Top pair production in association with a W boson

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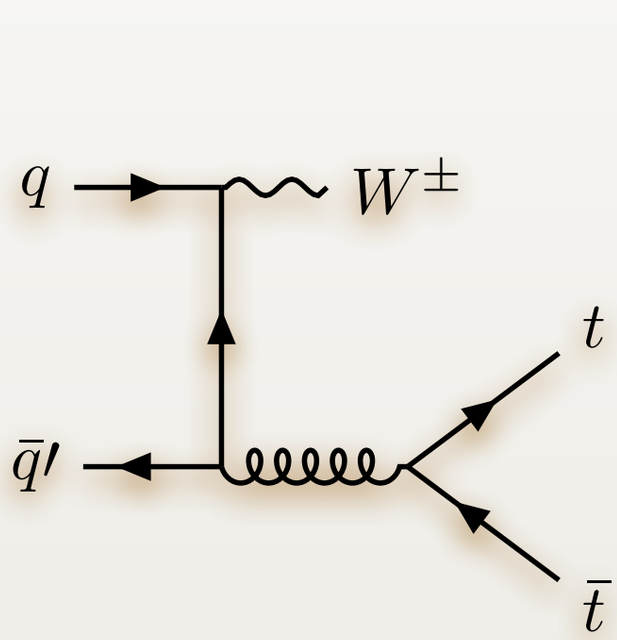
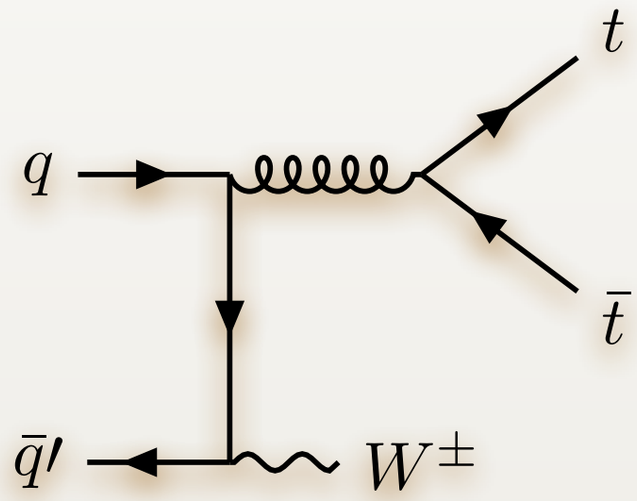
Why ttW?

- ttW is one of the **main backgrounds in ttH production** (with leptonic H decays)
- Also important background in 4-top production
- Hence, understanding it is important in the extraction of the top Yukawa coupling
- Some tension between measurement of the total cross section by both CMS and ATLAS: **data seem to prefer a larger cross section than what is expected from the SM**

What's special?

- **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

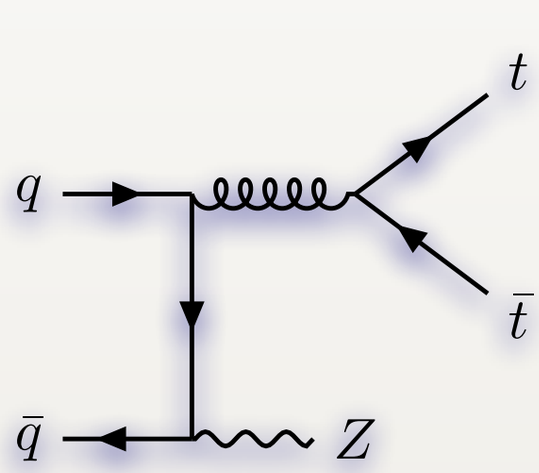


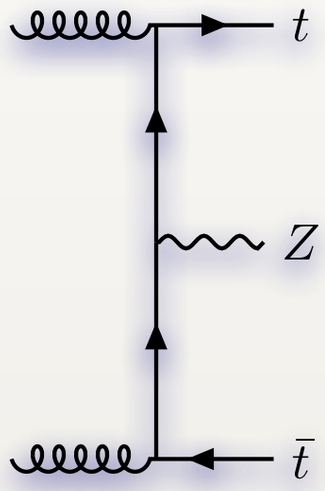


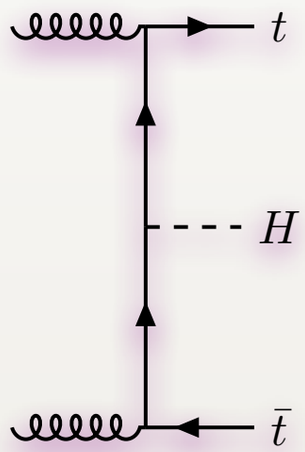
- Hence, **expect large higher order corrections**, and possibly underestimation of theory uncertainties at lowest order(s), due to opening of new channels, new colour structures, new flavour structures, etc.

The other tt+boson processes

- The ttH and ttZ processes do not have these 'constraints'







- ttZ has both qqbar and gg initial state at LO
- ttH has only gg initial state at LO, but no dominating structures appearing at higher orders

Total cross sections

arXiv:1907.04343

$$\sigma_{t\bar{t}W^+} = 384.17(9)^{+51.52(+13.4\%)+8.16(+2.1\%)}_{-32.36(-8.4\%)-8.16(-2.1\%)} \text{ ,}$$

$$\sigma_{t\bar{t}W^-} = 197.75(4)^{+26.41(+13.4\%)+5.41(+2.7\%)}_{-16.07(-8.1\%)-5.41(-2.7\%)} \text{ ,}$$

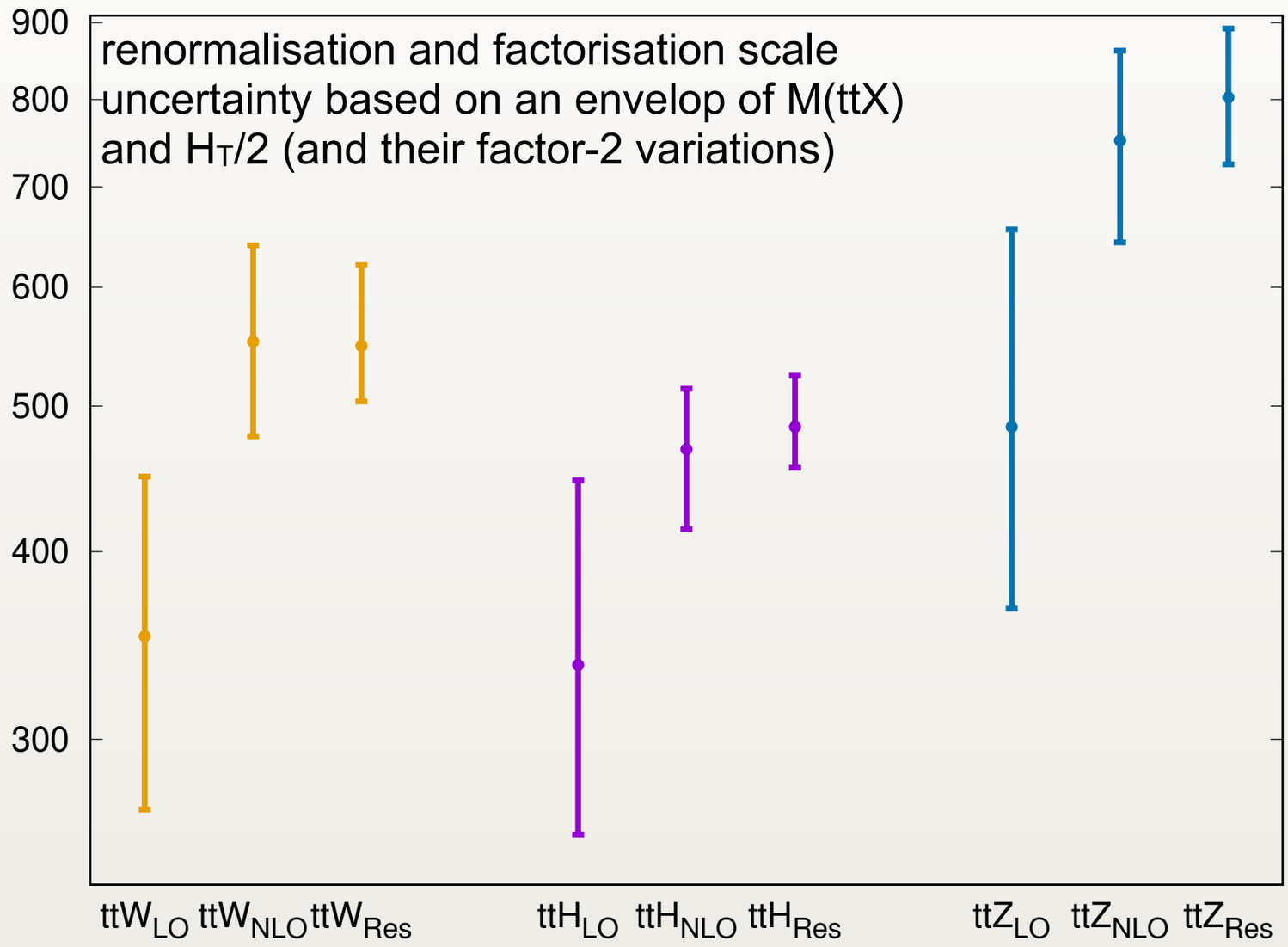
$$\sigma_{t\bar{t}H} = 496.36(7)^{+38.64(+7.8\%)+11.92(+2.4\%)}_{-29.35(-5.9\%)-11.92(-2.4\%)} \text{ ,}$$

$$\sigma_{t\bar{t}Z} = 810.9(2)^{+89.2(+11.0\%)+19.1(+2.4\%)}_{-77.8(-9.6\%)-19.1(-2.4\%)} \text{ .}$$

- Total cross sections at NLO+NNLL+EW accuracy, including scale and PDF uncertainties
- No multi-jet merging corrections

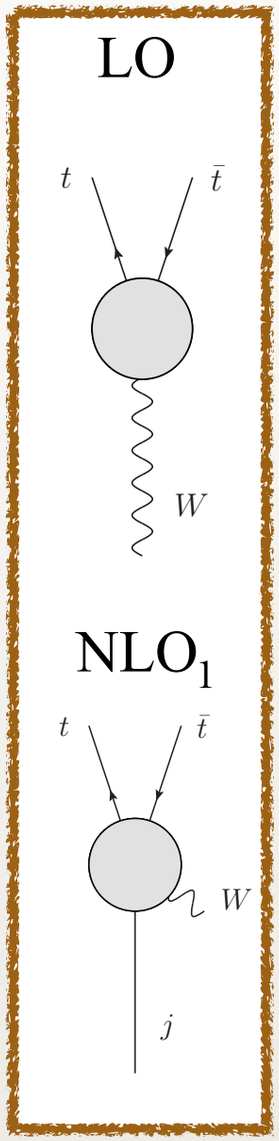
Total cross sections: LO vs NLO vs NLO+NNLL

- Most-accurate cross sections NLO+NNLL+EW are available **arXiv:1907.04343**
- LO vs. NLO
  - ttW: no overlap
  - ttH: plenty overlap
  - ttZ: marginal overlap
- uncert. NLO vs NLO+NNLL
  - ttW: smallest reduction
  - ttH: largest reduction
  - ttZ: medium reduction

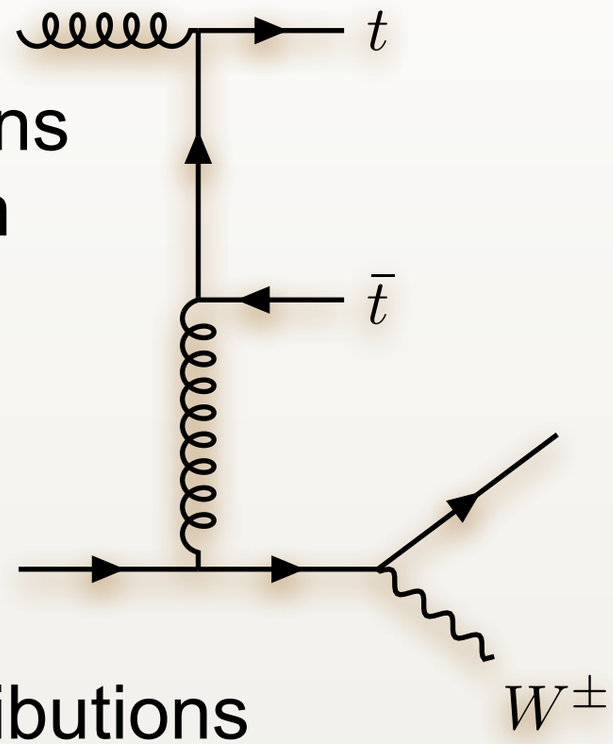


- ttH behaves "most-natural", and ttW "least-natural"

Opening of new channels

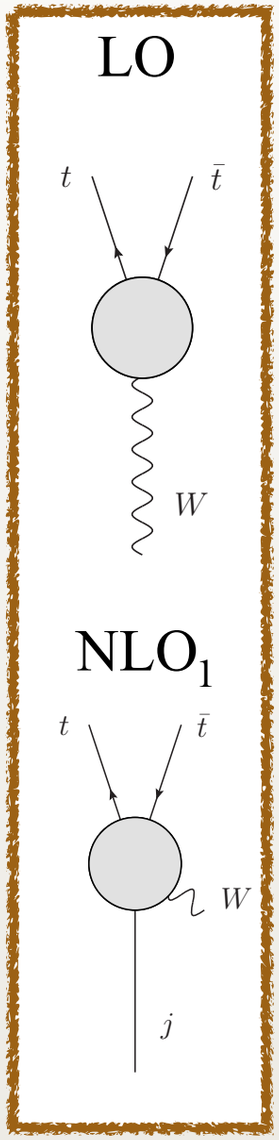


- In the (real-emission) NLO QCD corrections to ttW, top pair production via gluon fusion enters
- Also present for ttZ production — although less important since already gg induced contributions at LO

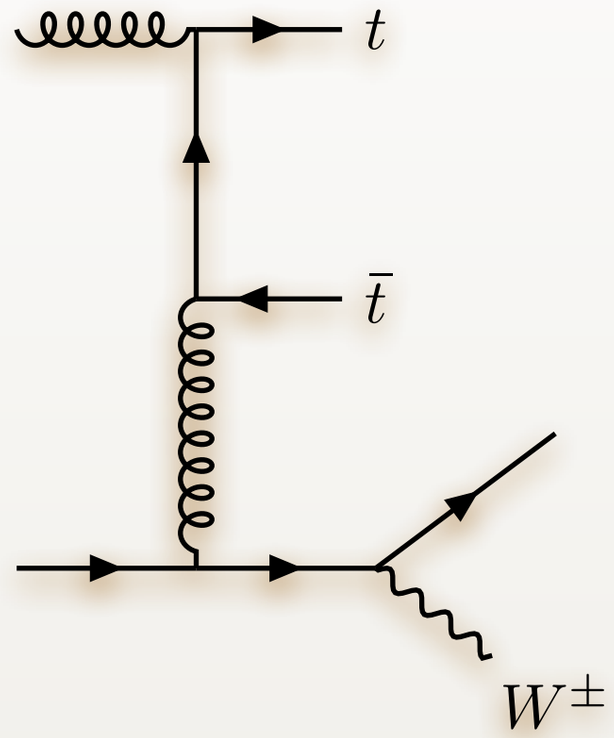


- These are essentially "almost-finite" contributions that enhance the cross section
- Dominant at large $p_T(tt)$
  - Captured at LO accuracy in an NLO computation
  - Captured at NLO accuracy in NLO multi-jet merging

Multi-jet merging

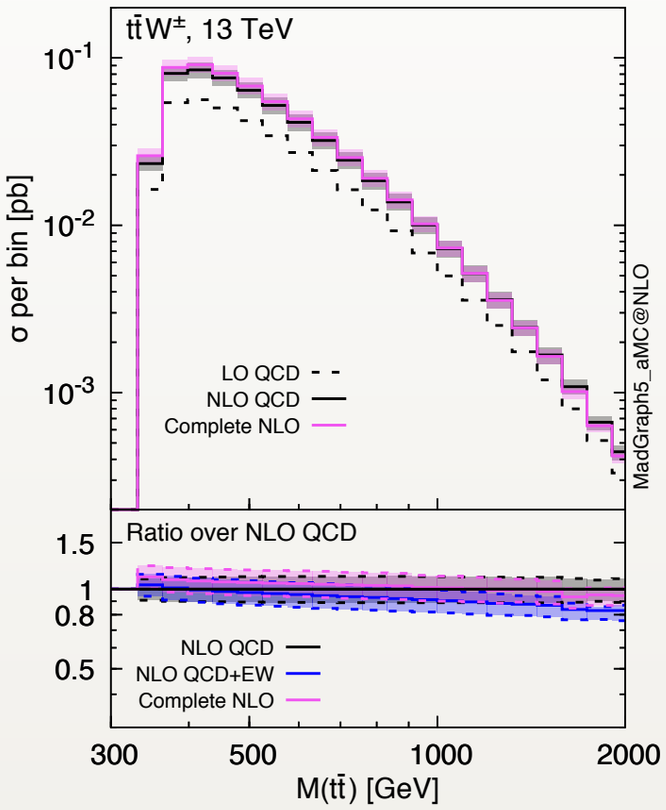


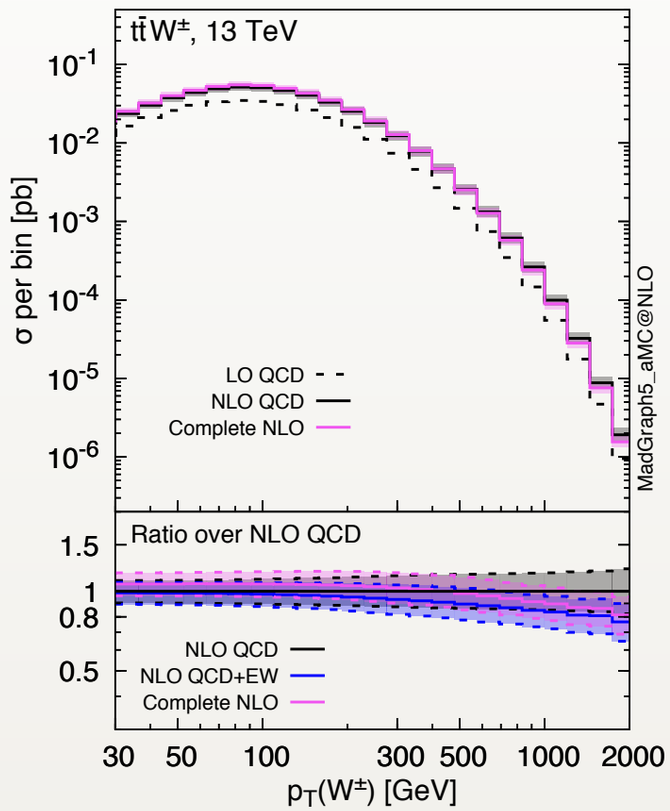
- Due to opening of this new structure, need smaller merging scale than expected from the process itself
- Might need some adaptation on the method itself: FxFx can be improved.
  - Currently under investigation
  - There might be a larger increase in cross section than currently taken into account
- [I don't know how Sherpa's MEPS@NLO handles these contributions]

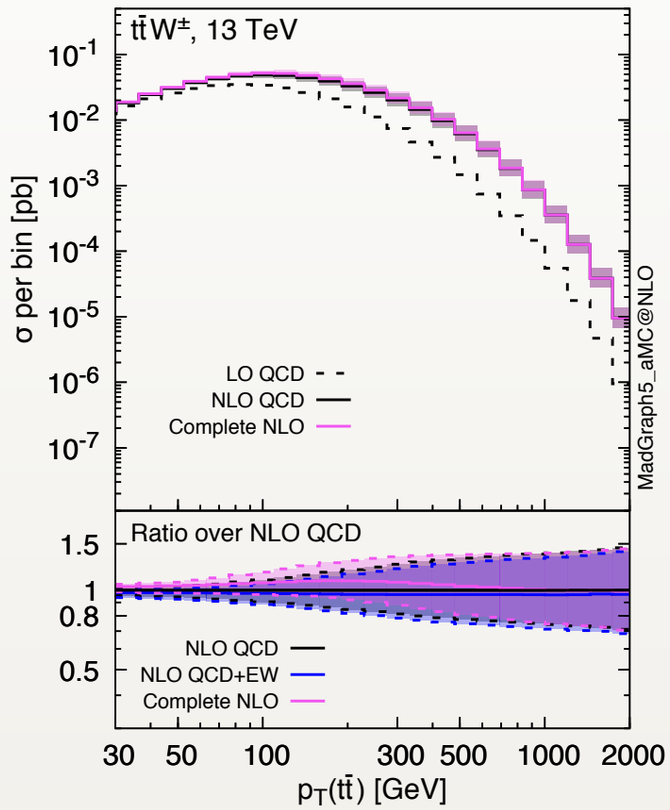


ttW differential

arXiv:1711.02116







- Large enhancement over LO also visible in differential distributions, in particular for $p_T(tt)$
- Tail of $p_T(tt)$ shows large scale uncertainty
- NLO EW corrections lower tail of M(tt) and $p_T(W)$
- Complete-NLO increases total cross section and induces marginal shape differences

ttW differential

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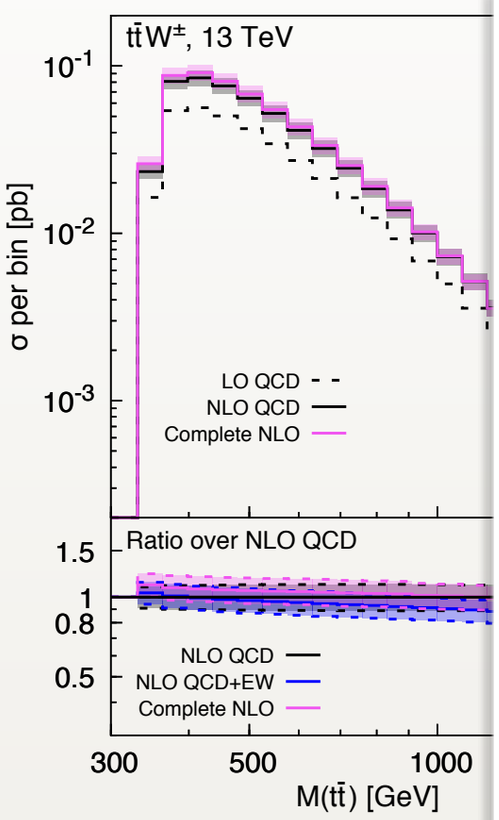
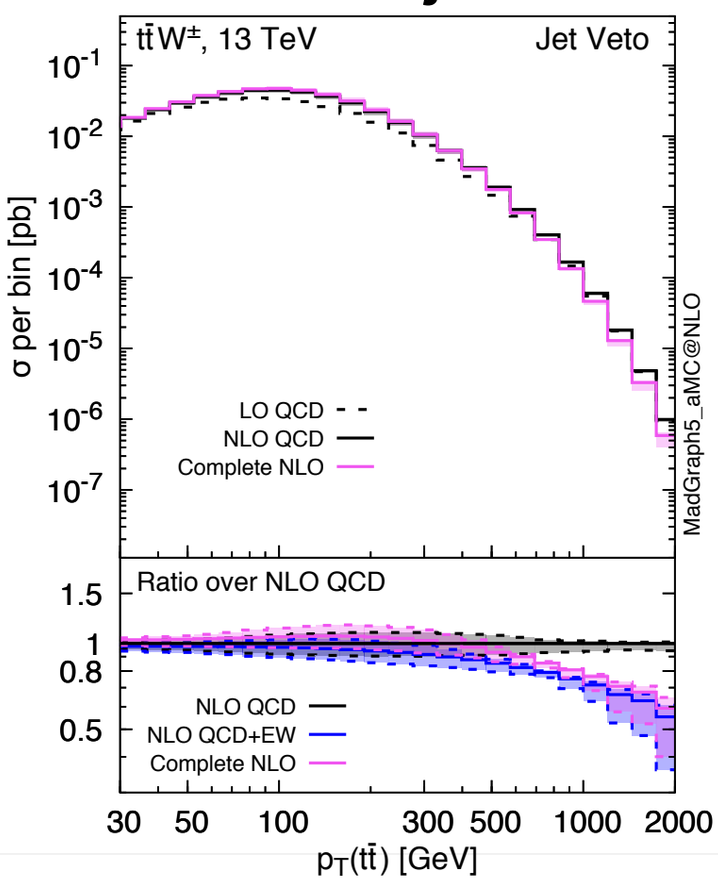
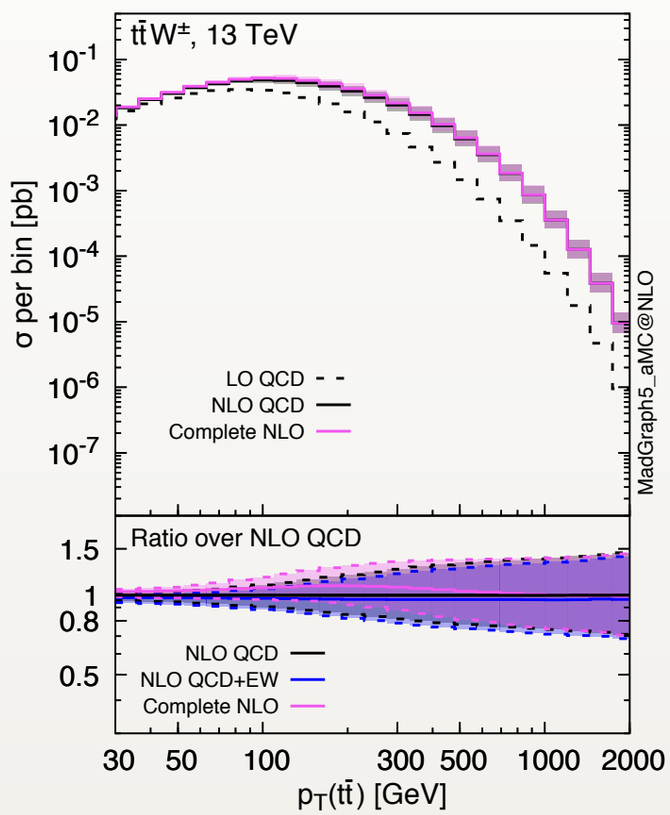


100 GeV jet veto





- Large enhancem differential distributions, in particular for p_T(t
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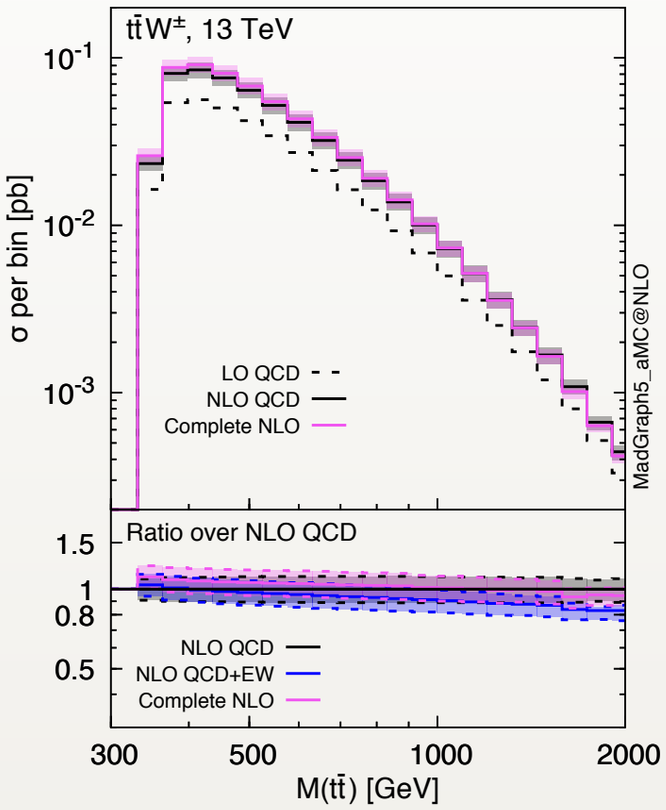

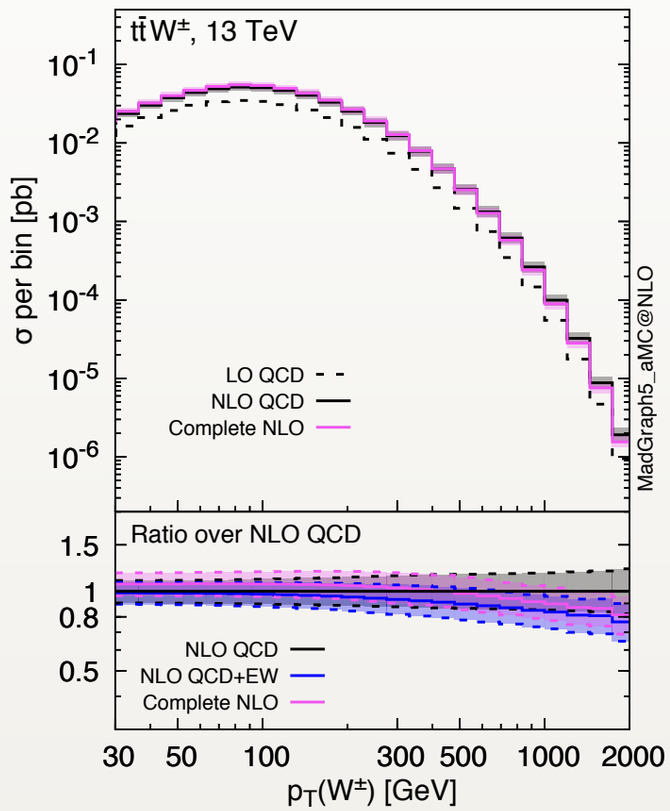

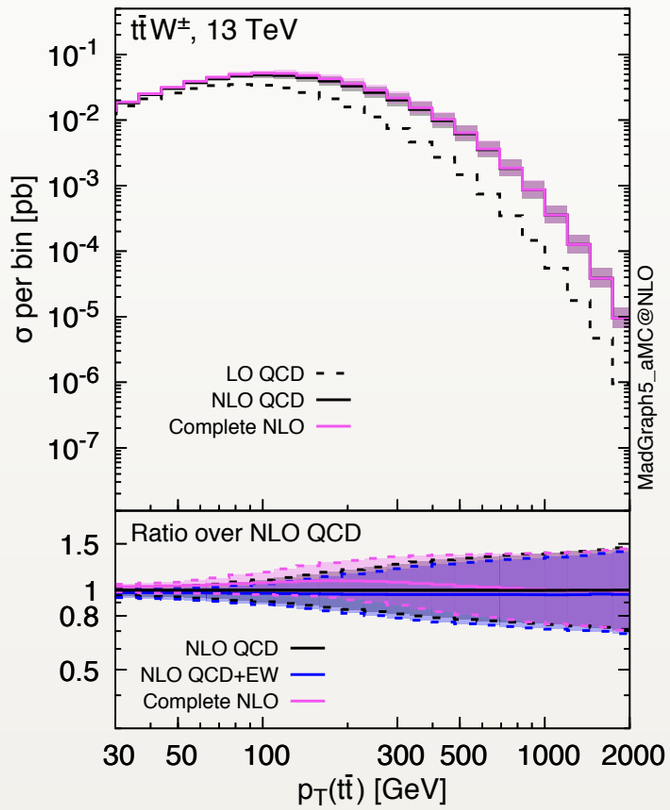

- Large enhancement over LO also visible in differential distributions, in particular for $p_T(tt)$
- Tail of $p_T(tt)$ shows large scale uncertainty
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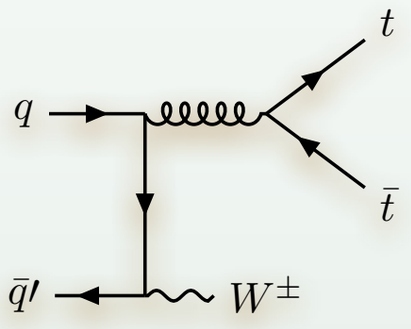
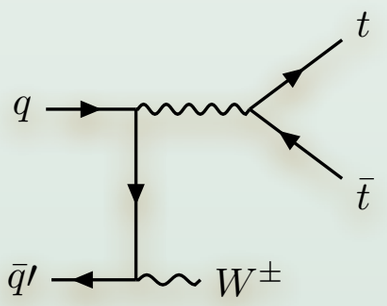
Complete NLO for ttW





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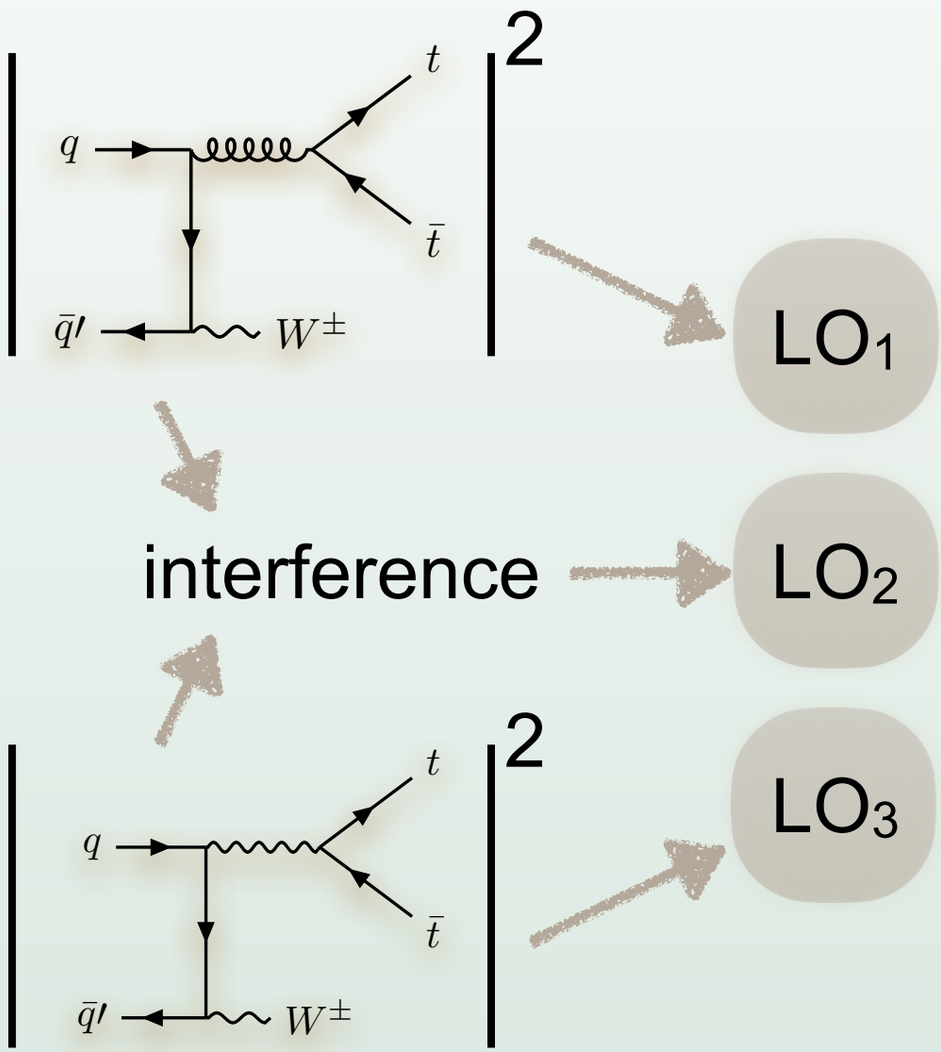

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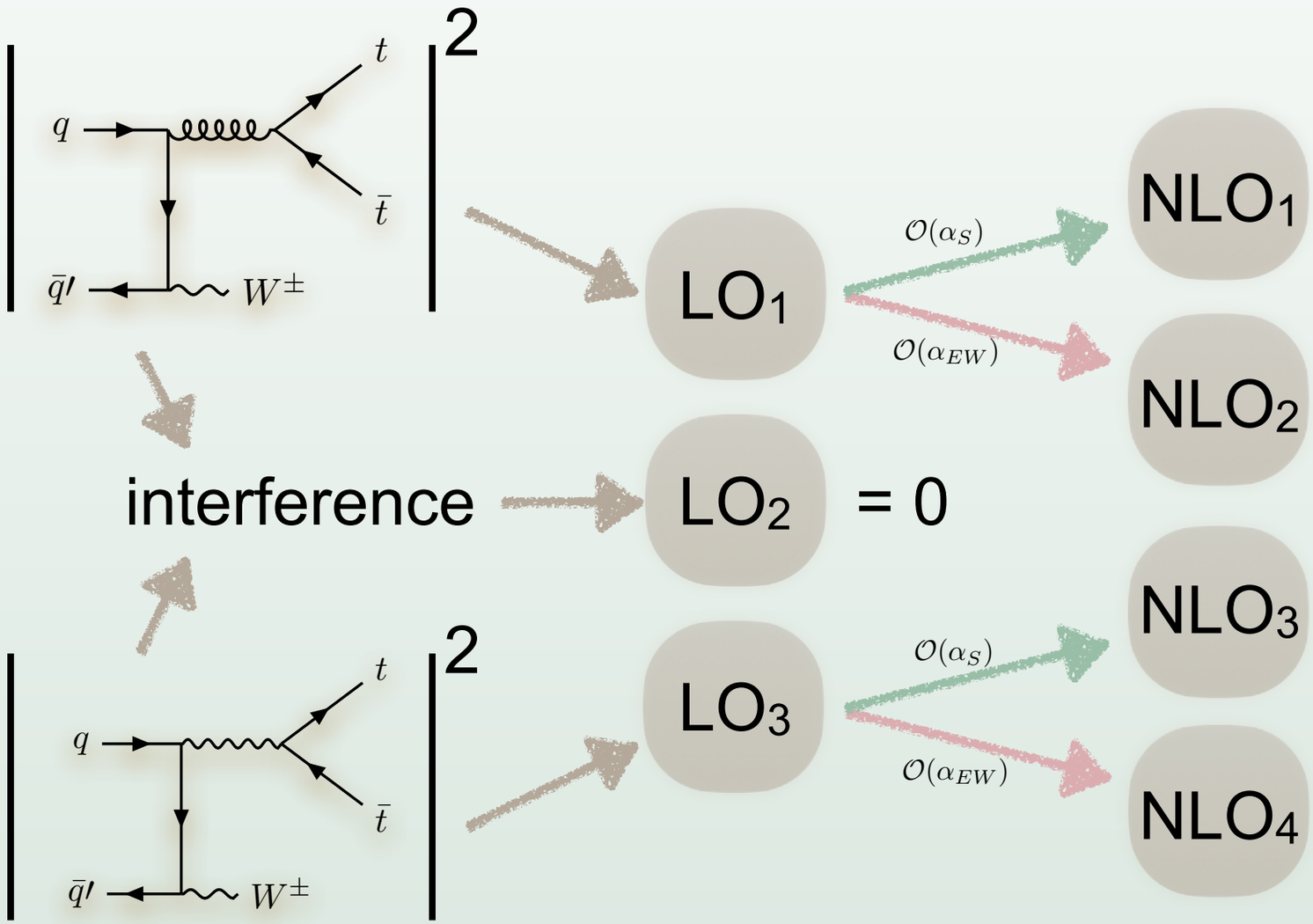

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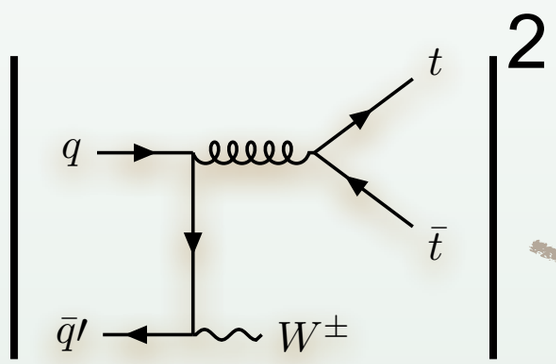
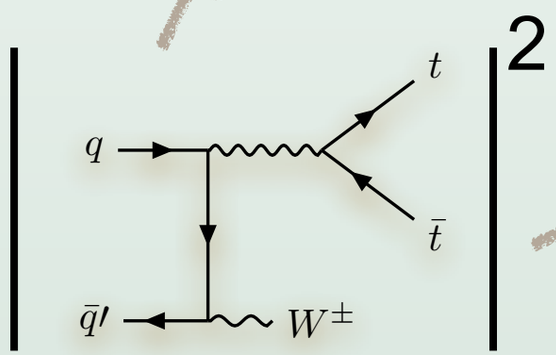


interference



LO_1

LO_2 = 0

LO_3

$\mathcal{O}(\alpha_S)$ → NLO_1

$\mathcal{O}(\alpha_{EW})$ → NLO_2

$\mathcal{O}(\alpha_S)$ → NLO_3

$\mathcal{O}(\alpha_{EW})$ → NLO_4

Naive expectation

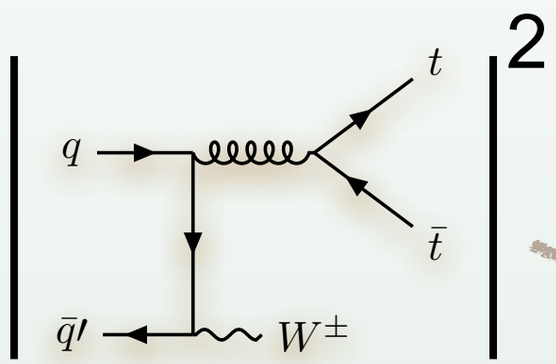
$\mathcal{O}(10\%)$

$\mathcal{O}(1\%)$

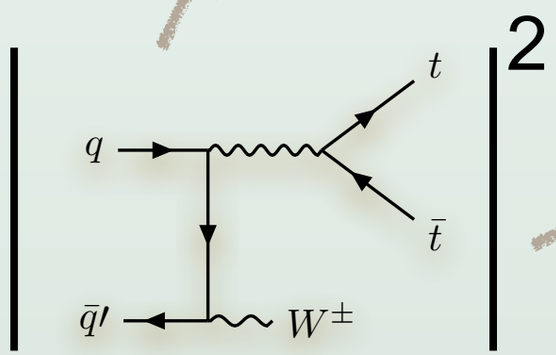
$\mathcal{O}(0.1\%)$

$\mathcal{O}(0.01\%)$

Complete NLO for ttW



interference → LO_2 = 0

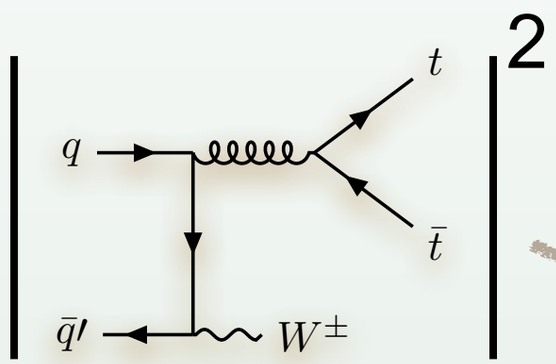


LO_1 → NLO_1 ($\mathcal{O}(\alpha_S)$), NLO_2 ($\mathcal{O}(\alpha_{EW})$)

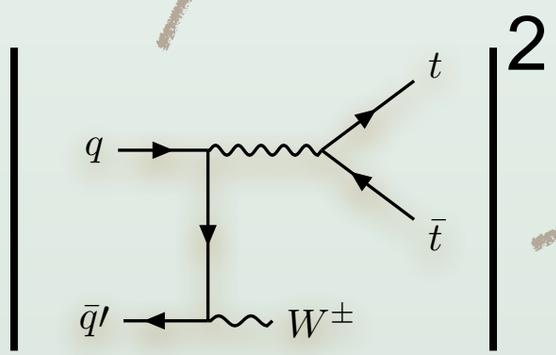
LO_3 → NLO_3 ($\mathcal{O}(\alpha_S)$), NLO_4 ($\mathcal{O}(\alpha_{EW})$)

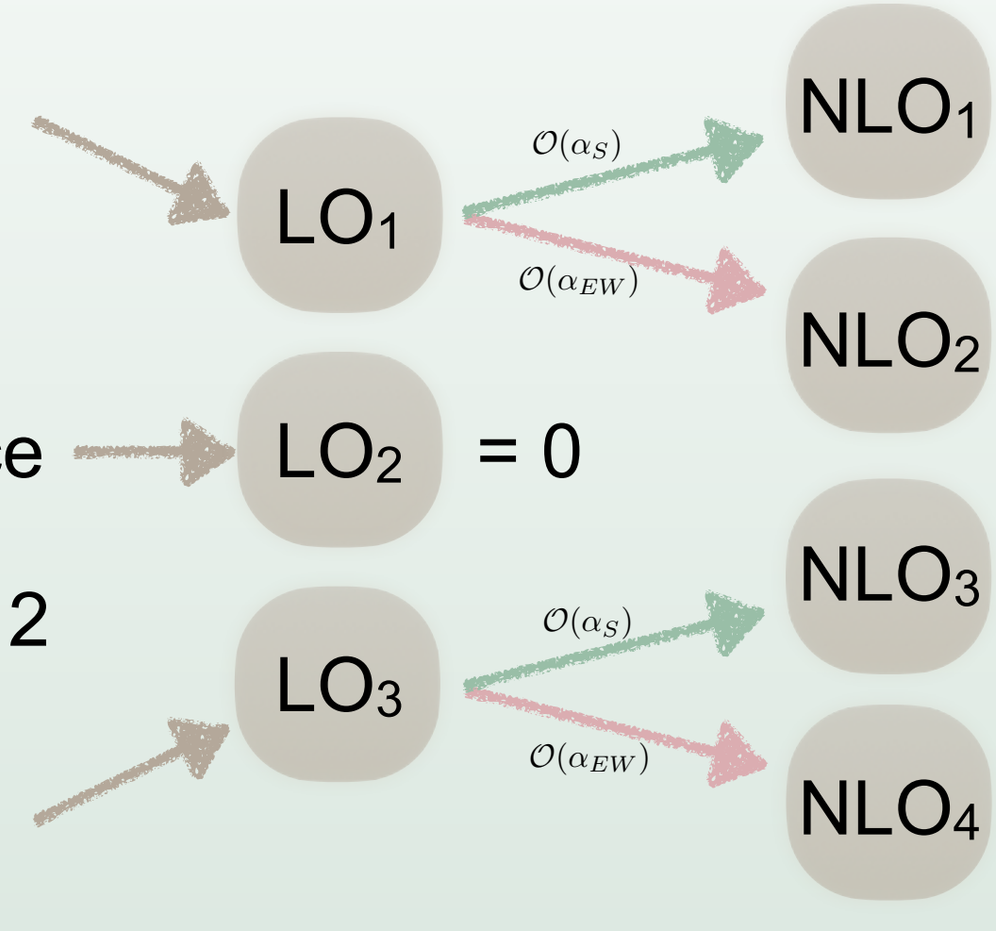
	Naive expectation	Actual correction
NLO_1	$\mathcal{O}(10\%)$	30-60%
NLO_2	$\mathcal{O}(1\%)$	$-(4.0\text{-}4.4)\%$
NLO_3	$\mathcal{O}(0.1\%)$	12-13%
NLO_4	$\mathcal{O}(0.01\%)$	0.02-0.05%

Complete NLO for ttW



interference

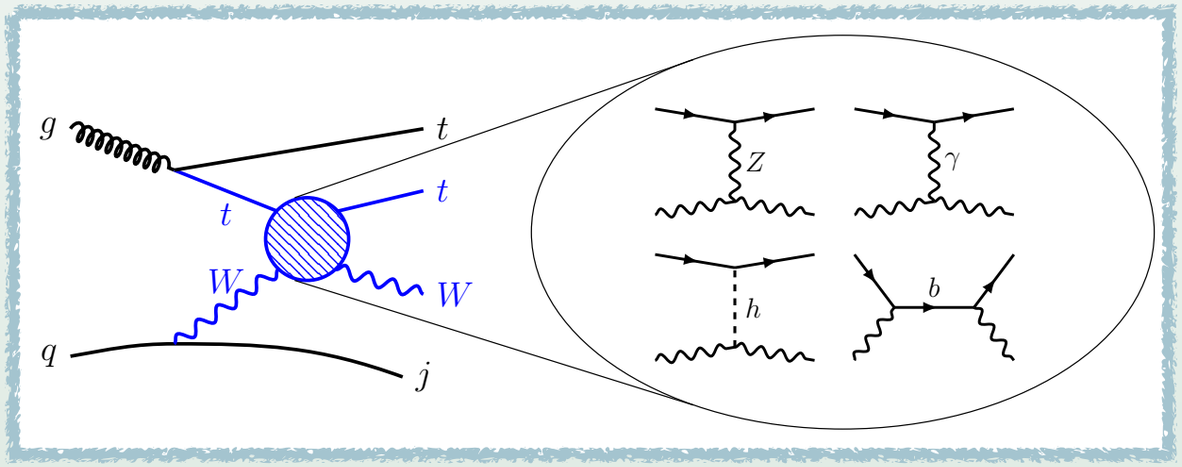




	Naive expectation	Actual correction
NLO1	$\mathcal{O}(10\%)$	30-60%
NLO2	$\mathcal{O}(1\%)$	$-(4.0\text{-}4.4)\%$
NLO3	$\mathcal{O}(0.1\%)$	12-13%
NLO4	$\mathcal{O}(0.01\%)$	0.02-0.05%

NLO_3 in ttW

- t-channel enhancements results in much-larger-than-expected NLO_3 corrections
  - Essentially the scattering of tops with W-bosons



- Consistent matrix element + parton shower matching unavailable for processes with NLO EW corrections

Fiducial region

- Explicit calculation for top pair production (and ttγ) show that truly **off-shell** and **non-resonant interference** effects are minimal (at least at the current accuracy)
  - "tt and tW can be summed incoherently"

- It is sufficient to generate ttW and decaying tops and W's at LO, keeping spin correlations, with extra radiation coming from parton shower

Summary

- ttW is a peculiar process from a theory point of view
  - somewhat "constraint" at LO: only 2 Feynman diagrams
    - one can expect large higher-order corrections, due to the appearance of new structures
      - theory uncertainties might be underestimated from scale variation alone
    - multi-jet merging necessary for reliable predictions

Outlook

- **NNLO**
  - would solve all issues discussed in this talk
  - very difficult…
  - …but maybe not hopeless?
- **Improvements in multi-jet merging**
  - Certainly relevant for FxFx…
    - …currently under investigation

- **LO_3+NLO_3 matching to parton shower**…
  - …should be possible with some hacks in MG5_aMC
- **NLO to fully decayed process**, including off-shell and non-resonant (interference) effects…
  - …hard, but doable, and relevant to cross check
- **Matching NLO EW** corrections to the parton shower