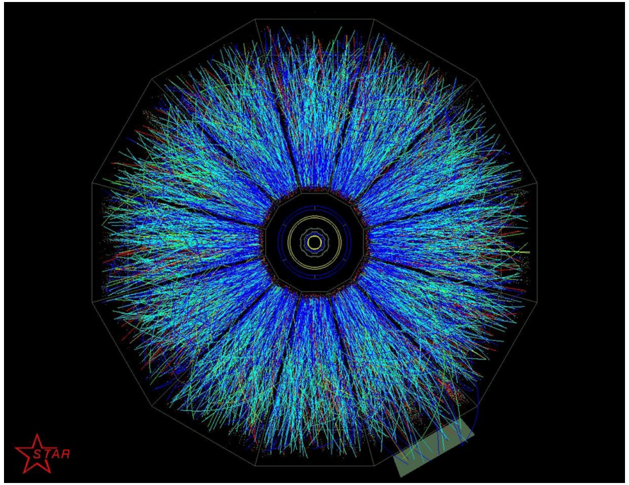
Jet shapes and fragmentation functions in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV in STAR



Joel Mazer (Rutgers University) for **the STAR Collaboration**

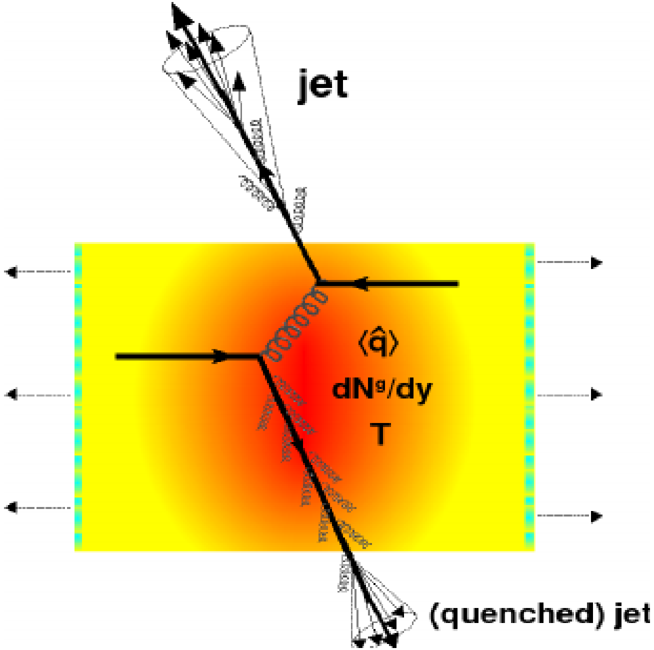
Hard Probes 2020, Parallel Session – Jets and High Momentum Hadrons
June 4th, 2020

In part supported by
U.S. DEPARTMENT OF ENERGY | Office of Science

Introduction

- Jets are a useful probe for studying the QGP
  - Resultant of hard-scattered partons generated at the early stages of heavy-ion collisions
  - Interactions between jets and the QCD medium modify the parton shower relative to that in vacuum

  How is the parton shower changed in A+A?



D. D'Enterria, B. Betz, "*The Physics of the Quark-Gluon Plasma: Introductory Lectures*", 2009

Introduction

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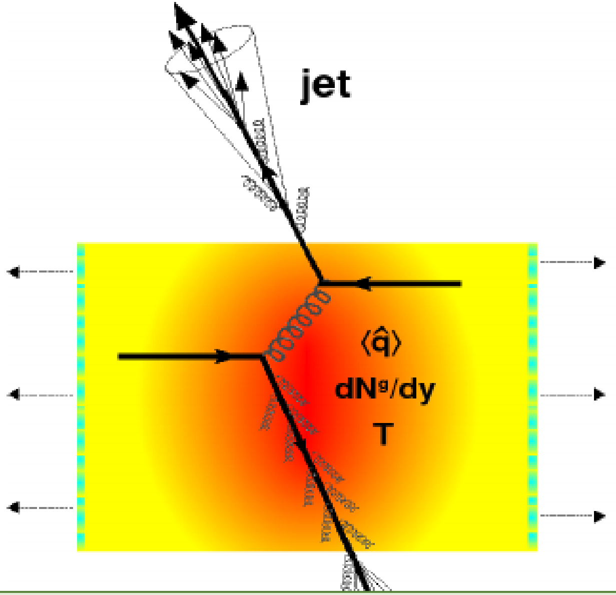
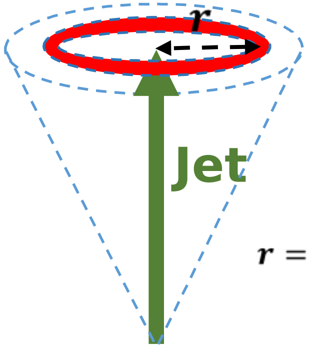


How does the **internal energy distribution** of jets change in heavy-ion collisions? → **Jet Shapes**

How does the **fragmentation** of jets change in heavy-ion collisions? → **Jet Fragmentation Functions**

Introduction

Jet Shapes

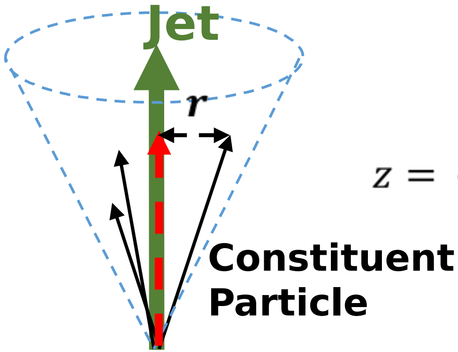


$$r = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$$

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jet}}\frac{\sum_{\text{track}\in(r-\delta r/2,\, r+\delta r/2)} p_{\text{T,track}}}{p_{\text{T,jet}}}$$

- Provides information about the radial distribution of momentum carried by the jet constituents (fragments)

Jet Fragmentation Functions



$$z = \frac{p_{\text{T,track}}\cos(r)}{p_{\text{T,jet}}}$$

Fragmentation function[1], $\frac{1}{N_{\text{jet}}}\frac{dN}{dz}$

- Provides information of the longitudinal momentum fraction of particles with respect to the jet

1. The name of this function is following the convention in relativistic heavy ion physics, although there is a more standard definition: http://pdg.lbl.gov/2019/reviews/rpp2018-rev-frag-functions.pdf

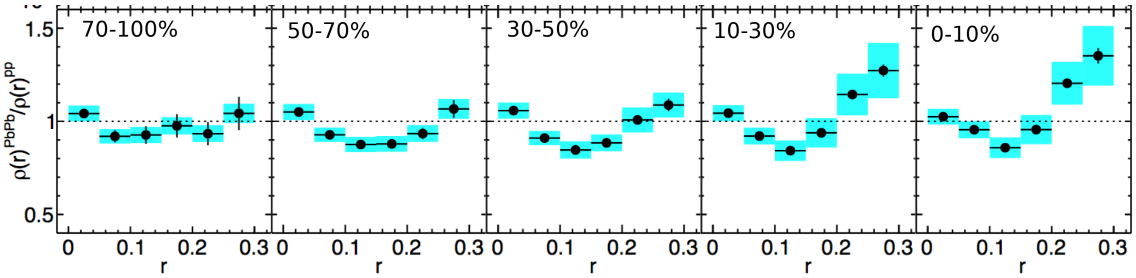
Introduction - LHC results

Jet Shapes

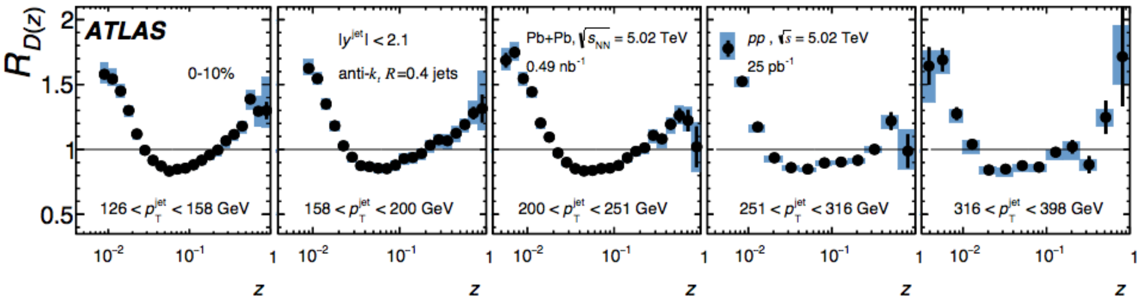
CMS, Phys. Lett. B **730** (2014) 243

Pb+Pb/*p*+*p* @ 2.76 TeV

$$r = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2}$$



Jet Fragmentation Functions



ATLAS, Phys. Rev. C **98** (2018) 024908

Pb+Pb/*p*+*p* @ 5.02 TeV

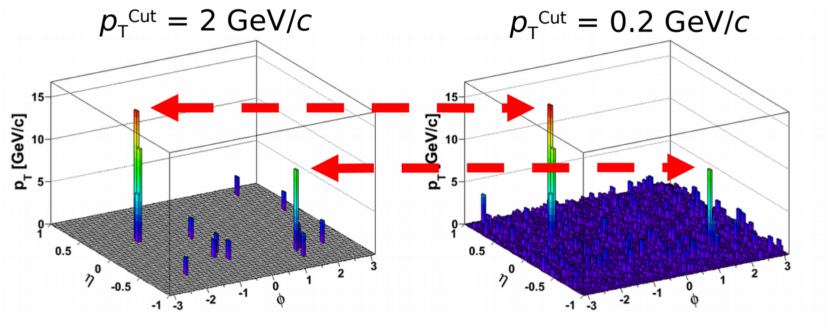
$$z = \frac{p_{\mathrm{T,track}}\cos(r)}{p_{\mathrm{T,jet}}}$$

At $\sqrt{s_{NN}} = 200$ GeV?

Jet measurements in A+A

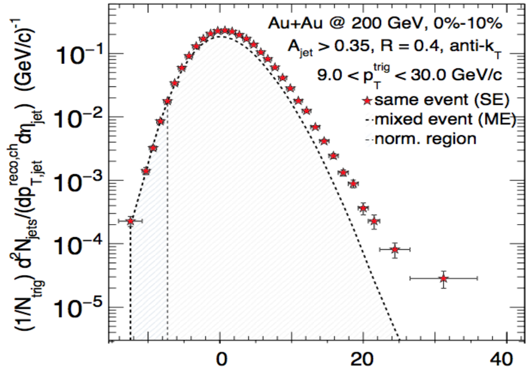
- Challenge in jet measurements in A+A → **Large fluctuating background**

Hard-core vs. matched jets



STAR, Phys. Rev. Lett. **119** (2017) 062301

Semi-inclusive measurement with ME



STAR, Phys. Rev. C **96** (2017) 24905

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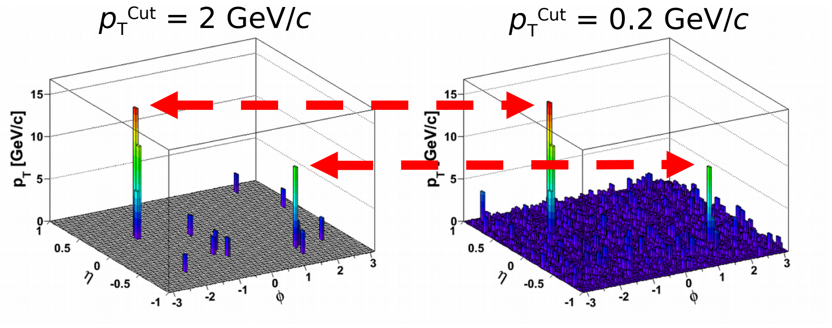

STAR, Phys. Rev. Lett. **119** (2017) 062301

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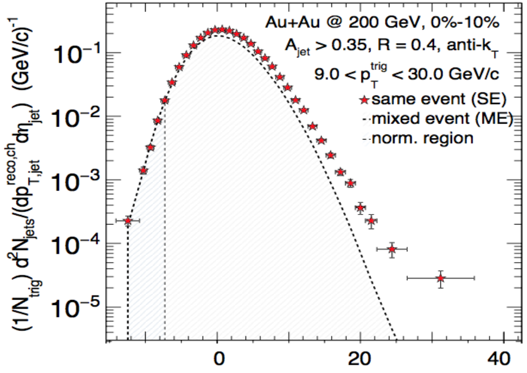


STAR, Phys. Rev. C **96** (2017) 24905

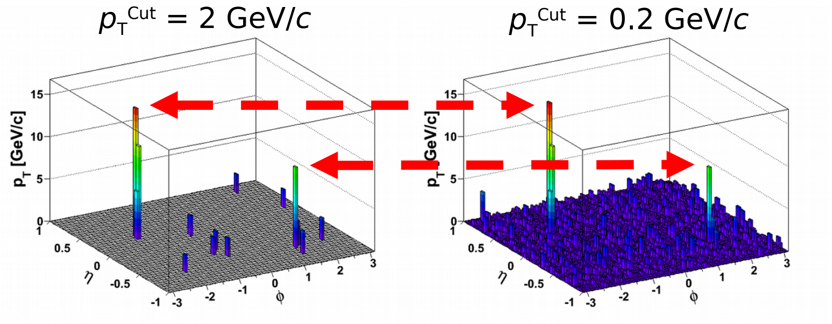
Used in the jet shape measurement

Jet reconstruction with high p_T constituents (HardCore jet)

Jet measurements in A+A

- Challenge in jet measurements in A+A → **Large fluctuating background**

Hard-core vs. matched jets



STAR, Phys. Rev. Lett. **119** (2017) 062301

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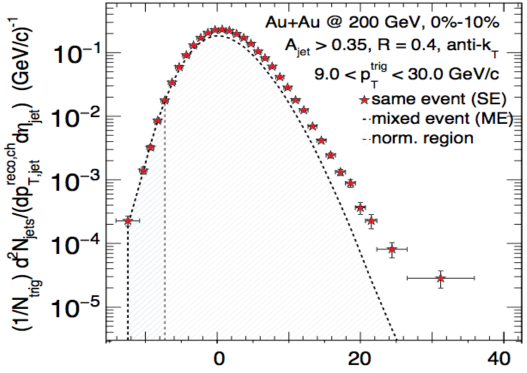


STAR, Phys. Rev. C **96** (2017) 24905

Jets in the recoil region of a high momentum particle (semi-inclusive approach)

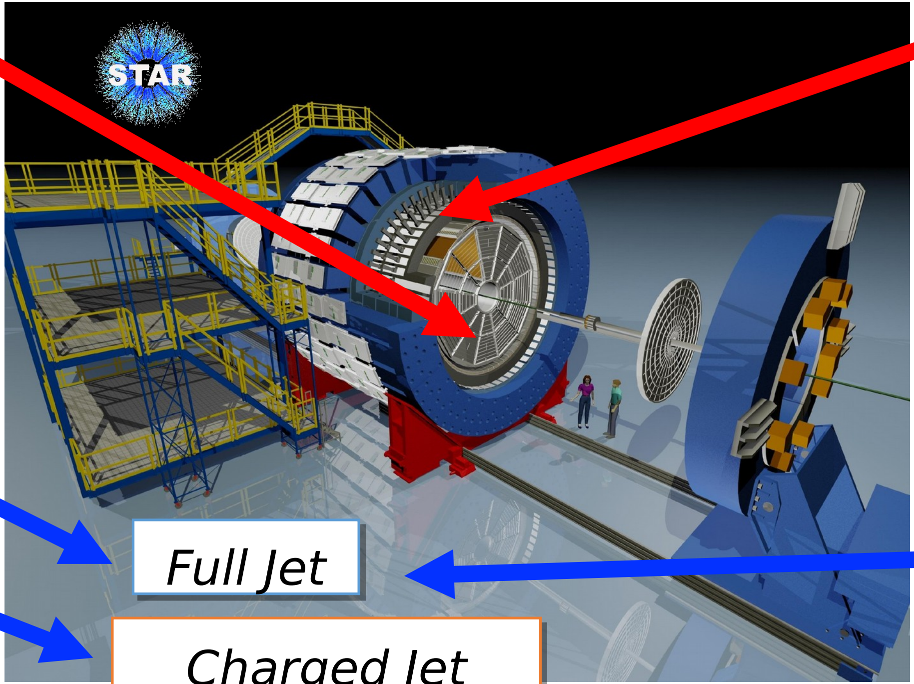
Used in the jet fragmentation function measurement

The STAR experiment

TPC

- Time Projection Chamber:
  - $|\eta| < 1.0$, $0<\varphi<2\pi$
  - Tracking, mometum, d*E*/dx, event plane reconstruction

Charged constituents



Full Jet

Charged Jet

BEMC

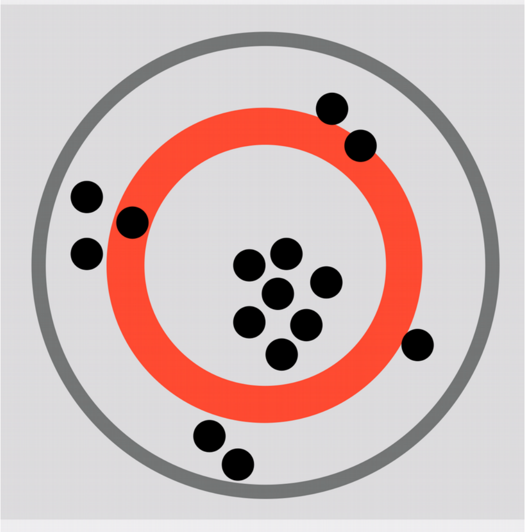
- Barrel Electromagnetic Calorimeter:
  - $|\eta| < 1.0$, $0<\varphi<2\pi$
  - Resolution: 0.05x0.05
  - Study high-p_T processes, triggering

EM neutral constituents

2014, Au+Au, $\sqrt{s_{NN}}$= 200 GeV

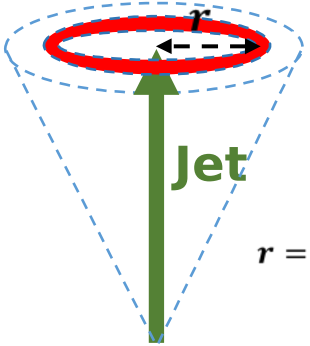
- Minimum-bias (MB) + high-tower (HT) triggered events
- Mixed events for background estimation – for each (centrality/track multiplicity, z_{vtx}, Ψ_{EP}) bin with MB events

Jet shapes



Gavin Salam – QM 2018

Jet shapes



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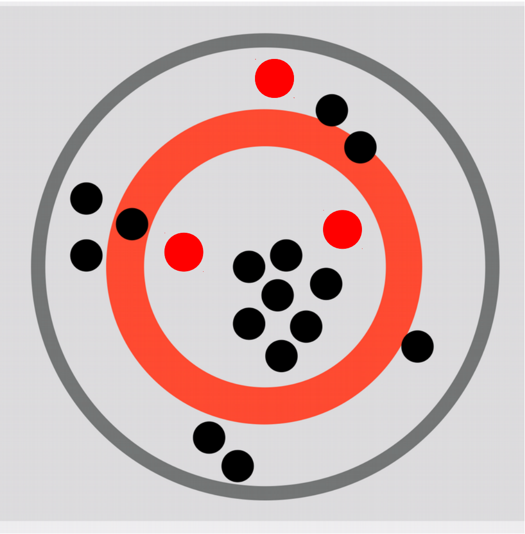
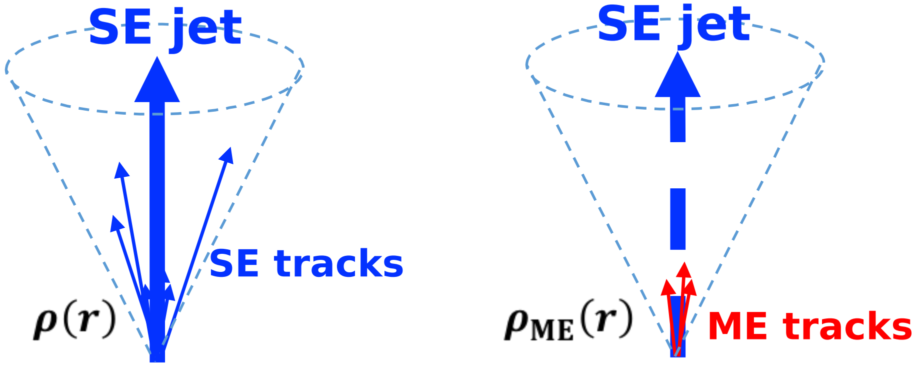
- Full (charged + neutral) jets reconstructed with high-momentum tracks and towers with $p_{\text{T,track}}$ ($E_{\text{T,tower}}$) > 2.0 GeV/c (**HardCore** jet selection)

Jet shapes

$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jet}} \frac{\sum_{\mathrm{track}\in(r-\delta r/2, r+\delta r/2)} p_{\mathrm{T,track}}}{p_{\mathrm{T,jet}}}$$

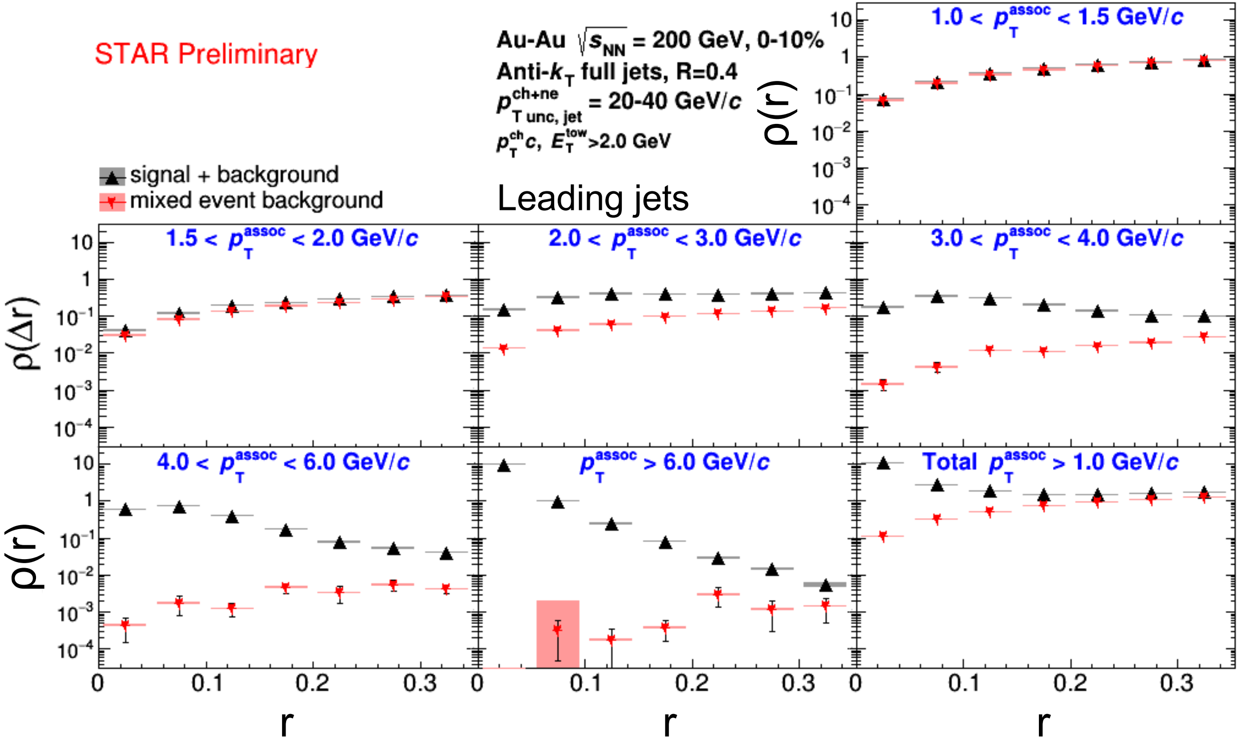


- Full (charged + neutral) jets reconstructed with high-momentum tracks and towers with $p_{\mathrm{T,track}}$ ($E_{\mathrm{T,tower}}$) > 2.0 GeV/c (**HardCore** jet selection)
- Background contributions in ρ(r) are estimated by placing same-event jets ($p_{\mathrm{T,jet}}$ and jet axis) into mixed-events. Background jet shape, ρ_{ME}(r), is calculated and then subtracted from ρ(r), accordingly



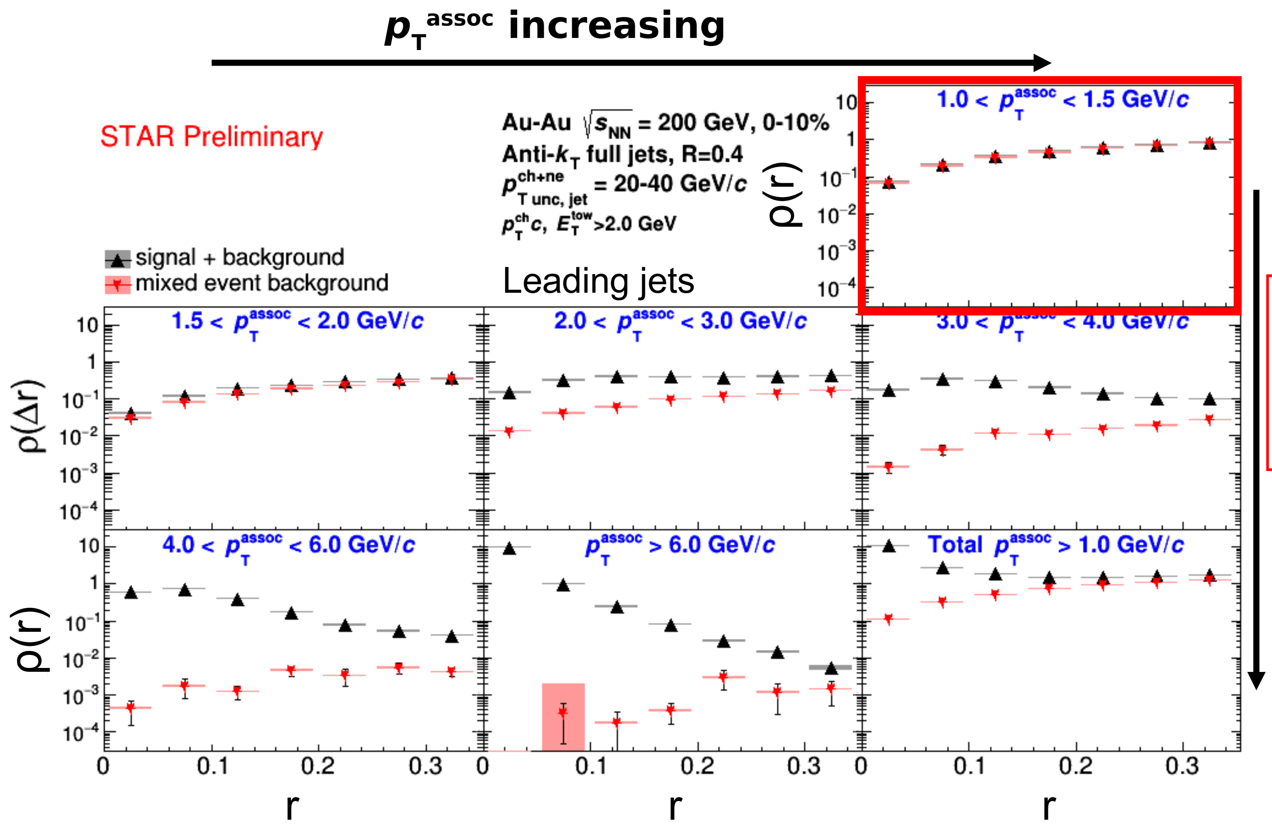
Jet shapes – Results

p_T^{assoc} increasing



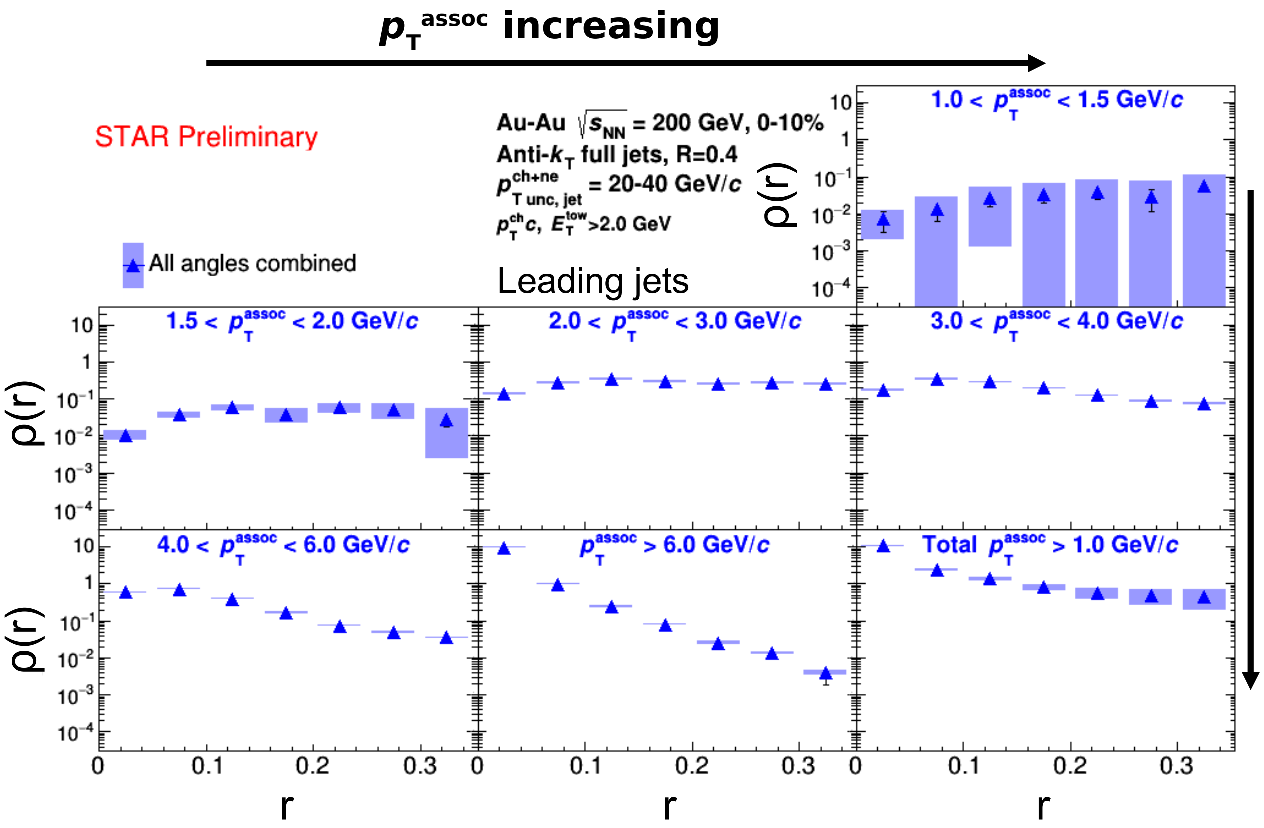
- Jet shapes for 0-10%

Jet shapes – Results



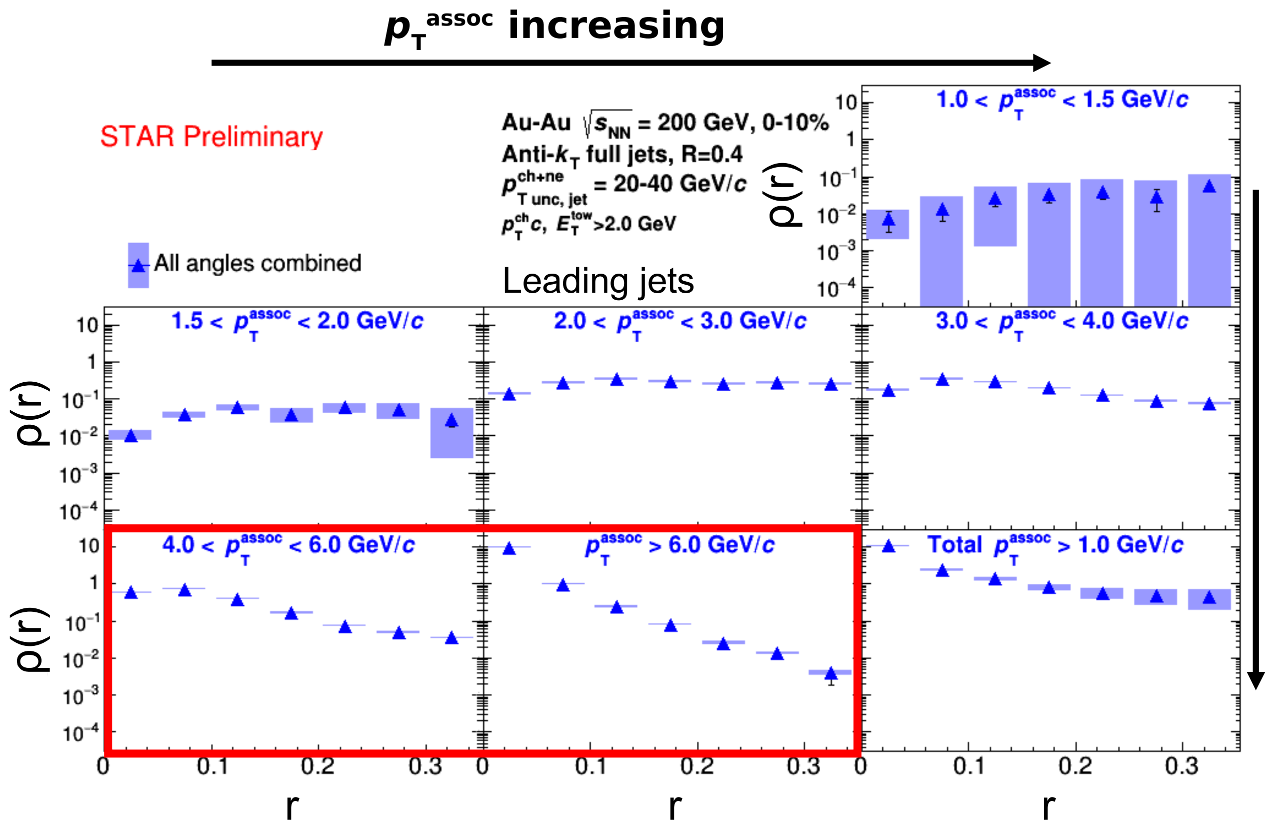
- Jet shapes for 0-10%
- At low $p_{T,assoc}$ and for most central collisions background contributions dominate ρ(r)

Jet shapes – Results



- Jet shapes for 0-10% centrality after background subtraction

Jet shapes – Results

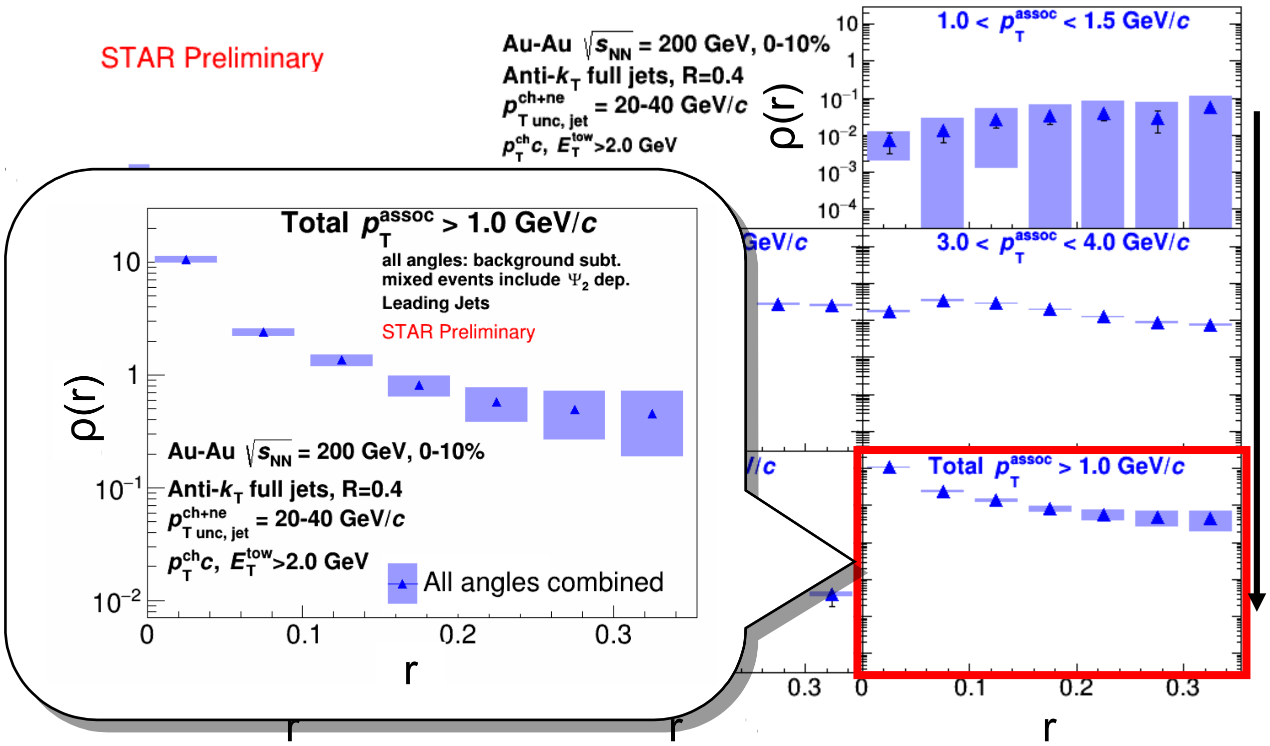


- Jet shapes for 0-10% centrality after background subtraction

- High-p_T tracks are located near the jet axis compared to low-p_T tracks, as expected

Jet shapes – Results

p_T^{assoc} **increasing**

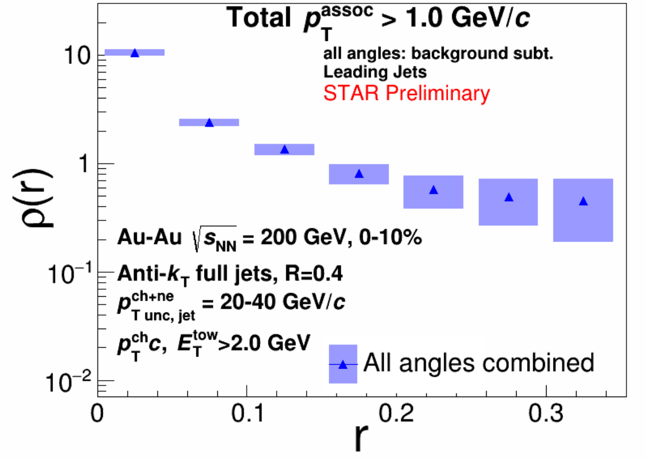


- Jet shapes for 0-10% centrality after background subtraction
- High-p_T tracks are located near the jet axis compared to low-p_T tracks, as expected

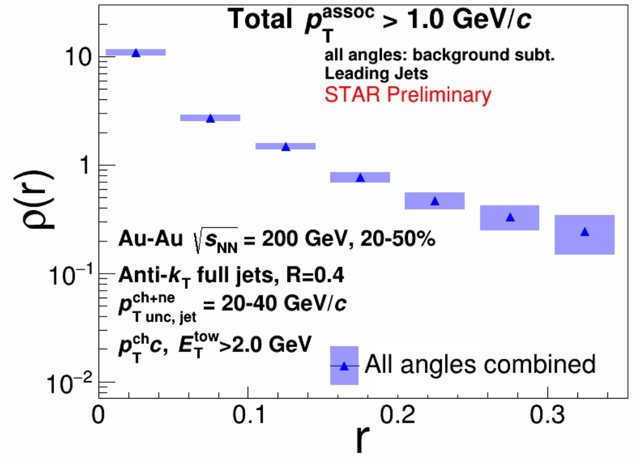
- First differential jet study at RHIC energies
- Total jet shape for:
  - 20-40 GeV/*c* jets
  - p_T^{assoc} > 1.0 GeV/*c*

Central and mid-peripheral jet shapes

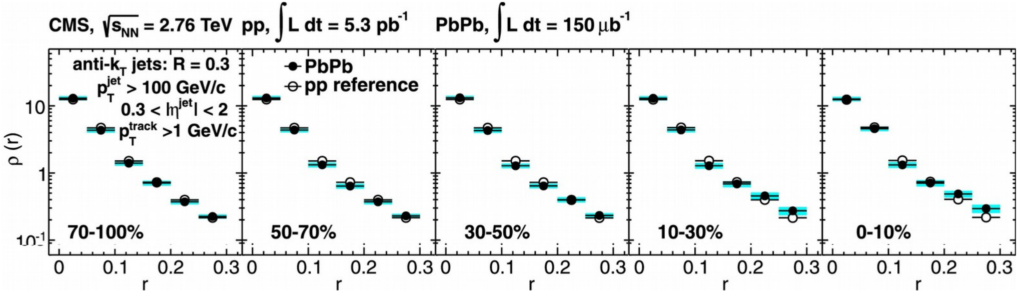
0-10% centrality



20-50% centrality

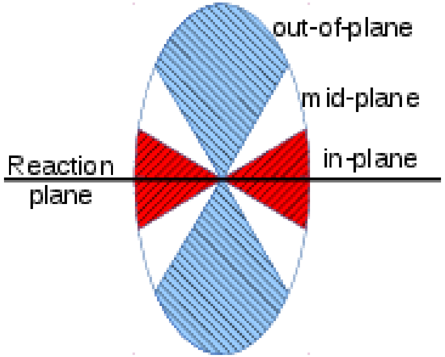


- Jet shapes are less steep at 200 GeV than at LHC energies
  - With variations in kinematics and jet selection



See talks: Robert Líčeník (**#237**, 6/1 12:20 ET) & Nihar Sahoo (**#238**, 6/2 12:20 ET)

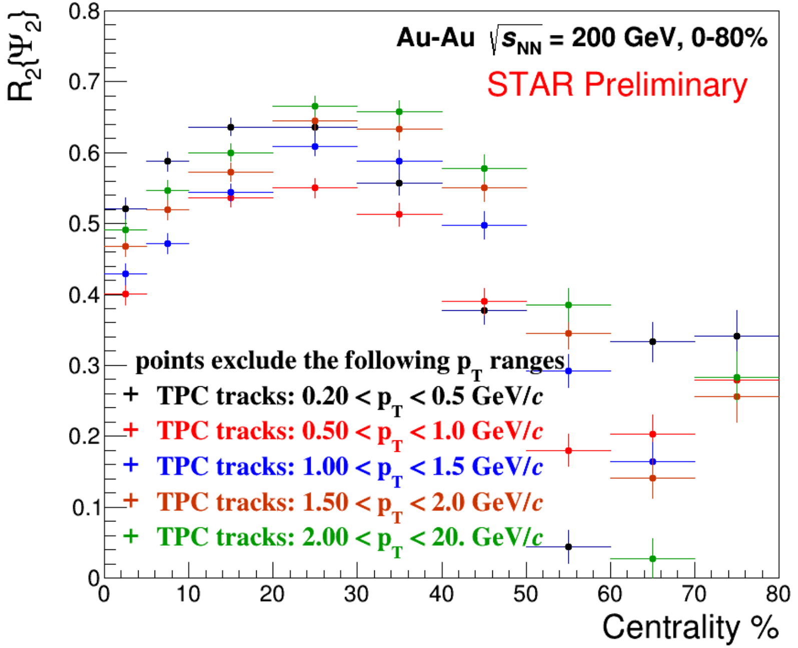
Jet shapes – Event-plane dependence



- Jet shapes can be measured more differentially based on jets' azimuthal angle relative to the 2nd-order event plane (EP)
  – In-plane: $0° \leq |\varphi_{jet} - \Psi_{EP}| < 30°$
  – Mid-plane: $30° \leq |\varphi_{jet} - \Psi_{EP}| < 60°$
  – Out-of-plane: $60° \leq |\varphi_{jet} - \Psi_{EP}| < 90°$
- Control *path-length* of jet quenching with centrality and *event-plane angle*
- Jets may experience different in-medium path length depending on their direction relative to the Ψ_{EP}
  – **Average path-length OUT > average path-length IN**

Are we sensitive enough ?

Jet shapes – Event-plane resolution

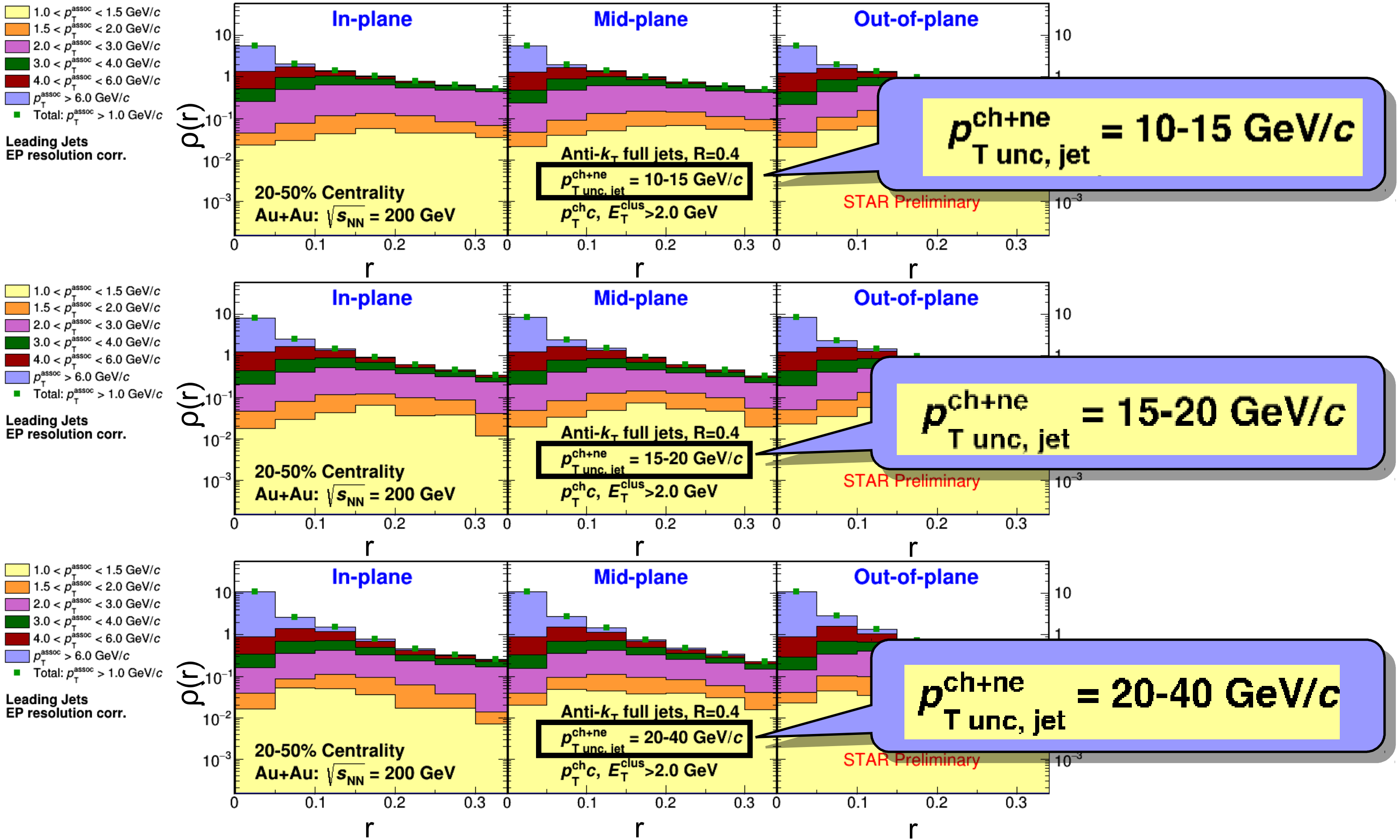


- Due to finite multiplicity of each event, there will be a difference between the reconstructed event plane and underlying symmetry plane: Ψ_2

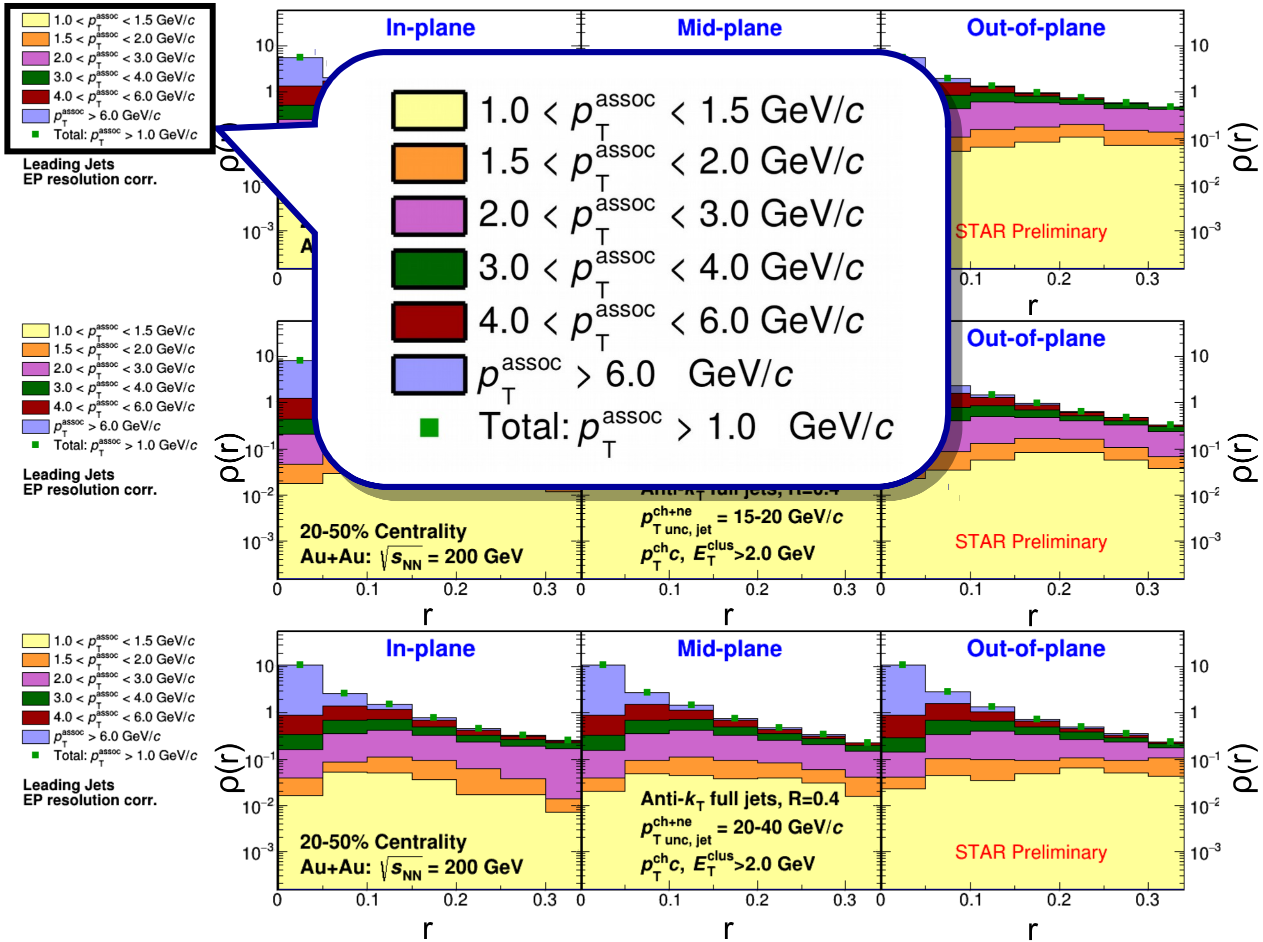
$$R_n = < \cos(n(\psi_{n,true} - \psi_{n,reco})) >$$

- Using modified reaction-plane (MRP) method, for p_T associated bins STAR, Phys. Rev. C **89** (2014) 041901(R)
  - Improvement over typical EP measurements with the TPC and BBC
- Peak for 20-30% and 30-40% centrality
- Excluding track with p_T = 0.5-1.0 GeV/*c* gives lowest R_2

Jet shapes – Results

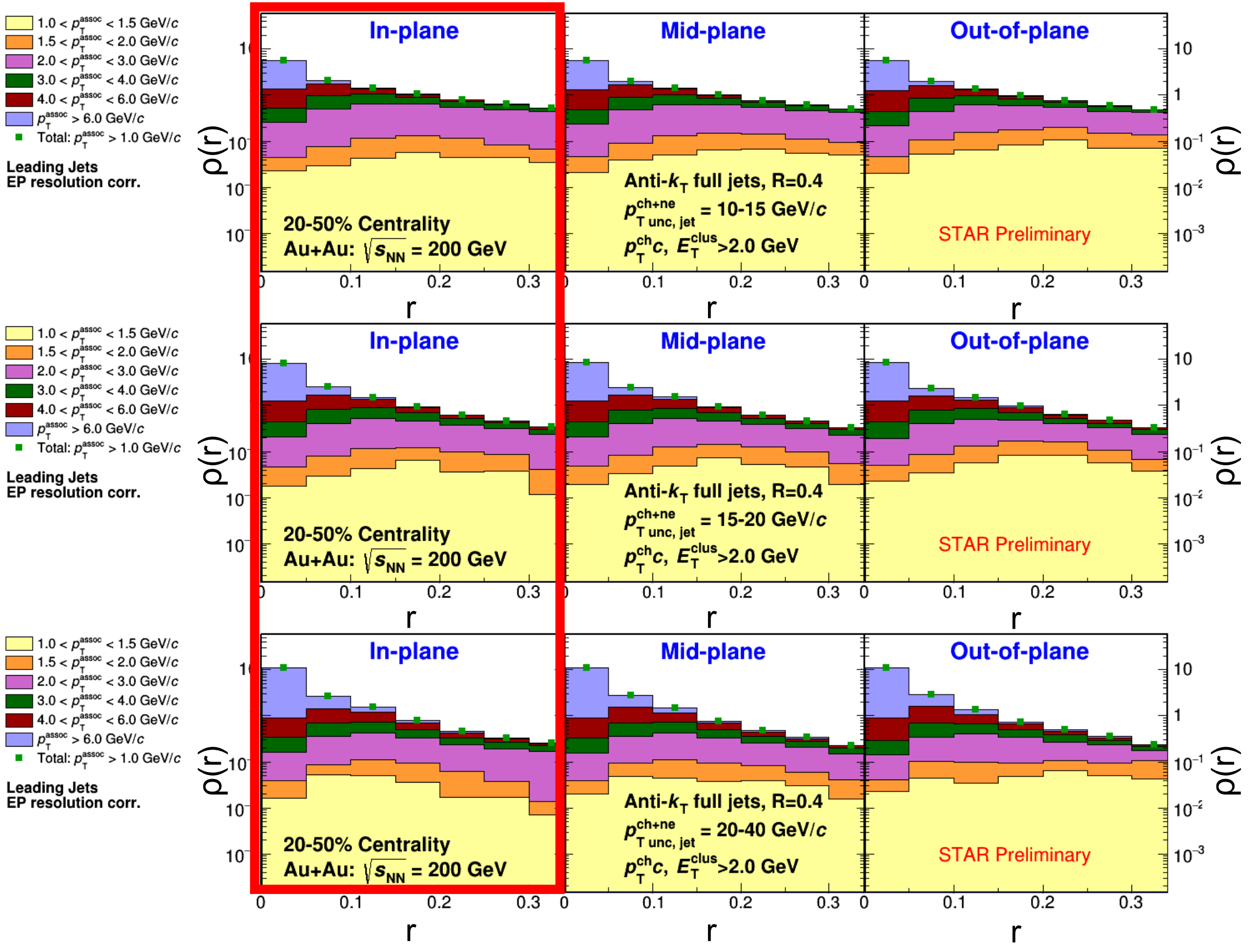


Jet shapes – Results



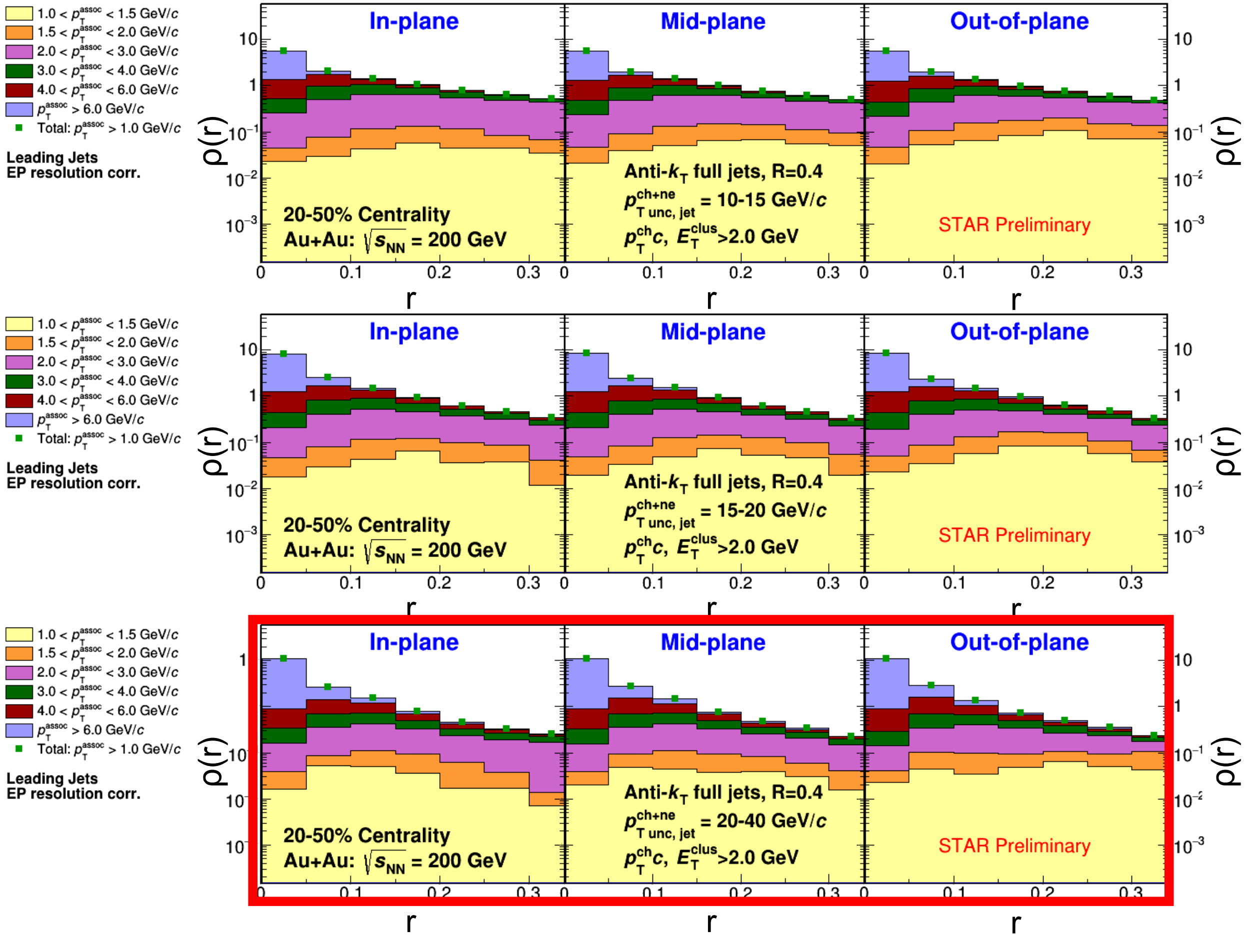
- Differentially separated further into associated p_T ranges

Jet shapes – Results



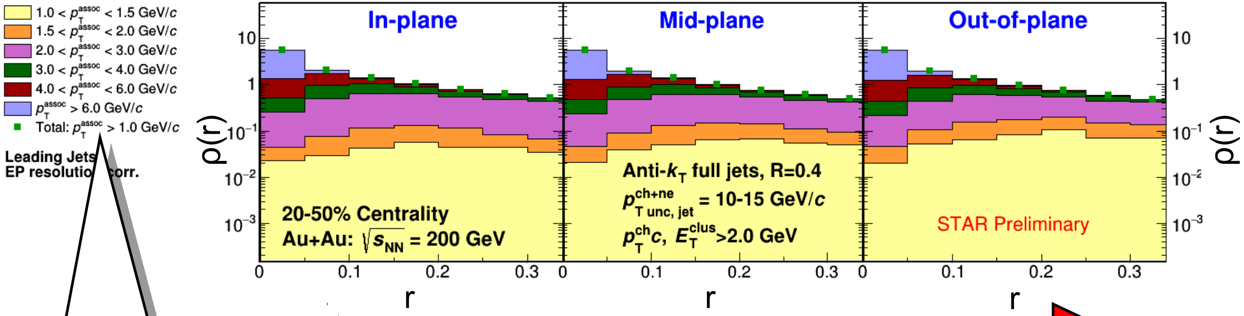
- Higher $p_{T,jet}$ are more collimated

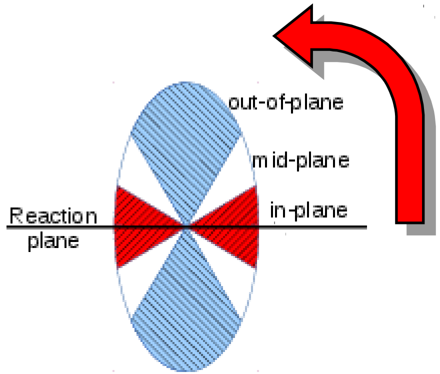
Jet shapes – Results



- Higher $p_{T,jet}$ are more collimated
- For low-p_T associated tracks, out-of-plane jet shape is flatter compared to in-plane

Jet shapes – Results





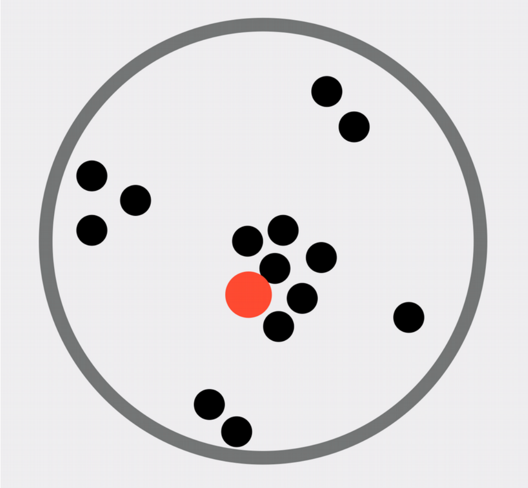
1.0 < p_T^{assoc} < 1.5 GeV/c
1.5 < p_T^{assoc} < 2.0 GeV/c
2.0 < p_T^{assoc} < 3.0 GeV/c
3.0 < p_T^{assoc} < 4.0 GeV/c
4.0 < p_T^{assoc} < 6.0 GeV/c
p_T^{assoc} > 6.0 GeV/c
Total: p_T^{assoc} > 1.0 GeV/c

- Low-p_T tracks are pushed toward farther distances in the out-of-plane direction relative to the in-plane direction
- Larger yields of low-p_T tracks in the out-of-plane direction

Are the larger effects in the out-of-plane direction due to longer in-medium path length?

Jet fragmentation functions

Poster 248 (JHMH). "Measurement of semi-inclusive jet **fragmentation functions** in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV in STAR", **Saehanseul Oh** (LBNL)



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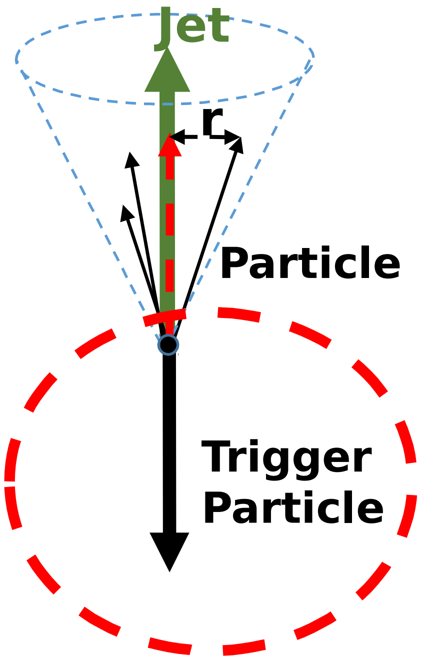
Jet fragmentation functions

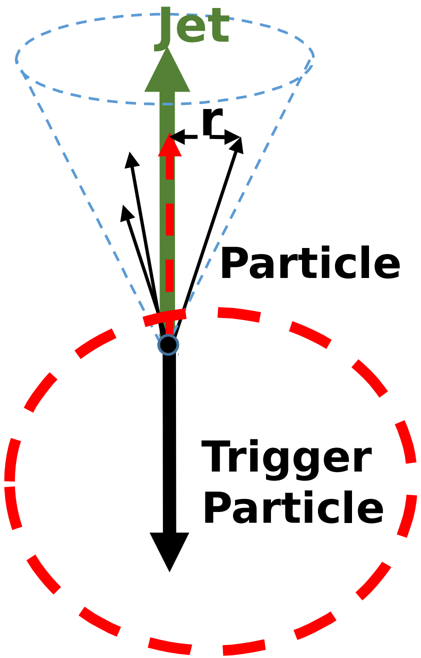


$$z = \frac{p_{\mathrm{T,track}} \cos(r)}{p_{\mathrm{T,jet}}}$$

$$\frac{1}{N_{\mathrm{jet}}(p_{\mathrm{T,jet}})} \frac{dN(p_{\mathrm{T,jet}}, z)}{dz} \text{ for tracks within } \Delta r_{\mathrm{jet-track}} < R = 0.4$$

- **Charged jets** are selected in the recoil region with respect to high momentum trigger particles (semi-inclusive, BEMC tower with $9.0 < E_T < 30.0$ GeV), $|\varphi_{trig} - \varphi_{jet}| > \pi - \pi/4$

Jet fragmentation functions



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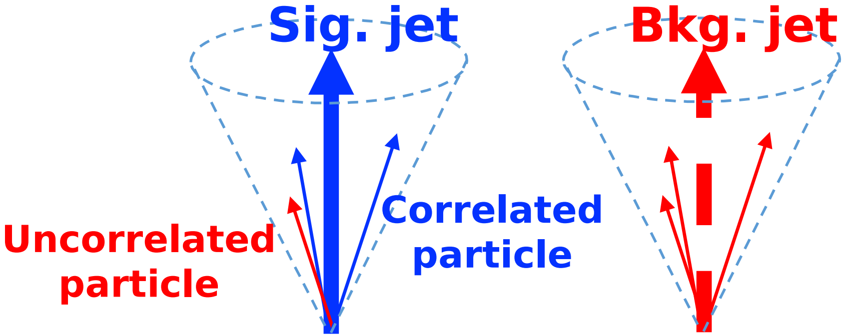
- **Charged jets** are selected in the recoil region with respect to high momentum trigger particles (semi-inclusive, BEMC tower with $9.0 < E_T < 30.0$ GeV), $|\varphi_{\mathrm{trig}} - \varphi_{\mathrm{jet}}| > \pi - \pi/4$
- In the recoil region, there are two types of jets
  - **Signal (Sig.) jet**, i.e. jets correlated to the trigger particle
    - These jets also contain *uncorrelated particles*
  - **Background (Bkg.) jet**, i.e. jets uncorrelated to the trigger particle



Jet fragmentation functions – Corrections

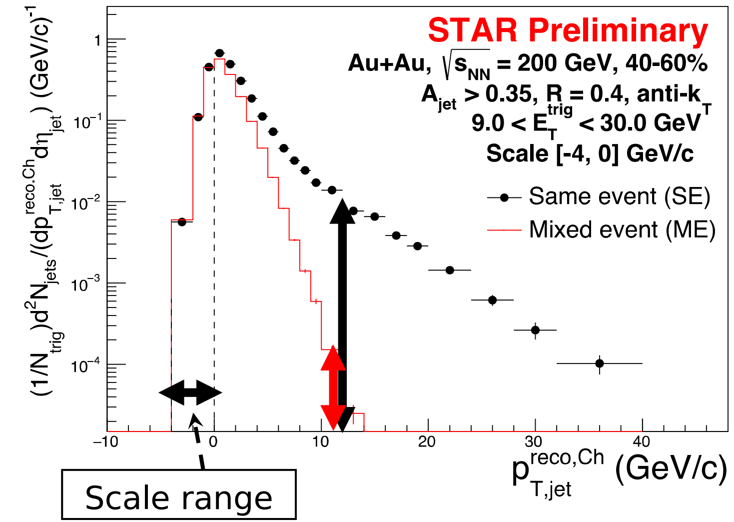
How can we remove the uncorrelated components?

$$\frac{1}{N_{\rm jet}(p_{\rm T,jet})}\frac{dN(p_{\rm T,jet},z)}{dz}$$

SE: same event
ME: mixed event

$$N_{\rm jet}(p_{\rm T,jet}) = N^{SE}_{\rm jet}(p_{\rm T,jet}) - N^{ME}_{\rm jet}(p_{\rm T,jet})$$

- $N_{\rm jet}^{\rm ME}(p_{\rm T,jet})$ are fitted to $N_{\rm jet}^{\rm SE}(p_{\rm T,jet})$ in the negative $p_{\rm T,jet}$ range, where uncorrelated jets are expected to dominate (STAR, Phys. Rev. C 96 (2017) 24905)
  - ***Removes Bkg. jets from N_{jet}***
- Contributions from background jets in $dN(p_{\rm T,jet}, z)/dz$ can be calculated by $dN^{\rm ME}(p_{\rm T,jet}, z)/dz$ and scaling it based on background jet fraction
  - ***Removes Bkg. jets from $dN(p_{T,jet}, z)/dz$***



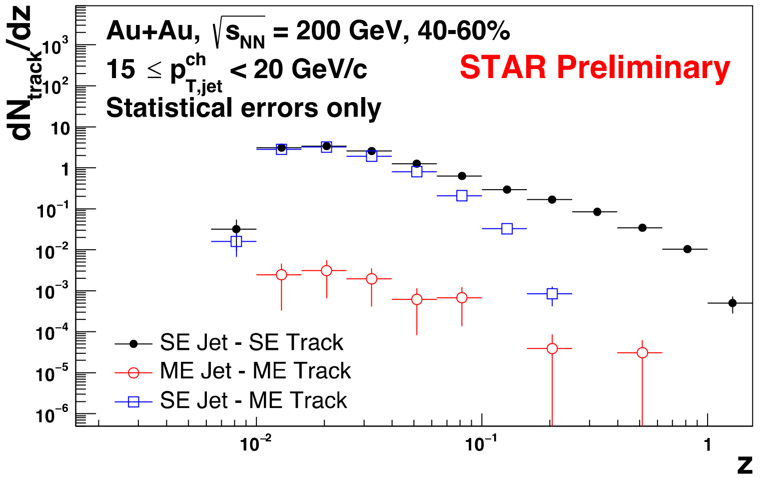
- Compare $N_{\rm jet}^{\rm ME}(p_{\rm T,jet})$ with $N_{\rm jet}^{\rm SE}(p_{\rm T,jet})$ to estimate fraction of Bkg. jets

Jet fragmentation functions – Corrections

How can we remove the uncorrelated components?

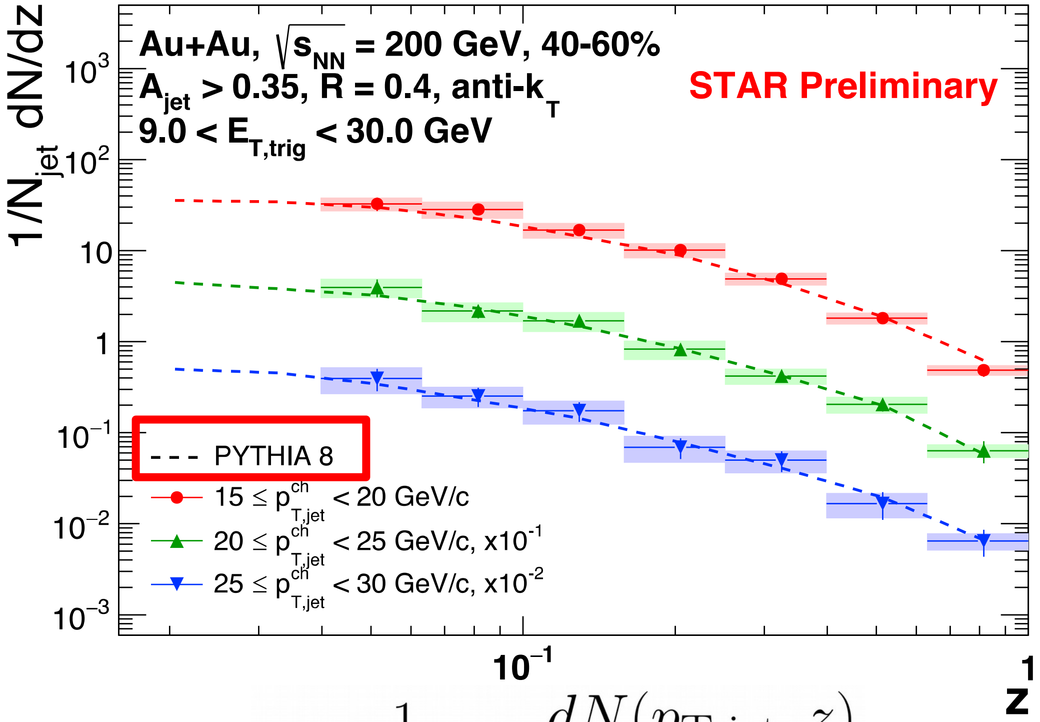
$$\frac{1}{N_{\mathrm{jet}}(p_{\mathrm{T,jet}})}\frac{dN(p_{\mathrm{T,jet}}, z)}{dz}$$

- $N_{jet}^{ME}(p_{T,jet})$ are fitted to $N_{jet}^{SE}(p_{T,jet})$ in the negative $p_{T,jet}$ range, where uncorrelated jets are expected to dominate (STAR, Phys. Rev. C 96 (2017) 24905)
  - ***Removes Bkg. jets from N_{jet}***
- Contributions from background jets in d$N(p_{T,jet}$, z)/dz can be calculated by dN^{ME} ($p_{T,jet}$, z)/dz and scaling it based on background jet fraction
  - ***Removes Bkg. jets from dN($p_{T,jet}$, z)/dz***
- Contributions from uncorrelated particles in signal jets can be estimated by placing SE jets into mixed events and pairing with ME tracks
  - ***Removes uncorrelated particle contributions from Sig. jets***



Corrected d*N*/dz = Black – Red – Blue

Jet fragmentation functions – Results



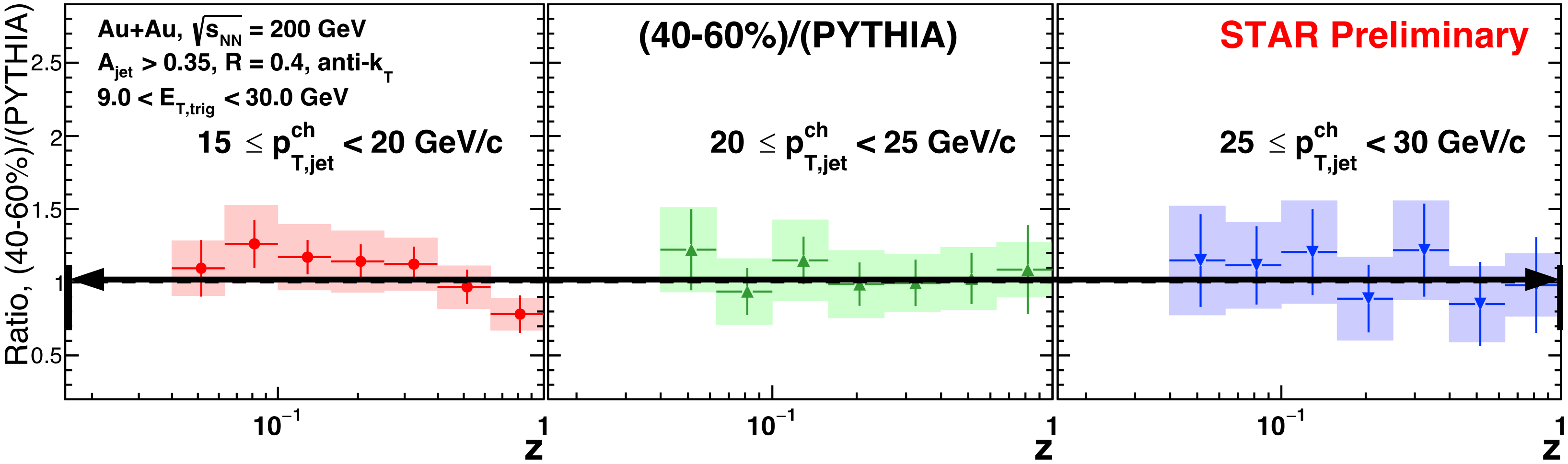
$$\frac{1}{N_{\mathrm{jet}}(p_{\mathrm{T,jet}})}\frac{dN(p_{\mathrm{T,jet}}, z)}{dz}$$

- Jet fragmentation functions for 40-60% centrality class and three $p_{\mathrm{T,jet}}$ ranges

- $N_{\mathrm{jet}}(p_{\mathrm{T,jet}})$ and $dN(p_{\mathrm{T,jet}}, z)/dz$ are separately unfolded via 1-D and 2-D Bayesian unfolding
  - Fragmentation function prior variations in unfolding are not included in the systematic uncertainties

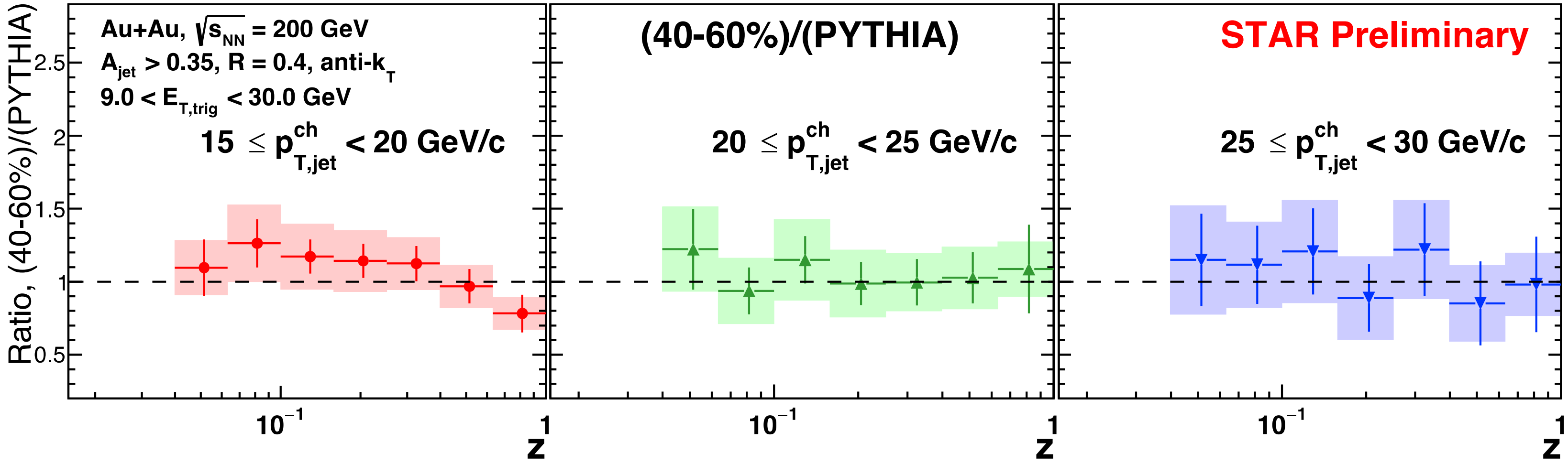
- PYTHIA 8 Monash 2013 tune: consistent with data, tuned to LHC, and needs further parameter tuning at RHIC energies
  - STAR PYTHIA6 tune: see **Nihar Sahoo's** talk (***#238***, 6/2 12:20 ET) for comparison

Jet fragmentation functions – Results



- 40-60% central Au+Au / *p*+*p* (PYTHIA) ratio at 200 GeV:
  - Remains near 1 within uncertainties throughout the full z range and for 3 separate charged jet p_T ranges spanning **15-30 GeV/*c***

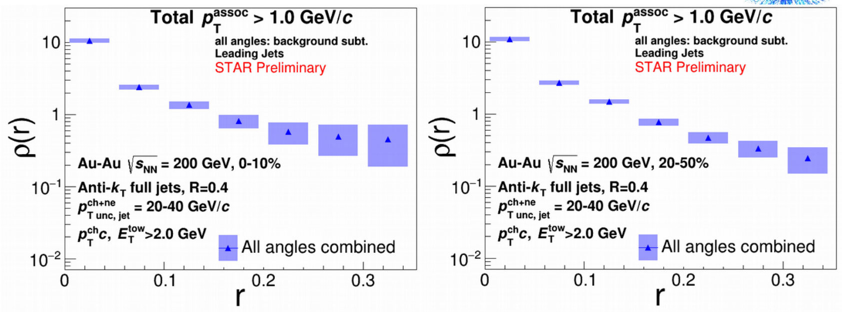
Jet fragmentation functions – Results

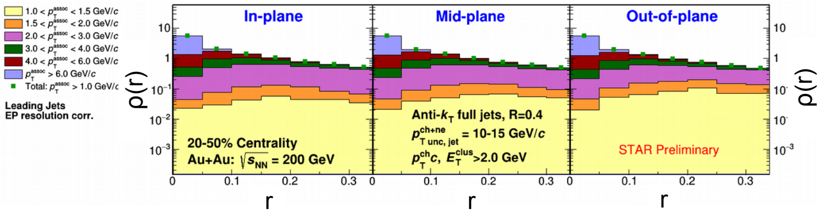


- 40-60% central Au+Au / *p+p* (PYTHIA) ratio at 200 GeV:
  - Remains near 1 within uncertainties throughout the full z range and for 3 separate charged jet p_T ranges spanning **15-30 GeV/*c***
- *These results can potentially be connected to various physics scenarios:*
  - Tangential jet selection with a high-p_T trigger particle and recoil jet configuration? which causes no significant in-medium path-length of the jet
  - Short path-length of jets in medium in 40-60% centrality?
  - Little jet-medium interactions in 40-60% centrality at 200 GeV?

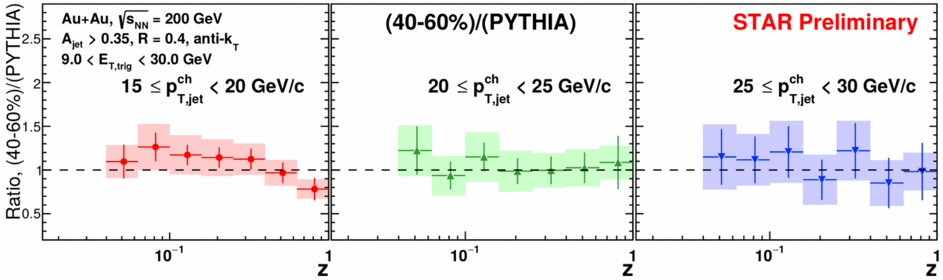
Summary

- Jet shapes
  - Less steep at 200 GeV than LHC energies (with variations in kinematics and jet selection)
  - *EP-dependent*: low-p_T tracks have larger yields and pushed toward farther distances in the out-of-plane direction → sensitivity on path length dependence of jet quenching
  - Results for *p*+*p* & different jet types are on their way



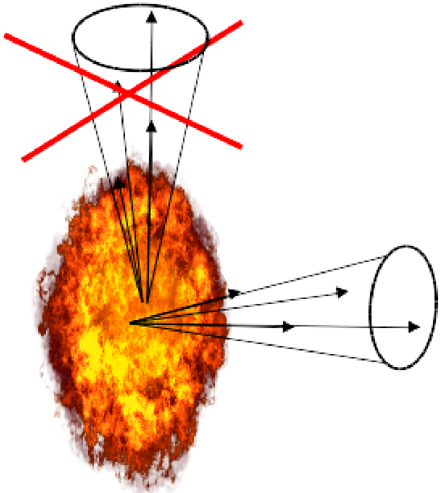


- Jet fragmentation functions
  - Charged recoil jets with respect to a high-momentum trigger particle studied
  - 40-60% Au+Au/PYTHIA at 200 GeV remains near 1 over full z within uncertainties for 15-30 GeV/*c* jets
    - PYTHIA 8 needs further tuning at RHIC energies
  - Results for central & *p*+*p* are on their way



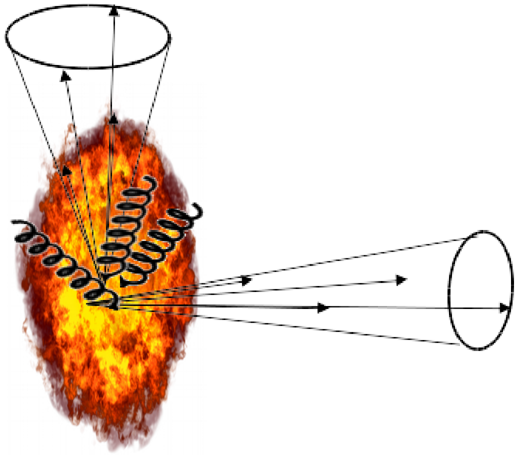
Backup slides

Jet shapes – Event-plane dependence



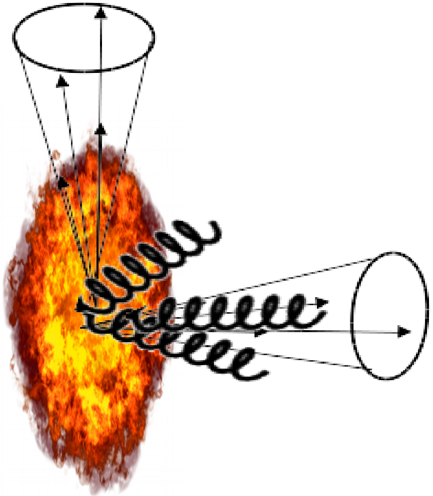
Equilibration in medium

Fewer jets, lower high-p_T yield out of plane



Bremsstrahlung

Softer, higher yield out of plane



Fluctuations

Individual jets' energy loss may vary

Jet fragmentation functions @ 5.02 TeV

ATLAS, Phys. Rev. C **98** (2018) 024908

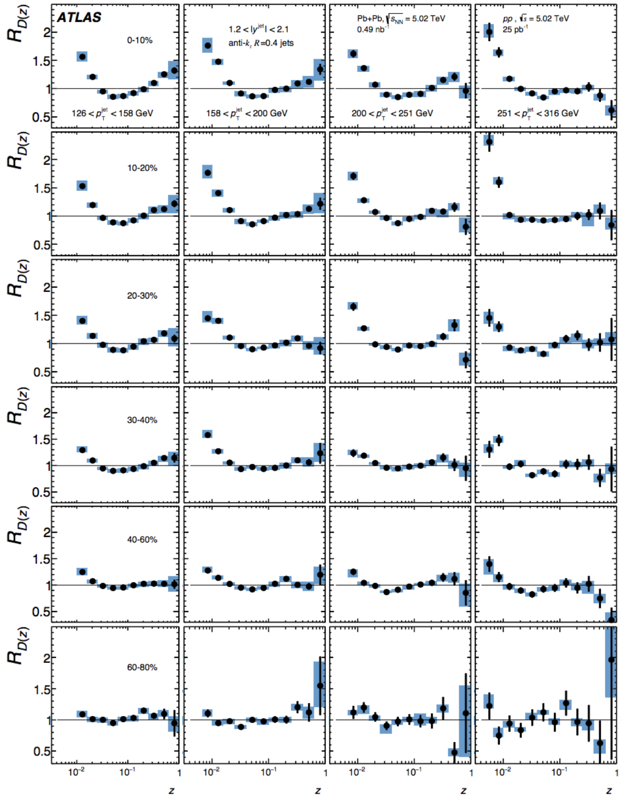


Figure 15: Ratios of $D(z)$ distributions in six centrality intervals of Pb+Pb collisions to *pp* collisions evaluated in four p_T^{jet} ranges for jets with $1.2 < |y^{jet}| < 2.1$. The vertical bars on the data points indicate statistical uncertainties, while the shaded bands indicate systematic uncertainties. Centrality decreases from top to bottom panels and p_T^{jet} increases from left to right panels.

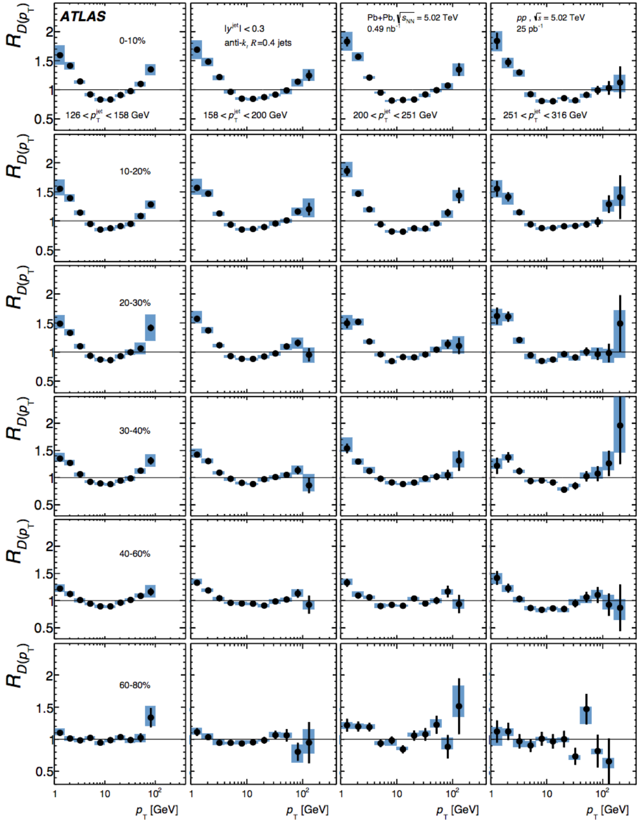
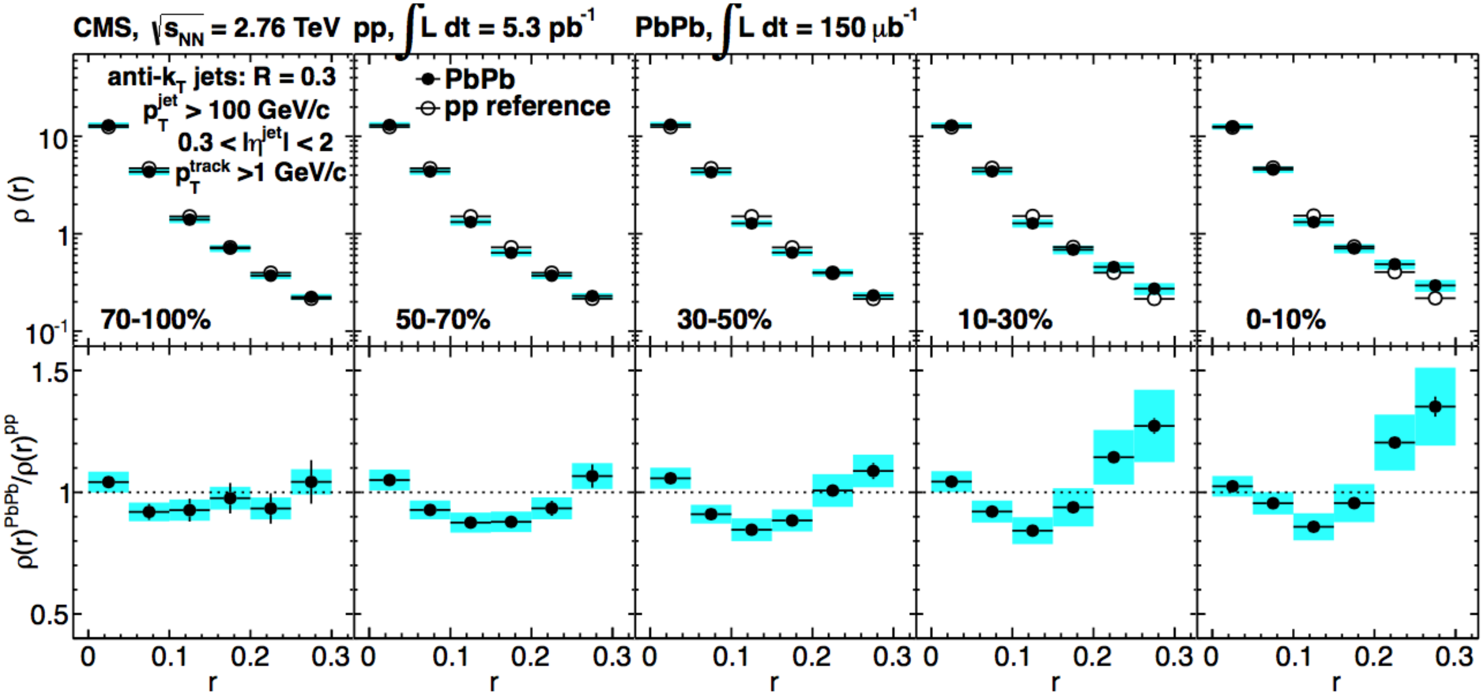


Figure 16: Ratios of $D(p_T)$ distributions in six centrality intervals of Pb+Pb collisions to *pp* collisions evaluated in four p_T^{jet} ranges for jets with $|y^{jet}| < 0.3$. The vertical bars on the data points indicate statistical uncertainties, while the shaded bands indicate systematic uncertainties. Centrality decreases from top to bottom panels and p_T^{jet} increases from left to right panels.

Jet shapes @ 2.76 TeV

CMS, Phys. Lett. B **730** (2014) 243



Analyses details

- In the presented measurements
  - 2014, Au+Au collisions at = 200 GeV
  - Minimum-bias + high-tower triggered events
  - Anti-k_T algorithm for jet reconstruction with R = 0.4 and $|\eta_{jet}| < 1.0 - R$
  - In the jet shape measurement:
    - HardCore $p_{T,jet}$ is estimated without a ρA subtraction
    - Mixed event class is defined with centrality, z_{vtx}, and Ψ_{EP} bins. There are 15 z_{vtx} bins, 4 Ψ_{EP} bins, and 16 centrality bins
  - In the fragmentation function measurement:
    - Raw $p_{T,jet}$ is estimated with a ρA subtraction, where ρ is estimated from jets reconstructed with the k_T algorithm
    - Mixed event class is defined with z_{vtx}, Ψ_{EP} track multiplicity bins. There are 15 z_{vtx} bins, 4 Ψ_{EP} bins, and 8 multiplicity bins
    - In fragmentation function unfolding, detector effects are simulated with Fast Simulation (efficiency and momentum resolution)

Little/no path length dependence

- Path length dependence naively predicted by every model
- No path length dependence seen in reaction plane dependent A_j either
- Insufficient sensitivity?

- Statistical variation in energy loss is more important than path length dependence
  - J. G. Milhano and K. C. Zapp, “Origins of the di-jet asymmetry in heavy-ion collisions,” Eur. Phys. J. C76 (2016) no. 5, 288
  - F. Senzel, O. Fochler, J. Uphoff, Z. Xu, and C. Greiner, “Influence of multiple in-medium scattering processes on the momentum imbalance of reconstructed di-jets,” J. Phys. G42 no. 11, (2015) 115104