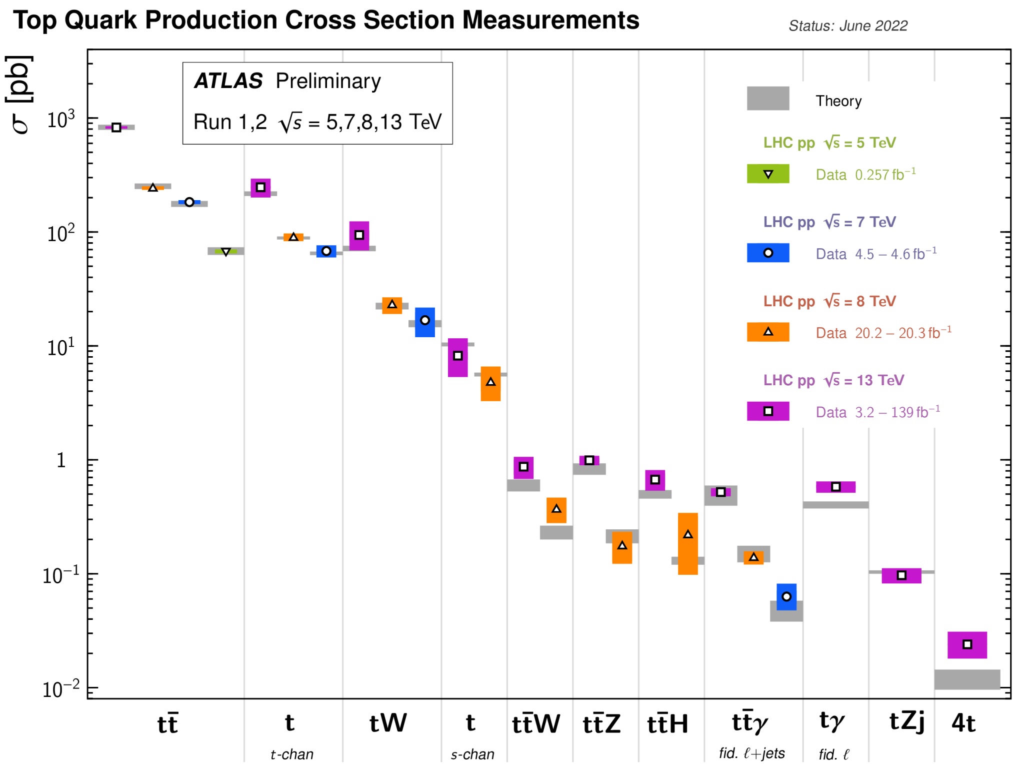
Theory advances for $t\bar{t}W^{\pm}$ multi-lepton predictions

Manfred Kraus

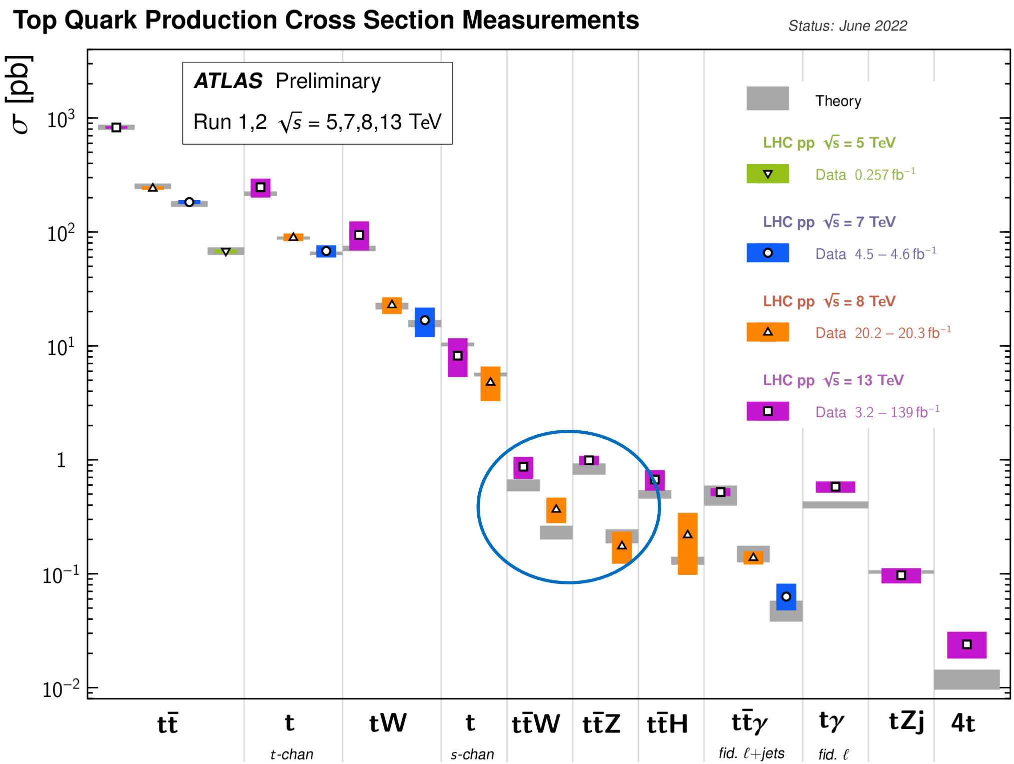
TOP 2022, University of Durham
5. September 2022

Introduction

Precision era at the LHC



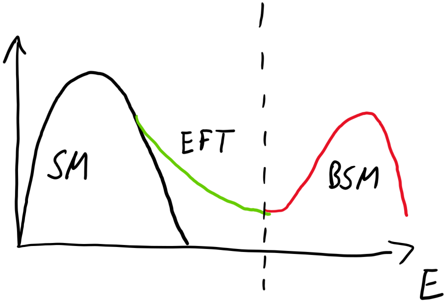
Precision era at the LHC

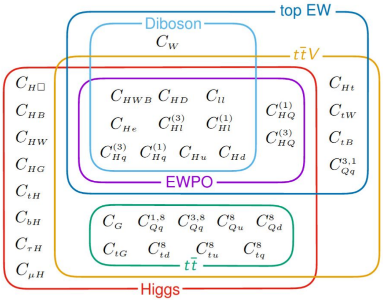


New Physics or just more QCD?

Search for New Physics via SM effective field theory

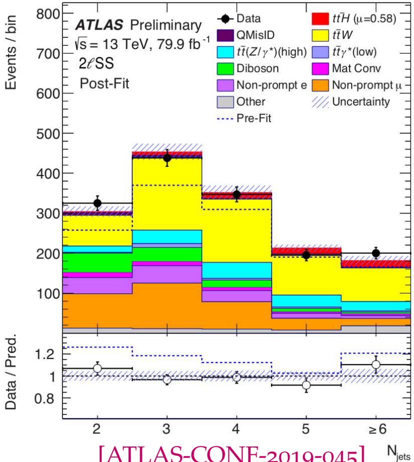
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \sum \frac{c_i}{\Lambda^2} O_i^{d=6} + \sum \frac{c_i}{\Lambda^4} O_i^{d=8} + \cdots$$



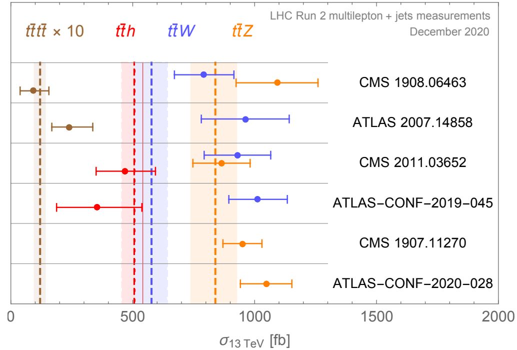


Needs precise predictions for the SM: **New Physics** vs **QCD**

Experimental status of $t\bar{t}W$ measurements – 2020



[ATLAS-CONF-2019-045]



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

Normalisation factors:

$$\lambda_{t\bar{t}W}^{2ss\ell} = 1.56 \pm 0.3\ , \qquad \lambda_{t\bar{t}W}^{3\ell} = 1.68 \pm 0.3$$

- Largest discrepancies for $t\bar{t}W$ in multi-lepton signatures
- How well do we understand the modeling of $t\bar{t}W$ signatures?

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 Pellicciolli'20] [Denner and Pellicciolli'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]

Theory status

NLO fixed order

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

$\longrightarrow$ stable top-quarks [Frixione et al'15, Frederix et al'17]

- NLO QCD: on-shell decay $\times$ production [Campbell and Ellis'12]

$\longrightarrow$ QCD corrections to production and decy, spin correlations

- NLO QCD + EW: complete off-shell

$\longrightarrow$ (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]

$\longrightarrow$ 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]

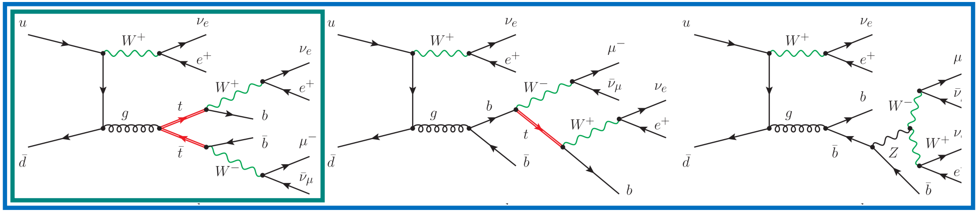
$\longrightarrow$ top decays at LO [Frederix and Tsinikos'20] [Febres Cordero, MK, Reina'21]

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

Modeling of multi-lepton signatures

Modeling of multi-lepton signatures

How to model leptonic final states?



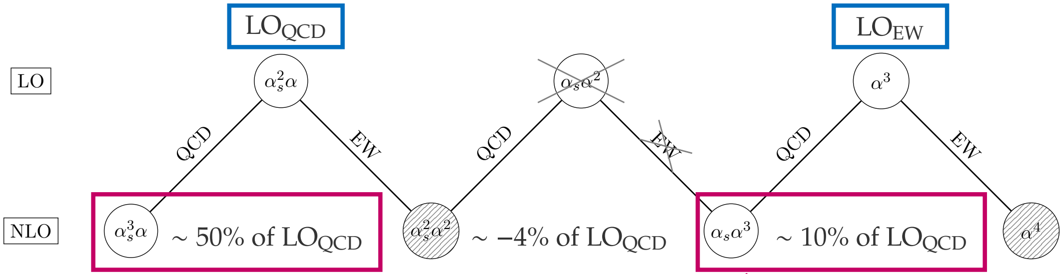
parton showers

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

fixed-order

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

How compatible are the different descriptions?

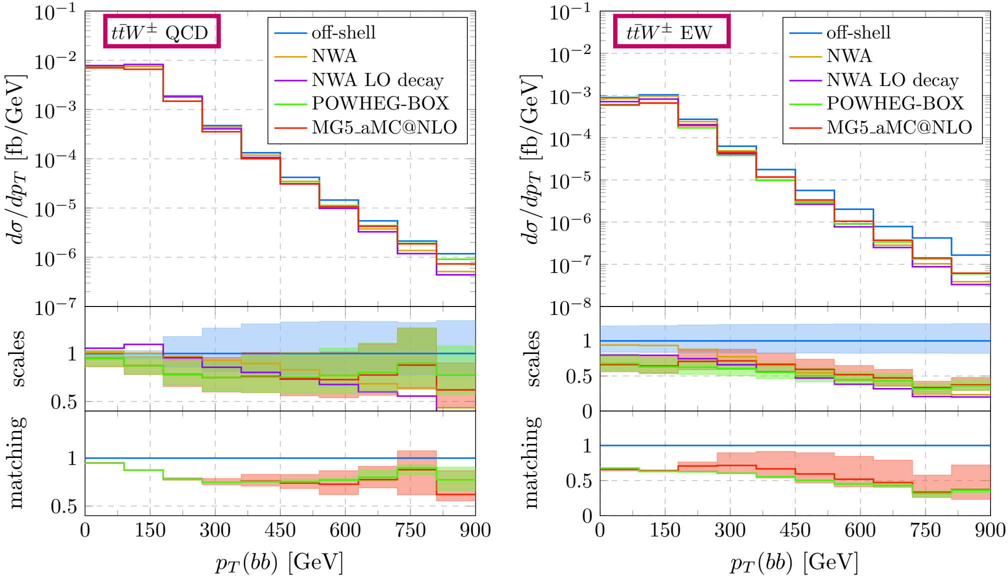


	$\sigma^{\text{NLO QCD}}$	$t\bar{t}W$ QCD	$t\bar{t}W$ EW
fixed-order	full off-shell	$1.58^{+3\%}_{-6\%}$	$0.206^{+22\%}_{-17\%}$
fixed-order	full NWA	$1.57^{+3\%}_{-6\%}$	$0.190^{+22\%}_{-16\%}$
fixed-order	NWA with LO decays	$1.66^{+10\%}_{-10\%}$	$0.162^{+22\%}_{-16\%}$
NLOPS	Powheg Box	$1.40^{+11\%}_{-11\%}$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

- $t\bar{t}W$ EW $\sim$ 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%)

Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181

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

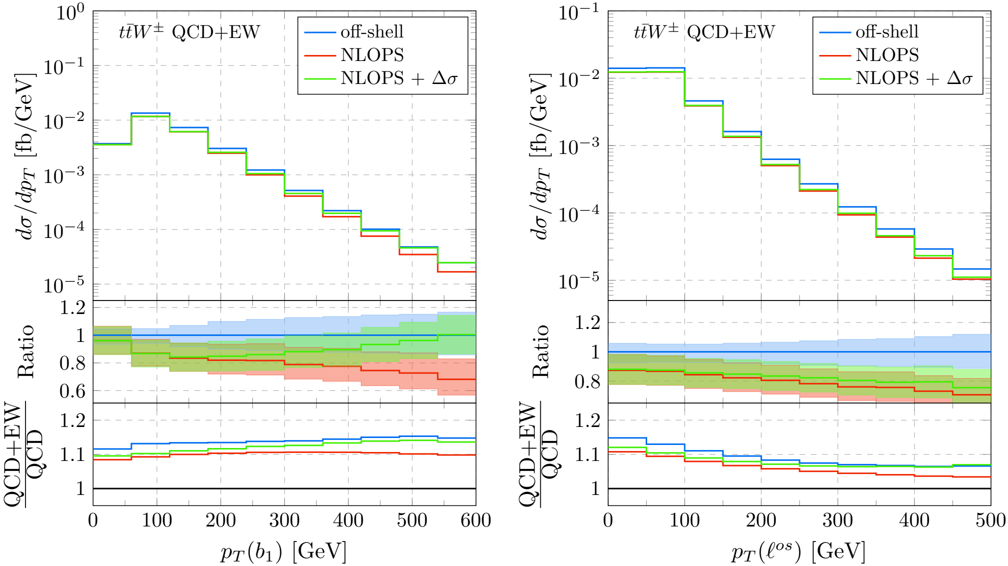
Solution:

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

	$t\bar{t}W$ 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

Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181



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

Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181

Multi-jet merging

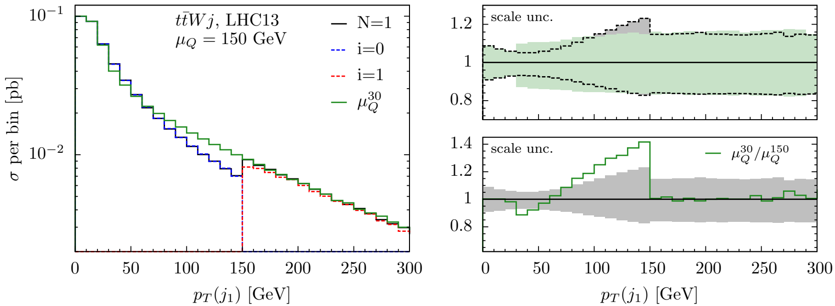
The need for improvements

Out-of-the-box FxFx merging:

- Combine several jet multiplicities for inclusive sample

$$\text{FxFx@1j} = \underbrace{t\bar{t}W@\mathcal{O}(\alpha_s^2\alpha, \alpha_s^3, \alpha)}_{\text{NLO}_{\text{QCD}},\ qg\text{@LO}} + \underbrace{t\bar{t}Wj@\mathcal{O}(\alpha_s^3\alpha, \alpha_s^4\alpha)}_{\text{qg@NLO},\ gg\text{@LO}}$$

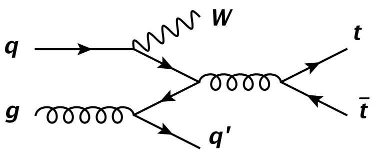
- Combination is done using merging scale parameter μ_Q
- Leads to spurious artifacts in theoretical predictions



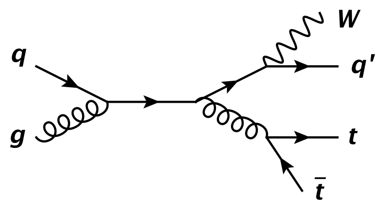
Frederix, Tsinikos, arXiv:2108.07826

Improved FxFx merging:

- During merging: Distinguish between

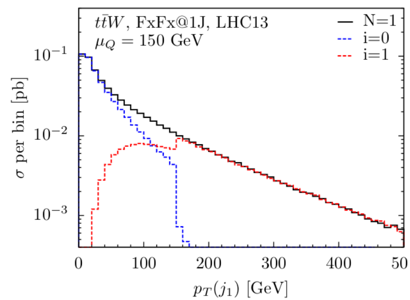


QCD jet



Weak jet

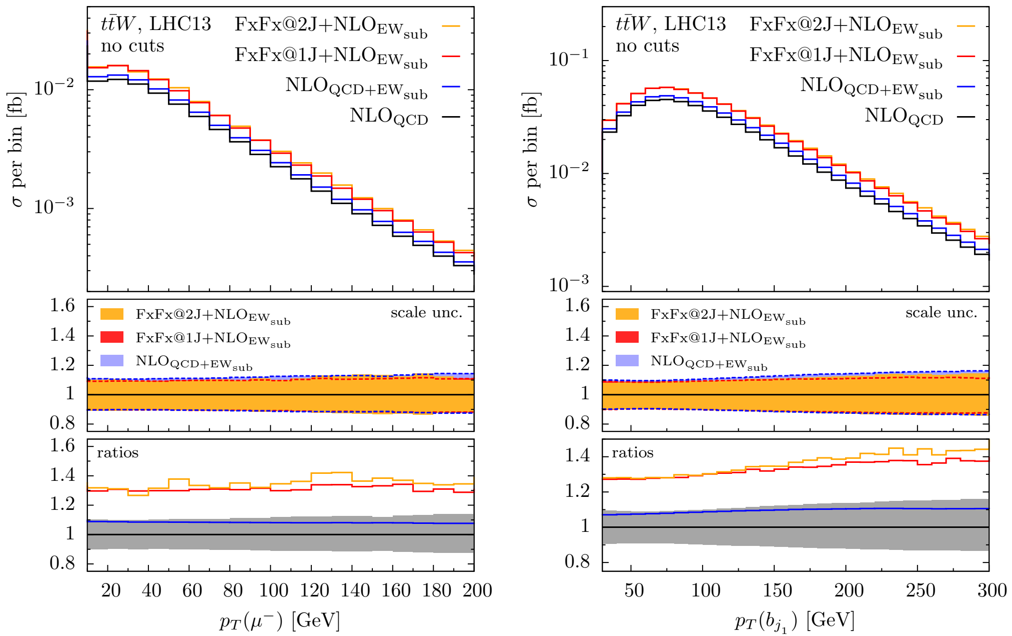
- QCD factorization: $t\bar{t}W j_{\text{QCD}} \sim t\bar{t}W \otimes P_{j_{\text{QCD}},g}$
- Weak jets not divergent for $p_T(j_{\text{weak}}) \rightarrow 0$
- Exclude Weak jets from merging procedure



Frederix, Tsinikos, arXiv:2108.07826

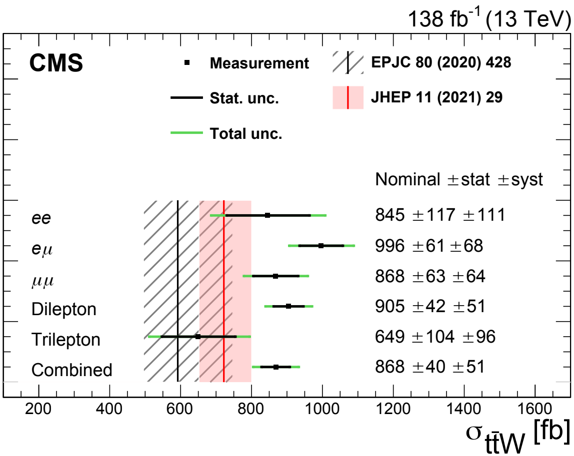
Multi-lepton signatures

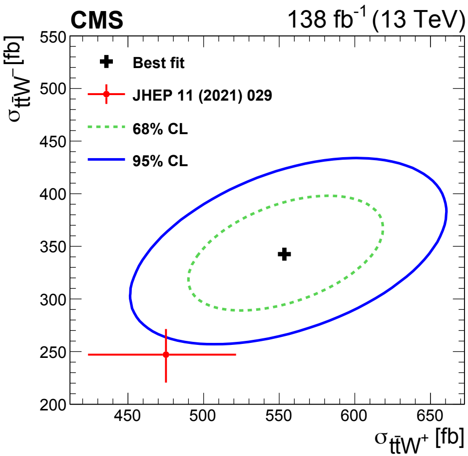
[Frederix, Tsinikos arXiv:2108.07826]



Jet merging has sizable impact!

Impact on measurements





- Recent $t\bar{t}W$ measurements: [CMS, arXiv:2208.06485]
- Multi-jet merging improves description of fiducial signatures
- Overall tension remains: 2σ level

Summary & Conclusions

Summary & Conclusions

Phenomenology of $pp \to t\bar{t}W$ multi-lepton signatures at the LHC

1) fixed-order vs. parton-shower

- We studied modelling of $t\bar{t}W$ in the 3 lepton signature
- 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:

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

2) multi-jet merging

- Proper treatment of weak jets necessary!
- hard higher-order corrections are significant
- improves description of data

Future:

- full off-shell @ NLO+PS desirable!
- NWA for $pp \to t\bar{t}W^{\pm}$ @ NNLO really necessary to settle things