Open Heavy Flavor and Quarkonia production in heavy ion collisions at RHIC

Sonia Kabana (Universidad de Tarapaca, Chile)

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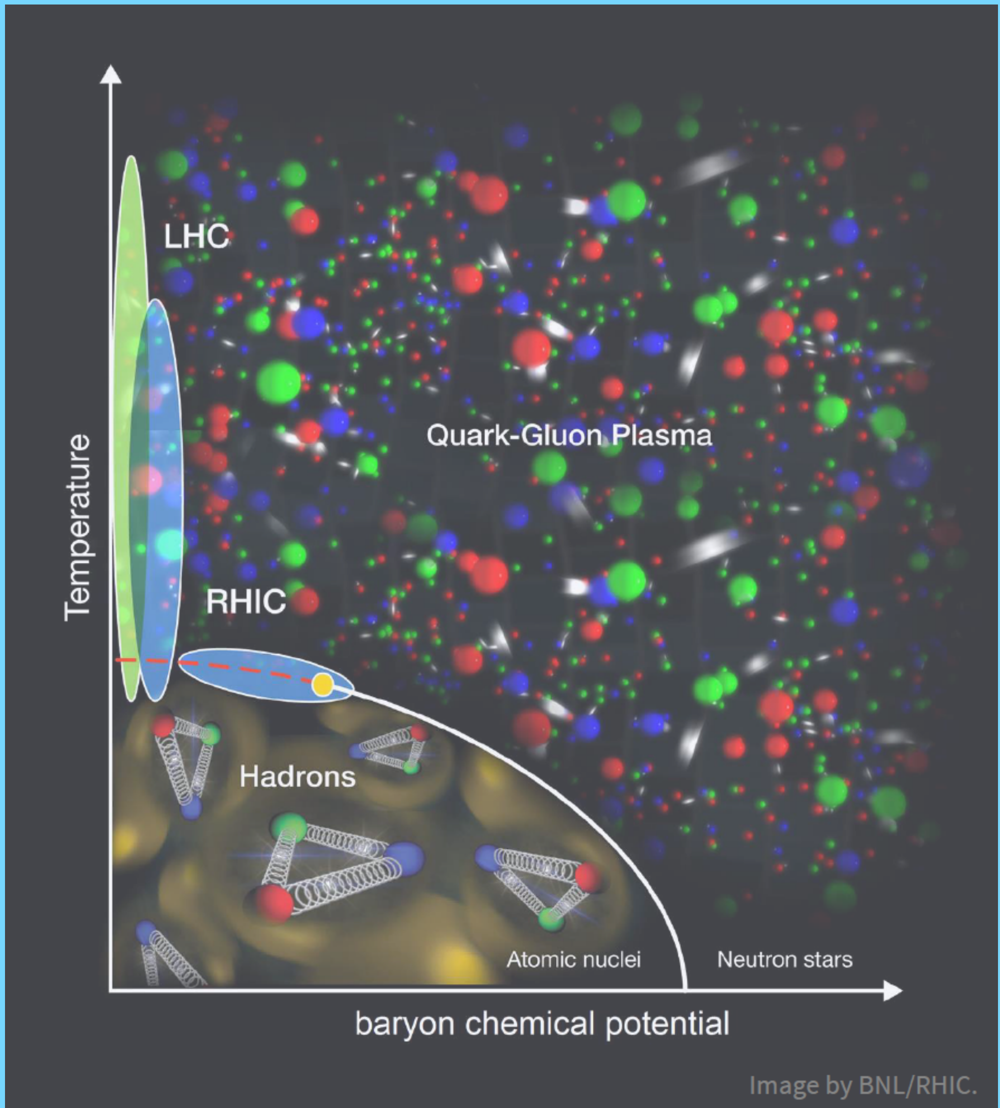
Outline

* Introduction
* Open heavy flavor
* Quarkonia
* Conclusions and outlook

* Introduction

Introduction
The QCD phase diagram



Phases of QCD Matter

Areas of different net baryon densities and temperatures can be probed using different collision energies and nuclei.

The order of the transition is expected to change with the net baryon density.

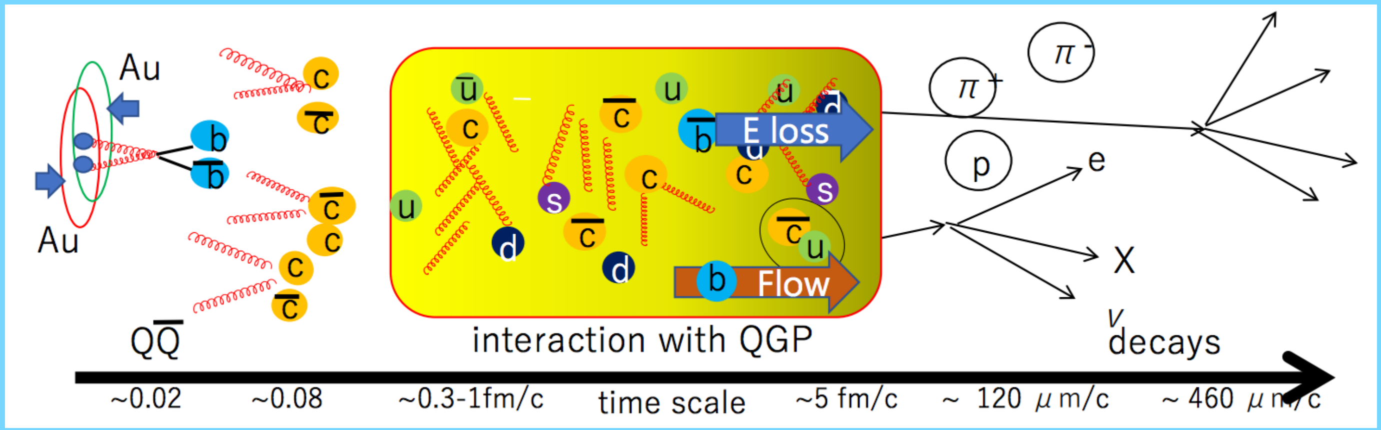
Goal: explore experimentally the QCD phase diagram (order of transition, critical point, properties of the QGP).

Open and hidden charm and beauty are an important tool in these studies

Introduction
Open Heavy Flavor

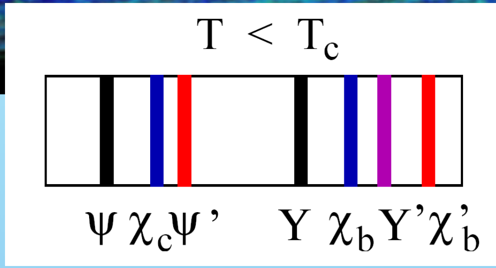
Charm and beauty (heavy flavor, HF) hadron production in ultrarelativistic heavy ion collisions are key observables for the study of sQGP :

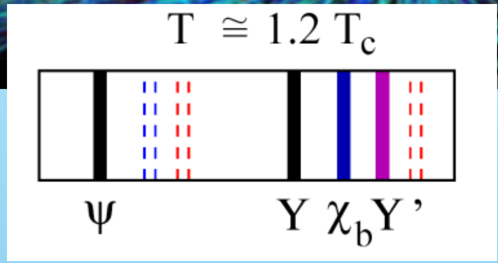
* Charm and beauty quarks are produced in initial hard scatterings and experience the entire evolution of A+A interactions
* Their masses are large compared with the thermal energy expected in heavy ion collisions
* The nuclear modification factors R_{AA} and R_{CP} of c and b can reveal imprints of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

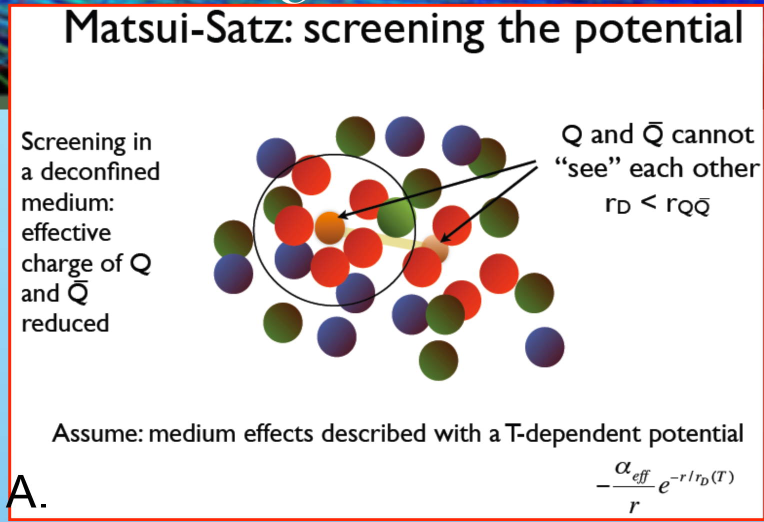


picture from T. Hachiya, PHENIX Collaboration, QM2022

Quarkonia suppression as QGP signature

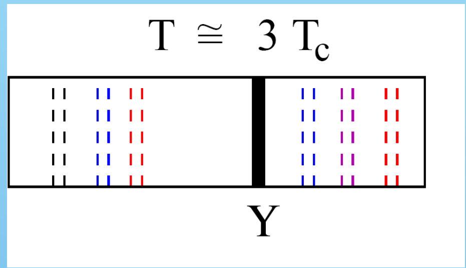




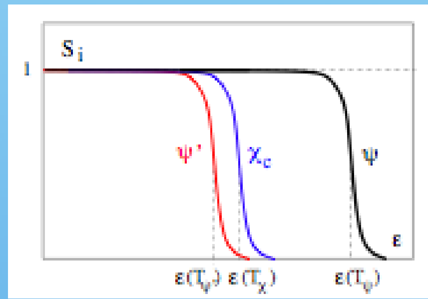


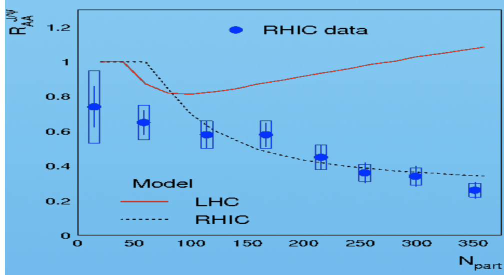
A.

H. Satz, Nucl. Phys. A (783): 249-260(2007)



state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.0	1.76	1.60	1.19	1.17





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, feeding, eg B mesons carry 10-25% of charmonia yields (B->J/Psi from J/Psi-h correlation STAR measurement)

Models: B. Kopeliovich et al, D. Kharzeev, E. Ferreiro, A. Capella, A. Kaidalov et al etc.

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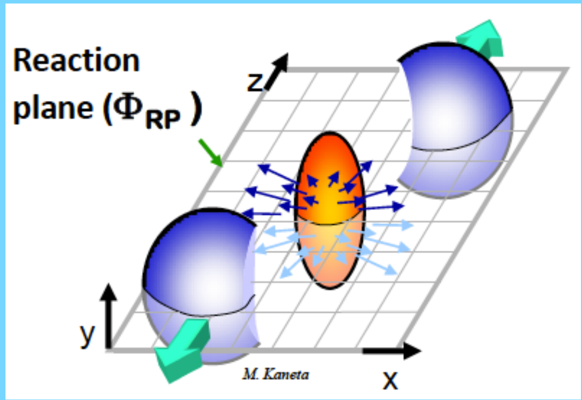
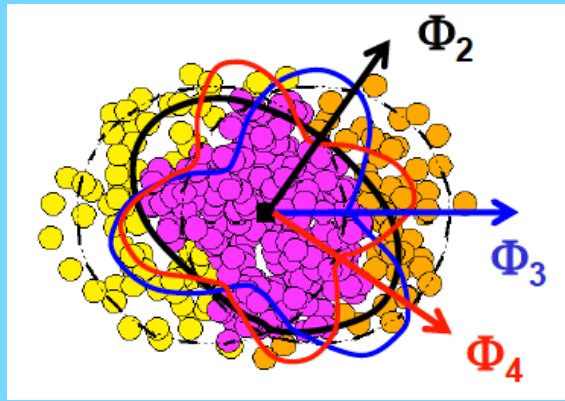
Flow coefficients v_n, n=1,2,3..





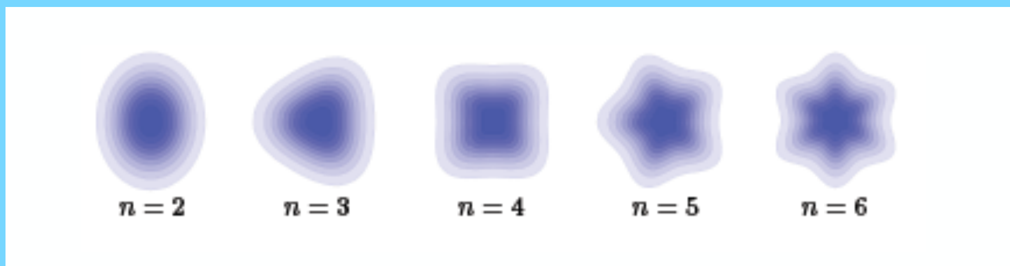
Matter in the overlapp area of two colliding nuclei gets compressed and heated

Initial anisotropy gets transfered into the momentum space via pressure gradients

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

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

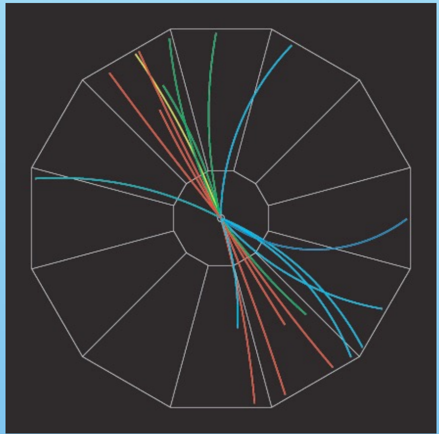
v : flow coefficients
(v1: directed flow,
v2: elliptic flow, ...)



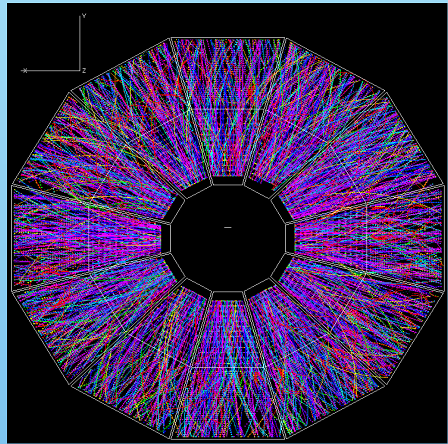
Higher harmonics

Jet quenching as QGP signature

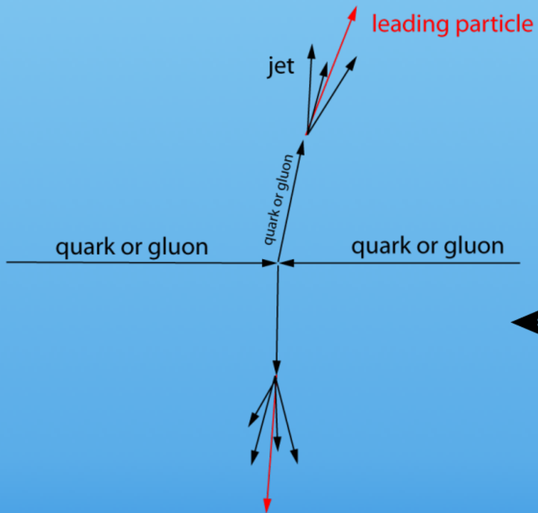
p+p Collision

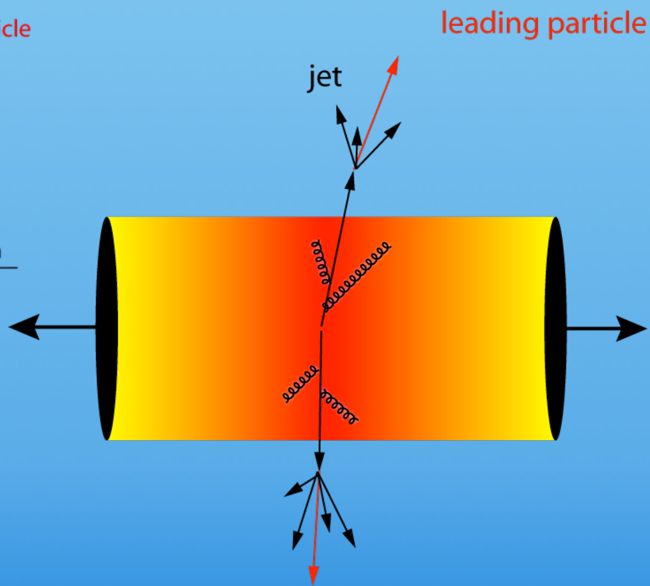


Au+Au Collision

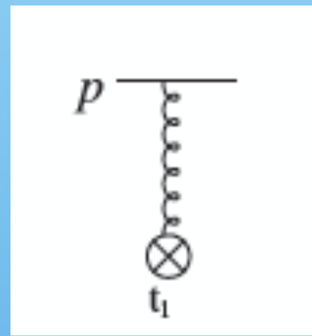


Partons interact with the medium and loose energy through eg gluon radiation

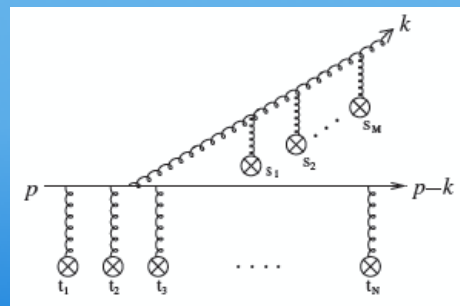




Collisional “elastic” energy loss: elastic interaction with the medium



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



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Jet quenching

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

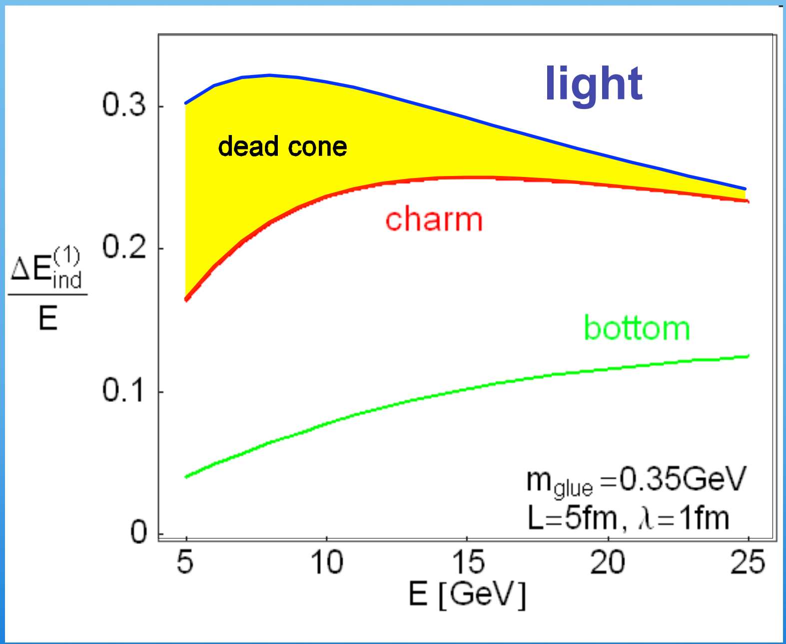
"The nuclear modification factor" R_{AA} compares A+A to expectations from p+p :

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

N coll : Average number of NN collisions in AA collision

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

M.Djordjevic PRL 94 (2004)



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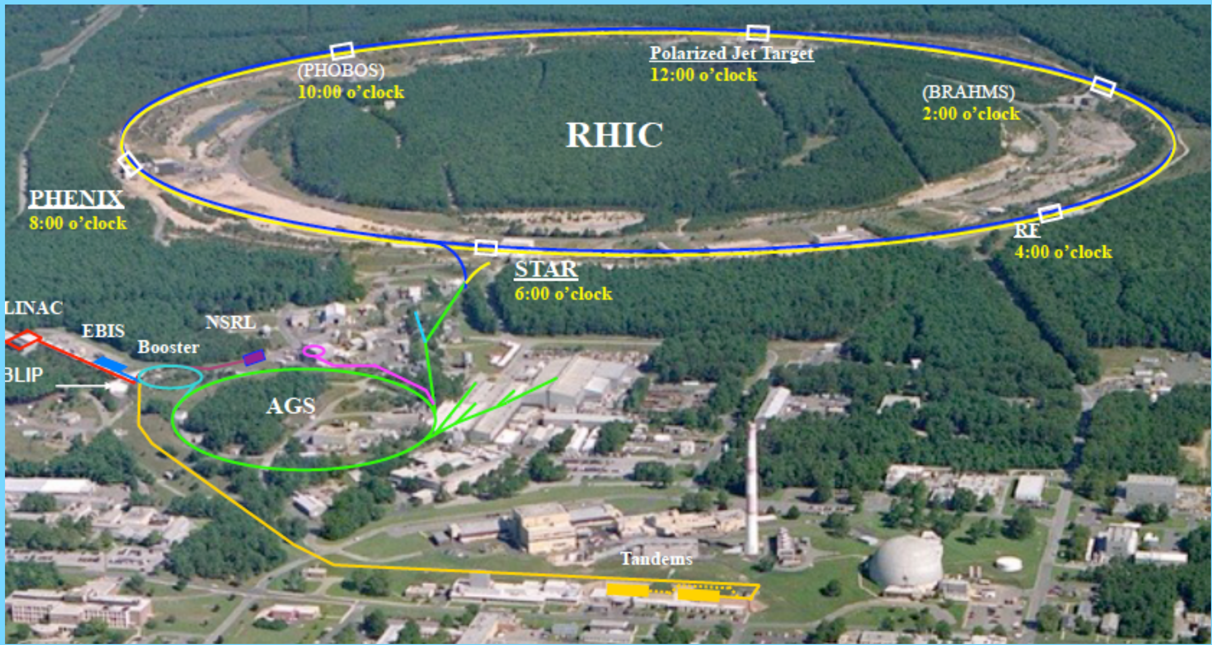
Accelerator facilities and experiments today

Relativistic Heavy Ion Collider

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



RHIC has been exploring nuclear matter at extreme conditions over the last 22 years, since 2000

4 experiments initially:
STAR PHENIX
BRAHMS PHOBOS

Still runing: STAR

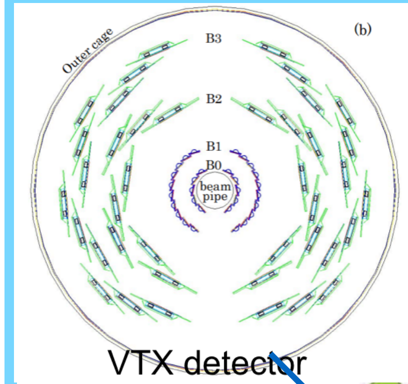
Still analysing data: PHENIX

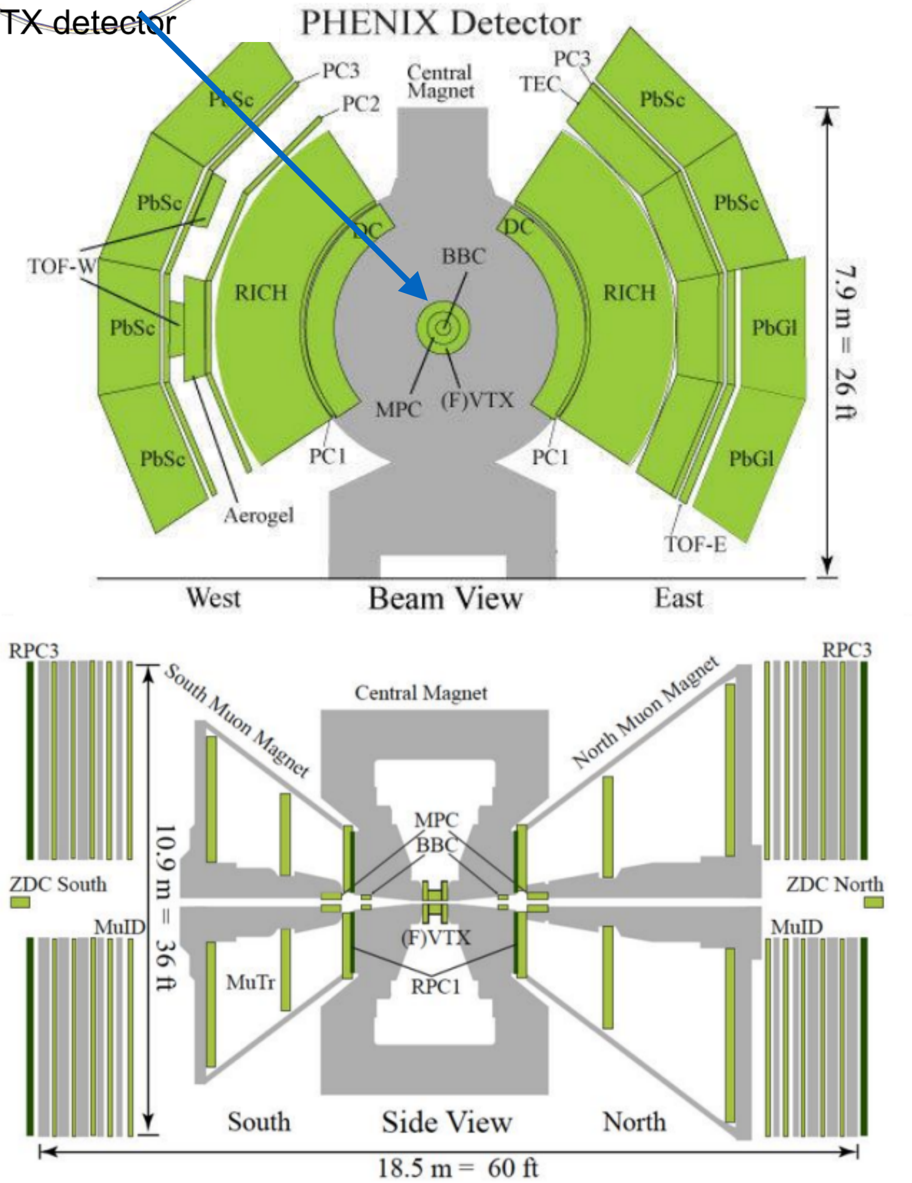
New: sPHENIX

Main colliding systems:
p+p, p+A, d+Au, Cu+Cu, Au+Au
Cu+Au, U+U, Zr+Zr, Ru+Ru

Main energies A+A :
$\sqrt{s_{NN}}$ = **62, 130, 200 GeV**
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39, 54 GeV
+ Fixed target

The PHENIX Experiment at RHIC





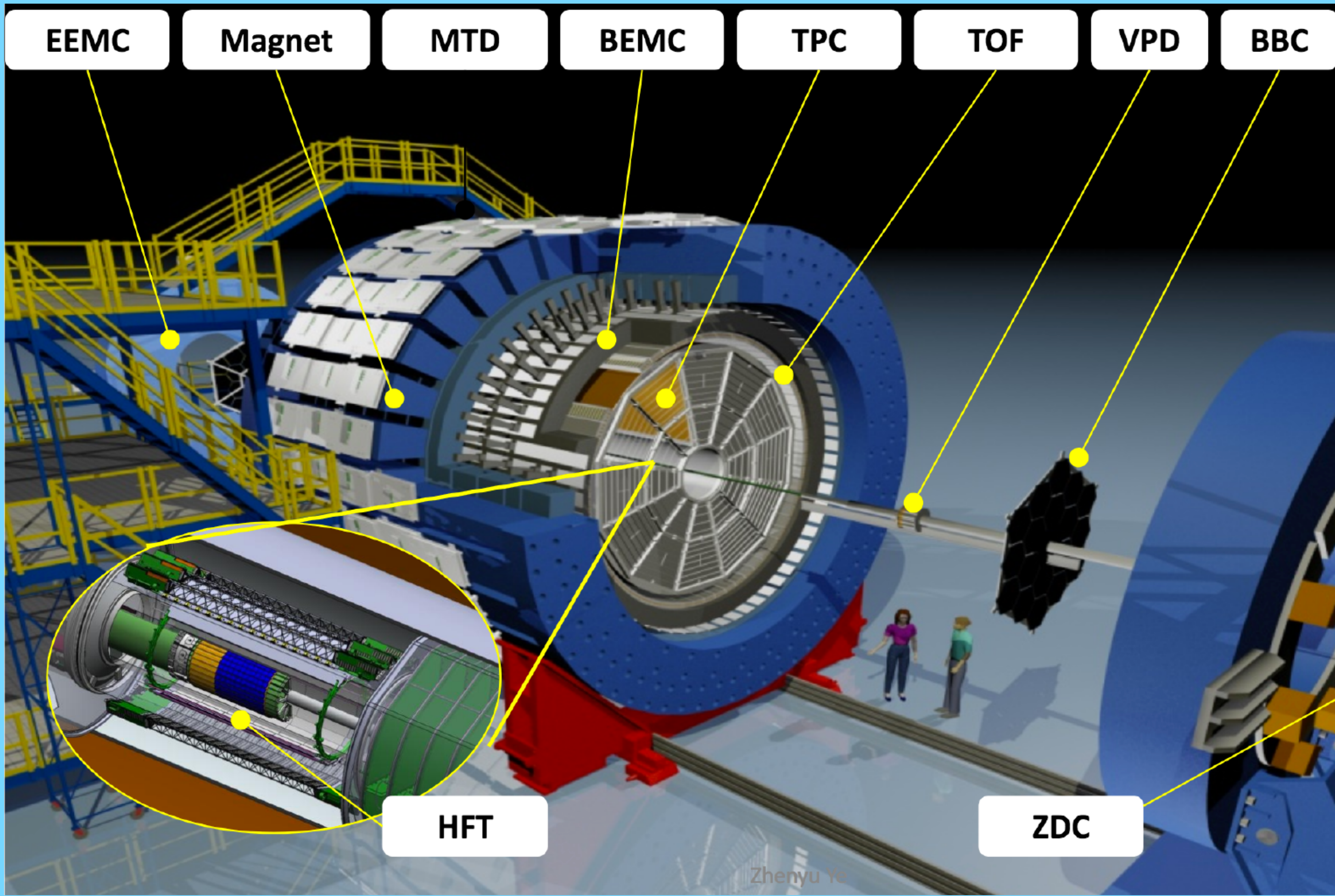
-Central spectrometer arms : ring imaging Cerenkov detector (RICH), electromagnetic calorimeter (EMCal), Drift Chambers (DC), multi-wire proportional pad chambers (PC) and silicon Vertex detector (VTX).

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

The STAR Experiment at RHIC

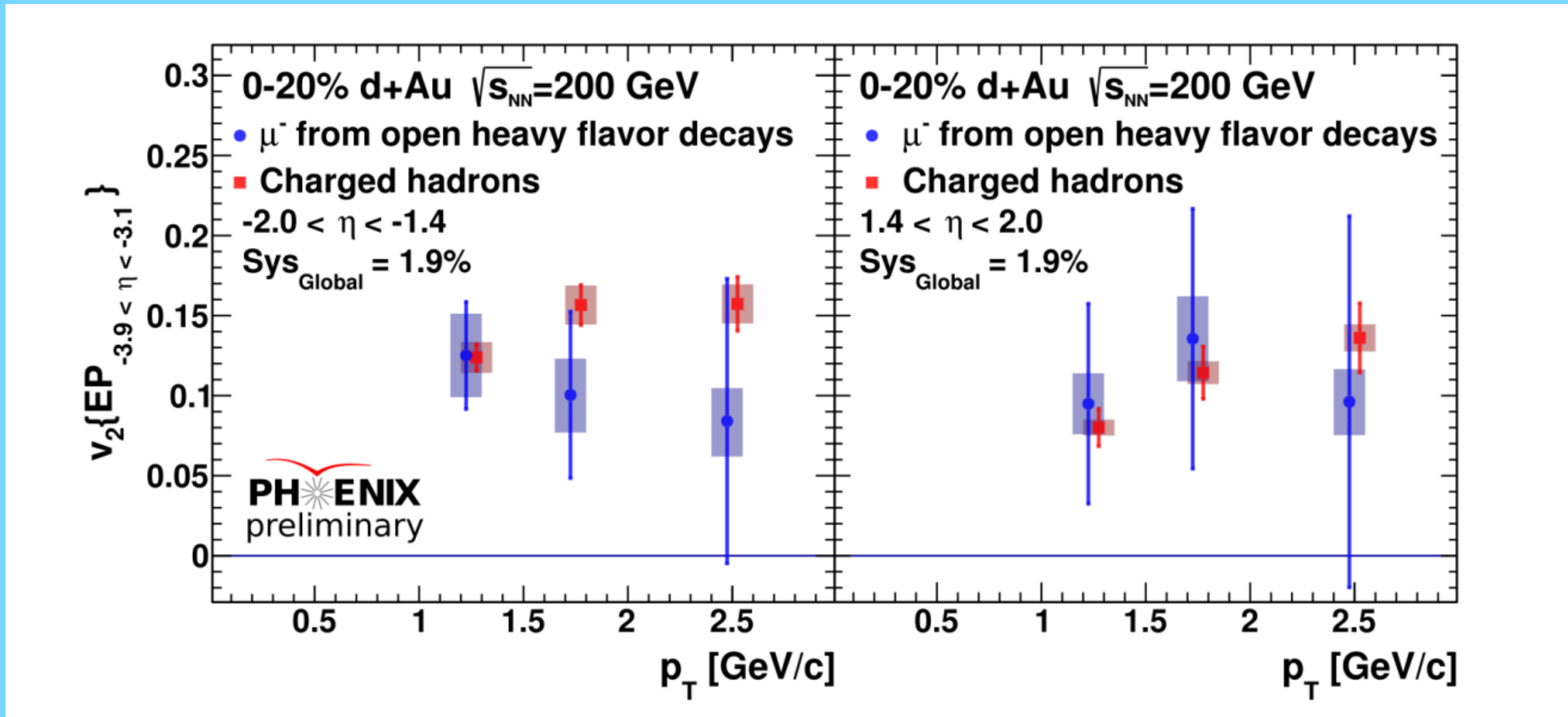


Heavy Flavor Tracker (HFT), Time Projection Chamber (TPC), Barrel Electromagnetic Calorimer (BEMC) , Muon Telescope Detector (MDT), Time-Of-Flight detector (TOF). Delta(phi)=4pi, |eta|<1

* Open heavy flavor
  Flow

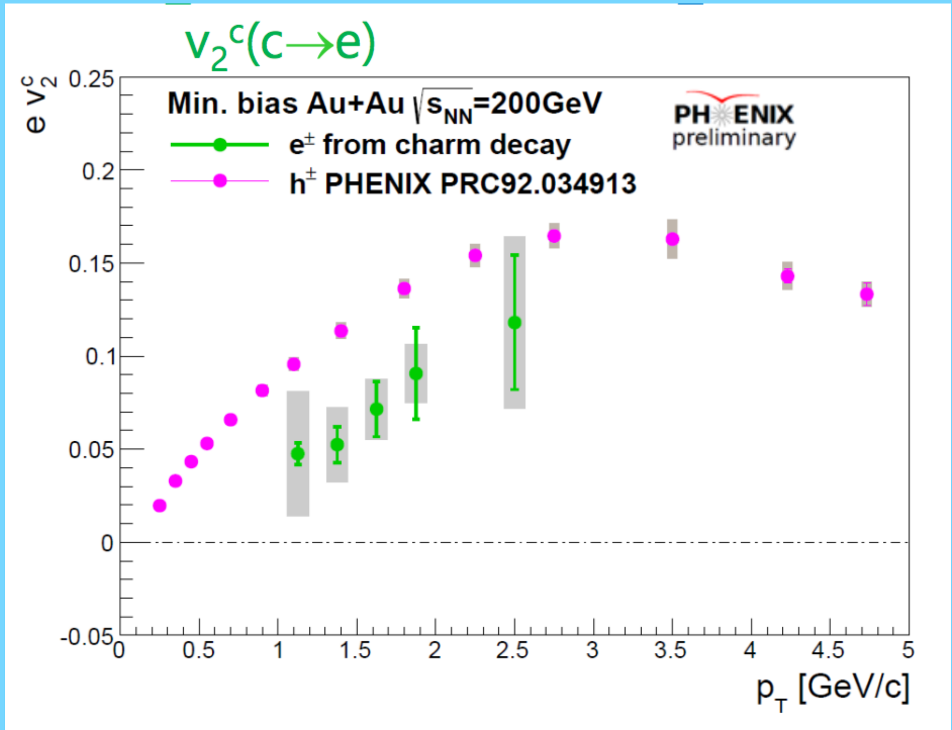
PHENIX (2017) elliptic flow of (bottom+charm) to muons in 0-20% d+Au 200 GeV

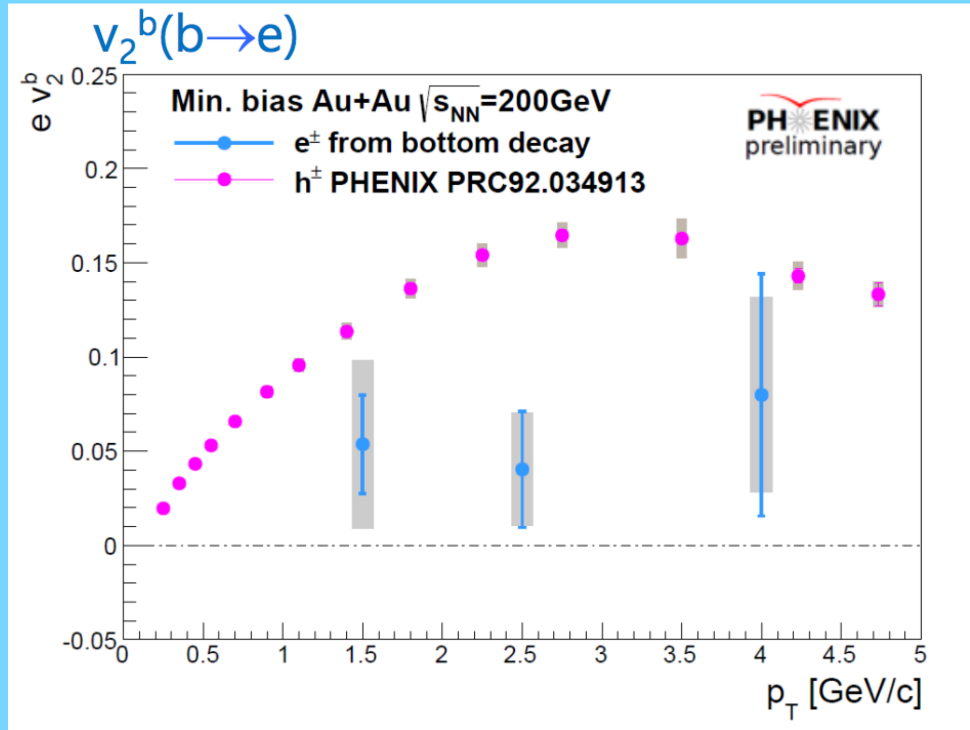
C. Aidala et al. (PHENIX collaboration), Phys. Rev. C 96, 064905 (2017).



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

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



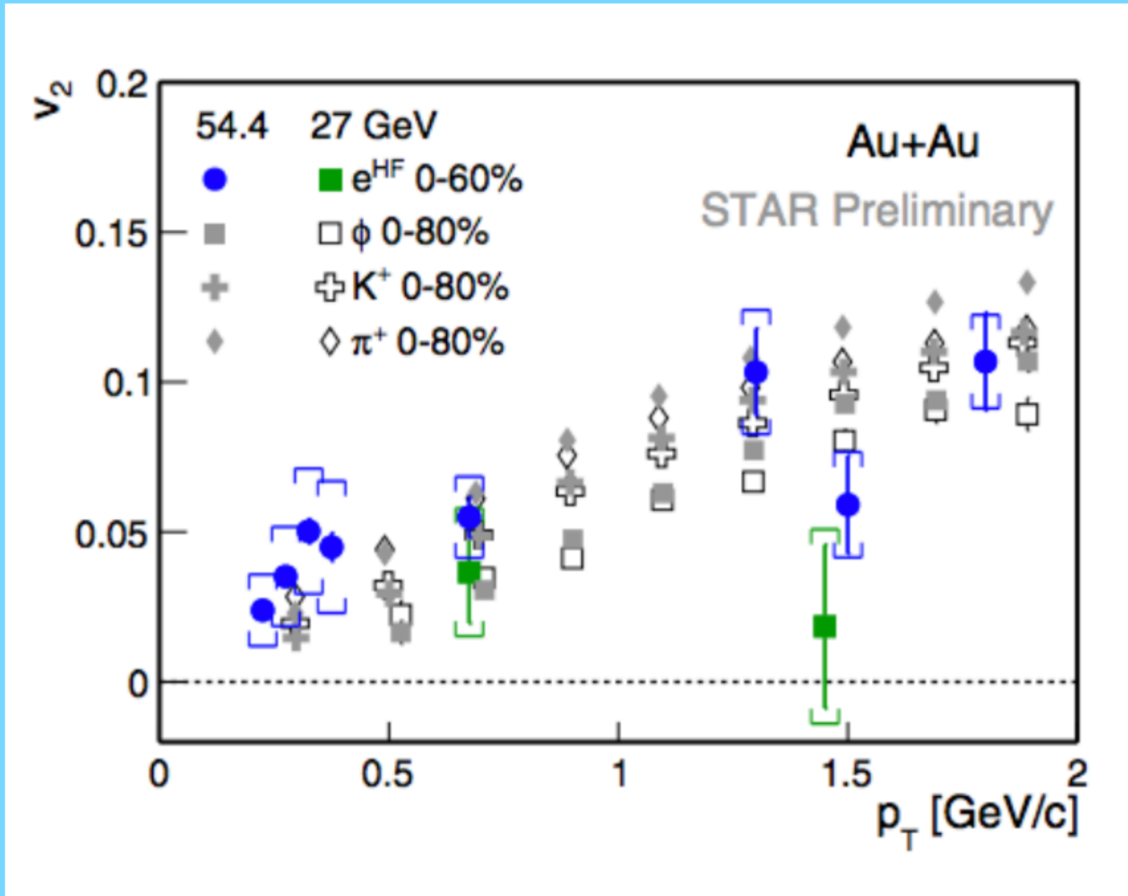


T Hachiya et al, PHENIX collaboration, QM2022

* 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 GeV

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



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

Open heavy flavor

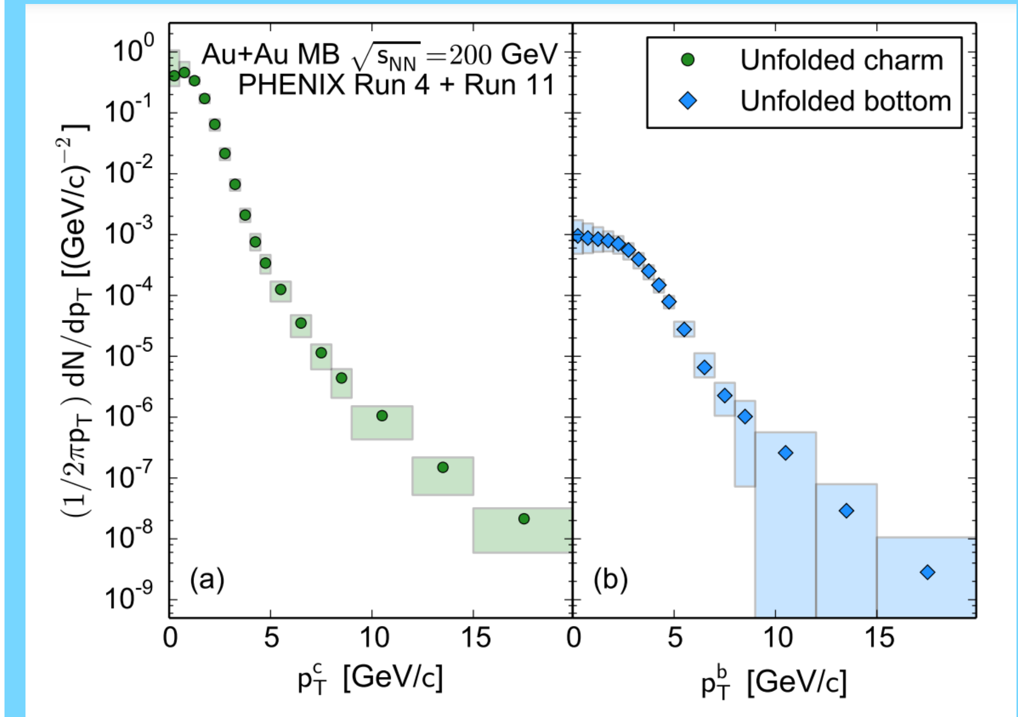
Nuclear modification factor and jet quenching

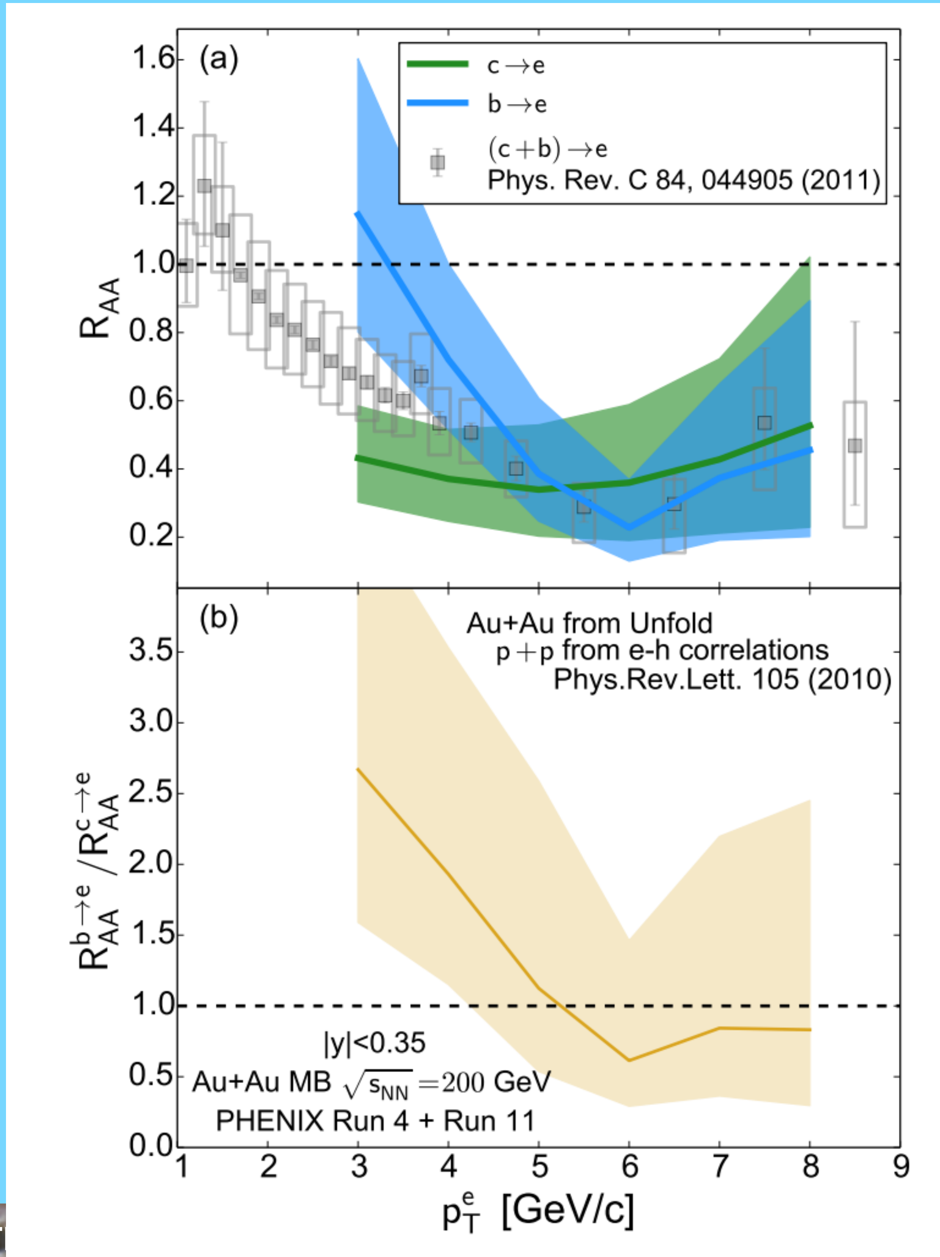
Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions at RHIC

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



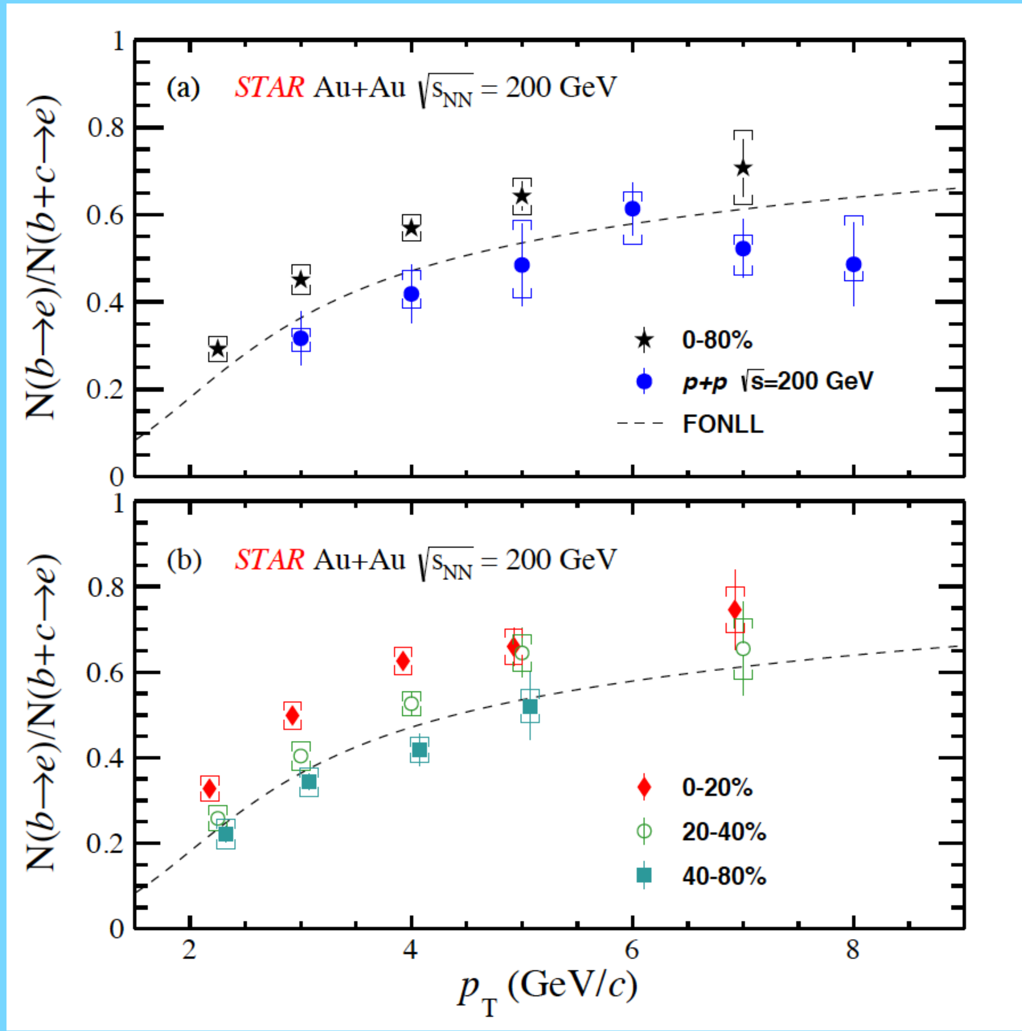


* Hint of less suppression for b —> e than c —> e observed in MB Au+Au collisions at 200 GeV at pT 3-4 GeV

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

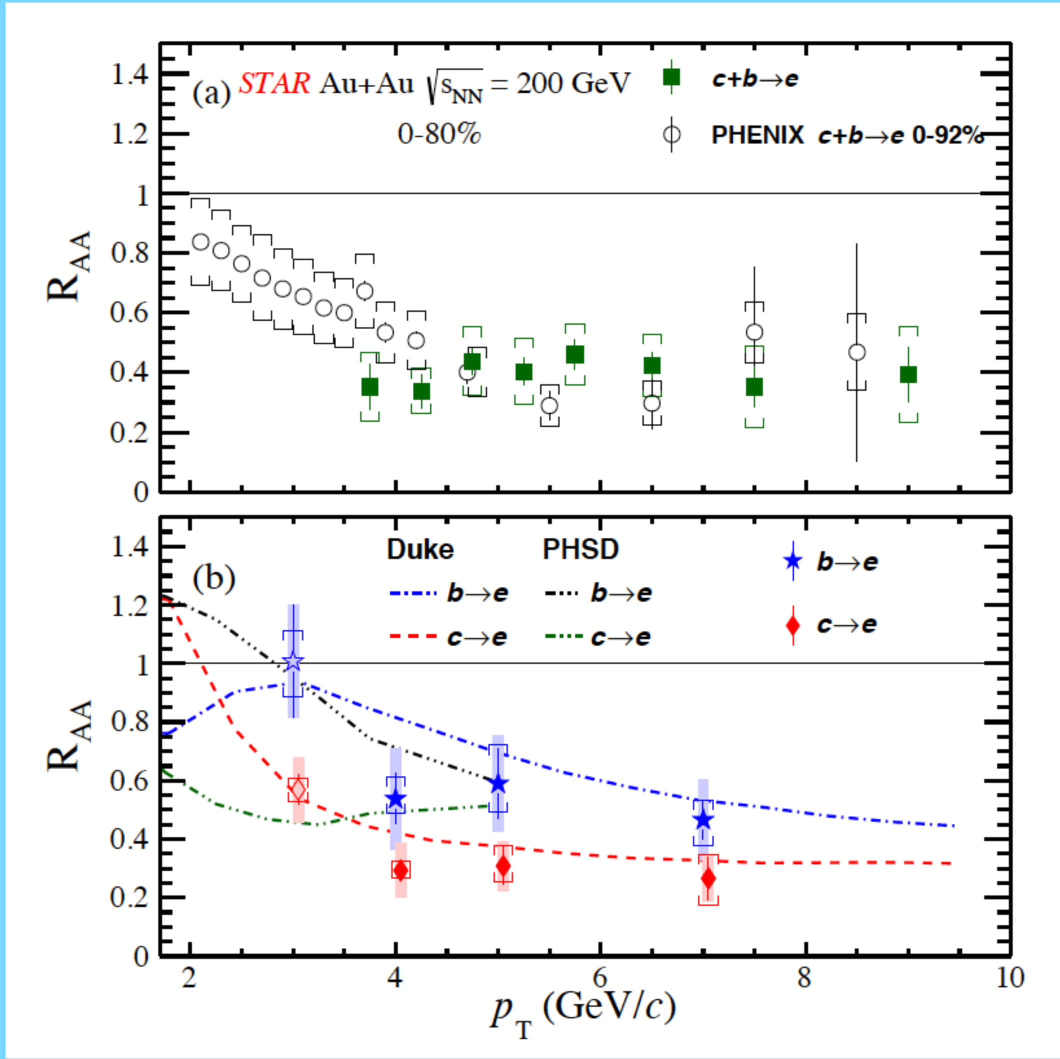


STAR (2022) Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions

* 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

STAR Collaboration, June 2022, arXiv:2111.14615

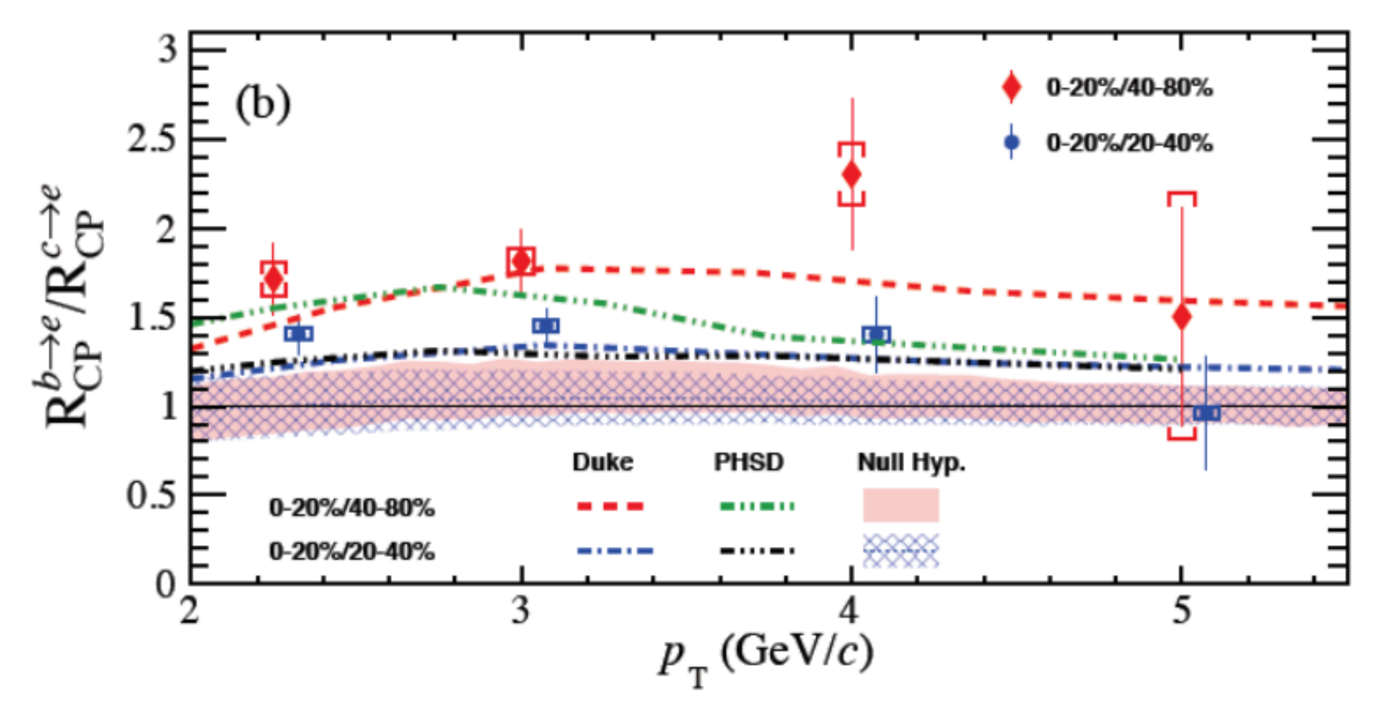
PHENIX Collaboration, PRC93, 034904 (2016), 1509.04662



* **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

STAR Collaboration, June 2022, arXiv:2111.14615

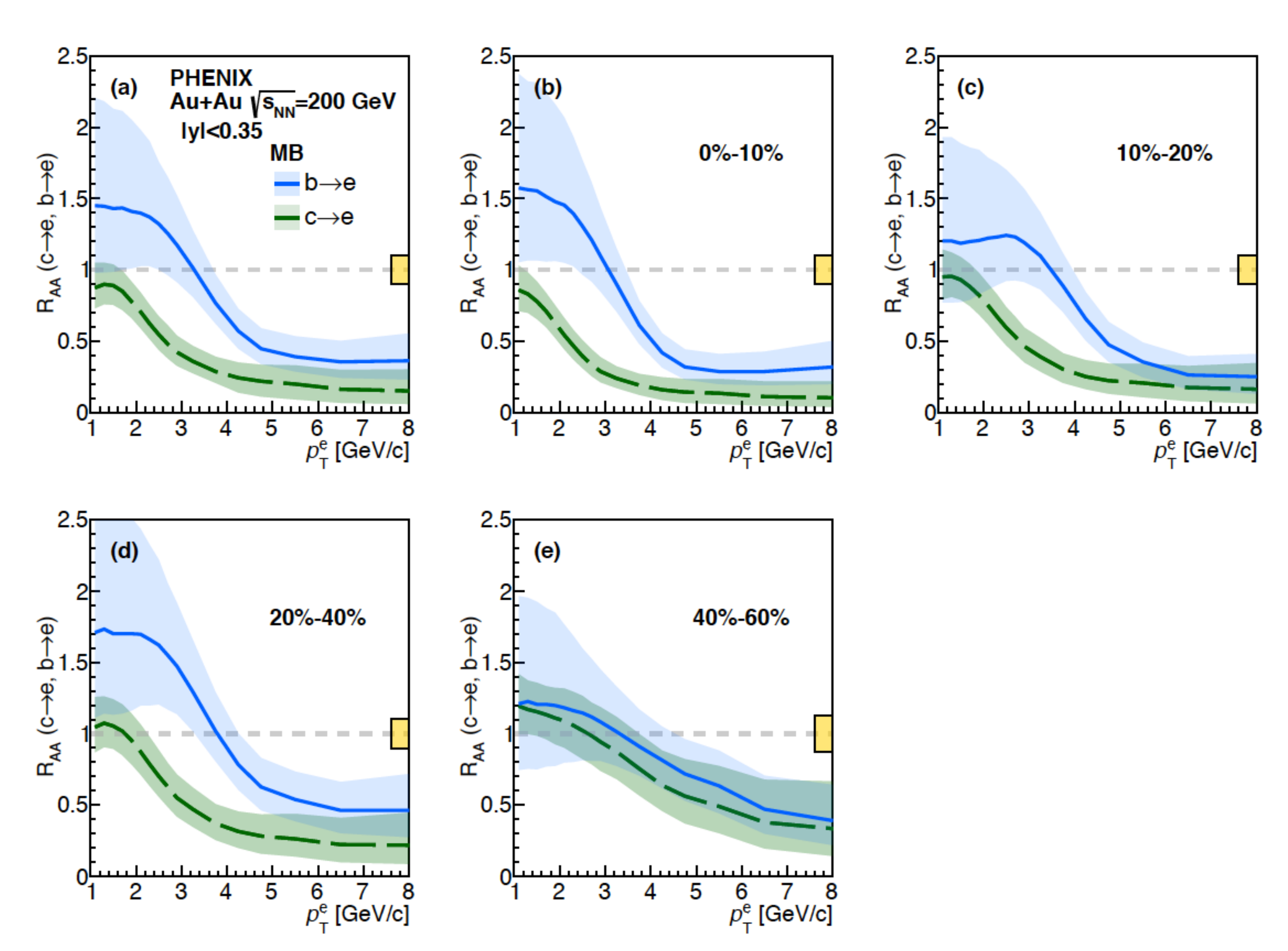


* PHSD: Parton-Hadron-String-Dynamics model
* Duke: modified Langevin transport model
* Both models include heavy quark (HQ) diffusion in the QGP medium, HQ hadronization through coalescence and fragmentation and mass-dependent energy loss mechanisms
* Data consistent with model predictions

* **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 models suggesting the mass ordering of parton energy loss in sQGP**

PHENIX (2022) 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

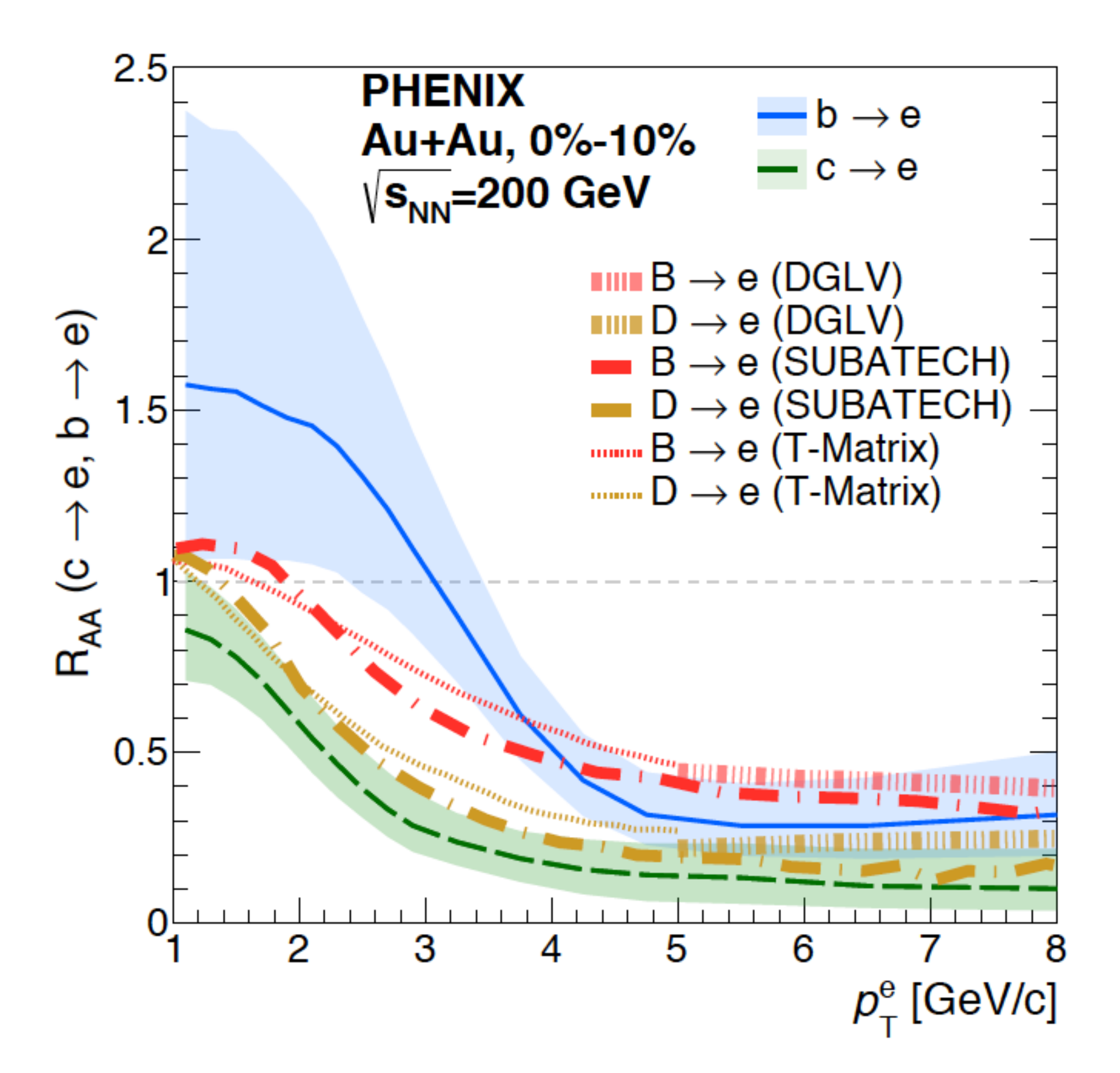


* b->e higher than c-> e in Au+Au 200 GeV Minimum Bias and various centralities exept the most peripheral collisions

* **Evidence of mass ordering of R_{AA} of electrons from bottom and charm in Au+Au collisions at 200 GeV is observed**

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

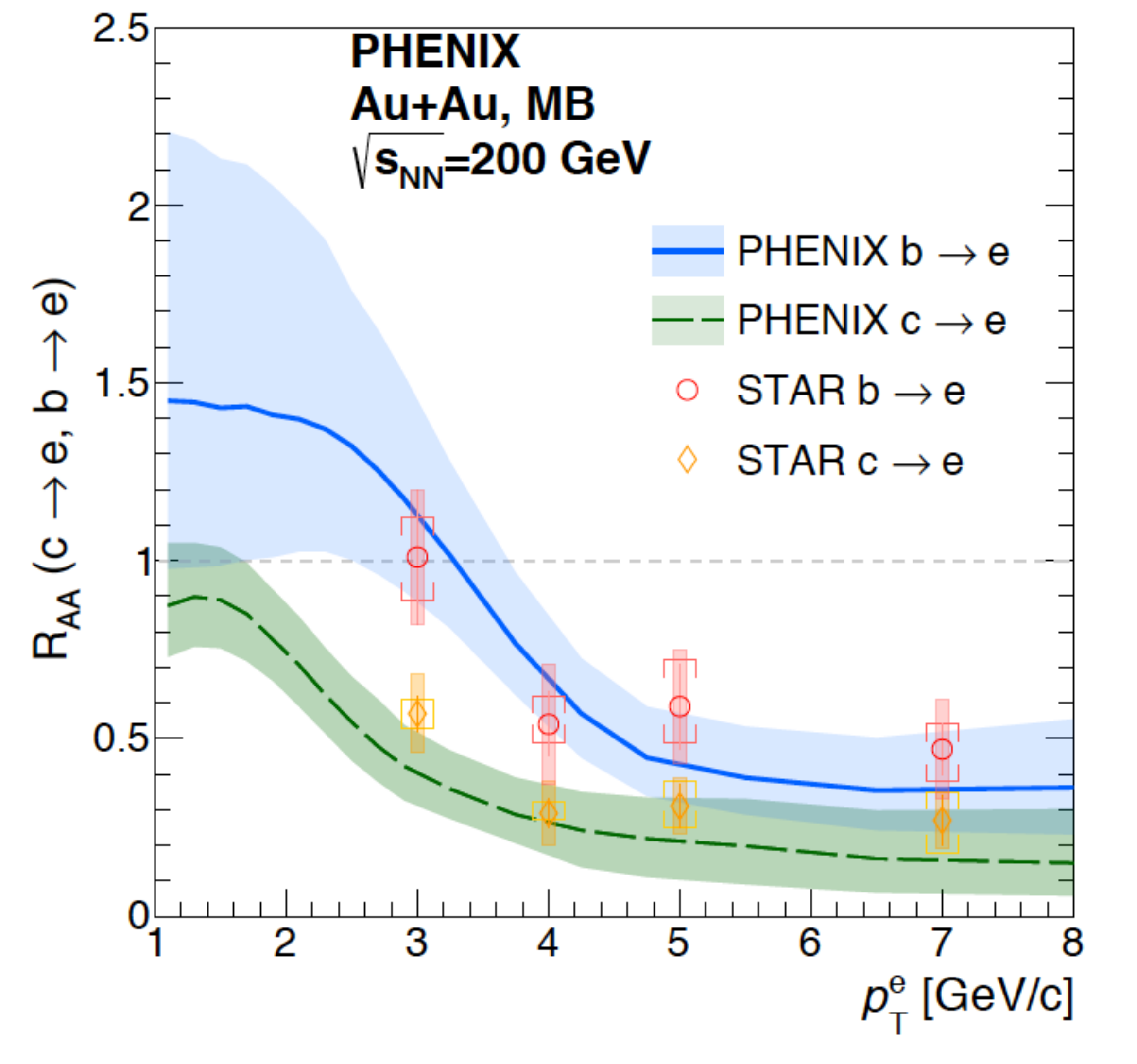
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058



* 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

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.

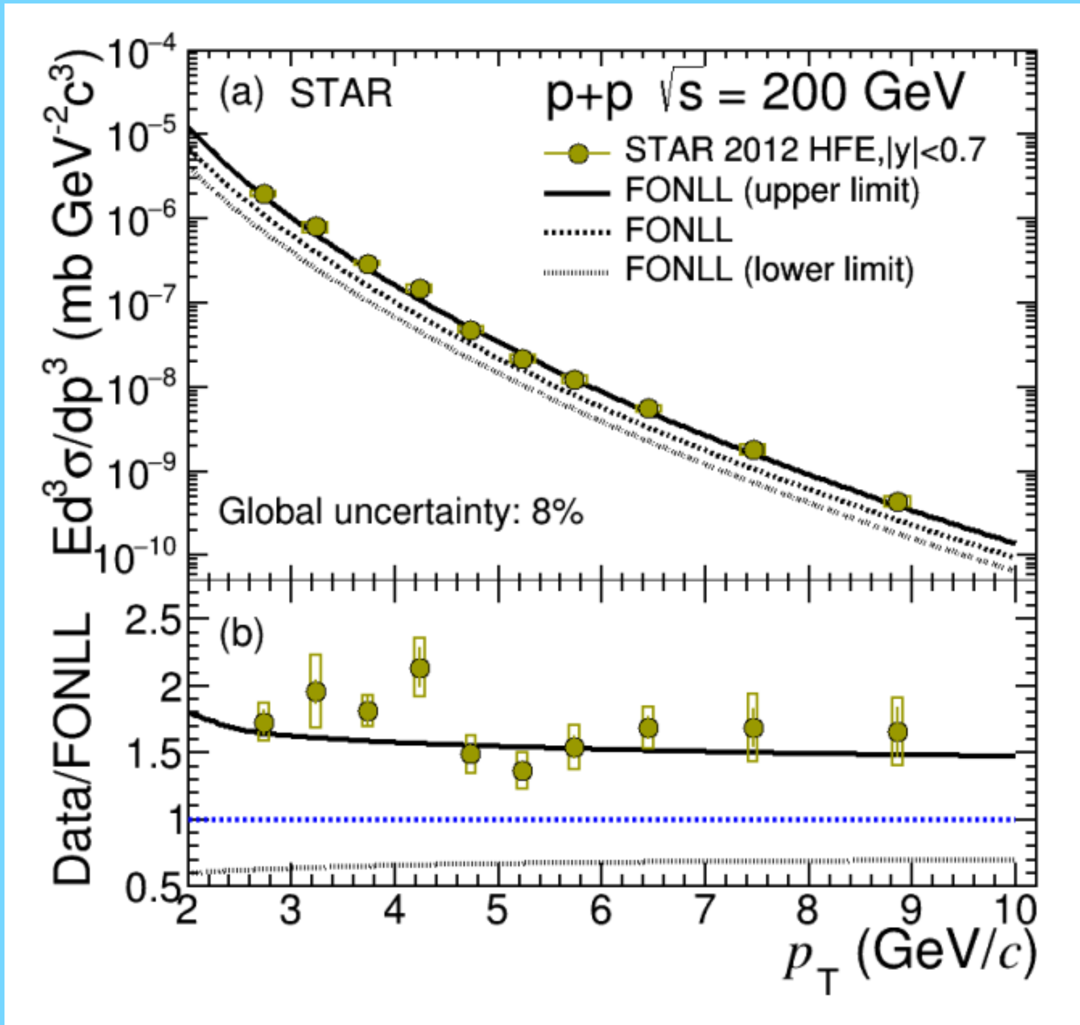
U.H.Acharya et al (PHENIX Collaboration) Charm- and Bottom-Quark Production in Au$+$Au Collisions at $\sqrt{s_{_{NN}}}$ = 200 GeV, 2203.17058

* 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

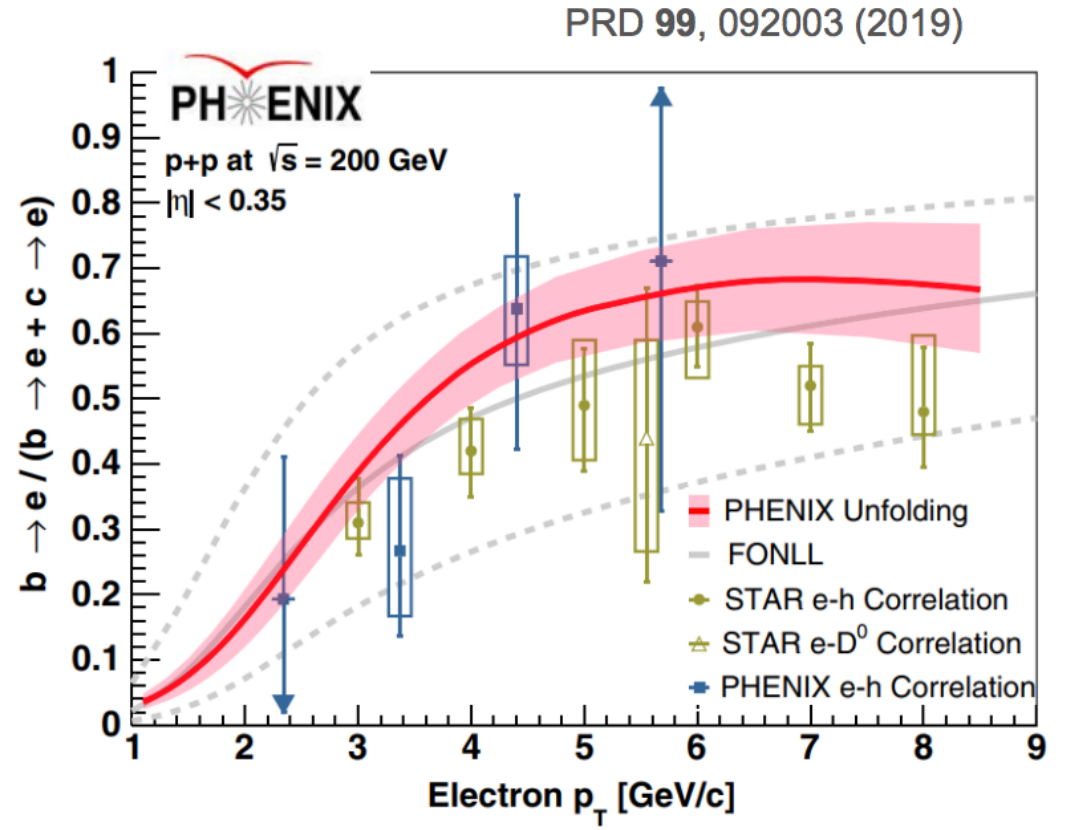
STAR (2022) Heavy Flavor -> electrons in p+p collisions at 200 GeV

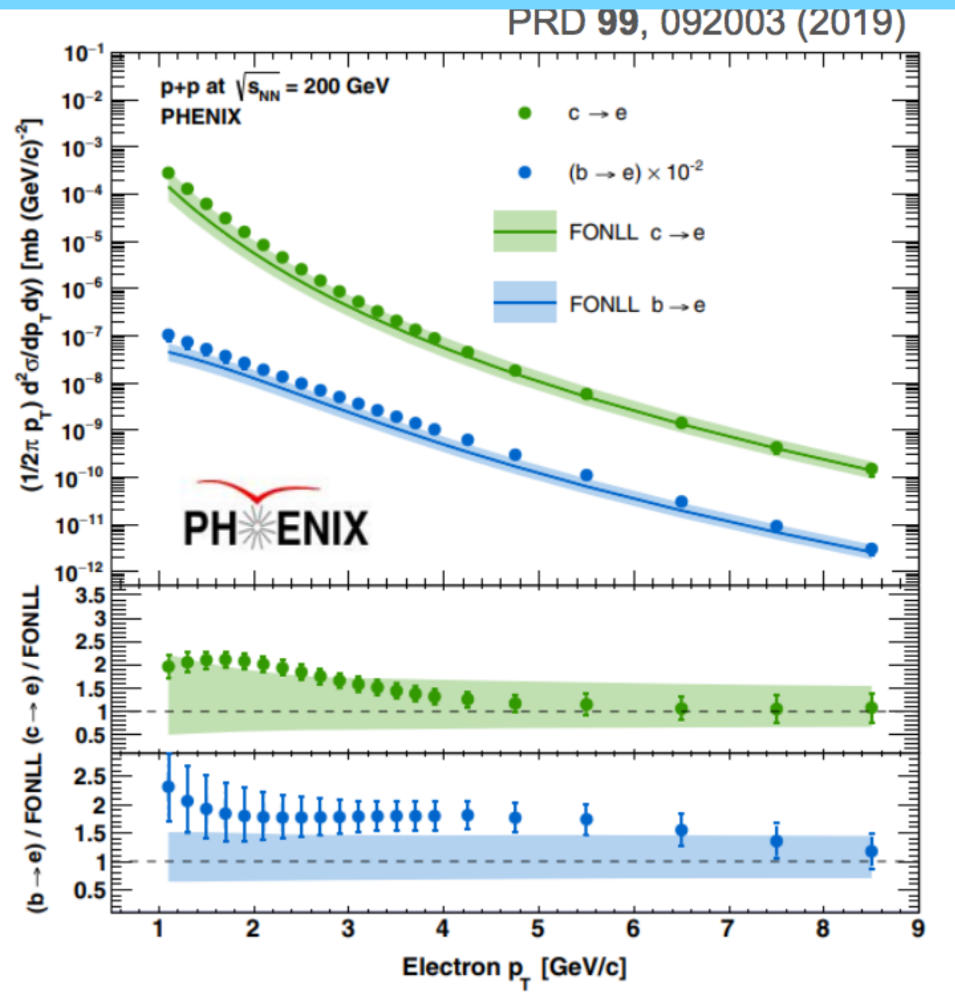
STAR Collaboration, Phys.Rev.D 105 (2022) 3, 032007, e-Print: 2109.13191 [nucl-ex]



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

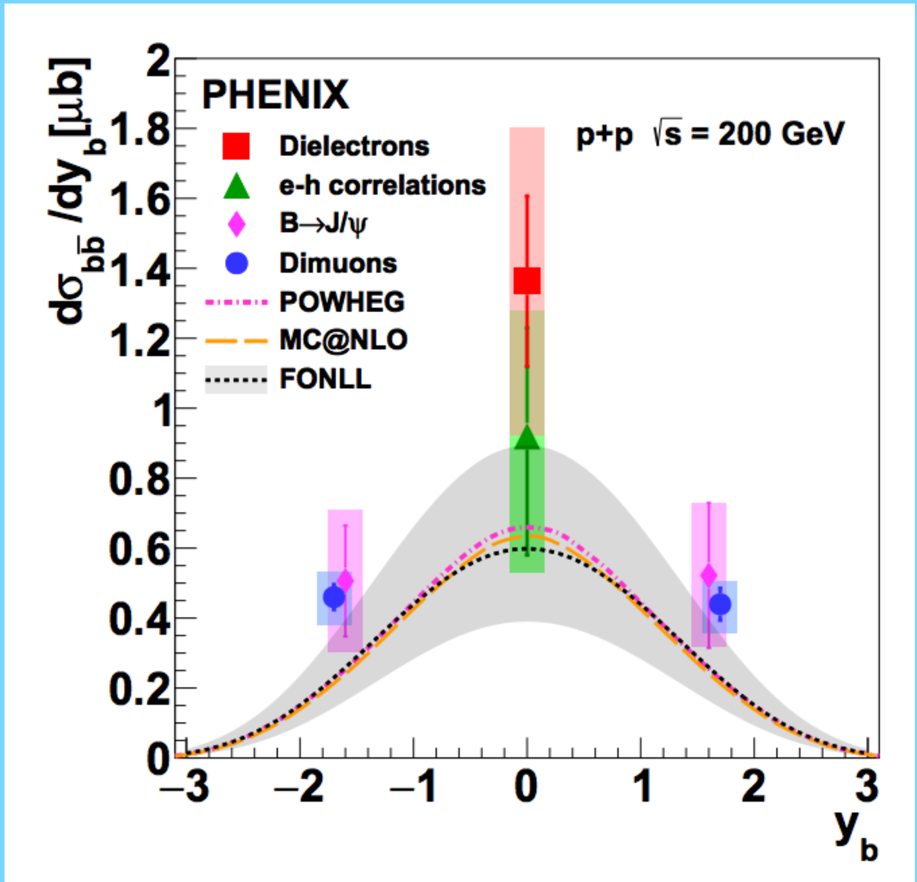
PHENIX (2019) new p+p baseline available for c and b

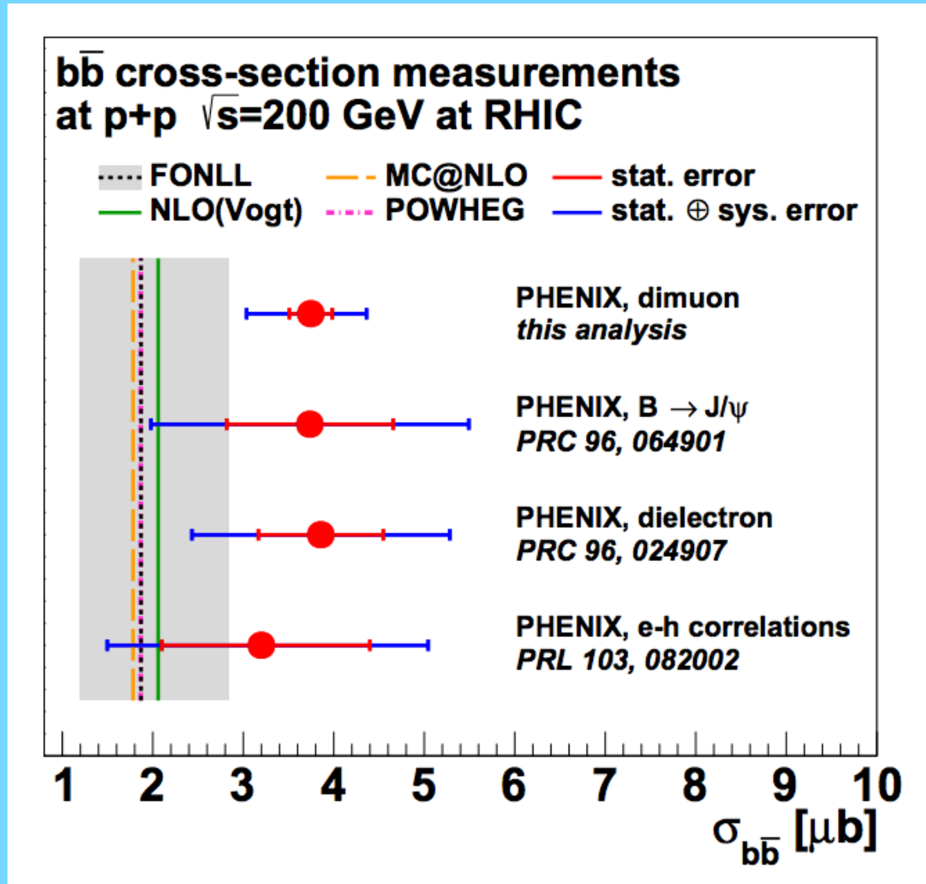




PHENIX (2019) bottom in p+p colisions at 200 GeV

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 collisions at 200 GeV

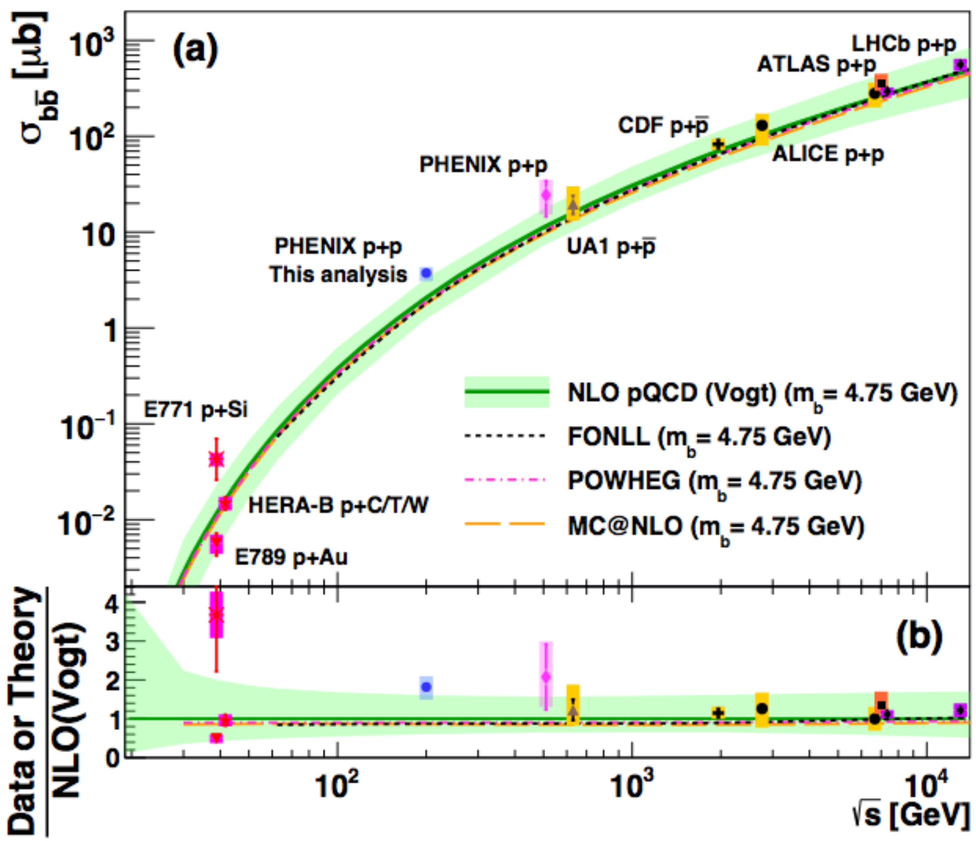
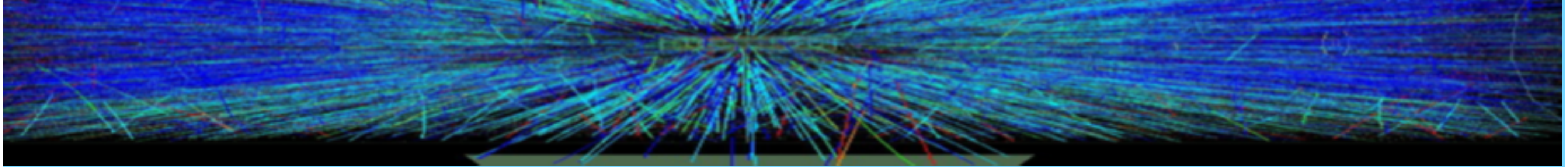


FIG. 29. Bottom cross section $\sigma_{b\bar{b}}$ as a function of $\sqrt{s}$. Uncertainties due to rapidity extrapolation are not included in the LHCb measurements. Measured cross sections are compared to NLL and NLO calculations.

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]

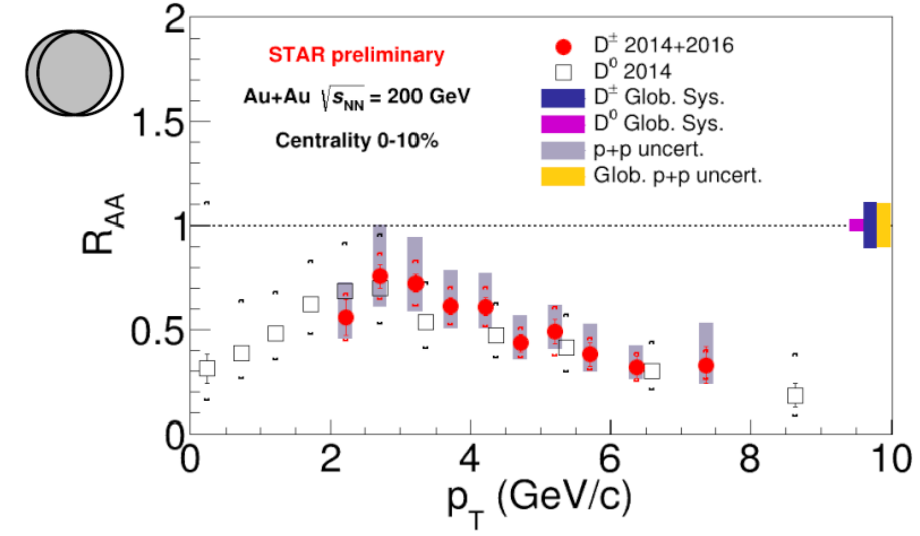
* At low energy models are less consistent with data

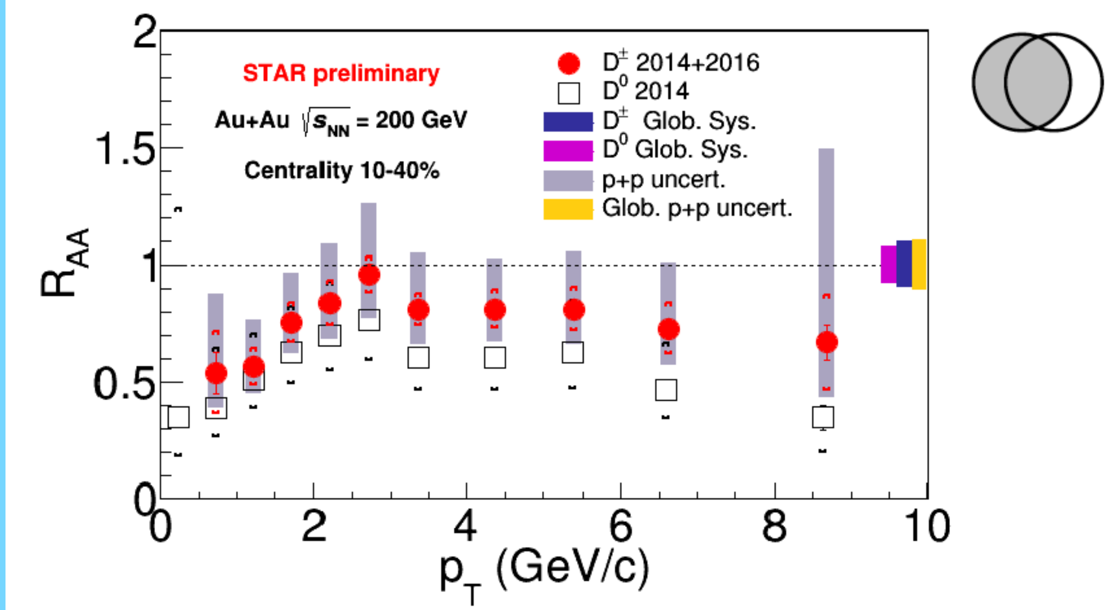


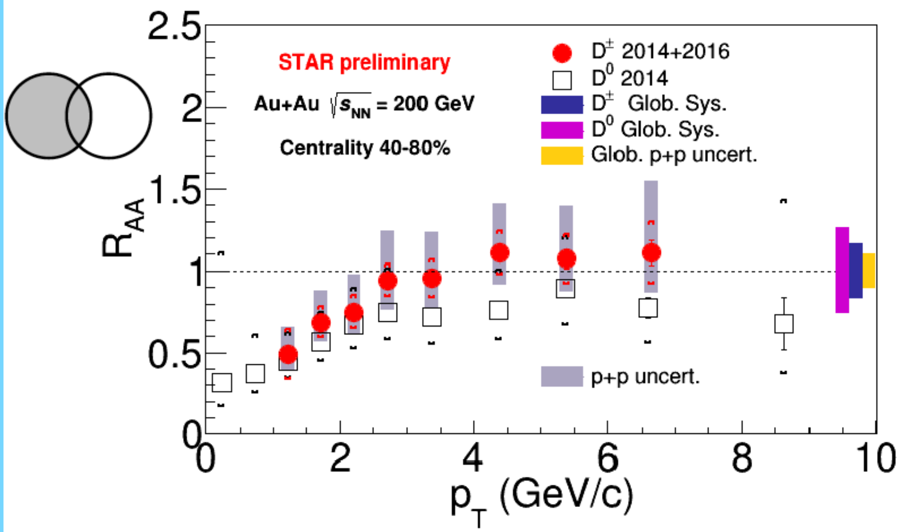
Charmed hadrons

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

J. Vanek et al, STAR Collaboration, QM2022





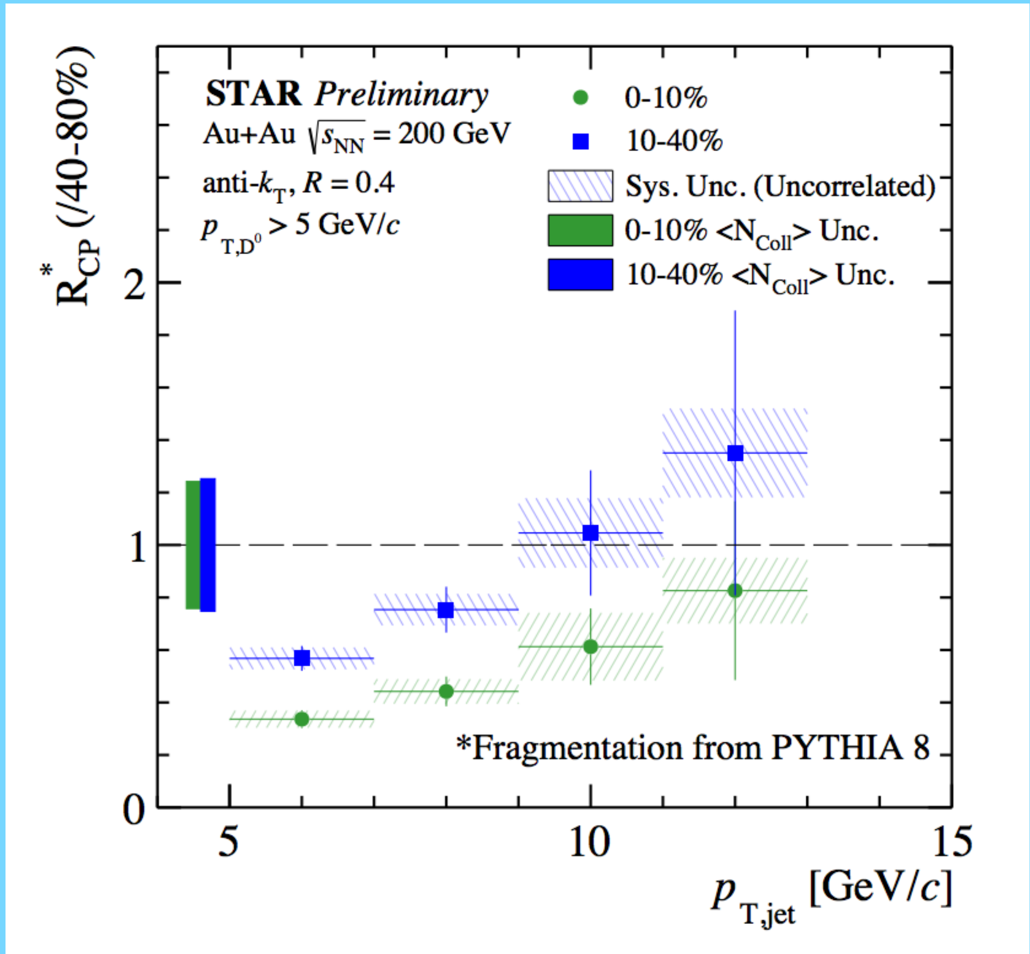


p+p reference (STAR): Phys. Rev. D 86, 072013, (2012)
D^0 (STAR): Phys. Rev. C 99, 034908, (2019).

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

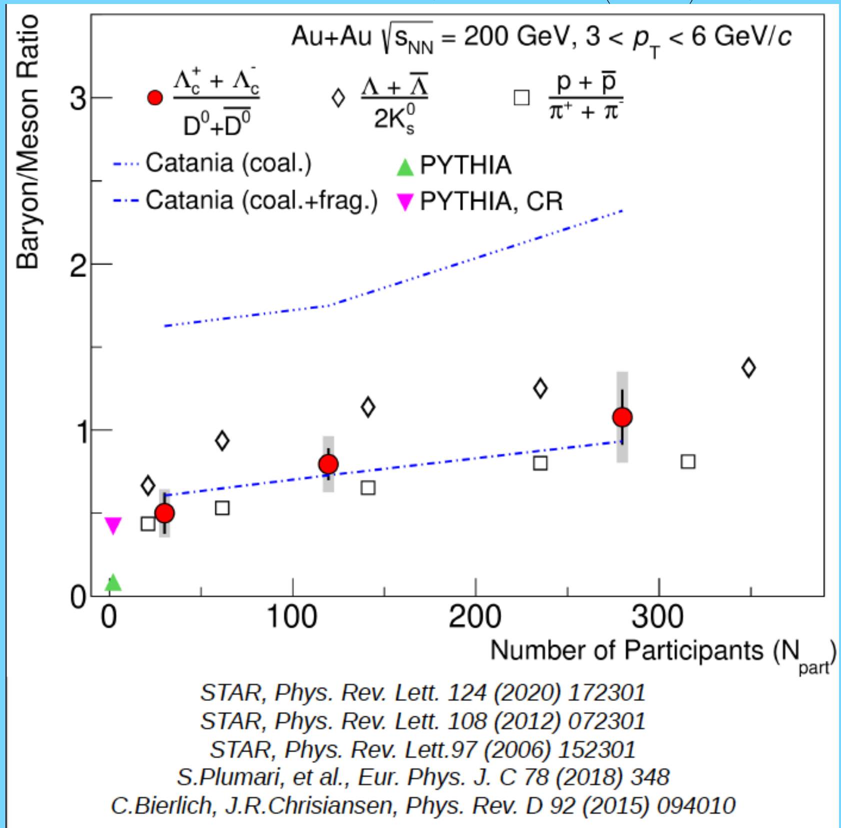


Niida et al, STAR Collaboration, AUM2022

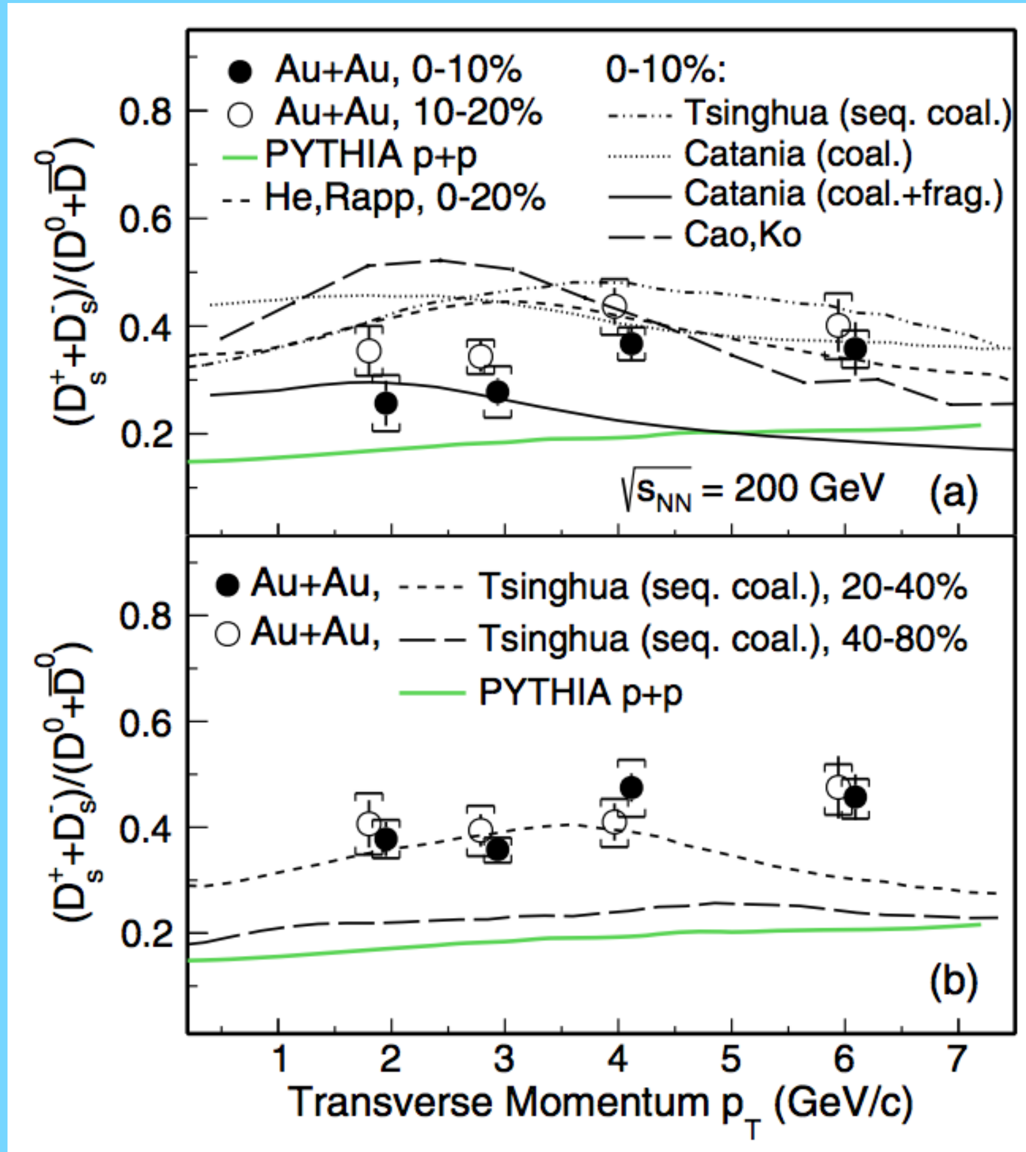
* R(CP) shows suppression at p_T < 9 and 11 GeV for 10-40% and 0-10% respectively

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

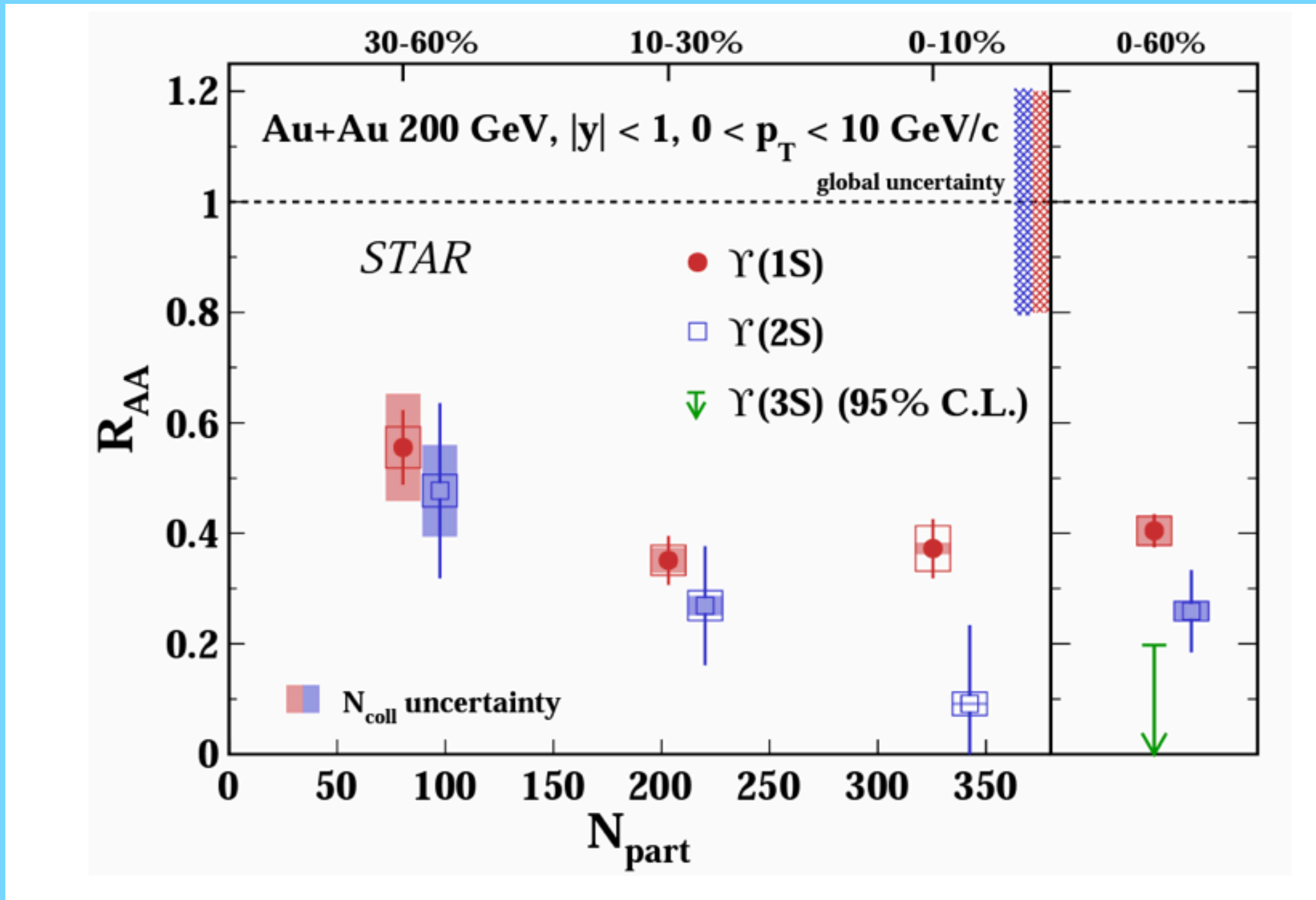


* Λ_c/D^0 and D_s/D^0 ratios in 200 GeV Au+Au are higher than PYTHIA
* Data are in accordance with models that include coalescence hadronization of charm hadrons

Quarkonia

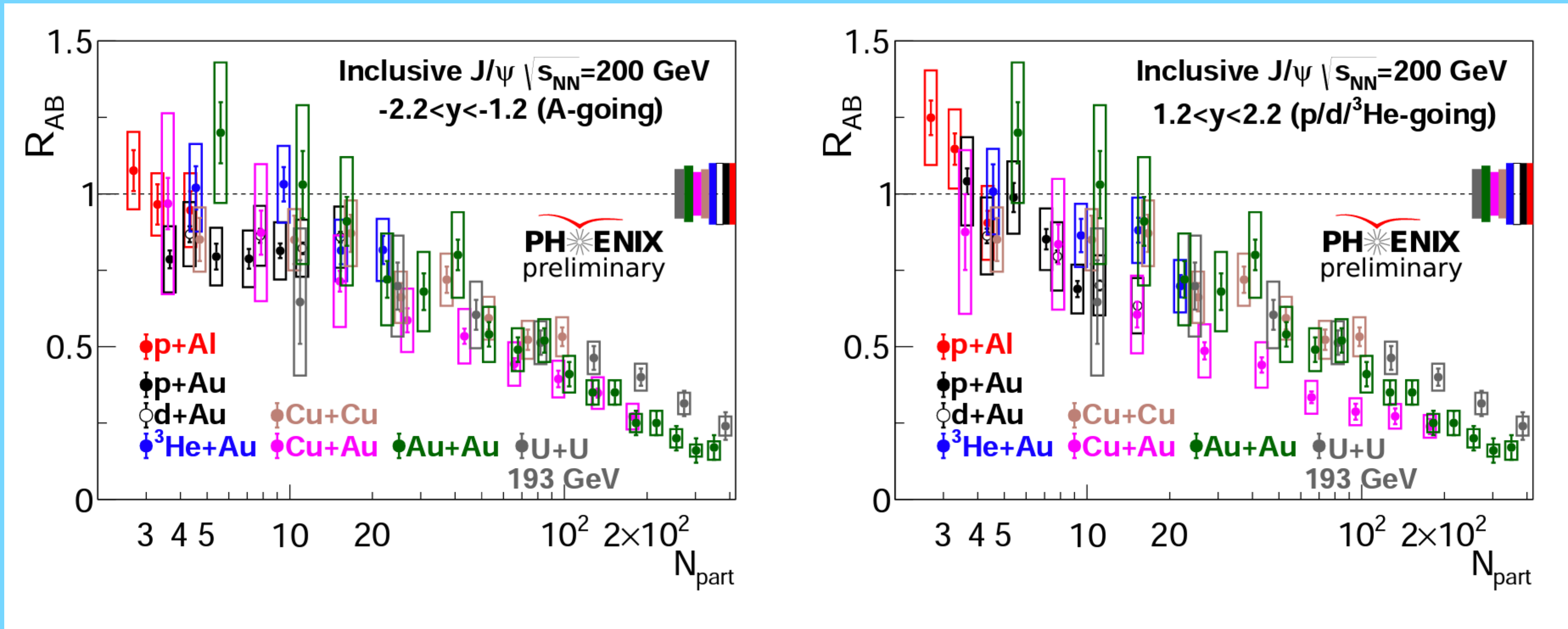
STAR Υ

STAR 2207.06568



Observation of Υ quarkonia sequential suppression by STAR in central Au+Au collisions

PHENIX J/Psi

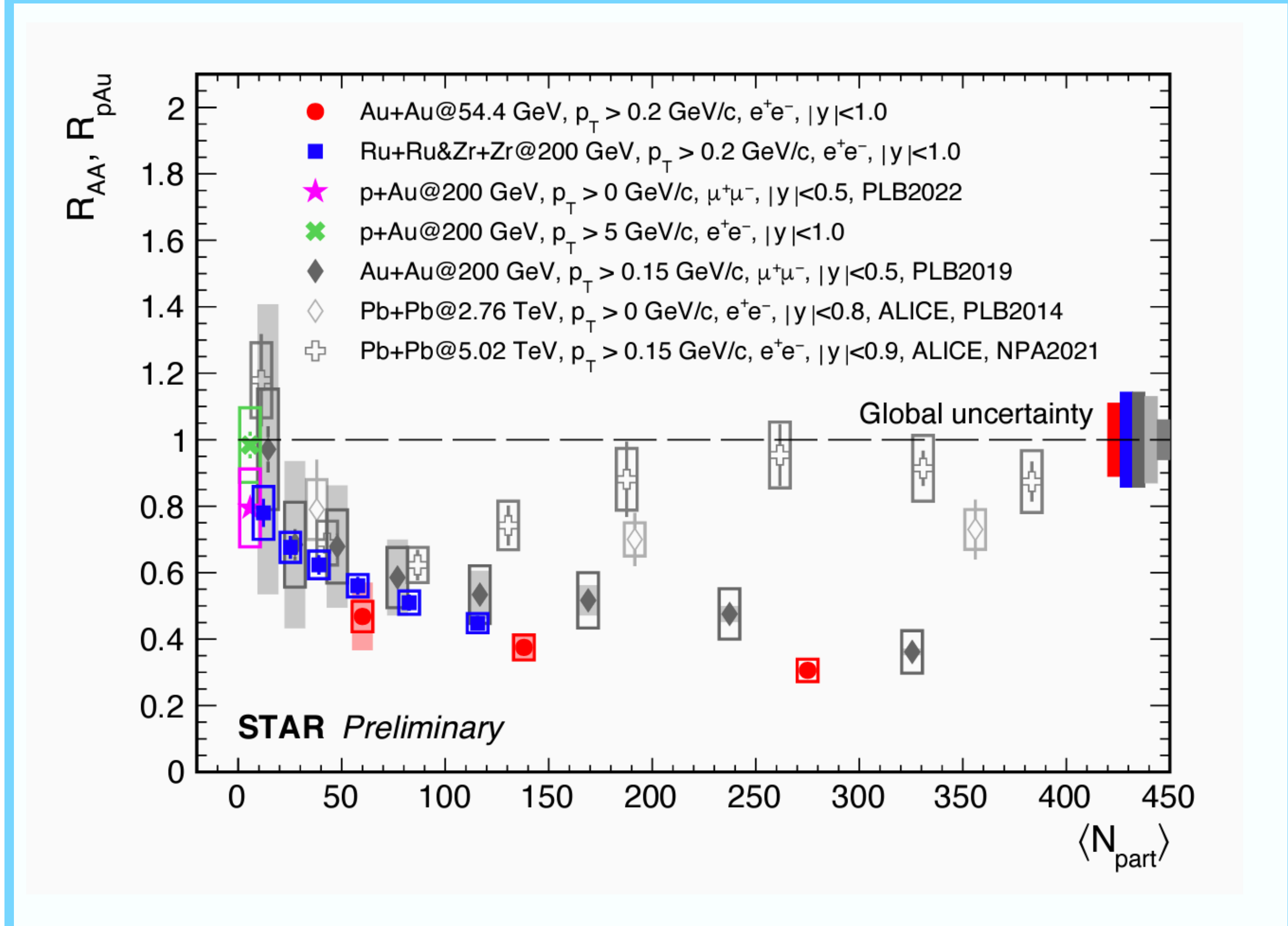


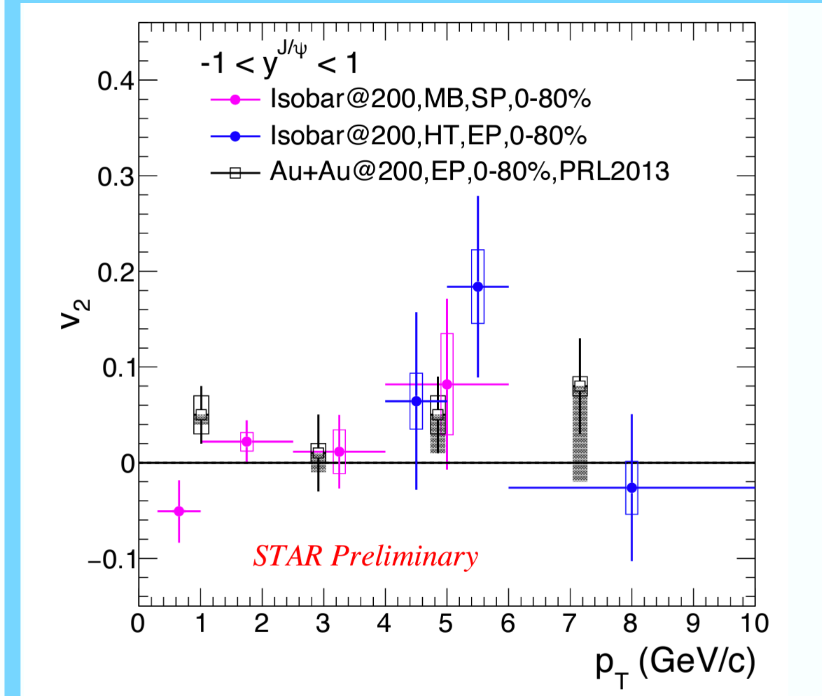
1807.09231

Across all collision systems similar suppression is observed vs Npart

Additional suppression effects are coming into play as the reaction volume increases

STAR J/Psi

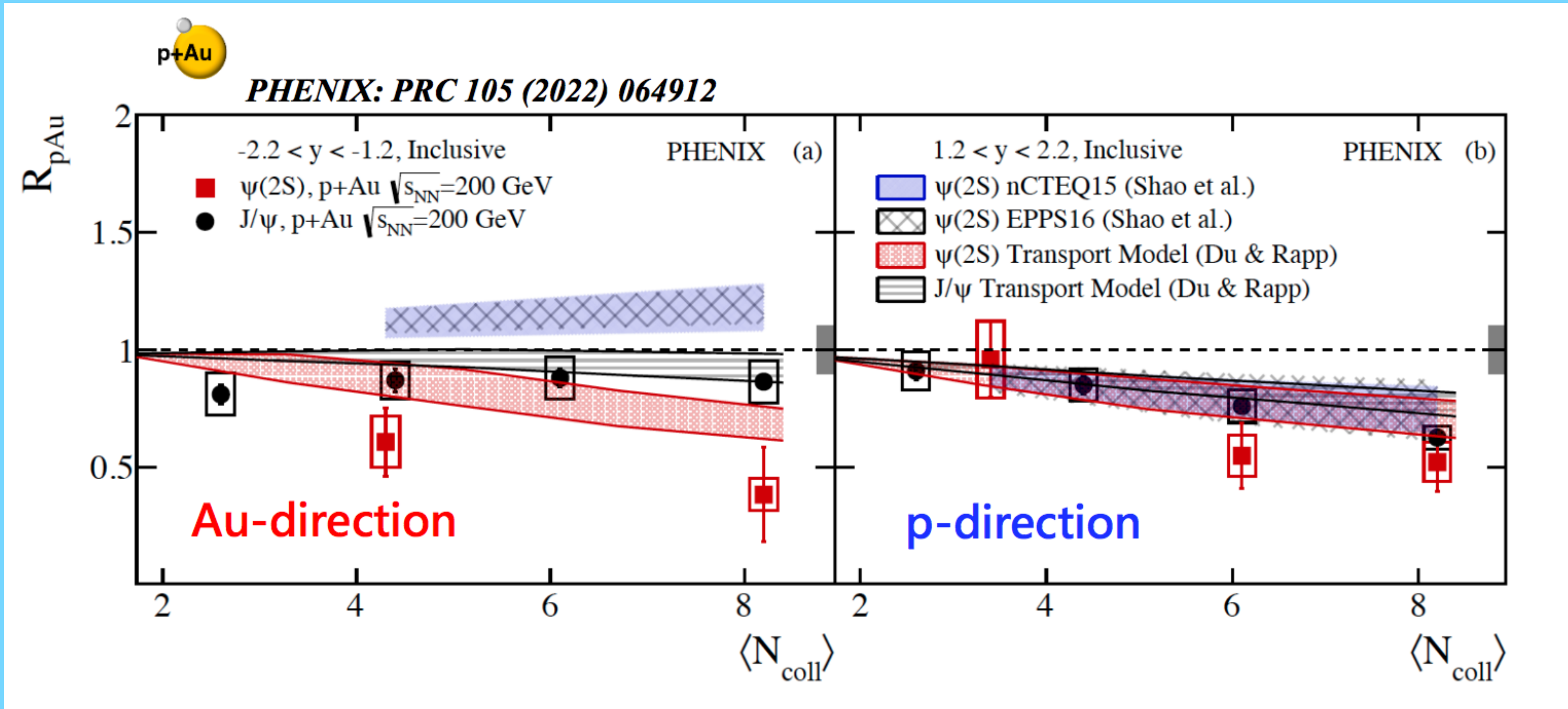




No significant collision system and energy dependence for J/Psi RAA at RHIC :
Jpsi in isobar systems (blue rectangles), in Au+Au 54.4 GeV (red)

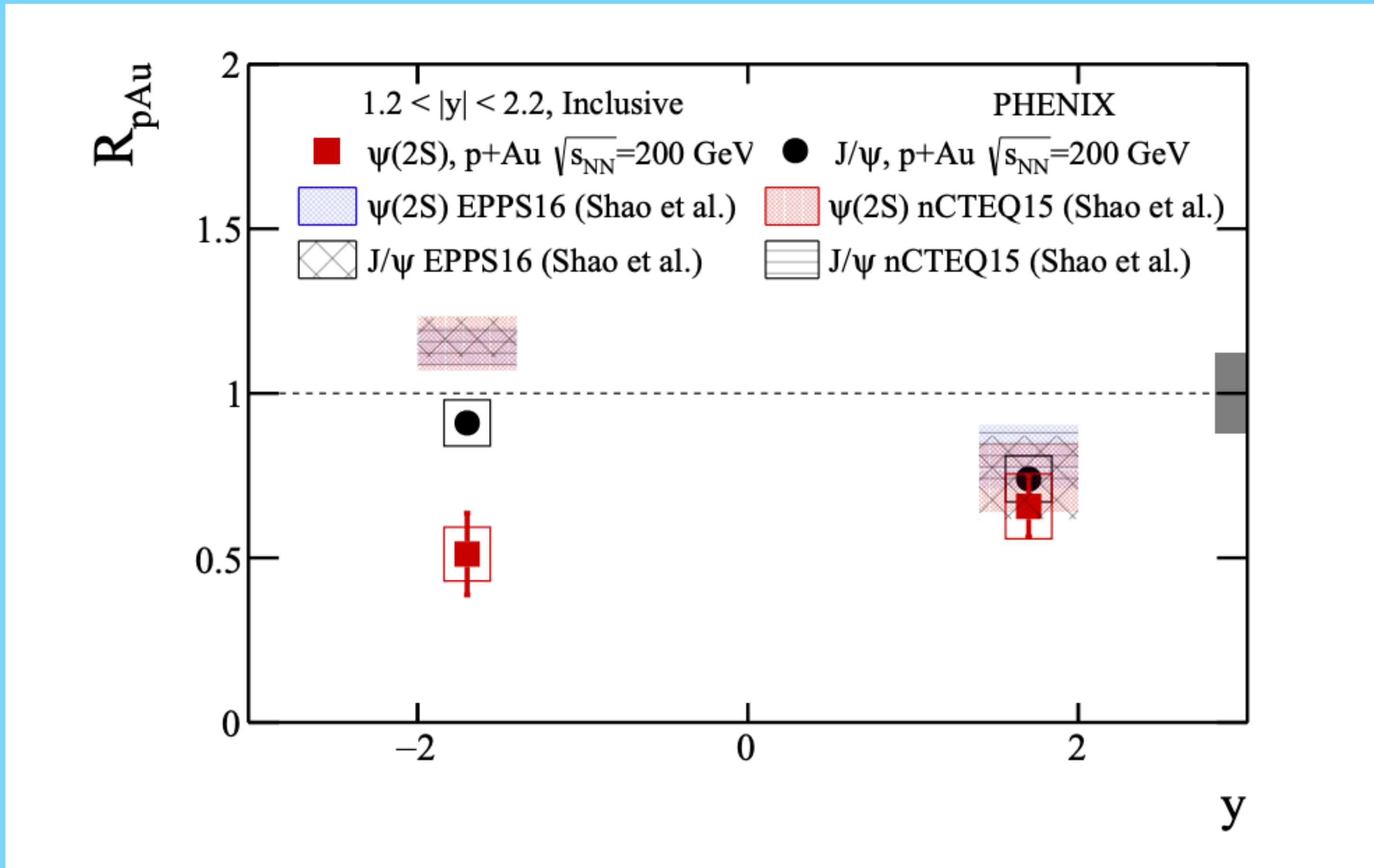
v2 pf J/Psi consistent with zero at low pT: small regeneration and/or flow

PHENIX quarkonia in small systems vs Ncoll



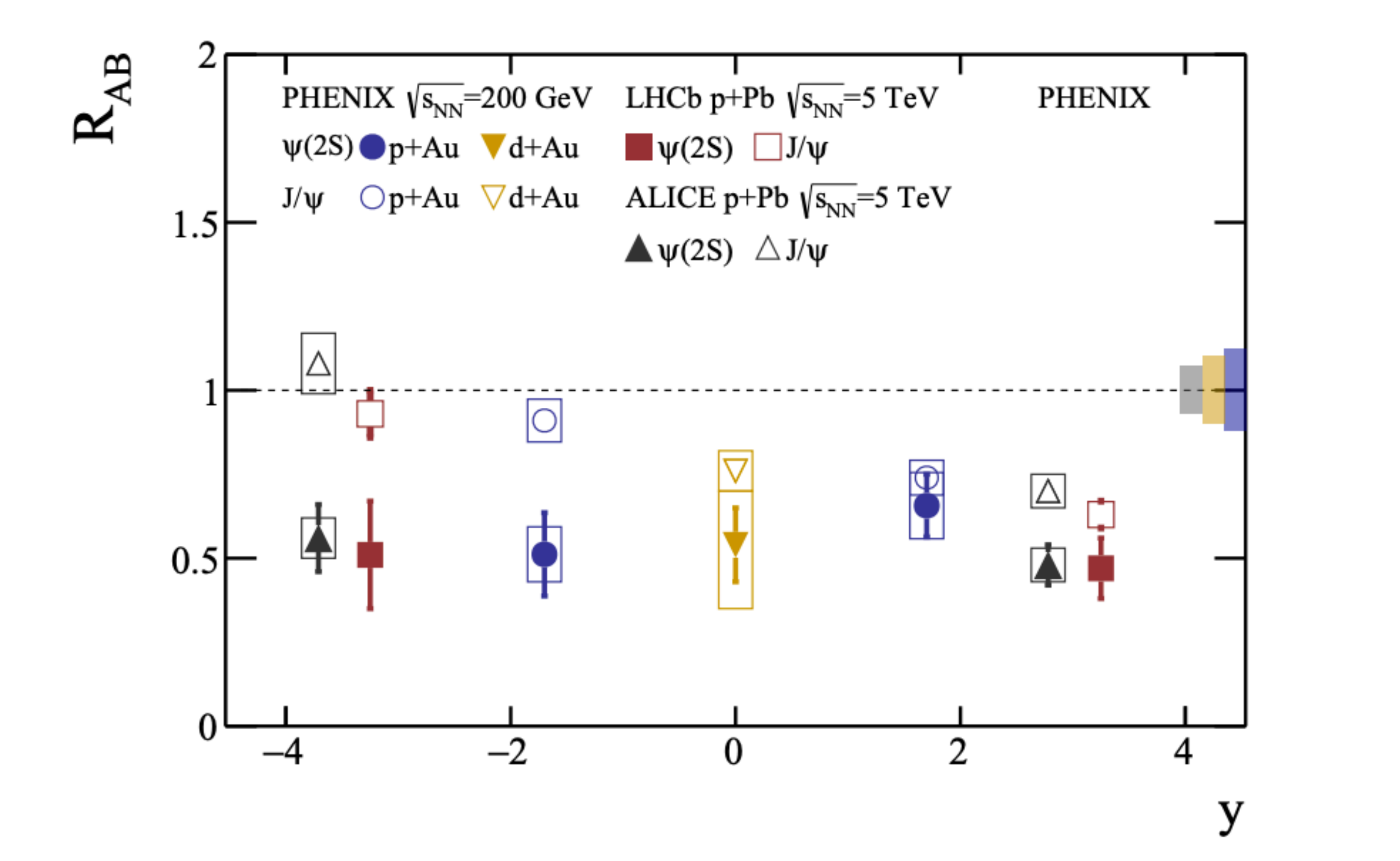
Psi(2S) is more suppressed than J/Psi in Au-direction
nPDF only cannot describe the data
Qualitatively consistent with QGP formation in p+Au collisions at RHIC

PHENIX quarkonia in small systems vs y



The pT and centrality integrated R(pA) as a function of rapidity
At forward y J/Psi and Psi prime coincide and are discribed by shadowing models
At backward y:
  Psi prime is more suppressed that J/Psi and shadowing models lie higher

PHENIX quarkonia in small systems vs LHC



The R(pA,dA) as a function of rapidity for J/Psi (open points) and Psi prime (solid points). At forward y J/Psi and Psi prime show a similar R factor indicating cold nuclear matter effects are dominant.
At backward y, psi prime is more suppressed that J/Psi in all 3 experiments strongly suggesting that final state effects are present in small collision systems

Conclusions and Outlook

Some results:

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

* Flow results suggest strong interaction of charm quarks with medium

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

* Sequential suppression of quarkonia is observed in both RHIC and LHC

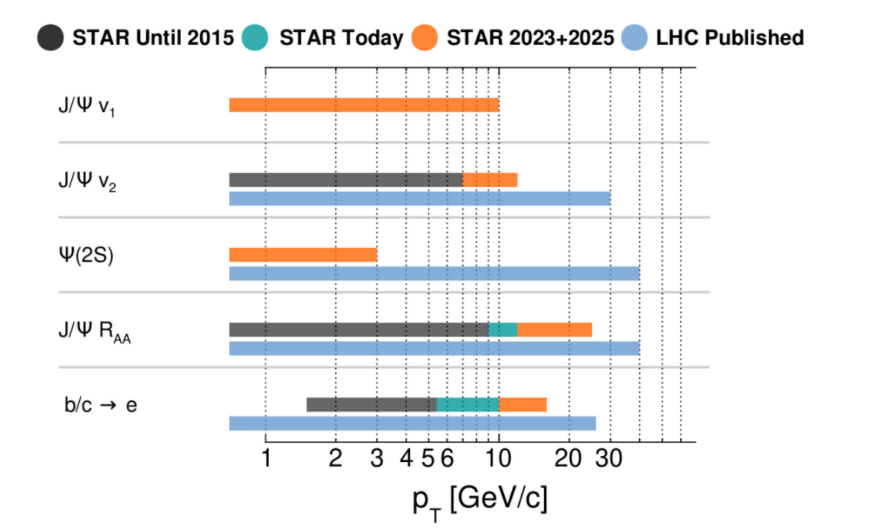
* Psi prime suppressed more than J/Psi in backward rapidity region in small systems

Outlook RHIC

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}



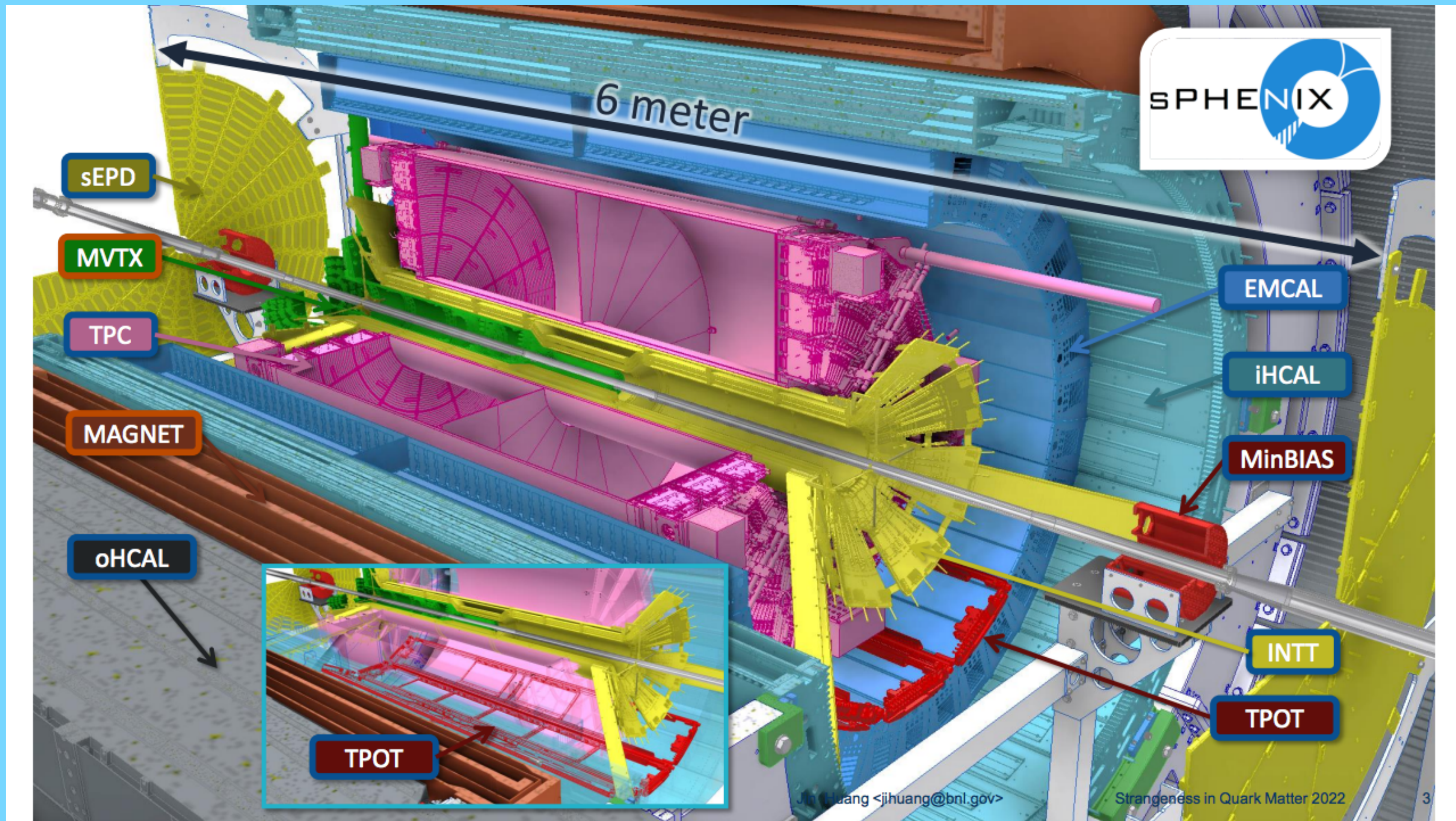
* STAR: Future data will extend the kinematic range for open heavy flavor hadron measurements via semileptonic decays

* 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

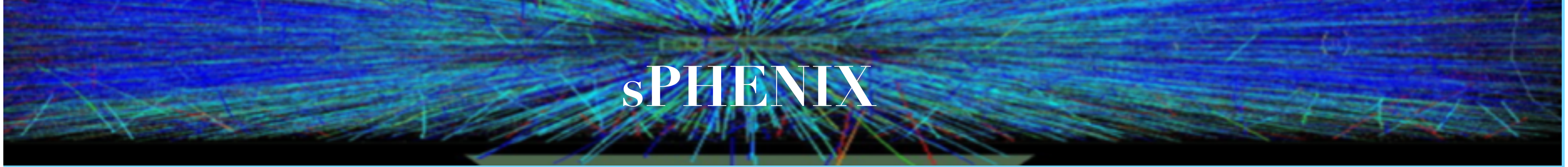
* sPHENIX: starts in 2023

sPHENIX

Extended Calorimetry
precision vertexing
and tracking for
jet quenching, charm,
beauty

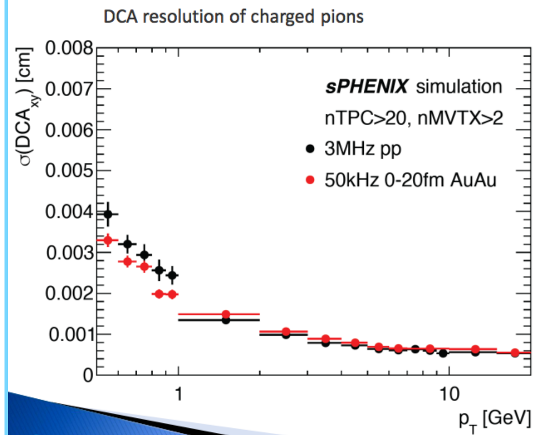


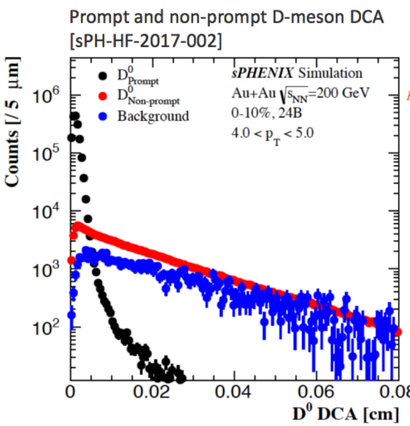
See talk by Sebastian Tapia Araya, Friday in HEP 2023

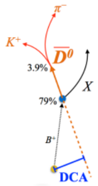


Exceptional performances expected for open heavy flavor

Cleanly separate open bottom meson via DCA

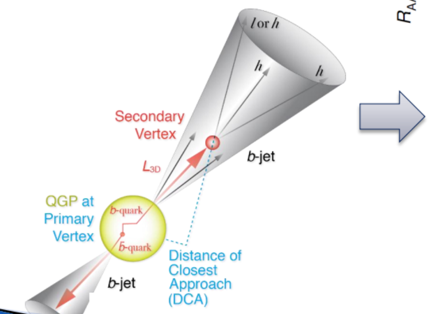


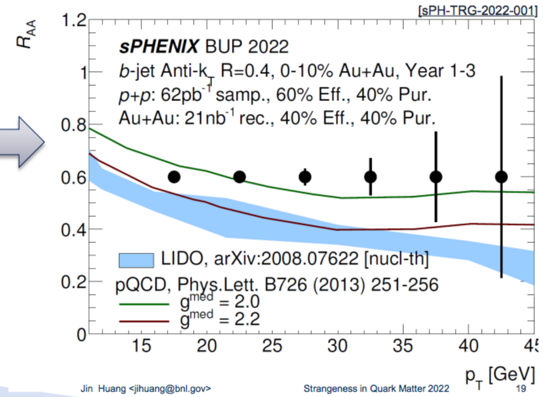




Higher p_T: bottom quark via b-jet

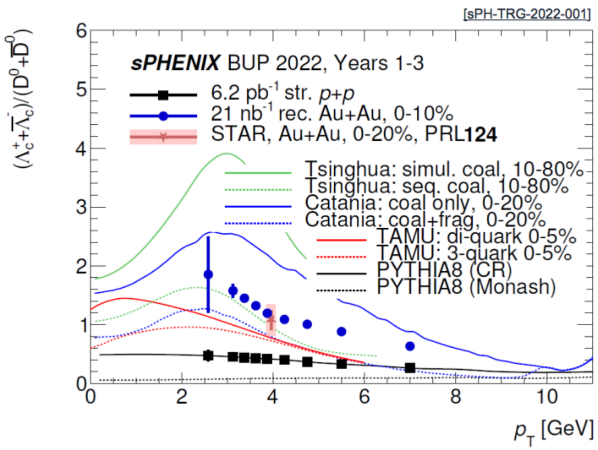
- New for RHIC, enabled by precision tracking and full calorimetric jet





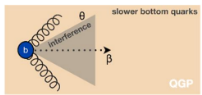
News from beam use proposal 2020 – hadronization

- 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

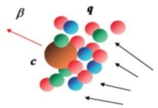


Access b-quark suppression/v2 via non-prompt D

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

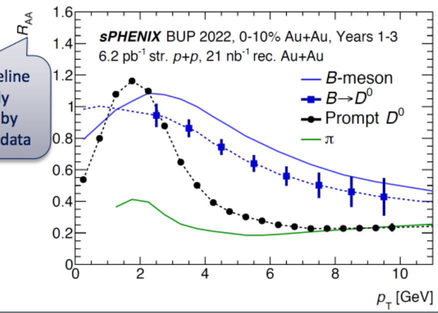


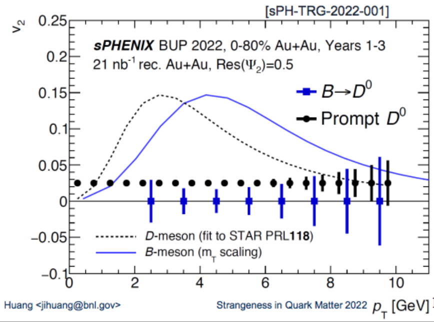
- Probe the mass dependence of quark energy loss in QGP, light → c → b
- Sensitive to pick up collision energy loss



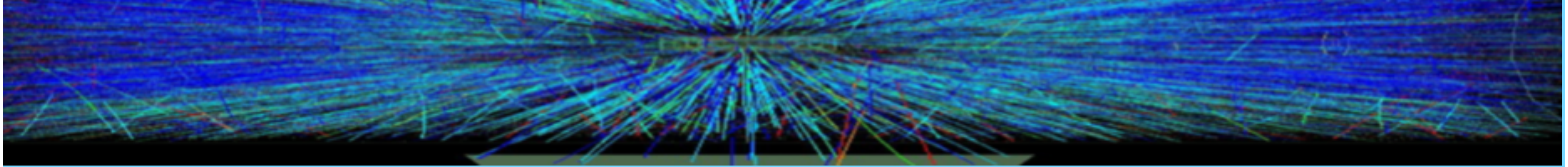
- Determine the bottom quark collectivity
- → clean access to D_{HQ} at RHIC energy

$p+p$ baseline uniquely enabled by streaming data



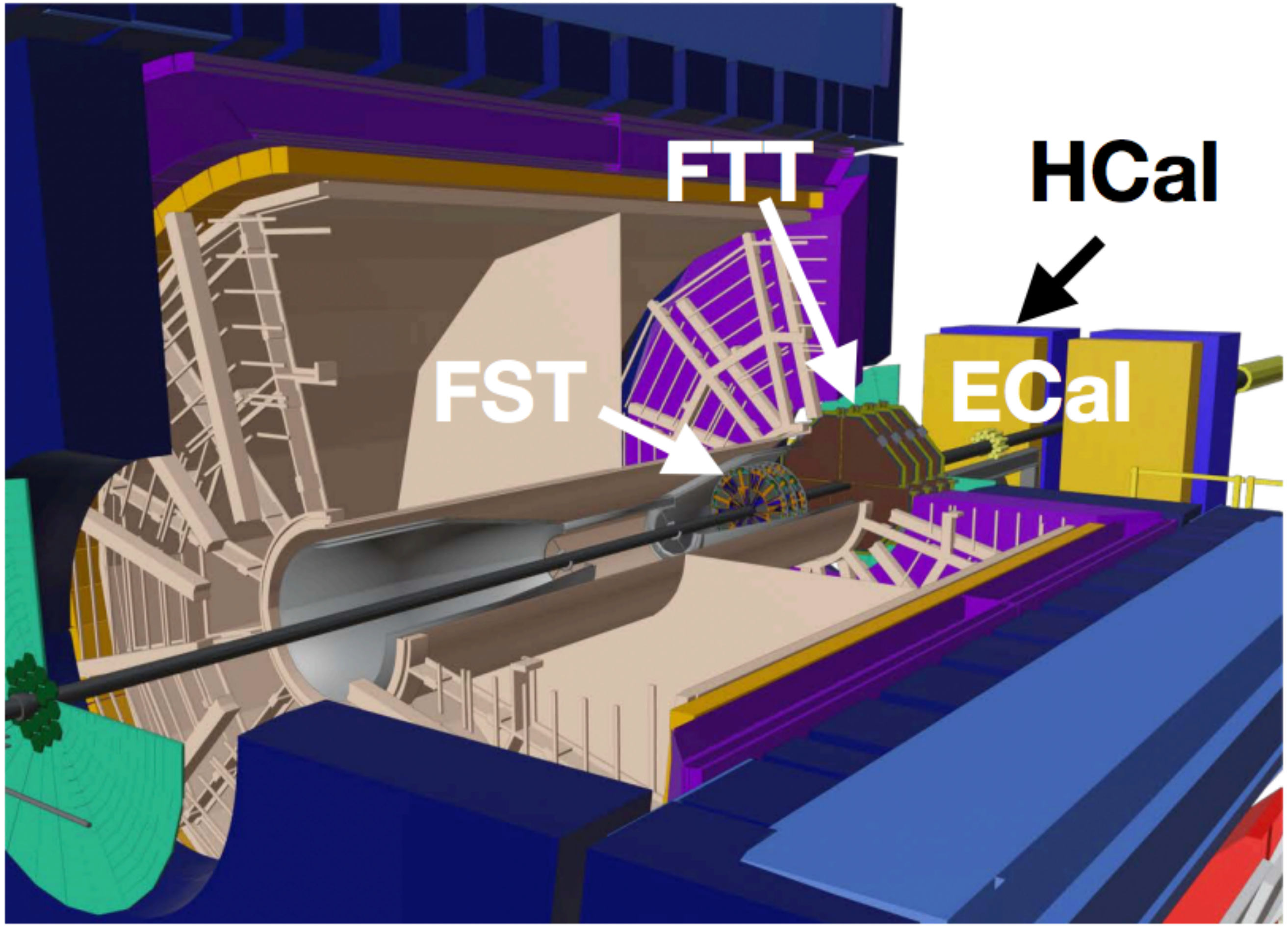


Jin Huang, PHENIX Collaboration, SQM2022



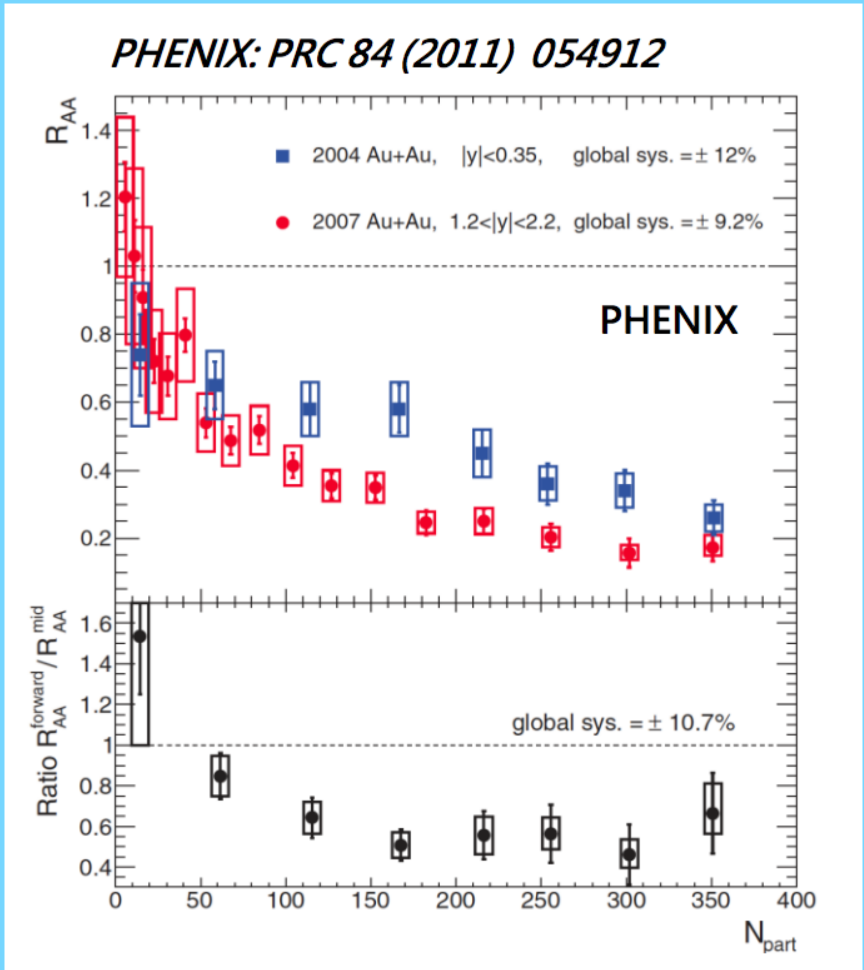
Thank you very much

STAR forward upgrade

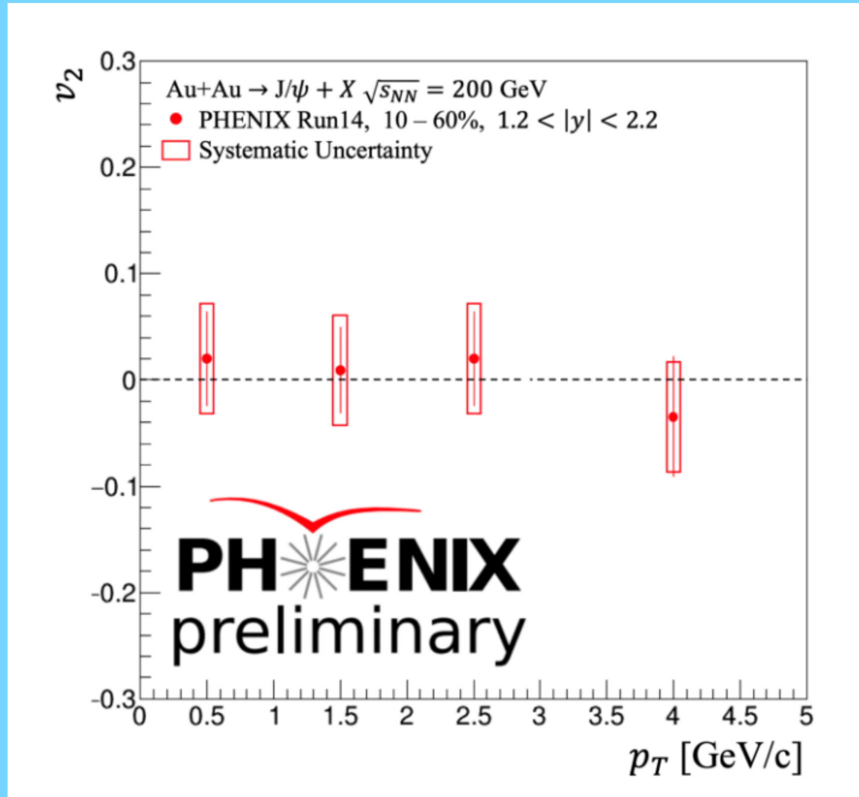


- Forward Tracking System (FTS)
  - Forward Silicon Tracker (FST)
  - Forward Small-strip Thin Gap Chambers Tracker (FTT)
- Forward Colorimeter System (FCS)
  - Electromagnetic Calorimeter
  - Hadronic Calorimeter

PHENIX quarkonia in Au+Au



More suppression of J/Psi observed in forward rapidity (red points) might be due to recombination in central rapidity

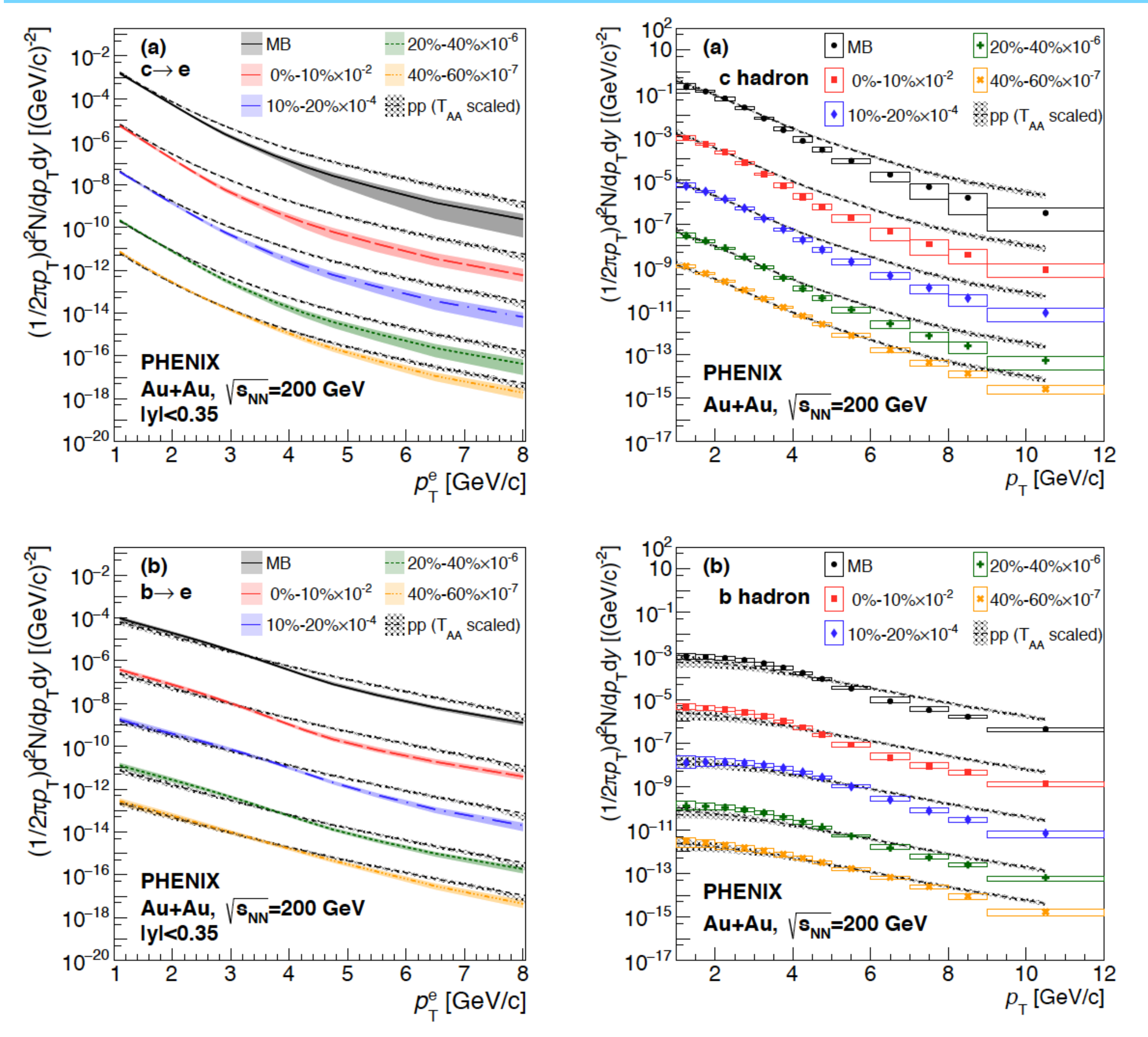


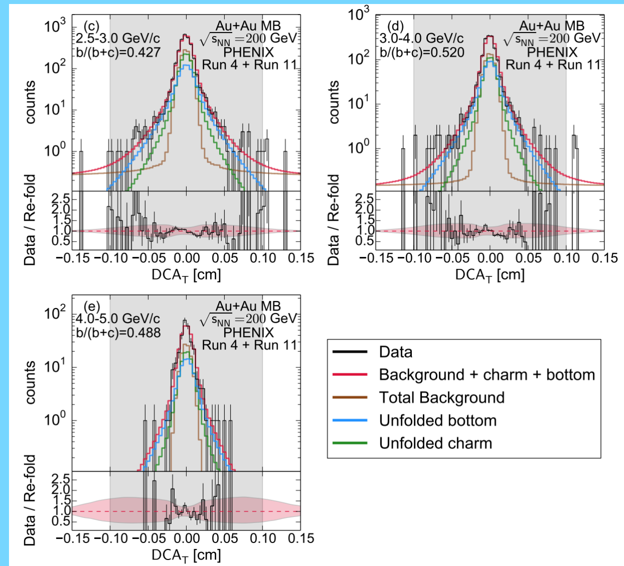
Elliptic flow of J/Psi in forward rapidity is consistent with zero supporting no recombination present at forward rapidity

A. Drees et al (PHENIX Collaboration)ICNFP 2022

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



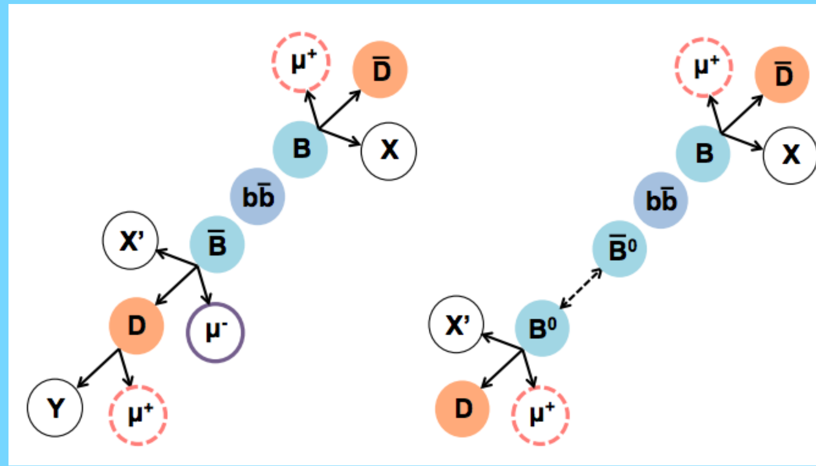


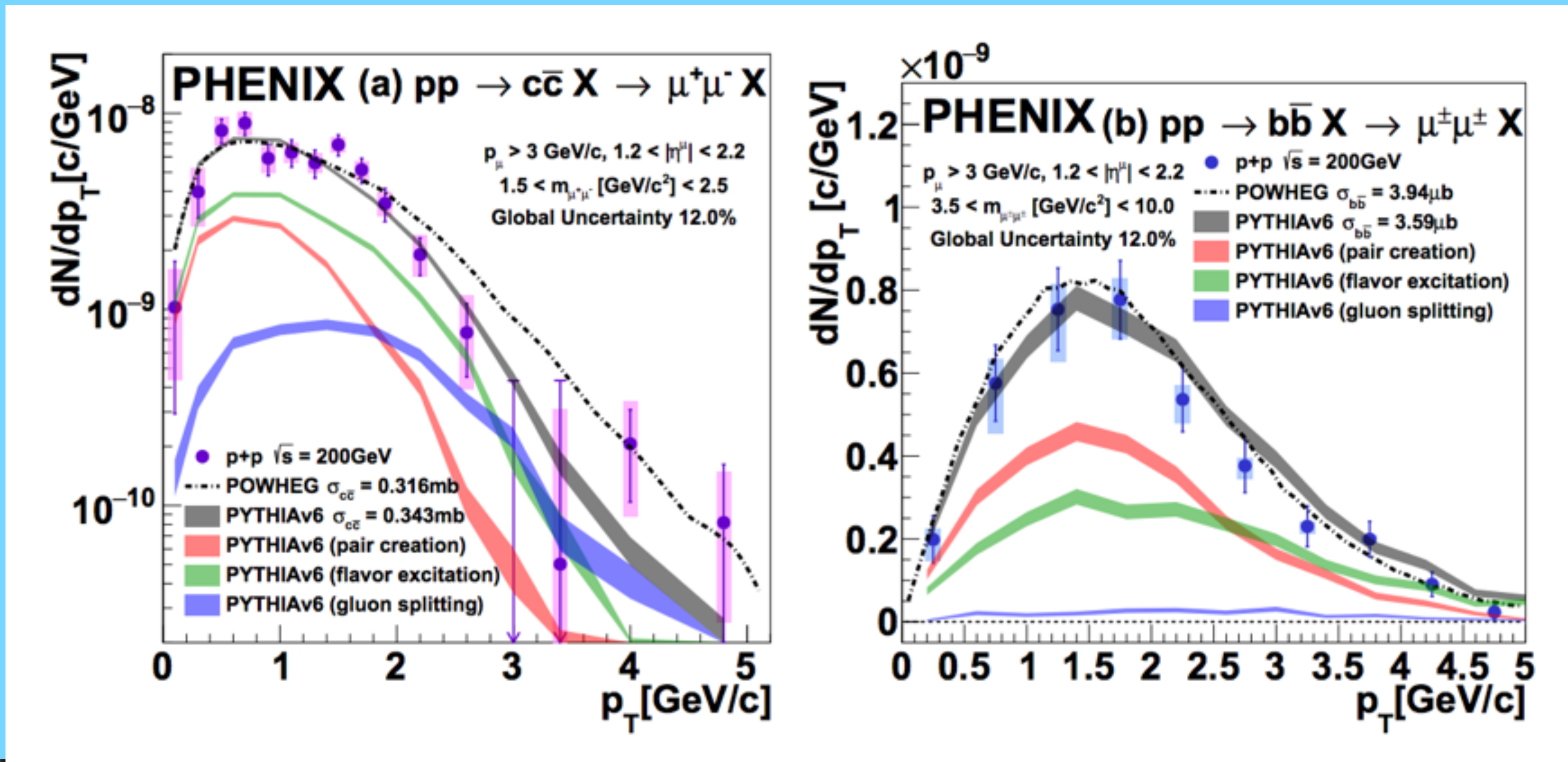
* Left c—> e and b—> e in Au+Au compared to p+p scaled by number of collisions

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

PHENIX (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 Total charm cross section

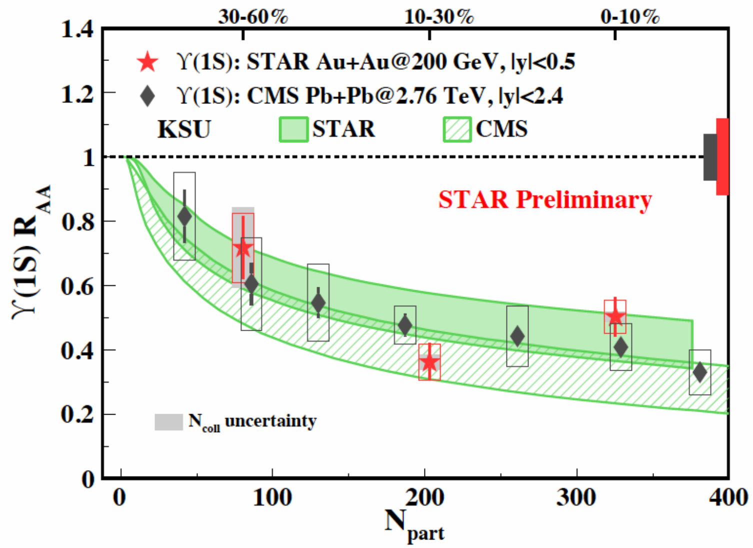
Collision System	Hadron	$d\sigma_{NN}/dy$ [μb]
Au+Au at 200 GeV Centrality: 10-40% $0 < p_T < 8$ GeV/c	D^0 [1]	39 ± 1 ± 1
	$D^{\pm}$	18 ± 1 ± 3*
	D_s [2]	15 ± 2 ± 4
	Λ_c [3]	40 ± 6 ± 27**
	Total	112 ± 6 ± 27
p+p at 200 GeV [4]	**Total**	130 ± 30 ± 26

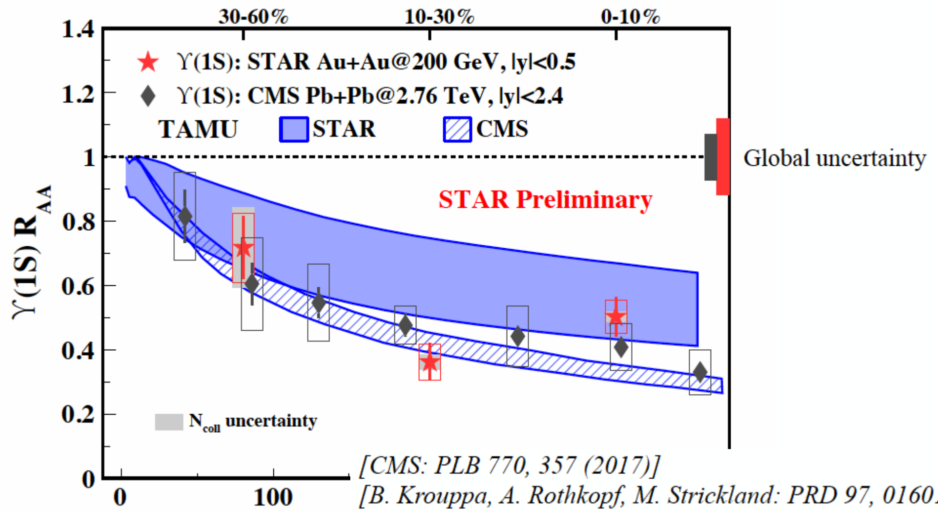
D^0 [1] STAR, Phys. Rev. C 99 (2019) 034908
D_s [2] STAR, Phys. Rev. Lett. 127 (2021) 092301
Λ_c [3]STAR, Phys. Rev. Lett. 124 (2020) 172301
p+p [4] STAR, Phys. Rev. D 86 (2012) 072013

* 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

Upsilon Υ(1S): STAR vs LHC vs models





[CMS: PLB 770, 357 (2017)]
[B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)]
[X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)]

KSU model: use a lattice-vetted heavy-quark potential

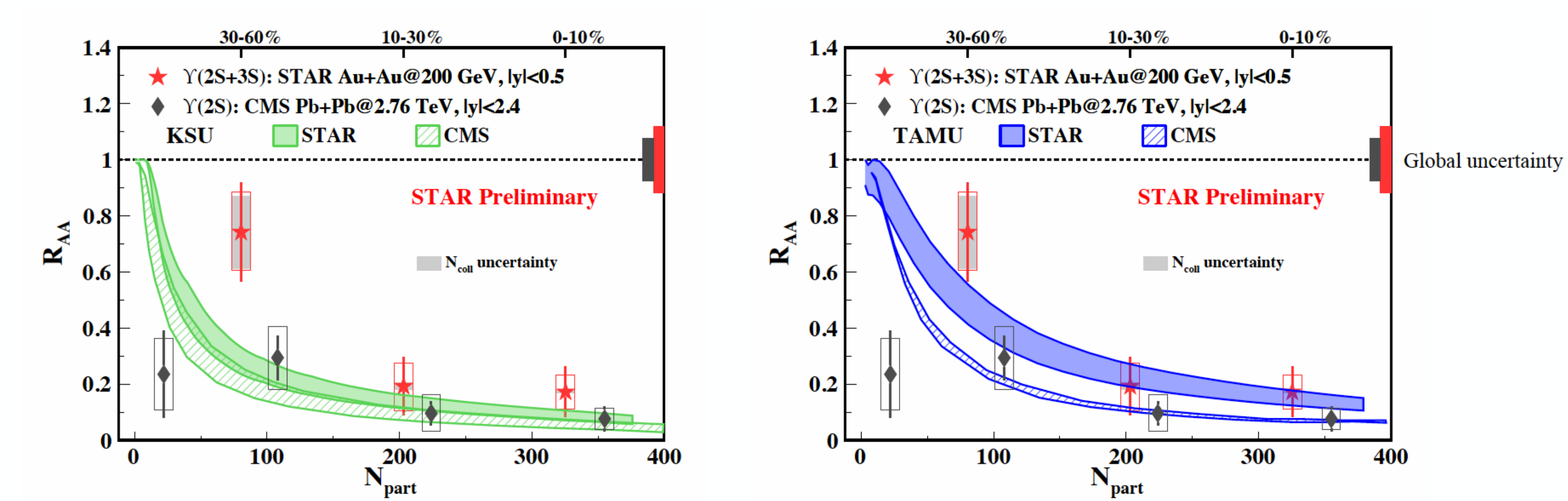
TAMU model: use in-medium binding energies predicted by thermodynamic T-matrix calculations using internal-energy potentials, from lattice QCD

T_0^{QGP} (MeV)	RHIC (0.2 TeV)	LHC (2.76 TeV)
KSU	440	546
TAMU	310	555

STAR data on Υ(1S) are consistent with LHC data

KSU and TAMU models are consistent with data on Υ(1S) from RHIC (STAR) and LHC (CMS)

Upsilon Υ(2S+3S): STAR vs LHC vs models



[CMS: PLB 770, 357 (2017)]
[B. Krouppa, A. Rothkopf, M. Strickland: PRD 97, 016017 (2018)]
[X. Du, M. He, and R. Rapp: PRC 96, 054901 (2017)]

Υ(2S+3S):

- **Indication of less suppression at RHIC than at LHC**

  STAR: Υ(2S+3S) R_{AA}: 0.35 ± 0.08 (stat.) ± 0.10 (sys.) ($0 < p_T < 10$ GeV/c, 0-60%)

  CMS: Υ(2S) R_{AA}: 0.08 ± 0.05 (stat.) ± 0.03 (sys.) ($0 < p_T < 5$ GeV/c, 0-100%)

KSU and TAMU models are consistent with data on Y(2S+3S) in central and semi-central collisions from RHIC (STAR) and LHC (CMS)

STAR Y data in central A+A collisions are consistent with "sequential melting" in QGP (Y(1S) vs Y(2S+3S))

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