

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

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Supported in part by



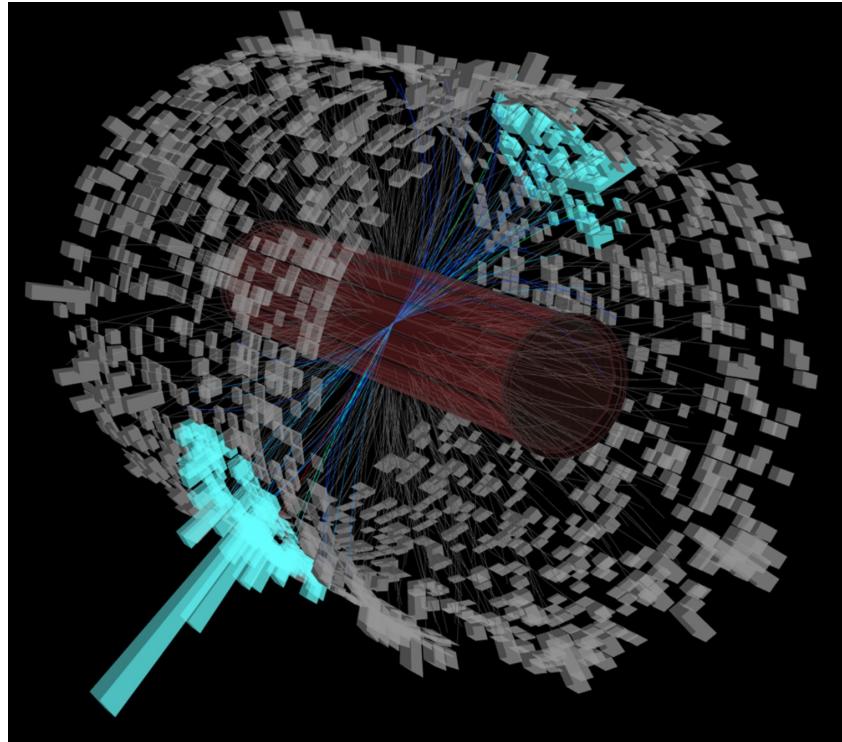
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Jets in Heavy Ion Collisions

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



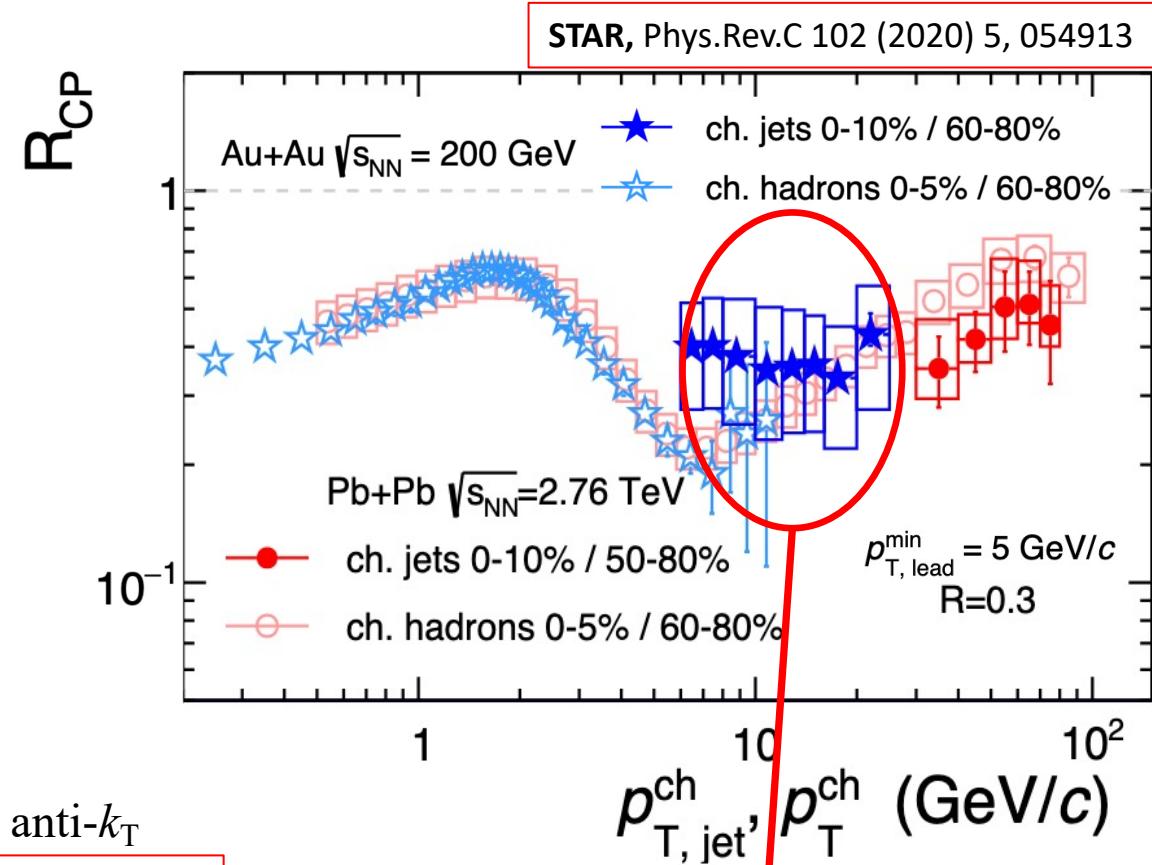
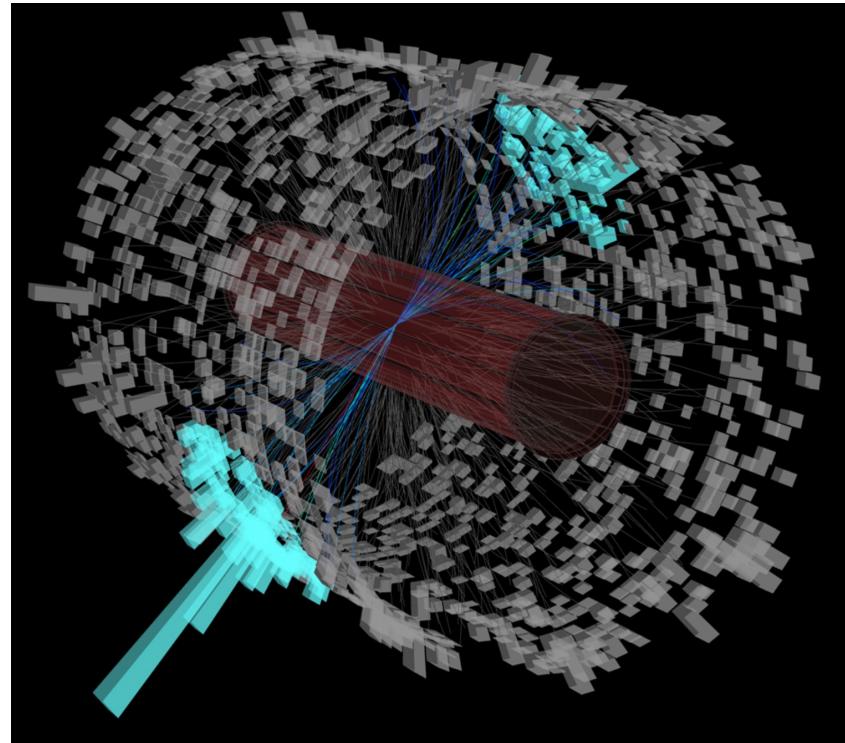
- Jets reconstructed by a sequential clustering algorithm, commonly anti- k_T
- Loss of parton energy in the QGP medium
- Parton shower broadened due to medium-induced radiation and scattering

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

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



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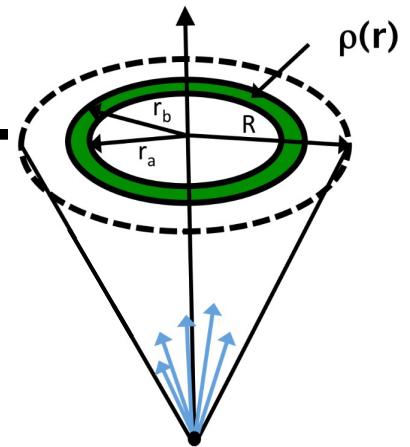
FASTJET, Phys. Lett. B 641 (2006) 57-61

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

Motivation

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

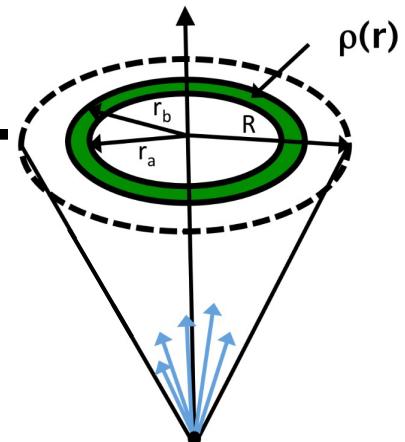
$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$



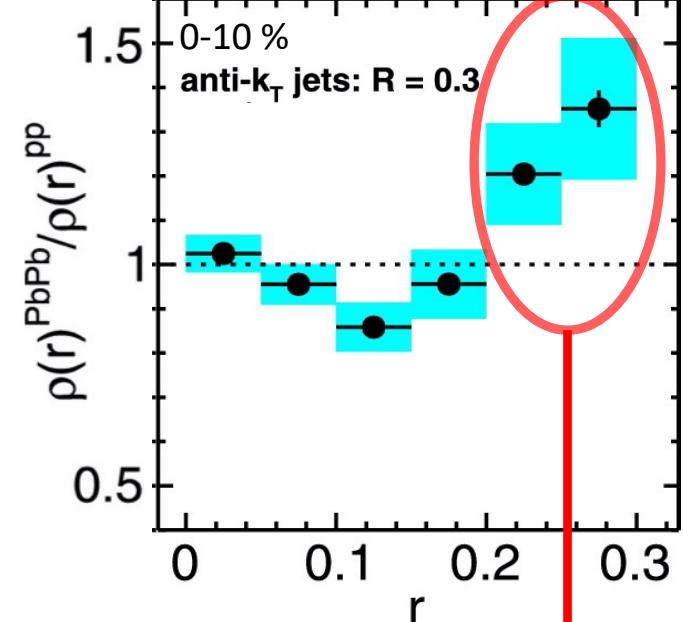
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CMS, $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ pp, PbPb



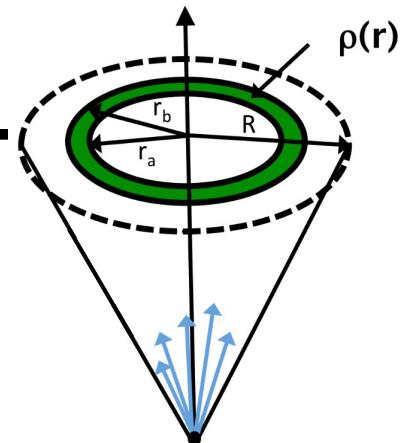
CMS, Phys. Lett. B 730 (2014) 243

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

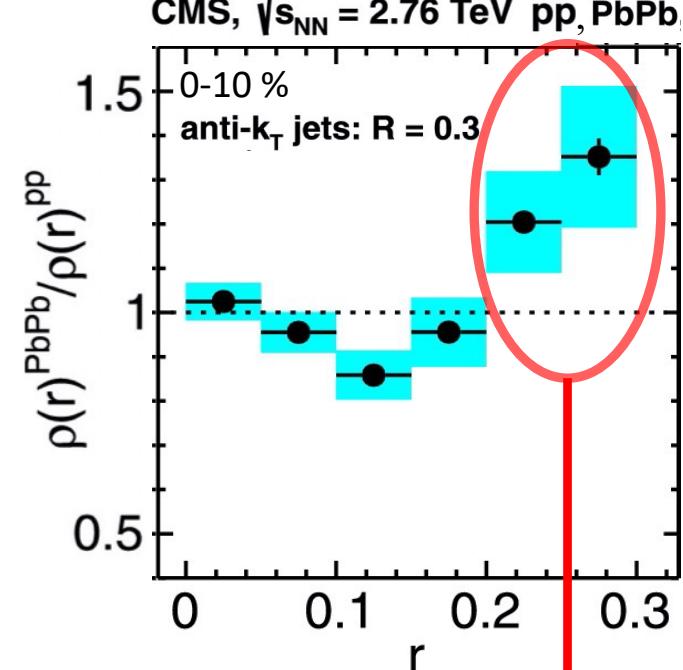
Motivation

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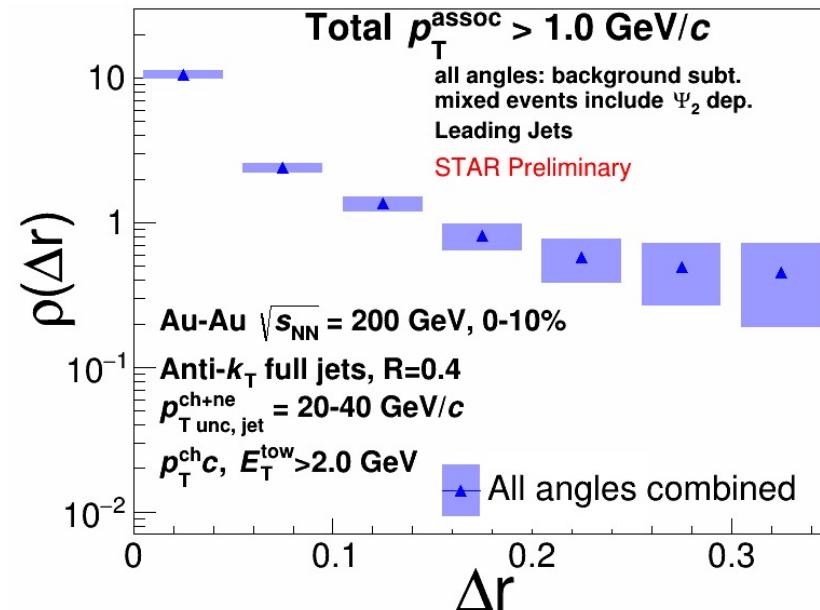
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CMS, Phys. Lett. B 730 (2014) 243

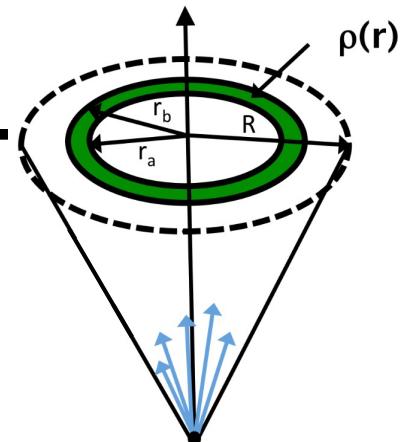


Jet energy is **redistributed to large distances**
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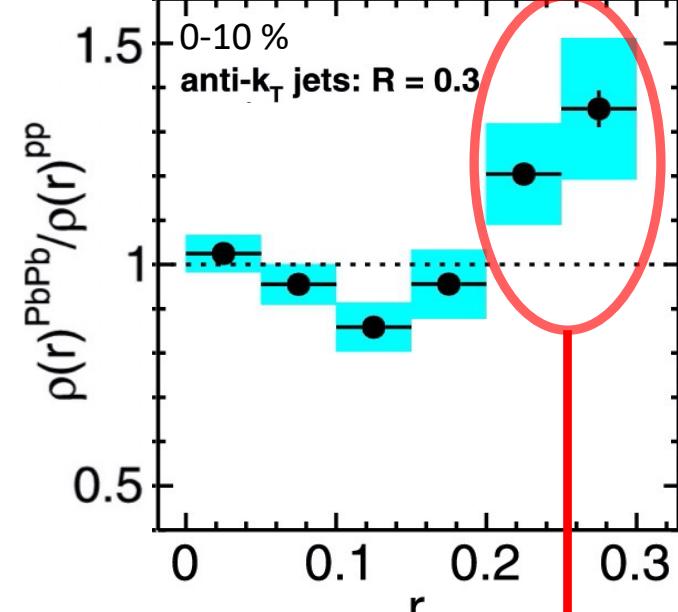
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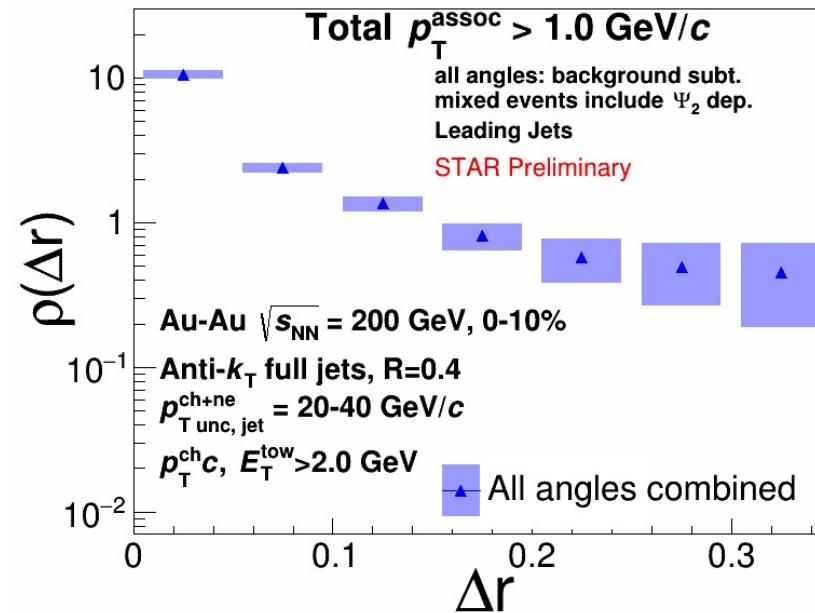


CMS, $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$ pp, PbPb



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

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



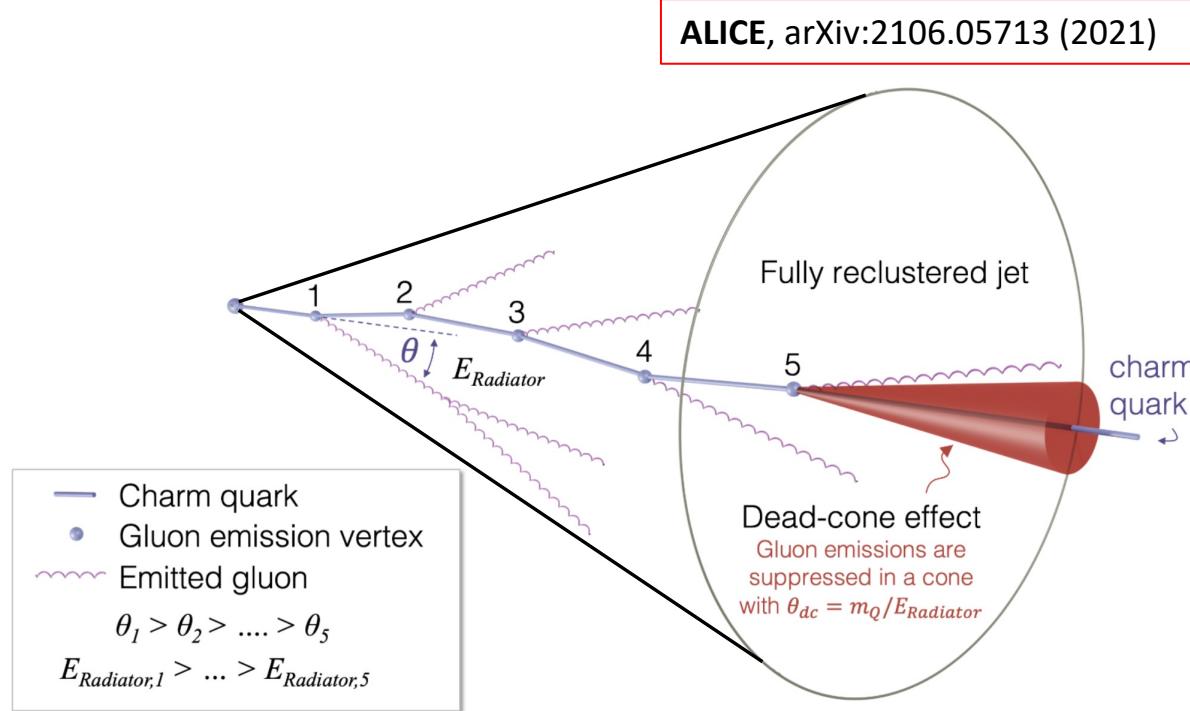
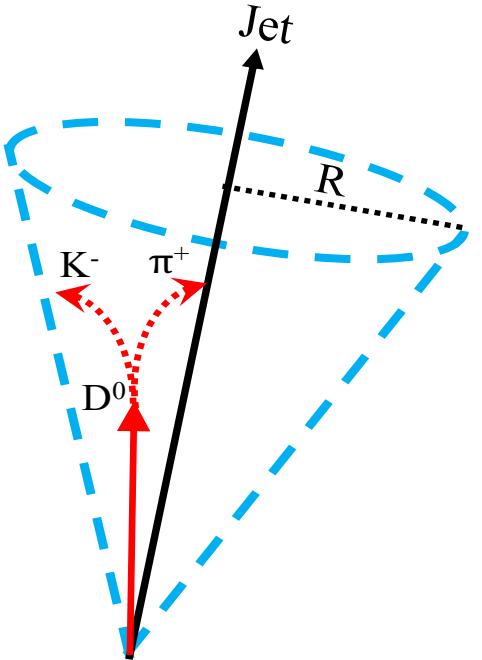
Possible mechanisms:

- Multiple scattering
- Medium-induced Bremsstrahlung
- Medium response

Dependent on the mass of the underlying parton

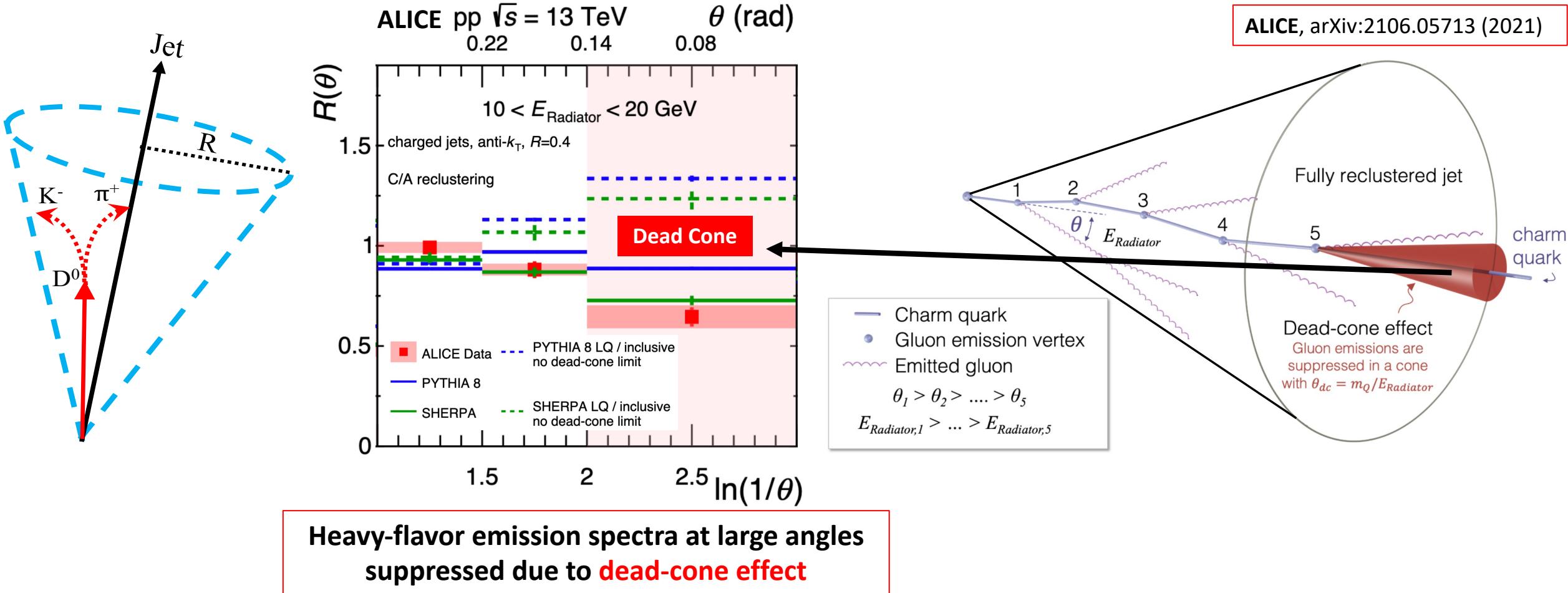
Motivation to study heavy-flavor jets

Heavy Flavor Tagged Jets



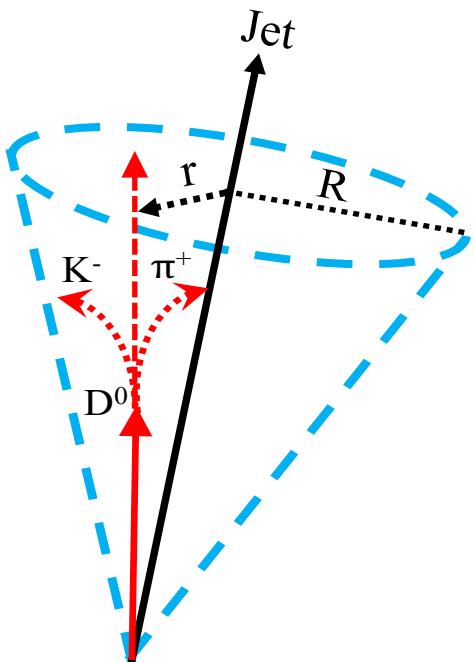
Heavy Flavor Tagged Jets

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

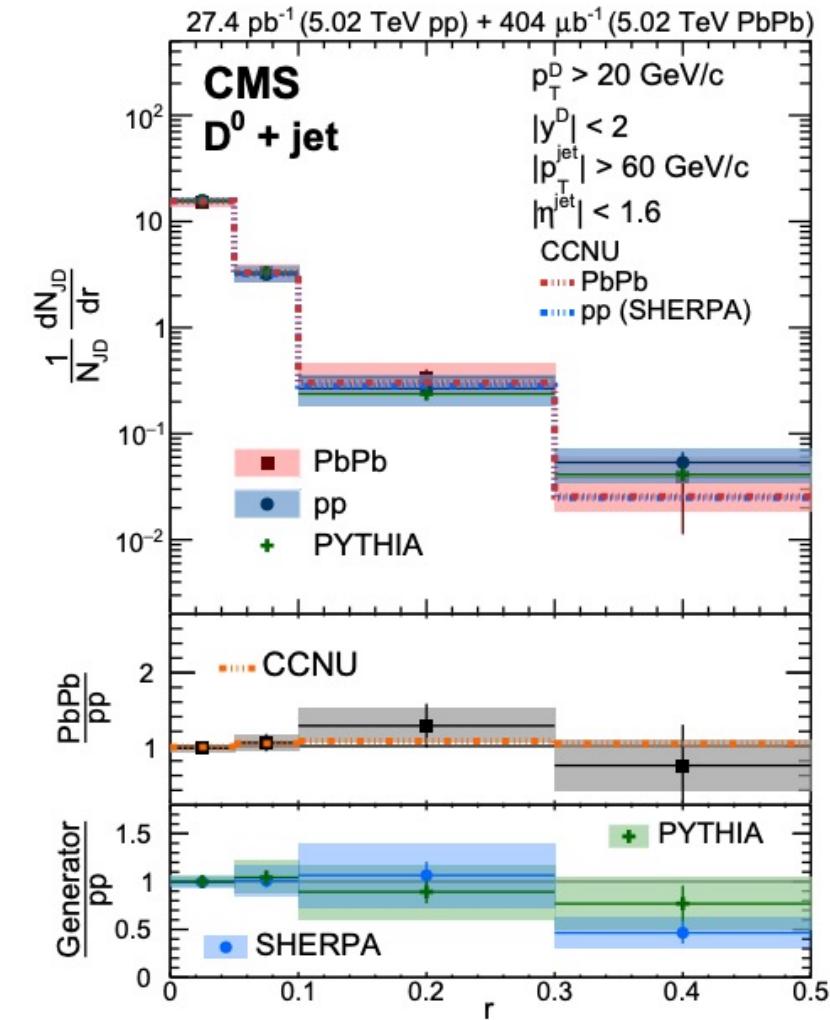
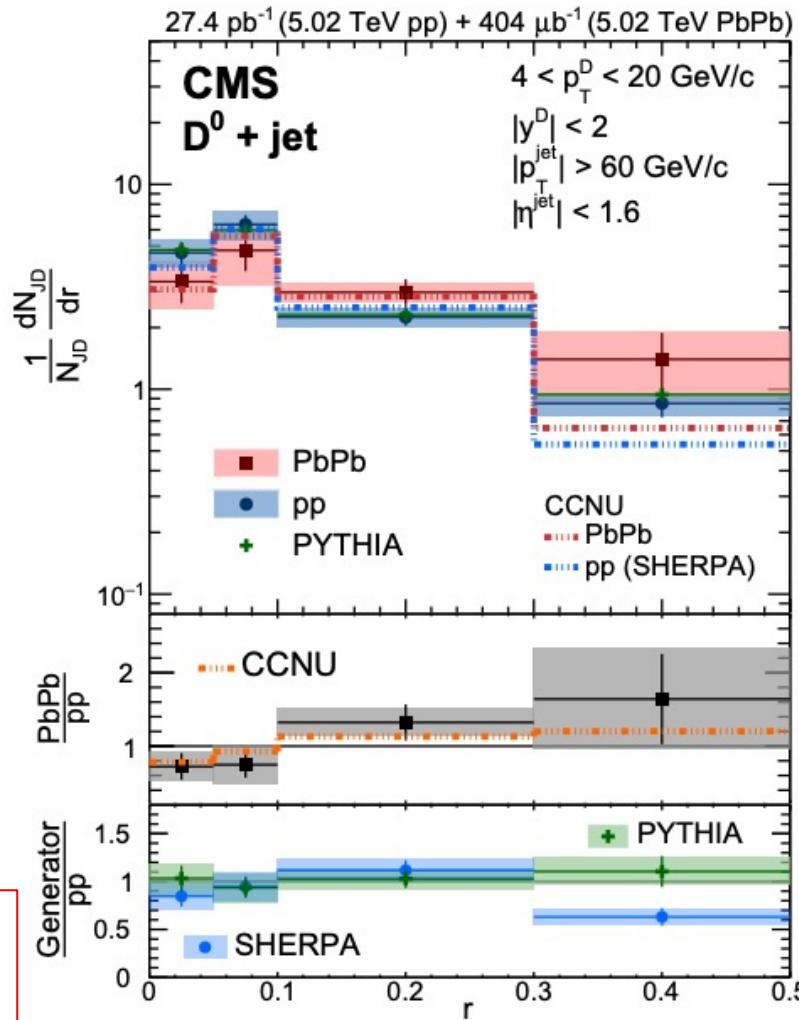


Heavy Flavor Tagged Jets

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

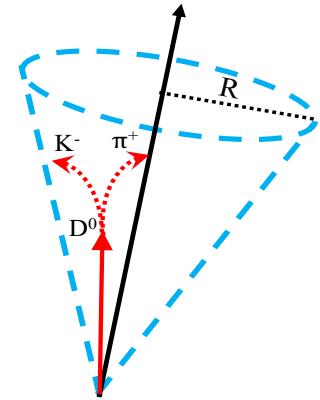


Low p_T D⁰ mesons appear to be diffused in the presence of QGP at LHC



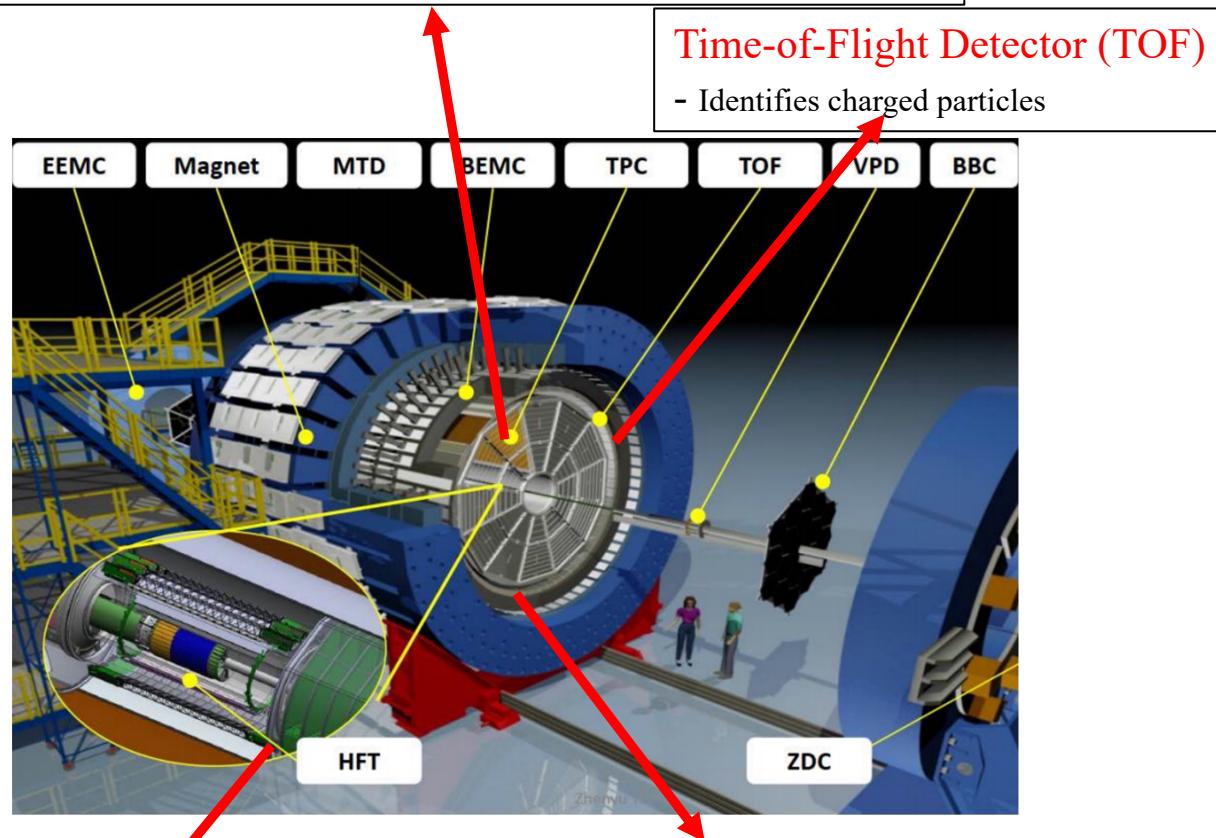
- Lower p_T D⁰ mesons can be reconstructed at RHIC energies
- Contribution from the underlying background is smaller at RHIC

STAR Detector & Selection Criteria



Time Projection Chamber (TPC)

- Measures momentum, track trajectory, and identifies charged particles



Time-of-Flight Detector (TOF)

- Identifies charged particles

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 need at least three hits on HFT
- $5 < p_{\text{T},D^0} [\text{GeV}/c] < 10$

D^0 Jet Selection:

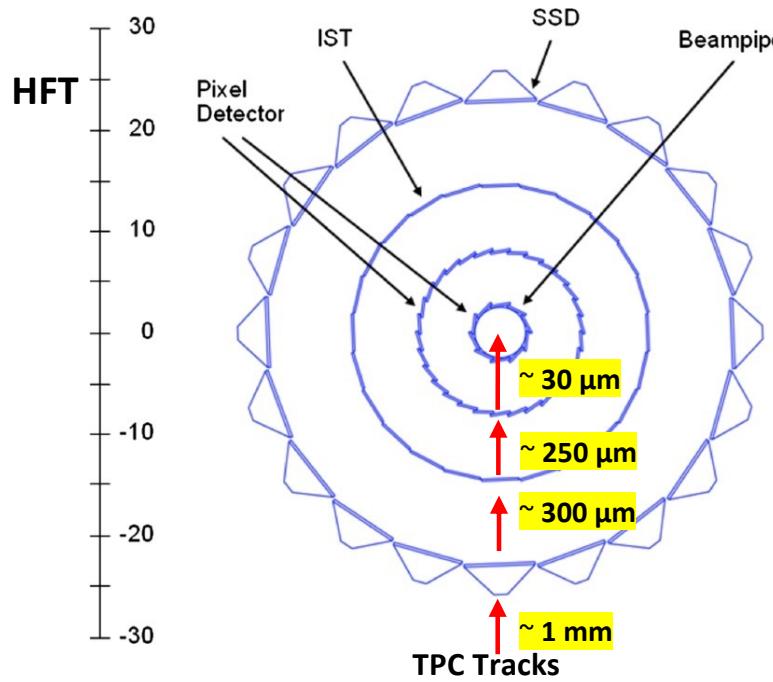
- Anti- k_{T} full jets of radius $R = 0.4$, area-based background subtraction
- $|\eta_{\text{Jet}}| < 0.6$

Heavy Flavor Tracker (HFT)

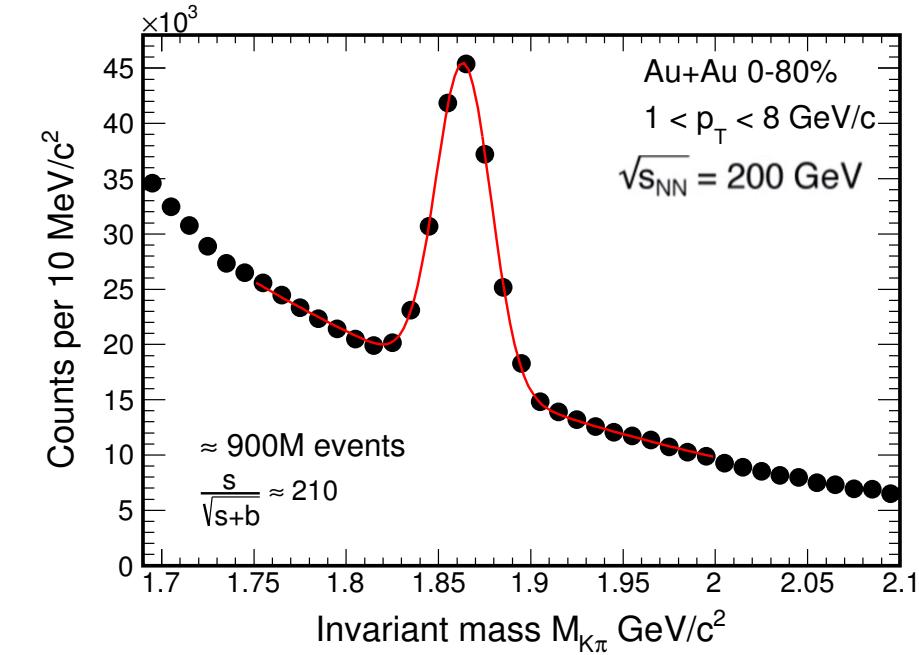
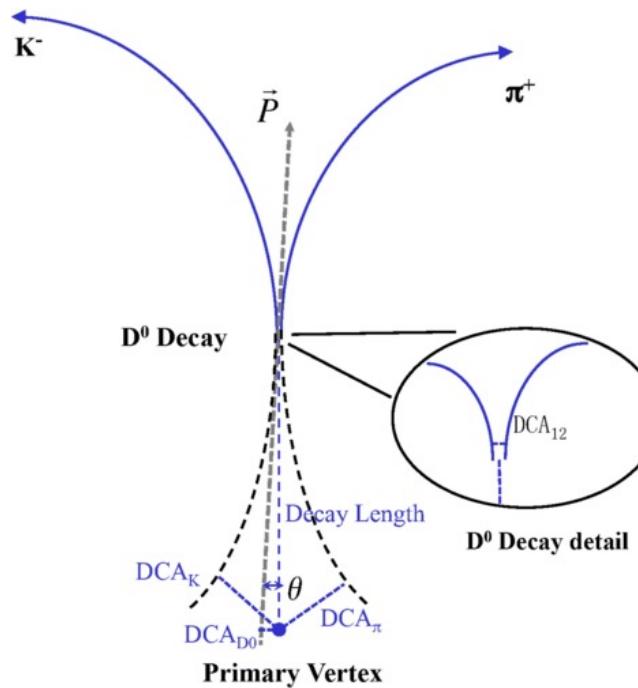
- Improves position resolution for tracks

D⁰ Reconstruction

- Kaons and Pions identified using TPC and TOF



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



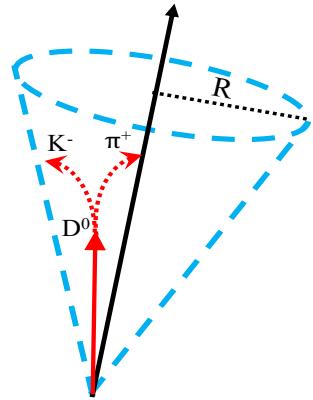
- Decay length of D⁰ $\sim 123 \mu\text{m}$.
- HFT has a resolution of 30 μm for kaons at $\sim 1.2 \text{ GeV}/c$
- HFT can reconstruct D⁰ candidates based on the decay topology

Topological cuts on the D⁰ candidates improve signal significance

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 distribution histograms with all D⁰-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)

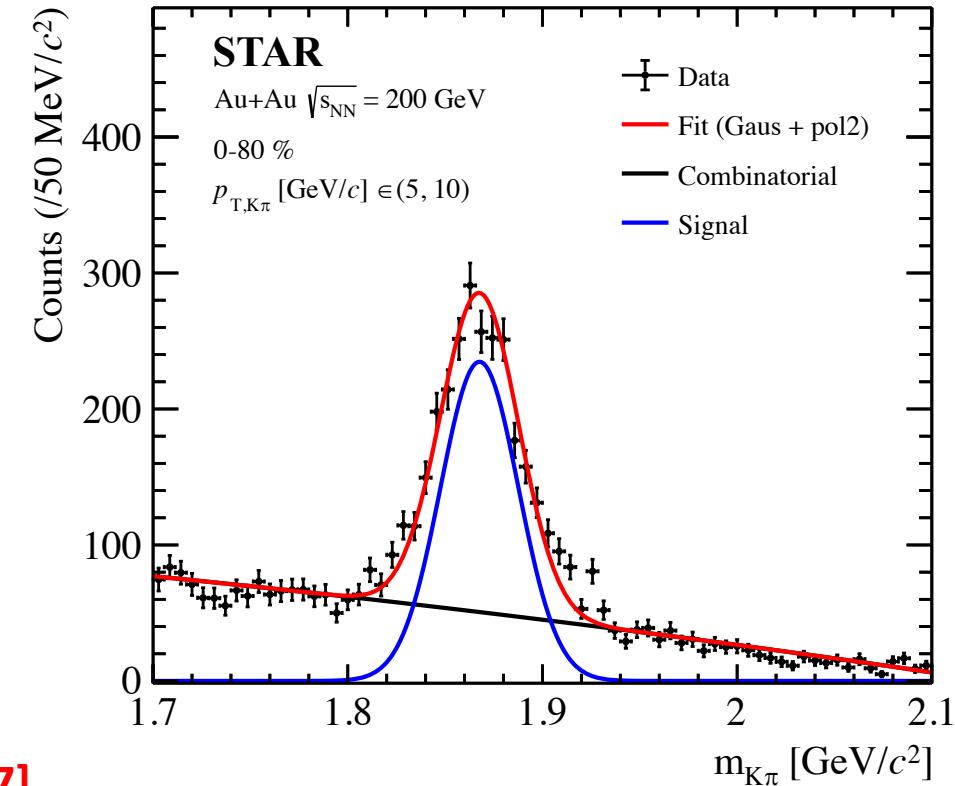
N_k = k -th yield (T=2)

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

V = cov. matrix

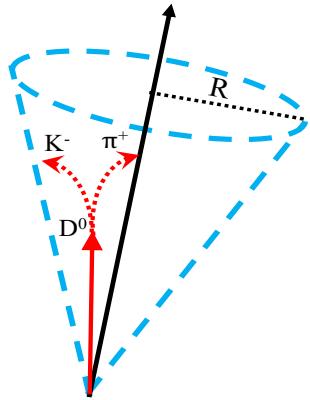
Efficiency Correction →

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

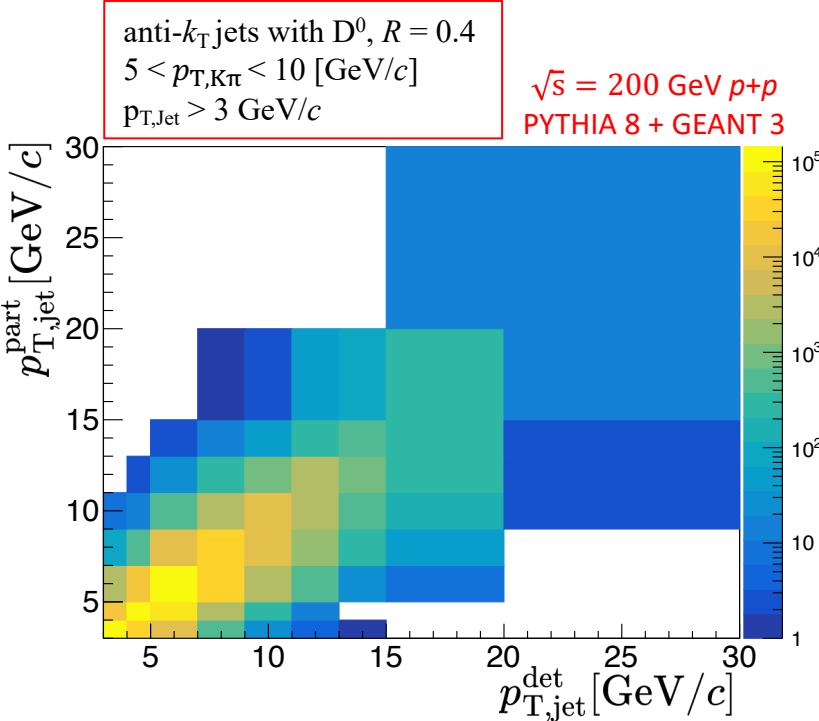


For more information about *s*Plot, visit poster by Matthew Kelsey [T11_2, #367].

Correction to the Jet Yield

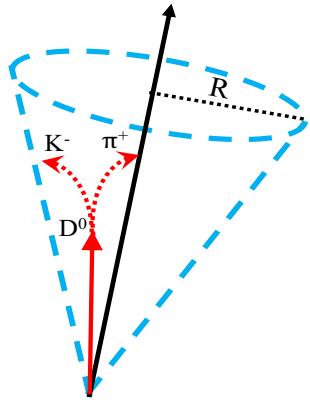


1. Response matrix for $p+p \sqrt{s} = 200$ GeV from PYTHIA and GEANT3 to mimic the detector response
2. Single Particle (SP) embedding in heavy ion event to model fluctuations in area-based background subtraction
3. Reweight PYTHIA with c-quark distribution from FONLL [1] to modify the shape of the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

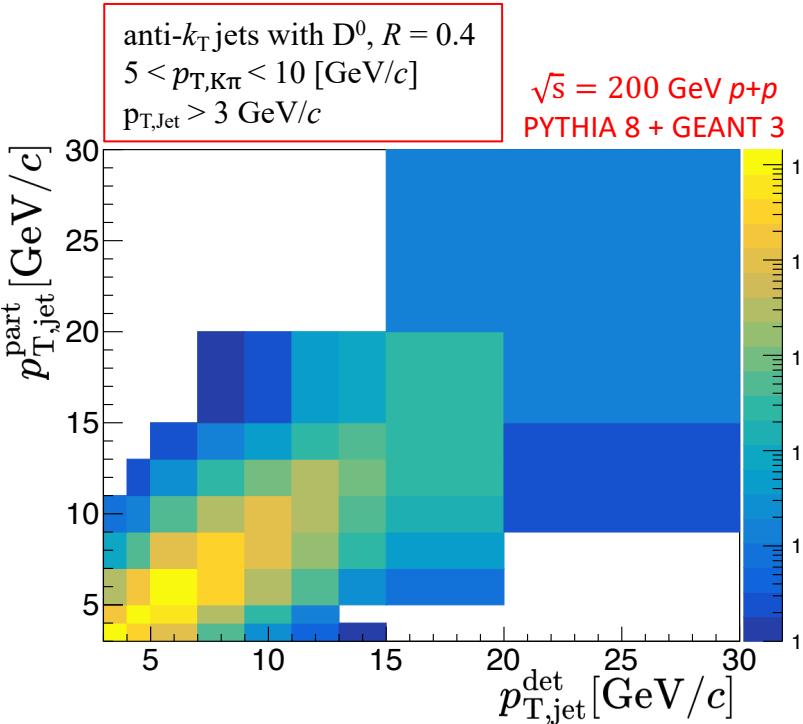


[1]. FONLL, JHEP03 (2001) 006

Correction to the Jet Yield

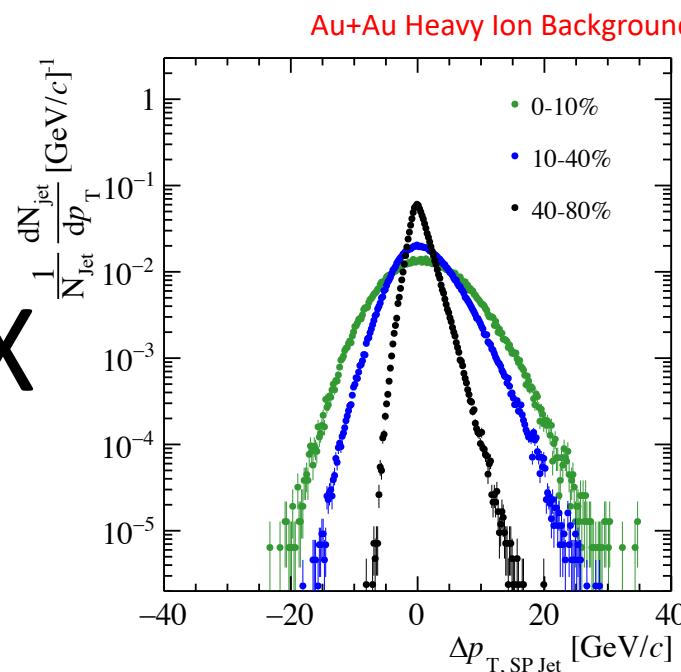


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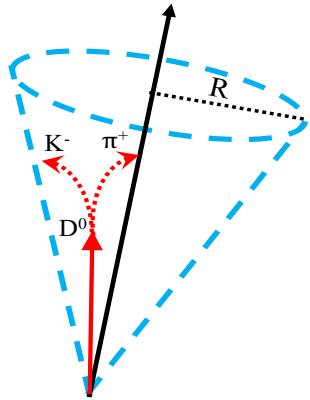
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April 7th, 2022

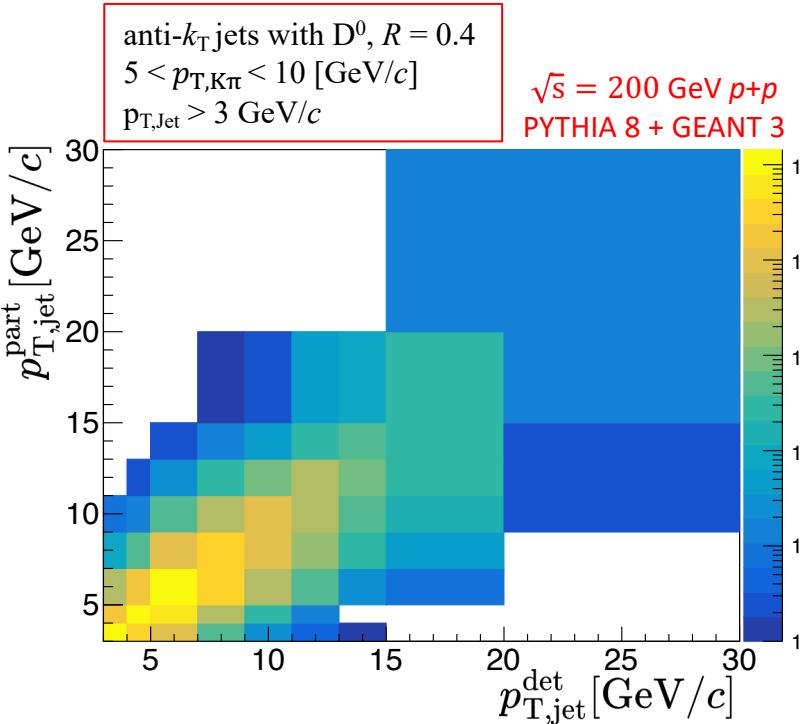


Diptanil Roy, Quark Matter 2022

Correction to the Jet Yield

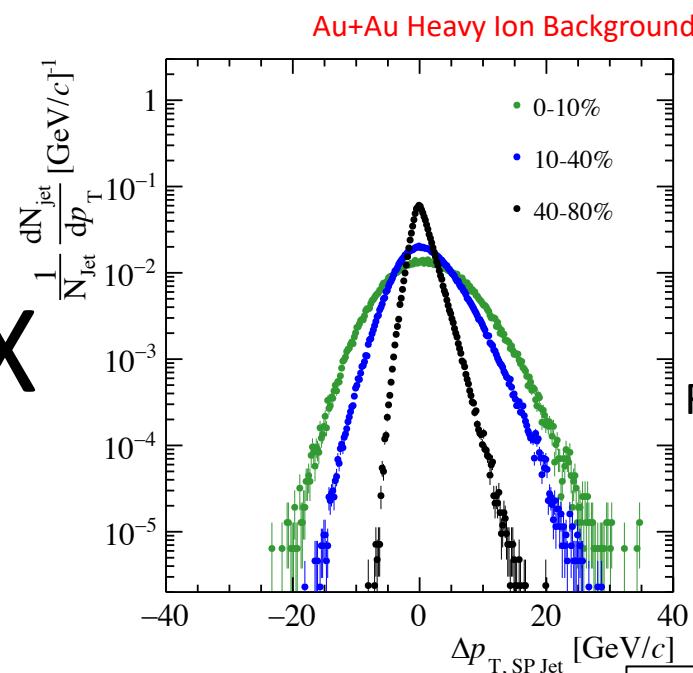


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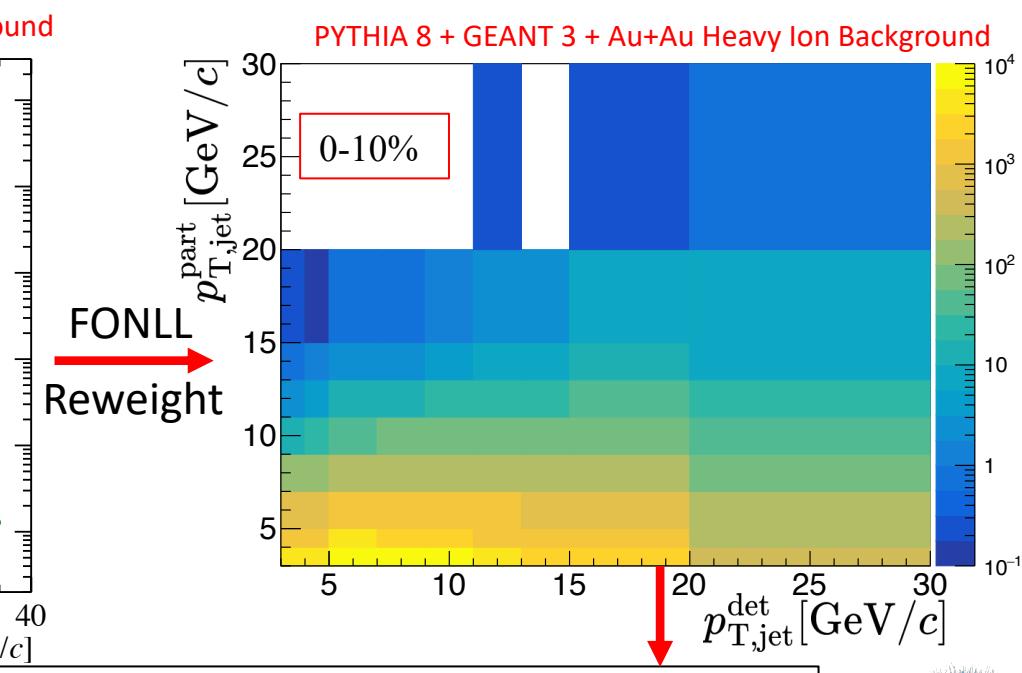


[1]. FONLL, JHEP03 (2001) 006

April 7th, 2022



Diptanil Roy, Quark Matter 2022



Complete response matrix to unfold $p_{T,\text{jet}}$



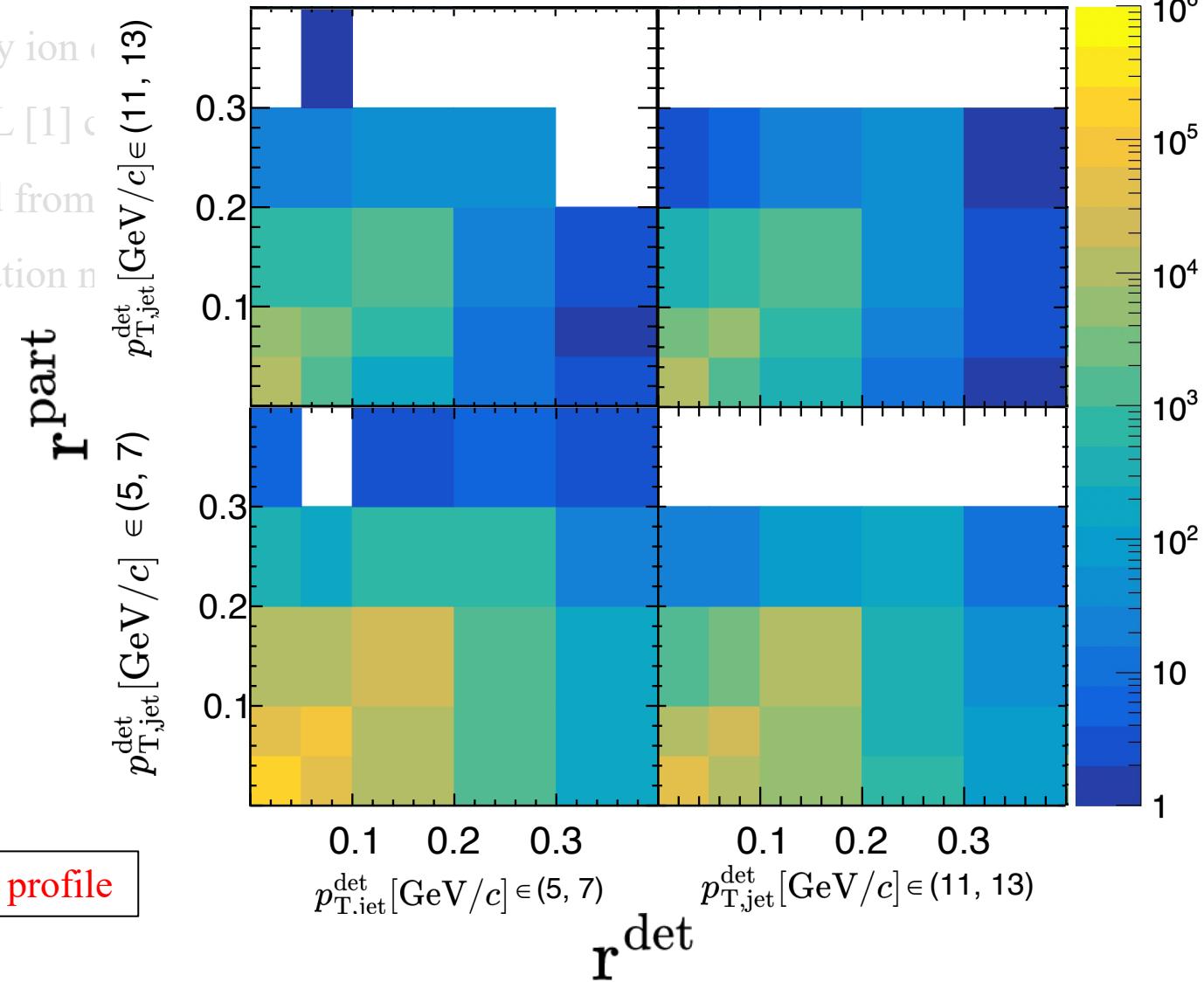
Correction to the Jet Yield

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 collisions
 3. Reweight PYTHIA with a prior (FONLL [1]) to get the signal
 4. Heavy-flavor jet fragmentation modeled from LHCb
 5. Systematics from variation in fragmentation parameters

anti- k_T jets with D^0 , $R = 0.4$
 $|\eta_{\text{jet}}| < 0.6$
 $p_{T,\text{const}} > 0.2 \text{ GeV}/c$
 $p_{T,\text{jet}} > 3 \text{ GeV}/c$
 $5 < p_{T,K\pi} < 10 \text{ (GeV}/c)$

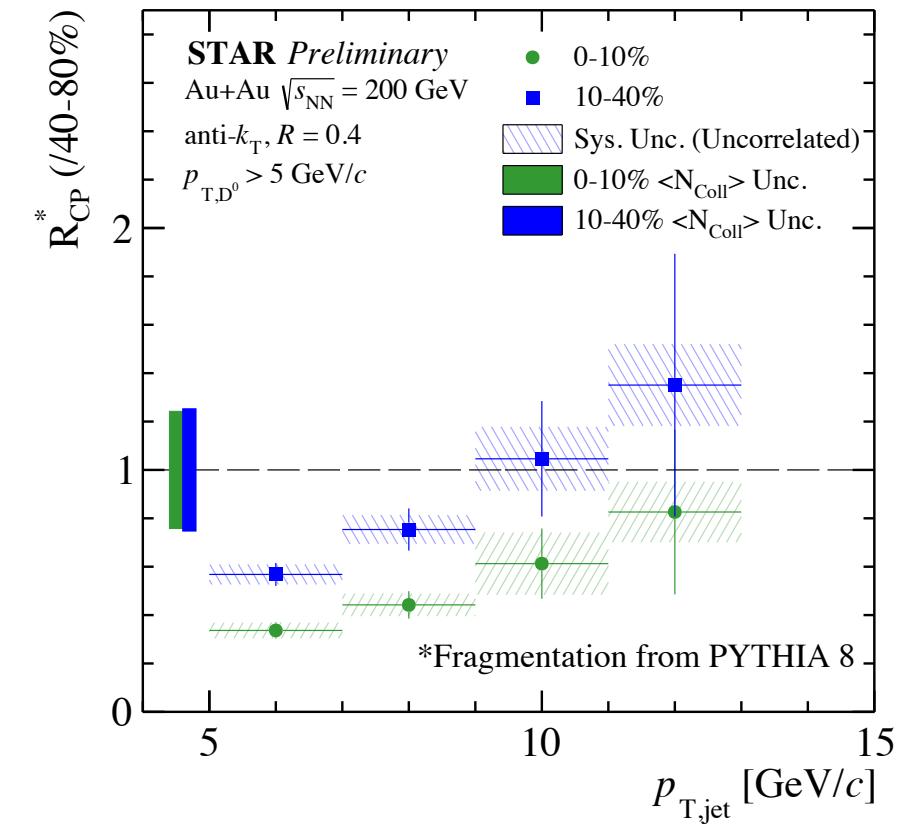
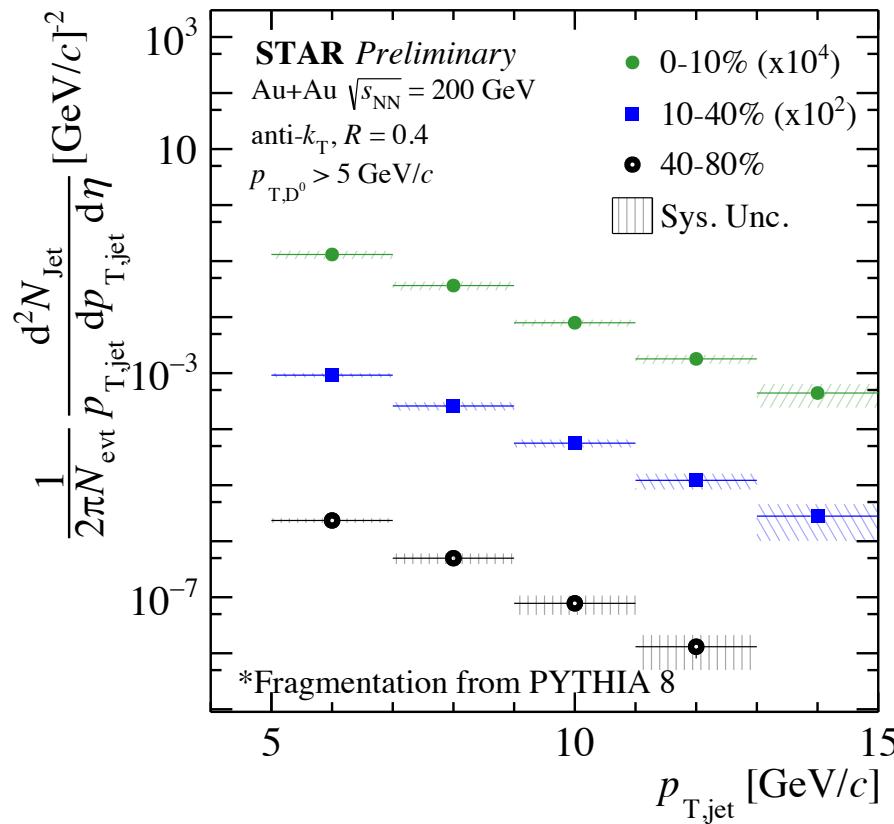
$\sqrt{s} = 200$ GeV $p+p$
PYTHIA 8 + GEANT 3
Au+Au Heavy Ion Background

Complete 4D response matrix to unfold radial profile



Jet Spectra

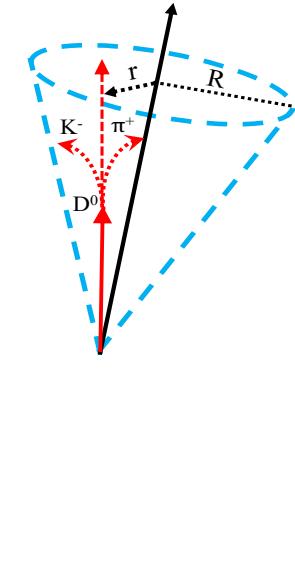
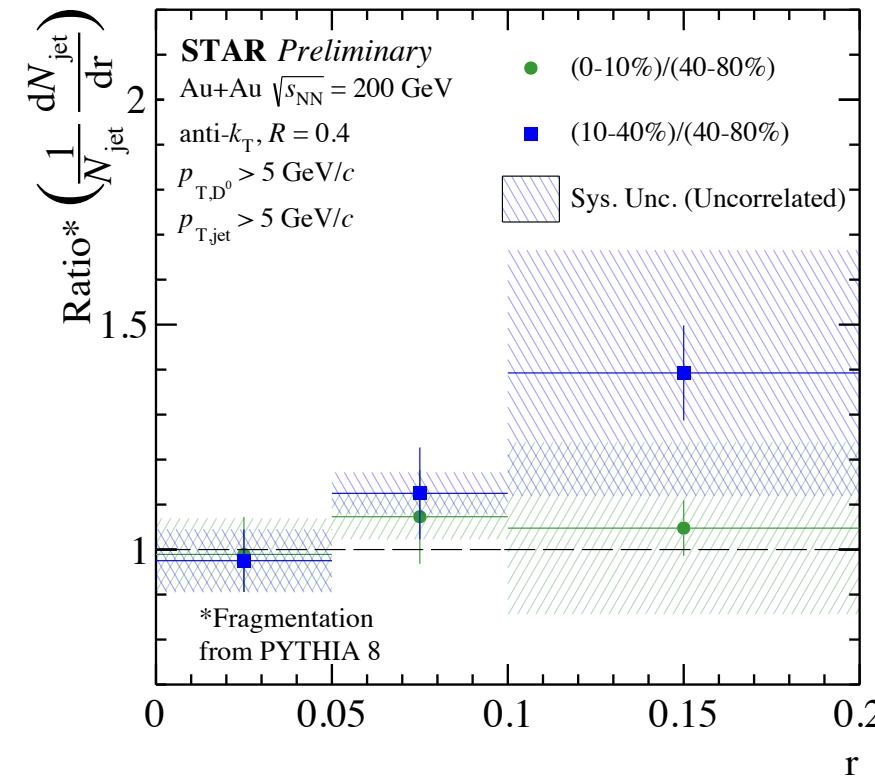
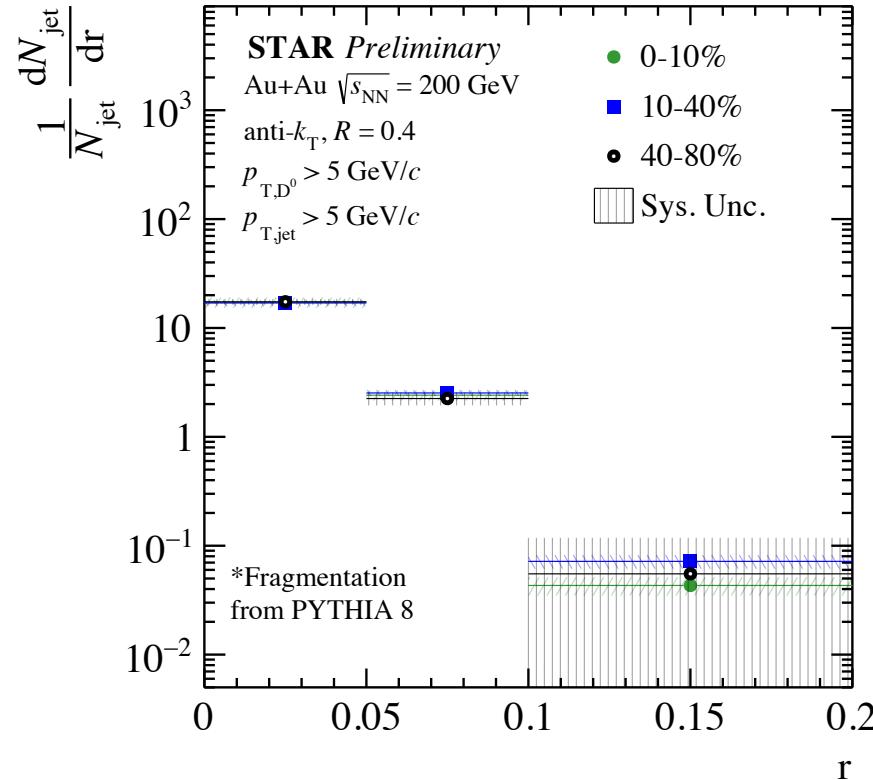
New For QM22



- Most central spectrum is more suppressed than mid-central
- R_{CP}^* shows strong suppression at low $p_{T,\text{jet}}$, hint of a increasing trend with $p_{T,\text{jet}}$
- Peripheral has limited statistics with the D^0 p_T selections
- Baseline $p+p$ calculation for R_{AA} measurement at STAR would be beneficial

Radial Profile of D⁰ Mesons in Jets

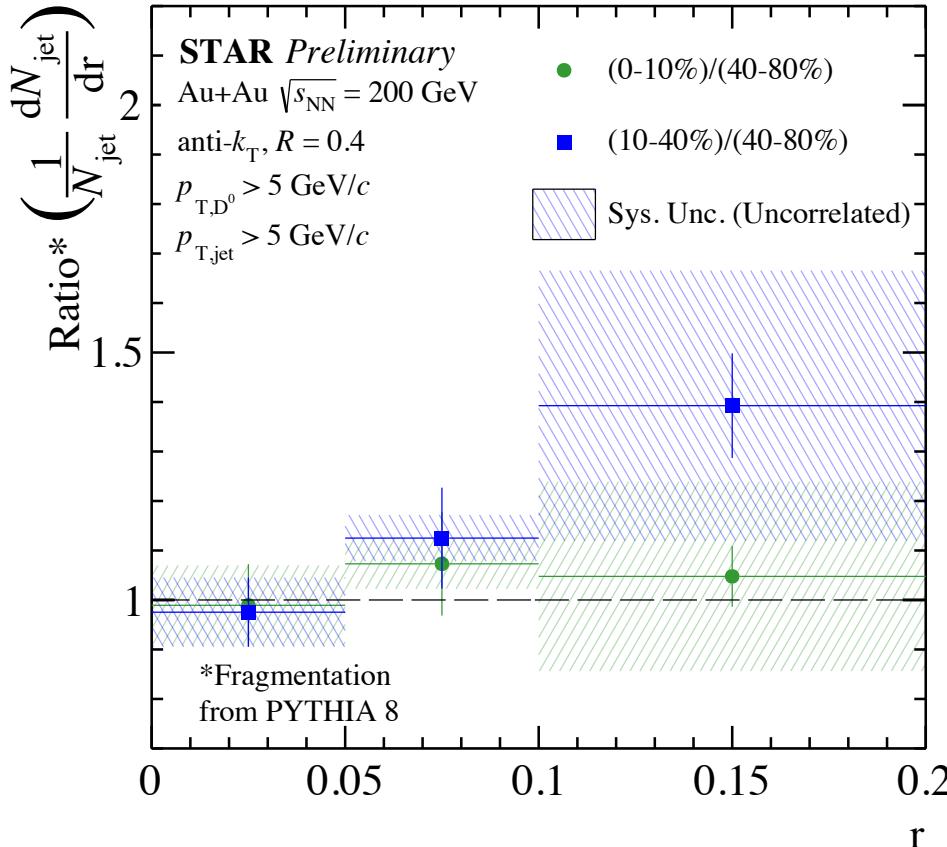
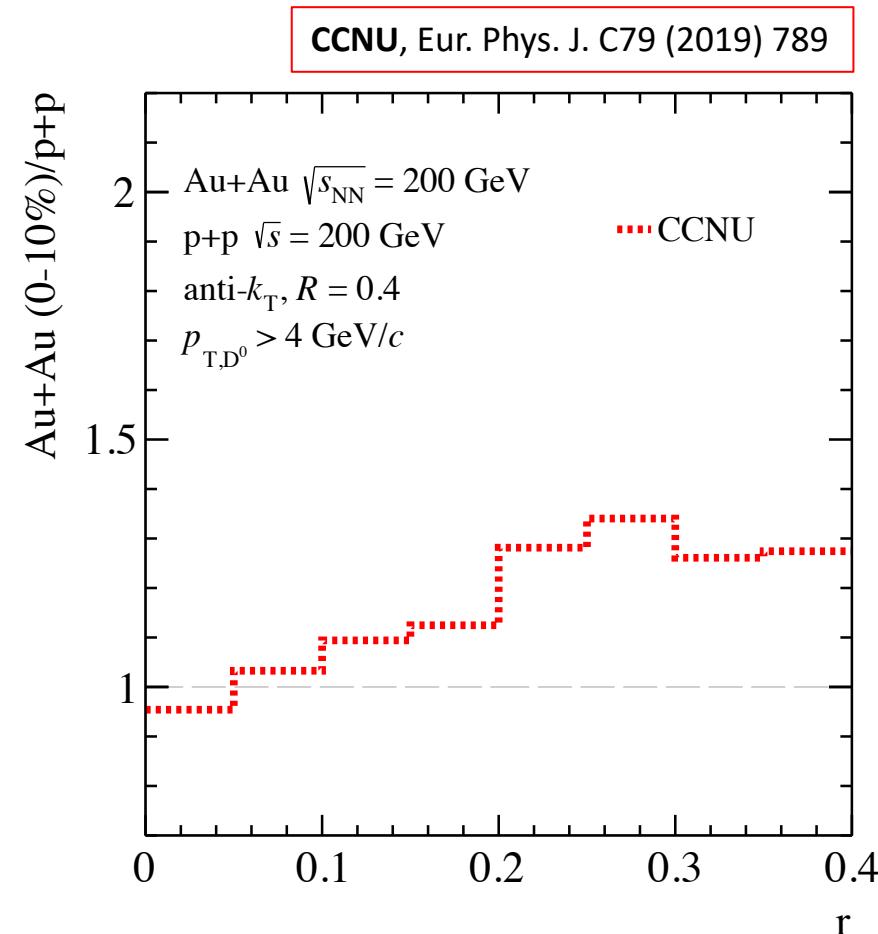
New For QM22



- For D⁰ $p_T > 5$ GeV/c, the ratio of radial distributions is consistent with unity within uncertainties
- Extending the analysis to lower D⁰ kinematics is essential to draw conclusions about D⁰ diffusion

Radial Profile: Data vs Model

New For QM22

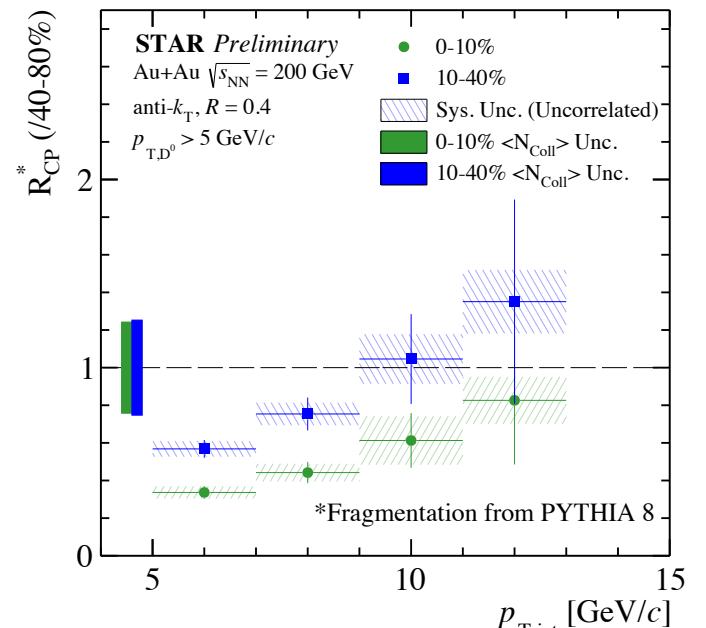


Note: calculation uses $p+p$ as reference

Theory calculation shows slight trend of diffusion - consistent with data within large uncertainties

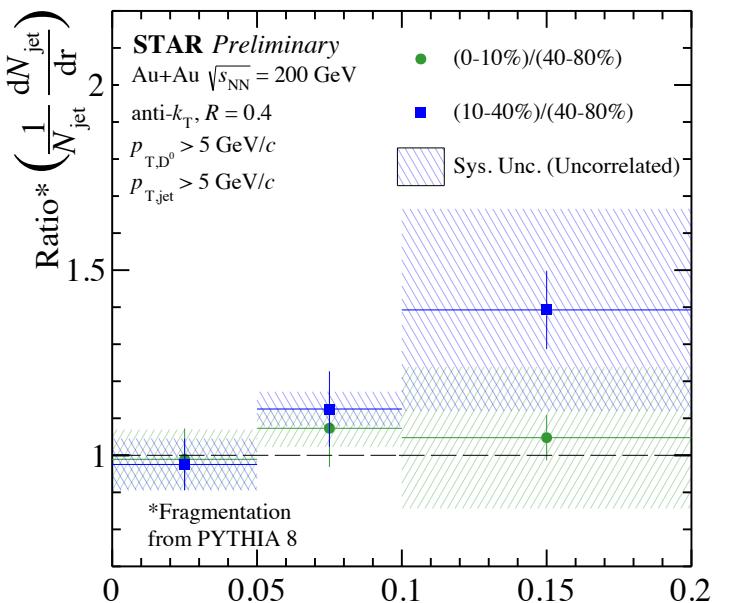
Summary

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



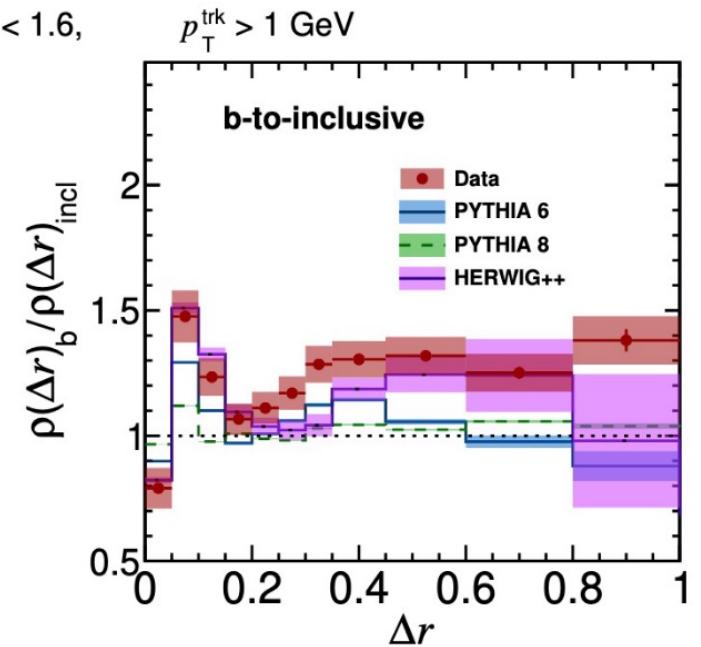
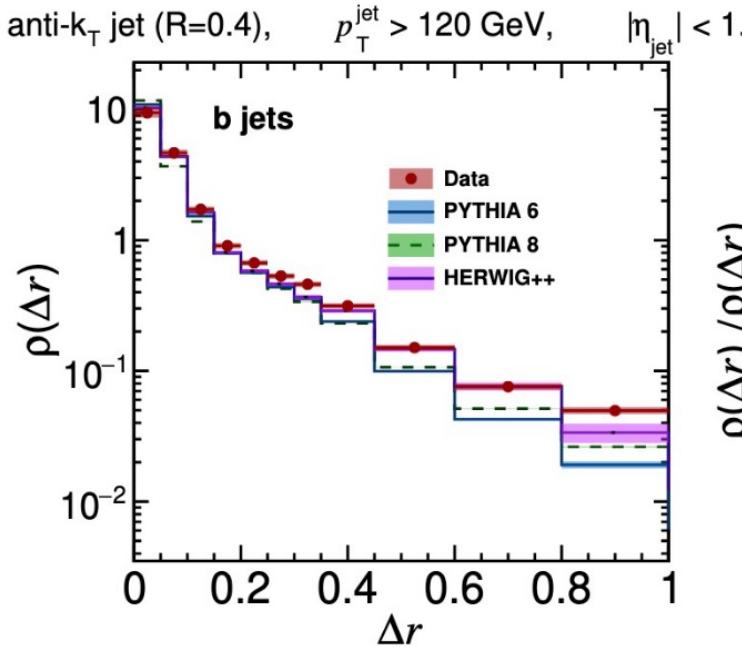
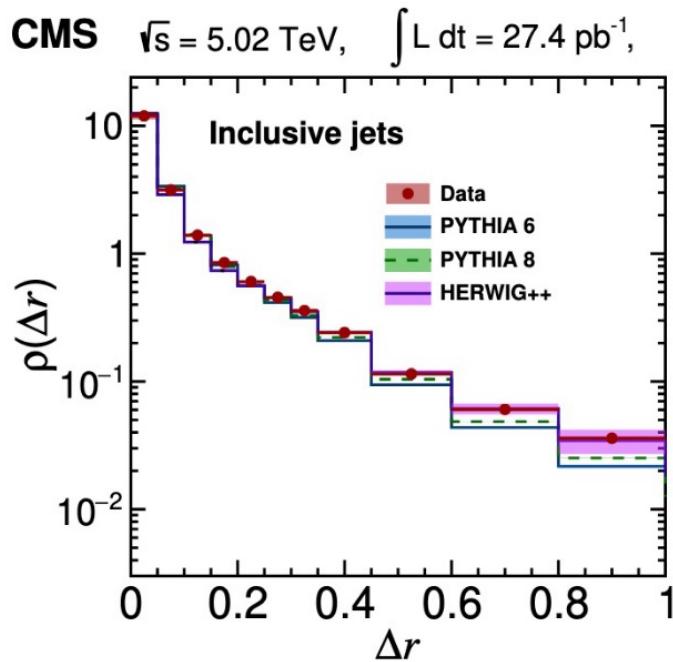
Outlook

- Study the dependence of the observables on the fragmentation function of heavy quarks in simulation
- Explore kinematic reach to low $D^0 p_T$ to get closer to charm quark mass



Backup

Differential jet shape for heavy quark in vacuum

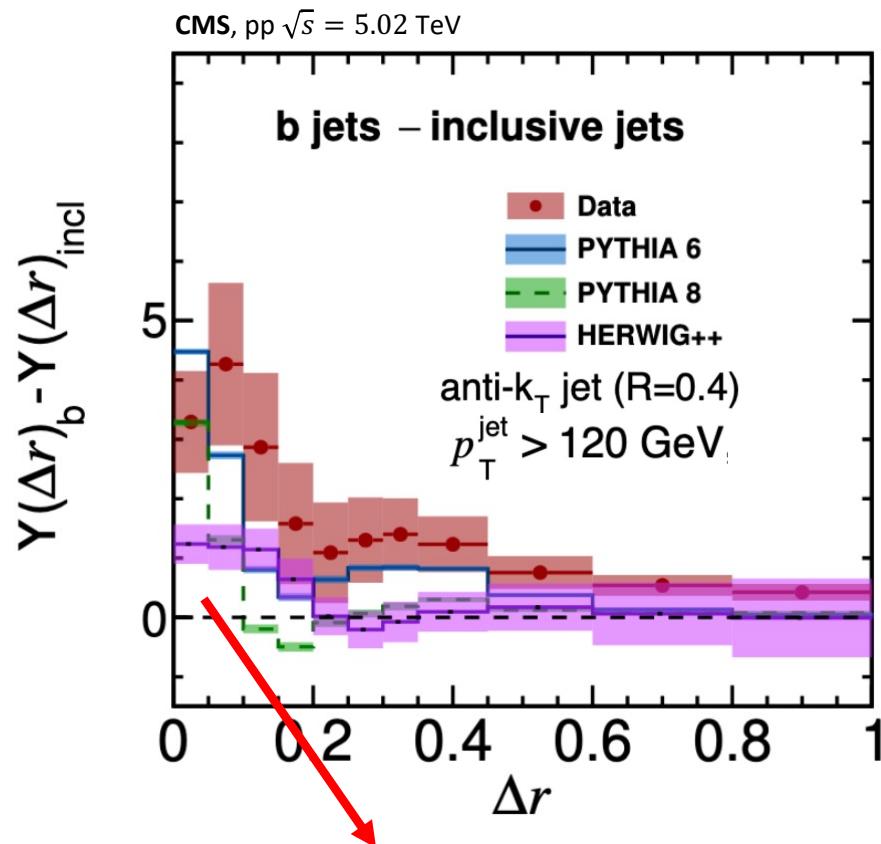


CMS, JHEP05 (2021) 054

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

Fragmentation pattern for heavy quark

CMS, JHEP05 (2021) 054

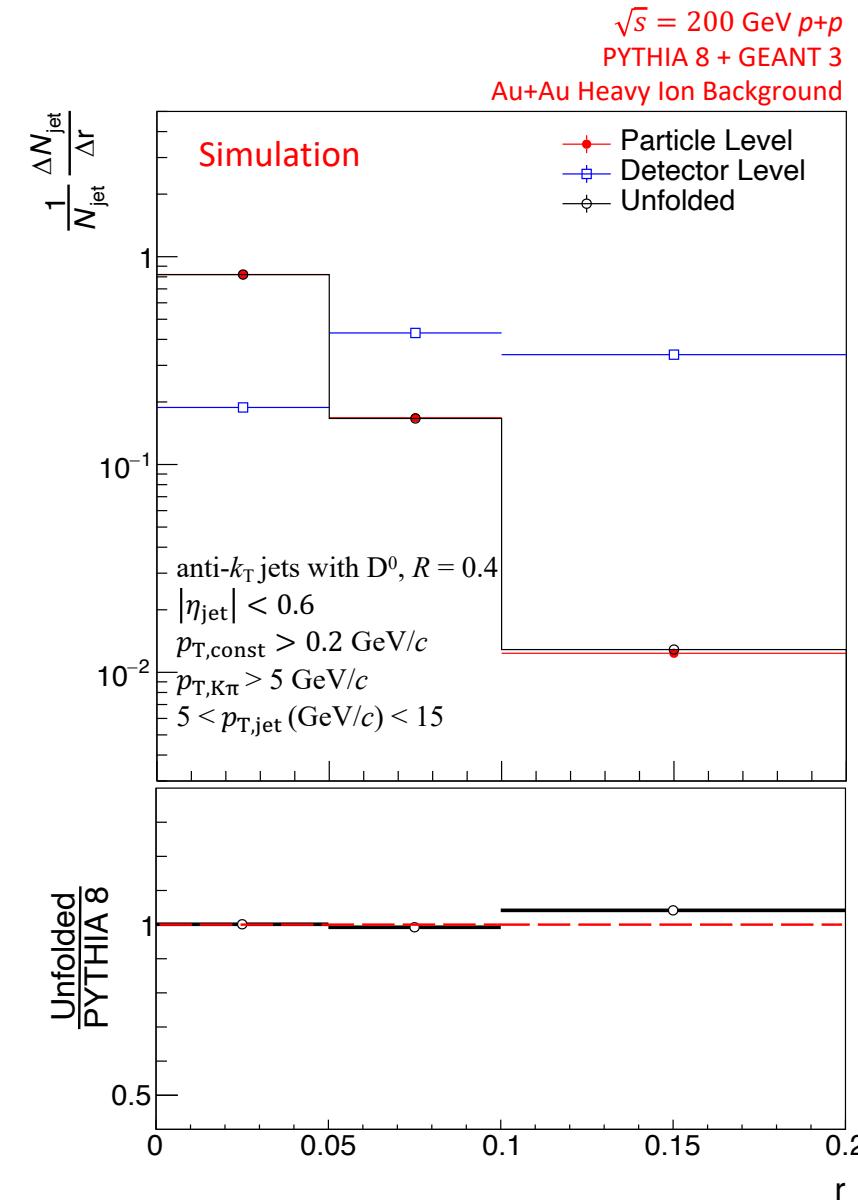
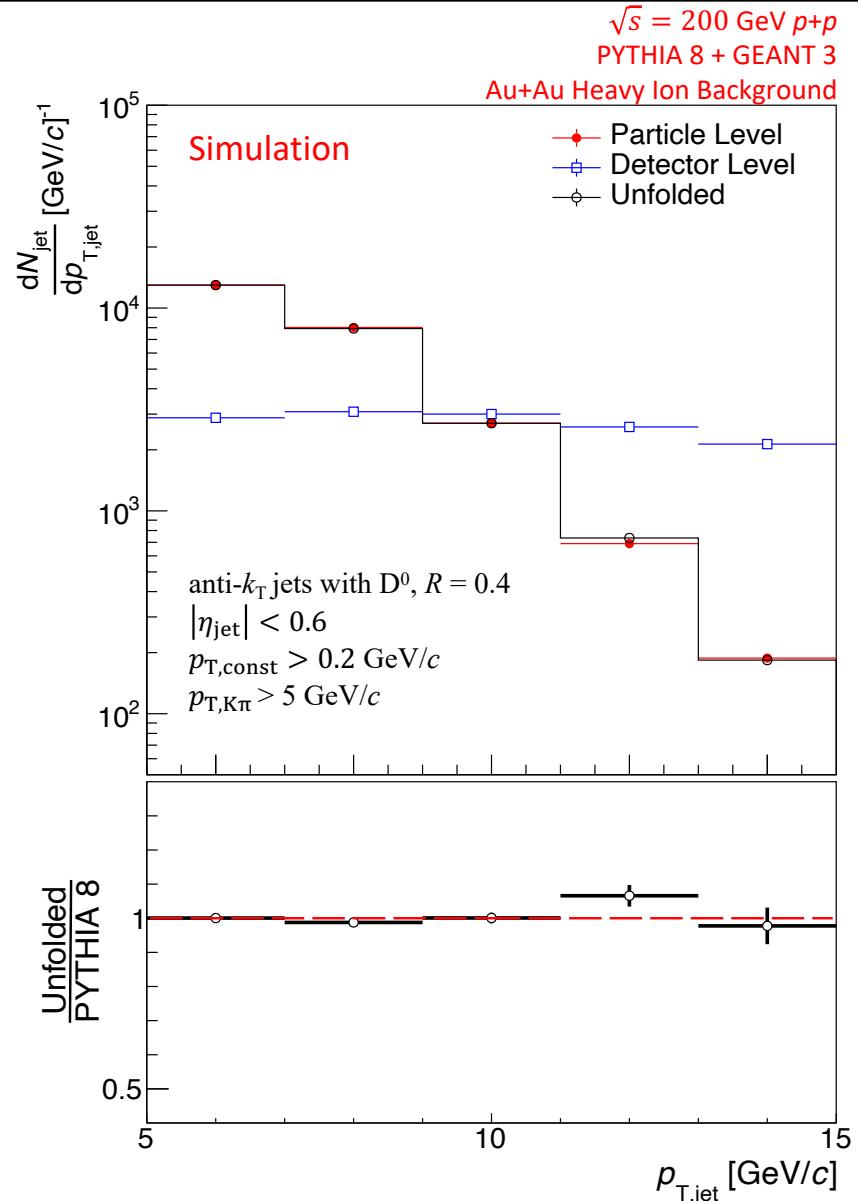


$$Y(\Delta r) = \frac{1}{N_{\text{jet}}} \frac{d^2 N_{\text{track}}}{d\Delta r dp_{T,\text{track}}}$$

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

\sim Different fragmentation pattern for heavy quarks

Closures For Unfolding



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