On ttW production

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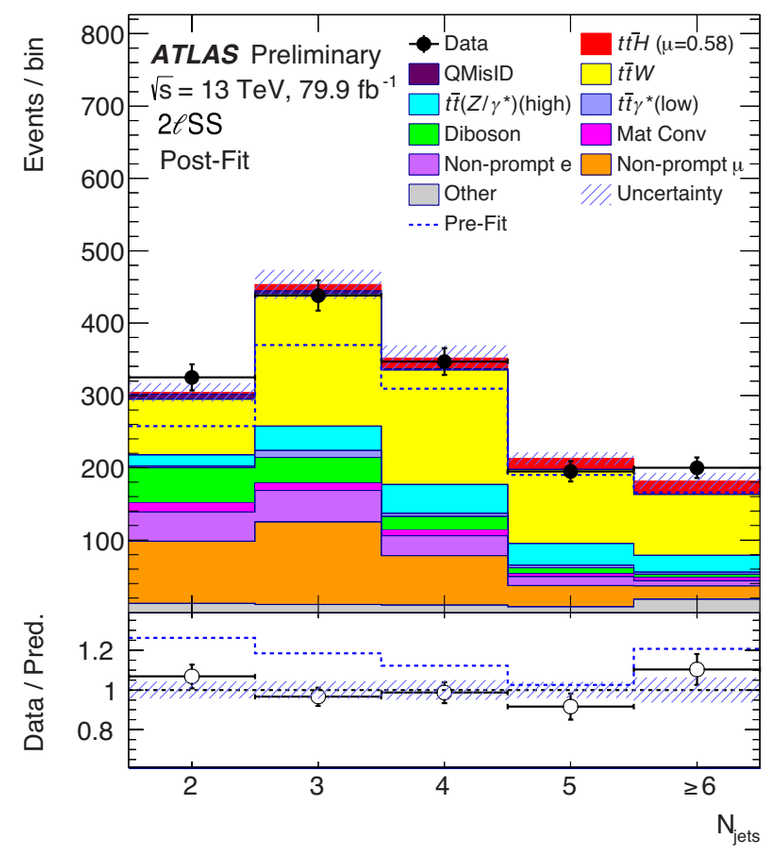
ttW production

- 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



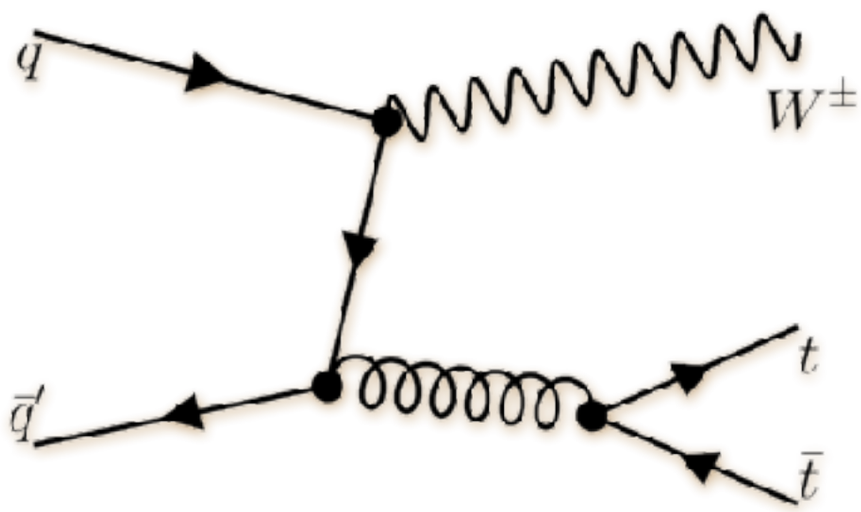
Normalisation factors of ttW background

$$\lambda_{ttW}^{2l,Nj=2,3} = 1.56^{+0.30}_{-0.28},\ \lambda_{ttW}^{2l,Nj\geq 4} = 1.26^{+0.19}_{-0.18},\ \lambda_{ttW}^{3l} = 1.68^{+0.3}_{-0.28}$$

Ana Cueto's talk this morning

"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

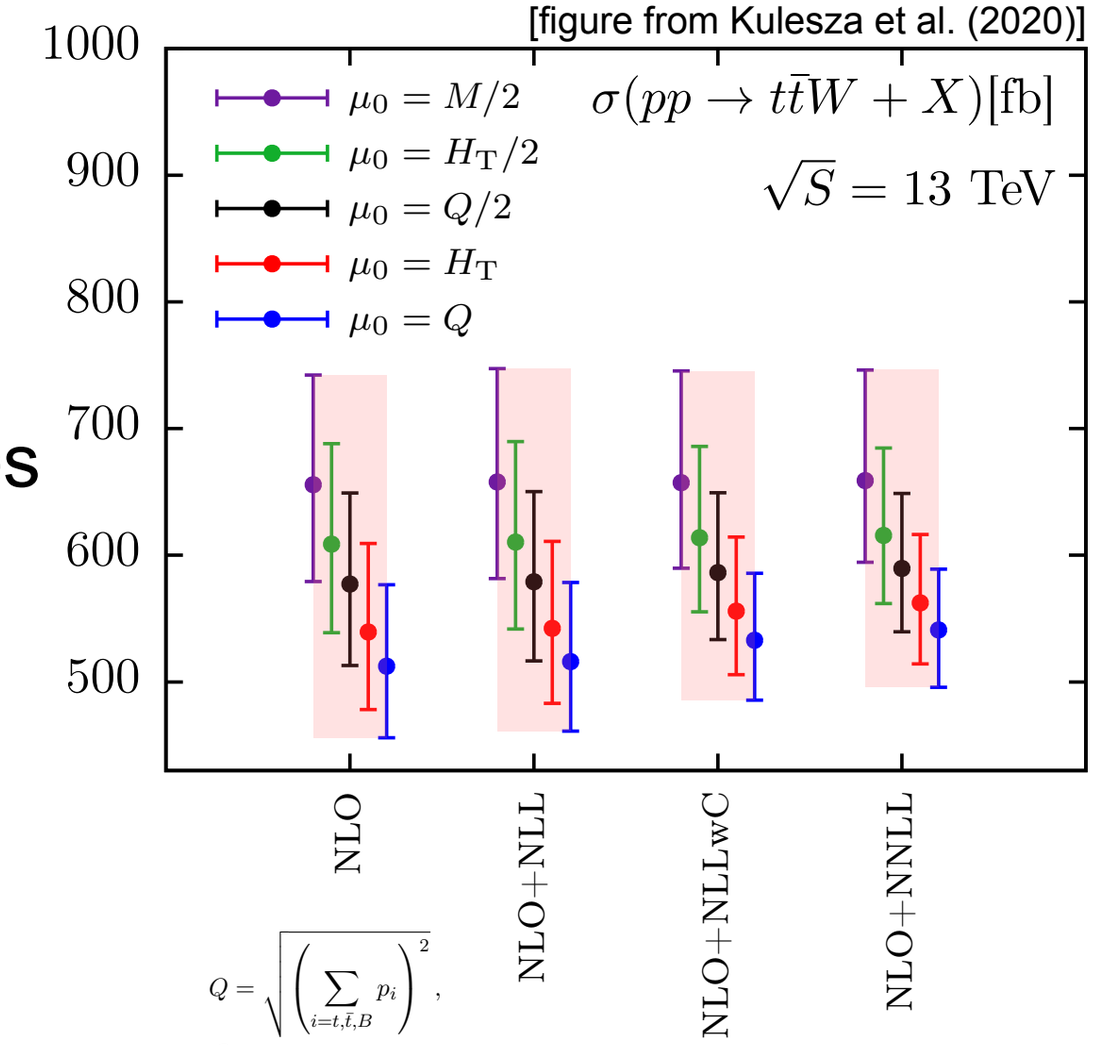


- Hence, expect large higher order corrections, and possibly underestimation of theory uncertainties at lowest order(s), due to opening of new channels, new colour structures, new flavour structures, etc.

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

[figure from Kulesza et al. (2020)]



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

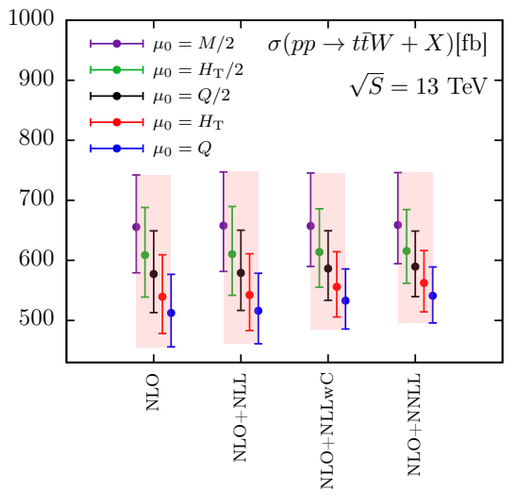
$$\frac{Q}{2},$$

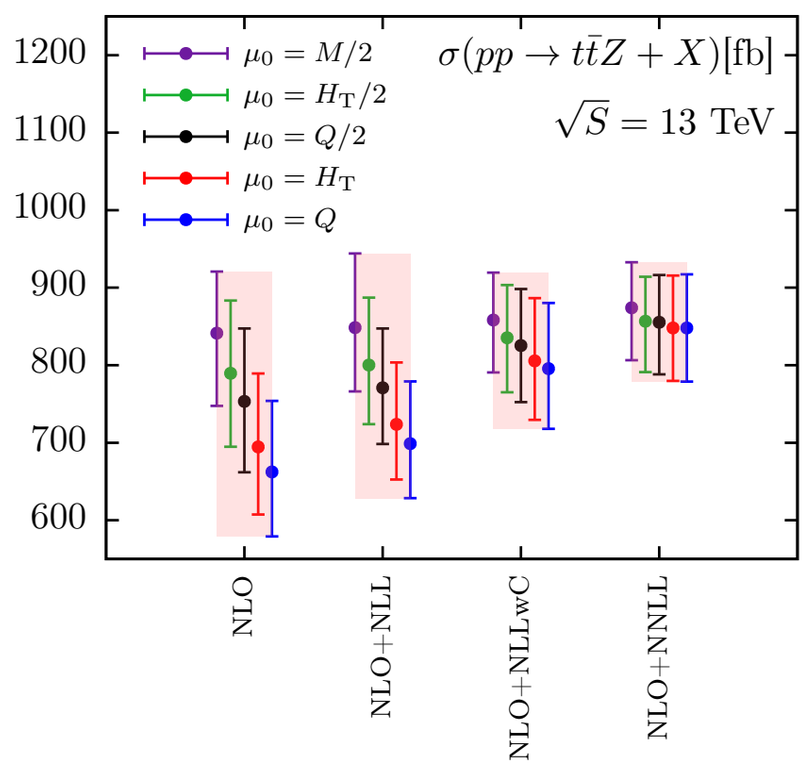
$$\frac{M}{2} = \frac{\sum_{i=t,\bar{t},B} m_i}{2},$$

$$H_T = \sum_{i=t,\bar{t},B} m_T(i) = \sum_{i=t,\bar{t},B} \sqrt{m_i^2 + p_T^2(i)},$$

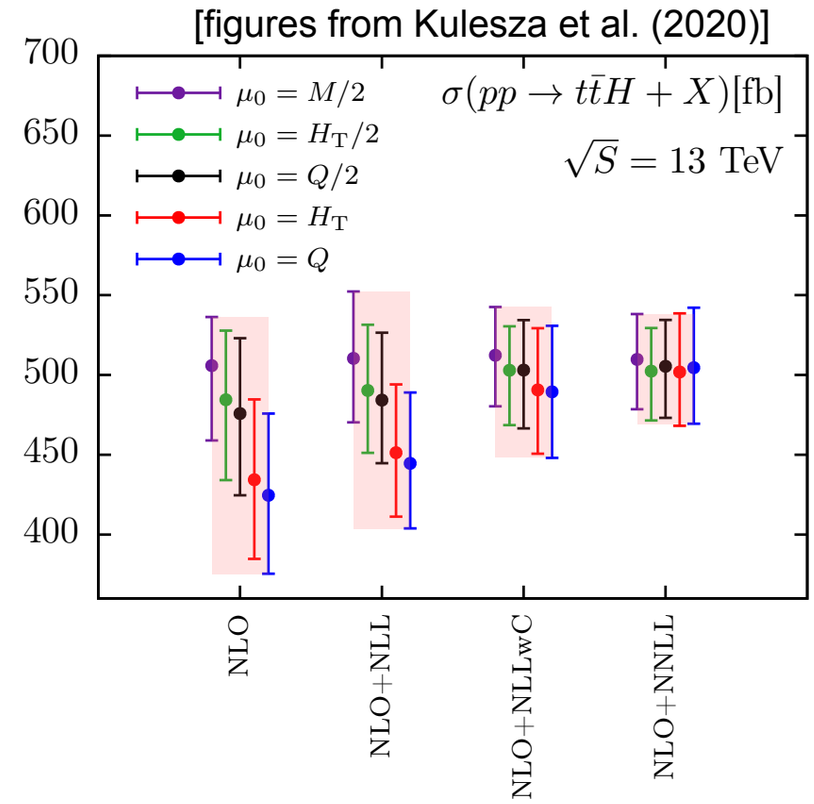
$$\frac{H_T}{2}.$$

ttZ and ttH



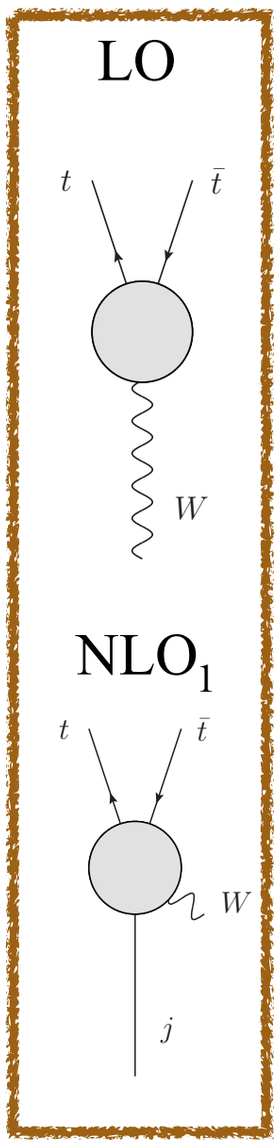


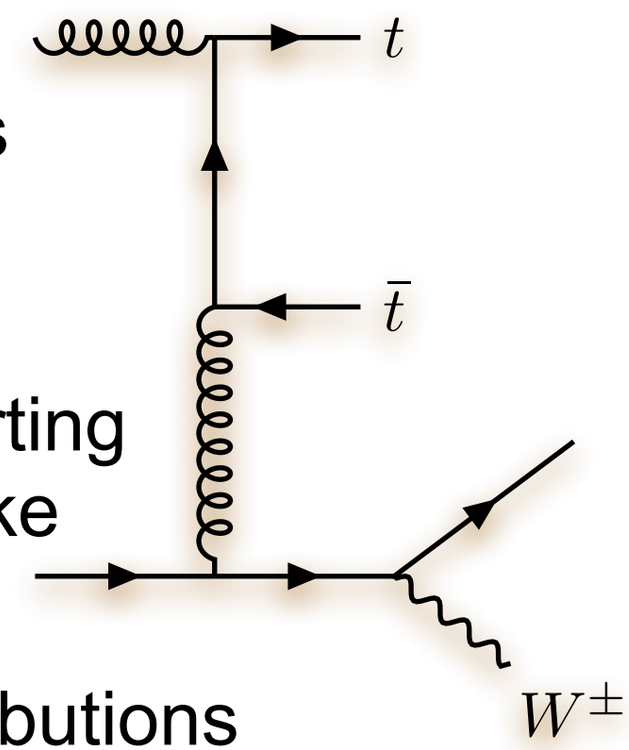
[figures from Kulesza et al. (2020)]



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

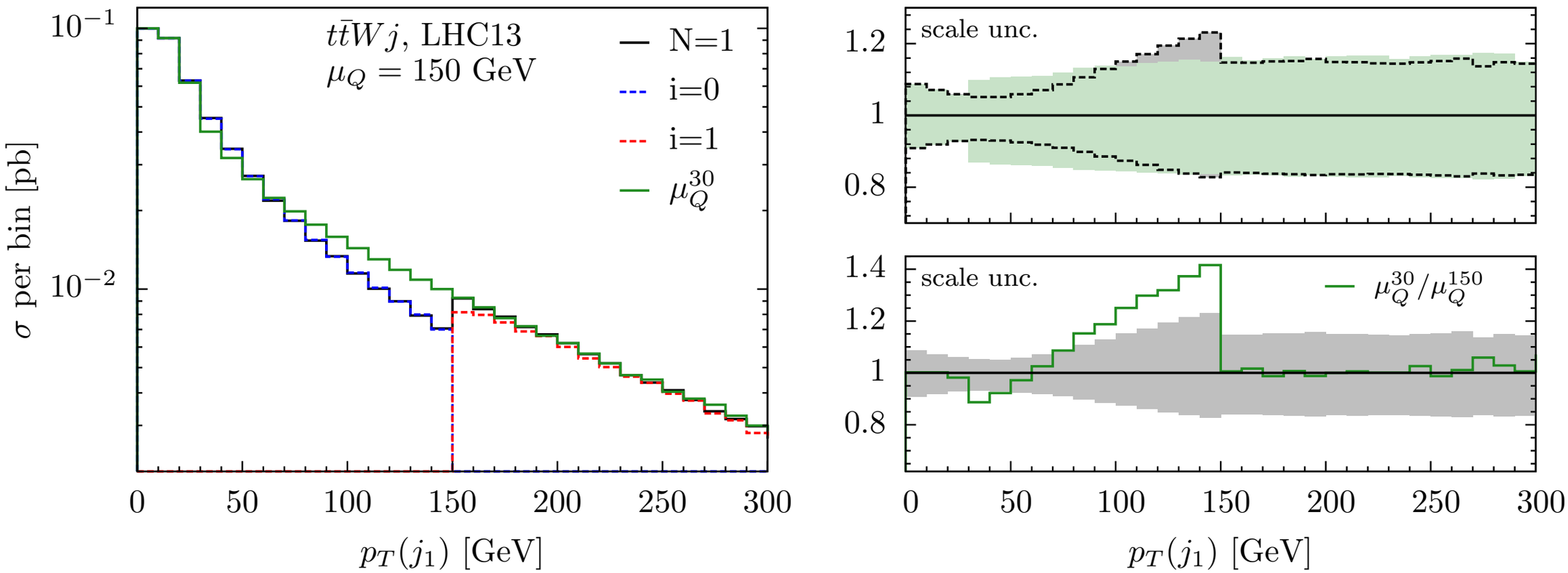
Opening of new channels





- 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

Default FxFx

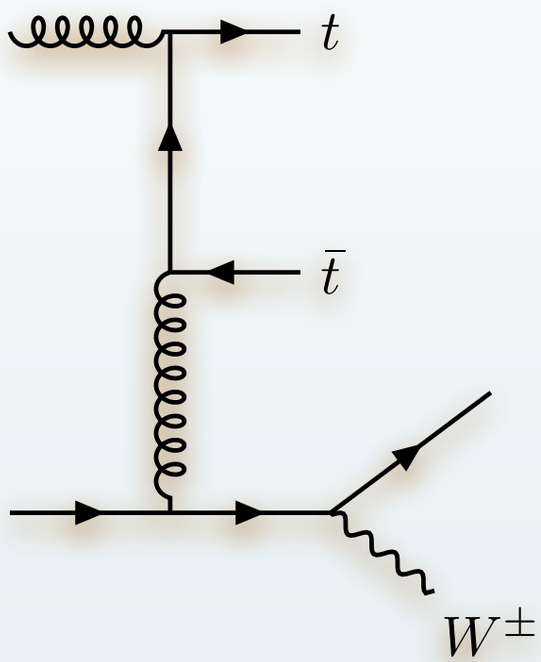


- Large dependence on the merging scale in total cross section
- Large merging scale choices results in non-smooth distributions
- Also for small merging scale choices, the new topologies are not treated correctly: they should not be part of the merging, since they are not IR soft/collinear enhanced (i.e., they have no shower equivalent)

Improved FxFx

[RF, Tsinikos (2021)]

- 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



Improved FxFx validation I

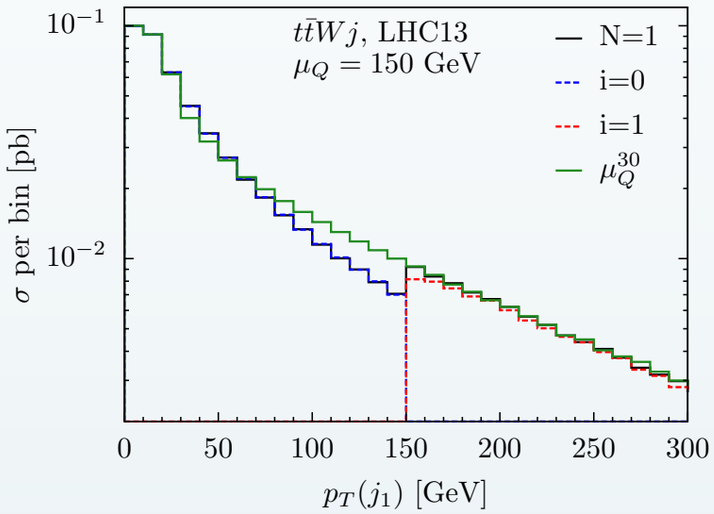
[RF, Tsinikos (2021)]

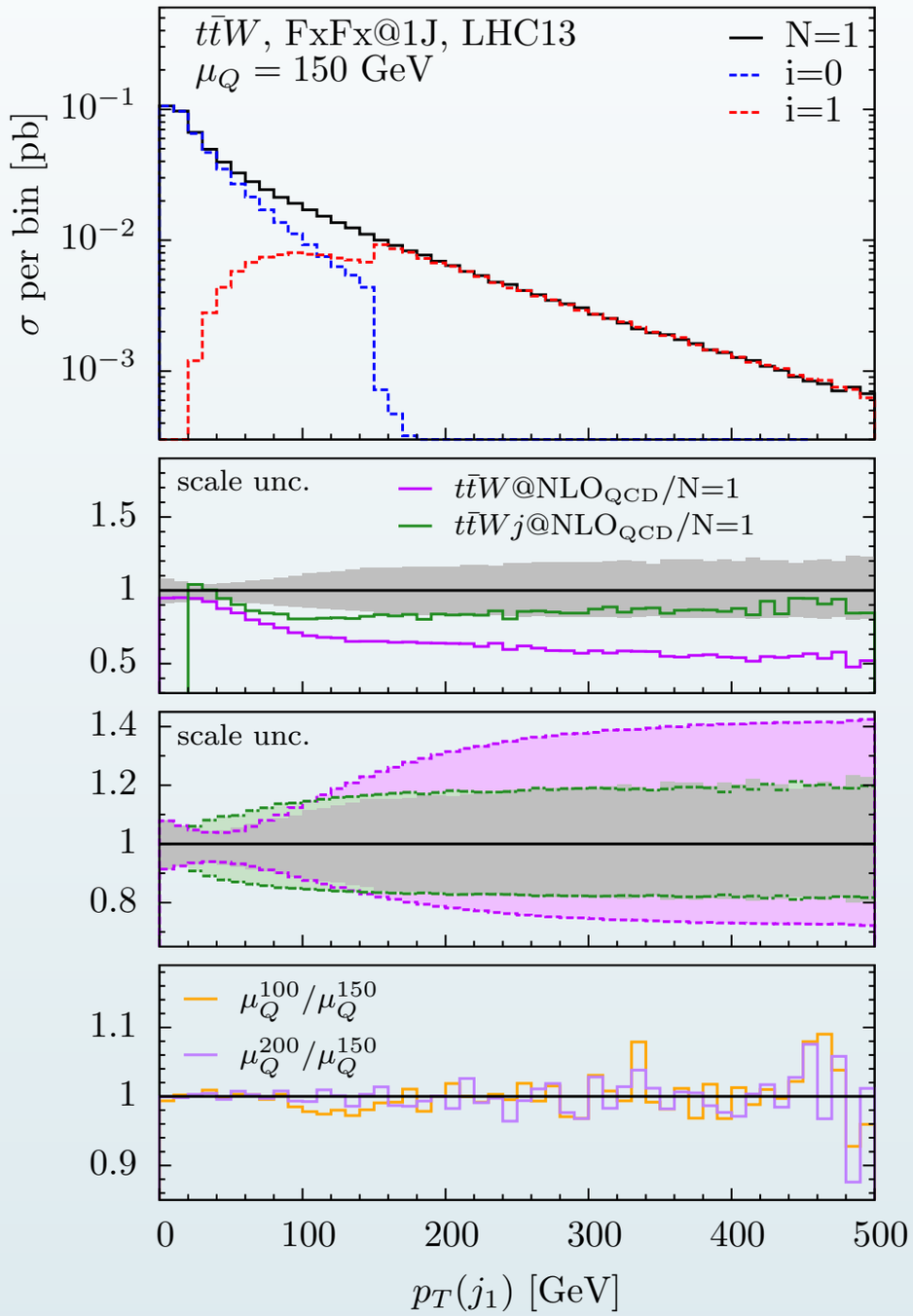
$t\bar{t}W$, FxFx@1J					
μ_Q [GeV]	25	50	75	100	125
σ[fb]	$668.2(9)^{+54.7(+8.2\%)}_{-77.5(-11.6\%)}$	$671.4(8)^{+60.0(+8.9\%)}_{-74.4(-11.1\%)}$	$673.6(8)^{+60.1(+8.9\%)}_{-71.9(-10.7\%)}$	$677.5(6)^{+60.8(+9.0\%)}_{-71.1(-10.5\%)}$	$677.2(8)^{+59.1(+8.7\%)}_{-69.5(-10.3\%)}$
μ_Q [GeV]	150	200	250	300	350
σ[fb]	$679.2(6)^{+60.5(+8.9\%)}_{-69.7(-10.3\%)}$	$679.1(6)^{+61.0(+9.0\%)}_{-69.5(-10.2\%)}$	$678.8(6)^{+61.5(+9.1\%)}_{-69.6(-10.3\%)}$	$678.3(6)^{+61.8(+9.1\%)}_{-69.6(-10.3\%)}$	$678.1(6)^{+62.0(+9.1\%)}_{-69.7(-10.3\%)}$

- 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)]

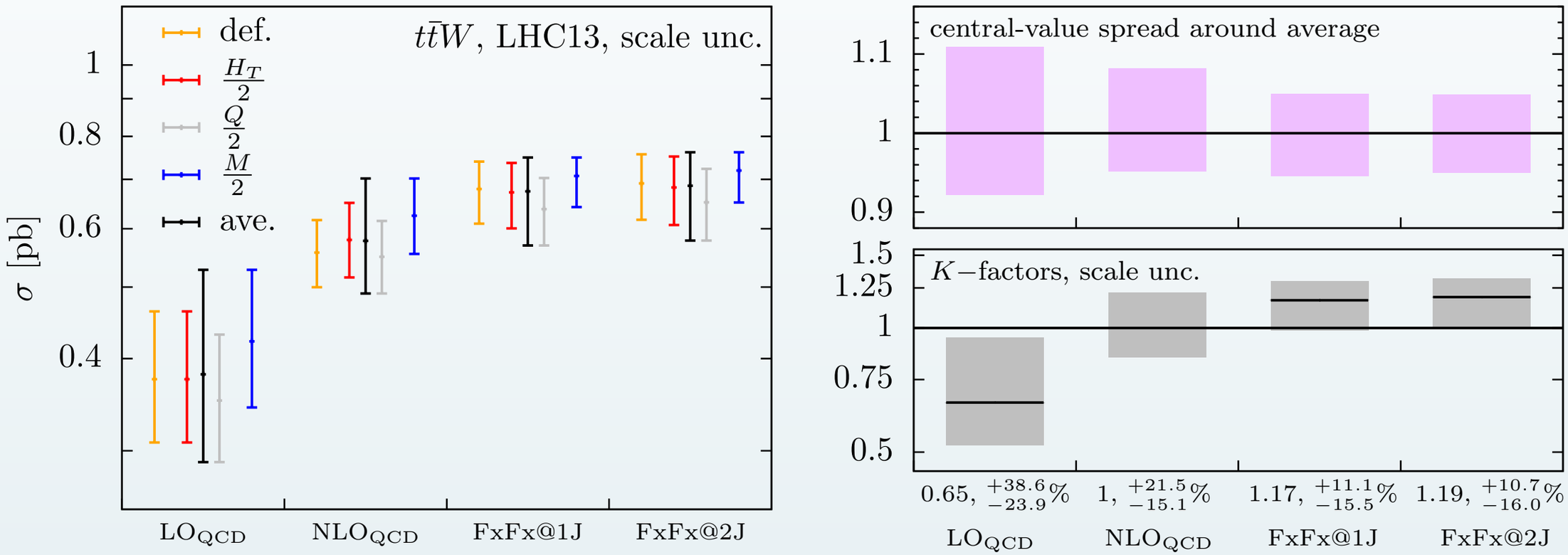




- Step at merging scale disappears
- Contributions from the EW jets in the ttW+1jet sample clearly visible below merging scale
- Large reduction in scale dependence at large $p_T(j_1)$ as compared to non-merged sample

Total cross section

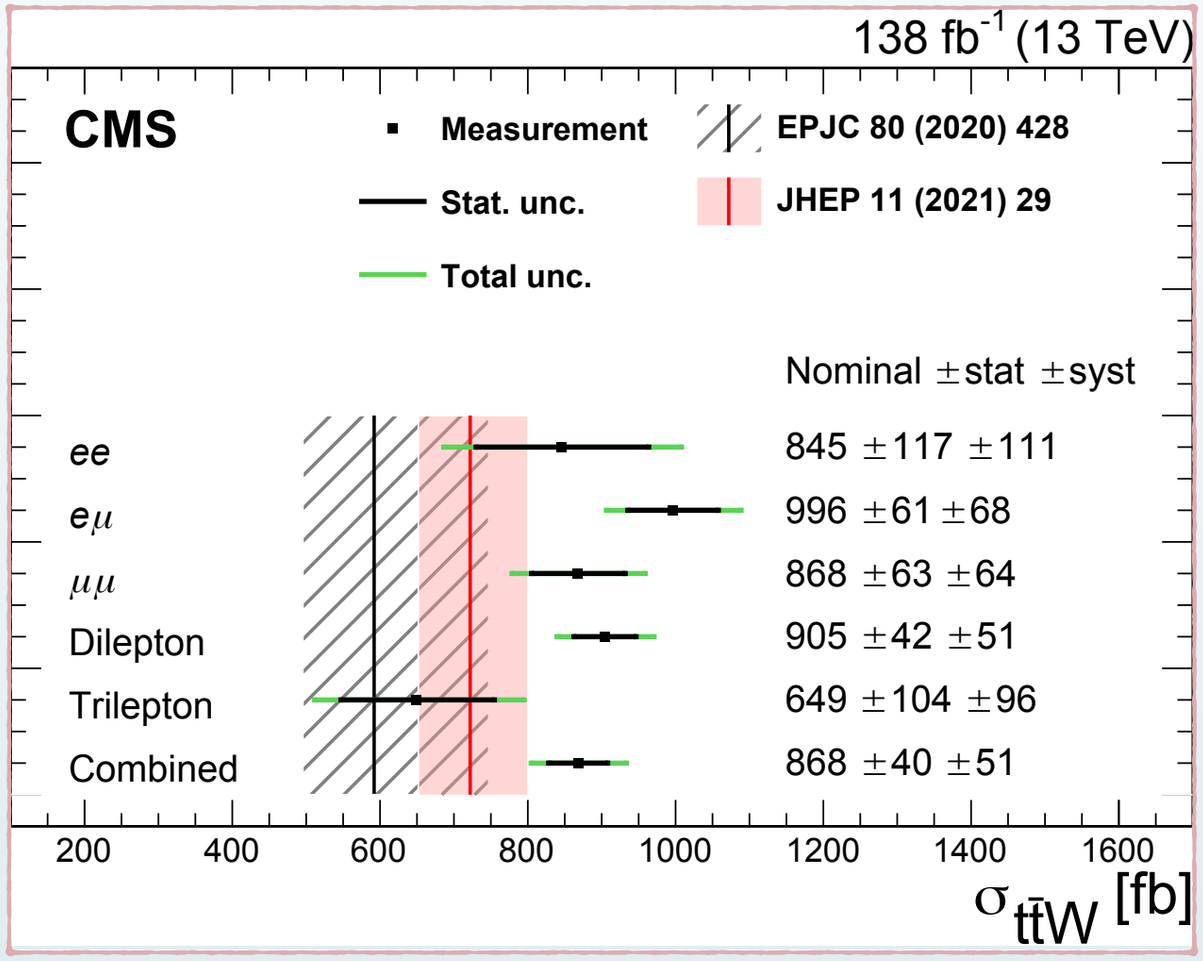
[RF, Tsinikos (2021)]



- Rate about 17-19% larger than NLO$_{\rm QCD}$
- 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 extend



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