Reference cross-sections and methods

used in analyses at ATLAS and CMS for

$t\bar{t}W$ production

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with support from Clara Ramón Álvarez
and Josh McFayden

Joint LHC Top and Higgs session
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Why do we want to know $t\bar{t}W$ better?

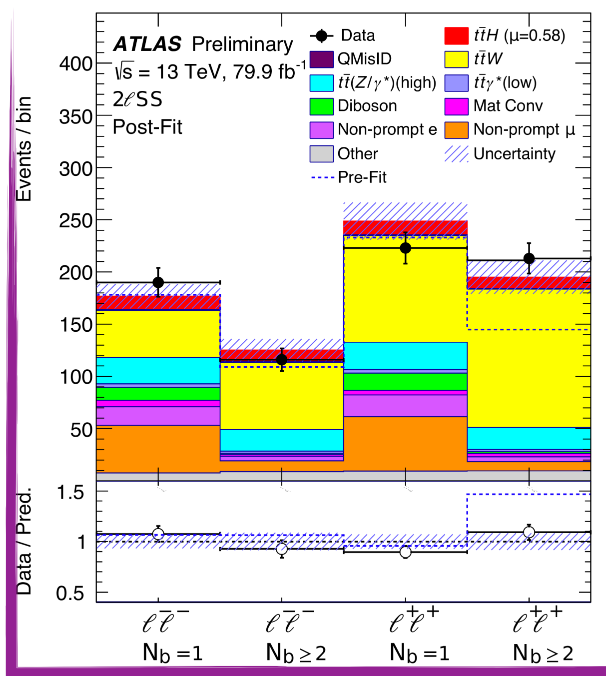
- $t\bar{t}W$ is a crucial background process for many measurements and searches
  - In particular in 2ℓSS/3ℓ (multilepton) final states, in some cases at high (b-)jet multiplicities and/or exploiting charge lepton asymmetry
- Having the most accurate $t\bar{t}W$ MC modelling and reference cross section can have an important impact on many results!
- In this talk, we highlight the role that $t\bar{t}W$ plays in high-profile measurements and searches in the multilepton final state in ATLAS and CMS
  - $t\bar{t}H$ measurement
  - 4tops measurement/search
  - g2HDM multilepton and multi-bjets search
  - SUSY RPV 2ℓ search

Disclaimer:

what is shown here is **not** the final word on $t\bar{t}W$ models in the experiments

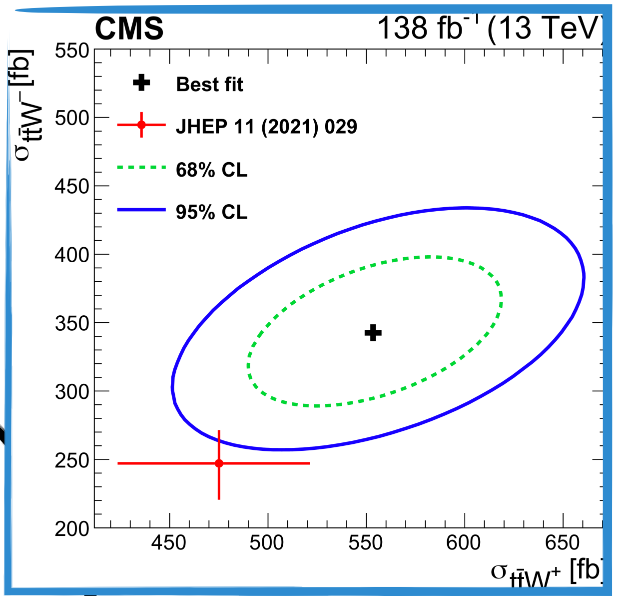
further developments on the theory side are being explored

Inter-connected: the $t\bar{t}W$ reach



$t\bar{t}W$

dedicated measurement



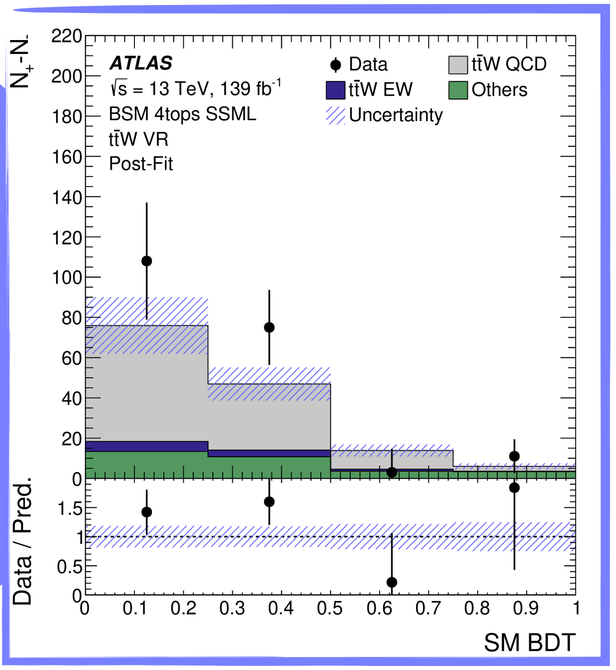
$t\bar{t}$H multiℓ

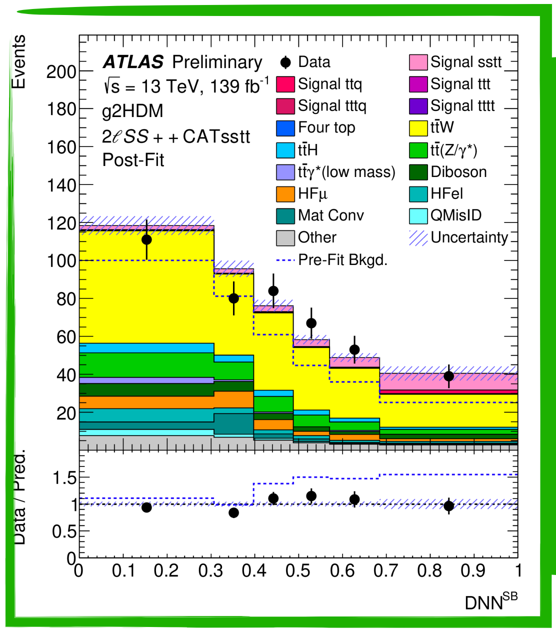
ATLAS also observed a charge-asymmetric tension at ≥2bj

4tops multiℓ

(SM analysis and BSM analysis)

ATLAS sees charge-asymmetric tension at high N_{jets} $t\bar{t}W$ VR





g2HDM multiℓ+b

including **charge-asymmetric** BSM signal in ATLAS

SUSY RPV 2ℓSS

fully data-driven $t\bar{t}W$ in ATLAS

$t\bar{t}W$ reference cross sections: ATLAS & CMS

- Evolution of reference $t\bar{t}W$ cross section across ATLAS and CMS
  - **New reference cross section** including latest and greatest calculations and highest precision necessary to be defined!

Handbook of LHC Higgs Cross Sections: 4 (a.k.a YR4)

$\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}}$	K_{QCD}	$\delta_{\mathrm{EW}}[\%]$	Scale[%]		PDF[%]		$\alpha_S[\%]$	
600.8(0.36)	1.50	−3.2	+12.9%	− 11.5%	+2.0%	− 2.0%	+2.7%	− 2.7%

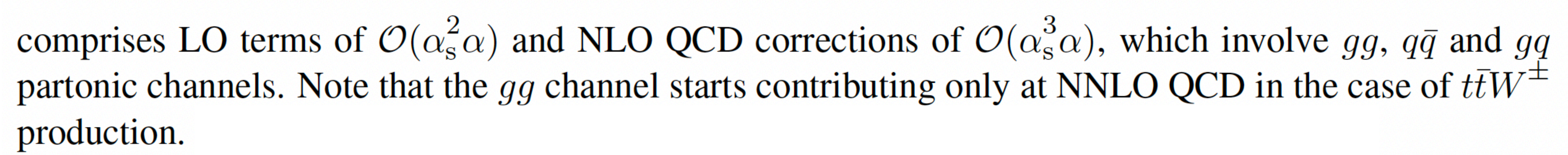
[ref. XS $\sigma_{t\bar{t}W\ \mathrm{YR4}}$ = 600.8 fb]

Multiℓ latest analyses	$\mathcal{L}$ [fb^{-1}]	σ_{ref} [fb]	μ	μ_{YR4}
$t\bar{t}W$ ATLAS Phys. Rev. D 99 (2019) 072009	36.1	600 ± 70	1.44 ± 0.32	1.44 ± 0.32
$t\bar{t}W$ CMS arXiv:2208.06485	138	592^{+155}_{-97} (NLO QCD + EW, QCD NNLL)	1.47 ± 0.11	1.49 ± 0.11
$t\bar{t}H$ ATLAS ATLAS-CONF-2019-045/	80	727 ± 92 (NLO QCD + full NLO EW, +0,1j@NLO)	$1.39^{+0.17}_{-0.16}$	$1.68^{+0.21}_{-0.19}$
$t\bar{t}H$ CMS Eur. Phys. J. C 81 (2021) 378	137	650 (NLO QCD + full NLO EW [1] [2])	1.43 ± 0.21	1.55 ± 0.23
$t\bar{t}t\bar{t}$ BSM ATLAS arXiv:2211.01136	139	639 (Sherpa 2.2.10 NLO QCD + full NLO EW*)	1.3 ± 0.3	1.22 ± 0.28
$t\bar{t}t\bar{t}$ CMS Eur. Phys. J. C 80 (2020) 75	137	610 (from https://arxiv.org/abs/2010.05915)	1.3 ± 0.2	1.3 ± 0.2
g2HDM ATLAS ATLAS-CONF-2022-039/	139	615 (Sherpa 2.2.10 NLO QCD + full NLO EW*)	1.50 ± 0.14	1.46 ± 0.14
SUSY RPV ATLAS Eur. Phys. J. C 81 (2021) 1023	139	Fully data-driven		

* $\alpha_S\alpha^3$ EW contributions partially accounted for (only real emission contribution)

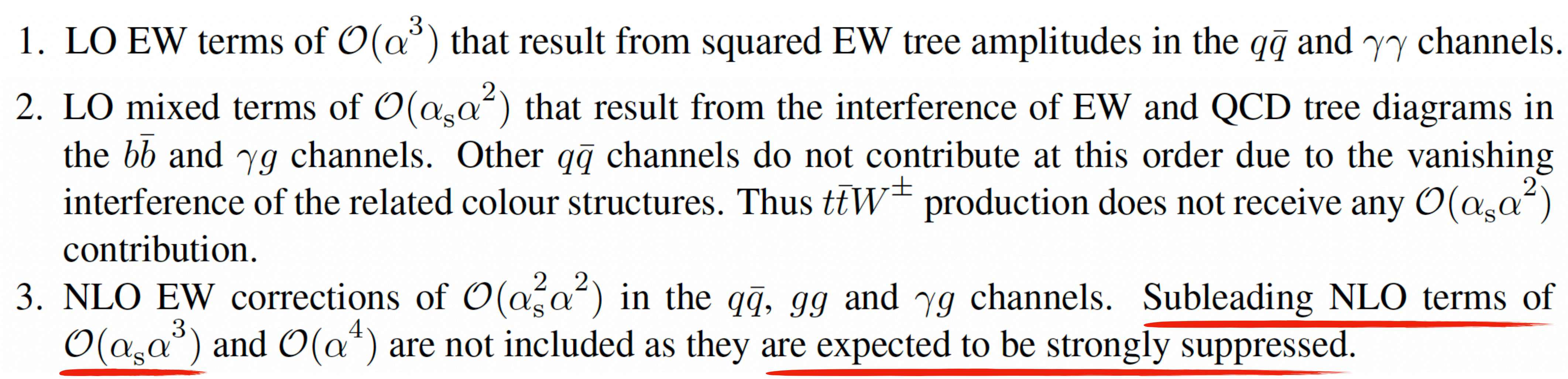
YR4 $t\bar{t}W$ reference cross section [2017]

- Handbook of LHC Higgs Cross Sections: 4 (a.k.a YR4)
- Renormalisation and factorisation scale choice: $\mu_0 = M_\mathrm{t} + M_\mathrm{V}/2\,.$
- Calculation accuracy: $\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}} = \sigma^{\mathrm{NLO}}_{\mathrm{QCD}} + \delta\sigma_{\mathrm{EW}}\,,$
- The NLO QCD cross section



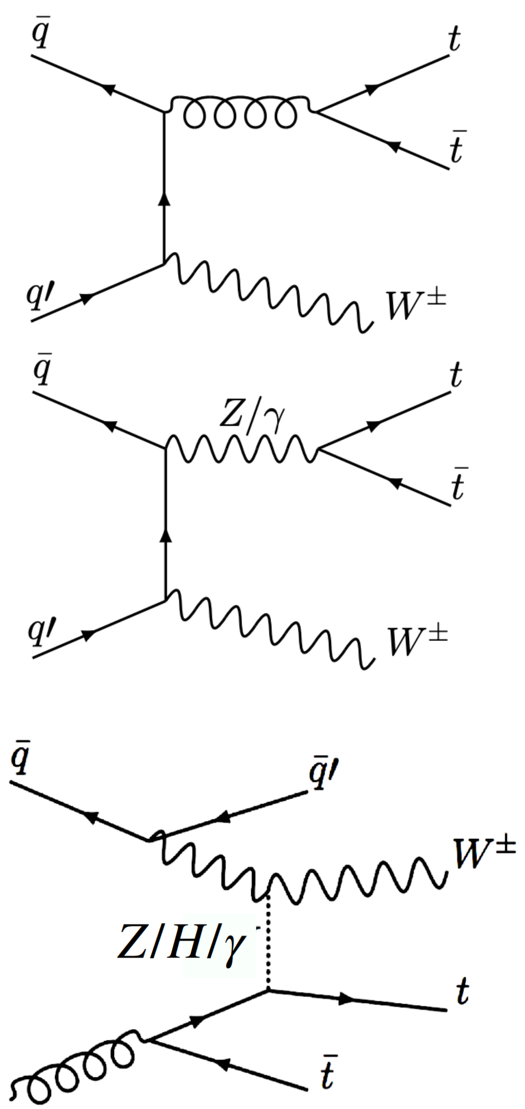
comprises LO terms of $\mathcal{O}(\alpha_\mathrm{s}^2\alpha)$ and NLO QCD corrections of $\mathcal{O}(\alpha_\mathrm{s}^3\alpha)$, which involve gg, $q\bar{q}$ and gq partonic channels. Note that the gg channel starts contributing only at NNLO QCD in the case of $t\bar{t}W^\pm$ production.

- The remaining EW corrections include three types of terms:



1. LO EW terms of $\mathcal{O}(\alpha^3)$ that result from squared EW tree amplitudes in the $q\bar{q}$ and $\gamma\gamma$ channels.
2. LO mixed terms of $\mathcal{O}(\alpha_\mathrm{s}\alpha^2)$ that result from the interference of EW and QCD tree diagrams in the $b\bar{b}$ and γg channels. Other $q\bar{q}$ channels do not contribute at this order due to the vanishing interference of the related colour structures. Thus $t\bar{t}W^\pm$ production does not receive any $\mathcal{O}(\alpha_\mathrm{s}\alpha^2)$ contribution.
3. ✗ NLO EW corrections of $\mathcal{O}(\alpha_\mathrm{s}^2\alpha^2)$ in the $q\bar{q}$, gg and γg channels. Subleading NLO terms of $\mathcal{O}(\alpha_\mathrm{s}\alpha^3)$ and $\mathcal{O}(\alpha^4)$ are not included as they are expected to be strongly suppressed.

$t\bar{t}W$ theory: new findings since 2017



$\mathrm{LO_{QCD}}$: $O(\alpha_s^2\alpha)$
$\mathrm{NLO_{QCD}}$: $O(\alpha_s^3\alpha)$

$\Downarrow$ QCD+EW

LO: $O(\alpha_s^2\alpha) + O(\alpha^3)$

NLO: $O(\alpha_s^3\alpha) + O(\alpha_s^2\alpha^2) + O(\alpha_s\alpha^3) + O(\alpha^4)$

$\downarrow$ Leading effect

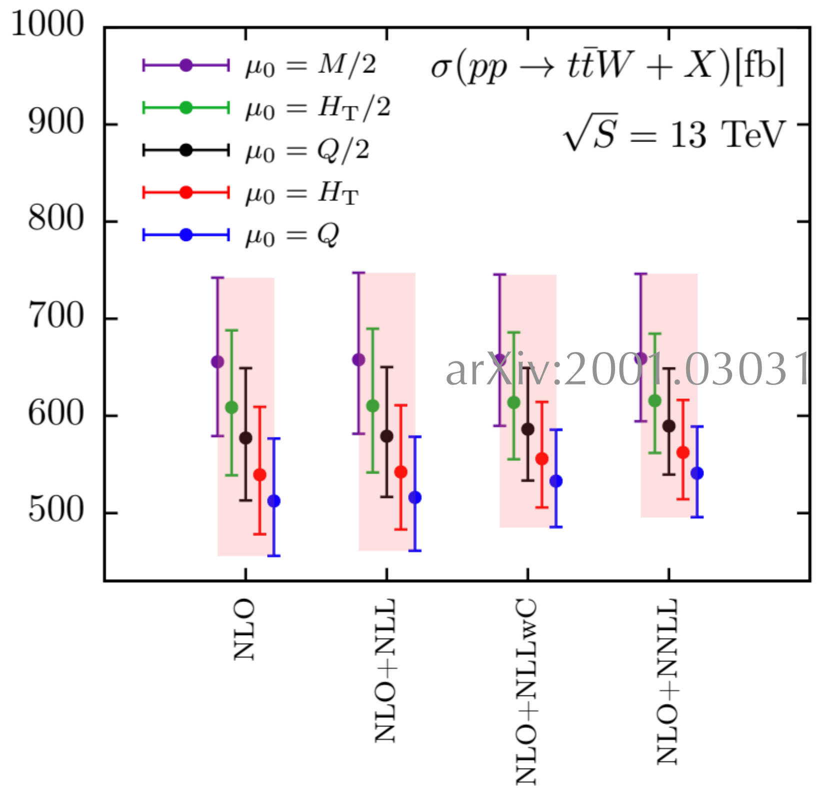
$\downarrow$ Main sub-leading effect ($\sim 6\%$)

Laura Reina, LHC XS WG'21

Large impact of qg radiative processes:
Wt scattering processes opened with NLO QCD+EW corrections

- Important corrections from "subleading" **NLO EW corrections**
  - It has been added by ATLAS and CMS to the reference $t\bar{t}W$ cross section in various ways…

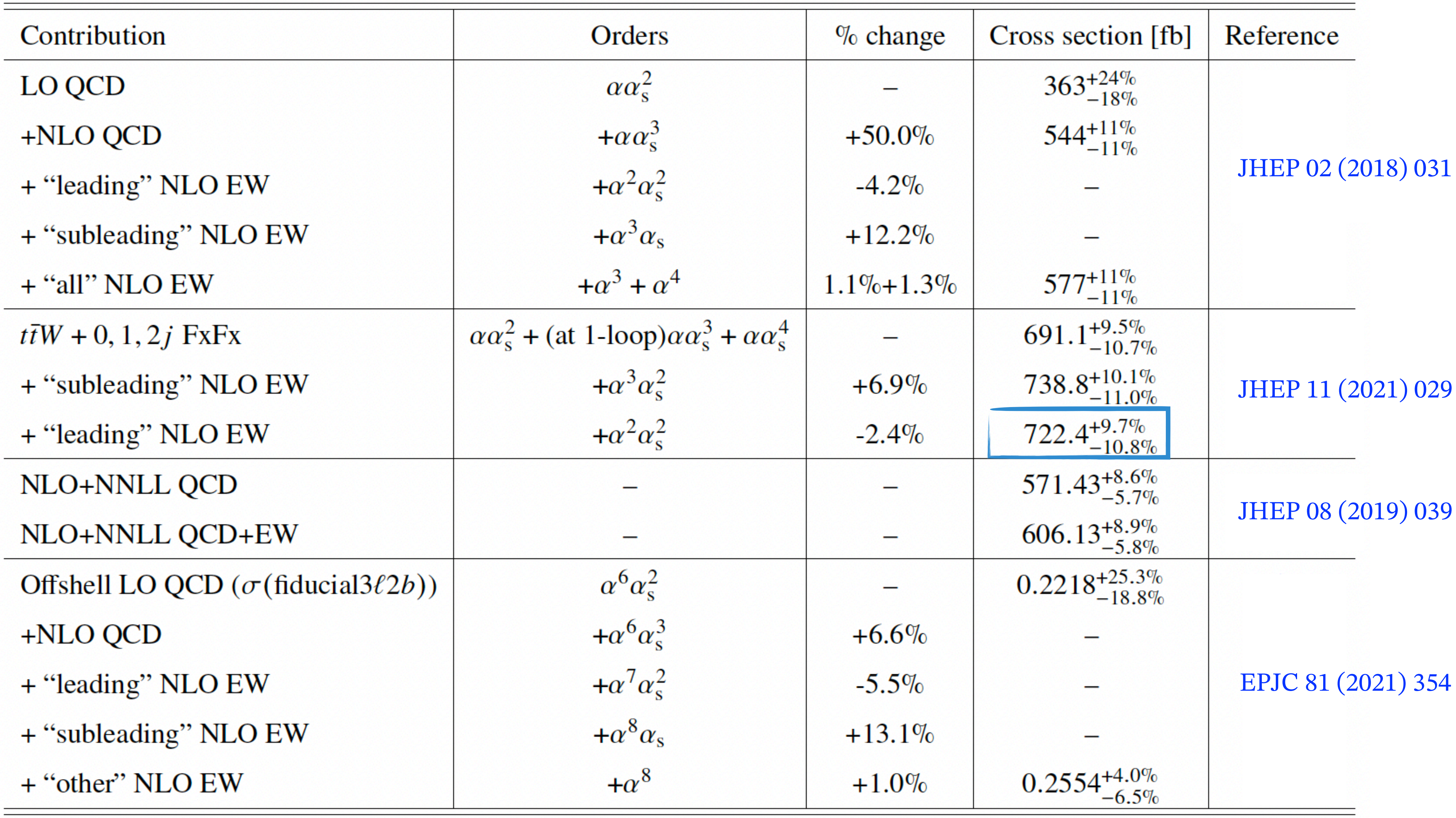
- $t\bar{t}W$ shows **large scale dependence** even after including NLO+NNLL (different from $t\bar{t}H$)
  - Indication of large NNLO QCD corrections?
  - More stability vs scale choice when considering +1,2j@NLO [arXiv:2108.07826]



arXiv:2001.03031

Need a new $t\bar{t}W$ reference cross section

- In addition to important "sub-leading" EW corrections and +0,1j@NLO in $t\bar{t}W$ MC simulations, new $t\bar{t}W$ calculations (e.g. off-shell, NLO+NNLL) and new generators (e.g. Powheg, MG aMC@NLO FxFx) have been made available
  - *We now need to agree on a* ***new $t\bar{t}W$ reference cross section for the LHC****!*



Contribution	Orders	% change	Cross section [fb]	Reference
LO QCD	$\alpha\alpha_s^2$	–	$363^{+24\%}_{-18\%}$	JHEP 02 (2018) 031
+NLO QCD	$+\alpha\alpha_s^3$	+50.0%	$544^{+11\%}_{-11\%}$	
+ "leading" NLO EW	$+\alpha^2\alpha_s^2$	-4.2%	–	
+ "subleading" NLO EW	$+\alpha^3\alpha_s$	+12.2%	–	
+ "all" NLO EW	$+\alpha^3+\alpha^4$	1.1%+1.3%	$577^{+11\%}_{-11\%}$	
$t\bar{t}W+0,1,2j$ FxFx	$\alpha\alpha_s^2$ + (at 1-loop)$\alpha\alpha_s^3+\alpha\alpha_s^4$	–	$691.1^{+9.5\%}_{-10.7\%}$	JHEP 11 (2021) 029
+ "subleading" NLO EW	$+\alpha^3\alpha_s^2$	+6.9%	$738.8^{+10.1\%}_{-11.0\%}$	
+ "leading" NLO EW	$+\alpha^2\alpha_s^2$	-2.4%	$\boxed{722.4^{+9.7\%}_{-10.8\%}}$	
NLO+NNLL QCD	–	–	$571.43^{+8.6\%}_{-5.7\%}$	JHEP 08 (2019) 039
NLO+NNLL QCD+EW	–	–	$606.13^{+8.9\%}_{-5.8\%}$	
Offshell LO QCD (σ(fiducial$3\ell2b$))	$\alpha^6\alpha_s^2$	–	$0.2218^{+25.3\%}_{-18.8\%}$	EPJC 81 (2021) 354
+NLO QCD	$+\alpha^6\alpha_s^3$	+6.6%	–	
+ "leading" NLO EW	$+\alpha^7\alpha_s^2$	-5.5%	–	
+ "subleading" NLO EW	$+\alpha^8\alpha_s$	+13.1%	–	
+ "other" NLO EW	$+\alpha^8$	+1.0%	$0.2554^{+4.0\%}_{-6.5\%}$	

From Josh McFayden

Systematic model tt̄W

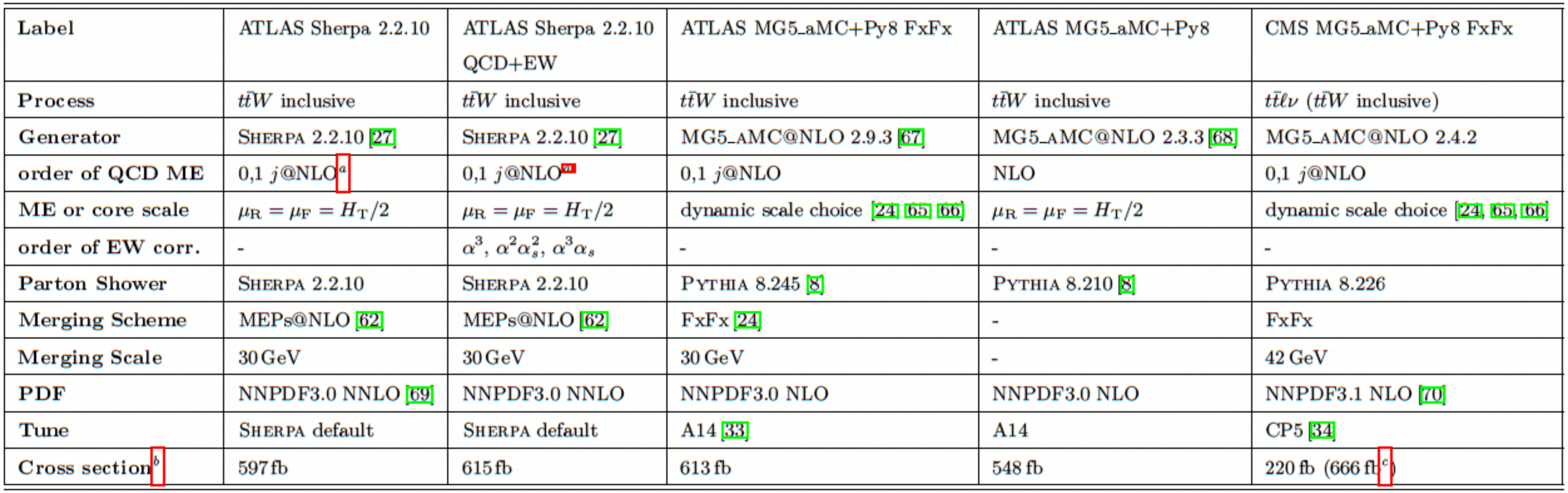
- In addition to updating the tt̄W reference cross section, it's also important to improve the tt̄W systematic model
  - Nominal and **alternative tt̄W ME generator** (`Sherpa, MG aMC@NLO, Powheg`), **PS and hadronisation** (`Sherpa, Pythia8, Herwig7`), and other variations (**ISR, FSR, renormalisation and factorisation scale, PDF**)
  - Multileg generators (`Sherpa, MG aMC@NLO FxFx`) can improve the modelling of the additional jets
  - Some analyses are very sensitive to **tt̄W + ≥1b/c jets**
    - Given the known mismodelling issues with tt̄ + ≥1b/c jets, it would be important to start putting some extra thought on this!
- Input from the theory side on **recommendations** on the **systematic uncertainty model** would be very valuable!
- NLO off-shell contributions are **not** included in the MCs so far
  - Since we don't exclude single- or non-resonant contributions in the analyses, this is missing…
  - Unfortunately, it's very hard to get these corrections at the per-event level. Even corrections to the ME+PS predictions that were derived in e.g. https://arxiv.org/abs/2109.15181 can only be produced **observable by observable** - not straightforward what to do when using e.g. DNNs to separate tt̄W and tt̄H?

Systematic model $t\bar{t}W$

Multiℓ latest analyses	**Nominal $t\bar{t}W$ MC**	**Alternative $t\bar{t}W$ MC**
$t\bar{t}W$ ATLAS Phys. Rev. D 99 (2019) 072009	MG5 aMC@NLO+Pythia8 NLO QCD	Sherpa 2.2 (+1,2j@LO)
$t\bar{t}W$ CMS arXiv:2208.06485	MG5 aMC@NLO 2.6.0+Pythia8 **FxFx** NLO QCD **+** $\alpha_S\alpha^3$ **EW (+0,1j@NLO)**	colour reconnection alternative model
$t\bar{t}H$ ATLAS ATLAS-CONF-2019-045/	Sherpa 2.2.10 NLO QCD **(+0,1j@NLO)**	MG5 aMC@NLO+Pythia8 NLO QCD
$t\bar{t}H$ CMS Eur. Phys. J. C 81 (2021) 378	MG5 aMC@NLO 2.2.2(2.3.3)+Pythia8 **FxFx** NLO QCD **+** $\alpha_S\alpha^3$ **EW (+0,1j@NLO)**	-
$t\bar{t}t\bar{t}$ BSM ATLAS arXiv:2211.01136	Sherpa 2.2.10 NLO QCD (+ EW weights for $\alpha_S^2\alpha^2$ and α^3) **+** $\alpha_S\alpha^3$ **real EW**	MG5 aMC@NLO+Pythia8 NLO QCD **+ LO EW**
$t\bar{t}t\bar{t}$ CMS Eur. Phys. J. C 80 (2020) 75	MG5 aMC@NLO 2.2.2(2.4.2)+Pythia8 **FxFx** NLO QCD **(+0,1j@NLO)**	-
g2HDM ATLAS ATLAS-CONF-2022-039/	Sherpa 2.2.10 NLO QCD (+ EW weights for $\alpha_S^2\alpha^2$ and α^3) **+** $\alpha_S\alpha^3$ **real EW**	MG5 aMC@NLO+Pythia8 NLO QCD **+ LO EW**
SUSY RPV ATLAS Eur. Phys. J. C 81 (2021) 1023	Fully data-driven	

tt̄W ATLAS vs CMS comparisons within the LHC Higgs XS WG

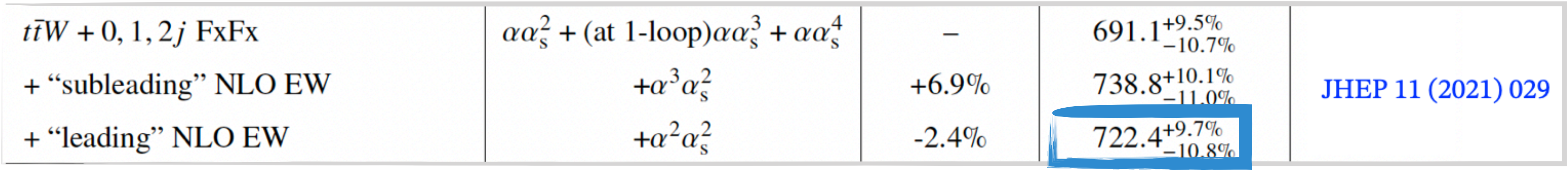
- Dedicated effort to compare Monte Carlo generators of the tt̄W process at particle level
  - Stable final-state particles in a fiducial phase space similar to the experimental measurements in the 2ℓSS channel as implemented in a dedicated routine in the `Rivet` analysis toolkit
- The aim is to compare the modelling of important backgrounds to tt̄H measurements and the treatment of the associated theory uncertainties for a combination of the full Run-2 tt̄H results from ATLAS and CMS
- As a first step, modelling and theory uncertainties as used in ATLAS an CMS are compared in the relevant analysis regions
- **Public note** circulated in July 2022: LHCHWG-2022-003
  - If the tt̄W reference cross section can be agreed quickly this could go into the **final version** *(before posting to arXiv)*



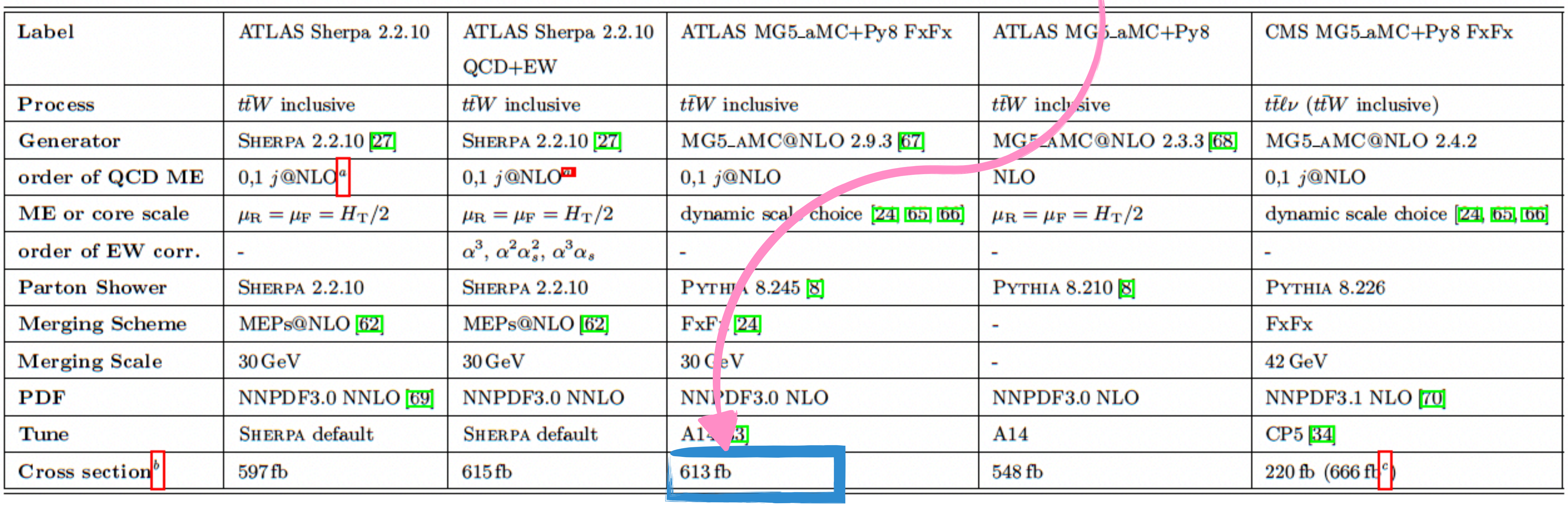
Label	ATLAS Sherpa 2.2.10	ATLAS Sherpa 2.2.10 QCD+EW	ATLAS MG5_aMC+Py8 FxFx	ATLAS MG5_aMC+Py8	CMS MG5_aMC+Py8 FxFx
Process	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}\ell\nu$ ($t\bar{t}W$ inclusive)
Generator	SHERPA 2.2.10 [27]	SHERPA 2.2.10 [27]	MG5_AMC@NLO 2.9.3 [67]	MG5_AMC@NLO 2.3.3 [68]	MG5_AMC@NLO 2.4.2
order of QCD ME	0,1 j@NLO[a]	0,1 j@NLO[a]	0,1 j@NLO	NLO	0,1 j@NLO
ME or core scale	$\mu_R = \mu_F = H_T/2$	$\mu_R = \mu_F = H_T/2$	dynamic scale choice [24, 65, 66]	$\mu_R = \mu_F = H_T/2$	dynamic scale choice [24, 65, 66]
order of EW corr.	-	α^3, $\alpha^2\alpha_s^2$, $\alpha^3\alpha_s$	-	-	-
Parton Shower	SHERPA 2.2.10	SHERPA 2.2.10	PYTHIA 8.245 [8]	PYTHIA 8.210 [8]	PYTHIA 8.226
Merging Scheme	MEPs@NLO [62]	MEPs@NLO [62]	FxFx [24]	-	FxFx
Merging Scale	30 GeV	30 GeV	30 GeV	-	42 GeV
PDF	NNPDF3.0 NNLO [69]	NNPDF3.0 NNLO	NNPDF3.0 NLO	NNPDF3.0 NLO	NNPDF3.1 NLO [70]
Tune	SHERPA default	SHERPA default	A14 [33]	A14	CP5 [34]
Cross section[b]	597 fb	615 fb	613 fb	548 fb	220 fb (666 fb[c])

tt̄W ATLAS vs CMS comparisons within the LHC Higgs XS WG

- Need to urgently understand the disagreement between the cross section derived in *R. Frederix and I. Tsinikos*, "On improving NLO merging for tt̄W production", JHEP 11 (2021) 029 **[722.4 fb]** and in an ~equivalent setup with Sherpa in ATLAS **[613 fb]**

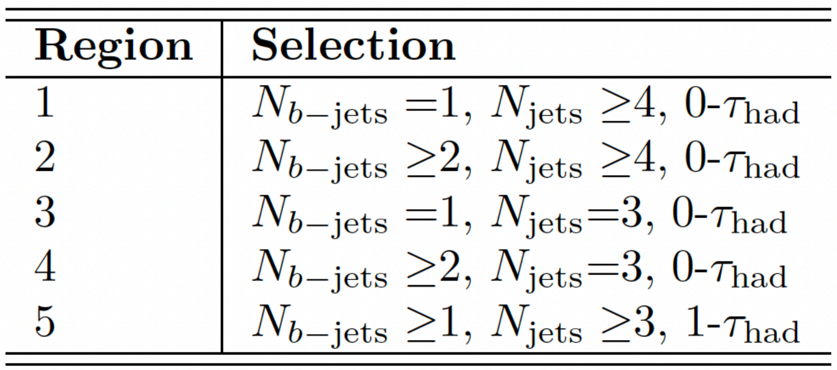


$t\bar{t}W + 0, 1, 2j$ FxFx	$\alpha\alpha_s^2$ + (at 1-loop)$\alpha\alpha_s^3 + \alpha\alpha_s^4$	–	$691.1^{+9.5\%}_{-10.7\%}$	JHEP 11 (2021) 029
+ "subleading" NLO EW	$+\alpha^3\alpha_s^2$	+6.9%	$738.8^{+10.1\%}_{-11.0\%}$	
+ "leading" NLO EW	$+\alpha^2\alpha_s^2$	-2.4%	$722.4^{+9.7\%}_{-10.8\%}$	



Label	ATLAS Sherpa 2.2.10	ATLAS Sherpa 2.2.10 QCD+EW	ATLAS MG5_aMC+Py8 FxFx	ATLAS MG5_aMC+Py8	CMS MG5_aMC+Py8 FxFx
Process	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}W$ inclusive	$t\bar{t}\ell\nu$ ($t\bar{t}W$ inclusive)
Generator	SHERPA 2.2.10 [27]	SHERPA 2.2.10 [27]	MG5_AMC@NLO 2.9.3 [67]	MG5_AMC@NLO 2.3.3 [68]	MG5_AMC@NLO 2.4.2
order of QCD ME	0,1 j@NLO[a]	0,1 j@NLO[a]	0,1 j@NLO	NLO	0,1 j@NLO
ME or core scale	$\mu_R = \mu_F = H_T/2$	$\mu_R = \mu_F = H_T/2$	dynamic scale choice [24, 65, 66]	$\mu_R = \mu_F = H_T/2$	dynamic scale choice [24, 65, 66]
order of EW corr.	-	α^3, $\alpha^2\alpha_s^2$, $\alpha^3\alpha_s$	-	-	-
Parton Shower	SHERPA 2.2.10	SHERPA 2.2.10	PYTHIA 8.245 [8]	PYTHIA 8.210 [8]	PYTHIA 8.226
Merging Scheme	MEPs@NLO [62]	MEPs@NLO [62]	FxFx [24]	-	FxFx
Merging Scale	30 GeV	30 GeV	30 GeV	-	42 GeV
PDF	NNPDF3.0 NNLO [69]	NNPDF3.0 NNLO	NNPDF3.0 NLO	NNPDF3.0 NLO	NNPDF3.1 NLO [70]
Tune	SHERPA default	SHERPA default	A14 [33]	A14	CP5 [34]
Cross section[b]	597 fb	615 fb	613 fb	548 fb	220 fb (666 fb[c])

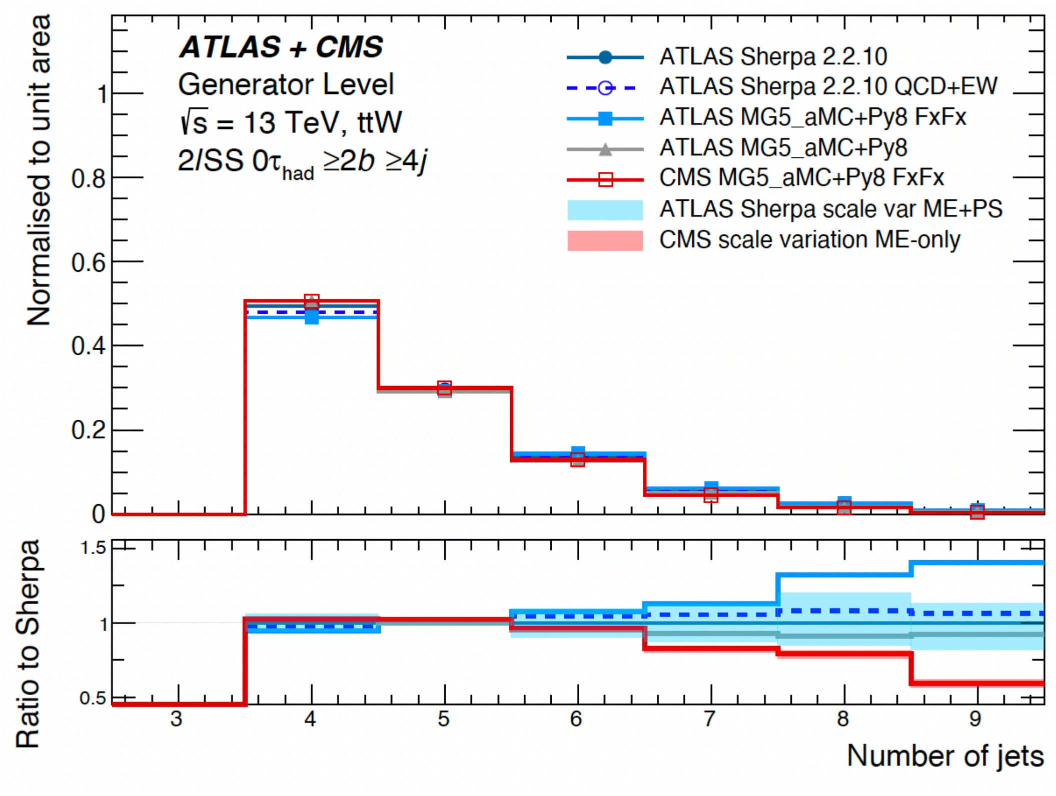
$t\bar{t}W$ ATLAS vs CMS comparisons within the LHC Higgs XS WG

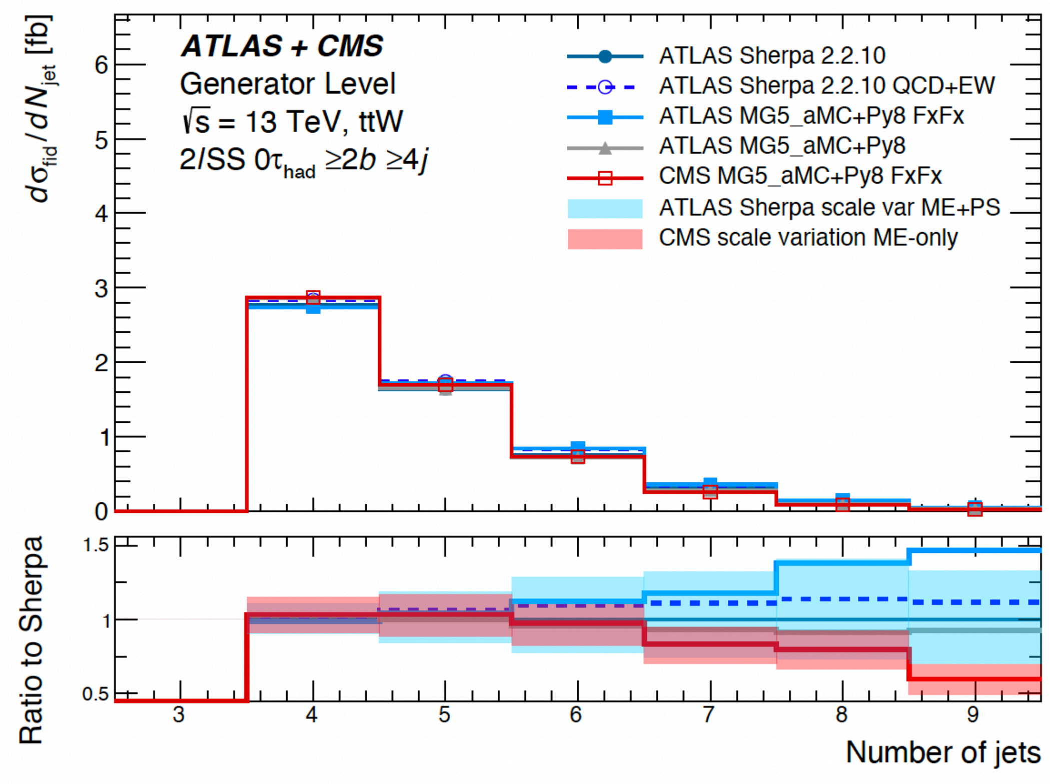


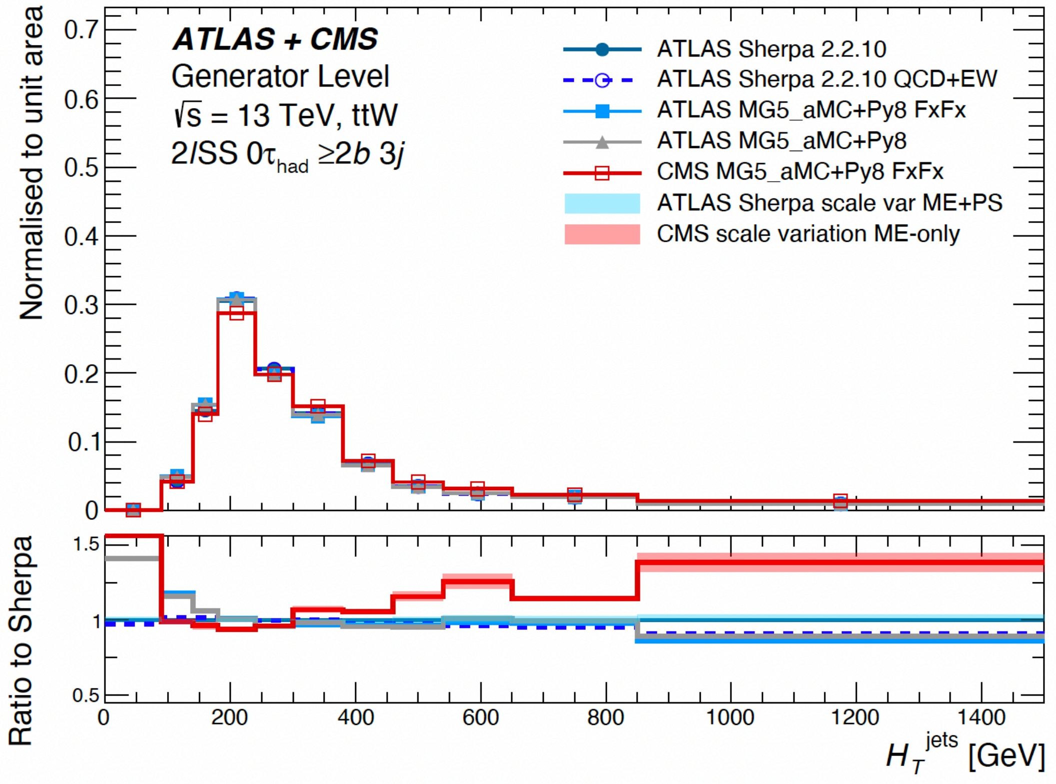
Region	Selection
1	$N_{b-\text{jets}}=1,\ N_{\text{jets}}\geq 4,\ 0\text{-}\tau_{\text{had}}$
2	$N_{b-\text{jets}}\geq 2,\ N_{\text{jets}}\geq 4,\ 0\text{-}\tau_{\text{had}}$
3	$N_{b-\text{jets}}=1,\ N_{\text{jets}}=3,\ 0\text{-}\tau_{\text{had}}$
4	$N_{b-\text{jets}}\geq 2,\ N_{\text{jets}}=3,\ 0\text{-}\tau_{\text{had}}$
5	$N_{b-\text{jets}}\geq 1,\ N_{\text{jets}}\geq 3,\ 1\text{-}\tau_{\text{had}}$

- ATLAS and CMS MG5 aMC@NLO FxFx samples have opposite behaviour of the N_{jets} compared to ATLAS Sherpa (!)

considering acceptance effects (normalised to YR4 $t\bar{t}W$ XS except for Sherpa)

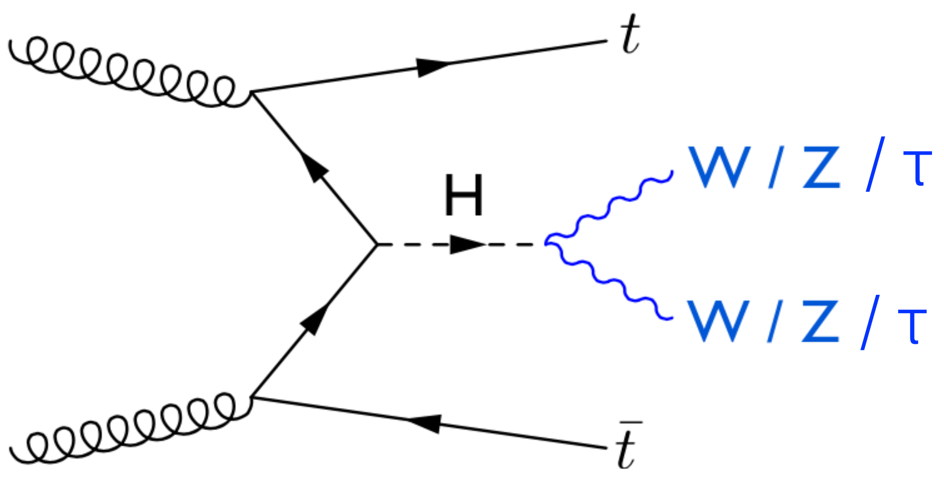






tt̄H multilepton

ATLAS-CONF-2019-045/
Eur. Phys. J. C 81 (2021) 378

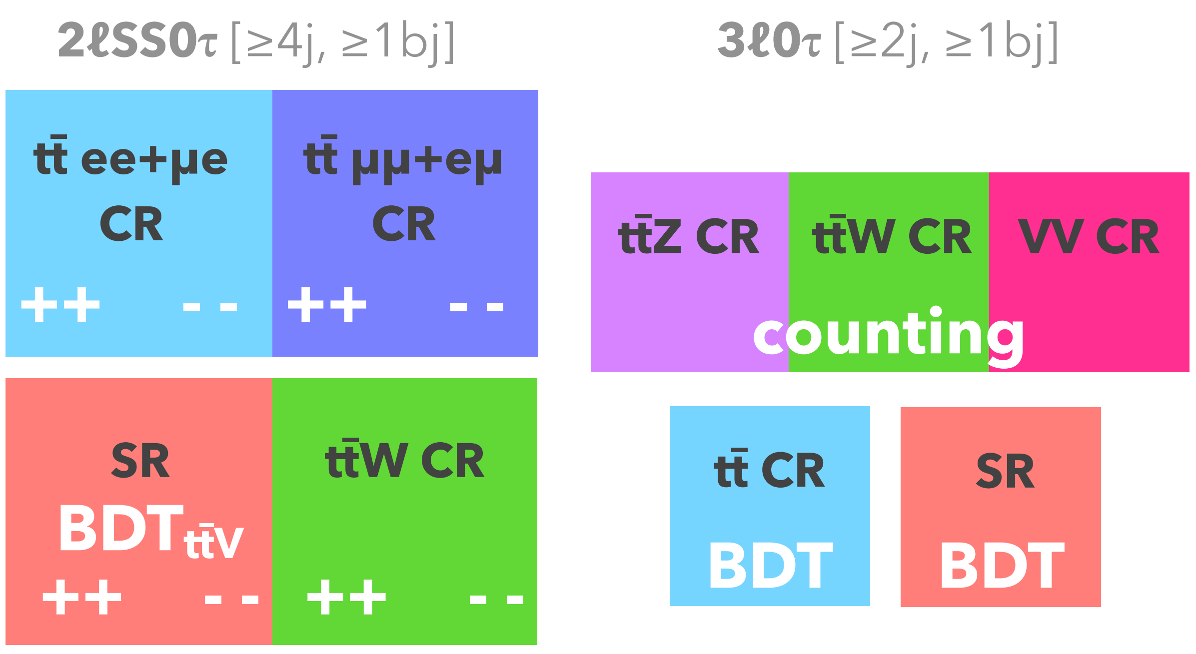


- **Target**: tt̄H with
  - H→WW/ZZ/ττ→≥1ℓ
  - tt̄→(ℓ+jets, dilepton)

→ **“multilepton” final state**

- **Rare in SM:** same-sign 2ℓ, 3ℓ, 4ℓ
- Main irreducible backgrounds are: tt̄Z, tt̄W, VV
- Simultaneous profile likelihood fit of SRs and CRs to data: free-floating tt̄H signal strength and background normalisation factors (e.g. tt̄W)

Categorisation of SRs and CRs based on **one- or multidimensional classification BDTs/DNNs**



2ℓSS0τ [≥4j, ≥1bj]

tt̄ ee+μe CR **++ - -**	**tt̄ μμ+eμ CR** **++ - -**
SR BDT$_{tt̄V}$ **++ - -**	**tt̄W CR** **++ - -**

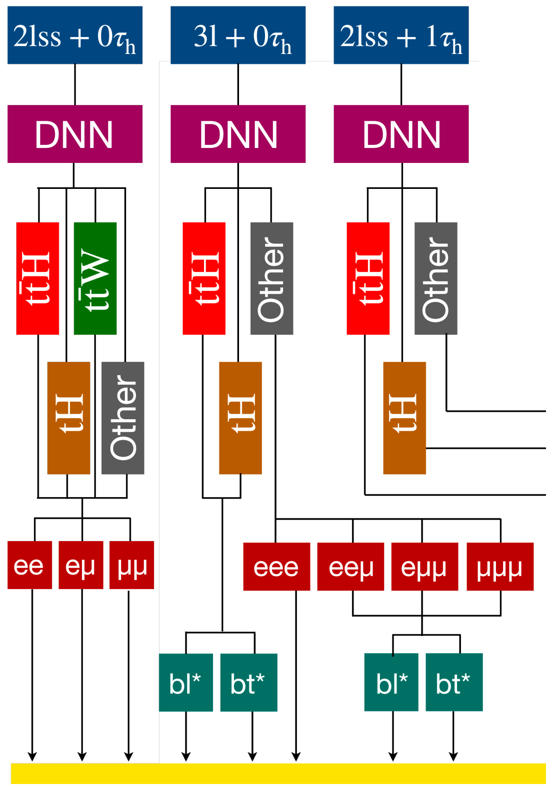
3ℓ0τ [≥2j, ≥1bj]

tt̄Z CR	**tt̄W CR**	**VV CR**

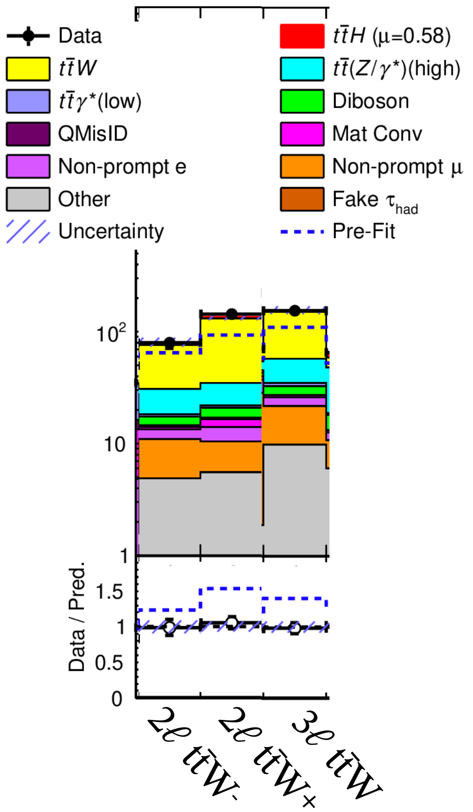
counting

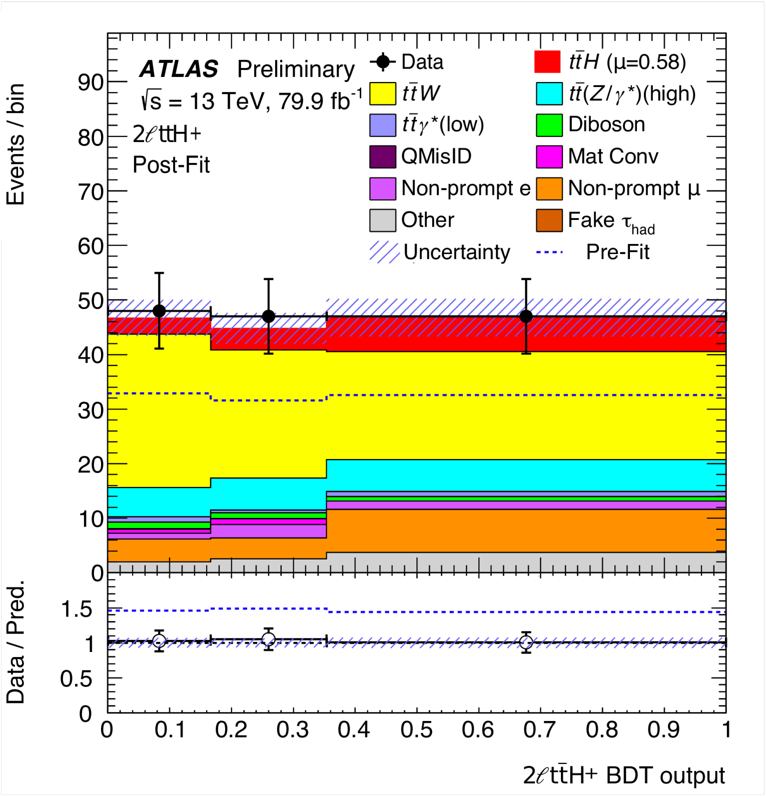
tt̄ CR **BDT**	**SR** **BDT**

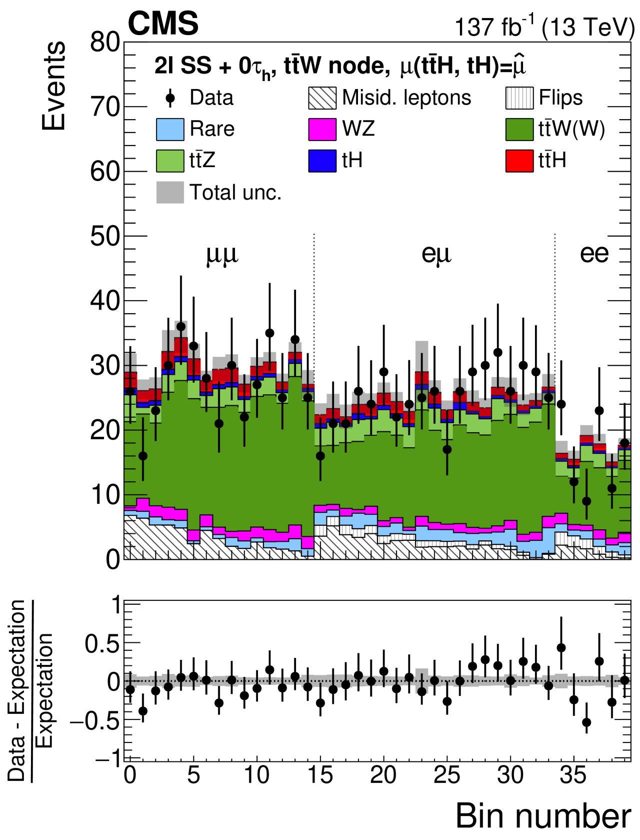
+ additional non-prompt ℓ-enriched CRs with tt̄W contamination

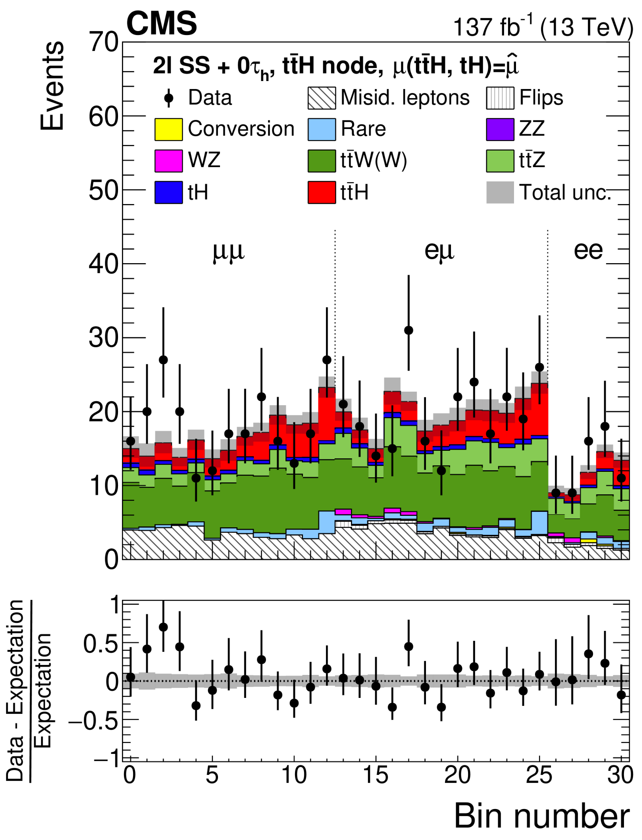


$t\bar{t}$H multilepton









Uncertainty source	$\Delta\hat{\mu}$	
Jet energy scale and resolution	+0.13	−0.13
$t\bar{t}(Z/\gamma^*)$ (high mass) modelling	+0.09	−0.09
$t\bar{t}W$ modelling (radiation, generator, PDF)	+0.08	−0.08
Fake τ_{had} background estimate	+0.07	−0.07
$t\bar{t}W$ modelling (extrapolation)	+0.05	−0.05
$t\bar{t}H$ cross section	+0.05	−0.05
Simulation sample size	+0.05	−0.05
$t\bar{t}H$ modelling	+0.04	−0.04
Other background modelling	+0.04	−0.04
Jet flavour tagging and τ_{had} identification	+0.04	−0.04
Other experimental uncertainties	+0.03	−0.03
Luminosity	+0.03	−0.03
Diboson modelling	+0.01	−0.01
$t\bar{t}\gamma^*$ (low mass) modelling	+0.01	−0.01
Charge misassignment	+0.01	−0.01
Template fit (non-prompt leptons)	+0.01	−0.01
Total systematic uncertainty	+0.25	−0.22
Intrinsic statistical uncertainty	+0.23	−0.22
$t\bar{t}W$ normalisation factors	+0.10	−0.10
Non-prompt leptons normalisation factors (HF, material conversions)	+0.05	−0.05
Total statistical uncertainty	+0.26	−0.25
Total uncertainty	+0.36	−0.33

Source	$\Delta\mu_{t\bar{t}H}/\mu_{t\bar{t}H}$ [%]	$\Delta\mu_{tH}/\mu_{tH}$ [%]	$\Delta\mu_{t\bar{t}W}/\mu_{t\bar{t}W}$ [%]	$\Delta\mu_{t\bar{t}Z}/\mu_{t\bar{t}Z}$ [%]
Trigger efficiency	2.3	8.1	1.2	1.9
e, μreconstruction and identification efficiency	2.9	7.1	1.7	3.2
τ_h identification efficiency	4.6	9.1	1.7	1.3
b tagging efficiency and mistag rate	3.6	13.6	1.3	2.9
Misidentified leptons and flips	6.0	36.8	2.6	1.4
Jet energy scale and resolution	3.4	8.3	1.1	1.2
MC sample and sideband statistical uncertainty	7.1	27.2	2.4	2.3
Theory-related sources affecting acceptance and shape of distributions	4.6	18.2	2.0	4.2
Normalization of MC-estimated processes	13.3	12.3	13.9	11.3
Integrated luminosity	2.2	4.6	1.8	3.1
Statistical uncertainty	20.9	48.0	5.9	5.8

4tops multilepton

arXiv:2211.01136

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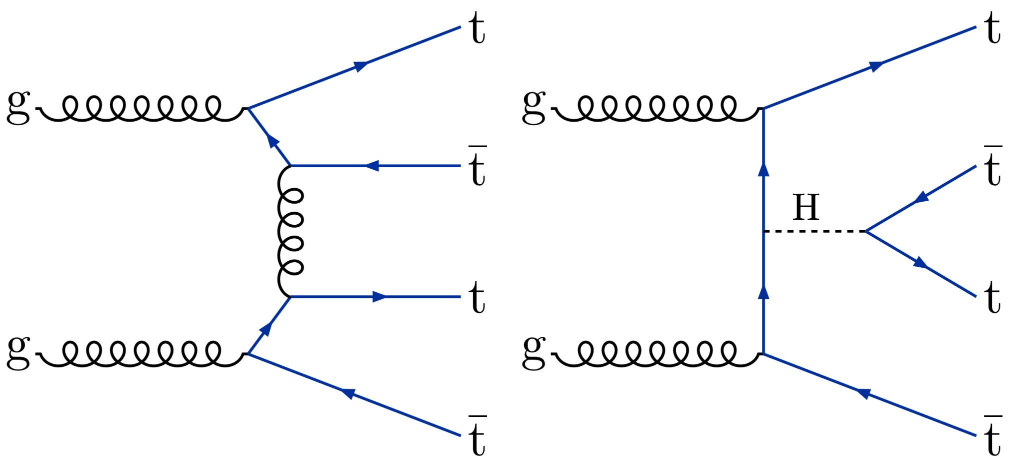


- **Higher jet and b-jet multiplicities** than in tt̄W and tt̄H core analyses
  - Sensitive to the modelling of **tt̄W+jets (light / b / c)**

- SM BDT: SM 4tops vs non-4tops background
- BSM pBDT: BSM 4tops vs SM backgrounds

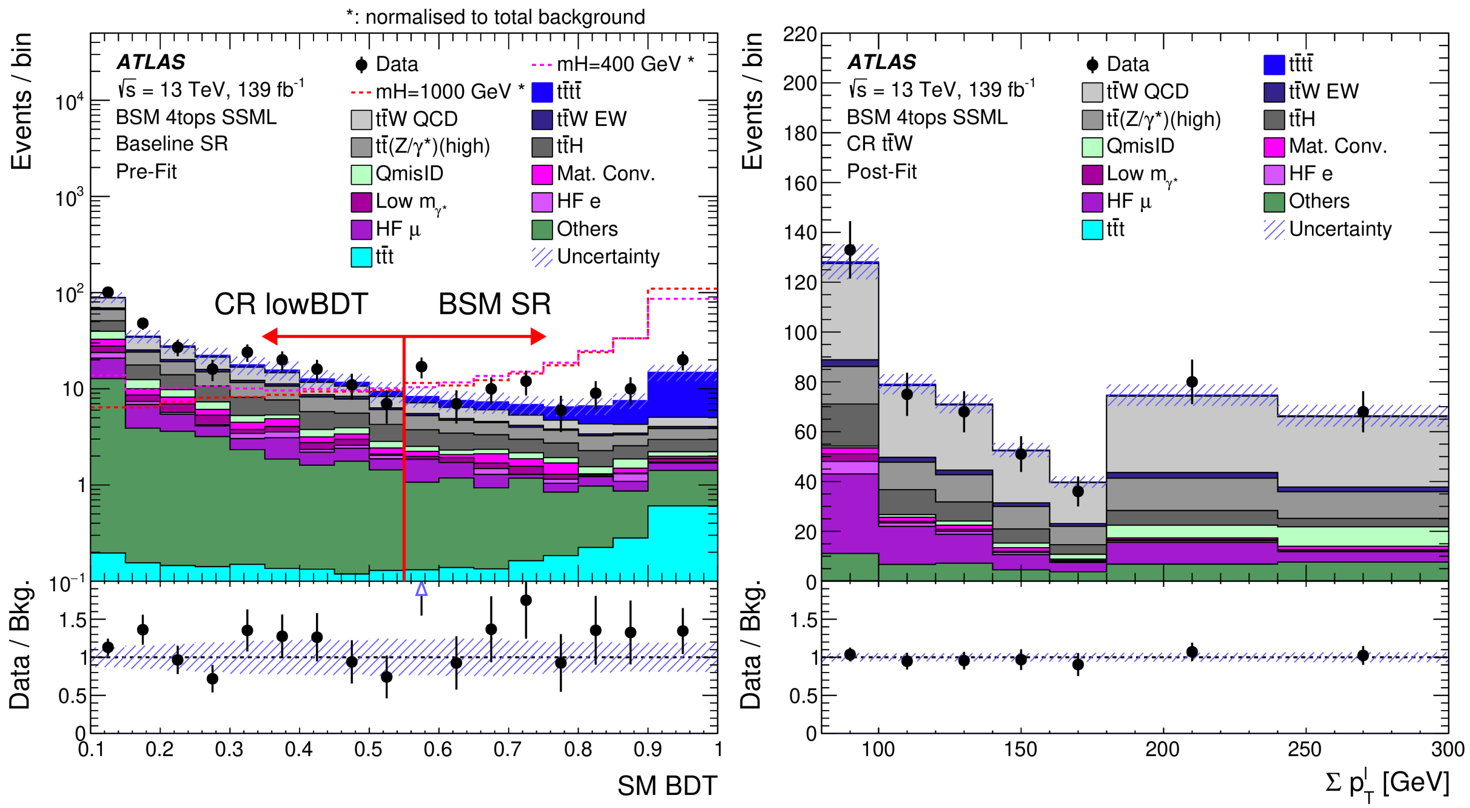
Region	Channel	N_j	N_b	Other selection requirements	Fitted variable
CR $t\bar{t}W$	$e^{\pm}\mu^{\pm} \mid\mid \mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1]$ GeV, $\lvert\eta(e)\rvert < 1.5$ for $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$; for $N_b \geq 3$, $H_T < 500$ GeV	$\sum p_T^{\ell}$

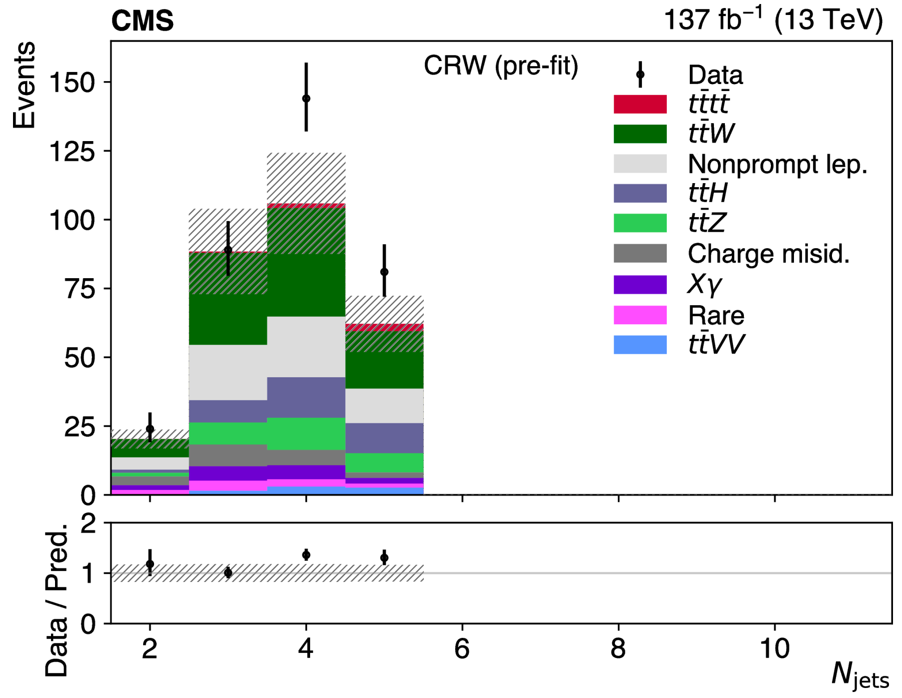
Two analysis strategies:

- Cut-based: lepton / jet / b-jet bins
- BDT-based

Dedicated tt̄W CR (cut-based analysis):

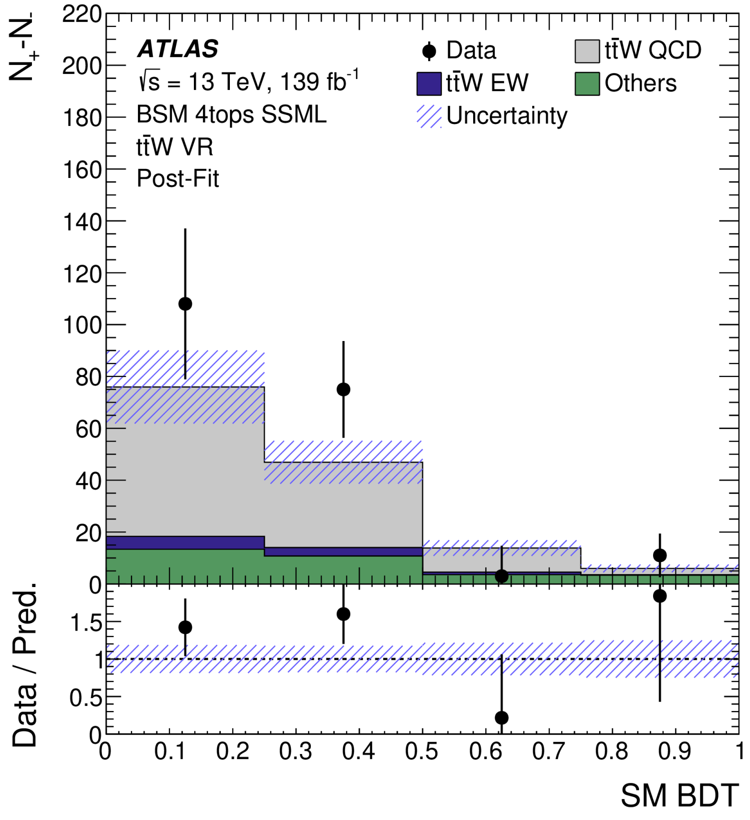
2ℓSS ≤5j, 2bj

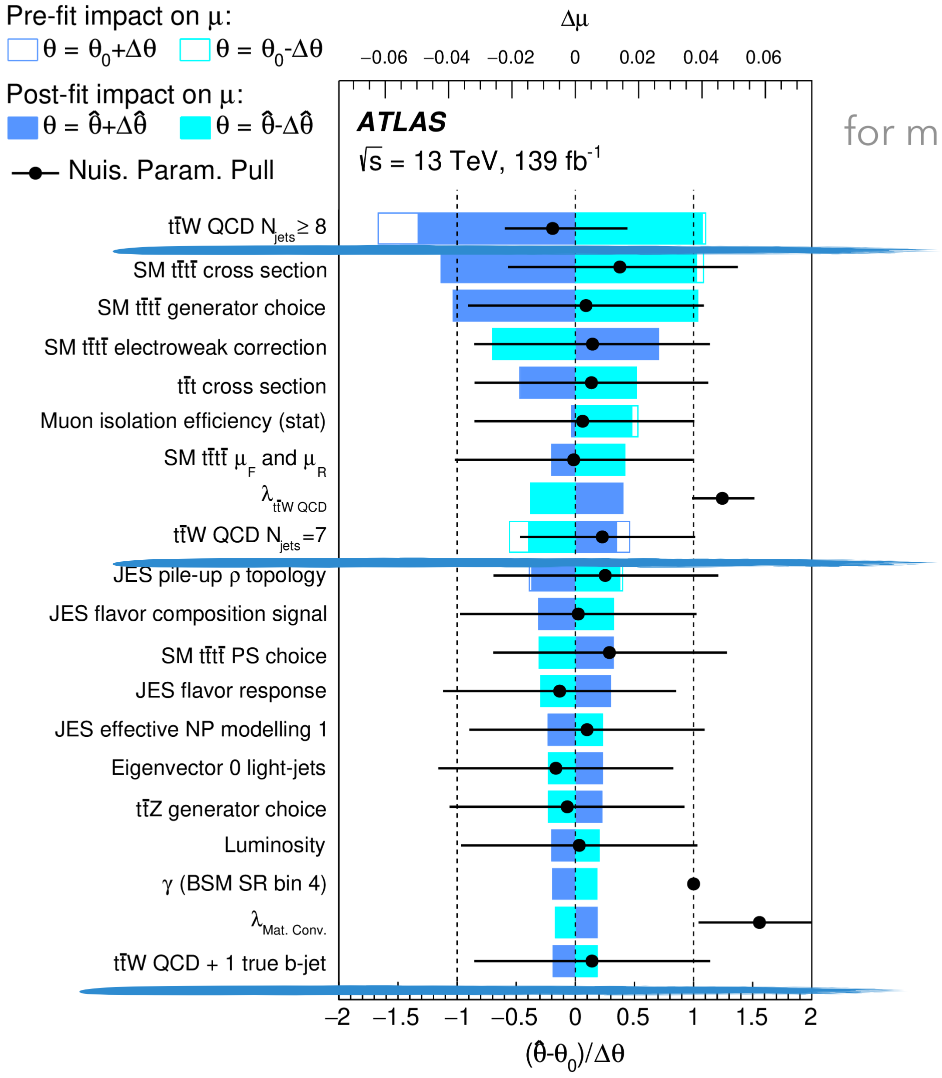




4tops multilepton

- Ad-hoc uncertainties for data/MC non-closure at high N_{jets} (7 and ≥8j) in $(N_+ - N_-)$ $t\bar{t}W$ VR
  - Nuisance parameter with the highest impact on the 4tops-like BSM signal strength!
- $t\bar{t}W$ QCD normalisation free-floated, $t\bar{t}W$ EW "fixed" and constrained by 20% uncertainty
- Uncorrelated 50% uncertainty assigned to $t\bar{t}W$ + 1 true b-jet and $t\bar{t}W$ + ≥ 2 true b-jets





for m_H = 1 TeV

- CMS assigns a $N_{\text{jets}}^{\text{ISR/FSR}}$ **reweighting** to $t\bar{t}W/Z/H$ based on a comparison of the light-flavour jet multiplicity in dilepton $t\bar{t}$ events in data and simulation: [0.77,1.46] for $N_{\text{jets}}^{\text{ISR/FSR}}$ between 1 and 4 (up to 8% uncertainty)
- Additionally, **$t\bar{t}W$+bb** is corrected with a factor of 1.7 based on the measured cross section of $t\bar{t}$+bb and $t\bar{t}$jj (up to 15% uncertainty in SRs)

g2HDM search

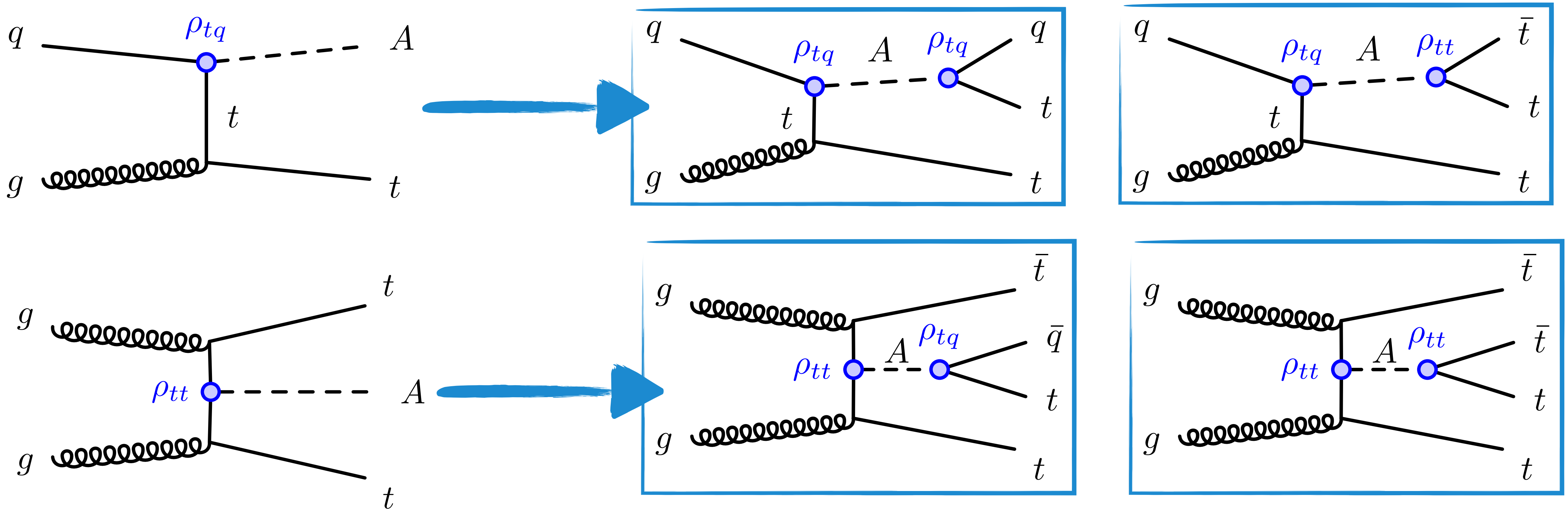
ATLAS-CONF-2022-039/

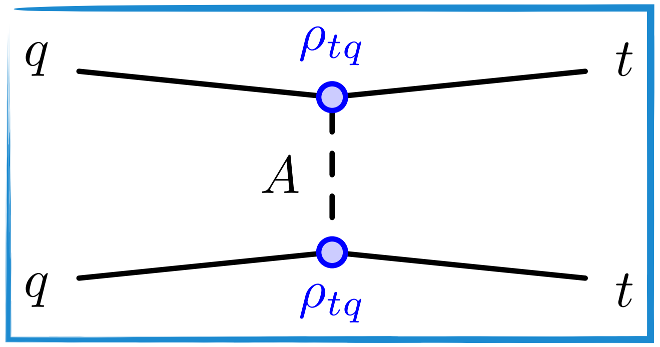
production:

tA, ttA, same-sign tt

production & decay:

ttq, ttt, tttq, tttt





q = u or c

Focusing on diagrams with **ρ_{tu}**, **ρ_{tc}**, and **ρ_{tt}** enabled

Expect **lepton charge asymmetry** from ug and uu initial states

(i.e. tt, ttq, ttt with ρ_{tu} != 0)

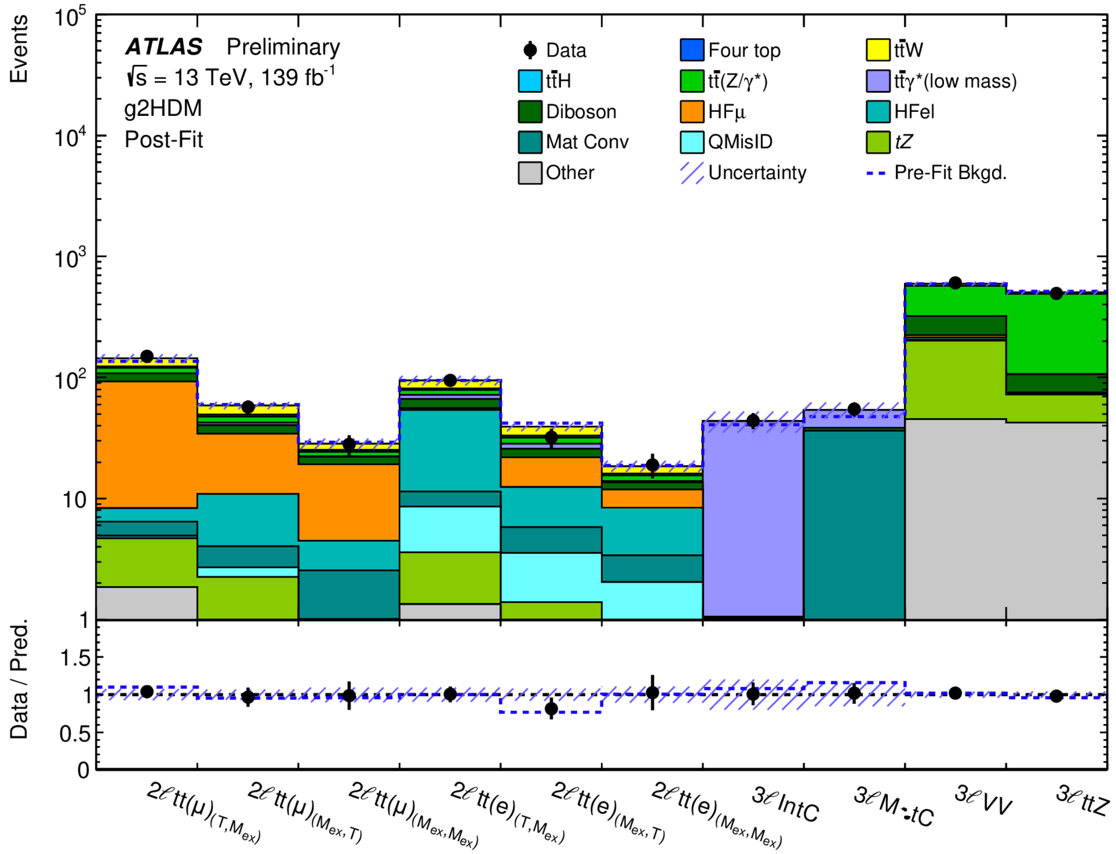
→ tt̄W crucial SM background to this search!

- NN-based multi-D classification used to categorise (BSM signal A vs BSM signal B)
  - Each category is also split in ++ and - - lepton charges
- Other NN trained in each CAT to discriminate BSM signal vs SM backgrounds

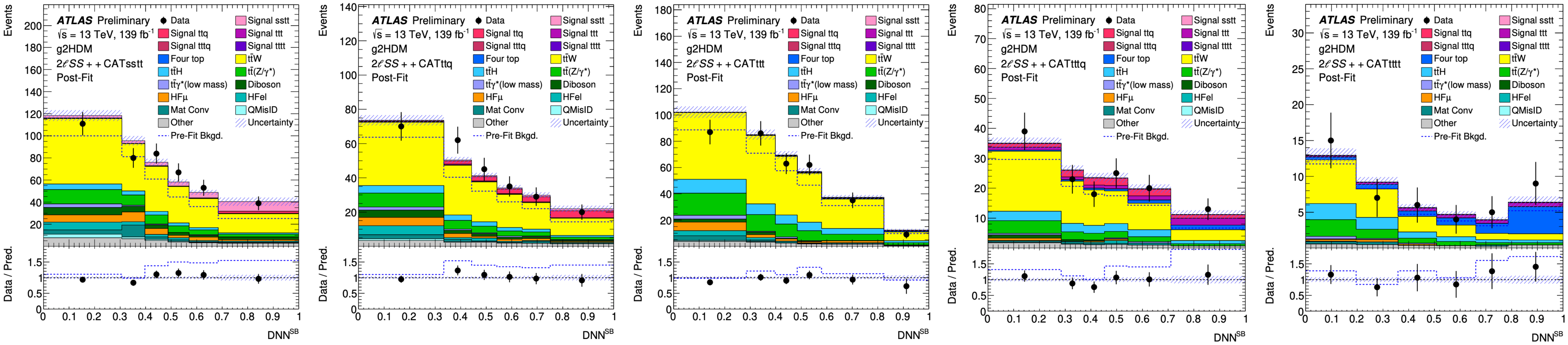
g2HDM multilepton search

- Improved depletion of $t\bar{t}W$ in non-prompt ℓ CRs compared to $t\bar{t}H$ multilepton ATLAS result

- NN provides great discrimination between most of the **BSM g2HDM signals and $t\bar{t}W$**



Systematic uncertainty	Components
Signal modelling	
Cross section (N)	1
$t\bar{t}W$ modelling	
QCD scale	3
Generator	2
Electroweak cross section	1
Additional heavy-flavour	1



SUSY RPV 2ℓSS

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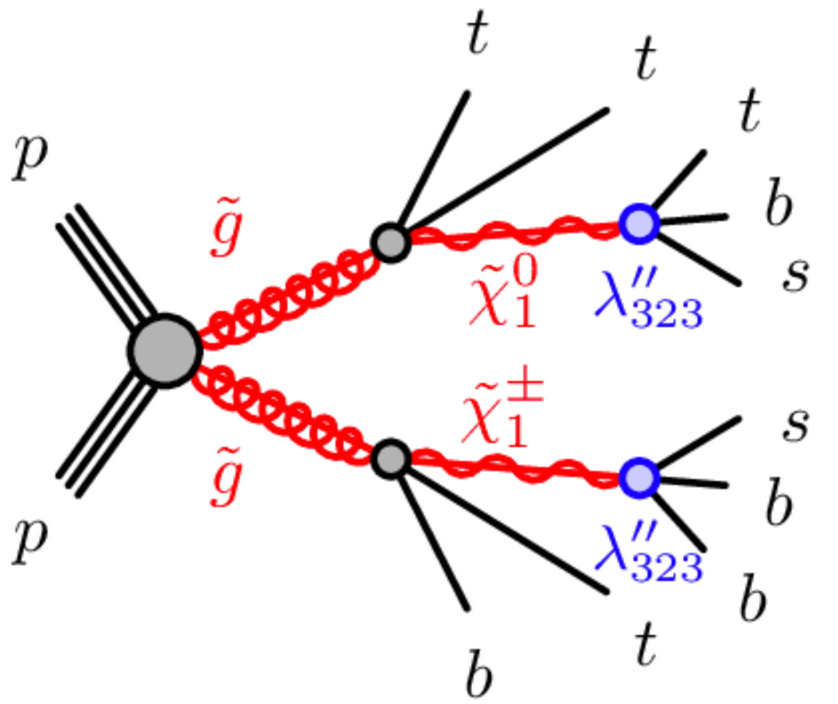
- Search for pair production of SUSY particles with RPV decays with ≥1ℓ, **≥8-15j (many of which can be b-jets)**, and no E_T^{miss}
- In 2ℓSS, main backgrounds from **tt̄W, tt̄ with non-prompt ℓ or misidentified electron charge → *tt̄X^SC***
- The theoretical modelling of these backgrounds at high N_{jets} suffers from large uncertainties, so they are estimated from the **data** by extrapolating the N_{bjets} distribution extracted at moderate jet multiplicities to the high jet multiplicities of the search region



Assume a functional form to describe the evolution of the number of background events for process X as a function of the

N_jets / bjets

$$r^X(j) = c_0^X + c_1^X/(j + c_2^X)$$

$$N_j^X = N_4^X \cdot \prod_{j'=4}^{j'=j-1} r^X(j')$$

$$f_{(j+1),b} = f_{j,b} \cdot x_0 + f_{j,(b-1)} \cdot x_1 + f_{j,(b-2)} \cdot x_2$$

$$N_{4,b}^{t\bar{t}\text{+jets}} = N_4^{t\bar{t}\text{+jets}} \cdot f_{4,b}$$

any term with $x_1 \cdot x_1$ is replaced by $x_1 \cdot x_1 \cdot \rho_{11}$

Final free-floating parameters in the fit

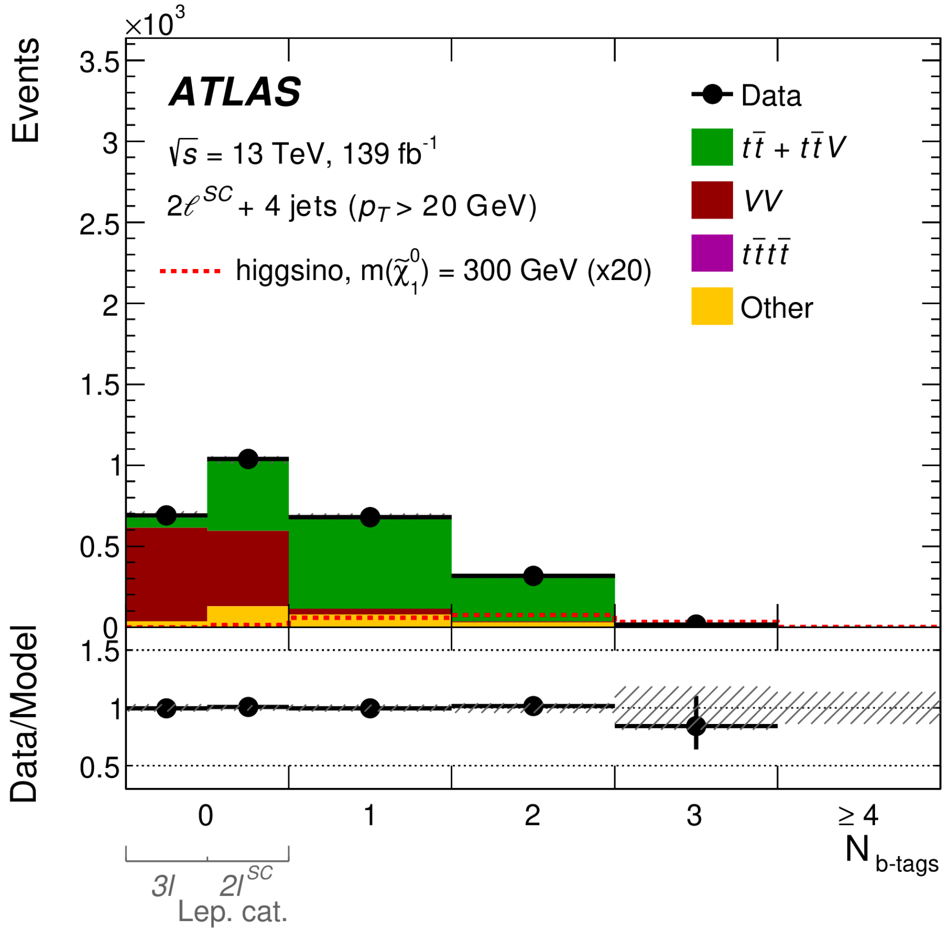
Parameters	$t\bar{t}$ +jets	$t\bar{t}X^{\mathrm{sc}}$	W+jets	Z+jets	VV+jets	Constraints
Normalization	$N_4^{t\bar{t}}$	$N_4^{t\bar{t}X^{\mathrm{sc}}}$	N_4^W	N_4^Z	N_4^{VV}	–
Jet scaling, $i \in \{0,1,2\}$	$c_i^{t\bar{t}}$	$c_i^{t\bar{t}X^{\mathrm{sc}}}$	$c_i^{W/Z}$		c_i^{VV}	$c_2^{W/Z} = c_2^{VV} = 1$
Initial b-jet fractions, $i \in \{0\ldots4\}$	$f_{4,i}^{t\bar{t}}$	$f_{4,i}^{t\bar{t}X^{\mathrm{sc}}}$	–	–	–	$\sum_i f_{4,i} = 1$
Extra heavy-flavour jets, $i \in \{0,1,2\}$	$x_i,\ \rho_{11}$					$\sum_i x_i = 1$
NN shape, $i \in \{1\ldots4\}$, $j \in \{4\ldots8\}$	$n_{j,i}$	–				$\sum_i n_{j,i} = 1$

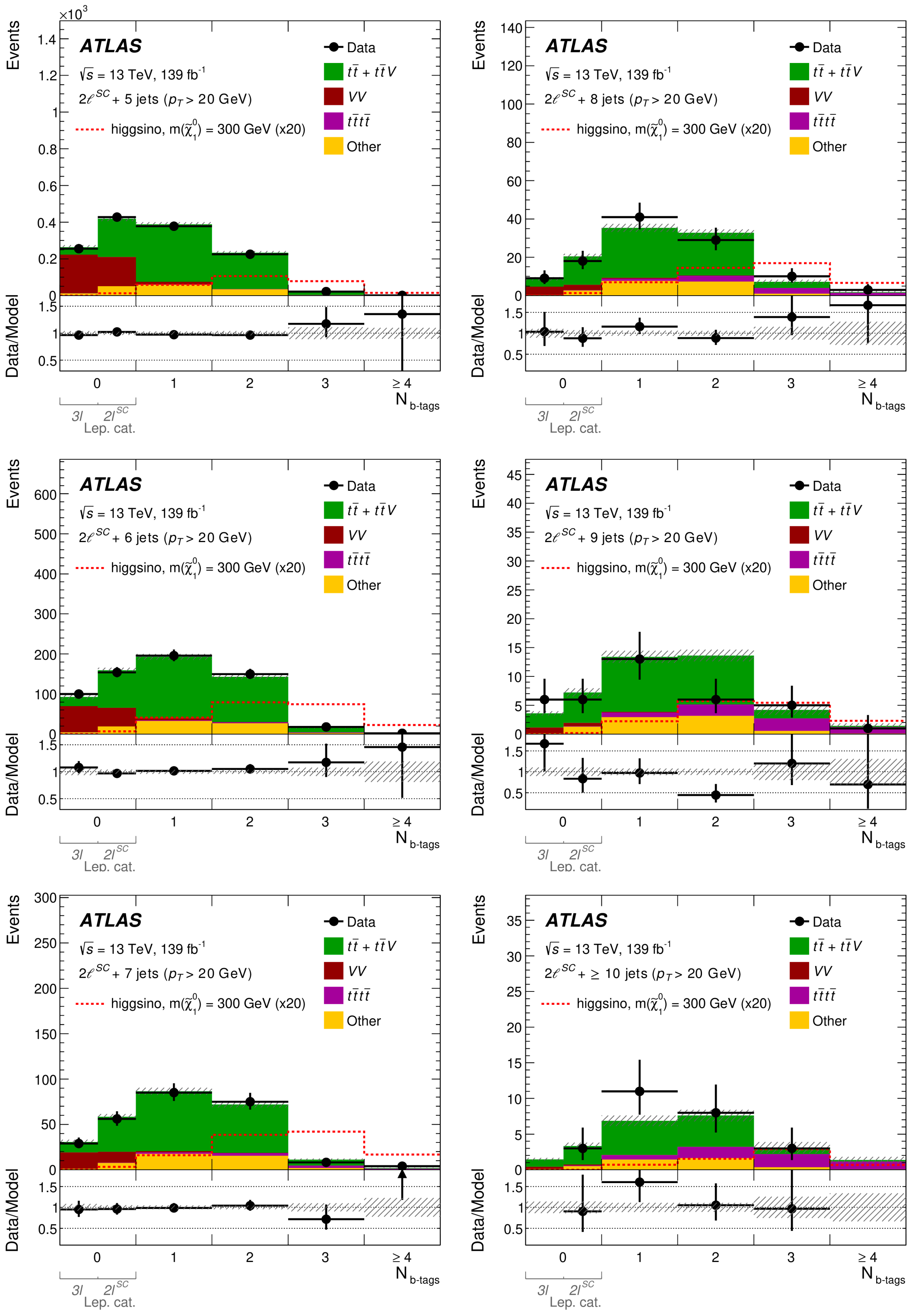
ρ_{11} = correlated production of 2-bjets as expected from gluon splitting

SUSY RPV 2ℓSS

Lepton category	Jet multiplicity	Analysis regions
1ℓ category	$4\ldots7$ jets	$0b\ \ell^-$, $0b\ \ell^+$, $0b\ m_{\ell\ell}$, $1b$, $2b$, $3b$, $\geq 4b$
	$8\ldots\geq N_{\text{last}}^{1\ell}$ jets	$0b$, $1b$, $2b$, $3b$, $\geq 4b$
$2\ell^{\text{sc}}$ category	$4\ldots\geq N_{\text{last}}^{2\ell^{\text{sc}}}$ jets	$0b\ 3\ell$, $0b$, $1b$, $2b$, $3b$, $\geq 4b$

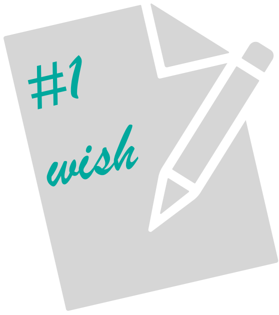
- Excellent data/MC agreement at very high jet and b-jet multiplicities





Conclusion

- **Plethora of new $t\bar{t}W$ calculations:** big thanks to the extraordinary effort from the theory side and Monte Carlo side!



- It is critical that we **update the YR4 $t\bar{t}W$ reference cross section** including these updates

- Similarly, it will be beneficial for both ATLAS and CMS to understand the **differences in the choice of MC generator** (versions, tunes, scales, etc.) and **agree on a minimal set of variations to make a robust systematic model** for $t\bar{t}W$