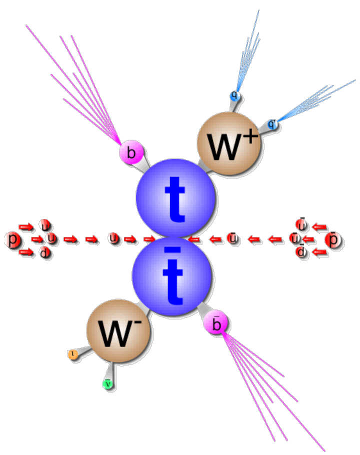
Brief overview of theory results for on-shell ttW production

(Stable Top Quarks)



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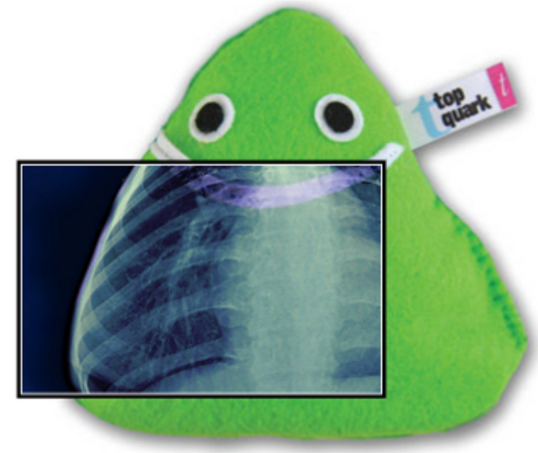
Status



- Analysis of ***ttH*** and ***ttW*** production in ***multilepton final states*** with the ATLAS detector

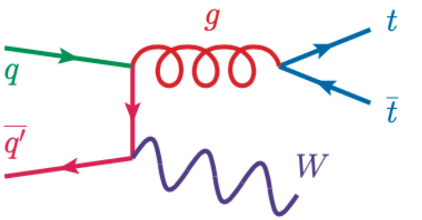
ATLAS-CONF-2019-045

- ***ttW*** represents dominant background
- Particularly in ***2lSS*** and ***3l*** channels
- Accurate modelling of additional QCD radiation in ***ttW*** remains challenging
- Disagreements between data and prediction from simulation
- Normalisation factor for ***ttW*** background

$$\lambda_{ttW}^{2\ell SS} = 1.56^{+0.30}_{-0.28} \qquad \lambda_{ttW}^{3\ell} = 1.68^{+0.30}_{-0.28}$$

- In both cases ***ttW*** theoretical cross section is lower in comparison with data

Various Aspects



- Standard for on-shell ***ttW*** production (stable top quarks) ⇨ NLO in QCD

  MadGraph5_aMC@NLO
  Sherpa

- Sub-leading EW corrections

  Frederix, Pagani, Zaro '18
  Frederix, Tsinikos '20

- Estimation of missing higher order contributions ⇨ $\mathcal{O}(\alpha_s^4 \alpha)$

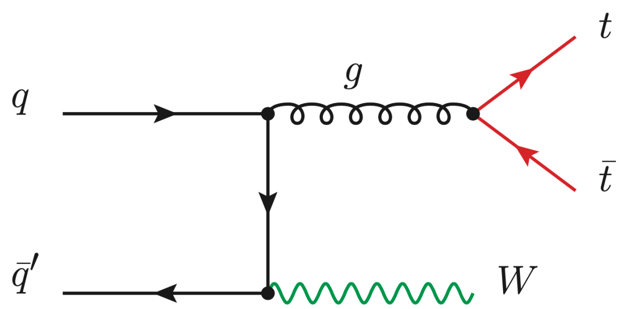
  - NNLL soft gluon resummation *Kulesza, Motyka, Schwartländer, Stebel, Theeuwes '20* *Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos '19*

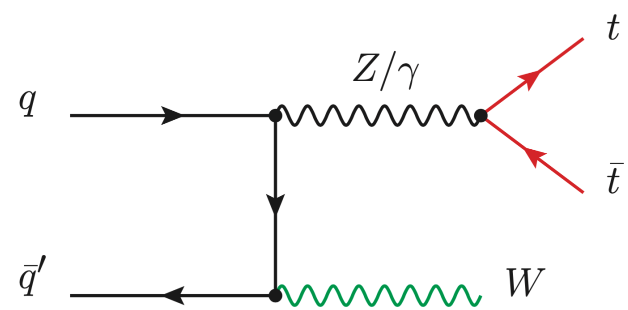
  - Multi-jet merging *Buddenbrock, Ruiz, Mellado, e-Print: 2009.00032 [hep-ph]* *Frederix, Frixione '12*

- *Spoiler Alert* ⇨ They do not resolve existing tension between SM predictions & LHC measurements

Sub-leading EW contributions

- Sub-leading EW corrections ⇨ ~ *6%* increase of total rate





LO	$\mathcal{O}(\alpha_s^2\alpha)$
NLO: QCD + EW	$\mathcal{O}(\alpha_s^3\alpha), \mathcal{O}(\alpha_s^2\alpha^2)$

LO	$\mathcal{O}(\alpha^3)$
NLO: EW$_{\text{sub}}$	$\mathcal{O}(\alpha_s\alpha^3), \mathcal{O}(\alpha^4)$

Frederix, Pagani, Zaro '18

σ[fb]	LO_{QCD}	$\text{LO}_{\text{QCD}} + \text{NLO}_{\text{QCD}}$	LO	LO + NLO	$\frac{\text{LO+NLO}}{\text{LO}_{\text{QCD}}+\text{NLO}_{\text{QCD}}}$
$\mu = H_T/2$	$363^{+24\%}_{-18\%}$	$544^{+11\%}_{-11\%}\,(456^{+5\%}_{-7\%})$	$366^{+23\%}_{-18\%}$	$577^{+11\%}_{-11\%}\,(476^{+5\%}_{-7\%})$	1.06 (1.04)

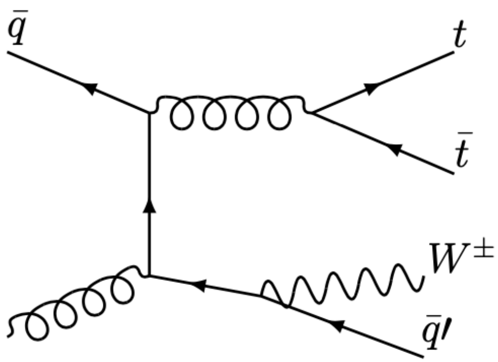
numbers in parentheses are obtained with jet veto

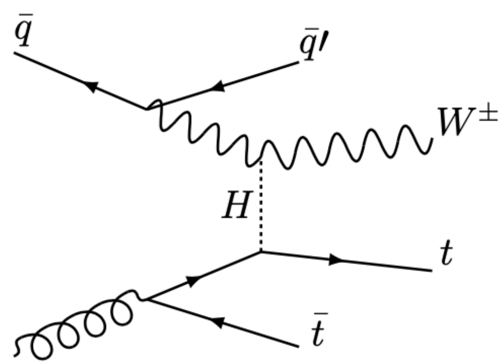
$p_T(j) > 100$ GeV and $|y(j)| < 2.5$

Sub-leading EW contributions

- They are not negligible ⇨ Positive contribution to ***ttW*** production ⇨ ***6%*** above NLO in QCD

  - Cancellations among virtual EW diagrams
  - Interference between mixed EW − QCD and pure EW diagrams
  - Real radiation ⇨ Opening of ***tW*** → ***tW*** scattering





Frederix, Pagani, Zaro '18

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO+NLO}}{\mathrm{LO_{QCD}+NLO_{QCD}}}$
$\mu = H_T/2$	$363^{+24\%}_{-18\%}$	$544^{+11\%}_{-11\%}\,(456^{+5\%}_{-7\%})$	$366^{+23\%}_{-18\%}$	$577^{+11\%}_{-11\%}\,(476^{+5\%}_{-7\%})$	1.06 (1.04)

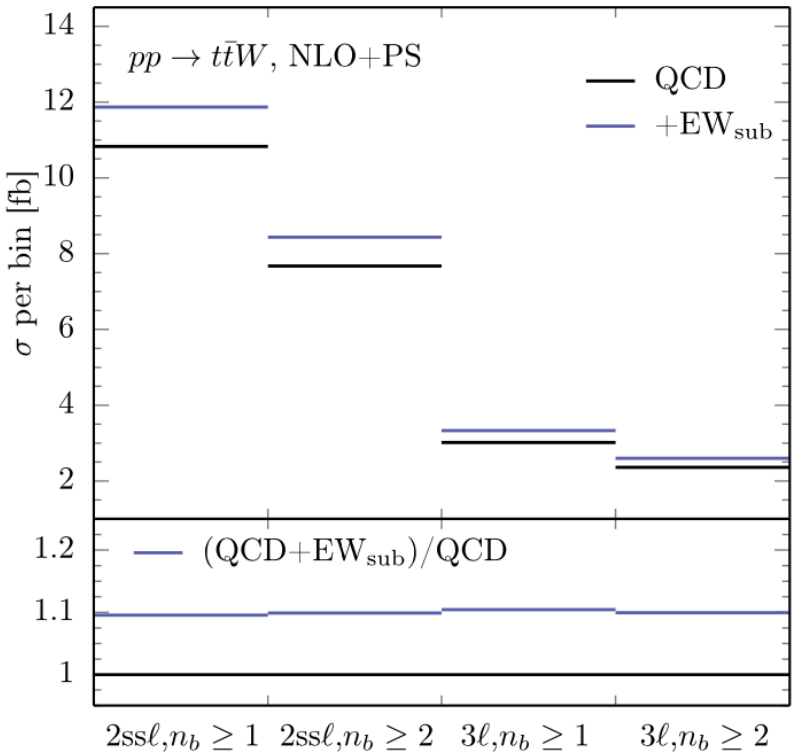
numbers in parentheses are obtained with jet veto

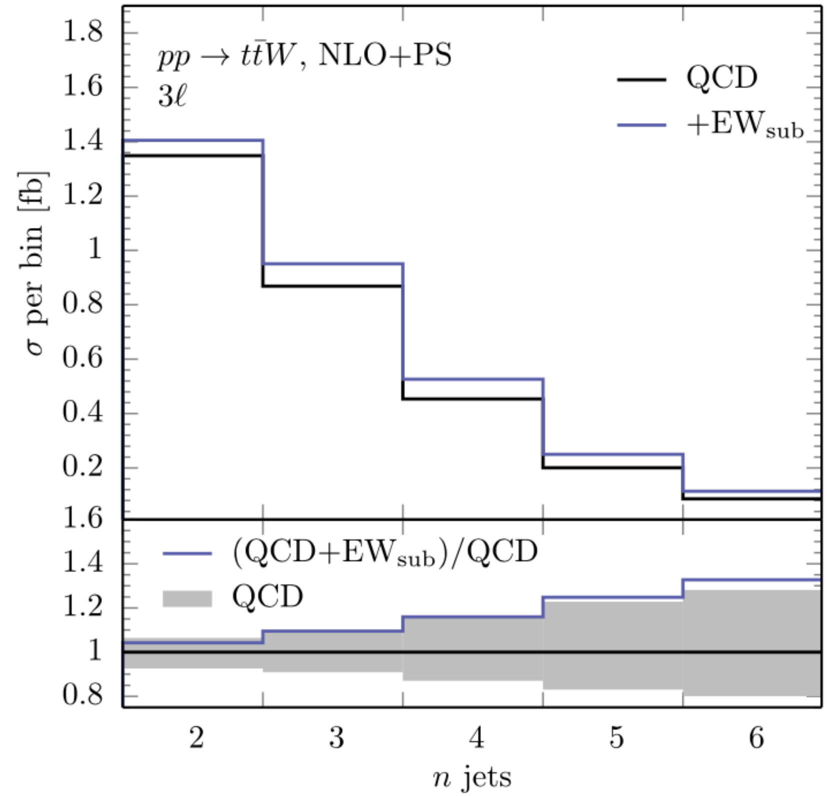
$p_T(j) > 100$ GeV and $|y(j)| < 2.5$

ttW @ EW_{sub}+ QCD

$$
\begin{aligned}
\Sigma_{\rm QCD} &= \alpha_s^2\alpha\Sigma_{3,0}^{t\bar{t}W} + \alpha_s^3\alpha\Sigma_{4,0}^{t\bar{t}W} \\
&= \Sigma_{\rm LO_1} + \Sigma_{\rm NLO_1} \\
\Sigma_{\rm EW_{sub}} &= \alpha^3\Sigma_{3,2}^{t\bar{t}W} + \alpha_s\alpha^3\Sigma_{4,2}^{t\bar{t}W} \\
&= \Sigma_{\rm LO_3} + \Sigma_{\rm NLO_3}\,.
\end{aligned}
$$

Frederix, Tsinikos '20





Effect of EW_{sub} contributions on cross section and jet multiplicities for 2ssl & 3l

- ***10%*** effect of ***EW_{sub}*** contributions
- Effects from the ***EW_{sub}*** are not flat ⇨ Larger effects in higher jet-multiplicity bins

Full NLO (QCD + EW) + NNLL

Kulesza, Motyka, Schwartländer, Stebel, Theeuwes '20

Process	μ_0	NLO[fb]	NLO+NLL[fb]	NLO+NLLwC[fb]	NLO + NNLL[fb]	K_{NNLL}
$t\bar{t}H$	Q	$425^{+12.1\%}_{-11.6\%}$	$445^{+10.0\%}_{-9.2\%}$	$489^{+8.4\%}_{-8.5\%}$	$505^{+7.5\%}_{-7.0\%}$	1.19
	H_T	$434^{+11.6\%}_{-11.4\%}$	$451^{+9.5\%}_{-8.9\%}$	$491^{+7.9\%}_{-8.2\%}$	$502^{+7.3\%}_{-6.7\%}$	1.16
	$Q/2$	$476^{+9.9\%}_{-10.8\%}$	$484^{+8.7\%}_{-8.2\%}$	$503^{+6.2\%}_{-7.3\%}$	$505^{+5.7\%}_{-6.4\%}$	1.06
	$H_T/2$	$484^{+8.9\%}_{-10.4\%}$	$490^{+8.4\%}_{-8\%}$	$503^{+5.5\%}_{-6.8\%}$	$502^{+5.4\%}_{-6.1\%}$	1.04
	$M/2$	$506^{+6\%}_{-9.3\%}$	$510^{+8.2\%}_{-7.8\%}$	$512^{+5.9\%}_{-6.2\%}$	$510^{+5.6\%}_{-6.1\%}$	1.01
$t\bar{t}Z$	Q	$661^{+13.8\%}_{-12.5\%}$	$698^{+11.5\%}_{-10.1\%}$	$795^{+10.6\%}_{-9.7\%}$	$847^{+8.1\%}_{-8.2\%}$	1.28
	H_T	$694^{+13.6\%}_{-12.6\%}$	$723^{+11.0\%}_{-9.8\%}$	$805^{+10.0\%}_{-9.5\%}$	$848^{+7.9\%}_{-8.0\%}$	1.22
	$Q/2$	$752^{+12.5\%}_{-12.1\%}$	$770^{+10.6\%}_{-9.4\%}$	$824^{+8.8\%}_{-8.8\%}$	$854^{+7.1\%}_{-7.8\%}$	1.14
	$H_T/2$	$788^{+11.7\%}_{-11.9\%}$	$798^{+10.7\%}_{-9.5\%}$	$834^{+8.1\%}_{-8.4\%}$	$855^{+6.6\%}_{-7.7\%}$	1.09
	$M/2$	$841^{+9.4\%}_{-11.1\%}$	$848^{+11.2\%}_{-9.7\%}$	$858^{+7.1\%}_{-7.9\%}$	$874^{+6.7\%}_{-7.8\%}$	1.04
$t\bar{t}W$	Q	$512^{+12.5\%}_{-11.1\%}$	$516^{+12.1\%}_{-10.6\%}$	$533^{+9.9\%}_{-8.9\%}$	$541^{+8.9\%}_{-8.4\%}$	1.06
	H_T	$539^{+13.0\%}_{-11.3\%}$	$542^{+12.6\%}_{-10.9\%}$	$556^{+10.5\%}_{-9.0\%}$	$562^{+9.6\%}_{-8.5\%}$	1.04
	$Q/2$	$577^{+12.5\%}_{-11.1\%}$	$579^{+12.3\%}_{-10.8\%}$	$586^{+10.7\%}_{-9.0\%}$	$590^{+10.0\%}_{-8.5\%}$	1.02
	$H_T/2$	$609^{+13.0\%}_{-11.5\%}$	$610^{+13\%}_{-11.2\%}$	$614^{+11.8\%}_{-9.5\%}$	$616^{+11.2\%}_{-8.8\%}$	1.01
	$M/2$	$656^{+13.2\%}_{-11.7\%}$	$658^{+13.6\%}_{-11.6\%}$	$657^{+13.4\%}_{-10.3\%}$	$659^{+13.3\%}_{-9.8\%}$	1.00

$$\mu_0 = Q = \sqrt{\left(\sum_{i=t,\bar{t},B} p_i\right)^2}$$

$$\mu_0 = \frac{Q}{2},$$

$$\mu_0 = \frac{M}{2} = \frac{\sum_{i=t,\bar{t},B} m_i}{2},$$

$$\mu_0 = H_T = \sum_{i=t,\bar{t},B} m_T(i) =$$

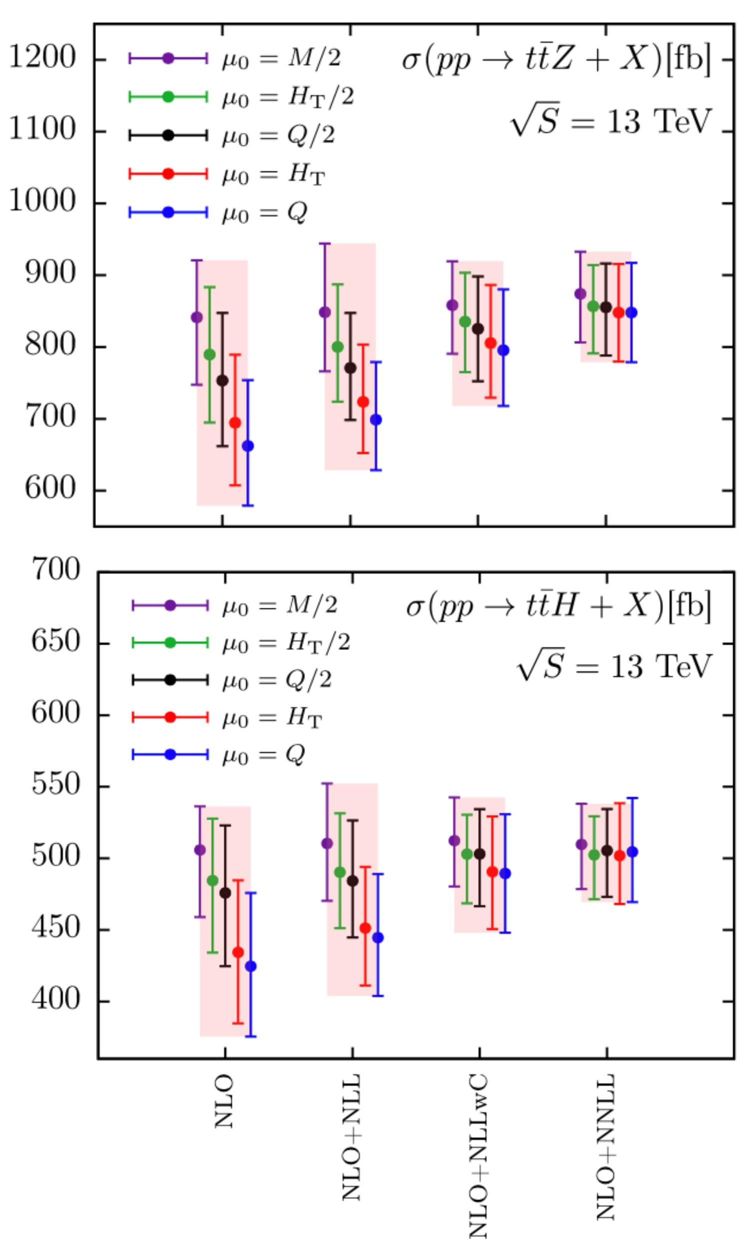
$$\mu_0 = \frac{H_T}{2}.$$

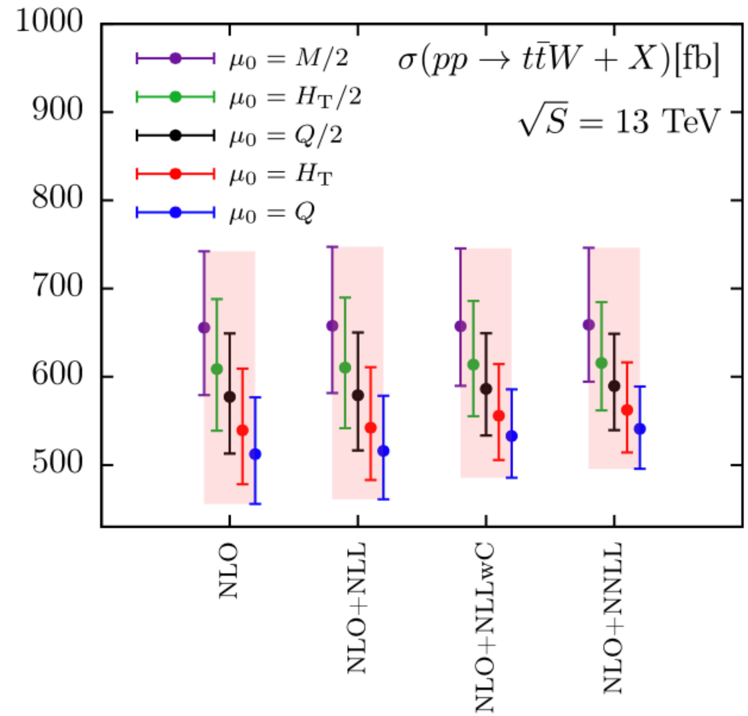
≥ 10% – 20%

- *ttH & ttZ stable with respect to central scale choice when NNLL included*
- NLO + NNLL reduces scale uncertainty in comparison with NLO
- For *ttW* spread larger than theoretical uncertainties

Full NLO (QCD + EW) + NNLL

Kulesza, Motyka, Schwartländer, Stebel, Theeuwes '20





Most conservative estimate of the theoretical uncertainty ⇨ Envelope

$$\sigma_{t\bar{t}H}^{\text{NLO+NNLL}} = 504^{+7.6\%+2.4\%}_{-7.1\%-2.4\%}\ \text{fb}\,,$$

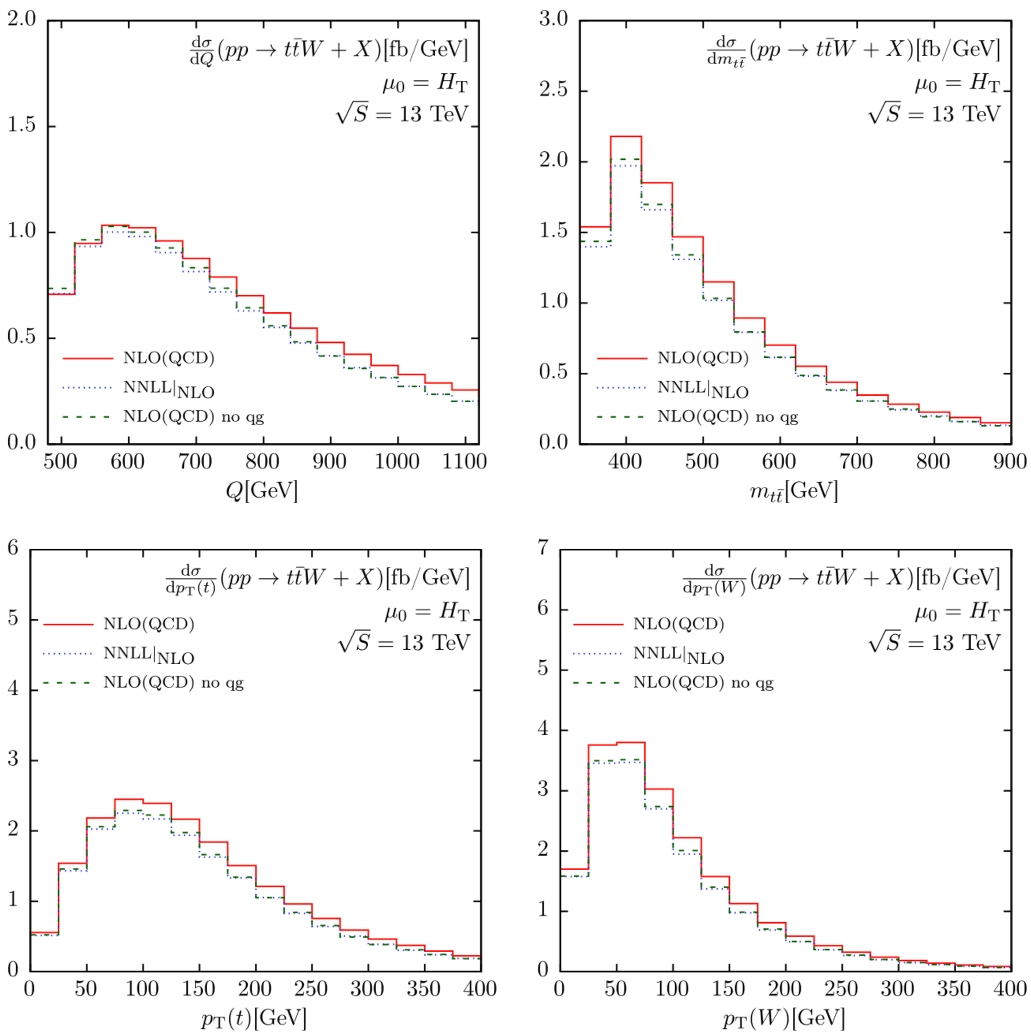
$$\sigma_{t\bar{t}Z}^{\text{NLO+NNLL}} = 859^{+8.6\%+2.3\%}_{-9.5\%-2.3\%}\ \text{fb}\,,$$

$$\sigma_{t\bar{t}W}^{\text{NLO+NNLL}} = 592^{+26.1\%+2.1\%}_{-16.2\%-2.1\%}\ \text{fb}$$

Full NLO (QCD + EW) + NNLL

Kulesza, Motyka, Schwartländer, Stebel, Theeuwes '20

- Threshold resummation for $pp \to t\bar{t}B$ in the invariant mass threshold limit



$$Q^2/\hat{s} \longrightarrow 1$$

$$Q^2 = (p_t + p_{\bar{t}} + p_B)^2$$

- Comparison between expansion of NNLL expression up to NLO accuracy in α_s
- Full NLO(QCD) result
- NLO(QCD) result without qg channels for $pp \to ttW$
- *D*ifferential distributions in
  - Q
  - m_{tt}
  - $p_T(t)$
  - $p_T(W)$

ttW + nj merging

- Complementary estimate of $\mathcal{O}(\alpha_s^4\alpha)$ contributions to *ttW* production
  - From *ttW + nj* ⇨ FxFx NLO multi-jet merging
- Examined role of $t\bar{t}W^{\pm}j, t\bar{t}W^{\pm}jj$

Buddenbrock, Ruiz, Mellado
e-Print: 2009.00032 [hep-ph]

- NLO multi-jet matching procedure FxFx
  - Non-unitarity procedure within MC@NLO ⇨ Promoting jet observables @ LO+LL to NLO+LL through CKKW-like reweighting
  - Hard, wide-angle emissions are included through exact MEs at 1-loop
  - Double counting is avoided by Sudakov reweighting
  - Cross sections at NLO augmented with terms that are $\mathcal{O}(\alpha_s^2)$ or higher
  - Cost of this improvement ⇨ Introduction of merging scale Q_{cut}^{FxFx}
- *FxFx1j* ⇨ *ttW & ttWj @ NLO* ⇨ Increases *ttW* rate by *10% − 12%*
  - Uncertainties essentially unchanged
  - For large values of merging scale *FxFx1j* rate reduced to NLO rate ⇨ Over suppression of *ttWj* multiplicity

ttW & ttZ

Buddenbrock, Ruiz, Mellado
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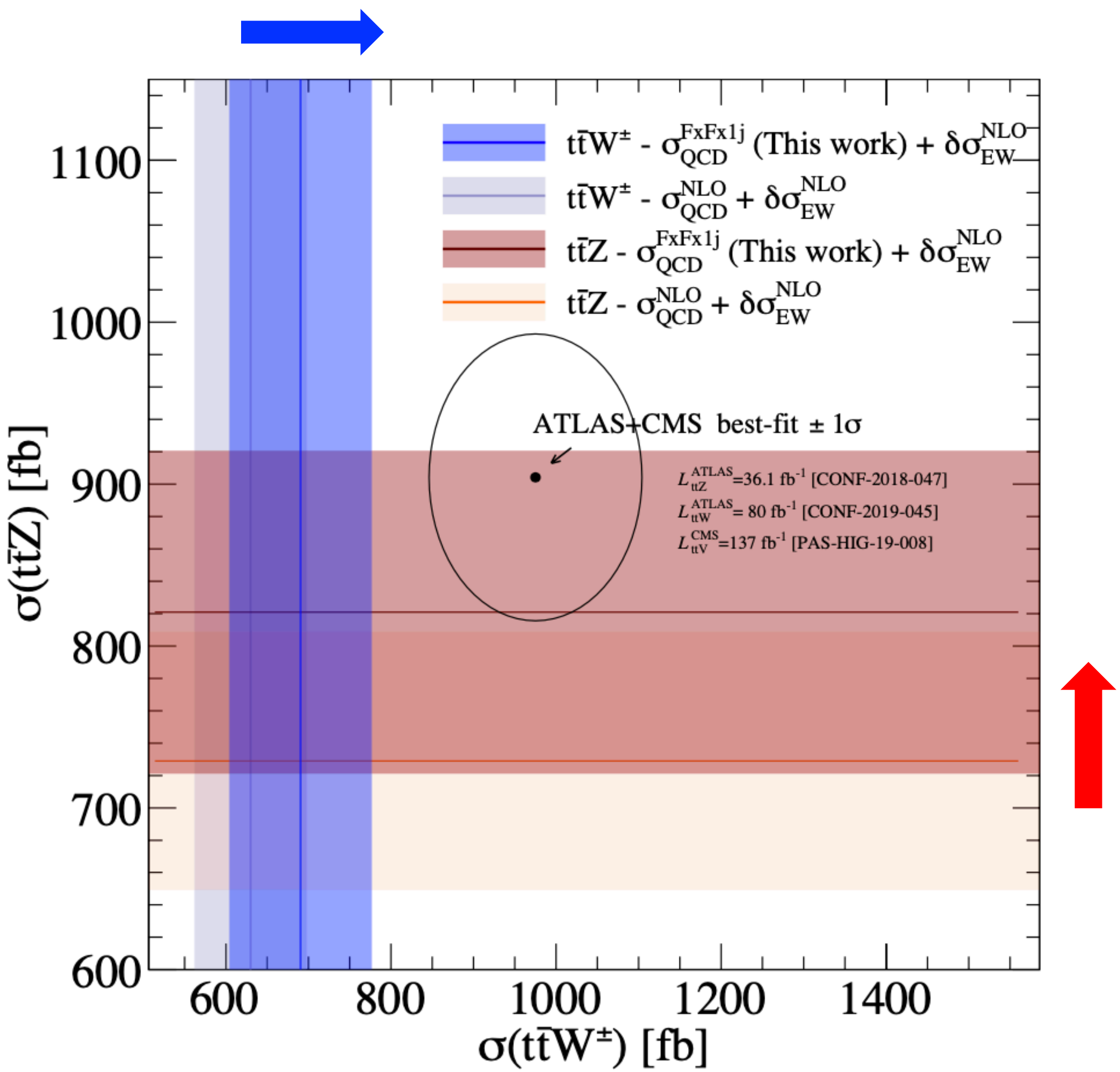

- Cross section predictions at 13 TeV with ***1σ*** uncertainty bands for ***ttW & ttZ***
- NLO in QCD + EW (light)
- NLO in QCD with ***FxFx1j*** + EW (dark)
- Also shown measurements from the ATLAS and CMS experiments
- ***Tension between SM predictions and LHC measurements for ttW***

Summary

- Neither EW_{sub} nor ***NLO+NNLL*** or ***FxFx1j*** resolved existing tension between SM predictions and LHC measurements

- For normalization of ***ttW*** ⇰ State-of-the-art results are full NLO + NNLL

- In absence of NNLO this is "good enough" approximation

- Be careful with your scale choice

- ***Lots of data, sophisticated analyses, precision measurements ⇰ Should be compared to state-of-the-art theoretical predictions***

- Comparisons between theory and data should be done for the same setups
    - Same scale choice, m_t PDF sets, SM parameters, …

- ***Would be time to have NNLO QCD + NNLL predictions for on-shell ttW***
    - ***gg channel opens up @ NNLO***