Measurement of open-charm hadron production in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV with the STAR experiment

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Operational Programme Research,
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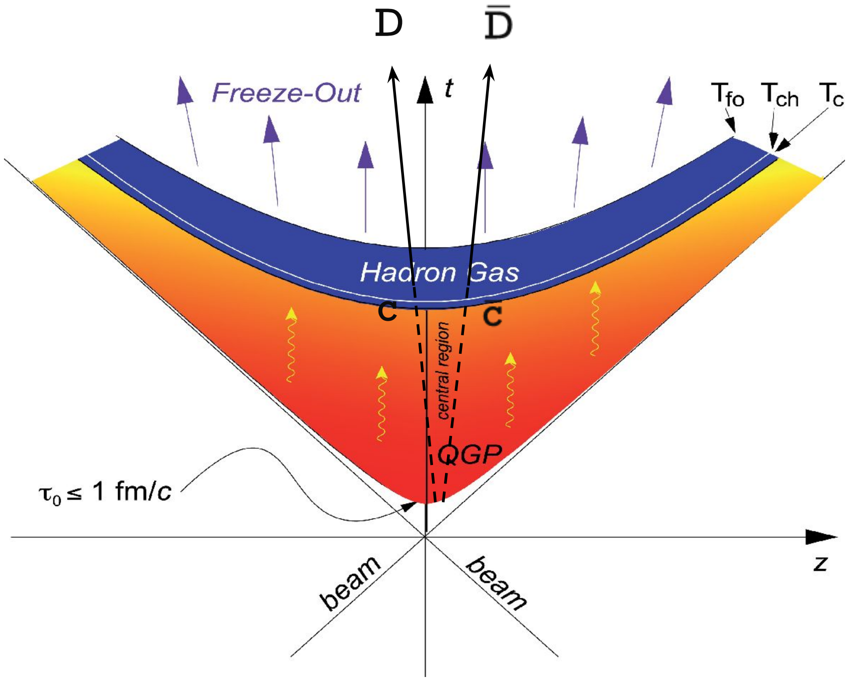
MINISTRY OF EDUCATION,
YOUTH AND SPORTS

PHYSICS MOTIVATION

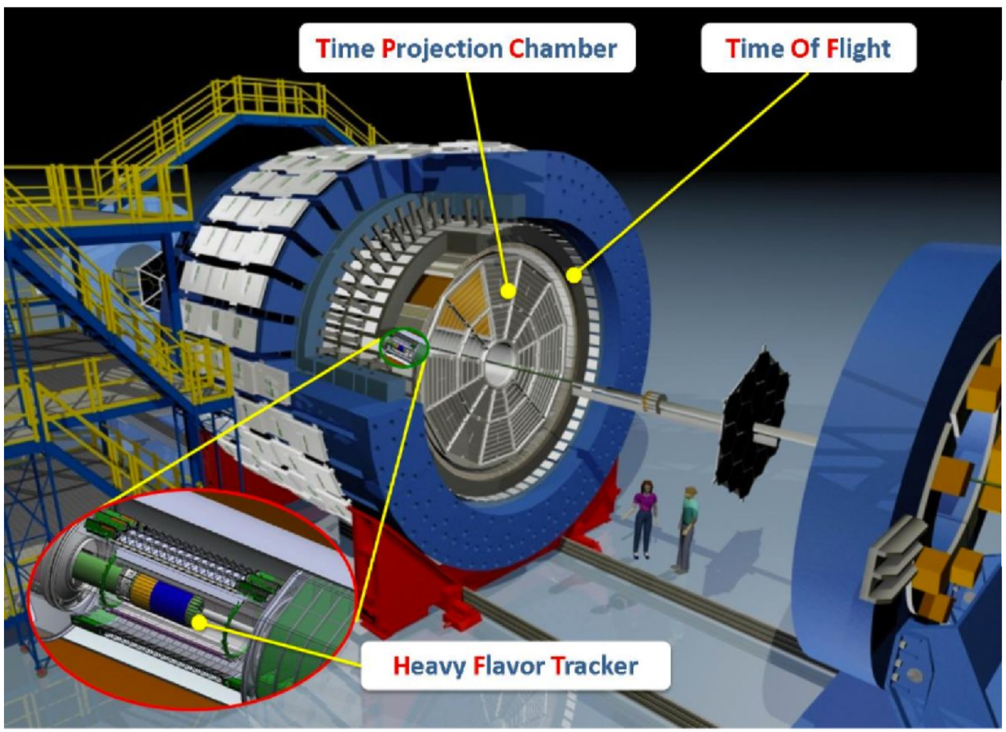
- In Au+Au collisions at RHIC energies, **charm quarks** are produced predominantly through initial hard partonic scatterings
  - They experience **entire evolution** of medium

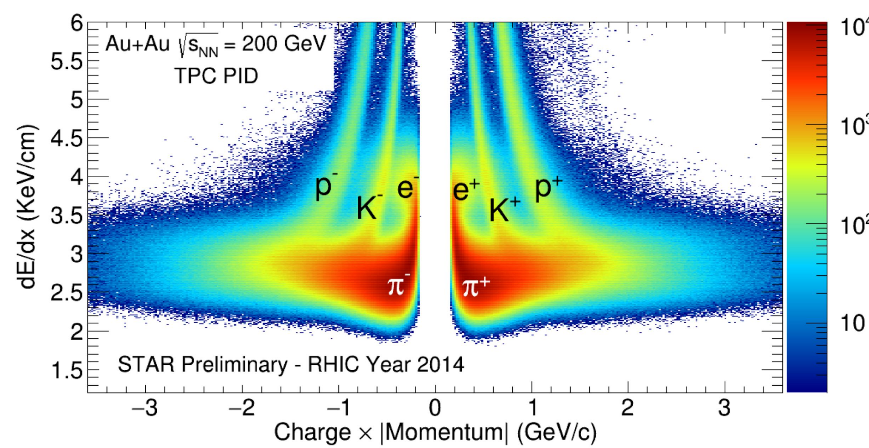
- Open-charm hadron measurements study:
  - **Charm quark energy loss in medium**
    - **D^0 and $D^{\pm}$ nuclear modification factor**
  - **Charm quark transport in medium**
    - **D^0 elliptic and triangular flow**
  - **Charm quark hadronization process**
    - **D_s/D^0 and Λ_c/D^0 yield ratio**
  - **Initial tilt of bulk + initial electromagnetic field**
    - **D^0 directed flow**



STAR DETECTOR

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





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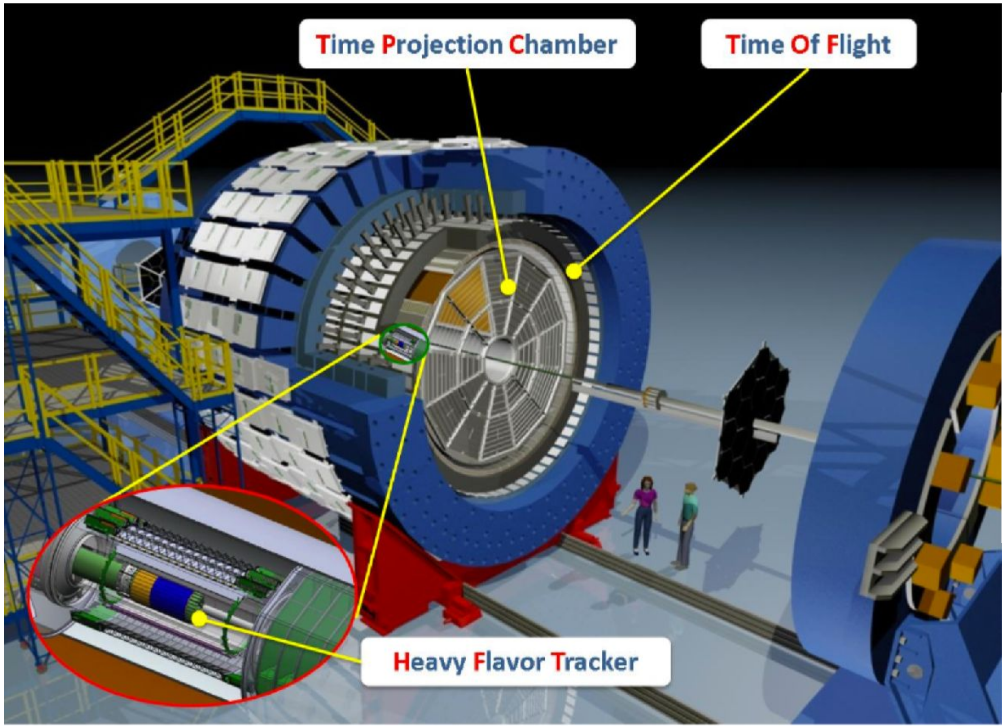

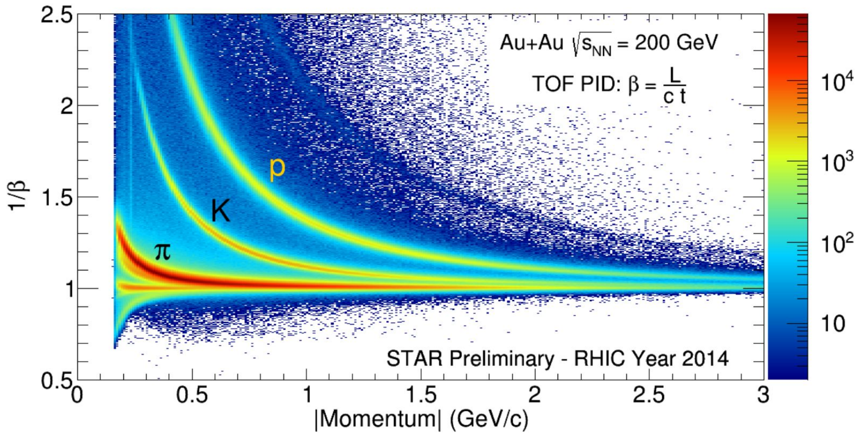

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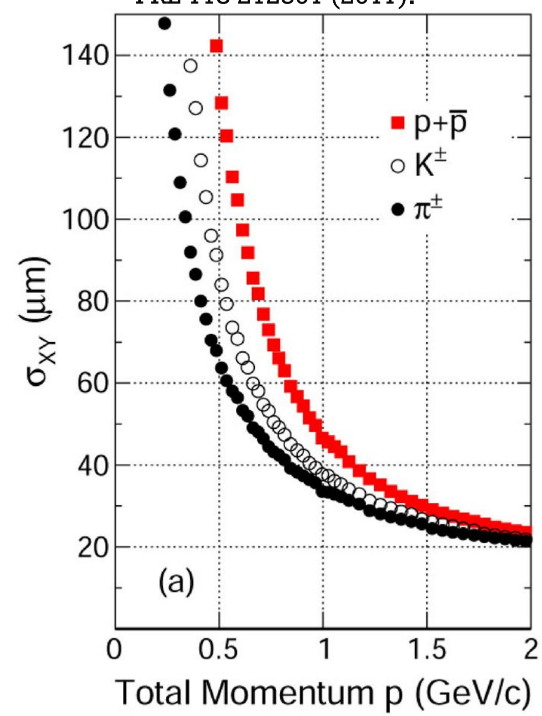
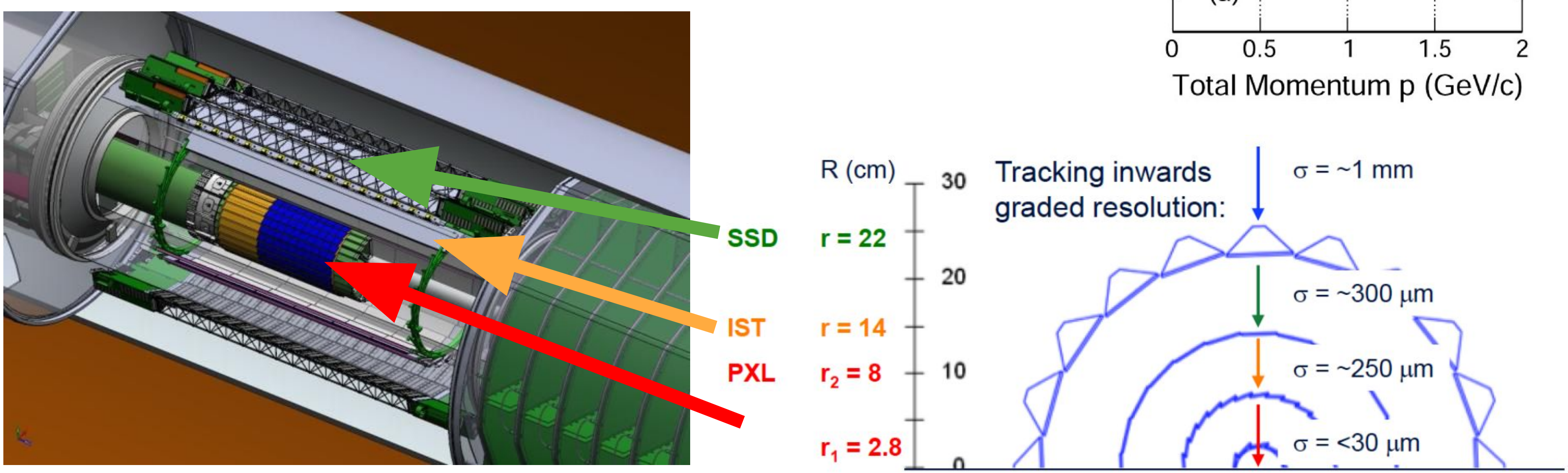
PRL 118 212301 (2017).



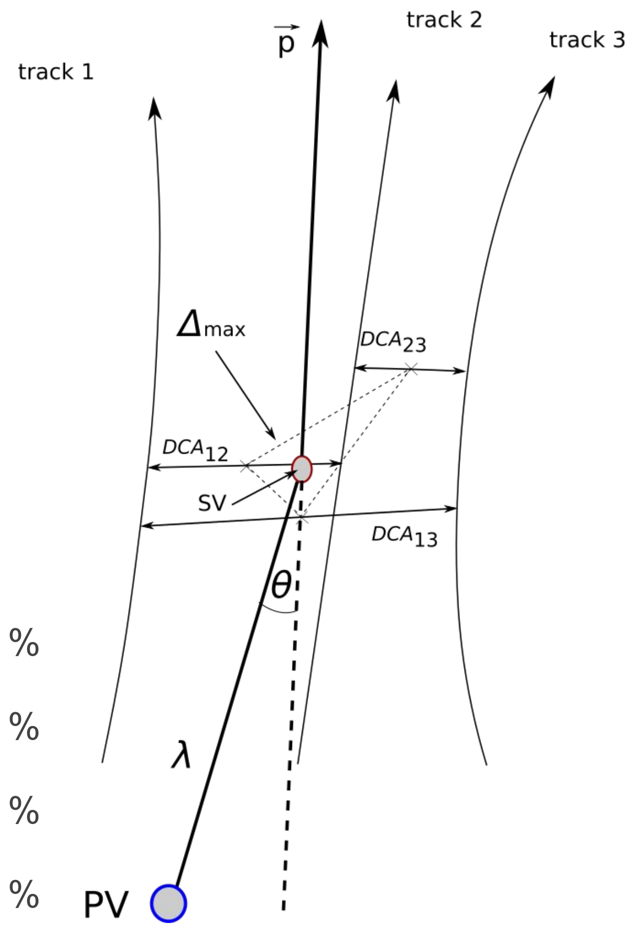


OPEN-CHARM HADRON RECONSTRUCTION

- Data from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV acquired with HFT in years 2014 and 2016
- HFT allows direct **topological reconstruction** of open-charm hadrons via their hadronic decays
- Significant suppression of combinatorial background

- Decay channels used*:
  - $D^+ \rightarrow K^-\pi^+\pi^+$ $c\tau$ = (311.8 ± 2.1) μm BR = (8.98 ± 0.28) %
  - $D^0 \rightarrow K^-\pi^+$ $c\tau$ = (122.9 ± 0.4) μm BR = (3.93 ± 0.04) %
  - $D_s \rightarrow \pi^+\phi$, $\phi \rightarrow K^-K^+$ $c\tau$ = (149.9 ± 2.1) μm BR = (2.27 ± 0.08) %
  - $\Lambda_c \rightarrow K^-\pi^+p$ $c\tau$ = (59.9 ± 1.8) μm BR = (6.35 ± 0.33) %

  *charge conjugates also reconstructed



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

D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
$\pi^\pm$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
h$^\pm$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

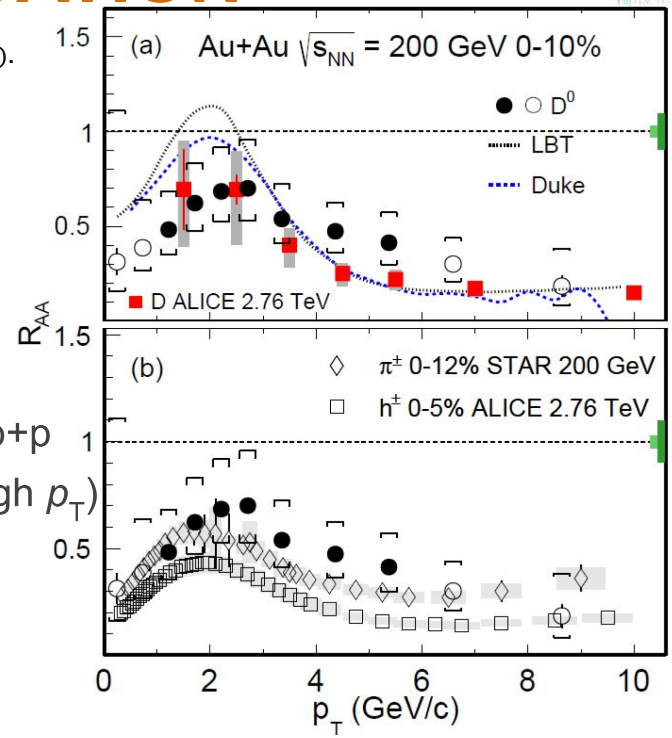
- **Nuclear modification factor:**

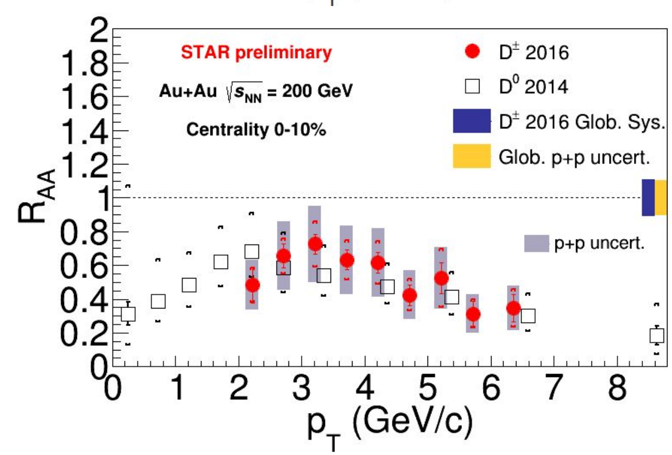
$$R_{AA}(p_T) = \frac{dN_D^{AA}/dp_T}{\langle N_{coll}\rangle dN_D^{pp}/dp_T}$$

- Reference: combined D^0 and D* measurement in 200 GeV p+p collisions using 2009 STAR data (extrapolated to low and high p_T)

- D mesons **suppressed** in central Au+Au collisions
  - Suppression of D^0 mesons at high p_T comparable to light-flavor hadrons at RHIC and D mesons at LHC
  - Reproduced by models incorporating both **radiative and collisional energy losses**
  - Similar level of suppression for D$^\pm$ and D^0

- **Strong interaction between charm quarks and medium**



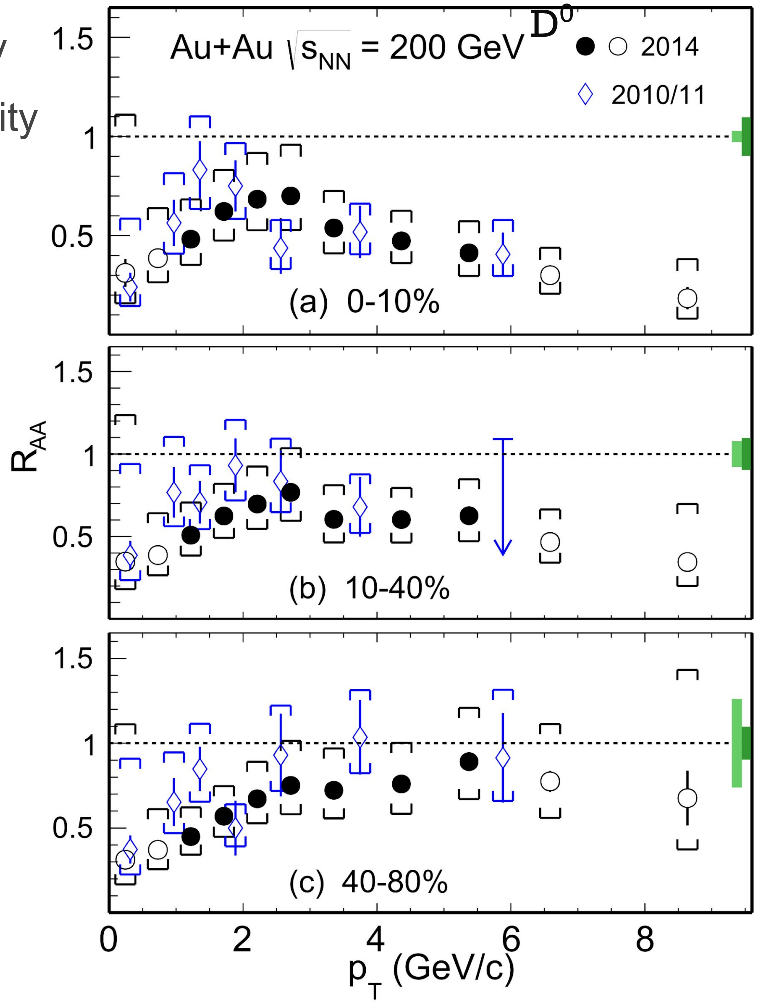


CENTRALITY DEPENDENCE OF D^0 $R_{AA}(p_T)$

- Suppression at high p_T **increases** with collision centrality
- D^0 with p_T < 2.5 GeV/c suppressed for all studied centrality classes of Au+Au collisions

- HFT dramatically **improves precision**
- Systematic errors dominated by p+p reference

D^0 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D^0 2010/11 (STAR): Phys. Rev. C 99, 034908, (2019).

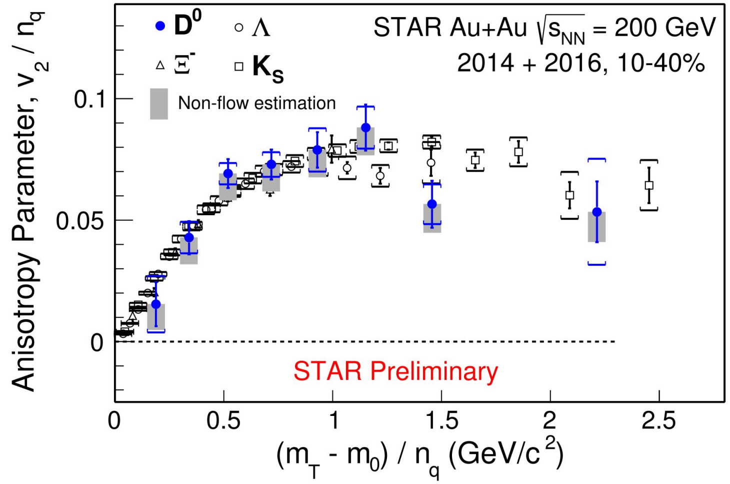


D^0 COLLECTIVE BEHAVIOR

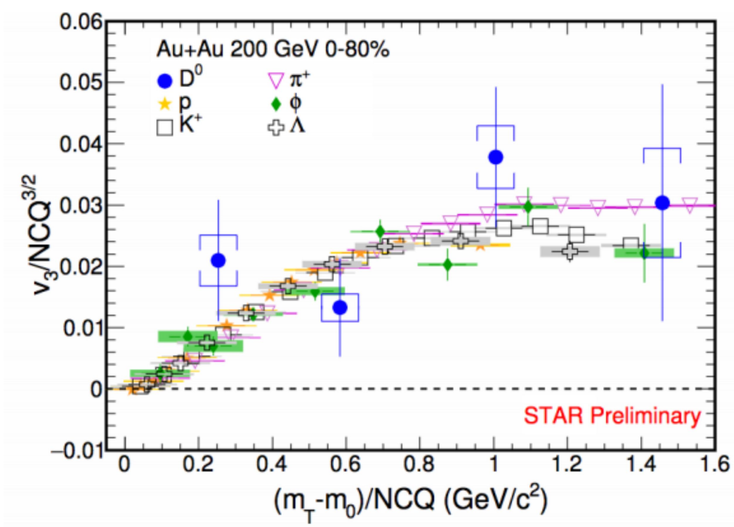
v_2 D^0 (2014): Phys. Rev. Lett, 118, 212301 (2017)
v_2, light flavor: Phys. Rev. C 77, 054901 (2008).

- Elliptic (triangular) flow = second (third) order Fourier coefficient v_2 (v_3) of azimuthal distribution:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_n))\right]$$



- Improved precision from combined 2014+2016 data than published 2014 results
- D^0 v_2 and v_3 follow Number of Constituent Quarks (NCQ) scaling
  - Significant elliptic and triangular flow of D^0
  - Strong **collective behavior** of charm quarks

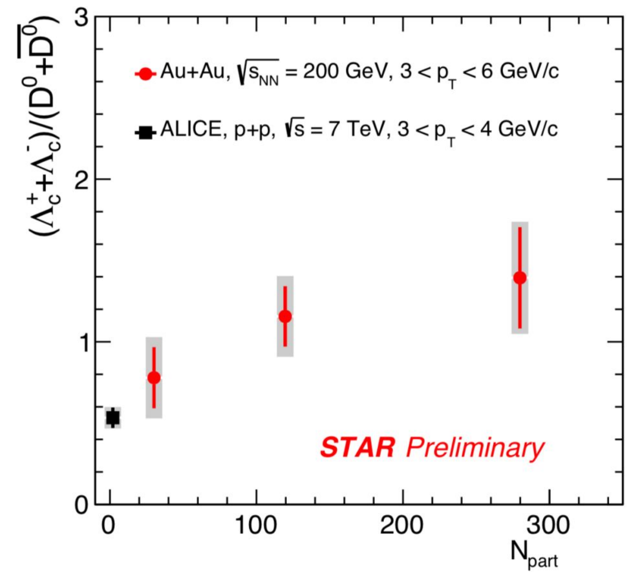


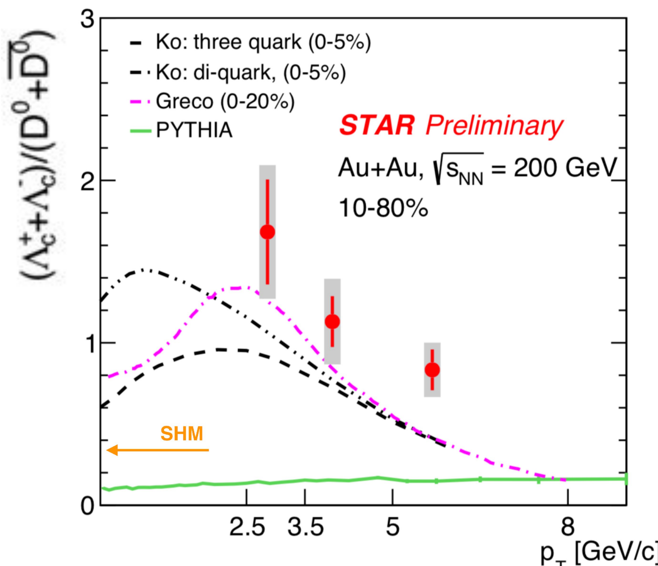
- **Charm quarks may have achieved local thermal equilibrium with QGP**

Λ_c/D^0 YIELD RATIO ENHANCEMENT

ALICE: JHEP 04 (2018) 108
Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys. Lett. B (2003), 571, 36-44

- Open-charm baryon/meson yield ratio
- **Centrality dependence**
  - Enhancement of ratio increases towards central collisions
  - Value in peripheral collisions consistent with ALICE p+p results at √s = 7 TeV
- **p_T dependence**
  - Significant **enhancement** with respect to PYTHIA 6.4 p+p prediction
  - Statistical Hadronization Model (SHM) under-predicts ratio from data extrapolated to zero p_T
  - Coalescence models closer to data than PYTHIA
  - **Importance of coalescence hadronization of charm quarks**

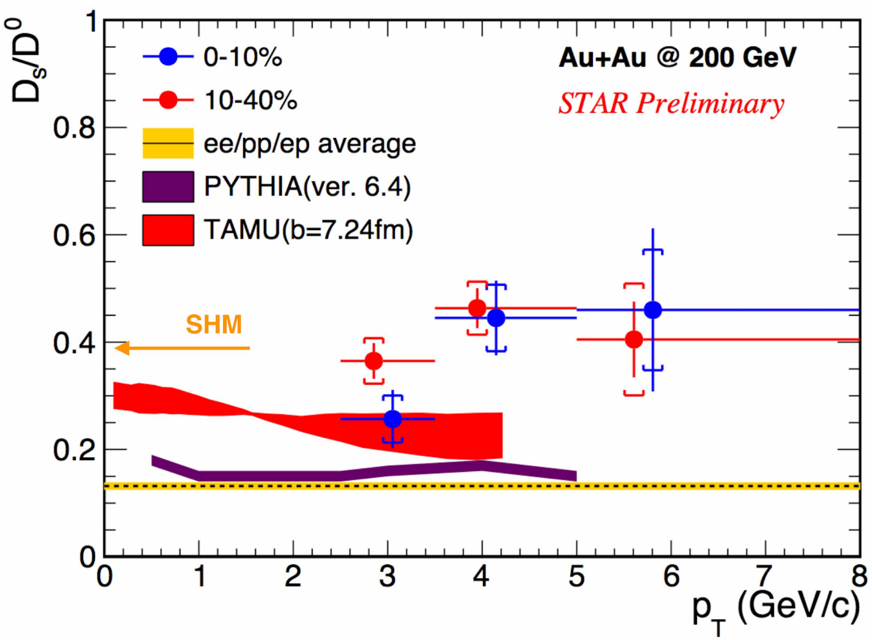




D_s/D^0 YIELD RATIO ENHANCEMENT

- D_s/D^0 yield ratio as a function of p_T
- **Enhancement** of D_s/D^0 ratio in Au+Au collisions with respect to PYTHIA p+p baseline and elementary collisions (ee/pp/ep average)
- Comparison to models:
  - TAMU model with coalescence hadronization shows enhancement, but underpredicts data
  - SHM in good agreement with data
- **Importance of coalescence hadronization of charm quarks together with enhanced strangeness production**

ep/pp/ep avg: EPJ C 76, 397 (2016)
TAMU: PRL 110, 112301 (2013)
SHM: Phys. Lett. B (2003), 571, 36-44



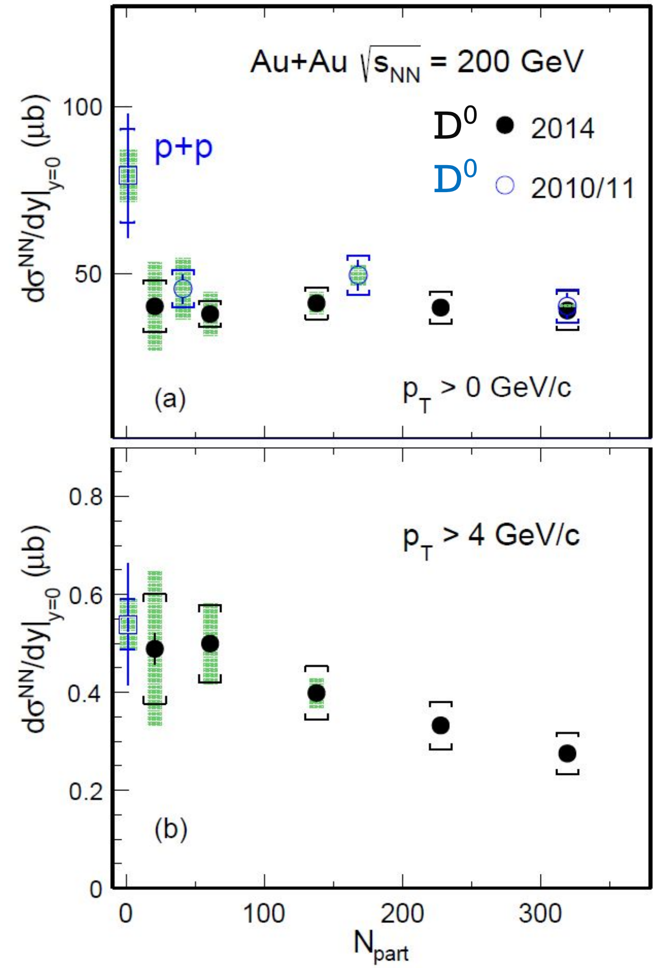
TOTAL CHARM PRODUCTION CROSS-SECTION

D^0 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D^0 2010/11 (STAR): Phys. Rev. C 99, 034908, (2019).
p+p (STAR): Phys. Rev. D 86 072013, (2012).

- Total charm production **cross-section per binary collision** in Au+Au extracted from measurements of open-charm hadrons
- Au+Au result is consistent with that measured in p+p collisions within uncertainties
- **Redistribution of charm quarks among open-charm hadron species**

Coll. system	Hadron	$d\sigma/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40%	D^0	41 ± 1 ± 5
	$D^\pm$	18 ± 1 ± 3
	D_s	15 ± 1 ± 5
	Λ_c	78 ± 13 ± 28 *
	Total:	**152 ± 13 ± 29**
p+p at 200 GeV	**Total:**	**130 ± 30 ± 26**

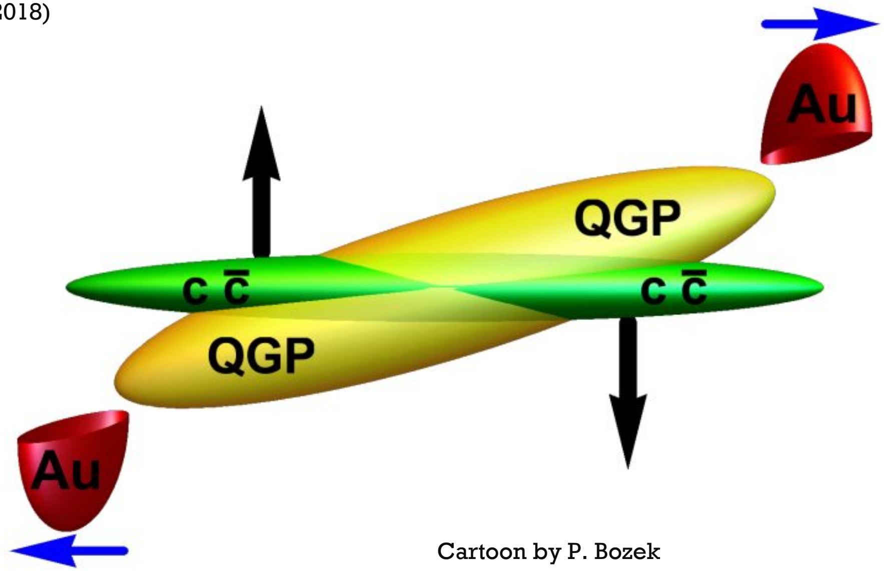
*Λ_c cross-section was derived using Λ_c/D^0 yield ratio



D^0 DIRECTED FLOW - MOTIVATION

- **Hydrodynamics**
  - Difference between tilt of bulk and longitudinal density profile of heavy flavor production
  - Expected larger slope dv_1/dy of charm than light flavors
- **Initial EM field from passing spectators**
  - Predicted negative dv_1/dy slope for D^0 and positive for $\overline{D}^0$
- **Hydrodynamics + EM field**
  - Expected larger slope for D^0 than $\overline{D}^0$
  - dv_1/dy slope stays negative for both D^0 and $\overline{D}^0$

Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)

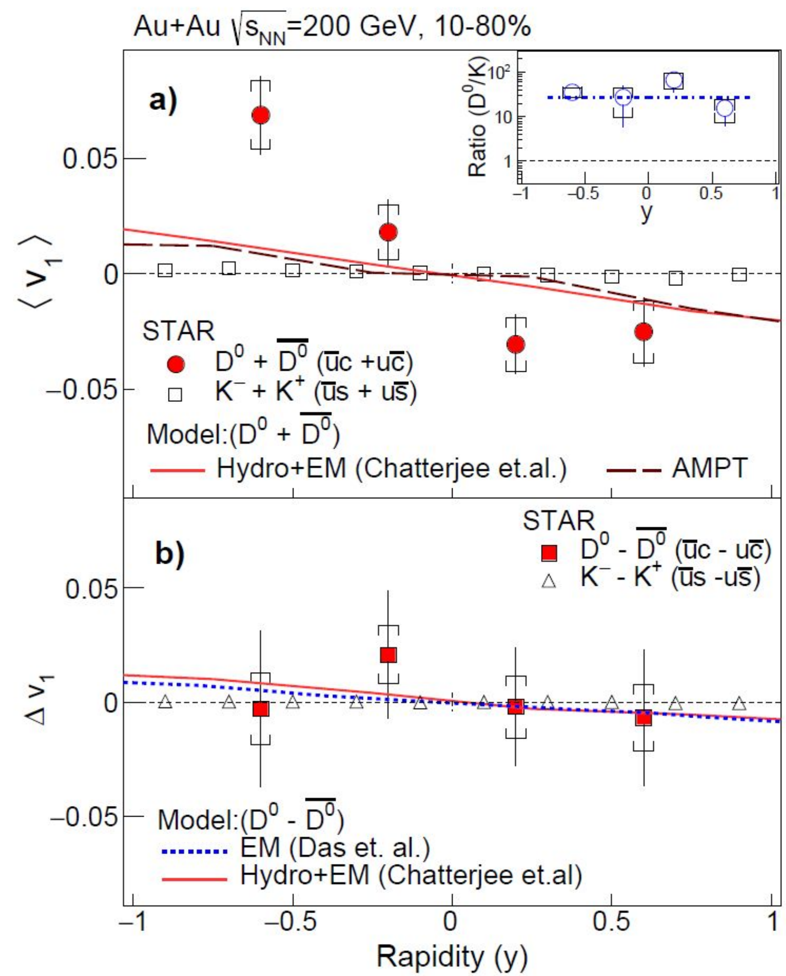


Cartoon by P. Bozek

Das et. al., Phys Lett B 768, 260 (2017)
Chatterjee, Bozek: arXiv:1804.04893

D^0 DIRECTED FLOW - RESULTS

- **First evidence of non-zero directed flow (v_1) of D^0 and $\overline{D}^0$ as function of rapidity (y)**
- **Negative dv_1/dy slope for both D^0 and $\overline{D}^0$**
- **Significantly larger dv_1/dy slope than kaons**
- No EM-induced splitting observed within uncertainties
- **Measurement of D^0 directed flow can be used to probe difference between tilt of QGP bulk and longitudinal density profile of heavy flavor production**



D^0: arXiv:1905.02052, submitted to PRL.
Kaons (STAR): PRL 120, 062301 (2018).

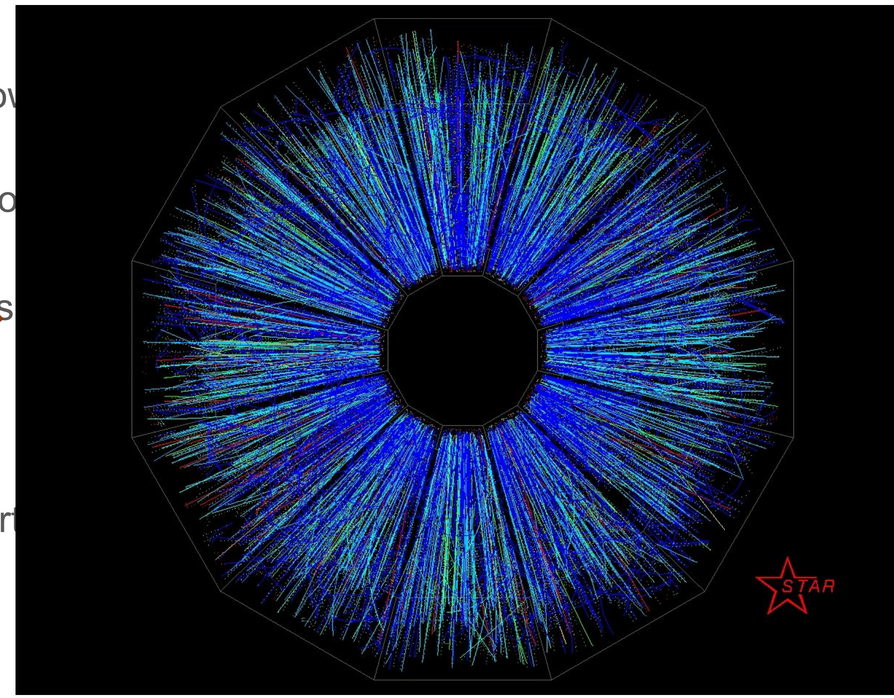
CONCLUSIONS

- STAR has extensively studied production of **open-charmed hadrons** in heavy-ion collisions utilizing **Heavy Flavor Tracker**
- Charm quarks interact strongly with QGP and are possibly in local **thermal equilibrium** with medium
  - D^0 and $D^{\pm}$ meson production in central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV is **significantly suppressed** at high-p_T
  - D^0 meson v_2 and v_3 **follow NCQ scaling**
- **Coalescence** likely plays important role in hadronization of charm quarks in A+A collisions
  - Λ_c/D^0 and D_s/D^0 yield ratios are **enhanced** in Au+Au collisions with respect to p+p collisions
- Total charm production **cross-section** per binary collision in Au+Au collisions is consistent with that measured in p+p collisions
  - **Redistribution of charm** quarks among open-charm hardon species
- Charm quarks can probe **initial tilt of QGP bulk** with respect to longitudinal density profile of heavy flavor production
  - D^0 mesons have larger v_1 slope than light-flavor mesons

BACKUP

EVENT AND TRACK SELECTION

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



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