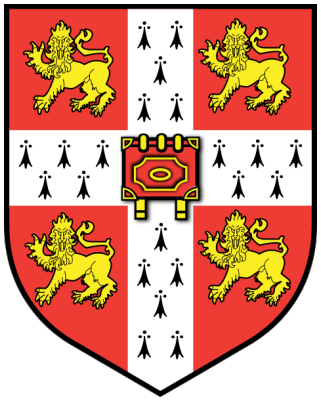


Current and future jet measurements at LHCb

LHCb Implications Workshop

William Barter

University of Cambridge

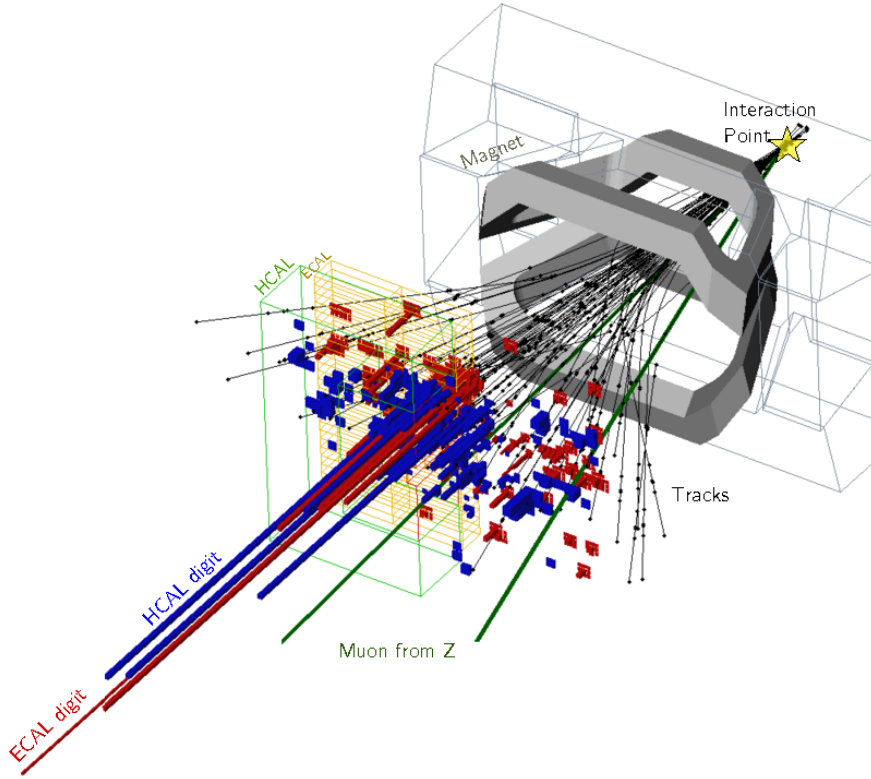
14th October 2013

Jet Reconstruction at LHCb

Introduction

- Jets are a key signature of new physics models, and a key part of Standard Model.

- Major points covered in this talk:
  - How does LHCb reconstruct jets?
  - Example of a current measurement using LHCb jet reconstruction.
  - Potential future measurements at LHCb.



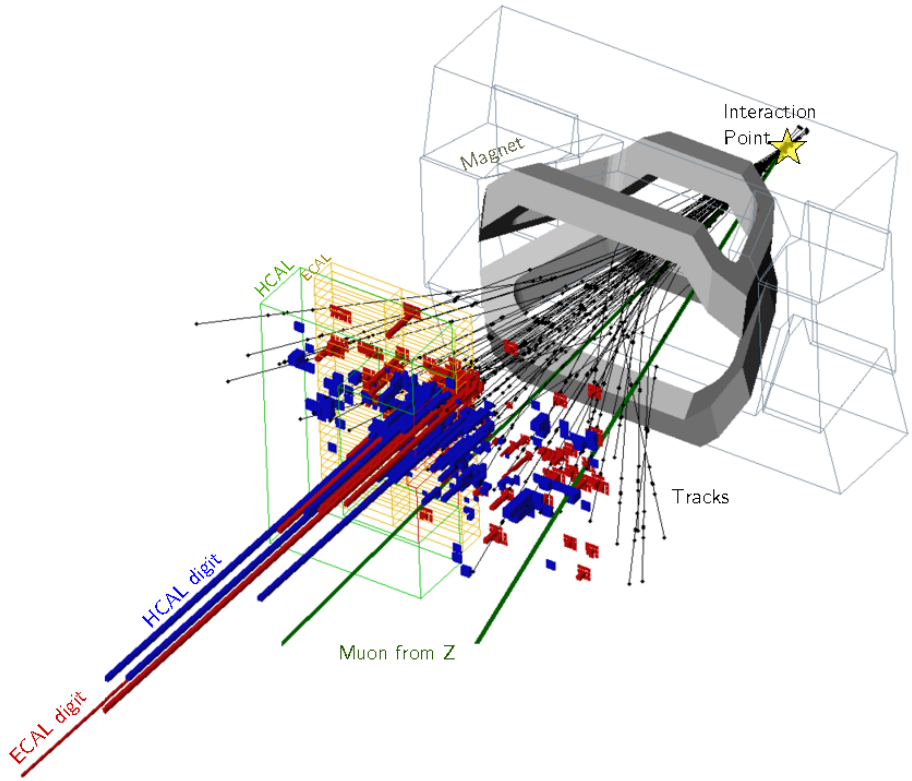
- Talk provides technical details of jet reconstruction and performance at LHCb. Other talks in session will describe how we can utilise these tools.

Jet Reconstruction at LHCb

Reconstructing jets at LHCb

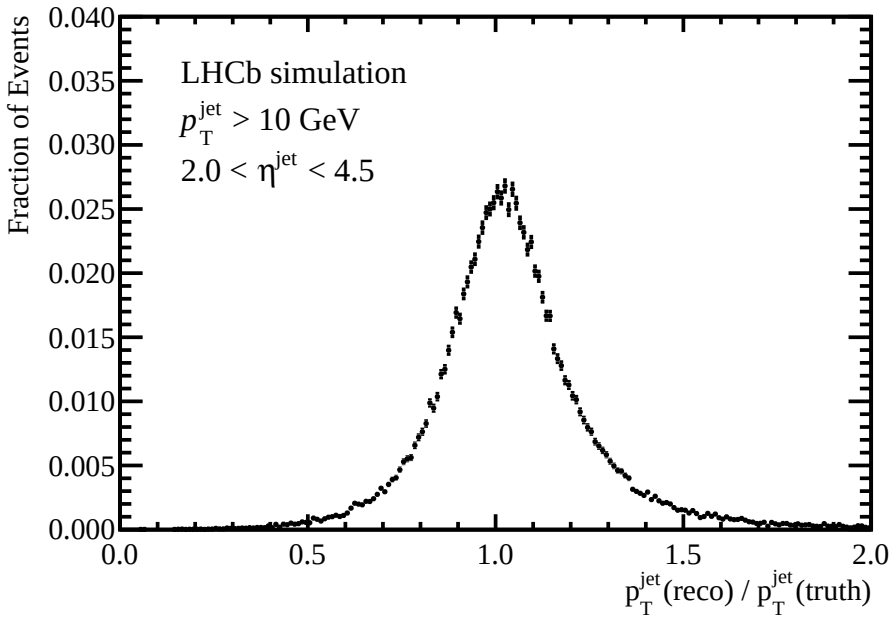
- Reconstruct jets using FastJet implementation of the anti-k_T algorithm, with distance parameter optimised to be $R = 0.5$.
  - radius parameter $R = 0.7$ also studied, reconstruction under development.
  - alternative seed based approach used to measure $\sigma(b\bar{b})$ - LHCb-CONF-2013-002.

- Use particle flow approach to select inputs for reconstruction:
  - Information about charged particles - well reconstructed tracks, using primary vertex information.
  - Information about neutral particles - energy deposits in the calorimeters with any track contribution matched to the cluster removed.



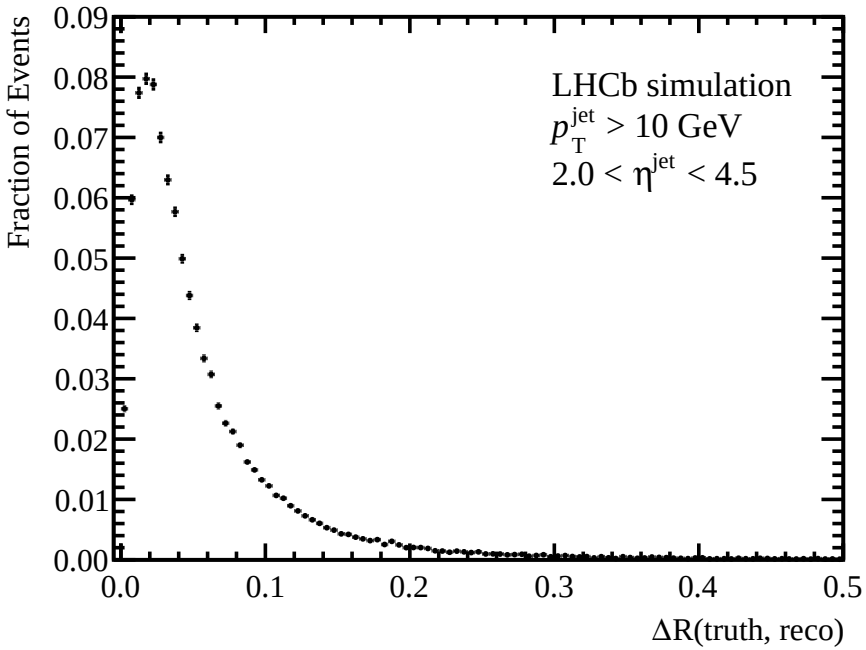
Performance of Jet Reconstruction at LHCb

- Measure jets at the hadron level - energy of jets is scaled to give an unbiased estimate of true energy in simulation:
  - scaling is found as function of number of primary vertices, p_T, η, and fraction of jet energy carried by charged particles.
  - scaling typically between 0.9 and 1.1.



- Energy resolution is $\sim 10 - 15\%$ - comparable with ATLAS and CMS in similar p_T region (10-50 GeV). LHCb uses luminosity levelling, so events are low pileup.

Performance of Jet Reconstruction at LHCb



- Direction of jets is well-measured: 90% of jets matched to truth level jets with $\Delta R < 0.13$.

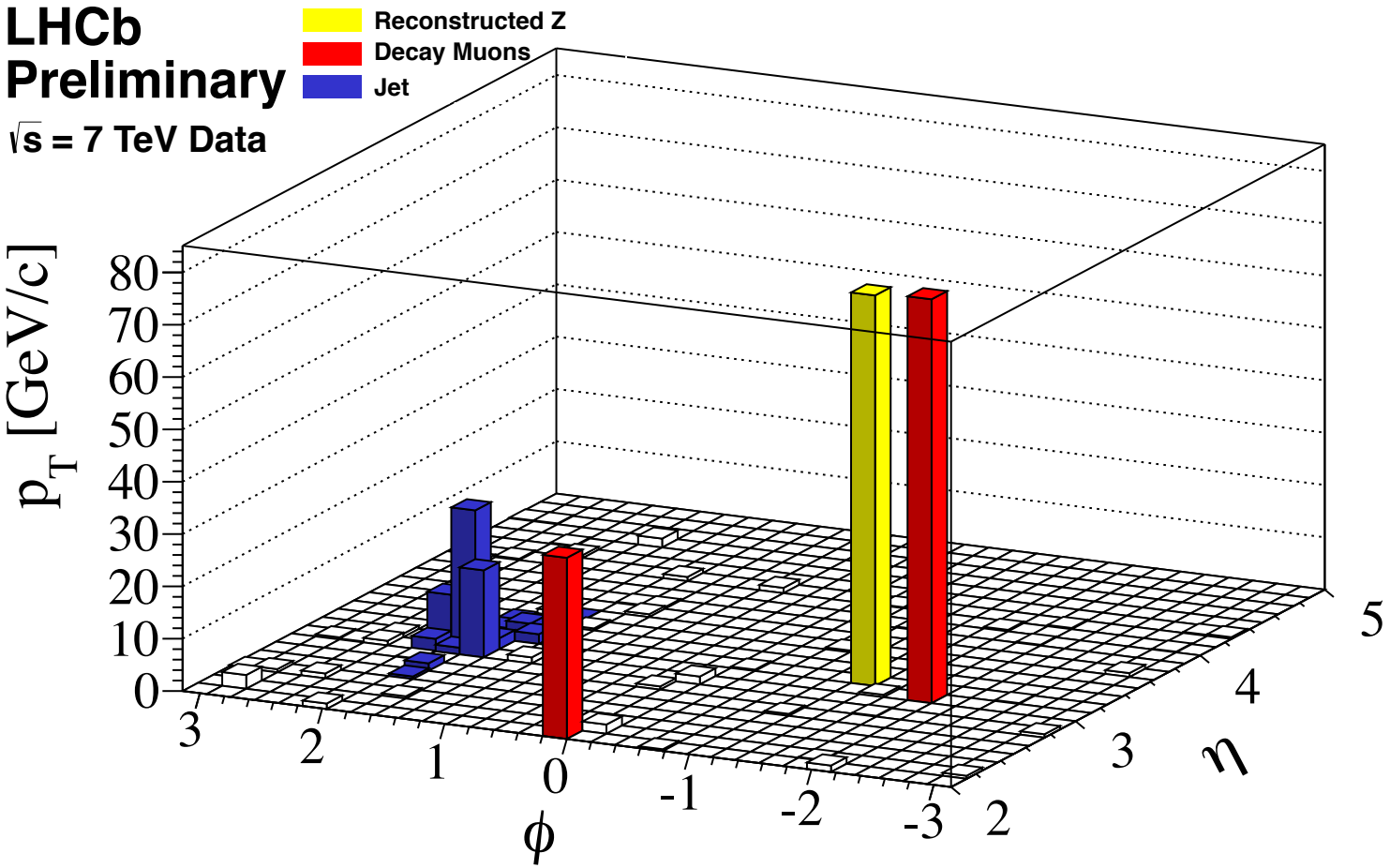
- In addition, we place requirements on the jets to reduce the number of fake/spurious jets and poorly measured jets, removing jets dominated by one high p_T particle. Also require jets are associated with a particular primary vertex.
- Jet reconstruction efficiency typically $\sim 75\%$ at low p_T and and $\sim 95\%$ at higher p_T.

Performance of Jet Reconstruction at LHCb

Systematic uncertainties associated with the jet energy scale:

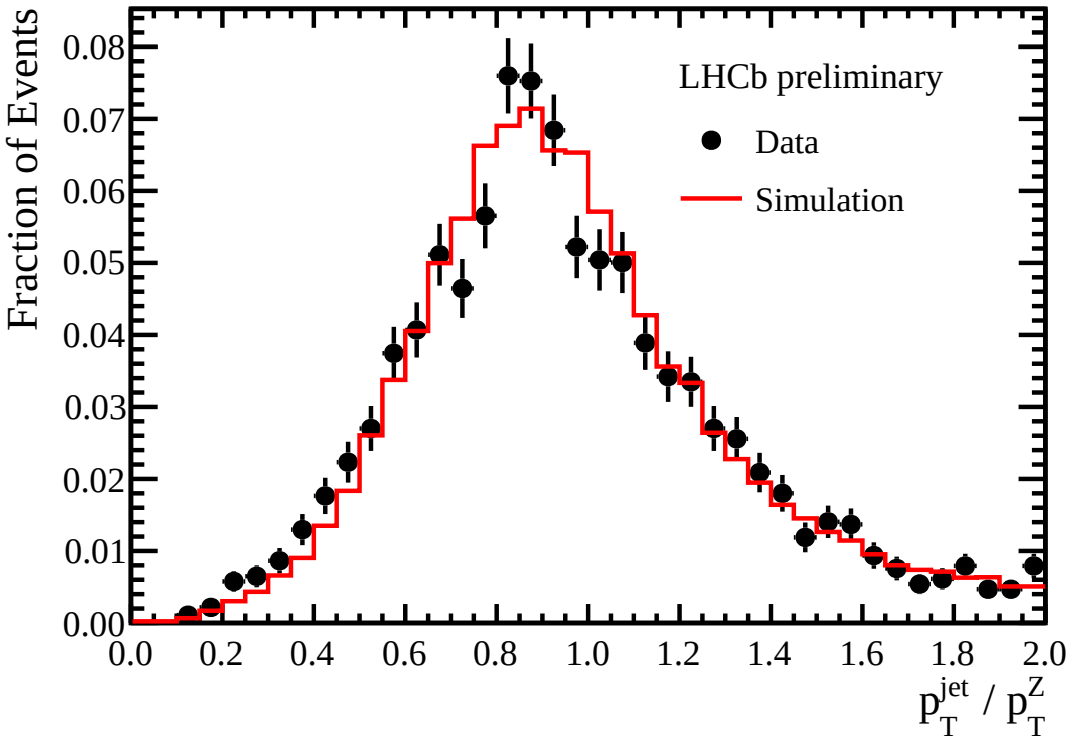
- methods used to extract jet energy scale - typically $\sim 1\%$.
- difference in performance from gluon initiated and quark initiated jets - typically $\sim 2\%$.
- Also want to validate the performance of the jet reconstruction algorithms at LHCb on data: how well is detector response to jets modelled in simulation?
- select Z+1-jet events at LHCb where the Z and jet are back-to-back in ϕ.
  - p_{T} of Z can be used as proxy for the true jet p_{T}.
  - compare $p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}}^{\mathrm{Z}}$ distributions in data and simulation.
  - extent of agreement sets systematic uncertainty on jet energy scale associated with how well simulation models data.

Performance of Jet Reconstruction at LHCb



Performance of Jet Reconstruction at LHCb

LHCb-PAPER-2013-058



- excellent agreement between data and simulation.
- investigate as function of η, p_T.
- vary detector response to jets in sim. by $\sim 3\%$ before discrepancy between data and varied-simulation.

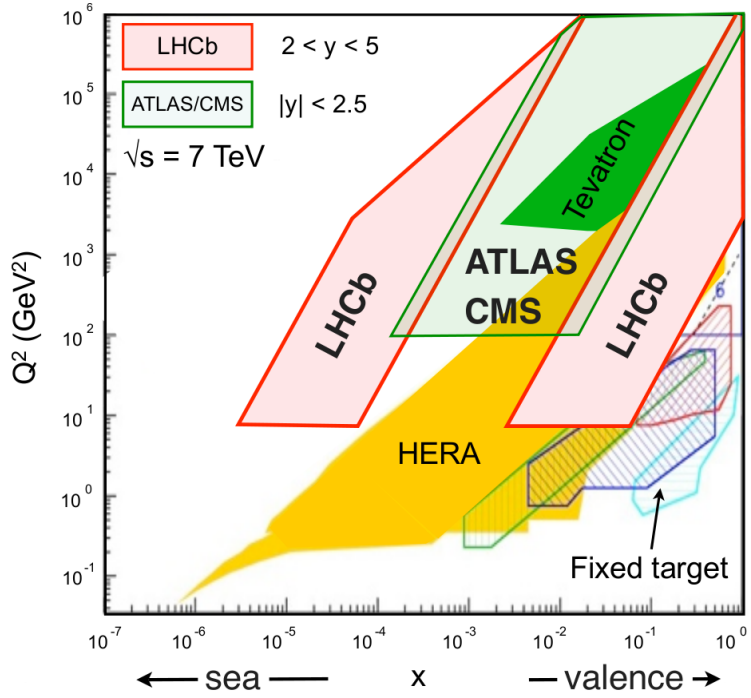
- typically $\sim 3\%$ uncertainty from modelling of detector response to jets.
- investigate modelling of resolution using similar techniques - can smear resolution in simulation at the level of $\sim 10\%$ before significant discrepancy with data.

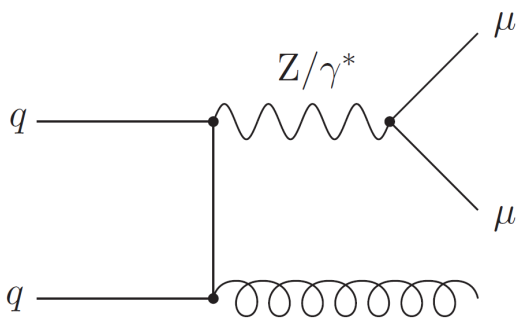
Jet Reconstruction at LHCb

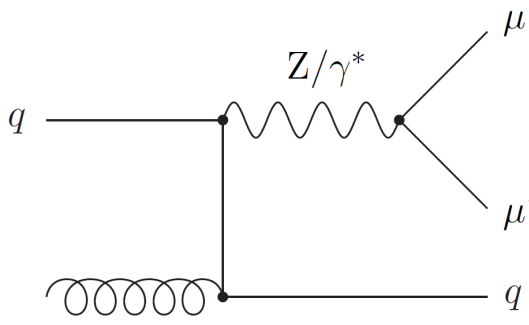
Z+jet at LHCb

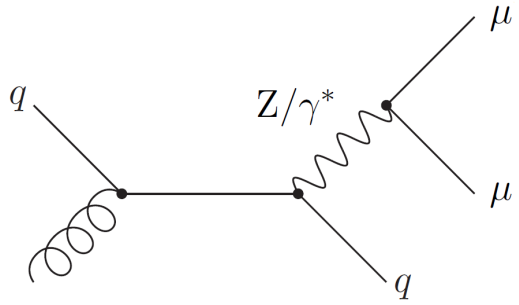
LHCb-PAPER-2013-058

- Studies of Z$\rightarrow \mu\mu$ + jet production at LHCb:
  - allow us to probe PDFs in a previously unexplored kinematic region (low x, high Q^2).
  - are also a useful test of pQCD in the forward region.
  - also provide a benchmark measurement of a Standard Model process.









Z+jet at LHCb

- The fiducial acceptance is:
  - $2.0 < \eta^{\mu} < 4.5$,
  - $p_{\mathrm{T}}^{\mu} > 20$ GeV,
  - $60 < M_{\mu\mu} < 120$ GeV,

  - $2.0 < \eta^{\mathrm{jet}} < 4.5$,
  - $p_{\mathrm{T}}^{\mathrm{jet}} > 20(10)$ GeV - measurement made for two jet p_{T} thresholds,
  - $\Delta R(\mu, \mathrm{jet}) > 0.4$.

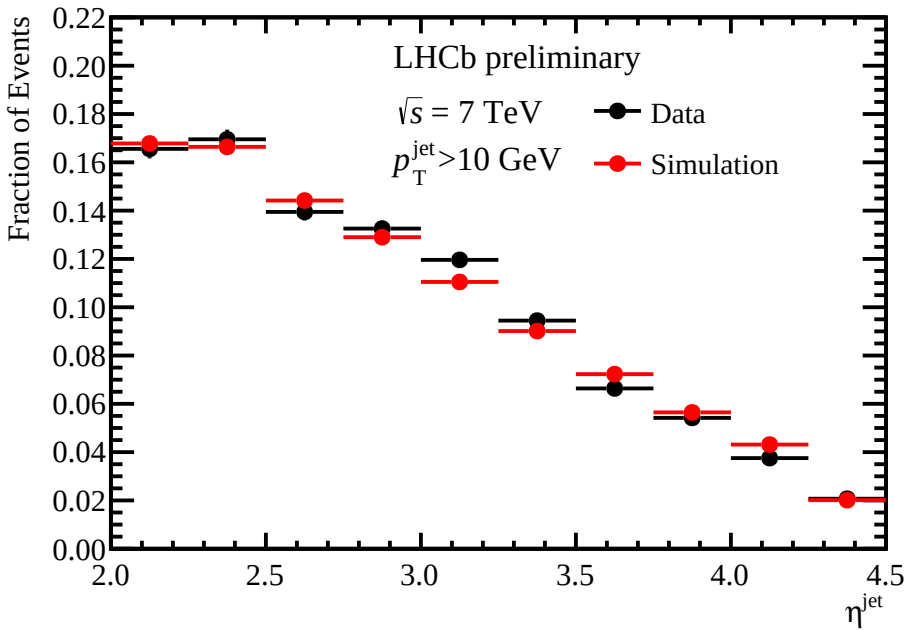
- Also apply selection requirements we correct for - these select high quality events:
  - trigger fired by a muon with $p_{\mathrm{T}} > 10$ GeV,
  - also select events with high quality track reconstruction,
  - jet reconstruction quality cuts.

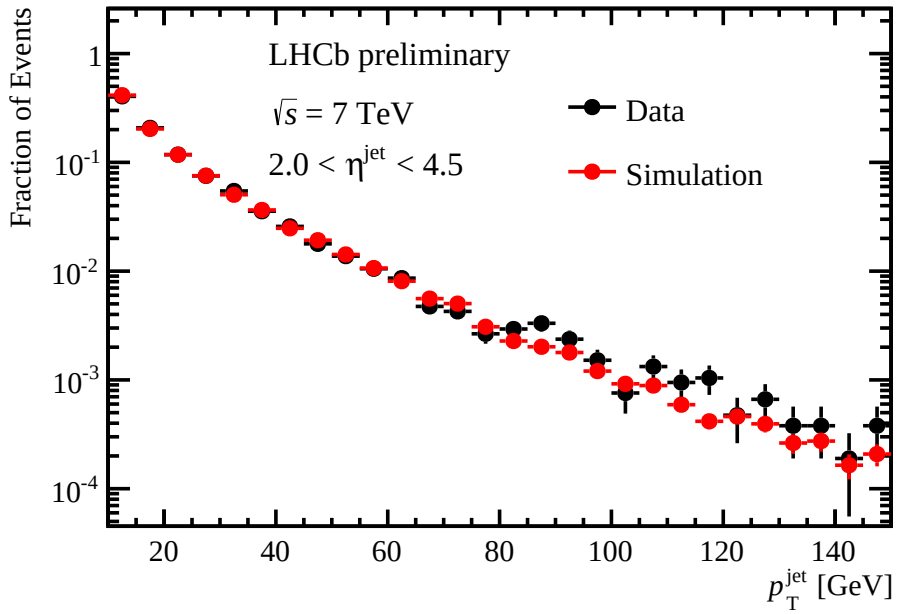
- Same $Z \rightarrow \mu\mu$ selection as papers on Z production - see LHCb-PAPER-2012-008.

Z+jet at LHCb

LHCb-PAPER-2013-058

- LHCb PYTHIA 6 Monte Carlo simulation compared to data in selected Z+jet events.





- Plots normalised to unit integral, and are uncorrected for detection efficiencies.
- LHCb simulation performs well - provides confidence that the LHCb jet reconstruction is well modelled.

Z+jet at LHCb

- Systematic Uncertainties:

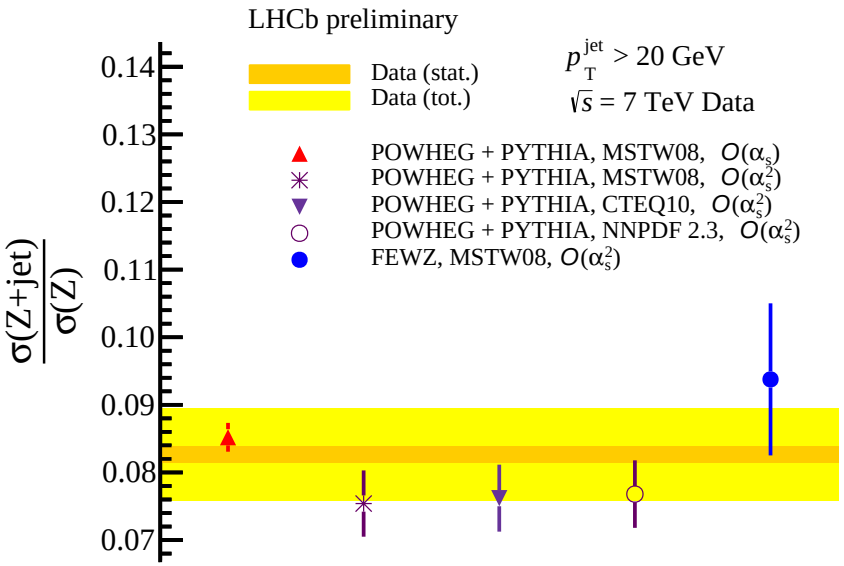
Source of Systematic Uncertainty	Relative Uncertainty (%)
Unfolding	1.5
Luminosity	3.5
Z detection and reconstruction	3.5
Jet energy scale, resolution and reconstruction	7.8
FSR	0.2
Total	9.3

- Uncertainty dominated by knowledge of the Jet Energy Scale (discussed earlier).

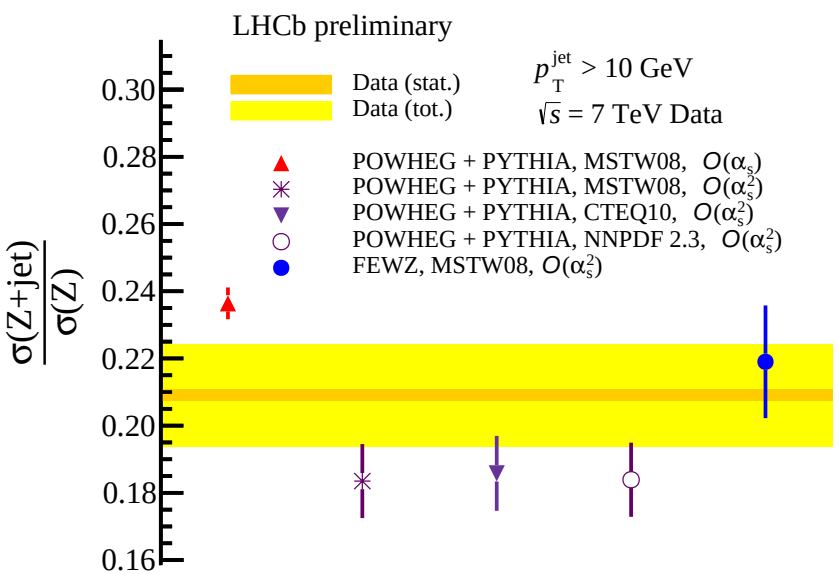
Z+jet at LHCb

LHCb-PAPER-2013-058

- Results - ratio with inclusive Z cross-section:



$p_T^{jet} > 20$ GeV



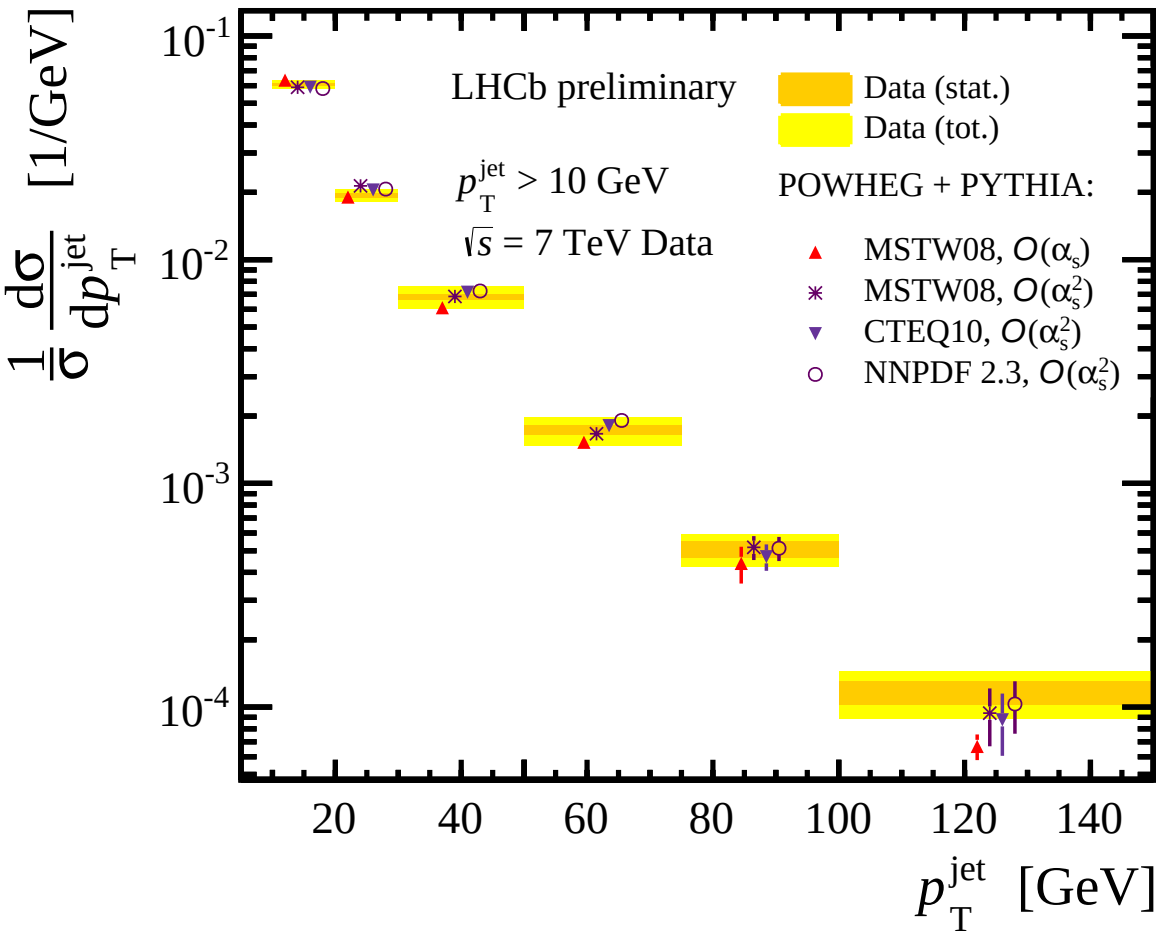
$p_T^{jet} > 10$ GeV

- Compare with theoretical predictions from POWHEG showered with PYTHIA for different PDF sets, and at different $\mathcal{O}(\alpha_s)$.
- parton level prediction from FEWZ included in cross-section ratio measurements to show size of effects from fragmentation, hadronisation and underlying event.

Z+jet at LHCb

LHCb-PAPER-2013-058

- Results - jet transverse momentum distribution:
  - normalised to total Z+jet cross-section

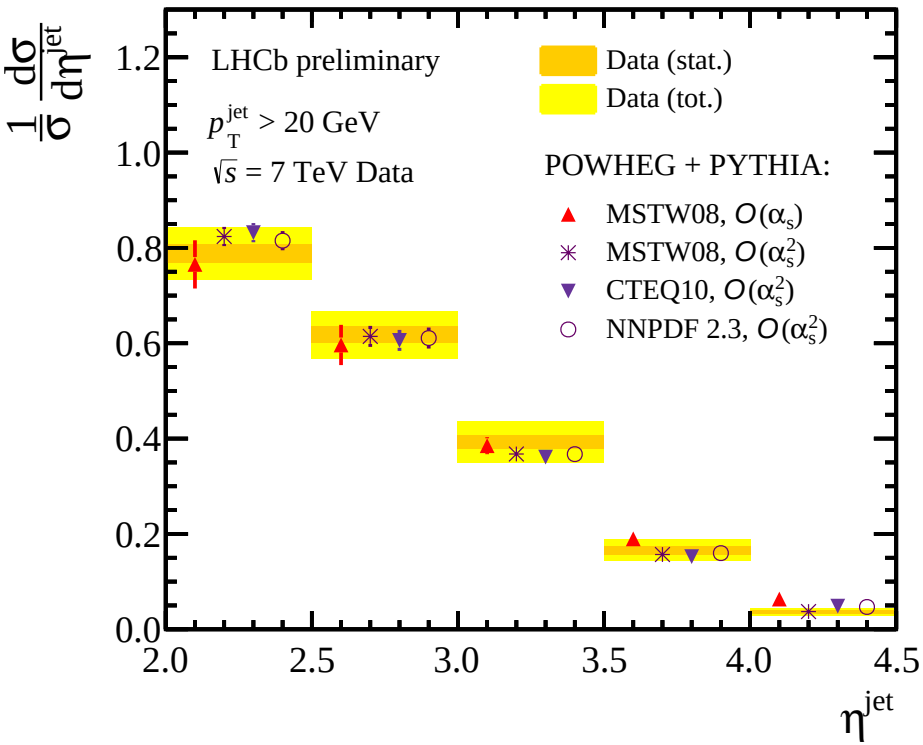


Z+jet at LHCb

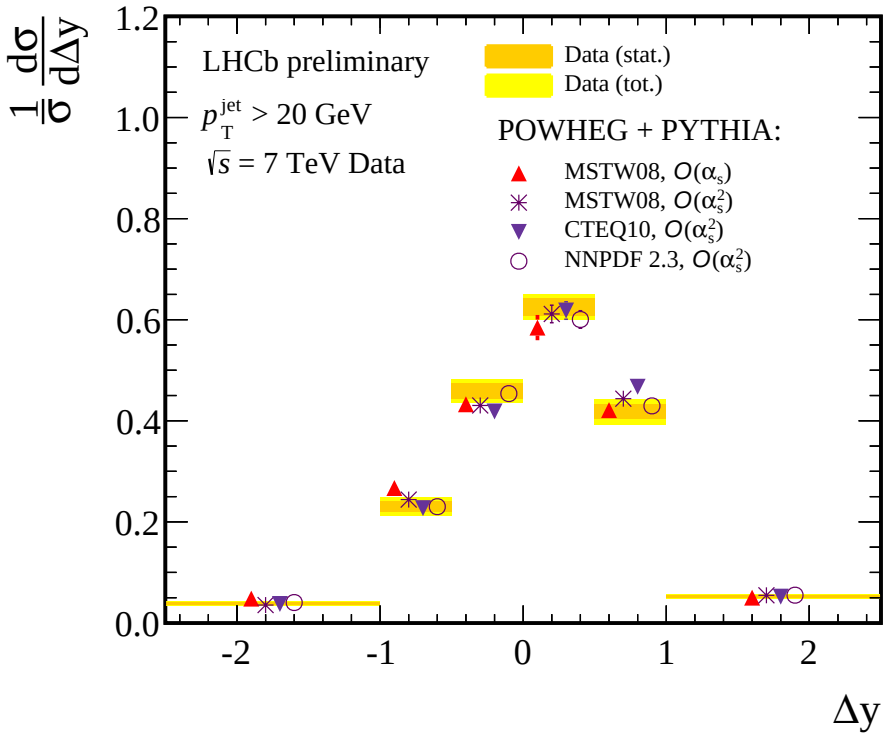
LHCb-PAPER-2013-058

- Results - kinematic distributions:
  - normalised to total Z+jet cross-section

η^{jet}



$y^Z - y^{\text{jet}}$



- more results available in paper and backup slides:
  - y^Z, p_T^Z, $\Delta\phi(Z, \text{jet})$
- Results show good agreement between LHCb measurement and the Standard Model.

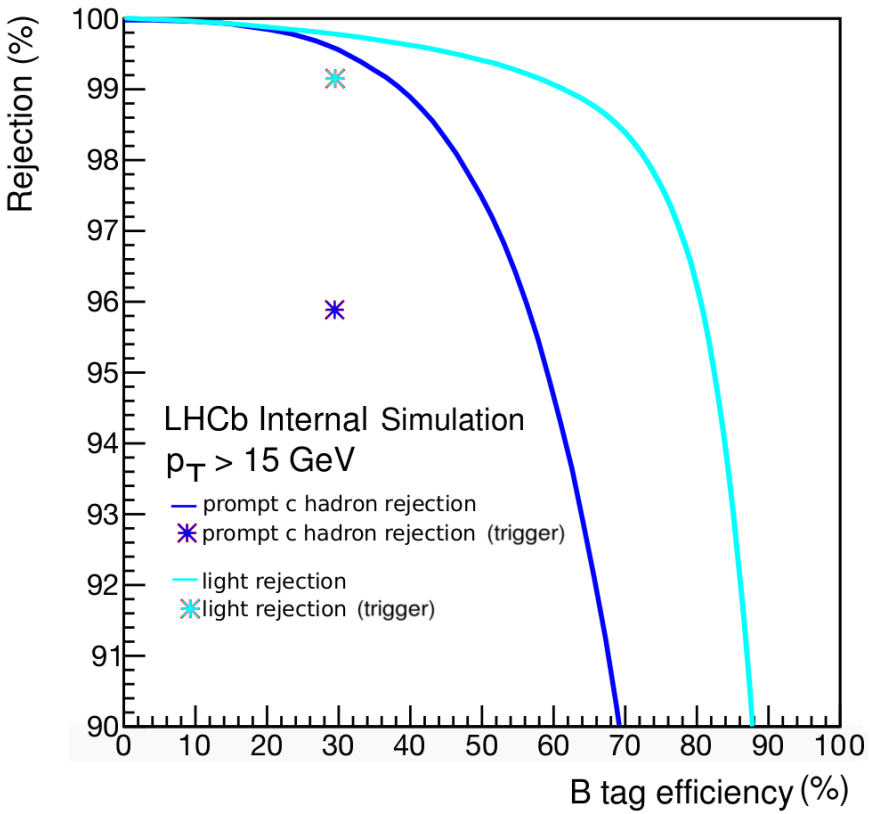
Jet Reconstruction at LHCb

Future measurements

- Z+b-jets:
  - LHCb designed to reconstruct particles containing b quarks
  - sensitive to bottom PDF
  - important background to new physics searches
- W+jet:
  - sensitive to PDFs, b-tagging would allow measurement of charm PDF
  - also sensitive to new physics mechanisms
- single and double top production
  - LHCb can probe possible $t\bar{t}$ asymmetry seen at Tevatron - see talk by Rhorry Gauld
- QCD jet production in the forward region
  - PDF sensitivity, test of pQCD in the forward region
  - Preliminary measurement: LHCb-CONF-2011-015
- Higgs production
  - see talk by Clara Matteuzzi

b-jet tagging

- LHCb has unique ability to perform b-tagging in forward region (see, for example, LHCb-CONF-2013-001)
- b-jet tagging at LHCb performed using multivariate techniques, based on topological information:

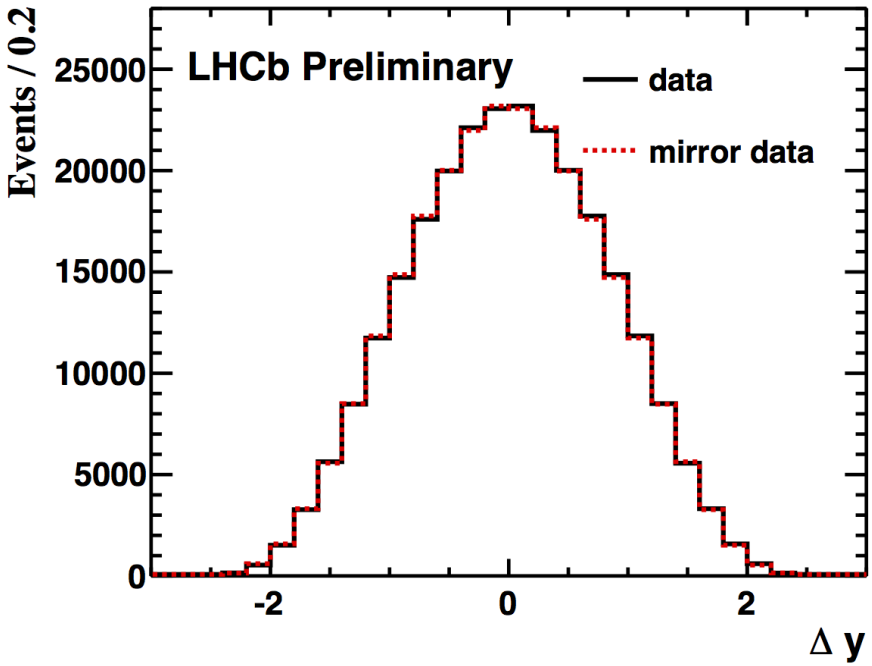


- numbers depend on sample studied - those shown here determined from LHCb Z+jet simulation.
- For 50% b-tag efficiency we achieve:
  - $\sim$ 97% c-jet rejection
  - better than 99% light-jet rejection
- ongoing work to improve this performance.

Forward-central $b\bar{b}$ production asymmetry

LHCb-CONF-2013-001

- how often is b produced in front of $\bar{b}$? $A_{\mathrm{FC}}^{b\bar{b}} = \dfrac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$

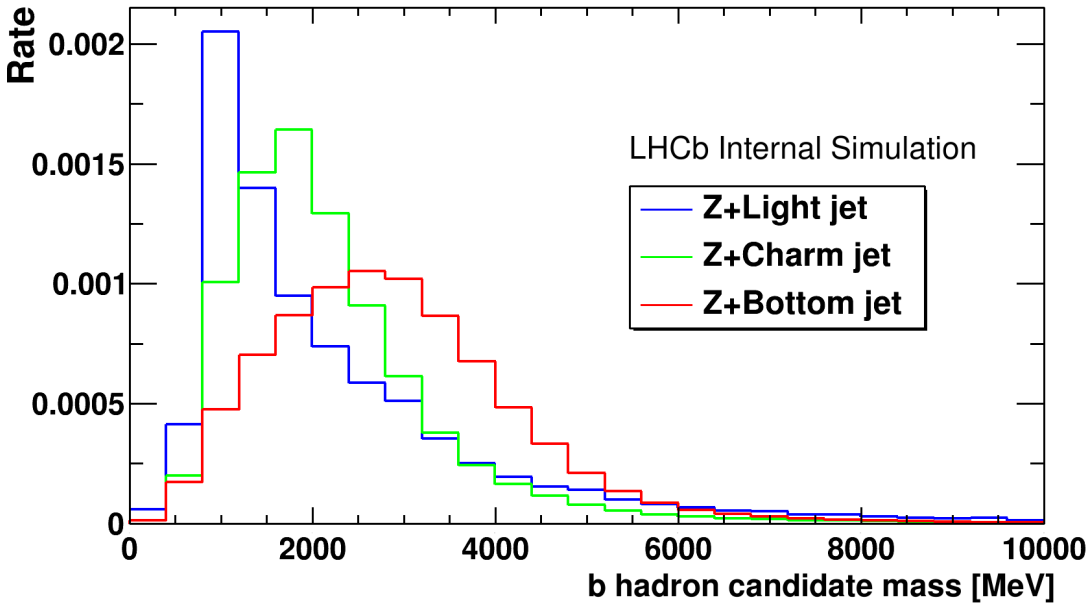


- measurement places constraints on possible mechanisms for $t\bar{t}$ asymmetry - Standard Model expectation is $\mathcal{O}(0.1\%)$.
- measurement consistent with Standard Model: $A_{\mathrm{FC}}^{b\bar{b}} = 0.5 \pm 0.5(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})\%$

Z+b-jet production

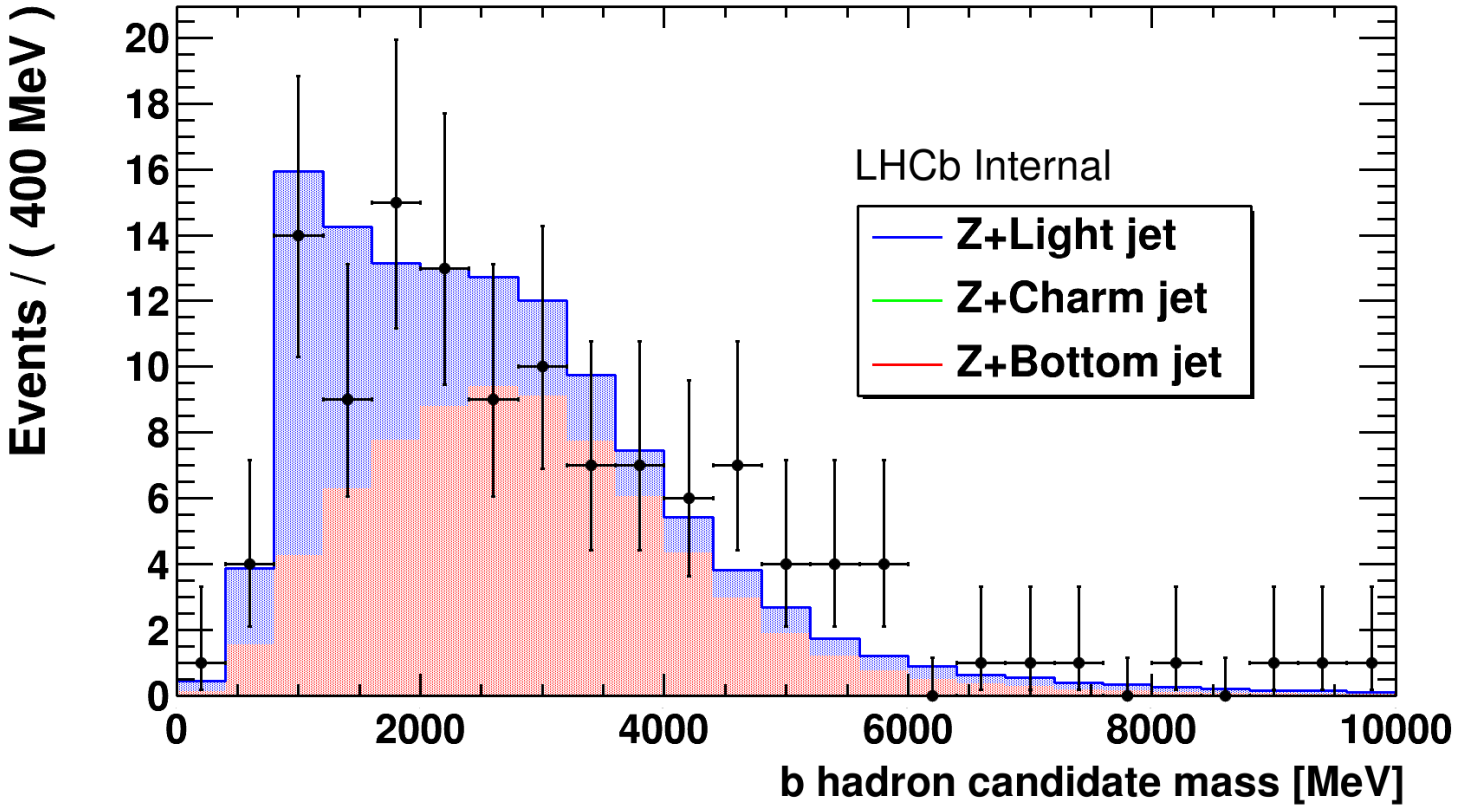
Analysis approach:

- select events based on b-tagging - which uses topological information
- selection reduces background contamination
- fit the mass of the b-hadron candidate (reconstructed using similar techniques to the LHCb topological trigger - http://dx.doi.org/10.1088/1748-0221/8/04/P04022)
- templates for fit taken from simulation



Z+b-jet production

- selection rejects majority of c-jet and light jet events,
- fit performs well: LHCb sees clear sample of Z+b-jet physics,
- work is ongoing to improve the selection and ability to discriminate signal from background.



Jet Reconstruction at LHCb

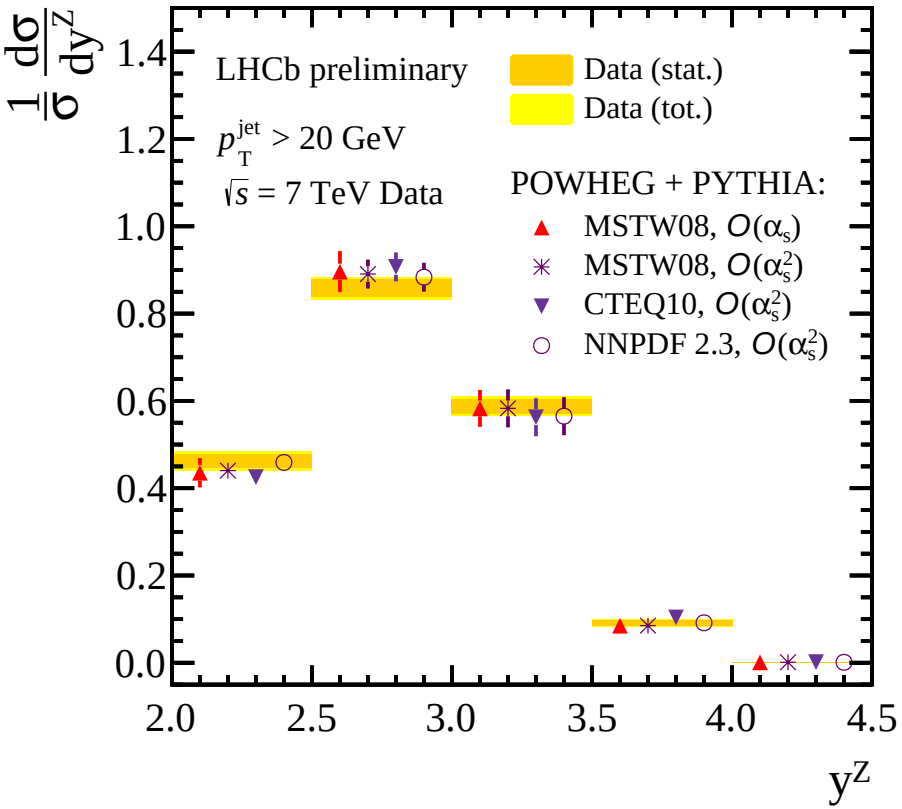
Summary

- Techniques to reconstruct jets at LHCb are well developed.
  - for jets with $p_T > 10$ GeV energy resolution is $\sim 10 - 15\%$
  - dominant uncertainty associated with jet reconstruction is the jet energy scale uncertainty.
  - production cross-section for Z+jet measured at LHCb: result is sensitive to PDFs, but also provides a benchmark study for jet reconstruction.
- We have many other measurements of interest lined up, making use of the ability of LHCb to tag particles containing b-quarks.
- Are there any other measurements we should add to this list?

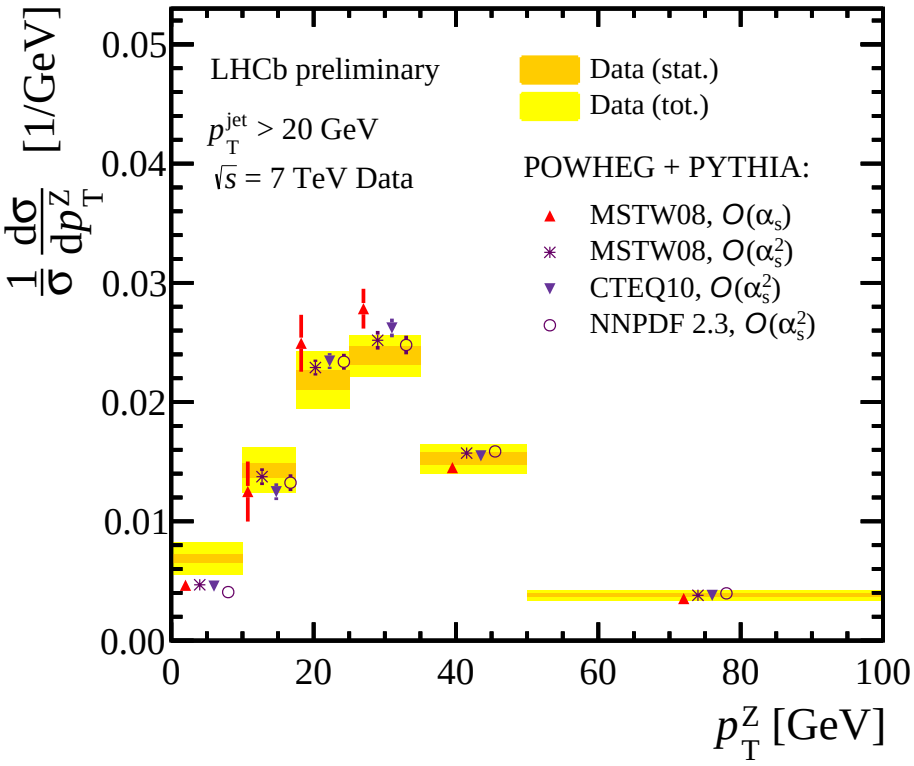
BACKUP SLIDES

Z+jet results

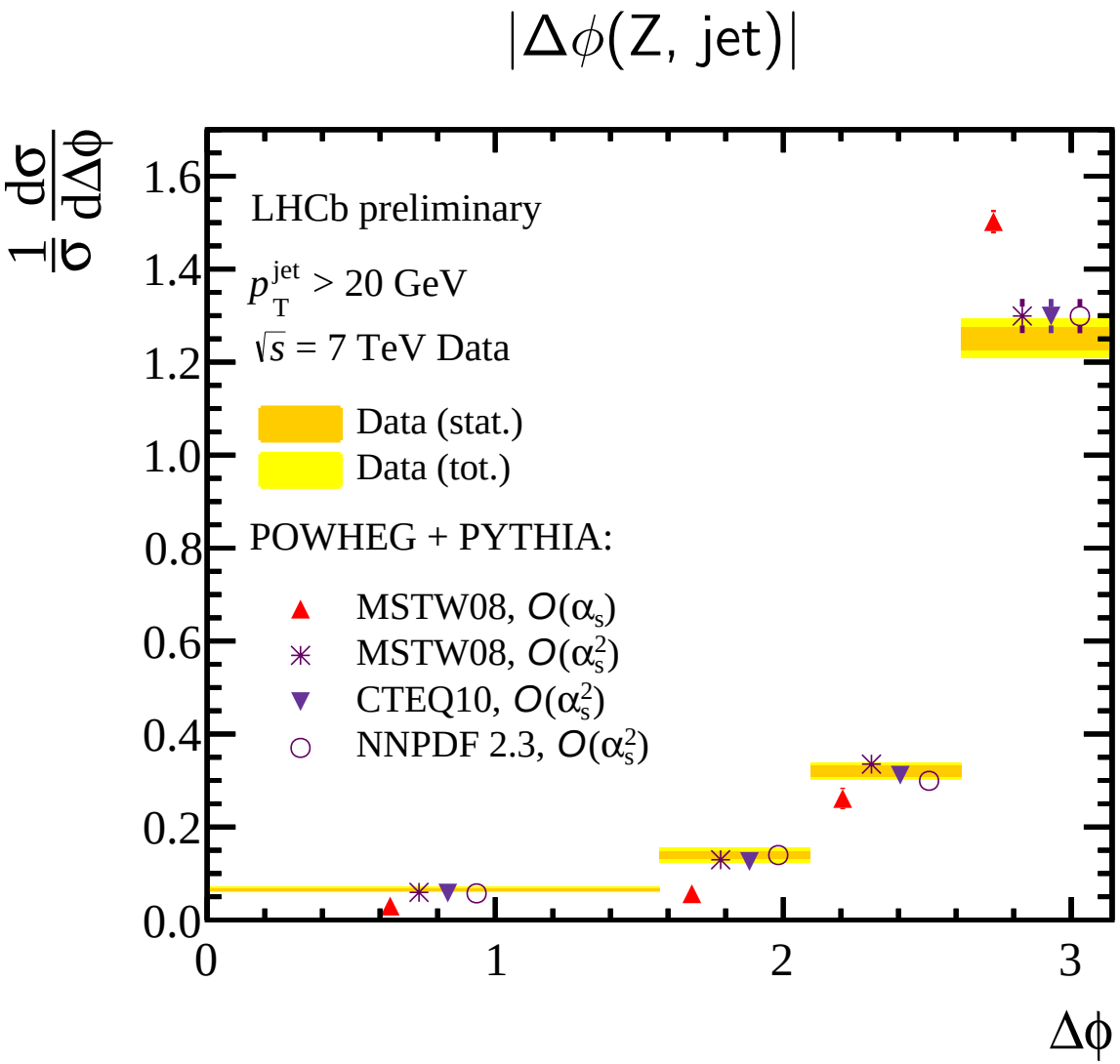
y^Z



p_T^Z



Z+jet results



Jet detection efficiency