ATLAS measurements of boosted object production

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On behalf of the ATLAS collaboration

BOOST 2015, Chicago
August 10-14, 2015

Outline

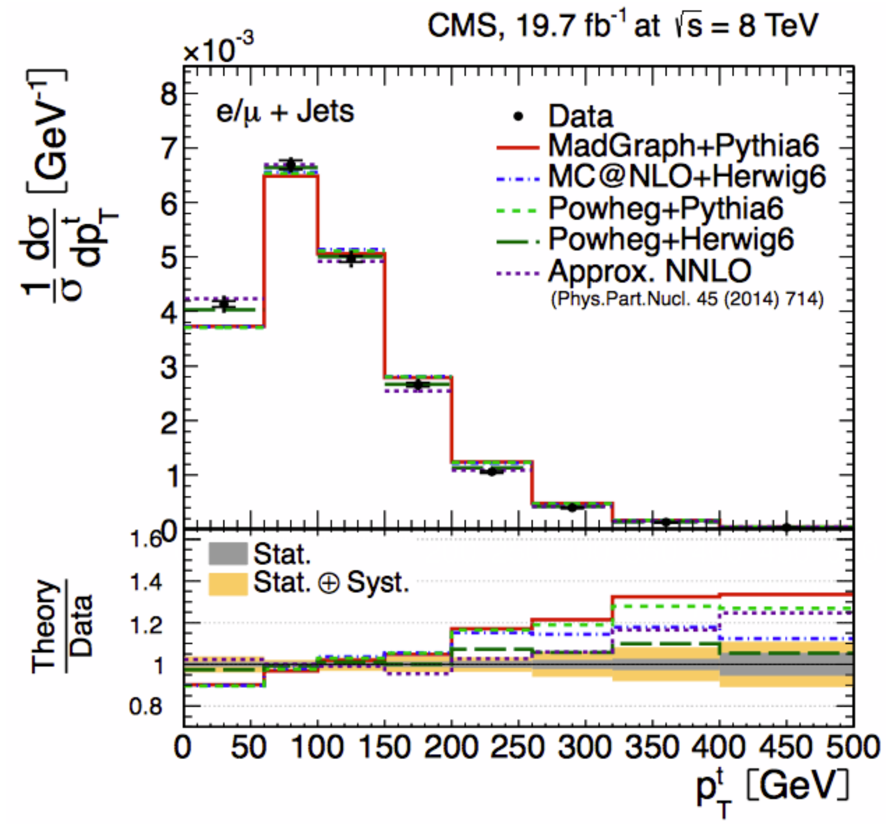
- Two public ATLAS Standard Model measurements that make use of boosted objets:
  - Differential cross-section of boosted top quarks vs top quark p_T
  - Cross-section measurement of boosted W and Z bosons

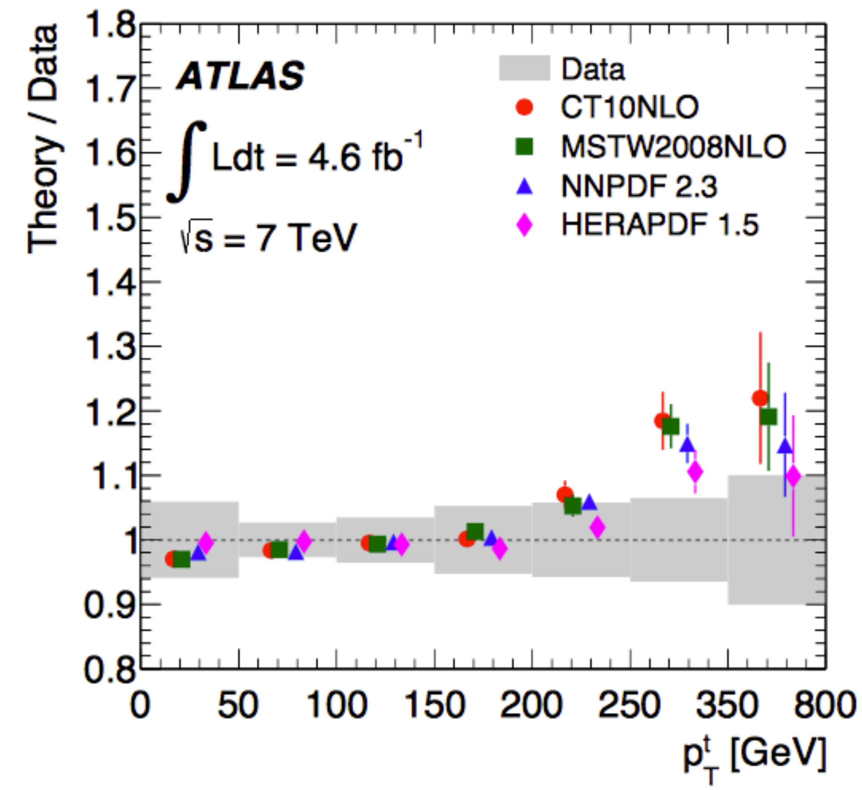
Differential cross-section of boosted top quarks versus top p_T

ATLAS-CONF-2014-057

Motivation

- Test predictions of high-p_T top production using boosted top quarks
- **Reaching higher top p_T is of high interest**
  - Most discrepant regions in previous measurements
  - Most sensitive to PDFs
  - Most relevant for new physics searches

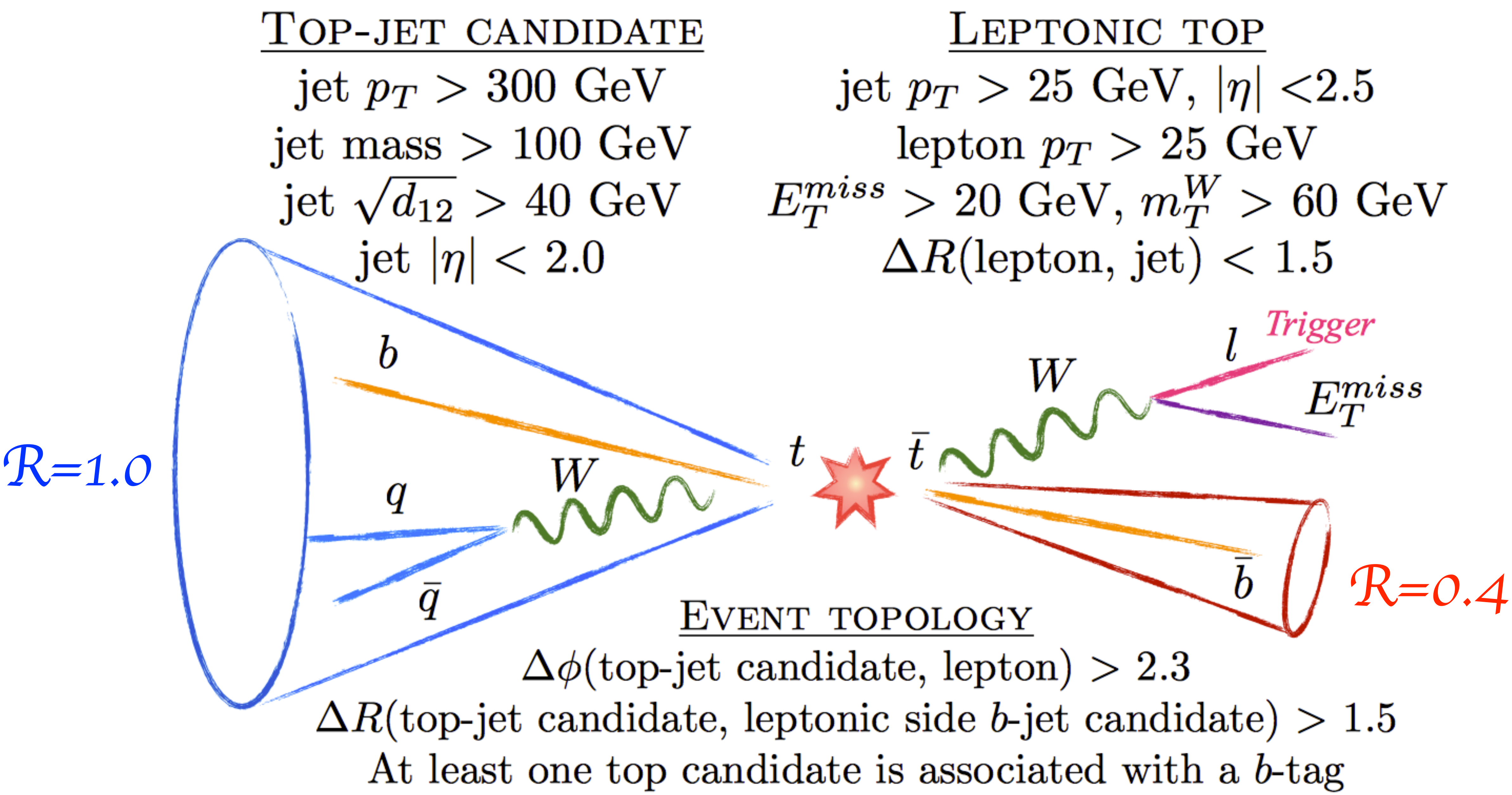




Overview of the analysis

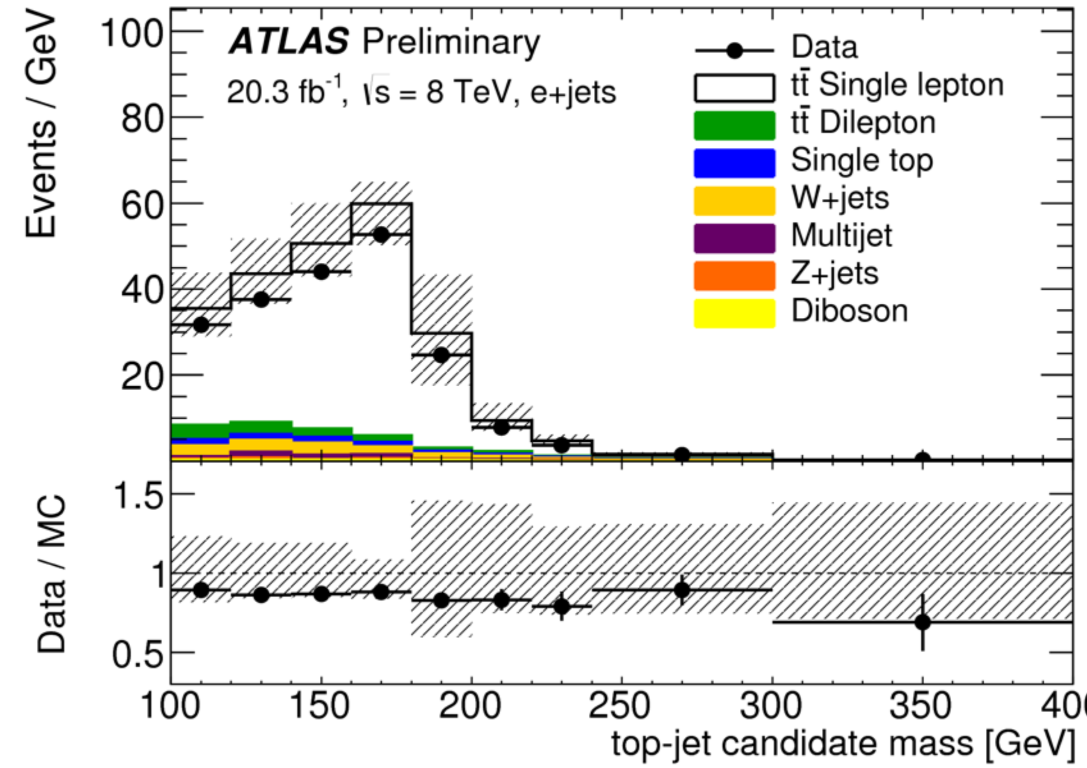
- Measure the absolute cross-section of top quarks with p_T > 300 GeV ($\sqrt{s}$ = 8 TeV, 20 fb^{-1})
  - using hadronically decaying top quarks reconstructed with anti-k_T trimmed (R_{sub}=0.3, f_{cut}=0.05) large-R jets inside lepton+jets channel
  - Use exactly the same selections as the ttbar resonance search in the boosted topology (see talk by M. Kagan)
- Unfold the data to correct for background and detector inefficiencies to:
  - Particle-level in fiducial phase-space close to detector-level selections → smaller uncertainties
  - Parton-level
- Compare with the predictions of many generators

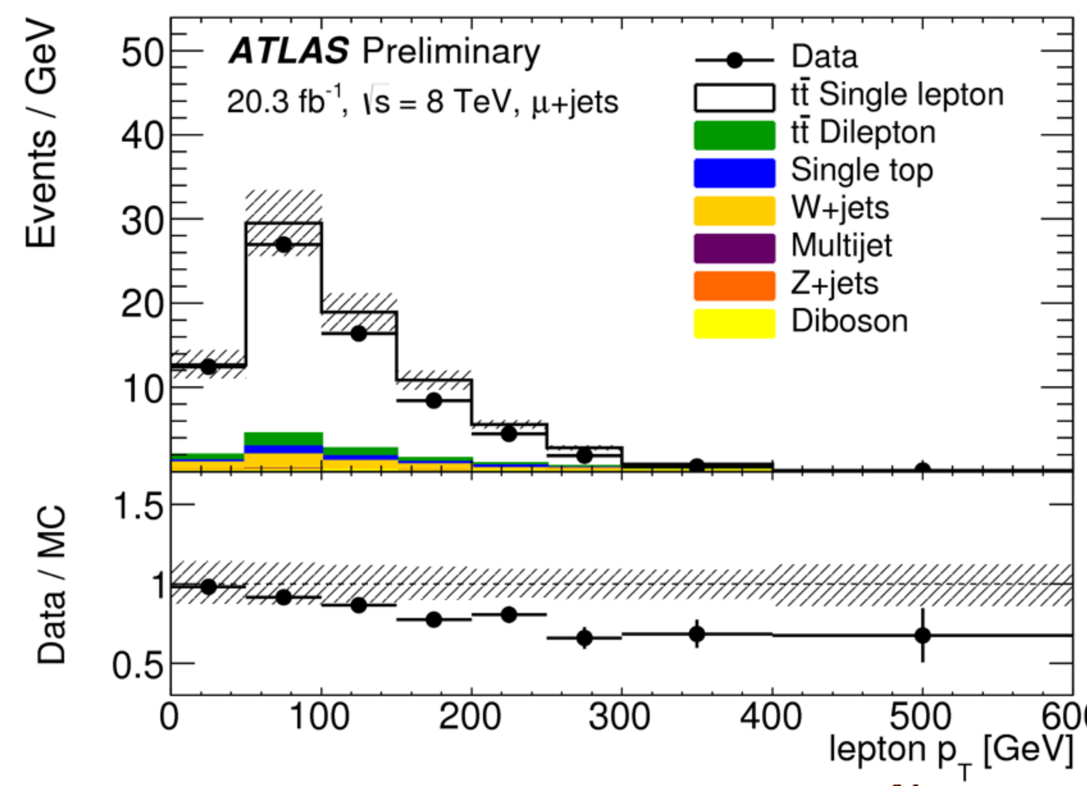
Event selection



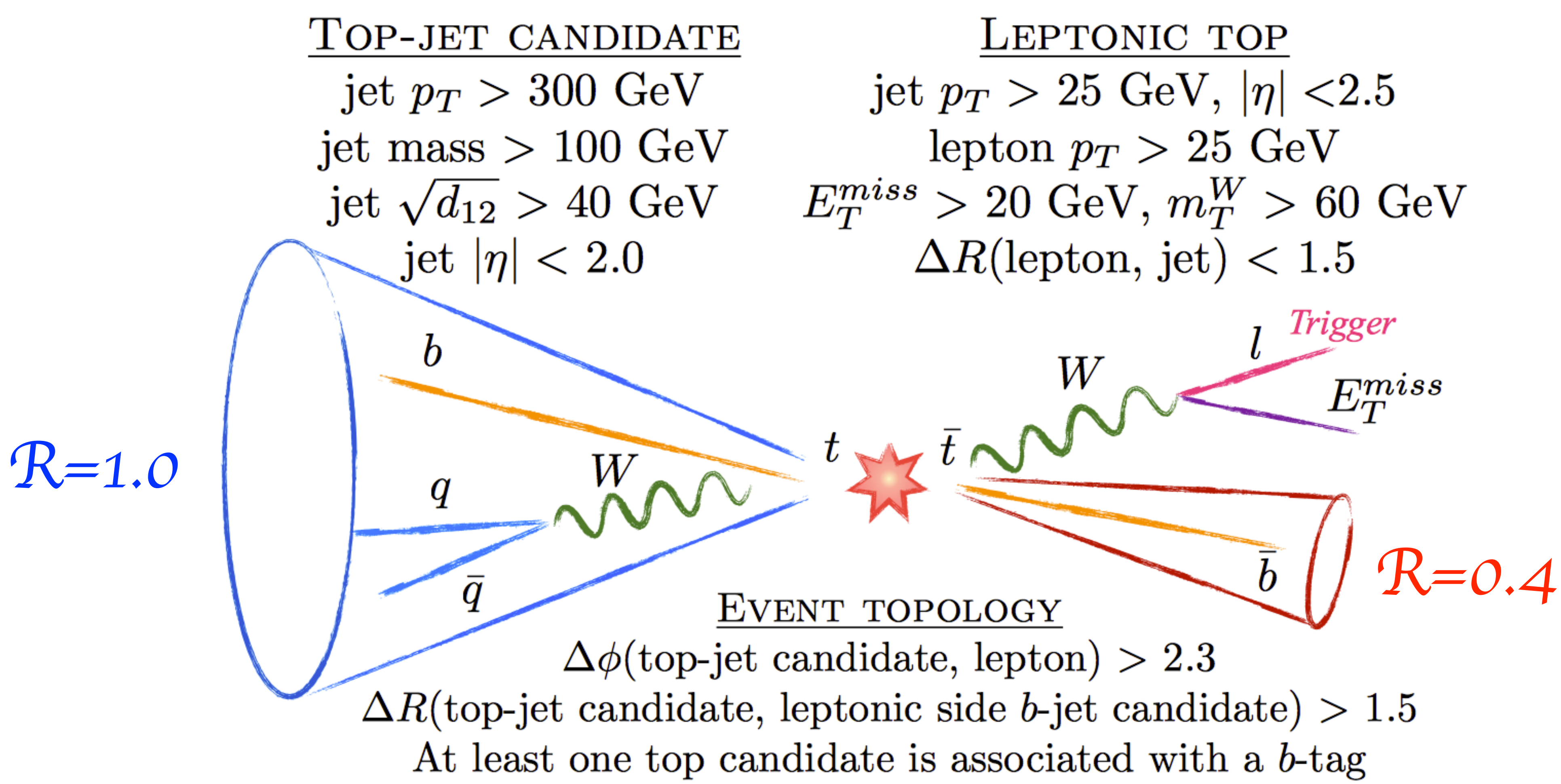
Sample composition

- Backgrounds are relatively small: sample is about ~85% pure in ttbar events in l+jets channel
  - ~6% W+jets
    - Estimated with MC with data-driven normalization corrections
  - ~5% ttbar dilepton
    - Estimated as an expected fraction from MC
  - The rest: Single-top, QCD multijets, Z+jets, diboson
- 4148 e+jets, 3604 μ+jets events





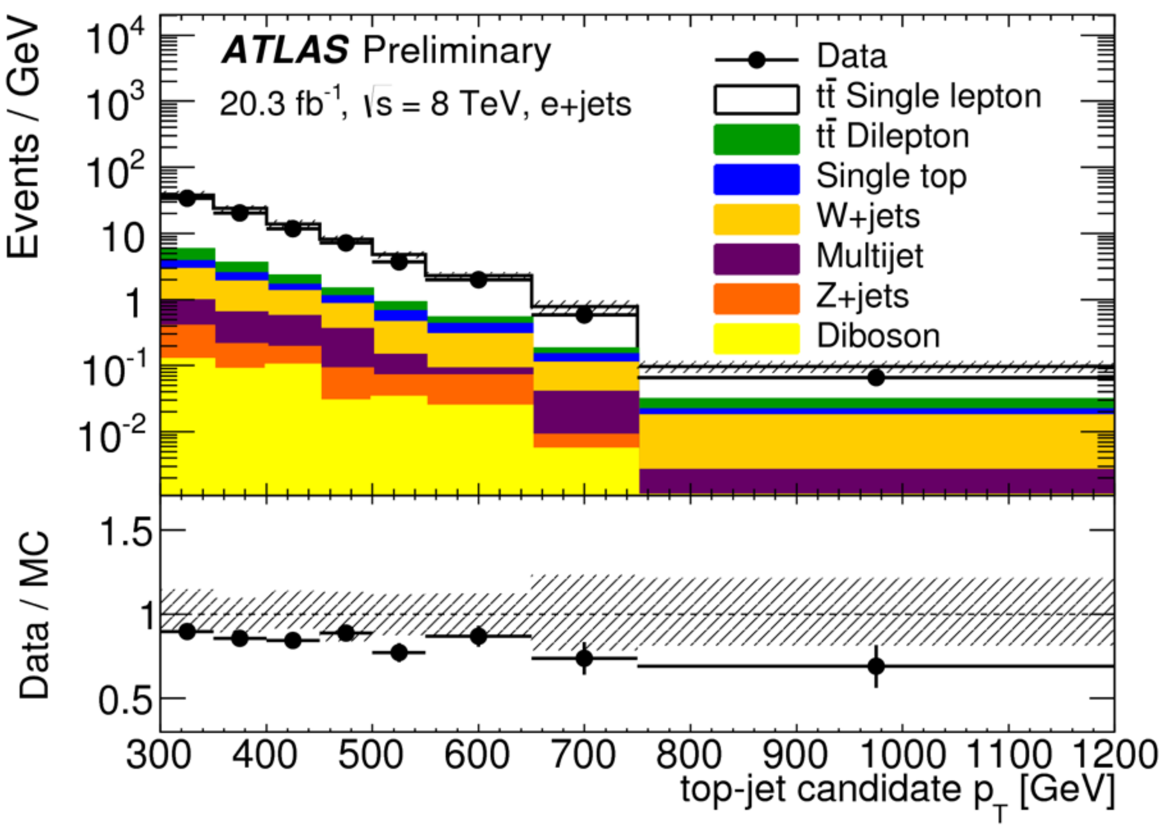
The fiducial region at particle-level follows as closely as possible the detector-level cuts

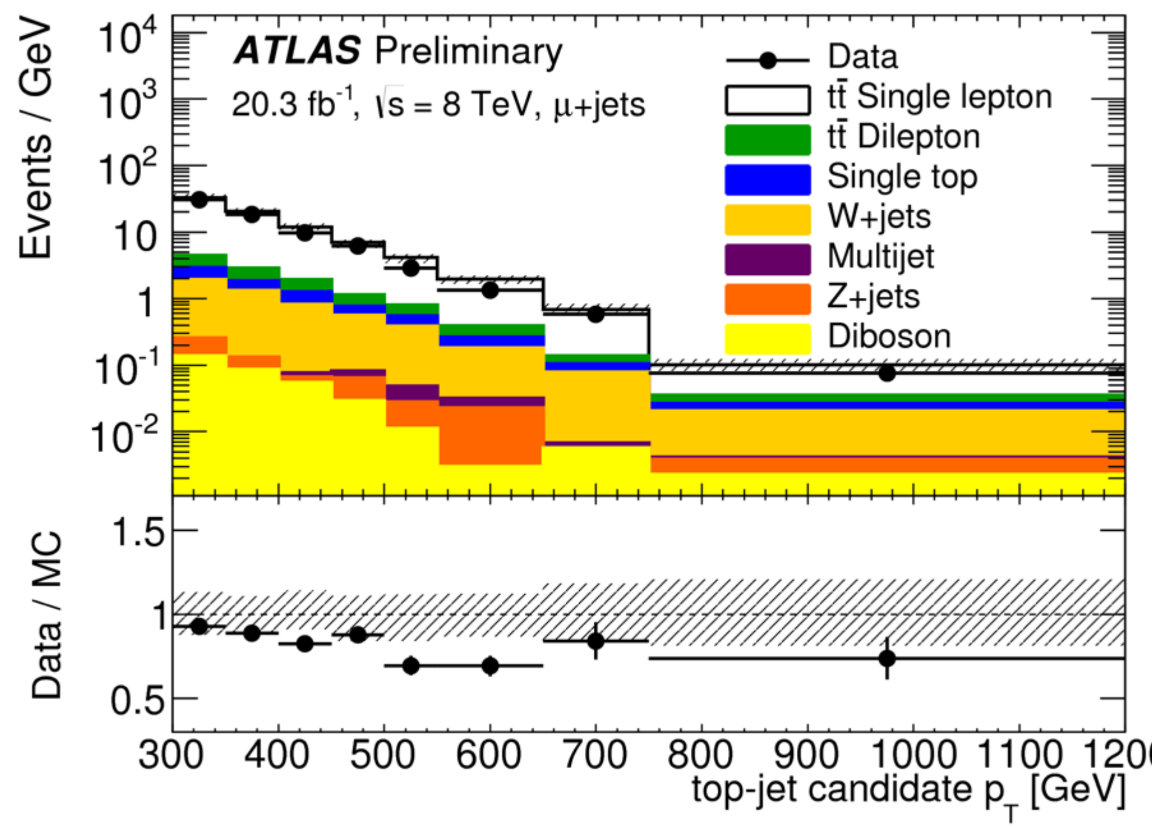


- Particle-level jets are reconstructed from particles with lifetime > 0.3 ×10^{-10}s (π, K, etc). Large-jets are trimmed like for the detector-level jets
- Leptons are “dressed” (adding photons with ΔR<0.1). “B-tagging” means a jet containing a B-hadron.

Unfolding: cross-section (the goal)

$$\frac{d\sigma_{t\bar{t}}}{dp^{\mathrm{i}}_{\mathrm{T,ptcl}}} = \frac{N^{\mathrm{i}}_{\mathrm{ptcl}}}{\Delta X^{\mathrm{i}}\mathcal{L}} = \frac{1}{\Delta X^{\mathrm{i}}\mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \sum_{\mathrm{j}} (M^{-1})^{\mathrm{ptcl,i}}_{\mathrm{reco,j}} f^{j}_{\mathrm{reco!ptcl}} (N^{\mathrm{j}}_{\mathrm{reco}} - N^{\mathrm{j}}_{\mathrm{reco,bgnd}})$$





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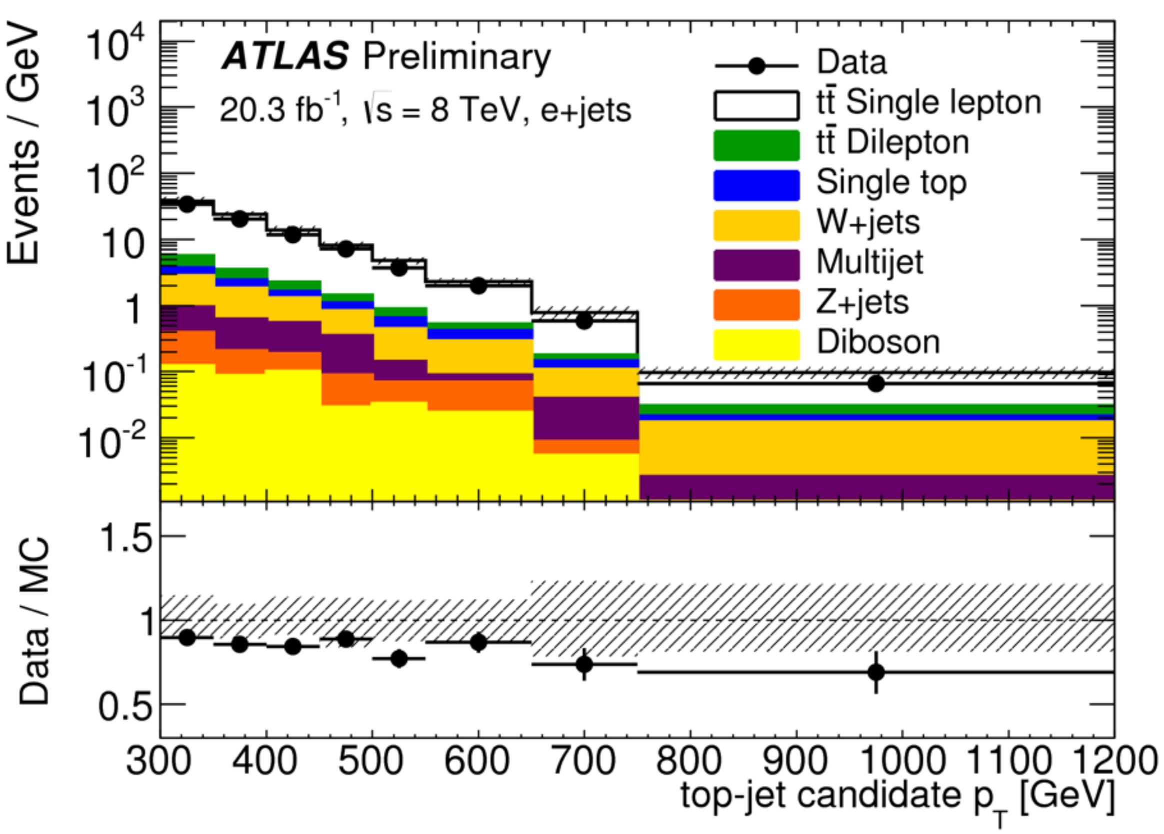
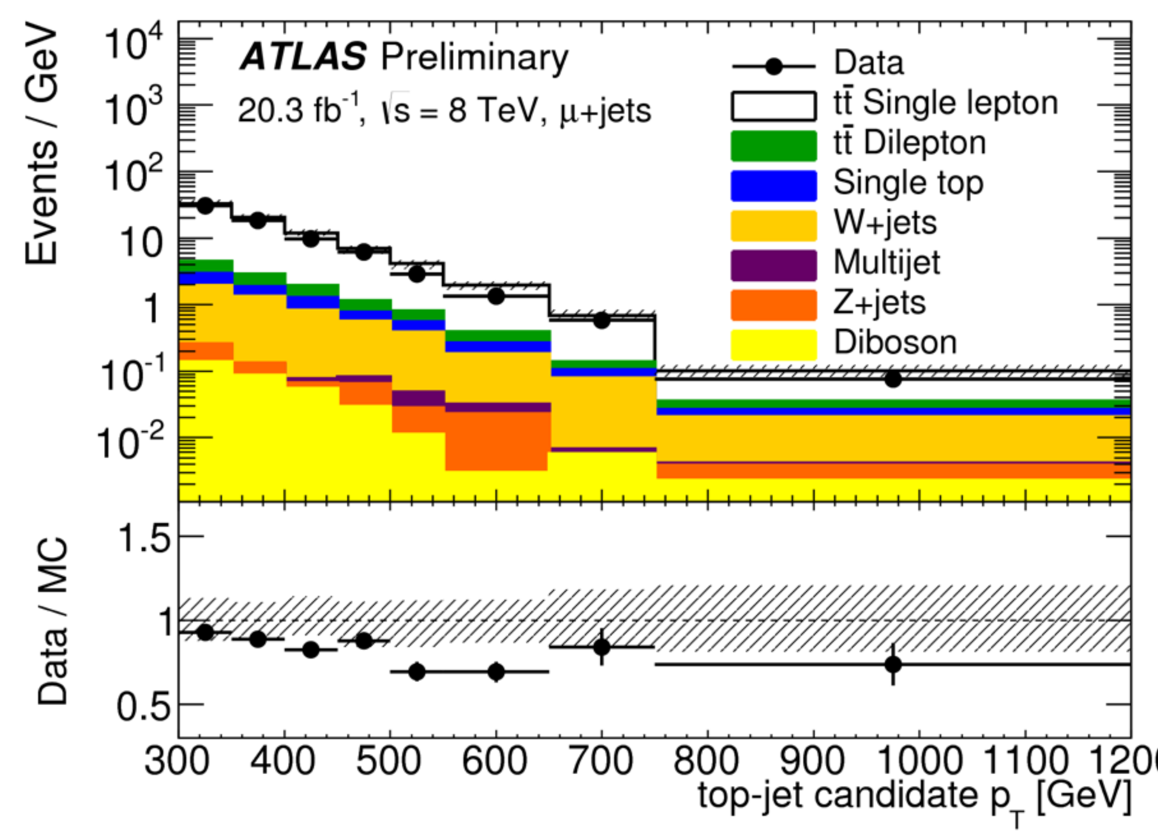
Unfolding: the particle-level cross-section

$$\frac{d\sigma_{t\bar{t}}}{dp^{\mathrm{i}}_{\mathrm{T,ptcl}}} = \frac{N^{\mathrm{i}}_{\mathrm{ptcl}}}{\Delta X^{\mathrm{i}}\mathcal{L}} = \frac{1}{\Delta X^{\mathrm{i}}\mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \sum_{\mathrm{j}} (M^{-1})^{\mathrm{ptcl,i}}_{\mathrm{reco,j}} f^{j}_{\mathrm{reco!ptcl}} (N^{\mathrm{j}}_{\mathrm{reco}} - N^{\mathrm{j}}_{\mathrm{reco,bgnd}})$$





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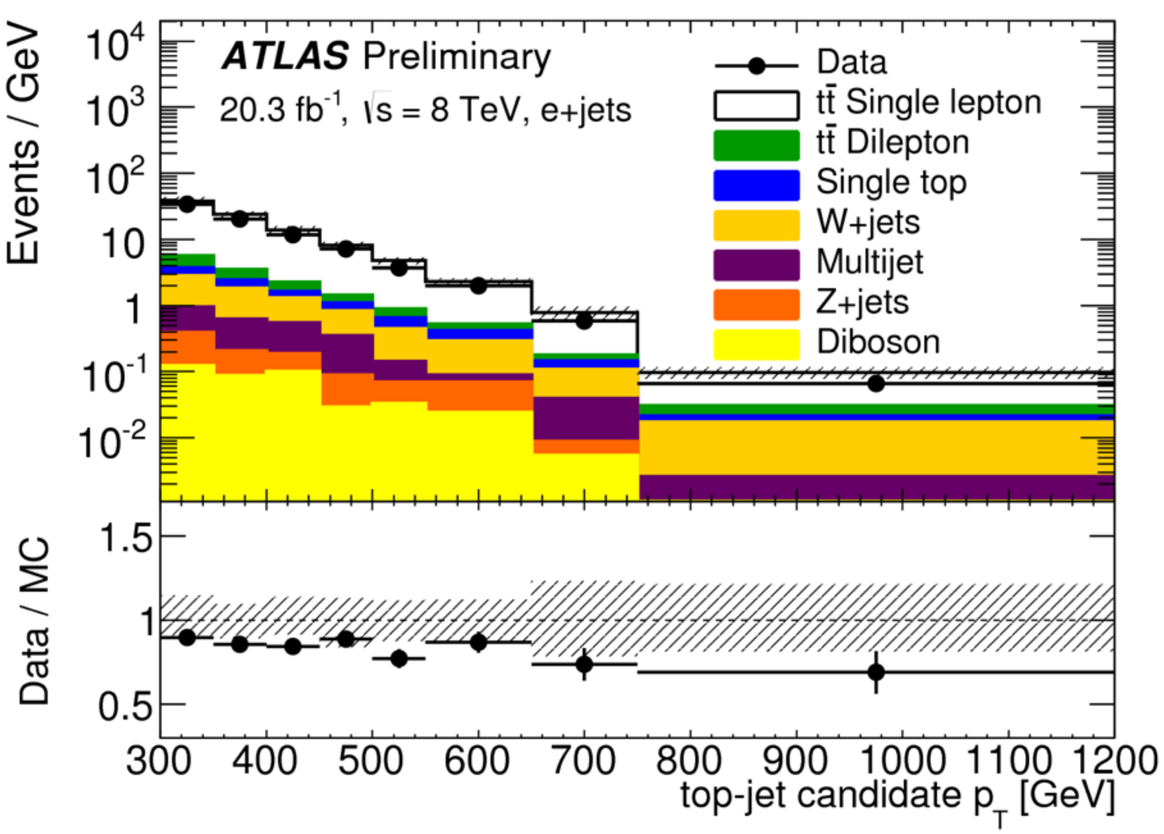
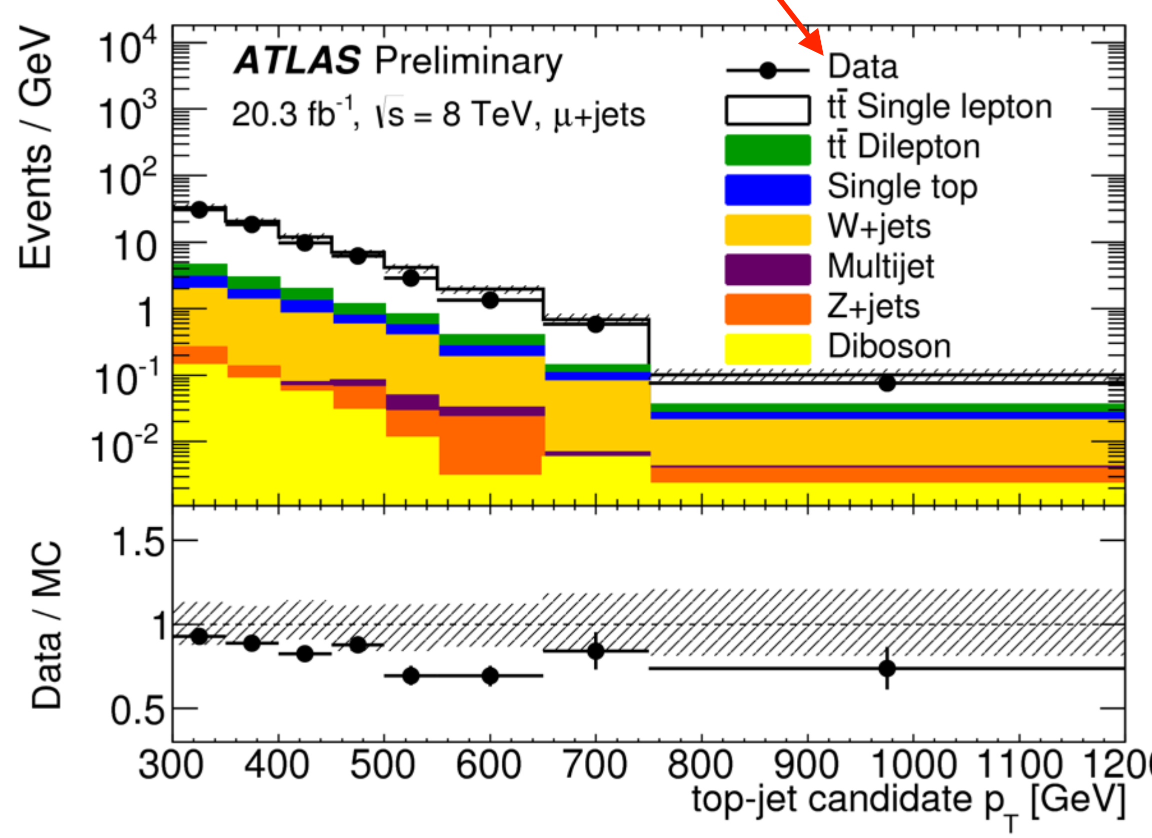
Unfolding: the input (i.e. the data)

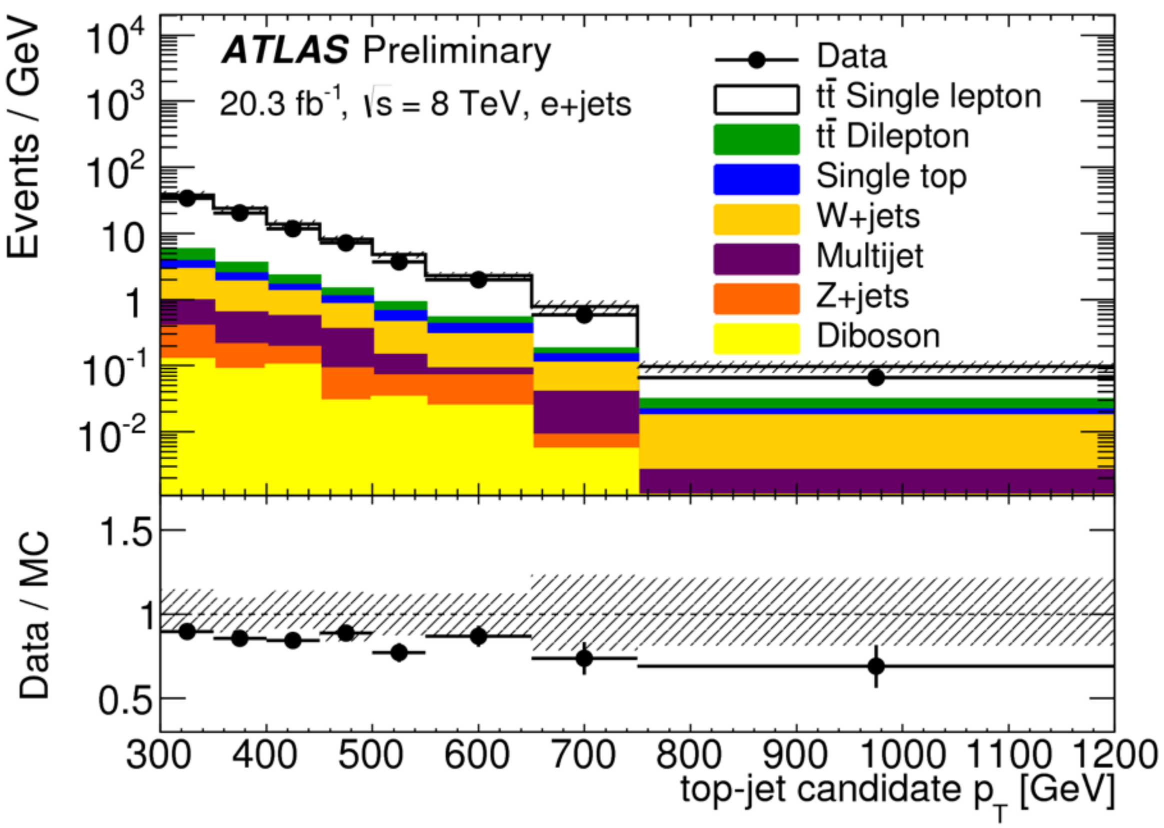
$$\frac{d\sigma_{t\bar{t}}}{dp^{\mathrm{i}}_{\mathrm{T,ptcl}}} = \frac{N^{\mathrm{i}}_{\mathrm{ptcl}}}{\Delta X^{\mathrm{i}}\mathcal{L}} = \frac{1}{\Delta X^{\mathrm{i}}\mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \sum_{\mathrm{j}} (M^{-1})^{\mathrm{ptcl,i}}_{\mathrm{reco,j}} f^{j}_{\mathrm{reco!ptcl}} (N^{\mathrm{j}}_{\mathrm{reco}} - N^{\mathrm{j}}_{\mathrm{reco,bgnd}})$$

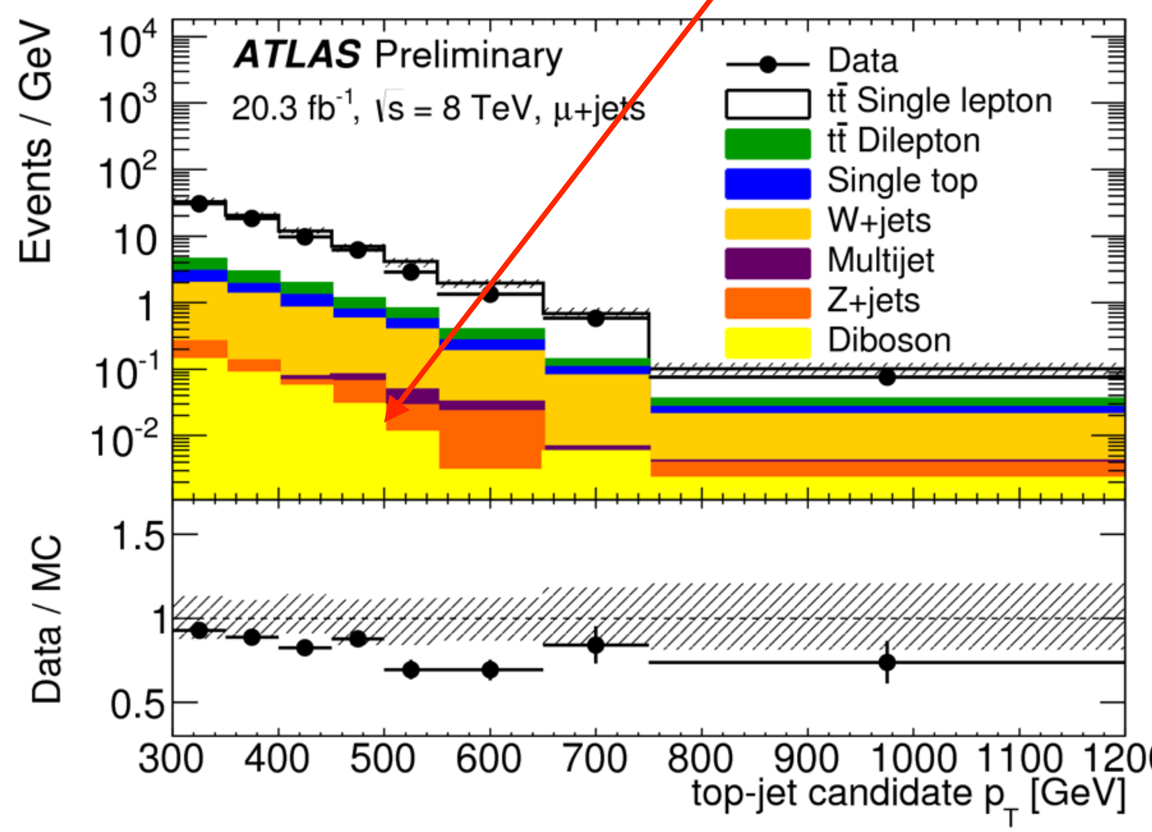




Unfolding: background subtraction

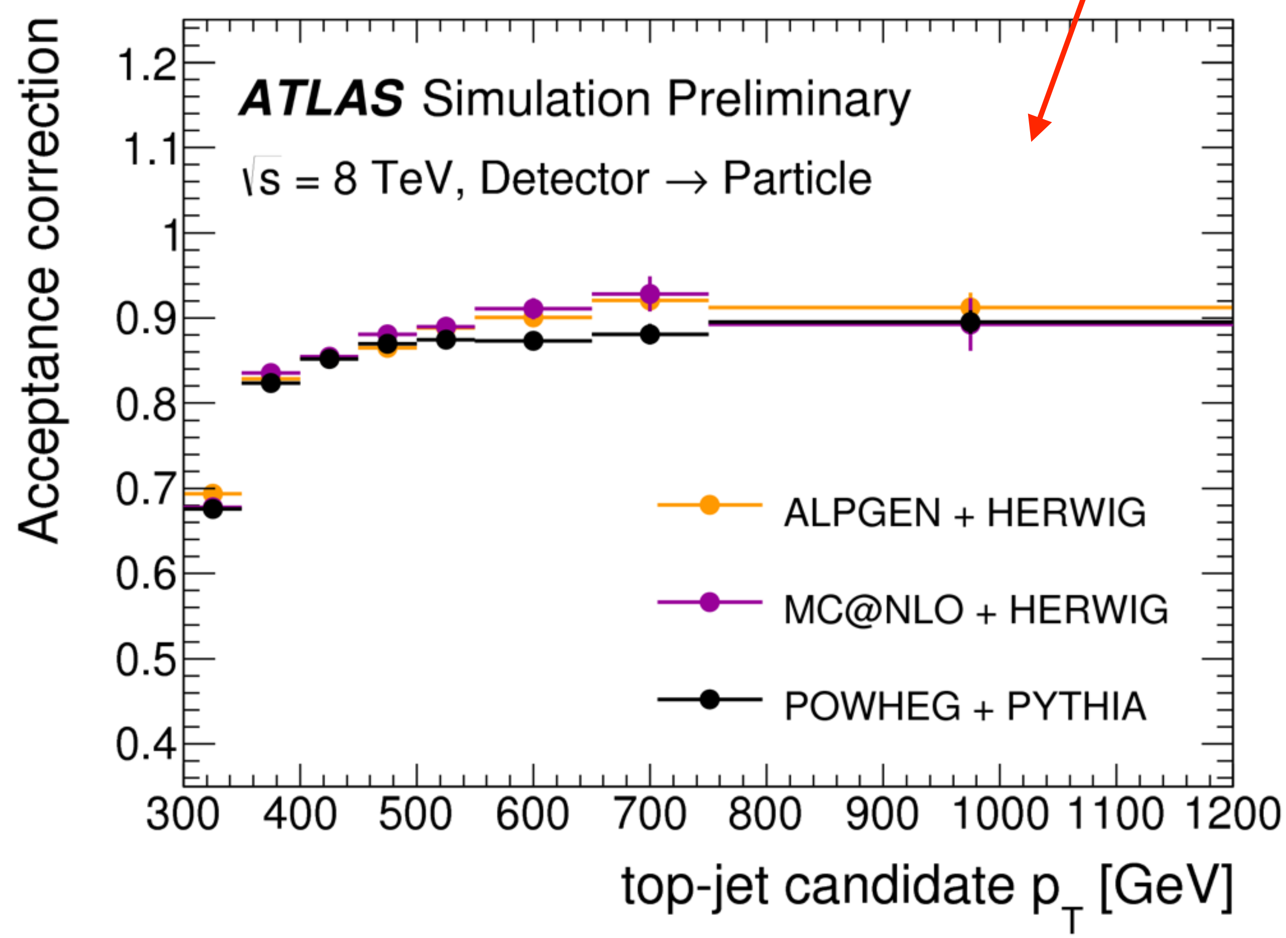
$$\frac{d\sigma_{t\bar{t}}}{dp^{\mathrm{i}}_{\mathrm{T,ptcl}}} = \frac{N^{\mathrm{i}}_{\mathrm{ptcl}}}{\Delta X^{\mathrm{i}}\mathcal{L}} = \frac{1}{\Delta X^{\mathrm{i}}\mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \sum_{\mathrm{j}} (M^{-1})^{\mathrm{ptcl,i}}_{\mathrm{reco,j}} f^{j}_{\mathrm{reco!ptcl}} (N^{\mathrm{j}}_{\mathrm{reco}} - N^{\mathrm{j}}_{\mathrm{reco,bgnd}})$$





Unfolding: the “fake” correction

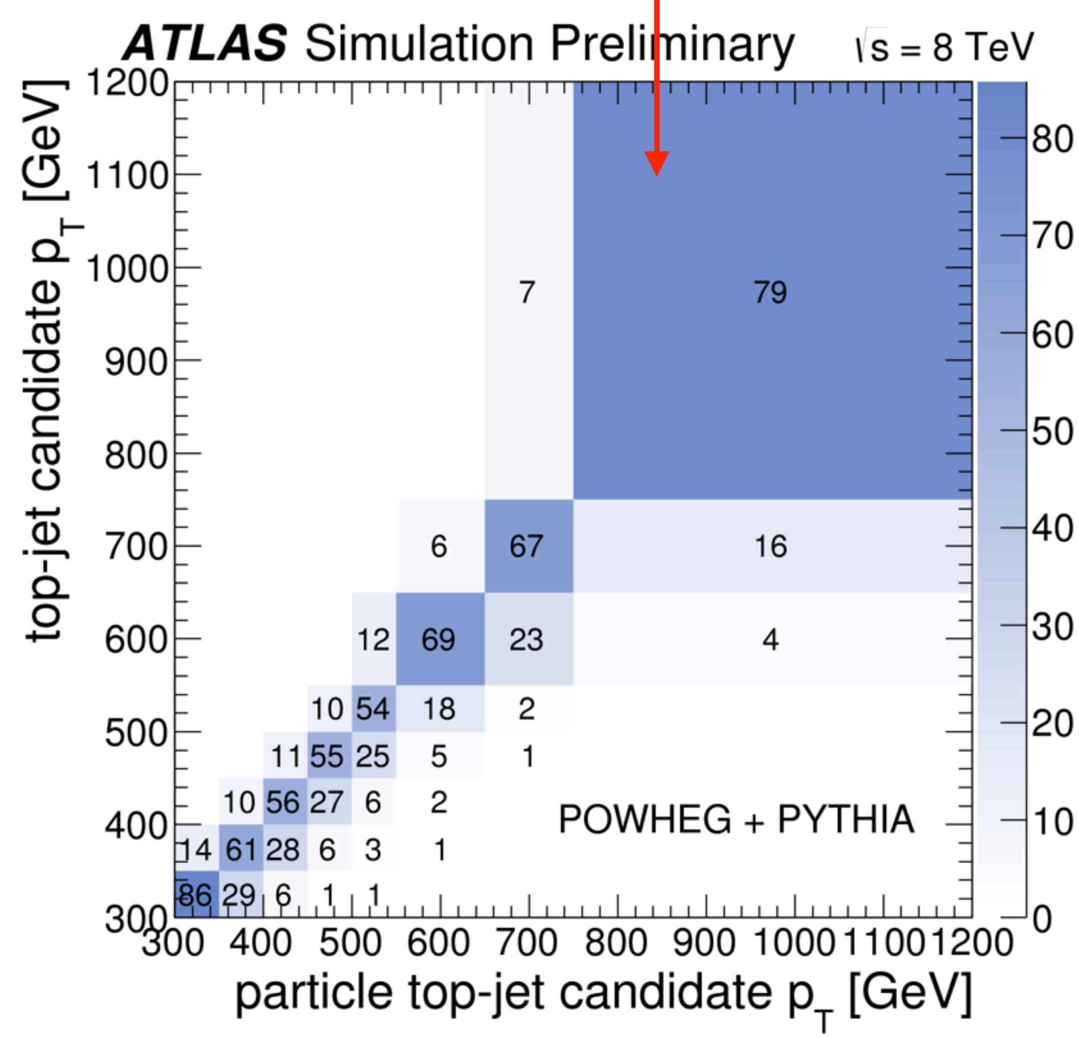
$$\frac{d\sigma_{t\bar{t}}}{dp^{\mathrm{i}}_{\mathrm{T,ptcl}}} = \frac{N^{\mathrm{i}}_{\mathrm{ptcl}}}{\Delta X^{\mathrm{i}}\mathcal{L}} = \frac{1}{\Delta X^{\mathrm{i}}\mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \sum_{\mathrm{j}} (M^{-1})^{\mathrm{ptcl,i}}_{\mathrm{reco,j}} f^{j}_{\mathrm{reco!ptcl}} (N^{\mathrm{j}}_{\mathrm{reco}} - N^{\mathrm{j}}_{\mathrm{reco,bgnd}})$$



This correct for the fraction of events which pass the detector-level cuts, but do not belong to the particle-level fiducial region. All of these (and subsequent) corrections are extracted with a Powheg+Pythia sample

Unfolding: migration matrix

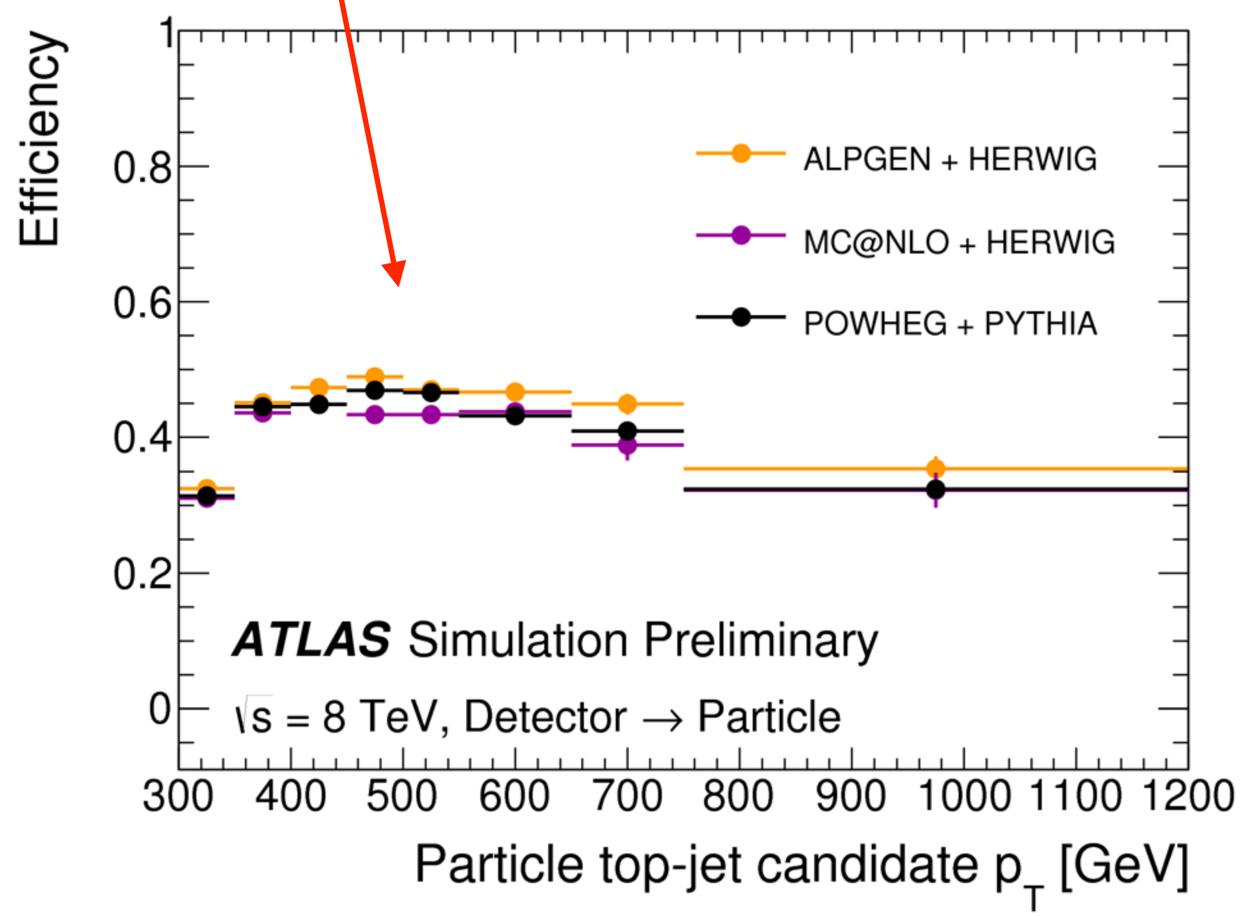
$$\frac{d\sigma_{t\bar{t}}}{dp^{\mathrm{i}}_{\mathrm{T,ptcl}}} = \frac{N^{\mathrm{i}}_{\mathrm{ptcl}}}{\Delta X^{\mathrm{i}} \mathcal{L}} = \frac{1}{\Delta X^{\mathrm{i}} \mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \sum_{\mathrm{j}} (M^{-1})^{\mathrm{ptcl,i}}_{\mathrm{reco,j}} f^{j}_{\mathrm{reco!ptcl}} (N^{\mathrm{j}}_{\mathrm{reco}} - N^{\mathrm{j}}_{\mathrm{reco,bgnd}})$$



Correct for events that migrate from one bin to another due to finite detector resolution

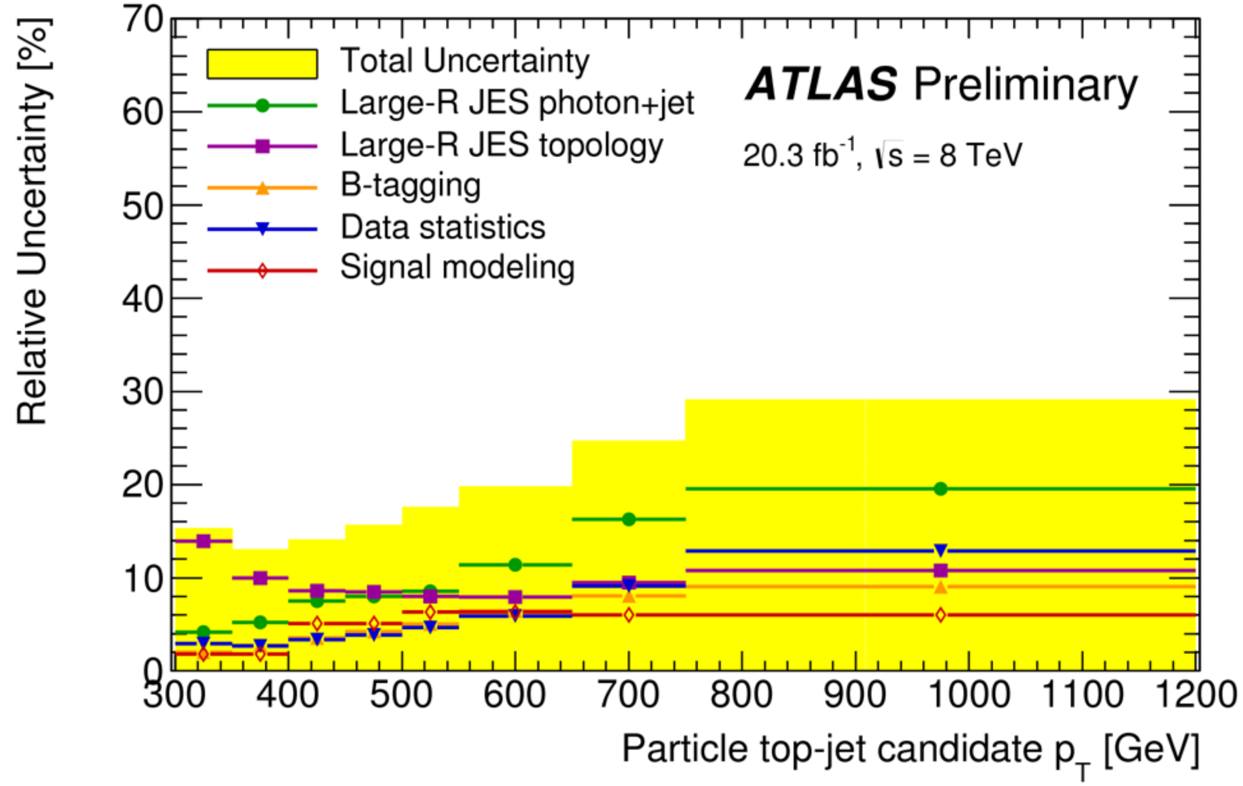
Unfolding: the efficiency correction

$$\frac{d\sigma_{t\bar{t}}}{dp^{\mathrm{i}}_{\mathrm{T,ptcl}}} = \frac{N^{\mathrm{i}}_{\mathrm{ptcl}}}{\Delta X^{\mathrm{i}}\mathcal{L}} = \frac{1}{\Delta X^{\mathrm{i}}\mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \sum_{\mathrm{j}} (M^{-1})^{\mathrm{ptcl,i}}_{\mathrm{reco,j}} f^{j}_{\mathrm{reco!ptcl}} (N^{\mathrm{j}}_{\mathrm{reco}} - N^{\mathrm{j}}_{\mathrm{reco,bgnd}})$$



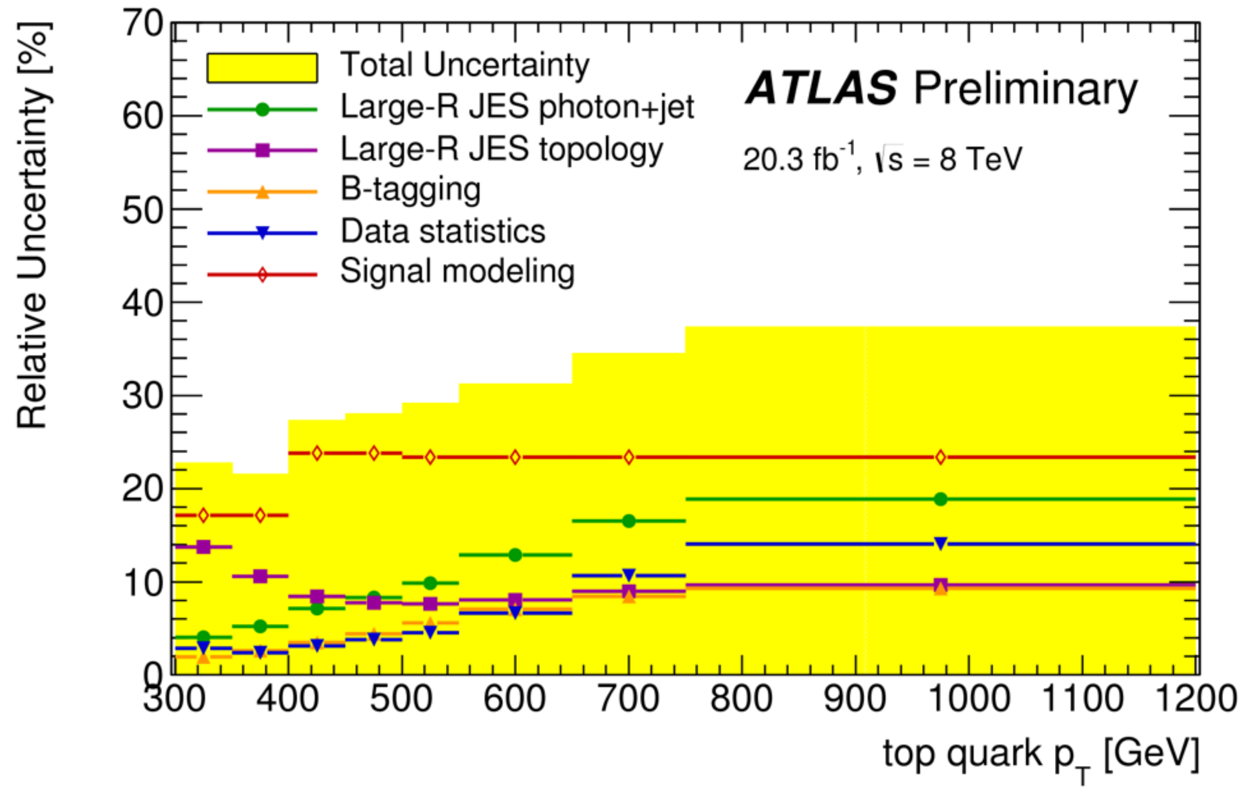
This corrects for events that pass the particle-level fiducial region but fail the detector-level cuts

Summary of systematics: particle-level



- **Total uncertainty ranges from ≈10-30%**
- High-p_T: dominated by photon+jet balancing calibration of large-R jets
- Low-p_T: dominated by "topology" large-R JES uncertainty (i.e. the fact that jets in photon+jet calibration are different than ttbar)
- Sub-dominant: Data statistics, b-tagging, signal modeling

Summary of systematics: parton-level



- A similar procedure as described before is used to unfold back to "**parton-level**", i.e. to the full phase space
- **Total uncertainty ranges from ≈20-40%**
- Significantly larger than particle-level because signal modeling uncertainty dominant everywhere
  - Much larger corrections to unfold back to full-phase → larger systematics

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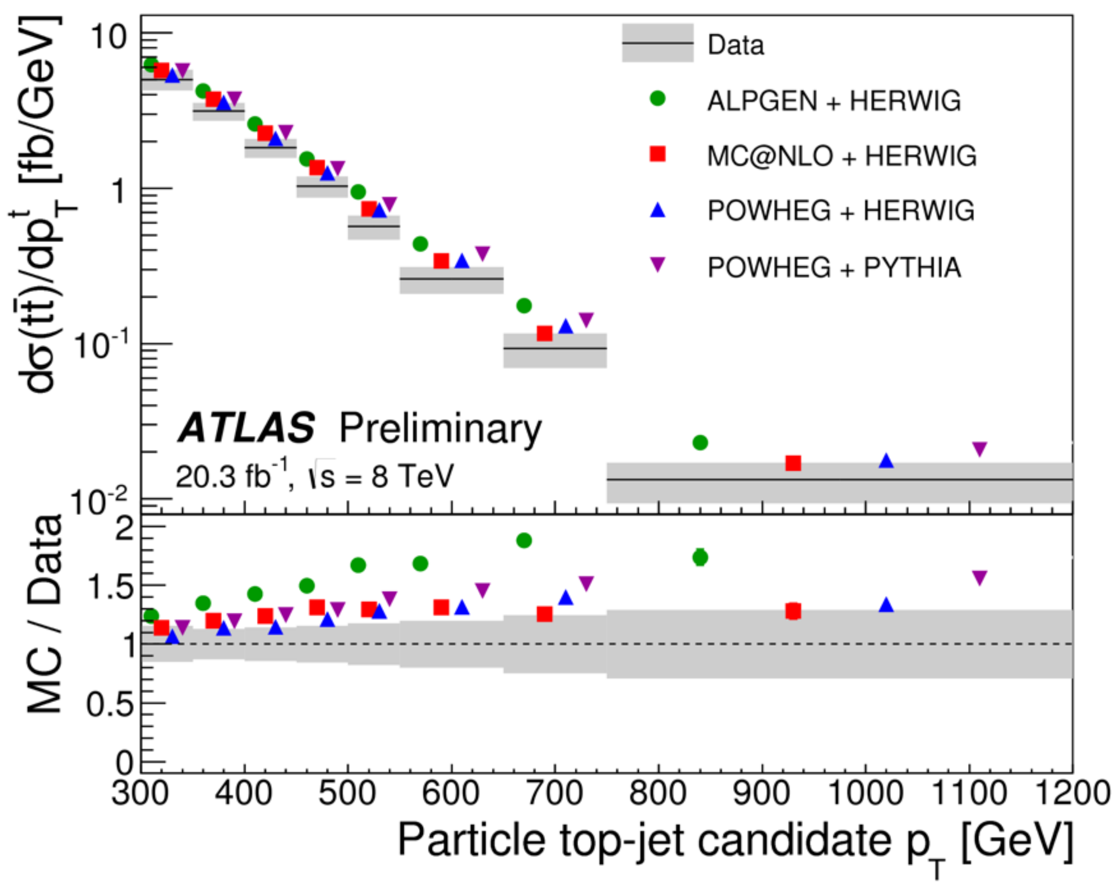
Results: comparison of MC generators



- Inclusive cross-section of generator predictions normalized NNLO
- Reasonable agreement in the lower low-p_T range
- MC spectrum tends to be harder than data: up-to 70% for Alpgen+Herwig in last bin
- Note that the measurement is dominated by systematics which are correlated between p_T bins

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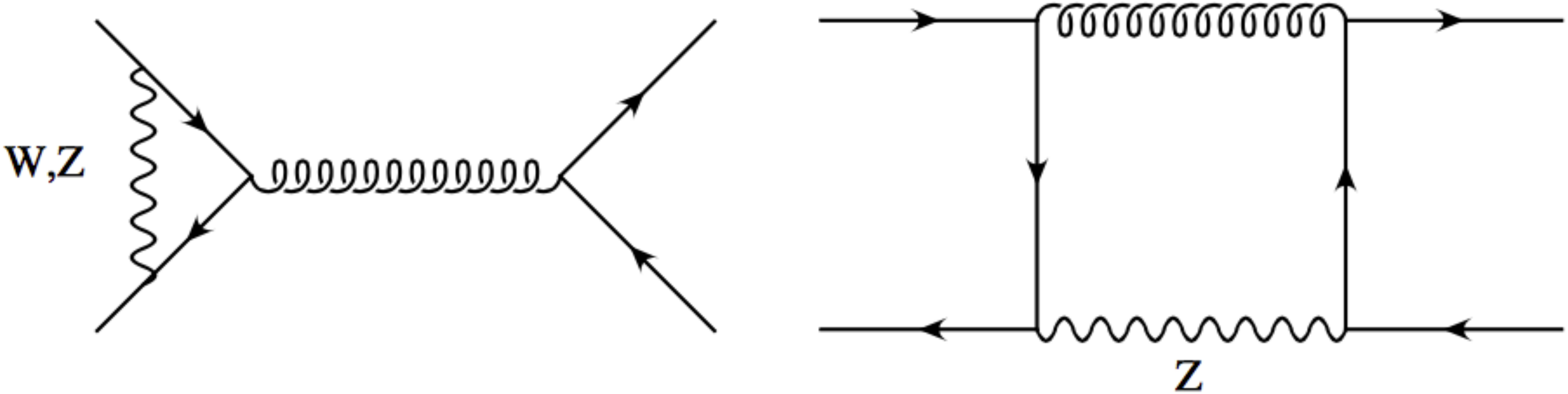
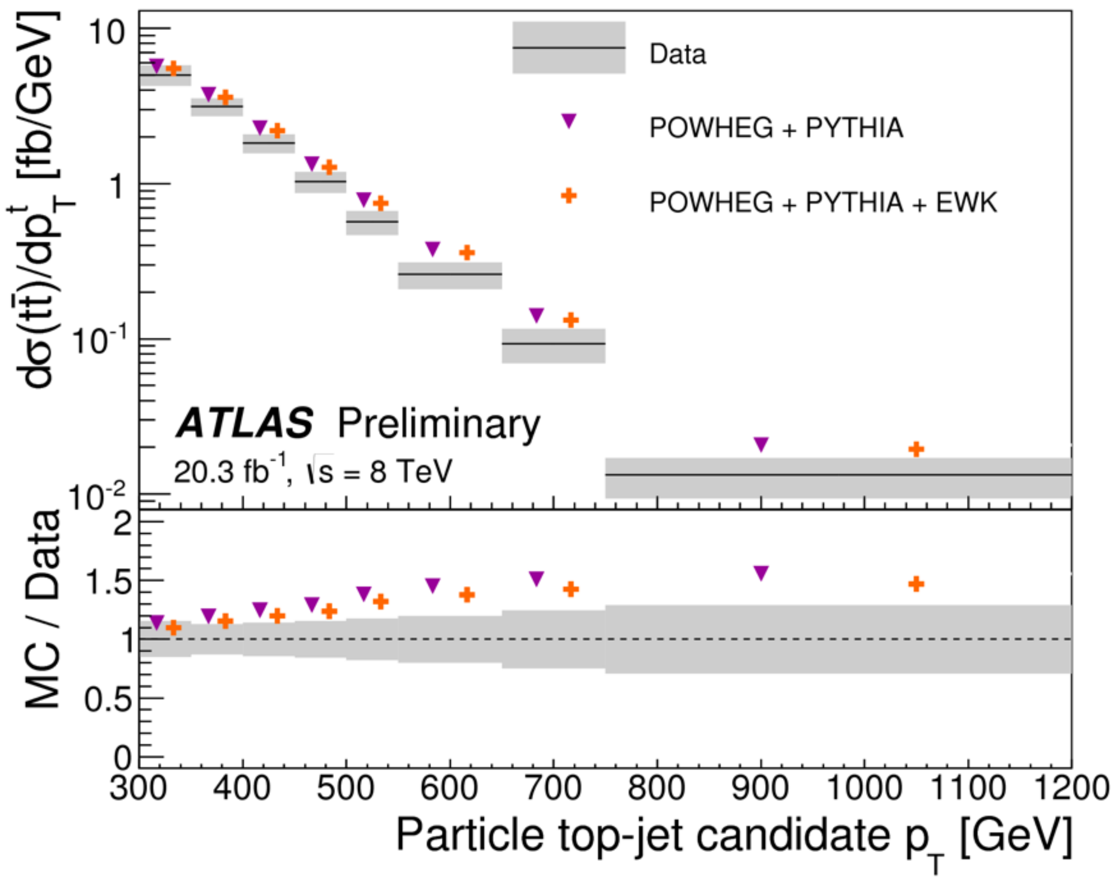
Results: do electroweak corrections help?



- **Electroweak corrections** to ttbar production are not used by default (negligible at low-p_T)
- This only slightly softens the p_T spectrum but is almost negligible

Results: do electroweak corrections help?



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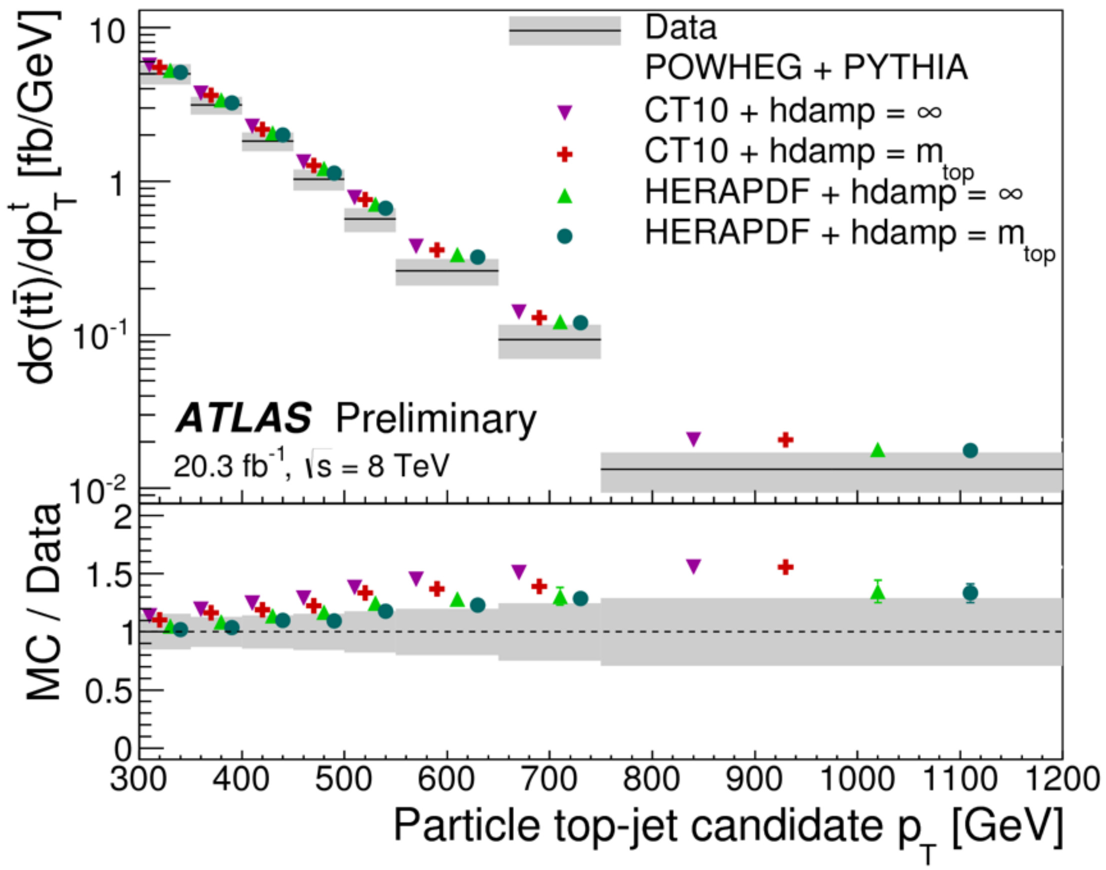
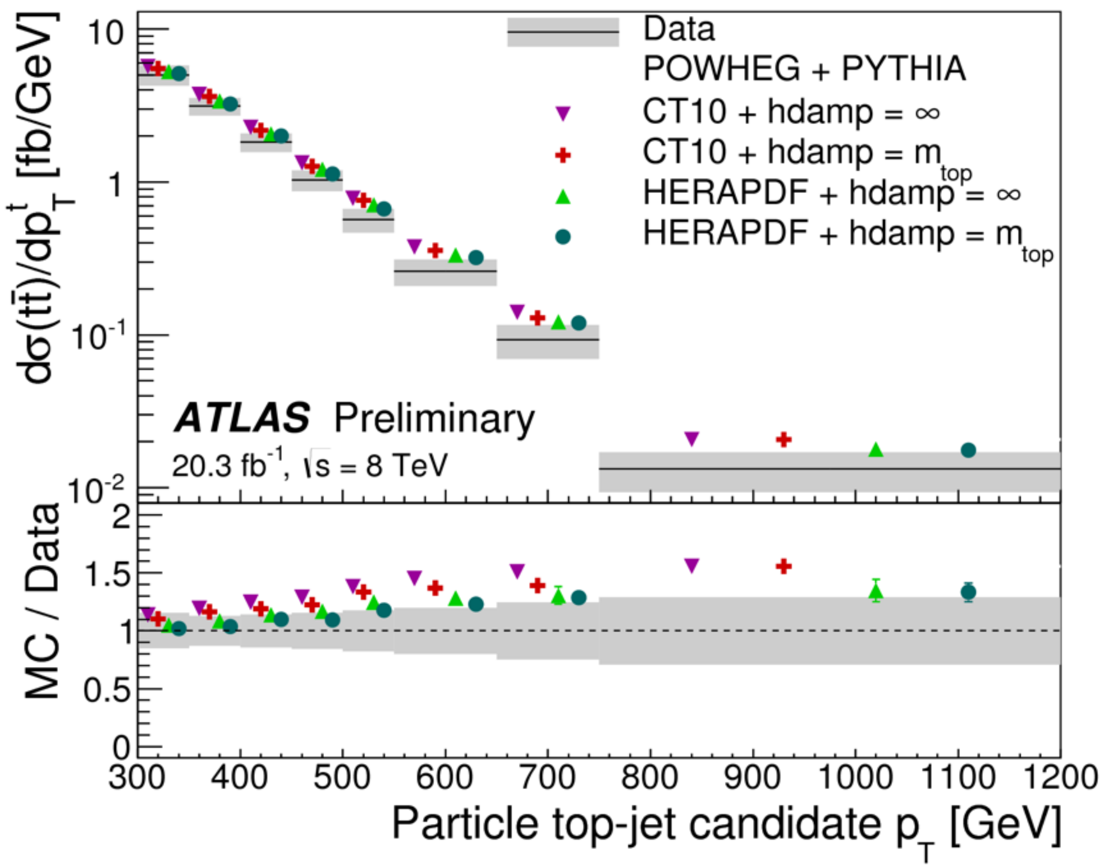
Results: what about different PDF sets?



- CT10 is the default, but HERAPDF yields a significantly softer spectrum

Results: what about radiation settings?



- "**hdamp**" is a parameter in Powheg which controls the amount high-p_T QCD radiation in the sample (Default value: hdamp = ∞)
- The value hdamp = m_{top} gives a better agreement with the data
- The combination HERAPDF + hdamp = m_{top} describes the data best, but still tends to be harder than data

Cross-section of boosted W and Z

[2014 New J. Phys. 16 113013, arXiv:1407.0800]

Introduction

- Motivation:
  - Many theories with TeV-scale resonance decaying to W, Z
  - Hadronic decays have a higher branching ratio and W/Z →qq will tend to appear as a single jet
  - Goal: Demonstrate ability to reconstruct W- and Z-jets in ATLAS
- Definition of measurement:
  - Measure sum of W and Z production

$$\sigma_{W+Z} = \sigma_W(p_{\mathrm{T}} > 320\ \mathrm{GeV}, |\eta| < 1.9) \times \mathcal{B}(W \to q\bar{q}') \\ + \sigma_Z(p_{\mathrm{T}} > 320\ \mathrm{GeV}, |\eta| < 1.9) \times \mathcal{B}(Z \to q\bar{q}),$$

  - MCFM CT10: $\sigma_{W+Z} = 5.1 \pm 0.5$ pb

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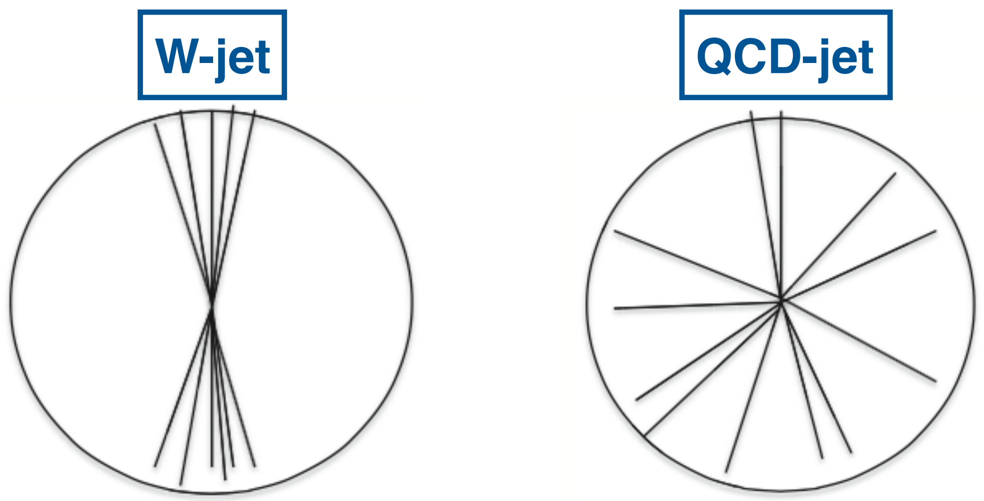
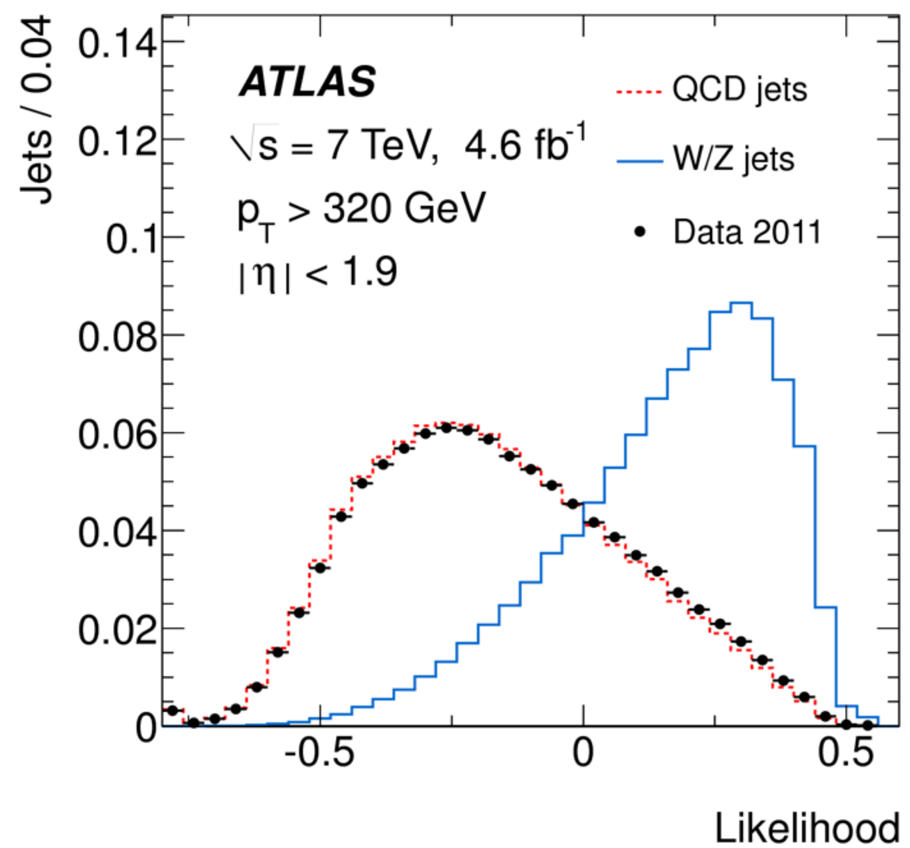
Event selection

- Dataset: 7 TeV, 4.6 fb^{-1}
- Anti-k_T R=0.6 jet with p_T>320 GeV, 50<m_{jet}<140 GeV
- Use variables measuring how **isotropic are jets in their rest frame**
- Combines 3 variables (thrust minor, sphericity and aplanarity) in one likelihood
- *L*>0.15 cut selects 590617 jets, only ~8500 expected from W, Z

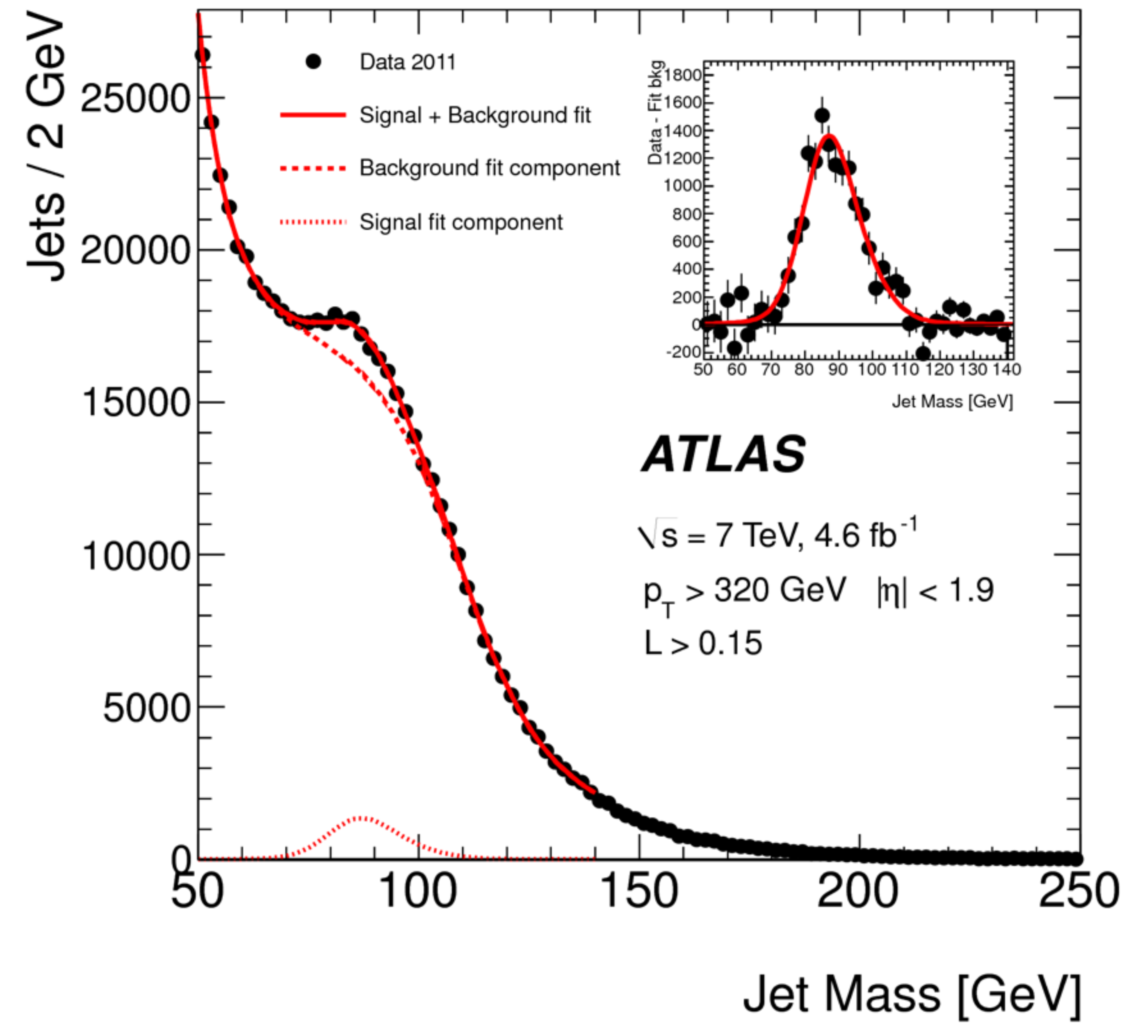
C. Chen, arXiv:1112.2567





Cross-section extraction

- Use binned maximum likelihood fit to extract N_{W+Z}
  - Signal pdf: analytical fit to HERWIG 6 W/Z simulation
  - Background pdf: two exponentials and sigmoid
  - Background from top and diboson subtracted
- Efficiency extracted from Herwig
- Largest systematics are background pdf and jet mass resolution
- Measured σ_{W+Z} is ~2 sigma above NLO MCFM prediction of 5.1±0.5 pb

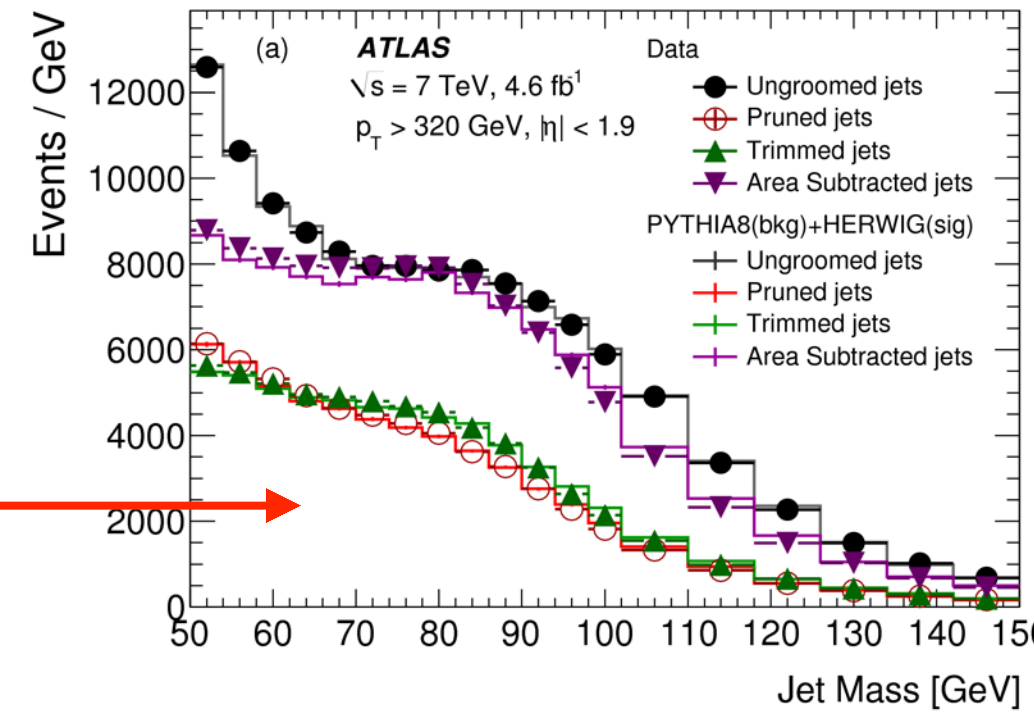


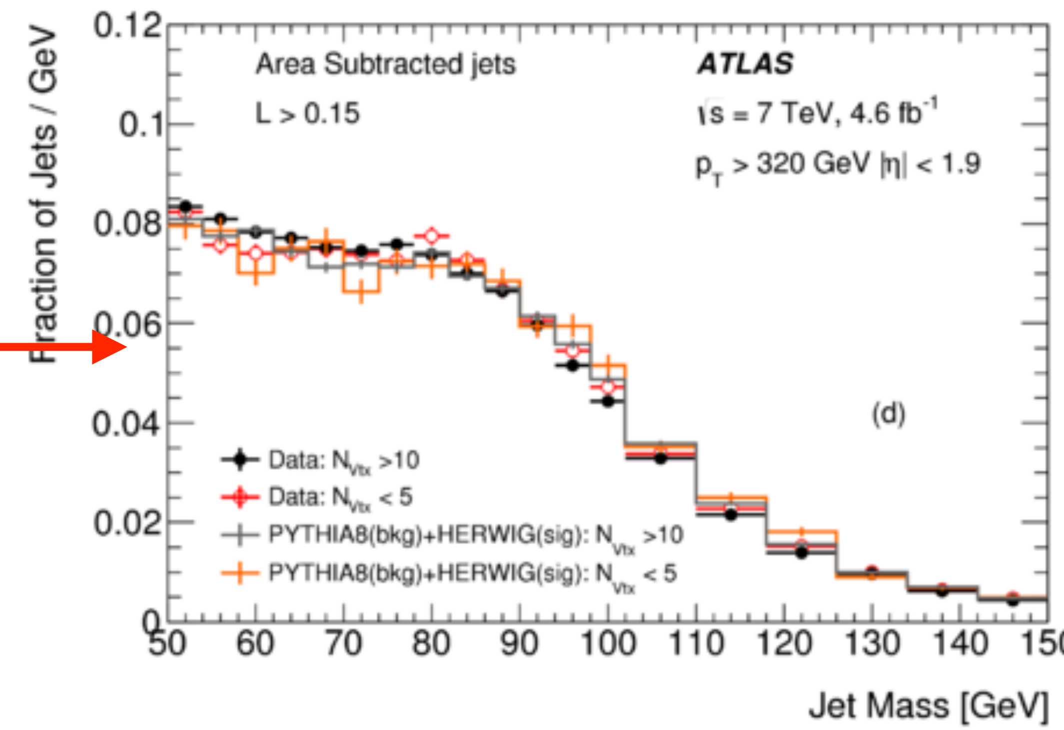
$$\sigma_{W+Z} = 8.5 \pm 0.8\,(\text{stat.}) \pm 1.5\,(\text{syst.})\ \text{pb}$$

For $p_T(W/Z) > 320$ GeV, $|\eta|<1.9$

Study of grooming techniques

- Study pruning, trimming and area subtraction
  - Likelihood re-optimized
- Good data/MC agreement
- Signal significance about unchanged
  - QCD bkgd is reduced (~50%), but signal also (~30%)
- Groomed jets behave similarly in low and high pileup events, both in data and MC





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Summary

- Boosted top differential cross-section vs top p_T
  - The cross-section of high-p_T top quarks is studied in details for the first time thanks to boosted top techniques
  - MC generators tend to overestimate the cross-section at very high-p_T
  - Electroweak corrections, HERAPDF and hdamp=m_{top} tend to improve the data/MC agreement
- Cross-section measurement of boosted W and Z
  - Measure cross-section of W/Z $\rightarrow$qq for p_T > 320 GeV (|η|<1.9)
  - Measure cross-section ~2sigma above NLO prediction
  - Jet grooming studied in data and MC
- ATLAS also measured cross-section for Z$\rightarrow$bb with p_T > 200 GeV, but using pairs of small-R jets (arXiv:1404.7042)
  - Result consistent with SM: σ=2.02 ± 0.33 pb

Additional material

Event selection

Cut	Detector-level		Particle-level
	e + jets	μ + jets	
Leptons	$\lvert z_0\rvert < 2$ mm $I_{mini} < 0.05$ $\lvert\eta\rvert < 1.37$ OR $1.52 < \lvert\eta\rvert < 2.47$ $p_T > 25$ GeV	$\lvert z_0\rvert < 2$ mm & $\lvert d_0/\sigma(d_0)\rvert < 3.$; $I_{mini} < 0.05$; $\lvert\eta\rvert < 2.5$ $p_T > 25$ GeV	$\lvert\eta\rvert < 2.5$ $p_T > 25$ GeV
Anti-k_t R=0.4 jets	$p_T > 25$ GeV $\lvert\eta\rvert < 2.5$ JVF > 0.5 (if $p_T < 50$ GeV)		$\lvert\eta\rvert < 2.5$ $p_T > 25$ GeV

Overlap removal	if $\Delta R(e, \text{jet}_{R=0.4}) < 0.4$:
	$\text{jet}'_{R=0.4} = \text{jet}_{R=0.4} - e$
	if $\Delta R(e, \text{jet}'_{R=0.4}) < 0.2$:
	e removed
		if $\Delta R(\mu, \text{jet}'_{R=0.4}) < 0.04 + 10.\ \text{GeV}/p_T(\mu)$:
		μ removed
			None

E_T^{miss}, m_T^W	$E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T^W > 60$ GeV		
Leptonic top	At least one anti-k_t R = 0.4 jet satisfying $\Delta R(l, \text{jet}_{R=0.4}) < 1.5$		
Hadronic top	The leading trimmed anti-k_t R = 1.0 jet $p_T > 300$ GeV, $m > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV $\Delta R(\text{jet}_{R=1.0}, \text{jet}_{R=0.4}) > 1.5$, $\Delta\phi(l, \text{jet}_{R=1.0}) > 2.3$		
B-tagging	At least one of: 1) the leading anti-k_t R = 0.4 jet satisfying $\Delta R(l, \text{jet}_{R=0.4}) < 1.5$ is b-tagged; 2) at least one anti-k_t R = 0.4 jet satisfying $\Delta R(\text{jet}_{R=1.0}, \text{jet}_{R=0.4}) < 1.0$ is b-tagged		

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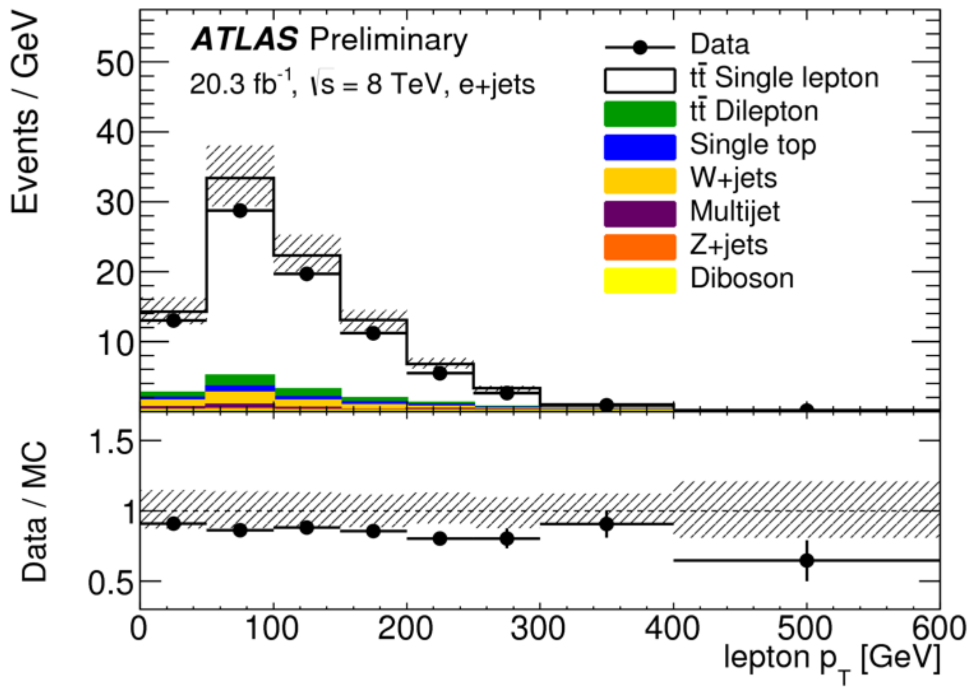
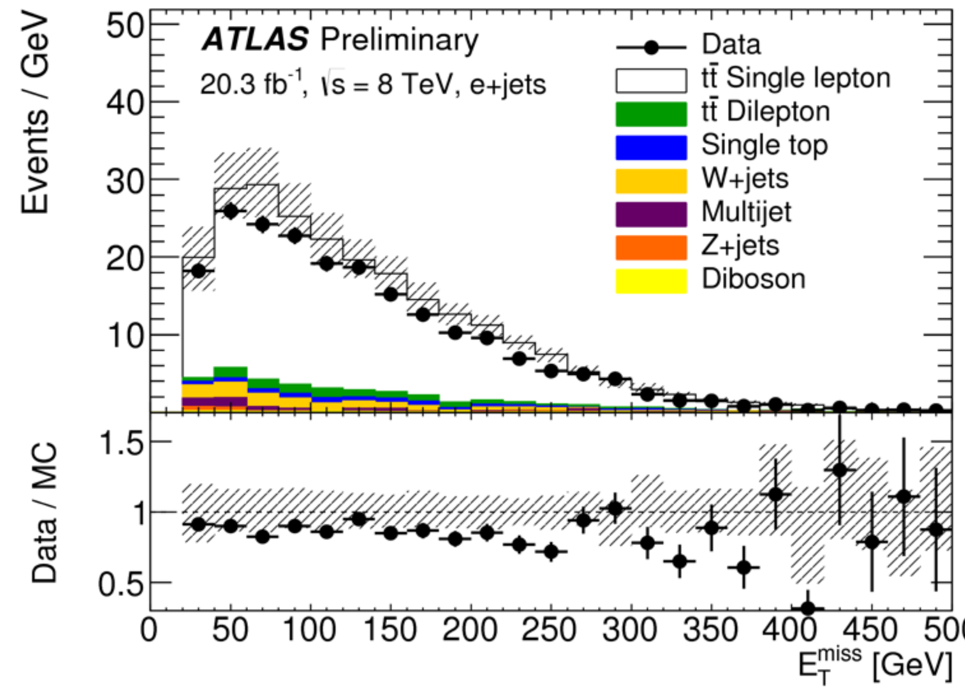
Background yield

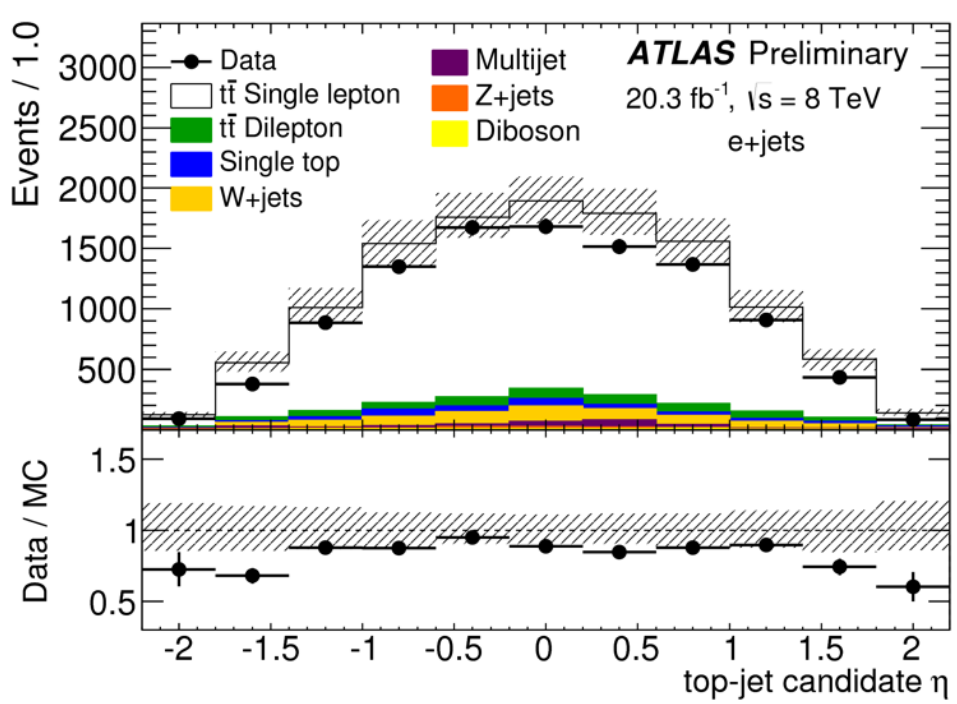
8 TeV, 20 fb^{-1}

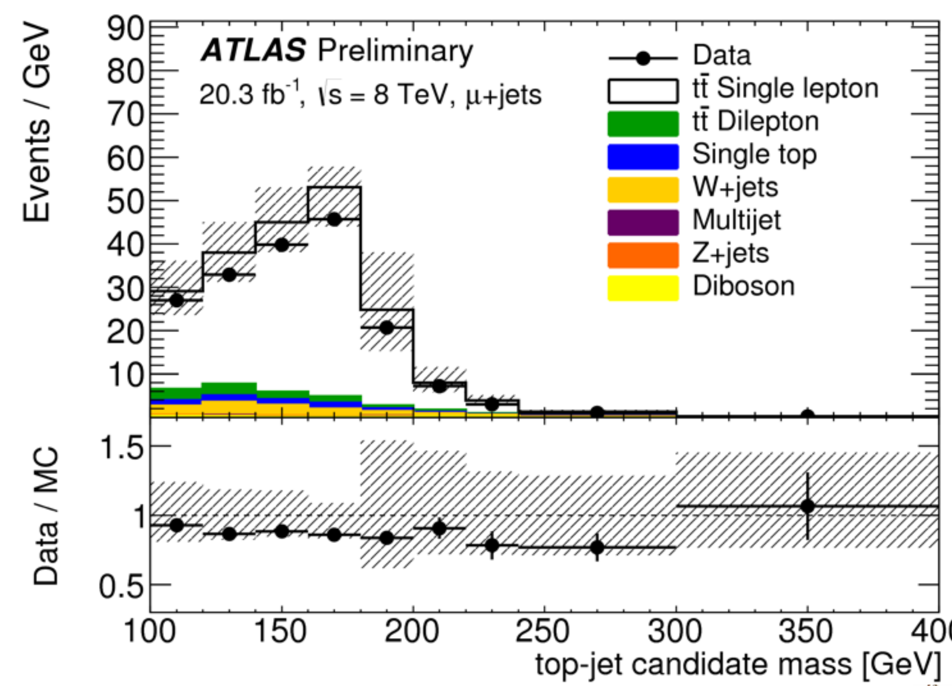
	e+jets	μ+jets
$t\bar{t}$ ℓ+jets	4020 ± 460	3500 ± 400
$t\bar{t}$ dilepton	227 ± 36	210 ± 26
W+jets	263 ± 50	252 ± 48
single top	136 ± 27	134 ± 25
Multijet	91 ± 17	3 ± 1
Z+jets	34 ± 18	14 ± 8
Dibosons	22 ± 11	18 ± 9
Prediction	4790 ± 540	4130 ± 470
Data	4148	3604

Data/MC comparison









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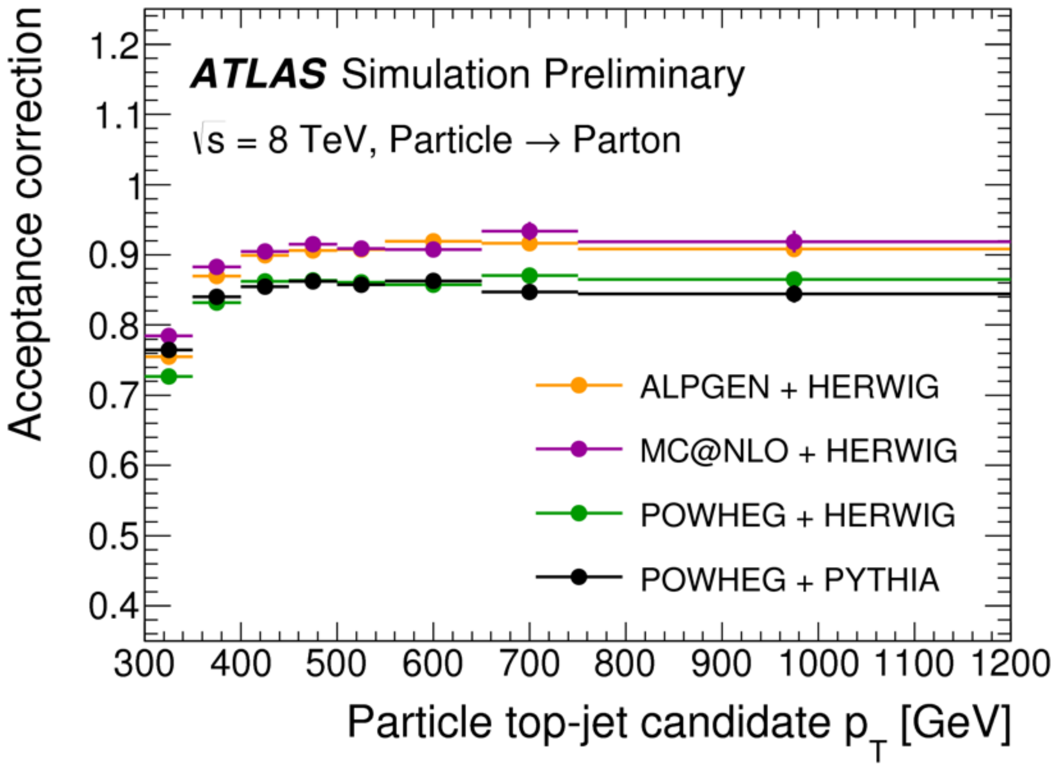
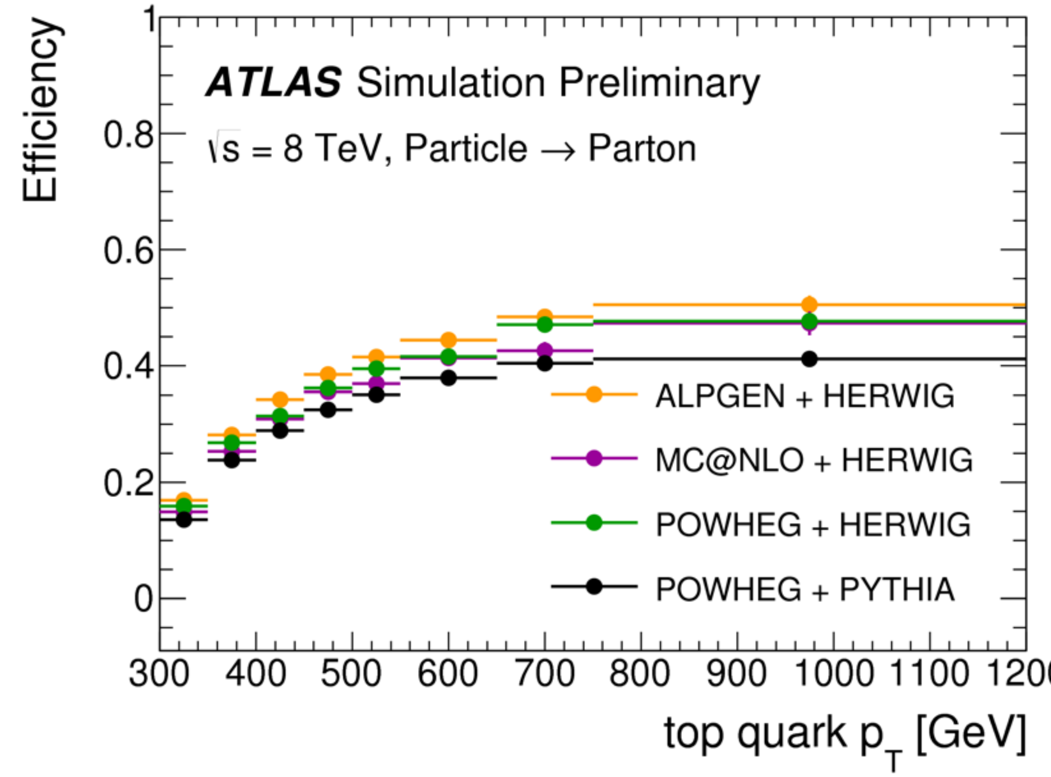
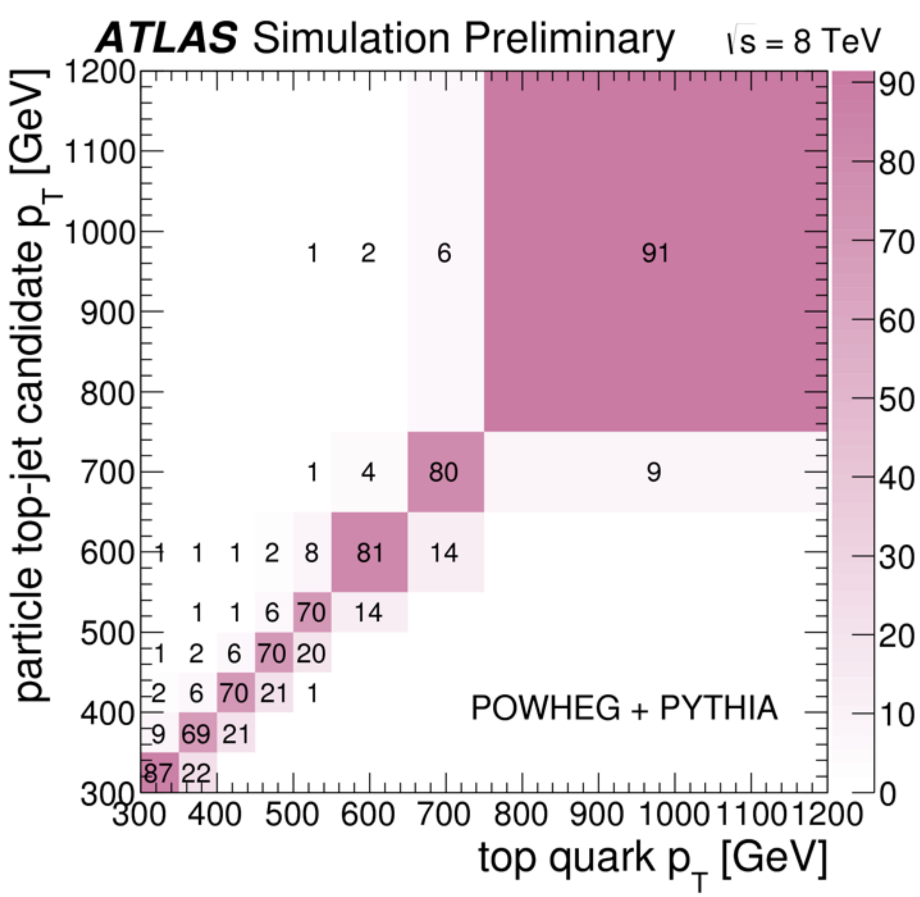
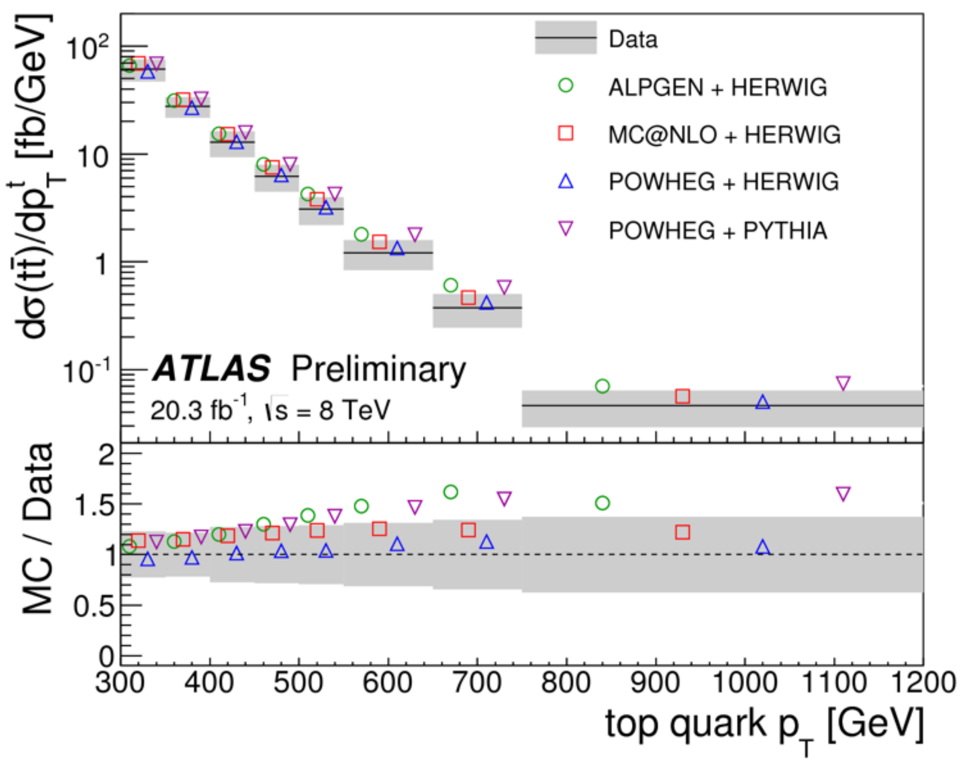
Parton-level unfolding input

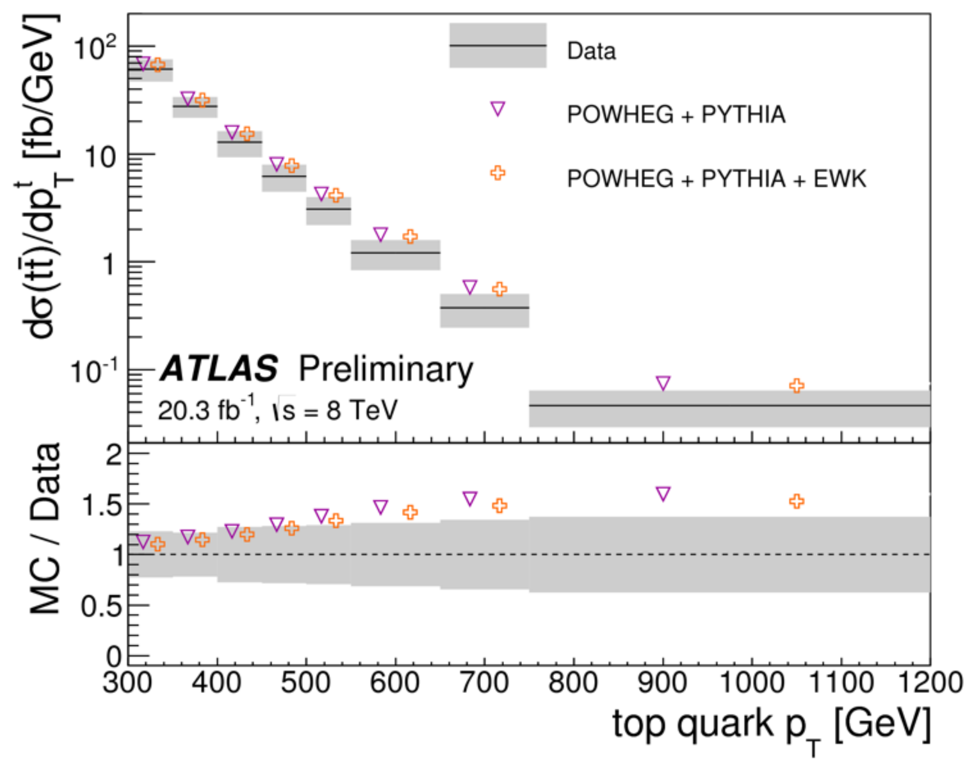


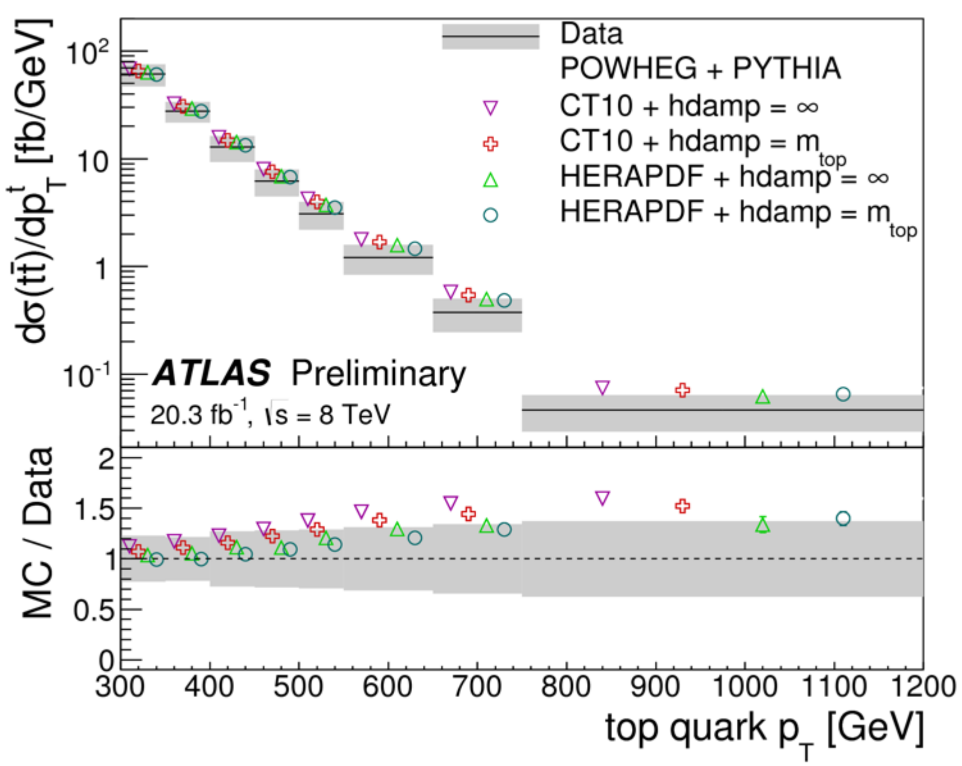




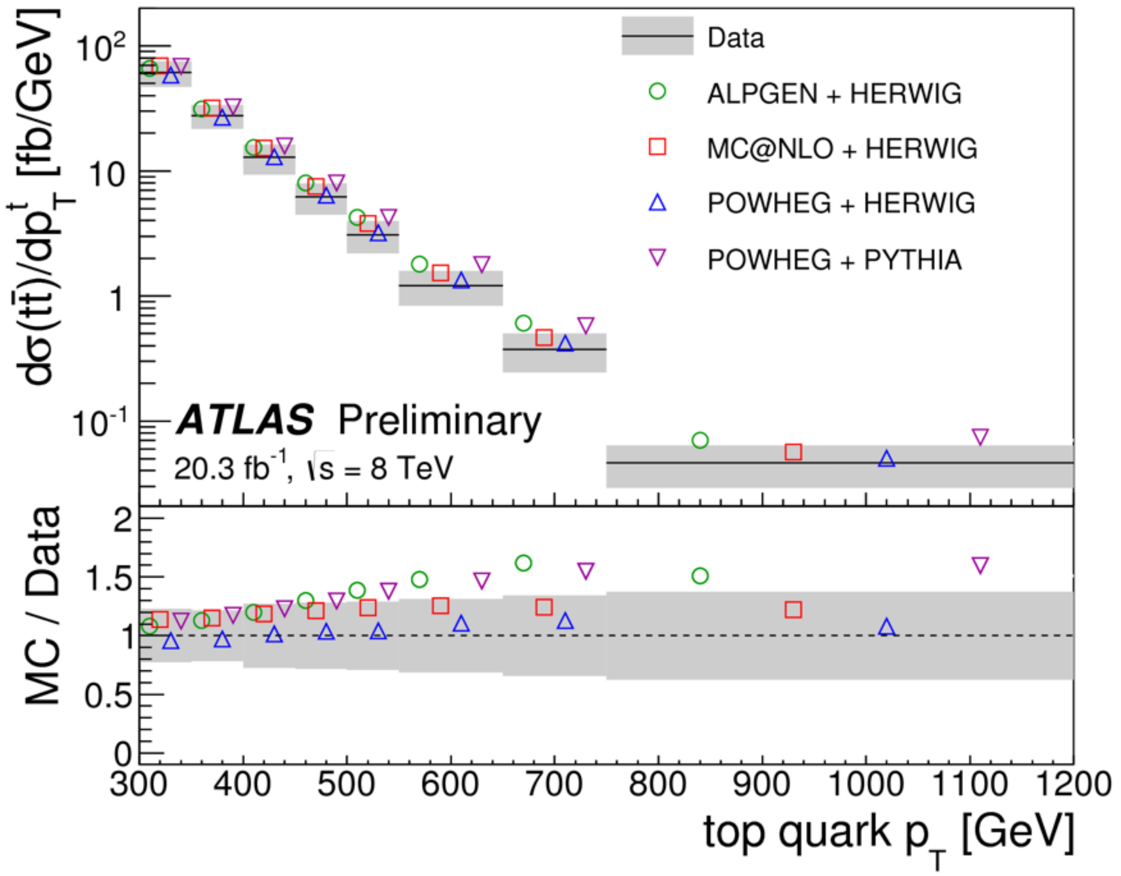
Parton-level results

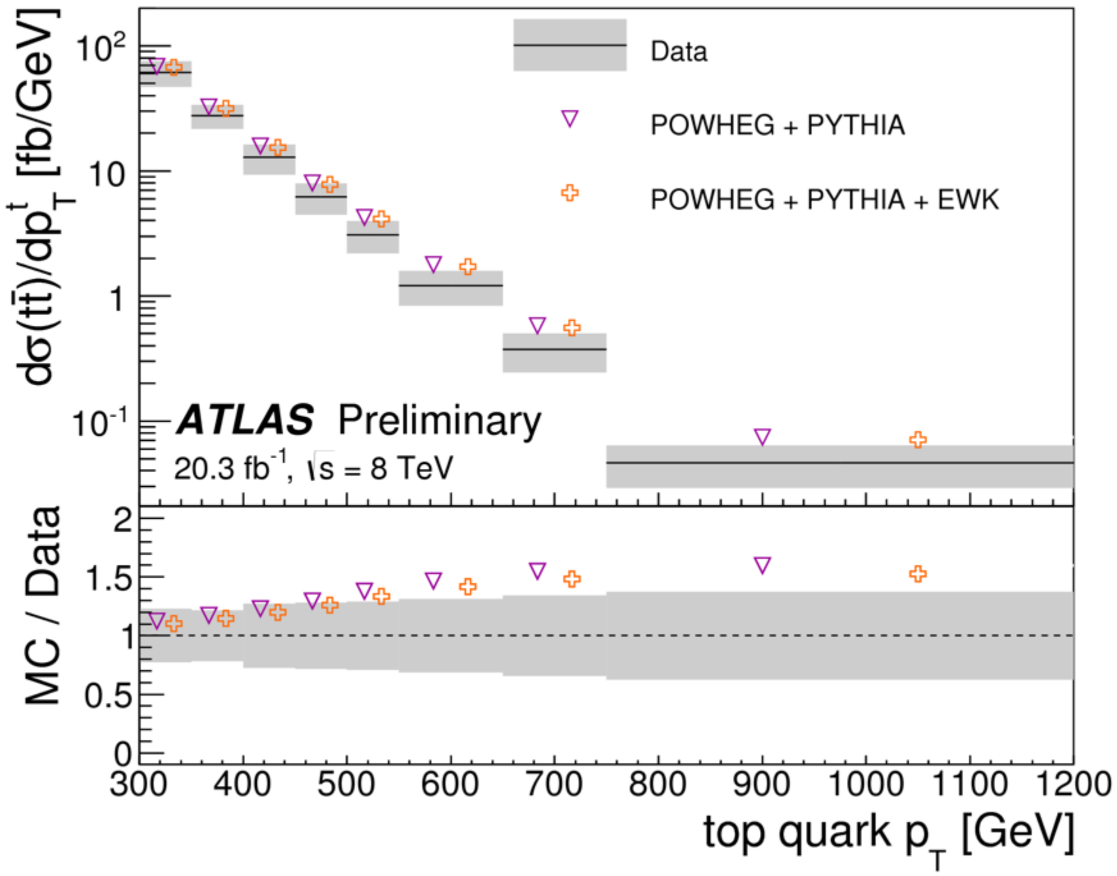




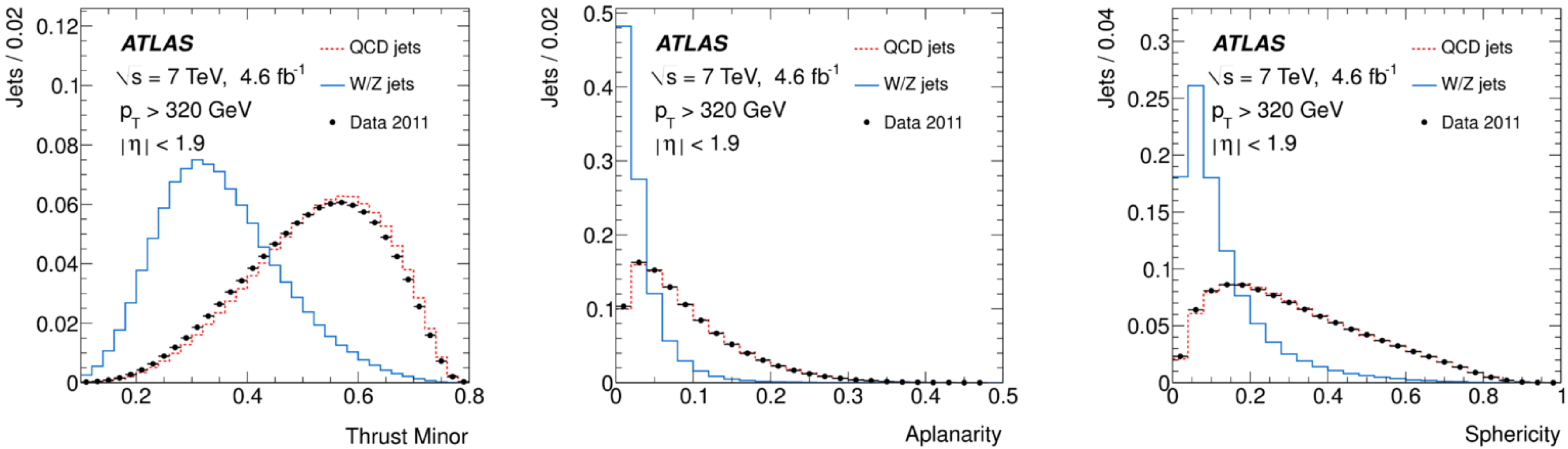


Parton-level results

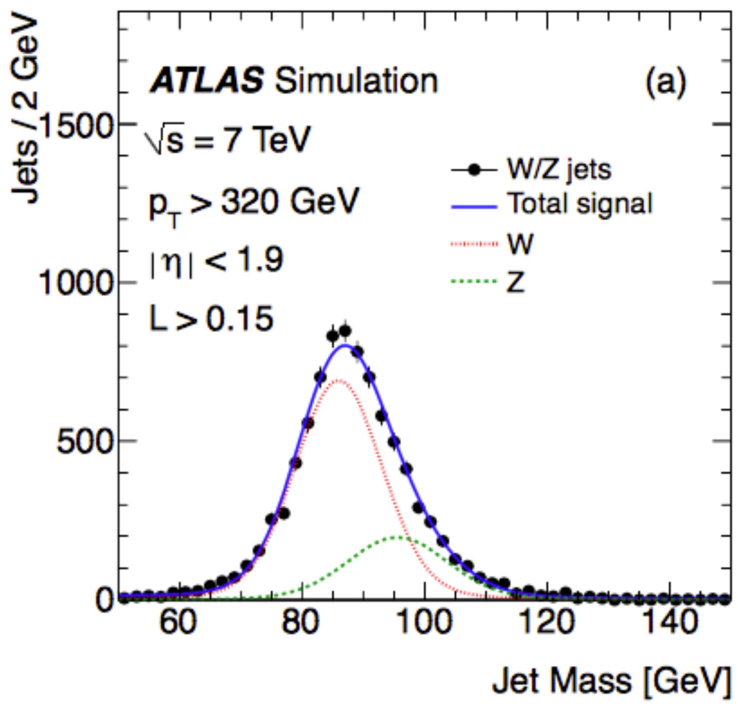


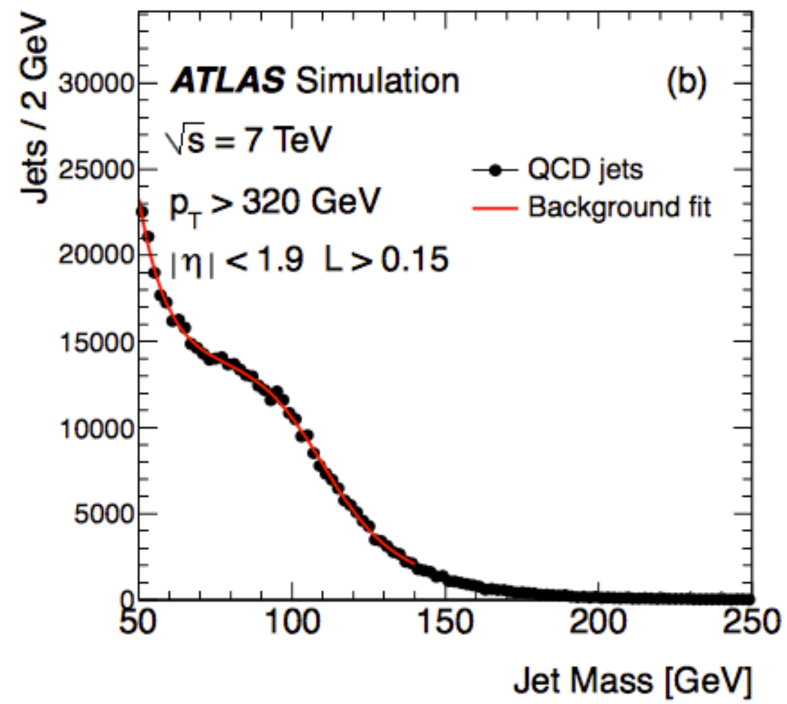


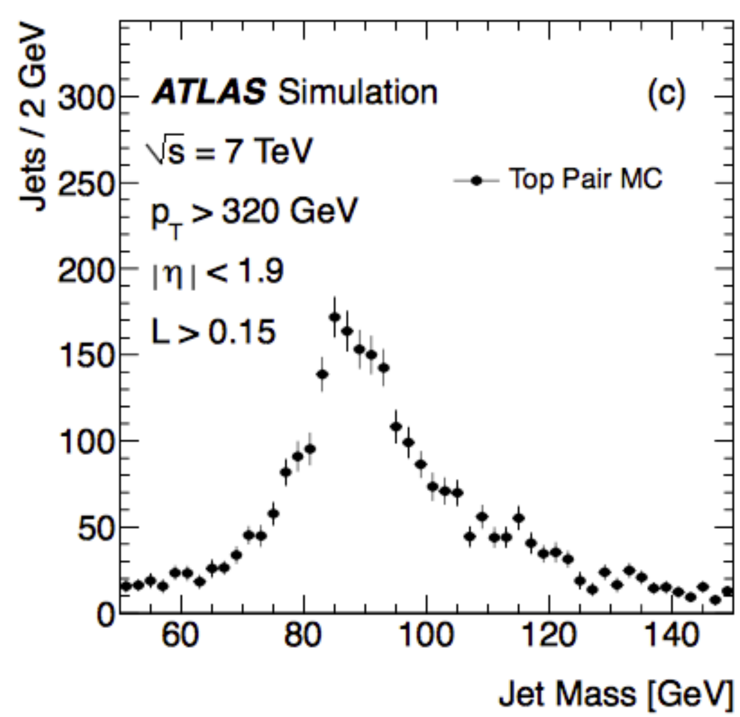
W,Z cross-section likelihood variables



W/Z boson cross-section: Likelihood fit PDFs







W/Z boson cross-section: Systematic uncertainty

Sources	σ_{W+Z}
MC modelling	4.4 %
Background pdf	8.8 %
Signal pdf	5 %
Jet energy scale	3.7 %
Jet energy resolution	< 1 %
Jet mass scale	2.2 %
Jet mass resolution	12.6 %
$t\bar{t}$ contribution	2.8 %
Single-top and diboson contribution	< 1 %
W and Z relative yield	2.9 %
Luminosity	1.8 %
Total	18 %

W/Z cross-section: more on grooming study