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

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NSF

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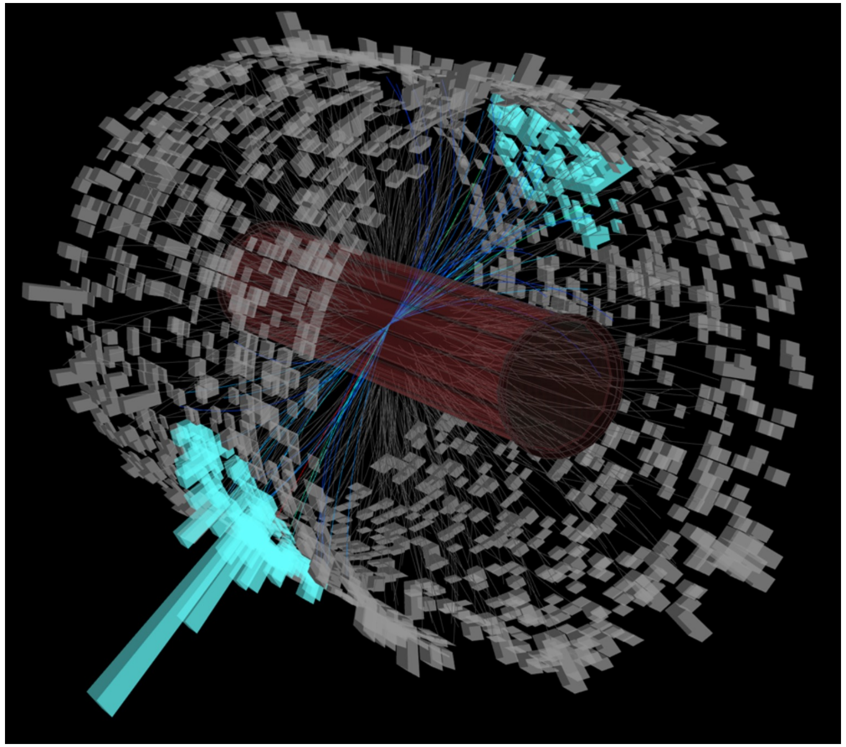
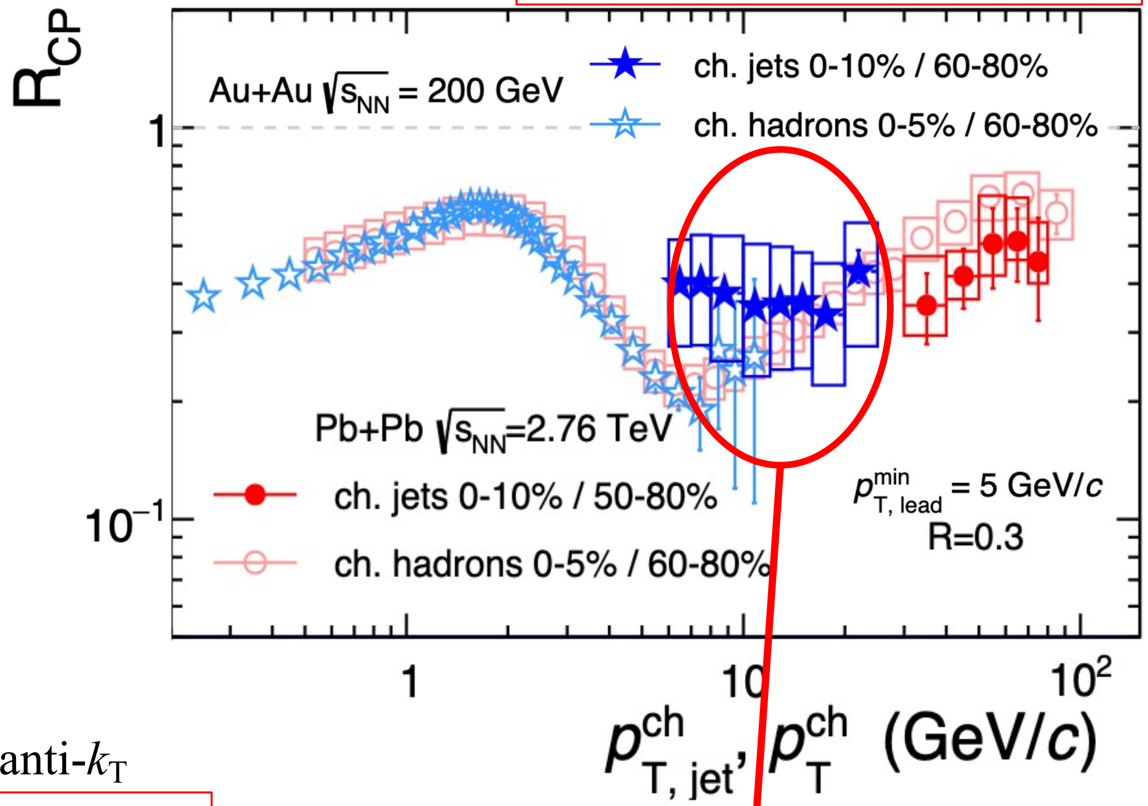
Jets in Heavy Ion Collisions

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

ALICE, JHEP03 (2014) 013

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





Inclusive jets are heavily quenched in the presence of QGP

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

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

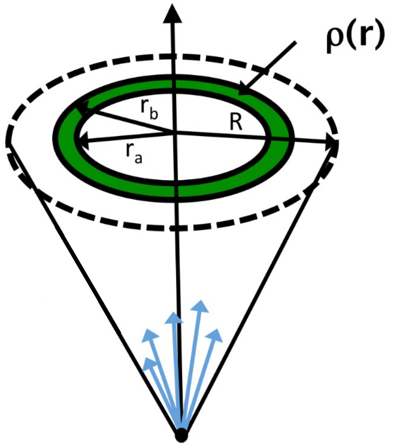
- **Loss of parton energy** in the QGP medium
- **Parton shower broadened** due to medium-induced radiation and scattering

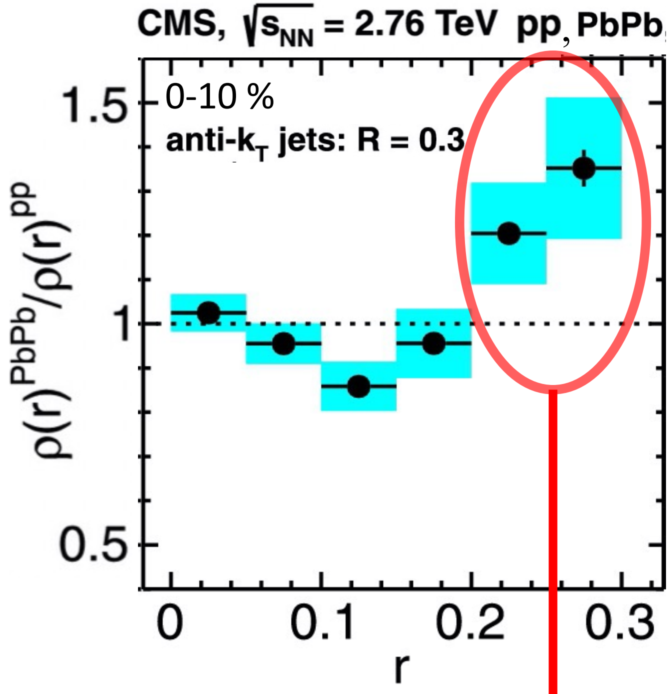
Motivation

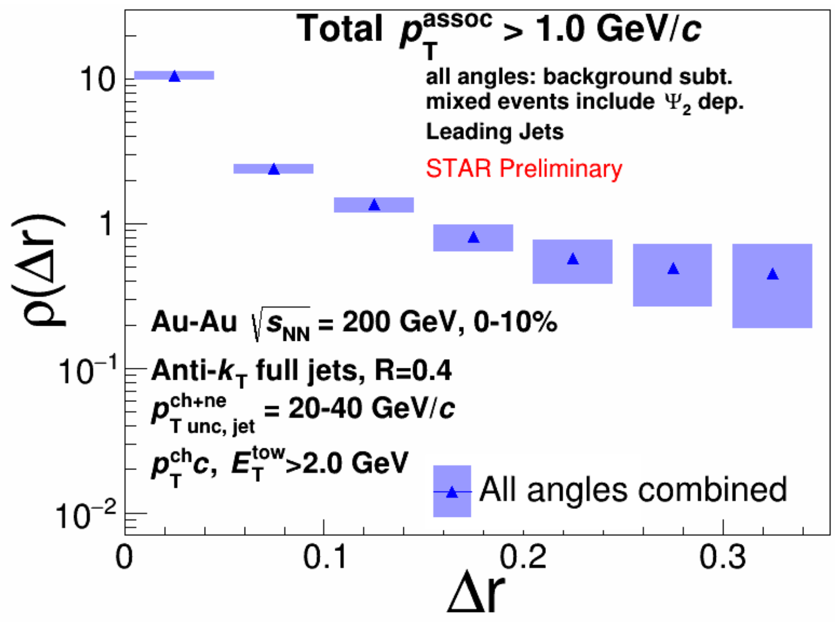
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jet}}\frac{\sum_{\text{track}\in(r_a,r_b)} p_{\text{T,track}}}{p_{\text{T,jet}}}$$

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

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

Motivation

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

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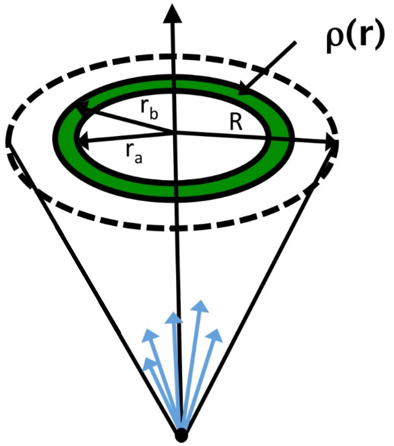
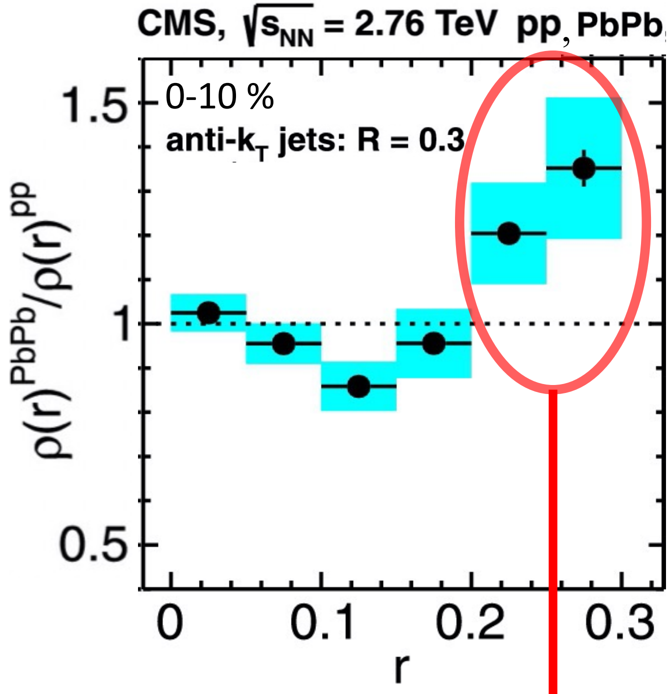
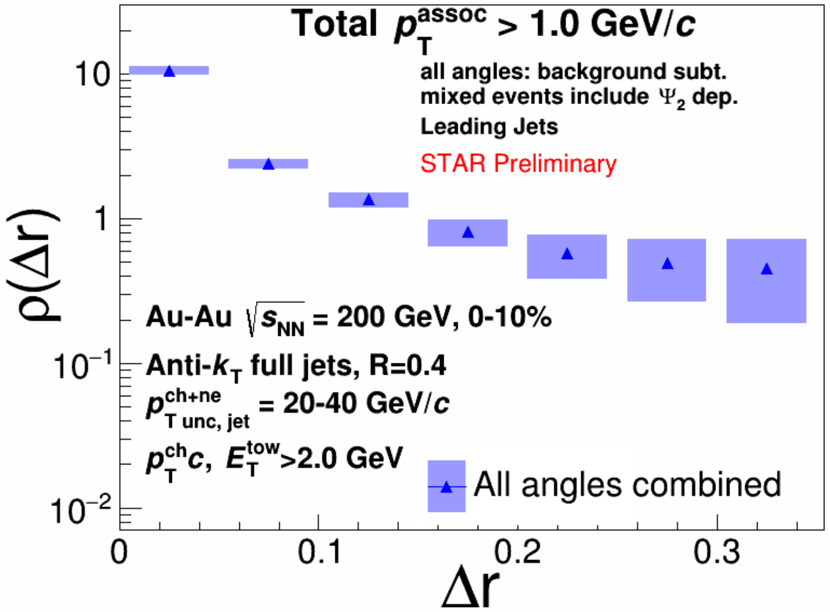




CMS, Phys. Lett. B 730 (2014) 243



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

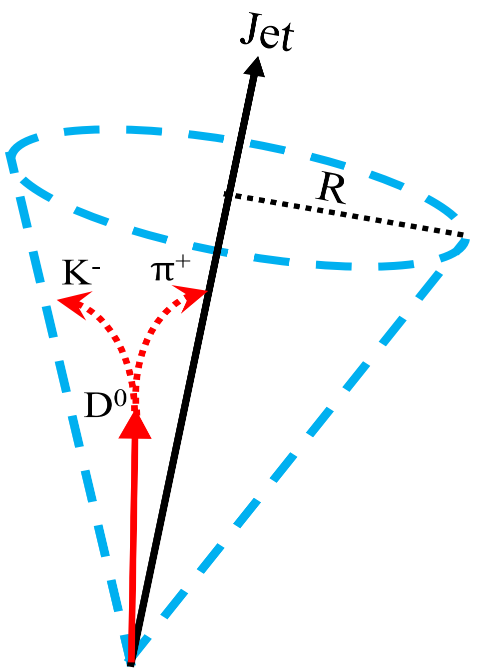
Dependent on the mass of the underlying parton

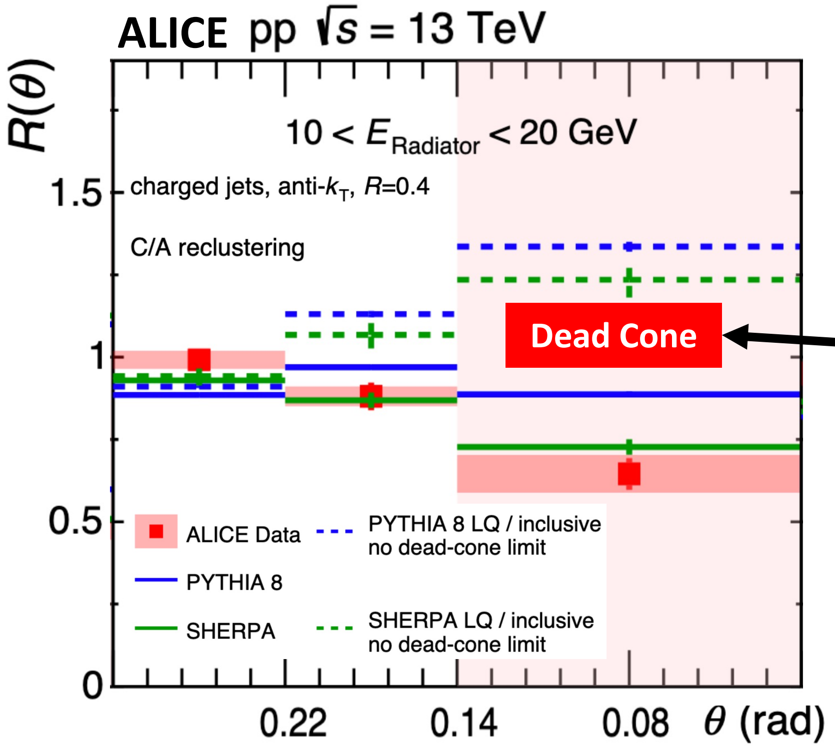
Motivation to study heavy-flavor jets

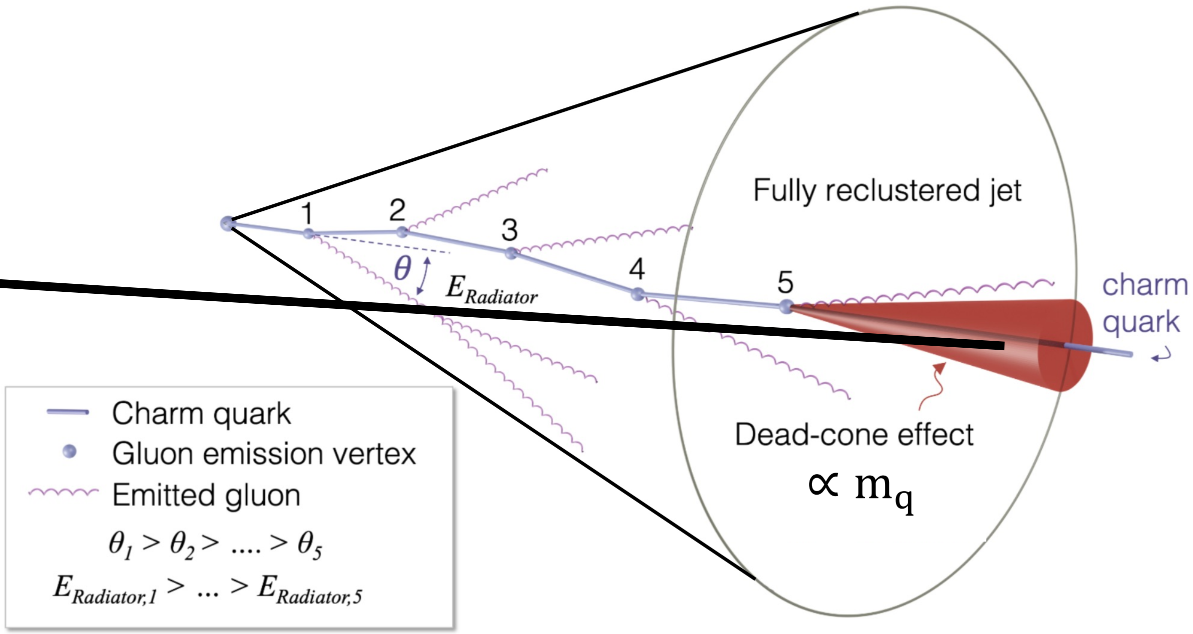
Heavy Flavor Tagged Jets

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

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





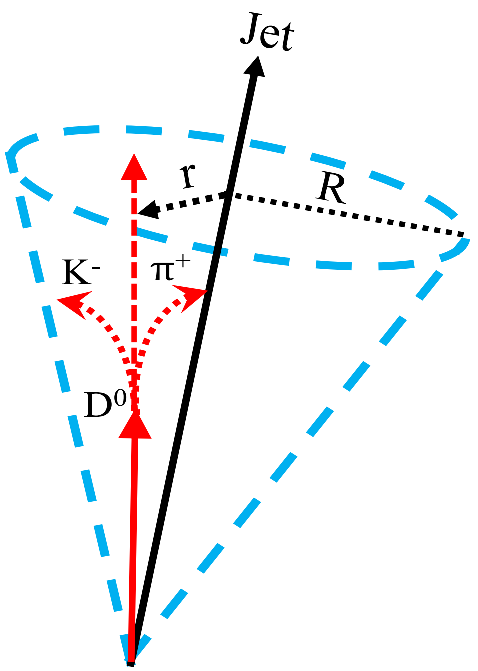


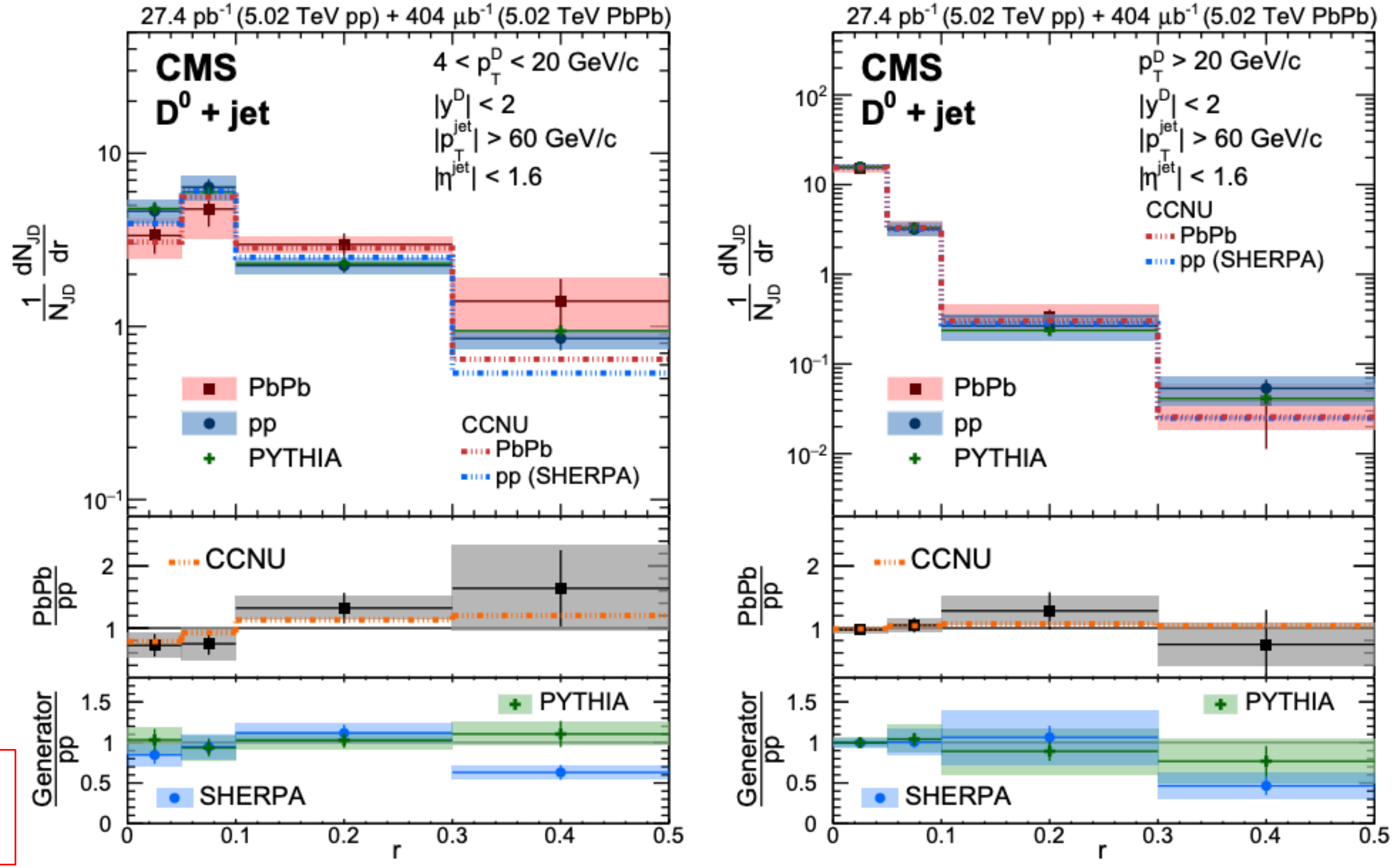
Heavy-flavor emission spectra at small angles suppressed due to dead-cone effect [1]

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

Heavy Flavor Tagged Jets

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

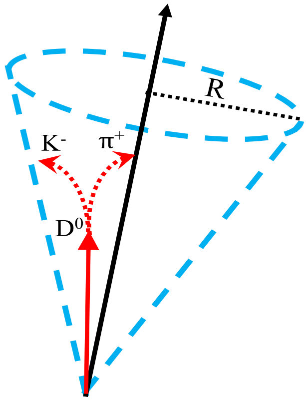




Low p_T D^0 mesons appear to be **diffused in the presence of QGP** at LHC

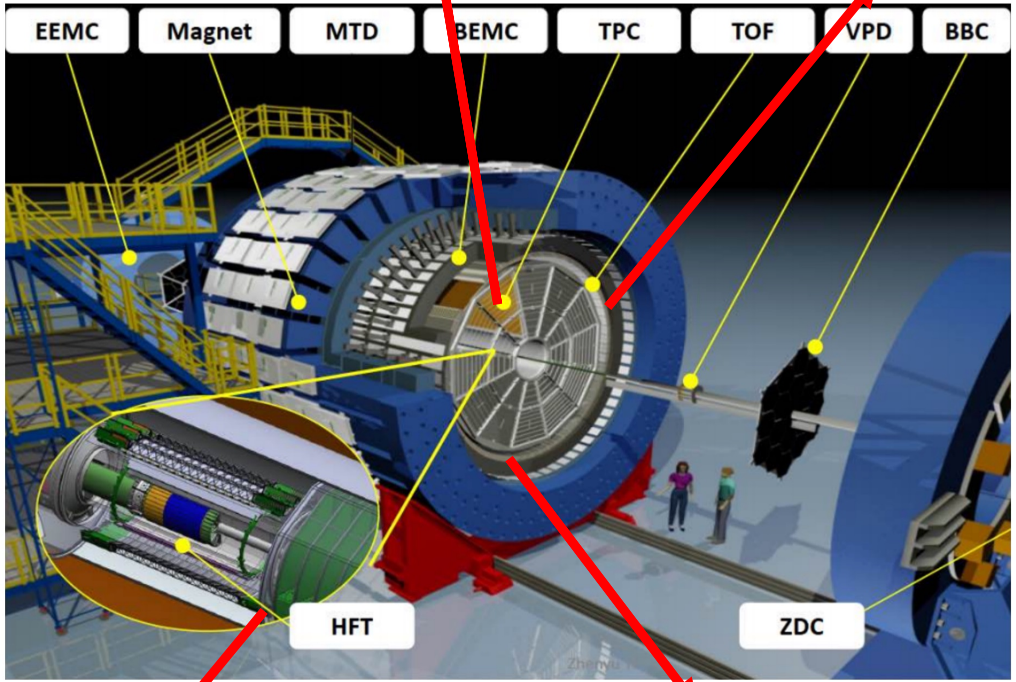
- Lower p_T D^0 mesons can be reconstructed at RHIC energies
- Contribution from the underlying background is smaller at RHIC

STAR Detector & Selection Criteria



Time Projection Chamber (TPC)
- Measures momentum, track trajectory, and identifies charged particles

Time-of-Flight Detector (TOF)
- Identifies charged particles



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])

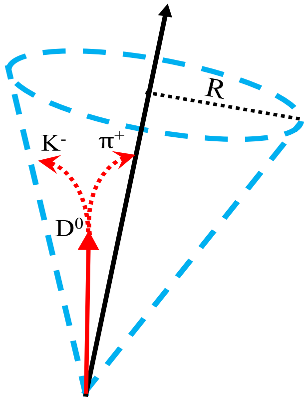
Constituent Selection:

- $0.2 < p_{T,track}$ [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 need at least three hits on HFT
- $5 < p_{T,D^0}$ [GeV/c] < 10

D^0 Jet Selection:

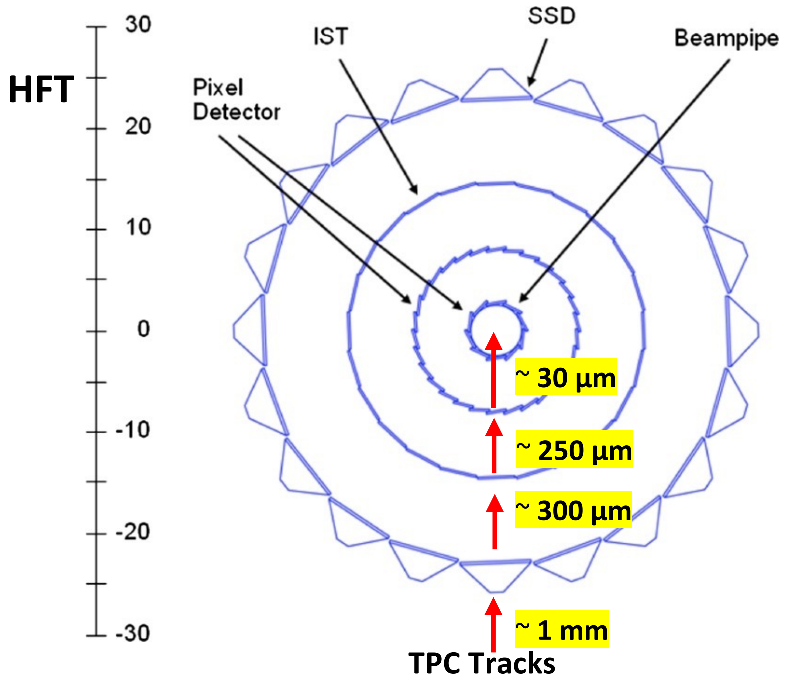
- Anti-k_T full jets of radius $R = 0.4$, area-based background subtraction
- $|\eta_{Jet}| < 0.6$

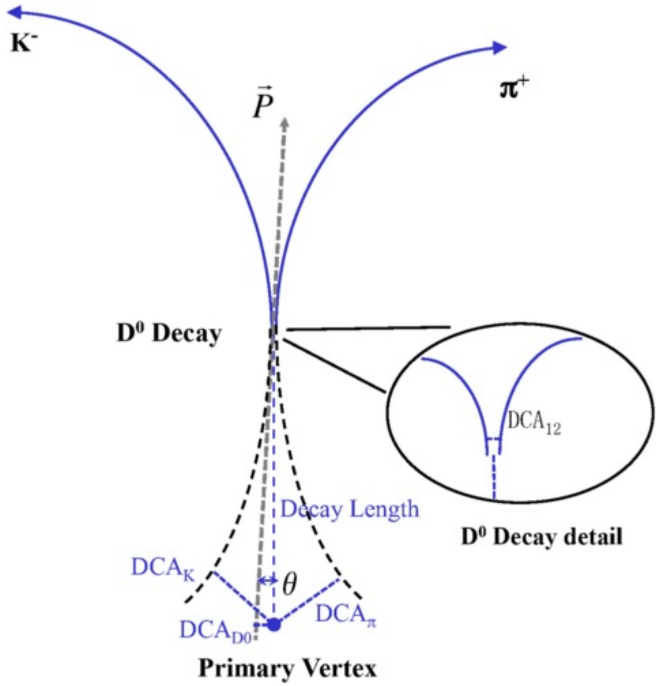
D^0 Reconstruction

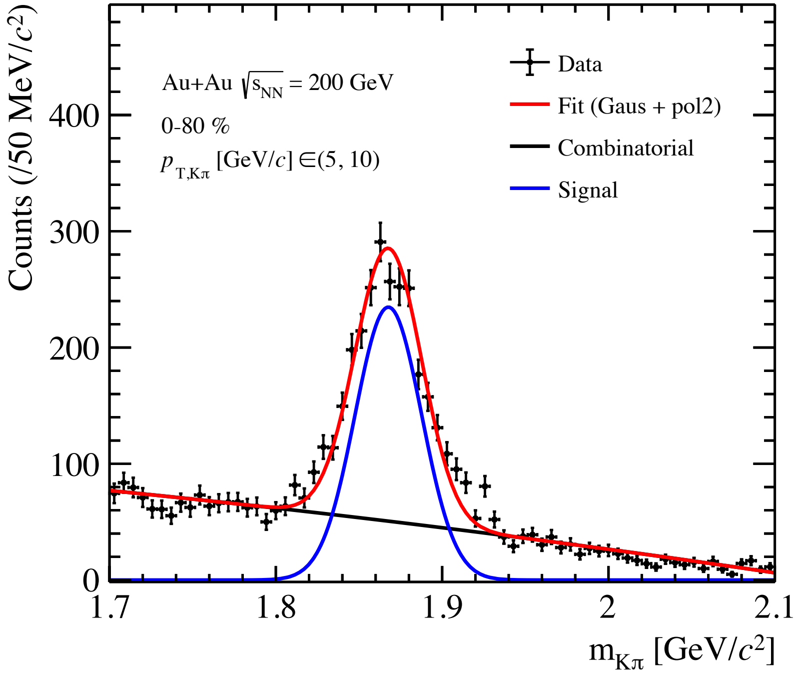


- Kaons and Pions identified using TPC and TOF

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





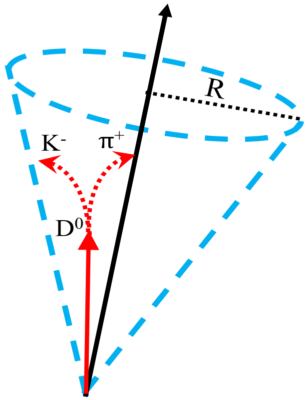


Topological cuts on the D^0 candidates improve signal significance

Yield is calculated using sPlot method [1]

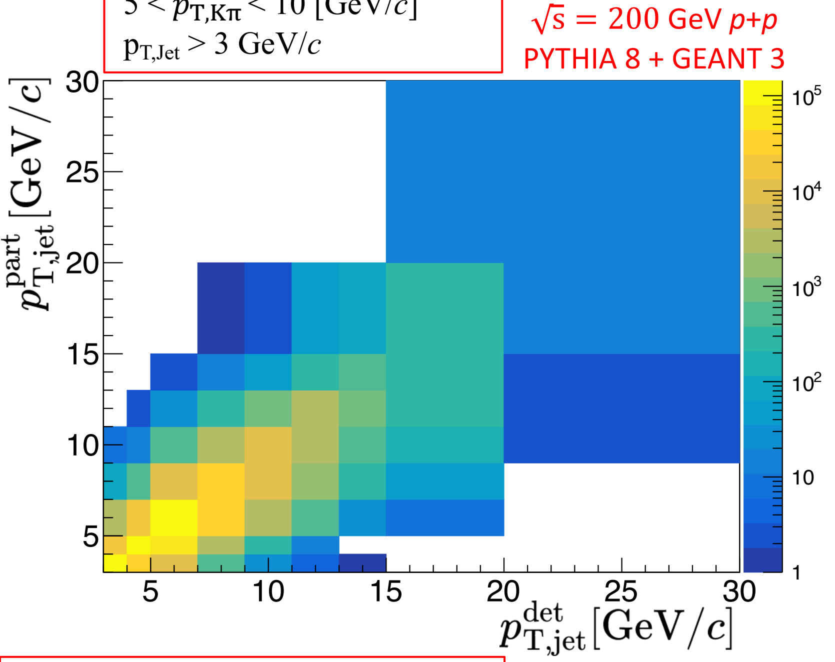
[1] Nucl. Instrum. Methods Phys. Res., A (2005) 555

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 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

anti-k_T jets with D^0, $R = 0.4$
$5 < p_{T,K\pi} < 10$ [GeV/c]
$p_{T,Jet} > 3$ GeV/c



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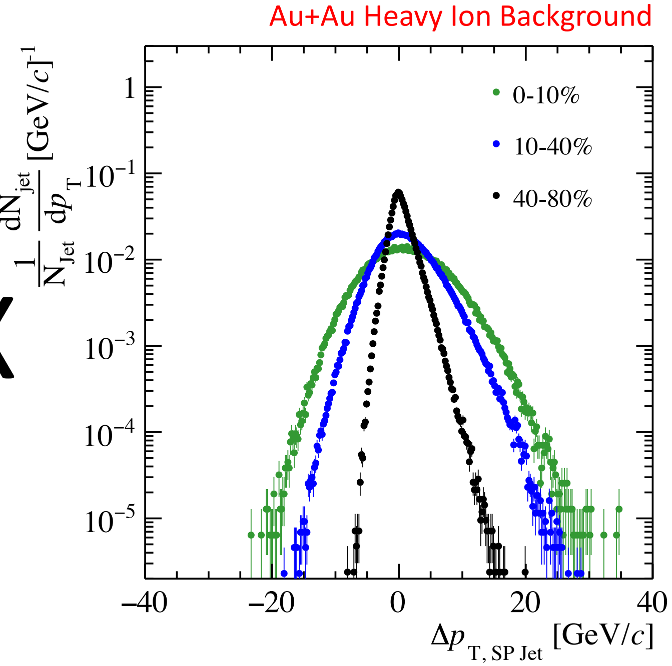
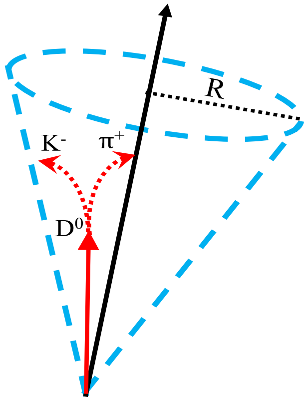


[1]. **FONLL,** JHEP03 (2001) 006

Correction to the Jet Yield



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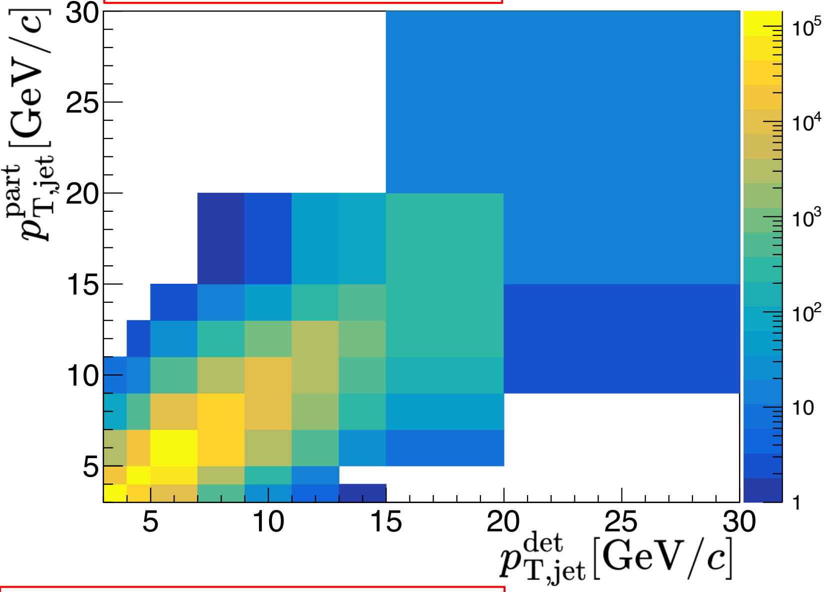

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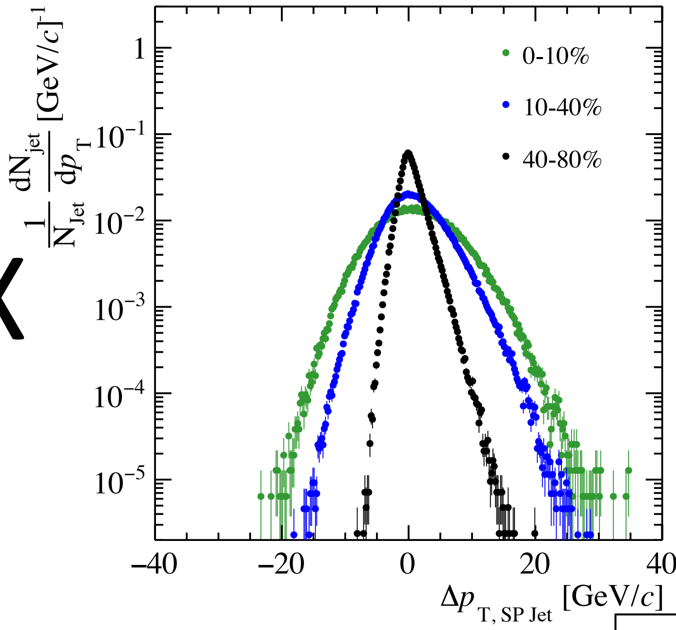
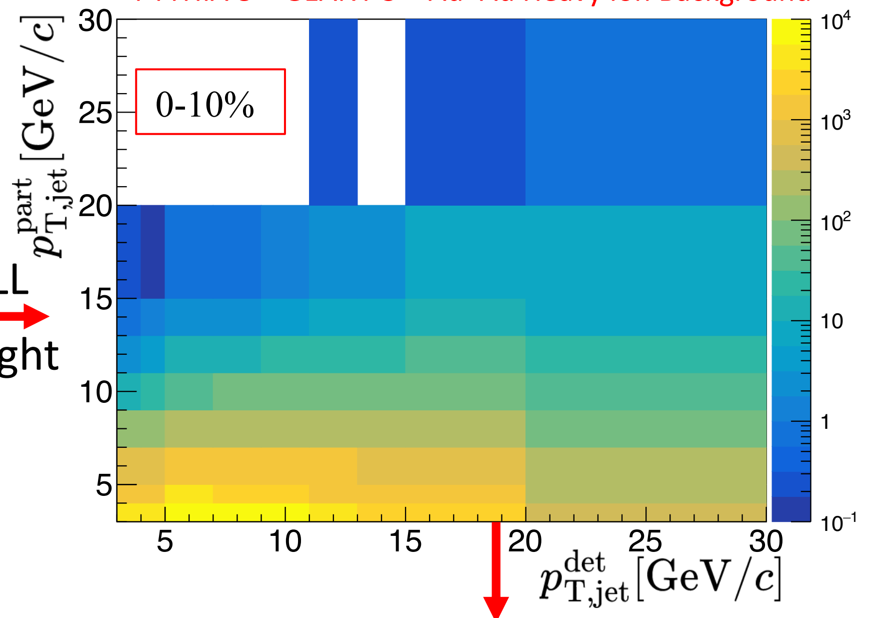


FONLL
Reweight



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

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

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
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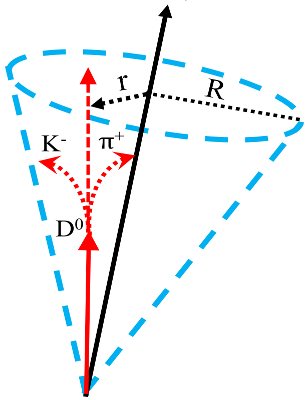
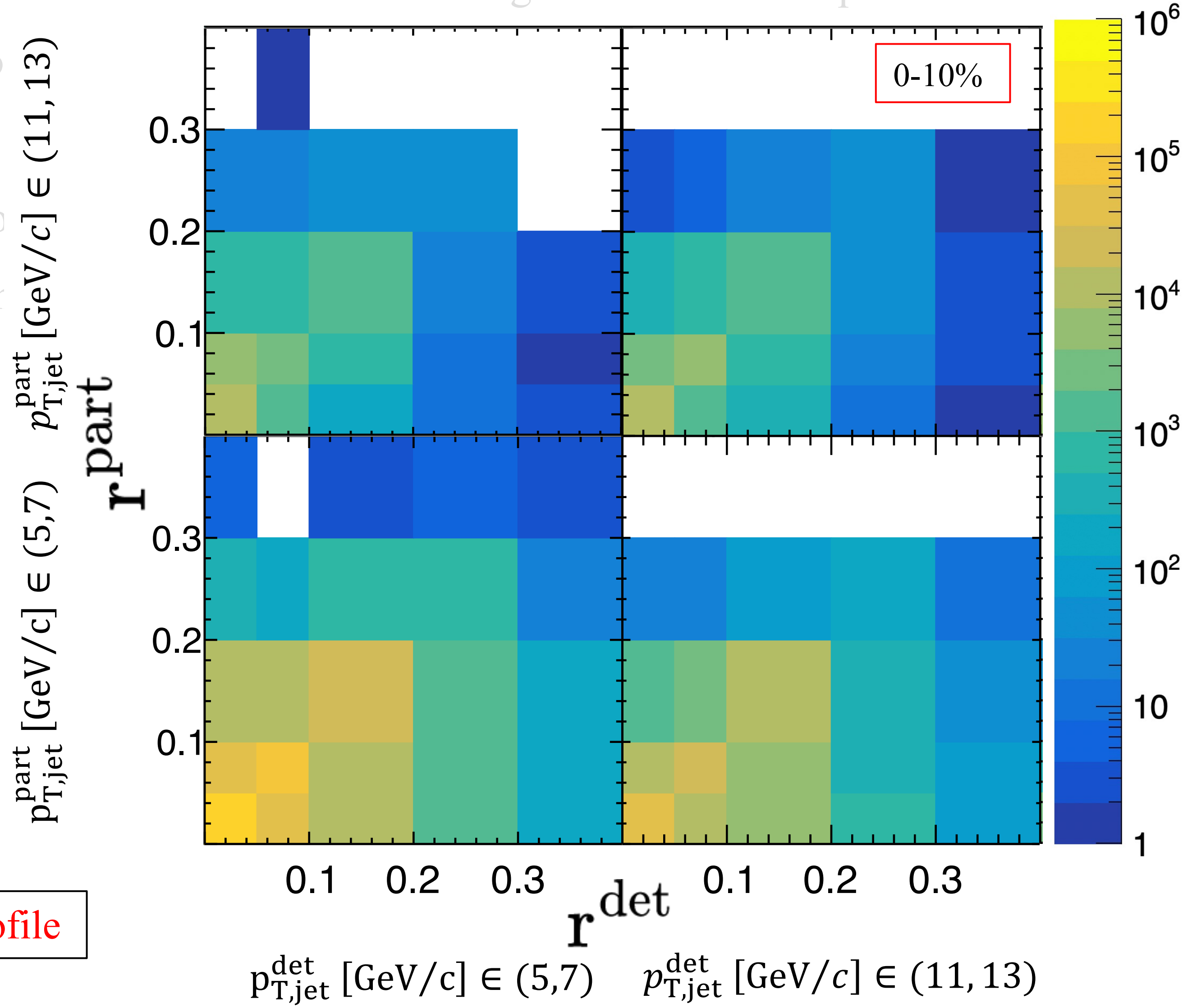


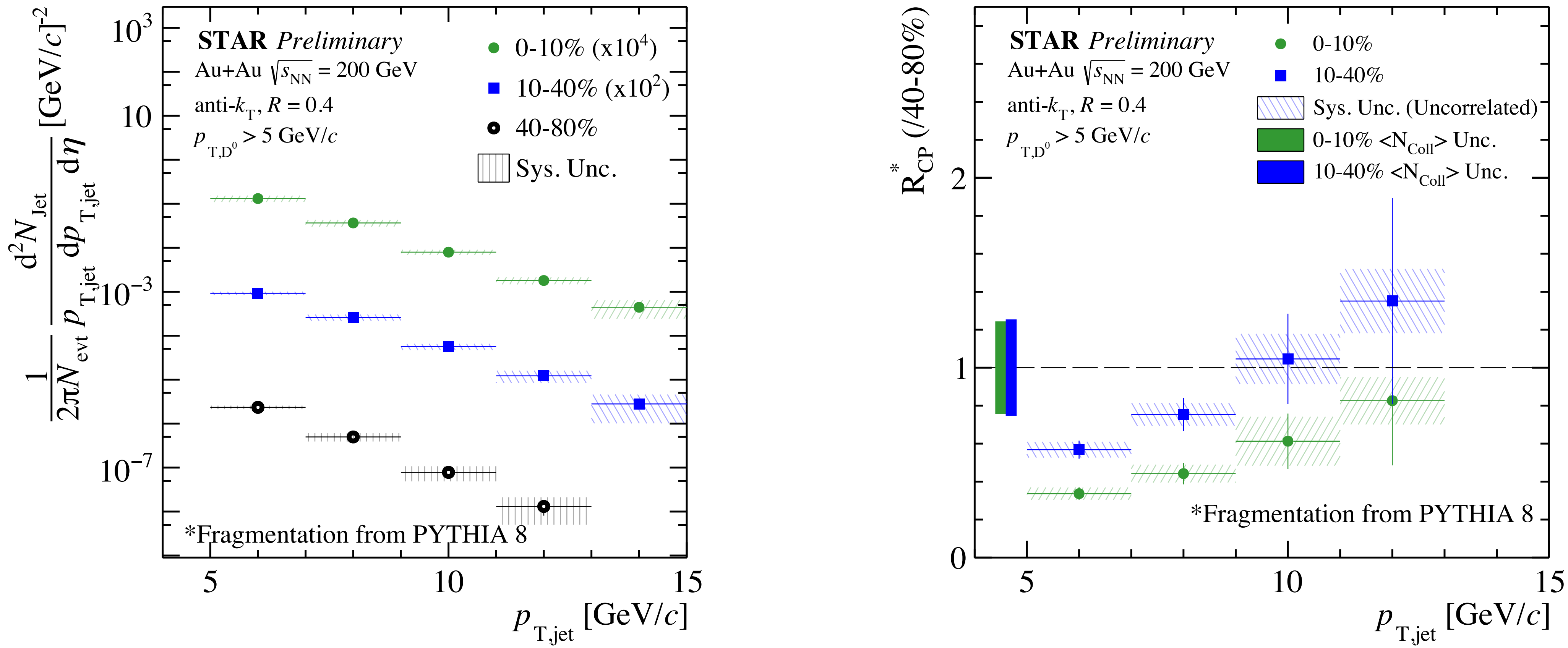


anti-k_T jets with D^0, $R = 0.4$
$|\eta_{jet}| < 0.6$
$p_{T,const} > 0.2$ GeV/c
$p_{T,jet} > 3$ GeV/c
$5 < p_{T,K\pi} < 10$ (GeV/c)

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

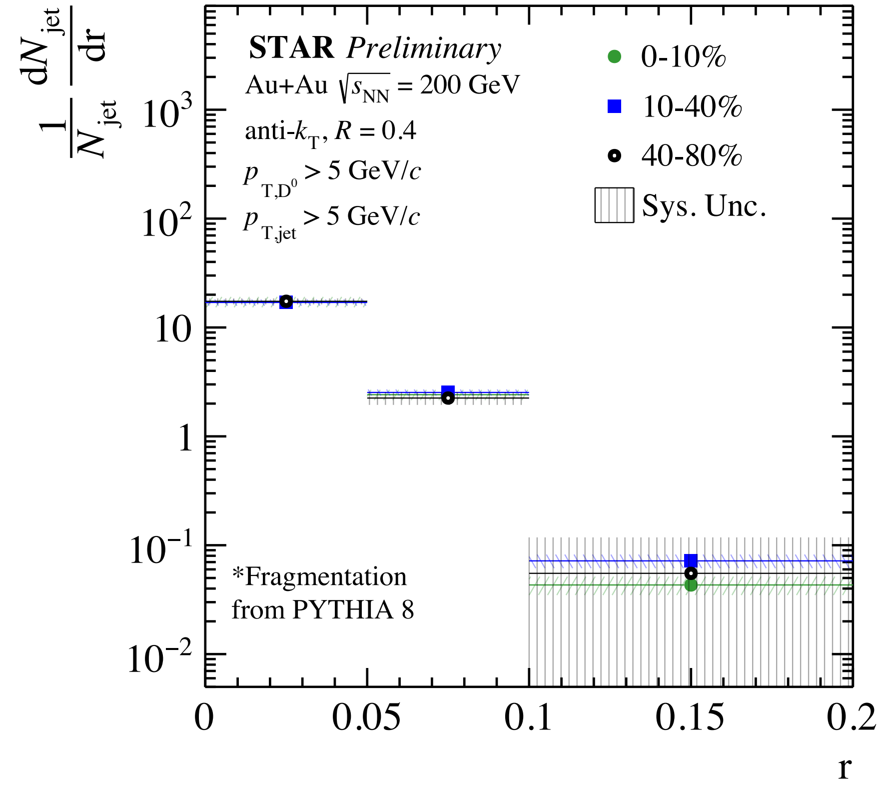
Complete 4D response matrix to unfold radial profile

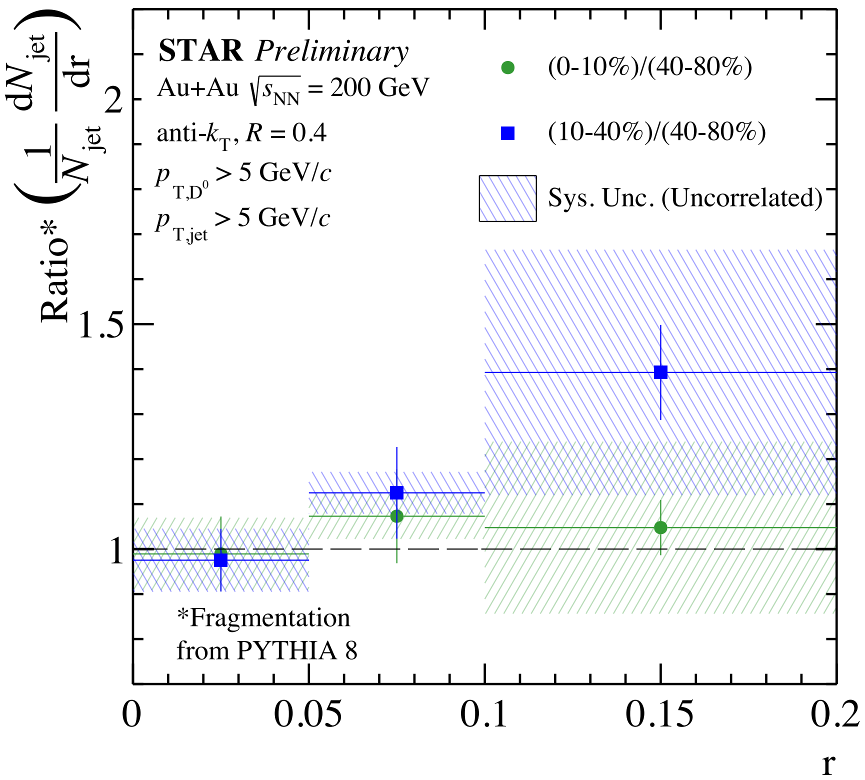
Jet Spectra

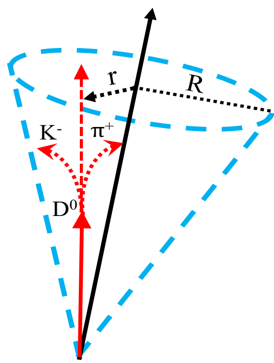


- Most central spectrum is more suppressed than mid-central
- R^*_{CP} shows strong suppression at low $p_{T,jet}$, hint of an increasing trend with $p_{T,jet}$
- Peripheral events have limited statistics with the D^0 p_T selections
- D^0-tagged jet measurement for R_{AA} will be explored using high-statistics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

Radial Profile of D^0 Mesons in Jets



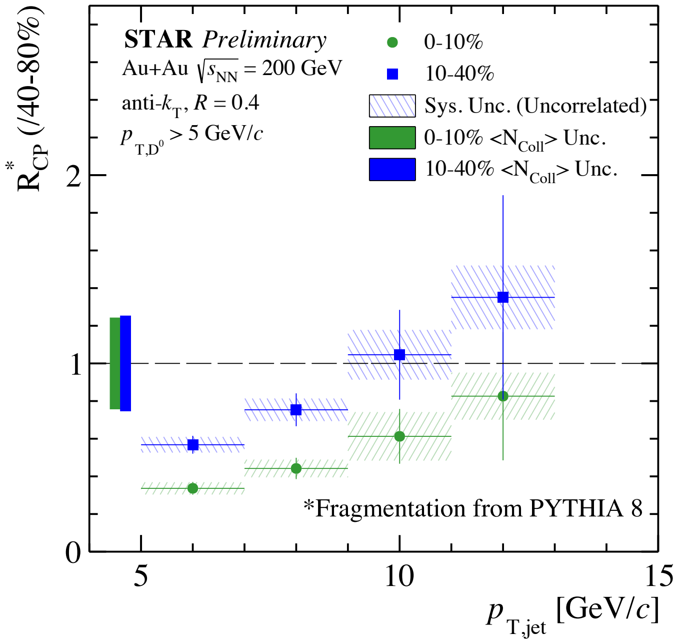


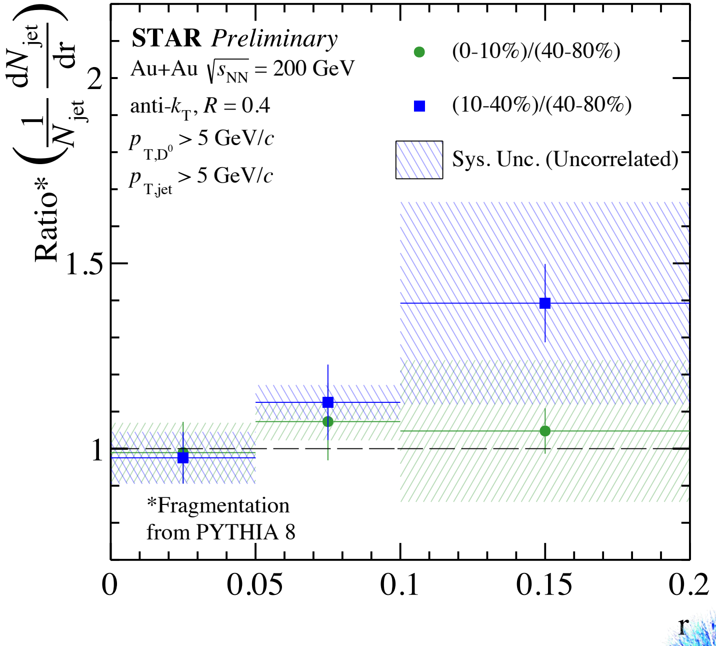


- For D^0 p_T > 5 GeV/c, the ratio of radial distributions is consistent with unity within uncertainties
- Extending the analysis to lower D^0 kinematics is essential to study D^0 diffusion

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 consistent with being suppressed with respect to peripheral events
  - ✓ Ratio of radial profile of D^0 mesons in jets consistent with unity within uncertainties.





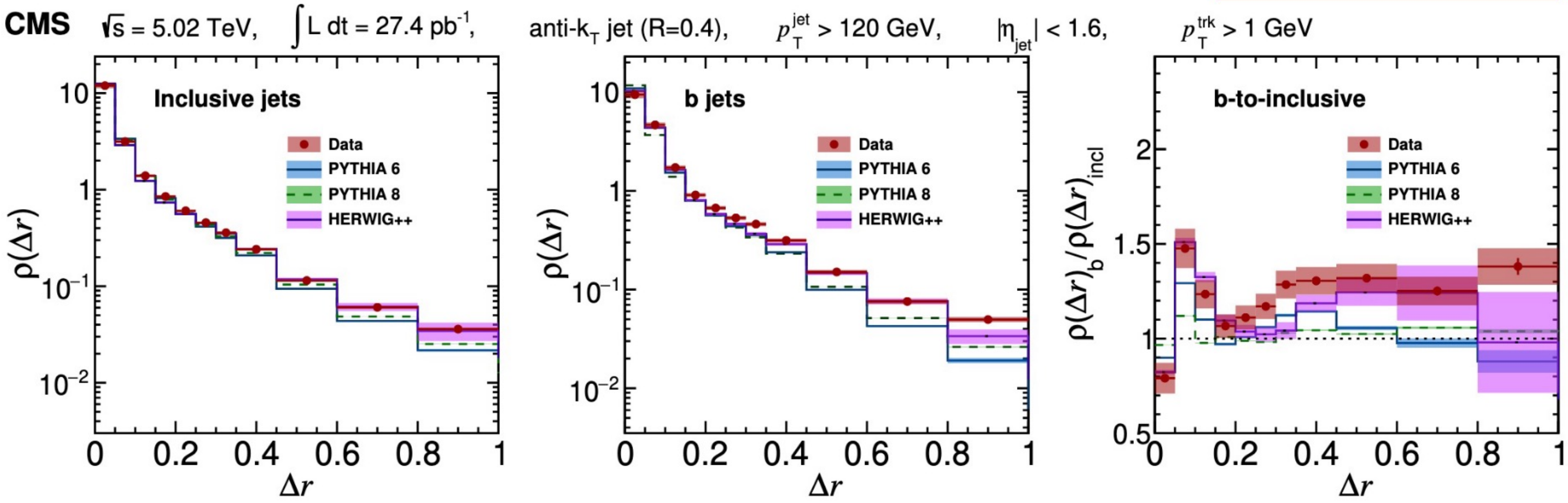
Outlook

- 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

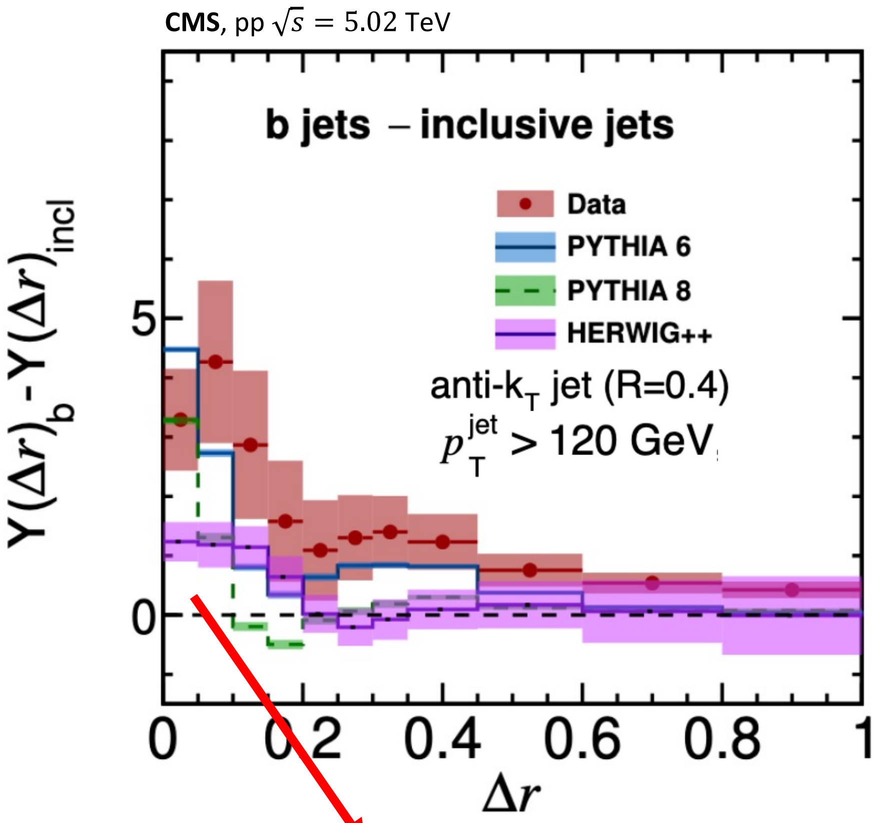


Bottom quark jet (b-jets) shapes **modified in vacuum****, possibly due to dead cone**

Fragmentation pattern for heavy quark

CMS, JHEP05 (2021) 054

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



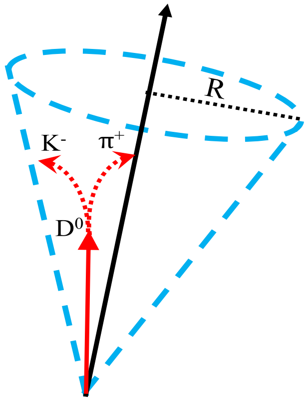
Higher yields of low p_T charged-particle close to jet axis in b-Jets vs inclusive jets in vacuum

~ 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

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

<u>Unbinned max. likelihood fit</u>

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

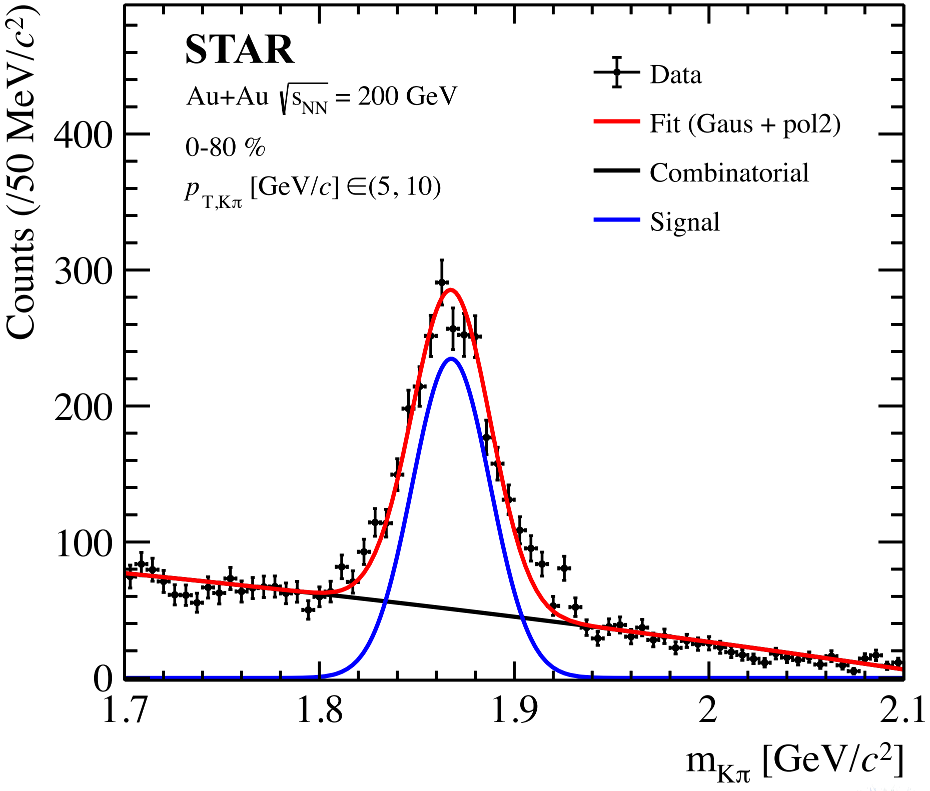
N_k = k-th yield (T=2)

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

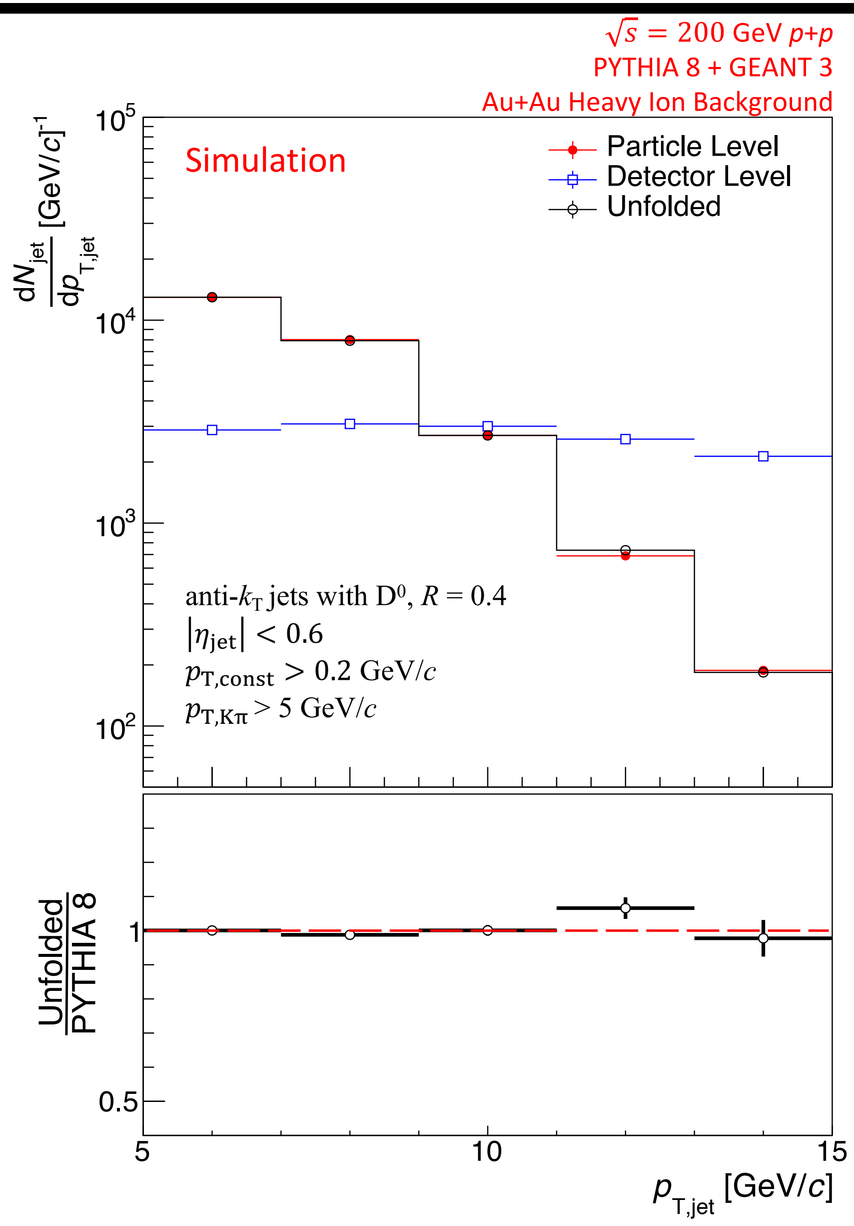
V = cov. matrix

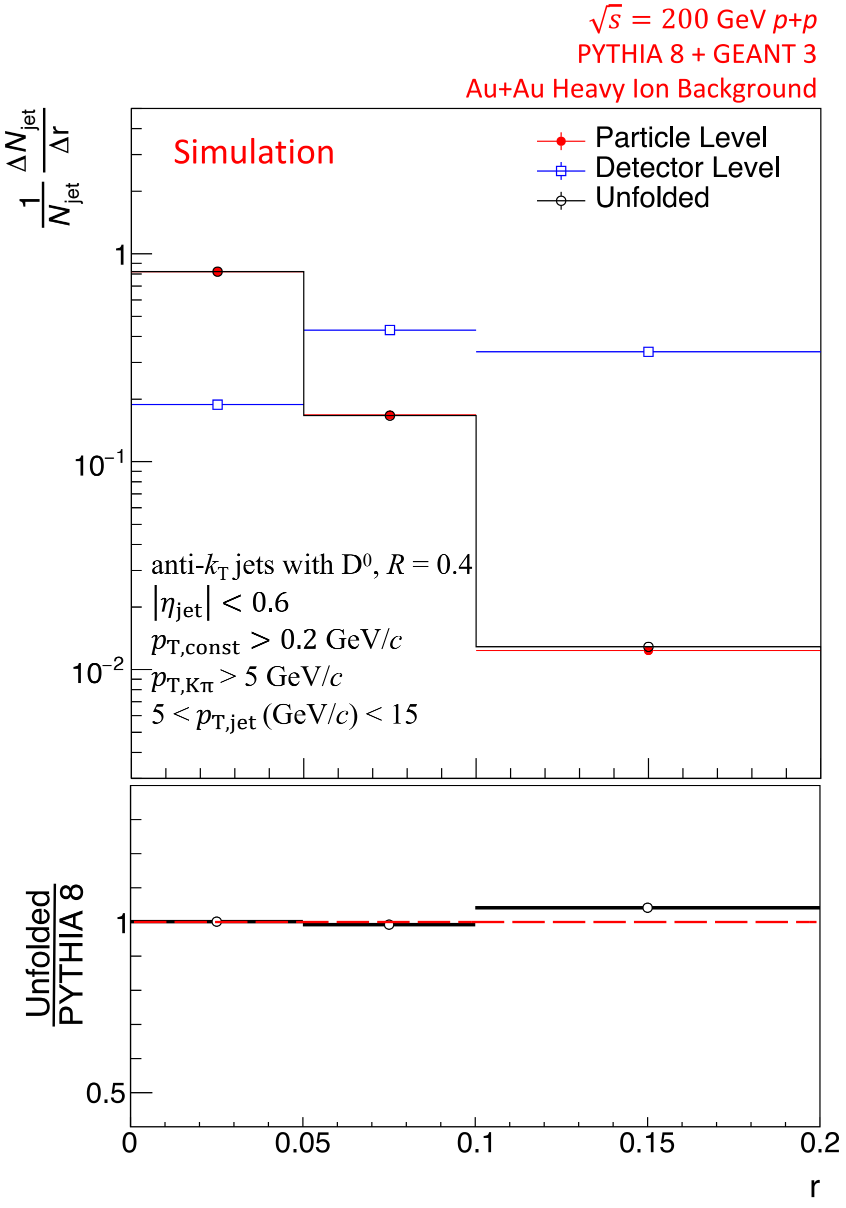
Efficiency Correction

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



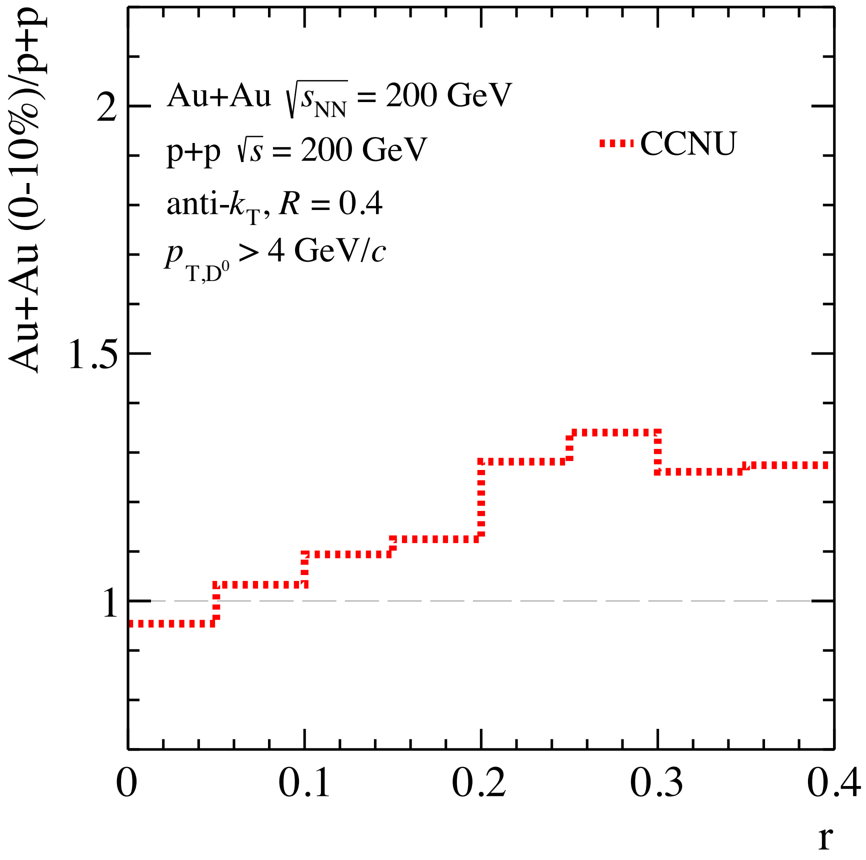
Closures For Unfolding

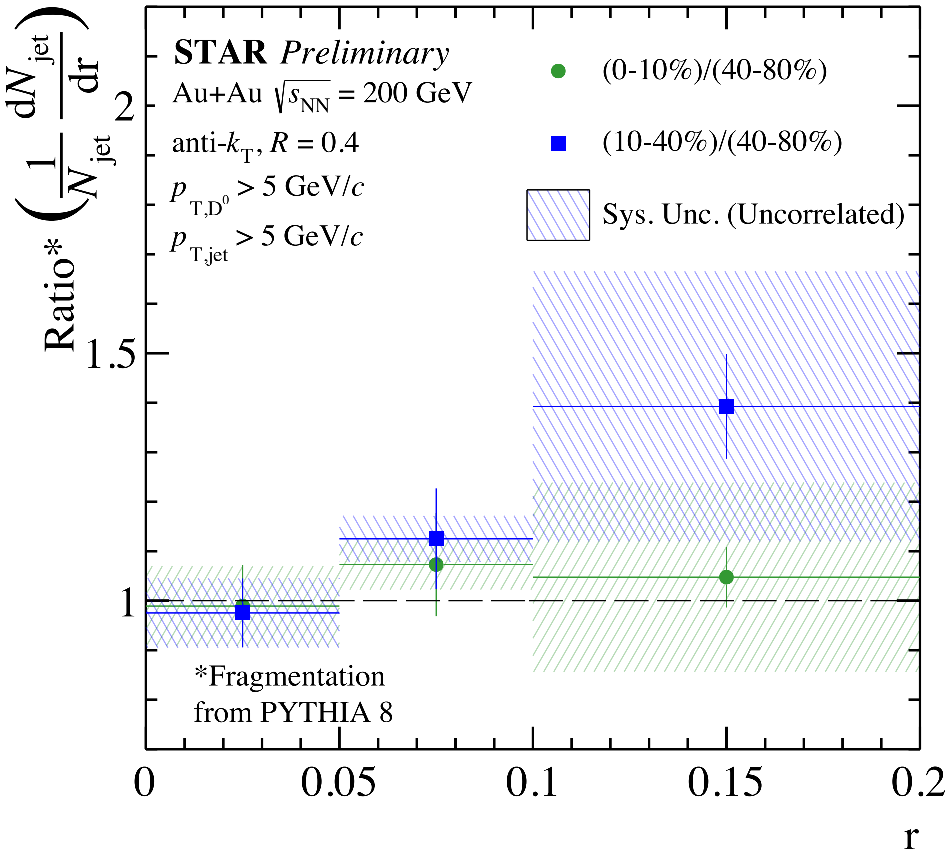


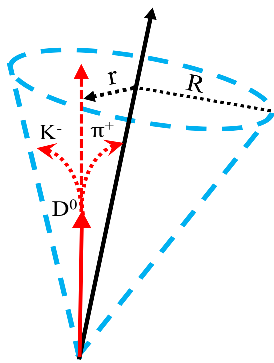


Radial Profile: Data vs Model

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