Quark Matter 2019, Wuhan, China
The 28th international conference on ultrarelatisvistic nucleus-nucleus collisions

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

Saehanseul Oh (Yale University–BNL) for **the STAR Collaboration**

Quark Matter 2019, Parallel Session – Jet Modifications I
November 5th, 2019

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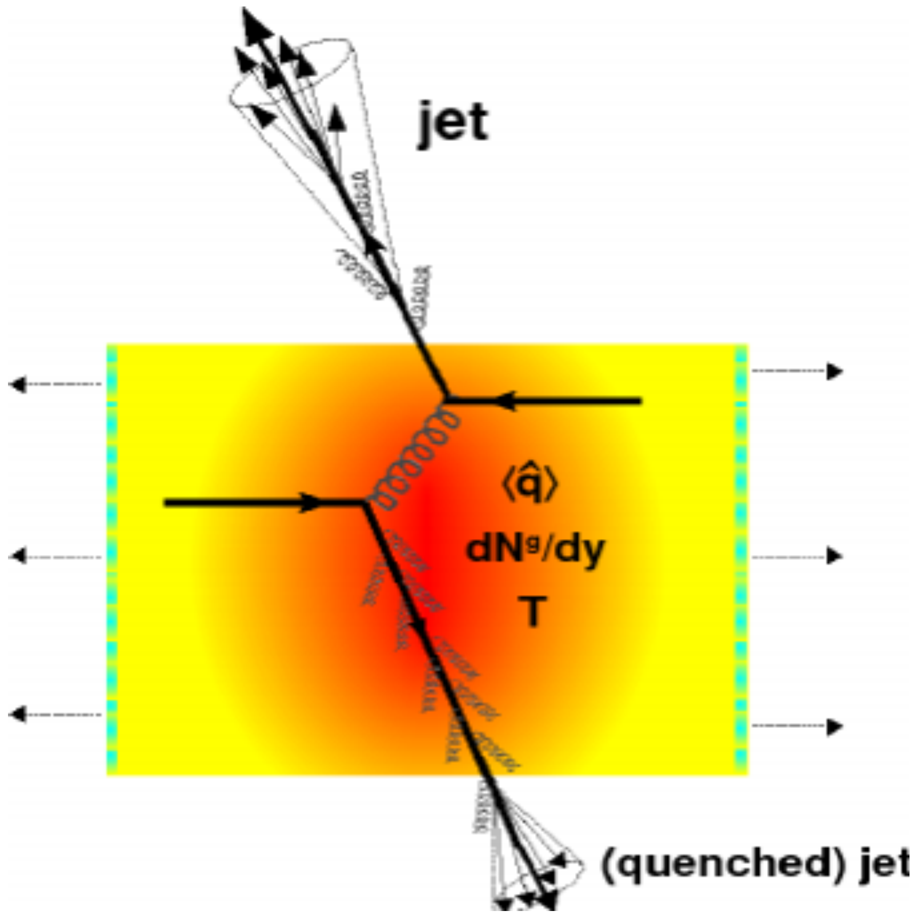
Introduction

- Jets probe the strongly interacting QCD medium
  - 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

➢ Jets probe the strongly interacting QCD medium
- Hard-scattered partons generated at the early stages of heavy-ion collisions
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How is the parton shower changed in A+A?

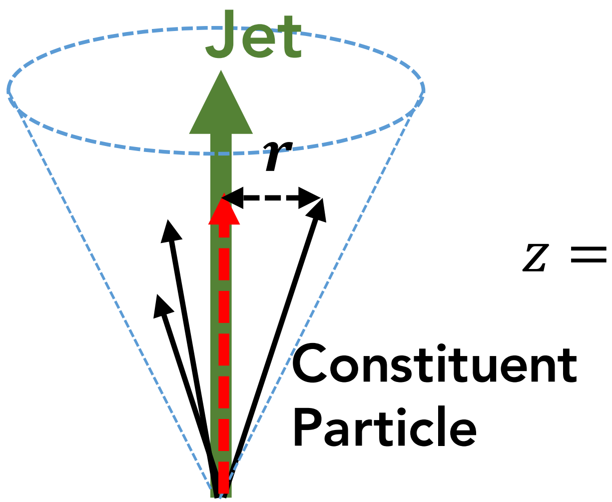
How does the **fragmentation** of jets change in heavy-ion collisions? → **Jet Fragmentation Functions**

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

Introduction

STAR

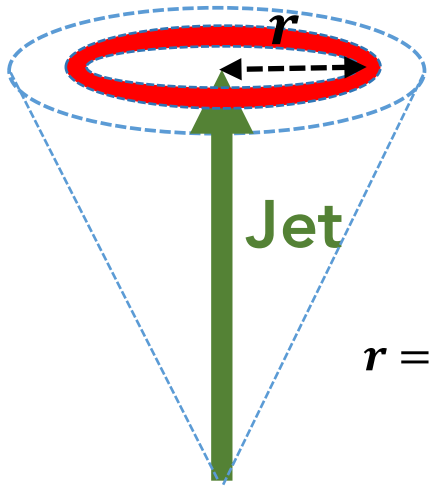
Jet Fragmentation Functions



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

- **Fragmentation function[1],** $\frac{1}{N_{\mathrm{jet}}}\frac{\mathrm{d}N}{\mathrm{d}z}$
- Distribution of longitudinal momentum fraction of particles with respect to the jet

Jet Shapes



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

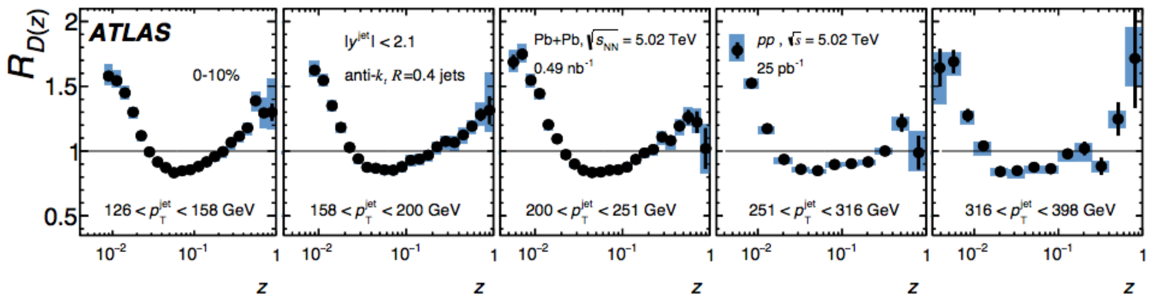
- $\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jet}} \frac{\sum_{\mathrm{track} \in (r-\delta r/2, r+\delta r/2)} p_{\mathrm{T,track}}}{p_{\mathrm{T,jet}}}$
- Distribution of jet energy as a function of distance from the jet axis

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

Jet Fragmentation Functions

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

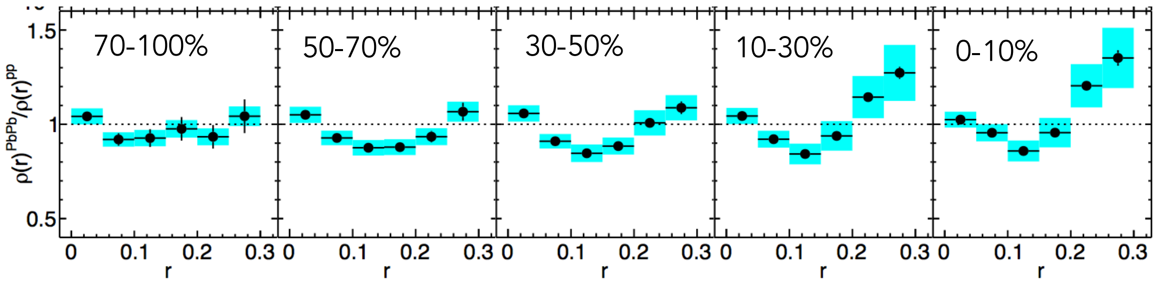


Pb+Pb/*p*+*p* @5.02 TeV

- **Fragmentation function,** $\frac{1}{N_{\text{jet}}} \frac{dN}{dz}$
- Distribution of longitudinal momentum fraction of particles with respect to the jet

Jet Shapes

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



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

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

Jet Fragmentation Functions

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Jet Shapes

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

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

- Fragmentation function, $\frac{\quad}{N_{\mathrm{jet}}}\frac{\quad}{\mathrm{d}z}$
- Distribution of longitudinal momentum fraction of particles with respect to the jet

- $\rho(r) = \frac{\quad}{\delta r}\frac{\quad}{N_{\mathrm{jet}}}\sum_{\mathrm{jet}}\frac{\ldots r+\delta r/2)\, p_{\mathrm{T,track}}}{p_{\mathrm{T,jet}}}$
- Distribution of jet energy as a function of distance from the jet axis

Jet measurements in A+A

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

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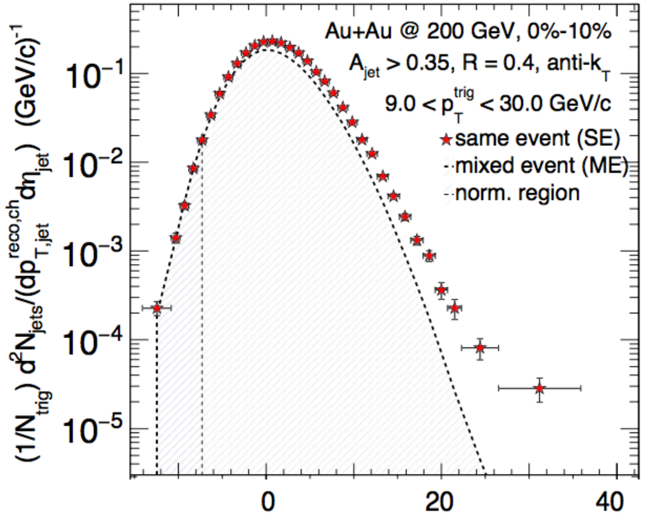
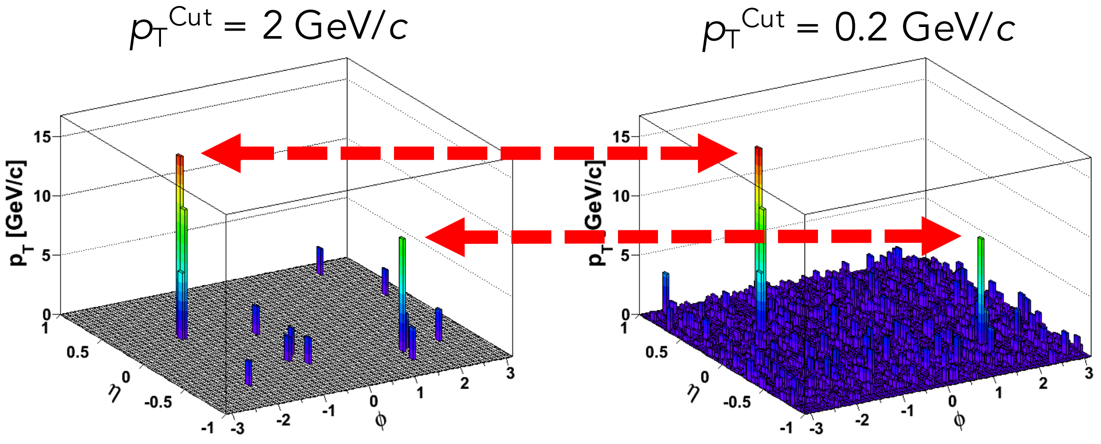
Semi-inclusive measurement with ME



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

Hard-core vs. matched jets



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

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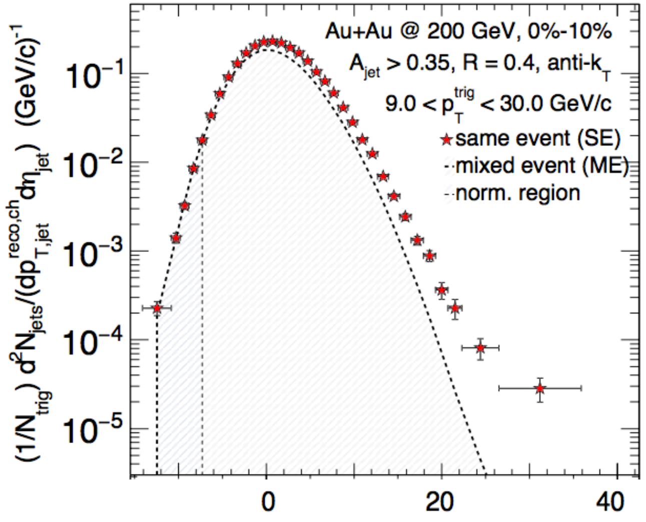


STAR, Phys. Rev. C **96** (2017) 24905

Hard-core vs. matched jets

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

Used in the jet fragmentation function measurement

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

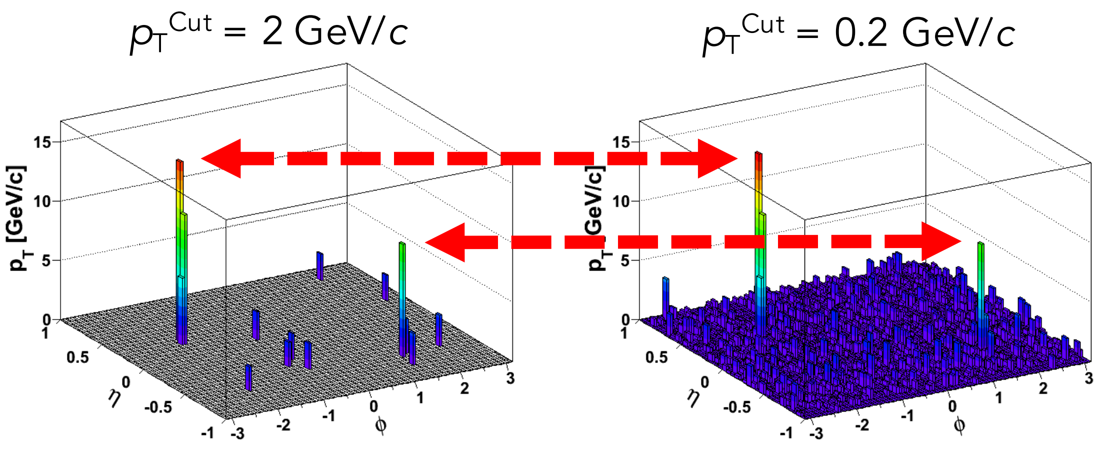
Jet measurements in A+A

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

Semi-inclusive measurement with ME

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

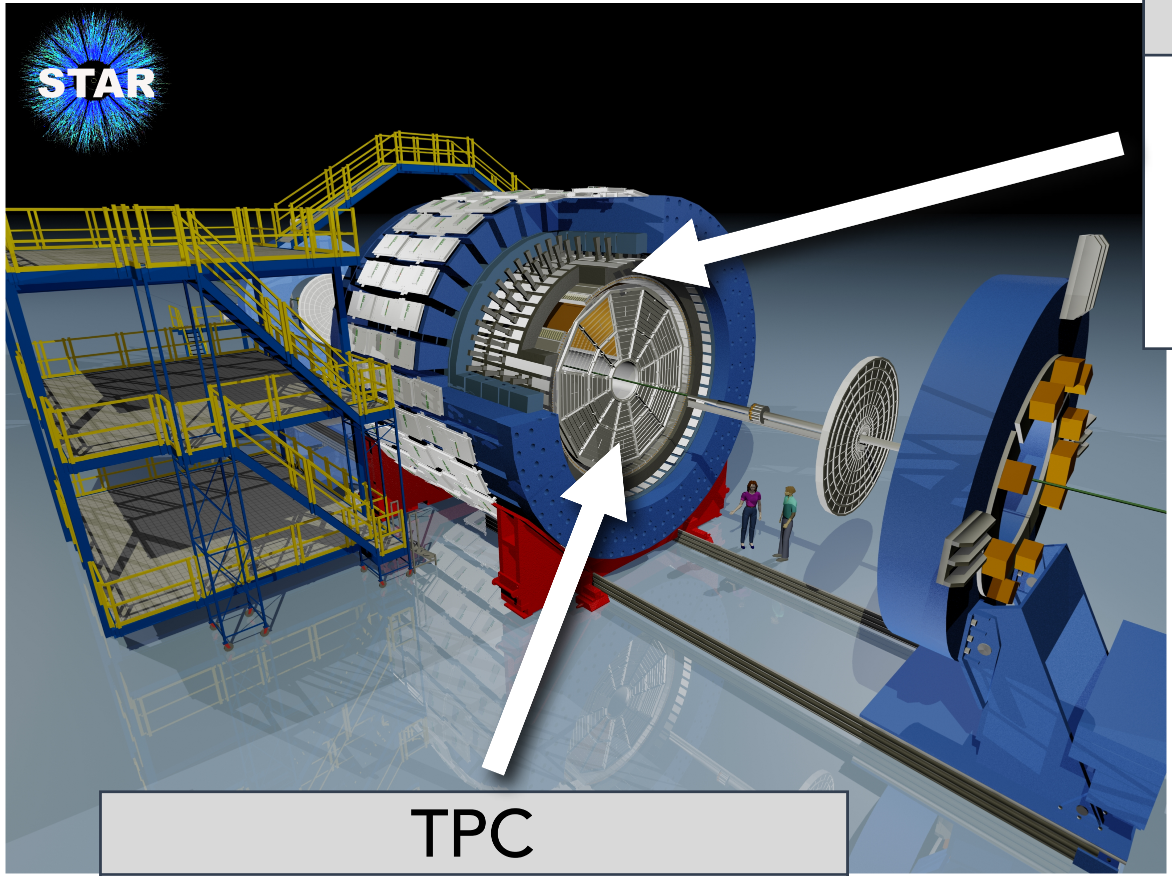
Hard-core vs. matched jets



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

Jet reconstruction with high p_T constituents (HardCore jet) → **Used in the jet shape measurement**

The STAR experiment



BEMC

- Barrel Electromagnetic Calorimeter
- $|\eta| < 1.0,\ 0 < \varphi < 2\pi$
- Trigger

EM neutral constituents

TPC

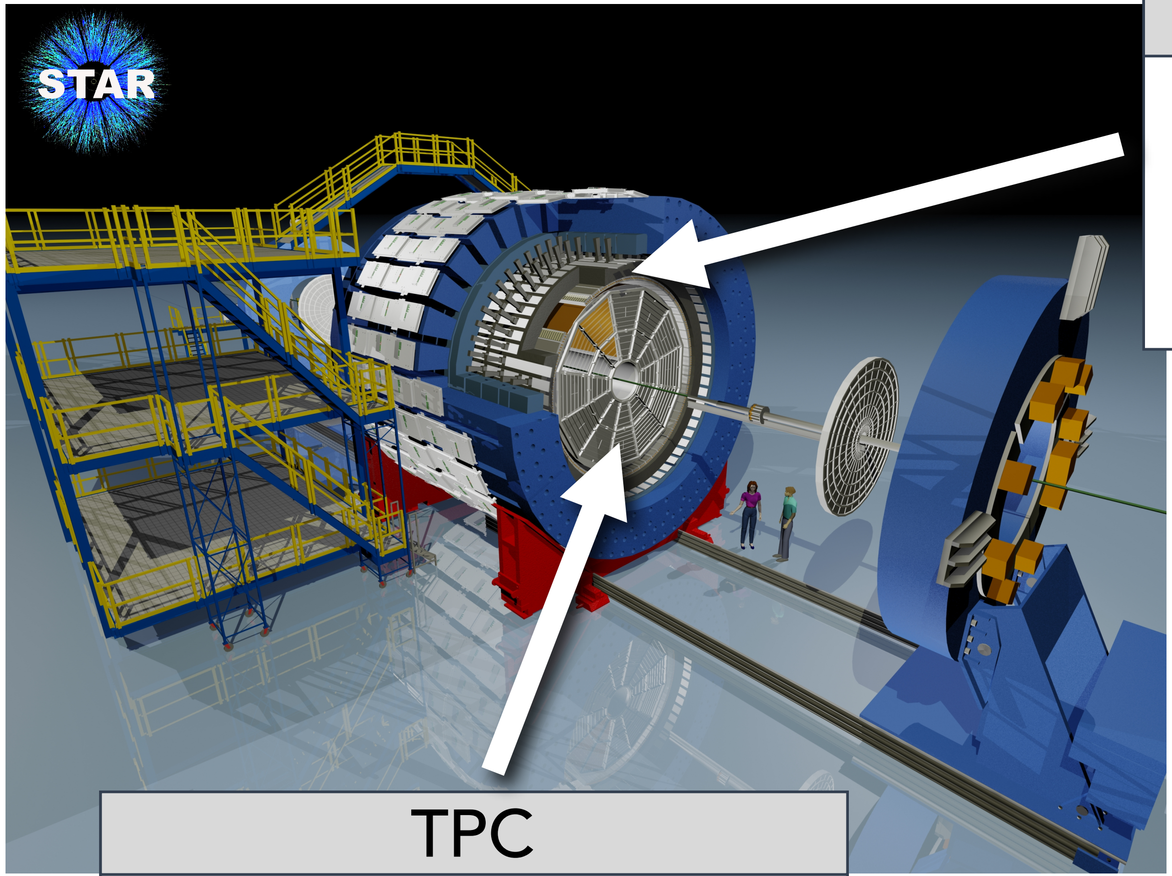
- Time Projection Chamber
- $|\eta| < 1.0,\ 0 < \varphi < 2\pi$
- Momentum, dE/dx

Charged constituents

Full Jet

Charged Jet

The STAR experiment



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Charged constituents

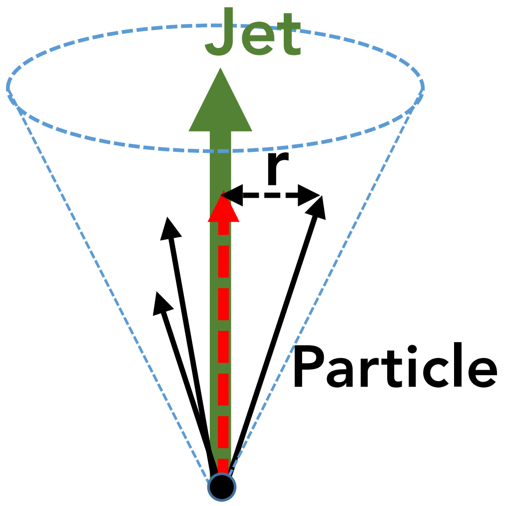
Full Jet

Charged Jet

- 2014, Au+Au, $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV
- Minimum-bias + high-tower triggered events
- Mixed events for the background estimation – for each (centrality, z_{vtx}, Ψ_{EP}, track multiplicity) bin with minimum-bias events

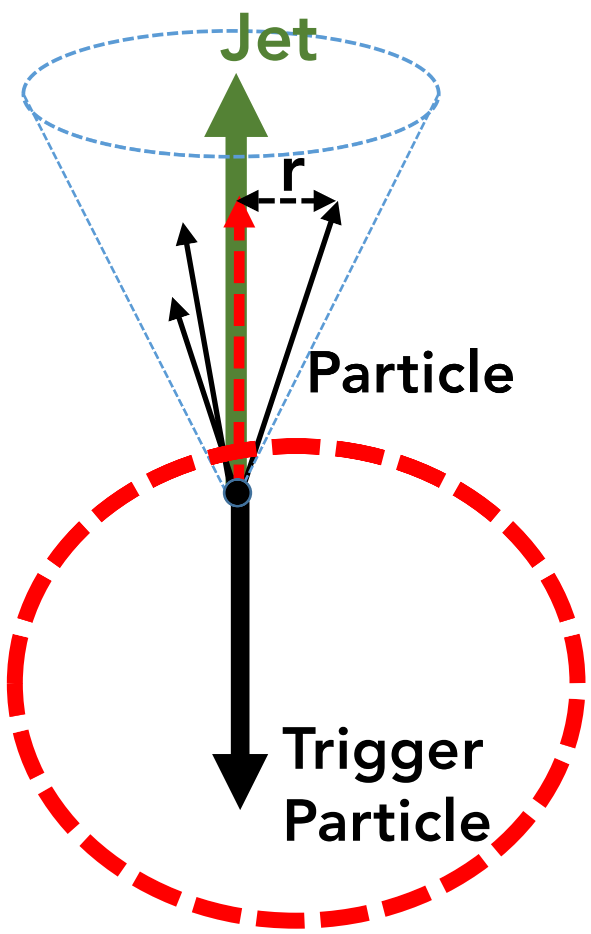
Jet Fragmentation Functions

Jet fragmentation functions



- $z = \frac{p_{\mathrm{T,track}} \cos(r)}{p_{\mathrm{T,jet}}}$
- $\frac{1}{N_{\mathrm{jet}}(p_{\mathrm{T,jet}})} \frac{\mathrm{d}N\,(p_{\mathrm{T,jet}}, z)}{\mathrm{d}z}$ for tracks within $\Delta r_{\mathrm{jet-track}} < \mathrm{R} = 0.4$

Jet fragmentation functions



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

Jet fragmentation functions – Corrections

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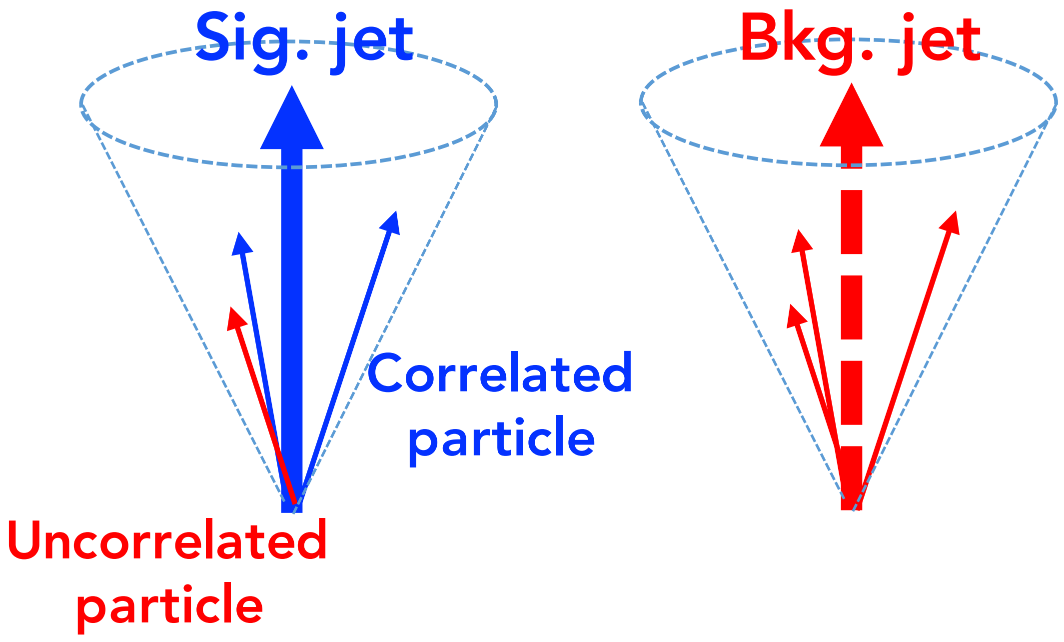

- In the recoil region, there are two types of jets
  - **Signal (Sig.) jet**, i.e. jets correlated to the trigger particle
  - **Background (Bkg.) jet**, i.e. jets uncorrelated to the trigger particle

  - In signal jets, there are uncorrelated particles

Jet fragmentation functions – Corrections

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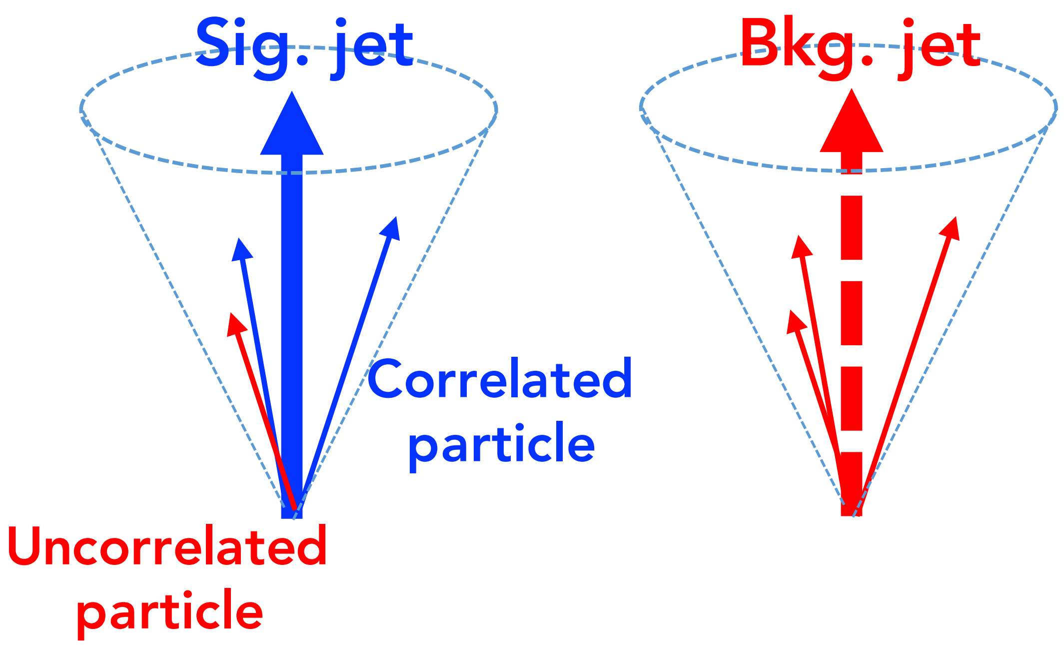

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  - **Signal (Sig.) jet**, i.e. jets correlated to the trigger particle
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  - In signal jets, there are uncorrelated particles

How can we remove the uncorrelated components?

Jet fragmentation functions – Corrections

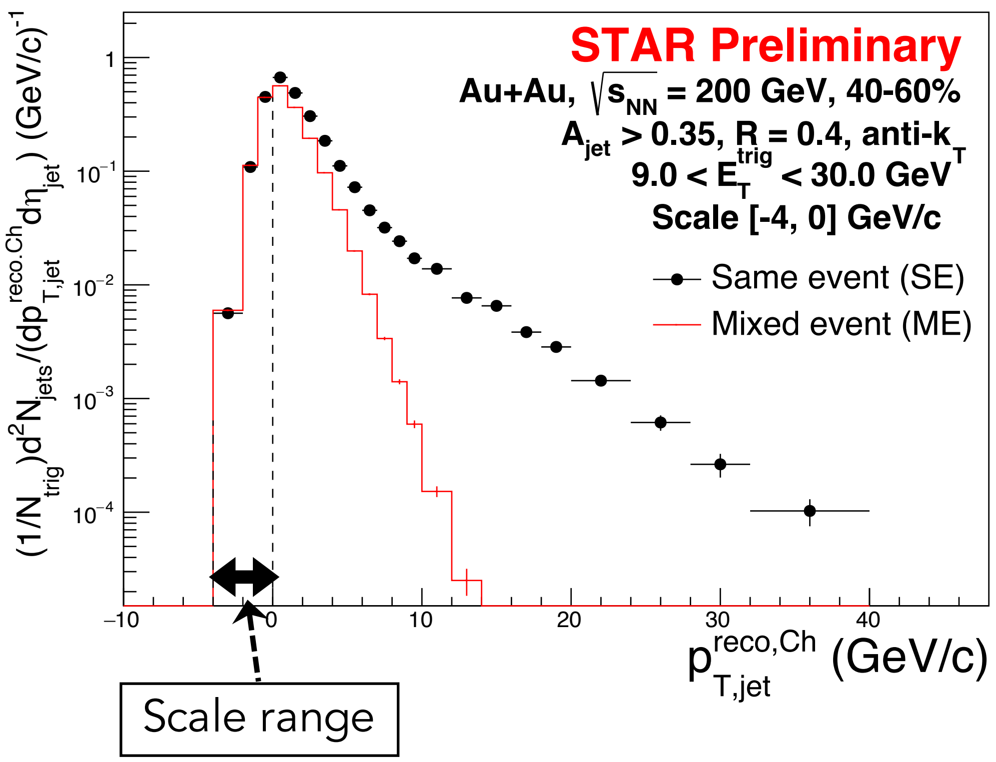
- $z = \frac{p_{\mathrm{T,track}}\cos(r)}{p_{\mathrm{T,jet}}}$
- $\frac{1}{N_{\mathrm{jet}}(p_{\mathrm{T,jet}})} \frac{\mathrm{d}N\,(p_{\mathrm{T,jet}}, z)}{\mathrm{d}z}$ for tracks within $\Delta r_{\mathrm{jet-track}} < \mathrm{R} = 0.4$

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

Jets reconstructed in same-events

Jets reconstructed in mixed-events

- $N_{\mathrm{jet}}^{\mathrm{ME}}(p_{\mathrm{T,jet}})$ are fitted to $N_{\mathrm{jet}}^{\mathrm{SE}}(p_{\mathrm{T,jet}})$ in the negative $p_{\mathrm{T,jet}}$ range, where uncorrelated jets are expected to dominate (STAR, Phys. Rev. C **96** (2017) 24905)



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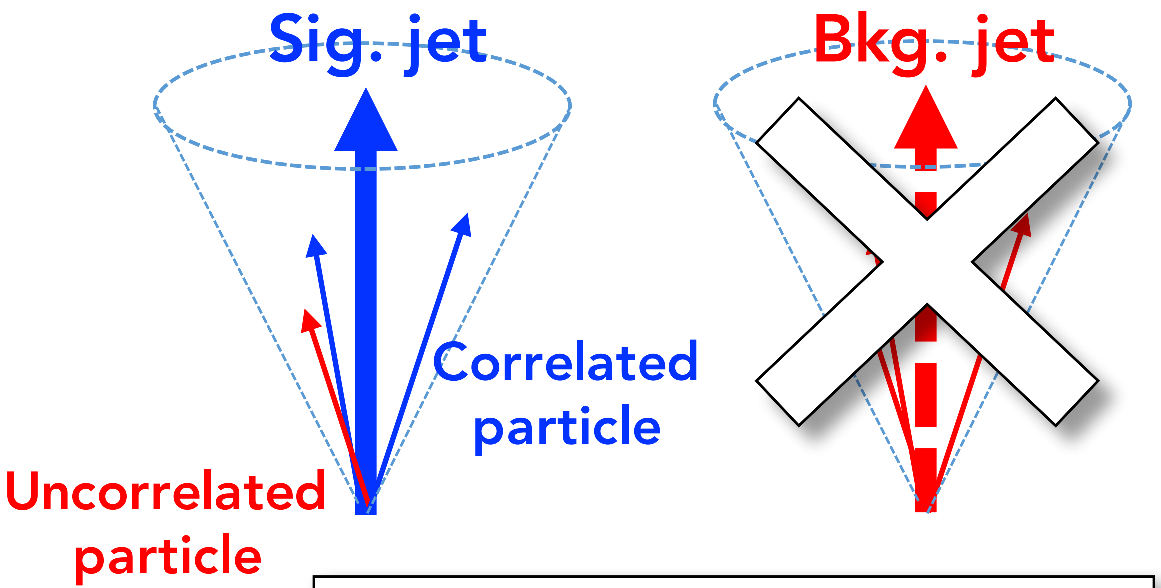

Removing Bkg. jet in N_{jet}

Jet fragmentation functions – Corrections

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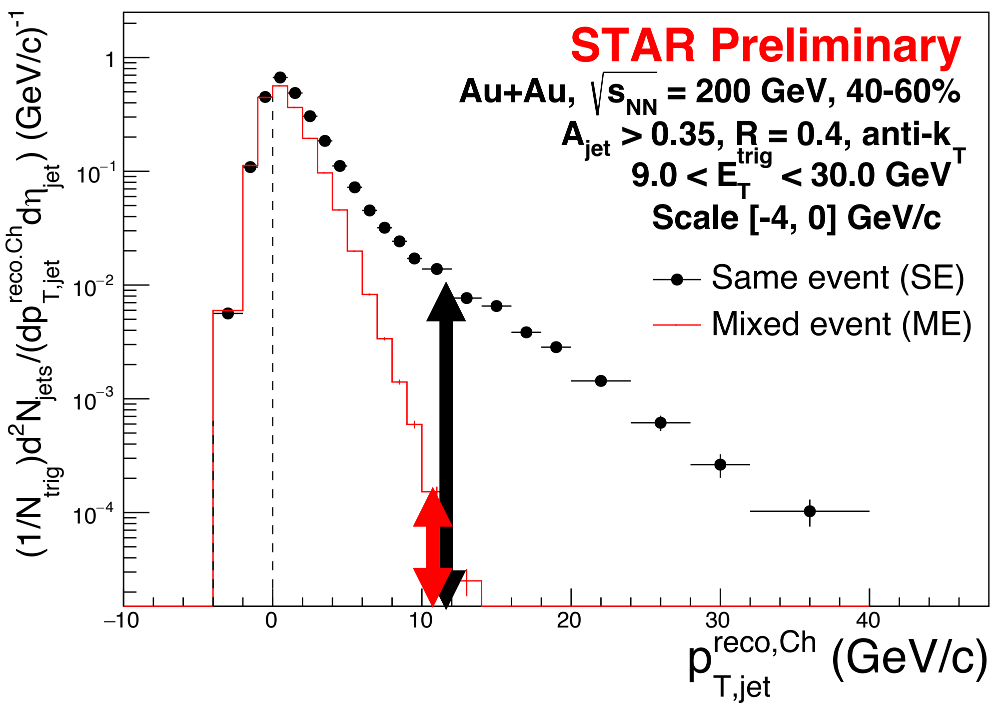
- The fraction of background jets to the all jets can be estimated by comparing $N_{\mathrm{jet}}^{\mathrm{ME}}\,(p_{\mathrm{T,jet}})$ and $N_{\mathrm{jet}}^{\mathrm{SE}}\,(p_{\mathrm{T,jet}})$
- Contributions from background jets in $\mathrm{d}N\,(p_{\mathrm{T,jet}}, z)/\mathrm{d}z$ can be calculated by $\mathrm{d}N^{\mathrm{ME}}\,(p_{\mathrm{T,jet}}, z)/\mathrm{d}z$ and scaling it based on the background jet fraction
- Contributions from uncorrelated particles in signal jets can be estimated by placing SE jets into mixed events and pairing with ME tracks



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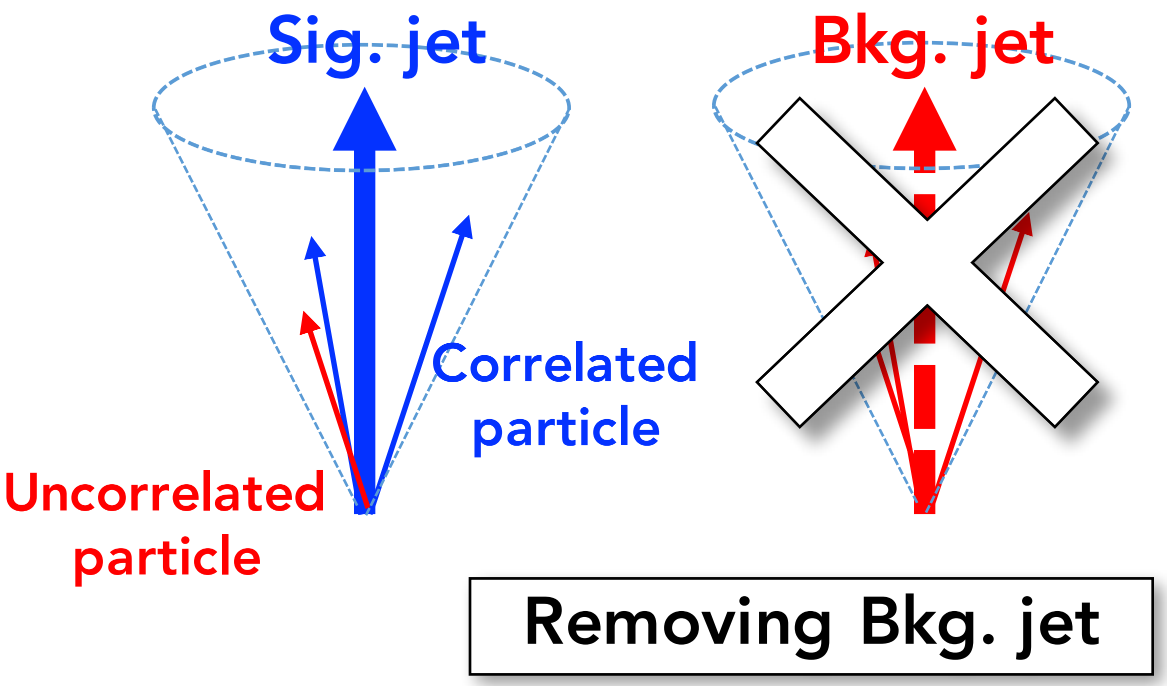

Jet fragmentation functions – Corrections

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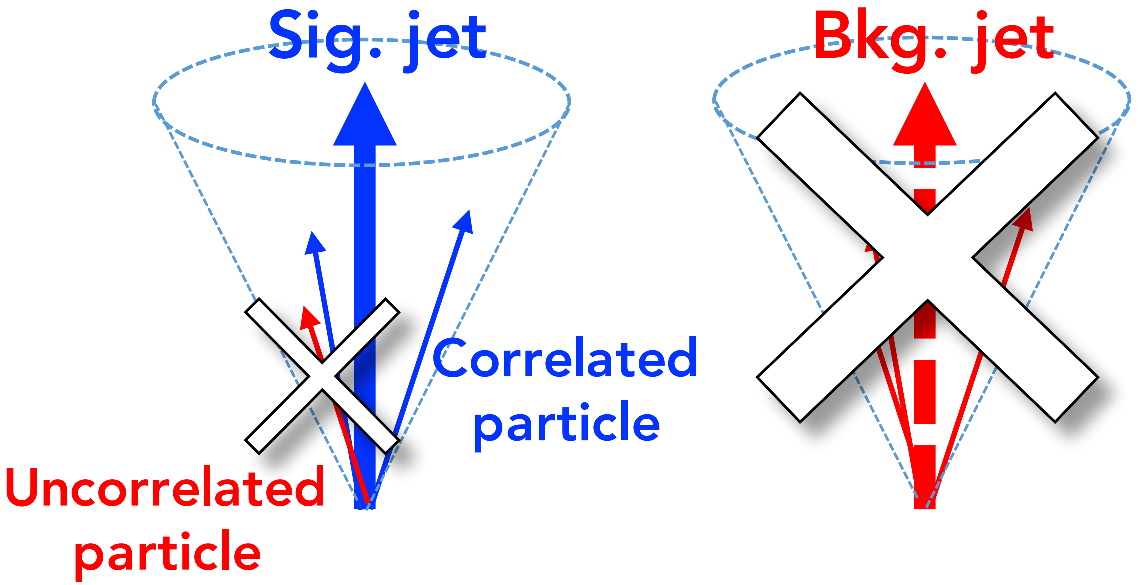

Removing uncorrelated particle contributions in Sig. jet

Jet fragmentation functions – Corrections

- $z = \dfrac{p_{\mathrm{T,track}} \cos(r)}{p_{\mathrm{T,jet}}}$
- $\dfrac{1}{N_{\mathrm{jet}}(p_{\mathrm{T,jet}})} \dfrac{\mathrm{d}N\ (p_{\mathrm{T,jet}}, z)}{\mathrm{d}z}$ for tracks within $\Delta r_{\mathrm{jet-track}} < \mathrm{R} = 0.4$

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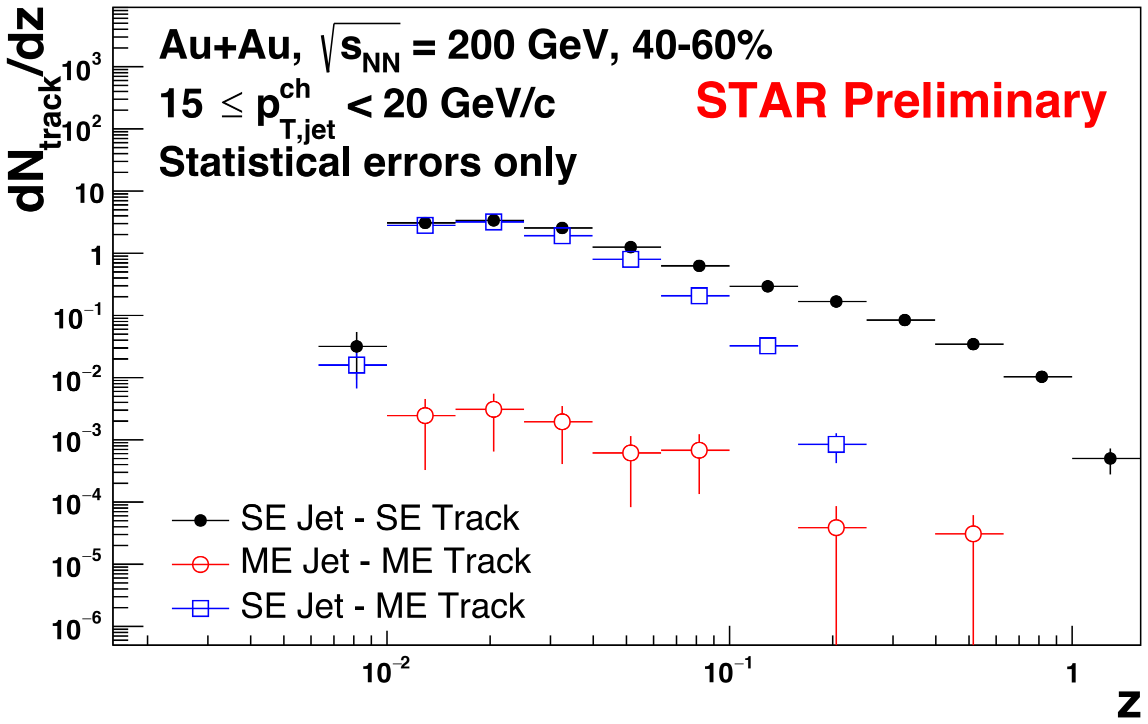
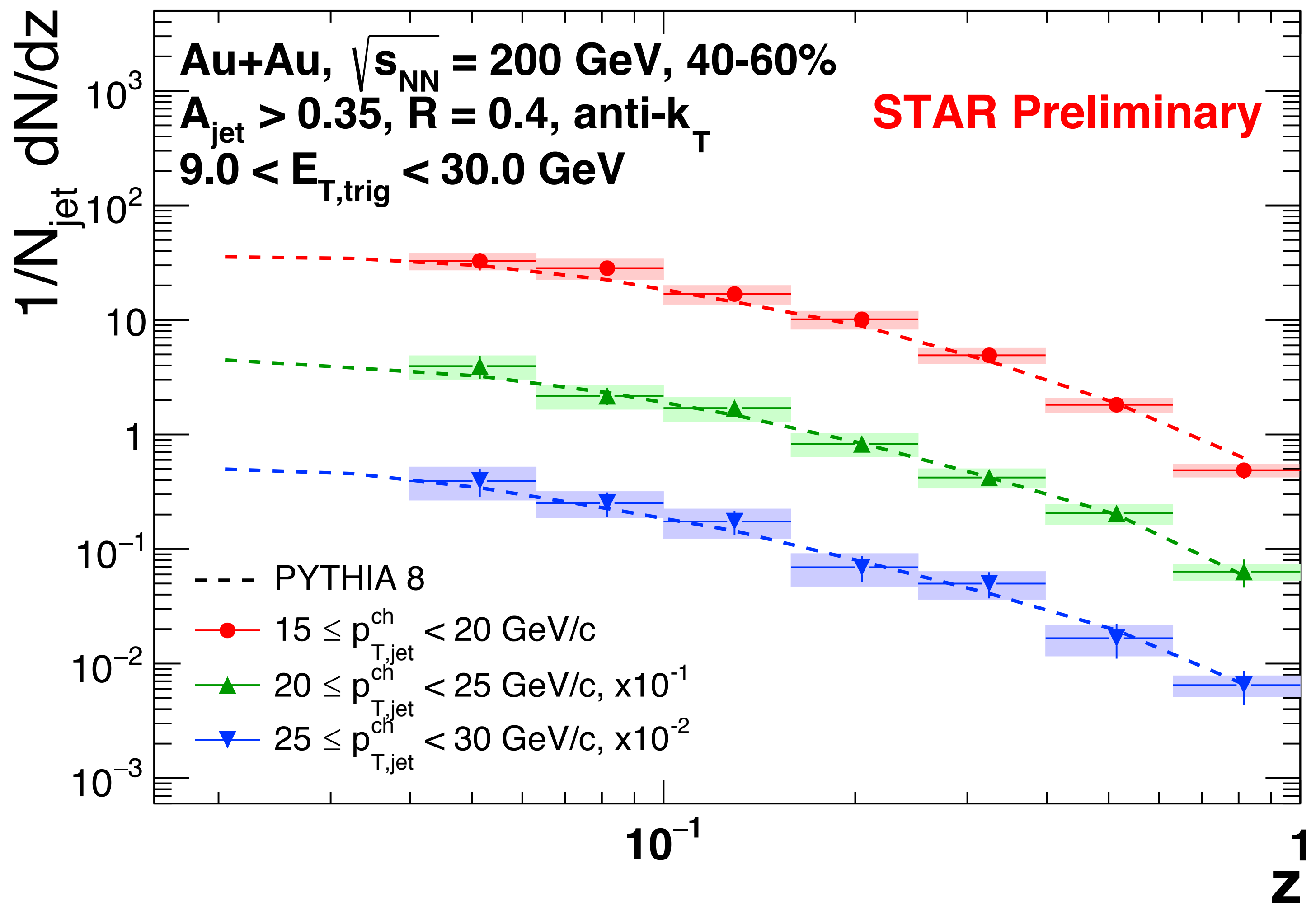


Corrected $\mathrm{d}N/\mathrm{d}z$ = Black – Red – Blue

Jet fragmentation functions – Results

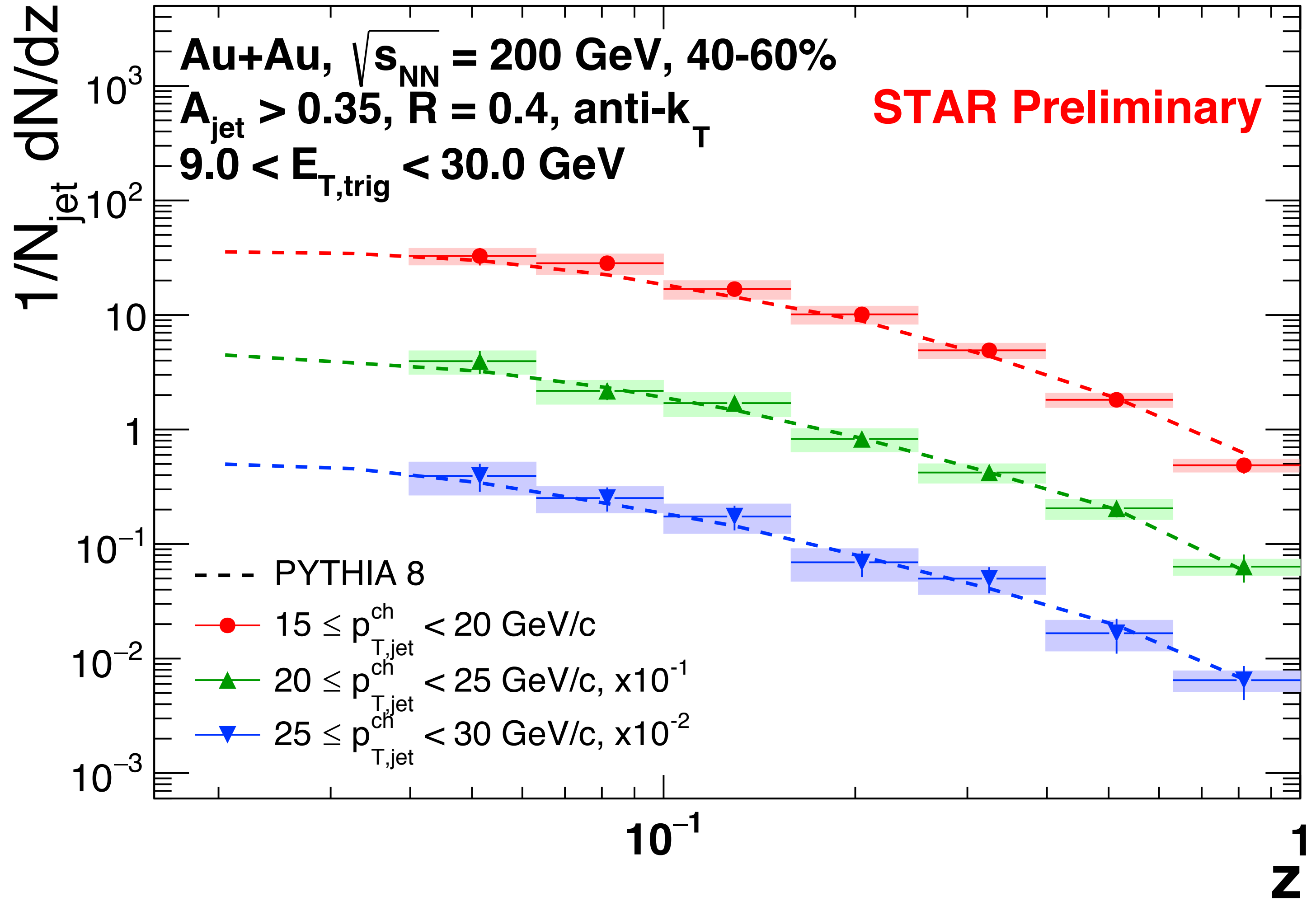


➢ $$\frac{1}{N_{jet}(p_{T,jet})} \frac{dN(p_{T,jet}, z)}{dz}$$

- $N_{jet}(p_{T,jet})$ and $dN(p_{T,jet}, z)/dz$ are separately unfolded via 1-D and 2-D Bayesian unfolding

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

Jet fragmentation functions – Results



$$\frac{1}{N_{\mathrm{jet}}(p_{\mathrm{T,jet}})} \frac{\mathrm{d}N\ (p_{\mathrm{T,jet}}, z)}{\mathrm{d}z}$$

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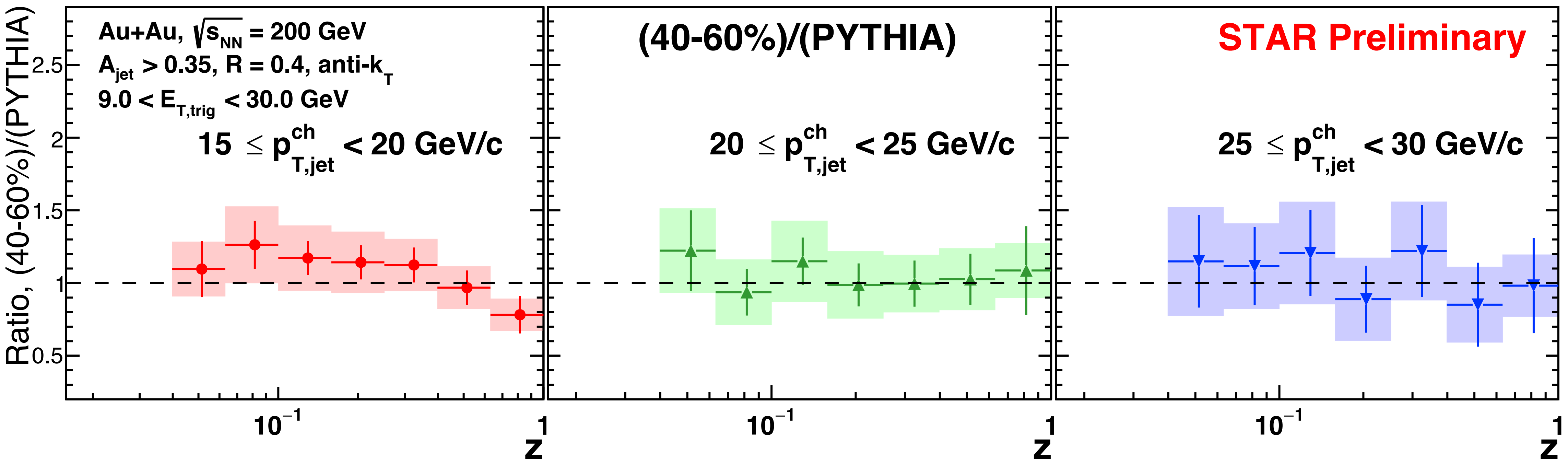
- **Jet fragmentation functions for 40-60% centrality class and three $p_{\mathrm{T,jet}}$ ranges**

- Fragmentation function prior variations in unfolding are not included in the systematic uncertainties

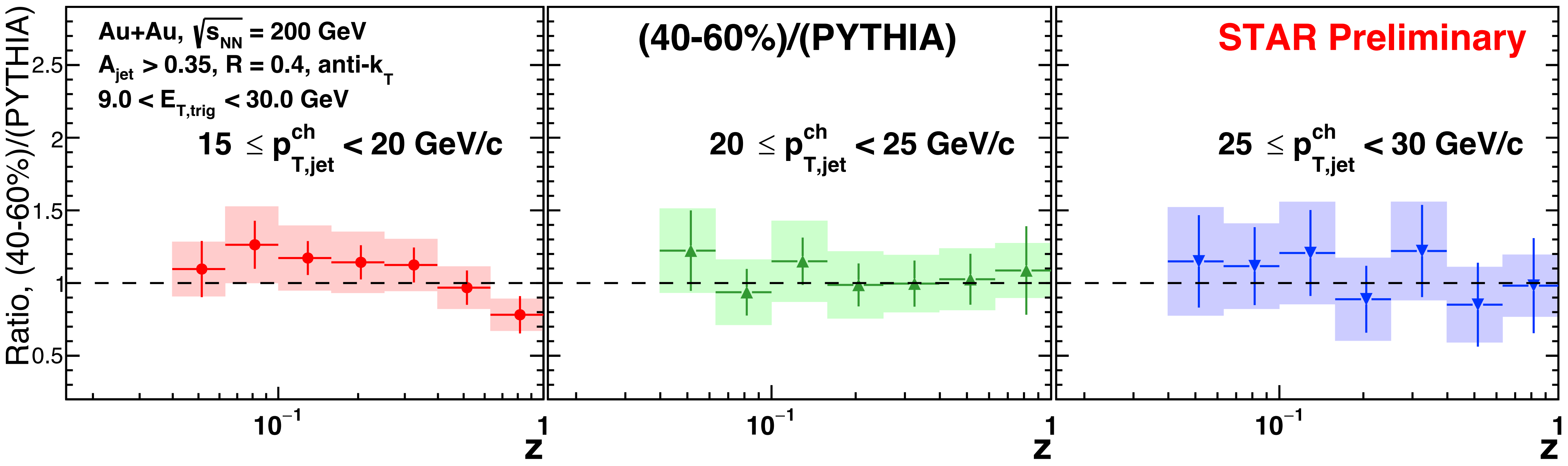
- PYTHIA 8 is tuned to LHC, and needs further parameter tuning (More details in Raghav Kunnawalkam Elayavalli's talk, Wed. 9:20)

Jet fragmentation functions – Results



- Ratios of jet fragmentation functions, (Au+Au 40-60%)/(PYTHIA 8)
- The ratio remains near 1 → Tangential jet selection with a high-p_T trigger particle and recoil jets? Less jet-medium interactions in 40-60% centrality? Short path-length in medium in 40-60% centrality? …
- Results for *p*+*p* and central events and overall higher statistics are on their way

Jet fragmentation functions – Results



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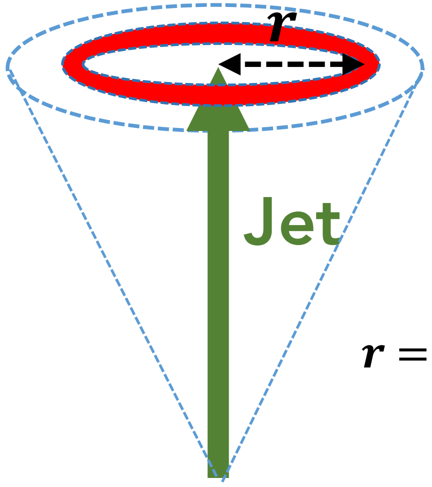
Jet Shapes

👉 **Poster 354 (JT12)**. "*Evolution of **jet shapes** in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR detector at RHIC*", **Joel Mazer** (Rutgers University)

Jet shapes



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

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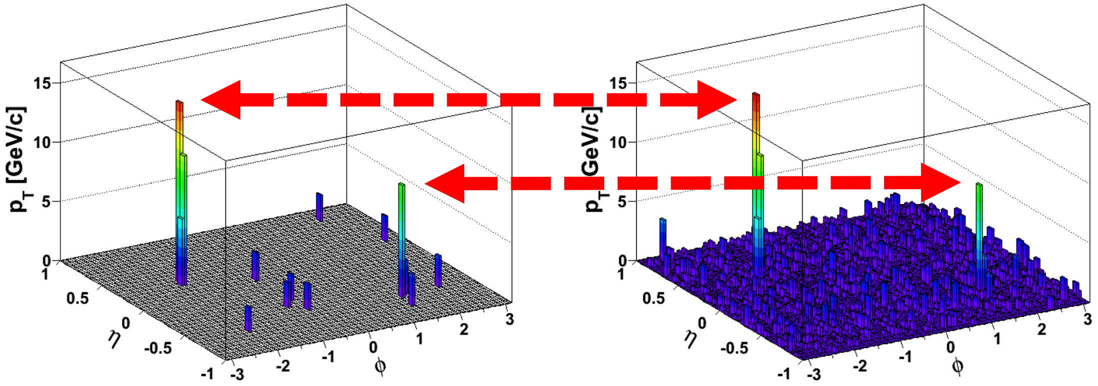
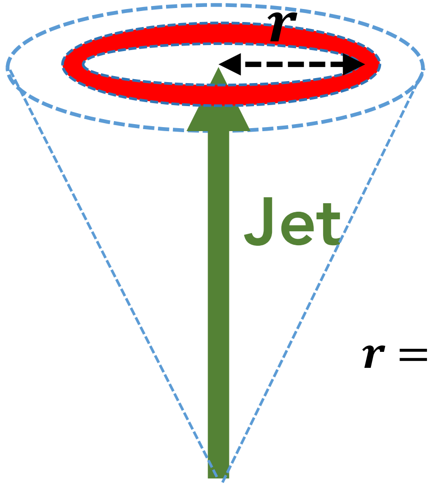
- Full (charged + neutral) jets are reconstructed with high-momentum tracks and towers with $p_{\mathrm{T,track}}(E_{\mathrm{T,tower}}) > 2.0\ \mathrm{GeV}/c$ (**HardCore** jet selection)
- Background contributions in $\rho(r)$ are estimated by placing same-event jets ($p_{\mathrm{T,jet}}$ and jet axis)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

p_T^{Cut} = 2 GeV/c p_T^{Cut} = 0.2 GeV/c



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

Jet shapes



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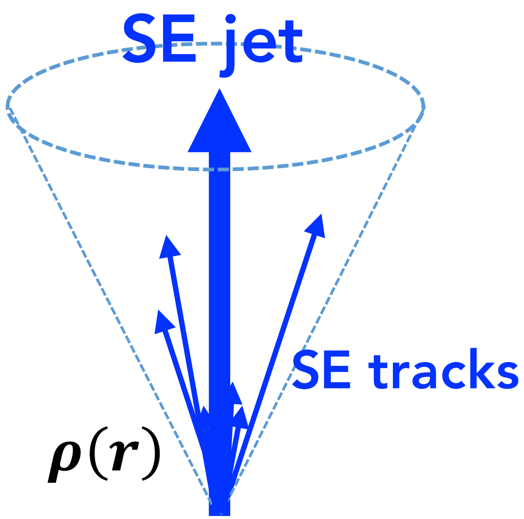
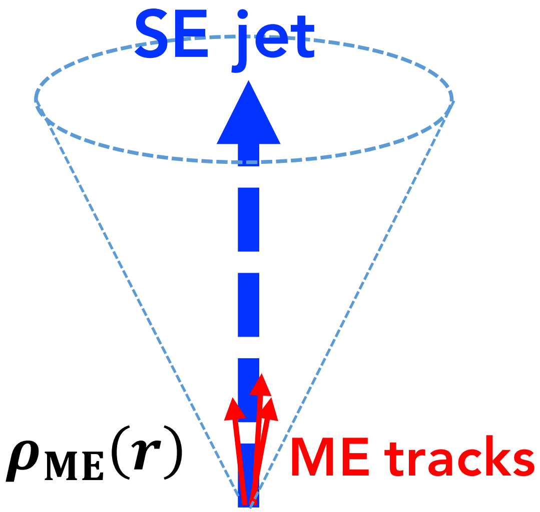
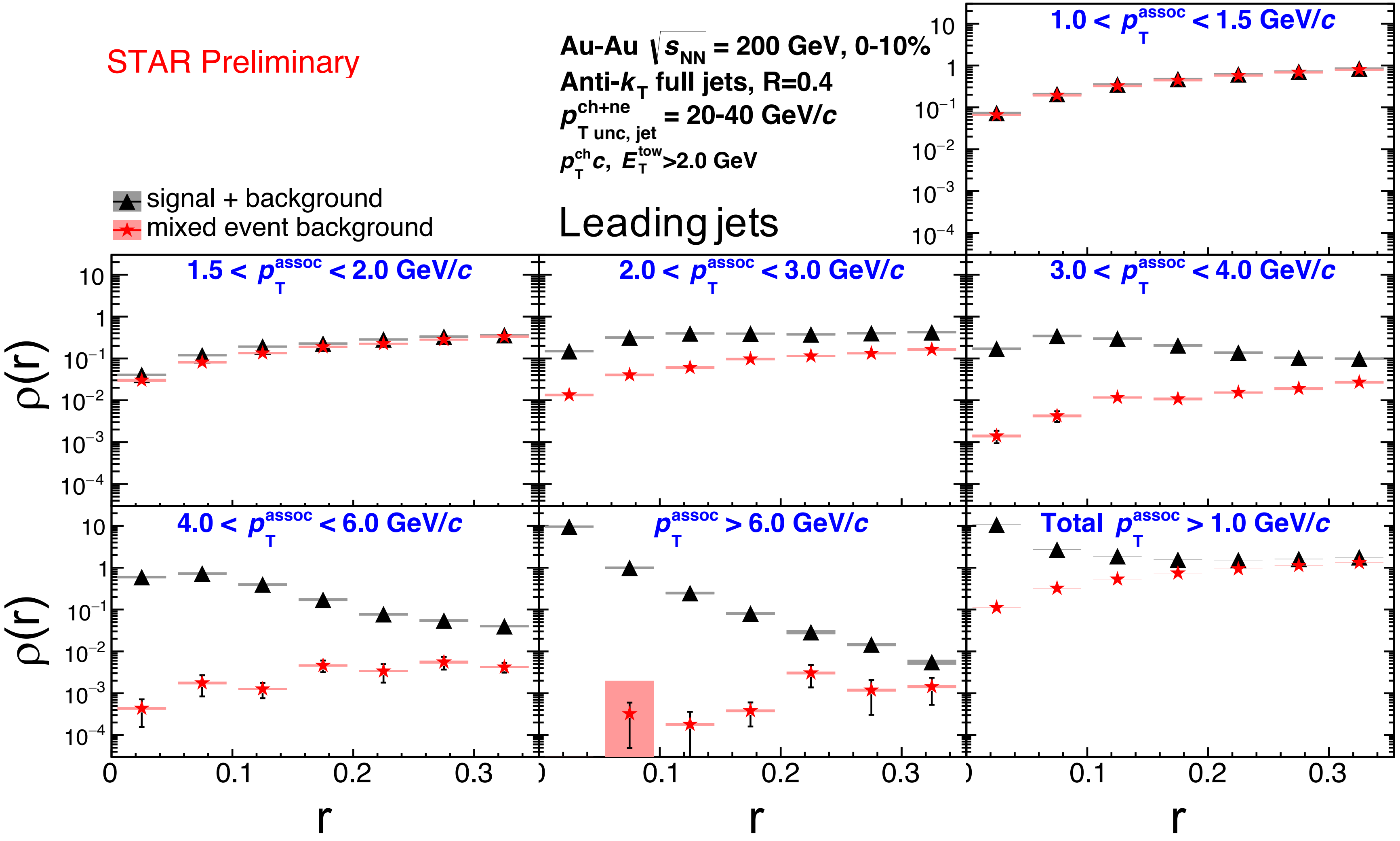


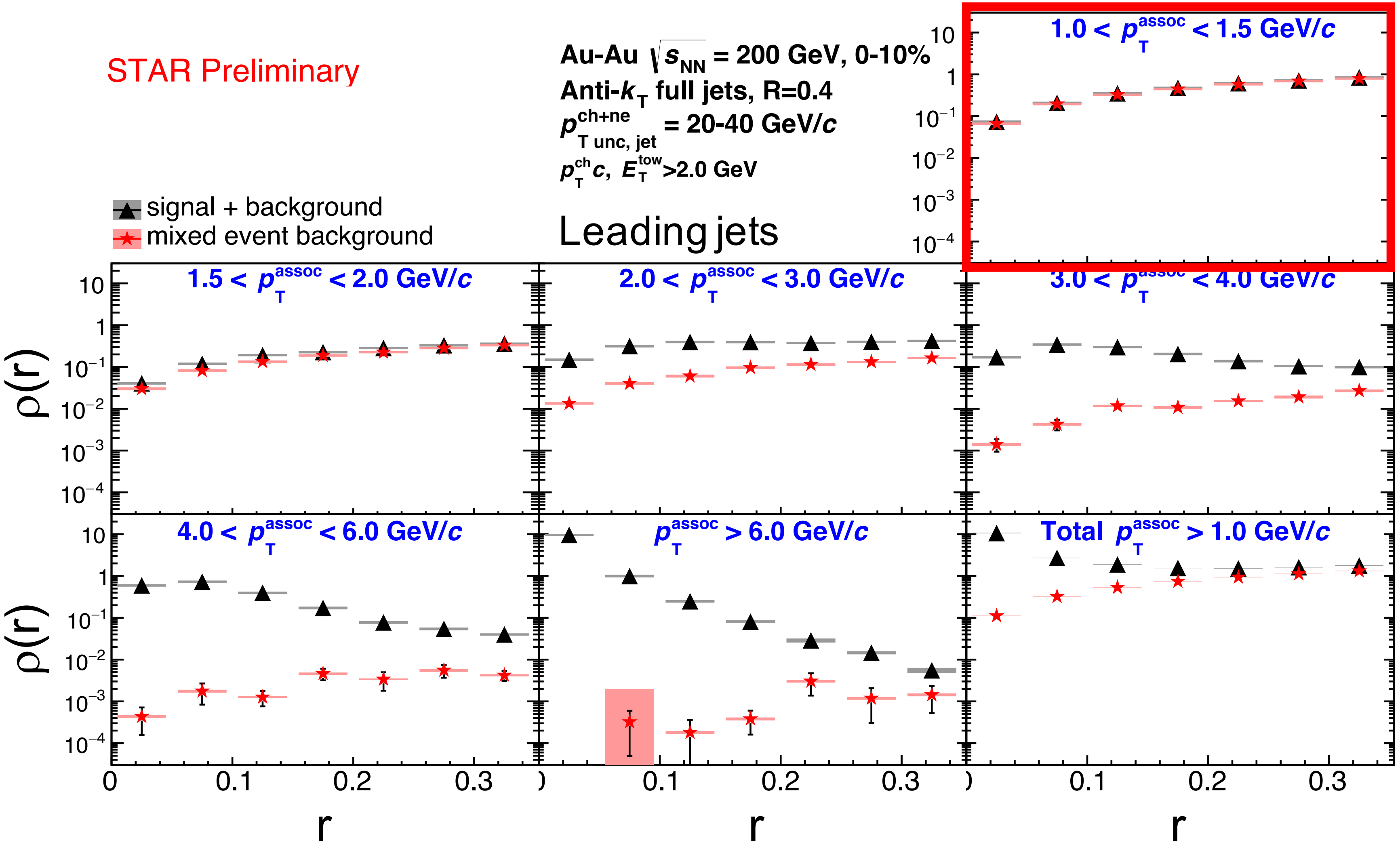


Jet shapes – Results



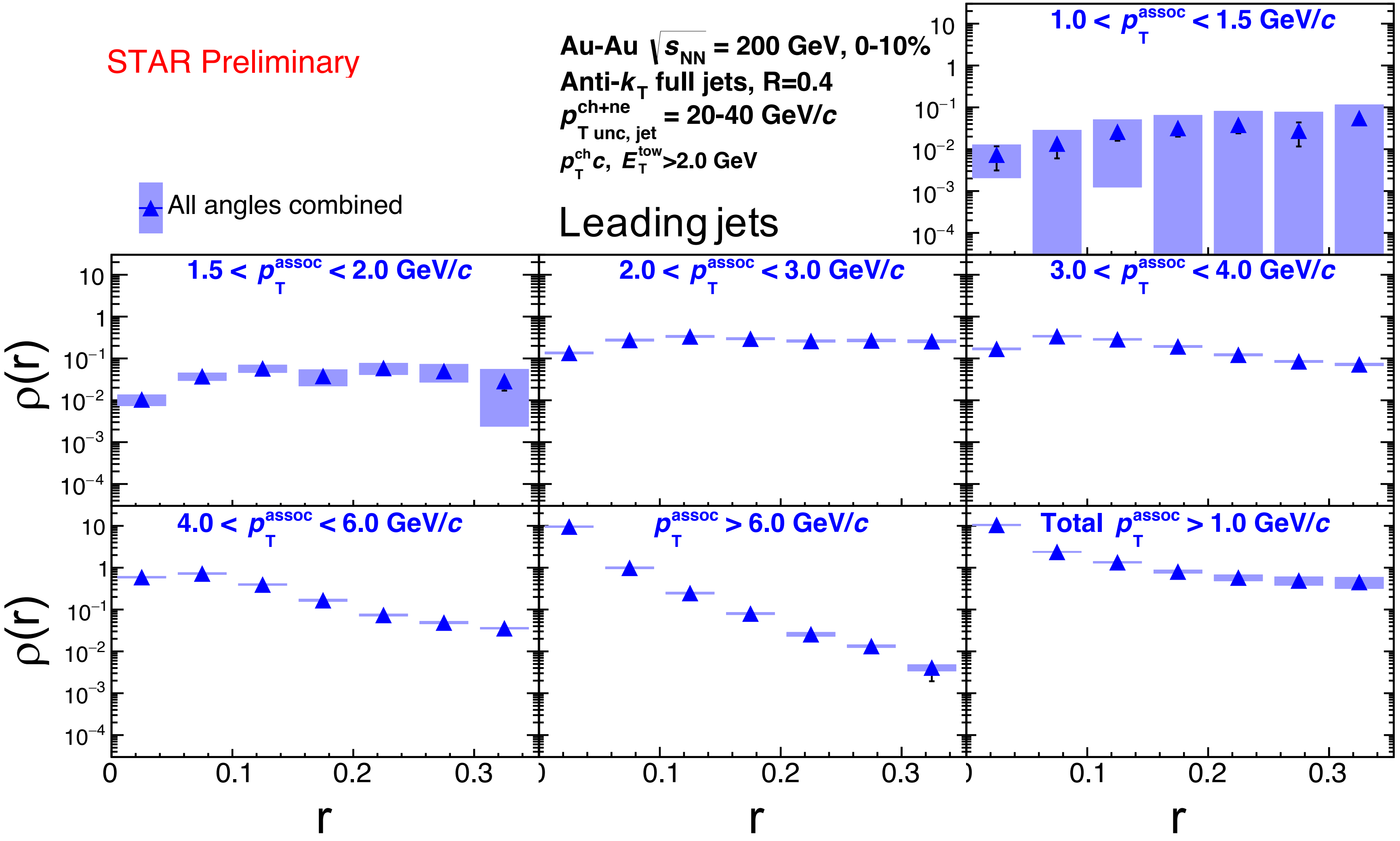
- Jet shapes for 0-10% centrality
- At low $p_{T,jet}$, background contributions dominate $\rho(\Delta r)$

Jet shapes – Results



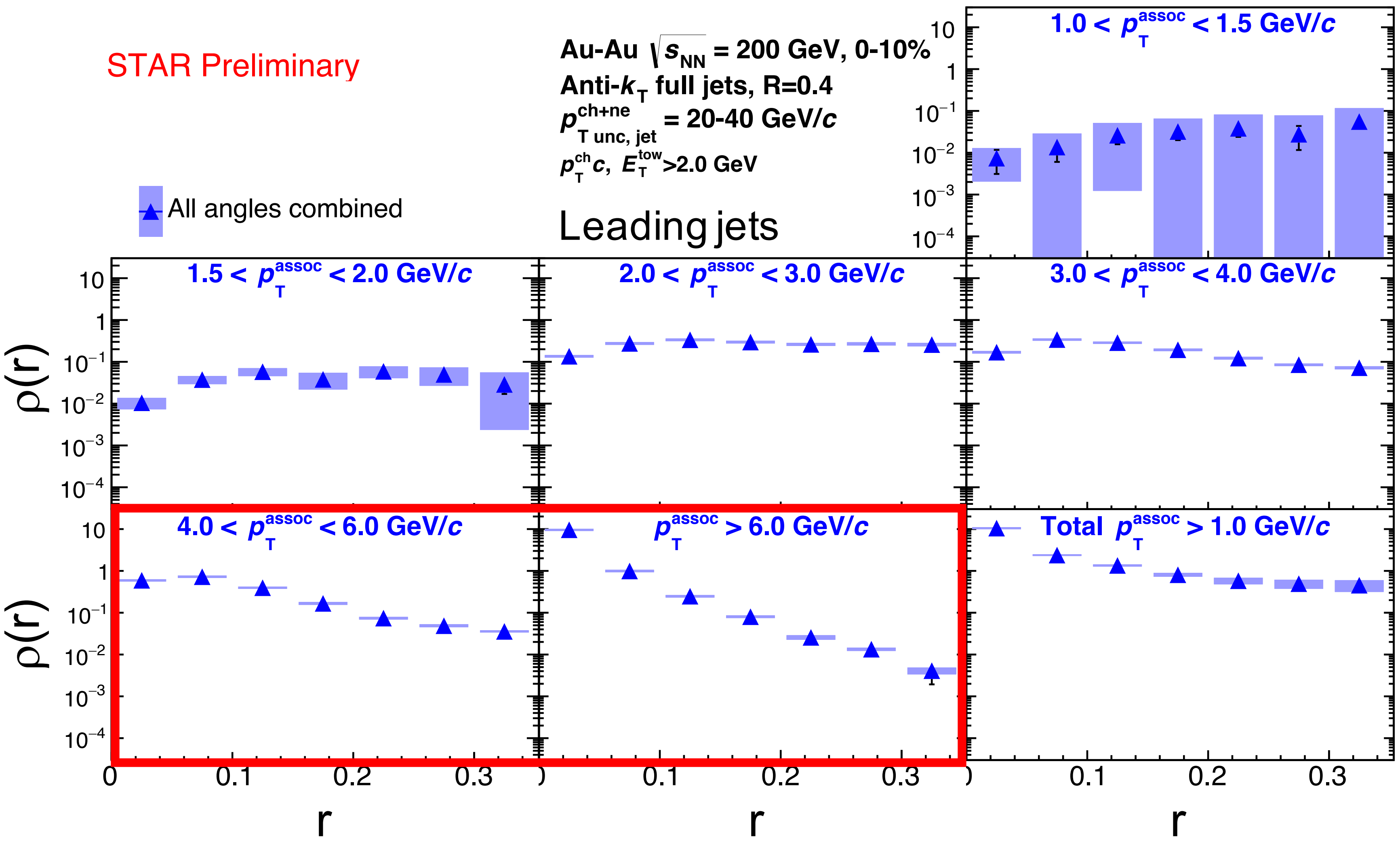
- Jet shapes for 0-10% centrality
- At low $p_{T,jet}$, background contributions dominate $\rho(r)$

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 are less steep at 200 GeV than those at the LHC

Jet shapes – Results



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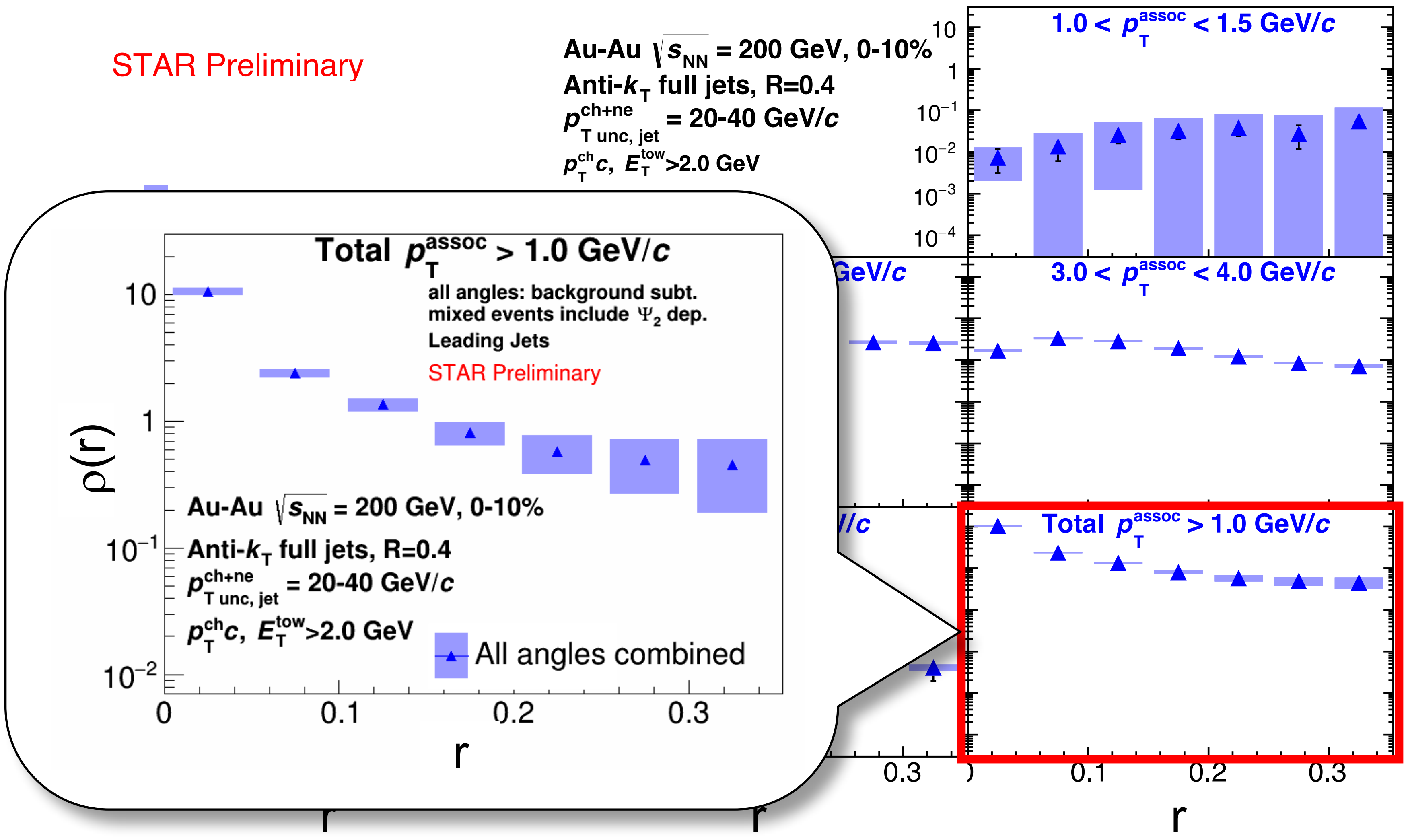
Jet shapes – Results



- 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
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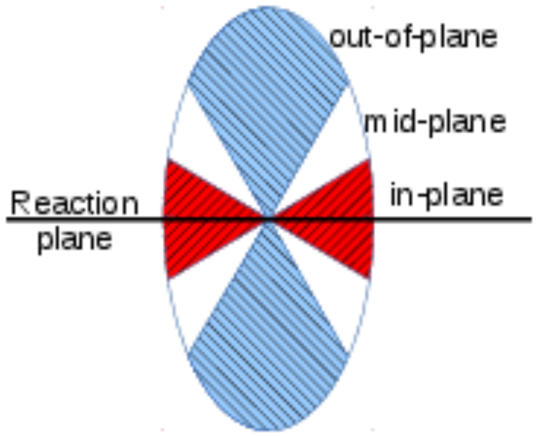
Jet shapes – Event-plane dependence



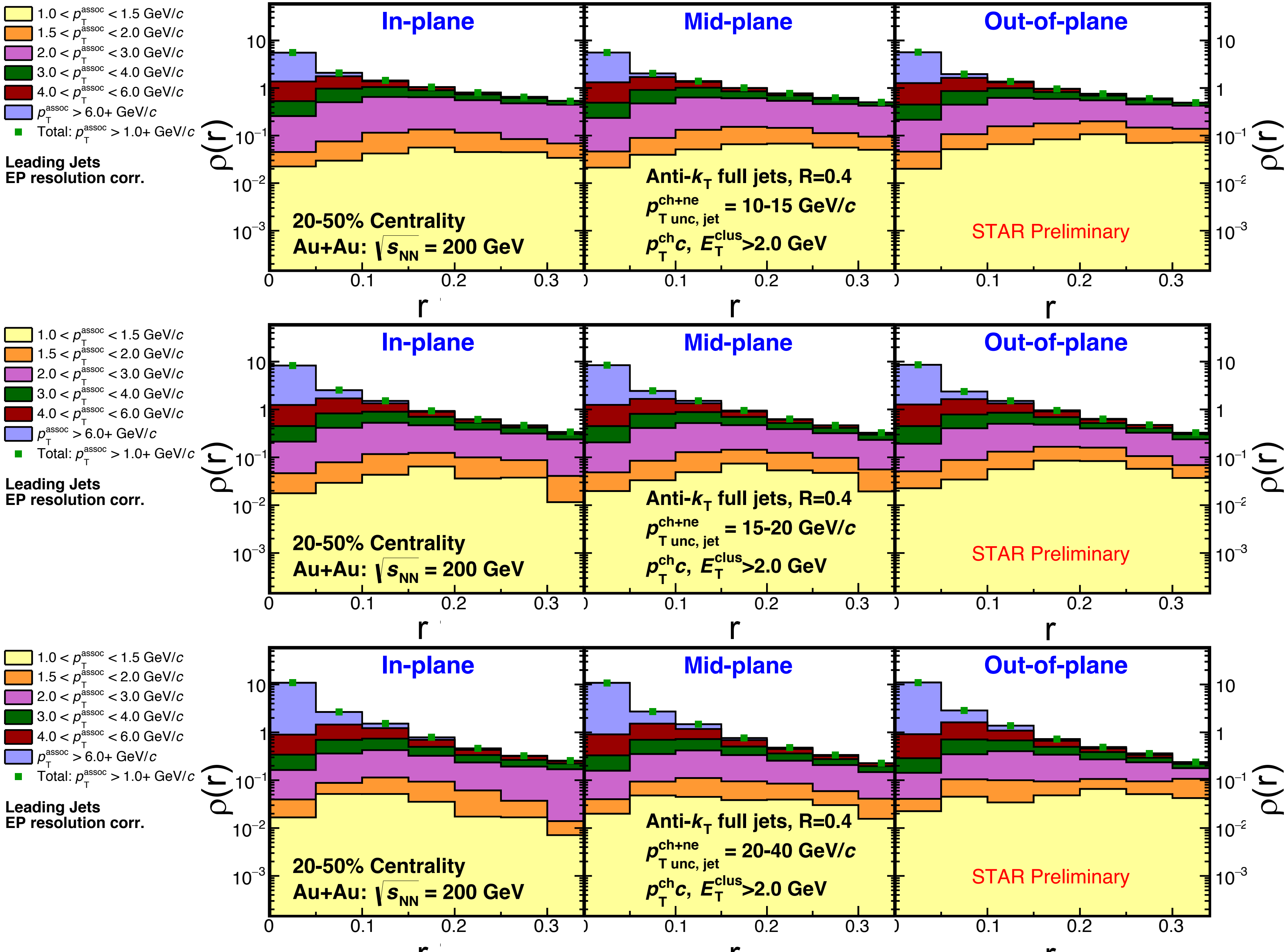
- Jet shapes can be measured more differentially based on jets' azimuthal angle relative to the 2nd-order event plane (EP)
  - In-plane: $0° \leq |\varphi_{\mathrm{jet}} - \Psi_{\mathrm{EP}}| < 30°$
  - Mid-plane: $30° \leq |\varphi_{\mathrm{jet}} - \Psi_{\mathrm{EP}}| < 60°$
  - Out-of-plane: $60° \leq |\varphi_{\mathrm{jet}} - \Psi_{\mathrm{EP}}| < 90°$

- Jets may experience different in-medium path length effects depending on their direction relative to the Ψ_{EP}

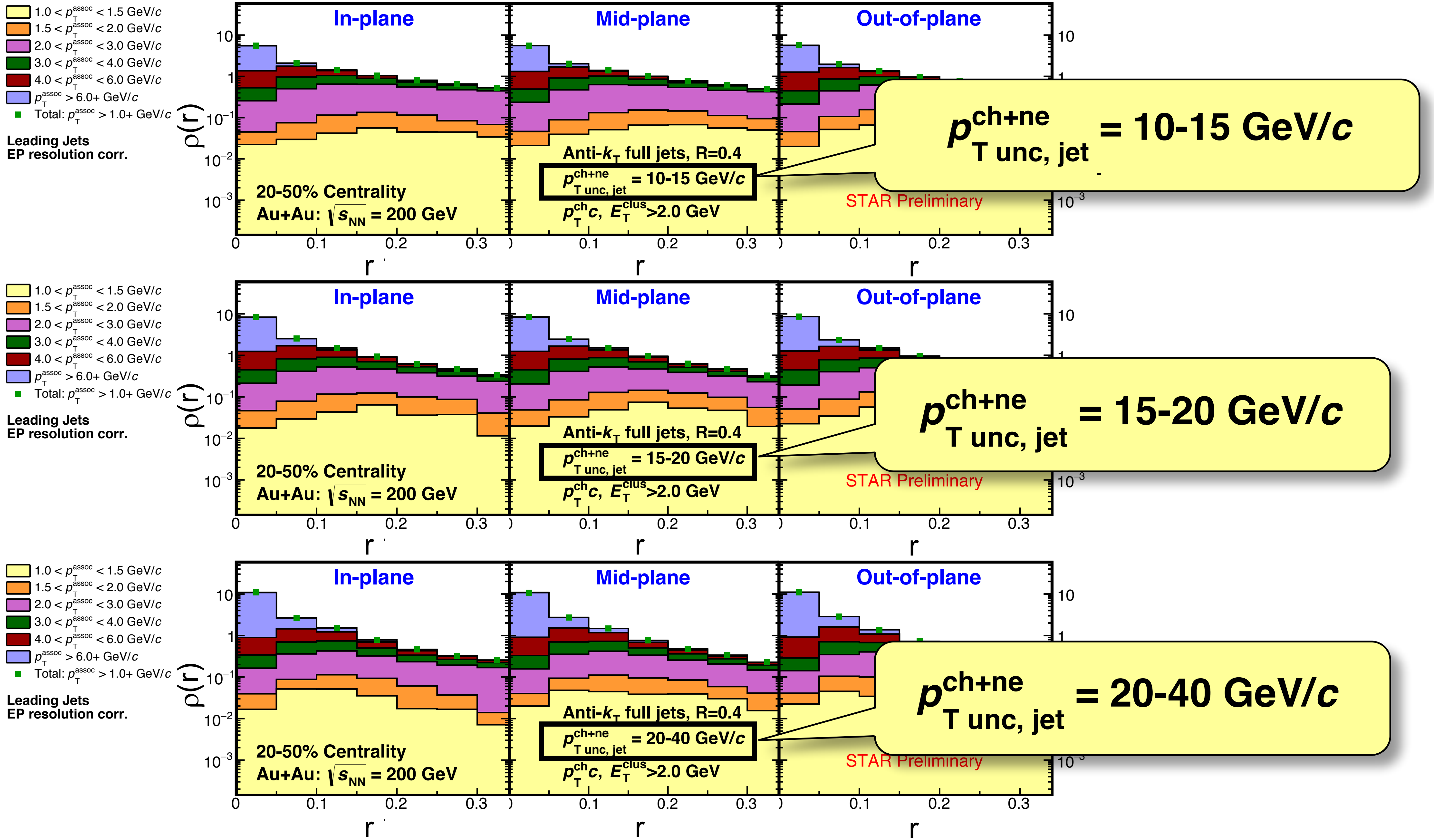
- Event-plane dependent results are corrected for the EP resolution effects
  - More details about the resolution correction at

👉 **Poster 354 (JT12)**. *"Evolution of **jet shapes** in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR detector at RHIC"*, **Joel Mazer** (Rutgers University)

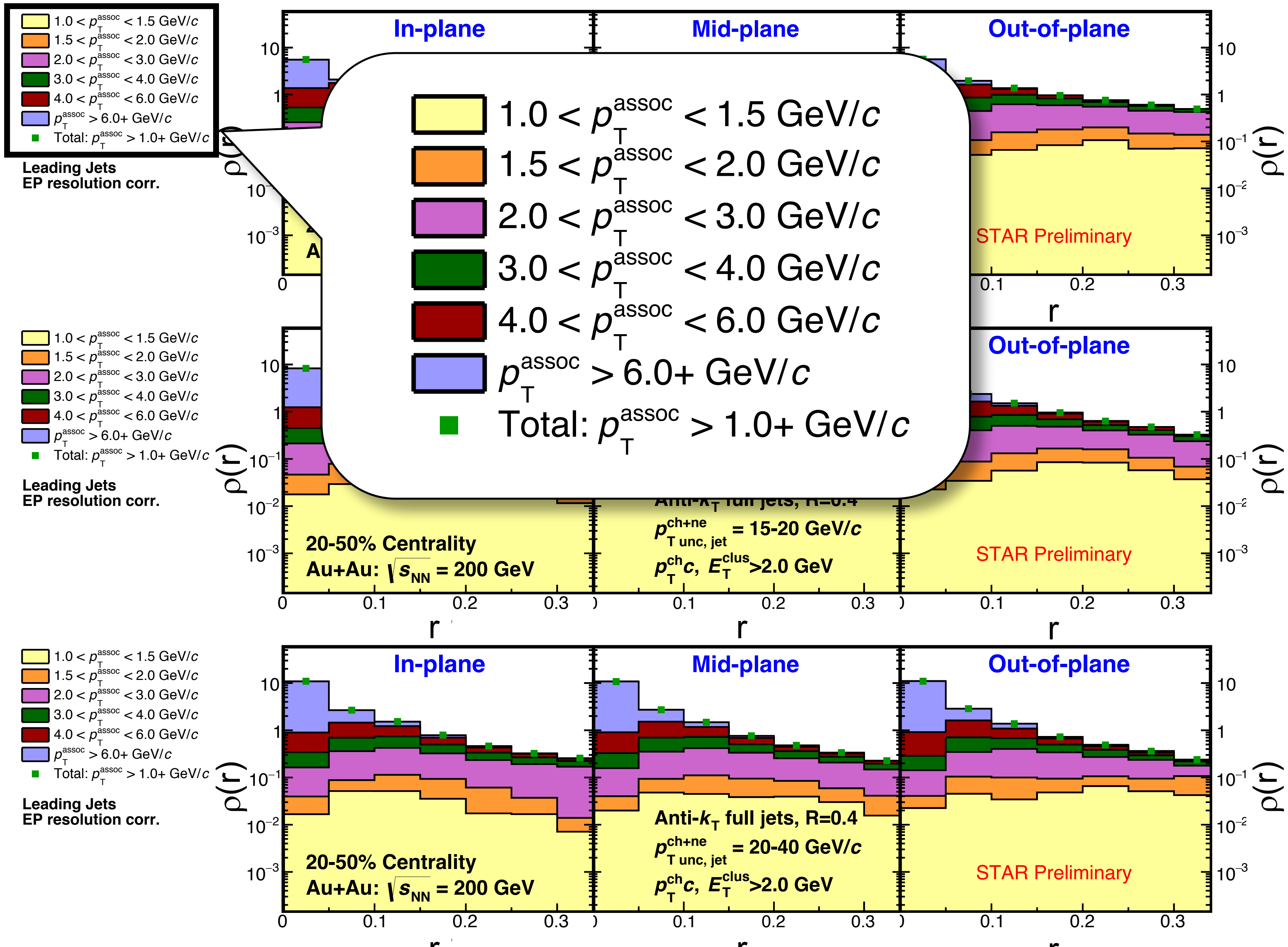
Jet shapes – Results



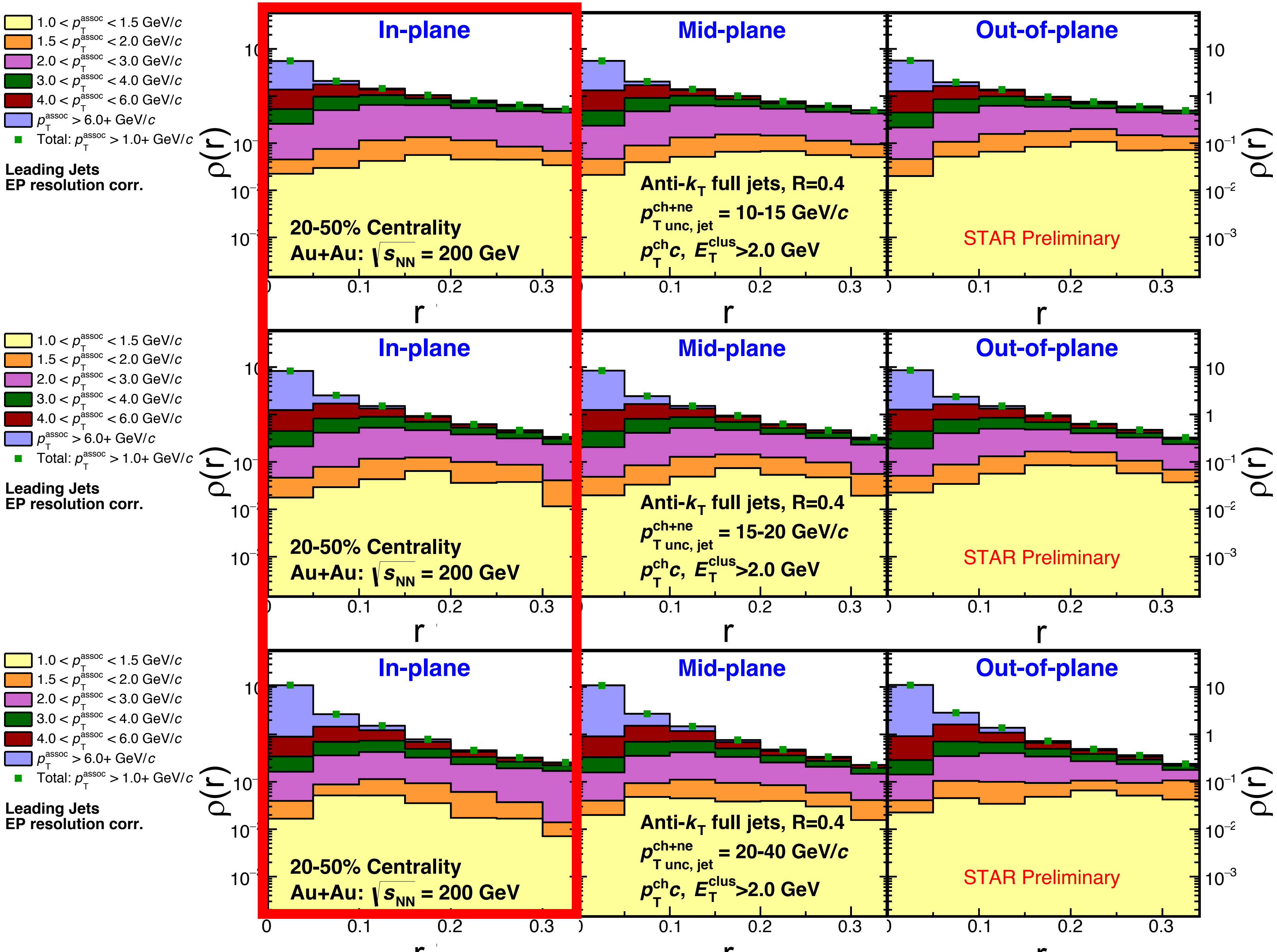
Jet shapes – Results



Jet shapes – Results

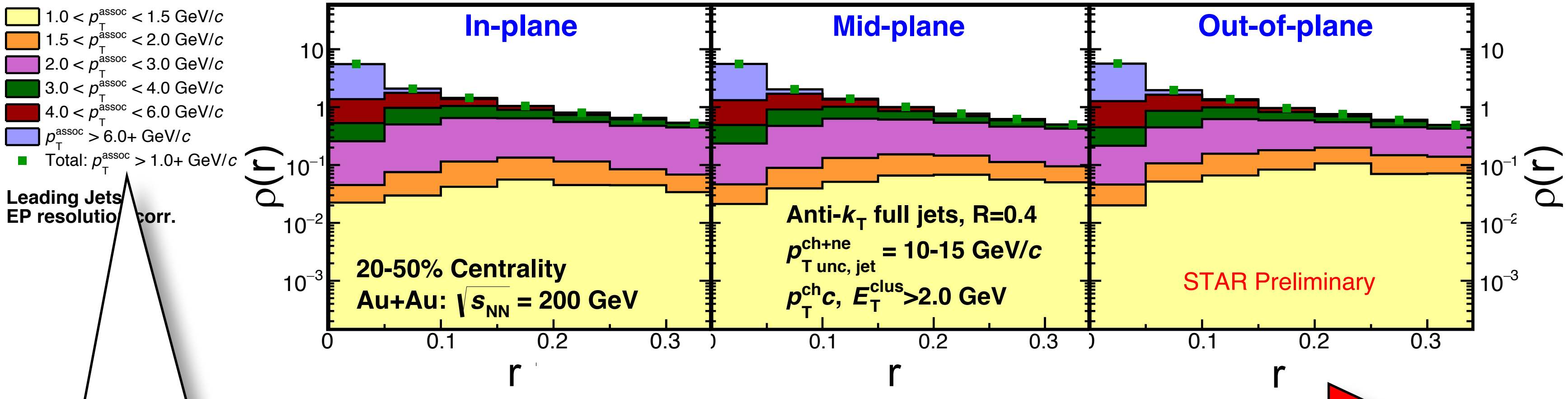


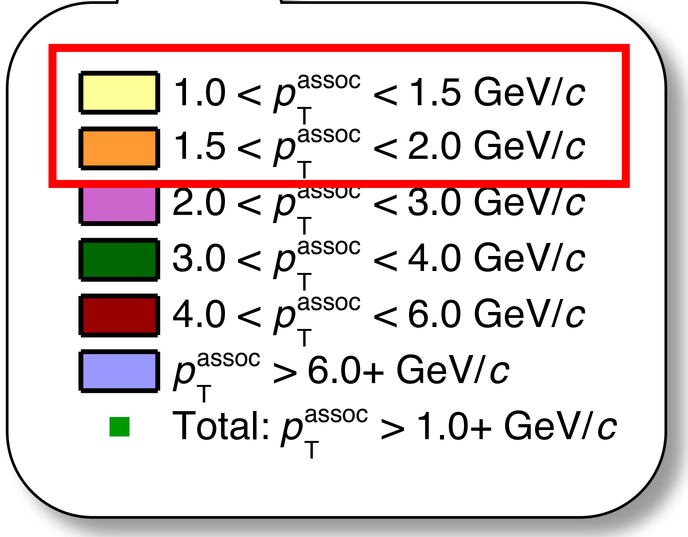
Jet shapes – Results

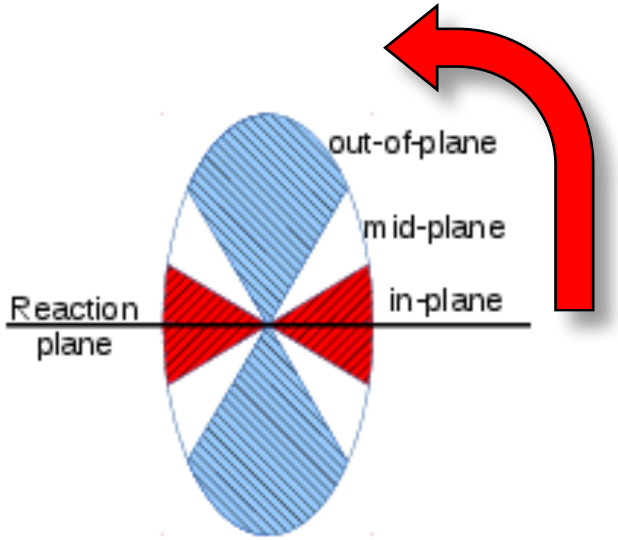


- Jets with higher $p_{\mathrm{T,jet}}$ are more collimated

Jet shapes – Results





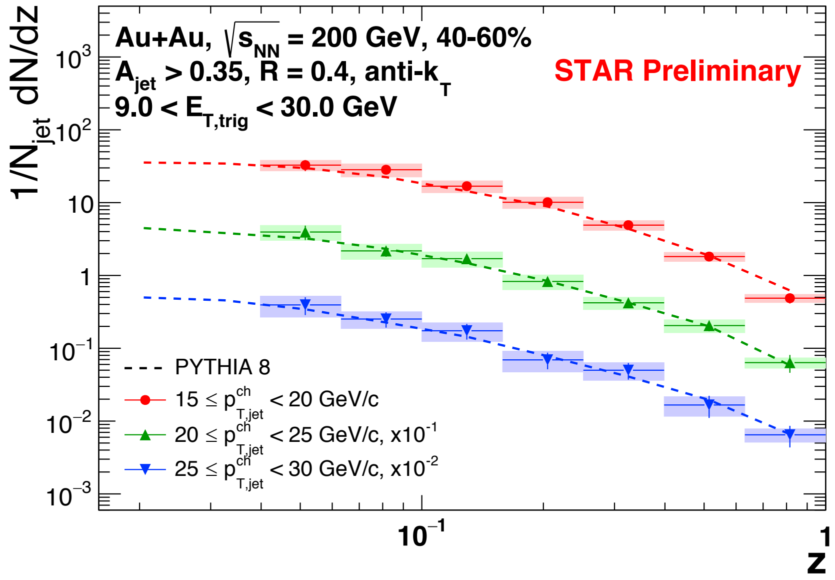


- Low-p_T tracks are pushed toward farther distances in the out-of-plane direction relative to the in-plane direction
- Larger yields of low-p_T tracks in the out-of-plane direction

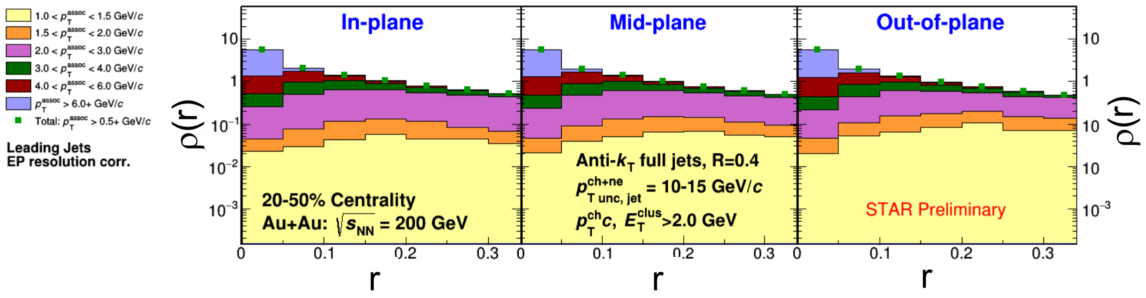
→ Larger effects in the out-of-plane direction due to longer in-medium path length?

Summary

- Jet fragmentation functions
  - Recoil jets with respect to a high momentum trigger particle in 40-60% centrality are studied
  - The unfolded fragmentation function results for three $p_{\mathrm{T,jet}}$ ranges are comparable to PYTHIA 8, but PYTHIA 8's reliability at RHIC energies is limited
  - Results for central and *p*+*p* events are on their way



- Jet shapes
  - Full jets with a high-momentum constituent cut are utilized in jet finding
  - In the event-plane dependent measurements, low-p_{T} tracks have larger yields and pushed toward farther distances in the out-of-plane direction → Sensitivity on the path-length dependence of jet quenching
  - Results for *p*+*p*, different centralities, and different jet *R* are on their way



Backup slides

Jet fragmentation functions @5.02 TeV

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

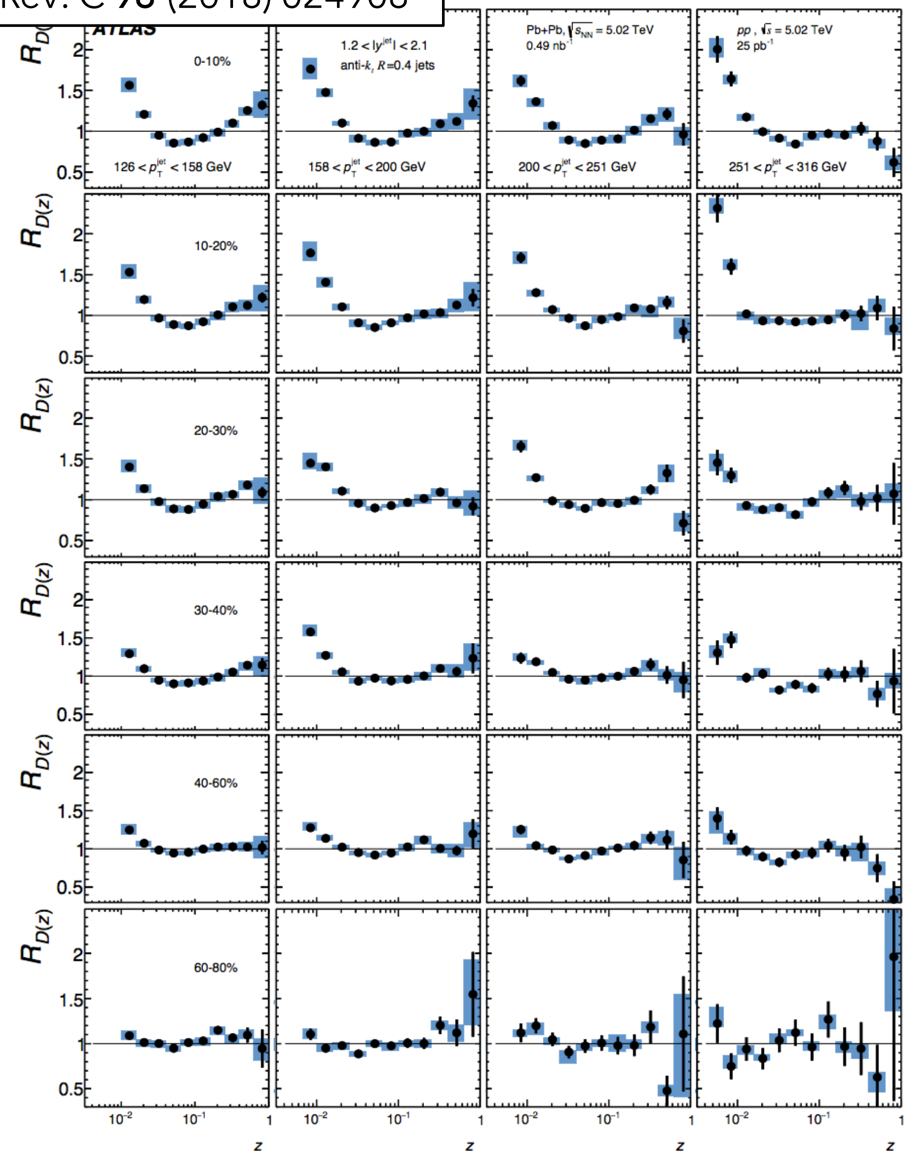


Figure 15: Ratios of $D(z)$ distributions in six centrality intervals of Pb+Pb collisions to pp collisions evaluated in four p_T^{jet} ranges for jets with $1.2 < |y^{jet}| < 2.1$. The vertical bars on the data points indicate statistical uncertainties, while the shaded bands indicate systematic uncertainties.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

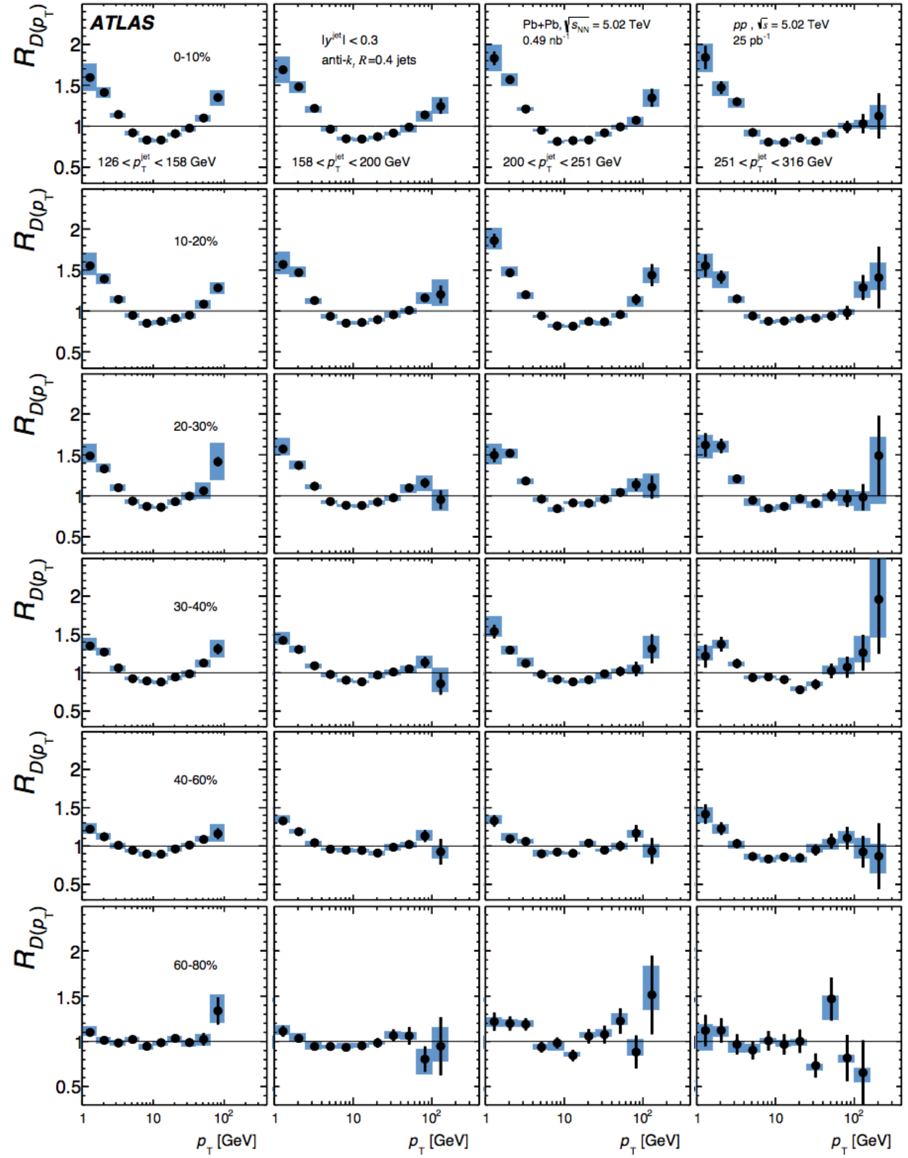
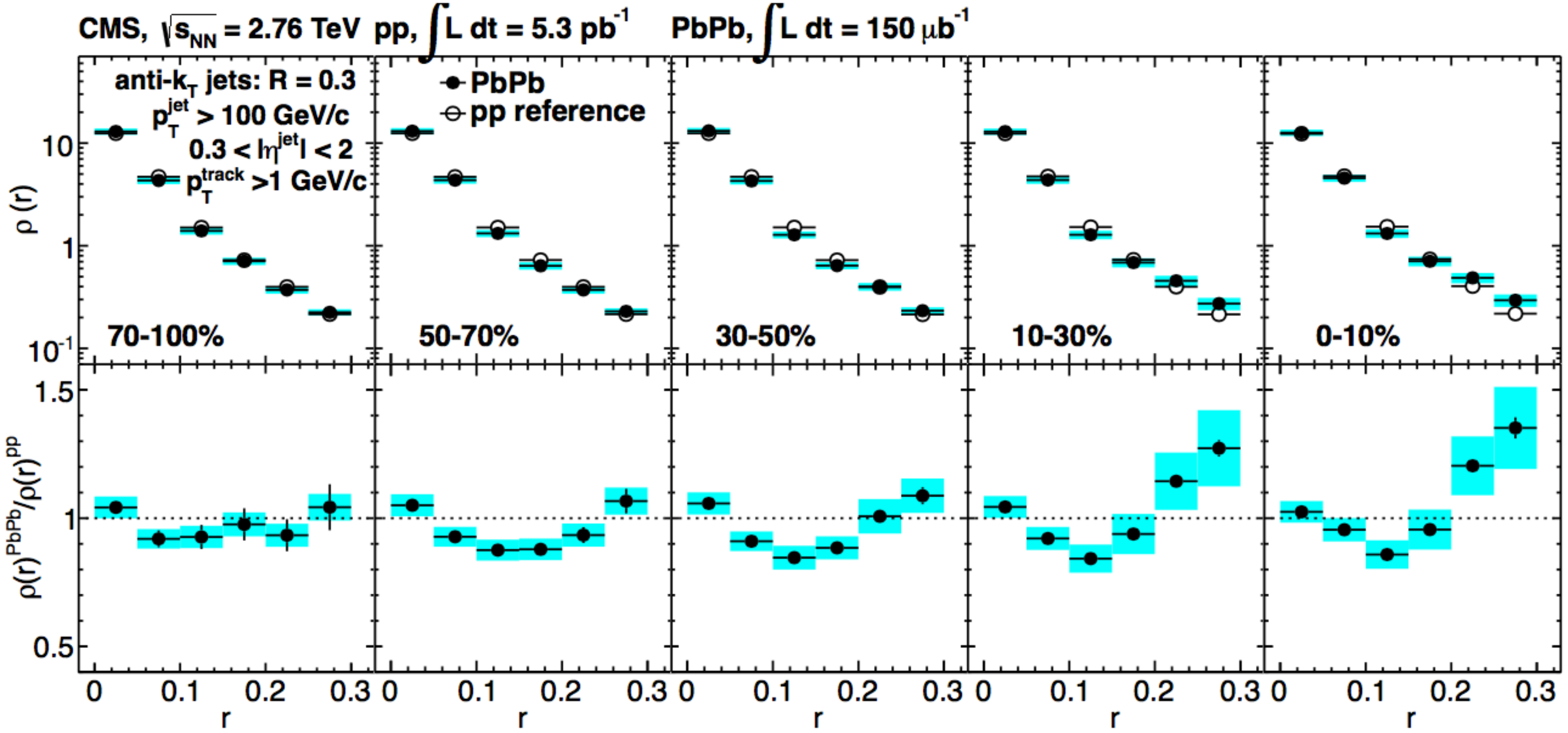


Figure 16: Ratios of $D(p_T)$ distributions in six centrality intervals of Pb+Pb collisions to pp collisions evaluated in four p_T^{jet} ranges for jets with $|y^{jet}| < 0.3$. The vertical bars on the data points indicate statistical uncertainties, while the shaded bands indicate systematic uncertainties. 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 $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV
  - Minimum-bias + high-tower triggered events
  - Anti-k_{T} algorithm for jet reconstruction with R = 0.4 and $|\eta_{\mathrm{jet}}| < 1.0 - R$
  - In the jet shape measurement,
    - ✓ HardCore $p_{\mathrm{T,jet}}$ is estimated without a ρA subtraction
    - ✓ Mixed event class is defined with centrality, z_{vtx}, Ψ_{EP}, track multiplicity bins. There are 14z_{vtx} bins, 4 Ψ_{EP} bins, and 16 multiplicity bins in each centrality
  - In the fragmentation function measurement,
    - ✓ Raw $p_{\mathrm{T,jet}}$ is estimated with a ρA subtraction, where ρ is estimated from jets reconstructed with the k_{T} algorithm
    - ✓ Mixed event class is defined with centrality, z_{vtx}, Ψ_{EP}, track multiplicity bins. There are 15 z_{vtx} bins, 4 Ψ_{EP} bins, and 8 multiplicity bins in each centrality
    - ✓ In fragmentation function unfolding, detector effects are simulated with Fast Simulation (efficiency and momentum resolution)