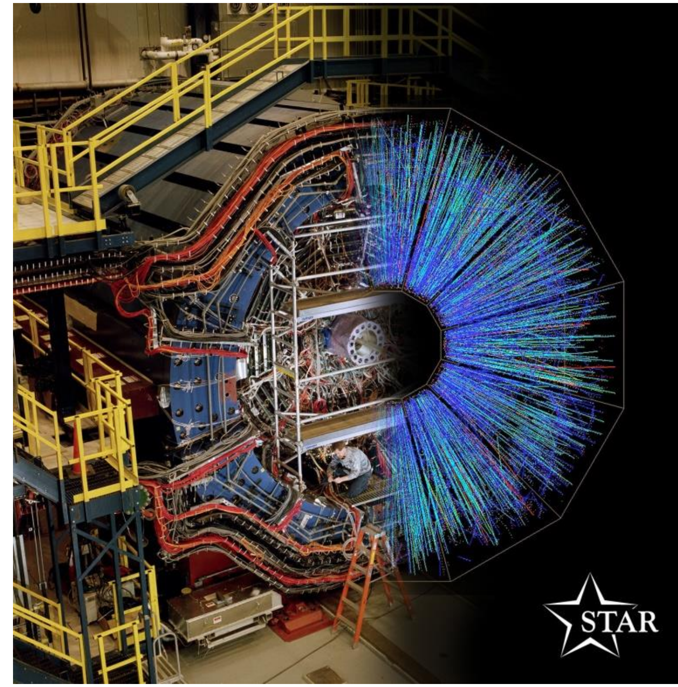
Heavy flavor measurements in STAR experiment



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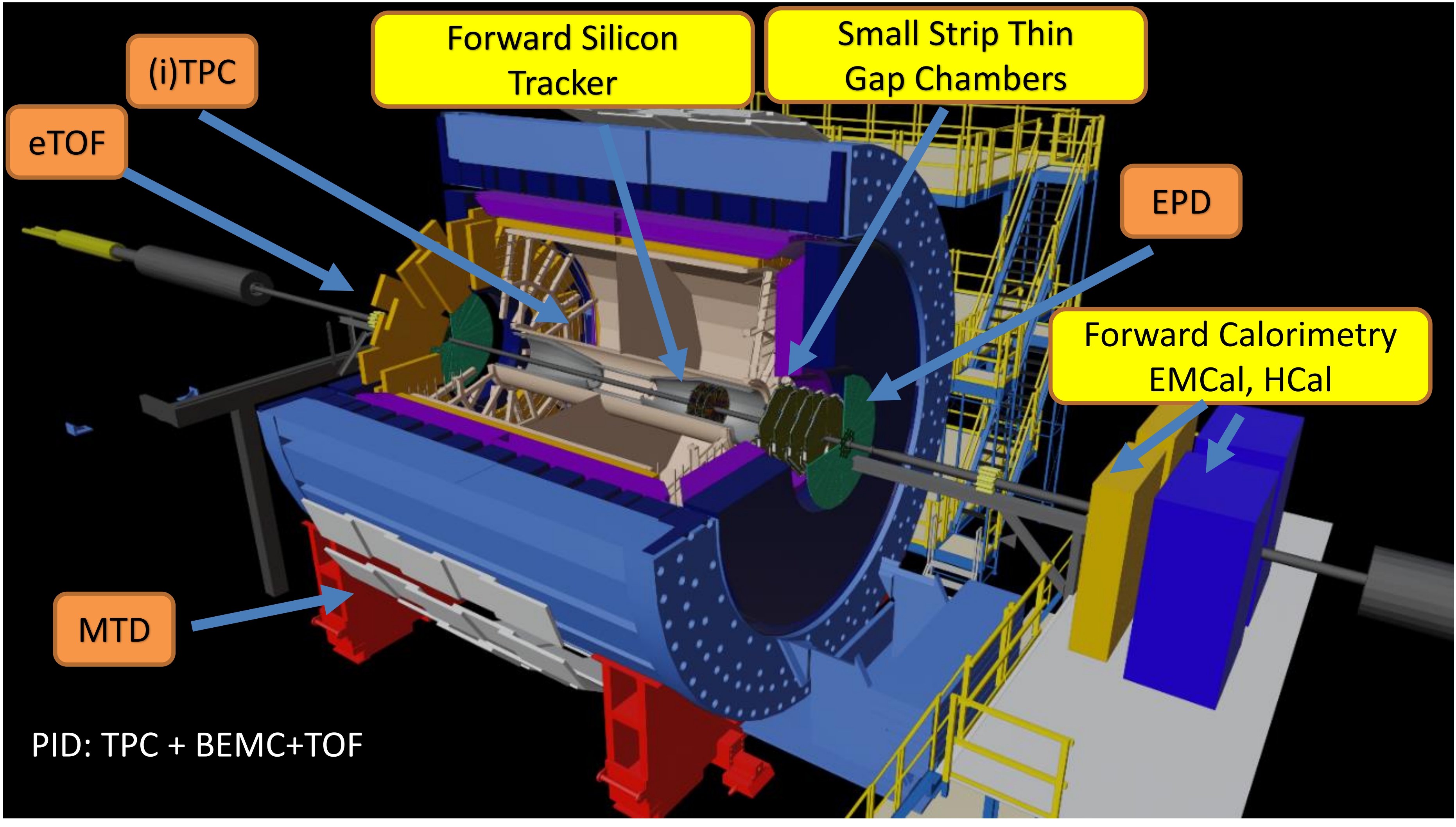
EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education

MINISTRY OF EDUCATION, YOUTH AND SPORTS

Exploring Quark-Gluon Plasma through soft and hard probes, 29.-31. May 2023, Belgrade

STAR experiment

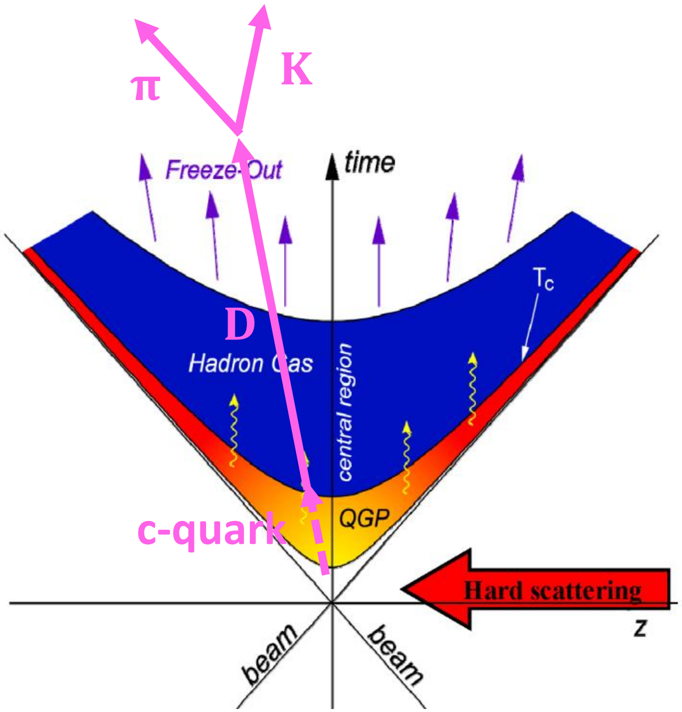
- Plan 2023-2025: Au+Au 200 GeV, p+p 200 GeV, p+Au 200 GeV

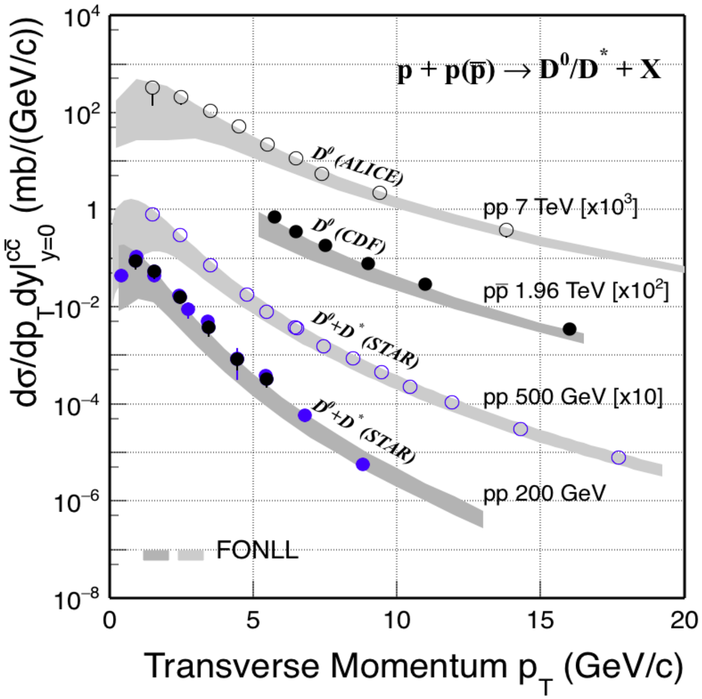


Forward upgrade: $2.5 < \eta < 4$

Heavy flavor tracker: 2014-2016

Probing Quark Gluon Plasma with charm quark





STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001

- **Charm quark: $m_c >> T_{QGP}, \Lambda_{QCD}$**
- Produced in hard scatterings at the early stage of nuclear collisions → experience the entire evolution of medium
- We aim to understand charm quark energy loss in the medium, charm quark transport and hadronization

- Its production rates are well described by pQCD in elementary collisions

Open charm hadron reconstruction

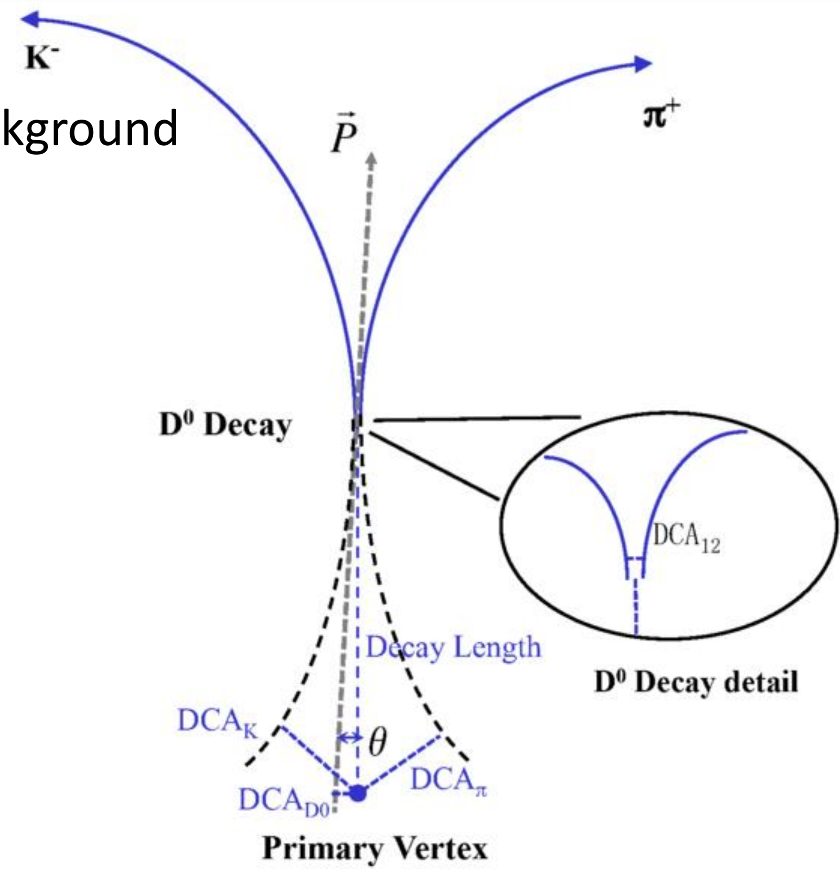
- Data from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV collected with Heavy flavor trigger in years 2014 and 2016
- HFT allows direct **topological reconstruction** of open-charm hadrons via their hadronic decays
- Significant suppression of combinatorial background
- Decay channels used:
  - $D^+ \rightarrow K^-\pi^+\pi^+$, $c\tau$ = (311.8 ± 2.1) μm

    BR = (8.98 ± 0.28) %
  - $D^0 \rightarrow K^-\pi^+$, $c\tau$ = (122.9 ± 0.4) μm

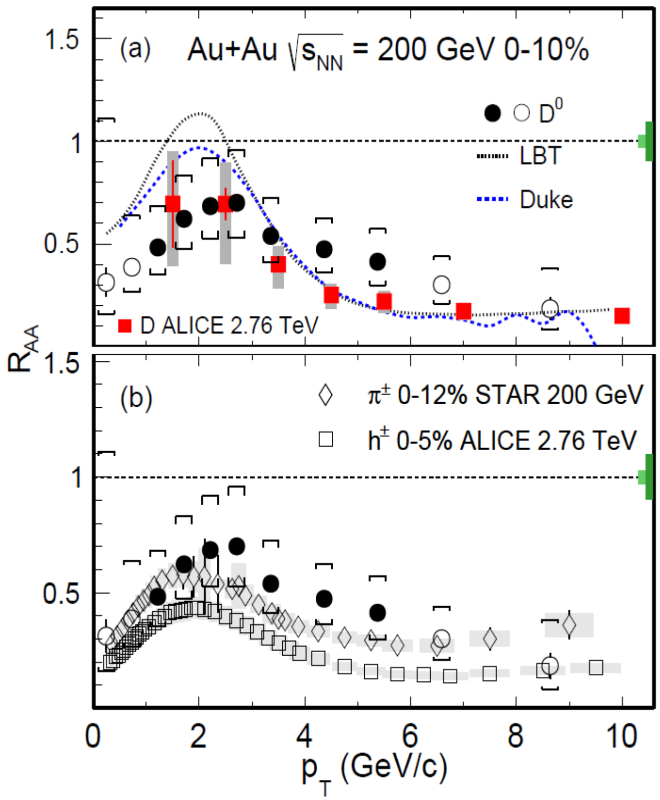
    BR = (3.93 ± 0.04) %
  - $D_s \rightarrow \pi^+\phi$, $\phi \rightarrow K^-K^+$, $c\tau$ = (149.9 ± 2.1) μm

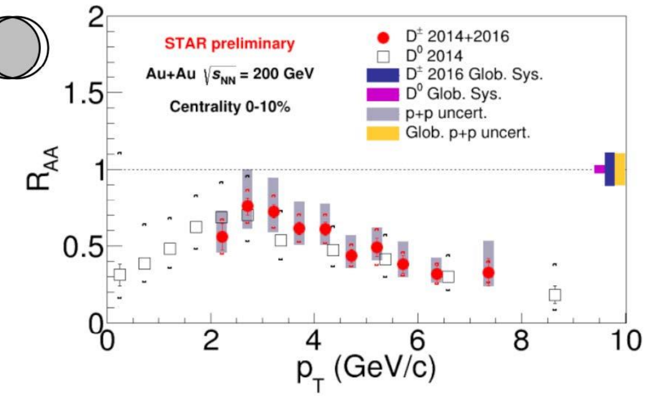
    BR = (2.27 ± 0.08) %
  - $\Lambda_c \rightarrow K^-\pi^+p$, $c\tau$ = (59.9 ± 1.8) μm

    BR = (6.35 ± 0.33) %

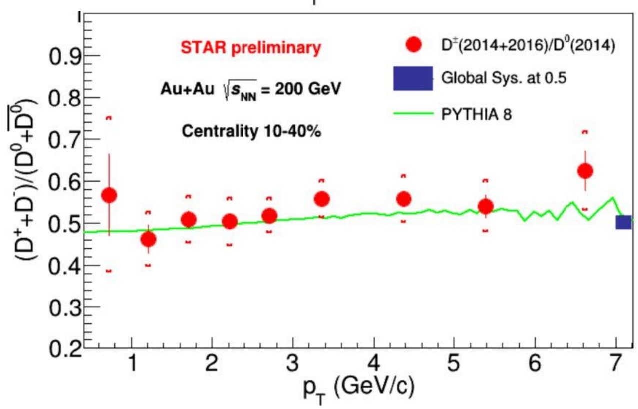


Nuclear modification factor R_{AA} of D^0 and $D^{\pm}$





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

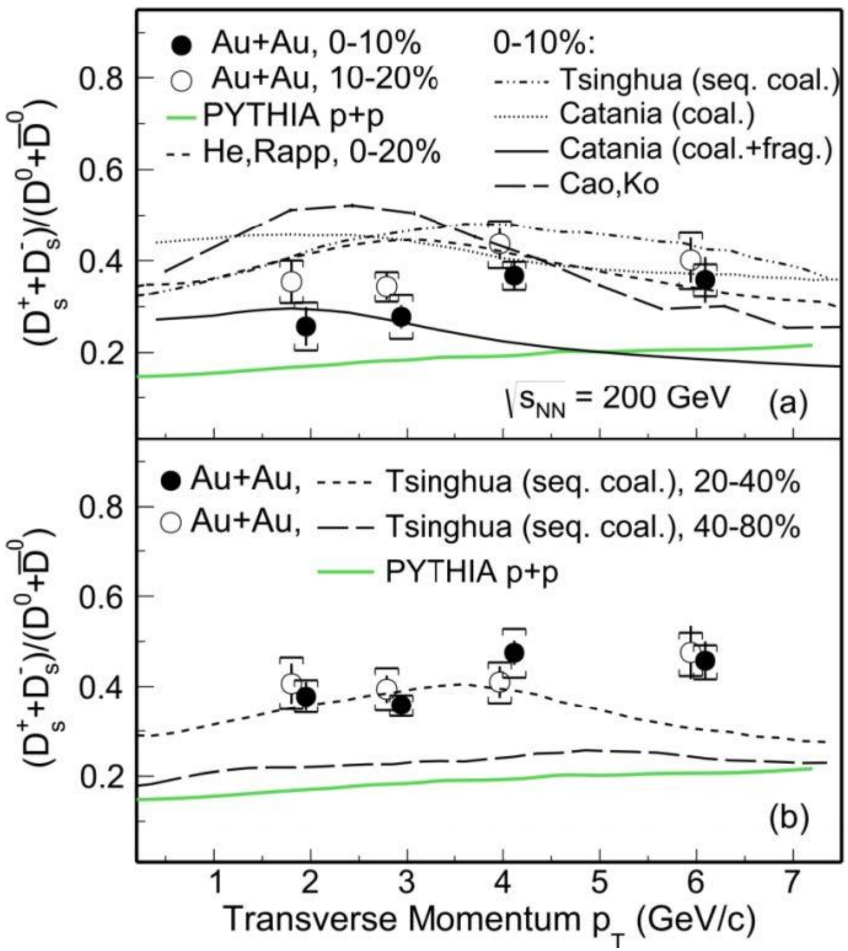


D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
$\pi^{\pm}$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
$h^{\pm}$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

Strong interaction between charm quarks and medium

- Suppression of D^0 and $D^{\pm}$ mesons at high p_T comparable to light-flavor hadrons at RHIC and D mesons at LHC
- It is reproduced by models incorporating both **radiative and collisional energy loss**
- $D^{+/-}/D^0$ yield ratio in Au+Au is consistent with PYTHIA8.

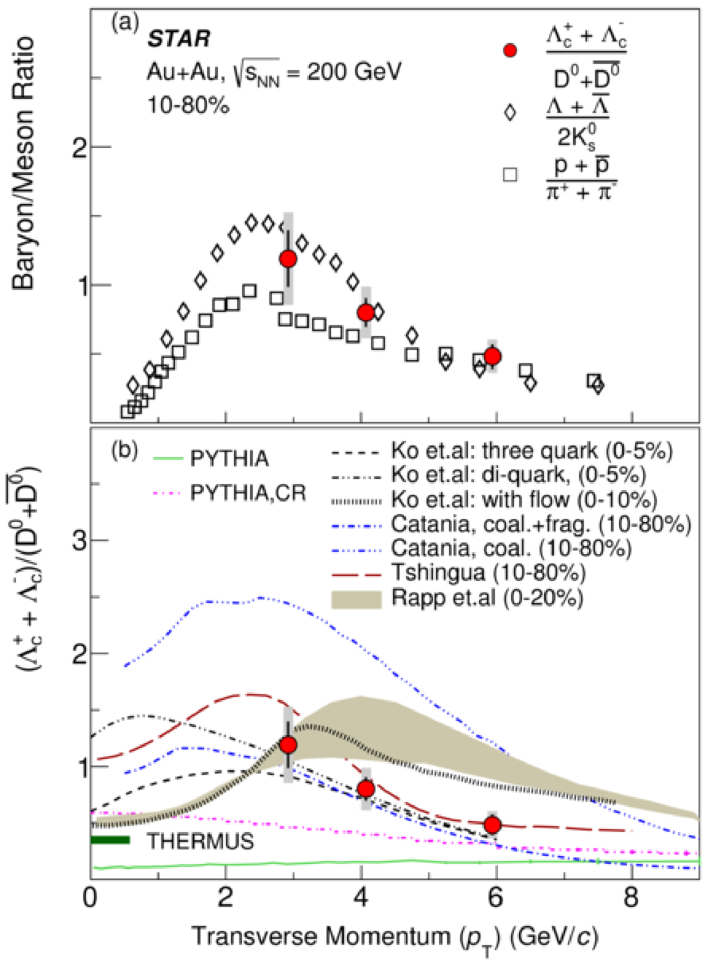
D_s/D^0 yield ratio enhancement



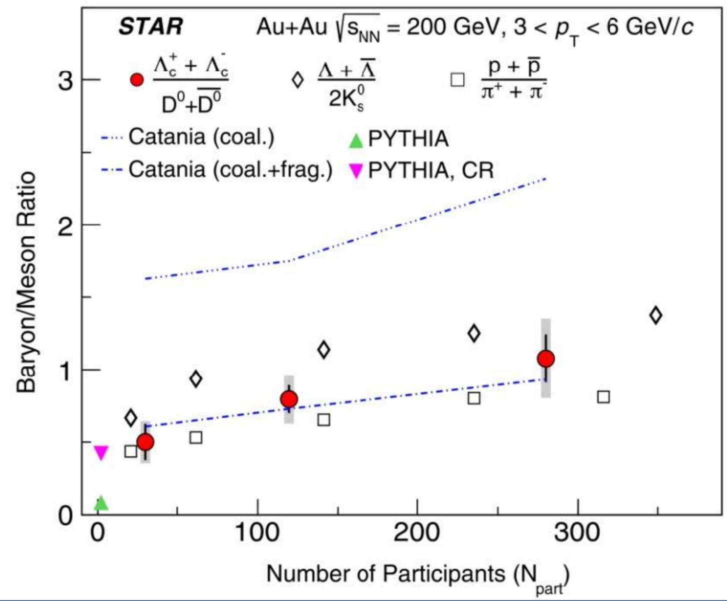
STAR, Phys. Rev. Lett. 127 (2021) 092301

- Observed strong enhancement of the D_s/D^0 yield ratio compared to PYTHIA version 6.4 p+p baseline
- The enhancement can be qualitatively described by model calculations incorporating thermal abundance of strange quarks in the QGP and coalescence hadronization
- **Recombination** of charm quarks with strange quarks in the QGP plays an important role

Λ_c/D^0 yield ratio



STAR, Phys. Rev. Lett. 124 (2020) 172301



- Λ_c/D^0 ratio is comparable to baryon-to-meson ratios of light-flavor hadrons
- Clear enhancement observed compared to PYTHIA 8.24
- Models incorporating charm quark hadronization via coalescence are consistent with data
- Enhancement of ratio increases in central collision

Importance of coalescence of charm quarks

Charm production cross section

Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0 [1]	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3*
	D_s [2]	15 ± 2 ± 4
	Λ_c [3]	40 ± 6 ± 27**
	Total	112 ± 6 ± 27
p+p at 200 GeV [4]	**Total**	130 ± 30 ± 26

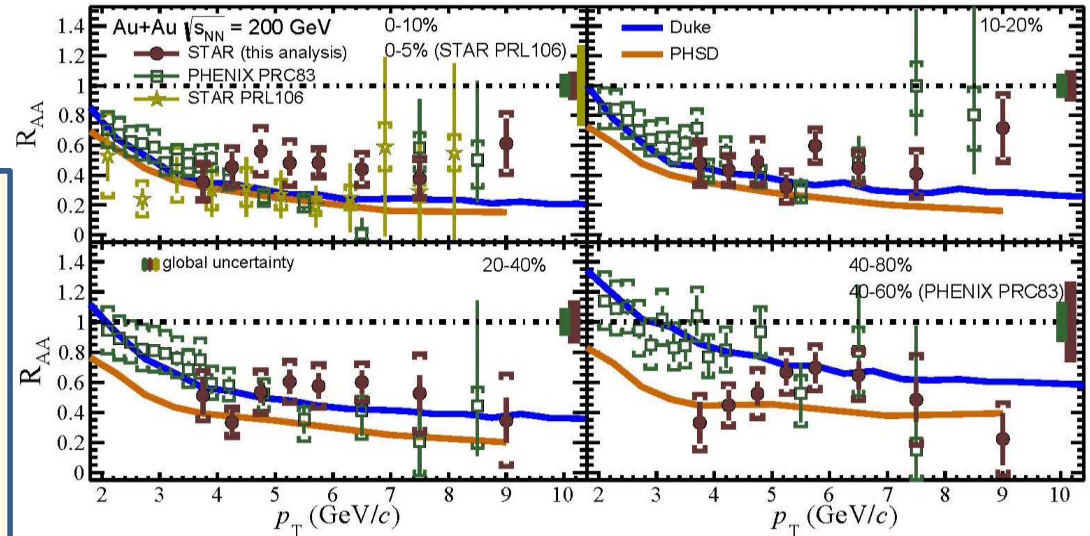
D^0 2014STAR, Phys. Rev. Lett. 127 (2021) 092301
Ds (STAR): Phys. Rev. C 99, 034908, (2019)
Lc STAR, Phys. Rev. Lett. 124 (2020) 172301
p+p (STAR): Phys. Rev. D 86 072013, (2012).

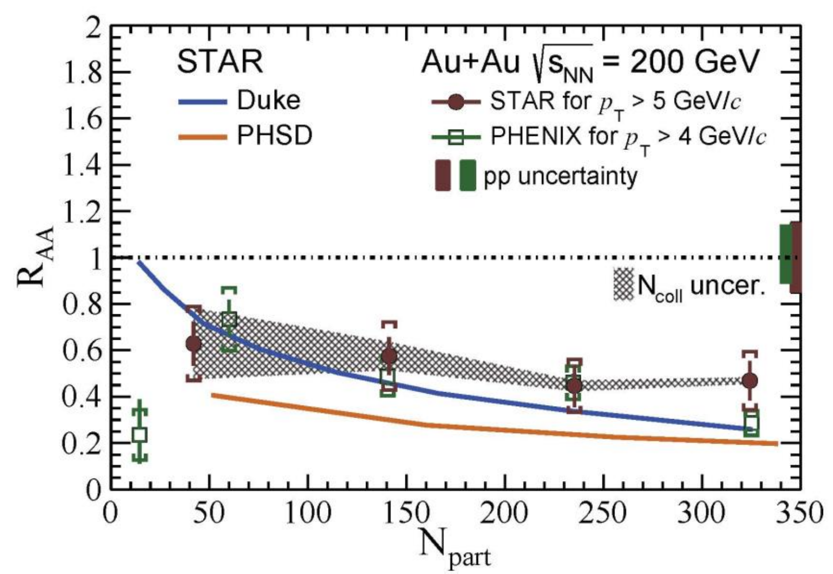
*Λ_c cross-section was derived using Λ_c/D^0 yield ratio

- p_T integrated total D^0 cross-section per binary collision is smaller in Au+Au than p+p
- Total charm production **cross-section per binary collision** in Au+Au
  - Au+Au result is consistent with that measured in p+p collisions within uncertainties
  - **Redistribution** of charm quarks among open-charm hadron species

Electrons from HF@ Au+Au 200GeV

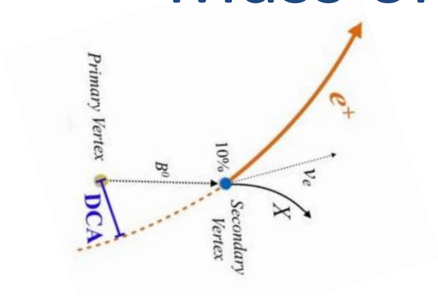
- Precise high-p_T measurement
  $3.5 < p_T < 9$ GeV/c
- A suppression by about a factor of 2 is observed in central and semi-central collisions
- No p_T dependence observed
- A hint of R_{AA} decreasing from peripheral to central collisions
- Models describe the data well
- Indication of substantial energy loss of heavy quarks in the QGP

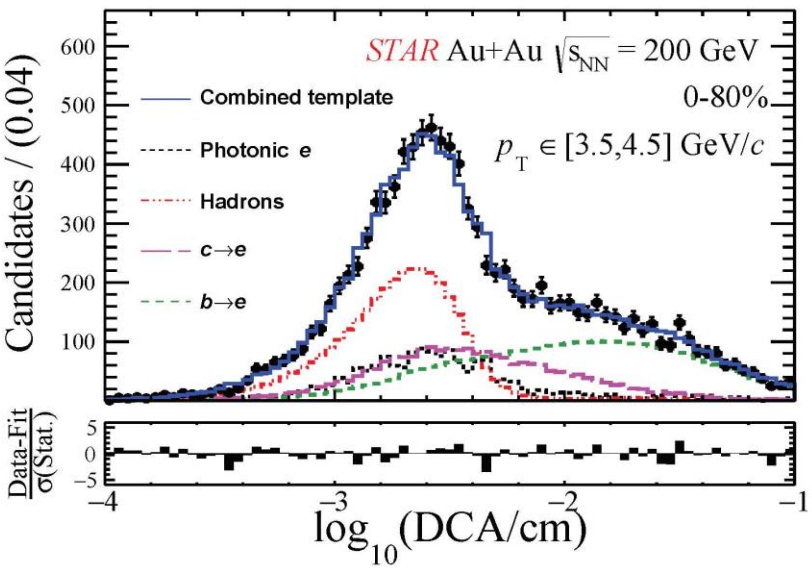




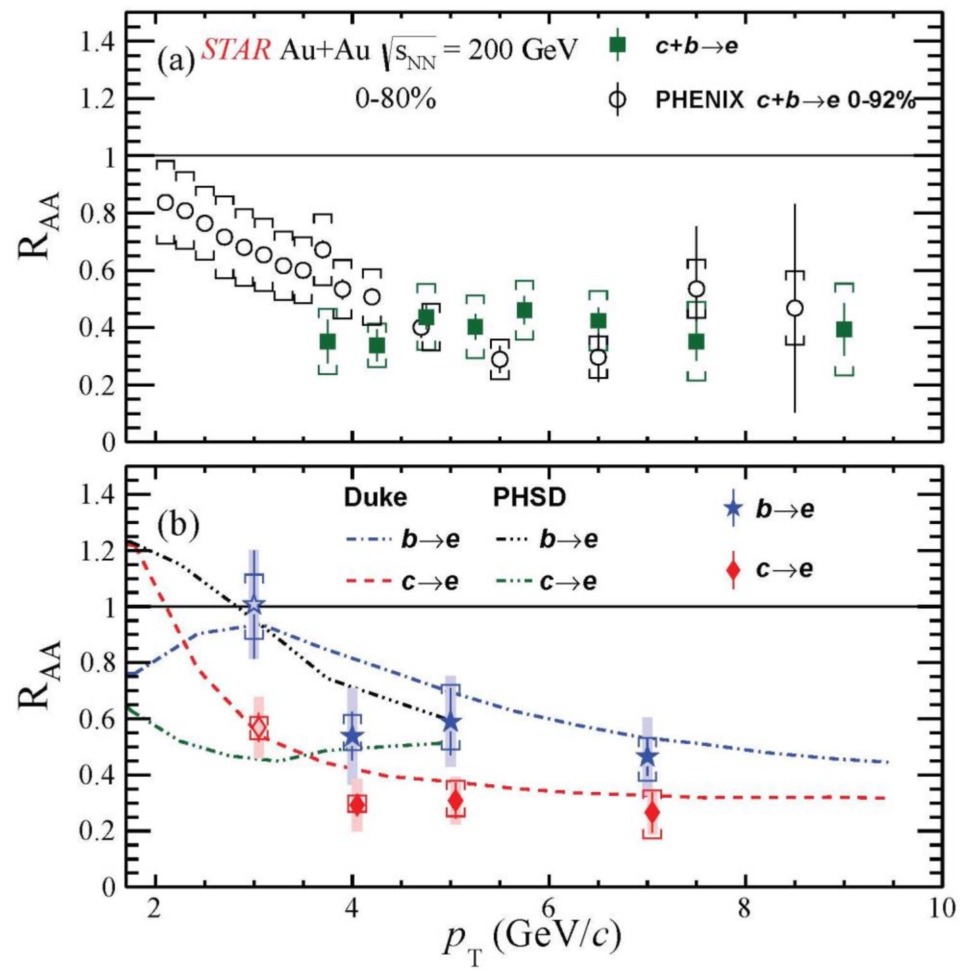
STAR: arXiv:2303.06590

Mass ordering of heavy quarks energy loss





STAR Eur. Phys. J. C 82, 1150 (2022)

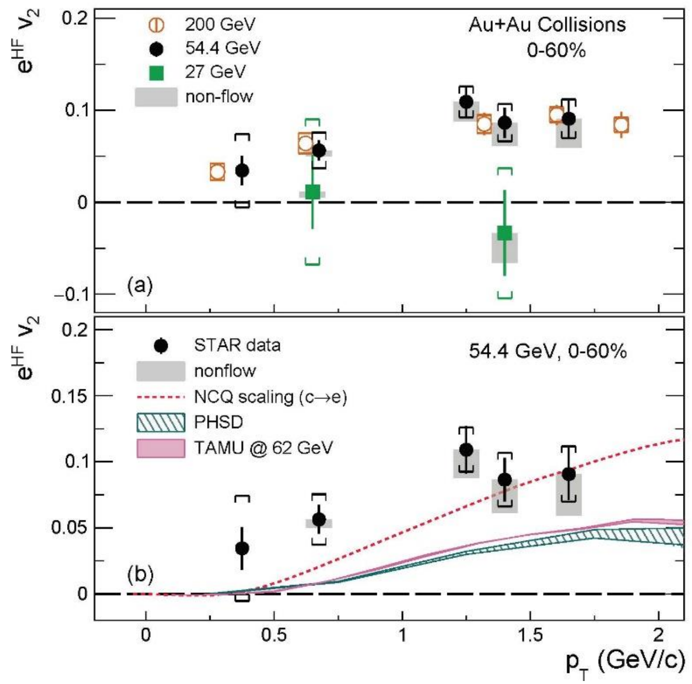


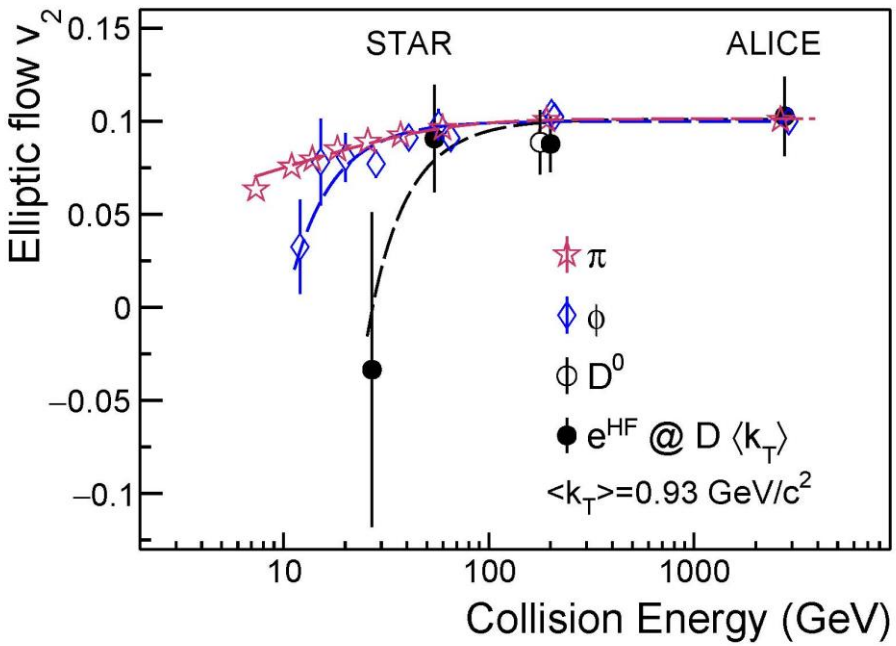
Heavy-flavor hadron decayed electrons: c → e and b → e separation **in 200 GeV Au+Au collisions** thanks to HFT

- Observation of less suppression for *B→e* than *D→e*
- Consistent with expected mass hierarchy for parton energy loss ***ΔE$_c$ > ΔE$_b$***

Energy dependence of HFE eliptic flow

$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$



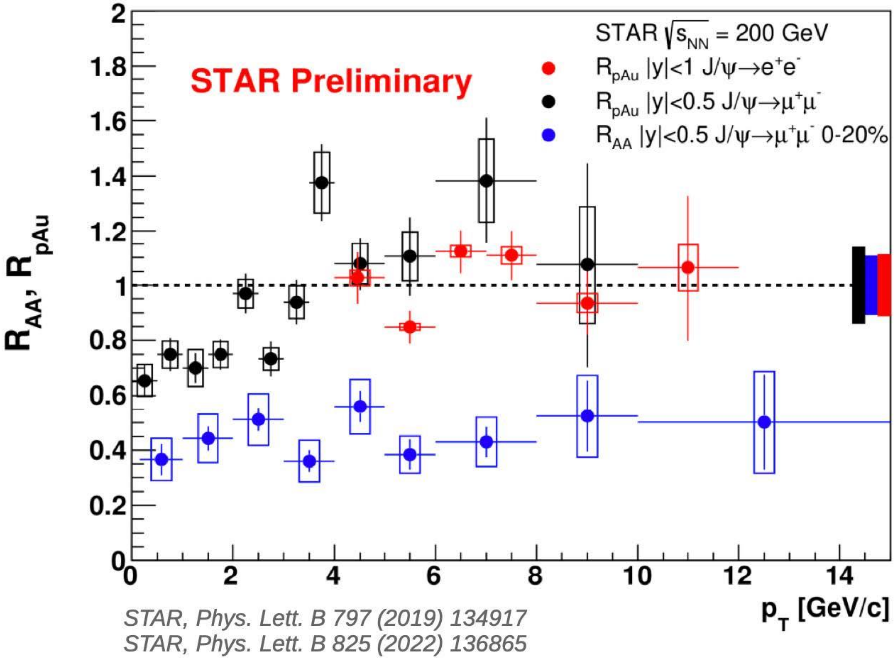


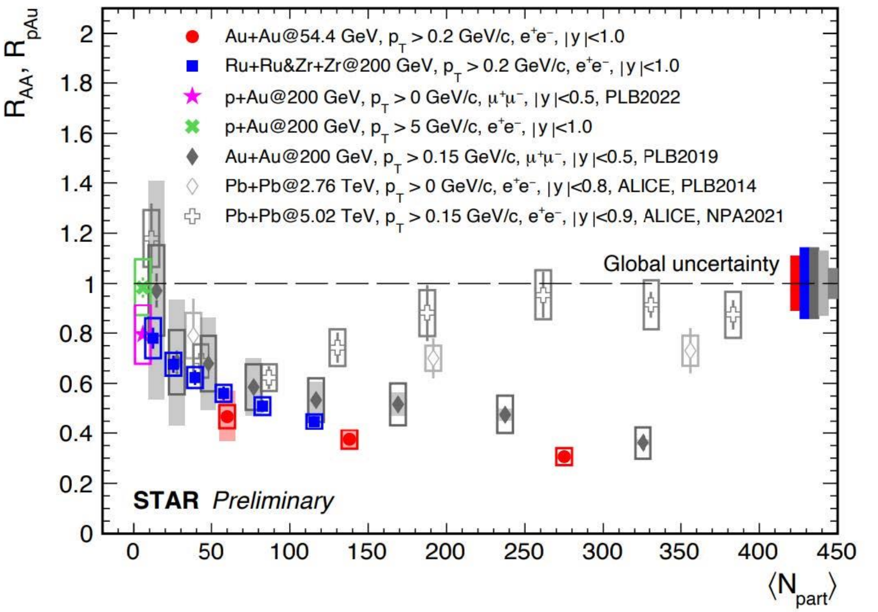
STAR: arXiv:2303.03546

- v_2 vs coll. energy → temperature dependence of charm quark diffusion coefficient
- At 27 GeV v_2 of c,b → e consistent with zero
- Significant non-zero v_2 of c,b → e at 54.4 – 200 GeV
- At low p_T models underestimate data
- **HF quarks interact strongly with the medium at 54.4 – 200 GeV**
- A hint of mass hierarchy is observed where the v_2 of heavier particles drops faster than lighter ones with decreasing collision energy

Quarkonia

J/ψ production in heavy-ion collisions

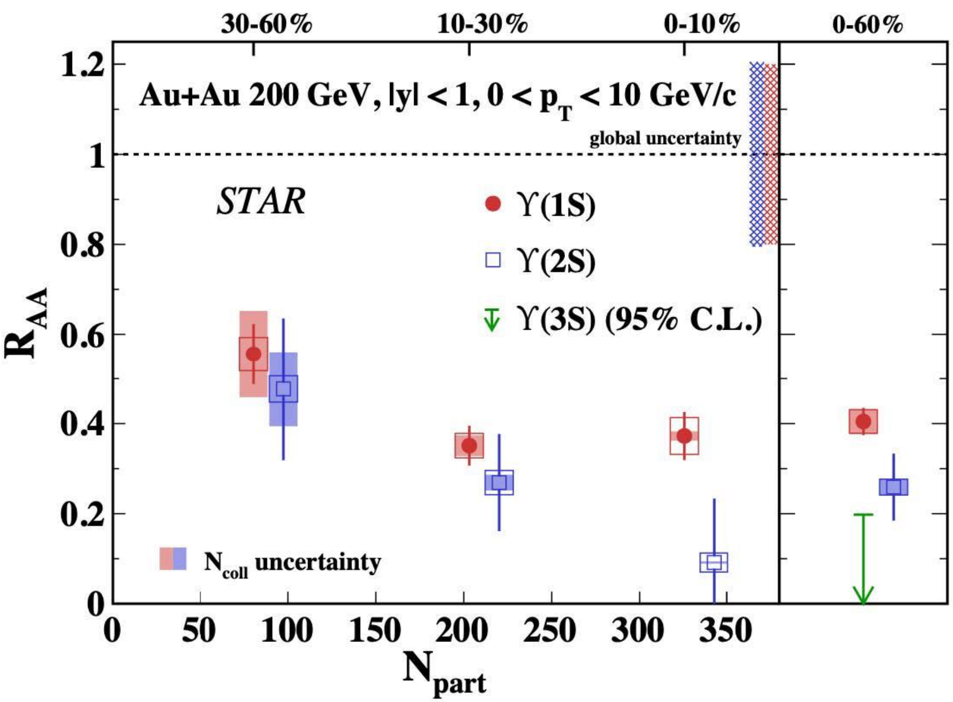


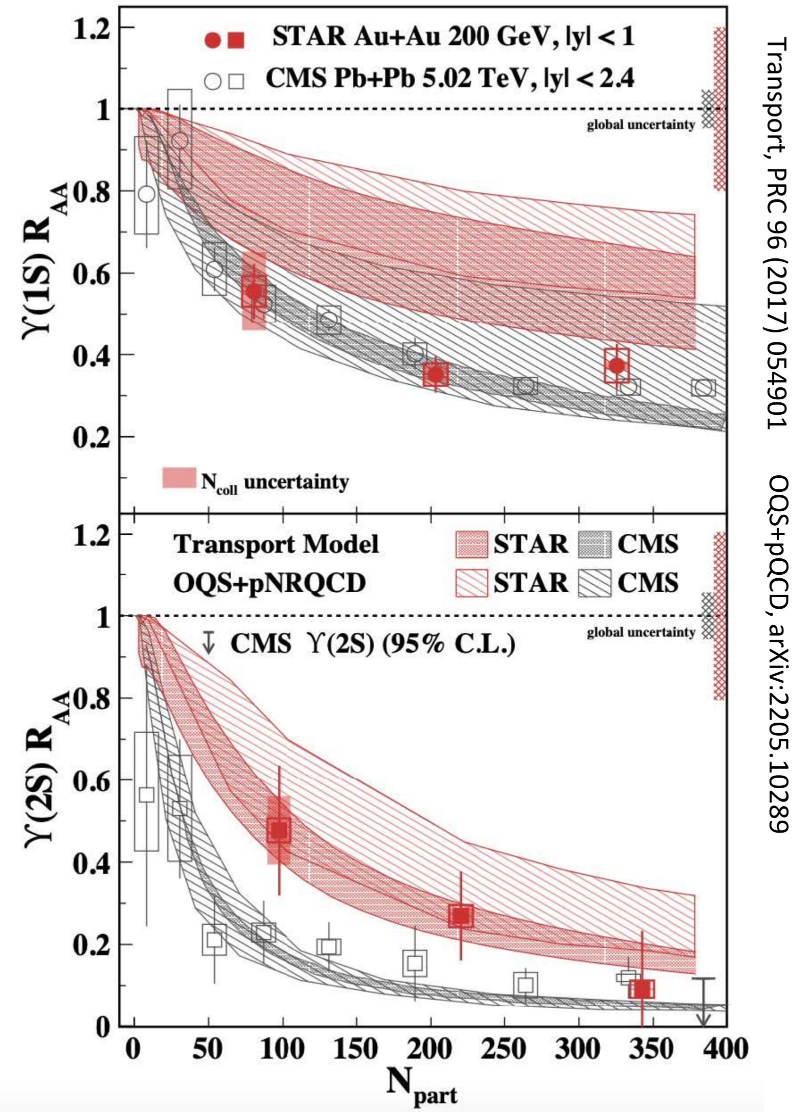


- Low p_T < 2 GeV/c: Cold nuclear matter effect
- High p_T: suppression in Au+Au due to QGP

- No significant collision system dependence of the J/ψ suppression at similar <N_{part}>
- Suppression driven by system size <N_{part}> not collision geometry
- At high p_T: Strong suppression at RHIC and regeneration at LHC

Υ(nS) suppression in heavy-ion collisions





Transport, PRC 96 (2017) 054901 OQS+pQCD, arXiv:2205.10289

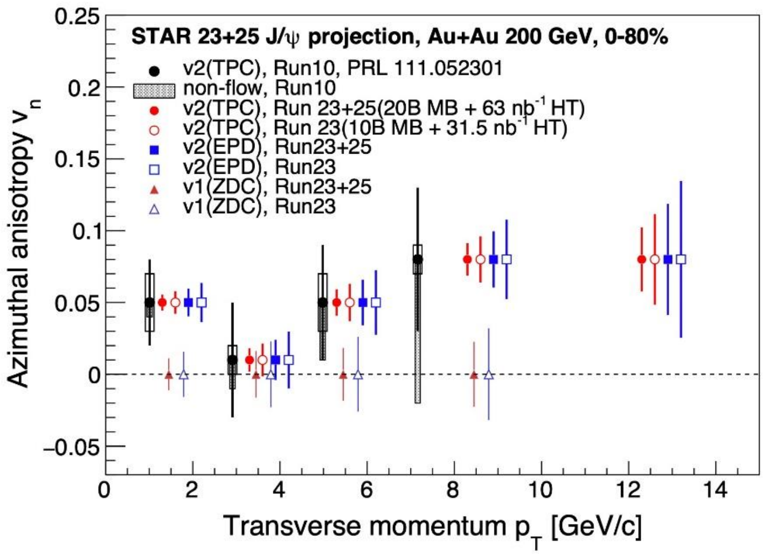
- Observed sequential suppression of different Υ(nS) states: R_{AA}[Υ(1S) > Υ(2S) > Υ(3S)]
- Υ(1S): Similar suppression at RHIC and LHC
- Υ(2S): Less suppression in peripheral collisions at RHIC

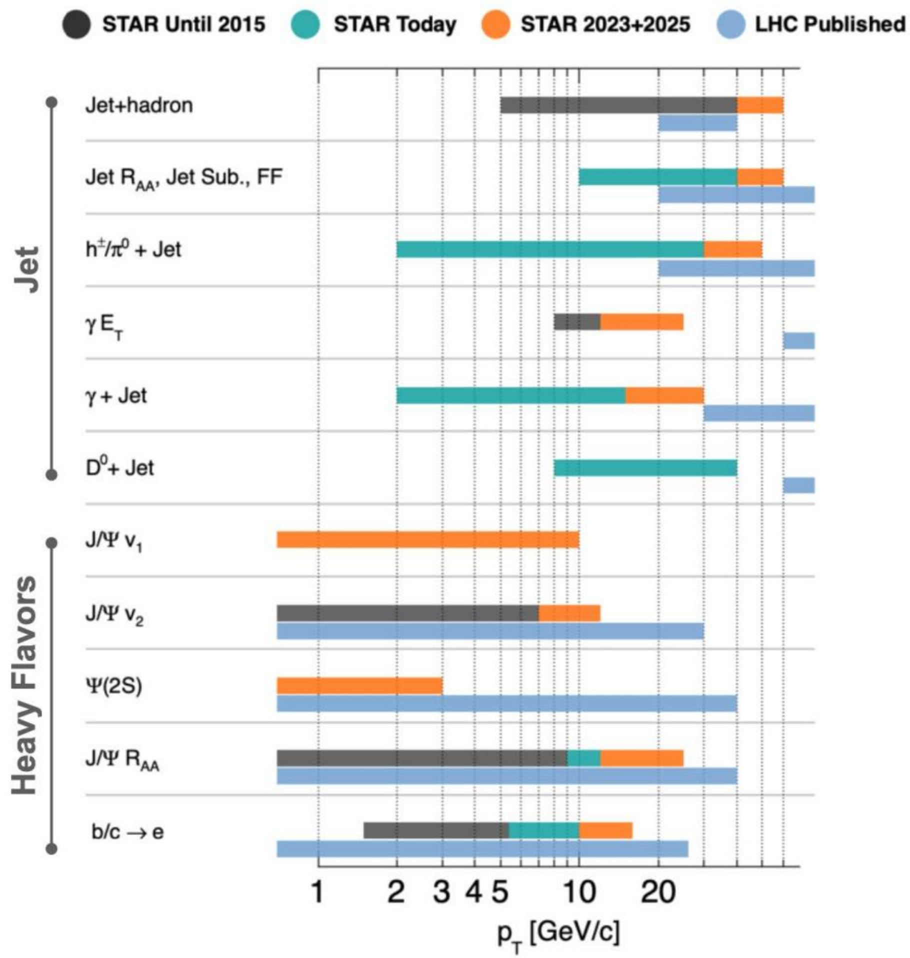
Phys. Rev. Lett. 130 (2023) 112301

Outlook of 2023-2025

STAR BUR-2022:

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	20B / 40 nb^{-1}	2023+2025
200	p+p	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024





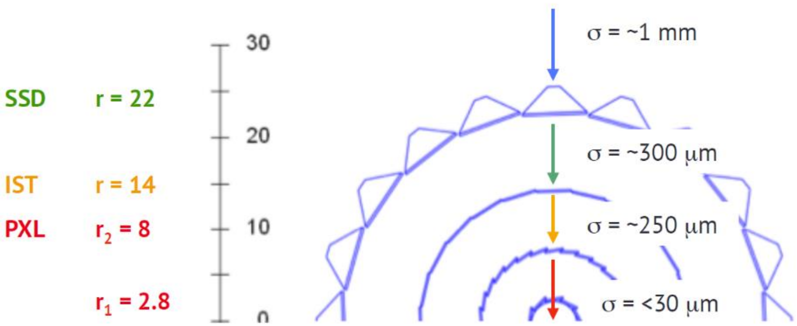
- Broader momentum coverage at RHIC
- Complementary between RHIC and LHC

https://indico.bnl.gov/event/15148/attachments/40846/68609/STAR_BUR_Runs23_25___2022 (1).pdf

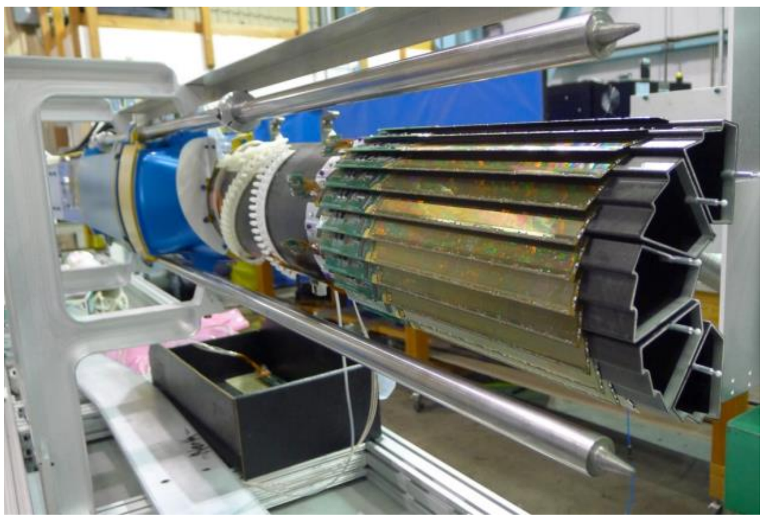
Summary

- STAR extensively studied production of open-charmed hadrons thanks to the successful HFT period in 2014-2016
- **D^0, $D^{\pm}$ meson R_{AA}** in Au+Au collisions:
  - Indicate strong charm-medium interactions
- $\boldsymbol{\Lambda_c/D^0}$ **and D_s/D^0** yield ratios are enhanced in Au+Au collisions with respect to p+p collisions
  - Coalescence plays an important role in charm quark hadronization
- Indication of less suppression for ***B→e* than *D→e***
  - Consistent with expected mass hierarchy of parton energy loss
- Observation of **non-zero flow** of HFE 54-200 GeV
- **J/ψ suppression**: no significant collision system and energy dependence
  - Interplay of dissociation and regeneration effects
- **Sequential Υ** suppression at RHIC
  - Thermodynamic properties of the medium

Heavy Flavor Tracker (HFT)



- Took data in 2014-2016.
- First application of Monolithic Active Pixel Sensors technology in collider experiments.
- Radiation length: 0.4 % X_0 for the 1st layer of pixel detectors.
- Pointing resolution ~50 μm for p_T =750 MeV/c Kaon.



STAR: PRL 118 (2017) 212301