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

Diptanil Roy
Rutgers University
For the *STAR Collaboration*
roydiptanil@gmail.com

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NSF

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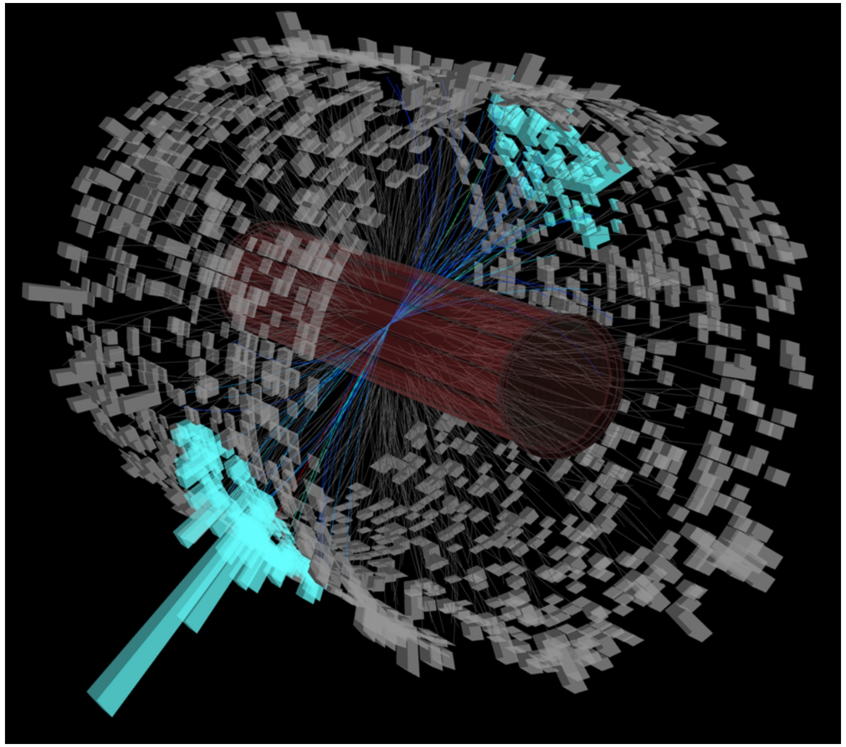
THE STATE UNIVERSITY OF NEW JERSEY

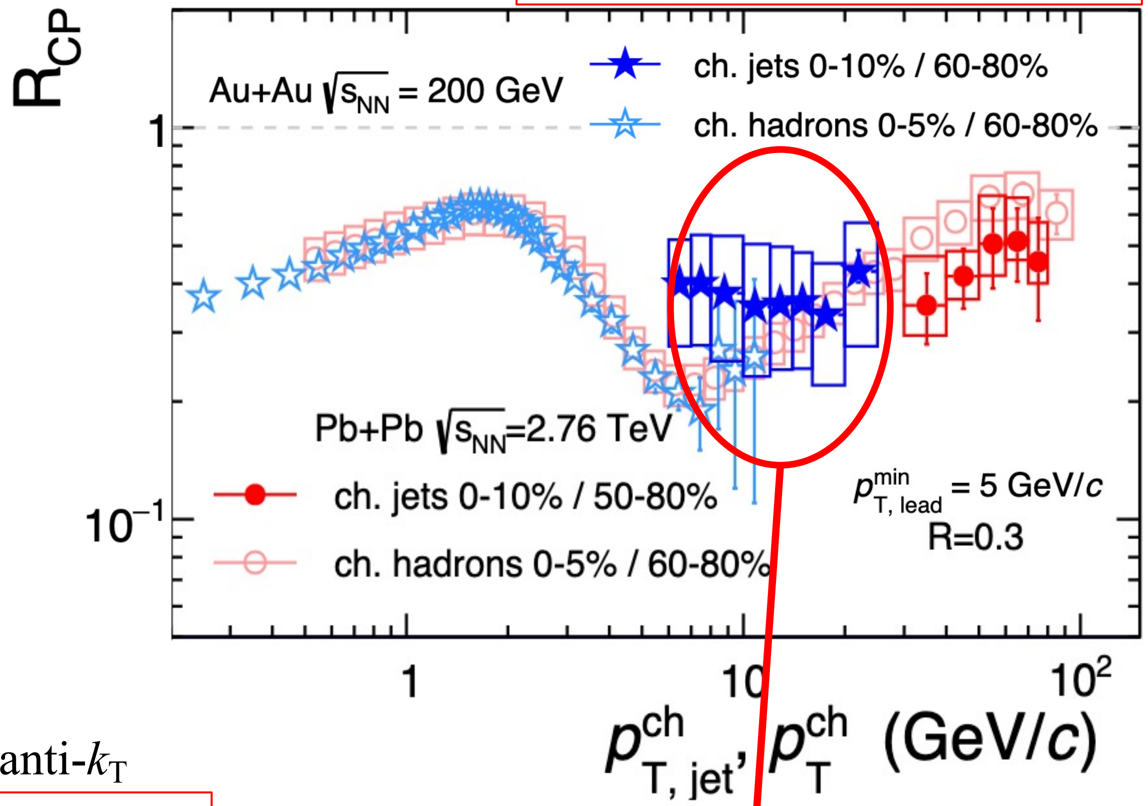
Jets in Heavy Ion Collisions

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

ALICE, JHEP03 (2014) 013

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





- Jets reconstructed by a sequential clustering algorithm, commonly anti-k_T

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

- **Loss of parton energy** in the QGP medium
- **Parton shower modified** due to medium-induced radiation and scattering

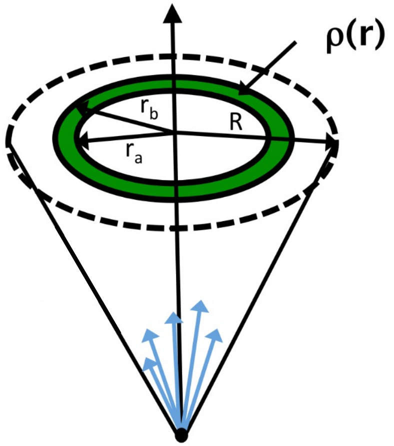
Inclusive jets are heavily quenched in the presence of QGP

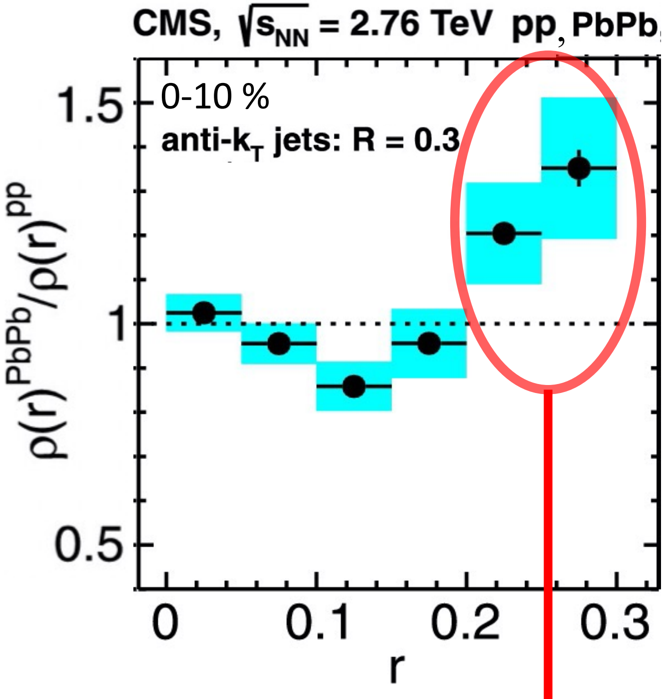
Motivation

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

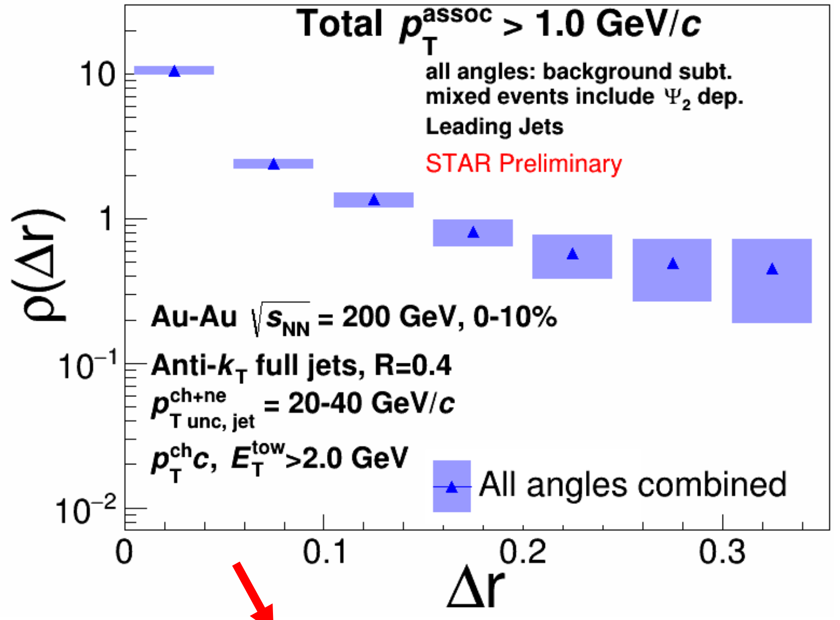
Differential Jet Shape

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





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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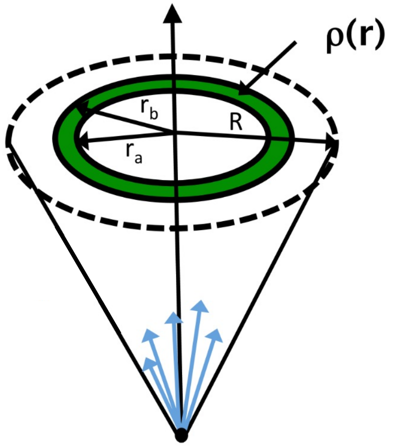
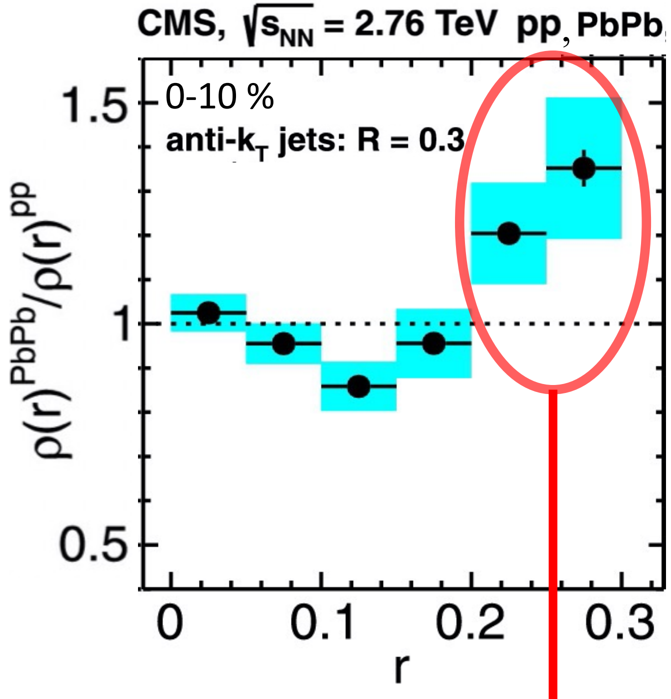
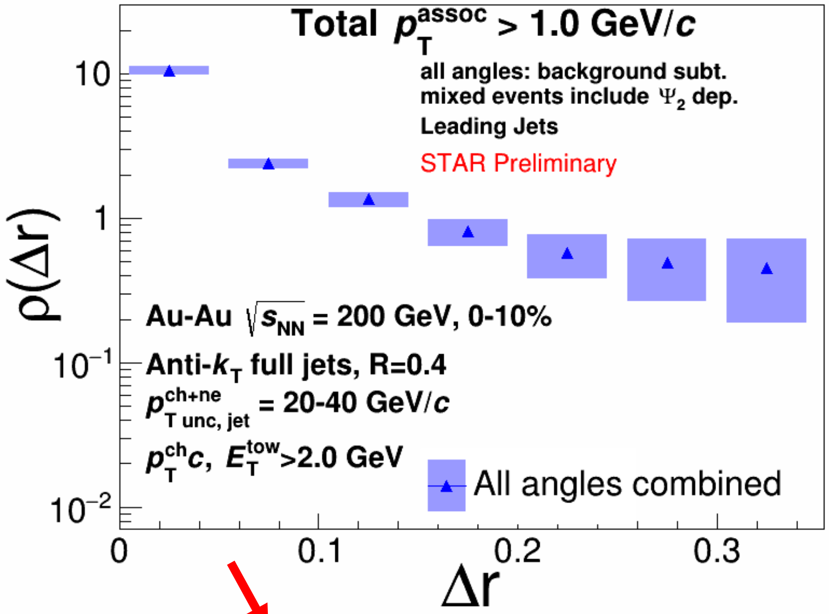




CMS, Phys. Lett. B 730 (2014) 243



Similar pp measurement from STAR underway

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

Possible mechanisms:

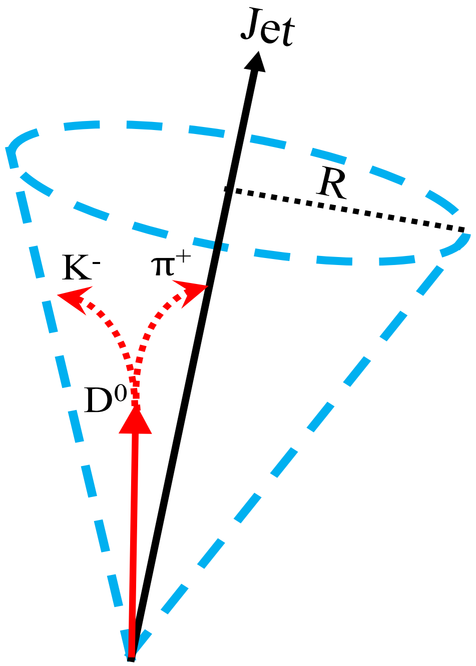
- Multiple scattering
- Medium-induced bremsstrahlung
- Medium response

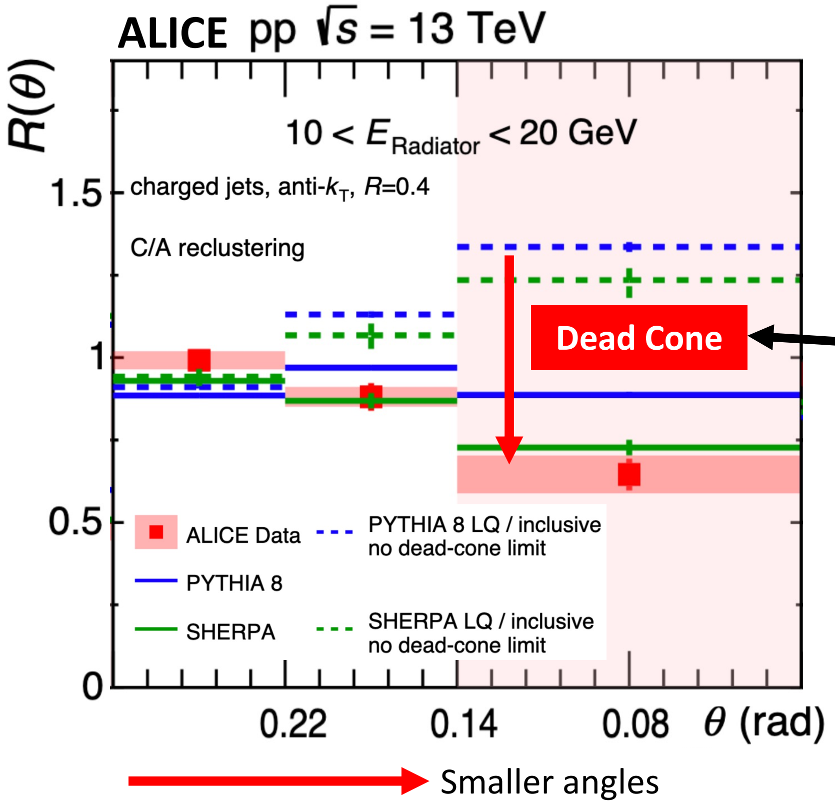
Dependent on the mass of the underlying parton

Motivation to study heavy-flavor jets

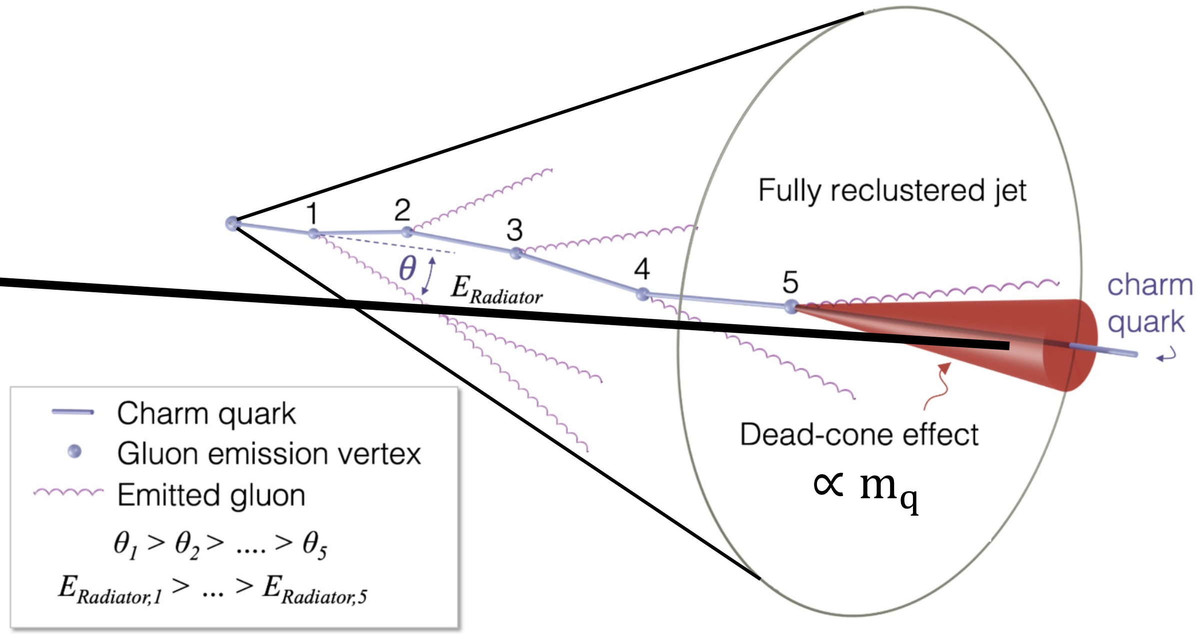
Heavy Flavor Tagged Jets

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





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

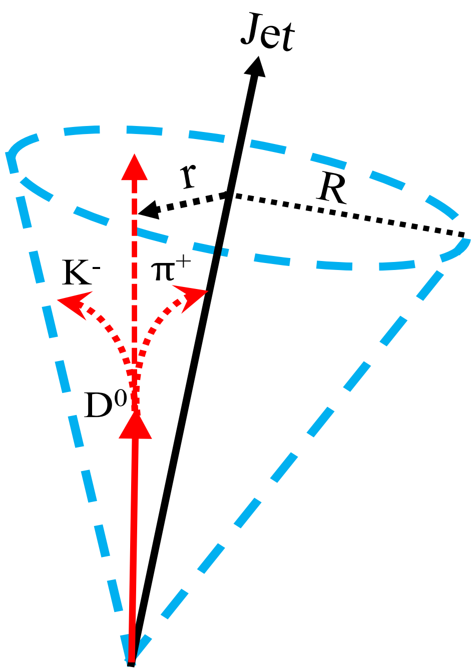


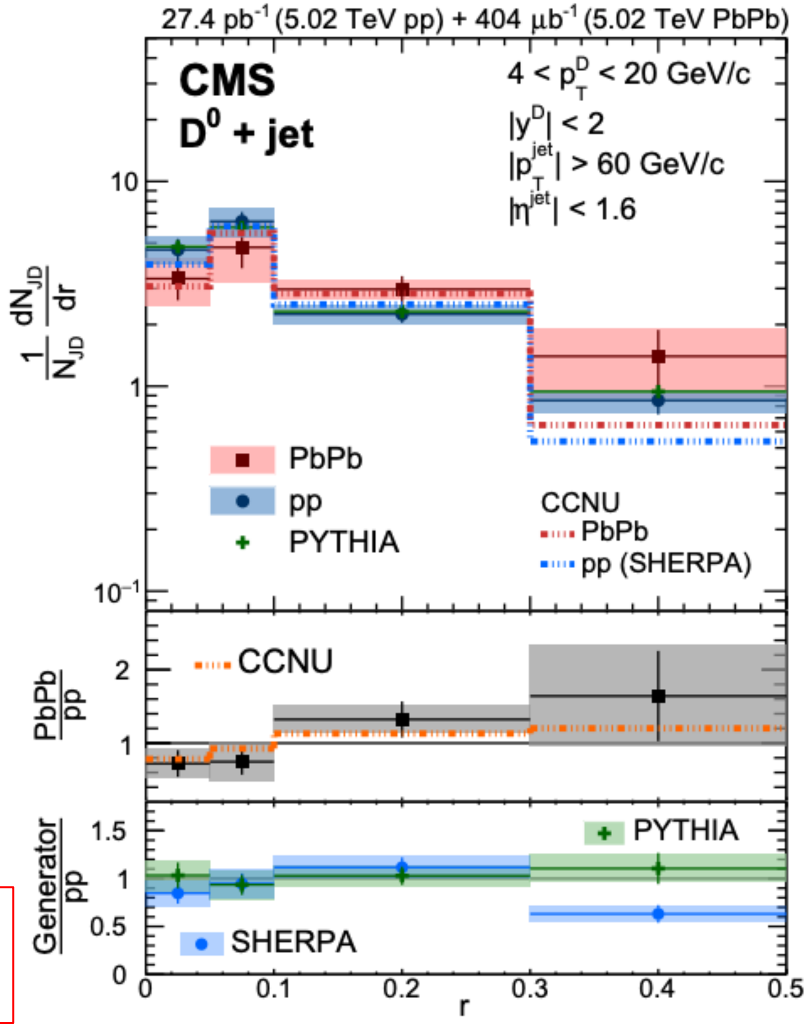
Heavy-flavor emission spectra at small angles suppressed due to dead-cone effect [1]

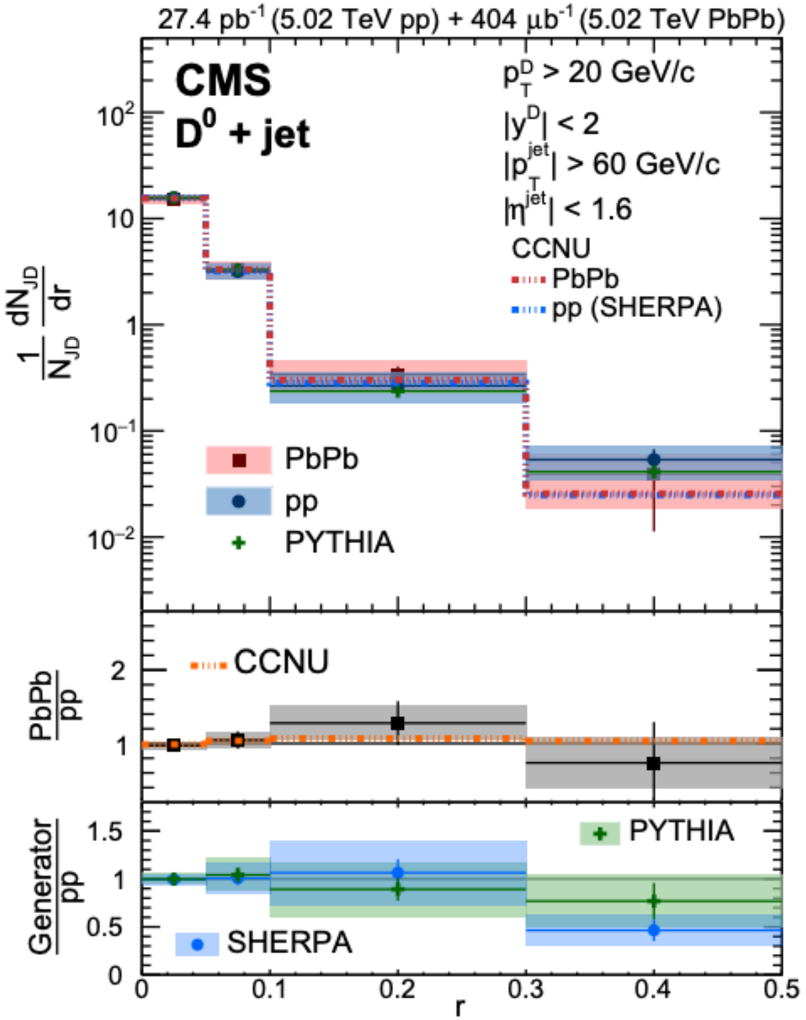
[1] J. Phys. G: Nucl. Part. Phys. **17** 1602 (1991)

Heavy Flavor Tagged Jets

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



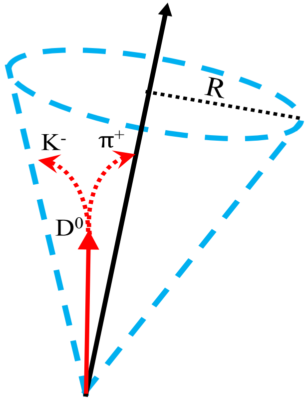




Low p_T D^0 mesons slightly diffused in the presence of QGP at LHC

- 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

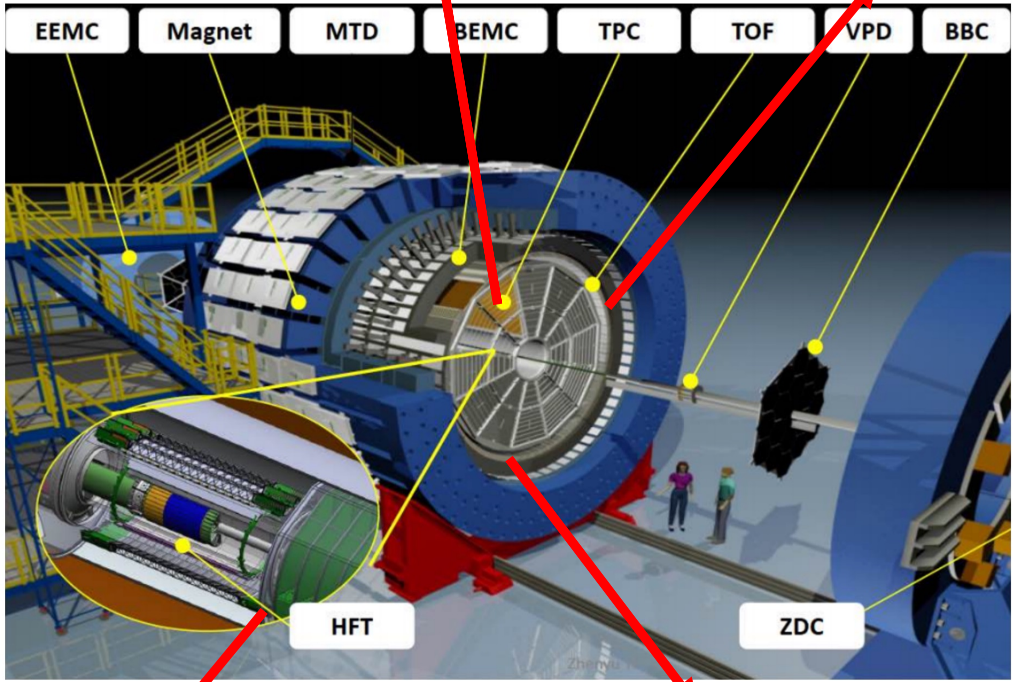


Time Projection Chamber (TPC)

- 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 ∈ [0, 80]% (3 bins: [0-10], [10-40], [40-80])

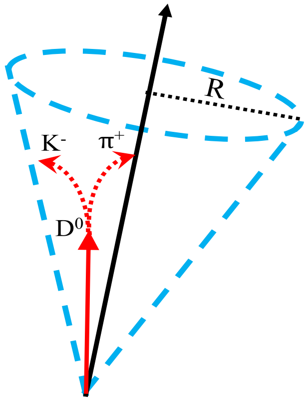
Constituent Selection:

- $0.2 < p_{T,track}$ [GeV/c] < 30 ; $0.2 < E_{T,tower}$ [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
- $5 < p_{T,D^0}$ [GeV/c] < 10

D^0 Jet Selection:

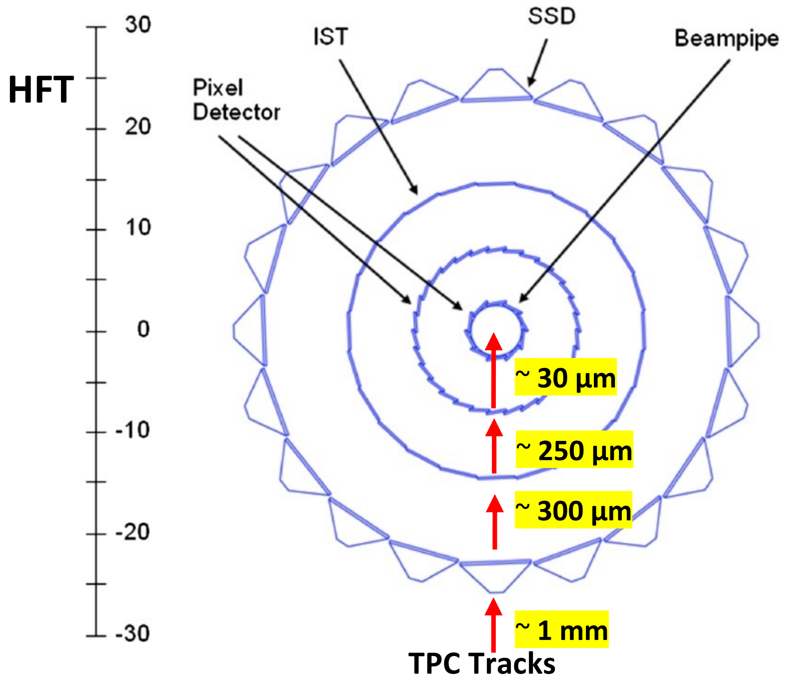
- Anti-k_T full jets of radius R = 0.4, area-based background subtraction
- $|\eta_{Jet}| < 0.6$

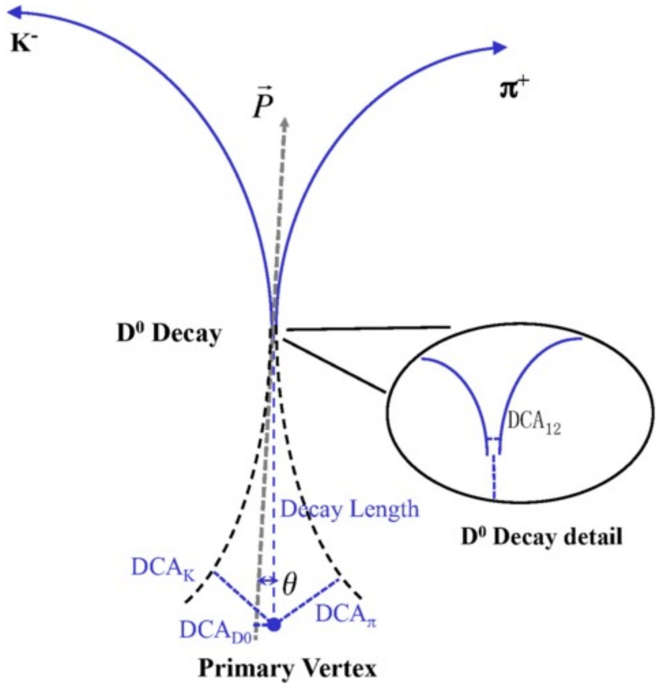
D^0 Reconstruction

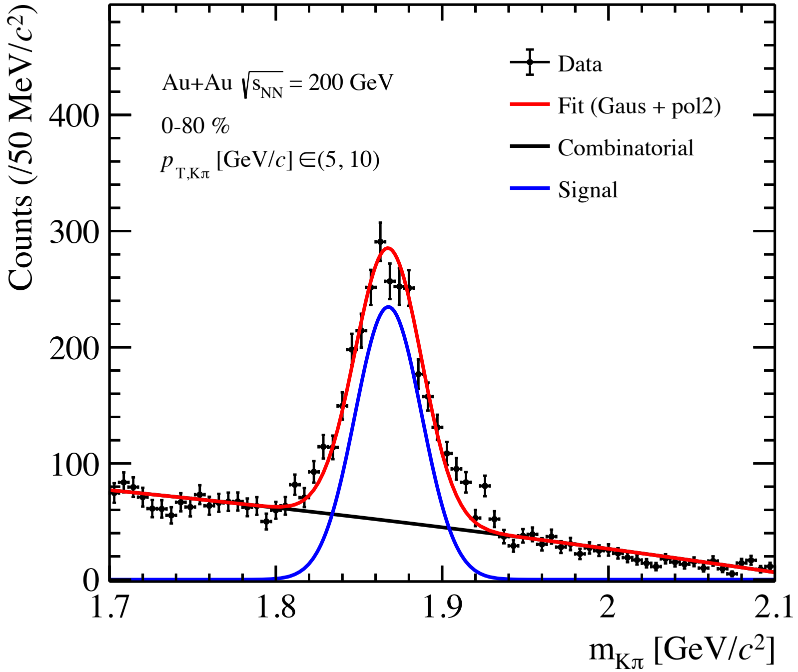


- Kaons and Pions identified using TPC and TOF

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





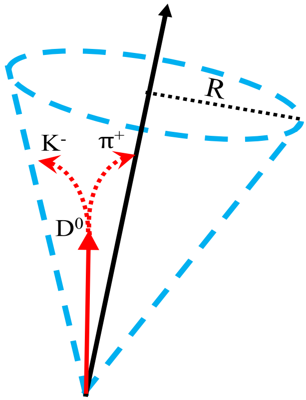


Topological cuts on the D^0 candidates improve signal significance

Yield is calculated using sPlot method [1]

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

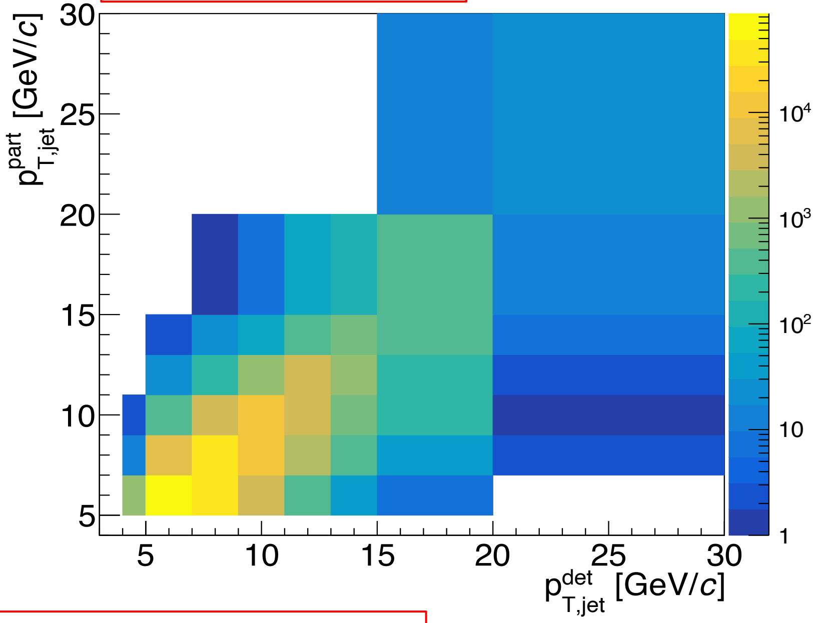
Correction to the Jet Yield



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

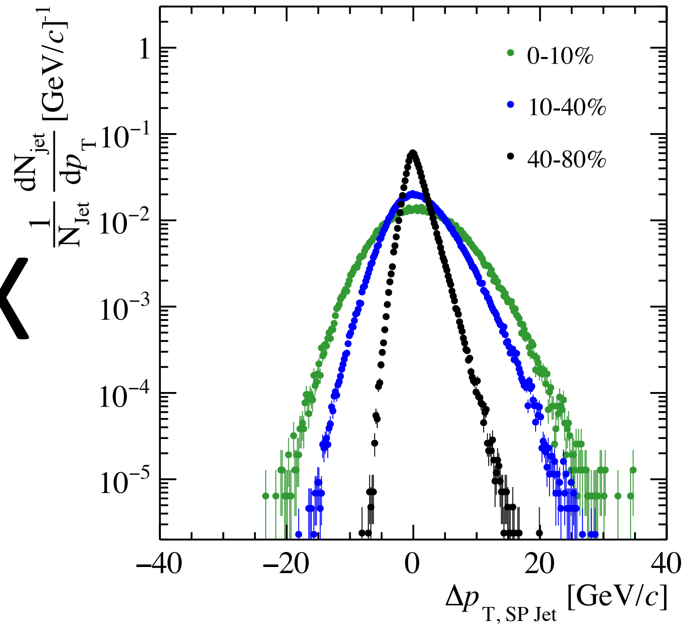
anti-k_T jets with D^0, R = 0.4
$5 < p_{T,K\pi} < 10$ [GeV/c]

$\sqrt{s}$ = 200 GeV p+p
PYTHIA 8 + GEANT 3



X

Au+Au Heavy Ion Background



[1]. **FONLL**, JHEP03 (2001) 006

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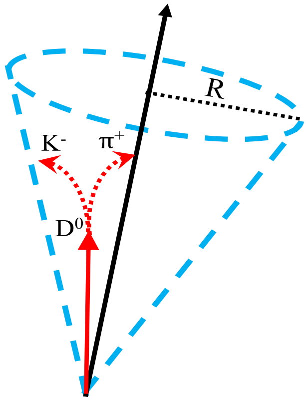

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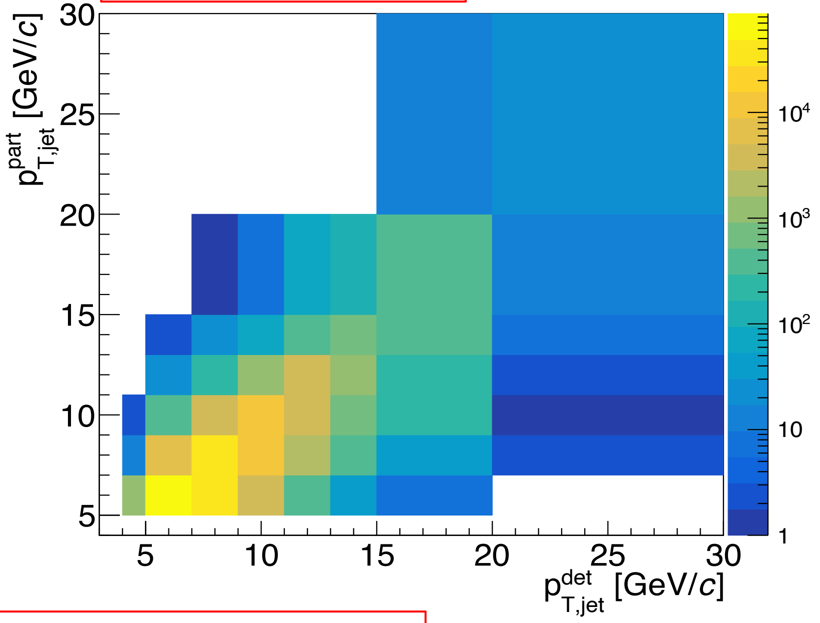

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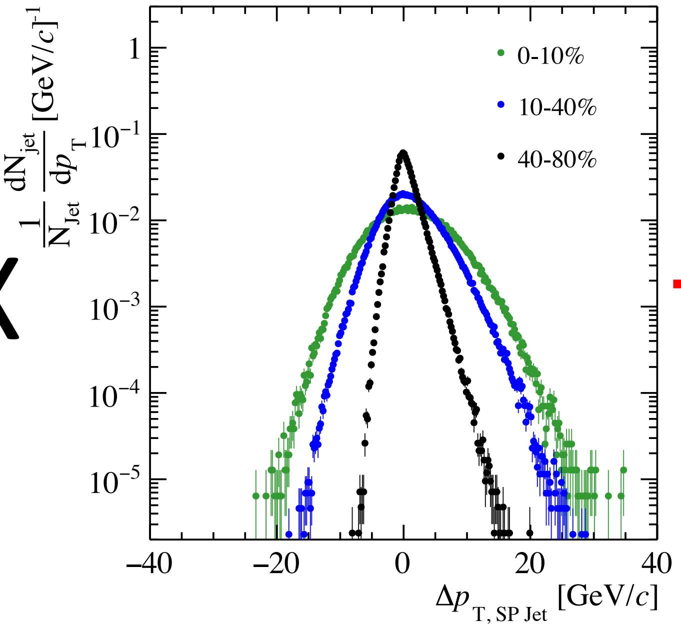
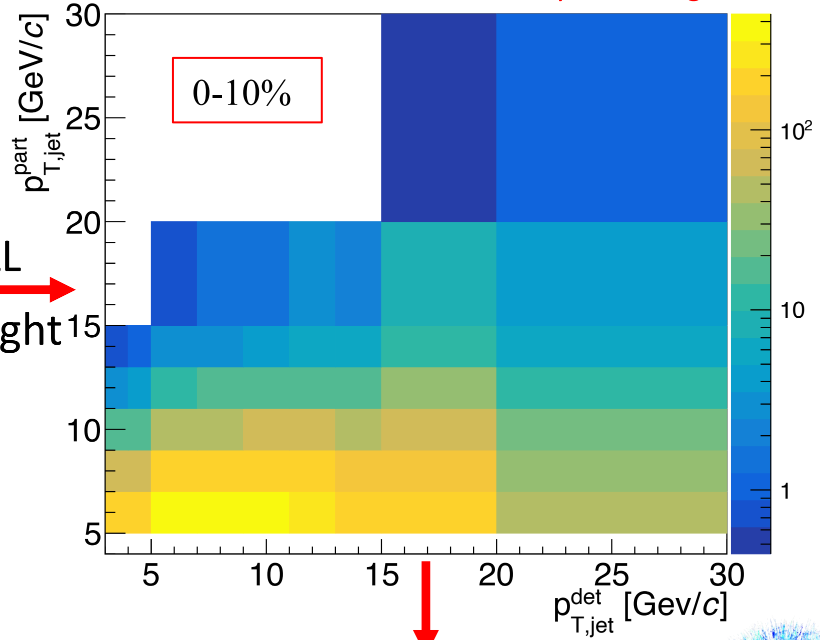


FONLL
Reweight

PYTHIA 8 + GEANT 3 + Au+Au Heavy Ion Background



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

[1]. FONLL, JHEP03 (2001) 006

Correction to the Jet Radial Profile

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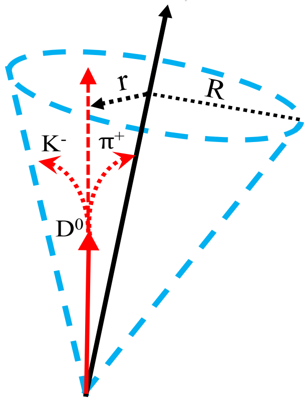
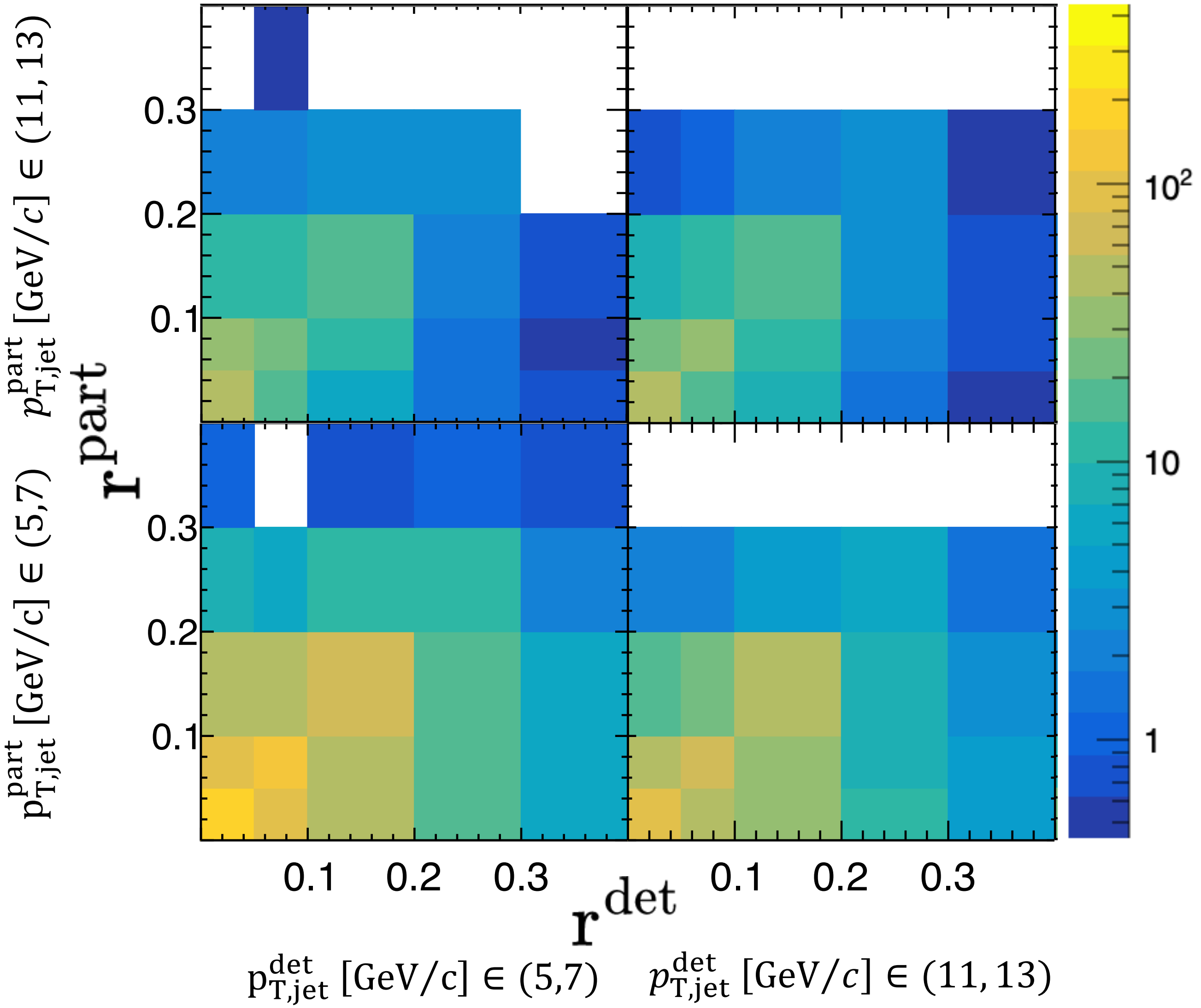


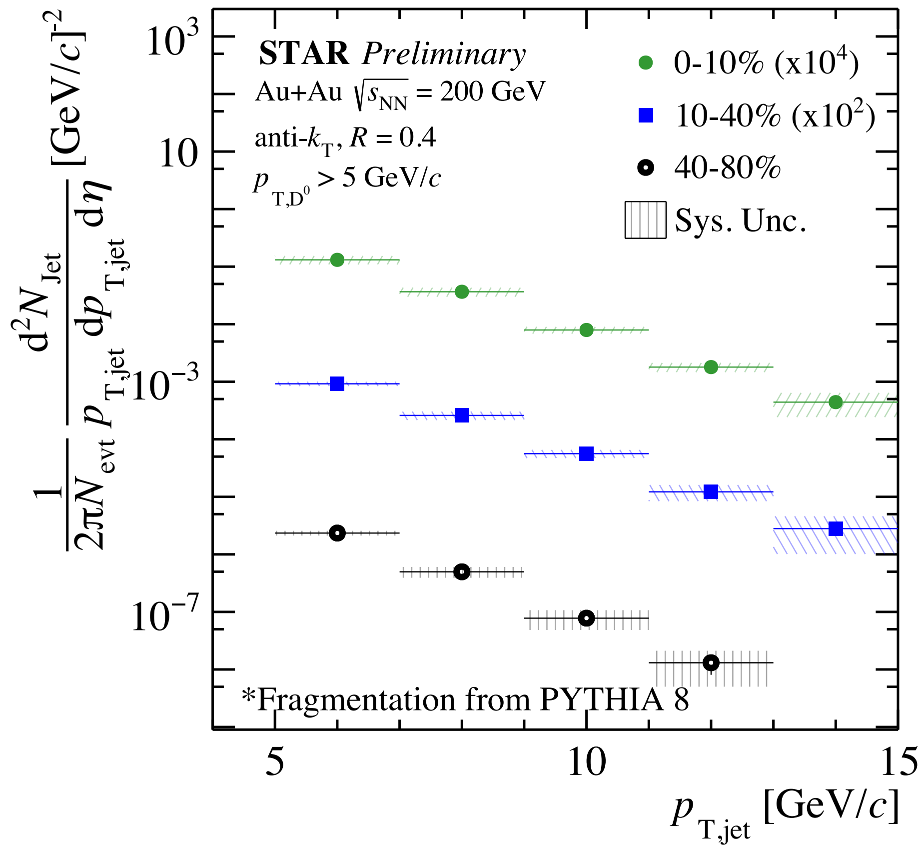


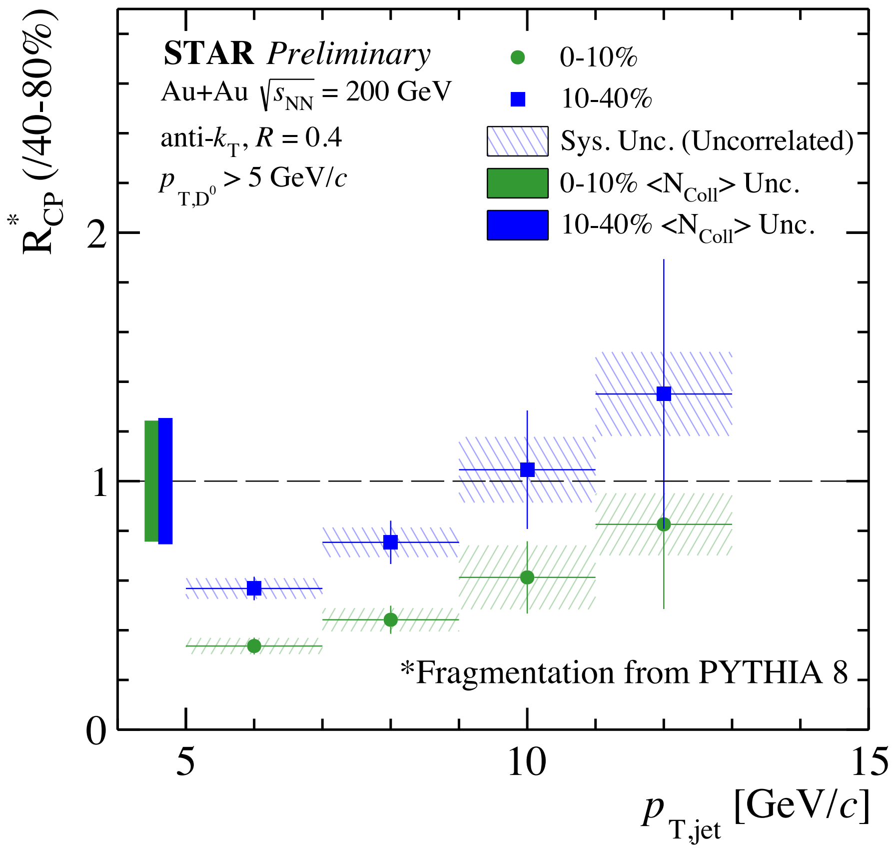
anti-k_T jets with D^0, R = 0.4
$|\eta_{jet}| < 0.6$
$p_{T,const} > 0.2$ GeV/c
$5 < p_{T,K\pi} < 10$ (GeV/c)

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

Complete 4D response matrix to unfold radial pro

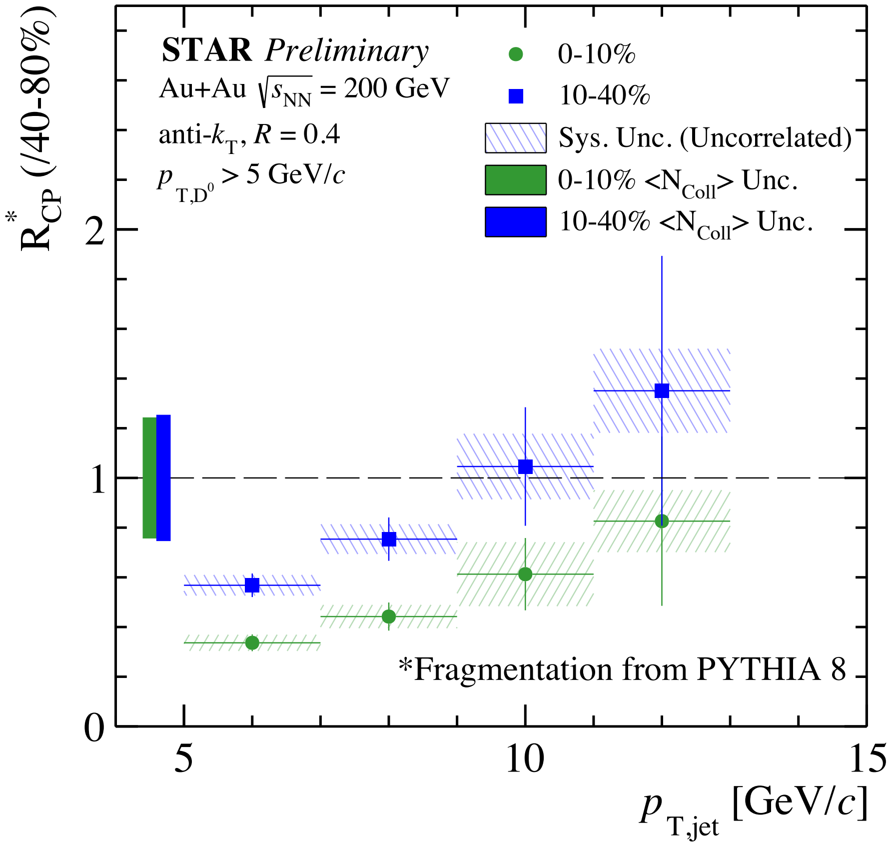
Jet Spectra

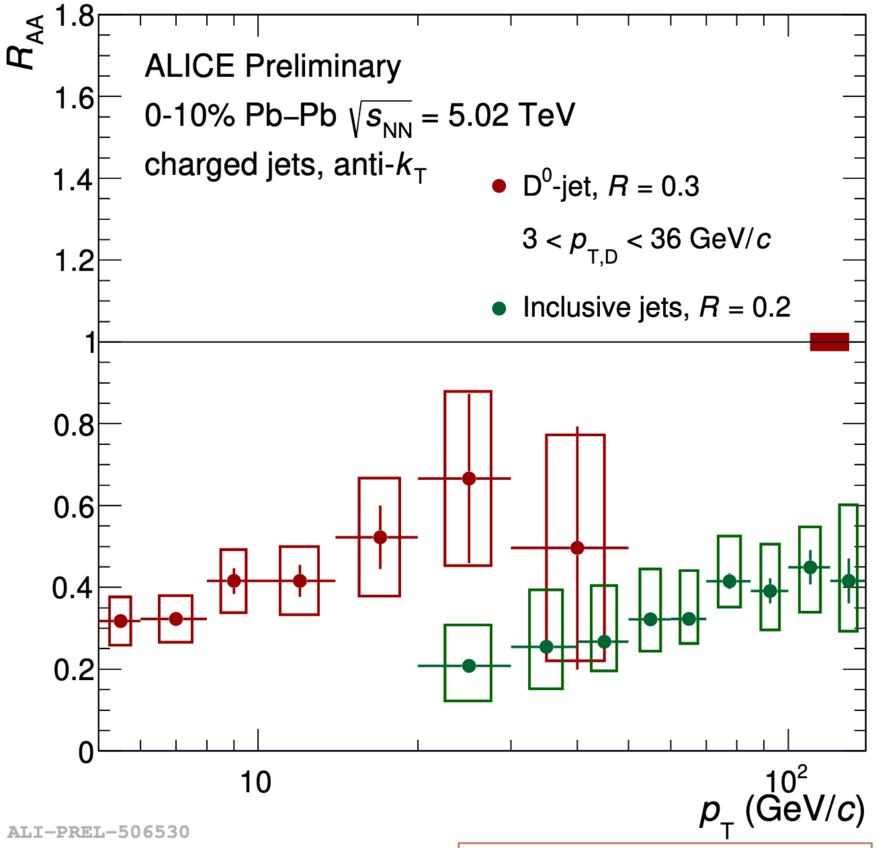




- Peripheral events have limited D^0 p_T reach
- Yields in most central collisions are more suppressed than mid-central
- R^*_{CP} shows strong suppression at low $p_{T,jet}$, hint of an increasing trend with $p_{T,jet}$
- D^0-tagged jet measurement for R_{AA} will be explored using high-statistics p+p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

Energy dependence

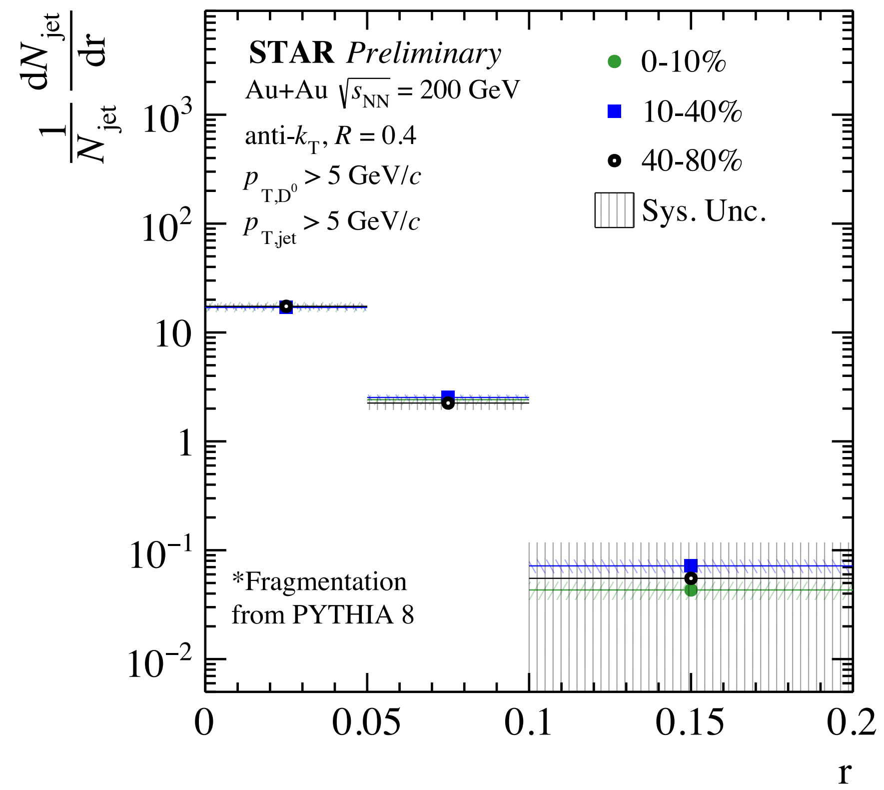


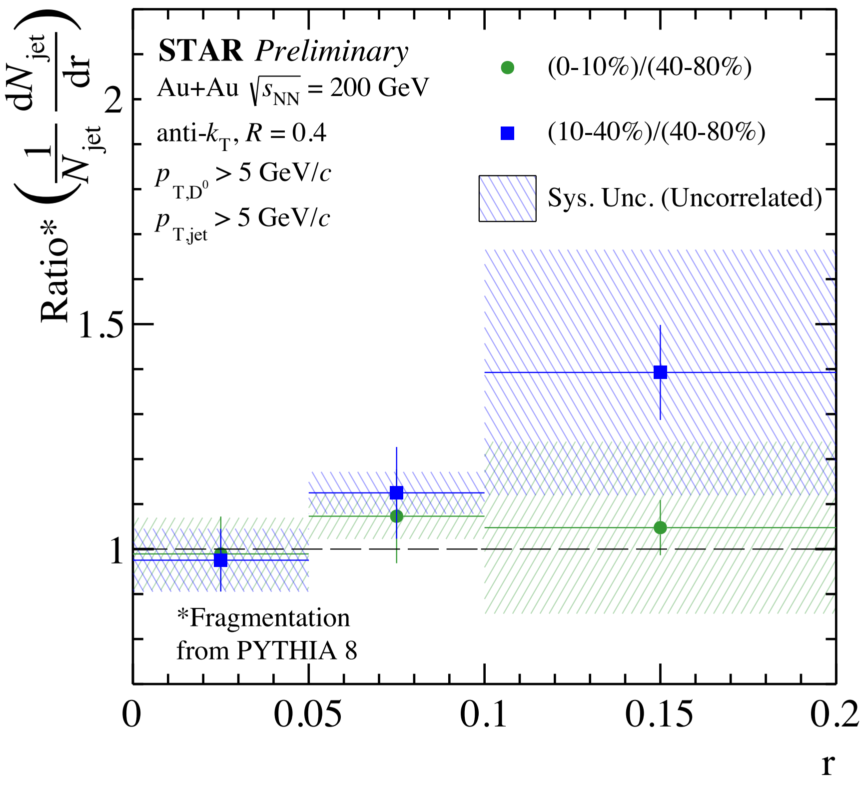


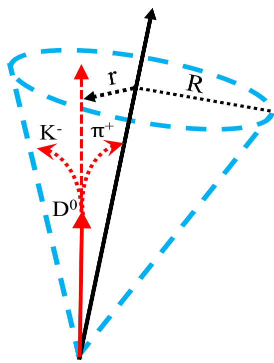
ALICE, arXiv:2208.10908

- Similar nuclear modifications of D^0-tagged jets at 200 GeV from STAR and 5 TeV from ALICE

Radial Profile of D^0 Mesons in Jets



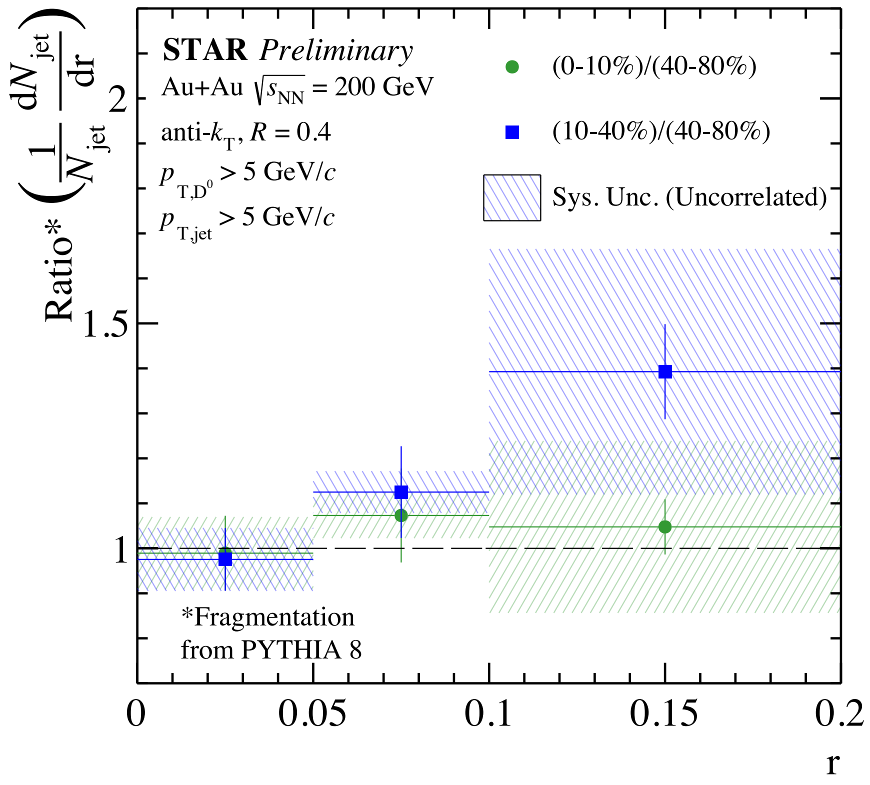


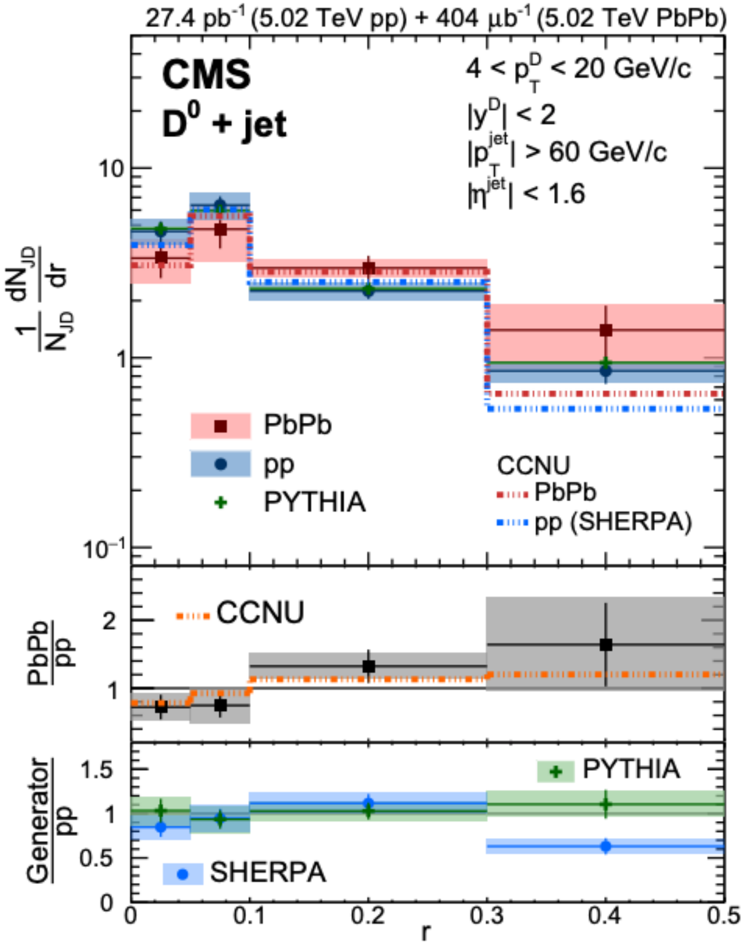


- For D^0 p_T > 5 GeV/c, the ratio of radial distributions is consistent with unity within uncertainties
- Extending the analysis to lower D^0 kinematics to further study D^0 diffusion

Energy dependence

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

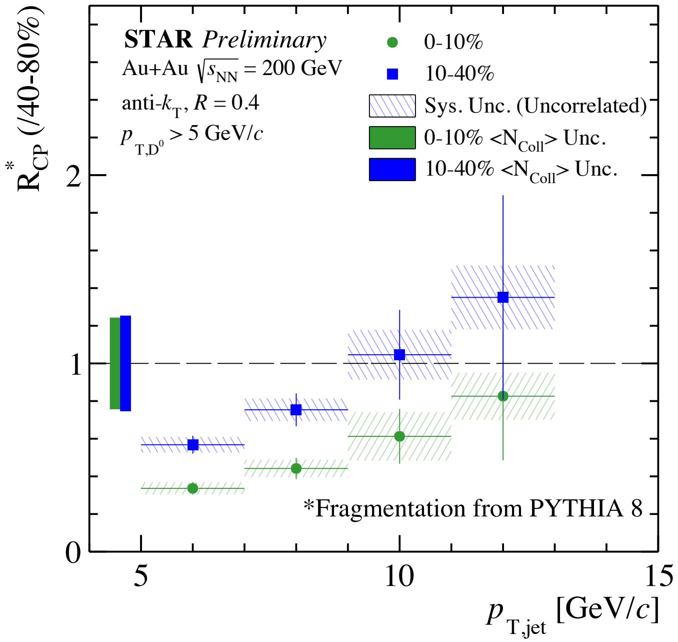


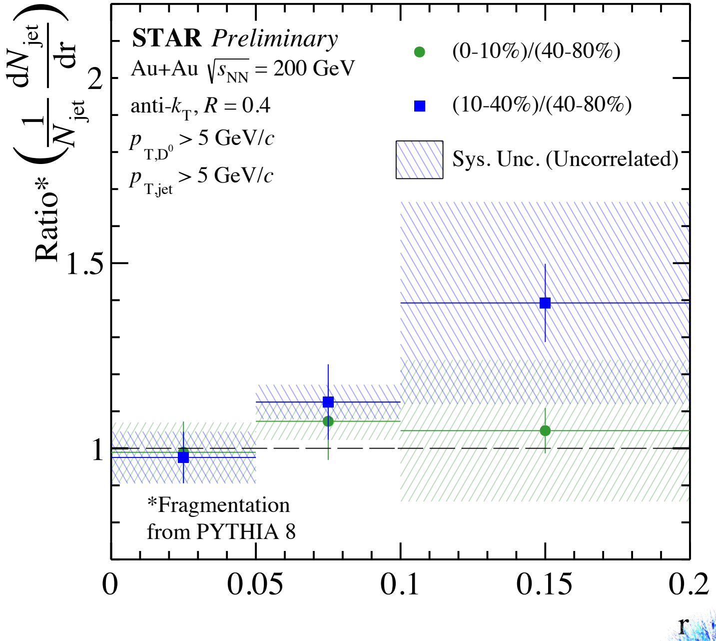


- No significant diffusion seen for D^0 mesons in tagged jets at 200 GeV from STAR for $p_{T,D^0} > 5$ GeV and $p_{T,Jet} > 5$ GeV
- Slight diffusion observed for D^0 mesons in tagged jets at 5 TeV from CMS for $4 < p_{T,D^0} < 20$ GeV and $p_{T,Jet} > 60$ GeV

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.





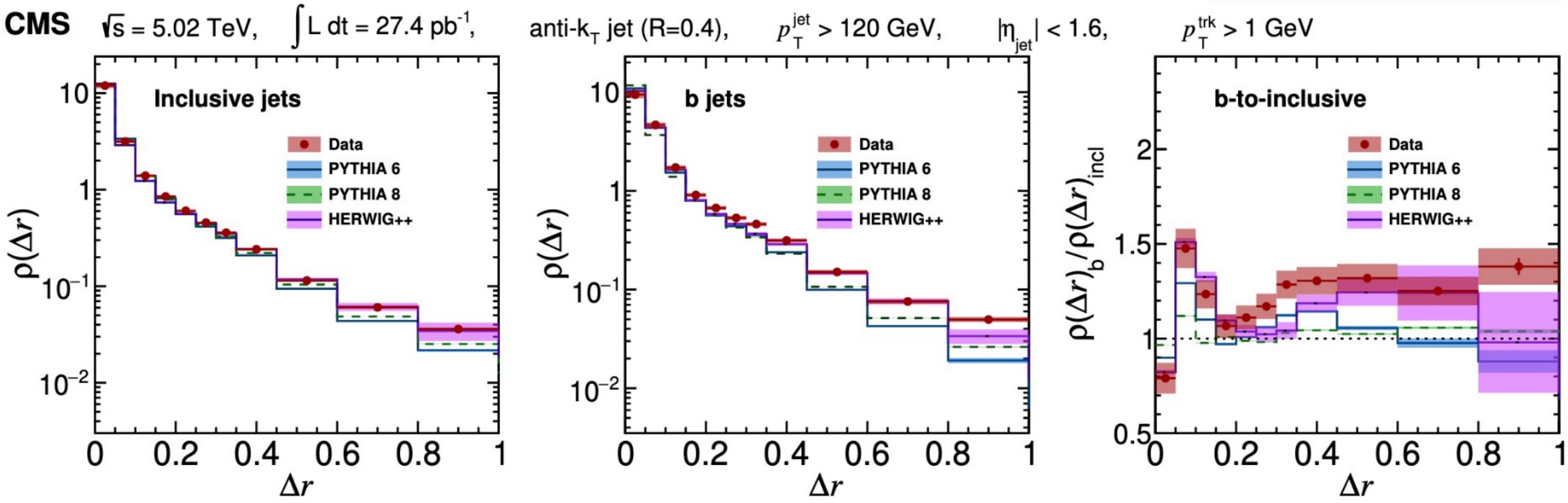
Outlook

- 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

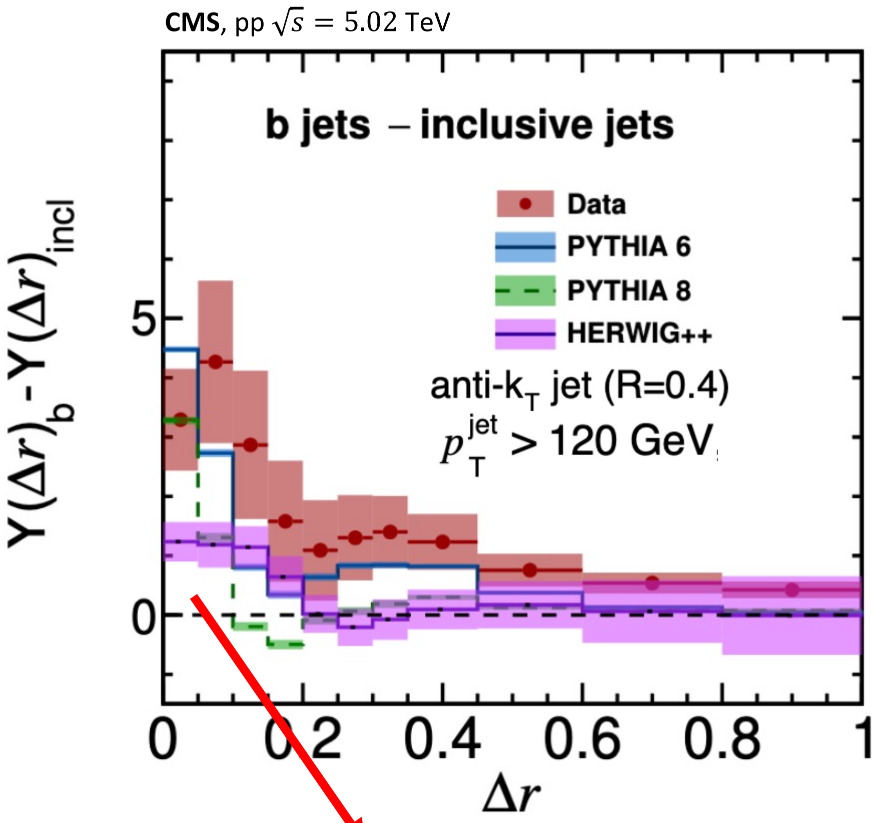


Bottom quark jet (b-jets) shapes modified in vacuum, possibly due to dead cone

Fragmentation pattern for heavy quark

CMS, JHEP05 (2021) 054

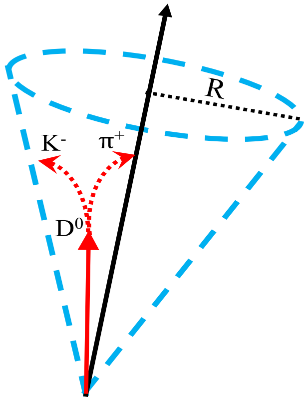
$$Y(\Delta r) = \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{track}}}{d\Delta r dp_{\text{T,track}}}$$



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

D^0-Jet Yield Extraction

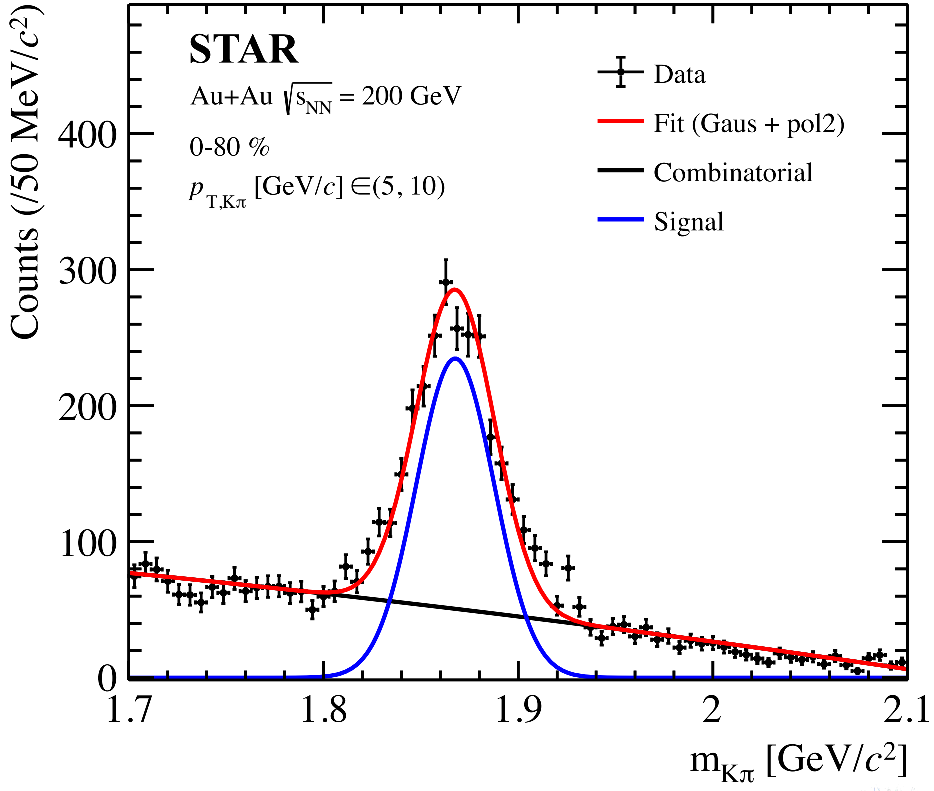


$_s\mathcal{P}lot$

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
- $p_{\mathrm{T,jet}}$ and radial distributions with all D^0-tagged jet candidates using sWeights
- Easy to include reconstruction efficiencies versus D^0 kinematics

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



Unbinned max. likelihood fit

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

N_k = k-th yield (T=2)

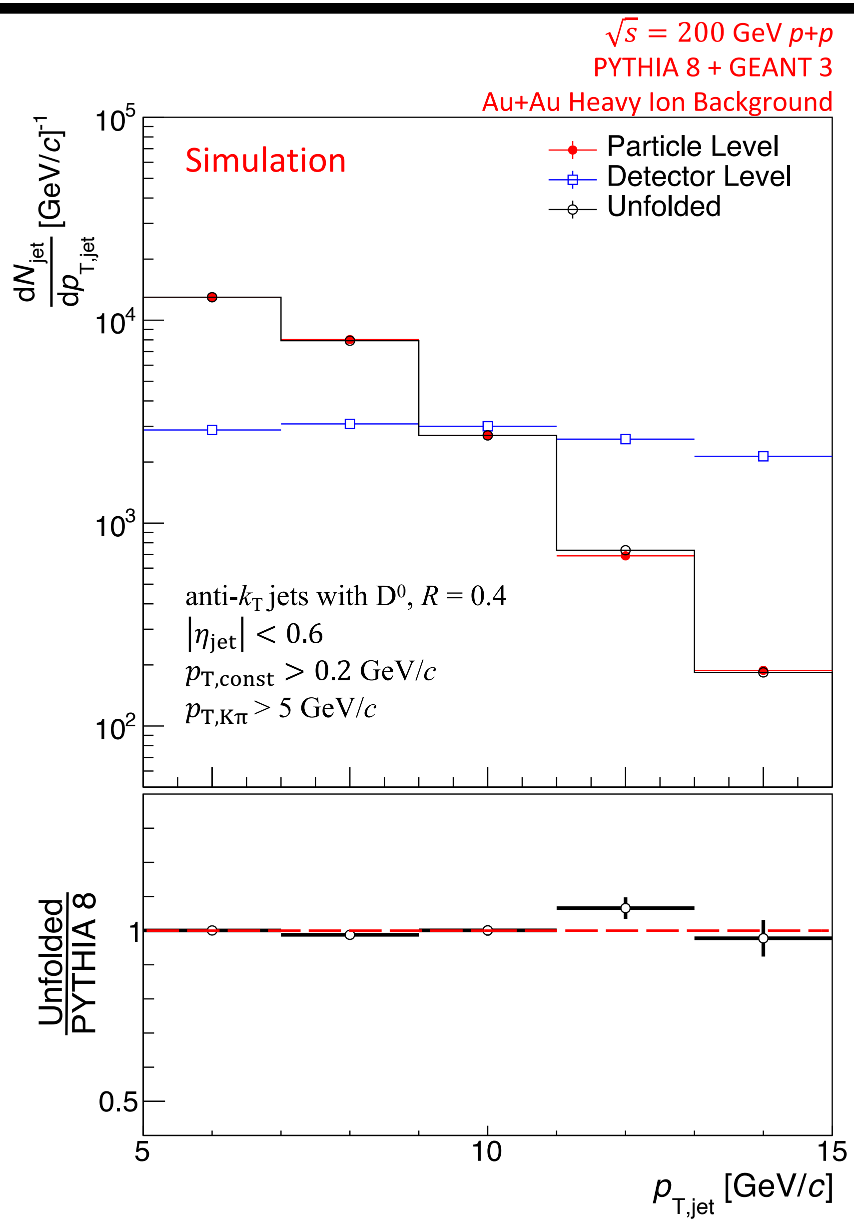
$f_k(m_{K\pi,i})$ = per-event PDF value with k^{th} hypothesis

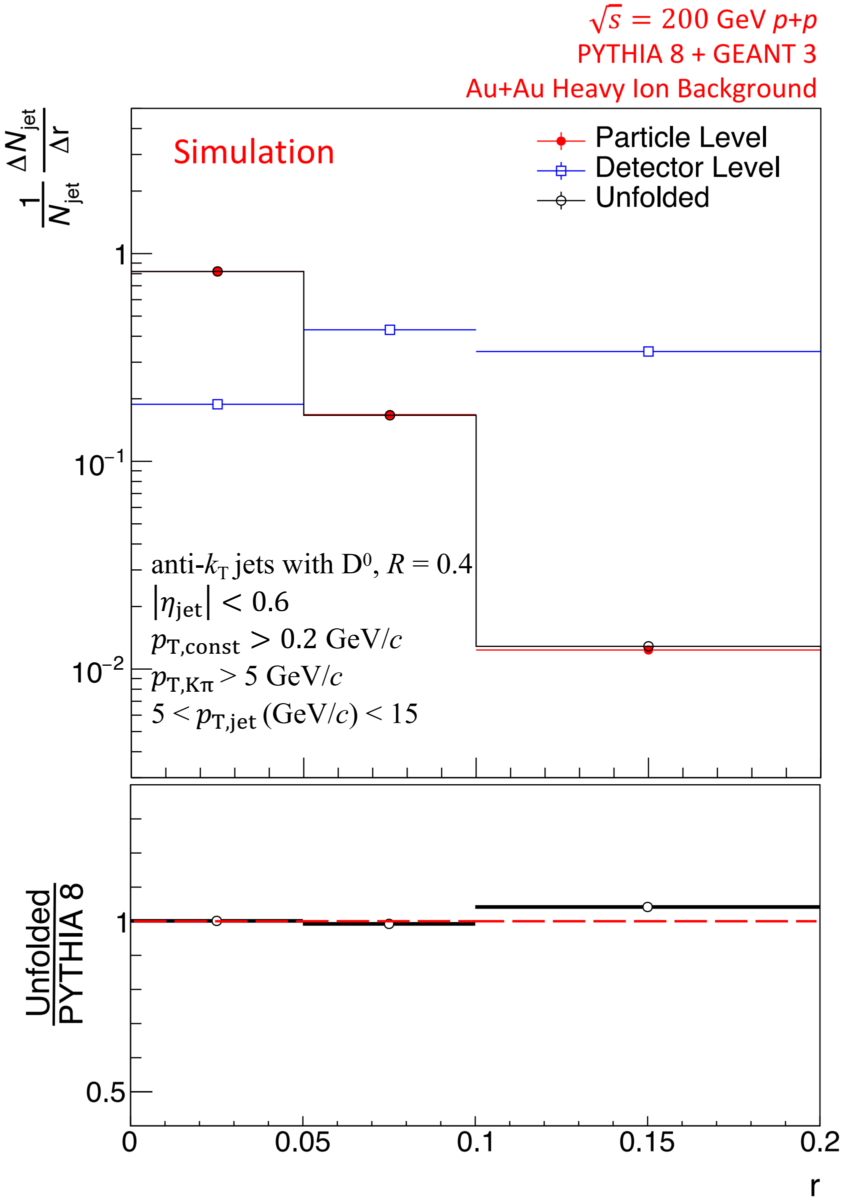
V = cov. matrix

Efficiency Correction

$$\boxed{{}_s\mathcal{P}_n(m_{K\pi,i}) \to \frac{{}_s\mathcal{P}_n(m_{K\pi,i})}{\varepsilon(m_{K\pi,i})}}$$

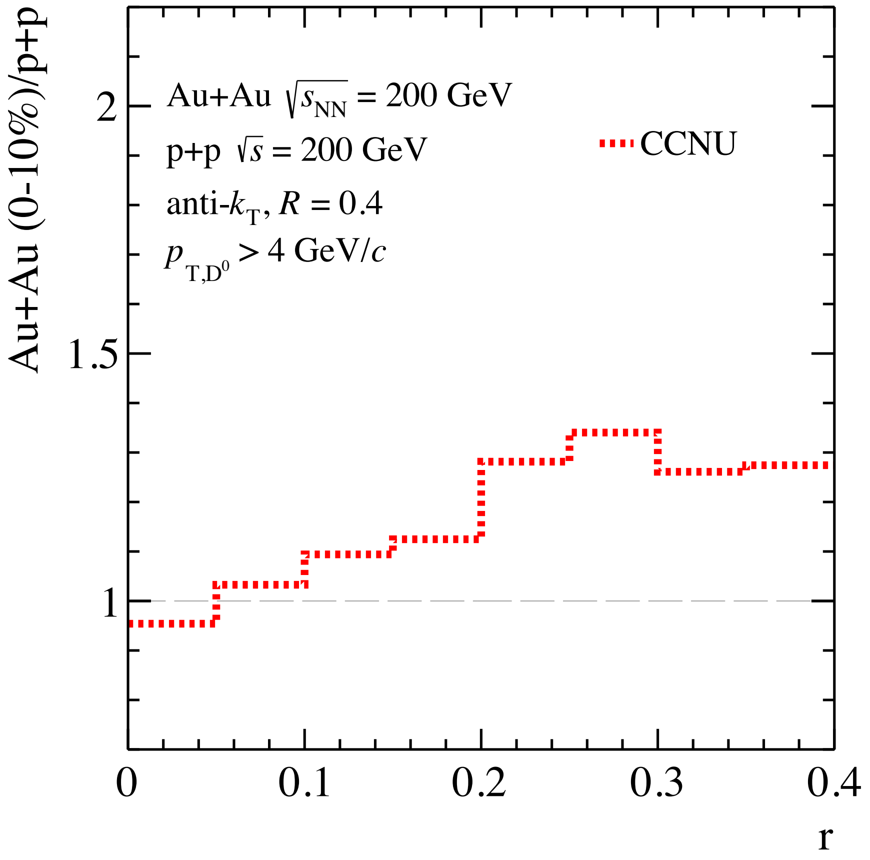
Closures For Unfolding



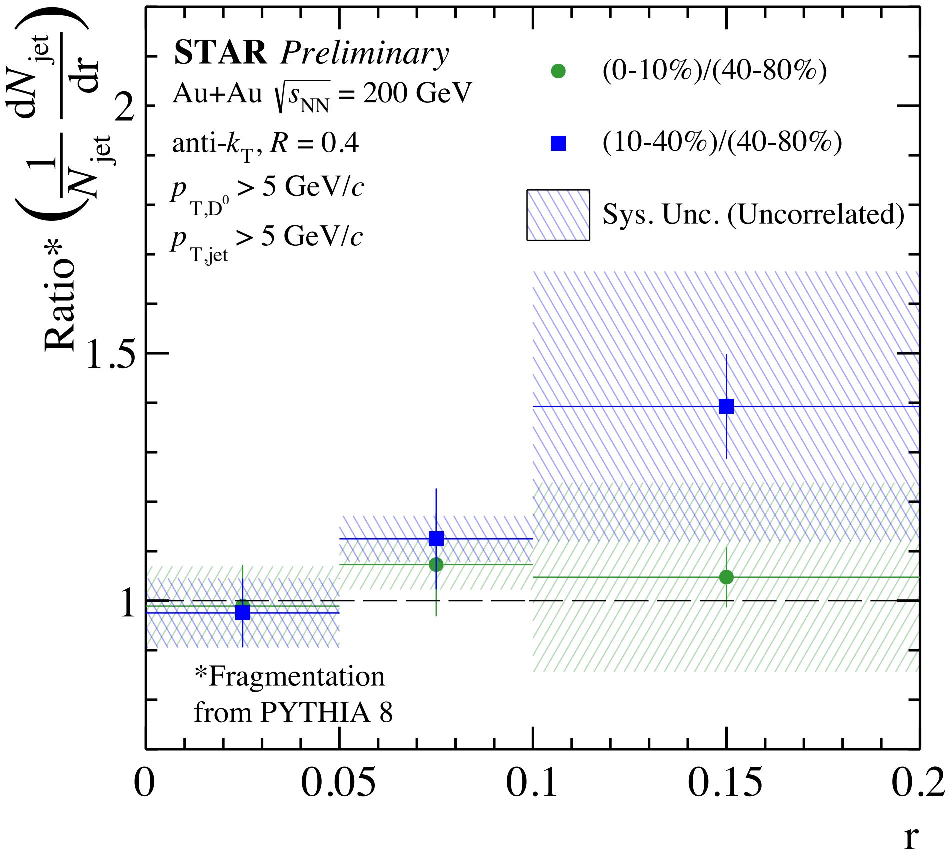


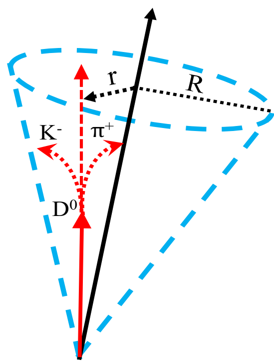
Radial Profile: Data vs Model

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, ${}_s\mathcal{P}lot$ 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