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

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For the *STAR Collaboration*

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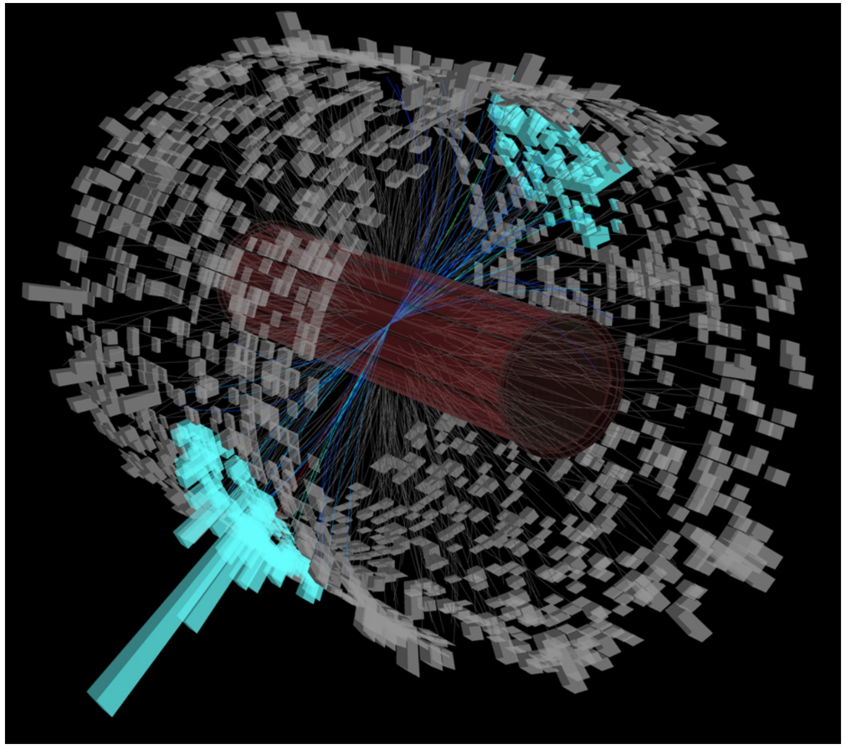
Supported in part by

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

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

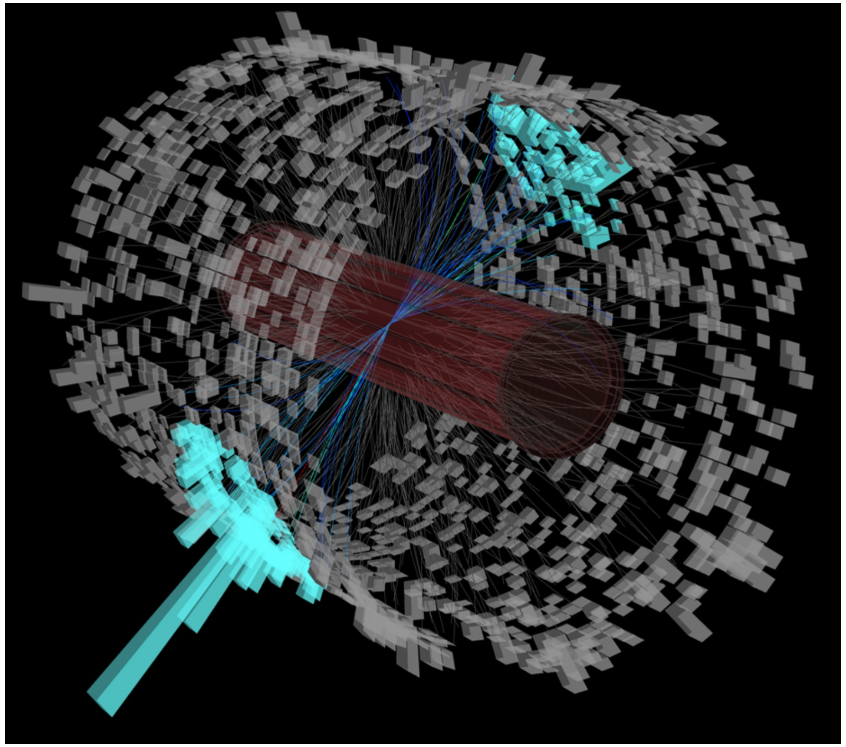
- **Loss of parton energy** in the QGP medium
- **Parton shower broadened** due to medium-induced radiation and scattering

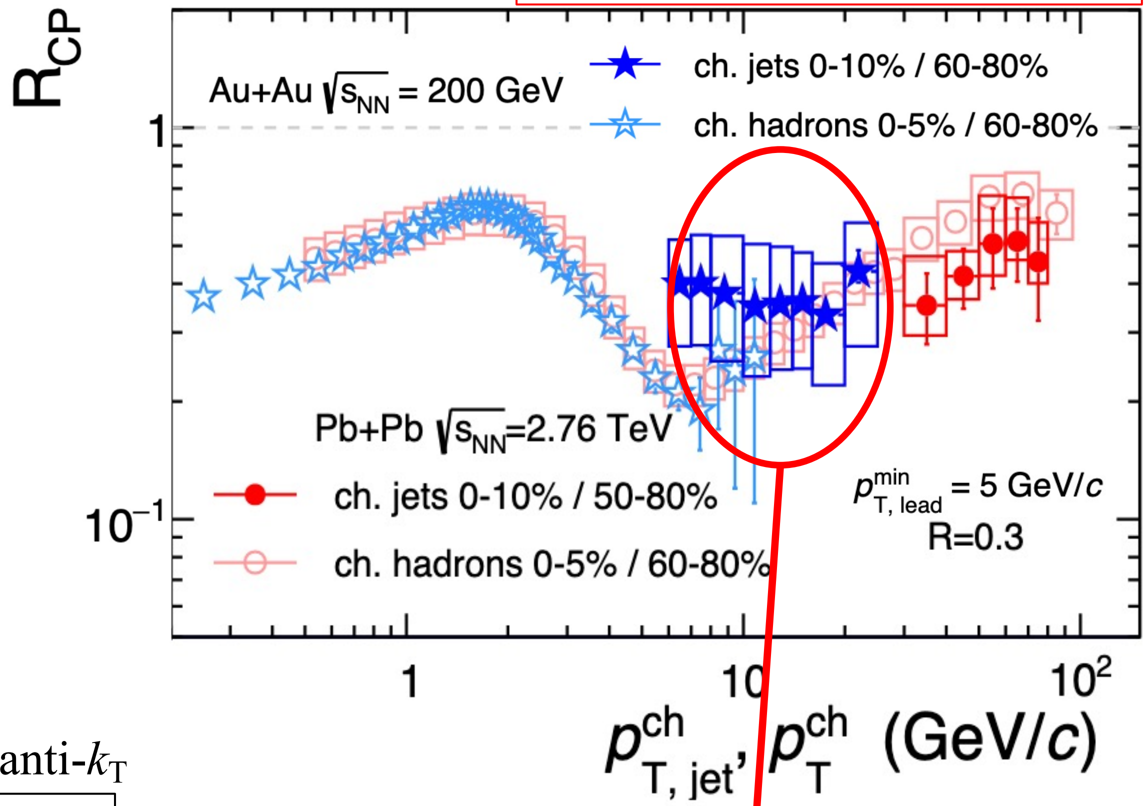
Jets in Heavy Ion Collisions

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

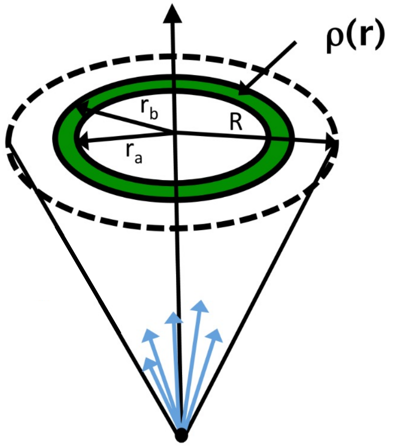
Phys. Lett. B 641 (2006) 57-61

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

Motivation

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

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



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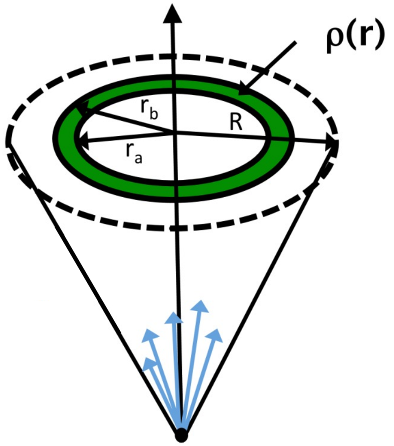

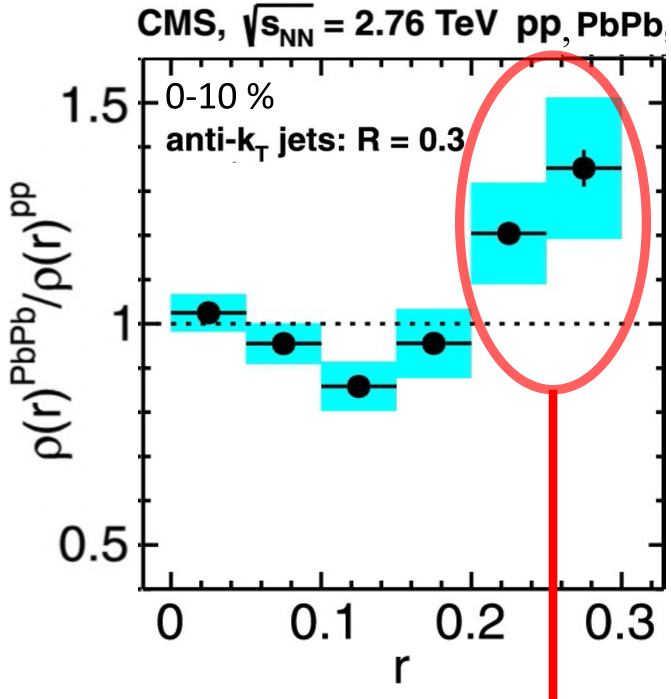

CMS, Phys. Lett. B 730 (2014) 243

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

Motivation

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

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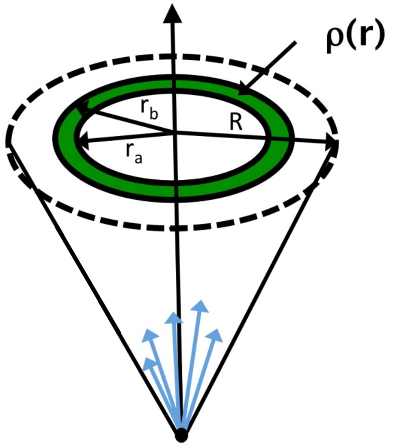
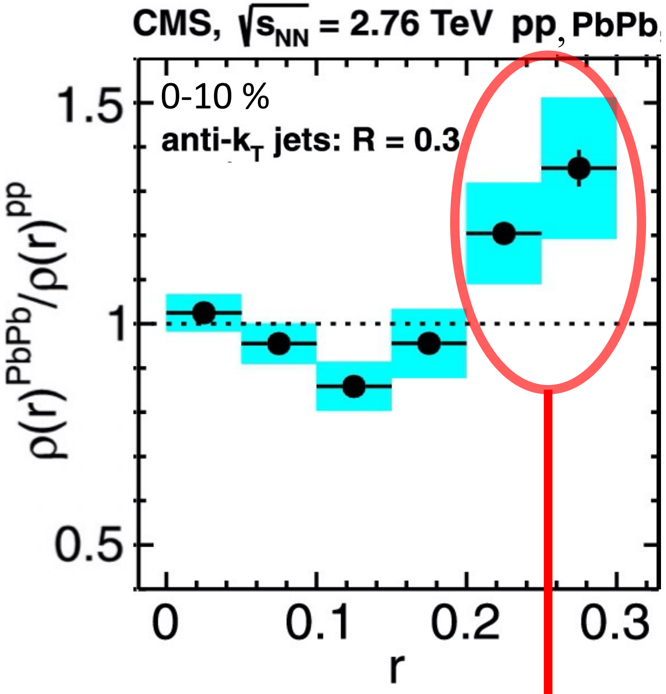
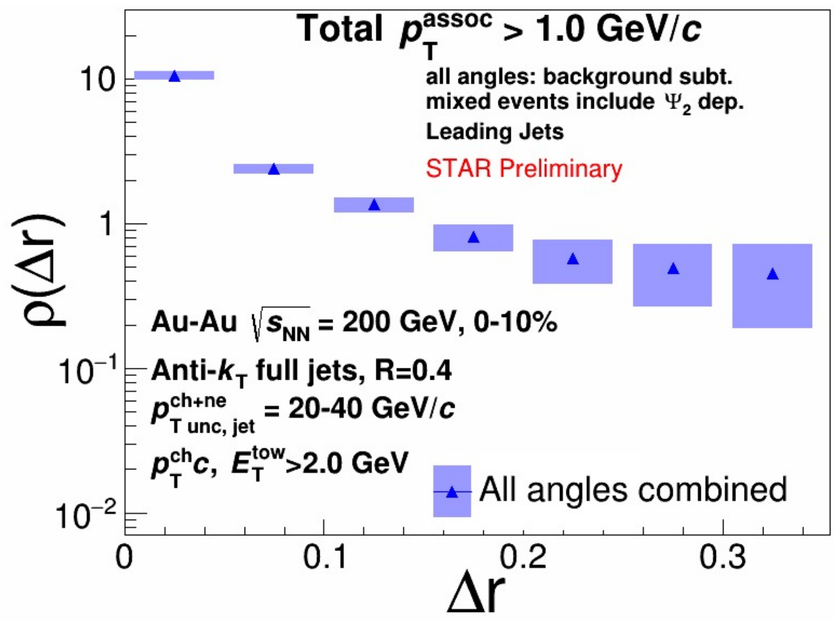






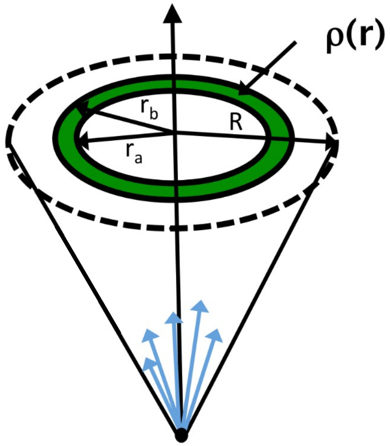
CMS, Phys. Lett. B 730 (2014) 243

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

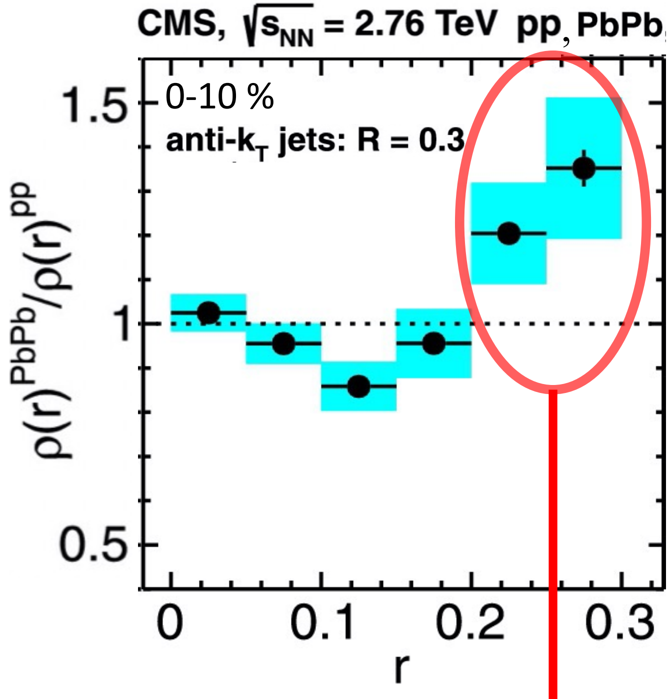
Motivation

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

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



LIDO, Phys. Rev. C 98 (2018 , 064901
DUKE, Phys. Rev. C 97 (2018), 014907
JETSCAPE, Nuclear Physics A (2021), 121965



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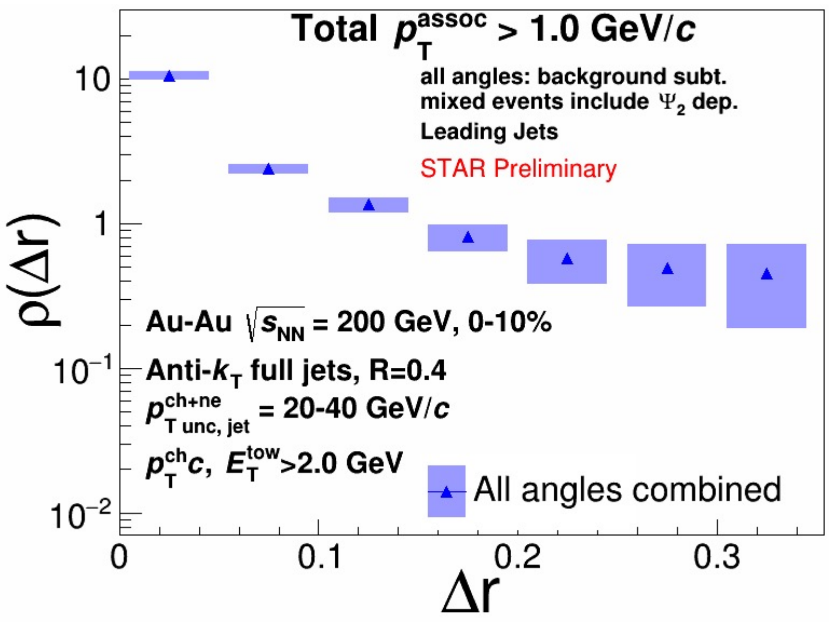


Jet energy is **redistributed to large distances from the jet axis** in the presence of QGP

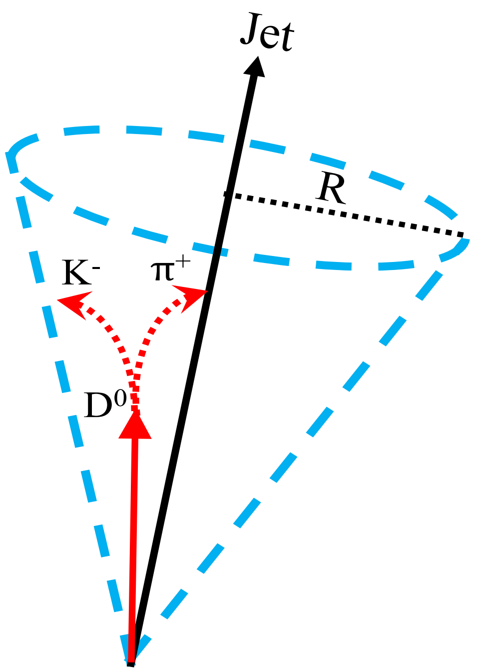
Possible mechanisms:

- Multiple-scattering
- Medium-induced Bremsstrahlung
- Medium response

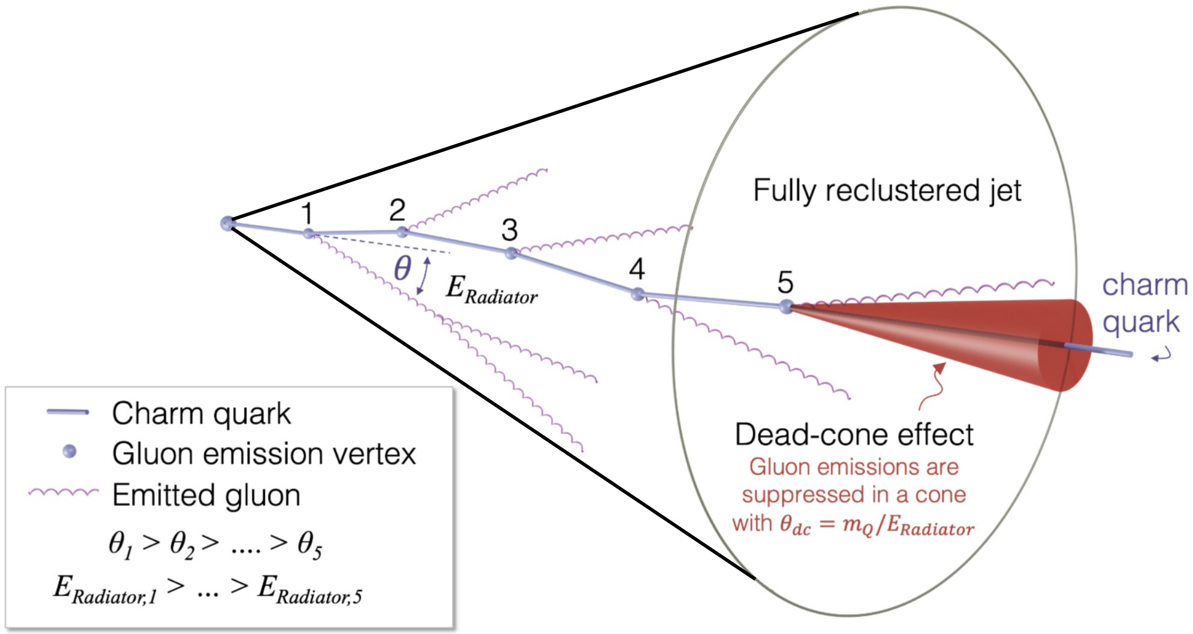
Dependent on the mass of the underlying parton

Motivation to look at heavy-flavor jets

Heavy Flavor Tagged Jets

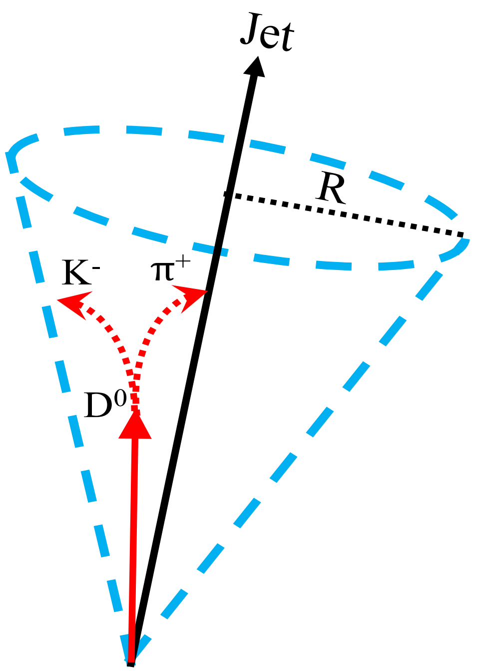


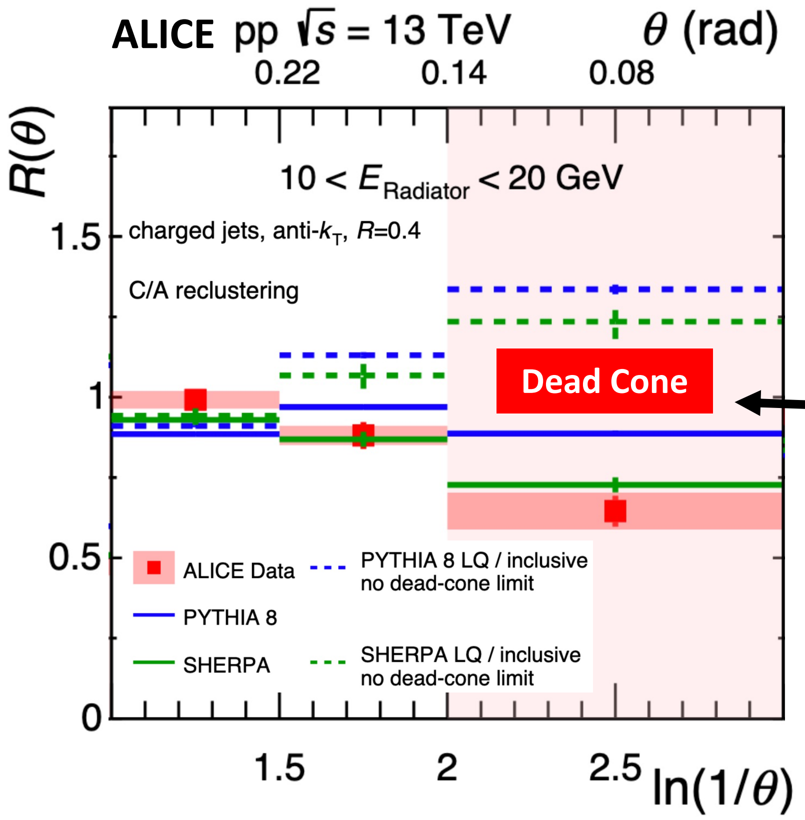
ALICE, arXiv:2106.05713 (2021)



Heavy Flavor Tagged Jets

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





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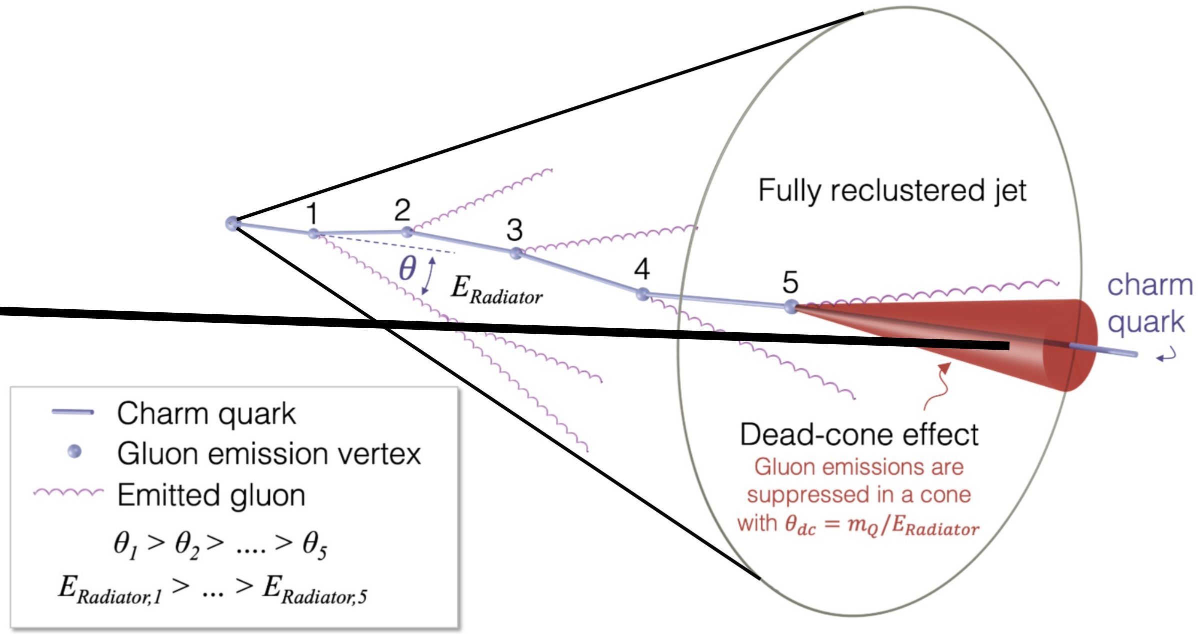
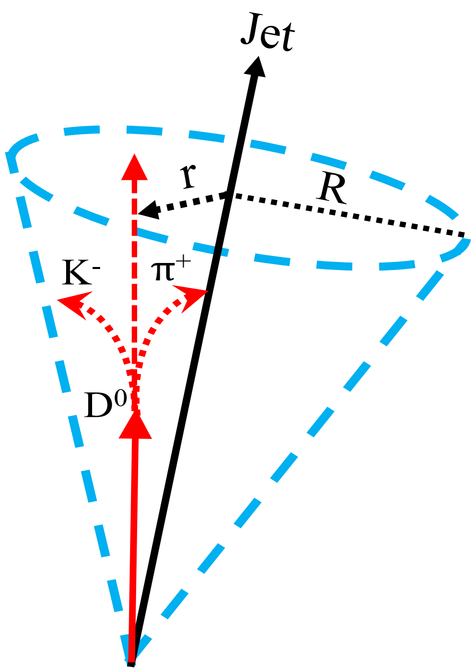
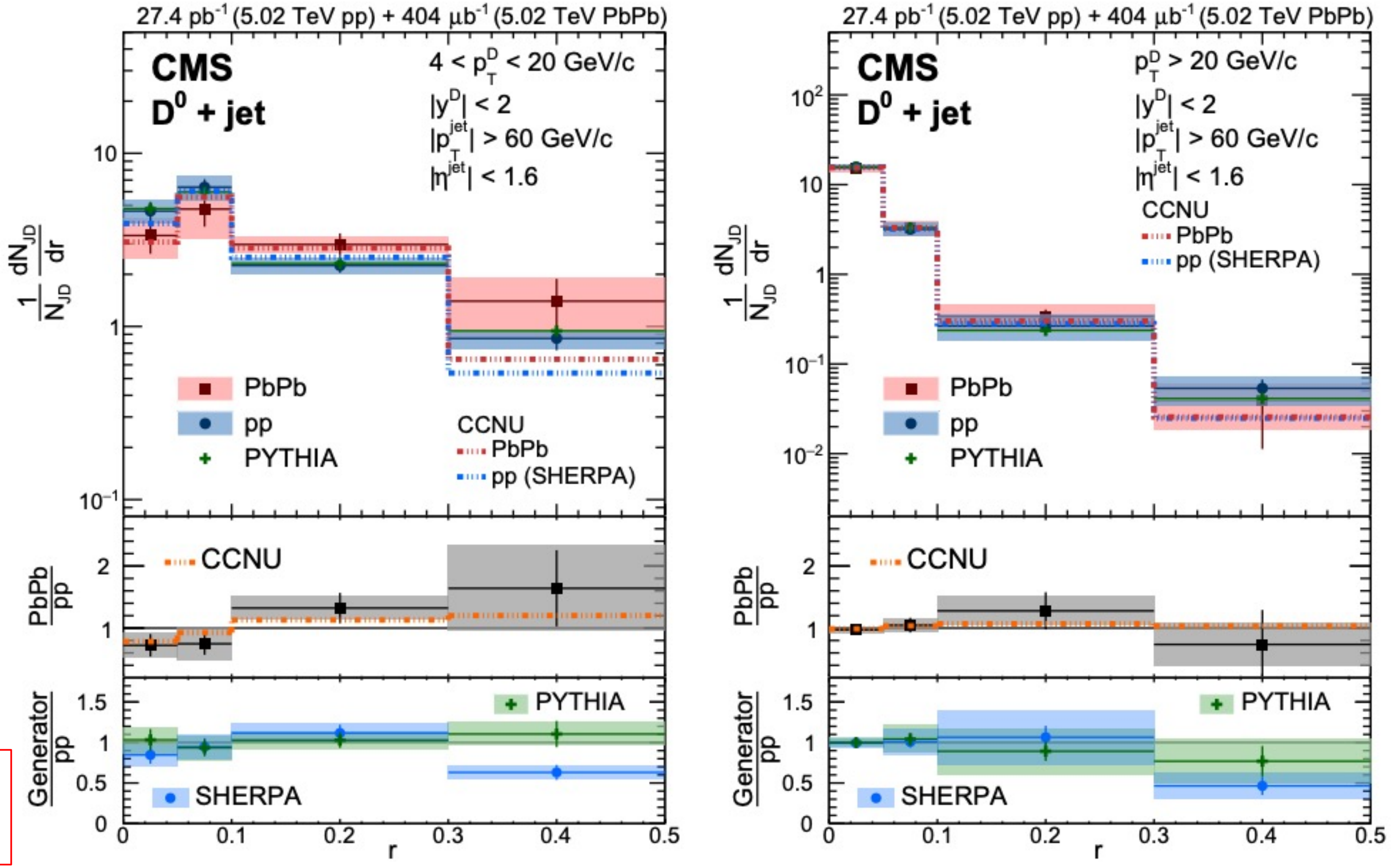


Heavy-flavor emission spectra at large angles suppressed due to dead-cone in vacuum

Heavy Flavor Tagged Jets

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

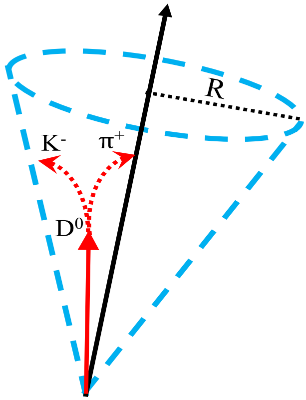




Low p_T D^0 mesons appear to be **diffused in the presence of QGP** at LHC

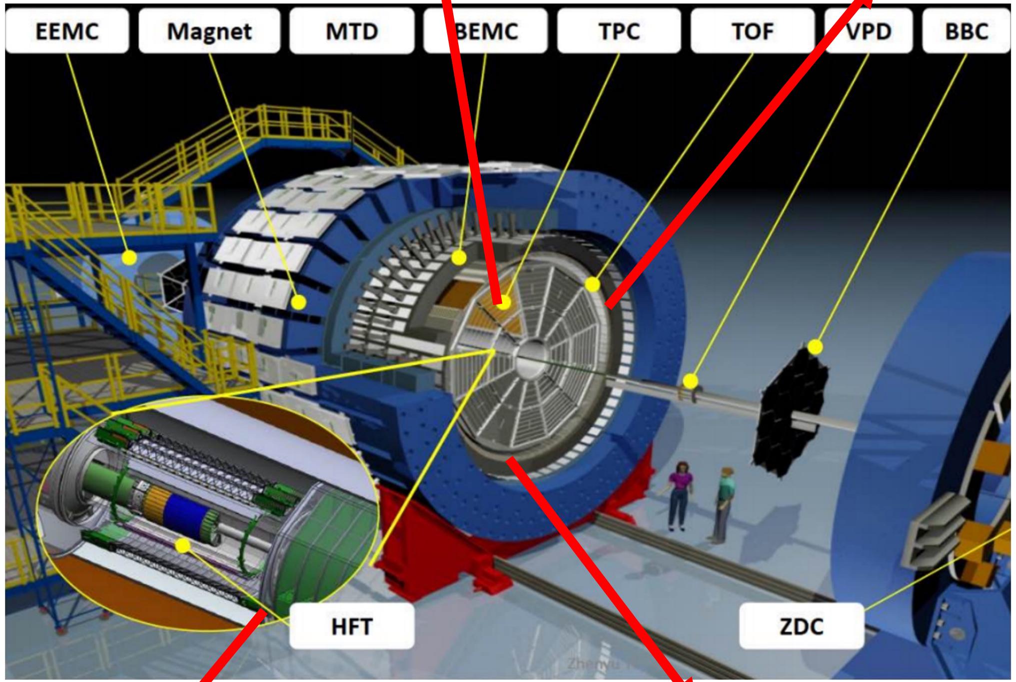
- Lower p_T D^0 mesons can be reconstructed at RHIC energies
- The contribution from the underlying background is smaller at RHIC

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])

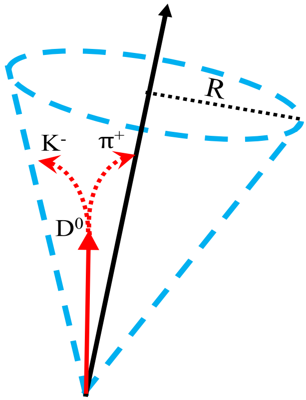
Constituent Selection :

- $0.2 < p_{T,track}$ [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 in HFT
- $5 < p_{T,D^0}$ [GeV/c] < 10

D^0 Jet Selection :

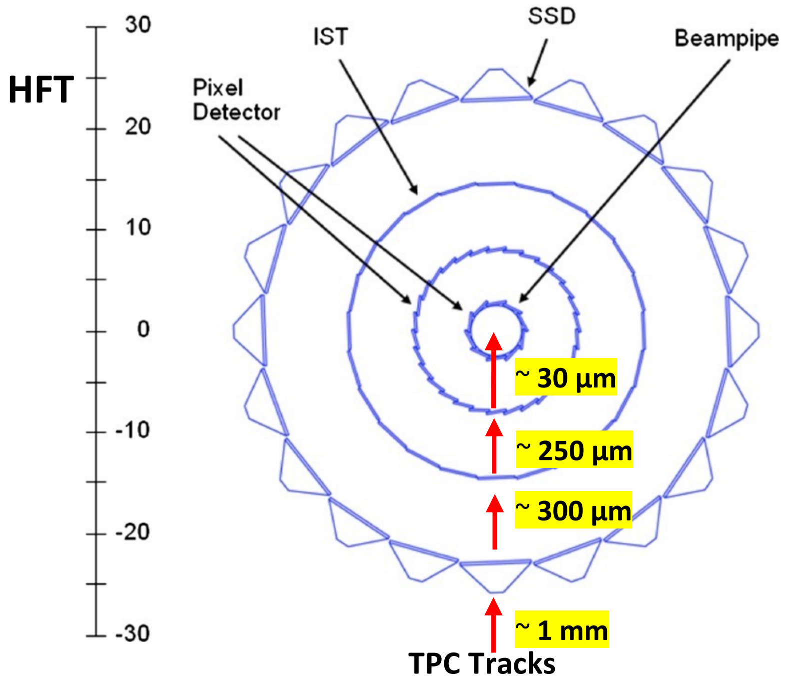
- Anti-k_T full-jets of radius R = 0.4, area-based background subtraction
- $|\eta_{Jet}| < 0.6$

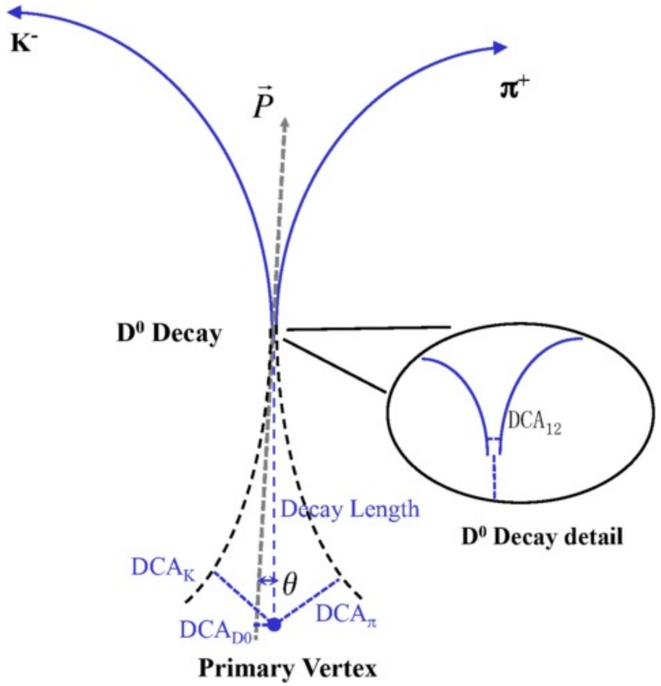
D^0 Reconstruction

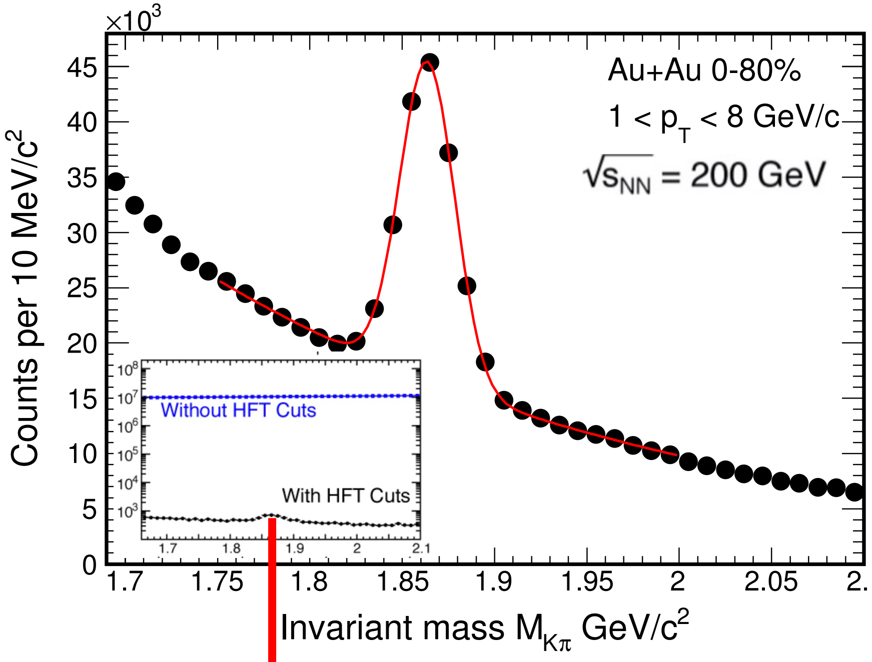


- Kaon and Pions identified using TPC and TOF

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







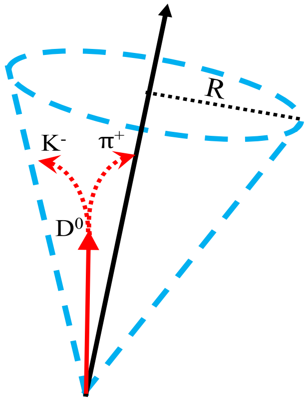
Topological cuts on the D^0 candidates improve signal significance

- Decay length of D^0 ~ 123 µm.
- HFT has a resolution of 30 µm for kaons at ~ 1.2 GeV/c
- HFT can reconstruct D^0 candidates based on the decay topology

D^0-Jet Yield Extraction

$_s\mathcal{P}lot$

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



- Native class in RooStats + widely used in HEP
- Unbinned maximum likelihood fit to invariant mass integrated over all kinematics
- $p_{\mathrm{T,jet}}$ and ΔR histograms with all D^0-jet candidates using sWeights
- Trivial to include reconstruction efficiencies versus D^0 kinematics

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

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

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

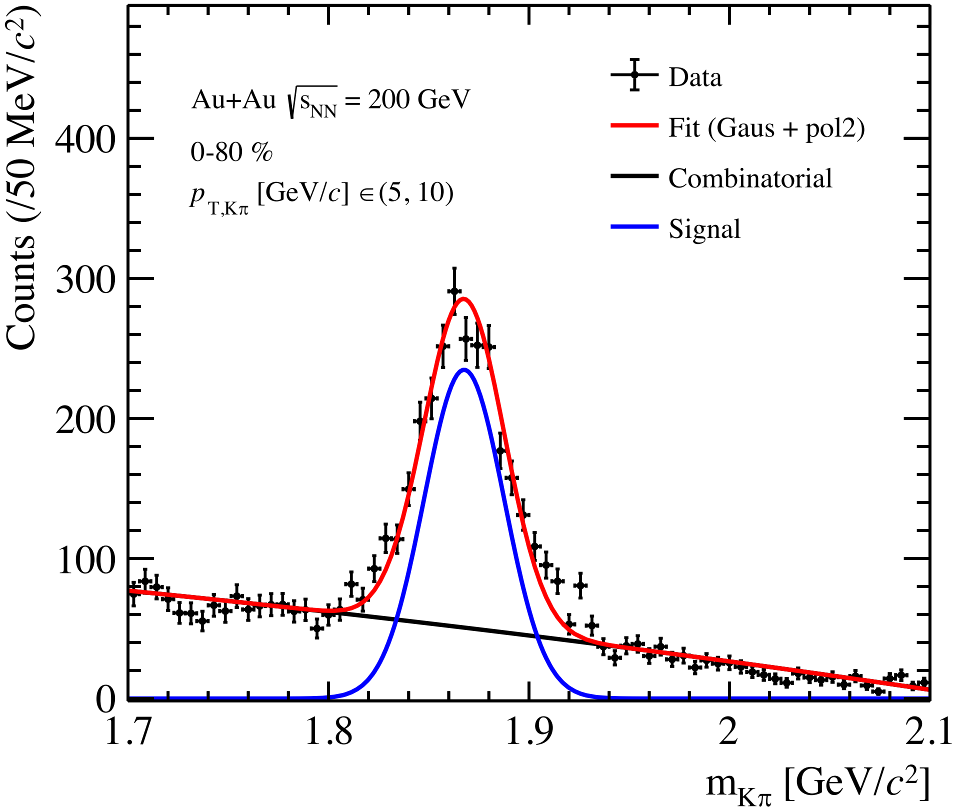
N_k = k-th yield (T=2)

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

V = cov. matrix

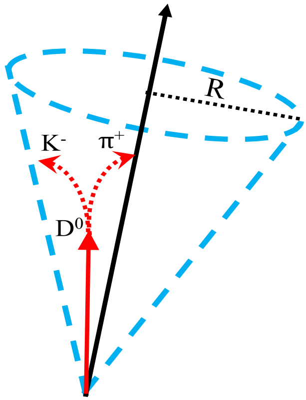
Efficiency Correction

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

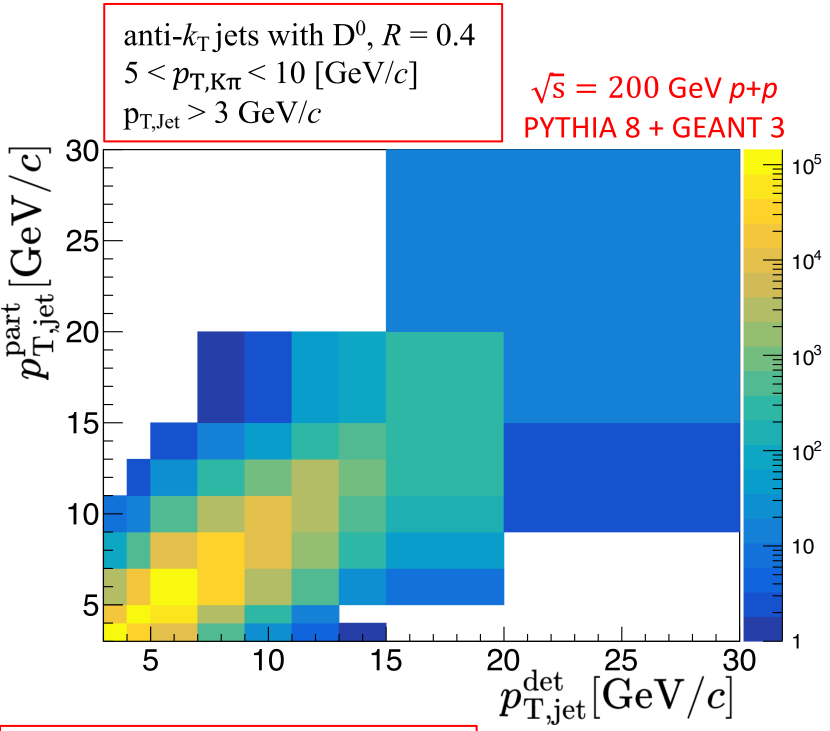


For more information about $_s\mathcal{P}lot$, **visit poster by Matthew Kelsey [T11_2, #367].**

Correction to the Jet Reconstruction

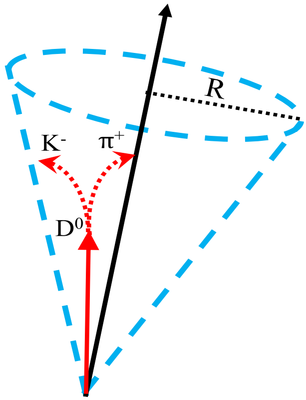


1. Response matrix for p+p $\sqrt{s}$ = 200 GeV from PYTHIA and GEANT3 to get the detector response
2. Single Particle (SP) Embedding in heavy ion event to model fluctuations in area-based background subtraction
3. Reweight PYTHIA with a prior (FONLL [1] c-quark) to match the shape of the jet p_T spectra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



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

Correction to the Jet Reconstruction



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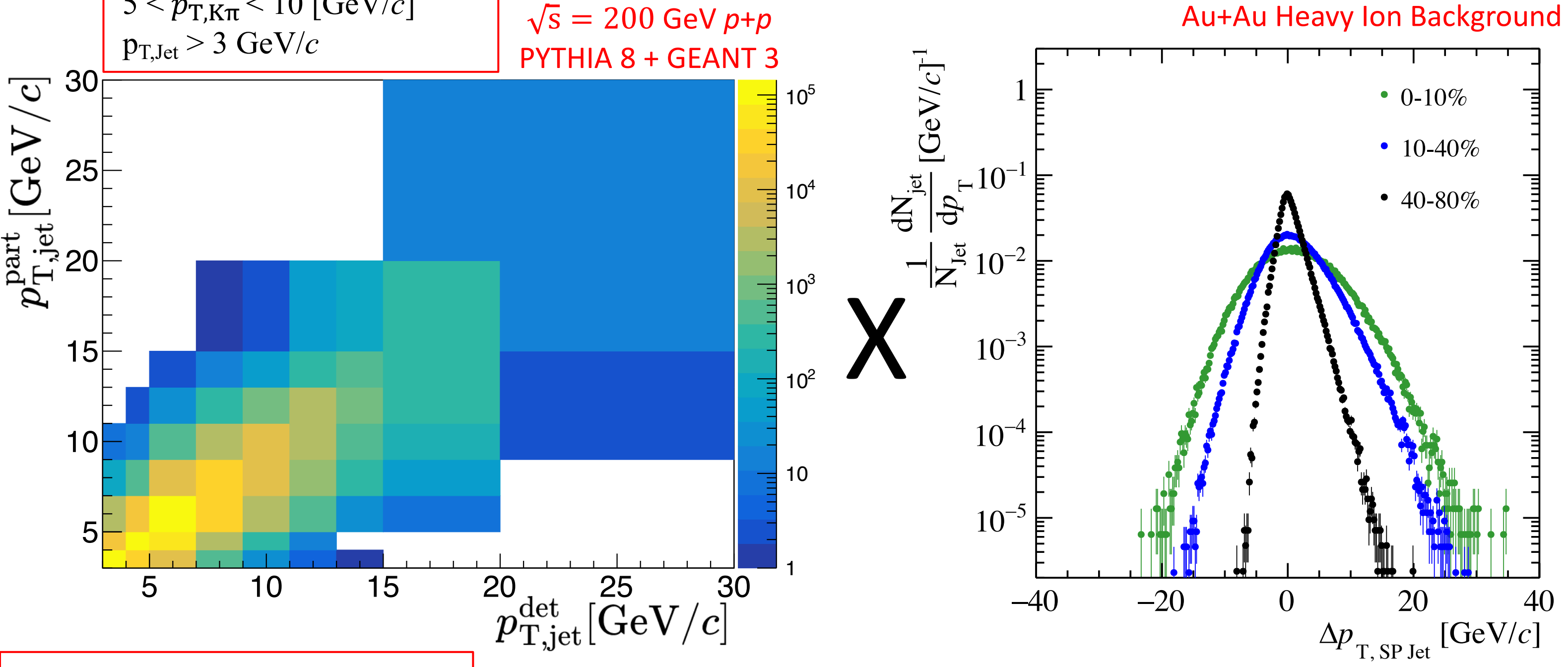

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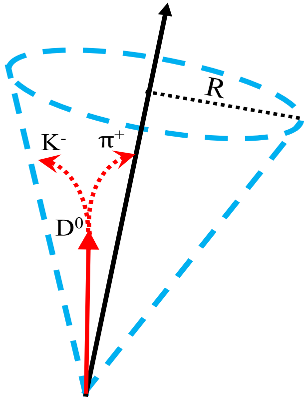

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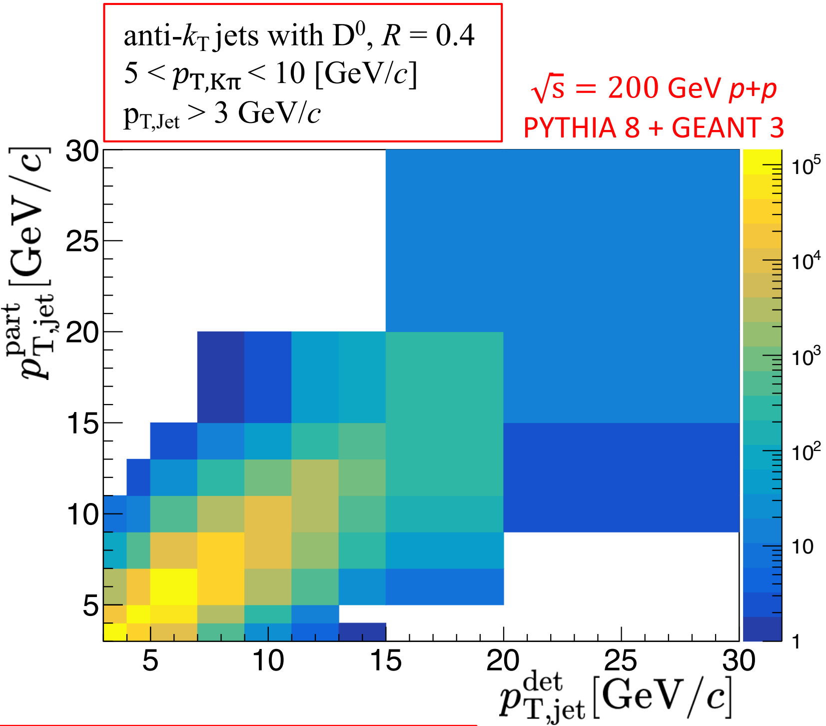
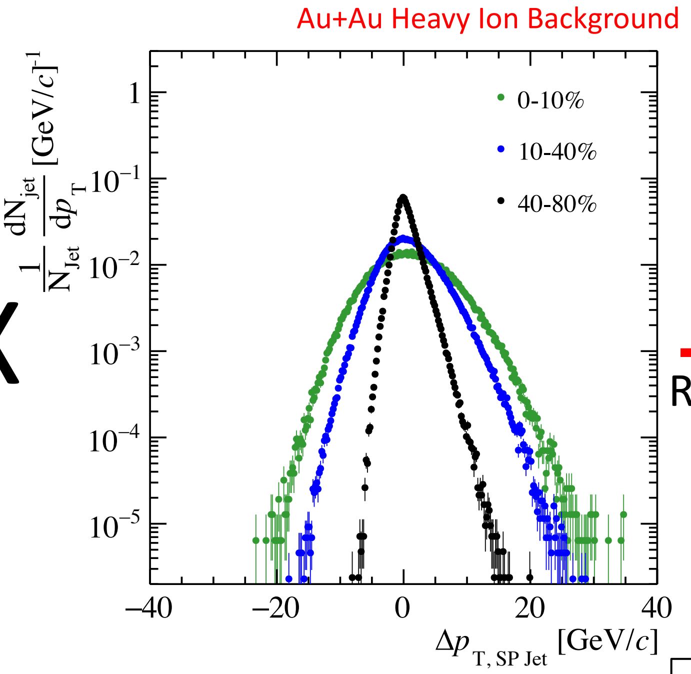
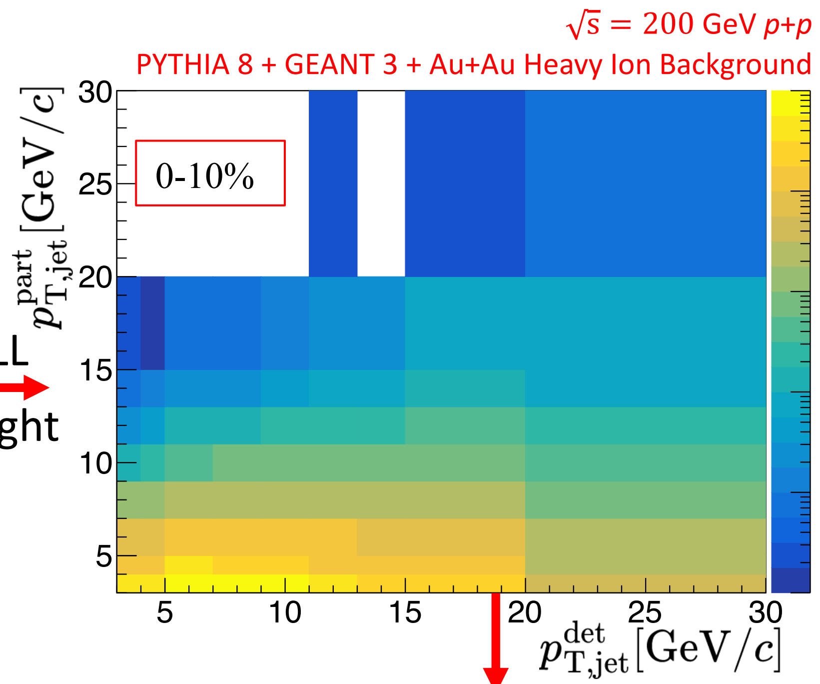


X



FONLL → Reweight



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

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

Correction to the Jet Reconstruction

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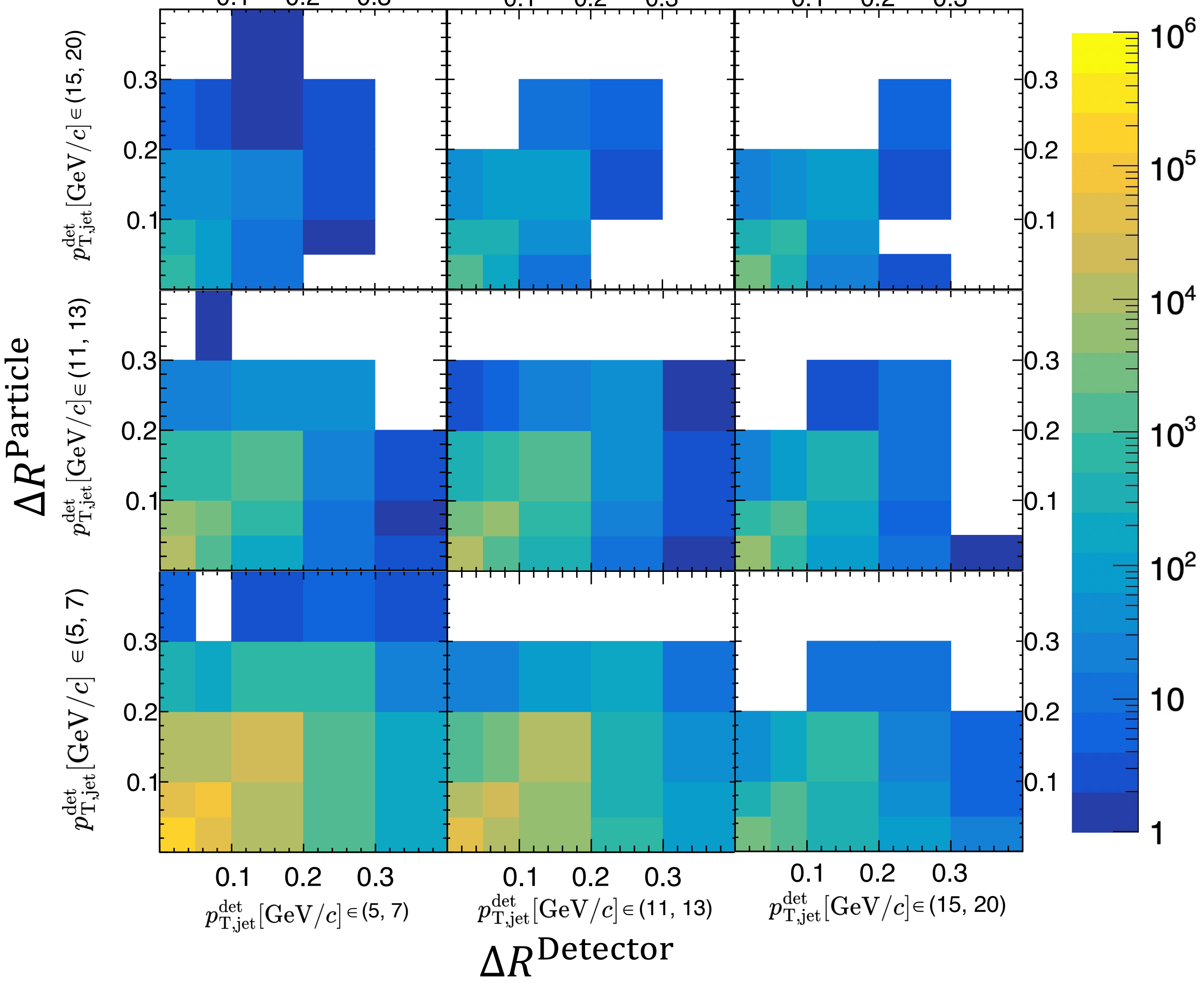
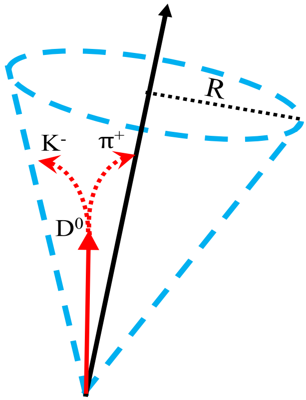


anti-k_T jets with D^0, R = 0.4
$|\eta_{\mathrm{jet}}| < 0.6$
$p_{\mathrm{T,const}} > 0.2$ GeV/c
$p_{\mathrm{T,jet}} > 3$ GeV/c
$5 < p_{\mathrm{T,K\pi}} < 10$ (GeV/c)

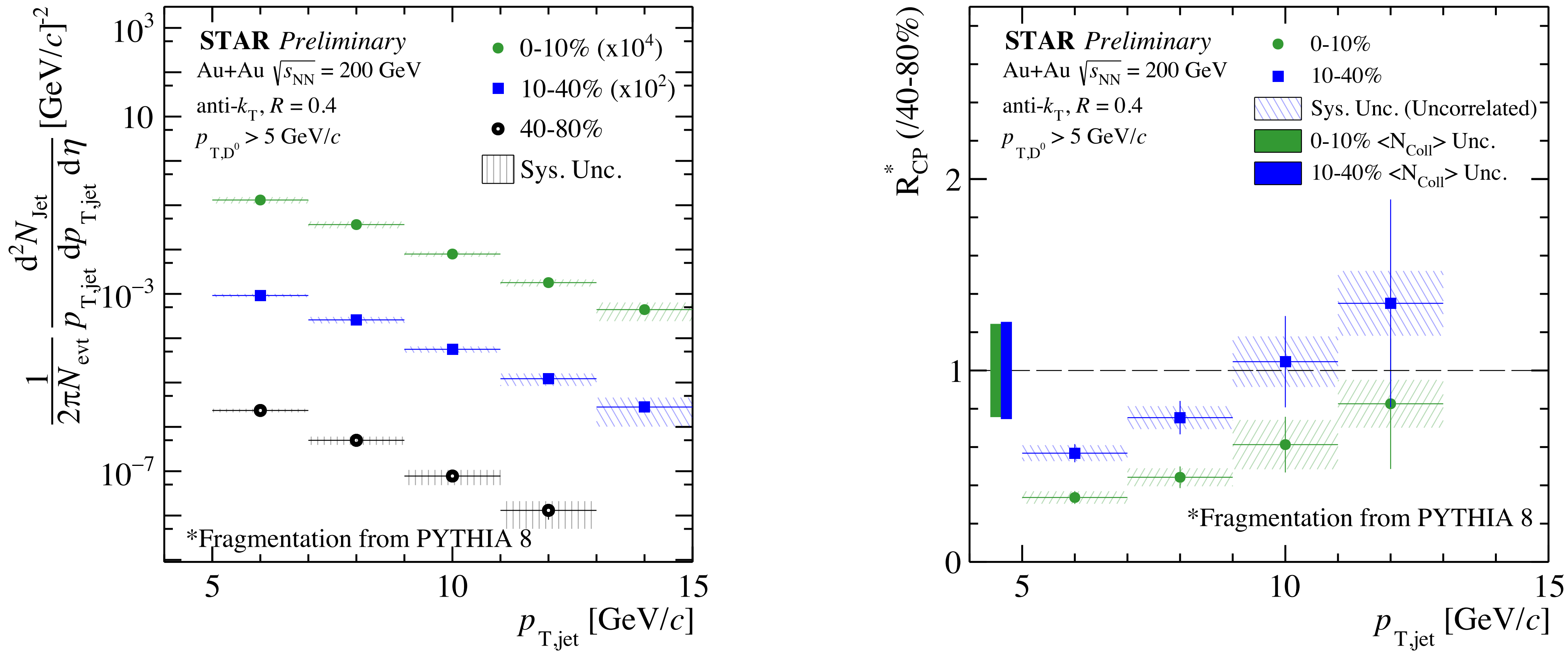
$\sqrt{s}$ = 200 GeV p+p
PYTHIA 8 + GEANT 3
Au+Au Heavy Ion Background

Final 2D response matrix to unfold ΔR



Jet Spectra

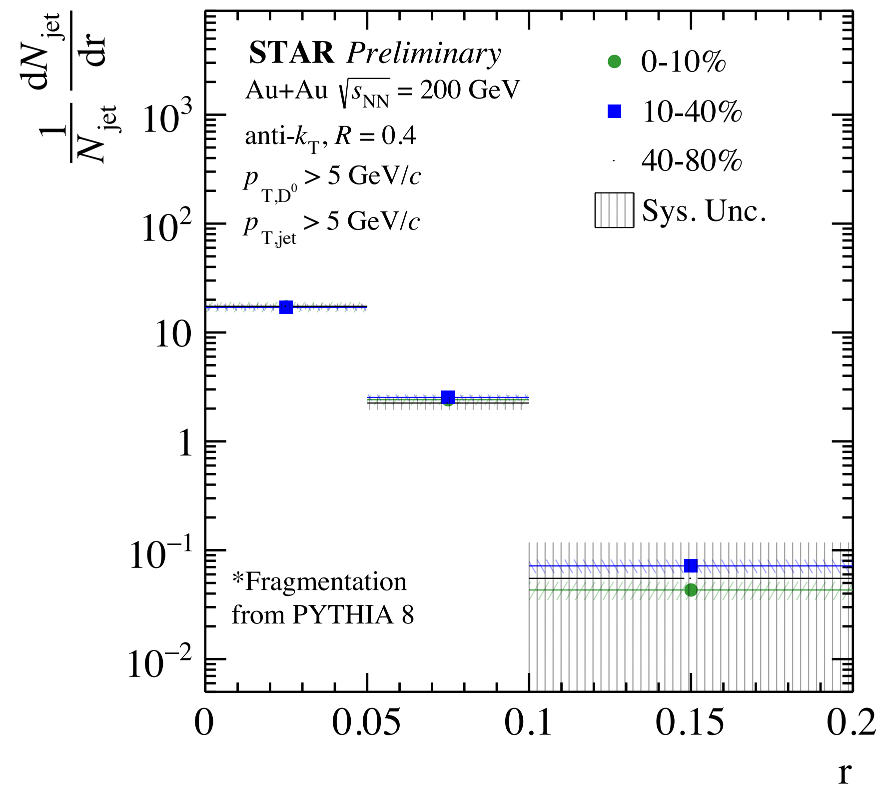
New For QM22

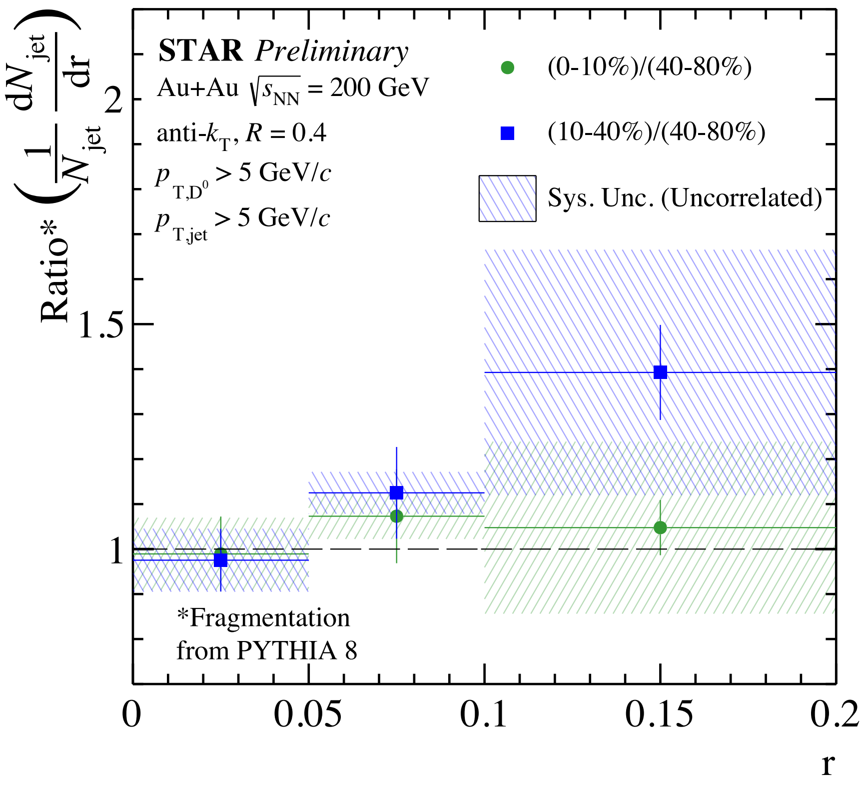


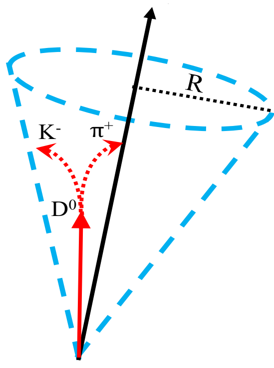
- Most central spectrum is more suppressed than mid-central
- R_{CP} for both central and mid-central show an increasing trend with $p_{T,jet}$
- Peripheral has limited statistics with the D^0 p_T selections
- Baseline p+p measurements for R_{AA} calculation at STAR would be beneficial

Radial Distribution of D⁰ Mesons in Jets

New For QM22





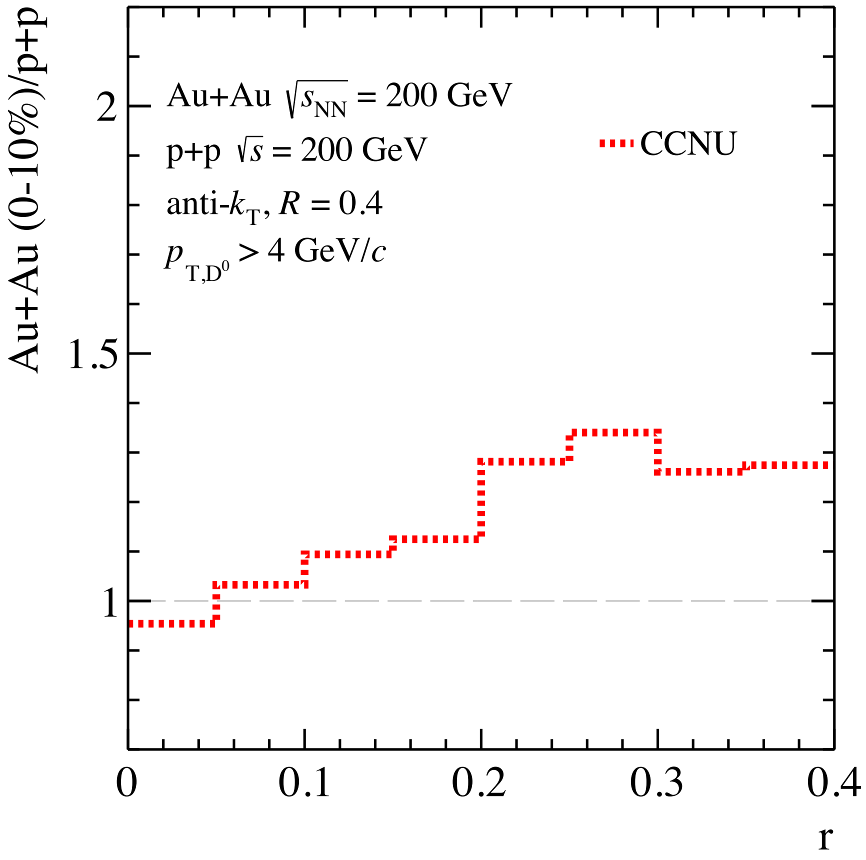


- For D^0 $p_T > 5$ GeV/c, the ratio of radial distributions is consistent with unity within uncertainties
- Extending the analysis to lower D^0 kinematics is essential to draw conclusions about D^0 diffusion

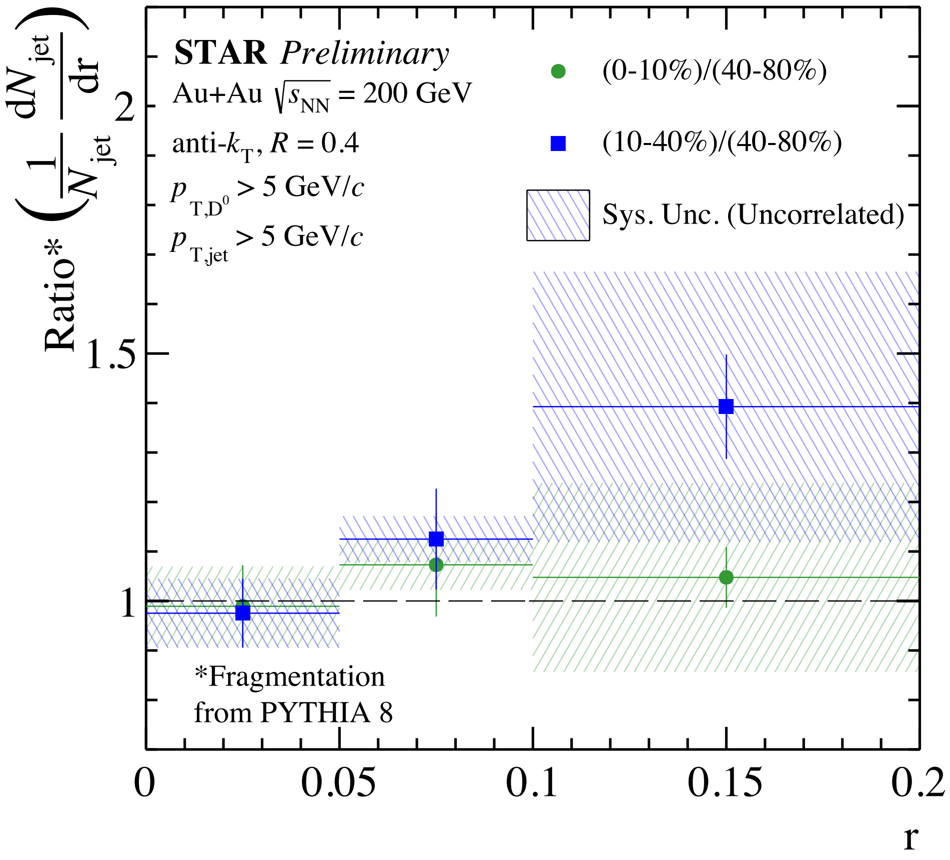
Ratio of Radial Distributions

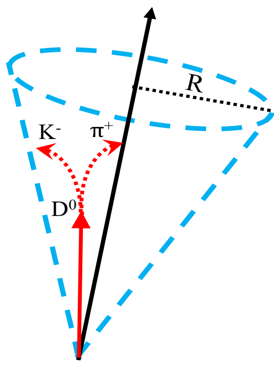
New For QM22

Eur. Phys. J. C79 (2019) 789



Note: calculation uses *p+p* as reference

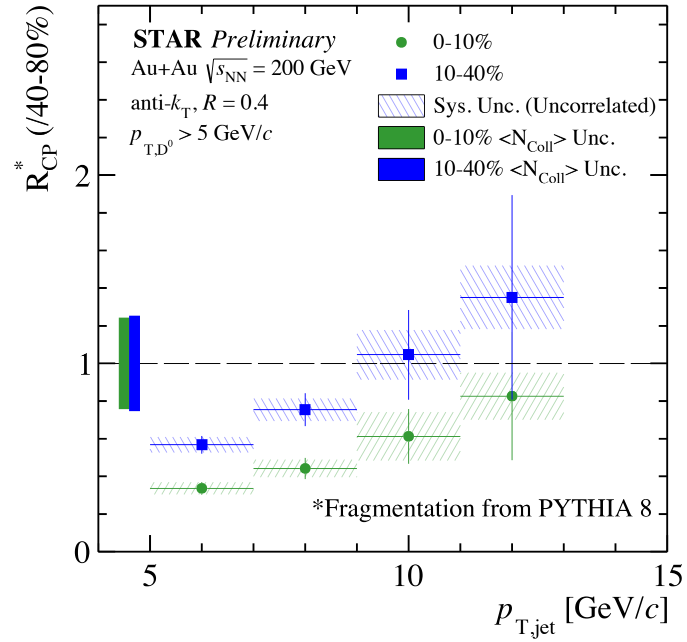


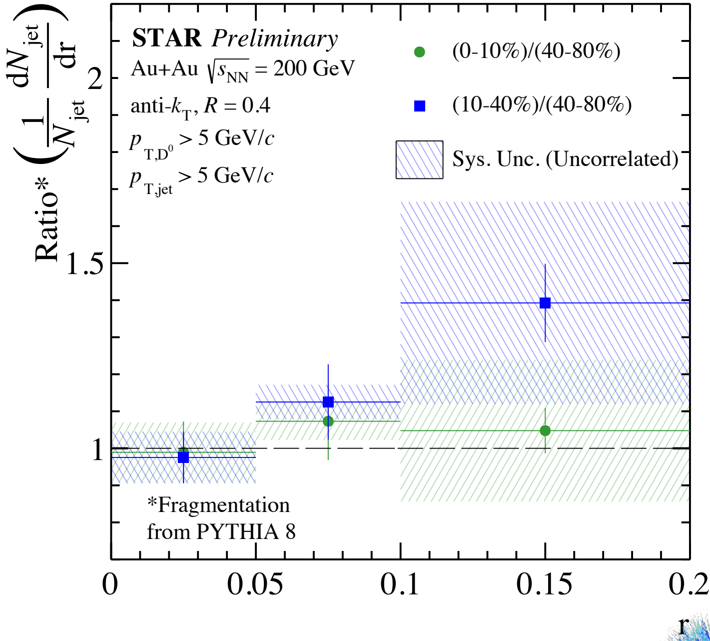


Theory calculation shows slight trend of diffusion - consistent with data within large uncertainties

Summary

- First charm tagged-jet measurement at RHIC energies
- Spectra for D^0-jets in central and mid-central events suppressed with respect to peripheral in the $p_{T,jet}$ range of 5-9 GeV/c
- Radial distribution of D^0 mesons in jets consistent with unity, within uncertainties.





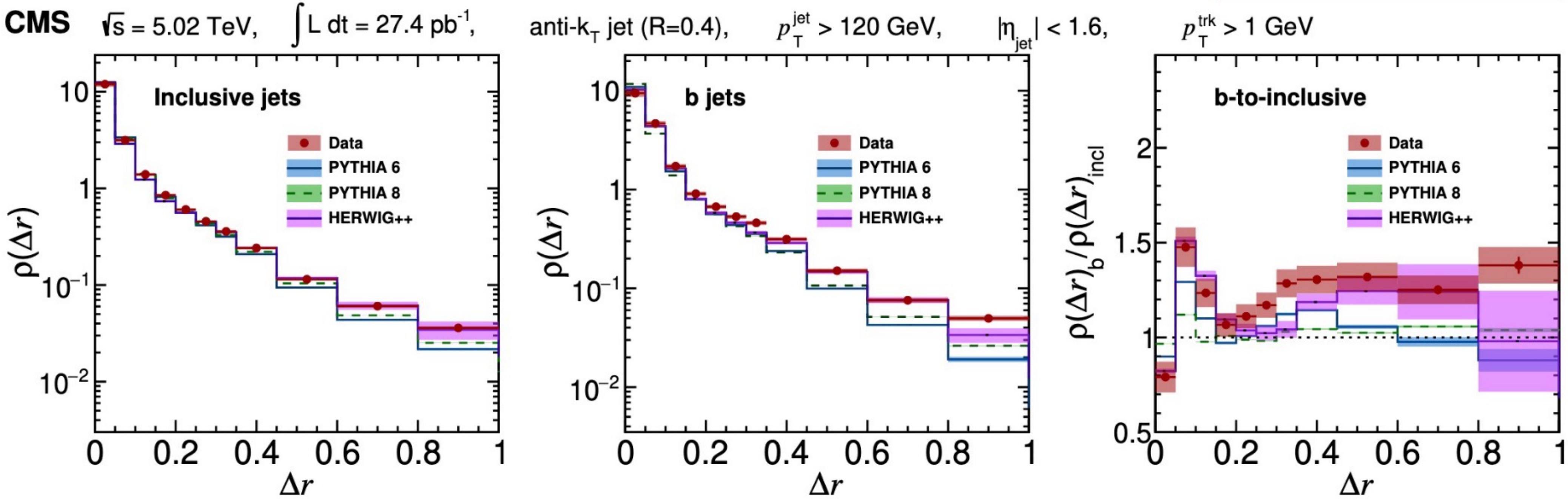
Outlook

- Study the dependence of the observables on the fragmentation function of heavy quarks in simulation
- Explore low D^0 p_T ranges to extend kinematic acceptance

Backup

Differential jet shape for heavy quark in vacuum

CMS, JHEP05 (2021) 054

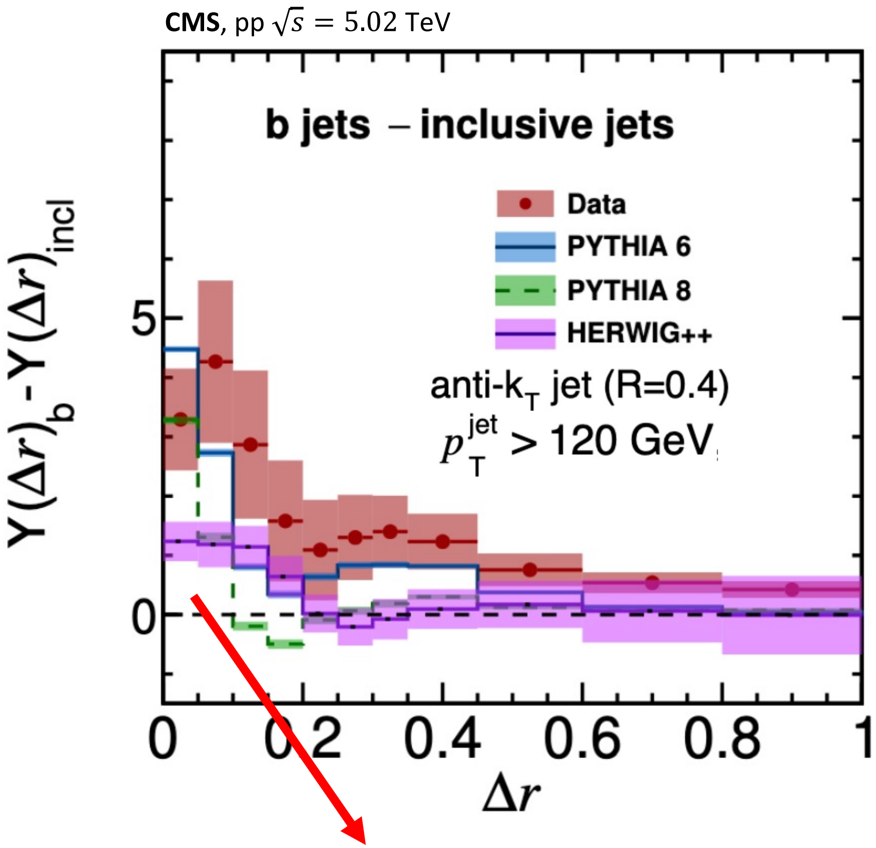


Bottom quark jet (b-jets) shapes modified in vacuum, possibly due to dead cone

Fragmentation pattern for heavy quark

CMS, JHEP05 (2021) 054

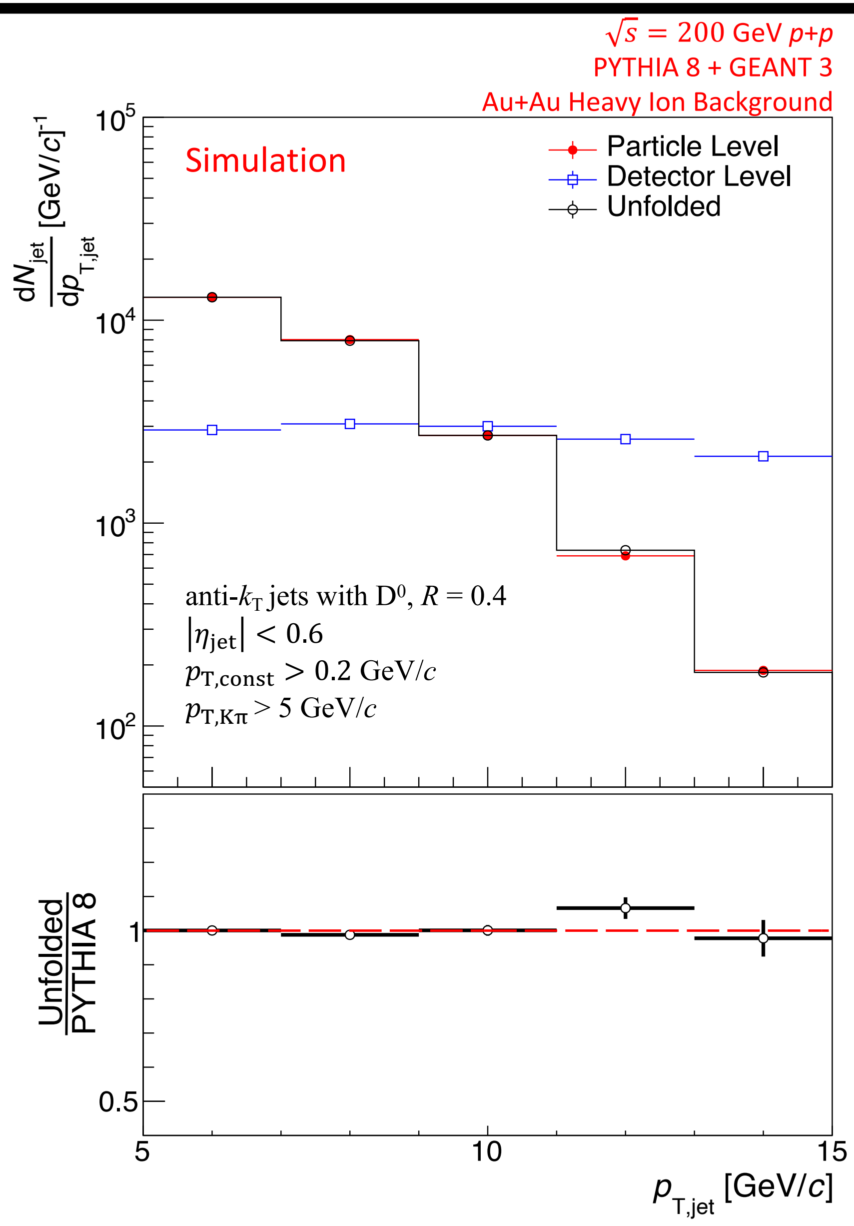
$$Y(\Delta r) = \frac{1}{N_{\rm jet}} \frac{{\rm d}^2 N_{\rm track}}{{\rm d}\Delta r {\rm d}p_{\rm T,track}}$$

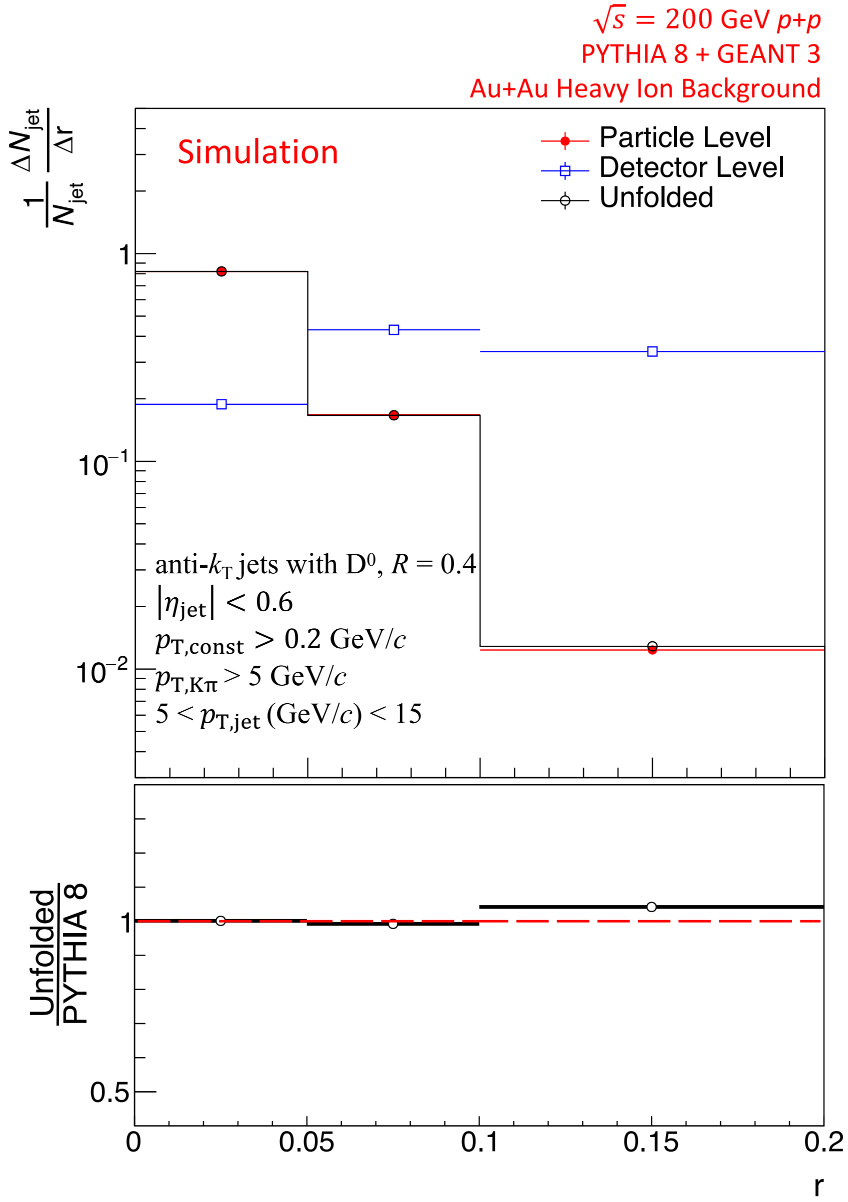


Higher yields of low p_T charged-particle close to jet axis in b-Jets vs inclusive jets in vacuum

~ Different fragmentation pattern for heavy quarks

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 before unfolding
- Iteration parameter in unfolding