Measuring *4 tops* and *ttW* with the ATLAS experiment

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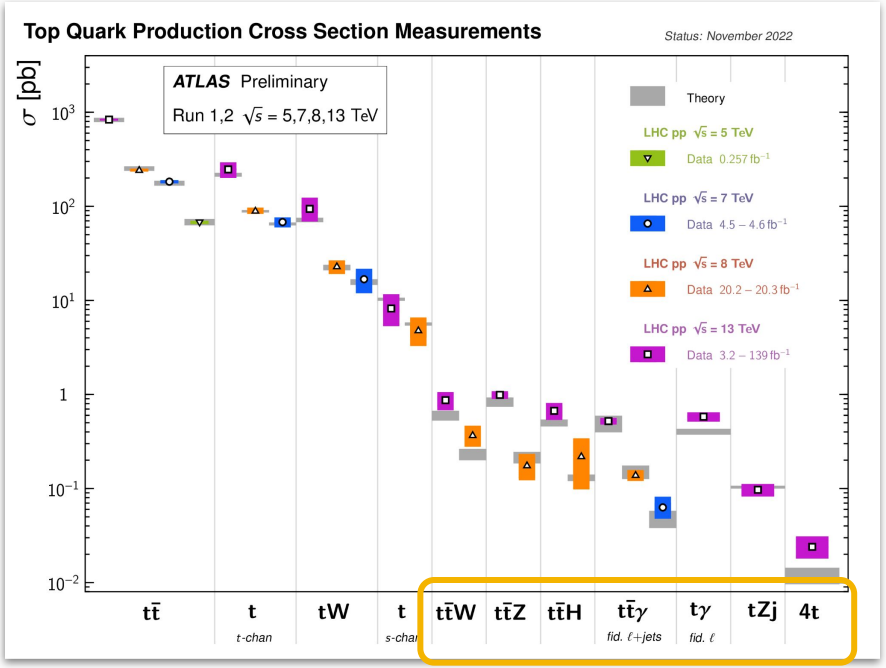
on behalf of the ATLAS collaboration

Introduction

Top quark is extremely interesting

- Heaviest SM particle
- Our window to measuring properties of bare quark
- Yukawa $y_t \approx 1$, key for measuring stability of Higgs
- Sensitive to many BSM models

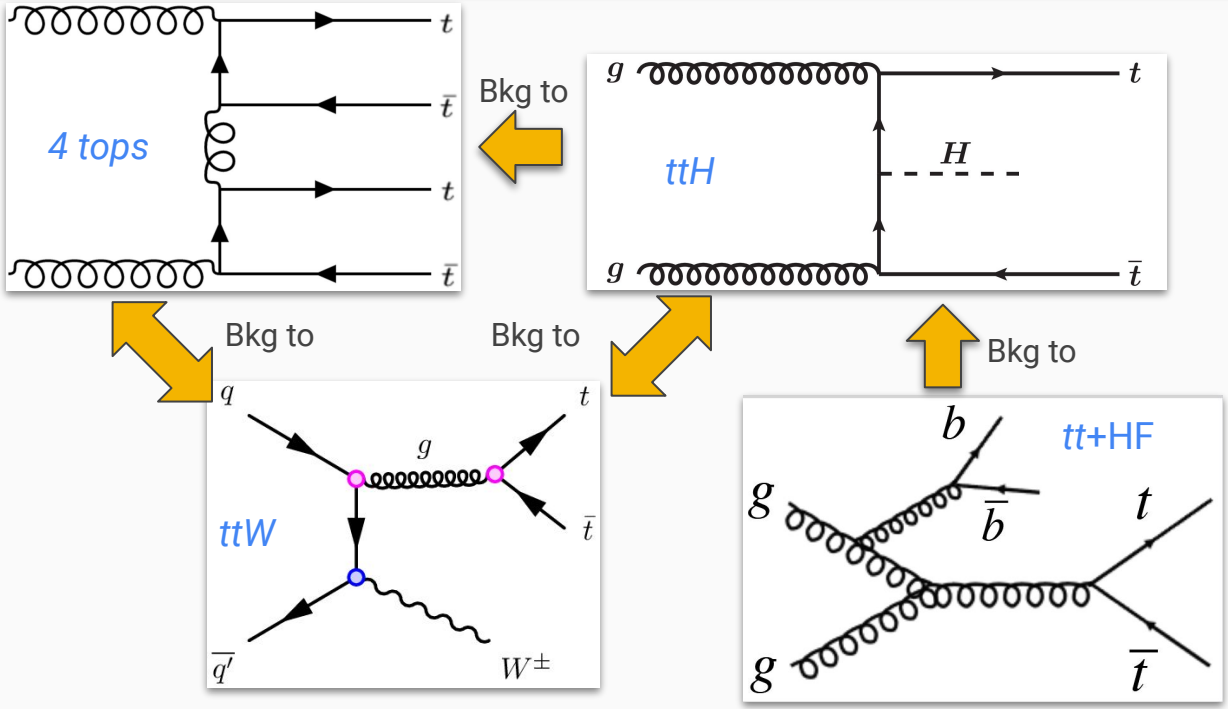
Many rare processes of interest within reach in Run 2+3!



Introduction - Motivation

Interdependence between rare top processes

All interesting in and of themselves



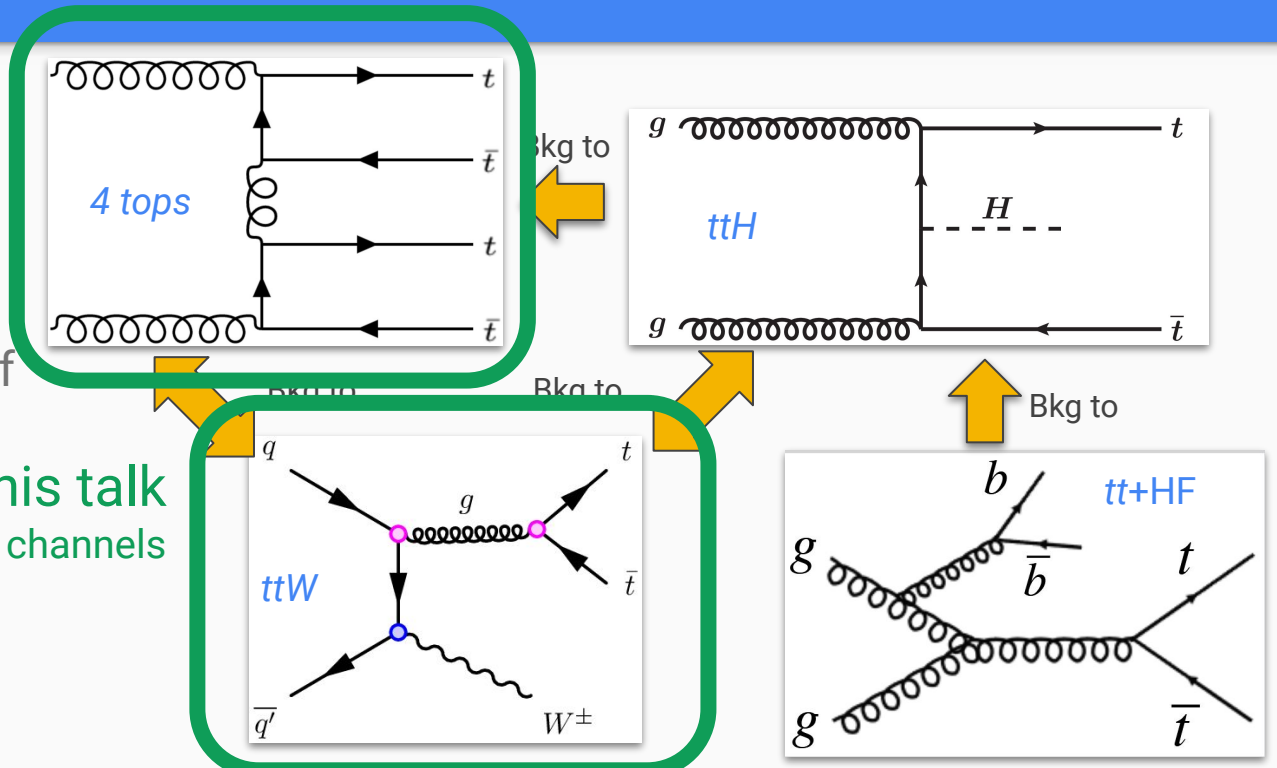
Introduction - Motivation

Interdependence between rare top processes

All interesting in and of themselves

This talk

Focus on multi-leptons channels



ttW

Overview

Main background in *4 tops* and many *ttH* decay channels

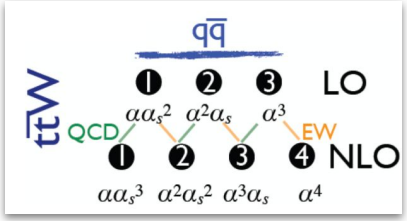
Very challenging process with QCD and EWK contributions

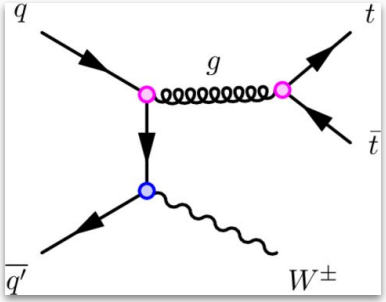
New nominal *ttW* prescription with Sherpa 2.2.10

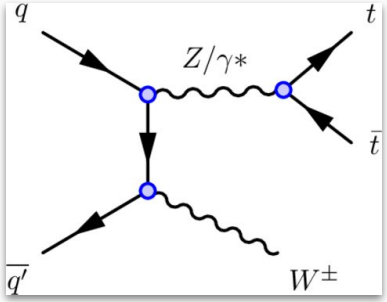
- Recent cross-section calculations *increase* expectation from 601 to **722 fb**[2108.07826]
  - **But** 10-20% variation across theoretical calculations

New nominal value

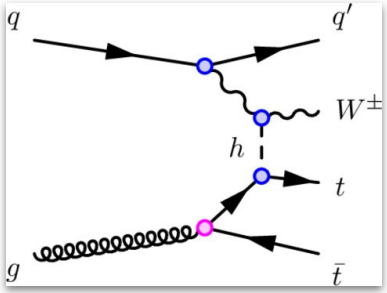
- Subleading EWK NLO corrections from extra sample LO in QCD
- Virtual EWK NLO corrections applied event-by-event







Leading order QCD and EWK diagrams



Example higher order QCD+EWK correction

Signal selection

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Measurement in multilepton final states: 2ℓSS and 3ℓ

- At least two jets
  1 *b*-tag @ 60% or 2 *b*-tags @ 77%
- Total charge=±1 and *Z* mass cut in 3ℓ
- Categorise into regions by jet multiplicity and lepton flavours
  (differ for inclusive and differential)

Signal region preselection	2ℓSS	3ℓ
Lepton definition	*TT*	*LTT*
Lepton p_{T} [GeV]	(20, 20)	(10, 20, 20)
N_{jets}	≥ 2	
$N_{b-\text{jets}}$	≥ 1 $b^{60\%}$ or ≥ 2 $b^{77\%}$	
$m^{\text{SF}}_{\ell^\pm\ell^\pm}$ or $m^{\text{SF}}_{\ell^+\ell^-}$ [GeV]	> 12	
$\lvert m^{\text{SF}}_{\ell^+\ell^-} - m_Z\rvert$ [GeV]	–	> 10
$\lvert m_{\ell\ell\ell} - m_Z\rvert$ [GeV]	–	> 10
	Inclusive cross section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Lepton flavour split	$(\mu\mu, e\mu, \mu e, ee)$	-
Jet multiplicity split	(3, 4, ≥5)	(2, ≥3)
b-jet multiplicity split	(1, ≥2)	
Total inclusive SRs	48	8
	Differential cross section measurement	
Lepton charge split	$(\ell^+\ell^+, \ell^-\ell^-)$	$(\ell^+\ell^-\ell^-, \ell^-\ell^+\ell^+)$
Number of OS-SF pairs split	–	(0, 1, 2)
Total differential SRs	2	6

Control regions

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Main backgrounds from *ttZ* and diboson

- Other contributions from non-prompt leptons and γ conversion
- 10 Dedicated control regions, simultaneous fit
- Charge mis-ID derived from data

Control regions for:	Diboson	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
$N_{b-\text{jets}}$	1 $b^{60\%}$	$\geq 1\ b^{60\%}$ or $\geq 2\ b^{77\%}$	0 $b^{77\%}$	1 $b^{77\%}$
Lepton requirement		3ℓ	$\mu\mu e^{*}$	2ℓSS
Lepton definition		(L, M, M)		$(T, M_{\text{ex}}) \parallel (M_{\text{ex}}, T) \parallel (M_{\text{ex}}, M_{\text{ex}})$
Lepton p_{T} [GeV]		(10, 20, 20)		(20, 20)
$m^{\text{SF}}_{\ell^+\ell^-}$ [GeV]		> 12	> 12	–
$\lvert m^{\text{SF}}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]		< 10	> 10	–
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]		–	< 10	–
$m_T(\ell_0, E_{\text{T}}^{\text{miss}})$ [GeV]		–		< 250 for TM_{ex} and $M_{\text{ex}}T$ pairs
Region split	–	–	internal / material	subleading $e/\mu \times (TM_{\text{ex}}, M_{\text{ex}}T, M_{\text{ex}}M_{\text{ex}})$
Region naming	3ℓVV	3ℓttZ	3ℓIntC	$2\ell\text{tt(e)}_{TM_{\text{ex}}}$, $2\ell\text{tt(e)}_{M_{\text{ex}}T}$, $2\ell\text{tt(e)}_{M_{\text{ex}}M_{\text{ex}}}$
			3ℓMatC	$2\ell\text{tt}(\mu)_{TM_{\text{ex}}}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}T}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}M_{\text{ex}}}$

Control regions

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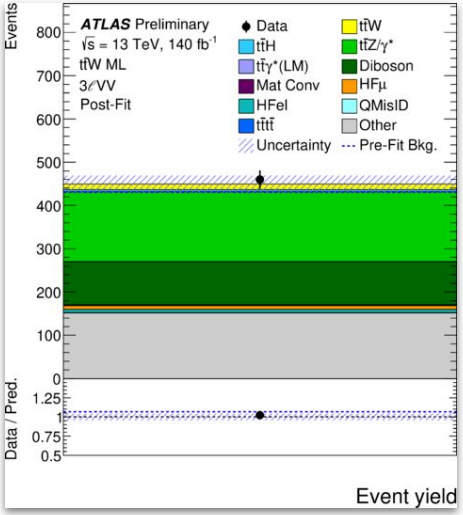
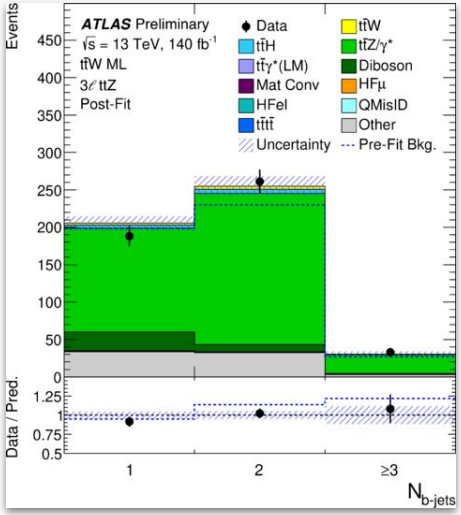
Very pure *ttZ* control region selecting *Z* mass

Extract data driven norm factors from CRs

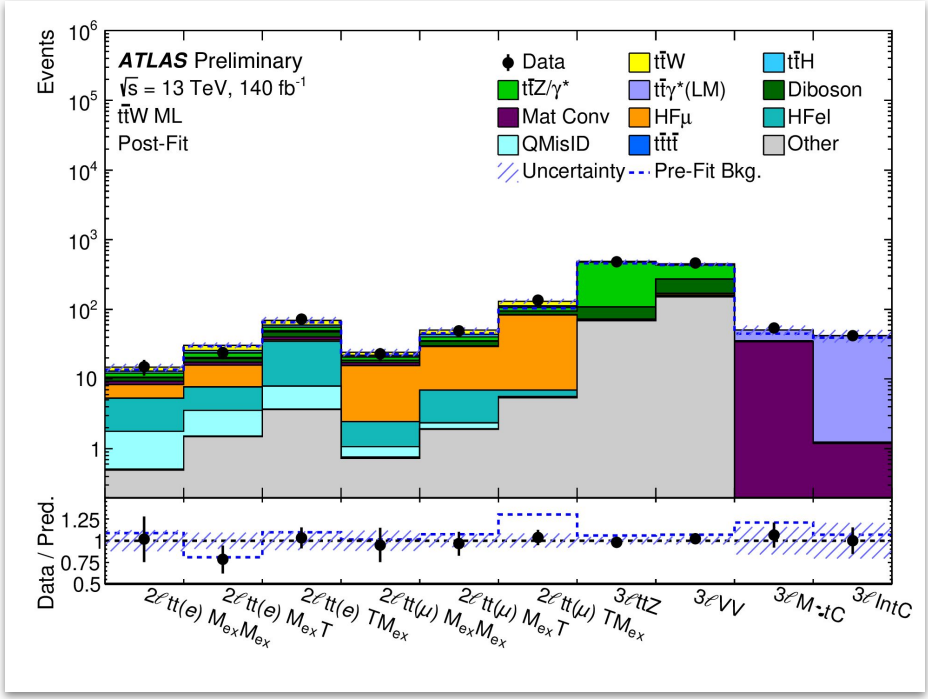
Diboson: 0.87 *ttZ*: 1.16



Diboson



ttZ



Good agreement post-fit across all control regions

Results - Inclusive cross section

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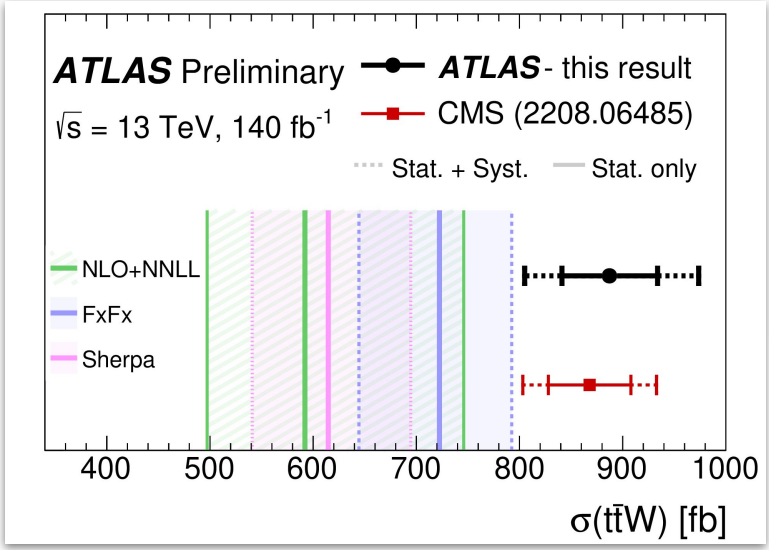
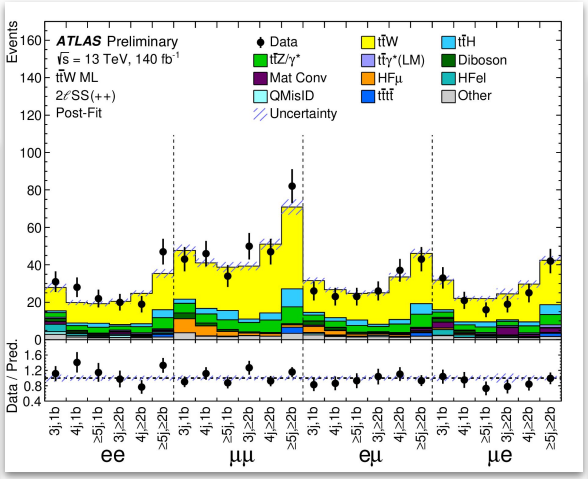
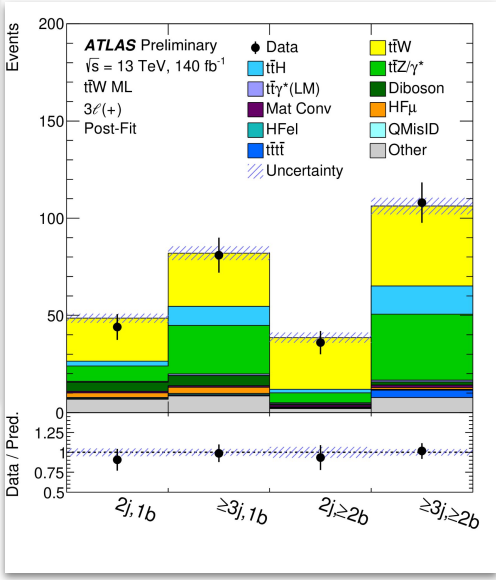
$$\sigma(t\bar{t}W) = 890 \pm 50\ (\text{stat.}) \pm 70\ (\text{syst.}) = 890 \pm 80\ (\text{tot.})\ \text{fb}$$

Compatible with FxFx prediction at 1.5σ







Results - Differential cross section

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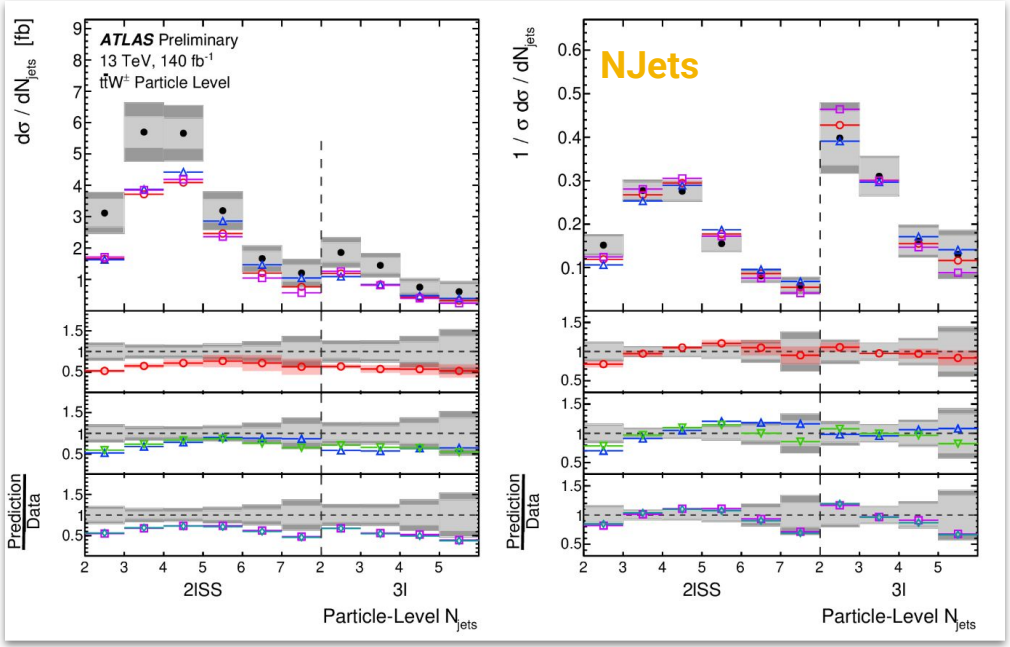
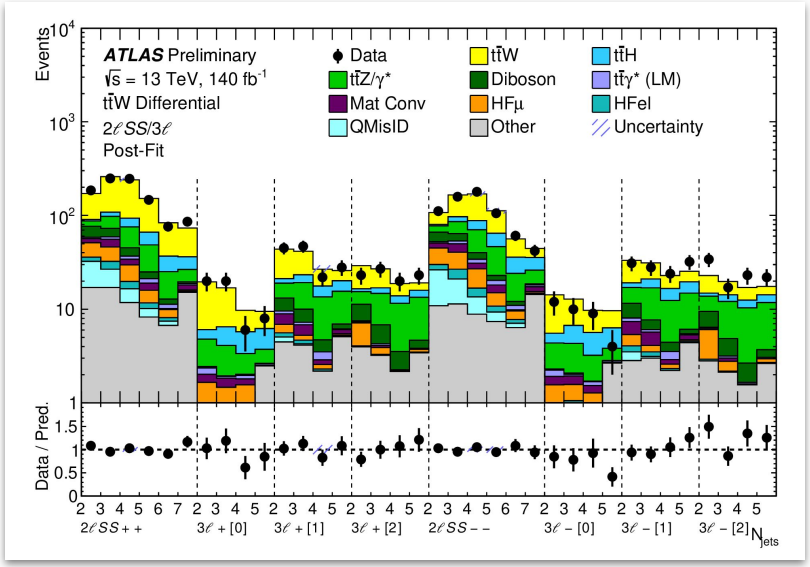
Observed excesses consistent with inclusive measurement

Normalised measurements show reasonable agreement with MC predictions





Using Profile Likelihood Unfolding

Differential measurement

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Observed excesses consistent with inclusive measurement

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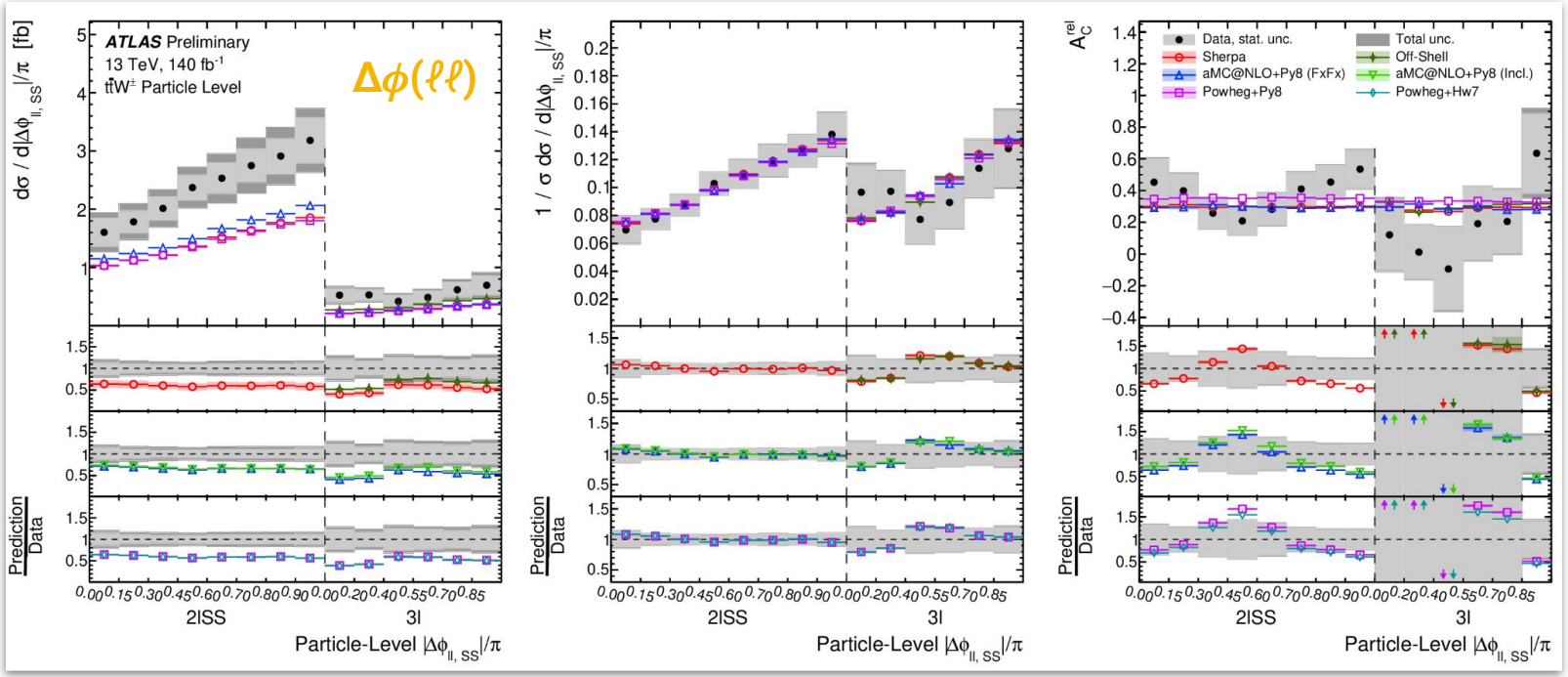


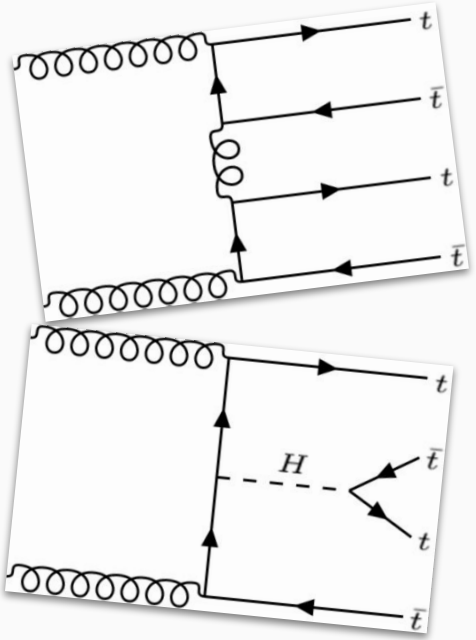
4 tops

Overview

2303.15061, accepted by EPJC

Multi-lepton 2ℓSS and 3ℓ channels on 140fb^{-1}

- Previous ATLAS result observed 4.3σ over background only



Key changes

- Optimised **lower p_T threshold** to select jets/leptons
- Improved *b*-jet ID, **lepton isolation**
- **Data driven *ttW*** background modelling
- Updated treatment of ***3 tops* background**
  - Using NLO cross section, with 35% total uncertainty
  - Covers renorm/factorisation scales, PDF choice, LO EW contribution and difference between 4FS and 5FS
- **Graph Neural Network** for signal/background separation in signal region

Method

2303.15061, accepted by EPJC

Eight control regions to handle backgrounds

- Use lepton flavour and charge
- Looser jet multiplicity selection

Signal region:

- ≥6j≥2b and H_T > 500 GeV

Fit GNN in signal region

- **Nodes**: All jets, leptons and MET
  Features: 4vec + charge/btag
- **Edges**: fully connected graph,
  Features: angular separation

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \le N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from virtual photon (γ^*) decay ℓ_1 and ℓ_2 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \le N_j < 6$	≥ 1	ℓ_1 or ℓ_2 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_T < 300$ GeV $E_T^{miss} > 50$ GeV total charge = ± 1	$p_T^{\ell_3}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_T < 275$ GeV $E_T^{miss} > 35$ GeV total charge = ± 1	$p_T^{\ell_3}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \ge 3$: $H_T < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_T < 500$ GeV or $N_j < 6$ when $N_b \ge 3$: $H_T < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_T > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_T > 500$ GeV	GNN score

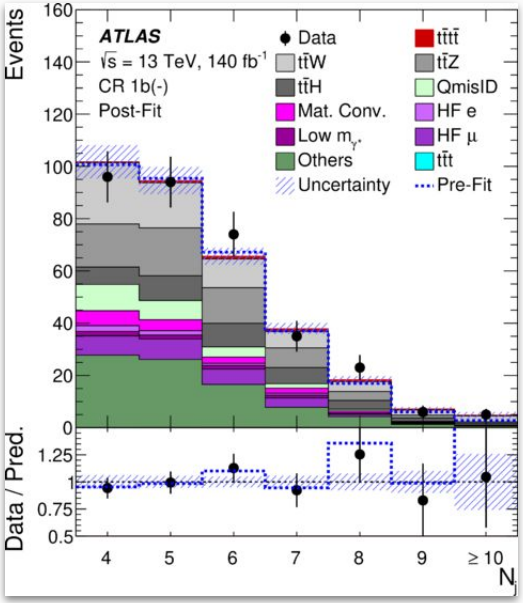
Data driven *ttW* normalisation

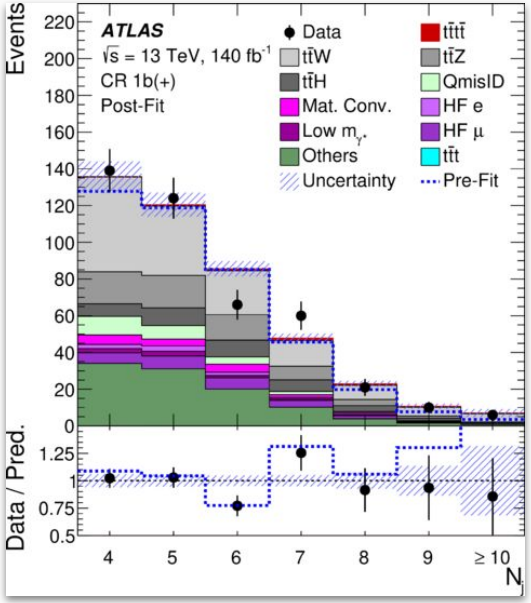
2303.15061, accepted by EPJC

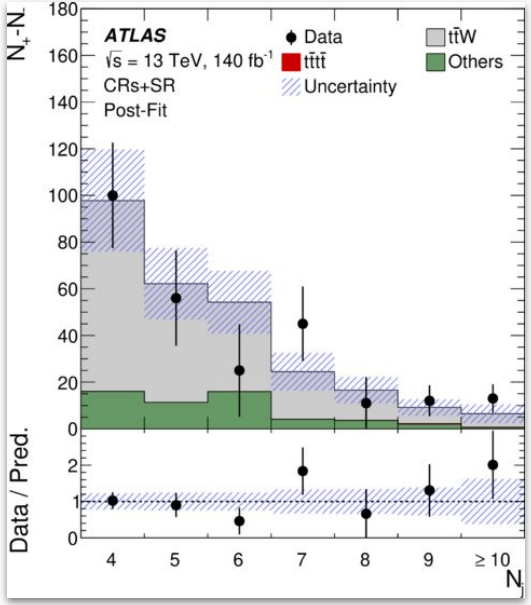
Shapes taken from MC

Normalisation in bins of jet multiplicity extracted from four *ttW* CRs

	Staircase scaling		*4jet norm.*	
$t\bar{t}W$ background	a_0	a_1	$NF_{t\bar{t}W^+(4jet)}$	$NF_{t\bar{t}W^-(4jet)}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$







Validated with charge asymmetry in *ttW*

Normalisation factors compatible with ttW measurement

Observation of *4 tops* at ATLAS

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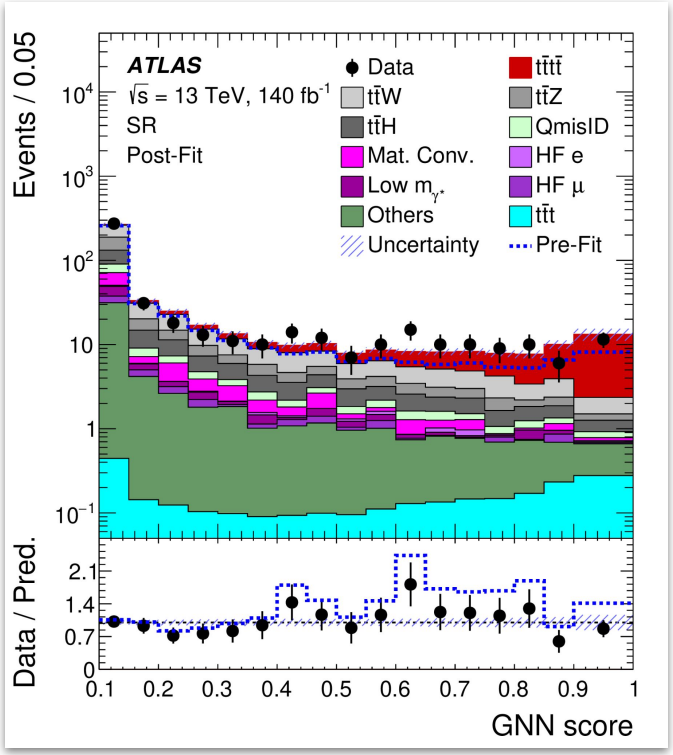


Measured

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\ \text{fb}$$

SM: $\sigma_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4\ \text{fb}$ [1711.02116]

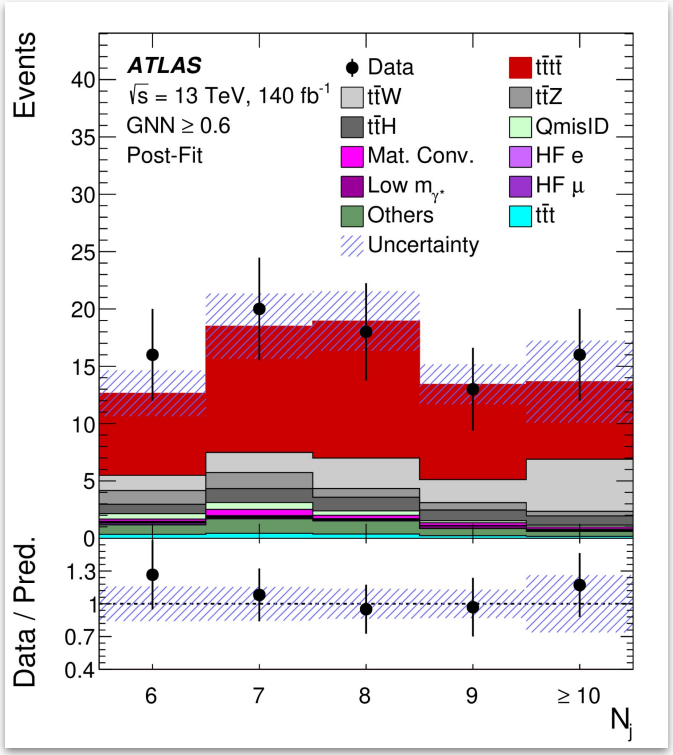
Observed 6.1σ

Over background only

(Expected 4.3σ)

Observed norm factor:

$$\mu = 1.9 \pm 0.4(\text{stat})\,^{+0.7}_{-0.4}(\text{syst})$$



Interpretations - 3 tops

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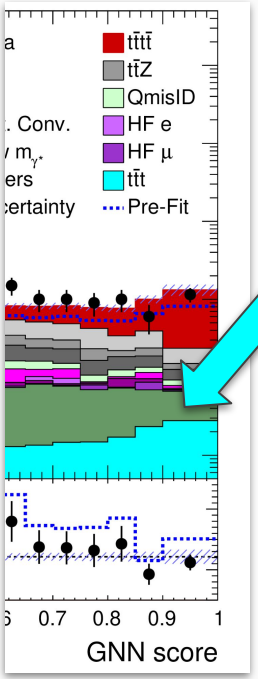
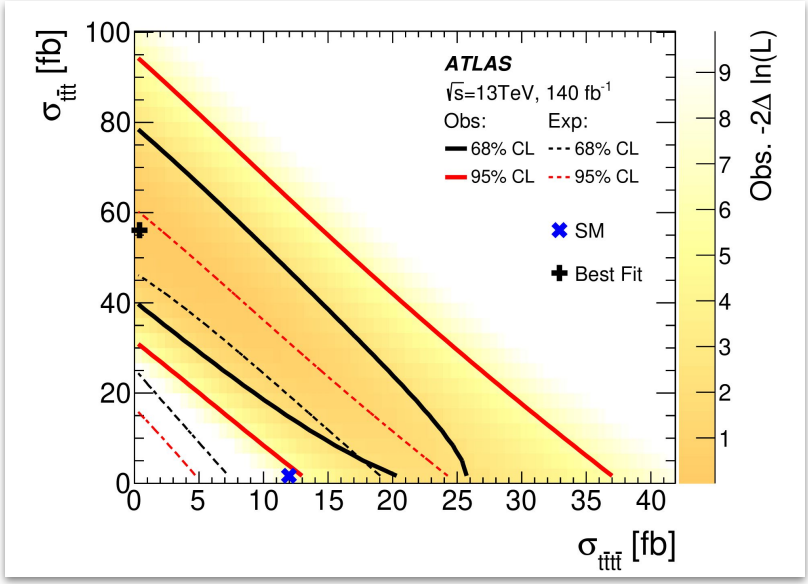
Set limits on *ttt* production cross section



Processes	95% CL cross section interval [fb]	
	$\mu_{t\bar{t}t\bar{t}} = 1$	$\mu_{t\bar{t}t\bar{t}} = 1.9$
$t\bar{t}t$	[4.7, 60]	[0, 41]
$t\bar{t}tW$	[3.1, 43]	[0, 30]
$t\bar{t}tq$	[0, 144]	[0, 100]

Free float both *4 tops* and *3 tops* (-93% anticorrelated)



Best fit value has μ_{tttt} close to zero, but equally compatible at μ_{tttt}=2

Interpretations - BSM

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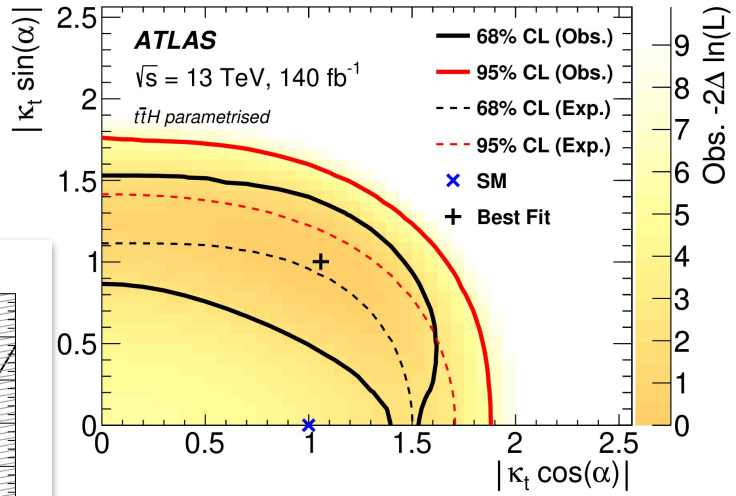
Probe Heavy Flavour fermion EFT operators

- Sensitive to BSM models enhancing interactions between third generation quarks

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O_{QQ}^1	[-2.4, 3.0]	[-3.5, 4.1]
O_{Qt}^1	[-2.5, 2.0]	[-3.5, 3.0]
O_{tt}^1	[-1.1, 1.3]	[-1.7, 1.9]
O_{Qt}^8	[-4.2, 4.8]	[-6.2, 6.9]

HF fermion EFT operators [1708.05928]

For CP-Even: $|\kappa_t| < 1.8\ (1.6)$



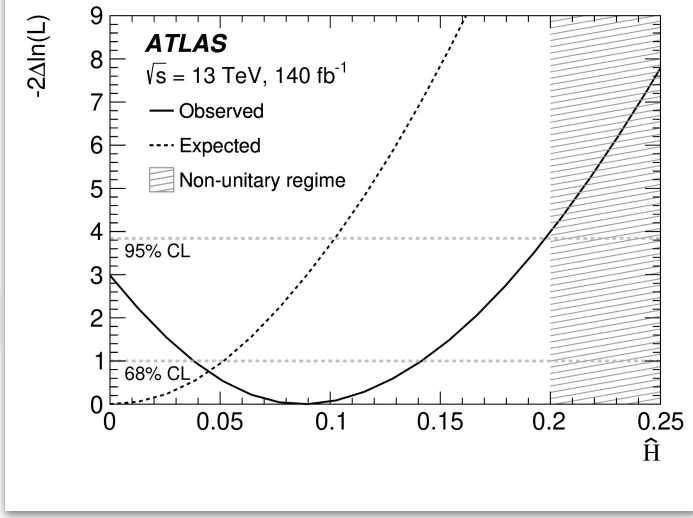
Sensitivity to top Yukawa and CP mixing angle α
From 4 top and *ttH* background

Higgs oblique parameter

extract from *ttH* background

$$\mu_{t\bar{t}H} = 1 - \hat{H}$$

Upper limit is at largest value preserving unitarity in perturbative theory



Summary

Conclusion

Improved measurement of *ttW* inclusive cross section and differential measurements in wide range of observables

- Inclusive measurement compatible with SM
  - However, similar excess observed as by CMS collaboration
- Charge ratio in good agreement with SM
- Normalised differential distributions in agreement with MC predictions

Four top quark production **observed at 6.1σ** (expected 4.3σ) with ATLAS

Backup

Norm factors *ttW*

VV: 0.87+-0.33

ttZ: 1.16+-0.15

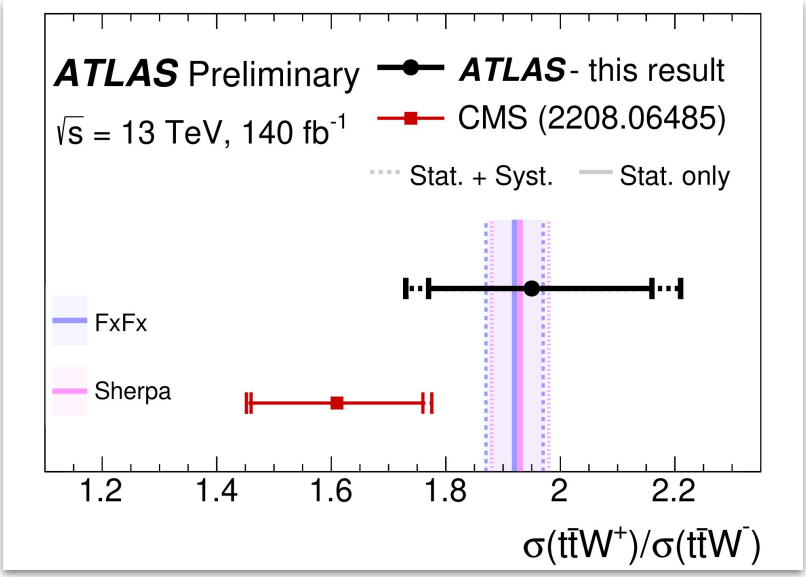
Internal conversion e: 1.07+-0.24

Material conversion e: 1.15+-0.31

Non-prompt e: 0.83+-0.31

Non-prompt μ: 1.02+-0.21

ttW Charge ratio



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

$$A_C^{\mathrm{rel}} = 0.32 \pm 0.05\ (\mathrm{stat.}) \pm 0.03\ (\mathrm{syst.}) = 0.32 \pm 0.06\ (\mathrm{tot.}).$$

Differential observables *ttW*

Variable	Definition
N_{jets}	Number of selected jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
$H_{\text{T,jets}}$	Scalar sum of the transverse momenta of selected jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$
$H_{\text{T,lep}}$	Scalar sum of the transverse momenta of selected leptons
$\Delta\text{R}_{\text{lb, lead}}$	Angular distance between the leading lepton and the leading b-tagged jet
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$	Absolute azimuthal separation between the two leptons of the same-sign pair
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$	Absolute pseudo-rapidity separation between the two leptons of the same-sign pair
$M_{\text{jj, lead}}$	Invariant mass of the two leading jets with $p_{\text{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$

4 tops - ttW reweighting

Four dedicated CRs to extract a_0, a_1 scaling params and *N(ttW)* in ==4jet regions

$$\mathrm{NF}_{t\bar{t}W\,(j)} = \mathrm{NF}_{t\bar{t}W^{+}(4\mathrm{jet})} \times \Pi_{j'=4}^{j'=j-1}\left[a_0 + \frac{a_1}{1+(j'-4)}\right] + \mathrm{NF}_{t\bar{t}W^{-}(4\mathrm{jet})} \times \Pi_{j'=4}^{j'=j-1}\left[a_0 + \frac{a_1}{1+(j'-4)}\right]$$

CRs are separate for + and - charge

Staircase scaling with a_0 and a_1 at higher jet multiplicities with Poisson scaling at lower

4 top EFT

Four independent operators in four top production

$$\mathcal{O}_{QQ}^{(+)} \equiv \frac{1}{2}\mathcal{O}_{qq}^{(1)(3333)} + \frac{1}{2}\mathcal{O}_{qq}^{(3)(3333)},$$
$$\mathcal{O}_{tt} \equiv \mathcal{O}_{uu}^{(3333)},$$
$$\mathcal{O}_{Qt}^{(1)} \equiv \mathcal{O}_{qu}^{(1)(3333)},$$
$$\mathcal{O}_{Qt}^{(8)} \equiv \mathcal{O}_{qu}^{(8)(3333)},$$

Modify 4 top cross section as

$$\sigma_{t\bar{t}t\bar{t}} = \sigma_{t\bar{t}t\bar{t}}^{SM} + \frac{1}{\Lambda^2}\sum_i C_i\sigma_i^{(1)} + \frac{1}{\Lambda^4}\sum_{i\leq j} C_iC_j\sigma_{i,j}^{(2)},$$

Linear term

Quadratic term: includes interference between EFT operators

Measure coupling constants for each of the four heavy-flavour fermion operators

Measure each coupling separately from 4 top yields, fix others to SM prediction of 0

tt+HF

Method

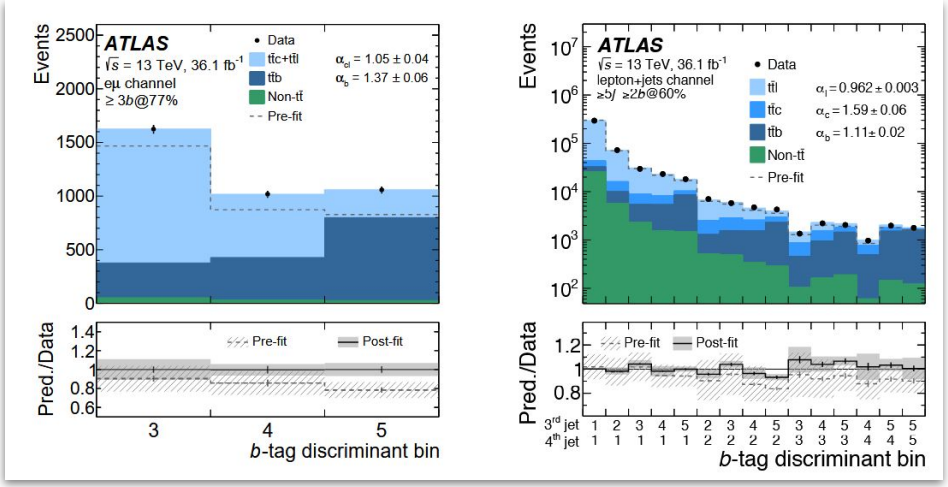
Fit tt+b, tt+c, and tt+light in l+jets and dilepton channels

- Fit flavour tagging score of additional jets
  - 5 efficiency bins per jet

Measure fiducial cross section of tt+bb

Normalised differential cross sections

- Event properties (Nbjet, HT)
- Kinematics of additional b (bb)



Results

Measured cross section generally exceed NLO tt+bb prediction but within uncertainties

Good agreement with differential observables