Soft Gluon Resummation at NNLL Accuracy for Associated $t\bar{t}H$ Production at the LHC

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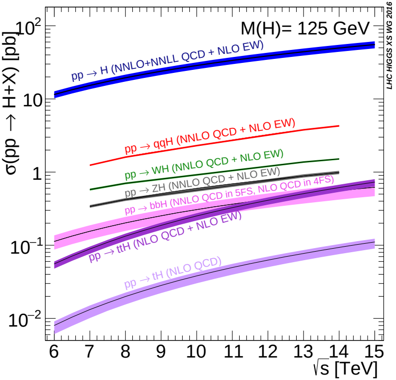
Importance of $pp \to t\bar{t}H$

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



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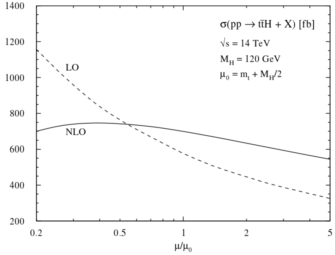
Current status of $pp \to t\bar{t}H$

- 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 et al., '14]*
- Including top decays *[Denner, Feger, '15]*
- Absolute threshold at NLL *[Kulesza, Motyka, Stebel, VT, '15]*
- NNLL in SCET, expansion *[Broggio, Ferroglia, Pecjak, Yang, '15]* and resummation *[Broggio, Ferroglia, Pecjak, Yang, '16]*

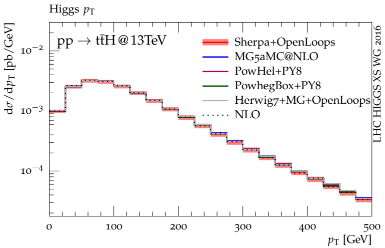


[Beenakker et al. , '02]

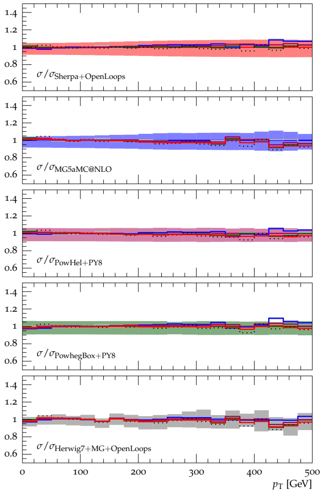
Parton showers

NLO 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]*

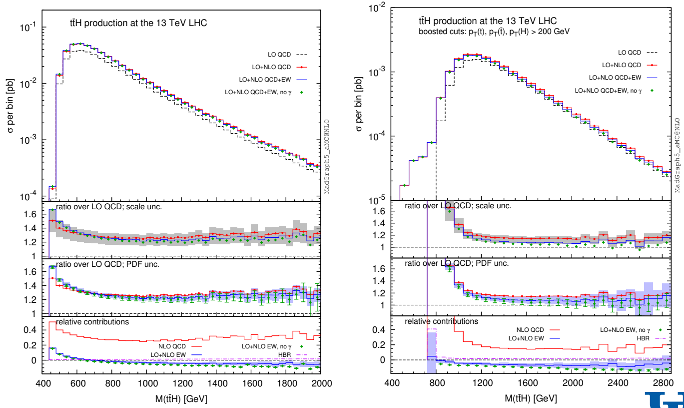


[YR4 , '16]



Electroweak corrections

- Electroweak correction *[Frixione et al. , '14,'15][Zhang et al., '14]*
- Contributions not proportional to Yukawa
- 1-2% corrections to inclusive cross section
- Larger corrections in certain regions of phase space



[Frixione et al. , '15]

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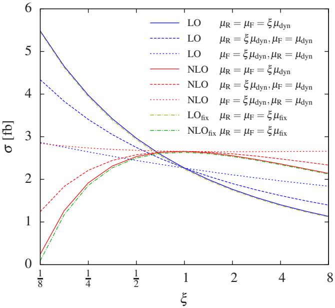
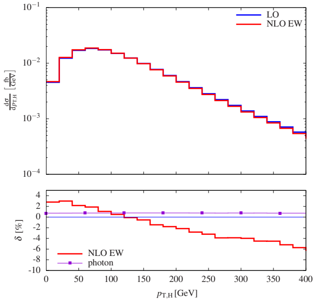
Top decay

- Including top decays *[Denner, Feger, '15]*
- Combined with electroweak corrections *[Denner, Lang, Pellen, Uccirati, '16]*





[YR4 , '16] [Denner, Lang, Pellen, Uccirati, '16]

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Background processes

- $pp \to t\bar{t}V$ (Electroweak correction)
- $pp \to t\bar{t}VV'$

- $pp \to t\bar{t}b\bar{b}$ (Flavor scheme)
- $pp \to t\bar{t} + X$ (Double counting with massless $b\bar{b}$)

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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 $\to$ no final state collinear divergences

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Pitfalls

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

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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:

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

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

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Mellin Transform

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

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

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

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

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

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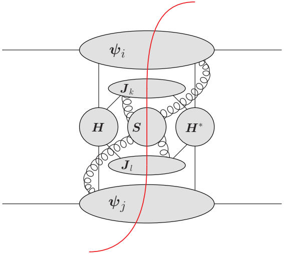
General factorization

In general cross section factorizes into:

$$\hat{\sigma}_{ij\to kl\ldots} = H_{ij\to kl\ldots,IJ} \otimes \psi_i \otimes \psi_j \otimes S_{JI} \otimes J_k \otimes J_l \ldots$$

- $H_{ij\to kl,IJ}$ Hard function
- $\psi_{i,j}$ Initial state collinear emission
- $J_{k,l,\ldots}$ Final state collinear emission
- S_{JI} Soft emission



Each of these functions is computed through renormalization group equations

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Orders of Resummation

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

Perturbation needs to be reordered in α_s and L:

$$\tilde{\sigma} \sim \tilde{\sigma}_{LO} \times \mathcal{C}(\alpha_s) \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \cdots \right]$$

With orders of precision:

	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]

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Soft anomalous dimension

Soft anomalous dimension

Calculated at the hand of UV divergences of eikonal integrals

$$\Gamma^{(1)}_{ij\to klB,IJ} = -C^{ab}_{IJ}\mathrm{Res}\left\{\omega^{ab}\right\} - \Gamma^{(1)}_{ij\to C}\,\delta_{IJ}$$

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

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Soft wide-angle

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

$$\tilde{S}_{ij\to kl}\left(\frac{Q}{\mu N}\right) = \bar{\mathrm{P}}\exp\left[\int_Q^{Q/N}\frac{dq}{q}\Gamma^{\dagger}_{ij\to kl}\left(\alpha_s\left(q^2\right)\right)\right]\tilde{S}_{ij\to kl}$$
$$\times \mathrm{P}\exp\left[\int_Q^{Q/N}\frac{dq}{q}\Gamma_{ij\to kl}\left(\alpha_s\left(q^2\right)\right)\right]$$

Path-order exponential solved at NNLL accuracy by

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

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

$$K_{IJ} = \delta_{IJ}\lambda_I^{(1)}\frac{b_1}{2b_0^2}-\frac{\left(\mathbf{\Gamma}_R^{(2)}\right)_{IJ}}{2\pi b_0+\lambda_I^{(1)}-\lambda_J^{(1)}}$$

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Hard Matching Coefficient (Schematically)

$$H(\alpha_s) = H^{(0)} + \frac{\alpha_s}{\pi} H^{(1)} + \dots$$

$$S(\alpha_s(Q/\bar{N})) = S^{(0)} + \frac{\alpha_s(Q/\bar{N})}{\pi} S^{(1)} + \dots$$

- Soft and collinear functions computed
- Virtual contribution split into color channels from modified version of PowHel *[Garzelli, Kardos, Papadopoulos, Trócsányi, '11]*
- Average has been confirmed using:
  PowHeg-Box *[Hartanto,Jäger,Reina,Wackeroth,'15]*
  aMC@NLO *[Hirschi,Frederix,Frixione,Garzelli,Maltoni,Pittau,'11]*
- Include Coulomb correction $\frac{1}{\beta_{34}}$

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Matching to Fixed Order

Resummed Cross Section

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

Matching to fixed order required to avoid double counting.

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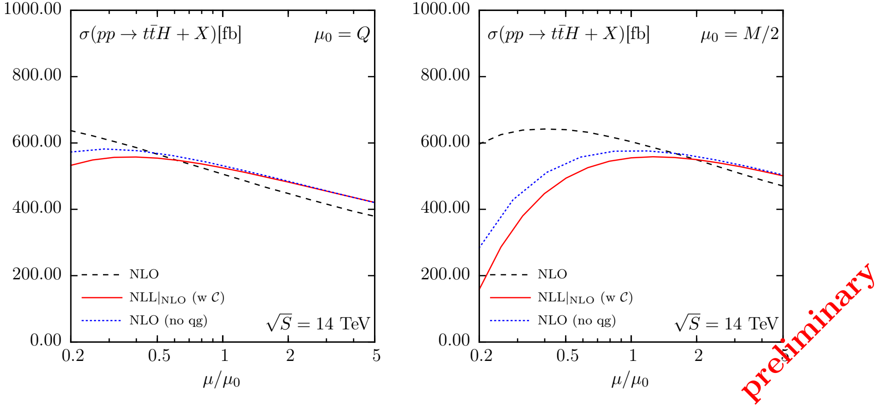
Results

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

PDFs used: PDF4LHC



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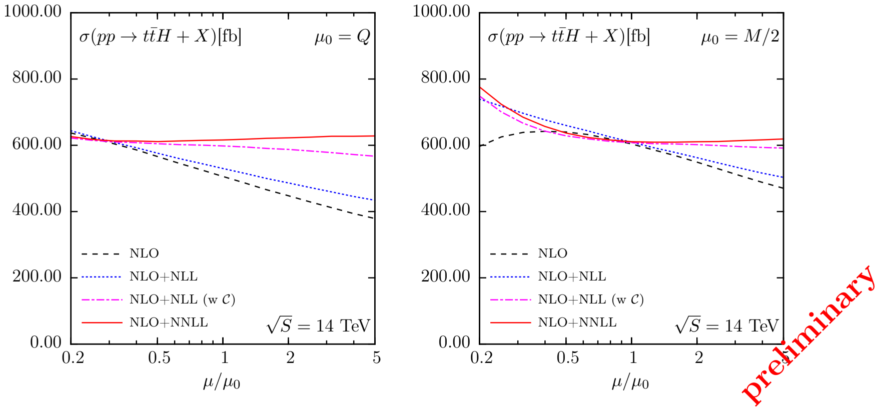

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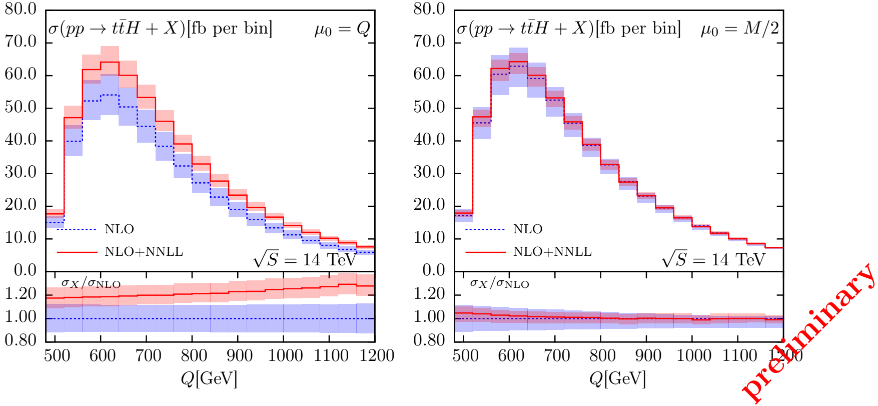

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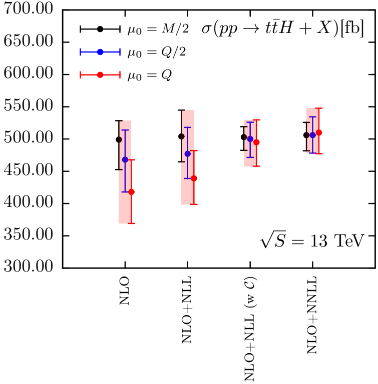

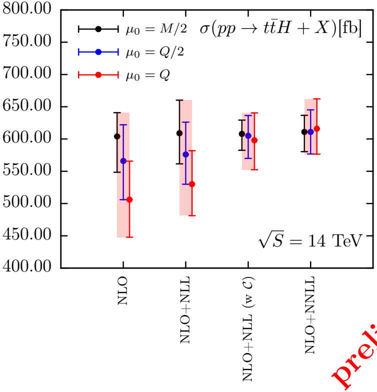

preliminary

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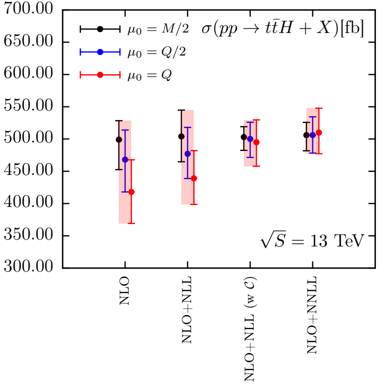

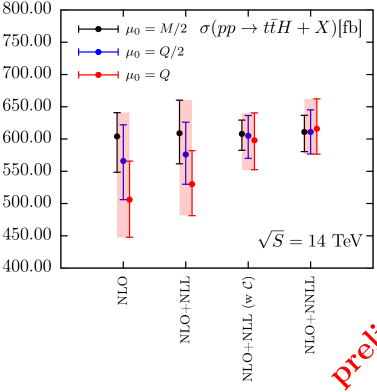

preliminary

Thank you for your attention

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