Top quark mass effects in Higgs boson pair production at the LHC

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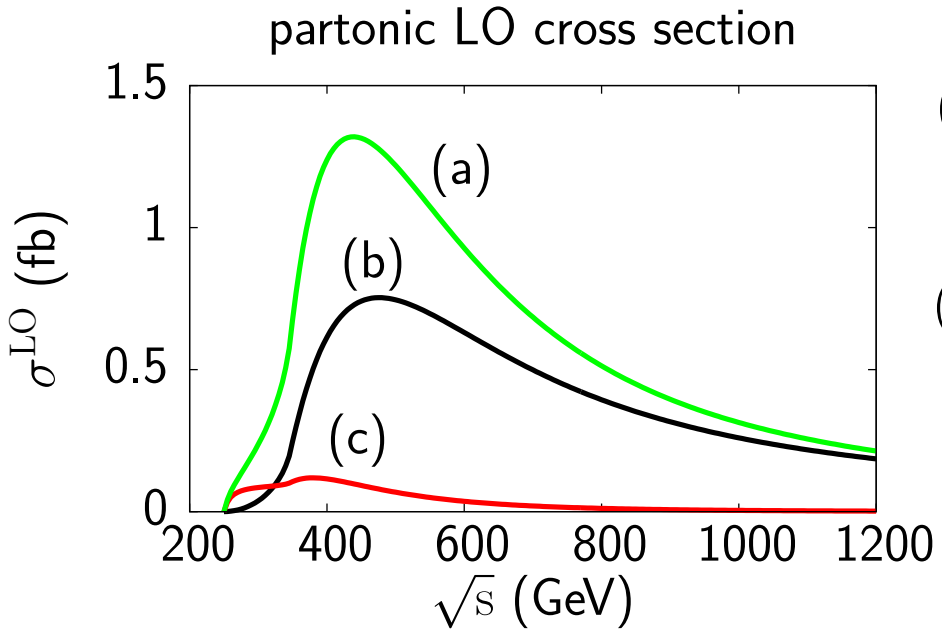
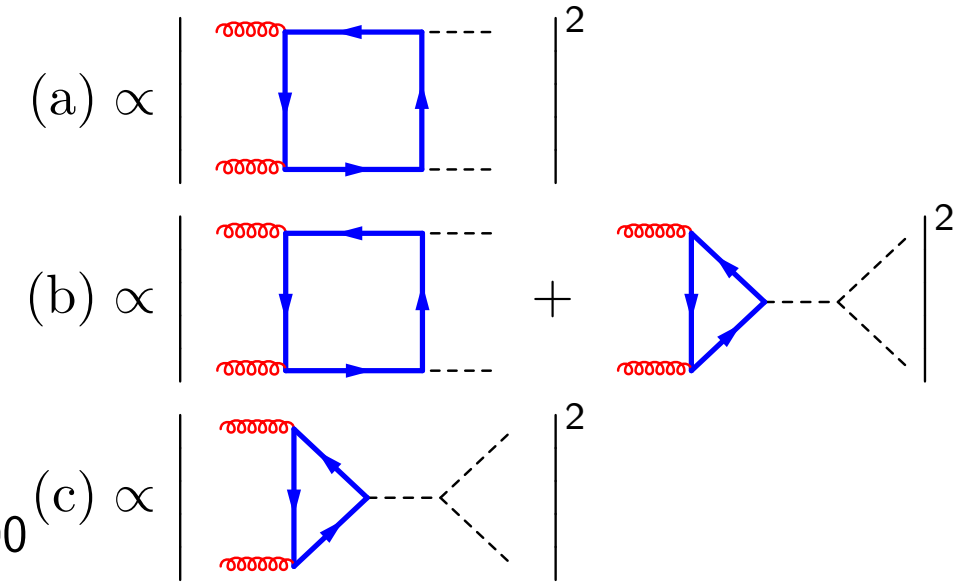
Motivation

Higgs potential in the Standard Model

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4 \quad \lambda = \frac{m_H^2}{2v^2} \approx 0.13 \quad v = \text{Higgs vev}$$





Measurement at the (14 TeV) LHC

- $b\bar{b}\gamma\gamma$ channel, 600 fb^{-1}: $\lambda \neq 0$ [Baur, Plehn, Rainwater '04]
- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$ channel: "promising"
  $b\bar{b}W^+W^-$ channel: "not promising"
  [Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira '13]
- ratio of double Higgs / single Higgs cross sections
  600 fb^{-1}: $\lambda > 0$
  3000 fb^{-1}: $\lambda^{+30\%}_{-20\%}$
  [Goertz, Papaefstathiou, Yang, Zurita '13]
- $b\bar{b}\gamma\gamma$ channel, 3000 fb^{-1}: $\lambda \pm 40\%$
  [Barger, Everett, Jackson, Shaughnessy '14]
- and many more, e.g.:
  [Papaefstathiou, Yang, Zurita '13]
  [Dolan, Englert, Spannowsky '12]

Theory status

- LO with full m_t dependence [Glover, van der Bij '88; Plehn, Spira, Zerwas '98]
- NLO in the limit $m_t \to \infty$ [Dawson, Dittmaier, Spira '98]
- NNLO$^{\text{approx.}}$ in the limit $m_t \to \infty$ [de Florian, Mazzitelli '13]
- resummation [Shao, Li, Li, Wang '13]
- matched and merged [Maierhöfer, Papaefstathiou '13; Li, Yan, Zhao '14; Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro '14]
- ...

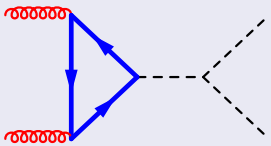
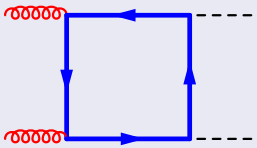
$$\sigma_{\text{total, hadronic}} \approx (20^{\text{LO}} + 20^{\text{NLO, } m_t \to \infty} + 8^{\text{NNLO, } m_t \to \infty})\ \text{fb}$$

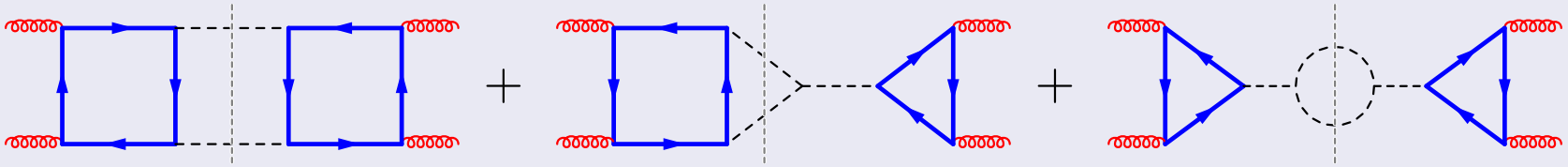
$$(\sqrt{s_{\text{had}}} = 14\ \text{TeV},\ \mu = 2m_H)$$

this talk: NLO corrections of $\mathcal{O}(1/m_{\text{top}}^n)$

Calculation via optical theorem

$$\sigma_{\text{total}}(\text{gg} \to \text{HH}) \propto \text{Disc}(\mathcal{M}(\text{gg} \to \text{gg}))$$

$\int \text{dPS} \Big|$  $+$  $\Big|^2 \propto$



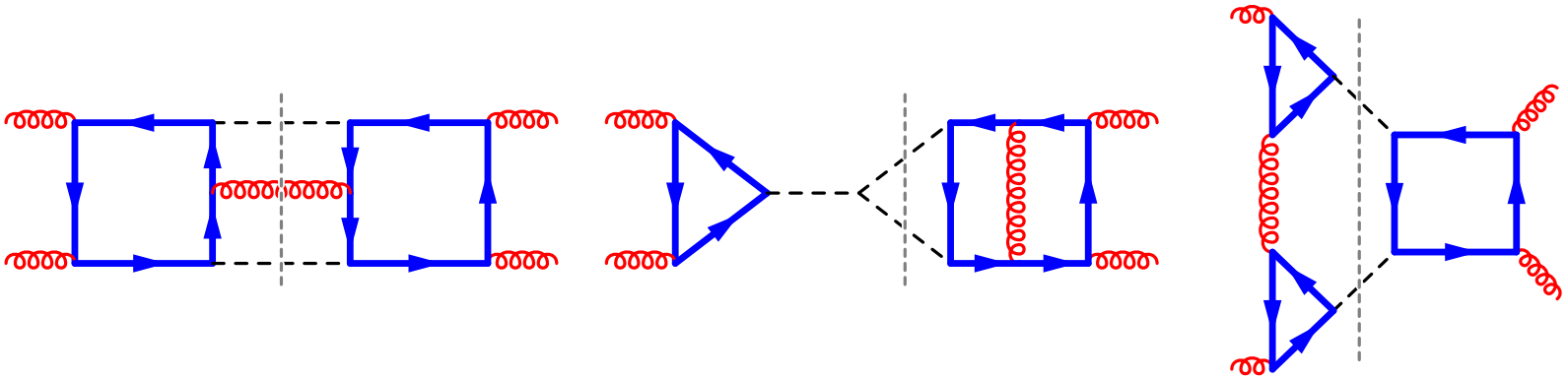
pro
- calculating Disc(...) possible at master integral level
- simplified kinematics
- master integrals and phase space integration at once

con
- ~~more loops~~, more diagrams
- only total cross section

Feynman diagrams

gluon-gluon channel

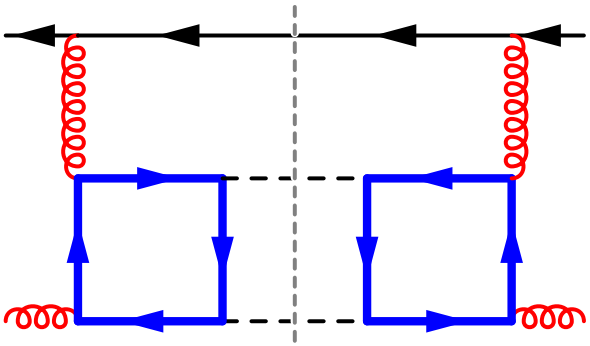
- virtual corrections
  - $gg \to hh$
    126 two loop diagrams
  - cross check: $gg \to gg$
    1052 four loop diagrams
- real corrections
  - $gg \to gg$
    1530 four loop diagrams



Feynman diagrams

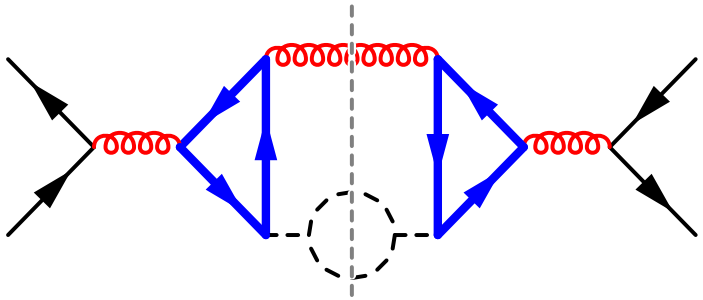
quark-gluon channel

- $qg \to qg$
  34 four loop diagrams



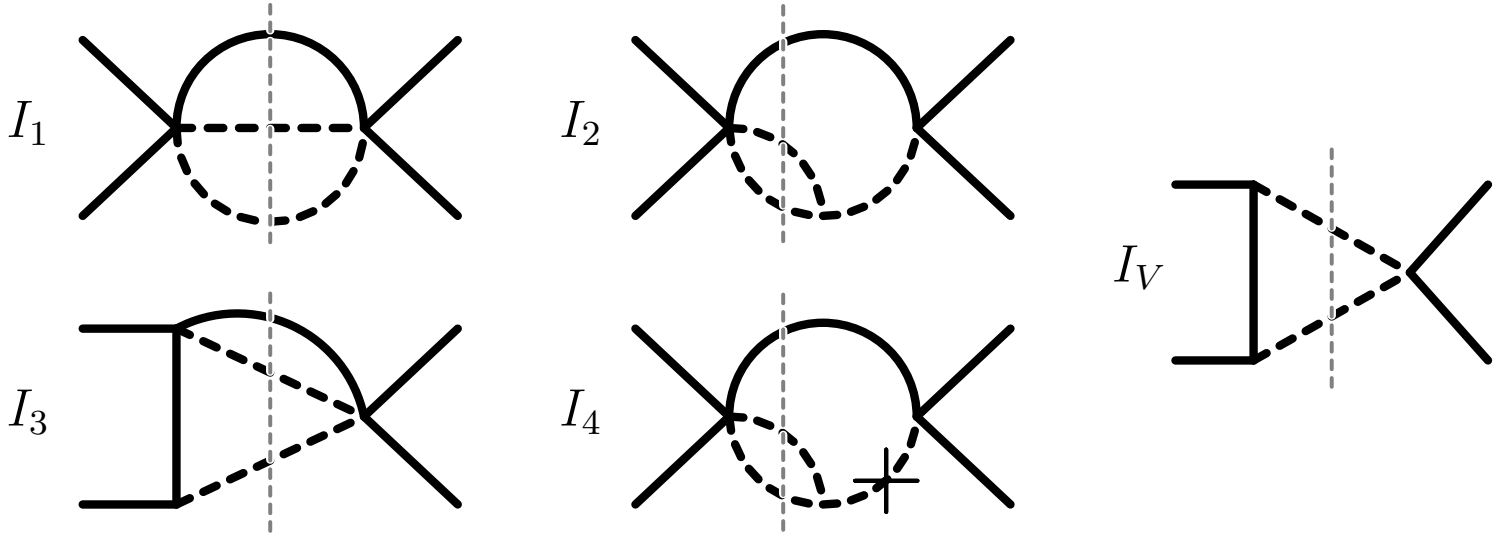
quark-anti-quark channel

- $q\bar{q} \to q\bar{q}$
  34 four loop diagrams

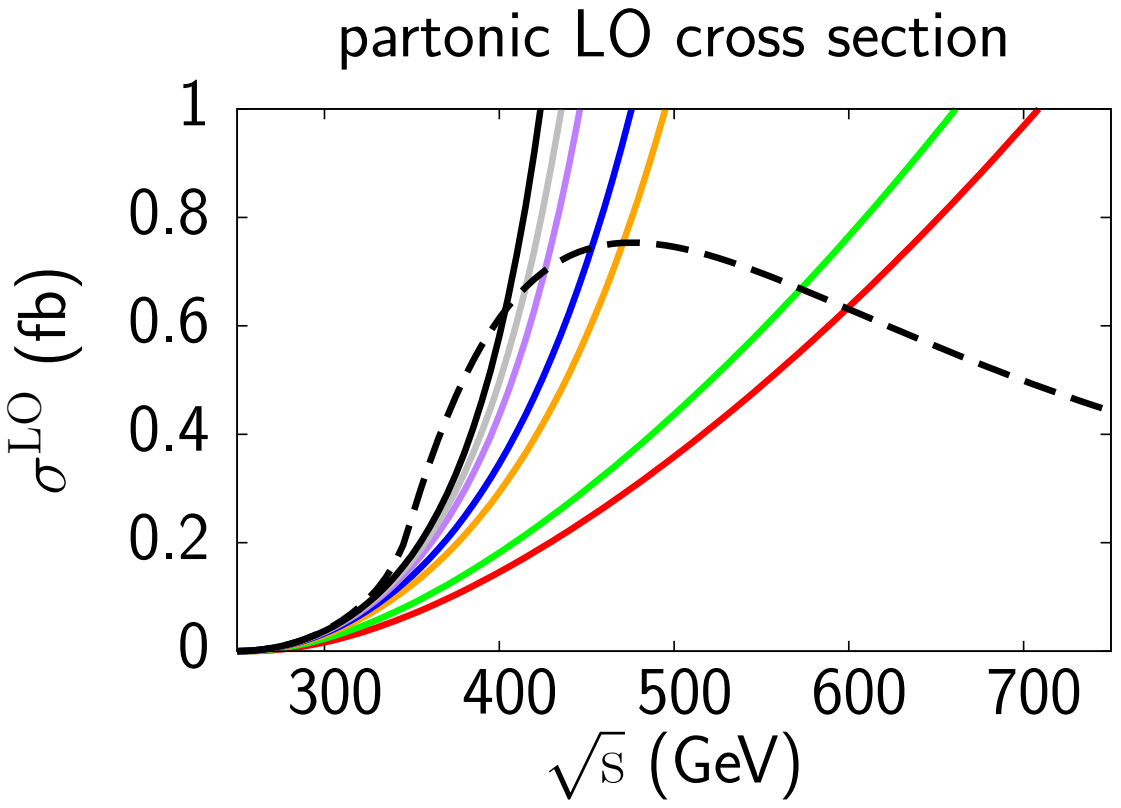


Master integrals

- at NLO: 4 (real) + 1 (virtual) master integrals
- $2 \to 3$ and $2 \to 2$ phase space integrals
- dependent on $s = (q_1 + q_2)^2$ and m_H
- simplification: expansion in $\delta = 1 - \frac{4m_H^2}{s}$ at least up to $\mathcal{O}(\delta^{50})$
  - converges very well
  - no visible numerical effect on cross section



Expansion in $1/m_t$



$$\rho = \frac{m_H^2}{m_t^2} \approx 0.5$$

ρ^0 ρ^1 ρ^2 ρ^3 ρ^4 ρ^5 ρ^6

scales:

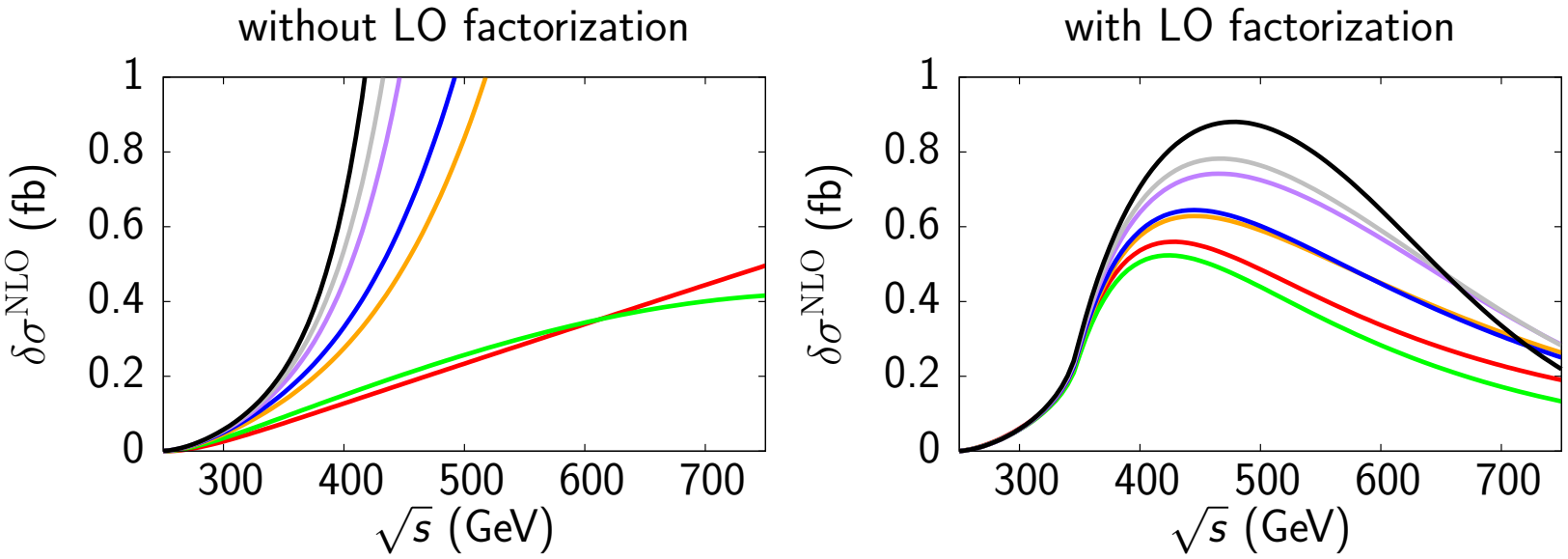
$$m_t = 173 \text{ GeV}$$
$$m_H = 126 \text{ GeV}$$
$$\sqrt{s} \geq 252 \text{ GeV}$$

dashed line exact in m_t

solid lines expansion in $1/m_t$

Partonic cross sections: gluon-gluon channel

Factorization of exact LO cross section



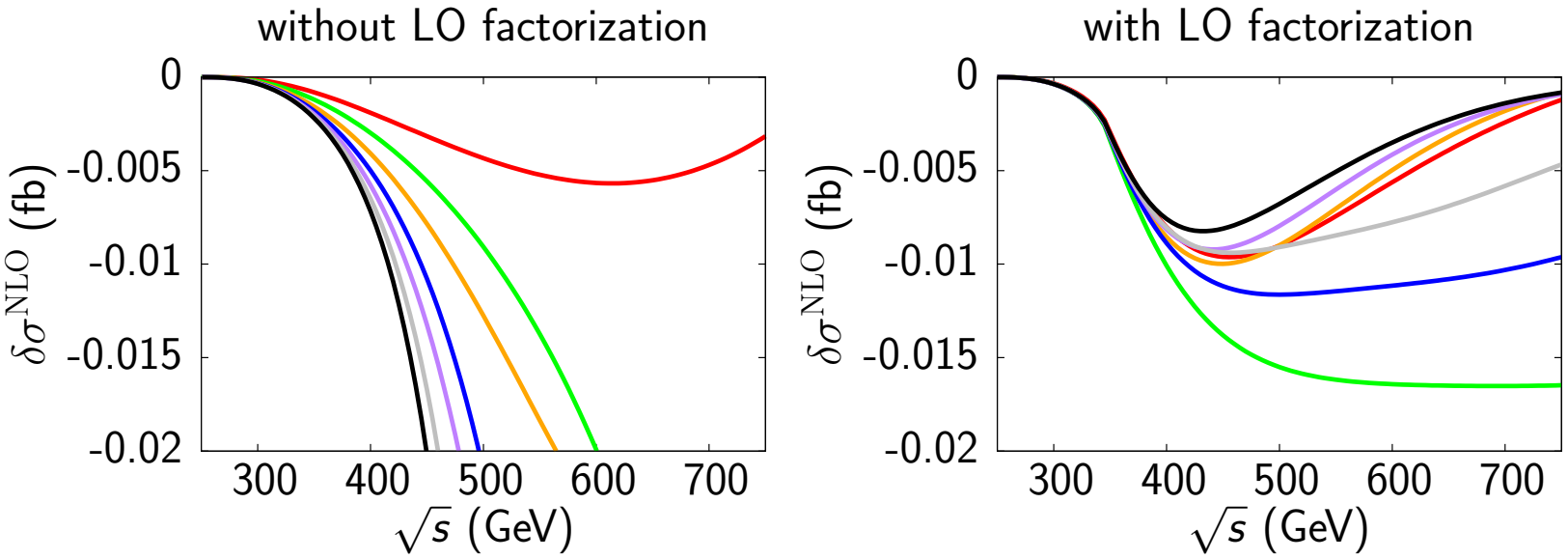
ρ^0 ρ^1 ρ^2 ρ^3 ρ^4 ρ^5 ρ^6

factorize exact LO cross section

$$\sigma^{\mathrm{NLO}}_{\mathrm{expanded}} \to \sigma^{\mathrm{LO}}_{\mathrm{exact}} \frac{\sigma^{\mathrm{NLO}}_{\mathrm{expanded}}}{\sigma^{\mathrm{LO}}_{\mathrm{expanded}}}$$

Partonic cross sections: quark-gluon channel

Factorization of exact LO cross section



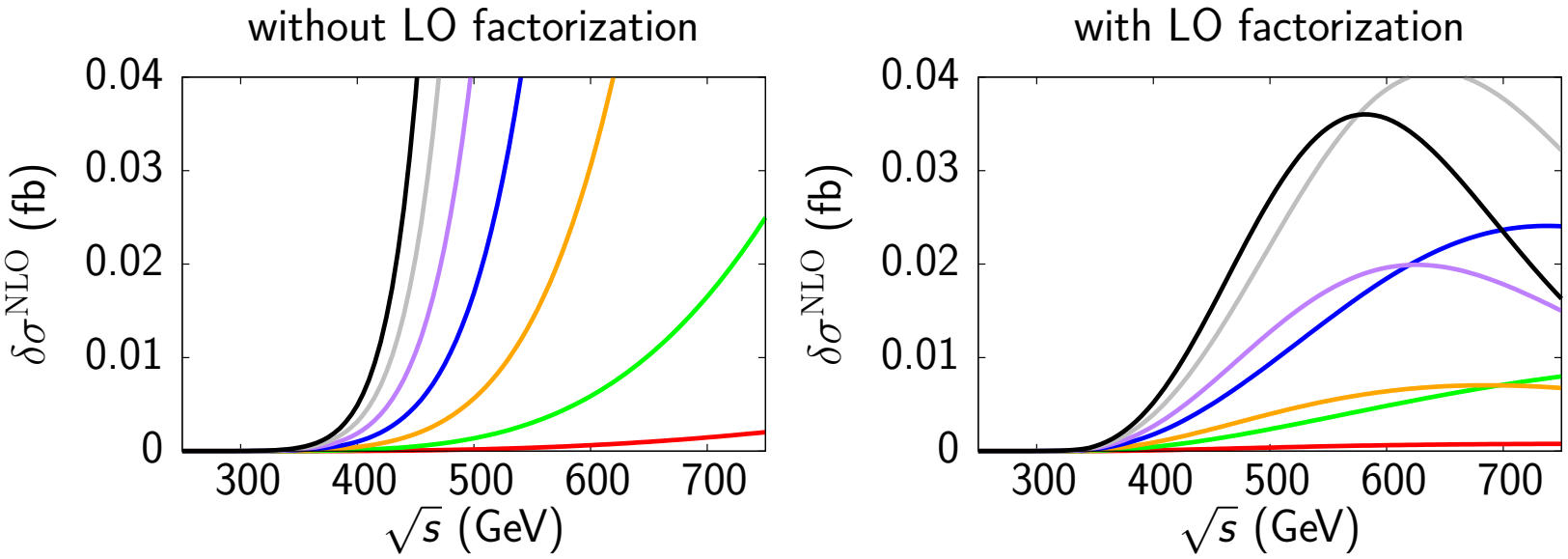
ρ^0 ρ^1 ρ^2 ρ^3 ρ^4 ρ^5 ρ^6

factorize exact LO cross section

$$\sigma^{\rm NLO}_{\rm expanded} \to \sigma^{\rm LO}_{\rm exact} \frac{\sigma^{\rm NLO}_{\rm expanded}}{\sigma^{\rm LO}_{\rm expanded}}$$

Partonic cross sections: quark-anti quark channel

Factorization of exact LO cross section

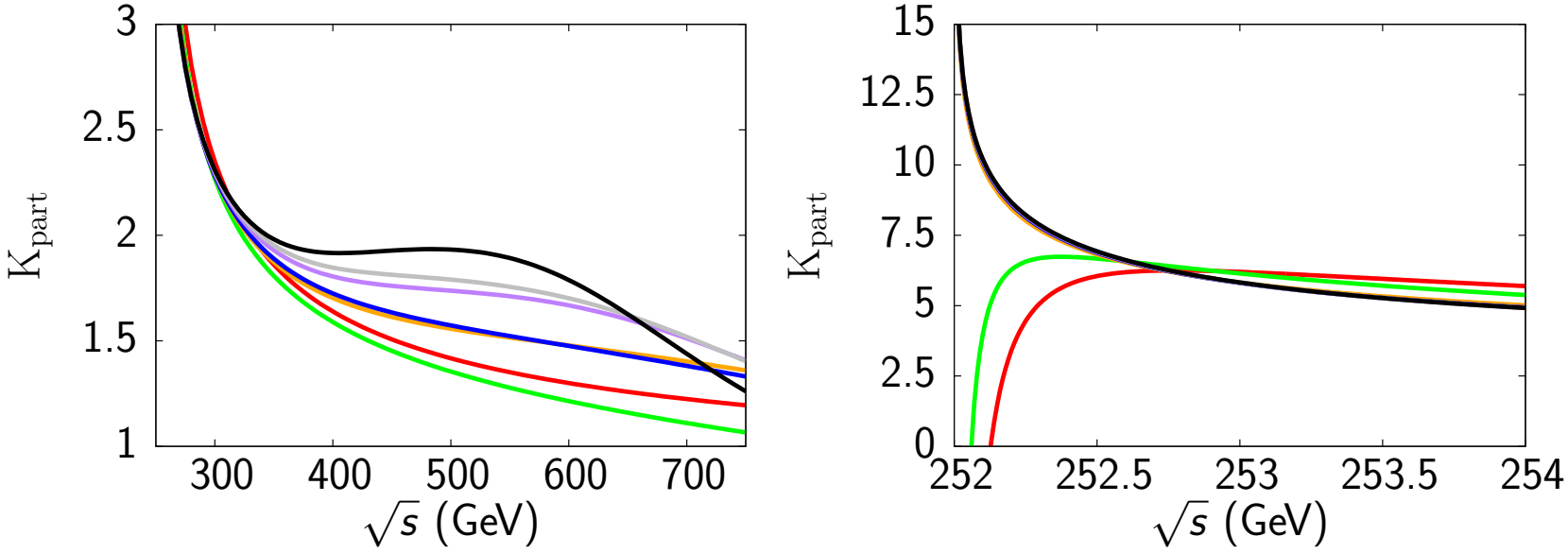


ρ^0 ρ^1 ρ^2 ρ^3 ρ^4 ρ^5 ρ^6

factorize exact LO cross section

$$\sigma^{\rm NLO}_{\rm expanded} \to \sigma^{\rm LO}_{\rm exact} \frac{\sigma^{\rm NLO}_{\rm expanded}}{\sigma^{\rm LO}_{\rm expanded}}$$

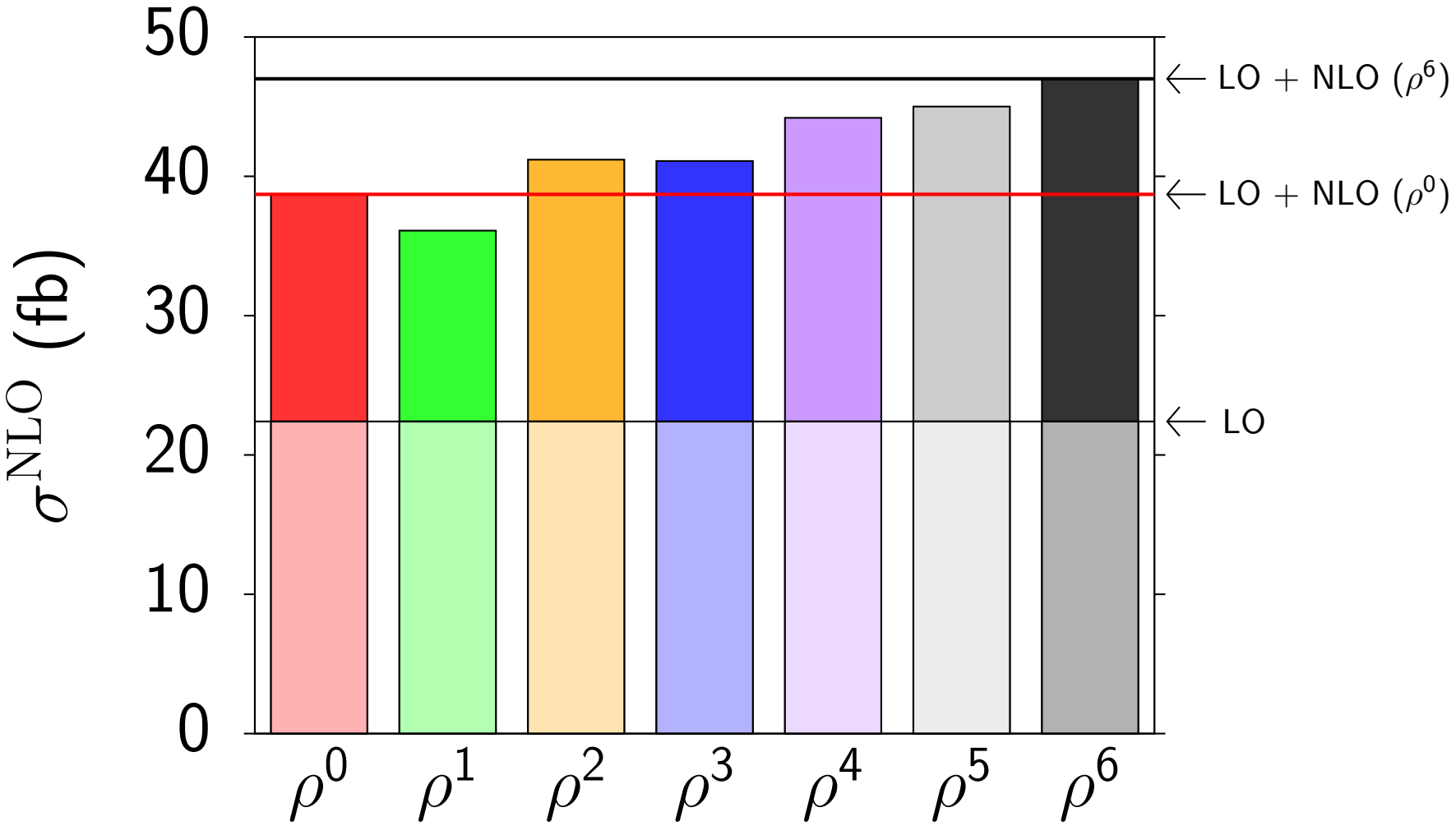
K-factors



- strong enhancement for $\sqrt{s} \lesssim 400$ GeV
  (remember: LO cross section vanishes at threshold)
- close to threshold highly dependent on $\mathcal{O}(\rho)$

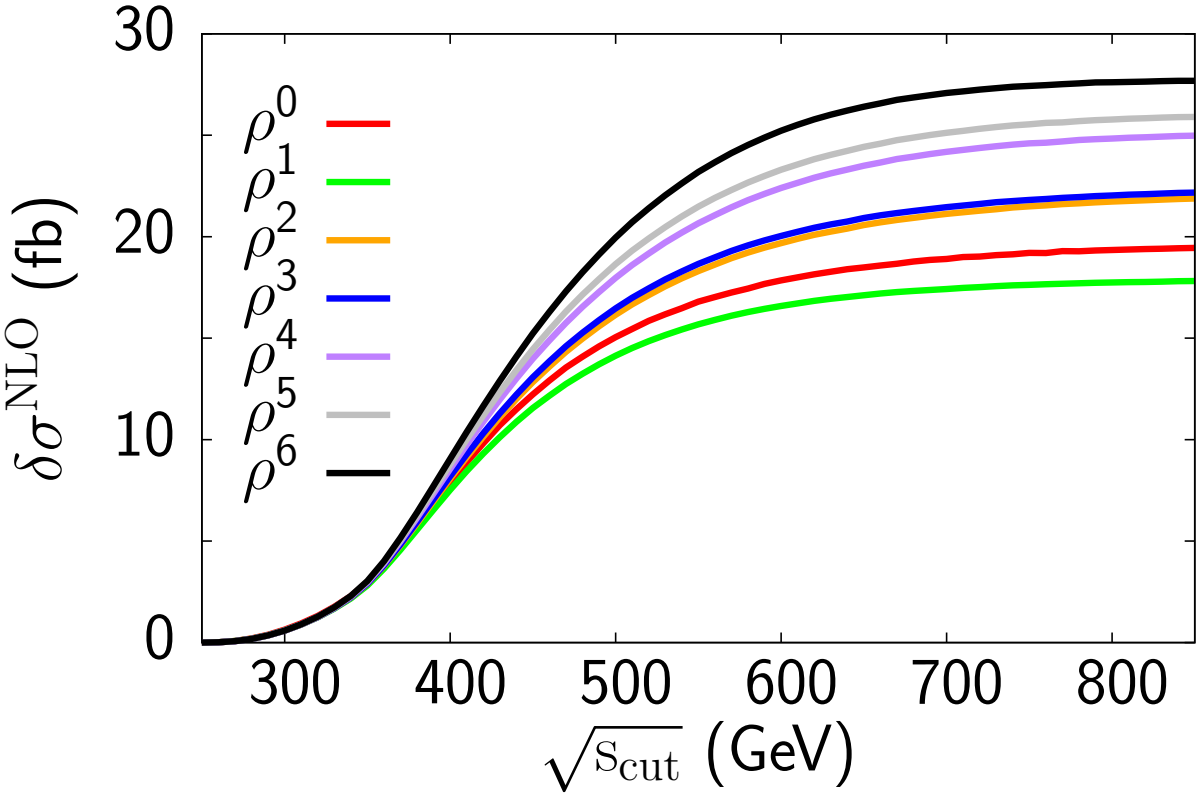
Total hadronic cross section (all channels)

MSTW2008 pdfs, $\sqrt{s_{\rm had}} = 14$ TeV, $\mu = 2m_H$

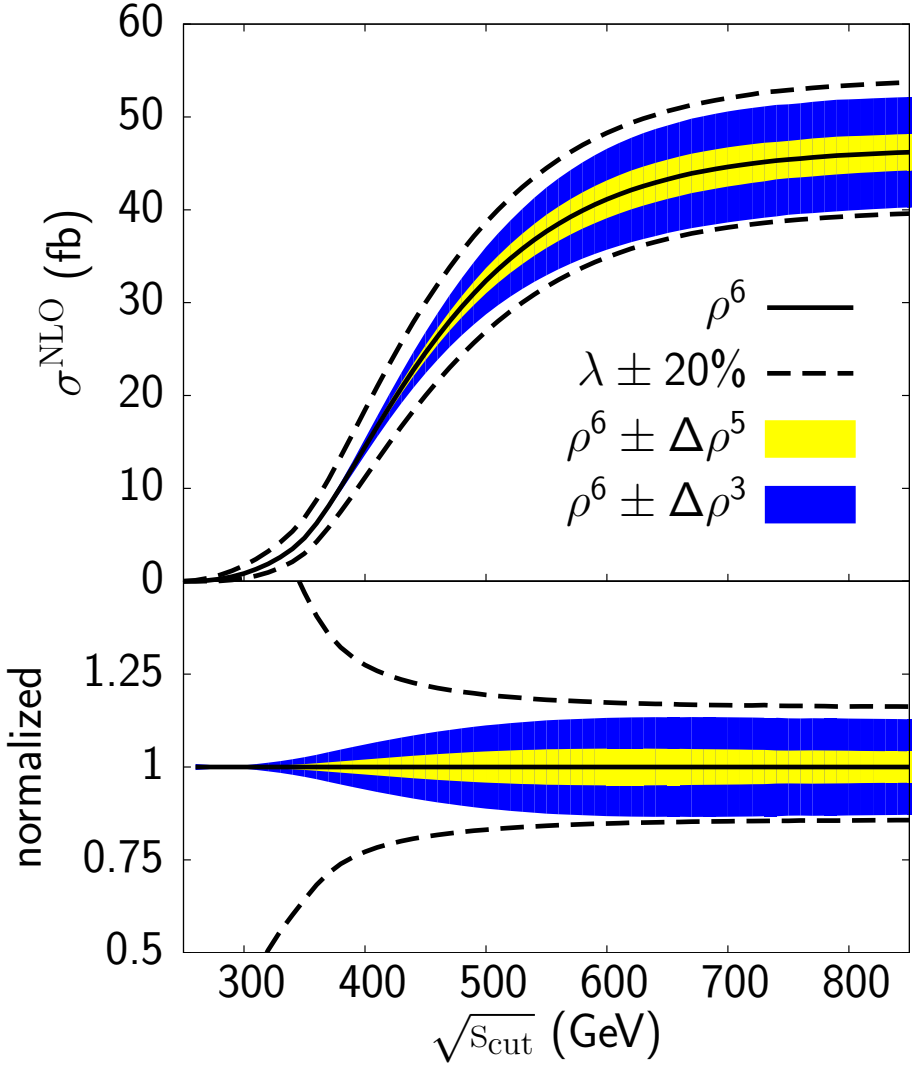


Behavior for low $\sqrt{s}$: estimation of Q^2 distribution

- virtual corrections: $\sqrt{\mathrm{s}} = \sqrt{Q^2}$ (invariant mass of Higgs pair)
- soft real corrections: $\sqrt{\mathrm{s}} \approx \sqrt{Q^2}$
- observation: cross section dominated by soft and virtual corrections



Sensitivity to triple Higgs coupling



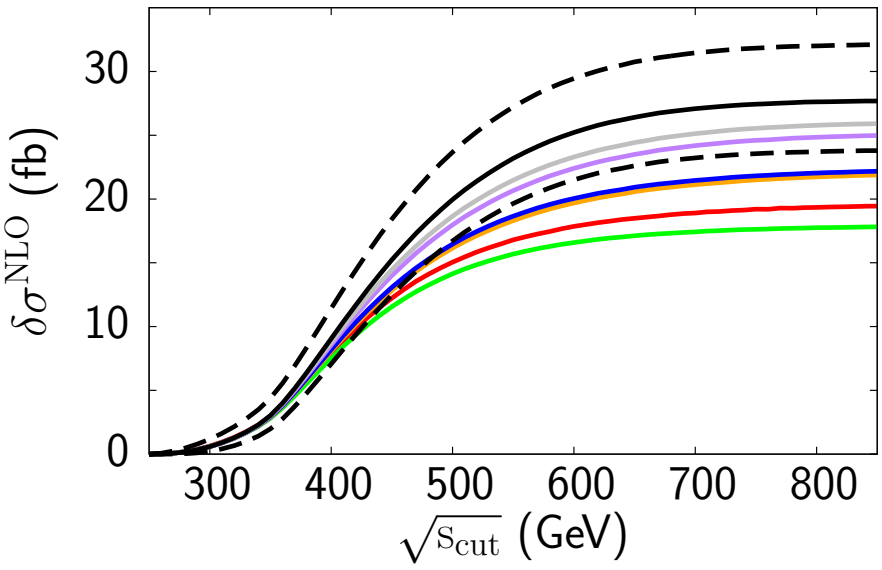
Conclusion

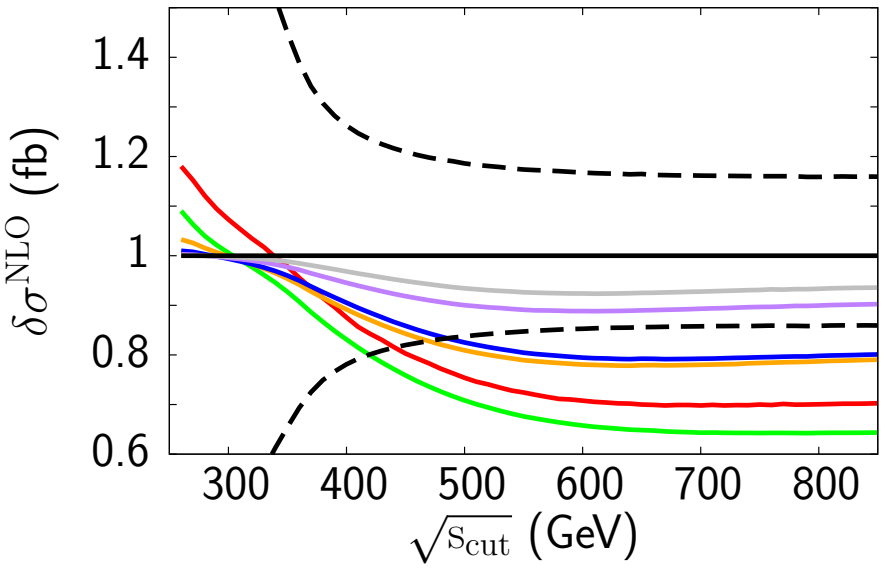
- $\sigma(pp \to HH)$ in the SM at NLO including $\mathcal{O}(1/m_t^{12})$ terms
- independent check of $m_t \to \infty$ result [Dawson, Dittmaier, Spira '98]
- top mass corrections are numerically important:
  $+20\%$ compared to $\sigma^{\mathrm{NLO}}(m_t \to \infty)$
- quantitative estimate of remaining $\mathcal{O}(1/m_t^n)$ uncertainties

backup

Hadronic cross section

MSTW2008 pdfs, $\sqrt{s_{\rm had}} = 14$ TeV, $\mu = 2m_H$





Hadronic cross section - numbers

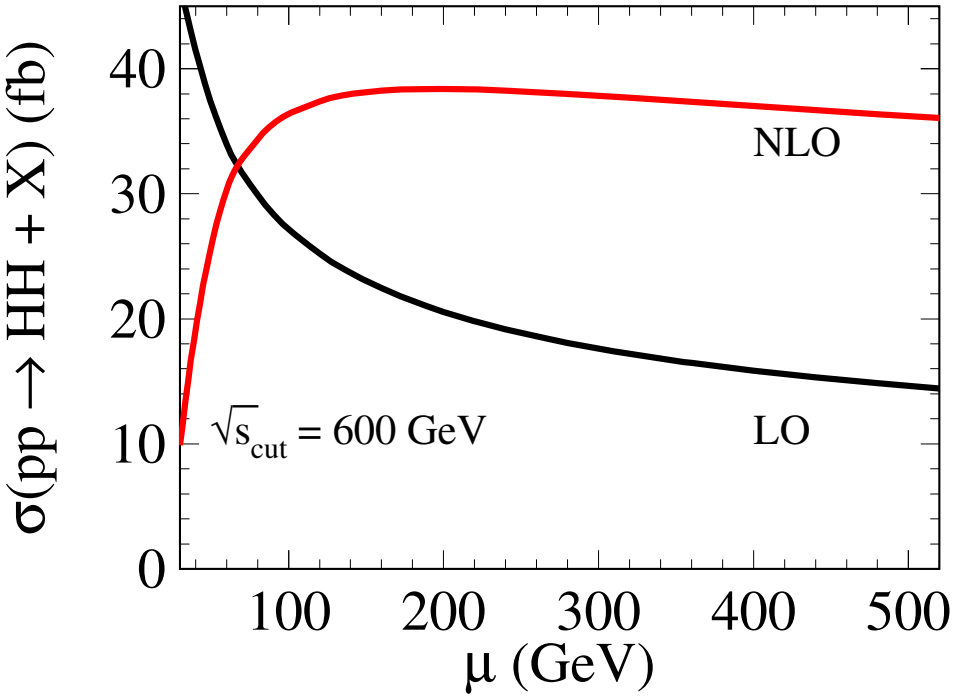
MSTW2008 pdfs, $\sqrt{s_{\rm had}} = 14$ TeV, $\mu = 2m_H$

total hadronic cross section in fb, all channels

LO	δNLO ρ^0	ρ^1	ρ^2	ρ^3	ρ^4	ρ^5	ρ^6	LO + δNLO
19.7 (22.4*)	19.0	16.4	21.5	21.4	24.5	25.3	27.3	47.0

* with LO pdfs

Scale dependence



$$\mu = \mu_{\mathrm{F}} = \mu_{\mathrm{R}}$$

$$\mu_{\mathrm{central}} = 2m_H$$

$$\sigma^{\mathrm{LO}} = 18^{+6}_{-4}\ \mathrm{fb}$$

$$\sigma^{\mathrm{NLO}} = 38^{+0}_{-2}\ \mathrm{fb}$$

Used software

1. create diagrams: QGRAF [Nogueira '93]
2. select diagrams with appropriate cuts [Hoff, Pak (unpublished)]
3. asymptotic expansion: Q2E and EXP [Harlander, Seidensticker, Steinhauser '98]
4. reduction to scalar integrals: (T)Form [Vermaseren '90; Tentyukov, Vermaseren '10; Kuipers, Ueda, Vermaseren, Vollinga '13]
5. reduction to master integrals: FIRE [Smirnov '08, '13]