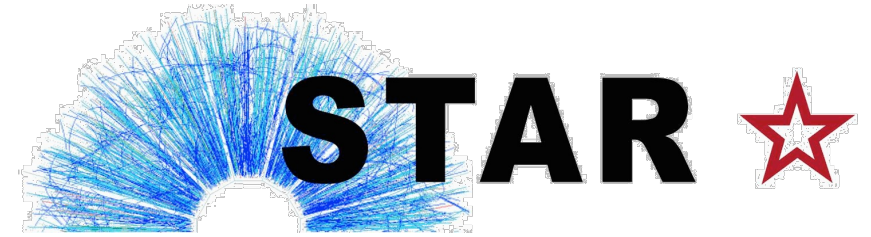


DNP2022



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

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Rutgers University

For the *STAR Collaboration*

roydiptanil@gmail.com

Supported in part by



U.S. DEPARTMENT OF
ENERGY

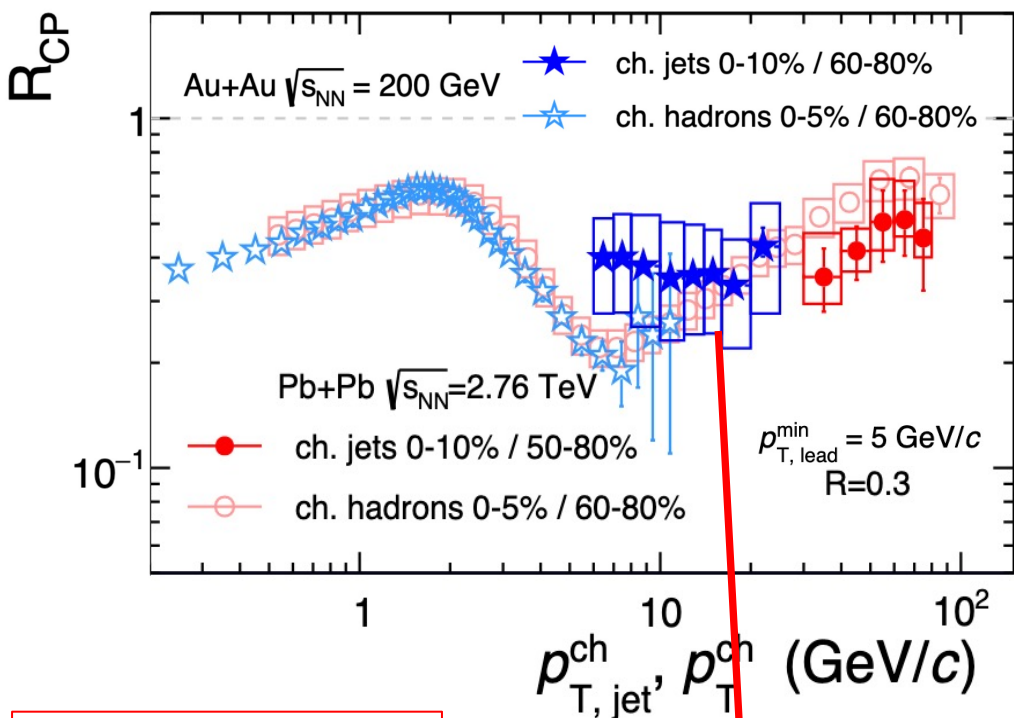
Office of
Science



RUTGERS
THE STATE UNIVERSITY
OF NEW JERSEY

Jets in Heavy Ion Collisions

Jet Quenching

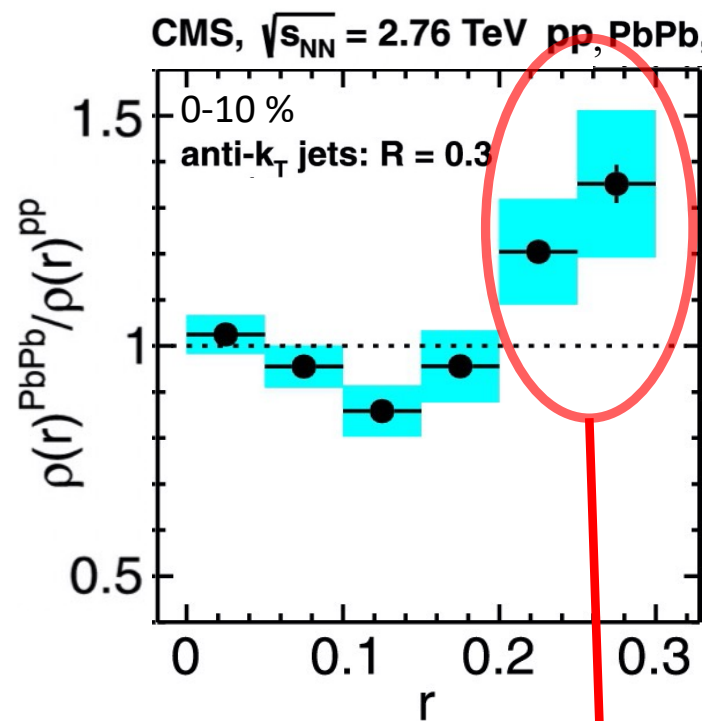


ALICE, JHEP03 (2014) 013

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

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

Jet Broadening

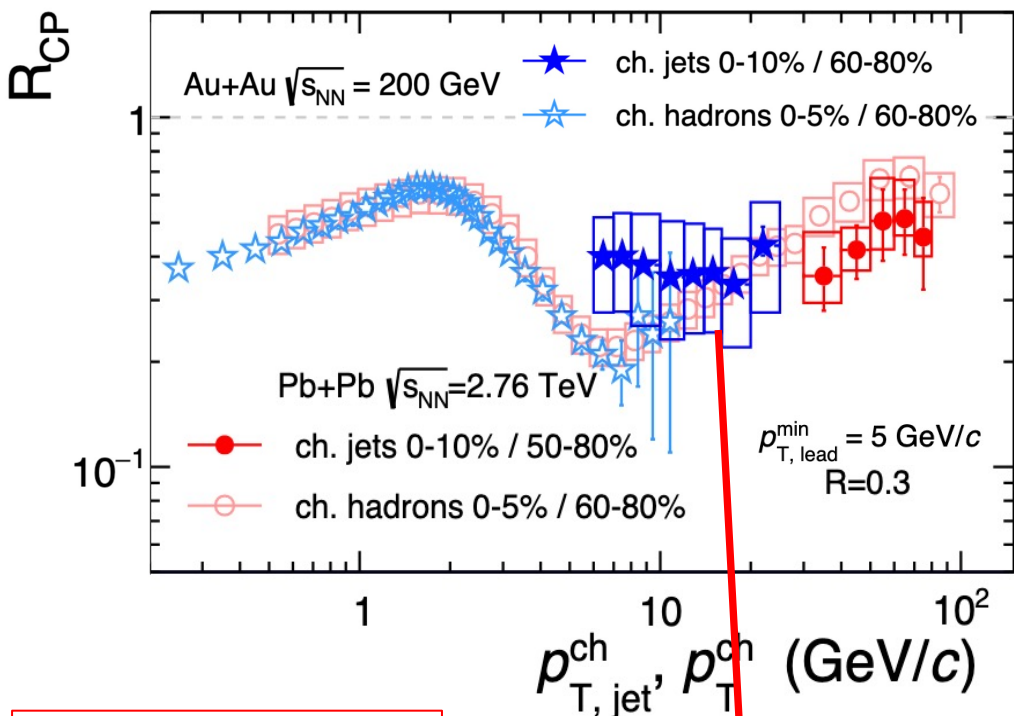


CMS, Phys. Lett. B 730 (2014) 243

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

Jets in Heavy Ion Collisions

Jet Quenching

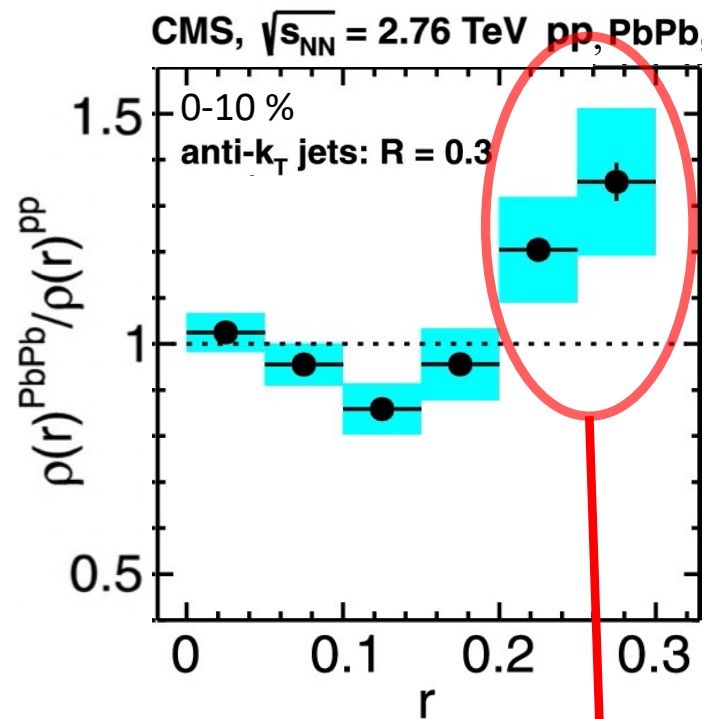


ALICE, JHEP03 (2014) 013

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

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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

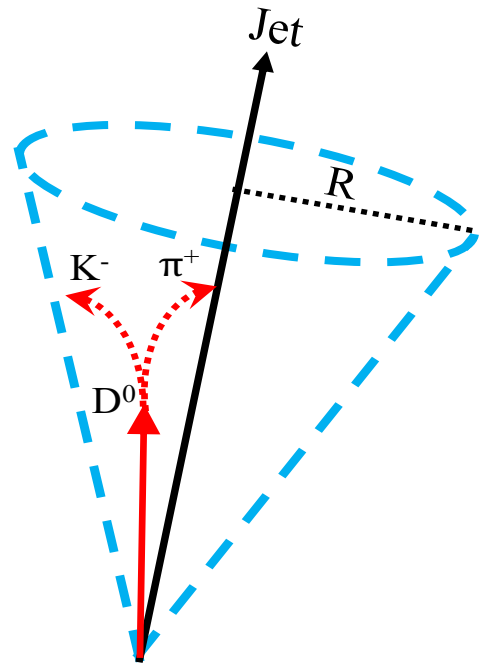
Possible mechanisms:

- Multiple scattering
- Medium-induced bremsstrahlung
- Medium response

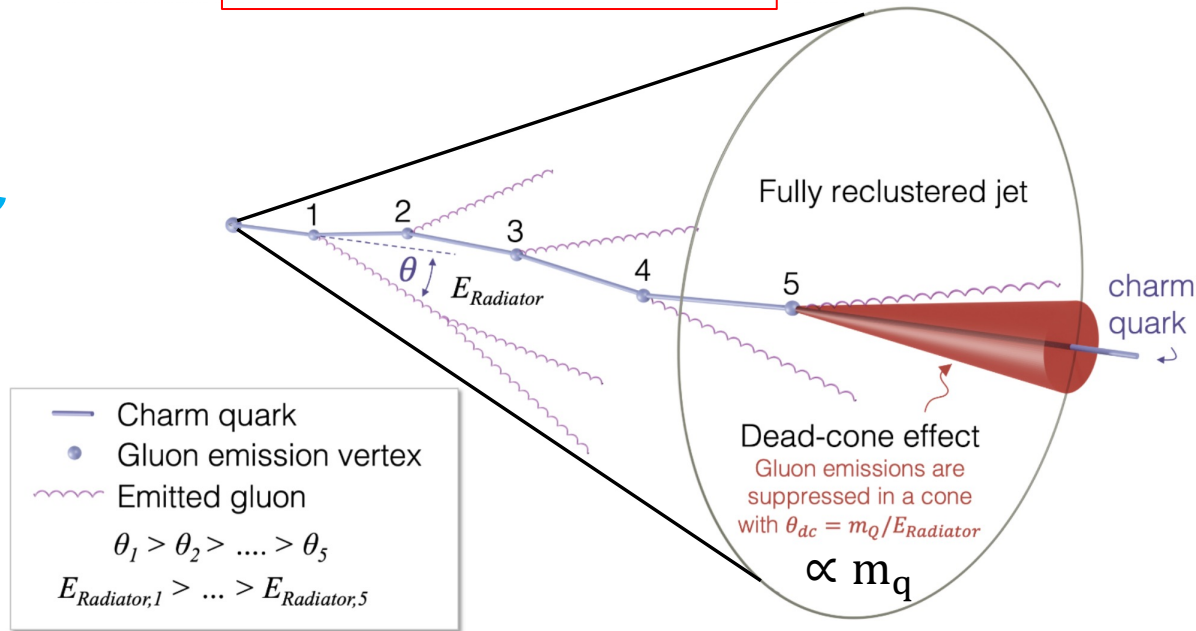
Dependent on the mass of the initiating parton

Motivation to study heavy-flavor jets

Heavy Flavor Tagged Jets



ALICE, Nature 605 (2022) 440-446

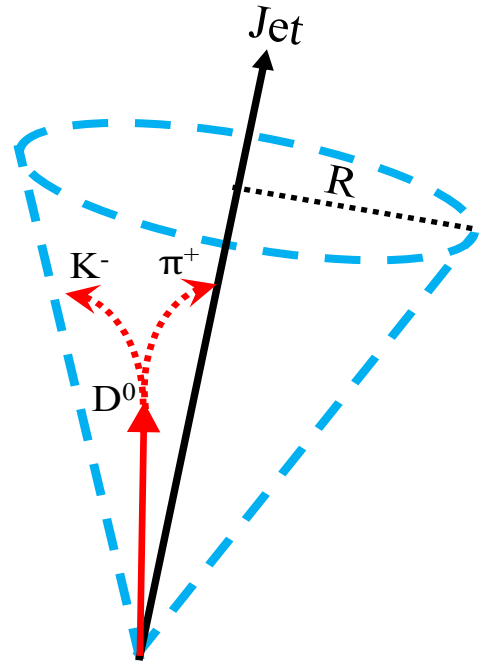


Heavy-flavor emission spectra at small angles suppressed due to **dead-cone effect** [1]

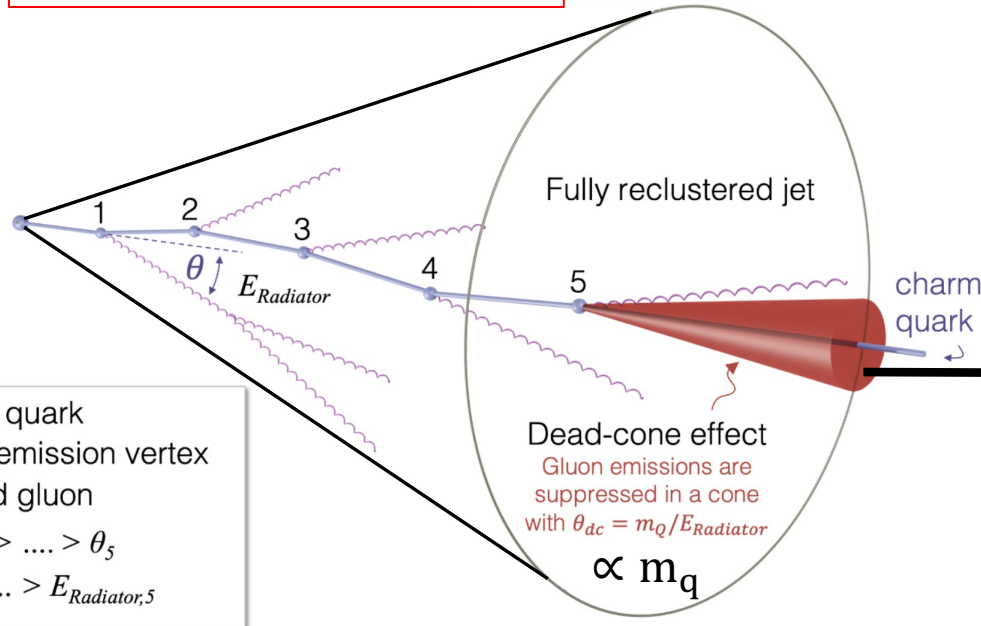
[1] J. Phys. G: Nucl. Part. Phys. **17** 1602 (1991)

Heavy Flavor Tagged Jets

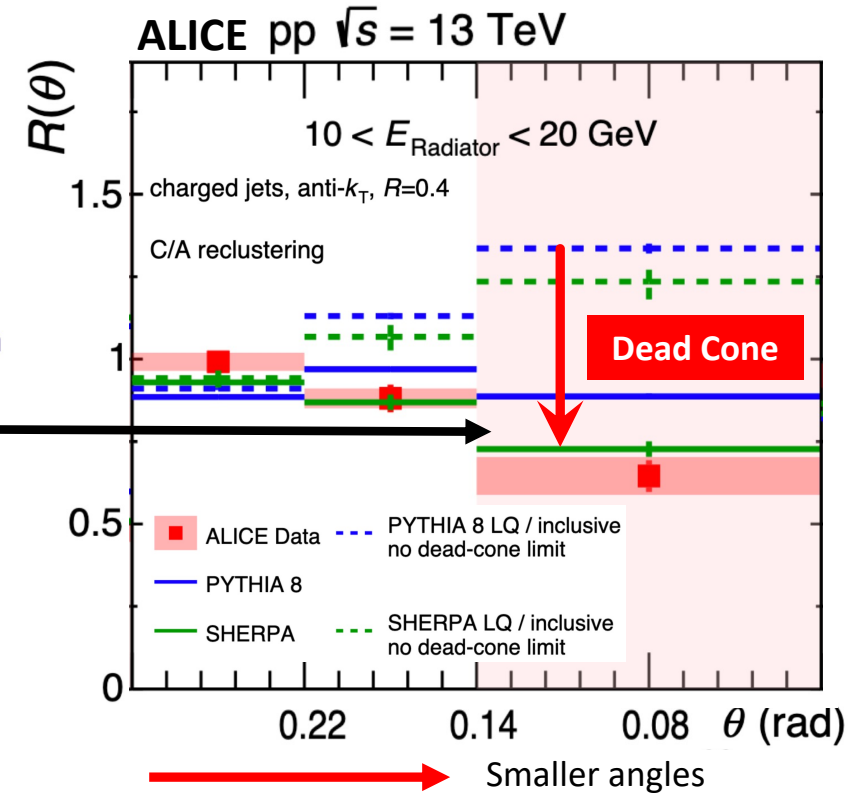
$$R(\theta) = \frac{1}{N_{D^0\text{jet}}} \frac{dn_{D^0\text{jet}}}{d \ln(1/\theta)} / \frac{1}{N_{\text{inclusive jet}}} \frac{dn_{\text{inclusive jet}}}{d \ln(1/\theta)}$$



ALICE, Nature 605 (2022) 440-446



- Charm quark
- Gluon emission vertex
- ~~~~~ Emitted gluon
- $\theta_1 > \theta_2 > \dots > \theta_5$
- $E_{\text{Radiator},1} > \dots > E_{\text{Radiator},5}$

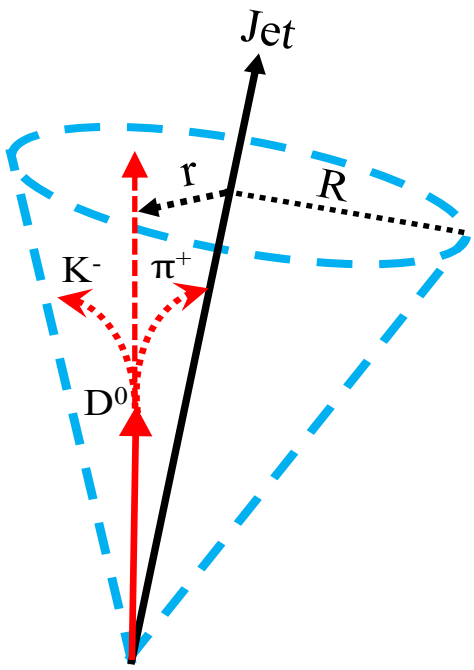


Heavy-flavor emission spectra at small angles suppressed due to **dead-cone effect** [1]

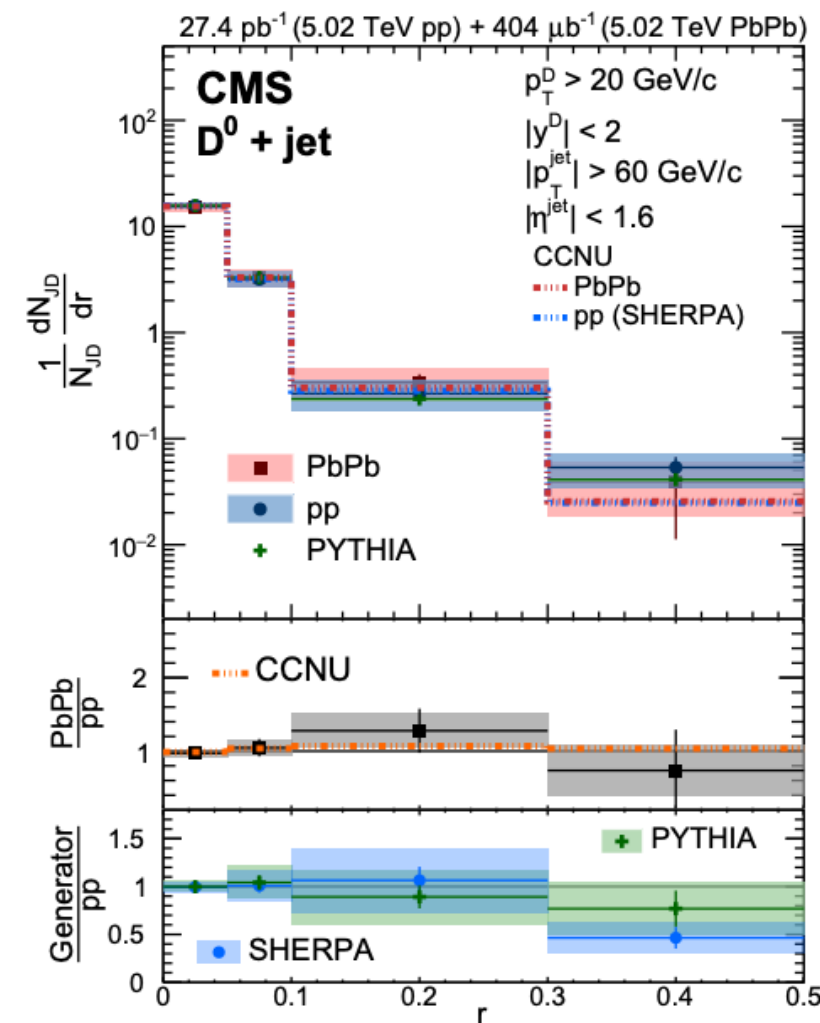
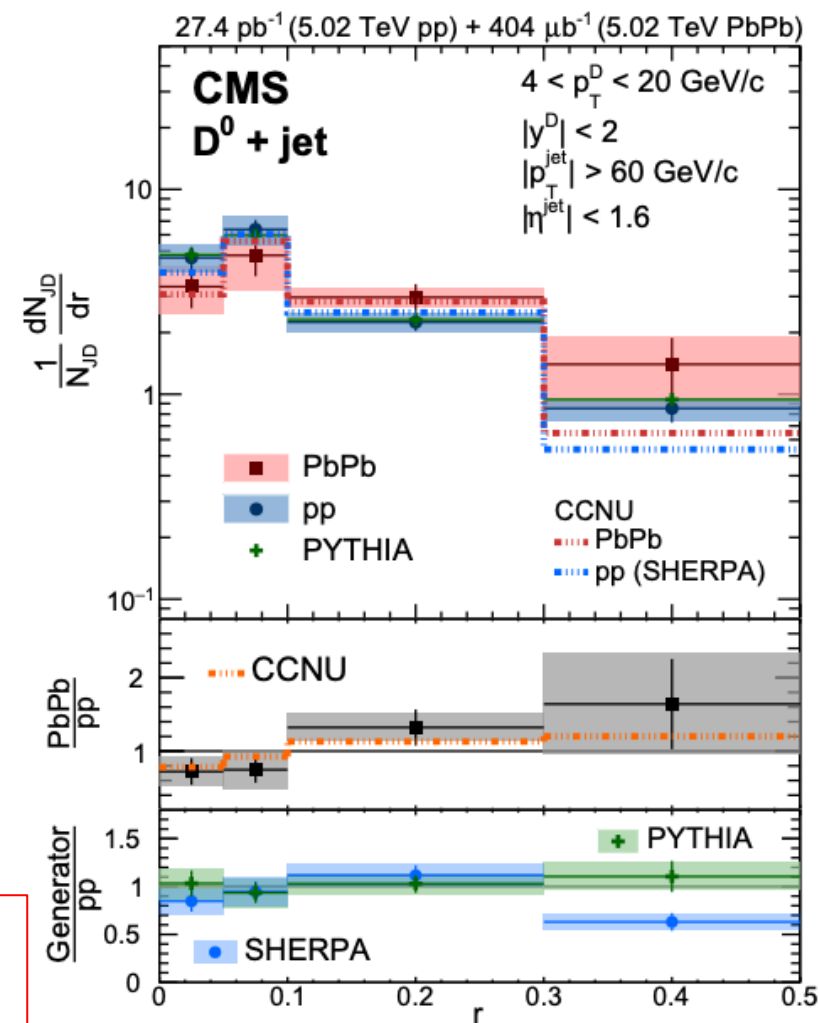
[1] J. Phys. G: Nucl. Part. Phys. **17** 1602 (1991)

Heavy Flavor Tagged Jets

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



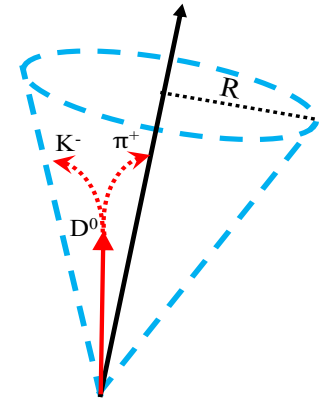
Low p_T D^0 mesons slightly **diffused** in the presence of QGP at LHC



- 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

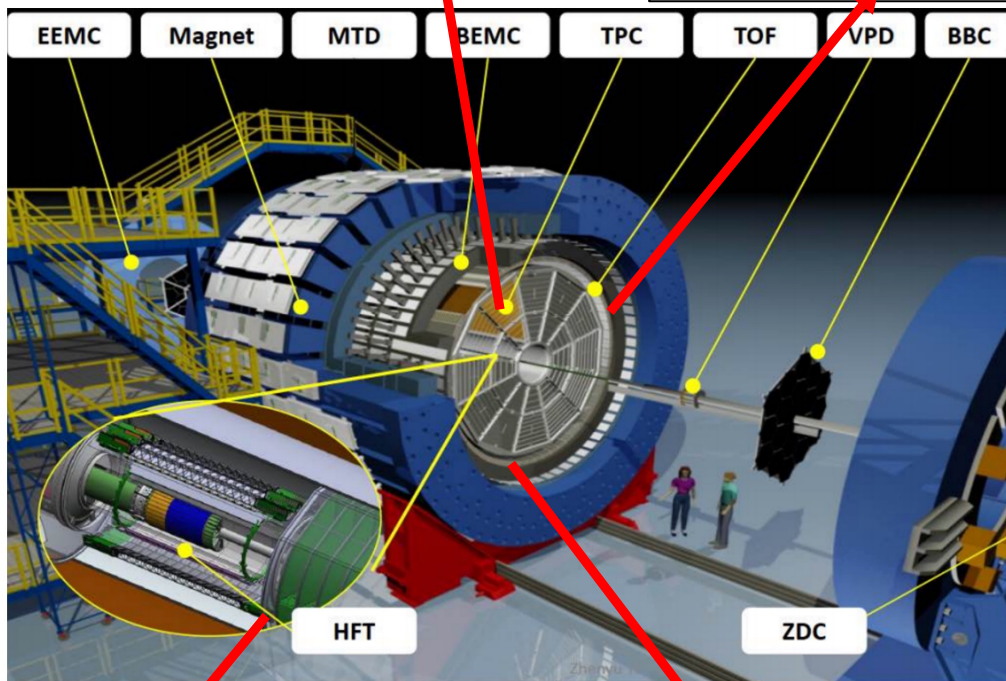


Time Projection Chamber (TPC)

- 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
- $5 < p_{T,D^0} [\text{GeV}/c] < 10$

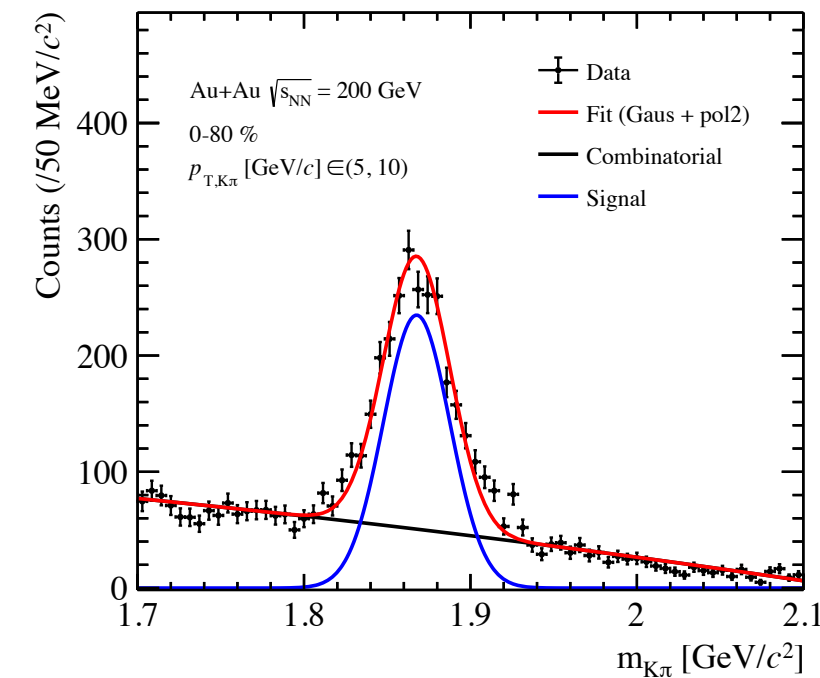
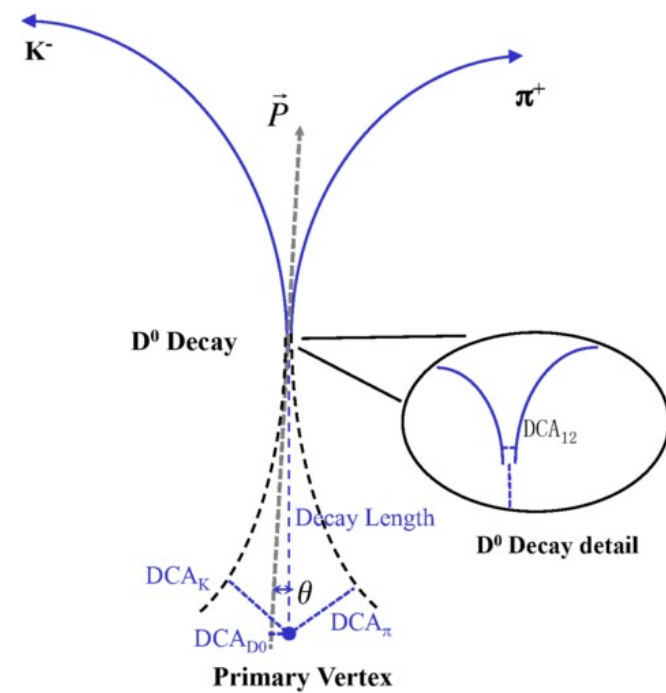
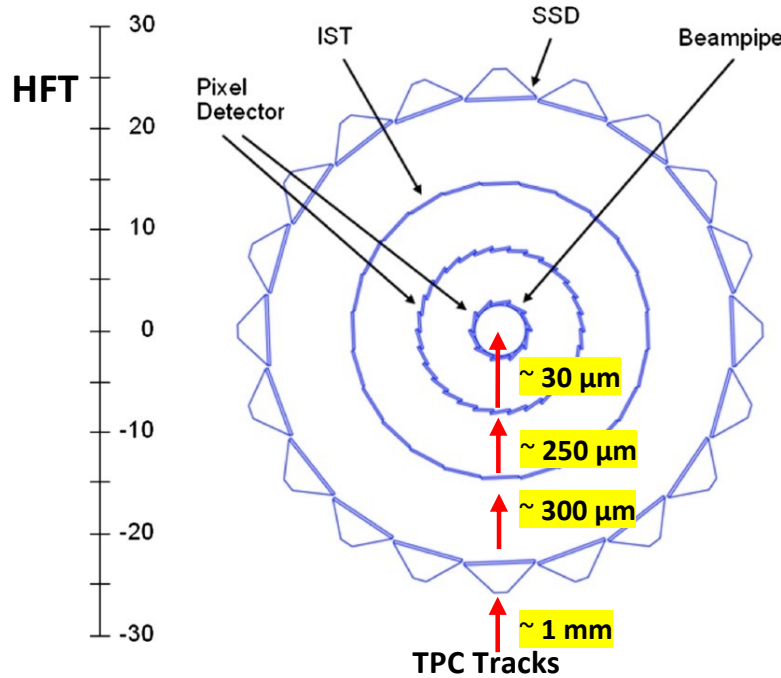
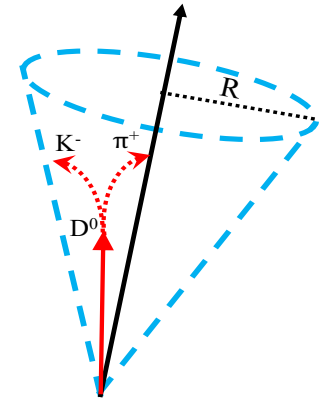
D^0 Jet Selection:

- 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



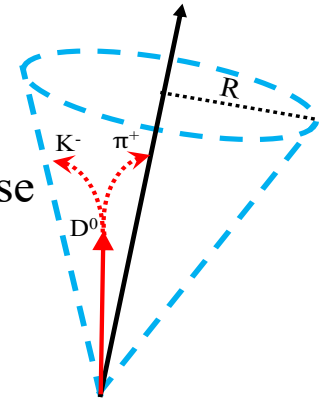
Topological cuts on the D⁰ candidates improve signal significance

Yield is calculated using sPlot method [1]

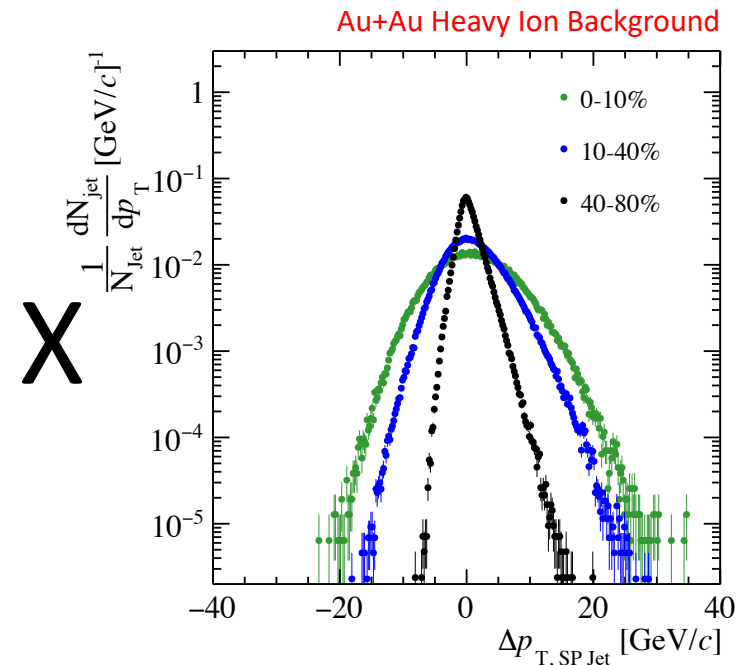
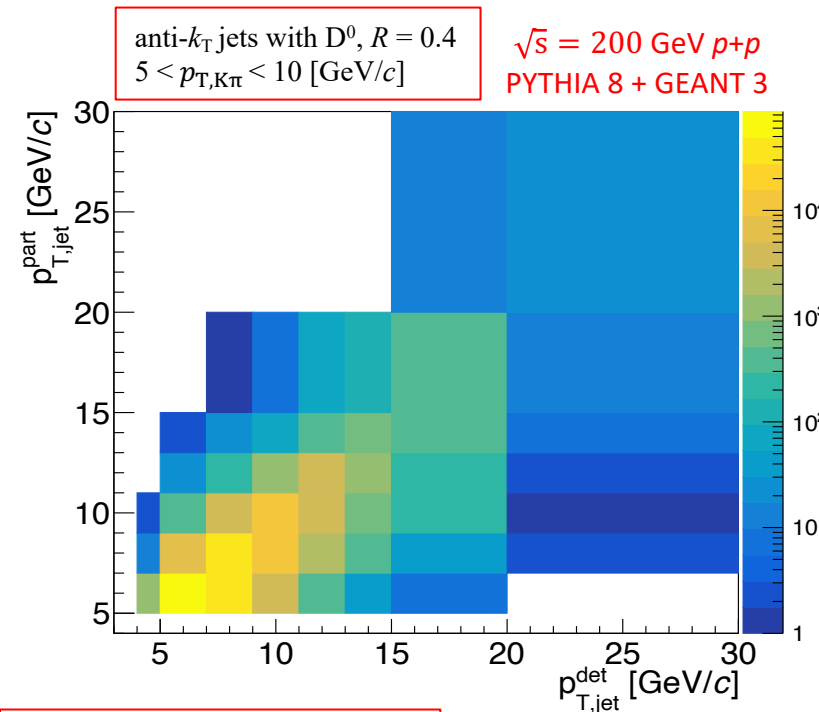
[1] Nucl. Instrum. Methods Phys. Res., A (2005) 555



Correction to the Jet Yield



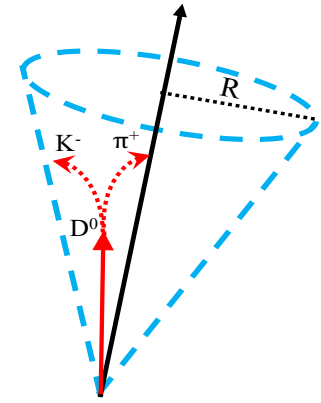
1. Response matrix for $p+p$ collisions at $\sqrt{s} = 200$ GeV from PYTHIA and GEANT3 to mimic the detector response
2. Single Particle (SP) embedding in heavy ion events to model fluctuations in area-based background subtraction
3. Reweight PYTHIA with c-quark distribution from FONLL [1] to modify 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



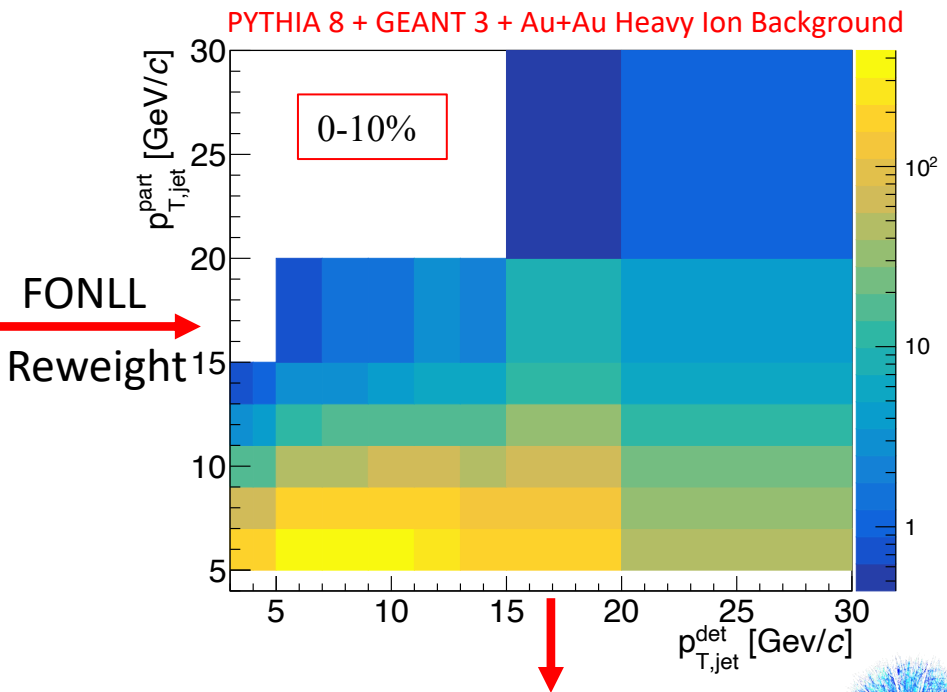
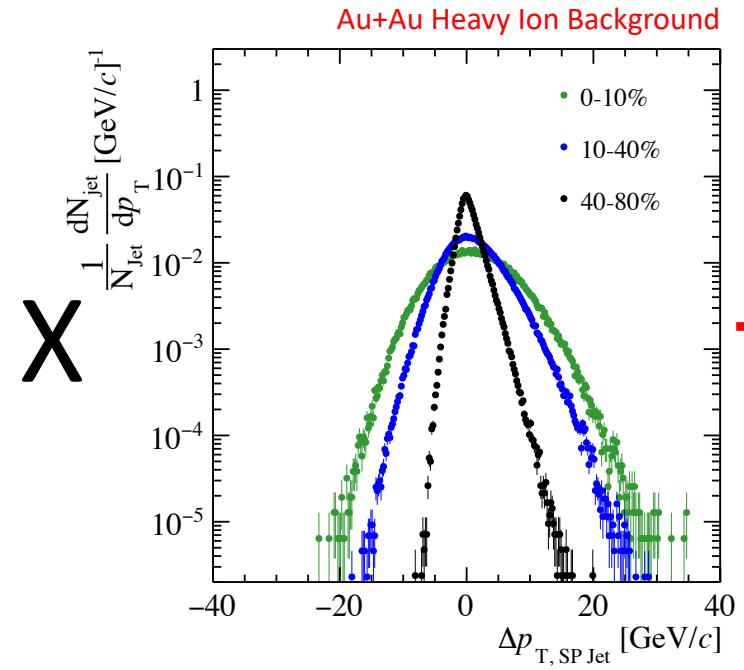
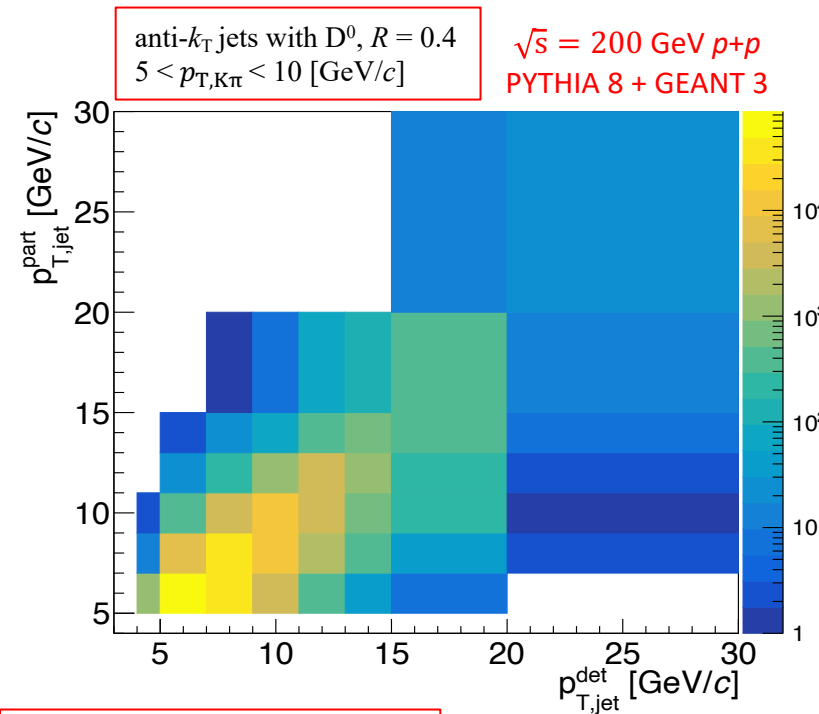
[1]. FONLL, JHEP03 (2001) 006



Correction to the Jet Yield



1. Response matrix for $p+p$ $\sqrt{s} = 200$ GeV from PYTHIA and GEANT3 to mimic the detector response
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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 28, 2022

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

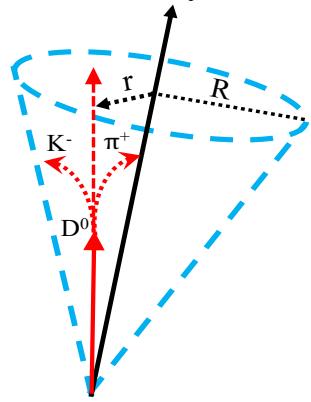
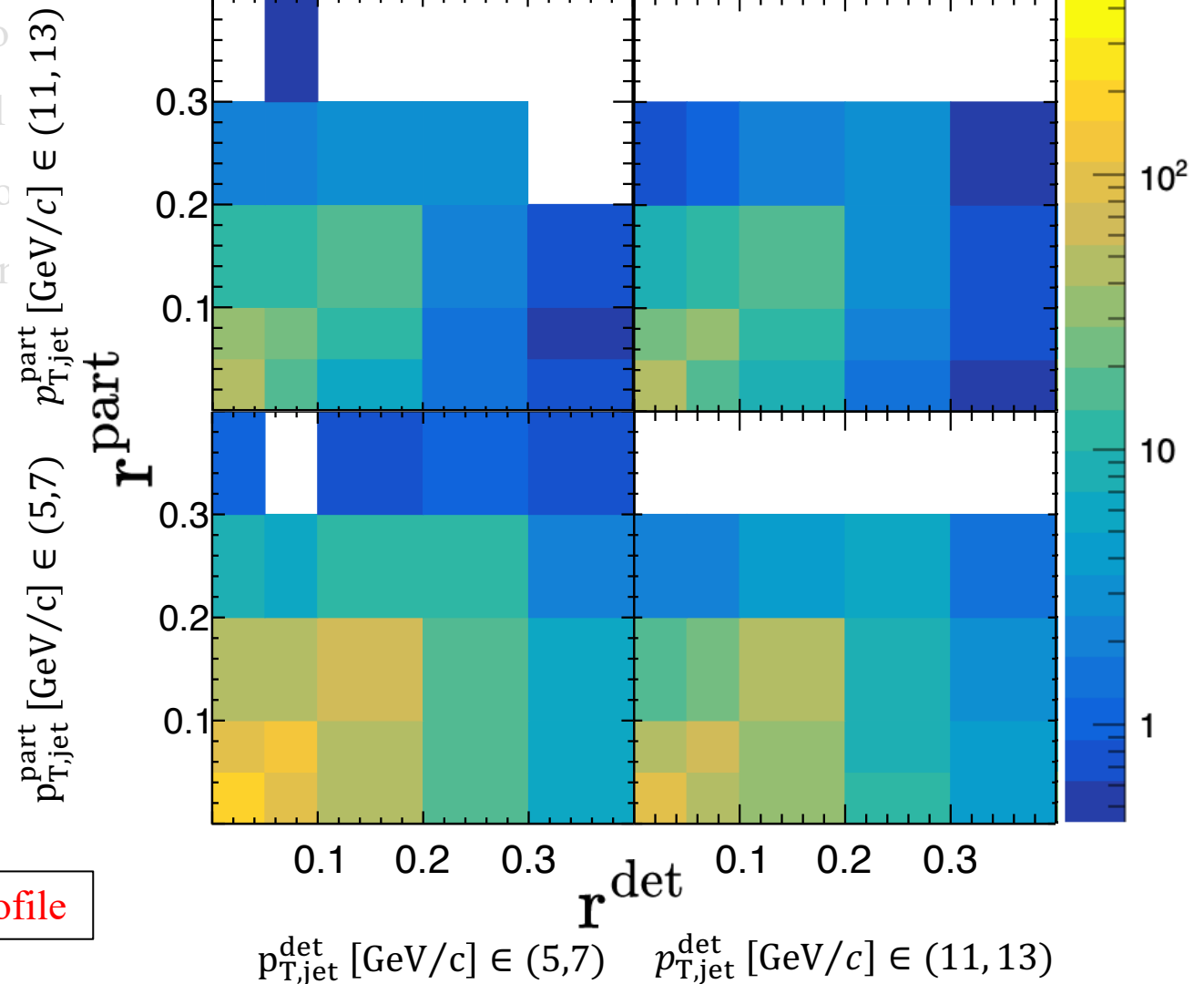


Correction to the Jet Radial Profile

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 FONLL [1]
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)

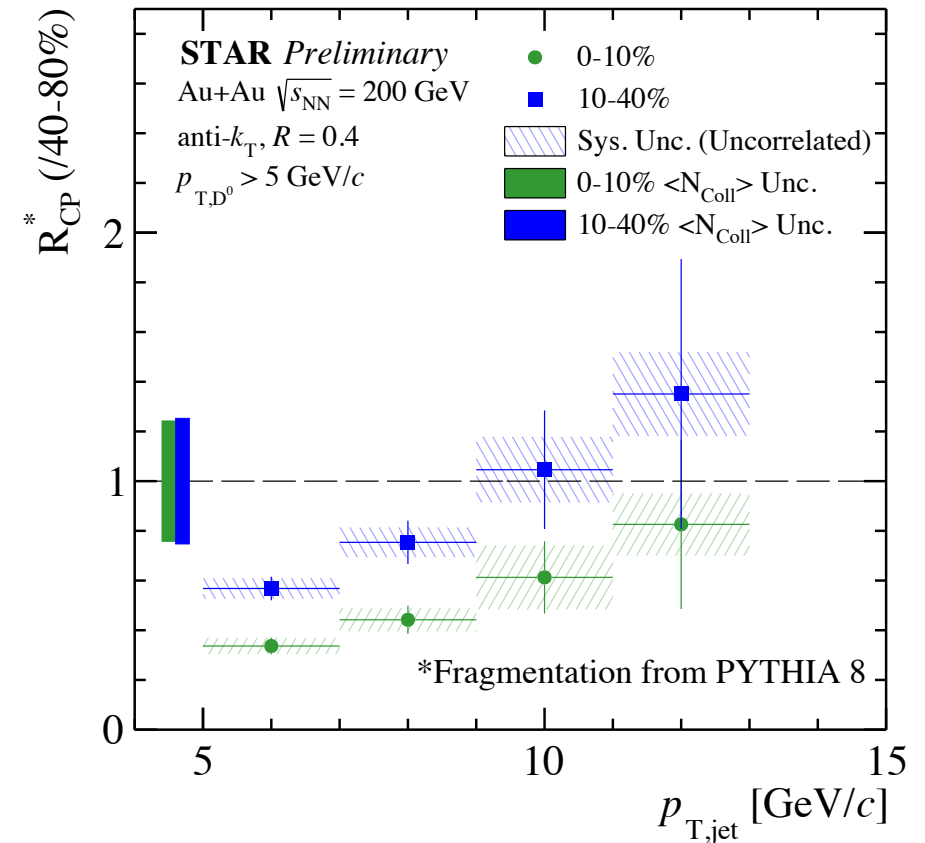
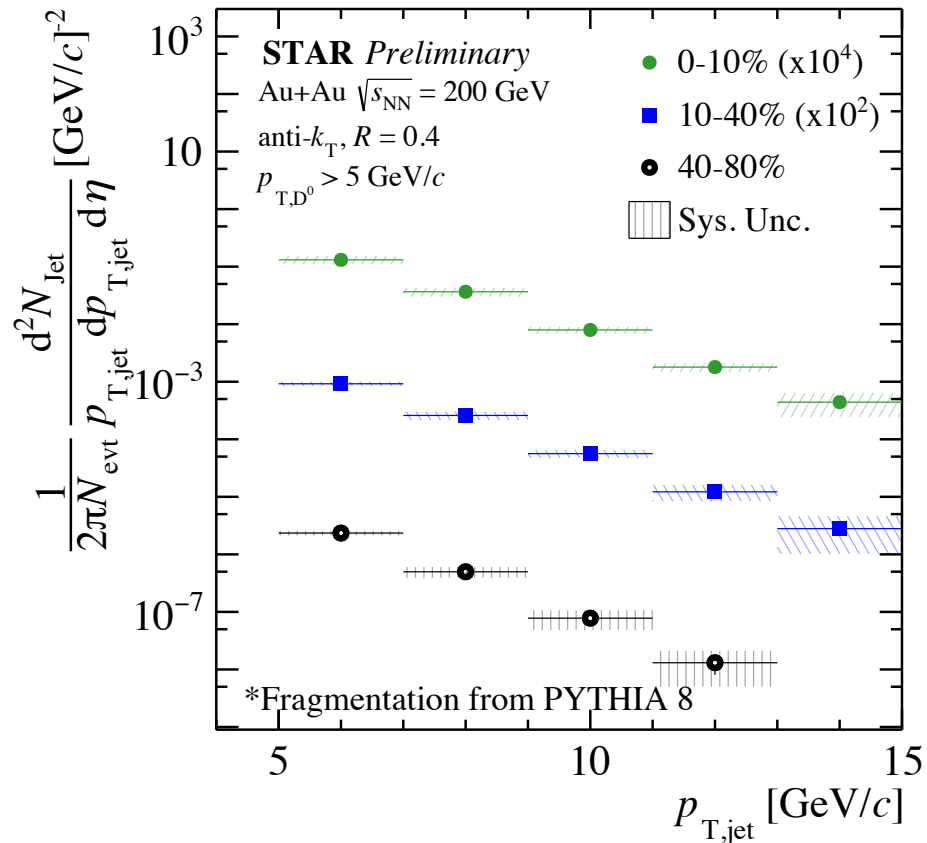
$\sqrt{s} = 200$ GeV $p+p$
 PYTHIA 8 + GEANT 3
 Au+Au Heavy Ion Background



Complete 4D response matrix to unfold radial profile

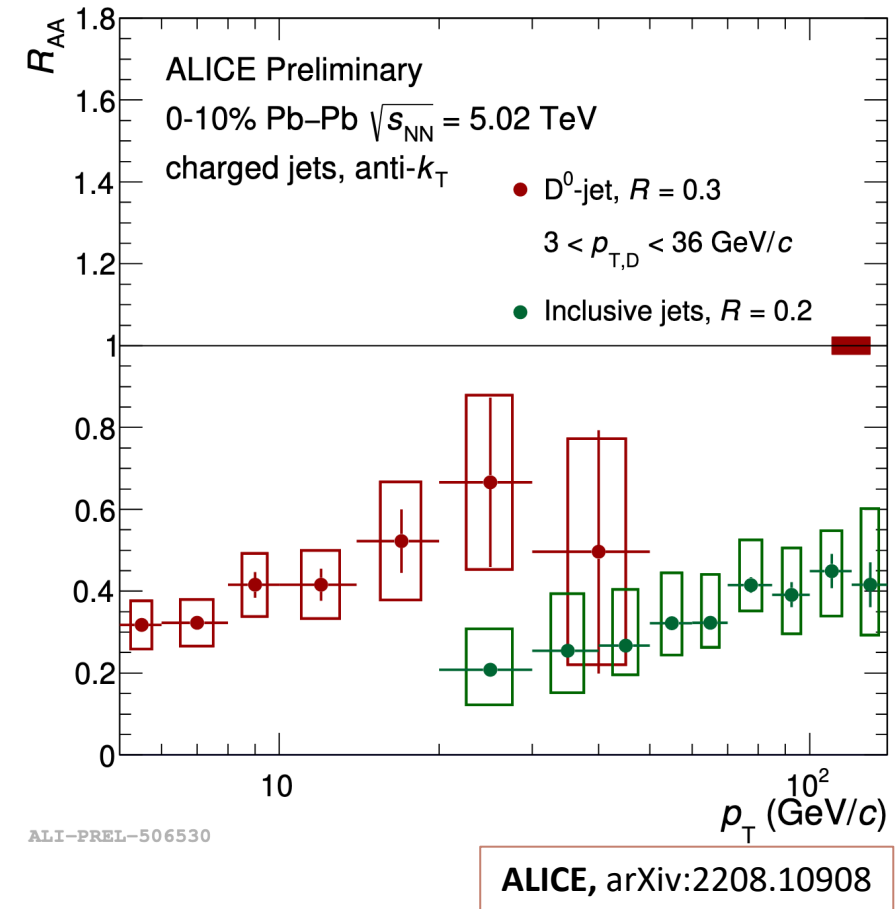
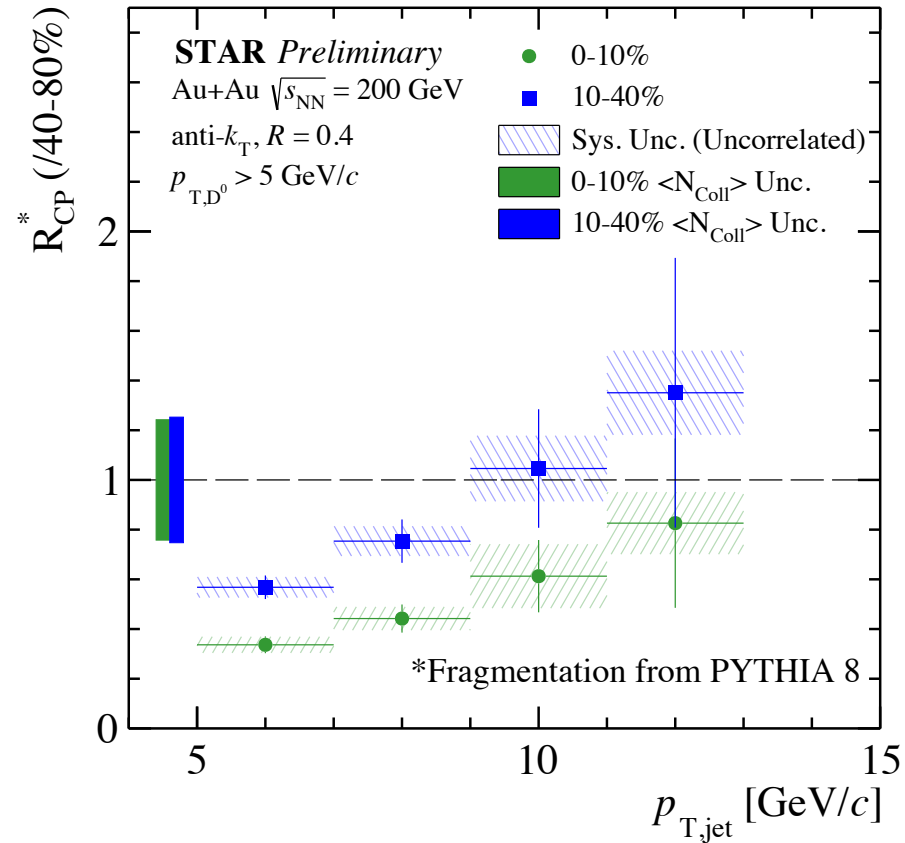


Jet Spectra



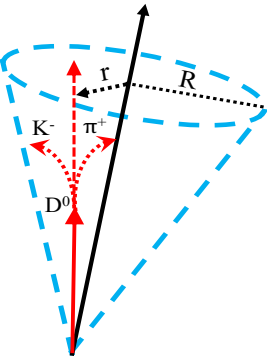
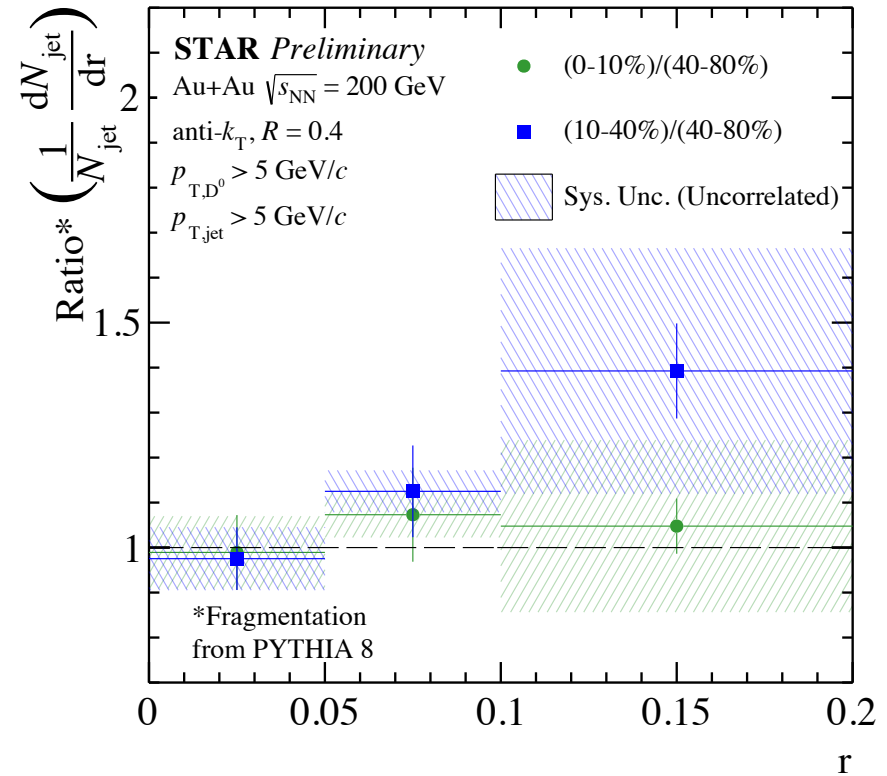
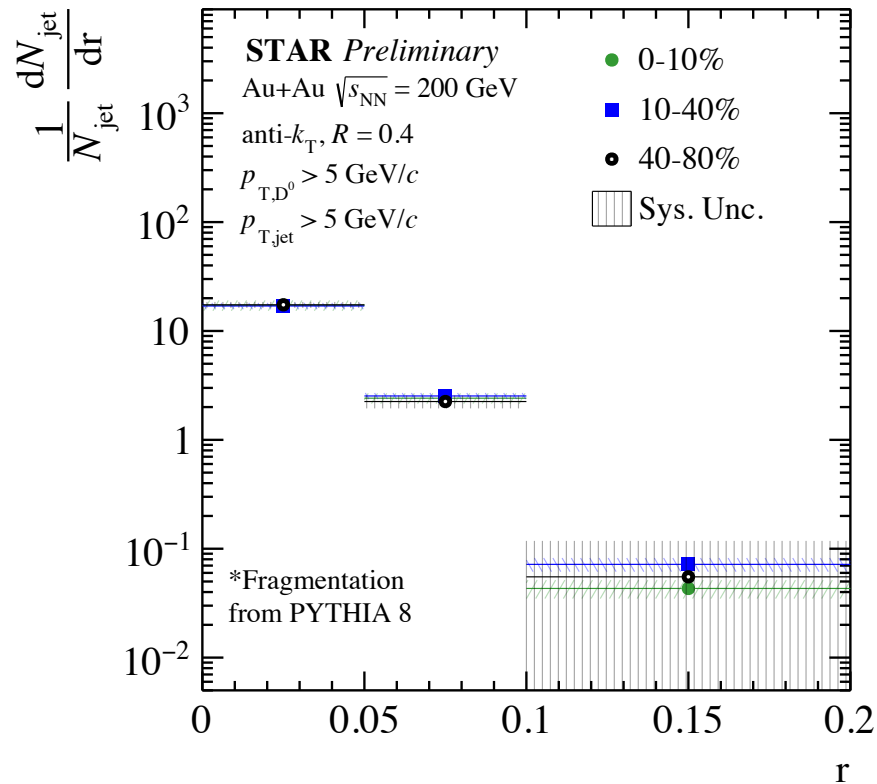
- Peripheral events have limited $D^0 p_T$ reach
- Yields in most central collisions are more suppressed than mid-central
- R_{CP}^* shows strong suppression at low $p_{T,jet}$, hint of an increasing trend with $p_{T,jet}$
- D^0 -tagged jet measurement for R_{AA} will be explored using high-statistics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

Energy Dependence



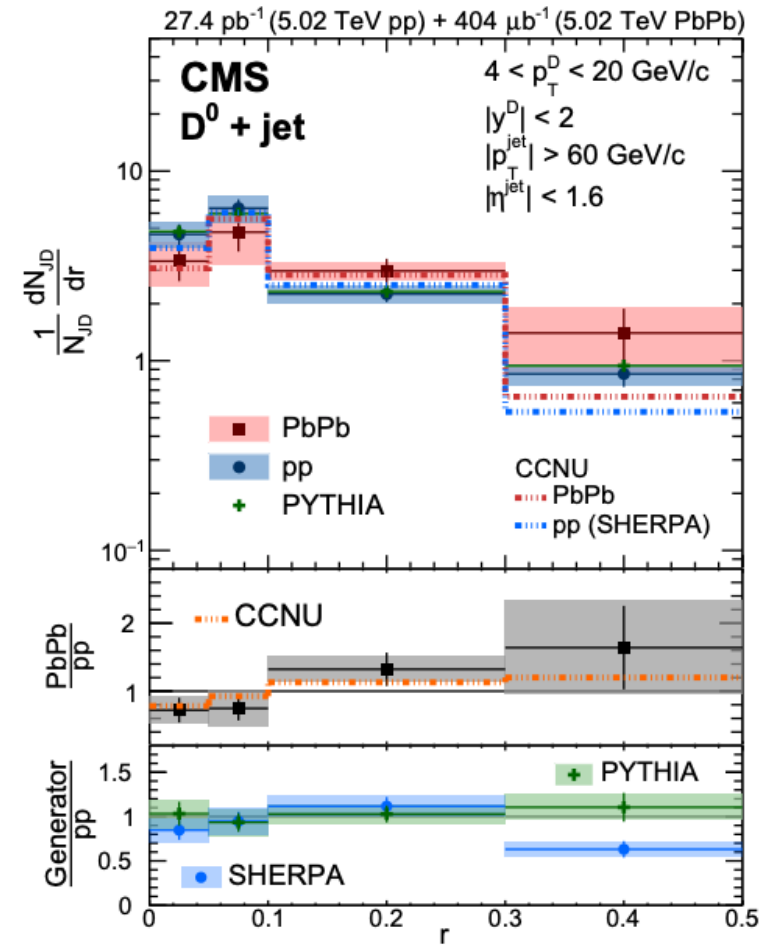
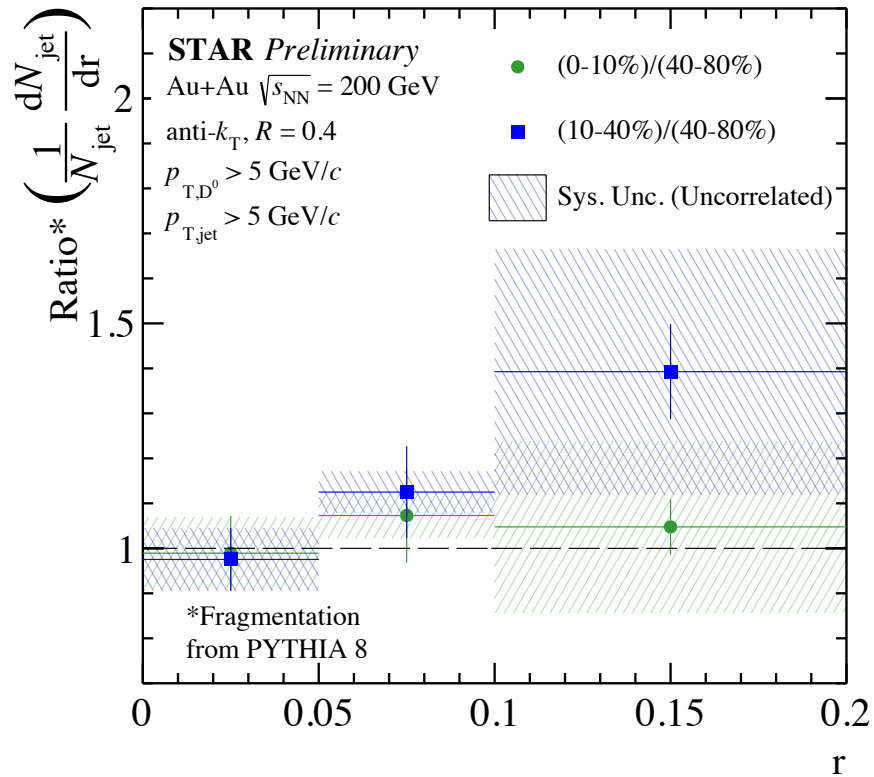
- Strong in-medium suppression for D^0 -tagged jets at low $p_{T,jet}$ at 200 GeV from STAR and 5.02 TeV from ALICE

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 strong diffusion, within uncertainty, seen at 200 GeV from STAR for D^0 $p_T > 5$ GeV/c and $p_{T,Jet} > 5$ GeV/c
- Hint of diffusion observed at 5.02 TeV from CMS for $4 < D^0 p_T < 20$ GeV/c and $p_{T,Jet} > 60$ GeV/c

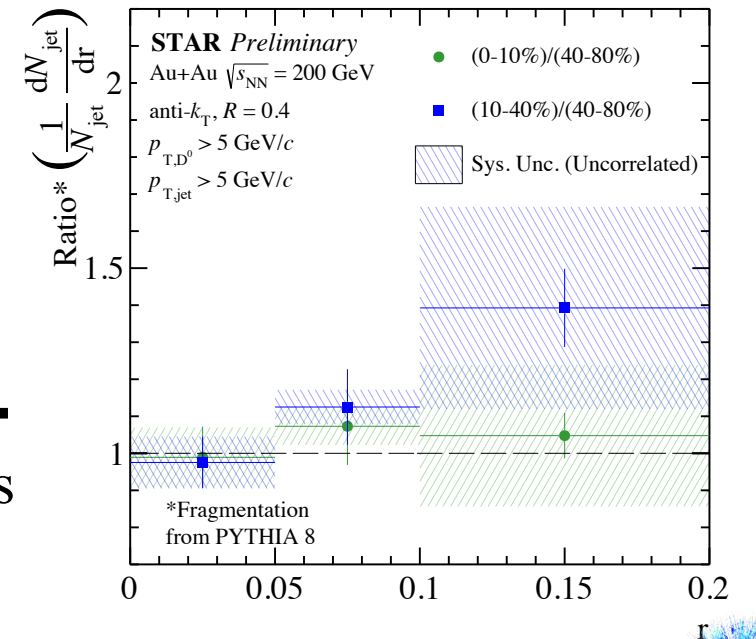
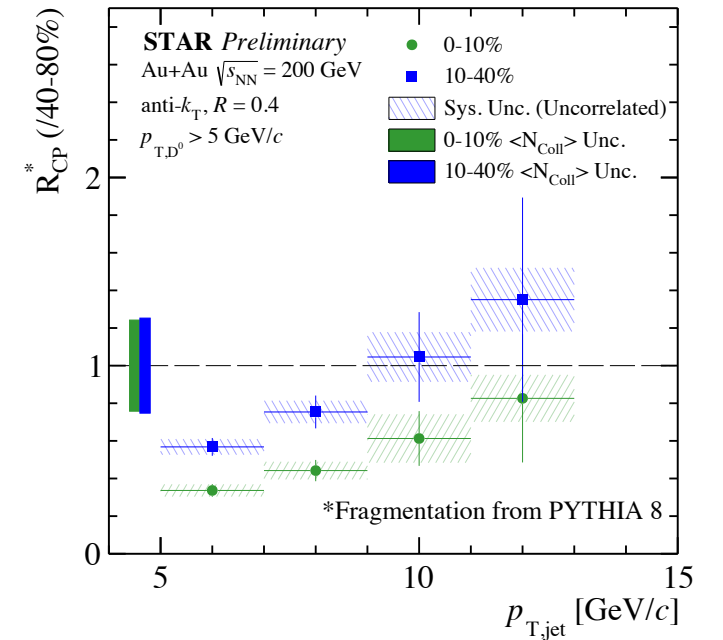


Summary

- 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

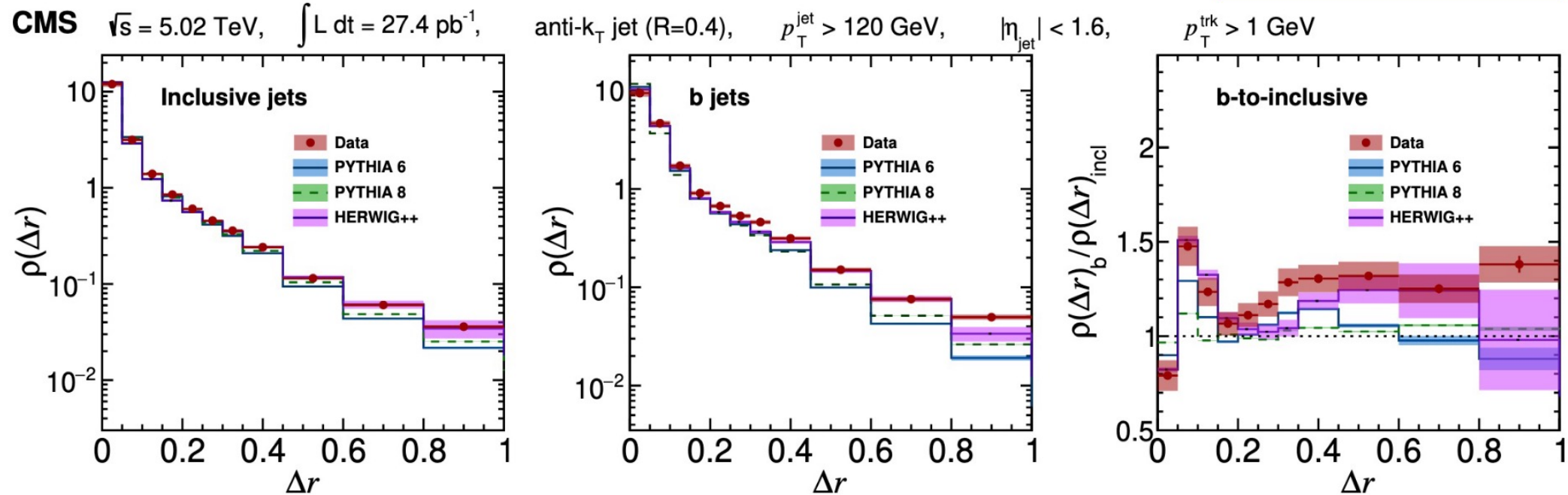


Backup



Differential jet shape for heavy quark in vacuum

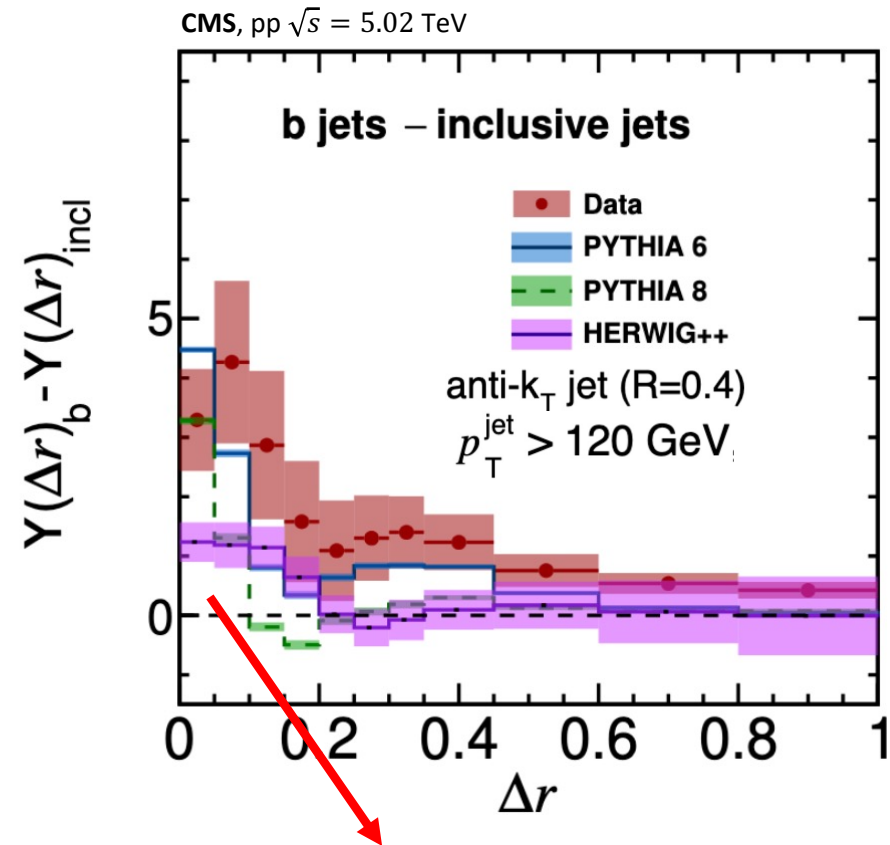
CMS, JHEP05 (2021) 054



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

Fragmentation pattern for heavy quark

CMS, JHEP05 (2021) 054

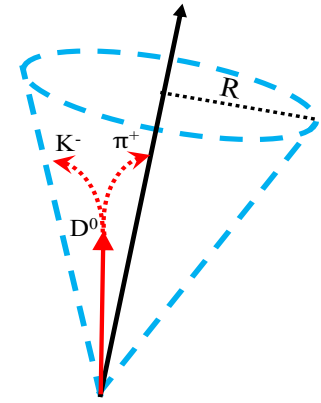


$$Y(\Delta r) = \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{track}}}{d\Delta r dp_{T,\text{track}}}$$

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



*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
- $p_{T,jet}$ 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)

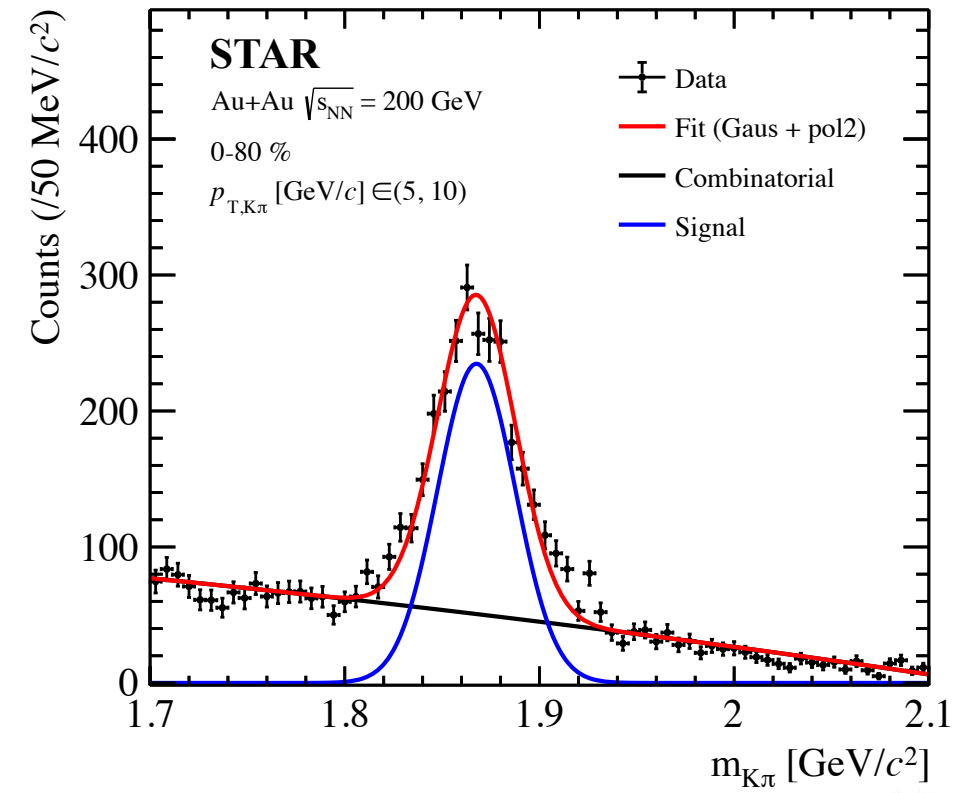
N_k = k -th yield (T=2)

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

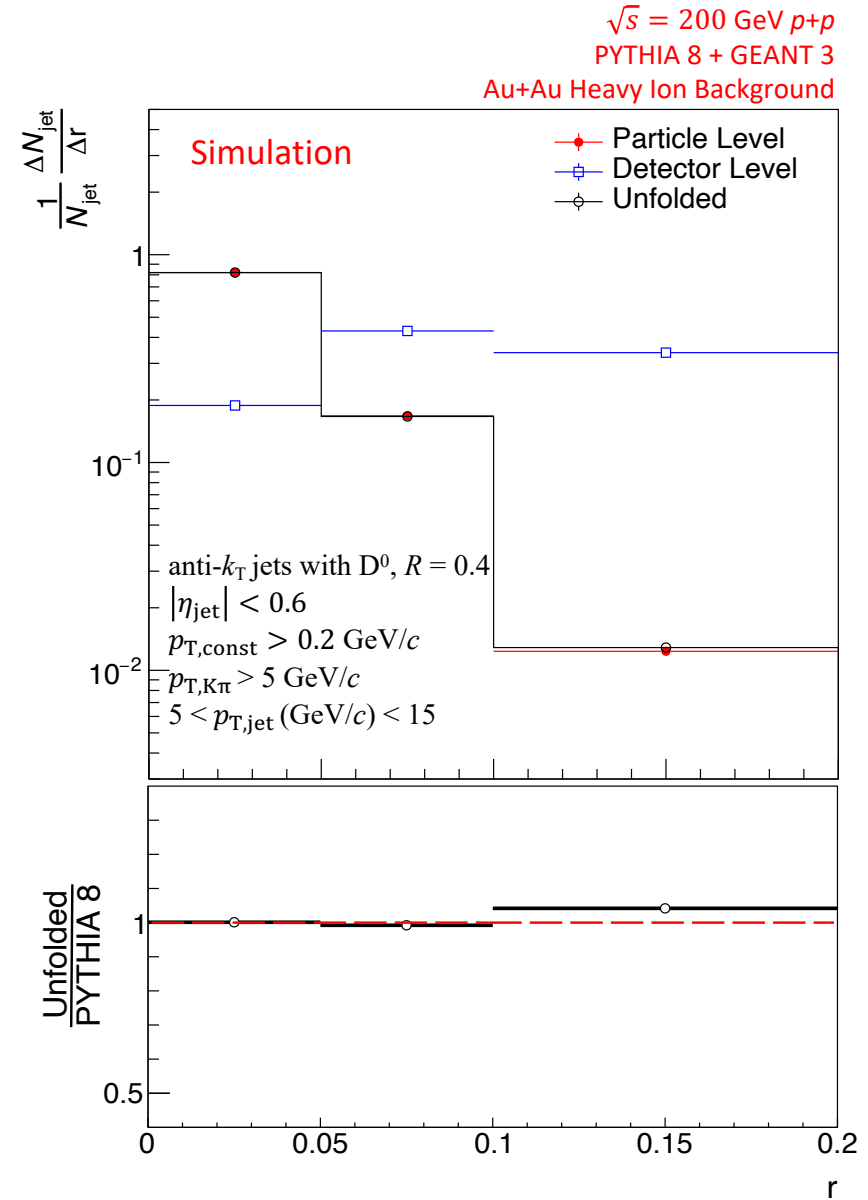
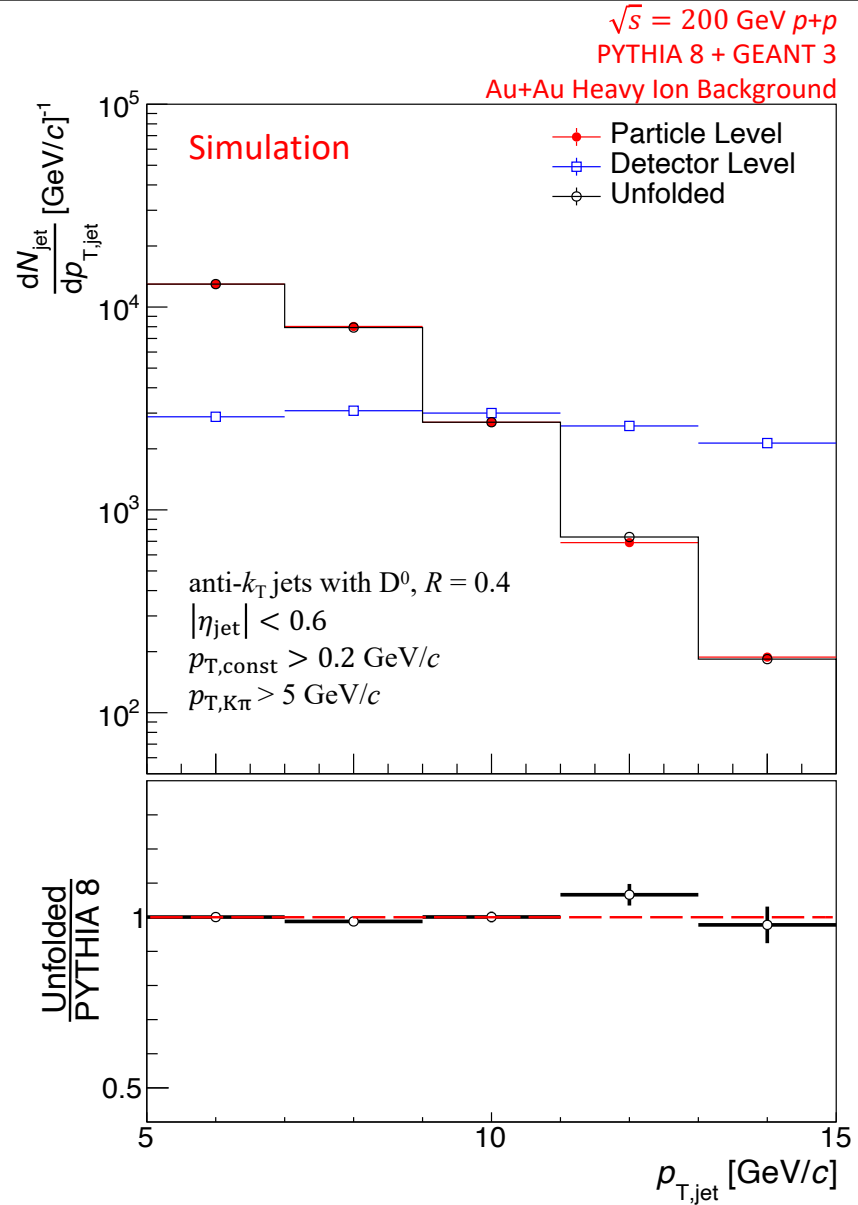
V = cov. matrix

Efficiency Correction ➔

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

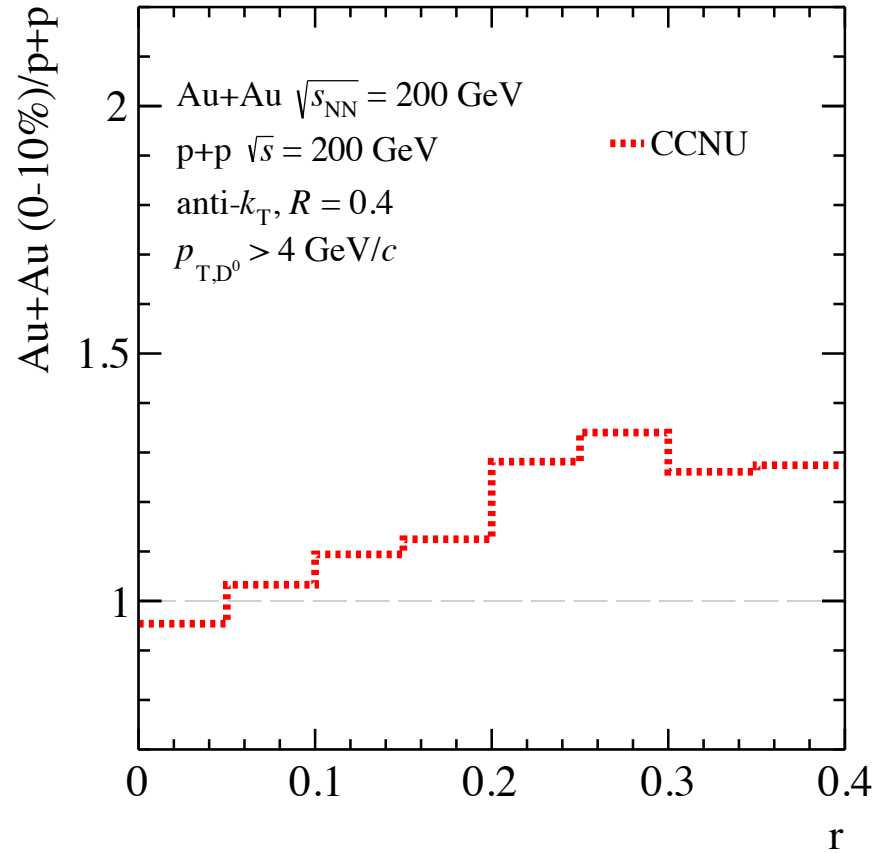


Closures For Unfolding

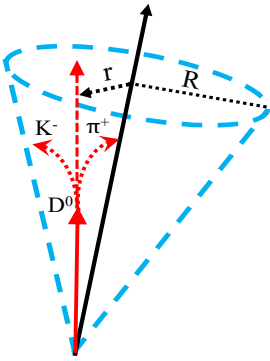
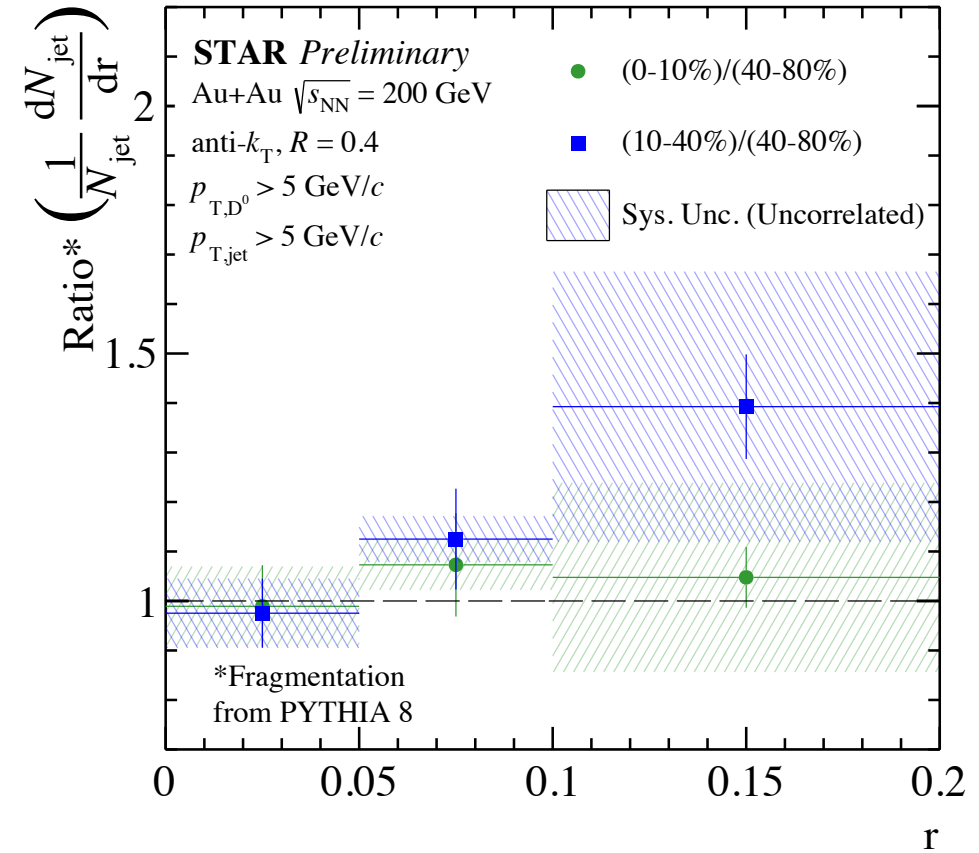


Radial Profile: Data vs Model

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

