Measurements with ATLAS detector of Jets containing Charm and Bottom quarks

D. Calvet for the ATLAS Collaboration

Laboratoire de Physique Corpusculaire de Clermont-Ferrand

DIS2012, Bonn, March 27th, 2012

Outline

Next slides are about...

Motivation

- Heavy quark (c and b) production in pp collisions $\Rightarrow$ test of perturbative QCD
- Next-to-leading order calculations of production cross-section
  - $\Rightarrow$ interest of comparison between predictions and measurements
- Heavy quarks are often in background to new physics search
  - $\Rightarrow$ need to understand the QCD production

Analyses presented today

- Measurements with ATLAS detector at $\sqrt{s} = 7$ TeV (2010)
- Measurement of inclusive b-jet and $b\bar{b}$-dijet production cross-sections:
  - measurement as function of jet p_T, jet rapidity y (inclusive)
  - measurement as function of dijet invariant mass m_{jj}, angle between jets $\Delta\phi$, angular variable $\chi = \exp|y_1 - y_2|$ $(b\bar{b})$
- Measurement of $D^{*\pm}$ meson production in jets:
  - measurement as function of jet p_T and $z = p_{||}(D^{*\pm})/E(\text{jet})$
- Comparison with theoretical predictions using simulated events

Next slides are about...

Inclusive b-jet and $b\bar{b}$-dijet production cross-sections

1. Selection of events with jets; jet reconstruction
2. Applying b-tagging on jets (with lifetime-based method)
3. b-tagging efficiency determination (with p_T^{rel} method)
4. b-jet purity determination (using secondary vertex mass)
5. Measurement of the production cross-sections
   - using the p_T^{rel} method for a complementary measurement (muon-based measurement)
   - bin-by-bin unfolding
6. Comparison with simulated data

Event selection and reconstruction

- 2010 ATLAS data, L$= 34.0 \pm 1.2$ pb^{-1} at $\sqrt{s} = 7$ TeV
- Trigger requires a jet (and a muon for the muon-based measurement)
- Jet reconstruction with anti-k_t algorithm ($R = 0.4$)
- Quality selections on jets
- b-tagging with lifetime-based method:
  - reconstruction of secondary vertex from tracks within jet
  - measurement of signed decay length significance L/σ_L

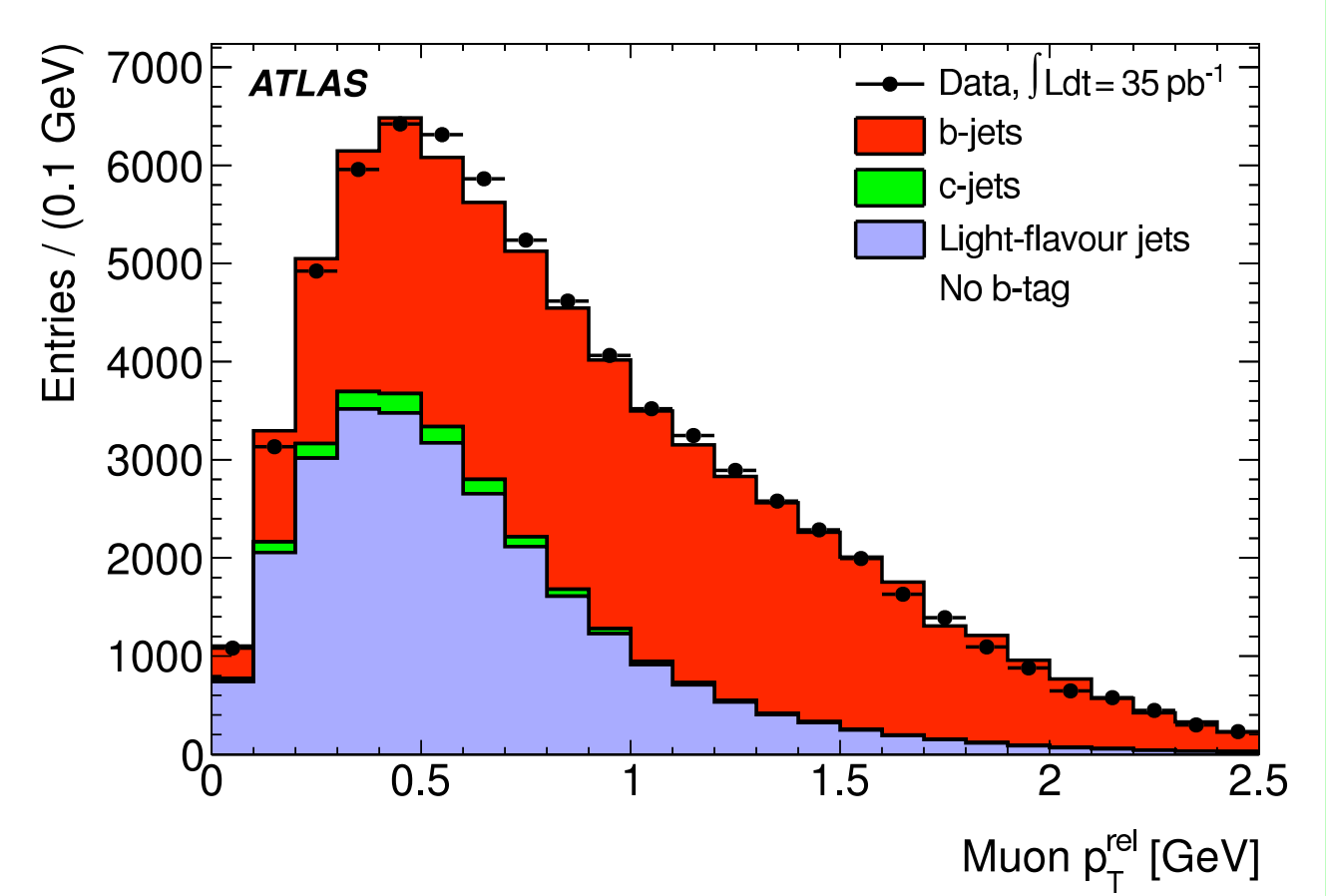
Estimation with p_T^{rel} method

- For jets containing a muon:
  - p_T^{rel} is momentum of muon, transverse to jet
  - $\Rightarrow$ p_T^{rel} spectrum harder for b-jets
- Templates of p_T^{rel} shape for each jet flavour:
  - from simulation for c-jets and b-jets
  - from data for light-jets (enriched sample)
- Fit of measured p_T^{rel} spectrum, adjusting templates, before and after b-tagging

$\Rightarrow$ b-tagging efficiency extraction

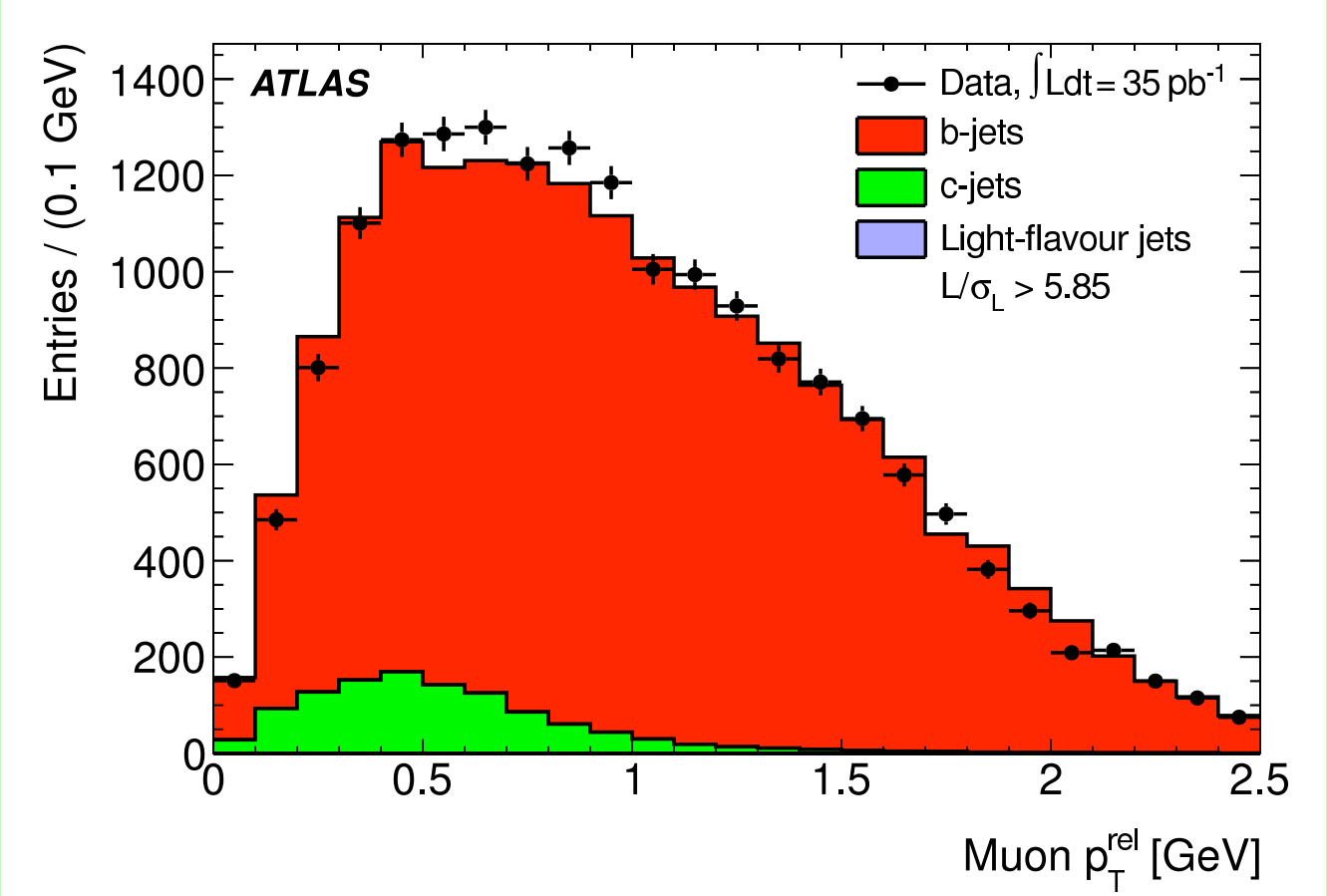
Estimation with p_T^{rel} method

Example of p_T^{rel} distribution for all jets



Estimation with p_T^{rel} method

Example of p_T^{rel} distribution for b-tagged jets



Muon-based analysis

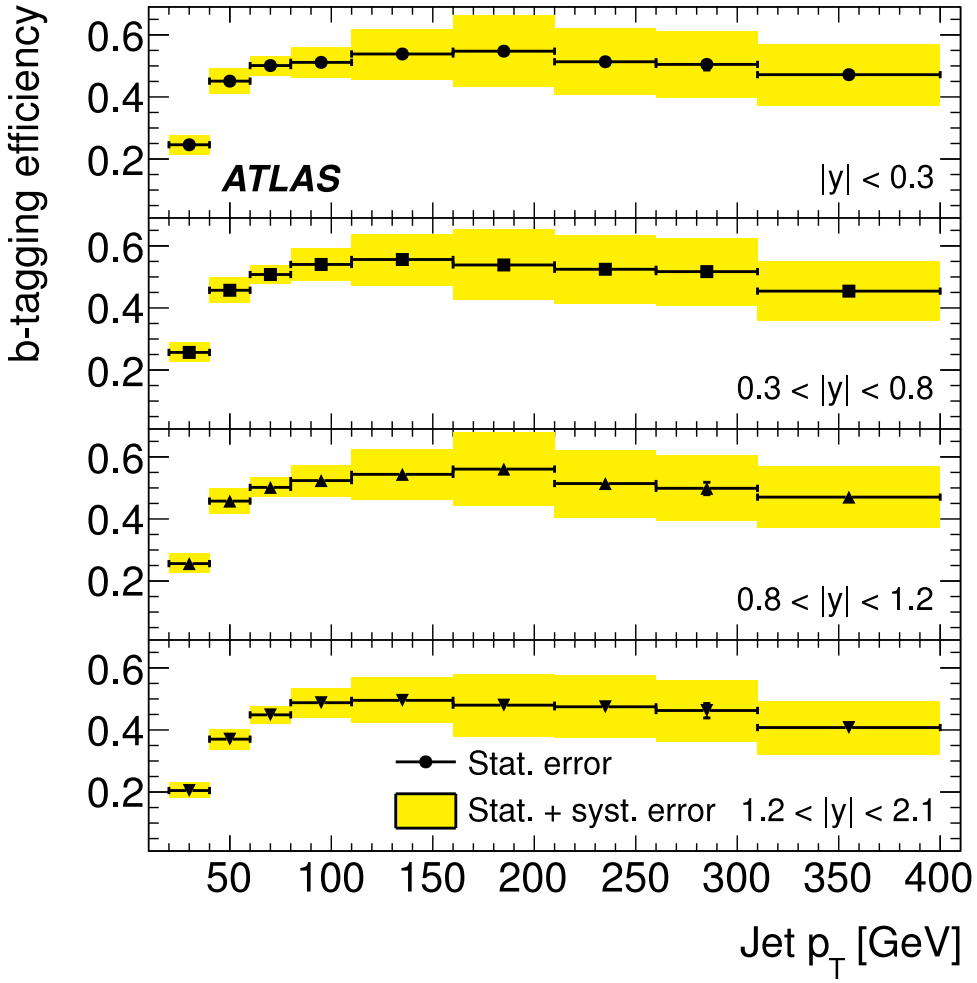
- Fit of measured p_T^{rel} spectrum before b-tagging

$\Rightarrow$ b-jet purity extraction

- Complementary to lifetime-based analysis because of different systematic uncertainties and event samples
- But: method only for jets with μ and with jet p_T in range $30 < p_T < 140$ GeV

$\Rightarrow$ Reduced statistics and range (only as a cross-check)

Efficiency as a function of p_T and y



- ~20% at low p_T and high y
- ~55% for $p_T \sim 200$ GeV and low y
- For $p_T > 140$ GeV: from simulation and correction factor (from p_T^{rel})

Secondary vertex mass method

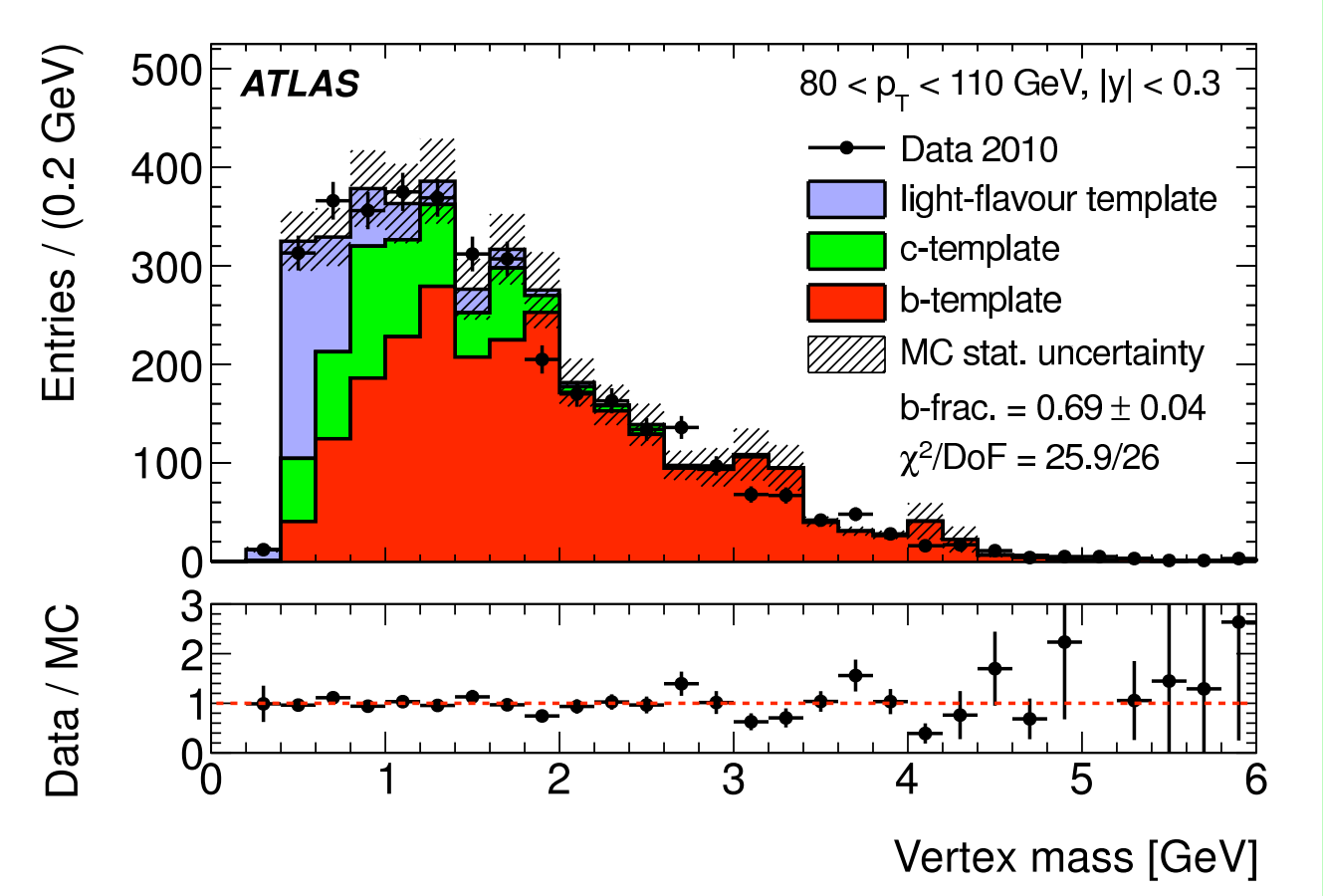
- Secondary vertex mass increases with flavour of jet
- Templates of vertex mass shape for each jet flavour (from simulation)
- Fit of measured vertex mass spectrum, adjusting templates

$\Rightarrow$ b-jet purity (fraction of b-jets in sample of b-tagged jets)

- For $b\bar{b}$-dijet sample:
  - fit of sum of masses of both b-jets secondary vertices
  - b-template with both jets matched to true b-jets (simulation)
  - non-b template when at least one of the jets is not matched
  - reduced statistics $\Rightarrow$ parameterization

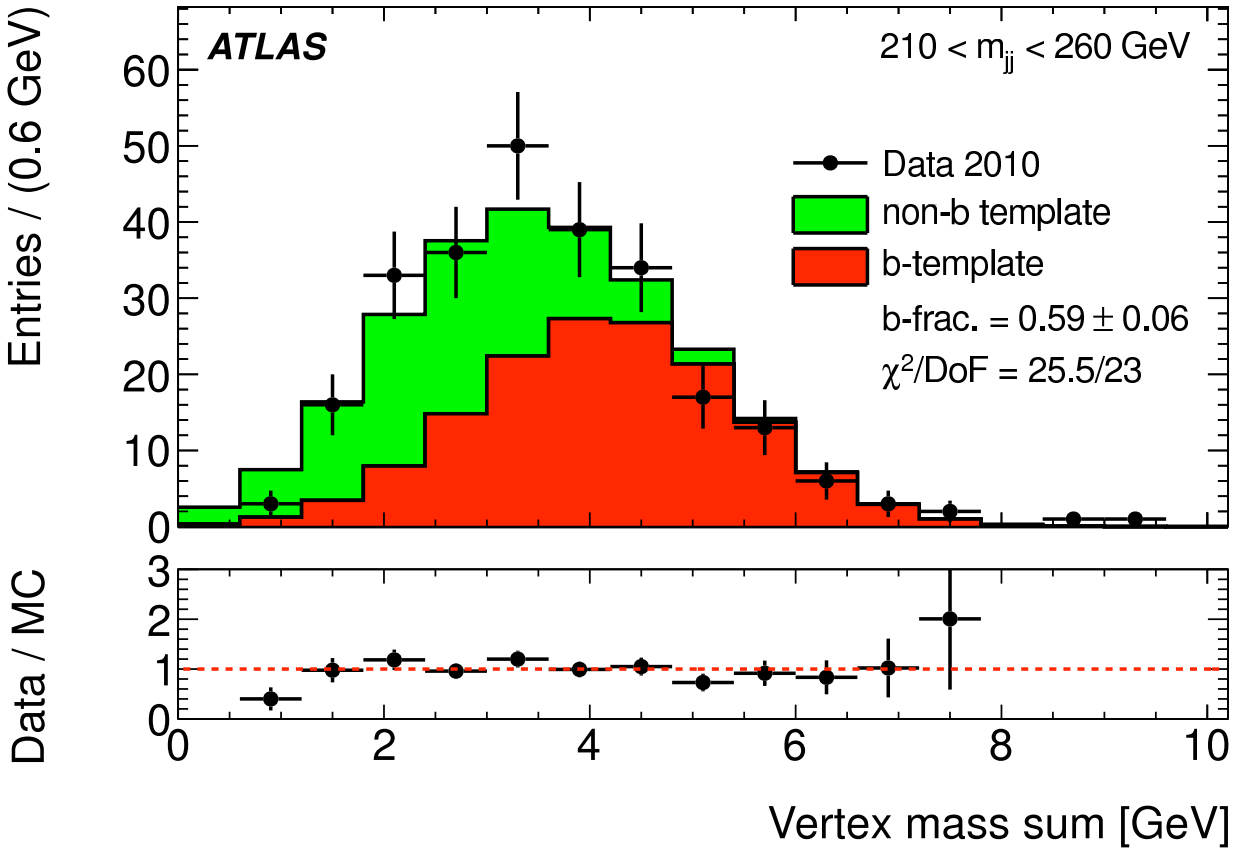
Secondary vertex mass method

Example of secondary vertex mass fit

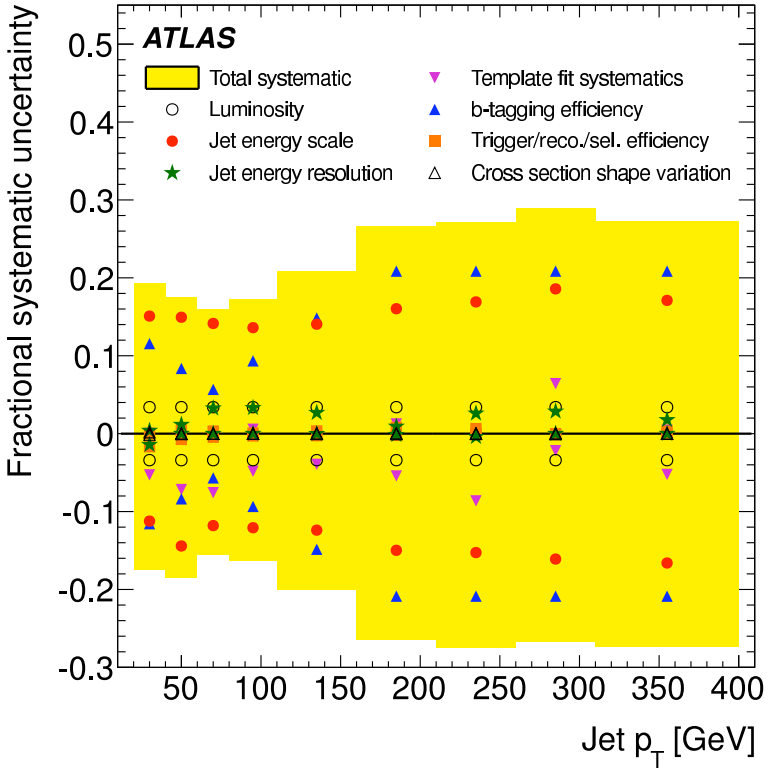


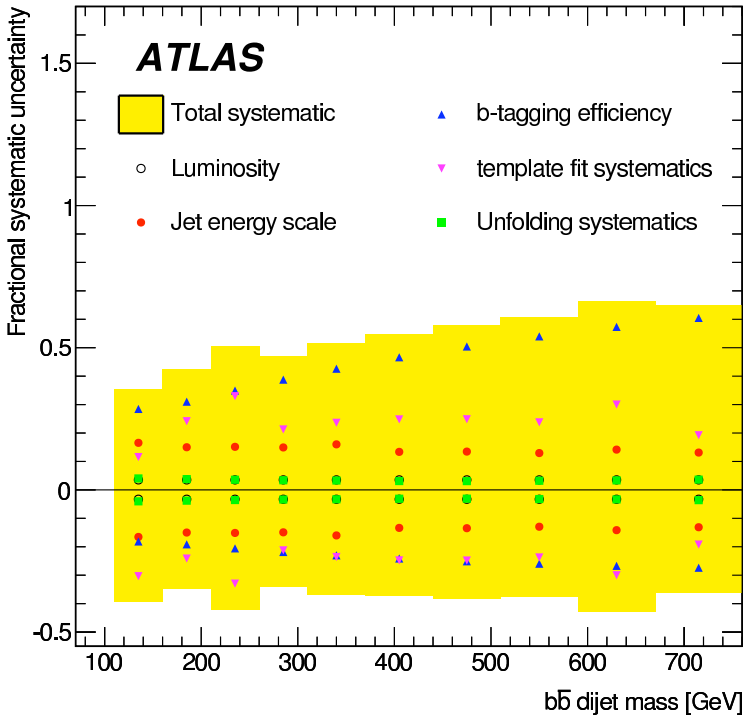
Secondary vertex mass method

Example of fit for the $b\bar{b}$-dijet



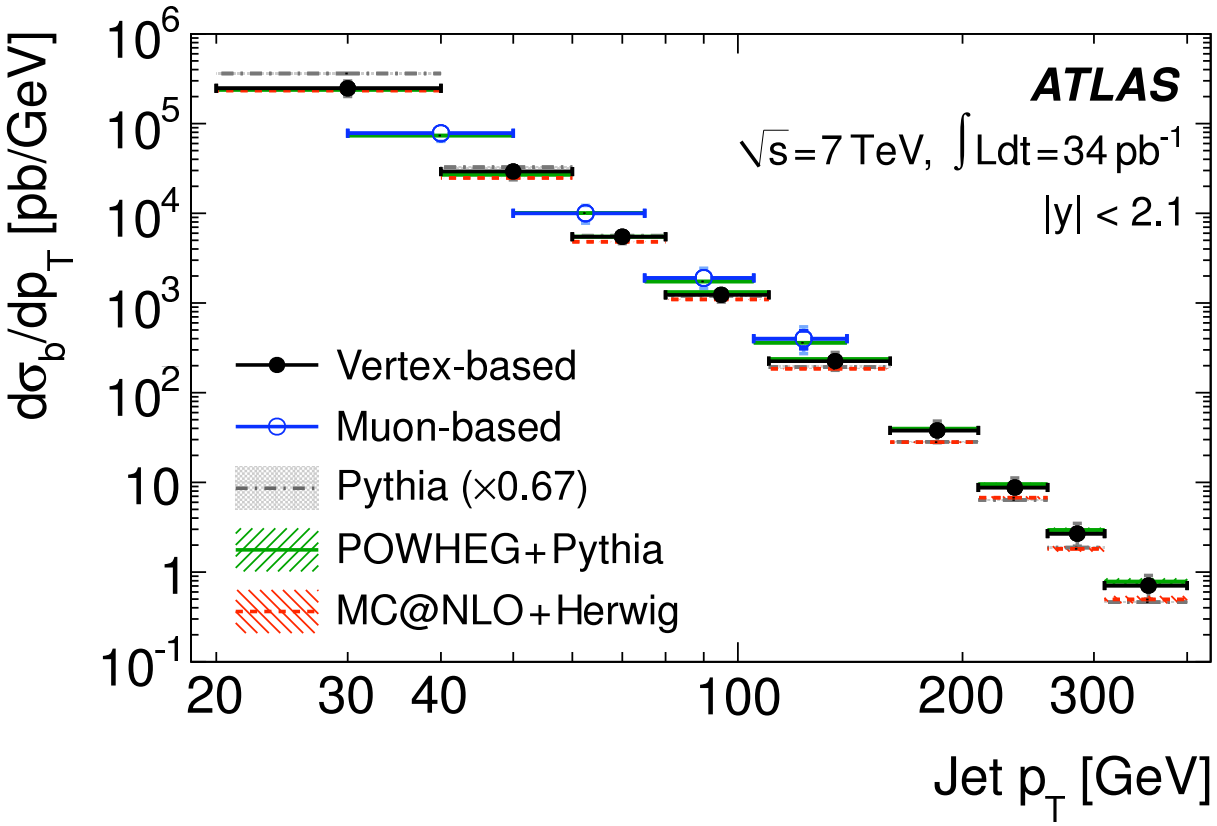
Systematic uncertainties for lifetime-based analysis





- Dominant: b-jet energy scale calibration, b-tagging efficiency and purity determinations

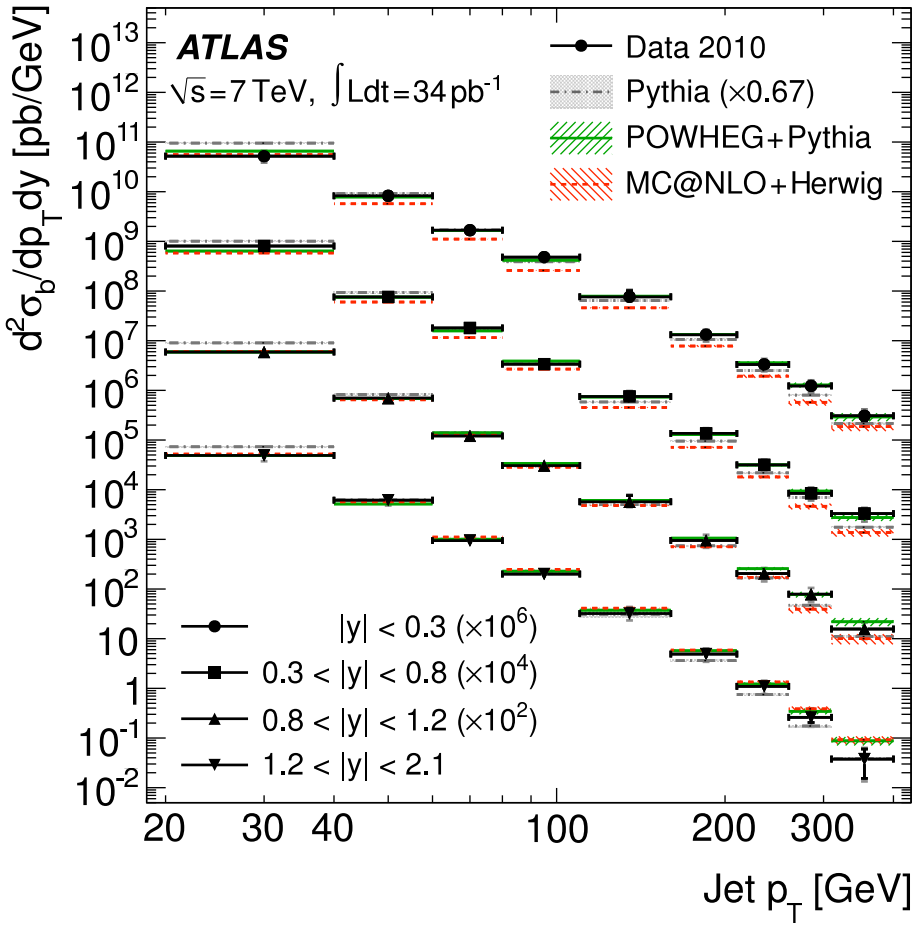
Inclusive b-jet cross-section measurement



⇒ Lifetime-based and muon-based analyses agree

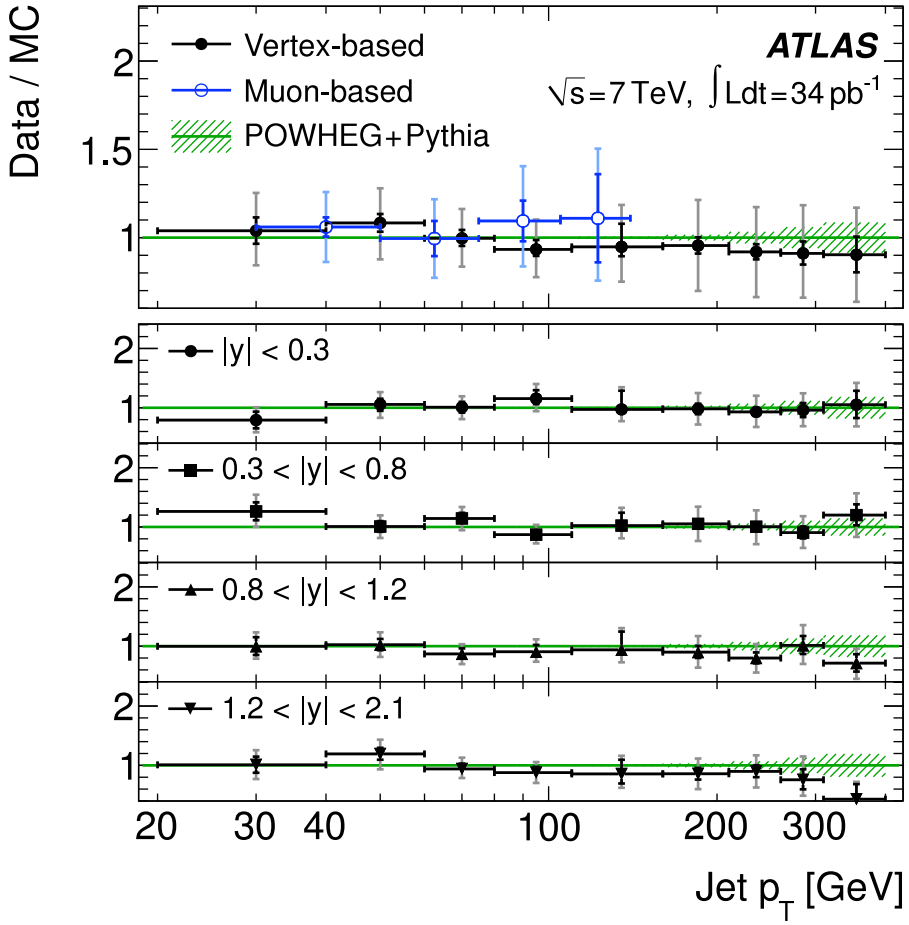
Different binnings ⇒ bin-by-bin comparison not possible

Inclusive b-jet cross-section measurement



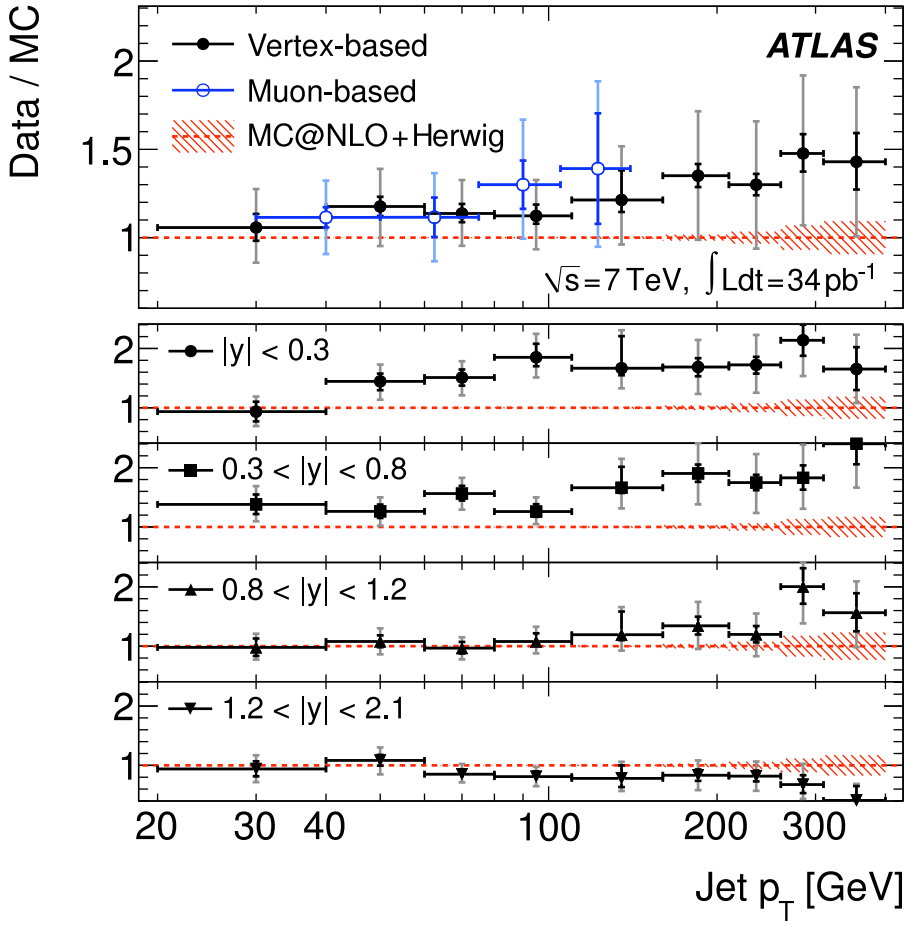
- Pythia prediction scaled by 0.67 to match measured integrated cross-section
- General features are reasonably well reproduced by simulation

Inclusive b-jet cross-section comparison: POWHEG+Pythia



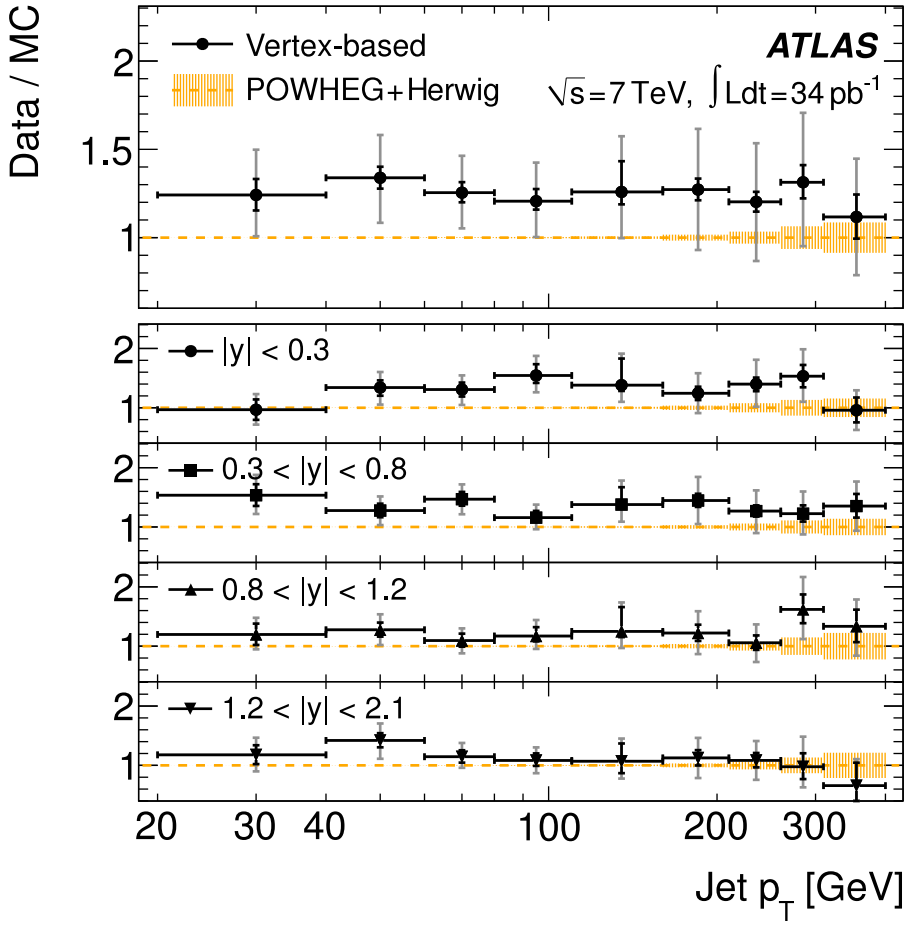
- Good agreement in all rapidity regions

Inclusive b-jet cross-section comparison: MC@NLO+Herwig



- Differences in different rapidity regions
- Effect averages out in integrated cross-section but still global deficit

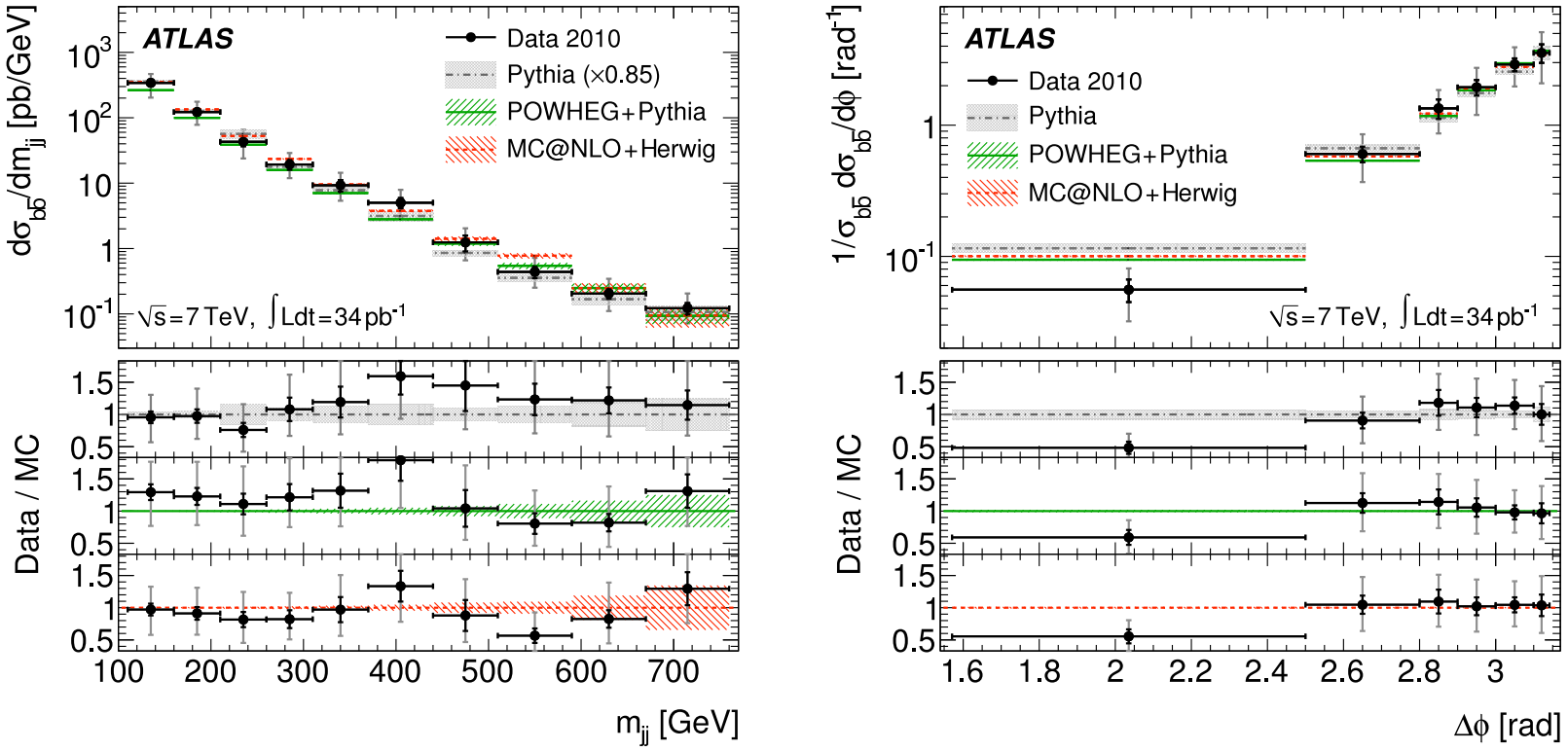
Inclusive b-jet cross-section comparison: POWHEG+Herwig



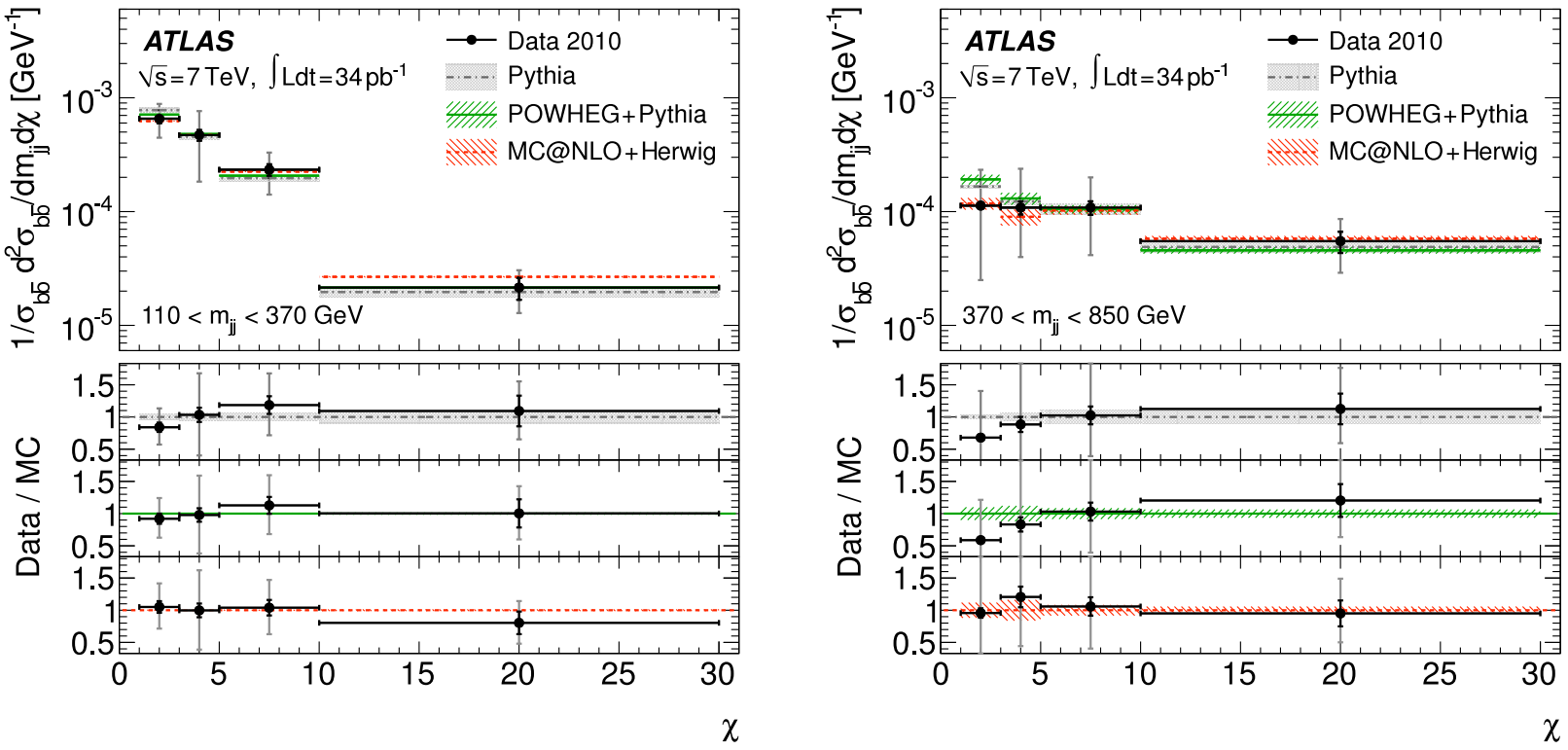
- POWHEG+Herwig: similar rapidity behaviour to POWHEG+Pythia, but lower cross-section

⇒ Deficit in MC@NLO+Herwig partly due to Herwig, but not the rapidity dependence

$b\bar{b}$-dijet cross-section measurement



$b\bar{b}$-dijet cross-section measurement



$$\chi = \exp|y_1 - y_2| \text{ for events with } |y_{boost}| = \frac{1}{2}|y_1 + y_2| < 1.1$$

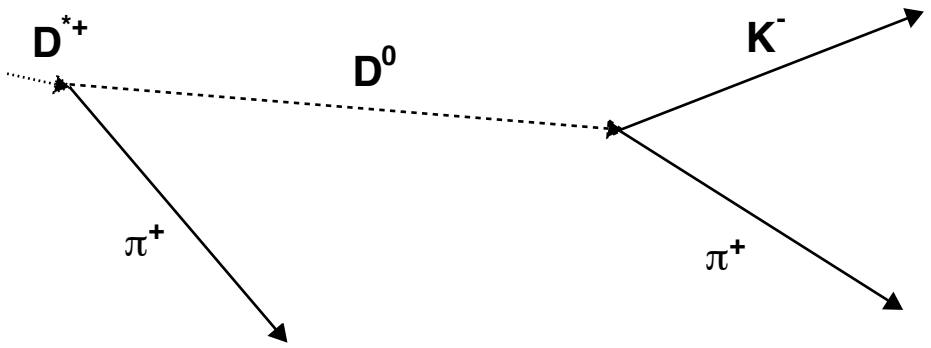
Next slides are about...

$D^{*\pm}$ meson production in jets

1. Selection of events with jets; jet reconstruction
2. Full reconstruction of $D^{*\pm}$ mesons
3. Mesurement of $\mathcal{R}(p_T, z) = \frac{N_{D^{*\pm}}(p_T,z)}{N_{jet}(p_T)}$ with $z = p_{||}(D^{*\pm})/E(\text{jet})$ ($p_{||}$ along jet axis)
   - Bayesian unfolding
4. Comparison with simulated data

- April-July 2010 ATLAS data, L$= 0.30 \pm 0.01$ pb^{-1} at $\sqrt{s} = 7$ TeV
- Trigger requires a jet
- Jet reconstruction with anti-k_t algorithm ($R = 0.6$)
- Quality selection on jets, $25 < p_T < 70$ GeV, $|\eta| < 2.5$

Full reconstruction of $D^{*\pm}$ meson



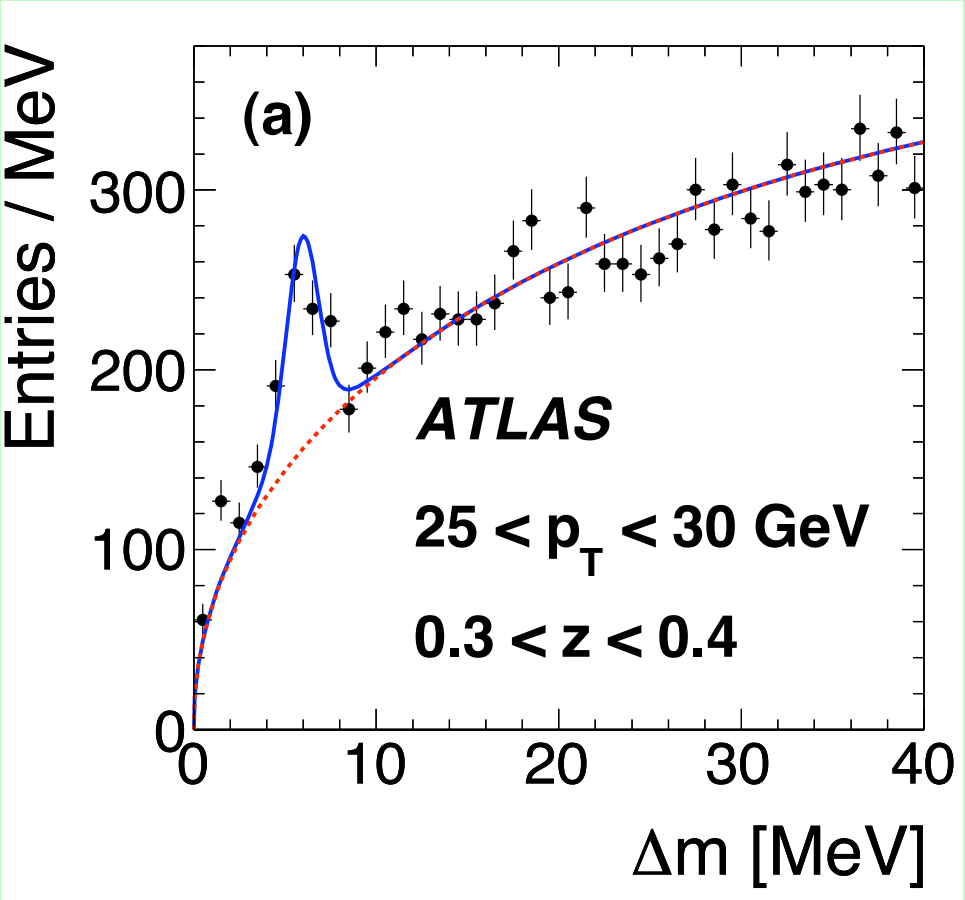
- Reconstructed decays:
  - $D^{*+} \to D^0\pi^+$ or $D^{*-} \to \bar{D}^0\pi^-$ ($p_T^\pi > 0.5$ GeV)
  - $D^0 \to K^-\pi^+$ or $\bar{D}^0 \to K^+\pi^-$ ($p_T^{K,\pi} > 1$ GeV)
- Selections criteria:
  - $D^0/\bar{D}^0$ candidate with positive transverse decay length, $|m_{K\pi} - m_{D^0}^{PDG}| < 50$ MeV
  - $D^{*\pm}$ candidate with $p_T > 7.5$ GeV

Jet matching and $D^{*\pm}$ jet yield

- Matching with a jet:
  - $D^{*\pm}$ direction within $\Delta R < 0.6$ of jet axis
  - $z > 0.3$
  - selected jets are $D^{*\pm}$ jets
- $D^{*\pm}$ jet yield:
  - distribution of $\Delta m = m(K^{\mp}\pi^{\pm}\pi^{\pm}) - m(K^{\mp}\pi^{\pm}) - m(\pi^{\pm})$
  - fit of distribution with double gaussian for signal, $\Delta m^{a} e^{b\Delta m}$ for background

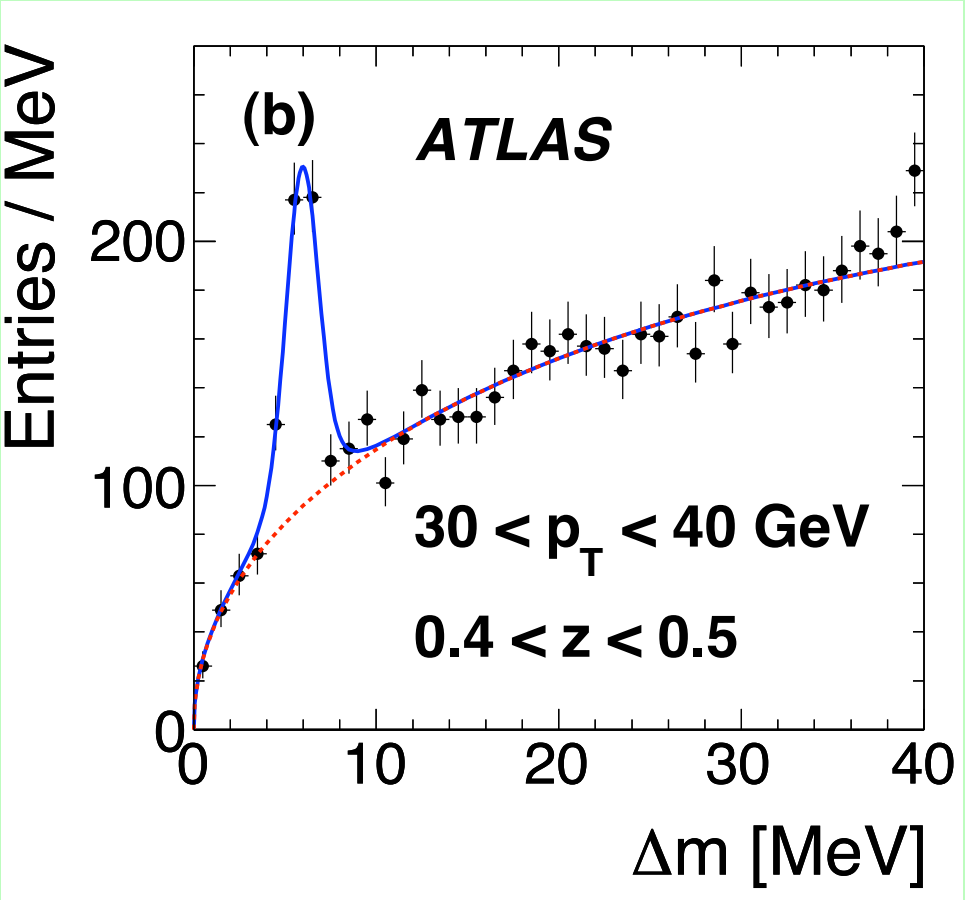
Jet matching and $D^{*\pm}$ jet yield

Example of Δm distribution



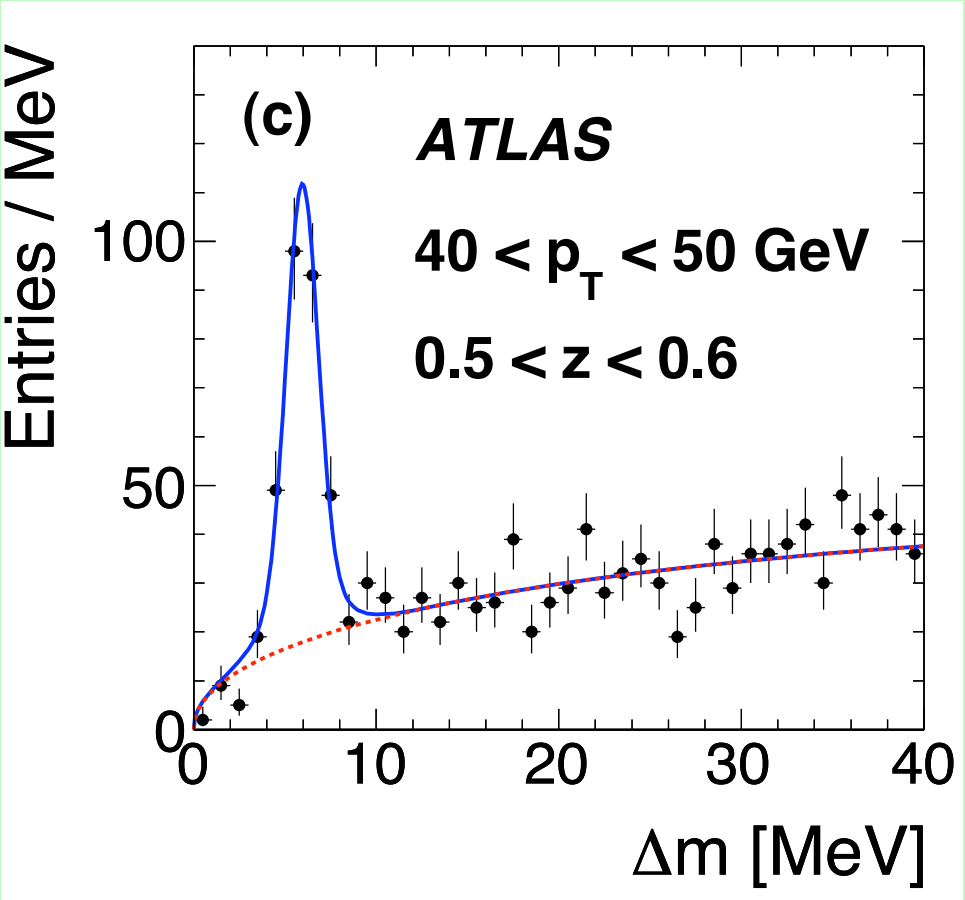
Jet matching and $D^{*\pm}$ jet yield

Example of Δm distribution



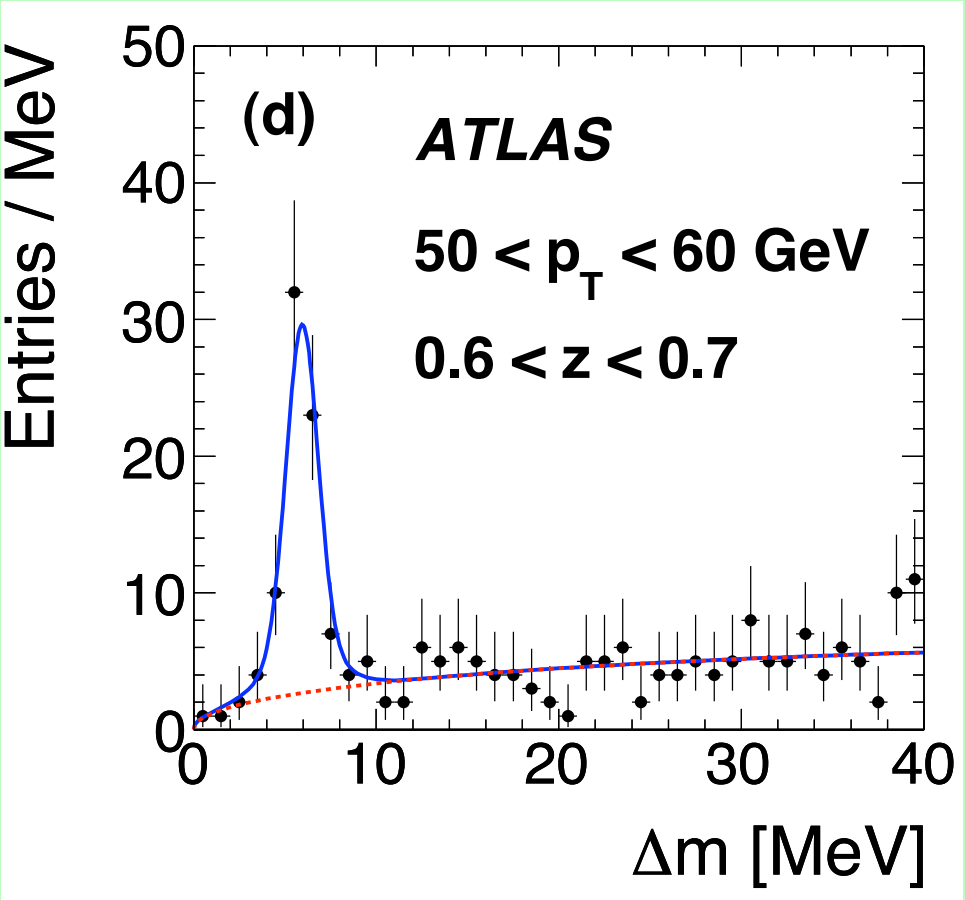
Jet matching and $D^{*\pm}$ jet yield

Example of Δm distribution



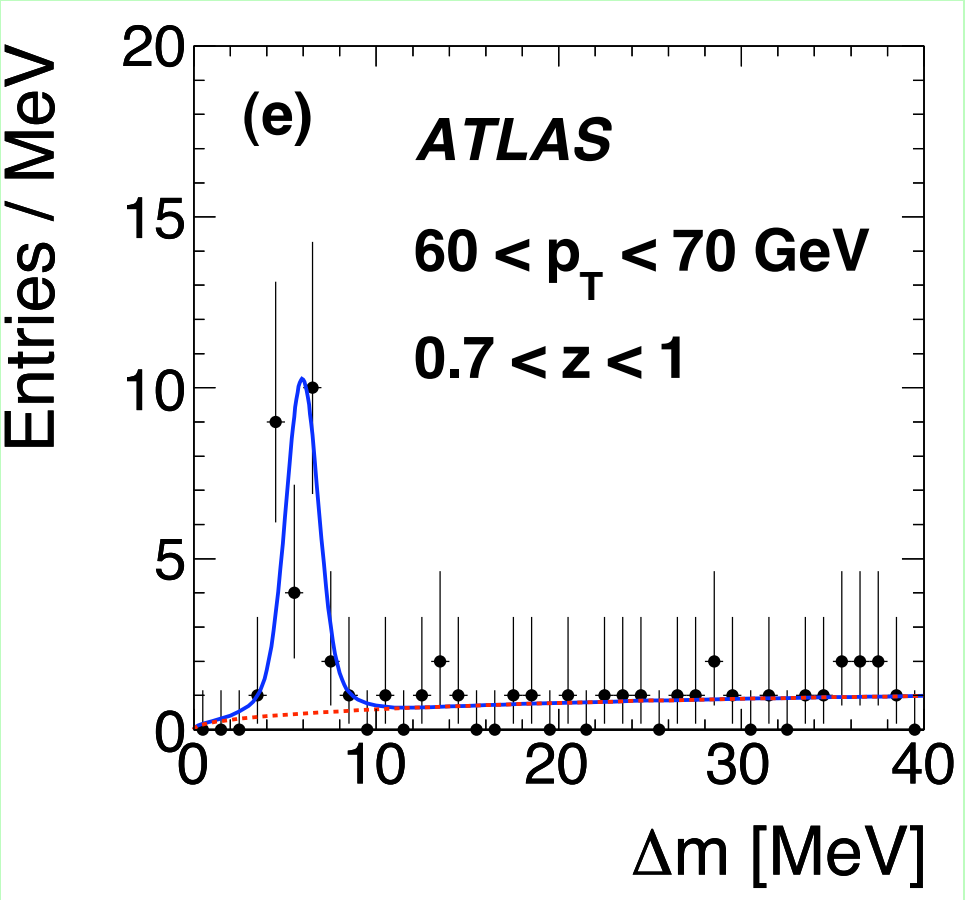
Jet matching and $D^{*\pm}$ jet yield

Example of Δm distribution



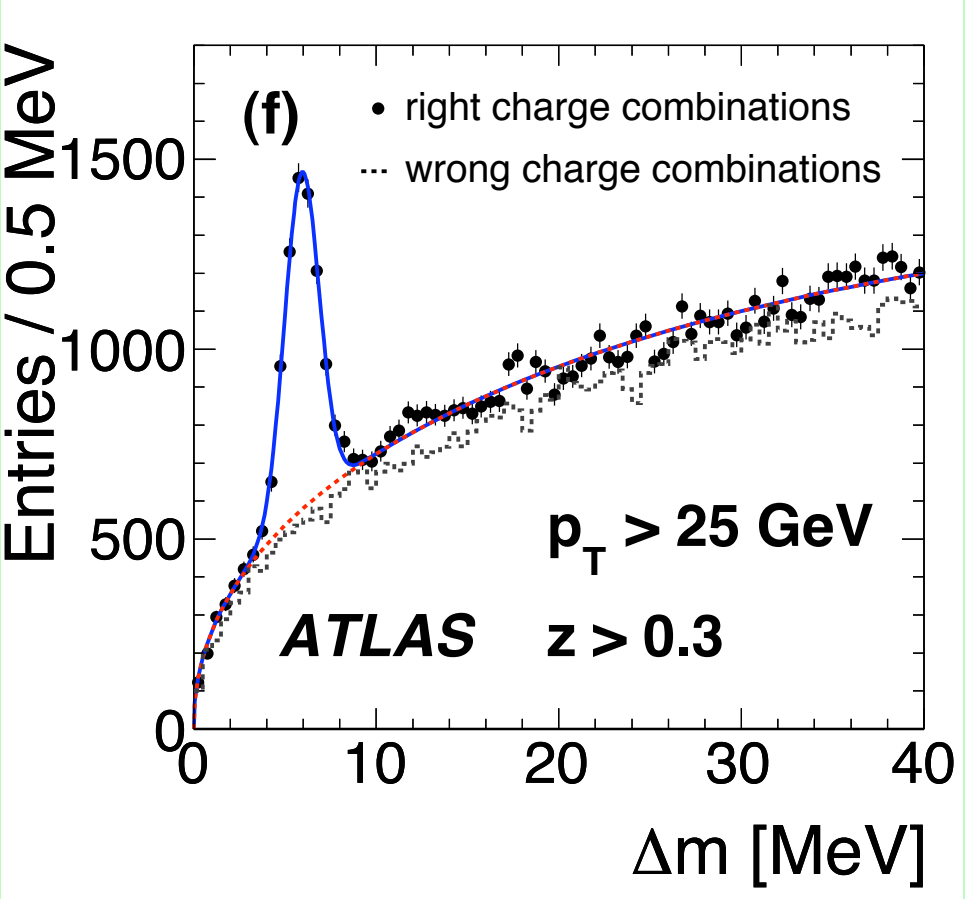
Jet matching and $D^{*\pm}$ jet yield

Example of Δm distribution

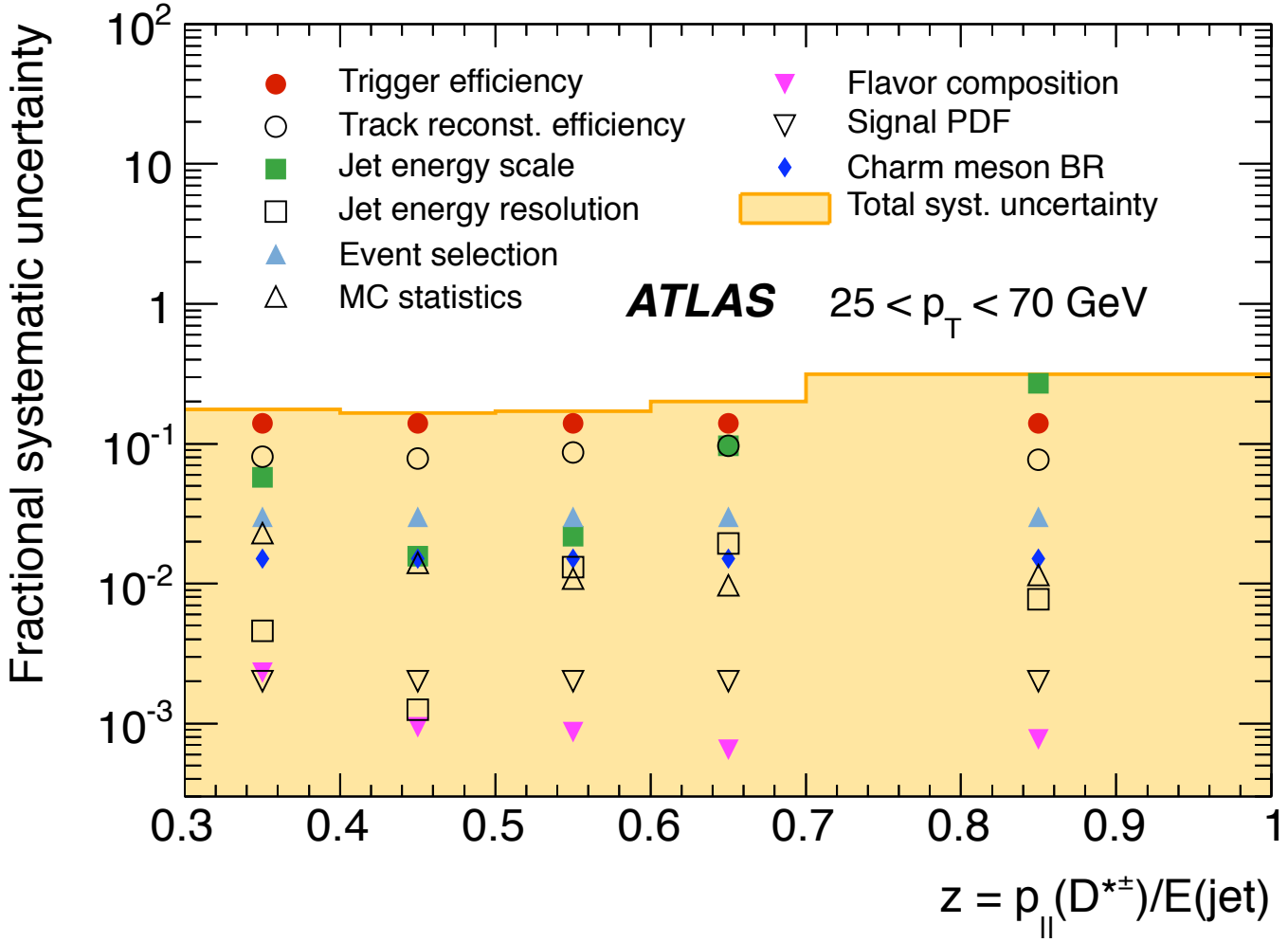


Jet matching and $D^{*\pm}$ jet yield

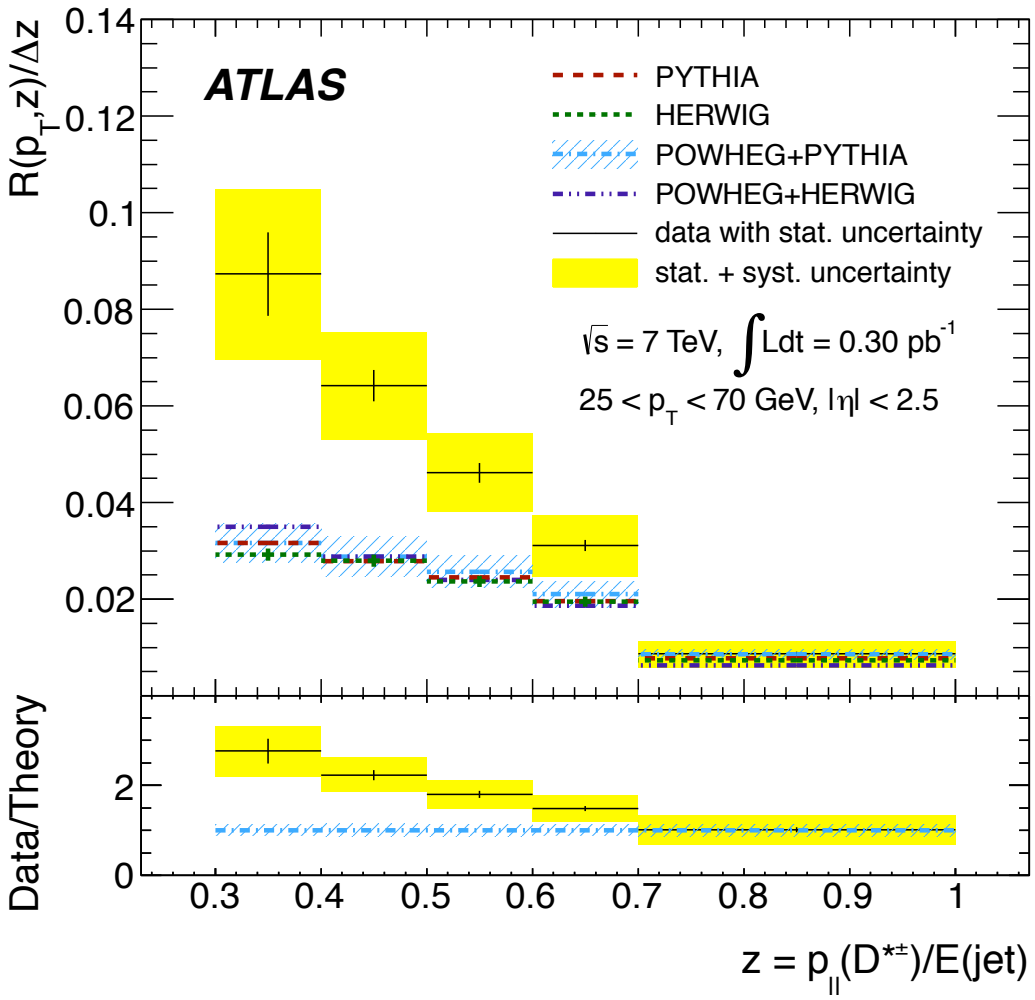
All reconstructed $D^{*\pm}$ candidates



Systematic uncertainties (integrated over all bins in p_T)



Measurement of $D^{*\pm}$ production in jets



- $\mathcal{R} = 0.025 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.})$
- Ratio $\Rightarrow$ LO and NLO predictions similar
- Theoretical predictions do not reproduce data for $z < 0.7$

Next slides are about...

Conclusions

- Measurement of inclusive b-jet production cross-section:
  - good agreement for POWHEG+Pythia
  - discrepancies for MC@NLO+Herwig in term of rapidity variation

Conclusions

- Measurement of inclusive b-jet production cross-section:
  - good agreement for POWHEG+Pythia
  - discrepancies for MC@NLO+Herwig in term of rapidity variation
- Measurement of $b\bar{b}$-dijet production cross-section:
  - good agreement with generators
  - only leading and sub-leading jets are b-tagged $\Rightarrow$ low contribution from gluon splitting

Conclusions

- Measurement of inclusive b-jet production cross-section:
  - good agreement for POWHEG+Pythia
  - discrepancies for MC@NLO+Herwig in term of rapidity variation
- Measurement of $b\bar{b}$-dijet production cross-section:
  - good agreement with generators
  - only leading and sub-leading jets are b-tagged $\Rightarrow$ low contribution from gluon splitting
- Measurement of fraction of jets which contain a $D^{*\pm}$ meson:
  - $\mathcal{R} = 0.025 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.})$
  - discrepancy with generators for $z < 0.7$

Conclusions

- Measurement of inclusive b-jet production cross-section:
  - good agreement for POWHEG+Pythia
  - discrepancies for MC@NLO+Herwig in term of rapidity variation
- Measurement of $b\bar{b}$-dijet production cross-section:
  - good agreement with generators
  - only leading and sub-leading jets are b-tagged $\Rightarrow$ low contribution from gluon splitting
- Measurement of fraction of jets which contain a $D^{*\pm}$ meson:
  - $\mathcal{R} = 0.025 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.})$
  - discrepancy with generators for $z < 0.7$
- Measurements are dominated by systematic uncertainties

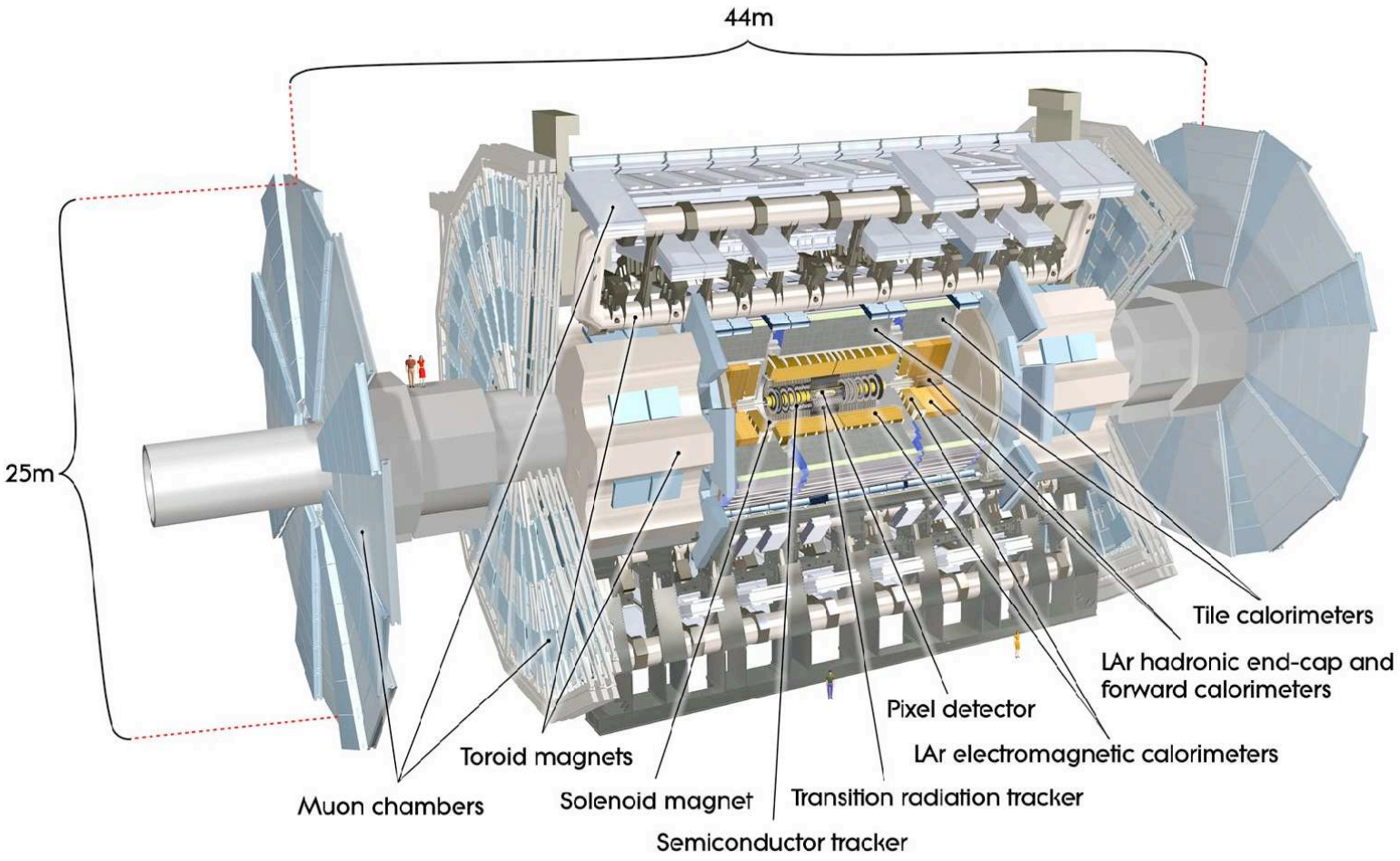
References

- Measurement of the inclusive and dijet cross-sections of b-jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector
  Eur. Phys. J. C (2011) 71:1846
  arXiv:1109.6833
- Measurement of $D^{*\pm}$ meson production in jets from pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector
  Accepted in Physical Review D (2012)
  arXiv:1112.4432

Thank you for your attention

Additional slides

ATLAS detector



Monte Carlo generators

- LO: Pythia 6.423
  - pQCD matrix elements for 2→2 processes
  - p_T-ordered parton-showers calculated in leading-log approximation
  - underlying event simulation with multi-parton interactions
  - Lund string model for hadronisation
  - set of parameters: AMBT1 with MRST LO* PDF
- NLO:
  - POWHEG + Pythia 6
  - MC@NLO + Herwig 6:
    - AUET1 tune
    - angular-ordered parton-shower model
    - cluster hadronisation
  - MSTW 2008 NLO PDFs
  - *b*-quark mass of 4.95 GeV

True jet flavour definition

- Tagged as *b*-jet if *b*-hadron (with $p_T > 5$ GeV) within $\Delta R = 0.3$ of jet axis
- Or *c*-jet if *c*-hadron within same distance
- Light-jet otherwise

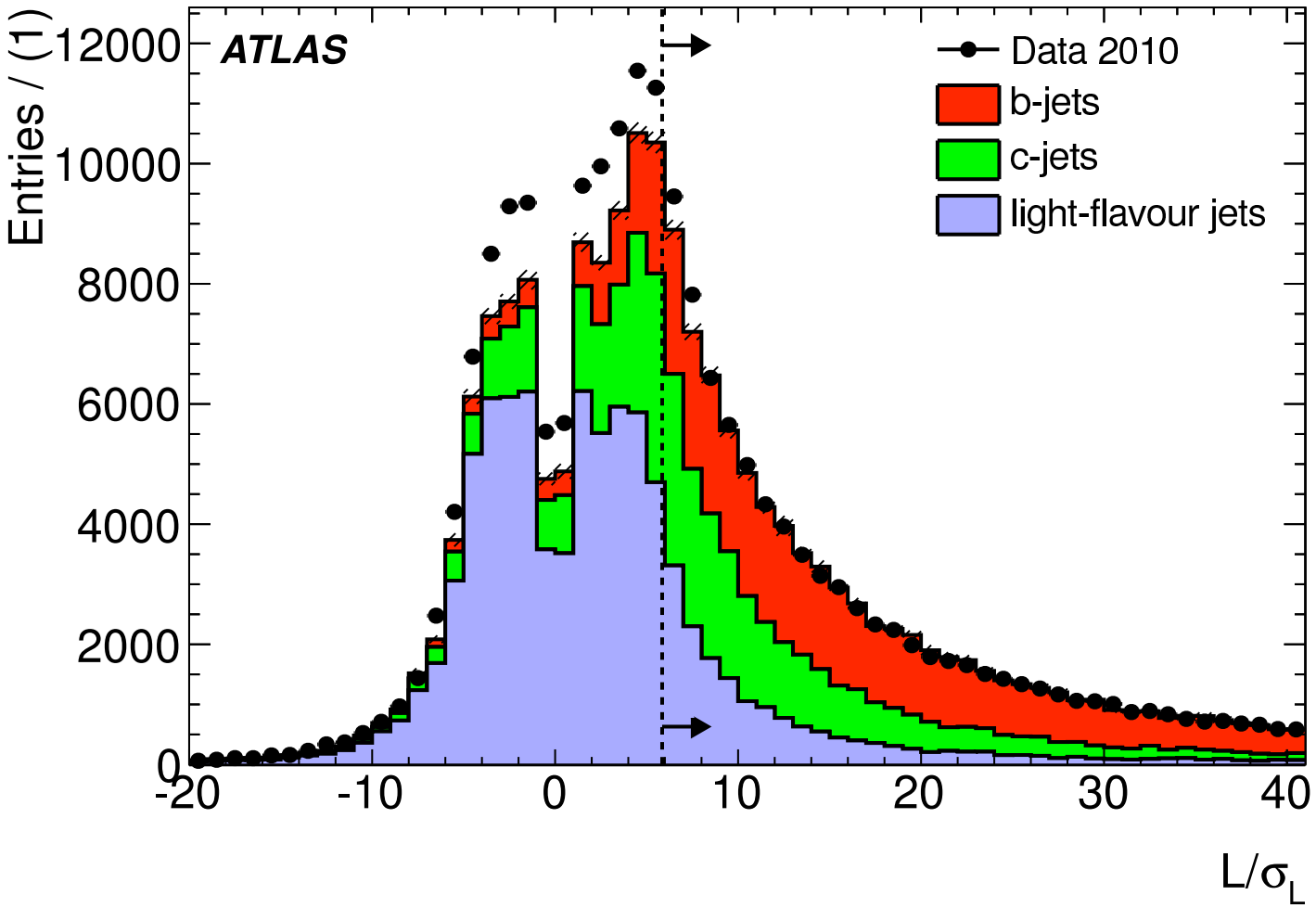
Event selection

- Lifetime-based analysis:
  - L1 or HLT jet triggers
  - MBTS trigger for $20 < p_T < 40$ GeV (inclusive cross-section)
  - Efficiency for *b*-jet above 97% (typically close to 100%)
- Muon-based analysis:
  - Combination of jet and μ triggers
  - Efficiency ~35% (p_T <50 GeV) to 65% (p_T >105 GeV)
  - Higher stat. due to different prescale than inclusive jet triggers
- Quality selections:
  - Reconstructed jets not produced by poorly calibrated or noisy cells
  - Charged particle tracks of good quality (for *b*-tagging)
  - Good reconstructed primary vertex (at least 10 tracks with p_T >150 MeV)
  - Reconstruction and quality req. efficiency above 96% for *b*-jets

Lifetime-based *b*-tagging algorithm

- SV0: reconstruction of secondary vertex from charged particles with high 3D impact parameter significance
- Reject vertex compatible with primary vertex or located at pixel detector layer
- Reject vertex with mass consistent with K_S^0/Λ^0 decay or γ conversion
- Signed decay length L (sign from projection onto jet axis)
- Jet is b-tagged if $L/\sigma_L > 5.85$
- Cut tuned for 50% efficiency in simulated $t\bar{t}$ events

Distribution of L/σ_L



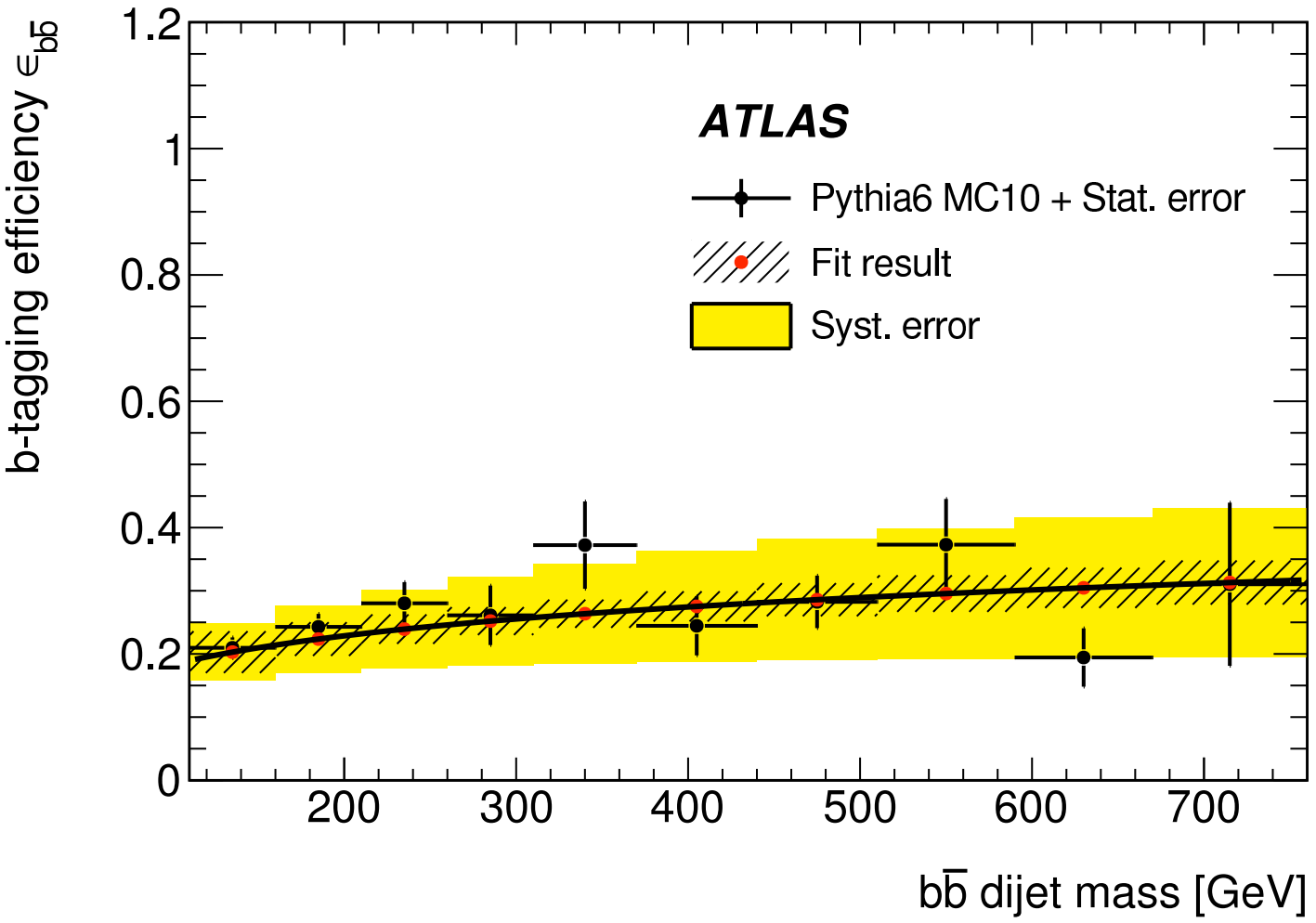
Lifetime-based *b*-tagging efficiency

- Efficiency estimated with data-driven method
- Jets containing a μ: p_T^{rel} (p_μ transverse to $p_\mu + p_{jet}$)
- p_T^{rel} spectrum harder for *b*-jets
- p_T^{rel} shape for each jet flavour:
  - simulation for *c*-jets and *b*-jets
  - data for light-jets (enriched sample)
- Fit of measured p_T^{rel} spectrum, adjusting templates

$\Rightarrow$ *b*-tagging efficiency from $\epsilon_b = \frac{f_b^{tag} N^{tag}}{f_b N} C$ ($C \sim$ few %)

- Estimation extended to all *b*-jets (not only decaying to μ), systematic uncertainty taken into account
- Only possible for p_T <140 GeV $\Rightarrow$ above use simulation and correction factor 0.88 ± 0.18 (from range 90-140 GeV)

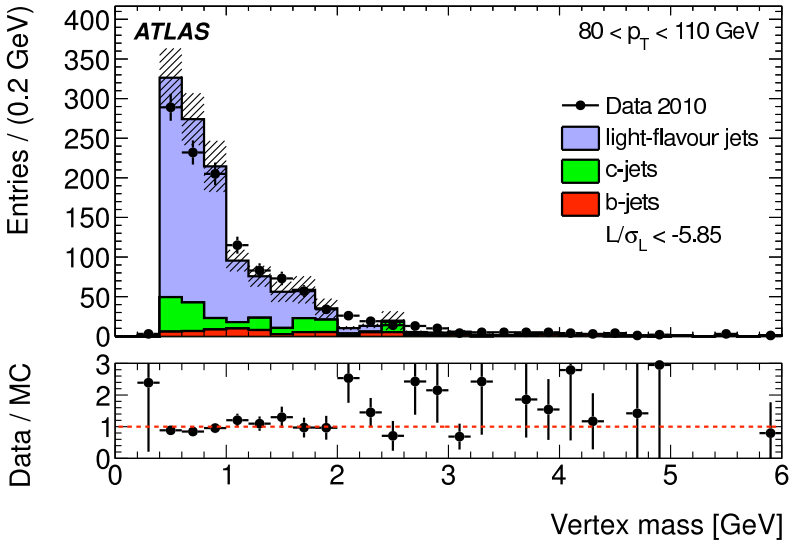
Lifetime-based *b*-tagging efficiency

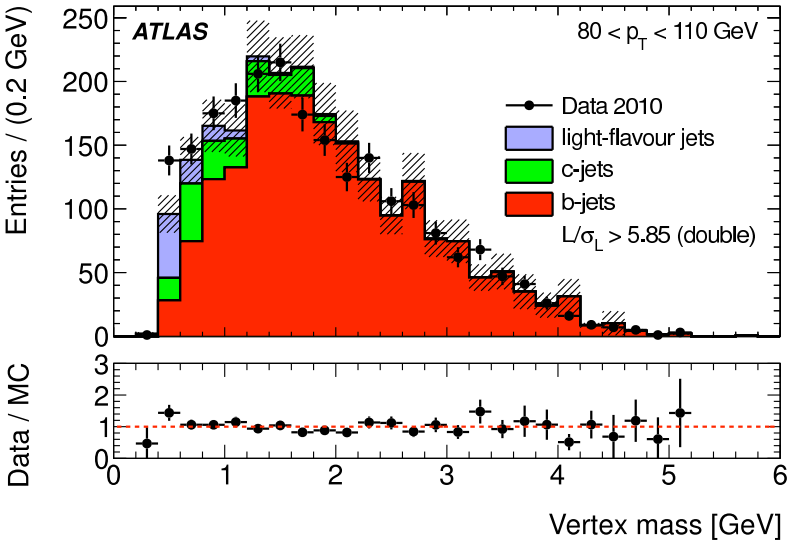


Systematic uncertainties for lifetime-based analysis

- 10-20% — *b*-jet energy scale calibration:
  - inclusive jet energy scale: 2-6%
  - +2.5% for *b*-jets (comparing particle-level jets to reconstructed jets in simulation)
  - includes different shower and hadronisation models
- 5-20% (incl.) 30-50% (dijet) — *b*-tagging efficiency:
  - modelling of μ in simulation
  - application of efficiency of jets with μ to all jets
  - limited stat. of templates for p_T^{rel} fits
- 3-8% (incl.) 20-30% (dijet) — *b*-jet purity:
  - study of secondary vertex mass distribution in light-jet/*b*-jet enriched samples
  - limited stat. of templates for $b\bar{b}$
- 3.4% — luminosity
- 2% — other sources (jet energy resolution, trigger efficiency, jet selection efficiency, ...)

Vertex mass uncertainty: studies of anti-*b*-tag and second *b*-jet





Muon-based analysis

- Jets with μ within $\Delta R < 0.4$ of jet axis and $p_{T\mu} > 4$ GeV
- Using p_T^{rel} in range $30 < p_T < 140$ GeV
- Template shapes for *c*-jets and *b*-jets from simulation
- Template shape for light-jets from data:
  - jets with anti-*b*-tagging, correction for *b*-jets contamination from simulation
  - inclusive jets without μ, taking charged track inside jet as μ
- Fit of measured p_T^{rel} spectrum, adjusting templates

$\Rightarrow$ *b*-jet fraction extraction

- Complementary to lifetime-based analysis because of different systematic uncertainties and event samples

Systematic uncertainties for muon-based analysis

- 15-20% — *b*-jet energy scale (same as lifetime-based study)
- 8-18% — *b*-jet purity:
  - different methods of light-jets shape estimation
  - limited stat. of templates fit
  - modelling of semileptonic *b*-hadron decays (variation of p_μ in *b*-hadron rest frame between two measurements: DELPHI and BaBar)
  - modelling of *b*-fragmentation (variation of $\pm 5\%$)
- 3.4% — luminosity
- 3% — other sources (jet energy resolution, trigger efficiency, jet selection efficiency, ...)

Unfolding

- Measured cross-sections corrected for experimental effects
- Bin-by-bin correction from Pythia dijets events:
  - cross-section for particle-level *b*-jets
  - cross-section for reconstructed *b*-jets

  $\Rightarrow$ ratio of cross-sections

References for inclusive b-jet and $b\bar{b}$-dijet

- CMS Collaboration, Inclusive b-jet production in pp collisions at $\sqrt{s} = 7$ TeV
  Subm. to the J. High Energy Phys. (2012) arXiv:1202.4617
- CMS Collaboration, Measurement of $B\bar{B}$ angular correlations based on secondary vertex reconstruction at $\sqrt{s} = 7$ TeV
  J. High Energy Phys. 03, 136 (2011) arXiv:1102.3194
- LHCb Collaboration, Measurement of $\sigma(pp \to b\bar{b}X)$ at $\sqrt{s} =$ 7 TeV in the forward region
  Phys. Lett. B 694, 209-216 (2010) arXiv:1009.2731

Monte Carlo generators

- LO:
  - Pythia 6.421 with MSTW LO PDF
  - Herwig 6 with AUET1 tune (underlying event with JIMMY)
- NLO: POWHEG
  - CTEQ 6.6
- c-quark mass of 1.5 GeV, b-quark mass of 4.75 GeV
- $f(c \to D^{*+}) = 0.224$, $f(b \to D^{*+}X) = 0.173$

Full reconstruction of $D^{*\pm}$ meson

- Two oppositely-charged tracks ($p_T > 1$ GeV) combined, two candidates:
  - $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^+\pi^-$
  - keep candidate within 50 MeV of PDG mass
  - keep candidate with positive transverse decay length
- Add track ($p_T > 0.5$ GeV) with same charge as selected pion:
  - $D^{*+} \to D^0\pi^+$ or $D^{*-} \to \bar{D}^0\pi^-$
  - keep candidate if $D^{*\pm}$ $p_T > 7.5$ GeV

Transverse decay length of D^0 candidate

- D^0 decay vertex reconstructed from K and π tracks
- $\vec{r}$ is displacement vector pointing from the primary vertex to the D^0 decay vertex, in the transverse plane
- $L_{xy} = \vec{r}.\vec{p}_T/|\vec{p}_T|$
- Cut on $L_{xy} > 0$:
  - rejects half of combinatorial background
  - keeps 89% of signal

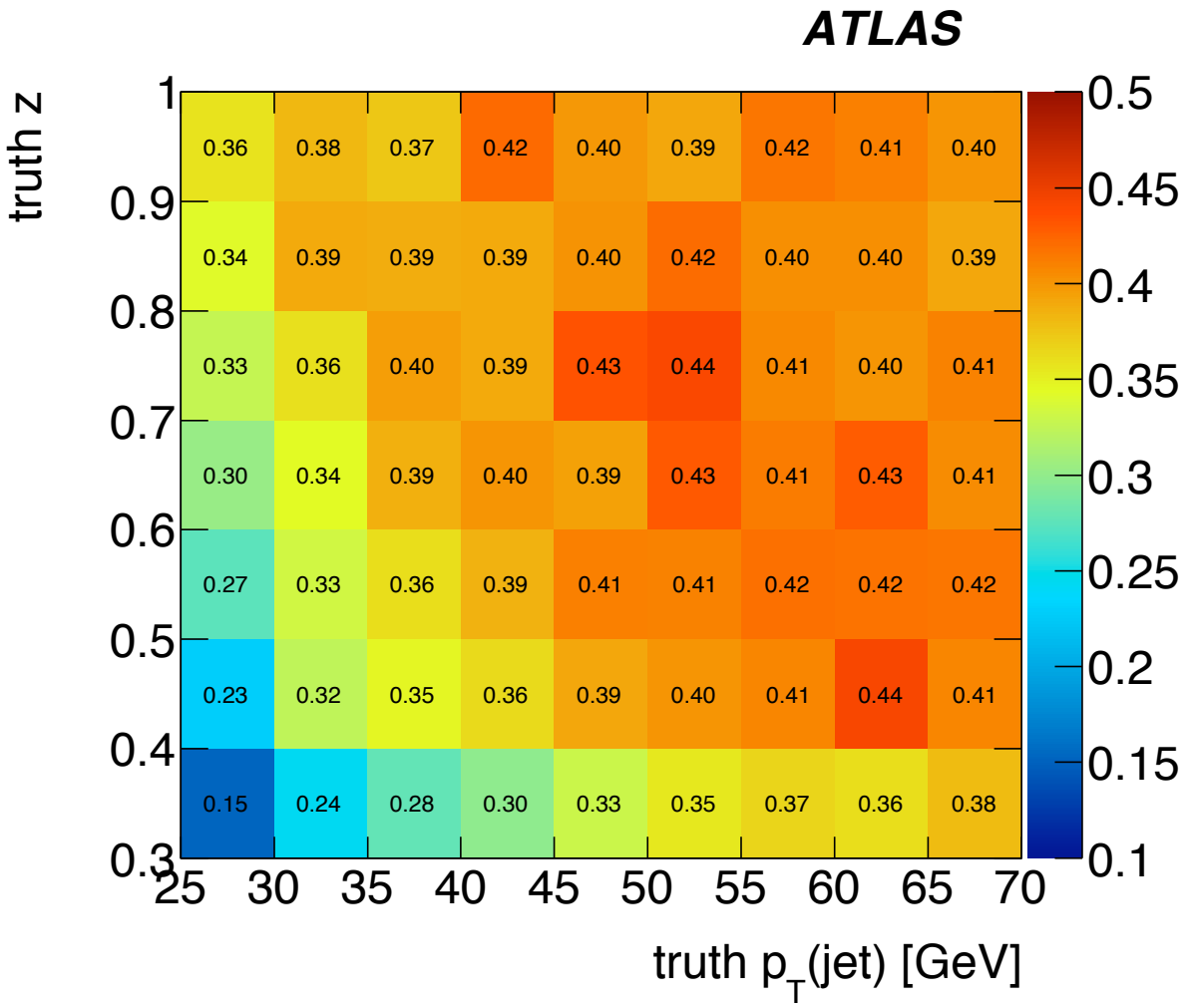
Unfolding

- $\mathcal{R}(p_T, z) = \frac{N^{reco}_{D^{*\pm}}(p_T,z)/\epsilon_{D^{*\pm}}(p_T,z)}{\mathcal{B}(D^{*\pm}\to K^{\mp}\pi^{\pm}\pi^{\pm})N^{reco}_{jet}(p_T)/\epsilon_{jet}(p_T)}$
- $\epsilon_{D^{*\pm}}(p_T, z) \sim$ 15-45% from simulation
- Finite resolution on jet energy $\Rightarrow$ reconstructed and particle-level p_T and z differ

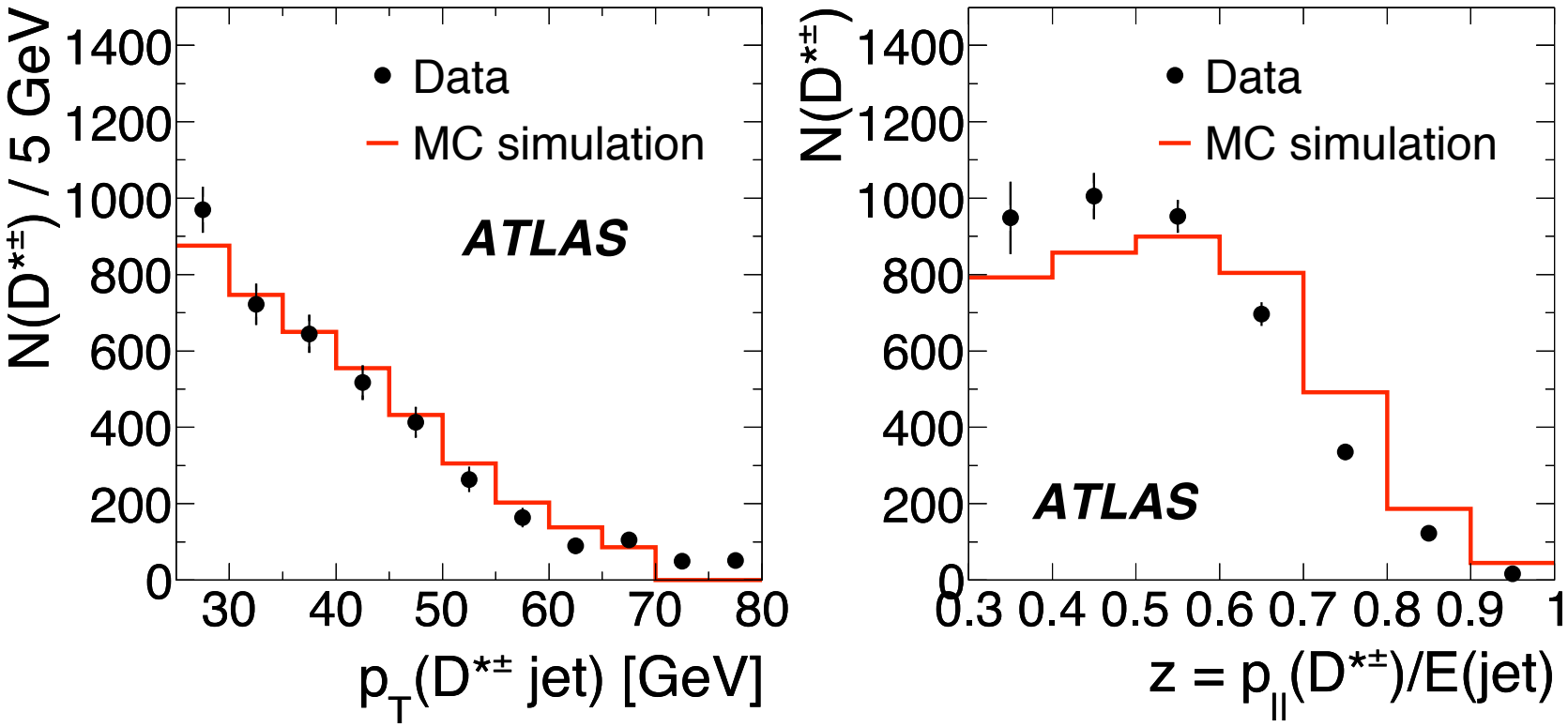
$\Rightarrow$ Bayesian iterative unfolding algorithm:

  - based on response matrix derived from simulated events
  - probability for a true $D^{*\pm}$ jet with a given p_T and z to be reconstructed in any given p_T and z bin
  - simulated distributions of p_T and z are reweighted to match measured distributions
  - same procedure for inclusive jets with p_T only
  - algorithm validated with 1000 simulated ensembles $\Rightarrow$ no bias

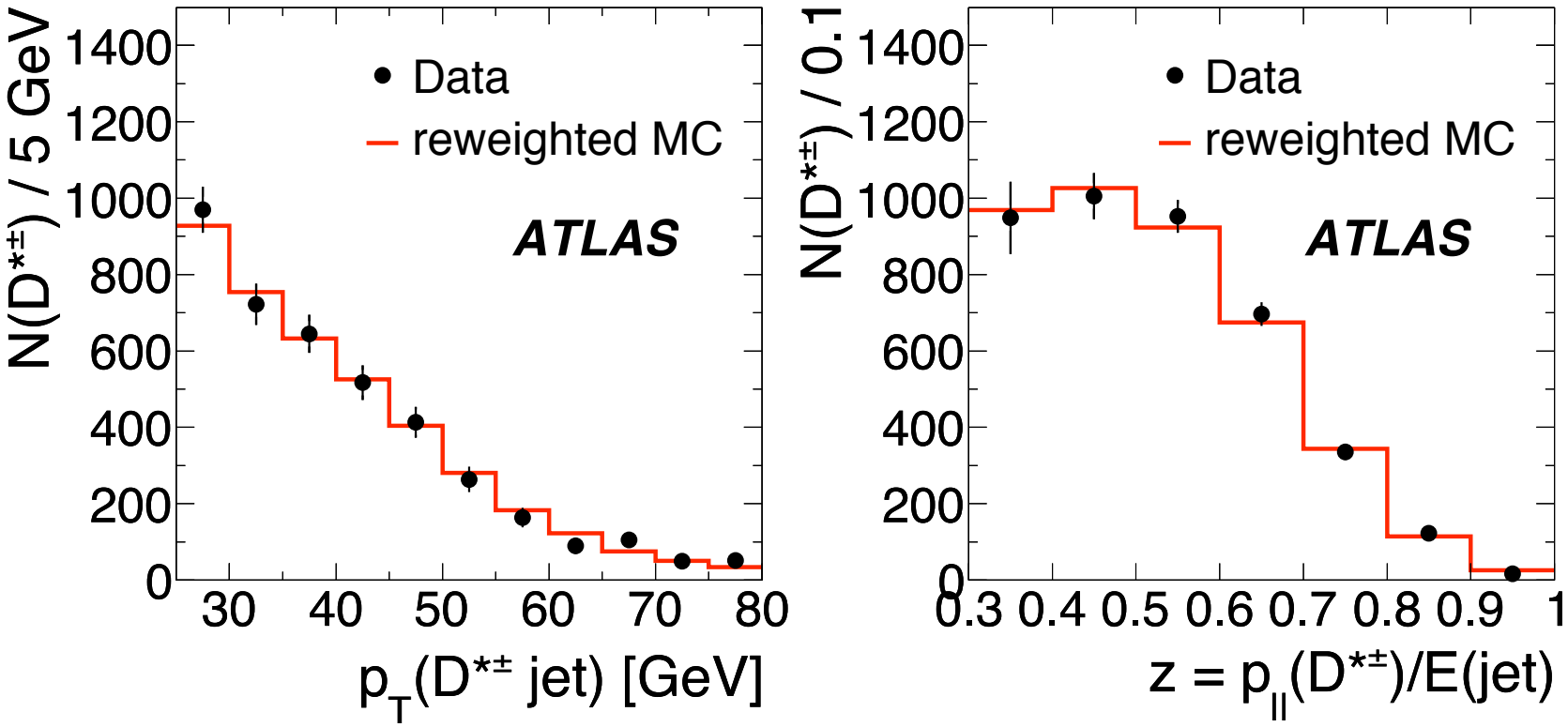
$D^{*\pm}$ jet reconstruction efficiency



Before reweighting simulation to data



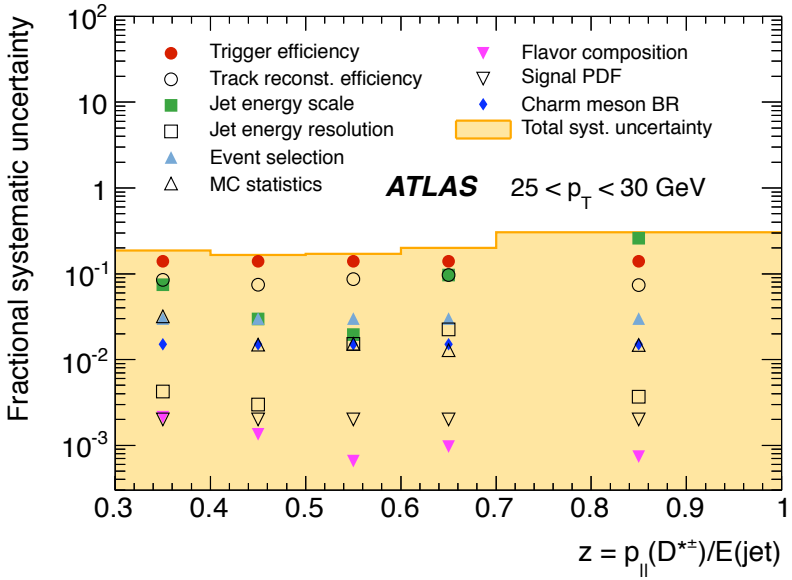
After reweighting simulation to data

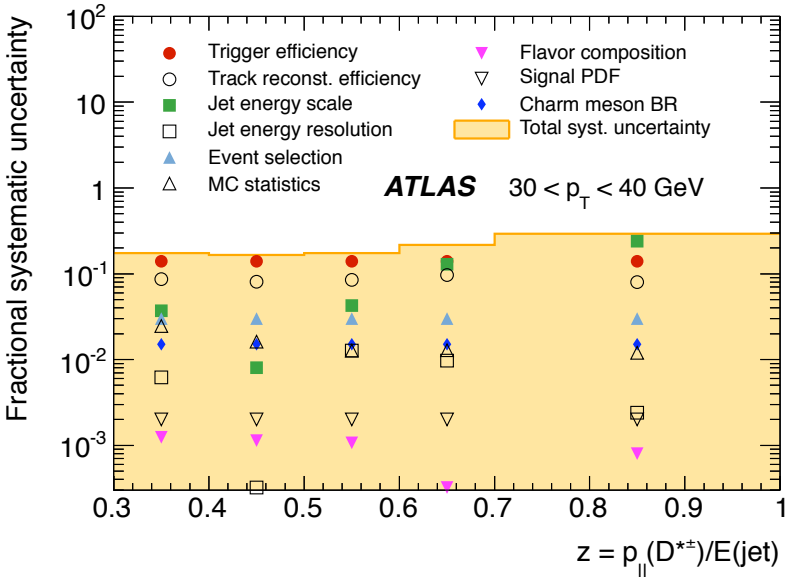


Systematic uncertainties

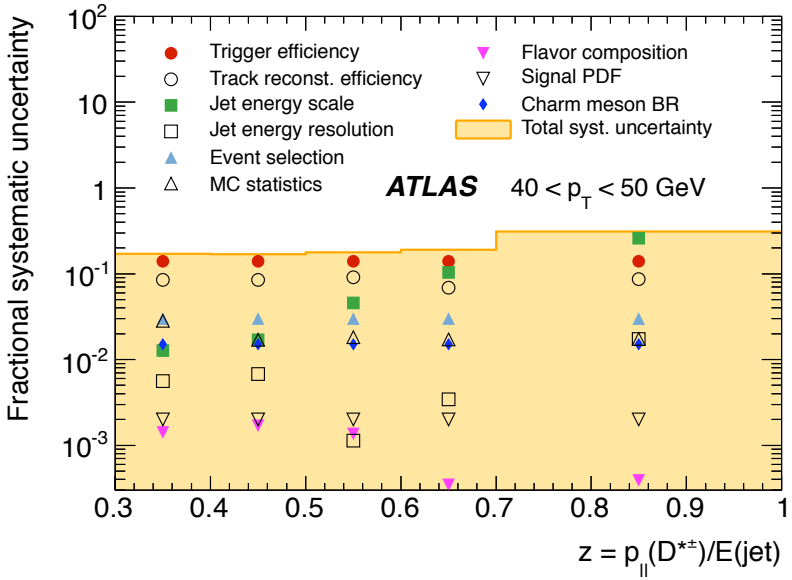
- 14% — trigger efficiency:
  - $r = N^{reco}_{D^{*\pm}} / N^{reco}_{jet}$ and $\rho = r_{jet-trig} / r_{MBTS}$
  - no jet selection in MBTS trigger
  - agreement for ρ in data and simulation
  - statistical uncertainty of 14% on ρ on data (due to limited size of MBTS sample)
- 8% — track reconstruction efficiency:
  - each reconstructed $D^{*\pm}$ has a weight w_{trks}
  - $w_{trks} = (1 + s_K) \times (1 + s_{\pi_1}) \times (1 + s_{\pi_2})$
  - $s_K, s_{\pi_1}, s_{\pi_2} = \pm 1\sigma$ of track reconstruction efficiency (depends on p_T and η, measured in data)
  - two measurements of $\mathcal{R}$ with $s = \sigma$ and $s = -\sigma$
- 3.4% — luminosity
- 3% — jet energy scale
- 3% — transverse decay length efficiency
- 1.5% — decay branching fraction of $D^{*\pm}$

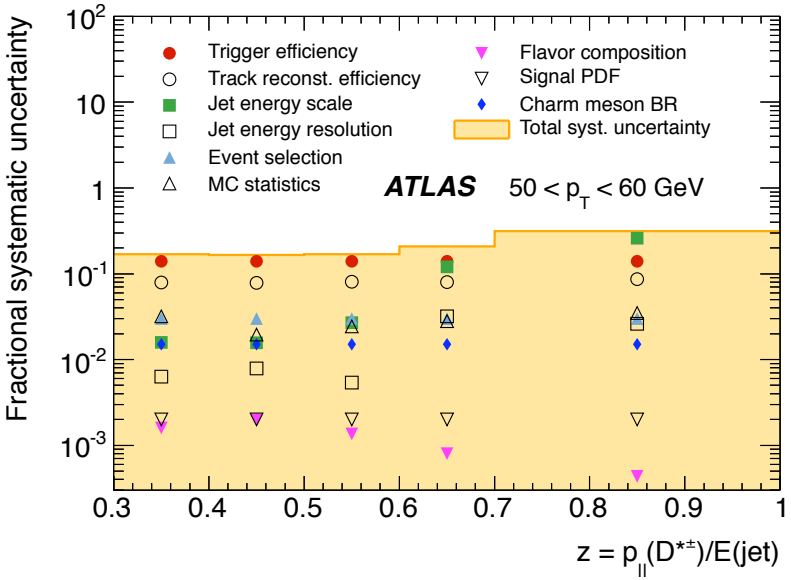
Systematic uncertainties



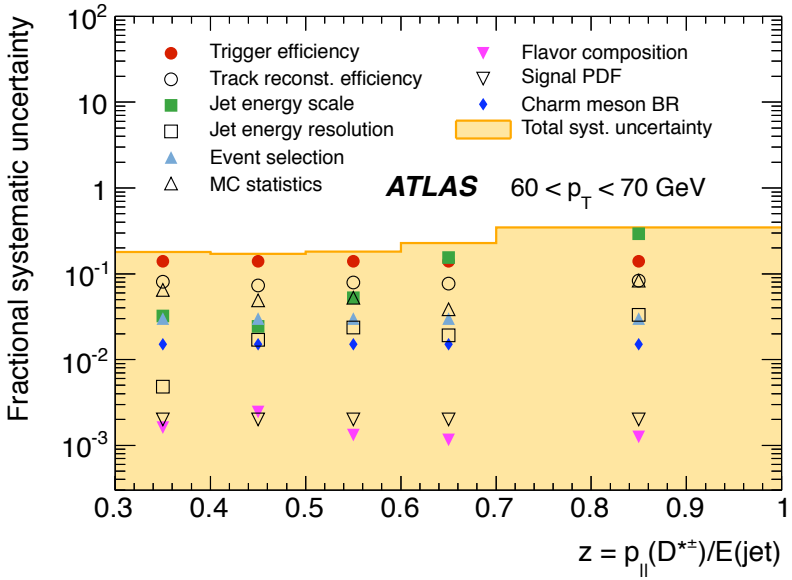


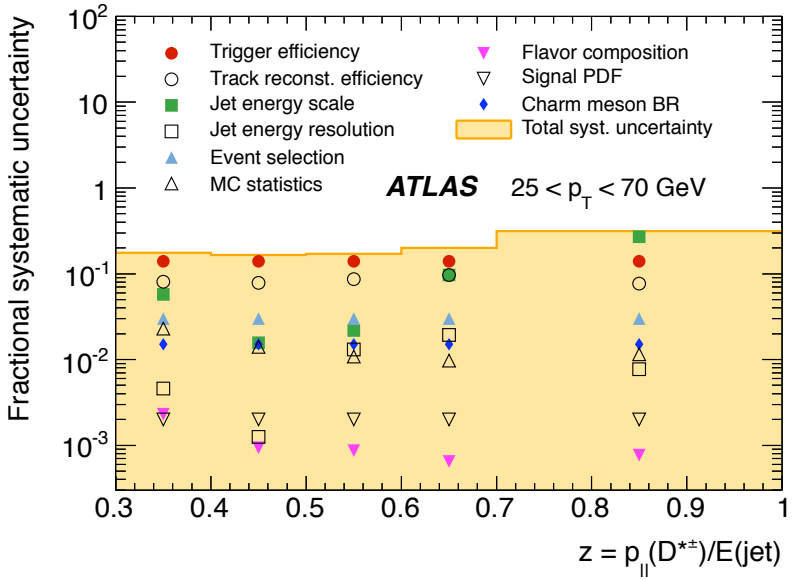
Systematic uncertainties



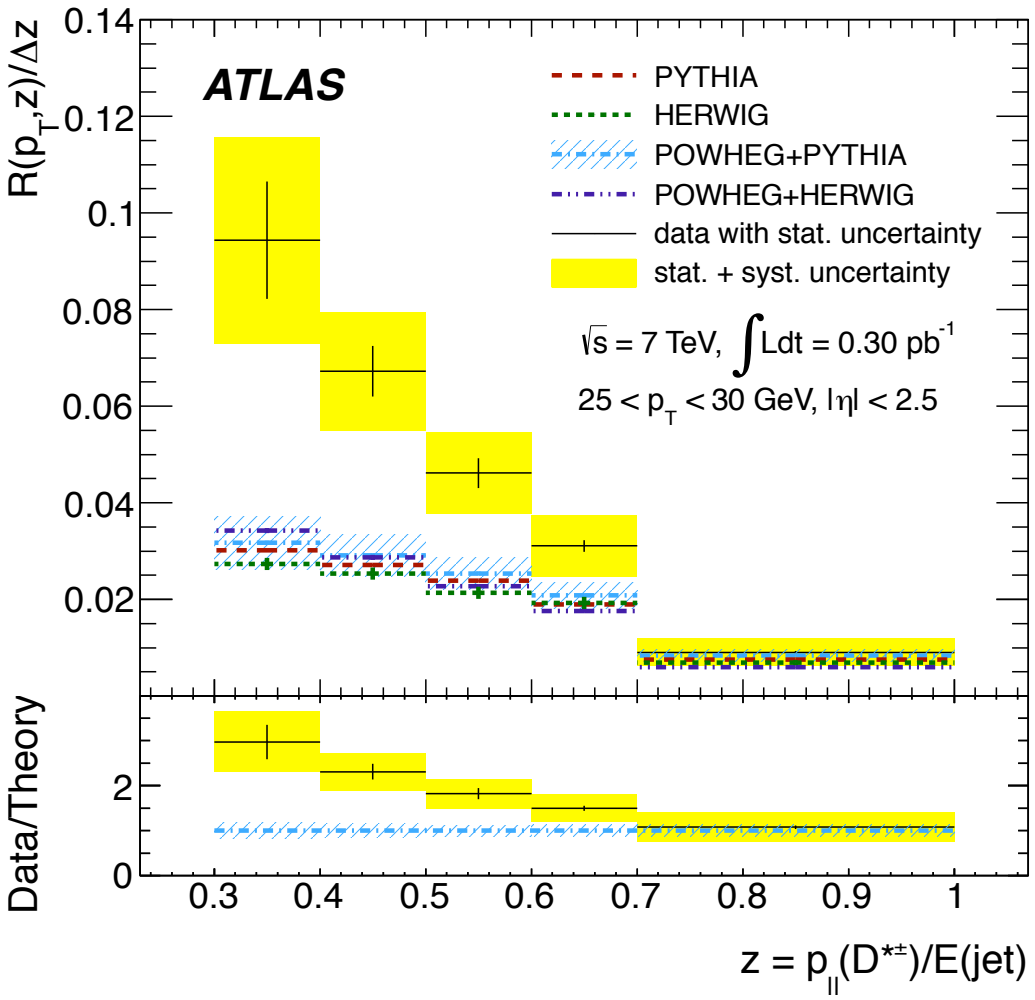


Systematic uncertainties

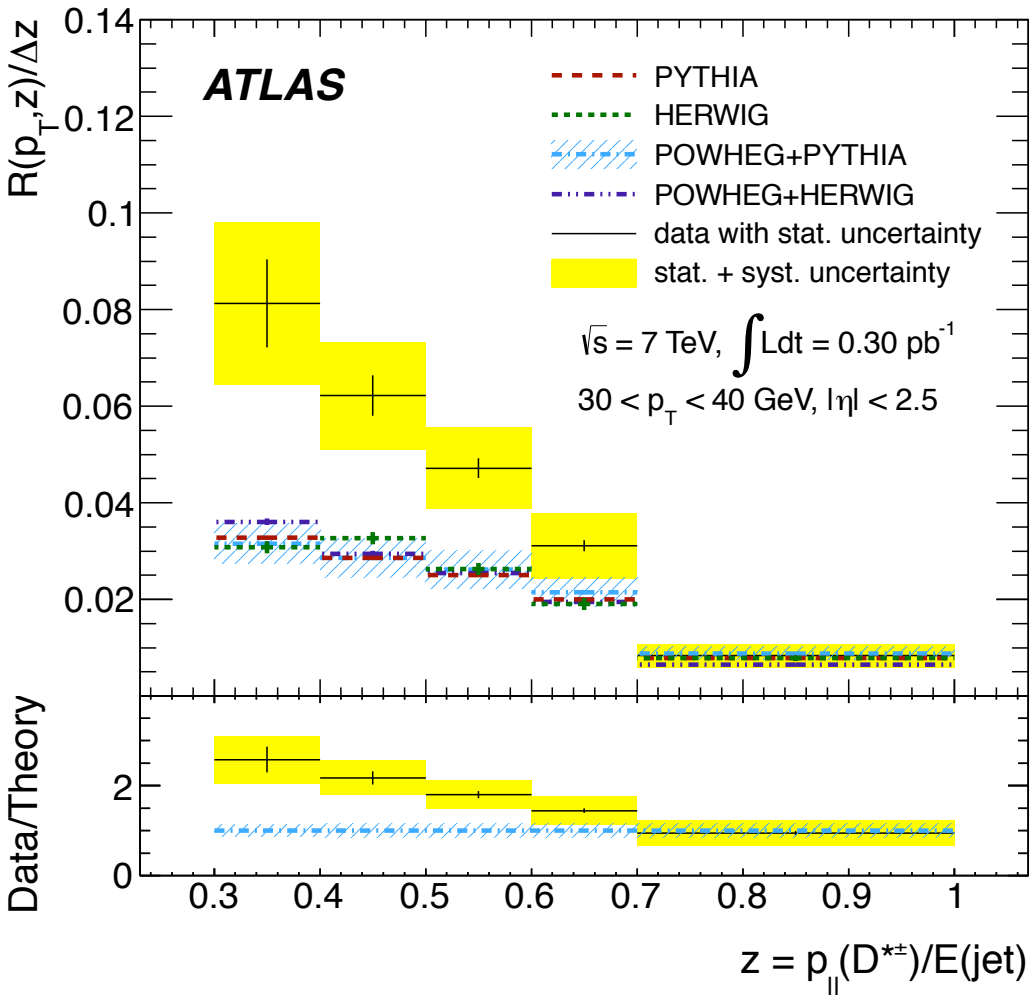




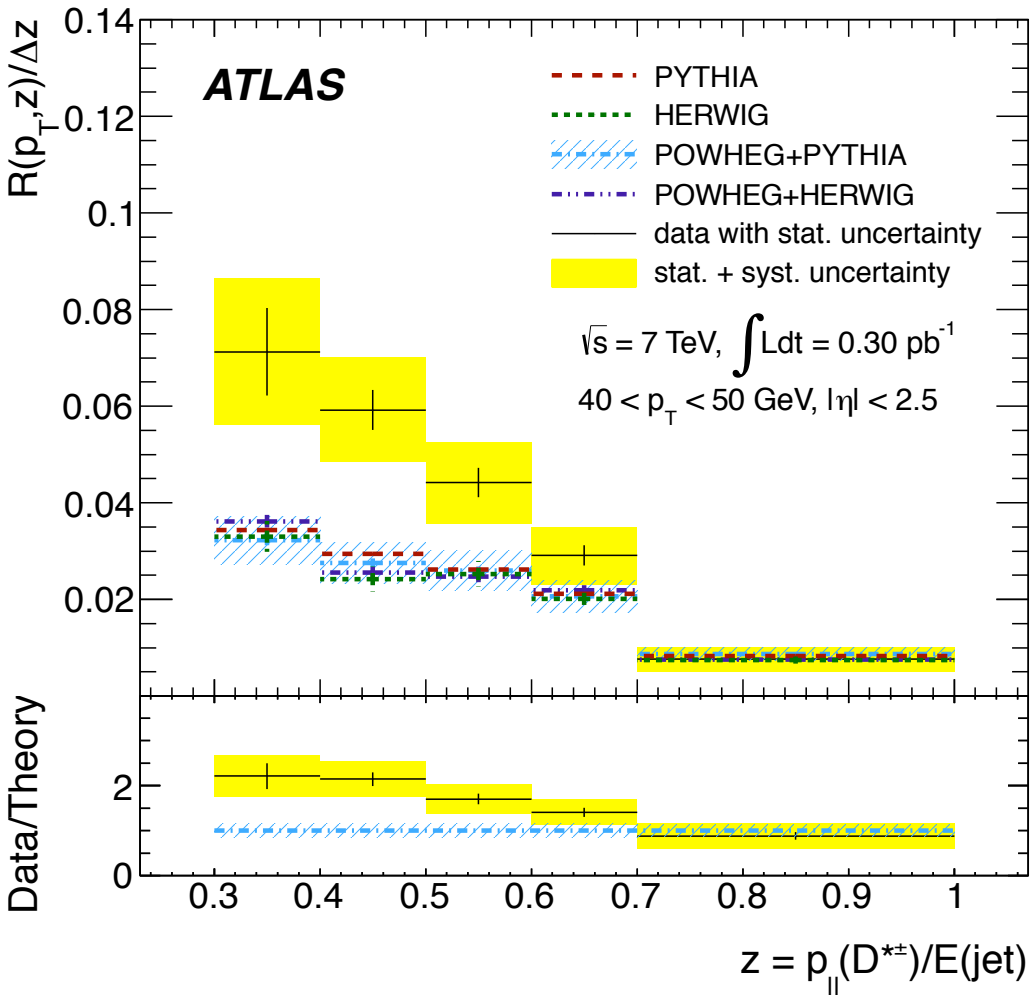
Measurement of $D^{*\pm}$ production in jets



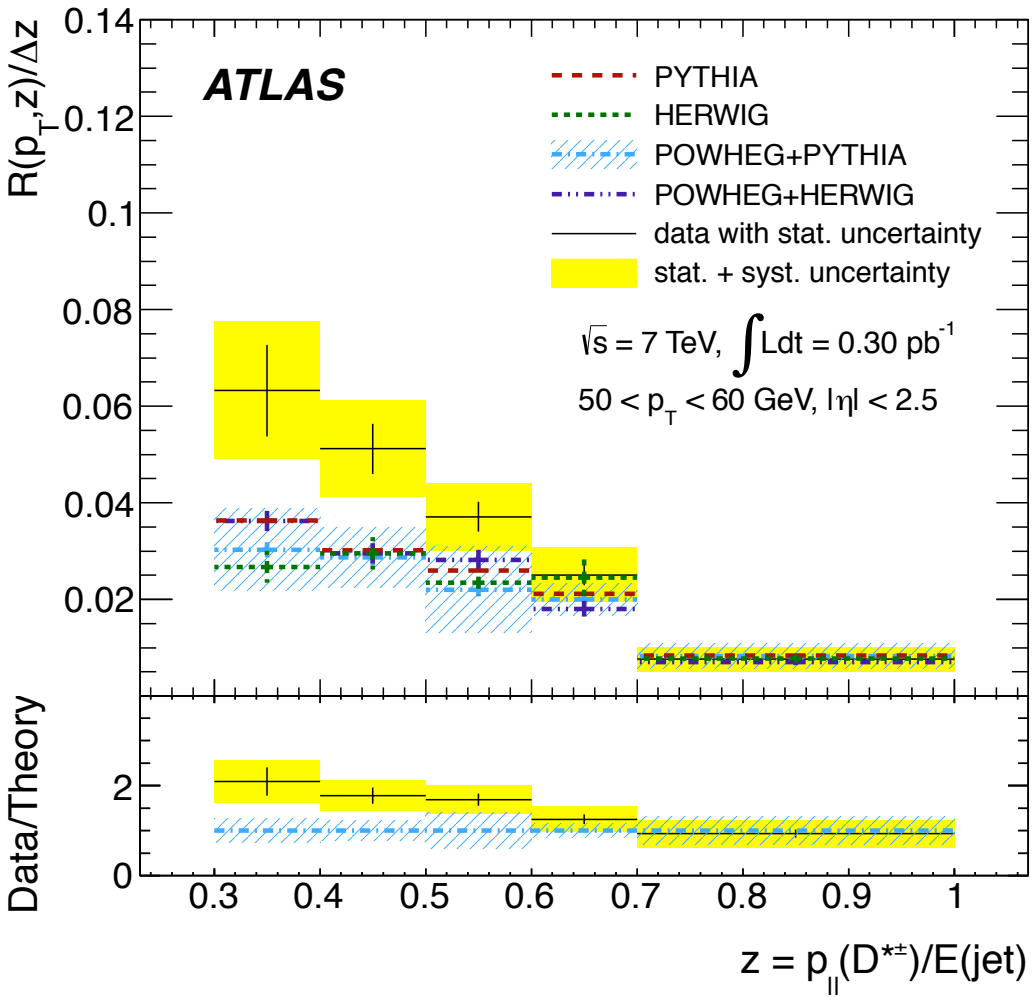
Measurement of $D^{*\pm}$ production in jets



Measurement of $D^{*\pm}$ production in jets



Measurement of $D^{*\pm}$ production in jets



Measurement of $D^{*\pm}$ production in jets