Heavy flavor and quarkonia from experiments at RHIC

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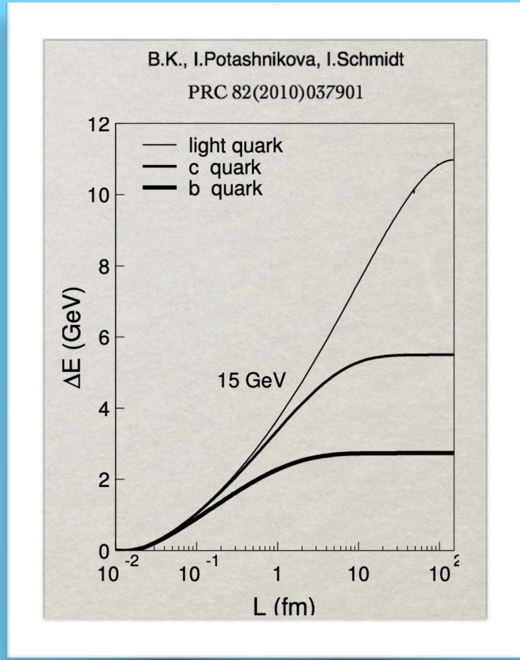
Outline

* Introduction
* Flow of HF in Au+Au
* Mass ordering of charm and beauty energy loss in Au+Au
* c and b in small systems
* Charmed hadrons
* Quarkonia
* Conclusions and outlook

Introduction

* Open heavy flavor: Charm and beauty quarks are produced in initial hard scatterings and experience the entire evolution of A+A interactions
* Mass dependence of jet quenching in sQGP is expected
* Flow of open heavy flavor hadrons helps elucidate interaction of HF with medium, thermalization and production mechanisms of HF and probe sQGP properties

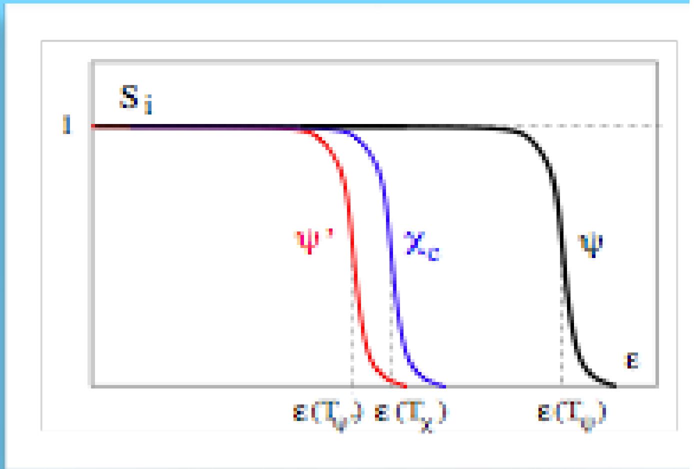
B. Kopeliovich, ISMD2023



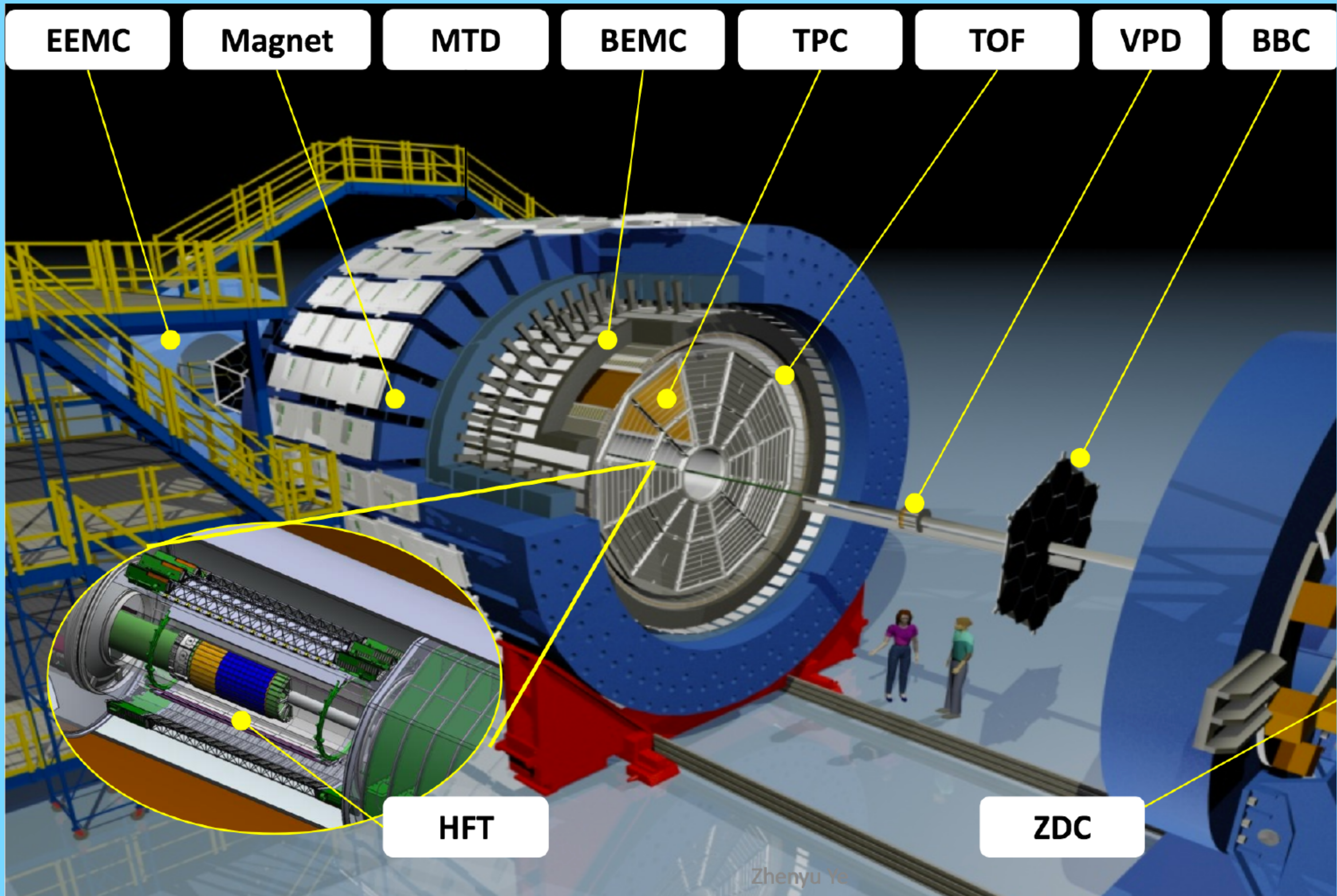
* Quarkonia: Thermometer of QGP via their suppression pattern (Satz, Matsui)

Many effects play a role like dissociation in QGP, cold matter absorption, recombination/coalescence from c, cbar

Andronic, P. B. Munzinger et al

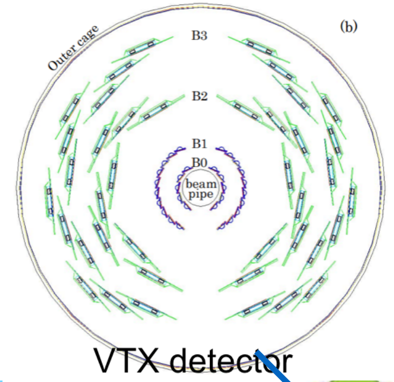


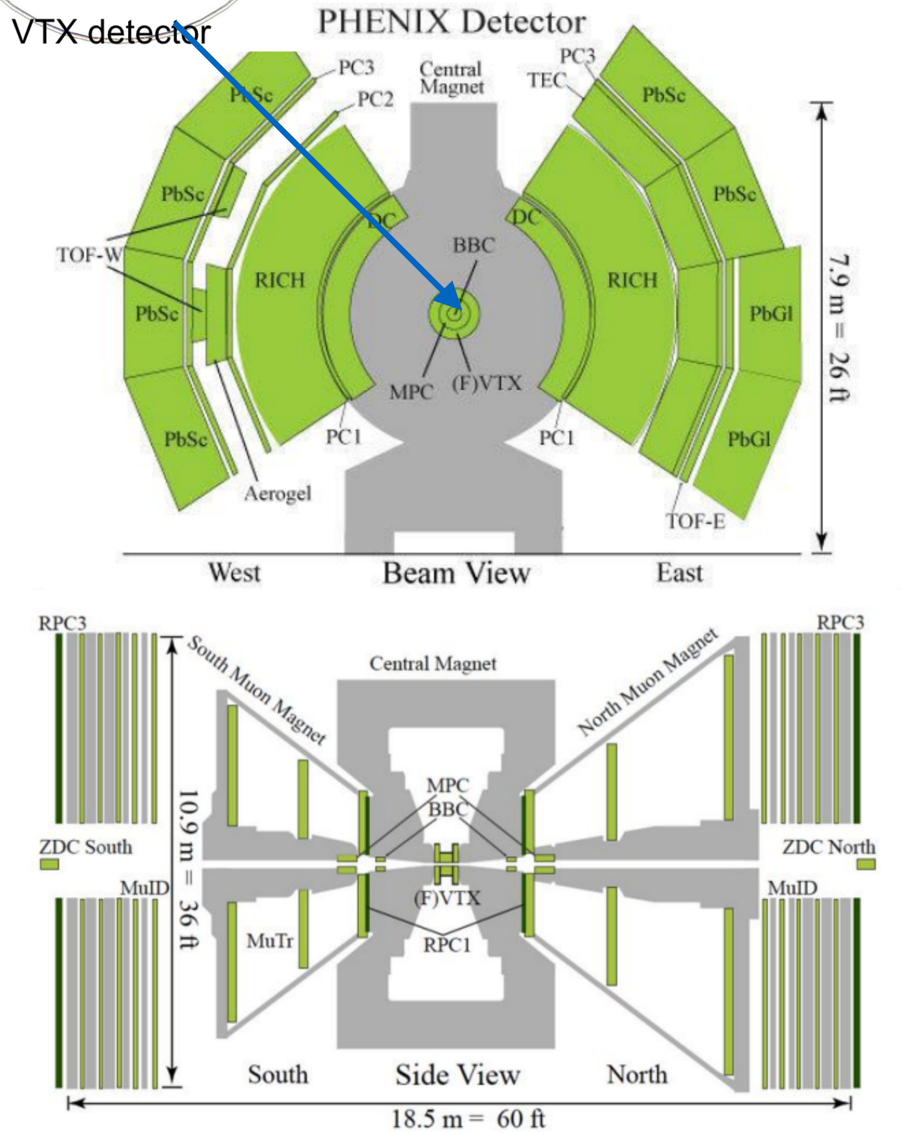
The STAR Experiment at RHIC



Detectors used for open heavy flavor: Heavy Flavor Tracker (HFT), Time Projection Chamber (TPC), Barrel Electromagnetic Calorimer (BEMC) Time-Of-Flight detector (TOF). Electron (e+,e—) identification : Delta(phi)=4pi, |eta|<1

The PHENIX Experiment at RHIC





Detectors used for open heavy flavor results:

-Central spectrometer arms : ring imaging Cerenkov detector (RICH), electromagnetic calorimeter (EMCal), Drift Chambers (DC), multi-wire proportional pad chambers (PC) and silicon Vertex detector (VTX).

Electron (e+,e-) identification: $|y|<0.35$ and azimuthal angle phi=2 pi/2

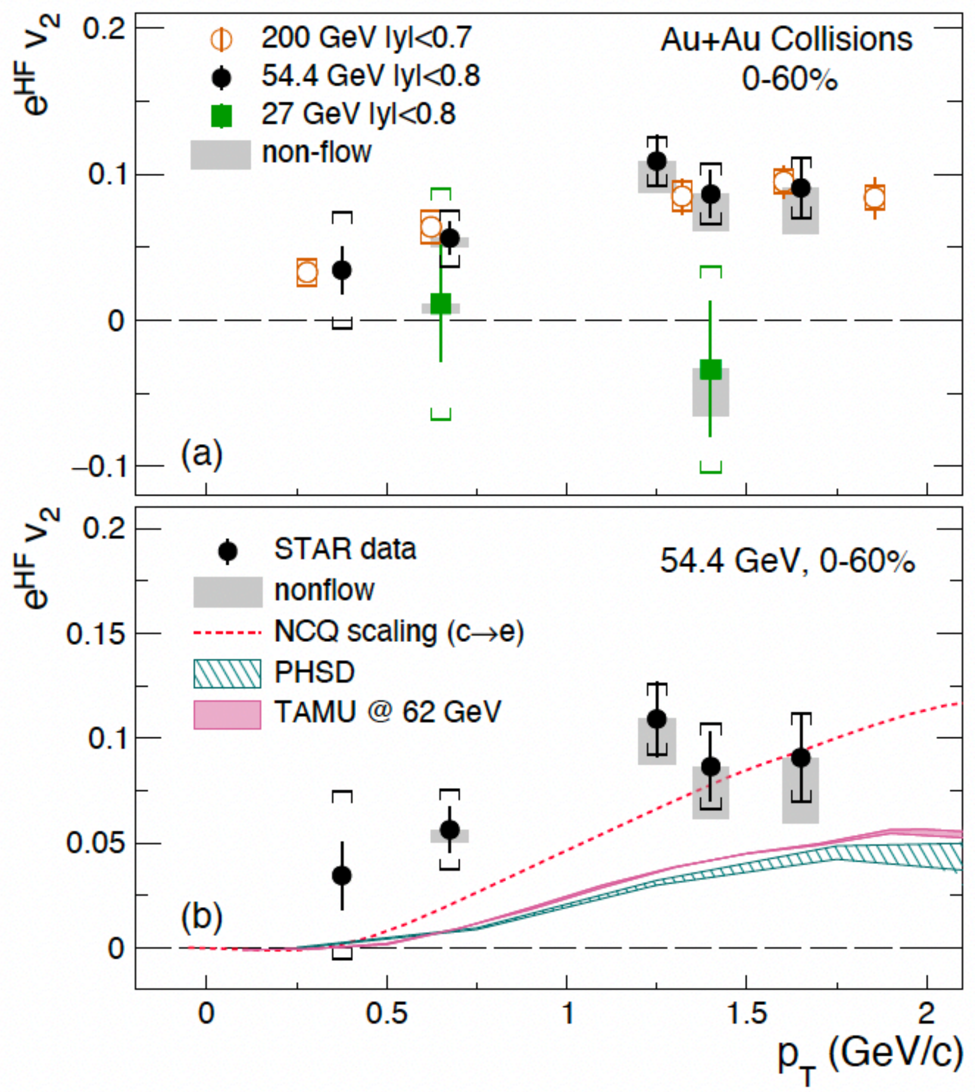
-Muon arms: $1.2<|y|<2.2$, phi=2 pi/2

Data taking completed in 2016

Charm and Bottom flow in Au+Au collisions

STAR new paper on heavy flavor decay electron elliptic flow (v2) in Au+Au collisions at 27, 54 (0-60%) compared to 200 GeV

STAR Collaboration, ArXivL 2303.03546, accepted by PLB



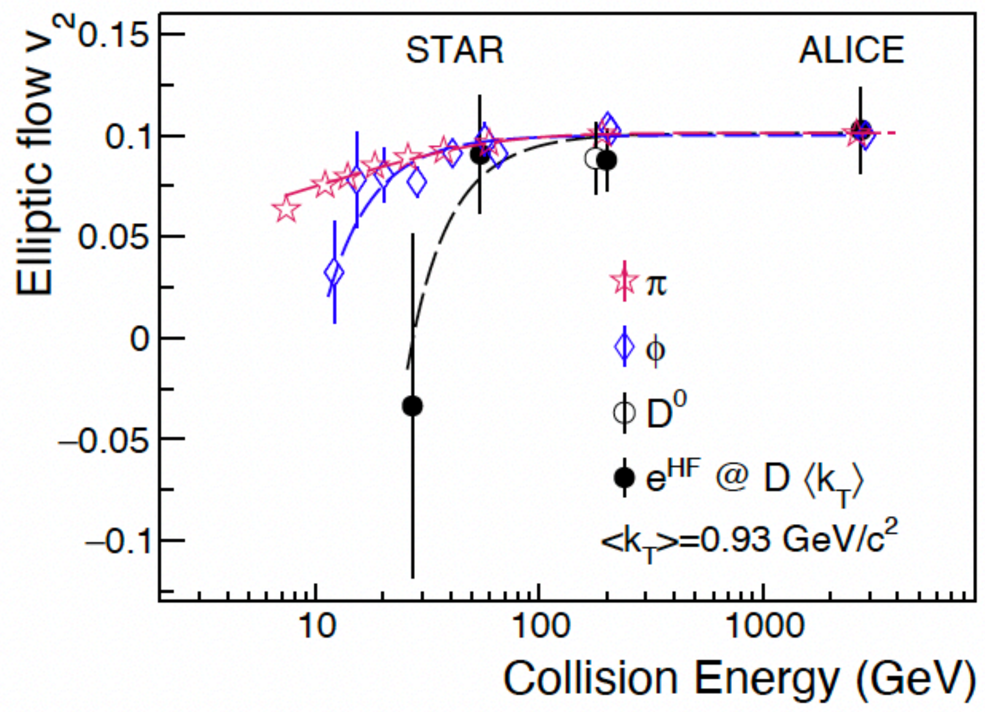
* The elliptic flow of heavy flavor electrons in Au+Au collisions at 54.4 GeV is comparable to 200 GeV, and non-zero above pT 0.5 GeV/c, indicating strong charm quark interactions with the medium

* The elliptic flow of heavy flavor electrons in Au+Au collisions at 27 GeV is consistent with zero at all pT within large uncertainties

* The elliptic flow of heavy flavor electrons in Au+Au collisions at 54.4 GeV at hight pT is consistent with the expected v2 assuming that the c quark follows the Number of constituent Quark scaling

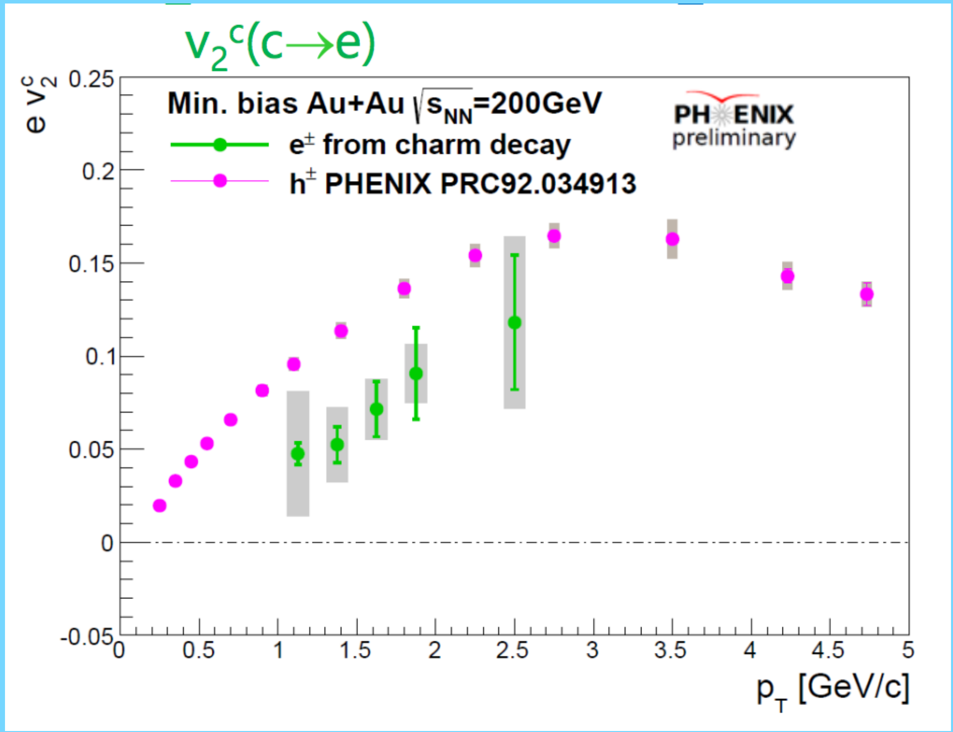
STAR new paper on heavy flavor elliptic flow (v2) in Au+Au collisions at 27, 54 (0-60%) compared to 200 GeV

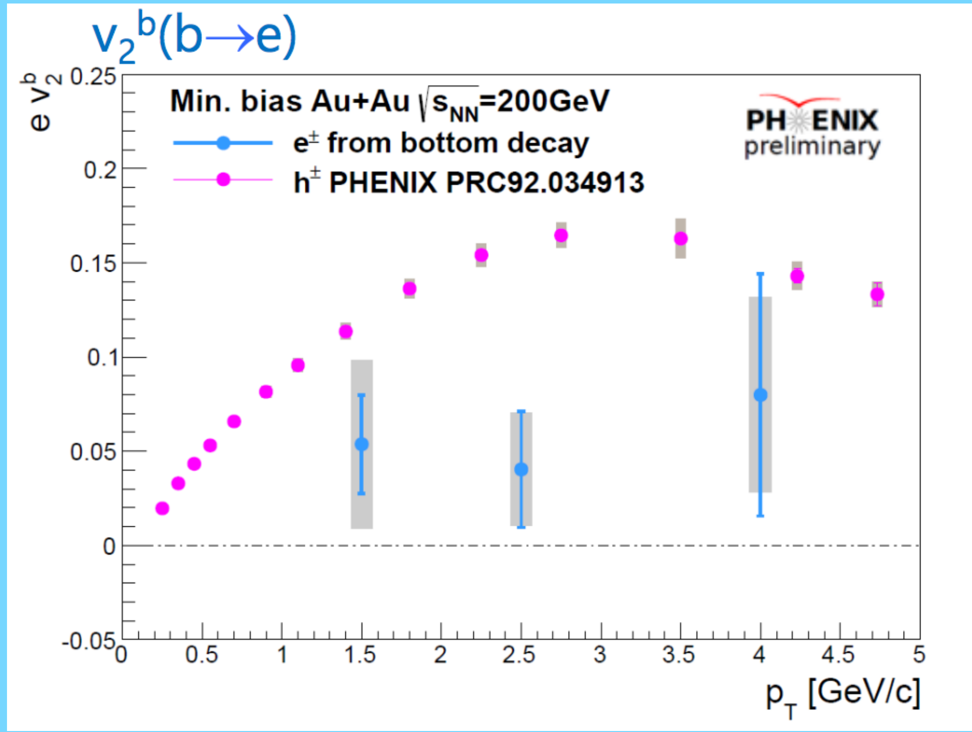
STAR Collaboration, ArXivL 2303.03546, accepted by PLB



* The elliptic flow of pions, phi, and D0 and heavy flavor electrons in Au+Au collisions at 54.4 GeV at <mT-m0>=0.93 GeV as a function of collision energy. The lines are for eye guidance.
* Indication of a mass hierarchy of the energy dependence of v2; the v2 of heavier particles drops faster than ligher ones with decreasing collision energy

PHENIX (preliminary) elliptic flow (v2) of electrons from charm and bottom decays in min. bias Au+Au 200 GeV





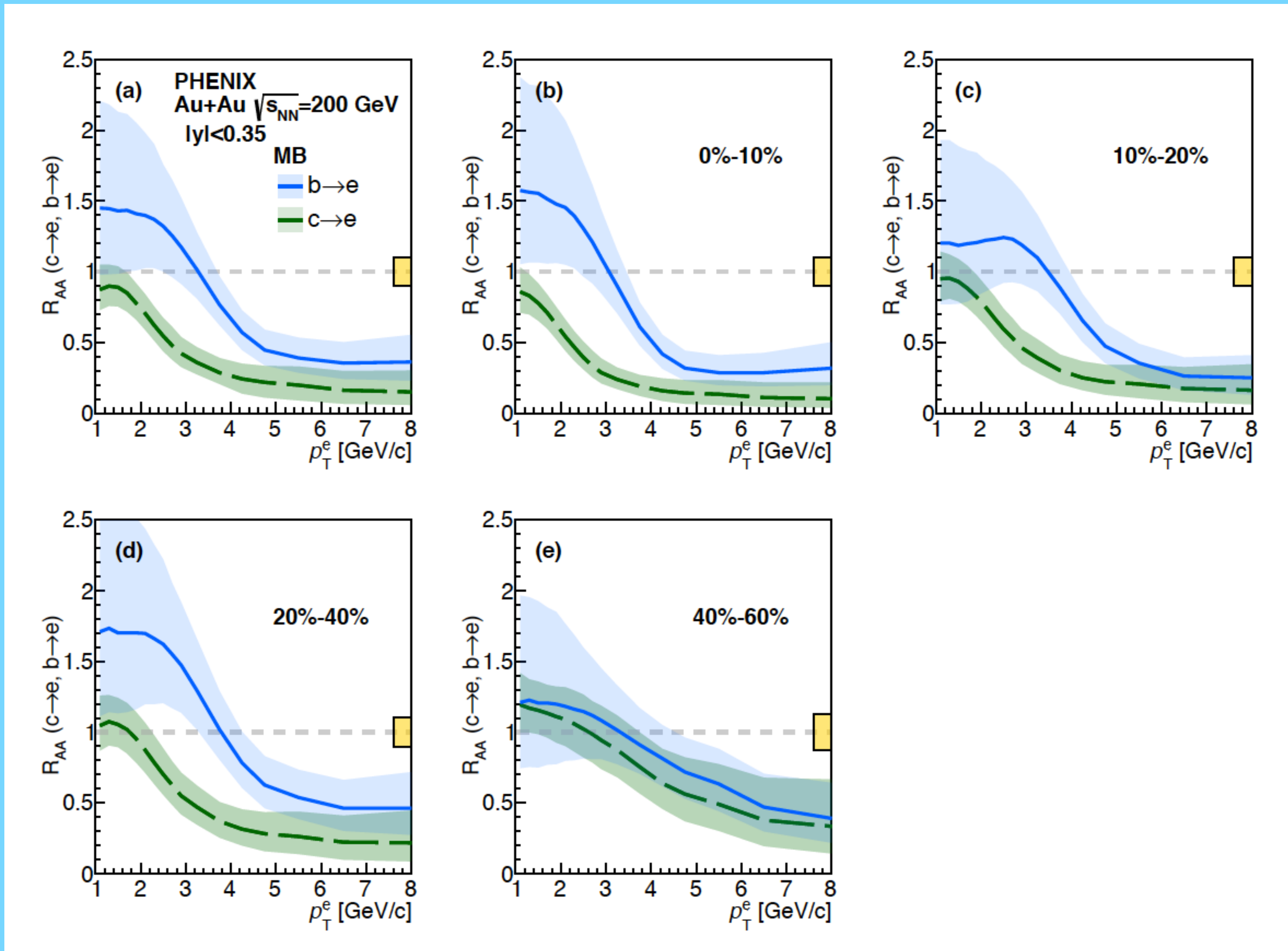
T Hachiya et al, PHENIX collaboration, QM2022

- v2 of charm —> electrons (e+-) is positive (with ˜3.5 sigma)
- hint of positive v2 of bottom —> electrons (e+-) (with ˜1.1 sigma)

Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

PHENIX hierarchy of suppression of b—>e and c—> e in Au+Au collisions at 200 GeV

U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058



* b->e higher than c-> e in Au+Au 200 GeV Minimum Bias and various centralities exept the most peripheral collisions

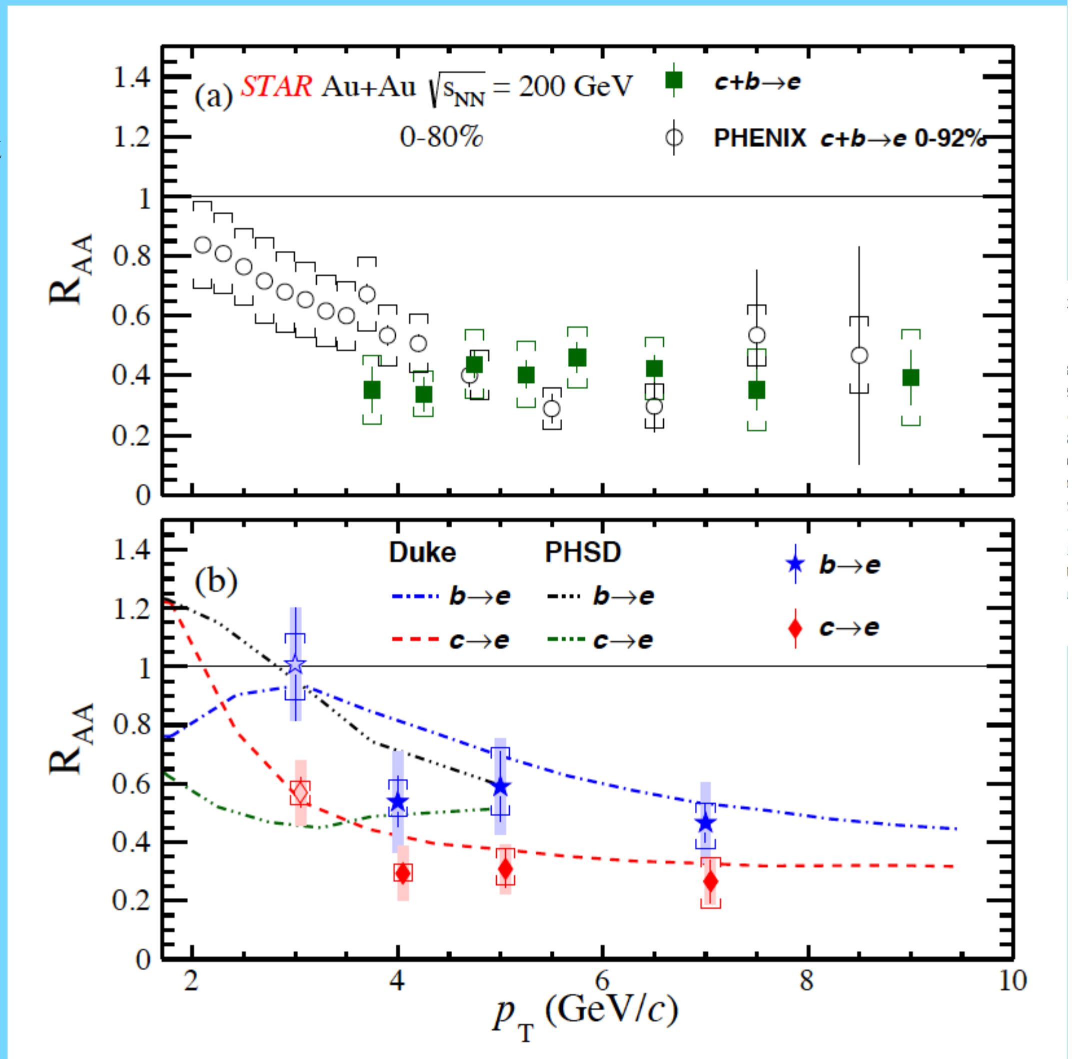
STAR (2022) Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

STAR Collaboration, EPJC **82** (2022) 1150, arXiv:2111.14615

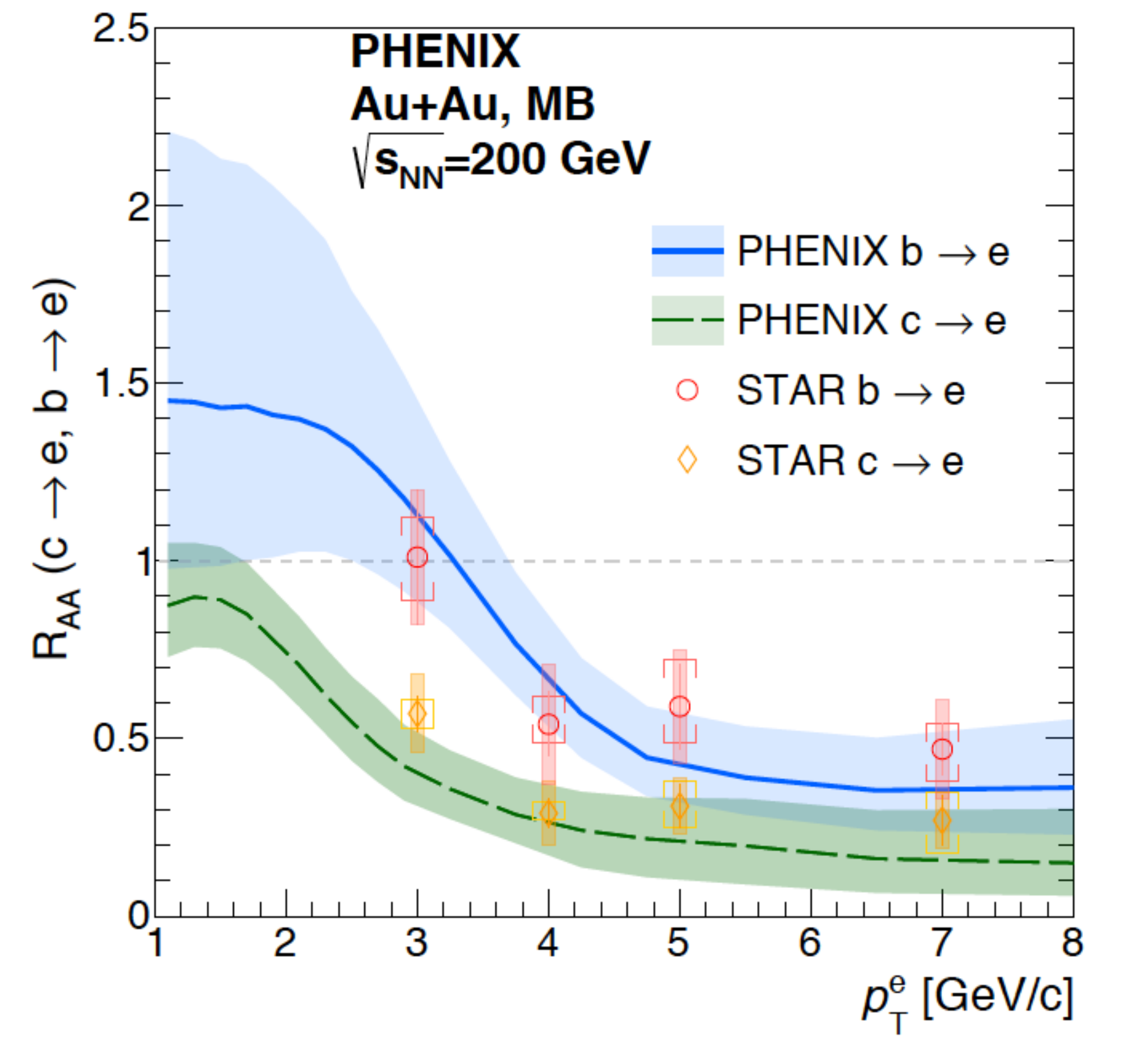
PHENIX Collaboration, PRC93, 034904 (2016), 1509.04662

* PHSD: Parton-Hadron-String-Dynamics model
* Duke: modified Langevin transport model
* Both models include heavy quark (HQ) diffusion in the QGP medium, HQ hadronization through coalescence and fragmentation and mass-dependnet energy loss mechanisms
* Data consistent with model predictions

* **R(AA) vs pT of c+b —> e: STAR and PHENIX are consistent**
* **Evidence of mass ordering of R_{AA} of electrons from bottom and charm in Au+Au collisions at 200 GeV is observed**
* **Results are consistent with models including mass-dependent energy loss mechanisms**



PHENIX vs STAR Minimum Bias Au+Au



M. S. Abdallah et al. (STAR Collaboration), Evi-
dence of Mass Ordering of Charm and Bottom Quark
Energy Energy Loss in Au+Au Collisions at RHIC,
arXiv:2111.14615.

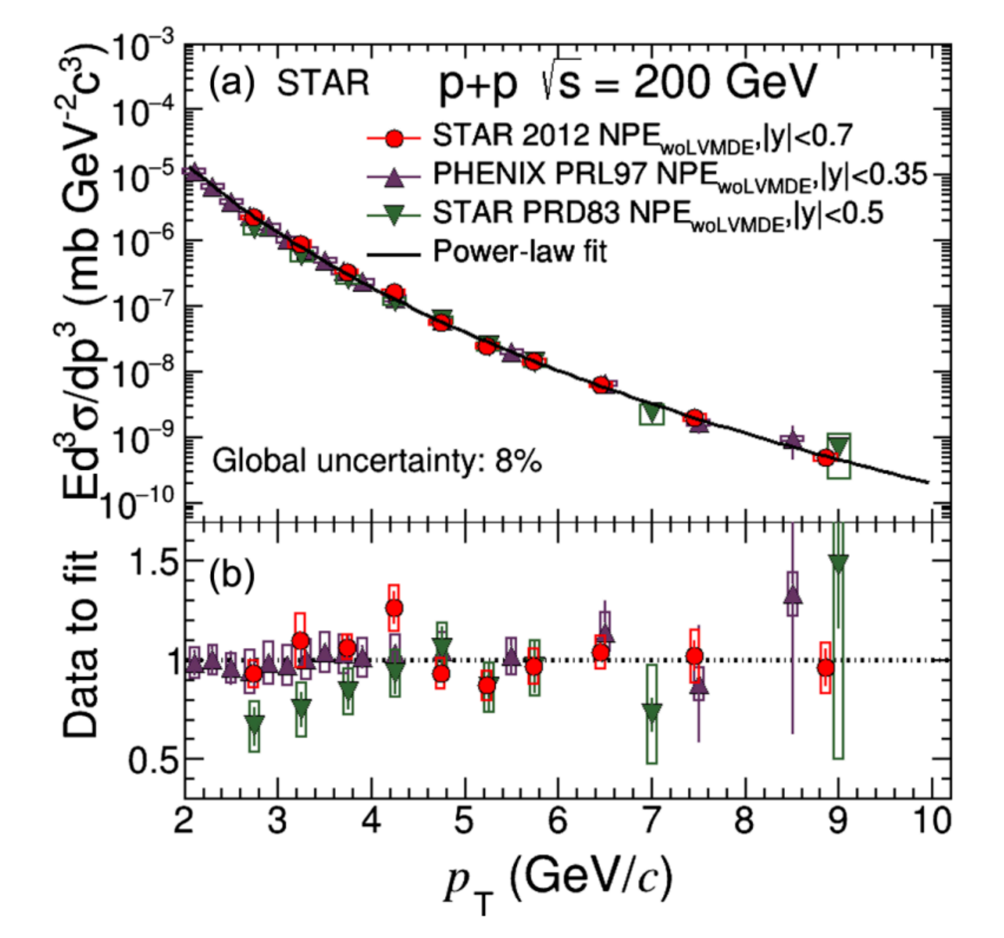
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058

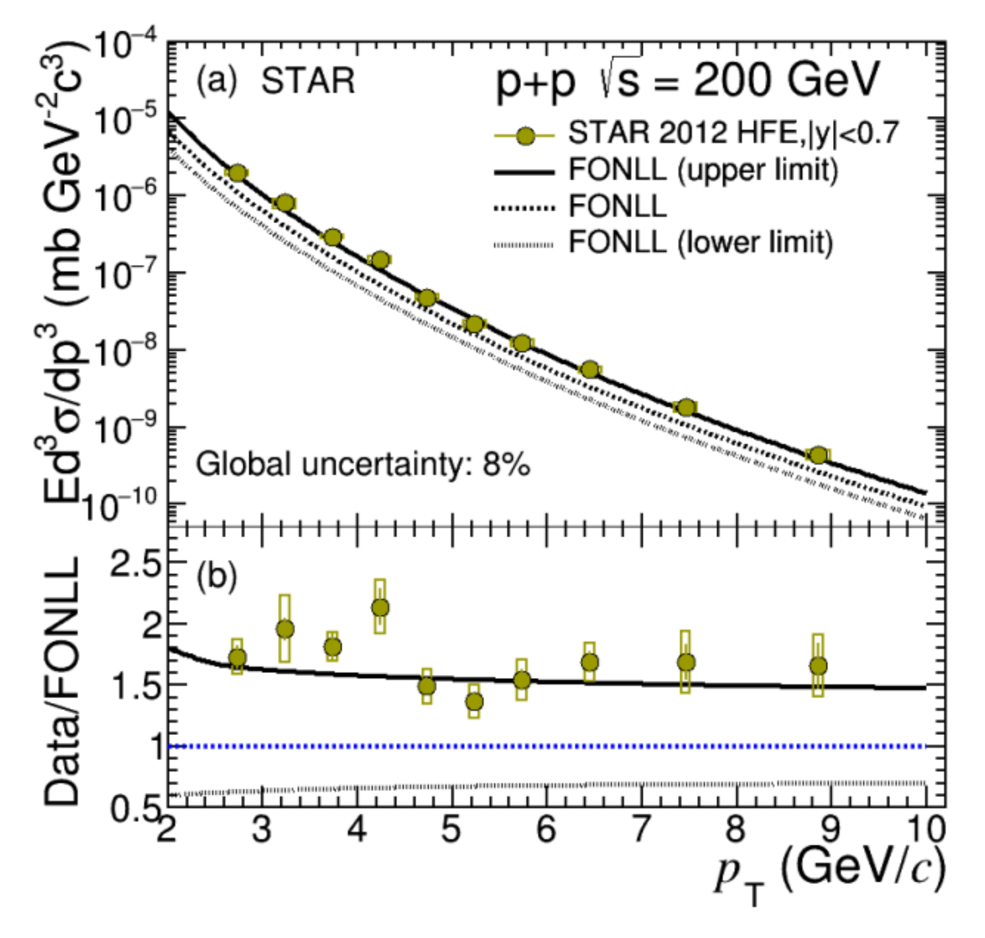
* STAR (points) and PHENIX (lines) b and c to electron measurements in Minimum Bias Au+Au 200 GeV are consistent

Charm and Bottom via semileptonic decays in small systems

HF -> electrons in p+p collisions at 200 GeV

STAR Collaboration, Phys.Rev.D 105 (2022) 3, 032007, e-Print: 2109.13191 [nucl-ex]





Results from STAR and PHENIX agree

HF decays in p+p collisions at 200 GeV is qualitatively consistent with the upper limit of FONLL calculations

PHENIX (2019) bottom cross section in p+p collisions at 200 GeV

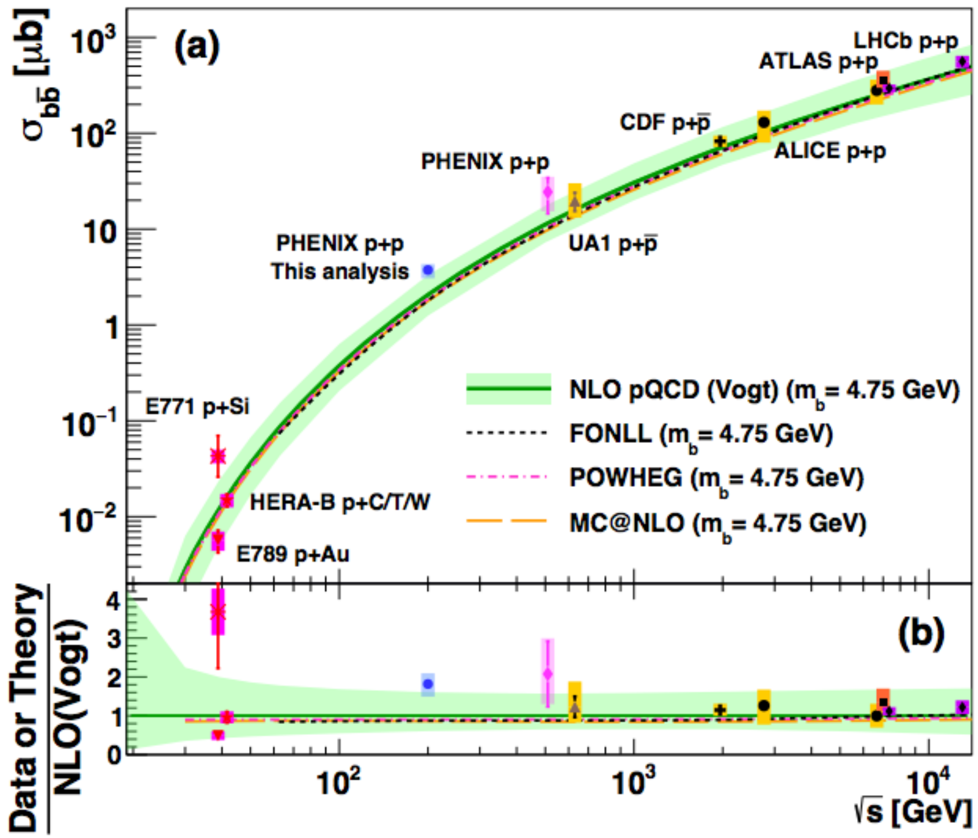


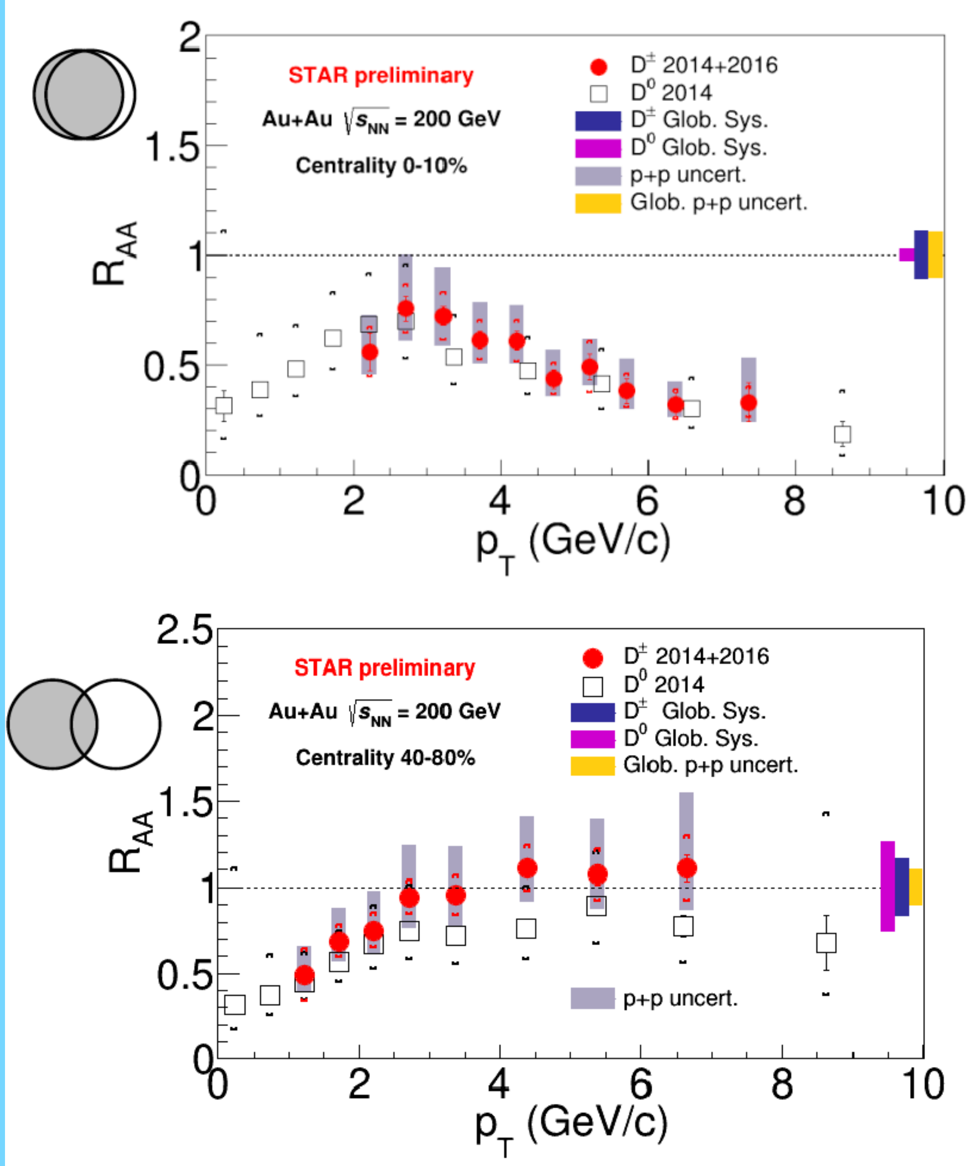
FIG. 29. Bottom cross section $\sigma_{b\bar{b}}$ as a function of $\sqrt{s}$. Uncertainties due to rapidity extrapolation are not included in the LHCb measurements. Measured cross sections are compared to NLL and NLO calculations.

Measurements of μμ pairs from open heavy flavor and Drell-Yan in p+p collisions at \sqrt{s} =200 GeV
PHENIX Collaboration, C. Aidala(Michigan U.) et al. (May 7, 2018)
Phys.Rev.D 99 (2019) 7, 072003 • e-Print: 1805.02448 [hep-ex]

* At low energy models are less consistent with data

Charmed hadrons in Au+Au collisions

STAR (preliminary) Charmed hadrons: D^{+-} and D^0 measurement



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

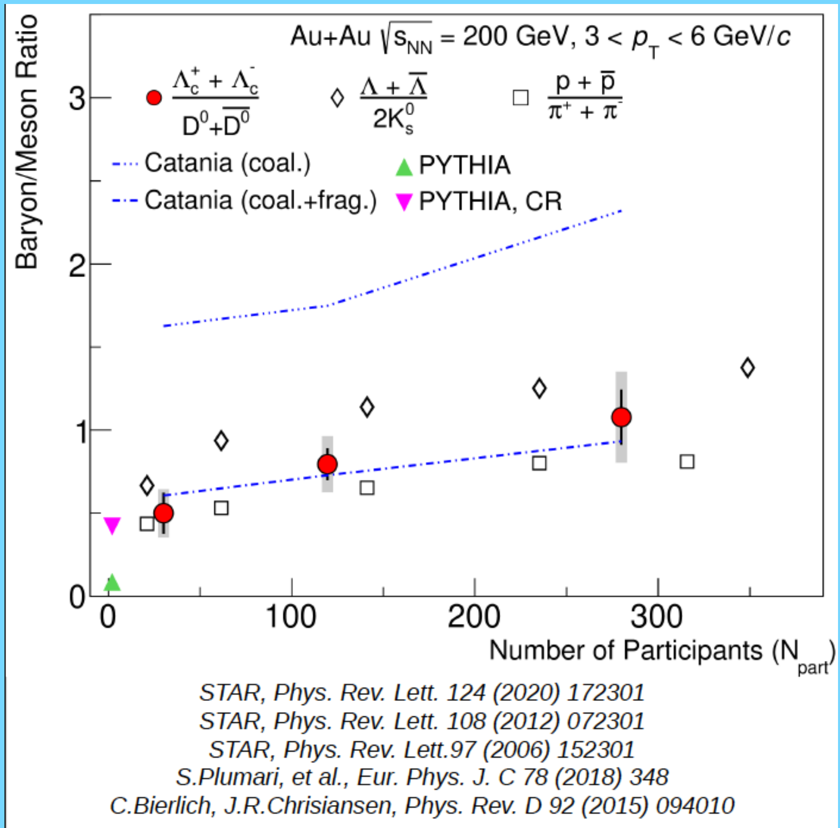
Jan Vanek, QM 2022

J. Vanek et al, STAR Collaboration, QM2022

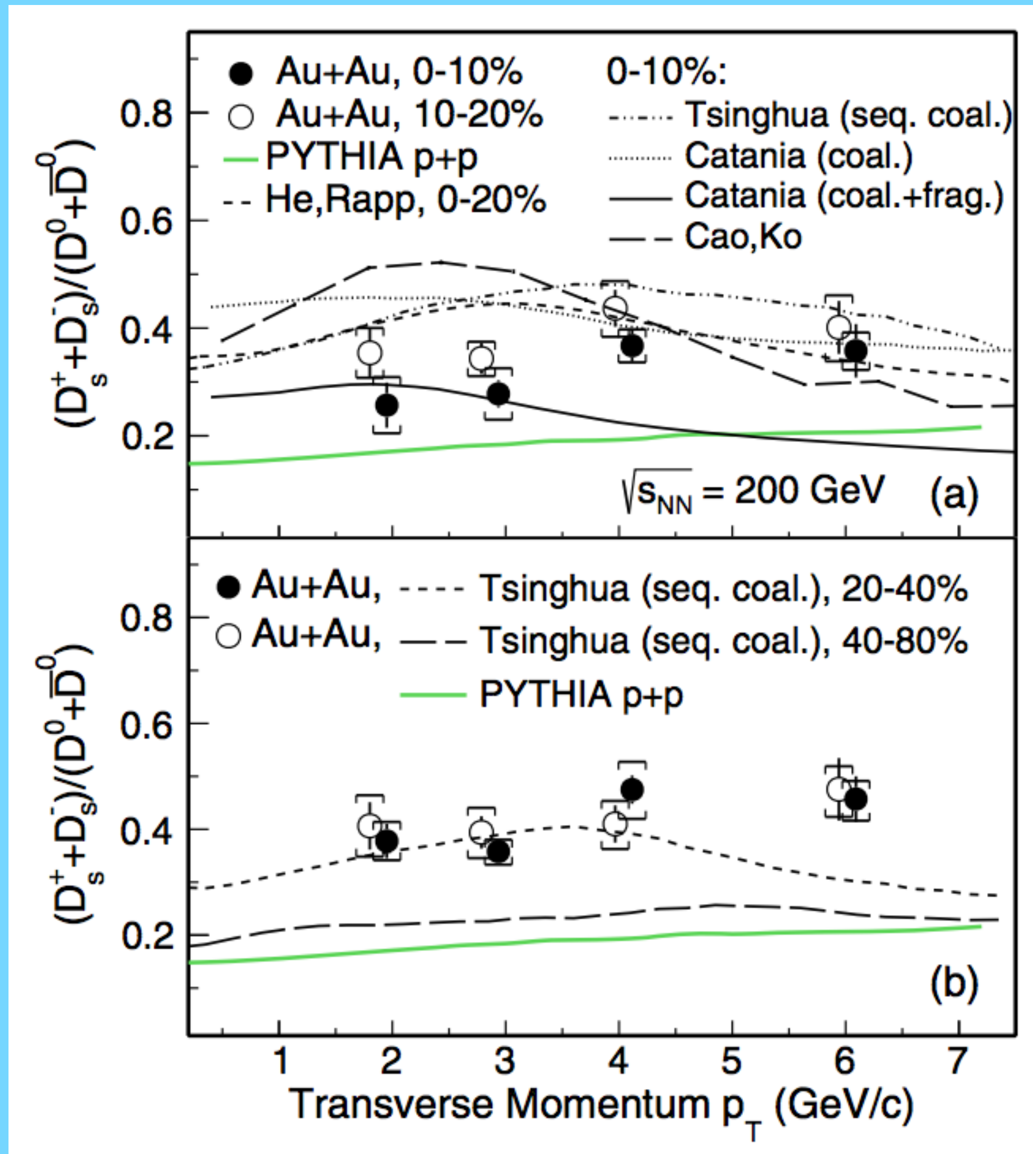
* Centrality dependence of R_{AA} of $D^{+/-}$ and D^0 measured
* R_{AA} of $D^{+/-}$ and D^0 are consistent with each other and suppressed at high p_T in central (0-10%) Au+Au collisions

STAR (2020,2021) First Λ_c and D_s measurements

STAR Collaboration, PRL 124 (2020) 17, 172301



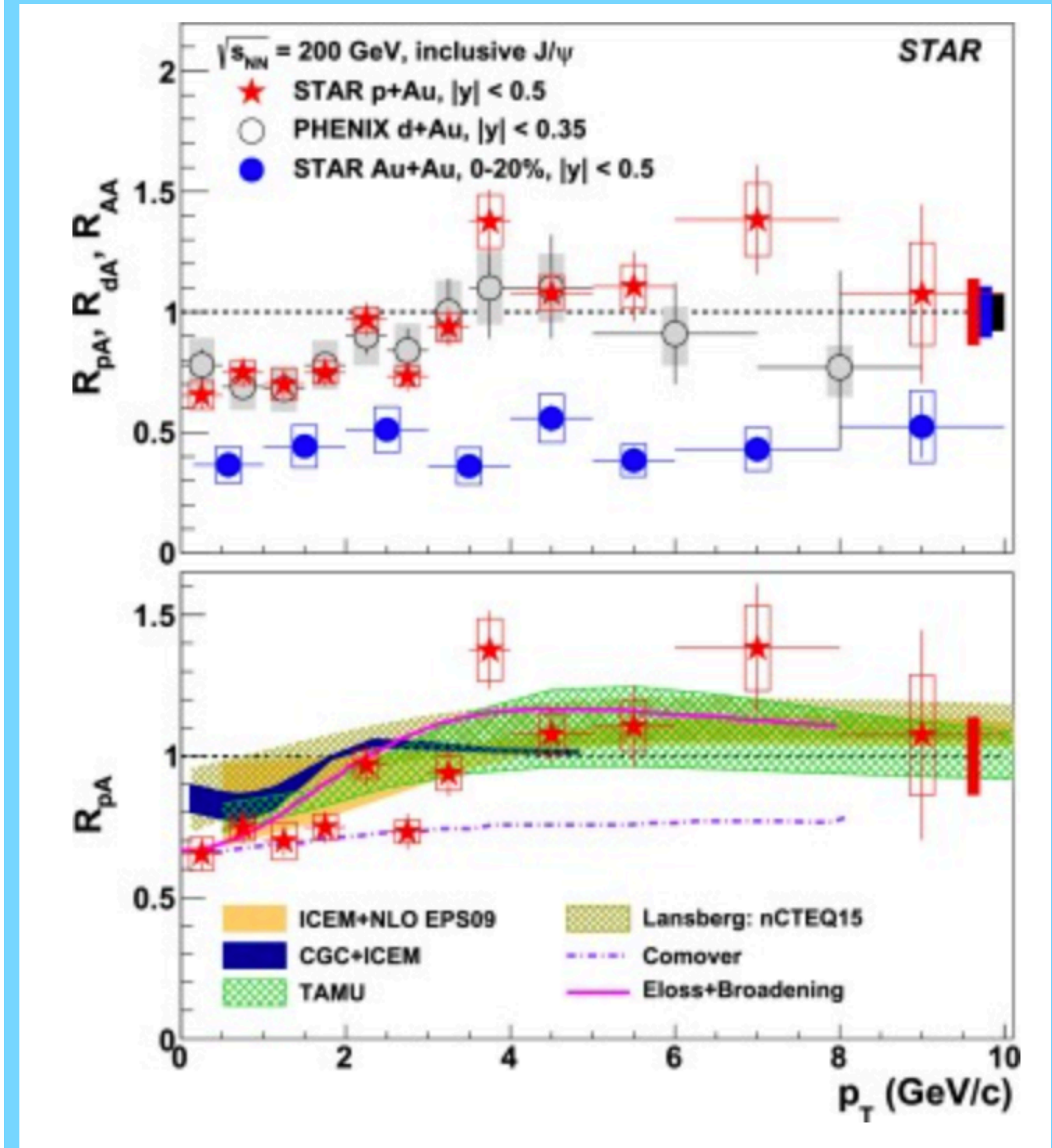
STAR Collaboration, Phys. Rev. Lett. 127, (2021), 092301



* Λ_c/D^0 and D_s/D^0 ratios in 200 GeV Au+Au are higher than PYTHIA
* Data are in accordance with models that include coalescence hadronization of charm hadrons

Quarkonia

J/Psi in p+Au and d+Au at 200 GeV



STAR, PLB 825 (2022) 136865
PHENIX PRC 87 (2013) 03904

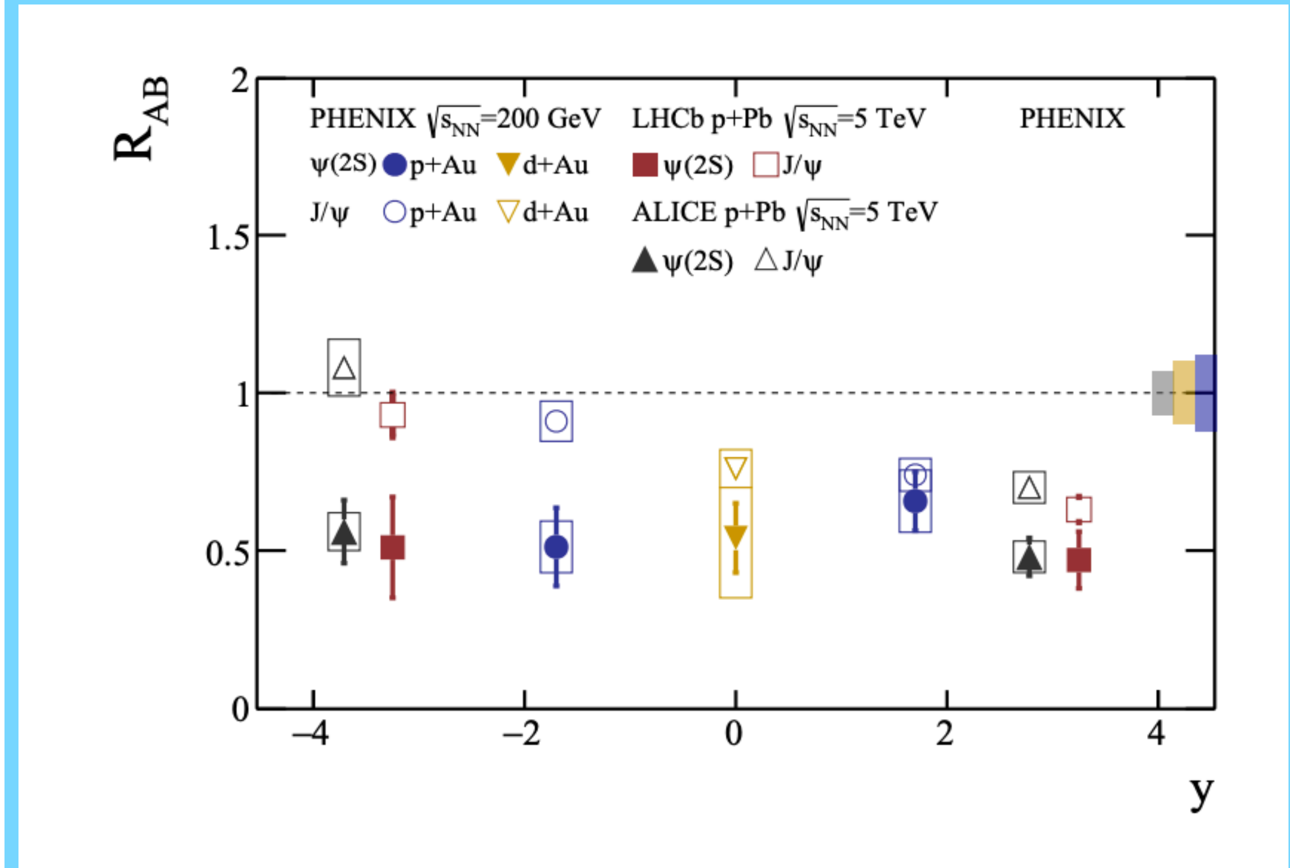
* Similar Cold Nuclear Matter (CNM) effects in p+Au and d+Au

* Au+Au 200 GeV 0-20% suppressed in all pT

* CNM contributes to CNM below pT 3 GeV

* Consistent with model calculations apart form comover model above pT 3 GeV/c

PHENIX J/Psi and Psi(2S) in small systems



- * At forward rapidity J/Psi and Psi(2S) similar, suggesting initial state effects dominate
- * At backward rapidity psi(2S) is suppressed and J/Psi is not

Conclusions and Outlook

* Flow results suggest strong interaction of heavy quarks with medium above sqrt(s)=27 GeV Au+Au

* Evidence for mass ordering of bottom and charm (measured via b, c-> e) in Au+Au 200 GeV has been observed at RHIC

* Lambda(c), D in agreeement with assumption of coalescnce

* p+Au , d+Au: J/Psi and Psi(2S) dominated by initial effects in forward rapidity. Psi(2S) suppreessed in backward rapidity.

Outlook

STAR and sPHENIX run period

sPHENIX BUP2022 [sPH-TRG-2022-001], 24 (& 28) cryo-week scenarios

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| <10$ cm	Samp. Lum. $\|z\| <10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^\uparrow p^\uparrow$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-str]	45 (62) pb^{-1}
2024	$p^\uparrow$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-str]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

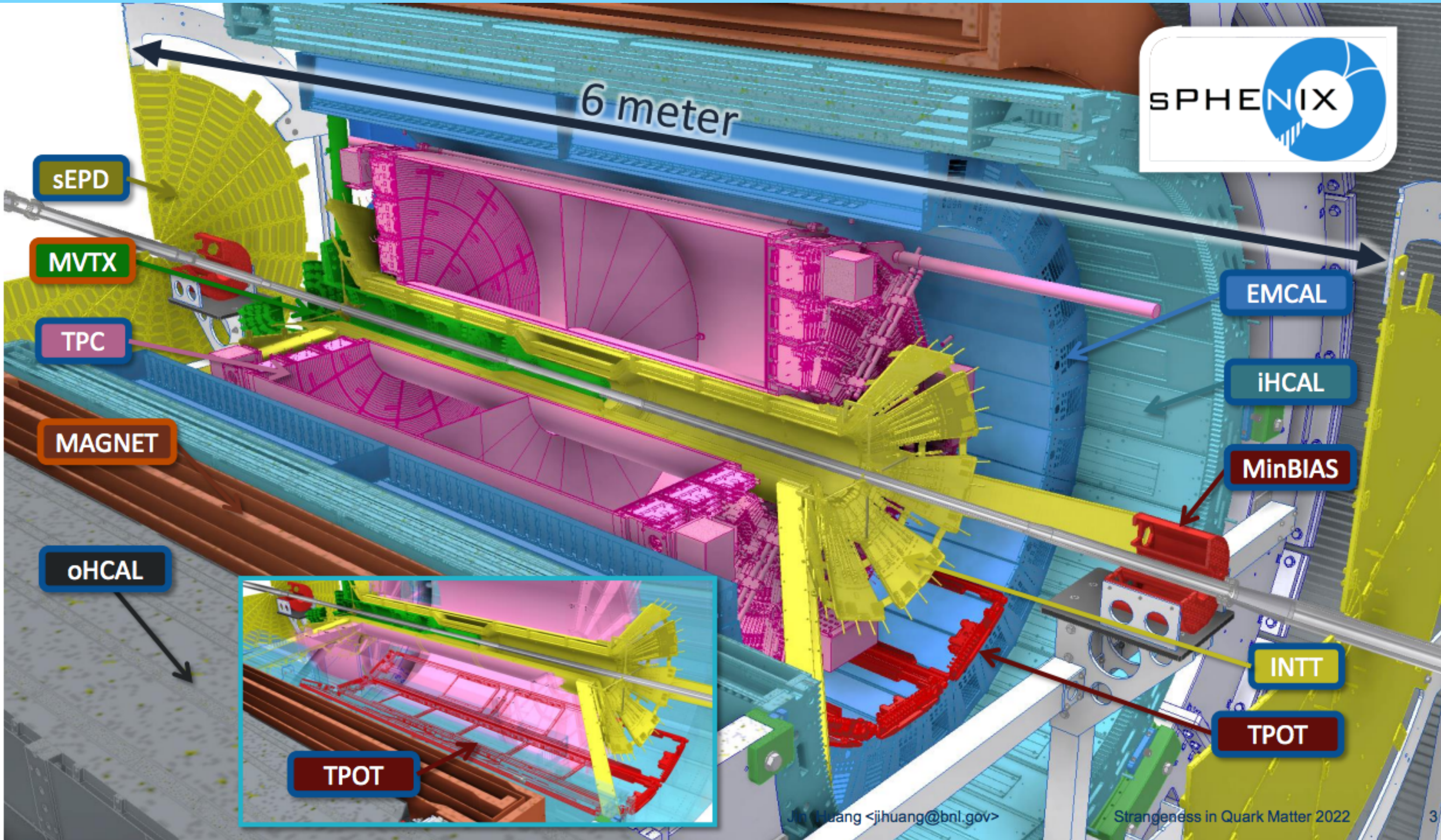
*** STAR: Future data will extend the kinematic range for open heavy flavor hadron measurements via semileptonic decays**

*** PHENIX:**
Will add to analysis the data Au+Au from 2016
New b and c results from Au+Au and small systems are coming soon

*** sPHENIX start: 2023**

Thank you very much

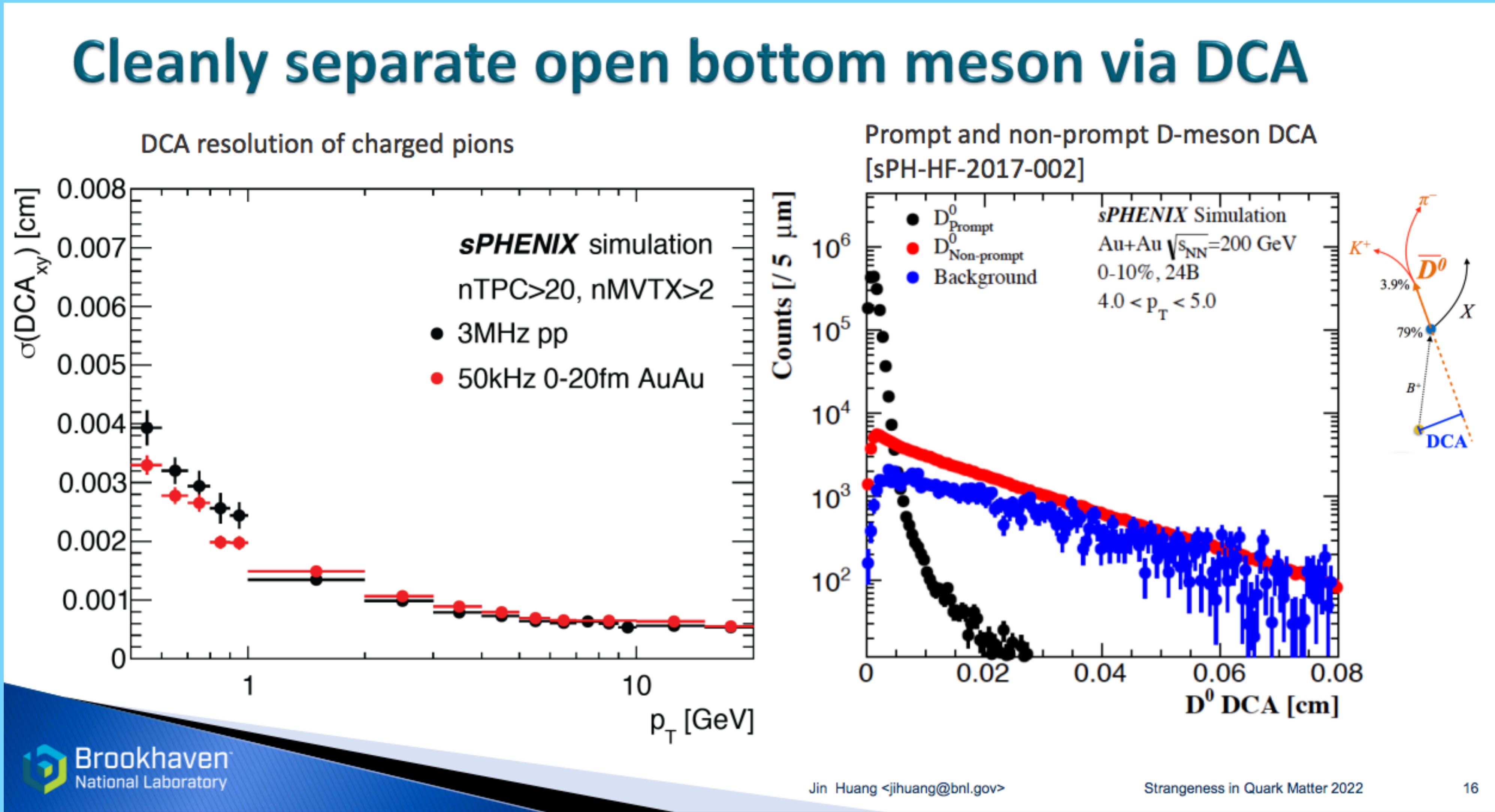
sPHENIX



6 meter
sPHENIX
sEPD
MVTX
TPC
MAGNET
oHCAL
EMCAL
iHCAL
MinBIAS
INTT
TPOT
TPOT
Jin Huang <jihuang@bnl.gov>
Strangeness in Quark Matter 2022
3

sPHENIX

Exceptional performances expected for open heavy flavor



Jin Huang, PHENIX Collaboration, SQM2022