

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

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Science

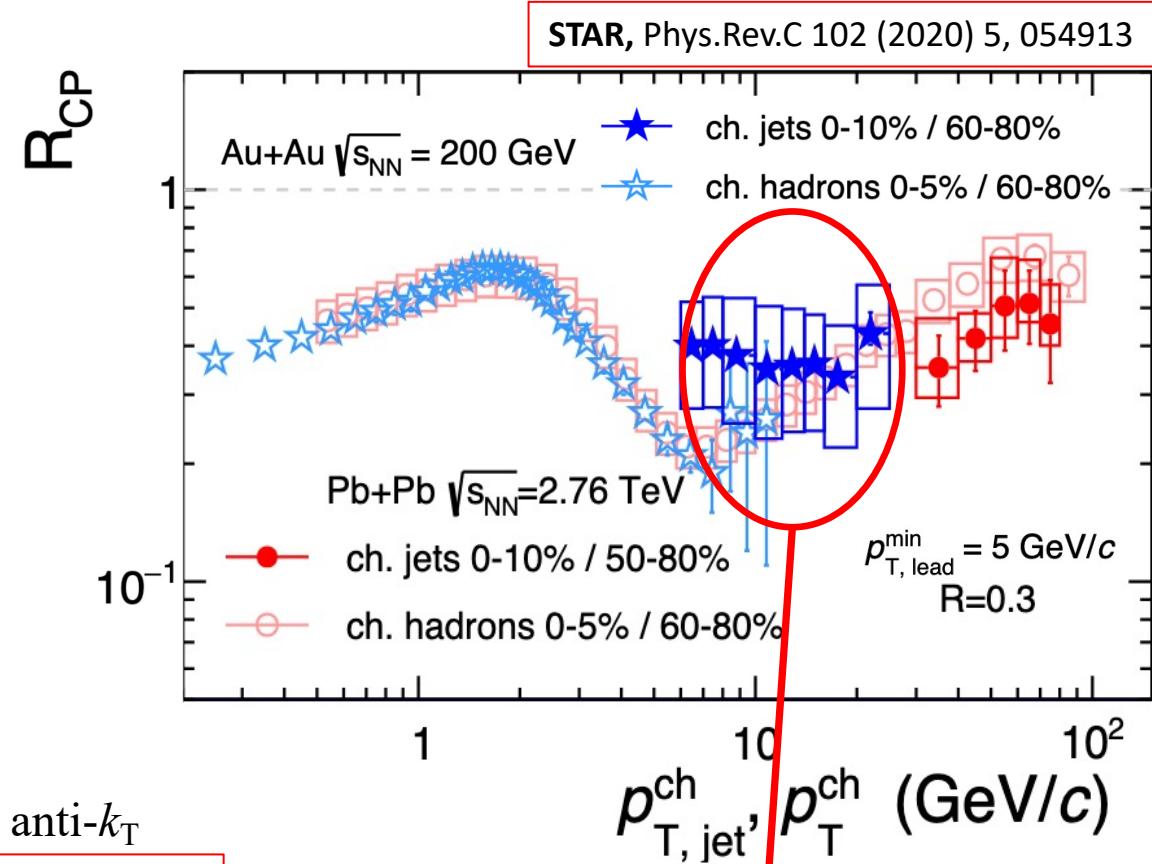
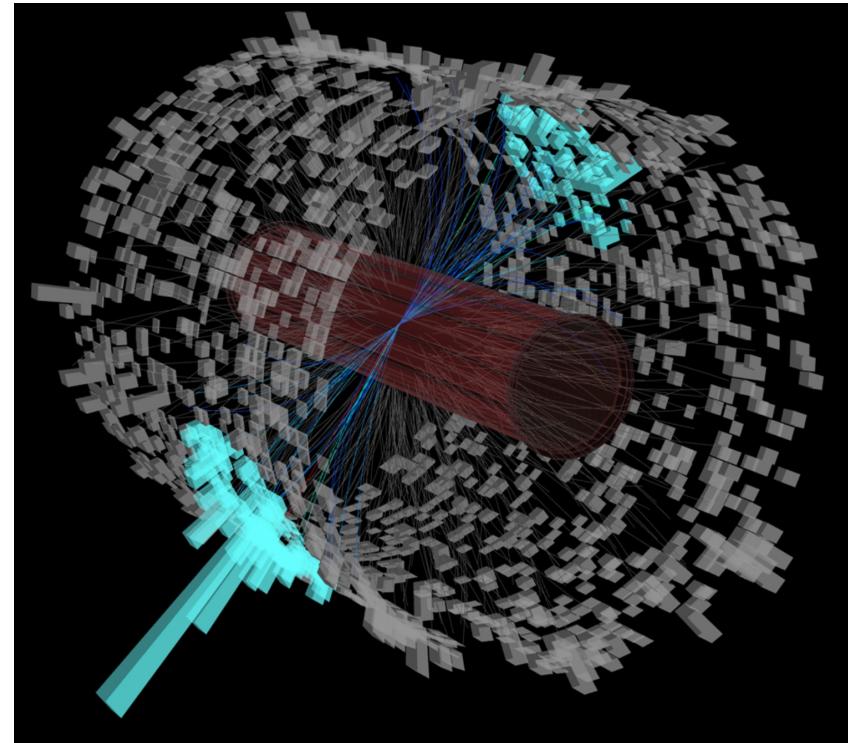


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Jets in Heavy Ion Collisions

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

ALICE, JHEP03 (2014) 013



- 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

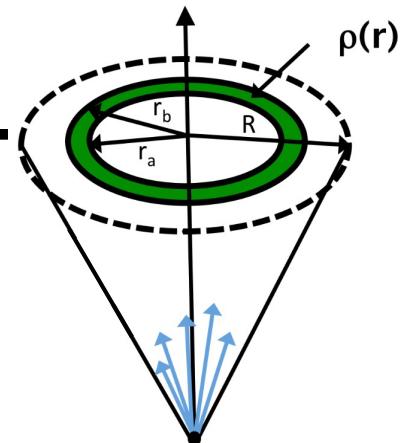
FASTJET, Phys. Lett. B 641 (2006) 57-61

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

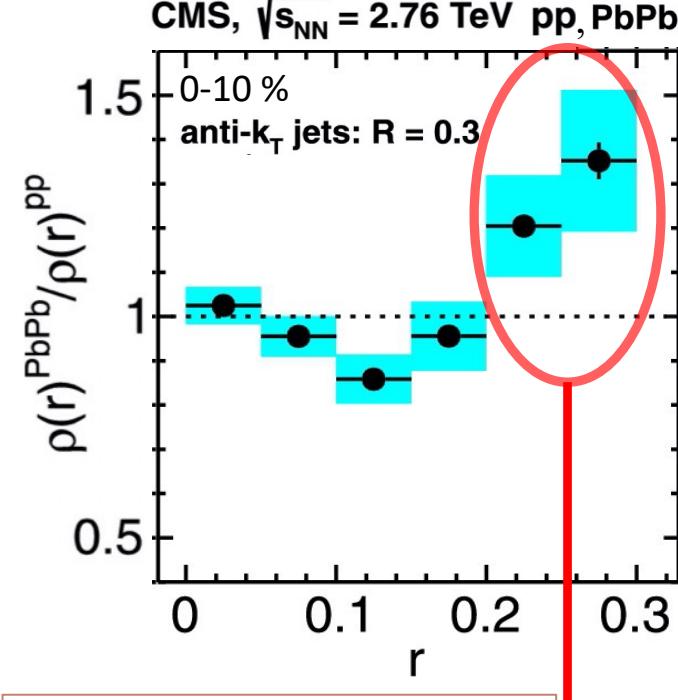
Motivation

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

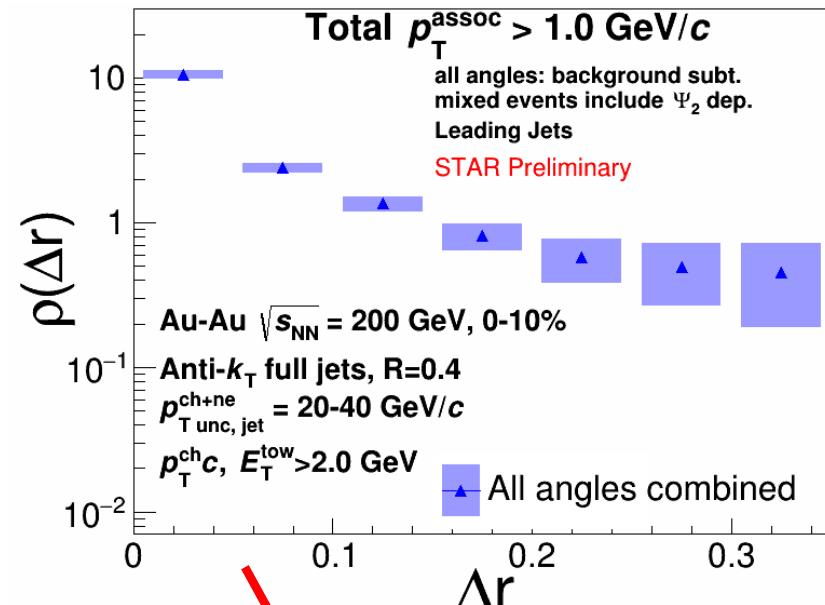
$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$



CMS, $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV pp, PbPb}$



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



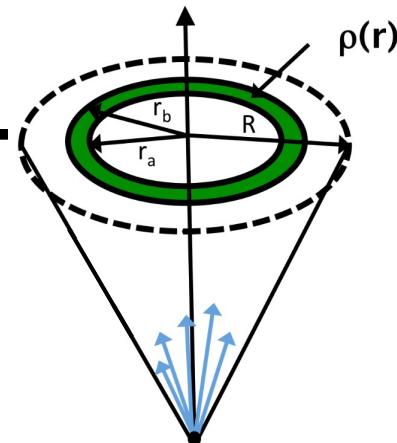
Similar pp measurement from STAR underway

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

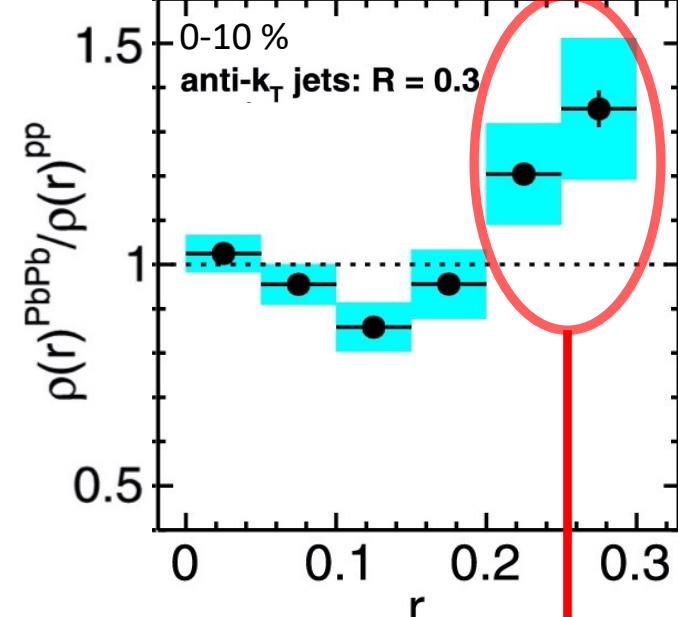
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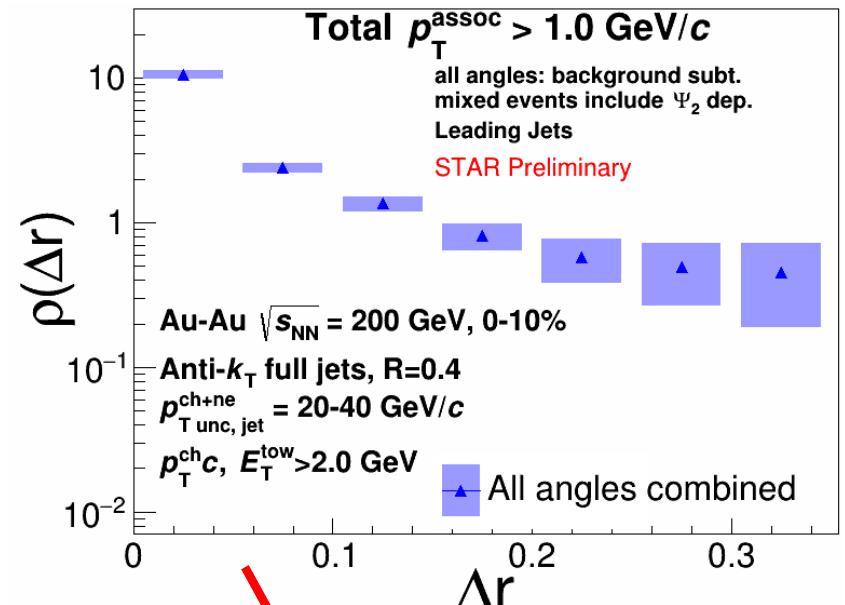


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CMS, Phys. Lett. B 730 (2014) 243

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



Similar pp measurement from STAR underway

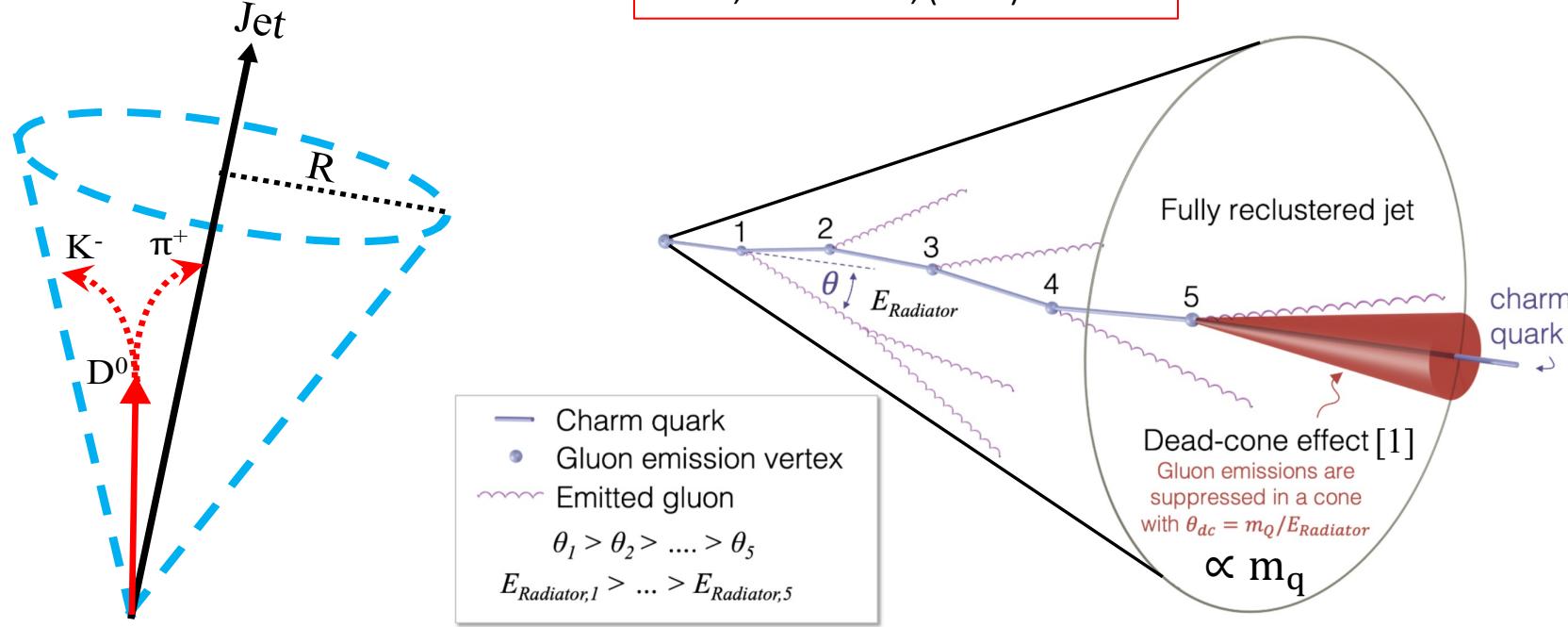
Possible mechanisms:

- Multiple scattering
- Medium-induced bremsstrahlung
- Medium response

Dependent on the mass of the underlying parton

Motivation to study heavy-flavor jets

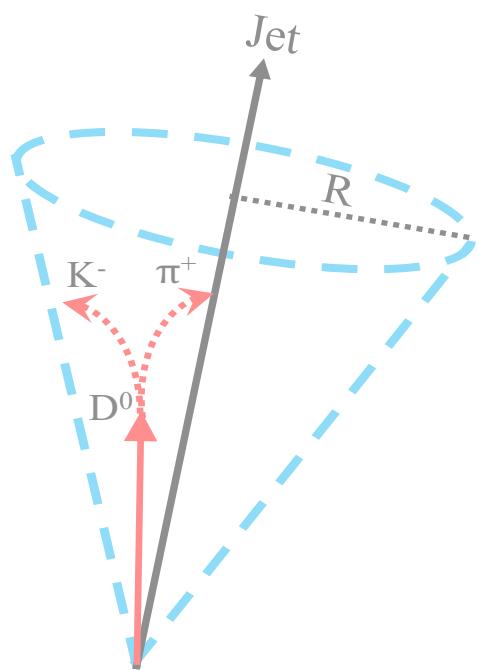
Heavy Flavor Tagged Jets



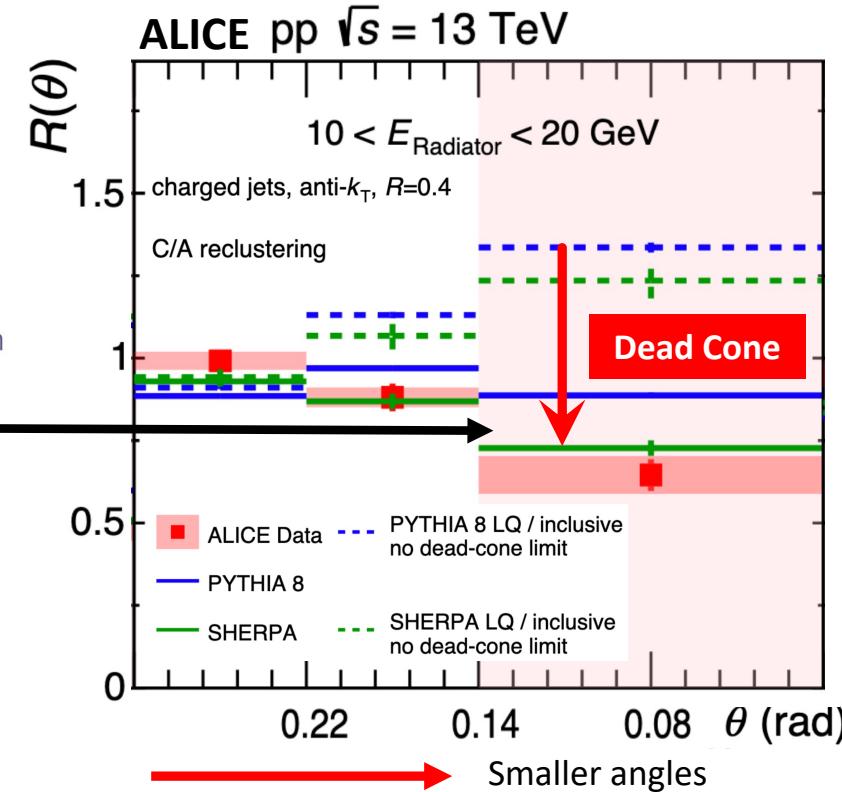
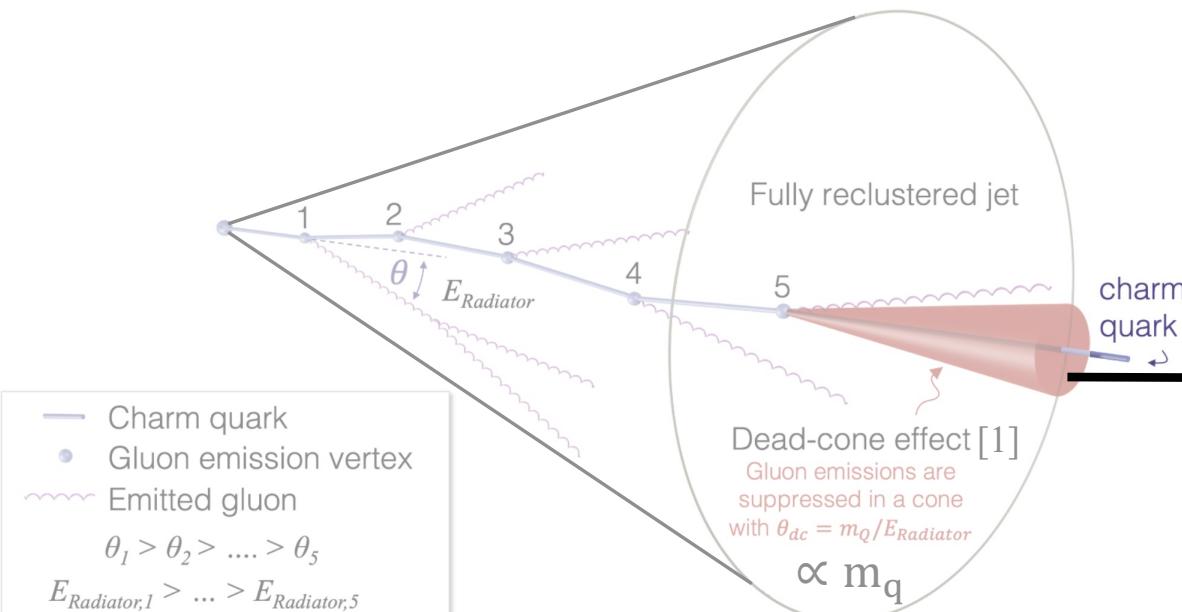
[1] J. Phys. G: Nucl. Part. Phys. **17** 1602 (1991)

Heavy Flavor Tagged Jets

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



ALICE, Nature 605, (2022) 440-446

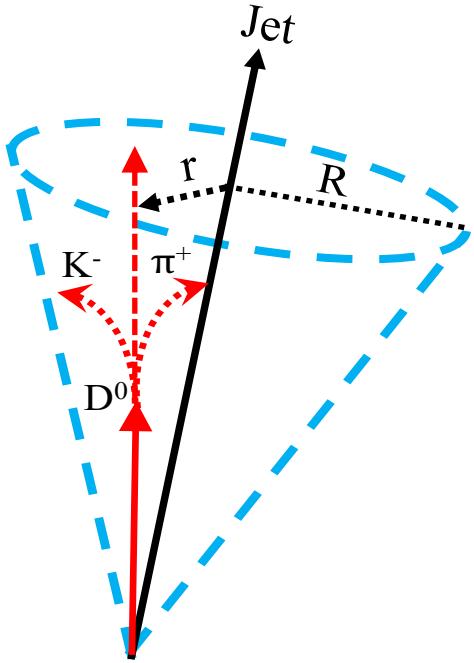


Heavy-flavor emission spectra at small angles suppressed due to dead-cone effect [1]

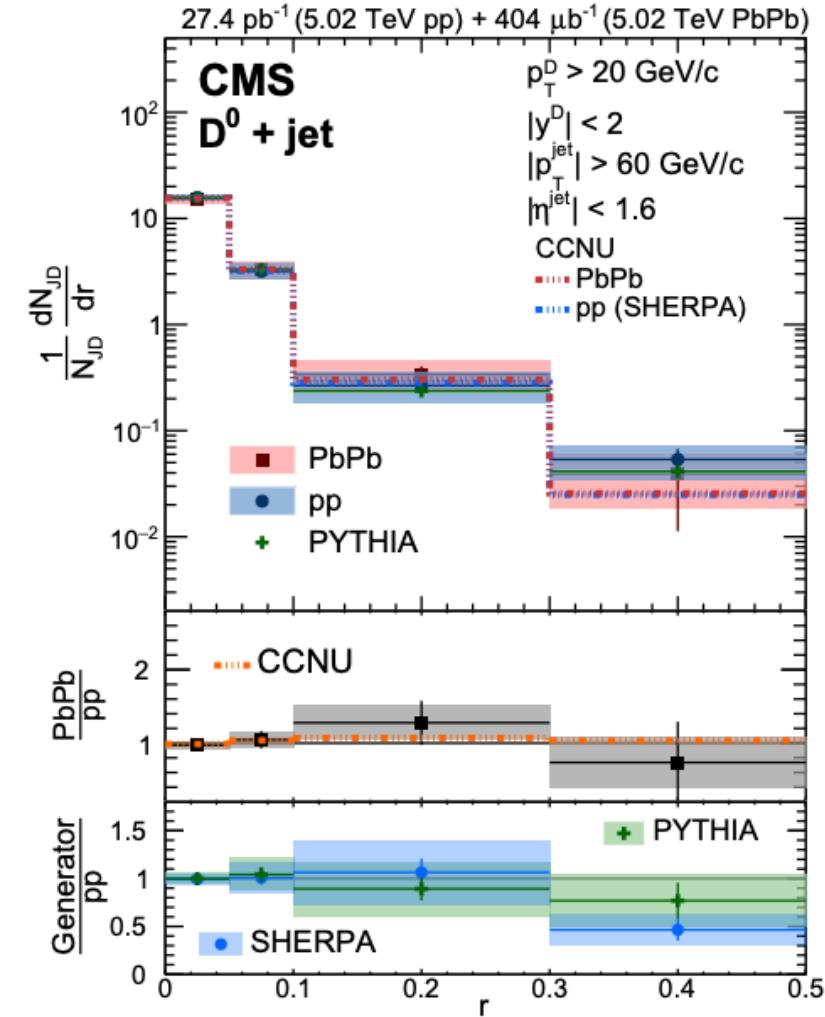
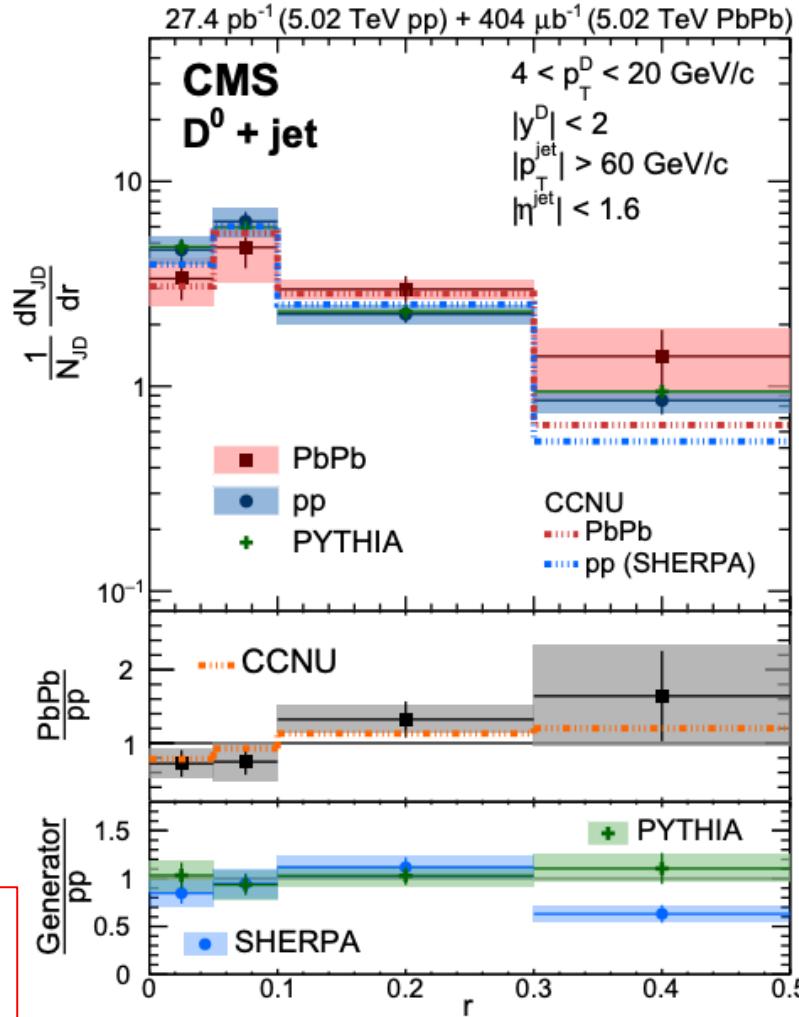
[1] J. Phys. G: Nucl. Part. Phys. **17** 1602 (1991)

Heavy Flavor Tagged Jets

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

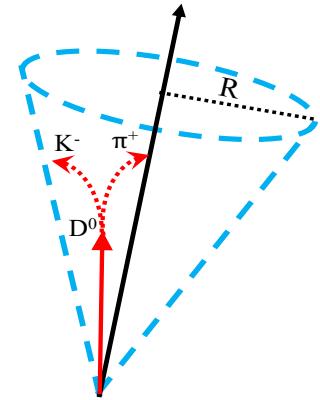


Low p_T D^0 mesons slightly diffused in the presence of QGP at LHC



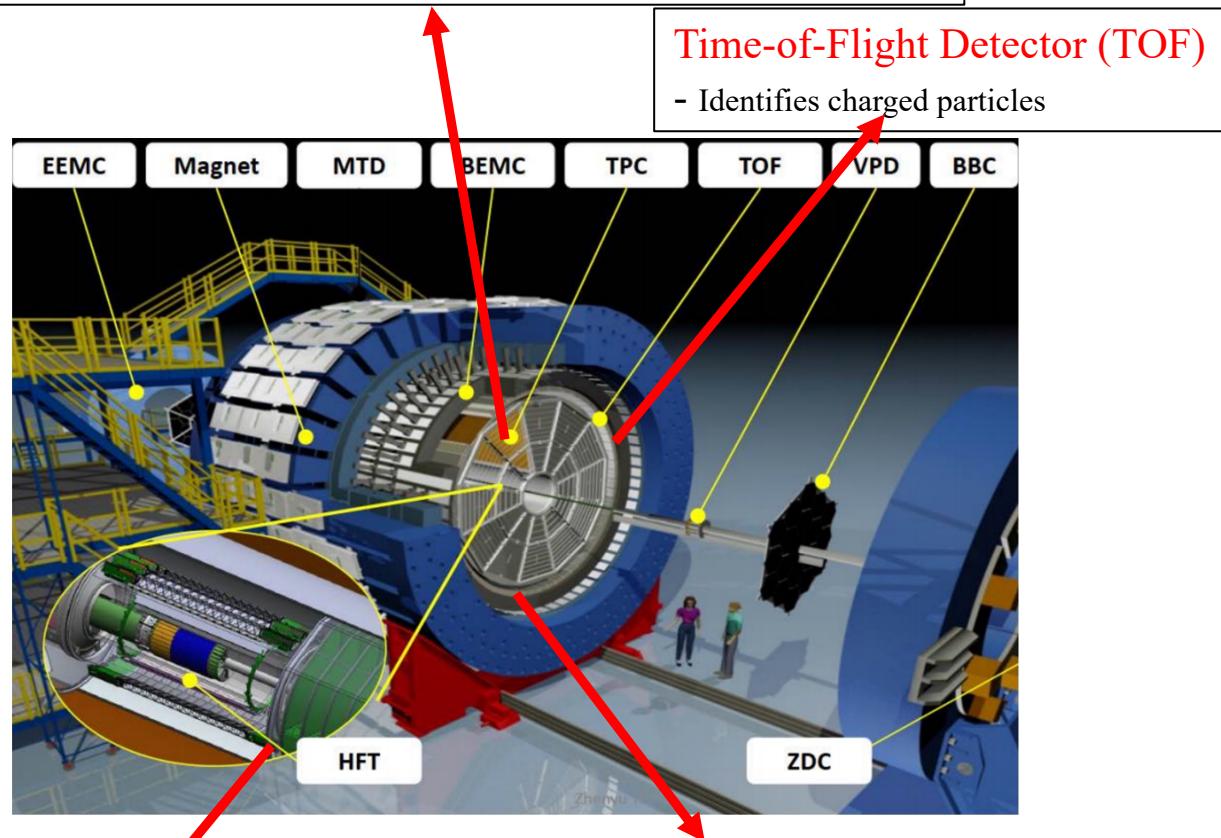
- Lower p_T D^0 mesons accessible at RHIC energies
- Contribution from the underlying background is smaller at RHIC for a given jet p_T

STAR Detector & Selection Criteria



Time Projection Chamber (TPC)

- Measures momentum, track trajectory, and identifies charged particles



Barrel Electromagnetic Calorimeter (BEMC)

- Measures neutral component of energy in jets

Heavy Flavor Tracker (HFT)

- Improves position resolution for tracks

Event Selection:

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

Constituent Selection:

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

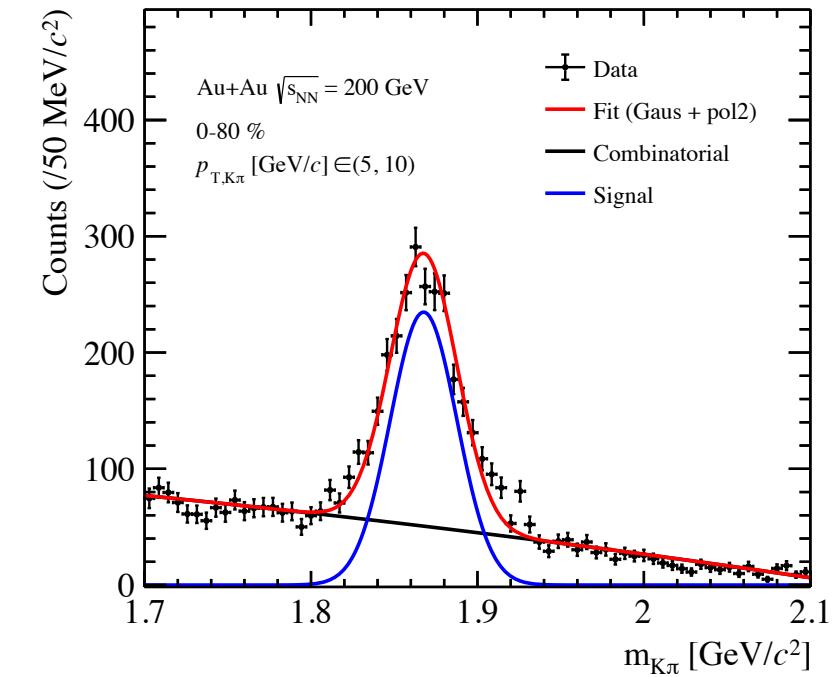
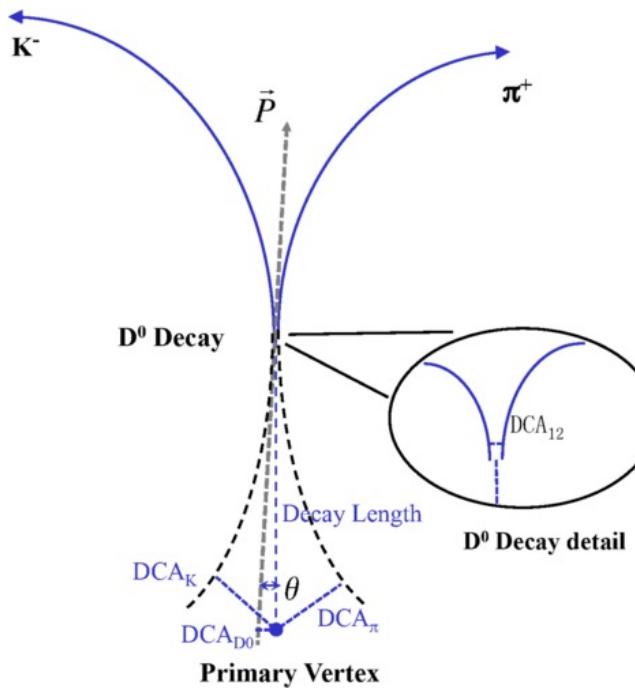
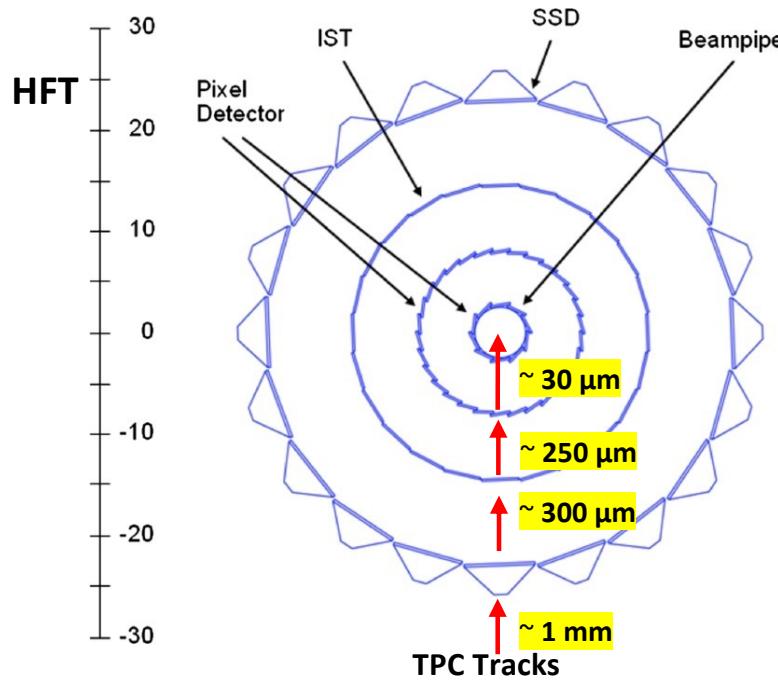
D^0 Jet Selection:

- Anti- k_{T} full jets of radius $R = 0.4$, area-based background subtraction
- $|\eta_{\text{Jet}}| < 0.6$

D⁰ Reconstruction

- Kaons and Pions identified using TPC and TOF

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

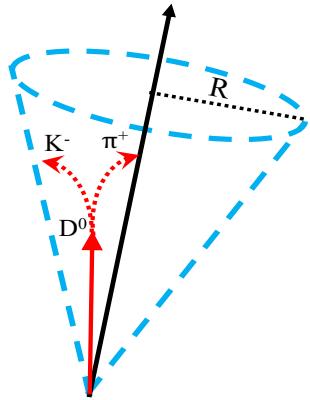


Topological cuts on the D⁰ candidates improve signal significance

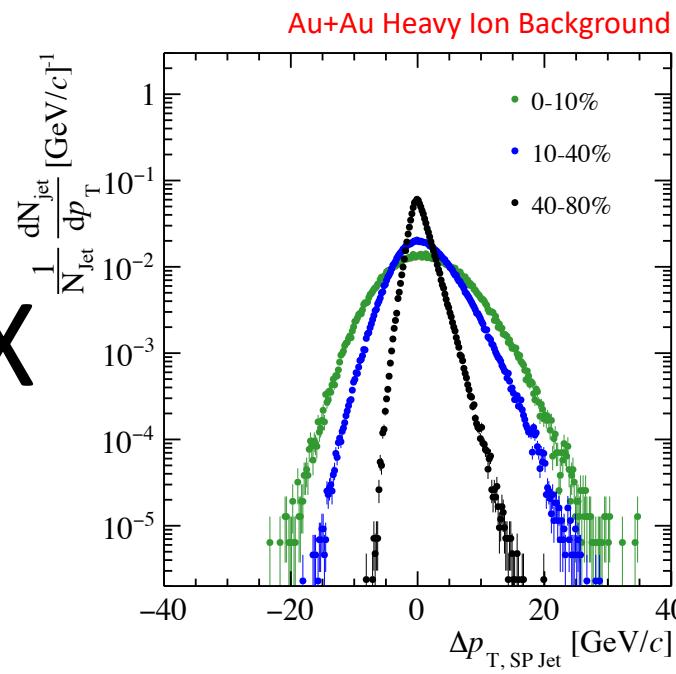
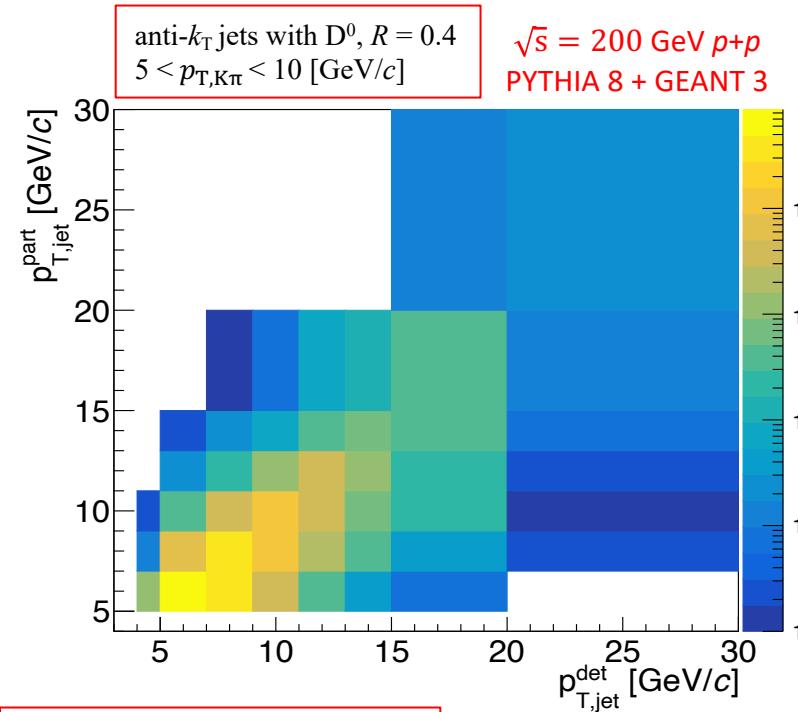
Yield is calculated using sPlot method [1]

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

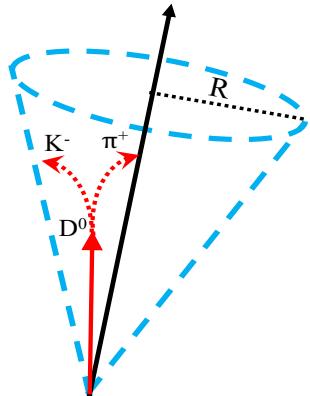
Correction to the Jet Yield



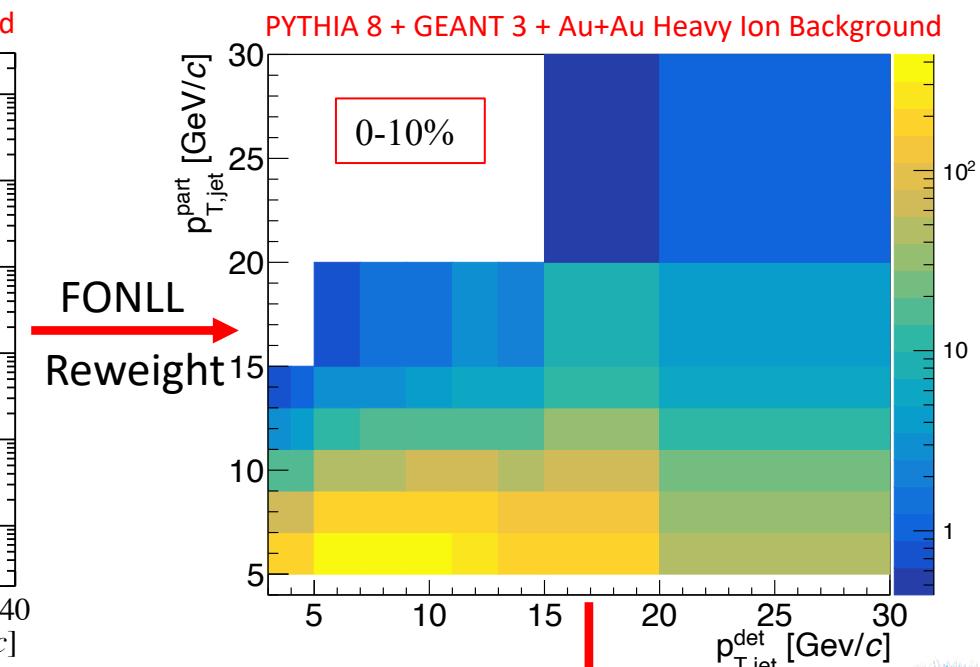
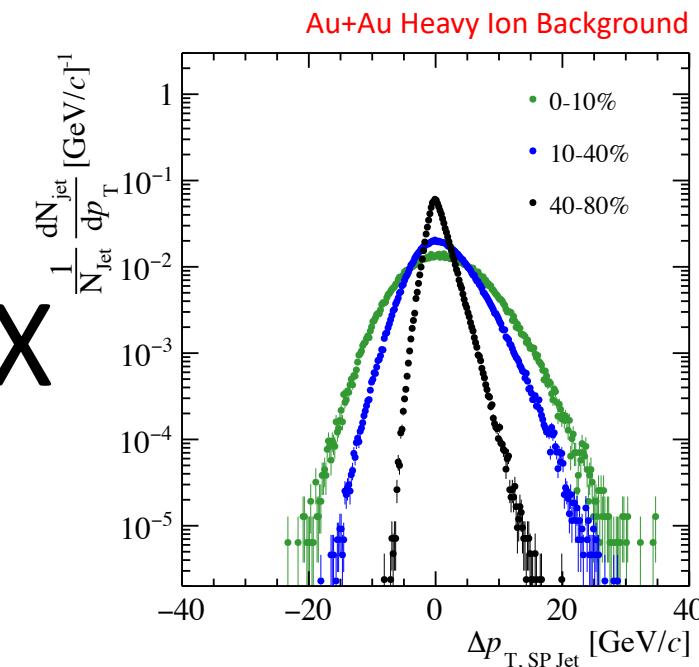
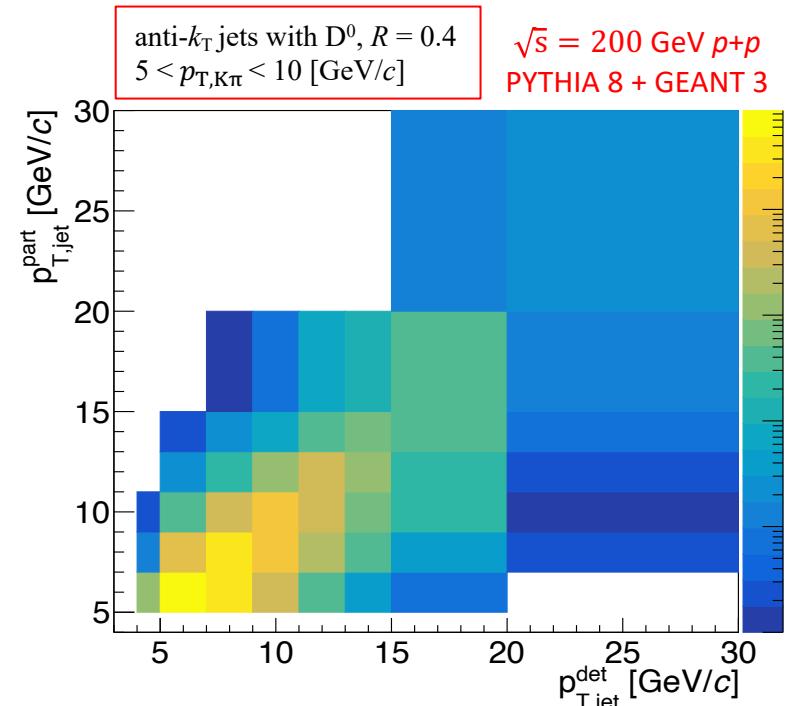
1. Response matrix for $p+p \sqrt{s} = 200$ GeV from PYTHIA and GEANT3 to mimic the detector response
2. Single Particle (SP) embedding in heavy ion events to model fluctuations in area-based background subtraction
3. Reweight PYTHIA with c-quark distribution from FONLL [1] to modify the shape of the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



Correction to the Jet Yield



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[1]. FONLL, JHEP03 (2001) 006

October 15, 2022

Diptanil Roy, Hot Quarks 2022

Complete response matrix to unfold $p_{T,Jet}$

11



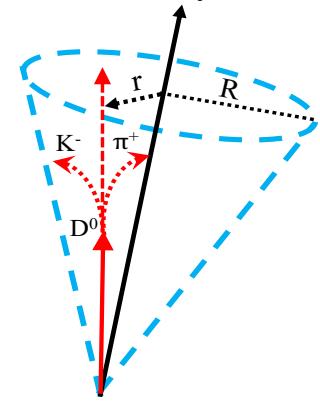
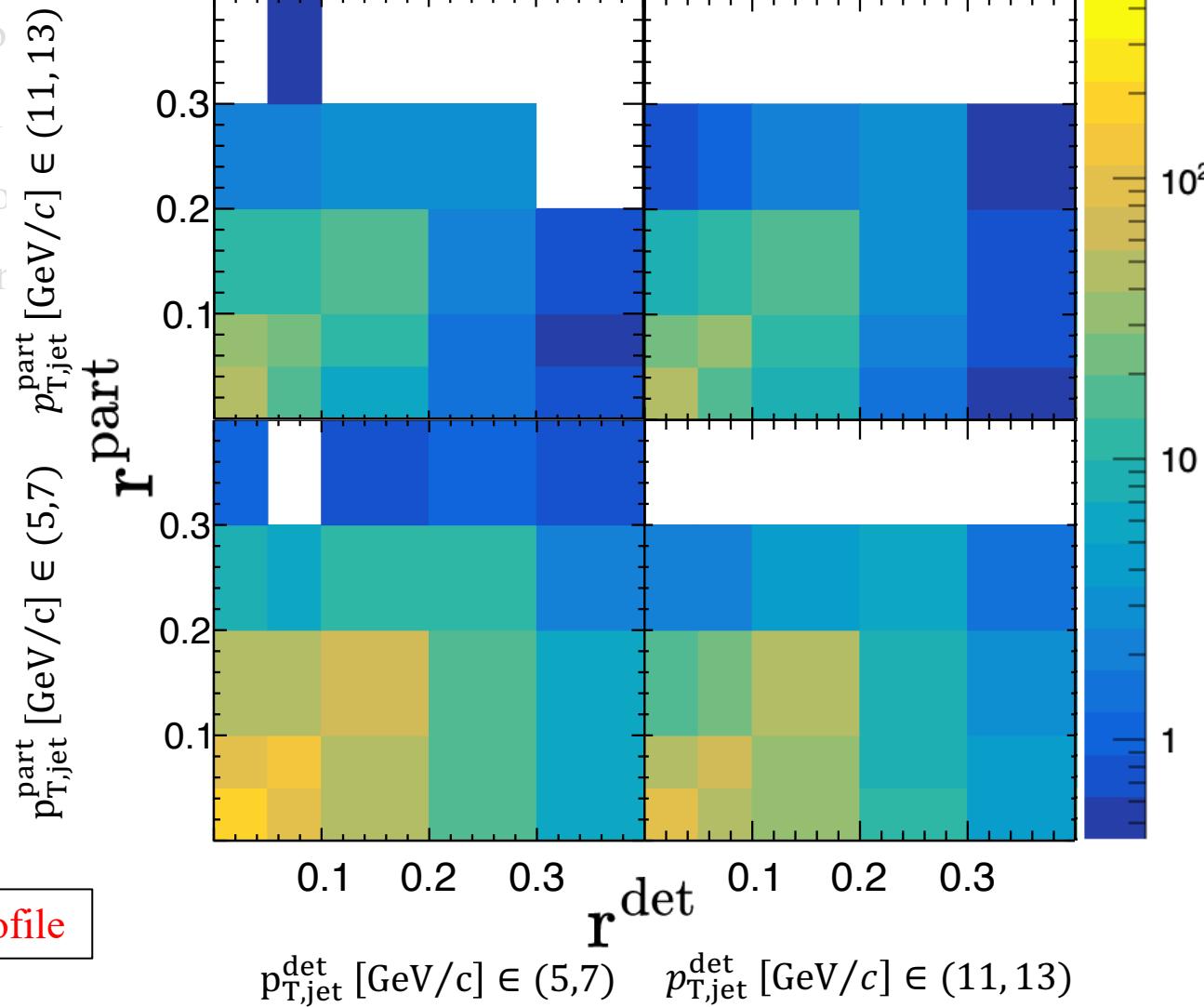
Correction to the Jet Radial Profile

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 $\Lambda_c \rightarrow D^0 + \pi^\pm$
5. Systematics from variation in fragmentation

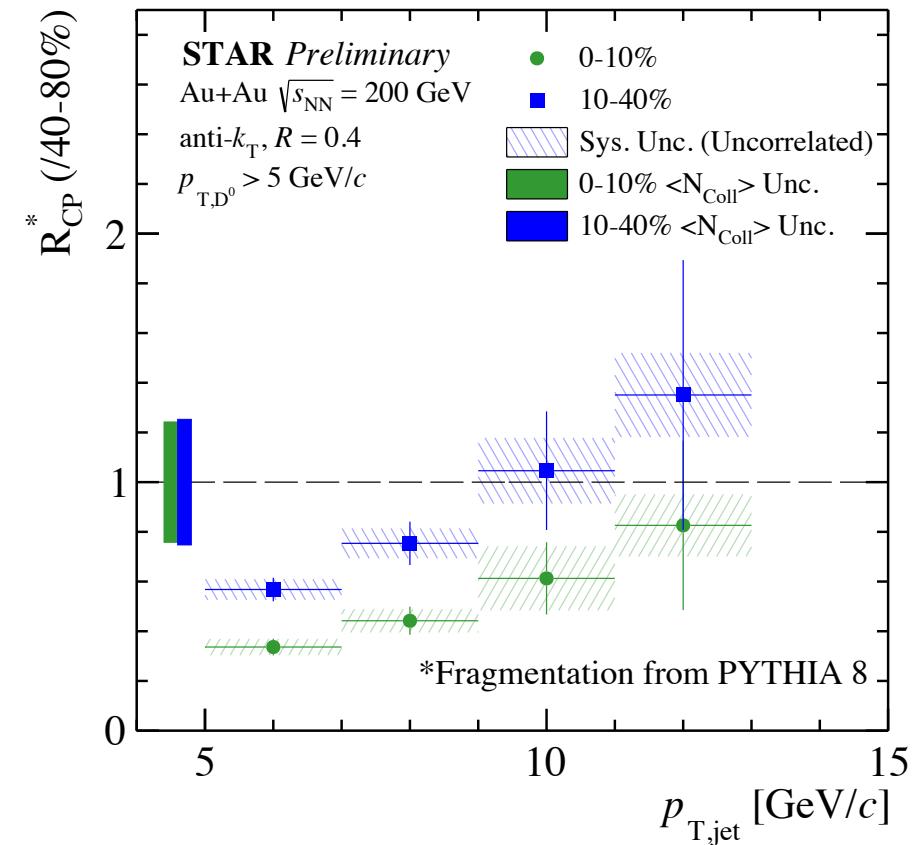
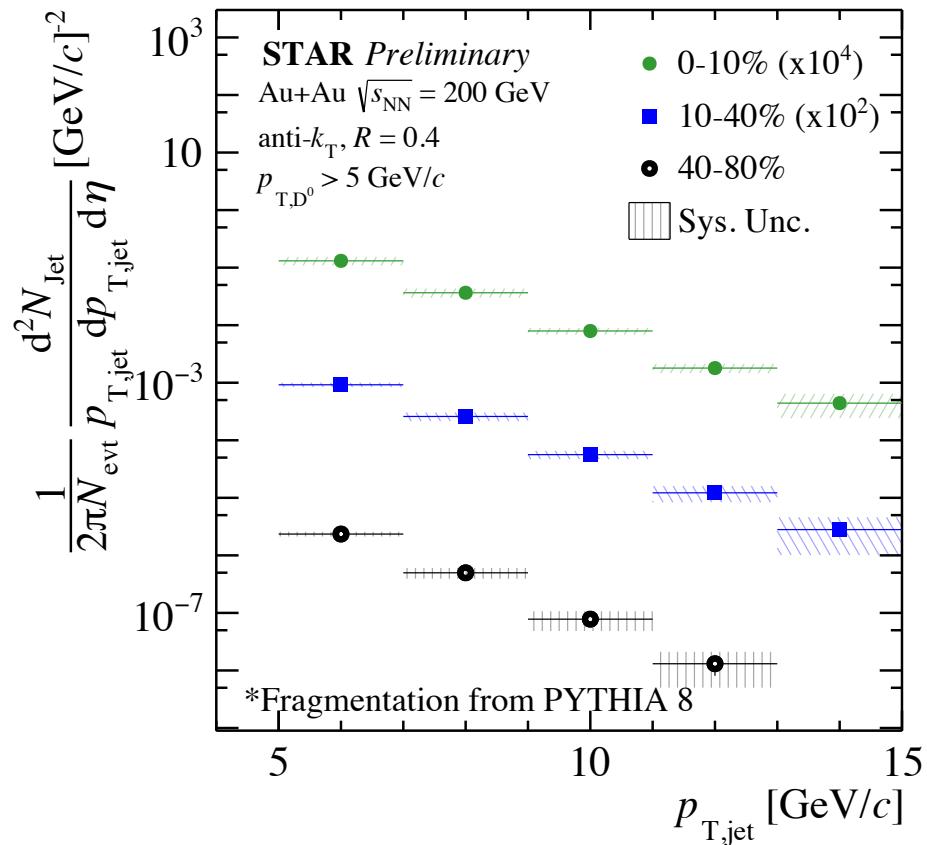
anti- k_T jets with D^0 , $R = 0.4$
 $|\eta_{jet}| < 0.6$
 $p_{T, \text{const}} > 0.2$ GeV/c
 $5 < p_{T, K\pi} < 10$ (GeV/c)

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

Complete 4D response matrix to unfold radial profile

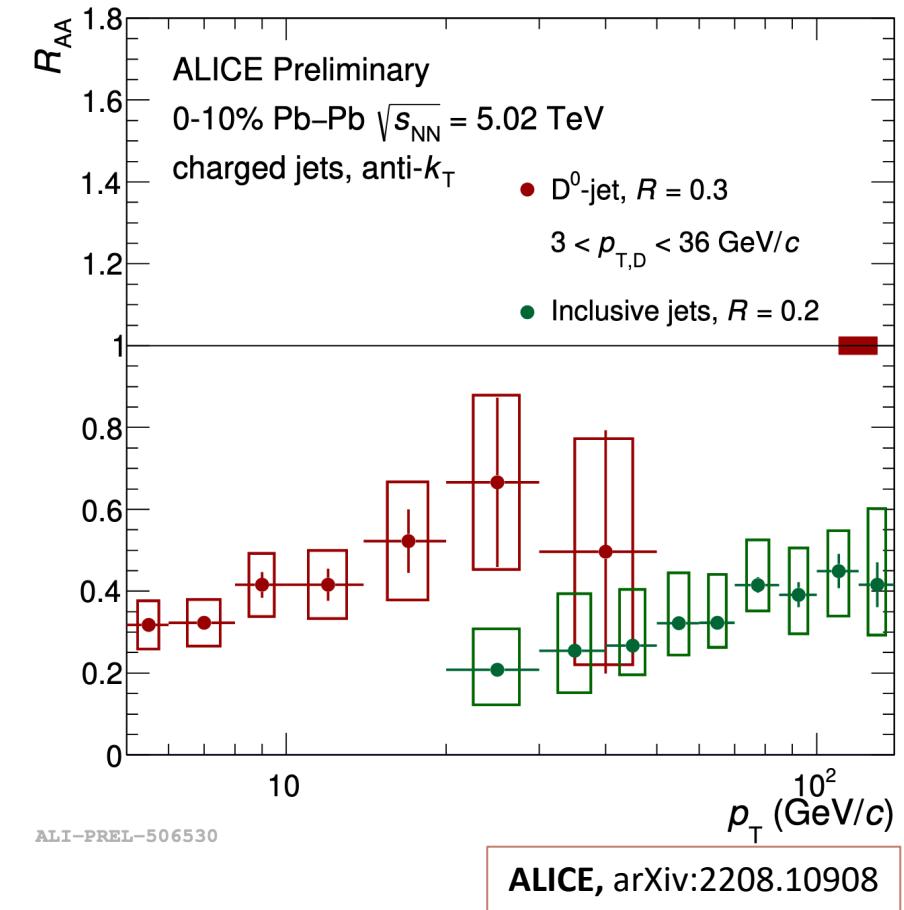
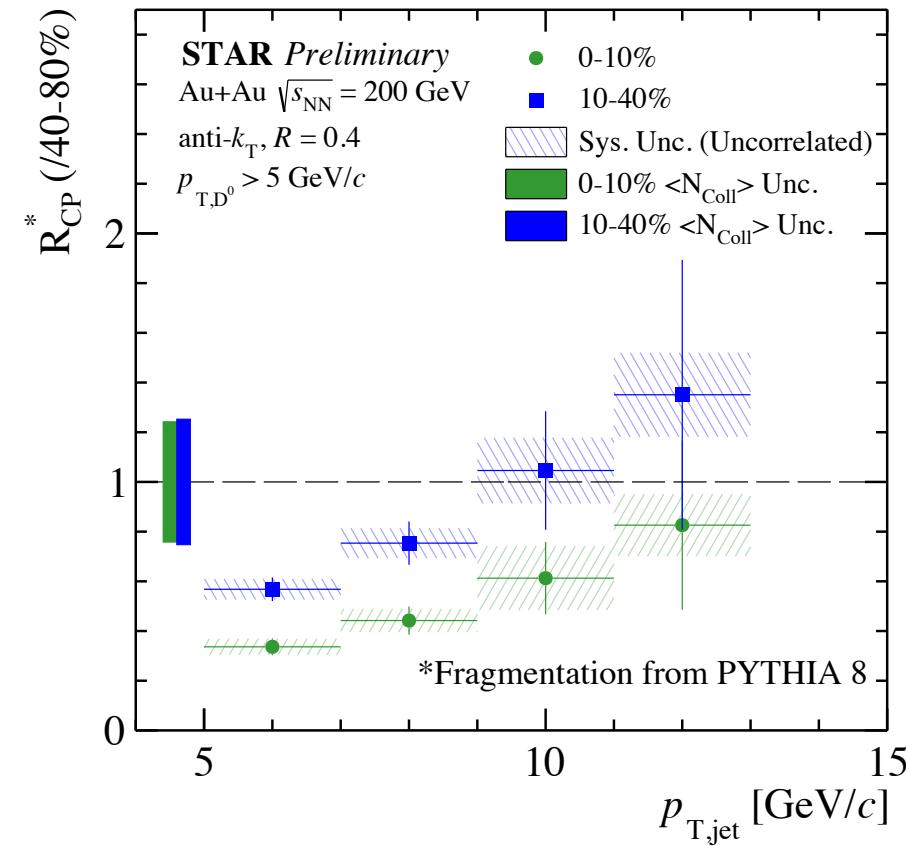


Jet Spectra



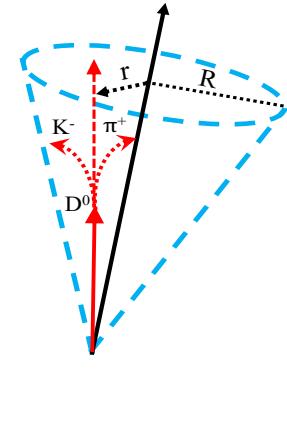
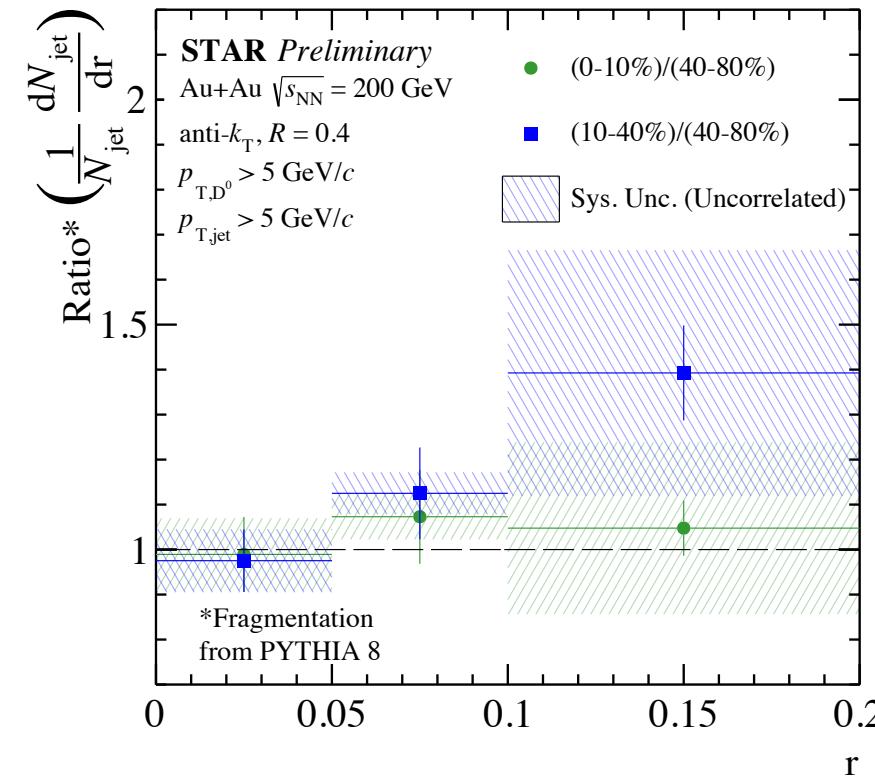
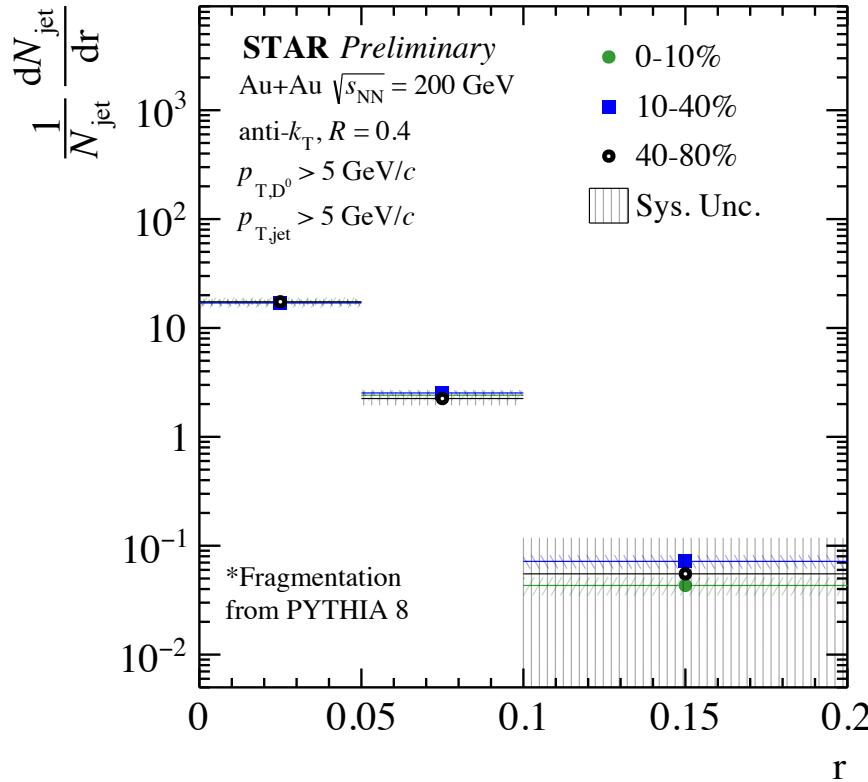
- Peripheral events have limited $D^0 p_T$ reach
- Yields in most central collisions are more suppressed than mid-central
- R_{CP}^* shows strong suppression at low $p_{T,\text{jet}}$, hint of an increasing trend with $p_{T,\text{jet}}$
- D^0 -tagged jet measurement for R_{AA} will be explored using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

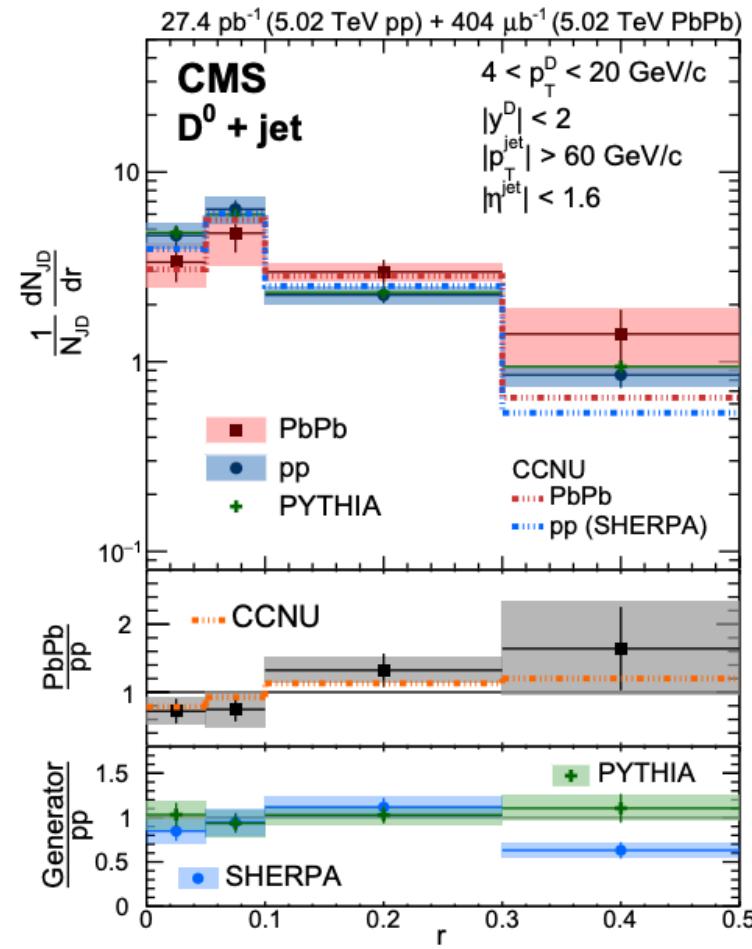
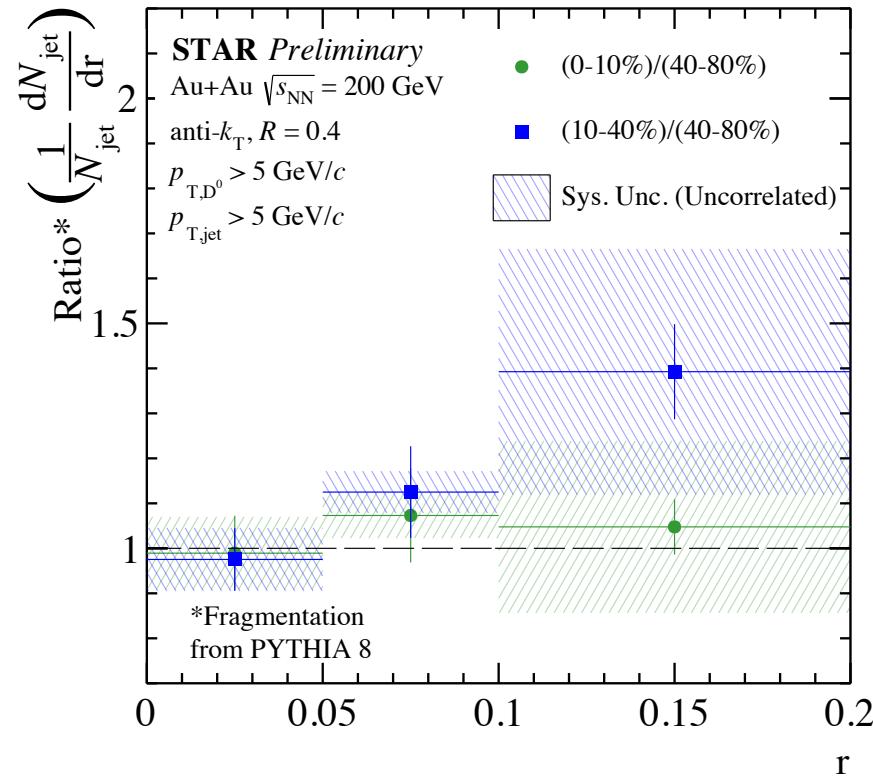
Radial Profile of D^0 Mesons in Jets



- 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

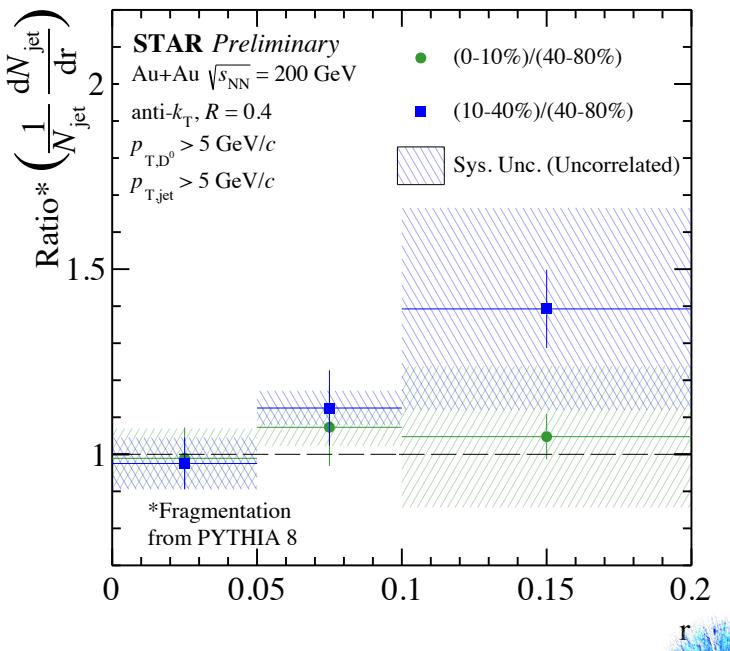
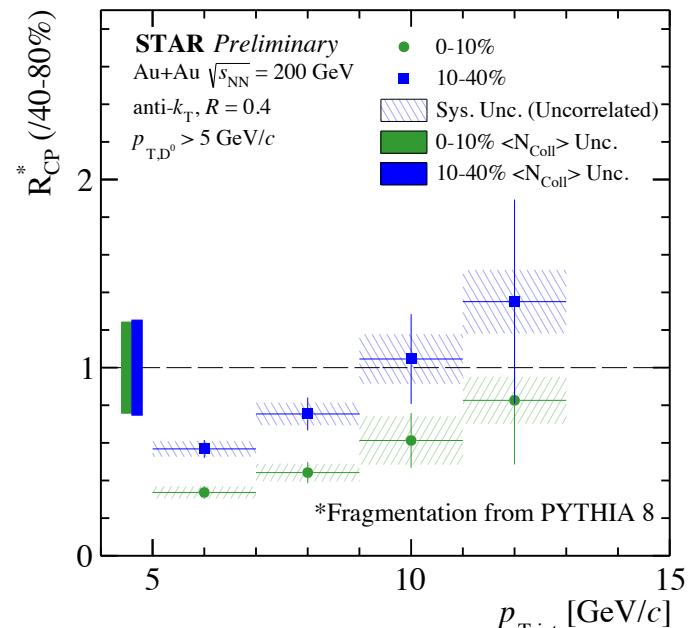
CMS, Phys. Rev. Lett. 125 (2020) 102001



- 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 $p_{T,\text{Jet}} > 5$ 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 $p_{T,\text{Jet}} > 60$ 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.

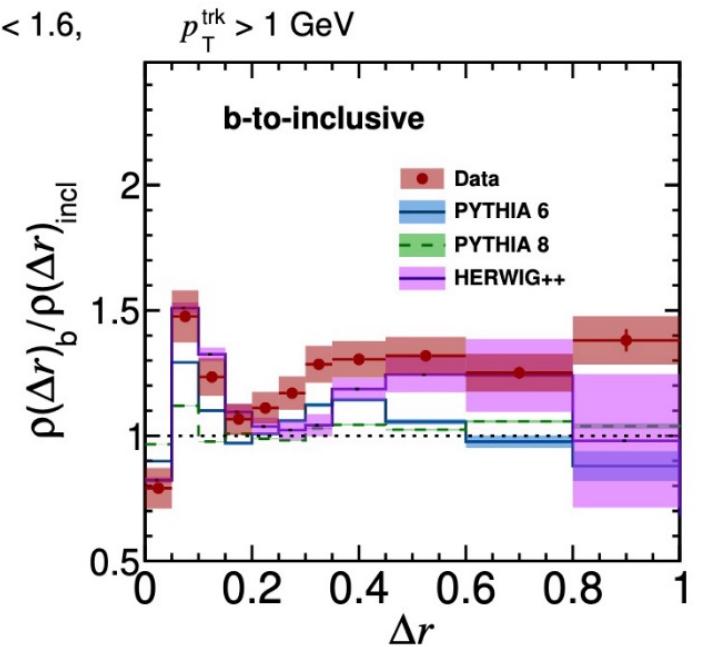
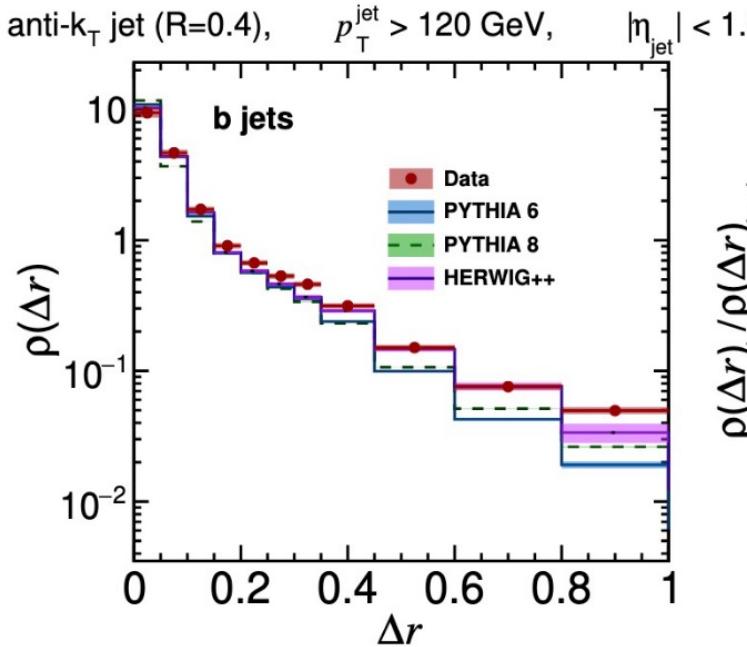
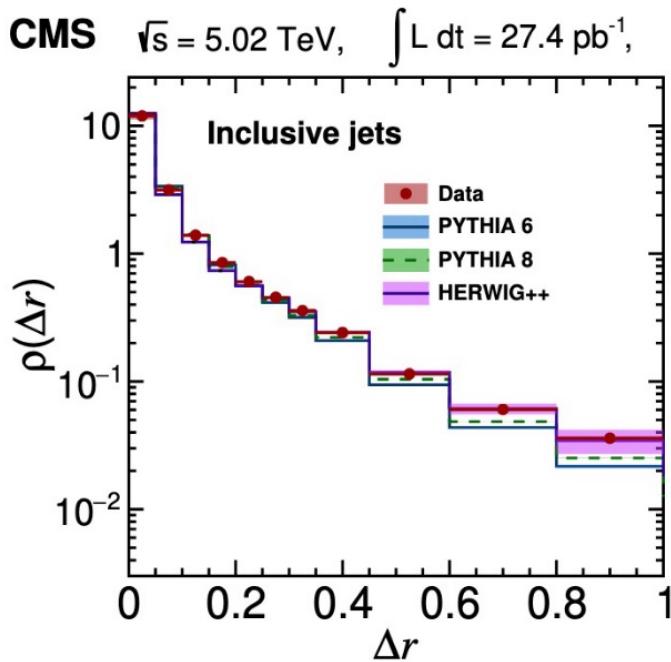


Outlook

- 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

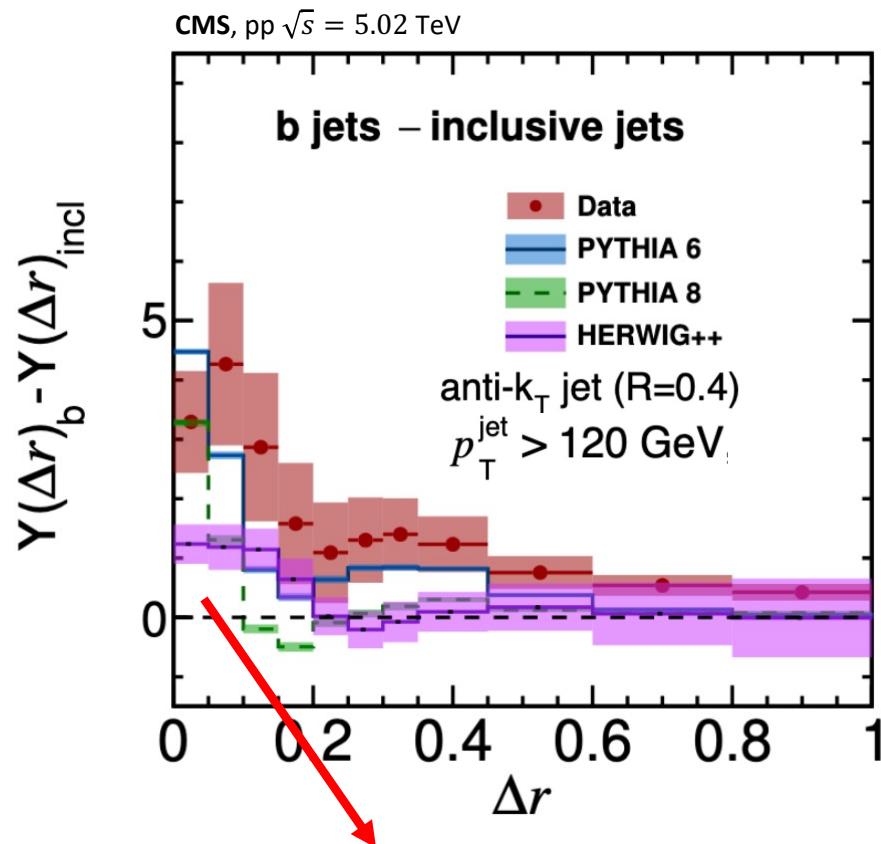


CMS, JHEP05 (2021) 054

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

Fragmentation pattern for heavy quark

CMS, JHEP05 (2021) 054



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

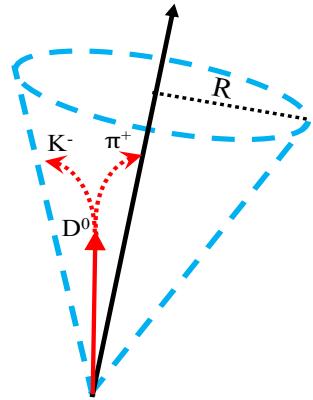
Higher yields of low p_T charged-particle close to jet axis in b-Jets
vs inclusive jets in vacuum

~ Different fragmentation pattern for heavy quarks

D⁰-Jet Yield Extraction

*s*Plot

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



- Native class in RooStats, and widely used in HEP
- Unbinned maximum likelihood fit to invariant mass integrated over all kinematics
- $p_{T,\text{jet}}$ 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)

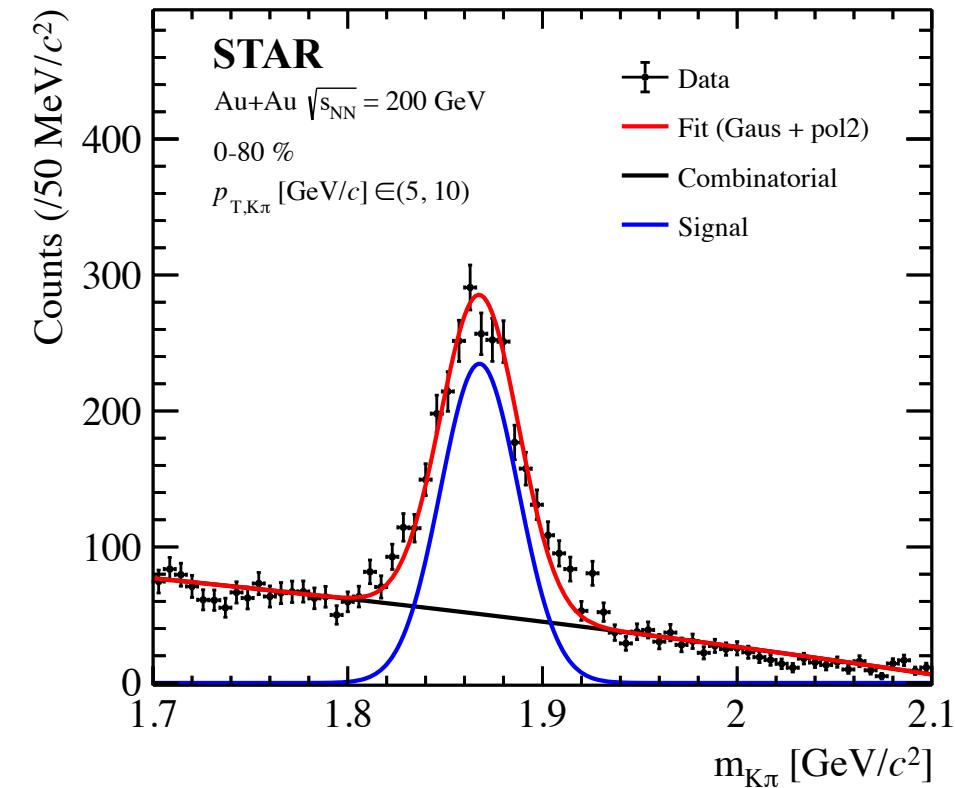
N_k = k -th yield (T=2)

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

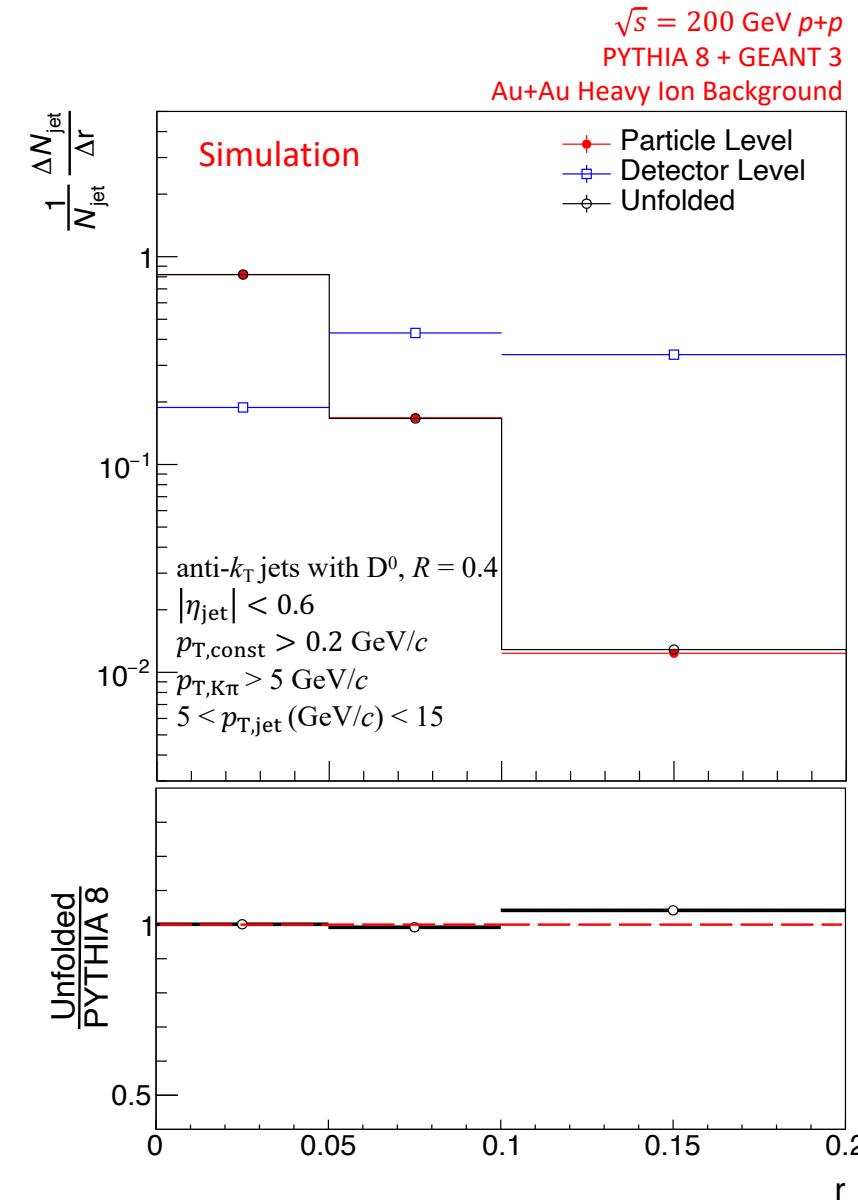
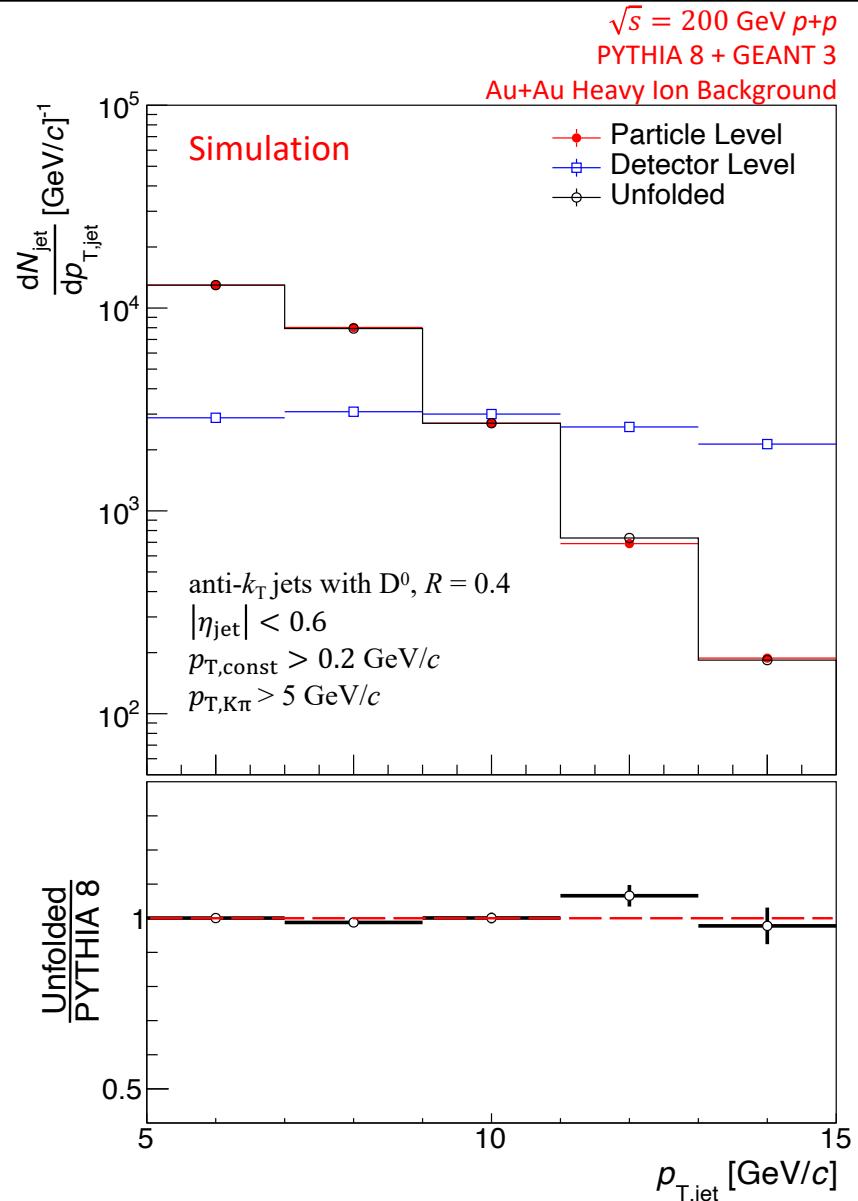
V = cov. matrix

Efficiency Correction →

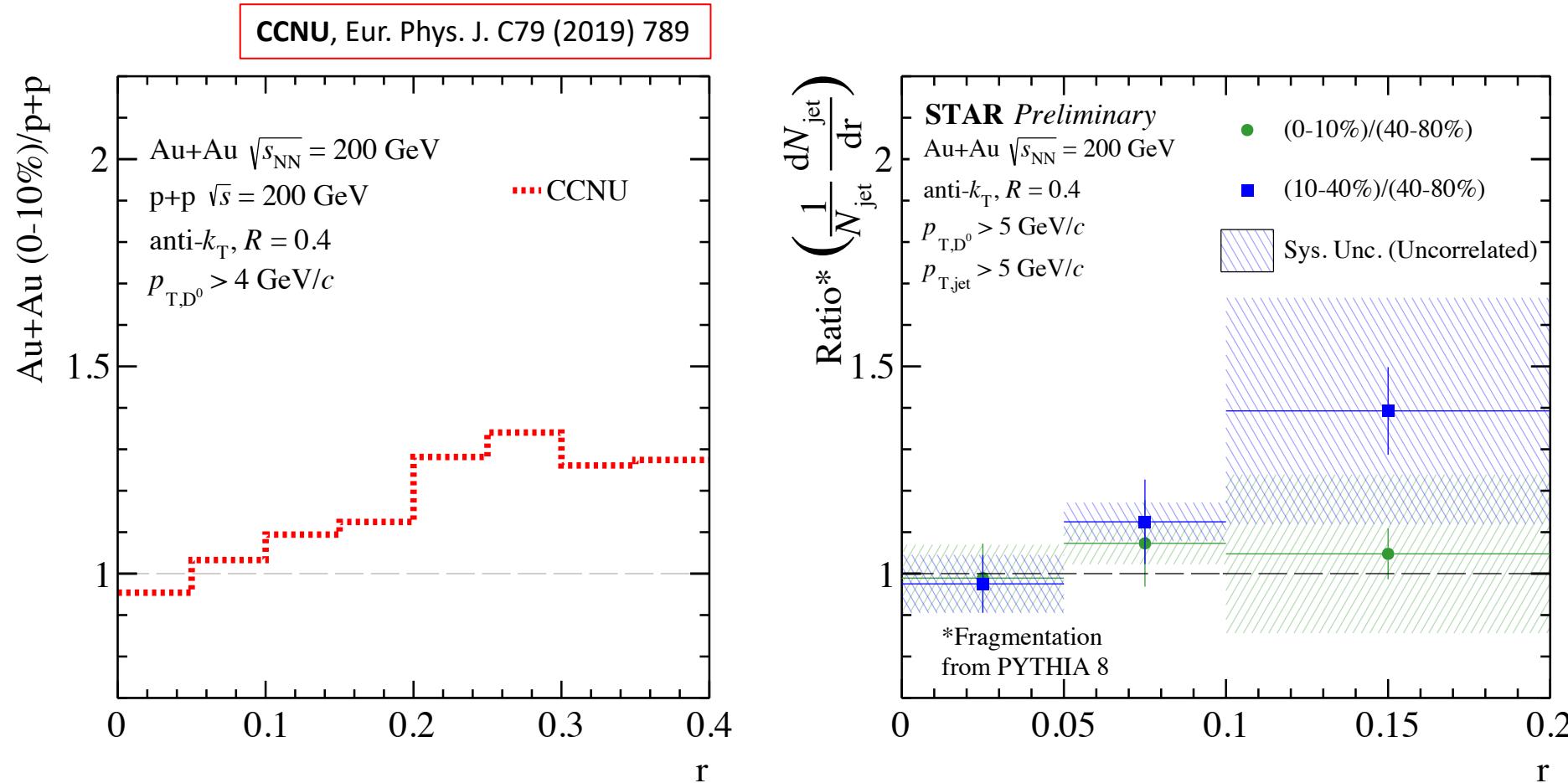
$${}^s\mathcal{P}_n(m_{K\pi,i}) \rightarrow \frac{{}^s\mathcal{P}_n(m_{K\pi,i})}{\varepsilon(m_{K\pi,i})}$$



Closures For Unfolding



Radial Profile: Data vs Model



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, $_s\mathcal{P}lot$ 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