Higher-order QCD corrections to the Higgs-boson qT distribution

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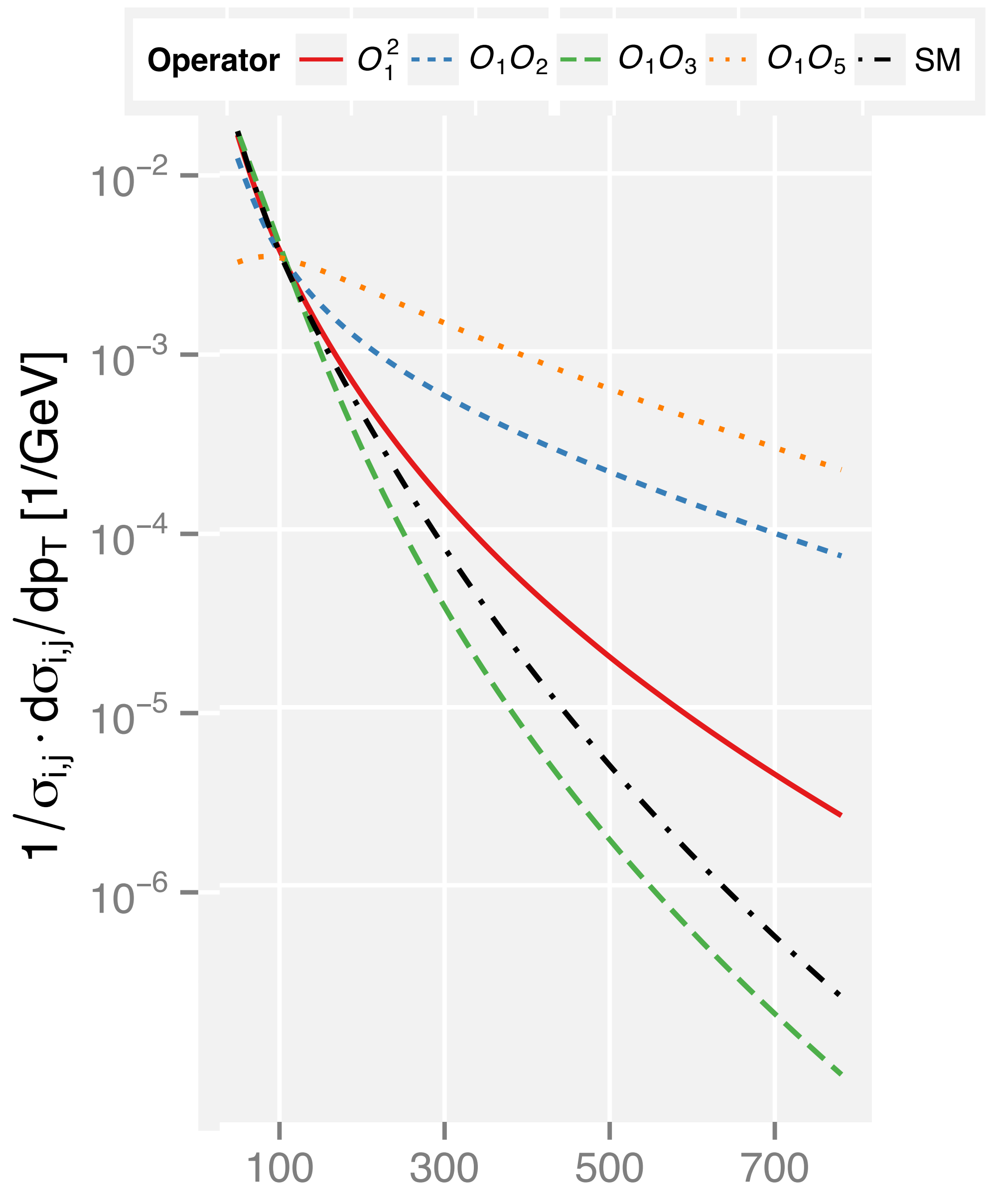
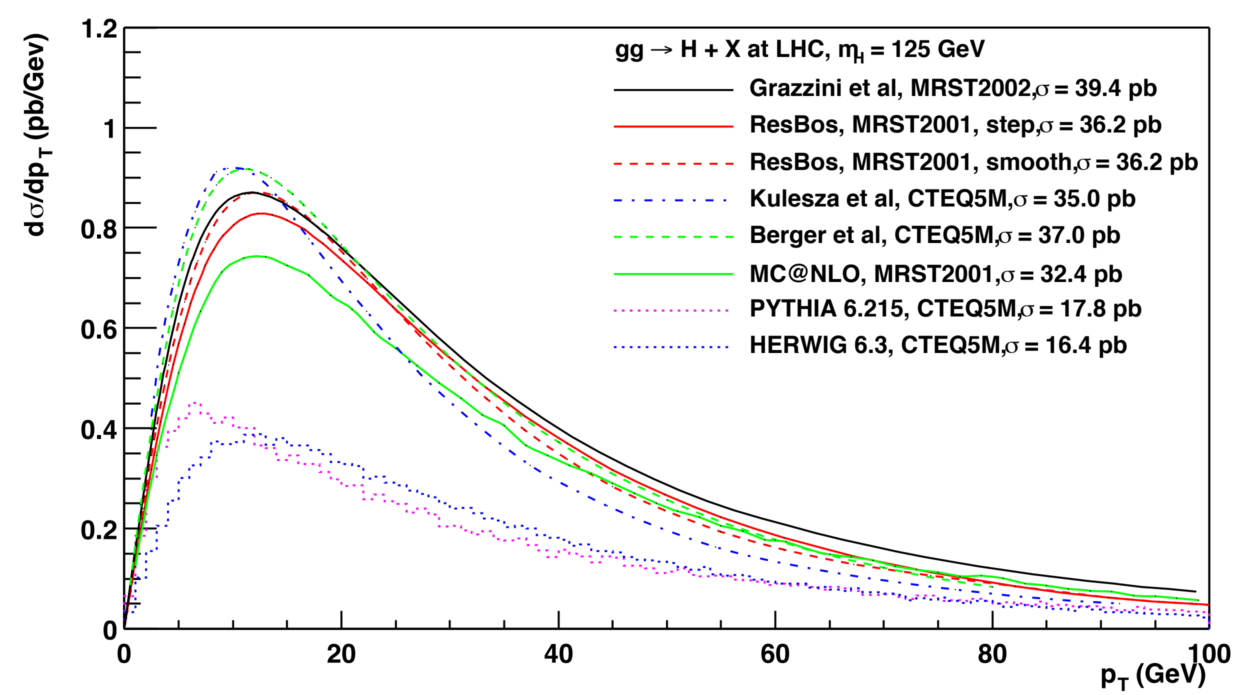
Motivation

- Transverse momentum distribution of the Higgs boson in gluon fusion: probe of standard model EW dynamics, test of QCD factorization



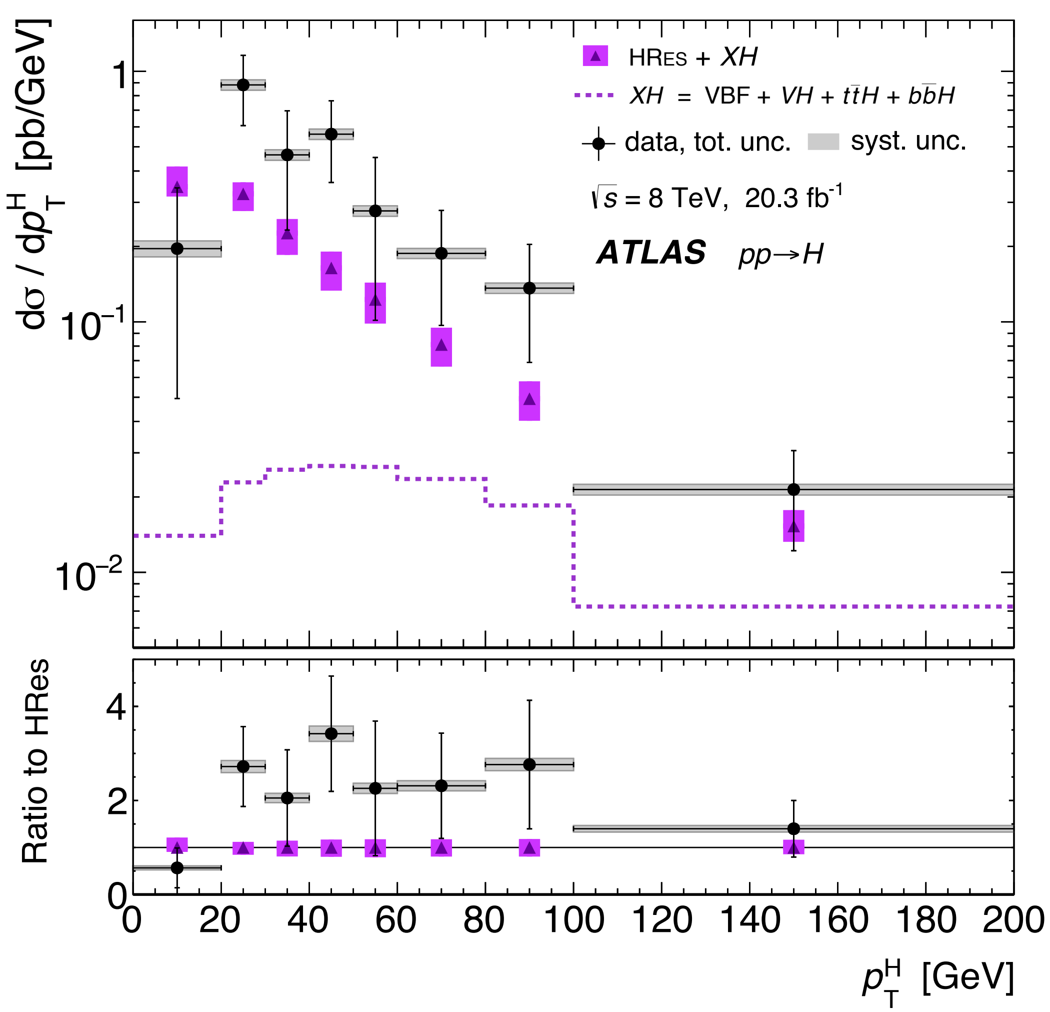
Harlander, Neumann, 1308.2225

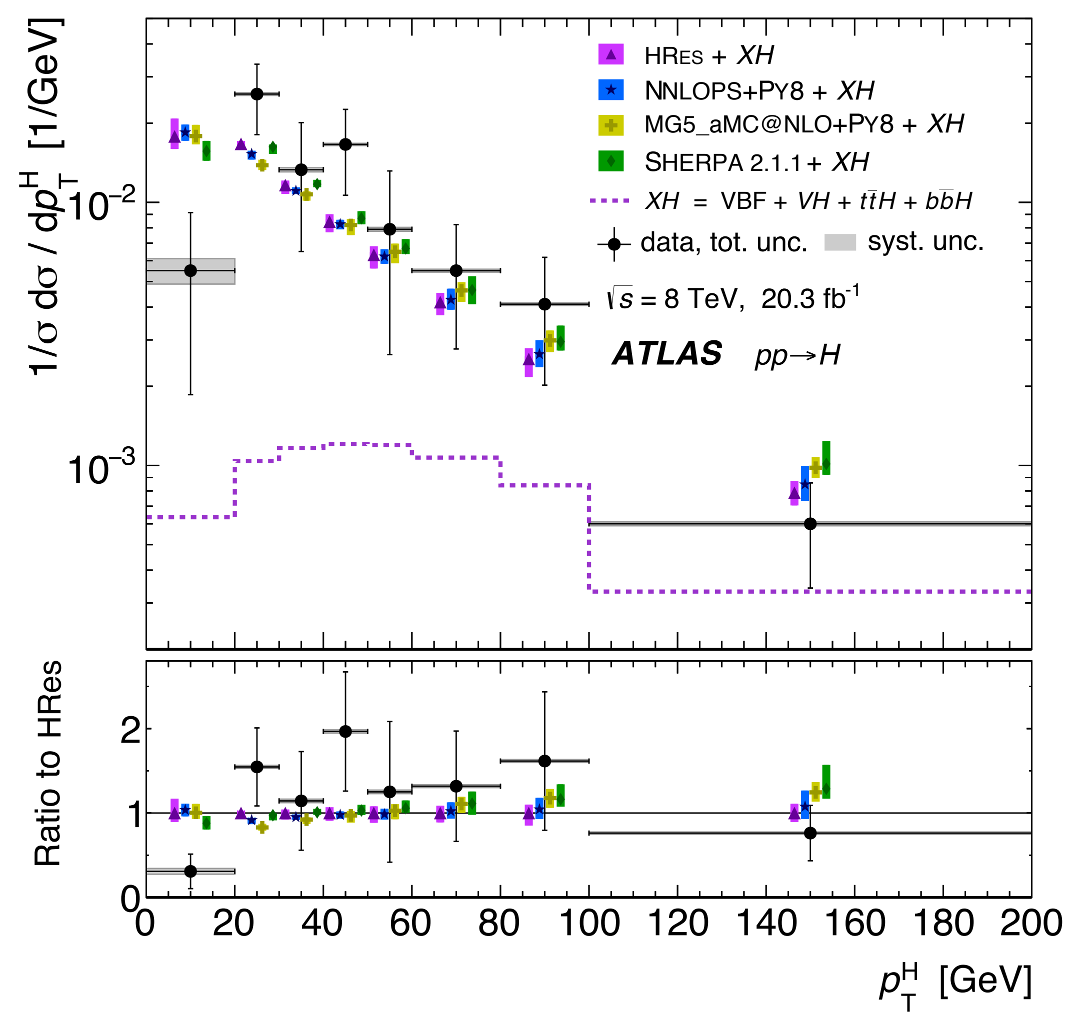
- differentiate different origins of ggH effective couplings
- probe production mechanism through QCD color structures
- ideal for testing QCD factorization in gluon fusion process



Balazs et al., hep-ph/0403052

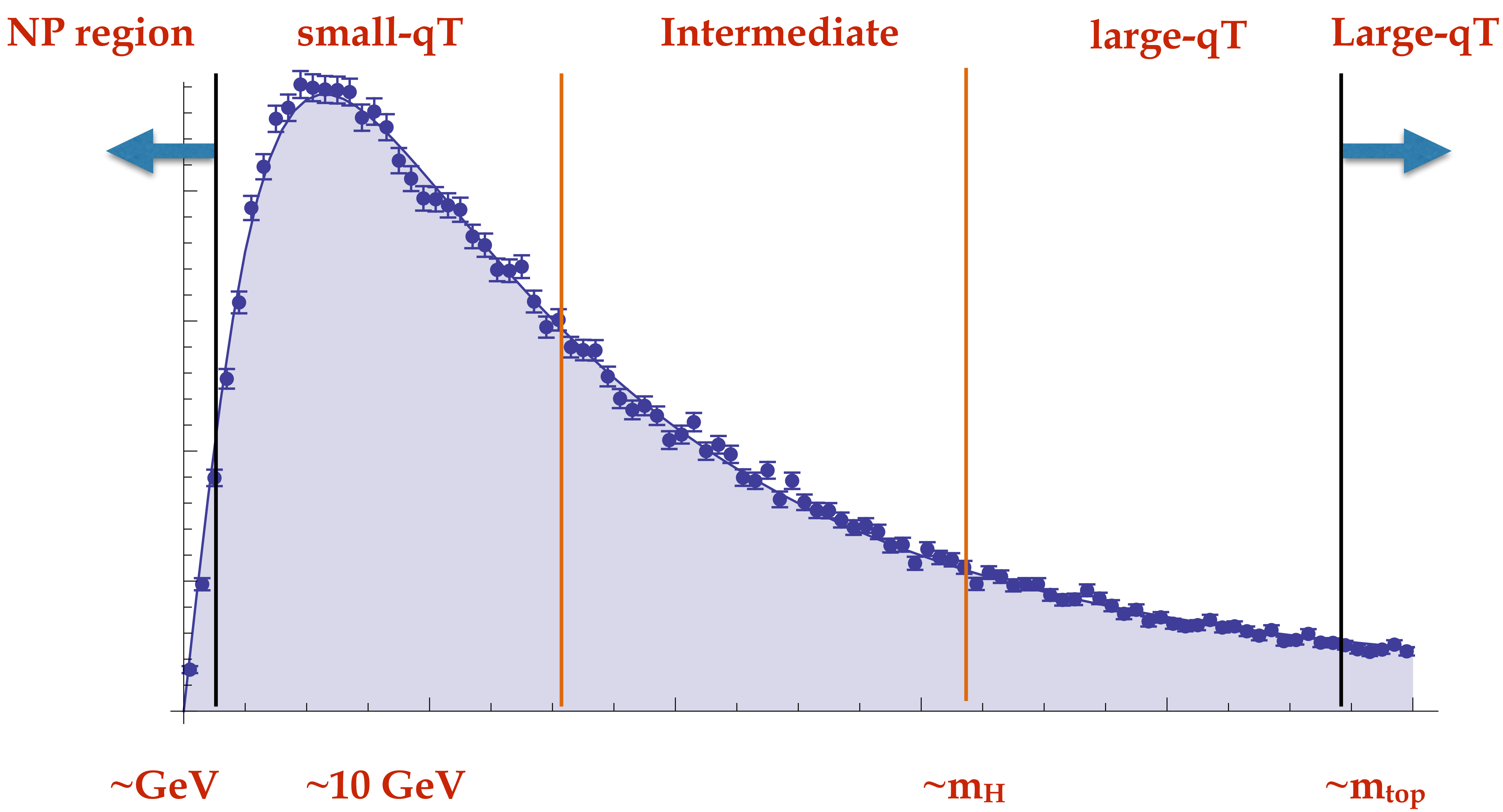
- Experimental precision at LHC run 1 is limited by statistics but could be largely improved at run 2 or high luminosity LHC; current uncertainties on theoretical predictions are not small



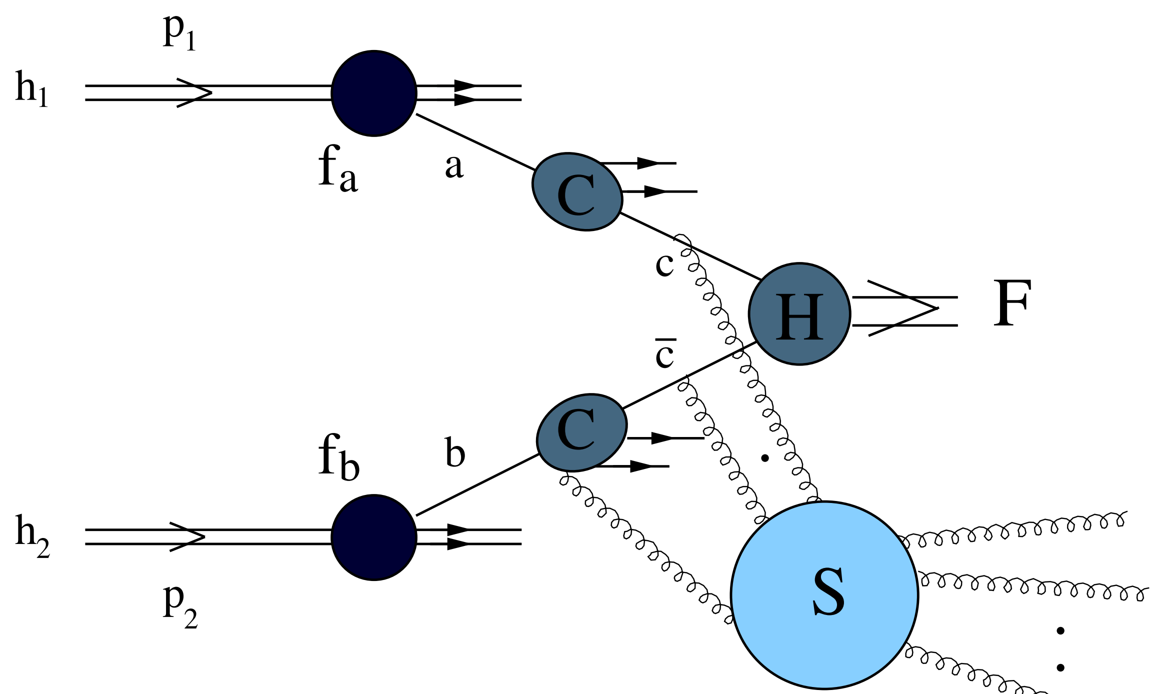


ATLAS, arXiv: 1504.05833

- Theoretical predictions on SM Higgs boson qT distribution in different kinematic region: 1, non-perturbative region; 2, small-qT; 3, intermediate qT; 4, large qT; 5, Large-qT



- Resummation of small-qT logarithms (Log(qT/Q)) to all-order in QCD in impact parameter space, first developed by Collins, Soper and Sterman (CSS, 1985)



Catani et al., hep-ph/0008184

Recent CSS application on Higgs boson production:

Florian et al., 2011, NNLL+NLO [HqT/HRes]

Wang et al., 2012, NNLL+NLO [Resbos]

$$\left[\frac{d\sigma_F}{dQ^2\,dq_\perp^2}\right]_{\text{res.}} = \sum_{a,b}\int_0^1 dx_1 \int_0^1 dx_2 \int_0^\infty db\,\frac{b}{2}\,J_0(bq_\perp)\; f_{a/h_1}(x_1, b_0^2/b^2)\; f_{b/h_2}(x_2, b_0^2/b^2) \cdot W_{ab}^F(x_1 x_2 s; Q, b)\;.$$

$$W_{ab}^F(s; Q, b) = \sum_c \int_0^1 dz_1 \int_0^1 dz_2\; C_{ca}(\alpha_S(b_0^2/b^2), z_1)\; C_{\bar{c}b}(\alpha_S(b_0^2/b^2), z_2)\; \delta(Q^2 - z_1 z_2 s) \cdot \sigma_{c\bar{c}}^F(Q^2, \alpha_S(Q^2))\; S_c(Q, b)\;.$$

- Higgs qT resummation based on Soft-Collinear effective theory [note the different convention in counting of matching order]

Y. Gao et al., 2005, Idilbi et al, 2005, Mantry, Petriello, 2009

NNLL+NLO: Becher, Neubert, 2010, Becher et al., 2013

NNLL+NNLO: Chiu et al., 2012, Neill et al., 2015

NNLL: Echevarria et al., 2015

- Fixed-order calculations on Higgs qT spectrum, NLO/NNLO QCD in heavy top-quark limit, NLO QCD with approx. top mass dependence

NLO: Florian et al., 1999, Ravindran et al., 2002, Glosser, Schmidt, 2002

NNLO: Boughezal et al., 2013, Chen et al., 2014, Boughezal et al., 2015

LO: Ellis et al., 1988, Baur, Glover, 1990

NLO (approx.): Dawson et al., 2014

Framework

- small-qT factorization and resummation in SCET [following the scheme by Becher, Neubert, 2010]

$$\boxed{\begin{matrix}\text{SM}\\ n_f=6\end{matrix}} \xrightarrow{\mu_t} \boxed{\begin{matrix}\text{SM}\\ n_f=5\end{matrix}} \xrightarrow{\mu_h} \boxed{\begin{matrix}\text{SCET}\\ hc,\overline{hc},s\end{matrix}}$$

$$d\sigma = \sigma_0(\mu)\, C_t^2(m_t^2,\mu)\, \left|C_S(-m_H^2,\mu)\right|^2 \frac{m_H^2}{\tau s}\, dy\, \frac{d^2 q_\perp}{(2\pi)^2} \int d^2 x_\perp\, e^{-iq_\perp\cdot x_\perp}$$

$$\times\, 2\mathcal{B}_c^{\mu\nu}(\xi_1,x_\perp,\mu)\, \mathcal{B}_{\bar{c}\,\mu\nu}(\xi_2,x_\perp,\mu)\, \mathcal{S}(x_\perp,\mu)$$

Collinear anomaly and refactorization, $q_T \ll m_H$

$$d\sigma = \sigma_0(\mu)\, C_t^2(m_t^2,\mu)\, \left|C_S(-m_H^2,\mu)\right|^2 \frac{m_H^2}{\tau s}\, dy\, \frac{d^2 q_\perp}{(2\pi)^2} \int d^2 x_\perp\, e^{-iq_\perp\cdot x_\perp}$$

$$\times\, 2 \left(\frac{x_T^2 m_H^2}{b_0^2}\right)^{-F_{gg}(x_T^2,\mu)} B_g^{\mu\nu}(\xi_1,x_\perp,\mu)\, B_g^{\rho\sigma}(\xi_2,x_\perp,\mu)$$

✦ small-qT factorization and resummation in SCET [following the scheme by Becher, Neubert, 2010]

Matching on to standard collinear PDFs, qT>>Λ_{QCD}

$$\frac{d^2\sigma}{dq_T^2\,dy} = \sigma_0(\mu)\, C_t^2(m_t^2,\mu)\, \left|C_S(-m_H^2,\mu)\right|^2 \sum_{i,j=g,q,\bar{q}} \int_{\xi_1}^1 \frac{dz_1}{z_1} \int_{\xi_2}^1 \frac{dz_2}{z_2}$$

$$\times\, \bar{C}_{gg\leftarrow ij}(z_1,z_2,q_T^2,m_H^2,\mu)\, \phi_{i/P}(\xi_1/z_1,\mu)\, \phi_{j/P}(\xi_2/z_2,\mu)$$

$$\bar{C}_{gg\leftarrow ij}(z_1,z_2,q_T^2,m_H^2,\mu) = \frac{1}{4\pi}\int d^2x_\perp\, e^{-iq_\perp\cdot x_\perp} \left(\frac{x_T^2 m_H^2}{b_0^2}\right)^{-F_{gg}(L_\perp,a_s)}$$

$$\times \sum_{n=1,2} I_{g\leftarrow i}^{(n)}(z_1,L_\perp,a_s)\, I_{g\leftarrow j}^{(n)}(z_2,L_\perp,a_s)$$

$$L_\perp = \ln\frac{x_T^2\mu^2}{b_0^2}$$

with qT>>Λ_{QCD} all colored objects can be calculated perturbatively; scale dependence are organized by RG equation with anomalous dimensions

✦ Resummation of Sudakov logarithms is accomplished by evolving hard functions from canonical scales to a proper scale at which the expansion of remaining kernel **C** can be perturbatively controlled

RG evolution of the hard function

$$C_t(m_t^2,\mu_f^2) = \frac{\beta\big(\alpha_s(\mu_f^2)\big)/\alpha_s^2(\mu_f^2)}{\beta\big(\alpha_s(\mu_t^2)\big)/\alpha_s^2(\mu_t^2)}\, C_t(m_t^2,\mu_t^2)$$

$$C_S(-m_H^2-i\epsilon,\mu_f^2)=\exp\left[2S(\mu_h^2,\mu_f^2) - a_\Gamma(\mu_h^2,\mu_f^2)\,\ln\frac{-m_H^2-i\epsilon}{\mu_h^2} - a_{\gamma^S}(\mu_h^2,\mu_f^2)\right] C_S(-m_H^2-i\epsilon,\mu_h^2)$$

proper scale (mu=<x_T>$^{-1}$) ~q*+qT, q*~8 GeV

$$q_* = m_H \exp\left(-\frac{2\pi}{\Gamma_0^A \alpha_s(q_*)}\right)$$

Improved expansion in momentum space, Lperp~1/as$^{1/2}$

$$\bar{C}_{gg\leftarrow ij}(z_1,z_2,q_T^2,m_H^2,\mu) = \frac{1}{2}\int_0^\infty dx_T\, x_T\, J_0(x_T q_T)\, \exp\left[g_A(\eta,L_\perp,a_s)\right]$$
$$\times \sum_{n=1,2} \bar{I}^{(n)}_{g\leftarrow i}(z_1,L_\perp,a_s)\, \bar{I}^{(n)}_{g\leftarrow j}(z_2,L_\perp,a_s)\,,$$

$$g_A(\eta,L_\perp,a_s) = -\left[\,\eta L_\perp\,\right]_{\epsilon^{-1/2}} - \left[a_s\left(\Gamma_0^A+\eta\beta_0\right)\frac{L_\perp^2}{2}\right]_{\epsilon^0} \quad +$$

- power counting and perturbative ingredients needed for the N3LL resummation

  - QCD beta function to 4-loop [Ritbergen et al., 1997], Cusp anomalous dimension to 4-loop [3-loop, Moch et al., 2004], quark and gluon anomalous dimension to 3-loop [Becher, Neubert, 2009], Ct and Cs to 2-loop [Ahrens et al, 2009] at matching scales

  - kernel of beam functions [scale independent terms] to 2-loop [Gehrmann et al, 2012, 2014], DGLAP splitting kernel to 2-loop [3-loop, Moch et al., 2004], collinear anomaly [scale independent terms] to 3-loop [2-loop, Becher, Neubert, 2011]

two unknown numbers

Pade approx. for cusp at 4-loop, effects are small as in many other studies

will vary 3-loop collinear anomaly (d3) in a reasonable range

- Fixed-order matching (non-singular/power corrections) is important even in peak region for Higgs case, NNLO/N3LO [Glosser , Schmidt, 2002, Boughezal et al., 2015]

$$\left[\frac{d\hat{\sigma}^{(\text{fin.})}_{F\,ab}}{dq_T^2}\right]_{\text{f.o.}} = \left[\frac{d\hat{\sigma}_{F\,ab}}{dq_T^2}\right]_{\text{f.o.}} - \left[\frac{d\hat{\sigma}^{(\text{res.})}_{F\,ab}}{dq_T^2}\right]_{\text{f.o.}}$$ **~ 10% in peak region**

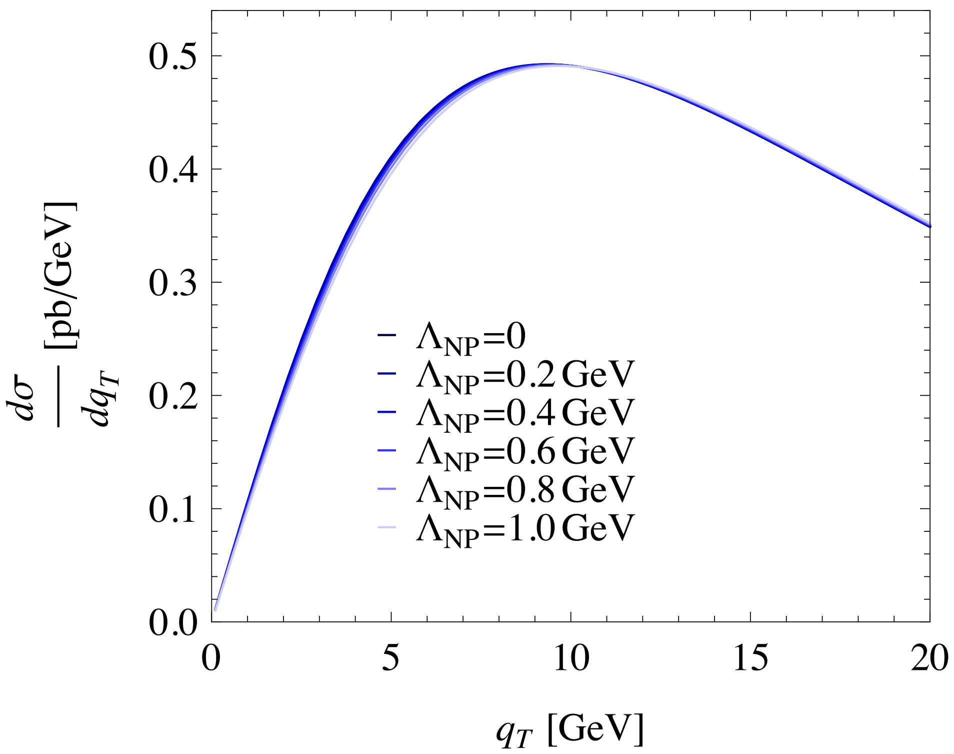
We adopt the order matching, NLL+NLO, NNLL+NNLO, N3LL+N3LO [also require 3-loop DGLAP kernel]; will vary the canonical scale choices/hard functions in non-singular piece to further investigate the perturbative convergence

- Long-distance effects are found to be small in peak region of the Higgs qT [Becher et al., 2013, Echevarria et al., 2015, Florian et al., 2011]

$$B_g^{(n)}(\xi, x_T^2, \mu) = f_{\text{hadr}}(x_T \Lambda_{\text{NP}})\, B_g^{(n)\,\text{pert}}(\xi, x_T^2, \mu)$$

$$f_{\text{hadr}}^{\text{gauss}}(x_T \Lambda_{\text{NP}}) = \exp\left(-\Lambda_{\text{NP}}^2\, x_T^2\right)$$

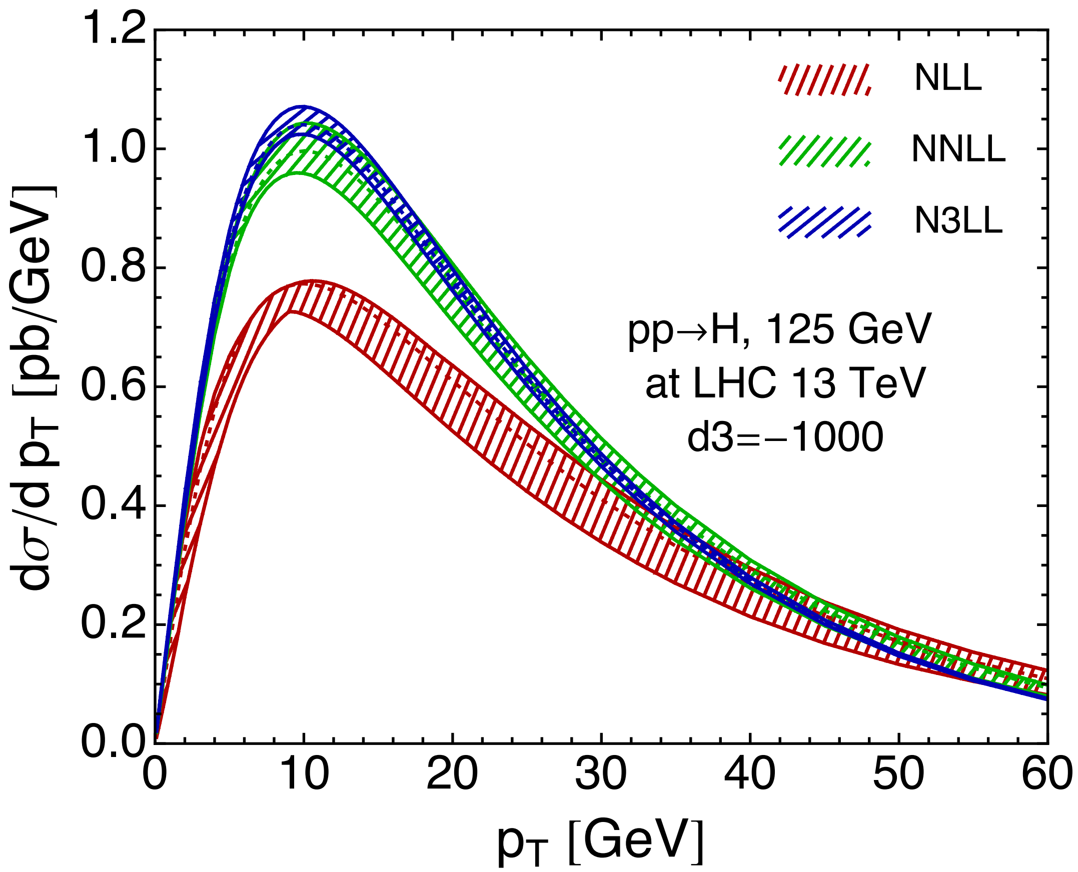
$$f_{\text{hadr}}^{\text{pole}}(x_T \Lambda_{\text{NP}}) = \frac{1}{1 + \Lambda_{\text{NP}}^2\, x_T^2}$$



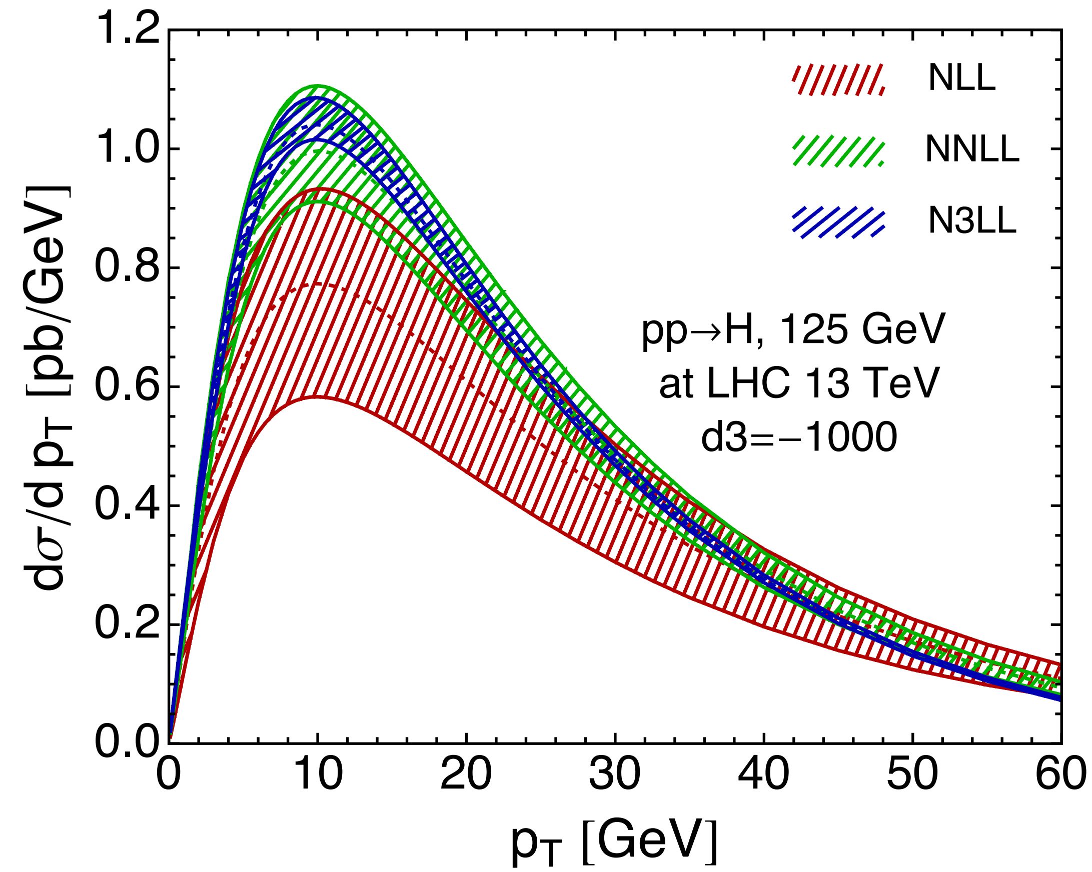
Numerical results [preliminary]

- resummed component and scale variation [two matching scales +resummation scale, factorization scale], qT distribution

no scale separation



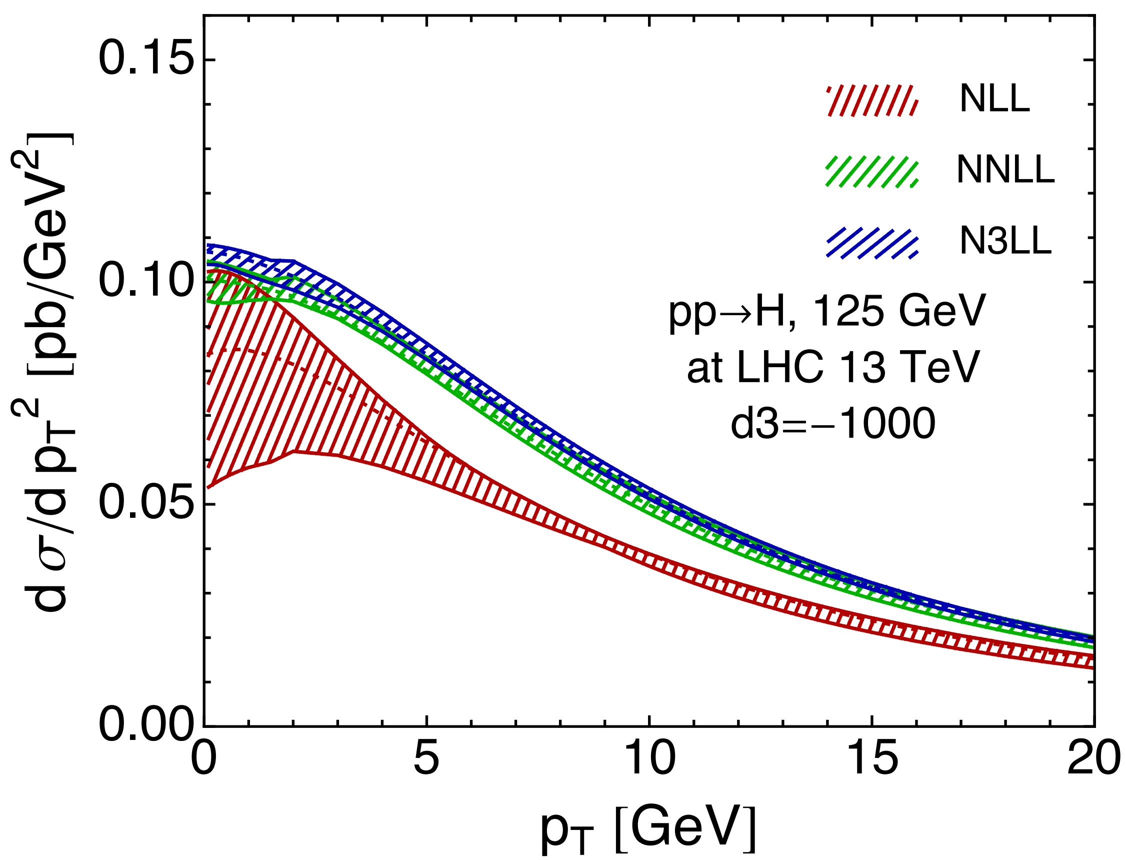
with scale separation



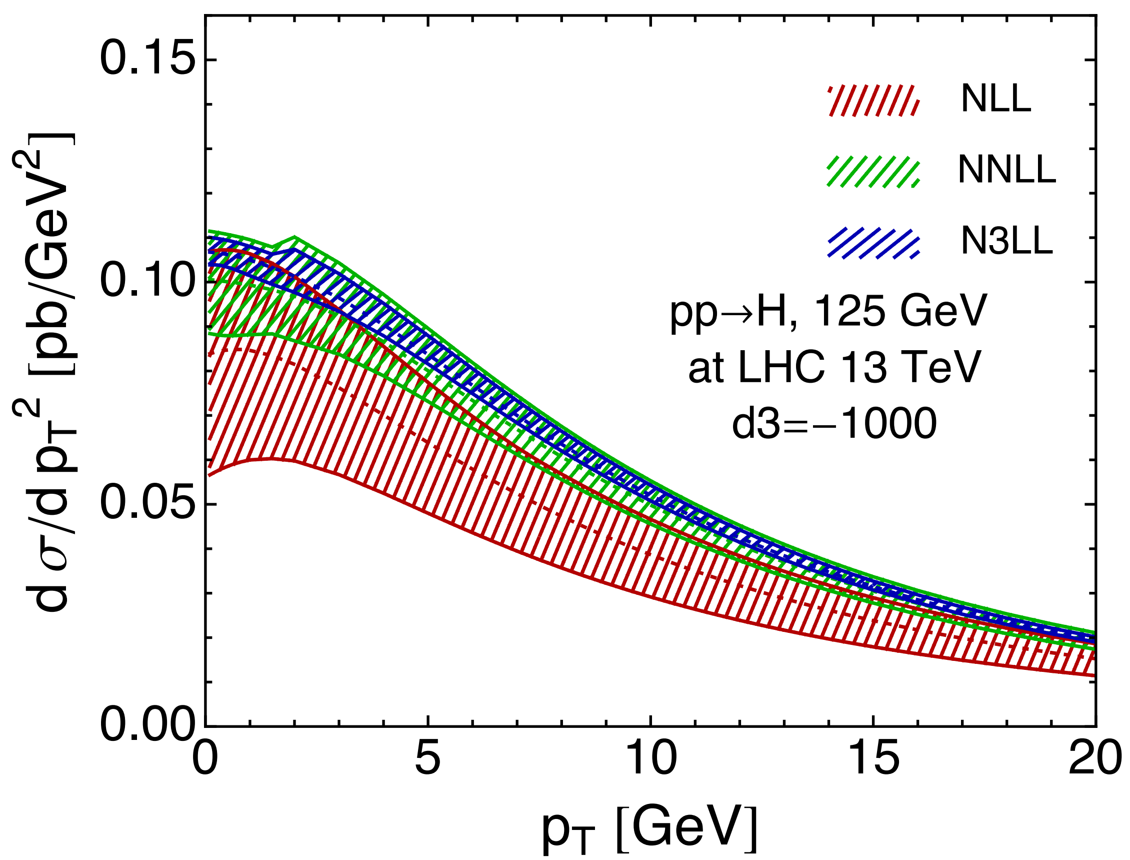
resummed cross sections can be divided into two separate scale invariant parts to have a better gauge on missing higher-order contributions [see Becher et al., 2013]

- resummed component and scale variation [two matching scales +resummation scale, factorization scale], intercept

no scale separation



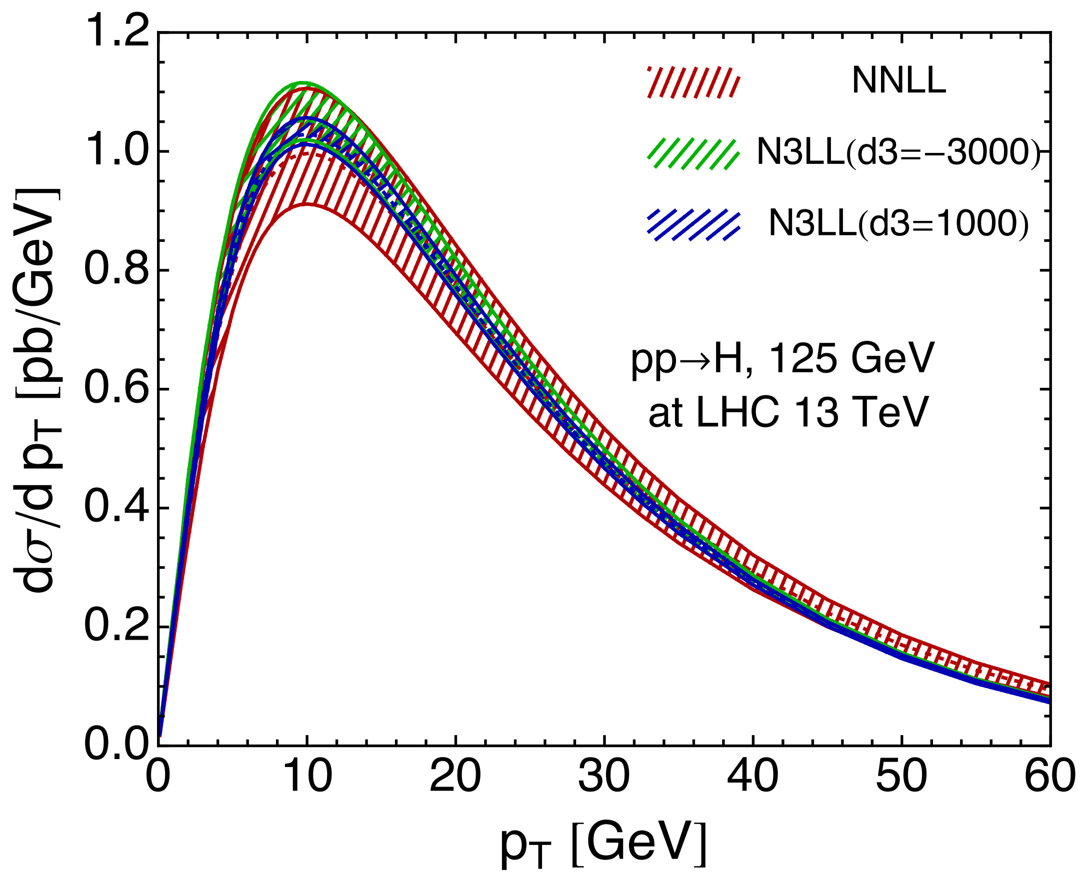
with scale separation



resummed cross sections can be divided into two separate scale invariant parts to have a better gauge on missing higher-order contributions [see Becher et al., 2013]

✦ resummed component and variation with d3 [variation with cusp at 4-loop is negligible]

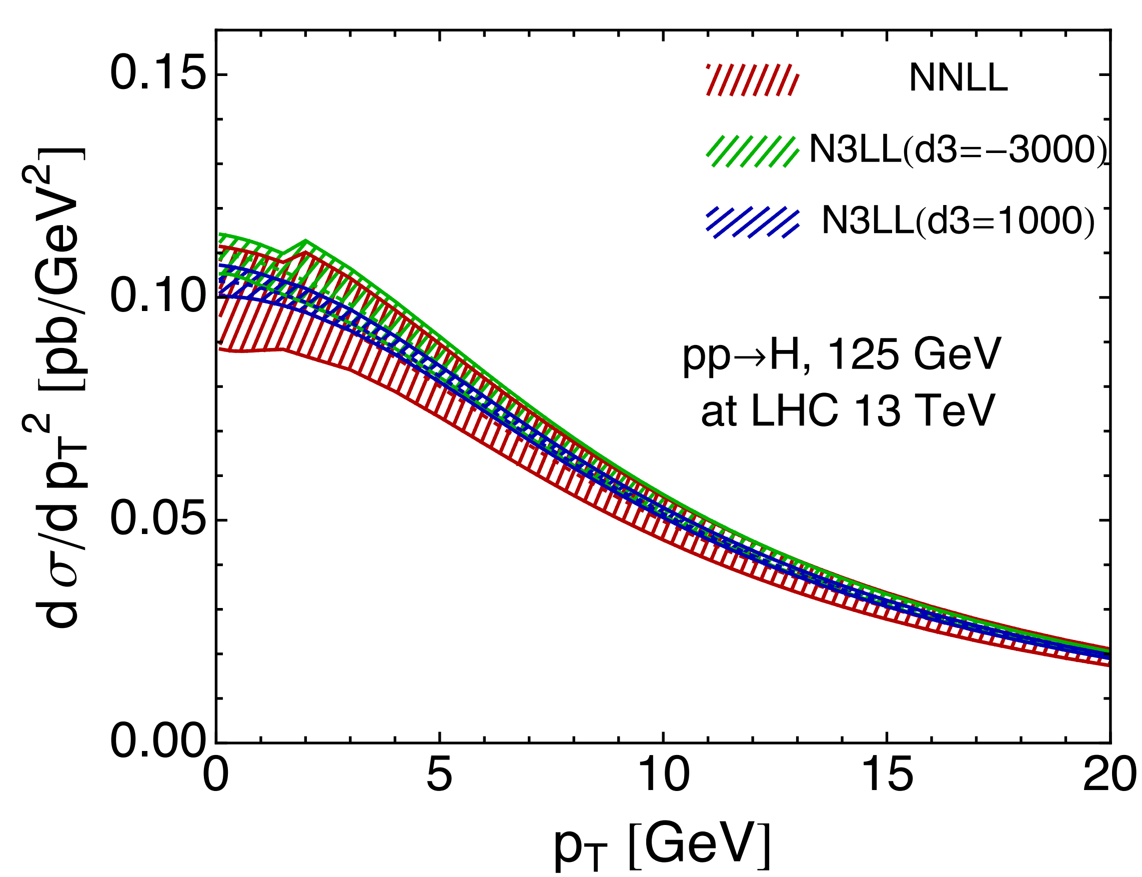
qT distribution



$$F_{gg}(L_\perp, \alpha_s) = \sum_1^\infty d_n^g(L_\perp) \left(\frac{\alpha_s}{4\pi}\right)^n$$

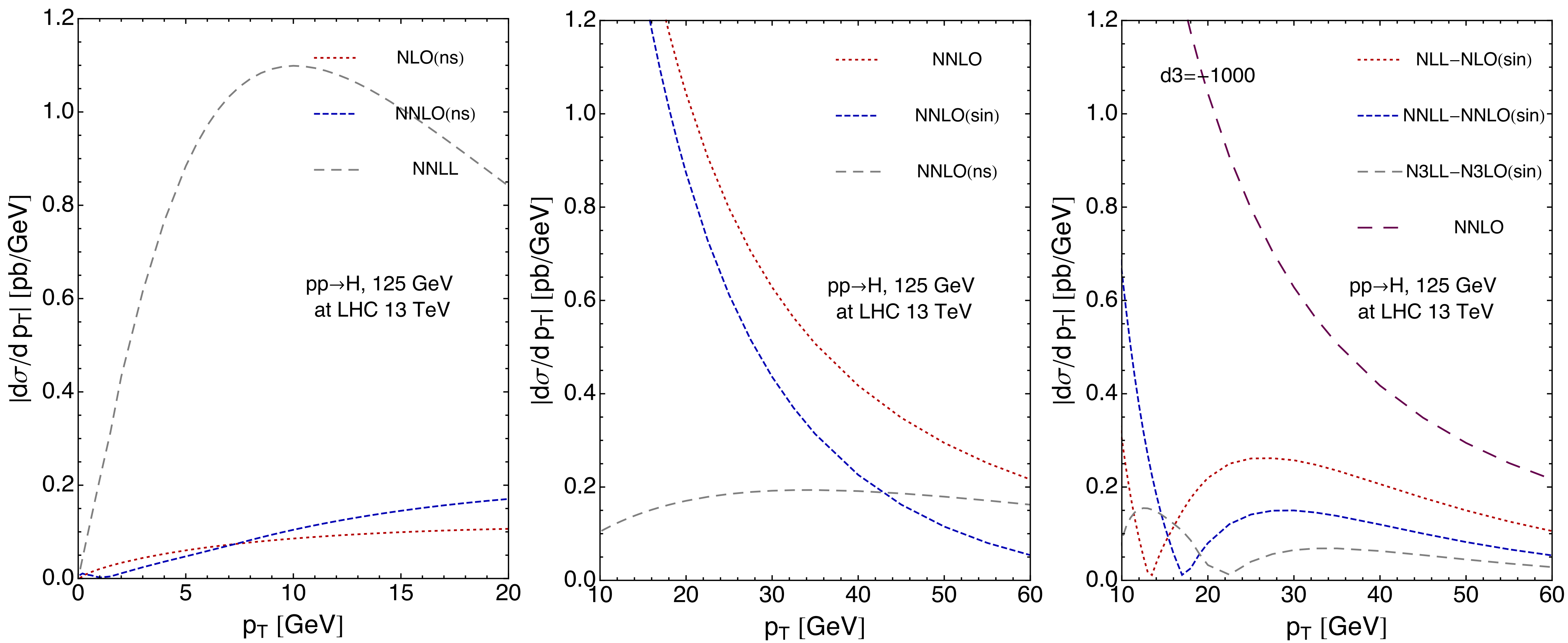
$$\frac{d_2^q}{C_F} = \frac{d_2^g}{C_A} = C_A\left(\frac{808}{27} - 28\zeta_3\right) - \frac{224}{27} T_F n_f$$

intercept



being the scale independent part in collinear anomaly exponent, d1=0, d2=-95.8, d3=?

✦ non-singular component in conventional scheme, canonical mu=mH, no RG improvement [restrict to NNLO here]

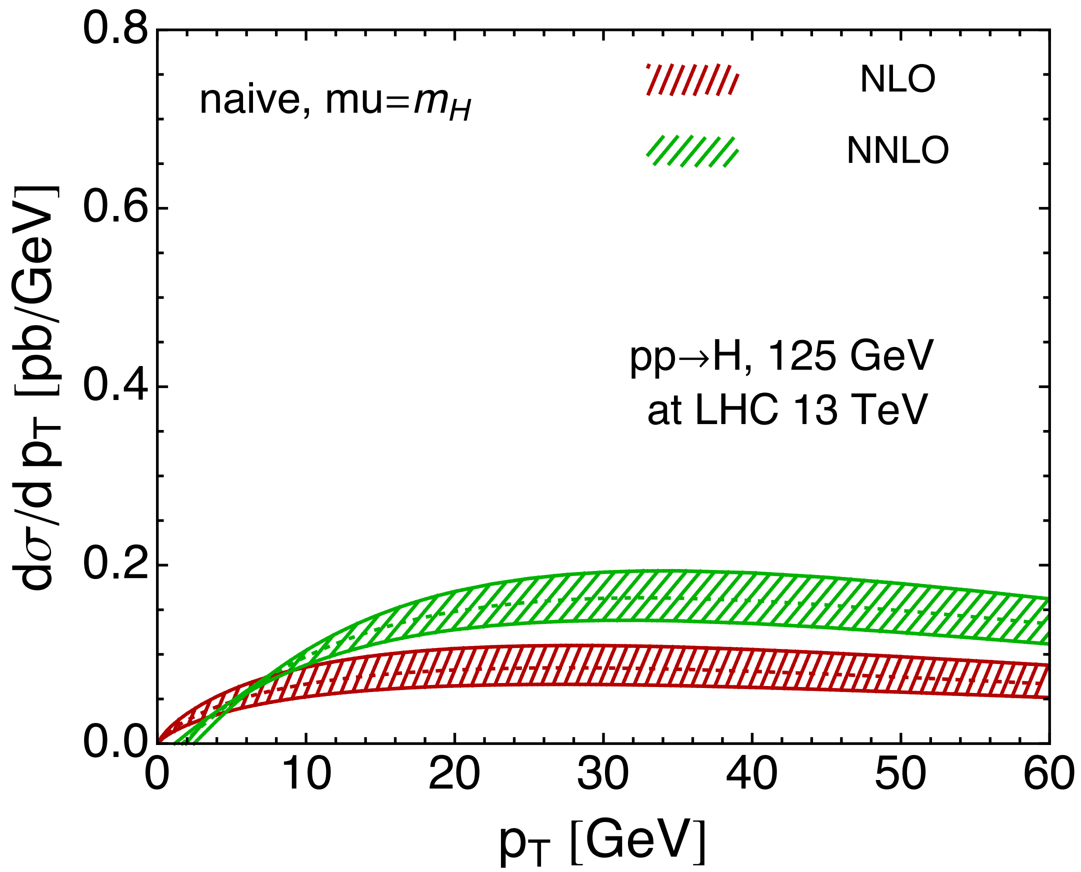


$$q_T^2 \frac{d\sigma_{sin}^{(n)}}{dq_T^2} \sim \alpha_s^n \ln^{2n-1}(\frac{q_T^2}{m_H^2}) \qquad q_T^2 \frac{d\sigma_{ns}^{(n)}}{dq_T^2} \sim \alpha_s^n \frac{q_T^2}{m_H^2} \ln^{2n-1}(\frac{q_T^2}{m_H^2})$$

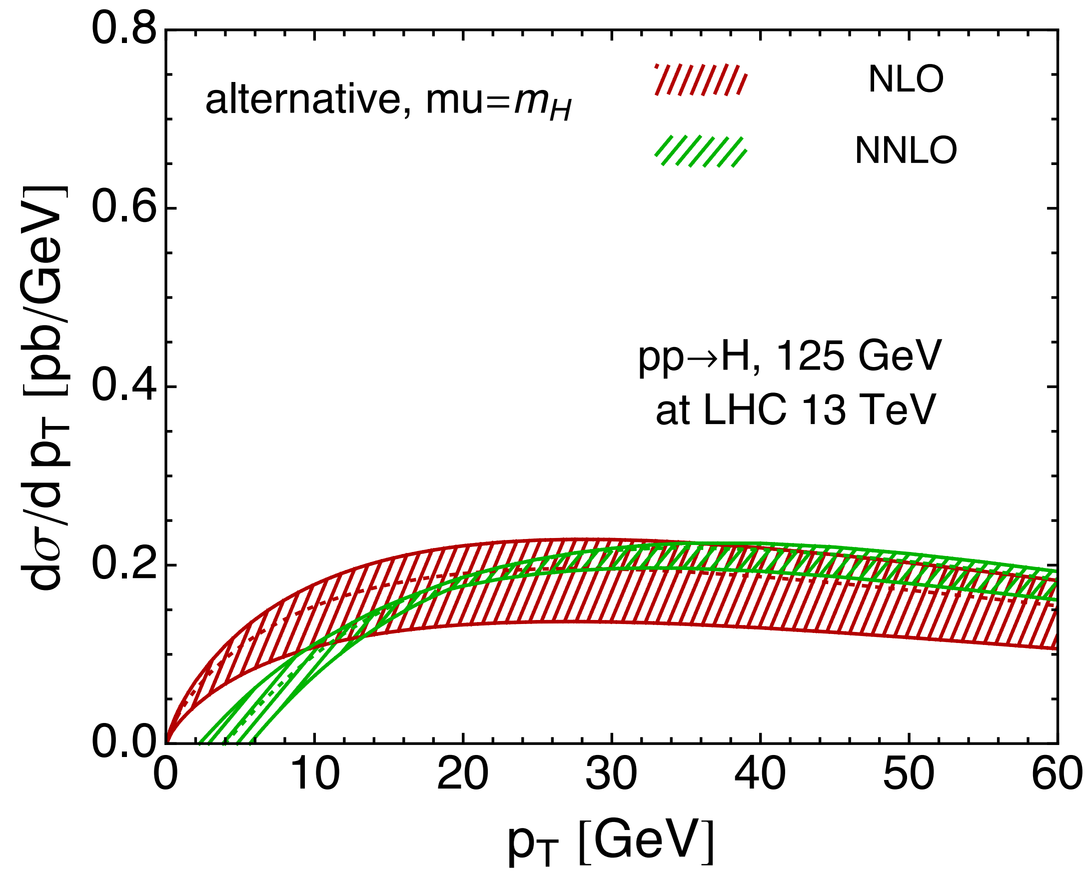
from left to right: vanishing of non-singular piece when qT->0; non-singular piece dominate in FO when qT~60 GeV; turn-off of resummation at high qT

✦ non-singular component in conventional/modified scheme, canonical mu=mH, no/with RG improvement [restrict to NNLO here]

naive(ns)



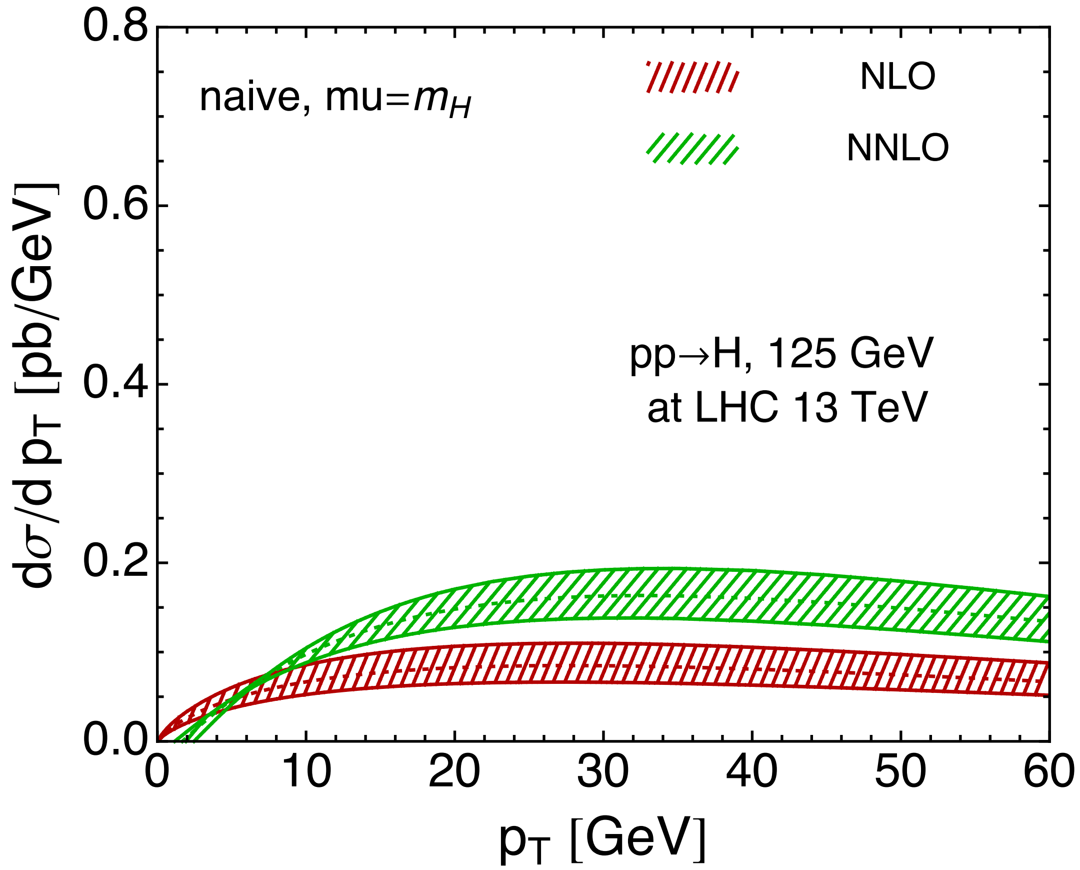
alternative(ns)



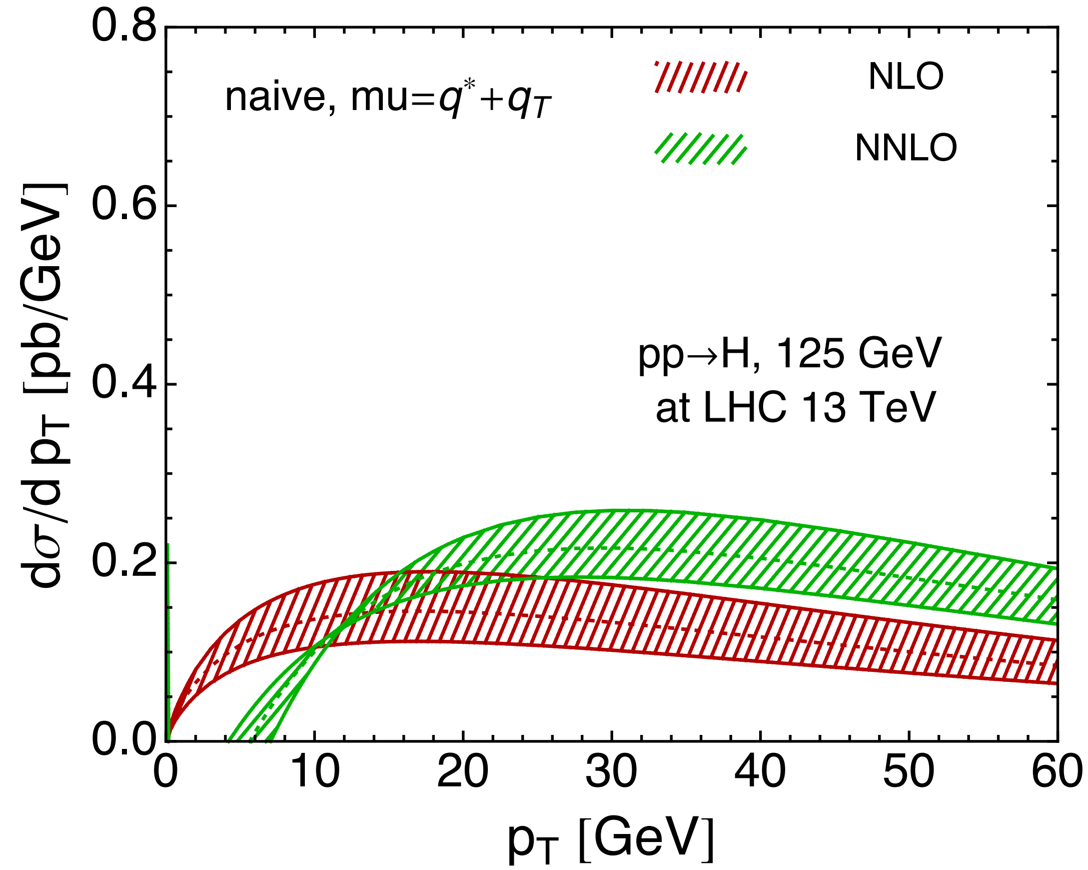
non-singular contributions are sensitive to the matching scheme used including choice of the canonical scale; uncertainties reduced from NLO to NNLO; N3LO must needed to match the precision in N3LL resummation

- non-singular component in conventional/modified scheme, canonical mu=mH/q*+qT, no RG improvement [restrict to NNLO here]

mu=mH(ns)



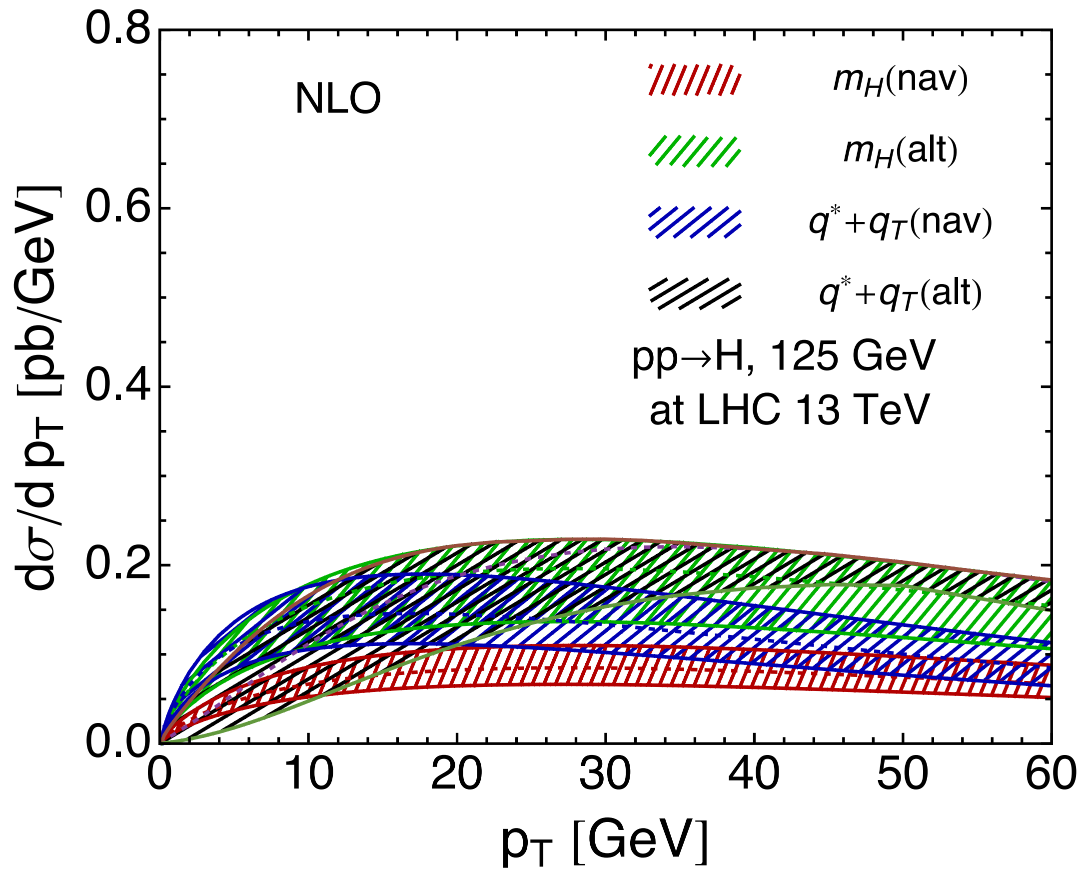
mu=q*+qT(ns)



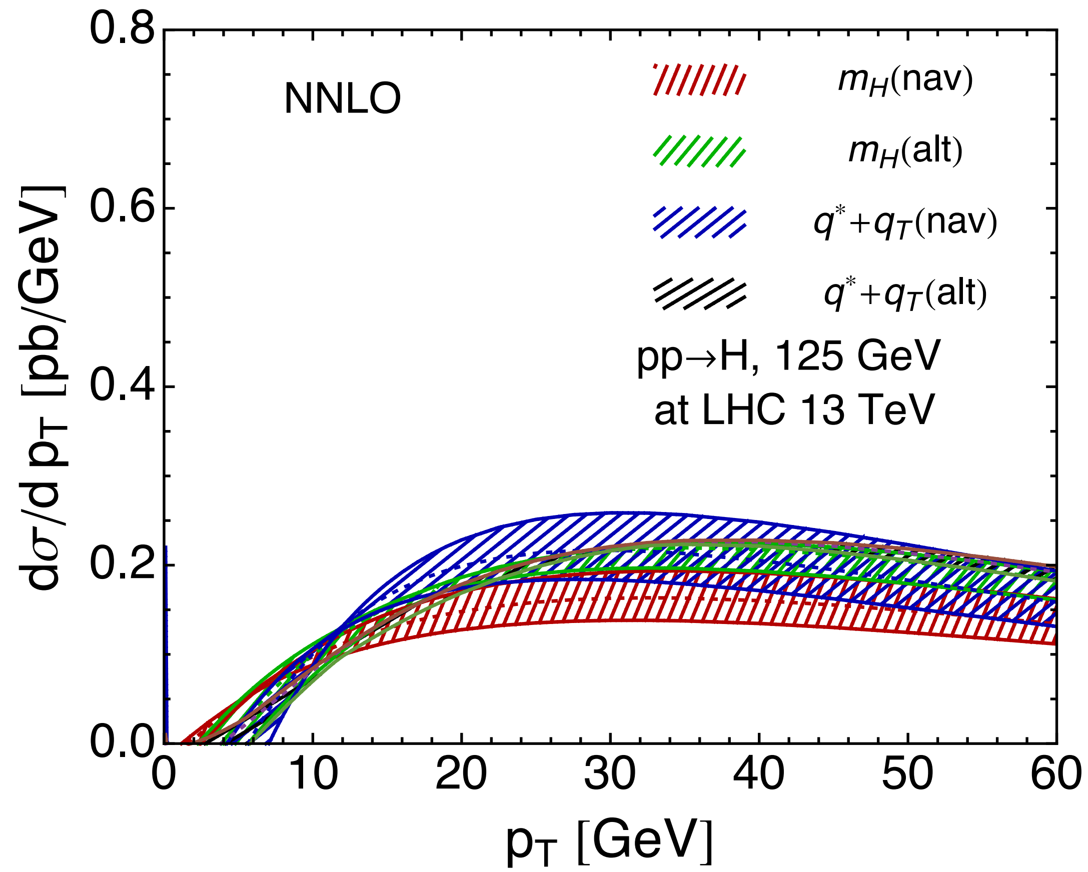
non-singular contributions are sensitive to the matching scheme used including choice of the canonical scale; uncertainties reduced from NLO to NNLO; N3LO must needed to match the precision in N3LL resummation

✦ non-singular component in conventional/modified scheme, mu=mH/q*+qT, no/with RG improvement [restrict to NNLO here]

NLO(ns)



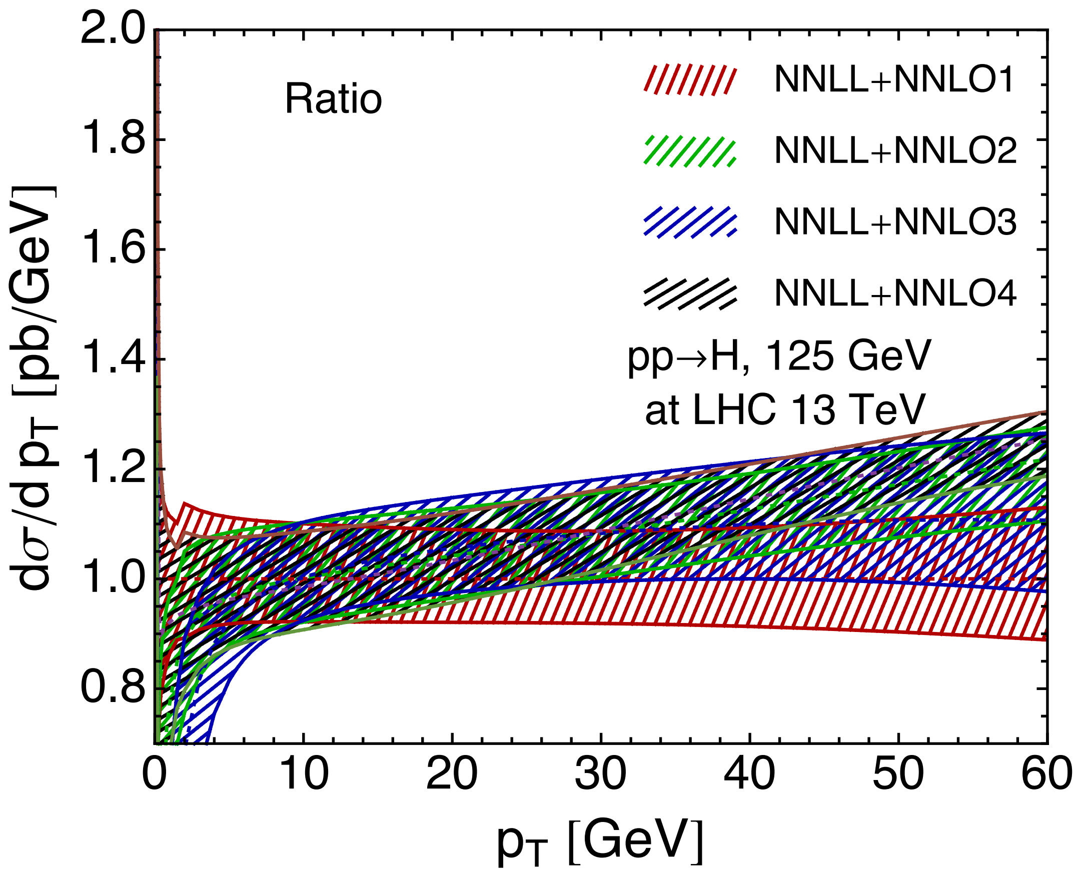
NNLO(ns)

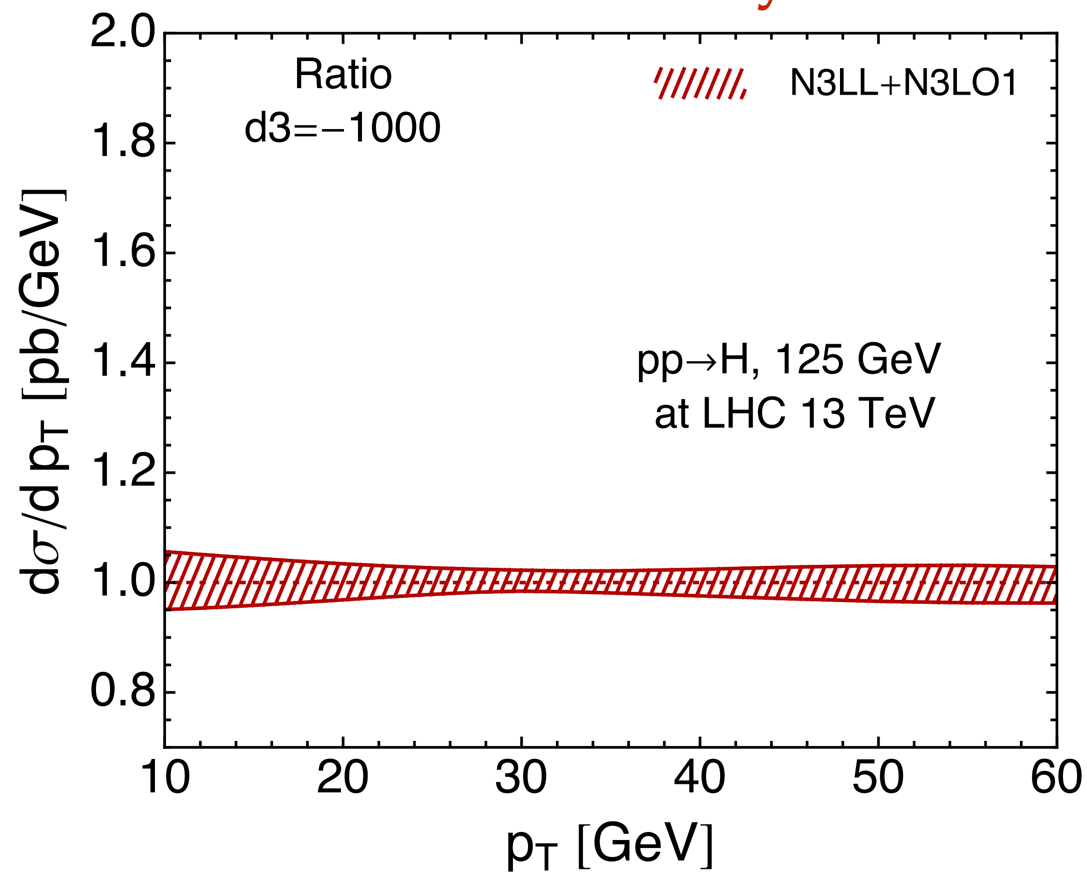


non-singular contributions are sensitive to the matching scheme used including choice of the canonical scale; uncertainties reduced from NLO to NNLO; N3LO must needed to match the precision in N3LL resummation

✦ uncertainties in the combined spectrum, for NNLL+NNLO and N3LL+N3LO [preliminary]

only shown for 10-60 GeV, and 1 mat. scheme yet





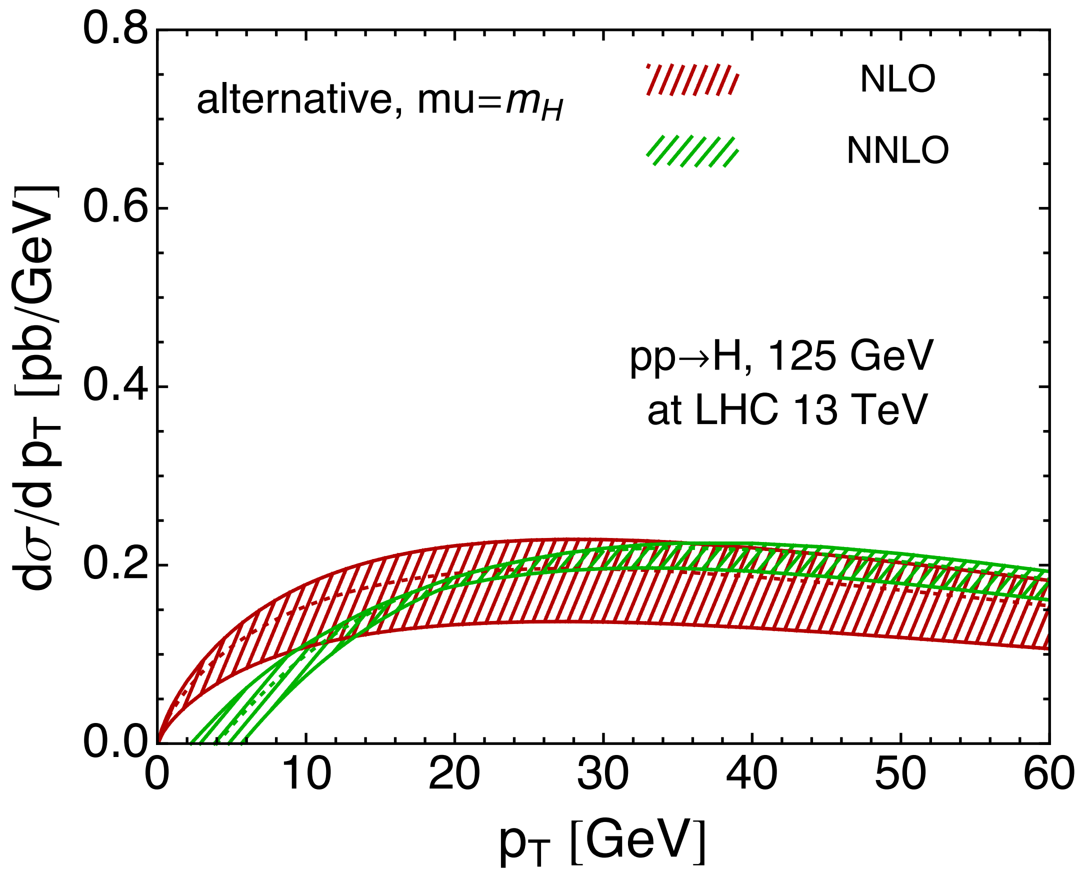
with N3LL+N3LO accuracy we expect to bring down the perturbative uncertainties to within 10% from peak region to large qT (not include uncertainties from unknown d3)

Summary

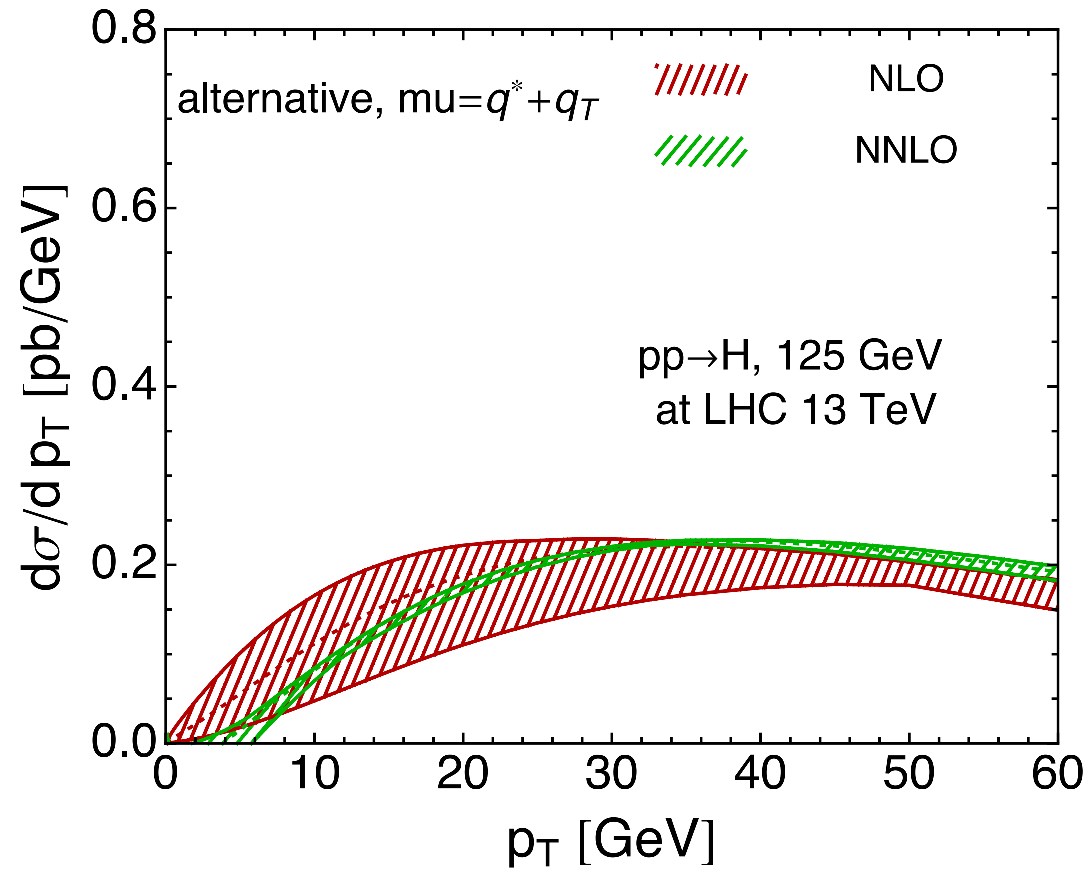
- We report progress in a N3LL+N3LO calculation of qT spectrum of the SM Higgs boson in gluon fusion production based on SCET
- N3LL resummation reduce the scale uncertainties significantly and the resummation show good convergence
- Non-singular component (FO matching) is important for predictions even around the peak region; N3LO contributions are needed
- With all available perturbative inputs a reduction of perturbative uncertainties to within 10% are expected for the spectrum from small-qT to ~mH

✦ non-singular component in conventional/modified scheme, canonical mu=mH/q*+qT, with RG improvement [restrict to NNLO here]

mu=mH(ns)



mu=q*+qT(ns)



non-singular contributions are sensitive to the matching scheme used including choice of the canonical scale; uncertainties reduced from NLO to NNLO; N3LO must needed to match the precision in N3LL resummation