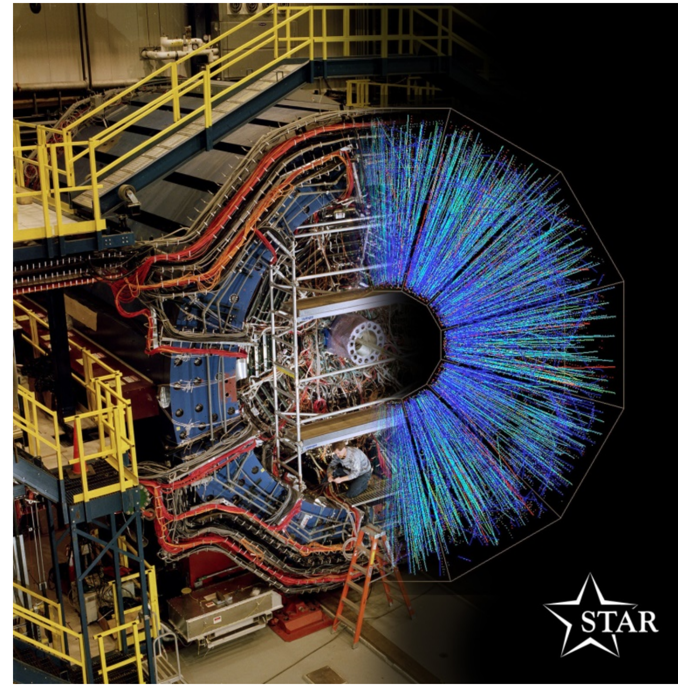
Overview of recent STAR open heavy flavor measurements



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EUROPEAN UNION
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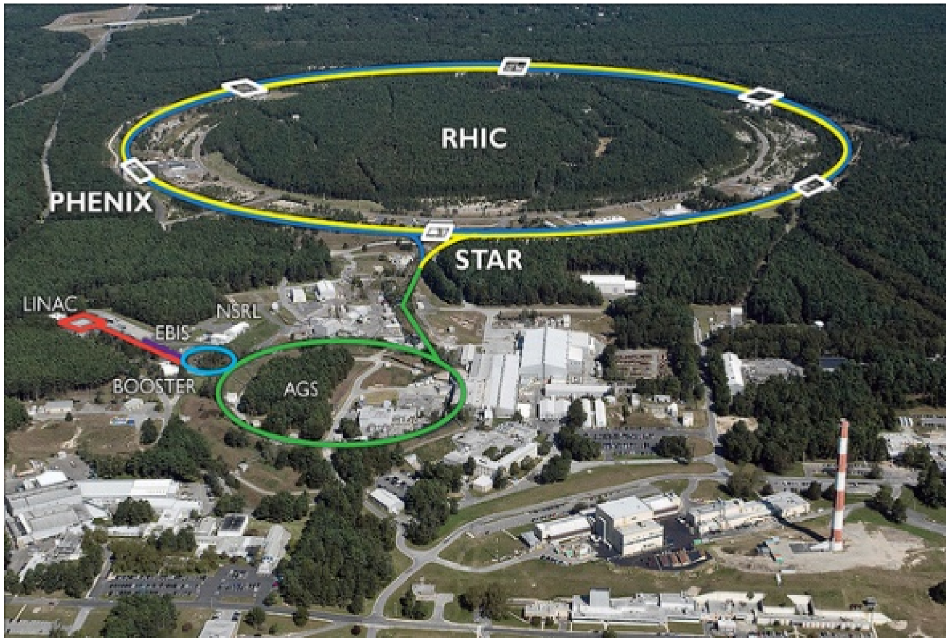
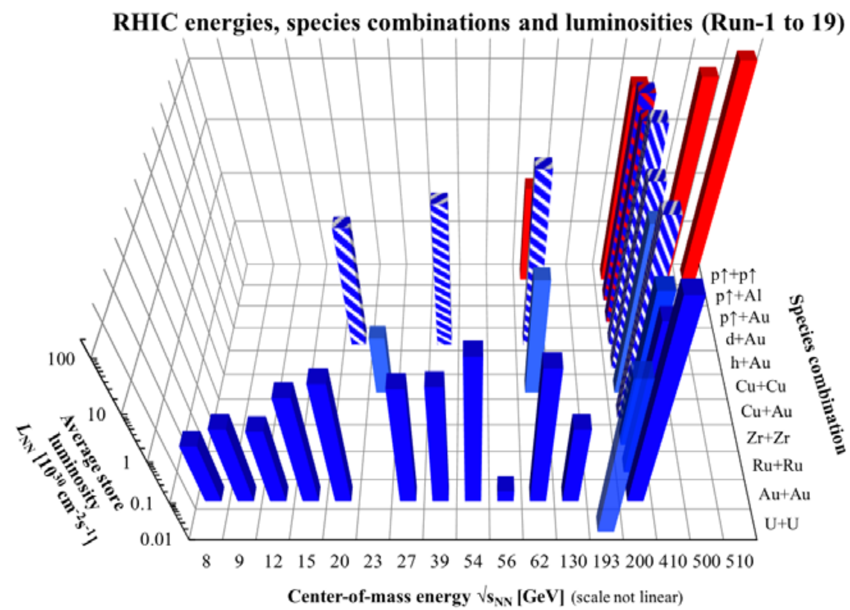
Operational Programme Research,
Development and Education

MINISTRY OF EDUCATION,
YOUTH AND SPORTS

8th International Conference on New Frontiers in Physics, 21.-29. August 2019, Crete, Greece

Relativistic Heavy Ion Collider

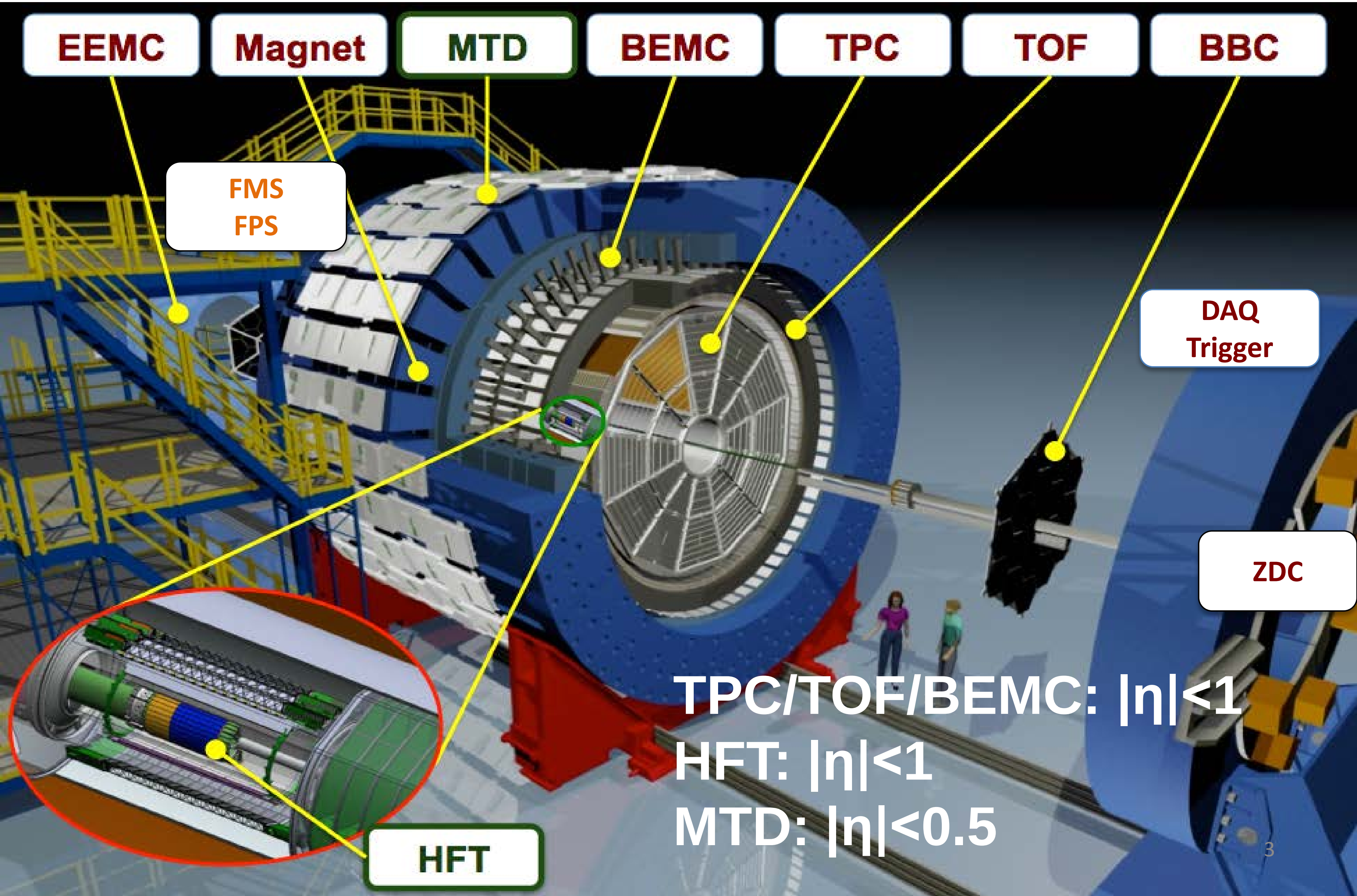




- Extremely versatile: has collected data colliding a large array of different heavy ions
  - Peak luminosity Au+Au 200 GeV : 155 x 10^{26} cm^{-2} s^{-1} ; p+p 200 GeV : 115 x 10^{30} cm^{-2} s^{-1}
- Only polarized proton collider in the world
  - Beam polarizations P~60% for p+p 200 GeV

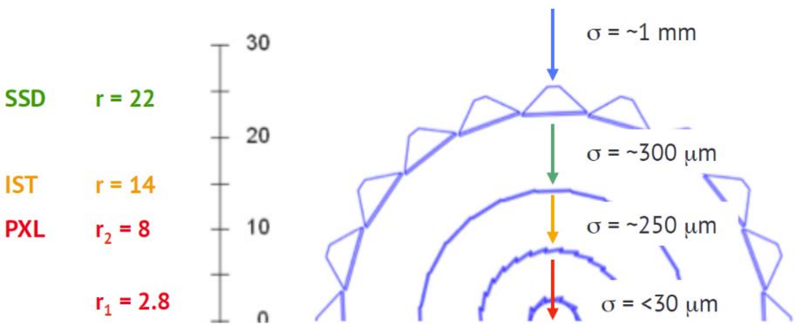
http://www.agsrhichome.bnl.gov/RHIC/Runs/

STAR experiment

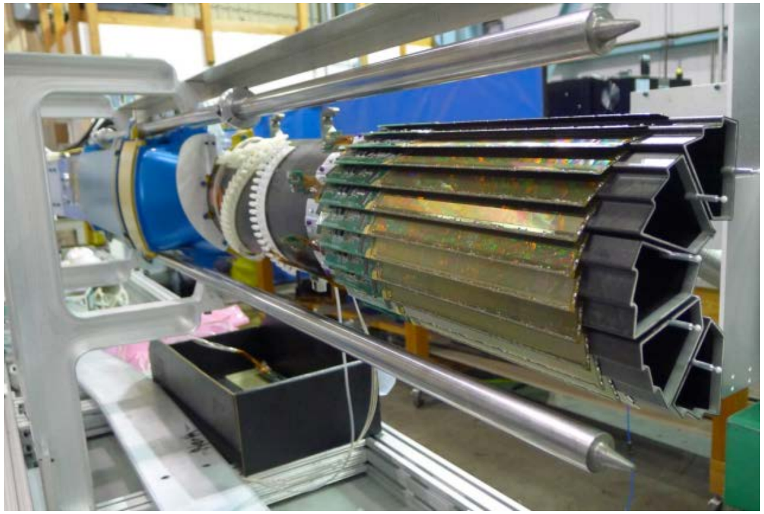


TPC/TOF/BEMC: |η|<1
HFT: |η|<1
MTD: |η|<0.5

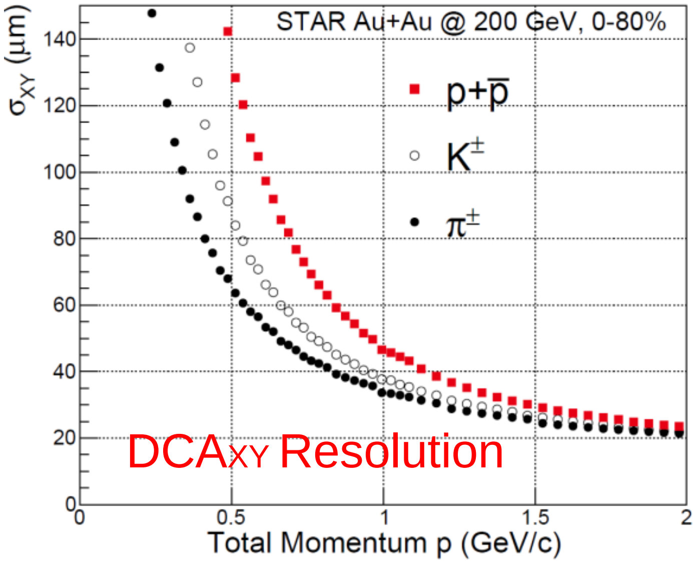
Heavy Flavor Tracker (HFT)



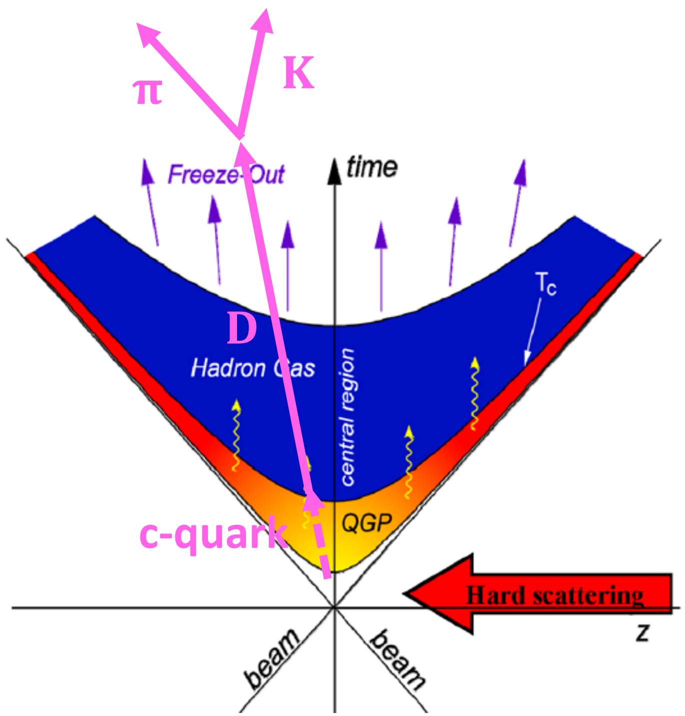
- Took data in 2014-2016.
- First application of Monolithic Active Pixel Sensors technology in collider experiments.
- Radiation length: 0.4 % X_0 for the 1st layer of pixel detectors.
- Pointing resolution ~50 µm for p_T=750 MeV/c Kaon.

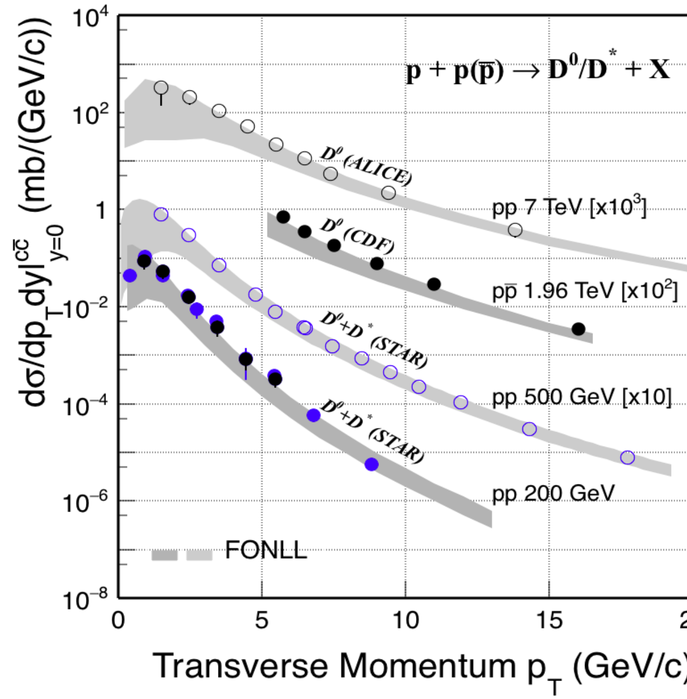


STAR: PRL 118 (2017) 212301



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: $m_c \gg T_{QGP}, \Lambda_{QCD}$**
- 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

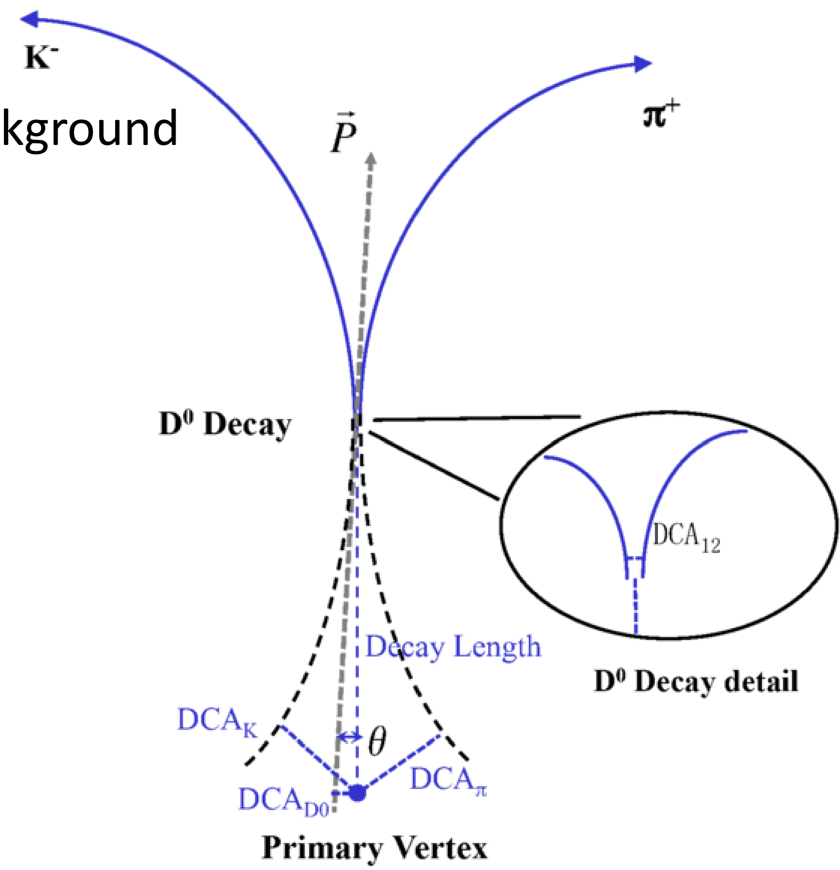
- Data from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV collected with HFT in years 2014 and 2016
- HFT allows direct **topological reconstruction** of open-charm hadrons via their hadronic decays
- Significant suppression of combinatorial background
- Decay channels used:
  - $D^+ \rightarrow K^-\pi^+\pi^+$,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

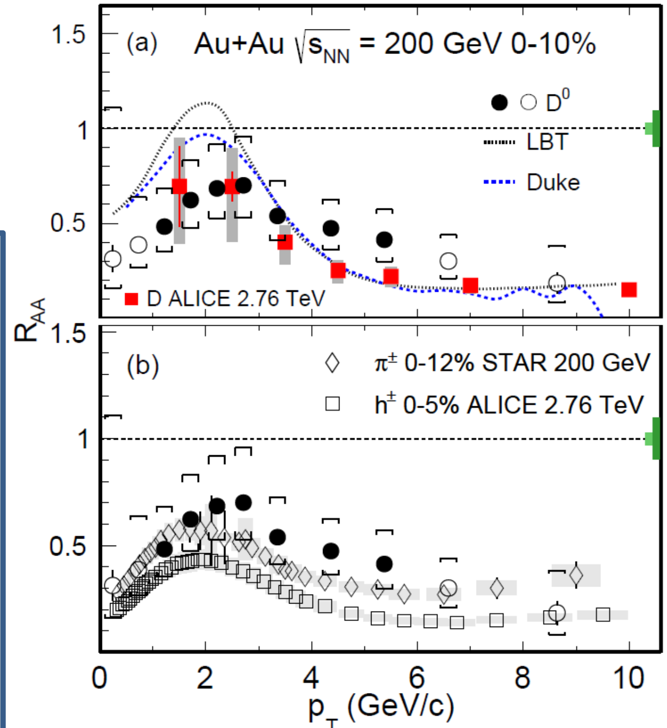
    BR = (6.35 ± 0.33) %

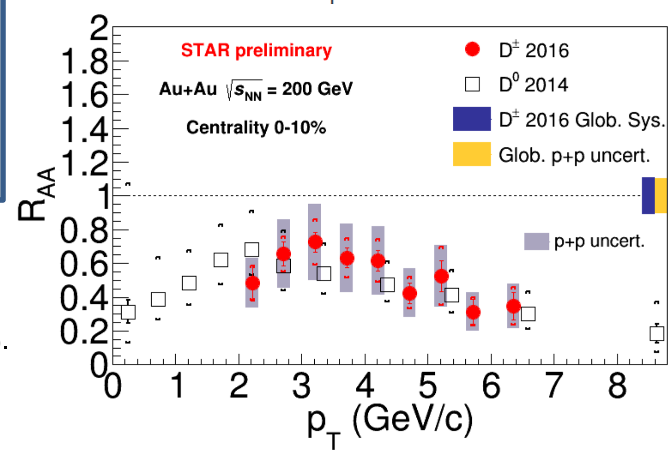


Nuclear modification factor R_{AA} of D^0 and $D^{\pm}$

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

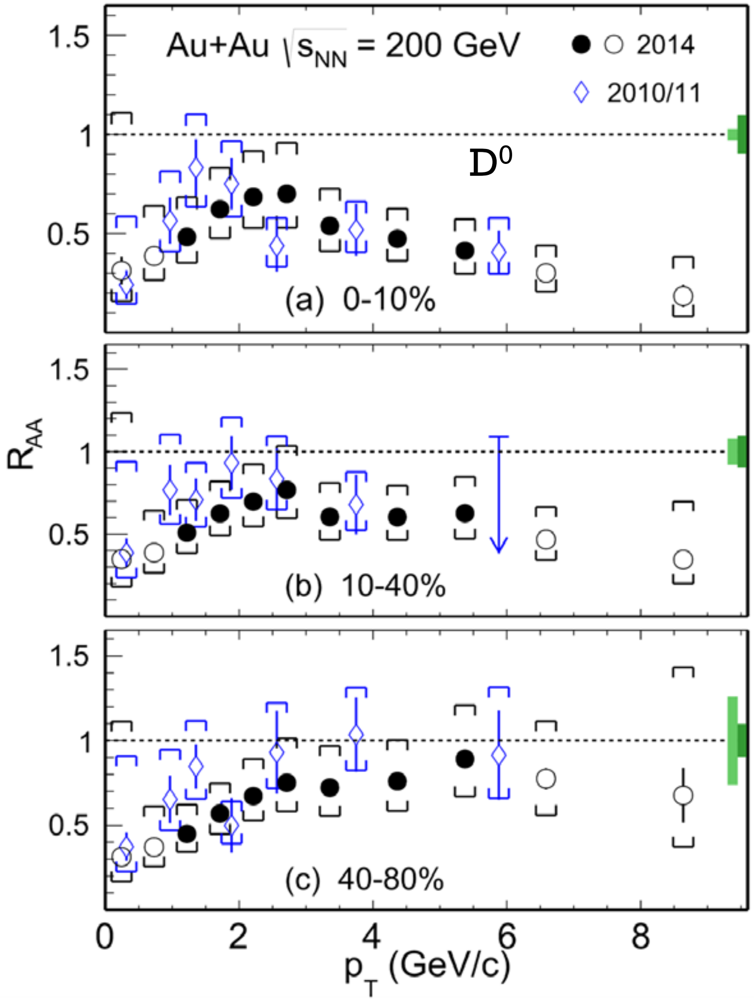
- D mesons **suppressed** in central Au+Au collisions
  - Suppression of D^0 mesons at high p_T comparable to light-flavor hadrons at RHIC and D mesons at LHC
  - It is reproduced by models incorporating both **radiative and collisional energy losses**
  - Similar level of suppression for $D^{\pm}$ and D^0
- **Strong interaction between charm quarks and medium**

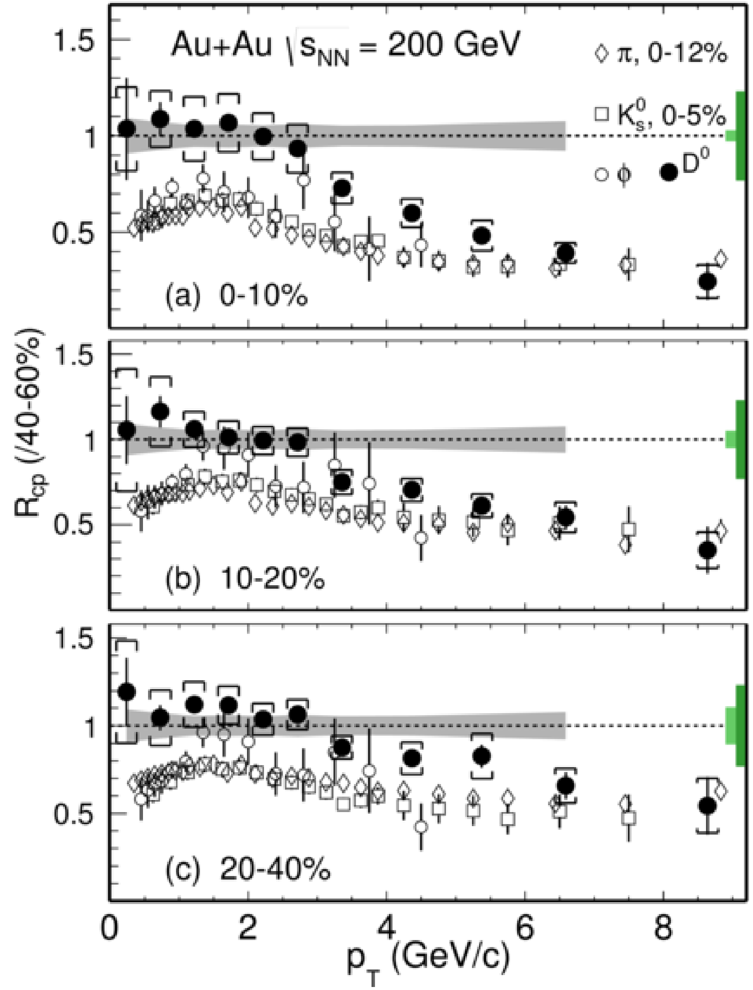




D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
$\pi^{\pm}$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
$h^{\pm}$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

Centrality dependence of D^0 R_{AA} and R_{CP}

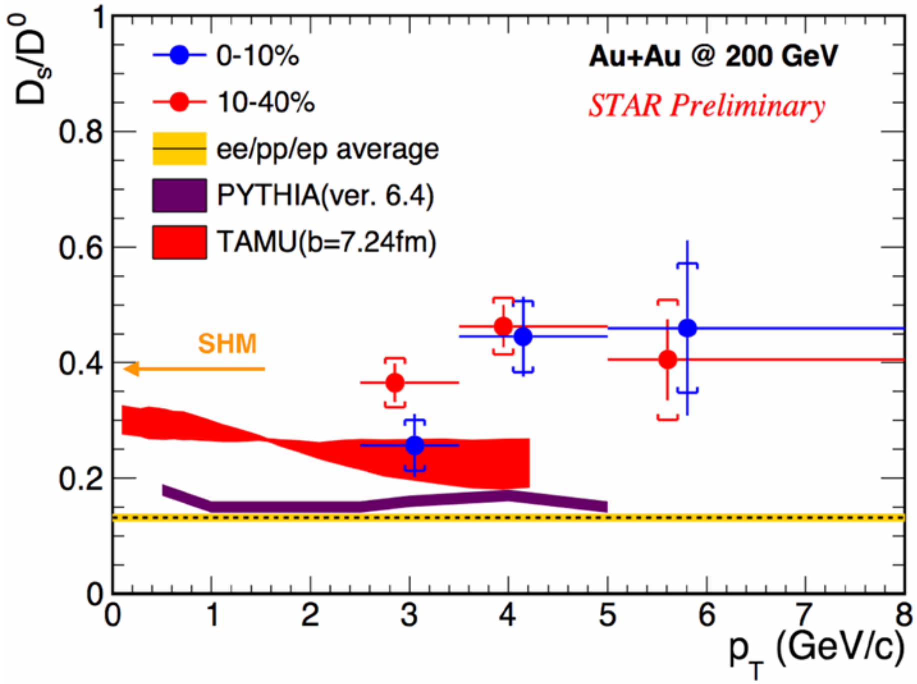




D^0 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D^0 2010/11 (STAR): Phys.Rev.Lett. 113 (2014) no.14, 142301,
Erratum: Phys.Rev.Lett. 121 (2018) no.22, 229901

- R_{AA} D^0 with low p_T < 2.5 GeV/c suppressed for all centralities
- Suppression at high p_T increases with centrality
- R_{CP} D^0 with low p_T < 3 GeV/c no suppression
- R_{CP} D^0 at high p_T suppression observed similar to light flavor-hadrons

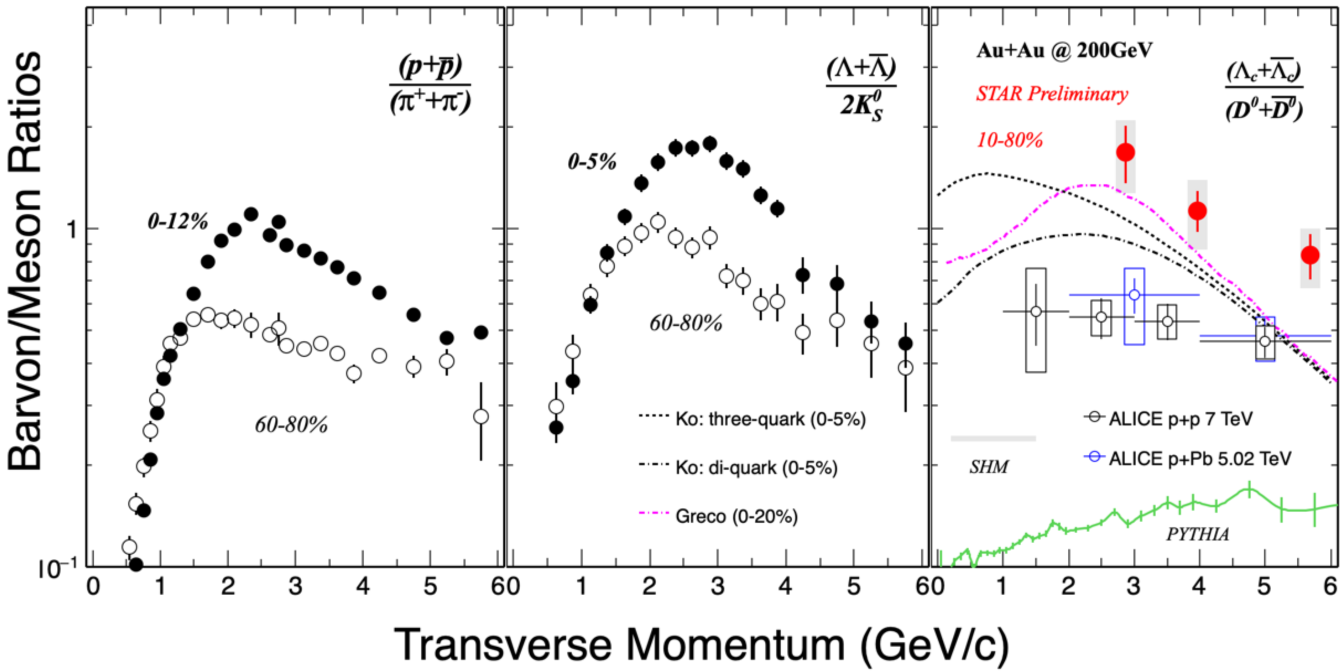
D_s/D^0 yield ratio enhancement

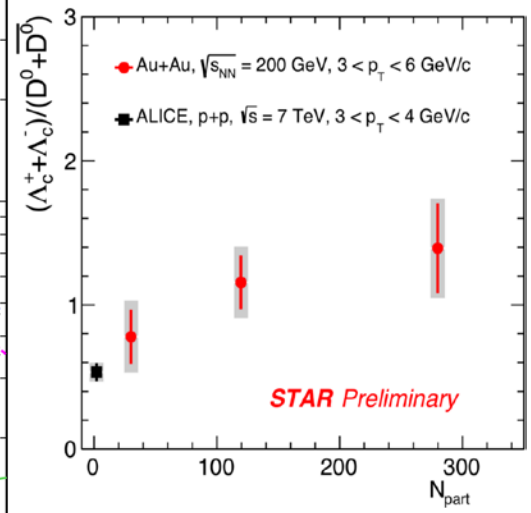


ep/pp/ep avg: EPJ C 76, 397 (2016)
TAMU: PRL 110, 112301 (2013)
SHM: Phys. Lett. B (2003), 571, 36-44

- Observed strong enhancement of the D_s/D^0 yield ratio, compared to:
  Average of fragmentation ratio from ee/pp/ep collisions
  PYTHIA version 6.4 p+p baseline
- Enhancement in 10–40 % centrality is stronger than the TAMU model calculation with charm quark coalescence
- Importance of coalescence hadronization of charm quarks together with enhanced strangeness production

Λ_c/D^0 yield ratio





Ko/SHM: PRC 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
ALICE: JHEP 04 (2018) 108
STAR:PRL 108 (2012) 072301

- Clear enhancement observed compared to PYTHIA/fragmentation baseline and p+p, p+Pb at LHC
- Enhancement of ratio increases towards central collisions
- Λ_c/D^0 ratio is comparable to baryon-to-meson ratios of light-flavor hadrons
- Models incorporating charm quark hadronization via coalescence are consistent with data although at high p_T they underpredict the data
- **Importance of coalescence hadronization of charm quarks**

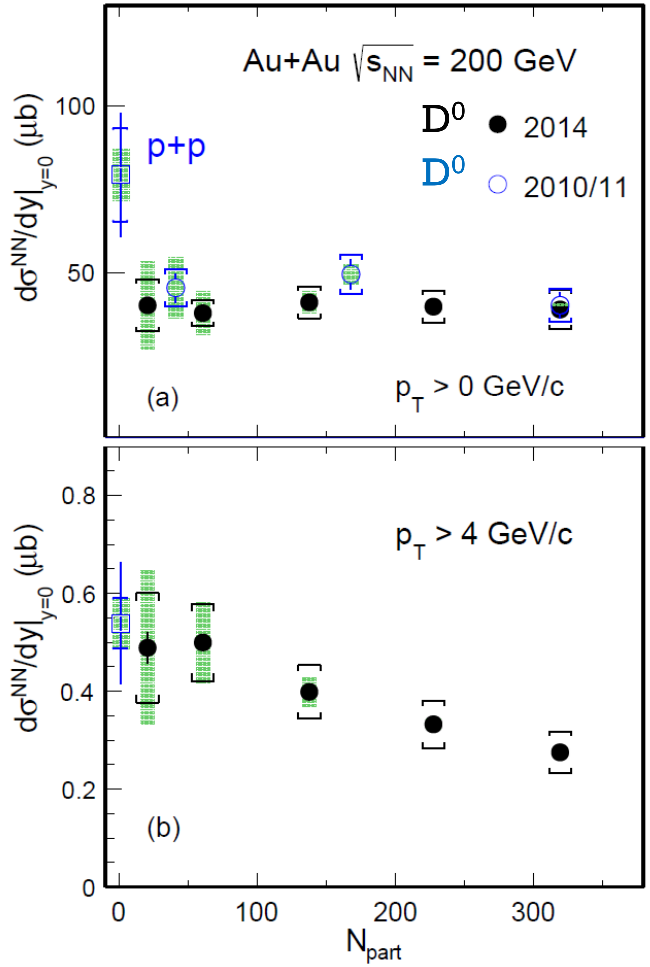
Charm production cross section

- 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 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

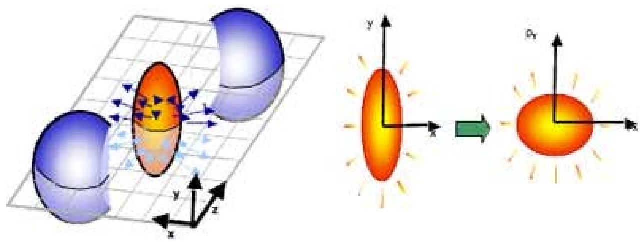
Coll. system	Hadron	$d\sigma/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40%	D^0	41 ± 1 ± 5
	$D^{\pm}$	18 ± 1 ± 3
	D_s	15 ± 1 ± 5
	Λ_c	78 ± 13 ± 28 *
	Total:	**152 ± 13 ± 29**
p+p at 200 GeV	**Total:**	**130 ± 30 ± 26**

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

D^0 2014 (STAR): Phys. Rev. C 99, 034908, (2019).
D^0 2010/11 (STAR): Phys.Rev.Lett. 113 (2014) no.14, 142301, Erratum: Phys.Rev.Lett. 121 (2018) no.22, 229901.
p+p (STAR): Phys. Rev. D 86 072013, (2012).



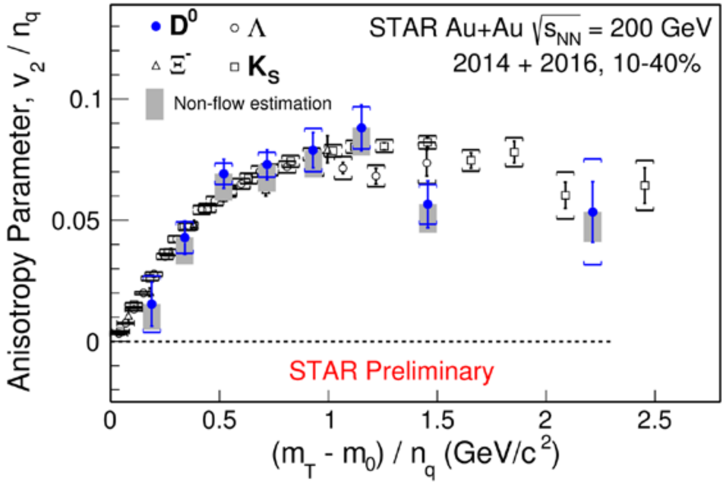
D^0 azimuthal anisotropy

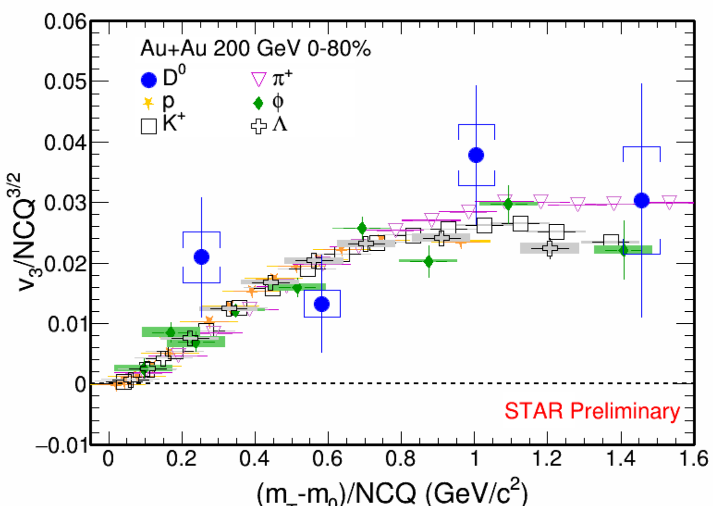


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi_n))\right]$$

- D^0 v_2 and v_3 follow Number of Constituent Quarks (NCQ) scaling
- Strong **collective behavior** of charm quarks
- **Charm quarks may have achieved local thermal equilibrium with QGP**

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

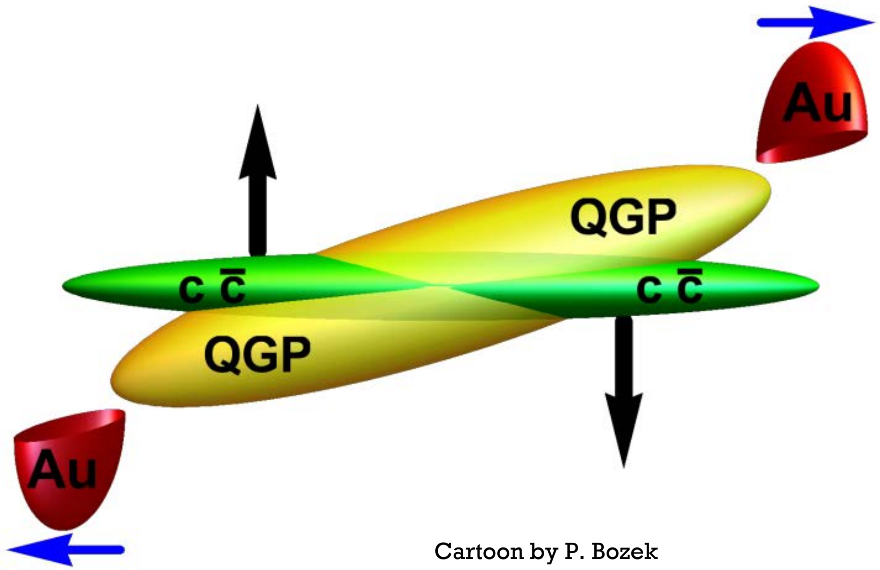




D^0 directed flow - motivation

- **Hydrodynamics**
  - Difference between tilt of bulk and longitudinal density profile of heavy flavor production
  - Additionally, drag by the titled bulk can induce large v_1 for charm quarks
  - Expected larger magnitude for slope of rapidity dependence of v_1 (dv_1/dy) for charm hadrons than for light flavor hadrons

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



Cartoon by P. Bozek

- **Initial EM field from passing spectators**
  - Predicted negative dv_1/dy slope for D^0 and positive for $\overline{D^0}$

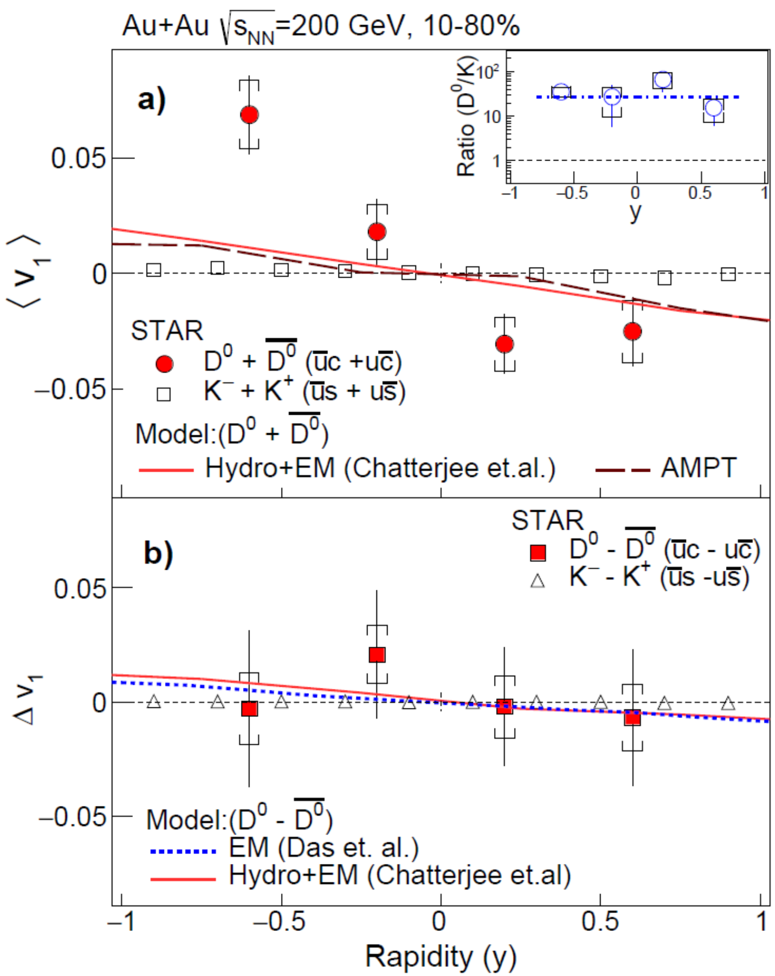
Das et. al., Phys Lett B 768, 260 (2017)

- **Hydrodynamics + EM field**
  - Expected larger magnitude of the slope dv_1/dy for D^0 than $\overline{D^0}$,though the sign stays negative for both

Chatterjee, Bozek: arXiv:1804.04893

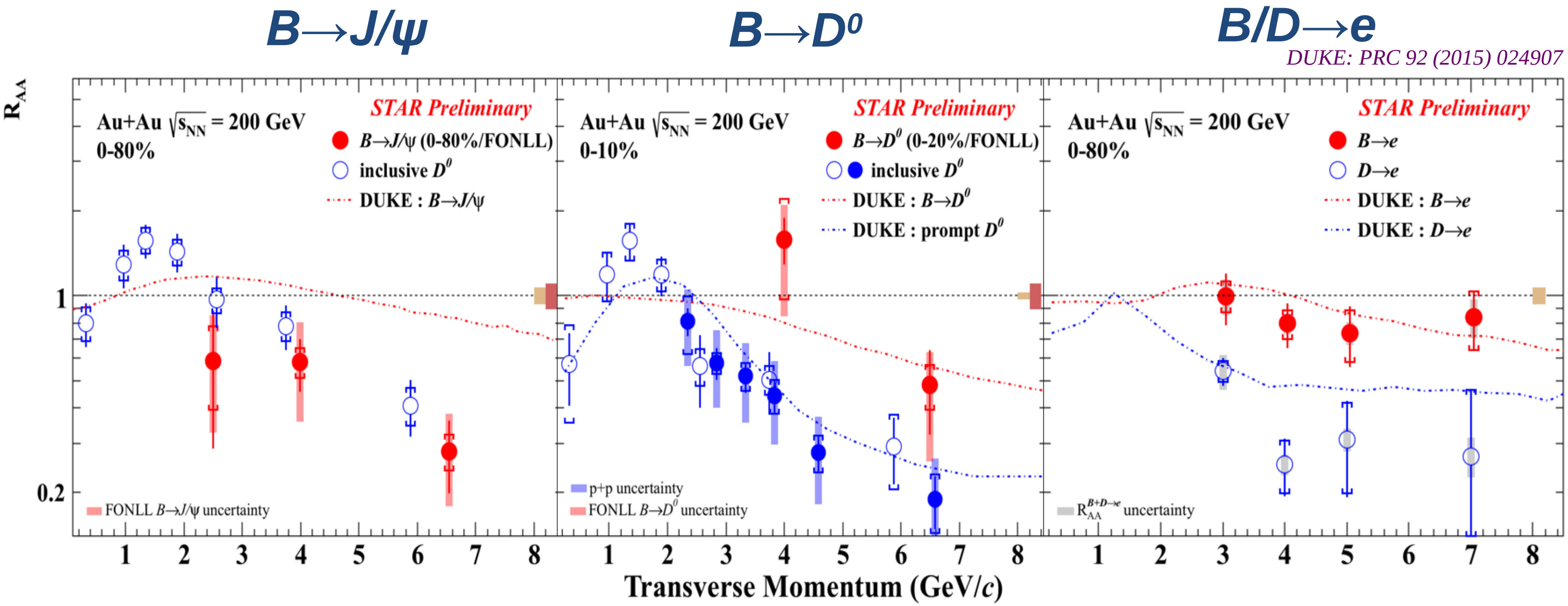
D^0 directed flow

- 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 that of 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)
Hydro+EM: Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018); Chatterjee, Bozek: 1804.04893v1
AMPT: Singha, Nasim: Phys Rev C 97, 064917 (2018)
EM: Das et. al., Phys Lett B 768, 260 (2017)

Nuclear modification factor of bottom quarks



STAR measured ***B* production** via non-prompt *J/ψ*, D^0 and electron decay channels **in 200 GeV Au+Au collisions**

- Strong suppression for *B*→ *J/ψ* and B→D^0 at high p_T.
- Indication of less suppression for *B*→*e* than *D*→*e* (~2 σ):
  consistent with expected mass hierarchy for parton energy loss $\Delta E_c > \Delta E_b$

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} and D^0 v_2 , v_3 in Au+Au collisions:
  - Indicate strong charm-medium interactions
  - Charm quarks are possibly in local thermal equilibrium with medium
- Λ_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
- D^0 mesons have larger v_1 slope than light-flavor mesons
  - Probe of initial longitudinal density profile of heavy flavor production
- Indication of less suppression for $B \rightarrow e$ than $D \rightarrow e$
  - Consistent with expected mass hierarchy of parton energy loss