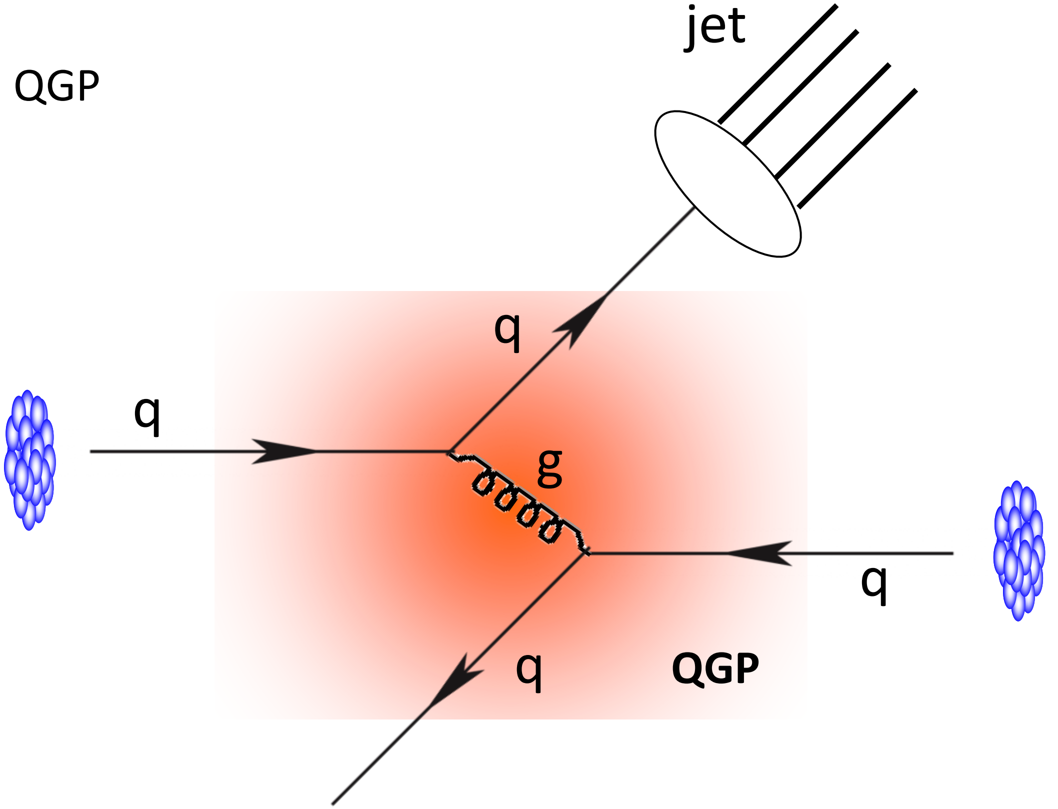
Jet Fragmentation Functions in PbPb and pp collisions

Dragos Velicanu
for the CMS collaboration

Analysis

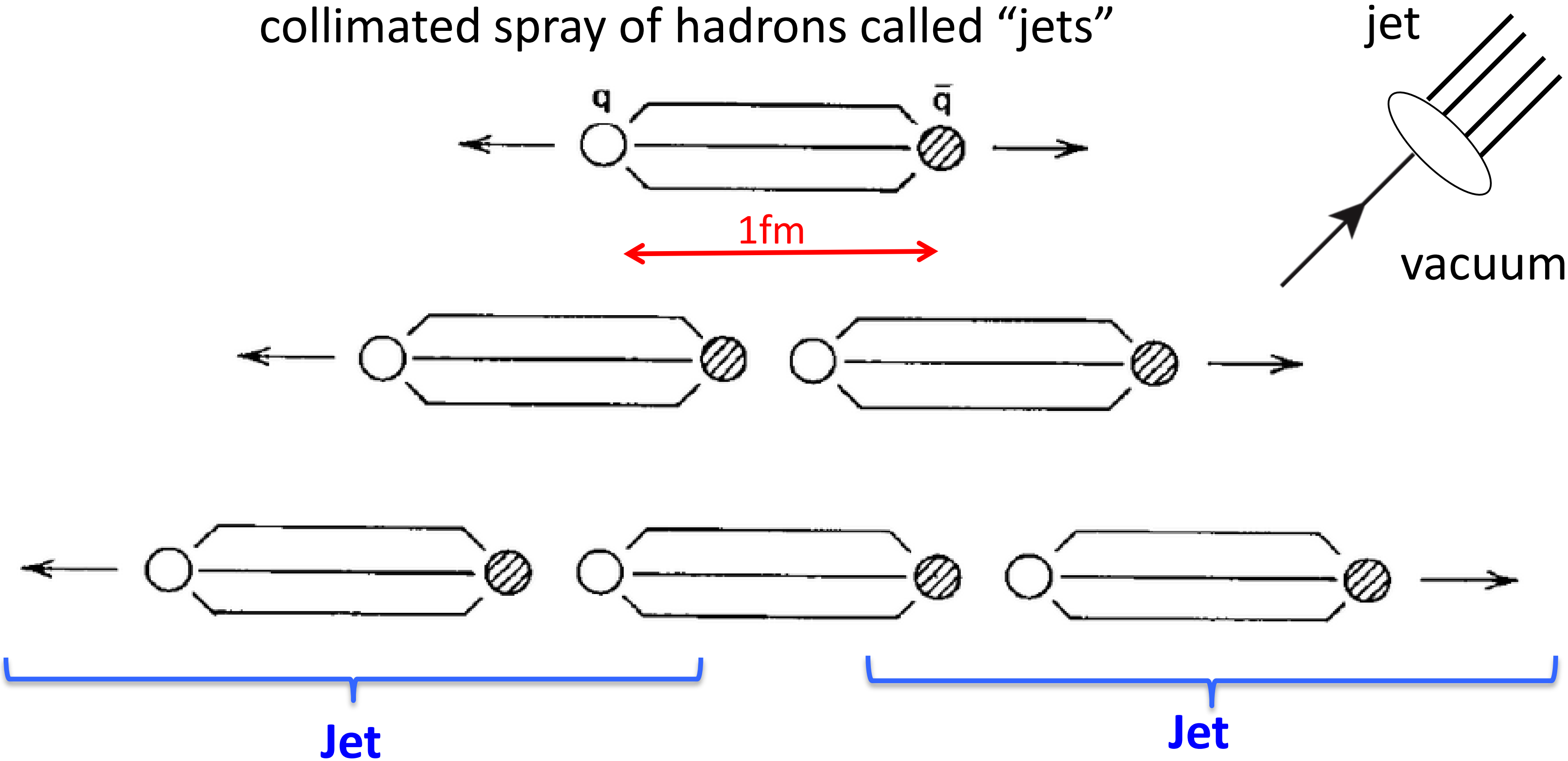
Bjorken (1982):
Use jet to probe QGP



Goal: Probe QGP by measuring jet fragmentation function.

What are Jets?

High momentum quarks or gluons create collimated spray of hadrons called “jets”

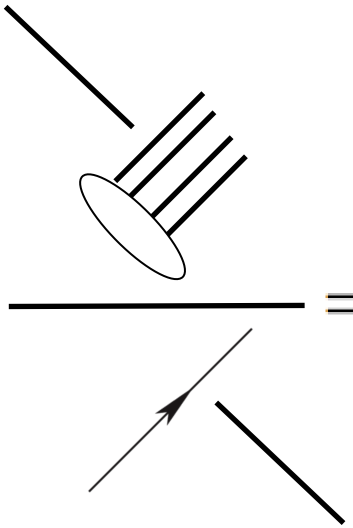


Jets are experimental observables of high energy quarks and gluons

Jet Fragmentation

Define Observables:

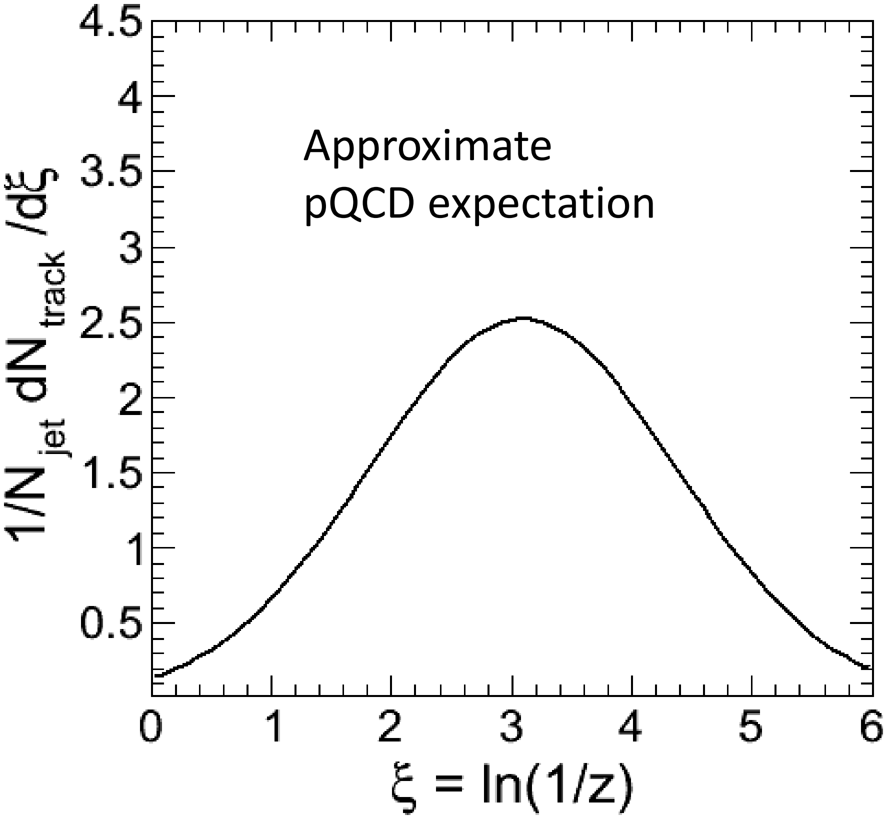
Jet fragmentation



jet energy

$$z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}$$

$$\xi = \ln \frac{1}{z}$$



High p_T Low p_T

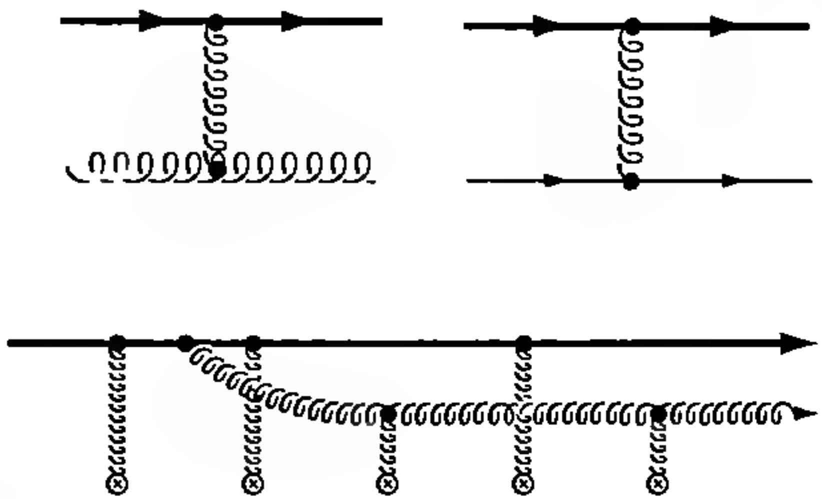
"Jet fragmentation function"

Jet interactions in QGP

Two ways of energy loss in QGP:

(a)

(b)

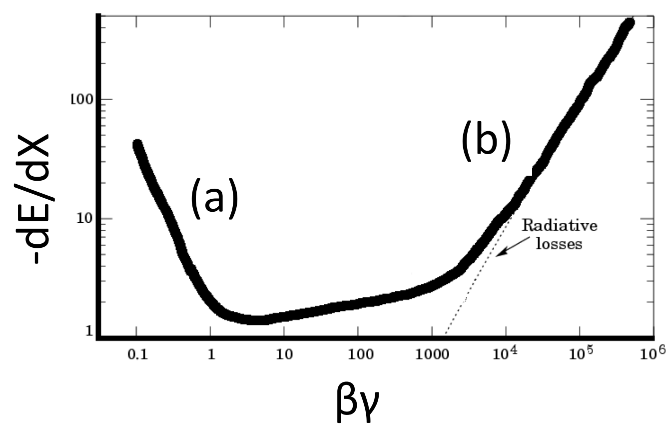


Inelastic collisions

Radiation

Can modify fragmentation function

Similar to charged particle passing through matter:



Introduce Analysis

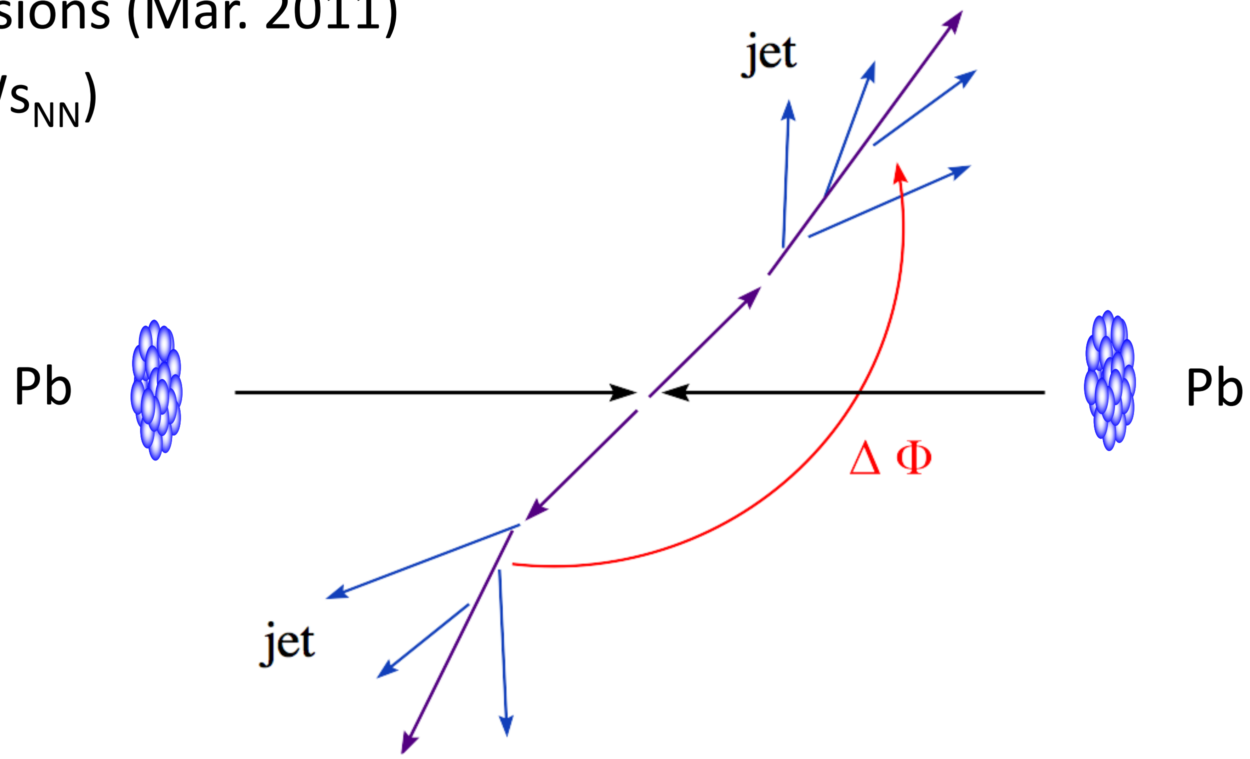
Raw Data from LHC:

PbPb collisions (Nov. 2011)

pp collisions (Mar. 2011)

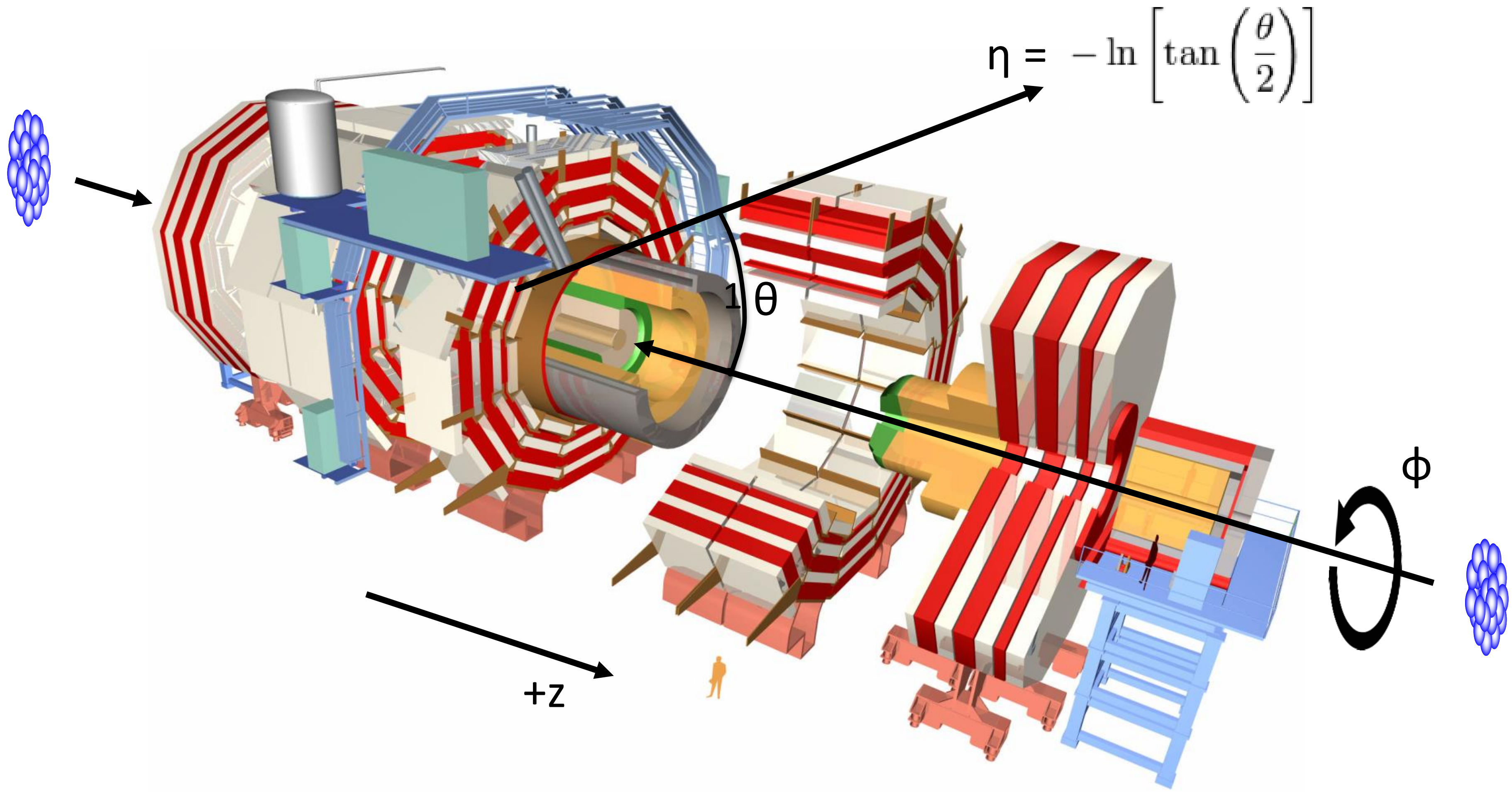
(same $\sqrt{s_{NN}}$)

$\sqrt{s_{NN}}$ = 2.76 TeV



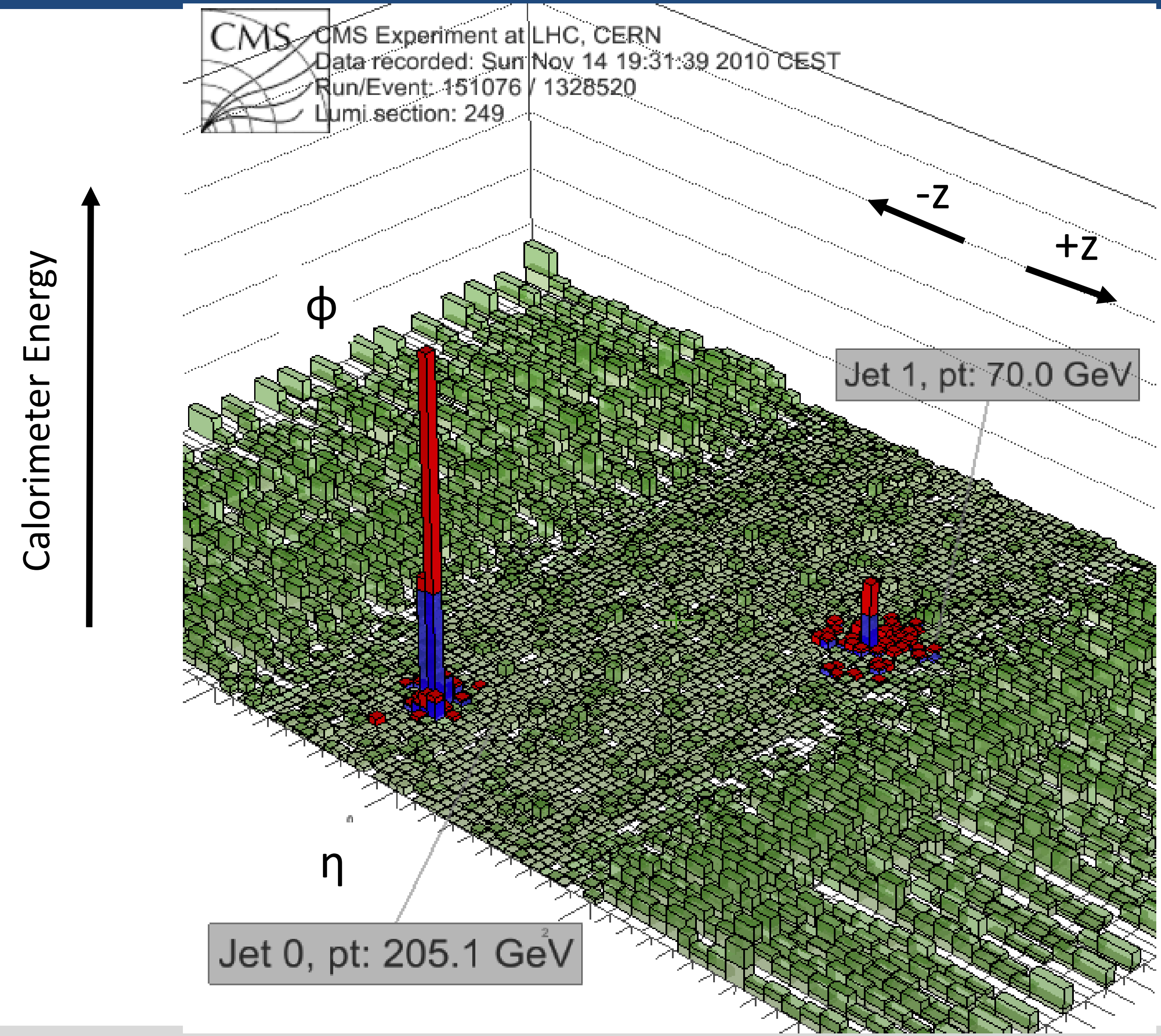
Jet triggered dataset recorded by CMS detector

CMS Detector



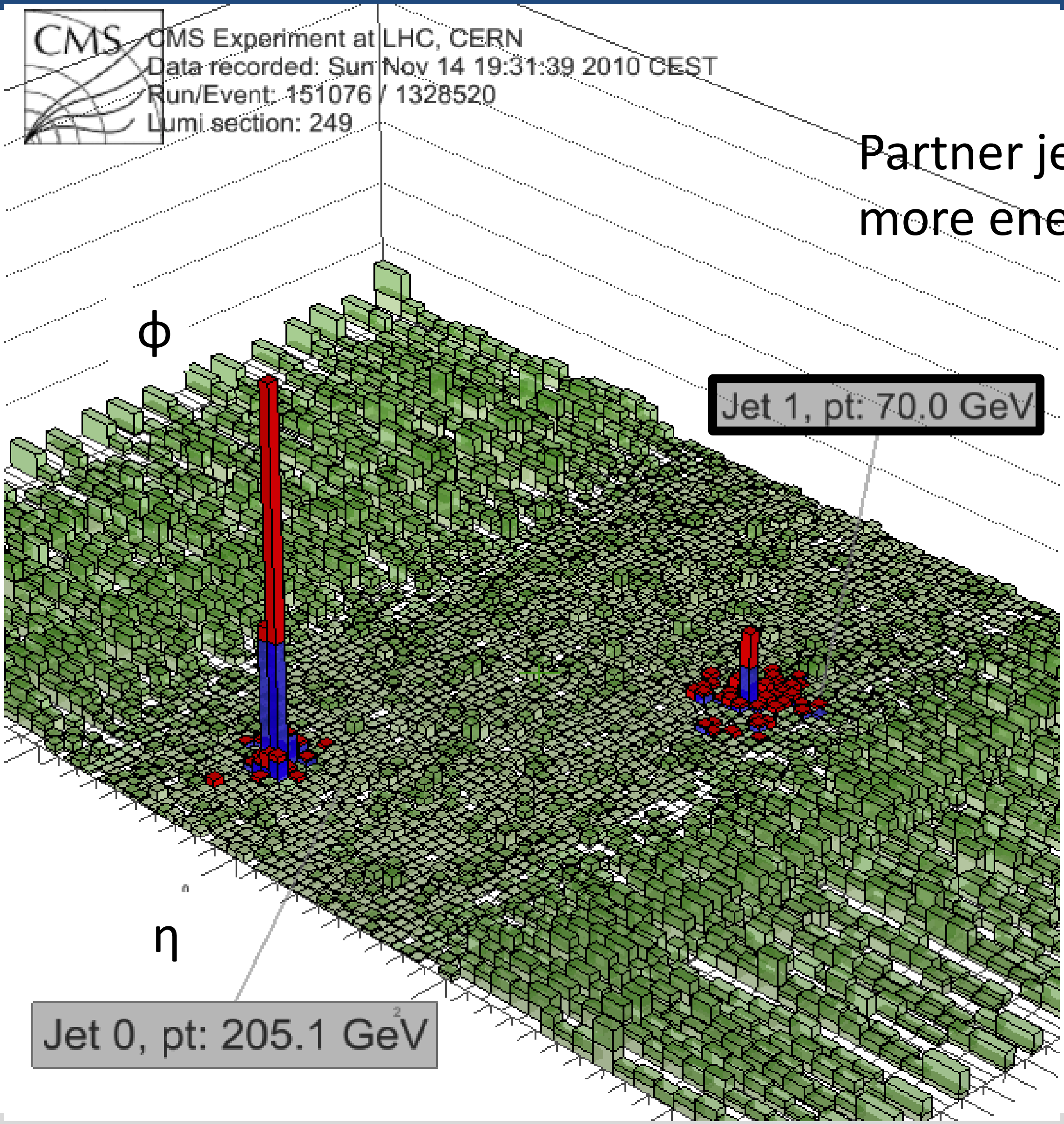
Rely on computer simulation to translate raw data into physical measurements of energy and momenta

Example PbPb Event



Unrolled η,ϕ view of CMS

Example PbPb Event

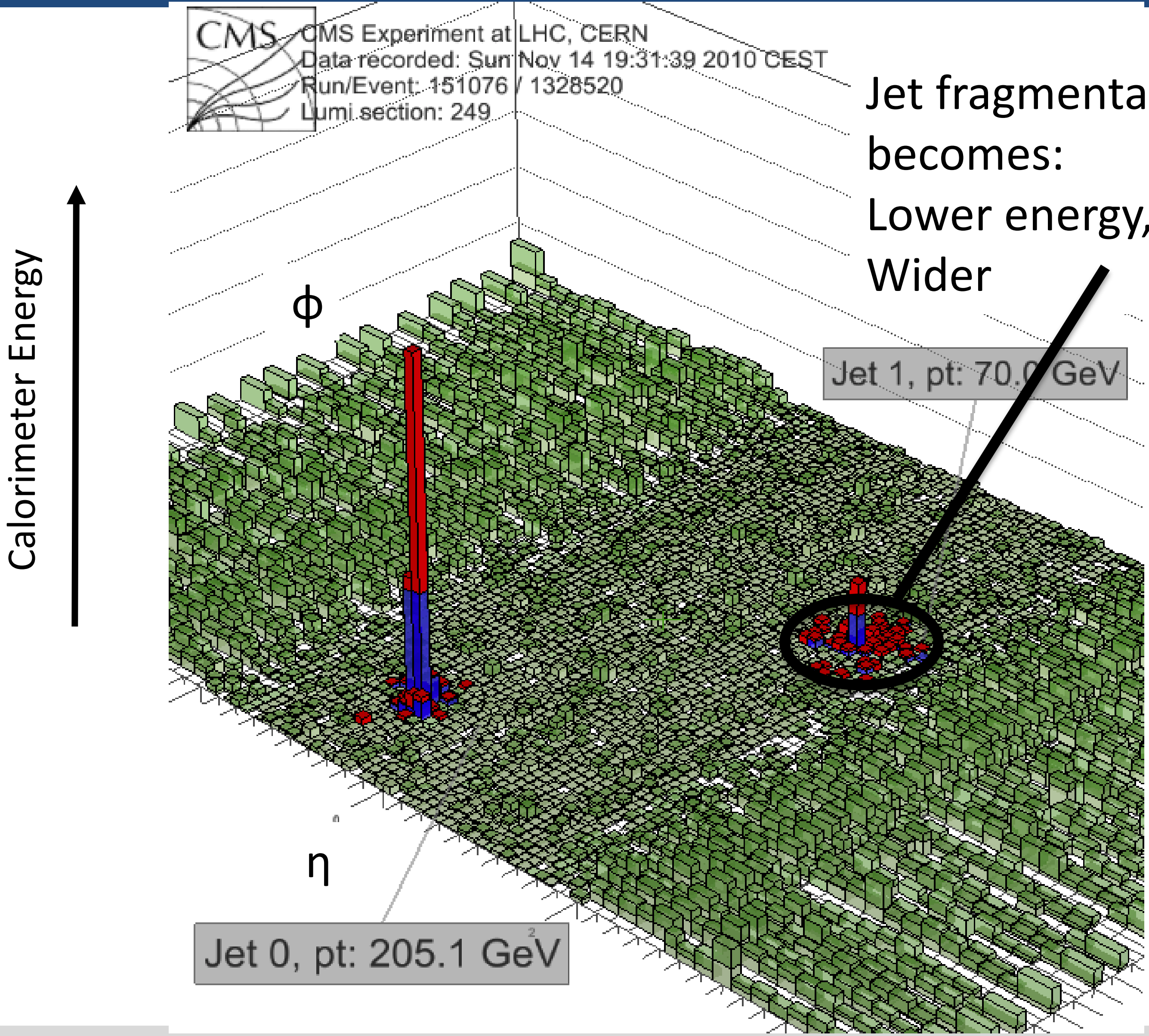


Calorimeter Energy

Partner jet lost more energy

Unrolled η,ϕ view of CMS

Example PbPb Event



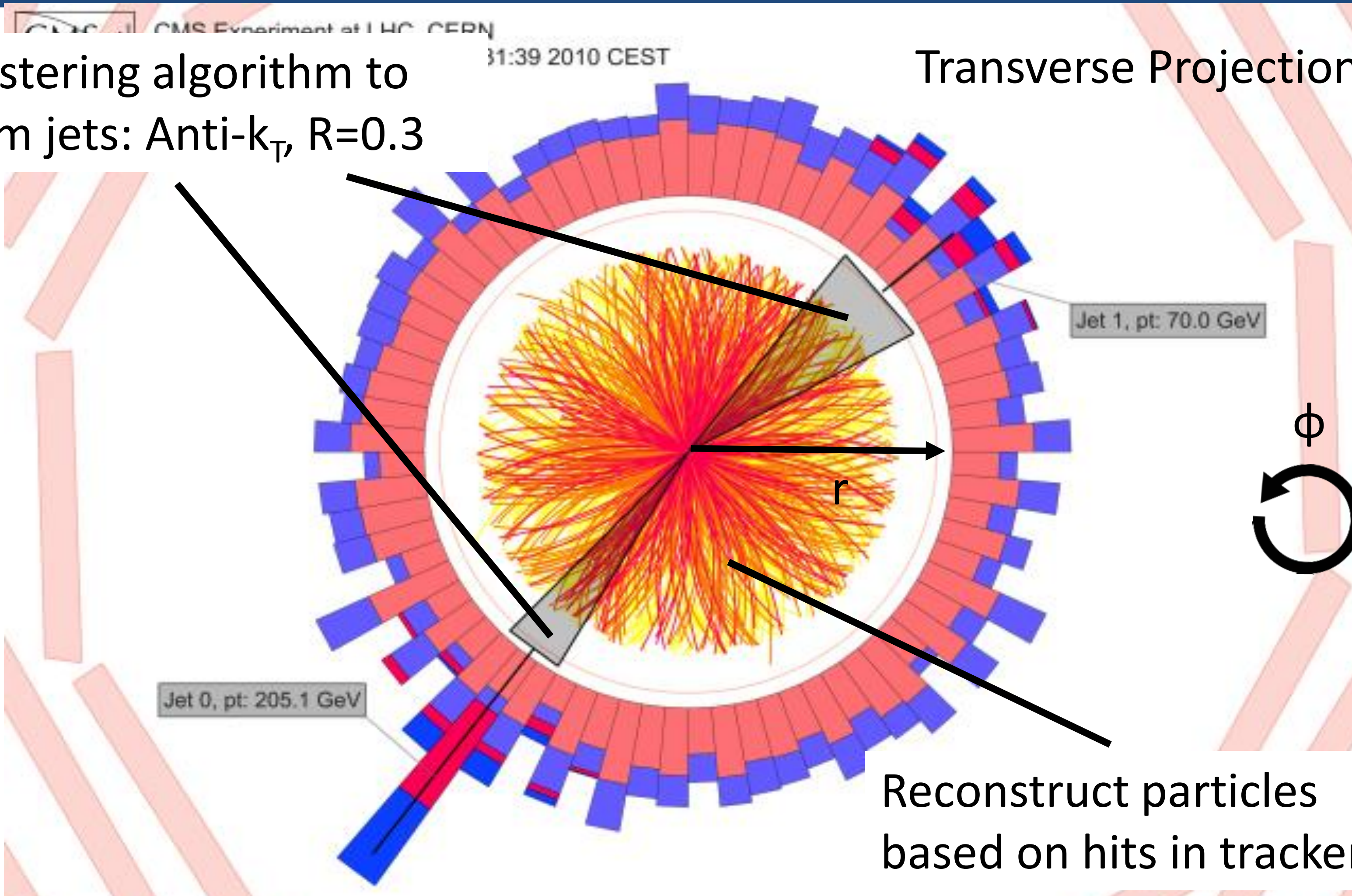
Jet fragmentation becomes:
Lower energy,
Wider

Unrolled η,ϕ view of CMS

Physics Reconstruction

Clustering algorithm to form jets: Anti-k_T, R=0.3

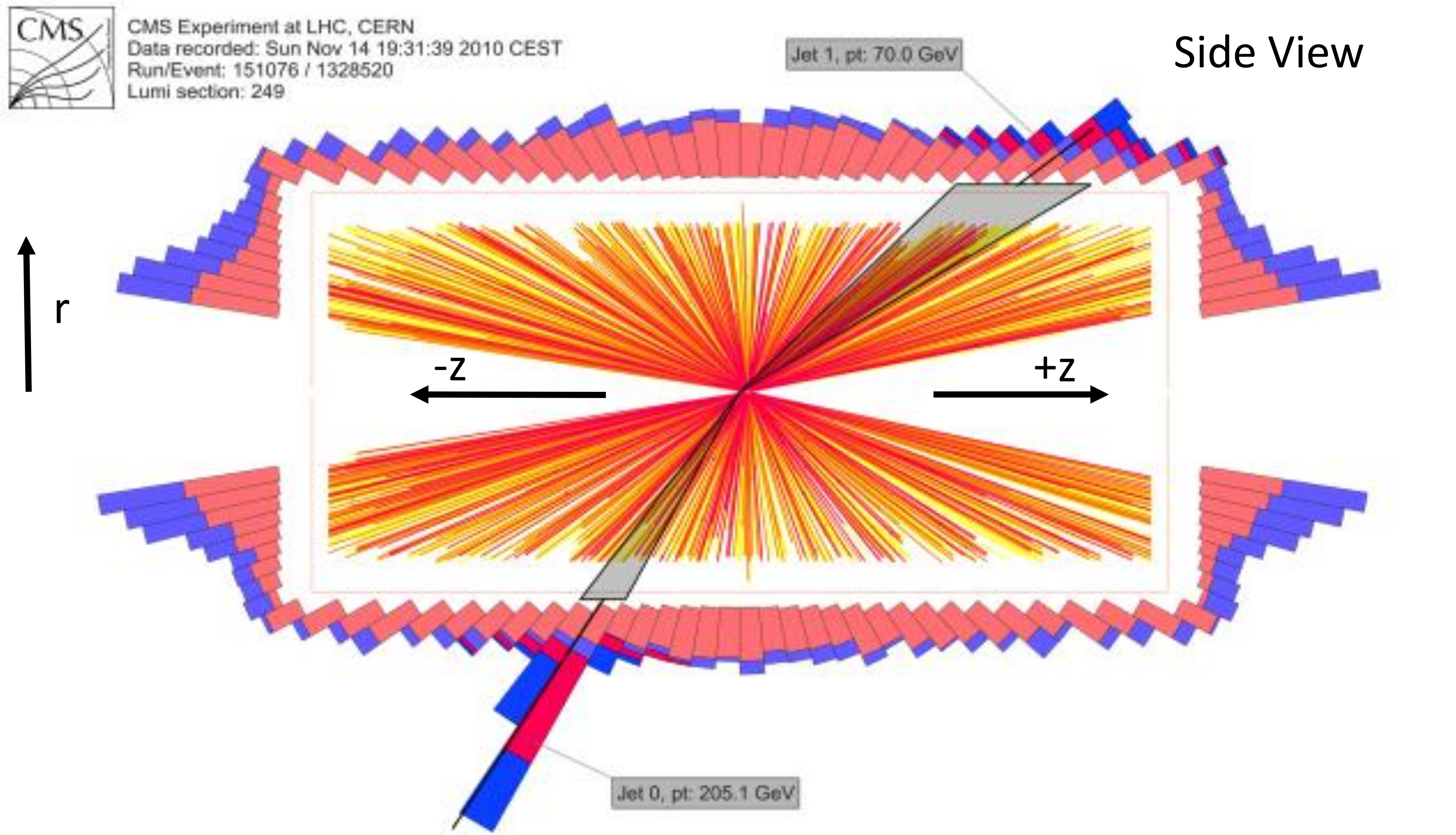
Transverse Projection



Reconstruct particles based on hits in tracker

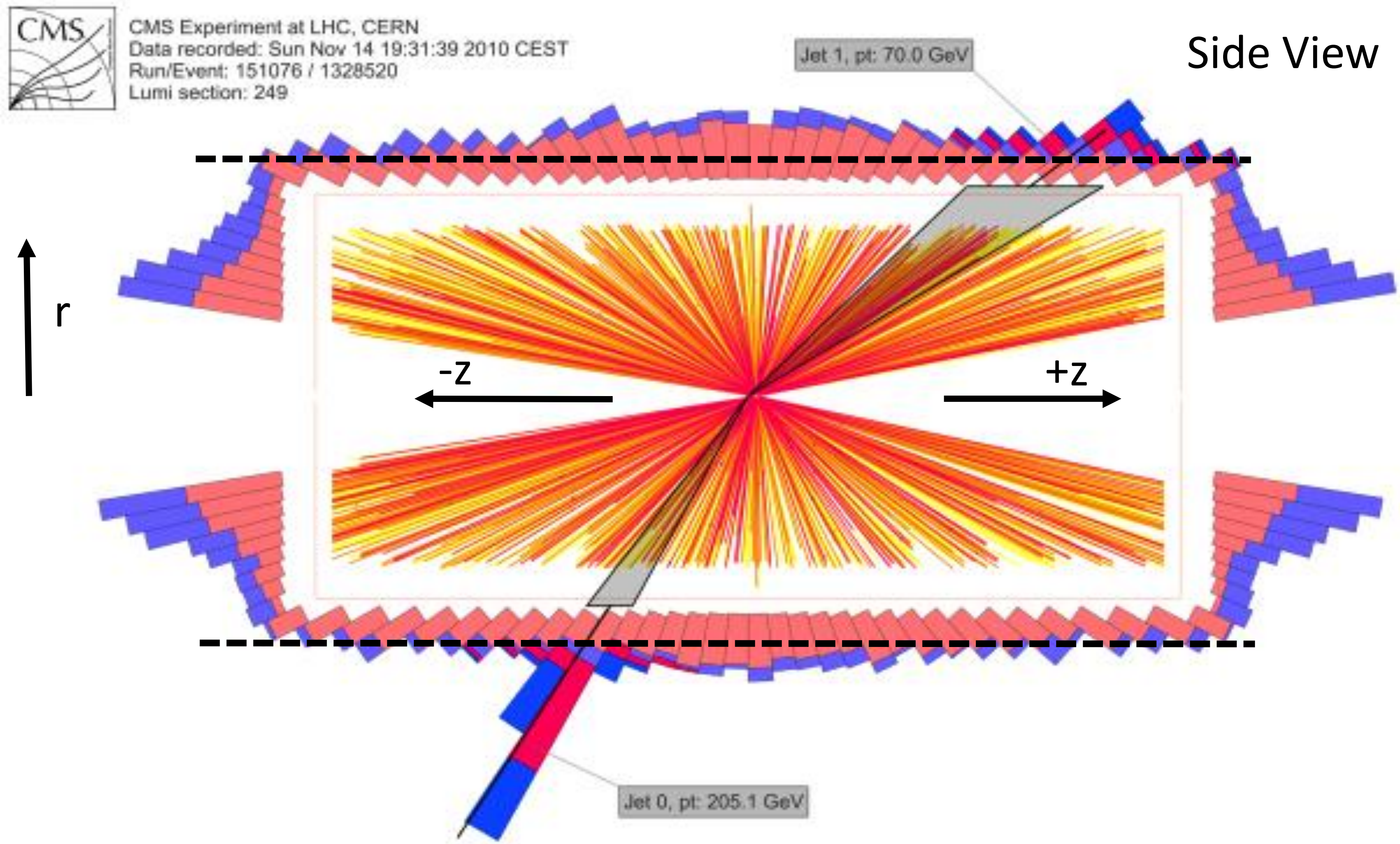
Rely on computer simulation to translate raw data into physical measurements of energy and momenta

Analysis Challenge



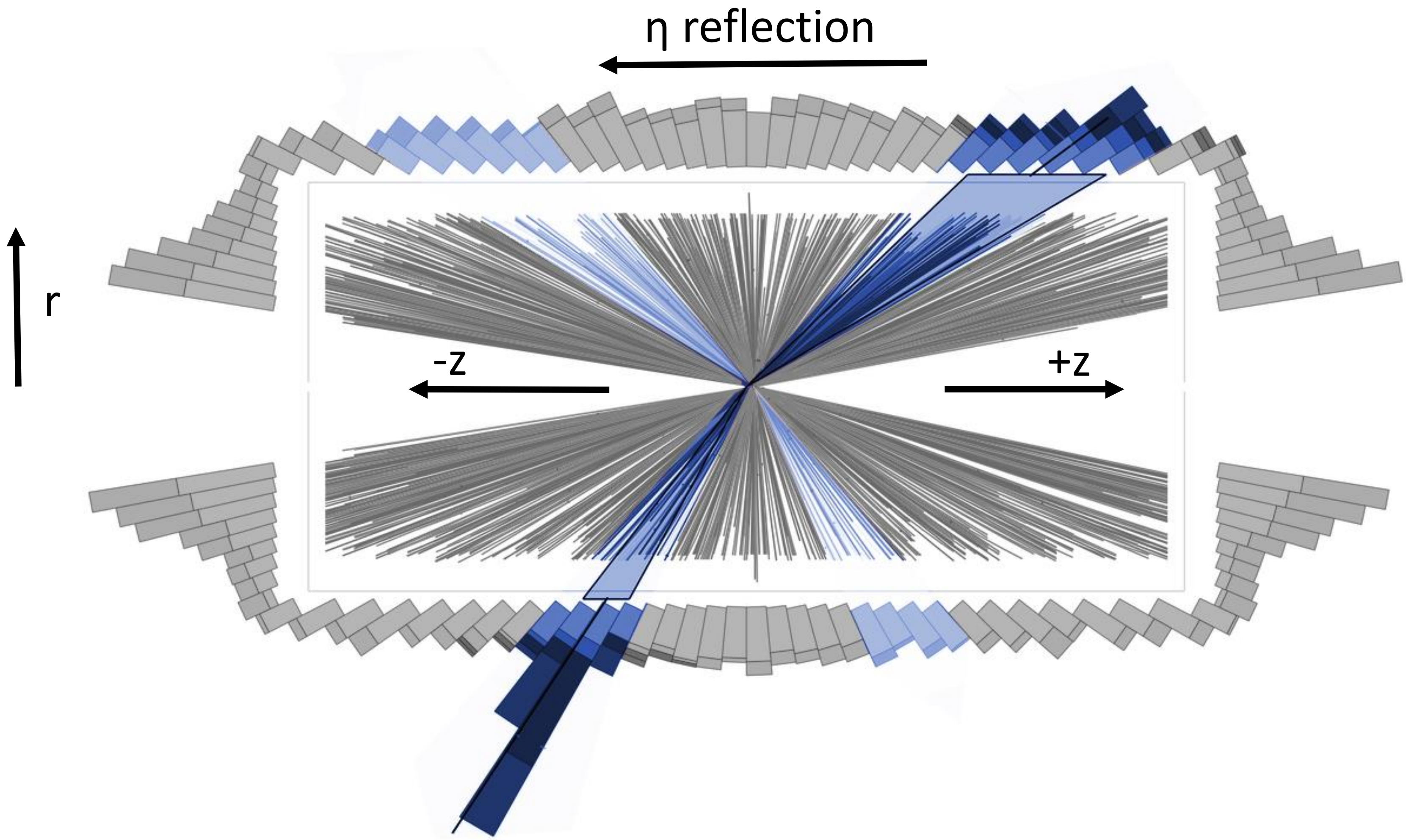
The underlying event contribution needs to be subtracted

Analysis Challenge



The underlying event is z symmetric

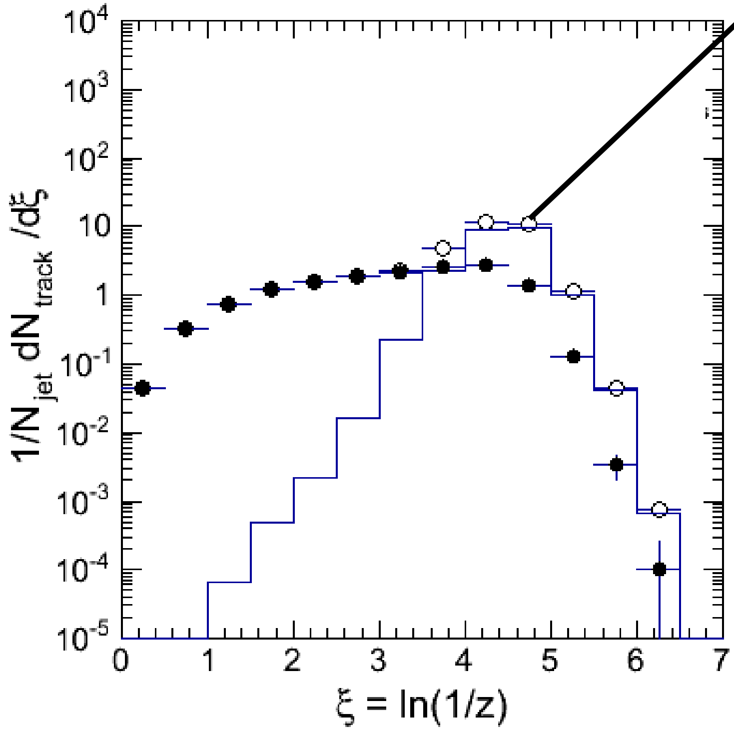
Background Subtraction

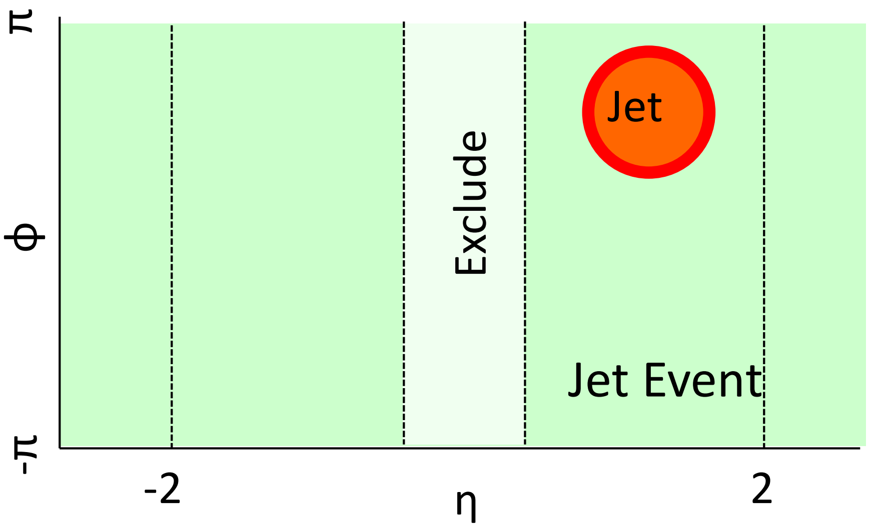


Exploit z symmetry of event to estimate background contribution in jet cone by a reflected cone.

Fragmentation Function Procedure

(1) Plot raw FF in jet cone





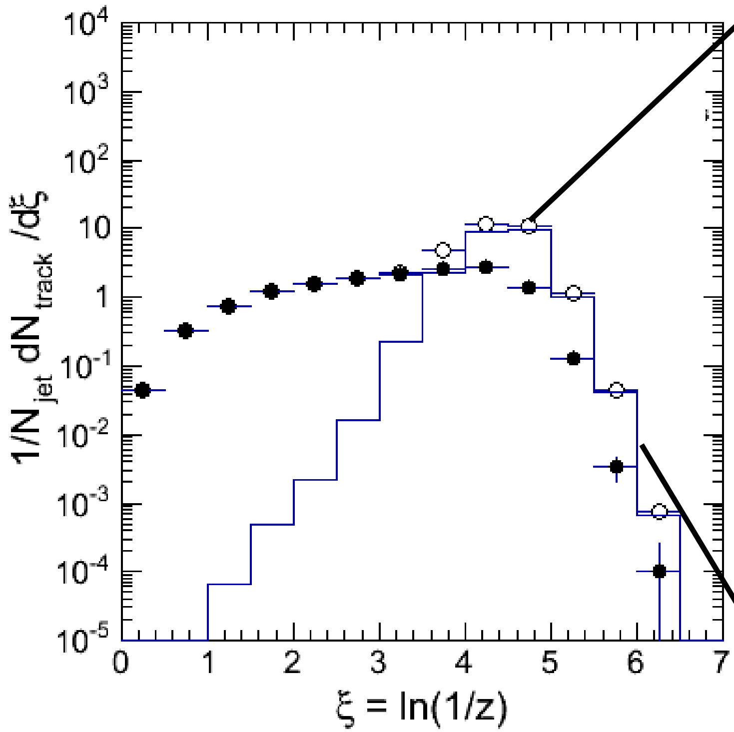
ΔR(particle, Jet) < 0.3

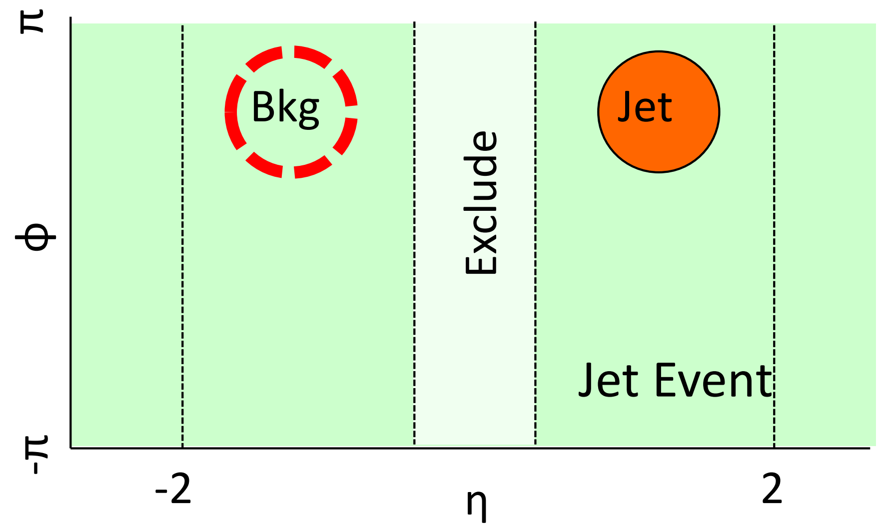
$$z = \frac{p_{\|}^{\mathrm{track}}}{p^{\mathrm{jet}}}$$

Fragmentation Function Procedure

(1) Plot raw FF in jet cone

○ **All tracks in jet cone**





(2) Obtain FF contribution from heavy ion background using η reflected cone.

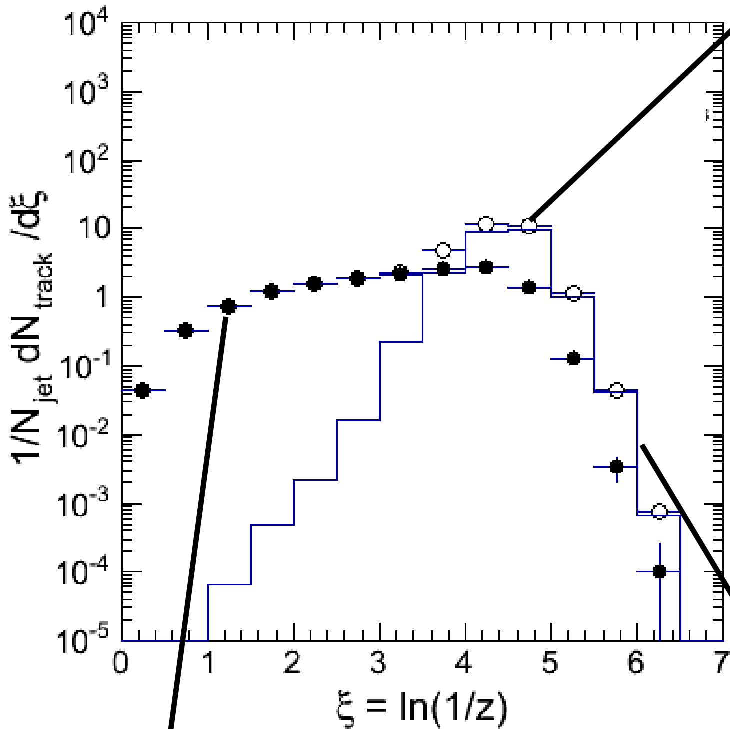
tracks from underlying events

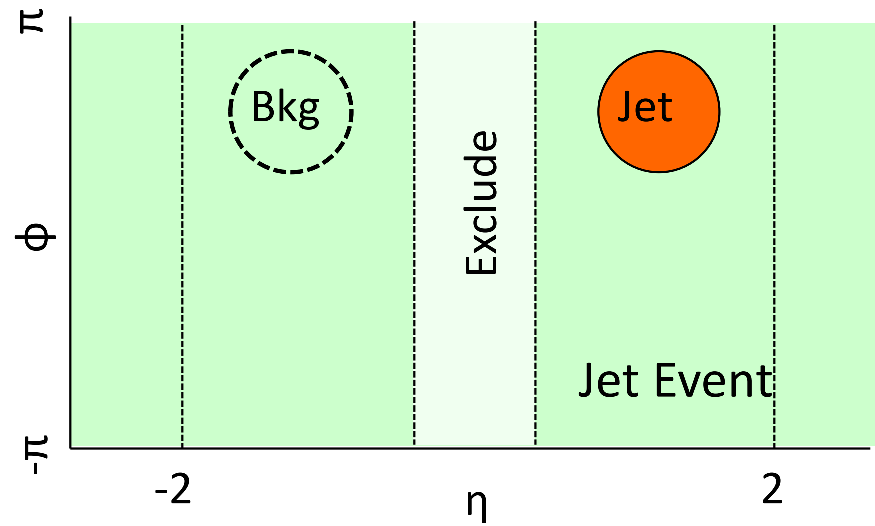
$$z = \frac{p_{||}^{\text{track}}}{p^{\text{jet}}}$$

Fragmentation Function Procedure

(1) Plot raw FF in jet cone

○ **All tracks in jet cone**





(2) Obtain FF contribution from heavy ion background using η reflected cone.

(3) Subtract (2) from (1)

● **After subtraction**

—— **tracks from underlying events**

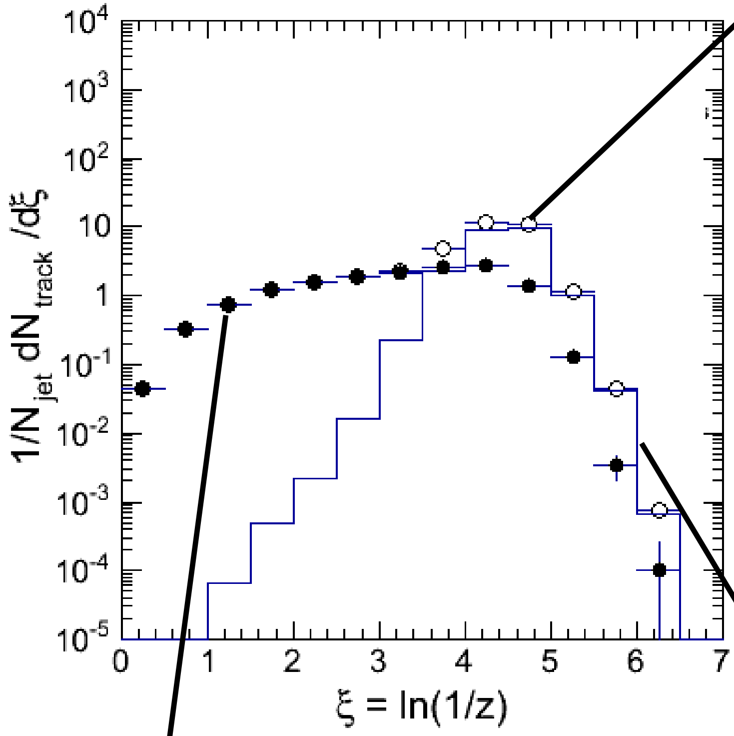
$$z = \frac{p_{\parallel}^{\mathrm{track}}}{p^{\mathrm{jet}}}$$

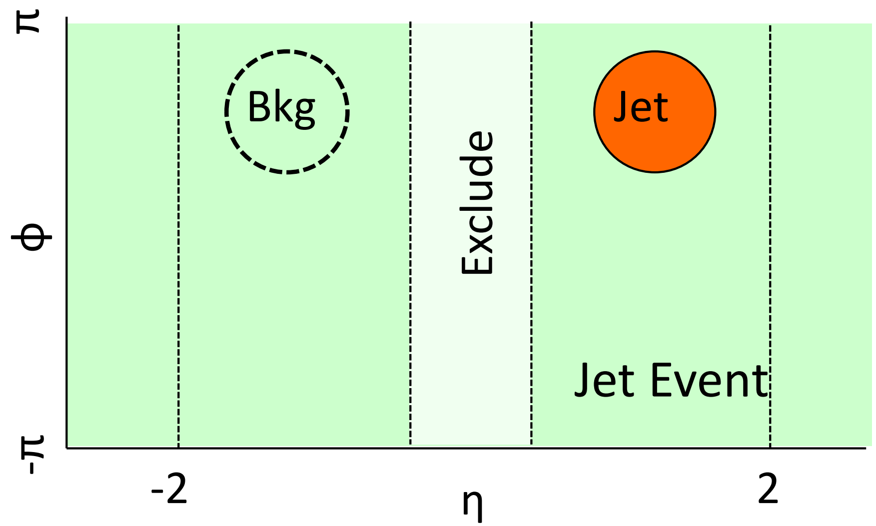
Fragmentation Function Procedure

(4) Compare to pp reference

(1) Plot raw FF in jet cone

○ **All tracks in jet cone**





(2) Obtain FF contribution from heavy ion background using η reflected cone.

(3) Subtract (2) from (1)

● **After subtraction**

—— **tracks from underlying events**

$$z = \frac{p_{\|}^{\text{track}}}{p^{\text{jet}}}$$

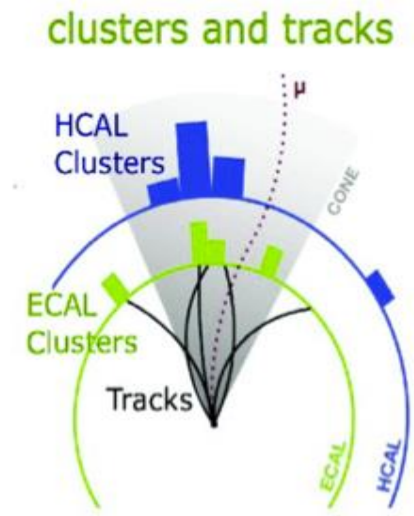
Data Sample/Inputs

- PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
  - 140/μb
  - Jet triggered dataset

- pp $\sqrt{s}$ = 2.76 TeV
  - 212/nb
  - Jet triggered dataset

All triggers fully efficient for jet p_T > 100 GeV/c

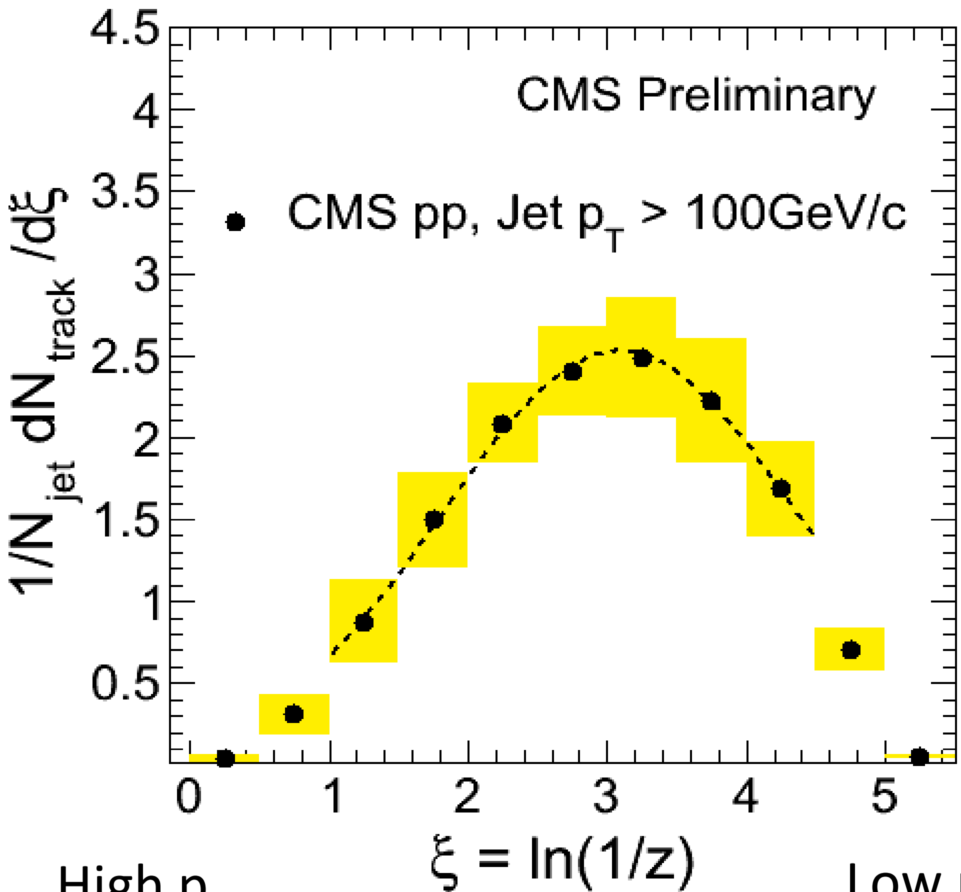
- Jet Reconstruction
  - arXiv:1205.5872
  - CMS particle flow jet
  - Background subtracted
  - Anti-k_T algorithm, R = 0.3
  - Corrected to particle jet



Systematic Uncertainties

Item	Input / Variation	$\xi < 1.5$	$1.5 < \xi < 4$	$4 < \xi < 5.5$
Jet Energy Resolution	10-20% smearing	5–11%	2%	5%
Jet Energy Scale	7% shift	5–20%	5%	20%
Tracking Efficiency	non-closure	8%	2%	10%
Tracking Efficiency	centrality variation	10%	10%	10%
Background Subtraction	Gen. level closure	0%	0%	10%
Background Subtraction	Difference between methods	7%	2%	9%
pp reweighting	before/after	6%	6%	6%

Results in pp



High p_T

Low p_T

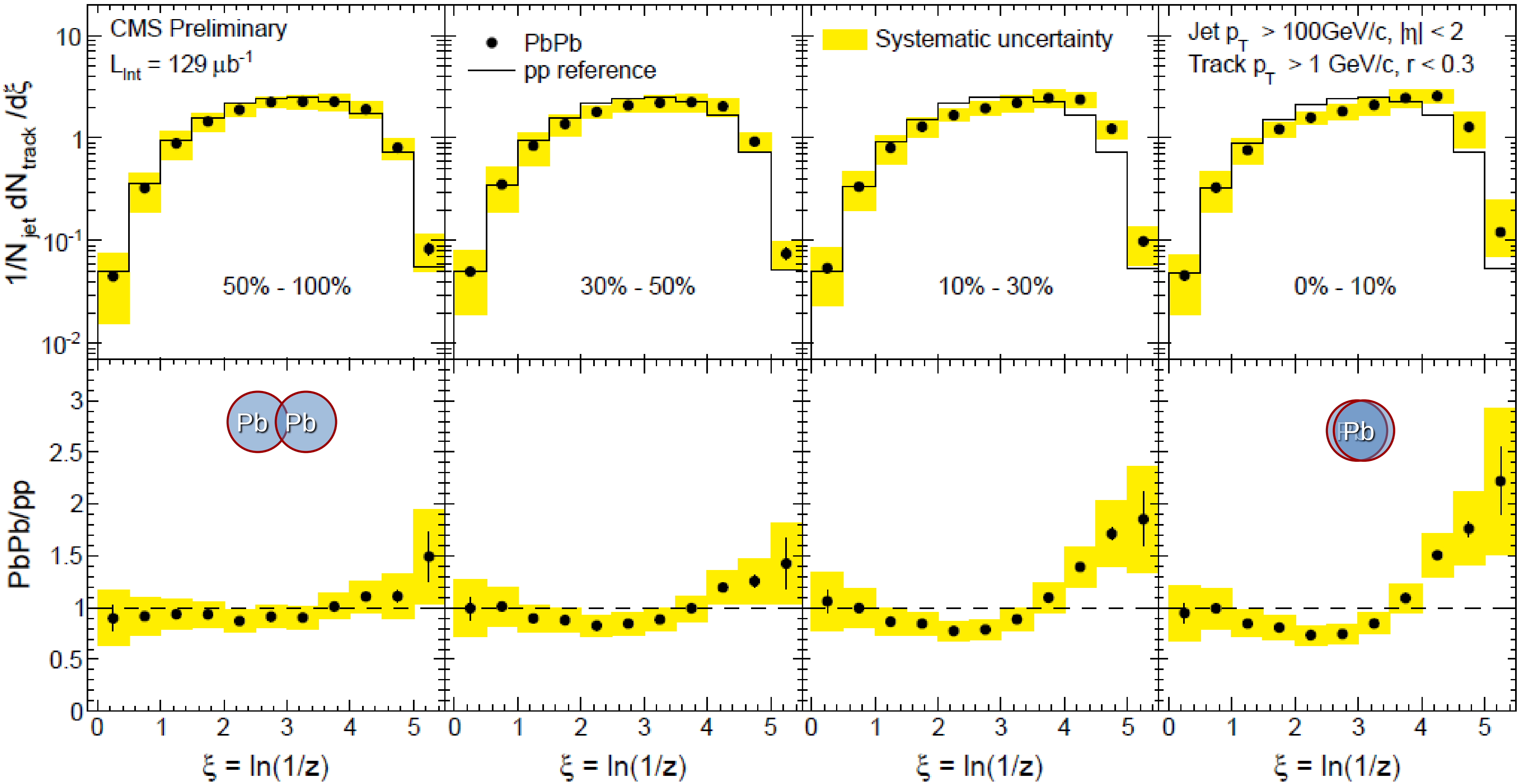
100 < Jet p_T < 300 GeV/c
Track p_T > 1 GeV/c

Area =
average number of charged particles per jet
~ 6

pp jet fragmentation function in agreement with pQCD expectation in vacuum

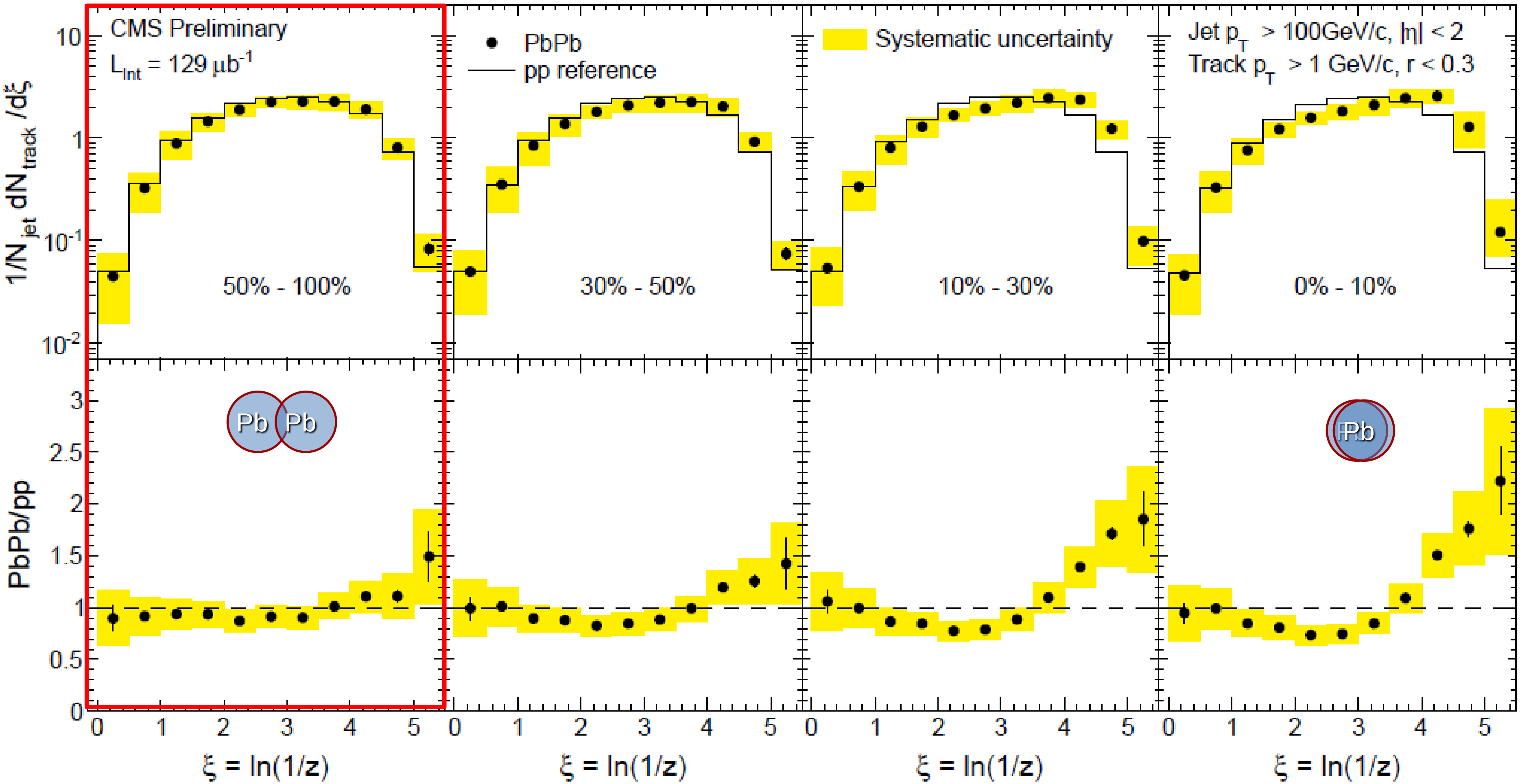
$$z = \frac{p_{\|}^{\mathrm{track}}}{p^{\mathrm{jet}}}$$

Results in PbPb vs pp



$$z = \frac{p_{\parallel}^{\mathrm{track}}}{p^{\mathrm{jet}}}$$

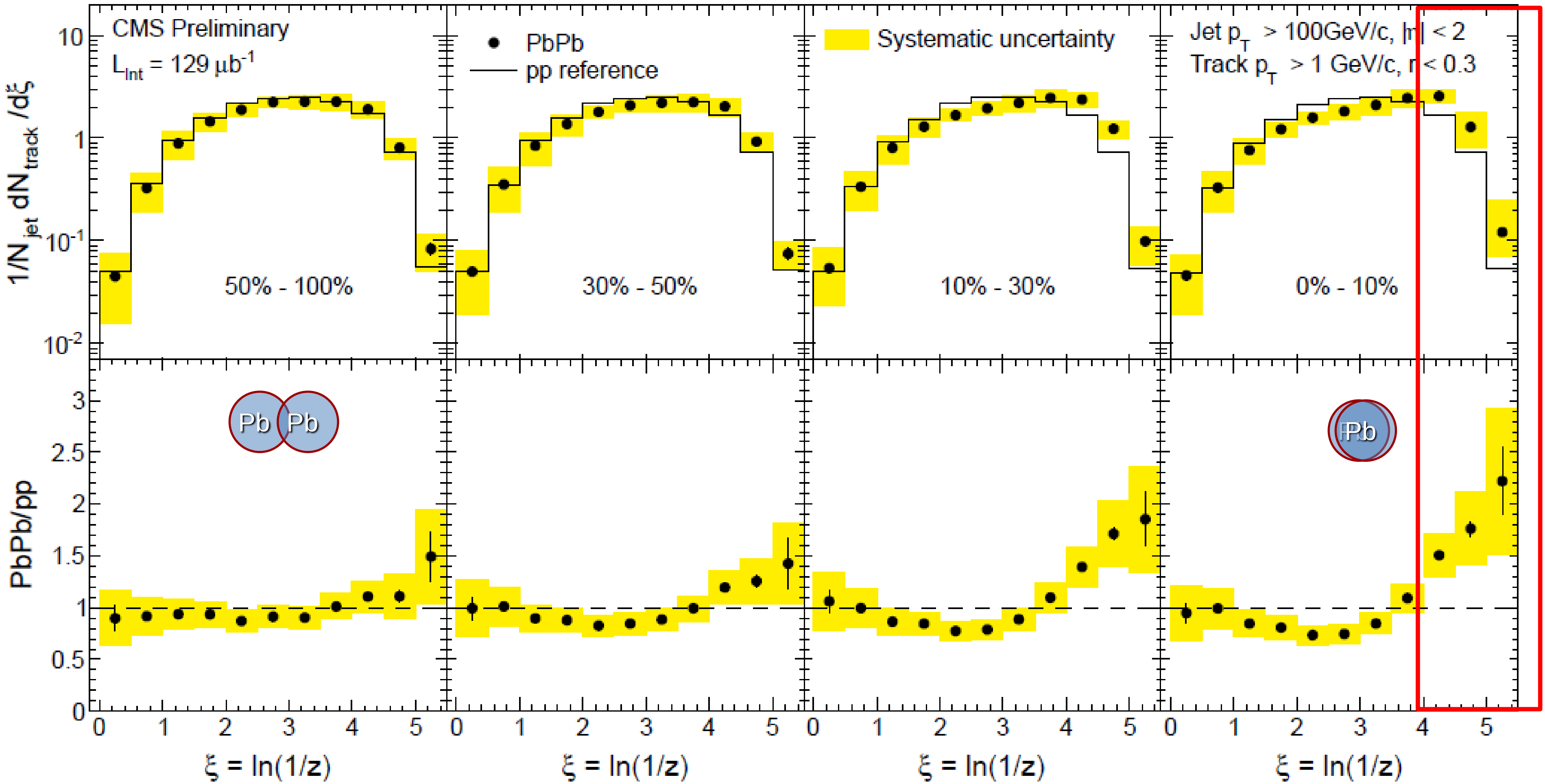
Results in PbPb vs pp



Jet fragmentation function in peripheral PbPb collisions look like pp

$$z = \frac{p_{||}^{\text{track}}}{p^{\text{jet}}}$$

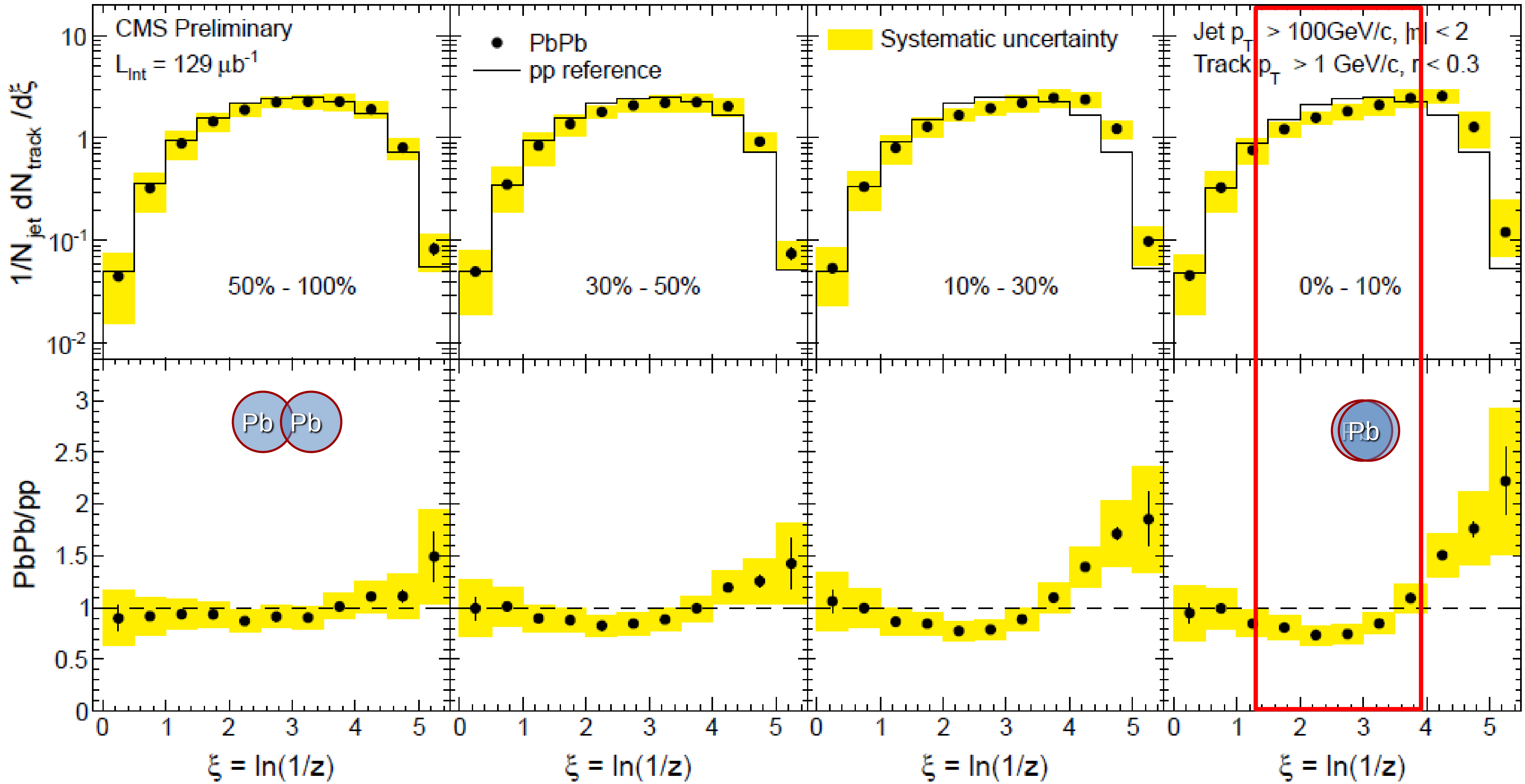
Results in PbPb vs pp



Excess of particles in low momentum part of the fragmentation function when medium is largest

$$z = \frac{p_{||}^{\mathrm{track}}}{p^{\mathrm{jet}}}$$

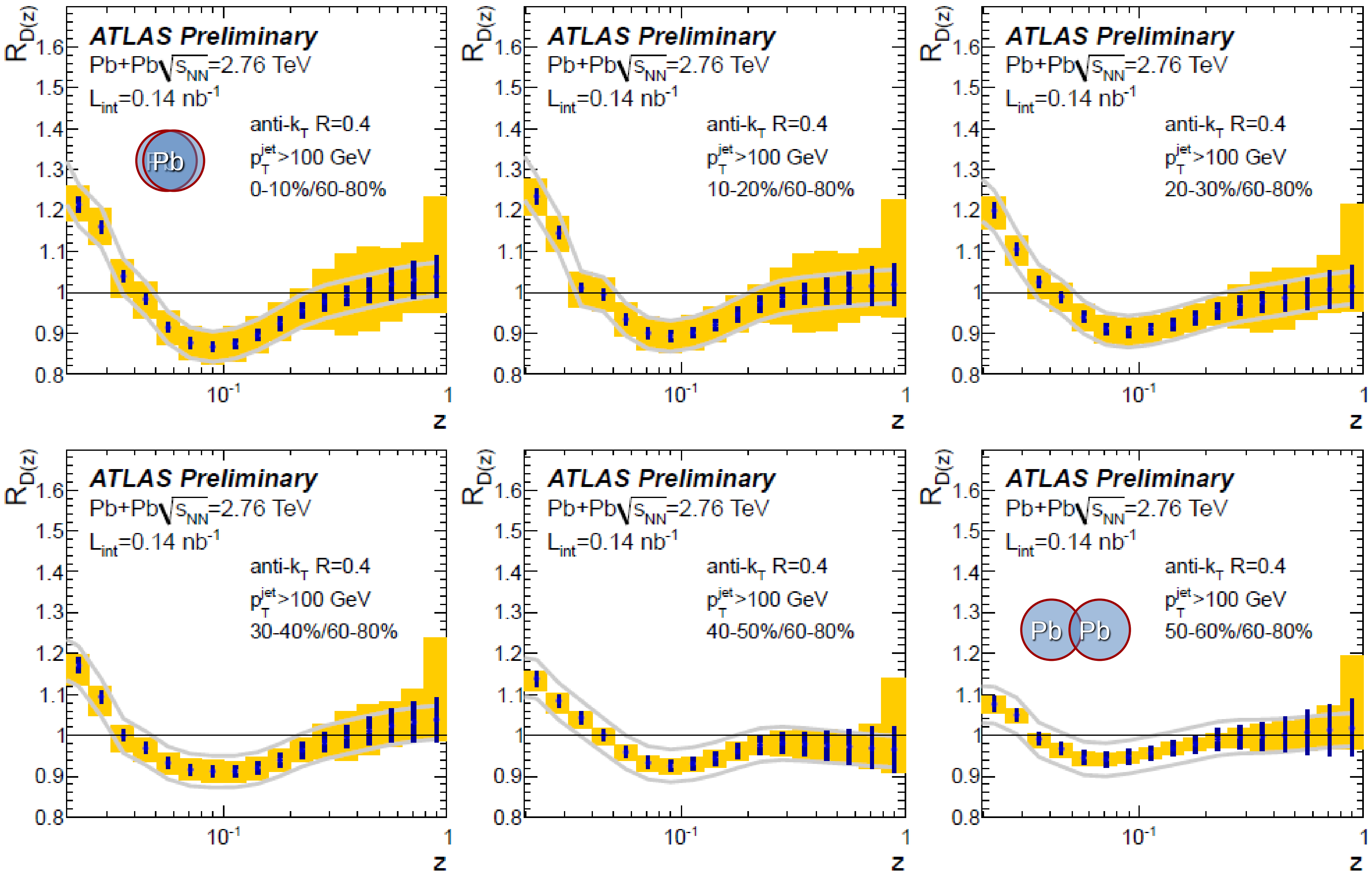
Results in PbPb vs pp



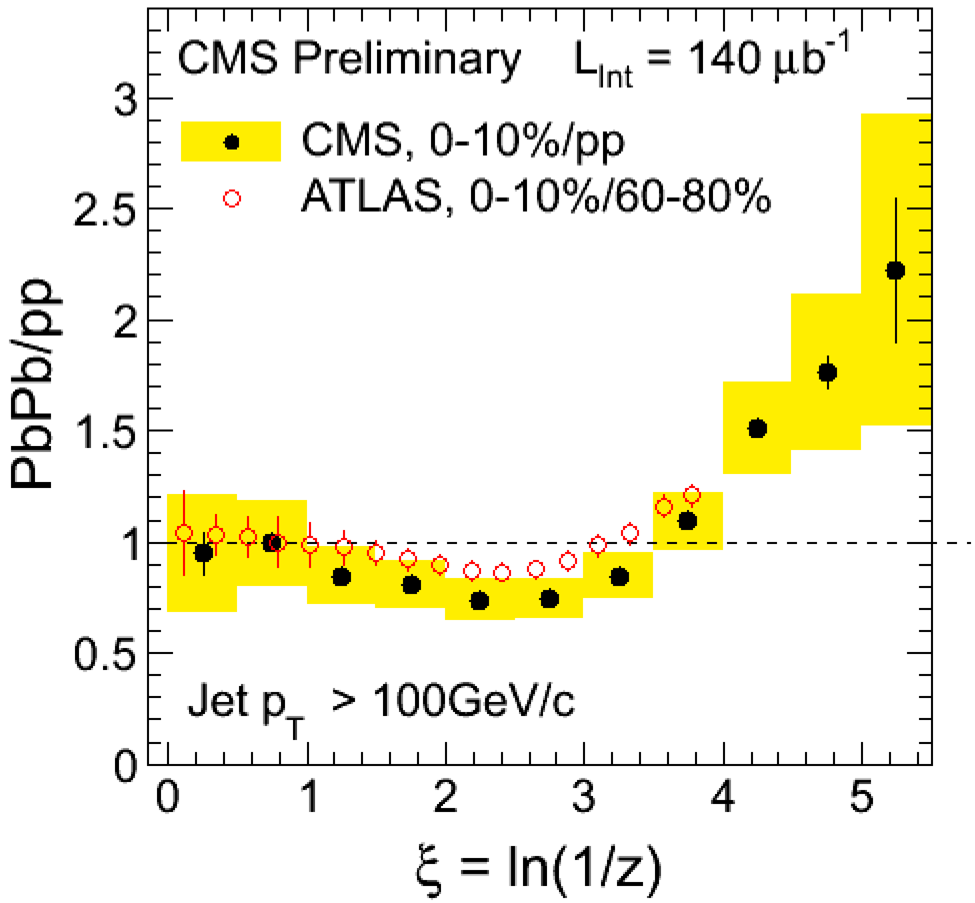
Deficit of mid momentum particles in fragmentation function when medium is largest

$$z = \frac{p_{||}^{\mathrm{track}}}{p^{\mathrm{jet}}}$$

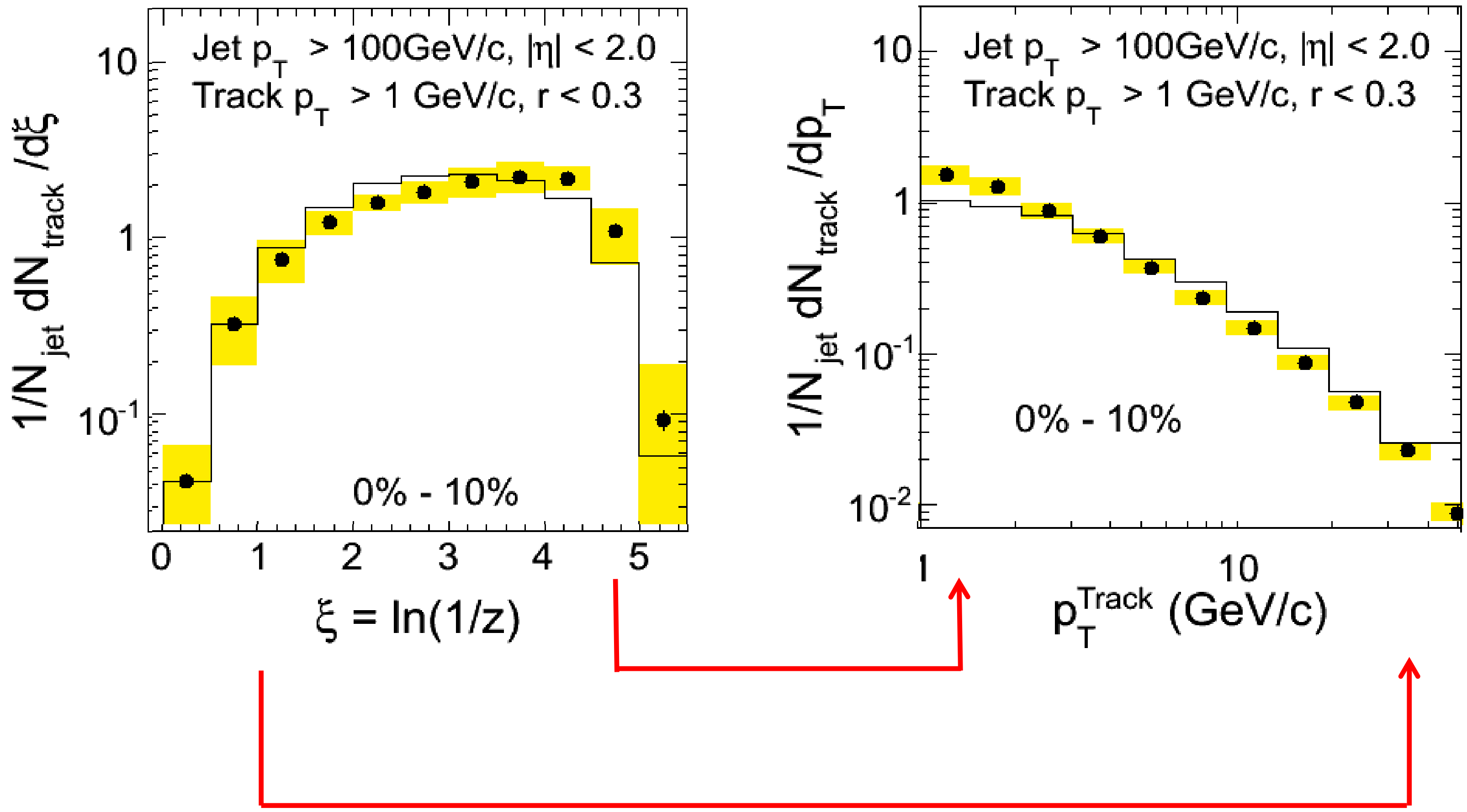
ATLAS Comparison



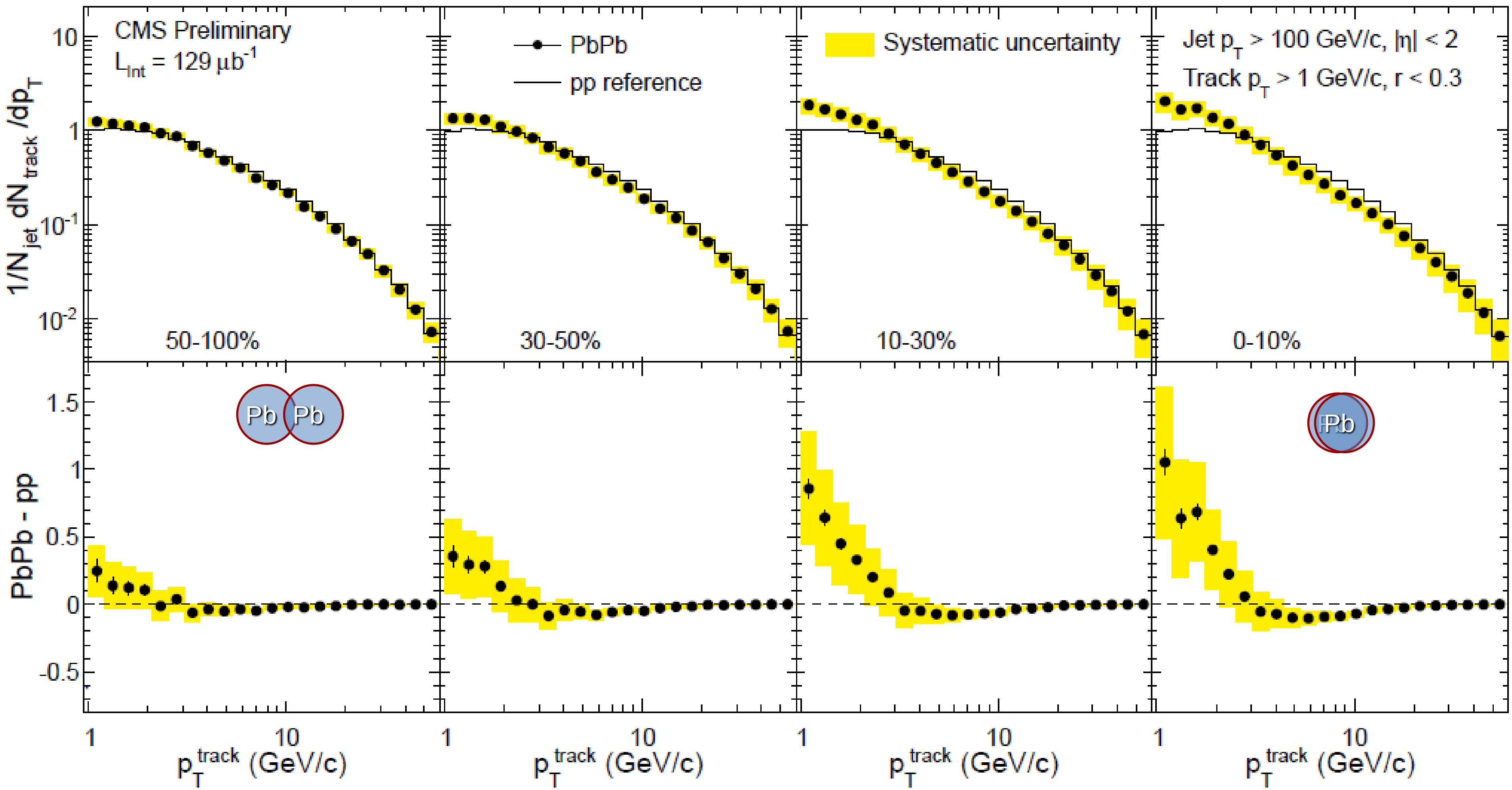
ATLAS Direct Comparison



Change of Variable



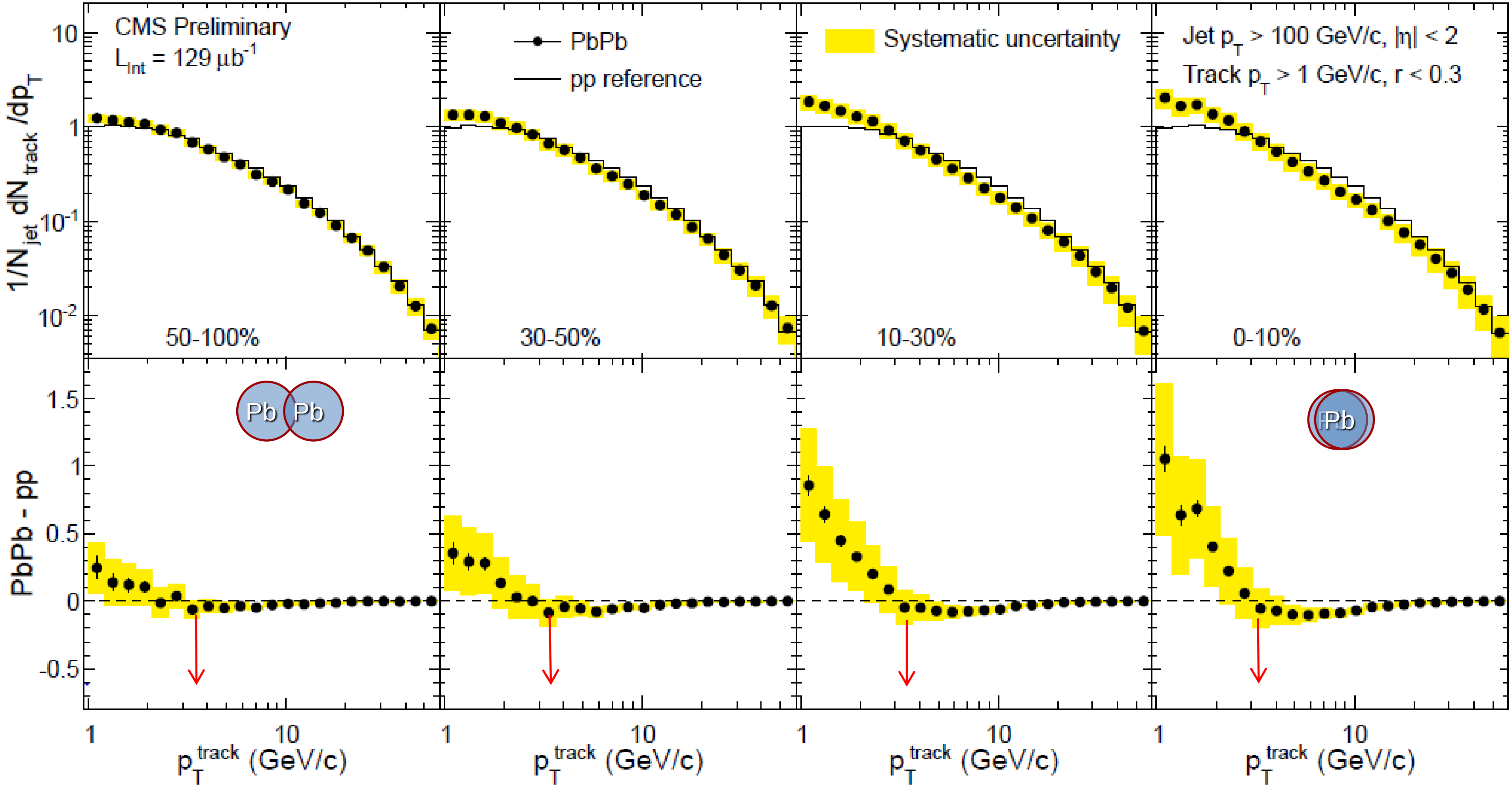
Results in PbPb vs pp



Explicitly see excess at low track momentum

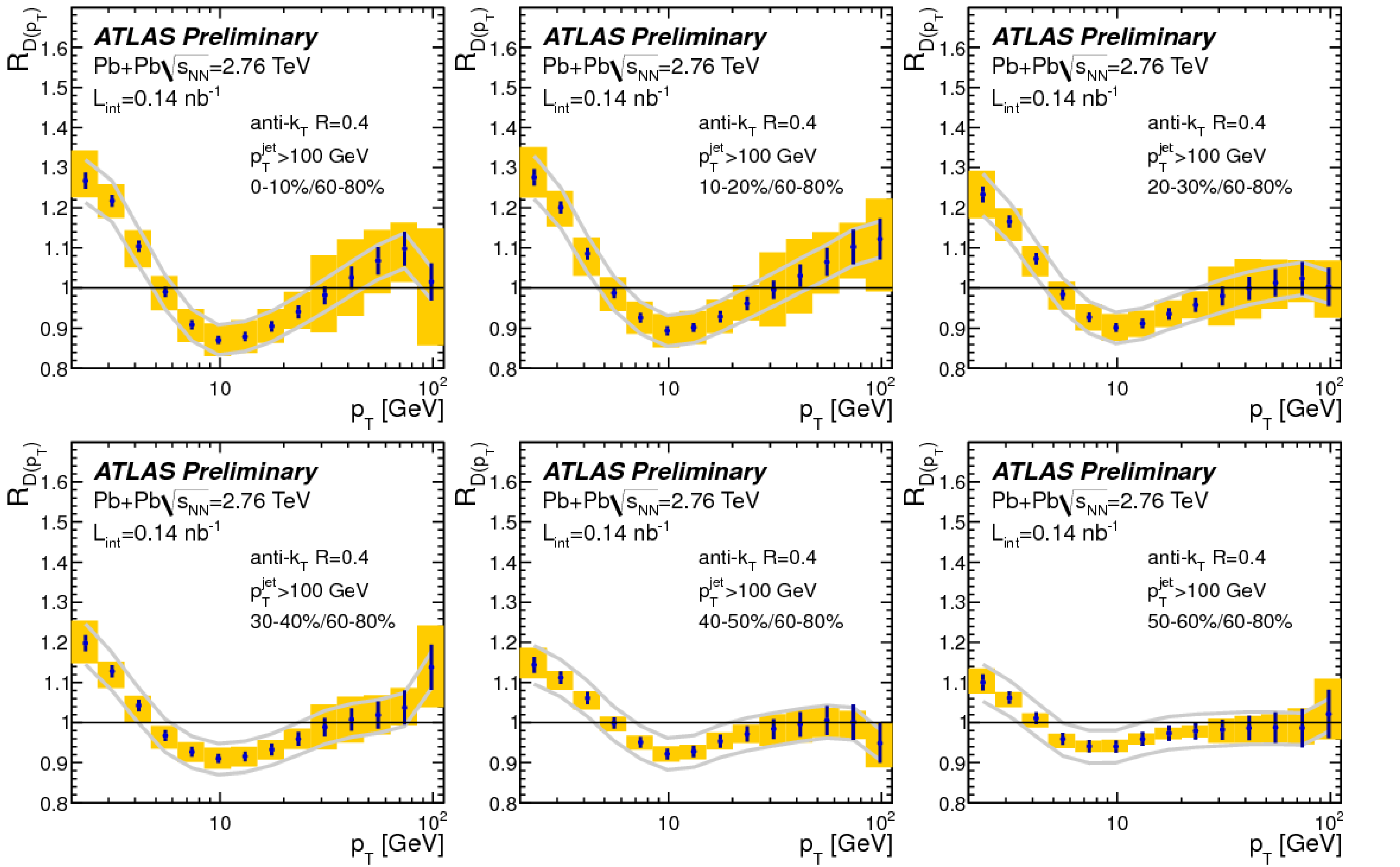
In most central events ~ 0.5 extra particles

Results in PbPb vs pp



Cross over occurs at ~ 3 GeV in all centralities.

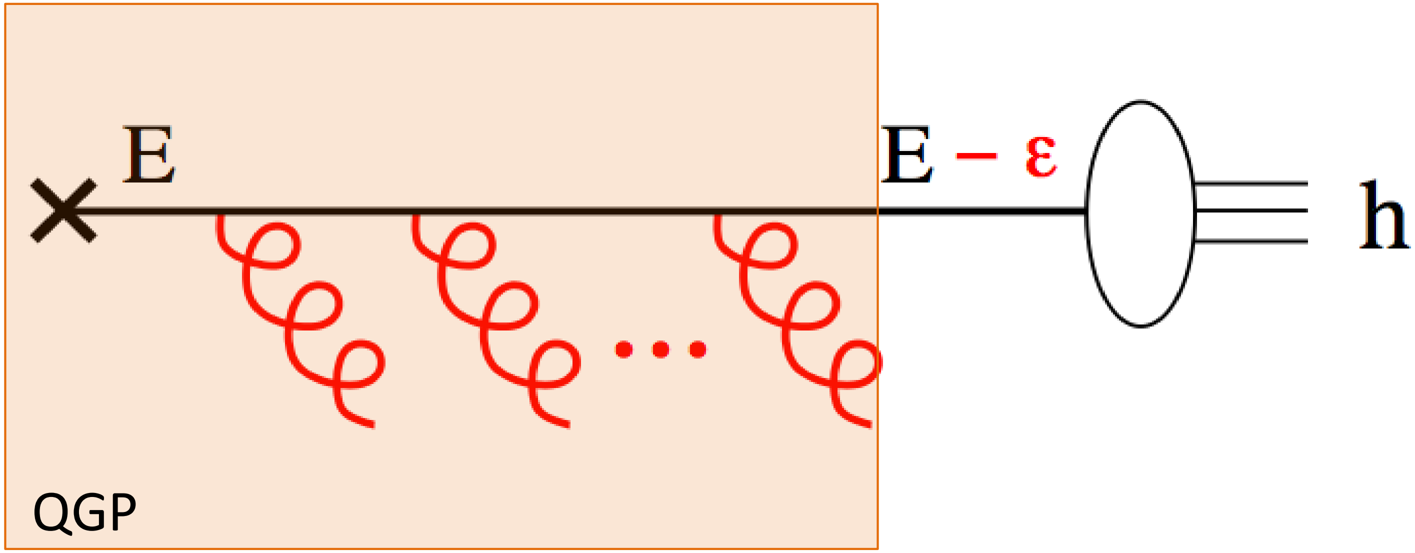
ATLAS comparison



Ratio instead of difference

ATLAS-CONF-2012-115

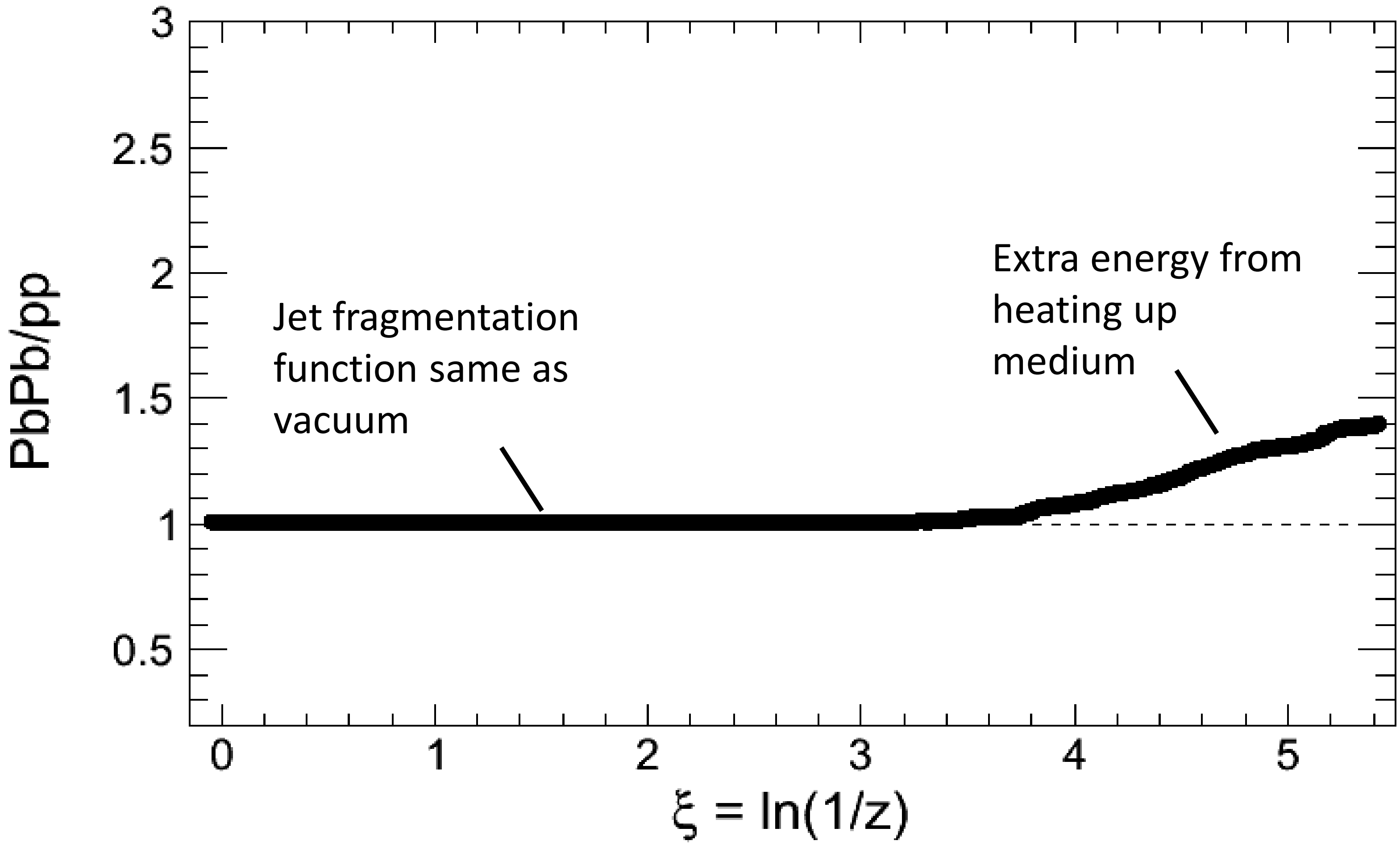
Energy Rescaling Model



Jets loss energy due to medium interaction, then fragments as in vacuum

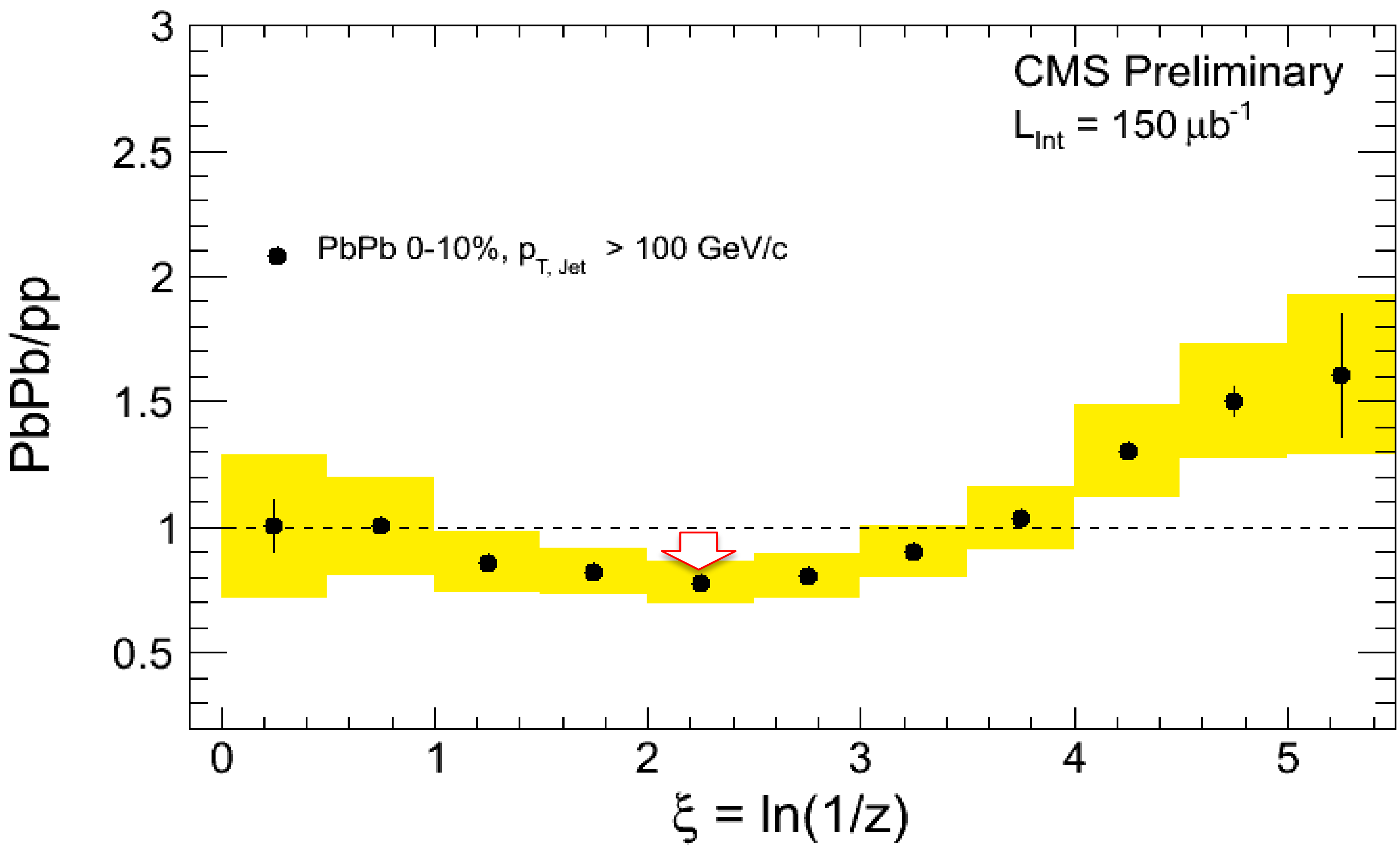
Was success to describe RHIC high p_T particle spectra

Energy Rescaling Model



Energy rescale model simple expectation

Examine Measured Data



Energy Rescale picture ruled out?

Gluon Jet vs Quark Jet

- One more free parameter
  - Jet can either be gluon jet or quark jet
  - Fit for fraction of gluon and quark jets as superposition of two fragmentation functions:

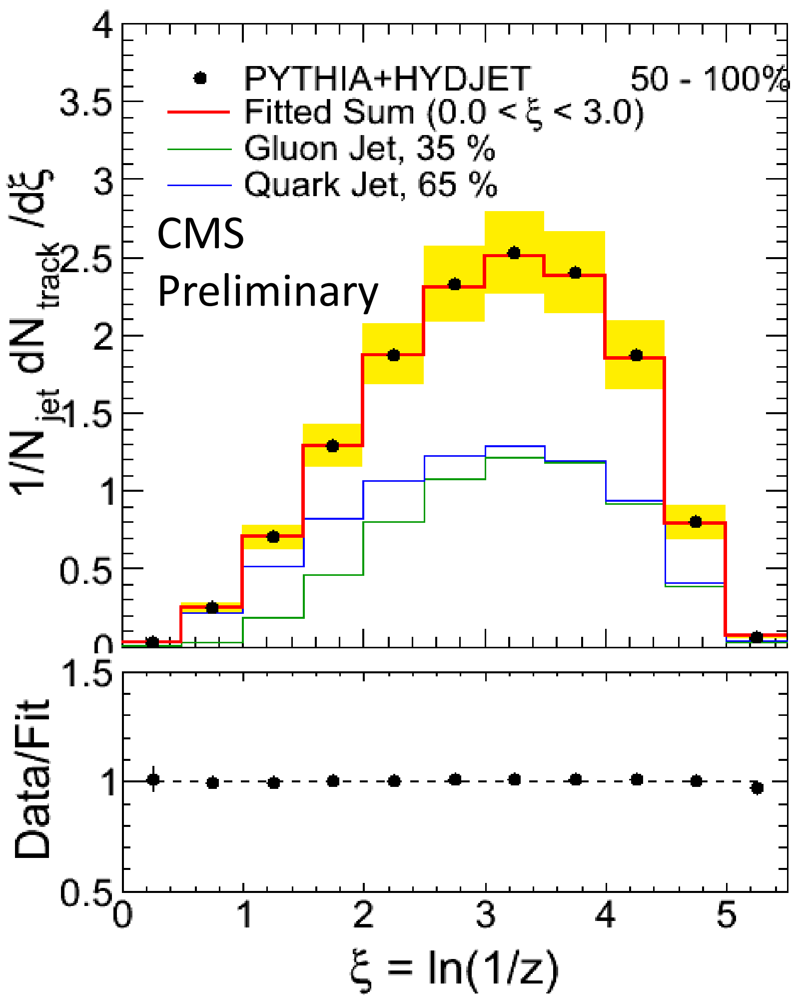
$$\frac{dN}{d\xi} = a\frac{dN}{d\xi}^{gluon} + (1-a)\frac{dN}{d\xi}^{quark}$$

Scan “a” until sum of templates best fits data

Fit only for the higher p_T part of fragmentation function: $0 < \xi < 3$

Comparison to Theory Models

PYTHIA
v6.423
tune Z2



100 < Jet p_T < 300 GeV/c

Gluon jets are softer than quark jets

Template fitting gets back MC ✓

Comparison to Theory Models

PYTHIA
v6.423
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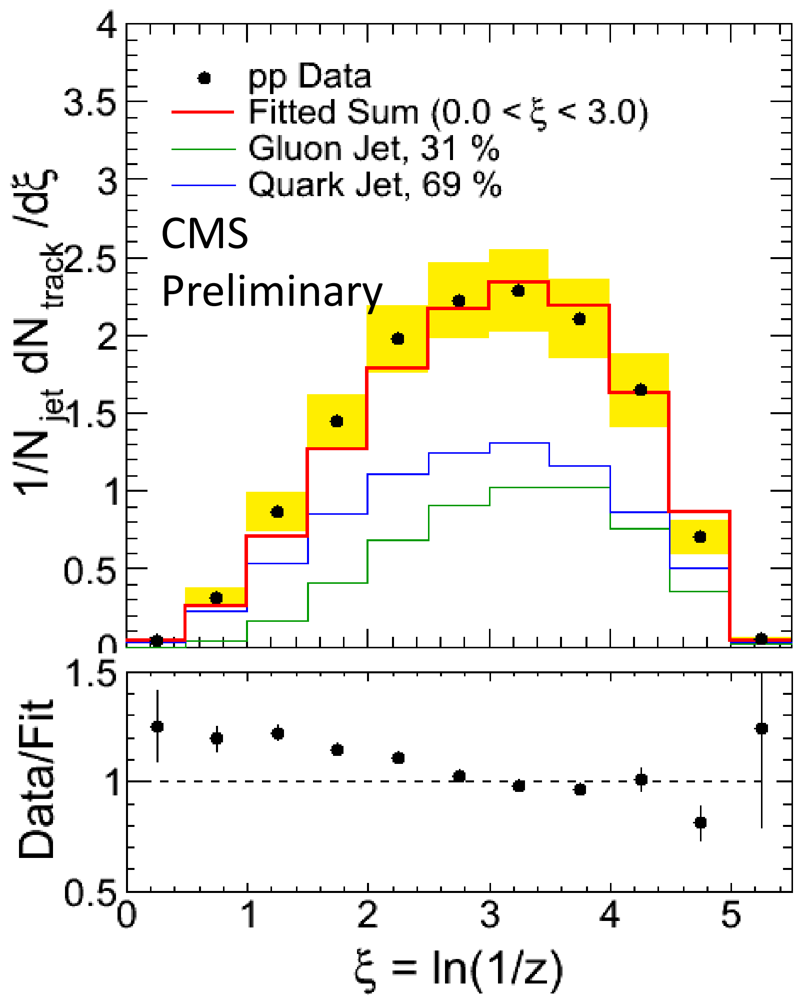

100 < Jet p_T < 300 GeV/c

pp data

Comparison to Theory Models

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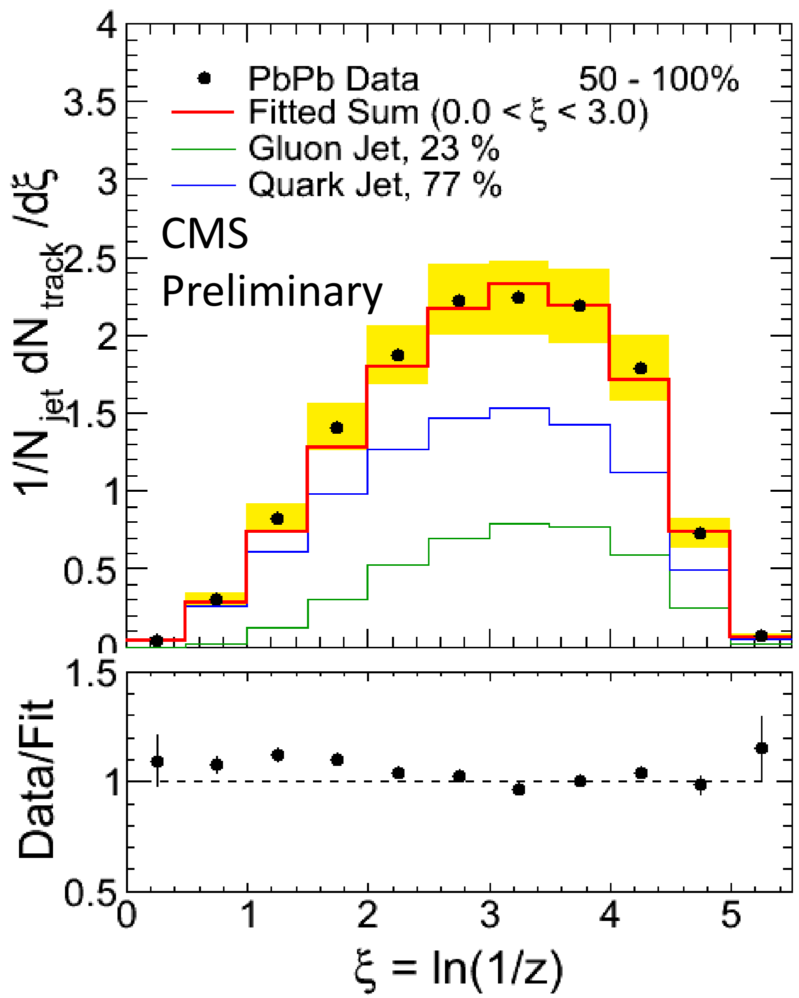
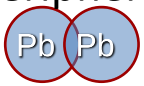


Peripheral PbPb data fits better, quark jet fraction increasing.

100 < Jet p_T < 300 GeV/c

PbPb data
Peripheral



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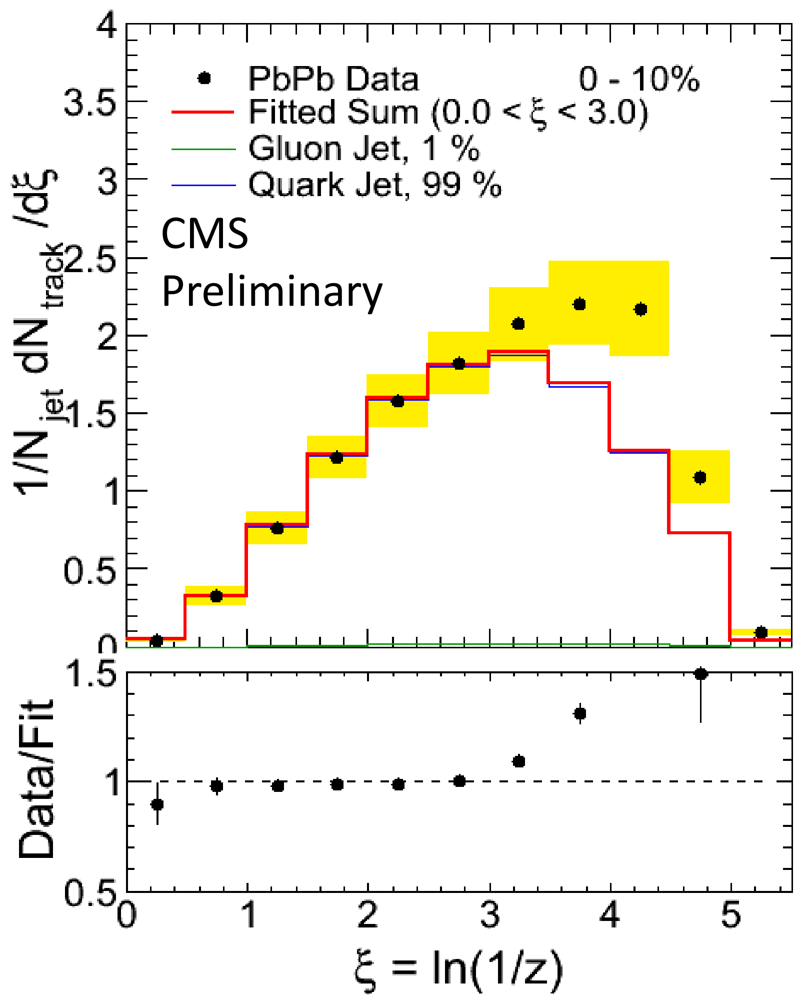


100 < Jet p_T < 300 GeV/c

PbPb data
Central

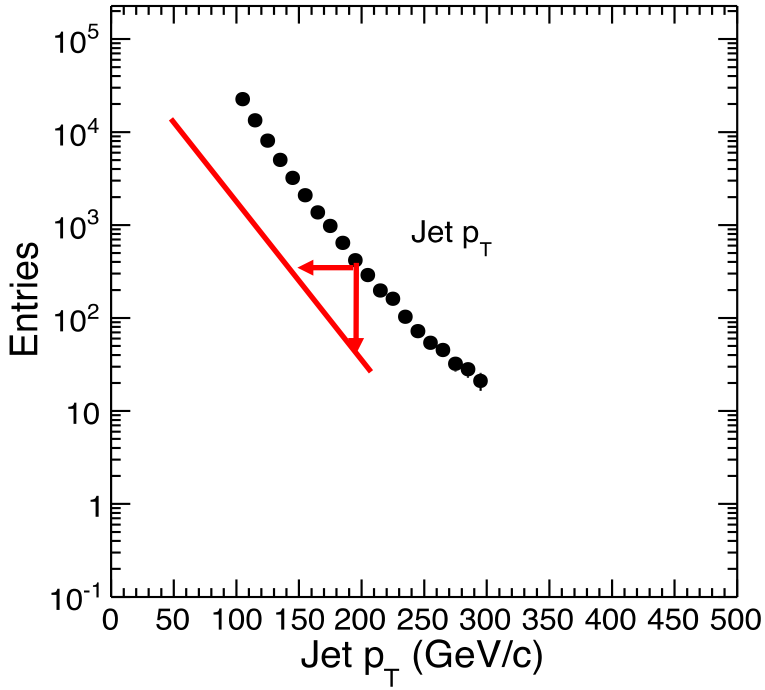
Pb

Central PbPb data fits well, prefers entirely quark jet

What does this mean?

Only quark jets in central PbPb events?

Gluon jets have bigger color factor than quark jets
→ Expect gluon jets to undergo more medium interaction than quark jets.



- If gluon jets lose ~ 30% more of their energy than quark jets they can experience a x10 reduction of relative rate.

(This is ballpark energy loss range from gamma-jet studies in PbPb collisions.)

Summary

1. Study QCD in the QGP produced in PbPb collisions.
2. Jet events in PbPb and pp collisions are studied and compared.
3. Centrality dependent modification of fragmentation function observed.
4. The high p_T part of the fragmentation function in PbPb can be described by PYTHIA quark jets fragmenting in vacuum.

What have we learned?

1. Modification of fragmentation function ➔ colored QCD medium in PbPb collisions.
2. There may be a simple picture to describe the in-medium modification of jets.
3. Evidence for gluons jets losing more energy than quark jets in PbPb central events
   ➔ In-medium energy loss is significant.
   ➔ The QCD medium is strongly coupled.

New Questions Raised

1. Flavor dependent fragmentation functions?
   – Eg. for γ-tagged jets, b-tagged jets
2. How much more energy does gluon jet lose than a quark jet?
3. What does the excess in low momentum particles say about the transport properties of the QCD medium?