# Jet shape and fragmentation function measurements with CMS


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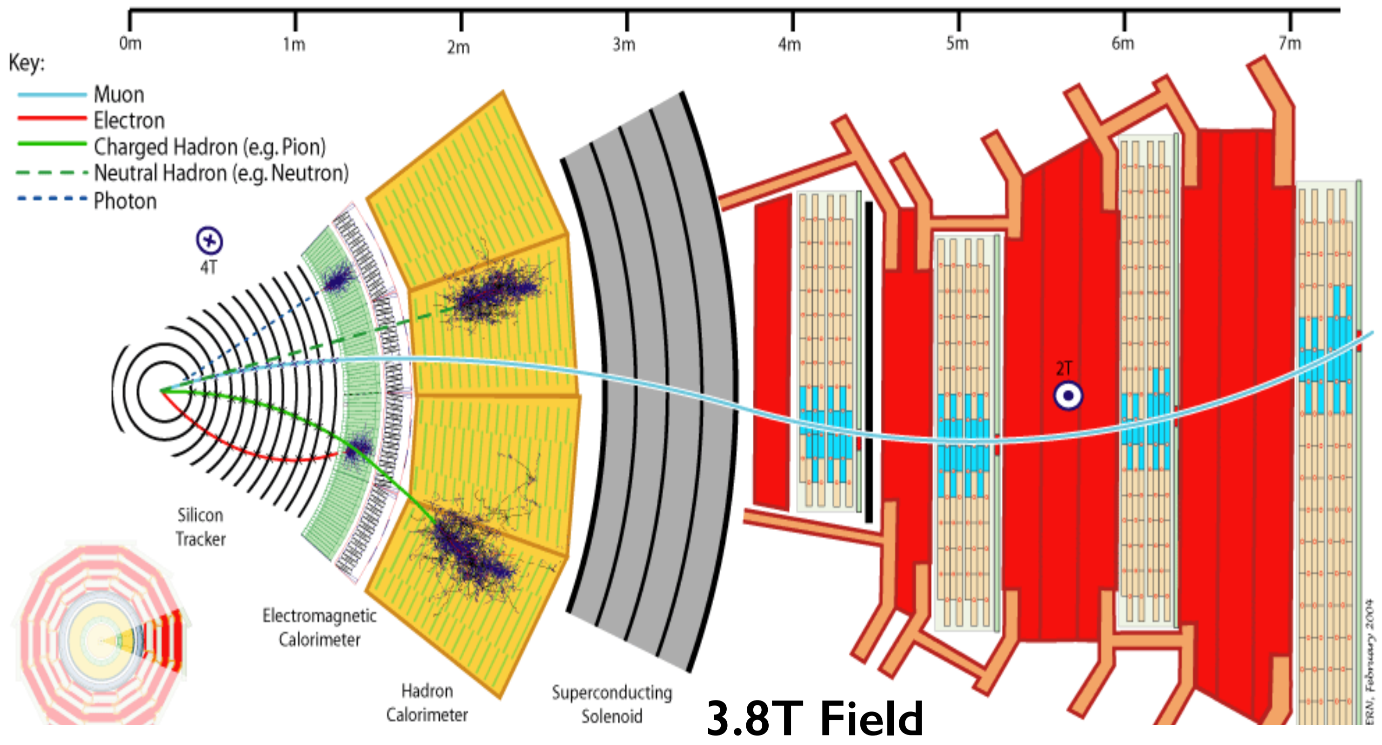
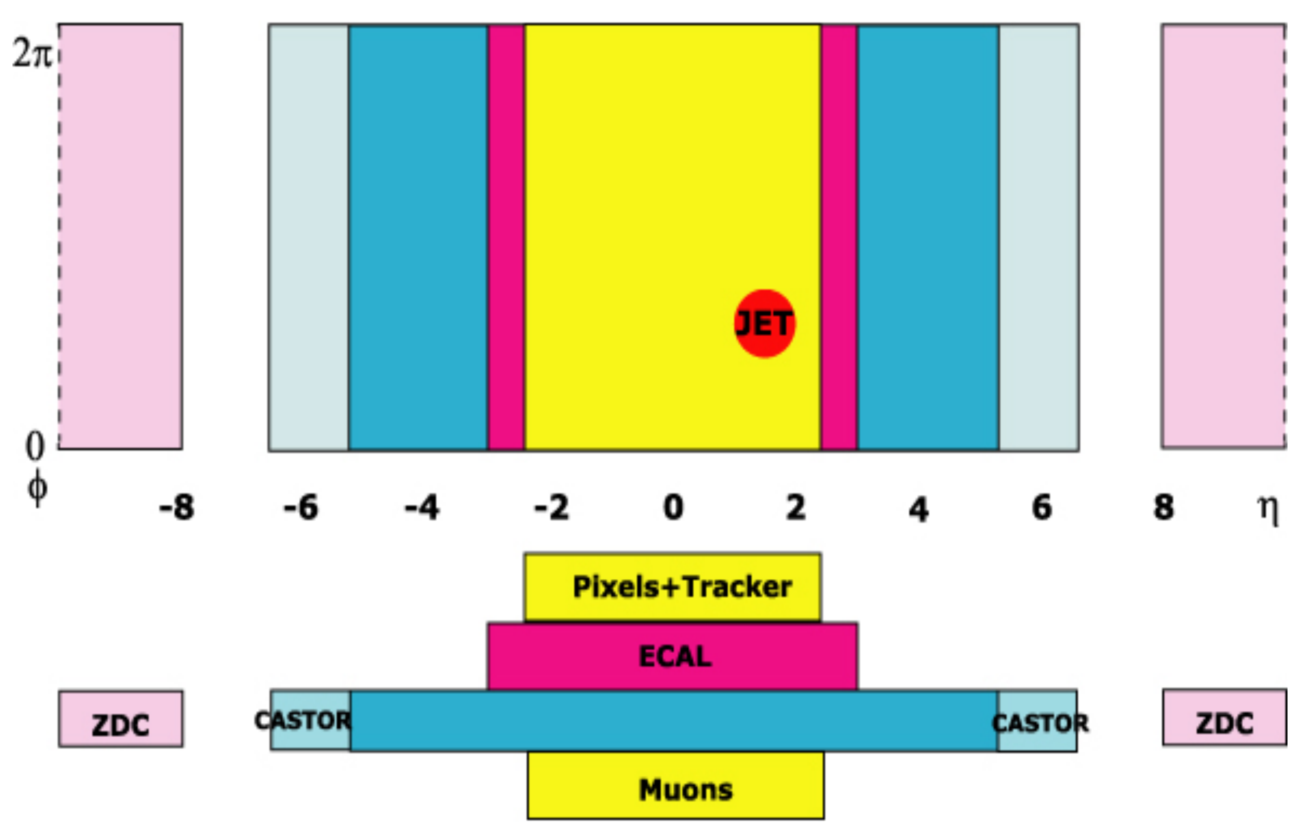
Hard Probes 2013

November 4-8th, 2013

# CMS detector: well suited for jet study



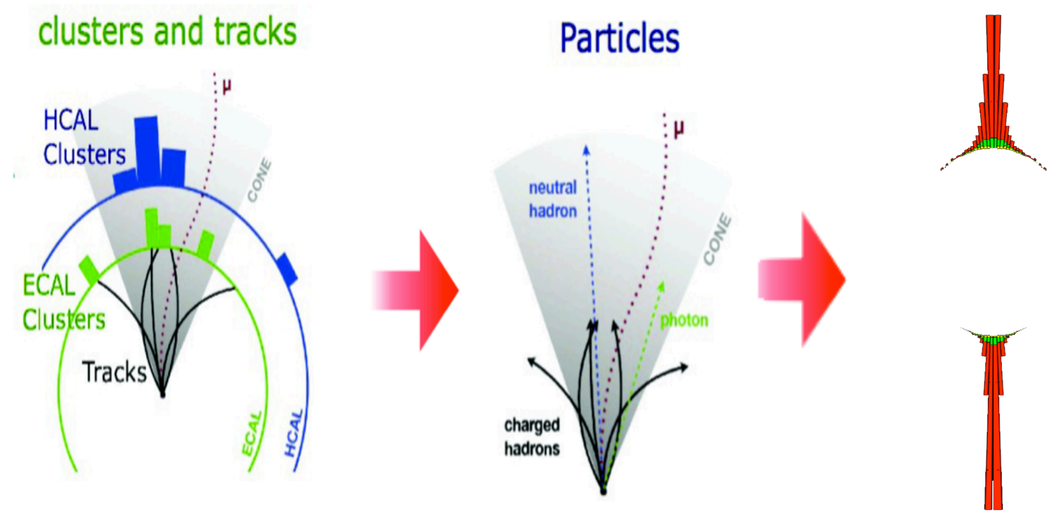




CMS is a multi-layer detector

- Excellent tracking capabilities
  - Momentum resolution of 1-2% to 100GeV/c
- Large coverage calorimetry
  - Directly identifiable jets
- High Level Trigger
  - High energy reach

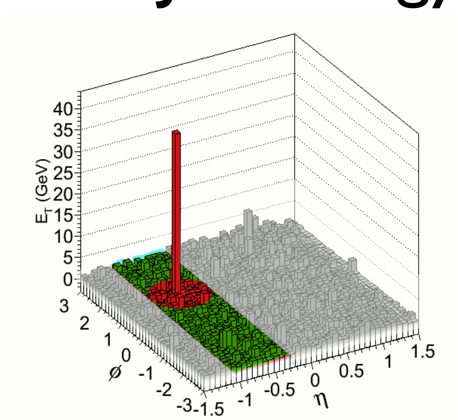
# Jet reconstruction and corrections

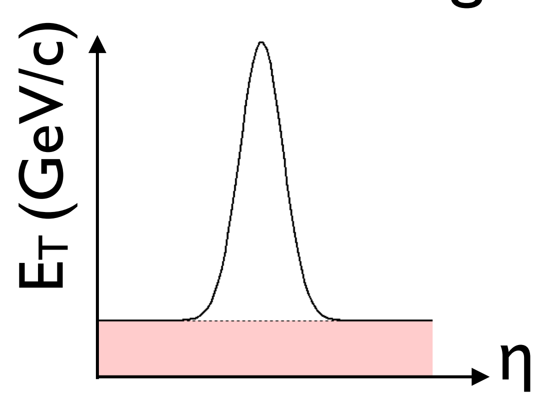
- Information from all sub-detectors combined into particle candidates
  "Particle flow" event reconstruction method[1-2]

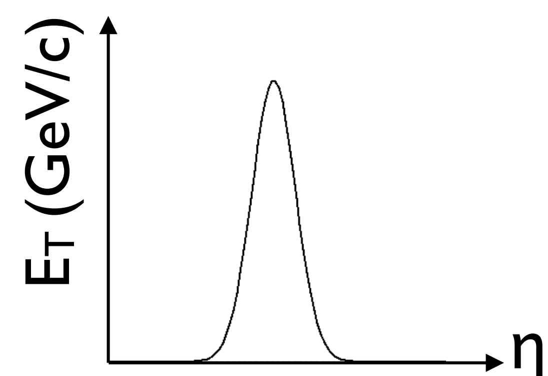


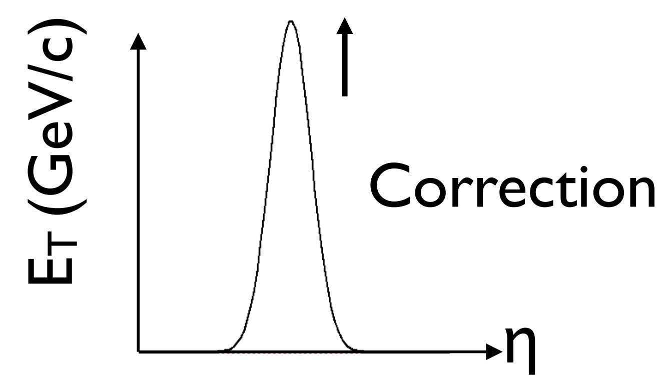

[1] arXiv:1107.0179
[2] CMS-PAS-PFT-09-001

- Jet energy corrected for background influence




Raw jet energy → Background subtraction → Jet energy Correction → Correct jet energy

anti-$k_T$ clustering algorithm

remove underlying events contribution

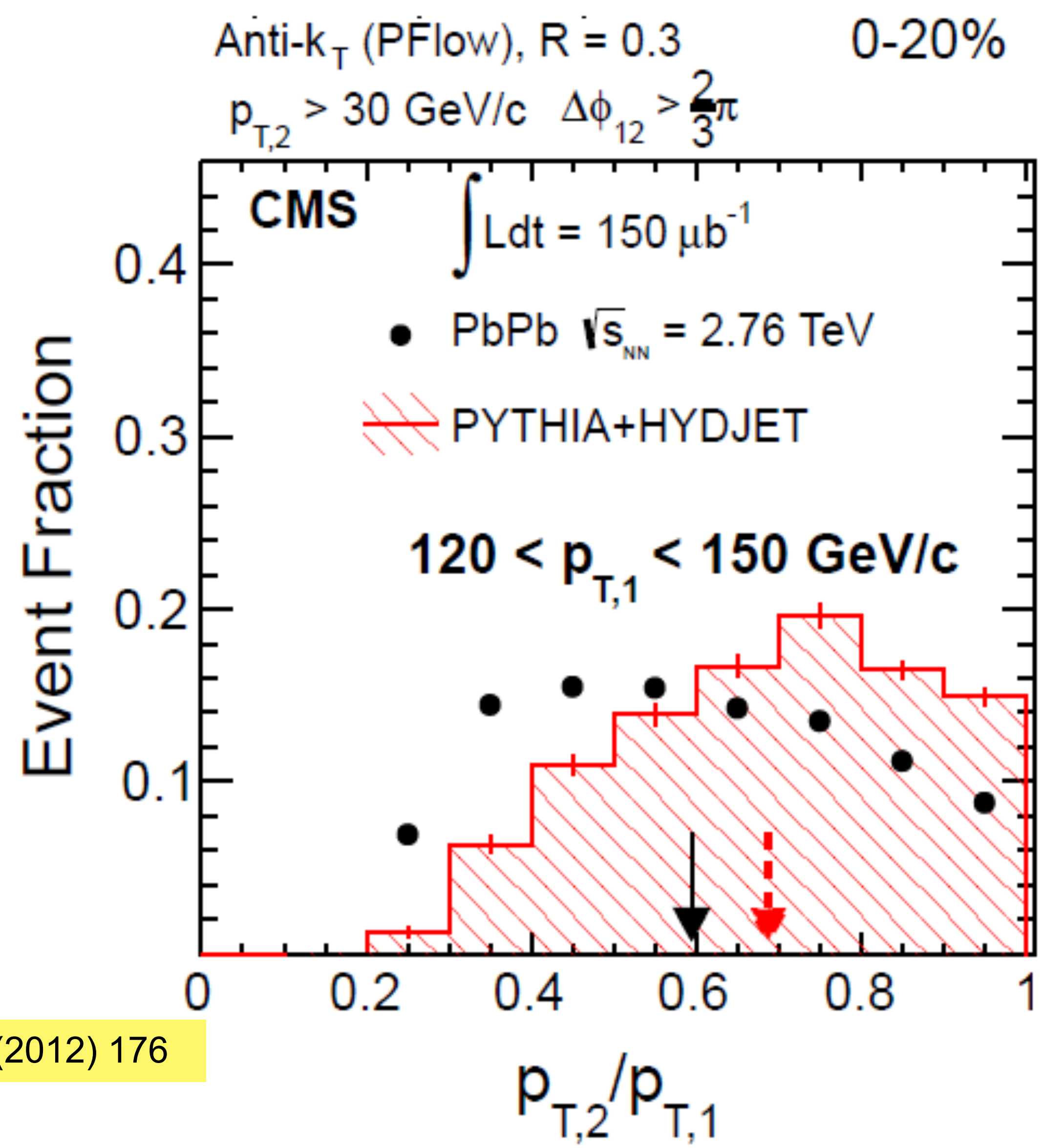
PYTHIA MC simulation
Data driven

CMS-PAS-PFT-09-001

EPJC 50 (2007) 117

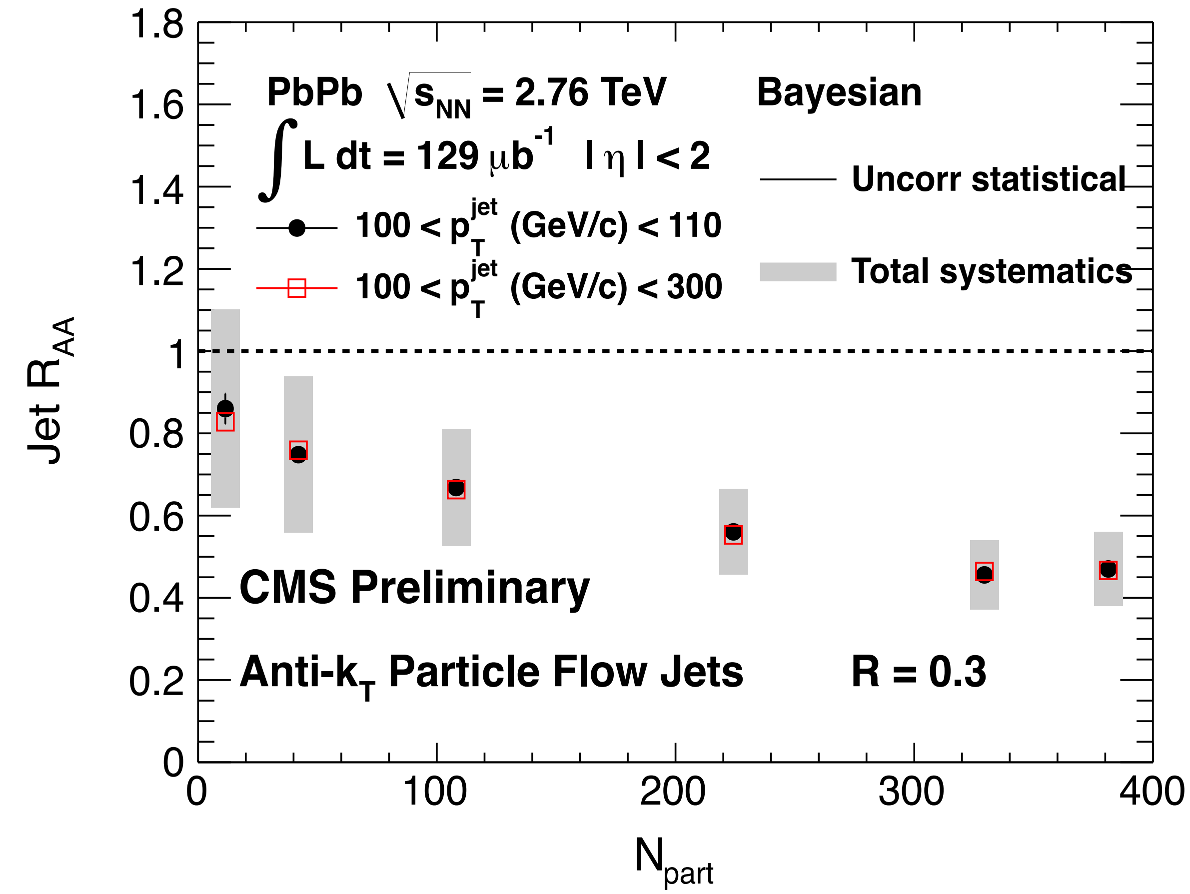
# What we already know about jets ...

## Dijet asymmetry




PLB 712 (2012) 176

## Nuclear modification factor $R_{AA}$



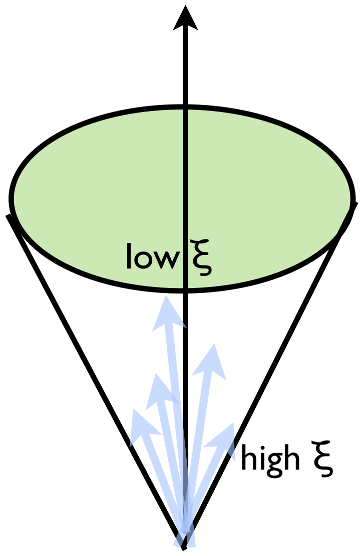

CMS PAS HIN-12-004

- Dijet $p_T$ imbalanced in most central PbPb collisions
- Jets ($R_{AA}$ ~ 0.5) are quenched in most central PbPb

# Anatomy of jets: how jets are modified

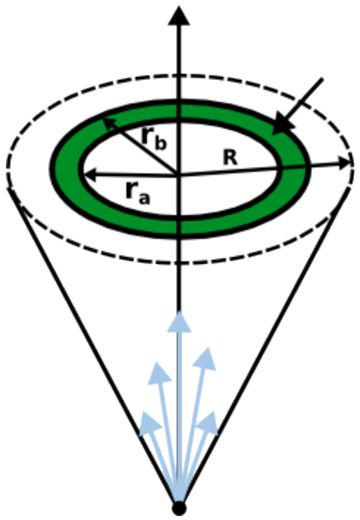
- How is the jet energy redistributed in AA collisions?
  - in momentum space (Fragmentation Function $dN/d\xi$): particle momenta projected onto the jet axis

$$\xi = \ln(1/z) = \ln(p^{jet}/p_{||})$$




  - radially (Jet Shape): transverse momenta-flow as a function of the distance from the jet axis (r) in the η-φ plane

$$\rho(r) = \frac{1}{f_{ch}}\frac{1}{\delta r}\frac{1}{N_{jet}}\sum_{jets}\frac{p_T(r-\delta r/2, r+\delta r/2)}{p_T^{jet}},$$

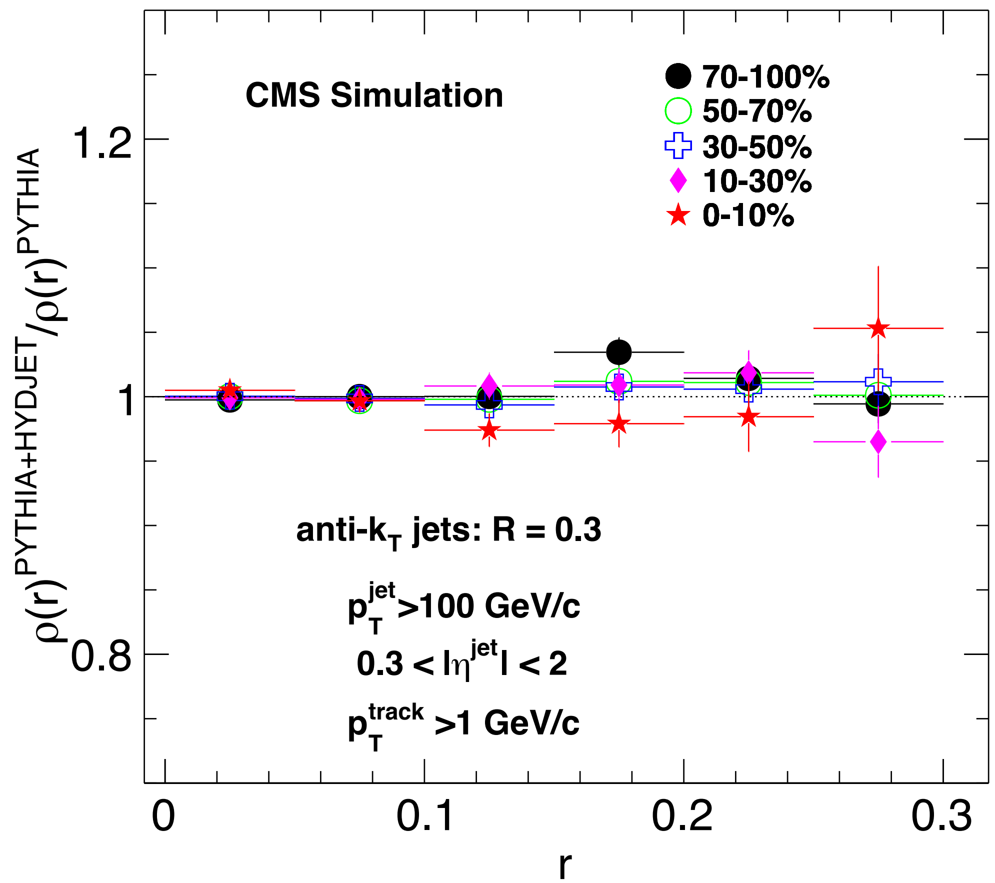


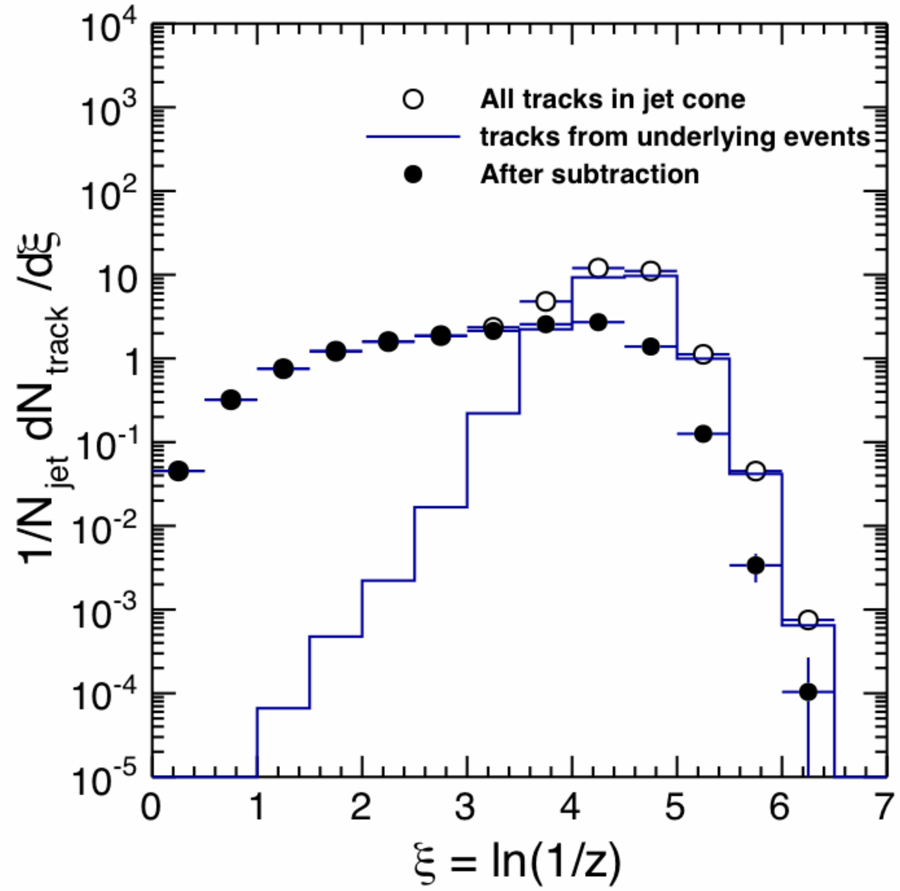

- Analysis cut:
  - inclusive jets (anti-$k_T$, R = 0.3, 0.3<|η|<2.0, $p_T^{jet}$ > 100 GeV/c)
  - charged particles (|η|<2.3, $p_T$ > 1 GeV/c)

# Underlying track subtraction

- Background tracks from underlying events need to be subtracted

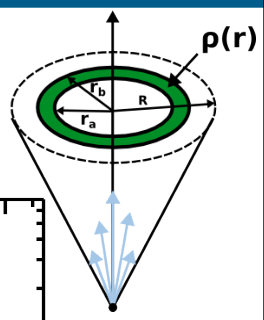
- Two methods:
  - η reflection technique (η(bkg_jet) = -η(jet))
  - event mixing



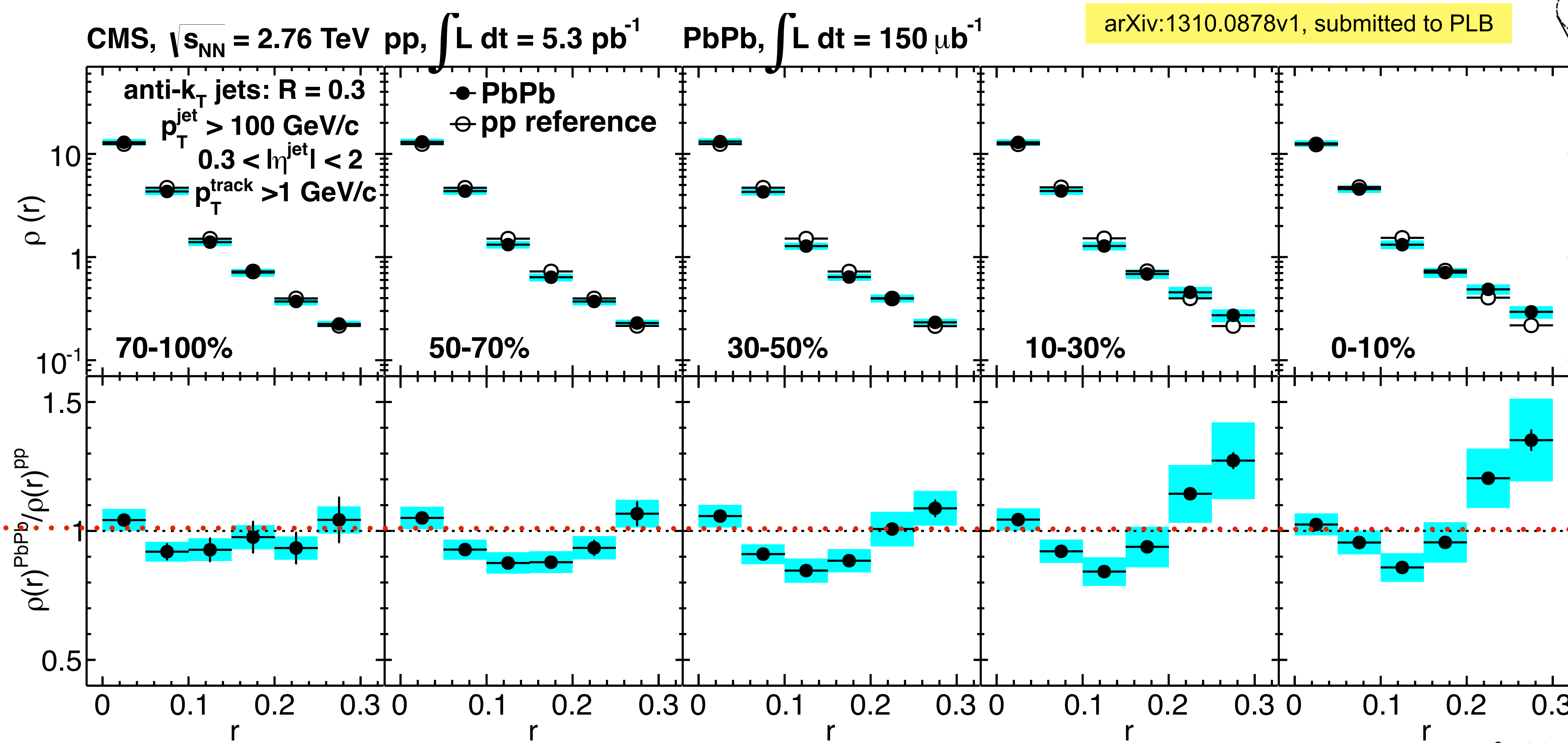




- Background subtraction works well (<~5%)

# Differential jet shapes




arXiv:1310.0878v1, submitted to PLB



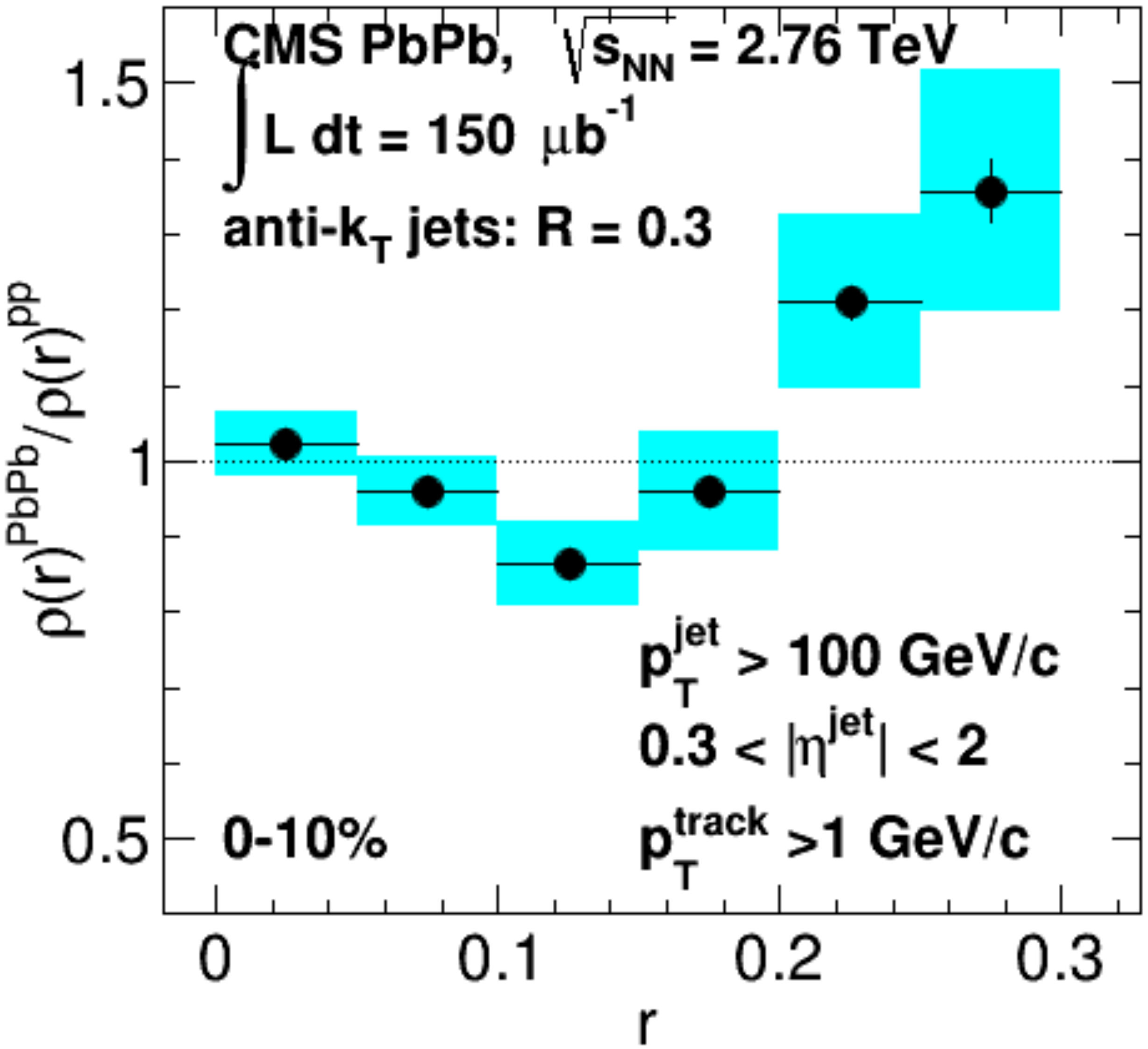

- Ratio close to unity for most peripheral collisions (70-100%)

$$\rho(r) = \frac{1}{f_{ch}}\frac{1}{\delta r}\frac{1}{N_{jet}}\sum_{jets}\frac{p_T(r-\delta r/2, r+\delta r/2)}{p_T^{jet}},$$

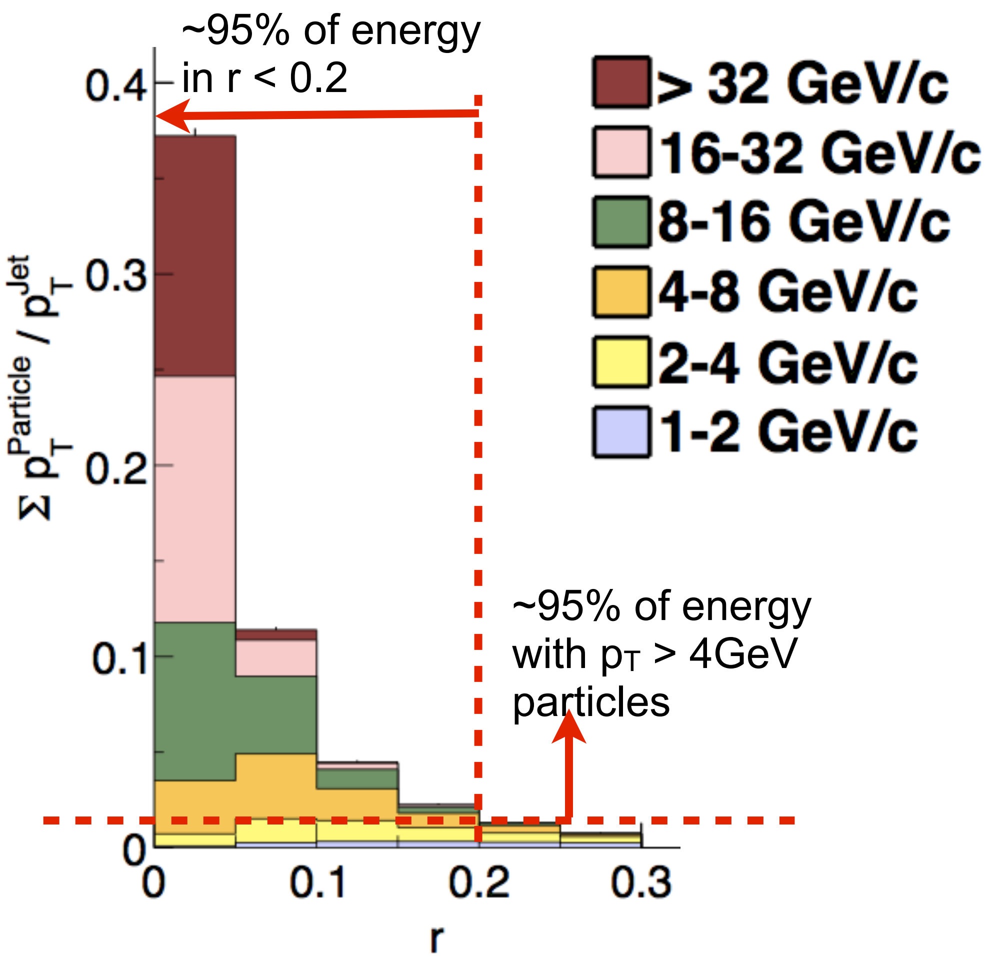
- A depletion is observed in the intermediate radius (0.1<r<0.2) for central PbPb collisions
- An excess of transverse momentum fraction at large radius (r>0.2) emerges for most central PbPb collisions

# Radial energy distribution to $p_T$ location

arXiv:1310.0878v1, submitted to PLB




PYTHIA 100 GeV inclusive jet
Anti-$k_T$ R=0.3 jet
Charged particle energy fraction

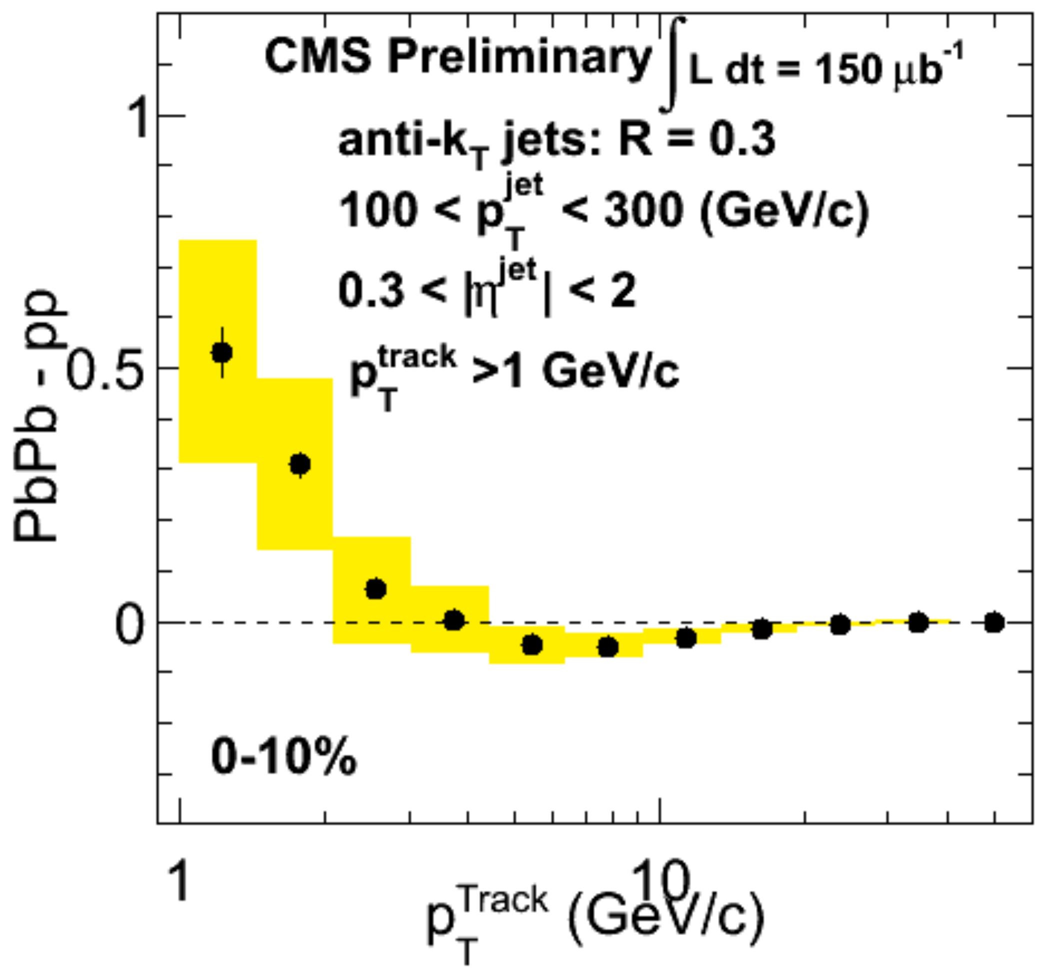


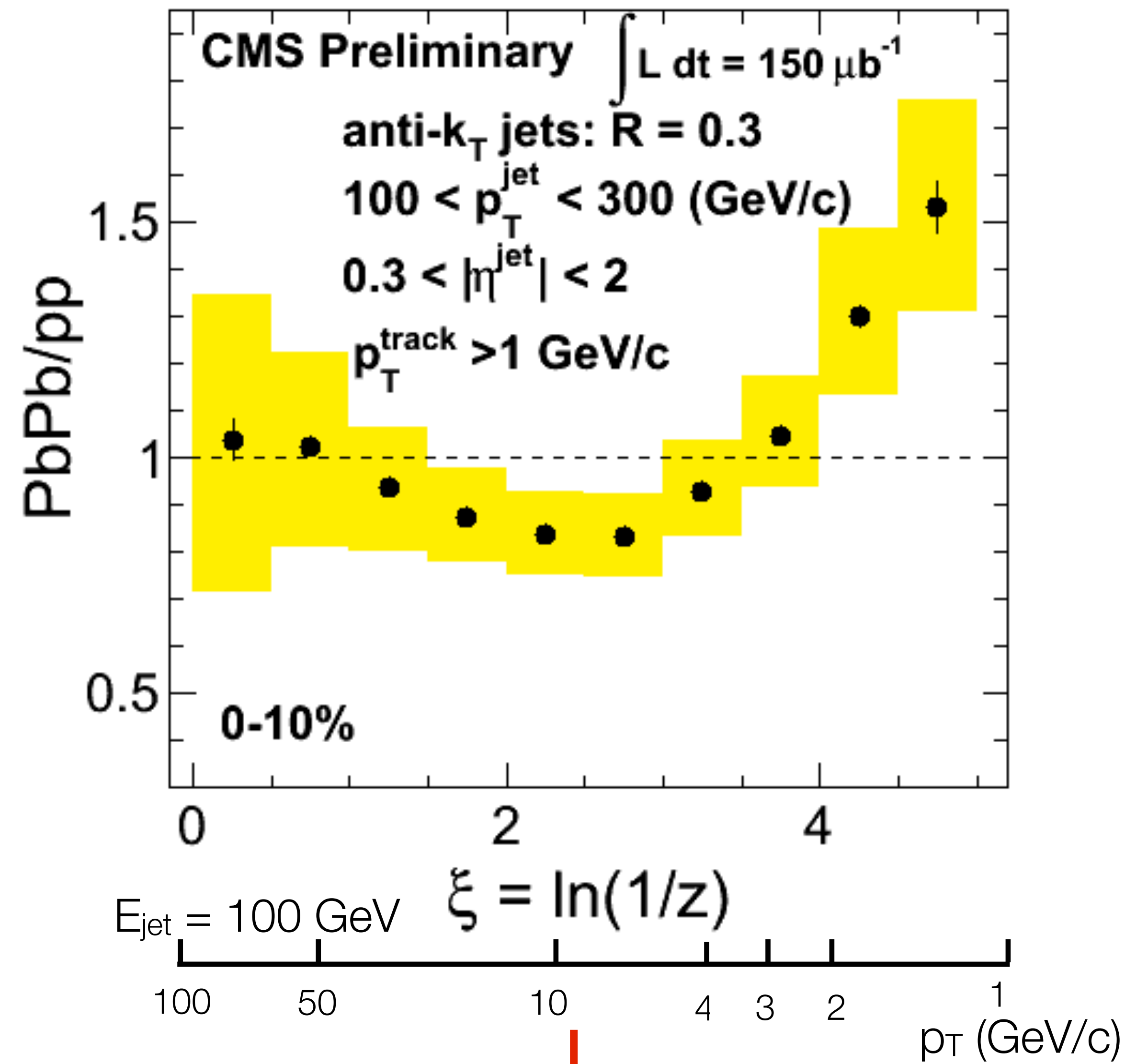

- The core of the jet dominated by high $p_T$ particles
- The depletion between 0.1<r<0.2 corresponds to intermediate $p_T$ particles
- The excess at large radii corresponds to low $p_T$ particles enhancement
  - ➡ Is this correspondence true?

# Measuring jet fragmentation patterns

- Track $p_T$ distribution inside the jet cone
- Jet fragmentation function vs. $\xi$

HIN-12-013




$$\xi = \ln(1/z) = \ln(p^{jet}/p_{||}^{track})$$

# Track $p_T$ distribution inside jet

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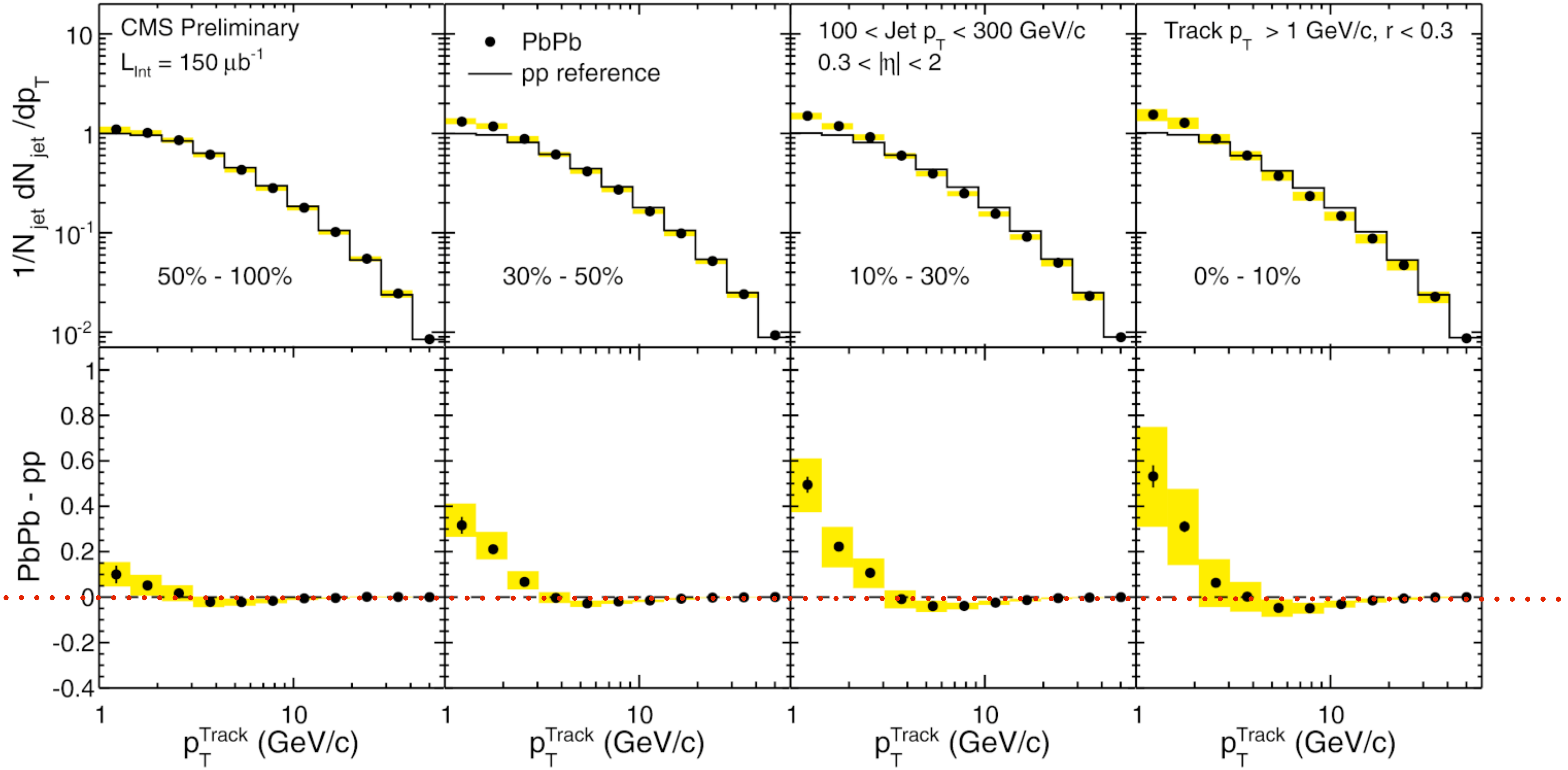


- Clearly centrality dependent difference observed
  - Significant excess below $p_T$ < 3 GeV/c

# Inclusive jet FF

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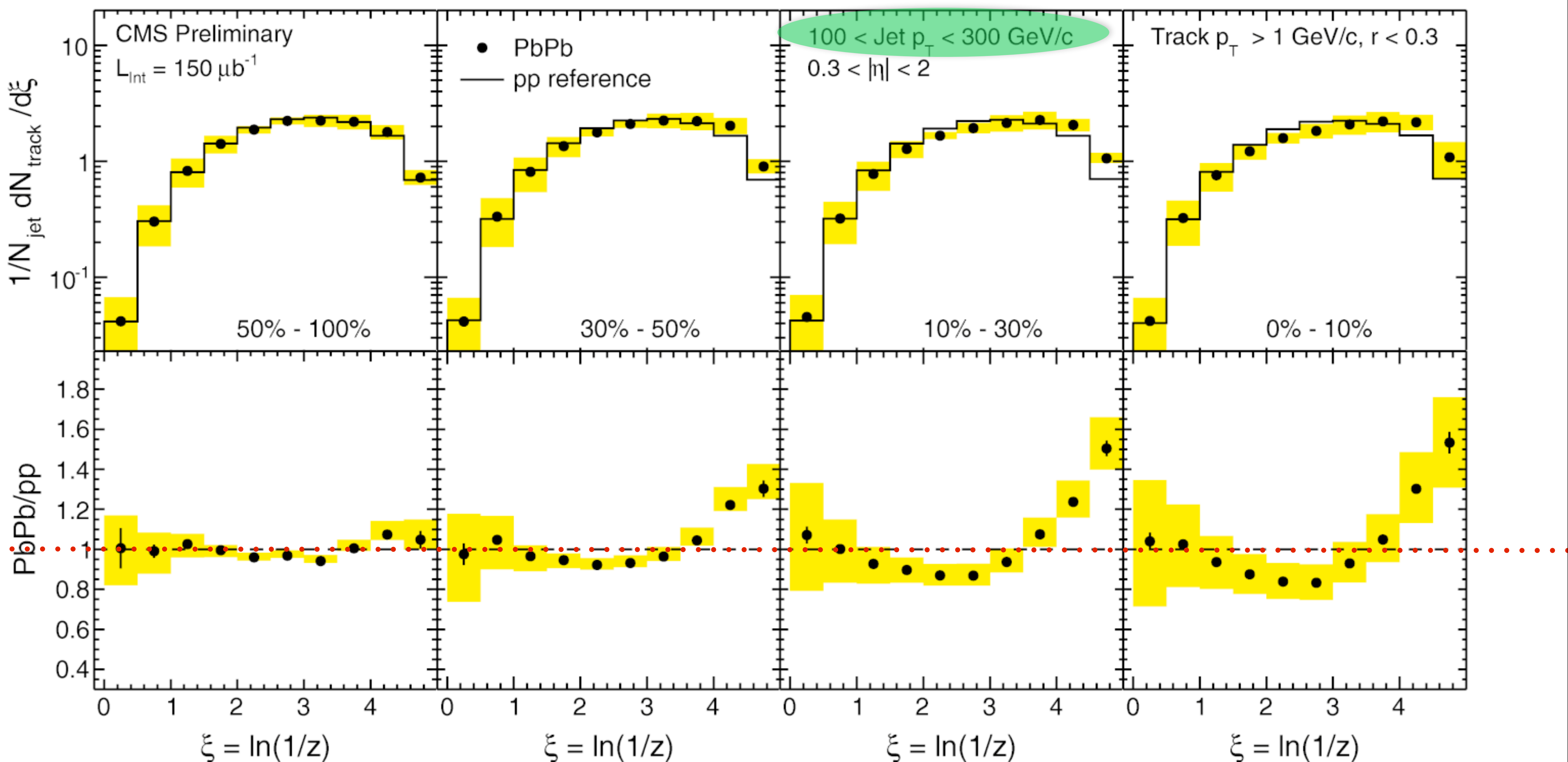


- Peripheral PbPb similar to pp
- Up to factor of 1.5 excess at ξ > 4 ($p_T$ < 3 GeV/c) in most central collisions
- A depletion at 1< ξ < 4 in more central collisions

# Jet $p_T$ dependent fragmentation function:I

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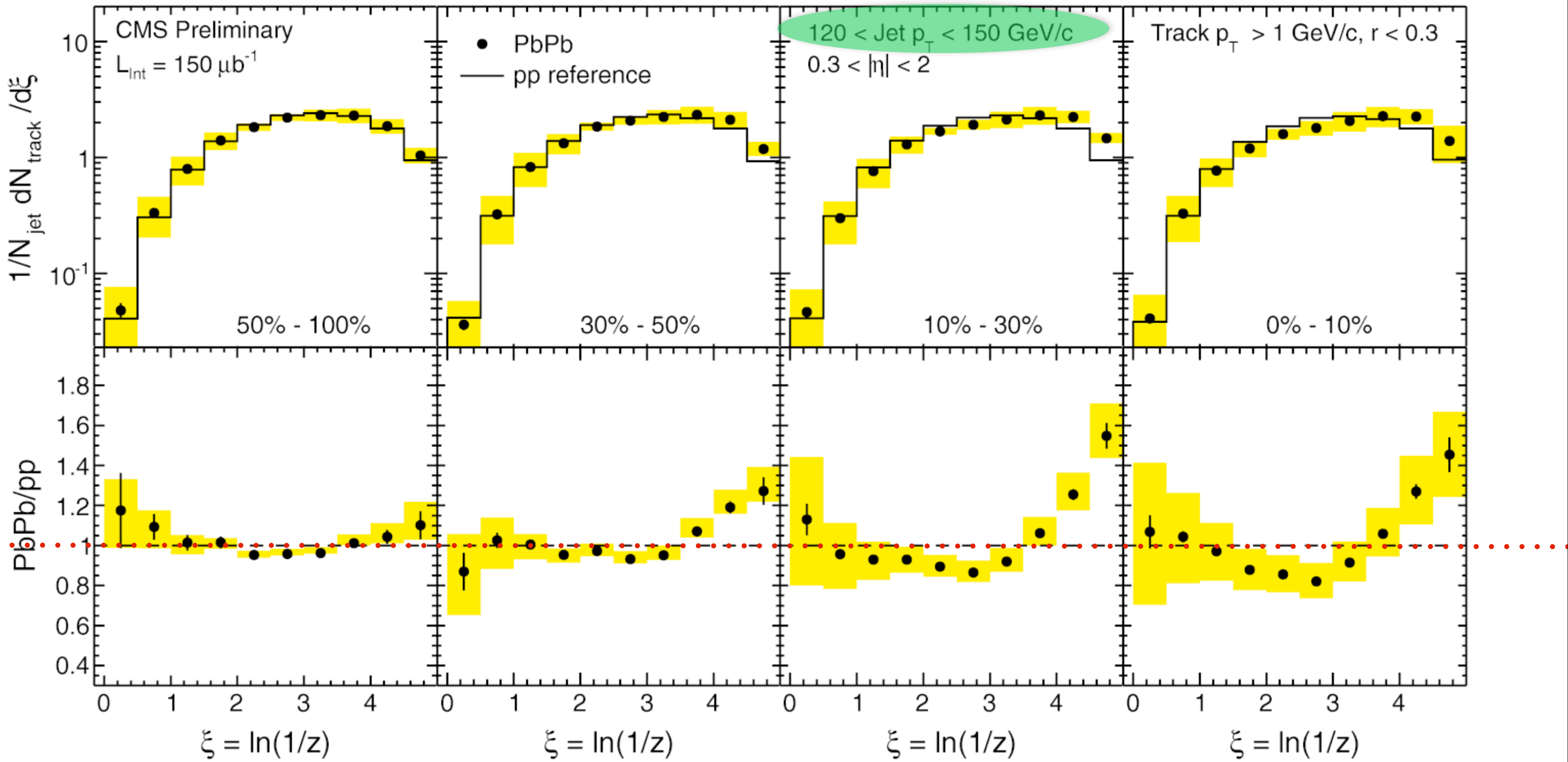


- Jet fragmentation functions for 120 < $p_T^{jet}$ < 150 GeV/c
- Very similar to inclusive jet FF

# Jet $p_T$ dependent fragmentation function:II

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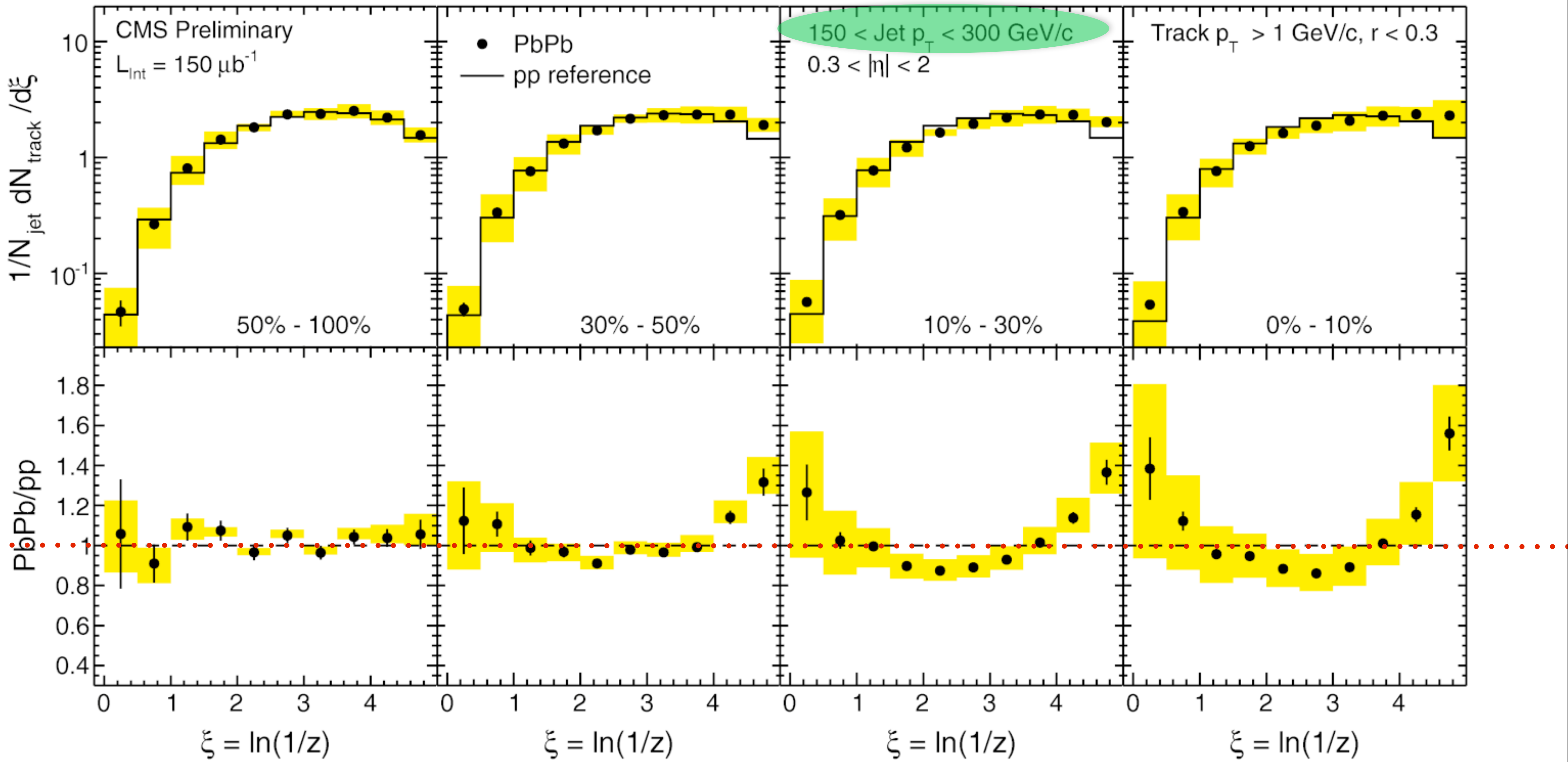


- Jet fragmentation functions for 150 < $p_T^{jet}$ < 300 GeV/c
- Weak jet $p_T$ dependence observed

# Summary of jet $p_T$ dependence

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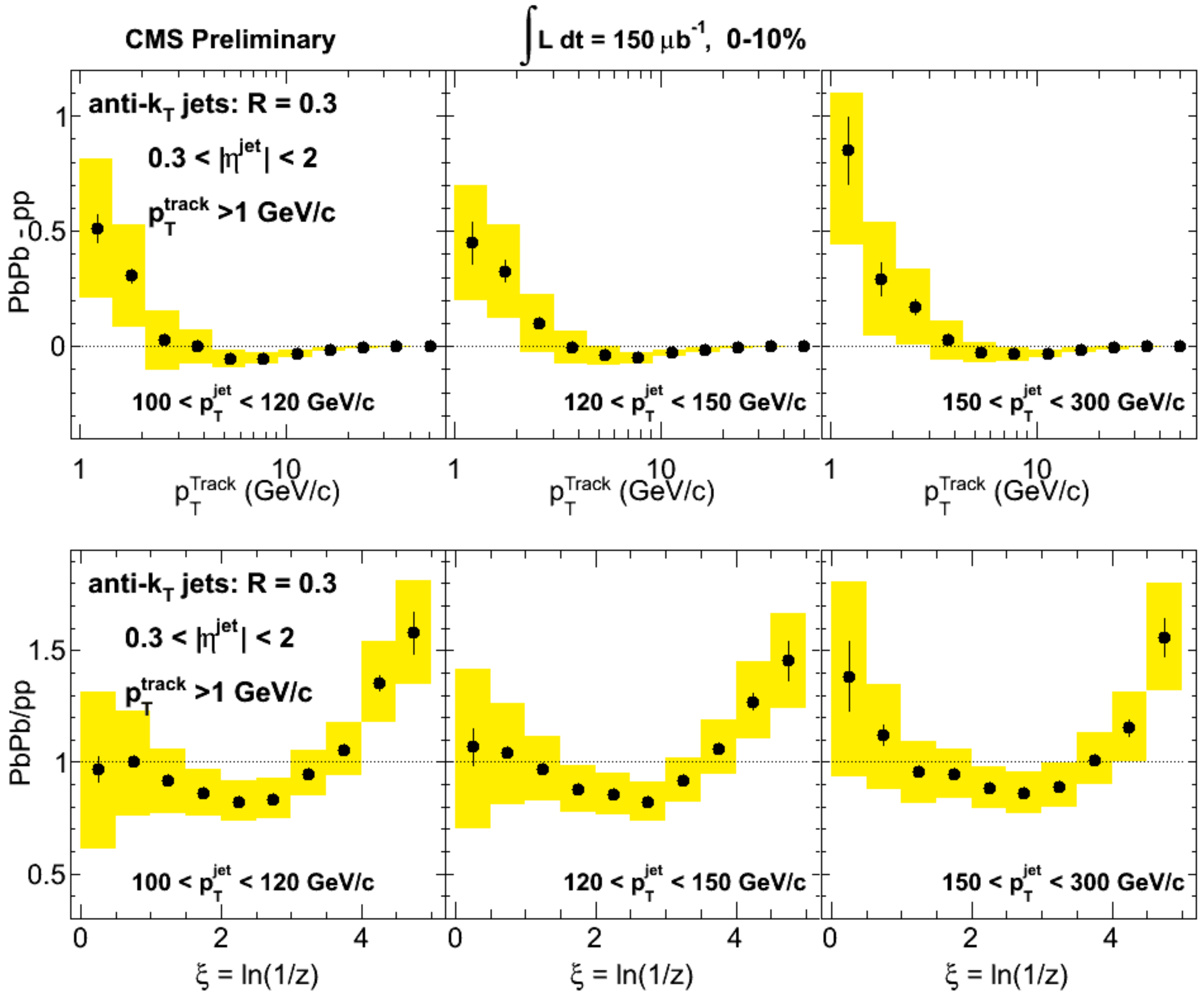
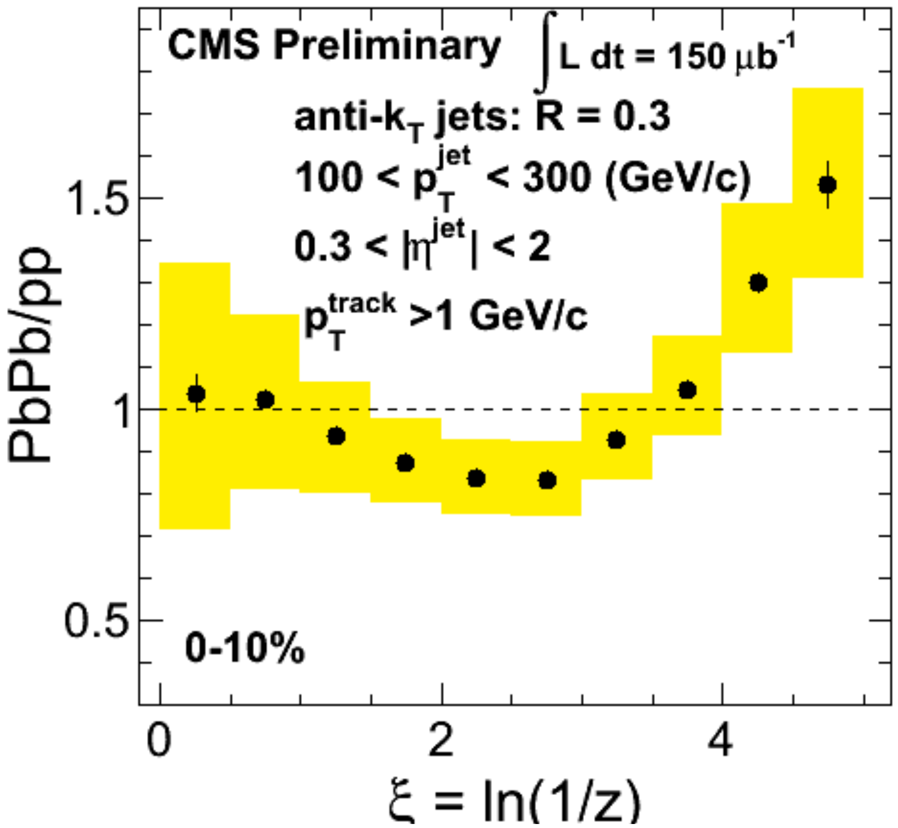



- No clear jet $p_T$ dependent fragmentation pattern observed within the uncertainty

# Summary: a consistent picture of jet quenching

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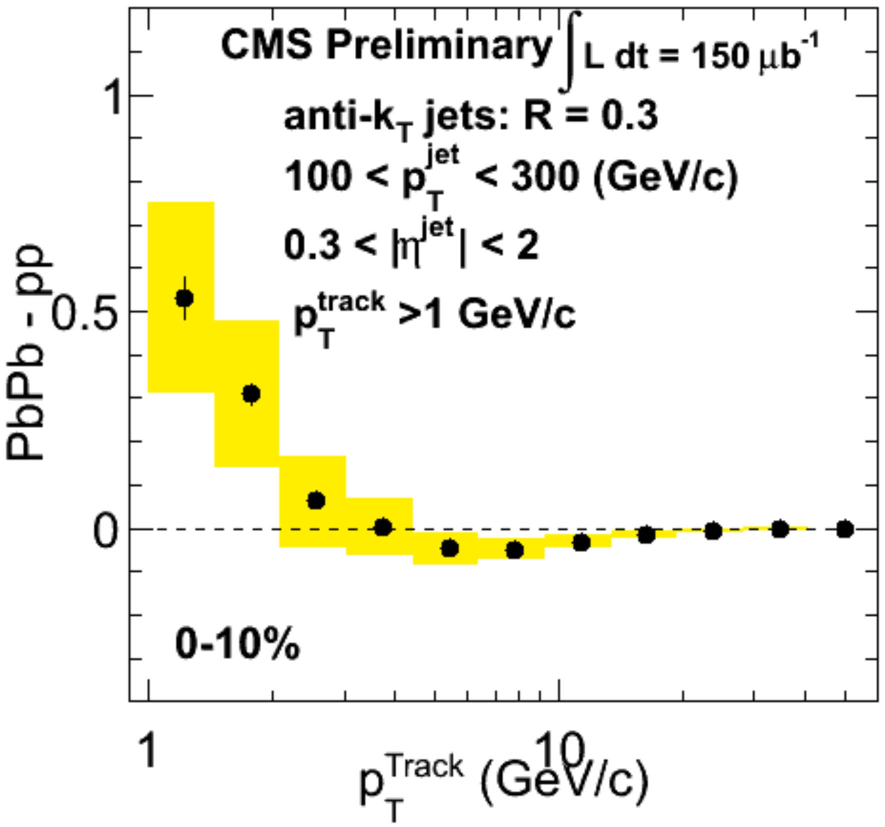
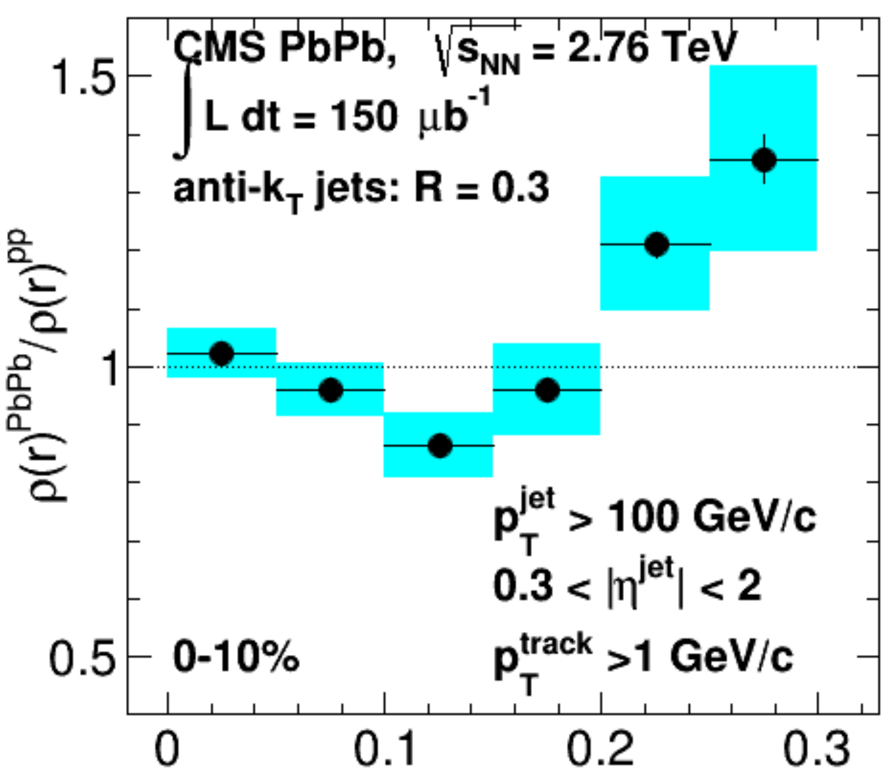
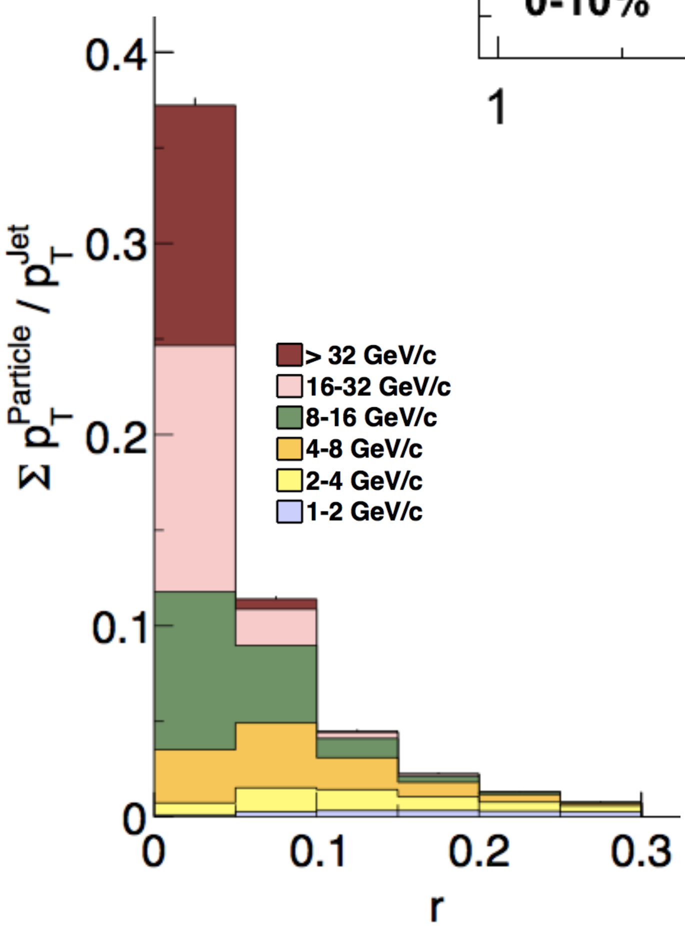
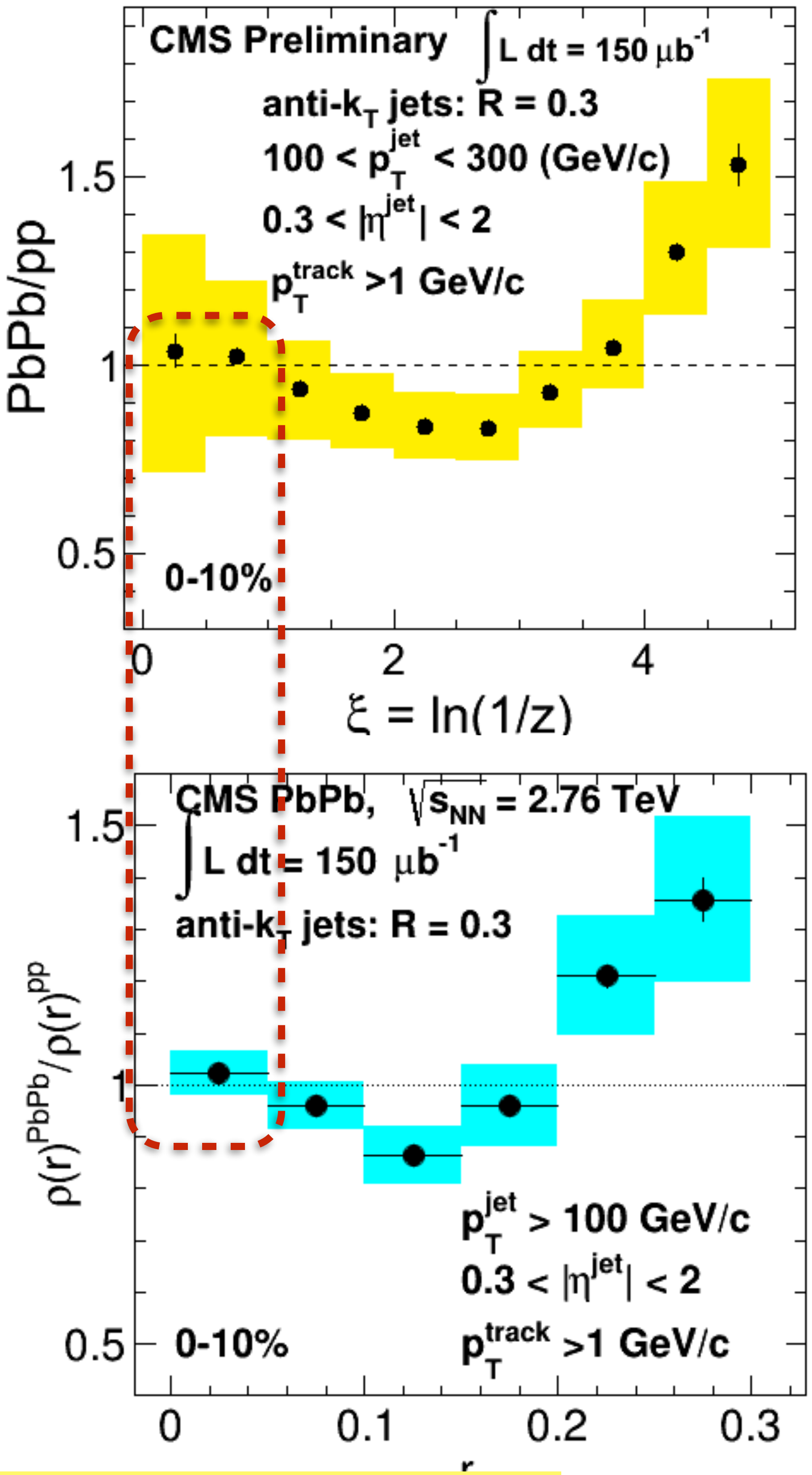



arXiv:1310.0878v1, submitted to PLB

# Summary: a consistent picture of jet quenching

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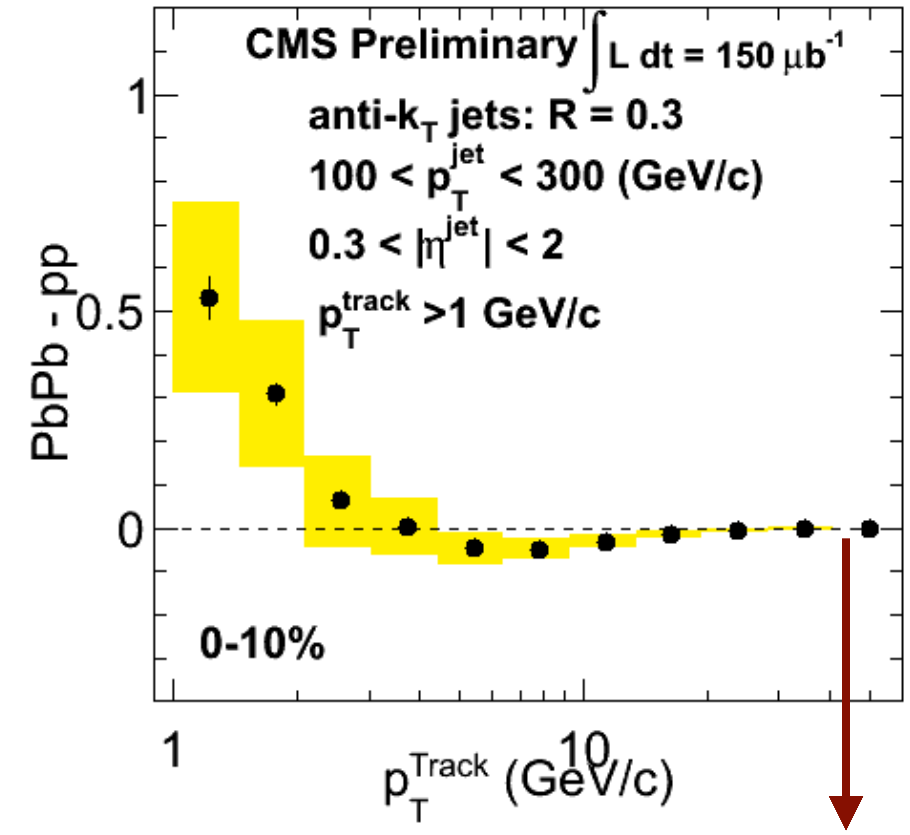


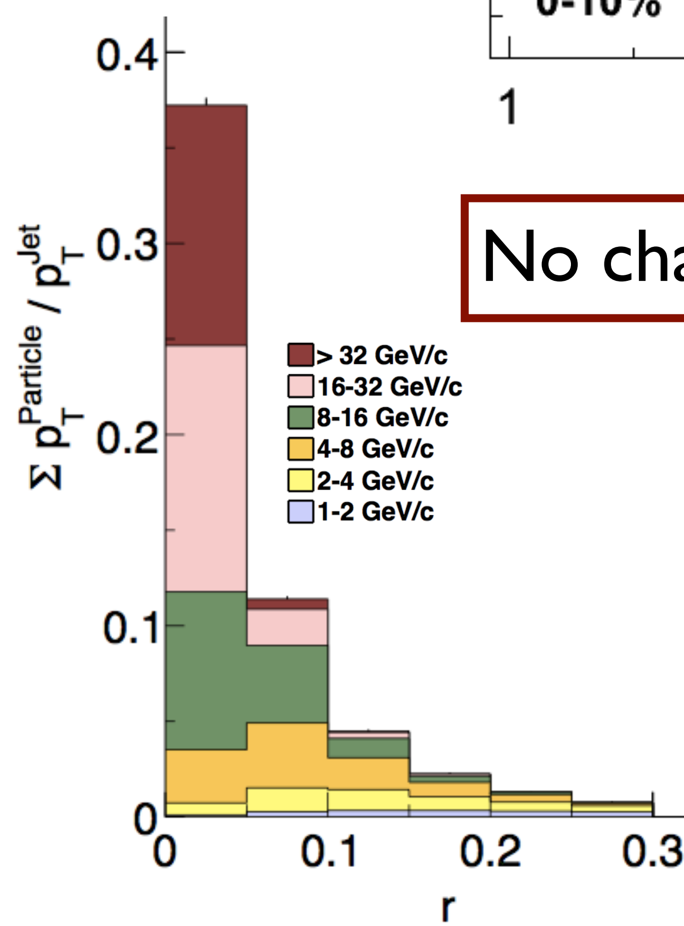


No change at small r, high $p_T$

arXiv:1310.0878v1, submitted to PLB

# Summary: a consistent picture of jet quenching

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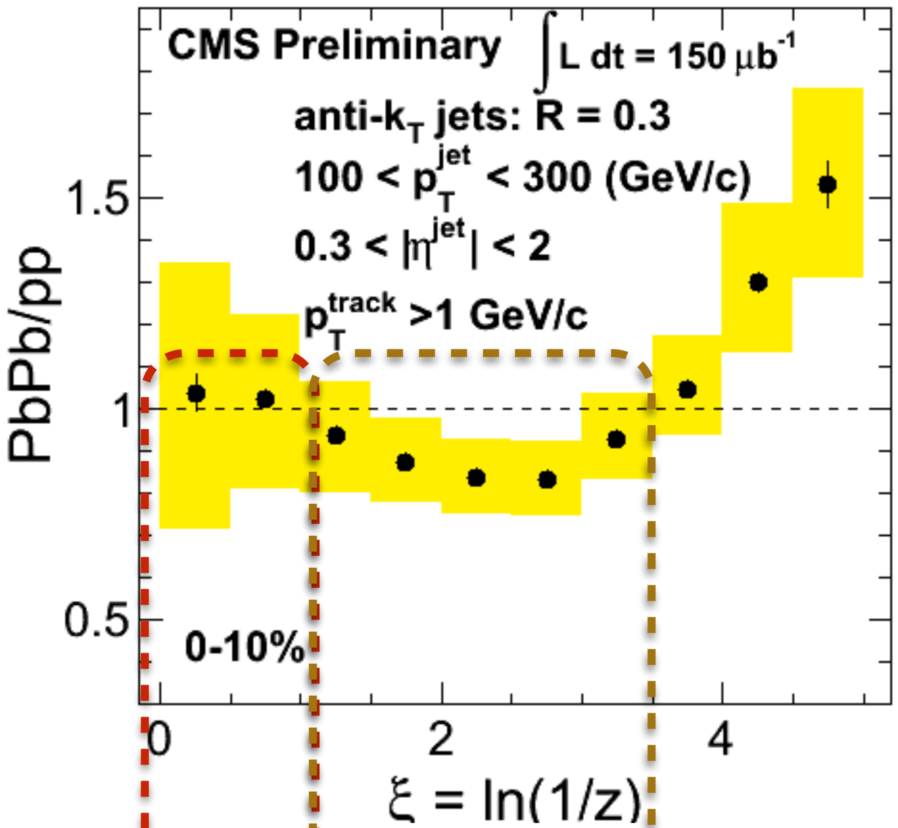
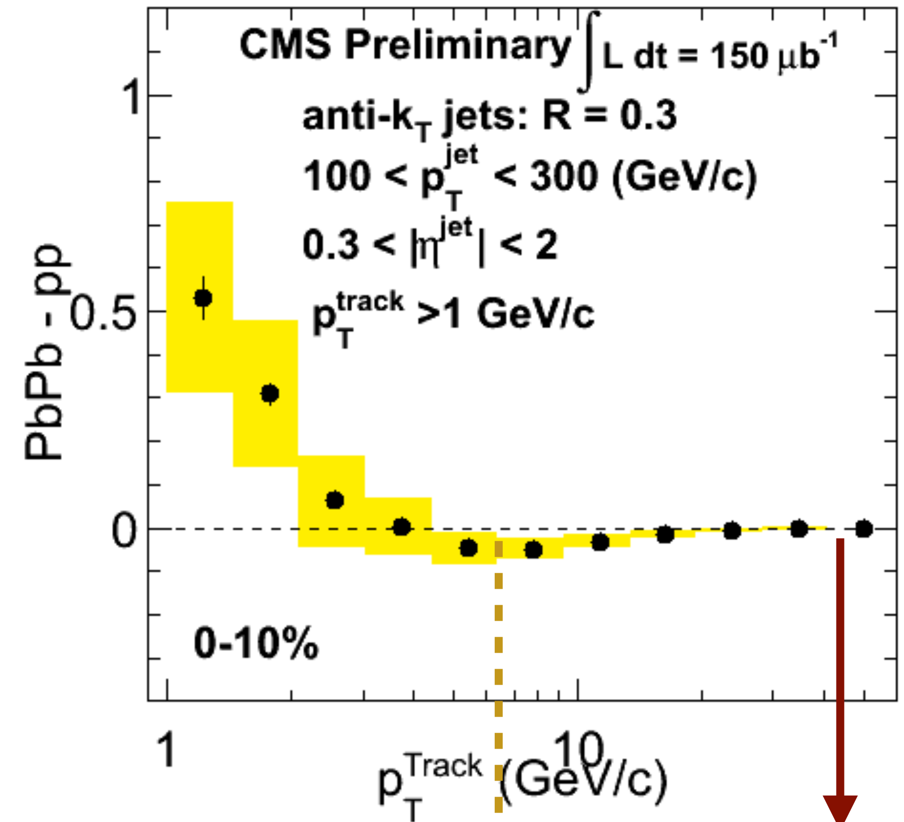
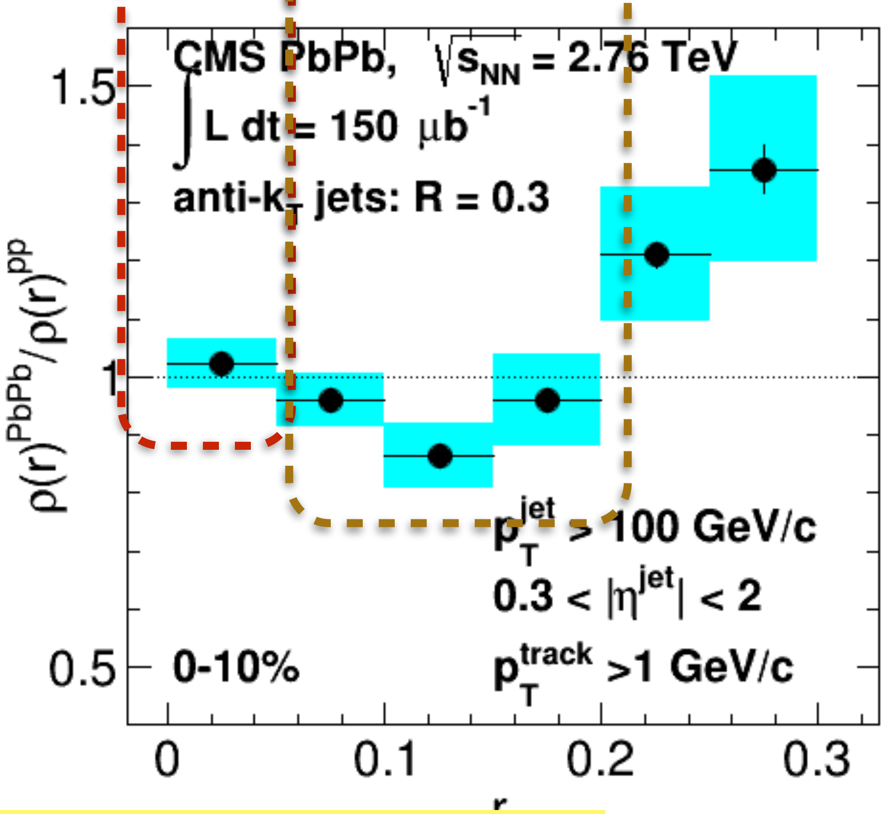
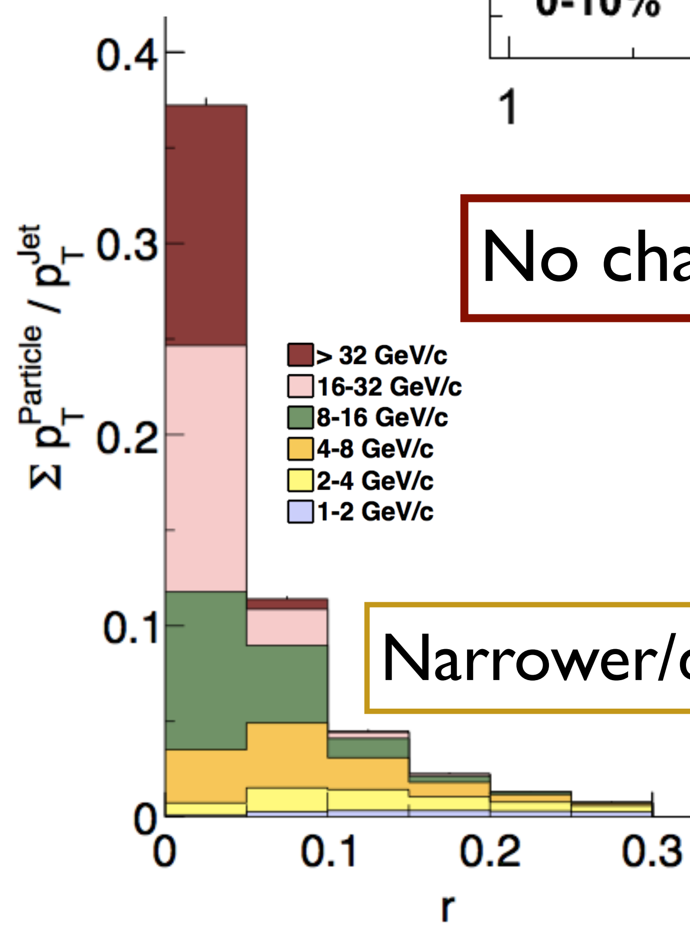


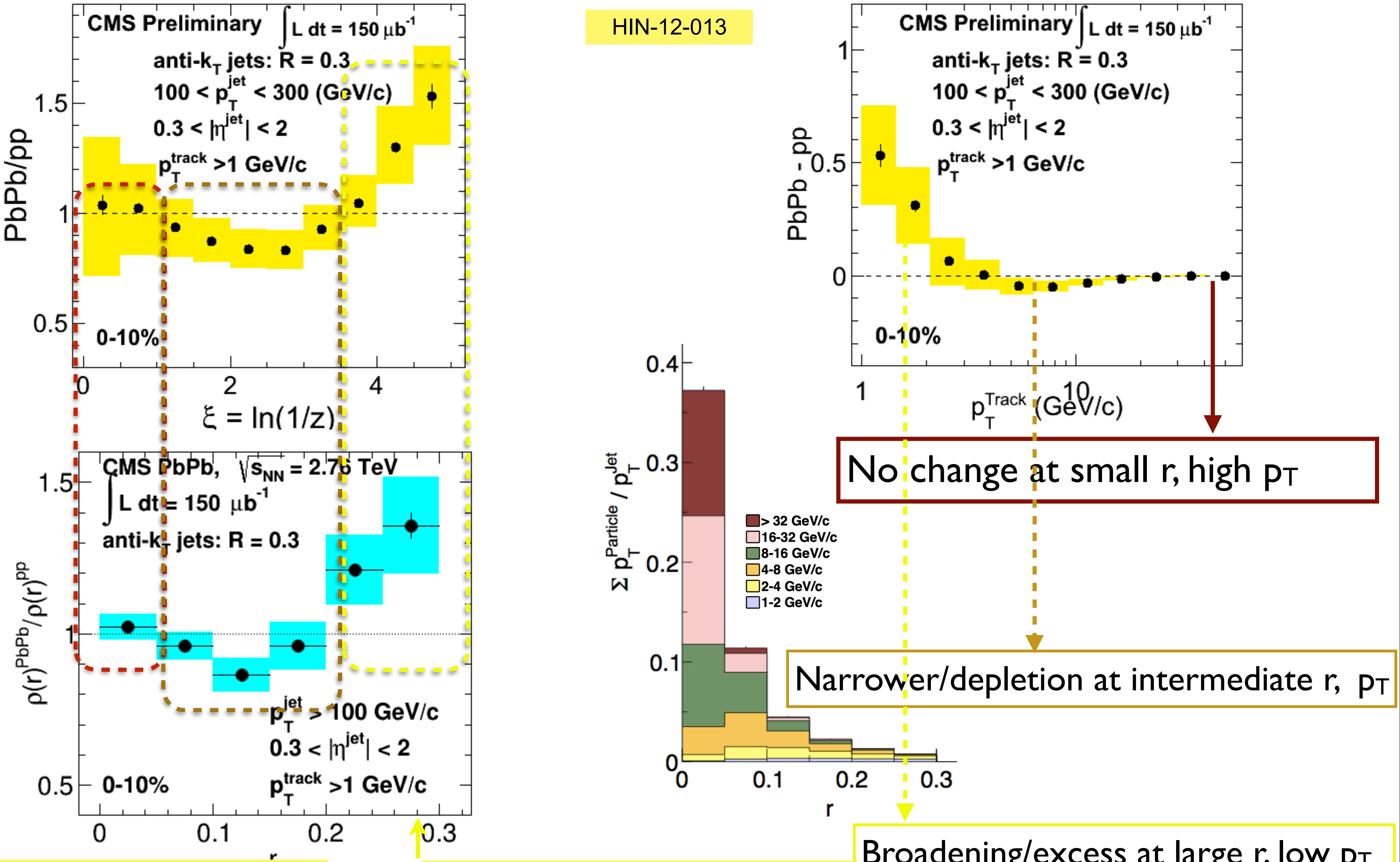




No change at small r, high $p_T$

Narrower/depletion at intermediate r, $p_T$

arXiv:1310.0878v1, submitted to PLB

# Summary: a consistent picture of jet quenching




arXiv:1310.0878v1, submitted to PLB

# Summary and conclusions

- Inclusive jet shape and fragmentation function measured in PbPb for jet $p_T$ > 100 GeV/c, with track $p_T$ > 1 GeV/c and compared to pp at the same jet energy
  - at very high $p_T$ (> 20 GeV/c) JS/JFF remains unmodified
  - at intermediate a depletion observed
  - at low $p_T$ (< 4 GeV/c) significant excess
  - no strong jet $p_T$ dependent fragmentation pattern observed within uncertainty
- Era of detailed quantitative jet tomography and probing of the nuclear effect has begun
  - fully exploit newly 2013 dataset
  - improvements in basic analysis
  - more differential physics analyses including dependence on color charge and quark mass

# Thank you very much for your attention!

# Jet $p_T$ dependent fragmentation function: I

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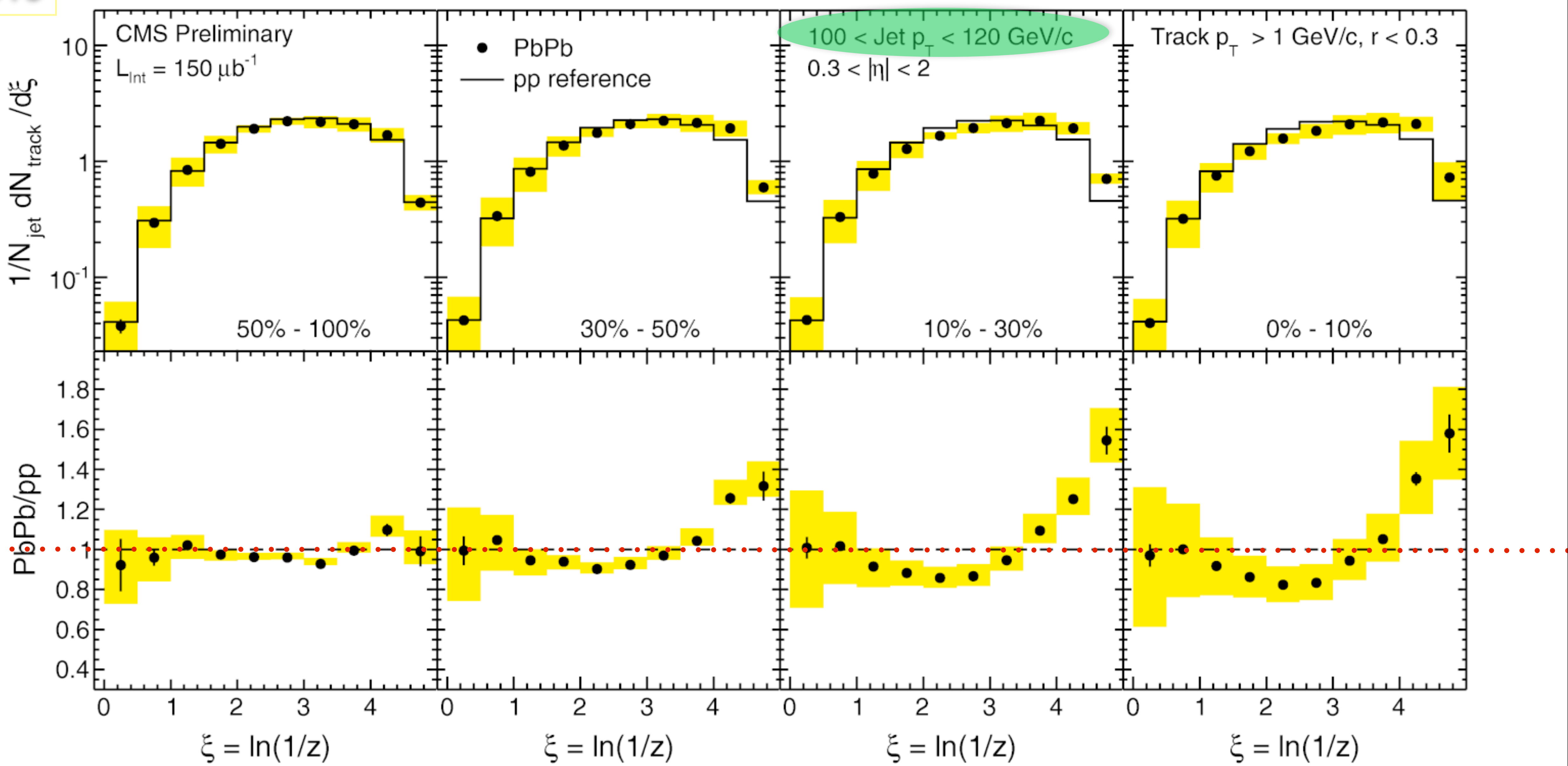
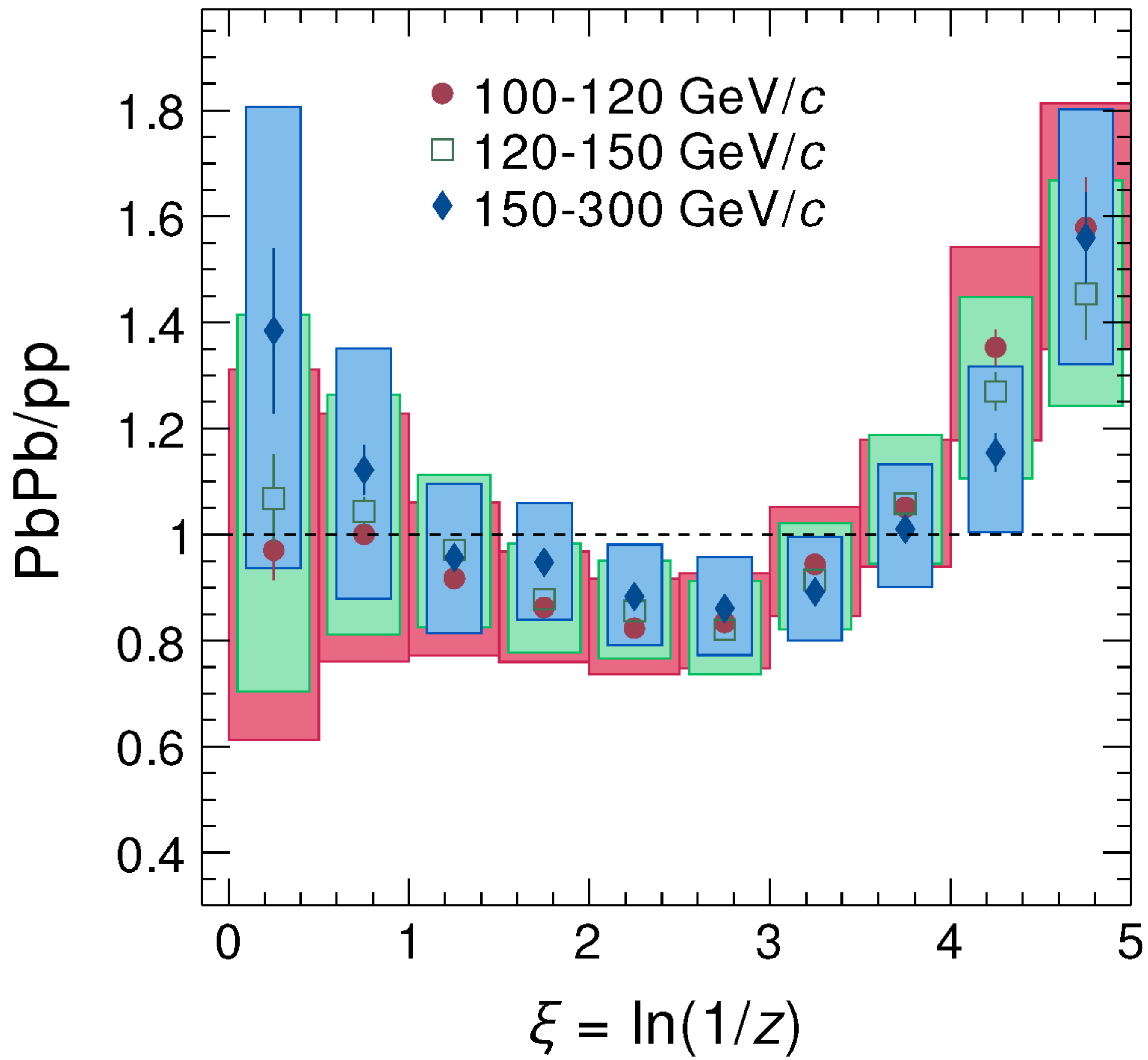



- Jet fragmentation functions for 100 < $p_T$ < 120 GeV/c
- Very similar to inclusive jet results

# Summary of jet $p_T$ dependent FF

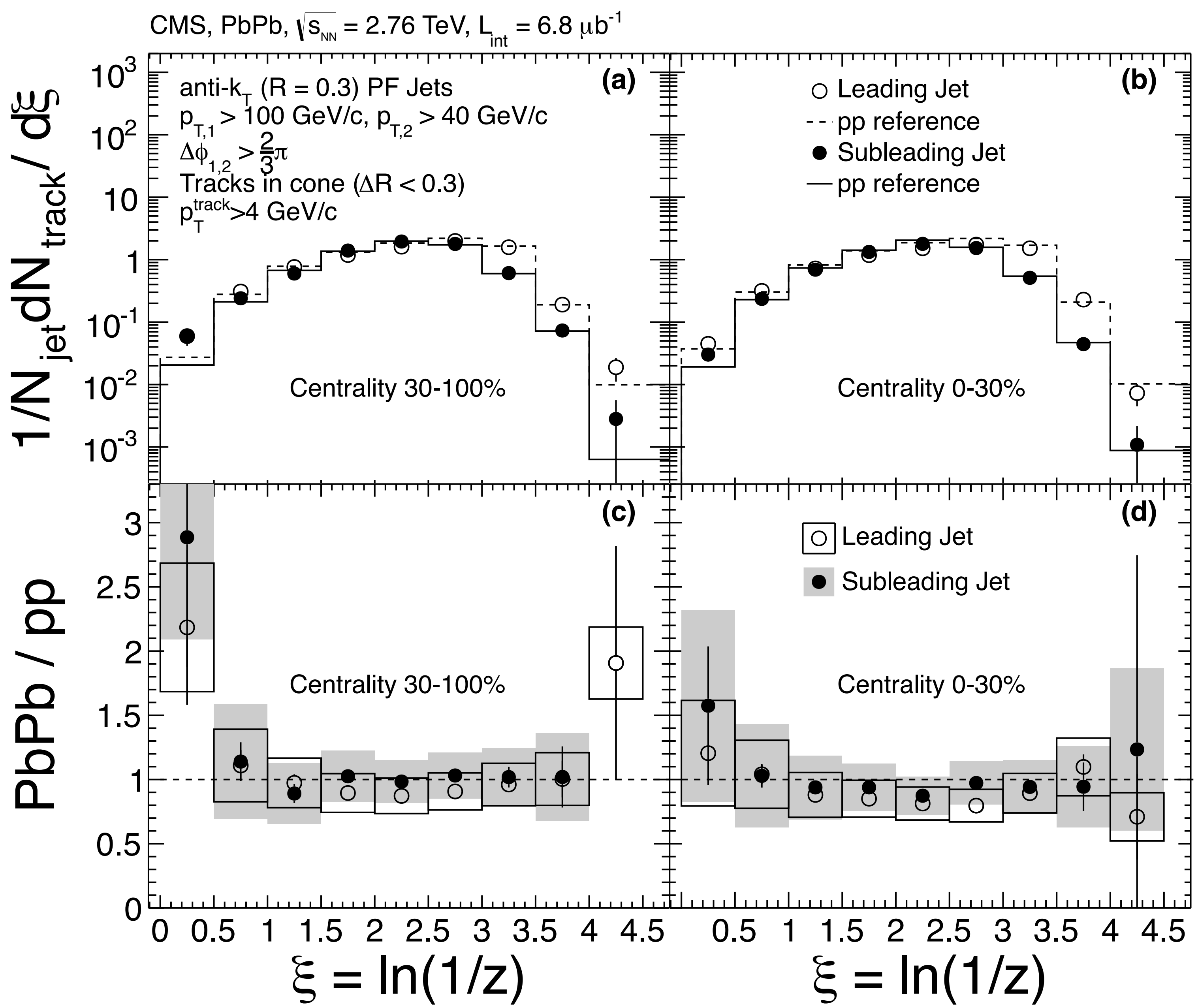


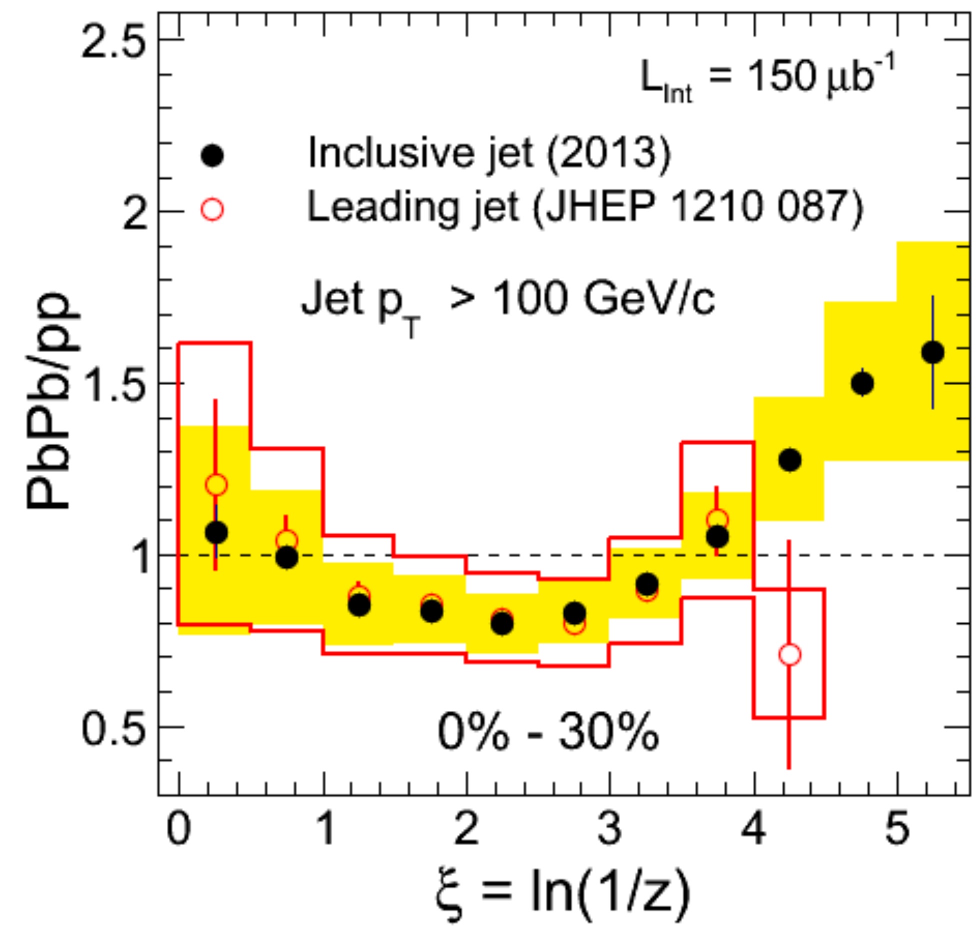

- No clear jet $p_T$ dependence within the uncertainty

# High $p_T$ particle fragments not changed

JHEP 10 (2012) 087

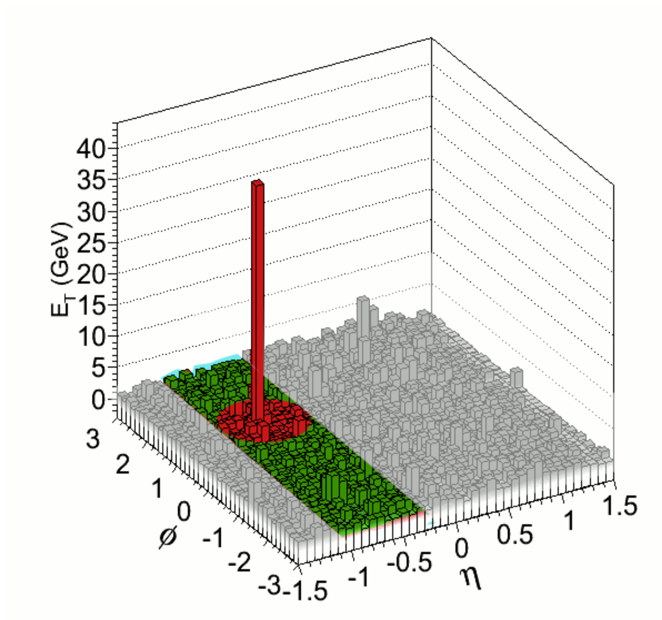
HIN-12-013

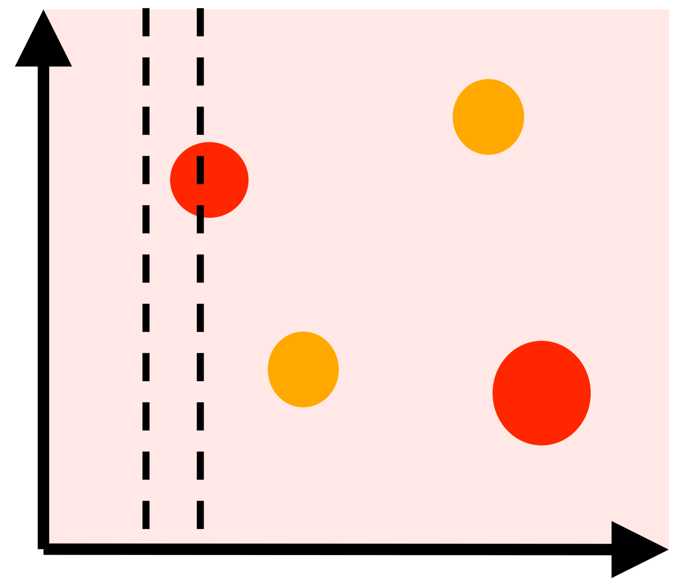


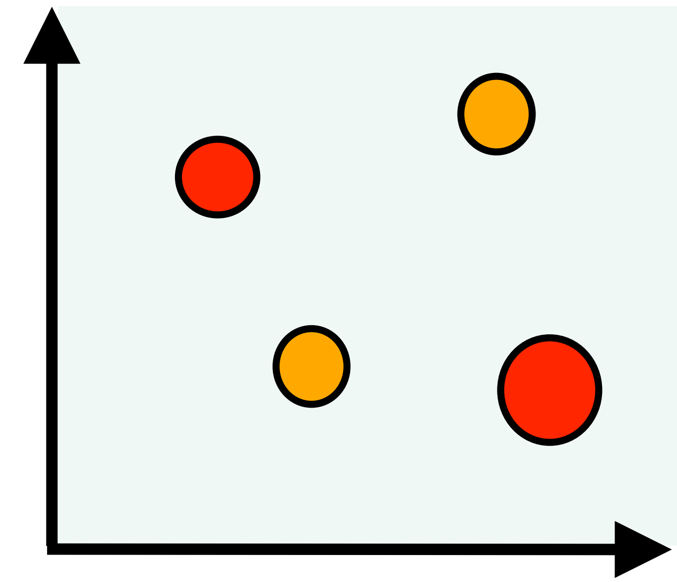

- The jet fragments into high $p_T$ particles (>4 GeV/c) the same way as in pp
- Inclusive jet fragmentation functions are similar to leading jets

# Jet underlying event subtraction

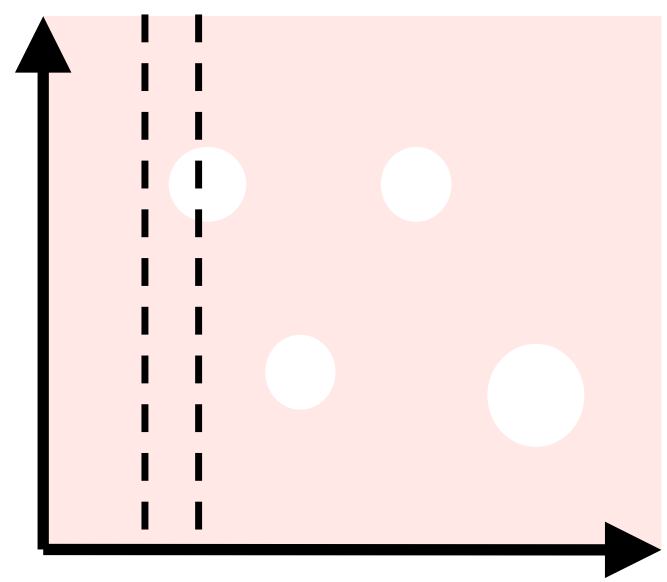


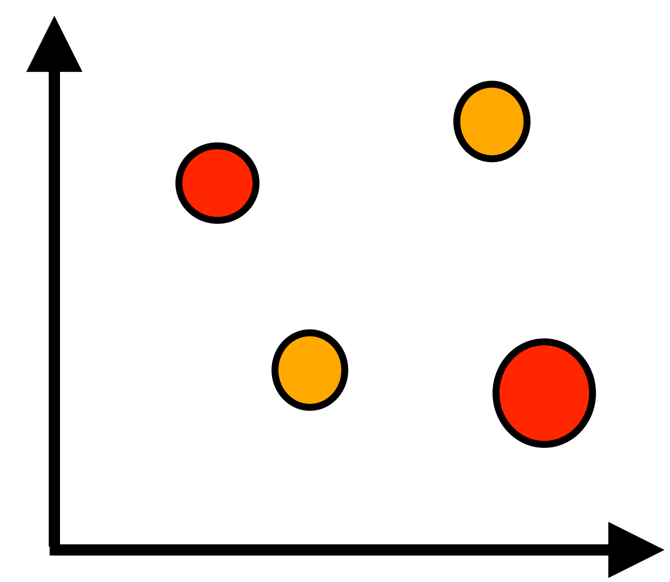
1. $<E_T>$ calculated in strips of η. Subtract $<E_T> + \sigma$



2. Run anti-$k_T$ algorithm on background-subtracted towers



3. Exclude reconstructed jets and re-estimate background

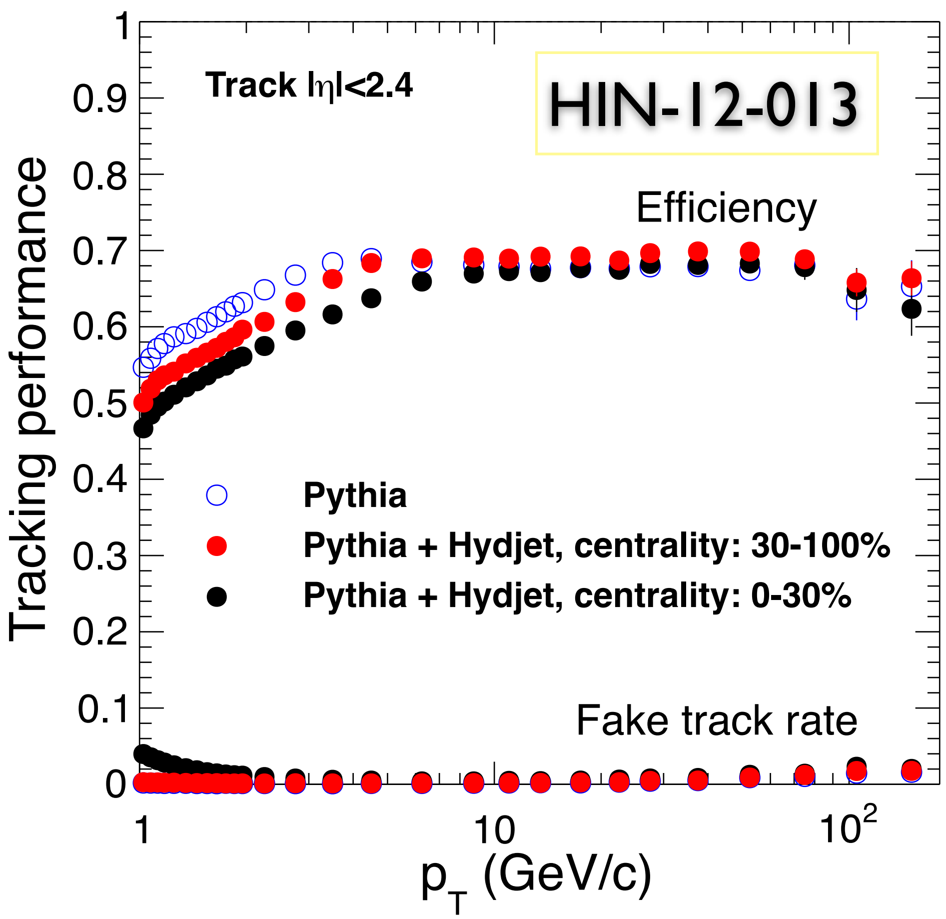


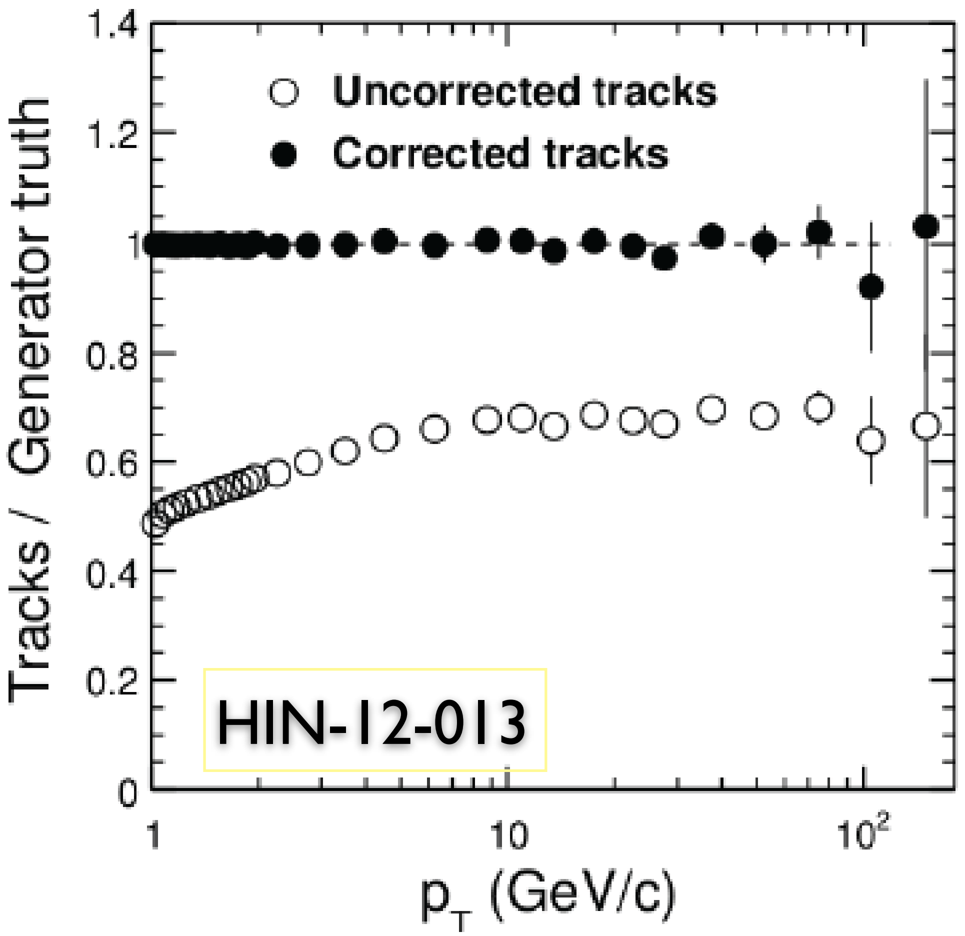
4. Re-run anti-$k_T$ algorithm to get final jets

- CMS, arXiv:1102.1957
- Kodolova et al., EPJC 50 (2007) 117

# Tracking selection and efficiency

- Tracks with $|\eta|<2.4$ and $p_T$ > 1 GeV/c used
- Fake rate < 5%
- Corrected track $p_T$ agrees reasonably well with the generator level particles $p_T$ spectrum

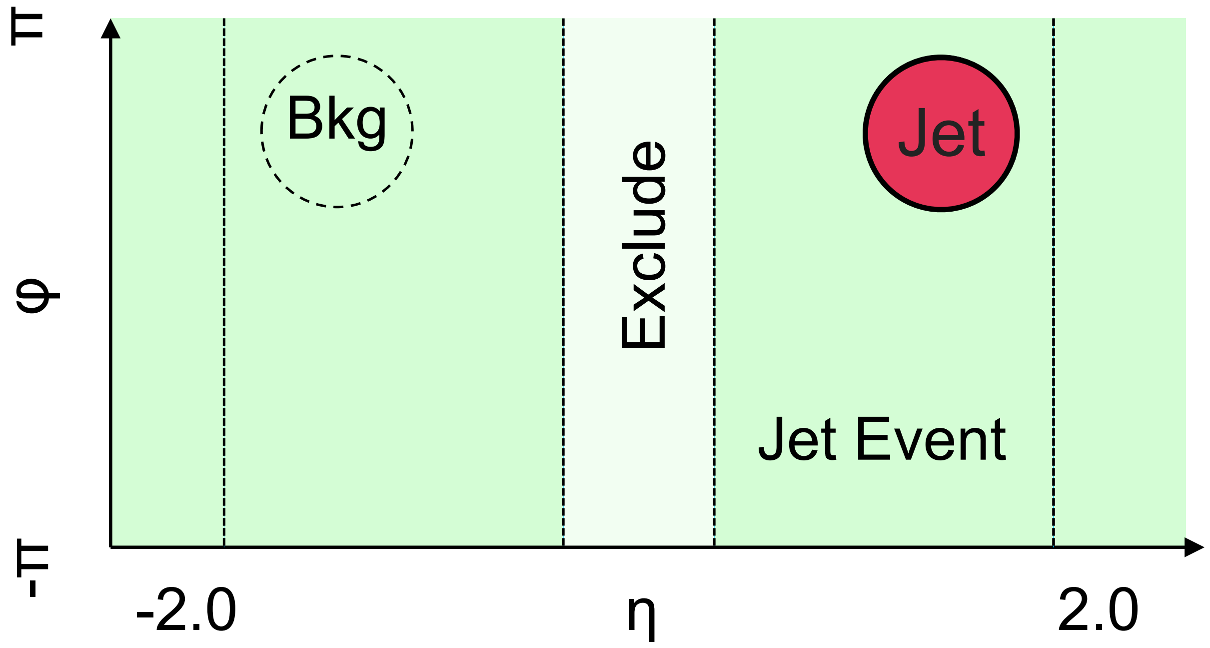


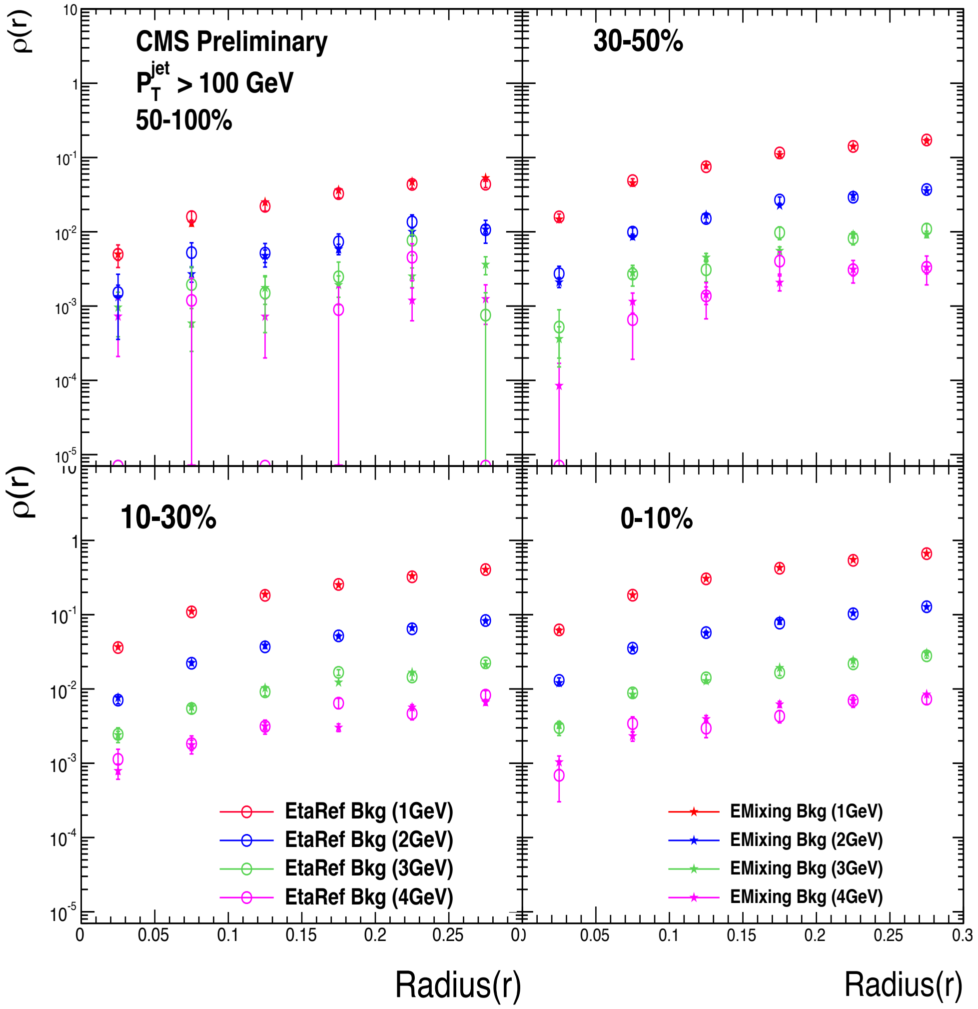



# Background track subtraction

## 1- Eta Reflection

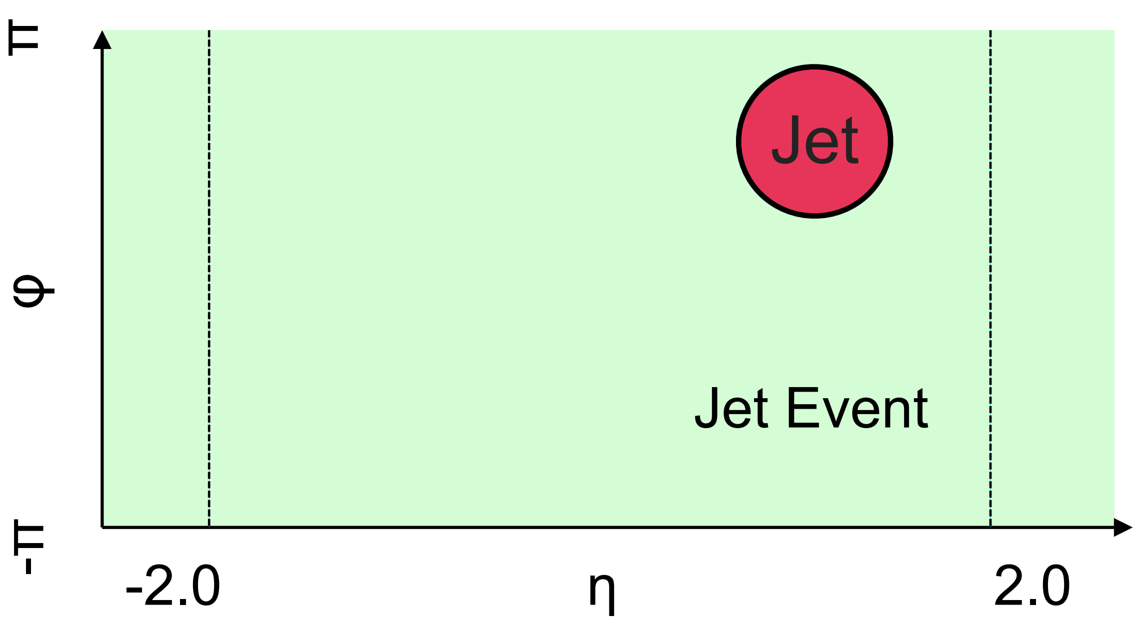
$\eta(bkg\_jet) = -\eta(jet)$

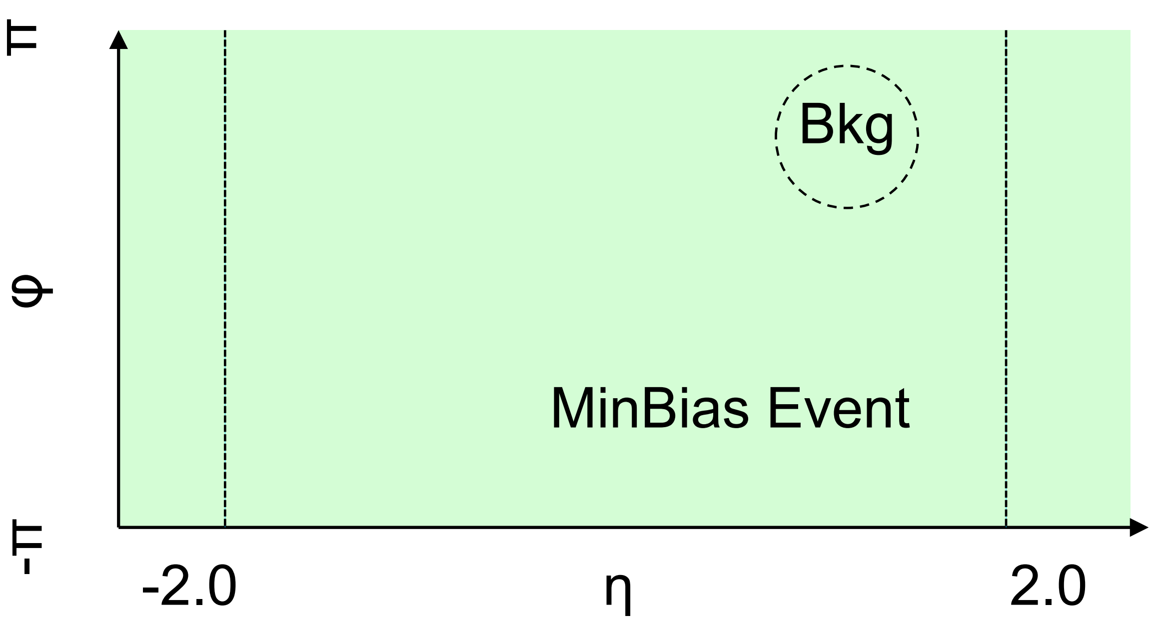



## 2- Event Mixing

Both techniques produce similar background



# Analysis procedure

- inclusive jet selection:
  - ➡ Anti-$k_T$ particle flow jet finding algorithm
  - ➡ R = 0.3, 0.3<|η|<2.0, $p_T^{jet}$ > 100 GeV/c
- track selection:
  - ➡ |η|<2.4, $p_T$ > 1 GeV/c
- background subtraction:
  - ➡ η reflected cone : R = 0.3, 0.3<|η|<2.0
- construct observables distribution:
  - ➡ jet fragmentation function (FF): $\xi = \ln(1/z) = \ln(p^{jet}/p_{||})$
  - ➡ jet shape: radius $r = \sqrt{(\eta_{jet}-\eta_{track})^2+(\varphi_{jet}-\varphi_{track})^2}$