Modelling of the $t\bar{t}W$ process

Ioannis Tsinikos

Theoretical Particle Physics, Department of Astronomy and Theoretical Physics,

Lund University

29 May 2020

online - LHCP2020

Exp: arXiv:1711.02547, 1901.03584, 1907.11270, ATLAS-CONF-2019-045

Th: arXiv:1406.3262, 1711.02116, 1804.10017, 1907.04343, 2001.03031, 2004.09552, 2005.09427

LUND UNIVERSITY

Contents

- $t\bar{t}V(V = W, Z)$ enter many LHC analyses either as signal or as background
- No BSM signs at the LHC up to now
  - Need to understand the details
- Already measured at the LHC
  - ATLAS LHC13, 1901.03584

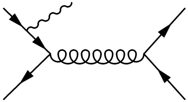
    $\sigma_{t\bar{t}W} = 870 \pm 130_{\rm stat} \pm 140_{\rm syst}$, $\sigma_{t\bar{t}Z} = 950 \pm 80_{\rm stat} \pm 100_{\rm syst}$ [fb]
  - CMS LHC13, 1711.02547, 1907.11270

    $\sigma_{t\bar{t}W} = 770^{+120}_{-110}({\rm stat})^{+130}_{-120}({\rm syst})$, $\sigma_{t\bar{t}Z} = 950 \pm 50_{\rm stat} \pm 60_{\rm syst}$ [fb]
- First measurements on differential distributions
  - Access to EW top quark couplings
  - EFT and BSM sensitive regimes
- Review of $t\bar{t}W$ modelling on the theoretical side

Focus on $t\bar{t}W$

- Main features of $t\bar{t}W$
  - Production modes

@LO: only $q\bar{q}$



@NLO: $+qg$ — New channels, large K-factors, large scale unc.

Maltoni et al.: 1406.3262

$t\bar{t}W^{+}$	13 TeV
qg	15 %

@NNLO: $+gg$ — Absence of gg even at NLO

  - Process properties

@LO: Polarised $t, \bar{t} \rightarrow$ Huge asymmetries in decay products

@NLO: Large $A_C^{t\bar{t}}$ (Absence of gg)

- Main irreducible background to signatures like $t\bar{t}H, t\bar{t}t\bar{t}$
- Data tend to give larger cross section w.r.t. theory prediction

Complete NLO

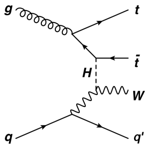
Frederix, Pagani, Zaro: 1711.02116

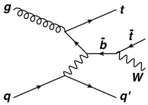
- complete NLO: Madgraph5_aMC@NLO publicly available, *Frederix et al.*:1804.10017

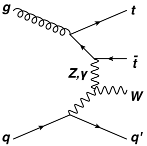
LO	$q\bar{q}$: $\alpha_s^2\alpha$ (LO1)	$\alpha_s\alpha^2$ (LO2=0)	$q\bar{q}$: α^3 (LO3)	
NLO	$q\bar{q},qg$: $\alpha_s^3\alpha$ (NLO1)	$q\bar{q},q\gamma$: $\alpha_s^2\alpha^2$ (NLO2)	$q\bar{q},qg$: $\alpha_s\alpha^3$ (NLO3)	$q\bar{q},q\gamma$: α^4 (NLO4)
Expectation	$\mathcal{O}(10\%)$	$\mathcal{O}(1\%)$	$\mathcal{O}(0.1\%)$	$\mathcal{O}(0.01\%)$
Contribution	$\sim 30-60\%$	$\sim -4\%$	$\sim 10\%$	$\sim 0.04\%$

- Importance of EW corrections

Large NLO3 ($tW \rightarrow tW$)





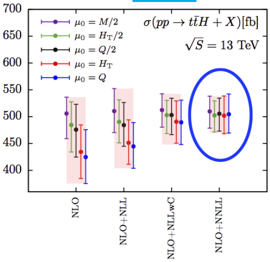


Beyond NLO

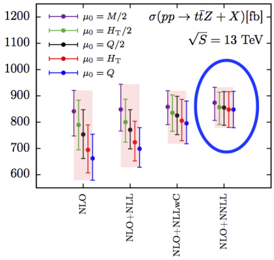
NLO+NNLL *Broggio et al.*: 1907.04343, *Kulesza et al.*: 2001.03031

- Soft-gluon resummation to all orders
- Gluon-induced channels absent at LO → not considered in resummation
- Scale dependence still large (combination of 5 different scales[2001.03031])

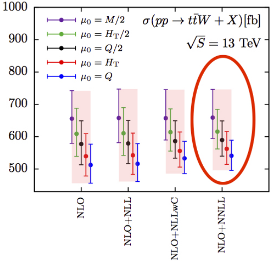
$\sigma(t\bar{t}H) = 504^{+7.6\%}_{-7.1\%}$ fb



$\sigma(t\bar{t}Z) = 859^{+8.6\%}_{-9.5\%}$ fb



$\sigma(t\bar{t}W) = 592^{+26.1\%}_{-16.2\%}$ fb

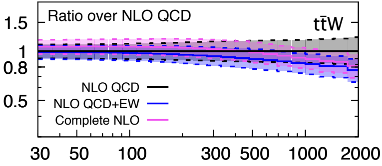


- Reminder: $\sigma^{\text{ATLAS}}_{t\bar{t}W} = 870 \pm 130_{\text{stat}} \pm 140_{\text{syst}}$ fb, $\sigma^{\text{CMS}}_{t\bar{t}W} = 770^{+120}_{-110}(\text{stat})^{+130}_{-120}(\text{syst})$
- Agreement given the large uncertainties

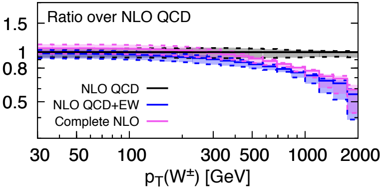
Differential distributions

- EW corrections already large at cross section → significant at differential level

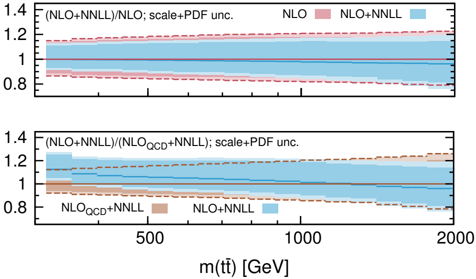
Frederix, Pagani, Zaro: 1711.02116



veto events:
$p_T(j) > 100$ GeV and $|y(j)| < 2.5$



Broggio et al.: 1907.04343 $t\bar{t}W^+$

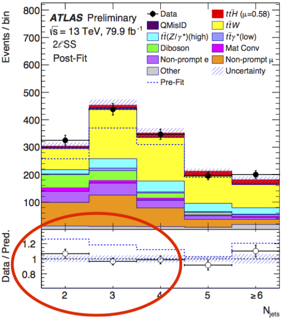


- Left: Importance of complete NLO, jet veto effects
- Right: Slight scale reduction at NLO+NNLL, shaped EW corrections

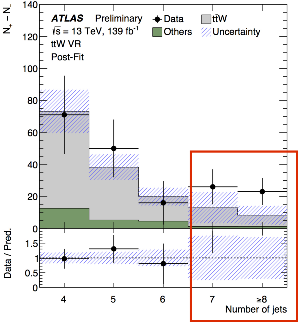
Final signatures

- $t\bar{t}W \to$ leptons + jets + $\not{E}_T$ $(2ss\ell, 3\ell, 4\ell, \ldots)$
- Spin correlations - Realistic cuts - Parton shower effects - off shell effects
- Cannot keep the same precision - very challenging calculationally
- Need to model the decay level (large background to $t\bar{t}H$ jet multiplicities)

ATLAS-CONF-2019-045



Elizaveta Shabalina - 26/05



Strategies:

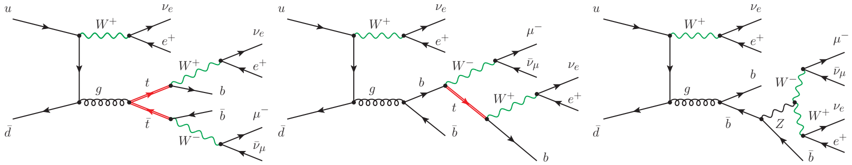
- $\mathrm{NLO_{QCD}}(t\bar{t}W)$+PS $\times$ Global K-factors
- Fixed Order $\mathrm{NLO_{QCD}}$ $(t\bar{t}W \to 2e1\mu\not{E}_T)$
- Parton shower $\mathrm{NLO_{QCD+EW_{sub}}}(t\bar{t}W)$ $\mathrm{LOdecay}$(multileptons)

Off shell effects at the decay level (FO)

Bevilacqua et al.: 2005.09427

- 3 lepton signature: $pp \to e^+\nu_e b\mu^-\bar{\nu}_\mu\bar{b}e^+\nu_e$ (off-shell+non-resonant contributions+interferences)

- Double-, single-, non- resonant diagrams: $\alpha_s^2\alpha^6$ + $\alpha_s^3\alpha^6$



- Cross sections [ab] ($\mu = H_T/3$, ATLAS-cuts)

$t\bar{t}W^-$: $\mathrm{NWA}_{\mathrm{LOdecay}} = 72.0^{+11\%}_{-11\%}$, $\mathrm{NWA} = 68.7^{+5\%}_{-7\%}$, full off-shell$= 68.6^{+5\%}_{-7\%}$

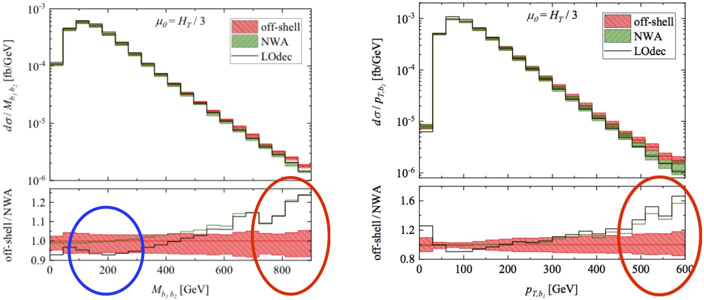
  – NLO decays reduce scale unc.

  – Off-shell effects do not alter significantly the cross section

Off shell effects at the decay level (FO)

Bevilacqua et al.: 2005.09427

- Differential distributions

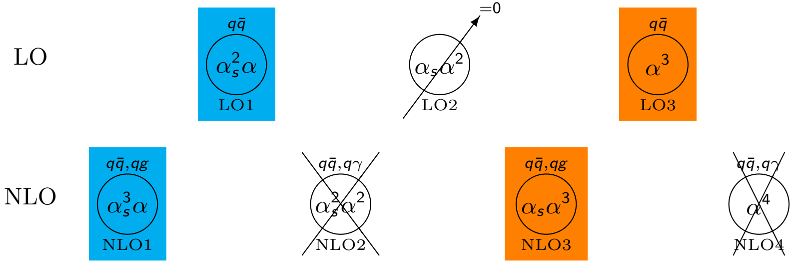


- Important effects of NLO decays even at bulk regions
- Large off-shell effects at the tails

Parton shower

Frederix, IT: 2004.09552

- Parton shower + Realistic analysis
- Include part of the EW corrections
  (NLO: the ones that can be obtained only by QCD corrections to any LO)



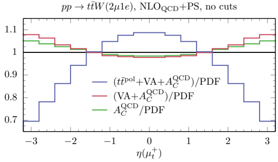
- $\underbrace{\mathrm{NLO_{QCD}}}_{\equiv\mathrm{LO1+NLO1}} + \underbrace{\mathrm{EW_{sub}}}_{\equiv\mathrm{LO3+NLO3}} + \mathrm{NWA_{LOdecay}} + \mathrm{PS} + \{$ had., cuts, Rivet, Detector $\}$
- Cross section: check the $\sim$ 10% of NLO3 in the fiducial region
- Differential level: check the jet multiplicities

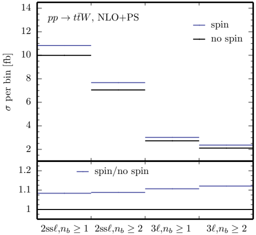
Parton shower

Frederix, IT: arXiv:2004.09552

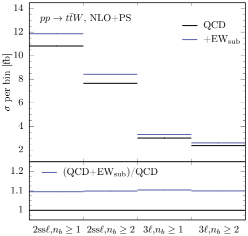
Cross section in multilepton signatures (2ssℓ, 3ℓ)

- Spin correlations (Already included in simulations)
  - Signature cuts affect the cross section





- EW$_{\mathrm{sub}}$



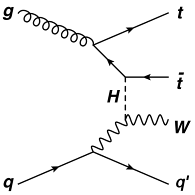
  - Agreement with the EW$_{\mathrm{sub}}$ effect to the inclusive cross section
  - $q\bar{q}, qg$ $\alpha_s\alpha^3$ (NLO3) $\sim 10\%$

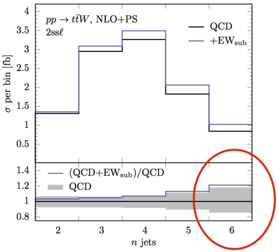
Parton shower

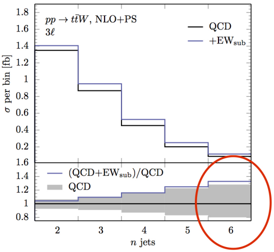
Frederix, IT: arXiv:2004.09552

Differential distributions in multilepton signatures (2ssℓ, 3ℓ)

- EW_{sub} structure
  - Extra parton
  - Extra source of radiation
  - Different kinematics
  - Different spin correlations
- Jet multiplicities (large effect at high n)







- Non flat K-factor
- Enhancement of the tails

Summary - Further research

- **Very active field:** $t\bar{t}W$ modelling is continuously being improved
  - Production level: $\text{NLO}_{\text{QCD+EW}} + \text{NNLL}$
  - Decay level
    - FO,3ℓ: NLO_{QCD} (off-shell effects)
    - PS: $\text{NLO}_{\text{QCD}} + \text{EW}_{\text{sub}} + \text{PS}$ (jet multiplicities)
- **Further research:**
  - Production level: NNLO (?)
  - Decay level
    - FO
      - $(t\bar{t}W \to 2\ell 2b + \text{jets} + \not{E}_T)$@$\text{NLO}_{\text{QCD}}$: scale unc.
      - $(t\bar{t}W \to 3\ell 2b + \not{E}_T)$@$\text{NLO}_{\text{EW}}$: EW_{corr}@decay
    - PS
      - $t\bar{t}W[+(2)j]$@NLO: gg(@NLO), njets, $p_T(j), p_T(t\bar{t})$
      - Correct treatment of 'Weak'-jets (in progress...)
  - Matching the EW corrections to PS
- zoom: $t\bar{t}W$-discussion-link, password: same as today's Webinars

Production

- EW corrections:

  Frederix, Pagani, Zaro: 1711.02116

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO+NLO}}{\mathrm{LO_{QCD}+NLO_{QCD}}}$
$\mu = H_T/2$	$363^{+24\%}_{-18\%}$	$544^{+11\%}_{-11\%}\,(456^{+5\%}_{-7\%})$	$366^{+23\%}_{-18\%}$	$577^{+11\%}_{-11\%}\,(476^{+5\%}_{-7\%})$	1.06 (1.04)

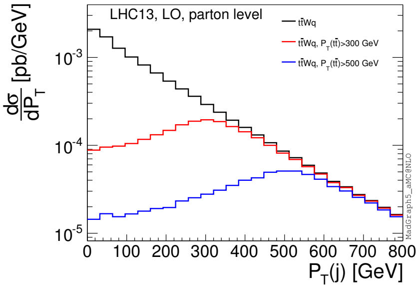
δ[%]	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
$\mathrm{LO_2}$	-	-	-
$\mathrm{LO_3}$	0.8	0.9	1.1
$\mathrm{NLO_1}$	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)
$\mathrm{NLO_2}$	−4.4 (−4.8)	−4.2 (−4.6)	−4.0 (−4.4)
$\mathrm{NLO_3}$	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)
$\mathrm{NLO_4}$	0.02 (−0.02)	0.04 (−0.02)	0.05 (−0.01)

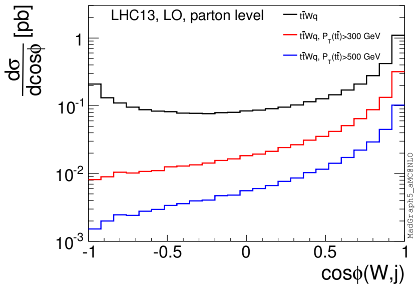
- NLO+NNLL:
  Large $A_C^{t\bar{t}}$ asymmetry:
  $A_C^{t\bar{t}}(t\bar{t}W^+) = 3.43(2)^{+6.2\%}_{-3.3\%}, A_C^{t\bar{t}}(t\bar{t}W^-) = 2.59(1)^{+6.0\%}_{-3.0\%}$

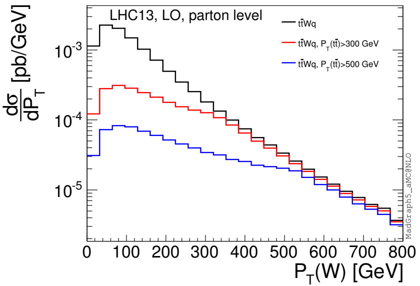
- $t\bar{t}Wq$ at LO

High $p_T(t\bar{t})$

- Hard jet
- Soft and collinear W







Decay - FO - Analysis *Bevilacqua et al.:* 2005.09427

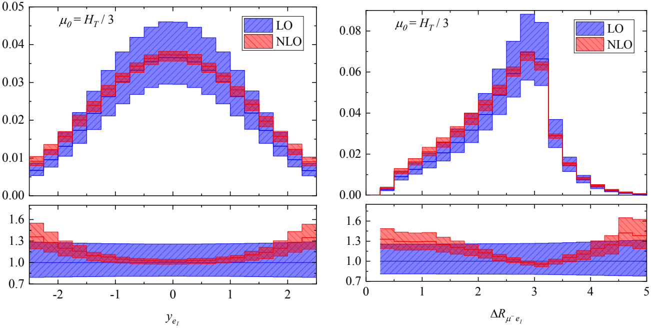
- ATLAS cuts:

$$p_T(\ell) > 25 \text{ GeV}, \qquad p_T(j_b) > 25 \text{ GeV},$$

$$|y(\ell)| < 2.5, \qquad |y(j_b)| < 2.5,$$

$$\Delta R(\ell\ell) > 0.4, \qquad \Delta R(\ell\, j_b) > 0.4,$$

- K-factors:



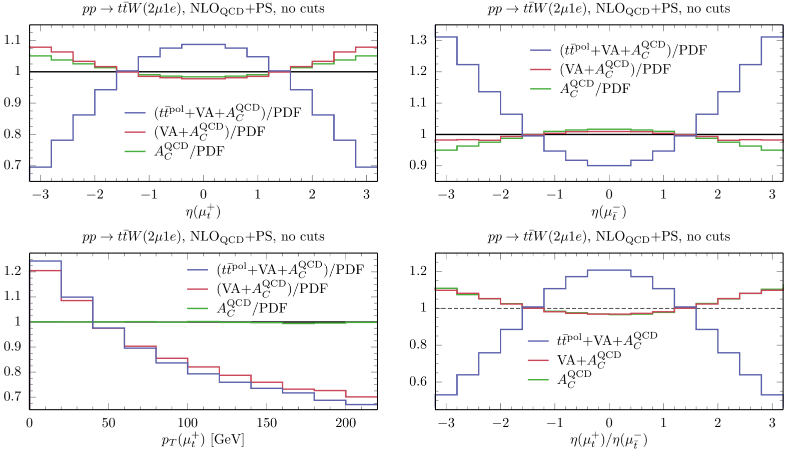
Decay - PS - Analysis

- $t\bar{t}W$ as background to $t\bar{t}H$ production
- Focus on 2ssℓ and 3ℓ signatures (ATLAS-CONF-2019-045)
- No misidentifications or lepton identification efficiencies

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two same-charge (SS) very tight (T*) leptons, $p_{\text{T}} > 20$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV for all SF pairs **13 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}$, mat. conv, int. conv., split by lepton flavour, charge, jet and b-jet multiplicity
3ℓ	Three loose (L) leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges = ±1 Two SS very tight (T*) leptons, $p_{\text{T}} > 15$ GeV One OS (w.r.t the SS pair) loose-isolated (L*) lepton, $p_{\text{T}} > 10$ GeV No τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOS pairs $\lvert m(3\ell) - 91.2\text{ GeV}\rvert > 10$ GeV **7 categories**: enriched with $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$, VV, $t\bar{t}$, mat. conv, int. conv

Decay - PS - Analysis

- $t\bar{t}W$ leptonic asymmetries

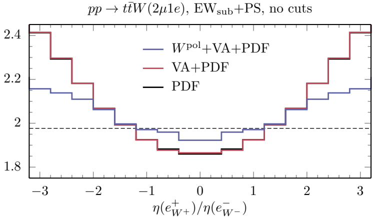


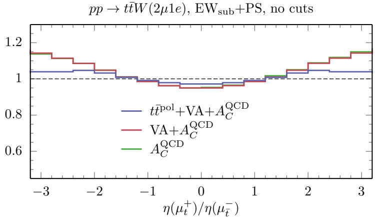
Decay - PS - Analysis

- $t\bar{t}W$ charge ratio

Jet multiplicity:	inclusive	0	1	2	3	4	5	6
no cuts	1.977(2)	2.88(4)	2.43(1)	2.218(7)	2.087(4)	2.003(3)	1.956(3)	1.916(3)
no cuts-no spin	1.977(1)	2.90(4)	2.45(1)	2.205(7)	2.087(5)	2.003(4)	1.956(3)	1.920(3)
$2\mathrm{ss}\ell$	1.99(2)	-	-	2.30(3)	2.02(2)	1.96(2)	1.94(3)	1.84(4)
$2\mathrm{ss}\ell$-no spin	1.84(1)			1.90(3)	1.84(2)	1.84(2)	1.84(3)	1.72(4)
3ℓ	1.88(2)	-	-	1.89(3)	1.92(4)	1.81(5)	1.83(8)	1.8(1)
3ℓ-no spin	1.84(2)			1.81(3)	1.82(4)	1.86(5)	1.90(8)	1.9(1)

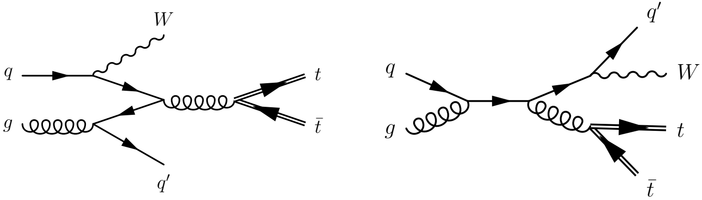
- $t\bar{t}W$@$\mathrm{EW_{sub}}$ leptonic asymmetries





Decay - PS - FxFx

- New ISR and FSR *qg* diagrams



- *qg* has significant contribution due to the *gg* absence up to NNLO
- In merging they are considered only above the merging scale
- Left (QCD jet): collinear factorization $t\bar{t}Wq' \sim t\bar{t}W \times P_{q'g}$
- Right (EW jet): regulated by m_W, no factorisation
- Finite contribution below μ_Q is lost
- Same effect but reduced is expected also in $t\bar{t}Z$, but not in $t\bar{t}H$