Production of open-charm hadrons in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV measured by the STAR experiment

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OUTLINE

INTRODUCTION

- Motivation for open-charm hadron measurements in heavy-ion collisions

OPEN-CHARM MEASUREMENT ($D^{\pm}$ AS AN EXAMPLE)

- STAR detector
- Selection criteria
- Raw yield extraction
- Detector efficiency and acceptance

RESULTS

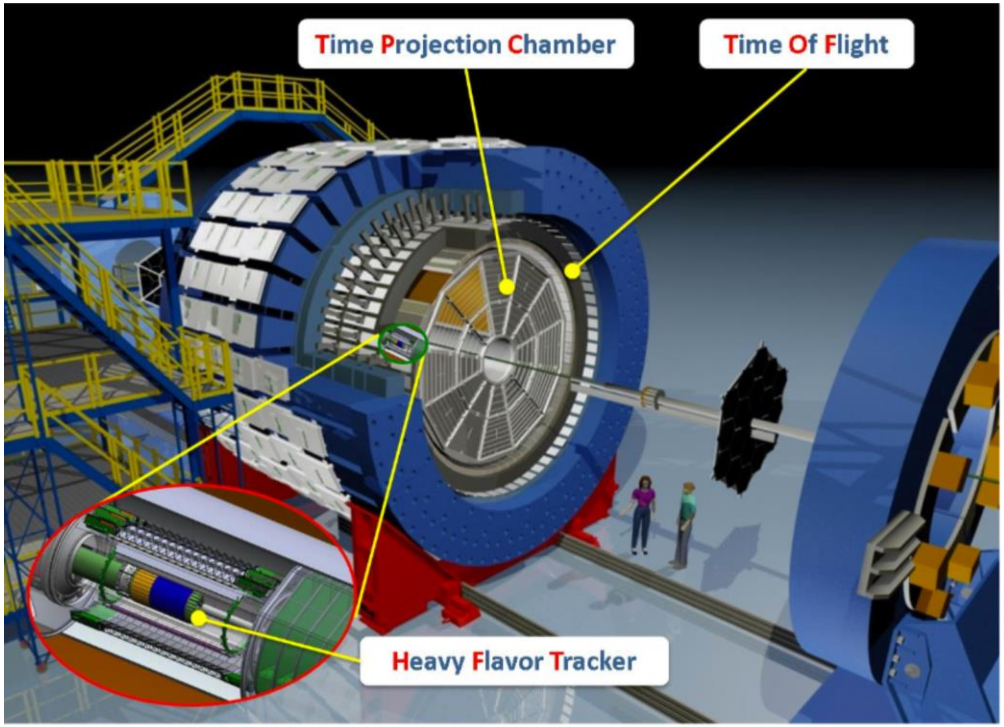
- $D^{\pm}$ and D^0 nuclear modification factor
- D_s nuclear modification factor and D_s/D^0 ratio
- Λ_c/D^0 ratio

PHYSICS MOTIVATION

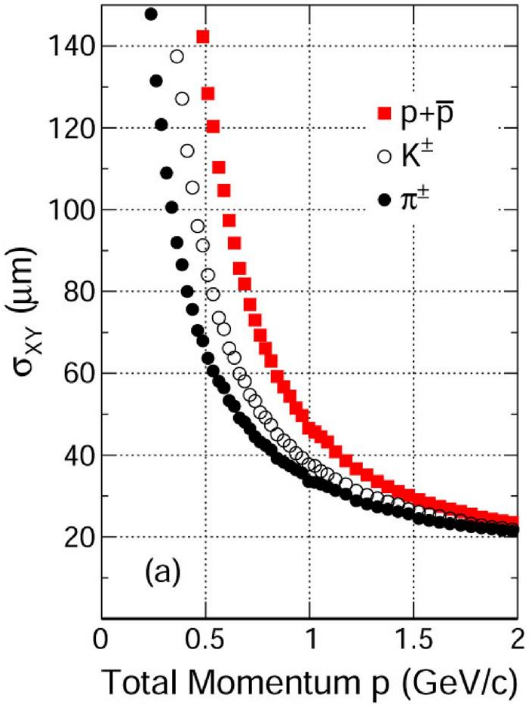
- At RHIC energies, charm and bottom quarks are produced predominantly through partonic hard scatterings at early stage of the A+A collisions
  - They experience the whole evolution of the system which makes them excellent probe to the QGP
  - Observed open-charm hadrons come primarily from hard charm quarks or decays of b-hadrons
- Study of multiple open-charm hadron species in A+A collisions is essential for understanding the production of charm quarks and their interaction with the QGP medium
  - **Energy loss in the medium**
    - $\mathbf{D^0}$, $\mathbf{D^\pm}$
  - **Hadronization**
    - $\mathbf{D_s}$, $\mathbf{\Lambda_c}$

STAR DETECTOR

- **S**olenoidal **T**racker **At** **R**HIC
- **Heavy Flavor Tracker** (HFT, 2014–2016) is a 4-layer silicon detector
  - MAPS – 2 layers, Strip detectors – 2 layers
- **Time Projection Chamber** (TPC) and **Time Of Flight** (TOF)
  - Particle momentum (TPC) and identification (TPC and TOF)

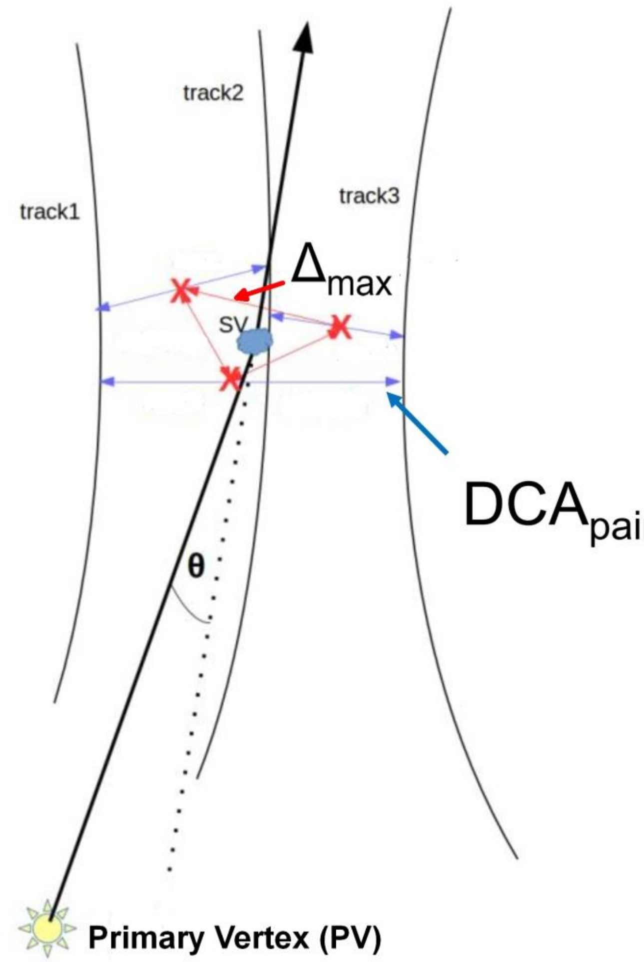


PRL 118 212301 (2017)



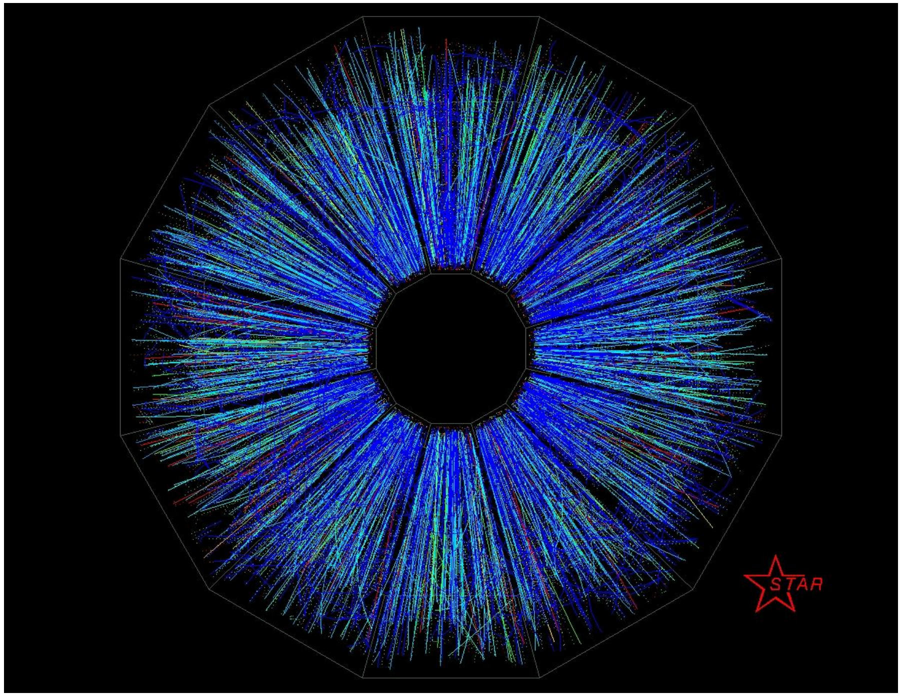
OPEN-CHARM MEASUREMENTS WITH THE HFT

- Decay channels used:
  - $D^+ \rightarrow K^-\pi^+\pi^+$, $c\tau$ = (311.8 ± 2.1) μm, BR = (9.46 ± 0.24) %
  - $D^0 \rightarrow K^-\pi^+$, $c\tau$ = (122.9 ± 0.4) μm, BR = (3.93 ± 0.04) %
  - $D_s^+ \rightarrow K^-K^+\pi^+$, $c\tau$ = (149.9 ± 2.1) μm, BR = (5.45 ± 0.17) %
  - $\Lambda_c^+ \rightarrow K^-\pi^+p$, $c\tau$ = (59.9 ± 1.8) μm, BR = (6.35 ± 0.33) %
- The HFT allows direct topological reconstruction of open-charm hadrons through their hadronic decays
- STAR 2014 and 2016, Au+Au, $\sqrt{s_{NN}}$ = 200 GeV data
  - 2014: ~900M minimum-bias events
  - 2016: ~1.3B minimum-bias events



EVENT AND TRACK SELECTION

- Event selection cuts
  - Position of primary vertex along the beam axis
- Track quality cuts
  - p_T – suppresses combinatorial background from low p_T particles
  - $|\eta| < 1$ – detector acceptance
  - Minimum number of hits in the TPC for each track – good track quality
- Particle identification (PID)
  - TPC – energy loss of charged particles in the TPC gas
  - TOF – velocity of the charged particles
- Topological cuts
  - Possible only with use of the HFT
  - Constrain topology of the reconstructed secondary vertex
  - Suppress combinatorial background



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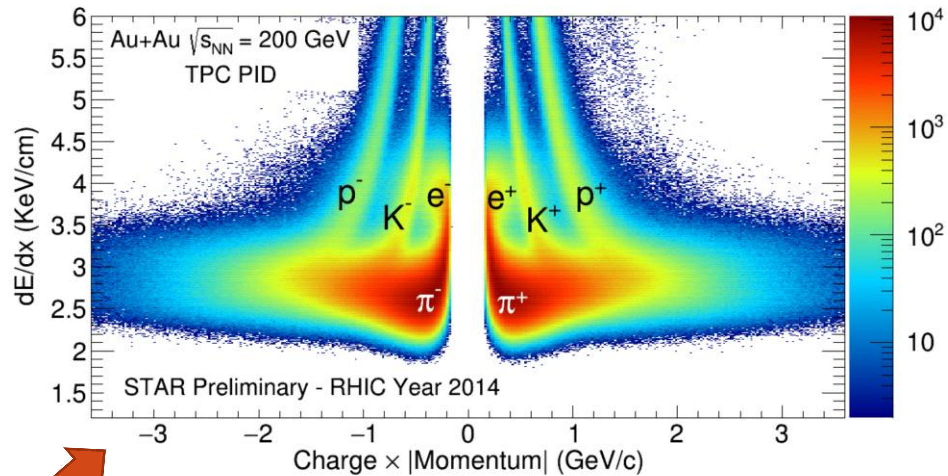

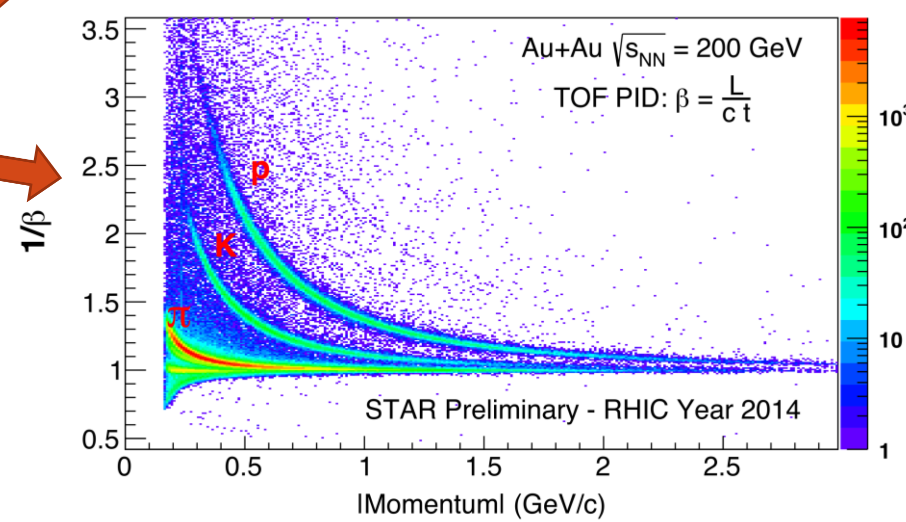

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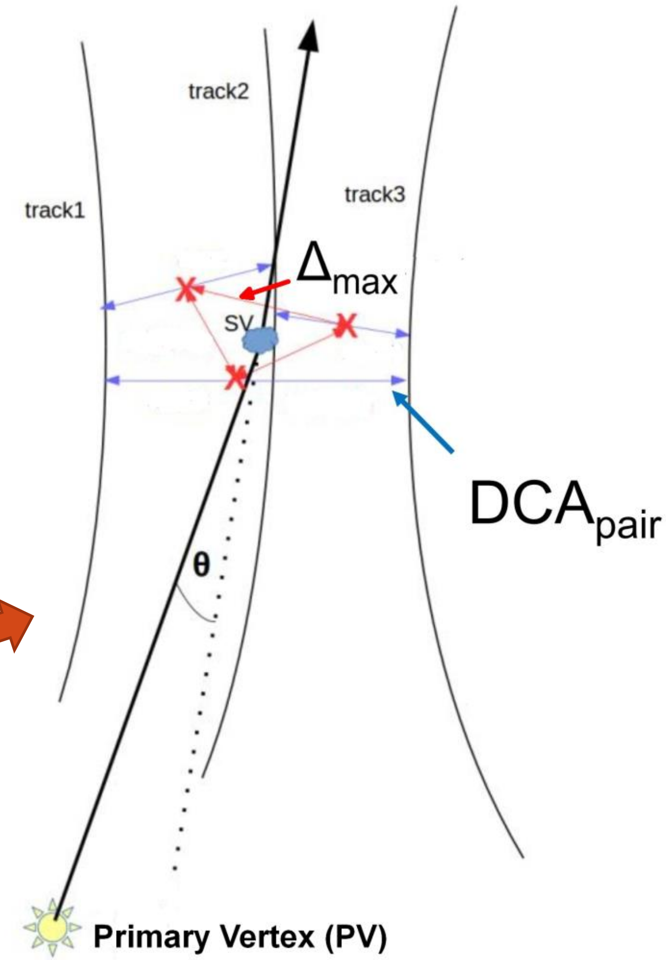
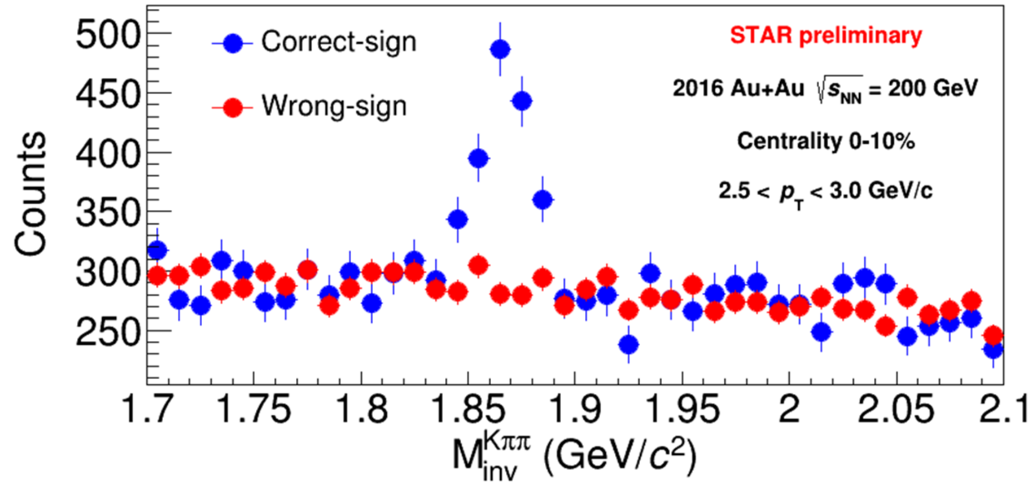
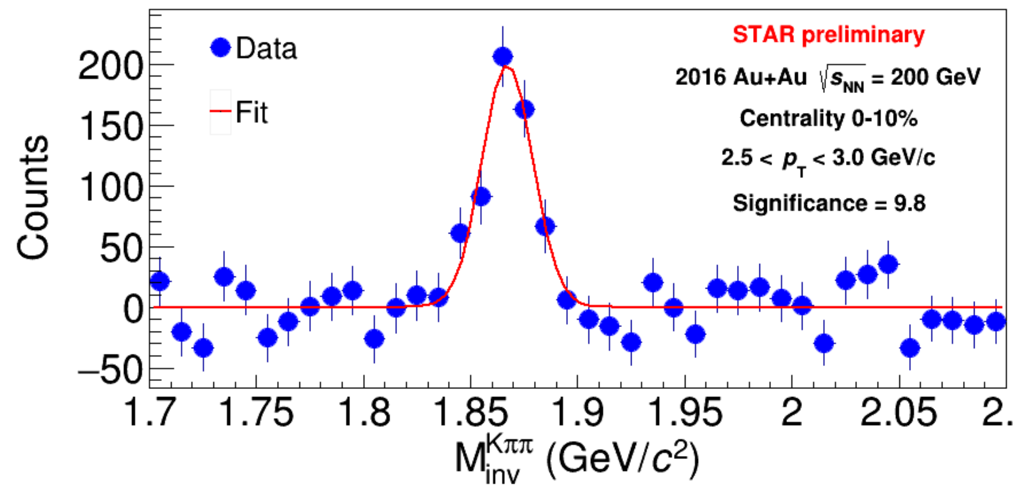


RAW YIELD EXTRACTION

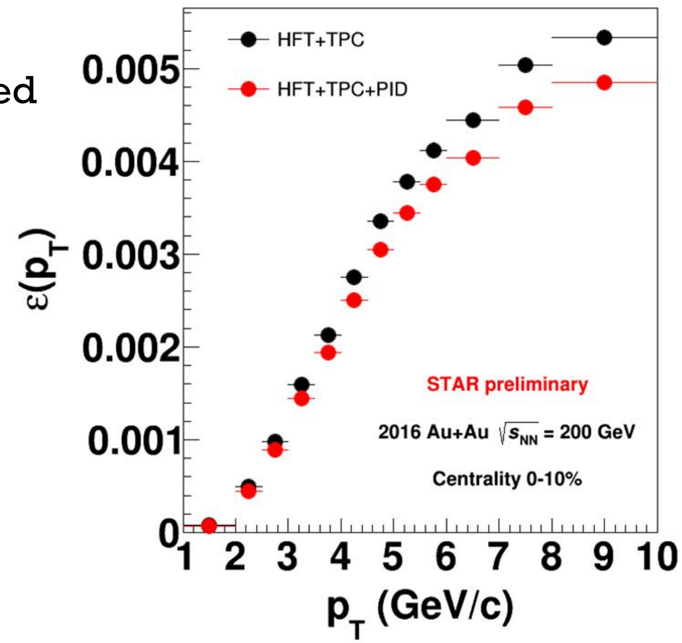
- $D^{\pm}$ signal is extracted from $K\pi\pi$ invariant mass $M_{\rm inv}^{K\pi\pi}$ spectrum
- Background: wrong-sign spectrum scaled using regions outside the mass peak
- The raw yield $Y_{\rm raw}$ is calculated by the bin-counting method in $\pm 3\sigma$ region





DETECTOR AND ACCEPTANCE CORRECTIONS

- **HFT+TPC efficiency** determined by data-driven fast-simulator with inputs from data and TPC embedding
  - $D^{\pm}$ are decayed by PYTHIA
  - Detector efficiency and resolution effects are applied to the $D^{\pm}$ decayed daughters:
    - HFT matching efficiency (data)
    - DCA resolution (data)
    - Primary vertex position along beam axis (data)
    - TPC momentum resolution (embedding)
    - TPC tracking efficiency (embedding)
  - Efficiency $\varepsilon(p_T)$ obtained from fraction of simulated $D^{\pm}$ passing the analysis cuts



- **PID efficiency** of TPC and TOF
  - Enriched K sample at low p_T from data using strict TOF or TPC PID cuts
  - Pure π sample obtained by reconstruction of K^0_S

$D^{\pm}$ AND D^{0} NUCLEAR MODIFICATION FACTOR

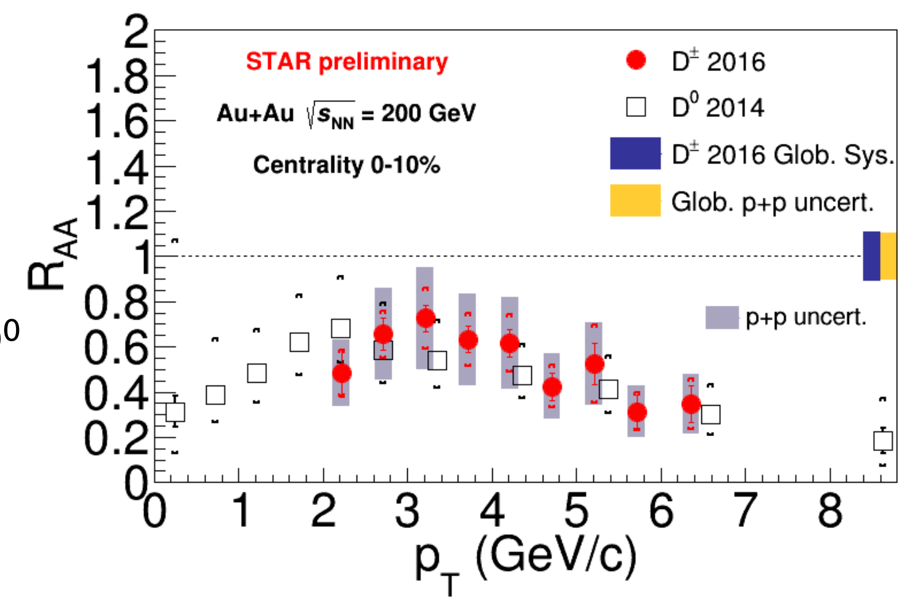
- Invariant yield is calculated according to:

$$\frac{\mathrm{d}^2 N}{2\,\pi\, p_{\mathrm{T}}\;\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{Y_{\mathrm{raw}}}{2\,\pi\, N_{\mathrm{evt}}\, BR\; p_{\mathrm{T}}\Delta p_{\mathrm{T}}\Delta y\; \varepsilon(p_{\mathrm{T}})}$$

- Nuclear modification factor:

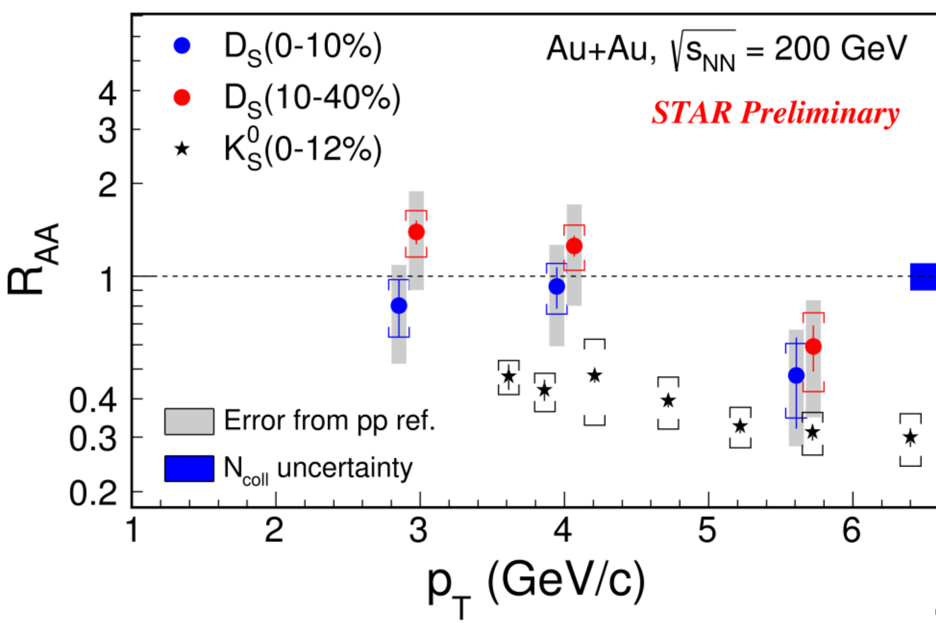
$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{D}}^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle\,\mathrm{d}N_{\mathrm{D}}^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

- High-p_{T} $D^{\pm}$ and D^{0} suppressed in central Au+Au collisions
  - Strong interactions between charm quarks and the medium
- Similar level of suppression for $D^{\pm}$ and D^{0}
- Reference: combined D^{0} and D* measurement in 200 GeV p+p collisions using 2009 data

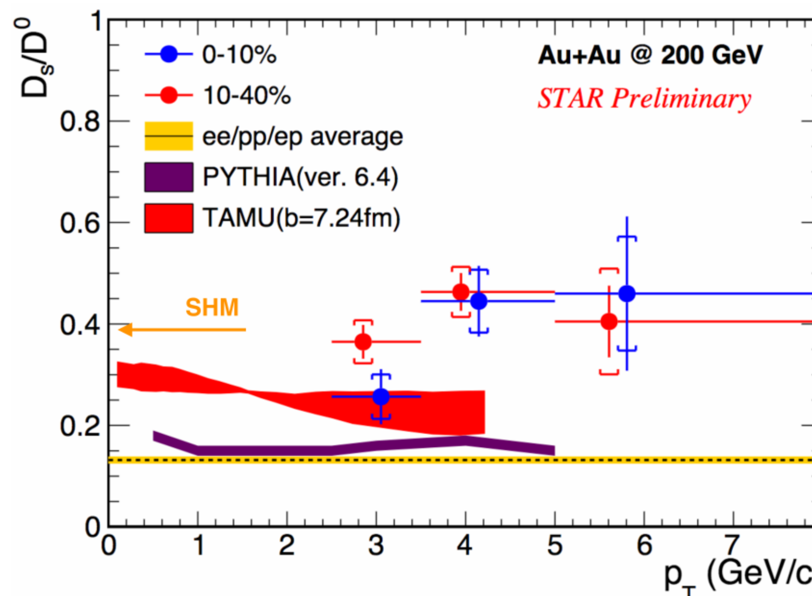


STRANGENESS ENHANCEMENT VIA D_s

- $R_{AA}(p_T)$ of D_s and K^0_S for different collision centralities
- Indication of smaller suppression of D_s than that of K^0_S
  - Suppression of D^0 and $D^\pm$ is comparable to that of K^0_S
  - Possibly due to coalescence



- D_s/D^0 ratio as a function of p_T
- Enhancement of D_s/D^0 ratio in A+A collisions with respect to PYTHIA and elementary collisions (ee/pp/ep)
- TAMU underpredicts measurements
- Reasonable agreement with SHM



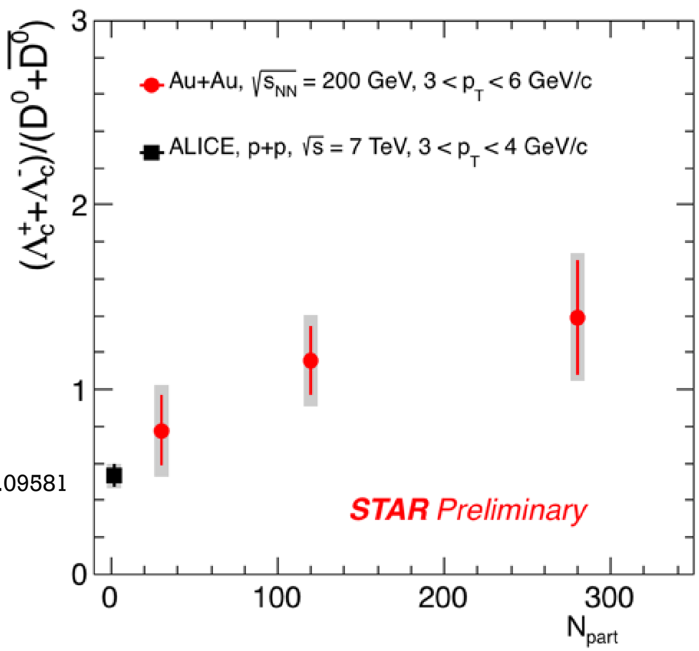
ep/pp/ep avg: EPJ C 76, 397 (2016)
TAMU: PRL 110, 112301 (2013)
SHM: Phys.Rev.C 79 (2009) 044905

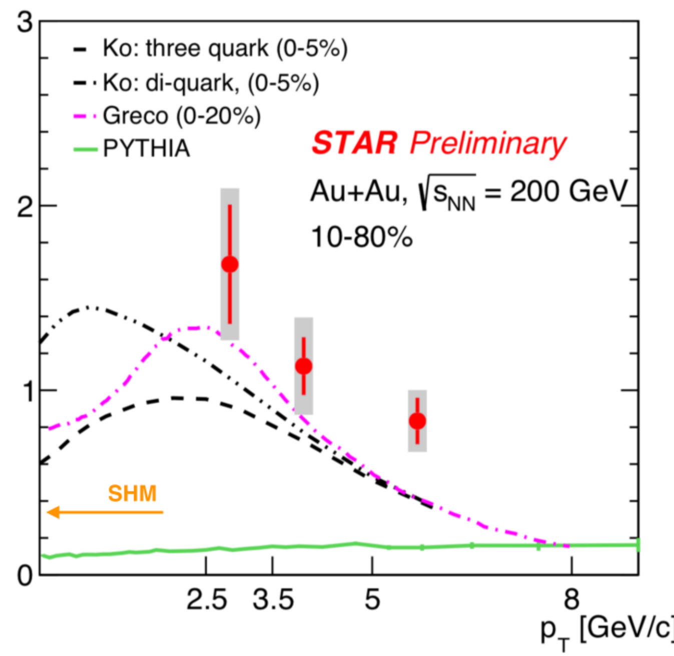
OPEN-CHARM BARYON/MESON RATIO

- Λ_c/D^0 ratio as a function of collision centrality
- Enhancement of the ratio increases towards central collisions and the value in peripheral collisions is consistent with p+p measurement by ALICE
- Due to effects of the QGP

- Λ_c/D^0 ratio as a function of transverse momentum
- Decreases with p_T
- Coalescence models closer to data than PYTHIA
- SHM underestimates measurements

ALICE: arXiv:1712.09581





Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905

CONCLUSION

- STAR extensively studies production of open-charm hadrons
  - Outstanding spatial resolution of the STAR HFT allows precise measurements of open-charm hadrons
  - Presented results provide significant constraints on model calculations
- Open-charm mesons are significantly suppressed in central A+A collisions
  - Important for understanding charm quark energy loss in the QGP
- Indication of D_s/D^0 enhancement in A+A collisions with respect to p+p collisions
  - Important for understanding hadronization process
- Λ_c/D^0 is enhanced in A+A collisions with respect to p+p collisions
  - Important for understanding hadronization process and baryon-to-meson ratio enhancement
  - Coalescence plays an essential role for charm quark hadronization in the QGP

OUTLOOK

- Development of KF Particle Finder
  - New, alternative, method for reconstruction of short-lived particles
  - Main advantages:
    - Better background rejection – higher significance of a signal
      - Ideal for rare particles or rare decay channels, inaccessible with standard method
    - Relatively fast with respect to the standard method
    - Possible to implement many particle species (open-charm, open-bottom, quarkonia, strangeness, hypernuclei, etc.) and reconstruct them at once

- Open charm production is also studied in d+Au and p+Au collisions at STAR with the HFT
  - Important for understanding Cold Nuclear Matter effects

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BACKUP

EVENT AND TRACK SELECTION, PID

STAR

- Example of analysis cuts for $D^{\pm}$ reconstruction using the HFT
- Event selection cuts
  - Position of primary vertex along the beam axis
- Track quality cuts
  - p_{T} – suppresses combinatorial background from low p_{T} particles
  - nHitsFit – large number of TPC hits used for track reconstruction to ensure good track quality
- PID: HFT+TPC+(TOF)
  - Hybrid TOF = use TOF only for tracks with valid TOF information
- Topological cuts
  - Possible only with use of the HFT
  - Constrain topology of the reconstructed secondary vertex
  - Suppress combinatorial background

Event selection cuts		$\|V_z\| < 6$ cm
		$\|V_z - V_{z(VPD)}\| < 3$ cm
Track quality cuts		$p_T > 500$ MeV/c
		$\|\eta\| < 1$
		nHitsFit > 20
		nHitsFit/nHitsMax > 0.52
PID cuts	TPC	$\|n\sigma_{\pi}\| < 3$
		$\|n\sigma_{K}\| < 2$
	Hybrid TOF	$\|1/\beta - 1/\beta_{\pi}\| < 0.03$
		$\|1/\beta - 1/\beta_{K}\| < 0.03$
Topological cuts		$DCA_{pair} < 80$ μm
		30 μm $< ct_{D\pm} < 2000$ μm
		$\cos(\vartheta) > 0.998$
		$\Delta_{max} < 200$ μm
		$DCA_{\pi\text{-}PV} > 100$ μm
		$DCA_{K\text{-}PV} > 80$ μm