Associated production of a top quark pair and a vector boson at NLO+NNLL

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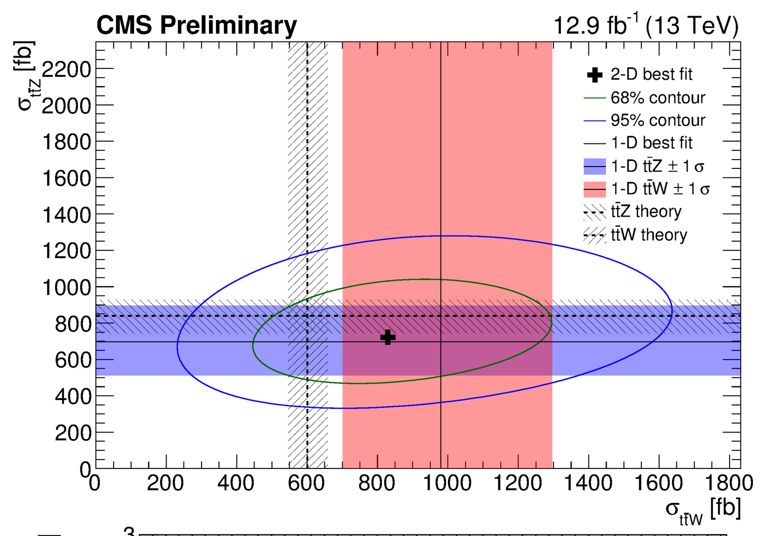
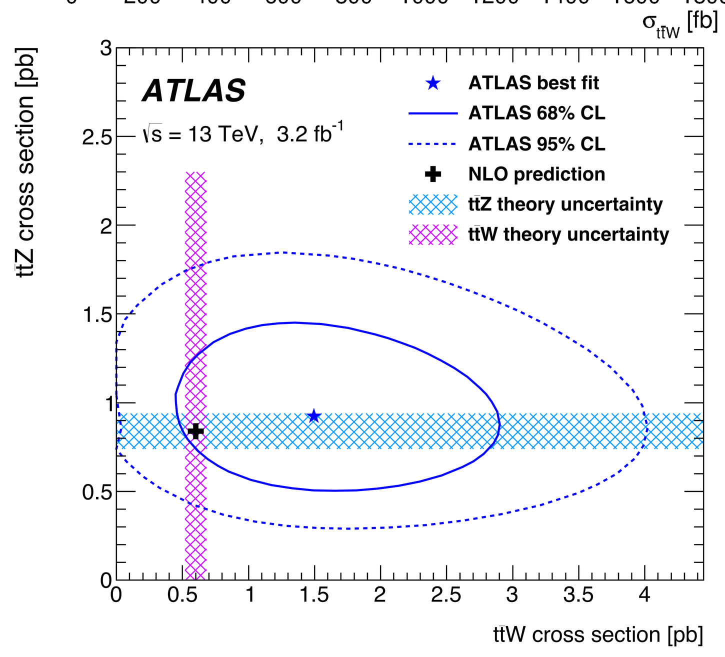
$t\bar{t}W/Z$ production

- key processes to measure the top quark couplings to W/Z $\rightarrow$ **test of the Standard Model**
- $t\bar{t}W/Z$ important background for new physics searches
- $t\bar{t}W/Z$ measured at LHC [ATLAS collaboration arXiv:1609.01599][CMS collaboration CMS PAS TOP-16-017]





- NNLO calculations for this particular type of 2 to 3 processes are currently out of reach
- **resummation**: class of corrections beyond NLO

Status of $t\bar{t}W/Z$

- NLO QCD, matched to PS, EW NLO corrections [Lazopoulos, Melnikov, Petriello, '08] [Lazopoulos, McElmurry, Melnikov, Petriello, '08]
- NLO QCD matched to PS [Garzelli, Kardos, Papadopoulos, Trocsanyi, '12] [Campbell, Ellis, '12] [Kardos, Trocsanyi, Papadopoulos '12] [Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14]
- EW NLO corrections [Frixione, Hirschi, Pagani, Shao, Zaro, '15]
- resummation at NLO+NNLL: SCET-based methods [H. T. Li, C. S. Li, S. A. Li, '14] [Broggio, Ferroglia, Ossola, Pecjak, '16] [Broggio, Ferroglia, Ossola, Pecjak, Sameshima '17]

Resummation

- cancellation of IR divergences leaves logarithms
- depending on the observable: logarithms large for different kinematic limits
- resummation takes logarithms into account at all orders
- emission of multiple gluons can be factorised in the soft/collinear limit
- Mellin space for factorisation of phase space

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

- invariant mass threshold limit $\hat{\tau} = \frac{Q^2}{\hat{s}} \rightarrow 1$ with $Q^2 = (p_{t,1} + p_{t,2} + p_W)^2$

Resummed cross section

Resummed cross section in Mellin-space:

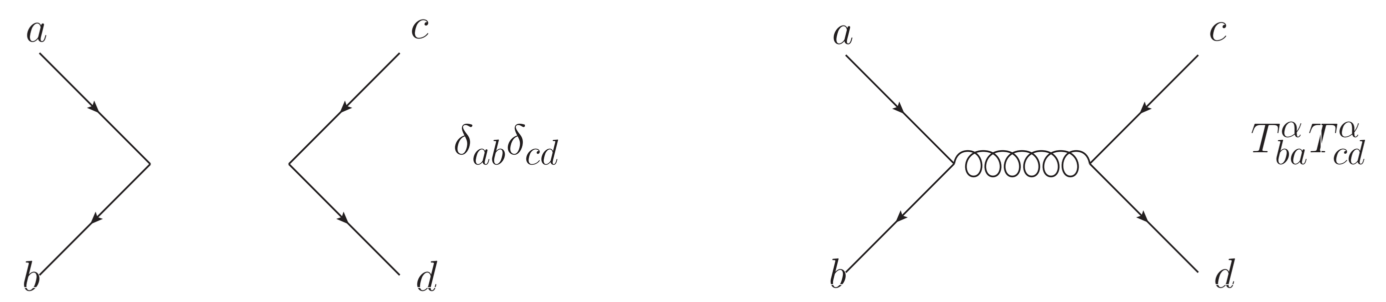
$$\frac{d\tilde{\sigma}^{\text{res}}_{ij\rightarrow t\bar{t}V}}{dQ^2} = \text{Tr}[\mathbf{H}_{ij\rightarrow t\bar{t}V}\mathbf{S}_{ij\rightarrow t\bar{t}V}]\Delta_i\Delta_j$$

- Δ_i describes the collinear and soft-collinear radiation for incoming partons
- $\mathbf{S}_{ij\rightarrow t\bar{t}V}$ describes the soft wide angle radiation, **colour matrix**
- $\mathbf{H}_{ij\rightarrow t\bar{t}V}$ describes the hard contributions, **colour matrix**
- NNLL accuracy: $\mathbf{S}_{ij\rightarrow t\bar{t}V}$ and Δ_i known [Kidonakis, Oderda, Sterman, 98] [Kidonakis, Sterman, 97] [Dixon, Magnea, Sterman, 08] [Kidonakis, Oderda, Sterman, 98] [Ferroglia, Neubert, Pecjak, Yang, 09] [Ferroglia, Neubert, Pecjak, Yang, 09] [Catani, Mangano, Nason, Trentadue, 96] [Catani, de Florian, Grazzini, Nason, 03] [Bonciani, Catani, Mangano, Nason, 98]
- $\mathbf{H}_{ij\rightarrow t\bar{t}V}$ are **process dependent** and **need to be known at 1-loop for NNLL accuracy**

Hard contributions in colour basis

In order to calculate the hard contributions $\mathbf{H}_{ij\rightarrow t\bar{t}V}$ one needs the virtual corrections in the **s-channel colour basis**

- example: $q\bar{q} \rightarrow q\bar{q}$ 2 dimensional colour space $3 \otimes \bar{3} = 1 \oplus 8$



- the virtual corrections are taken from the PowHel implementations [Garzelli, Kardos, Papadopoulos, Trocsanyi '11][Garzelli, Kardos, Papadopoulos, Trocsanyi '12], which uses the so-called colour flow basis for amplitudes
- **colour flow representation** provides a unified description of the colour of quarks and gluons, where every amplitude is decomposed:

$$M^{i_1,i_2,\ldots,i_k}_{j_1,j_2,\ldots,j_k} = \sum_{\sigma} \delta_{i_{\sigma_1},j_1}\delta_{i_{\sigma_2},j_2}\ldots\delta_{i_{\sigma_k},j_k}A_{\sigma}$$

- $\delta_{i_{\sigma_1},j_1}\delta_{i_{\sigma_2},j_2}\ldots\delta_{i_{\sigma_k},j_k}$ are the so-called colour flow basis vectors

- results in colour flow basis need to be transformed to s-channel basis: $\rightarrow$ **relate s-channel basis to colour flow representation basis**

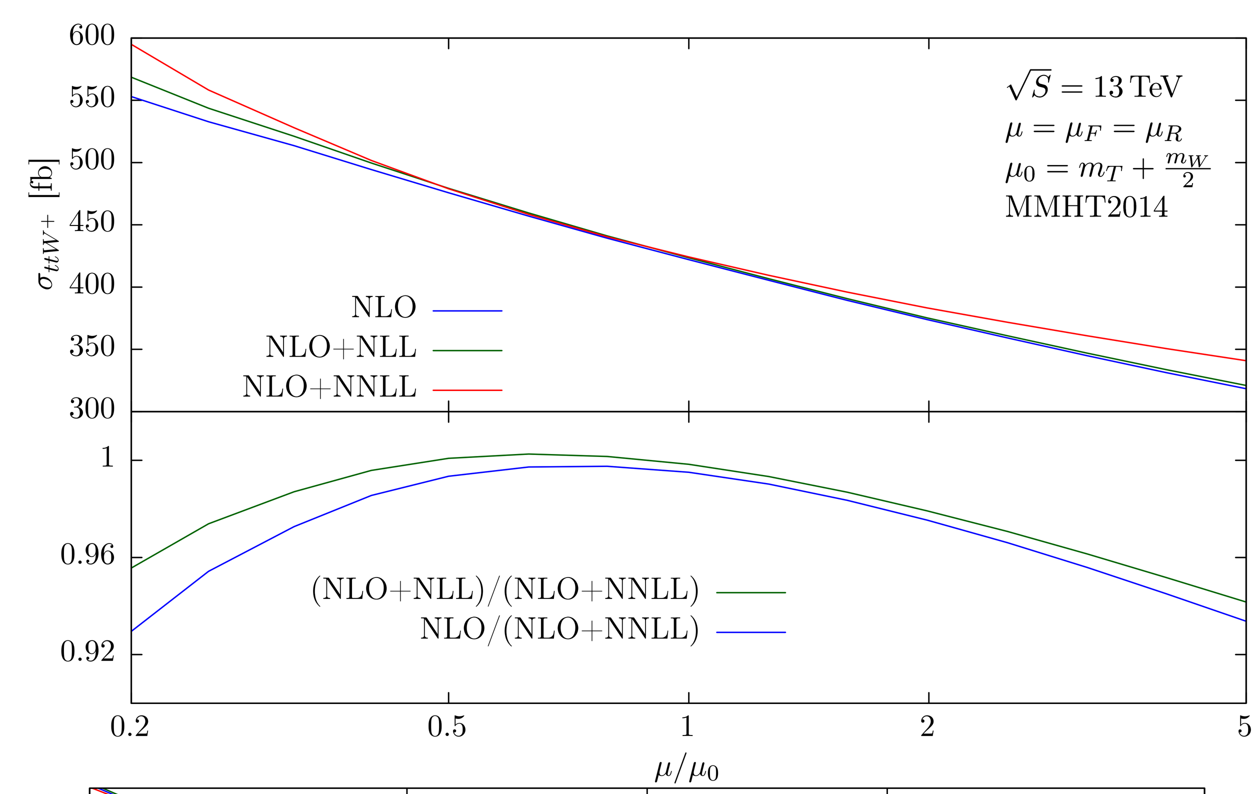
Numerical results (preliminary)

NLO calculated with PowHel, $\sqrt{S} = 13$ TeV, PDFs: MMHT2014

Two scale choices: $\frac{M^2}{2} = \frac{(2m_t+m_W)^2}{2}$ and $Q^2 = (p_{t,1} + p_{t,2} + p_W)^2$

$\mu_R = \mu_F = \frac{M^2}{2}$

- **NLO**: $\sigma_{t\bar{t}W^+} = 422.1^{+12.8\%}_{-11.5\%}$ fb
- **NLO + NLL**: $\sigma_{t\bar{t}W^+} = 423.5^{+13.2\%}_{-11.4\%}$ fb
- **NLO + NNLL**: $\sigma_{t\bar{t}W^+} = 424.2^{+12.9\%}_{-9.7\%}$ fb



$\mu_R = \mu_F = Q$

- **NLO**: $\sigma_{t\bar{t}W^+} = 329.9^{+12.5\%}_{-11.0\%}$ fb
- **NLO + NLL**: $\sigma_{t\bar{t}W^+} = 332.1^{+12.0\%}_{-10.6\%}$ fb
- **NLO + NNLL**: $\sigma_{t\bar{t}W^+} = 347.9^{+8.9\%}_{-7.6\%}$ fb