Comparison of theory predictions for $t\bar{t}W$ in the 3ℓ channel

Manfred Kraus
G. Bevilacqua, H. Y. Bi, F. Febres Cordero, H. B. Hartanto, J. Nasufi, L. Reina, M. Worek

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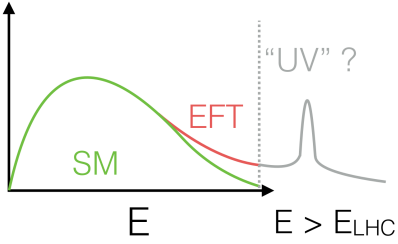
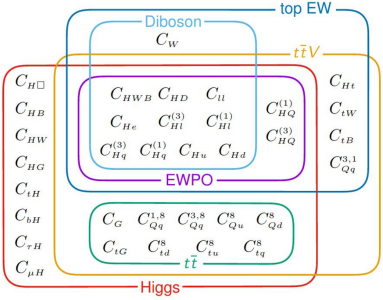
The Quest for New Physics

- The LHC has entered the Precision Era
- Search for New Physics via SM effective field theory

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\mathscr{L}_5 + \frac{1}{\Lambda^2}\mathscr{L}_6 + \frac{1}{\Lambda^3}\mathscr{L}_7 + \frac{1}{\Lambda^4}\mathscr{L}_8 + \cdots$$



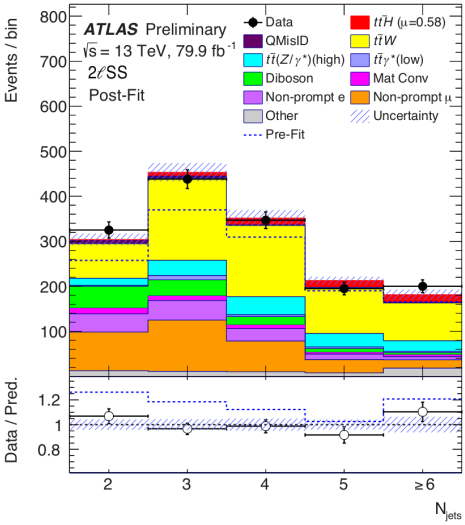
[K. Mimasu TOP2021]

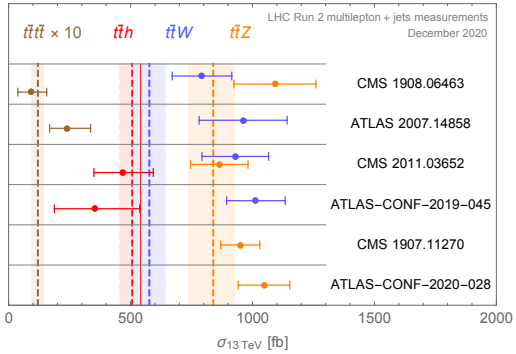


[N. Castro Snowmass Workshop]

- Needs precise predictions for the SM: new physics vs QCD

Experimental status of $t\bar{t}X$ measurements



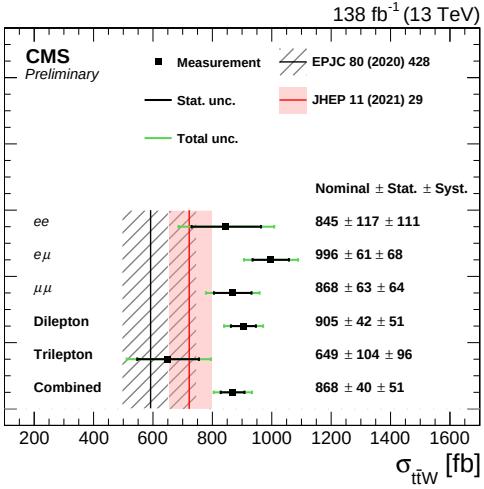


[Banelli et al, JHEP 02 (2021) 043]

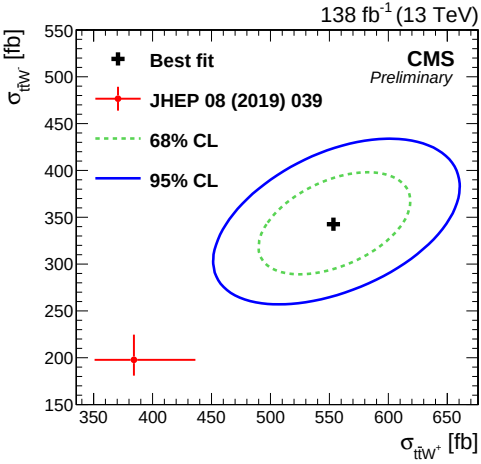
ATLAS-CONF-2019-045

- Largest discrepancies for $t\bar{t}W$ in multi-lepton signatures
- Disrepancies: New Physics or QCD?
- How well is the modeling of $t\bar{t}W$ signatures?

Experimental status of $t\bar{t}X$ measurements



[CMS-PAS-TOP-21-011]



- Recent $t\bar{t}W$ measurement: [CMS '21]
- Previous tension reduced by multi-jet merging [Frederix and Tsinikos '21]
- Overall tension remains: 2σ – level

Theory status

NLO fixed order

- NLO QCD + EW: inclusive production [Hirschi et al'11, Maltoni et al'15]

→ stable top-quarks [Frixione et al'15, Frederix et al'17]

- NLO QCD: on-shell decay × production [Campbell and Ellis'12]

→ QCD corrections to production and decy, spin correlations

- NLO QCD + EW: complete off-shell

→ (non-) resonant diagrams, finite width-effects

[Bevilacqua, Bi, Hartanto, MK, (Nasufi), Worek'20 ('21)]

[Denner and Pellicciolí'20] [Denner and Pellicciolí'21]

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek'21]

NLO + resummation

-NLO+NNLL QCD + EW: inclusive production [Li et al'14, Broggio et al'16]

→ stable top-quarks [Broggio et al'19, Kulesza et al'18'20]

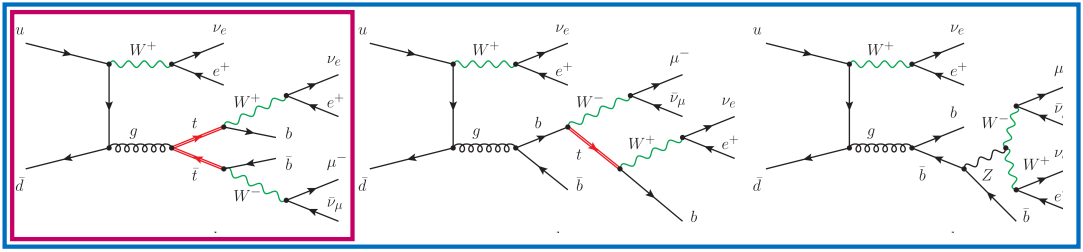
NLO + parton shower

- NLO+PS QCD + EW: on-shell [Garzelli et al'12, Maltoni et al'14'15]

→ top decays at LO [Frederix and Tsinikos'20] [Febres Cordero, MK, Reina'21]

- Multi-jet merging [von Buddenbrock et al'20, ATLAS'20] [Frederix and Tsinikos'21]

Beyond stable tops



Narrow-Width-Approximation (NWA):

- on-shell propagators

$$\frac{1}{(p^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \rightarrow \frac{\pi}{m_t\Gamma_t}\delta(p^2 - m_t^2)$$

- only double resonant contributions
- Factorization: Production $\otimes$ decay

Full off-shell:

- Breit-Wigner propagators
- All double, single and non-resonant contributions
- Non-factorizable contributions
- Interferences

Modeling of multi-lepton signatures

How to model leptonic final states?

$$pp \to b\bar{b}\ell^{\pm}\nu_{\ell}\ell^{\pm}\nu_{\ell}\ell^{\pm}\nu_{\ell}$$

fixed-order

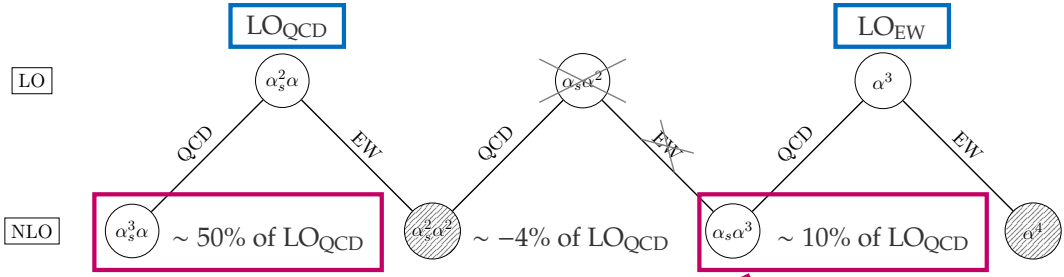
- top decay at NLO
- spin correlations
- double, single and non-resonant contributions or NWA
- only one extra parton

parton showers

- Additional radiation
- Hadronization
- More flexiable
- NLO only for production
- LO spin correlations

How compatible are the different descriptions?

Inclusive cross sections



	$\sigma^{\rm NLO\ QCD}$	$t\bar{t}W$ QCD	$t\bar{t}W$ EW
fixed-order	full off-shell	$1.58^{+3\%}_{-6\%}$	$0.206^{+22\%}_{-17\%}$
fixed-order	full NWA	$1.57^{+3\%}_{-6\%}$	$0.190^{+22\%}_{-16\%}$
fixed-order	NWA with LO decays	$1.66^{+10\%}_{-10\%}$	$0.162^{+22\%}_{-16\%}$
NLOPS	Powheg Box	$1.40^{+11\%}_{-11\%}$	$0.133^{+21\%}_{-16\%}$
NLOPS	MG5	$1.40^{+11\%}_{-11\%}$	$0.136^{+21\%}_{-16\%}$

- $t\bar{t}W$ EW ~ 13% of $t\bar{t}W$ QCD
- 9% off-shell effects for $t\bar{t}W$ EW
  Expected: $\Gamma_t/m_t \sim 0.8\%$
- $t\bar{t}W$ QCD uncertainty dependend on decay modelling
- $t\bar{t}W$ EW uncertainty LO like
- NLO+PS cross sections smaller due to radiation in decays (11 – 34%)

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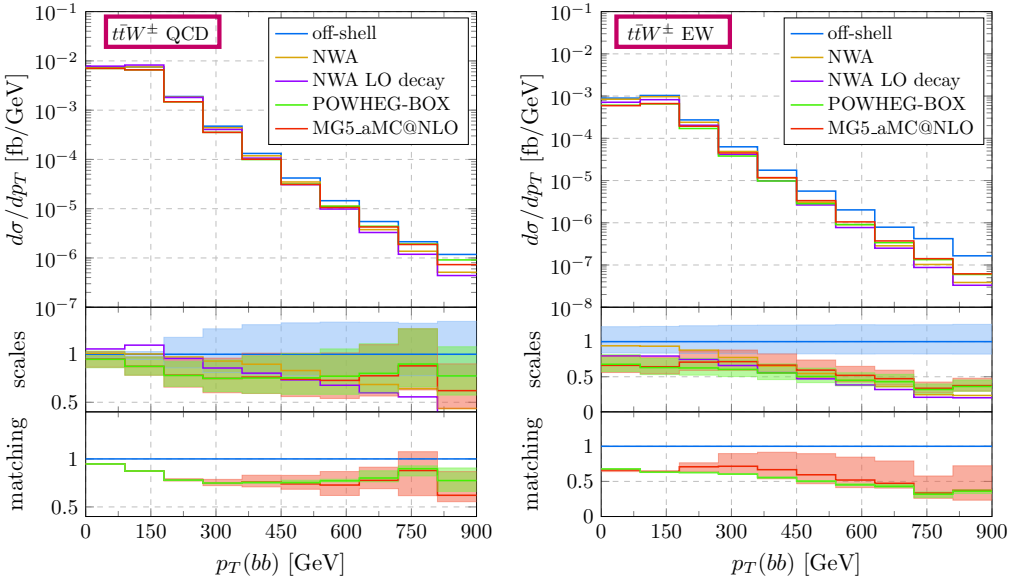
Differential distributions



- off-shell has harder spectrum → single resonant contributions
- NLO+PS are in good agreement
- $t\bar{t}W$ EW shows larger modelling dependence
- Matching uncertainties can dominate

Improving NLOPS predictions

Idea: Complement NLOPS results with off-shell effects

$$\frac{d\sigma^{\text{th}}}{dX} = \frac{d\sigma^{\text{NLOPS}}}{dX} + \frac{d\Delta\sigma_{\text{off-shell}}}{dX}$$

Problem: Double counting of double resonant contributions

Solution:

$$\frac{d\Delta\sigma_{\text{off-shell}}}{dX} = \frac{d\sigma^{\text{NLO}}_{\text{off-shell}}}{dX} - \frac{d\sigma^{\text{NLO}}_{\text{NWA}}}{dX}$$

	$t\bar{t}W$ QCD+EW
full off-shell	$1.79^{+6\%}_{-7\%}$
NLOPS	$1.53^{+12\%}_{-11\%}$
NLOPS+$\Delta\sigma$	$1.56^{+13\%}_{-13\%}$

- $\Delta\sigma$ contains single and non-resonant contributions, interferences and NLO QCD decays
- Enhanced NLOPS results by 2%
- Theory uncertainty of NLOPS mostly unchanged

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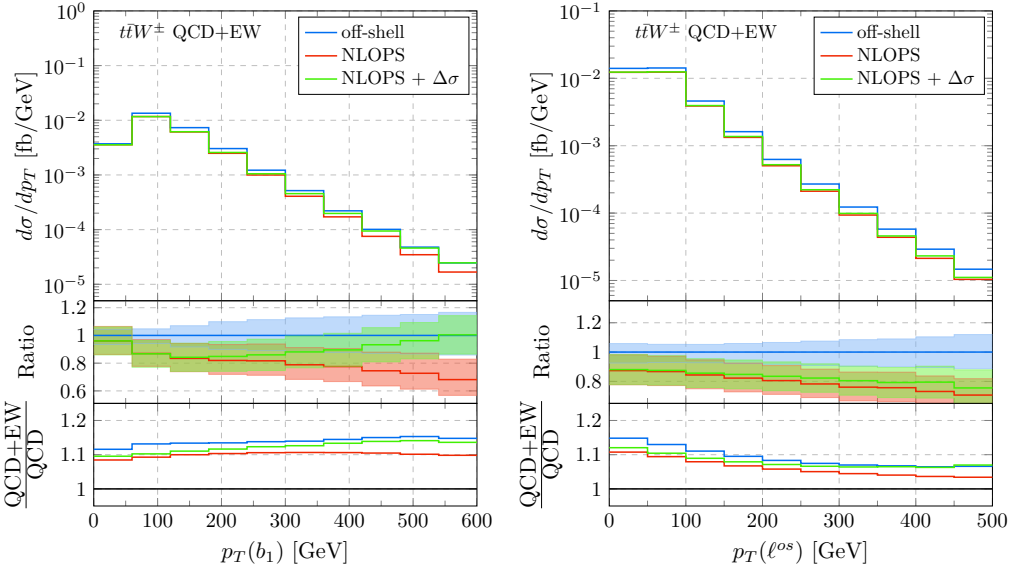
Differential NLOPS+$\Delta\sigma$



- impact on hadronic observables larger than on leptonic ones
- EW contribution receives large corrections

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Conclusions

Phenomenology of $pp \to t\bar{t}W$ at the LHC

- Much progress has been made in recent months
- We studied modelling of $t\bar{t}W$ in the 3 lepton signature using
  - NLO fixed-order
  - NLO matched to parton showers
- Fiducial signature described differently
  - Full off-shell results have most impact at high p_T
  - parton shower affects shapes over a broader range
- We proposed a simple combination:

$$\frac{d\sigma^{\text{th}}}{dX} = \frac{d\sigma^{\text{NLOPS}}}{dX} + \frac{d\Delta\sigma_{\text{off-shell}}}{dX}$$

Where do we go from here?

- In the long run we will need:
  - full off-shell $pp \to t\bar{t}W$ @ NLO+PS
  - Higher-order corrections for hadronic decays
  - Even higher-order corrections: $pp \to t\bar{t}W$ @ NNLO