On ttW production

Rikkert Frederix
Lund University
ttW production

- ttW is
  - a main source of same-sign charged leptons + multiple jets
  - one of the main backgrounds in ttH production (with leptonic H decays)
  - important background in 4-top production
  - relevant for SMEFT limit setting
- Hence, understanding it is important in the extraction of the top Yukawa coupling
- First data extractions show a slight tension: theory predicted a somewhat smaller cross section than needed

Normalisation factors of ttW background

\[ \lambda_{\ell \ell \bar{\nu} \nu}^{2l, Nj=2,3} = 1.56^{+0.30}_{-0.28}, \quad \lambda_{\ell \ell \bar{\nu} \nu}^{2l, Nj \geq 4} = 1.26^{+0.19}_{-0.18}, \quad \lambda_{\ell \ell \bar{\nu} \nu}^{\ell} = 1.68^{+0.3}_{-0.28} \]
"Constraint" at lowest order

- At lowest order in perturbation theory, ttW production is rather 'constraint'
  - Only two Feynman diagrams: W-boson is attached to a light quark line that attaches to the two colliding protons, while the top pair can only come from a gluon splitting

- Hence, expect large higher order corrections, and possibly underestimation of theory uncertainties at lowest order(s), due to opening of new channels, new colour structures, new flavour structures, etc.
Total cross section

- Significant uncertainties due to scale variation
  - In particular: great variation due to choice for central value of scales
- Including soft-gluon resummation does not improve the picture
  [Broggio et al. (2019) & Kulesza et al. (2020)]
- For the true uncertainty an envelope over multiple scale choices seems necessary
- Clear sign of new structures/topologies opening at NLO
ttZ and ttH

- ttZ (left) and ttH (right) production does show the expected uncertainty reduction —particularly related to the functional form of the central scale choice
Opening of new channels

- In the real-emission NLO QCD corrections to $ttW$, top pair production via gluon fusion enters.
- Not possible to generate this topology starting from LO and adding only parton-shower like emissions (soft-col approx).
- These are essentially "almost-finite" contributions that enhance the cross section.
- Dominant at large $p_T(tt)$:
  - Captured at LO accuracy in an NLO computation.
  - Captured at NLO accuracy in NLO multi-jet merging.
• Large dependence on the merging scale in total cross section
• Large merging scale choices results in non-smooth distributions
• Also for small merging scale choices, the new topologies are not treated correctly: they should not be part of the merging, since they are not IR soft/collinear enhanced (i.e., they have no shower equivalent)
Improved FxFx

• Include all particles in the clustering to find the "most-likely branching history"

• If, for a given event, it is more likely that a final state quark is clustered with the W-boson than with another QCD parton, that quark forms an "EW jet" and not a normal "QCD jet"
  • contributions from EW jets are finite (the W-boson mass screens the IR divergence)
  • EW jets should not be part of the merging procedure, and are included also below the merging scale

• New topology in ttW production can therefore be included at NLO accuracy in the complete phase space
In this section we investigate dijet production with a study on dijet mass distributions at the production level.

### Table 2: Cross section comparisons for \( t\bar{t}W \), FxFx@1J

<table>
<thead>
<tr>
<th>( \mu_Q ) [GeV]</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma ) [fb]</td>
<td>668.2(9) +54.7(+8.2%)</td>
<td>671.4(8) +60.0(+8.9%)</td>
<td>673.6(8) +60.1(+8.9%)</td>
<td>677.5(6) +60.8(+9.0%)</td>
<td>677.2(8) +59.1(+8.7%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \mu_Q ) [GeV]</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma ) [fb]</td>
<td>679.2(6) +60.5(+8.9%)</td>
<td>679.1(6) +61.0(+9.0%)</td>
<td>678.8(6) +61.5(+9.1%)</td>
<td>678.3(6) +61.8(+9.1%)</td>
<td>678.1(6) +62.0(+9.1%)</td>
</tr>
</tbody>
</table>

- Hardly any dependence on the merging scale in the total cross section
  - from 25 - 350 GeV only percent-level differences
  - well within scale uncertainties
**Improved FxFx validation II**

[RF, Tsinikos (2021)]

- Step at merging scale disappears
- Contributions from the EW jets in the ttW+1jet sample clearly visible below merging scale
- Large reduction in scale dependence at large $p_T(j_1)$ as compared to non-merged sample
Total cross section

- Rate about 17-19% larger than $\text{NLO}_{\text{QCD}}$
- Stabilisation of scale dependence
- As expected, adding 2nd jet at NLO in the merging does not change predictions significantly
Data comparison

- With the improved FxFx, the cross section increased significantly, bringing it closer to the data
  - uncertainty bands almost overlap
  - tension is resolved to a large extent

![Graph showing data comparison and CMS measurements](chart.png)

- Measurement
- Stat. unc.
- Total unc.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Nominal ± stat ± syst</th>
</tr>
</thead>
<tbody>
<tr>
<td>ee</td>
<td>845 ± 117 ± 111</td>
</tr>
<tr>
<td>e(\mu)</td>
<td>996 ± 61 ± 68</td>
</tr>
<tr>
<td>(\mu\mu)</td>
<td>868 ± 63 ± 64</td>
</tr>
<tr>
<td>Dilepton</td>
<td>905 ± 42 ± 51</td>
</tr>
<tr>
<td>Trilepton</td>
<td>649 ± 104 ± 96</td>
</tr>
<tr>
<td>Combined</td>
<td>868 ± 40 ± 51</td>
</tr>
</tbody>
</table>

138 fb\(^{-1}\) (13 TeV)
Conclusions

• There used to be a small tension for the total cross section of ttW production between theory and experiment.

• From a theory point of view, ttW is special and very "constraint" at lowest order(s):
  - Large corrections from higher orders in QCD
  - Large corrections due to non-logarithmically enhanced radiation
  - Large corrections from formerly subleading EW corrections

• The improved FxFx merging allows for a consistent inclusion of NLO corrections to topologies opening at higher multiplicities.

• For ttW production this increases the predicted cross section, resolving the tension between theory and experiment to a large extend.