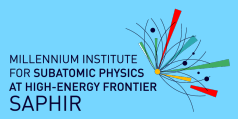
Open Heavy Flavor production at RHIC

Sonia Kabana (Universidad de Tarapaca, Chile)



ICNFP 2022, 30 August - 11 September 2022, Kolymbari, Greece,
and extended session 21 December 2022

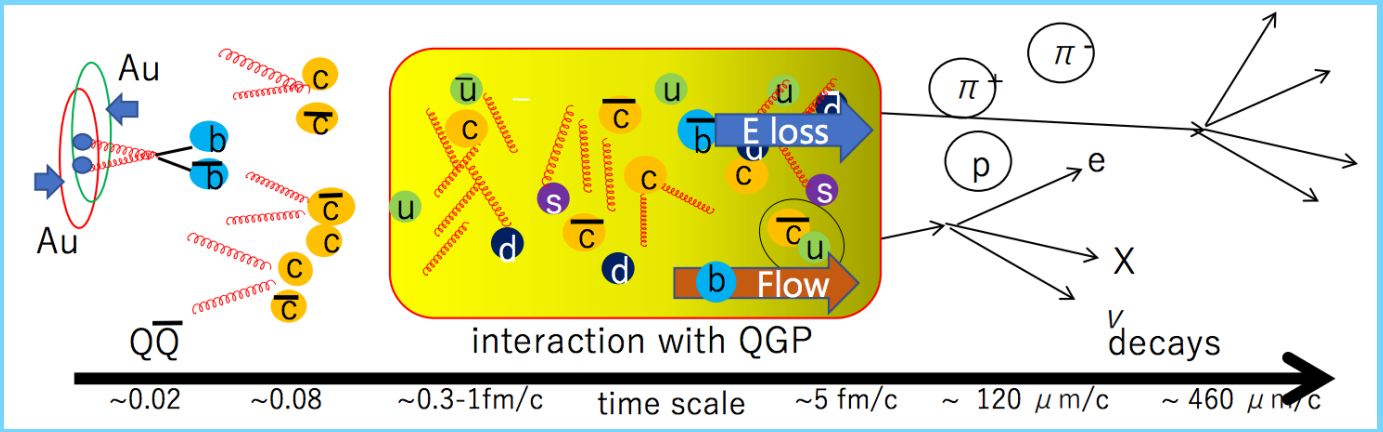
Outline

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

Introduction

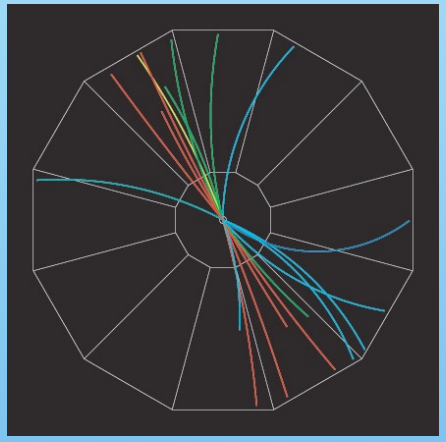
Charm and beauty (heavy flavor, HF) hadron production in ultrarelativistic heavy ion collisions are key observables for the study of sQGP :

* Charm and beauty quarks are produced in initial hard scatterings and experience the entire evolution of A+A interactions
* Their masses are large compared with the thermal energy expected in heavy ion collisions
* The nuclear modification factors R_{AA} and R_{CP} of c and b can reveal imprints of jet quenching in sQGP
* 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

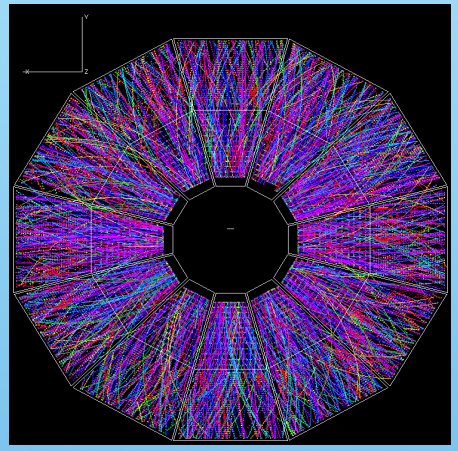


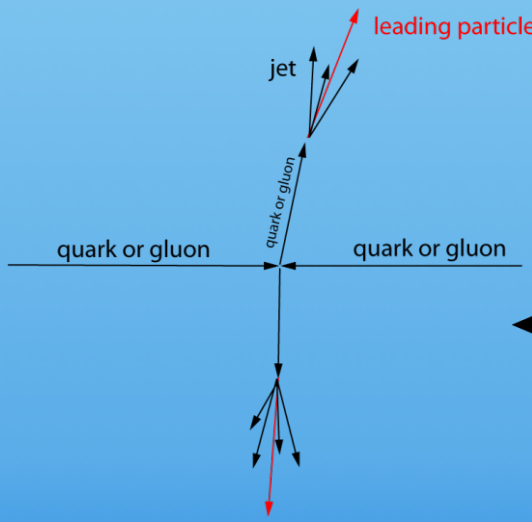
Jet quenching as QGP signature

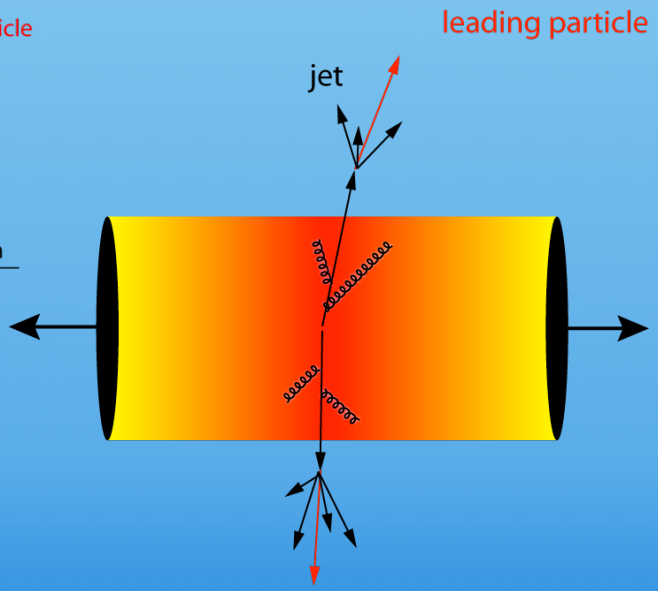
p+p Collision



Au+Au Collision

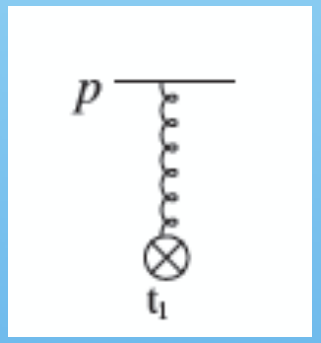




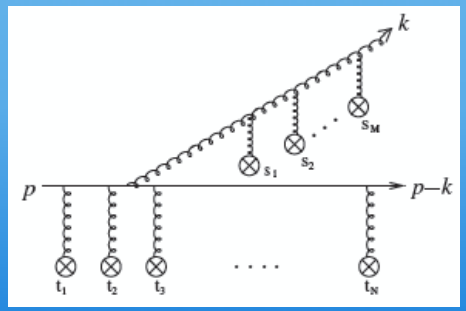


Partons interact with the medium and loose energy through eg gluon radiation

Collisional "elastic" energy loss: elastic interaction with the medium



Radiative energy loss: parton radiation due to interaction with the medium



Jet quenching

Suppression of jets in AuAu: $R_{AA} < 1$

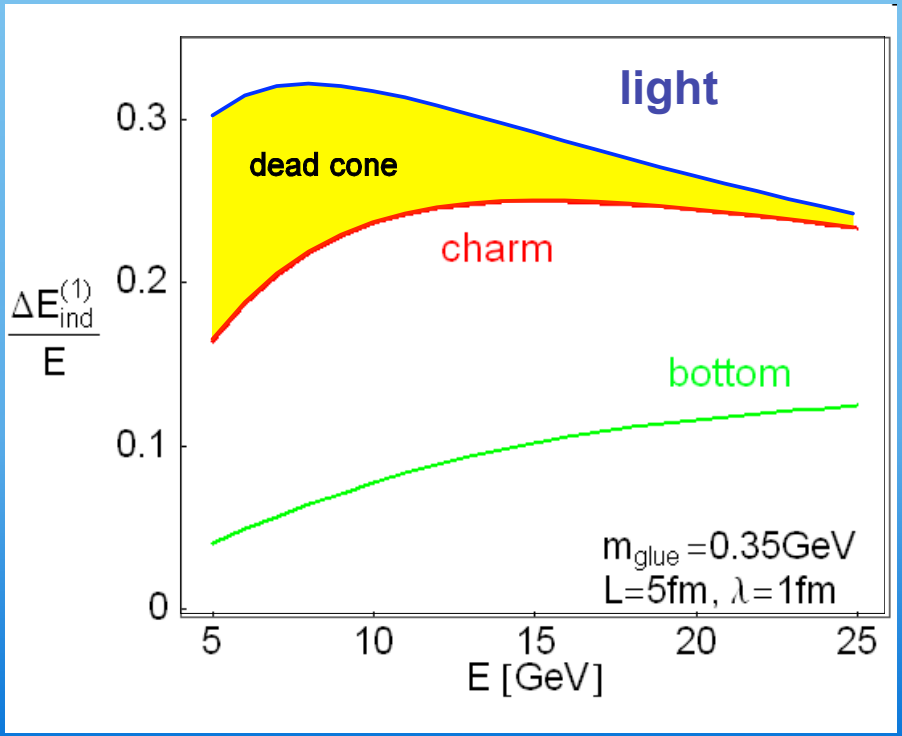
Quarks are expected to exhibit different radiative energy loss depending on their mass (**D.Kharzeev et al. Phys Letter B. 519:1999**)

"The nuclear modification factor" R_{AA} compares A+A to expectations from p+p :

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p) \times \langle N_{coll} \rangle}$$

N coll : Average number of NN collisions in AA collision

M.Djordjevic PRL 94 (2004)



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

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

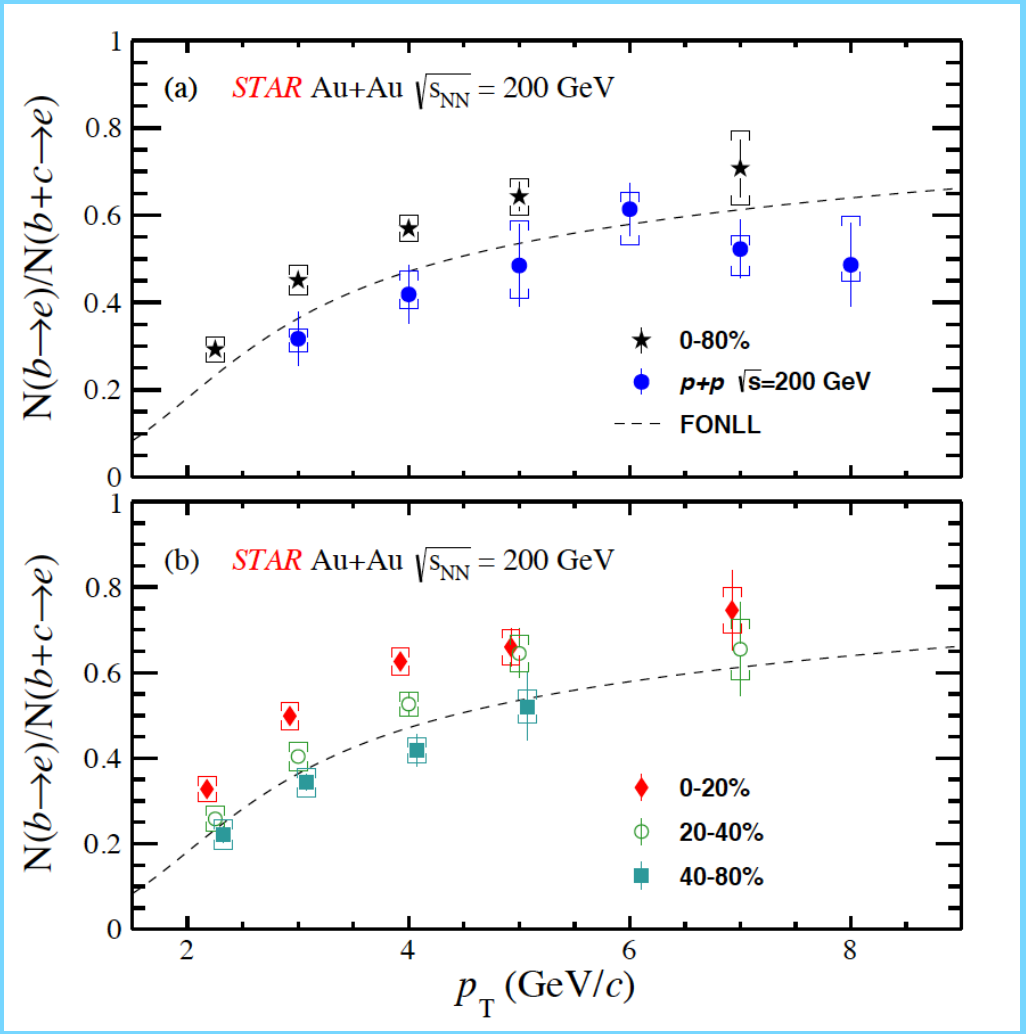
STAR Collaboration, June 2022, arXiv:2111.14615

* Enhanced b—> e fractions measured in 0-20% and 0-80% Au+Au 200 GeV compared to p+p and FONLL

* Peripheral collisions are in agreement with FONLL

* p+p collisions are in agreement with FONLL

* Centrality dependence observed for pT < 4.5 GeV

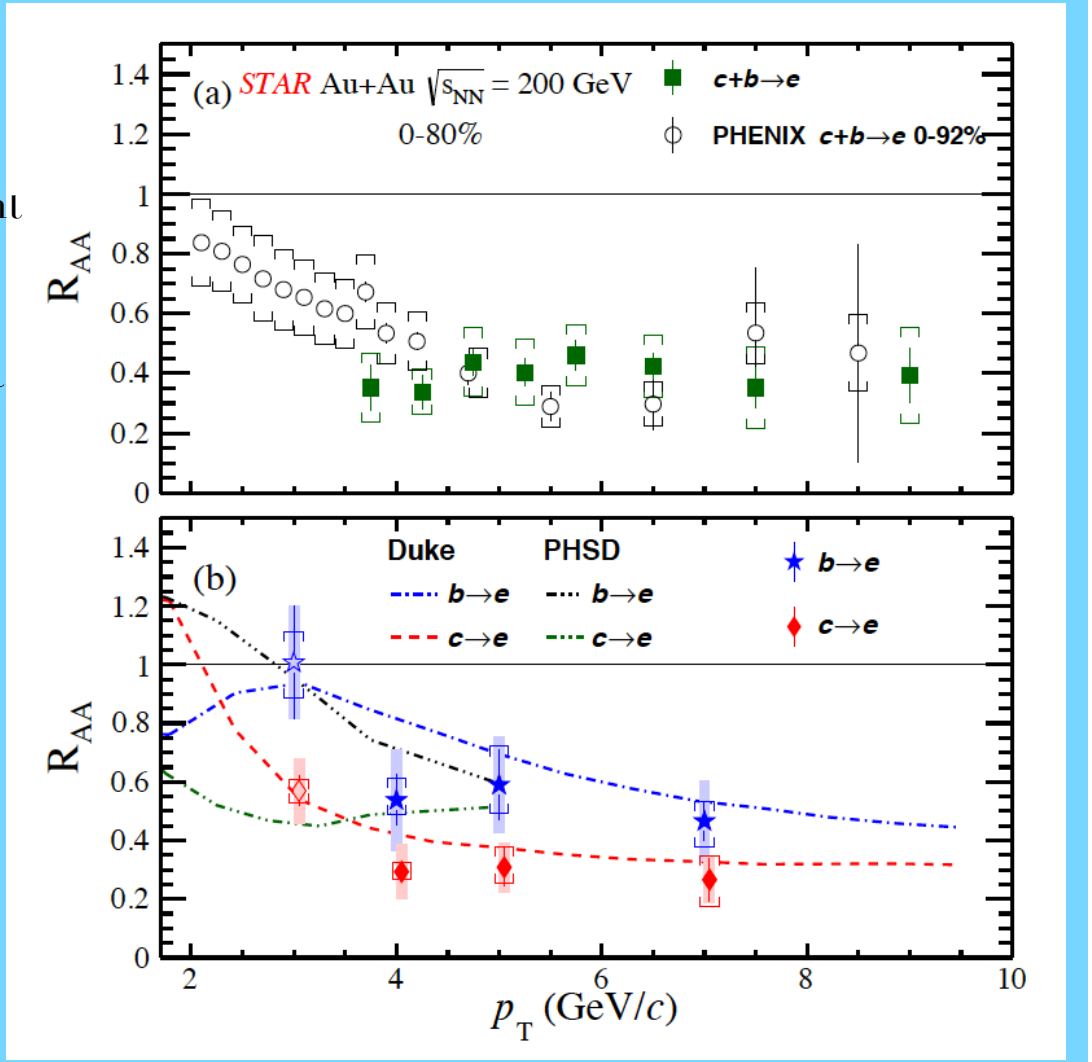


STAR (2022) Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

* 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
* **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**

STAR Collaboration, June 2022, arXiv:2111.14615

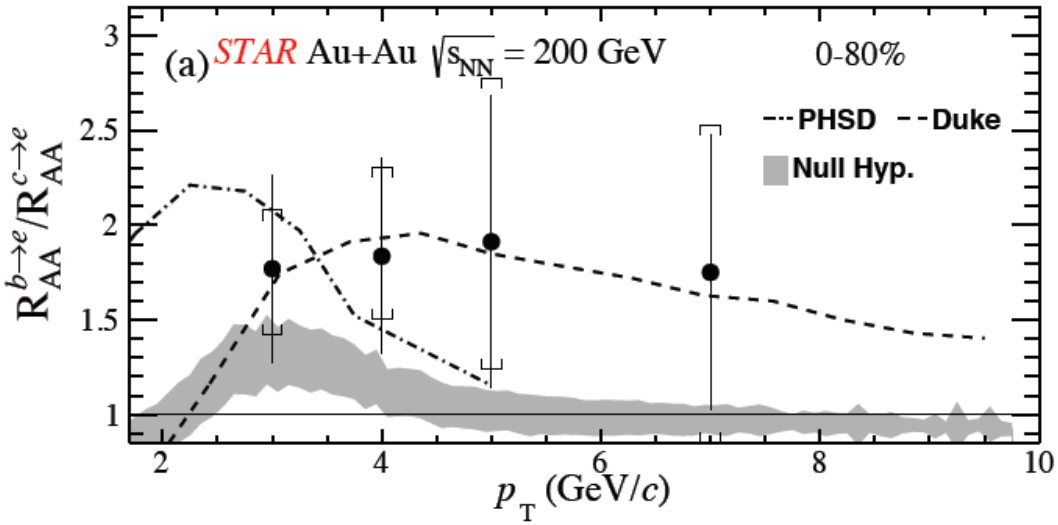
PHENIX Collaboration, PRC93, 034904 (2016), 1509.04662

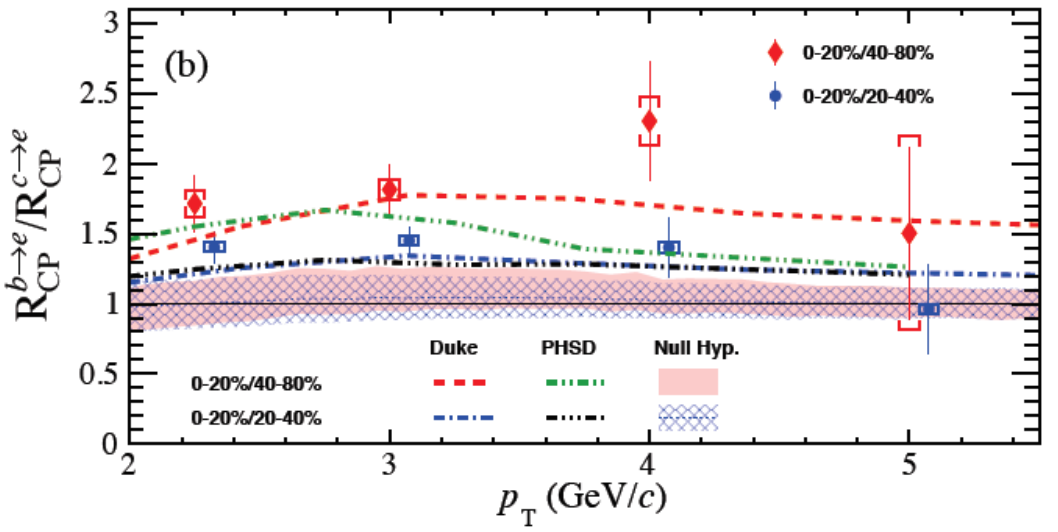


STAR (2022) Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

* 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
* **b to c R(AA) consistent with null hypothesis in pT=2.5-4.5 GeV**
* **b to c R(CP) of (0-20%/40-80%) and R(CP)(0-20%/20-40%) reject the null hypothesis at 4.2 and 3.3 standard deviations respectively.**
* **b to c R(AA) and R(CP) can be reproduced by both models suggesting the mass ordering of parton energy loss in sQGP**

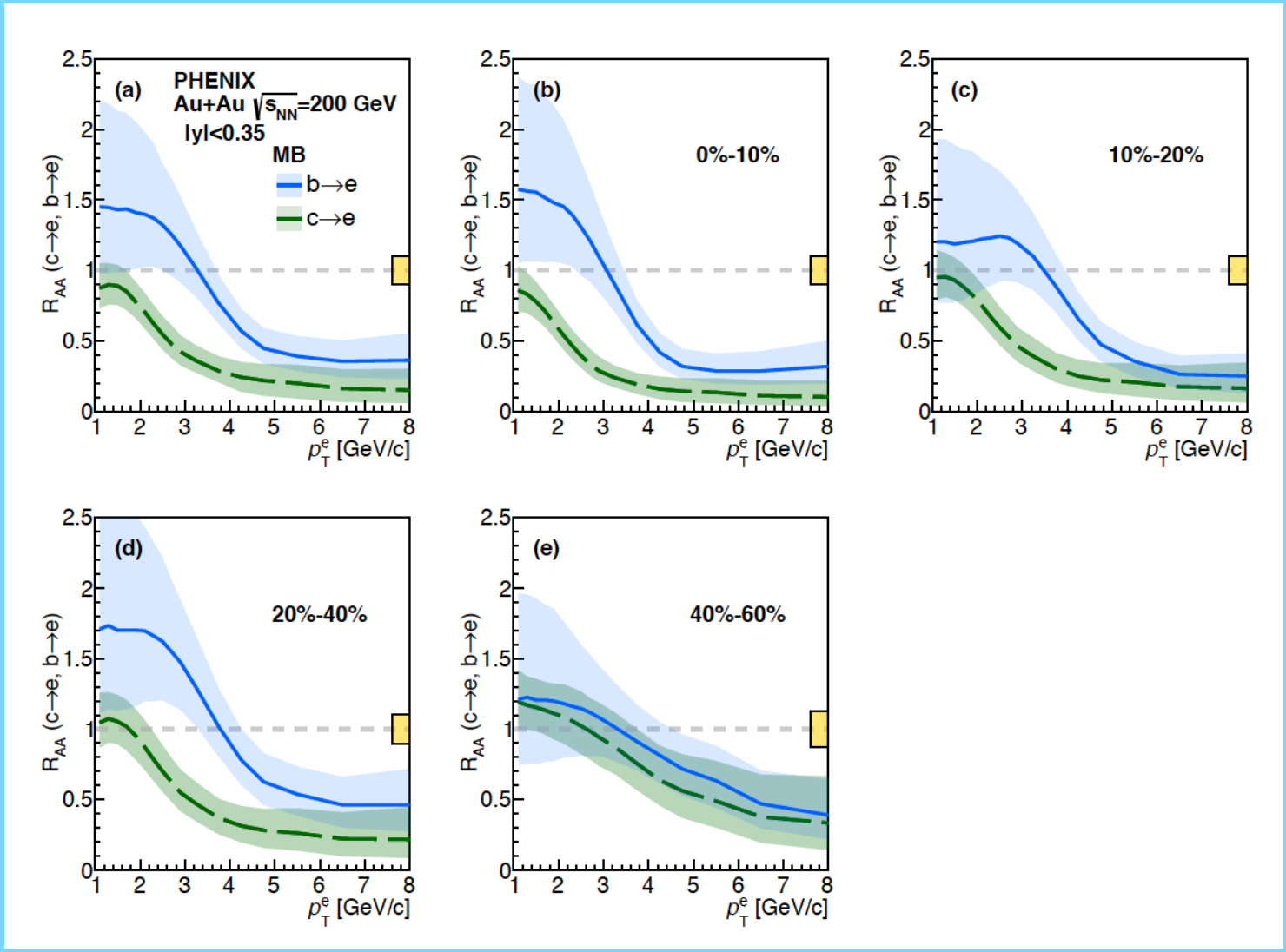
STAR Collaboration, June 2022, arXiv:2111.14615





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

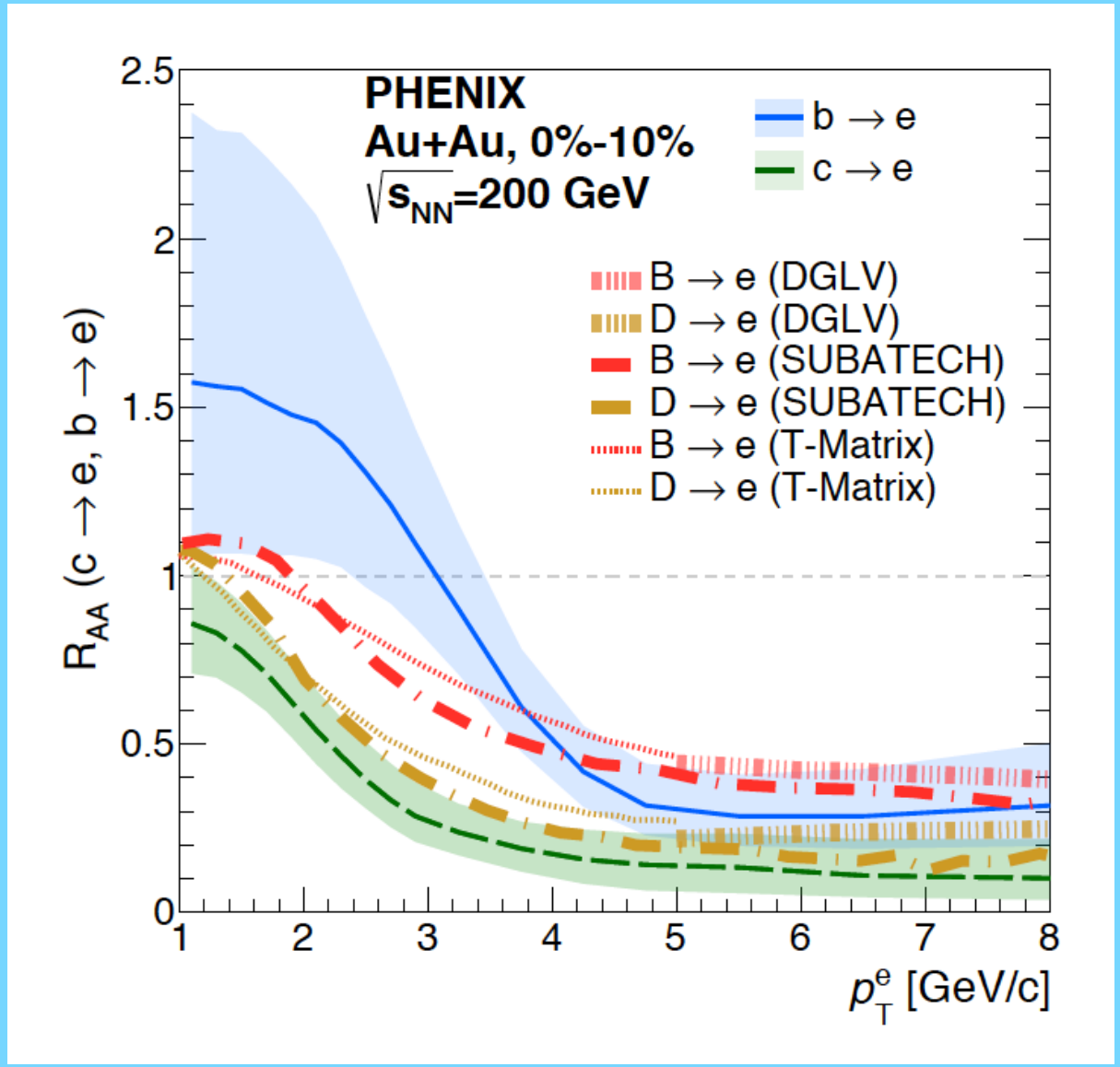
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058



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

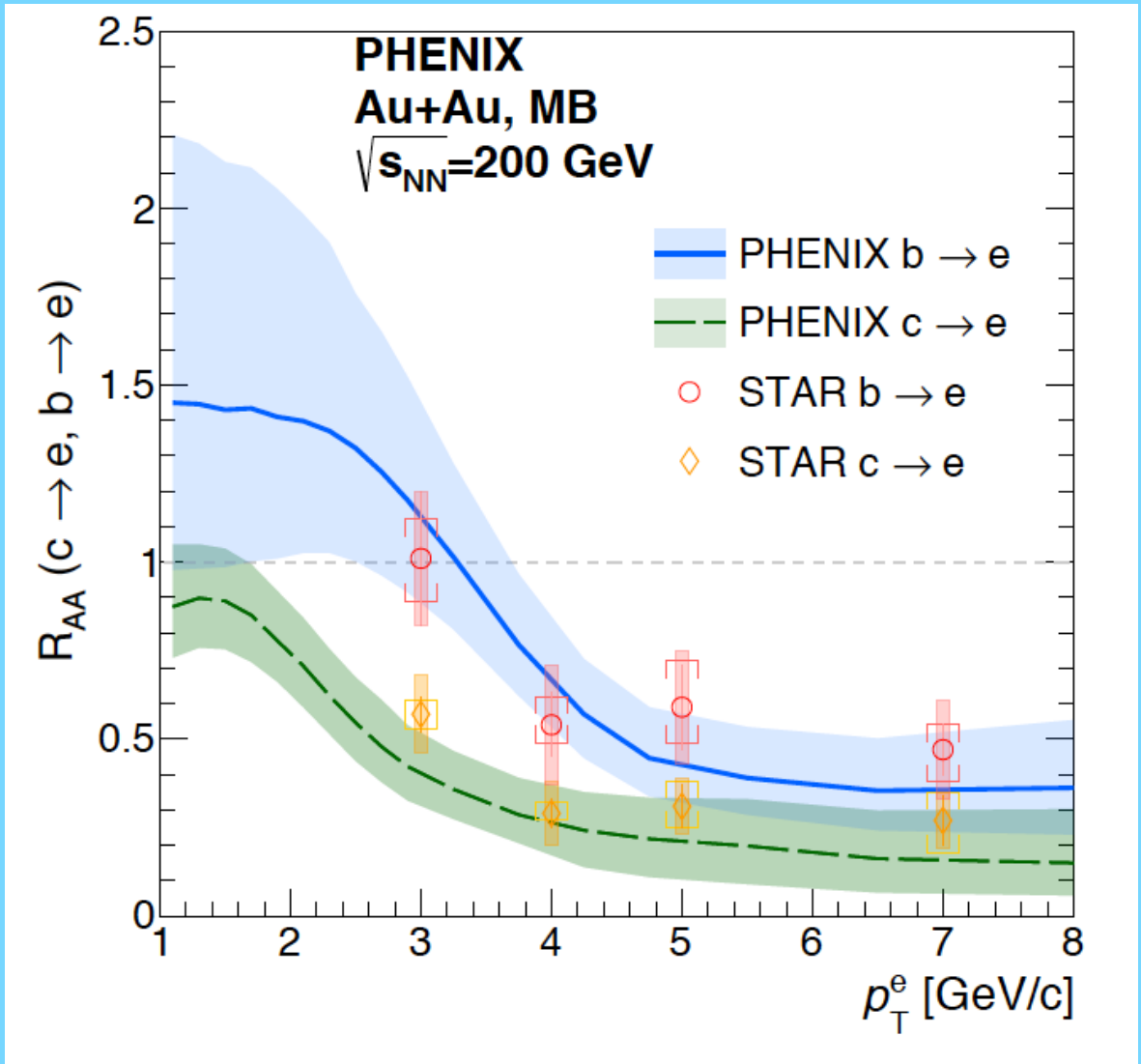
PHENIX b—>e and c—> e in 0-10% Au+Au collisions at 200 GeV vs models

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 model assumes formation of hadronic resonance by a heavy quark in the QGP based on lattice QCD
* SUBATECH model employs hard thermal loop calculation for the collisional energy loss
* DGLV model calculates both collisional and radiative energy loss assuming an effectively static medium
* Data agree at high pT with models predicting less suppression of b —> e than c —> e
* At low pT SUBATECH model is consistent with c—> e while T-Matrix model partly overestimated

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.

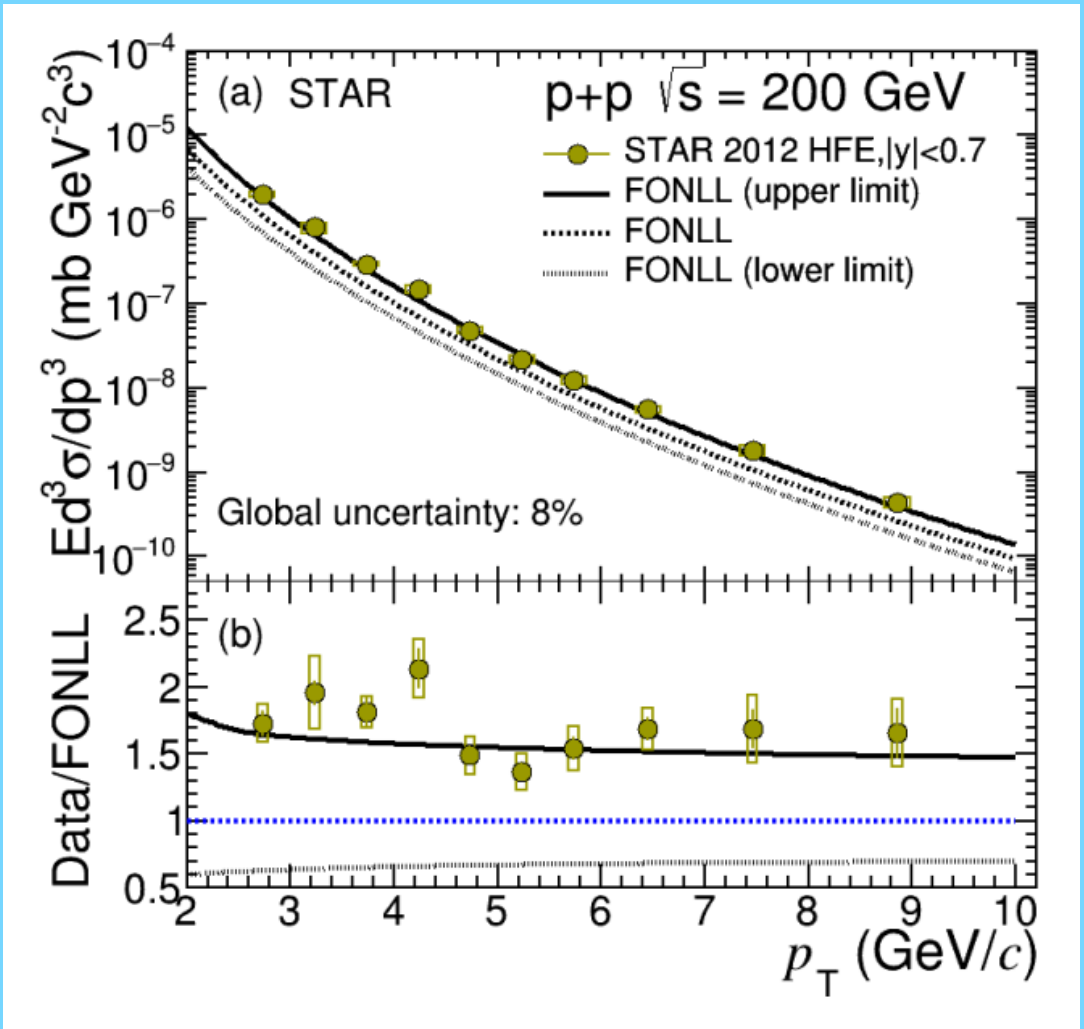
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058

* 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

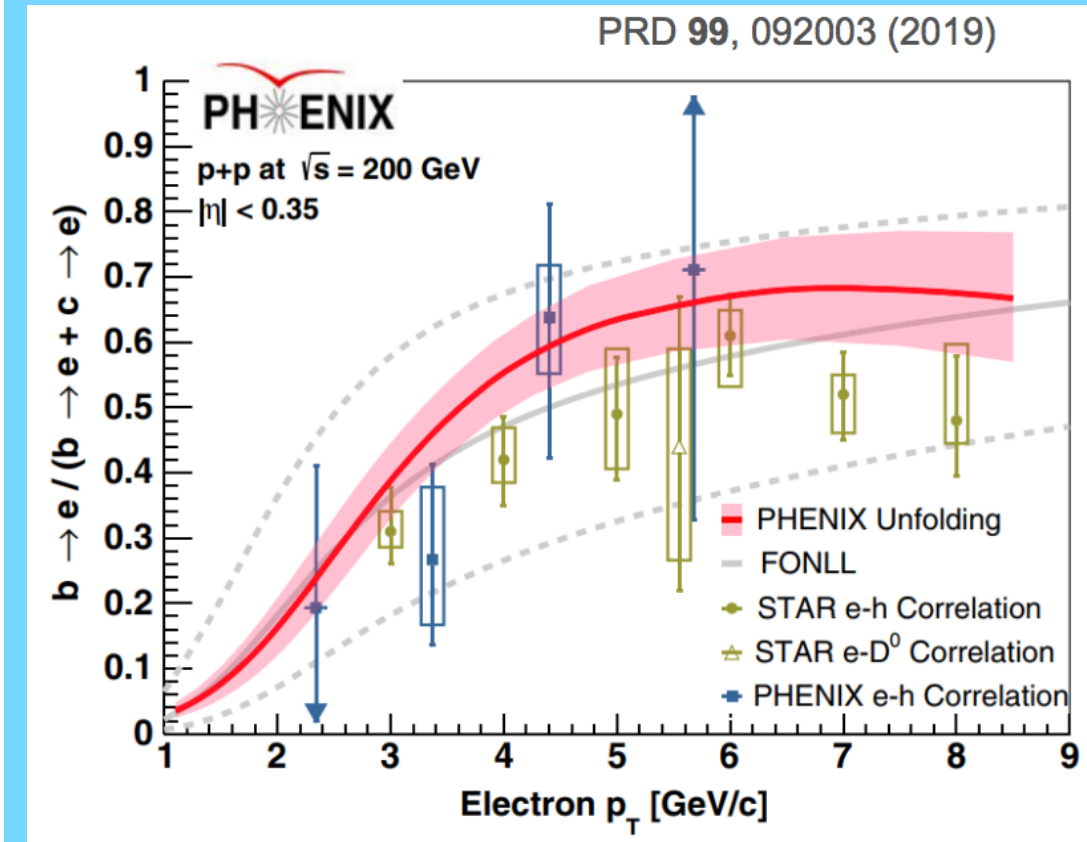
STAR (2022) Heavy Flavor -> electrons in p+p collisions at 200 GeV

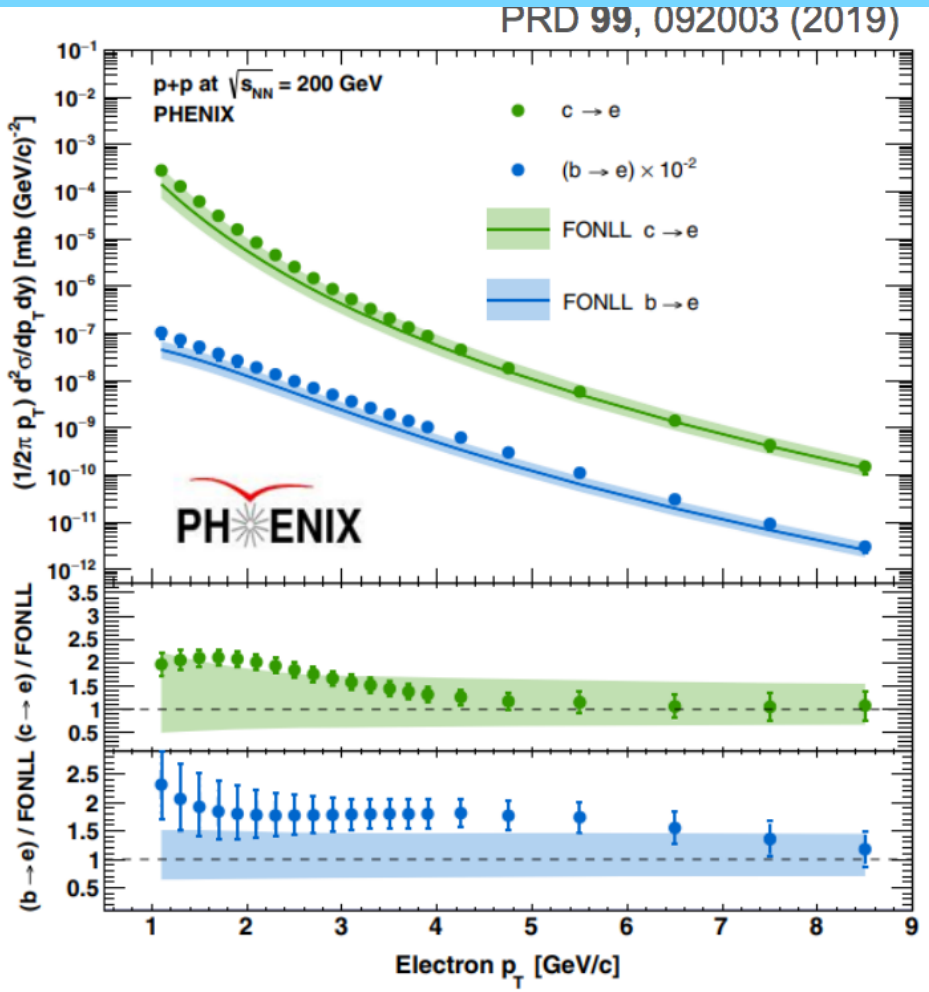
STAR Collaboration, Phys.Rev.D 105 (2022) 3, 032007, e-Print: 2109.13191 [nucl-ex]



The transverse momentum spectra of electrons from HF decays in p+p collisions at 200 GeV is qualitatively consistent with the upper limit of FONLL calculations

PHENIX (2019) new p+p baseline available for c and b





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

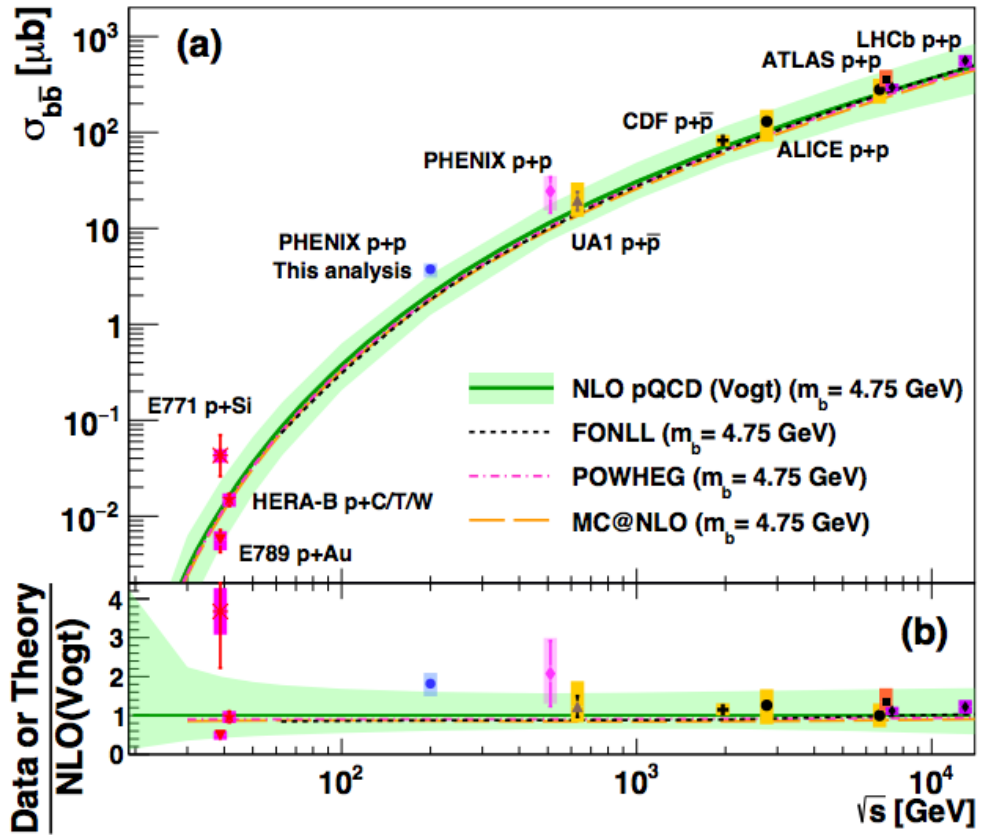


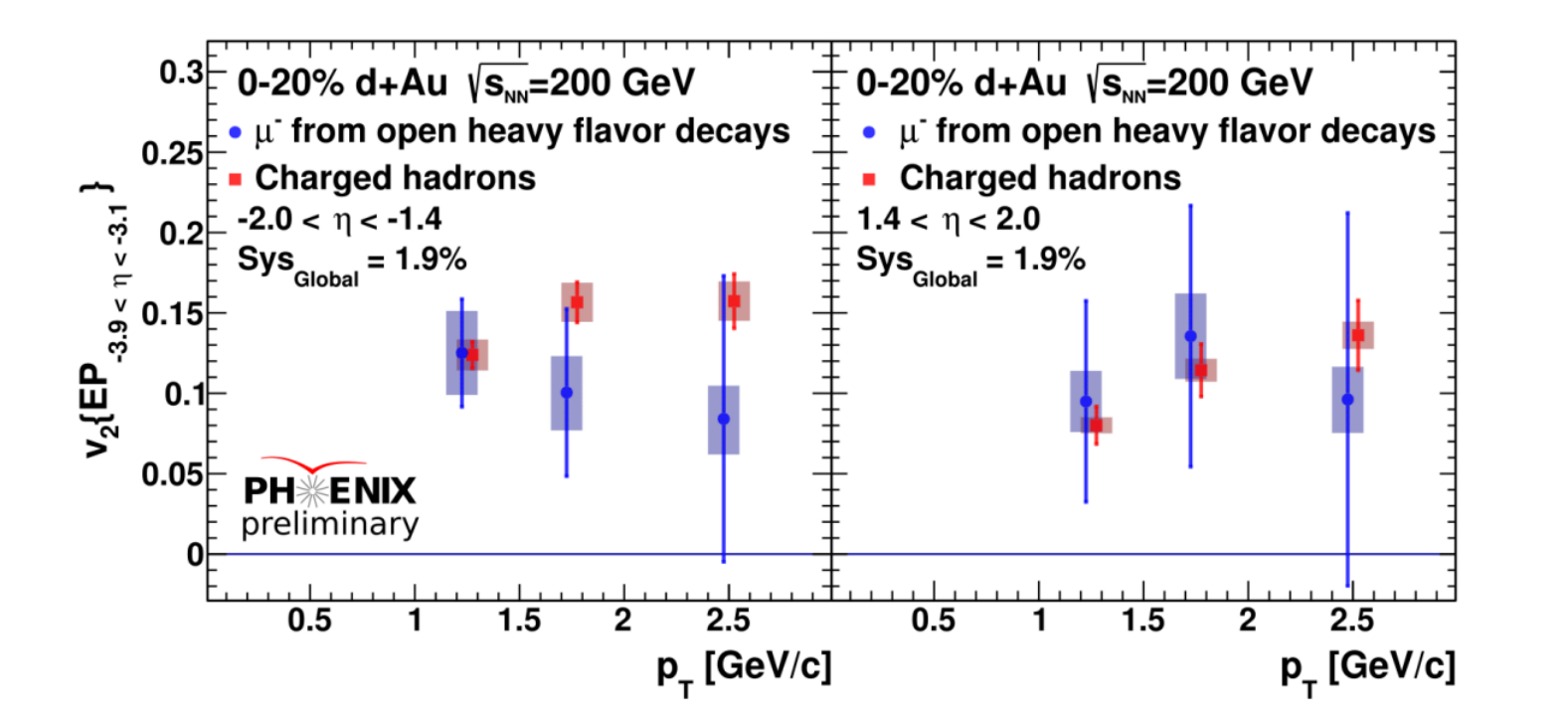
FIG. 29. Bottom cross section $\sigma_{b\bar{b}}$ as a function of $\sqrt{s}$. Uncertainties due to rapidity extrapolation are not included in the LHCb measurements. Measured cross sections are compared to NLL and NLO calculations.

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

PHENIX (2017) elliptic flow of (bottom+charm) to muons in 0-20% d+Au 200 GeV

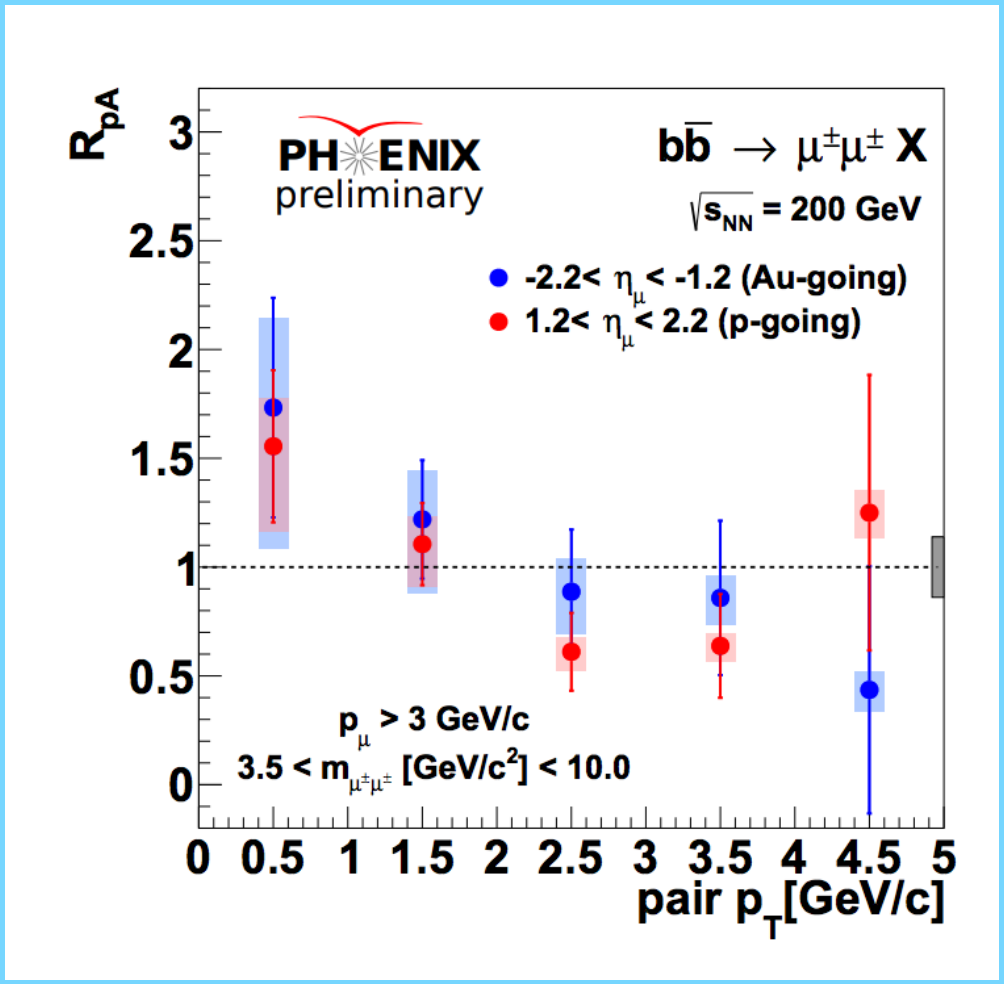
C. Aidala et al. (PHENIX collaboration), Phys. Rev. C 96, 064905 (2017).



* Finite v2 observed for (bottom+charm) to muons at pT 1-2 GeV

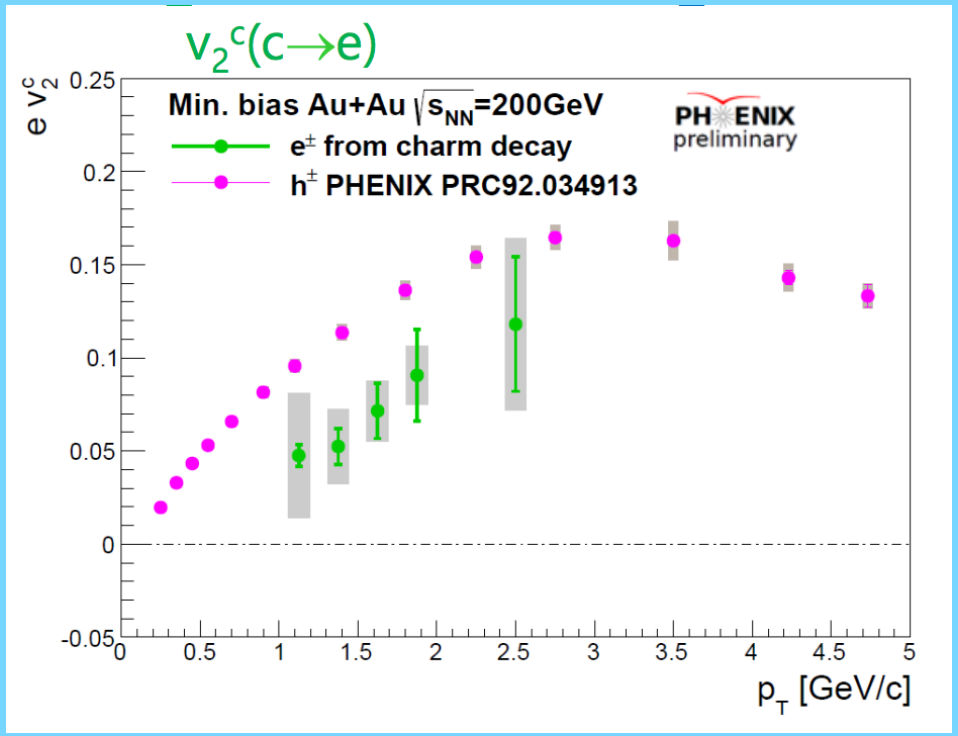
PHENIX(2018) R(pAu) of bottom to dimuons in p+Au collisions at 200 GeV

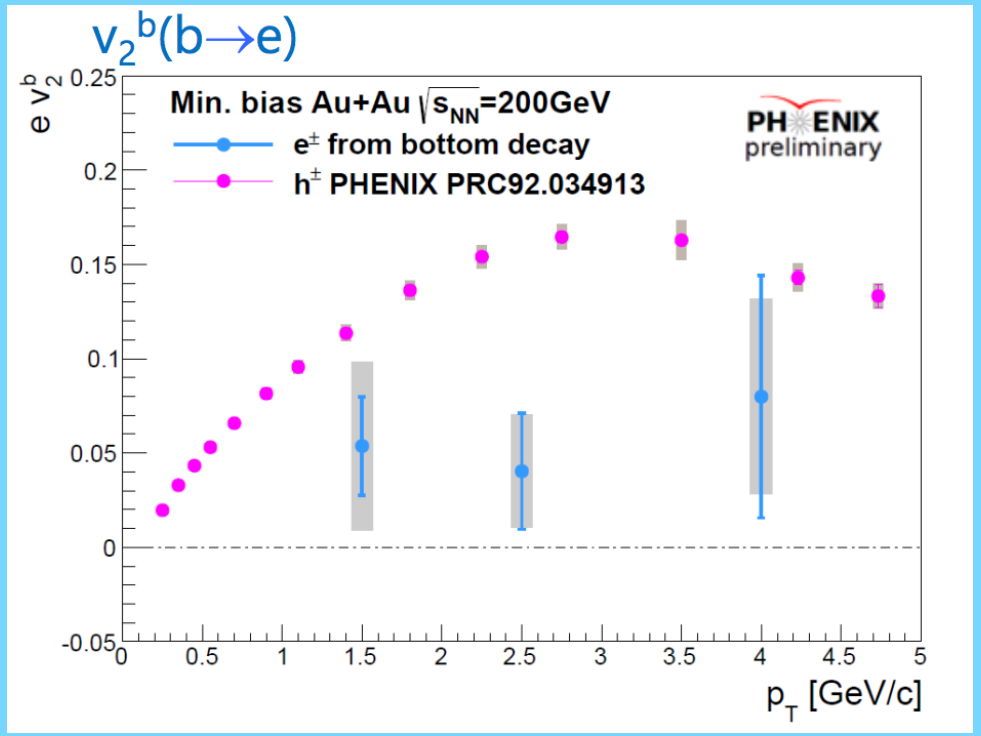
Xuan Li et al, PHENIX Collaboration, https://arxiv.org/pdf/1809.09247.pdf



Charm and Bottom flow in Au+Au collisions

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



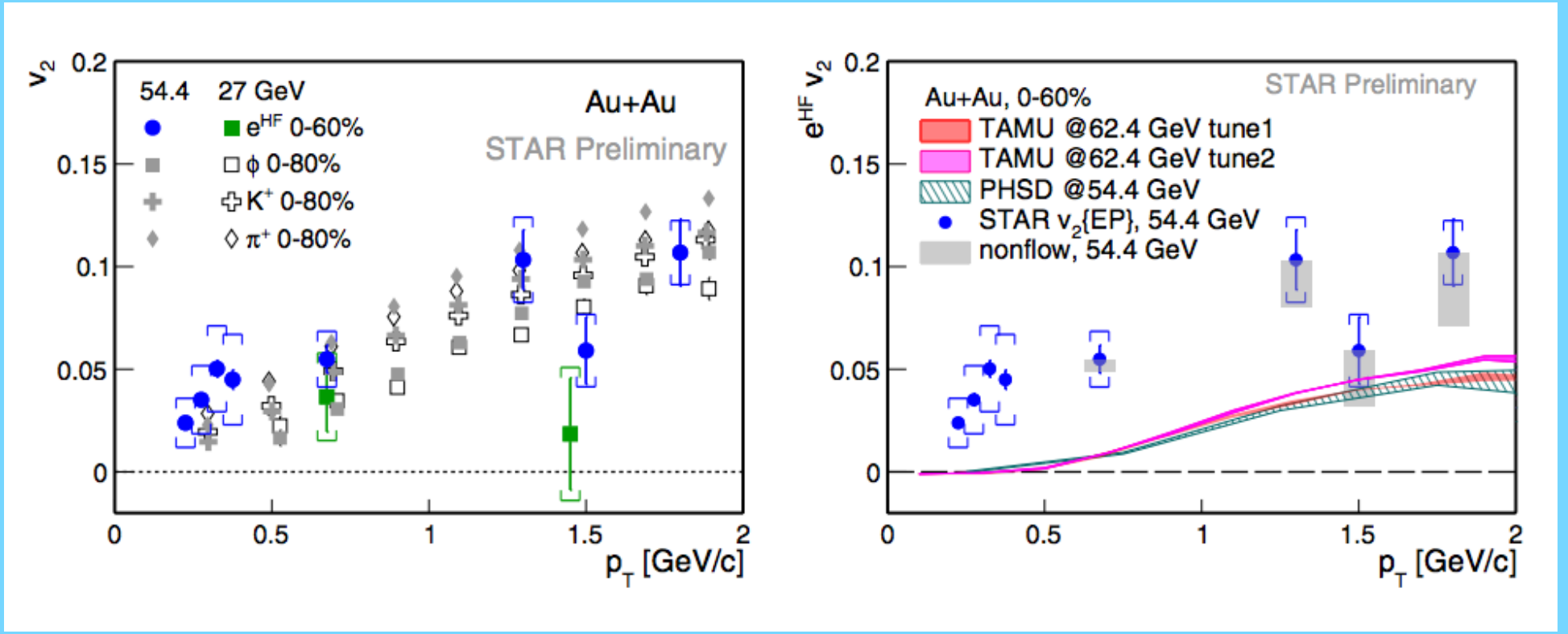


T Hachiya et al, PHENIX collaboration, QM2022

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

STAR (preliminary) Heavy Flavor elliptic flow (v2) in Au+Au collisions at 27, 54 and 200 GeV

https://inspirehep.net/files/455b29474e322e64d513aad916bd6030

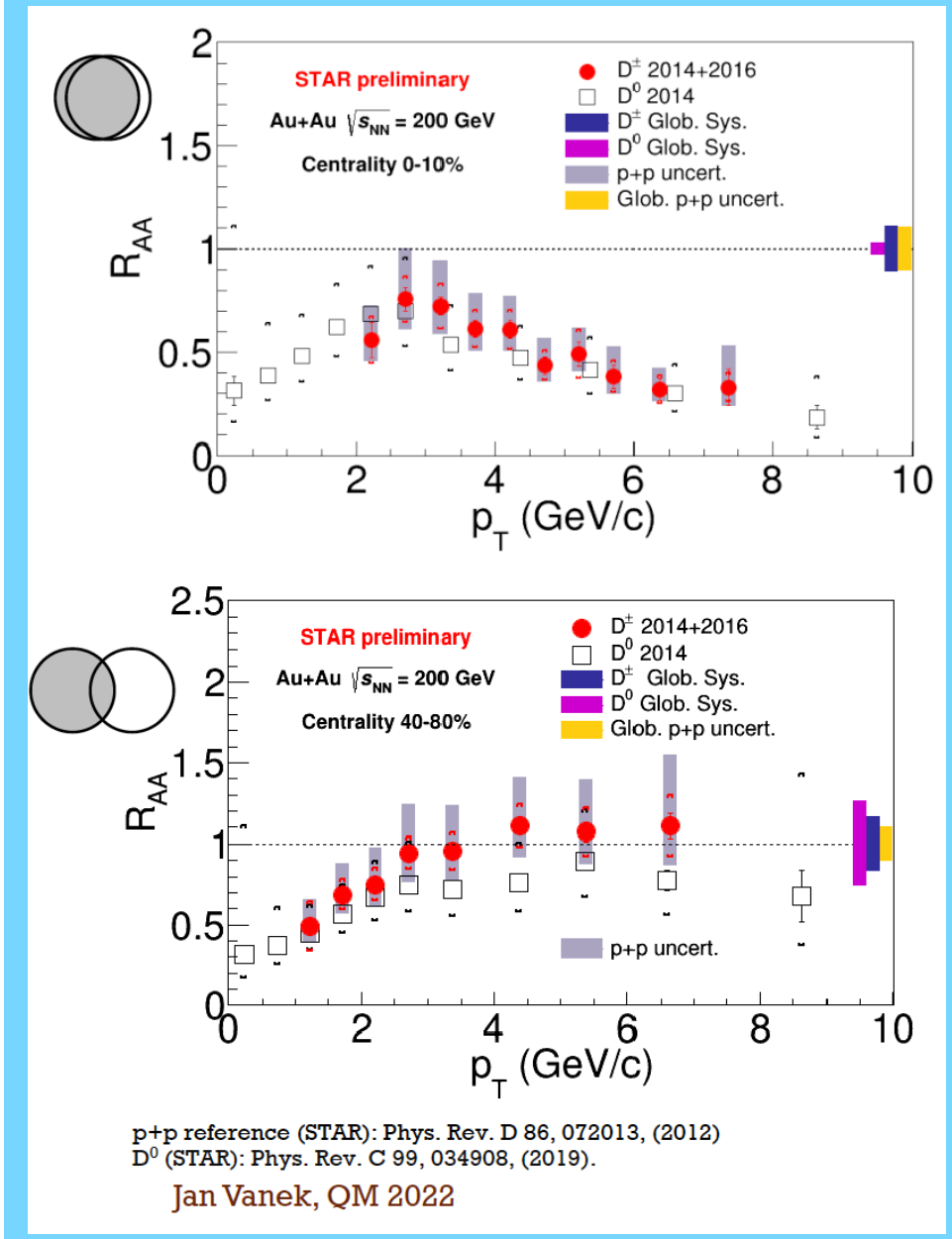


* The large elliptic flow of heavy flavor electrons in Au+Au collisions at 54.4 GeV indicates strong charm quark interactions with the medium

Charmed hadrons in Au+Au collisions

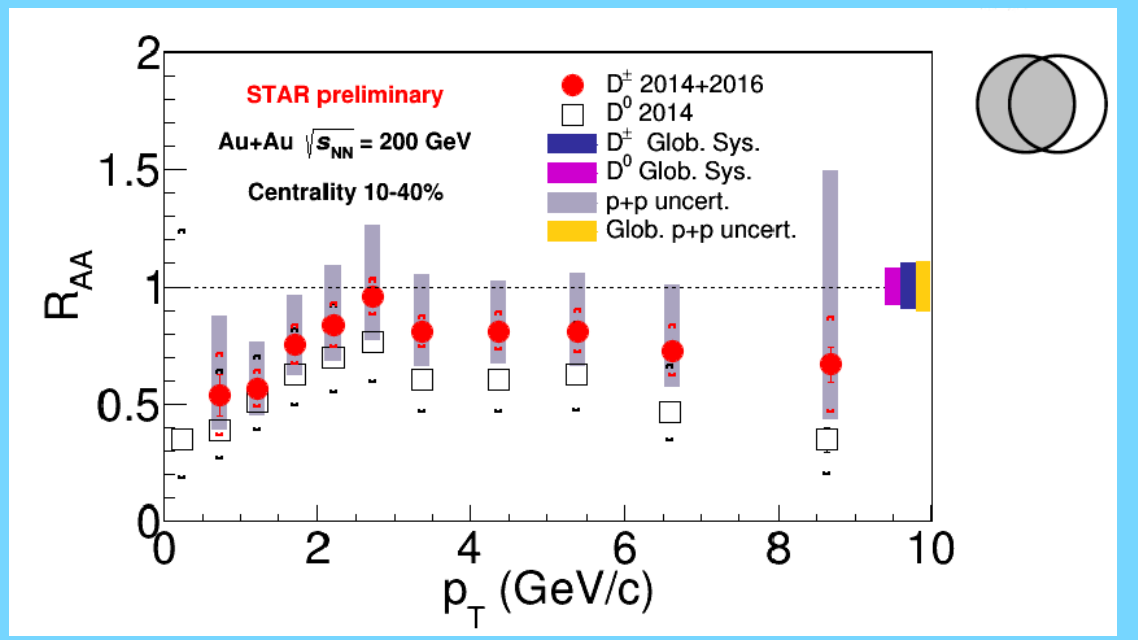
STAR (preliminary) Charmed hadrons: D^{+-} and D^0 measurement

J. Vanek et al, STAR Collaboration, QM2022



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

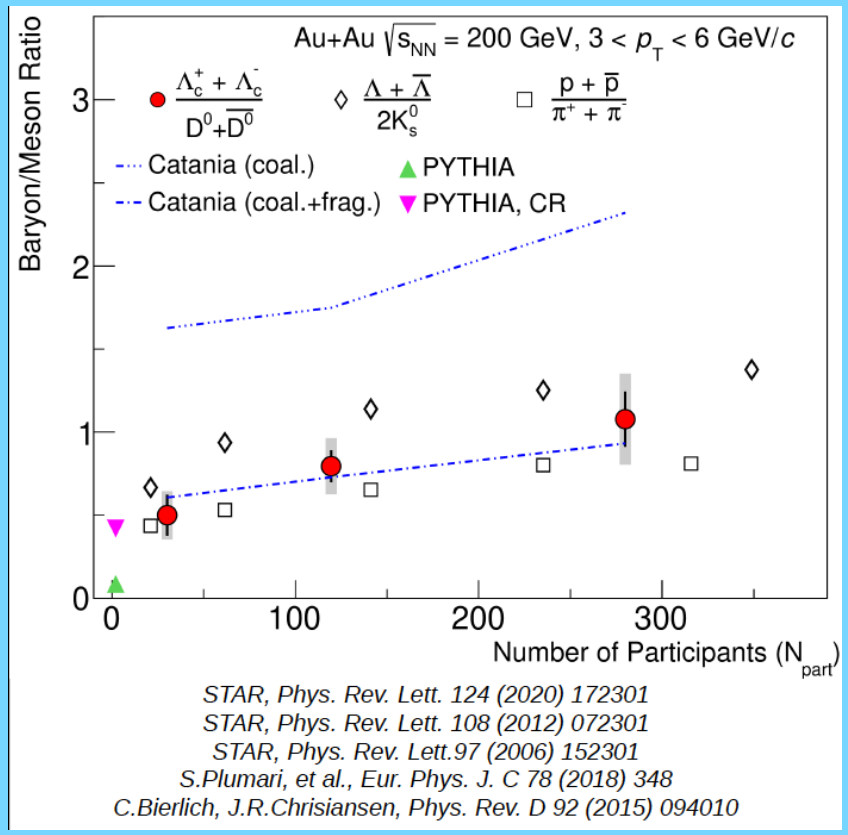
Jan Vanek, QM 2022



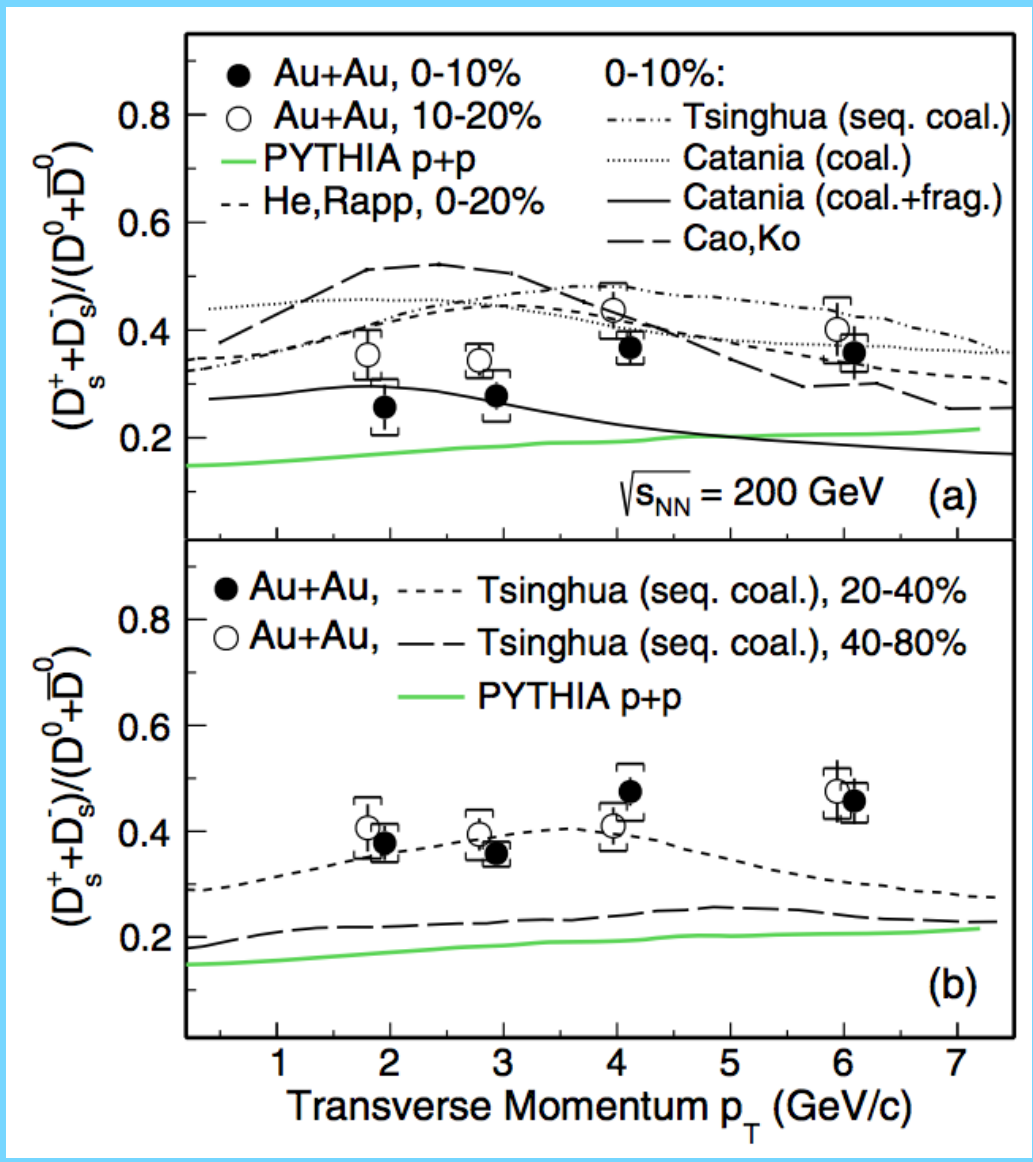
* Centrality dependence of R_{AA} of $D^{+/-}$ and D^0 measured
* R_{AA} of $D^{+/-}$ and D^0 show a similar trend and are suppressed at high p_T in central (0-10%) Au+Au collisions

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

Conclusions and Outlook

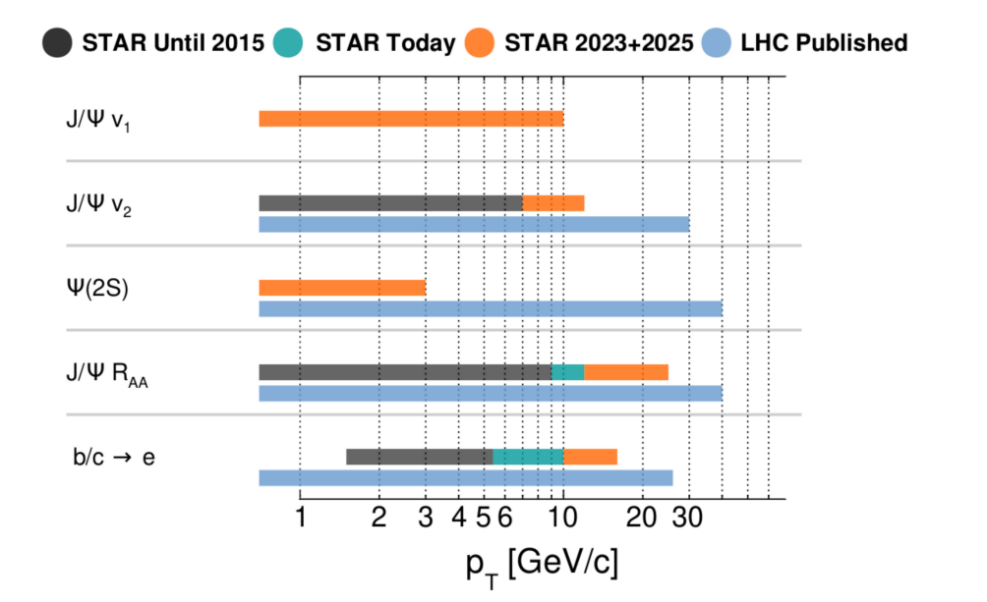
* Evidence for mass ordering of bottom and charm (measured via b, c-> e) in Au+Au 200 GeV has been observed at RHIC

* Flow results in Au+Au suggest strong interaction of heavy quarks with medium

* Charmed hadron production in Au+Au agrees with hypothesis of coalescence hadronization of charm hadrons

Outlook

STAR and sPHENIX upcoming run period



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

*** PHENIX:**

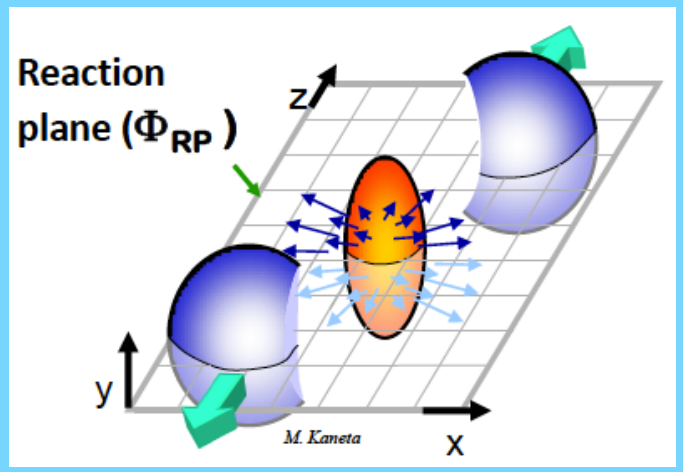
Will add to analysis the data Au+Au from 2016

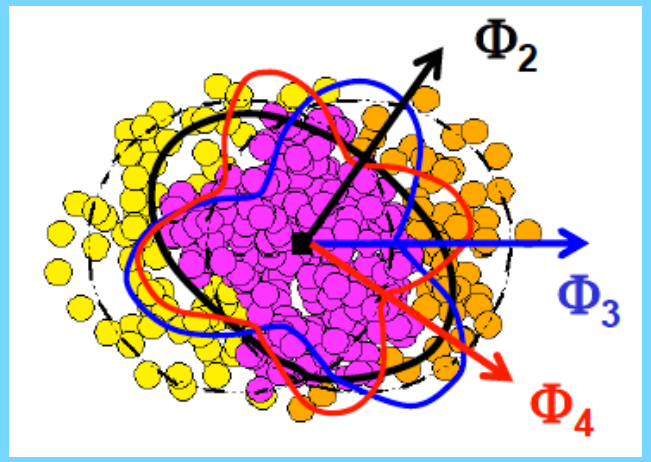
New b and c results from Au+Au and small systems are coming soon

*** sPHENIX coming up soon ! (first collision in 2023)**

Thank you very much

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





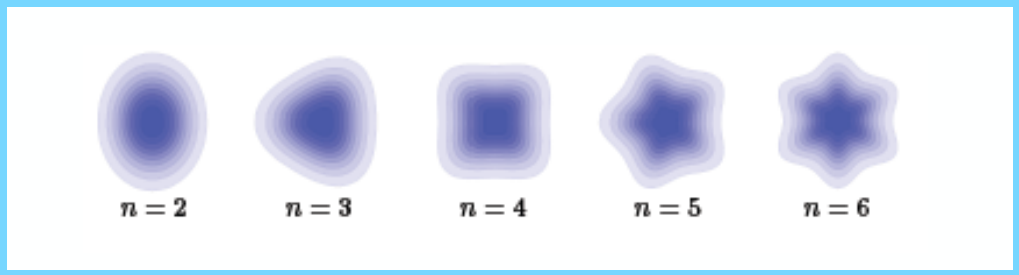
Matter in the overlapp area of two colliding nuclei gets compressed and heated

Initial anisotropy gets transfered into the momentum space via pressure gradients

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

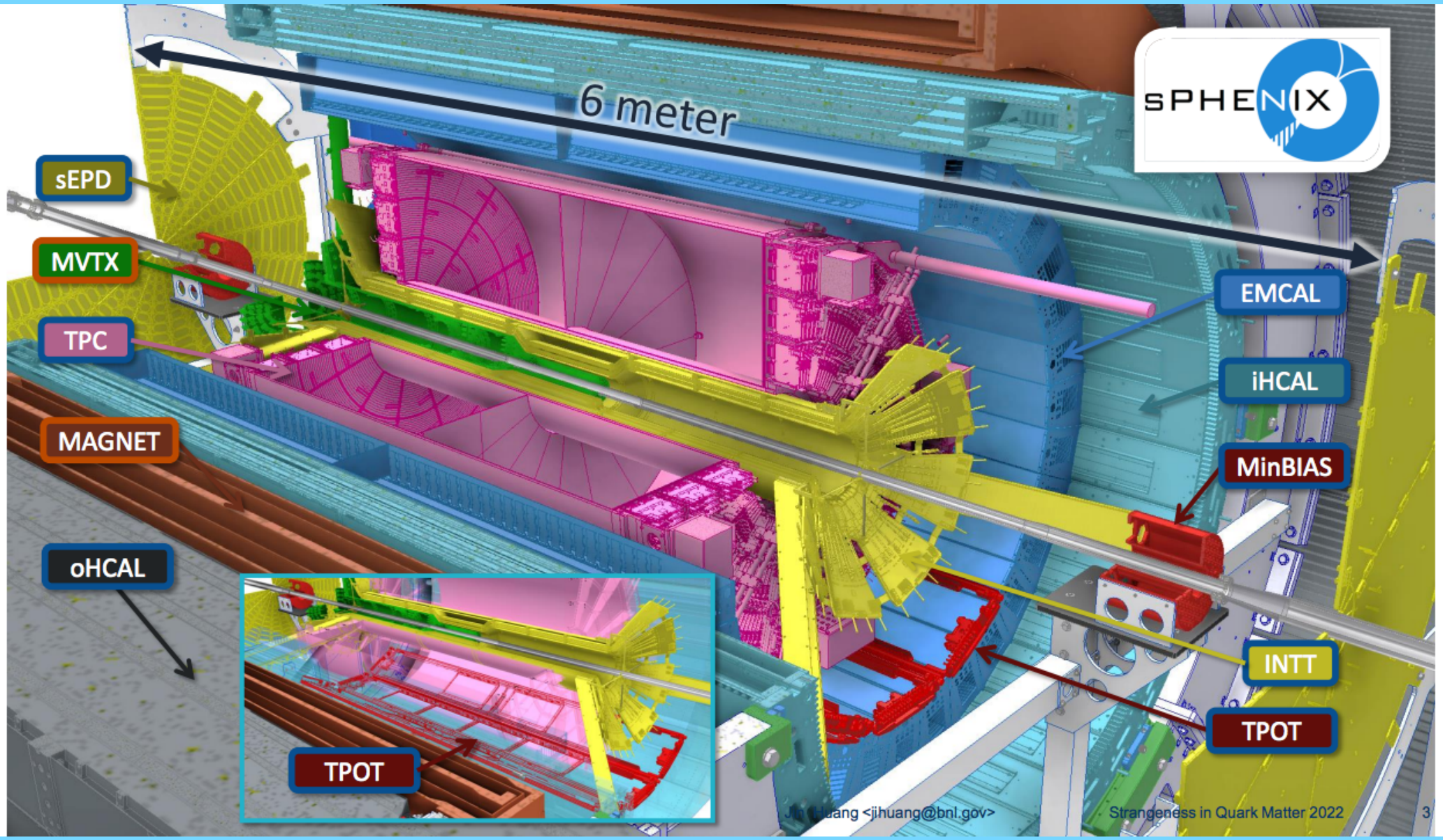
$$v_n = <\cos[n(\phi - \Phi_n)]>$$

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



Higher harmonics

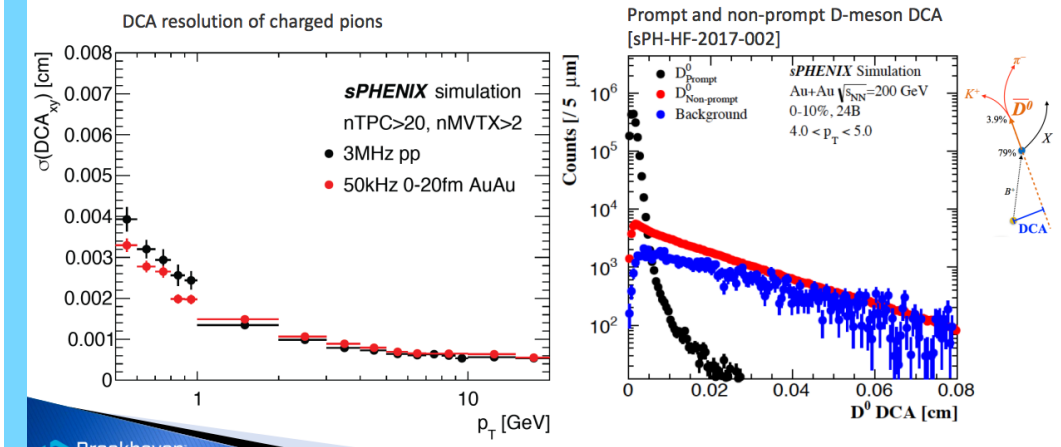
sPHENIX


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

sPHENIX

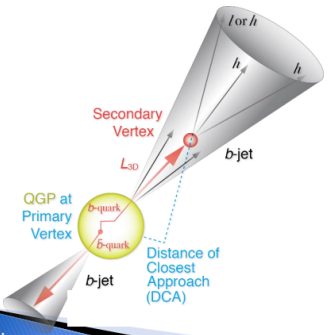
Exceptional performances expected for open heavy flavor

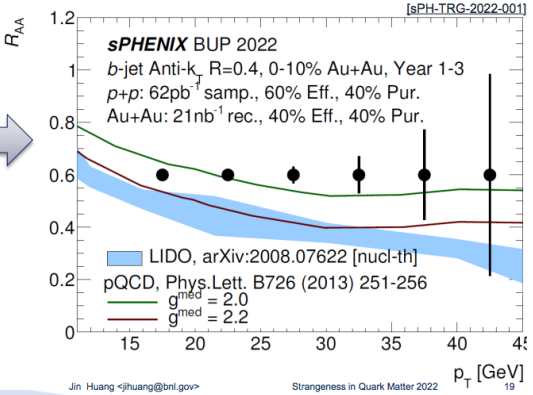
Cleanly separate open bottom meson via DCA



Higher p_T: bottom quark via b-jet

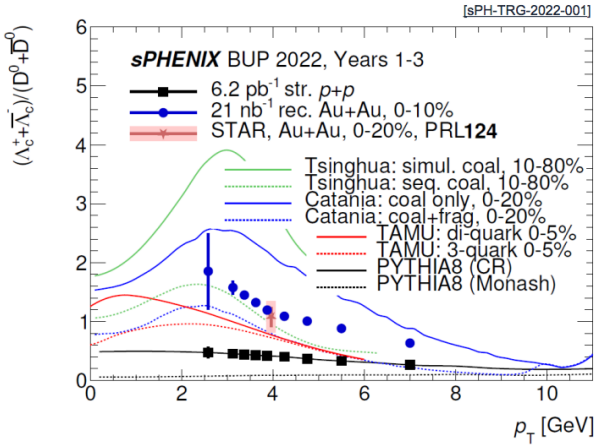
- New for RHIC, enabled by precision tracking and full calorimetric jet





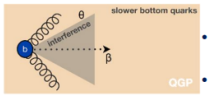
News from beam use proposal 2020 – hadronization

- STAR and ALICE collaboration reported enhanced charm baryon to meson ratio → challenging hadronization models
- sPHENIX streaming readout will deliver first $p+p$ measurement at RHIC
- sPHENIX will also map out the Λ_c/D ratio over momentum dependence

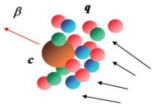


Access b-quark suppression/v2 via non-prompt D

- Bringing high precision non-prompt-*D* suppression and flow to RHIC

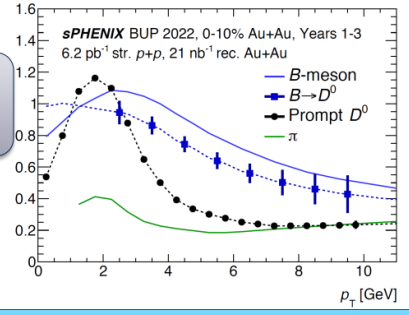


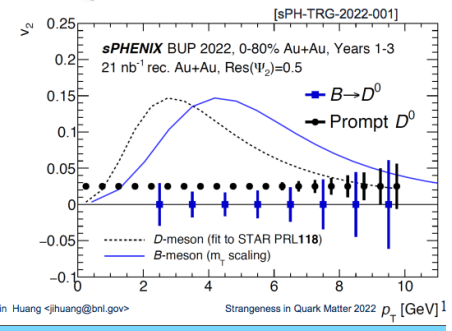
- Probe the mass dependence of quark energy loss in QGP, light → c → b
- Sensitive to pick up collision energy loss



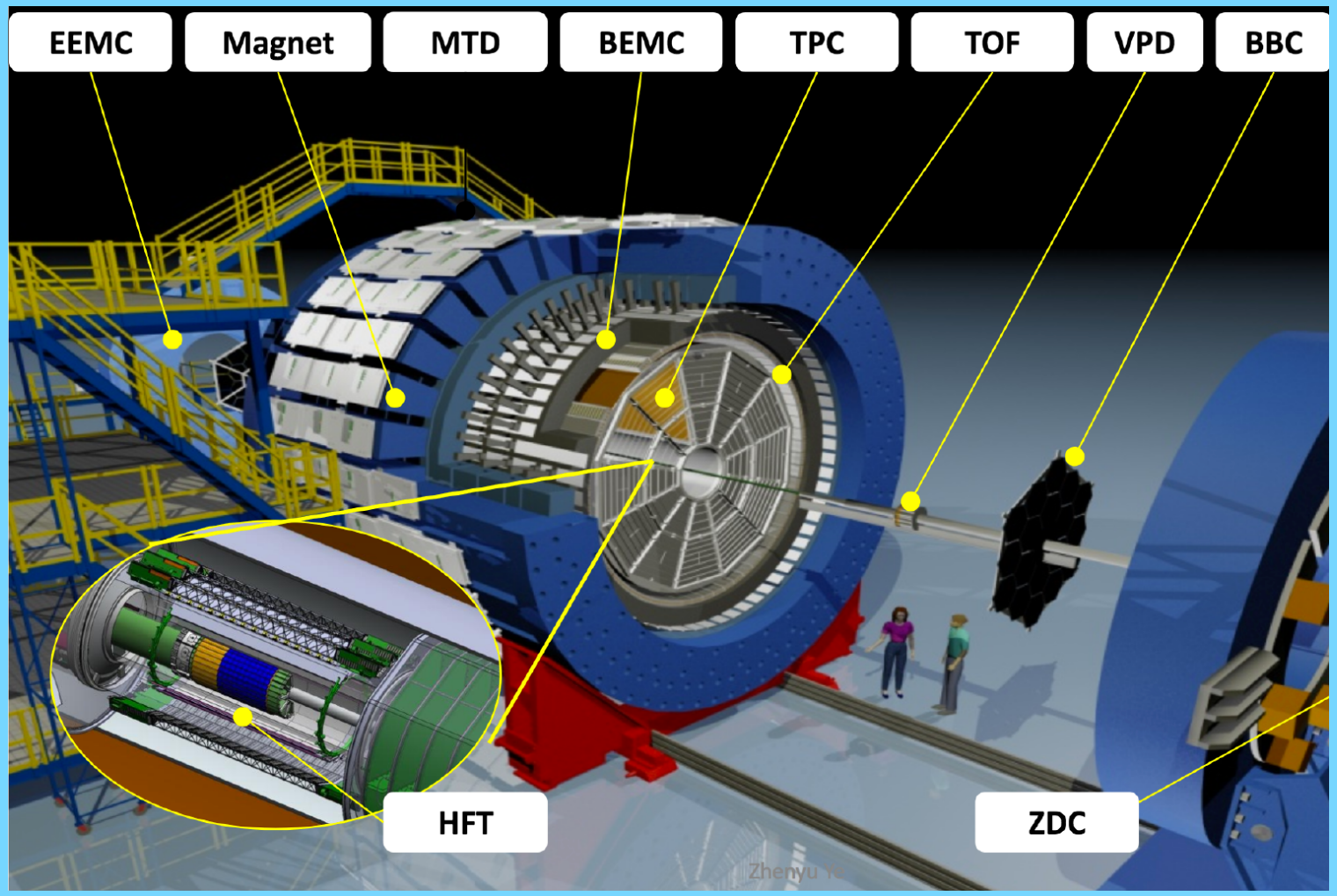
- Determine the bottom quark collectivity
- → clean access to D_{HQ} at RHIC energy

$p+p$ baseline uniquely enabled by streaming data



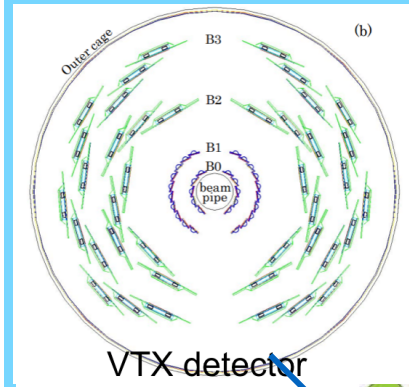


The STAR Experiment at RHIC



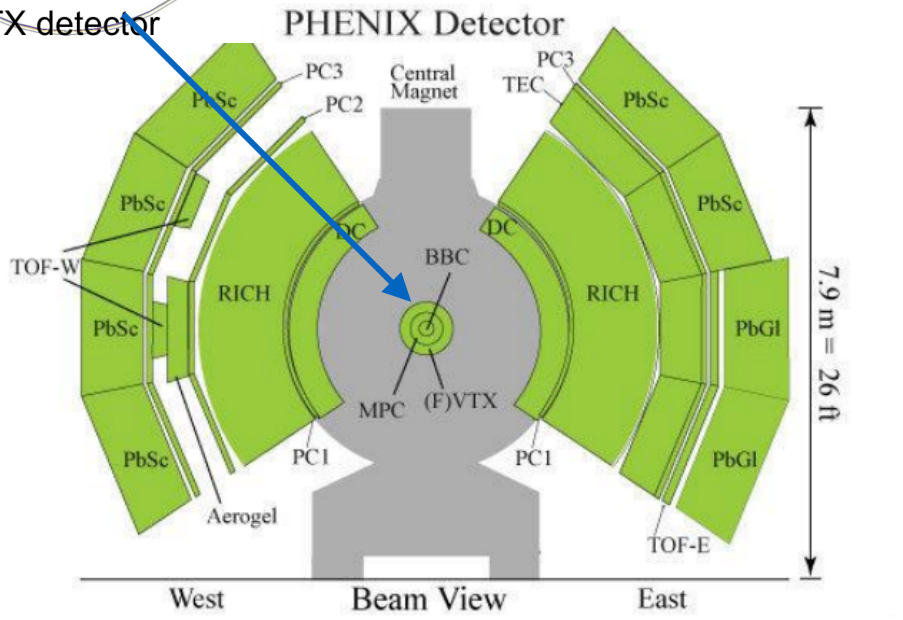
Detectors used for open heavy flavor: Heavy Flavor Tracker (HFT), Time Projection Chamber (TPC), Barrel Electromagnetic Calorimer (BEMC) Time-Of-Flight detector (TOF). Electron (e+,e—) identification : Delta(phi)=4pi, |eta|<1

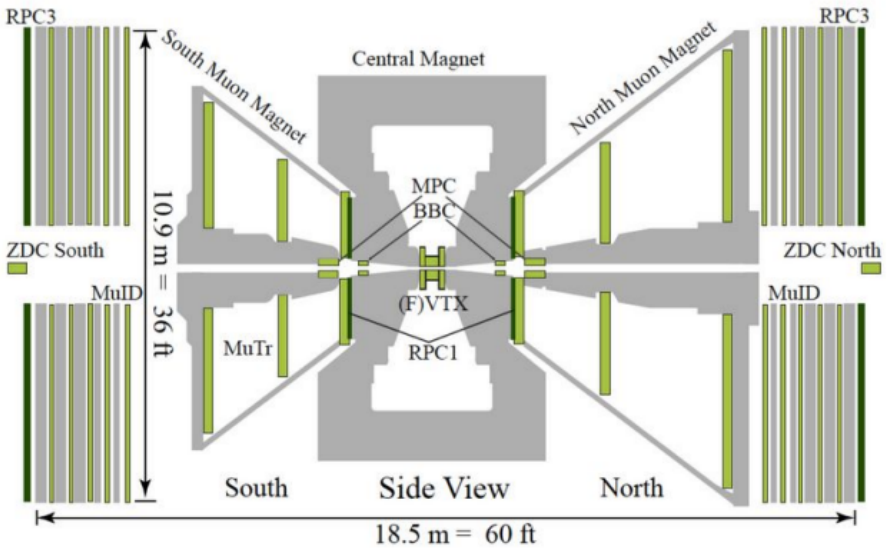
The PHENIX Experiment at RHIC



VTX detector

PHENIX





Detectors used for open heavy flavor results:

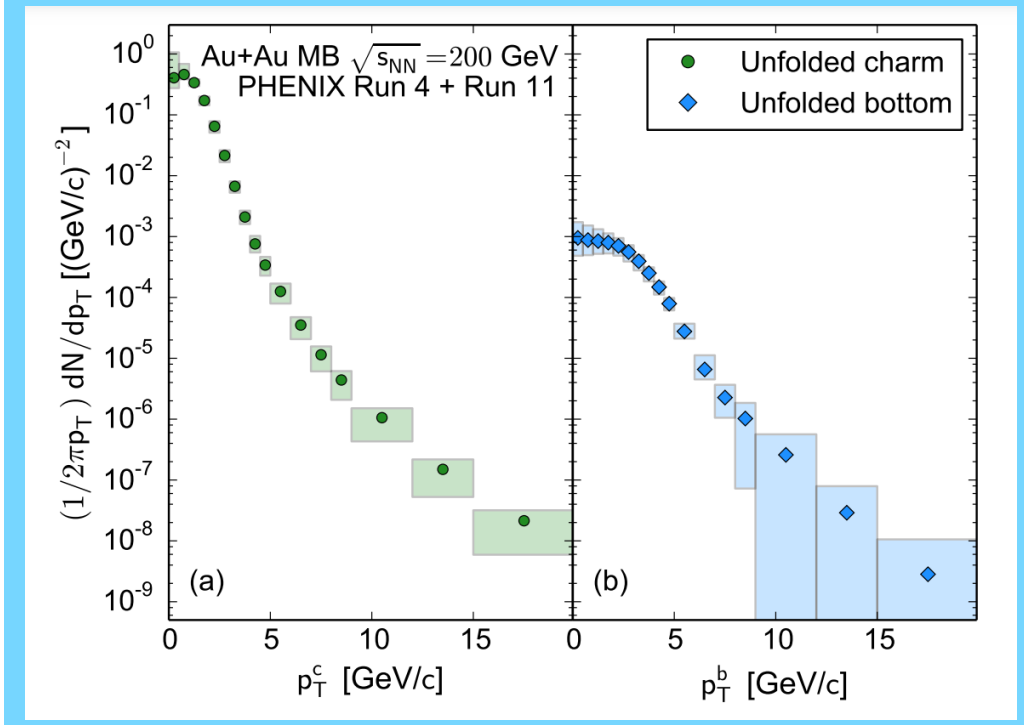
-Central spectrometer arms : ring imaging Cerenkov detector (RICH), electromagnetic calorimeter (EMCal), Drift Chambers (DC), multi-wire proportional pad chambers (PC) and silicon Vertex detector (VTX).
Electron (e+,e-) identification: $|y|<0.35$ and azimuthal angle phi=2 pi/2
-Muon arms: $1.2<|y|<2.2$, phi=2 pi/2

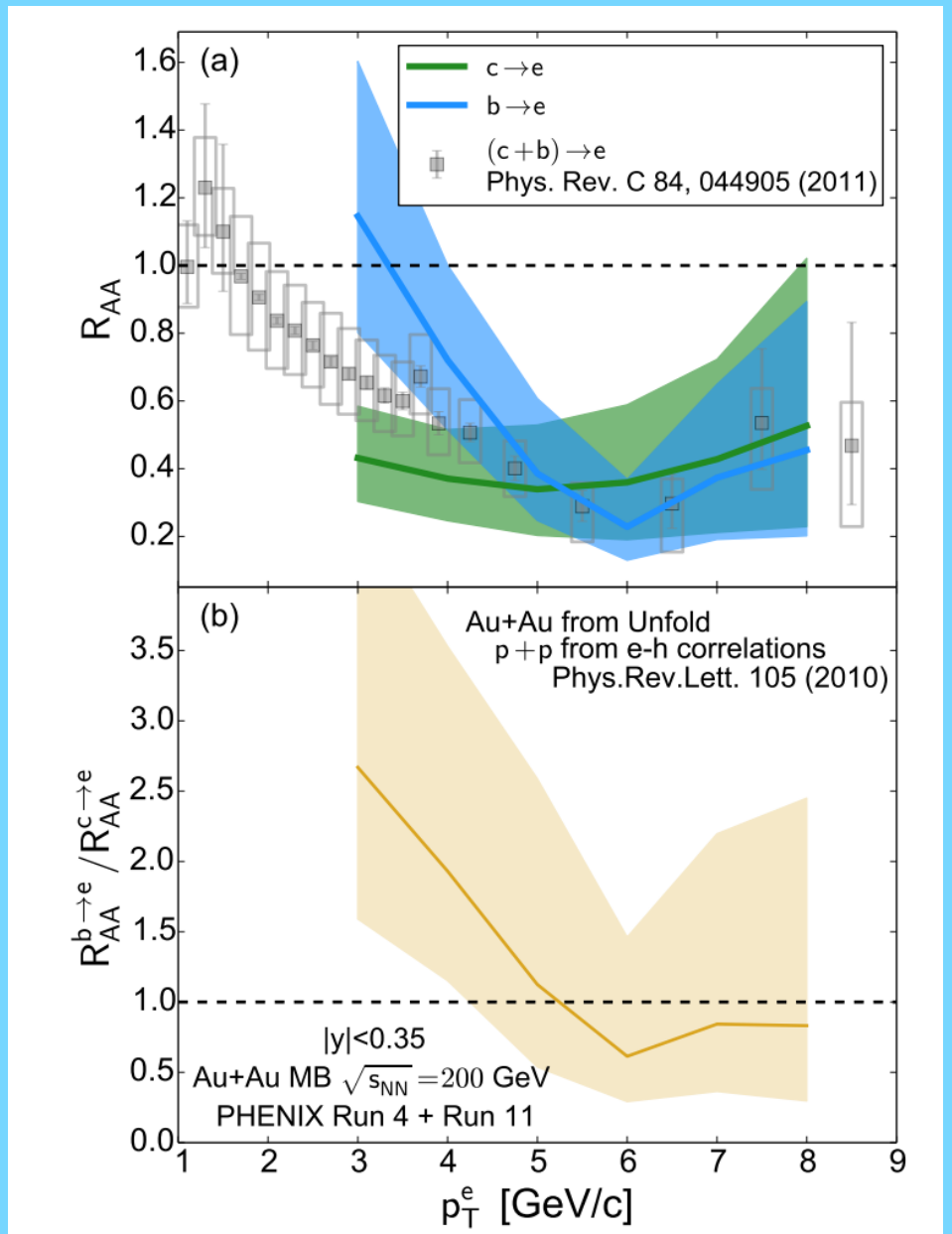
Data taking completed in 2016

PHENIX (2016) hierarchy of suppression of heavy flavor b,c to electrons

A. Adare et al. (PHENIX Collaboration), Single electron yields from semileptonic charm and bottom hadron decays in Au+Au collisions at √sNN = 200 GeV, Phys. Rev. C 93, 034904 (2016). https://arxiv.org/pdf/1509.04662.pdf

R_{AA} = yield in A+A/ yield in p+p scaled by number of binary collisions





* Hint of less suppression for b —> e than c —> e observed in MB Au+Au collisions at 200 GeV at pT 3-4 GeV

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

STAR Collaboration, June 2022, arXiv:2111.14615

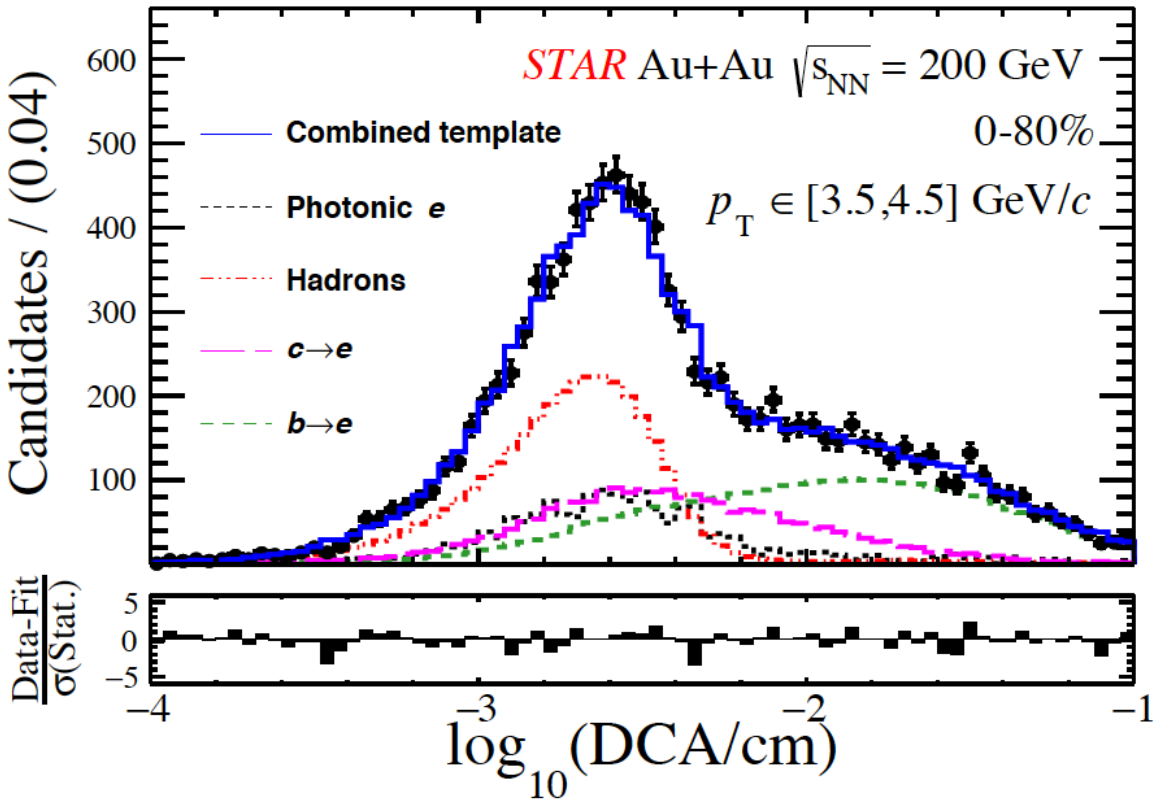
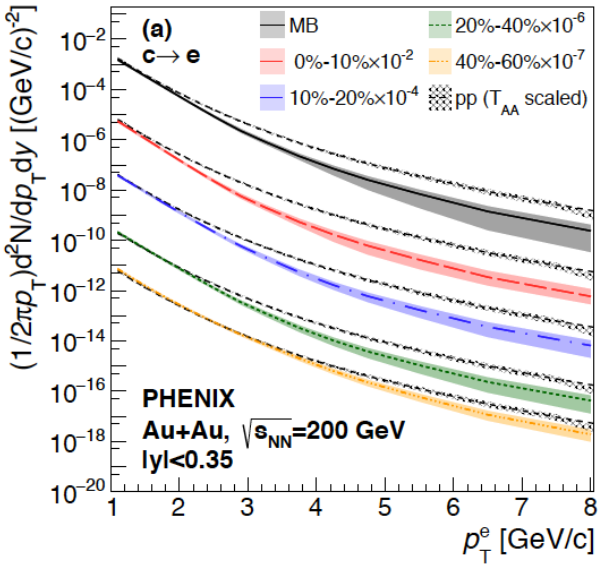
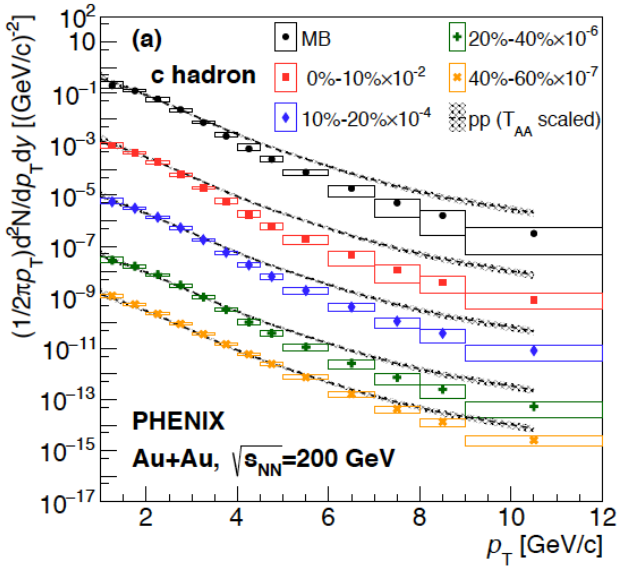


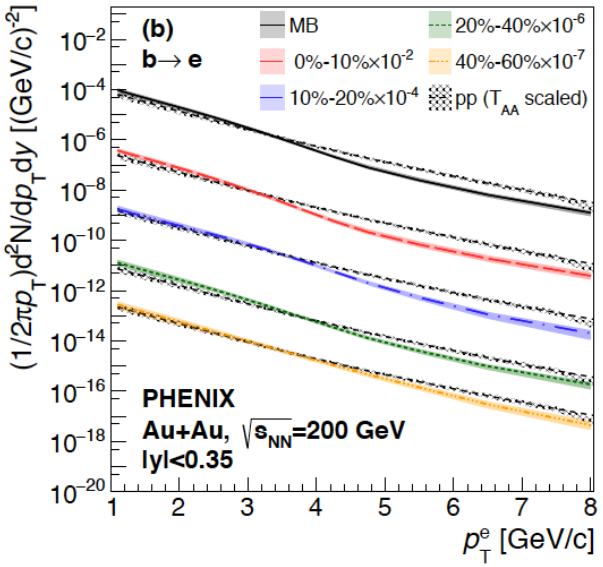
Fig. 5 Fit to the $\log_{10}$(DCA/cm) of candidate electrons with $p_T \in [3.5,4.5]$ GeV/c in 2014 data. The solid blue line shows the full template fit, and the various other lines show the individual components. The bottom panel shows the residual distribution of the template fit scaled by the statistical uncertainties.

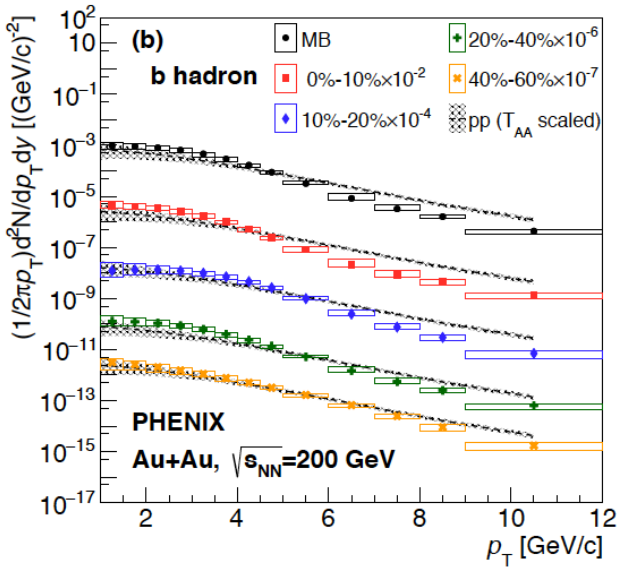
PHENIX (2022) b—>e and c—> e and c,b hadrons in Au+Au collisions at 200 GeV

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









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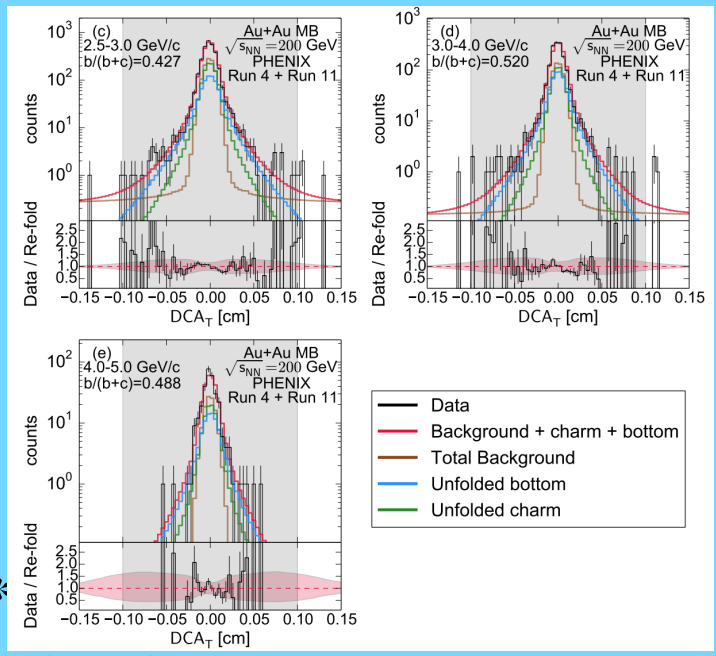
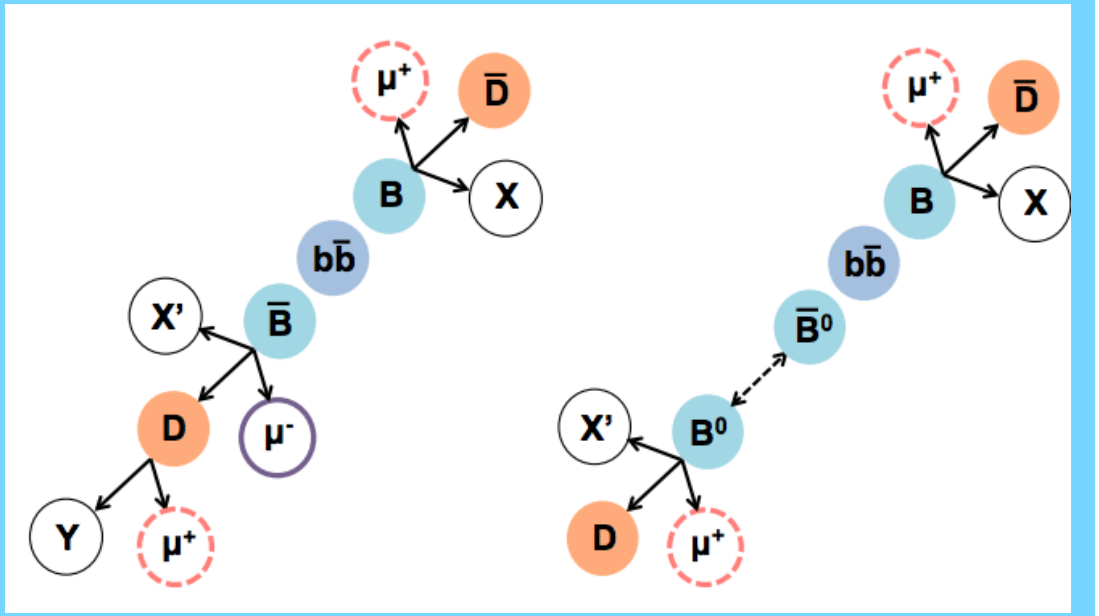


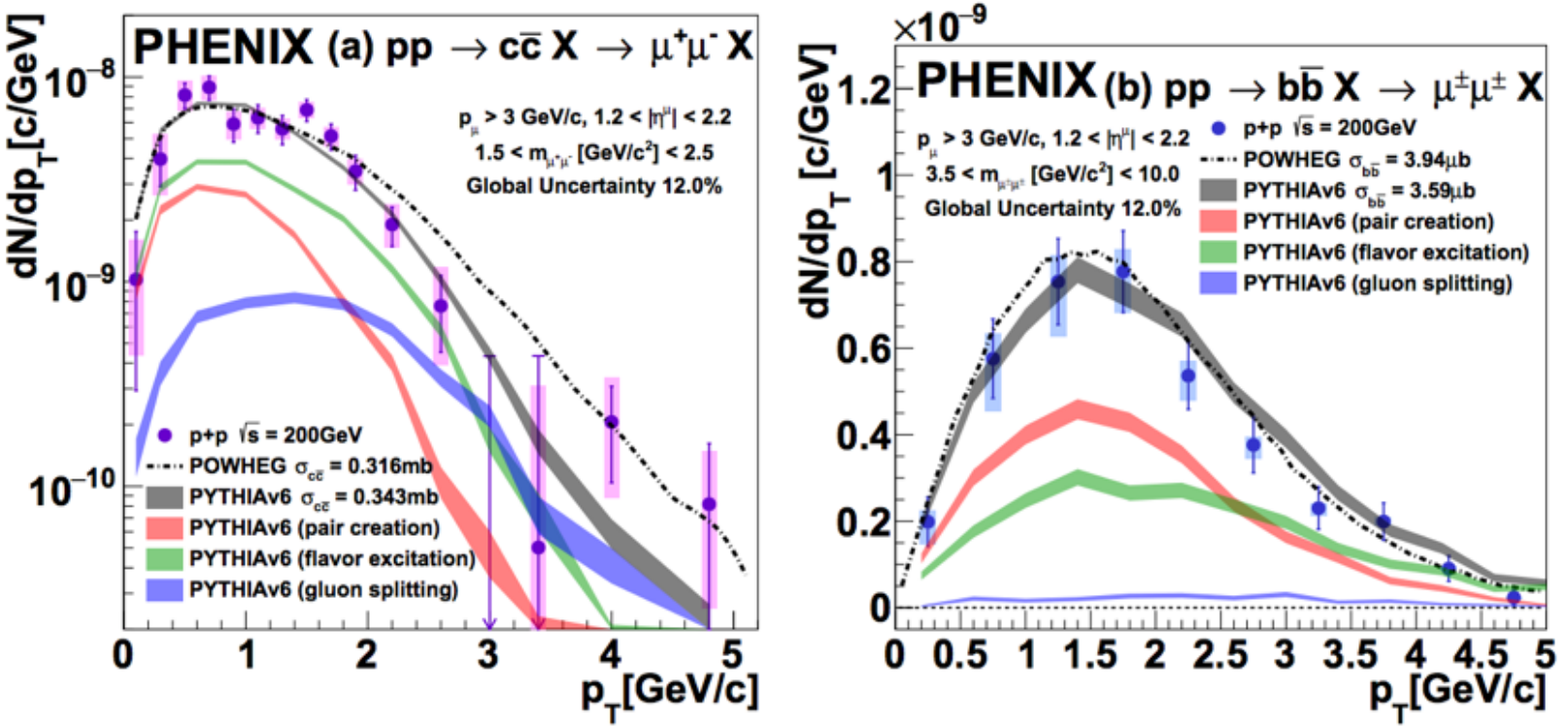
Au+Au compared to p+p scaled by number of collisions

* Right up and down unfolded c hadrons and b hadrons Au+Au compared to p+p scaled by number of collisions

PHENIX (2019) c and b to mumu in p+p collisions 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]





STAR and sPHENIX upcoming 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. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <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}