

Soft gluon resummation for the associated production of a top quark pair with a W or Z boson at the LHC

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in collaboration with

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Graduiertenkolleg 2149
Research Training Group

associated production of $t\bar{t}$

with a massive boson

important processes: $pp \rightarrow t\bar{t}W/Z/H$



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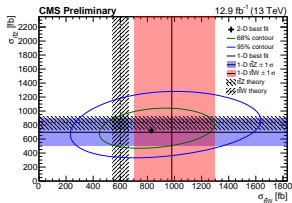
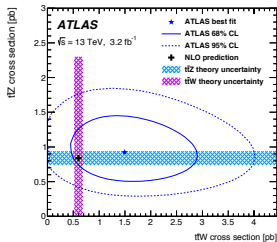


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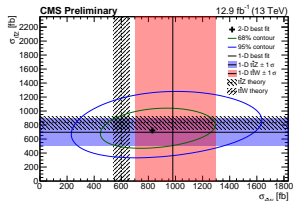
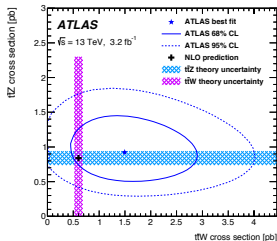


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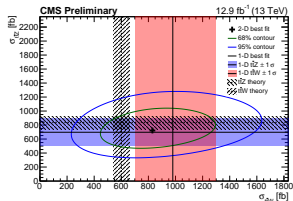
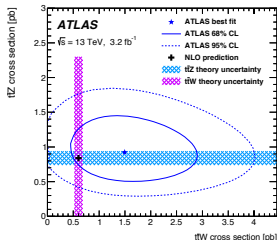


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- ▶ resummation: class of corrections beyond NLO



Status of $t\bar{t}V$



- ▶ $t\bar{t}W/t\bar{t}Z$: NLO QCD, matched to PS, EW NLO corrections
[Lazopoulos, Melnikov, Petriello, '08] [Lazopoulos, McElmurry, Melnikov, Petriello, '08] [Garzelli, Kardos, Papadopoulos, Trocsanyi, '12] [Campbell, Ellis, '12] [Kardos, Trocsanyi, Papadopoulos '12] [Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14] [Frixione, Hirschi, Pagani, Shao, Zaro, '15]

Status of $t\bar{t}V$



resummation:

- ▶ $t\bar{t}H$:
 - ▶ direct QCD approach (Mellin space approach) [Kulesza, Motyka, Stebel, Theeuwes, '15 '16 '17]
 - ▶ SCET-based methods [Broggio, Ferrogli, Pecjak, Signer, Yang, '16] [Broggio, Ferrogli, Pecjak, Yang, '17]
- ▶ $t\bar{t}W/t\bar{t}Z$:
 - ▶ SCET-based methods [H. T. Li, C. S. Li, S. A. Li, '14] [Broggio, Ferrogli, Ossola, Pecjak, '16] [Broggio, Ferrogli, Ossola, Pecjak, Sameshima '17]

Soft gluon resummation



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- ▶ emission of multiple gluons factorises in the soft/collinear limit
- ▶ Mellin space for factorisation of phase space

$$\sigma(N) = \int_0^1 \tau^{N-1} \sigma(\tau)$$



Soft gluon resummation

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invariant mass threshold resummation:

- ▶ resummed logarithms

$$\alpha_S^m \left(\frac{\log^n(1 - \hat{\tau})}{1 - \hat{\tau}} \right)_+ \quad m \leq 2n - 1$$
$$\int_0^1 dx (f(x))_+ = \int_0^1 dx (f(x) - f(x_0))$$



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- ▶ turn into $\log(N) = L$ in Mellin space

Soft gluon resummation



processes with more than 3 coloured partons

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resummed cross section in Mellin space:

$$\frac{d\tilde{\sigma}_{ij \rightarrow t\bar{t}V}^{res}}{dQ^2} = \text{Tr}[\mathbf{H}_{ij \rightarrow t\bar{t}V} \mathbf{S}_{ij \rightarrow t\bar{t}V}] \Delta_i \Delta_j$$

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calculations done in singlet octet colour basis

Soft gluon resummation



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- ▶ Δ_j : logarithmic contributions from (soft-)collinear radiation of incoming partons

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$\mathbf{H}_{ij \rightarrow t\bar{t}V}$: hard contributions



Soft gluon resummation

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- ▶ can be calculated perturbatively in α_S :

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- ▶ $\mathbf{H}_{ij \rightarrow t\bar{t}V}^{(0)}$: leading order cross section



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- ▶ $\mathbf{H}_{ij \rightarrow t\bar{t}V}^{(1)}$: non-logarithmic contributions of $\mathcal{O}(\alpha_S)$ in the large N limit
- ▶ $\mathbf{H}_{ij \rightarrow t\bar{t}V}^{(1)}$ includes virtual loop corrections, numerically extracted from PowHel [Garzelli, Kardos, Papadopoulos, Trocsanyi '11][Garzelli, Kardos, Papadopoulos, Trócsányi '12]

Soft gluon resummation



$S_{ij \rightarrow t\bar{t}V}$ soft wide angle radiation:



Soft gluon resummation

$\mathbf{S}_{ij \rightarrow t\bar{t}V}$ soft wide angle radiation:

- ▶ given by a solution of the renormalization group equation

$$\mathbf{S}_{ij \rightarrow t\bar{t}V} = \bar{\mathbf{U}}_{ij \rightarrow t\bar{t}V} \tilde{\mathbf{S}}_{ij \rightarrow t\bar{t}V} \mathbf{U}_{ij \rightarrow t\bar{t}V}$$



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- ▶ $\mathbf{U}_{ij \rightarrow t\bar{t}V}$: path-ordered exponent

$$\mathbf{U}_{ij \rightarrow t\bar{t}V} = \text{P exp} \left(\int_{\mu_F}^{Q/\bar{N}} \frac{dq}{q} \Gamma_{ij \rightarrow t\bar{t}V}(\alpha_S(q^2)) \right)$$

with soft anomalous dimension

$$\Gamma_{ij \rightarrow t\bar{t}V} = \frac{\alpha_S}{\pi} \Gamma_{ij \rightarrow t\bar{t}V}^{(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \Gamma_{ij \rightarrow t\bar{t}V}^{(2)} + \dots$$



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- ▶ calculated perturbatively: $\tilde{\mathbf{S}}_{ij \rightarrow t\bar{t}V} = \tilde{\mathbf{S}}_{ij \rightarrow t\bar{t}V}^{(0)} + \frac{\alpha_S}{\pi} \tilde{\mathbf{S}}_{ij \rightarrow t\bar{t}V}^{(1)} + \dots$

Soft gluon resummation



cross section matched to NLO results:

Soft gluon resummation



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$$\frac{d\sigma_{H_1 H_2 \rightarrow t\bar{t}V}^{\text{matched}}}{dQ^2} = \frac{d\sigma_{H_1 H_2 \rightarrow t\bar{t}V}^{\text{NLO}}}{dQ^2} + \frac{d\sigma_{H_1 H_2 \rightarrow t\bar{t}V}^{\text{res}}}{dQ^2} - \left. \frac{d\sigma_{H_1 H_2 \rightarrow t\bar{t}V}^{\text{res}}}{dQ^2} \right|_{\text{NLO}}$$

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- ▶ NLL requires: $\mathbf{H}_{ij \rightarrow t\bar{t}V}^{(0)}$, $\tilde{\mathbf{S}}_{ij \rightarrow t\bar{t}V}^{(0)}$, $\Gamma_{ij \rightarrow t\bar{t}V}^{(1)}$ and Δ_i^{NLL}

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Cross sections for $t\bar{t}W$

total inclusive cross sections, $\sqrt{S} = 13 \text{ TeV}$, $\mu_R = \mu_F = m_t + \frac{m_V}{2}$,
PDF4LHC15

NLO: [Garzelli, Kardos, Papadopoulos, Trocsanyi '11][Garzelli, Kardos,
Papadopoulos, Trócsányi '12]:

- ▶ $\sigma_{t\bar{t}W^+} = 403.8^{+12.8\%}_{-11.4\%} \text{ fb}$
- ▶ $\sigma_{t\bar{t}W^-} = 203.8^{+13.4\%}_{-11.7\%} \text{ fb}$



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NLL matched to NLO:

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Preliminary



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Preliminary



Cross sections for $t\bar{t}W$

total inclusive cross sections $\mu_F = \mu_R = Q$

NLO:

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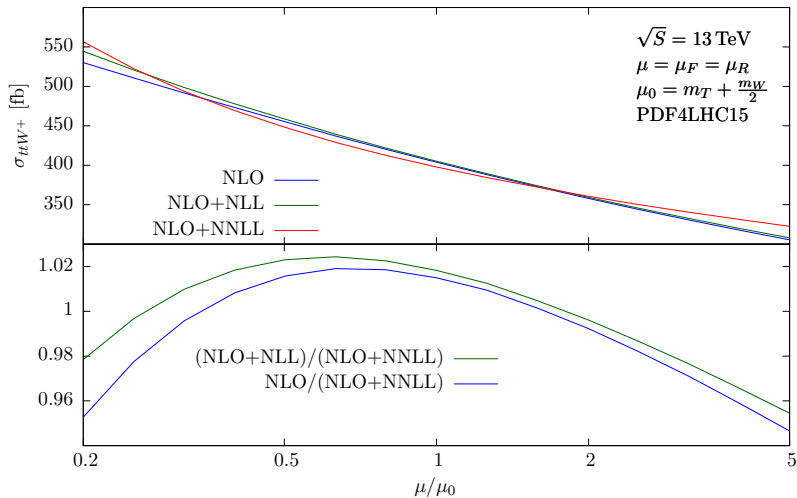
NNLL to NLO:

$$\blacktriangleright \sigma_{t\bar{t}W^+} = 328.9^{+8.7\%}_{-8.5\%} \text{ fb}$$

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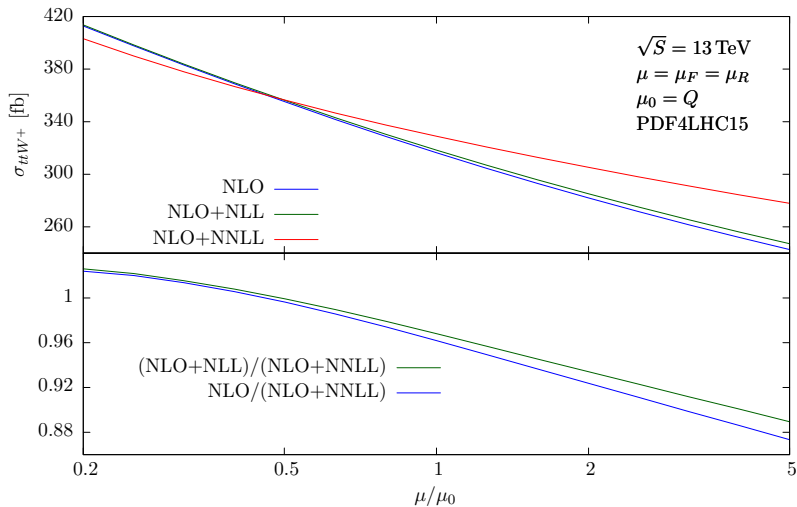
Preliminary

Scale dependence $t\bar{t}W^+$ $\mu = m_t + \frac{m_W}{2}$



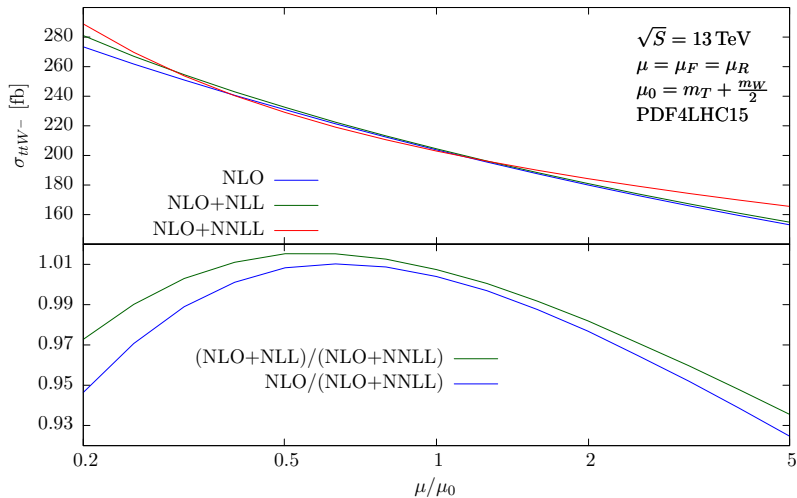
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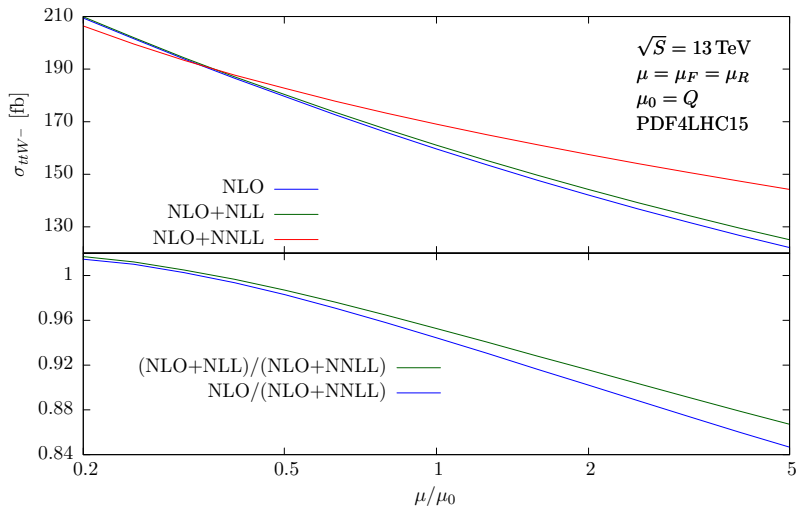
Preliminary

Scale dependence $t\bar{t}W^-$ $\mu = m_t + \frac{m_W}{2}$



Preliminary

Scale dependence $t\bar{t}W^-$ $\mu = Q$



Preliminary

Summary and Outlook



- ▶ NLO+NLL and NLO+NNLL resummation in Mellin space for $t\bar{t}W$



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Outlook:

- ▶ $t\bar{t}Z$



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Outlook:

- ▶ $t\bar{t}Z$
- ▶ differential distributions