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MODELLING $t\bar{t}W$ IN THE $3l$ CHANNEL

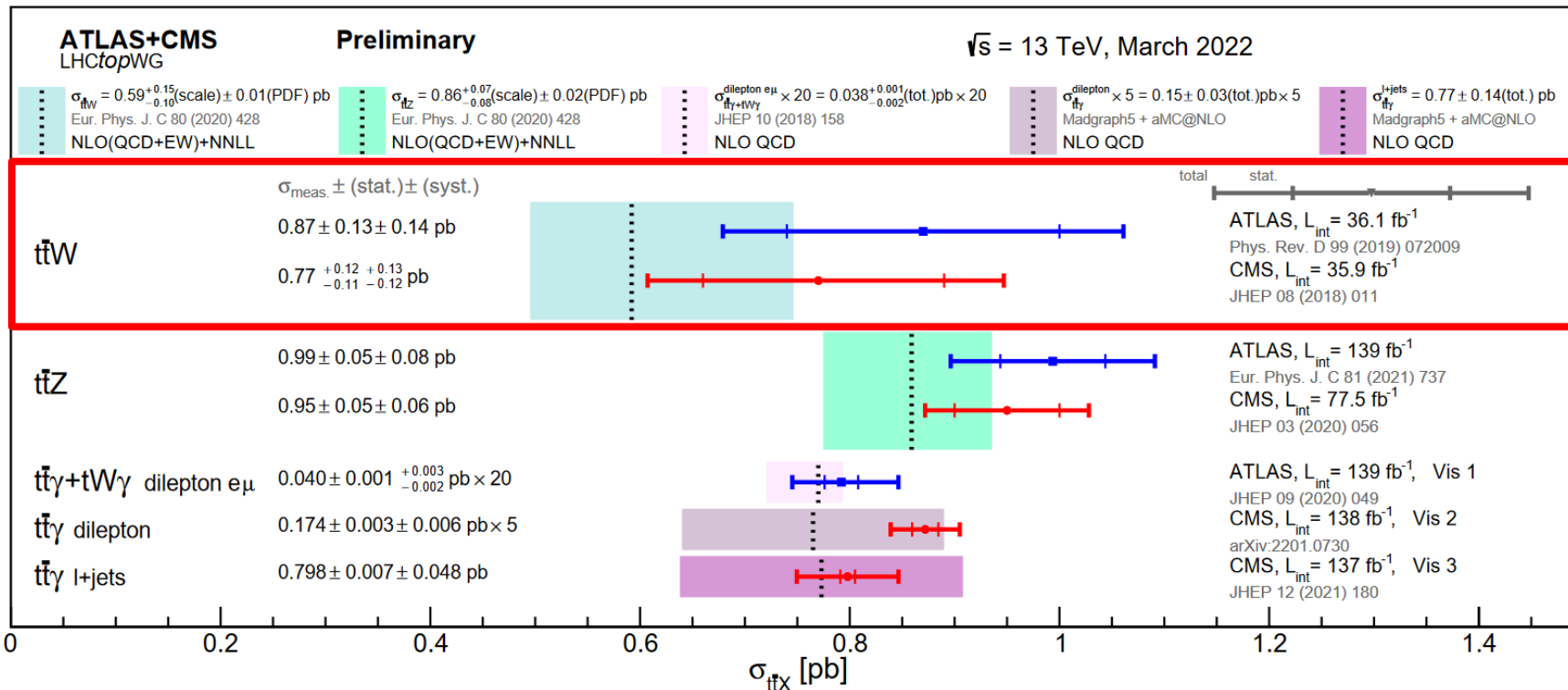
G. Bevilacqua, H.Y. Bi, F. Febres Cordero, H.B. Hartanto, M. Kraus, [J. Nasufi](#), L. Reina, M. Worek

10th Edition of the LHCP Conference
Taipei, Taiwan 2022



LHC STATUS REPORT: $t\bar{t}W$

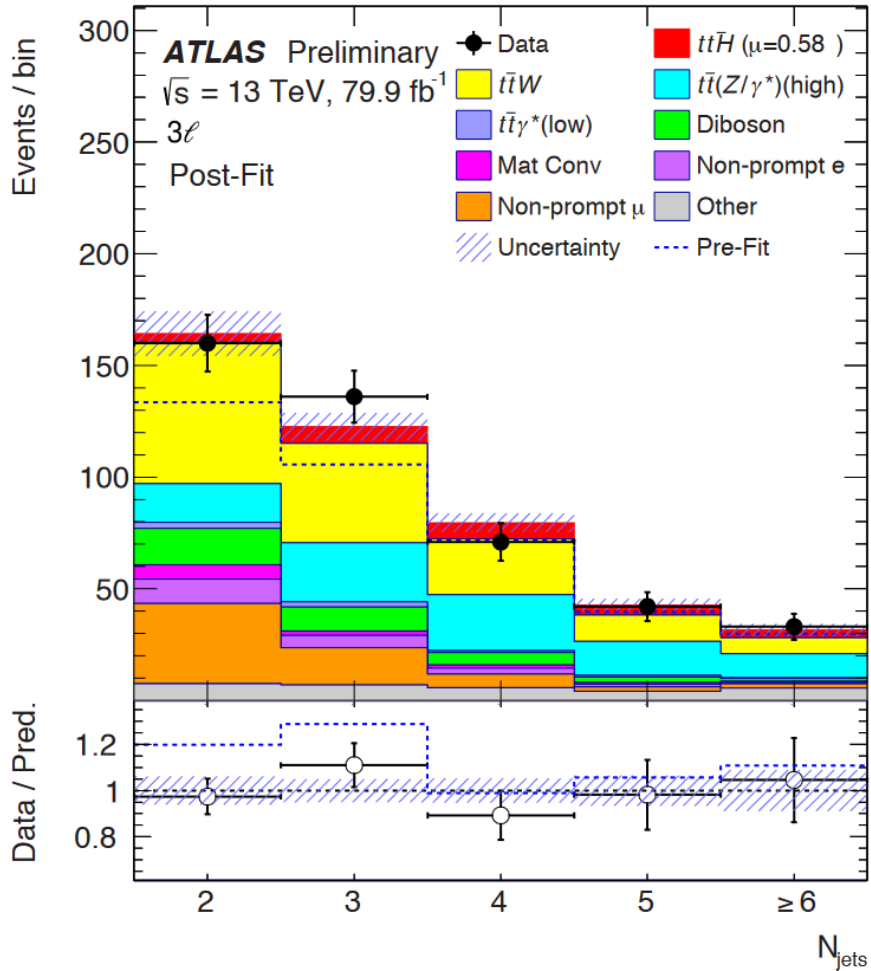
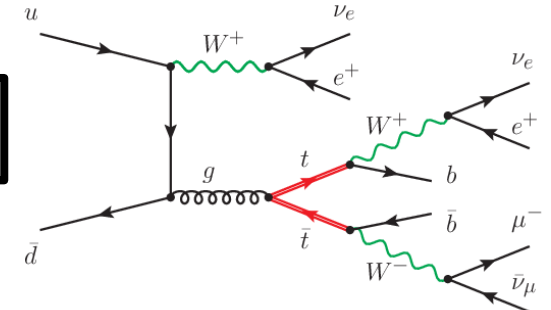
@8TeV: [[ATLAS'15](#)] [[CMS'15](#)]
 @13TeV: [[ATLAS'17](#)] [[CMS'17](#)]
 [[ATLAS'19](#)]



- First observed at the LHC in 2015 with a 5σ significance.
- The measurement was performed in 2ℓ , 3ℓ and 4ℓ decay channels.
- Experimental result in agreement with SM, but ...
- Also $\sim 1\sigma$ tension @8TeV.
- Slight excess of $t\bar{t}W$ events confirmed @13TeV.

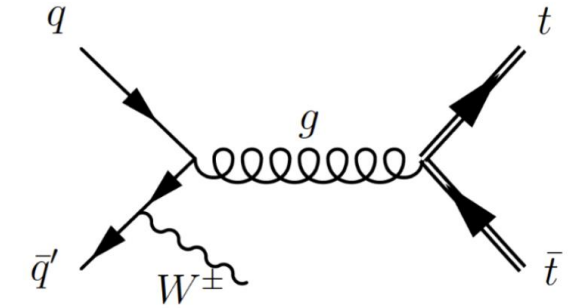
SM MOTIVATION

$$pp \rightarrow t\bar{t}W^{\pm} \rightarrow l^+ \bar{\nu}_{\ell} l^- \nu_{\ell} l^{\pm} \bar{\nu}_{\ell} b\bar{b}$$



- $t\bar{t}W$ is the **dominant background to $t\bar{t}H$ and $t\bar{t}t\bar{t}$** in the multi-lepton channels.
- [[ATLAS'19](#)] reports in the 3ℓ channel :
 - **30%-70% discrepancies in the normalization** (very inclusive cuts!)
 - Issues with the modelling of the final states
 - **Shape differences** between the exp. data and MC theory predictions
- Main sources of syst. uncertainties:
 - Modelling of QCD multiplicities
 - b-jet multiplicity
 - W-gauge boson charge asymmetry

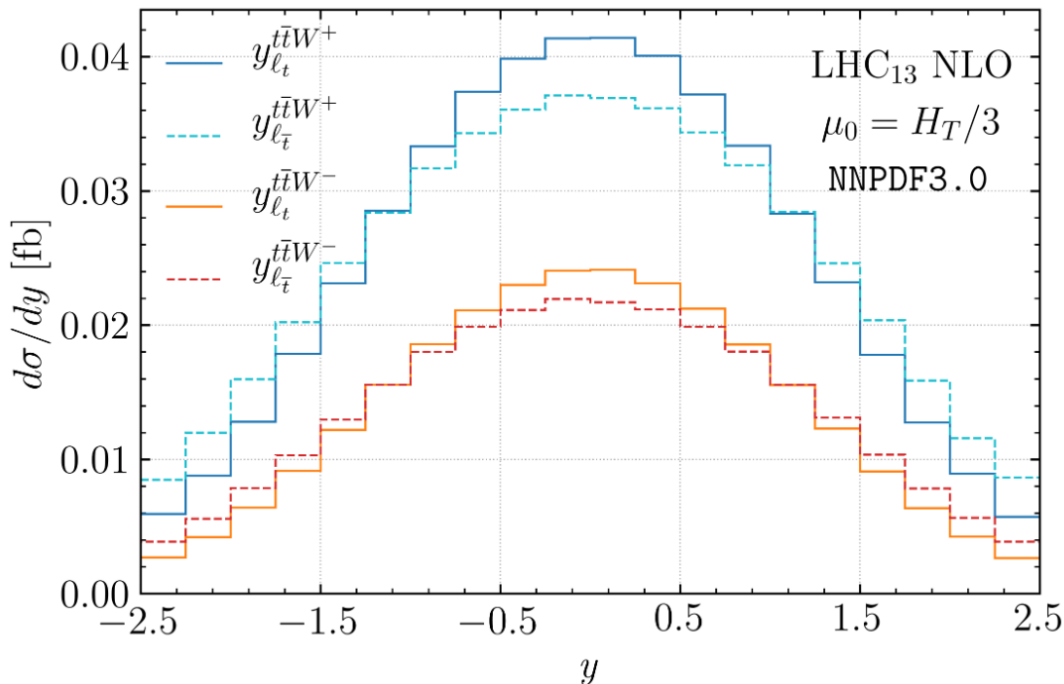
PHENOMENOLOGY MOTIVATION



Charge asymmetries of tops
and decay products.

$$A_c^t = \frac{\sigma_{\text{bin}}^+ - \sigma_{\text{bin}}^-}{\sigma_{\text{bin}}^+ + \sigma_{\text{bin}}^-}, \quad \sigma_{\text{bin}}^\pm = \int \theta(\pm \Delta|y|) \theta_{\text{bin}} d\sigma$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



- W -gauge boson acts as polarizer for the tops
- gg – initial state first appears at NNLO
- Relatively large asymmetry for the tops and the decay products of the tops
- **Sensitive to modelling** and potentially new physics!

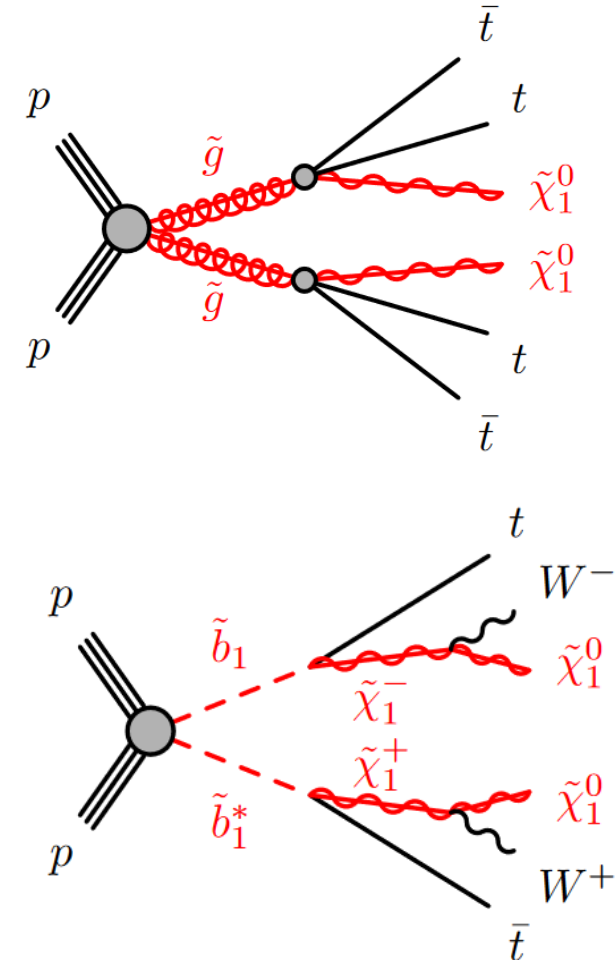
[[Maltoni, Mangano, Tsinikos, Zaro'14](#)]

[[Bevilacqua, Bi, Hartanto, Kraus, JN, Worek'21](#)]

BSM MOTIVATION

$$pp \rightarrow t\bar{t}W^\pm \rightarrow \ell^+ \bar{\nu}_\ell \ell^- \nu_\ell \ell^{\pm(-)} \bar{\nu}_\ell \ell^{\pm(-)} b\bar{b}$$

- Rare SM 2SS ℓ (Same-Sign) signature with small cross section!
- **Important background to many BSM searches**
 - Signature search : 2SS ℓ +missing p_T+2j
 - BSM predicts bigger cross sections \rightarrow constrain New Physics
 - Relevant for various extensions of SM, e.g.:
 - SuSy
 - Min. Universal Extra Dimensions
 - Heavy Majorana neutrino searches
 - SS top resonance searches
 - EFTs
 - Anomalous top couplings



[ATLAS'17]

[CMS'17]

[ATLAS'16]

[CMS'16]

THEORY STATUS REPORT : NLO

Fixed order :

Stable ttW :	(QCD)	[Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau'11]
	(QCD+EW)	[Frixione, Hirschi, Pagani, Shao, Zaro'15] [Dror, Farina, Salvioni, Serra'16] [Frederix, Pagani, Zaro'18]
NWA:	(QCD)	[Campbell, Ellis'12] [Bevilacqua, Bi, Hartanto, Kraus, Worek'20]
Full off-shell :	(QCD)	[Bevilacqua, Bi, Hartanto, Kraus, Worek'20] [Denner, Pelliccioli'20]
	(QCD+EW)	[Denner, Pelliccioli'21]

Parton Shower :

NLO+PS :	(QCD)	[Garzelli, Kardos, Papadopoulos, Trocsanyi'12] [Maltoni, Pagani, Tsinikos'16]
	(QCD+EW)	[Frederix, Tsinikos'20] [Febres Cordero, Kraus, Reina'21] [Bevilacqua, Bi, Febres Cordero, Hartanto, Kraus, JN, Reina, Worek'21]
Jet merging :	(QCD)	[von Buddenbrock, Ruiz, Mellado'20] [ATLAS'20]
	(QCD+EW)	[Frederix, Tsinikos'21]

Resummation :

NLO+NNLL :	(QCD)	[Li, Li, Li'14] [Broggio, Ferroglia, Ossola, Pecjak'16]
	(QCD+EW)	[Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos'19] [Kulesza, Motyka, Schwartländer, Stebel, Theeuwes'18] ['20]

MODELLING

$$pp \rightarrow t\bar{t}W^{\pm} \rightarrow l^{+}\bar{\nu}_{\ell}l^{-}\nu_{\ell}l^{\pm(\bar{\nu})}_{\ell}b\bar{b}$$

Goal: Comparison

NLO Fixed Order:

- At most only one extra emission
- NLO spin correlations
- Resonant and non-resonant diagrams
- Non-factorizable corrections and interference effects

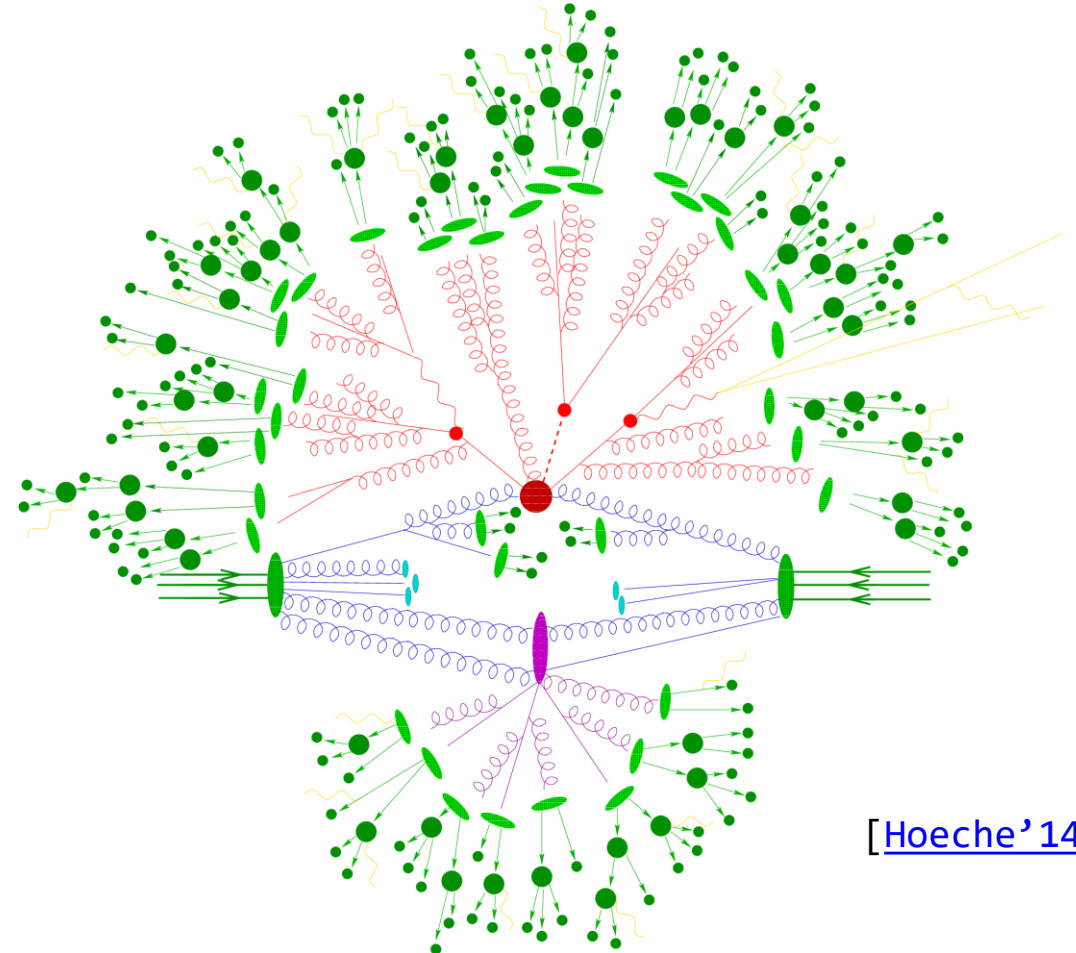
via HELAC-NLO

vs

NLO+ PS :

- Multiple emissions
- LO spin correlations
- NLO production + LO decays + PS
- Only double resonant diagrams
- Breit-Wigner smearing for top and W boson

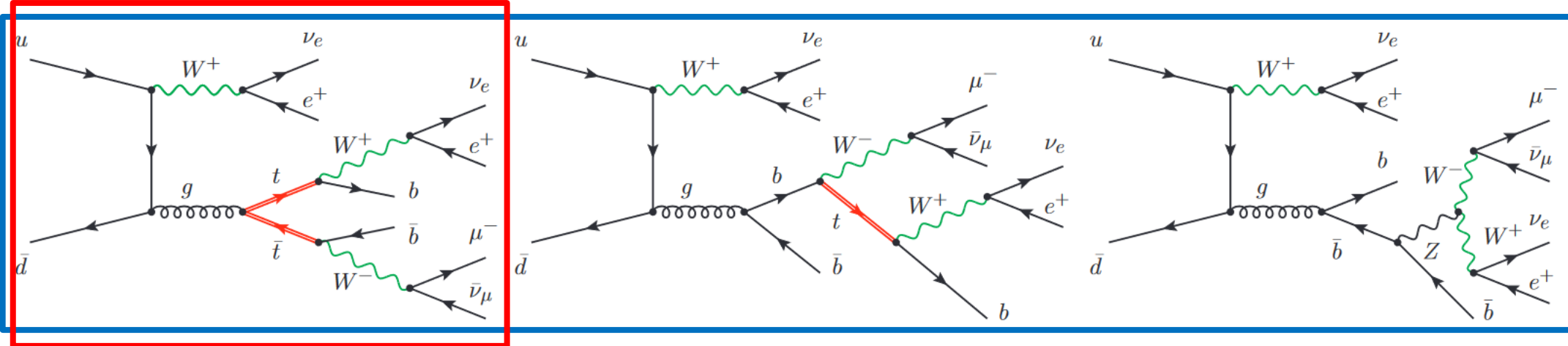
via Powheg-Box and
MG5_aMC@NLO



[[Hoeche'14](#)]

FIXED ORDER MODELLING

$$pp \rightarrow t\bar{t}W^\pm \rightarrow \ell^+\bar{\nu}_\ell \ell^-\nu_\ell \ell^{\pm(-)}\bar{\nu}_\ell b\bar{b}$$



Narrow-Width-Approximation (NWA) :

- On-shell propagators

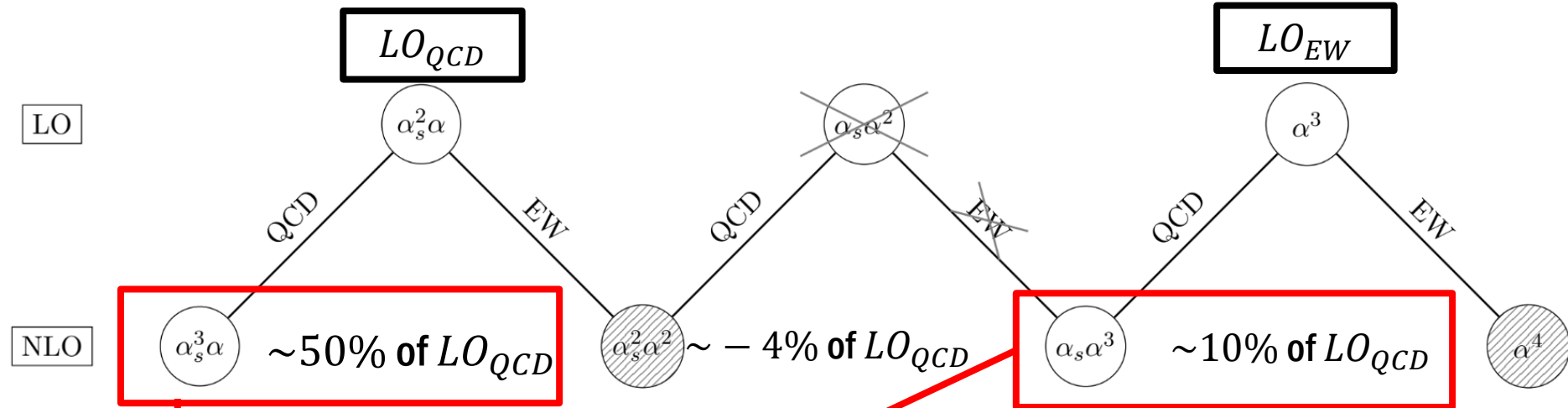
$$\frac{1}{(p^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} \rightarrow \frac{\pi}{m_t \Gamma_t} \delta(p^2 - m_t^2)$$

- Includes only double-resonant diagrams
- Factorization : Production x Decay
- NLO corrections can be applied separately to Production and Decay

Full Off-shell :

- Breit-Wigner propagators for the top and W
- All double-, single- and non-resonant diagrams as well as interference effects included
- Also contains non-factorizable corrections
- All consistently incorporated at the matrix element level

RESULTS



[Frederix, Pagani, Zaro'18]

Only NLO QCD corrections

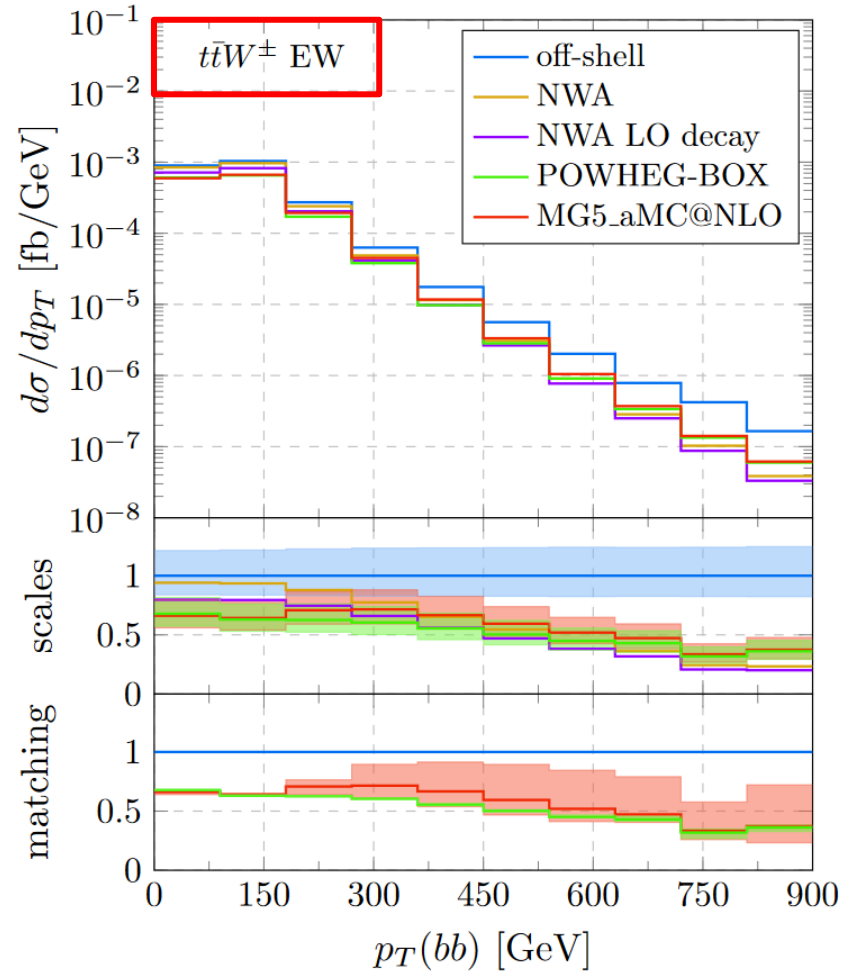
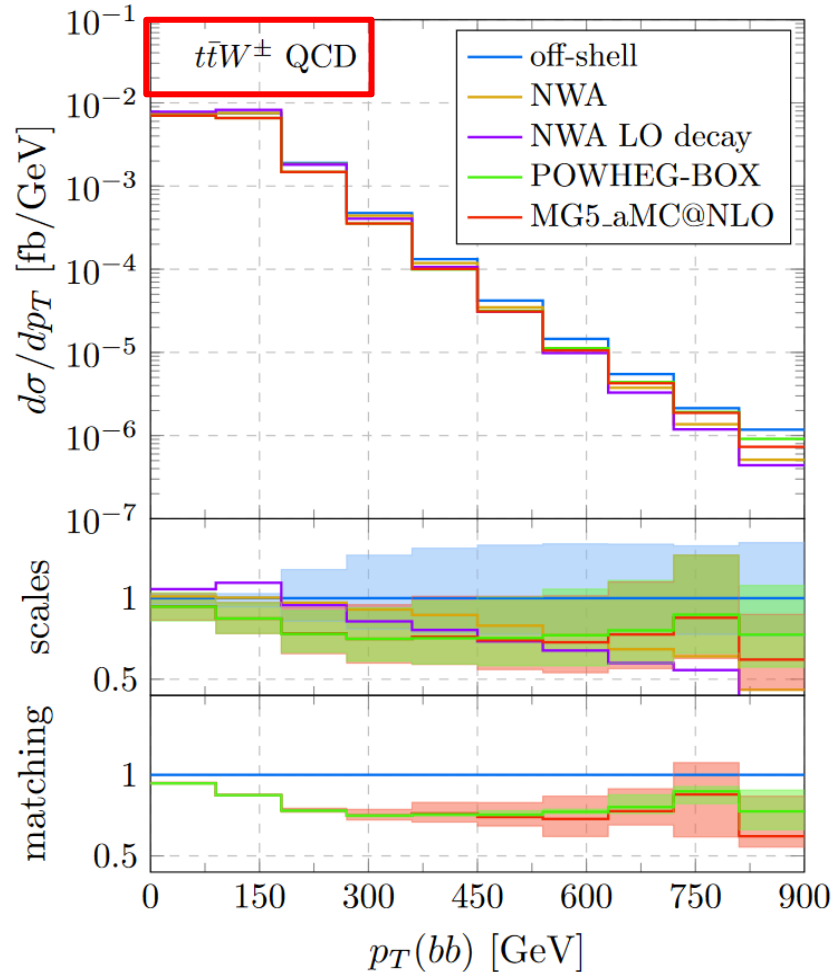
$\sigma^{NLO\ QCD}$	$t\bar{t}W$ QCD	$t\bar{t}W$ EW
1. Full off-shell	$1.58^{+3\%}_{-6\%}$	$0.206^{+22\%}_{-17\%}$
2. Full NWA	$1.57^{+3\%}_{-6\%}$	$0.190^{+22\%}_{-16\%}$
3. NWA with LO decays	$1.66^{+10\%}_{-10\%}$	$0.162^{+22\%}_{-16\%}$
4. POWHEG Box	$1.40^{+11\%}_{-11\%}$	$0.133^{+21\%}_{-16\%}$
5. MG5	$1.40^{+11\%}_{-11\%}$	$0.136^{+21\%}_{-16\%}$

- $t\bar{t}W$ EW is around 13% of dominant $t\bar{t}W$ QCD
- Full off-shell effects sizeable at 9% for $t\bar{t}W$ EW
- Expected: $\frac{\Gamma_t}{m_t} \approx 0.8\%$
- Scale uncertainty for $t\bar{t}W$ QCD is affected by modelling
- Scale uncertainty for $t\bar{t}W$ EW like LO
- Smaller cross section for NLO+PS because of multiple radiations (11%-34% smaller)

[Bevilacqua, Bi, Febres Cordero, Hartanto, Kraus, JN, Reina, Worek'21]

DIFFERENTIAL RESULTS

[Bevilacqua, Bi, Febres Cordero, Hartanto, Kraus, JN, Reina, Worek' 21]



- **Off-shell has a harder high p_T spectrum (single resonant contributions!)**
- **Full NWA in good agreement with off-shell in the bulk of the distribution**
- **NLO+PS approaches in good agreement with each other**
- **Differences between modelling approaches more pronounced for $t\bar{t}W$ EW**
- **Matching uncertainties can become comparable to scale uncertainties or bigger for high p_T**

IMPROVE PS PREDICTIONS

Idea : Complement PS matched results with (fixed order) full off-shell effects :

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



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

Problem : Double counting of double resonant contributions

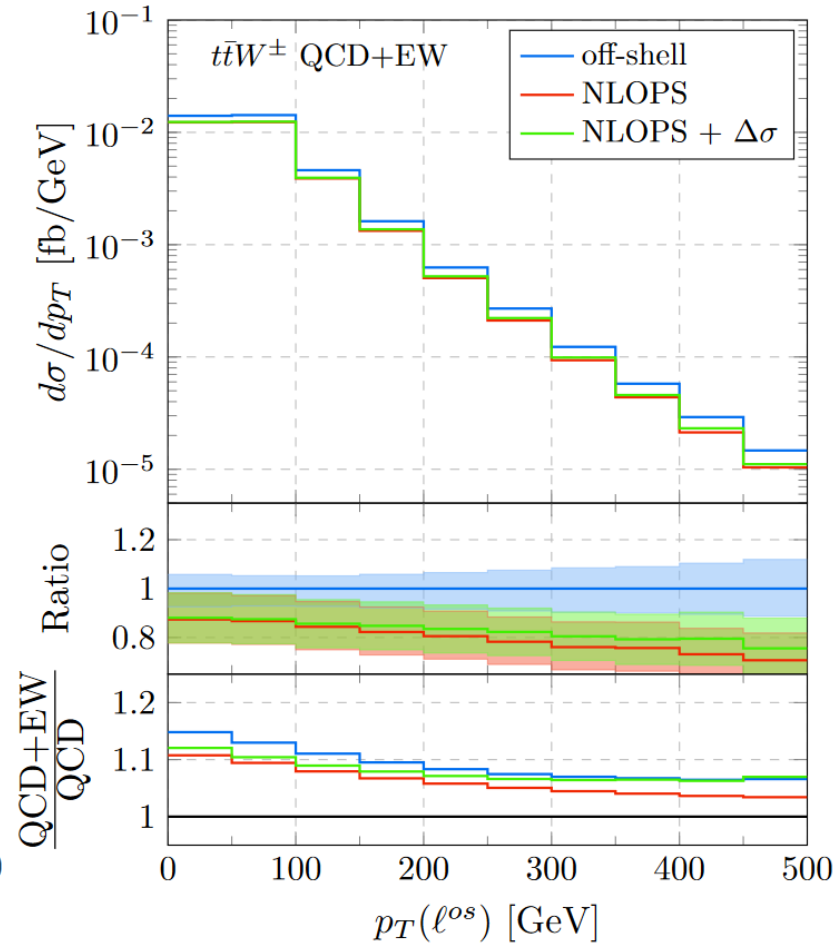
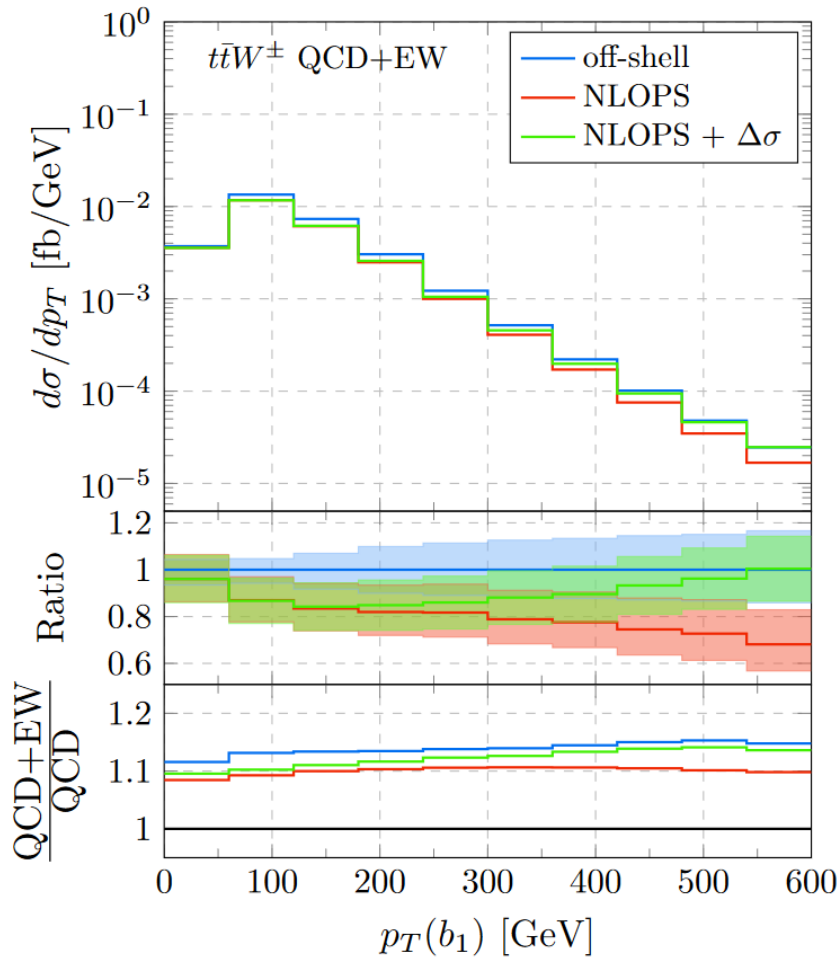
Solution :

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

- $\Delta\sigma$ contains contributions from single- and non-resonant diagrams, interferences, exact NLO spin correlations and NLO QCD corrections to decays.
- Enhanced PS results increased by 2%
- Theoretical uncertainty of PS unchanged

DIFFERENTIAL NLOPS+ $\Delta\sigma$

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



- In the bulk of the distribution, NLOPS+ $\Delta\sigma$ matches NLOPS
- NLOPS+ $\Delta\sigma$ matches off-shell in the high p_T spectrum
- The $\Delta\sigma$ enhancement impacts jet observables more than leptonic observables
- In both cases, the EW component of NLOPS+ $\Delta\sigma$ receives sizeable corrections in the tails

SUMMARY

- We have studied modelling ttW in the 3lepton channel using
 - NLO fixed order
 - NLO + PS matched results
- They describe phase space regions differently:
 - Full off-shell results impact particular phase space regions e.g. high p_T
 - NLO+PS impact shape over broader range
- We suggest to improve NLO+PS results by supplementing them with off-shell effects :

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

- NLOPS+ $\Delta\sigma$ have sizeable shape differences compared to NLO+PS and the full off-shell results
- $\Delta\sigma$ is independent of the PS generator
- **In the absence of the matching of the full off-shell to parton showers for the ttW process, we suggest this prescription for comparison with unfolded experimental data.**

Further discussion:

Where: [Zoom](#)

When : 16:45-17:00 CET

Meeting ID: 953 9144 1387

Passcode: 948169

Contact:

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