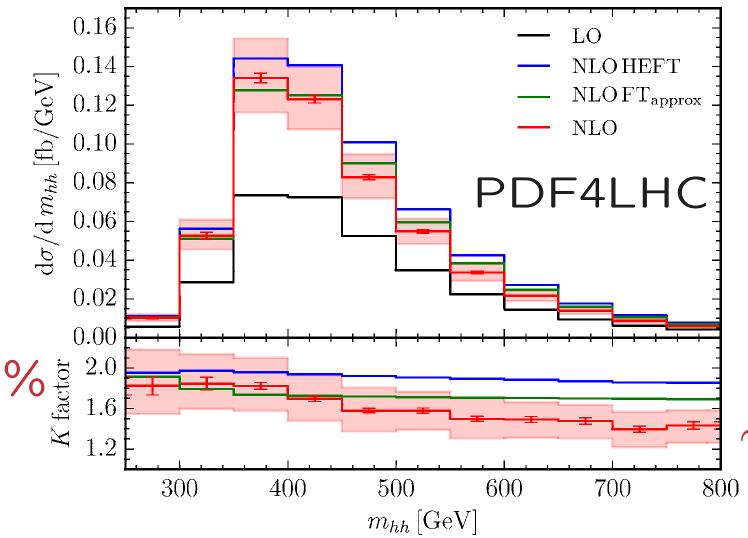
⇒ 20% effects beyond NLO

• NLO: matching to parton showers

Heinrich, Jones, Kerner, Luisoni, Vryonidou

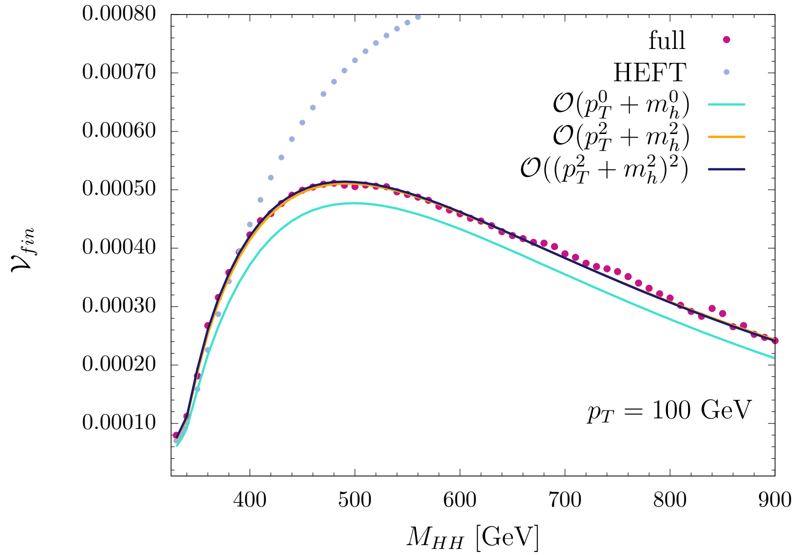
Full NLO calculation: top only

Numerical integration, sector decomposition, tensor reduction, contour deformation ($M_H = 125$ GeV, $m_t = 173$ GeV)



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

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



Bonciani, Degrassi, Giardino, Gröber

- 14 TeV: ($m_t = 173$ GeV) $\sigma_{NLO} = 32.91(10)^{+13.6\%}_{-12.6\%}\ fb$

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

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

- new expansion/extrapolation methods:

(i) $1/m_t^2$ expansion + conformal mapping + Padé approximants

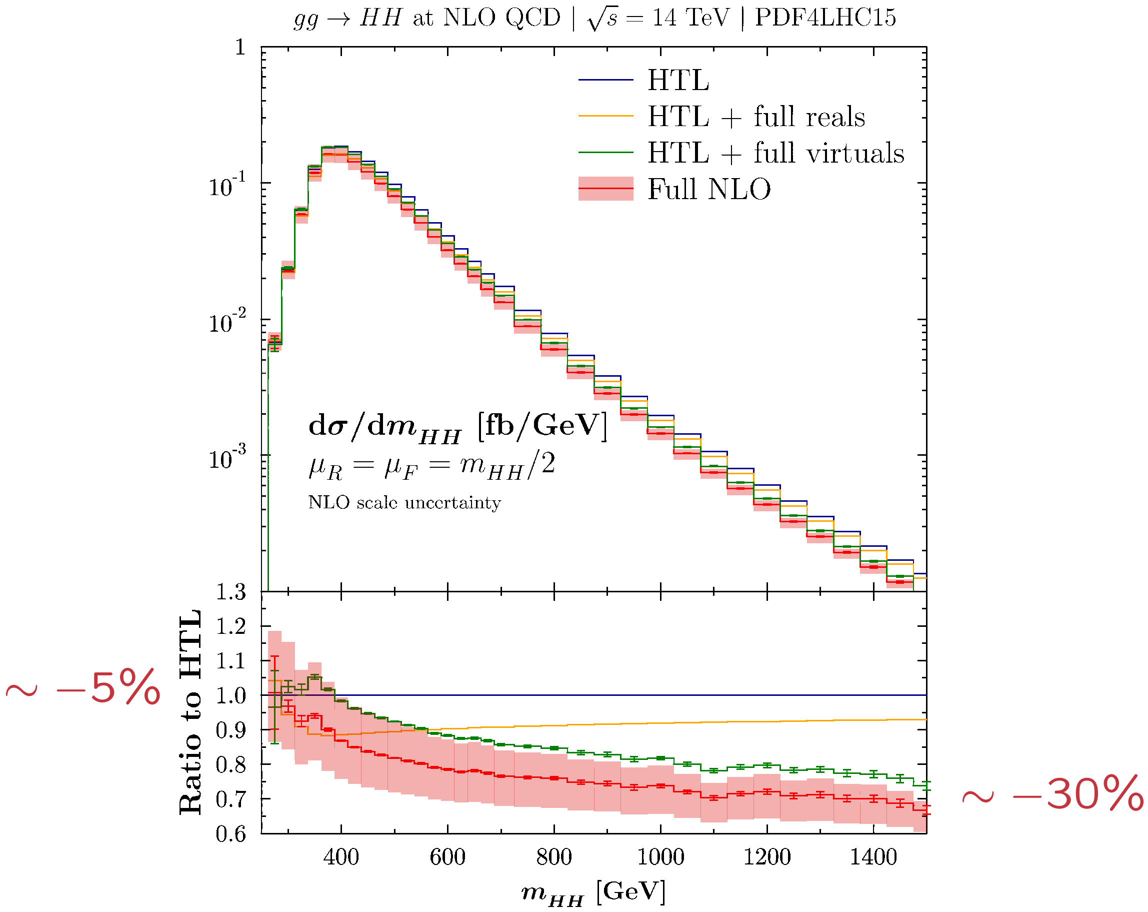
Gröber, Maier, Rauh

(ii) p_T^2 expansion

Bonciani, Degrassi, Giardino, Gröber

Full NLO calculation: top only

Numerical integration, IR subtraction, no tensor reduction, Richardson extrapolation



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

- 14 TeV: ($m_t = 172.5$ GeV)

$$\sigma_{NLO} = 32.78(7)^{+13.5\%}_{-12.5\%}\ fb$$

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

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

III CALCULATION

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

$$\sigma_{\text{LO}} = \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\text{LO}}(Q^2 = \tau s)$$

$$\Delta\sigma_{\text{virt}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\text{LO}}(Q^2 = \tau s) \; C$$

$$\Delta\sigma_{gg} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) \left\{ -zP_{gg}(z) \log \frac{\mu_F^2}{\tau s} + d_{gg}(z) + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\}$$

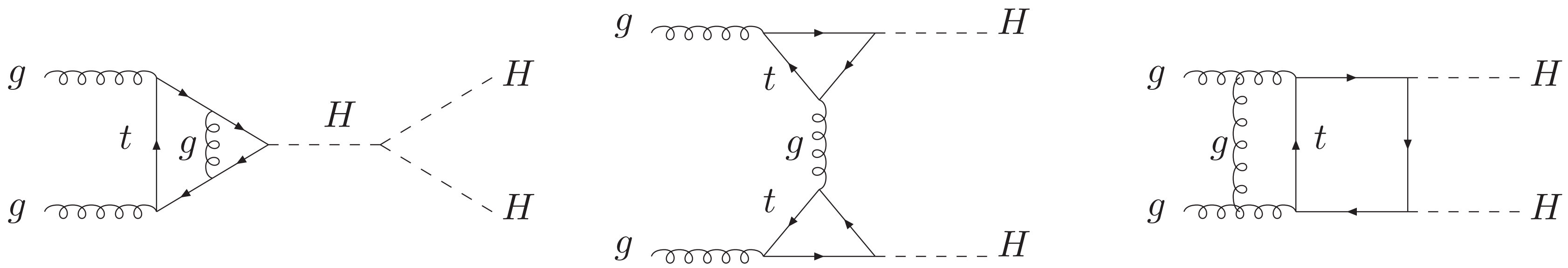
$$\Delta\sigma_{gq} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) \left\{ -\frac{z}{2} P_{gq}(z) \log \frac{\mu_F^2}{\tau s(1-z)^2} + d_{gq}(z) \right\}$$

$$\Delta\sigma_{q\bar{q}} = \frac{\alpha_s(\mu_R)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\text{LO}}(Q^2 = z\tau s) \; d_{q\bar{q}}(z)$$

$$C \to \pi^2 + \frac{11}{2} + C_{\triangle\triangle} + \frac{33 - 2N_F}{6} \log \frac{\mu_R^2}{Q^2}, \quad d_{gg} \to -\frac{11}{2}(1-z)^3, \quad d_{gq} \to \frac{2}{3}z^2 - (1-z)^2, \quad d_{q\bar{q}} \to \frac{32}{27}(1-z)^3$$

(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 $[m_t^2 \to m_t^2(1-ih)]$

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

- 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]

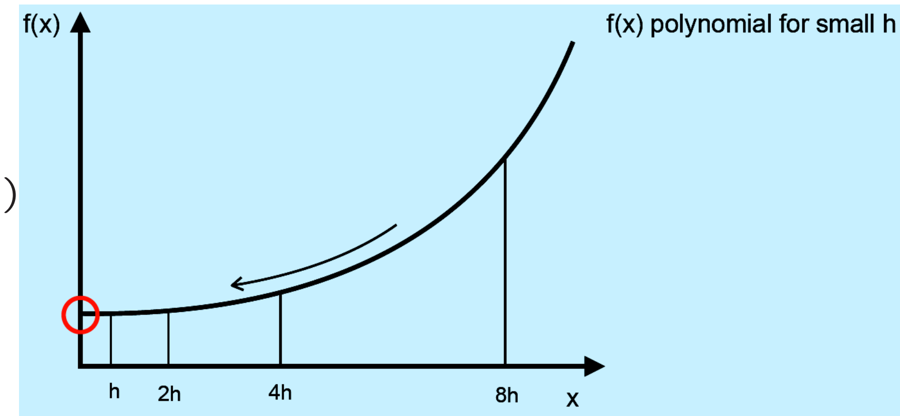
- extrapolation to NWA ($h \to 0$): Richardson extrapolation

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

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

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

etc.



$[h \geq 0.025]$

(ii) real corrections

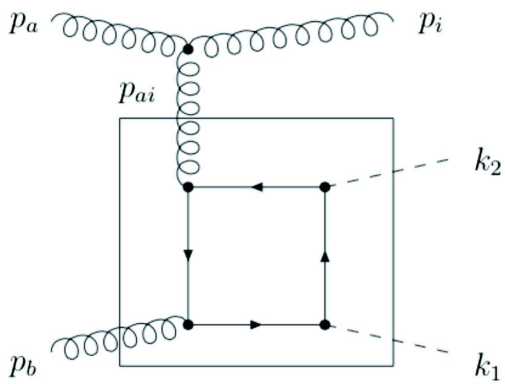
- full matrix elements generated with FeynArts and FormCalc

- matrix elements in HTL involving full LO sub-matrix elements subtracted $\to$ IR-, COLL-finite [adding back HTL results $\leftarrow$ HPAIR]

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

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

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



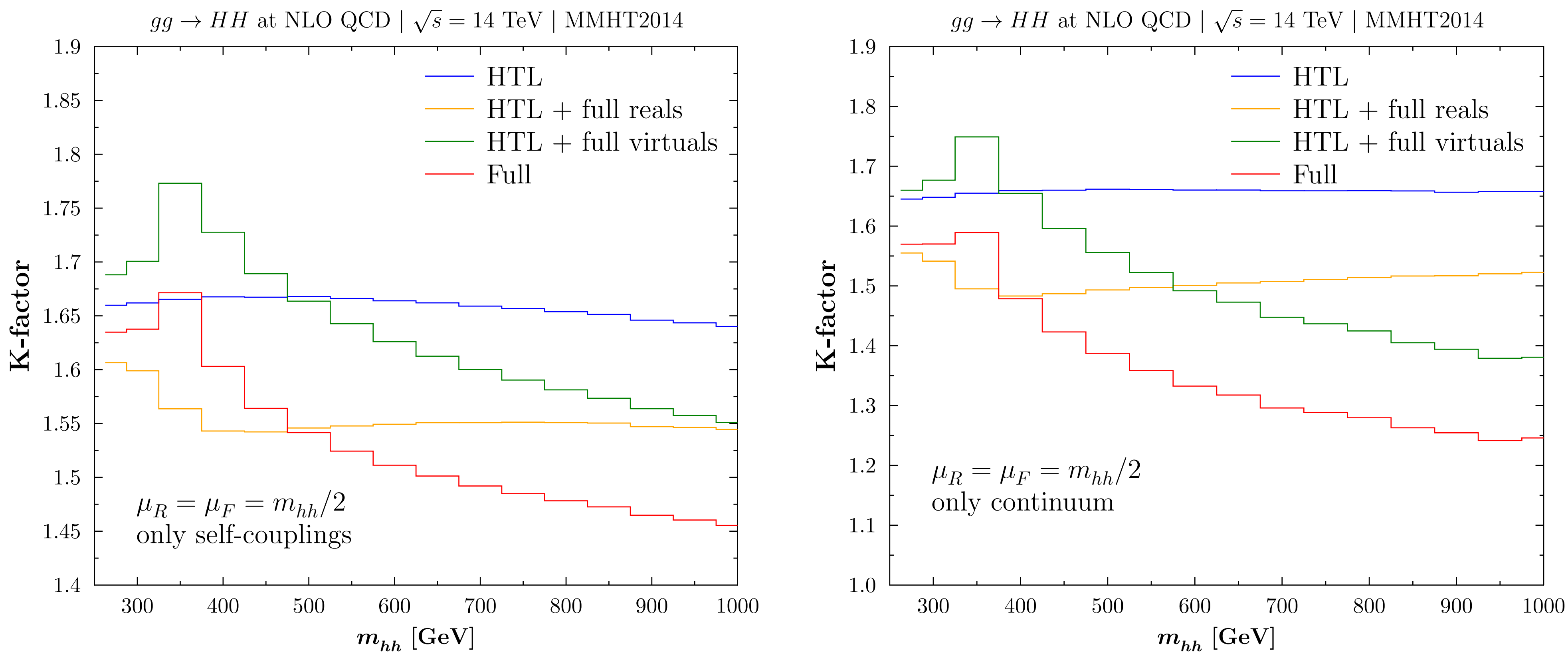
- PDFs: $\overline{\text{MS}}$ scheme, 5 flavours

(iii) results

	PDF4LHC15	MMHT2014
σ_{LO}	19.80 fb	23.75 fb
σ_{NLO}^{HTL}	38.66 fb	39.34 fb
σ_{NLO}	32.78(7) fb	33.33(7) fb

(iv) individual corrections

• take K-factors for triangle ($\leftarrow$ single Higgs) and box diagrams separately: total K-factor approximated by single Higgs K-factor?



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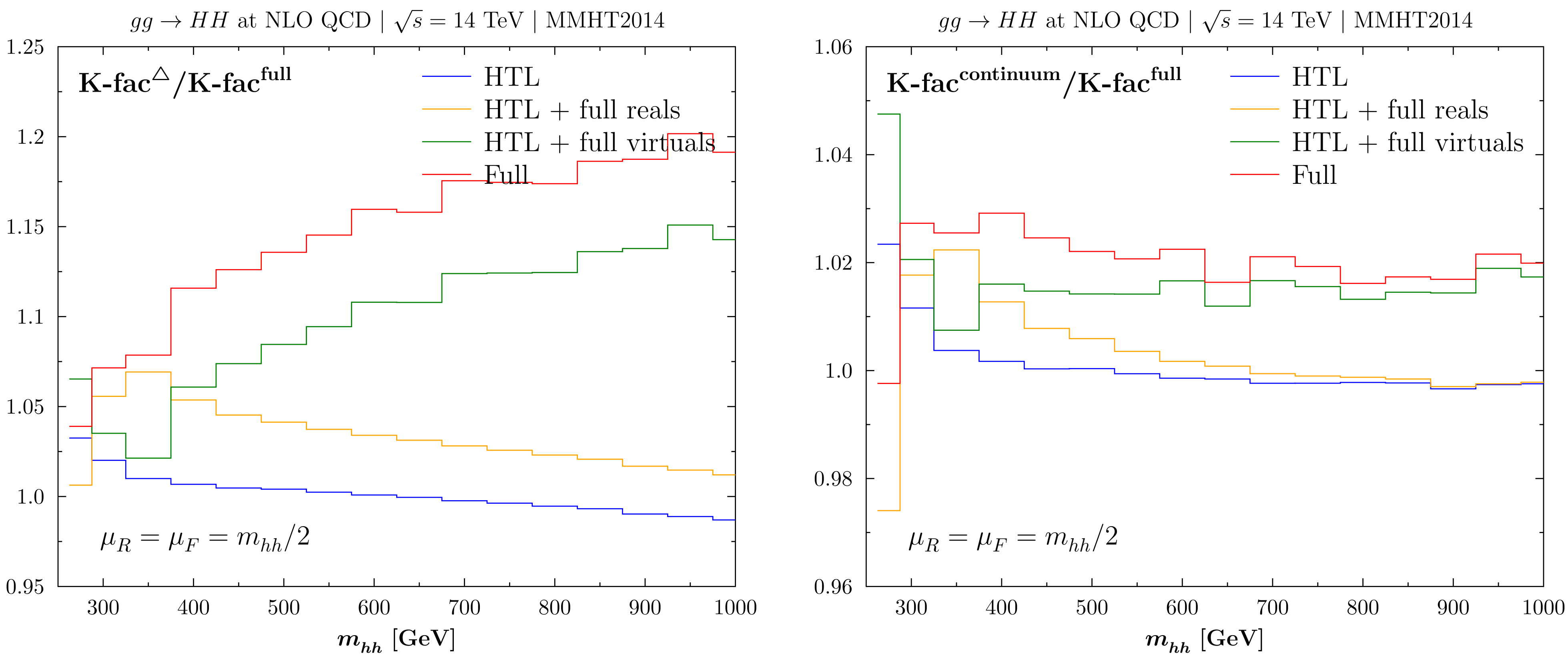

(v) PDF+α_s uncertainties

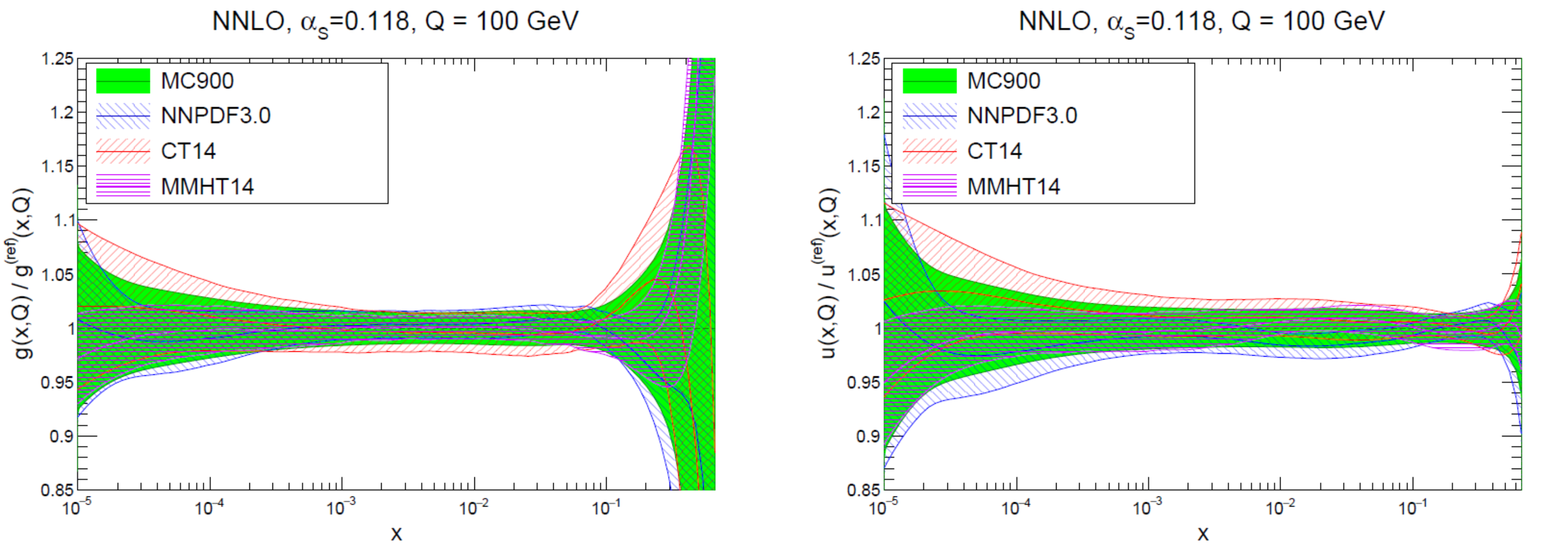

Figure 2: Comparison of the MC900 PDFs with the sets that enter the combination: CT14, MMHT14 and NNPDF3.0 at NNLO. We show the gluon and the up quark at $Q = 100$ GeV. Results are normalized to the central value of the prior set MC900.

- $\delta\sigma/\sigma \sim \pm 3.0\%$ @ LHC

(vi) 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:

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=300\ \text{GeV}} = 0.031(1)^{+4\%}_{-33\%}\ \text{fb/GeV},$$

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

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

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=1200\ \text{GeV}} = 0.000435(4)^{+0\%}_{-34\%}\ \text{fb/GeV}$$

- preliminary interpolation:

$$\sigma(gg \to HH) = 32.78^{+6\%}_{-21\%}\ \text{fb} \qquad \text{(very preliminary)}$$

(vi) uncertainties due to m_t for single Higgs

- 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:

$$\begin{aligned}
\sigma(gg \to H)|_{M_H=125\ \text{GeV}} &= 42.17^{+0.4\%}_{-0.5\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=300\ \text{GeV}} &= 9.85^{+7.5\%}_{-0.3\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=400\ \text{GeV}} &= 9.43^{+0.1\%}_{-0.9\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=600\ \text{GeV}} &= 1.97^{+0.0\%}_{-15.9\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=900\ \text{GeV}} &= 0.230^{+0.0\%}_{-22.3\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=1200\ \text{GeV}} &= 0.0402^{+0.0\%}_{-26.0\%}\ \text{pb}
\end{aligned}$$

IV CONCLUSIONS

- Higgs pair production: first *direct* access to trilinear self-coupling
- NLO QCD corrs known $\rightarrow \Delta_{scale} \lesssim 10\%$ @ LHC
- NLO top mass effects: $\sim -15\%$ for σ_{tot}, $\sim -5 \ldots -30\%$ for distr.
- sizeable uncertainties due to scheme and scale of top mass
- top mass effects beyond NLO: $\sim 5\%$? Grigo, Hoff, Steinhauser
- extension to BSM: bottom loops
- important to develop NLO event generators [$\leftarrow$ backgrounds]

BACKUP SLIDES

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x} g(x,\mu_F^2) g\left(\frac{\tau}{x},\mu_F^2\right)$$

$$\frac{d\mathcal{L}^{gq}}{d\tau} = \int_\tau^1 \frac{dx}{x} \left[q(x,\mu_F^2) g\left(\frac{\tau}{x},\mu_F^2\right) + g(x,\mu_F^2) q\left(\frac{\tau}{x},\mu_F^2\right)\right]$$

$$\frac{d\mathcal{L}^{q\bar{q}}}{d\tau} = \int_\tau^1 \frac{dx}{x} \left[q(x,\mu_F^2) \bar{q}\left(\frac{\tau}{x},\mu_F^2\right) + \bar{q}(x,\mu_F^2) q\left(\frac{\tau}{x},\mu_F^2\right)\right]$$