Measurement of b-quark Jet Shapes at CDF

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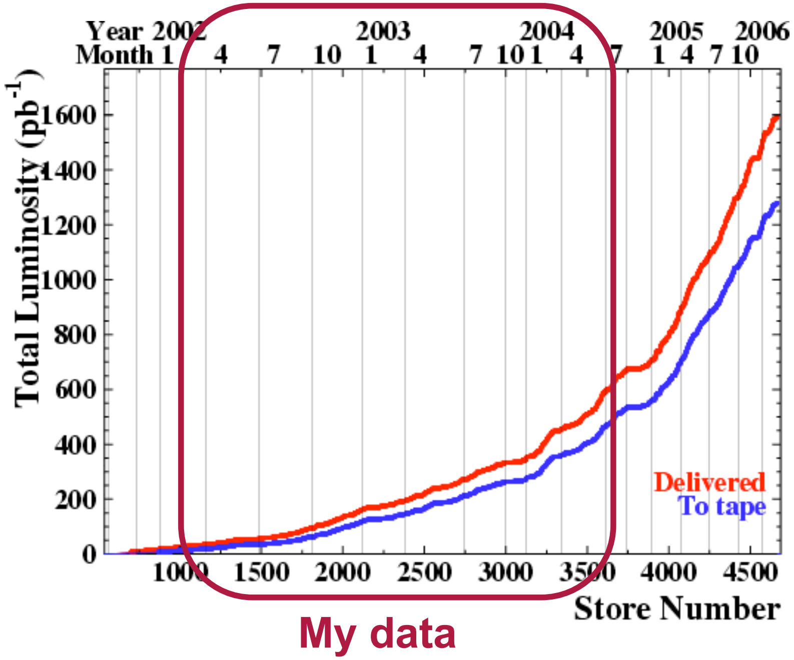
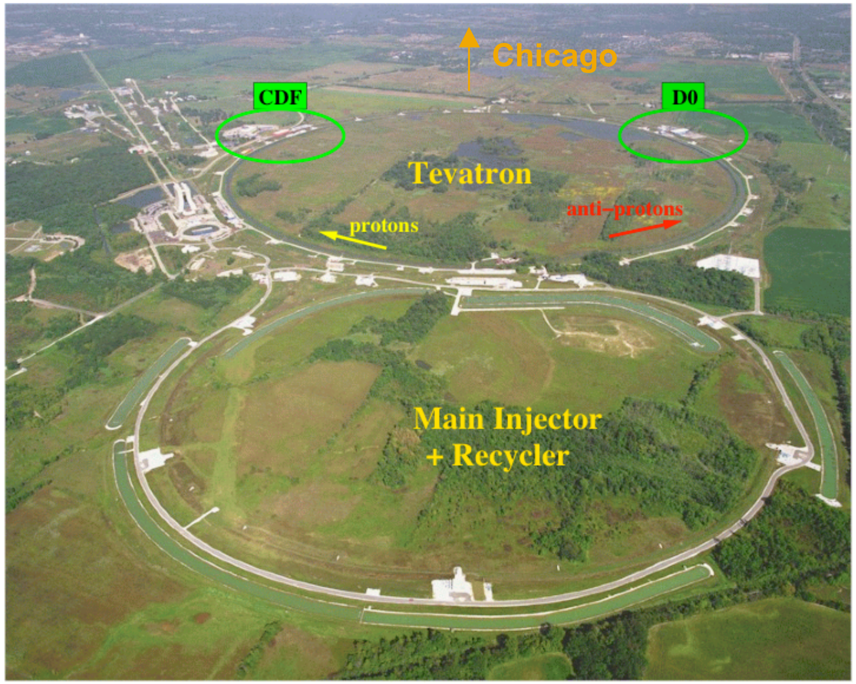
Outline

- CDF + Tevatron
- b-quark Jet Shapes
  - Definition
  - Motivation
  - Analysis Methodology
  - Systematics
  - Results
- Conclusions

Tevatron

- Located at Fermi National Laboratory
  - Near Chicago, USA
- Highest energy collider currently in operation
- Proton antiproton collisions
  - $\sqrt{s}$ = 1.96 TeV (Run II)
  - Compare to LHC: $\sqrt{s}$ = 14 TeV
- Run II started April 2001

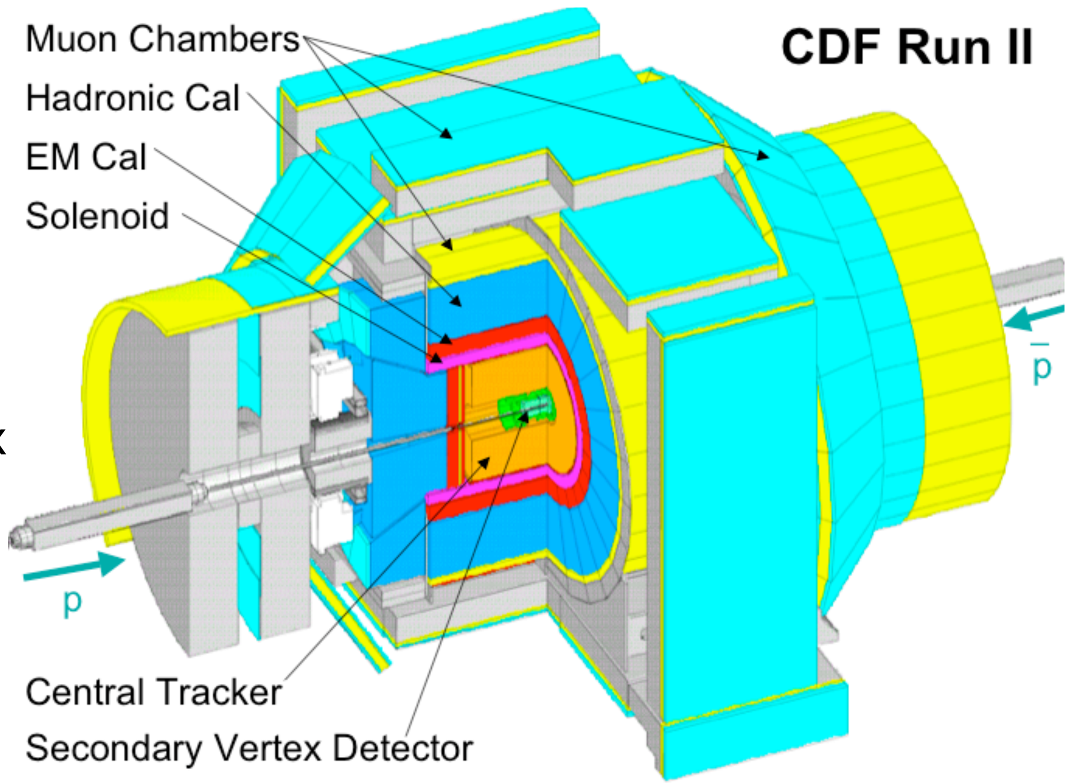




- Record instantaneous luminosity
  - L = 1.70 10^{32} s^{-1} cm^{-2} (January 2006)
  - Goal: 5 10^{32} s^{-1} cm^{-2}
- Integrated luminosity to tape (CDF)
  - 1 fb^{-1} (July 2005)
  - Goal 4-8 fb^{-1} by 2008

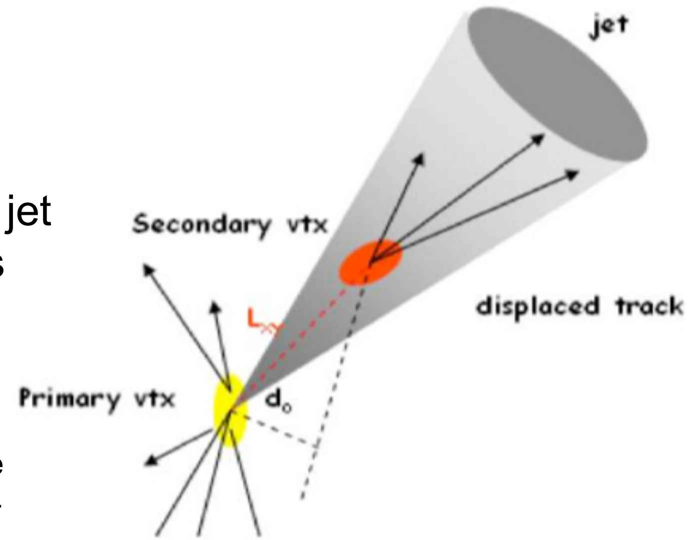
CDF

- CDF - Collider Detector at Fermilab
- “Multipurpose” detector
- Symmetric around beam axis
- Front-back symmetric
- ~100 tons
- 1.4 Tesla magnetic field outside tracker
- Dedicated secondary vertex detectors
  - 3 sub-detectors
    - From 1.6 cm to 28 cm from centre of the beam-pipe
  - Very important for b-jet physics



Secondary Vertex Tagging

- b-quark jet content in inclusive jet production only ~4%
  - Too low to extract precision measurement of b-jet properties
- Need to enhance heavy flavour fraction of jets
- Secondary vertex tagging
  - Look for displaced vertices inside cone about jet axis ($R_{sub\text{-}cone}$ = 0.4)
- Tagging increases b-quark jet content to 25-40%
- Secondary vertex algorithm optimised for a different jet algorithm (JetClu) than used for most QCD analyses (MidPoint)
  - Checked behaviour of algorithm independent of jet algorithm and of jet cone size
    - Found to be true as long as the sub-cone inside which the algorithm looks for displaced tracks is kept at a size of 0.4



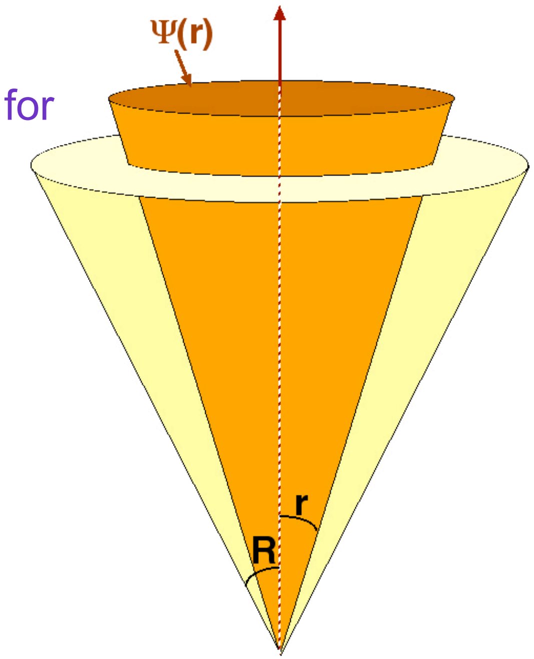
Jet Shape Definition

- Integrated shape
  - Fractional p_T of jet inside cone of size r around jet axis

p_T sum over towers inside cone of radius r

$$\Psi(r) = \int_0^r \frac{p_T(r')}{p_T^{jet}} dr' = \frac{1}{N_{jets}} \sum_{jets} \frac{p_T(0,r)}{p_T(0,R)}$$

Divide by total p_T inside jet cone R to account for splitting/merging effects on jets



  - Limit

$$\Psi(r = R) = 1$$

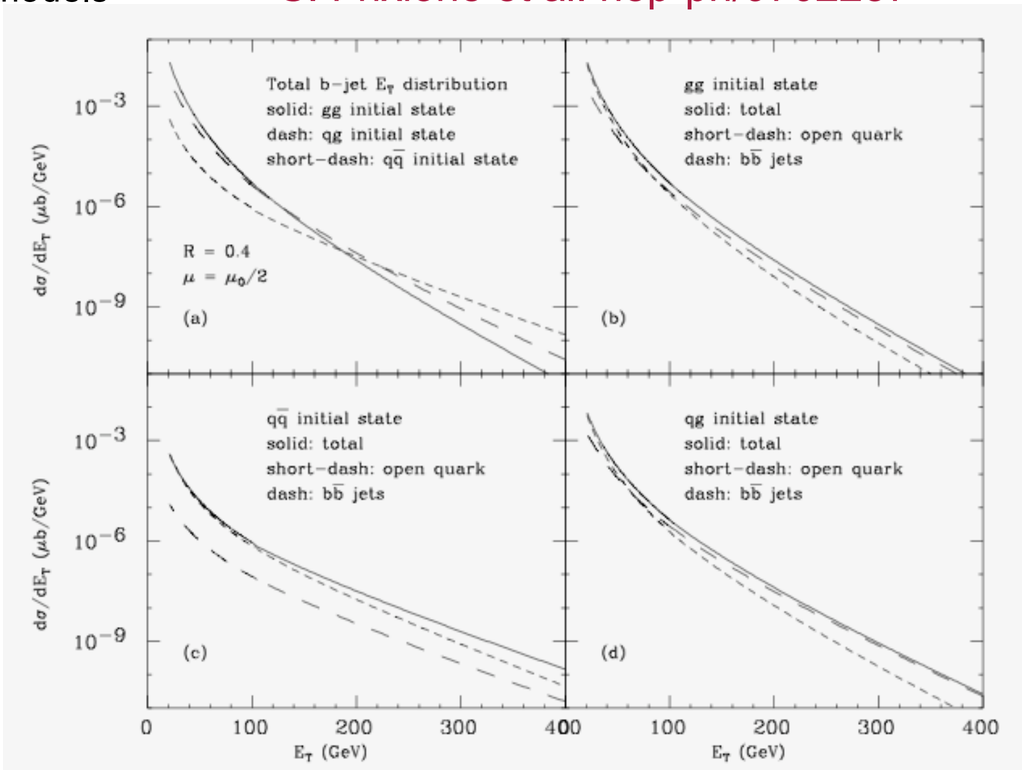
  - R is angular opening of jet in (Y, Φ)-space

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta Y)^2}$$

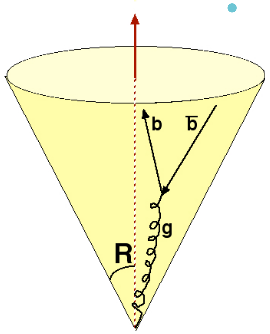
Motivation

- Jet shapes
  - Probe internal structure of jets
  - Study multi-gluon emission from primary outgoing parton
  - Dependence on initial parton: quark or gluon, flavour of quark
  - Testing Monte Carlo simulation
    - Underlying event models
    - Fragmentation and hadronisation models

S. Frixione et al. hep-ph/9702287



- b-quark jet shapes
  - First measurement of shapes of b-quark jets at hadron colliders
  - Is fraction of b-quark jets from gluon splitting well modeled in Leading Order (LO) MC?
    - b-quarks from gluon splitting events most of the time inside the same jet



b-jet Shapes Unfolding

- Fraction of b-quark jets after tagging not 100%
  - Need to separate statistically b-quark jet shapes from background of c- and light+gluon-jets
  - Need to know the purity of the jet sample, after tagging
- Tagging requirement biases measured shapes
  - Makes b-jet shapes narrower
  - Makes nonb-jet shapes wider
  - Need to correct back both b- and nonb-jet shapes
- Basic unfolding equation

We want

$$\Psi_{\mathrm{meas}}(r) = p_{\mathrm{b}} b^{\mathrm{b}}(r) \Psi^{\mathrm{b}}_{\mathrm{det}}(r) + (1 - p_{\mathrm{b}}) b^{\mathrm{nonb}}(r) \Psi^{\mathrm{nonb}}_{\mathrm{det}}(r)$$

Measured after tagging | Purity | Biases | Purity | Biases | Measured ~inclusive jet shape

- Detector independent measurement
  - Compare to future measurements or theoretical models
  - Correct jet shapes back to hadron level
- Unfolding equation can be re-written as

$$\Psi^{\mathrm{b}}_{\mathrm{had}}(r) = C_{\mathrm{had}}(r) \frac{\Psi_{\mathrm{meas}}(r) - (1 - p_{\mathrm{b}}) b^{\mathrm{nonb}}(r) \Psi^{\mathrm{nonb}}_{\mathrm{det}}(r)}{p_{\mathrm{b}} b^{\mathrm{b}}(r)}$$

Datasets + MC Samples

- Jet datasets
  - ~300 pb^{-1} of CDF Run II data
    - Feb 2002 - September 2004
  - 3 level trigger
    - Relies only on calorimeter tower energy deposits
  - Use datasets only when trigger efficiency above 99%
    - Avoid any trigger bias to measurement

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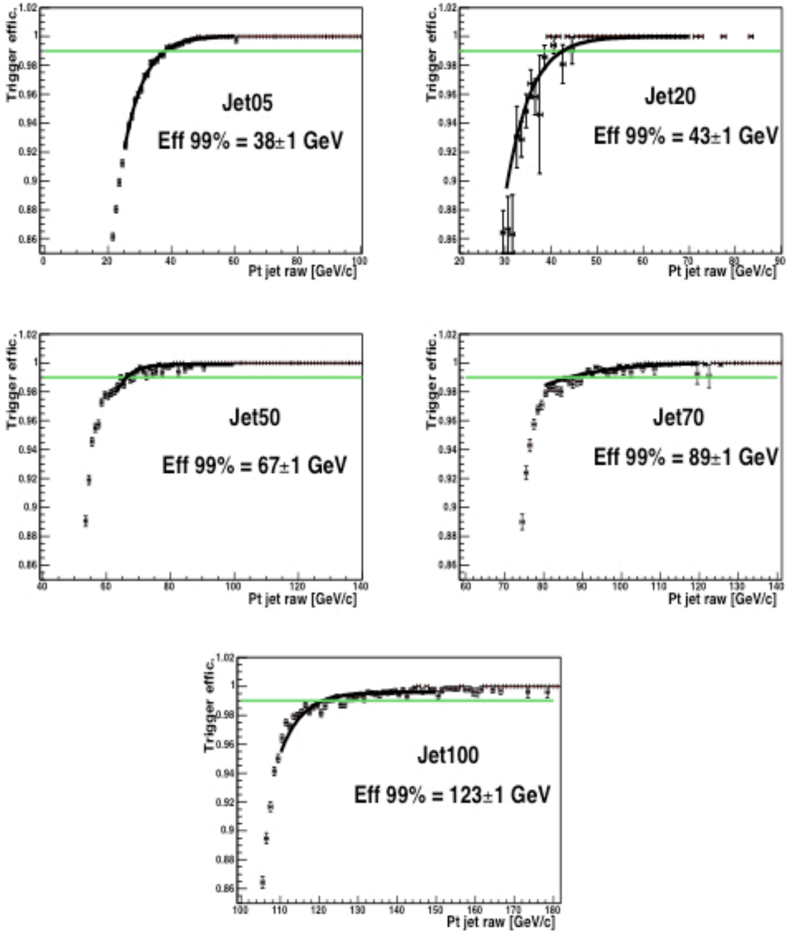


- Pythia Tune A di-jet Monte Carlo (MC) samples
  - Tuned to CDF Run I underlying event
  - Used for unfolding and comparison to data

Analysis Cuts

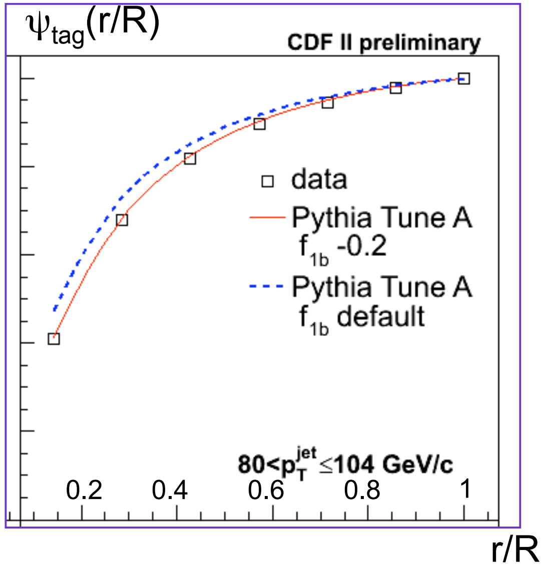
- Jets
  - Reconstructed with MidPoint cone algorithm
    - Cone size 0.7
    - Merge fraction 75%
  - Jet p_T corrected back to hadron level
- One and only one well reconstructed primary vertex with $|Z_{vtx}| < 50$ cm
  - Allow good secondary vertex tagging
  - Removes multiple parton interactions
- Missing E_T significance cut: 3.5 → 7.0 $GeV^{1/2}$ (depending on jet p_T)
  - Remove large fraction of background due to cosmics
- Central jets with $|Y| < 0.7$
  - Where the SecVtx is best understood
- Use 4 p_T bins
  - From 52 to 300 GeV

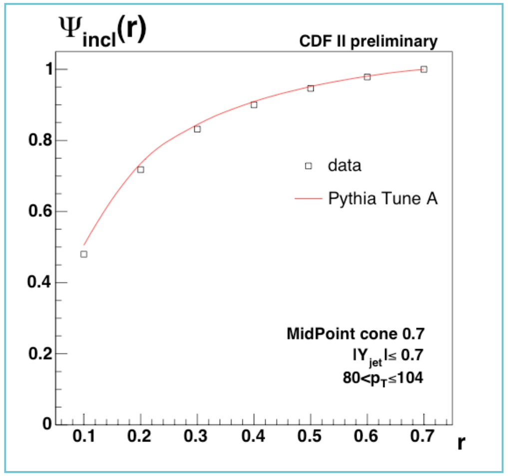
p_T limits [GeV/c]	Dataset	MC sample	N_{jets}	$N_{\text{tagged jets}}$
52-80	Jet20	Pt18	161'524	4'677
80-104	Jet50	Pt40	354'922	13'367
104-142	Jet70	Pt60	134'907	5'874
142-300	Jet100	Pt90	377'650	18'673

Unfolding parameters

$$\Psi^{\mathrm{b}}_{\mathrm{had}}(r) = C_{\mathrm{had}}(r)\,\frac{\Psi_{\mathrm{meas}}(r) - (1 - p_{\mathrm{b}})\, b^{\mathrm{nonb}}(r)\, \Psi^{\mathrm{nonb}}_{\mathrm{det}}(r)}{p_{\mathrm{b}}\, b^{\mathrm{b}}(r)}$$

- The different parameters needed for the unfolding are
  - Raw detector level jet shapes for tagged jets
    - Average jet shape of all tagged jets
  - Raw detector level jet shapes for inclusive jets
    - Average jet shapes for all jets
  - Purity of the samples
  - Tagging biases on b-jets
    - Obtained from Pythia Tune A
  - Tagging biases on nonb-jets
    - Obtained from Pythia Tune A
  - Hadron level corrections to b-jets
    - Obtained from Pythia Tune A

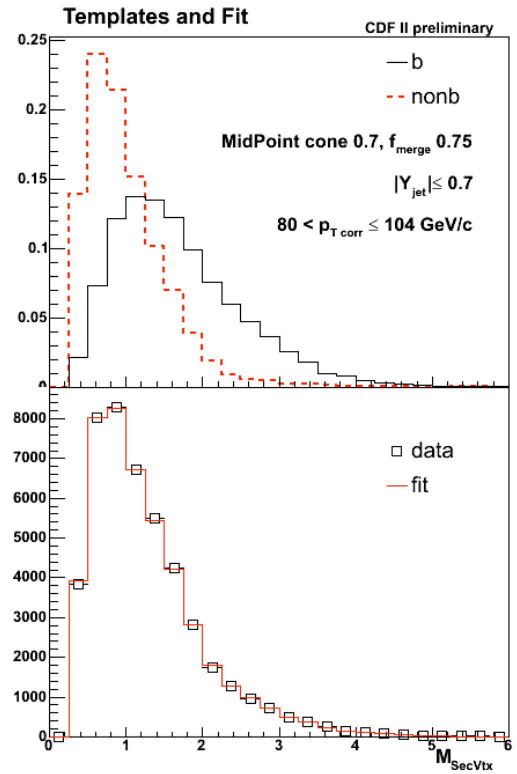


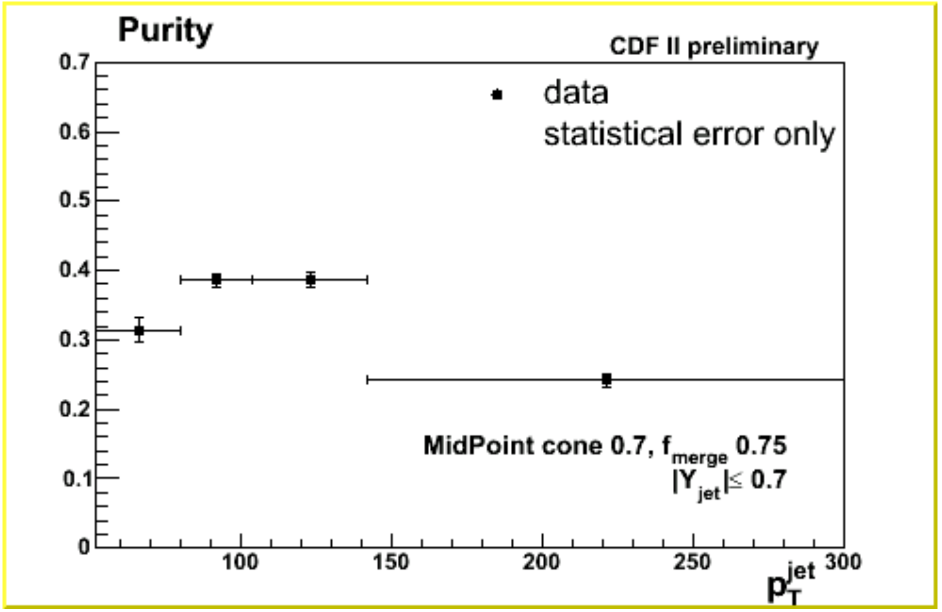


$$C^{\mathrm{had}}(r) = \frac{\Psi^{\mathrm{had}}_{\mathrm{MC}}(r)}{\Psi^{\mathrm{det}}_{\mathrm{MC}}(r)}$$

Purity Extraction

- Look at the secondary vertex mass distribution of tagged jets
  - Total mass of the tracks associated with the secondary vertex
  - Different for b-jets and nonb-jets
  - Define secondary vertex mass distributions for b- and nonb-jets from Pythia Tune A MC



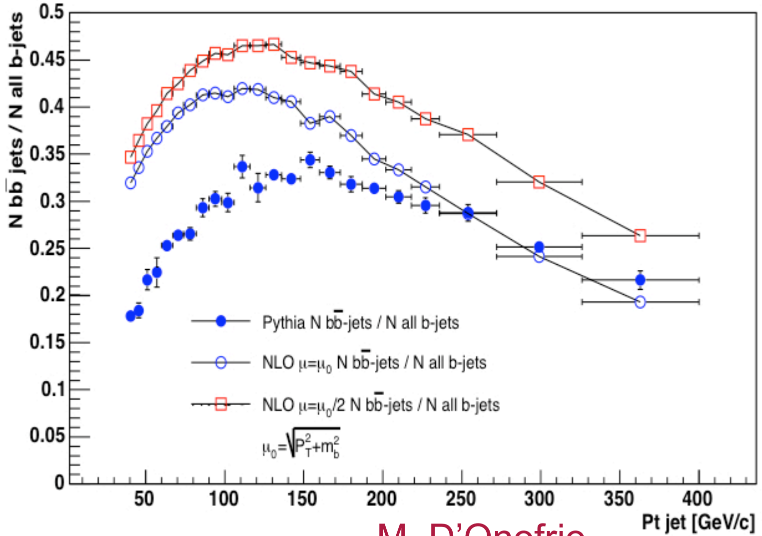


Fit data distribution to templates

- Binned χ^2 fit
- Extract fraction of tagged jets which have a b-quark inside jet cone (p_b)
- Fit is good
- Fit stable wrt change of fit range and number of bins used in histograms

Dominant Systematic Uncertainties

- Fraction of b-quark jets which contain only one b-quark inside jet cone
  - Compare Pythia Tune A at hadron level with NLO calculation at hadron level
  - Max difference ~17% (absolute)
  - Similar as found for best agreement with measured tagged jet shapes (20%)
  - Pythia Tune A re-weighted before tagging bias and hadron level corrections computed
  - Not included as a systemetic uncertainty



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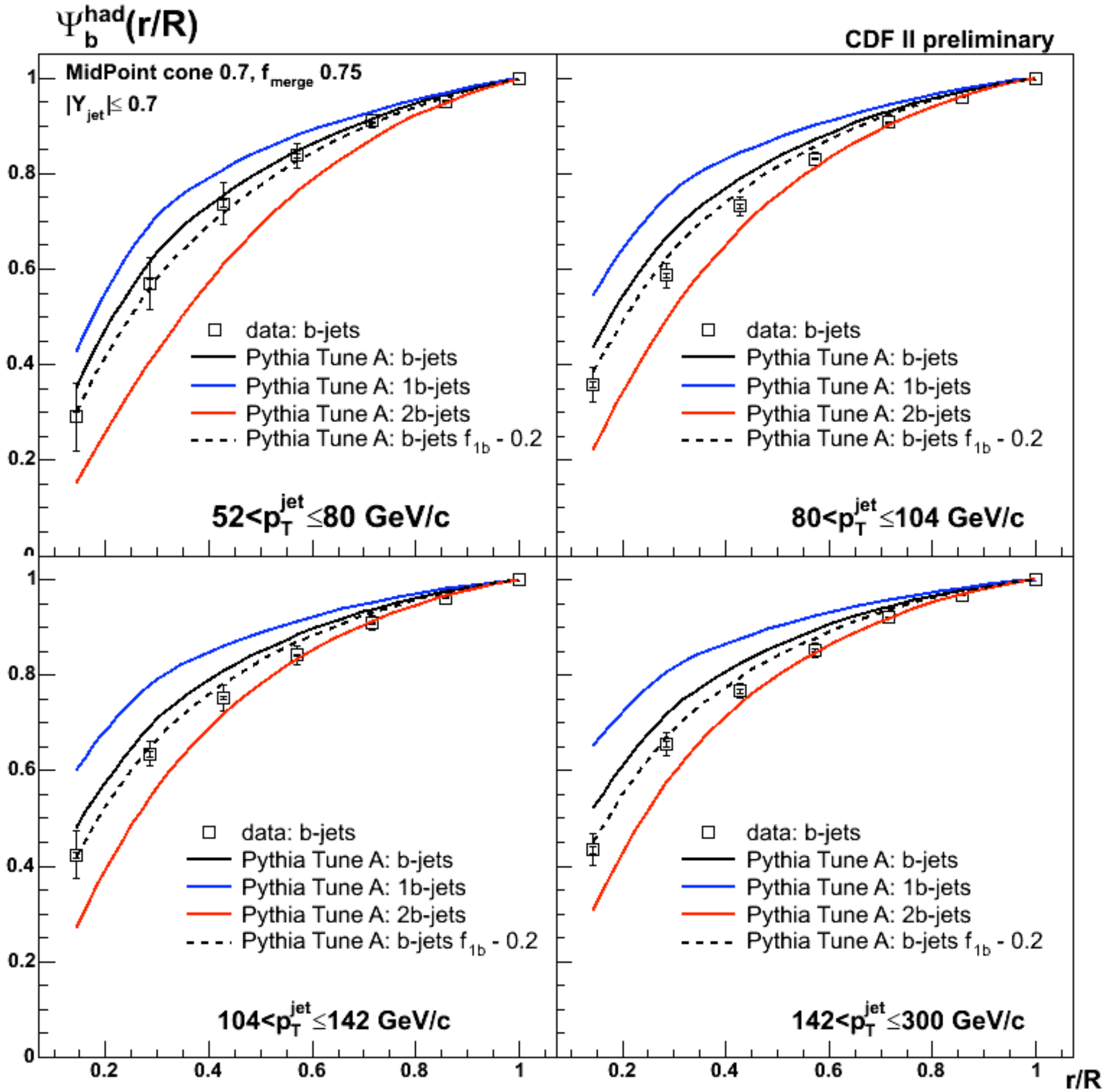
- Fraction of c-quark jets which contain only one c-quark inside jet cone
  - 20% (absolute)

- b-quark jet shapes reconstructed from raw track shapes
  - Whole analysis is re-done measuring shapes using tracks instead of calorimeter towers

- MC statistics for unfolding parameters
  - Particularly for tagged nonb-jets
  - Increasing statistics would not decrease total systematic error significantly

Hadron Level b-jet Shapes

- Including all systematic uncertainties
  - Statistical errors shown but often smaller than points
- Comparing b-jet shapes to Pythia Tune A
  - b-jet shapes
  - Shapes for 1b and 2b jets
  - b-jet shapes decreasing f_{1b} by 20%
- All but first p_T bin show significant deviations from Pythia Tune A predictions for b-quark jet shapes

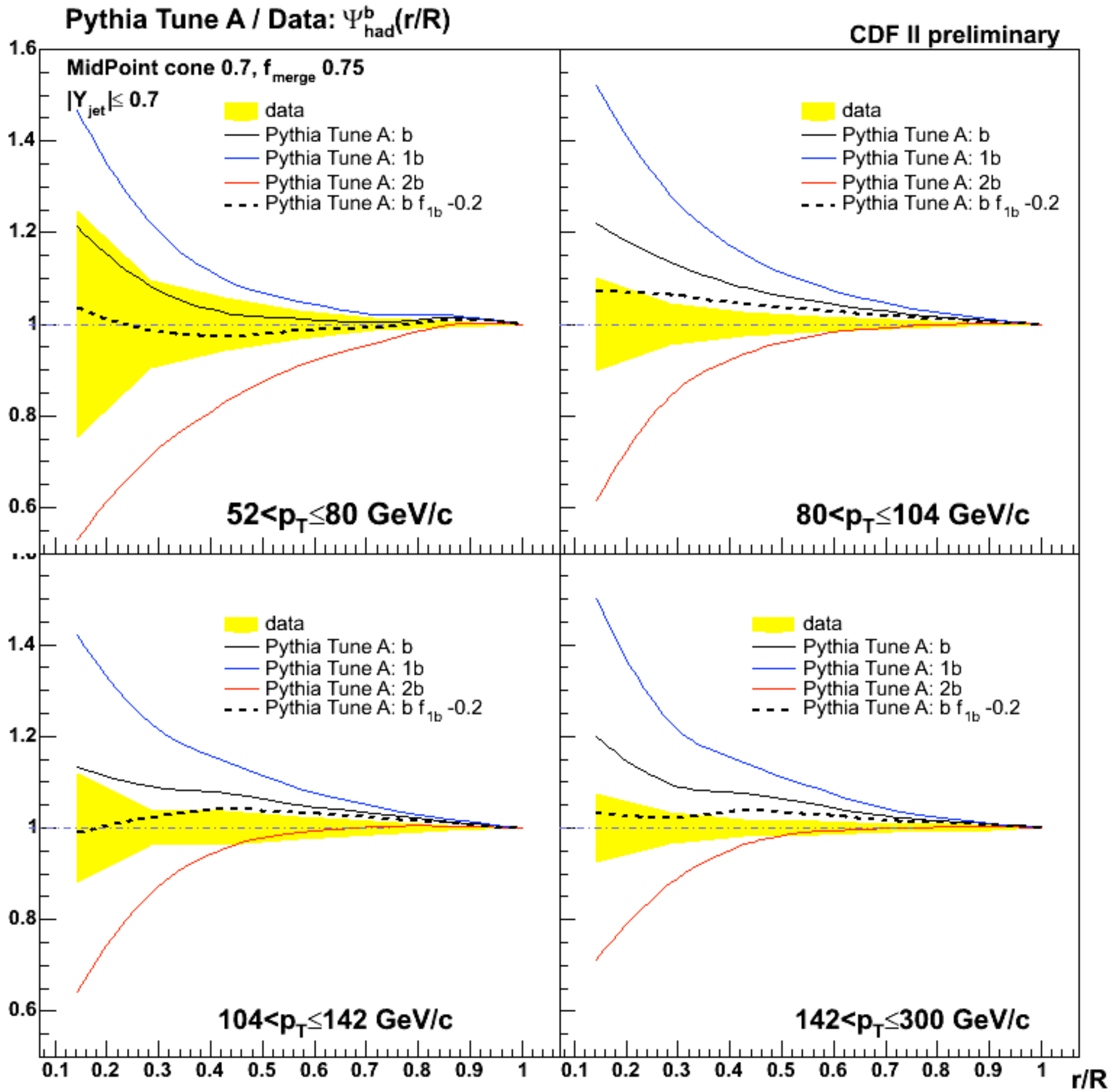


Hadron Level b-jet Shapes

- Ratio
  - Pythia Tune A / Data

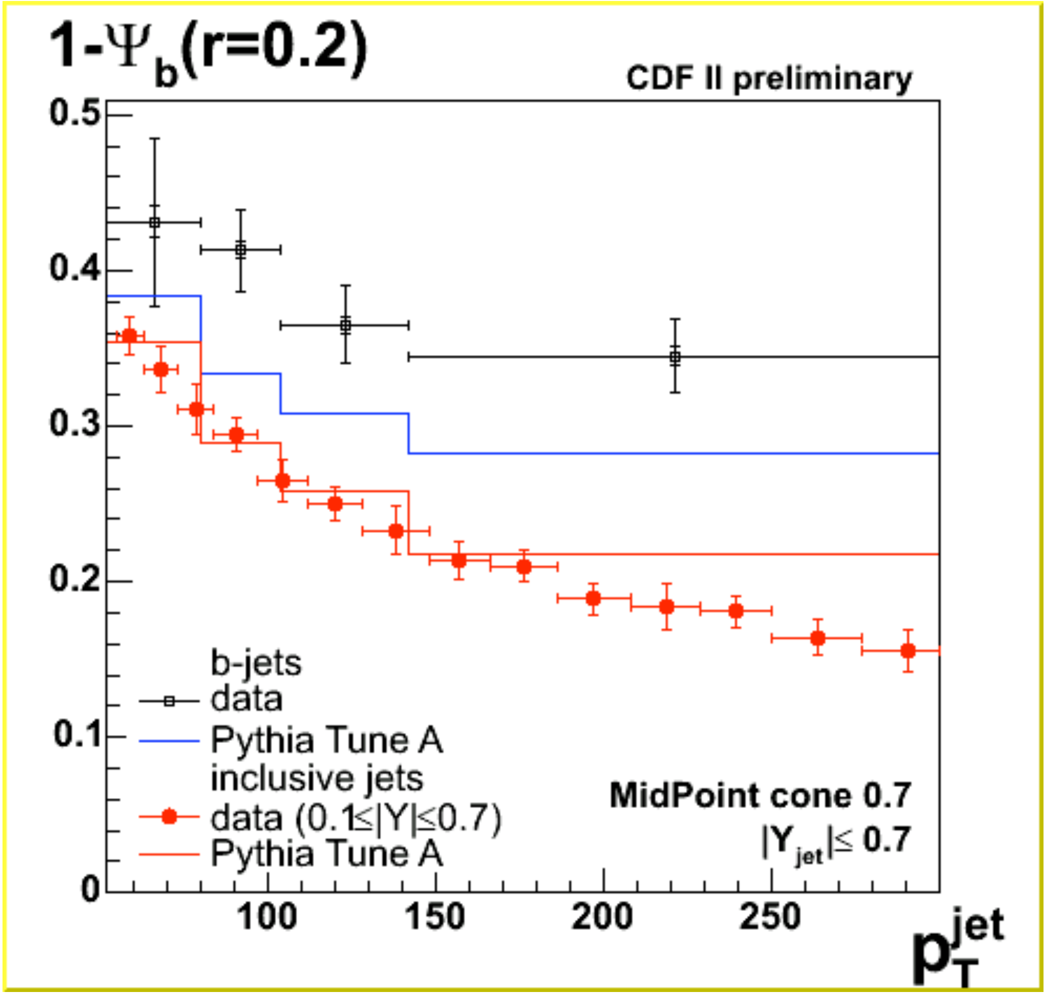
- Yellow band: total errors on measurement

- Agreement between data and MC much better with lower f_{1b} fraction



Hadron Level b-jet Shapes vs p_T

- Fractional p_T outside sub-cone of size 0.2
  - Larger fraction means wider jets
- Compare results to
  - Pythia Tune A predictions for
    - Inclusive jets
    - b-jets (default $f1_b$ fraction)
  - Previously published inclusive jet shape results
    - Measured using rapidity cut 0.1<|Y|<0.7
    - Showing total error
- Difference observed between inclusive and b-quark jet shapes
- Evolution with p_T flatter for b-jets than for inclusive jets



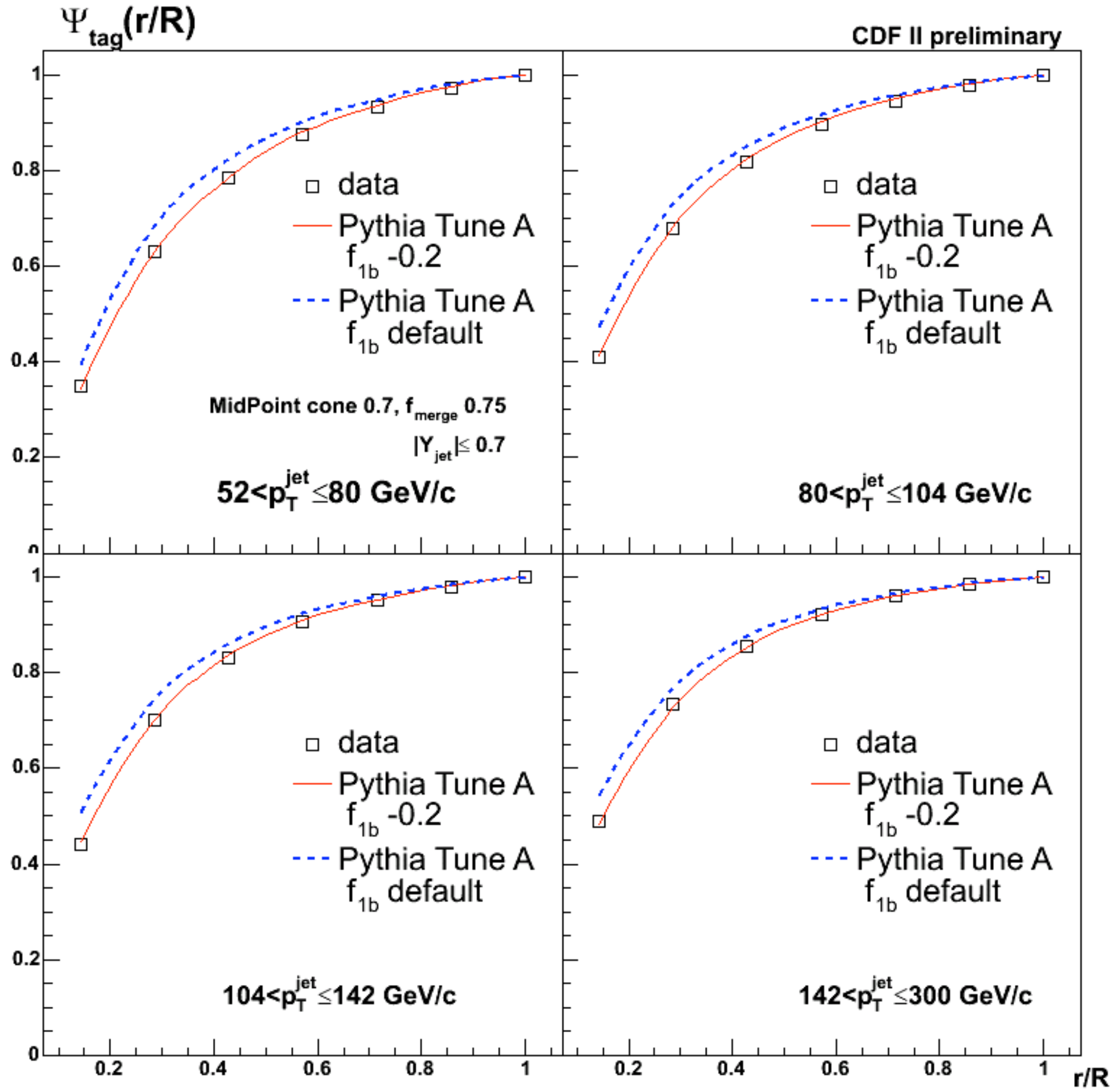
Conclusions

- b-jet shapes measured for the first time at a hadron collider
  - Important for the understanding of b-jets
    - Needed for many discovery channels at Tevatron and LHC
- Fraction of b-jets with two b-quarks inside the same jet cone seems to be significantly underestimated in LO MC
  - Most likely the rate of gluon splitting to b bbar pairs is underestimated
  - Fraction of 2b-jets should be increased by ~0.2 (absolute) for agreement to be best
- Further comparisons needed to see the effect of using Pythia Tune A for the unfolding

Backup Slides

Raw Jet Shapes: Tagged Jets

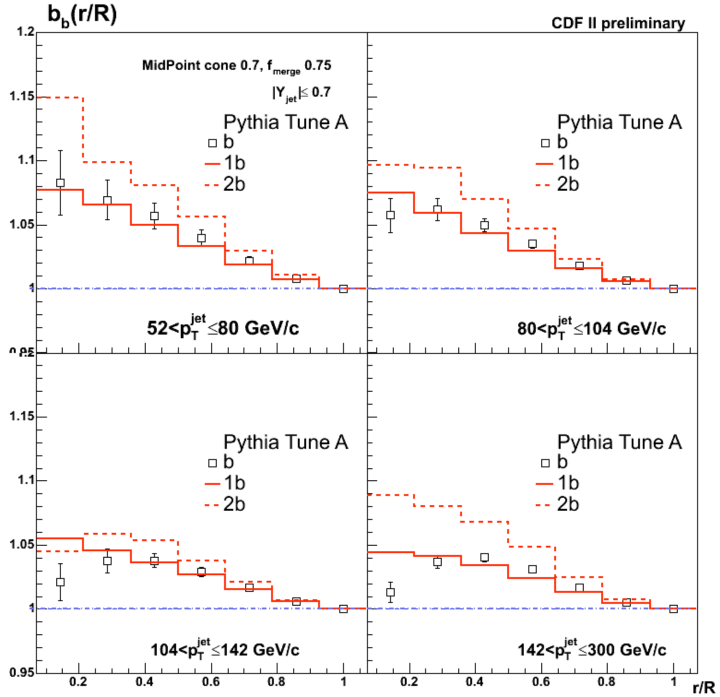
- Average integrated jet shapes for tagged jets
- Data and MC expected to be different because of different b-jet purities
- Statistical errors shown but smaller than points

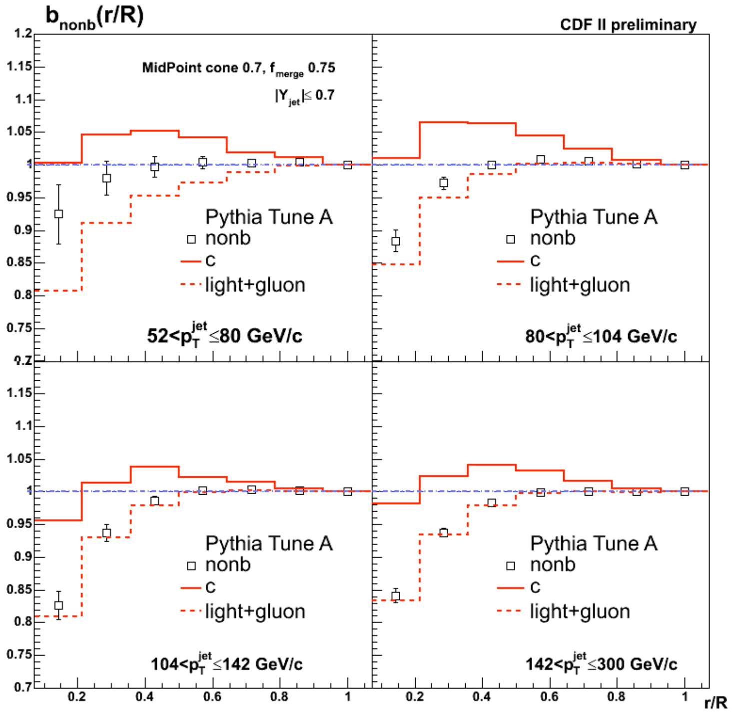


Tagging Biases

- Define tagging biases as ratios between b-(nonb-)quark jet shapes after and before the secondary vertex tagging requirement
  - Calculated in Pythia Tune A

$$b_{\mathrm{b}}(r) = \frac{\Psi^{\mathrm{tag}}_{\mathrm{b\,MC}}(r)}{\Psi^{\mathrm{incl}}_{\mathrm{b\,MC}}(r)} \qquad b_{\mathrm{nonb}}(r) = \frac{\Psi^{\mathrm{tag}}_{\mathrm{nonb\,MC}}(r)}{\Psi^{\mathrm{incl}}_{\mathrm{nonb\,MC}}(r)}$$



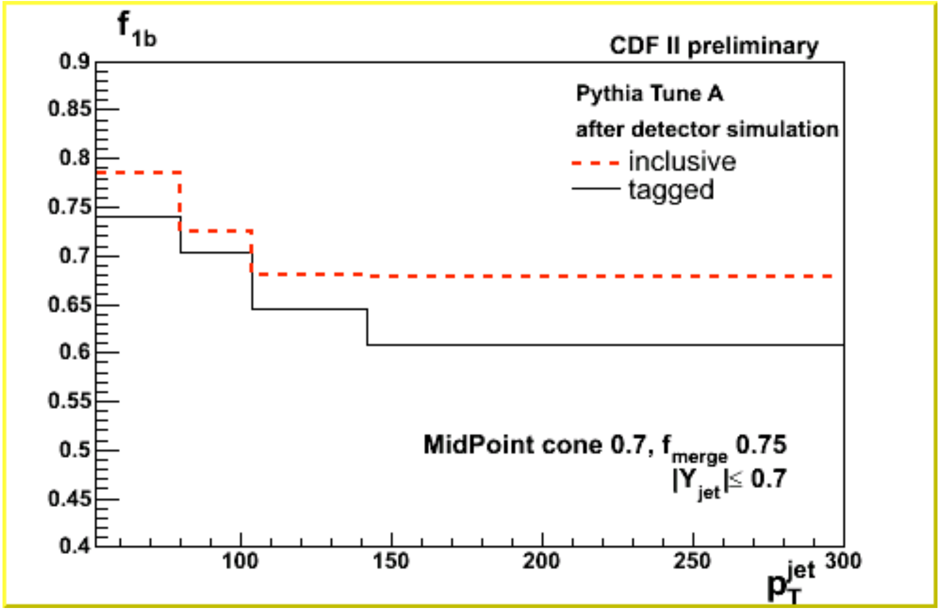


- b-jets
  - Max correction ~7%
  - Jet shapes get narrower
- Nonb-jets
  - Max correction ~18%
  - Jet shapes get wider
- Only MC statistical errors shown

Tagging Biases on b-jets

- Bias for b-jets not always between 1b and 2b
  - Tagging
    - selects narrower b-quark jets
  - Tagging efficiency higher for double than for single b-quark jets
    - Fraction of double b-quark jets (i.e gluon splitting) higher after tagging than before tagging
    - Wider jets
  - Net bias can be smaller than single or double b-quark biases

- f_{1b} = 1- fraction of double b-quark jets
- Max ~ 10% difference between f_{1b} fraction before and after tagging

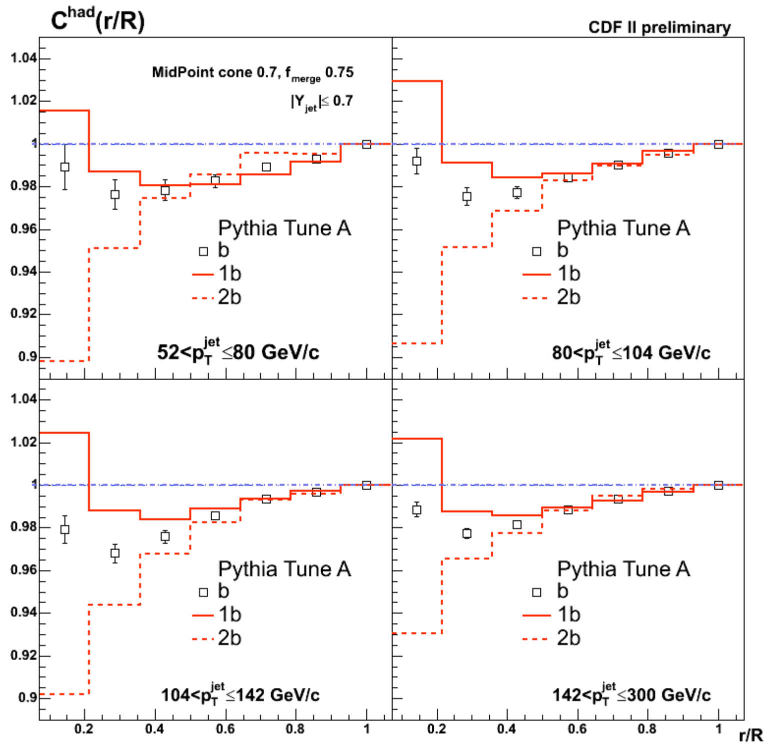


Hadron Level Corrections

- Want detector independent measurement
  - Compare to future theoretical models or measurements
- Correct measured b-quark jet shapes back to hadron level
- Defined as ratio of hadron level over detector level b-quark jet shapes
  - Calculated in Pythia Tune A

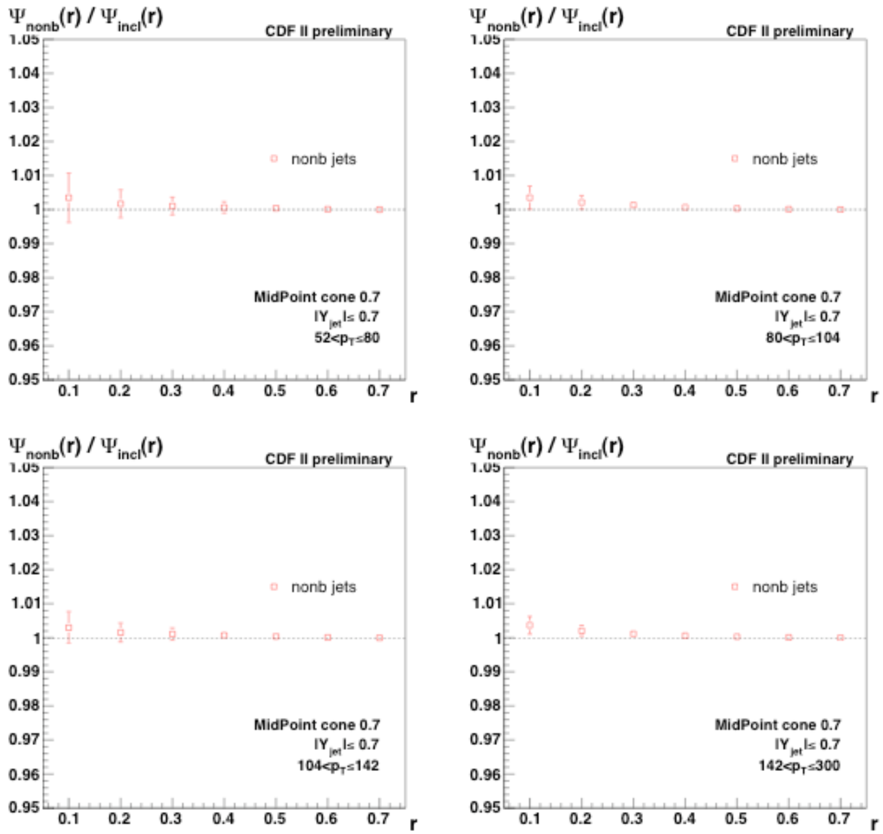
$$C^{\text{had}}(r) = \frac{\Psi^{\text{had}}_{\text{MC}}(r)}{\Psi^{\text{det}}_{\text{MC}}(r)},$$

- Max corrections ~ 4%
- MC statistical errors shown



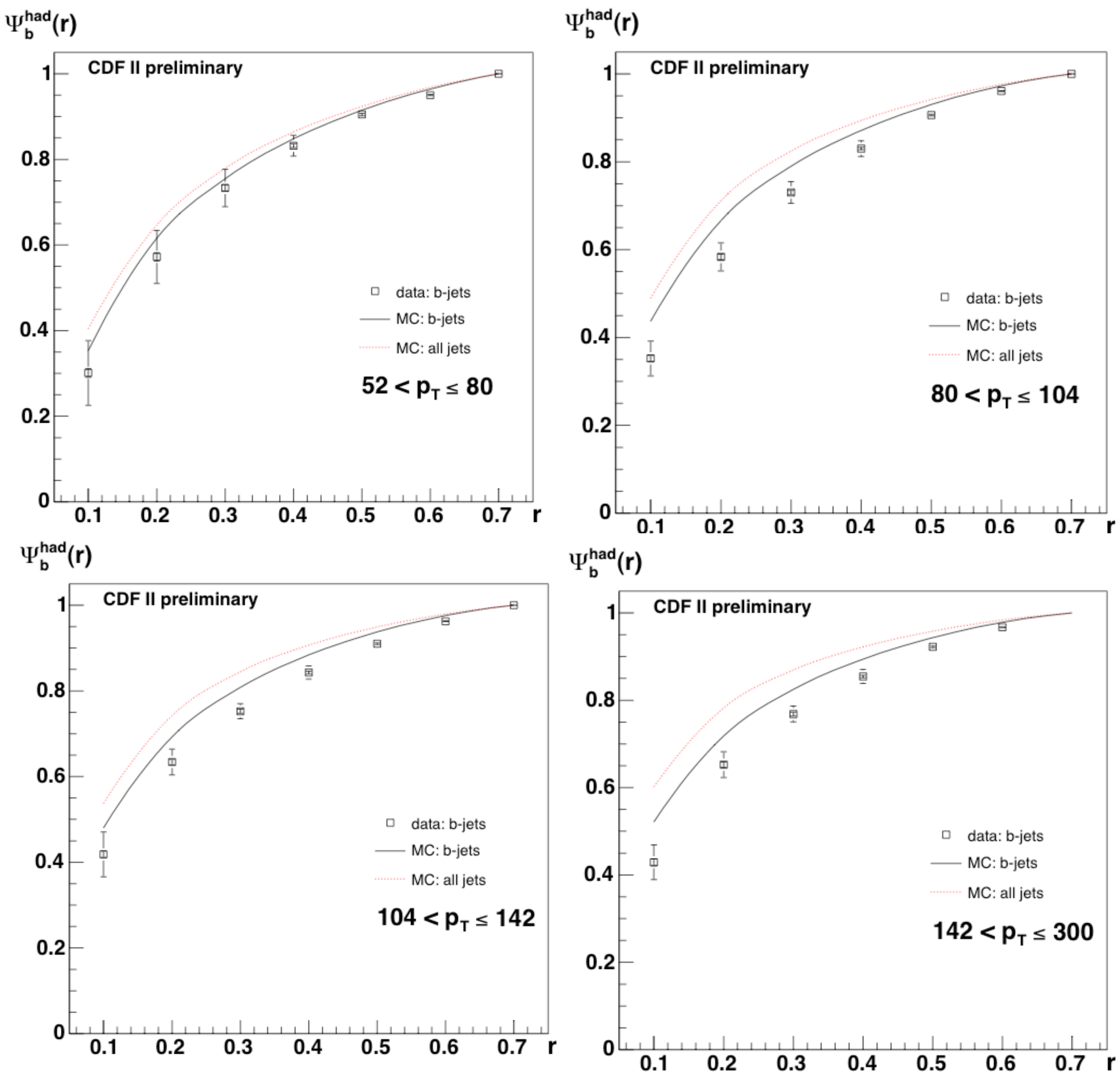
Use of Inclusive vs. nonb-jet Shapes

- Compare Pythia Tune A MC predictions for inclusive and nonb-jets
- Difference smaller than statistical errors in MC
- Not included as systematic error



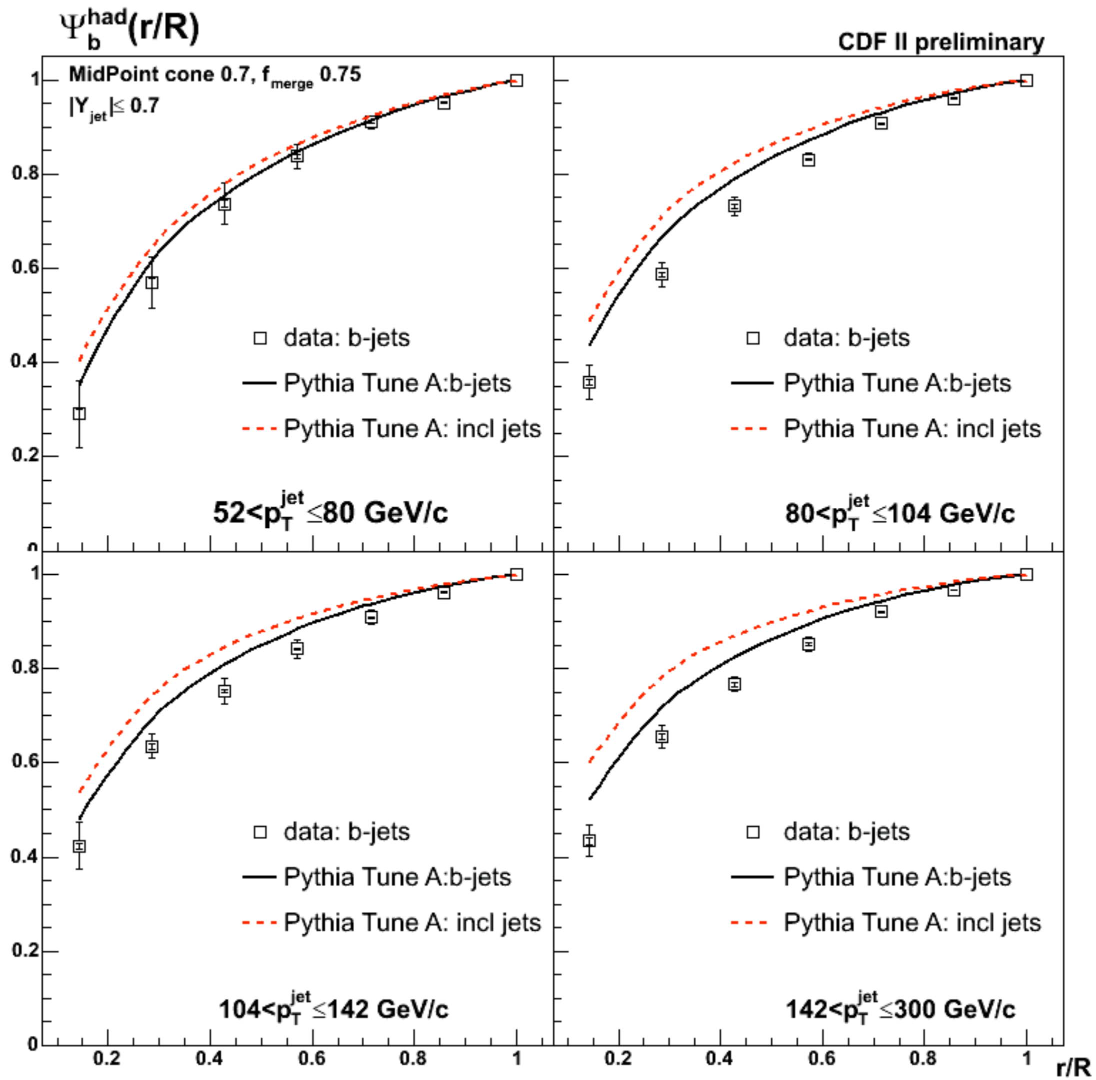
Hadron Level b-jet Shapes

- Including all systematic uncertainties
- Comparing b-jet shapes to Pythia Tune A predictions for b-jet shapes and inclusive jet shapes
- Difference between inclusive and b-quark jet shapes is seen



Hadron Level b-jet Shapes

- Including all systematic uncertainties
  - Statistical errors shown but often smaller than points
- Comparing b-jet shapes to Pythia Tune A
  - b-jet shapes
  - Inclusive jet shapes
- Measurement for b-jet shapes not compatible with predictions for inclusive jet shapes



Hadron Level b-jet Shapes vs p_T

- Fractional p_T outside a sub-cone of size 0.1 and 0.2
- Compare results to Pythia Tune A predictions for
  - b-jets
  - 1b- and 2b-jets
  - b-jets with f_{1b} reduced by 10% and by 20%
- Data agree much better with larger fraction of gluon splitting jets
- Evolution with p_T flatter for double b-quark jets than single b-quark jets