

Beyond the heavy top limit in partonic Higgs production at the LHC

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in collaboration with Matthias Steinhauser and Alexey Pak

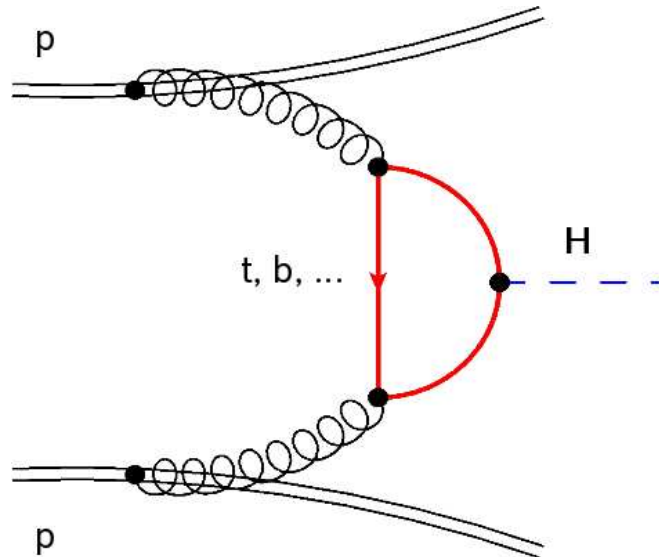
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Higgs boson production at the LHC: $pp \rightarrow H + X$

- Dominant channel (for intermediate m_H):
 $gg \rightarrow H$ via a top-quark loop



⇒ **Very well studied process!**

- **Scales of process**

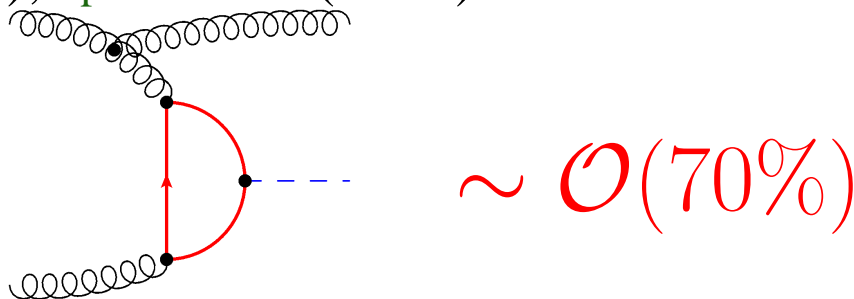
- $\sqrt{S_{part}} \sim 100 - 14000 \text{ Gev}$
- Higgs mass $m_H \sim 100 - 300 \text{ Gev}$
- Top-quark mass $m_t \sim 170 \text{ Gev}$

■ Leading order: **Geordi, Glashow, Machacek, Nanopoulos '78]**
(full dependence on m_H/m_t)

QCD corrections: large!

- Next-to-leading order:

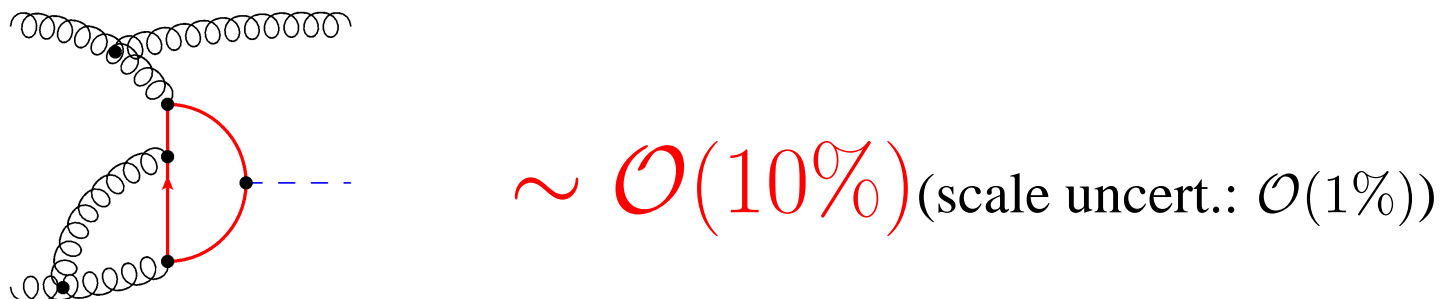
Dawson; Djouadi, Spira, Zerwas '91 (effective theory); Dawson and Kauffman '94 (up to $\sim 1/m_t^2$); Spira et al '95 (exact)



- Next-to-next-to-leading order:

Harlander, Kilgore '02 (soft expansion); Anastasiou, Melnikov '02; Ravindran, Smith, van Neerven '03

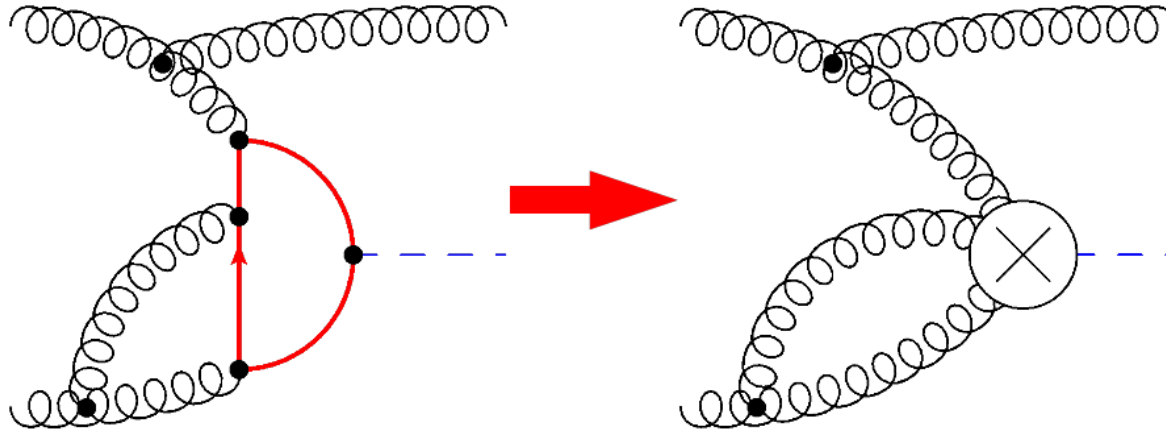
Until recently, only available in the heavy top limit



Also available: *EW*, *QCD - EW*, *NNLO + NNLL*, *N³LO* threshold enhanced, π^2 -resummation, *NNLO* differential distributions...

Catani, de Florian, Grazzini, Nason; Ahrens, Becher, Neubert, Yang; Actis, Passarino, Sturm, Uccirati; Anastasiou, Boughezal, Petriello; de Florian, Grazzini

Effective theory for heavy top limit

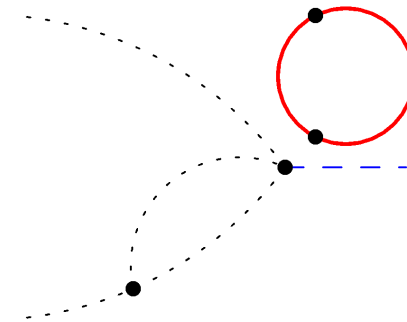
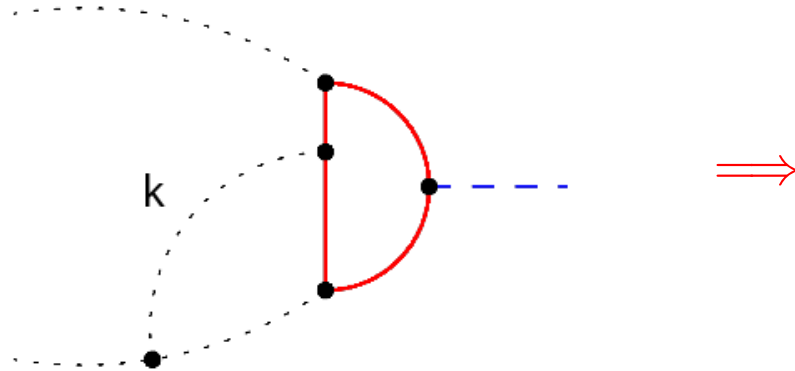


Effective Lagrangian :

$$L_{eff} \sim C \cdot G_{\mu\nu} G^{\mu\nu}$$

- Assumptions $\frac{m_H}{m_t} \rightarrow 0$, $\frac{\sqrt{S_{part}}}{m_t} \rightarrow 0$
- How important the $O(\frac{1}{m_t})$ terms ???

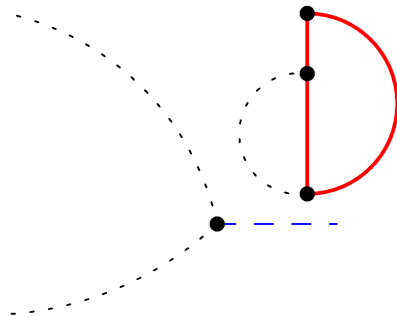
Asymptotic expansion in m_H/m_t



$$k \sim m_H, \sqrt{S_{part}} \implies$$



$$k \sim m_t \implies$$

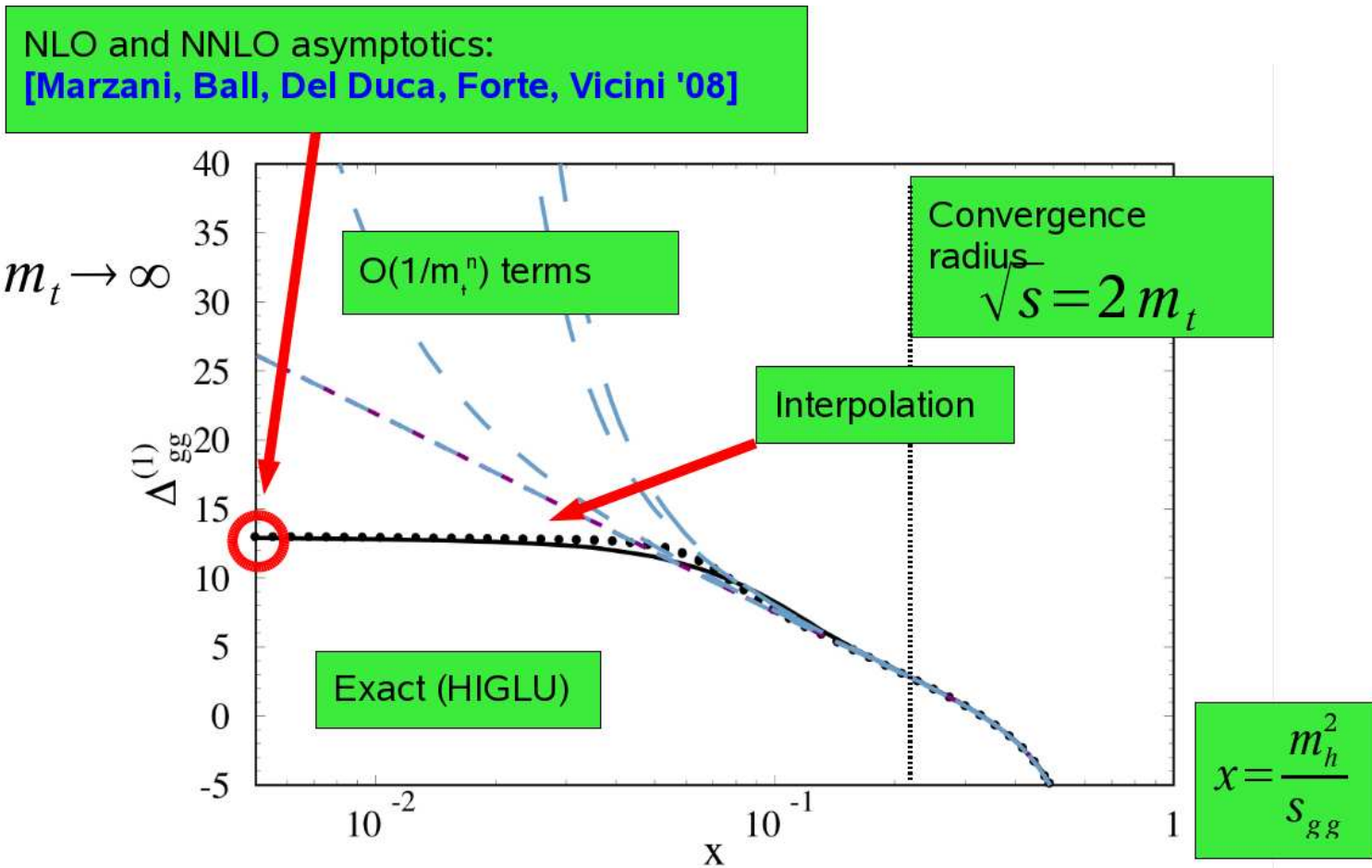


- At NNLO, need to calculate (1,2,3-loop vacuum bubbles) \otimes (2-loop $2 \rightarrow 1$, 1-loop $2 \rightarrow 2$, tree-level $2 \rightarrow 3$ functions)

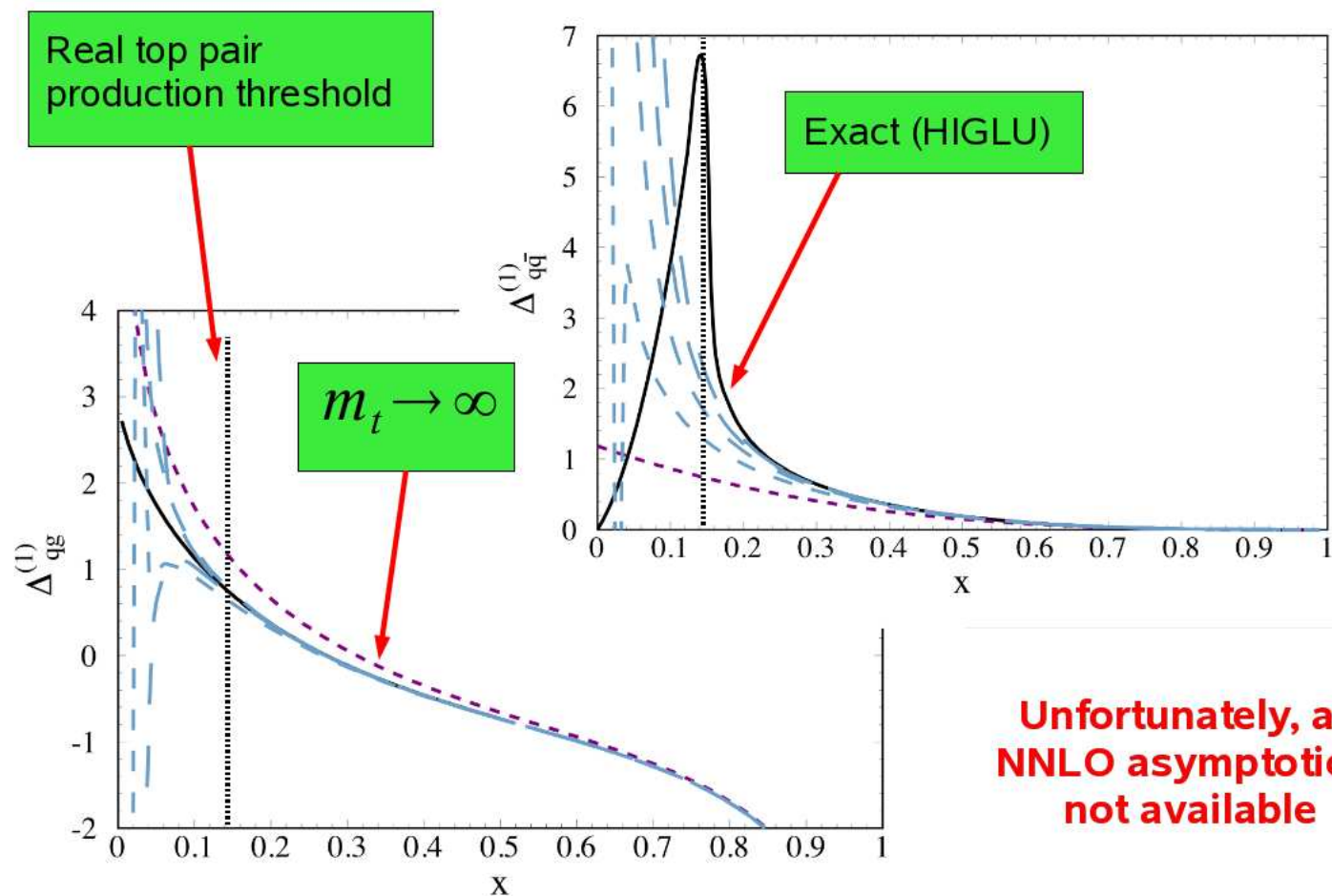
No need for higher order operators!

NLO gg channel: effects $O(1/m_t)$

$$\sigma_{partonic} = LO \times (\Delta^{(0)} + (\alpha_s/\pi)\Delta^{(1)} + (\alpha_s/\pi)^2\Delta^{(2)})$$

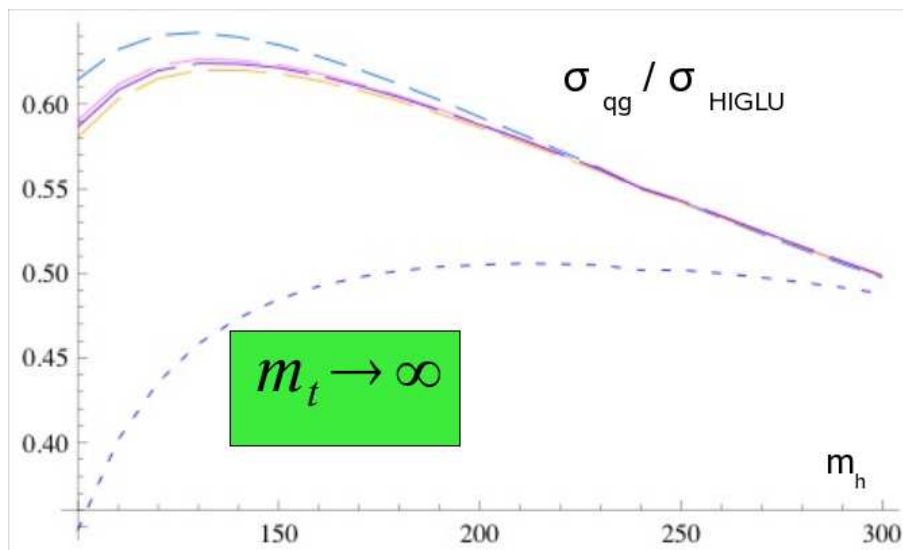


NLO qg and $q\bar{q}$ channels @ part. level



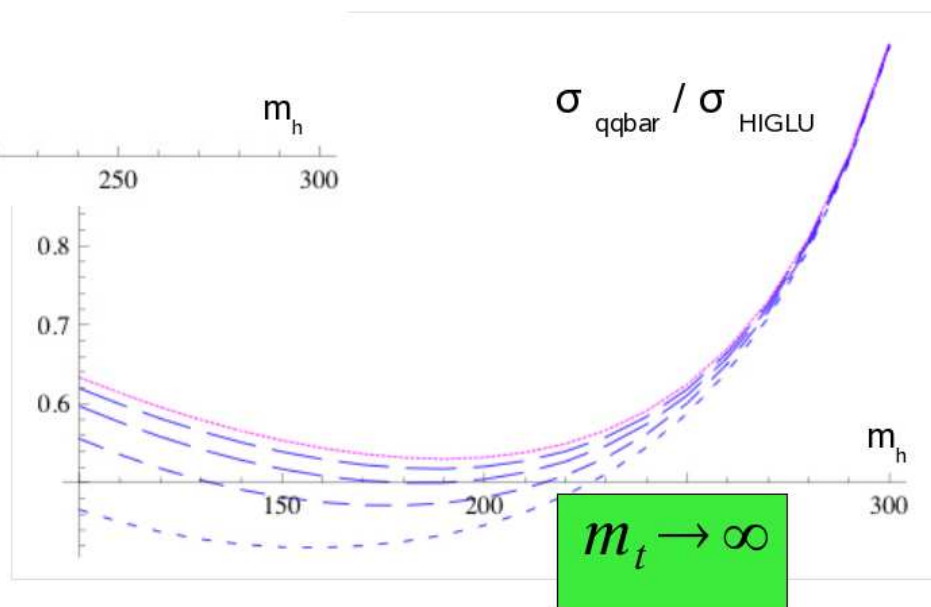
Unfortunately, at NNLO asymptotics not available

NLO qg and $q\bar{q}$ channels @ hadr. level



Poor-man's recipe:
use $1/m_t$ expansion
below threshold, and
heavy top limit above

**Not particularly bad:
O(40%) difference
for subleading terms**



NNLO top mass effects

- Virtual corrections calculated up to $\mathcal{O}\left(\frac{1}{m_t^8}\right)$

Harlander, Ozeren '09

Pak, Rogal, Steinhauser '09

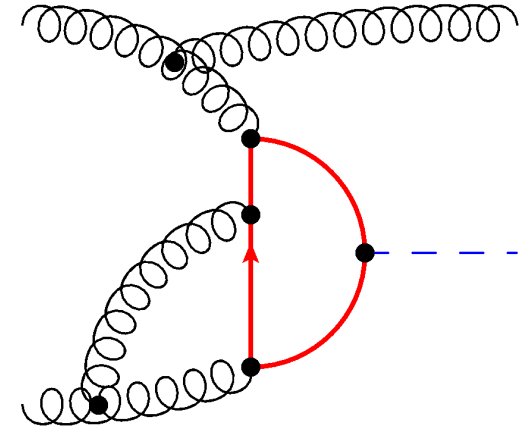
- Full NNLO result: (see K.Ozeren's talk)

Harlander, Ozeren '09

$\mathcal{O}\left(\frac{1}{m_t^6}\right)$ corrections calculated

$2 \rightarrow 2, 2 \rightarrow 3$ phase space integration

Result as a series in $(1 - x)$ up to $13 - th$ order



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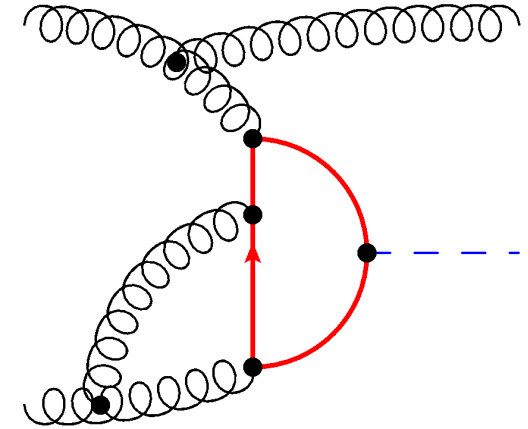
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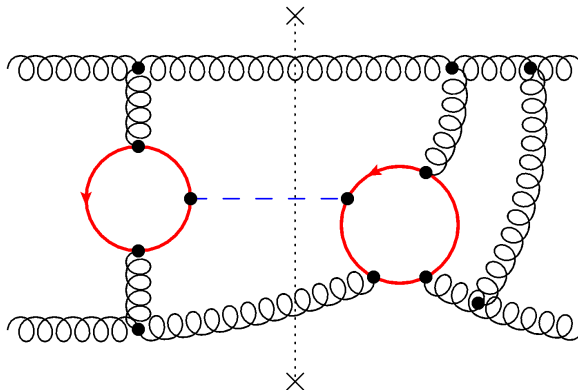


Very complicated calculations.

Cross-check is important!

Chain of calculations:

- Use of Optical Theorem: imaginary part of *4-loop* diagrams



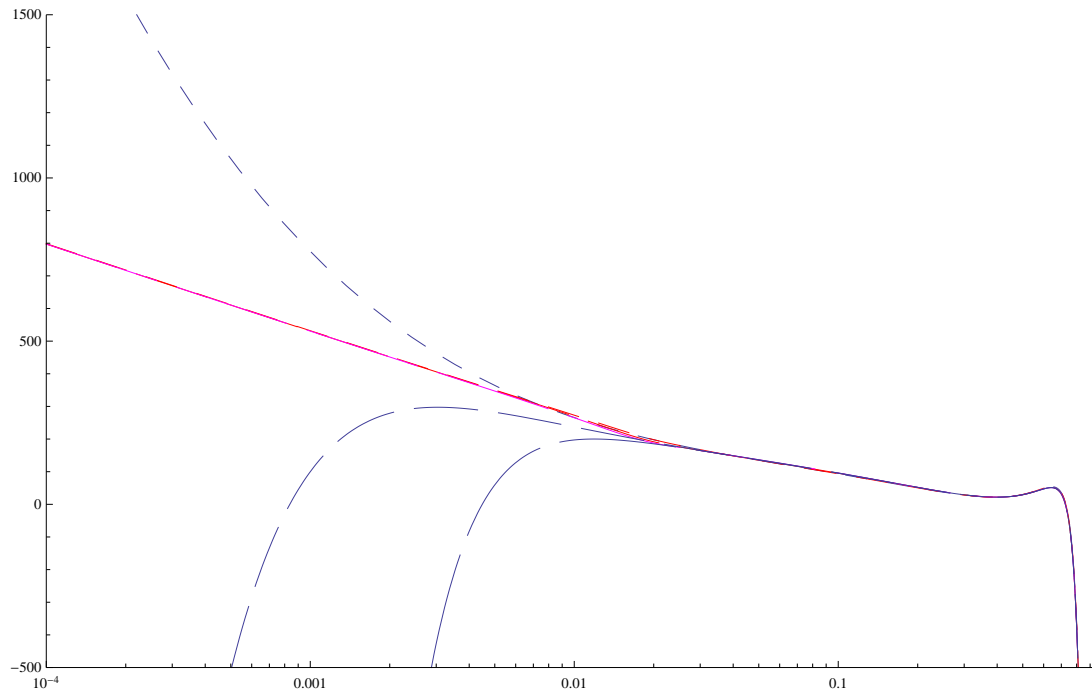
- Diagrams: QGRAF Nogueira '93, zeros filtered
- Two independent calculations (Q2E / EXP / MATAD + a custom program)
- Reduction by Laporta algorithm (retaining full x -dependence)
- 2-loop x -dependent master integrals: recalculated using differential equations and soft expansion in terms of *HPLs*

~ 20000 non-zero diagrams, ~ 1 month of 100 x CPU for $\mathcal{O}(1/m_t^6)$ terms !!!

Result: few first terms in $\left(\frac{m_H^2}{m_t^2}\right)$ expansion, full dependence on $x = \frac{m_H^2}{S_{part}}$

NNLO results @ part. level: gg channel

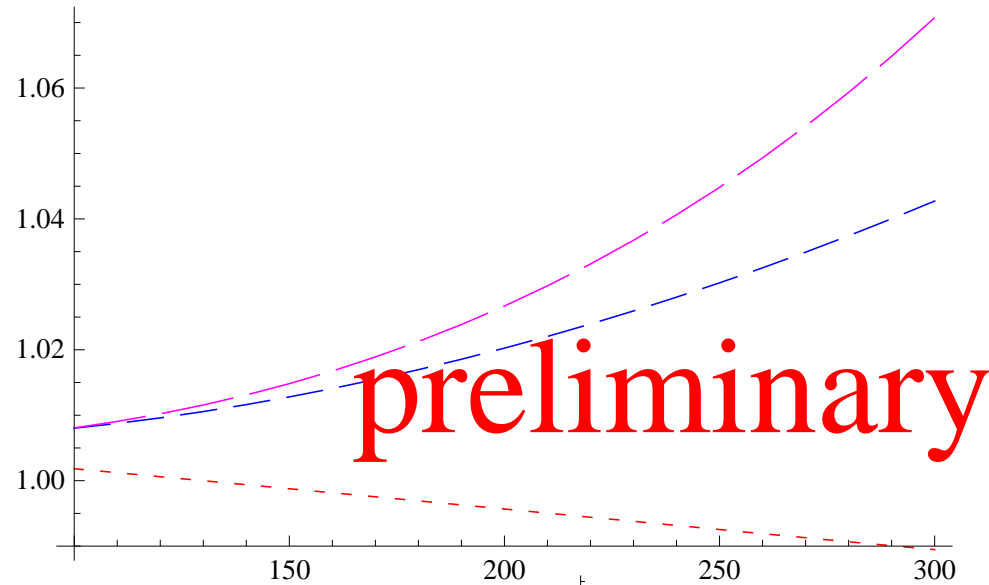
- $\Delta_{gg}^{(2)}$: longer dashed lines - higher terms in $1/m_t$,
red lines - *modified* NNLO asymptotics of Marzani, Ball, Del Duca, Forte, Vicini



- Expanding in $(1 - x)$ - **full analytic agreement** with results by R. Harlander and K. Ozeren!

NNLO results @ hadr. level: gg channel

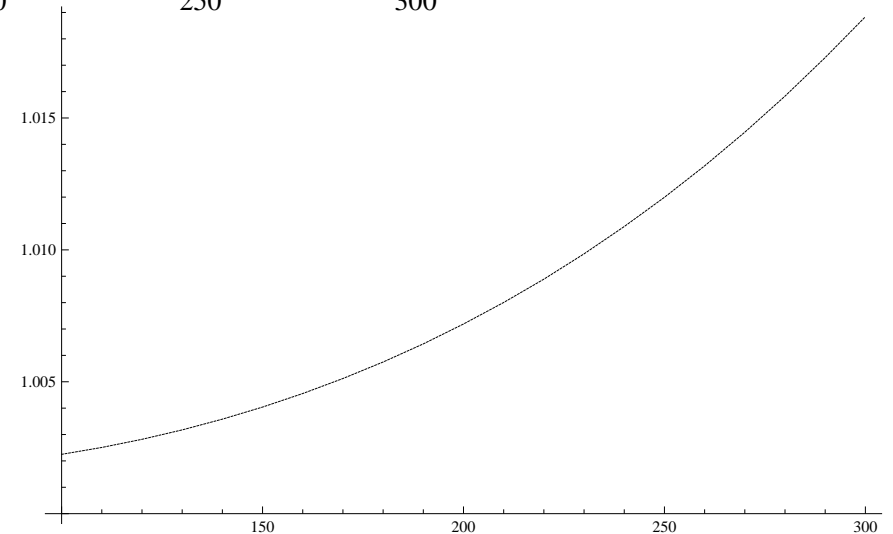
- ratios $\sigma_{gg, approx.}^{(2)} / \sigma_{gg, heavy top, no approx.}^{(2)}$



- Effect on the full cross-section (LO+NLO+NNLO):

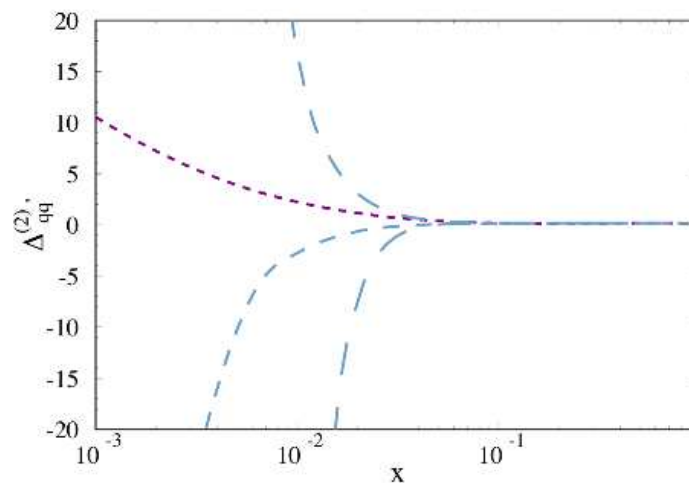
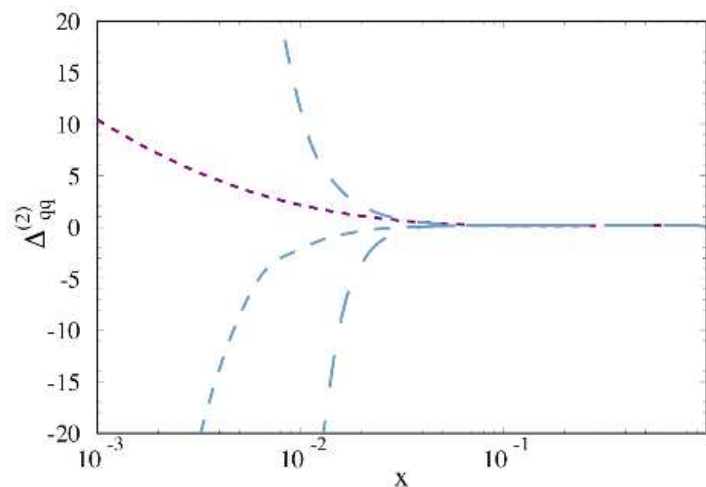
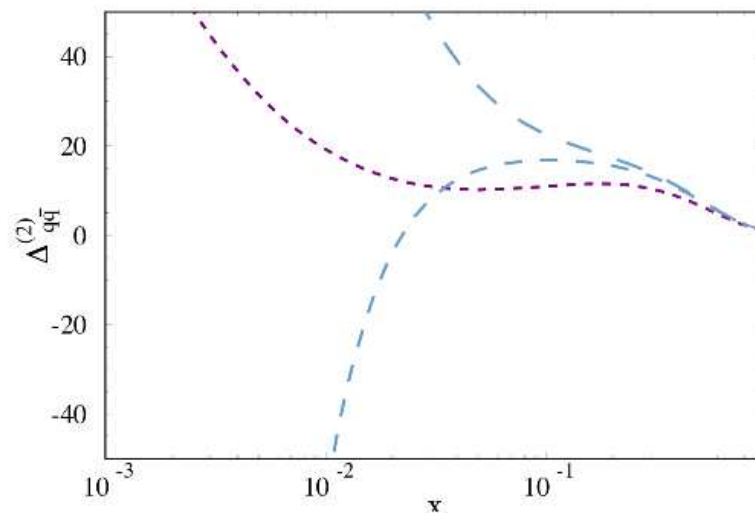
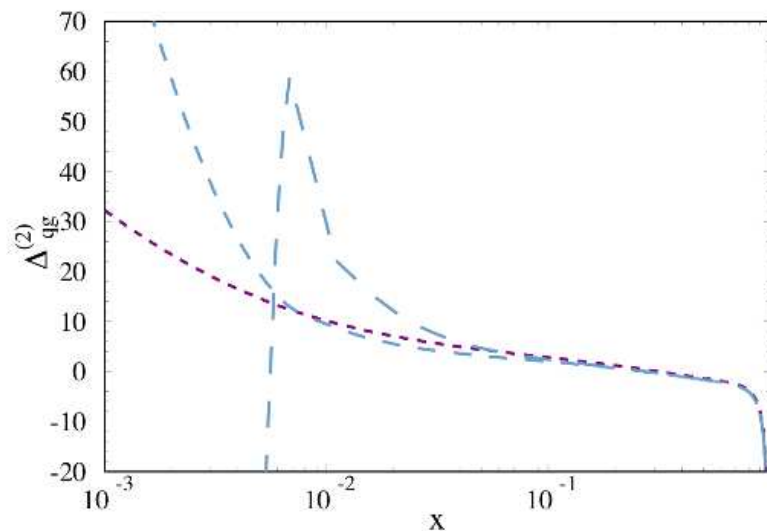
$$\frac{\sigma_{approx.}^{highest(1/m_t)}}{\sigma_{heavy top}}$$

< 1% for m_h up to 240 GeV



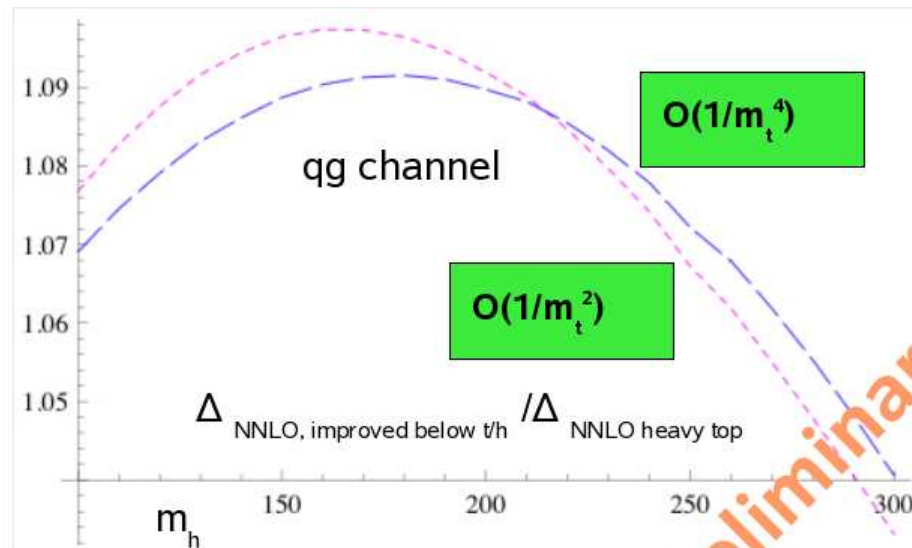
Subleading channels @ parton level

● $\Delta_{qg, q\bar{q}, qq, qq'}^{(2)}$: longer dashed lines - higher terms in $1/m_t$,



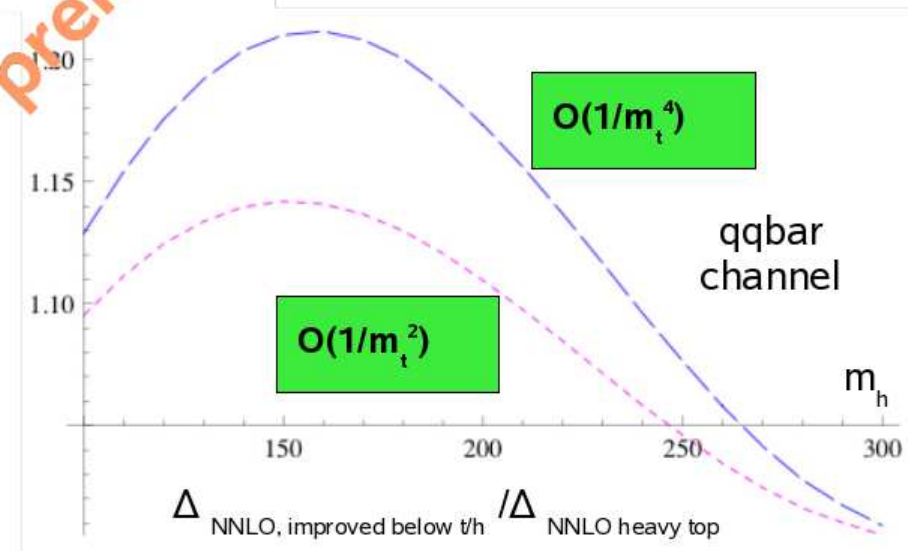
Subleading channels @ hadron level

- Ratios of $\sigma_{qg, q\bar{q}}^{(2)}$ ($1/m_t$ expansion below threshold + heavy top limit above) to $\sigma_{qg, q\bar{q}; heavy\ top}^{(2)}$



preliminary!

Shifts not dramatic,
very small impact



Summary

- m_t corrections to Higgs production @ NNLO **have been found exactly** retaining full x -dependence
- Expansions around soft limit ([R.Harlander](#) and [K.Ozeren](#)) are **confirmed**
- Shift of hadronic results is smaller than scale uncertainties (**a non-trivial result!**)
- Results and a more detailed phenomenology analysis **are ready** to be published