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

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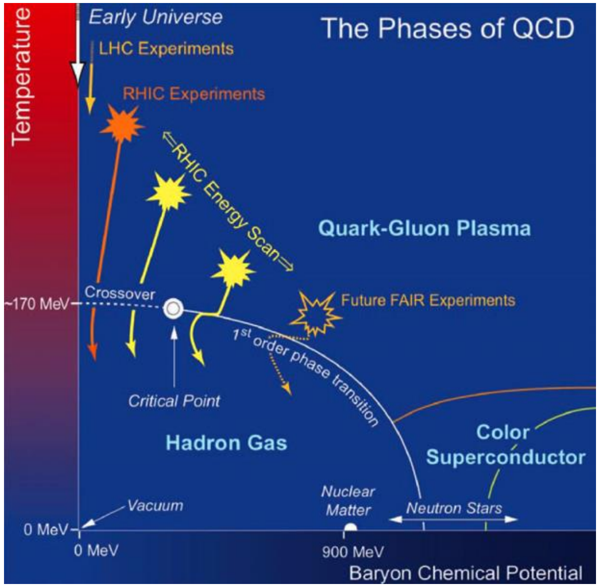
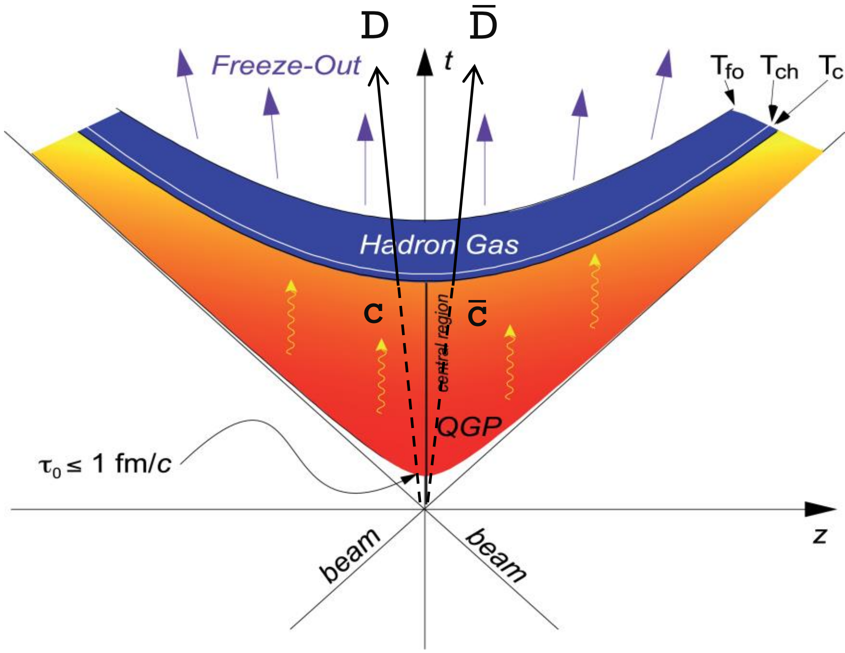
PHYSICS MOTIVATION

- **Quark-Gluon Plasma** (QGP) is the state of matter where quarks and gluons are no longer trapped inside colorless hadrons

- QGP can be studied using relativistic heavy-ion collisions

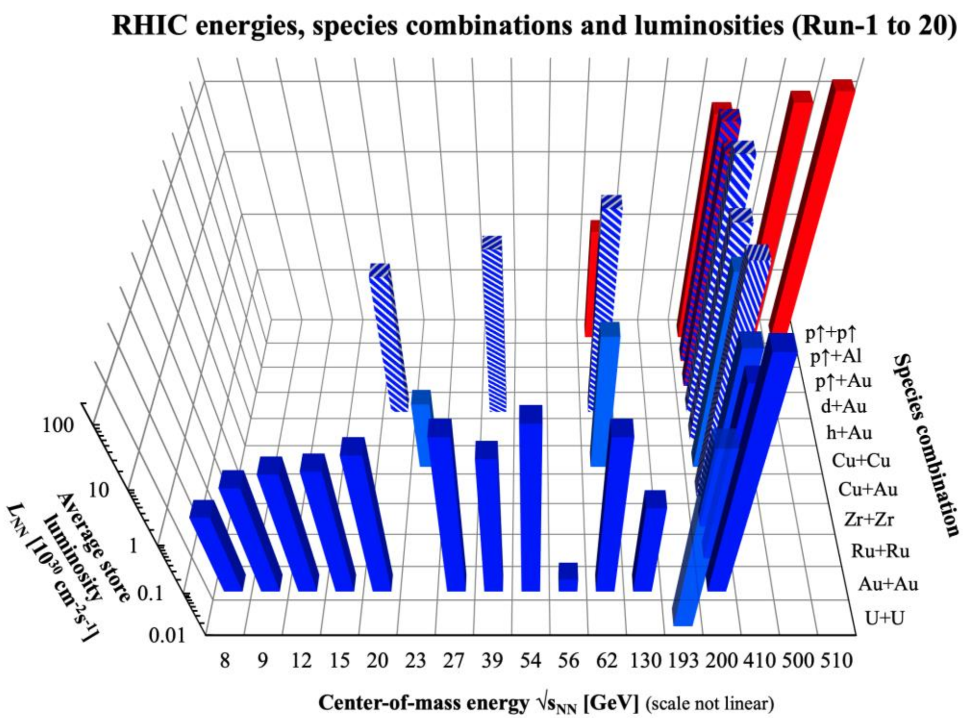
- At RHIC energies, **charm quarks** are produced predominantly through hard partonic scatterings at **early stage** of Au+Au collisions
  - They experience **the whole evolution of the medium**

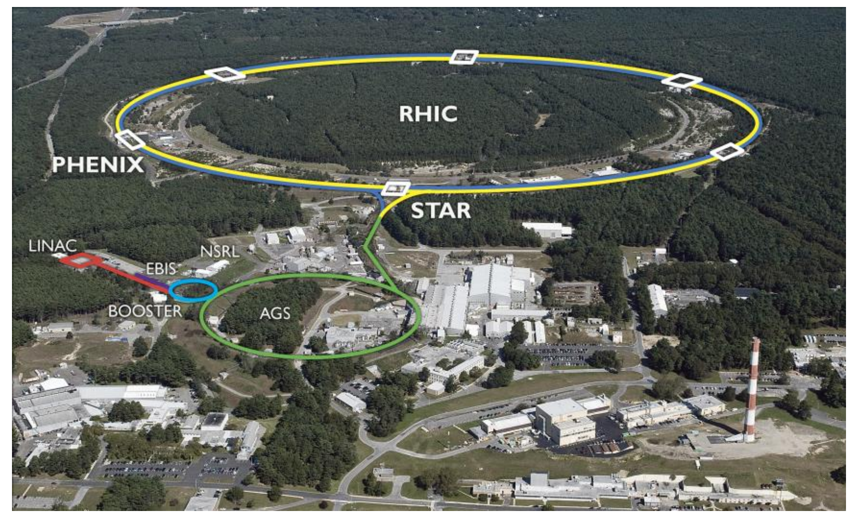




RELATIVISTIC HEAVY-ION COLLIDER

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

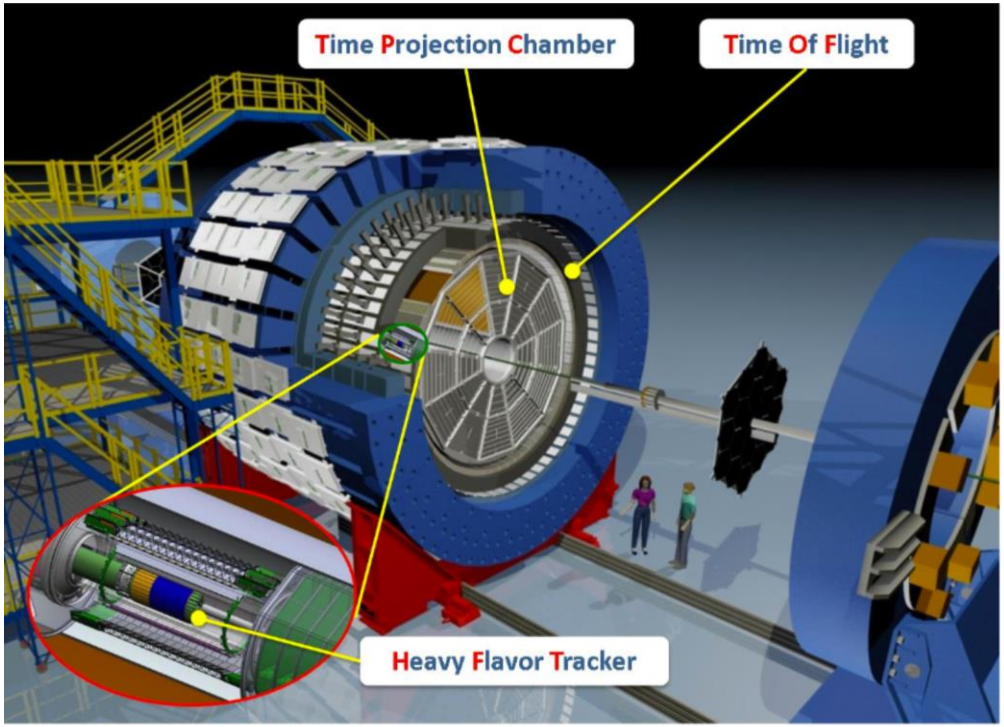


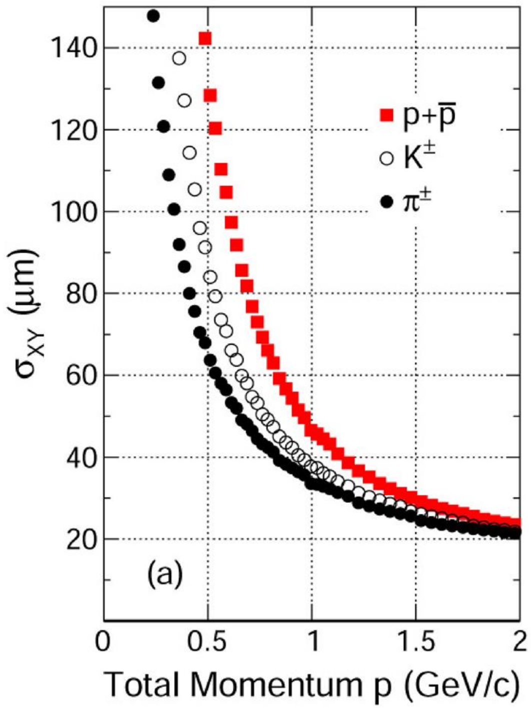


STAR DETECTOR

- **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)



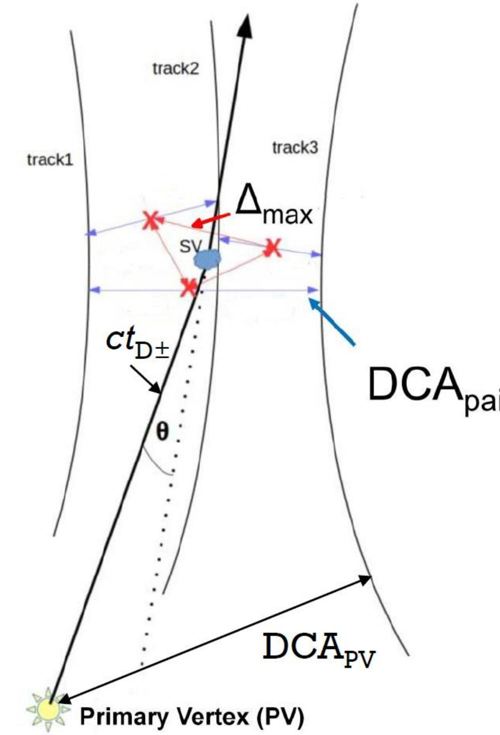


OPEN-CHARM MEASUREMENTS WITH THE HFT

- 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 [%]
D^+ $(c\bar{u})$	$D^+ \rightarrow K^-\pi^+\pi^+$	311.8 ± 2.1	8.98 ± 0.28
D^0 $(c\bar{d})$	$D^0 \rightarrow K^-\pi^+$	122.9 ± 0.4	3.93 ± 0.04
D_s^+ $(c\bar{s})$	$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$	149.9 ± 2.1	2.27 ± 0.08
Λ_c^+ (udc)	$\Lambda_c^+ \rightarrow K^-\pi^+p$	59.9 ± 1.8	6.35 ± 0.33

- *Charge conjugate particles are also measured



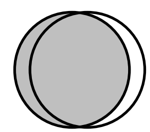
Cartoon of $D^{\pm}$ decay topology

D^0 NUCLEAR MODIFICATION FACTOR

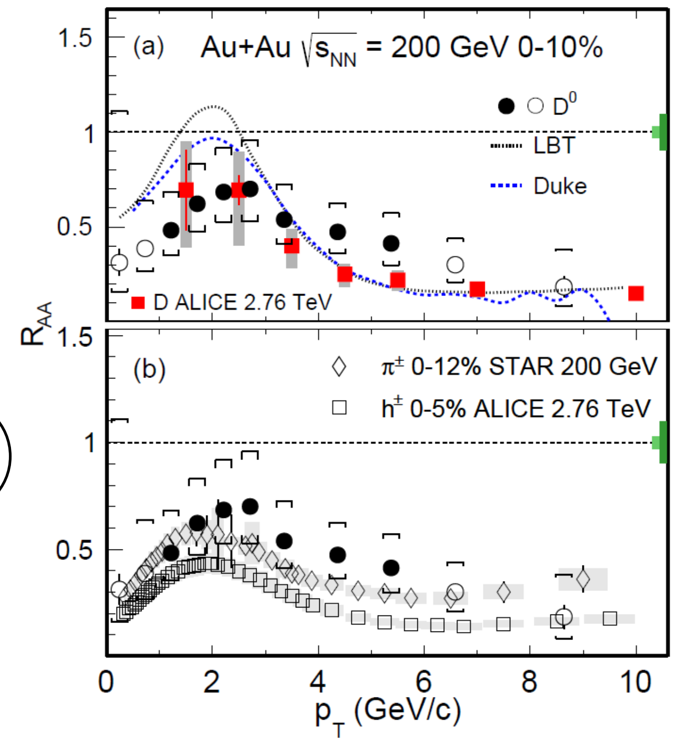
- Nuclear modification factor:

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

- Reference: combined D^0 and D* measurements in 200 GeV p+p collisions using 2009 STAR data
- D^0 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

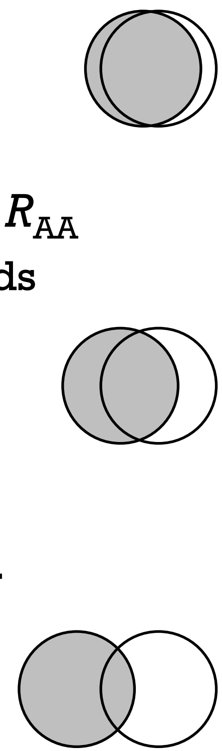


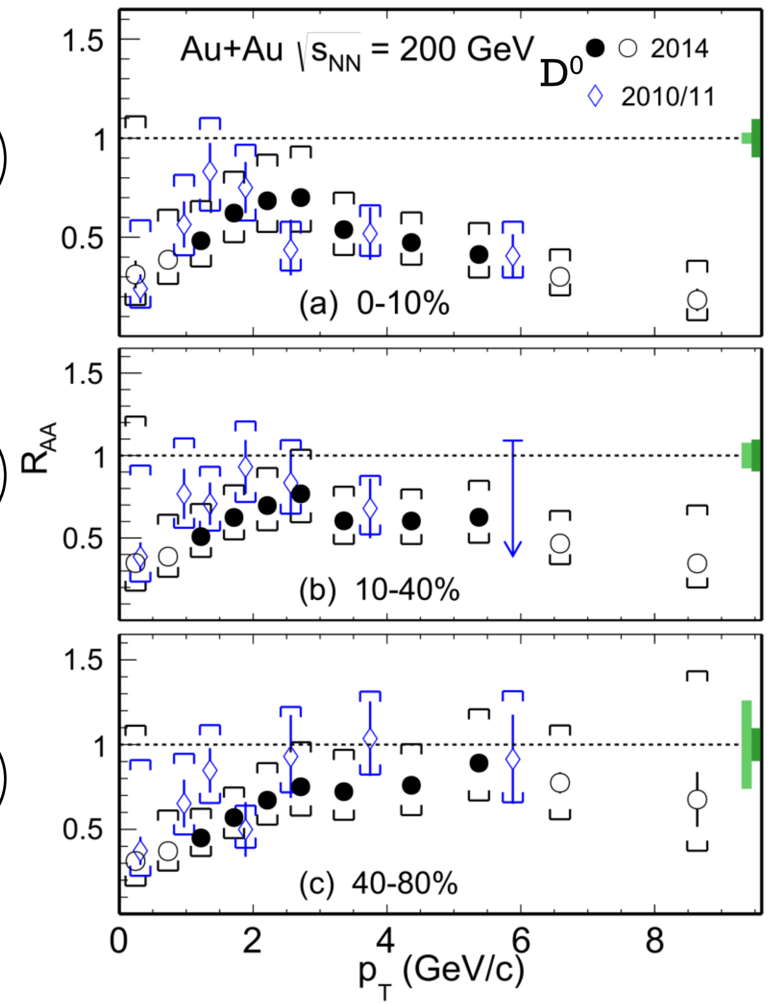
D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
$\pi^{\pm}$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
$h^{\pm}$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

- **Strong interactions between charm quarks and the medium**

D^0 NUCLEAR MODIFICATION FACTOR

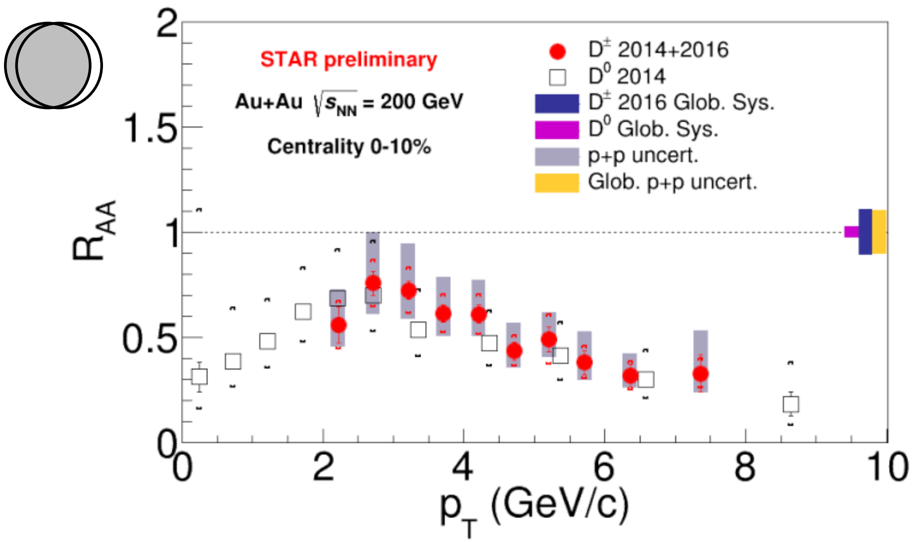
- Centrality dependence of D^0 mesons R_{AA}
  - Suppression at high p_T increases towards more central collisions
  - Low-p_T D^0 suppressed for all studied centrality classes of Au+Au collisions
- **Integrated R_{AA} < 1 for D^0 mesons in central and peripheral collisions**

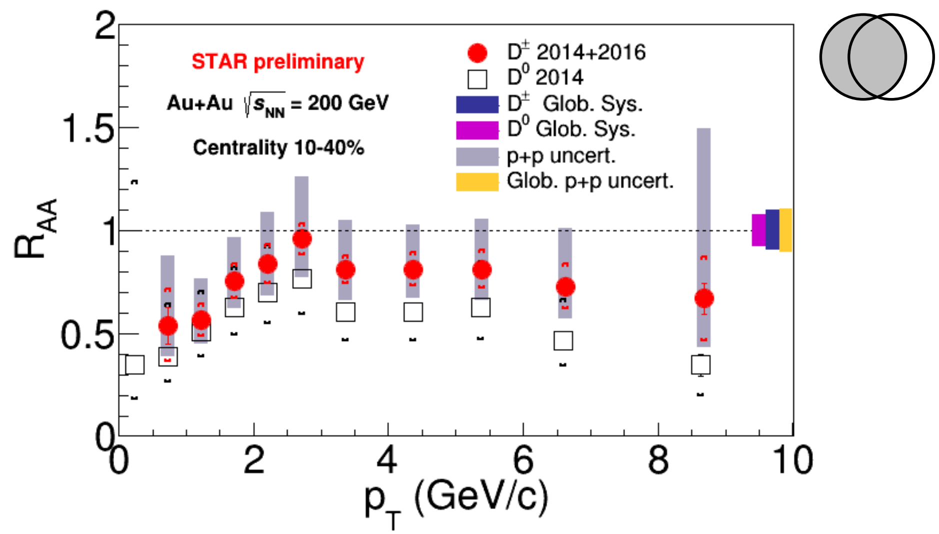


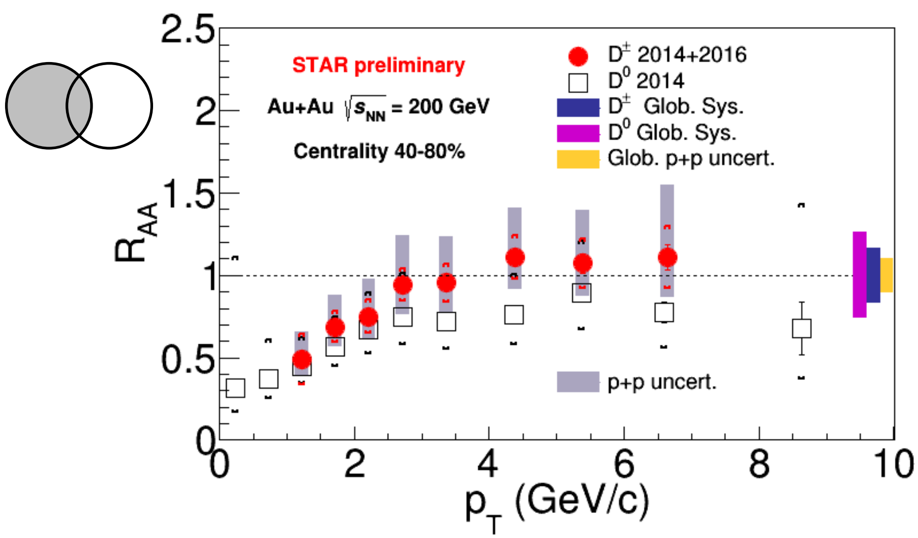


D^0 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D^0 2010/11 (STAR): Phys. Rev. Lett. 113, 142301 (2014), erratum: Phys. Rev. Lett. 121, 229901 (2018).

$D^{\pm}$ NUCLEAR MODIFICATION FACTOR





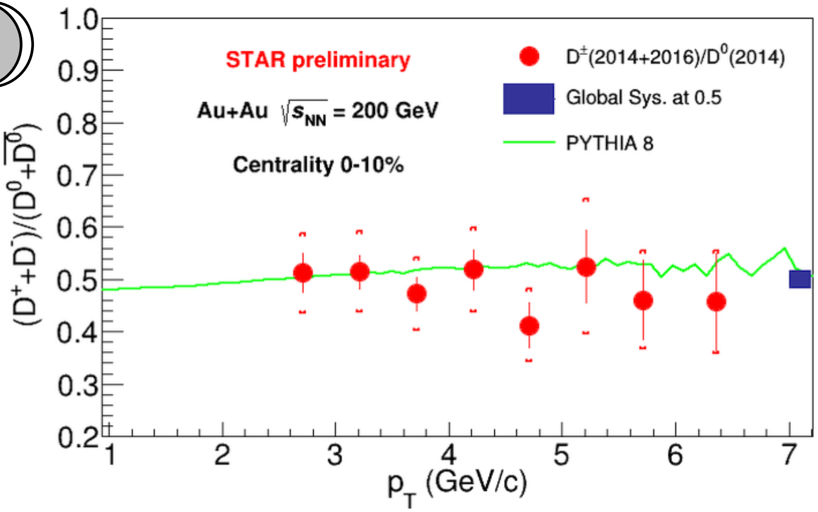


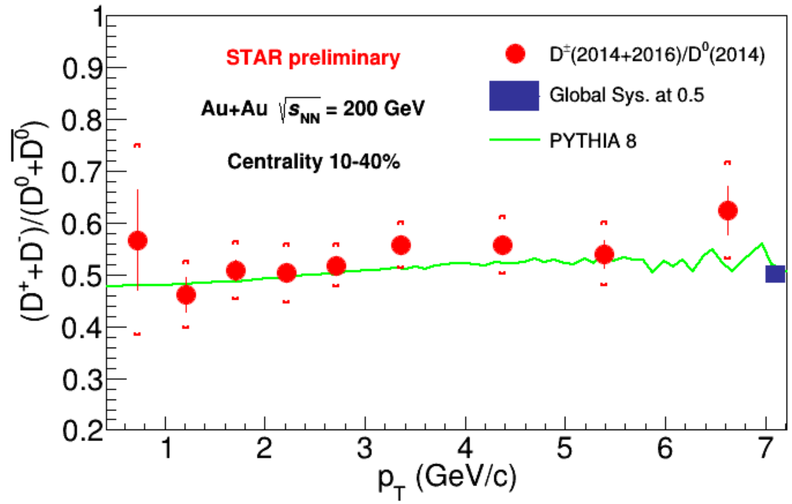
- Reference: combined D^0 and D^* measurements in 200 GeV p+p collisions using 2009 data
- Similar level of suppression and centrality dependence for $D^{\pm}$ and D^0
- High-p_T $D^{\pm}$ and D^0 suppressed in central Au+Au collisions
  - Strong interactions between charm quarks and the medium

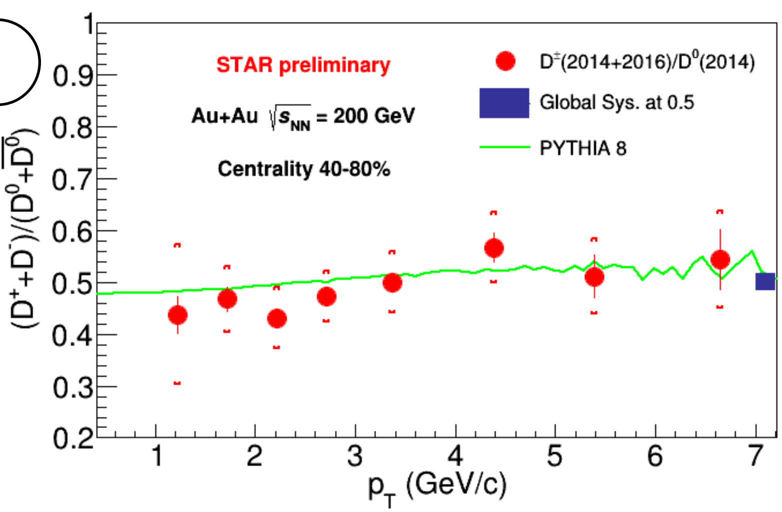
p+p reference (STAR): Phys. Rev. D 86, 072013, (2012)

D^0 (STAR): Phys. Rev. C 99, 034908, (2019).

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



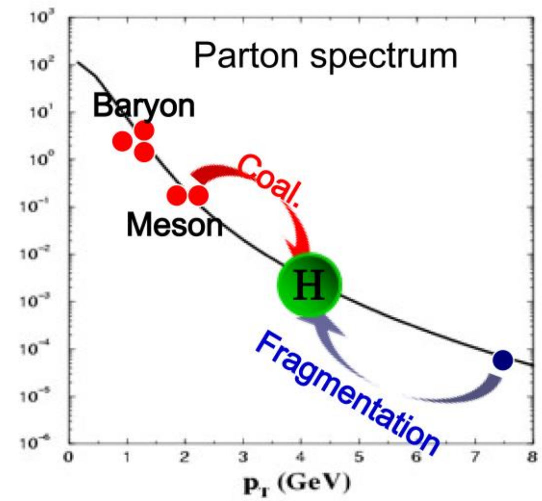




- The $D^{\pm}/D^0$ yield ratio in Au+Au collisions is compared to that from MC simulation of p+p collisions (PYTHIA 8)
  - Good agreement in all Au+Au centrality classes
- No modification of the $D^{\pm}/D^0$ yield ratio compared to PYTHIA

HADRONIZATION IN A+A COLLISIONS

- **Fragmentation**
  - As a parton propagates through medium (or vacuum) it radiates gluons which then fragment into quark-antiquark pairs
  - Remaining quarks then hadronize
- **Coalescence**
  - Quarks propagating through medium hadronize with surrounding (anti-)quarks
    - Important at intermediate hadron p_T ($2 < p_T < 8$ GeV/c)
  - More likely to enhance 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
  - Known in light flavor and strange sector
- **How about heavy-flavor hadrons?**



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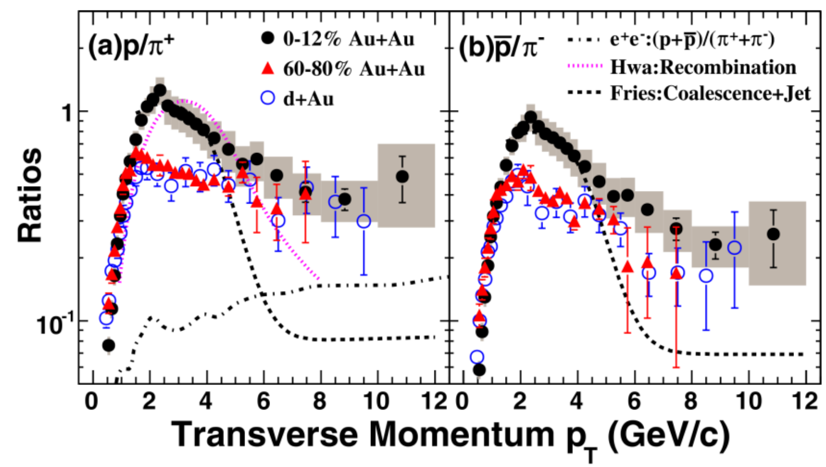


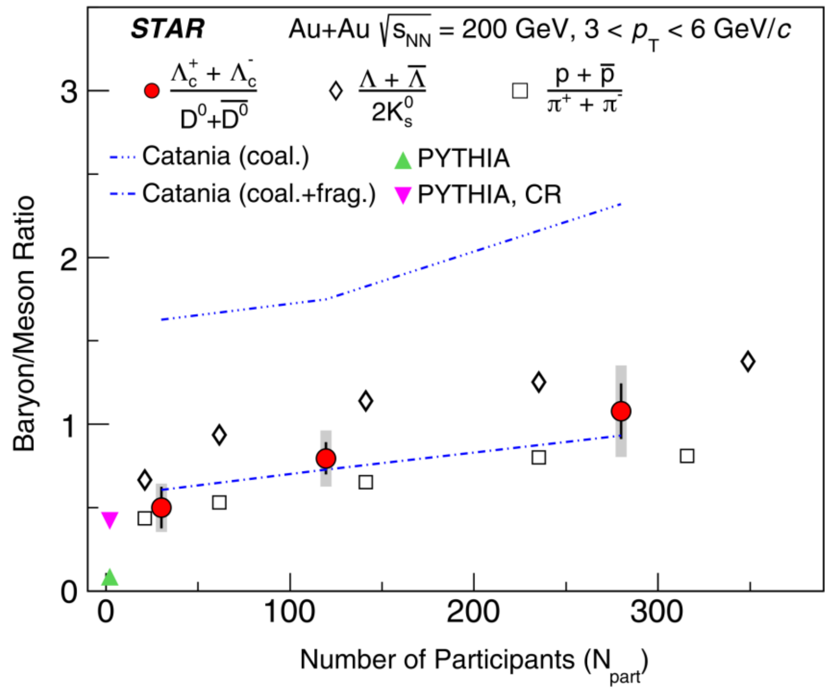
p/π (STAR): Phys. Rev. Lett. 97, 152301 (2006)

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

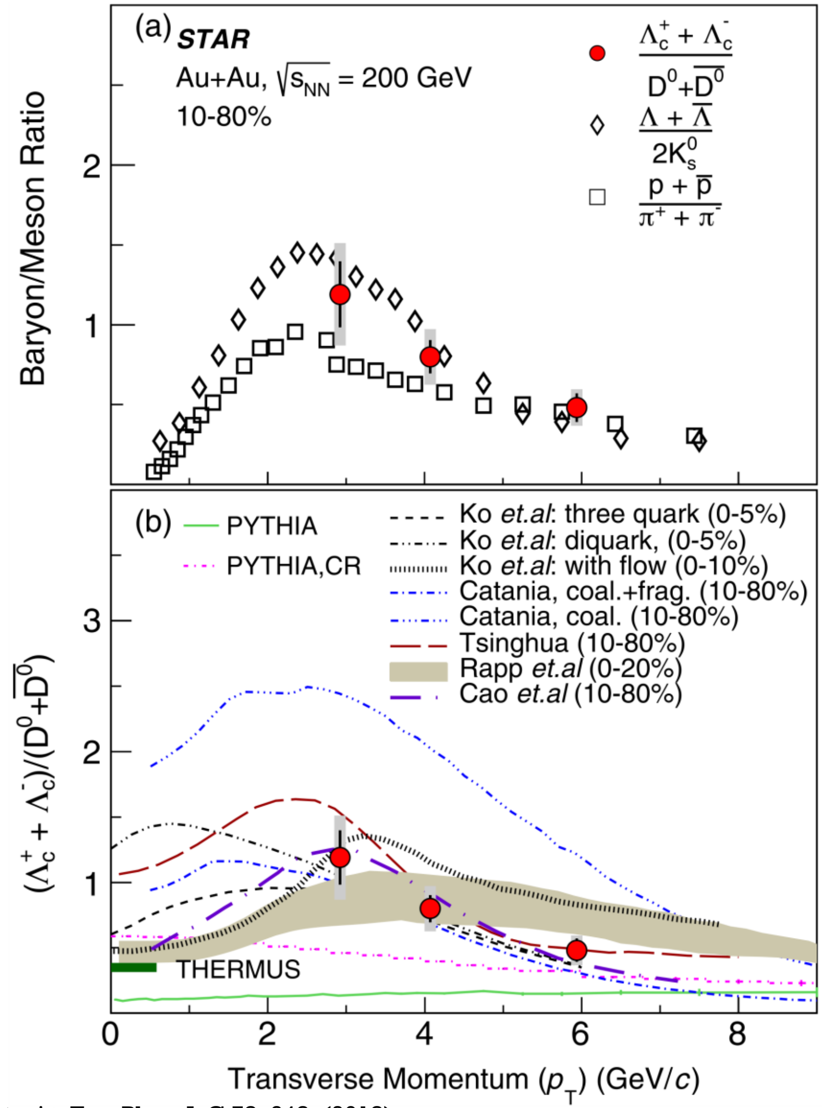
CENTRALITY DEPENDENCE

- Enhancement of the ratio increases towards central collisions
- 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

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

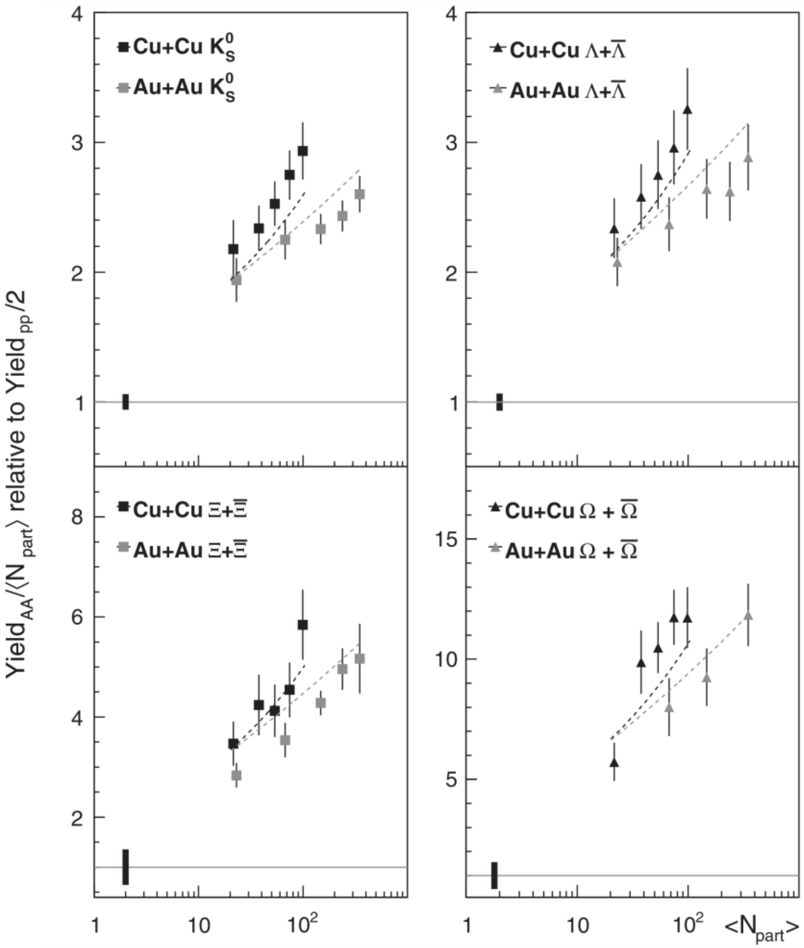


Λ_c (STAR): Phys. Rev. Lett. 124, 172301, (2020)
p/π (STAR): Phys. Rev. Lett. 97, 152301 (2006)
Λ/K (STAR): Phys. Rev. Lett. 108, 072301 (2012)
Ko *et al.*: Phys. Rev. C 101, 024909, (2020)

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

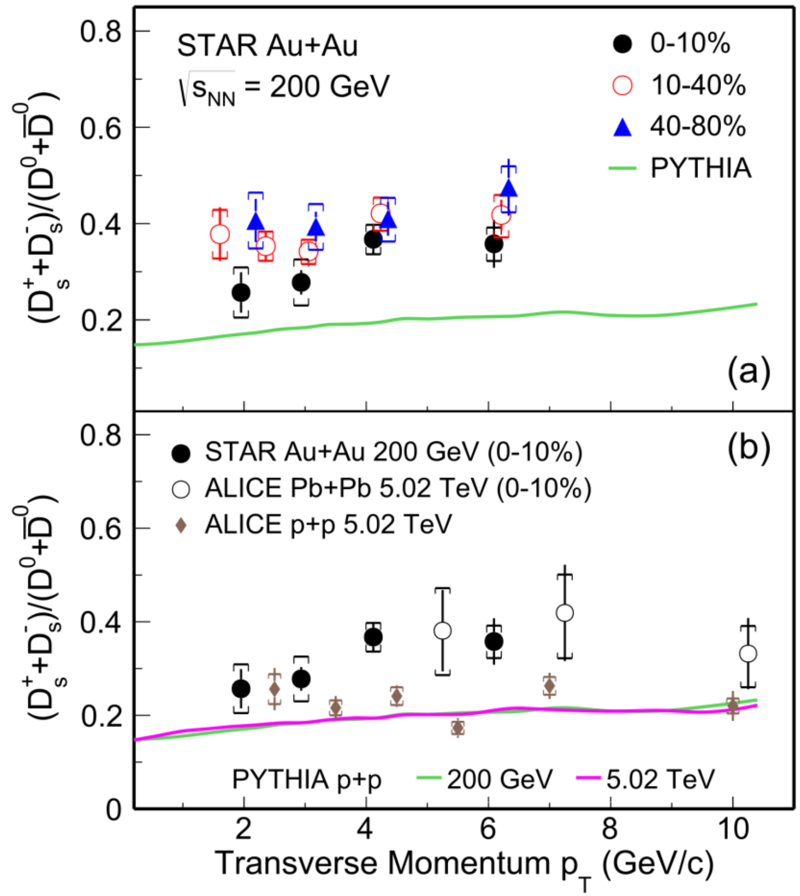
- Another very important phenomenon observed in heavy-ion collisions is **strangeness enhancement**
- Protons and neutrons do not contain any (valence) strange quarks
  - Need a mechanism of strangeness production
- Fragmentation of gluons
  - Present in both p+p and Au+Au
- Strange quark-antiquark pairs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

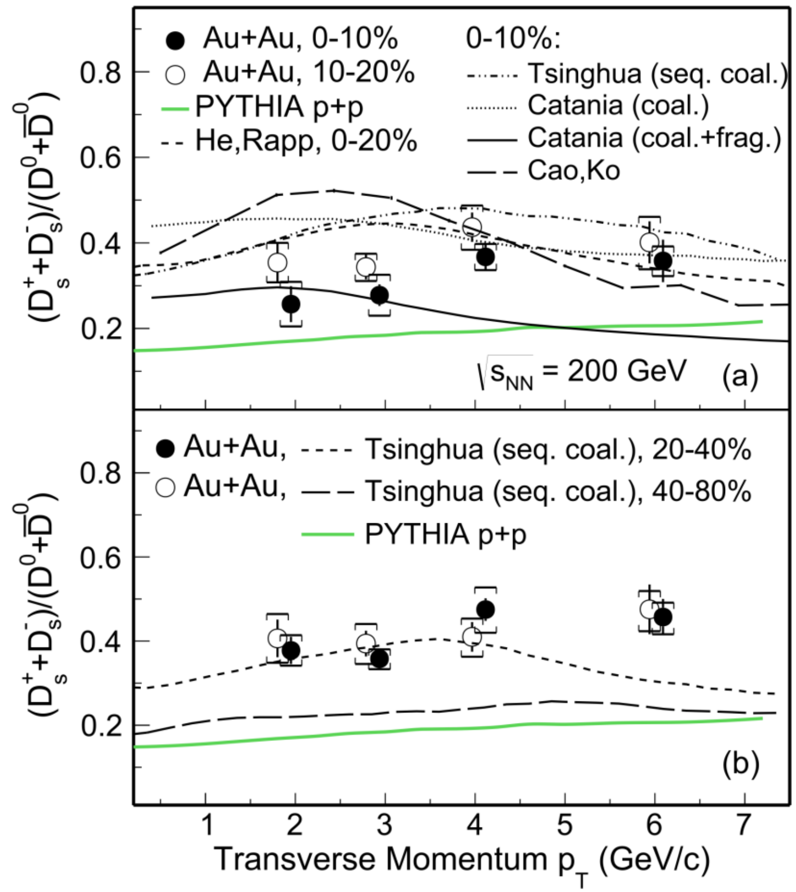
- D_s/D^0 yield ratio as a function of p_T
- Enhancement of D_s/D^0 ratio in Au+Au collisions with respect to:
  - PYTHIA baseline at 200 GeV
- Comparable to ALICE Pb+Pb at 5.02 TeV



STAR: arXiv:2101.11793
ALICE p+p: Eur. Phys. J. C 79, 388 (2019).
ALICE Pb+Pb: JHEP 10, 174 (2018).

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 $p_T < 3$ GeV/c
  - Tsinghua model with sequential coalescence hadronization is closer to data overall
- **Importance of coalescence hadronization of charm quarks**



STAR: arXiv:2101.11793
Catania: Eur. Phys. J. C 78, 348, (2018).
Tsinghua: arXiv1805.10858, (2018).
He, Rapp, Phys. Rev. Lett. 124, 042301 (2020)
Cao, Ko *et al.*: Phys. Lett. B 807, 135561 (2020).

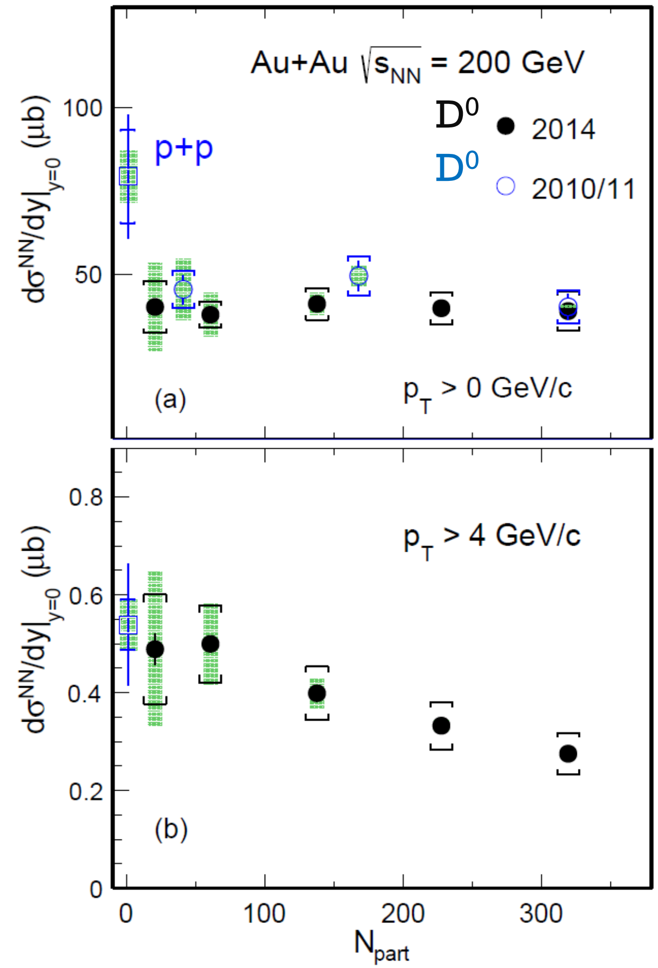
TOTAL CHARM PRODUCTION CROSS SECTION

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

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**

*The Λ_c cross section is derived using the Λ_c/D^0 yield ratio

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)



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
  - 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

THANK YOU FOR ATTENTION