

Charm Quark Jet Spectrum and Shape Modifications in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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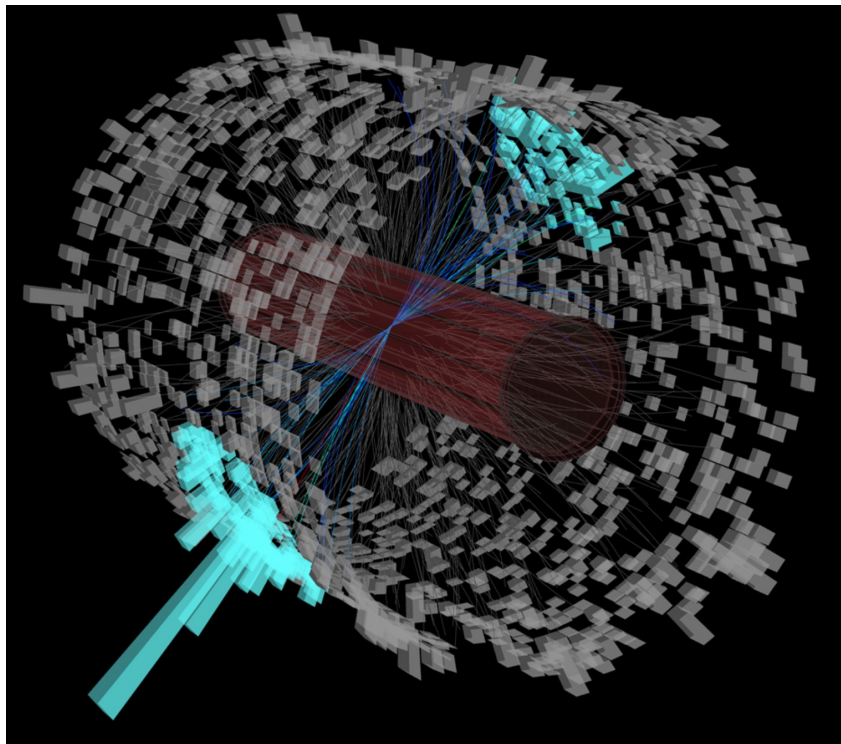
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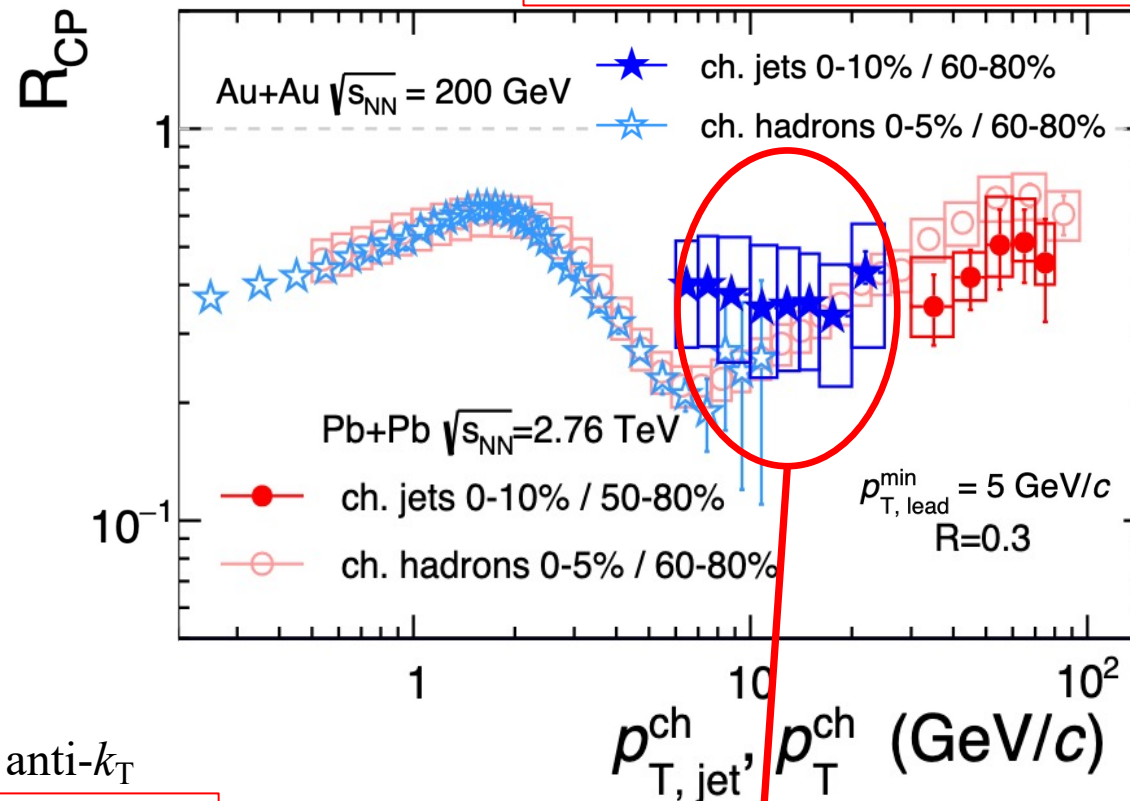
Jets in Heavy Ion Collisions

Strong interaction between high p_T partons and medium \rightarrow Way to probe QGP's transport properties

ALICE, JHEP03 (2014) 013



STAR, Phys.Rev.C 102 (2020) 5, 054913



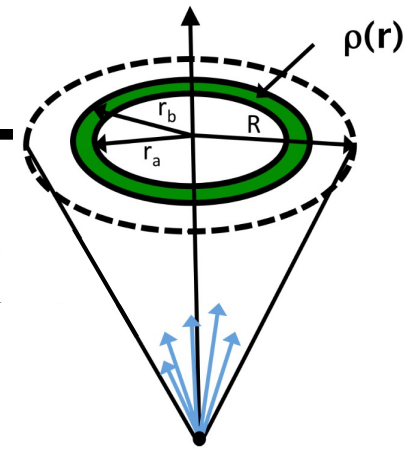
- Jets reconstructed by a sequential clustering algorithm, commonly anti- k_T
- **Loss of parton energy** in the QGP medium
- **Parton shower modified** due to medium-induced radiation and scattering

FASTJET, Phys. Lett. B 641 (2006) 57-61

Inclusive jets are heavily **quenched** in the presence of QGP



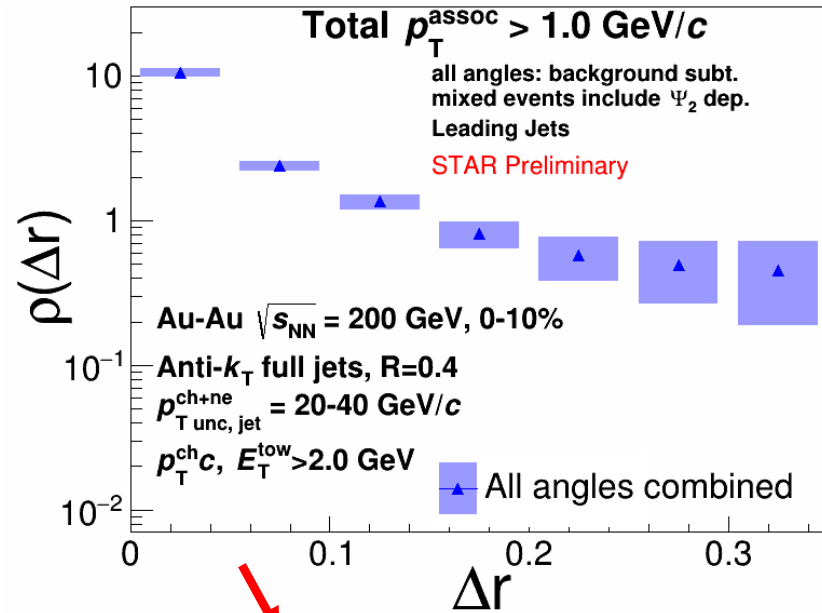
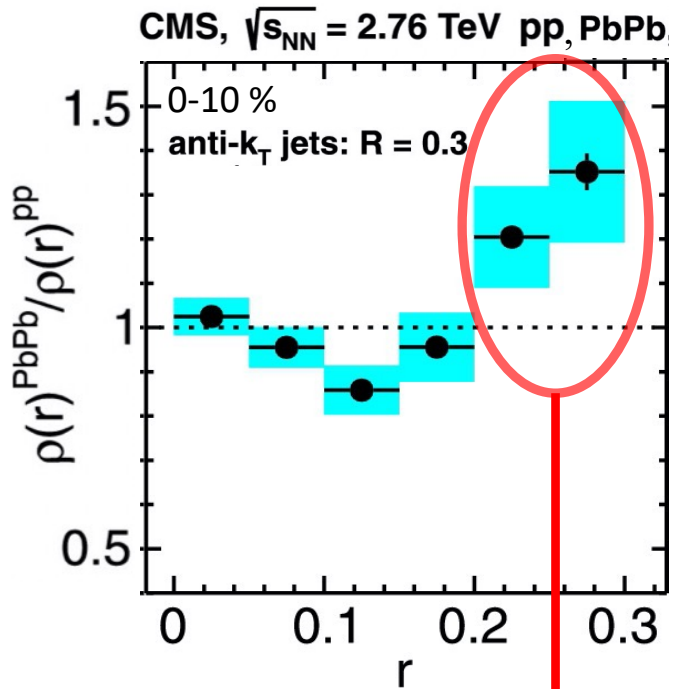
Motivation



$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{track} \in (r_a, r_b)} p_{T, \text{track}}}{p_{T, \text{jet}}}$$

Differential Jet Shape

$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$

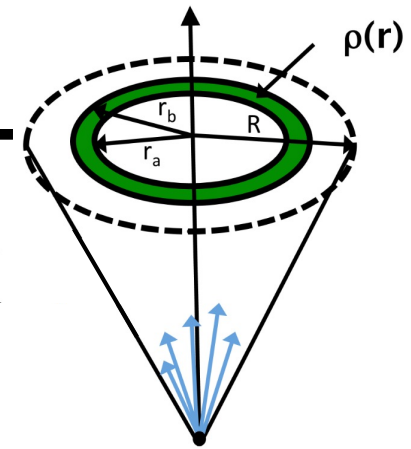


Similar pp measurement from STAR underway

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

Jet energy is **redistributed to large distances from the jet axis** in the presence of QGP

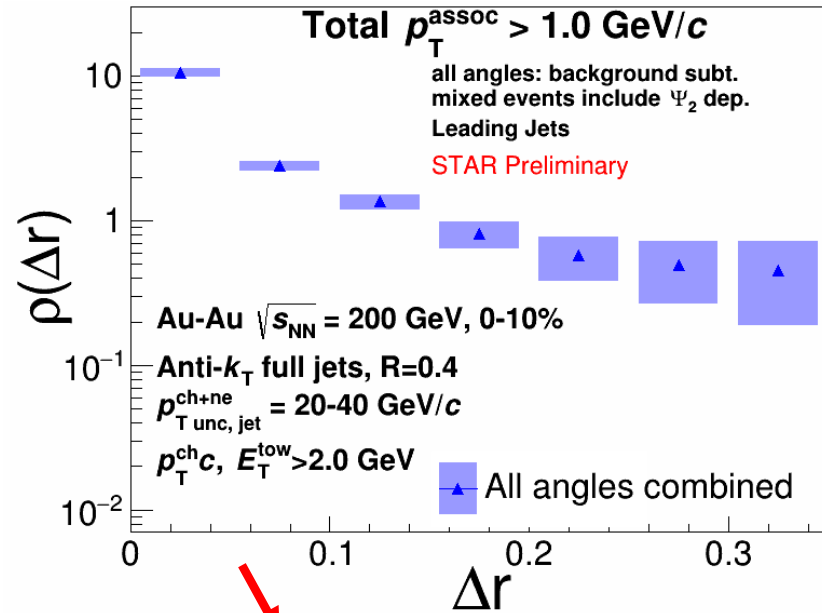
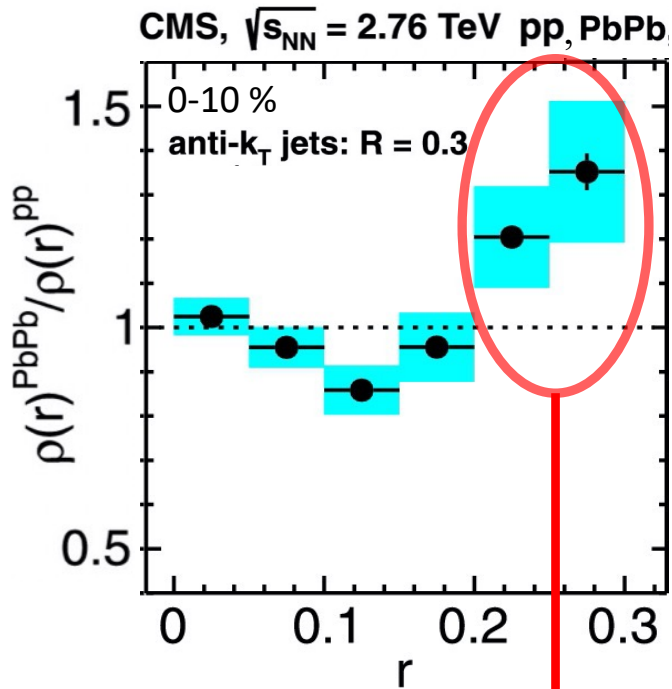
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Differential Jet Shape

$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$



Similar pp measurement from STAR underway

Possible mechanisms:

- Multiple scattering
- Medium-induced bremsstrahlung
- Medium response

Dependent on the mass of the underlying parton

Motivation to study heavy-flavor jets

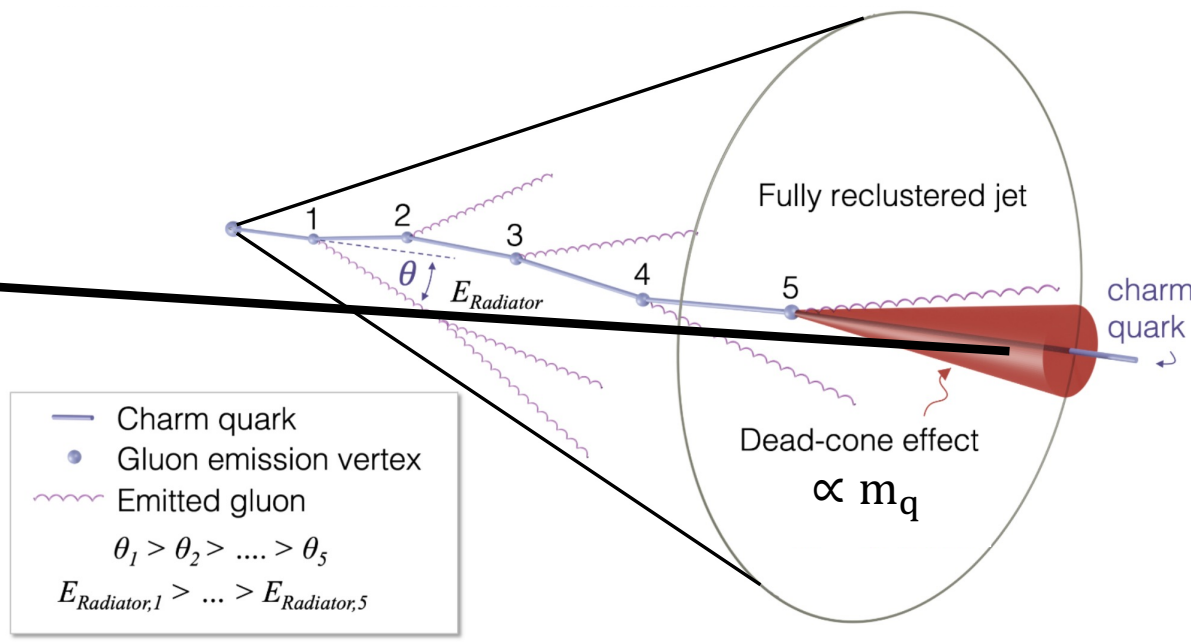
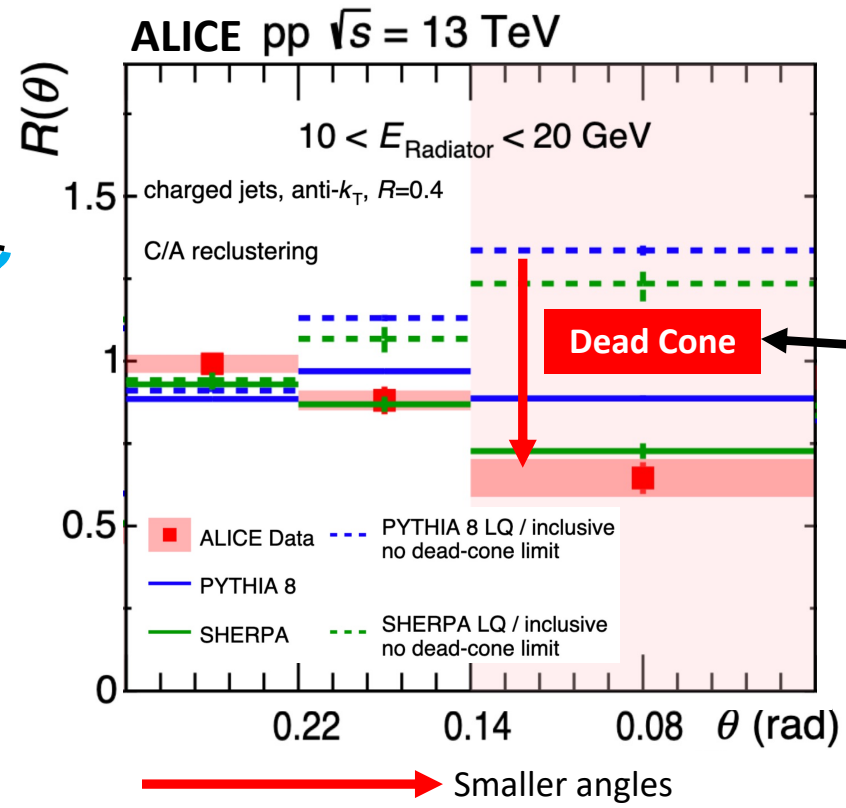
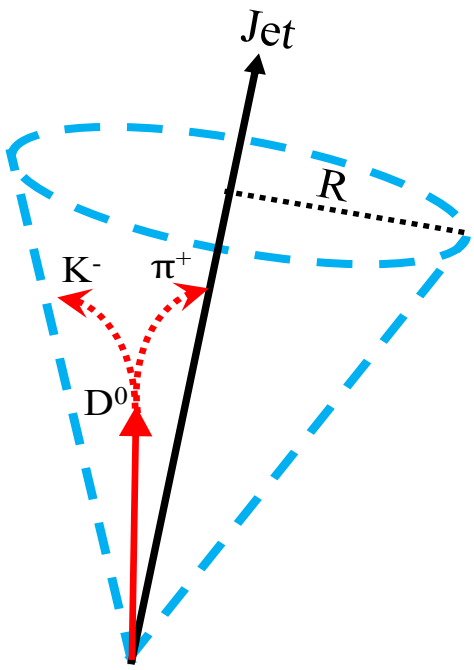
CMS, Phys. Lett. B 730 (2014) 243

Jet energy is redistributed to large distances from the jet axis in the presence of QGP

Heavy Flavor Tagged Jets

$$R(\theta) = \frac{1}{N_{D^0\text{jet}}} \frac{dn_{D^0\text{jet}}}{d \ln(1/\theta)} \bigg/ \frac{1}{N_{\text{inclusive jet}}} \frac{dn_{\text{inclusive jet}}}{d \ln(1/\theta)}$$

ALICE, Nature 605, pages 440–446 (2022)



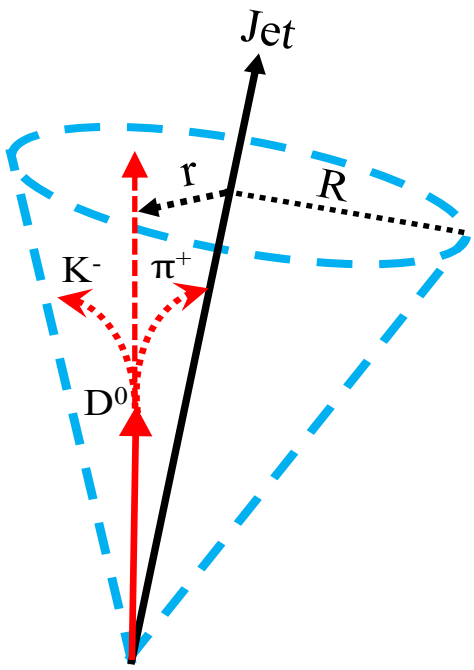
Heavy-flavor emission spectra at small angles suppressed due to **dead-cone effect** [1]

[1] J. Phys. G: Nucl. Part. Phys. **17** 1602 (1991)

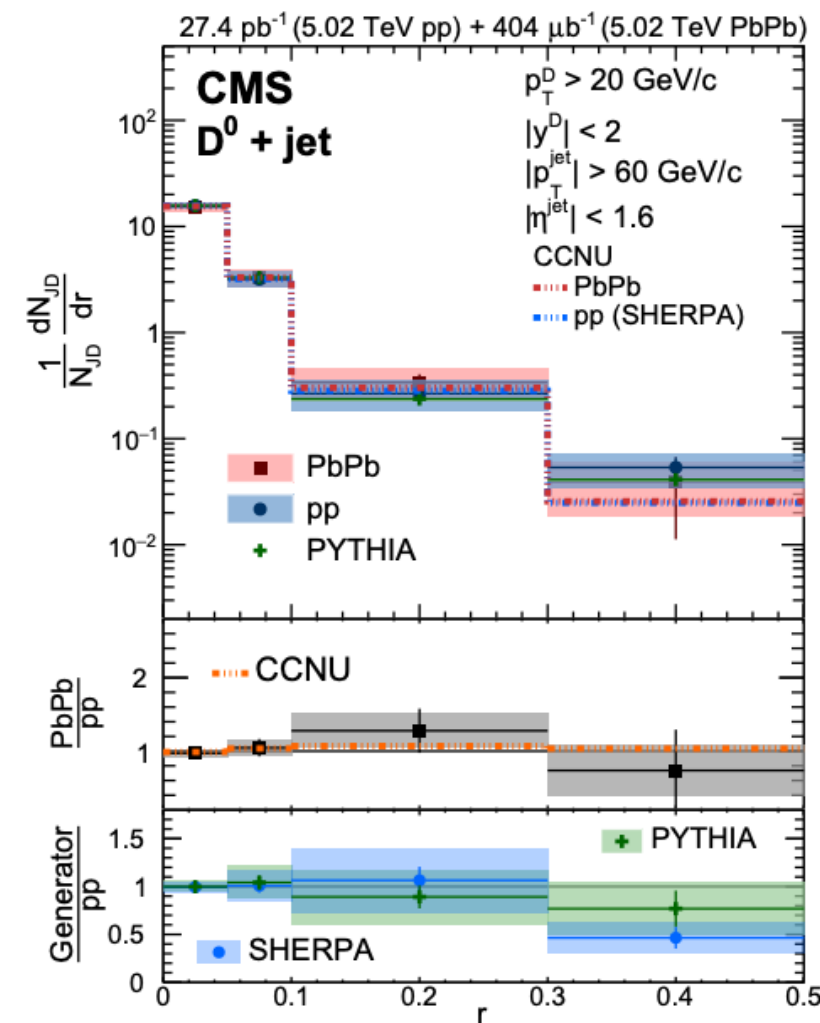
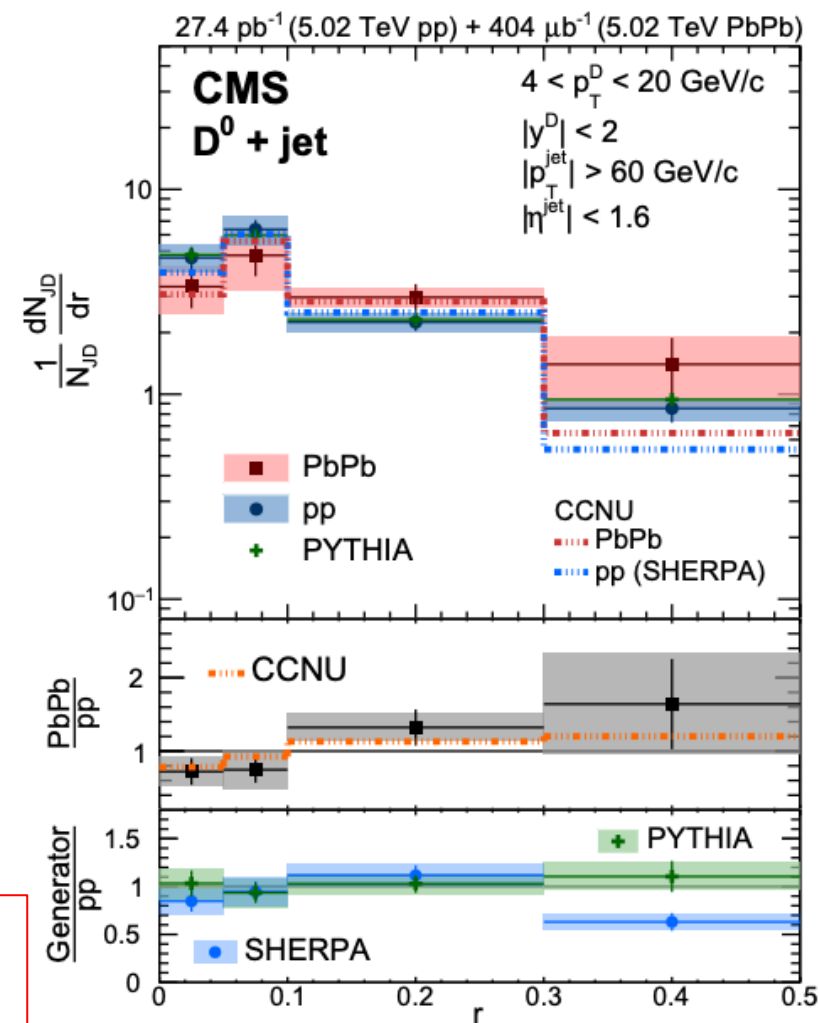


Heavy Flavor Tagged Jets

CMS, Phys. Rev. Lett. 125 (2020) 102001



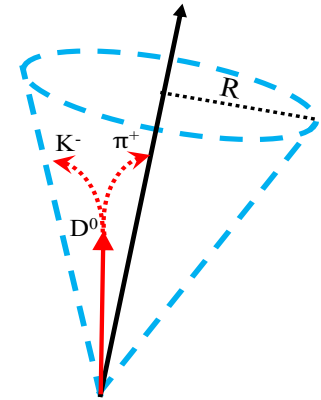
Low p_T D^0 mesons slightly **diffused** in the presence of QGP at LHC



- Lower p_T D^0 mesons accessible at RHIC energies
- Contribution from the underlying background is smaller at RHIC for a given jet p_T



STAR Detector & Selection Criteria

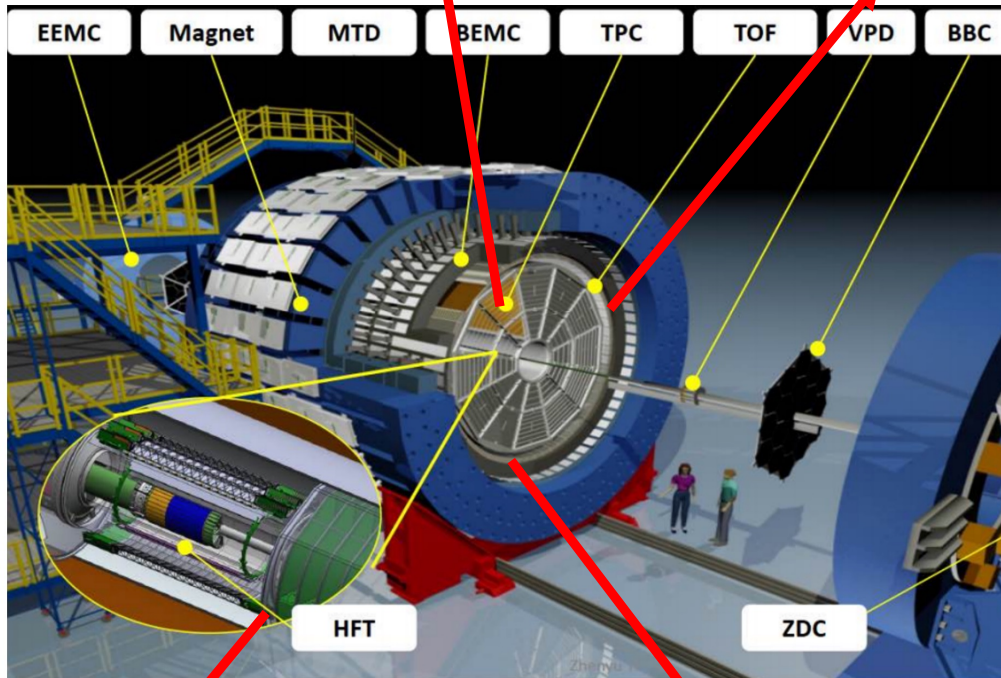


Time Projection Chamber (TPC)

- Measures momentum, track trajectory, and identifies charged particles

Time-of-Flight Detector (TOF)

- Identifies charged particles



Barrel Electromagnetic Calorimeter (BEMC)

- Measures neutral component of energy in jets

Heavy Flavor Tracker (HFT)

- Improves position resolution for tracks

Event Selection:

- Au+Au $\sqrt{s_{NN}} = 200$ GeV, Year 2014
- Minimum bias (MB)
- Centrality $\in [0, 80]\%$ (3 bins: [0-10], [10-40], [40-80])

Constituent Selection:

- $0.2 < p_{T,track} [\text{GeV}/c] < 30$; $0.2 < E_{T,tower} [\text{GeV}] < 30$
- $|\eta_{track}| < 1$; $|\eta_{tower}| < 1$
- $D^0 \rightarrow K^{\mp} + \pi^{\pm}$ [B.R. = 3.82 %]
- For D^0 reconstruction: Tracks contain at least three hits on HFT
- $5 < p_{T,D^0} [\text{GeV}/c] < 10$

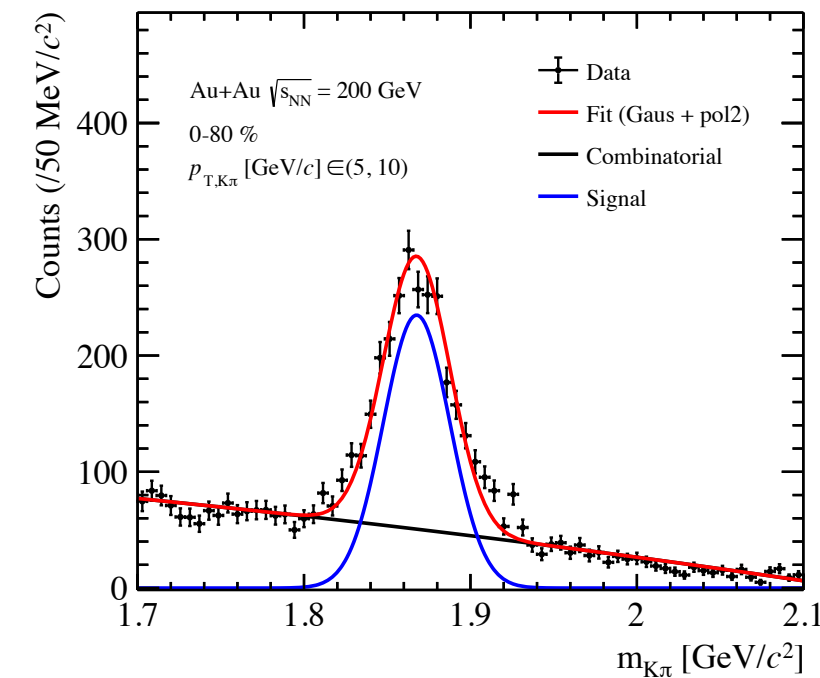
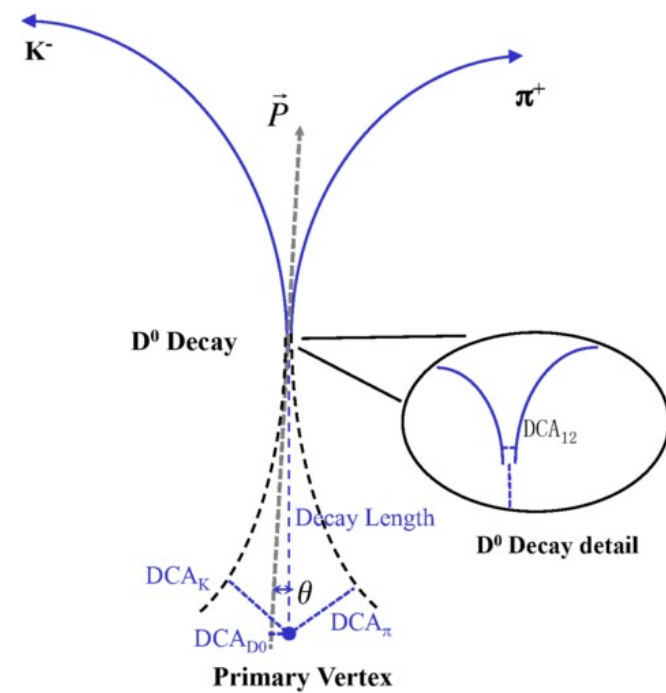
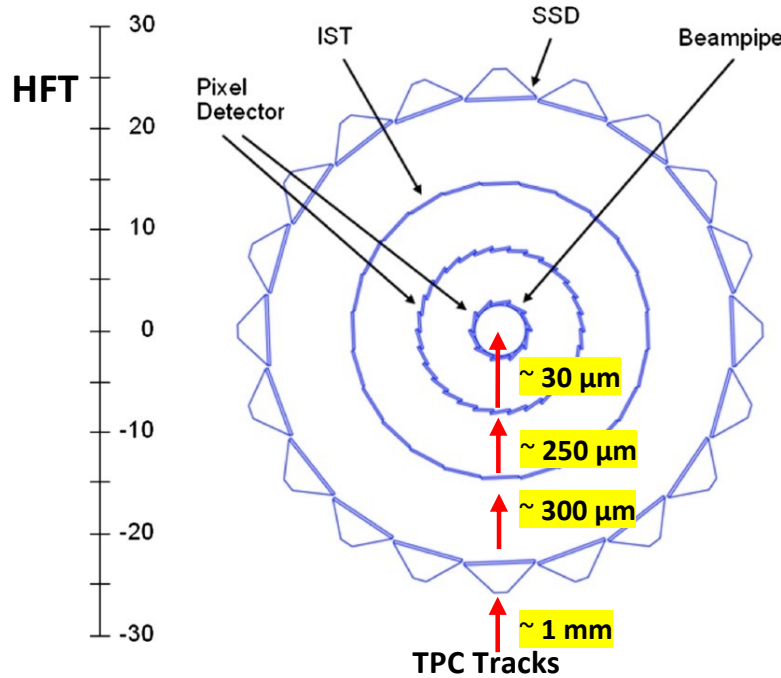
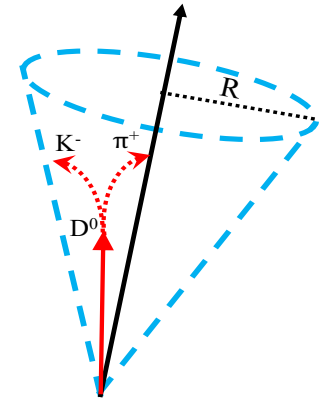
D^0 Jet Selection:

- Anti- k_T full jets of radius $R = 0.4$, area-based background subtraction
- $|\eta_{jet}| < 0.6$

D⁰ Reconstruction

- Kaons and Pions identified using TPC and TOF

STAR, Phys. Rev. C 99 (2021) 034908



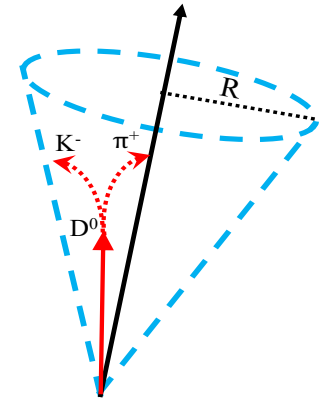
Topological cuts on the D⁰ candidates improve signal significance

Yield is calculated using sPlot method [1]

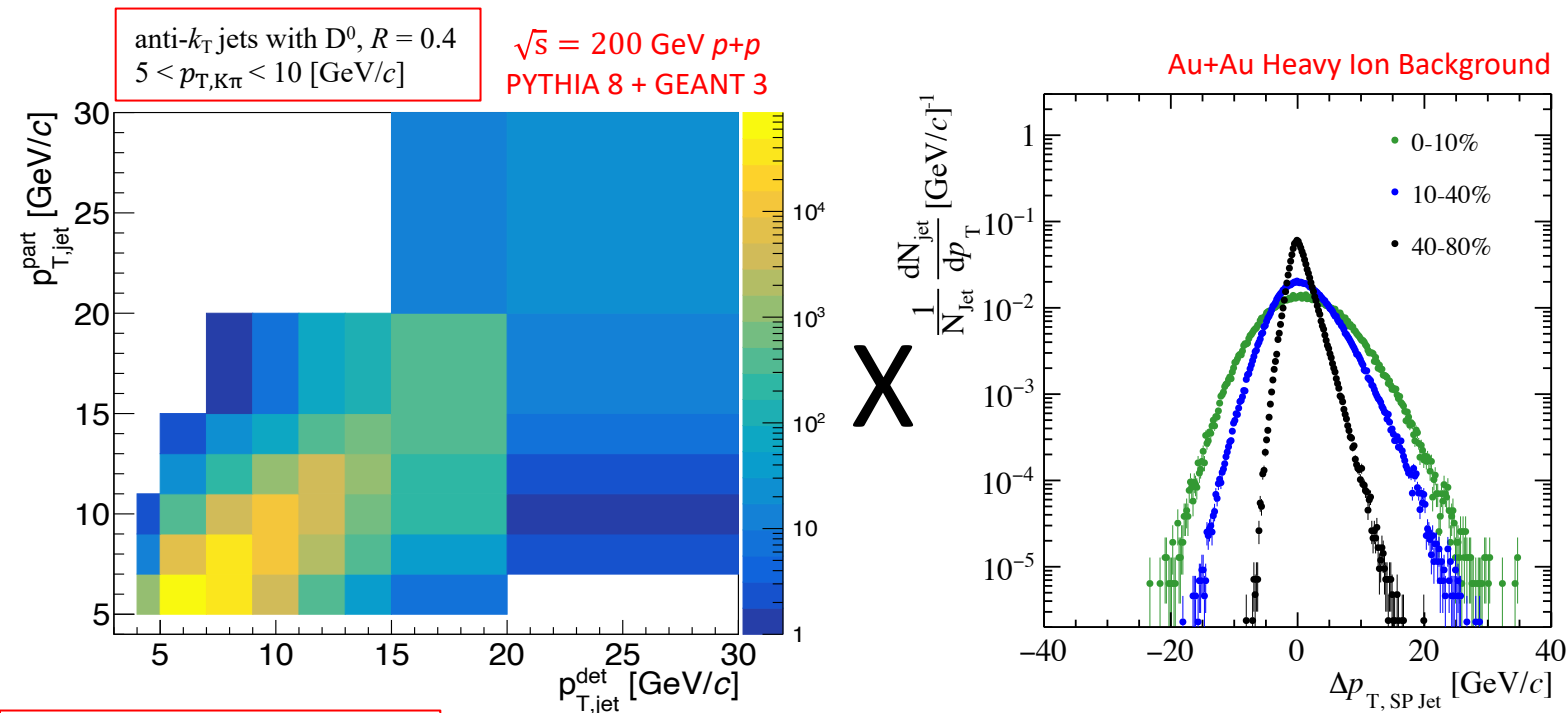
[1] Nucl. Instrum. Methods Phys. Res., A (2005) 555



Correction to the Jet Yield



1. Response matrix for $p+p$ $\sqrt{s} = 200$ GeV from PYTHIA and GEANT3 to mimic the detector response
2. Single Particle (SP) embedding in heavy ion events to model fluctuations in area-based background subtraction
3. Reweight PYTHIA with c-quark distribution from FONLL [1] to modify the shape of the jet p_T spectra
4. Heavy-flavor jet fragmentation modeled using PYTHIA
5. Systematics from variation in fragmentation model will be studied later



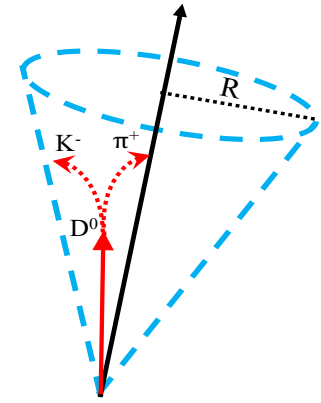
[1]. FONLL, JHEP03 (2001) 006

October 15, 2022

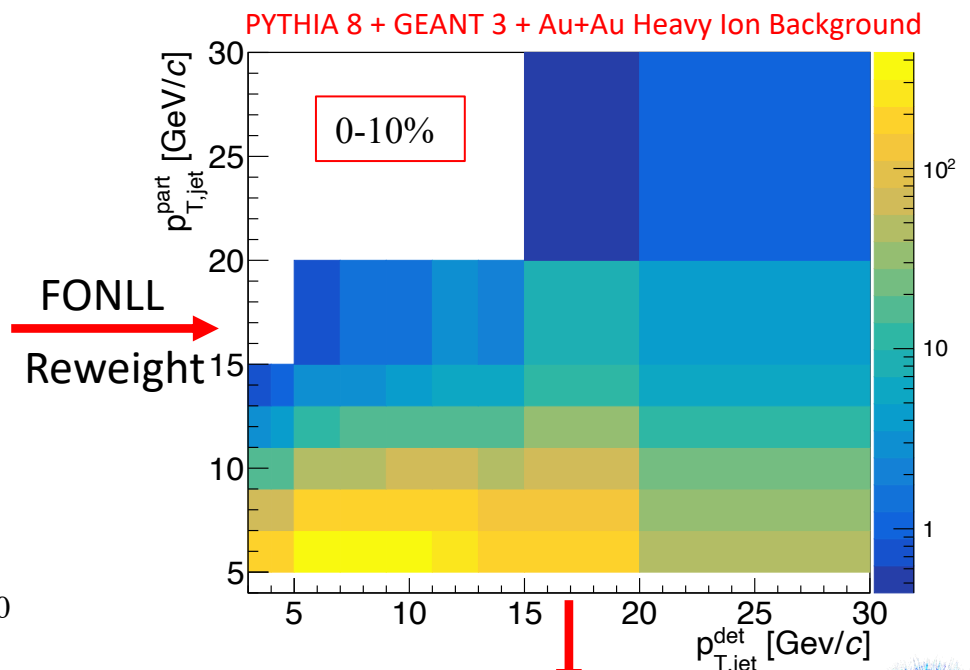
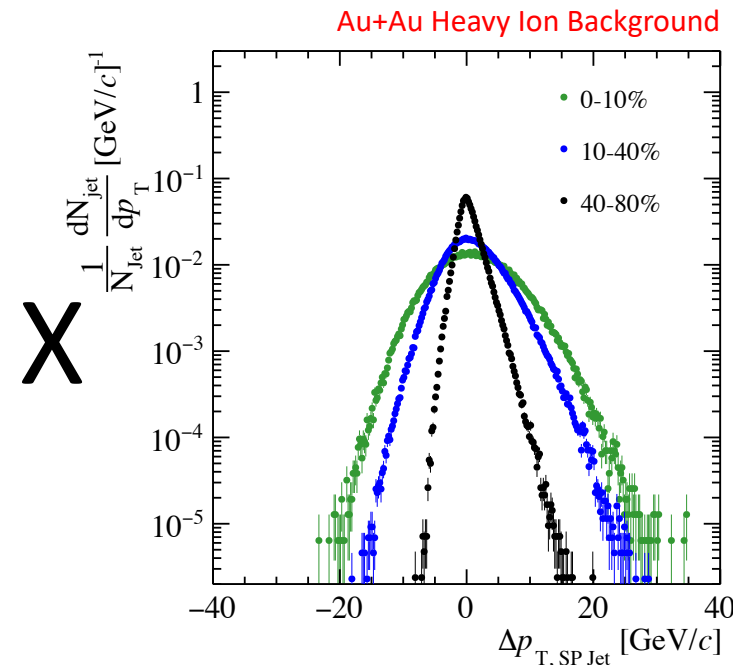
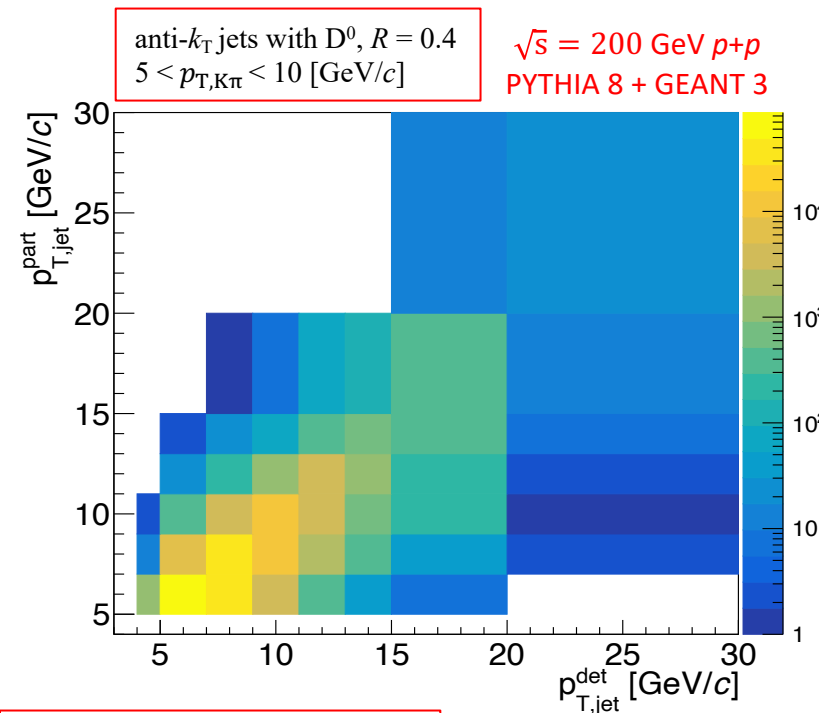
Diptanil Roy, Hot Quarks 2022



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[1]. FONLL, JHEP03 (2001) 006
 October 15, 2022



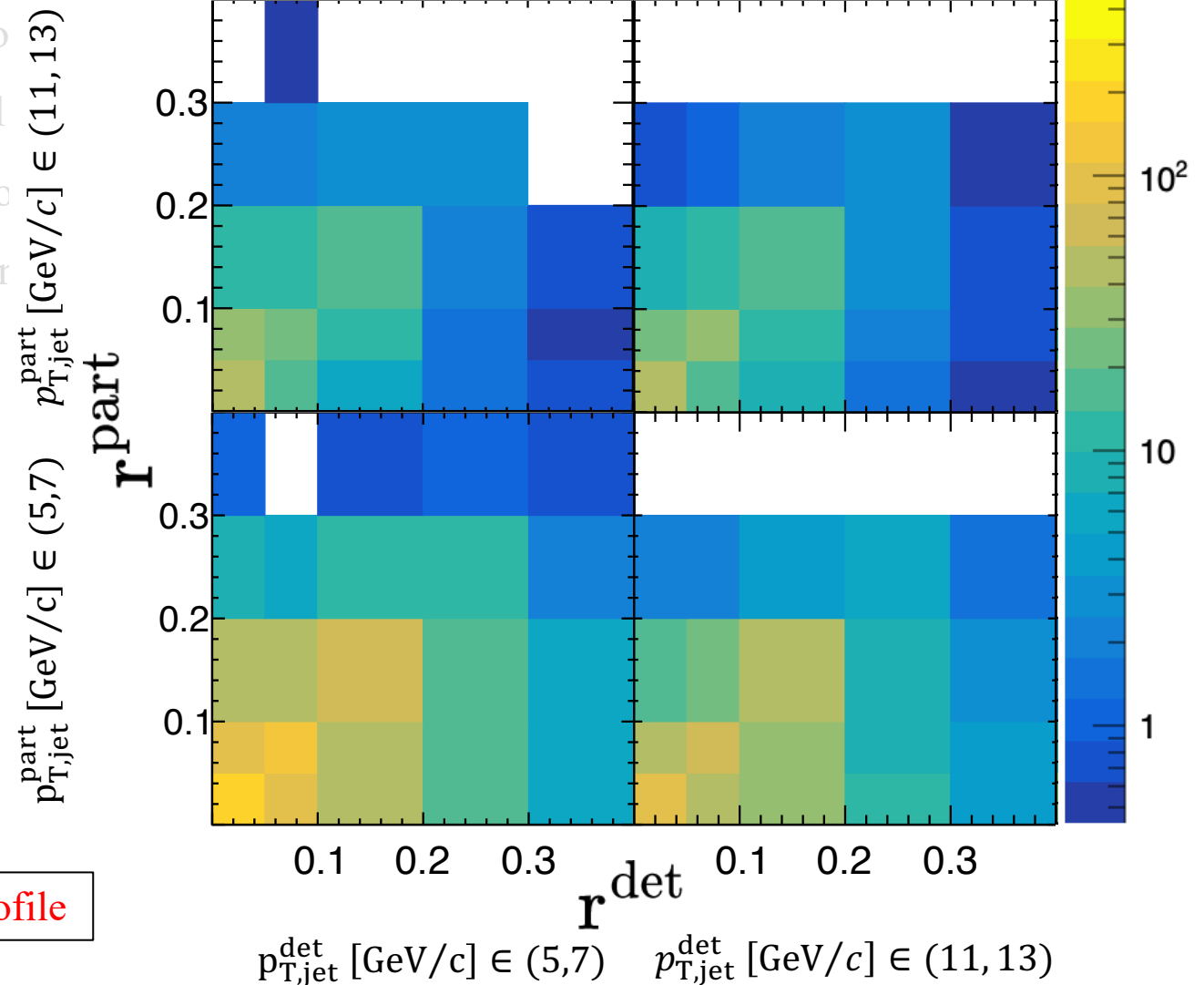
Correction to the Jet Radial Profile

1. Response matrix for $p+p$ $\sqrt{s} = 200$ GeV from PYTHIA and GEANT3 to get the detector response
2. Single Particle (SP) Embedding in heavy ion
3. Reweight PYTHIA with a prior (FONLL [1])
4. Heavy-flavor jet fragmentation modeled from
5. Systematics from variation in fragmentation

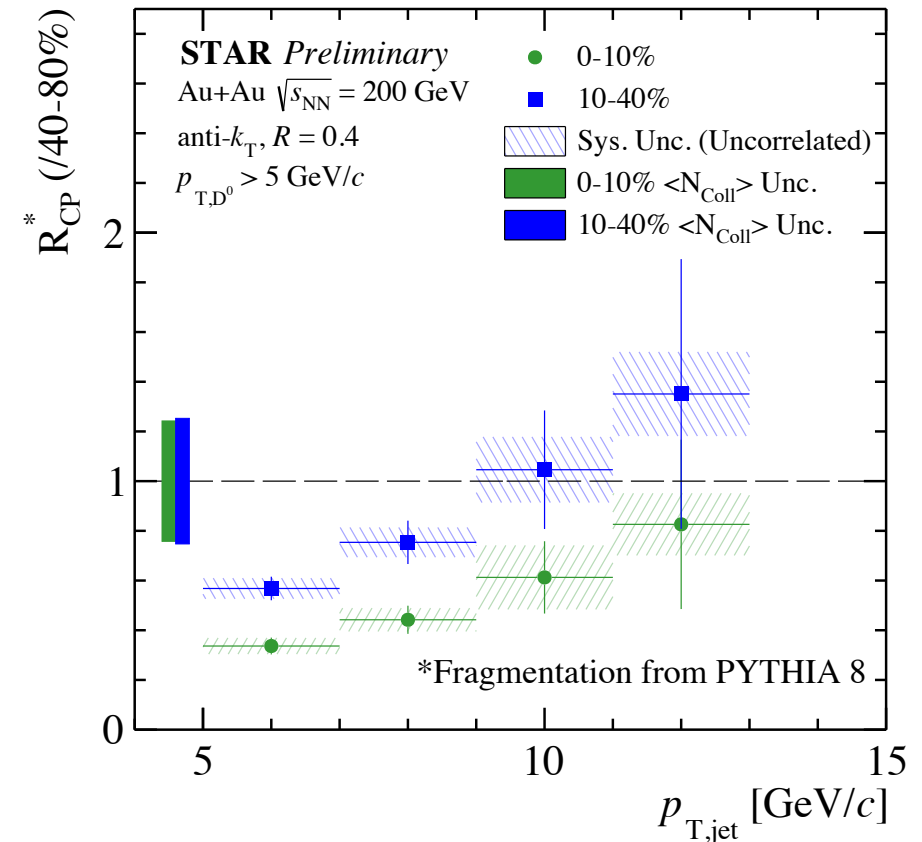
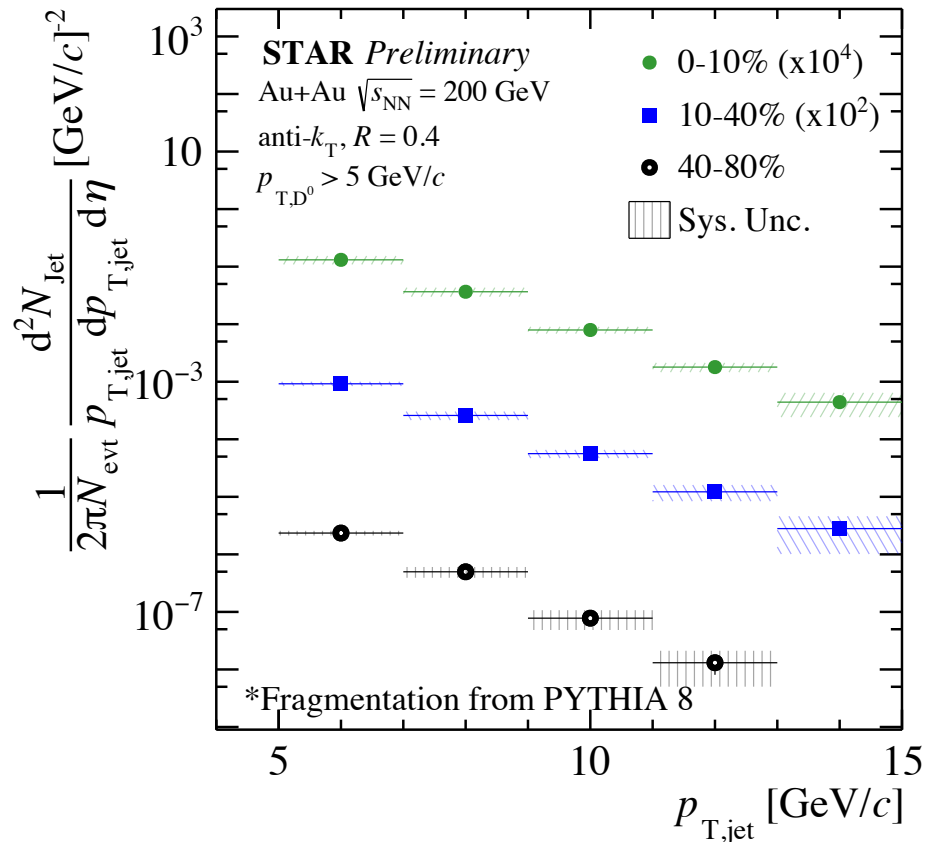
anti- k_T jets with D^0 , $R = 0.4$
 $|\eta_{\text{jet}}| < 0.6$
 $p_{T,\text{const}} > 0.2$ GeV/c
 $5 < p_{T,K\pi} < 10$ (GeV/c)

$\sqrt{s} = 200$ GeV $p+p$
 PYTHIA 8 + GEANT 3
 Au+Au Heavy Ion Background

Complete 4D response matrix to unfold radial profile



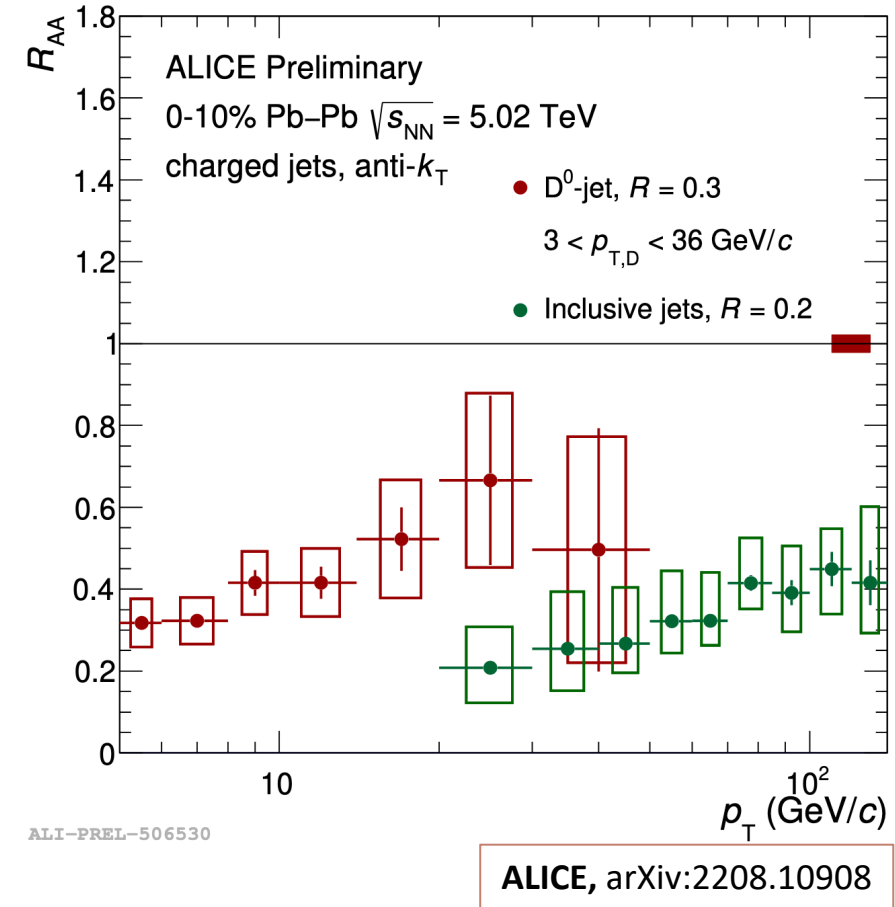
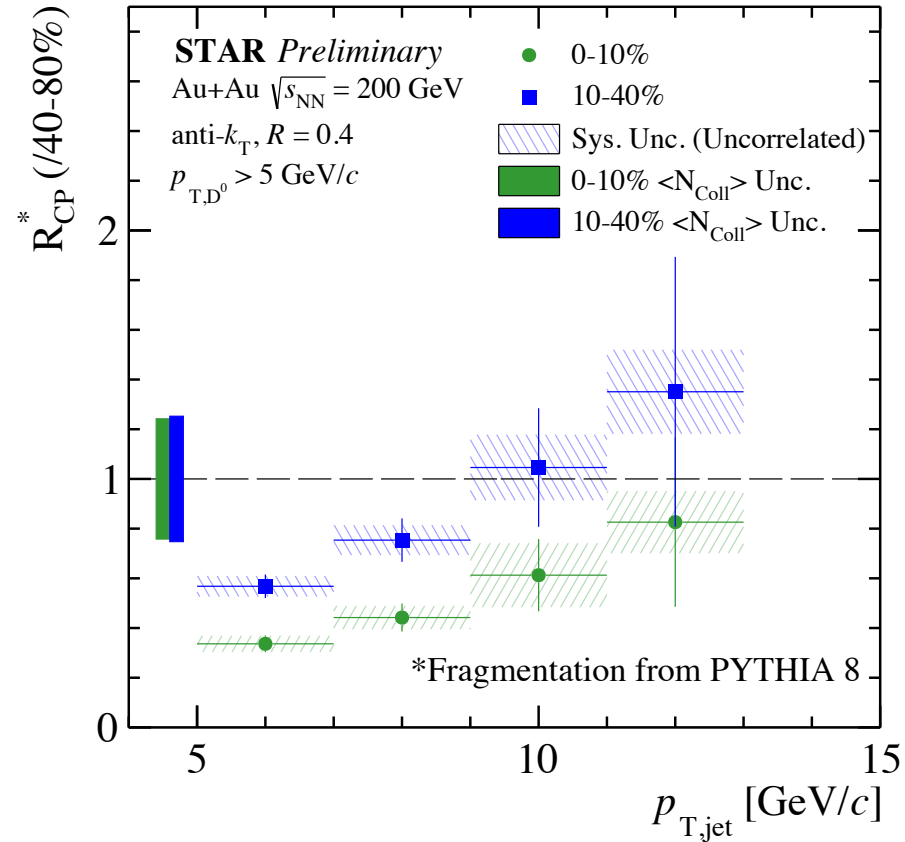
Jet Spectra



- Peripheral events have limited $D^0 p_T$ reach
- Yields in most central collisions are more suppressed than mid-central
- R_{CP}^* shows strong suppression at low $p_{T,jet}$, hint of an increasing trend with $p_{T,jet}$
- D^0 -tagged jet measurement for R_{AA} will be explored using high-statistics $p+p$ data in 2024

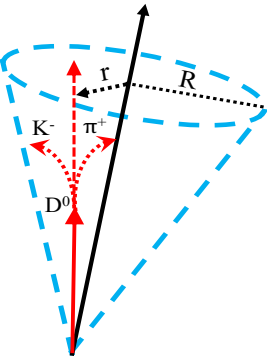
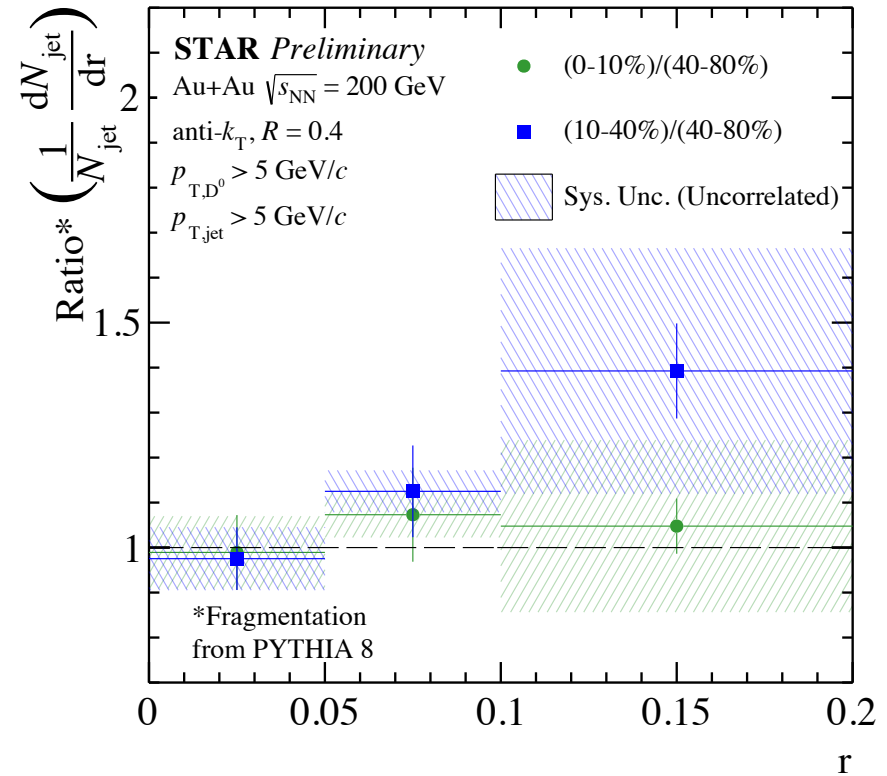
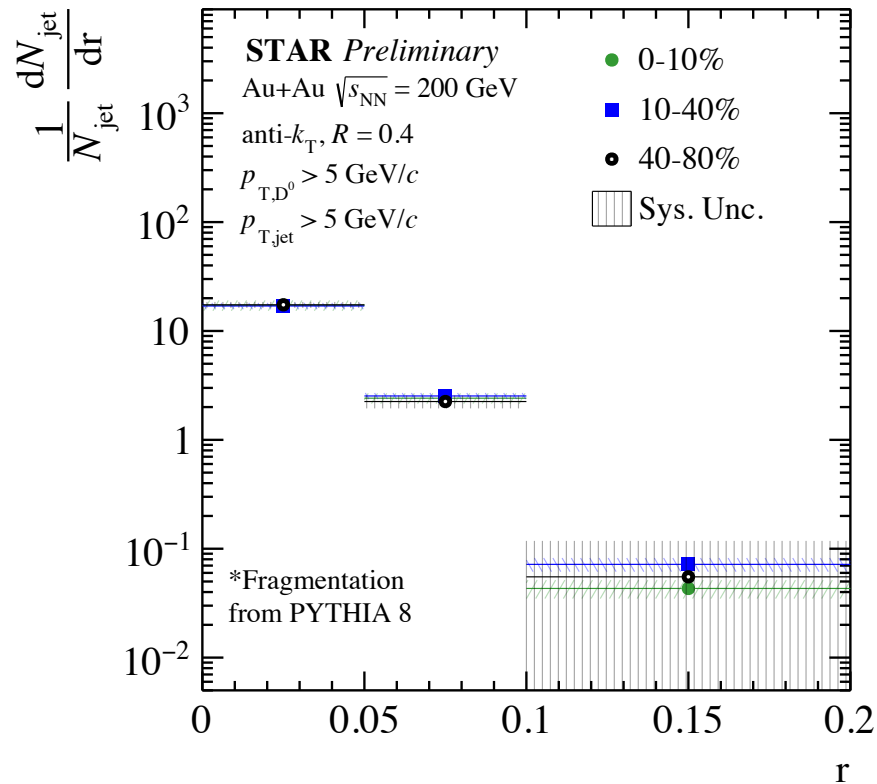


Energy dependence



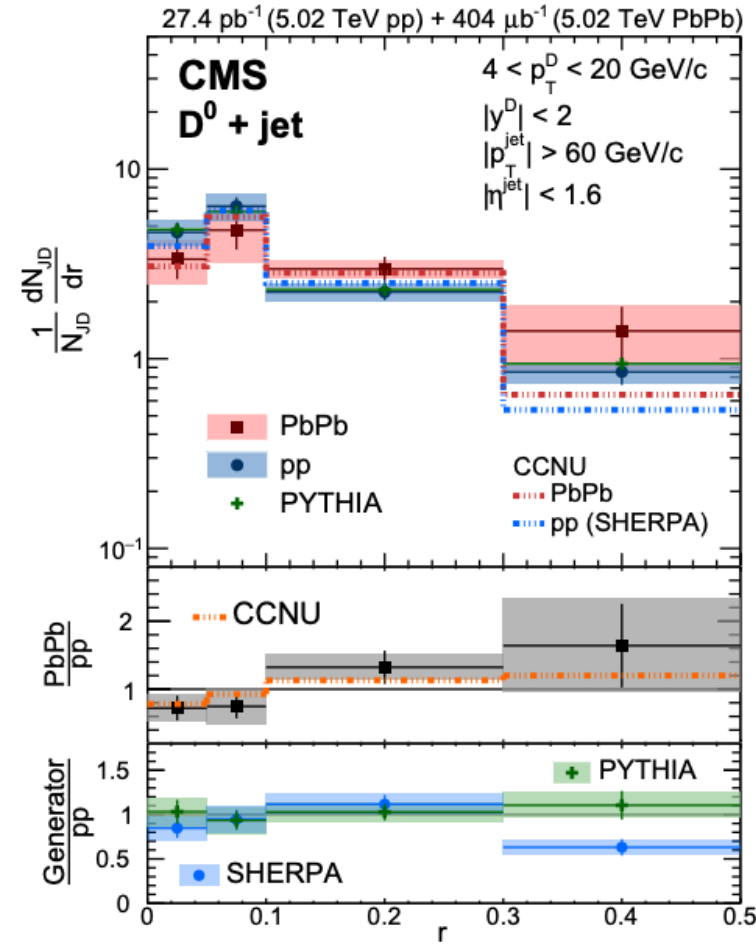
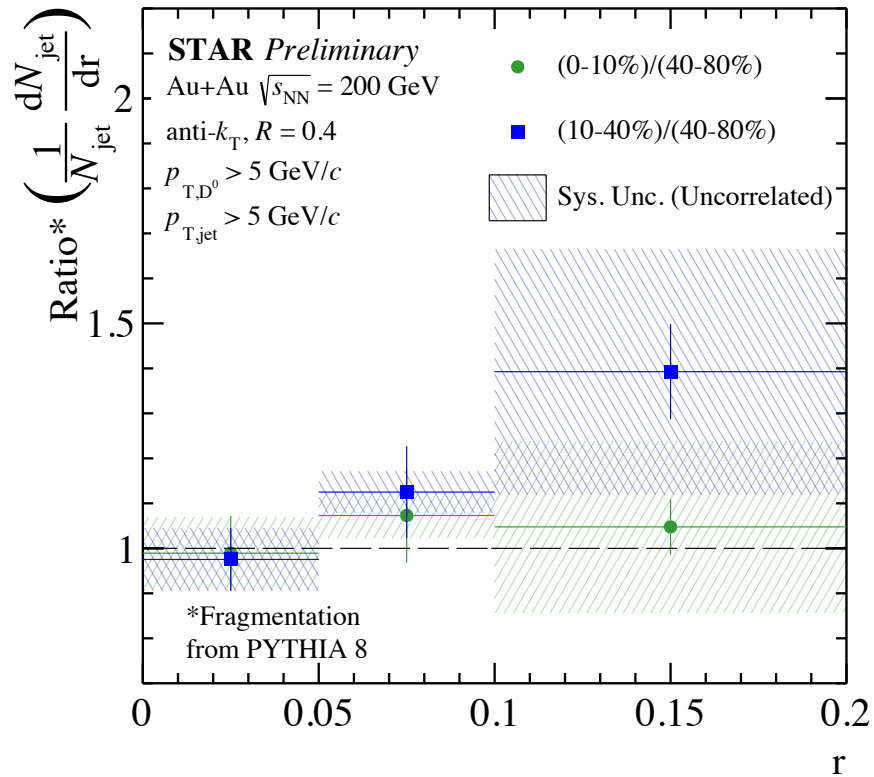
- Similar nuclear modifications of D^0 -tagged jets at 200 GeV from STAR and 5.02 TeV from ALICE

Radial Profile of D^0 Mesons in Jets



- For D^0 $p_T > 5$ GeV/c, the ratio of radial distributions is consistent with unity within uncertainties
- Extending the analysis to lower D^0 kinematics to further study D^0 diffusion

Energy dependence



- No significant diffusion seen for D^0 mesons in tagged jets at 200 GeV from STAR for $D^0 p_T > 5$ GeV/c and $p_{T,jet} > 5$ GeV/c
- Slight diffusion observed for D^0 mesons in tagged jets at 5.02 TeV from CMS for $4 < D^0 p_T < 20$ GeV/c and $p_{T,jet} > 60$ GeV/c

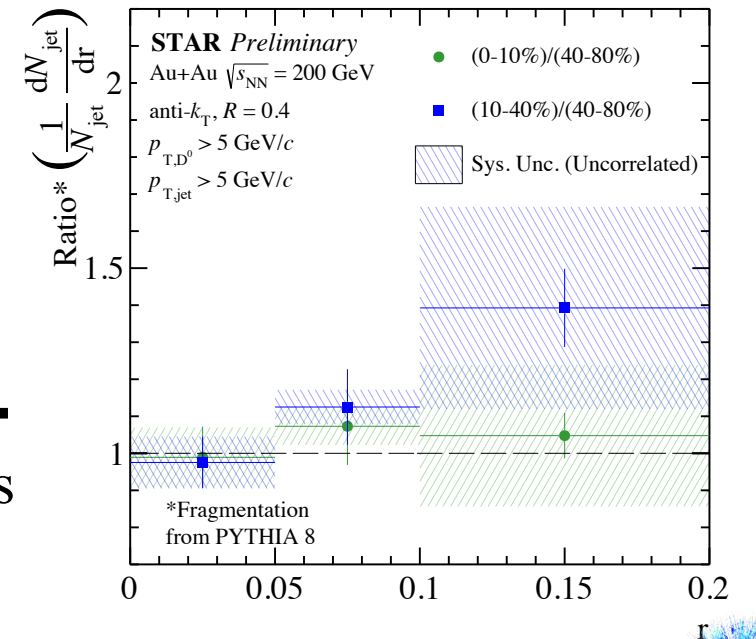
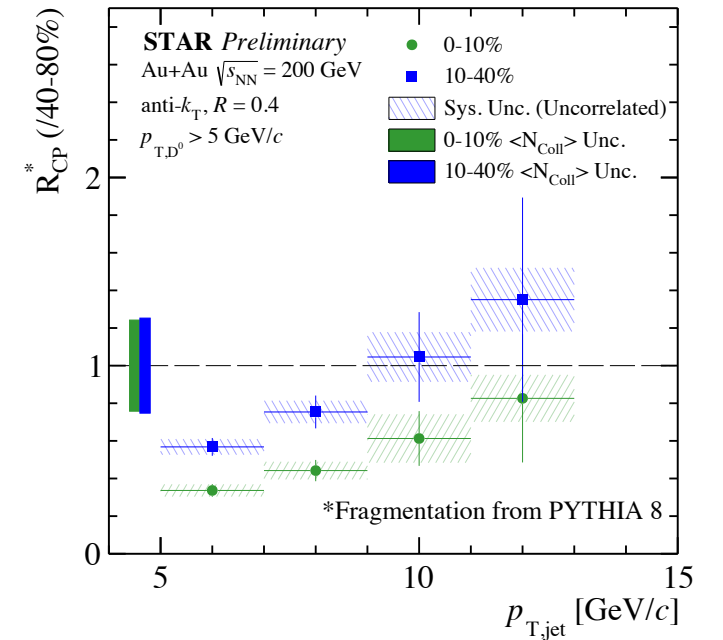


Summary

- First D^0 -tagged jet measurement at RHIC energies
- Fragmentation from PYTHIA 8 used for correcting jet momenta and substructure
 - ✓ Spectra for D^0 -tagged jets in central and mid-central events are suppressed with respect to peripheral events
 - ✓ Ratio of radial profiles of D^0 mesons in jets consistent with unity within uncertainties.

Outlook

- Measure fragmentation function for D^0 -tagged jets in Au+Au collisions
- Extend kinematic reach to low D^0 p_T to get closer to charm quark mass

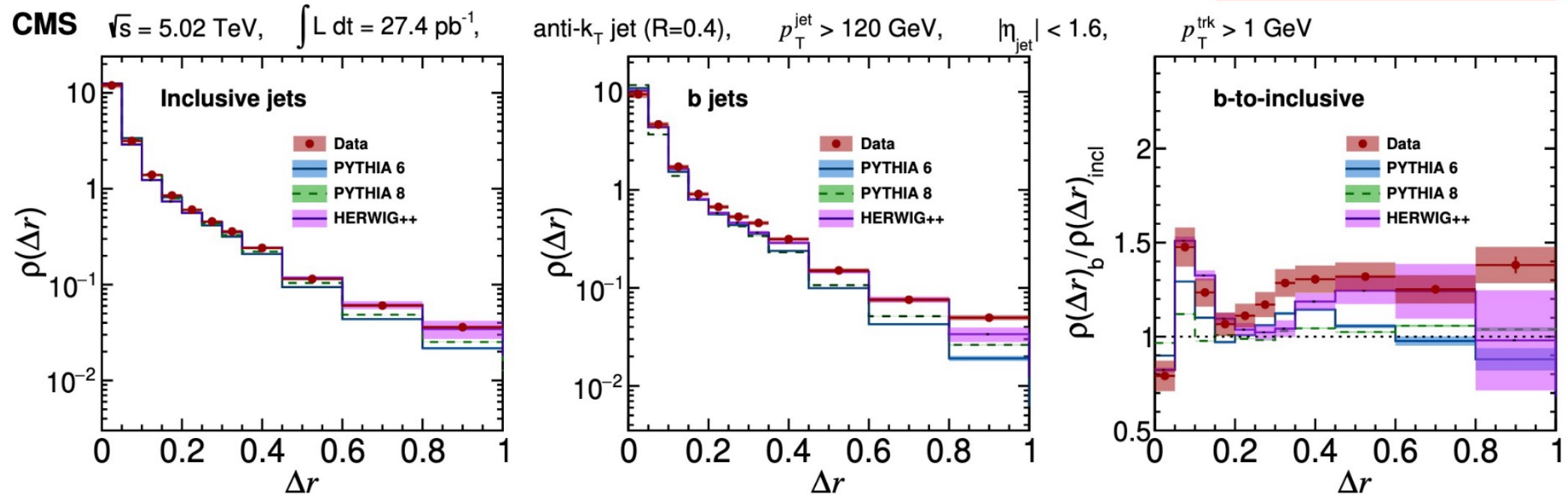


Backup



Differential jet shape for heavy quark in vacuum

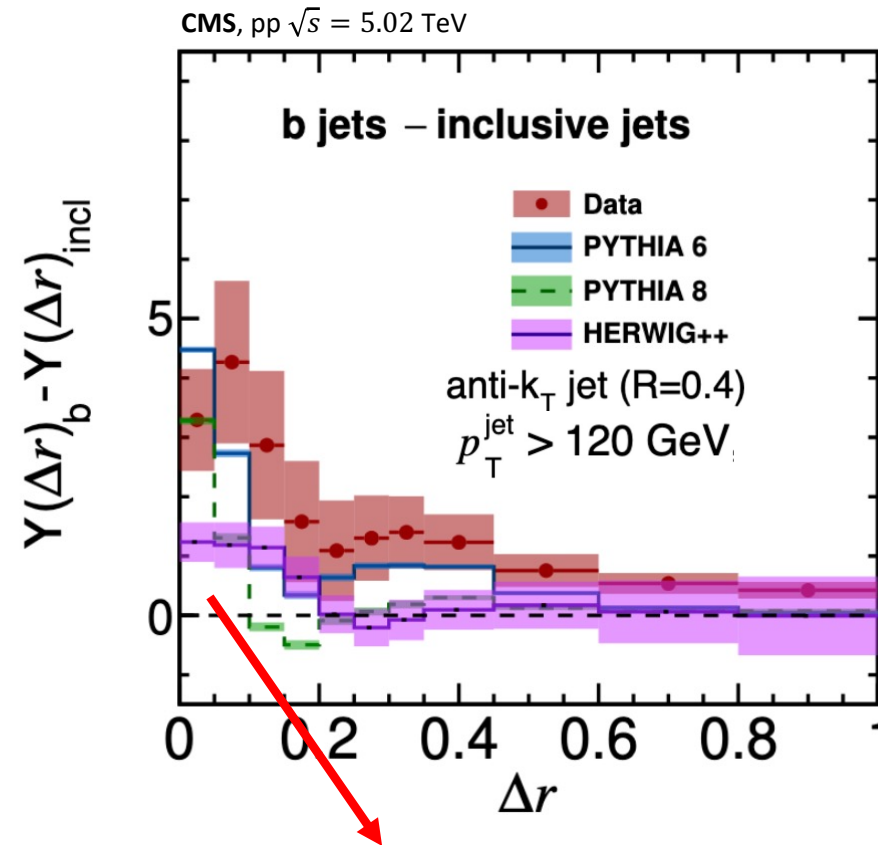
CMS, JHEP05 (2021) 054



Bottom quark jet (b-jets) shapes **modified in vacuum**, possibly due to dead cone

Fragmentation pattern for heavy quark

CMS, JHEP05 (2021) 054

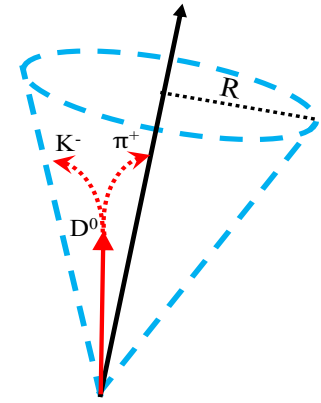


$$Y(\Delta r) = \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{track}}}{d\Delta r dp_{T,\text{track}}}$$

Higher yields of low p_T charged-particle close to jet axis in b-Jets vs inclusive jets in vacuum

~ Different fragmentation pattern for heavy quarks

D⁰-Jet Yield Extraction



Nucl. Instrum. Methods Phys. Res., A (2005) 555

*s*Plot

- Native class in RooStats, and widely used in HEP
- Unbinned maximum likelihood fit to invariant mass integrated over all kinematics
- $p_{T,jet}$ and radial distributions with all D⁰-tagged jet candidates using sWeights
- Easy to include reconstruction efficiencies versus D⁰ kinematics

$${}_s\mathcal{P}_n(m_{K\pi,i}) = \frac{\sum_{j=1}^{N_T} V_{nj} f_j(m_{K\pi,i})}{\sum_{k=1}^{N_T} N_k f_k(m_{K\pi,i})}$$

Unbinned max. likelihood fit

n = n -th fit component(sig/bkg)

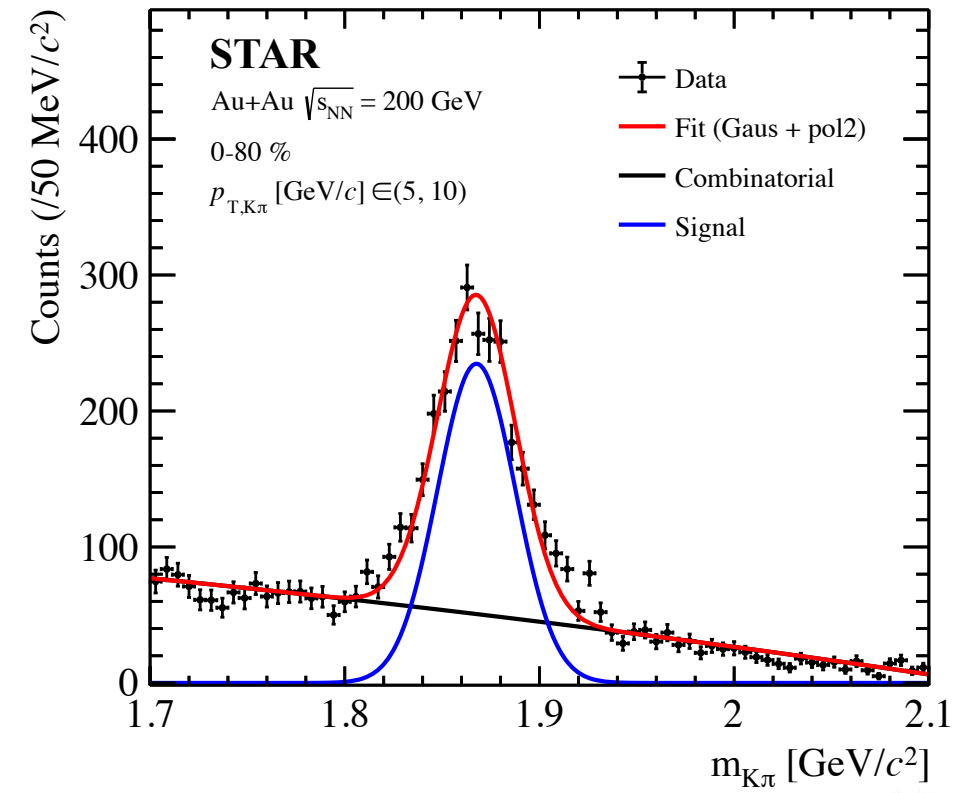
N_k = k -th yield (T=2)

$f_k(m_{K\pi,i})$ = per-event PDF value with k^{th} hypothesis

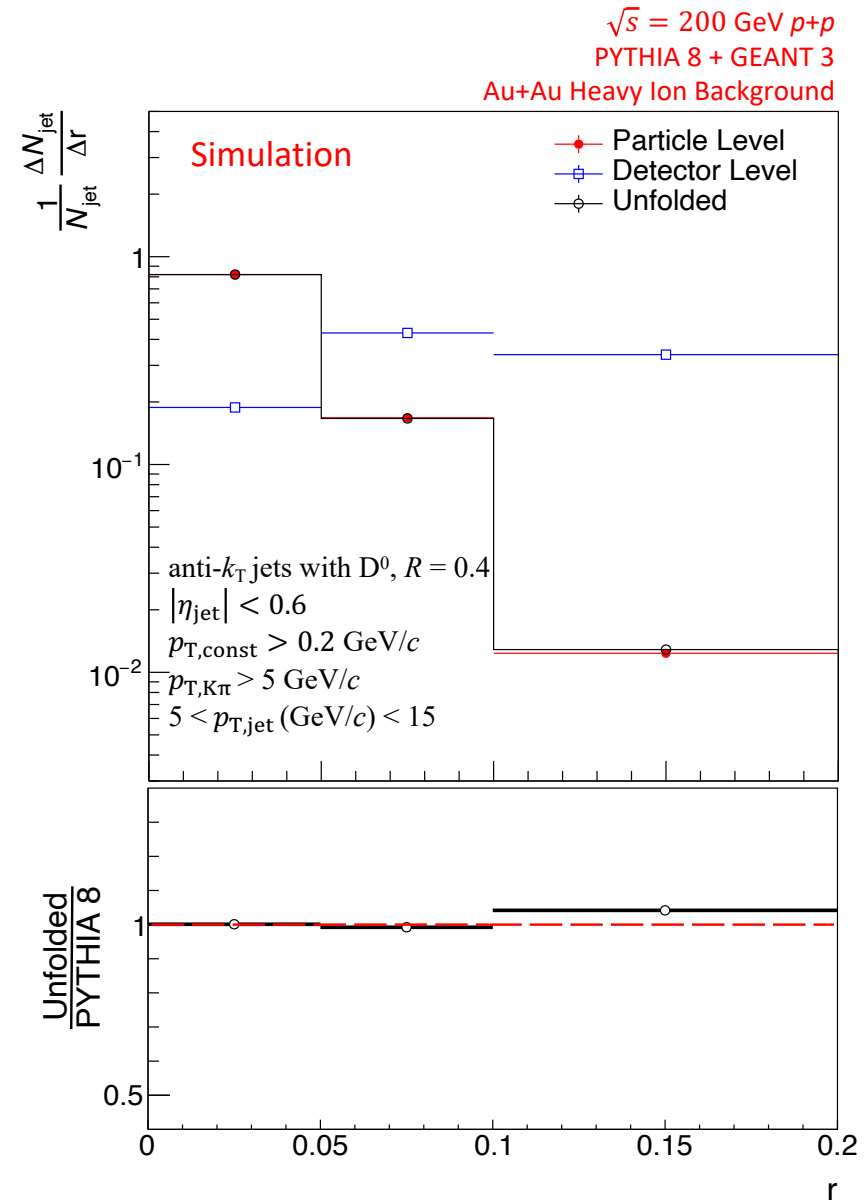
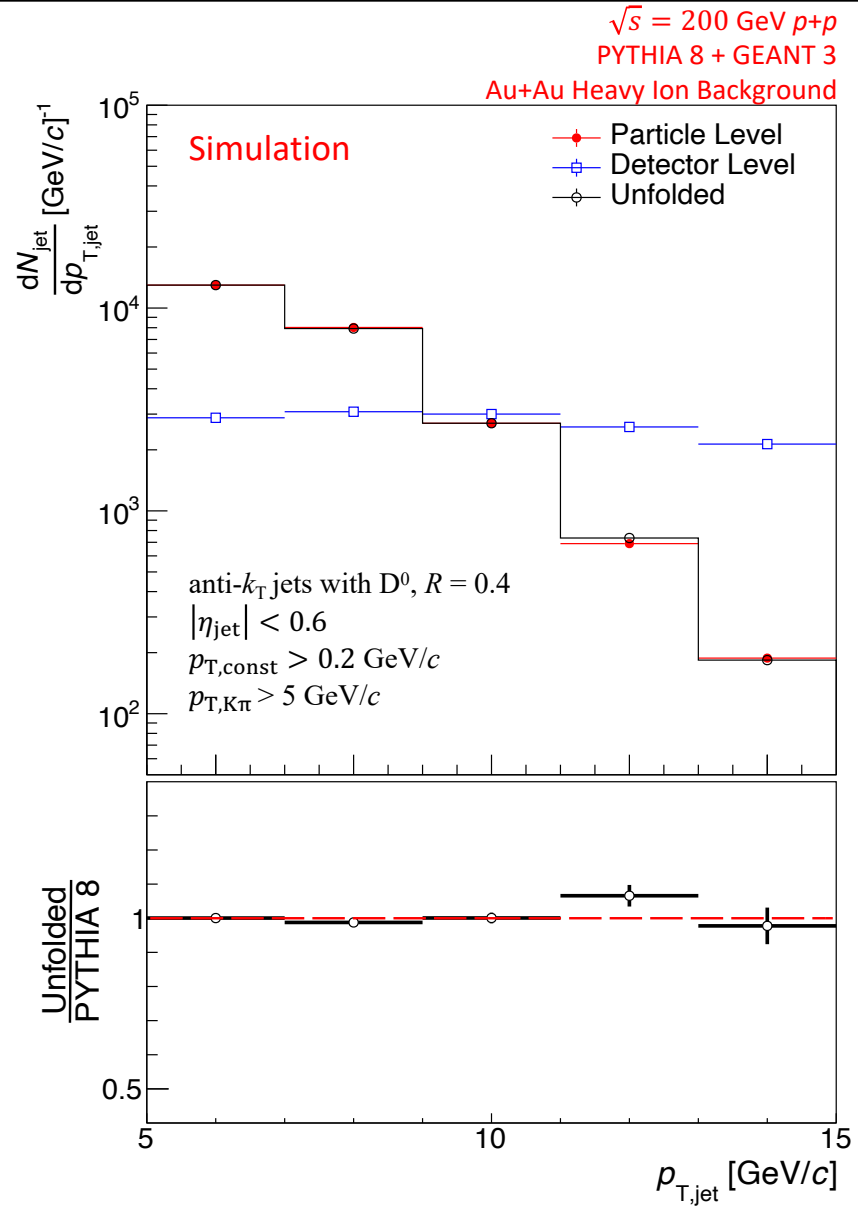
V = cov. matrix

Efficiency Correction ➔

$${}_s\mathcal{P}_n(m_{K\pi,i}) \rightarrow \frac{{}_s\mathcal{P}_n(m_{K\pi,i})}{\epsilon(m_{K\pi,i})}$$

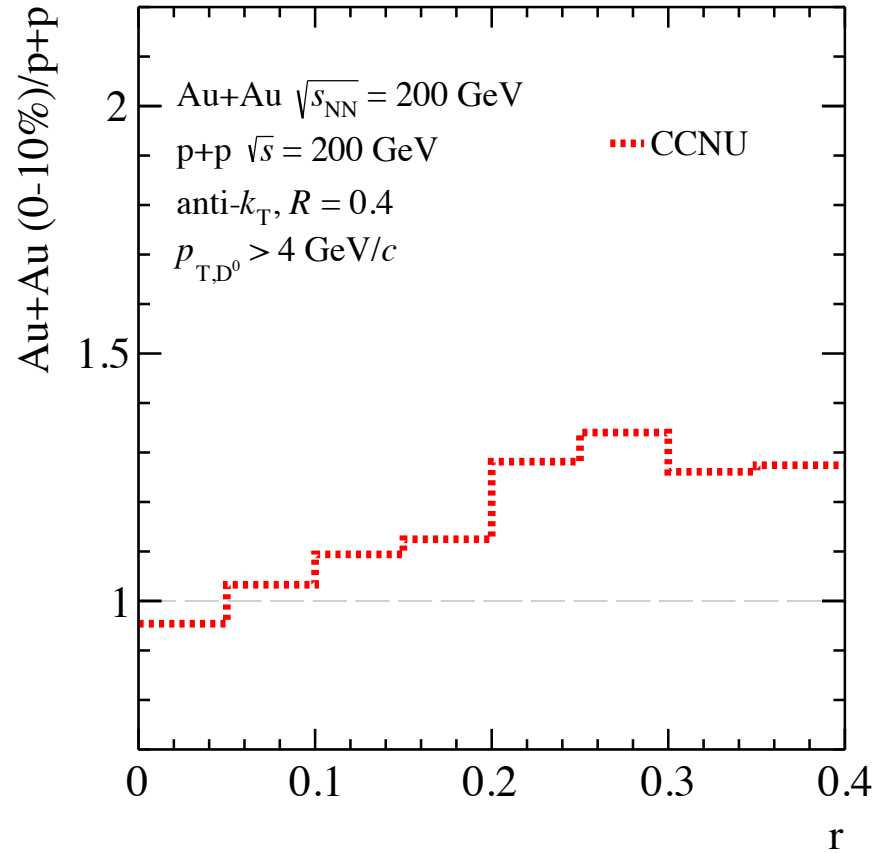


Closures For Unfolding

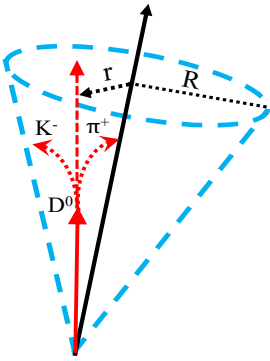
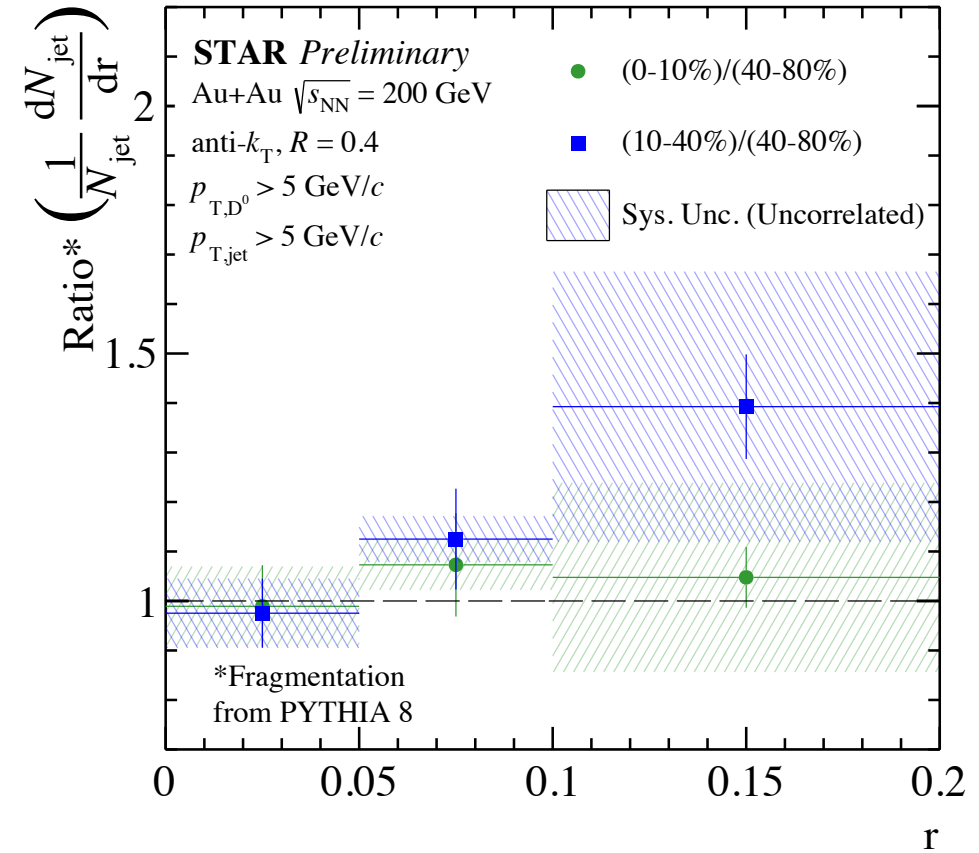


Radial Profile: Data vs Model

CCNU, Eur. Phys. J. C79 (2019) 789



Note: calculation uses $p+p$ as reference



Theory calculation shows small amount of diffusion - consistent with data within uncertainties



Sources of Systematics

Dominant systematic uncertainties are:

- Difference in yield extraction from the two methods, $sPlot$ and like sign subtraction
- Systematics from D^0 reconstruction (Details here: Phys. Rev. C 99 (2021) 034908)

Sub-dominant systematic uncertainties are:

- FONLL as a prior vs PYTHIA 8 as a prior for the jet spectrum for unfolding
- Iteration parameter in unfolding

