Associated production of a top quark pair with a heavy boson at NLO+NNLL accuracy

Vincent Theeuwes

Georg-August-University Göttingen

In Collaboration with:
Anna Kulesza, Leszek Motyka, Daniel Schwartländer, Tomasz Stebel

[arXiv:1704.03363] [arXiv:1812.08622] [arXiv:1905.07815]

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DAAD

Federal Ministry of Education and Research

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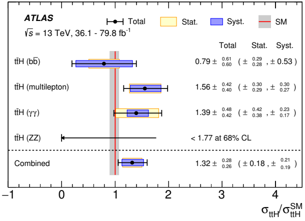
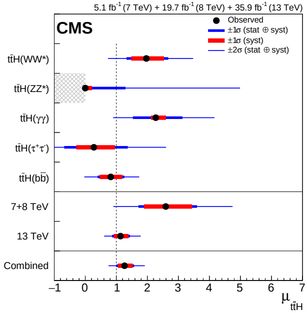
Importance of $pp \to t\bar{t}H$

- $t\bar{t}H$ production has been measured at 5.8σ *[ATLAS,'18]* and 5.2σ *[CMS, '18]*
- Direct way to access Yukawa coupling
- Precision study needed to determine deviations from SM Higgs



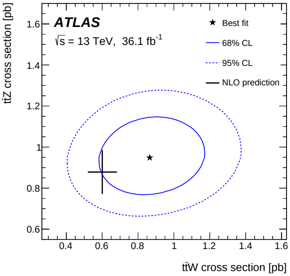
[ATLAS, '18]



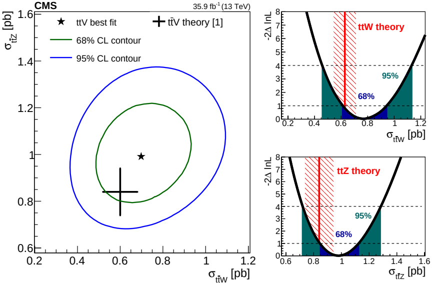
[CMS, '18]

Importance of $pp \to t\bar{t}Z/W$

- Interaction to top quarks
- Important background process to searches and SM
- Latest $t\bar{t}Z$ result $\sigma(t\bar{t}Z) = 1.0^{+0.06}_{-0.05}$ (stat)$^{+0.07}_{-0.06}$ (syst) *[CMS, '19]* higher precision than NLO theory



[ATLAS, '19]



[CMS, '17]

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

$t\bar{t}H$

- NLO QCD *[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 et al., '15]*

$t\bar{t}Z/W$

- NLO QCD *[Lazopoulos et al., '07] [Kardos et al., '12]*
- Matched to parton showers by: aMC@NLO *[Maltoni et al., '14]*, POWHEG-BOX *[Garzelli et al., '12]*
- Electroweak correction *[Frixione et al., '14,'15][Frederix et al., '18]*
- Including decays at NLO *[Campbell et al., '12][Roentsch et al., '14]*

Resummation

Gains

- NNLO corrections out of reach
- Resummation can help reduce scale uncertainty

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Status

- $t\bar{t}W$ resummation in SCET *[Li, Li, Li, '14]*
- Absolute threshold at NLL *[Kulesza, Motyka, Stebel, VT, '15]*
- NNLL SCET: expansion $(t\bar{t}H)$ *[Broggio, Ferroglia, Pecjak, Singer, Yang, '15]*

  resummation *[Broggio, Ferroglia, Ossola, Pecjak, '16]*

  [Broggio, Ferroglia, Pecjak, Yang, '16]

  [Broggio, Ferroglia, Ossola, Pecjak, Samoshima, '17]

  Combined with EW *[Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos, '19]*
- NNLL dQCD *[Kulesza, Motyka, Stebel, VT, '17]*

  [Kulesza, Motyka, Schwartländer, Stebel, VT, '18]
- Absolute threshold NLL′ Coulomb *[Ju, Yang, '19]*

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:

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

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

Mellin Transform

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

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

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

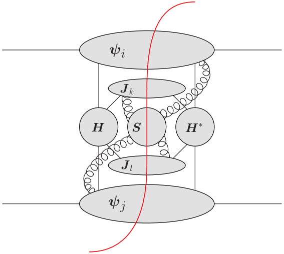
$\log^n(1-\hat{\tau}) \Rightarrow \log^n N$ and threshold $\hat{\tau} \to 1 \sim N \to \infty$

General factorization

In general cross section factorizes into:

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

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



Each of these functions is computed through renormalization group equations

Orders of Resummation

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

Perturbation needs to be reordered in α_s and L:

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

	$\Downarrow$	$\Downarrow$	$\Downarrow$
With orders of precision:	LL	NLL	NNLL
	$\Downarrow$	$\Downarrow$	$\Downarrow$
	$\alpha_\mathrm{s}^n \log^{n+1}(N)$	$\alpha_\mathrm{s}^n \log^{n}(N)$	$\alpha_\mathrm{s}^{n+1} \log^{n}(N)$

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

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

- 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

Soft wide-angle

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

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

Path-order exponential solved at NNLL accuracy by

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

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

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

Hard Matching Coefficient (Schematically)

$$H(\alpha_{\rm s}) = H^{(0)} + \frac{\alpha_{\rm s}}{\pi} H^{(1)} + \ldots$$

$$S(\alpha_{\rm s}(Q/\bar{N})) = S^{(0)} + \frac{\alpha_{\rm s}(Q/\bar{N})}{\pi} S^{(1)} + \ldots$$

- Soft and collinear functions computed
- Virtual contribution split into color channels from from
  aMC@NLO *[Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli, '11]*
  PowHel ($t\bar{t}H$) *[Garzelli, Kardos, Papadopoulos, Trócsányi, '11]*
- Include Coulomb correction $\frac{1}{\beta_{34}}$

Matching to Fixed Order

Resummed Cross Section

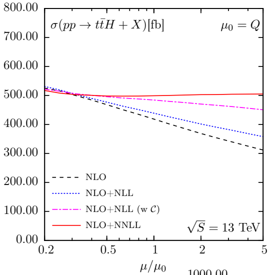
$$\sigma^{(\mathrm{NLO+NLL})}(\tau) = \sigma^{(\mathrm{NLO})}(\tau) + \int_{\mathrm{CT}} \frac{dN}{2\pi i} \tau^{-N} \tilde{f}_{g/p}(N+1) \tilde{f}_{g/p}(N+1) \times \left[\tilde{\hat{\sigma}}^{(\mathrm{NLL})}(N) - \tilde{\hat{\sigma}}^{(\mathrm{NLL})}(N)\big|_{(\mathrm{NLO})} \right]$$

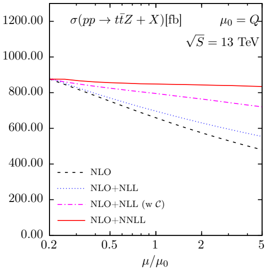
Matching to fixed order required to avoid double counting.

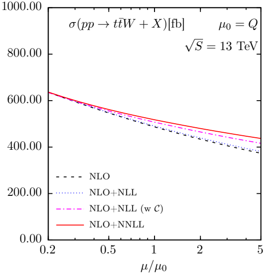
Results

PDFs used: PDF4LHC

[Kulesza, Motyka, Stebel, VT, '17][Kulesza, Motyka, Schwartländer, Stebel, VT, '18]







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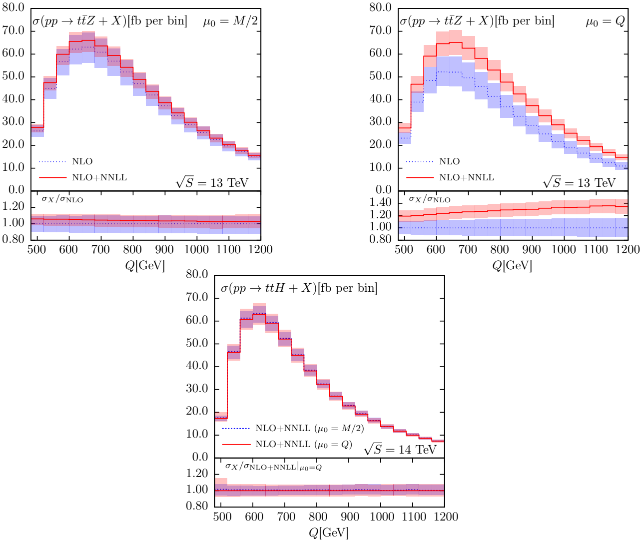

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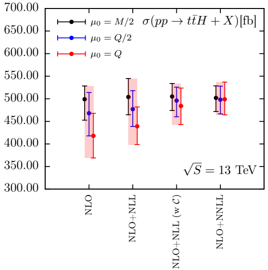

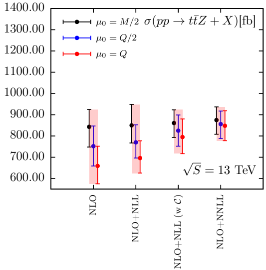

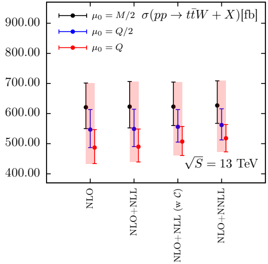

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Including (additively) NLO EW *[Frixione et al., '14,'15]*

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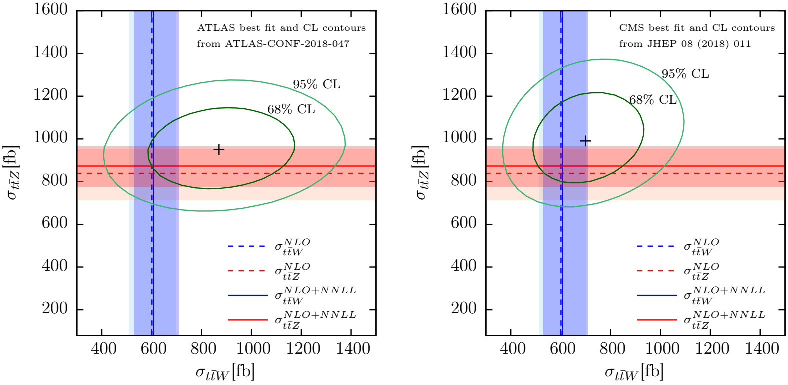

[ATLAS, '18] *[CMS, '17]*

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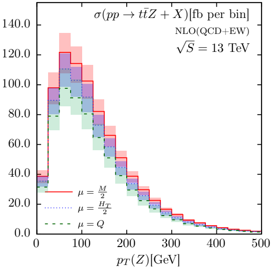

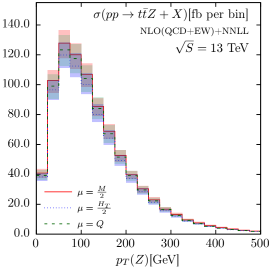

Summary

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- $t\bar{t}Z$ CMS experimental uncertainty below fixed order

- Resummation can help reduce uncertainty
- Stabilization of central scale choice dependence

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Thank you for your attention