Improving predictions for associated $t\bar{t}H$ production at the LHC: soft gluon resummation through NNLL accuracy

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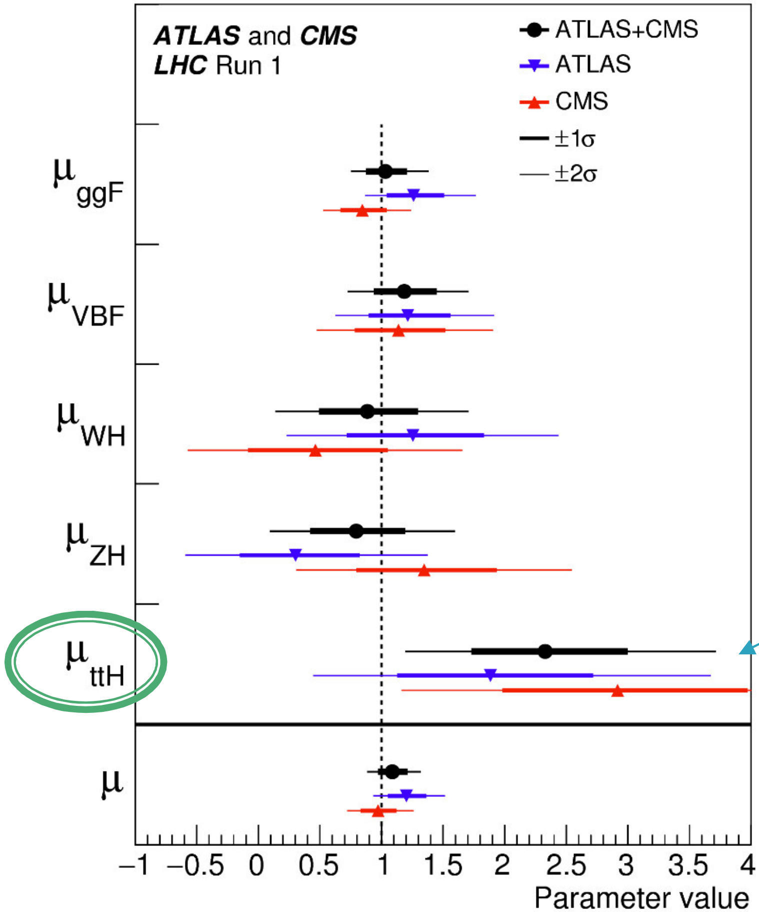
Why resummation for $pp \to t\bar{t}H$?

- Measure of top-Higgs Yukawa coupling → New Physics.
- It is $2 \to 3$ process, new area for resummation.
- NLO: $\sim 10\%$ scale uncertainty.
- NNLO: not available yet.
- Eagerly awaited measurement at LHC Run 2

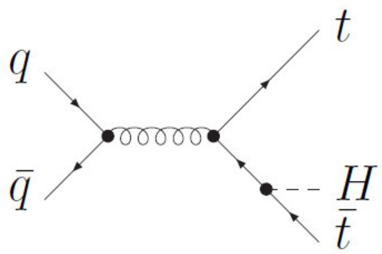
Higgs production at the LHC

Run 1 results for the signal strength $\mu_i = \sigma_i / \sigma_{i,SM}$:



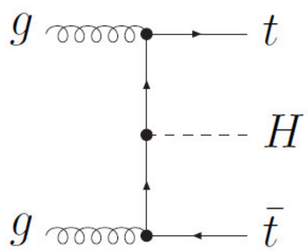
~2σ excesses

$pp \to t\bar{t}H$ at the leading order (LO)



Color channels:

Octet $T^{j}_{a_q a_{\bar{q}}}\, T^{j}_{a_t a_{\bar{t}}}$



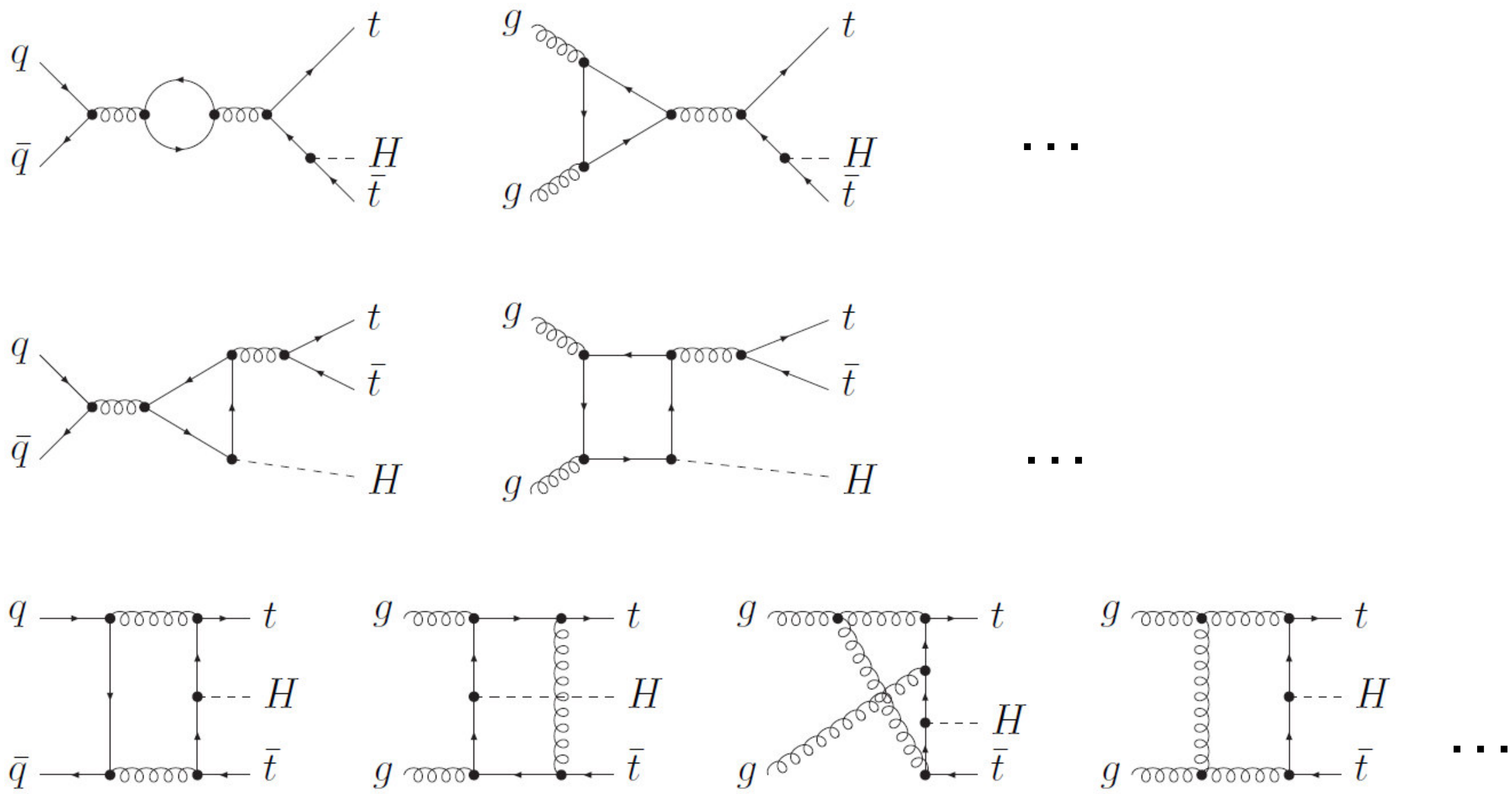
Singlet $\delta^{A_{g1}A_{g2}}\delta_{a_t a_{\bar{t}}}$

Sym. octet $d^{A_{g1}A_{g2}\,j}\, T^{j}_{a_t a_{\bar{t}}}$

Antisym. octet $if^{A_{g1}A_{g2}\,j}\, T^{j}_{a_t a_{\bar{t}}}$

- 3 particles in the final state ➡ 5 independent Mandelstam variables

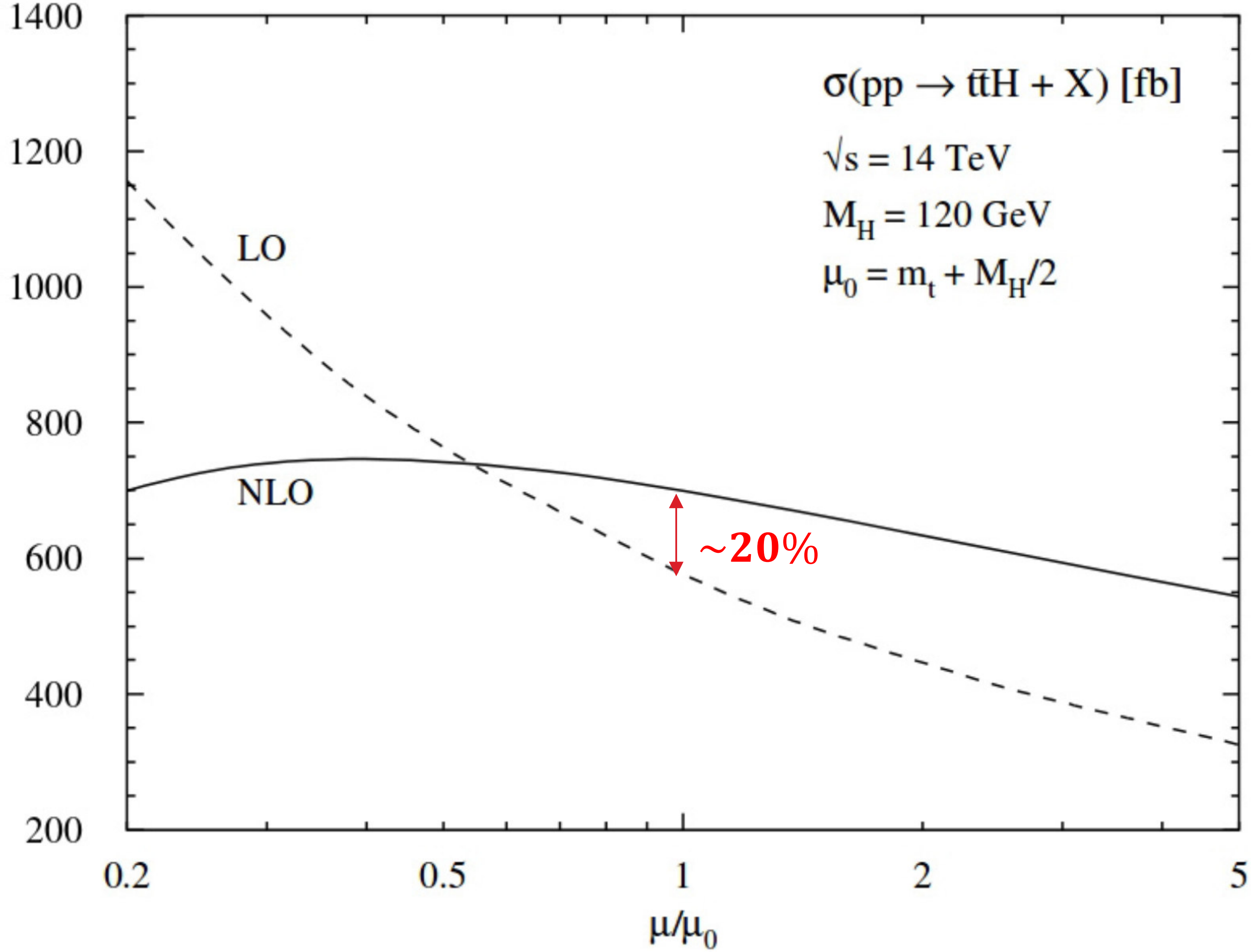
Next-to-leading order (NLO)



Beenakker et. al (2001,03): hep-ph/0107081, hep-ph/0211352,
Reina et. al (2001-03): hep-ph/0107101, hep-ph/0109066, hep-ph/0211438, hep-ph/0305087

LO vs. NLO

Beenakker et. al, *hep-ph/0211352*



$\mu = \mu_F = \mu_R$

Resummation status for $t\bar{t}H$

- Direct QCD: NLO+NLL for absolute threshold $\hat{s} \rightarrow (2m_t + m_H)^2$

  Kulesza, Motyka, TS, Theeuwes *JHEP 1603 (2016) 065*

- SCET: NLO + (NNLL at NNLO) for invariant mass threshold $\hat{s} \rightarrow (p_t + p_{\bar{t}} + p_H)^2$

  Broggio, Ferroglia, Pecjak, Signer, Yang, *JHEP 1603 (2016) 124*

- Direct QCD: NLO+NLL for invariant mass threshold

  Kulesza, Motyka, TS, Theeuwes *PoS LHCP2016 (2016) 084*

- SCET: NLO + NNLL for invariant mass threshold

  Broggio, Ferroglia, Pecjak, Yang, *JHEP 1702 (2017) 126*

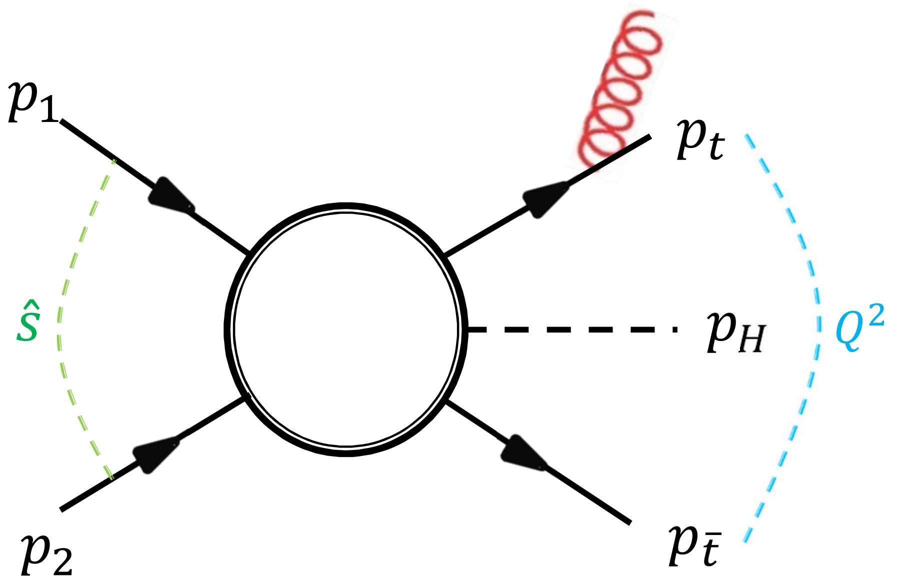
Here:

- Direct QCD: NLO+NNLL for invariant mass threshold

  Kulesza, Motyka, TS, Theeuwes *arXiv:1704.03363*

Invariant mass resummation

Partonic amplitude:



$\hat{s} = (p_1 + p_2)^2$

$Q^2 = (p_t + p_{\bar{t}} + p_H)^2$

Invariant mass of $t\bar{t}H$ state

$$z = \frac{Q^2}{\hat{s}}$$

Invariant mass threshold:

$$z \to 1$$

Resummation of terms:

$$\alpha_s^n \left[\frac{\log^m(1-z)}{1-z}\right]_+ \qquad m < 2n - 1$$

Mellin space technique

Sterman 1987

Mellin transform:

$$\tilde{\sigma}(N,\Pi) = \int_0^1 dz\ z^{N-1}\,\sigma(z,\Pi) \qquad z = \frac{Q^2}{\hat{s}}$$

Large logarithms:

$$\alpha_s^n \left[\frac{\log^m(1-z)}{1-z}\right]_+,\ \ z \to 1 \longrightarrow \alpha_s^n \log^m N\,,\quad N \to \infty\ (complex)$$

Next-to-Next-to-Leading Logarithmic (NNLL) resummation.

Soft gluon resummation at NNLL

- Factorization in the Mellin space:

$$\frac{d\hat{\sigma}^{(\mathrm{res})}_{ij\to klB}}{dQ^2}(N) = Tr\left[\mathbf{H}_{ij\to klB}\,\bar{\mathbf{U}}_{ij\to klB}(N)\,\tilde{\mathbf{S}}_{ij\to kl}\,\mathbf{U}_{ij\to klB}(N)\right]\,\Delta^i(N+1)\Delta^j(N+1)$$

Hard part (contains NLO contribution)

Soft wide angle

Soft collinear, collinear contributions (initial partons)

where:

$$\mathbf{U}_{ij\to klB}(N) = \mathrm{P}\exp\left[\int_\mu^{Q/\bar{N}}\frac{dq}{q}\mathbf{\Gamma}_{ij\to klB}\left(\alpha_s\left(q^2\right)\right)\right]$$

Soft anomalous dimension (2-loop)

$$\tilde{\mathbf{S}}_{ij\to klB} = \tilde{\mathbf{S}}^{(0)}_{ij\to klB} + \frac{\alpha_s}{\pi}\tilde{\mathbf{S}}^{(1)}_{ij\to klB} + \ldots$$

boundary condition for evolution of soft matrix

Soft gluon resummation at NNLL

All contributions constant in N (from hard and soft parts). It is averaged over colors.

$$\frac{d\tilde{\hat{\sigma}}^{(\mathrm{NNLL})}_{ij\to klB}}{dQ^2}(N, Q^2, \{m^2\}, \mu_F^2, \mu_R^2) = \left(1 + \frac{\alpha_s(\mu_R^2)}{\pi}\mathcal{C}^{(1)}_{ij\to klB}(Q^2, \{m^2\}, \mu_F^2, \mu_R^2)\right)$$
$$\times \mathrm{Tr}\Big[\boldsymbol{\sigma}^{(0)}_R(Q^2, \{m^2\}, \mu_R^2)\,\bar{\mathbf{U}}_R(N+1, Q^2, \{m^2\}, Q^2, \mu_R^2)\,\tilde{\mathbf{S}}^{(0)}_R$$
$$\times \mathbf{U}_R(N+1, Q^2, \{m^2\}, Q^2, \mu_R^2)\Big]\,\Delta^i(N+1, Q^2, \mu_F^2, \mu_R^2)\Delta^j(N+1, Q^2, \mu_F^2, \mu_R^2)$$

color matrix

LO cross-section (matrix in color space)

Soft collinear, collinear contributions

Matching to the NLO

$$\sigma^{(\mathrm{match})}_{h_1 h_2 \to kl}(\rho, \{m^2\}, \mu^2) = \sum_{i,j=q,\bar{q},g} \int_{C_{\mathrm{MP}}-i\infty}^{C_{\mathrm{MP}}+i\infty} \frac{dN}{2\pi i}\, \rho^{-N}\, f^{(N+1)}_{i/h_1}(\mu^2)\, f^{(N+1)}_{j/h_2}(\mu^2)$$
$$\times \left[\, \hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(\{m^2\},\mu^2) - \hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(\{m^2\},\mu^2)\Big|_{NLO} \right]$$
$$+ \sigma^{\mathrm{NLO}}_{h_1 h_2 \to kl}(\rho, \{m^2\}, \mu^2)\,,$$

where:

$$\hat{\sigma}^{(\mathrm{res},N)}_{ij\to kl}(\{m^2\},\mu^2) = \left(1 + \frac{\alpha_{\mathrm{s}}(\mu_{\mathrm{R}}^2)}{\pi} \mathcal{C}^{(1)}_{ij\to klB}(Q^2,\{m^2\},\mu_{\mathrm{F}}^2,\mu_{\mathrm{R}}^2)\right)$$
$$\times \mathrm{Tr}\left[\boldsymbol{\sigma}^{(0)}_R(Q^2,\{m^2\},\mu_{\mathrm{R}}^2)\, \bar{\mathbf{U}}_R(N+1,Q^2,\{m^2\},Q^2,\mu_{\mathrm{R}}^2)\, \tilde{\mathbf{S}}^{(0)}_R \right.$$
$$\left. \times\, \mathbf{U}_R(N+1,Q^2,\{m^2\},Q^2,\mu_{\mathrm{R}}^2)\right] \Delta^i(N+1,Q^2,\mu_{\mathrm{F}}^2,\mu_{\mathrm{R}}^2)\Delta^j(N+1,Q^2,\mu_{\mathrm{F}}^2,\mu_{\mathrm{R}}^2)$$

(previous slide)

RESULTS

NLO calculated using aMC@NLO *J. Alwall et. al, arXiv:1405.0301*

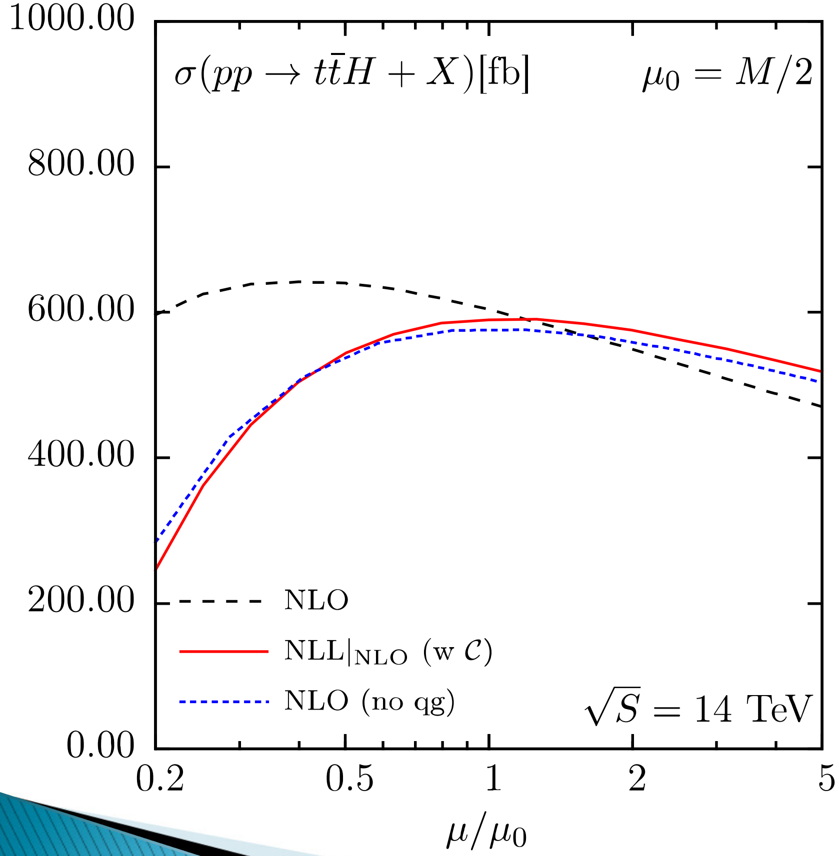
PDF4LHC15 pdf set used *J. Butterworth et al., arXiv: 1510.03865*

NLO without qg vs. resummation at NLO

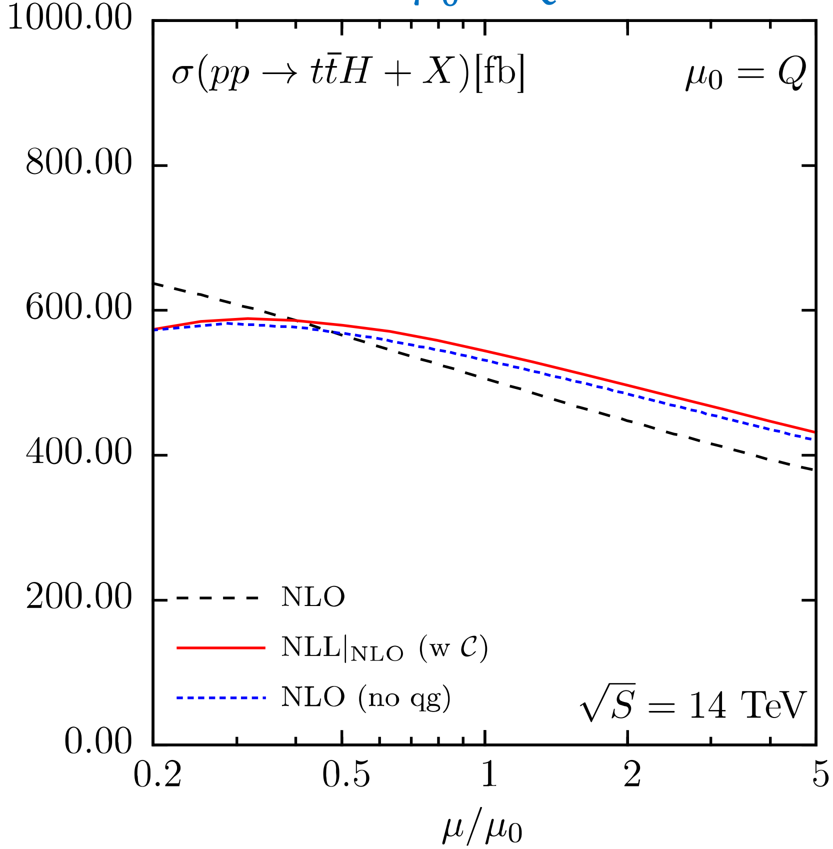
$\mu = \mu_F = \mu_R$

Two choices of central scale:

$\mu_0 = m_t + m_H/2$

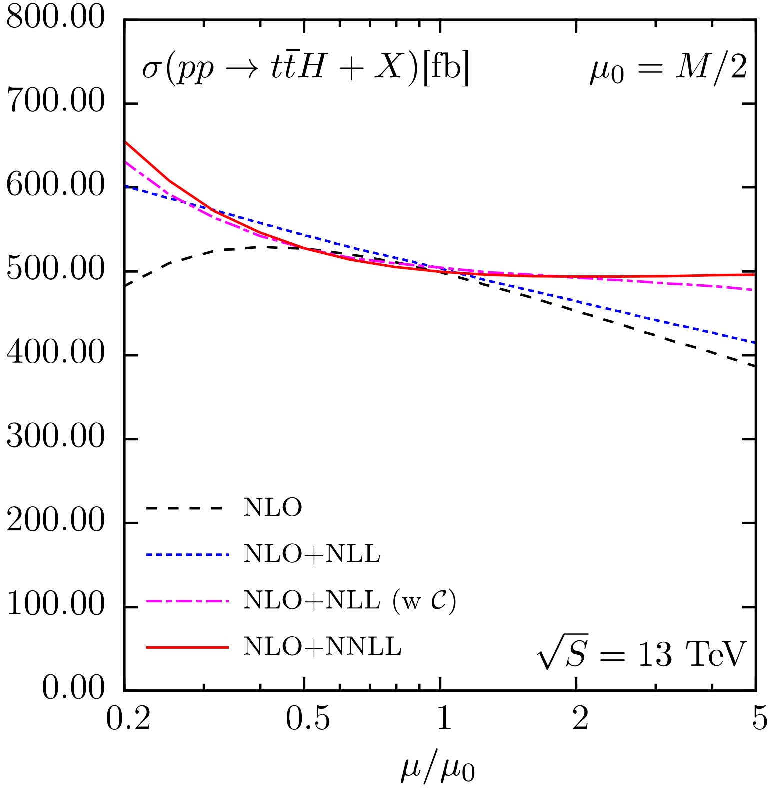


$\mu_0 = \mathrm{Q}$

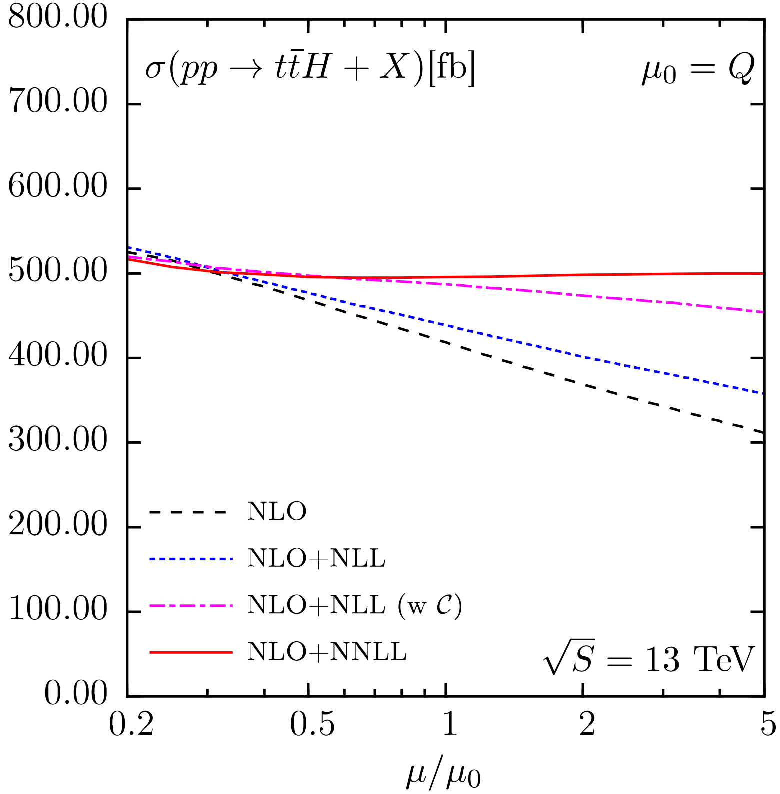


Total cross section for $pp \to t\bar{t}H$

$\mu_0 = m_t + m_H/2$



$\mu_0 = Q$



7-point method for error estimation

- Changing μ_F and μ_R <u>independently:</u>

μ_F \ μ_R	$\mu_0/2$	μ_0	$2\mu_0$
$\mu_0/2$	✖	✖	
μ_0	✖	✖	✖
$2\mu_0$		✖	✖

$$\mu_0 = m_t + m_H/2$$

Estimate error using $\min(\ldots)$ and $\max(\ldots)$

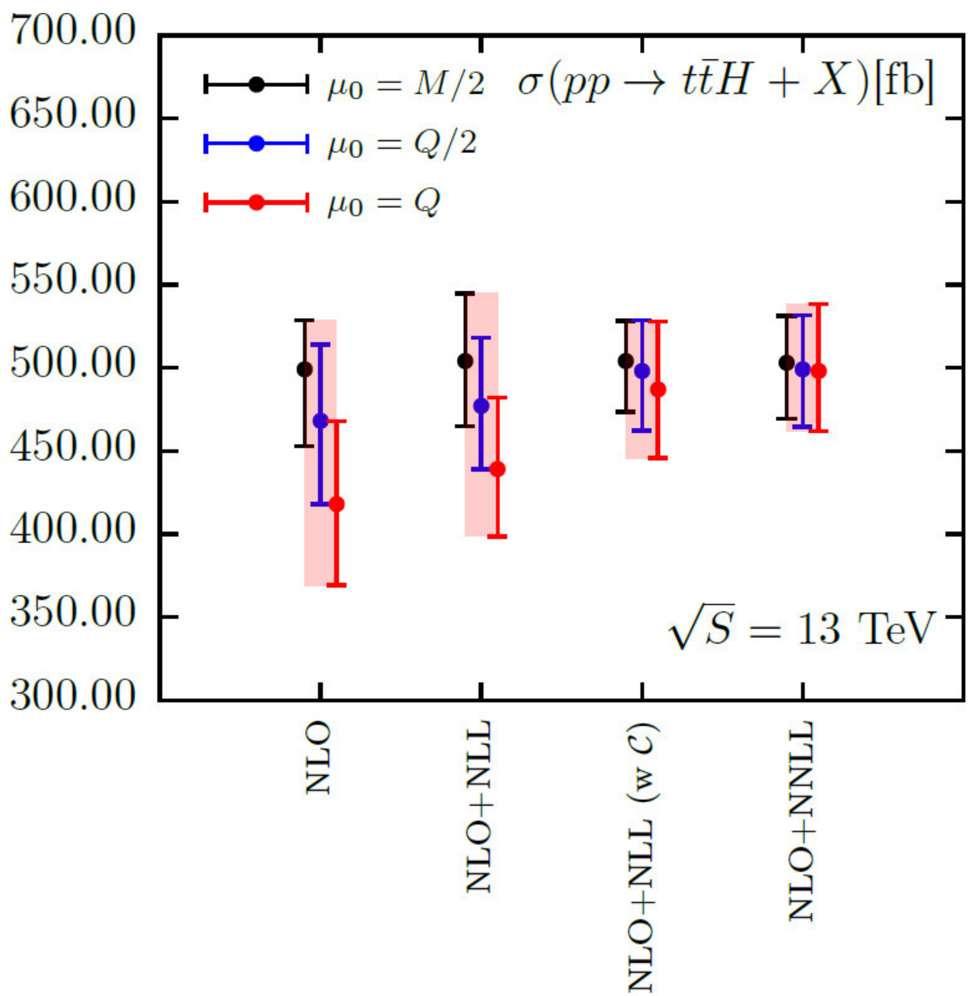
Total cross section for $pp \to t\bar{t}H$

23% reduction of the scale error for $\mu_0 = Q$

$\sqrt{S}$ [TeV]	μ_0	NLO [fb]	NLO+NLL[fb]	NLO+NLL with C [fb]	NLO+NNLL[fb]
13	Q	$418^{+11.9\%}_{-11.7\%}$	$439^{+9.8\%}_{-9.2\%}$	$487^{+8.4\%}_{-8.5\%}$	$496^{+8.0\%}_{-7.3\%}$
	$Q/2$	$468^{+9.8\%}_{-10.7\%}$	$477^{+8.6\%}_{-8.0\%}$	$498^{+6.1\%}_{-7.2\%}$	$496^{+6.4\%}_{-6.8\%}$
	$M/2$	$499^{+5.9\%}_{-9.3\%}$	$504^{+8.1\%}_{-7.8\%}$	$504^{+4.8\%}_{-6.1\%}$	$500^{+5.6\%}_{-6.6\%}$

20% reduction of the scale error for $\mu_0 = m_t + m_H/2$

Total cross section for $pp \to t\bar{t}H$



Summary

- We applied direct QCD resummation technique for $t\bar{t}H$ production.
- The resummation is applied at invariant mass threshold, up to NNLL accuracy.
- We reduced the scale uncertainty of the theoretical prediction for total cross section by ~20% (comparing to NLO).
- The NLO+NNLL result is much more stable with respect to the scale variation than the NLO.

Thank You