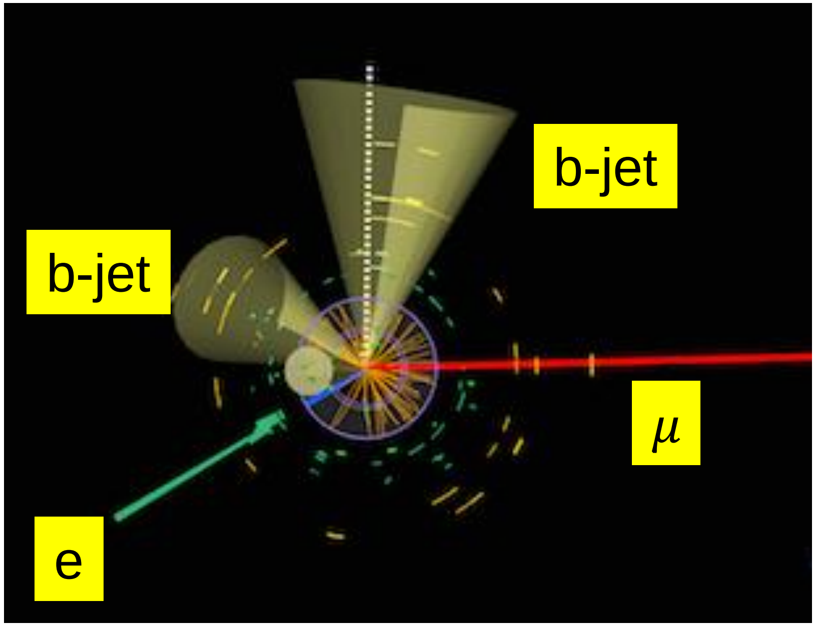
Measurements of top quark production cross-sections with the ATLAS detector

Richard Hawkings (CERN)

on behalf of the ATLAS collaboration

ICHEP2022 conference, Bologna, Italy, 7/7/2022

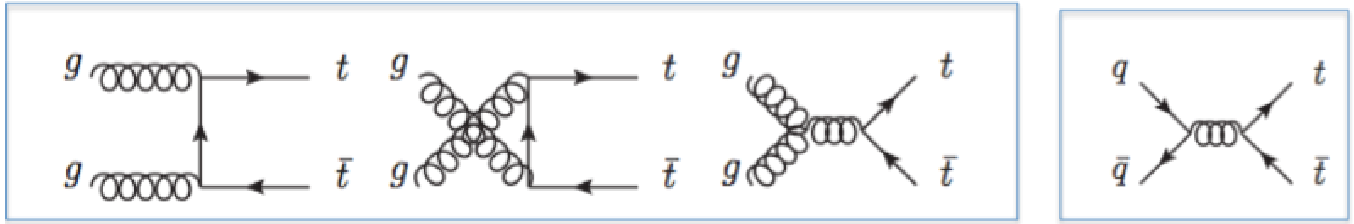
- Inclusive top quark production at LHC
  - Introduction
  - Top-pair measurements at 13 TeV
  - Top-pair measurements at 5.02 TeV
  - Run-1 combination of ATLAS+CMS results
  - Single top: s-channel with full Run-2 dataset
  - More information: ATLAS TopPublicResults

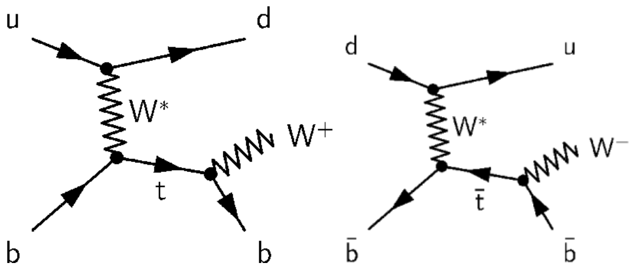


Introduction – top production at LHC

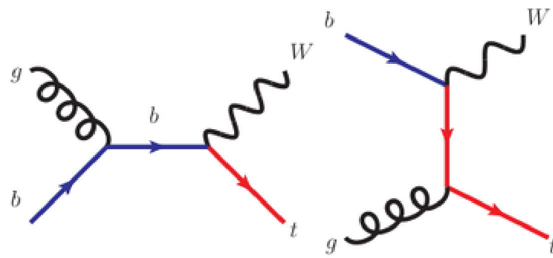
- Top quarks are copiously produced at LHC – some leading-order diagrams

Top-pair:
$\sigma_{tt} \approx$ 830 pb @ 13 TeV
gg fusion dominant

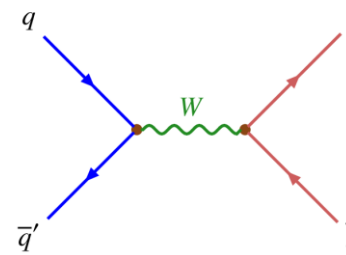




t-channel: $\sigma_{tq+t\sim q} \approx$ 220 pb



Wt: $\sigma_{Wt} \approx$ 72 pb



s-channel: $\sigma_s \approx$ 10 pb

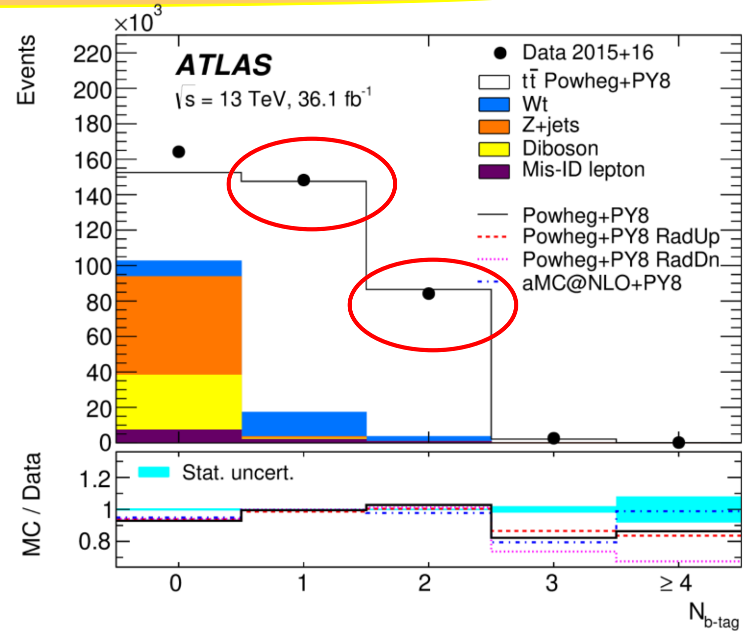
- Top quarks decay t→Wb, → lνb or qqb
  - Final states include leptons, missing transverse energy, b-tagged jets and jets
- Top pair-production can be selected with high purity, especially in dilepton
  - But only ~2% produce the ‘golden’ eμ final state, so l+jets events also useful
- Cross-sections for single top channels are much smaller
  - Rely on final states with leptons (t→lνb), and need multivariate techniques

Double-tagging in eμ events at 13 TeV

- Count $e^{\pm}\mu^{\mp}$ events with 1 or 2 b-tagged jets
  - Assume top quarks decay independently
  - Fit $\sigma_{t\bar{T}}$ and probability ε_b to select and b-tag jet:

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}C_b{\epsilon_b}^2 + N_2^{\mathrm{bkg}}$$

  - $\varepsilon_{e\mu}$ is efficiency to to select the two leptons
  - 1/2 b-tag regions 88/96% pure in top-pair events



EPJ C80 (2020) 528

- Method minimises uncertainties due to top-pair modelling, jets and background
  - Remaining uncertainty dominated by luminosity and top-pair modelling (eμ acceptance)

$$\sigma_{t\bar{t}} \quad = \quad 826.4 \pm 3.6 \pm 11.5 \pm 15.7 \pm 1.9\,\mathrm{pb}$$

  - Precise result also used to measure m_t^{pole} and constrain PDFs via ratios σ_{tt}/σ_Z

Category	Uncertainty (%)
Statistics	0.4
Top-pair modelling	1.0
Leptons	0.6
Jets / b-tagging	0.2
Backgrounds	0.8
Luminosity/beam energy	1.9
Total	**2.4**

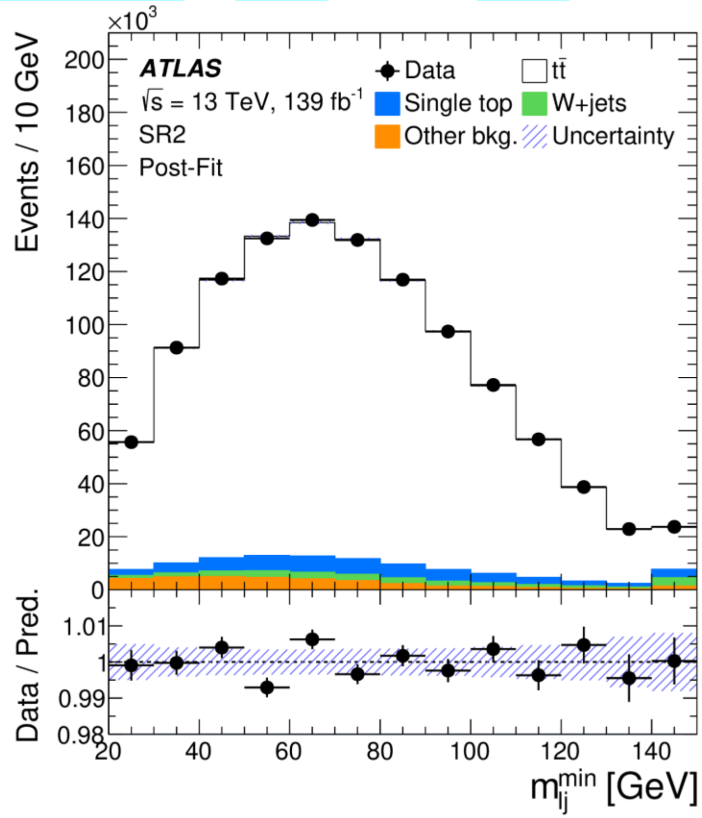
Lepton+jets events at 13 TeV

- Lepton+jets channel uses events with one lepton, at least 4 jets and E_T^{miss}
  - Almost 7M selected events, but lower top-pair purity than in dilepton selection
- Select 3 signal regions:
  - SR1: ≥4 jets, 1 b-tagged jet
  - SR2: 4 jets, 2 b-tagged jets
  - SR3: ≥5 jets, 2 b-tagged jets
- Fit to a different discriminating variable in each region, e.g. m_{lj}^{min} in SR2
  - Profile likelihood to constrain physics, detector modelling and background systs.

$$\sigma_{\text{inc}} = 830 \pm 0.4\ (\text{stat.}) \pm 36\ (\text{syst.}) \pm 14\ (\text{lumi.})\ \text{pb}$$

  - Uncertainties dominated by top modelling and jet energy scale – heavy use of jets
    - 4.6% uncertainty; factor 2 larger than $e\mu$

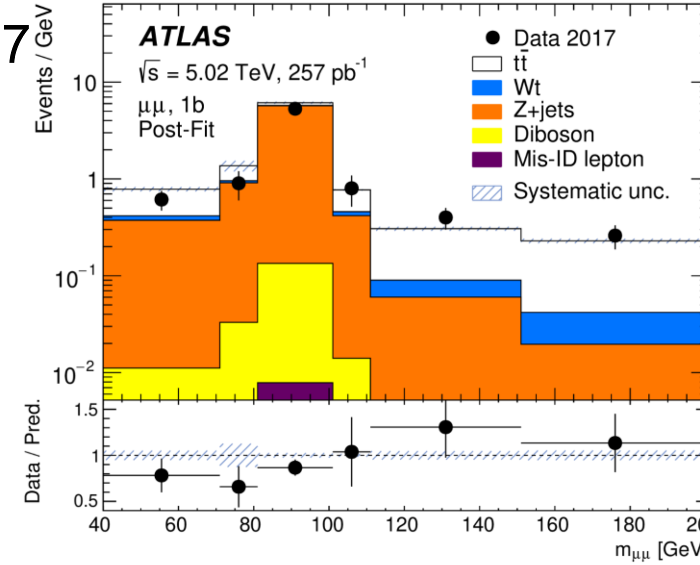
	SR1	SR2	SR3
$t\bar{t}$	3 630 000 ± 210 000	990 000 ± 90 000	980 000 ± 100 000
W+jets	350 000 ± 160 000	24 000 ± 10 000	17 000 ± 9000
Single top	255 000 ± 31 000	52 000 ± 7000	37 000 ± 8000
Z+jets & diboson	80 000 ± 40 000	8000 ± 4000	5800 ± 3000
$t\bar{t}X$	15 600 ± 2100	2110 ± 290	7200 ± 1000
Multijet	210 000 ± 80 000	28 000 ± 10 000	22 000 ± 8000
Total prediction	4 540 000 ± 310 000	1 110 000 ± 100 000	1 070 000 ± 100 000
Data	4 540 886	1 100 558	1 103 317
S/B (%):	80	89	92



PLB 810 (2020) 135797

Dilepton events at 5.02 TeV

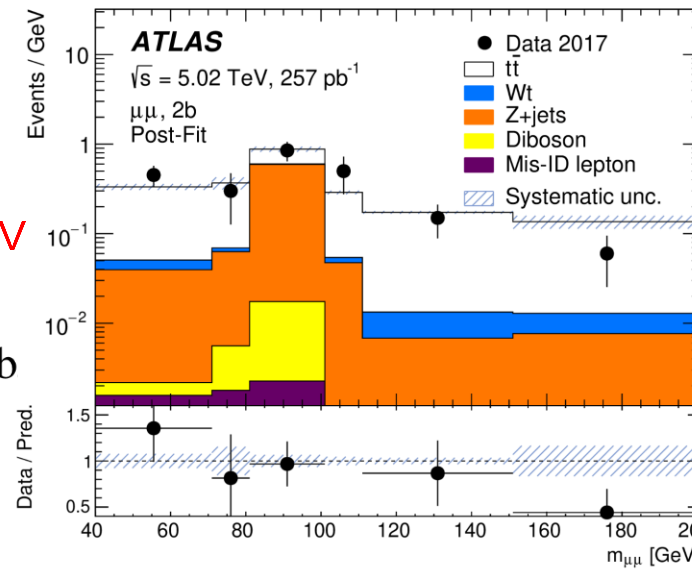
- ATLAS recorded 257 pb^{-1} at $\sqrt{s}$=5.02 TeV in 2017
  - σ_{tt} ~12x smaller than at 13 TeV, but qqbar fraction increased from 11% to 25%, and average x larger
    - Opportunity for complementary PDF constraints
- Small data sample, dilepton channel stat. limited
  - Increase lepton acceptance (p_T>18 GeV)
  - Use 85% efficient b-tagging WP (70% @ 13 TeV)



- Use ee / $\mu\mu$ channels in addition to eμ
  - Dominant Z→ee/$\mu\mu$ b/g, require E_T^{miss}>30 GeV
    - Fit m_{ll} distribution to determine N_1, N_2 vs. m_{ll}
    - 1/2 b-tag samples 60/94% pure tt for $|m_{ll}-m_Z|$>10 GeV
    - c.f. 80/96% in eμ channel

$$\sigma_{t\bar{t}} = 65.7 \pm 4.5\,(\text{stat.}) \;\pm 1.6\,(\text{syst.}) \;\pm 1.2\,(\text{lumi.}) \;\pm 0.2\,(\text{beam})\,\text{pb}$$

  - Total uncertainty of 7.5%; 6.8% stat, 2.4% syst
    - eμ channel alone has total uncertainty of 8.4%



arXiv:2207.01354

Lepton+jets events at 5.02 TeV

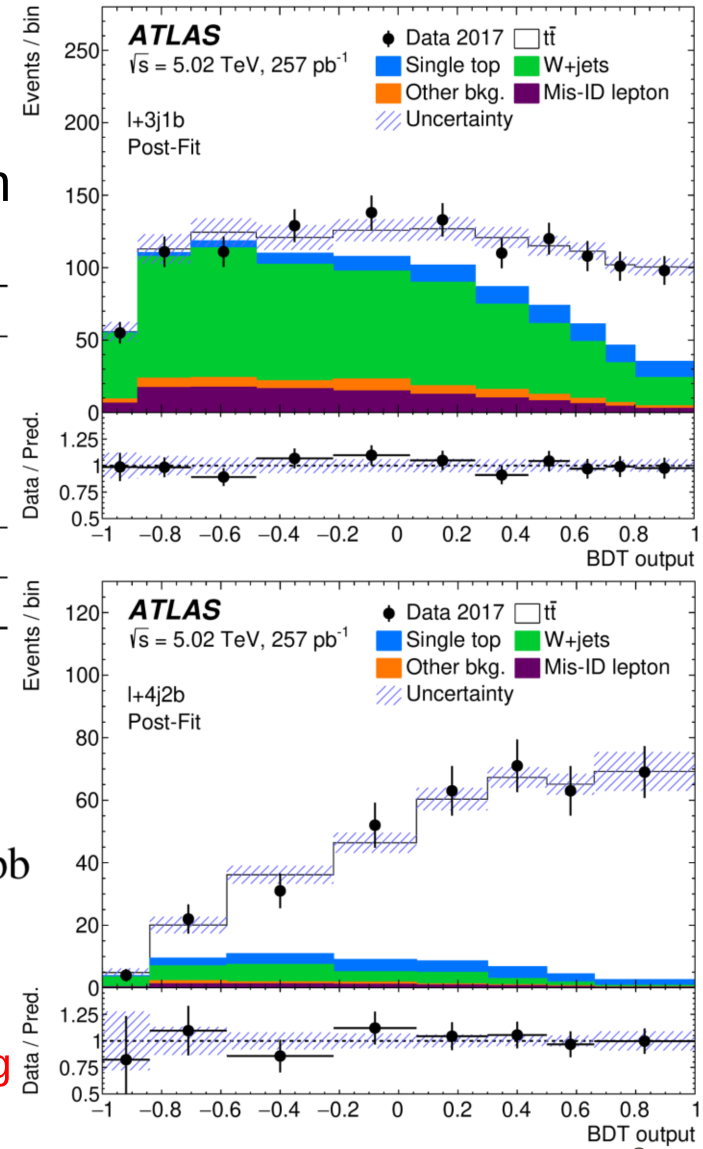
- Select events with 1 lepton, ≥2 jets and ≥1 b-tag
  - Together with cuts on E_T^{miss} and m_T^W
- 6 subsamples with different n_{jet}, $n_{b\text{-tag}}$ to constrain backgrounds in profile likelihood fit:

	$\ell+2j \geq 1b$	$\ell+3j\ 1b$	$\ell+3j\ 2b$	$\ell+\geq 4j\ 1b$	$\ell+4j\ 2b$	$\ell+\geq 5j\ 2b$
$t\bar{t}$	194 ± 27	310 ± 33	199 ± 24	690 ± 60	318 ± 32	380 ± 60
Single top	195 ± 22	98 ± 12	38 ± 5	67 ± 9	22 ± 4	15.9 ± 2.7
W+jets	1700 ± 400	690 ± 210	58 ± 23	350 ± 120	30 ± 14	19 ± 10
Other bkg.	110 ± 40	55 ± 23	7.2 ± 3.0	29 ± 12	3.5 ± 1.5	3.7 ± 1.7
Misidentified leptons	250 ± 130	110 ± 60	10 ± 5	60 ± 30	6 ± 3	8 ± 5
Total	2500 ± 400	1260 ± 210	312 ± 34	1200 ± 160	380 ± 40	430 ± 70
Data	2411	1214	293	1135	375	444
S/B (%):	8	25	64	58	84	89

- Fit to output of BDTs based on kinematic info in each of the six regions

$$\sigma_{t\bar{t}} = 68.2 \pm 0.9\,(\text{stat.}) \pm 2.9\,(\text{syst.}) \pm 1.1\,(\text{lumi.}) \pm 0.2\,(\text{beam})\ \text{pb}$$

- Total uncertainty 4.5%, syst. dominated (W+jets)
  - Slightly smaller uncertainty than the 13 TeV result !
  - Much less radiation at 5 TeV – smaller top modelling uncertainties



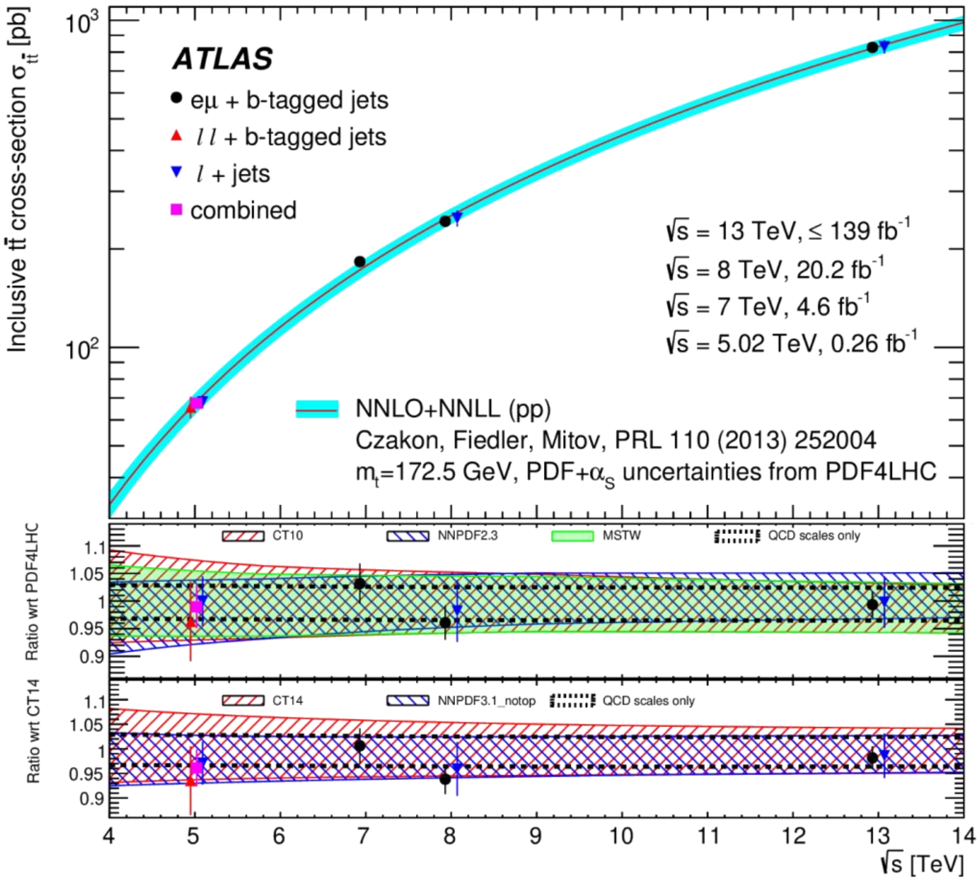
arXiv:2207.01354

Top-pair cross-section vs. √s

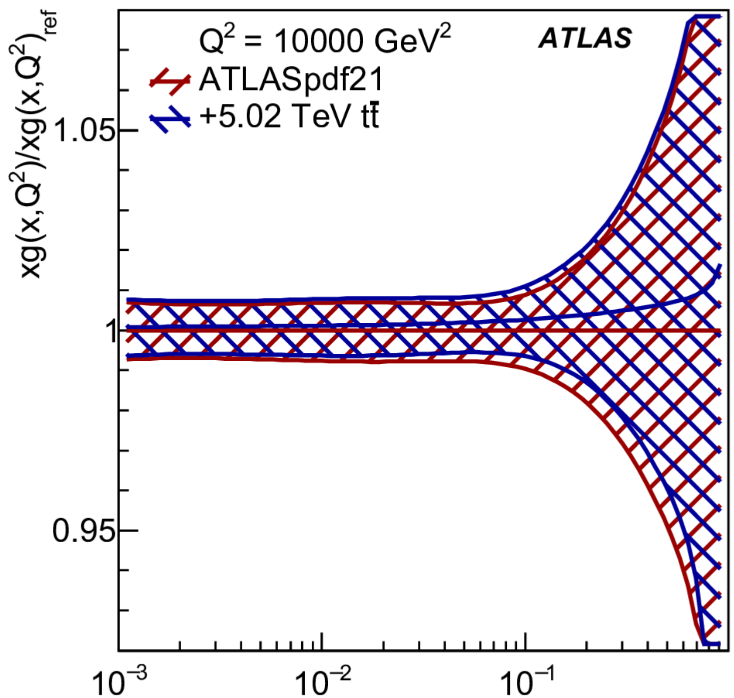
- Combine 5.02 TeV results from both channels with Convino tool

$$\sigma_{t\bar{t}} = 67.5 \pm 0.9(\text{stat.}) \pm 2.3(\text{syst.}) \pm 1.1(\text{lumi.}) \pm 0.2(\text{beam})\,\text{pb}$$

  - Combined uncertainty 3.9%, result compatible with QCD NNLO+NNLL prediction
- Impressive agreement of measurements with predictions from 5-13 TeV



- 5.02 TeV result added to ATLASpdf21 fit to show additional constraint on gluon PDF
  - 5% reduction on uncertainty at x≈0.1



arXiv:2207.01354

ATLAS+CMS top-pair combination at 7+8 TeV

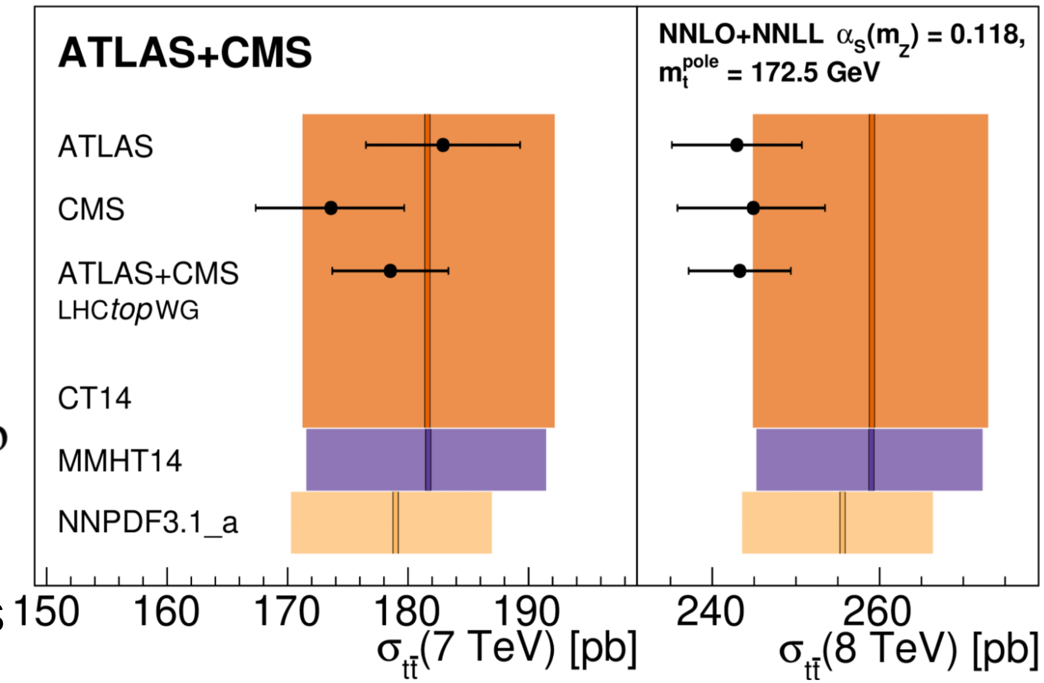
- Legacy eμ results from ATLAS+CMS at √s=7, 8 TeV have been combined
  - ATLAS measurements used simple tag-counting
  - CMS used profile likelihood fit inducing post-fit correlations between systematics
- Combination of all data at 7+8 TeV using χ^2 minimisation with Convino tool
  - Careful accounting of correlations between experiments and beam energies
- Total uncertainties:

arXiv:2205.13830

Uncert. (%)	σ_{tt}(7 Tev)	σ_{tt}(8 Tev)
ATLAS	3.5	3.2
CMS	$^{+3.6}_{-3.5}$	$^{+3.7}_{-3.5}$
Comb^n	$^{+2.7}_{-2.6}$	$^{+2.5}_{-2.4}$

  - 25/28% better c.f. most precise input

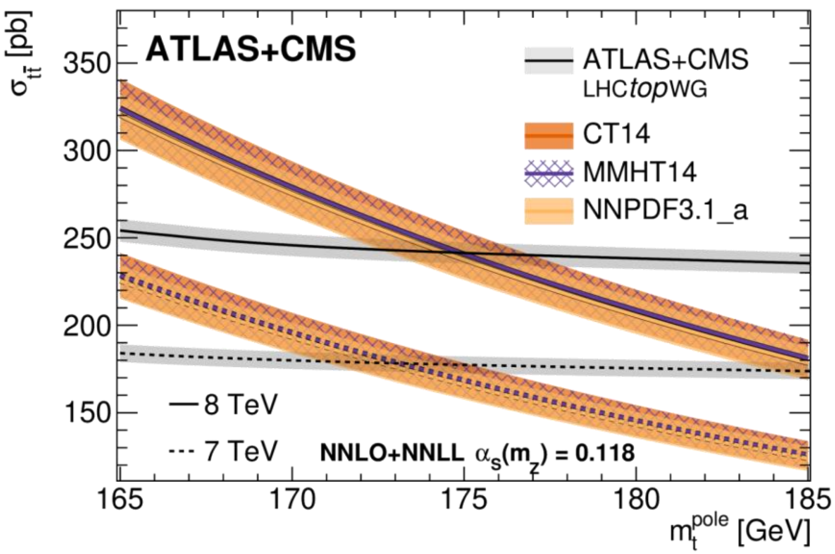
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 7\,\text{TeV}\ ) \quad = \quad 178.5 \pm 4.7\ \text{pb}$$
$$\sigma_{t\bar{t}}\ (\sqrt{s} = 8\,\text{TeV}\ ) \quad = \quad 243.3^{+6.0}_{-5.9}\ \text{pb},$$

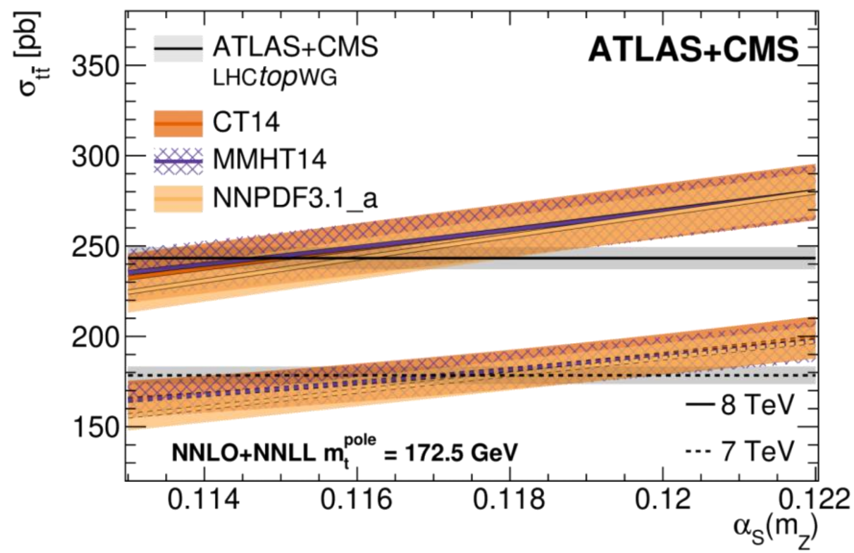


- Results compatible with recent PDFs

Extraction of m_t and α_S from 7+8 TeV comb^n

- Measured σ_{tt} can be used to extract pole mass m_t^{pole}, assuming a value of α_S
  - Or vice versa – assume m_t^{pole} and extract α_S
  - σ_{tt} results depend on assumed MC mass as acceptance/kinematics depend on m_t
    - Have to assume m_t^{pole} and m_t^{MC} are equal within a few GeV





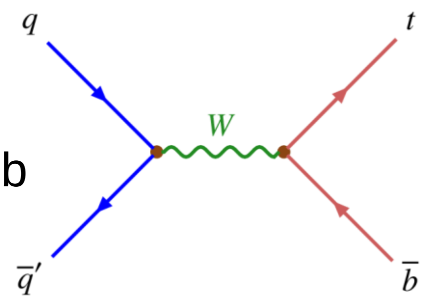
- Simultaneous χ^2 fits to 7+8 TeV σ_{tt}
  - Precision of ~2 GeV on m_t^{pole}, limited by PDF and scale uncertainties on pred^n
  - Most precise α_S extraction from top events

PDF set	m_t^{pole} ($\alpha_s = 0.118 \pm 0.001$)	$\alpha_s(m_Z)$ ($m_t = 172.5 \pm 1.0$ GeV)
CT14	$174.0^{+2.3}_{-2.3}$ GeV	$0.1161^{+0.0030}_{-0.0033}$
MMHT2014	$174.0^{+2.1}_{-2.3}$ GeV	$0.1160^{+0.0031}_{-0.0030}$
NNPDF3.1_a	$173.4^{+1.8}_{-2.0}$ GeV	$0.1170^{+0.0021}_{-0.0018}$

s-channel single top production at 13 TeV

- Most difficult single-top channel at LHC

predicted
σ_s=10.3±0.4 pb

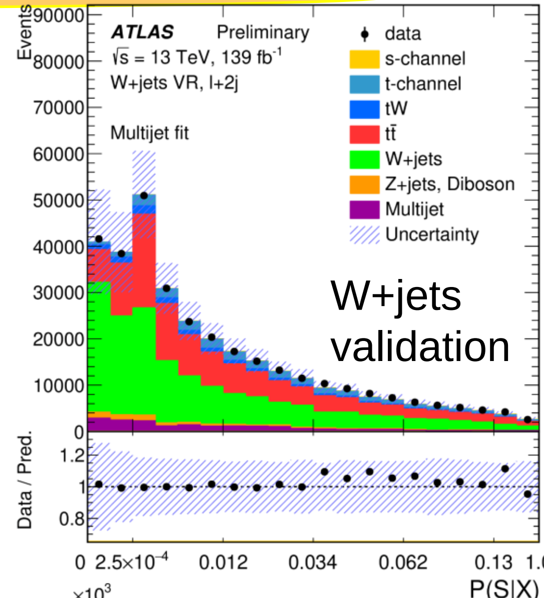


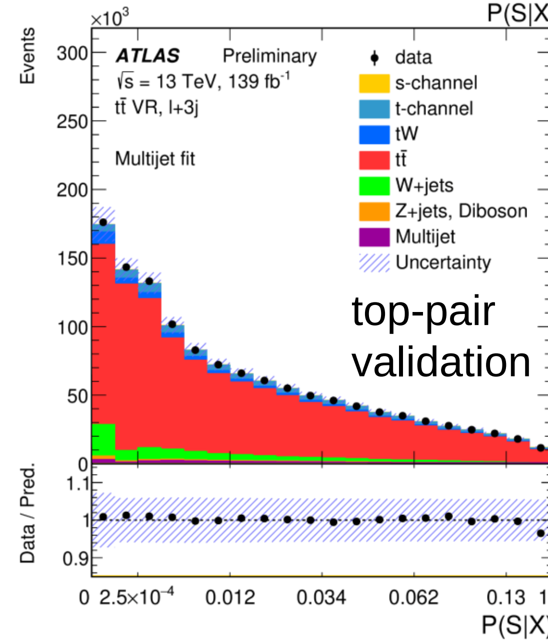
$t \to b\ell\nu$

  - Select events with lepton + 2 jets, both b-tagged
    - E_T^{miss}>35 GeV and m_T^W>30 GeV, veto 2nd lepton
  - 130k events selected, 3% s-chan, 60% top-pair
- Matrix-element based likelihoods for signal/bkg
  - Convolution of diff. x-sec and transfer function, based on reconstructed event kinematics X

$$\mathcal{P}(X \mid H_{\mathrm{proc}}) = \int \mathrm{d}\Phi \, \frac{1}{\sigma_{H_{\mathrm{proc}}}} \frac{\mathrm{d}\sigma_{H_{\mathrm{proc}}}}{\mathrm{d}\Phi} T_{H_{\mathrm{proc}}}(X \mid \Phi)$$

    - Compute per-event signal probability P(S|X)
  - Modelling checked in validation regions for W+jets (looser b-tag) and top-pair (3 or 4 jets)



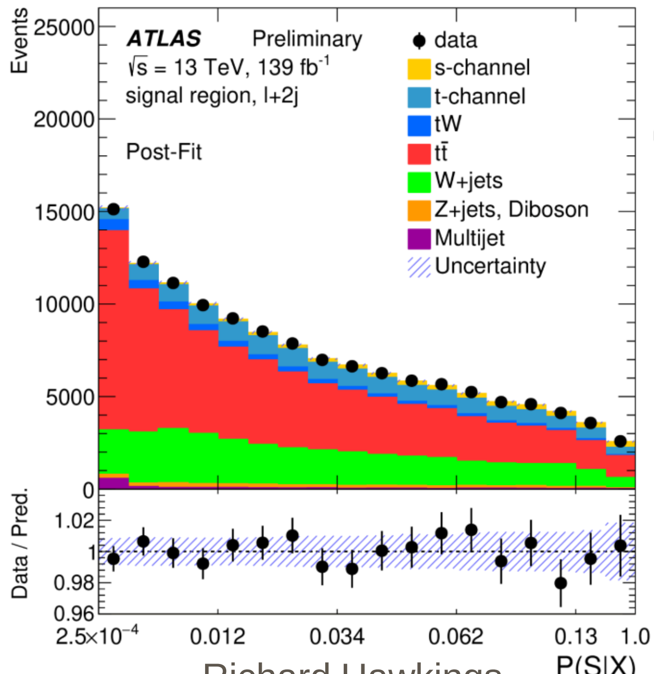


ATLAS-CONF-2022-030

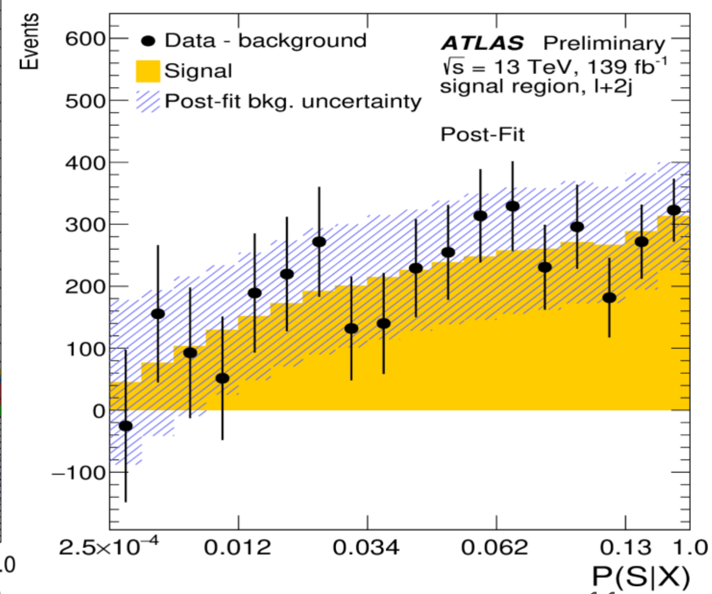
s-channel single top production at 13 TeV

- Fit to P(S|X) distribution in SR constrains main backgrounds, extracts signal
  - Normalisation factors for top-pair $0.81^{+0.13}_{-0.12}$ and W+jets $1.37^{+0.35}_{-0.31}$
  - s-channel cross-section measured to be $\sigma_s = 8.2 \pm 0.6\,(\text{stat})\ ^{+3.4}_{-2.8}\,(\text{syst})$ pb
    - Largest uncertainties from top-pair normalisation and jet energy scale
    - S/B around 10% in highest-purity bins
- Observed significance 3.3σ compared with expectation of 3.9σ
  - Compared to obs. 3.2σ / expected 3.9σ at 8 TeV where S/B is more favourable

Process	Event yield Pre-fit	Event yield Post-fit
s-channel	$4\,200 \pm 710$	$3\,700 \pm 1\,100$
t-channel	$13\,000 \pm 2\,000$	$15\,000 \pm 2\,300$
tW	$3\,680 \pm 970$	$4\,250 \pm 1\,100$
$t\bar{t}$	$76\,000 \pm 12\,000$	$70\,600 \pm 4\,200$
W+jets	$21\,500 \pm 2\,900$	$32\,200 \pm 5\,000$
Z+jets, VV	$2\,400 \pm 1\,400$	$2\,900 \pm 1\,600$
Multijet	$2\,150 \pm 650$	$1\,700 \pm 540$
Total	$123\,000 \pm 17\,000$	$130\,310 \pm 620$
Data	$130\,310$	

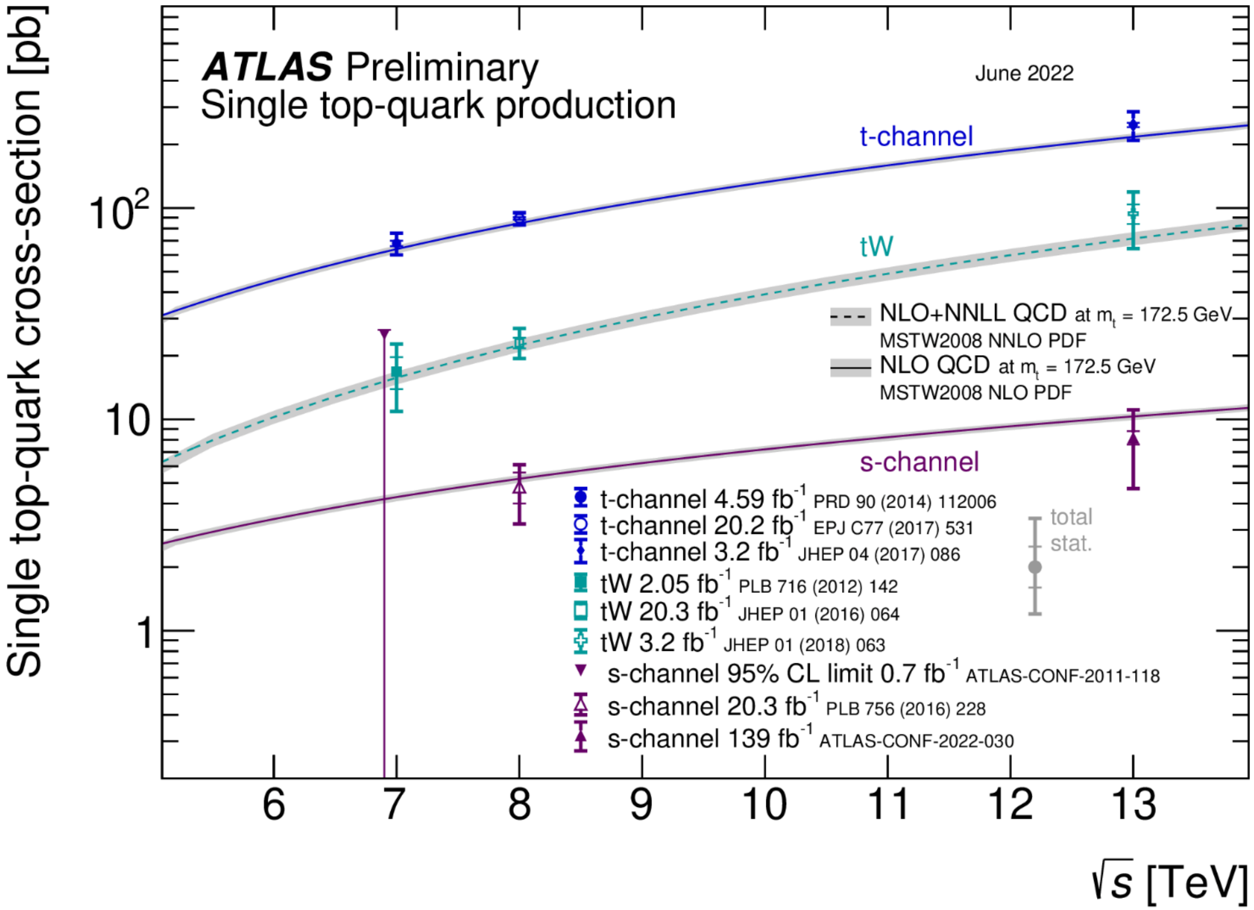


background-subtracted P(S|X)



s-channel, t-channel and Wt measurements

- 13 TeV t-channel and Wt measurements still based on 3.2 fb^{-1} from 2015



σ(13 TeV)	stat, syst, lumi (pb)
t-channel	156 ± 27 ± 3 (t) 91 ± 4 ± 18 ± 2 (t~)
Wt	$94 \pm 10^{+28}_{-22} \pm 2$
s-channel	$8.2 \pm 0.6\ ^{+3.4}_{-2.8}$
top-pair	826 ± 4 ± 12 ± 16

- Inclusive measurements are all systematics limited
- Good agreement with QCD predictions at NLO to NLO+NNLL
  - Including √s dependence

Conclusions

- Inclusive top-pair cross-section measurements reaching maturity at Run-2
  - Precise measurements in eμ (2.4%) and lepton+jets (4.6%) channels at 13 TeV
  - Now joined by competitive measurements at 5.02 TeV, complementing earlier Run-1 measurements at 7 and 8 TeV, where ATLAS+CMS have been combined
  - All measurements in good agreement with QCD NLLO+NLLL predictions, over >1 order of magnitude
    - Can extract m_t^{pole} or α_S, or constrain PDFs
    - Measurements more precise than theory – need even higher-order calculations?
- Single top measurements more difficult due to large backgrounds
  - s-channel measurements reached 3σ significance at 13 and 8 TeV
  - Full Run2 t-channel and Wt results still to come
- A wealth of differential measurements also available ...
  - See Friday talk from Christopher Garner

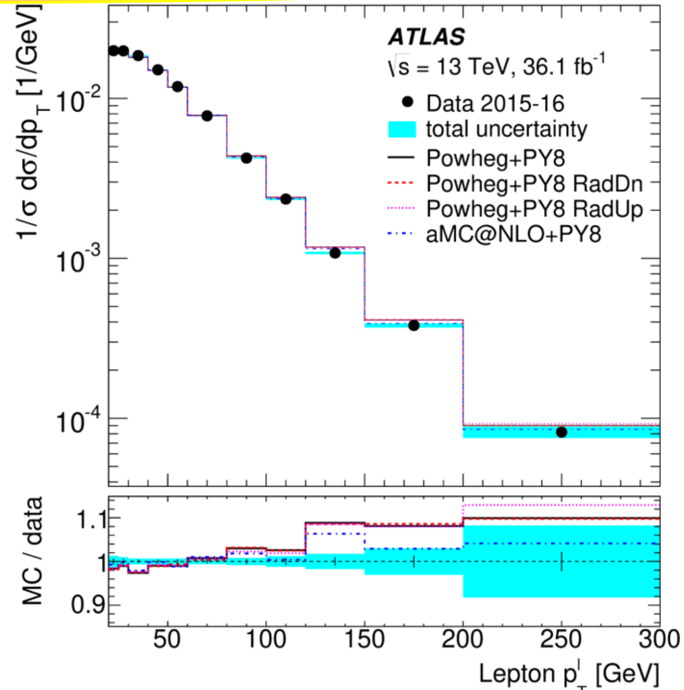
- More details at TopPublicResults

Backup slides

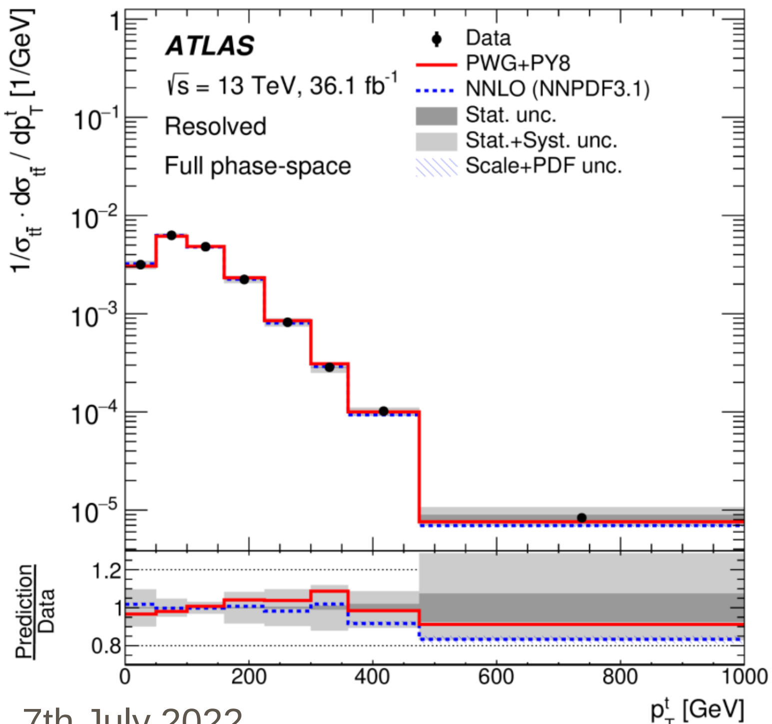
- Backup slides

Beyond inclusive cross-sections ...

- Large data samples → differential cross-sections
  - Compare to predictions of MC generators and fixed-order QCD calculations
  - E.g. in eμ channel, precise measurements of final state lepton kinematics
    - Baseline Powheg+Pythia8 predicts harder lepton p_T spectrum than seen in data



EPJ C79 (2019) 1028



EPJ C79 (2019) 1028

- In lepton+jets channel, fully reconstruct top-pair
  - Unfold to 'parton-level' top quarks
  - Many measurements of 1D and 2D distributions
    - E.g. 1D top-quark p_T well described by Powheg+Pythia8 and NNLO fixed order
  - Efforts now focusing on 'boosted' regime with high p_T collimated top quark decays
    - See Friday talk from Christopher Garner

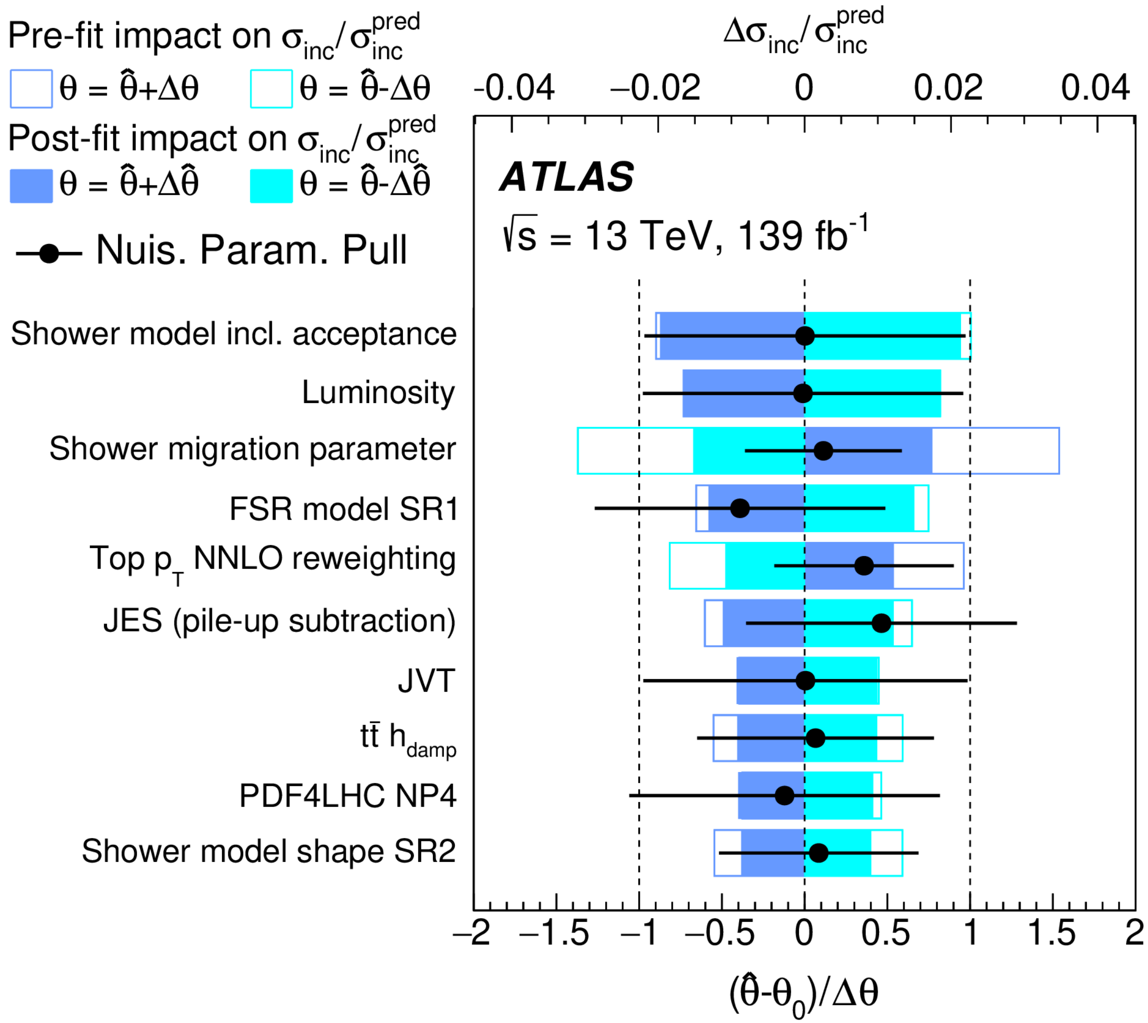
13 TeV dilepton uncertainty breakdown for σ_{tT}

- Uncertainties for
  - Efficiency $\varepsilon_{e\mu}$, reconstruction efficiency $G_{e\mu}$ for fiducial, C_b
  - Inclusive and fiducial cross-sections
- Categories:
  - tT modelling
  - Leptons – efficiency, energy scale/resolution, isolation
  - Jets and b-tagging
  - Backgrounds
  - Luminosity and E_{beam}

	Uncertainty source	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta G_{e\mu}/G_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma^{\mathrm{fid}}_{t\bar{t}}/\sigma^{\mathrm{fid}}_{t\bar{t}}$ (%)
	Data statistics				0.44	0.44
$t\bar{t}$ mod.	$t\bar{t}$ generator	0.38	0.05	0.05	0.43	0.10
	$t\bar{t}$ hadronisation	0.24	0.42	0.25	0.49	0.67
	Initial/final-state radiation	0.30	0.26	0.16	0.45	0.41
	$t\bar{t}$ heavy-flavour production	0.01	0.01	0.26	0.26	0.26
	Parton distribution functions	0.44	0.05	-	0.45	0.07
	Simulation statistics	0.22	0.15	0.17	0.22	0.18
Lept.	Electron energy scale	0.06	0.06	-	0.06	0.06
	Electron energy resolution	0.01	0.01	-	0.01	0.01
	Electron identification	0.34	0.34	-	0.37	0.37
	Electron charge mis-id	0.09	0.09	-	0.10	0.10
	Electron isolation	0.22	0.22	-	0.24	0.24
	Muon momentum scale	0.03	0.03	-	0.03	0.03
	Muon momentum resolution	0.01	0.01	-	0.01	0.01
	Muon identification	0.28	0.28	-	0.30	0.30
	Muon isolation	0.16	0.16	-	0.18	0.18
	Lepton trigger	0.13	0.13	-	0.14	0.14
Jet/b	Jet energy scale	0.02	0.02	0.06	0.03	0.03
	Jet energy resolution	0.01	0.01	0.04	0.01	0.01
	Pileup jet veto	-	-	-	0.02	0.02
	b-tagging efficiency	-	-	0.04	0.20	0.20
	b-tag mistagging	-	-	0.06	0.06	0.06
Bkg.	Single-top cross-section	-	-	-	0.52	0.52
	Single-top/$t\bar{t}$ interference	-	-	-	0.15	0.15
	Single-top modelling	-	-	-	0.34	0.34
	Z+jets extrapolation	-	-	-	0.09	0.09
	Diboson cross-sections	-	-	-	0.02	0.02
	Diboson modelling	-	-	-	0.03	0.03
	Misidentified leptons	-	-	-	0.43	0.43
	Analysis systematics	0.91	0.75	0.44	1.39	1.31
L/E_b	Integrated luminosity	-	-	-	1.90	1.90
	Beam energy	-	-	-	0.23	0.23
	Total uncertainty	0.91	0.75	0.44	2.40	2.36

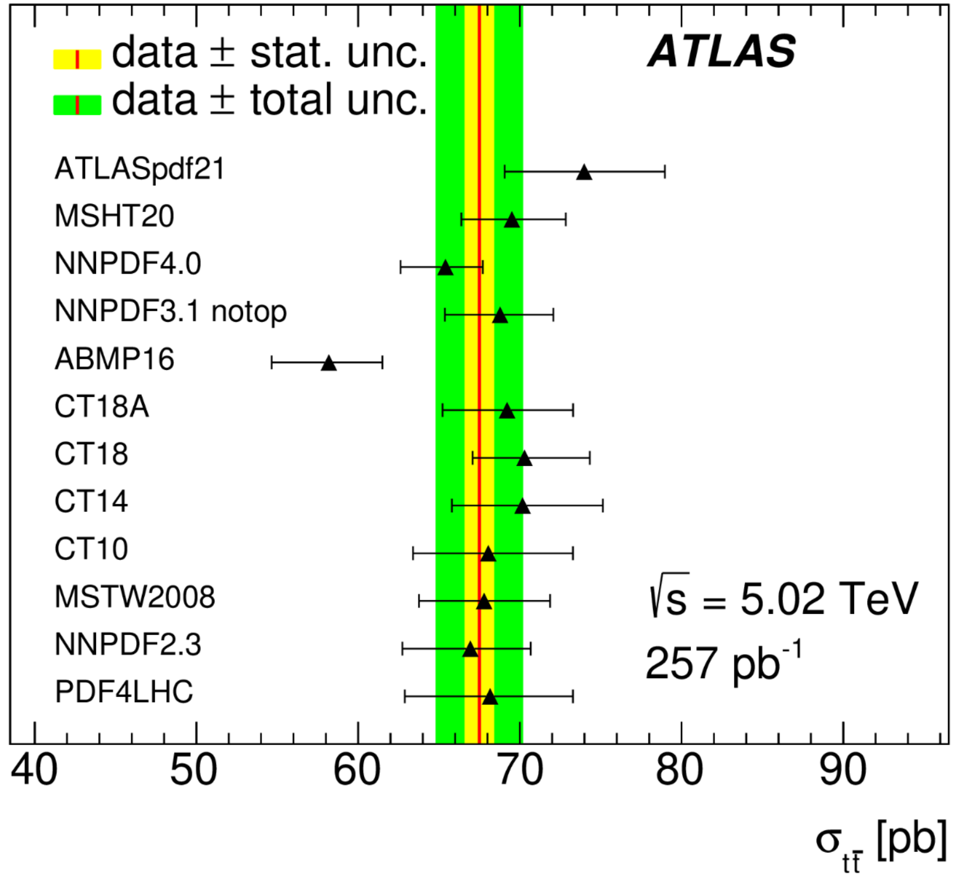
13 TeV lepton+jets uncertainties and pulls

Category	$\frac{\Delta\sigma_{fid}}{\sigma_{fid}}$ [%]	$\frac{\Delta\sigma_{inc}}{\sigma_{inc}}$ [%]
Signal modelling		
$t\bar{t}$ shower/hadronisation	±2.8	±2.9
$t\bar{t}$ scale variations	±1.4	±2.0
Top p_T NNLO reweighting	±0.4	±1.1
$t\bar{t}$ h_{damp}	±1.5	±1.4
$t\bar{t}$ PDF	±1.4	±1.5
Background modelling		
MC background modelling	±1.8	±2.0
Multijet background	±0.8	±0.6
Detector modelling		
Jet reconstruction	±2.5	±2.6
Luminosity	±1.7	±1.7
Flavour tagging	±1.2	±1.3
E_T^{miss} + pile-up	±0.3	±0.3
Muon reconstruction	±0.6	±0.5
Electron reconstruction	±0.7	±0.6
Simulation stat. uncertainty	±0.6	±0.7
Total systematic uncertainty	±4.3	±4.6
Data statistical uncertainty	±0.05	±0.05
Total uncertainty	±4.3	±4.6



5.02 TeV uncertainties and PDF comparison

Category	$\delta\sigma_{t\bar{t}}$ [%] Dilepton	Single lepton	Combination
$t\bar{t}$ generator†	1.2	1.0	0.8
$t\bar{t}$ parton-shower/hadronisation*,†	0.3	0.9	0.7
$t\bar{t}$ h_{damp} and scale variations†	1.0	1.1	0.8
$t\bar{t}$ parton-distribution functions†	0.2	0.2	0.2
Single-top background	1.1	0.8	0.6
W/Z+jets background*	0.8	2.4	1.8
Diboson background	0.3	0.1	< 0.1
Misidentified leptons*	0.7	0.3	0.3
Electron identification/isolation	0.8	1.2	0.8
Electron energy scale/resolution	0.1	0.1	< 0.1
Muon identification/isolation	0.6	0.2	0.3
Muon momentum scale/resolution	0.1	0.1	0.1
Lepton-trigger efficiency	0.2	0.9	0.7
Jet-energy scale/resolution	0.1	1.1	0.8
$\sqrt{s} = 5.02$ TeV JES correction	0.1	0.6	0.5
Jet-vertex tagging	< 0.1	0.2	0.2
Flavour tagging	0.1	1.1	0.8
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.1	0.4	0.3
Simulation statistical uncertainty*	0.2	0.6	0.5
Data statistical uncertainty*	6.8	1.3	1.3
Total systematic uncertainty	3.1	4.2	3.7
Integrated luminosity	1.8	1.6	1.6
Beam energy	0.3	0.3	0.3
Total uncertainty	7.5	4.5	3.9



13 TeV s-channel uncertainty breakdown

Source	$\Delta\sigma/\sigma$ [%]
$t\bar{t}$ normalisation	$+24/-17$
Jet energy resolution	$+18/-12$
Jet energy scale	$+18/-13$
Other s-channel modelling sources	$+18/-8$
Top-quark processes ISR/FSR	$+13/-11$
MC statistics	$+13/-11$
Other $t\bar{t}$ shape modelling sources	$+12/-10$
Flavour tagging	$+12/-10$
W+jets normalisation	$+11/-8$
Top-quark processes PDFs	$+10/-9$
W+jets μ_R/μ_F shape	$+6/-5$
Other processes normalisation	$+6/-5$
Pileup	$+5/-3$
Other t-channel modelling sources	±5
Luminosity	$+4/-3$
Other tW modelling sources	$+1/-2$
Missing transverse energy	±1
Multijet shape modelling	±1
Other sources	<1
Systematic uncertainties	$+42/-34$
Data statistics	±8
Total	$+42/-35$