Differential Top Cross-section Measurements at ATLAS

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Outline

I consider myself something of a moral relativist.

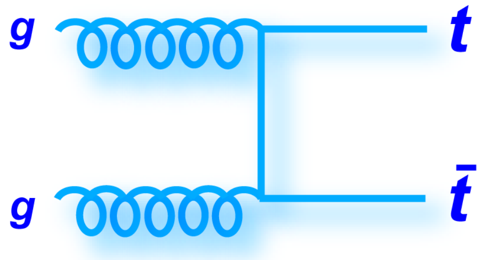
Why do differential measurements of $t\bar{t}$ processes? [1/2]

The top quark is unique in the SM due to its large mass:

- decay before hadronisation
  - $\rightarrow$ only quark that can be studied in isolation
  - $\hookrightarrow$ precision QCD test
- same order as V.E.V in SM
  - $\rightarrow$ $m_t \simeq 173$ GeV, $v = 246$ GeV
  - $\hookrightarrow$ direct sensitivity to new physics

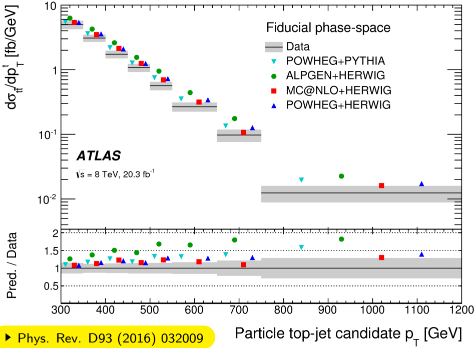
$$m_t = y_t v/\sqrt{2}$$

$$\Delta m_h^t \sim -\frac{m^2}{v^2}\frac{\Lambda}{4\pi^2}$$

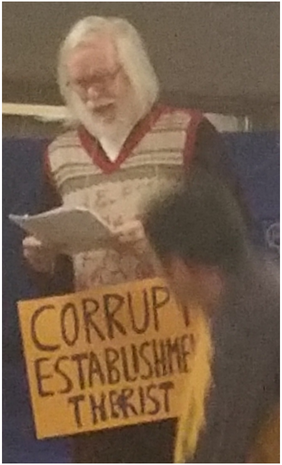


Why do differential measurements of $t\bar{t}$ processes? [2/2]

- Major background to many interesting searches like $t\bar{t}H$ or SUSY
  - Not always well described in current MC generators
  - → Differential measurements crucial input to MC tuning efforts!



▸ Phys. Rev. D93 (2016) 032009

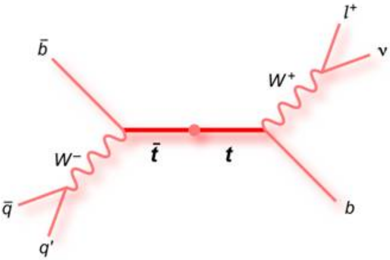


- Differential data very useful to theorists:
  - constraining EFT operators: ▸ TopFitter
  - gluon PDF at large x: ▸ Czakon et al
  - highly sensitive to NNLO effects ▸ Czakon et al

Outline

Analysis Strategy

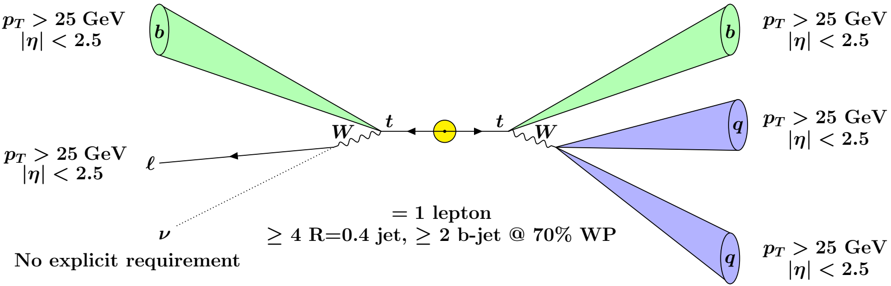
- Use 3 fb^{-1} of $\sqrt{s} = 13$ TeV recorded by ATLAS in 2015
- Utilise lepton+jets decay mode
  - Top Decay: $\sim$100% $t \rightarrow Wb$
    - $\rightarrow$ Channel determined by decay of the two W's
  - The goldilocks branching ratio, backgrounds, trigger efficiency

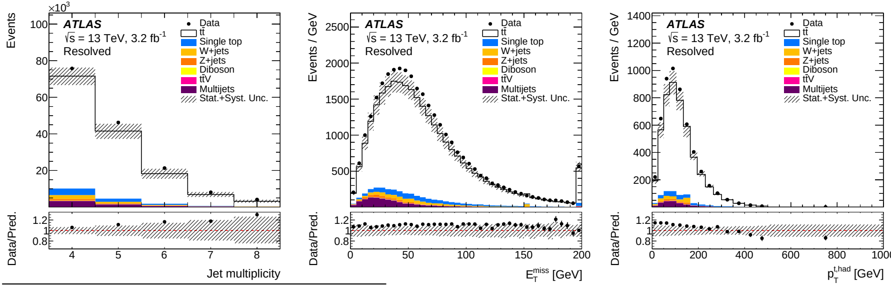


- Reconstruct in both resolved and boosted topologies
  - Sensitivity to both low and high p_T in same publication
- Publish both absolute and relative distributions
- Compare to many different MC predictions

▸ Publication Webpage

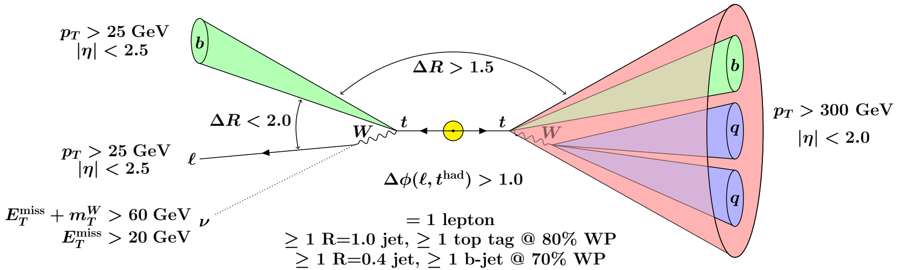
Resolved Selection

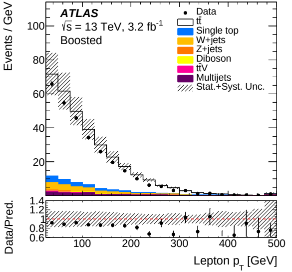


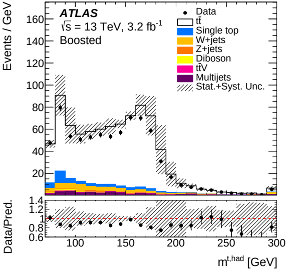


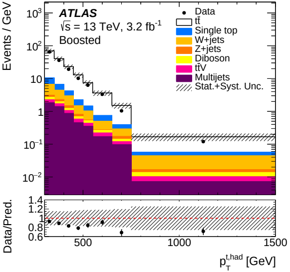
Pseudotop from LHCTopWG guidelines ▸ Twiki

Boosted Selection

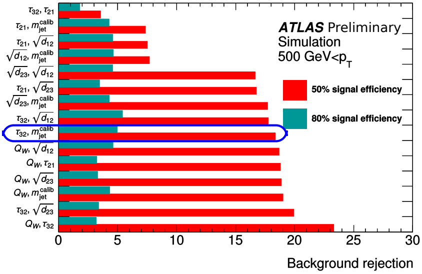




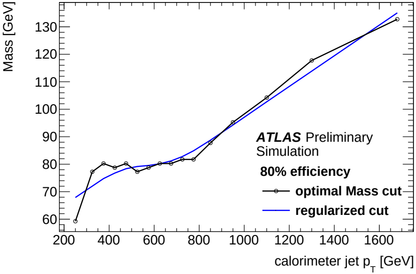


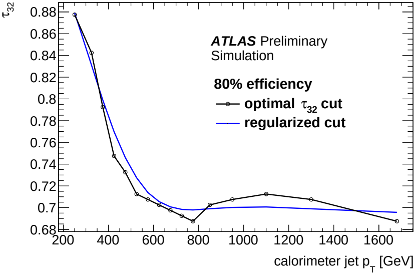


Boosted Top Tagger



- Scan over combinations of substructure variables
  - Best combination over full p_T range and for 50% and 80% WPs: jet mass and τ_{32}
- Define p_T dependent cuts for 50% and 80% WPs
  - In this measurement, we use the **80% WP**





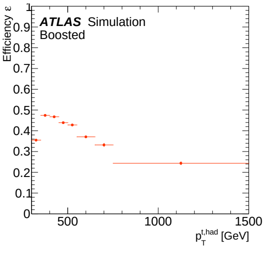
Early RunII Tagger Pub Note ATL-PHYS-PUB-2015-053

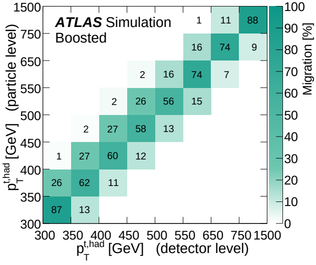
Unfolding procedure

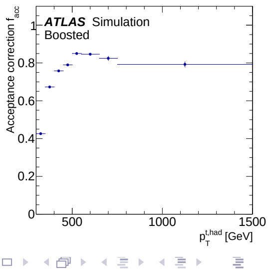
- Using the Iterative Bayesian method in RooUnfold with 4 iterations
- Master formula:

$$\frac{d\sigma^{\mathrm{fid}}}{dX^i} \equiv \frac{1}{\mathcal{L} \cdot \Delta X^i} \cdot f^i_{\mathrm{eff}} \cdot \sum_j \mathcal{M}^{-1}_{ij} \cdot f^j_{\mathrm{acc}} \cdot \left(N^j_{\mathrm{reco}} - N^j_{\mathrm{bkg}}\right) \quad (1)$$

$$f^i_{\mathrm{eff}} \equiv \left(\frac{N_{\mathrm{part}}}{N_{\mathrm{reco\&part}}}\right)^i, f^j_{\mathrm{acc}} \equiv \left(\frac{N_{\mathrm{reco\&part}}}{N_{\mathrm{reco}}}\right)^j$$



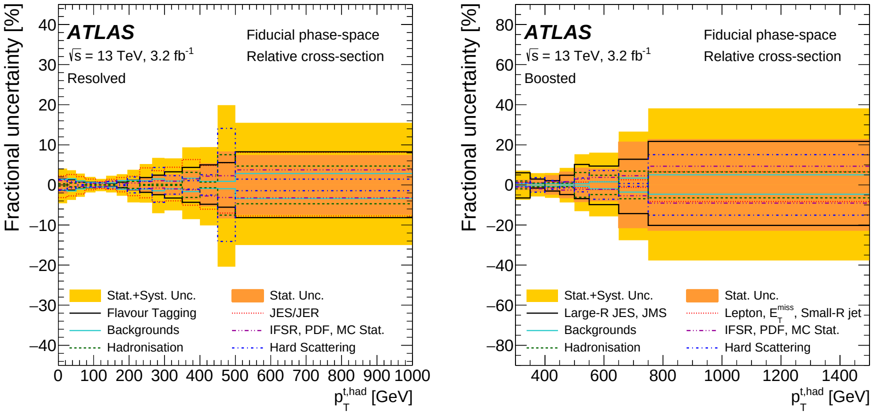




Outline

OH ALICE.. YOU'RE THE ONE FOR ME
BUT BOB.. IN A QUANTUM WORLD HOW CAN WE BE SURE?
Physics World

Uncertainties

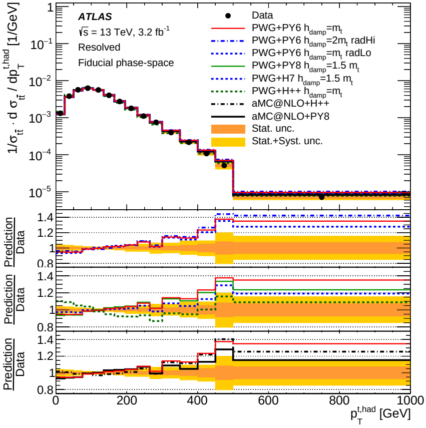


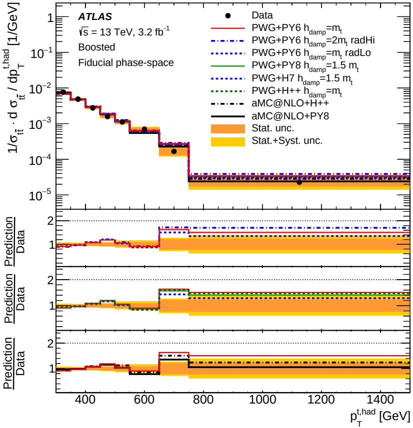
- Small-R jet (resolved) and large-R jet (boosted) dominant
  - Energy scale/resolution (both), b-tagging (resolved), JSS modelling (boosted)
- Generator systematics important in both analyses
  - e.g. Powheg vs aMC@NLO, Pythia vs Herwig...

Outline

Sorry Birmingham

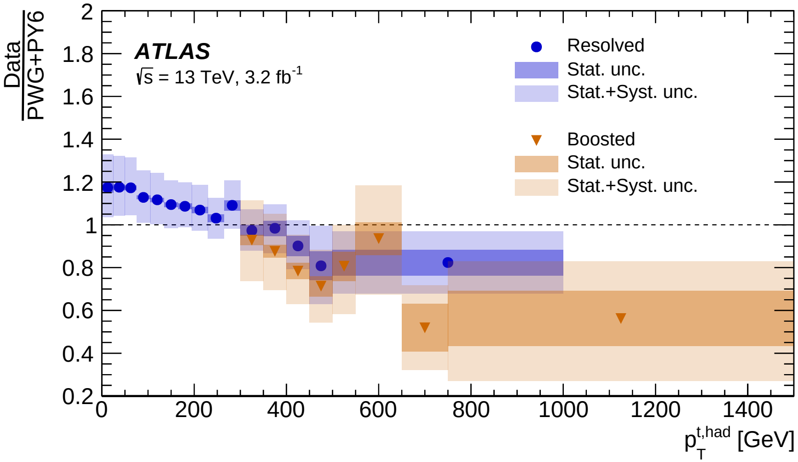
Top p_T





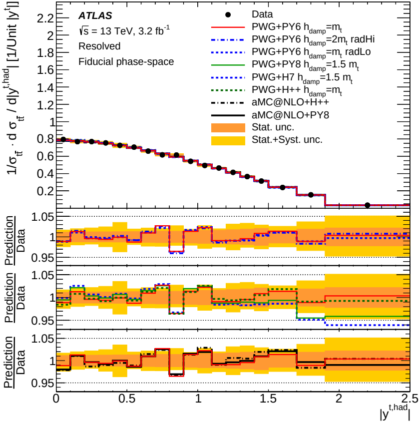
- MC predicts harder spectrum than observed in data
- Similar slope seen in both regions, as has been observed previously in l+jets and dilepton by ATLAS and ▸ CMS

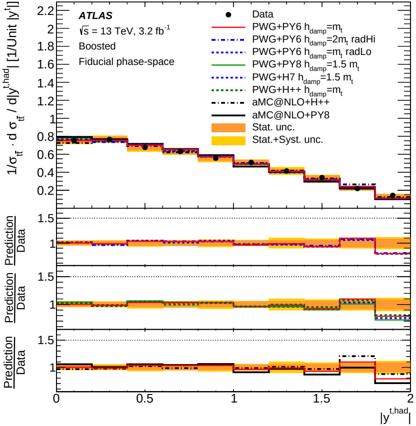
Top p_T : Comparison of Resolved and Boosted



- p_T ranges are complementary
- Very similar trend in overlapping region between resolved and boosted reconstruction techniques

Top Rapidity





- Good agreement with all generators
- Very little sensitivity to extra radiation

χ^2 and p-vals

Resolved

	$p_T^{t,had}$ χ^2/NDF	$p_T^{t,had}$ p-val	$\|y^{t,had}\|$ χ^2/NDF	$\|y^{t,had}\|$ p-val
POWHEG+PYTHIA6	23.0/14	0.06	8.1/17	0.96
POWHEG+PYTHIA6 (radHi)	23.8/14	0.05	8.5/17	0.95
POWHEG+PYTHIA6 (radLo)	25.9/14	0.03	7.5/17	0.98
MADGRAPH5_aMC@NLO+HERWIG++	24.4/14	0.04	10.8/17	0.87
POWHEG+HERWIG++	24.0/14	0.05	7.4/17	0.98
MADGRAPH5_aMC@NLO+PYTHIA8	21.8/14	0.08	7.8/17	0.97
POWHEG+PYTHIA8	21.5/14	0.09	9.6/17	0.92
POWHEG+HERWIG7	15.4/14	0.35	9.3/17	0.93

Boosted

	$p_T^{t,had}$ χ^2/NDF	$p_T^{t,had}$ p-val	$\|y^{t,had}\|$ χ^2/NDF	$\|y^{t,had}\|$ p-val
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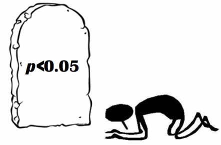
POWHEG+HERWIG7	9.9/7	0.20	3.6/9	0.94



- Numerical evaluation of agreement between data and MC
  - Takes into consideration relative importance of each bin as well as correlations
- One must take into consideration the NDF for χ^2
  - Can see more immediately in p-values

χ^2 and p-vals

Resolved

	$p_T^{t,\mathrm{had}}$		$\lvert y^{t,\mathrm{had}}\rvert$	
	χ^2/NDF	p-val	χ^2/NDF	p-val
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"Numbers don't lie. That's where we come in."

- Agreement for p_T is overall pretty poor in both topologies
  - But surprisingly, resolved has worse p-vals than boosted!
  - → Highlights the deficit at low p_T , often overlooked due to high p_T bins being bigger and drawing the eye

χ^2 and p-vals

Resolved

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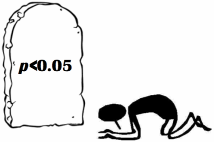

- aMC@NLO+Herwig++ with the biggest $\lvert y^{t,had}\rvert$ disagreement in resolved, also present in boosted
    - Herwig++ now a legacy generator, and no longer used

χ^2 and p-vals

Resolved

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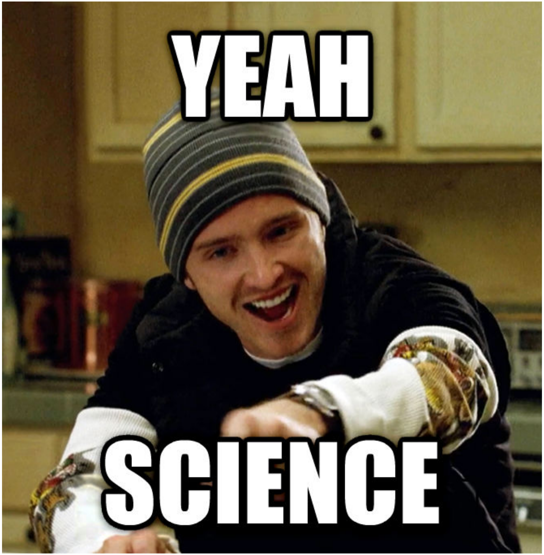
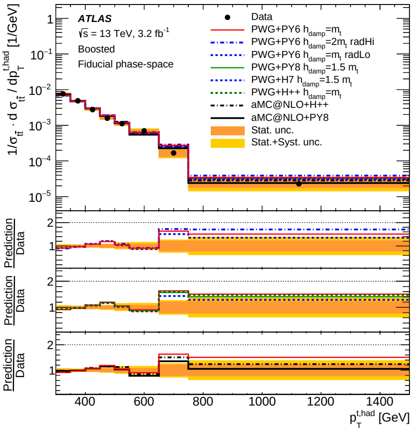
- Most concerning: Boosted $\left|y^{t,\mathrm{had}}\right|$ aMC@NLO+Pythia8
  - With Powheg+Pythia8 the new nominal $t\bar{t}$ sample, we would use this sample to evaluate our Matrix Element systematic
  - $\rightarrow$ A perfect example of where we have since used these results to tune and improve MC

Outline



Summary

- Differential cross sections of $t\bar{t}$ production important in SM and BSM physics, experiment and theory, both as a signal and a background

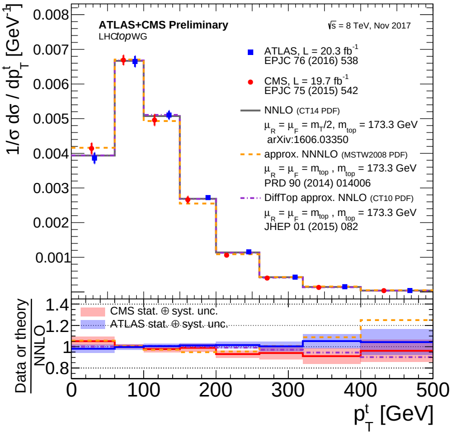


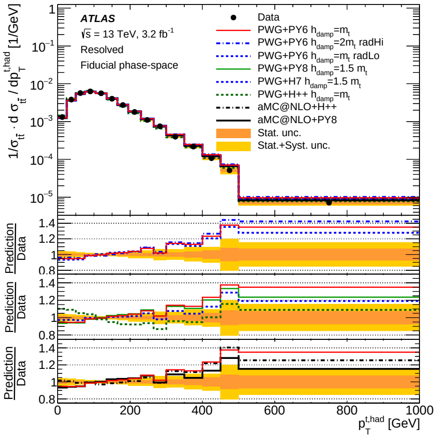
- Run 2 data confirms slope in the top p_T modelling
  - This was also seen in all Run1 measurements
  - NNLO corrections may account for this
- Biggest systematic is often the signal modelling
  - Can use these results to improve the MC going forward
- Modelling of $t\bar{t}$ process is generally good otherwise

▸ Publication Webpage

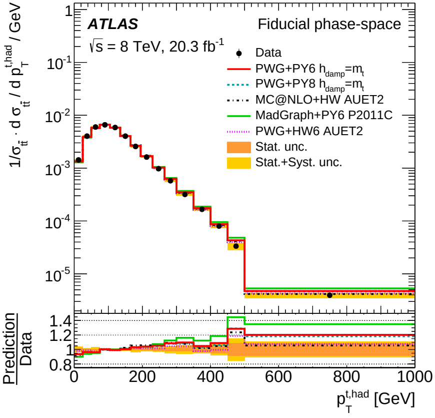
BACKUP

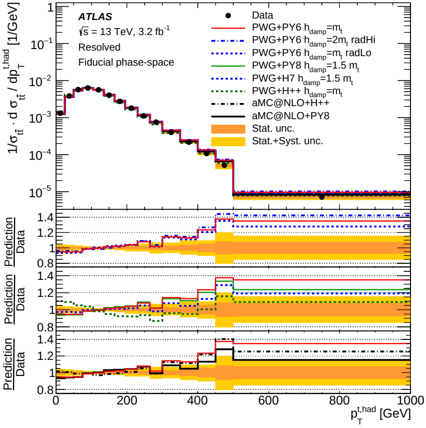
Run 1 NNLO Comparison



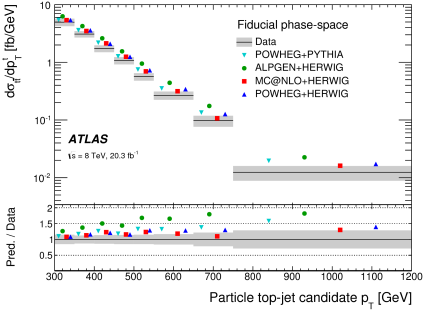


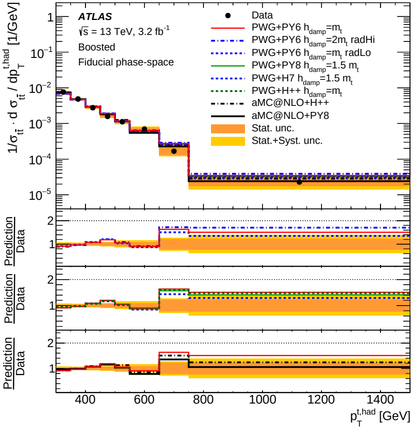
Resolved 8TeV vs 13TeV





Boosted 8TeV vs 13TeV





Object Definitions

Level	Detector		Particle
Topology	Resolved	Boosted	
Leptons	$\lvert d_0\rvert/\sigma(d_0) < 5$ and $\lvert z_0 \sin\theta\rvert < 0.5$ mm Track and calorimeter isolation $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.47$ (e), $\lvert\eta\rvert < 2.5$ (μ) E_T (e), p_T (μ) > 25 GeV		$\lvert\eta\rvert < 2.5$ $p_T > 25$ GeV
Small-R jets	$\lvert\eta\rvert < 2.5$ $p_T > 25$ GeV JVT cut (if $p_T < 60$ GeV and $\lvert\eta\rvert < 2.4$)		$\lvert\eta\rvert < 2.5$ $p_T > 25$ GeV
Num. of small-R jets	≥ 4 jets	≥ 1 jet	Same as detector level
E_T^{miss}, m_T^W		$E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T^W > 60$ GeV	Same as detector level
Leptonic top	Kinematic top-quark reconstruction for detector and particle level	At least one small-R jet with $\Delta R(\ell$, small-R jet$) < 2.0$	
Hadronic top	Kinematic top-quark reconstruction for detector and particle level	The leading-p_T trimmed large-R jet has: $\lvert\eta\rvert < 2.0$, 300 GeV $< p_T <$ 1500 GeV, $m > 50$ GeV, Top-tagging at 80% efficiency ΔR(large-R jet, small-R jet associated with lepton) > 1.5, $\Delta\phi(\ell$, large-R jet$) > 1.0$	**Boosted:** $\lvert\eta\rvert < 2.0$ $300 < p_T < 1500$ GeV Top-tagging: $m > 100$ GeV, $\tau_{32} < 0.75$
b-tagging	At least 2 b-tagged jets	At least one of: 1) the leading-p_T small-R jet with $\Delta R(\ell$, small-R jet$) < 2.0$ is b-tagged 2) at least one small-R jet with ΔR(large-R jet, small-R jet$) < 1.0$ is b-tagged	Ghost-matched b-hadron

Samples

Physics process	Event generator	Cross-section normalisation	PDF set for hard process	Parton shower	Tune
$t\bar{t}$ Nominal	Powheg-Box v2	NNLO+NNLL	CT10	Pythia 6.428	Perugia2012
$t\bar{t}$ PS syst.	Powheg-Box v2	NNLO+NNLL	CT10	Herwig++ v2.7.1	UE-EE-5
$t\bar{t}$ ME syst.	MadGraph5_aMC@NLO	NNLO+NNLL	CT10	Herwig++ v2.7.1	UE-EE-5
$t\bar{t}$ rad. syst.	Powheg-Box v2	NNLO+NNLL	CT10	Pythia 6.428	'radHi/Lo'
Extra $t\bar{t}$ model	Powheg-Box v2	NNLO+NNLL	NNPDF3.0NLO	Pythia 8.210	A14
Extra $t\bar{t}$ model	Powheg-Box v2	NNLO+NNLL	NNPDF3.0NLO	Herwig v7.0.1	H7-UE-MMHT
Extra $t\bar{t}$ model	MadGraph5_aMC@NLO	NNLO+NNLL	NNPDF3.0NLO	Pythia 8.210	A14
Single top t-channel	Powheg-Box v1	NLO	CT10f4	Pythia 6.428	Perugia2012
Single top s-channel	Powheg-Box v2	NLO	CT10	Pythia 6.428	Perugia2012
Single top Wt-channel	Powheg-Box v2	NLO+NNLL	CT10	Pythia 6.428	Perugia2012
$W(\to \ell\nu)+$ jets	Sherpa v2.1.1	NNLO	CT10	Sherpa	Sherpa
$Z(\to \ell\bar{\ell})+$ jets	Sherpa v2.1.1	NNLO	CT10	Sherpa	Sherpa
WW, WZ, ZZ	Sherpa v2.1.1	NLO	CT10	Sherpa	Sherpa
$t\bar{t}+W/Z/WW$	MadGraph5_aMC@NLO	NLO	NNPDF2.3LO	Pythia 8.186	A14

Background Estimates

Most backgrounds are estimated from Monte-Carlo samples out of the box, but we can do slightly better for W+Jets and QCD Multijet

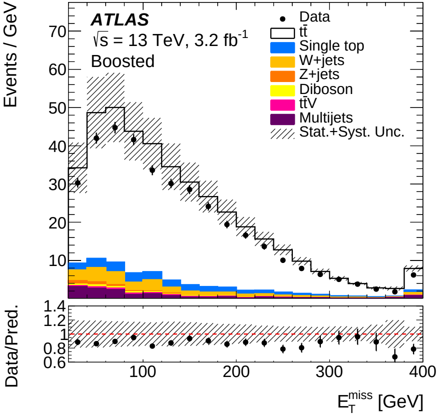
W+Jets

- Exploit known charge-asymmetry in $W^{\pm}$ production at *pp* collider to correct normalisation of MC
- Further, use data to correct poorly-modelled W+(b,c,light) fractions of MC prediction
  - Measure in control regions split by no. of 0.4 jets
  - Extrapolate to signal region

Process	Expected events	
	Resolved	Boosted
$t\bar{t}$	123800 ± 10600	7000 ± 1100
Single top	6300 ± 800	500 ± 80
Multijets	5700 ± 3000	300 ± 80
W+jets	$3600\ ^{+2000}_{-2400}$	500 ± 200
Z+jets	1300 ± 700	60 ± 40
$t\bar{t}V$	400 ± 100	70 ± 10
Diboson	300 ± 200	60 ± 10
Total prediction	$142000\ ^{+11000}_{-12000}$	8300 ± 1300
Data	155593	7368

Background Estimates

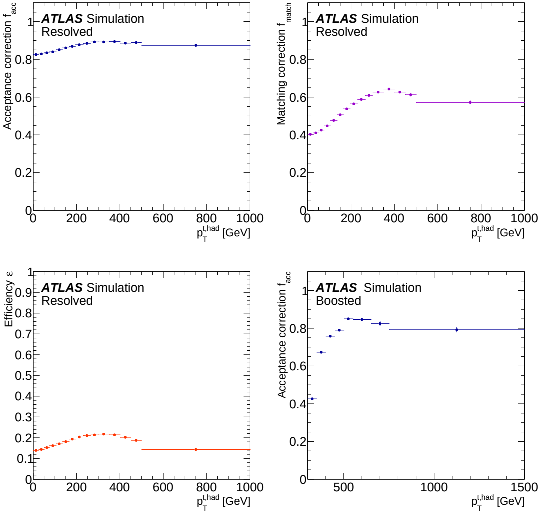
Most backgrounds are estimated from Monte-Carlo samples out of the box, but we can do slightly better for W+Jets and QCD Multijet



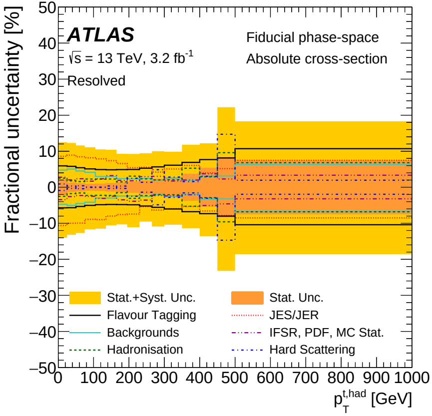
QCD Multijet

- Multijet MC not reliable enough for our desired precision
- Instead derive fully from data using "matrix-method"
  - Estimate number of real/fake leptons in a control region by comparing loose / tight isolation
  - Extrapolate to tight isolated signal region

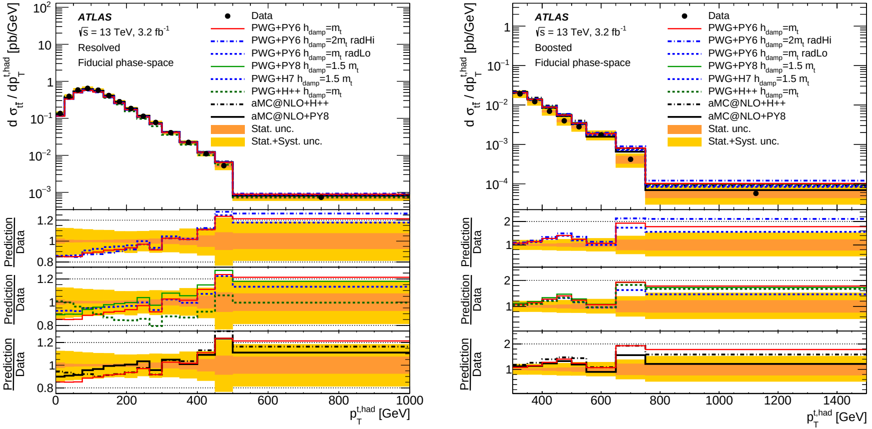
Resolved Unfolding Distributions



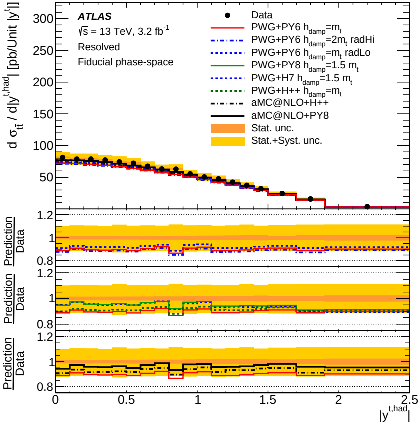
Uncertainties for Absolute Spectra

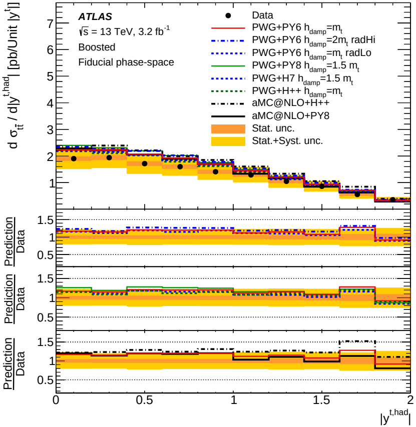


Top p_T (Absolute)



Top Rapidity (Absolute)





$t\bar{t}$ kinematics (Absolute)