Heavy flavor measurements at RHIC

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Diffraction and Low-x 2024, 8-14 September 2024,
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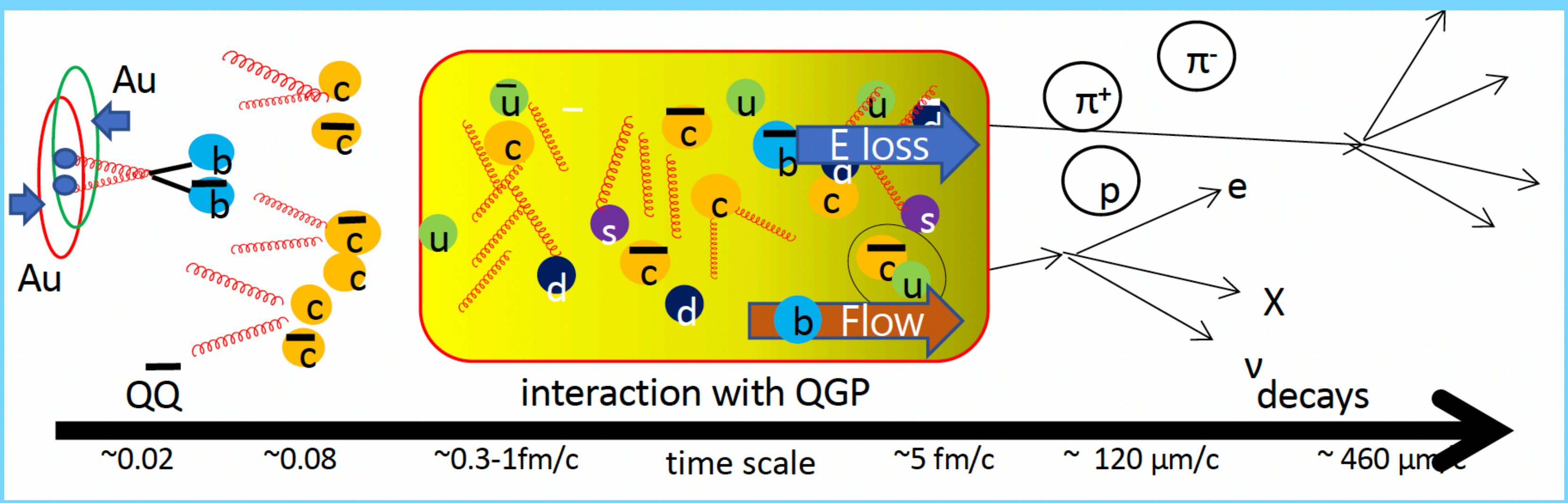
Outline

* 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
* Conclusions and outlook

Introduction

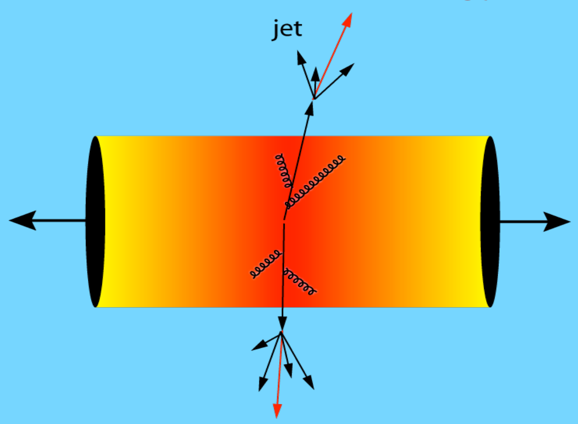
* Open heavy flavor: Charm and beauty quarks are produced in initial hard scatterings and experience the entire evolution of A+A interactions

* Flow of open heavy flavor hadrons helps elucidate interaction of HF with medium, thermalization and production mechanisms of HF and probe sQGP properties

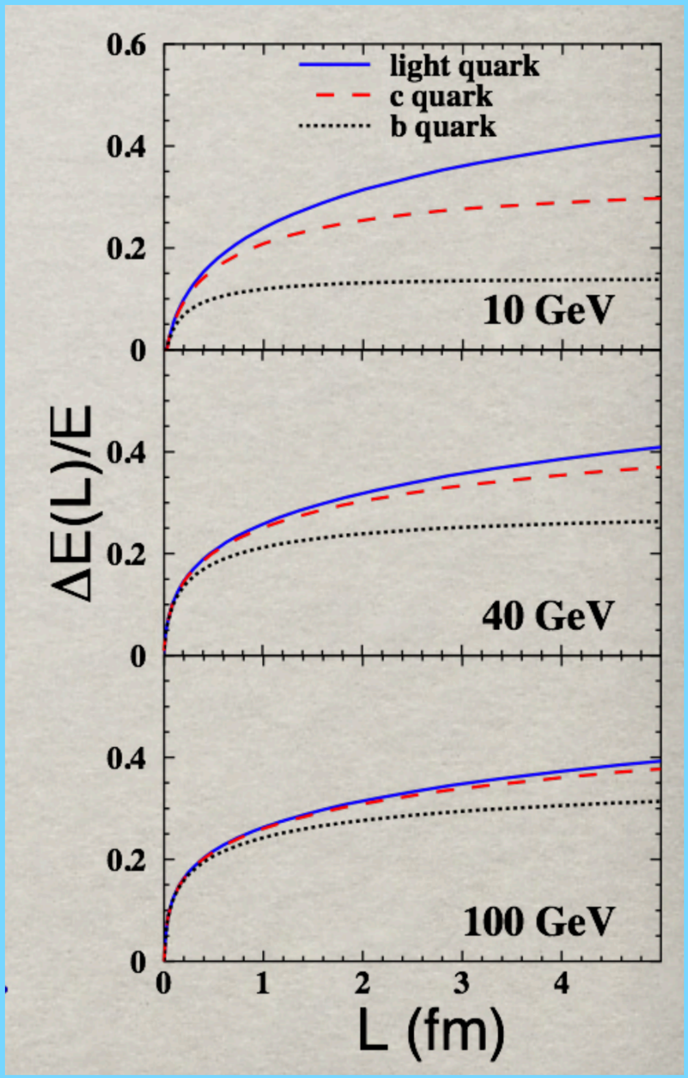


M. Shimomura, PHENIX, SQM2024

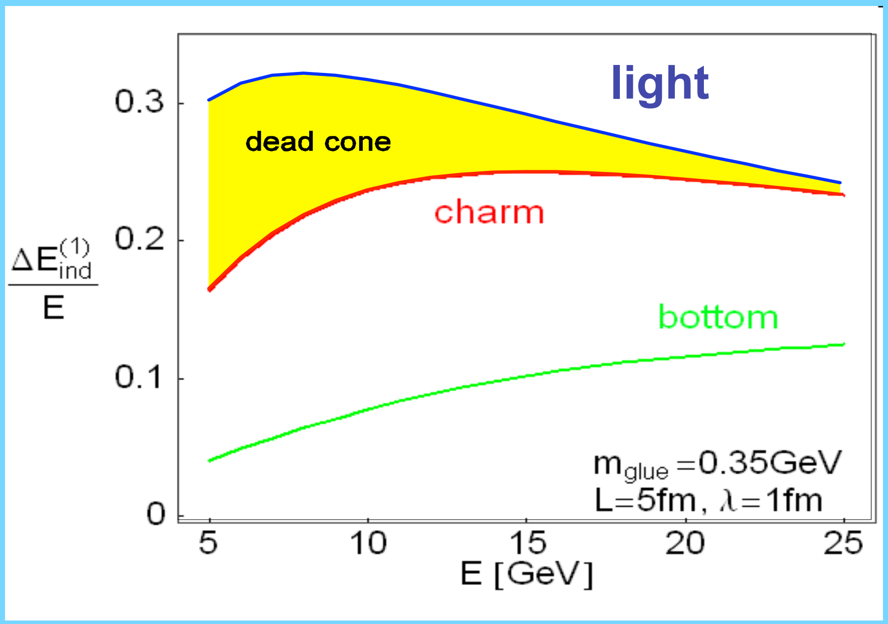
Introduction



B. Kopeliovich, ISMD2023



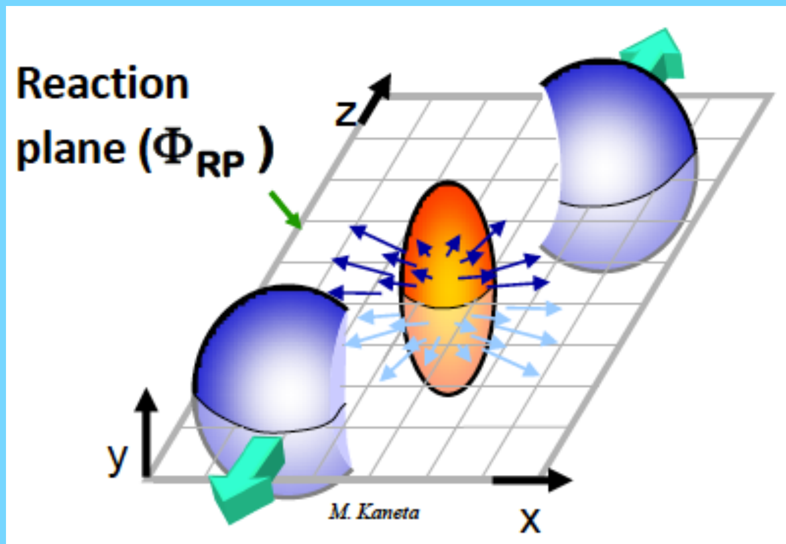
* Mass dependence of jet quenching in sQGP is expected

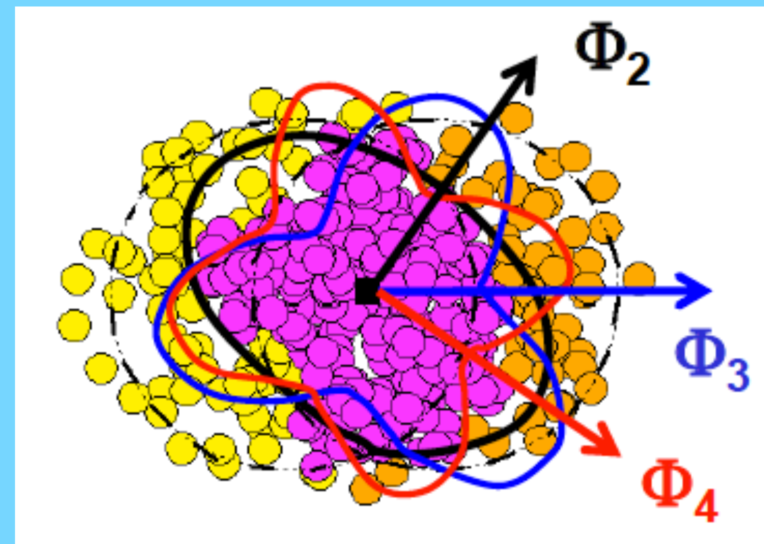


M.Djordjevic PRL 94 (2004)

B.Kopeliovich., I.Potashnikova,I.Schmidt, PRC 82(2010)037901

Flow coefficients v_n, n=1,2,3..





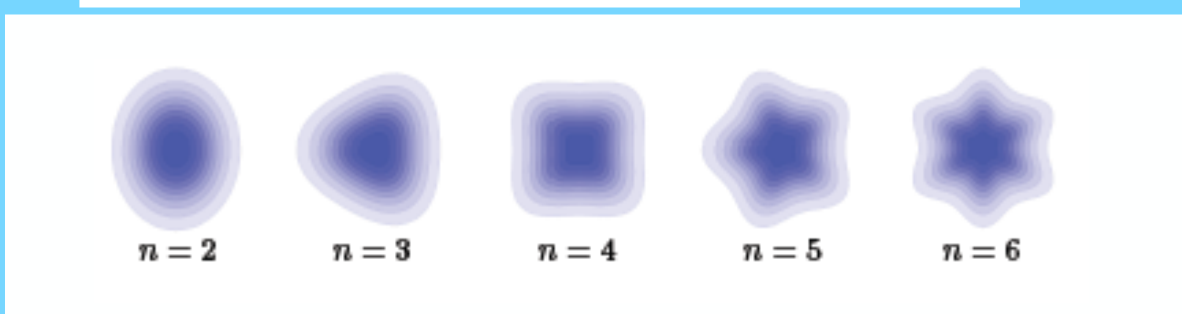
Matter in the overlapp area of two colliding nuclei gets compressed and heated

Initial anisotropy gets transfered into the momentum space via pressure gradients

$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)]$$

$$v_n = \langle \cos[n(\phi - \Phi_n)] \rangle$$

v : flow coefficients
(v1: directed flow,
v2: elliptic flow, ...)

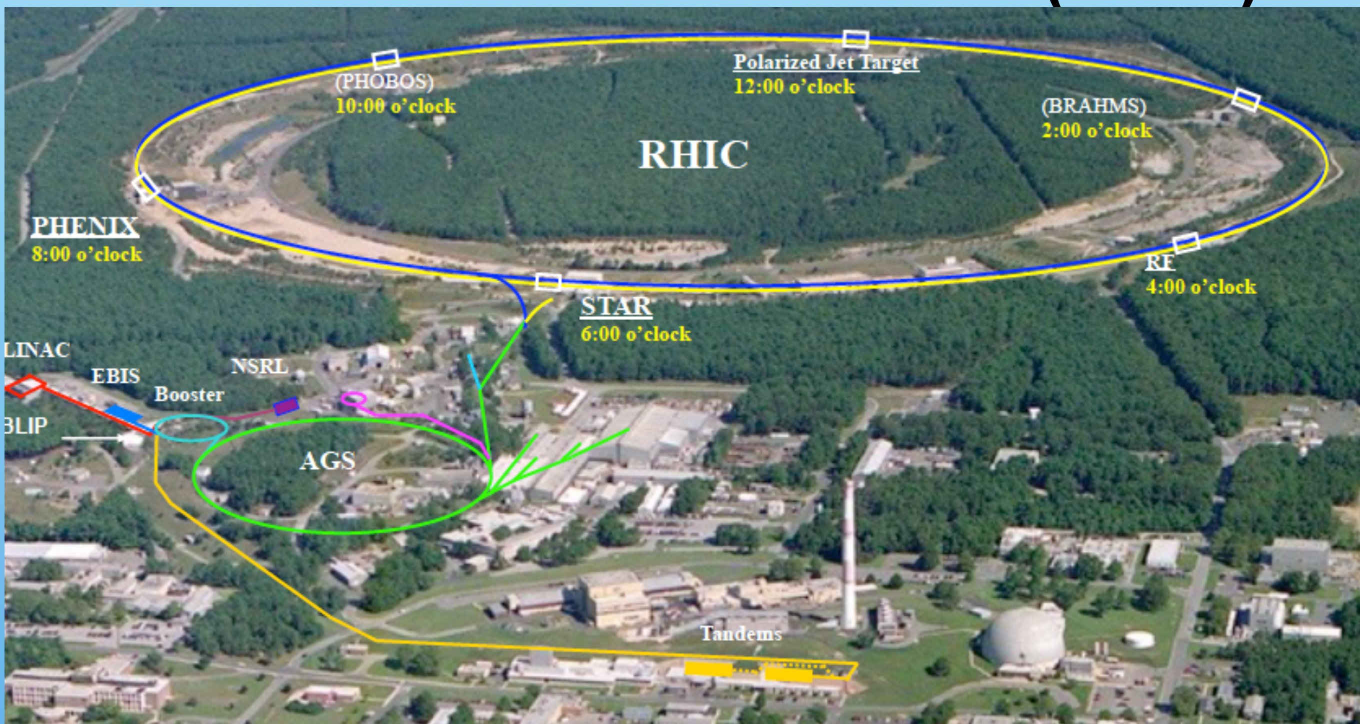


Higher harmonics

Relativistic Heavy Ion Collider

at the Brookhaven Lab, Long Island, New York, USA

Relativistic Heavy Ion Collider (RHIC)



RHIC has been exploring nuclear matter at extreme conditions since 2000

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still runing: STAR

Still analysing data:
PHENIX
New: sPHENIX

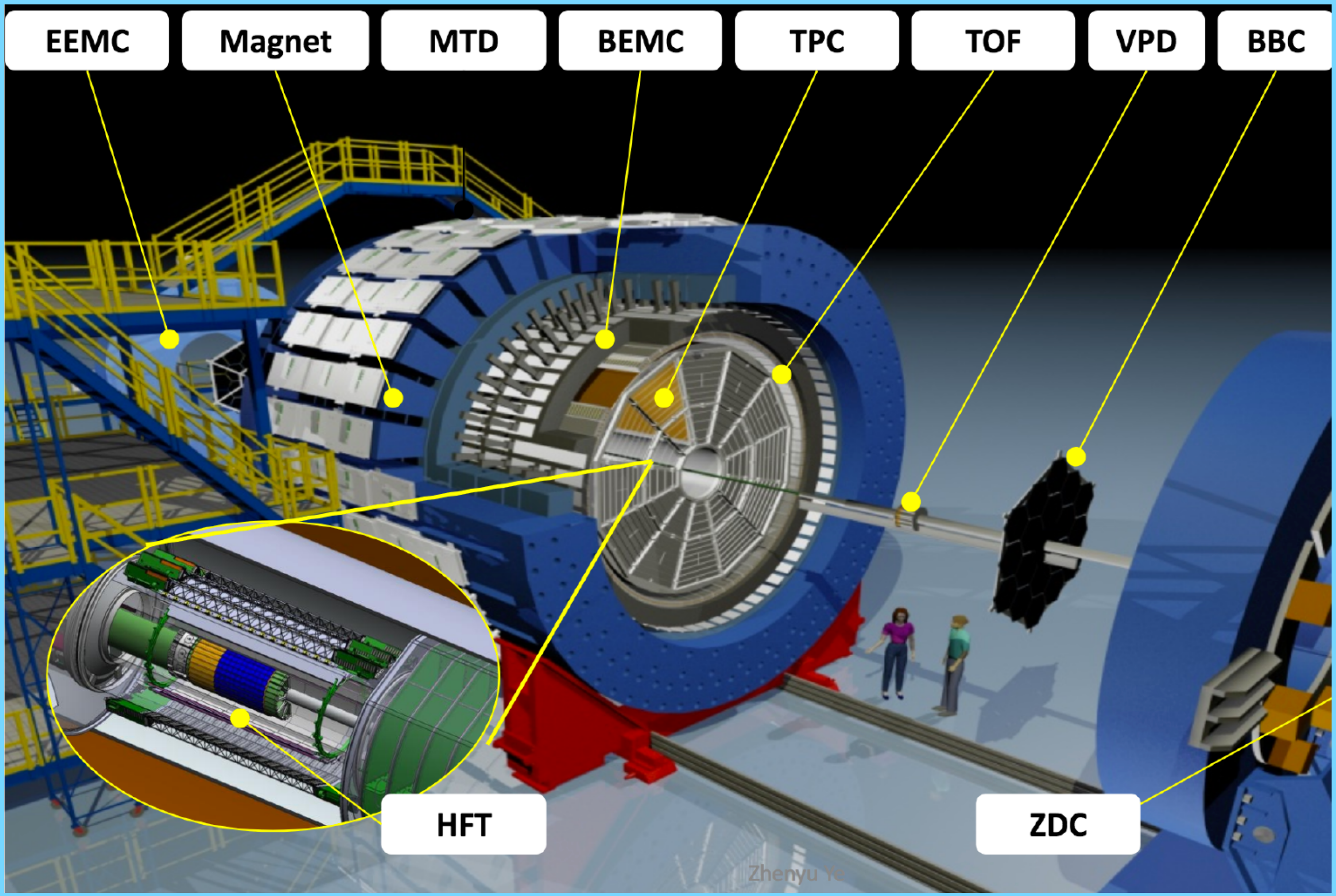
Some of the colliding systems:

p+p, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U, Zr+Zr, Ru+Ru

Some of the energies A+A :

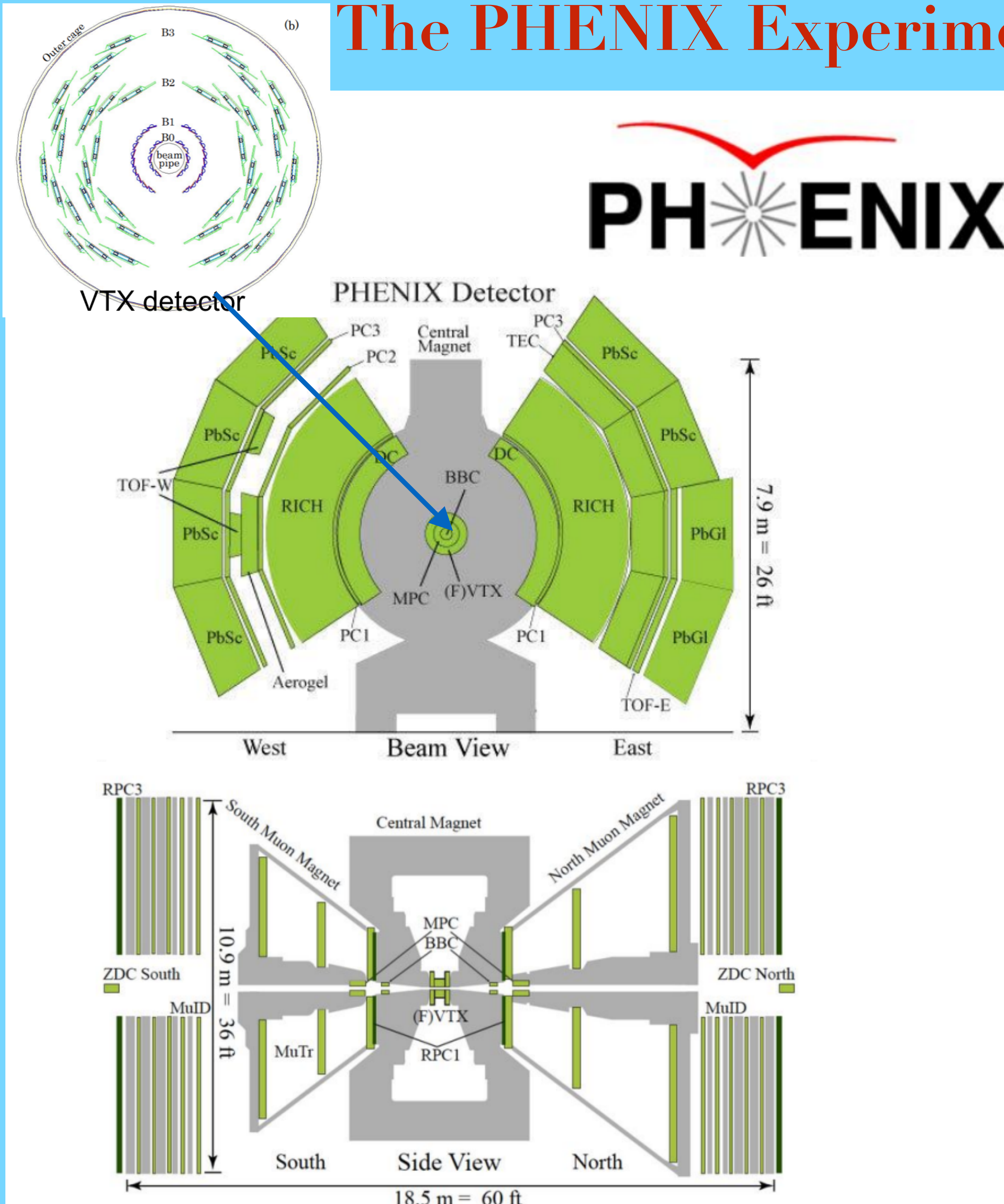
$\sqrt{s_{NN}}$ = 62, 130, 200 GeV
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39 GeV
+ Fixed target

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

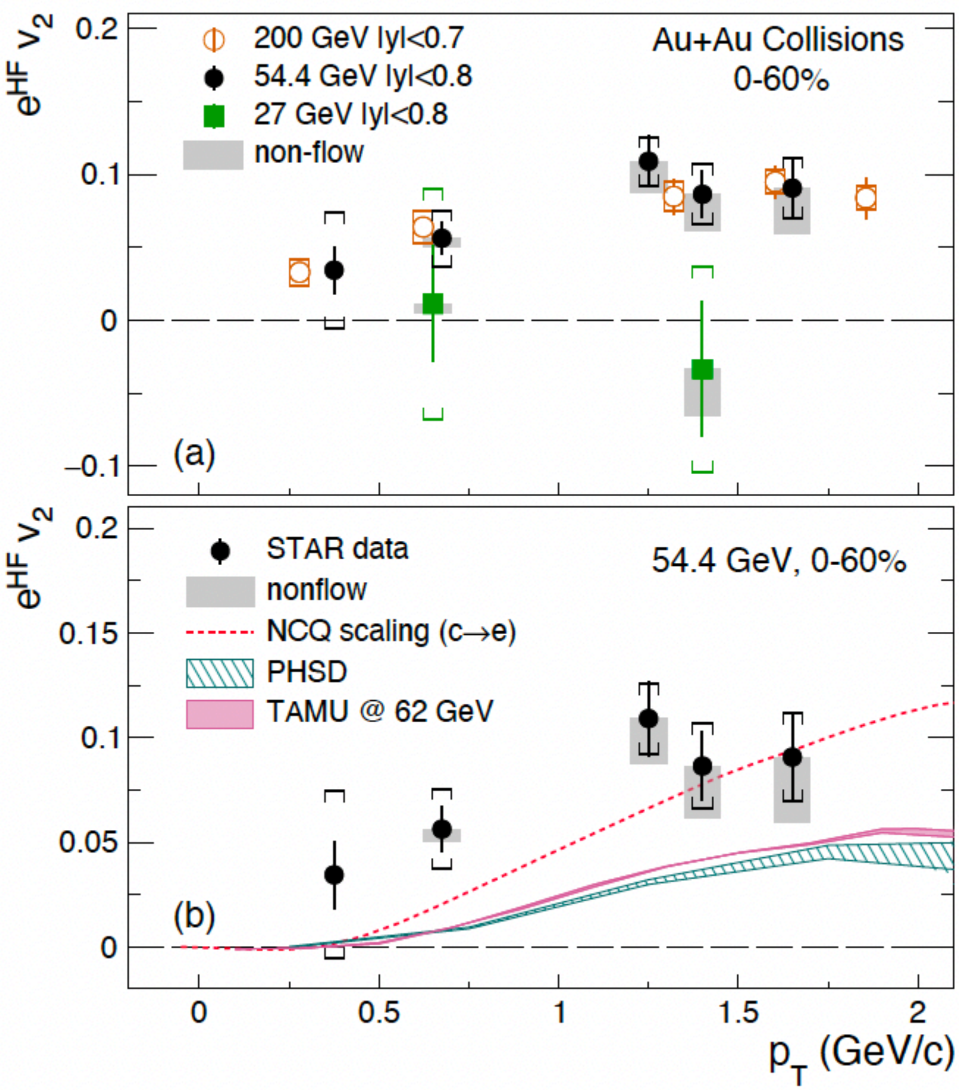
-Muon arms: $1.2<|y|<2.2$, phi=2 pi/2

Data taking completed in 2016

Charm and Bottom flow in Au+Au collisions

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

STAR Collaboration, ArXiv 2303.03546, *Phys.Lett.B* 844 (2023) 138071



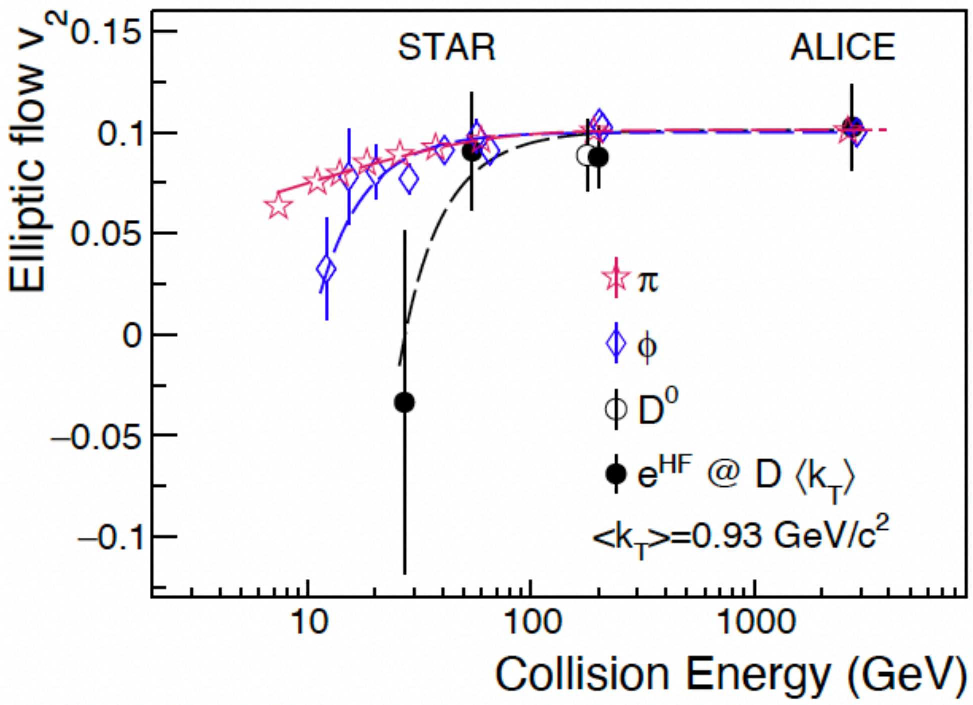
* The elliptic flow of heavy flavor electrons in Au+Au collisions at 54.4 GeV is comparable to 200 GeV, and non-zero above pT 0.5 GeV/c, indicating strong charm quark interactions with the medium

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

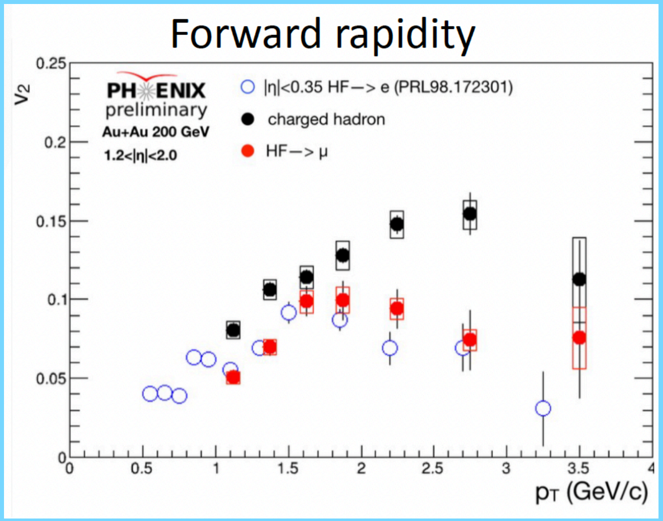
STAR Collaboration, ArXiv 2303.03546, *Phys.Lett.B* 844 (2023) 138071



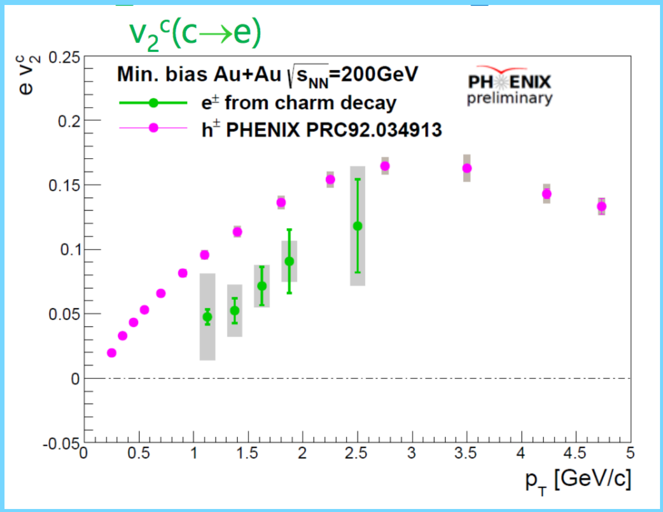
* The elliptic flow of pions, phi, and D0 and heavy flavor electrons in Au+Au collisions at 54.4 GeV at <mT-m0>=0.93 GeV as a function of collision energy. The lines are for eye guidance.
* Indication of a mass hierarchy of the energy dependence of v2; the v2 of heavier particles drops faster than ligher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

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

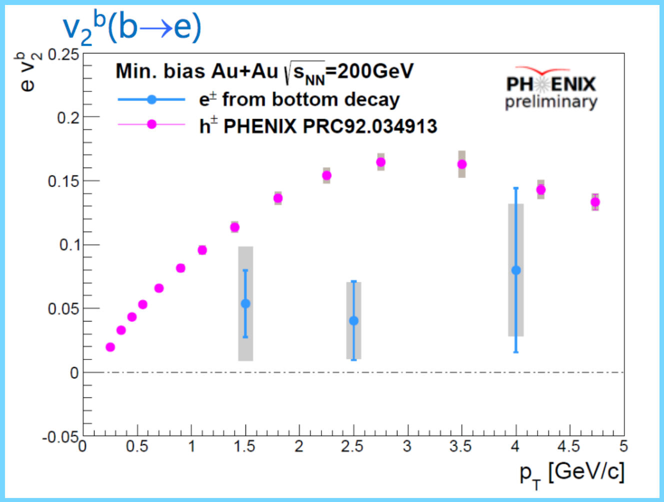
Forward rapidity
HF (b+c)



Midrapidity
charm



Midrapidity
bottom



T Hachiya et al, PHENIX collaboration, QM2022
M. Shimomura, SQM2024

* v2 of Heavy Flavor is positive at both midrapidity and at forward rapidity and mostly consistent

* v2 of hadrons is larger than v2 of charm

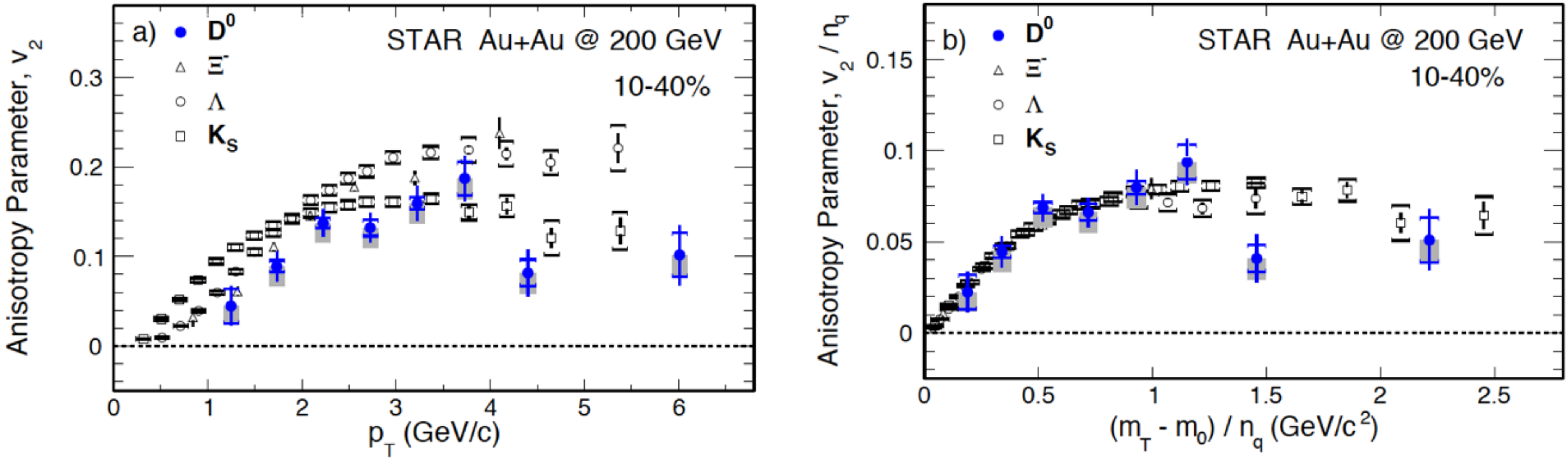
* hint of positive v2 of bottom —> electrons (e+-) (with ˜1.1 sigma)

* v2 of charm is larger than v2 of bottom -> Heavier quarks have less flow

Strangeness and charm v2
STAR D0 v2 from STAR Heavy Flavor Tracker

L. Adamczyk et al, STAR, Phys. Rev. Lett. 118, 212301 (2017), 1701.06060

Mass ordering **NCQ scaling**



v2 of D0 in Au+Au follows Number-of-Constituent-Quarks scaling of other hadrons

-> Evidence for thermalization of u,d,s,c mesons

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

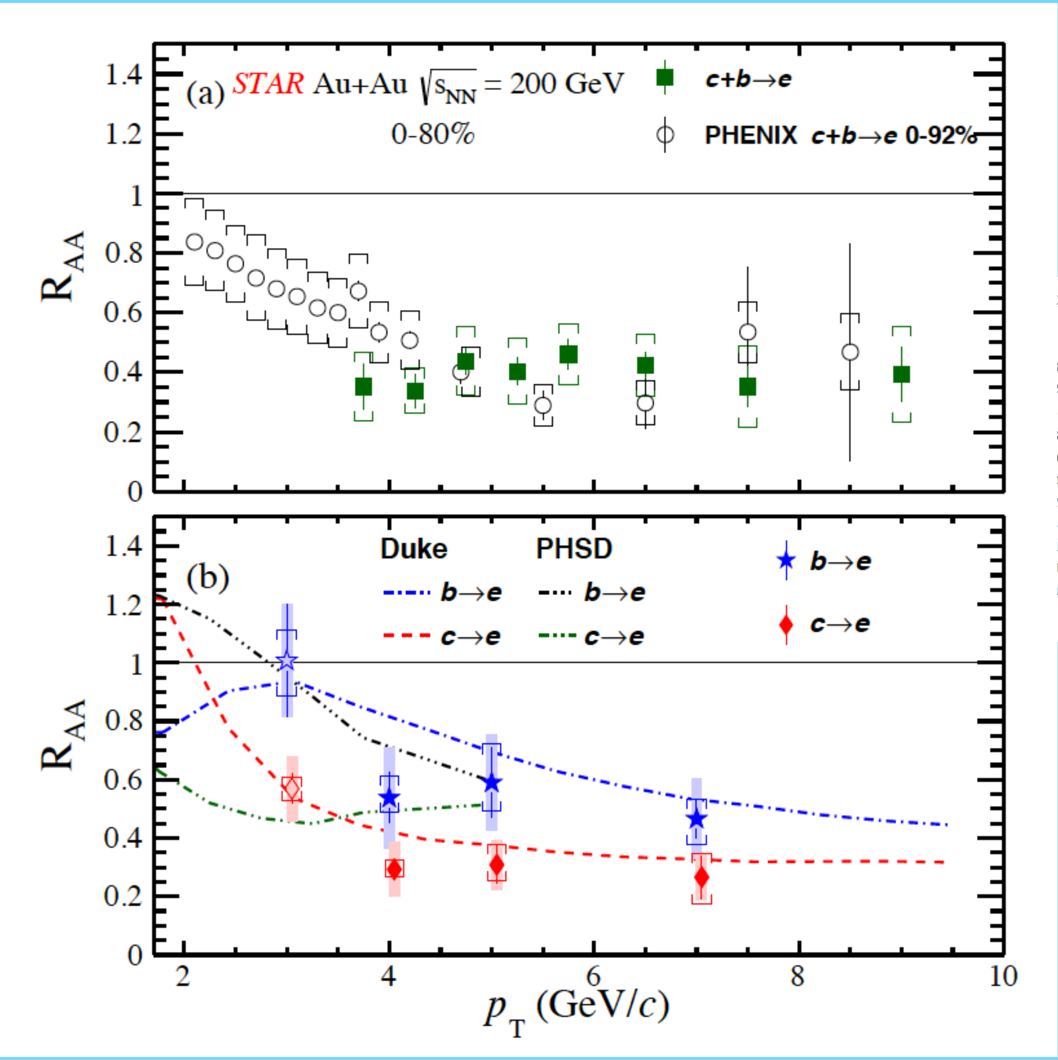
STAR Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

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-dependent energy loss mechanisms
* Data consistent with model predictions

* **R(AA) vs pT of c+b —> e in AuAu 0-80%: 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**

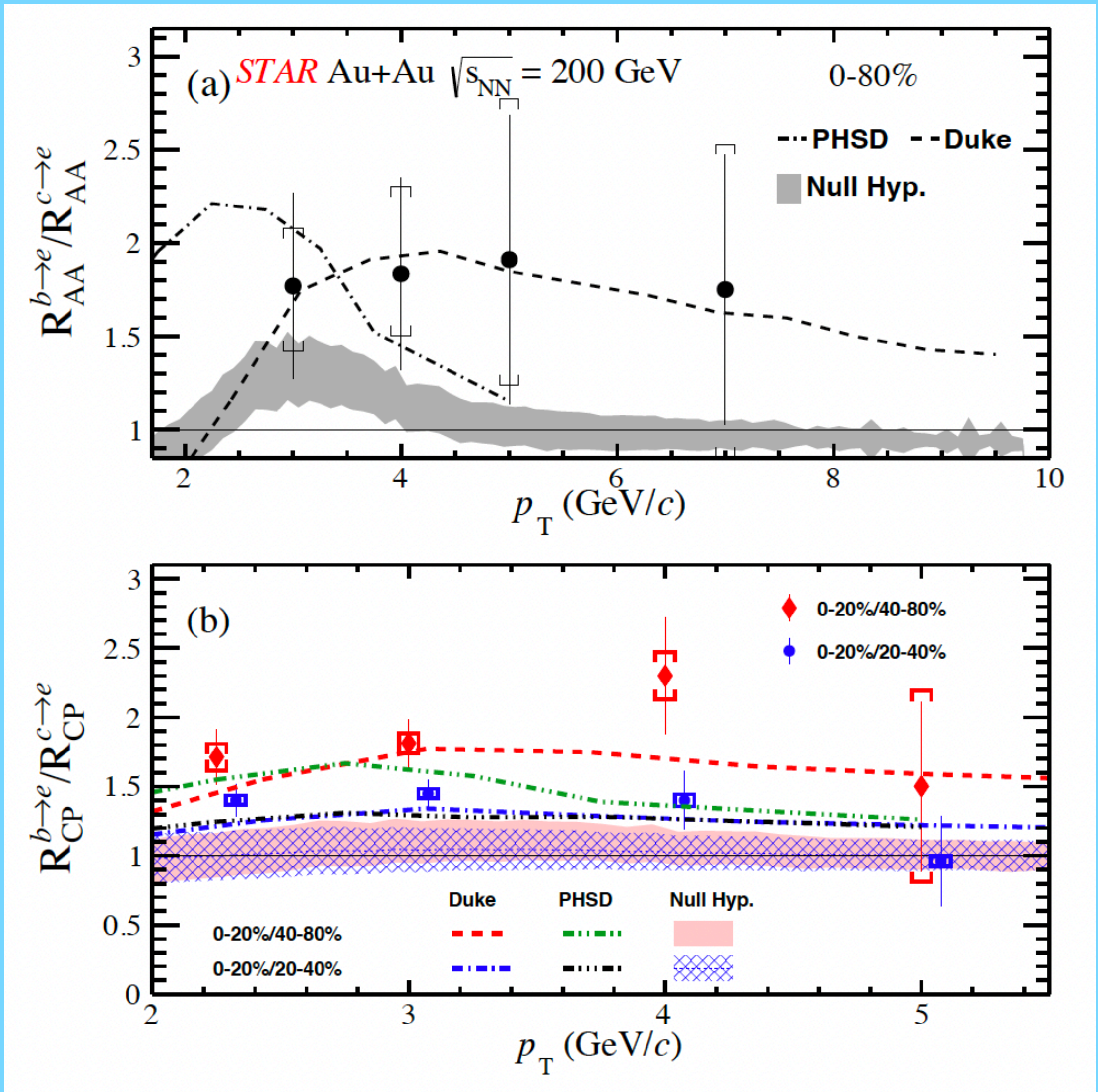


STAR Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

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

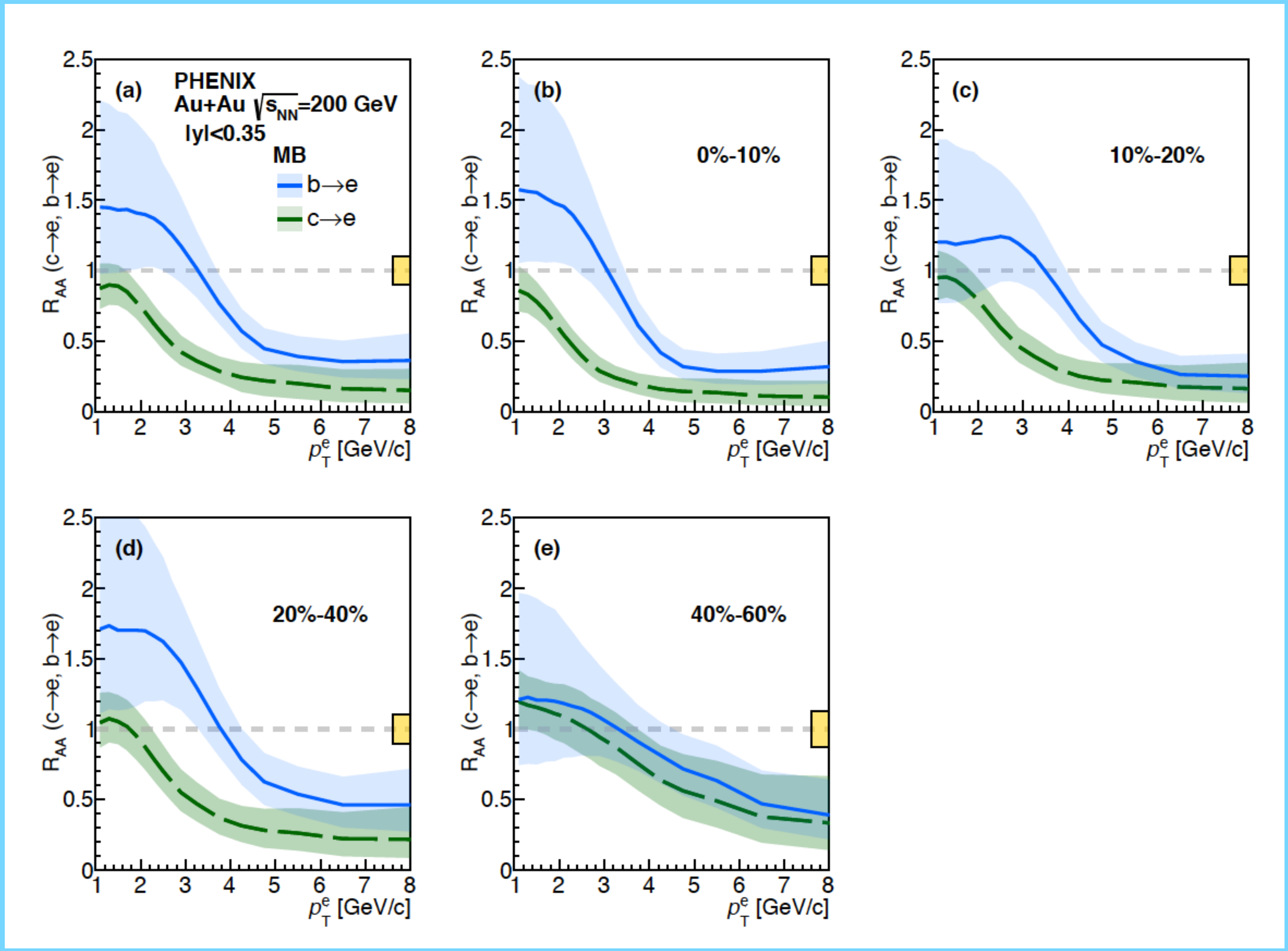
- Ratios of R(AA) and R(CP) of bottom->e to charm->e vs pT

- The R(CP) ratios of b->e and c-> e for (0-20%)/(40-80%) show a significant deviation from unity



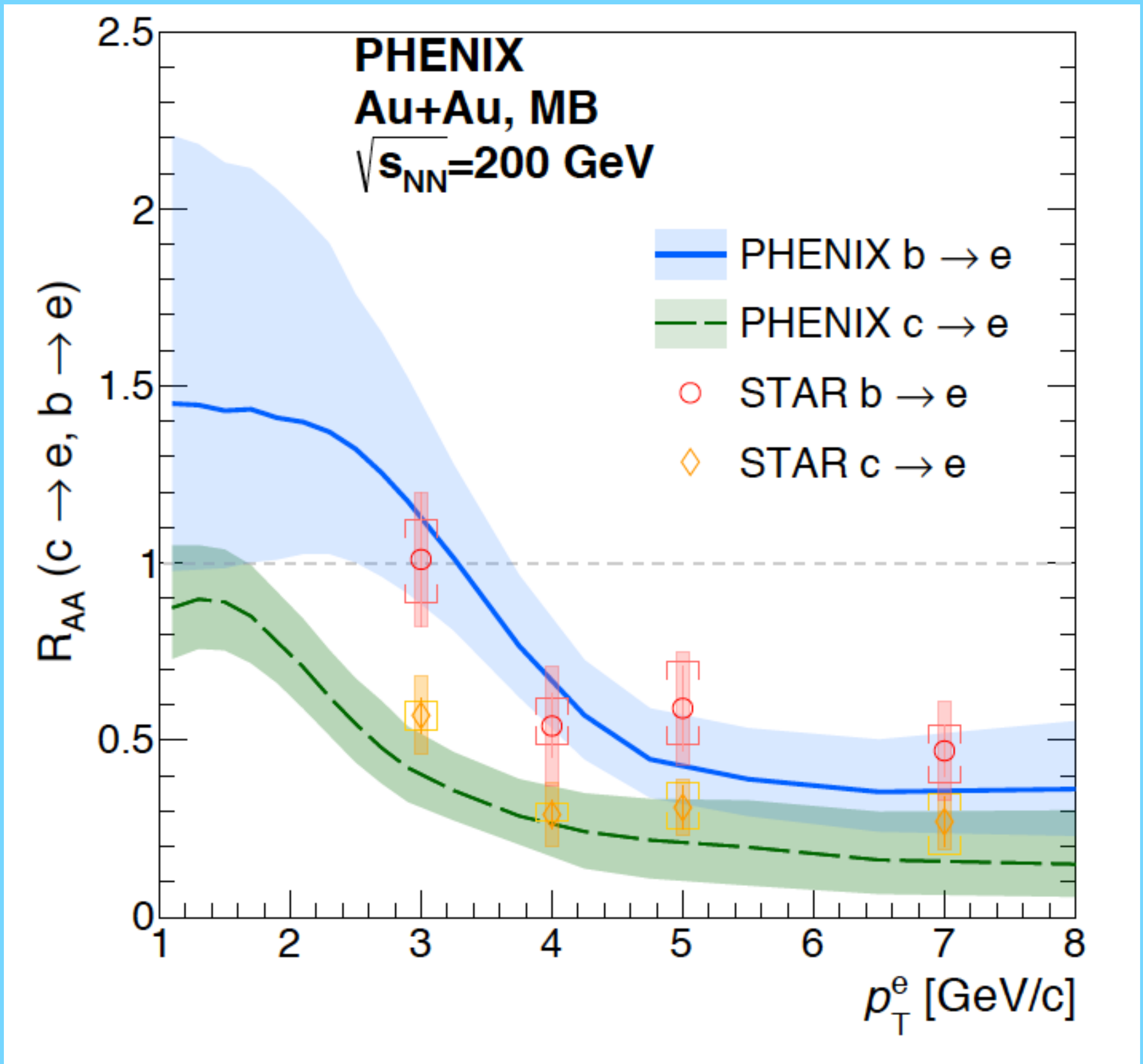
PHENIX hierarchy of suppression of b—>e and c—>e in Au+Au collisions at 200 GeV

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

PHENIX vs STAR Minimum Bias Au+Au



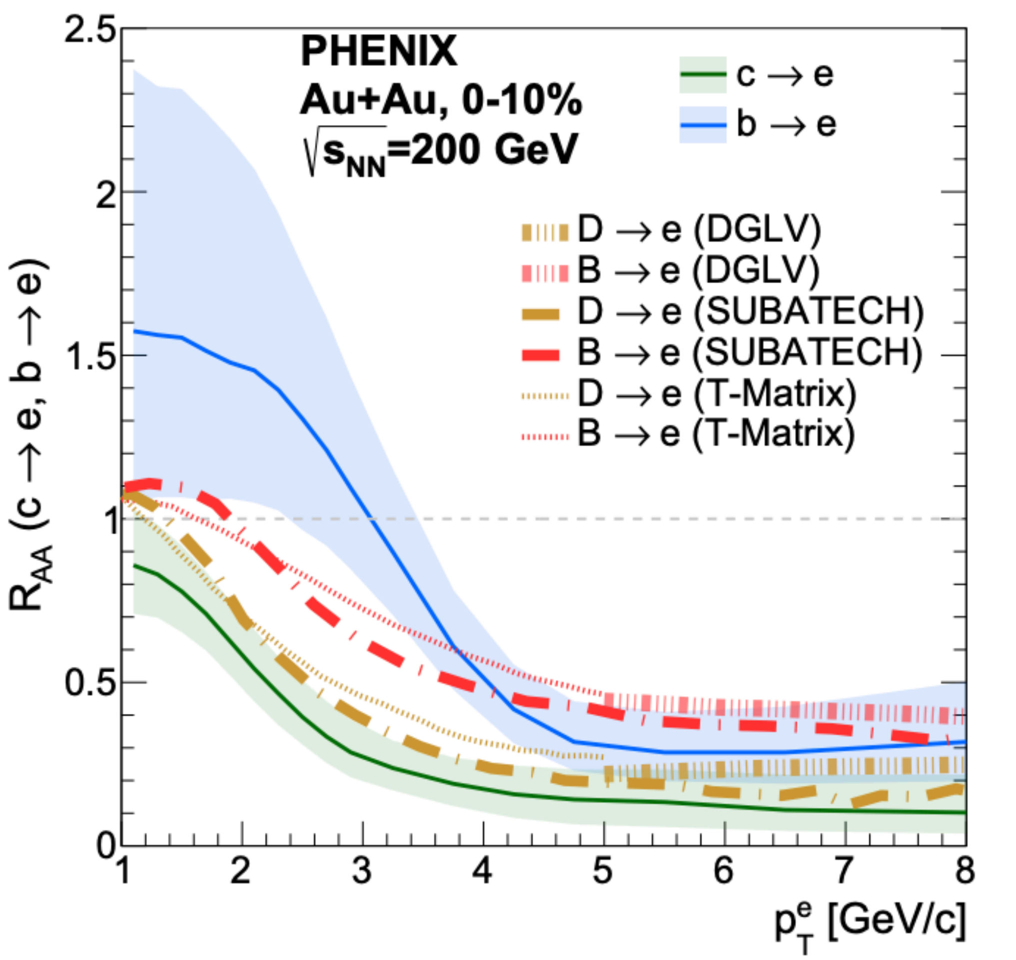
M. S. Abdallah et al. (STAR Collaboration), Evi-
dence of Mass Ordering of Charm and Bottom Quark
Energy Energy Loss in Au+Au Collisions at RHIC,
arXiv:2111.14615.

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

PHENIX vs Models, 0-10% Au+Au

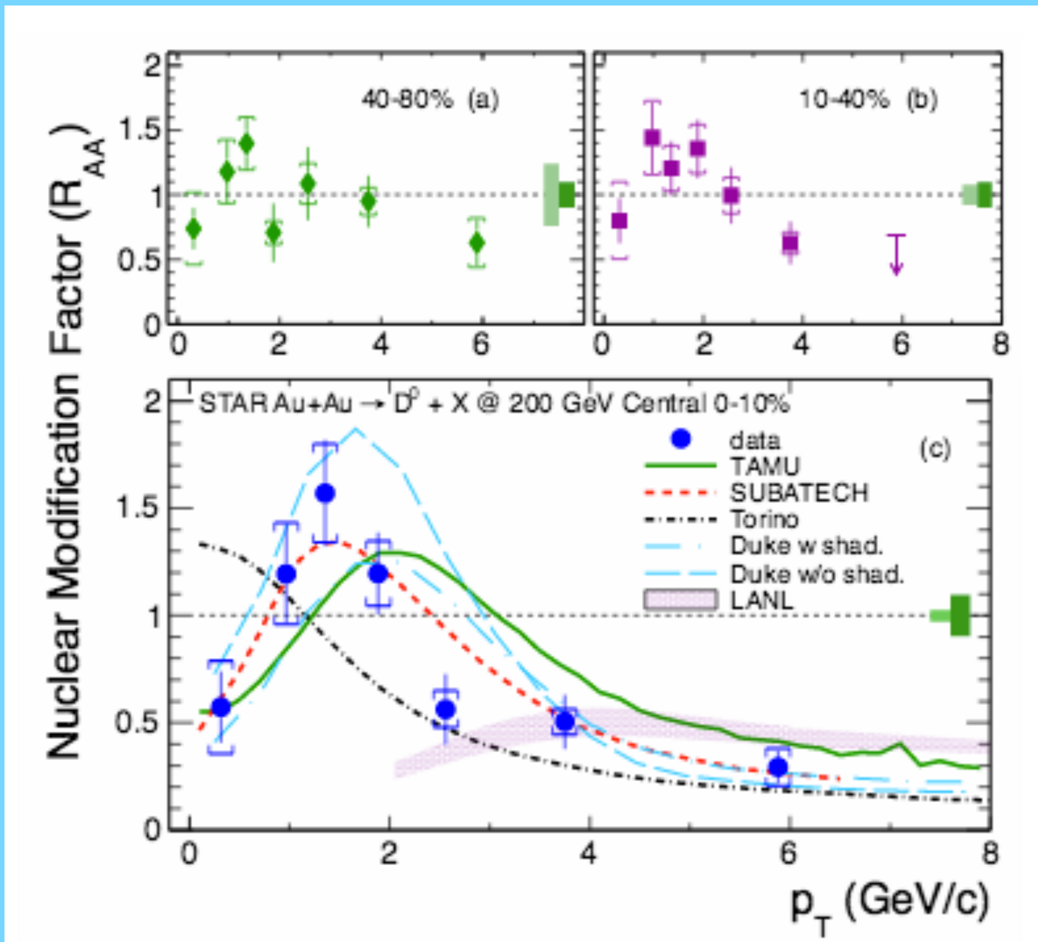
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058



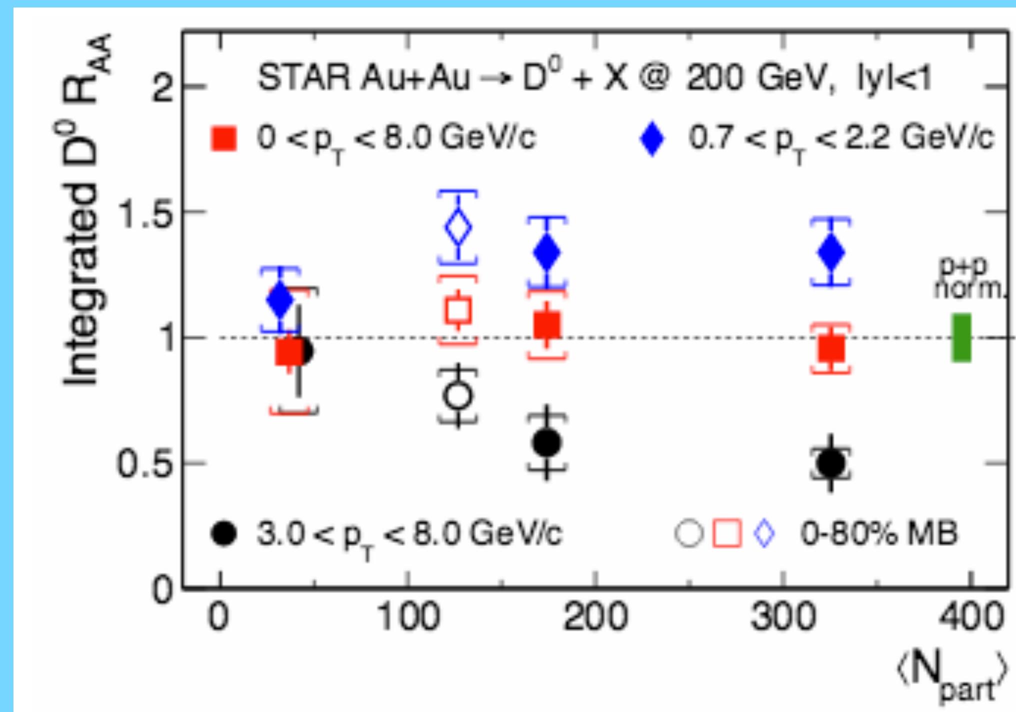
* T-Matrix approach is assuming formation of a hadronic resonance by a heavy quark in the QGP based on lattice quantum chromodynamics.
* The SUBATECH model employs a hard thermal loop calculation for the collisional energy loss.
* The DGLV model calculates both the collisional and radiative energy loss assuming an effectively static medium (shown for pT > 5 GeV).

* All shown models expect a quark mass ordering for the energy loss in the QGP medium, as observed in the data.
* The measured bottom nuclear modification is larger than the calculations at pT 2 to 4 GeV/c.

STAR R_{AA} of D_0 in Au+Au 200 GeV



STAR: Phys. Rev. Lett. **113** (2014) 142301 and 1404.6185



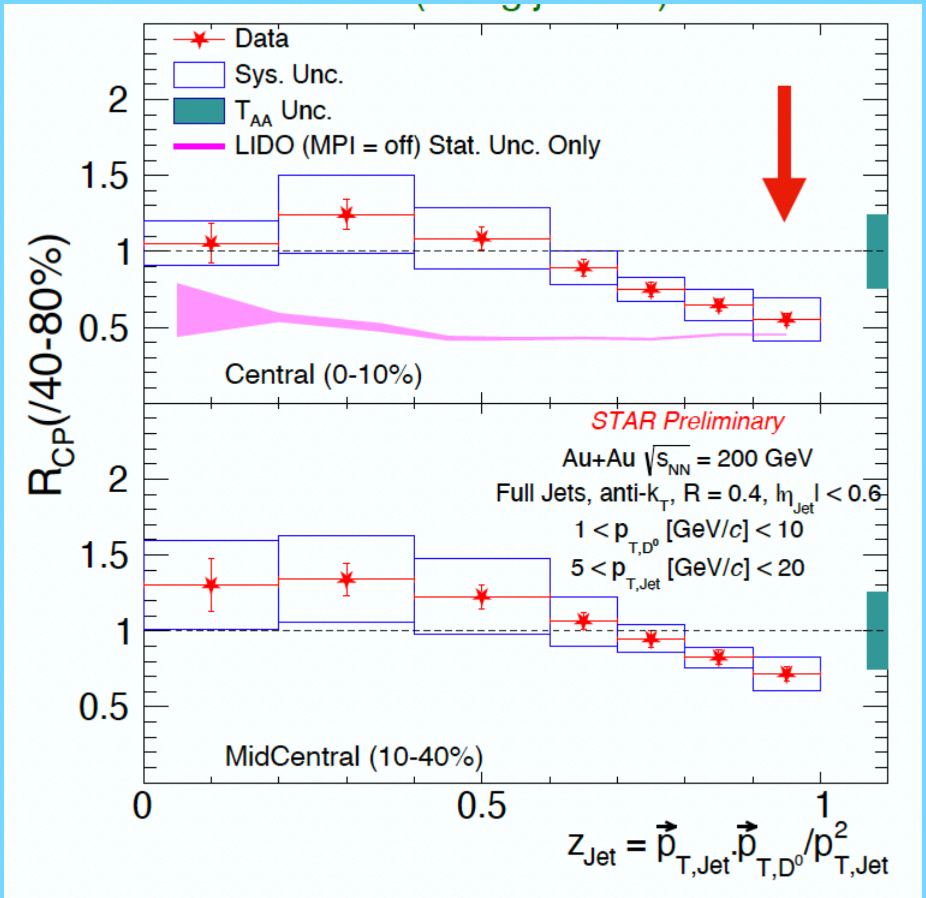
R_{AA} of D_0 at high p_T:

- RAA D0 suppression in central Au+Au 200 GeV
- suppression at high p_T similar to pions
- Enhancement at pT~0.7-2 GeV (described eg by models with charm quark coalescence with light quarks)

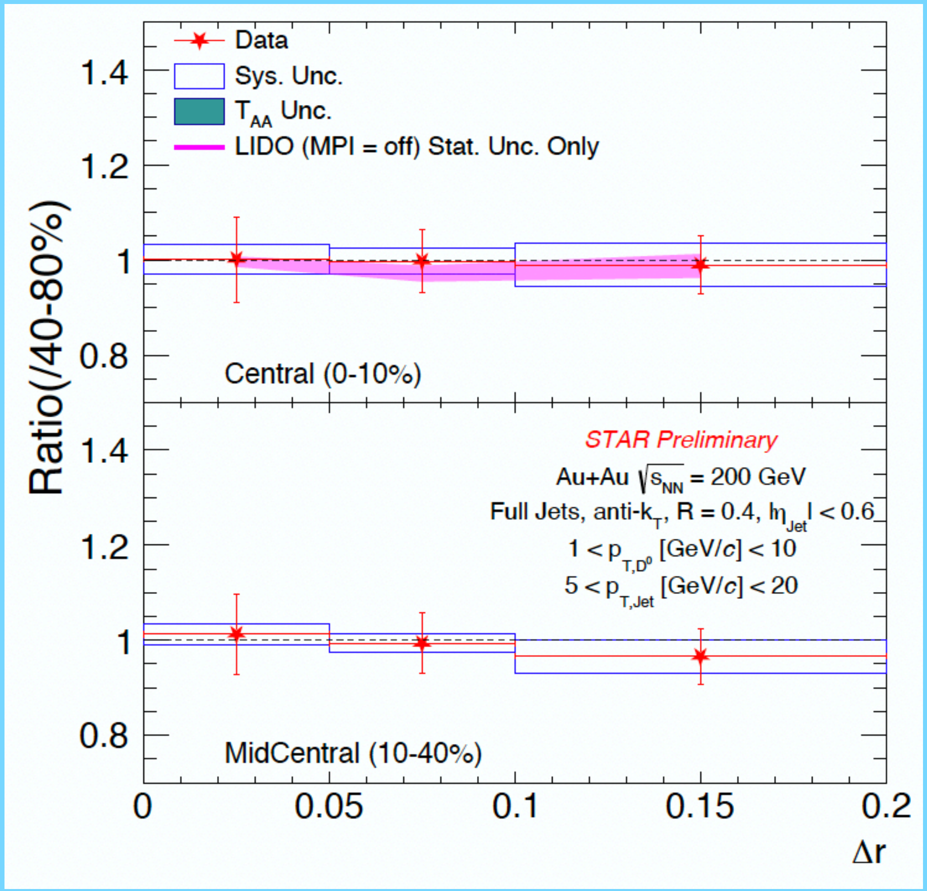
D0 tagged jet measurements

STAR D^0 tagged jet measurements in Au+Au 200 GeV

Fragmentation function modification (along jet axis)



Radial profile modification (perpendicular to jet axis)



O. Lomicky et al, STAR, SQM2024

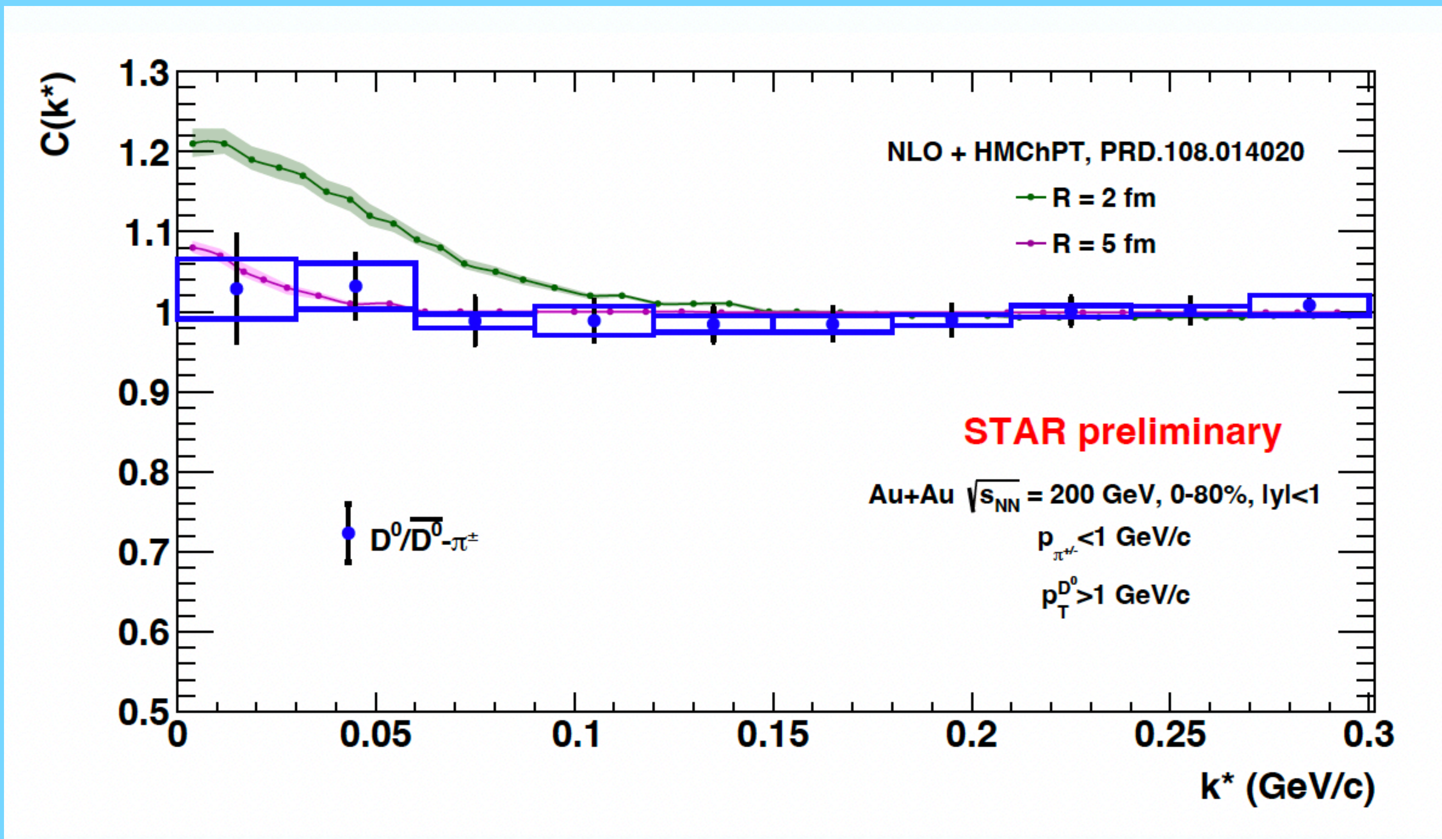
$$\Delta r = \sqrt{(\eta_{\mathrm{Jet}} - \eta_{\mathrm{D^0}})^2 + (\phi_{\mathrm{Jet}} - \phi_{\mathrm{D^0}})^2}$$

* Suppression of hard fragmented charm jets in central collisions 0-10% AuAu

* Consistent radial profile from central to peripheral collisions, no hint of modification of radial profile

D^0 - hadron femtoscopy

STAR D^0 - hadron femtoscopic correlation measurements in Au+Au 200 GeV



P. Roy et al, STAR, SQM2024

$$C(\vec{k}^*) = \mathcal{N}\frac{A(\vec{k}^*)}{B(\vec{k}^*)}$$

A: correlated pairs

B: uncorrelated pairs (from mixed events)

k* : reduced momentum difference

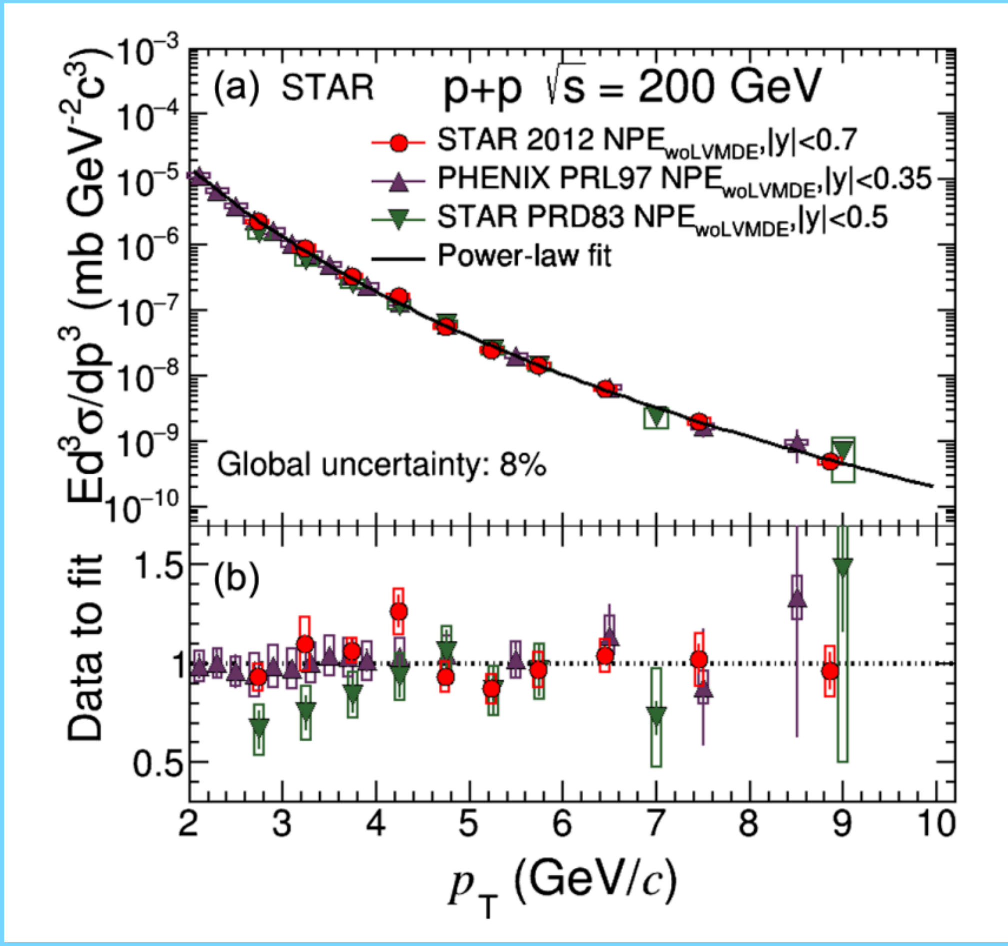
$$k^* = ½\,(p_1 - p_2)$$

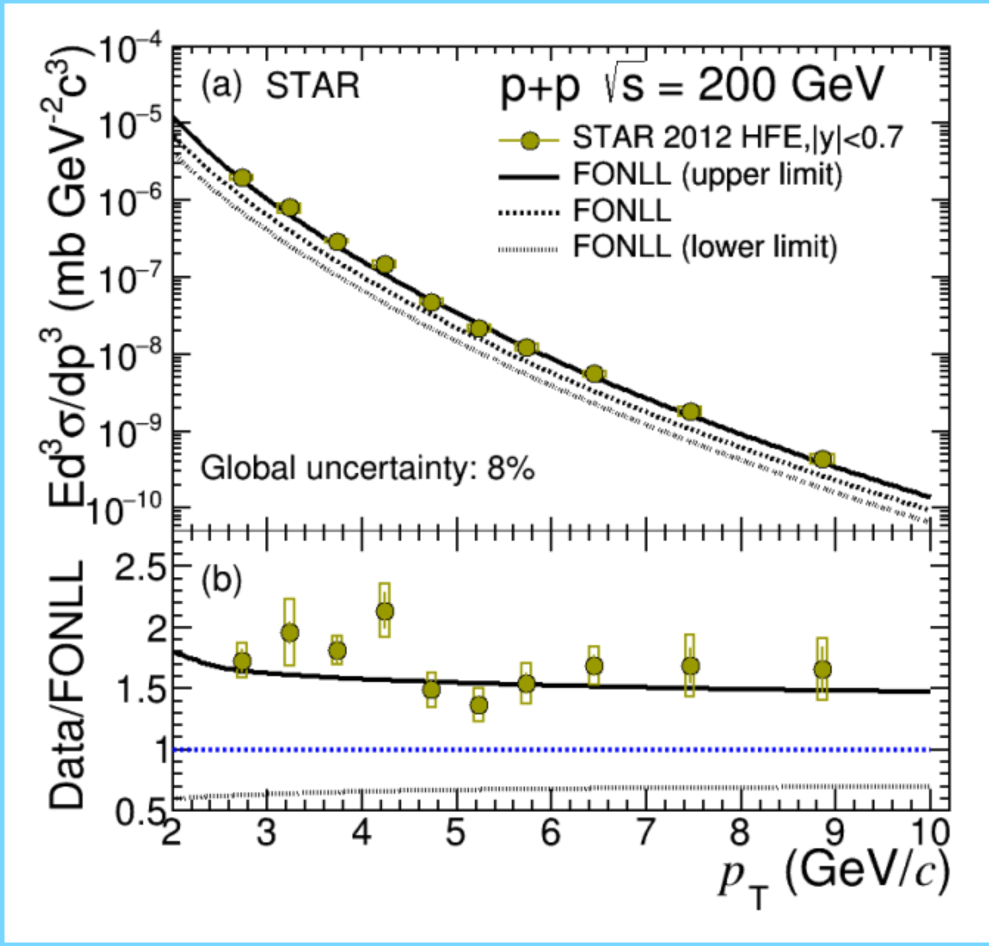
* No significant correlation measured for D0-pi pair
* Data on D0-pi correlation are consistent with calculations with a large emission source size

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]

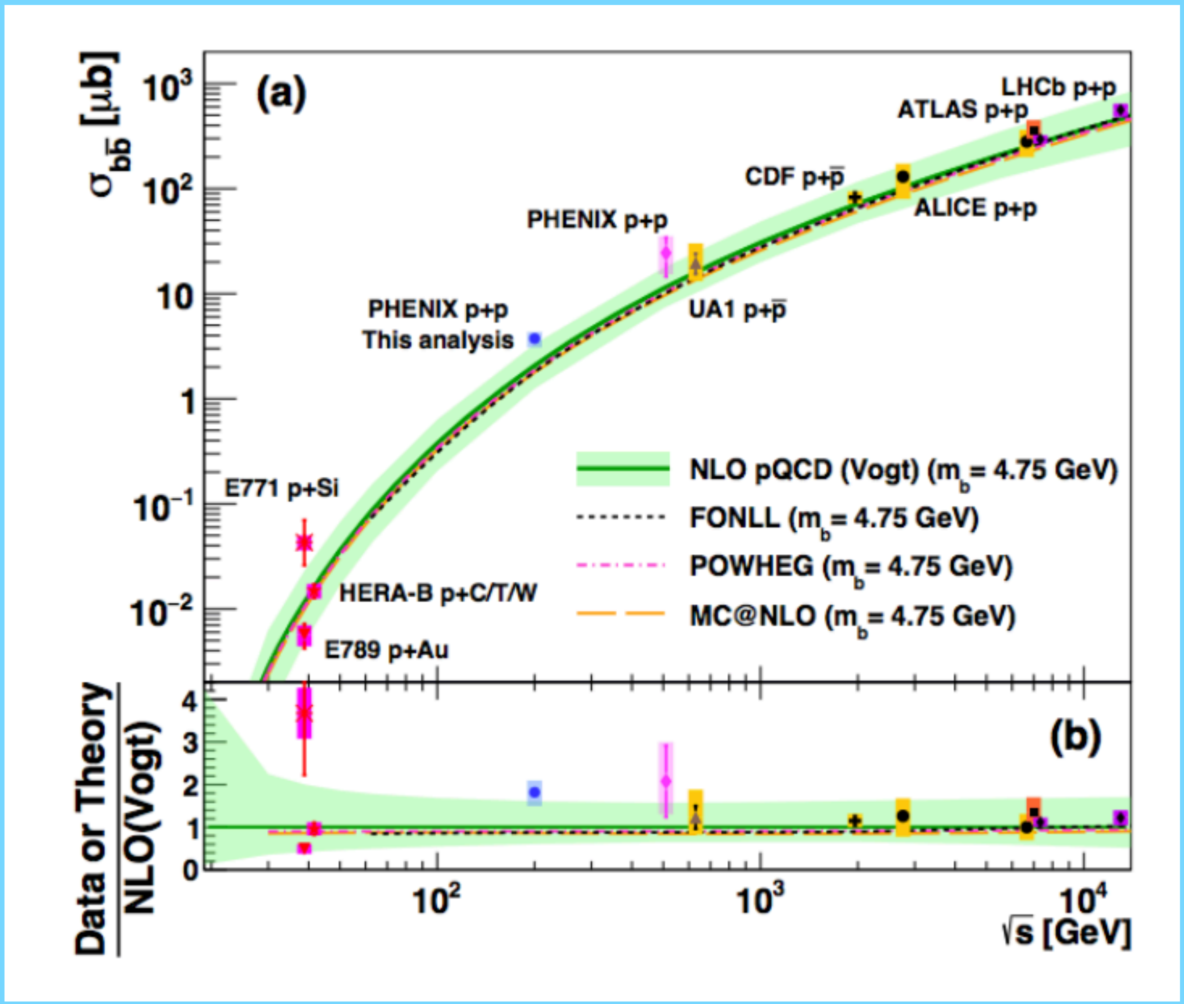




Results from STAR and PHENIX agree

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

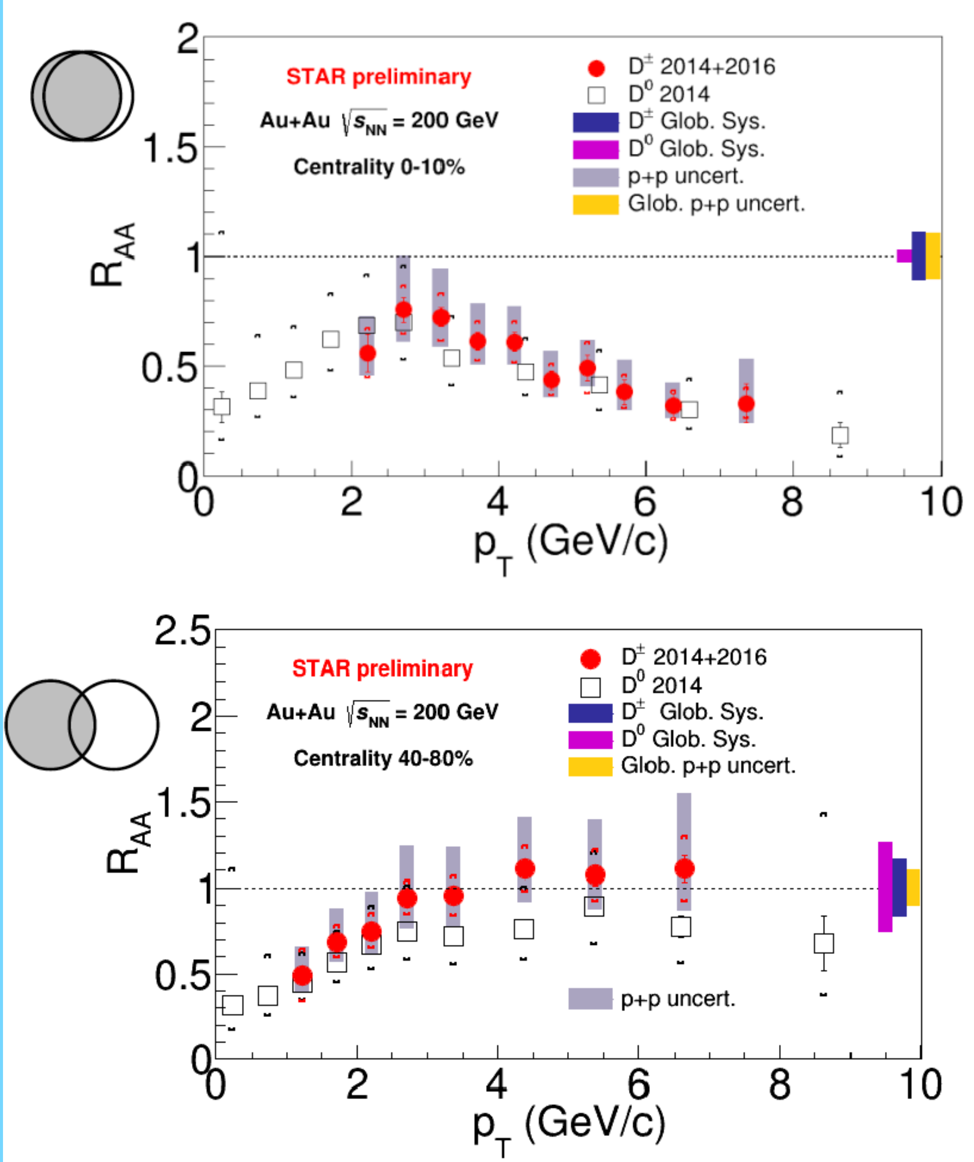


Measurements of μμ pairs from open heavy flavor and Drell-Yan in p+p collisions at \sqrt{s} =200 GeV
PHENIX Collaboration, C. Aidala(Michigan U.) et al. (May 7, 2018)
Phys.Rev.D 99 (2019) 7, 072003 • e-Print: 1805.02448 [hep-ex]

* 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).

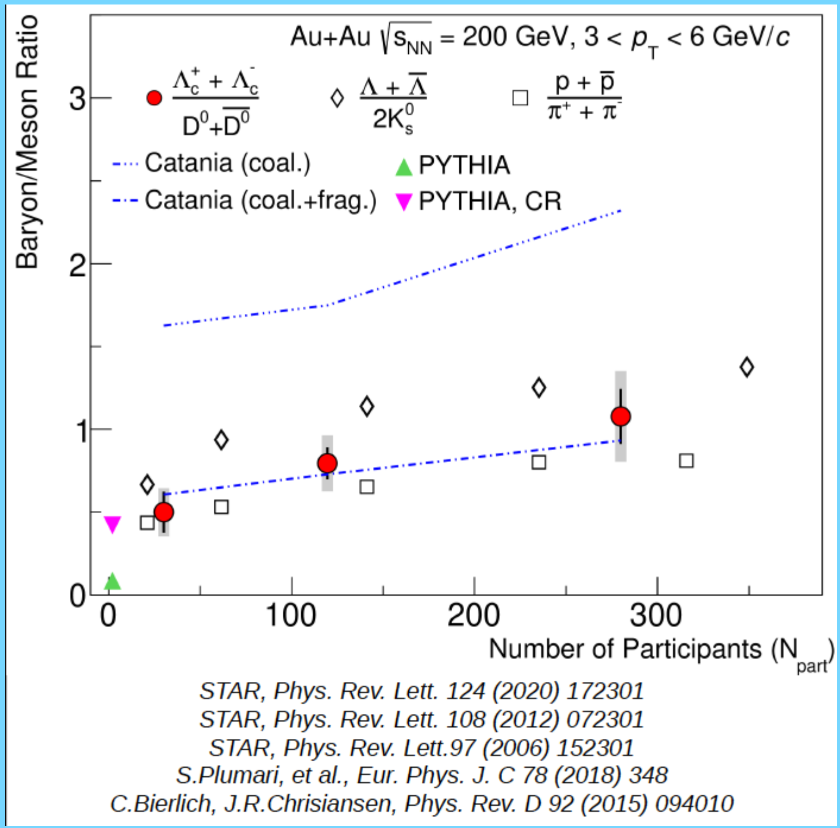
Jan Vanek, QM 2022

J. Vanek et al, STAR Collaboration, QM2022

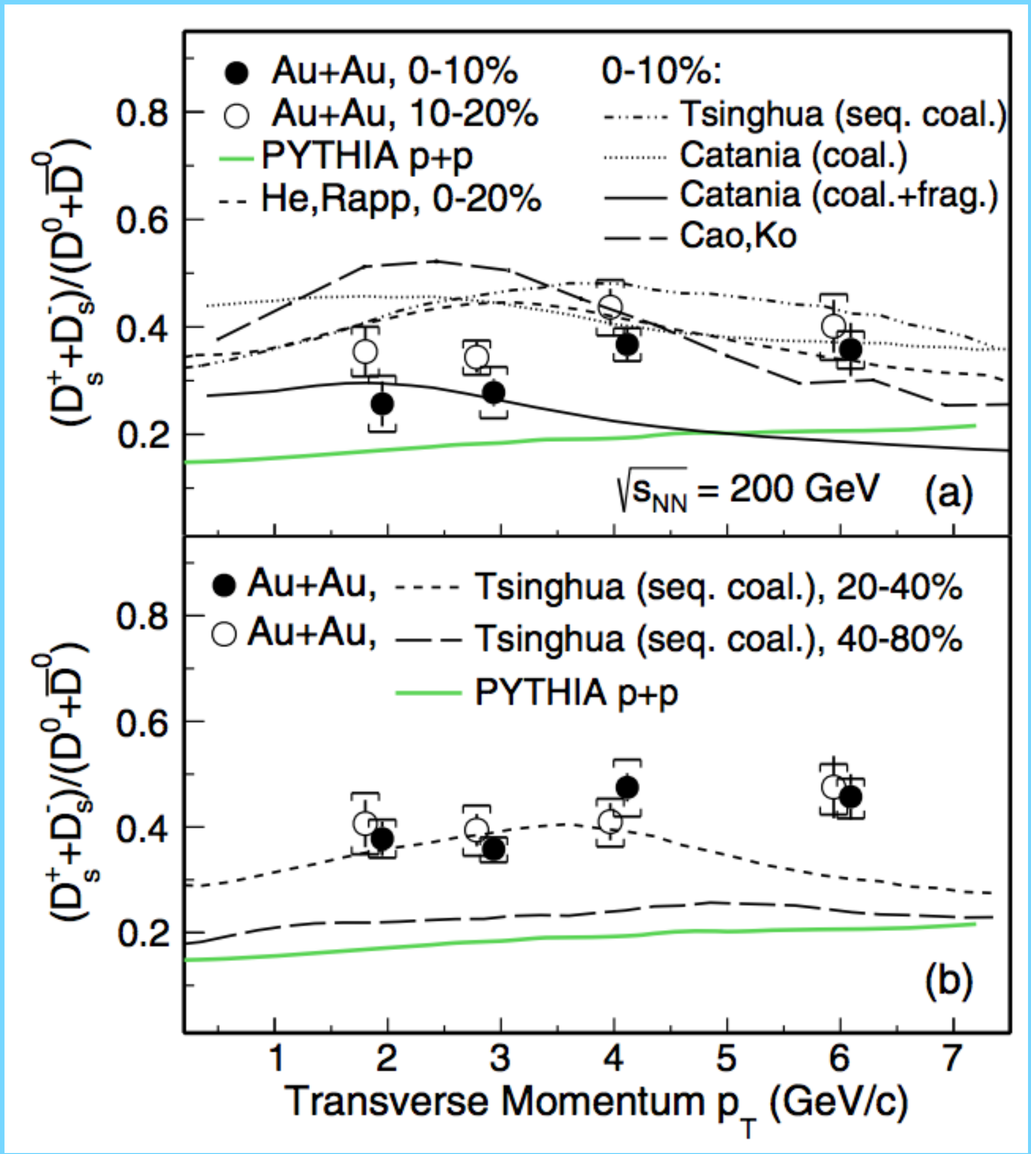
* Centrality dependence of R_{AA} of $D^{+/-}$ and D^0 measured
* R_{AA} of $D^{+/-}$ and D^0 are consistent with each other and suppressed at high p_T in central (0-10%) Au+Au collisions

STAR, 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

Conclusions and Outlook

* Flow (v2) results suggest strong interaction of heavy quarks with medium above sqrt(s)=27 GeV Au+Au

* Flow (v2) of charm higher than v2 of bottom.

* 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

Outlook

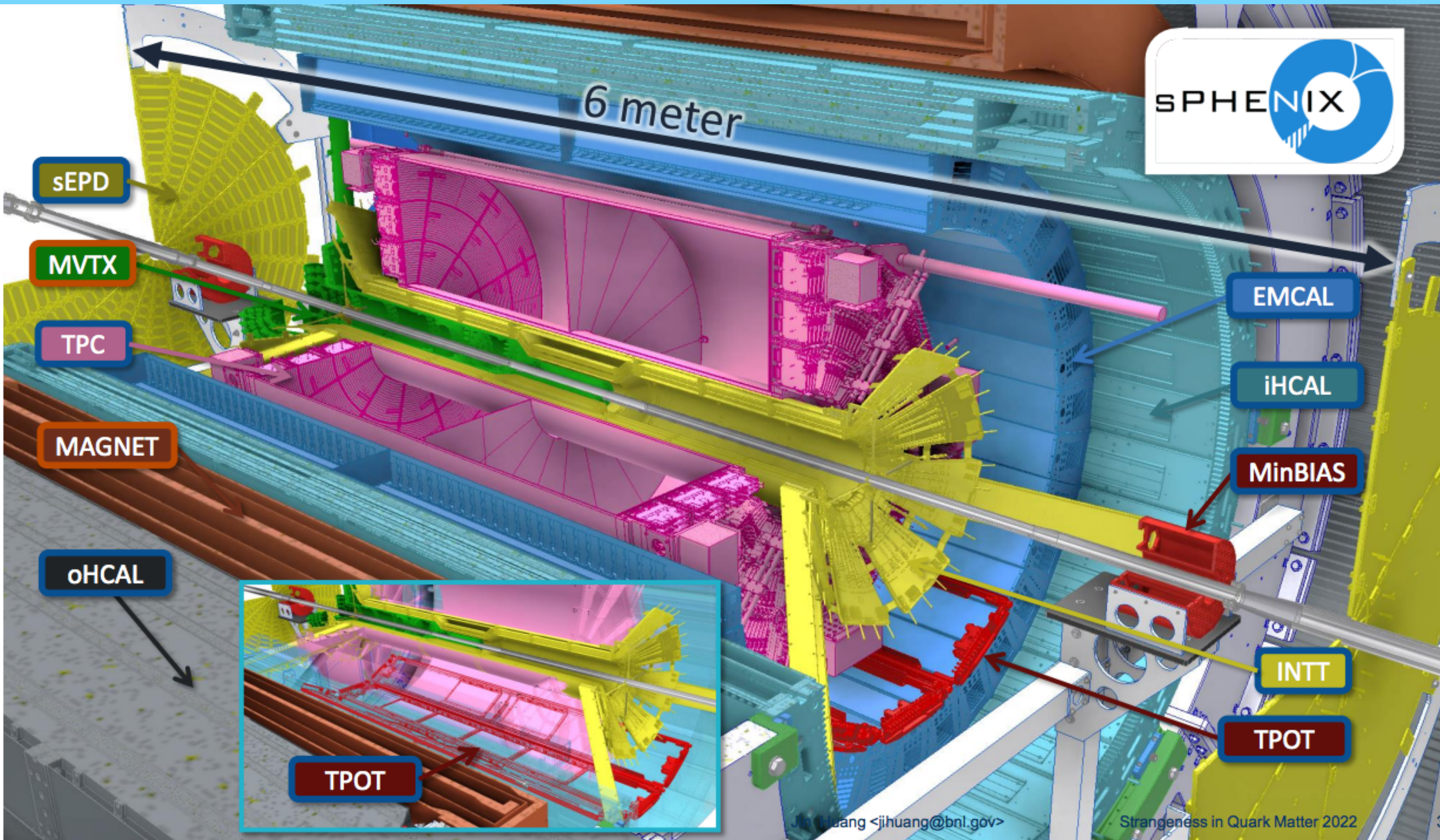
STAR and sPHENIX run period

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}

* sPHENIX: commissioned

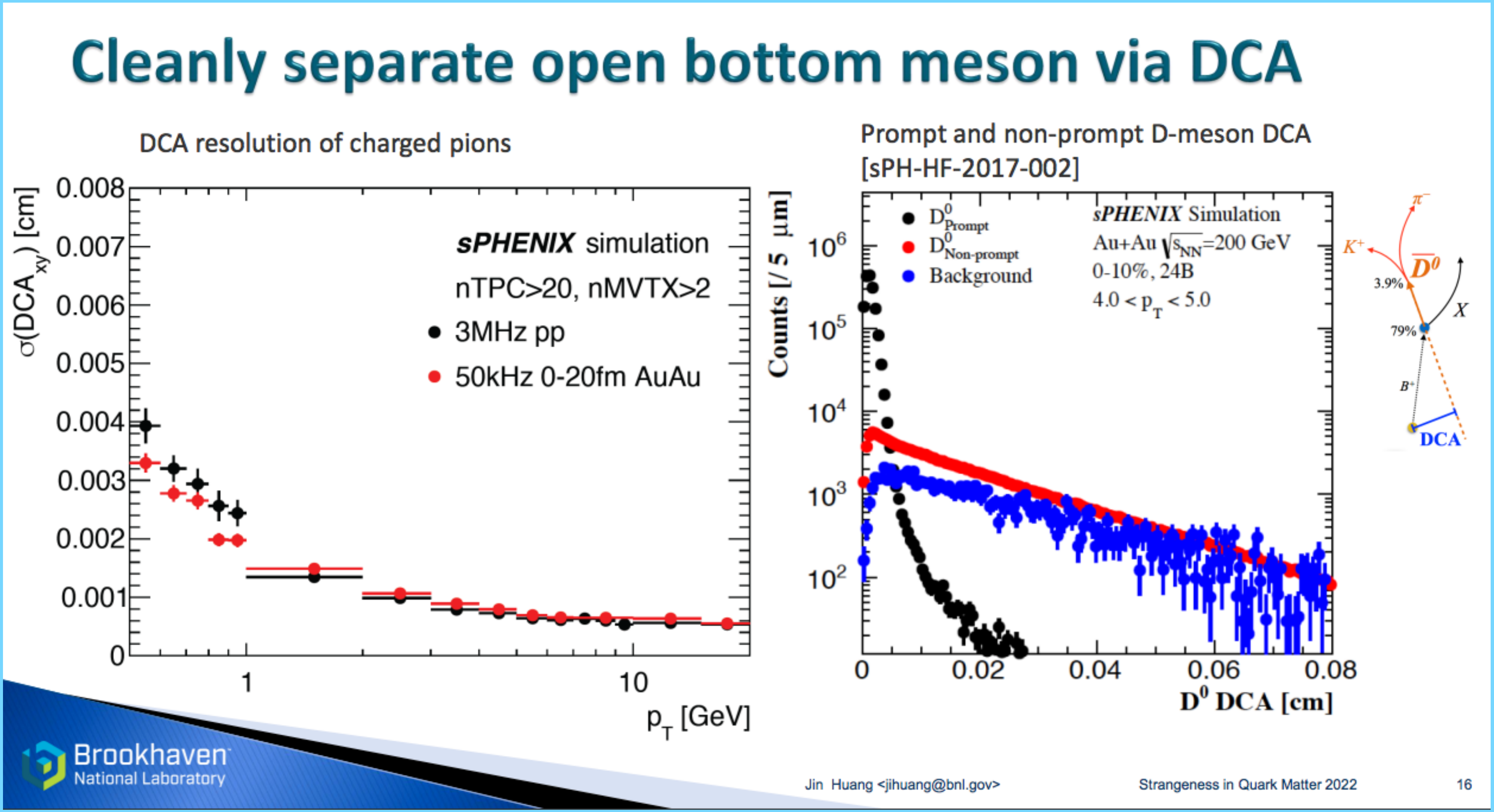
sPHENIX


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

Thank you very much

sPHENIX

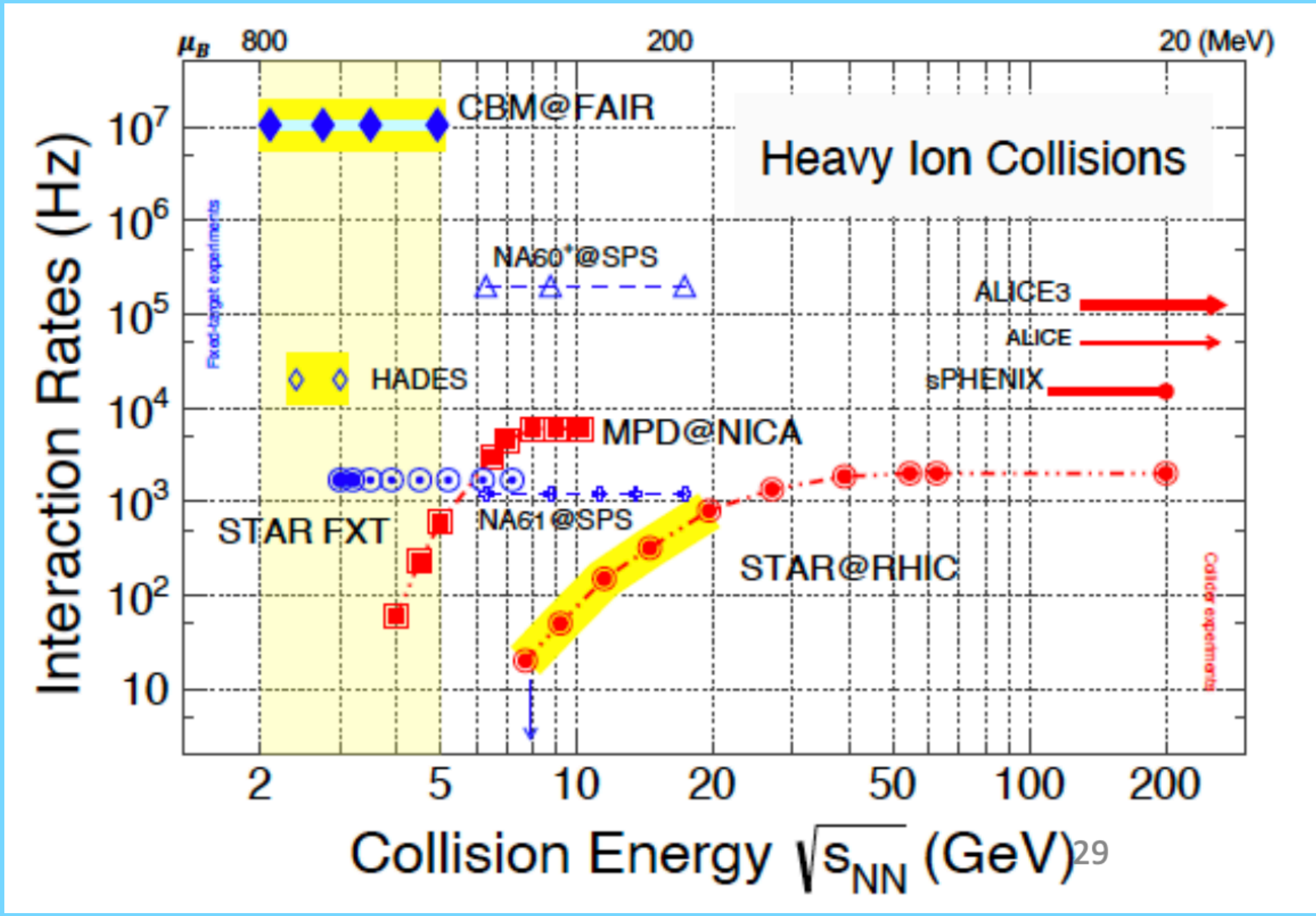
Exceptional performances expected for open heavy flavor



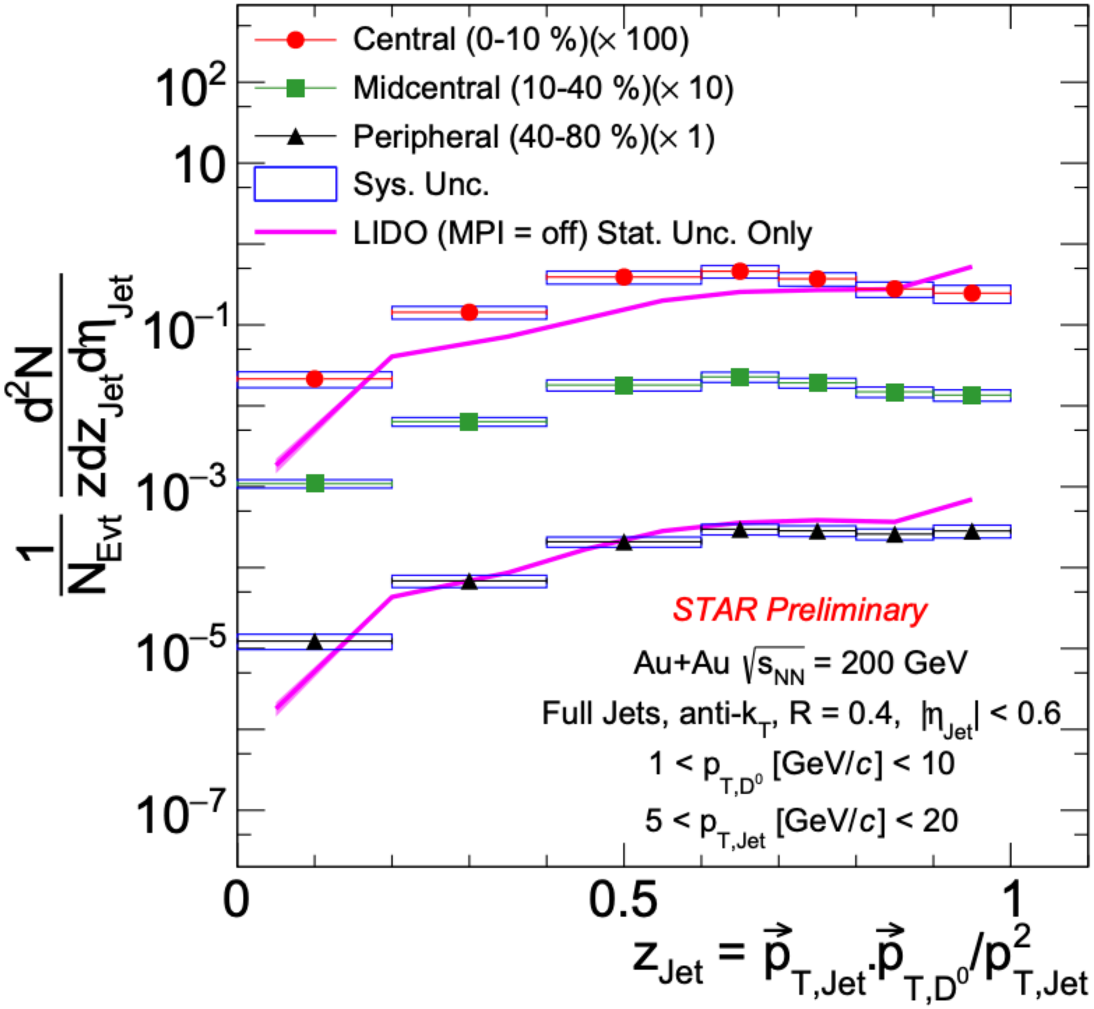
Jin Huang, PHENIX Collaboration, SQM2022

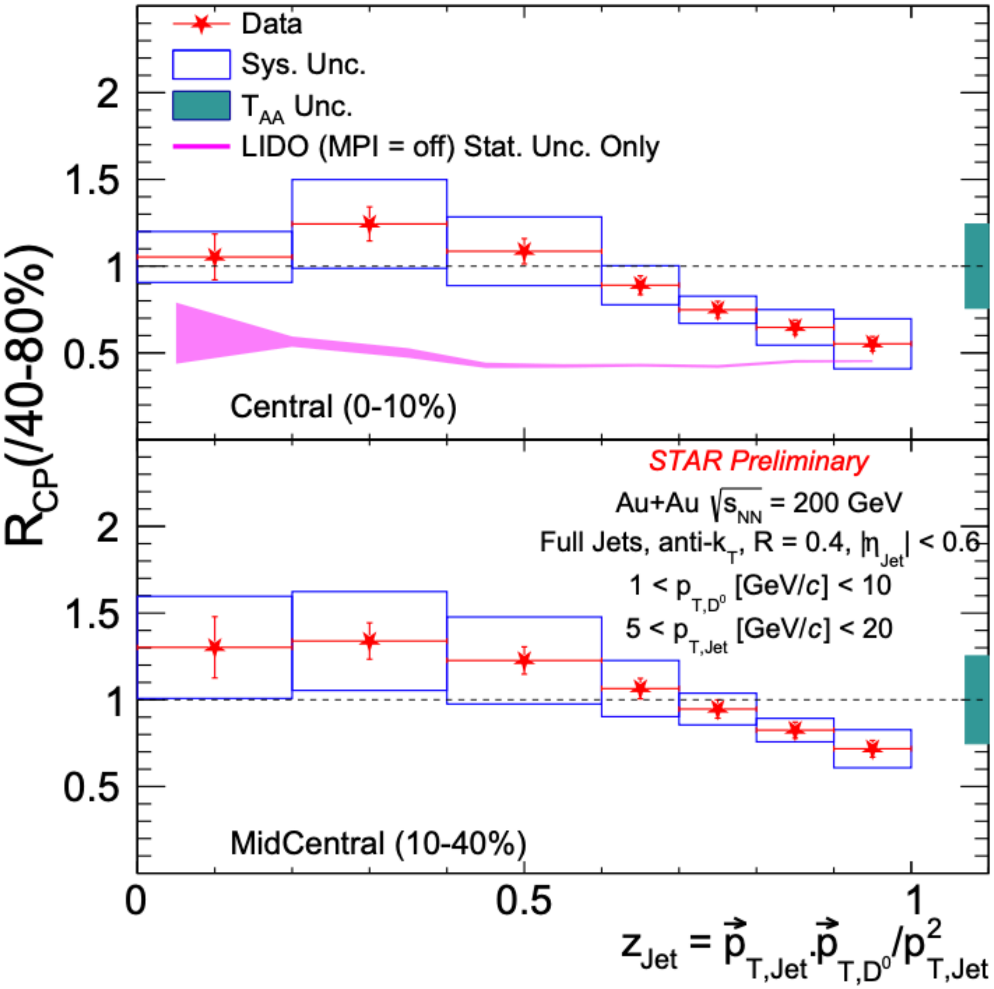
Outlook

RHIC, BNL: sPHENIX, STAR, (PHENIX data analysis) (2024 pp AuAu), 2025 (AuAu)



STAR

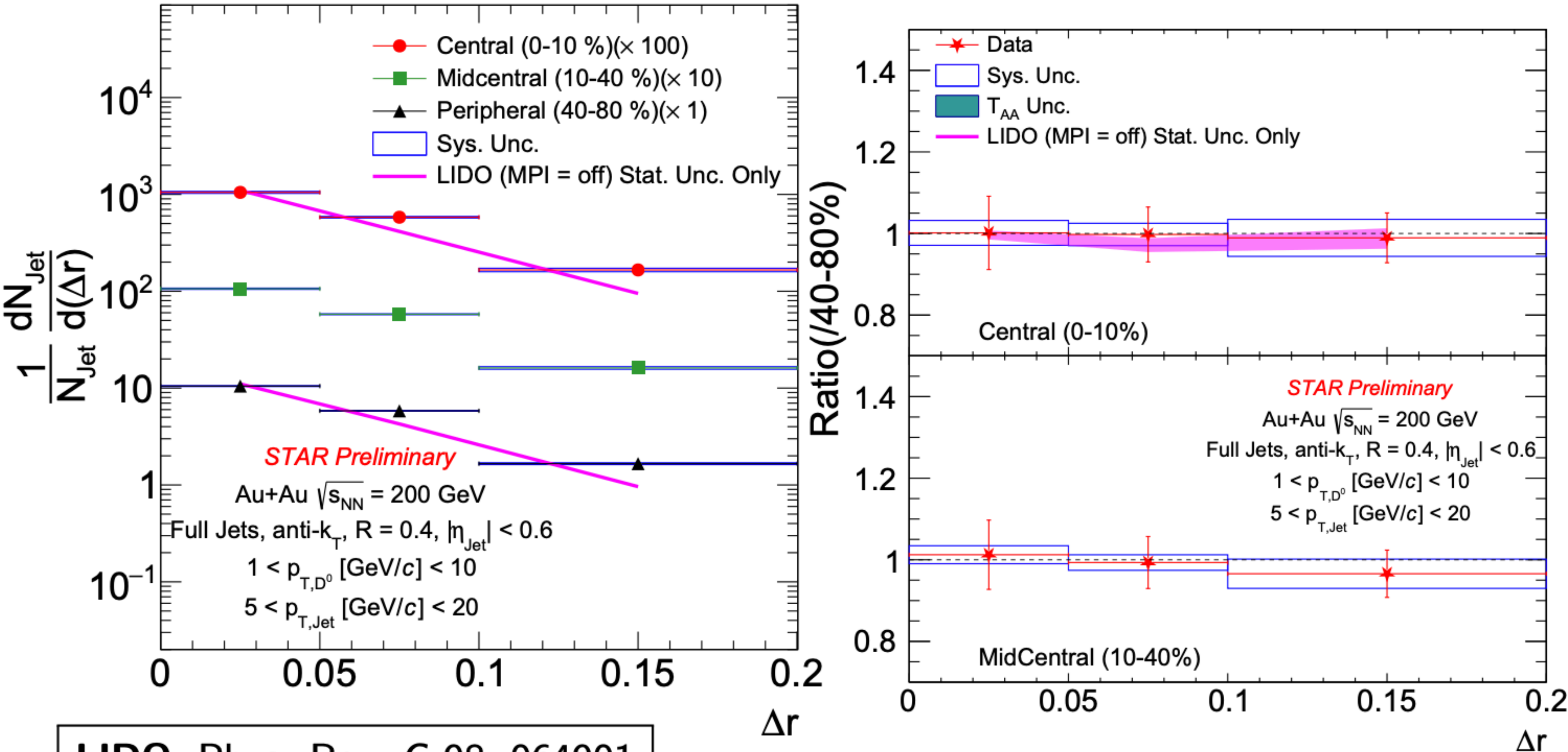




LIDO, Phys. Rev. C 98, 064901

O. Lomicky et al, STAR, SQM2024

STAR



LIDO, Phys. Rev. C 98, 064901

O. Lomicky et al, STAR, SQM2024