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

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Strangeness in Quark Matter, Bari, Italy

11. 06. 2019

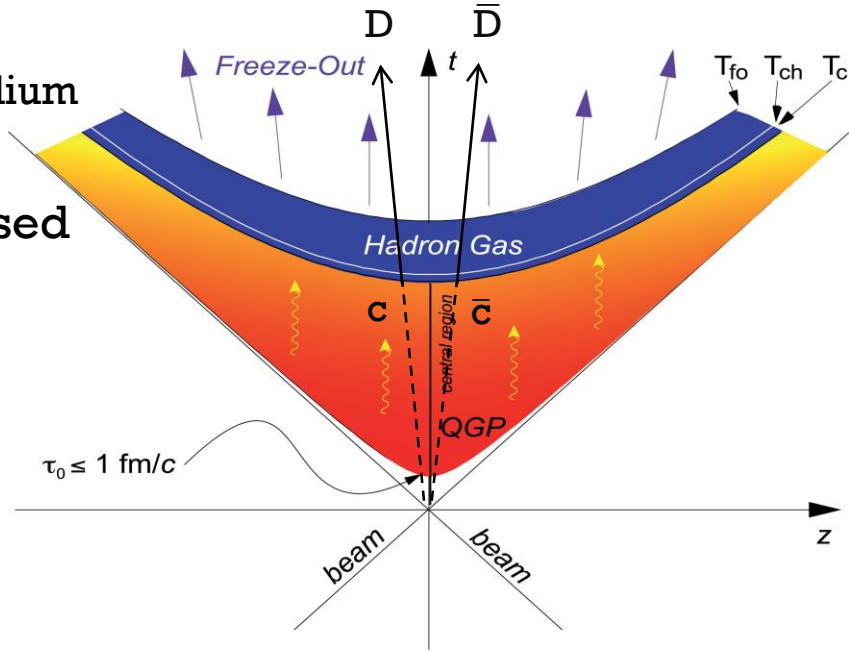
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

PHYSICS MOTIVATION

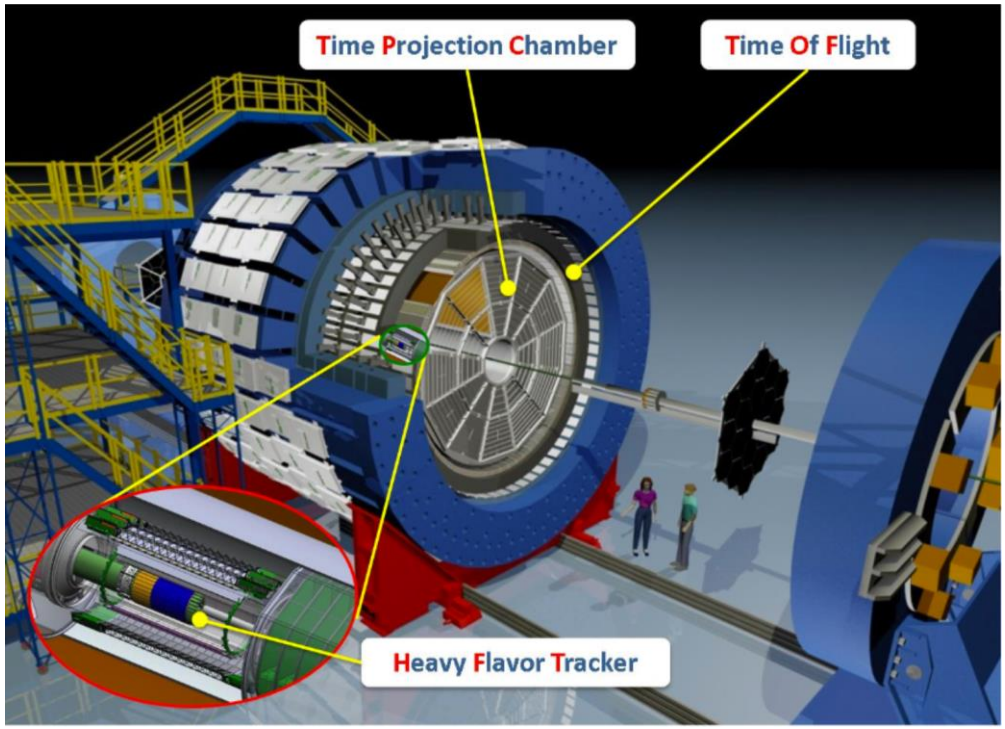
- At RHIC energies, charm quarks are produced predominantly through hard partonic scatterings at early stage of Au+Au collisions
  - They experience the whole evolution of the medium

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

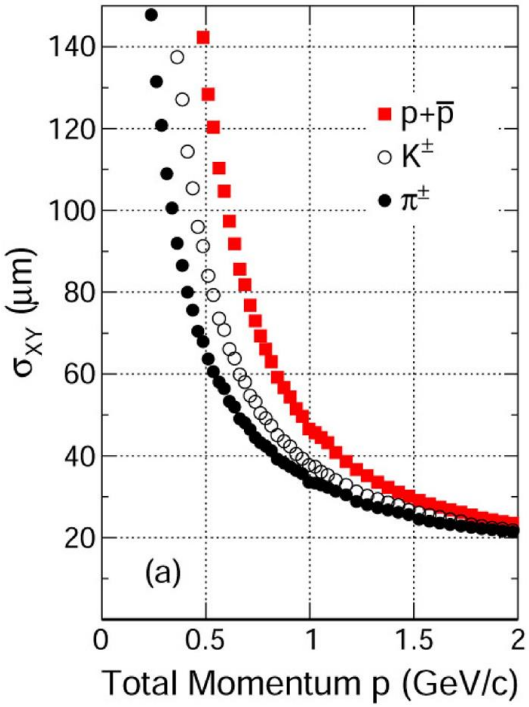


STAR DETECTOR

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



PRL 118 212301 (2017)

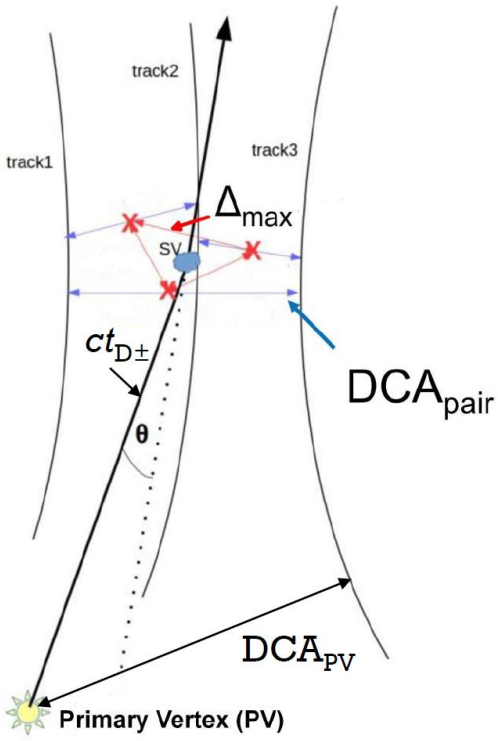


OPEN-CHARM MEASUREMENTS WITH THE HFT

- STAR took data with the HFT in 2014 and 2016 for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

- The HFT allows direct topological reconstruction of open-charm hadrons through their hadronic decays

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



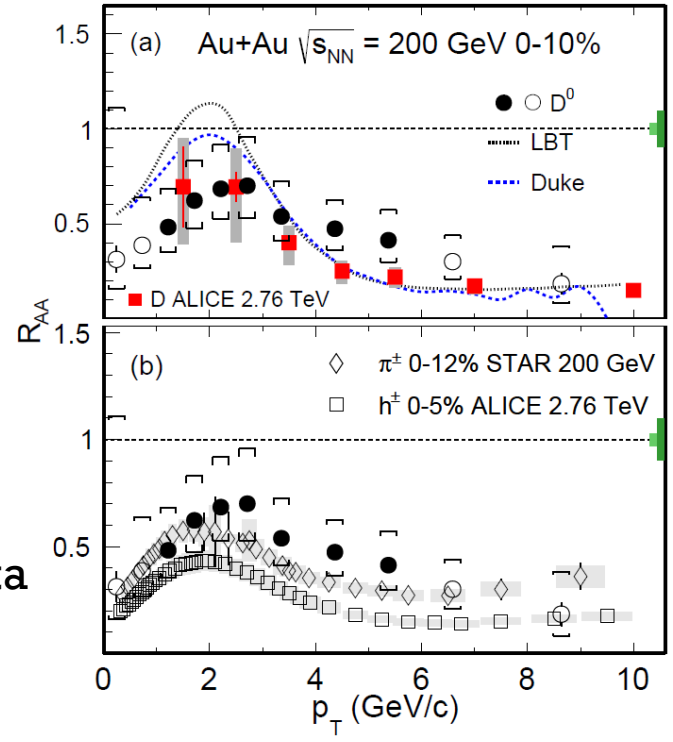
$D^{\pm}$ AND D^0 NUCLEAR MODIFICATION FACTOR

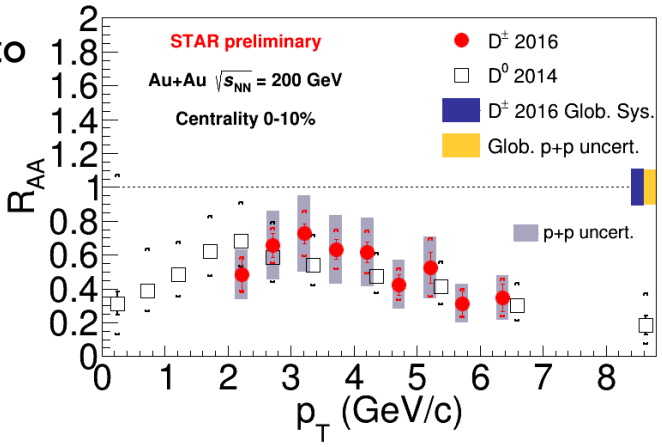
D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
$\pi^{\pm}$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
$h^{\pm}$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

- 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
- 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 interactions between charm quarks and the medium**





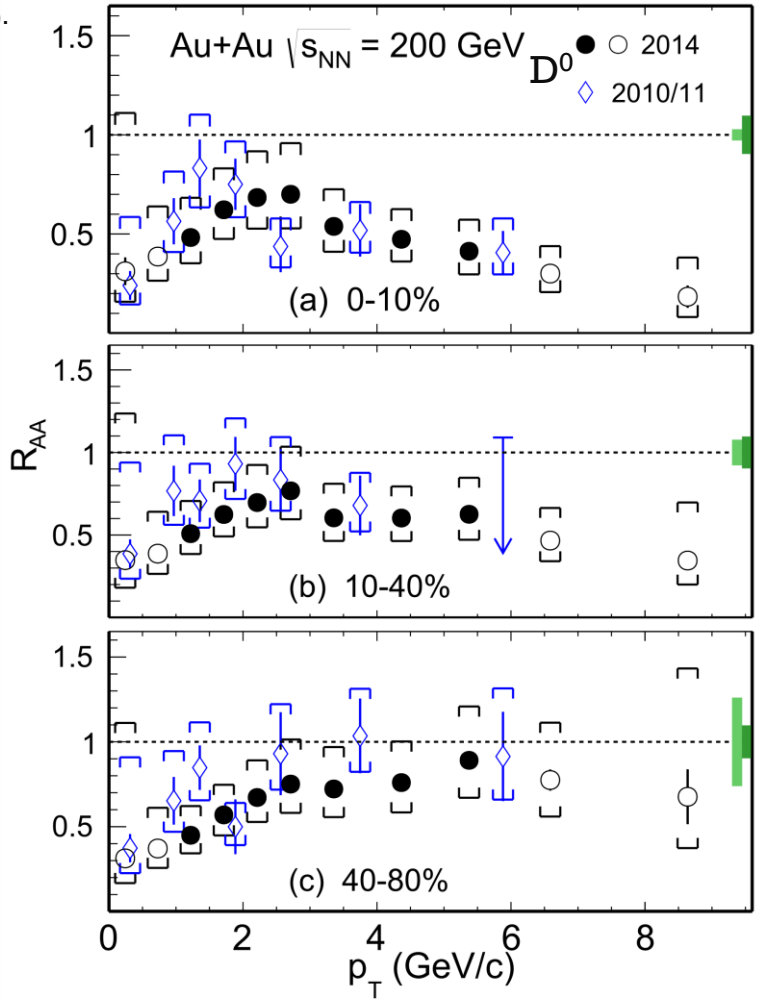
$D^{\pm}$ AND D^0 NUCLEAR MODIFICATION FACTOR

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

- Nuclear modification factor:

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

- Centrality dependence of D^0 mesons R_{AA}
  - Suppression at high p_T increases with collision centrality
  - Low-p_T D^0 suppressed for all studied centrality classes of Au+Au collisions
- **Integrated R_{AA} < 1 for D^0 mesons**



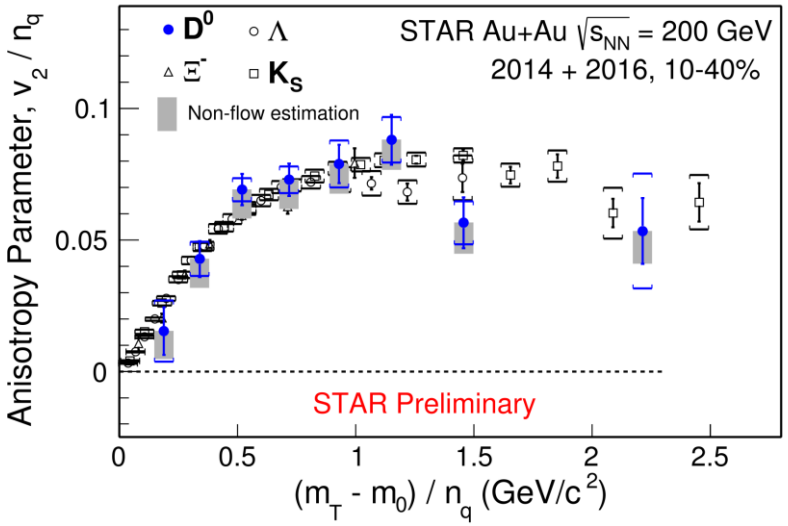
D^0 COLLECTIVE FLOW

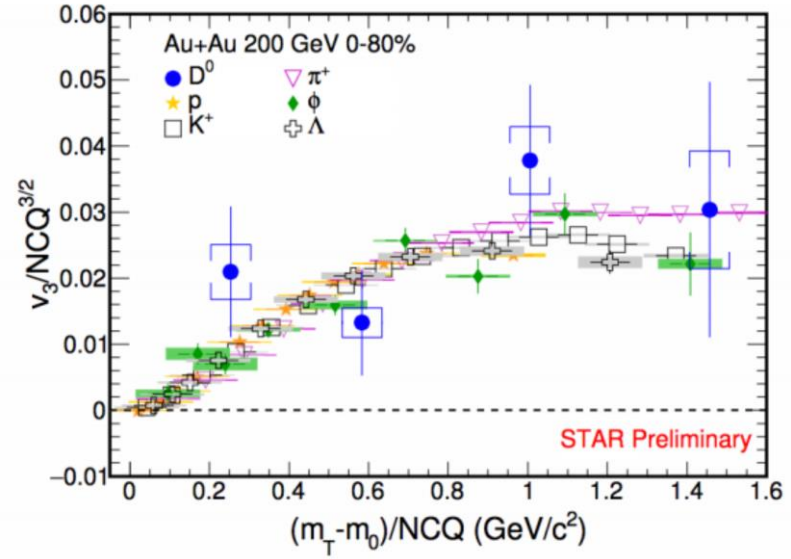
- Elliptic (triangular) flow = second (third) order Fourier coefficient v_2 (v_3) of the azimuthal distribution:

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

- D^0 v_2 and v_3 follow the Number of Constituent Quarks (NCQ) scaling
  - Significant elliptic and triangular flow of D^0
  - Strong collective behavior of the charm quarks

- **The c quarks might have achieved local thermal equilibrium with the QGP**





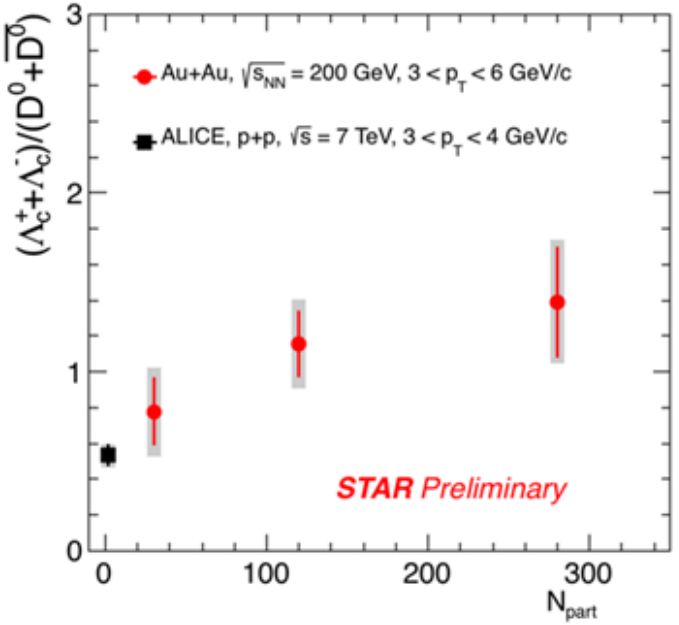
v_2 D^0 (2014): Phys. Rev. Lett, 118, 212301 (2017)
v_2, light flavor: Phys. Rev. C 77, 054901 (2008).

Λ_c/D^0 YIELD RATIO ENHANCEMENT

- Open-charm baryon/meson yield ratio

CENTRALITY DEPENDENCE

- Enhancement of the ratio increases towards central collisions
- The value in peripheral collisions is consistent with p+p measurement at $\sqrt{s} = 7$ TeV by ALICE

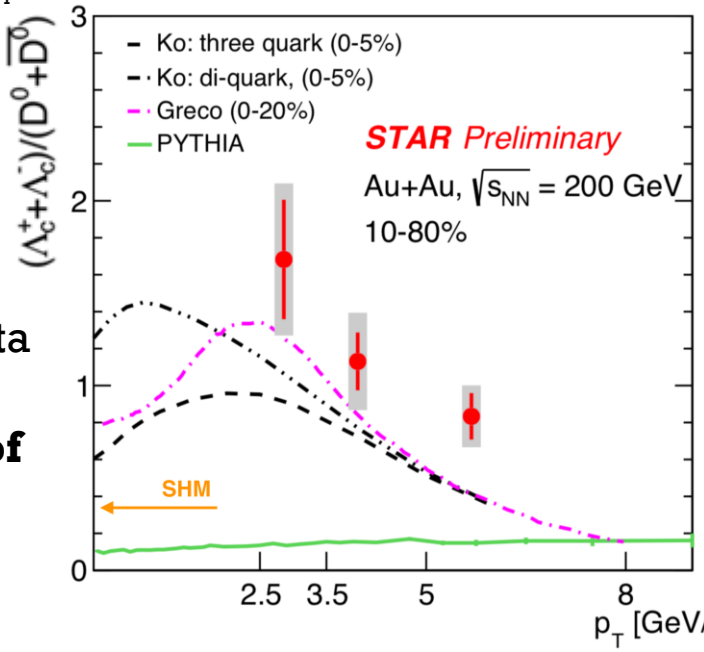


ALICE: JHEP 04 (2018) 108
Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys. Lett. B (2003), 571, 36-44

p_T DEPENDENCE

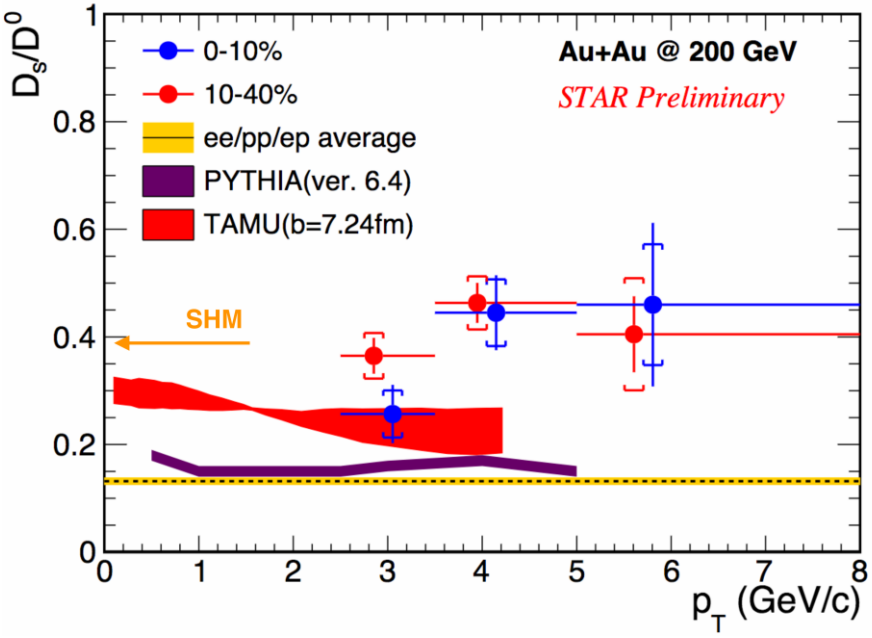
- Significant enhancement with respect to PYTHIA prediction
- Coalescence models closer to data than PYTHIA
- Extrapolated ratio from the Statistical Hadronization Model (SHM) underpredicts data

- **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 baseline and elementary collisions (ee/pp/ep average)
- Comparison to models:
  - TAMU model with coalescence hadronization shows enhancement, but under-predicts data
  - SHM in good agreement with data
- **Importance of coalescence hadronization of charm quarks together with enhanced strangeness production**



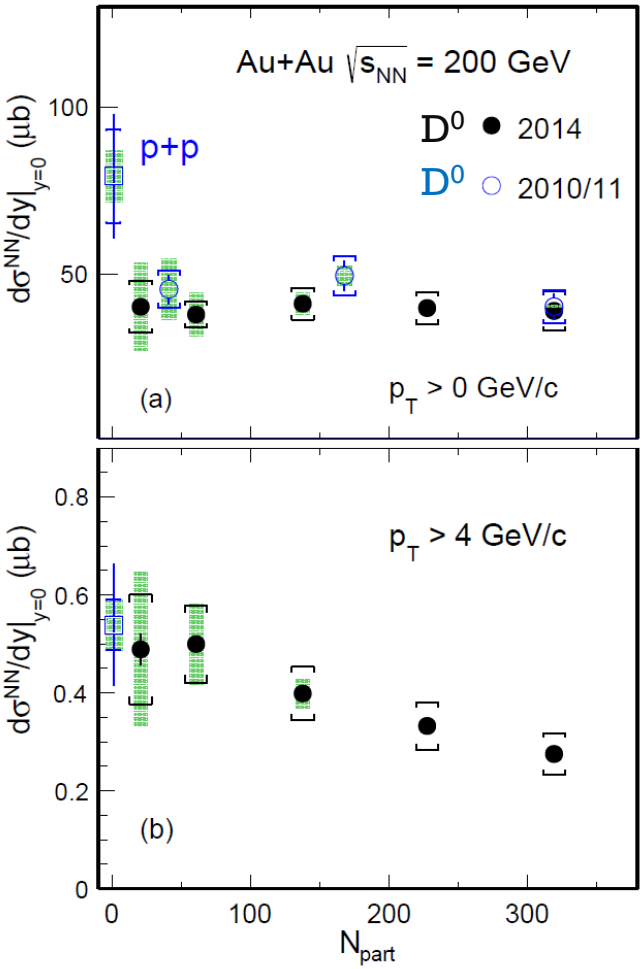
ep/pp/ep avg: EPJ C 76, 397 (2016)
TAMU: PRL 110, 112301 (2013)
SHM: Phys. Lett. B (2003), 571, 36-44

TOTAL CHARM PRODUCTION CROSS-SECTION

- Total charm production **cross-section per binary collision** in Au+Au extracted from the measurements of open-charm hadrons
  - *The Λ_c cross-section was derived using the Λ_c/D^0 yield ratio
- The Au+Au result is consistent with that measured in p+p collisions within the uncertainties
- **Redistribution of charm quarks among open –charm hadron species**

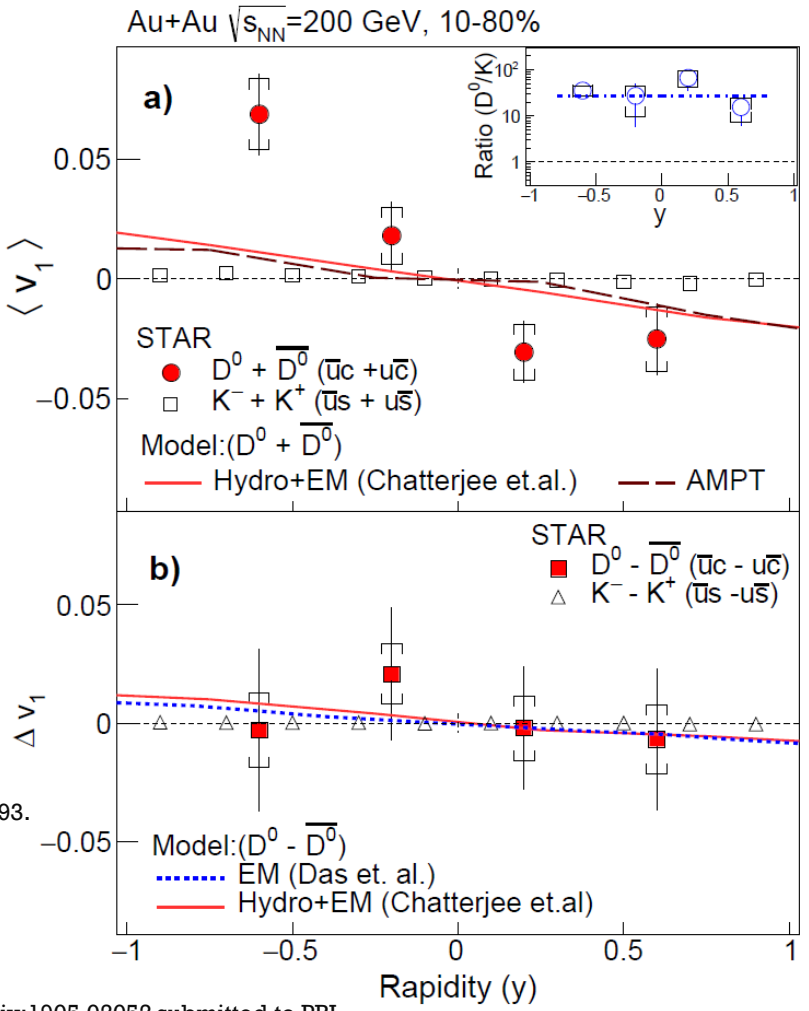
Coll. system	Hadron	$d\sigma/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40%	D^0	$41 \pm 1 \pm 5$
	$D^{\pm}$	$18 \pm 1 \pm 5$
	D_s	$15 \pm 1 \pm 5$
	Λ_c	$78 \pm 13 \pm 28$ *
	Total:	**$152 \pm 13 \pm 29$**
p+p at 200 GeV	**Total:**	**$130 \pm 30 \pm 26$**

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)



D^0 DIRECTED FLOW

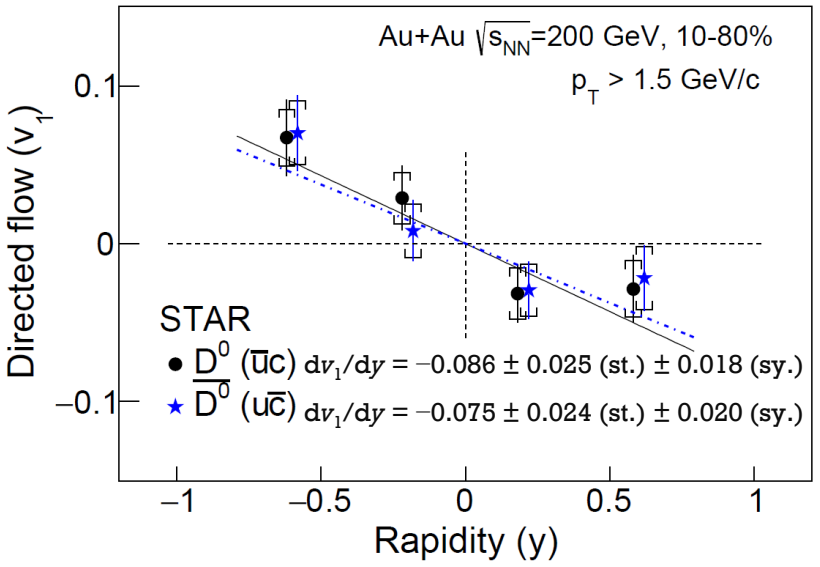
- **Hydrodynamics** Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)
  - Difference between the tilt of the bulk and the longitudinal density profile of HF production
  - Larger slope dv_1/dy of charm than light flavors
- **Initial EM field from passing spectators**
  - Predicted negative dv_1/dy slope for D^0 and positive one for $\overline{D^0}$ Das et. al., Phys Lett B 768, 260 (2017)
- **Hydrodynamics + EM field**
  - Negative dv_1/dy slope for both for D^0 and $\overline{D^0}$
  - Larger slope for D^0 than $\overline{D^0}$ Chatterjee, Bozek: arXiv:1804.04893.



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

D^0 DIRECTED FLOW

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



D^0: arXiv:1905.02052 submitted to PRL.

CONCLUSIONS

- STAR has extensively studied production of open-charm hadrons in heavy-ion collisions utilizing the Heavy-Flavor Tracker
- The c quarks interact strongly with the QGP and are possibly in local thermal equilibrium with the medium
  - D^0 and $D^{\pm}$ mesons are significantly suppressed at high-p_T in central Au+Au collisions
  - D^0 mesons v_2 and v_3 follow the NCQ scaling
- Coalescence likely plays an important role in hadronization of the 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 the 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 the QGP bulk with respect to the longitudinal density profile of HF production
  - D^0 mesons have larger v_1 slope than light-flavor mesons

THANK YOU FOR ATTENTION

Acknowledgement: This presentation is supported by OPVVV grant CZ.02.1.01/0.0/0.0/16_013/0001569 of the Ministry of Education, Youth and Sports of the Czech Republic