$\mathrm{t\bar{t}W^{\pm}}$ at NLO accuracy with realistic final states

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13th International Workshop on Top Quark Physics (TOP 2020)

Durham (virtual edition)

September 15, 2020

Outline

- Motivations for $t\bar{t}W$ at the LHC

- Theory status of $t\bar{t}W^{\pm}$ production
  - impact of EW corrections, NNLL resummation, multi-jet merging

- $t\bar{t}W^{\pm}$ with realistic final states
  - interface to Parton Shower, complete off-shell effects

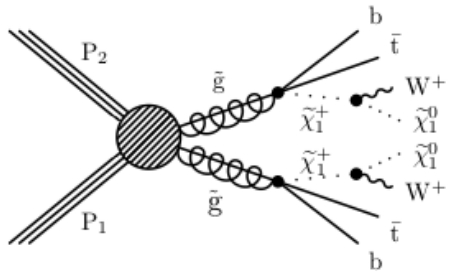
- Conclusions and outlook

Motivations for $t\bar{t}W^{\pm}$

- $t\bar{t}W^{\pm}$ ranges among the rarest channels for associated $t\bar{t}$ production at LHC
  $\hookrightarrow$ window for New Physics

  - direct BSM searches

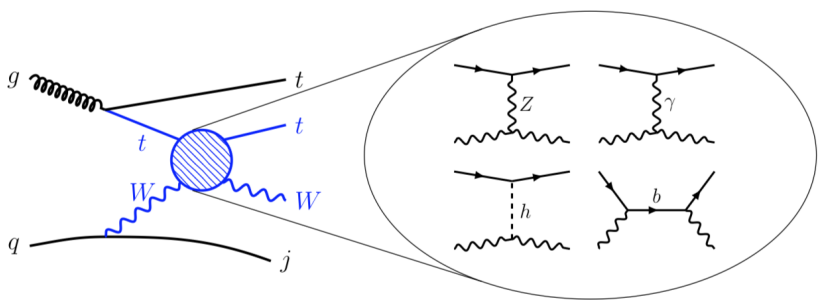
e.g. SUSY



ATLAS 1602.09058 [hep-ex]
ATLAS 1706.03731 [hep-ex]
CMS 1605.03171 [hep-ex]
CMS 1704.07323 [hep-ex]
...

  - non-standard top quark couplings, EFT interpretations

$tW \to tW$ scattering



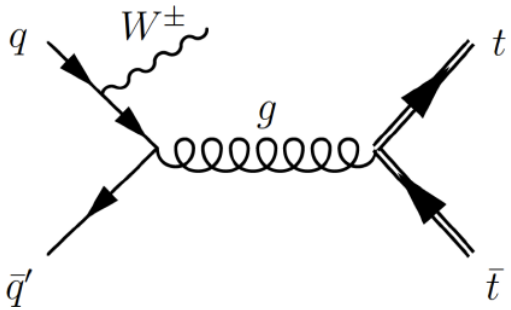
Dror *et al.*, 1511.03674 [hep-ph]

- Challenging background for multi-lepton signatures ($2ss\ell$, 3ℓ, ...)

Motivations for $t\bar{t}W^{\pm}$

- The produced tops are highly polarised

↪ large charge asymmetries in decay products

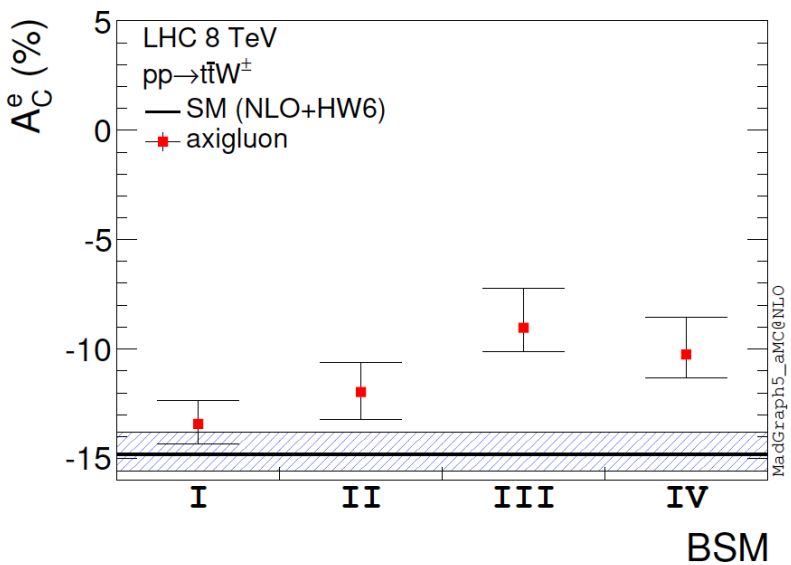


- Initial-state gg channel opens up only at NNLO:

LO: $\mathbf{q\bar{q}'}$ $\longrightarrow$ **NLO:** $\mathbf{q\bar{q}'}$ **+** $\mathbf{qg}$ $\longrightarrow$ **NNLO:** $\mathbf{q\bar{q}'}$ **+** $\mathbf{qg}$ **+** $\mathbf{gg}$

		8 TeV	13 TeV	14 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$
$t\bar{t}W^{\pm}$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$
	$A_c^t(\%)$	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$
	$A_c^b(\%)$	$8.50^{+0.15}_{-0.10}$	$7.54^{+0.19}_{-0.17}$	$7.50^{+0.24}_{-0.22}$
	$A_c^e(\%)$	$-14.83^{-0.65}_{+0.95}$	$-13.16^{-0.81}_{+1.12}$	$-12.84^{-0.81}_{+1.11}$

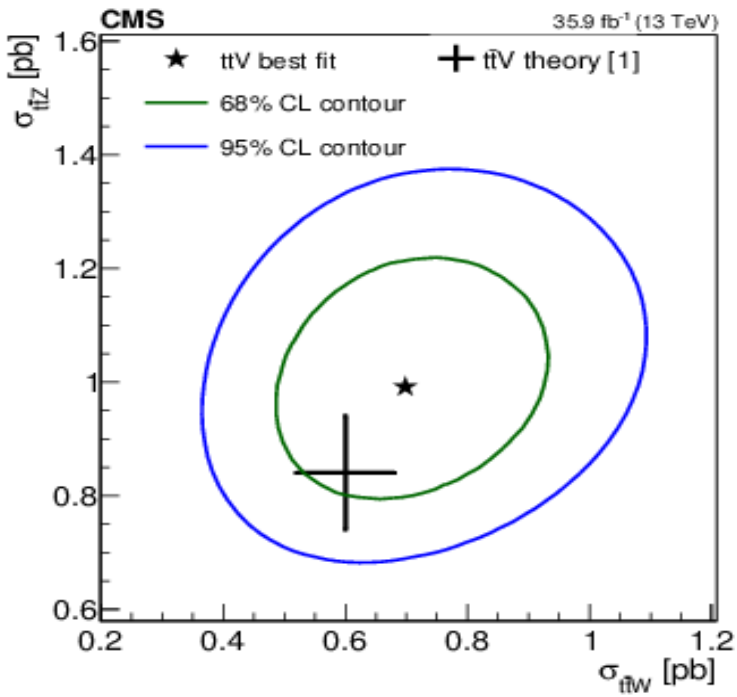
Maltoni *et al.*, Phys. Lett. B **736** (2014), 252-260



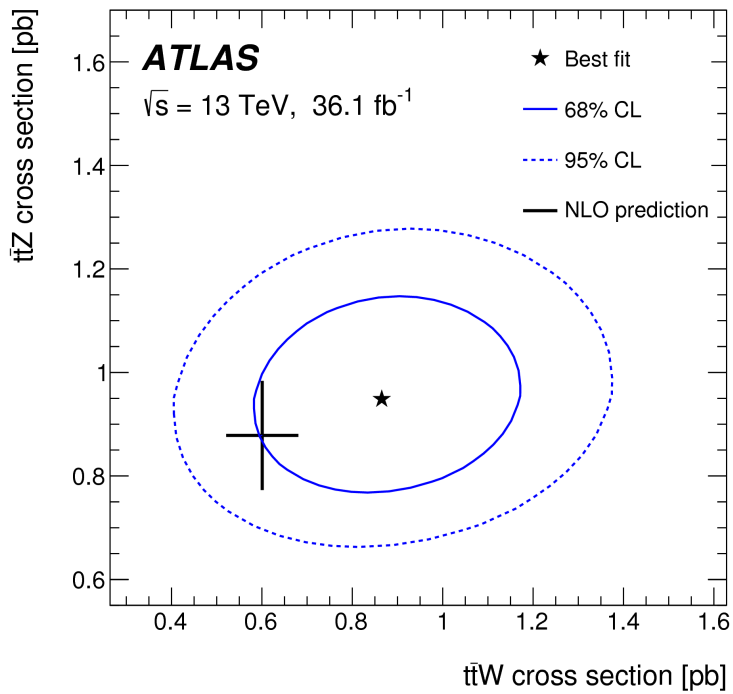
Measurements at LHC (13 TeV)

- $t\bar{t}W^{\pm}$ vs $t\bar{t}Z$ cross sections at $\sqrt{s}$ = 13 TeV, $\mathcal{L} = 36$ fb^{-1}

CMS Collab., JHEP 08 (2018) 011



ATLAS Collab., Phys. Rev. D 99 (2019) 072009



- Improved ATLAS and CMS measurements confirm excess of $t\bar{t}W$ events over the expected SM benchmarks

ATLAS-CONF-2019-045 CMS-PAS-HIG-19-008

CERN-EP-2020-111

Theory status of $t\bar{t}W^{\pm}$

NLO fixed order

- **NLO QCD + EW: inclusive production**

  Hirschi *et al.* '11 Maltoni *et al.* '15 Frixione *et al* '15 Frederix *et al* '17

  ↪ top quarks undecayed: impact of NLO corrections to total rates

- **NLO QCD: on-shell production $\times$ decay**

  Campbell and Ellis '12

  ↪ QCD corrections to production and decays, including spin correlations

- **NLO QCD : complete off-shell**

  G.B, Bi, Hartanto, Kraus and Worek '20
  Denner and Pelliccioli '20

  ↪ resonant and non-resonant diagrams, interferences and finite-width effects (3ℓ channel)

NLO + resummation

- **NLO+NNLL QCD + EW: inclusive production**

  Li *et al.* '14 Broggio *et al.* '16 Broggio *et al.* '19 Kulesza *et al.* '18 '20

  ↪ top quarks undecayed

NLO + Parton Shower

- **NLOPS QCD + EW: on-shell**

  Garzelli, Kardos, Papadopoulos and Trocsanyi '12
  Maltoni *et al.* '14 '15 Frederix and Tsinikos '20

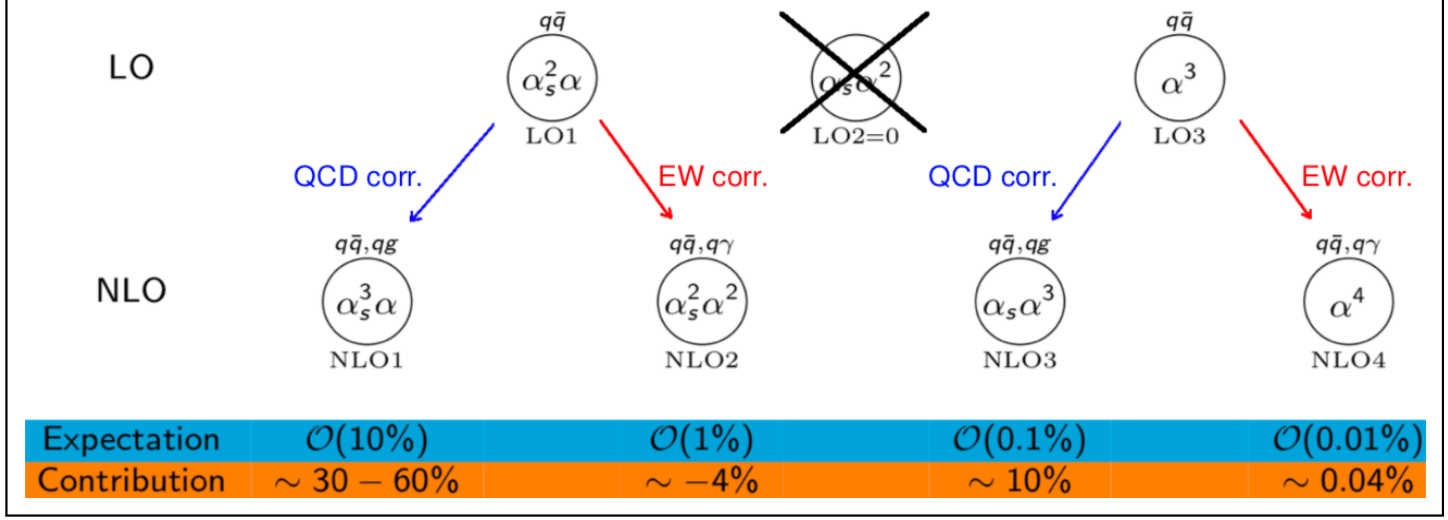
  ↪ top quark decays modeled at LO

Inclusive $t\bar{t}W^{\pm}$: impact of EW corrections

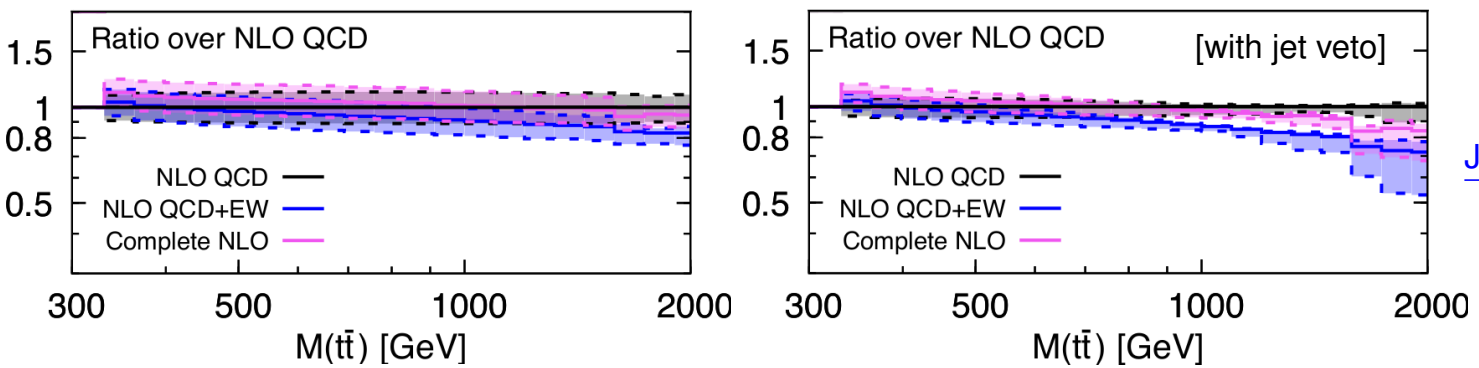
Complete NLO [I. Tsinikos, LHCP2020]

Frederix, Pagani, Zaro: 1711.02116

complete NLO: Madgraph5_aMC@NLO publicly available, *Frederix et al.*:1804.10017



Expectation	$\mathcal{O}(10\%)$	$\mathcal{O}(1\%)$	$\mathcal{O}(0.1\%)$	$\mathcal{O}(0.01\%)$
Contribution	$\sim 30-60\%$	$\sim -4\%$	$\sim 10\%$	$\sim 0.04\%$



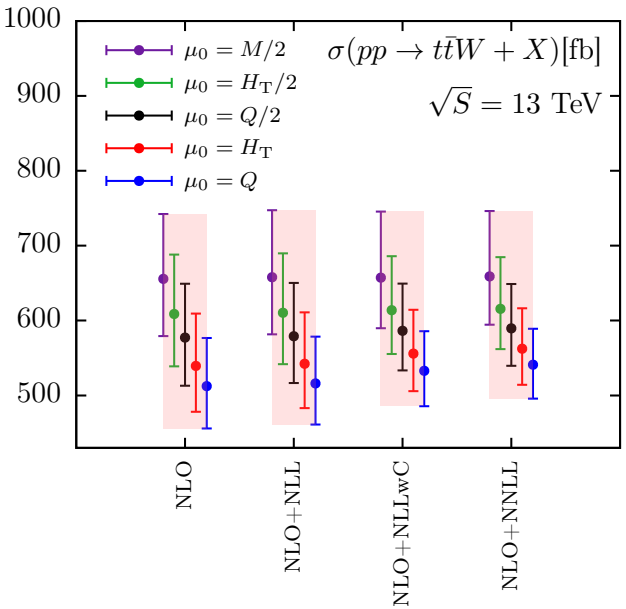
Frederix *et al.*, JHEP 02 (2018), 031

↪ Large NLO3 contribution due to opening of $tW \to tW$ channel

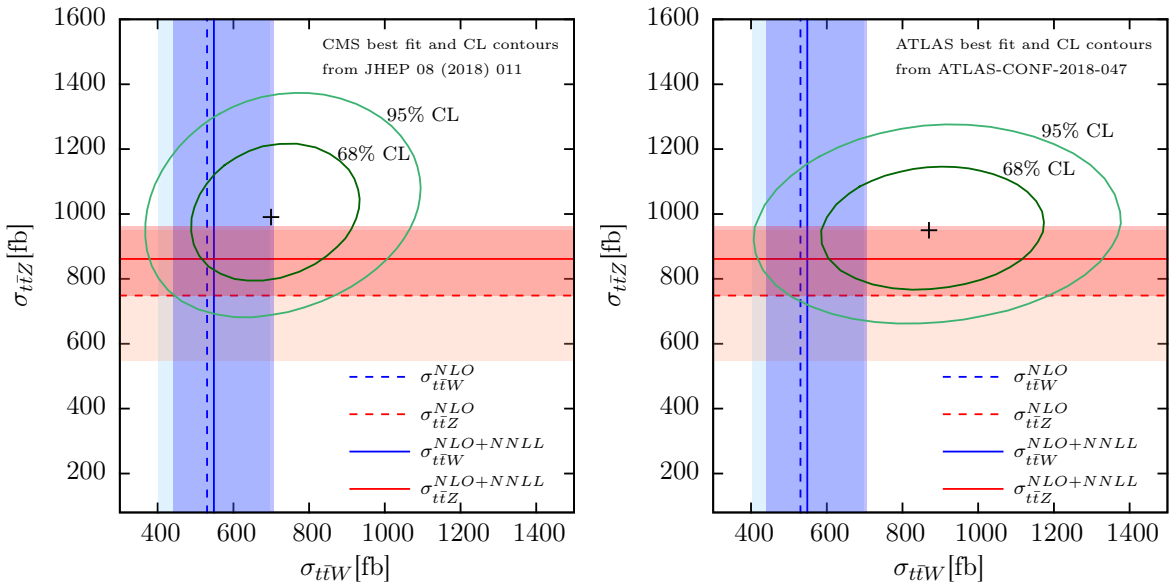
see also Dror *et al.*, JHEP 01 (2016) 071

Inclusive $t\bar{t}W^{\pm}$: impact of NNLL resummation

Kulesza *et al.*, Eur. Phys. J. C 80 (2020) 5, 428



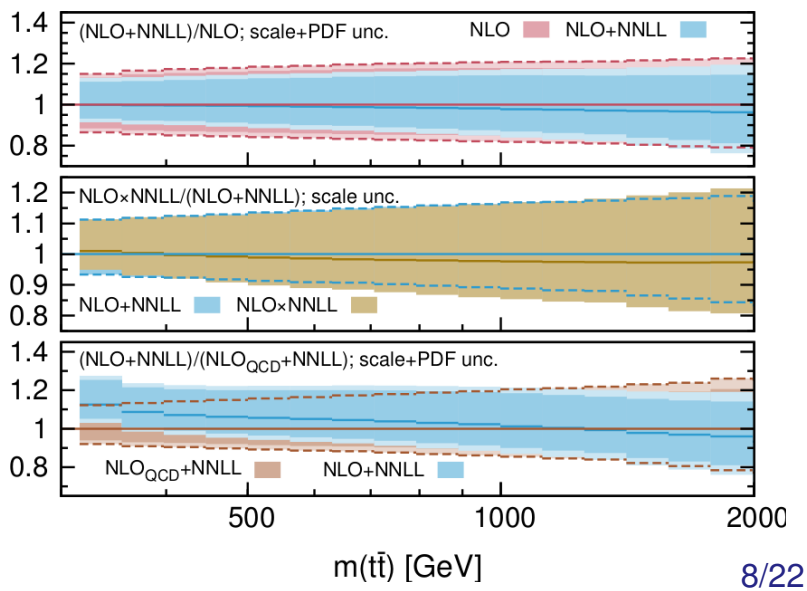
Kulesza *et al.*, Eur. Phys. J. C 79 (2019) 3, 249



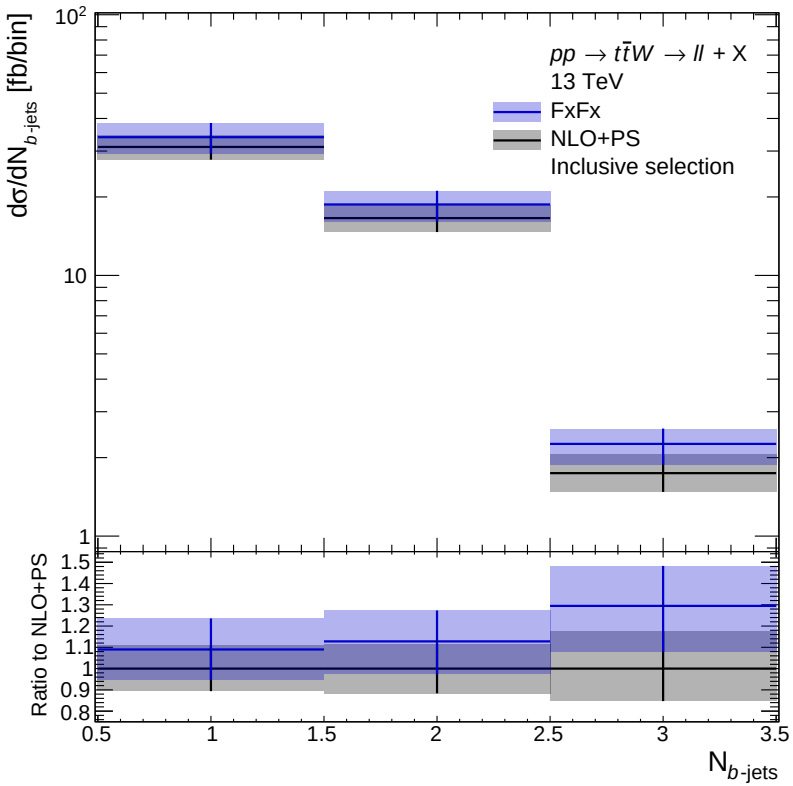
- Central value of the $t\bar{t}W^{\pm}$ prediction brought closer to the measured ones; no significant reduction of scale uncertainties is observed

- For comparison: in the $t\bar{t}Z$ case theory errors reduce by almost half

Broggio *et al.*, JHEP 08 (2019), 039



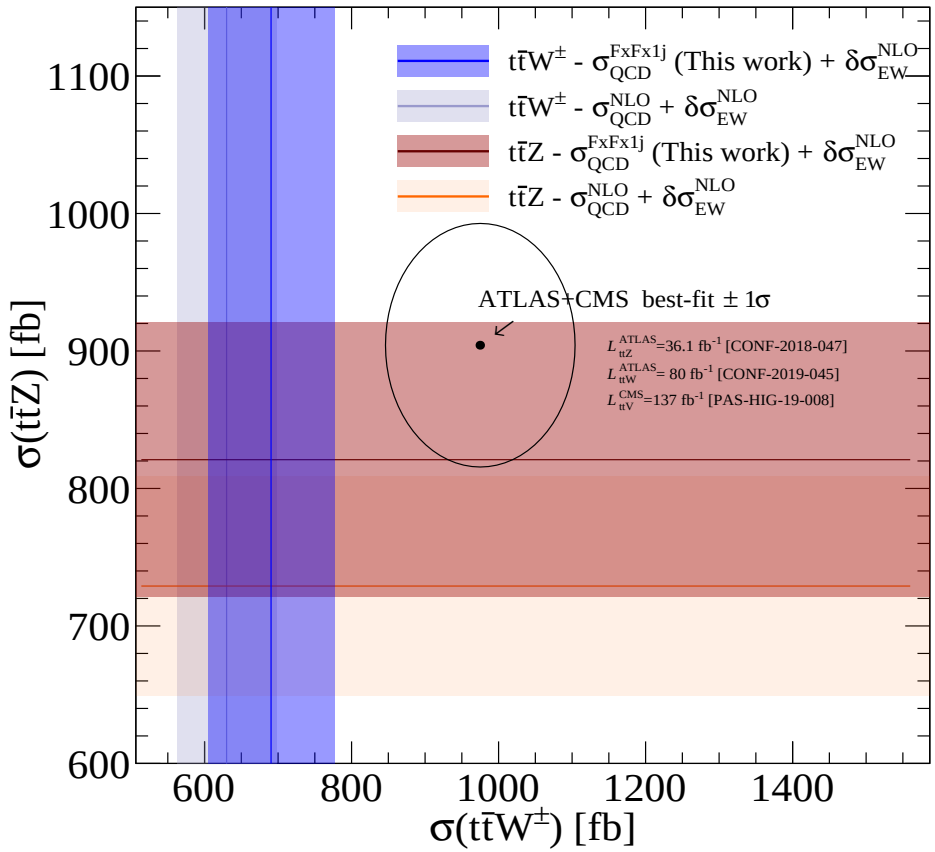
Inclusive $t\bar{t}W^{\pm}$: impact of multi-jet merging



FxFx NLO multi-jet matching

Frederix and Frixione '12

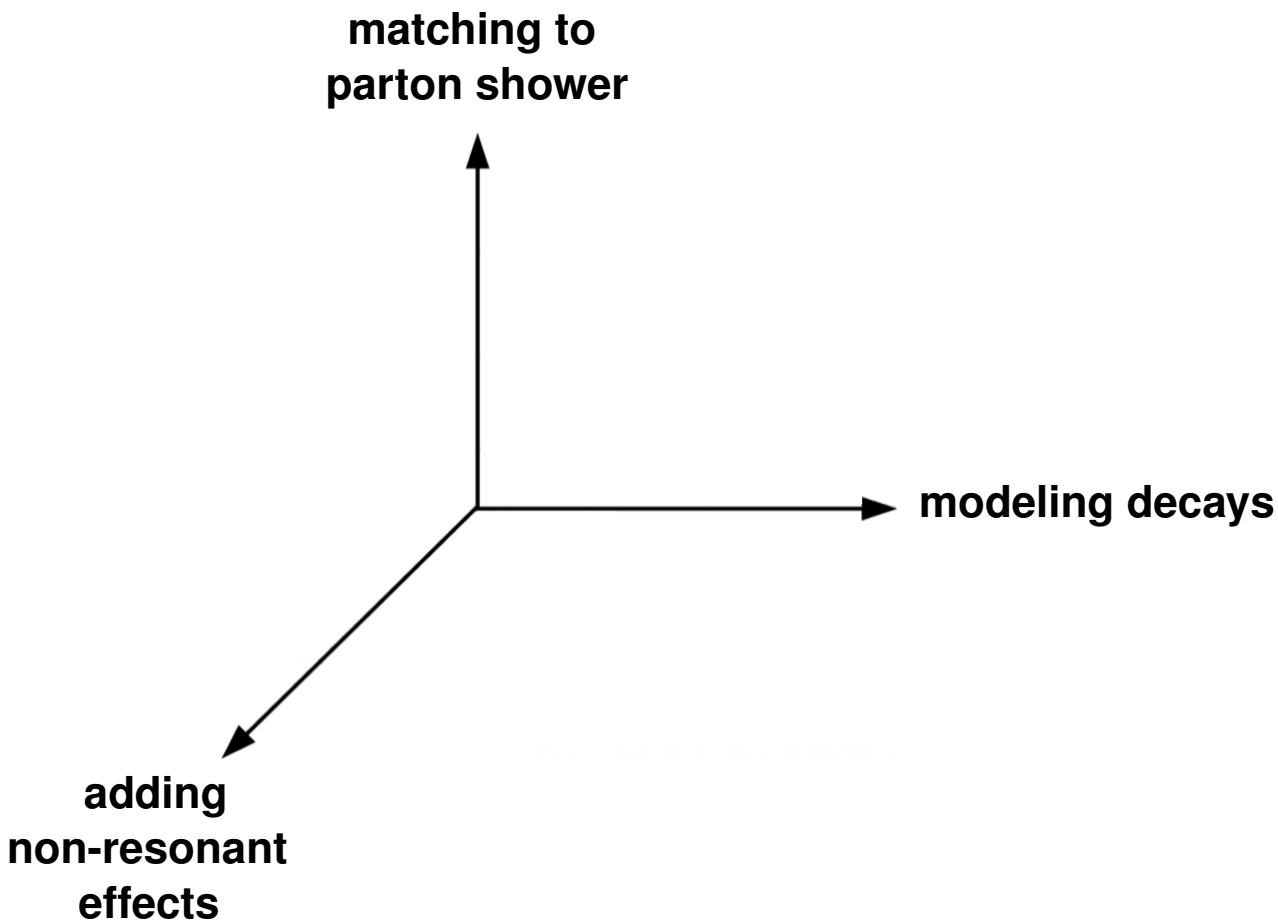
von Buddenbrock, Ruiz and Mellado, arXiv:2009.00032 [hep-ph]



- FxFx predictions enhance jet multiplicities slightly favoured by data but do not resolve the existing tension with LHC measurements

Towards realistic final states

For more exclusive analyses ($\rightarrow$ fiducial regions) one needs accurate modeling of fully decayed final states



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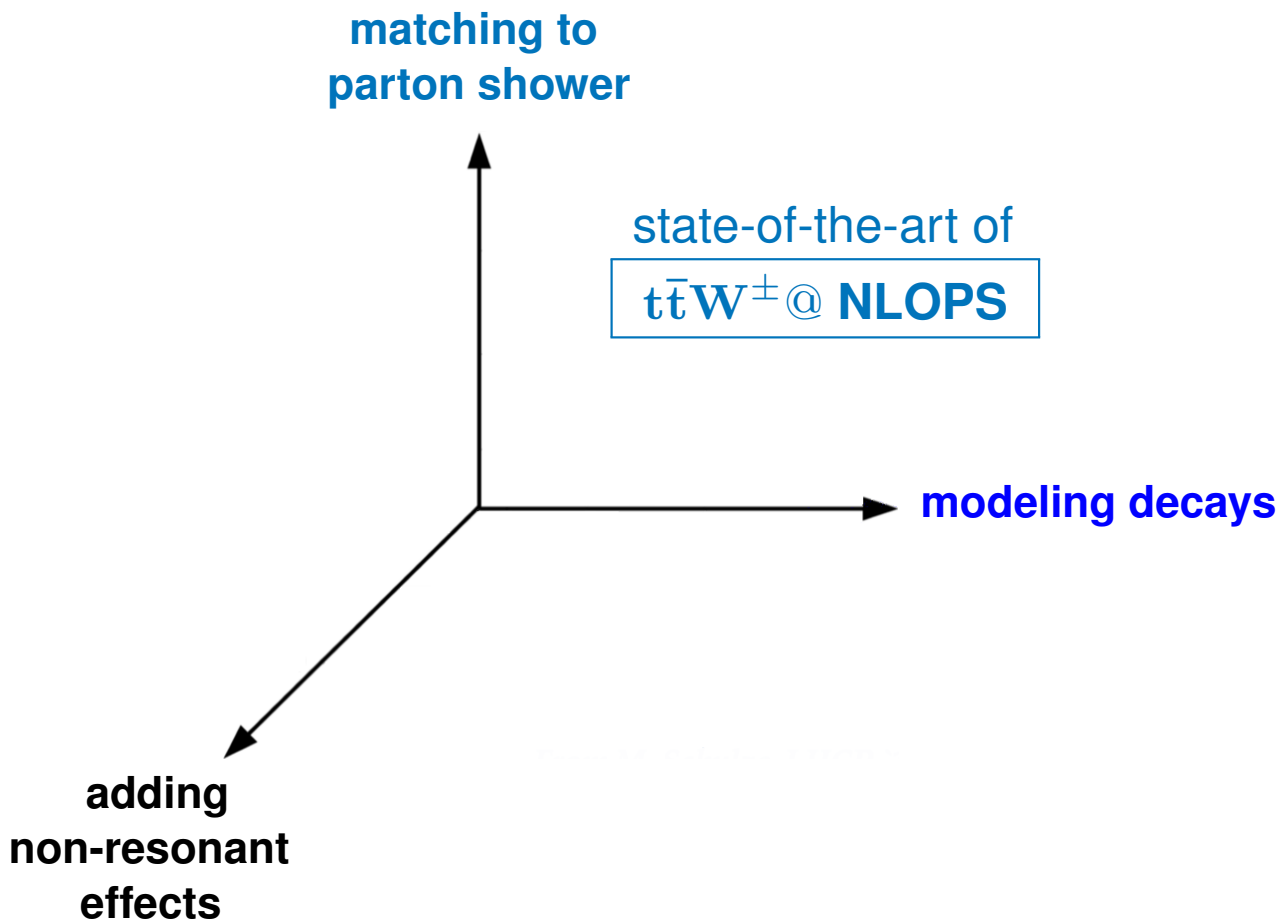

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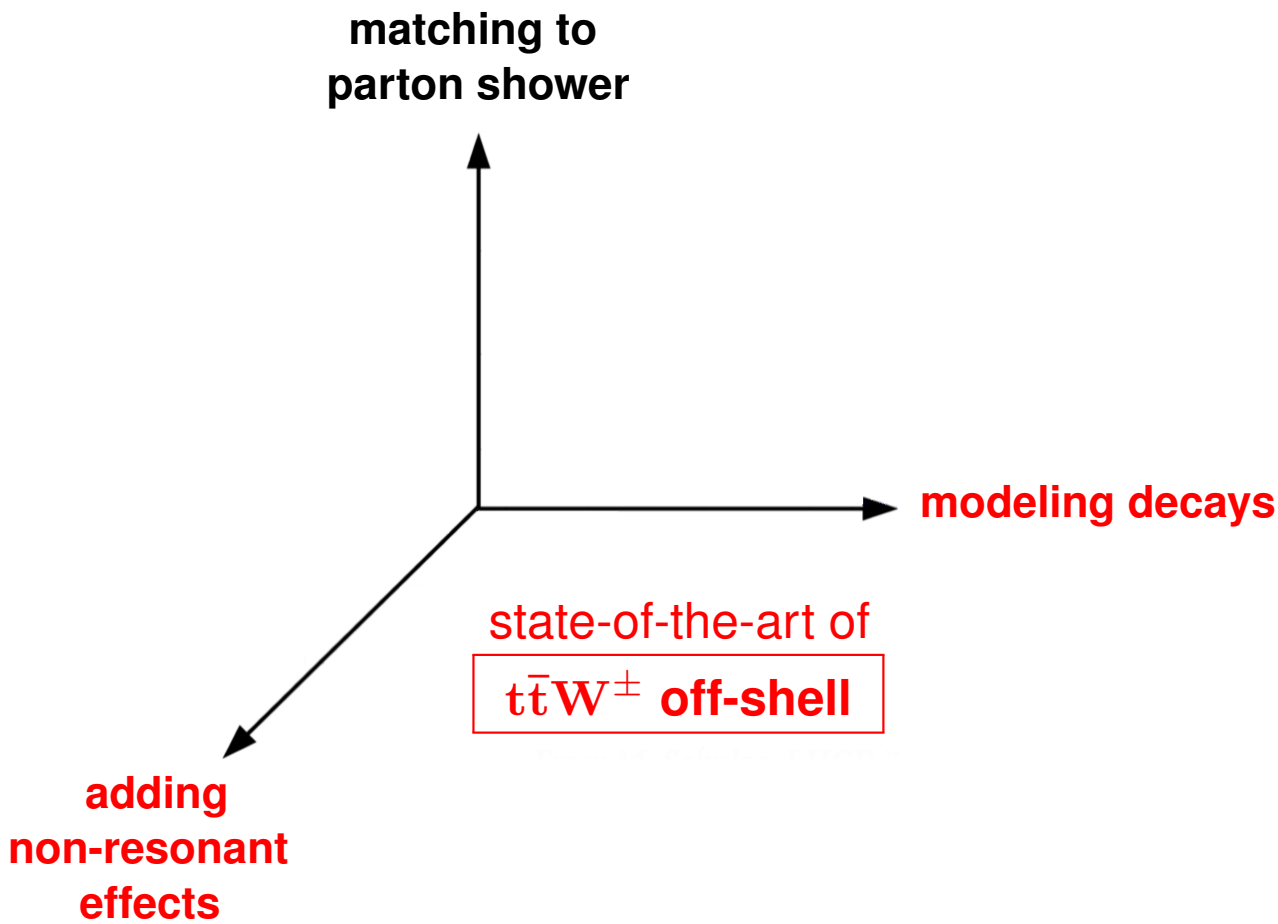

Towards realistic final states

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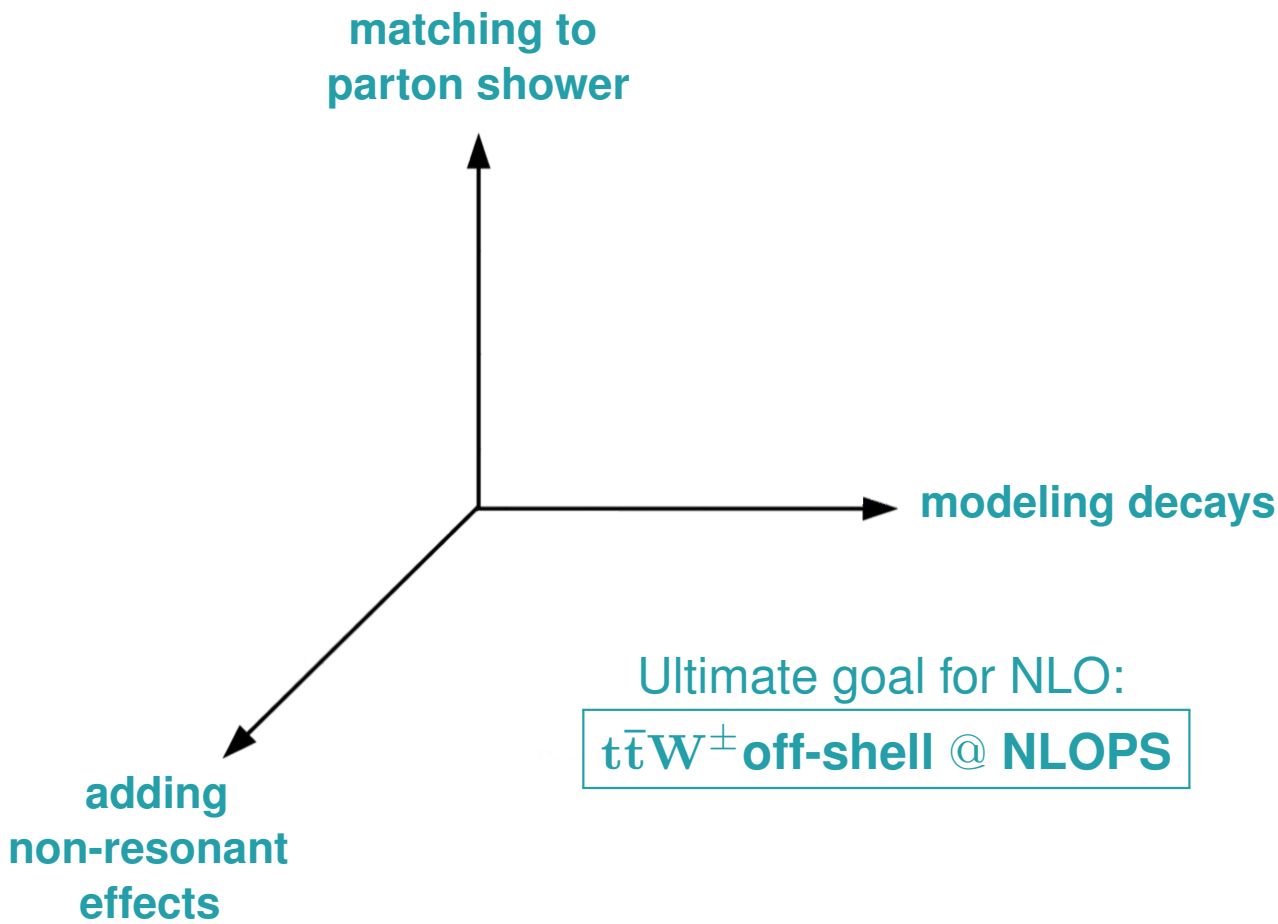


Ultimate goal for NLO:

$\mathrm{t\bar{t}W^{\pm}}$ **off-shell @ NLOPS**

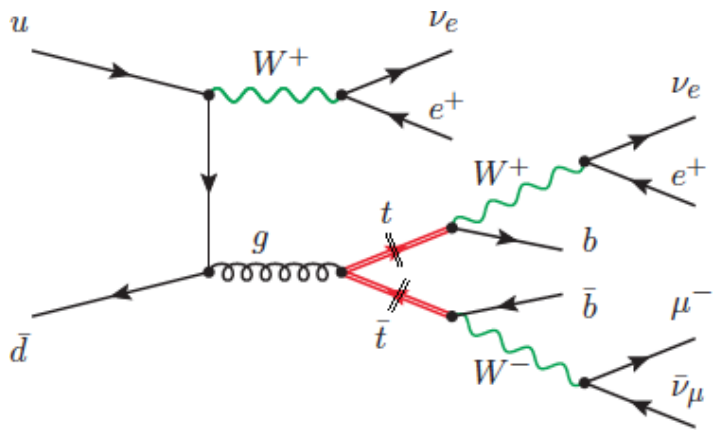
Modeling decays: Narrow Width Approximation

Based on the narrow-width limit:

$$\frac{1}{(p_t^2-m_t^2)^2+m_t^2\Gamma_t^2} \overset{\Gamma_t\to 0}{\sim} \frac{\pi}{m_t\Gamma_t}\,\delta(p_t^2-m^2)+\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

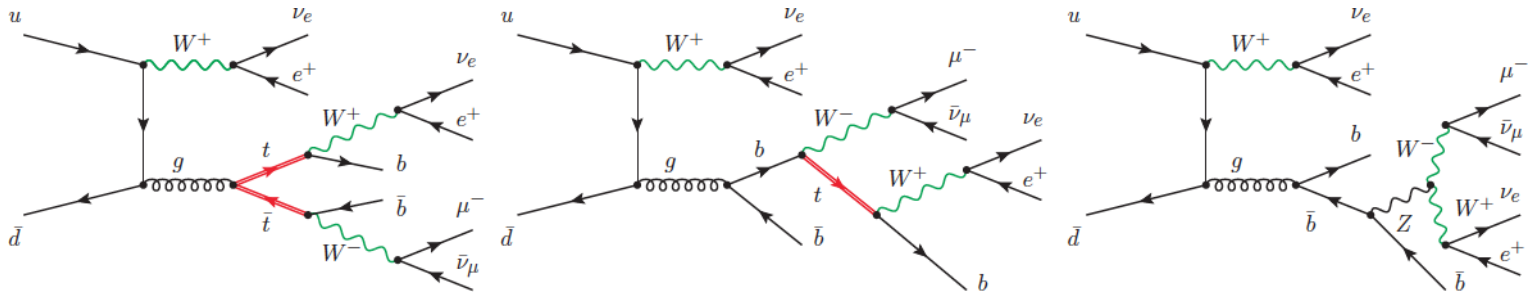
- cross section factorizes into on-shell $t\bar{t}W$ *production* $\otimes$ *decays*
  $\hookrightarrow$ keep only doubly-top-resonant diagrams
- non-factorizable contributions are suppressed by powers of $\Gamma_t/m_t = \mathcal{O}(1\%)$ for *sufficiently inclusive* observables
- QCD corrections apply to both production and decay subprocesses
  What's the impact of LO vs NLO decay modeling?

e.g. $t\bar{t}W^+$



Beyond Narrow Width Approximation

Representative Feynman diagrams for the case of $t\bar{t}W^+$:



Double-Resonant (DR) Single-Resonant (SR) Non-Resonant (NR)

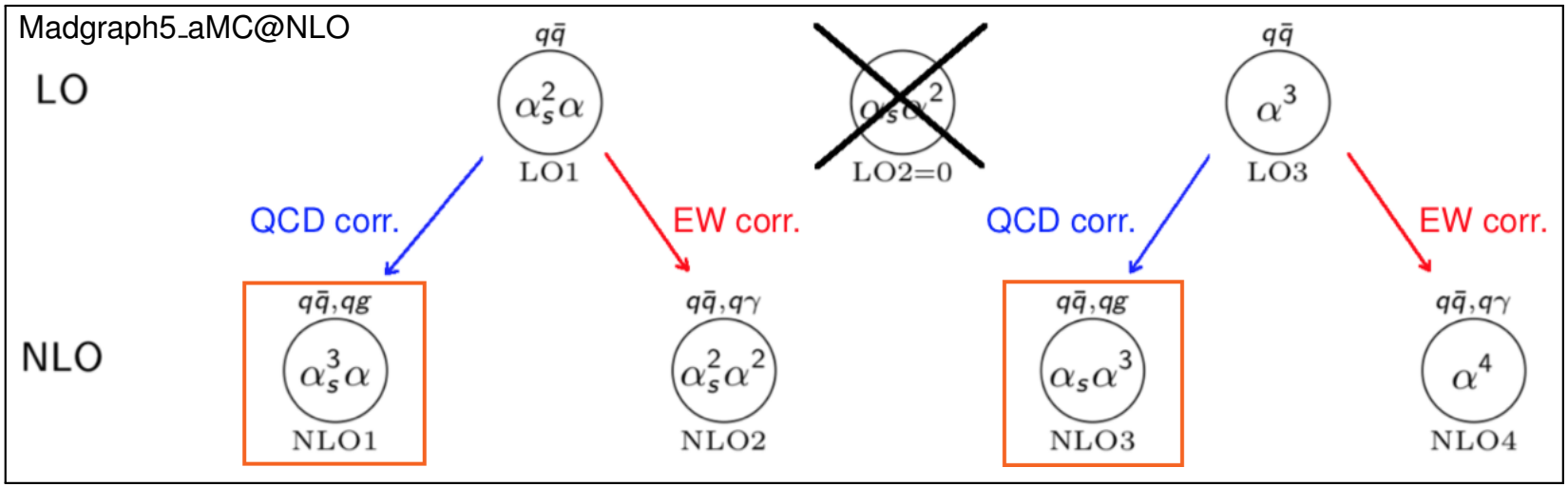
- all resonant and non-resonant contributions are taken into account
- most complete calculation of ME's at fixed perturbative order
- computationally demanding: $\mathcal{O}(10)$ increase in complexity w.r.t. NWA

"Off-shell effects" = finite-width effects for tops and W's
+ SR + NR contributions
+ interferences among DR, SR, NR

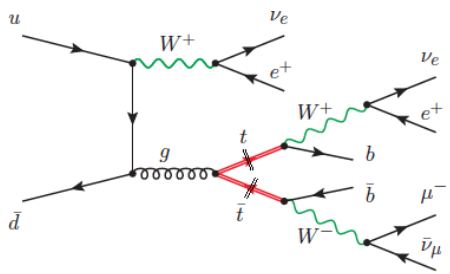
$t\bar{t}W^{\pm}$ with Parton Shower

Frederix and Tsinikos '20

- Production process modeled at NLO1+NLO3 accuracy



- Only Double-Resonant contributions in matrix elements

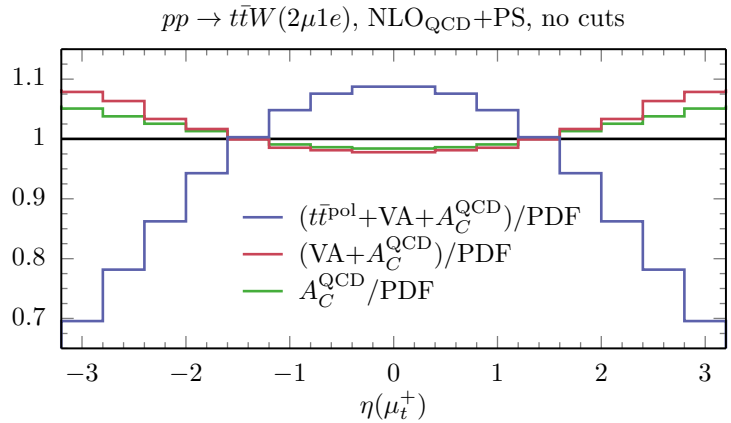


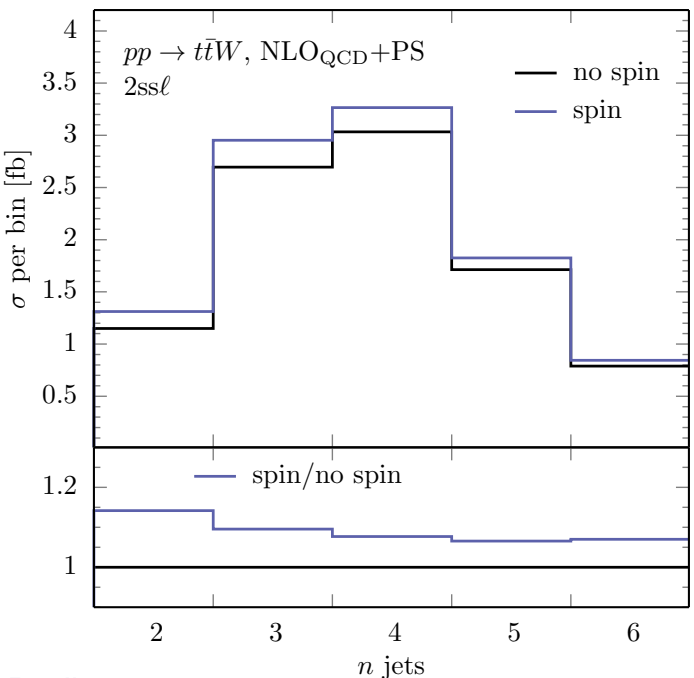
- Decays modeled at LO including spin correlations (MadSpin)

Artoisenet *et al.*, 1212.3460 [hep-ph]

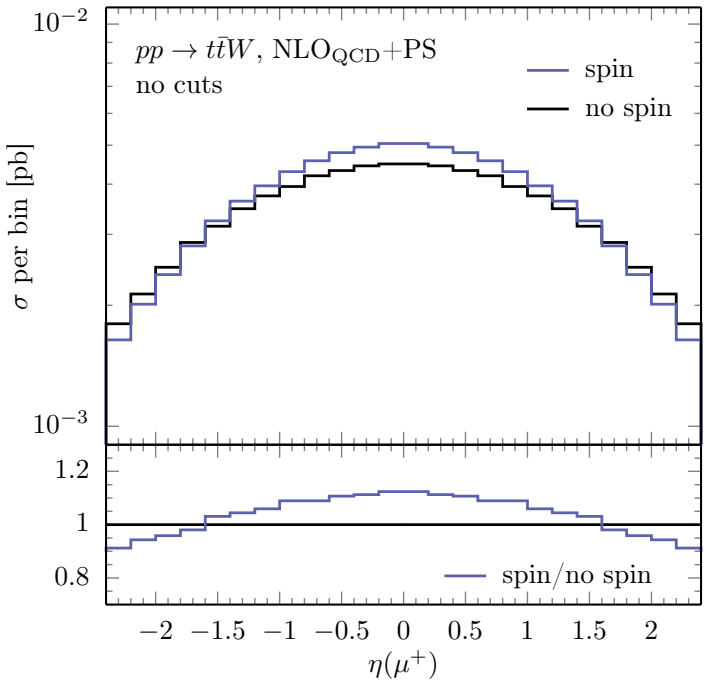
$t\bar{t}W^{\pm}$ with Parton Shower

Impact of spin correlations at differential level





Frederix and Tsinikos, Eur. Phys. J. C 80 (2020) no.9, 803



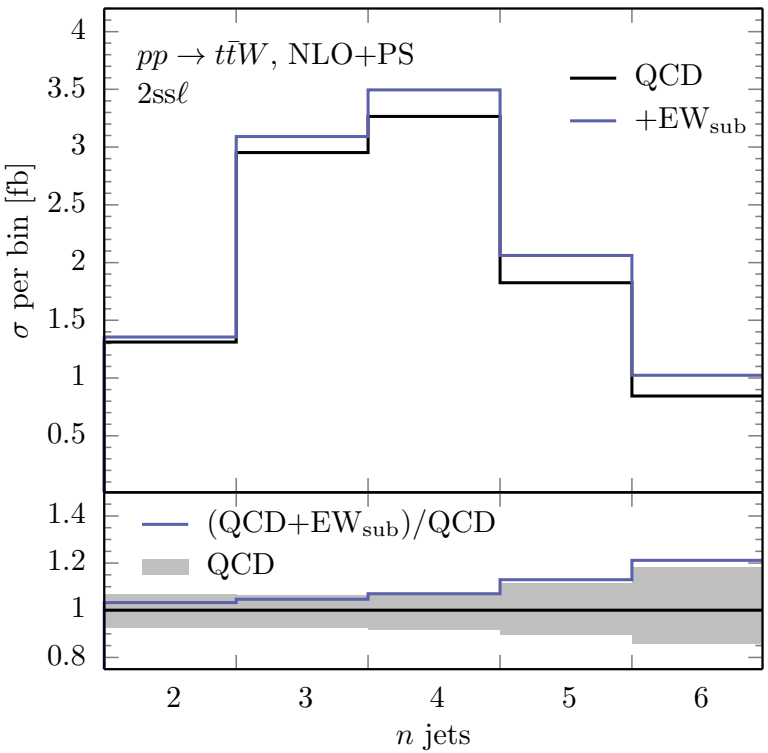
- Top-quark polarization signicantly impacts leptonic rapidities

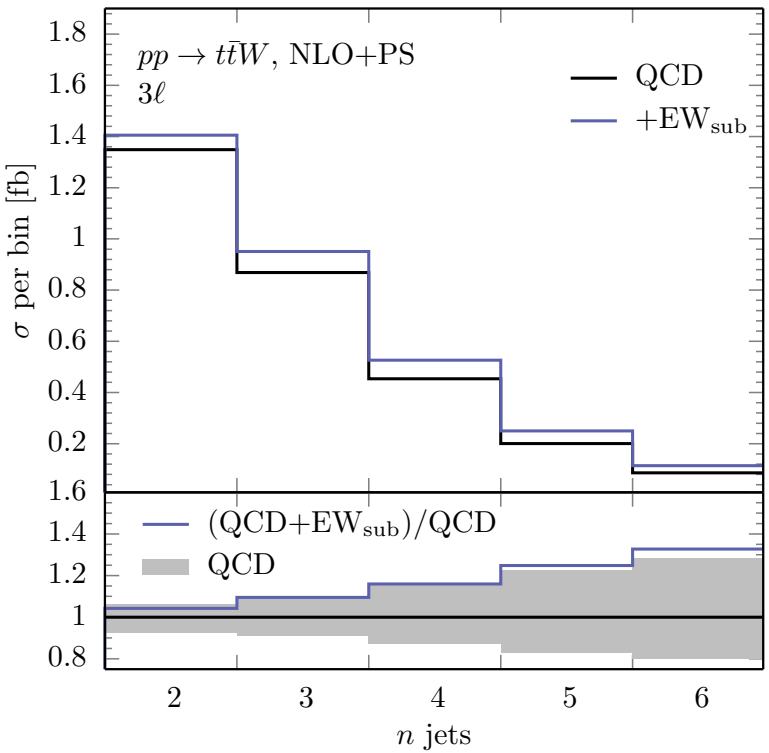
- Spin correlation effects enhance more low-jet multiplicities

$t\bar{t}W^{\pm}$ with Parton Shower

Impact of EW_{sub} corrections on jet multiplicities

Frederix and Tsinikos, Eur. Phys. J. C 80 (2020) no.9, 803



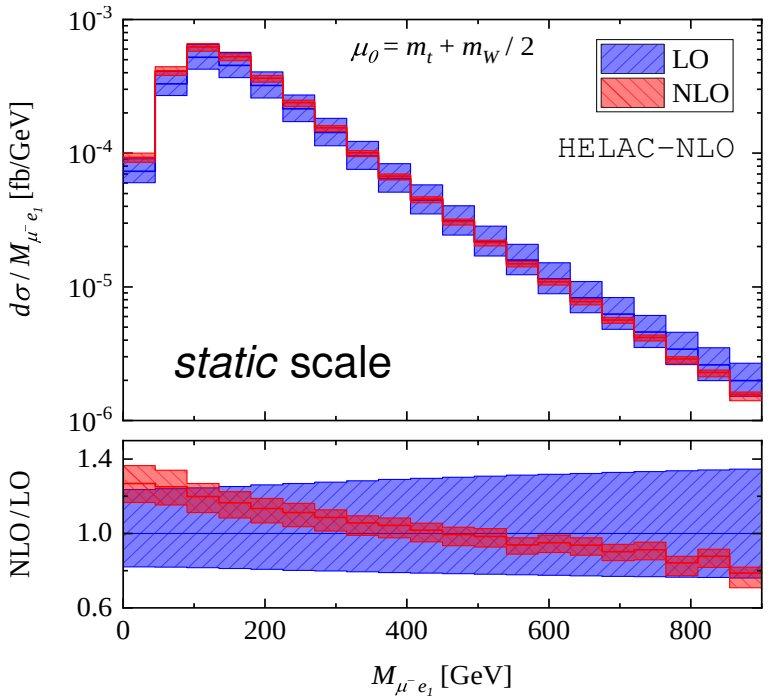


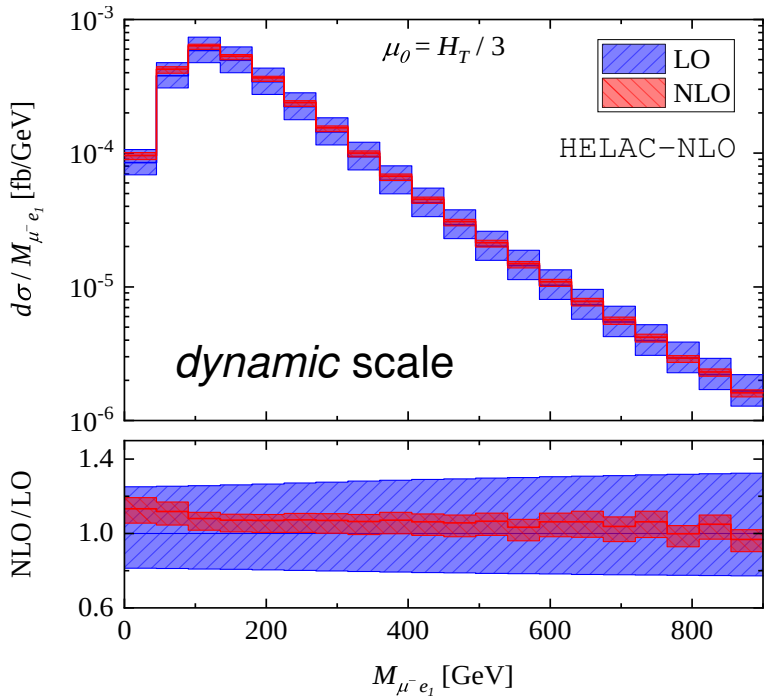
- EW_{sub} contributions enhance more larger jet multiplicities $\rightarrow$ non-flat K factor

$t\bar{t}W^{\pm}$ with off-shell effects

$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, e^+\nu_e\, b\bar{b} + X$ @ 13 TeV

G.B, Bi, Hartanto, Kraus and Worek, JHEP 08 (2020), 043





PDF	$p_T(j_b)$	$\sigma^{\rm LO}$ [ab]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [ab]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\sigma^{\rm NLO}/\sigma^{\rm LO}$
CT14	25	111.7	$^{+29.3\ (26\%)}_{-21.6\ (19\%)}$	124.1	$^{+3.9\ (3\%)}_{-7.5\ (6\%)}$	$^{+3.0\ (2\%)}_{-3.5\ (3\%)}$	1.11
MMHT14	25	110.0	$^{+29.6\ (27\%)}_{-21.7\ (20\%)}$	124.3	$^{+3.9\ (3\%)}_{-7.4\ (6\%)}$	$^{+2.7\ (2\%)}_{-2.4\ (2\%)}$	1.13
NNPDF3.0	25	115.1	$^{+30.5\ (26\%)}_{-22.5\ (20\%)}$	124.4	$^{+4.3\ (3\%)}_{-7.7\ (6\%)}$	$^{+2.1\ (2\%)}_{-2.1\ (2\%)}$	1.08

- Dynamical scale $H_T/3$ helps stabilizing pert. convergence

$$H_T = \sum_{i,vis} p_{T,i} + \not{p}_T$$

- Scale uncertainties $\sim \mathbf{6}\%$
- PDF uncertainties $\sim \mathbf{2\text{-}3}\%$

$t\bar{t}W^{\pm}$ with off-shell effects

$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, e^+\nu_e\, b\bar{b} + X$ @ 13 TeV

G.B, Bi, Hartanto, Kraus and Worek, JHEP 08 (2020), 043

Impact of top-quark decay modeling on integrated cross sections

Modelling Approach	$\sigma^{\rm LO}$ [ab]	$\sigma^{\rm NLO}$ [ab]
full off-shell ($\mu_0 = m_t + m_W/2$)	$106.9\,^{+27.7\,(26\%)}_{-20.5\,(19\%)}$	$123.2\,^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
full off-shell ($\mu_0 = H_T/3$)	$115.1\,^{+30.5\,(26\%)}_{-22.5\,(20\%)}$	$124.4\,^{+4.3\,(3\%)}_{-7.7\,(6\%)}$
NWA ($\mu_0 = m_t + m_W/2$)	$106.4\,^{+27.5\,(26\%)}_{-20.3\,(19\%)}$	$123.0\,^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
NWA ($\mu_0 = H_T/3$)	$115.1\,^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2\,^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = m_t + m_W/2$)		$127.0\,^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = H_T/3$)		$130.7\,^{+13.6\,(10\%)}_{-13.2\,(10\%)}$

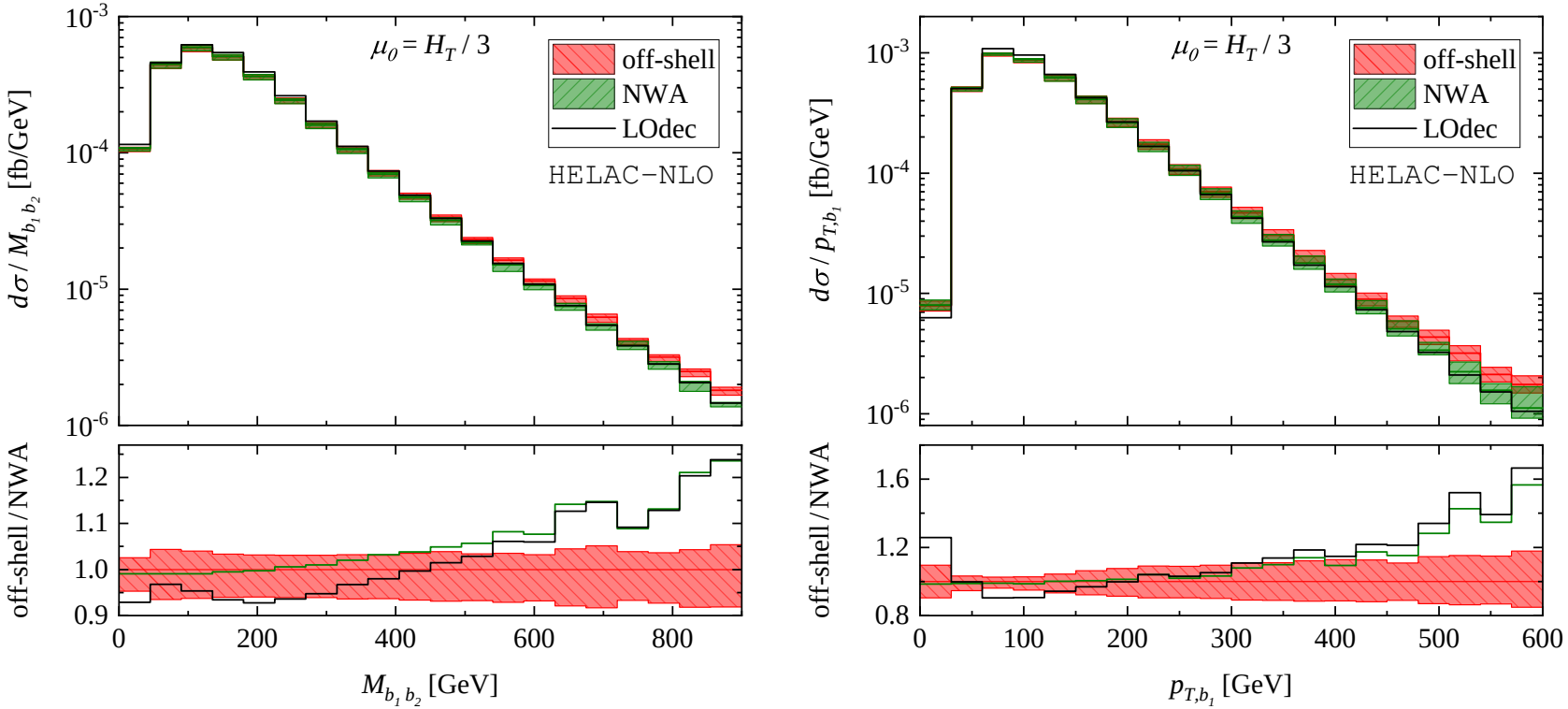
- The full NWA result approximates very well the complete NLO calculation
- Predictions based on LO decays ($\text{NWA}_{\text{LOdecay}}$) have larger scale uncertainties

$t\bar{t}W^{\pm}$ with off-shell effects

$pp \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, e^+\nu_e\, b\bar{b} + X$ @ 13 TeV

G.B, Bi, Hartanto, Kraus and Worek, JHEP 08 (2020), 043

Impact of top-quark decay modeling at the differential level



- Off-shell effects increase up to $\mathbf{30\text{-}50}\%$ in tails, well above scale uncertainties
- Full NWA and $\text{NWA}_{\text{LOdecay}}$ differ even in the bulk of distributions

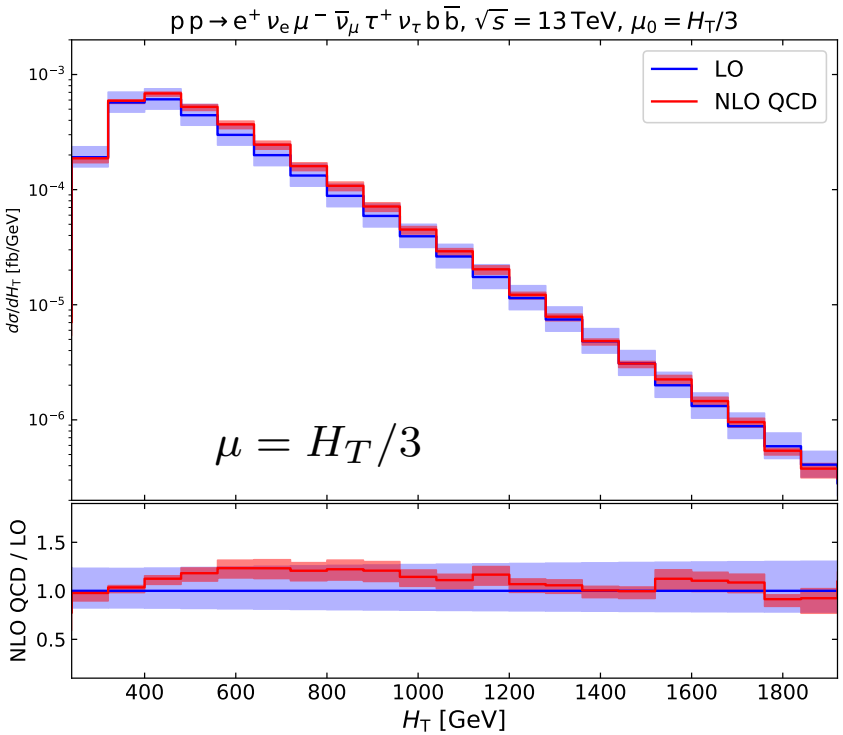
$t\bar{t}W^{\pm}$ with off-shell effects

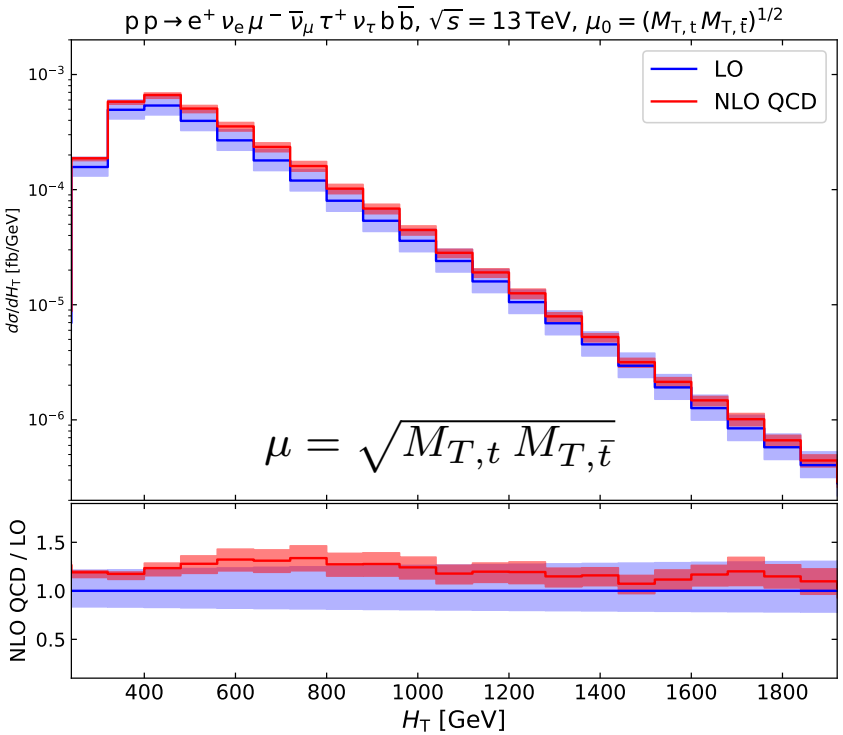
→ see poster by G. Pelliccioli

$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau\,b\bar{b} + X$ @ 13 TeV

Denner and Pelliccioli, arXiv:2007.12089 [hep-ph]

Comparison of different dynamical scale definitions





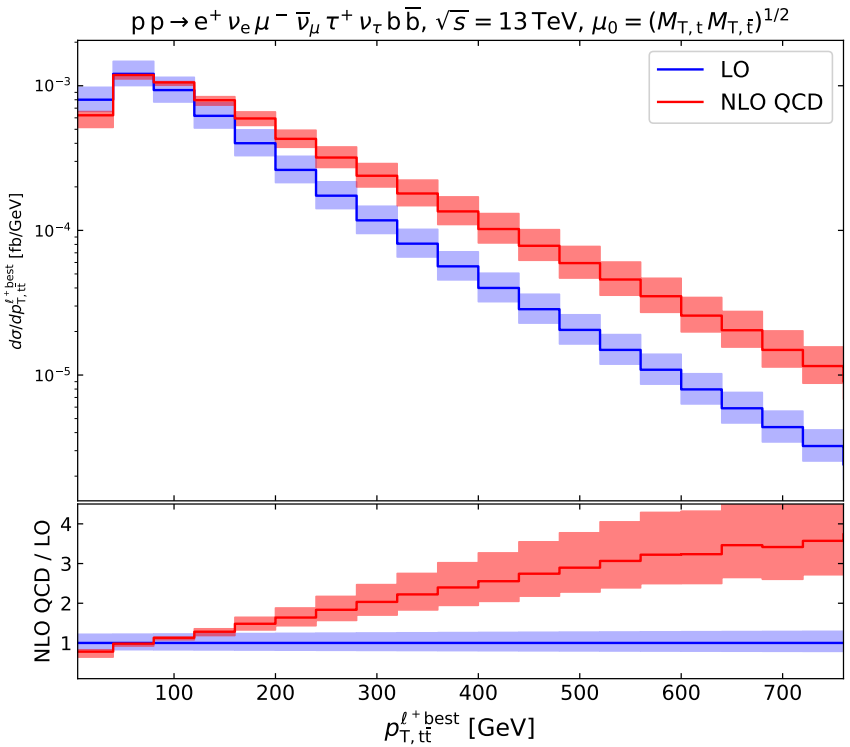
- Alternative scale based on transverse mass of reconstructed t and $\bar{t}$ momenta
- "Resonance-aware" (M_T) and "resonance-blind" (H_T) scales in equally good shape

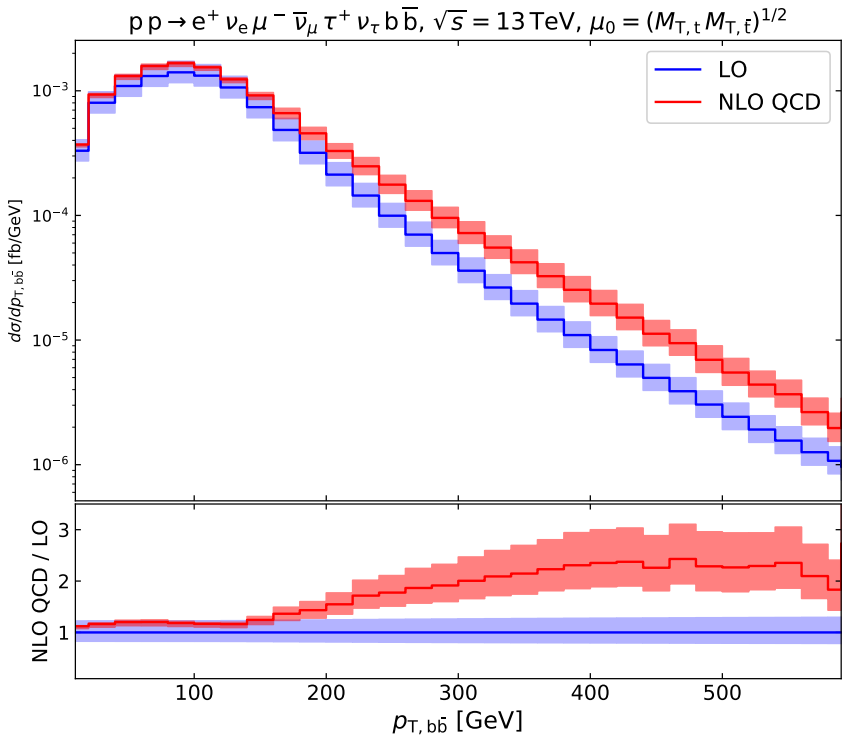
$t\bar{t}W^{\pm}$ with off-shell effects

$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau\,b\bar{b} + X$ @ 13 TeV

Denner and Pelliccioli, arXiv:2007.12089 [hep-ph]

Differential cross sections with large K-factors





$t\bar{t}$ recoils against W + additional light jet at NLO: large real-radiation contribution

$\hookrightarrow$ large QCD corrections + large scale uncertainties (LO-accurate)

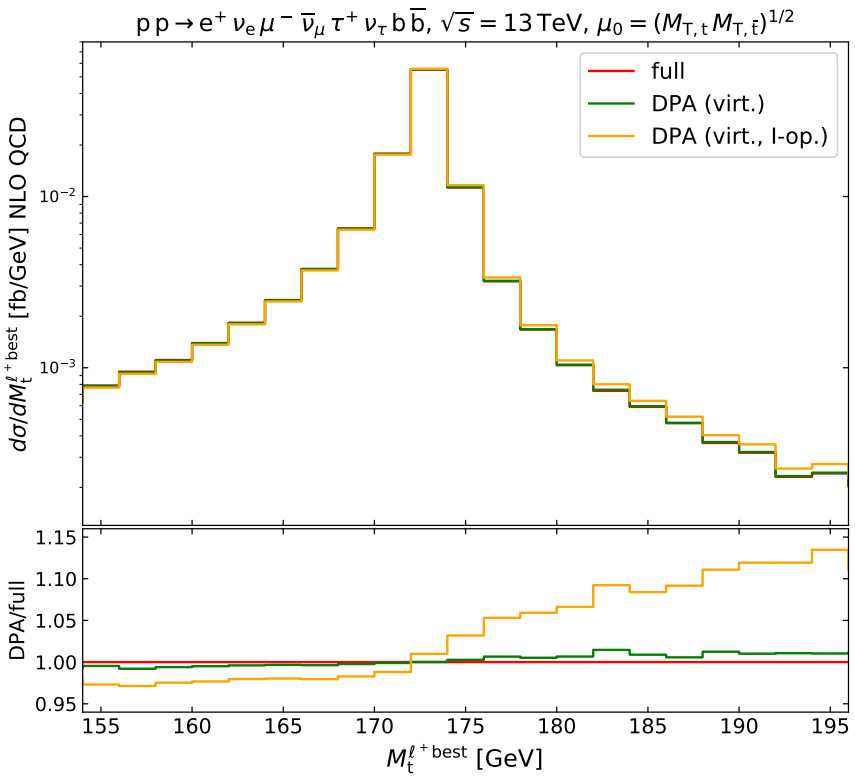
$t\bar{t}W^{\pm}$ with off-shell effects

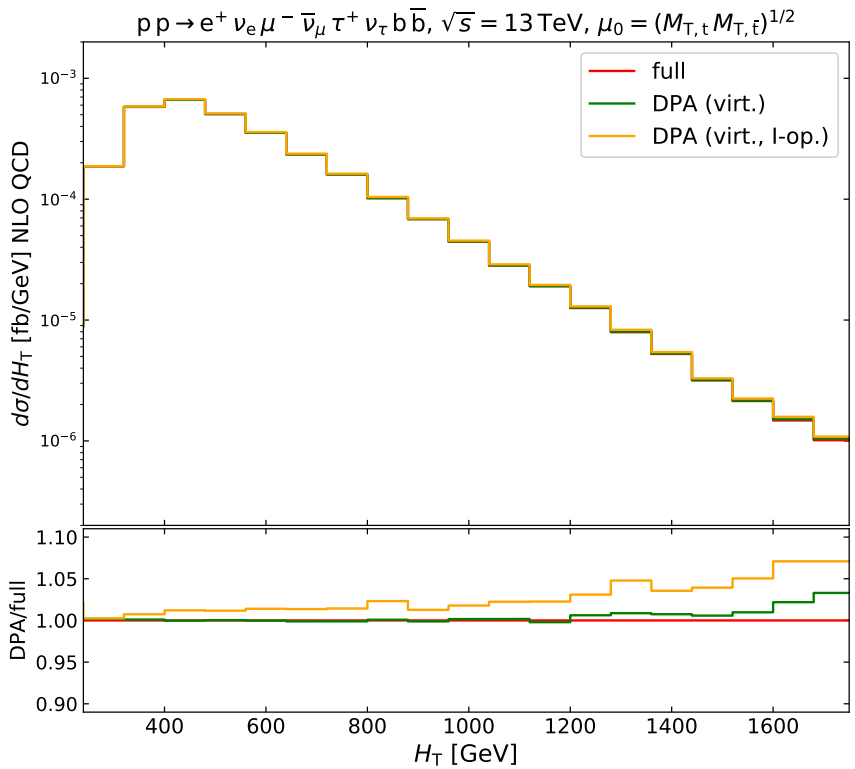
$pp \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,\tau^+\nu_\tau\,b\bar{b} + X$ @ 13 TeV

Denner and Pelliccioli, arXiv:2007.12089 [hep-ph]

Comparison with Double Pole Approximation

$\hookrightarrow$ DPA applied to virt. contributions only or to virt. + α_{dipole}-independent part of I-op.





$$\sigma^{\text{full}}_{\text{NLO}} = 0.2394(6)\,\text{fb}\,, \qquad \sigma^{\text{DPA,V}}_{\text{NLO}} = 0.2395(7)\,\text{fb}\,, \qquad \sigma^{\text{DPA,V+I}}_{\text{NLO}} = 0.2422(7)$$

Conclusions

Many improvements in the calculation of both $t\bar{t}W$ production rates and exclusive predictions this year!

State-of-the-art accuracy for the modeling of $t\bar{t}W$ final states is NLO:

- FO level: NLO_{QCD} with off-shell effects
- PS level: $\text{NLO}_{\text{QCD+EW}_{sub}}$ with on-shell, spin-correlated decays

Outlook

- NNLO QCD is an important perspective goal
  $\hookrightarrow$ still out of reach
- off-shell effects for $t\bar{t}W^{\pm}$ in the lepton+jets channel
  $\hookrightarrow$ technically feasible with currently available tools
- NLO+PS with complete NLO accuracy
  $\hookrightarrow$ requires to incorporate EW effects in PS
- interface off-shell calculations with PS
  $\hookrightarrow$ highly challenging from the CPU viewpoint