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

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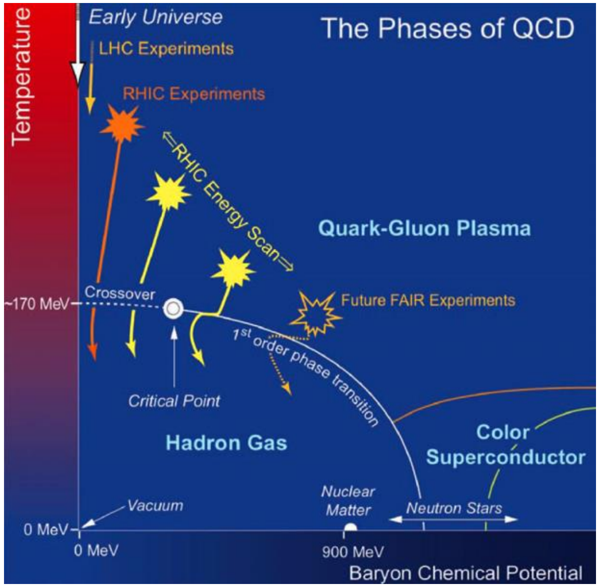
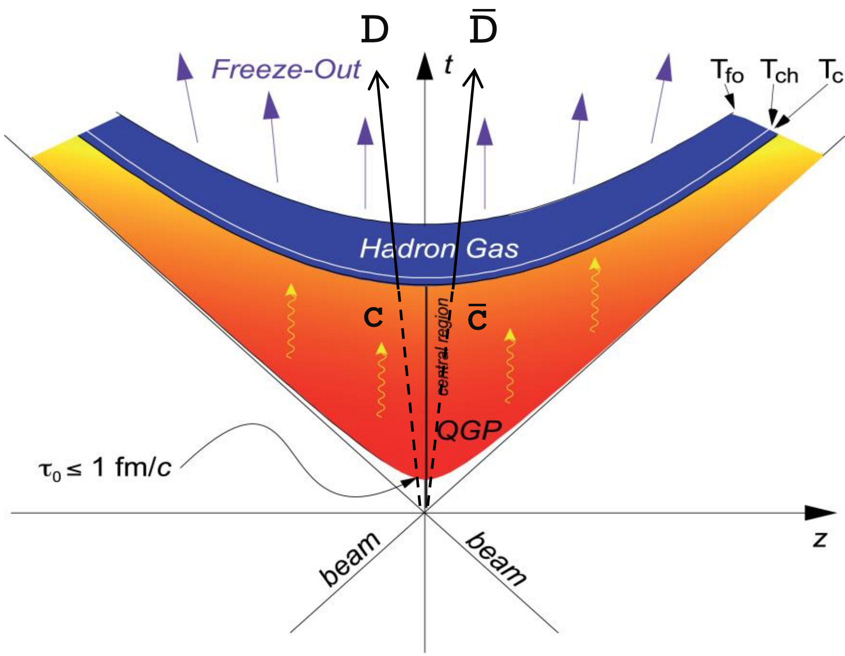
PHYSICS MOTIVATION

- **Quark-Gluon Plasma** (QGP) is an extreme state of matter where quarks and gluons are no longer trapped inside colorless hadrons
- QGP can be studied using relativistic heavy-ion collisions
- 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**

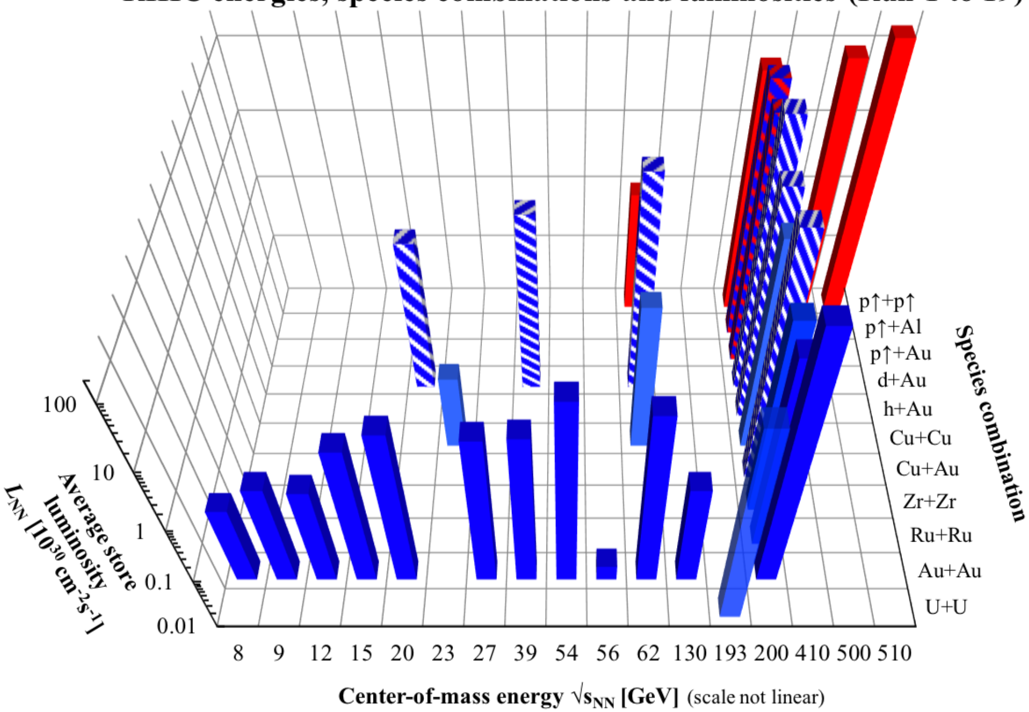


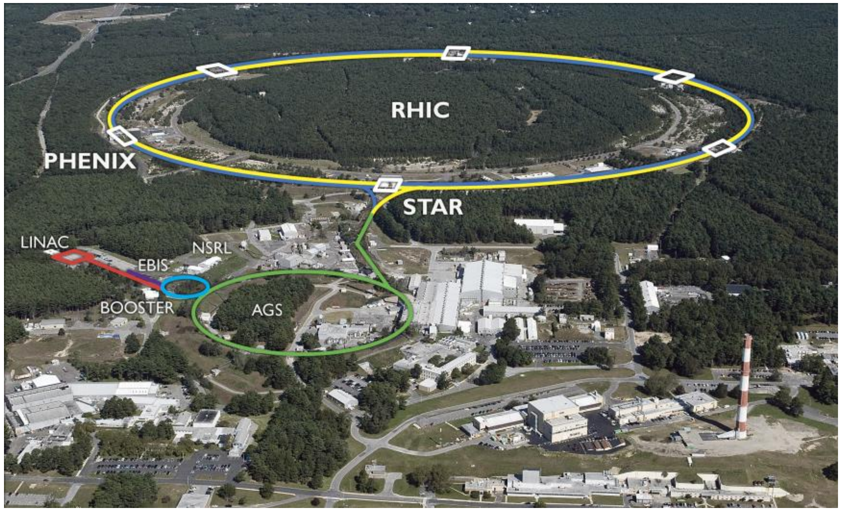


RELATIVISTIC HEAVY-ION COLLIDER

- Relativistic Heavy-Ion Collider (RHIC) is located in Brookhaven National Laboratory (BNL), Long Island, New York
  - RHIC is 3.8 km long with total of 6 interaction regions (IR)
  - STAR is located at 6'o clock IR and is the only running experiment at RHIC today
- RHIC is very versatile collider:

RHIC energies, species combinations and luminosities (Run-1 to 19)

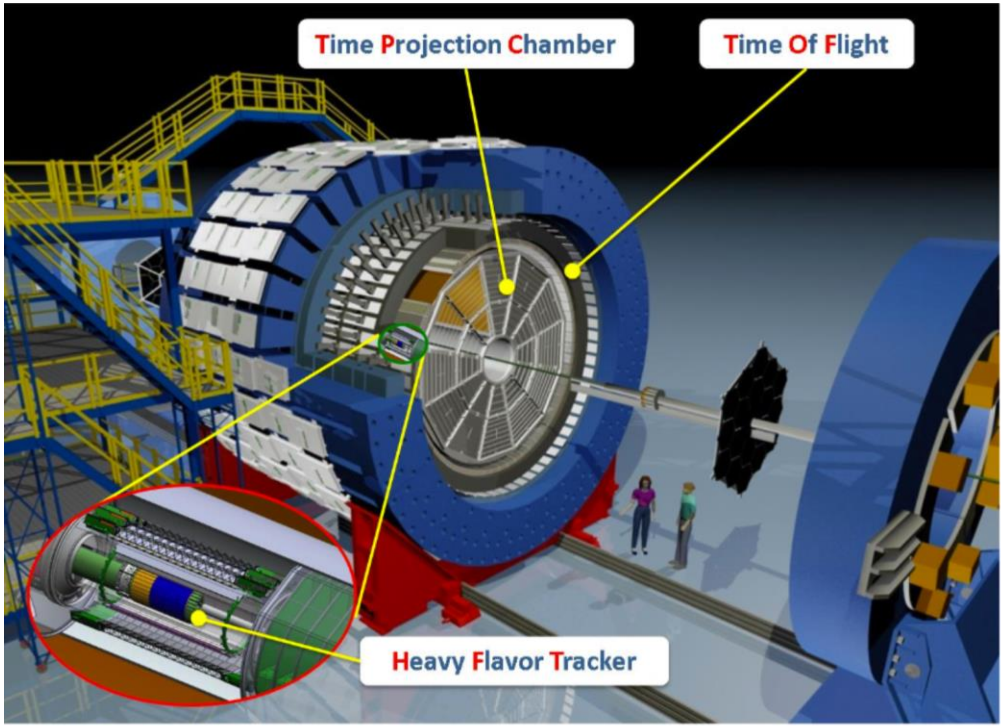


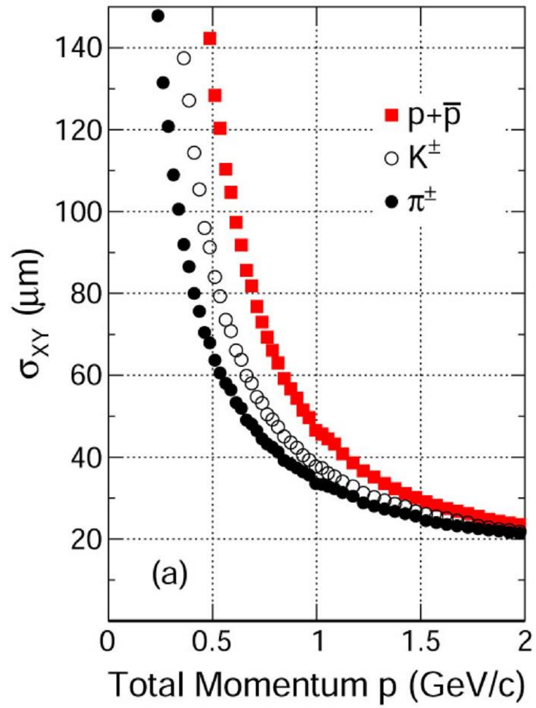


STAR DETECTOR

- **S**olenoidal **T**racker **A**t **R**HIC
- **H**eavy **F**lavor **T**racker (HFT, 2014–2016) is a 4-layer silicon detector
  - MAPS – 2 innermost layers (PXL1, PXL2), Strip detectors – 2 outer layers (IST, SSD)
- **T**ime **P**rojection **C**hamber (TPC) and **T**ime **O**f **F**light (TOF)
  - Particle momentum (TPC) and identification (TPC and TOF)

STAR: PRL 118, 212301, (2017)





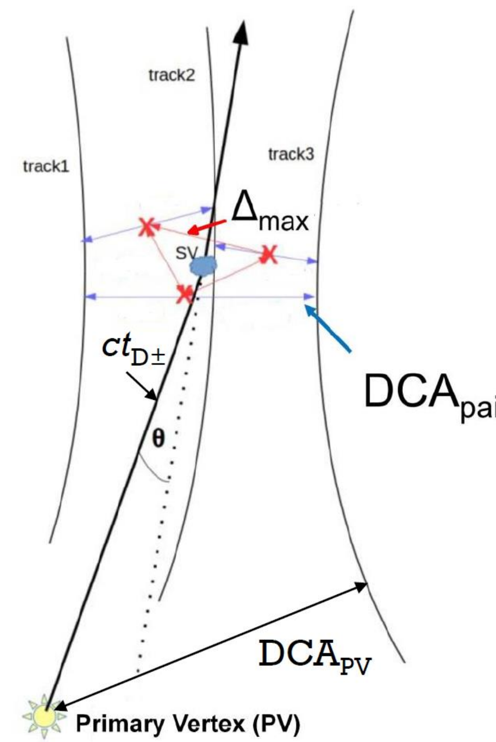
OPEN-CHARM MEASUREMENTS WITH THE HFT

- 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

Mothers*	Decay channel*	$c\tau$ [μm]	*BR* [%]
$\mathrm{D}^+ (c\bar{u})$	$\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$	311.8 ± 2.1	8.98 ± 0.28
$\mathrm{D}^0 (c\bar{d})$	$\mathrm{D}^0 \to \mathrm{K}^-\pi^+$	122.9 ± 0.4	3.93 ± 0.04
$\mathrm{D}_s^+ (c\bar{s})$	$\mathrm{D}_s^+ \to \phi\pi^+ \to \mathrm{K}^-\mathrm{K}^+\pi^+$	149.9 ± 2.1	2.27 ± 0.08
$\Lambda_c^+ (udc)$	$\Lambda_c^+ \to \mathrm{K}^-\pi^+\mathrm{p}$	59.9 ± 1.8	6.35 ± 0.33

  - *Charge conjugate particles are also measured



Cartoon of $\mathrm{D}^\pm$ decay topology

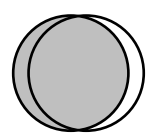
D^0 NUCLEAR MODIFICATION FACTOR

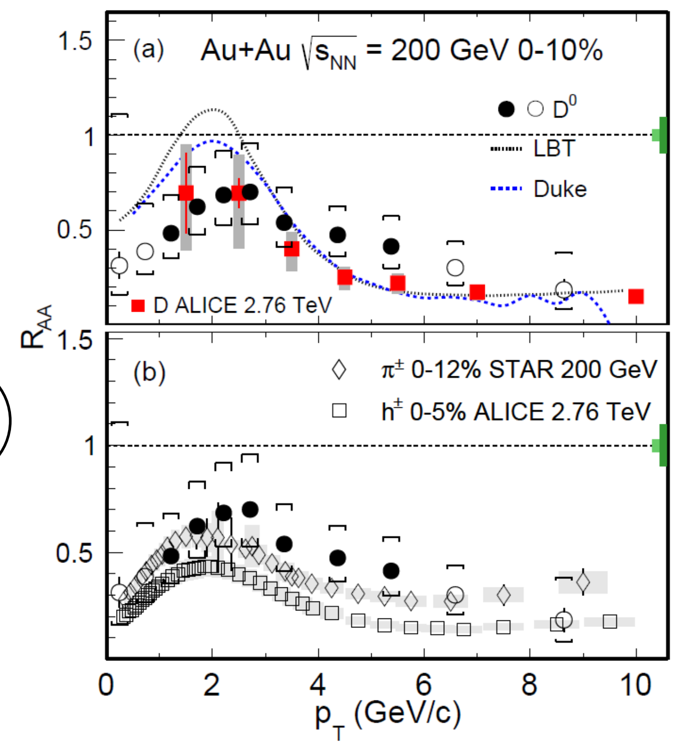
D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
π$^\pm$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
h$^\pm$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

- Nuclear modification factor:

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

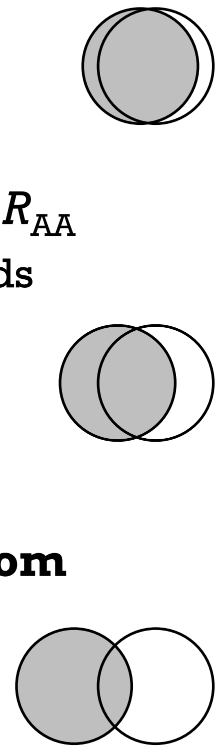
- Reference: combined D^0 and D* measurement in 200 GeV p+p collisions using 2009 STAR data
- D mesons suppressed in **central** Au+Au collisions
  - Suppression of D^0 mesons at high p_{T} comparable to light flavor hadrons at RHIC and D mesons at LHC
  - Reproduced by models incorporating both radiative and collisional energy losses
- **Strong interactions between charm quarks and the medium**

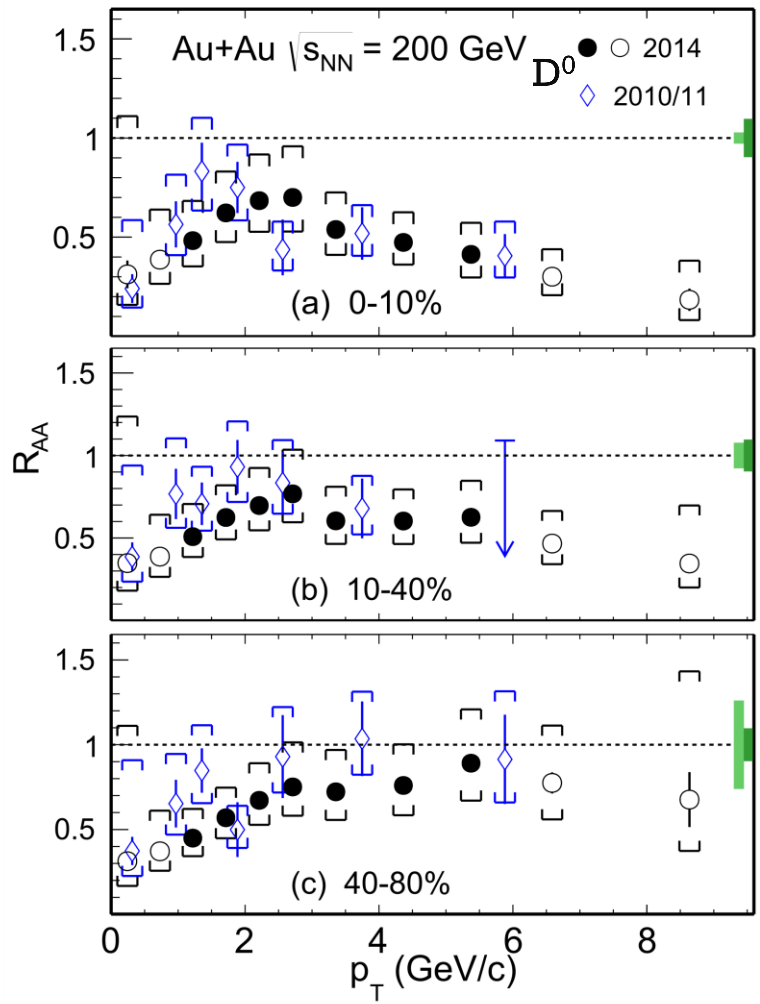




D^0 NUCLEAR MODIFICATION FACTOR

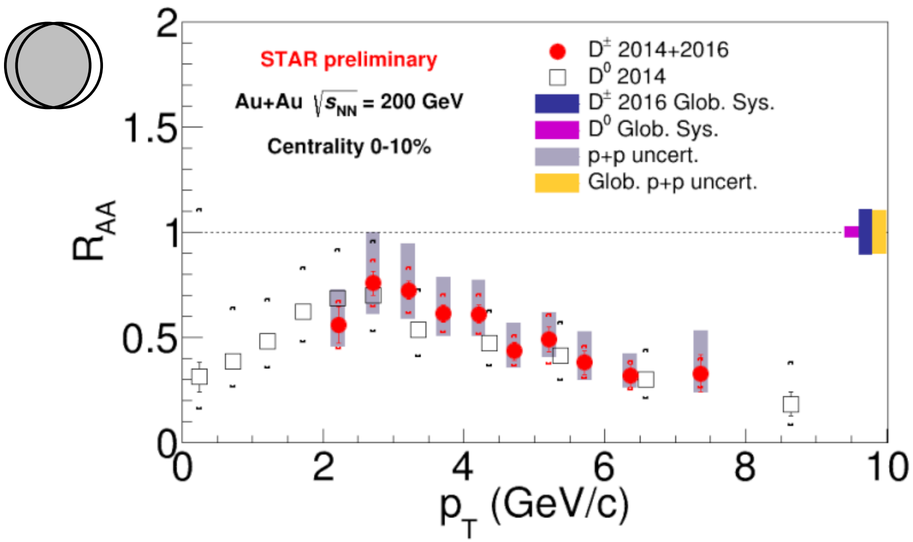
- Centrality dependence of D^0 mesons R_{AA}
  - Suppression at high p_T increases towards more central collisions
  - Low-p_T D^0 suppressed for all studied centrality classes of Au+Au collisions
- **Integrated R_{AA} < 1 for D^0 mesons from central to peripheral collisions**

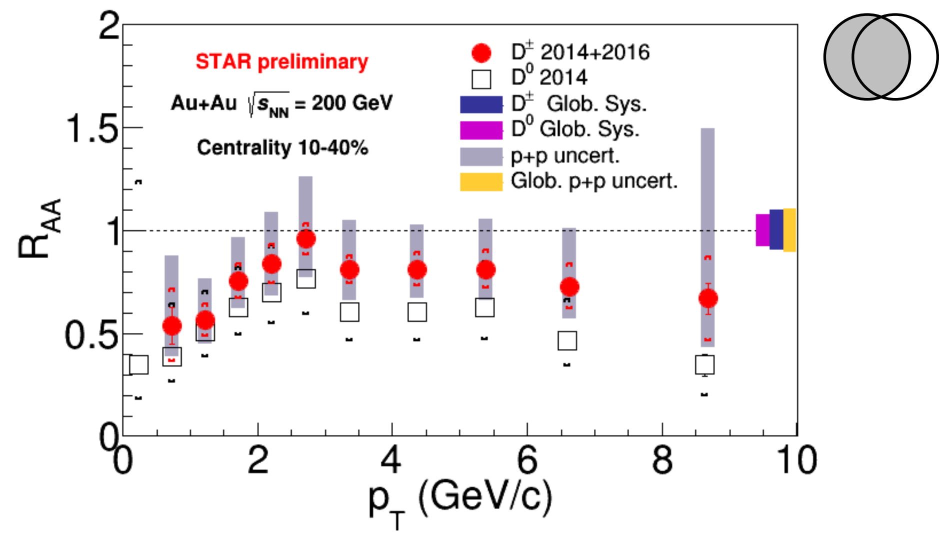


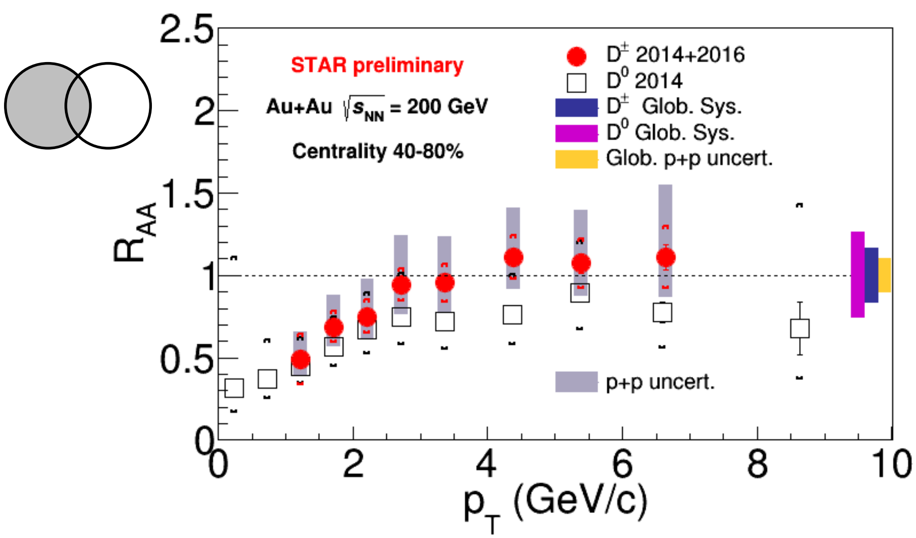


D^0 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D^0 2010/11 (STAR): Phys. Rev. Lett. 113, 142301 (2014), erratum: Phys. Rev. Lett. 121, 229901 (2018).

$D^{\pm}$ Nuclear Modification Factor



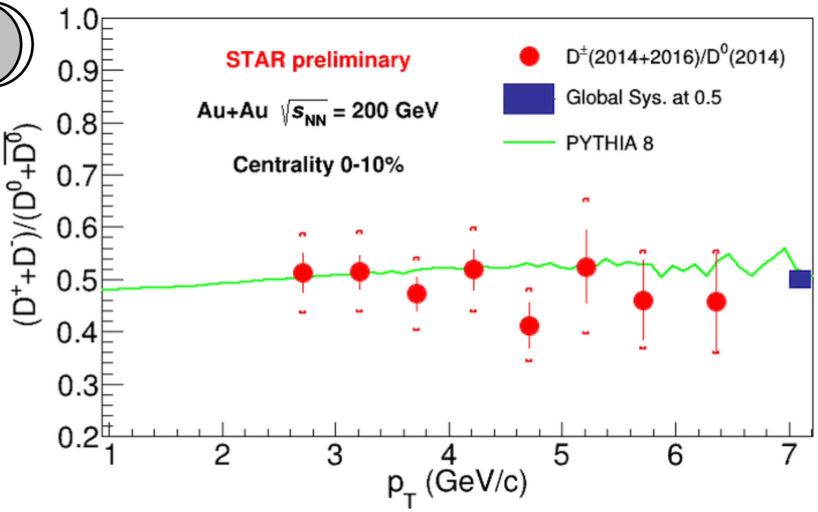


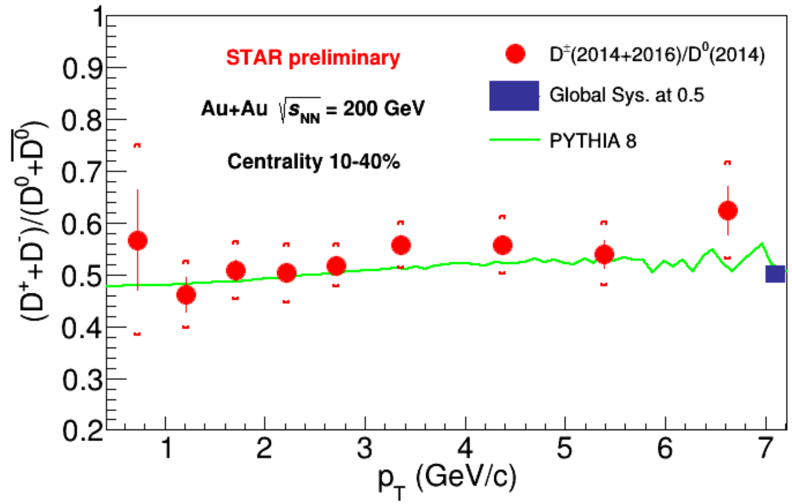


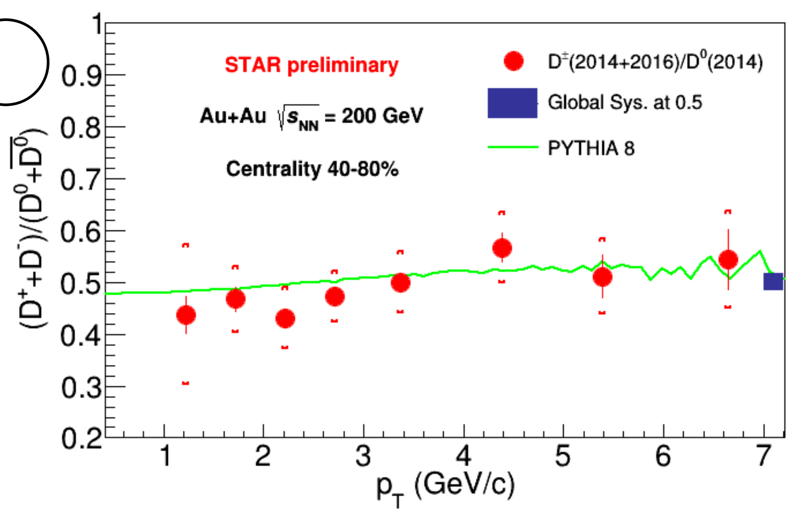
- Reference: combined D^0 and D^* measurement in 200 GeV p+p collisions using 2009 data
- Similar level of suppression and centrality dependence for $D^{\pm}$ and D^0
- High-p_T $D^{\pm}$ and D^0 suppressed in central Au+Au collisions
  - Strong interactions between charm quarks and the medium

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

$D^{\pm}/D^0$ YIELD RATIO



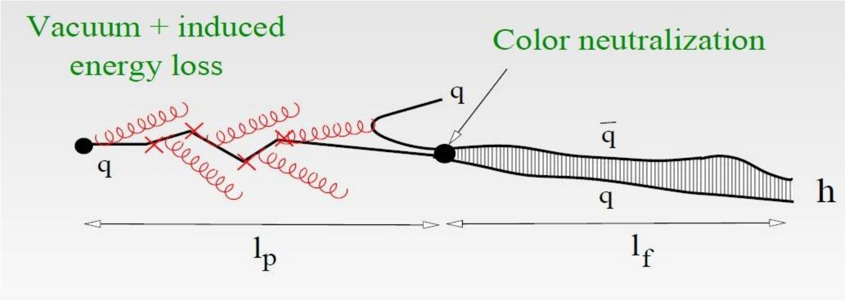




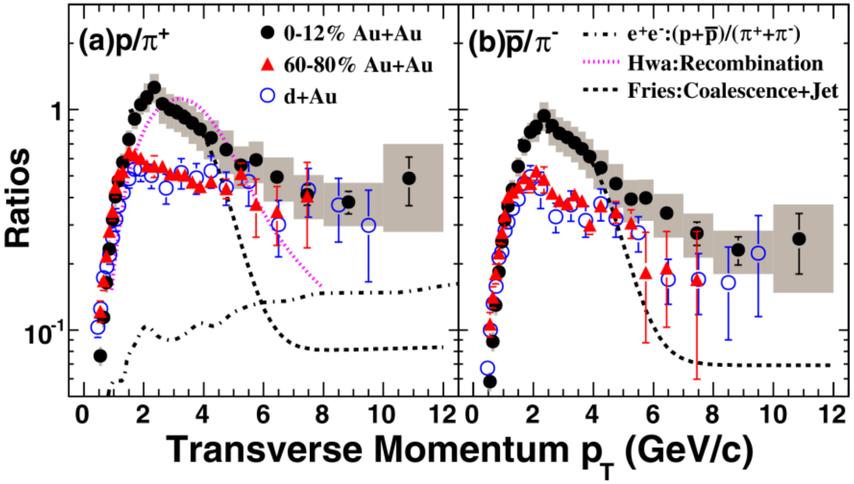
- The $D^{\pm}/D^0$ yield ratio in Au+Au collisions is compared to that from MC simulation of p+p collisions (PYTHIA 8)
  - Good agreement in all Au+Au centrality classes
- No modification of the $D^{\pm}/D^0$ yield ratio compared to PYTHIA

Hadronization of quarks in A+A collisions

- **Fragmentation**
  - As a quark propagates through medium (or vacuum) it radiates gluons which then fragment into quark-antiquark pairs
  - Those pairs and the original quark then hadronize



- **Coalescence**
  - Quark propagating through medium hadronizes with surrounding (anti-)quarks
    - At intermediate hadron p_T ($2 < p_T < 8$ GeV/c)
    - Quarks need to be close in kinematic phase space
  - More likely to produce **light flavor** baryon (3 quarks) than meson (2 quarks) for given hadron p_T compared to vacuum case
    - Due to larger abundance of low p_T quarks in medium



p/π (STAR): Phys. Rev. Lett. 97, 152301 (2006)

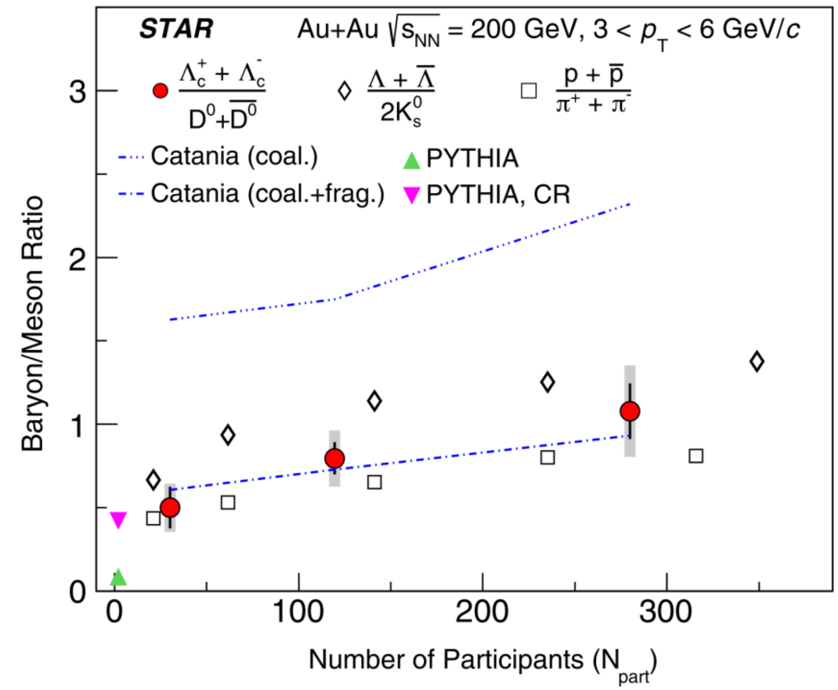
- **How about heavy-flavor hadrons?**

Λ_c/D^0 YIELD RATIO ENHANCEMENT

- **Open-charm** baryon/meson yield ratio

CENTRALITY DEPENDENCE

- Enhancement of the ratio increases towards central collisions
- Data well described by Catania model with coalescence and fragmentation



Λ_c (STAR): Phys. Rev. Lett. 124, 172301, (2020)
p/π (STAR): Phys. Rev. Lett. 97, 152301 (2006)
Λ /K (STAR): Phys. Rev. Lett. 108, 072301 (2012)
Catania: Eur. Phys. J. C 78, 348, (2018)

Λ_c/D^0 YIELD RATIO ENHANCEMENT

- **Open-charm** baryon/meson yield ratio

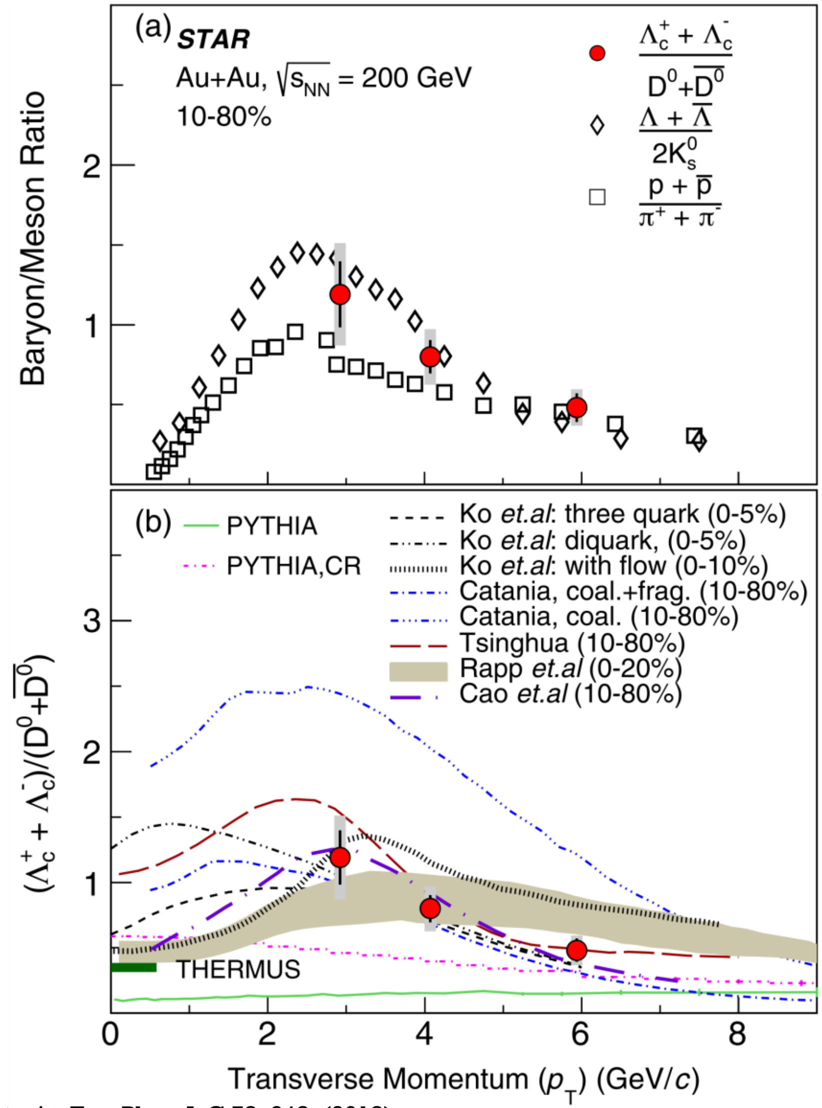
CENTRALITY DEPENDENCE

- Enhancement of the ratio increases towards central collisions
- The data well described by Catania model with coalescence and fragmentation

p_T DEPENDENCE

- Significant enhancement with respect to PYTHIA prediction
- Coalescence models closer to data than PYTHIA

- **Importance of coalescence and fragmentation hadronization of charm quarks**

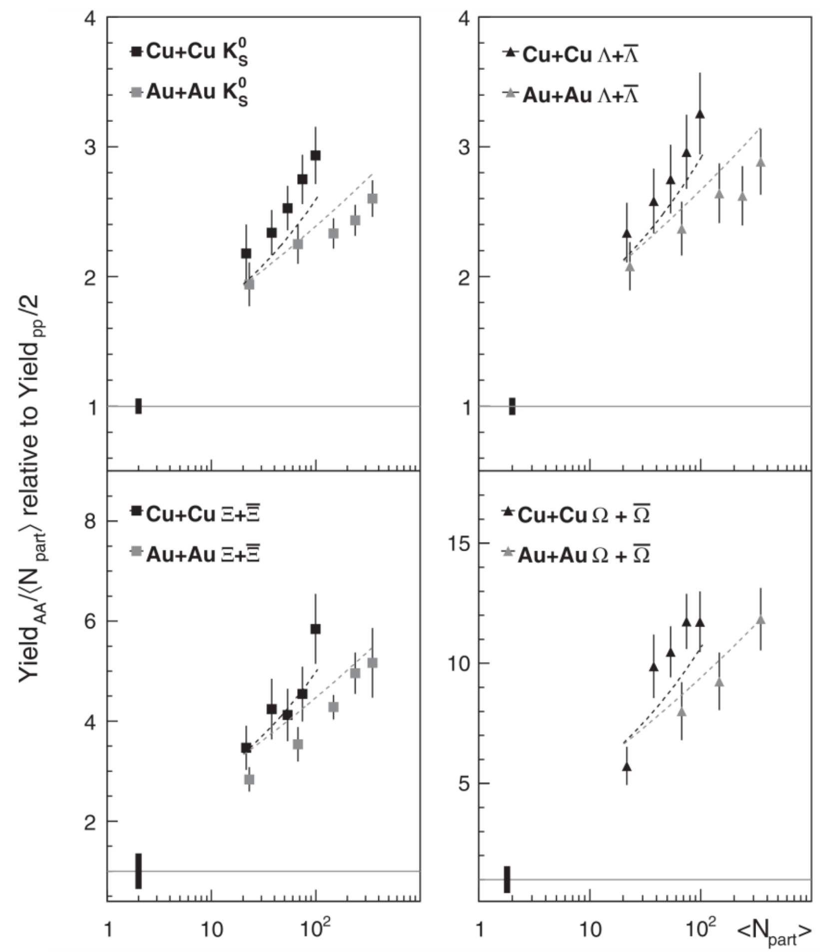


Λ_c (STAR): Phys. Rev. Lett. 124, 172301, (2020)
p/π (STAR): Phys. Rev. Lett. 97, 152301 (2006)
Λ/K (STAR): Phys. Rev. Lett. 108, 072301 (2012)
Ko *et al.*: Phys. Rev. C 101, 024909, (2020)

Catania: Eur. Phys. J. C 78, 348, (2018)
Tsinghua: arXiv:1805.10858, (2018)
Rapp *et al.*: Phys. Rev. Lett. 124, 042301 (2020)
Cao *et al.*: arXiv:1911.00456, (2019)

STRANGENESS ENHANCEMENT

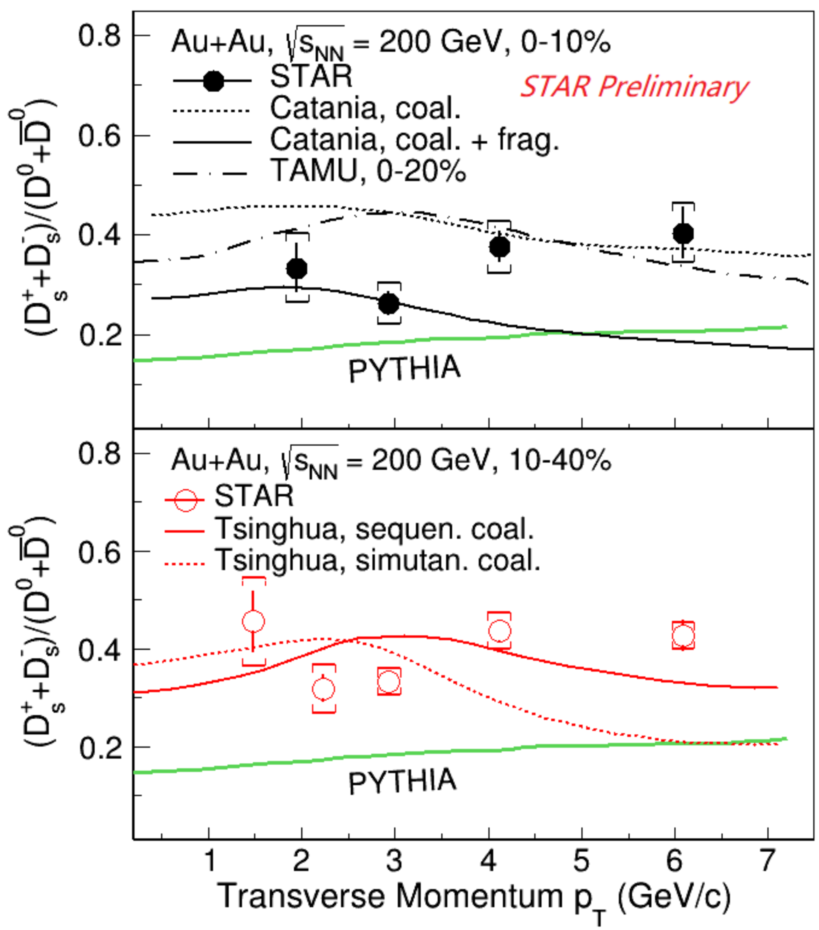
- Another very important phenomenon observed in heavy-ion collisions is **strangeness enhancement**
- Protons and neutrons do not contain any (valence) strange quarks
  - Need a mechanism of strangeness production
- Fragmentation of gluons
  - Present in both p+p and Au+Au
- Strange quark-antiquark pairs from QGP
  - Only in Au+Au
  - This additional mechanism leads to enhanced strangeness production per participant in Au+Au with respect to p+p for light hadrons
- **How about strange heavy-flavor hadrons?**



Strangeness enhancement (STAR): Phys. Rev. Lett. 108, 072301 (2012)

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
- Comparison to models:
  - Catania model with only coalescence describes data for p_T > 4 GeV/c
  - Catania model with coalescence and fragmentation describes data for lower p_T
  - Tsinghua model with sequential coalescence hadronization is closer to data for both low and high p_T
- **Importance of coalescence hadronization of charm quarks with enhanced strangeness production**



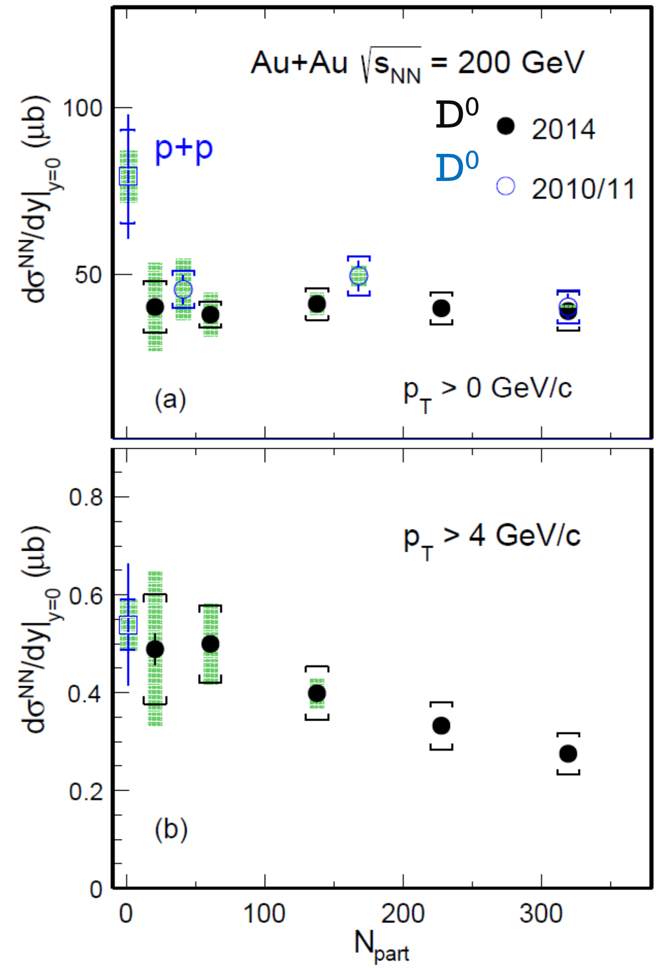
Catania: Eur. Phys. J. C 78, 348, (2018).
TAMU: Phys. Rev. Lett. 110, 112301 (2013)
Tsinghua: arXiv1805.10858, (2018).

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 is 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**

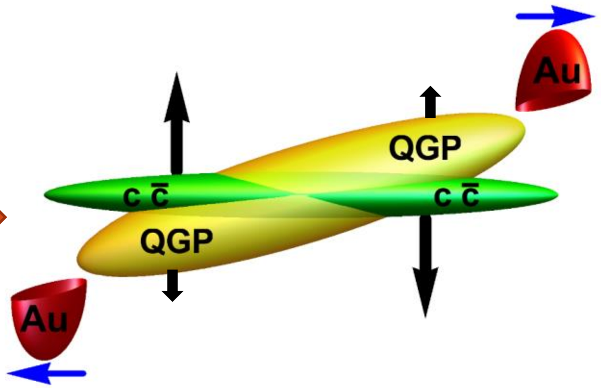
Coll. system	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40%	D^0	41 ± 1 ± 5
	$D^{\pm}$	18 ± 1 ± 3
	D_s	15 ± 1 ± 5
	Λ_c	78 ± 13 ± 28 *
	Total:	**152 ± 13 ± 29**
p+p at 200 GeV	**Total:**	**130 ± 30 ± 26**

D^0 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D^0 2010/11 (STAR): Phys. Rev. Lett. 113, 142301 (2014), erratum: Phys. Rev. Lett. 121, 229901 (2018).
p+p (STAR): Phys. Rev. D 86 072013, (2012)



D^0 DIRECTED FLOW

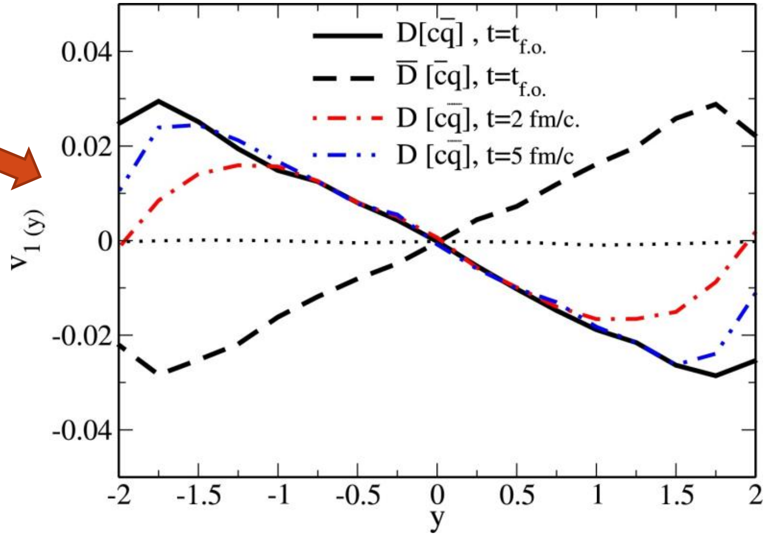
- **Hydrodynamics** Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)
  - Difference between the tilt of the bulk and the longitudinal density profile of HF production
  - Larger slope dv_1/dy of charm quarks than light flavor quarks



- **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)

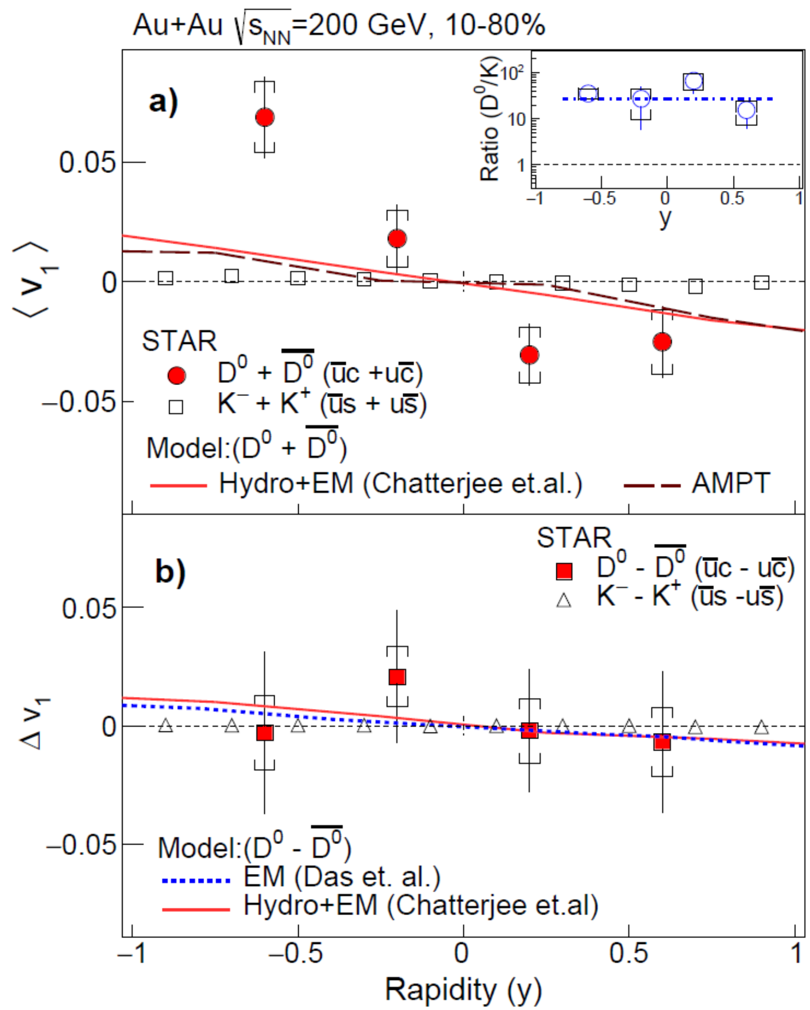
- **Hydrodynamics + EM field**
  - Negative dv_1/dy slope for both D^0 and $\overline{D^0}$
  - Larger magnitude of slope for D^0 than $\overline{D^0}$

Chatterjee, Bozek: Phys. Lett. B 798, 134955, (2019).



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 constrain the difference between the tilt of the QGP bulk and the longitudinal density profile of HF production**



D^0 (STAR): Phys. Rev. Lett. 123, 162301 (2019).
Kaons (STAR): Phys. Rev. Lett. 120, 062301 (2018).

CONCLUSIONS

- STAR has extensively studied production of open-charm hadrons in heavy-ion collisions utilizing the Heavy-Flavor Tracker
- The charm 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
- 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