Top quark production cross-section measurements

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ATLAS EXPERIMENT

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Why care about the top?

- Unique role in the SM due to its large $m_t \approx 173\ \mathrm{GeV}$
- Same order as VEV of the Higgs field ($v \approx 246\ \mathrm{GeV}$)
  - Top quark regime one of the "likely" places for beyond-SM observations to manifest
- Broad decay width, short lifetime ($\tau \sim 10^{-25}\mathrm{s}$)
  - Study of "bare" quark properties
  - Precision measurements of QCD
- Background to many BSM and exotic searches
  - Modelling uncertainties have become limiting factor
  - Experimental results help in constraining them
- Other than that, top quarks are exciting!

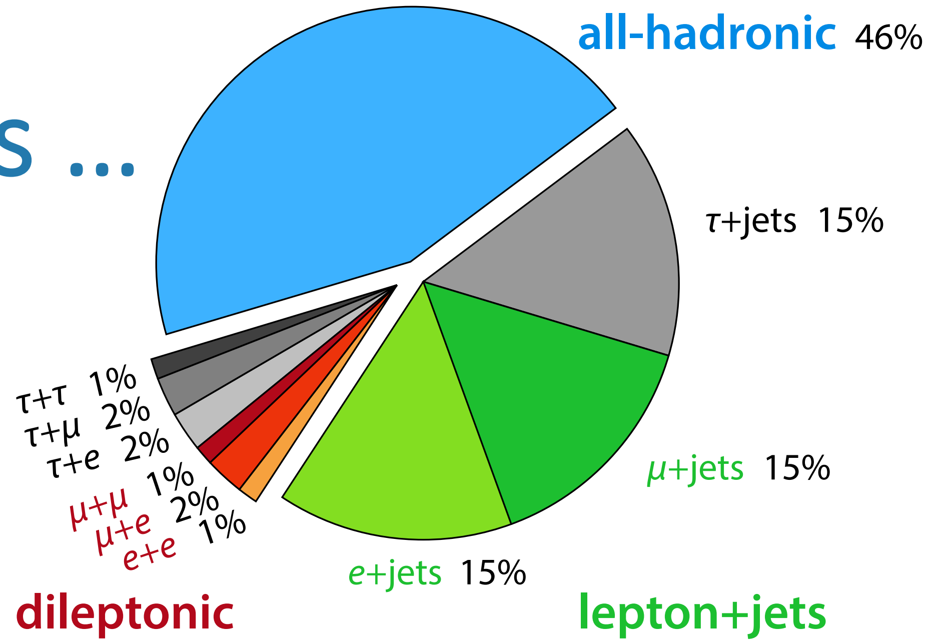
ATLAS has a rich catalogue of top physics results:

- Many Run 2 results already published
- More in preparation
- This talk only covers a fraction of what's available!

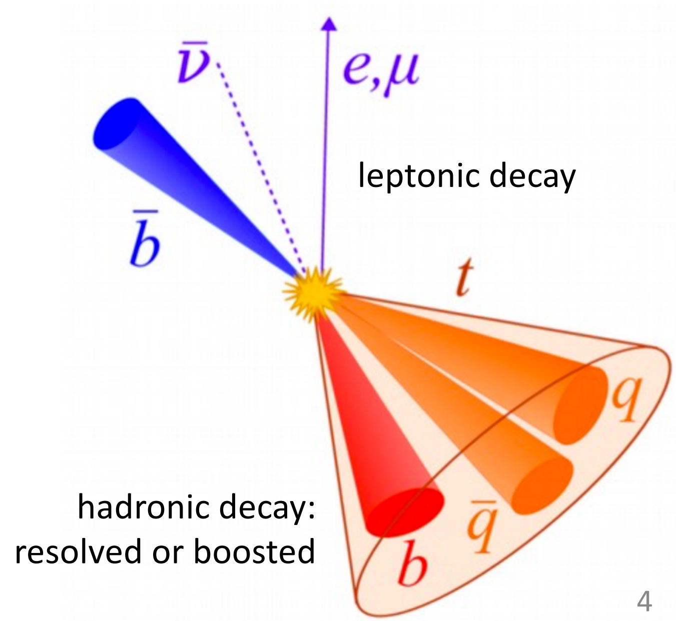
Link: ATLAS TopPublicResults

Top-pair production

Tops come in pairs …



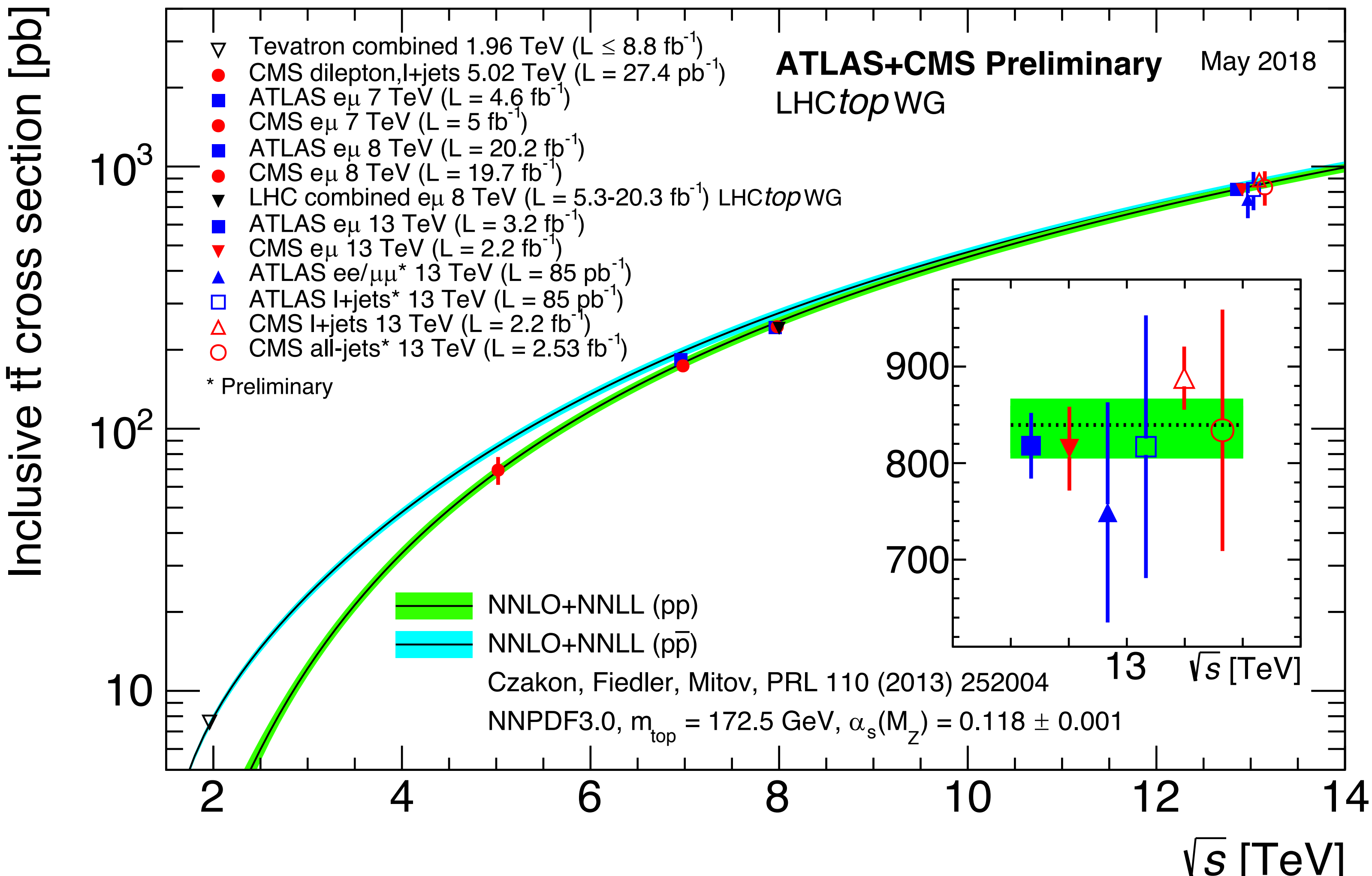
- Inclusive measurements have reached high precision (<5%!)
- Lots of data from the LHC: differential measurements now also feasible
- Stringent tests of our predictions:
  - Sensitive to higher order corrections
  - Sensitive to PDFs
- Major background to many BSM searches → Accurate description pivotal!



Most precise theory predictions with ~ 5.5%:
at 8 TeV: $\sigma_{t\bar{t}} \approx 250^{+13}_{-14}$ pb
at 13 TeV: $\sigma_{t\bar{t}} \approx 820^{+40}_{-45}$ pb
Main limitations: PDF + α_s uncertainties

calculated with Top++

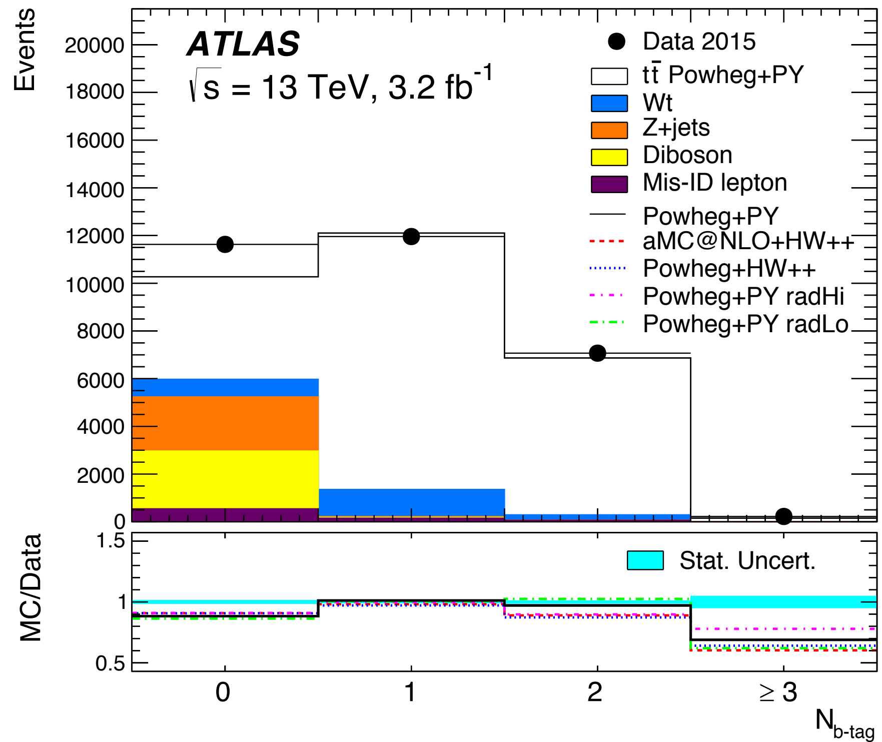
… and we catch 'em (precisely)



Inclusive results

- Generally the most precise: dilepton (eμ) channel
  - $\sigma_{t\bar{t}}(13\text{ TeV}) = 818 \pm 8\text{ (stat)} \pm 27\text{ (syst)} \pm 19\text{ (lumi)} \pm 12\text{ (beam) pb}$
  - Relative uncertainty: 4.4% (!)
  - Very little background
  - Low systematic uncertainties
- l+jets: more stats, but also larger systematics
  - Dominantly: jet-related uncertainties, modelling
  - At 8 TeV: 5.7% precision reached

MC/data in the eμ channel



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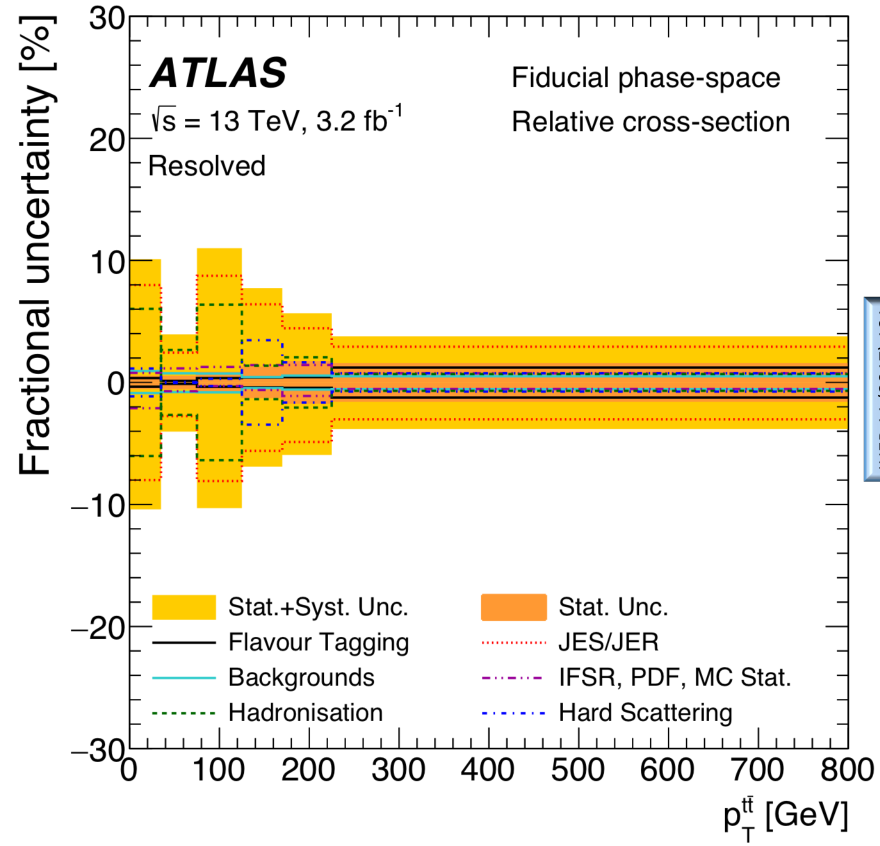
All measurements at 8 and 13 TeV in good agreement with SM predictions!

And differential?

- Cross-sections unfolded to:
  - Particle level, i.e. stable particles after hadronisation
  - Parton level, i.e. top quarks before decay
- Important constraints on various modelling predictions
- Different channels have different uncertainties, but usually:
  - Limited modelling of $t\bar{t}$ (ME and PS)
  - Jet energy scale, especially in the boosted topologies
- ATLAS has performed measurements at 7, 8, and 13 TeV with various final states

Dominant uncertainties in l+jets (resolved) unfolding



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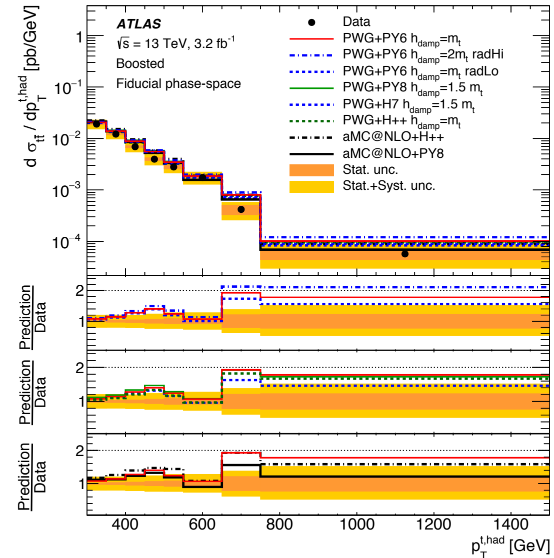
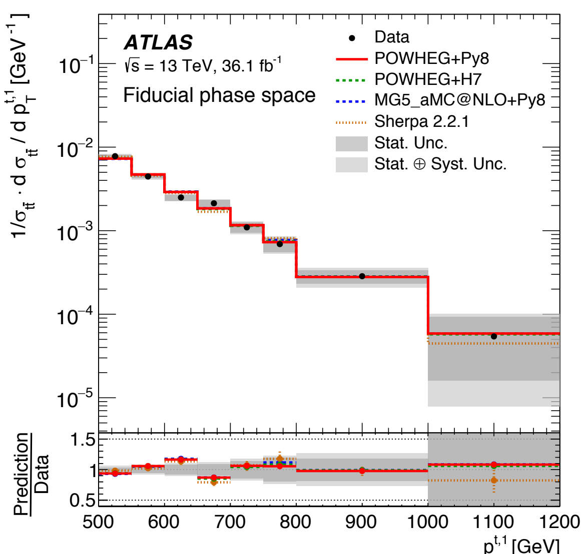
Unfolded top p_T

- Predicted p_T^t spectra harder than observed
- Different trends also among predictions
- Uncertainties generally dominated by modelling (ME and showering), jet energy resolution

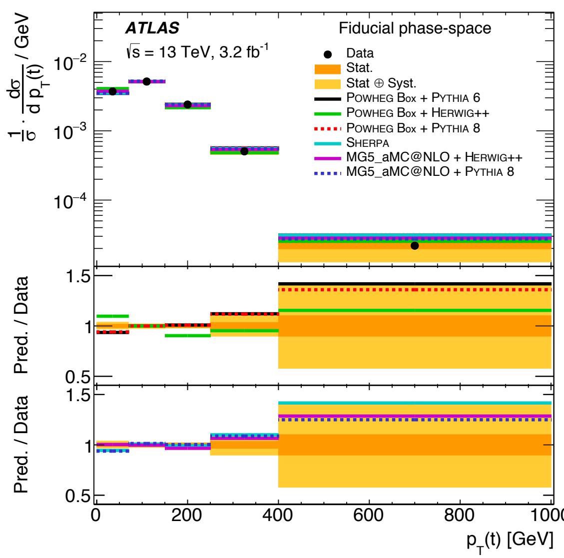
l+jets boosted



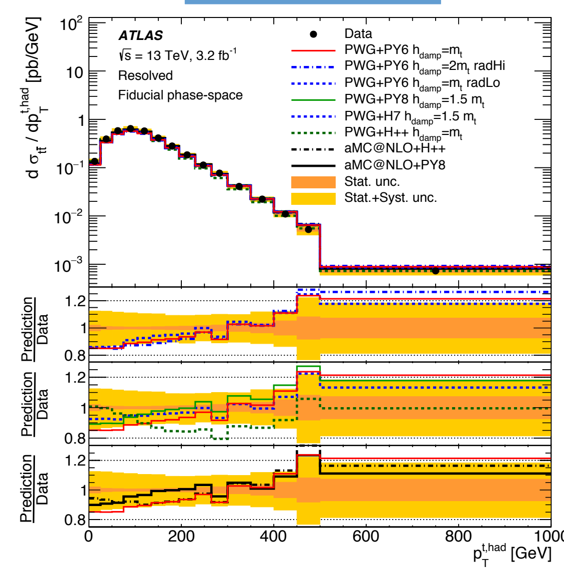
All-hadr. boosted



eμ channel



l+jets resolved



Phys. Rev. D 98 (2018) 012003

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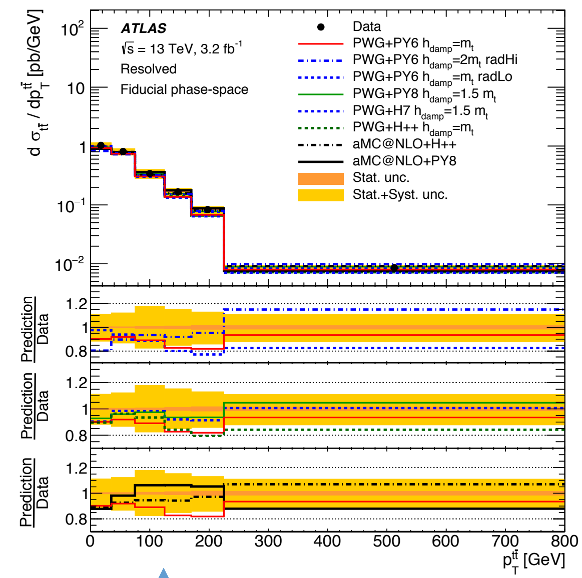
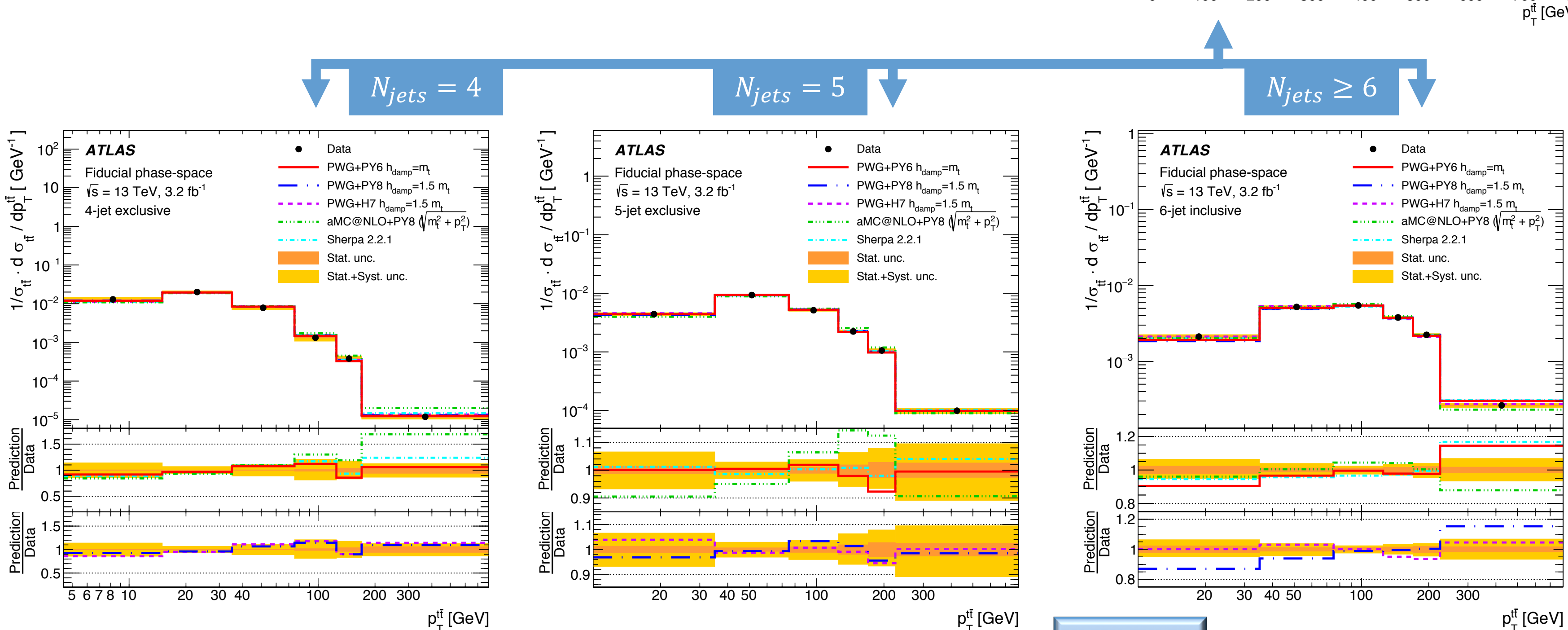
Unfolded in Njets

- Split-up in jet multiplicity with separate unfolding
- Reveals previously unseen discrepancies
- Several predictions disfavoured in $p_T^{t\bar{t}}$ for high jet multiplicities (6incl)

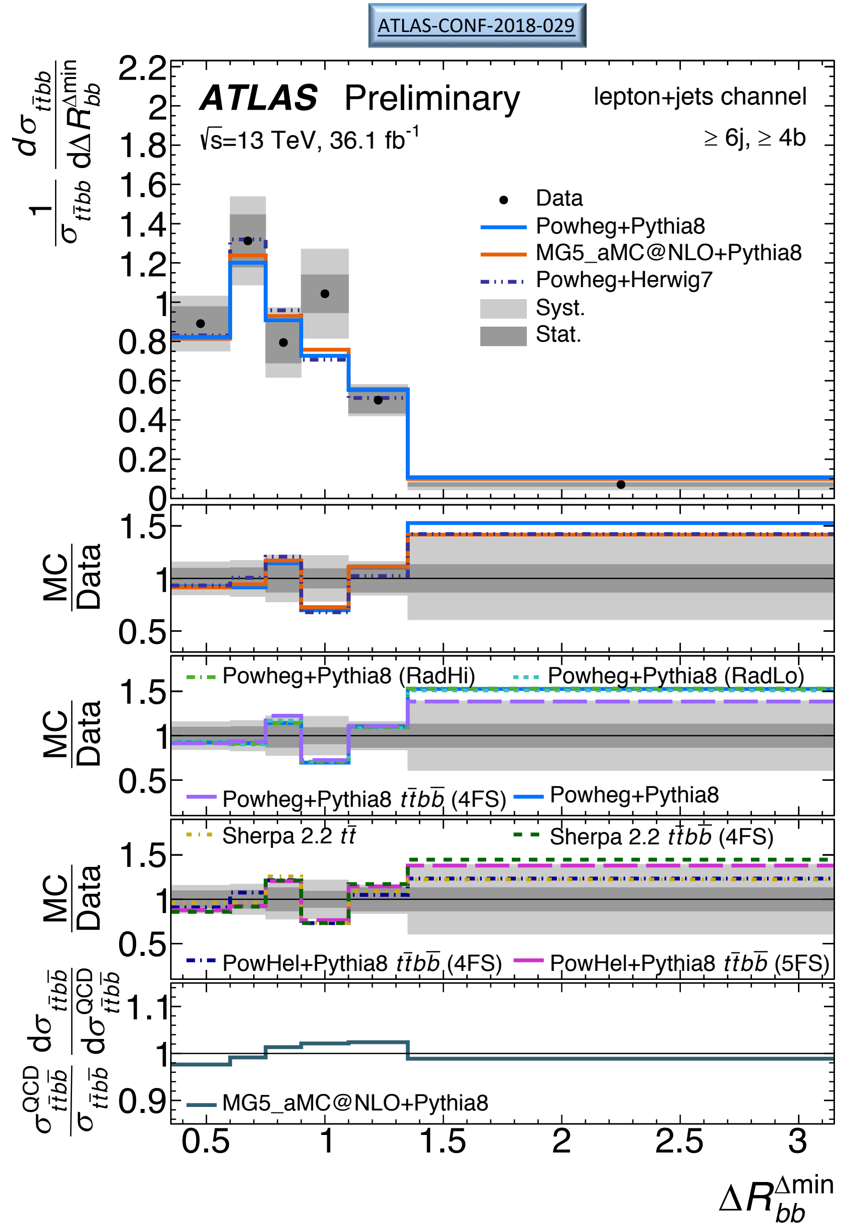




arXiv:1802.06572

$t\bar{t}$ with heavy-flavour jets

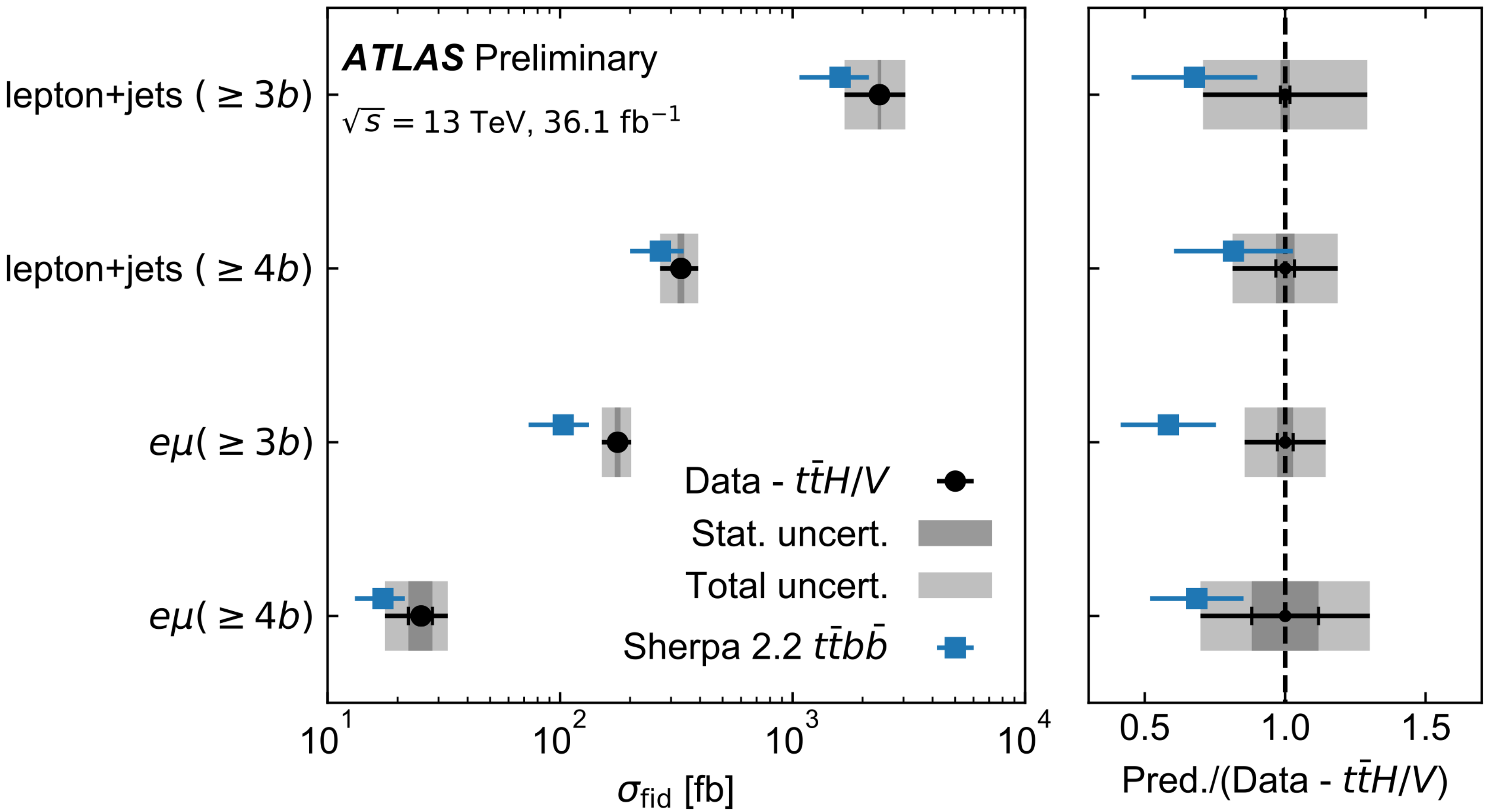
- Stringent test of QCD calculations, due to non-zero b-quark mass
- Major background for ttH (H→bb)
- Measurements = valuable input for MC tuning



- Disagreements in combined variables (e.g. in $\Delta R_{bb}^{\Delta min}$ of l+jets)
- Overall best description: Sherpa 2.2 (next talk!)

$t\bar{t}$ with heavy-flavour jets (2)

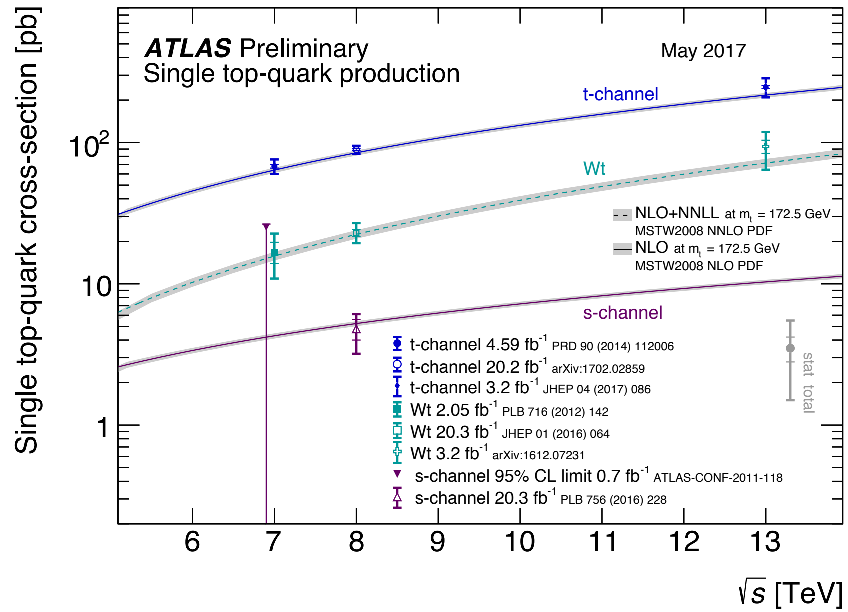
ATLAS-CONF-2018-029



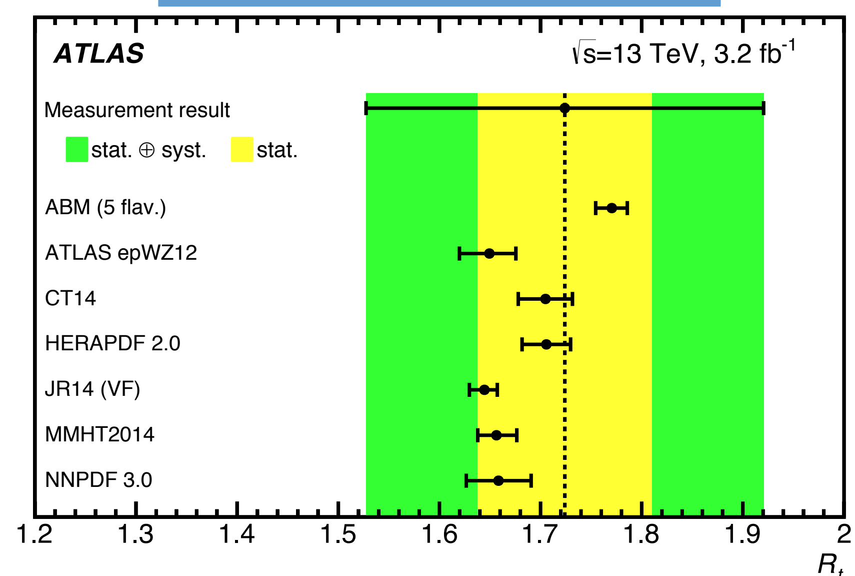
Single-top production

Overview

- Single-top production?
  - Possibility to constrain PDFs
  - Possibility to tune generators
  - Tests of CKM matrix unitarity
  - Sensitivity to BSM in the Wtb vertex
- Three channels: s, t, and associated with W (tW)
  - Various precision measurements in tW and t-channel
  - Evidence for s-channel at 8 TeV, and tqZ at 13 TeV

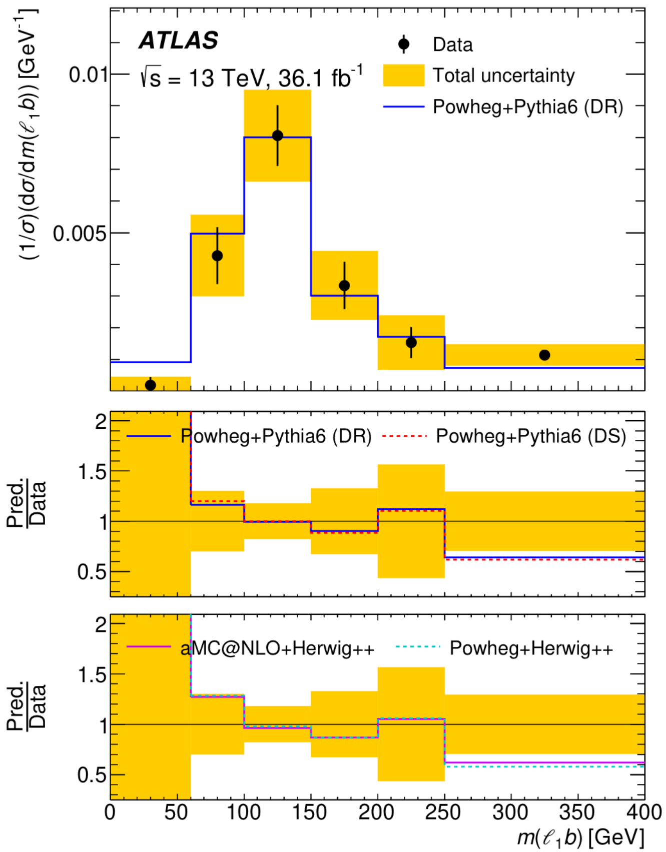


Comparison to different PDFs in $R_t = \sigma(tq)/\sigma(\bar{t}q)$



JHEP 04 (2017) 086

Probing Wtb in tW production



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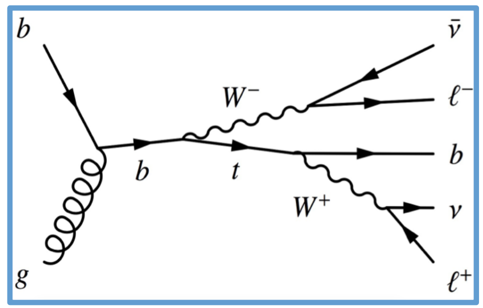
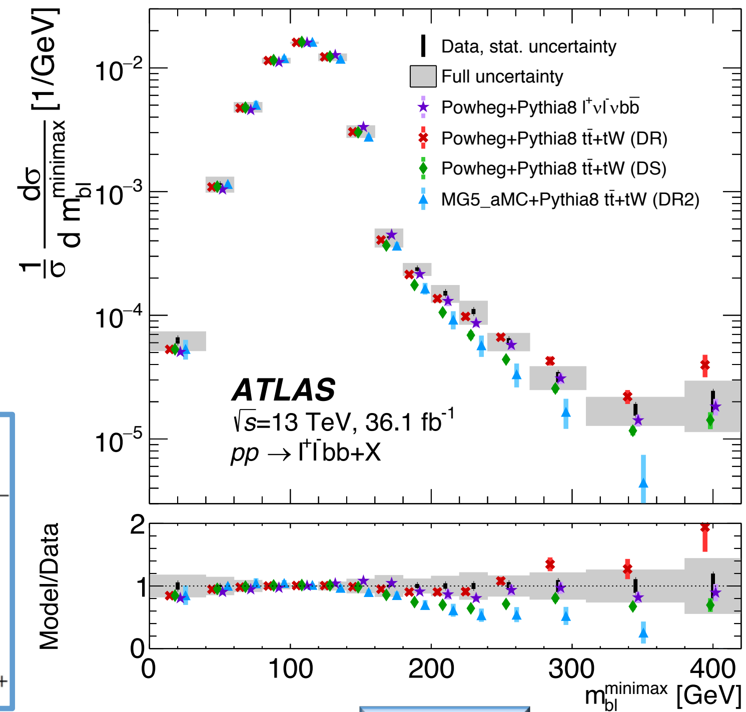
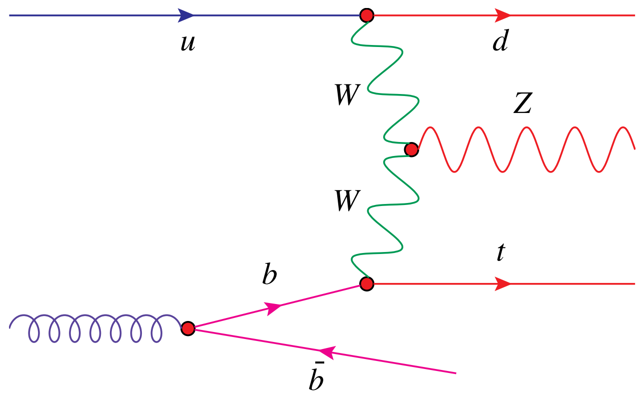




arXiv:1806.04667

- Strong interference between tW and $t\bar{t}$:
  - Predictions use diagram removal (DR)
  - Large uncertainties estimated with diagram subtraction (DS) scheme
- Recent measurement sensitive to interference terms in $m_{bl}^{minimax}$
- Good agreement with four-flavour scheme Powheg+Pythia8 $l^{\pm}\nu l^{\mp}\bar{\nu}b\bar{b}$

Evidence for tZ



- Rare SM process ($\sigma \approx 800$ fb)
  - Sensitive to tZ and WWZ coupling
  - Background to tH and FCNC
- Trileptonic channel
- Neural network to maximise separation between signal and BG
- Binned likelihood fit of NN output
- $\sigma = 600 \pm 170$ (stat) $\pm$ 140 (syst) fb
- Observed (expected) significance for signal+BG of 4.2 (5.4)

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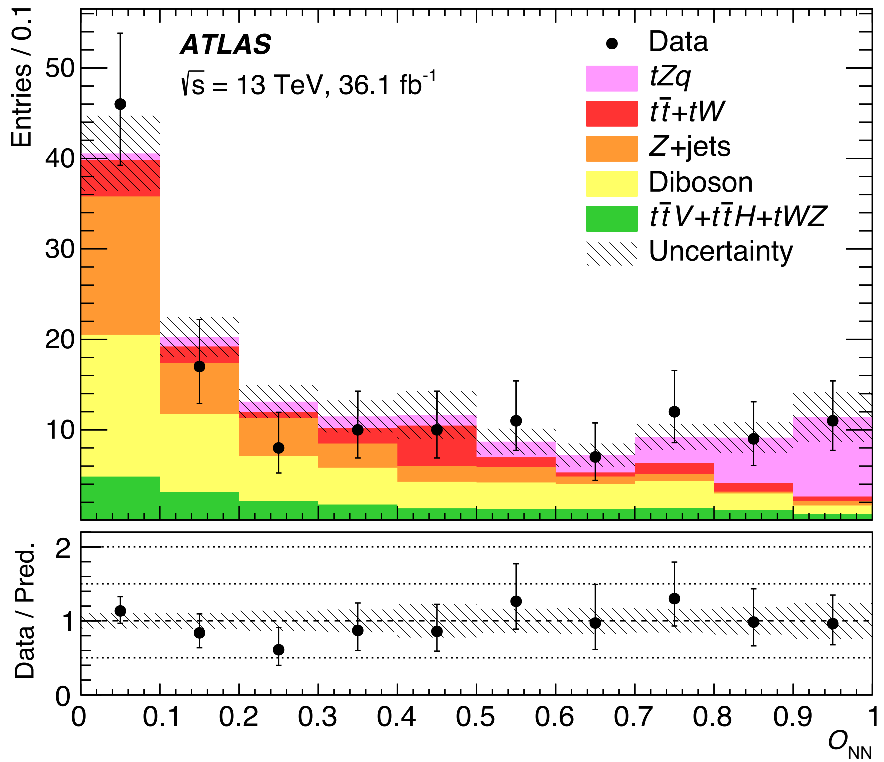
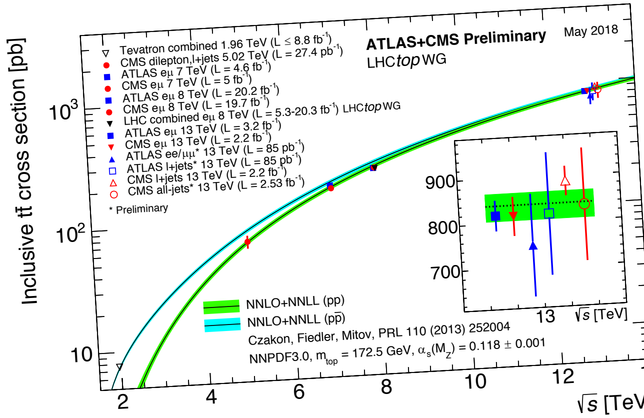
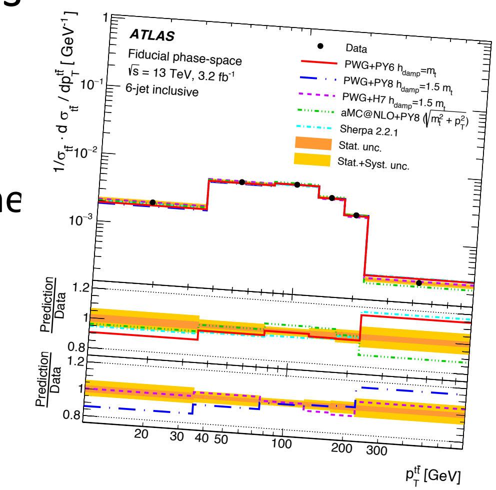


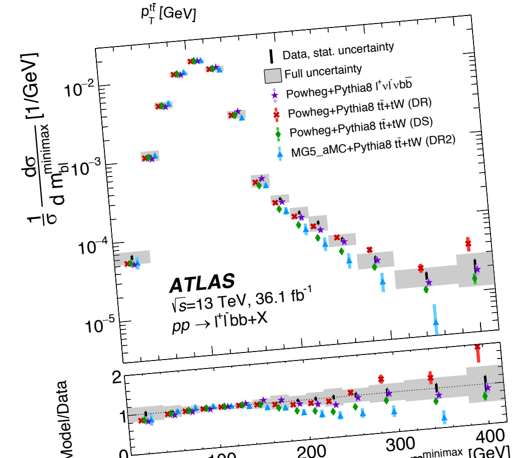
Summary

- ATLAS has a rich programme in top physics*
- Inclusive cross-section measurements:
  - Have reached same precision as modelling
  - Constrain BSM theories in the top-quark regime
- Differential measurements:
  - Unfolded to particle or parton level
  - Reveal modelling limitations, e.g. in p_T^t
  - Important input for generator tuning
- Single-top measurements:
  - Precision measurements in t-channel and tW
  - Evidence for tZ production (and for the s-channel at 8 TeV)

*Top quark properties talk tomorrow afternoon in the “Heavy Quarks” session!





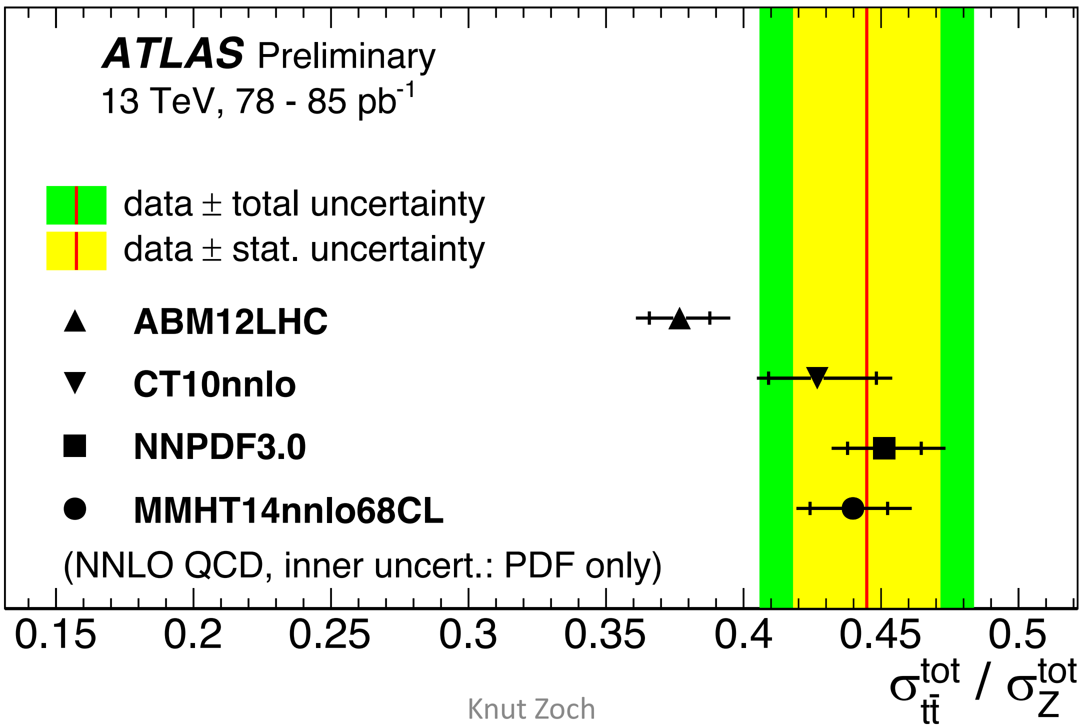


Backup

ATLAS-CONF-2015-049

- Preliminary results at 13 TeV, using only 85/pb of data
  - Measured in both in l+jets and eμ channels
  - $\sigma_{t\bar{t}}(13\text{ TeV, l+jets}) = 817 \pm 13\text{ (stat)} \pm 103\text{ (syst)} \pm 88\text{ (lumi) pb}$
  - $\sigma_{t\bar{t}}/\sigma(Z \to ee, \mu\mu)$ cancels many uncertainties

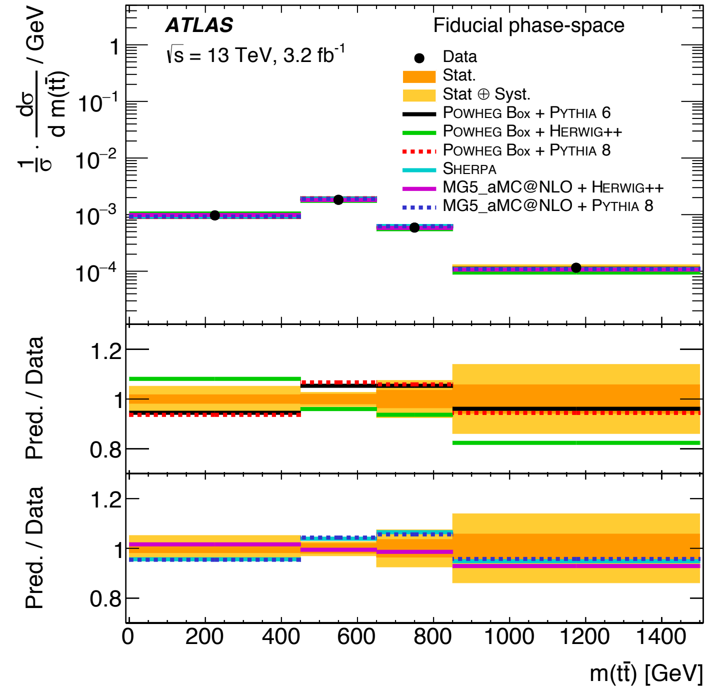
Ratio of $t\bar{t}$ over Z → ee, μμ

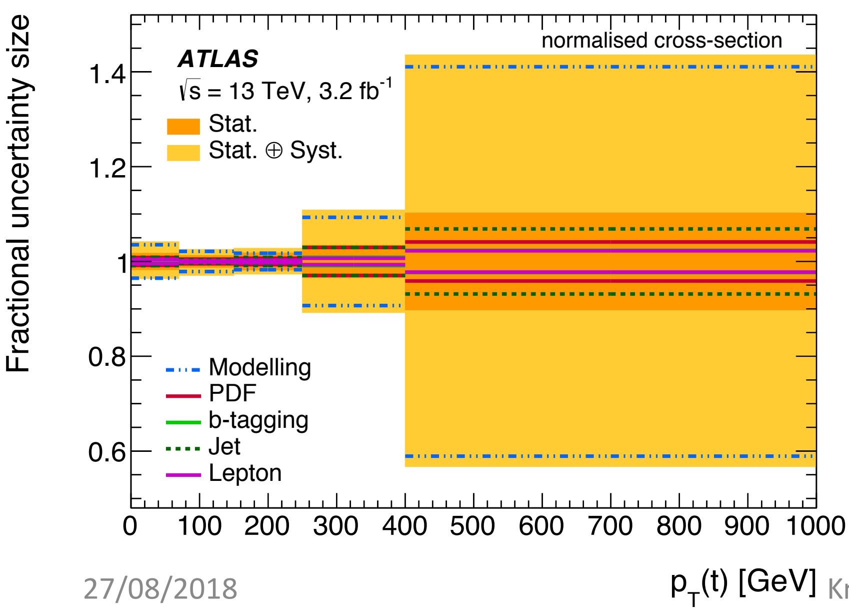


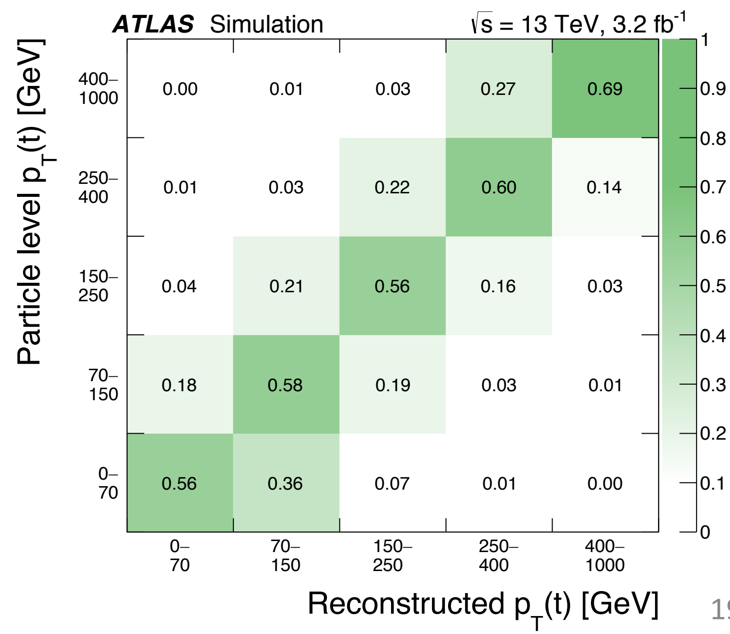
ATLAS-CONF-2015-049

TOPQ-2016-04

- 13 TeV, 3.2/fb, eμ channel
- Selection: two jets, at least one b-tag, no MET requirements
- Reconstruction: neutrino weighting method
- Discrepancies in particular for Powheg-Box + Herwig++ in distributions of p_T^{top} and m(tt)

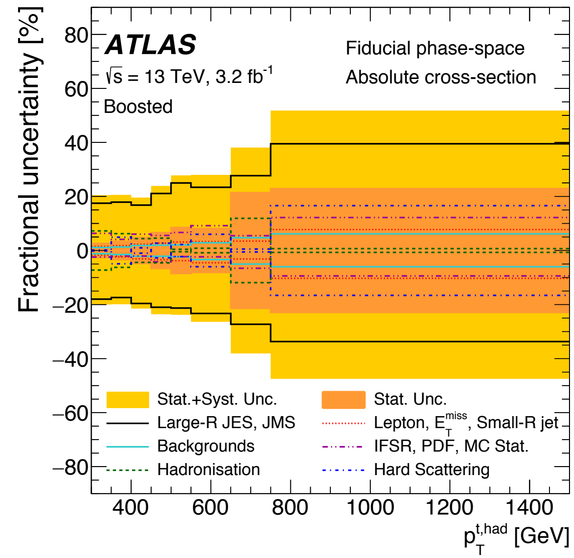


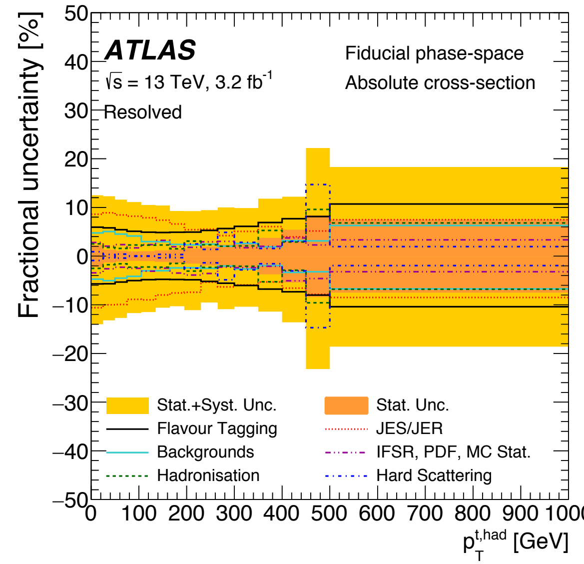


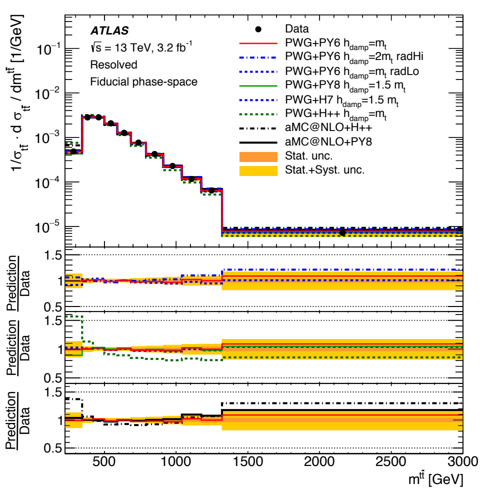


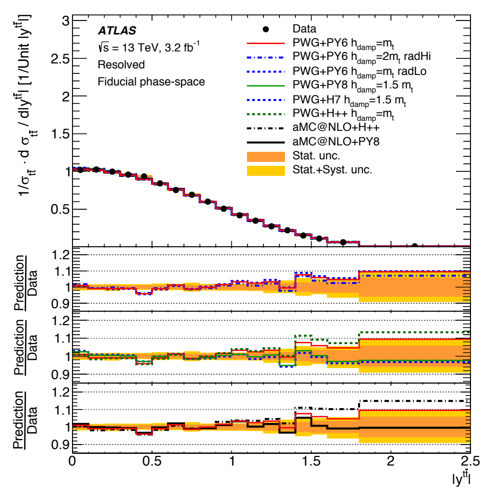
TOPQ-2016-01

- Resolved: one lepton, at least four small-R jets (0.4), at least 2 b-tags
- Boosted: one lepton, at least one large-R and one small-R jet (1.0, 0.4)
  - Small-R jet close to the lepton ($\Delta R \leq 2.0$)
  - Large-R jet <u>top-tagged</u> (p_T > 300 GeV), separated from lepton and jet ($\Delta R \geq 1.0$)
  - At least one small-R jet with b-tag (77%): either inside large-R jet, or close to lepton
  - MET ≥ 20 GeV, MET + transverse m_W ≥ 60 GeV



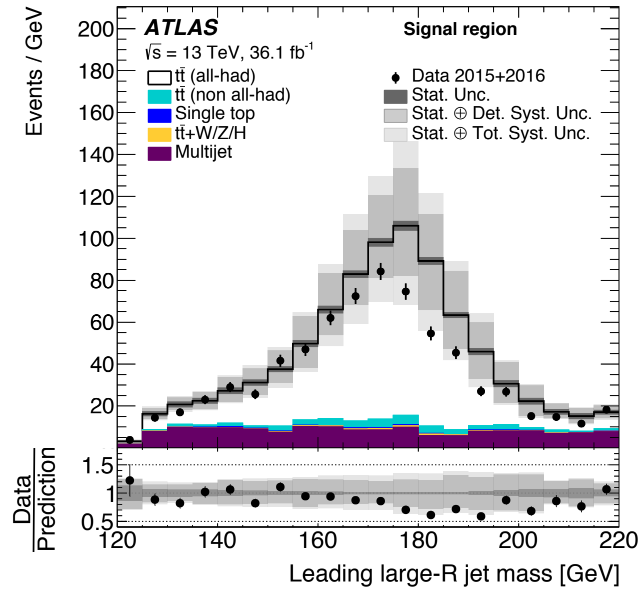


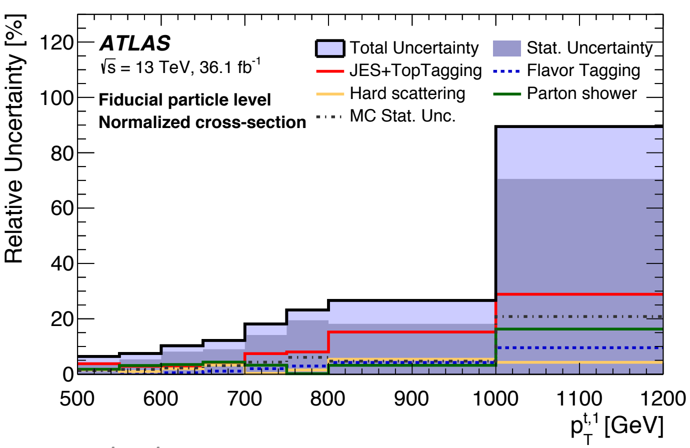


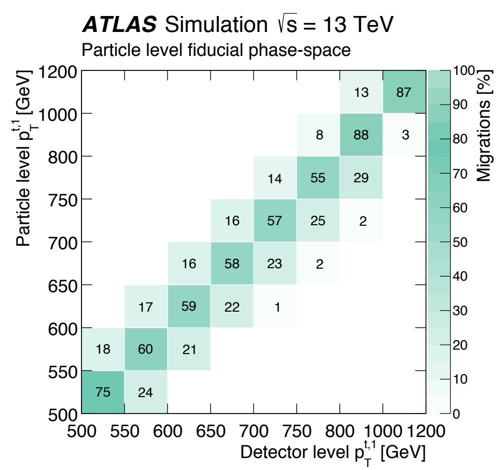


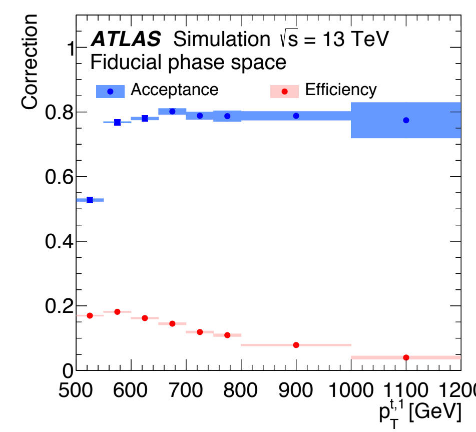
TOPQ-2016-09

- 13 TeV, 36/fb (2015+16), all-hadronic
- At least two large-R jets (1.0):
  - All required to fulfil $p_T > 350$ GeV and $|m_J - m_t| < 50$ GeV
  - At least two of them top-tagged, and both with associated b-jet (ΔR ≤ 1.0)
  - Leading large-R jet with $p_T > 500$ GeV
- At least two small-R jets (0.4), at least two of which b-tagged



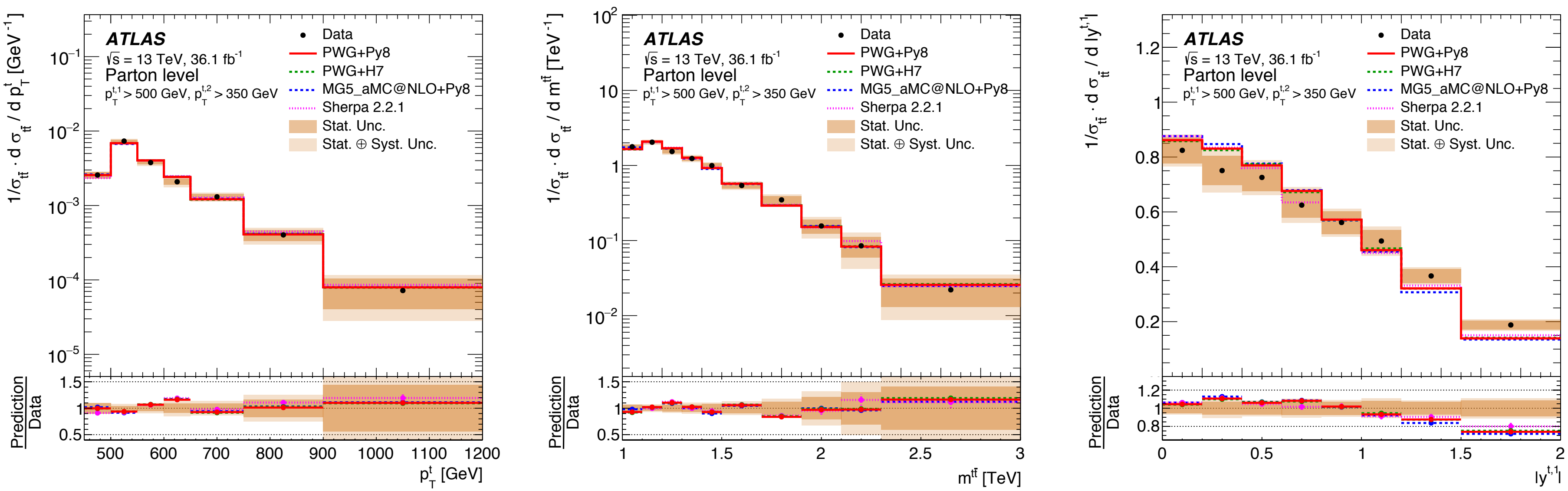






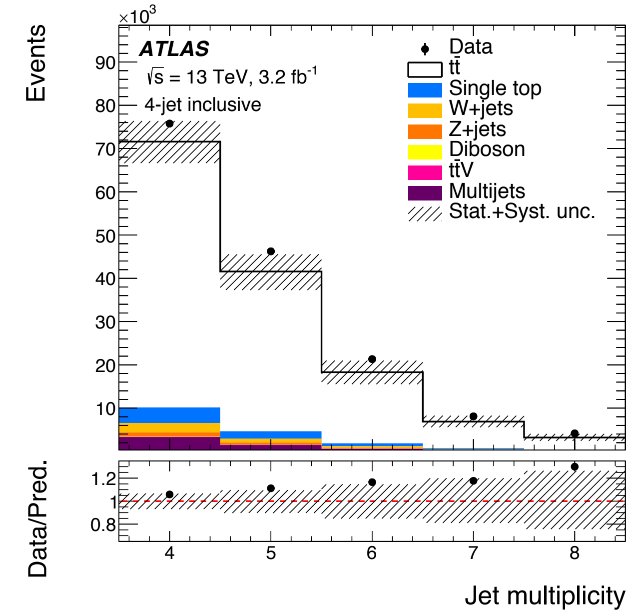
TOPQ-2016-09 (2)

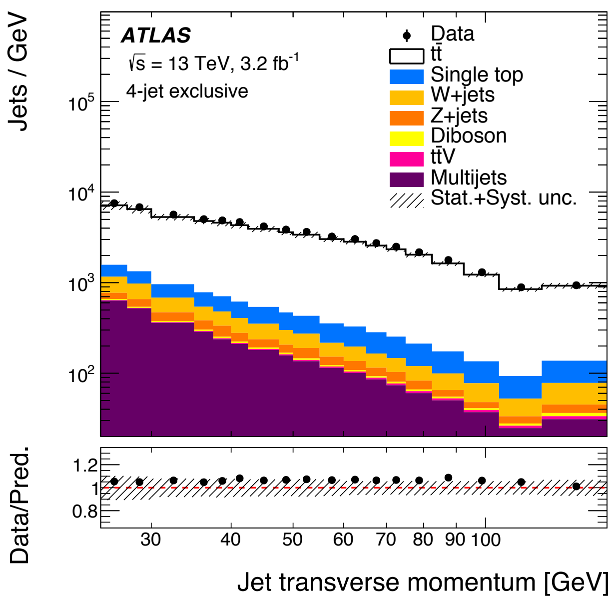
- Additional unfolding to parton level: two top quarks with $p_T^{t1} > 500\text{ GeV}$ and $p_T^{t2} > 350\text{ GeV}$
- Generally a lot more dominated by statistical uncertainties (both in MC and data), due to extrapolation from fiducial phase space
- Discrepancies observed in rapidity distributions (broader in data)

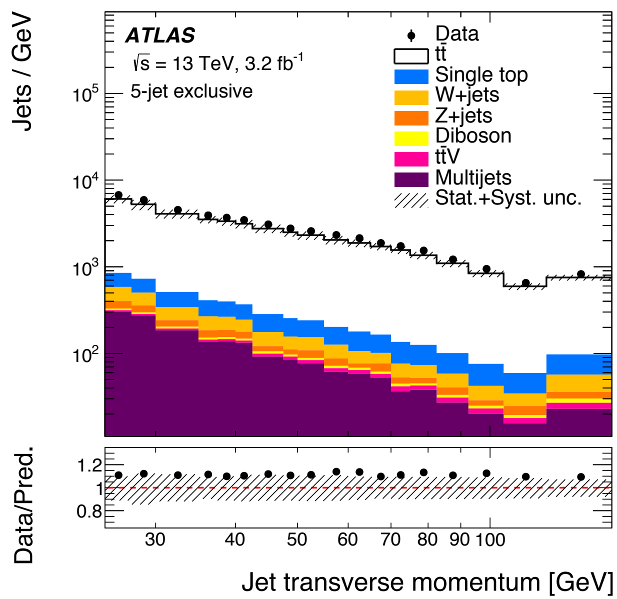


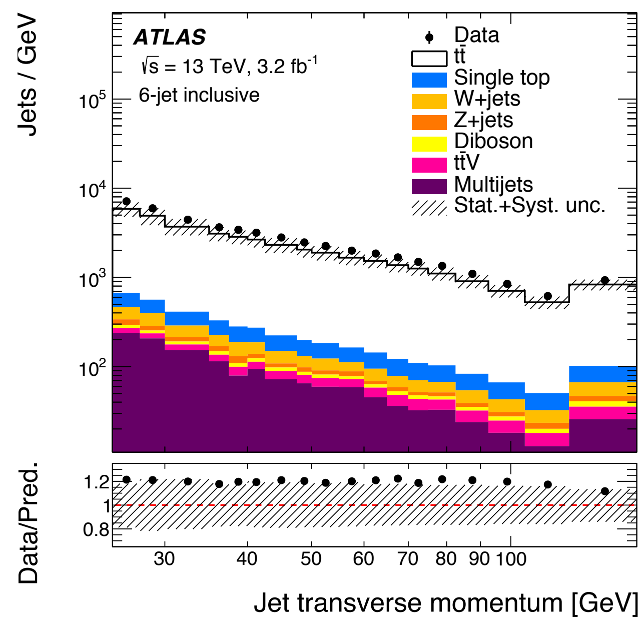
TOPQ-2017-01

- Submitted to JHEP (pre-print: 1802.06572v1)
- 13 TeV, 3.2/fb, l+jets channels
- $|p_{out}^{tt}| = \left|\vec{p}^{\,t,had} \cdot \frac{\vec{p}^{\,t,lep}\times\hat{z}}{|\vec{p}^{\,t,lep}\times\hat{z}|}\right|$
- Exactly one lepton, at least four (two) jets (b-jets)
- Events categorised according to n_jets





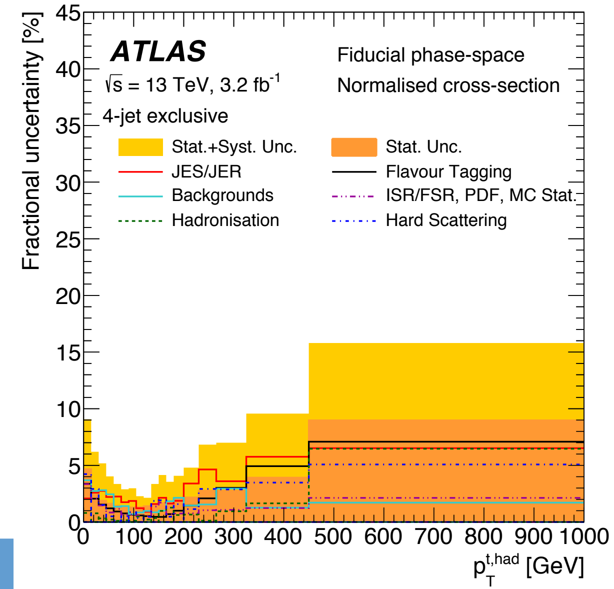




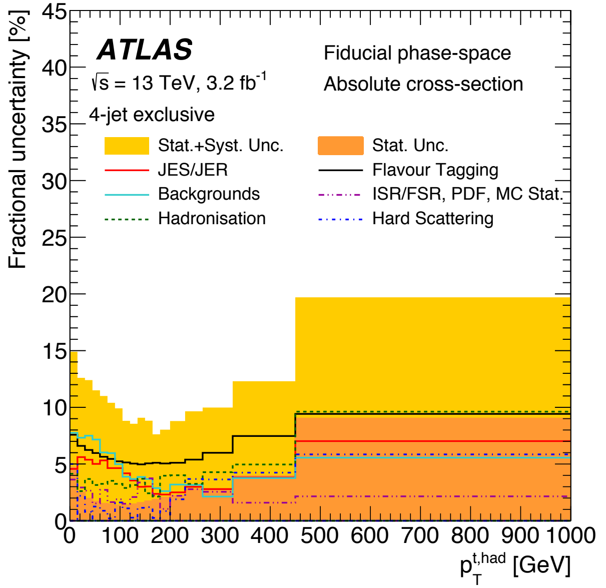
TOPQ-2017-01 (2)

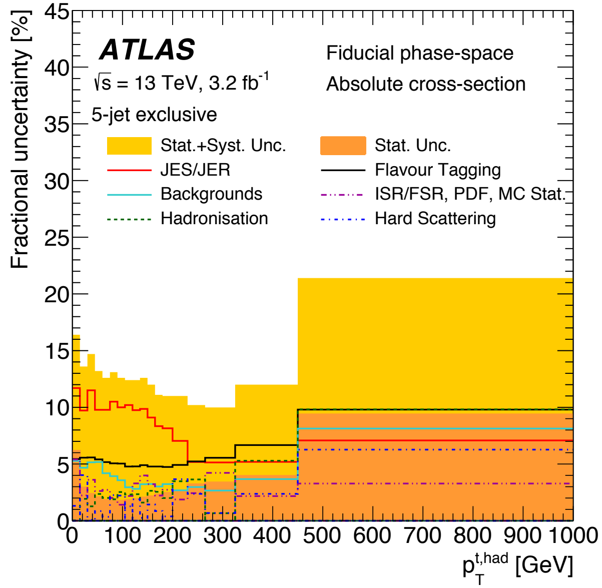
- Dominant for 6incl: JES (jet energy scale)
- Dominant for 4excl: flavour-tagging
- Total uncertainties reduced for normalised Xsec due to cancellation of correlated uncertainties

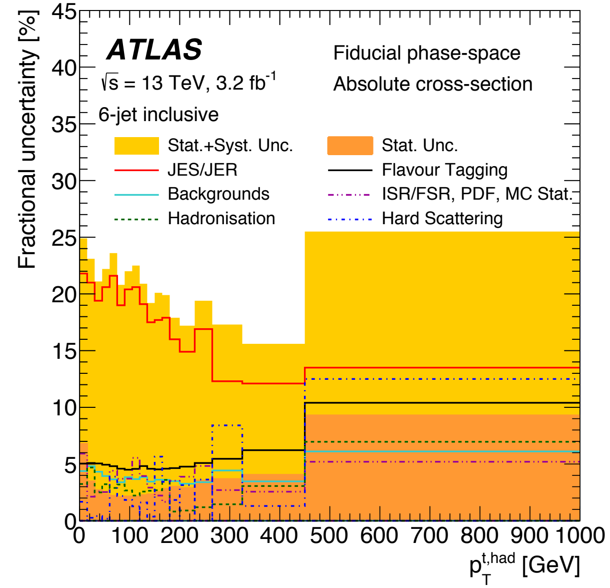
normalised Xsec (4excl)



absolute Xsec (4excl, 5excl, 6incl)







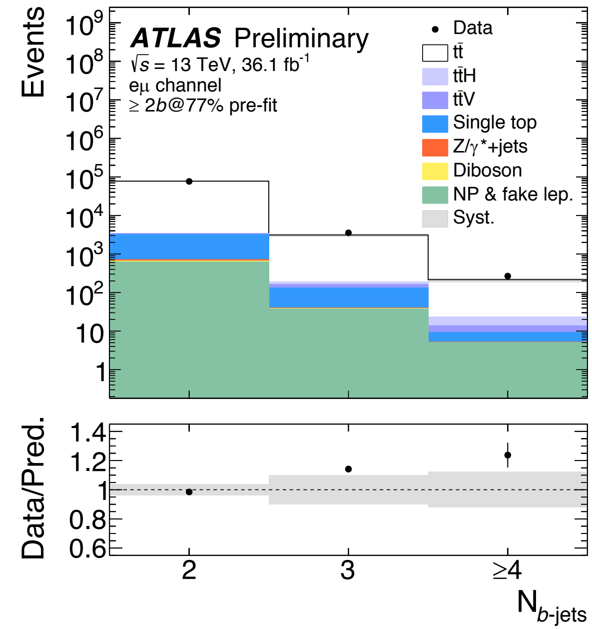
TOPQ-2017-01 (3)

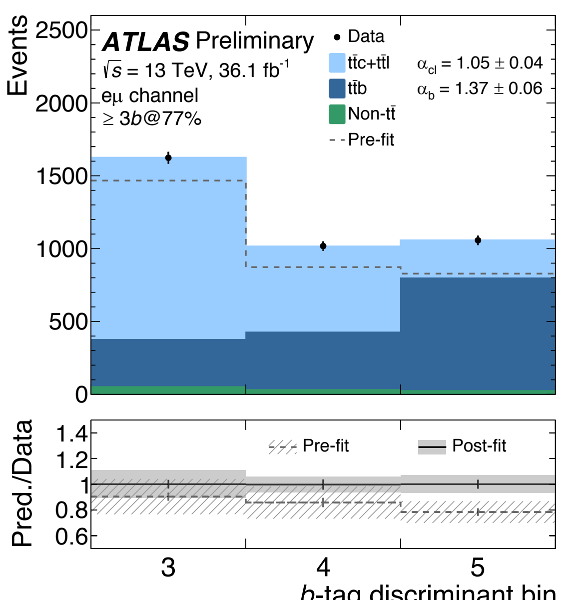
Table 6: Comparison of the measured fiducial phase space normalised differential cross sections as a function of $p_{T}^{t\bar{t}}$ and the predictions from several MC generators in different n-jet configurations. For each prediction a χ^2 and a p-value are calculated using the covariance matrix of the measured spectrum. The number of degrees of freedom (NDF) is equal to the number of bins in the distribution minus one.

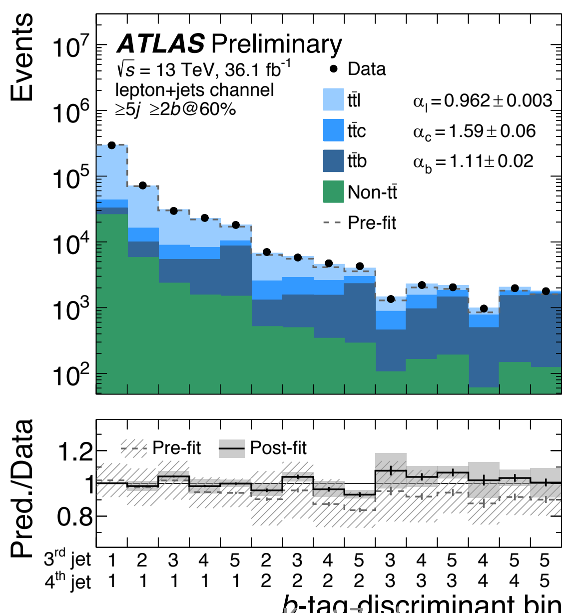
	4-jet exclusive		5-jet exclusive		6-jet inclusive	
	χ^2/NDF	p-value	χ^2/NDF	p-value	χ^2/NDF	p-value
Powheg+Pythia6	4.3/5	0.51	3.0/5	0.70	3.9/5	0.56
Powheg+Pythia6 (radHi)	5.2/5	0.40	6.3/5	0.28	9.8/5	0.08
Powheg+Pythia6 (radLo)	6.2/5	0.29	3.5/5	0.62	5.2/5	0.39
Powheg+Pythia8 ($h_{\mathrm{damp}} = m_t$)	7.6/5	0.18	4.5/5	0.48	4.7/5	0.46
Powheg+Pythia8 ($h_{\mathrm{damp}} = 1.5\, m_t$)	5.5/5	0.36	3.9/5	0.57	6.2/5	0.28
Powheg+Pythia8 (radHi) ($h_{\mathrm{damp}} = 3\, m_t$)	6.5/5	0.26	4.0/5	0.55	10.5/5	0.06
Powheg+Pythia8 (radLo) ($h_{\mathrm{damp}} = 1.5\, m_t$)	5.2/5	0.39	5.6/5	0.35	7.6/5	0.18
Powheg+Herwig7	10.5/5	0.06	5.1/5	0.41	3.1/5	0.68
Powheg+Herwig++	18.6/5	<0.01	16.2/5	<0.01	19.4/5	<0.01
MadGraph5_aMC@NLO+Herwig++	12.8/5	0.03	10.0/5	0.07	9.3/5	0.10
MadGraph5_aMC@NLO+Pythia8 ($H_{\mathrm{T}}/2$)	26.8/5	<0.01	10.2/5	0.07	8.2/5	0.14
MadGraph5_aMC@NLO+Pythia8 ($\sqrt{m_t^2 + p_{\mathrm{T}}^2}$)	17.3/5	<0.01	10.0/5	0.07	7.8/5	0.17
Sherpa 2.2.1	7.5/5	0.19	1.7/5	0.89	2.2/5	0.82

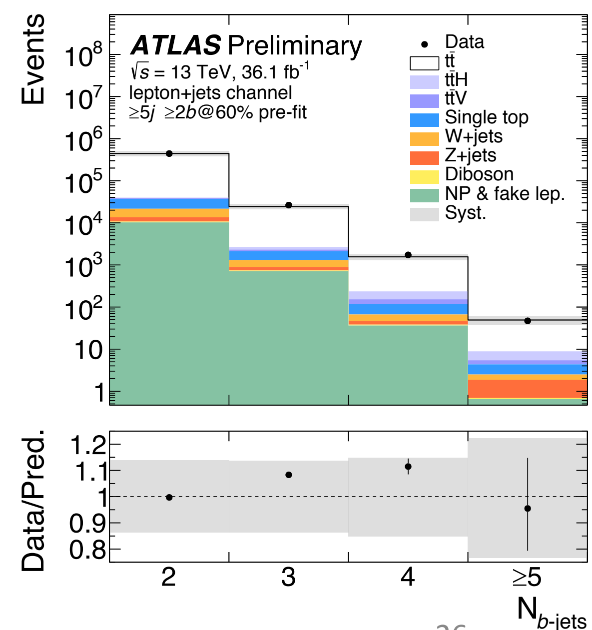
ATLAS-CONF-2018-029

- 13 TeV, 36.1/fb (2015+16)
- eμ: exactly one each, opposite charge, at least one trigger-matched, at least two jets with at least two b-tags (@77%)
- l+jets: exactly one lepton, trigger-matched, at least five jets with at least two b-tagged (@60%)
- Data-driven correction factors for flavour composition
- Templates for different b-tag discriminant bins (corresponding to efficiency ranges)



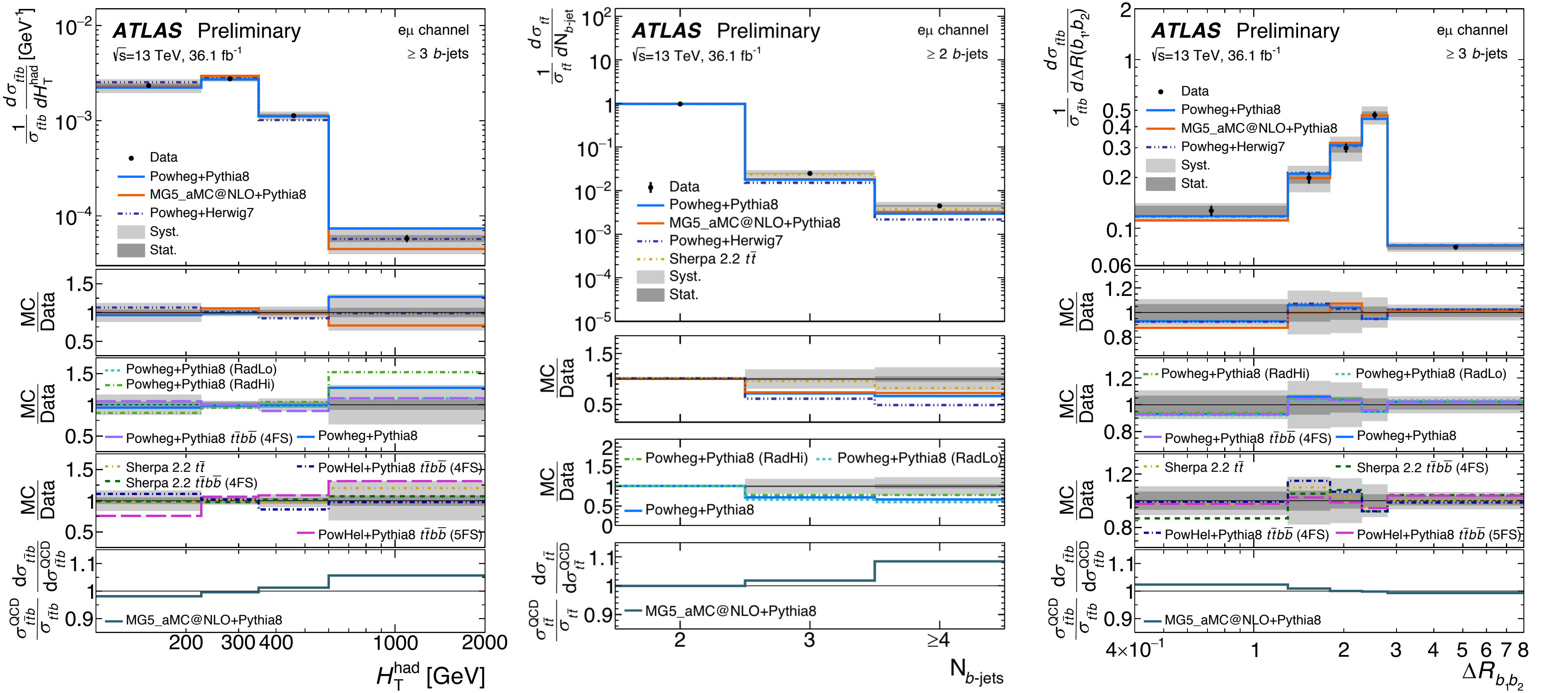






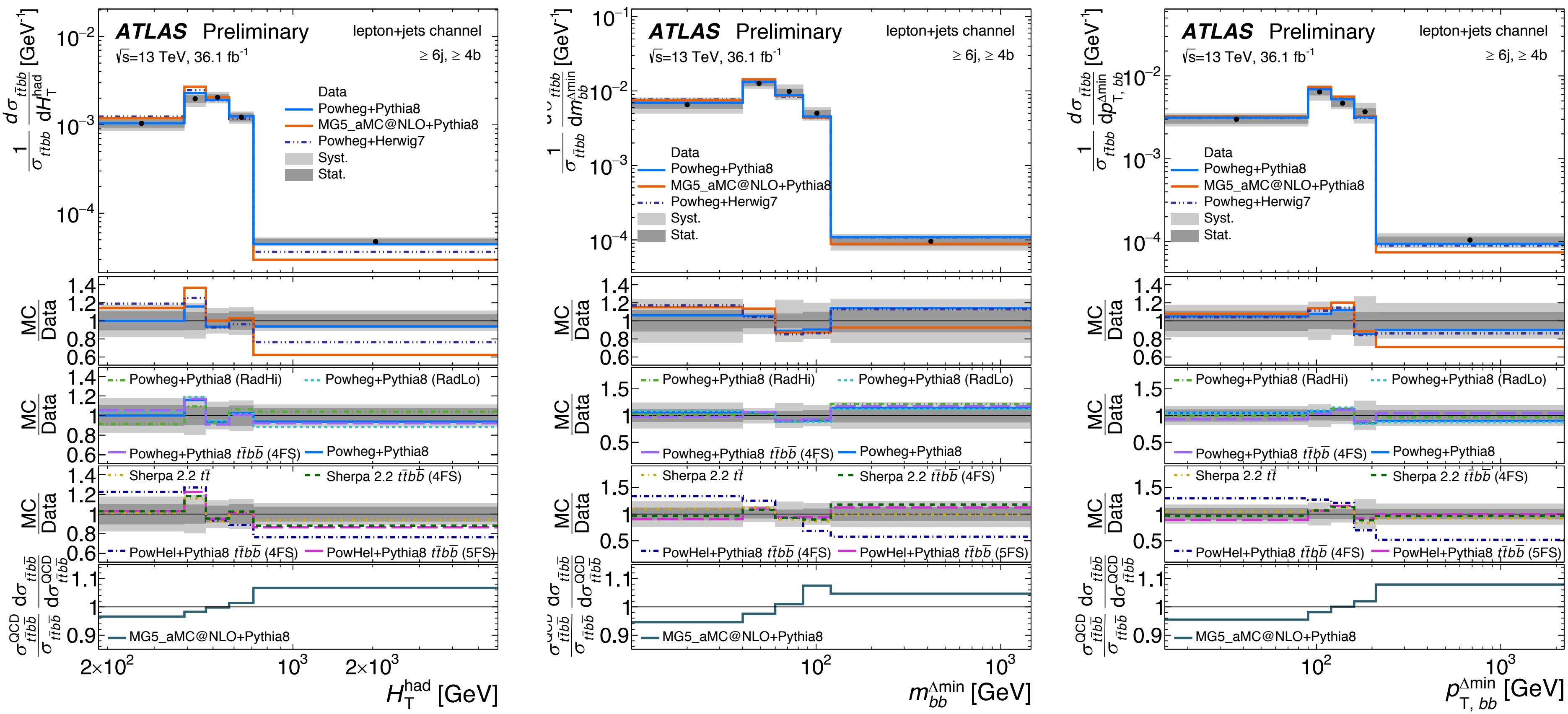
ATLAS-CONF-2018-029 (2)

eμ channel distributions



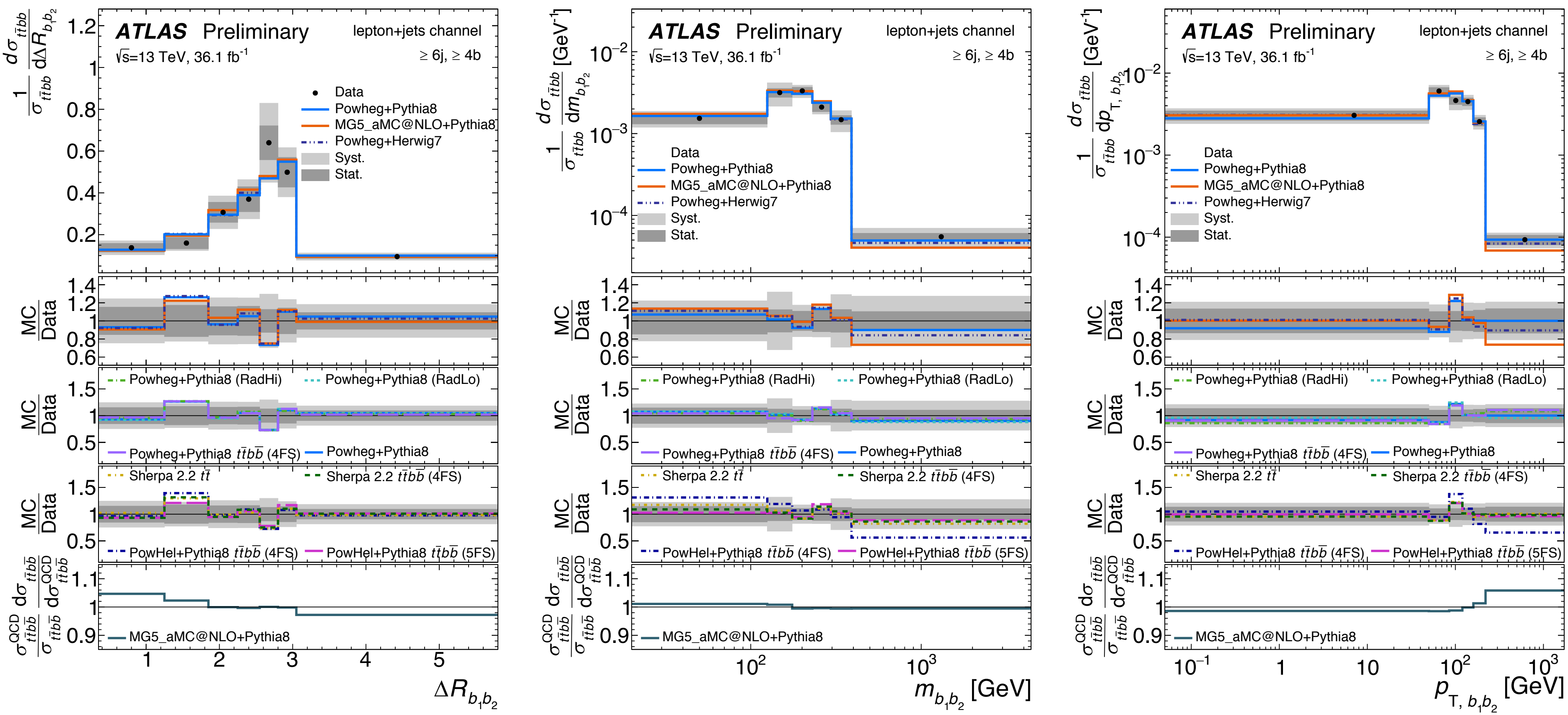
ATLAS-CONF-2018-029 (3)

l+jets channel distributions



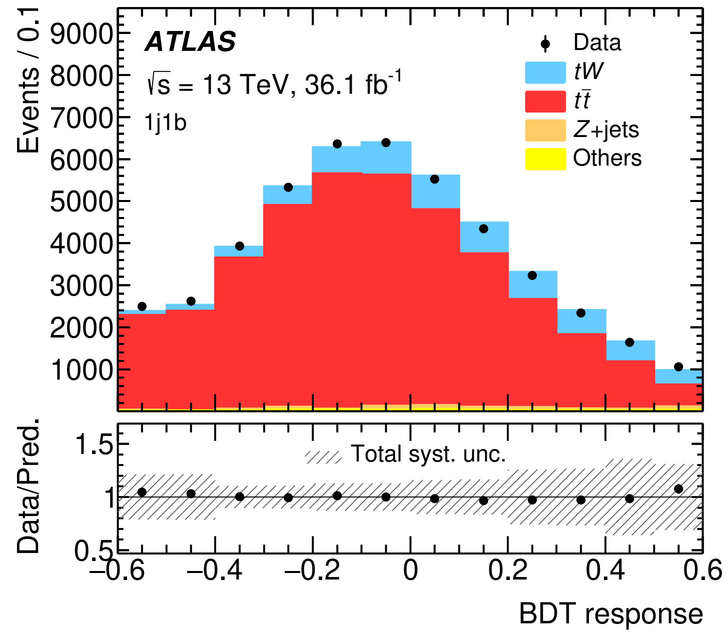
ATLAS-CONF-2018-029 (4)

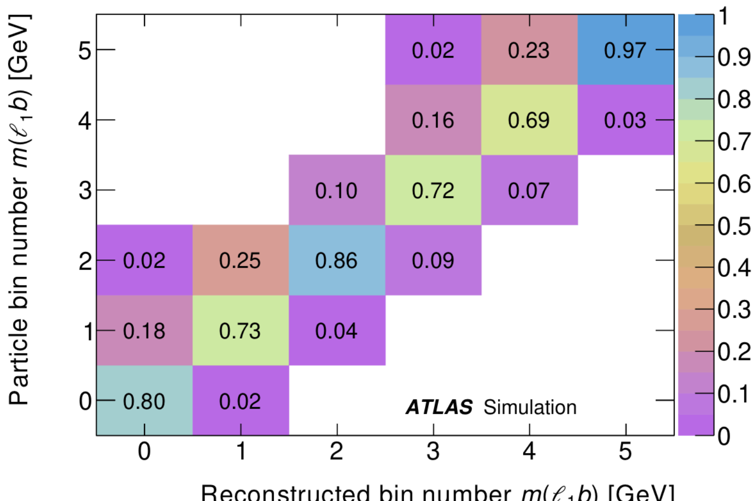
l+jets channel distributions

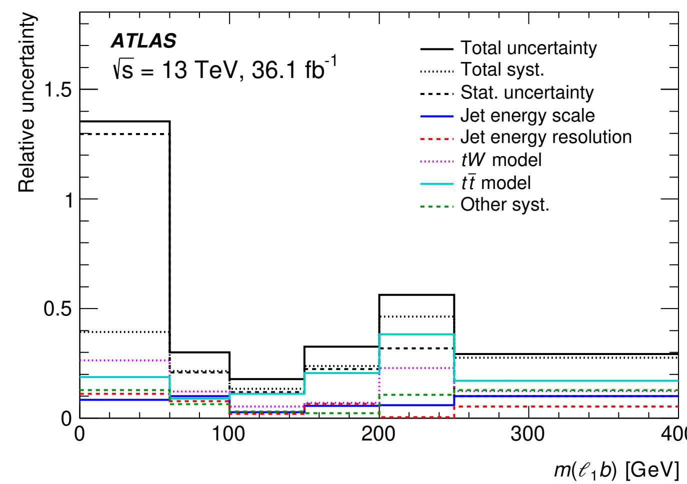


TOPQ-2016-12

- 13 TeV, 36/fb, Wt production
- Exactly one jet with b-tag (77%), lepton pair with opposite charge, complex requirements on MET and m_{ll} to reduce $t\bar{t}$ and Z+jets backgrounds
- Cut on BDT response > 0.3 to further reduce $t\bar{t}$ contamination

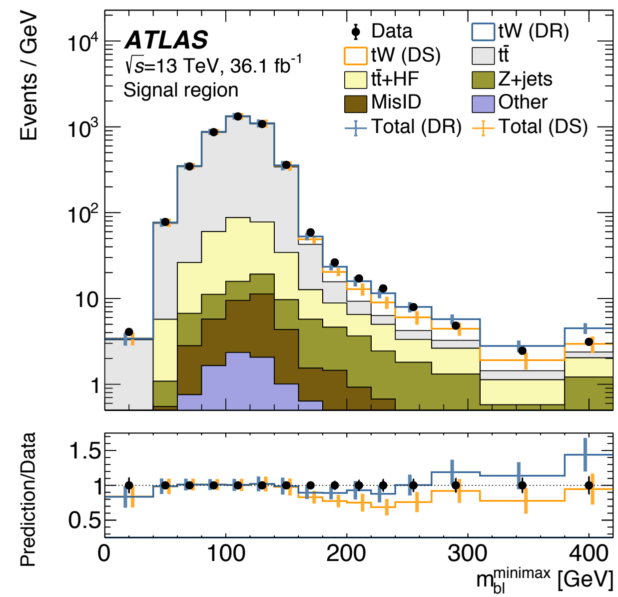




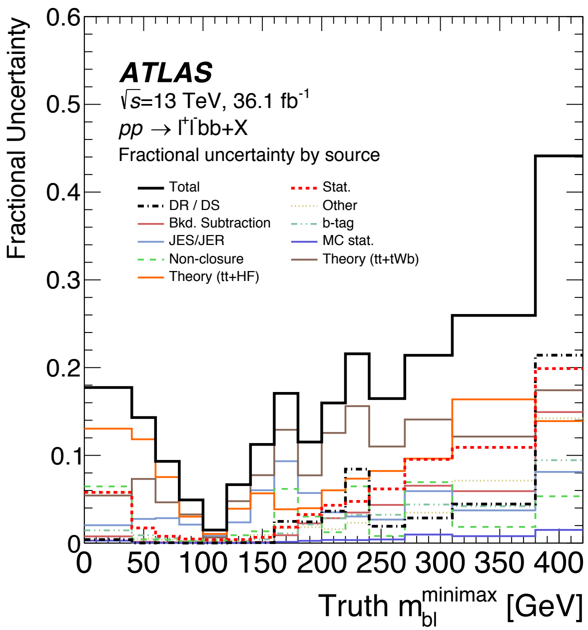


TOPQ-2017-05

- 13 TeV, 36/fb, $Wt + t\bar{t}$ interference
- Lepton pair with opposite charge, exactly two b-tagged jets (@60%), no other b-jets passing 85%
- Dominant: $t\bar{t}$ + HF, SFs extrapolated from data (3b region)
- $m_{bl}^{minimax} = \min\{\max(m_{b1l1}, m_{b2l2}), \max(m_{b1l2}, m_{b2l1})\}$
- At leading order, doubly-resonant $t\bar{t}$ suppressed due to: $m_b^{minimax} < \sqrt{m_t^2 - m_W^2}$



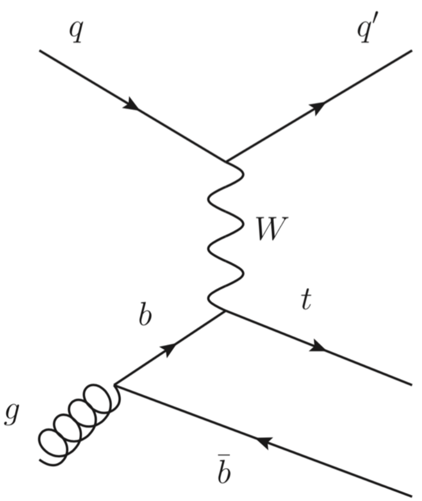
Model	Full Distribution		$m_{b\ell}^{\text{minimax}} > 160$ GeV	
	χ^2 / nDOF	p-value	χ^2 / nDOF	p-value
Powheg+Pythia8 $t\bar{t} + tW$ (DR)	10 / 14	0.71	8.5 / 8	0.40
Powheg+Pythia8 $t\bar{t} + tW$ (DS)	10 / 14	0.77	6.6 / 8	0.56
Powheg+Pythia8 $\ell^+\nu\ell^-\nu bb$	5.9 / 14	0.92	2.0 / 8	0.95
MG5_aMC+Pythia8 $t\bar{t} + tW$ (DR1)	26 / 14	0.14	13 / 8	0.17
MG5_aMC+Pythia8 $t\bar{t} + tW$ (DR2)	36 / 14	0.02	20 / 8	0.08
Powheg+Herwig++ $t\bar{t} + tW$ (DR)	26 / 14	0.07	7.3 / 8	0.48
MG5_aMC+Herwig++ $t\bar{t} + tW$ (DR)	30 / 14	0.04	11 / 8	0.23
Powheg+Pythia6 $t\bar{t} + tW$ (DR)	14 / 14	0.49	11 / 8	0.23
Powheg+Pythia6 $t\bar{t} + tW$ (DS)	14 / 14	0.49	10 / 8	0.32
MG5_aMC+Pythia8 (LO) $WWbb$	12 / 14	0.68	8.2 / 8	0.42
MG5_aMC+Pythia8 (LO) $WWbb$, no int.	28 / 14	0.05	22 / 8	0.005

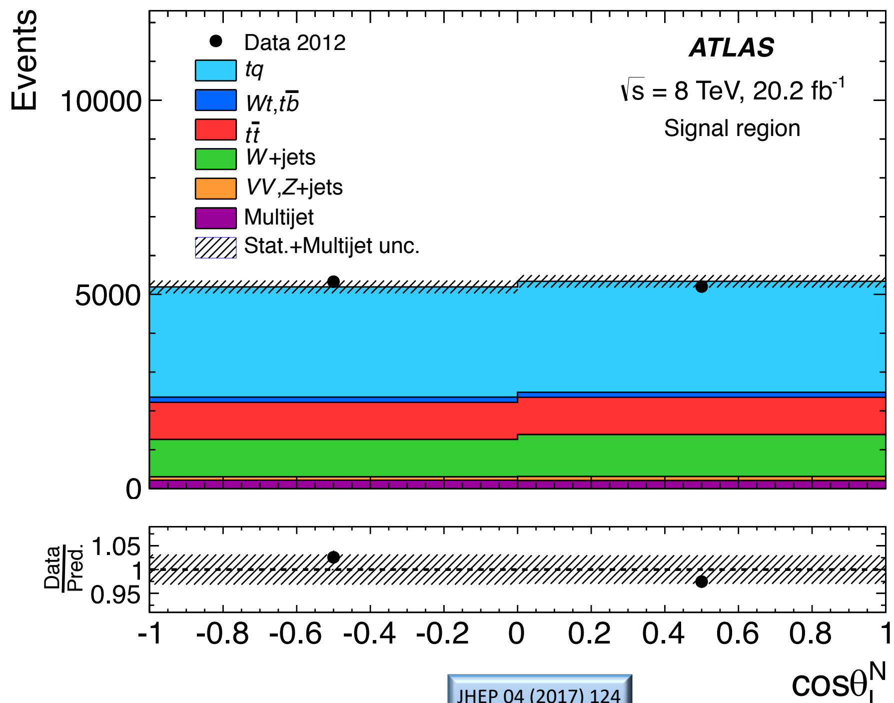


TOPQ-2015-11*

- Top quark spin polarisation transferred to decay products
  - Sensitivity to $Im(g_R)$ in polarisation observables of decay products x_i
  - $\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_x)} = \frac{1}{2}(1 + \alpha_x P \cos\theta_x)$ in the top quark rest frame
- Largest sensitivities in A_{FB}^{N}
  - I.e. forward-backward asymmetry in $\cos\theta_l^N$ distribution of the lepton
  - Normal axis: $\vec{N} = \hat{s}_t \times \vec{q_l}$

spin analysing power $\lesssim 1$ for lepton (at NLO)





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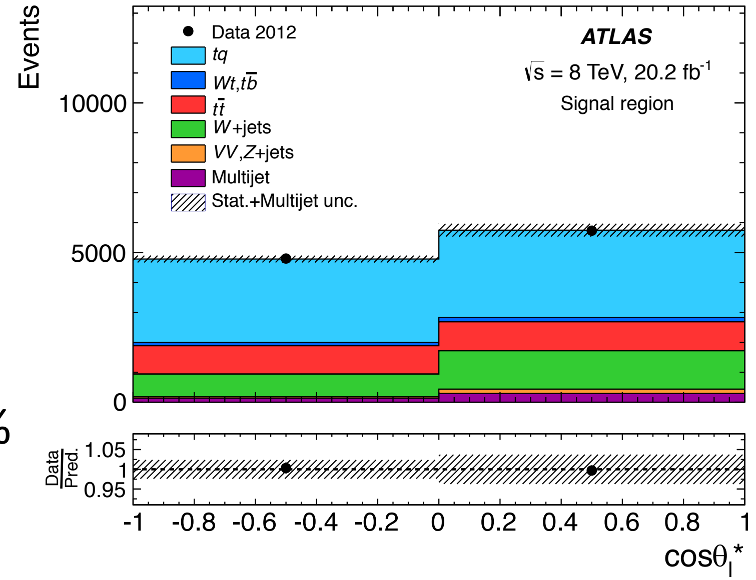
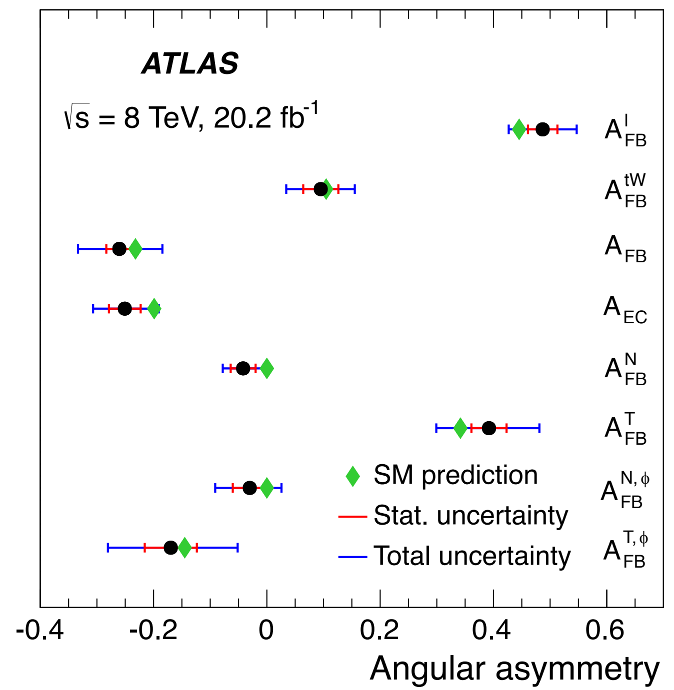
$$A_{FB}^{N} = -0.04 \pm 0.02\ (\text{stat}) \pm 0.03\ (\text{syst})$$

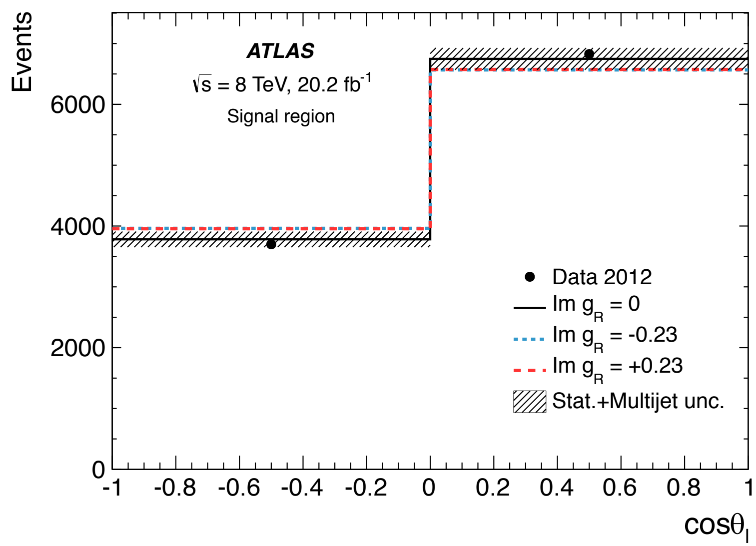
$$Im(g_R) \in [-0.18, 0.06] \text{ at 95\% C.L.}$$

TOPQ-2015-11 (2)

- Exactly one lepton (e/μ), large MET, exactly two jets, with one of them b-tagged (@50% efficiency)
- Spectator b-jet expected to be softer in p_T and broader in $|\eta|$, and is therefore excluded intentionally
- All asymmetries compatible with predicted values by SM

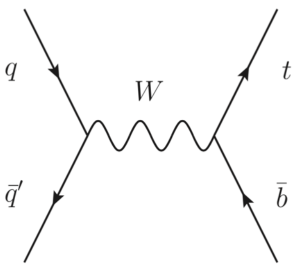






TOPQ-2015-01*

- Matrix Element Method (MEM) to calculate per-event signal probability
- Dominant uncertainties:
  - Data and MC statistics
  - Jet energy resolution
  - t-channel generator choice
- $\sigma_s = 4.8 \pm 0.8\ \text{(stat)}\ ^{+1.6}_{-1.3}\ \text{(syst) pb}$
- Signal strength: $\mu = 0.86^{+0.31}_{-0.28}$ with an observed (expected) significance of 3.2 (3.9)



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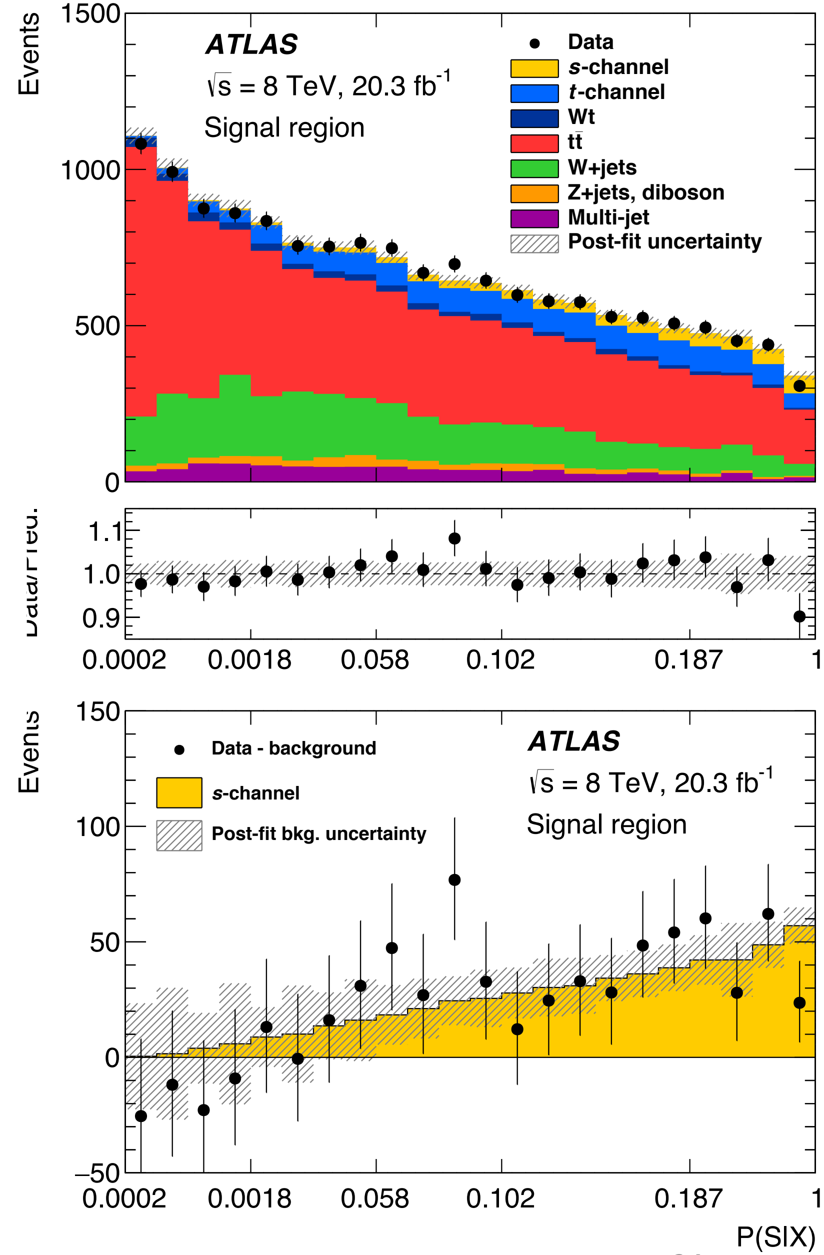

*again, at $\sqrt{s} = 8$ TeV