

Soft Gluon Resummation beyond NLL for associated $t\bar{t}H$ Production at the LHC

Vincent Theeuwes

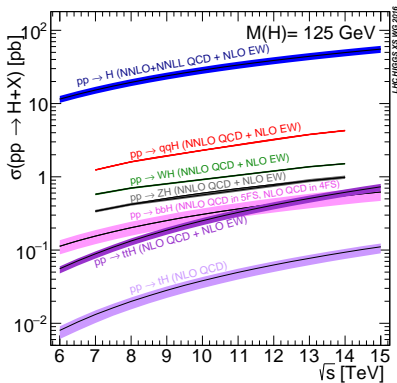
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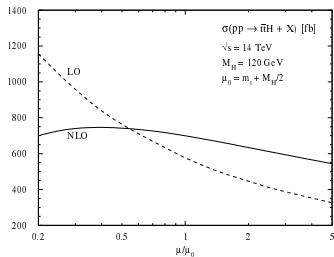
Importance of $pp \rightarrow t\bar{t}H$

- A Higgs boson found with a mass of 125 GeV
- Precision study needed to determine if it is SM Higgs
- Direct way to access Yukawa coupling



Current status of $pp \rightarrow t\bar{t}H$

- QCD Corrections up to NLO [*Beenakker et al. , '02*] [*Dawson et al. , '02*]
- Matched to parton showers by: aMC@NLO [*Frederix et al. , '11*], PowHel [*Garzelli et al. , '11*], Sherpa [*Hoeche et al., '12*], POWHEG-BOX [*Hartanto et al. , '14*]
- Electroweak correction [*Frixione et al. , '14,'15*][*Zhang, '14*]
- Including top decays [*Denner, Feger, '15*]
- Absolute threshold at NLL [*Kulesza, Motyka, Stebel, VT, '15*]
- Expansion of NNLL in SCET [*Broggio et al., '15*]



[*Beenakker et al. , '02*]

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

Gains

- NNLO corrections out of reach
- Resummation can help reduce scale uncertainty
- Good process to start:
 - Simple color structure
 - Massive particles \rightarrow no final state collinear divergences

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Pitfalls

- $2 \rightarrow 3$ phase space suppressed near threshold ($\sigma \propto \beta^4$)
- Small corrections from near absolute threshold

Definition of Threshold

Threshold variable $\hat{\tau} = \frac{Q^2}{\hat{s}}$

Q^2 : the invariant mass final state particles

$$1 - \hat{\tau} = 1 - \frac{Q^2}{\hat{s}}$$

$$\sim \frac{\text{energy of the emitted gluons}}{\text{total available energy}}$$

The IR divergences lead to logarithms:

$$(1 - \hat{\tau})^{-1-2\epsilon} = -\frac{1}{2\epsilon} \delta(1 - \hat{\tau}) + \left(\frac{1}{1 - \hat{\tau}} \right)_+ - 2\epsilon \left(\frac{\log(1 - \hat{\tau})}{1 - \hat{\tau}} \right)_+$$

$$\alpha_s^n \left(\frac{\log^m(1 - \hat{\tau})}{1 - \hat{\tau}} \right)_+$$

Mellin Transform

Mellin transform is used with respect to τ (needed for factorization of phase space):

$$\begin{aligned}\tilde{\sigma}_{pp \rightarrow t\bar{t}H}(N) &\equiv \int_0^1 d\tau \tau^{N-1} \sigma_{pp \rightarrow t\bar{t}H}(\tau, \mu_R, \mu_F) \\ &= \sum_{i,j} \tilde{f}_{i/p}(N+1, \mu_F) \tilde{f}_{j/p}(N+1, \mu_F) \tilde{\sigma}_{ij \rightarrow t\bar{t}H}(N, \mu_R, \mu_F)\end{aligned}$$

- $\tilde{f}_{i/p}(N+1, \mu_F)$: Mellin transform with respect to x
- $\tilde{\sigma}_{ij \rightarrow t\bar{t}H}(N, \mu_R, \mu_F)$: Mellin transform with respect to $\hat{\tau}$

$\log^n(1 - \hat{\tau}) \Rightarrow \log^n N$ and threshold $\hat{\tau} \rightarrow 1 \sim N \rightarrow \infty$

First application for $2 \rightarrow 3$ in Mellin space

Orders of Resummation

Large logarithms $\log N \equiv L$ for $N \rightarrow \infty$

Perturbation needs to be reordered in α_s and L :

$$\tilde{\sigma} \sim \tilde{\sigma}_{LO} \times \mathcal{C}(\alpha_s) \exp [Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \dots]$$

With orders of precision: \Downarrow \Downarrow \Downarrow

LL NLL NNLL

\Downarrow \Downarrow \Downarrow

$\alpha_s^n \log^{n+1}(N)$ $\alpha_s^n \log^n(N)$ $\alpha_s^{n+1} \log^n(N)$

Exponential functions are universal for initial state emission

[Kodaira, Trentadue, '82][Sterman, '87][Catani, d'Emilio, Trentadue, '88][Catani, Trentadue, '89]

Soft anomalous dimension

Soft anomalous dimension

Calculated at the hand of UV divergences of eikonal integrals

$$\Gamma_{ij \rightarrow klB, IJ}^{(1)} = -C_{IJ}^{ab} \text{Res} \{ \omega^{ab} \} - \Gamma_{ij \rightarrow C}^{(1)} \delta_{IJ}$$

- I and J : color indices
- a and b : colored particle indices
- C_{IJ}^{ab} : color factor of the exchange
- ω^{ab} : UV divergent terms of eikonal integrals

Soft wide-angle

[Kidonakis et al., '97-'01]

$$\begin{aligned} \tilde{S}_{ij \rightarrow kl} \left(\frac{Q}{\mu N} \right) &= \bar{P} \exp \left[\int_Q^{Q/N} \frac{dq}{q} \Gamma_{ij \rightarrow kl}^\dagger (\alpha_s(q^2)) \right] \tilde{S}_{ij \rightarrow kl} \\ &\quad \times P \exp \left[\int_Q^{Q/N} \frac{dq}{q} \Gamma_{ij \rightarrow kl} (\alpha_s(q^2)) \right] \end{aligned}$$

Path-order exponential solved at NNLL accuracy by

[Buras, '80][Ahrens, Ferroglia, Neubert, Pecjak, Yang, '10]

$$\mathbf{U}_R = \left(\mathbf{1} + \frac{\alpha_s(Q/\bar{N})}{\pi} \mathbf{K} \right) \left[\left(\frac{\alpha_s(Q)}{\alpha_s(Q/\bar{N})} \right)^{\frac{\vec{\lambda}^{(1)}}{2\pi b_0}} \right]_D \left(\mathbf{1} - \frac{\alpha_s(Q)}{\pi} \mathbf{K} \right)$$

$$K_{IJ} = \delta_{IJ} \lambda_I^{(1)} \frac{b_1}{2b_0^2} - \frac{(\Gamma_R^{(2)})_{IJ}}{2\pi b_0 + \lambda_I^{(1)} - \lambda_J^{(1)}}$$

Hard Matching Coefficient (Schematically)

$$\mathcal{C}(\alpha_s) = 1 + \frac{\alpha_s}{\pi} \mathcal{C}^{(1)} + \dots$$

- Massive final state dipoles [*Catani, Dittmaier, Seymour, Trócsányi, '02*]
- Virtual contribution from PowHeg-Box [*Hartanto, Jäger, Reina, Wackerath, '15*]
confirmed by aMC@NLO [*Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau, '11*]
- Include Coulomb correction $\frac{1}{\beta_{34}}$
- Averaged over color channels

Matching to Fixed Order

Resummed Cross Section

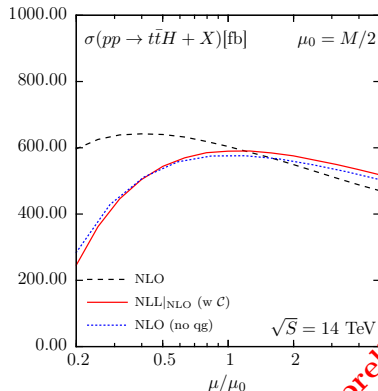
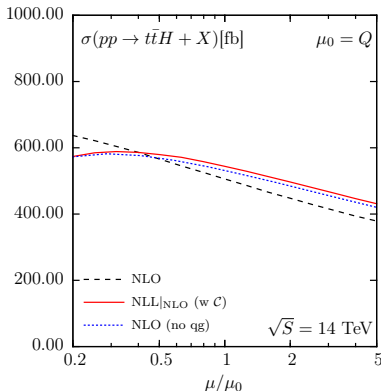
$$\begin{aligned}
 \sigma^{(\text{NLO+NLL})}(\tau) &= \sigma^{(\text{NLO})}(\tau) \\
 &+ \int_{\text{CT}} \frac{dN}{2\pi i} \tau^{-N} \tilde{f}_{g/p}(N+1) \tilde{f}_{g/p}(N+1) \\
 &\times \left[\tilde{\sigma}^{(\text{NLL})}(N) - \tilde{\sigma}^{(\text{NLL})}(N)|_{(\text{NLO})} \right]
 \end{aligned}$$

Matching to fixed order required to avoid double counting.

Results

[Kulesza, Motyka, Stebel, VT, in preparation]

PDFs used: PDF4LHC

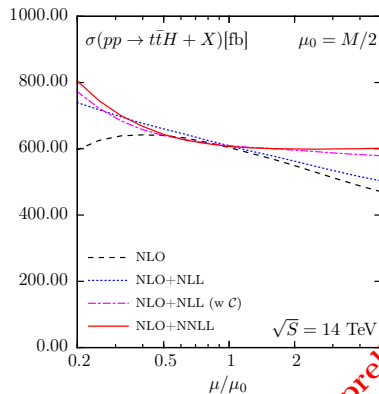
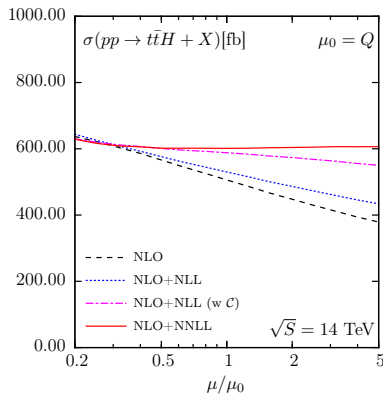


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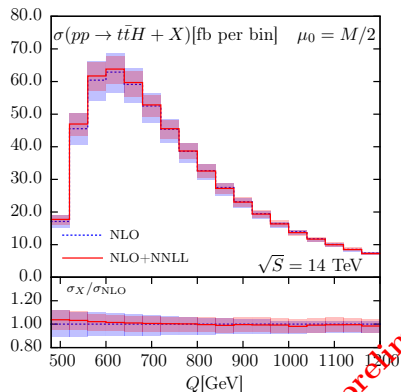
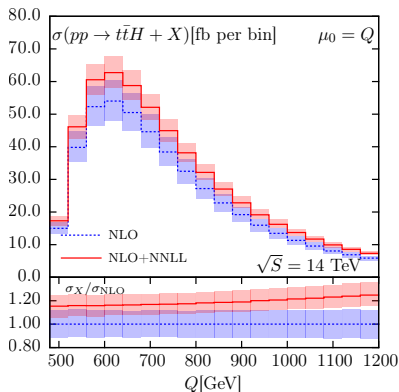


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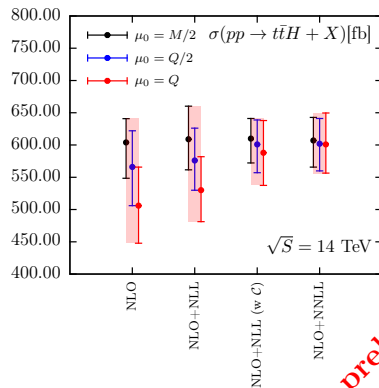
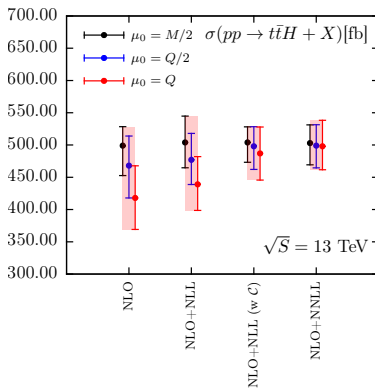


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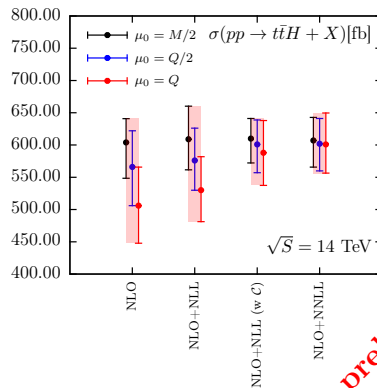
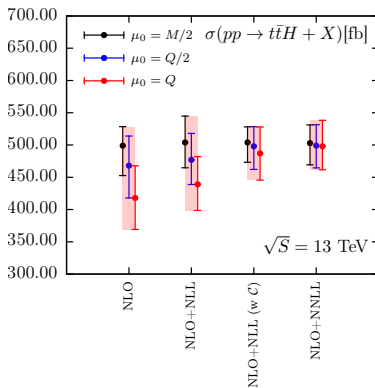


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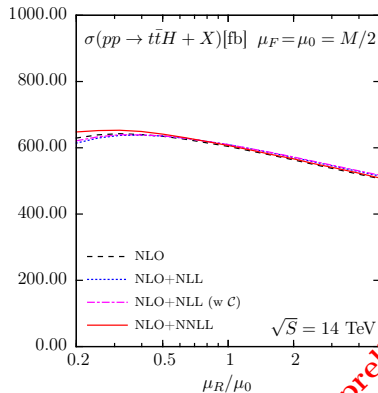
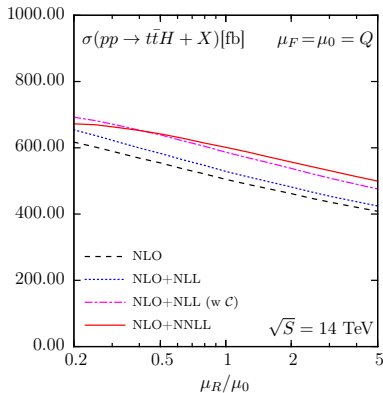
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Thank you for your attention

Backup

[Kulesza, Motyka, Stebel, VT, in preparation]

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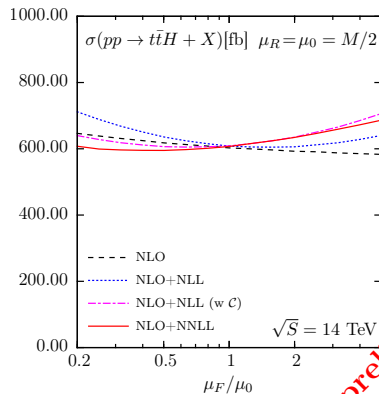
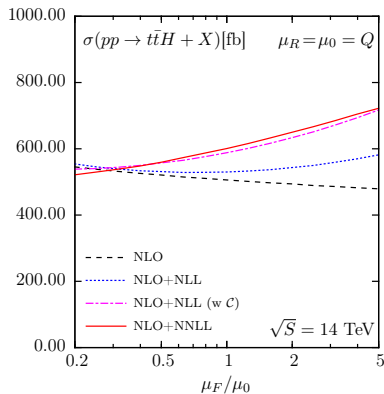


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