17th International Workshop on Top Quark Physics
top 2024
September 22 to 27
Saint-Malo, France

t + V

TOP2024 Conference
23.09.2024, St. Malo

Jan van der Linden
on behalf of the
ATLAS and CMS
Collaborations

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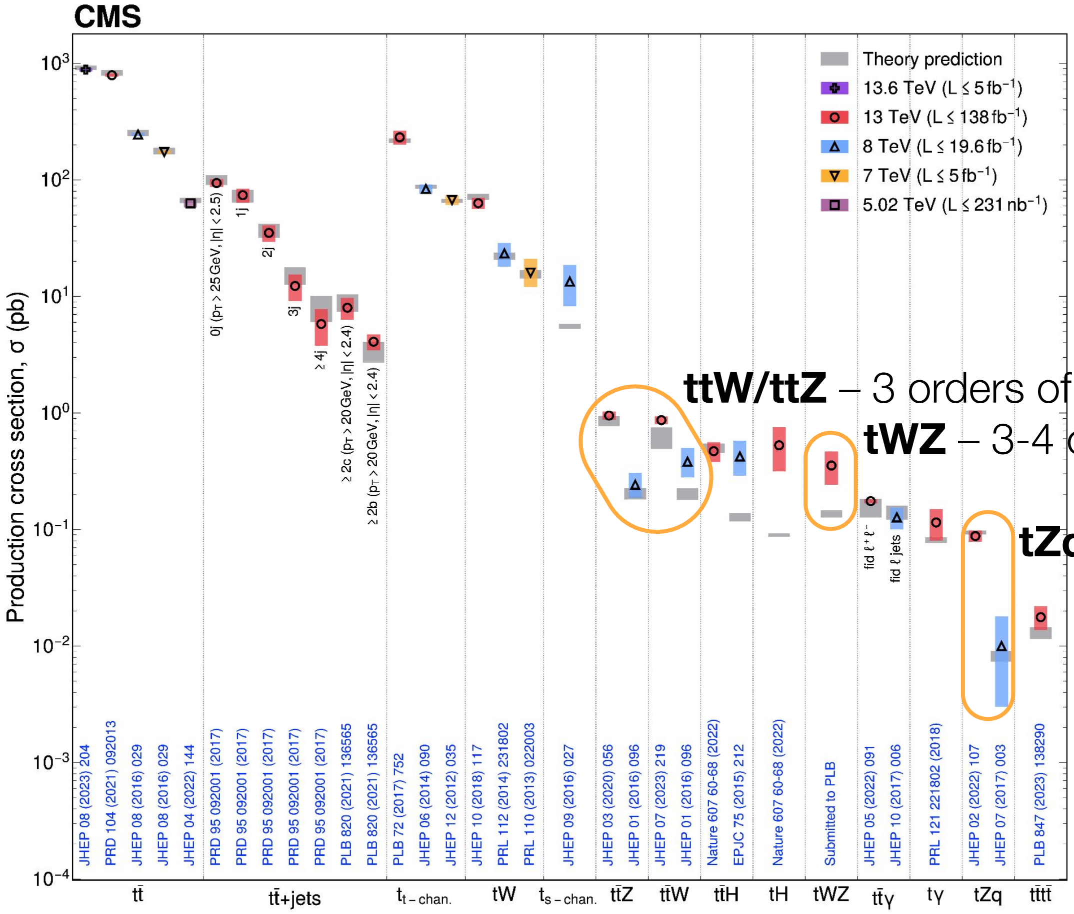
t+V measurements



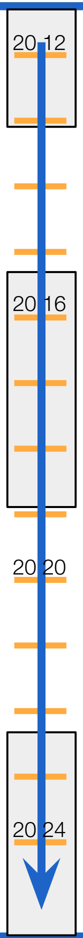
ttW/ttZ – 3 orders of magnitude below tt

tWZ – 3-4 orders below tt

tZq – 5 orders below tt

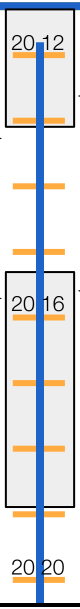
arXiv:2405.18661

Historical analysis of t+V measurements



What did we achieve since the first t+V measurements in Run 1?

Historical analysis of ttZ/ttW measurements



Run 1 ttZ search by ATLAS
(CONF-2012-126)

First ttZ/ttW measurement by CMS
(PRL 110 (172002))

Run 1 ttZ/ttW observation by ATLAS
(JHEP 11 (2015) 172)

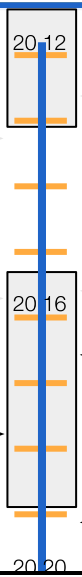
Run 1 ttZ/ttW observation by CMS
(JHEP 01 (2016) 096)

Overlap of processes mostly in 3L regions

Run 1 ttZ/ttW measurement precision
23% / 30% ttZ
27% / 25% ttW

ttW/ttZ analyses performed together

Historical analysis of ttZ/ttW measurements



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Run 2 ttZ/ttW measurement by ATLAS
(PRD 99 (2019) 072009)

2016 ttZ/ttW measurement precision

12% / 13% ttZ

14% / 22% ttW

Both measured cross sections tend to higher values than NLO predictions

Historical analysis of ttZ/ttW measurements

2012

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2020

2LSS regions
(+3L regions)

Separate ttW
measurements

Separate ttZ
measurements

3L+4L regions
OS-SF lepton pairs

Focus on higher individual precision and differential measurements

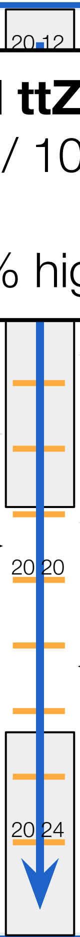

ttZ
t + V

Historical analysis of ttZ measurements

First differential ttZ measurements

8% CMS / 10% ATLAS

Measurements ~10% higher than predictions



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ttZ differential measurement by CMS
(JHEP 03 (2020) 056)

ttZ differential measurement by ATLAS
(EPJC 81 (2021) 737)

Historical analysis of ttZ measurements

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(2017) 40)

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(JHEP 03 (2020) 056)

neasurement by ATLAS
2019) 072009)

Latest ttZ measurement precision

6% CMS (ttZ+tWZ) / 6% ATLAS

Compared to
NLO QCD+EW (12% unc.)
+NNLL corrections (10% unc.)

EPJC 79 (2019) 3

CMS measurement ~10% higher than predictions

ttZ differential measurement by ATLAS
(EPJC 81 (2021) 737)

2024

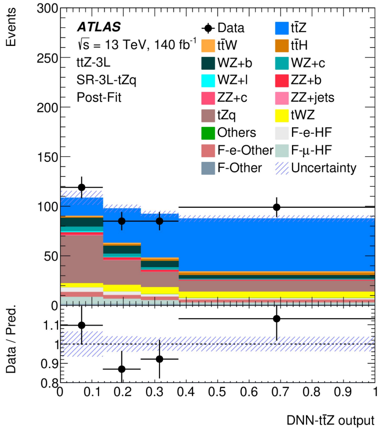
ttZ/tWZ/tZq measurement by CMS
(PAS-TOP-23-004)

ttZ differential measurement by ATLAS
(JHEP 07 (2024) 163)

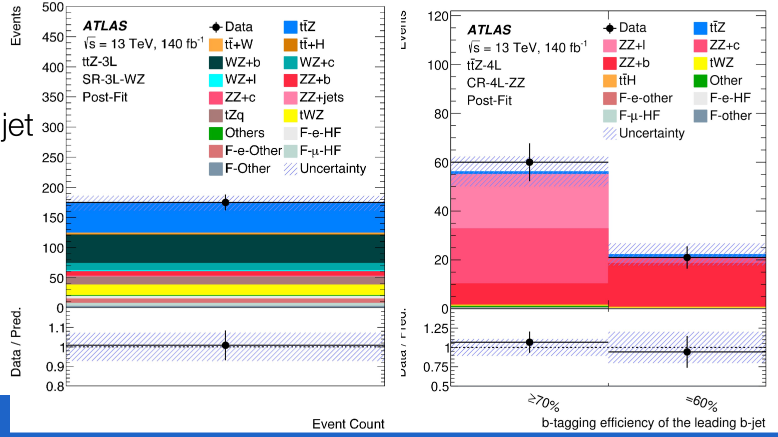
What improved in ttZ?

Latest ATLAS measurements: ~same dataset but improved precision (10% → 6%)

- **Dedicated tZq control region!**
  → better bkg. control and estimation



- **Improved control of ZZ/WZ backgrounds**
  → Unreliable prediction by simulation at high N_{jet}
  → VV + b/c/light split, tagging bins

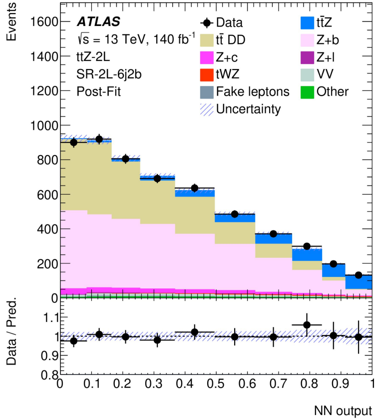


EPJC 81 (2021) 737, JHEP 07 (2024) 163

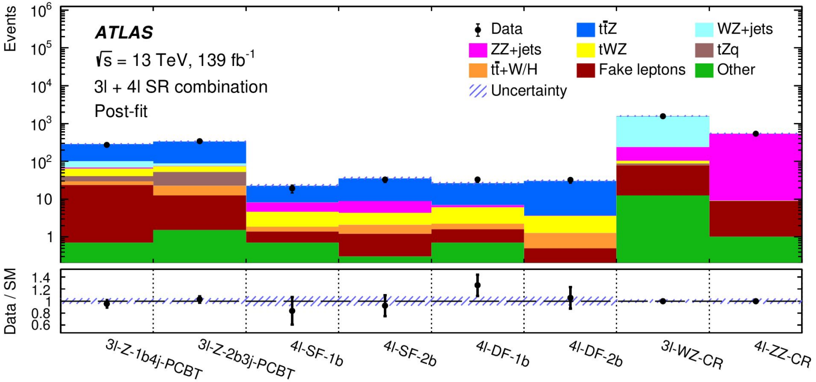
What improved in ttZ?

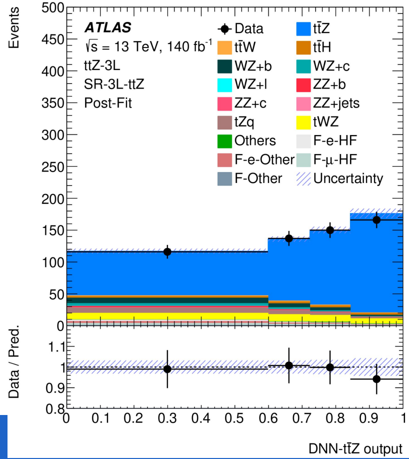
Latest ATLAS measurements: ~same dataset but improved precision (10% → 6%)

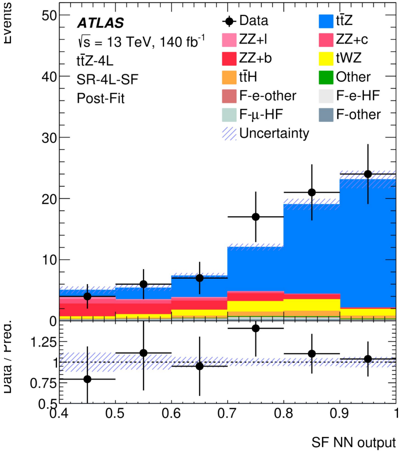
- **Inclusion of 2L SR** (13% precision alone)
  → Difficult prompt backgrounds



- **From fitting yields to DNN distributions**



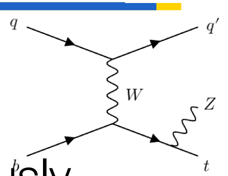




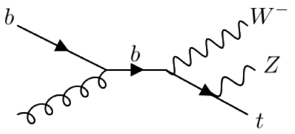
EPJC 81 (2021) 737, JHEP 07 (2024) 163

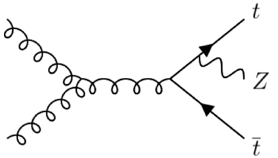
What improved in ttZ?

CMS approach – simultaneous measurements:

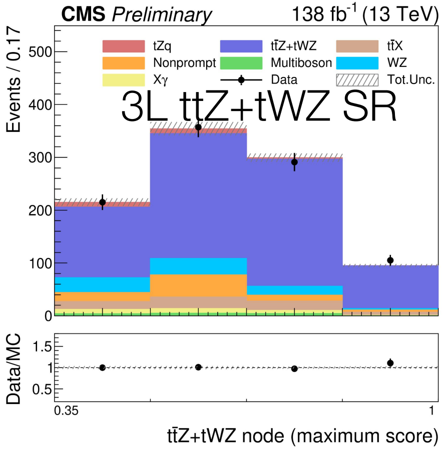


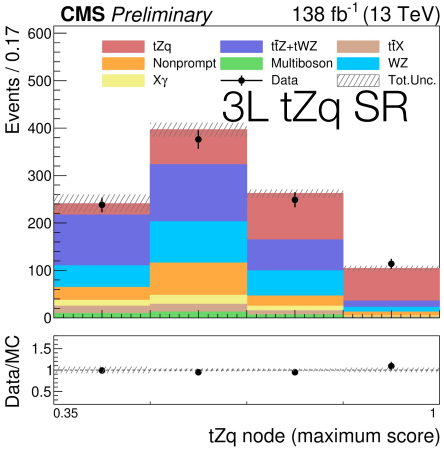
- In 3L: tWZ, tZq backgrounds large impact on results → Measure simultaneously

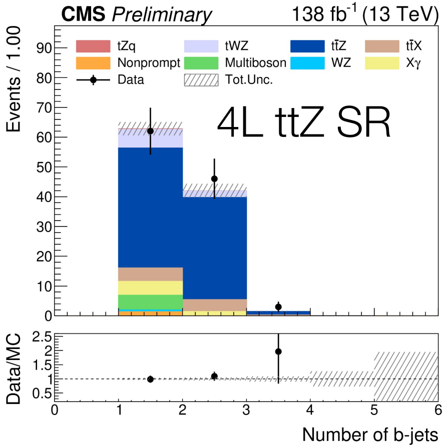


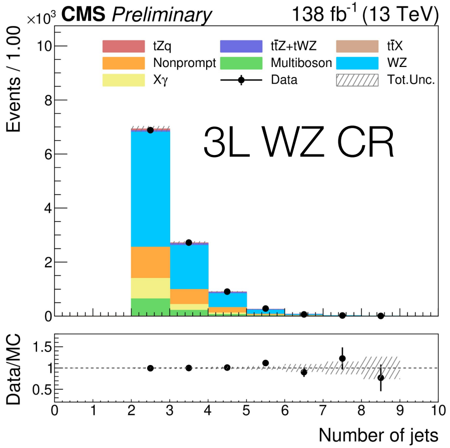


- DNN in 3L signal region → distinguish processes
  - + 4L region for more ttZ, binned in N_b
  - + 3L0b control region for WZ, binned in jet multiplicity







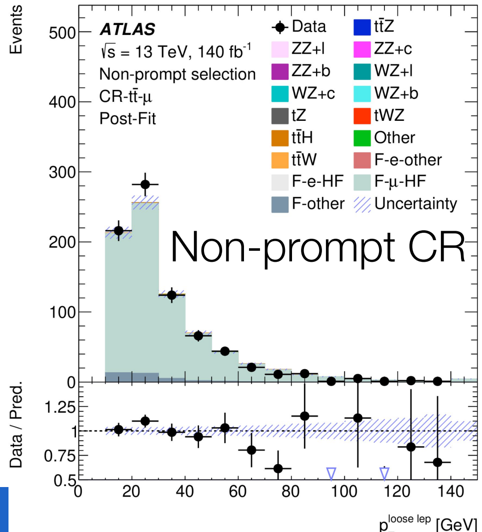


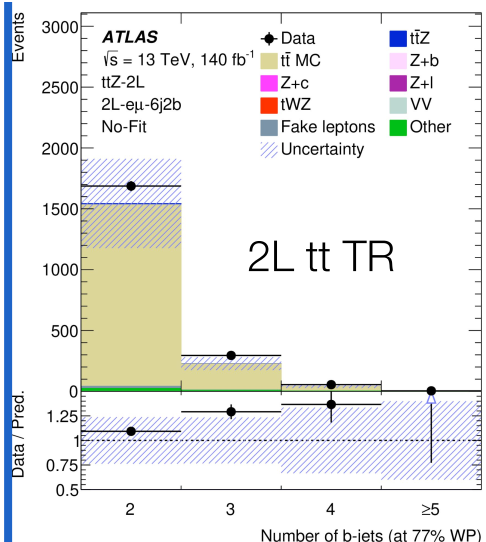
Difficulties of ttZ

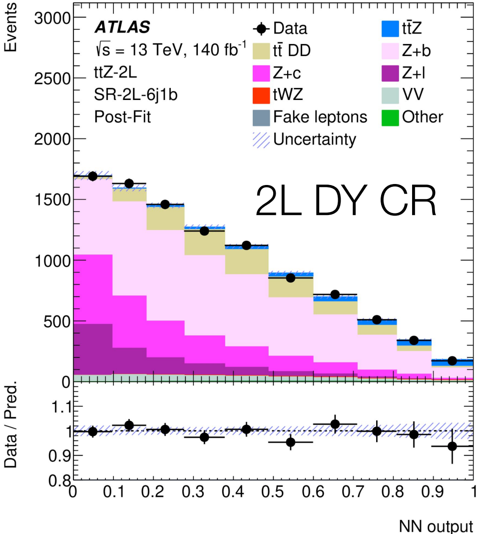
JHEP 07 (2024) 163

Common challenges:

- **Non-prompt background:** fake leptons from tt and DY+jets events
  - Difficult to estimate well from simulation → **data-driven estimations**
- **2L prompt background from tt and DY+jets** → also data-driven
  - Description of tt and DY at high N_{jet} bad → do not want to rely on it
  - tt: eμ transfer region; DY: free-floating parameter for Z+b/c/light







CMS combined results

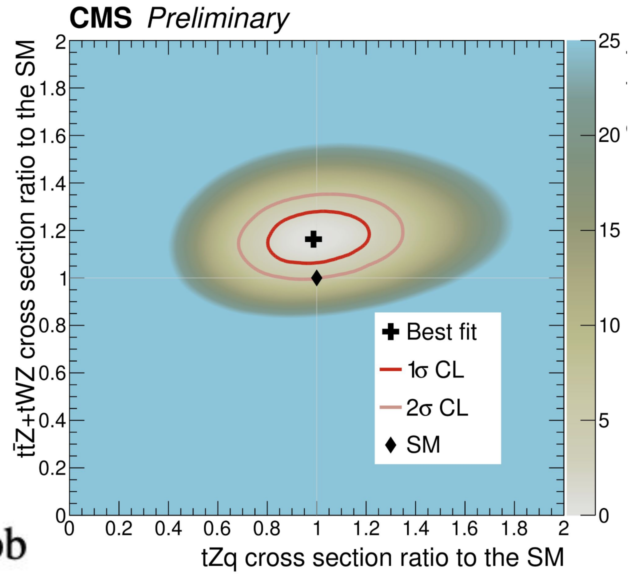
$$\sigma(t\bar{t}Z + tWZ) = 1.14 \pm 0.05\ (\mathrm{stat}) \pm 0.04(\ \mathrm{syst})\ \mathrm{pb},$$
$$\sigma(tZq) = 0.81 \pm 0.07\ (\mathrm{stat}) \pm 0.06\ (\mathrm{syst})\ \mathrm{pb}.$$

Impact of fitting one process without the other

→ tZq, tWZ fixed + norm. unc.: ttZ = $0.99 \pm 0.07\,\mathrm{pb}$

→ tZq fixed, ttZ fixed + norm. unc.: tWZ = $0.39 \pm 0.16\,\mathrm{pb}$

→ tZq fixed + norm. unc.: ttZ+tWZ = $0.88 \pm 0.16\,\mathrm{pb}$



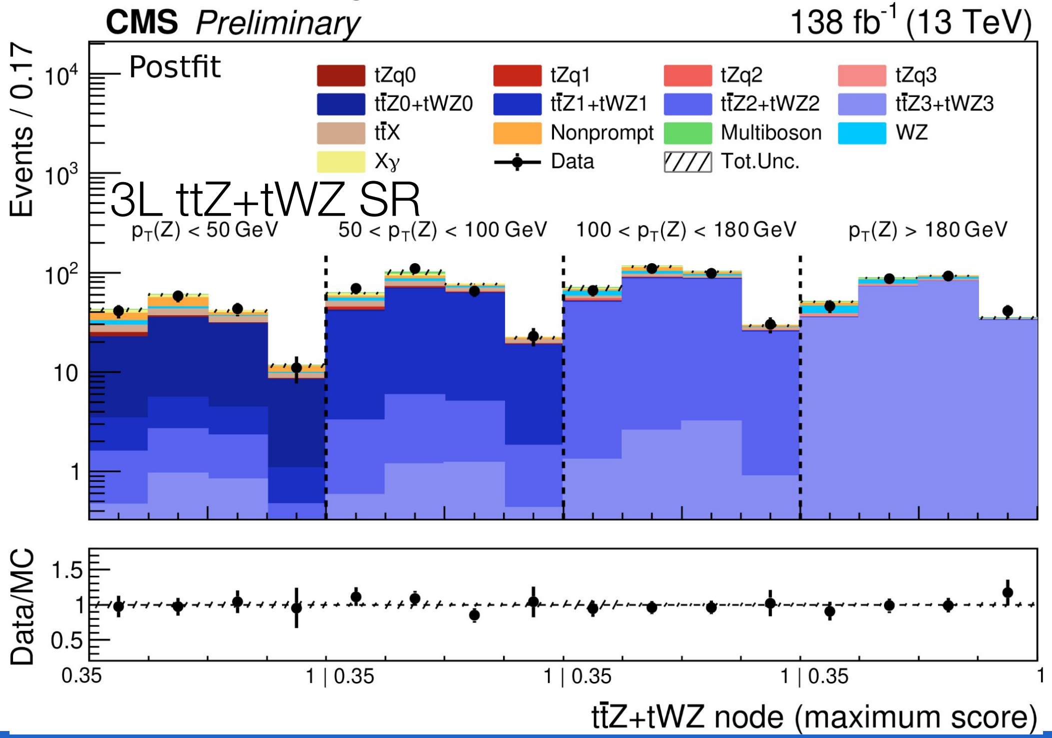
ATLAS result $0.86 \pm 0.05\,\mathrm{pb} = 0.86 \pm 0.04\,(\mathrm{stat.}) \pm 0.04\,(\mathrm{syst.})\,\mathrm{pb}$

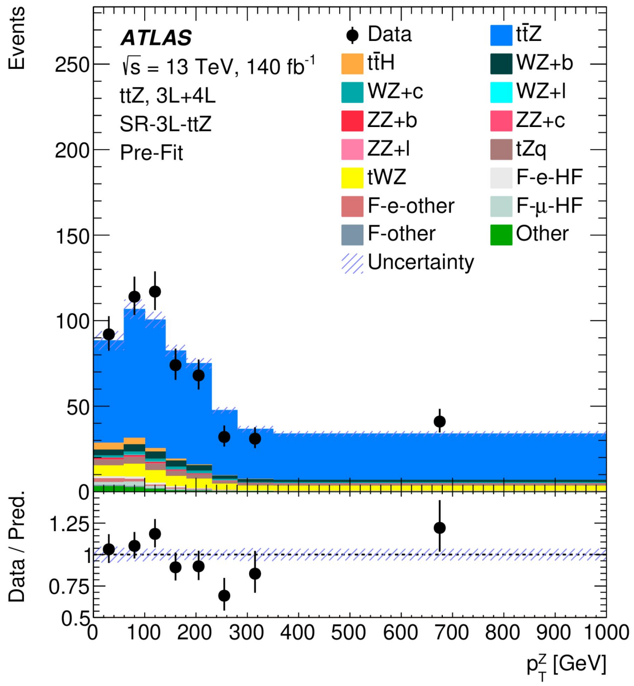
Major limitations

- Data statistics, luminosity
- Background normalizations+modeling, signal modeling
- Calibrations of jets, b-tagging, leptons

Differential ttZ results

- Both ATLAS and CMS – profile LLH unfolding
  - CMS uses DNN-binning for additional sensitivity and ttZ / tZq / bkg. separation
  - Only 3L region for diff. XS in CMS (tZq and tWZ negligible in 4L)





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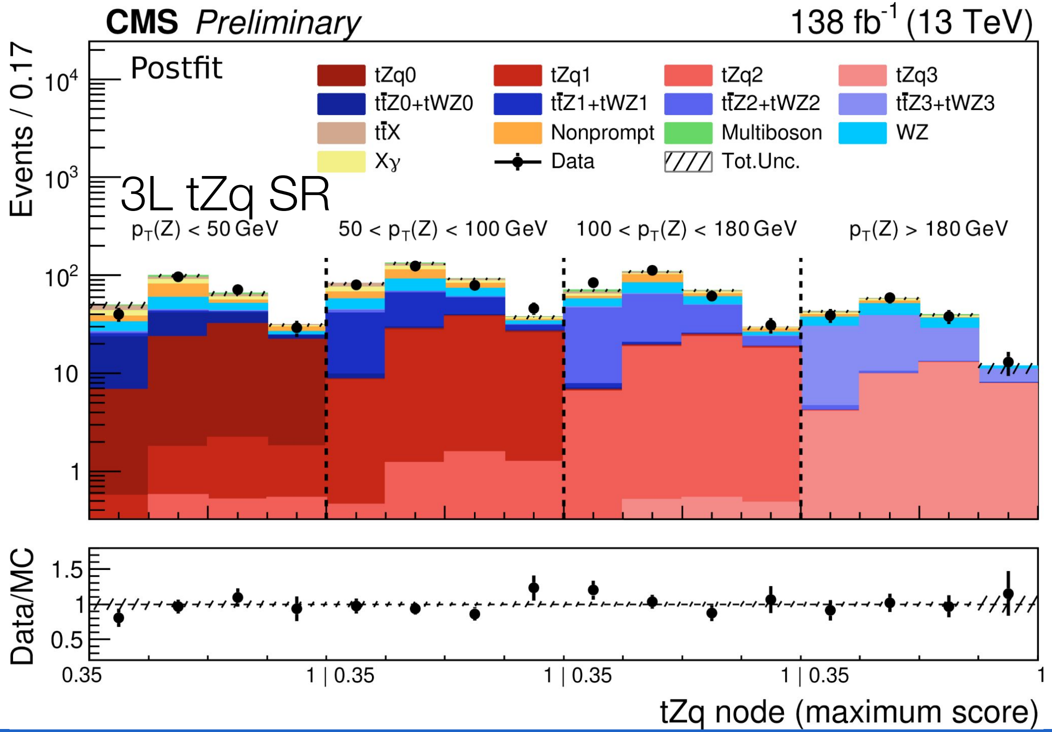
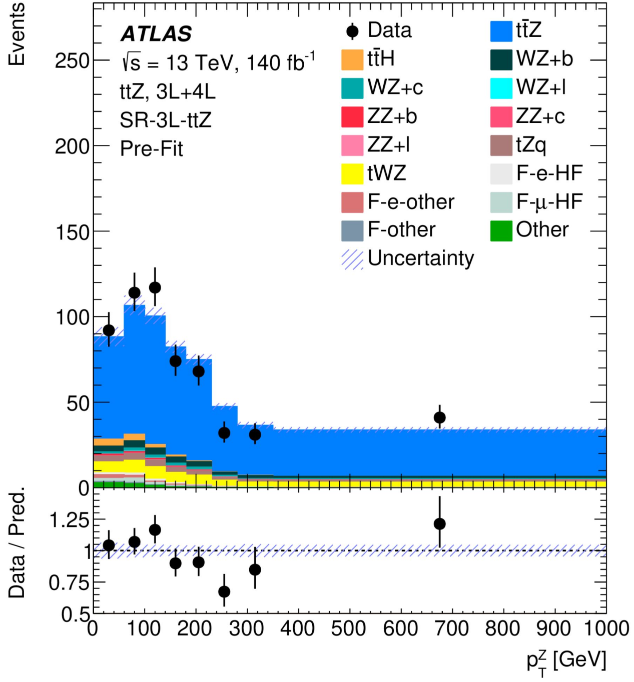
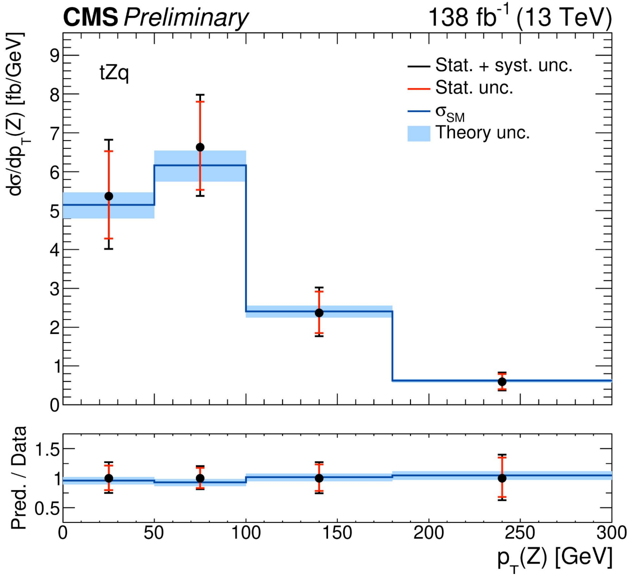
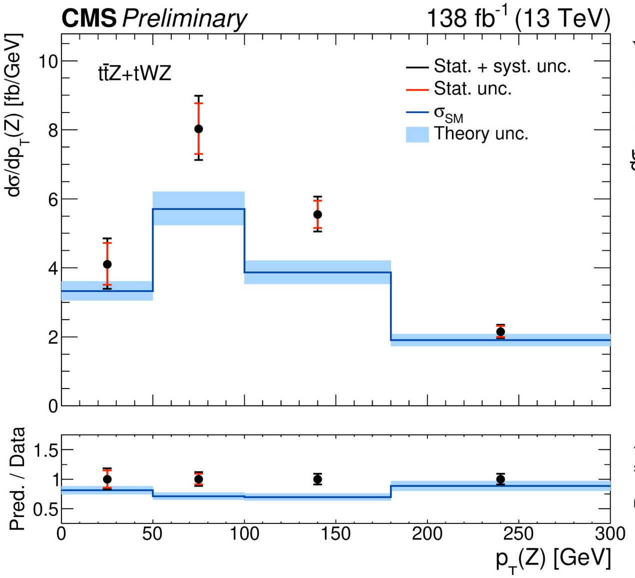


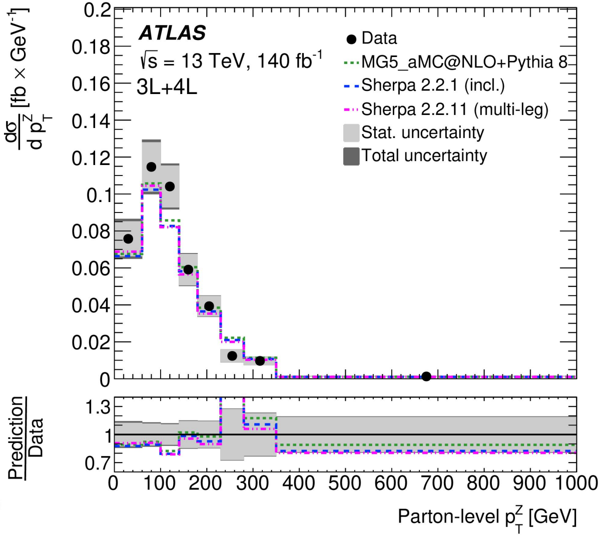


Differential ttZ results

- Both ATLAS and CMS – profile LLH unfolding
  - CMS uses DNN-binning for additional sensitivity and ttZ / tZq / bkg. separation
    - Simultaneous ttZ and tZq differential cross section extraction → fewer ttZ bins limited by tZq binning, larger uncertainties

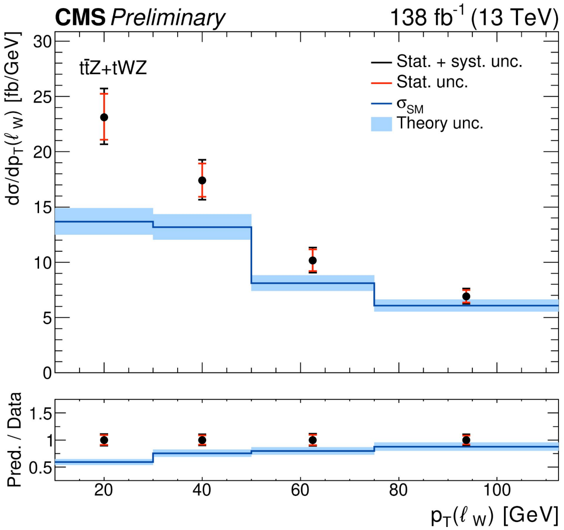




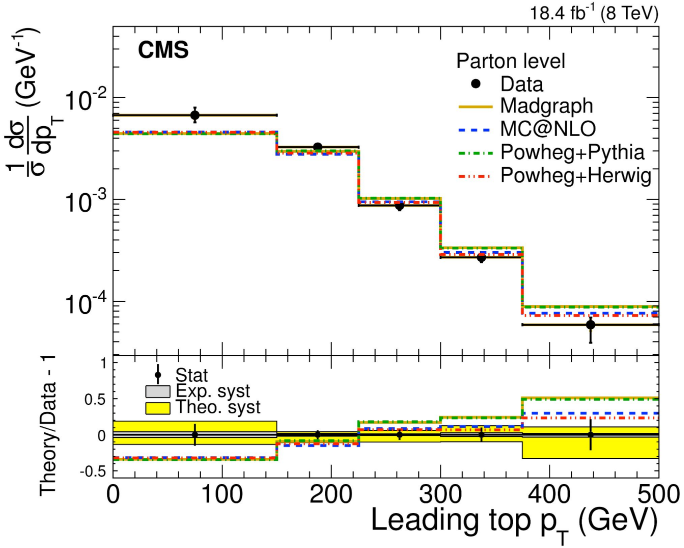


Differential ttZ results

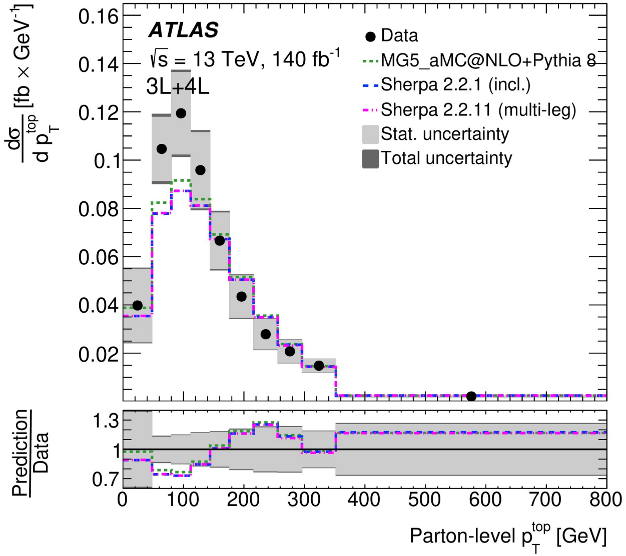
- First measurement of tt system in ttZ → also observing **trends in p_T of top quarks?**
  - Uses ~550 signal events in ATLAS measurement
  - Compare to first indication of tt differential p_T trends (~3500 tt events)



Indirect access to p_T(top) via $p_T(lep_W)$

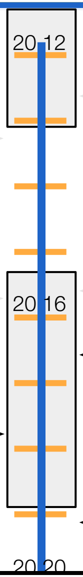


EPJC 76 (2016) 128




ttW
t + V

Historical analysis of ttZ/ttW measurements



First ttZ/ttW measurement by CMS
(PRL 110 (172002))

Run 1 ttZ/ttW observation by CMS
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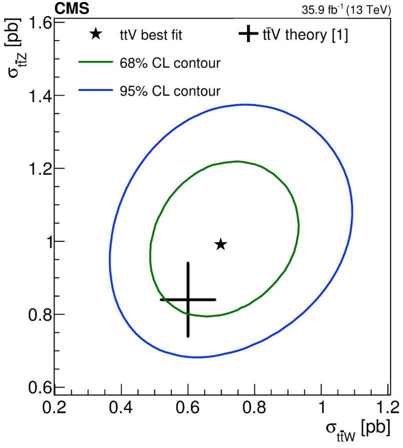
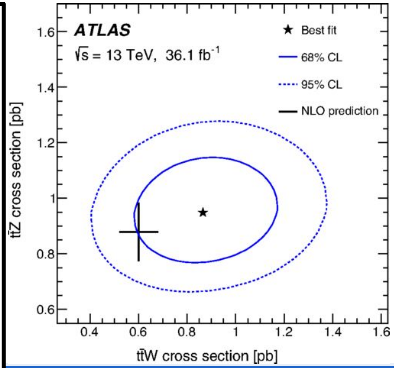


2016 ttZ/ttW measurement precision

12% / 13% ttZ

14% / 22% ttW

Both measured cross sections tend to higher values than NLO predictions



First ttZ/ttW measurement
(PRL 110 (172002))

Run 1 ttZ/ttW observation

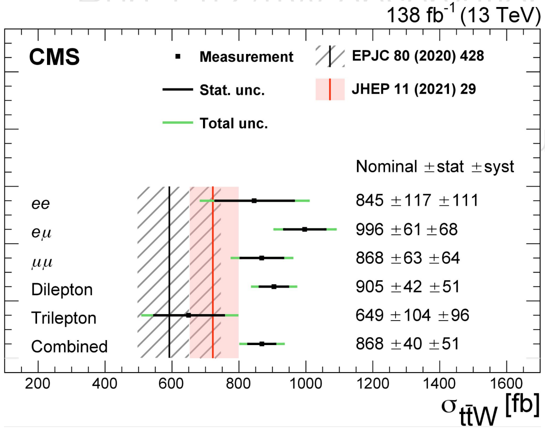
ation by ATLAS

ttW measurement precision
8% CMS / 9% ATLAS

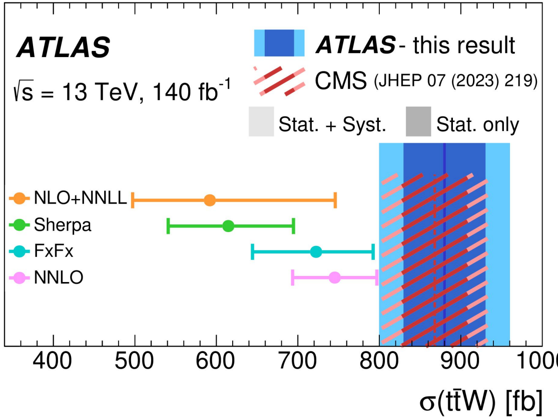
PRL 131 (2023) 23

Compared to
NNLO QCD (7% unc.)
NNLO QCD + NLO EW (7% unc.)

ATLAS / CMS
measurements ~17/18%
higher than predictions



ttW measurement by CMS
(JHEP 07 (2023) 219)



2012

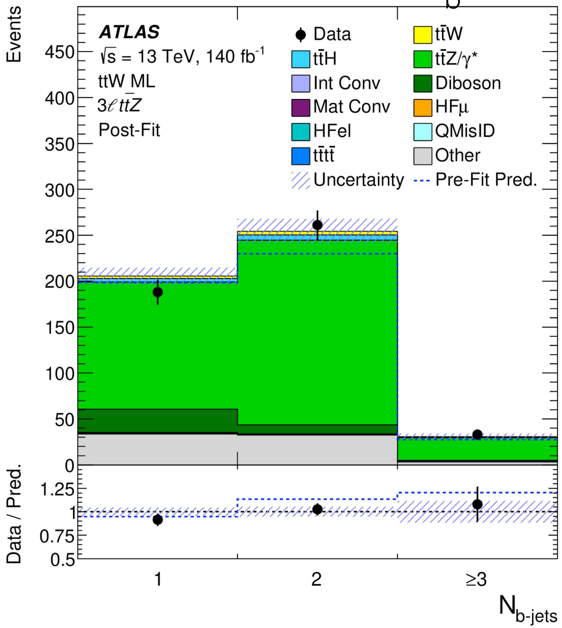
2024

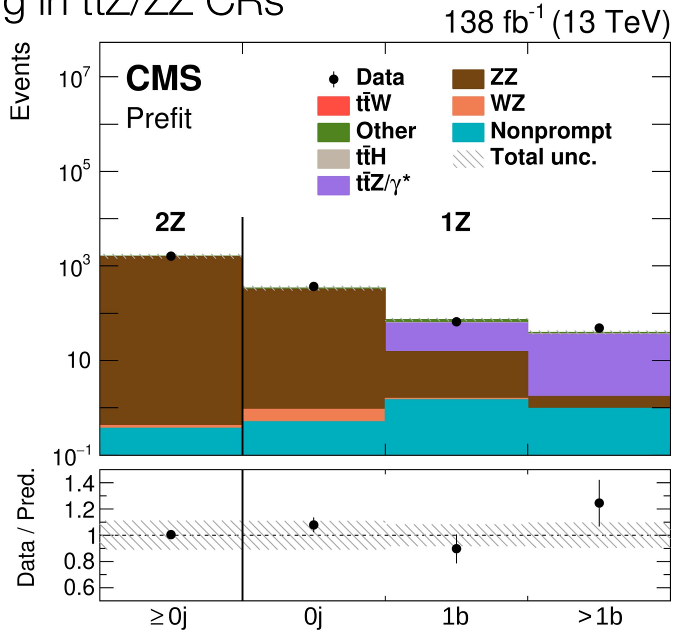
ttW differential measurement by ATLAS
(JHEP 05 (2024) 131)

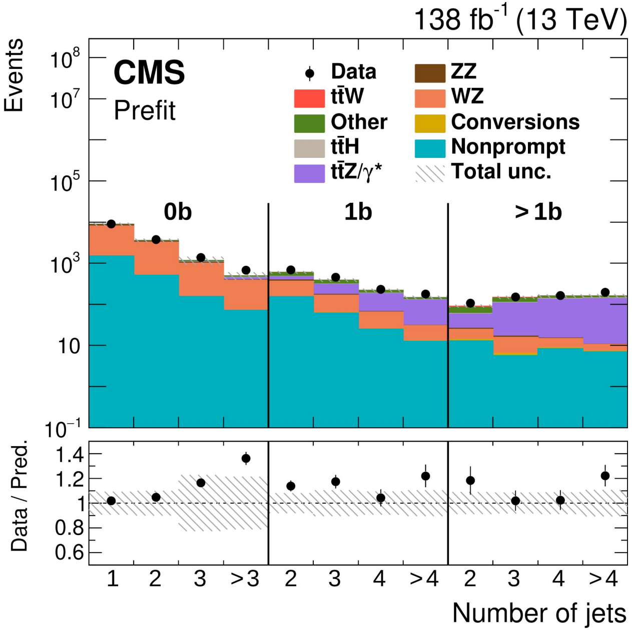
Complicated backgrounds

- ttZ / ttH / diboson
  → N_b / N_{jet} bins in CRs

N_b binning in ttZ/ZZ CRs



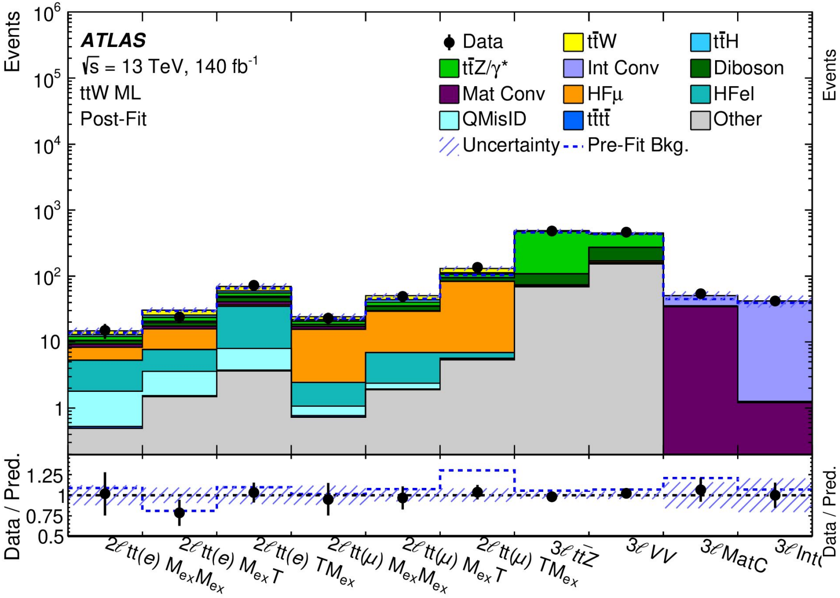




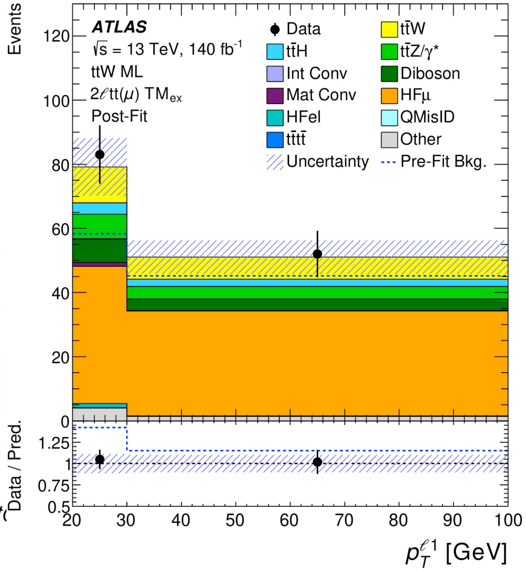
Difficulties of ttW?

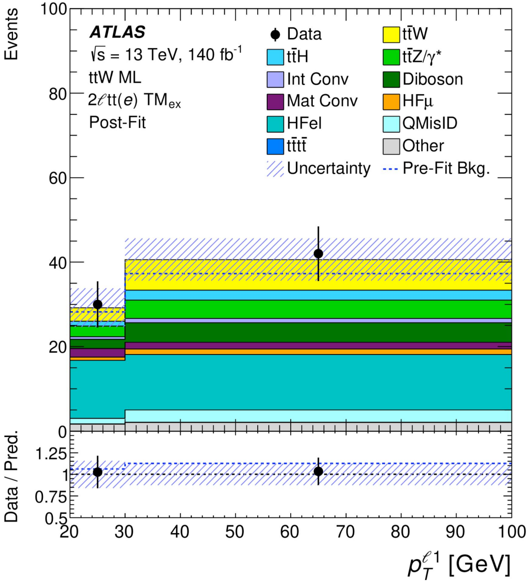
Complicated backgrounds

- Non-prompt: fake leptons, photon conversions, etc
- ➢ Many control regions, data-driven corrections
- ➢ Most normalizations determined in situ



Non-prompt lepton p_T





Inclusive XS strategies

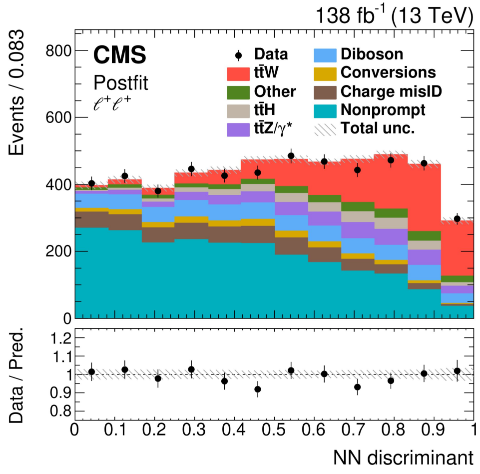
CMS:

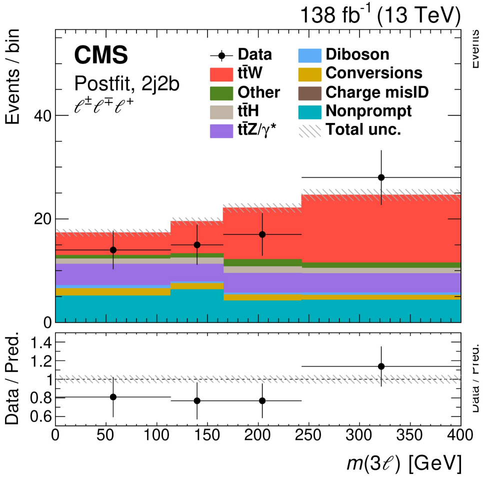
- Neural network in 2L SR, split by lepton charges
- m(3L) in 3L, split by lepton charges an N_{jet}

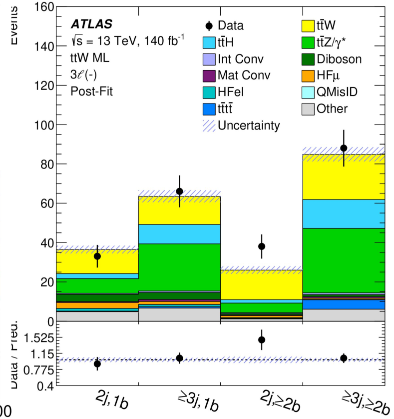
ATLAS:

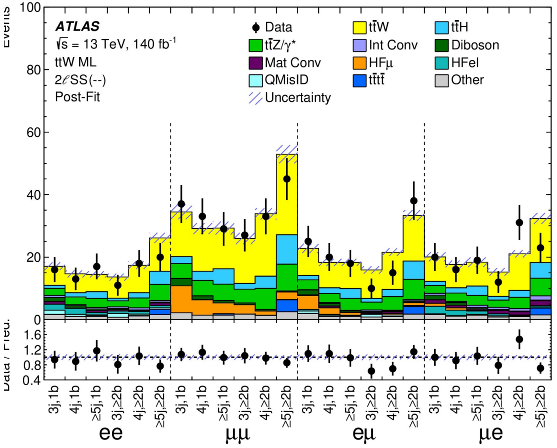
- N_{jet}, N_{bjet}, lepton charge bins in 2L and 3L
- Additional Lepton flavor bins in 2L

First individual ttW measurements
→ Newly established measurement strategies





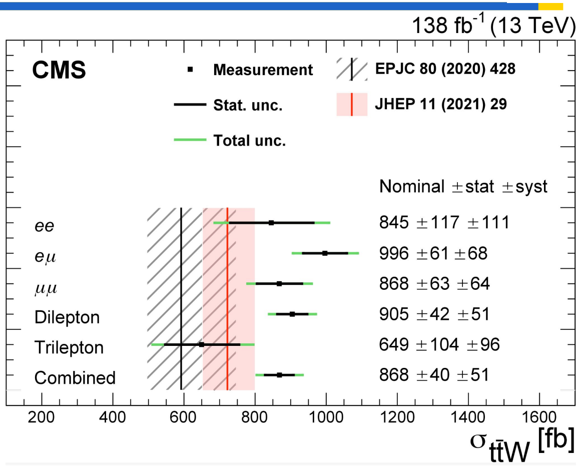




Inclusive ttW XS results

CMS result

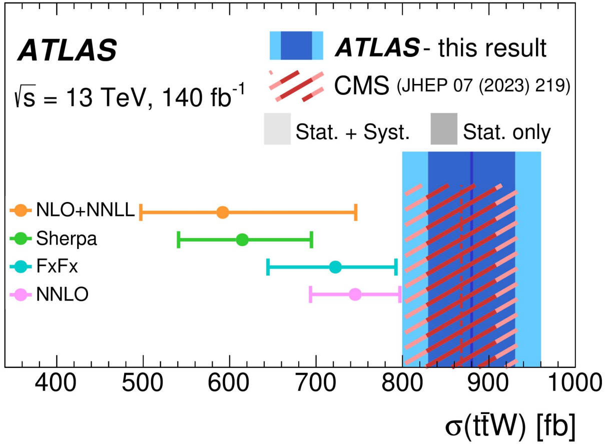
$$\sigma_{\mathrm{t\bar{t}W}} \qquad 868 \pm 40\,(\mathrm{stat}) \pm 51\,(\mathrm{syst})\,\mathrm{fb}$$



ATLAS result

$$\sigma(t\bar{t}W) = 880 \pm 50\,(\mathrm{stat.}) \pm 70\,(\mathrm{syst.}) = 880 \pm 80\ \mathrm{fb}.$$

$$\sigma_{\mathrm{fid}}(t\bar{t}W) = 20.9 \pm 1.1\,(\mathrm{stat.}) \pm 1.9\,(\mathrm{syst.}) = 20.9 \pm 2.2\ \mathrm{fb}.$$

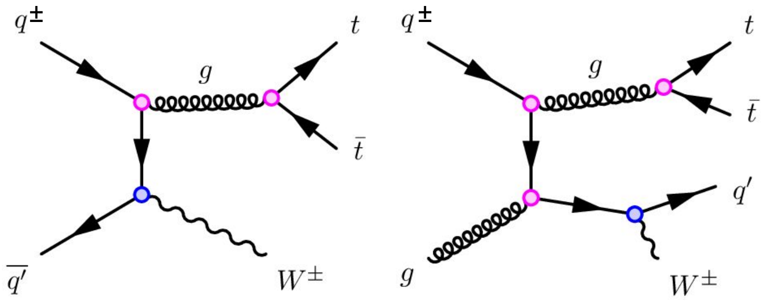


Major limitations

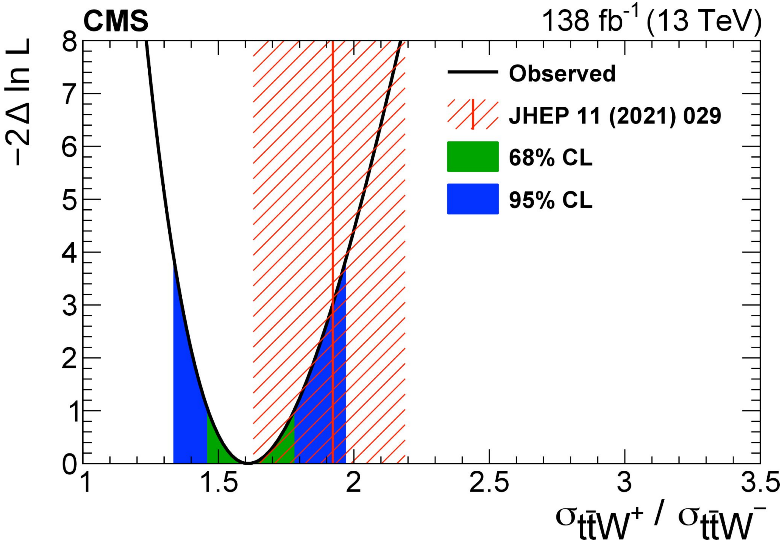
- ttW modeling, background normalization+modeling
- Calibrations of leptons, (b-tagging, jets)

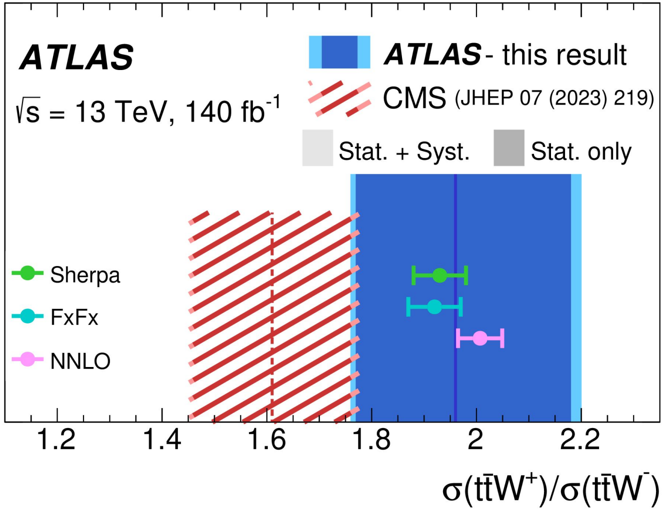
ttW charge ratio

- Process has strong charge asymmetry → probes different valence quarks in pdf
- SM prediction: **R = ttW⁺ / ttW⁻ ~ 2**



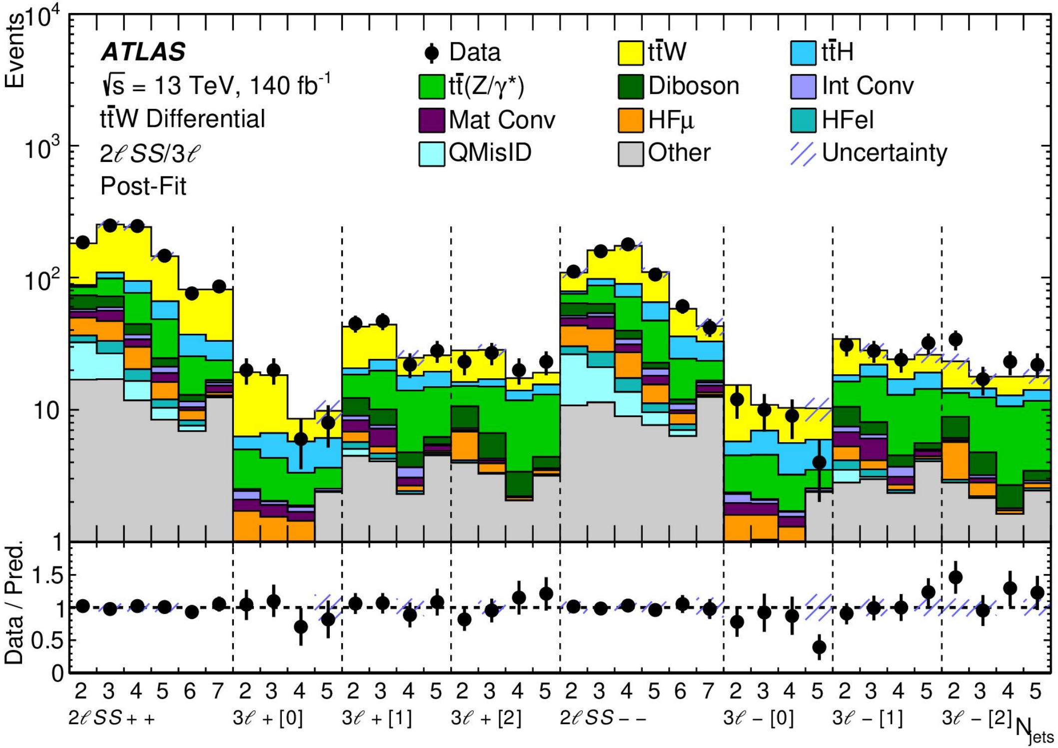
➢ Reparameterization of inclusive fit strategies
➢ CMS: R ~ 1.6 (rather low)
➢ ATLAS: R ~1.96 (good agreement)





Differential cross section results (ATLAS)

- Simultaneous differential measurement in 2LSS and 3L regions
  - Distributions binned in observable, lepton charges, number OS-SF pairs in 3L



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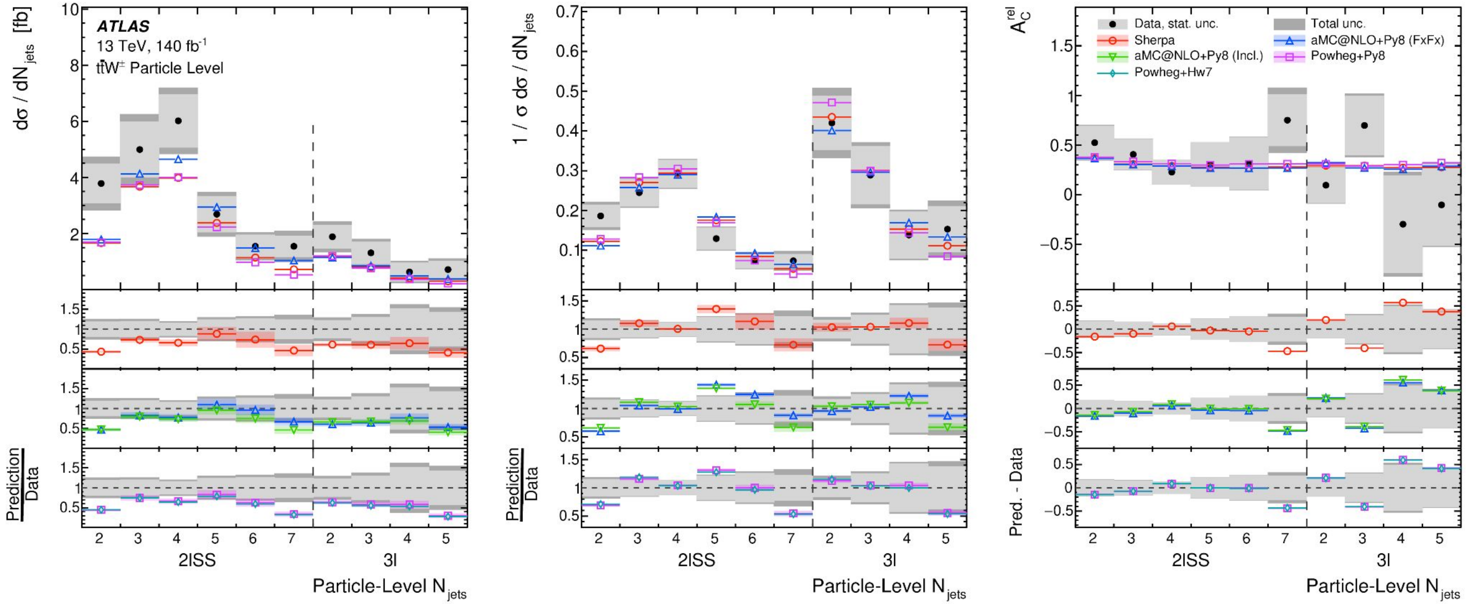
Differential cross section results (ATLAS)

JHEP 05 (2024) 131

- Simultaneous differential measurement in 2LSS and 3L regions
  - Provides **diff. XS**, **normalized diff. XS** and **diff. charge asymmetry**
- Comparison to a range of simulation approaches
  - Mostly the inclusive XS is off → differential distributions still limited in precision
  - N_{jet} largest discrepancies at low N_{jet} → independent of add. partons and merging schemes

$$A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$



Summary

ttZ

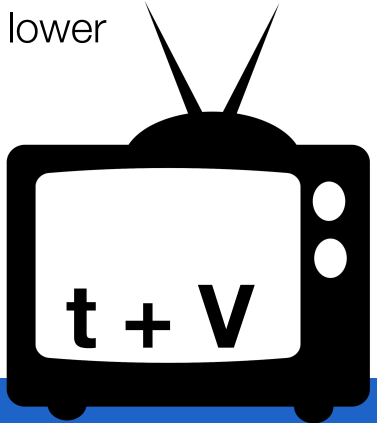
- Inclusive measurements at 6% level → surpass precision of predictions
- First combined ttZ, tWZ, tZq measurement by CMS
- Improvements in ZZ and WZ background estimations

From
23% / 30% precision in Run 1
To
6% precision at end of Run 2

ttW

- Inclusive measurements at 10% level → remain 1–2 sigma higher than predictions
- Differential XS by ATLAS start showing some (not yet very significant) differences to simulation
- Charge ratio of ATLAS agrees with PDF predictions, CMS ratio significantly lower

From
27% / 25% precision in Run 1
To
8% / 9% precision at end of Run 2



Backup

ttZ uncertaintes

Source	$\sigma(\mathrm{t\bar{t}Z} + \mathrm{tWZ})$	$\sigma(\mathrm{tZq})$
Trigger	2%	2%
Trigger prefiring	<1%	2%
Lepton identification efficiencies	1%	2%
b tagging	1%	2%
Jet energy scale	1%	3%
Jet energy resolution	<1%	1%
Missing transverse momentum	<1%	3%
Nonprompt background	2%	3%
Pileup	<1%	1%
Luminosity	2%	2%
Statistical	3.7%	10%
Background modeling	2%	4%
Factorization scale	1%	1%
Renormalization scale	1%	2%
Parton shower	<1%	2%
PDF and α_S	<1%	<1%
Underlying event and color reconnection	1%	2%
tWZ modeling	<1%	<1%
MC statistical	<1%	1%
Total	6%	13%

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_{f} and μ_{r} scales	1.6
Leptons	1.6
Z+jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14 tune	1.0
Luminosity	1.0
Diboson modelling	0.8
tZq modelling	0.7
PDF (signal & backgrounds)	0.6
MC statistical	0.5
Other backgrounds	0.5
Fake leptons	0.4
Pile-up	0.3
Data-driven $t\bar{t}$	0.1

ttZ diff XSs

	Variable	Regularisation	τ^{particle}	τ^{parton}	Definition
$3\ell + 4\ell$	p_{T}^{Z}	No	-	-	Transverse momentum of the Z boson
	$\lvert y^{Z}\rvert$	No	-	-	Absolute rapidity of the Z boson
	$\cos\theta_{Z}^{*}$	No	-	-	Angle between the direction of the Z boson in the detector reference frame and the direction of the negatively charged lepton in the rest frame of the Z boson
	p_{T}^{t}	Yes	1.5	1.4	Transverse momentum of the top quark
	$p_{\mathrm{T}}^{t\bar{t}}$	Yes	1.6	1.5	Transverse momentum of the $t\bar{t}$ system
	$\lvert\Delta\Phi(t\bar{t}, Z)\rvert/\pi$	Yes	2.4	2.1	Absolute azimuthal separation between the Z boson and the $t\bar{t}$ system
	$m^{t\bar{t}Z}$	Yes	1.5	1.6	Invariant mass of the $t\bar{t}Z$ system
	$m^{t\bar{t}}$	Yes	1.5	1.4	Invariant mass of the $t\bar{t}$ system
	$\lvert y^{t\bar{t}Z}\rvert$	Yes	1.5	1.5	Absolute rapidity of the $t\bar{t}Z$ system
3ℓ	H_{T}^{ℓ}	No	-	-	Sum of the transverse momenta of all the signal leptons
	$\lvert\Delta\Phi(Z, t_{\text{lep}})\rvert/\pi$	No	-	-	Absolute azimuthal separation between the Z boson and the top (anti-top) quark featuring the $W \to \ell\nu$ decay
	$\lvert\Delta y(Z, t_{\text{lep}})\rvert$	No	-	-	Absolute rapidity difference between the Z boson and the top (anti-top) quark featuring the $W \to \ell\nu$ decay
	$p_{\mathrm{T}}^{\ell,\text{non-}Z}$	No	-	-	Transverse momentum of the lepton that is not associated with the Z boson
	N_{jets}	No	-	-	Number of selected jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
4ℓ	H_{T}^{ℓ}	No	-	-	Sum of the transverse momenta of all the signal leptons
	$\lvert\Delta\Phi(\ell_{t}^{+}, \ell_{\bar{t}}^{-})\rvert/\pi$	No	-	-	Absolute azimuthal separation between the two leptons from the $t\bar{t}$ system
	N_{jets}	No	-	-	Number of selected jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$

What improved in ttZ?

ATLAS measurements: ~same dataset, improved precision (10% → 6%)

- tWZ/tZq, ttZ, WZ/ZZ modeling impacts all decrease with new analysis
  → Improved simulations, more bins in fits, more detailed background estimation?
- Fake lepton impact decreased

Uncertainty	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
$t\bar{t}Z$ parton shower	3.1
tWZ modelling	2.9
b-tagging	2.9
WZ/ZZ + jets modelling	2.8
tZq modelling	2.6
Lepton	2.3
Luminosity	2.2
Jets + E_T^{miss}	2.1
Fake leptons	2.1
$t\bar{t}Z$ ISR	1.6
$t\bar{t}Z$ μ_f and μ_r scales	0.9
Other backgrounds	0.7
Pile-up	0.7
$t\bar{t}Z$ PDF	0.2
Total systematic	8.4
Data statistics	5.2
Total	10

→

Uncertainty Category	$\Delta\sigma_{t\bar{t}Z}/\sigma_{t\bar{t}Z}$ [%]
Background normalisations	2.0
Jets and E_T^{miss}	1.9
b-tagging	1.7
$t\bar{t}Z$ μ_f and μ_r scales	1.6
Leptons	1.6
Z+jets modelling	1.5
tWZ modelling	1.1
$t\bar{t}Z$ showering	1.0
$t\bar{t}Z$ A14 tune	1.0
Luminosity	1.0
Diboson modelling	0.8
tZq modelling	0.7
PDF (signal & backgrounds)	0.6
MC statistical	0.5
Other backgrounds	0.5
Fake leptons	0.4
Pile-up	0.3
Data-driven $t\bar{t}$	0.1

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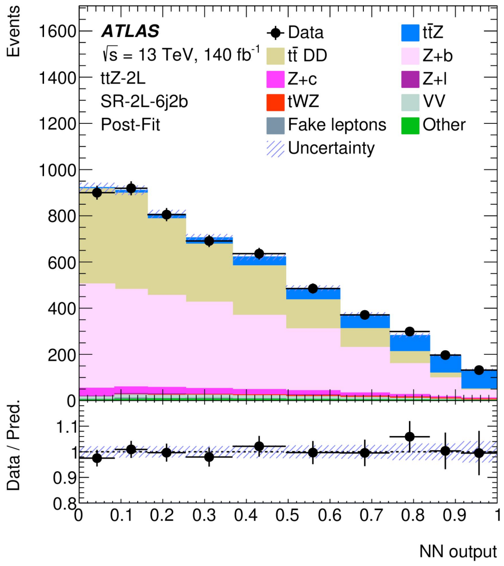
What improved in ttZ?

ATLAS measurements: ~same dataset, improved precision (10% → 6%)

- **3L** (11% → 8%) and **4L** (15% → 12%) channels **improved individually**
  - + **inclusion of 2L** channel for incl. measurement (13% precision)
    - Adds to the precision, but difficult tt and DY+hf-jets backgrounds

- Higher signal efficiency / background reduction
  - 3L SR: 370 events (62% signal fraction)
    → 440 events (75% signal fraction)
  - 4L SR: 100 events (70% signal fraction)
    → 75 events (70% signal fraction)
  - Improved calibrations (leptons + b-tagging)



EPJC 81 (2021) 737, JHEP 07 (2024) 163

What improved in ttZ?

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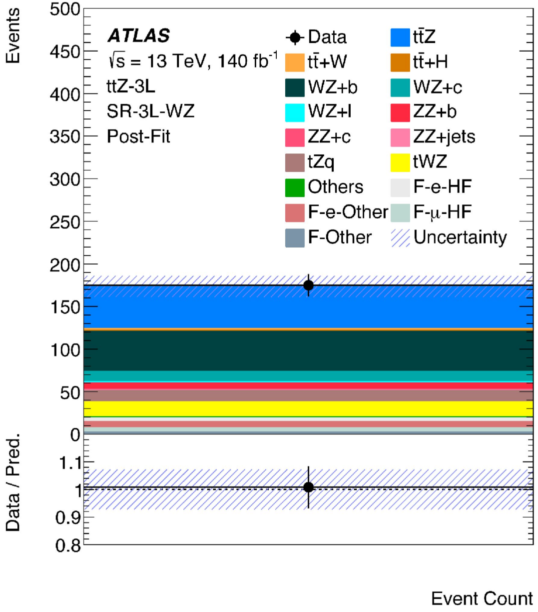
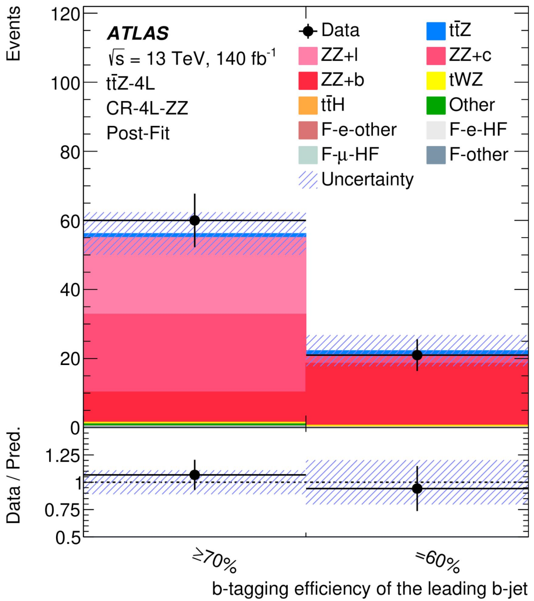
- More involved treatment of diboson backgrounds (ZZ, WZ)
  - Especially VV+b/c/light backgrounds difficult (relatively bad predictions from sim.)
- Beyond TOP measurements → dedicated ZZ+b and WZ+b measurements?
  - Improve our knowledge of these backgrounds + potential for improved sim.?

Norm. factor	Value
$\mathcal{N}_{ZZ+b}$	$1.1\ ^{+0.4}_{-0.4}$
$\mathcal{N}_{WZ+b}$	$0.9\ ^{+0.4}_{-0.4}$
$\mathcal{N}_{Z+b}$	$1.08\ ^{+0.11}_{-0.10}$
$\mathcal{N}_{Z+c}$	$0.61\ ^{+0.23}_{-0.20}$
$\mathcal{N}_{e,\mathrm{HF}}$	$0.89\ ^{+0.09}_{-0.09}$
$\mathcal{N}_{e,\mathrm{other}}$	$1.2\ ^{+0.4}_{-0.4}$
$\mathcal{N}_{\mu,\mathrm{HF}}$	$1.02\ ^{+0.08}_{-0.08}$





Additional content in ATLAS measurement

Spin correlation measurements

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- ttZ has different tt spin correlation w.r.t. tt (different qq/qg fractions)
  → good cross check
- + small longitudinal polarization induced by Z emission
  → probe additional parameters which are 0 in tt

Definition of observables (down-type t→W decay product carries top spin information)

- **4L:** all observables defined via leptons (but low yield)
  3L: requires down type quark ID
  → s jet candidates in W decay: c jets more likely to be tagged than s jets
  → 42% ID eff

- **Results mostly stat dominated**
- **Combination favors spin correlation hypothesis**

$$O = f_{\mathrm{SM}} \cdot O_{\text{spin-on}} + (1 - f_{\mathrm{SM}}) \cdot O_{\text{spin-off}}. \qquad f_{\mathrm{SM}}^{\mathrm{obs.}} = 1.20 \pm 0.63\ (\mathrm{stat.}) \pm 0.25\ (\mathrm{syst.}) = 1.20 \pm 0.68\ (\mathrm{tot.}).$$

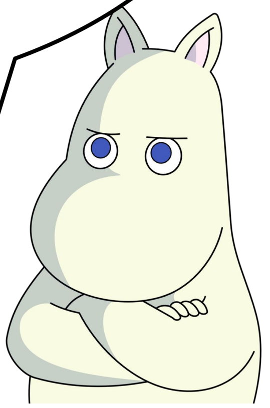
Why is ttW a difficult process?

A theorist's view…

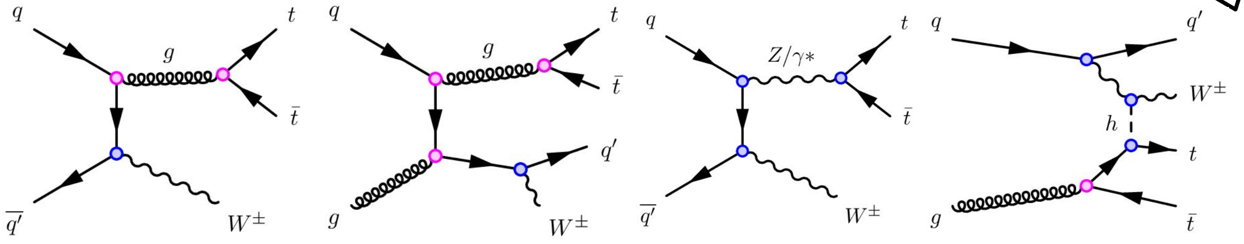
- qq-induced at LO ($\sim\alpha_S^2\alpha$)
- qg-induced at NLO ($\sim\alpha_S^3\alpha$)
- qq-induced LO EW contributions ($\sim\alpha^3$)
- qg-induced NLO EW contributions ($\sim\alpha^3\alpha_S$)
- virtual 2-loop contributions at NNLO difficult

NNLO QCD + NLO EWK

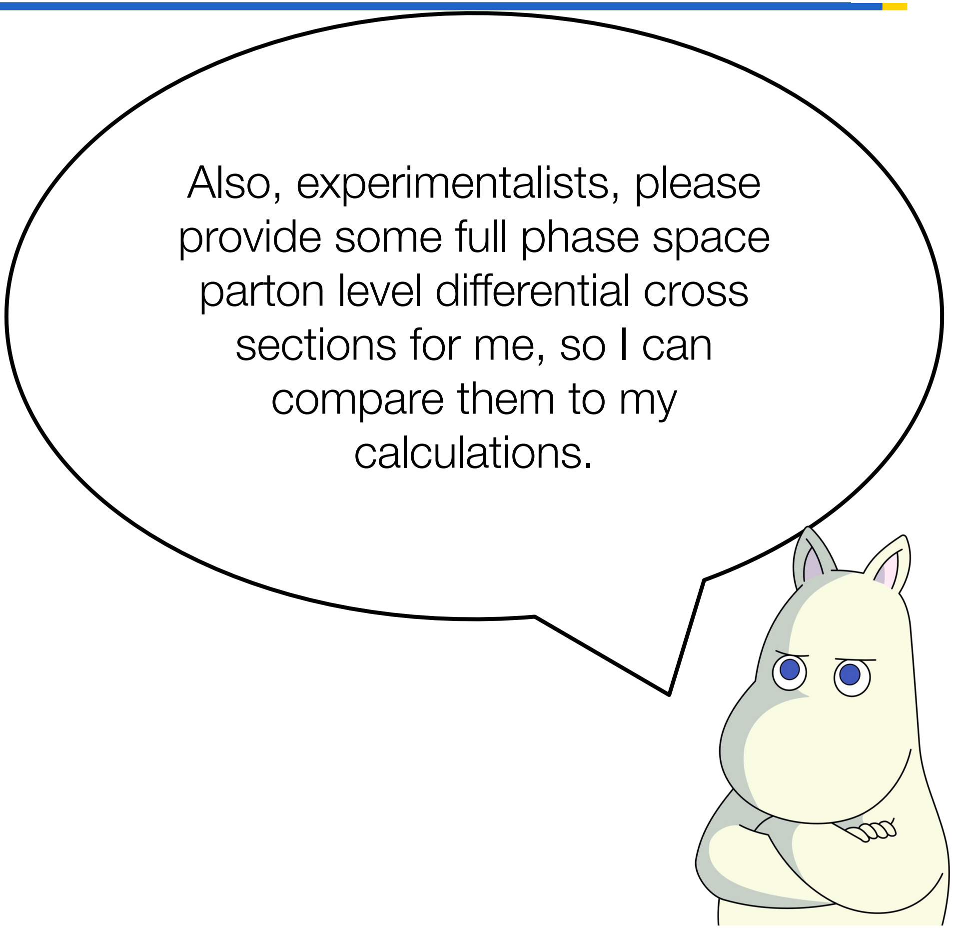
σ(ttW) = 745 fb ± 50 fb (scale)
± 13 fb (2-loop approx.)
± 19 fb (PDF, α_S)



NLO QCD only: 711 fb, real NLO EW +5%, virtual EW -2.4%, remaining EW +7%



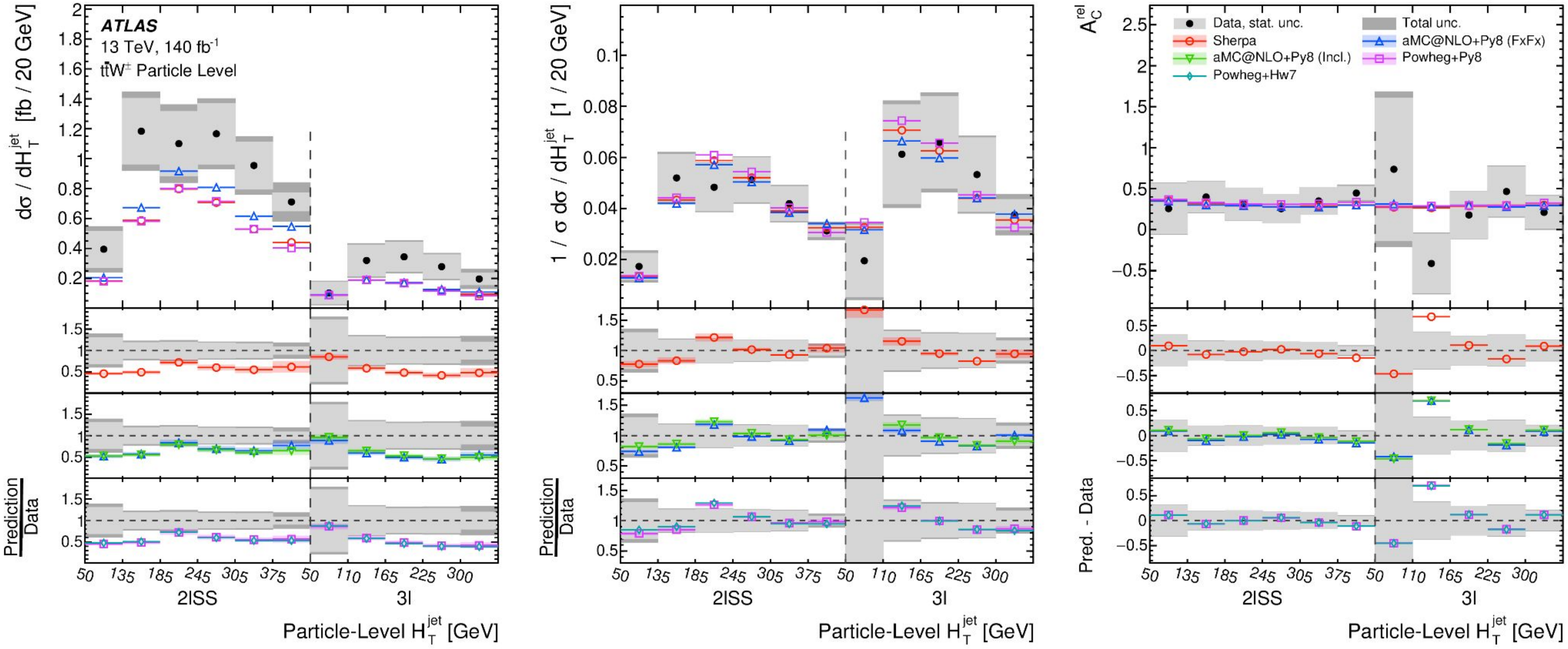
A theorist’s view…



Differential cross section results (ATLAS)

- Comparison to range of simulation approaches
  - Slight improvement at high H_T for FxFx merged simulation

$$A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$$

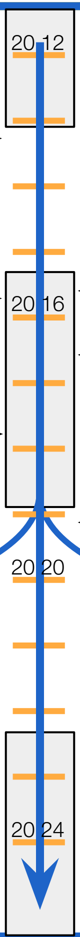


Historical analysis of ttZ/ttW measurements

First ttZ/ttW measurement by CMS
(PRL 110 (172002))

Run 1 ttZ/ttW observation by CMS
(JHEP 01 (2016) 096)

First Run 2 ttZ/ttW measurement by CMS
(JHEP 08 (2018) 011)



Run 1 ttZ/ttW observation by ATLAS
(JHEP 11 (2015) 172)

First Run 2 ttZ/ttW measurement by ATLAS
(EPJC 77 (2017) 40)

Run 2 ttZ/ttW measurement by ATLAS
(PRD 99 (2019) 072009)

Separate ttW measurements

Separate ttZ measurements

Historical analysis of ttZ measurements

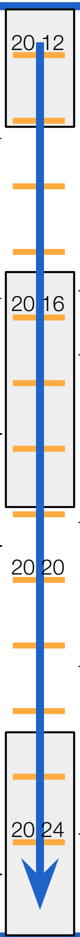
First ttZ/ttW measurement by CMS
(PRL 110 (172002))

Run 1 ttZ/ttW observation by CMS
(JHEP 01 (2016) 096)

First Run 2 ttZ/ttW measurement by CMS
(JHEP 08 (2018) 011)

ttZ differential measurement by CMS
(JHEP 03 (2020) 056)

ttZ/tWZ/tZq measurement by CMS
(PAS-TOP-23-004)



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First Run 2 ttZ/ttW measurement by ATLAS
(EPJC 77 (2017) 40)

Run 2 ttZ/ttW measurement by ATLAS
(PRD 99 (2019) 072009)

ttZ differential measurement by ATLAS
(EPJC 81 (2021) 737)

ttZ differential measurement by ATLAS
(JHEP 07 (2024) 163)

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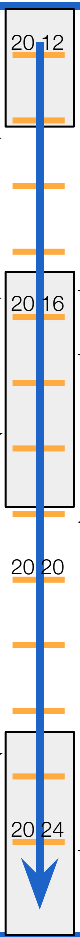


ttW measurement by CMS
(JHEP 07 (2023) 219)

ttW differential measurement by ATLAS
(JHEP 05 (2024) 131)

Historical analysis of tZ measurements

Run 1 tZq search by CMS
(JHEP 07 (2017) 003)

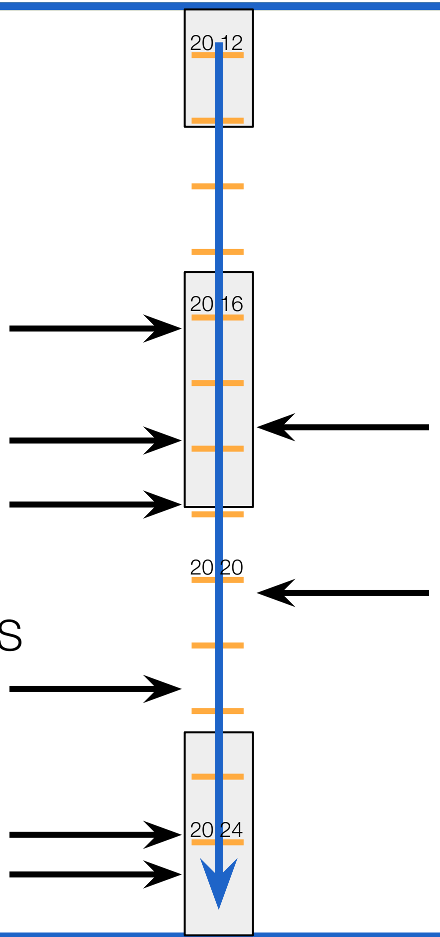
Run 2 tZq search by CMS
(PLB 779 (2018) 358)

First tZq observation by CMS
(PRL 122 (2019) 132003)

tZq differential measurement by CMS
(JHEP 02 (2022) 107)

First tWZ evidence by CMS
(PLB 855 (2024) 138815)

ttZ/tWZ/tZq measurement by CMS
(PAS-TOP-23-004)



tZq search by ATLAS
(PLB 780 (2018) 557)

First tZq observation by ATLAS
(JHEP 07 (2020) 124)

Historical analysis of tW measurements

Run 1 tW evidence by CMS
(PRL 110 (2013) 022003)

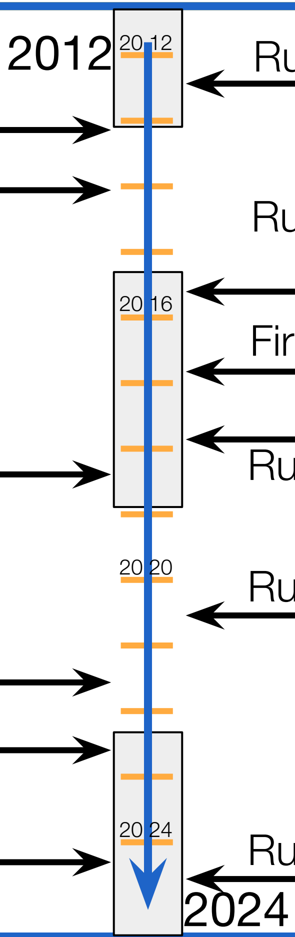
Run 1 tW observation by CMS
(PRL 112 (2014) 231802)

Run 2 tW observation by CMS
(JHEP 10 (2018) 117)

Run 2 tW observation in 1L by CMS
(JHEP 11 (2021) 111)

tW differential measurement by CMS
(JHEP 07 (2023) 046)

Run 3 tW observation by CMS
(PAS-TOP-23-008)



Run 1 tW evidence by ATLAS
(PLB 716 (2012) 142)

Run 1 tW observation by ATLAS
(JHEP 01 (2016) 064)

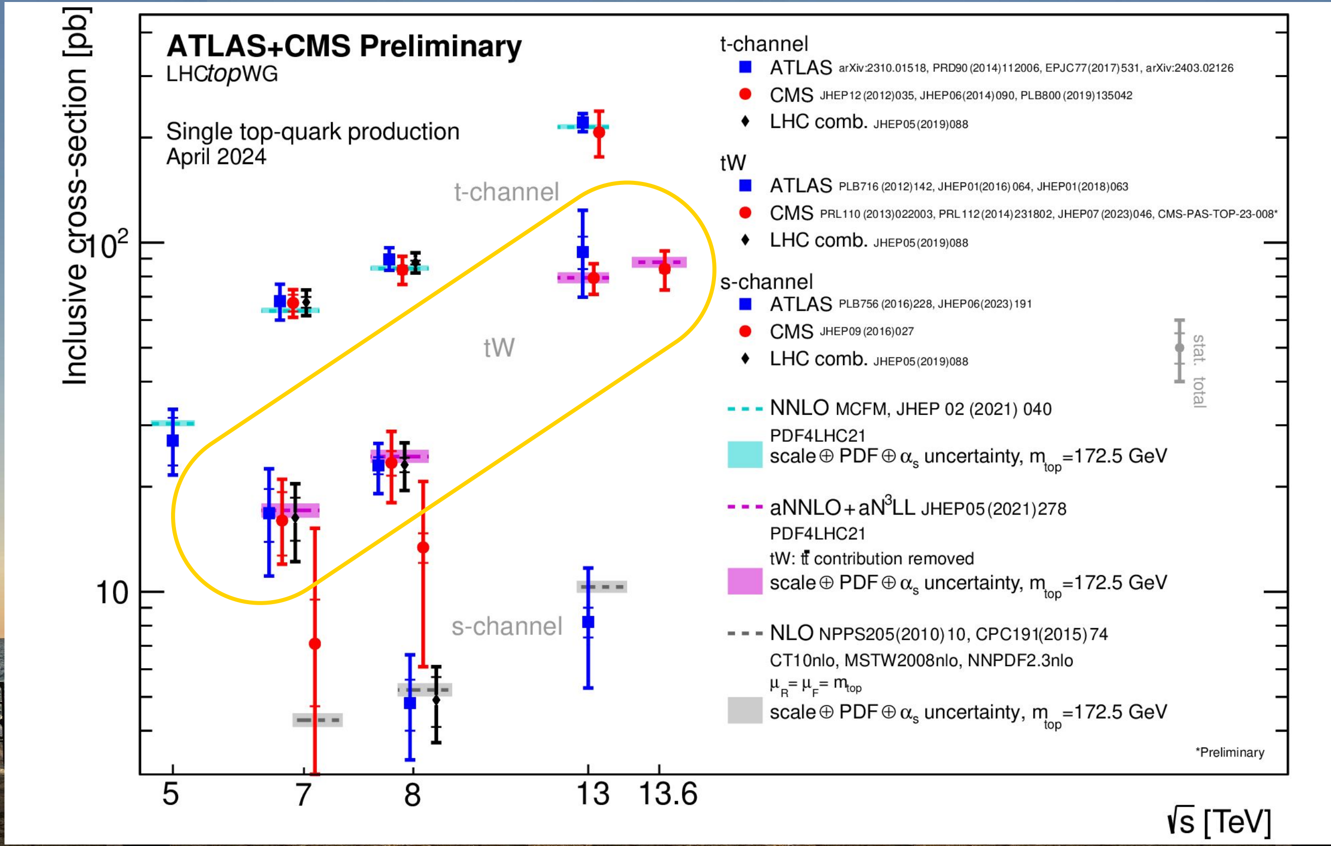
First Run 2 tW measurement by ATLAS
(JHEP 01 (2018) 063)

Run 2 tW differential measurement by ATLAS
(EPJC 78 (2018) 186)

Run 1 tW observation in 1L by ATLAS
(EPJC 81 (2021) 720)

Run 2 tW measurement by ATLAS
(arXiv:2407.15594)

tW

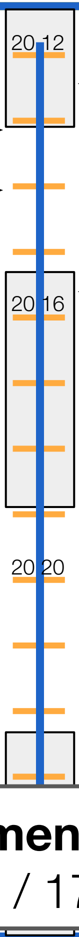


[LHCTopWG Summary Figures]

Historical analysis of tW measurements

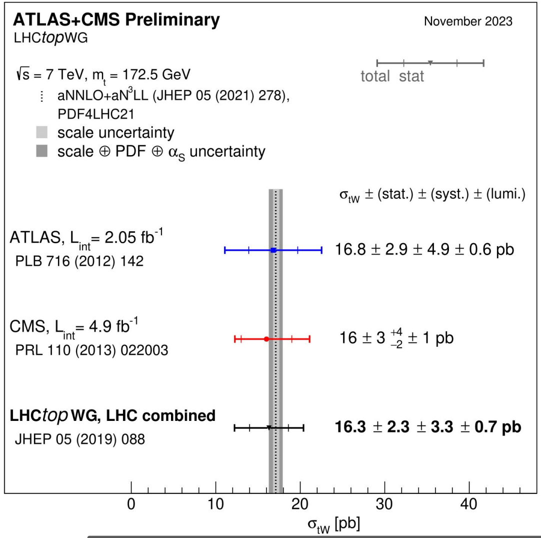
Run 1 tW **evidence** by CMS
(PRL 110 (2013) 022003)

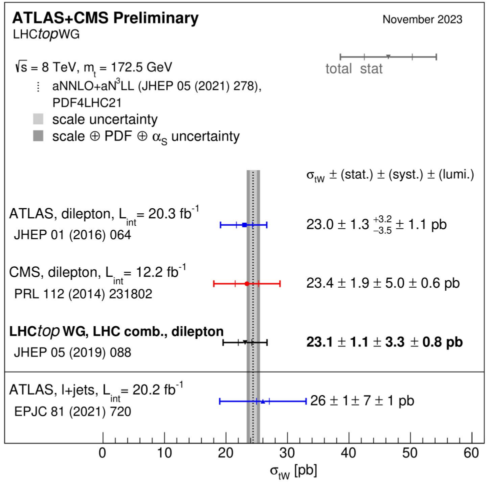
Run 1 tW **observation** by CMS
(PRL 112 (2014) 231802)



Run 1 tW **evidence** by ATLAS
(PLB 716 (2012) 142)

Run 1 tW **observation** by ATLAS
(JHEP 01 (2016) 064)





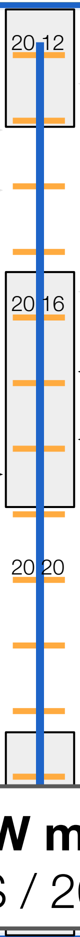
Run 1 tW measurement precision at 8 TeV
23% CMS / 17% ATLAS

Historical analysis of tW measurements

Run 1 tW evidence by CMS
(PRL 110 (2013) 022003)

Run 1 tW observation by CMS
(PRL 112 (2014) 231802)

Run 2 tW observation by CMS
(JHEP 10 (2018) 117)



Run 1 tW evidence by ATLAS
(PLB 716 (2012) 142)

Run 1 tW observation by ATLAS
(JHEP 01 (2016) 064)

First Run 2 tW measurement by ATLAS
(JHEP 01 (2018) 063)

Run 2 tW differential measurement by ATLAS
(EPJC 78 (2018) 186)

First Run 2 tW measurements
(2016 dataset) 11% CMS / 26% ATLAS (2015 dataset)

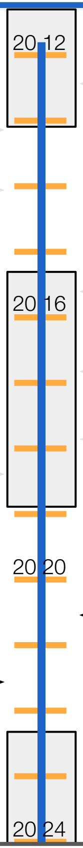
Historical analysis of tW measurements

Run 1 tW evidence by CMS
(PRL 110 (2013) 022003)

Run 1 tW observation by CMS
(PRL 112 (2014) 231802)

Run 2 tW observation by CMS
(JHEP 10 (2018) 117)

Run 2 tW observation in 1L by CMS
(JHEP 11 (2021) 111)



Run 1 tW evidence by ATLAS
(PLB 716 (2012) 142)

Run 1 tW observation by ATLAS
(JHEP 01 (2016) 064)

First Run 2 tW measurement by ATLAS
(JHEP 01 (2018) 063)

Run 2 tW differential measurement by ATLAS
(EPJC 78 (2018) 186)

Run 1 tW observation in 1L by ATLAS
(EPJC 81 (2021) 720)

Explorations of the 1L channel

Historical analysis of tW measurements

Run 1 tW evidence by
(PRL 110 (2013) 0220

Run 1 tW observation
(PRL 112 (2014) 2318

y ATLAS
12) 142)

Full Run 2 tW measurement precision

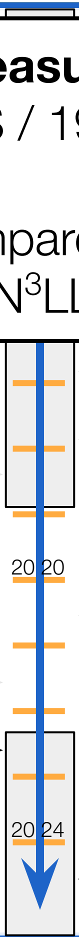
10% CMS / 19% ATLAS

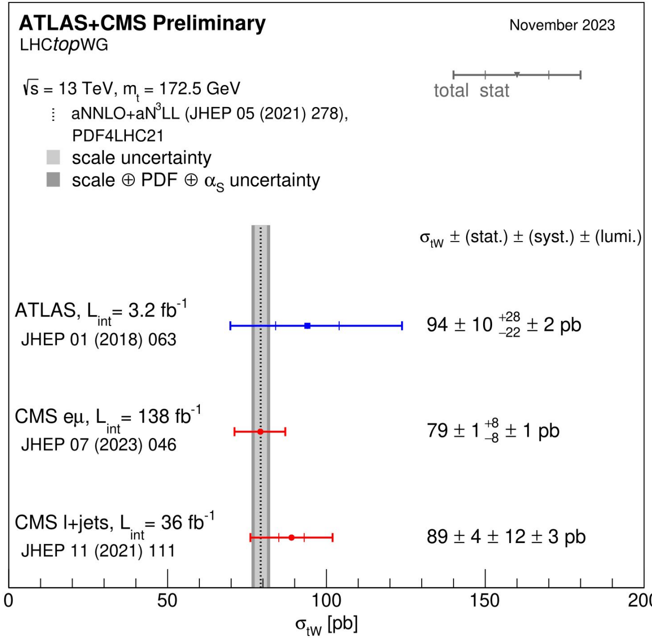
Compared to
aNNLO+aN^{3}LL (4% unc.)

Run 2 tW observation by CMS
(JHEP 10 (2018) 117)

Run 2 tW observation in 1L by CMS
(JHEP 11 (2021) 111)

tW differential measurement by CMS
(JHEP 07 (2023) 046)





Run 2 tW measurement by ATLAS
(arXiv:2407.15594)

Historical analysis of tW measurements

Run 1 tW evidence by CMS
(PRL 110 (2013) 022003)

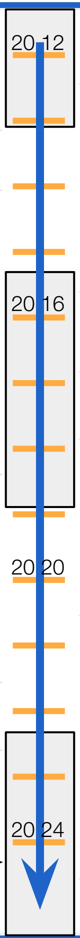
Run 1 tW observation by CMS
(PRL 112 (2014) 231802)

Run 2 tW observation by CMS
(JHEP 10 (2018) 117)

Run 2 tW observation in 1L by CMS
(JHEP 11 (2021) 111)

tW differential measurement by CMS
(JHEP 07 (2023) 046)

Run 3 tW observation by CMS
(arXiv:2409.06444)



Run 1 tW evidence by ATLAS
(PLB 716 (2012) 142)

Run 1 tW observation by ATLAS
(JHEP 01 (2016) 064)

First Run 2 tW measurement by ATLAS
(JHEP 01 (2018) 063)

Run 2 tW differential measurement by ATLAS
(EPJC 78 (2018) 186)

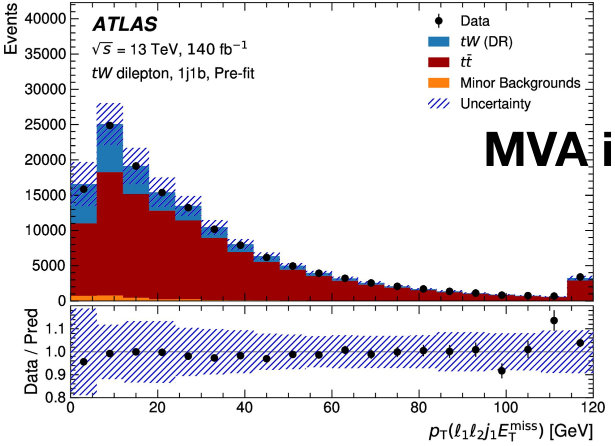
Run 1 tW observation in 1L by ATLAS
(EPJC 81 (2021) 720)

Covered in Javier's talk

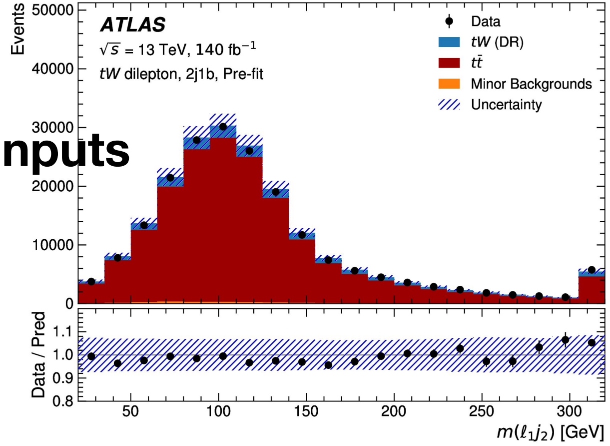
The challenges

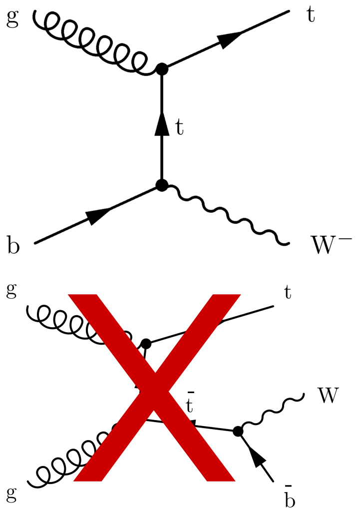
arXiv:2407.15594

- Overlap with tt at NLO → requires diagram removal / subtraction (DR/DS) schemes
  - More appropriate / the future: combined measurement of tt+tW → bb4l simulations
- tW cross section 1 order of magnitude smaller and similar to tt → difficult to isolate
  - Exploit small kinematic differences in some MVA



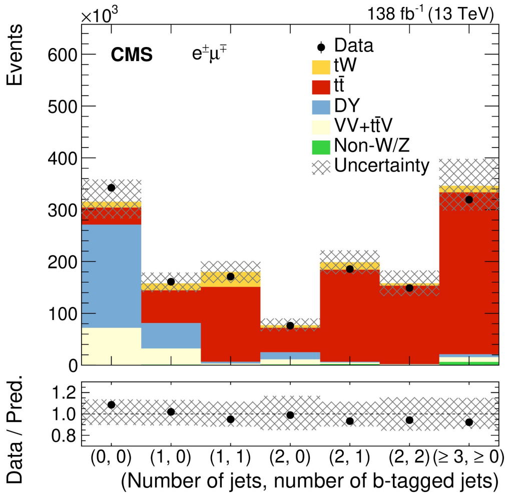
MVA inputs





Removed by DR scheme

Comparison of CMS and ATLAS approaches

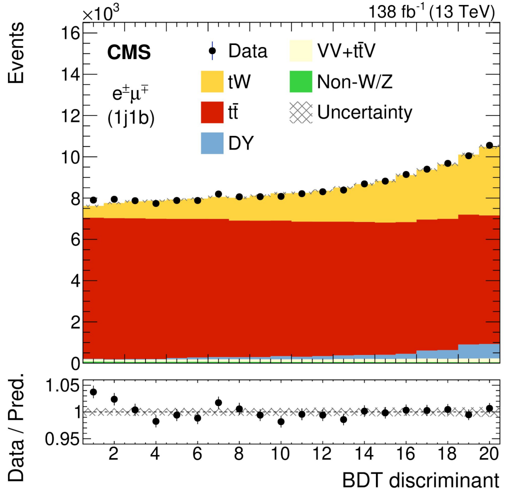


Common features

Analysis in eμ channel (no Z background)
Separate jet / b-tag categories
BDT for tW / tt separation

Cross section agrees with predictions

Limited by tt modeling and
jet energy corrections



CMS

- Full range of BDT used in fit
- Only tW cross section extraction

ATLAS

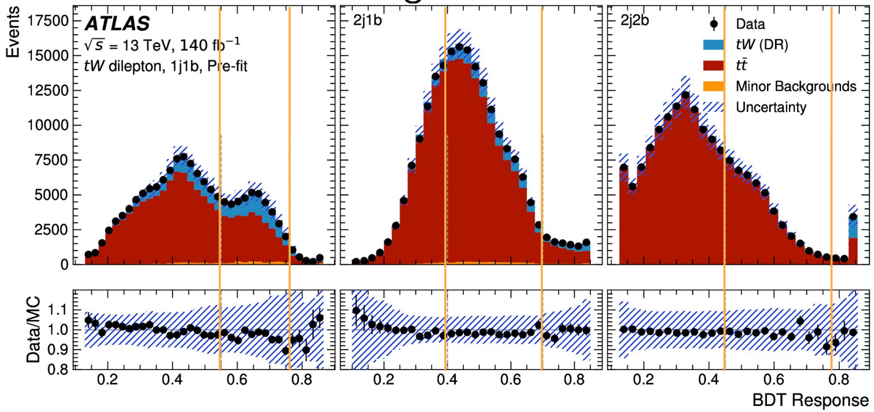
- Restrict BDT range to not constrain DR/DS uncertainties and tt PS uncertainties
- Simultaneous tW and tt cross section extraction

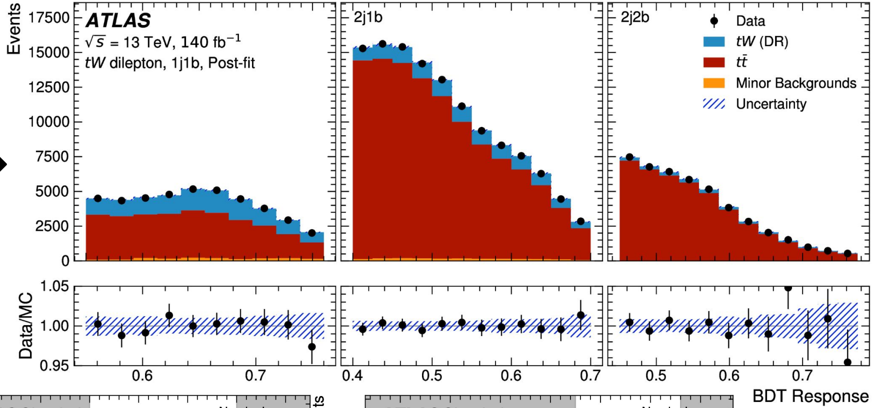
[JHEP 07 (2023) 046]

Removing constraints on modeling parameters

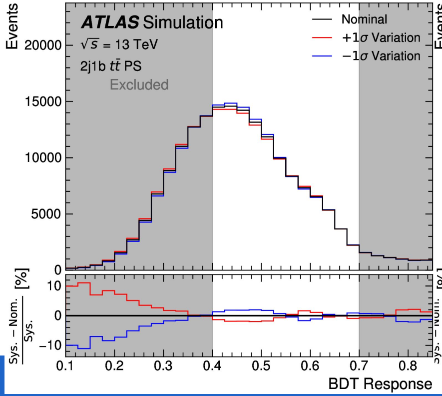
ATLAS measurement strategy

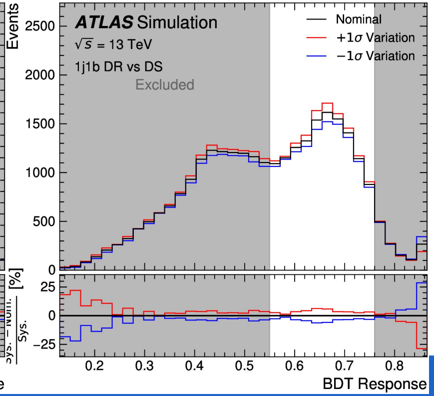
- Full range of BDT distributions → fit constrains DR/DS and tt PS modeling parameters
  → Reduce fit range to relax constraints





- **Increased tW uncertainty:** from 13% → 19%

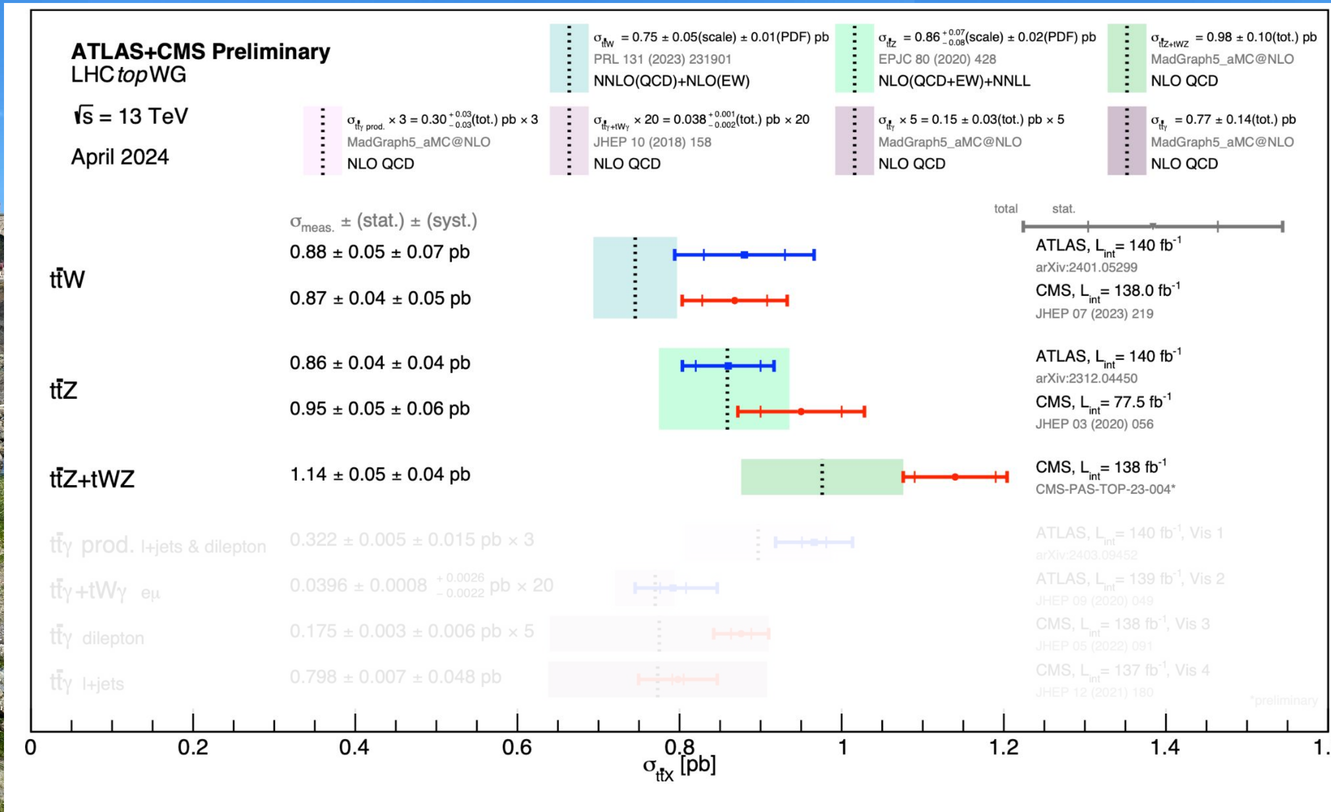




arXiv:2407.15594

Common ancestry

t + V



[LHCTopWG Summary Figures]

Comparison of tW leading impacts