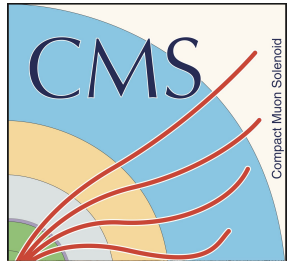
Measurement of ttW and ttbb from ATLAS and CMS

Stergios Kazakos (MSU)

(on behalf of the ATLAS & CMS collaborations)



11th Large Hadron Collider Physics Conference

MICHIGAN STATE
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Motivation for detailed ttW and ttbb measurements

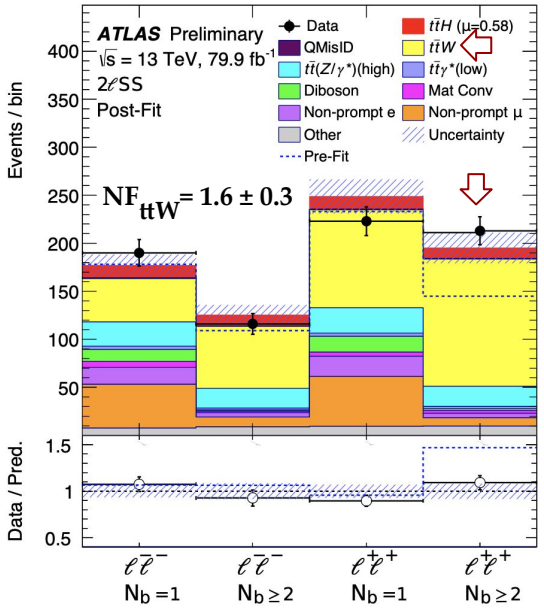
★ **ttW** and **ttbb** are quite important irreducible backgrounds in many measurements and BSM searches e.g.:

- In the **ttH** measurement, gathering large interest as a direct probe of the top-Higgs Yukawa coupling.
- In the **4-top** measurement, with a bit higher measured cross section than the SM.

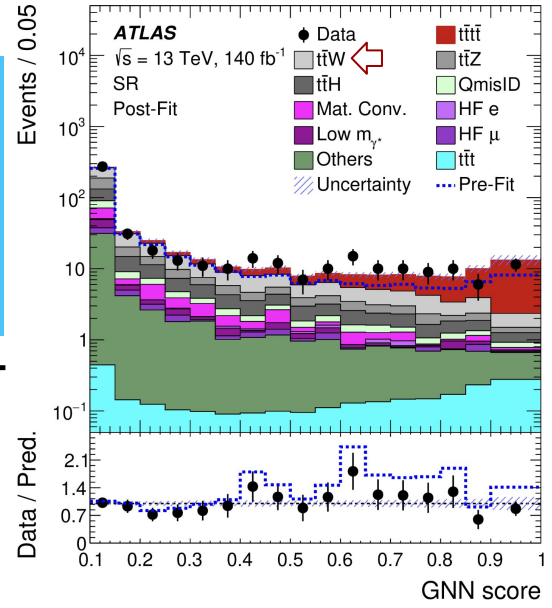
★ Additional motivation for the **ttW** & **ttbb** measurements:

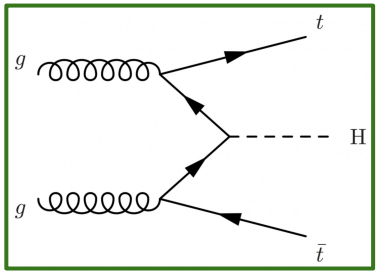
- Improve their overall uncertainty.
- Challenging modelling, contribution often underestimated from MC.

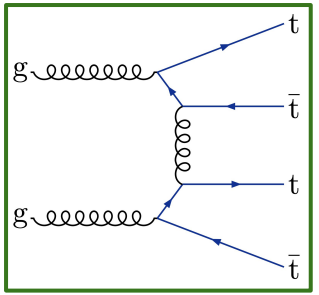
ttH-ML ATLAS-CONF-2019-045



SM 4-top arXiv:2303.15061

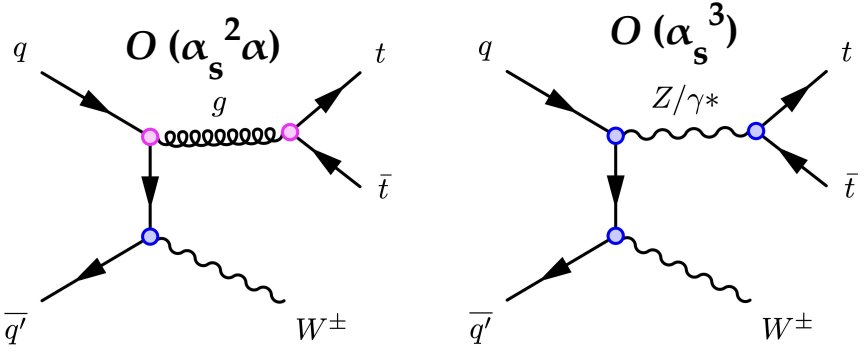




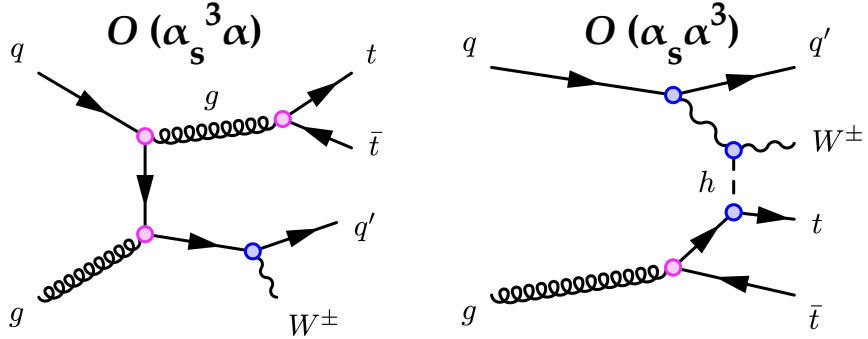


Associated production of a W boson with a top-quark pair (ttW)

★ Produced at **LO** from Initial State Radiation (**ISR**) from qq′-initiated diagrams.



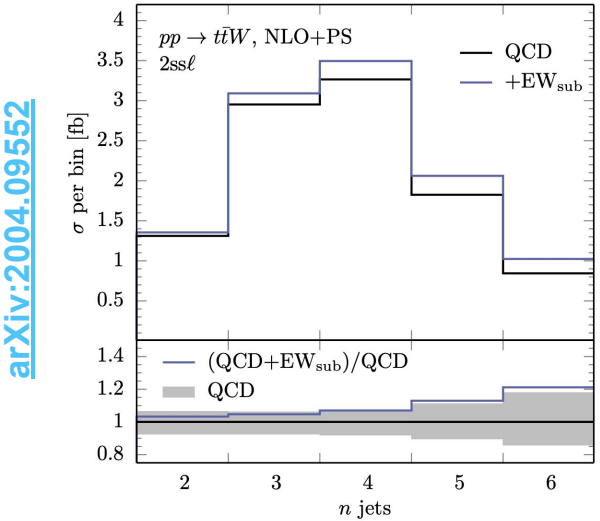
★ **NLO QCD** processes increase the cross section up to 50%.



★ ttW is an asymmetric process due to the different u-, d-quark PDFs.

★ Non-trivial modelling due to:

1) new channels opening up at higher orders,
2) **large** electroweak (EW) NLO corrections.



Inclusive ttW measurement

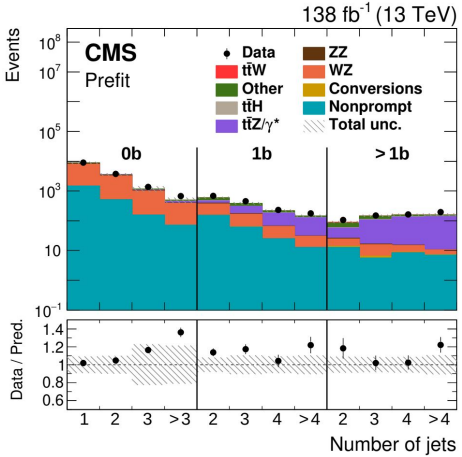
Also presented by K. W. Coldham on Wed!

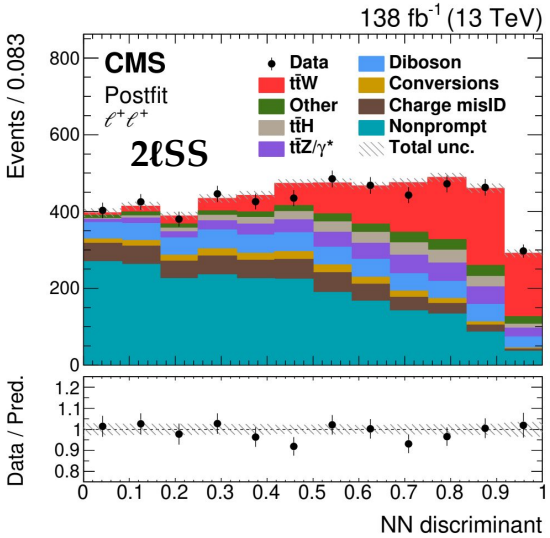
★ Main bkg contributions in SRs:

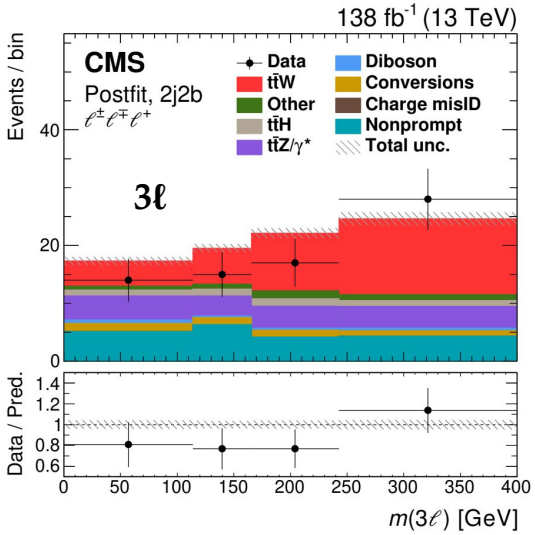
- tt w/ non-prompt ℓ, ttZ, VV, ttH

★ Definition of signal depleted CRs to constrain the normalisation of VV, ttZ & some syst uncertainties.

★ $\sigma_{t\bar{t}W}$ extracted from the fitted μ after a maximum likelihood **Template Fit** to data in CRs & SRs.







arXiv:2208.06485

★ Events selection:

⇒ 2ℓSS channel (semi-leptonic tt decay):

- Split by charge, *fitted variable:* S-vs-B **NN discriminant**

⇒ 3ℓ channel (dileptonic tt decay):

- Split by charge, event categorisation based on the N_{jet} & $N_{\text{b-jet}}$
- *Fitted variable*: **m(3ℓ)**

Inclusive ttW measurement

Also presented by K. W. Coldham on Wed!

★ ttW modelling using an improved NLO FxFx-merging sample.

★ Measured higher cross section compared to the state-of-art LHC reference:

$\sigma(t\bar{t}W) = 868 \pm 40\,(\text{stat}) \pm 51\,(\text{syst})$ fb (measured), $\sigma(t\bar{t}W) = 722\,^{+70}_{-78}\,(\text{scale}) \pm 7\,(\text{PDF})$ fb (SM reference)

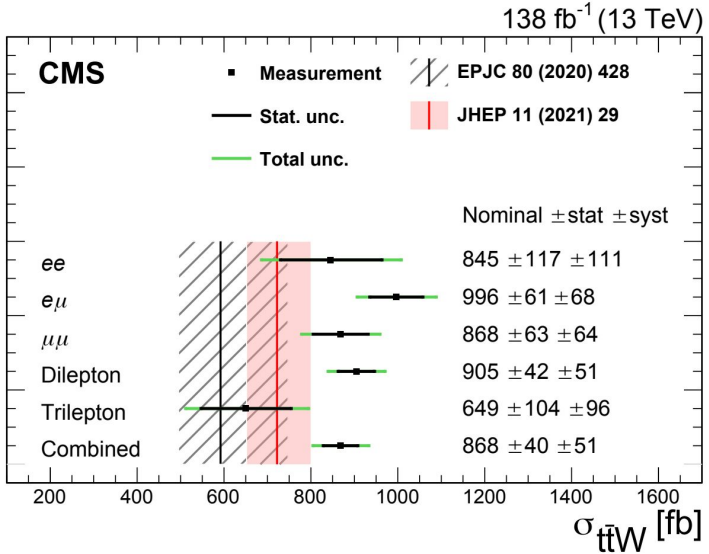
★ Parameters measured:

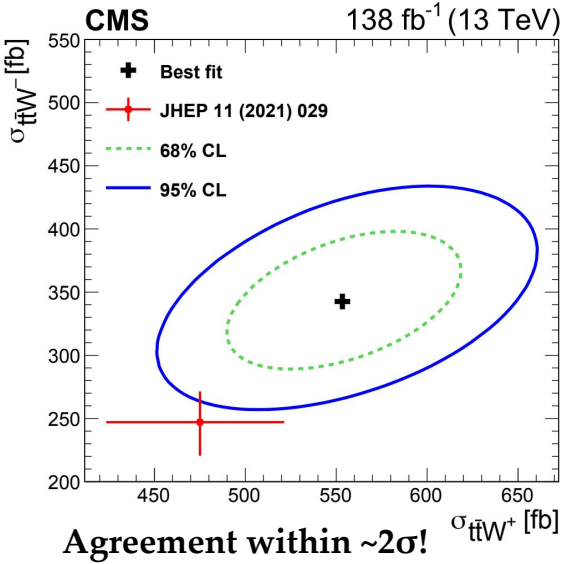
- Inclusive σ_{ttW} (+ per channel 2ℓSS/3ℓ, ee, eμ, μμ)
- σ_{ttW+} & σ_{ttW-} (+ ratio)

★ Comparable stat & syst uncertainties.

★ Dominant systematics related to:
- e charge misID,
- lumi, b-tagging
- normalisation of prompt bkg (ttH, VVV & ttVV).

- Consistent results with ttH & 4-top efforts in CMS & ATLAS. arXiv:2208.06485





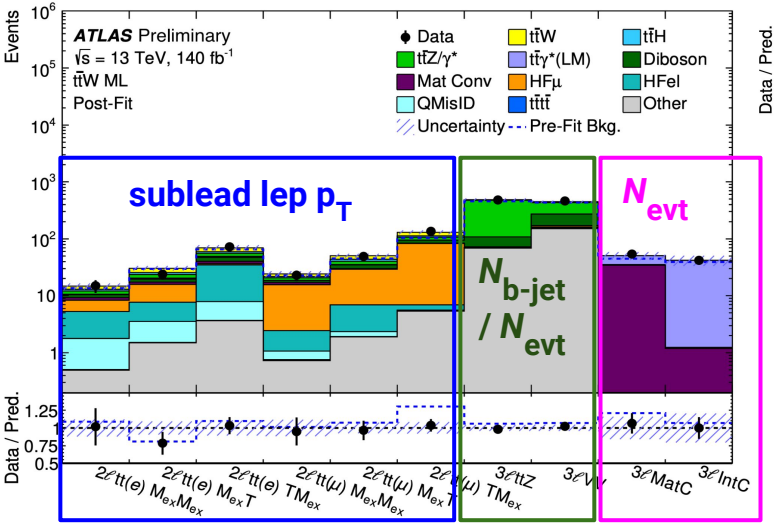
Inclusive ttW measurement

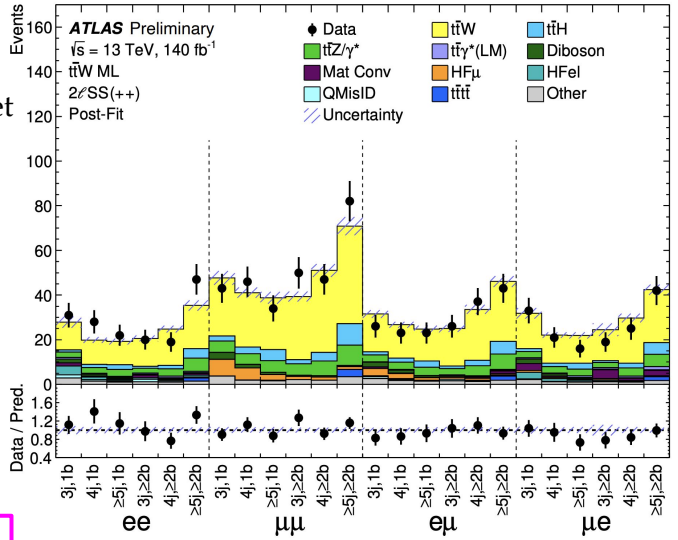
Also presented by J. Raine & C. Diez Pardos!

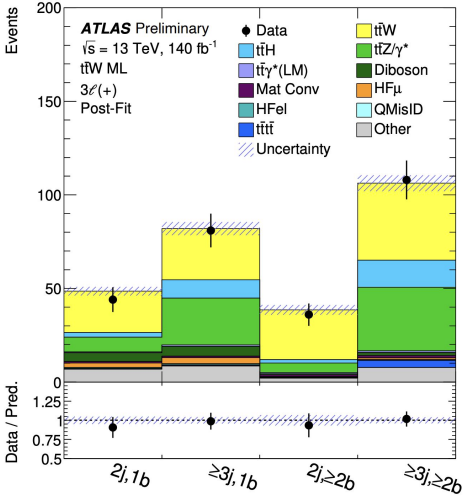
★ Events selection:

- Split based on flavour, charge, N_{jet} & $N_{\text{b-jet}}$
- 2ℓSS channel (48 bins), 3ℓ channel (8 bins)
- Fitted variable: **event yield**

★ Definition of signal depleted CRs to constrain the normalisation of major bkgs.







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★ Bkg estimation w/ maximum likelihood **Template Fit** in CRs & SRs, fitting simultaneously in all regions the normalisation of:

- "Fakes" (non-prompt HFe/μ, e material conversion)
- Internal Conversion (γ*→ℓℓ), ttZ (LF), VV (HF)

★ Inclusive σ_{ttW} extracted from the fitted μ.

Inclusive ttW measurement

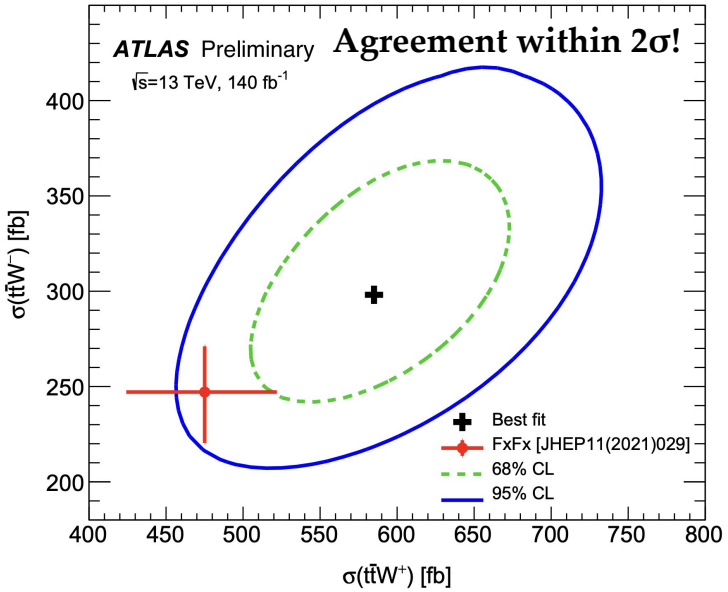
Also presented by J. Raine & C. Diez Pardos!

ATLAS EXPERIMENT

★ Parameters measured:

- Inclusive and fiducial σ_{ttW}
- σ_{ttW+} & σ_{ttW-} (and their ratio)
- Rel. charge asymmetry $A_C^{rel} = \frac{\sigma(t\bar{t}W^+) - \sigma(t\bar{t}W^-)}{\sigma(t\bar{t}W^+) + \sigma(t\bar{t}W^-)}$

ATLAS-CONF-2023-019



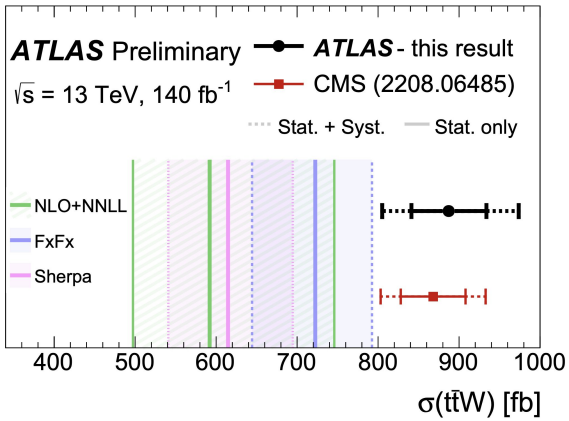
★ Higher cross section than the state-of-art reference & from CMS:

$$\sigma(t\bar{t}W^+) = 585\ ^{+58}_{-55}\ \text{(tot.) fb}$$
$$\sigma(t\bar{t}W^-) = 301\ ^{+45}_{-41}\ \text{(tot.) fb}$$
$$\sigma_{\text{fid}}(t\bar{t}W) = 21.7\ ^{+2.4}_{-2.2}\ \text{(tot.) fb}$$

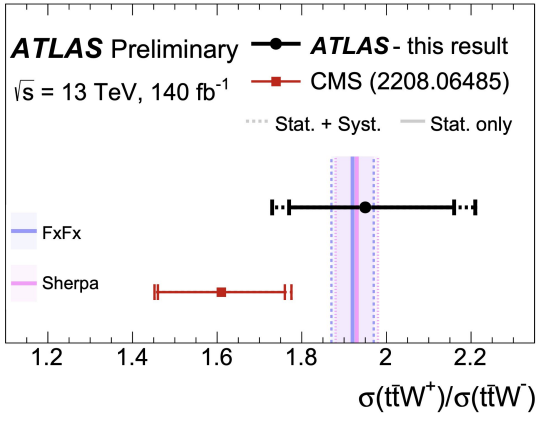
★ $A_C^{rel} = 0.32 \pm 0.06\ \text{(tot.)}$ (SM, Sherpa)

compared to $A_C^{rel} = 0.322 \pm 0.003\text{(scale)} \pm 0.007\text{(PDF)}$

$\sigma(t\bar{t}W) = 890\ ^{+90}_{-80}\ \text{(tot.) fb}$



$R(t\bar{t}W) = 1.95^{+0.26}_{-0.22}\ \text{(tot.)}$

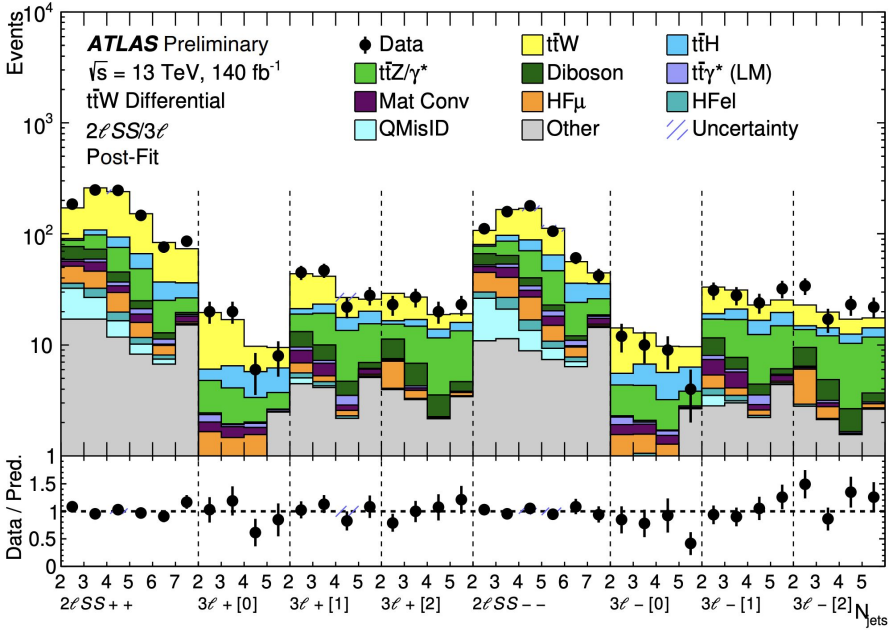


Differential ttW measurement

Also presented by J. Raine & C. Diez Pardos!

★ Use Profile Likelihood Unfolding (PLU) at particle level.
⇒ Using Tikhonov regularisation.

★ All channels in SRs are "stitched" together in a single distribution, where the ttW (signal) is unfolded.



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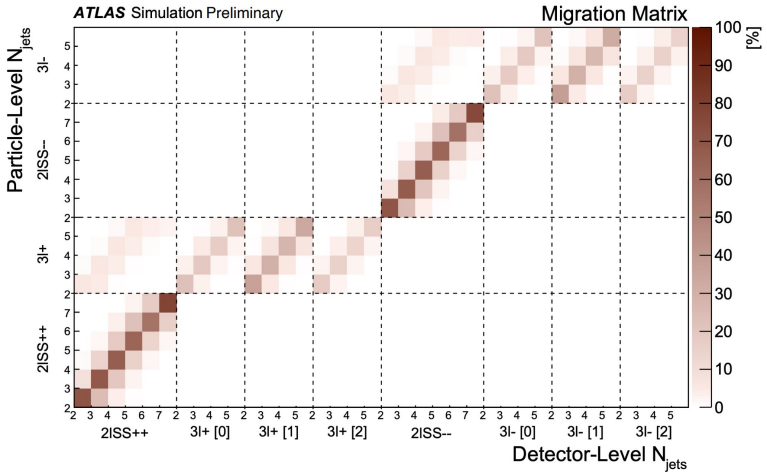
★ Definition of fiducial phase space close to the reco one.

★ Unfolding takes place after the bkg estimation from the CRs.

★ 7 observables are unfolded: N_{jet}, $H_{\text{T, jet}}$, $H_{\text{T, lep}}$, $\Delta R_{\ell b,\text{ lead}}$, $|\Delta\varphi_{\ell\ell,\text{ SS}}|$, $|\Delta\eta_{\ell\ell,\text{ SS}}|$, $M_{\text{jj, lead}}$



Differential ttW measurement

Also presented by J. Raine & C. Diez Pardos!

- Comparing the ttW unfolding using different generators.
- Including off-shell effects in the 3ℓ channel.
- Higher cross section than expected, tension seen in high and low N_{jet}.

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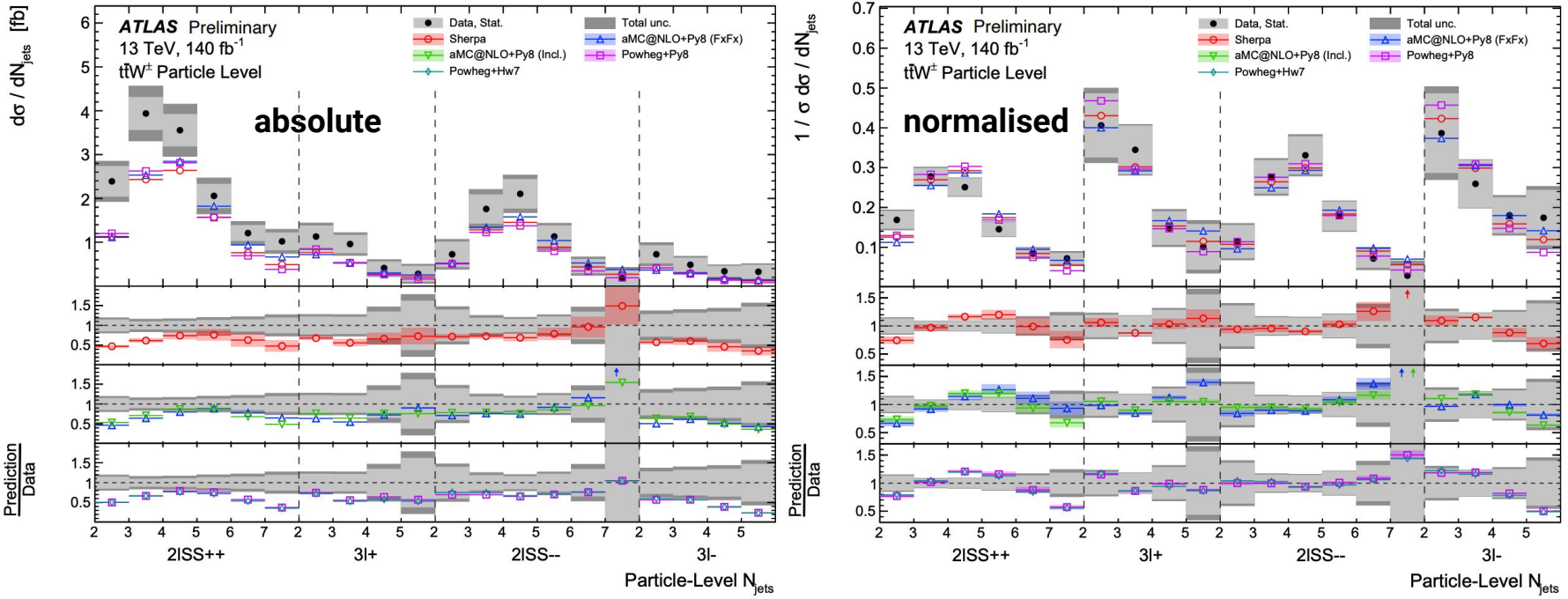


Differential ttW measurement

Also presented by J. Raine & C. Diez Pardos!

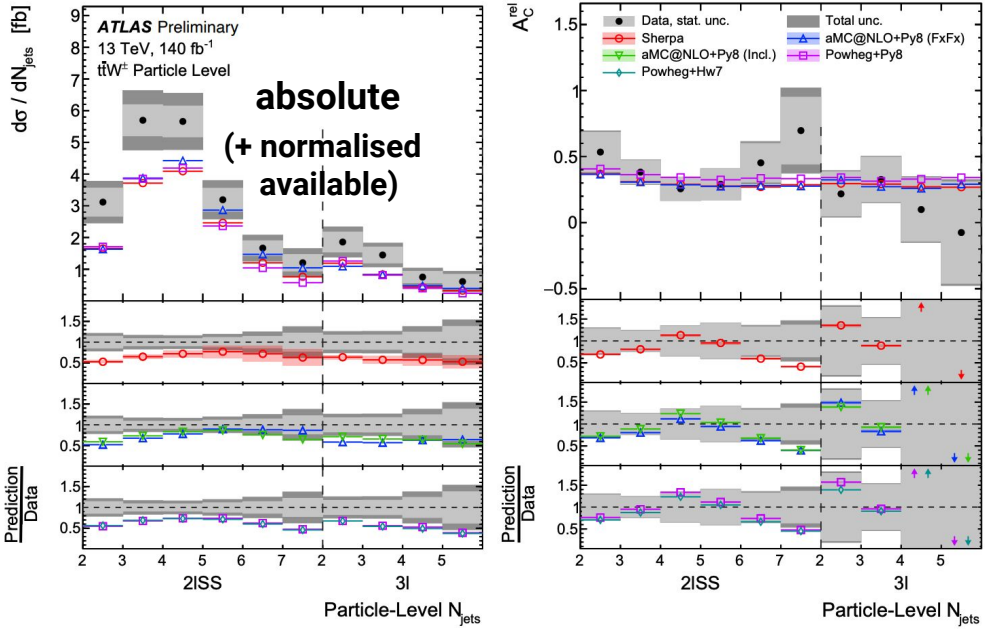
ATLAS EXPERIMENT

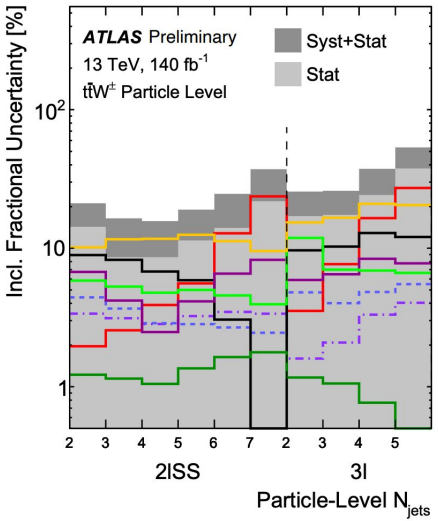
★ Measurements shown in 2ℓSS/3ℓ charge incl. channels.

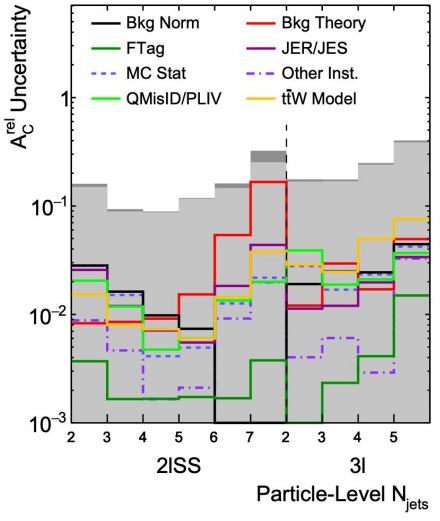
★ Statistically dominated measurement.

★ A_C^{rel} not universal across all bins.

- Significant cancelation of systematic unc.







ATLAS-CONF-2023-019

★ Dominant systematics related to:

- ttW modelling & parton showering
- Bkg modelling and normalisation
- JES / JER

ttW lep charge asymmetry measurement

Also presented by C. Diez Pardos on Thu!

ATLAS EXPERIMENT

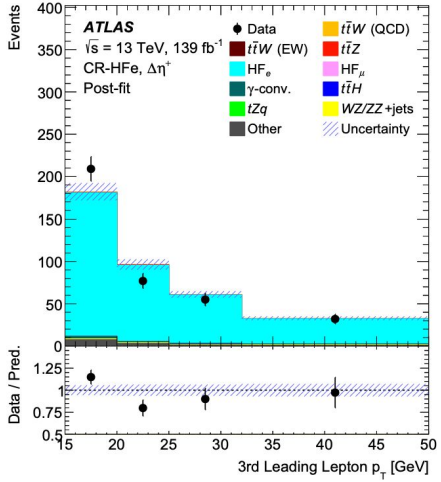
★ Measurement performed in 3ℓ channel.

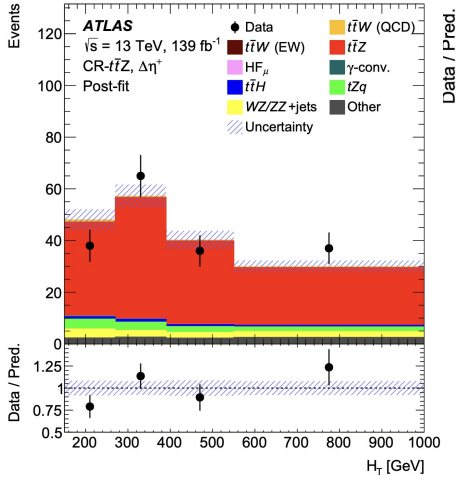
★ Parameter measured:

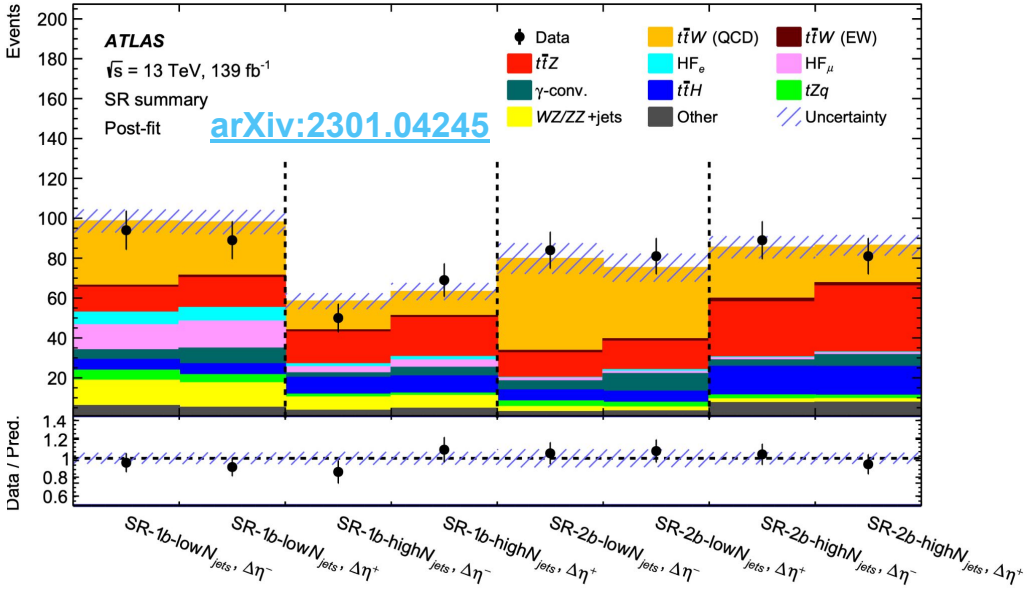
$$A_c^{\ell} = \frac{N(\Delta\eta^{\ell} > 0) - N(\Delta\eta^{\ell} < 0)}{N(\Delta\eta^{\ell} > 0) + N(\Delta\eta^{\ell} < 0)}$$

where $\Delta\eta^{\ell} = |\eta_{\ell}| - |\eta_{\bar{\ell}}|$

★ BDT used to assign the SS lepton to the top quark.







★ SRs split by $N_{\text{b-jet}}$ & **sign of** $\Delta\eta^{\ell}$.

★ Definition of bkg-enriched CRs for $\Delta\eta^{\ell} > 0$ & $\Delta\eta^{\ell} < 0$ to estimate the corresponding bkgs.

★ Maximum likelihood Template Fit in SRs and CRs to measure A_c^{ℓ} at detector level.

ttW lep charge asymmetry measurement

Also presented by C. Diez Pardos on Thu!

ATLAS EXPERIMENT

★ Measured A_c^{ℓ} at **detector level**:

$$A_c^{\ell}(t\bar{t}W) = -0.123 \pm 0.136\,(\text{stat.}) \pm 0.051\,(\text{syst.})$$

compared to the reference SM value:

$$A_c^{\ell}(t\bar{t}W)_{\text{SM}} = -0.084\,^{+0.005}_{-0.003}\,(\text{scale}) \pm 0.006\,(\text{MC stat.})$$

★ PLU at particle level w/o regularisation.

★ Measured A_c^{ℓ} at **particle level**:

$$A_c^{\ell}(t\bar{t}W)^{\text{PL}} = -0.112 \pm 0.170\,(\text{stat.}) \pm 0.054\,(\text{syst.})$$

compared to the reference SM value:

$$A_c^{\ell}(t\bar{t}W)^{\text{PL}}_{\text{SM}} = -0.063\,^{+0.007}_{-0.004}\,(\text{scale}) \pm 0.004\,(\text{MC stat.})$$

★ Statistically limited analysis.

- Dominant systematics related to:
  ⇒ ttV modelling
  ⇒ Decorrelating bkg NFs in $\Delta\eta$ bins

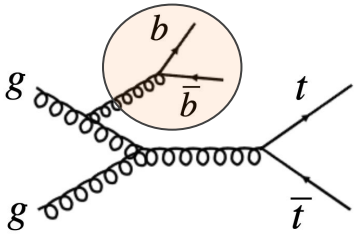
	$\Delta A_c^{\ell}(t\bar{t}W)$
Experimental uncertainties	
Jet energy resolution	0.013
Pile-up	0.007
b-tagging	0.005
Leptons	0.004
E_T^{miss}	0.004
Jet energy scale	0.003
Luminosity	0.001
MC modelling uncertainties	
$t\bar{t}W$ modelling	0.013
$t\bar{t}Z$ modelling	0.010
$\text{HF}_{e/\mu}$ modelling	0.006
$t\bar{t}H$ modelling	0.005
Other uncertainties	
$\Delta\eta^{\pm}$ CR-dependency	0.046
MC statistical uncertainty	0.019
Data statistical uncertainty	0.136
Total uncertainty	0.145

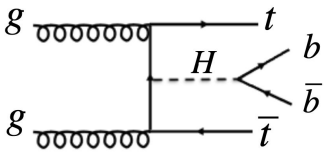
arXiv:2301.04245

Associated production of top-quark and b-quark pairs (ttbb)

★ **bb pair** usually produced **from ISR**.

- Irreducible bkg to ttH(bb) & 4-top.



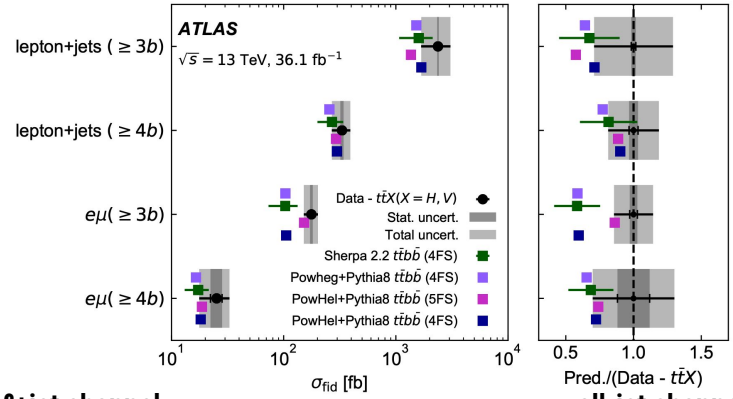


★ Challenging modelling due to the non-negligible b-quark mass (**4-** vs **5-flavour scheme**) & difference in energy scales.

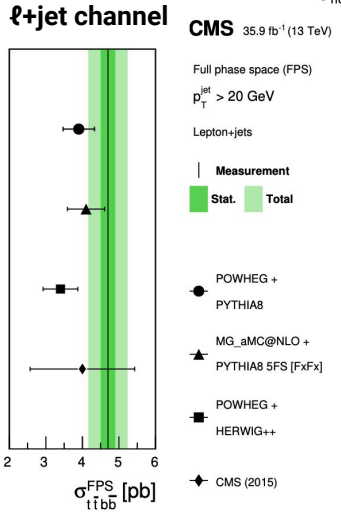
★ Previous results from ATLAS & CMS measured higher cross sections than the state-of-art predictions.

+ Common MC modelling note on ttbb/ttW published by the Higgs cross-section WGs: arXiv:2301.11670

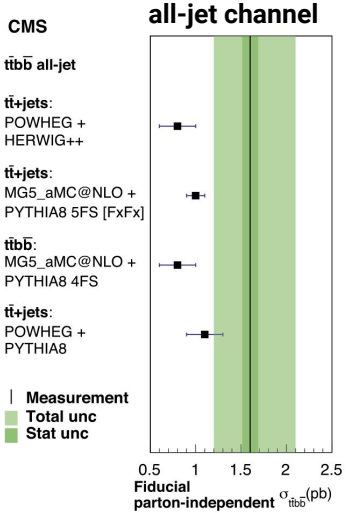
JHEP 04 (2019) 046



JHEP 07 (2020) 125



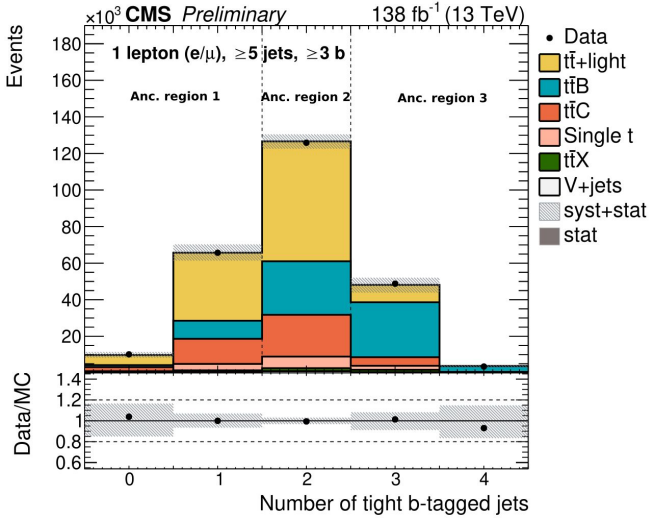
PLB 803 (2020) 135285

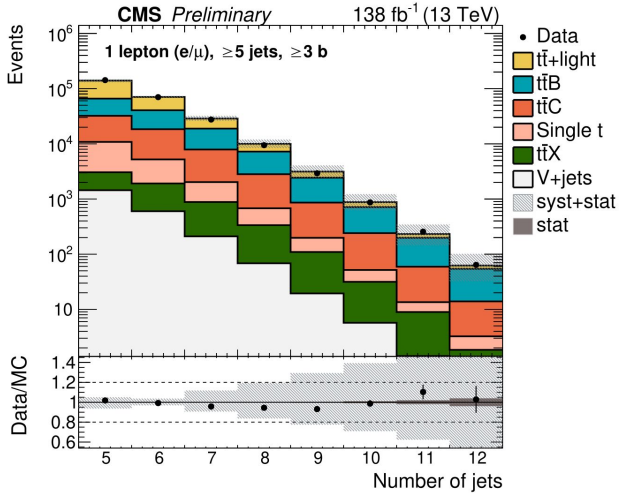


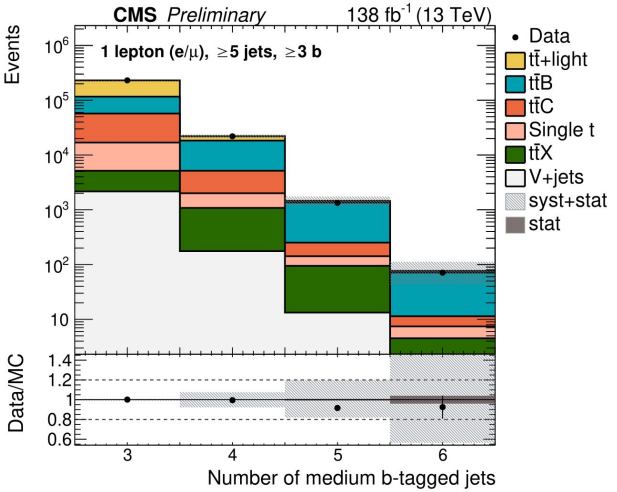
Inclusive ttbb measurement

Also presented by F. Colombina on Wed!

- Measurement in the ℓ+jet channel w/ full Run 2 dataset.
- Event selection: **e/μ, ≥ 5j, ≥ 3b**
- DNN algorithm to identify the additional b-jets.







CMS-PAS-TOP-22-009

- Definition of "ancillary" variables to define signal- & bkg- enriched regions.
  - Fitted simultaneously using a maximum likelihood template fit.
  - Also useful for background estimation & constraining b-tagging related uncertainties.

Inclusive ttbb measurement

Also presented by F. Colombina on Wed!

★ Most precise ttbb measurement so far.

★ Measured in 4 fiducial regions, w/ different jet & b-jet requirements.

- Comparing the unfolding of different generators.

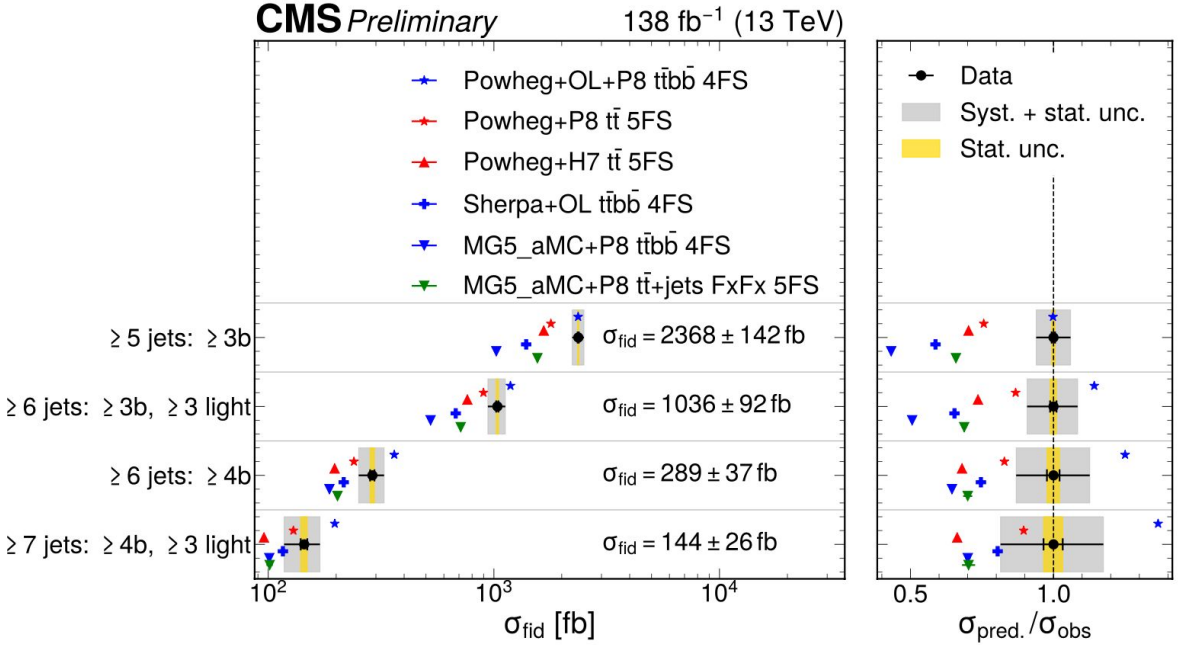
★ Modelling approaches vary:

- **POWHEG+OL+P8 (4 FS)** dedicated ttbb sample as nominal.

  ⇒ performs better in the inclusive region (≥ 5j), overpredicts the cross section in the regions w/ ≥ 6j.

- **POWHEG+P8 (5 FS)** tt sample as alternative (tt+ ≥1b from truth classif).

  ⇒ provides a similar or better result in the ≥ 6j region.



CMS-PAS-TOP-22-009

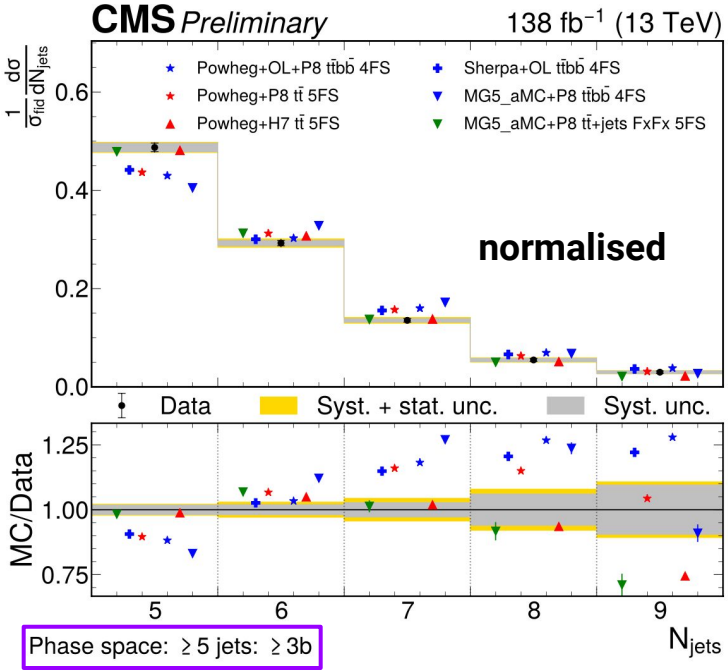
★ Dominant systematic uncertainties:

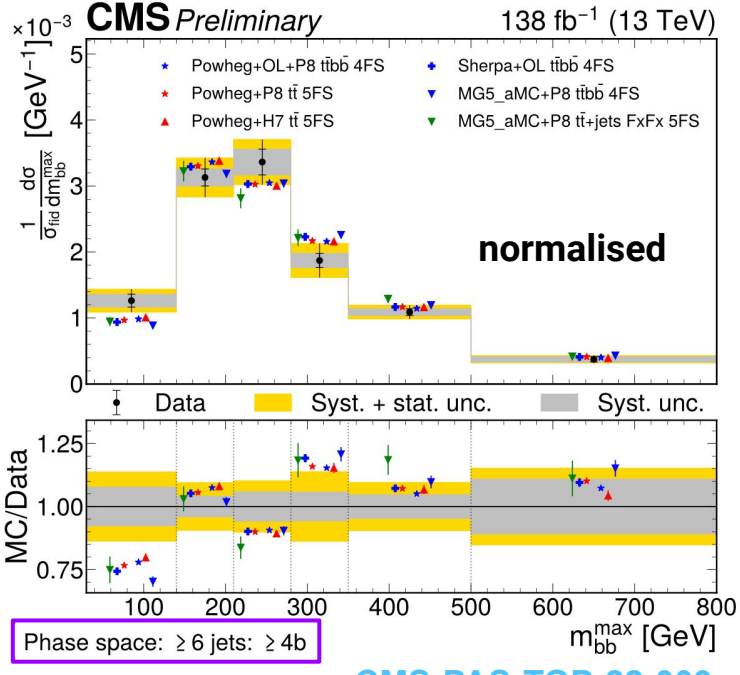
- $\mu_{R/F}$ scale, ISR/FSR modelling
- b-tagging, JES/JER

Differential ttbb measurement

Also presented by F. Colombina on Wed!

- ★ Using Profile Likelihood Unfolding to unfold to particle level.
- ★ Unfolding various kinematic & angular variables including inv masses, p_T, $|\eta|$, ΔR of b-quarks, N_{jet}, $N_{b\text{-}jet}$, H_T^{jet}, etc.
- ★ Two approaches for probing additional b-jet radiation in **6j4b** region:
  1) At particle level selecting the 2b closest in ΔR.
  2) Using the b-jets not originating from top-quark decays at generator level, identifying them at detector level w/ a DNN.





CMS-PAS-TOP-22-009

Summary & outlook

★ **ttW** and **ttbb** processes are quite challenging to model.

- **ttW**: Due to electroweak (EW) NLO corrections & more channels opening up at higher orders.
- **ttbb**: Large scale dependence, non-negligible difference in 4- & 5-FS.

⇒ Both needed for the measurements of other processes (e.g. ttH, tttt) and found to be underestimated by MC.

★ Measurements of **inclusive ttW cross section** & $\sigma_{ttW+}/\sigma_{ttW-}$ from both ATLAS & CMS w/ full Run-2 dataset.

- **Larger cross section** wrt the SM reference by both experiments (up to ~ x1.46), larger ratio observed by ATLAS.

★ First **ttW** differential and lepton charge asymmetry measurements at the LHC from ATLAS!

- Interesting behaviour for some of the unfolded variables.
- Try to interpret the results together with theorists.

★ Measurements of **inclusive ttbb cross section** from both ATLAS & CMS w/ partial Run-2 dataset.

★ First inclusive & differential **ttbb** measurement w/ full Run-2 dataset from CMS!

More interesting results to come, stay tuned!