Soft Gluon Resummation for the Associated Single Top and Higgs Production at the LHC

Laura Moreno Valero

in collaboration with Anna Kulesza, Vincent Theeuwes

Institute for Theoretical Physics, University of Münster

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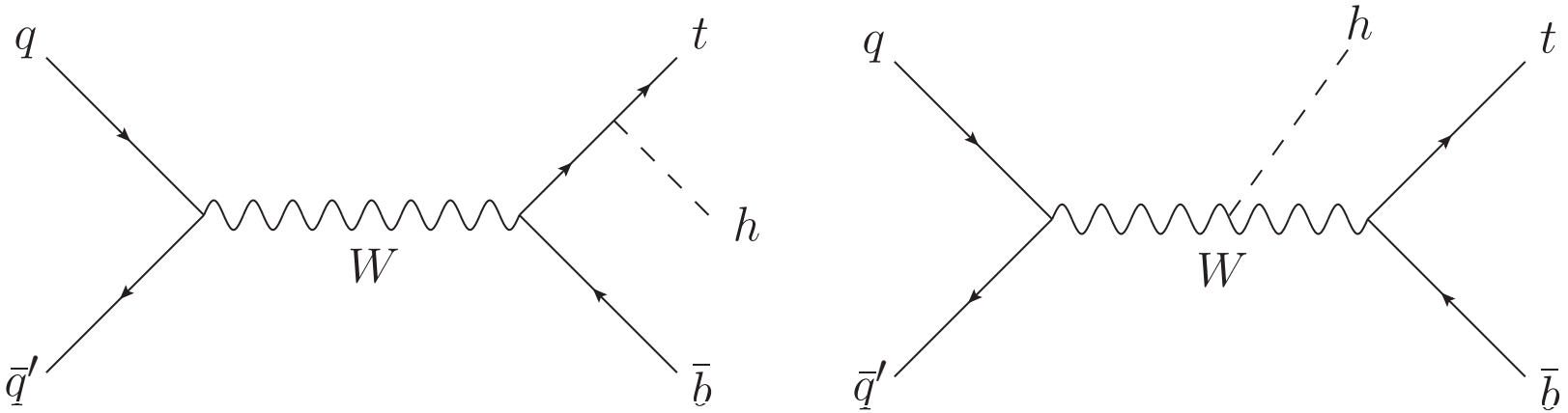
- Beyond-the-Standard Model (BSM) physics search
  - Precision calculations $\Rightarrow$ find deviations between theoretical predictions and experimental data
  - Higgs and top quark processes are of particular interest: direct access to Yukawa coupling
- $pp \to Htj$: very small cross section, $g_{hWW}/g_{ht\bar{t}}$, very **sensitive** to new physics, currently being measured together with $t\bar{t}H$

  [ATLAS Collaboration PRL.125.061802 (2015)] *[CMS Collaboration PRD.99.092005 (2019)]*

GOAL: extend the precision of theoretical predictions beyond the known NLO accuracy by resumming soft-gluon corrections to all-orders for the Htj production

FIRST STEP: s-channel (ca. 30% NLO QCD corrections)

- Tree-level Feynman diagrams in s-channel $pp \to Htj$



$$\sigma_{pp\to Htj}(\{m^2\}) = \sum_{i,k} \int \mathrm{d}x_1 \int \mathrm{d}x_2 \quad \underbrace{f_i(x_1,\mu_F^2) \quad f_k(x_2,\mu_F^2)}_{\text{parton distribution functions (PDFs)}}$$
$$\times \underbrace{\hat{\sigma}_{ik\to Htj}(x_1,x_2,\alpha_s(\mu_R^2),\{m^2\},\mu_F^2)}_{\text{partonic cross section}}$$

- Higher order contributions to σ
  - Next-to-leading order (NLO) known *[Demartin, Maltoni, Mawatari, Zaro (2015)]*
  - NLO QCD+EW corrections for all combined channels *[Pagani, Tsinikos, Vryonidou (2020)]*
  - Full NNLO for Htj not available
    - aNNLO t-channel recently calculated *[Forslund, Kidonakis (2020, 2021)]*
  - Soft gluon corrections: well-defined class of higher-order corrections, can be resummed to all orders (achieved for $t\bar{t}H$) *[Kulesza, Motyka, Schwartländer, Stebel, Theeuwes (2020)] [Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos (2019)]*

- Improving theoretical precision: adding contributions from soft gluon emission
  - Gluons emitted from coloured particles
  - Close to production threshold, only soft gluons
  - Logarithmic form with logarithms becoming large as threshold is approached
  - Depending on the observable, various measures of softness w ($\sim$ distance to threshold) are used

$$w = 1 - z = 1 - Q^2/s \quad \text{(Invariant Mass Threshold)} \quad \rightarrow \quad \left[\frac{\ln(1-z)}{1-z}\right]_+$$

- Soft Gluon Resummation
  - Large logs can invalidate predictive power of perturbative series in α_s
  - Systematic treatment to all orders: resummation
  - Relies on: $|\mathcal{M}|^2$ and Phase Space factorization $\rightarrow$ Mellin space

$$\int_0^1 \mathrm{d}z\, z^{N-1} f(z) = \{\mathcal{M}f\}(N) \equiv f_N \equiv \tilde{f}_N$$

- Technically complicated
- Resummed Logarithms: $\alpha_s^n \left[\frac{\ln^k(1-z)}{1-z}\right]_+, \; k \leq 2n-1$

- Resummed partonic cross section for $pp \to Htj$

$$\tilde{\tilde{\sigma}}^{(\mathrm{NLL})}_{ij\to tHk} = \mathrm{Tr}\left[\mathbf{H}_{ij\to tHk}\,\mathbf{S}_{ij\to tHk}\right]\Delta_i\,\Delta_j\,\mathcal{J}_k$$

$$= \mathrm{Tr}\left[\mathbf{H}_{ij\to tHk}\,\bar{\mathbf{U}}_{ij\to tHk}\,\tilde{\mathbf{S}}_{ij\to tHk}\,\mathbf{U}_{ij\to tHk}\right]\Delta_i\,\Delta_j\,\mathcal{J}_k$$

$$\mathbf{U}_{ij\to tHk}(N, Q^2, \mu_F^2, \mu_R^2) = \mathrm{P}\ \exp\left[\int_{\mu_F}^{Q/\tilde{N}} \frac{dq}{q}\,\mathbf{\Gamma}_{ij\to tHk}\left(\alpha_s(q^2)\right)\right]$$

- One-loop Soft Anomalous Dimension $\mathbf{\Gamma}^{(1)}_{ij\to tHk}$ checked with *[Forslund, Kidonakis (2020)]*

$$\mathbf{\Gamma}_{ij\to tHk}(\alpha_s) = \left(\frac{\alpha_s}{\pi}\right)\mathbf{\Gamma}^{(1)}_{ij\to tHk} + \left(\frac{\alpha_s}{\pi}\right)^2\mathbf{\Gamma}^{(2)}_{ij\to tHk} + \dots$$

$$\mathbf{\Gamma}^{(1)}_{11,ij\to tHk} = C_F\left(\log\frac{s_{34}-m_t^2}{m_t\sqrt{s}} - \frac{1}{2}\right)$$

$$\mathbf{\Gamma}^{(1)}_{12,ij\to tHk} = \frac{C_F}{2N_c}\log\frac{\tilde{t}_{13}\tilde{t}_{24}}{\tilde{t}_{23}\tilde{t}_{14}} \qquad \mathbf{\Gamma}^{(1)}_{21,ij\to tHk} = \log\frac{\tilde{t}_{13}\tilde{t}_{24}}{\tilde{t}_{23}\tilde{t}_{14}} \qquad \text{with } \tilde{t}_{ik} = (p_i - p_k)^2 - m_k^2$$

$$\mathbf{\Gamma}^{(1)}_{22,ij\to tHk} = C_F\left(\log\frac{s_{34}-m_t^2}{m_t\sqrt{s}} - \frac{1}{2}\right) + \frac{4C_F - N_c}{2}\log\frac{\tilde{t}_{13}\tilde{t}_{24}}{\tilde{t}_{23}\tilde{t}_{14}} + \frac{N_c}{2}\log\frac{\tilde{t}_{14}\tilde{t}_{23}}{s(s_{34}-m_t^2)}$$

- We take exponential functions at NLL accuracy
- $\mathbf{H}$ and $\tilde{\mathbf{S}}$ up to $\mathcal{O}(\alpha_s)$

$$\mathbf{H}(\mu_R, \mu_F) = \mathbf{H}^{(0)} + \frac{\alpha_s(\mu_R)}{\pi}\mathbf{H}^{(1)}(\mu_R, \mu_F)$$

$$\tilde{\mathbf{S}}(1) = \tilde{\mathbf{S}}^{(0)}\left(1 + \frac{\alpha_s(\mu_R)}{\pi}\tilde{\mathbf{S}}^{(1)}(1)\right)$$

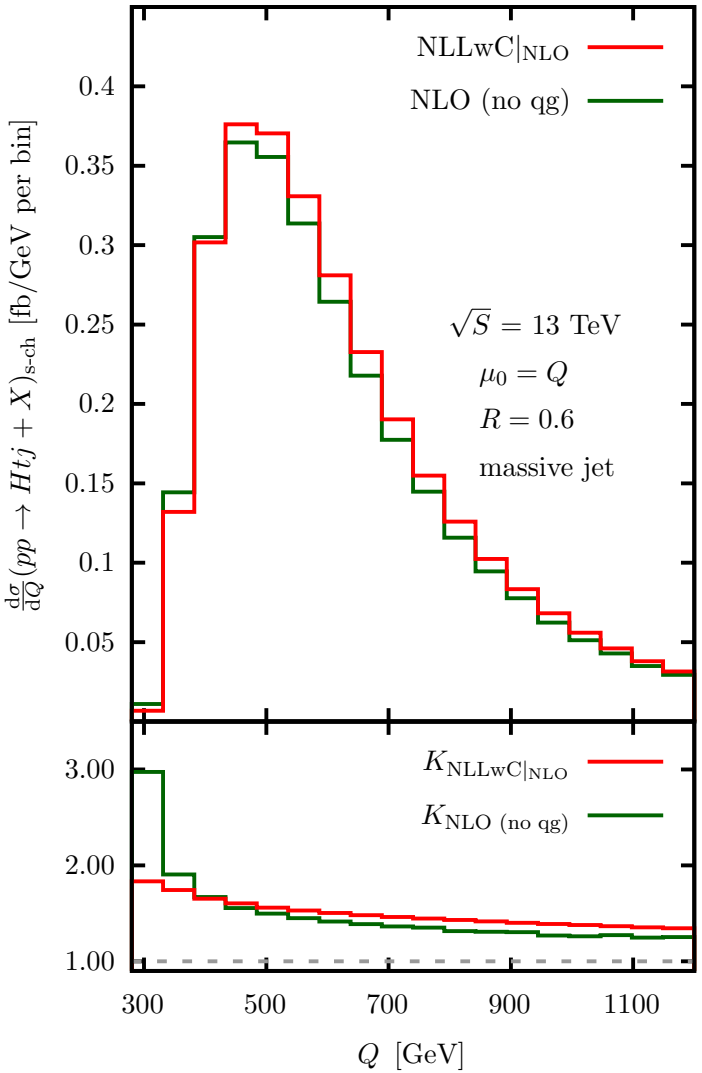
- Resulting in NLLwC accuracy (NLL' in SCET notation)
- Invariant mass threshold:
  - Massless jet at threshold ($p_j^2 = 0$): $1 - z = 1 - \frac{(p_H+p_t)^2+2p_j\cdot(p_H+p_t)}{\hat{s}}$
  - Massive jet at threshold: $1 - z = 1 - \frac{Q^2}{\hat{s}}$, with $Q^2 = (p_H + p_t + p_j)^2$

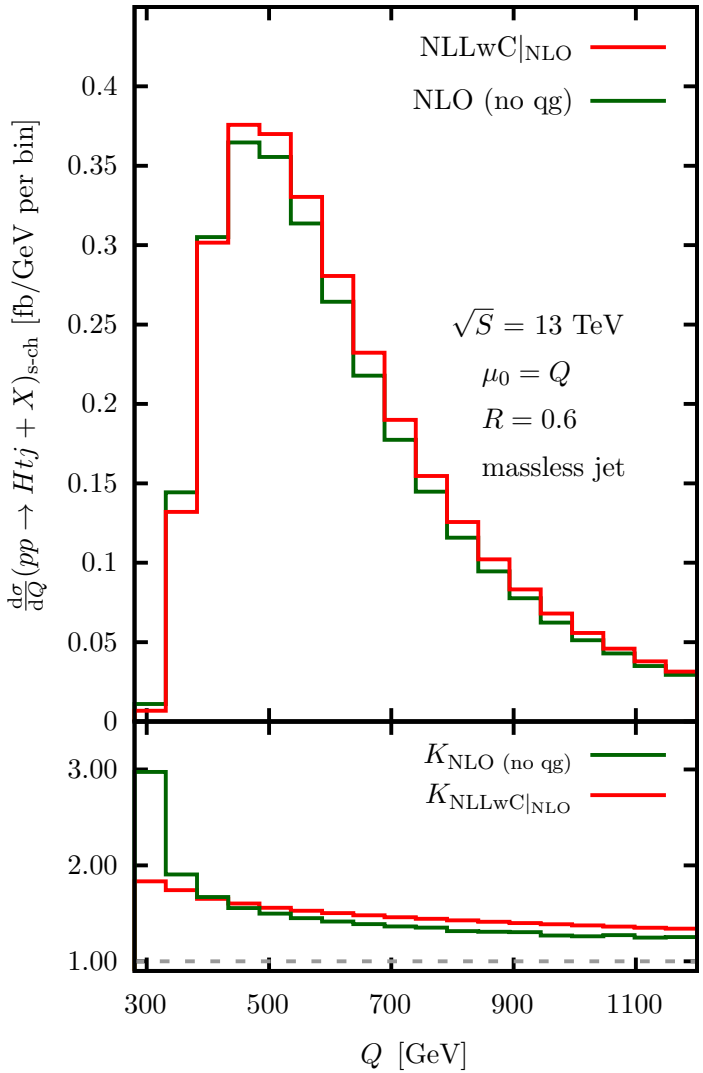
[Kidonakis, Oderda, Sterman (1998)]

- Matching to NLO cross section

$$\sigma^{NLO+NLLwC}_{pp\to Htj} = \sigma^{NLO}_{pp\to Htj} + \sum_{i,k}\int \frac{dN}{2\pi i}\rho_h^{-N}\tilde{f}_i(N+1,\mu_F^2)\tilde{f}_k(N+1,\mu_F^2) \times \underbrace{\left[\tilde{\sigma}^{NLLwC}_{ik\to Htj}(N) - \tilde{\sigma}^{NLLwC}_{ik\to Htj}(N)\Big|_{NLO}\right]}_{\text{avoid double counting with NLO!}}$$

- $q\bar{q}'$ channel at NLO+NLLwC
- qg channel at NLO


NLLwC|NLO
NLO (no qg)
$\sqrt{S} = 13$ TeV
$\mu_0 = Q$
$R = 0.6$
massive jet
$K_{\text{NLLwC|NLO}}$
$K_{\text{NLO (no qg)}}$
$\frac{d\sigma}{dQ}(pp \to Htj + X)_{\text{s-ch}}$ [fb/GeV per bin]
Q [GeV]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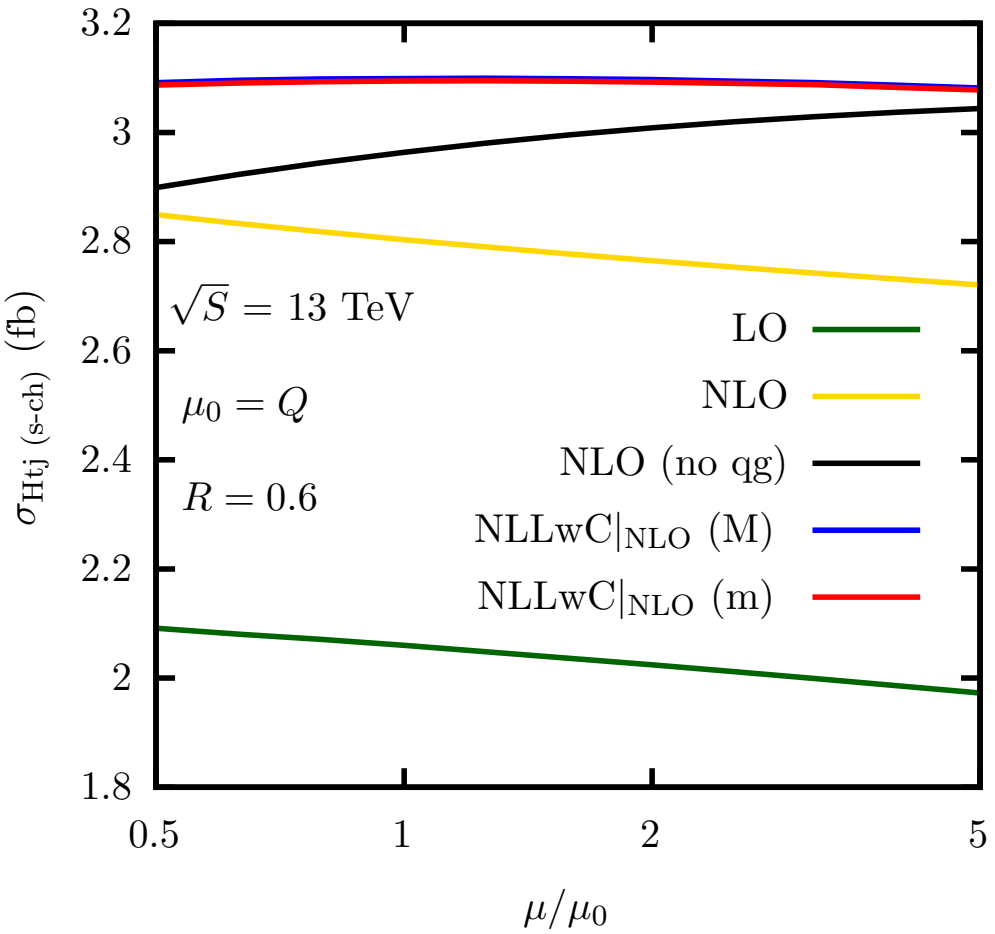
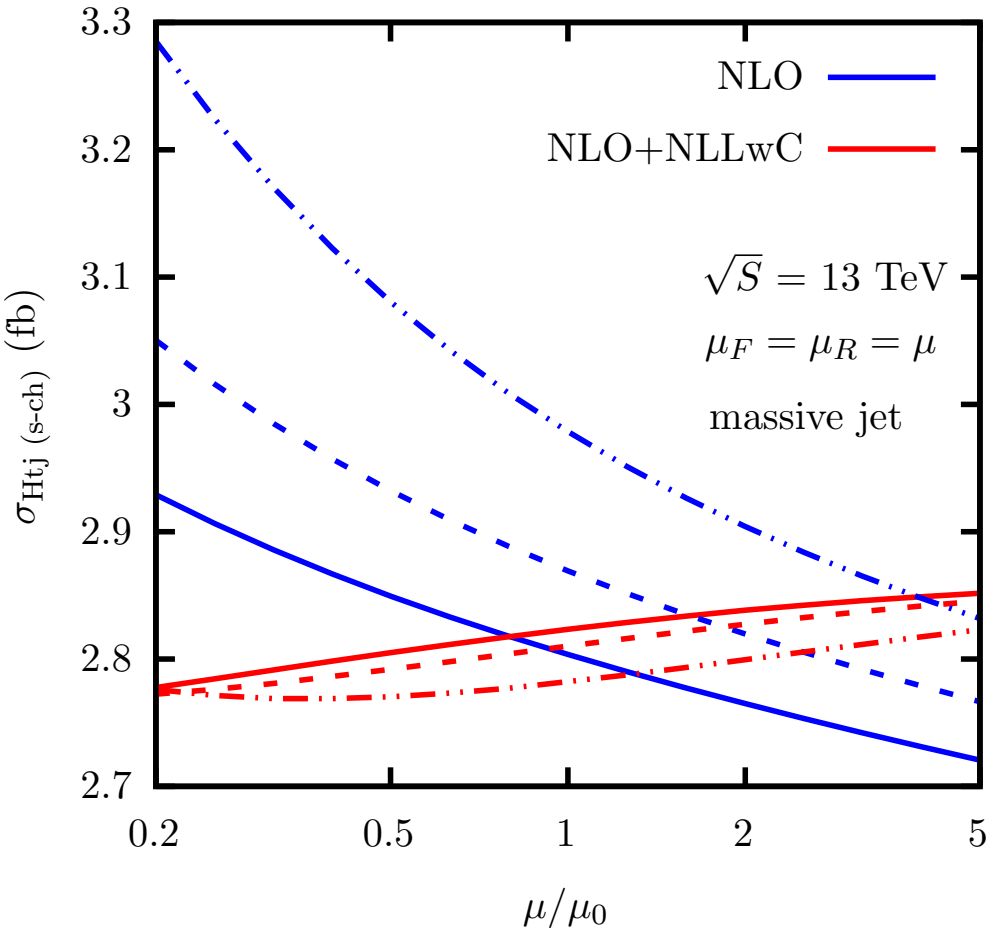

3.2
3
2.8
2.6
2.4
2.2
2
1.8
0.5
1
2
5
$\sigma_{\mathrm{Htj\ (s\text{-}ch)}}$ (fb)
μ/μ_0
$\sqrt{S} = 13$ TeV
$\mu_0 = Q$
$R = 0.6$
LO
NLO
NLO (no qg)
NLLwC$|_{\mathrm{NLO}}$ (M)
NLLwC$|_{\mathrm{NLO}}$ (m)

Different central scale choices: Q: —, $H_T/2$: - - -, $H_T/6$:–··–



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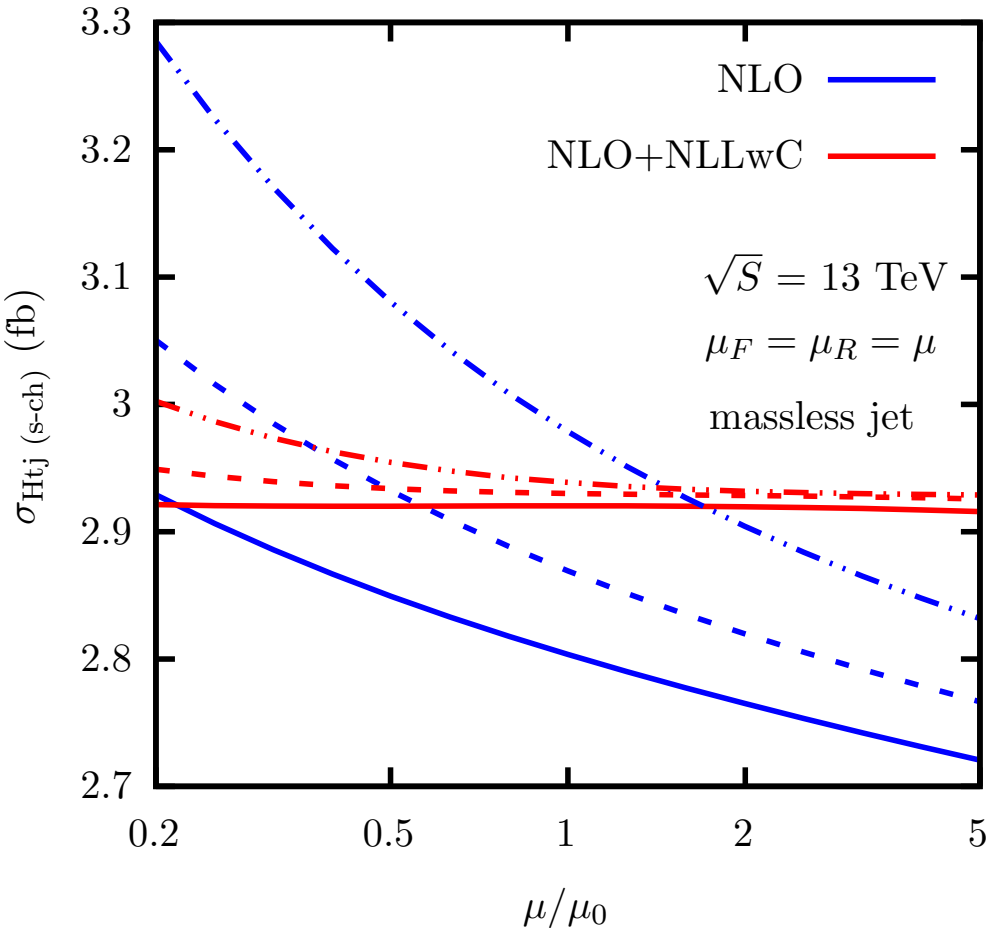

- Associated top and Higgs production very important for BSM searches: coupling $t\bar{t}H$
- Extending precision of theoretical calculations beyond NLO
- Effects of soft gluon emission at NLLwC
- Different jet treatment: massive and massless at threshold
- Reduced scale dependence NLO+NLLwC

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