Open Heavy Flavor production with the STAR and PHENIX experiments at RHIC

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HF 2022, 14-17 July 2022,
Torino, Italy

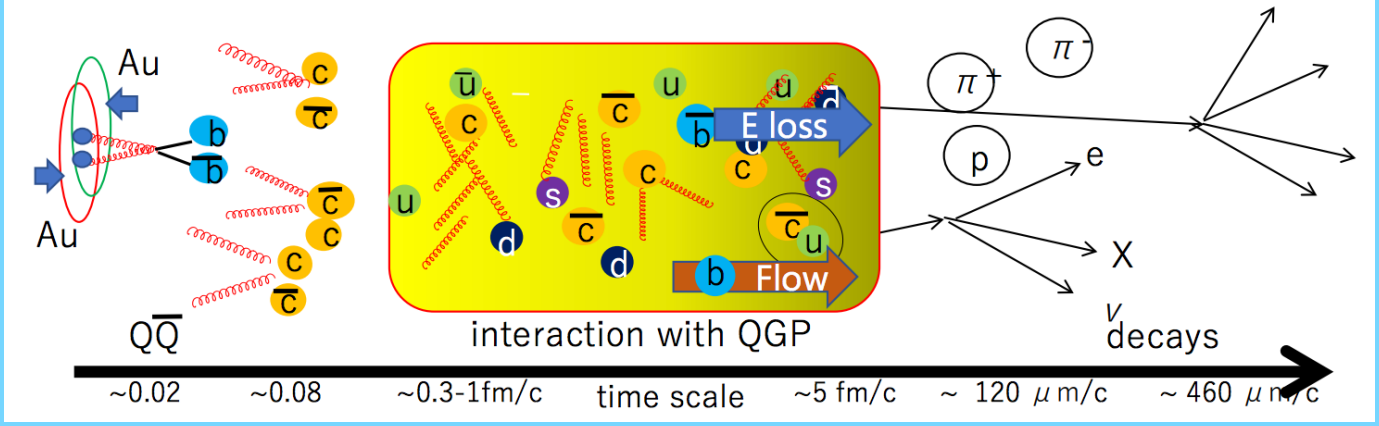
Outline

* 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

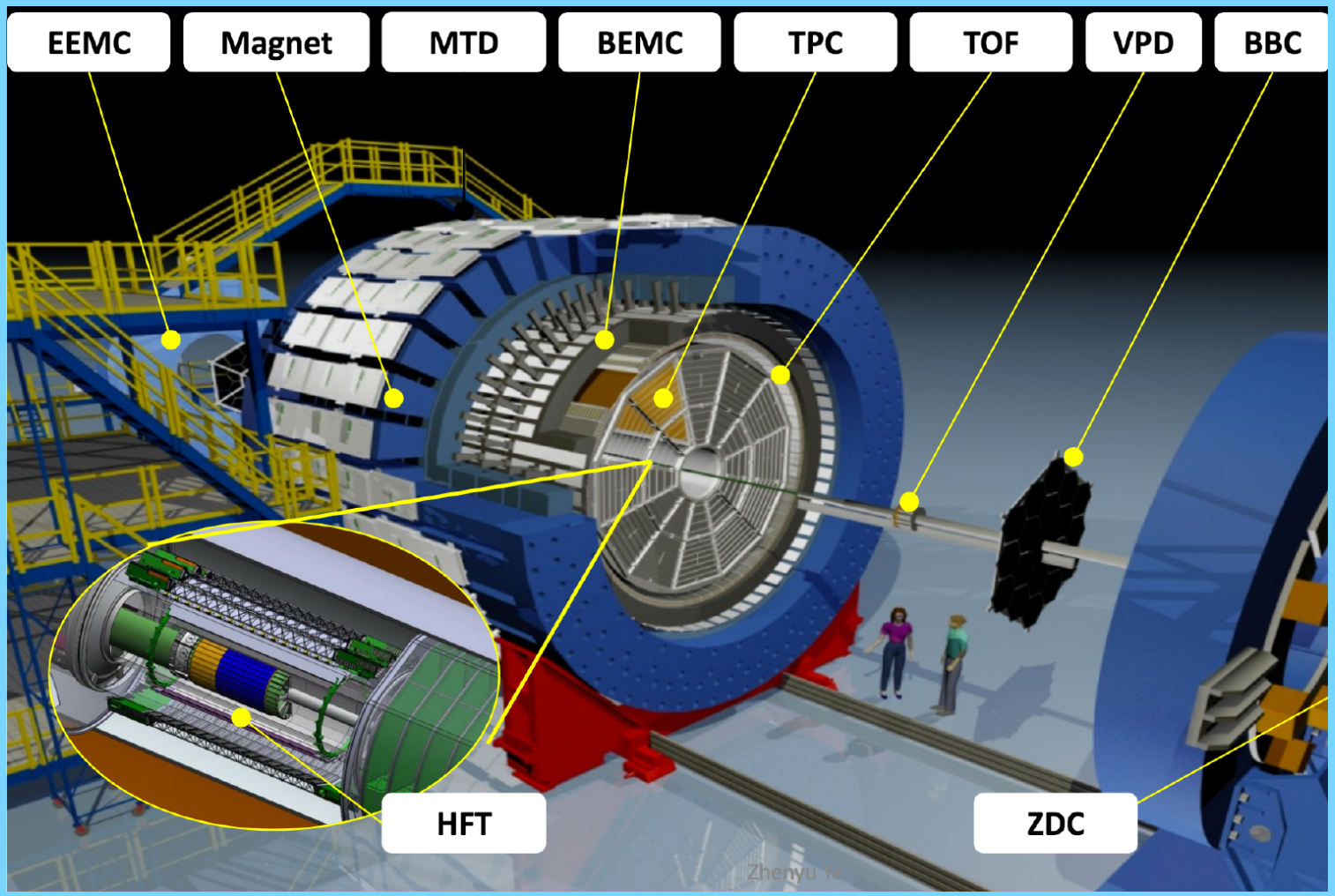
Charm and beauty (heavy flavor, HF) hadron production in ultrarelativistic heavy ion collisions are key observables for the study of sQGP :

* 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



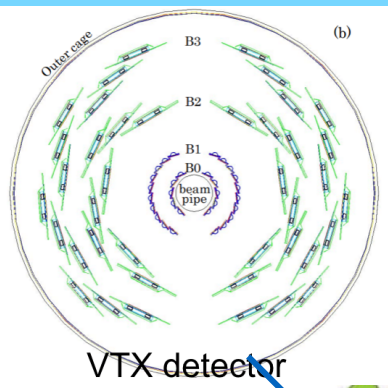
T. Hachiya, PHENIX Collaboration, QM2022

The STAR Experiment at RHIC

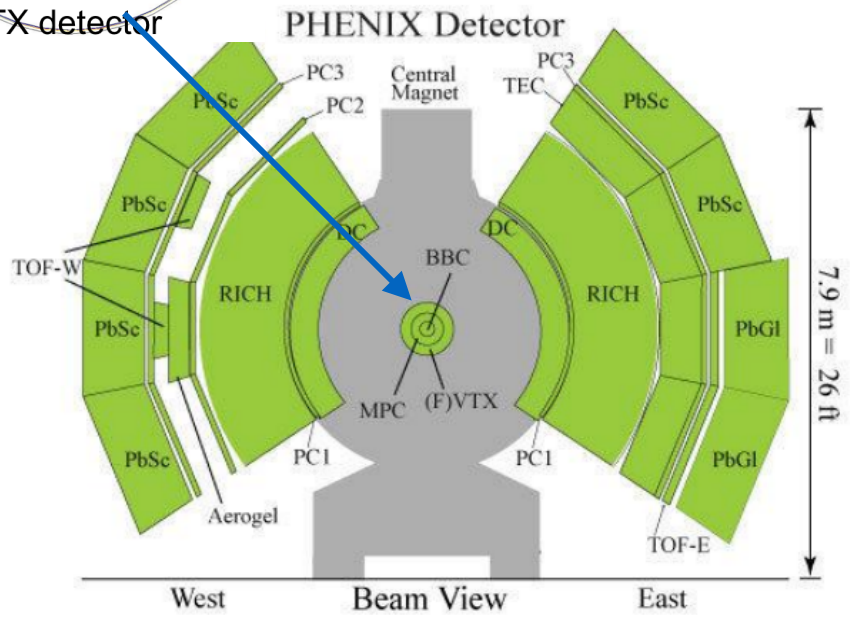


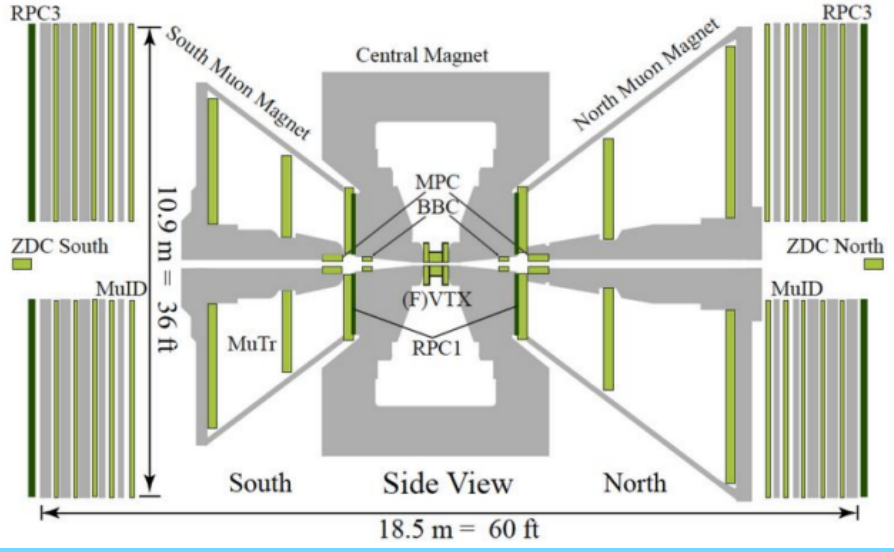
Detectors used for open heavy flavor: Heavy Flavor Tracker (HFT), Time Projection Chamber (TPC), Barrel Electromagnetic Calorimer (BEMC) Time-Of-Flight detector (TOF). Electron (e+,e—) identification : Delta(phi)=4pi, |eta|<1

The PHENIX Experiment at RHIC



VTX detector





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

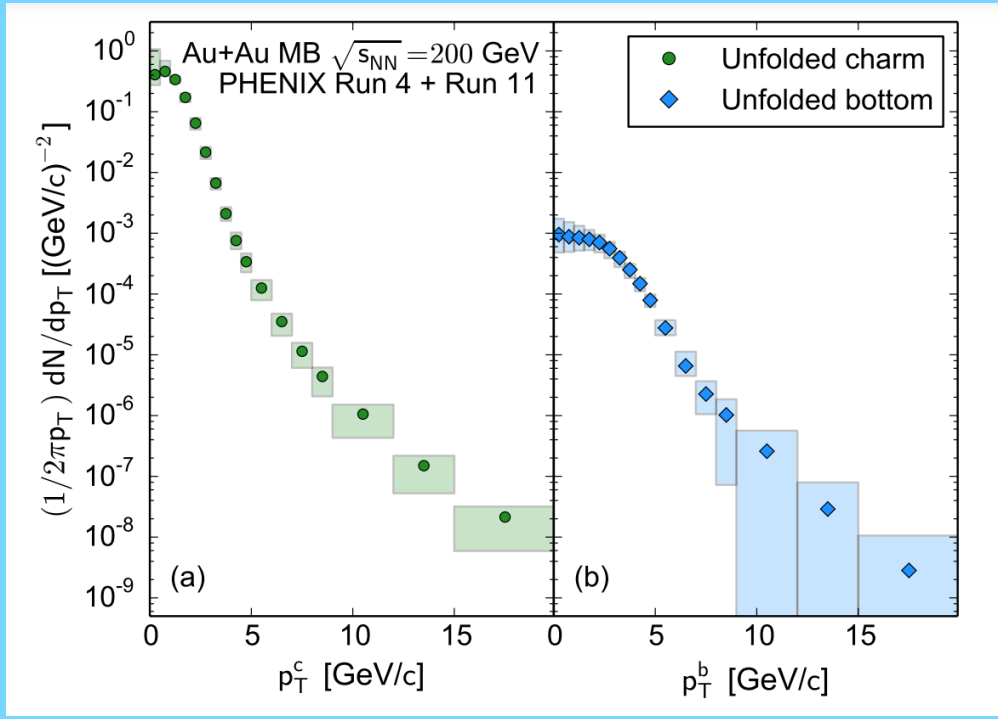
Data taking completed in 2016

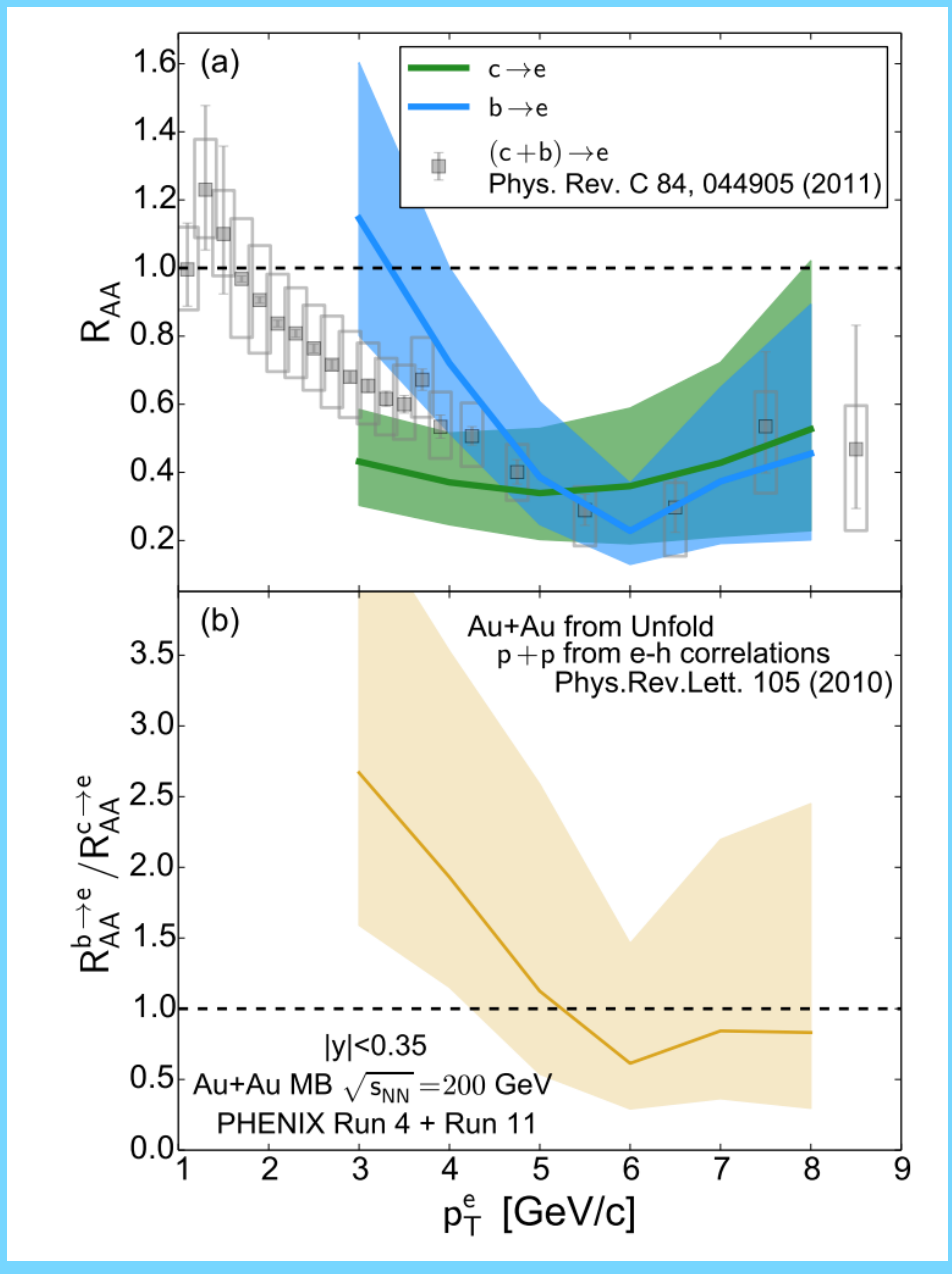
Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

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

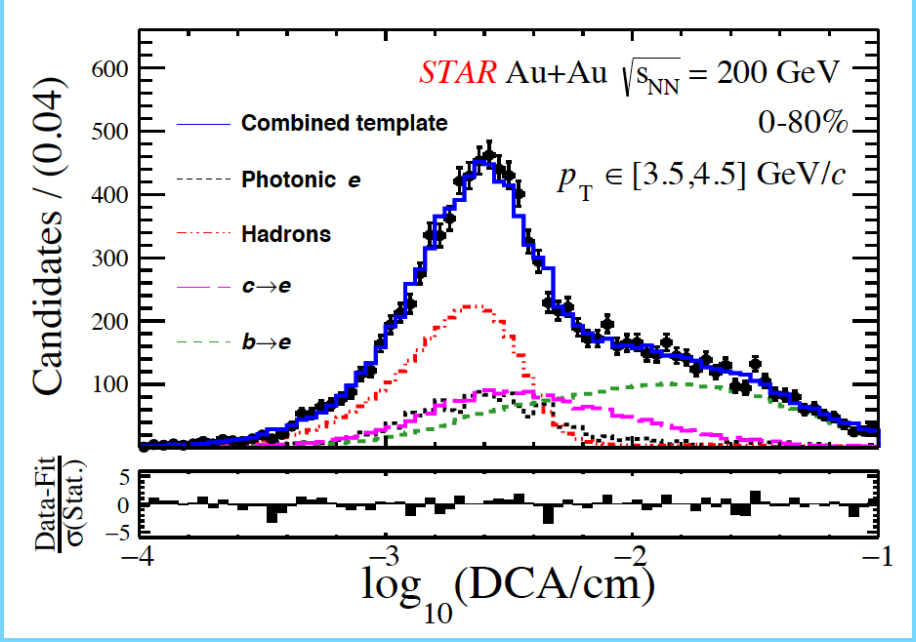
R_{AA} = yield in A+A/ yield in p+p scaled by number of binary collisions



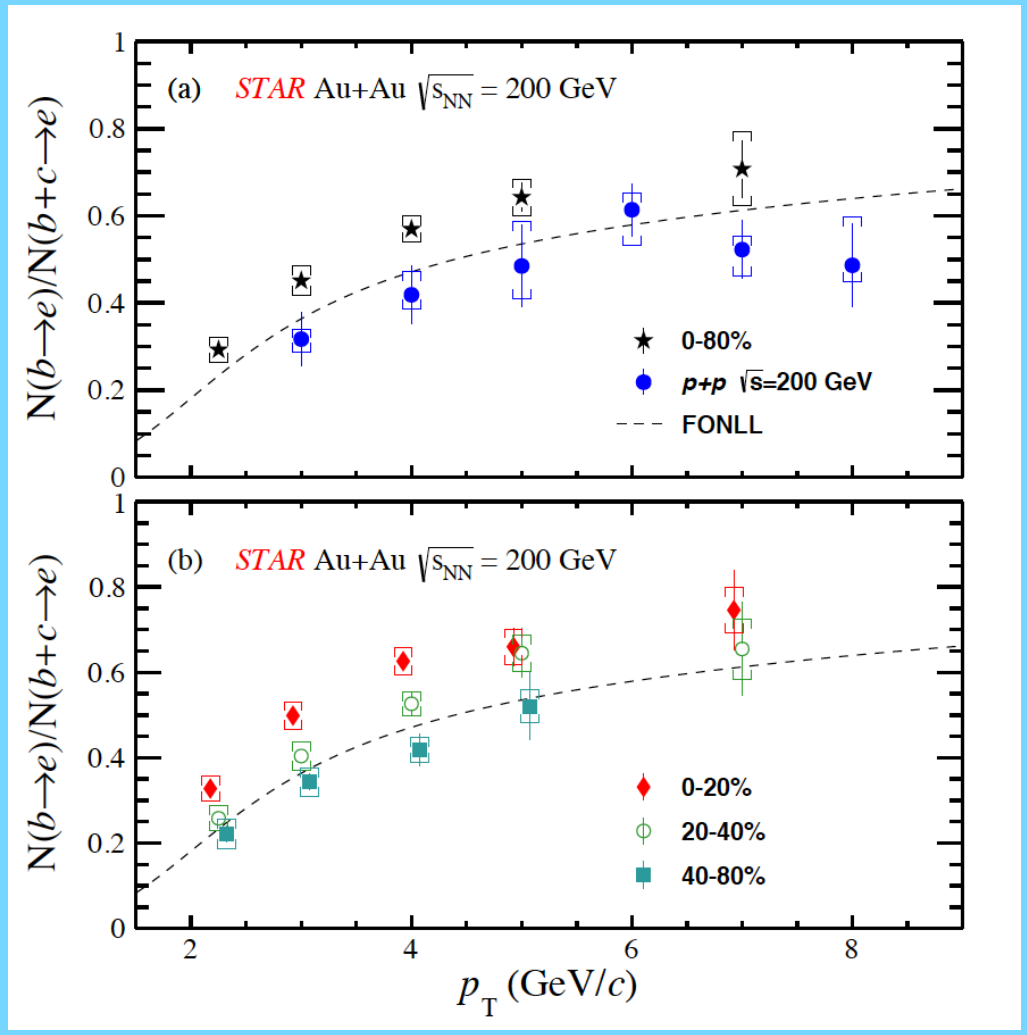


* Hint of less suppression for b —> e than c —> e observed in MB Au+Au collisions at 200 GeV at pT 3-4 GeV

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



STAR Collaboration, June 2022, arXiv:2111.14615



* Enhanced b—> e fractions measured in 0-20% and 0-80% Au+Au 200 GeV compared to p+p and FONLL
* Results in 40-80% are in agreement with p+p and FONLL
* Centrality dependence observed for pT < 4.5 GeV

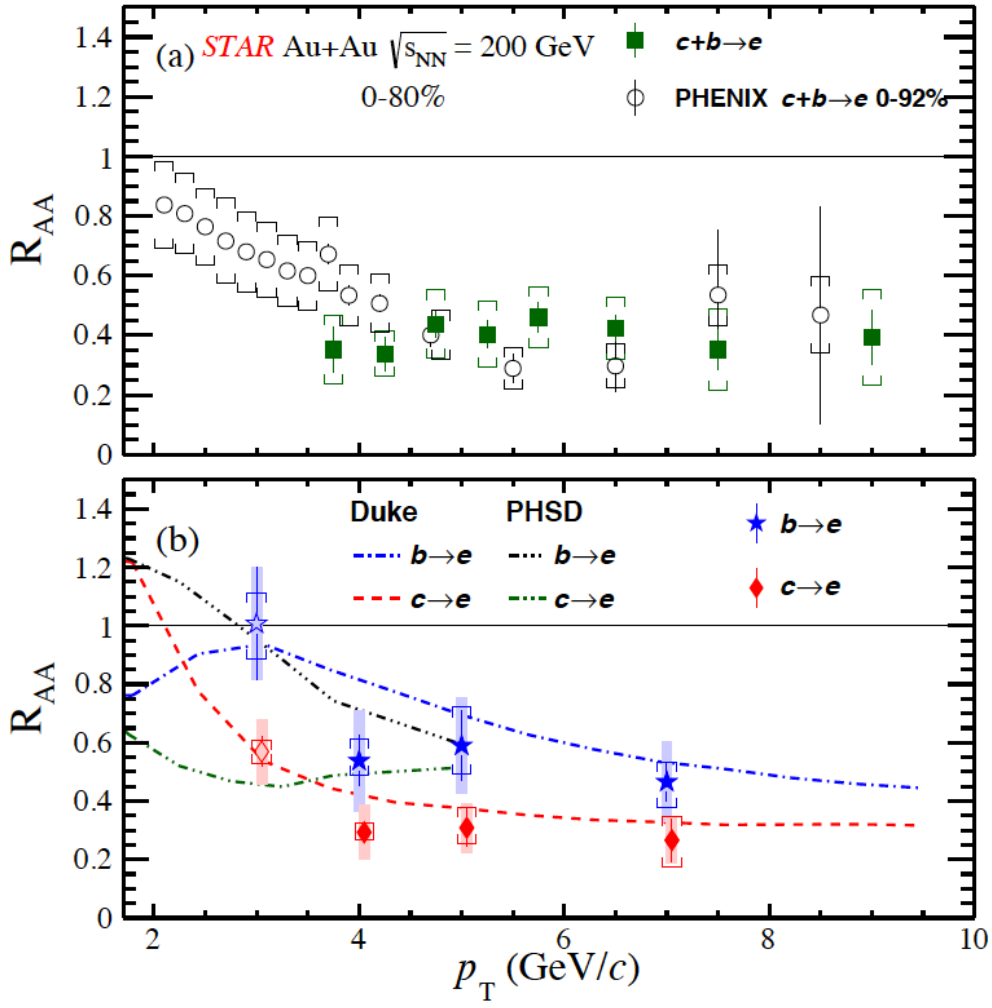
STAR (2022) Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

STAR Collaboration, June 2022, 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**



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

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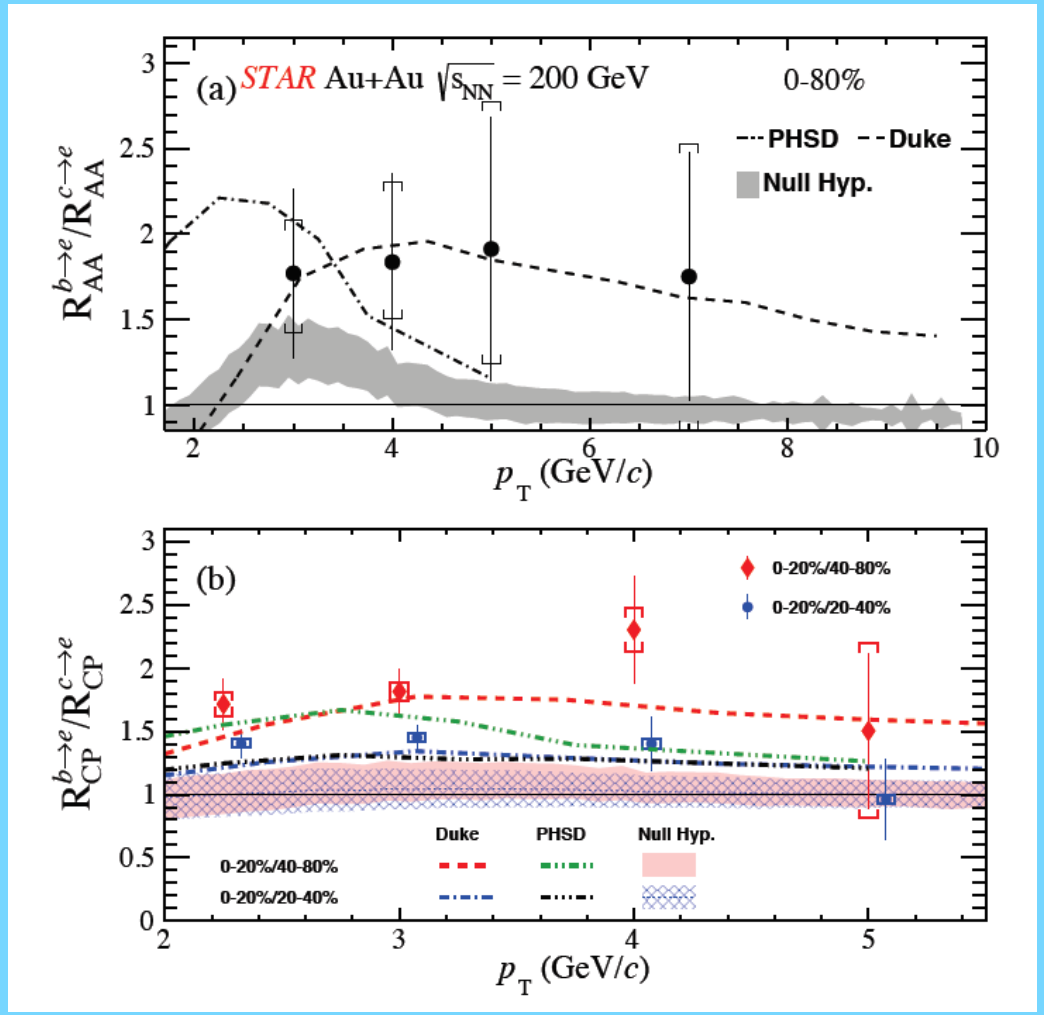
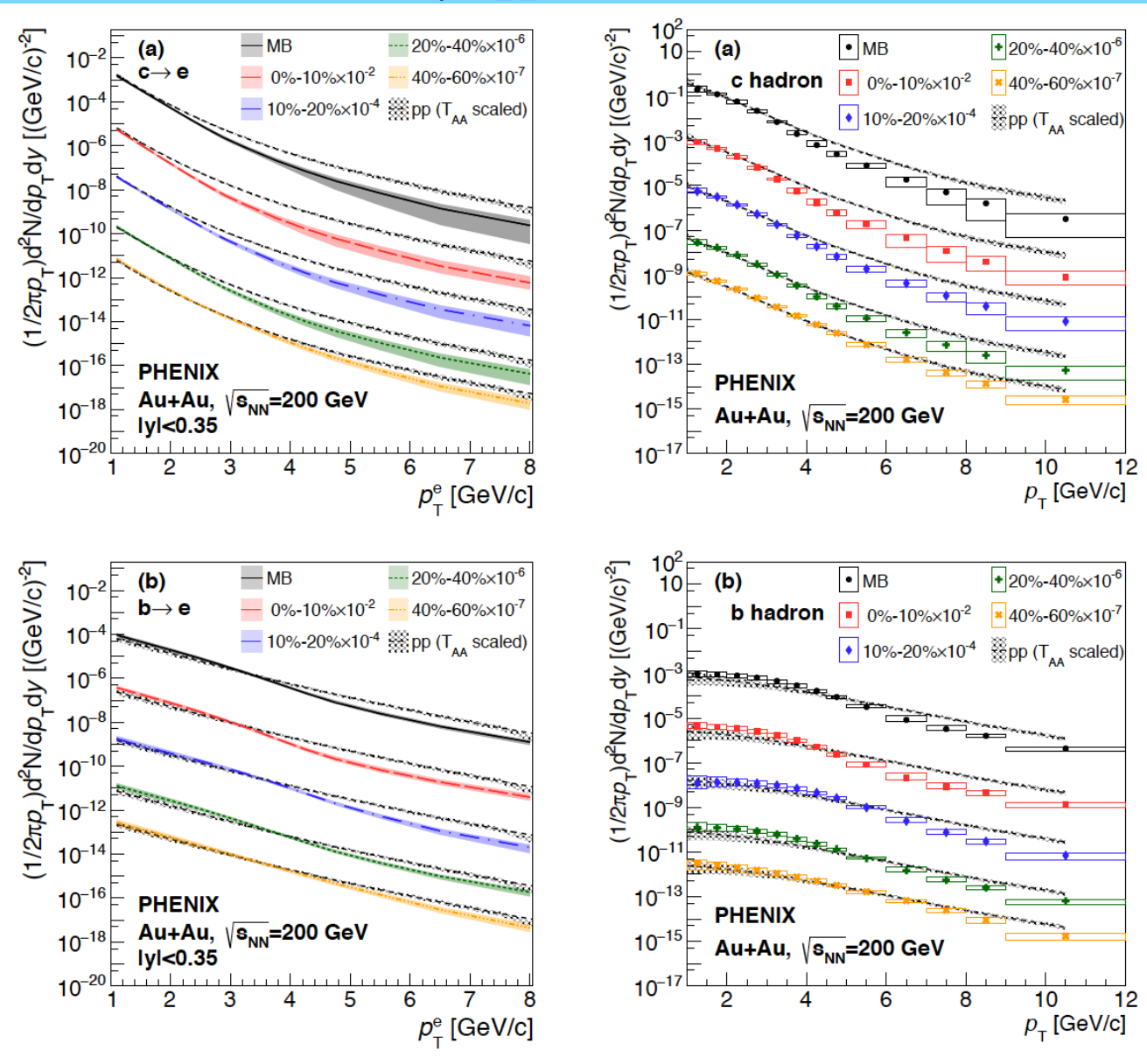
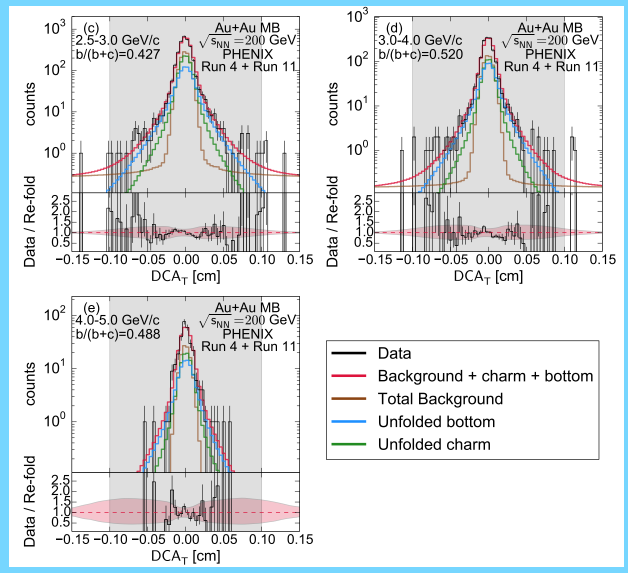


* **b to c R(AA) consistent with null hypothesis in pT=2.5-4.5 GeV**
* **b to c R(CP) of (0-20%/40-80%) and R(CP)(0-20%/20-40%) reject the null hypothesis at 4.2 and 3.3 standard deviations respectively.**
* **b to c R(AA) and R(CP) can be reproduced by both models suggesting the mass ordering of parton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

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



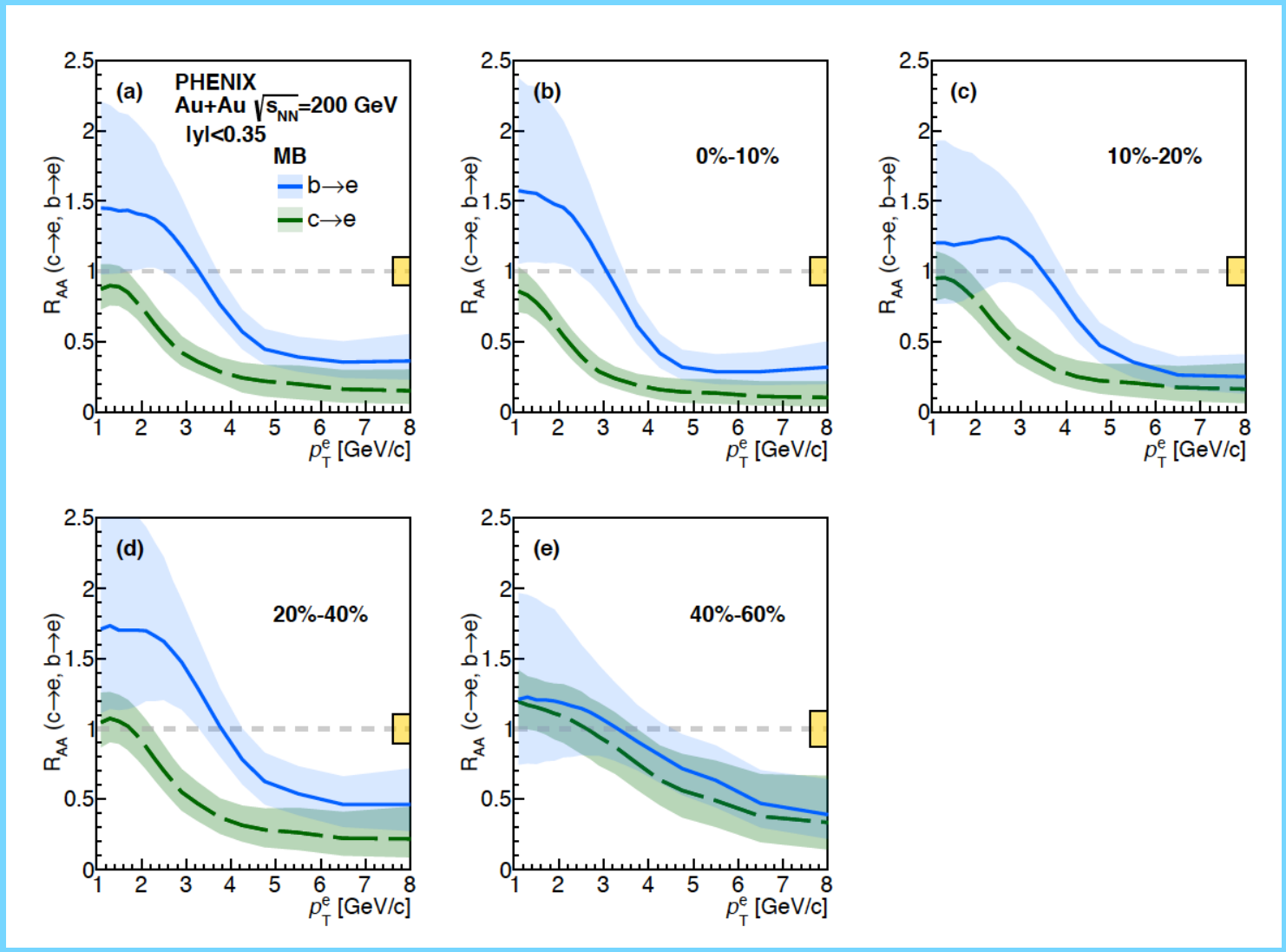


* Left c—> e and b—> e in Au +Au compared to p+p scaled by number of collisions

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

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

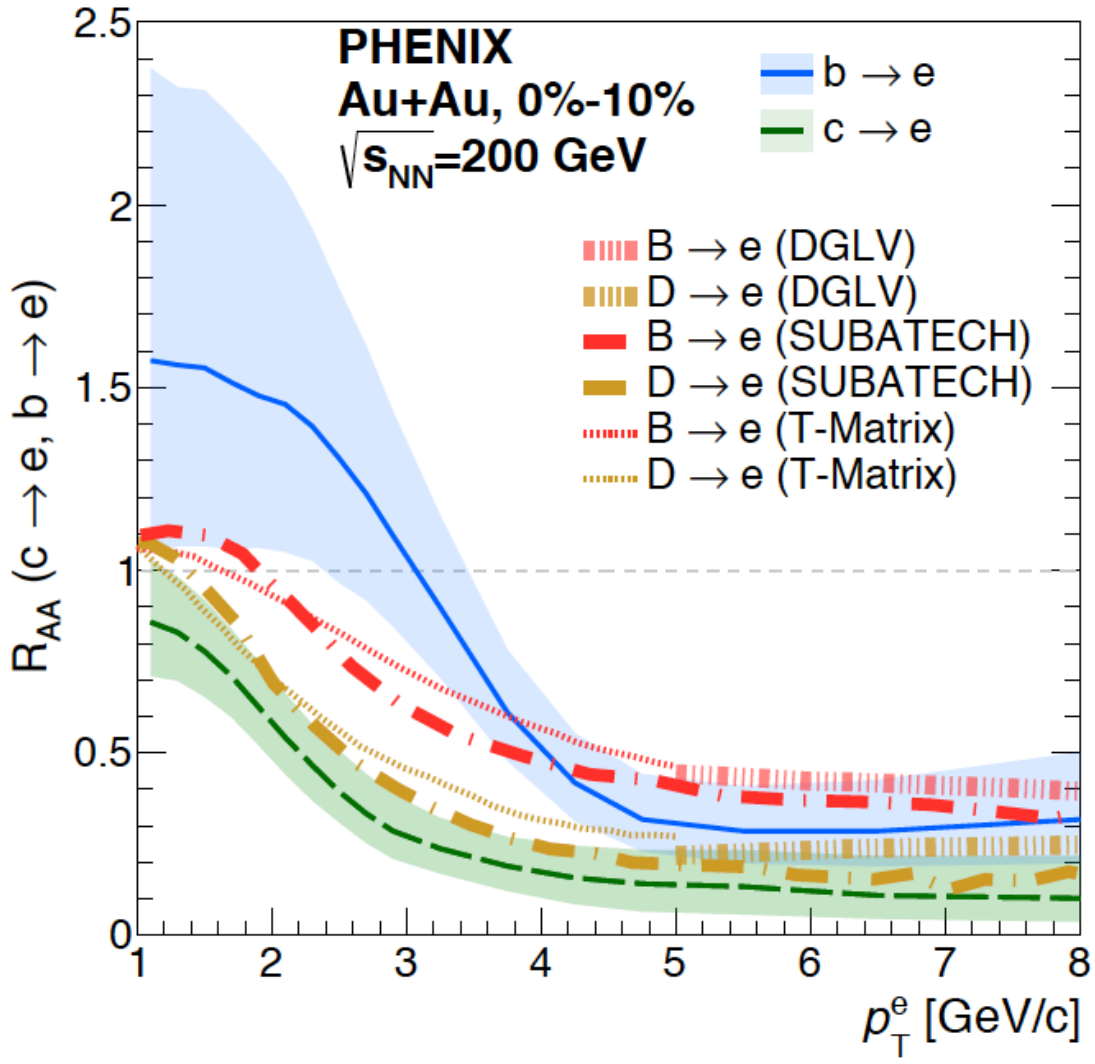
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058



* 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

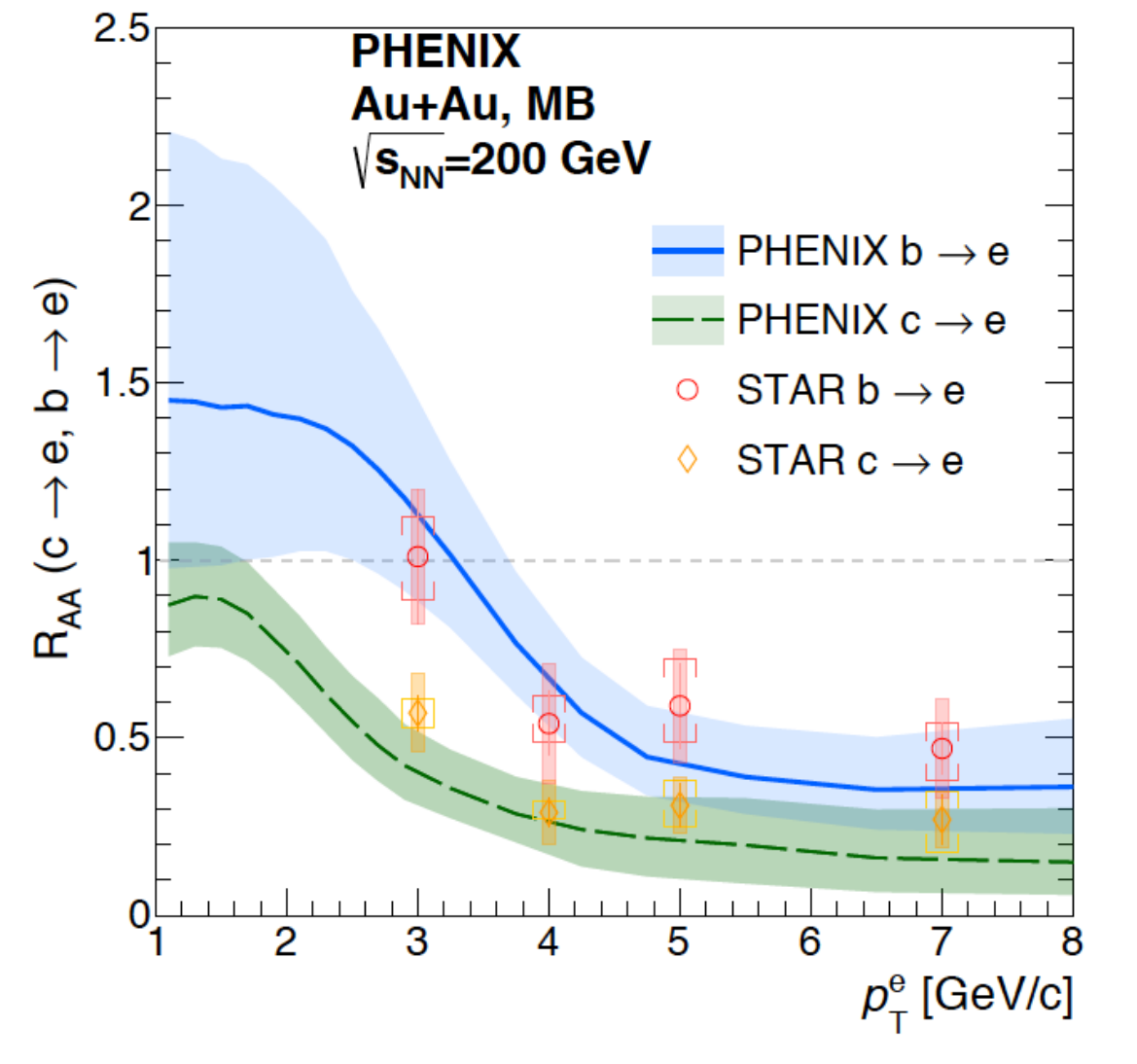
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058



* 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.

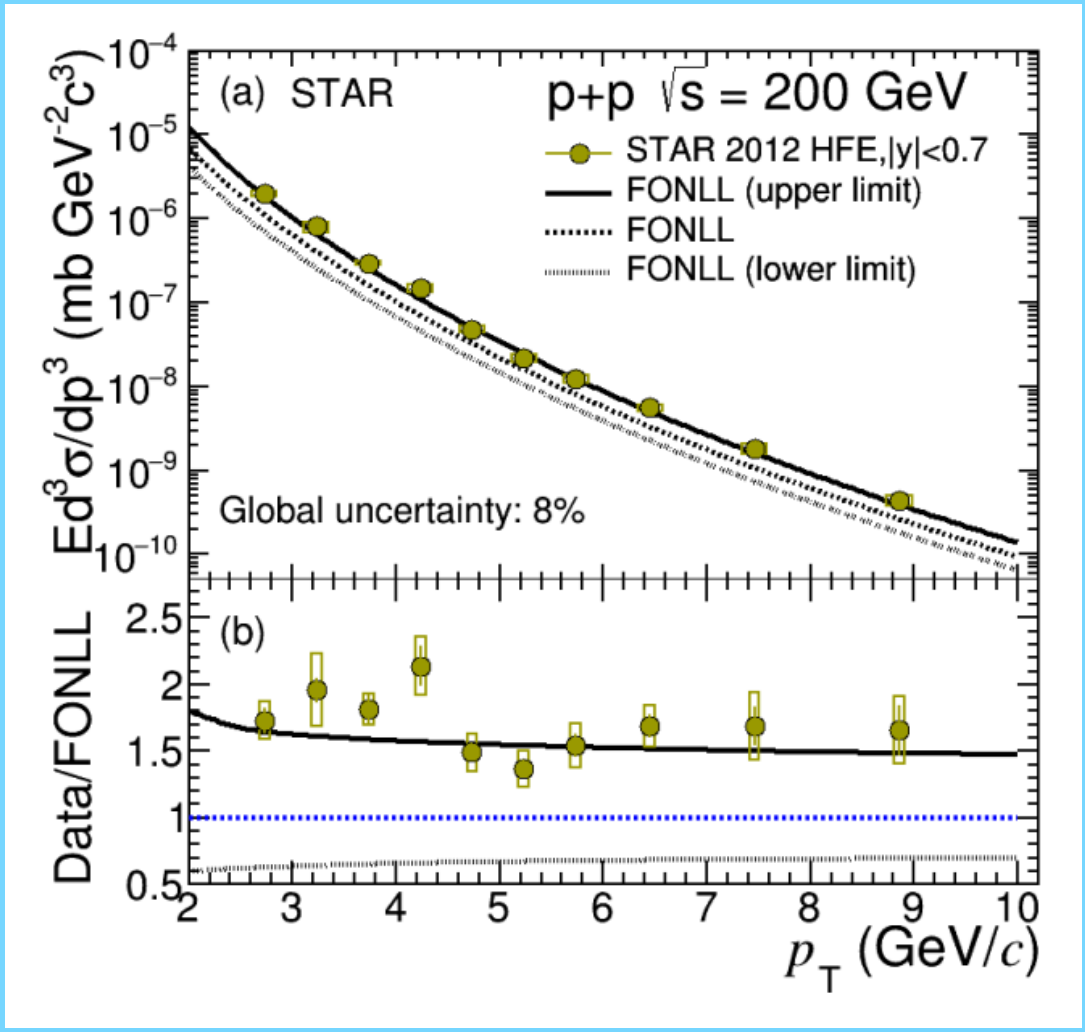
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058

* 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

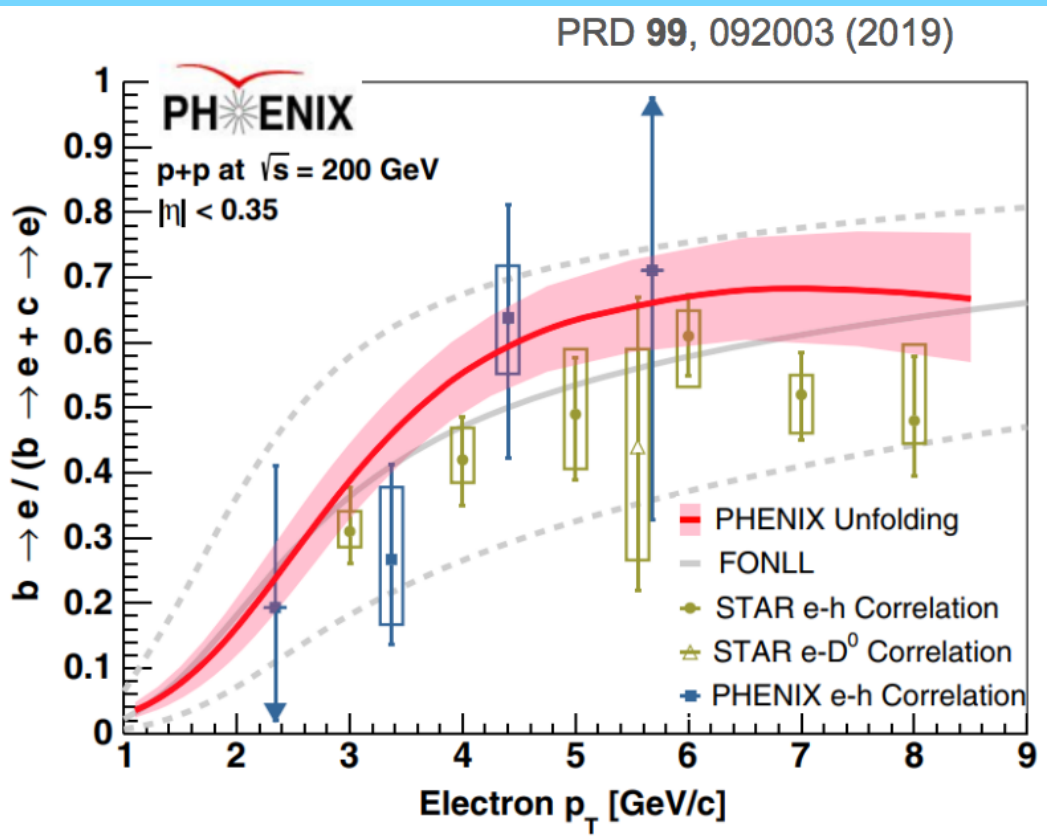
STAR (2022) Heavy Flavor -> electrons in p+p collisions at 200 GeV

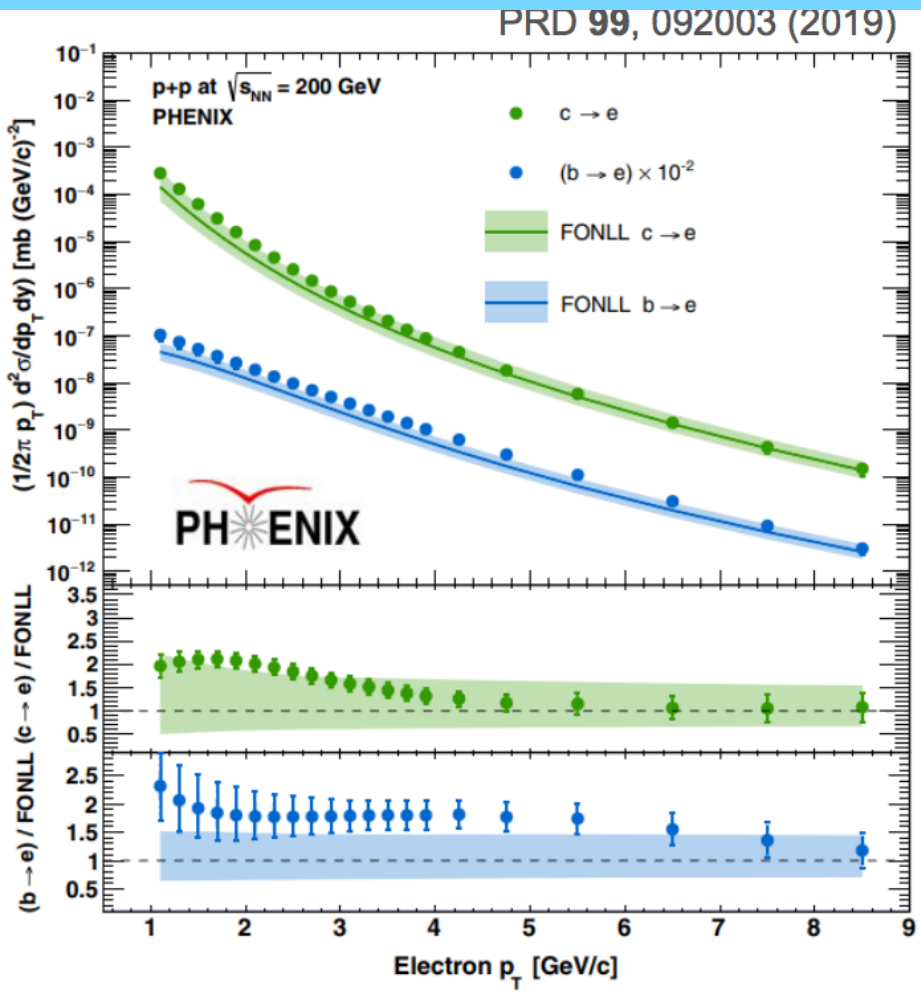
STAR Collaboration, Phys.Rev.D 105 (2022) 3, 032007, e-Print: 2109.13191 [nucl-ex]



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

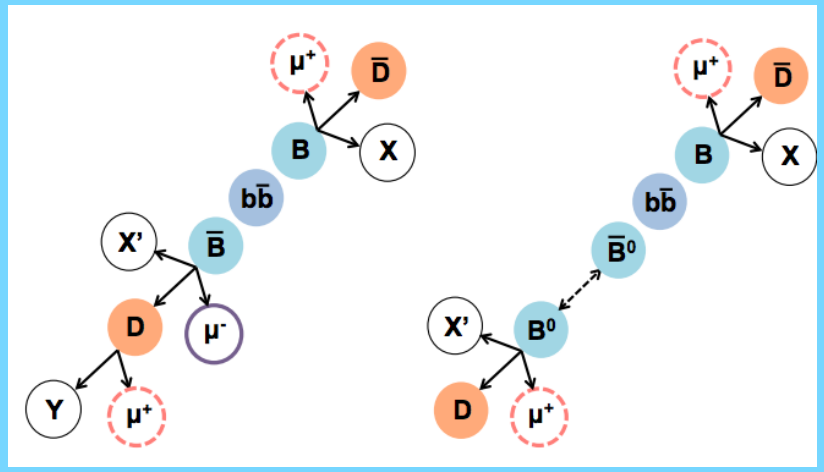
PHENIX (2019) new p+p baseline available for c and b

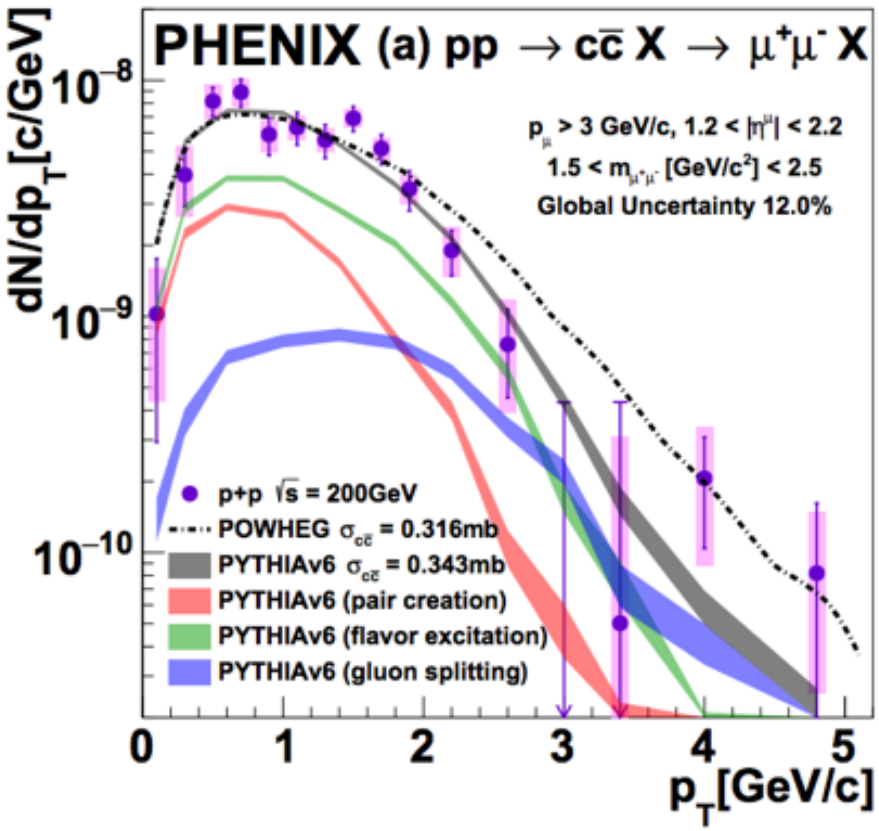


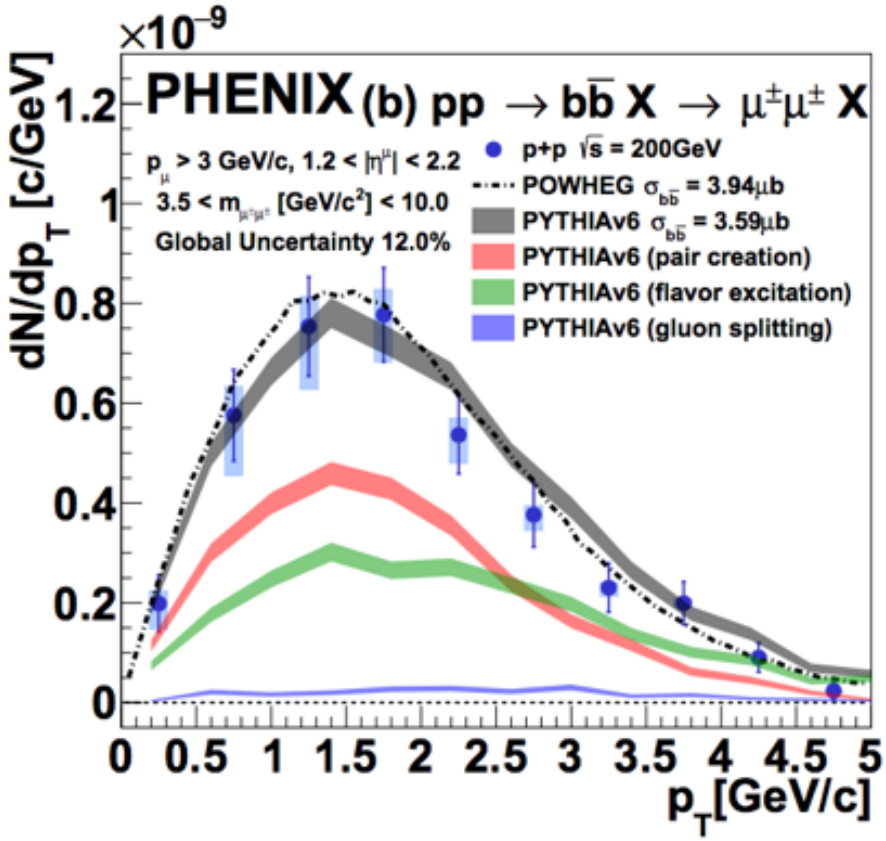


PHENIX (2019) c and b to mumu in p+p collisions 200 GeV

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]

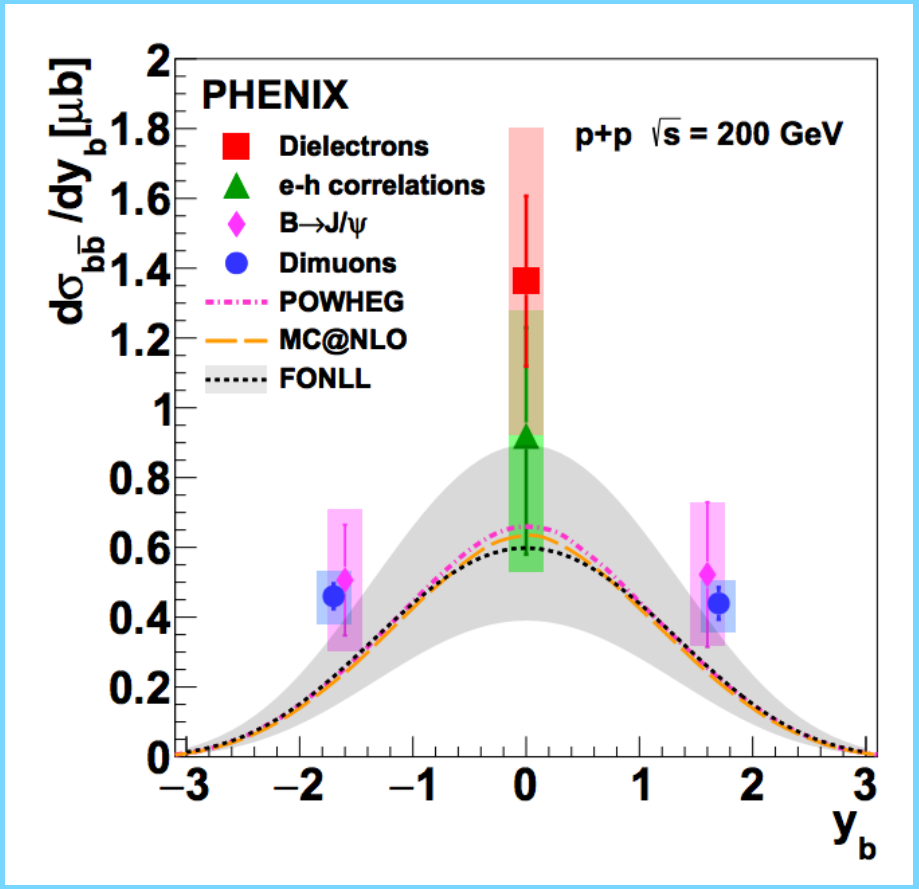


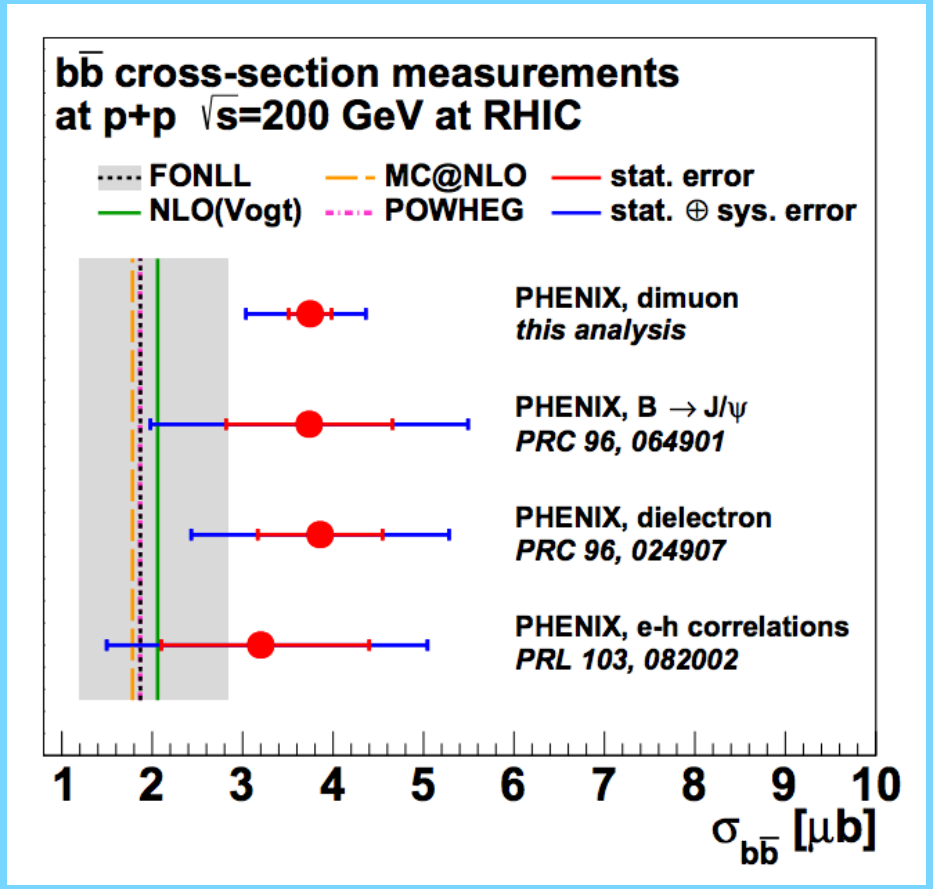




PHENIX (2019) bottom in p+p colisions at 200 GeV

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]





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

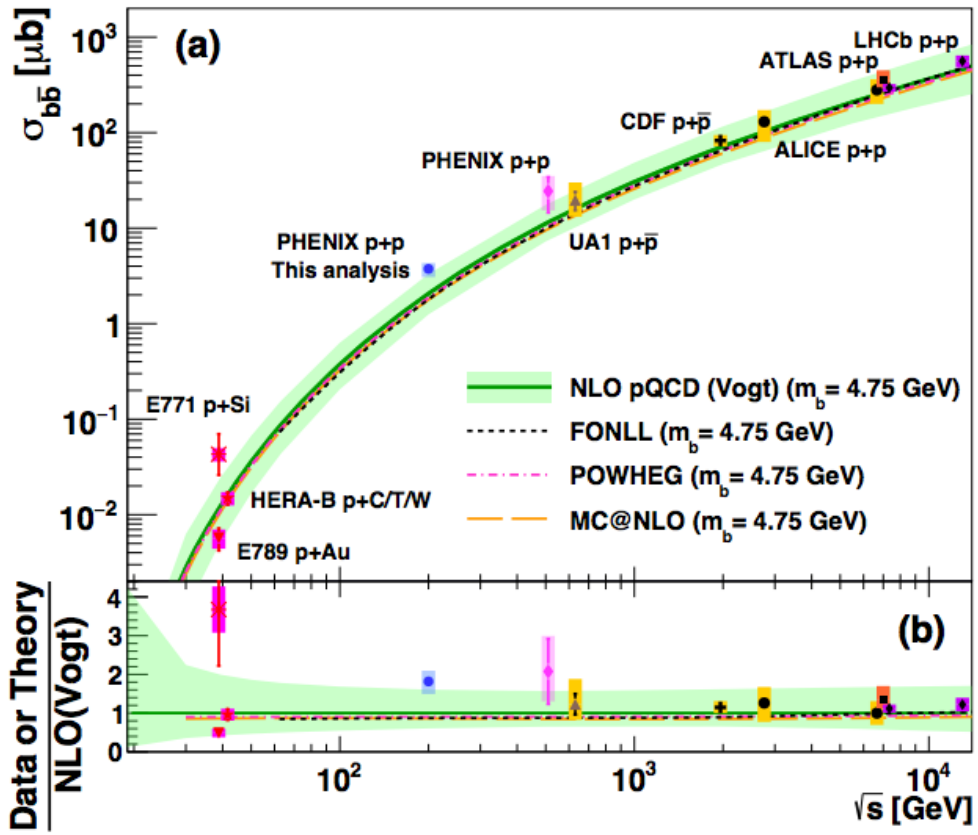


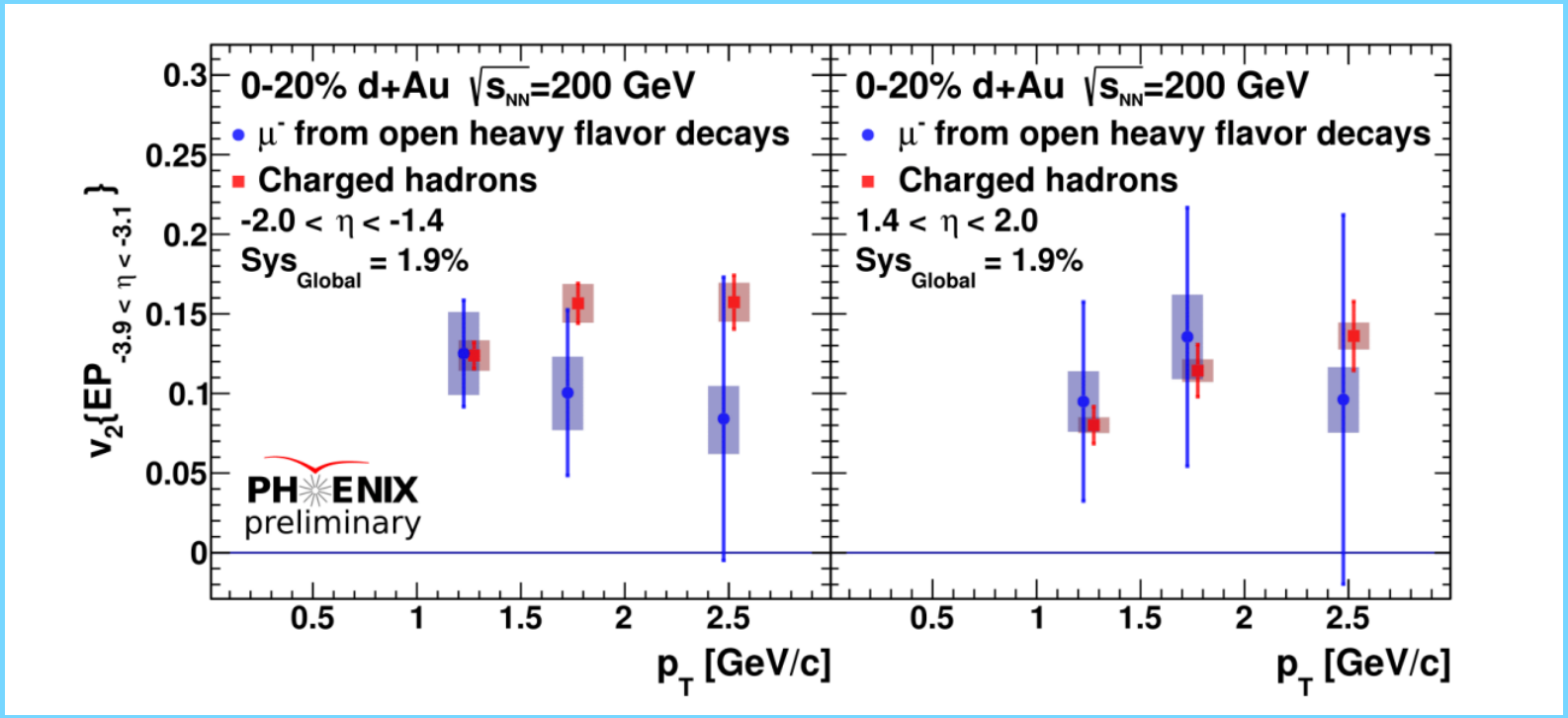
FIG. 29. Bottom cross section $\sigma_{b\bar{b}}$ as a function of $\sqrt{s}$. Uncertainties due to rapidity extrapolation are not included in the LHCb measurements. Measured cross sections are compared to NLL and NLO calculations.

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

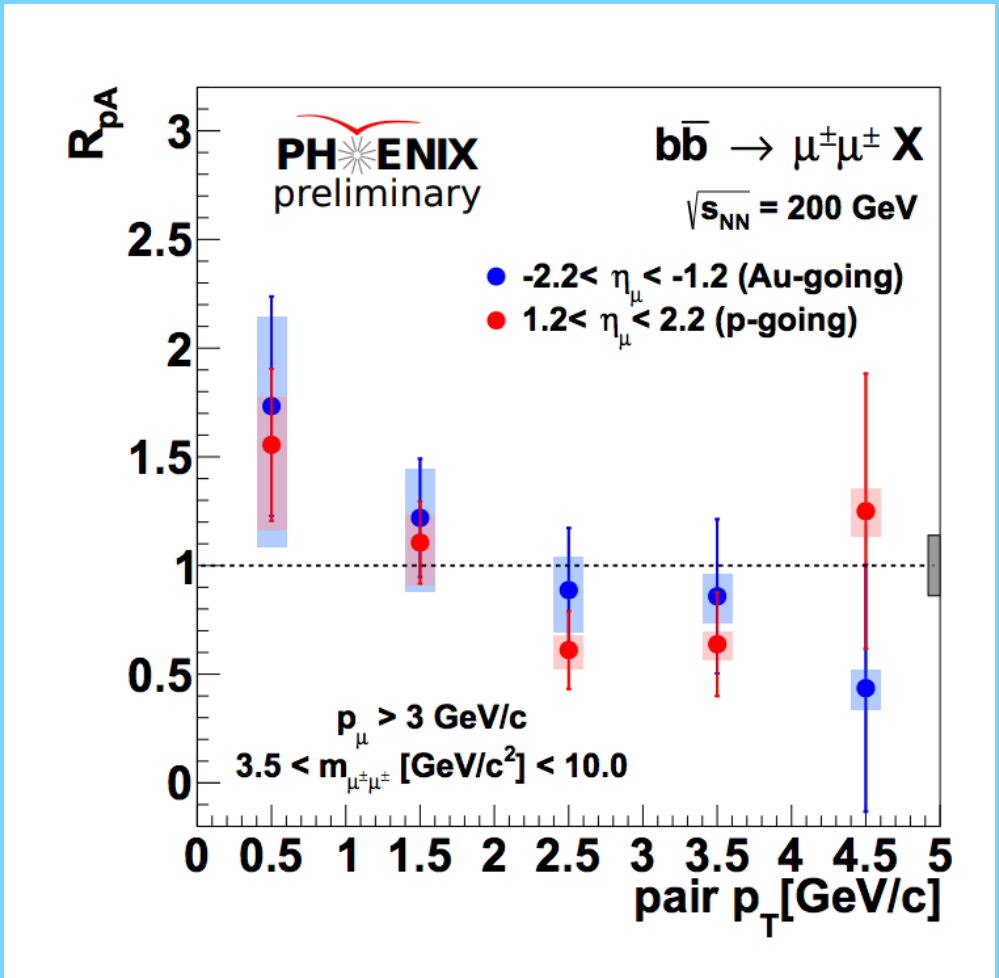
C. Aidala et al. (PHENIX collaboration), Phys. Rev. C 96, 064905 (2017).



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

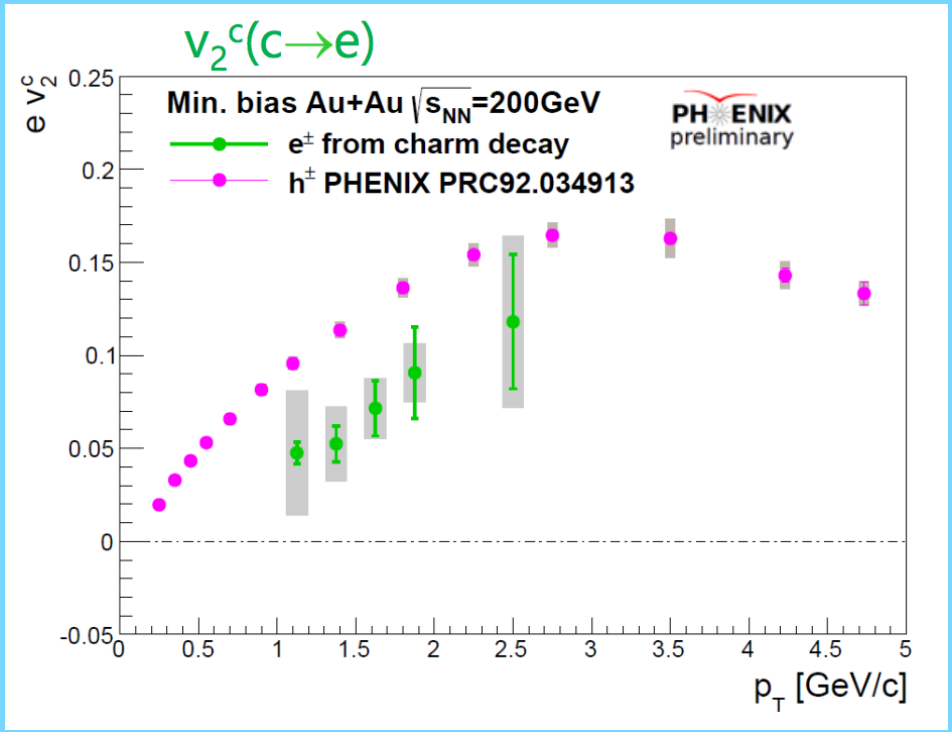
PHENIX(2018) R(pAu) of bottom to dimuons in p +Au collisions at 200 GeV

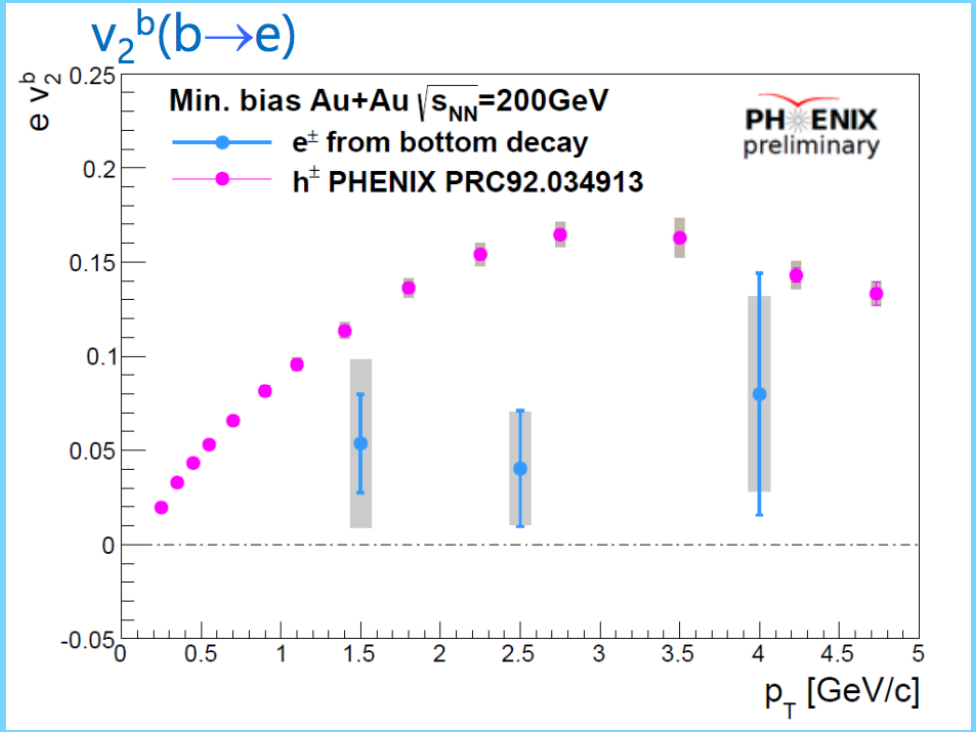
Xuan Li et al, PHENIX Collaboration, https://arxiv.org/pdf/1809.09247.pdf



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



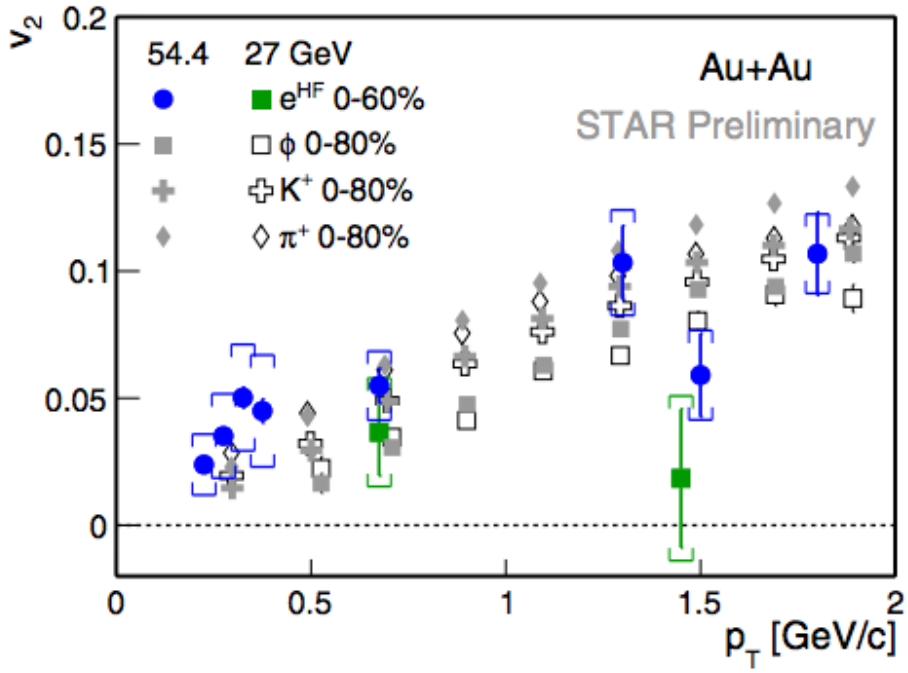


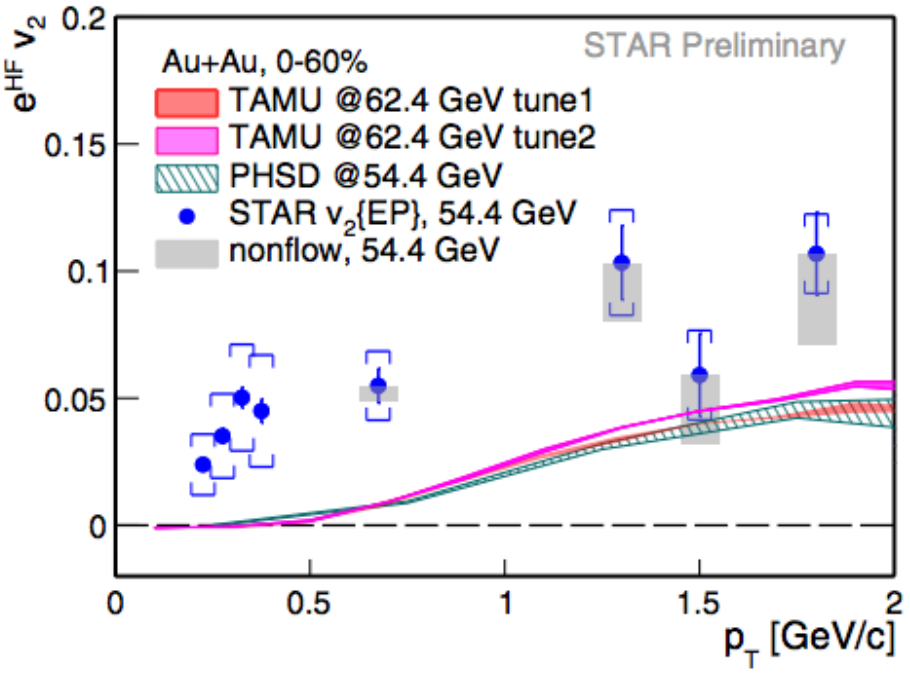
T Hachiya et al, PHENIX collaboration, QM2022

* 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





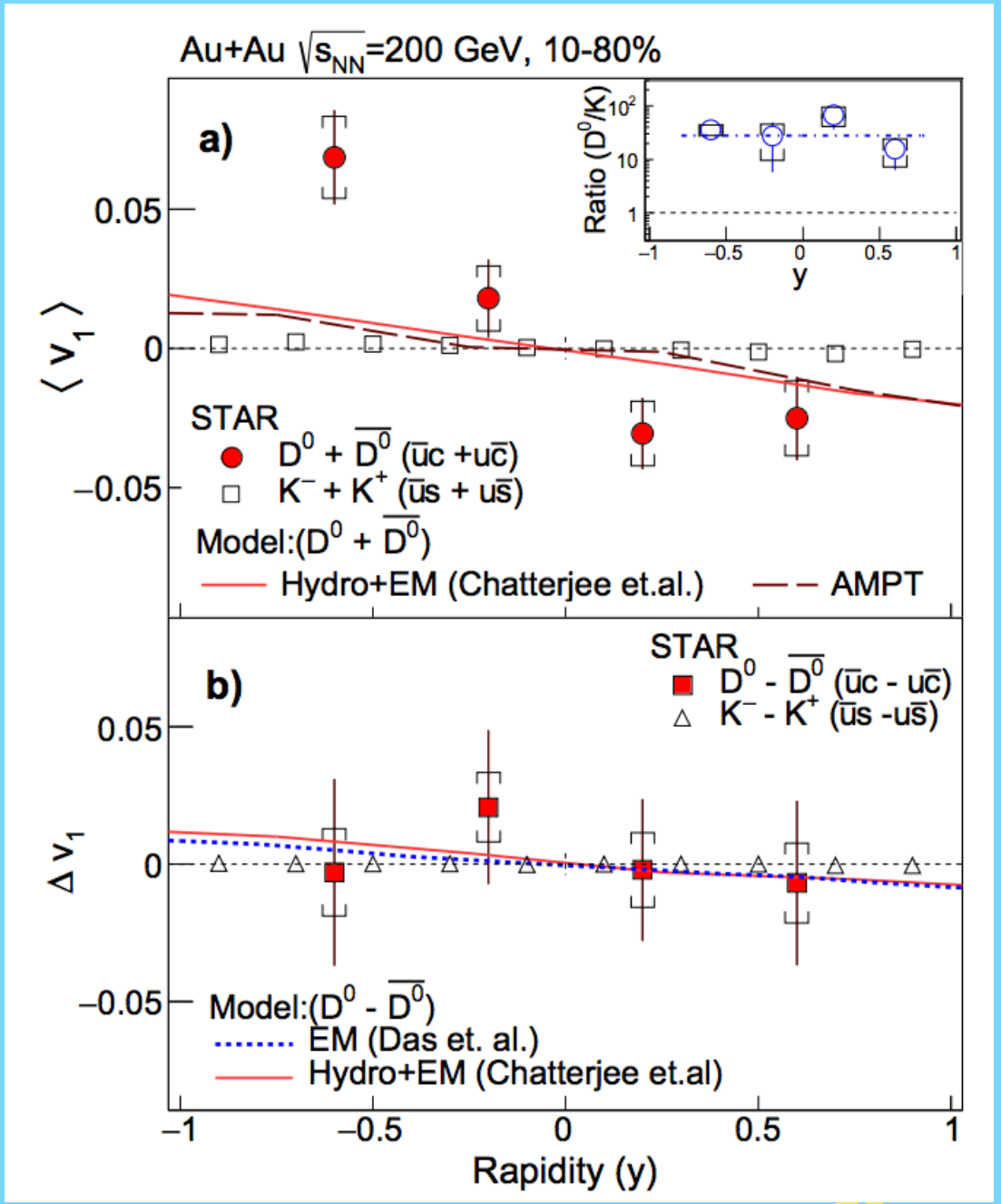
* The elliptic flow of heavy flavor electrons in Au+Au collisions at 54.4 GeV is comparable to 200 GeV, indicating strong charm quark interactions with the medium

STAR (2019) First measurement of directed flow of D^0 and D^0-bar

STAR Collaboration, PRL 123 (2019) 16, 162301

* Directed flow of D^0 and D^0-bar in Au+Au collisions at 200 GeV is a factor of 25 higher than that for charged kaons

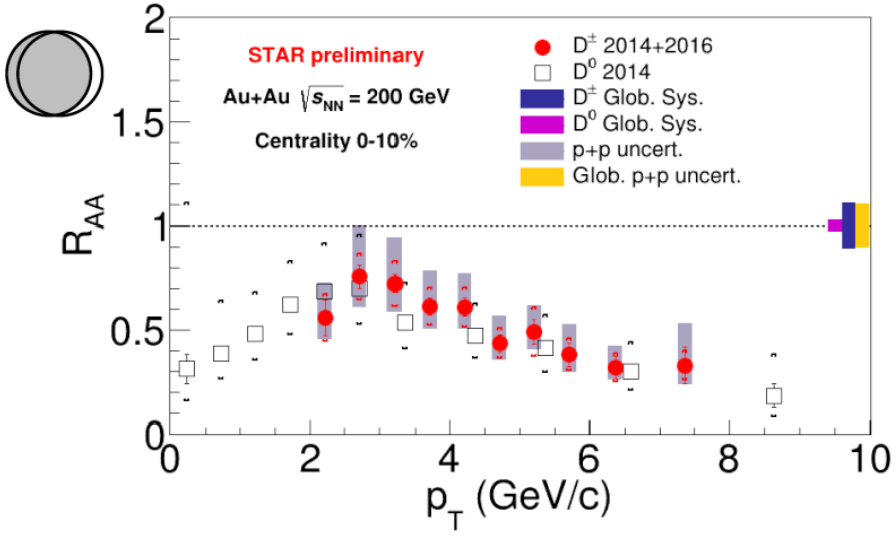
* The results are qualitatively described by a hydrodynamic model with an initially tilted QGP source and EM field, and the AMPT model

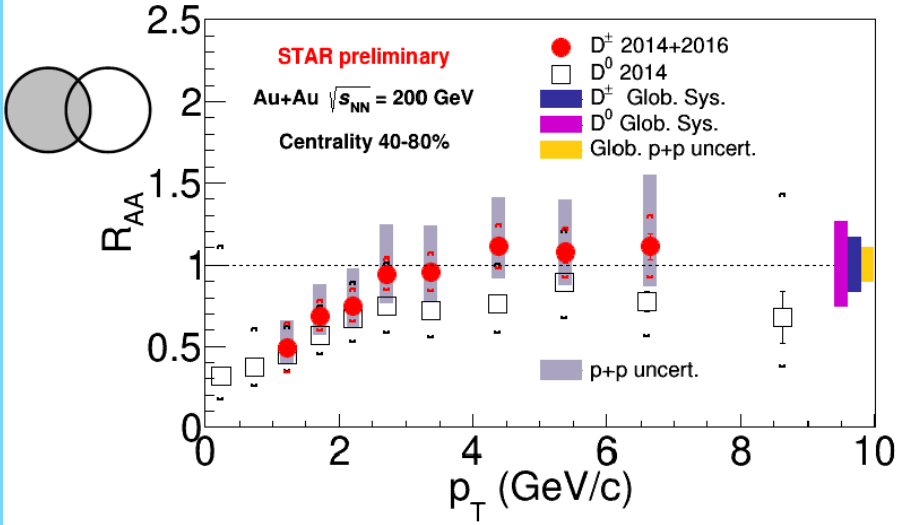


Charmed hadrons in Au+Au collisions

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

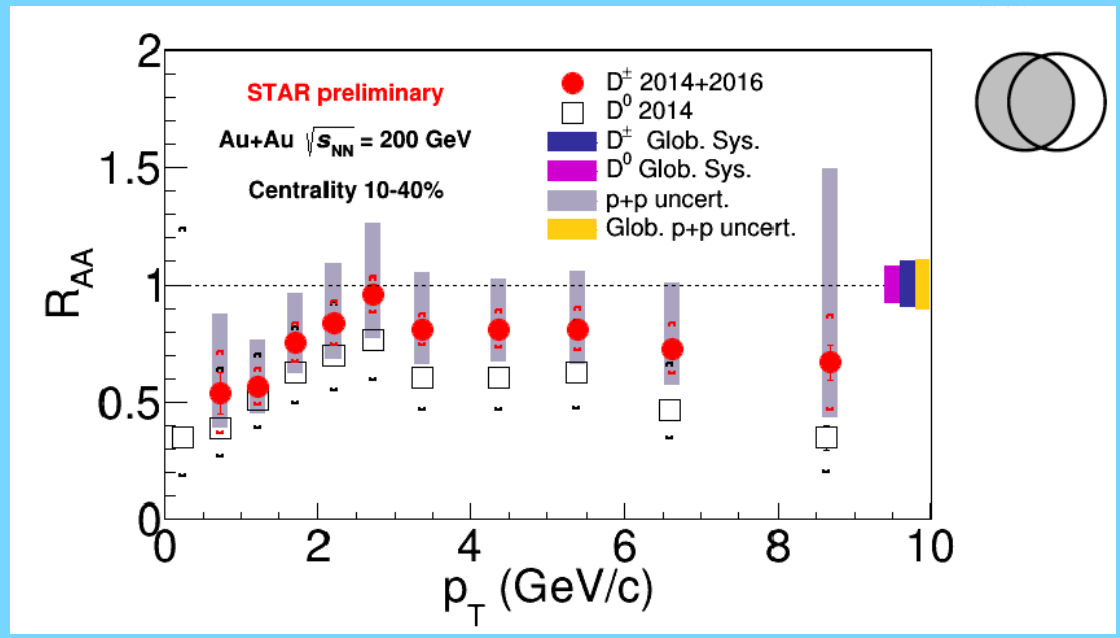
J. Vanek et al, STAR Collaboration, QM2022





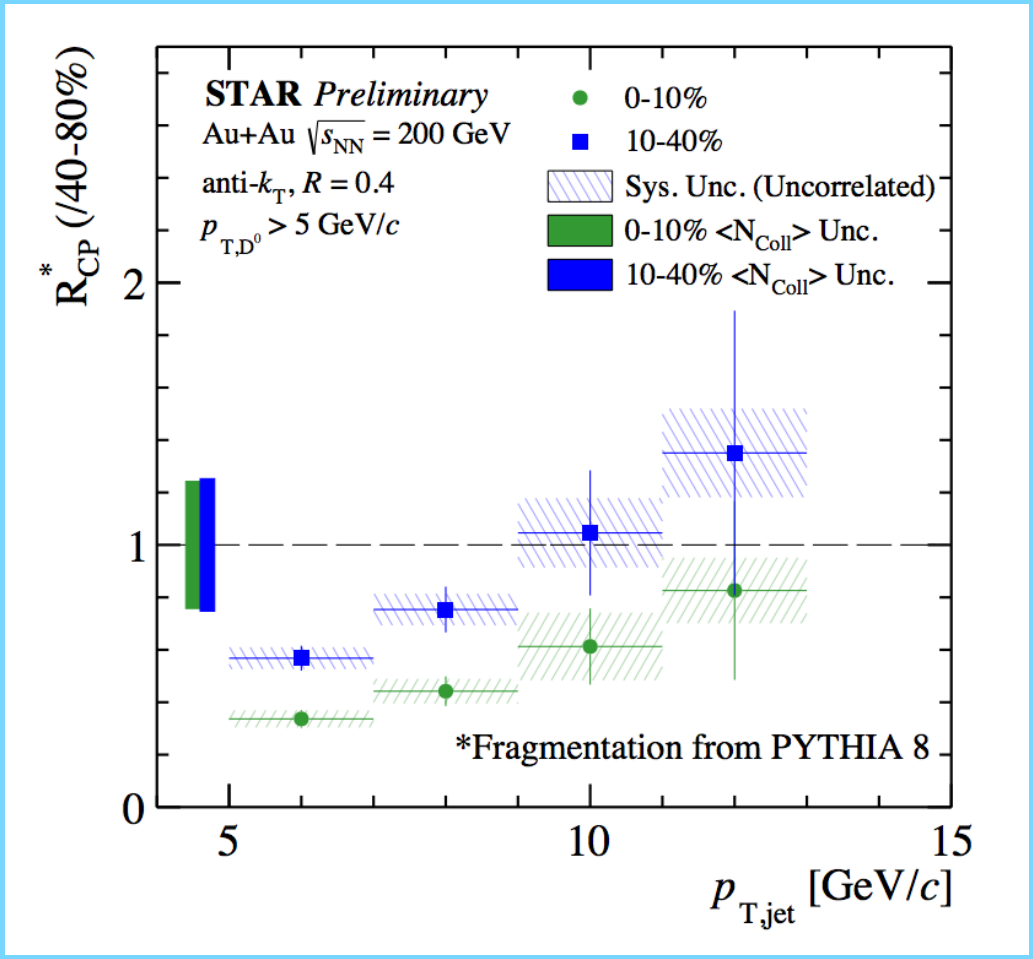
p+p reference (STAR): Phys. Rev. D 86, 072013, (2012)
D^0 (STAR): Phys. Rev. C 99, 034908, (2019).

Jan Vanek, QM 2022



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

First measurement of D_0-tagged jets at RHIC

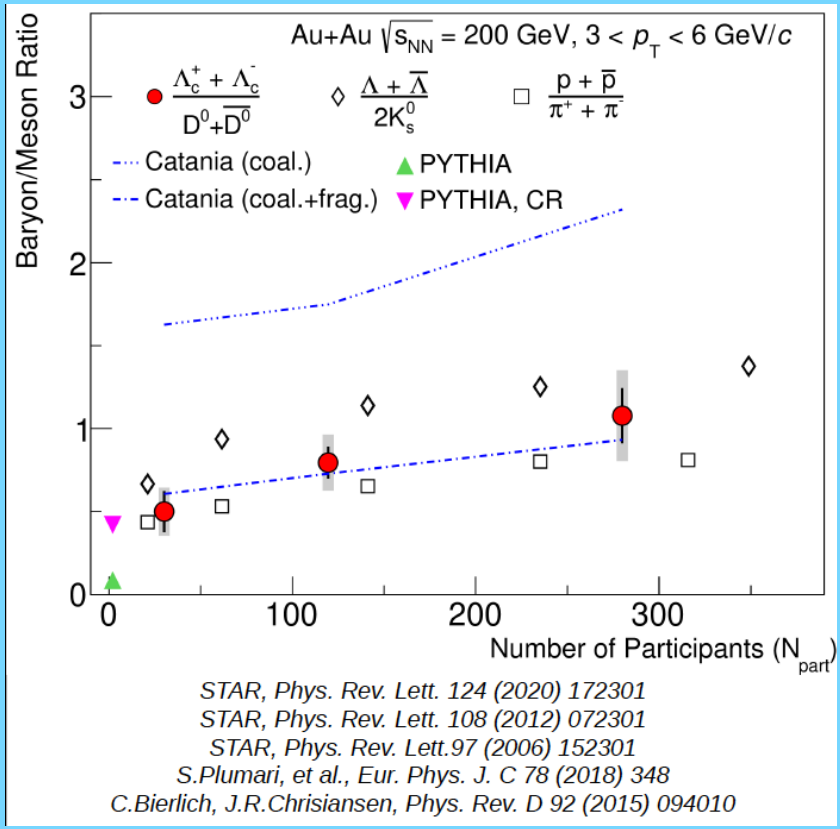


Niida et al, STAR Collaboration, AUM2022

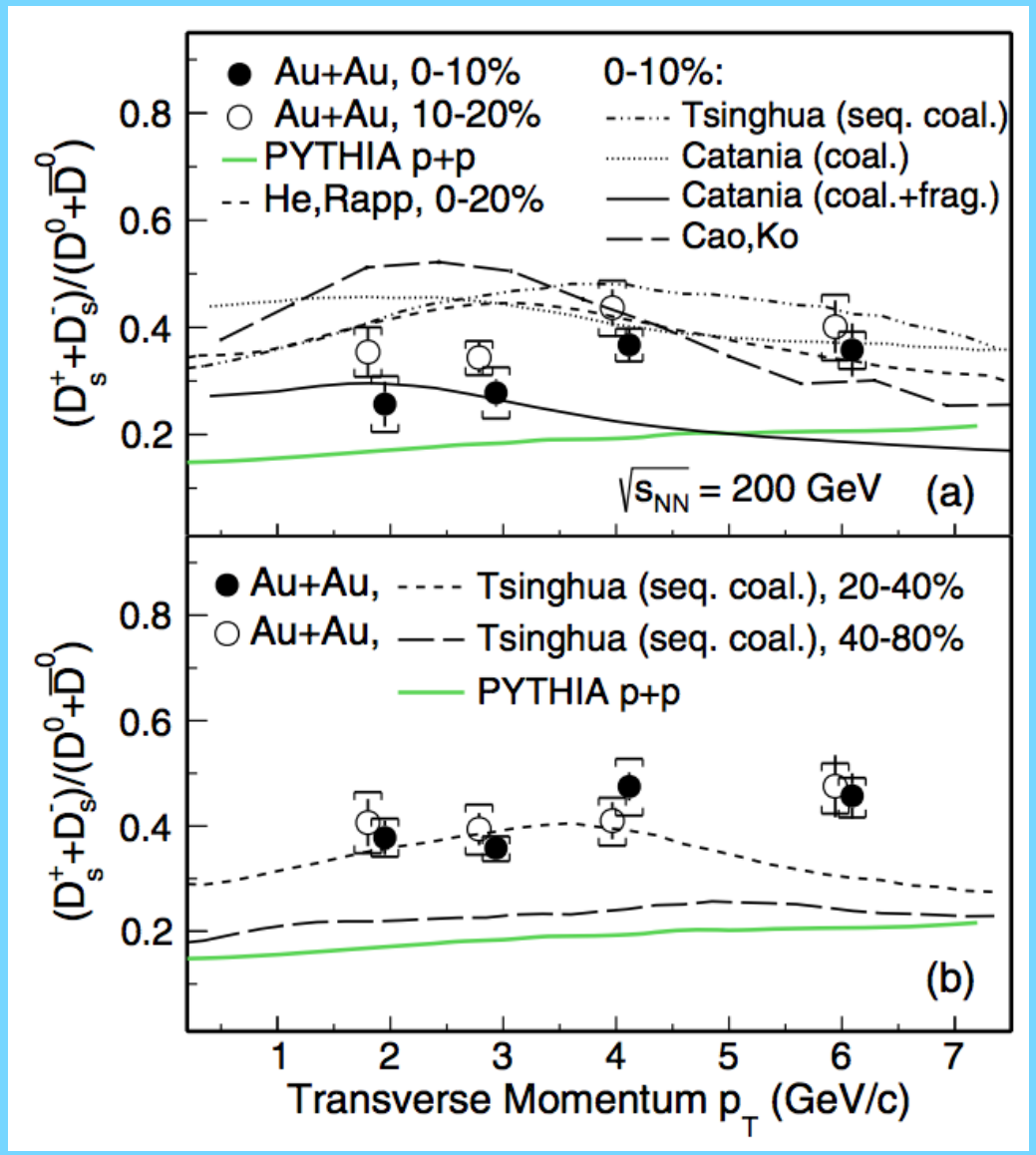
* R(CP) shows suppression at $p_T < 9$ to 11 GeV for 10-40% and 0-10% respectively

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

STAR Total charm 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]	$39 \pm 1 \pm 1$
	$D^{\pm}$	$18 \pm 1 \pm 3^{*}$
	D_s [2]	$15 \pm 2 \pm 4$
	Λ_c [3]	$40 \pm 6 \pm 27^{**}$
	Total	$112 \pm 6 \pm 27$
p+p at 200 GeV [4]	**Total**	$130 \pm 30 \pm 26$

D^0 [1] STAR, Phys. Rev. C 99 (2019) 034908
D_s [2] STAR, Phys. Rev. Lett. 127 (2021) 092301
Λ_c [3]STAR, Phys. Rev. Lett. 124 (2020) 172301
p+p [4] STAR, Phys. Rev. D 86 (2012) 072013

* D^{+-} data : preliminary

* Total charm production cross section per binary NN collision in Au+Au collisions, is consistent with that in p+p collisions within uncertainties

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 suggest strong interaction of heavy quarks with medium

* First measurement of D_0-tagged jets R(AA) at RHIC and suppression observed

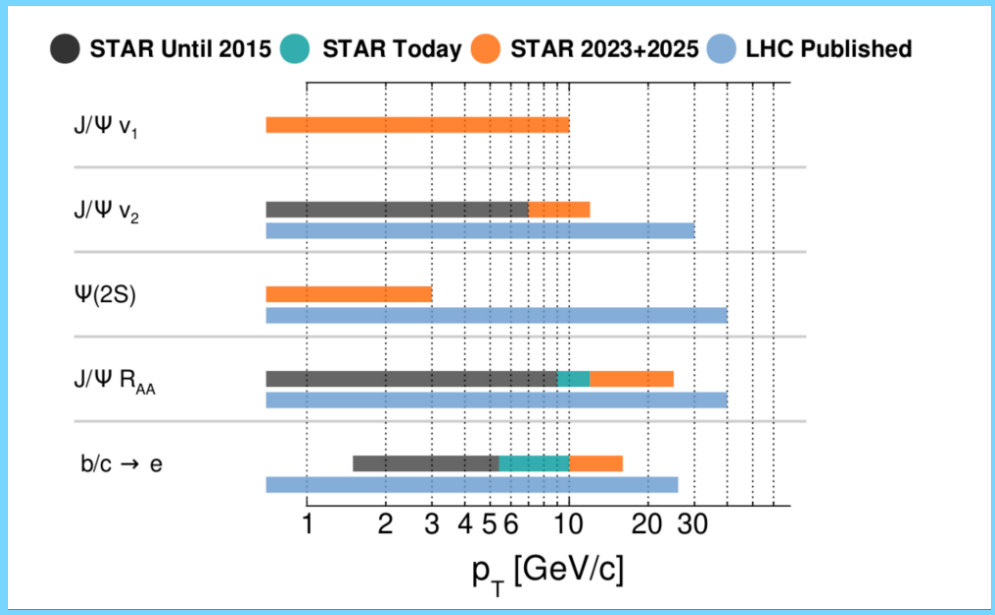
* Total charm production cross section per binary N+N collision measured in Au +Au collisions at 200 GeV is consistent with p+p collisions at 200 GeV within uncertainties

Outlook

STAR and PHENIX 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}

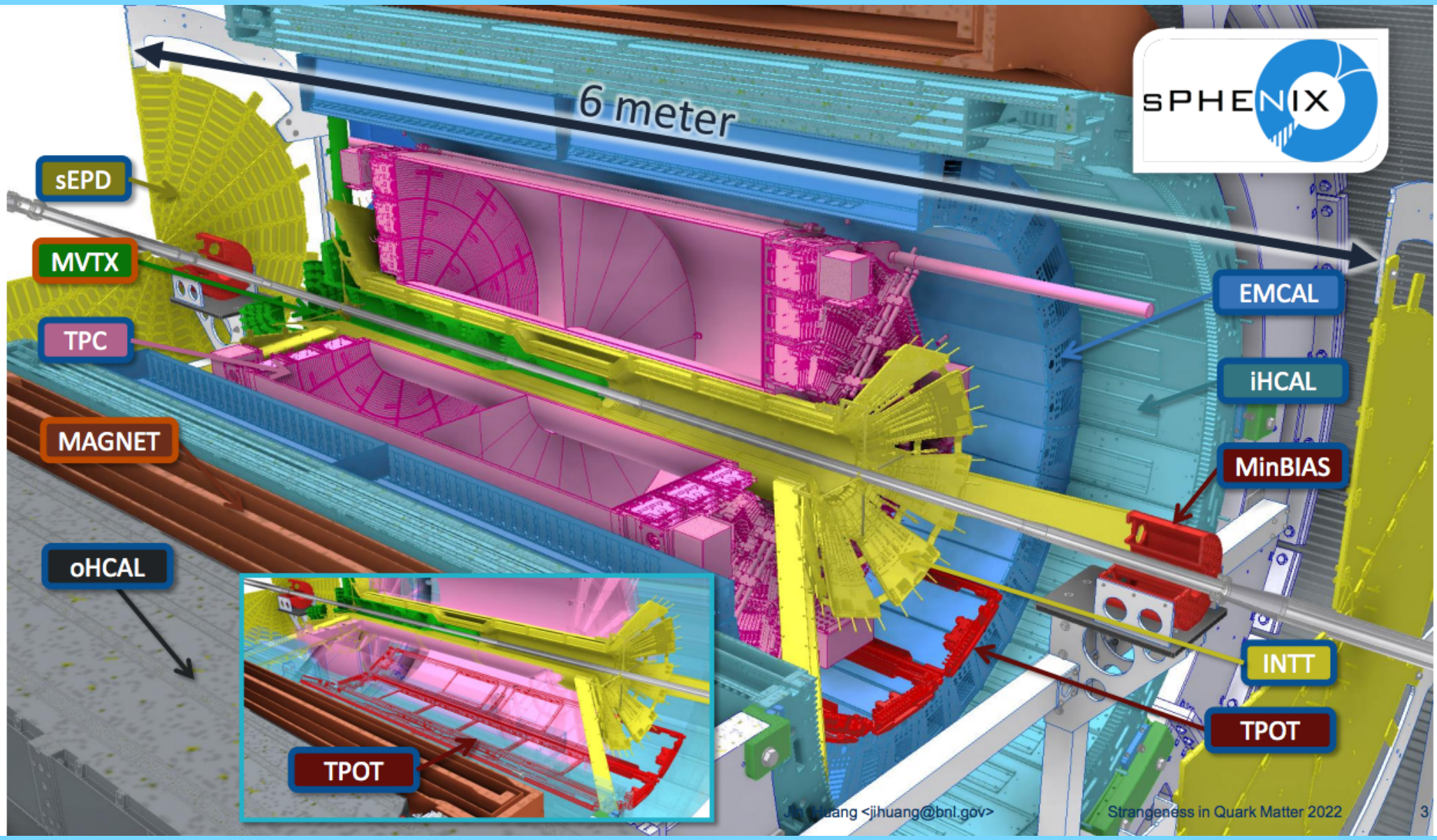


*** STAR: Future data will extend the kinematic range for open heavy flavor hadron measurements via semileptonic decays**

*** 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)**

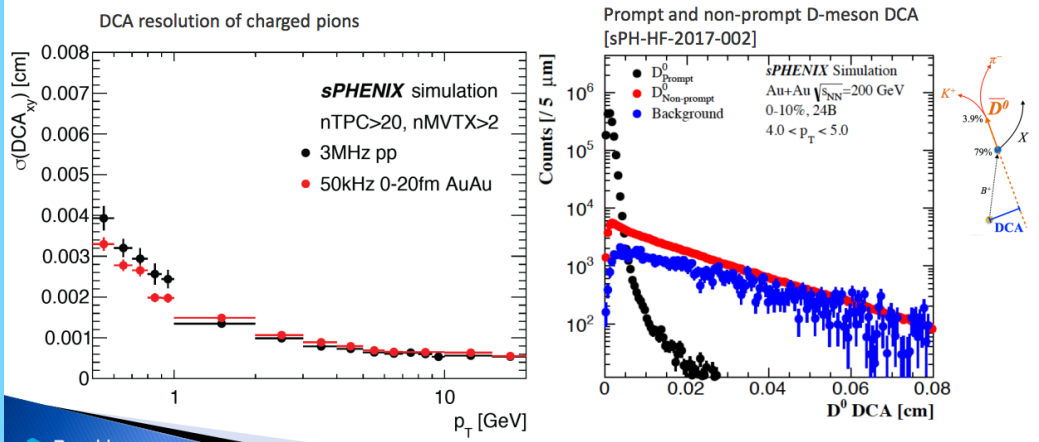
sPHENIX


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

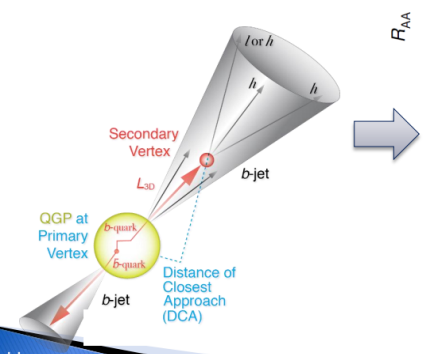
Exceptional performances expected for open heavy flavor

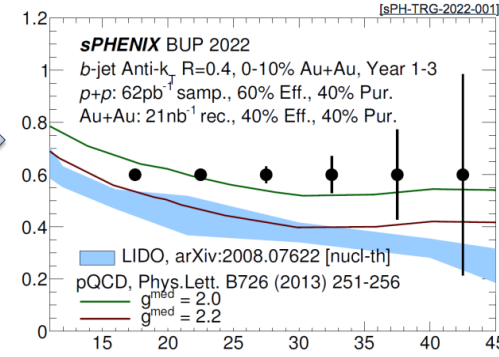
Cleanly separate open bottom meson via DCA



Higher p_T: bottom quark via b-jet

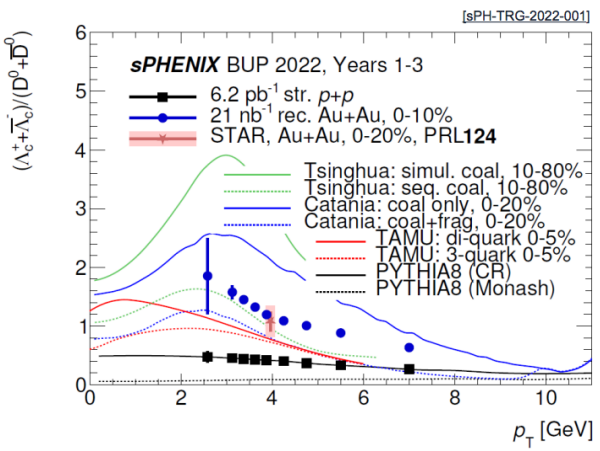
- New for RHIC, enabled by precision tracking and full calorimetric jet





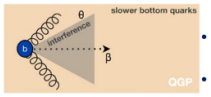
News from beam use proposal 2020 – hadronization

- 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

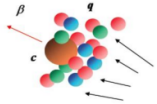


Access b-quark suppression/v2 via non-prompt D

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

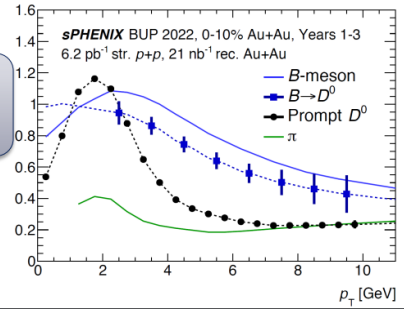


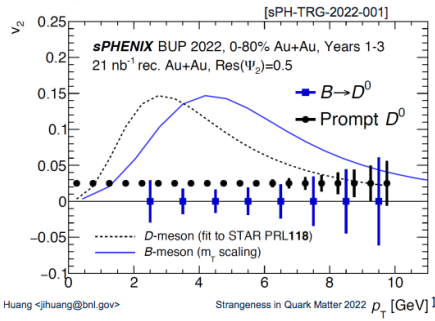
- Probe the mass dependence of quark energy loss in QGP, light → c → b
- Sensitive to pick up collision energy loss



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

$p+p$ baseline uniquely enabled by streaming data





Thank you very much