STRONG-2020

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Energy Dependence of *Open and Hidden* Heavy Flavor Production at RHIC

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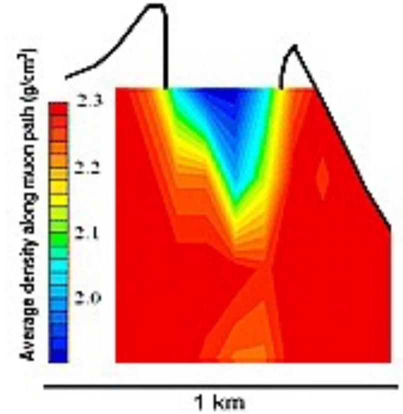
Outline

- Introduction
- Open heavy flavor
- Quarkonium
- Outlook

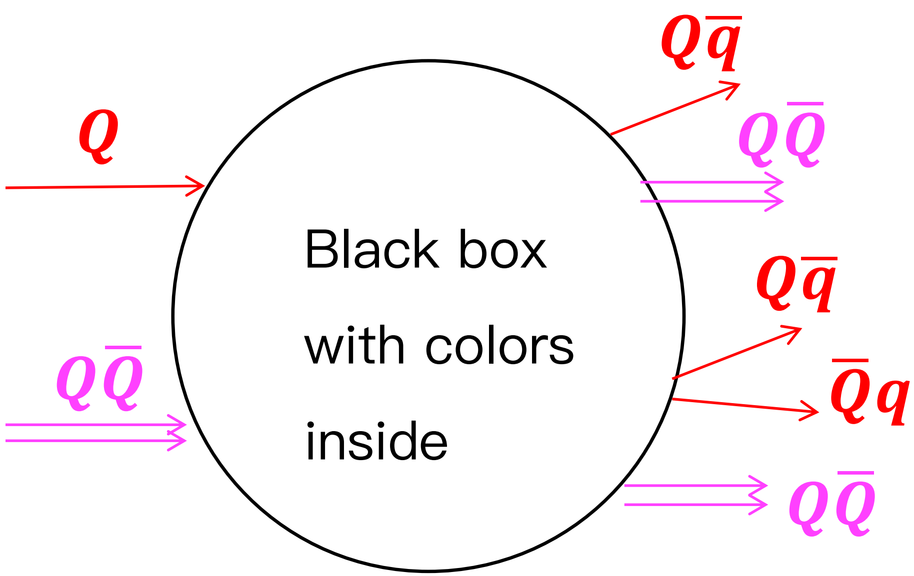
Heavy Flavor Tomography of QGP

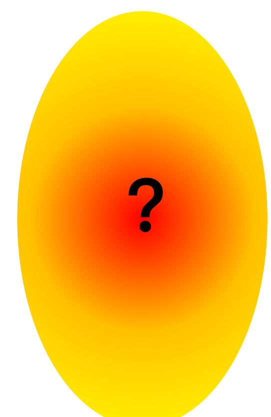
Muon Tomography



H. Tanaka et. al., JGR 115, B12332 (2015)

HF Tomography





Complications in HF Tomography

Initial condition

- Production mechanism not well understood
- Cold nuclear matter effects contribute crucial background

Transport in QGP ➔ Goal

- Properties of the medium and its evolution
- Interaction of HF with the medium

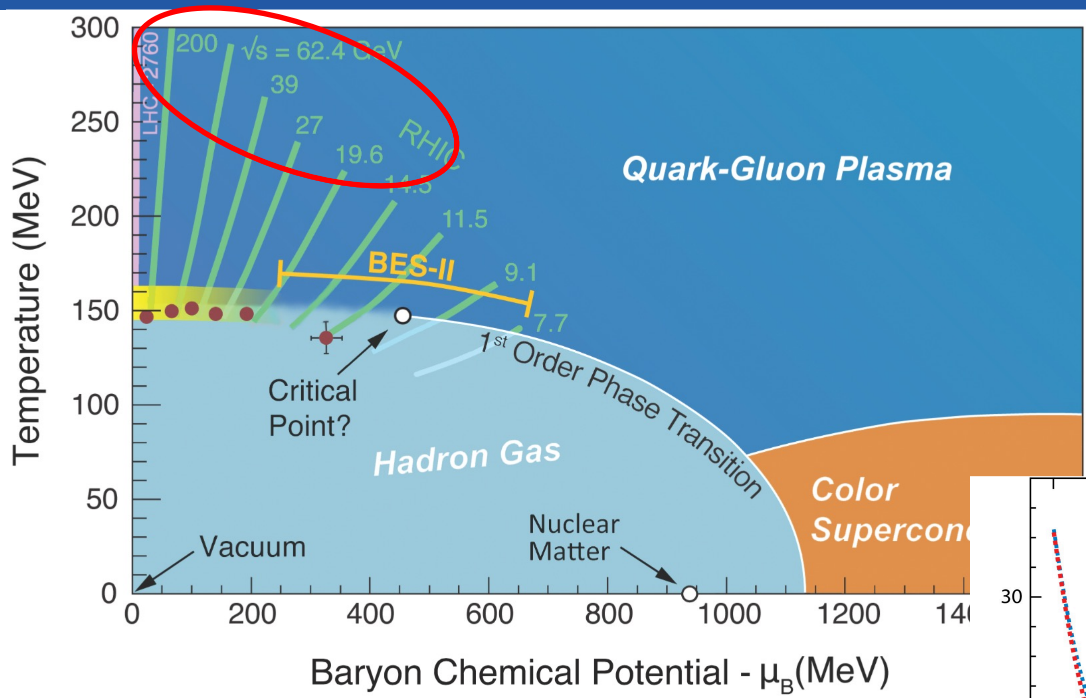
Hadronization

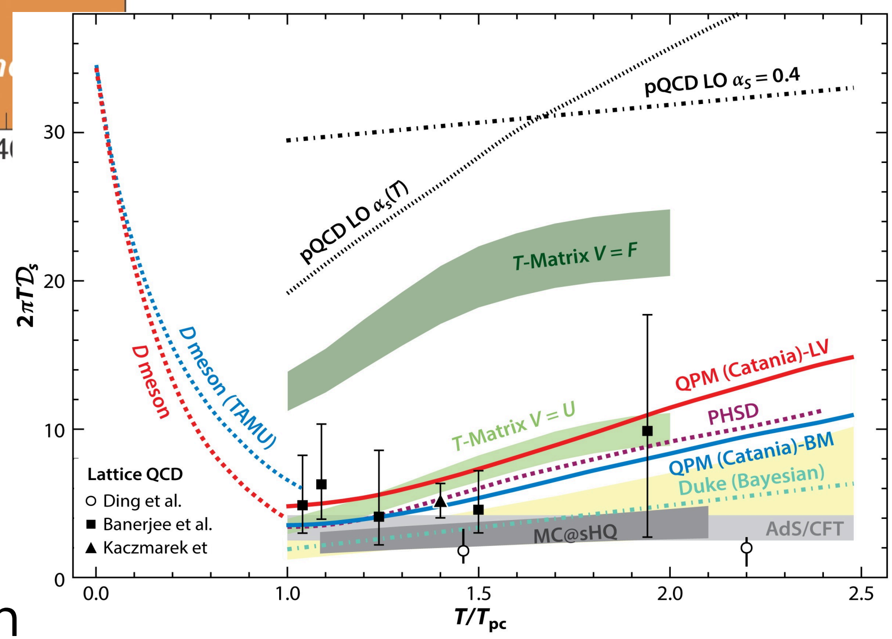
- Coalescence vs. fragmentation
  - Different charm hadrochemistry in *pp* vs. *ee* observed

Transport in hadronic phase

+ Measuring the outgoing particles is also very challenging

Tune QGP Pars. by Scanning $\sqrt{s_{NN}}$





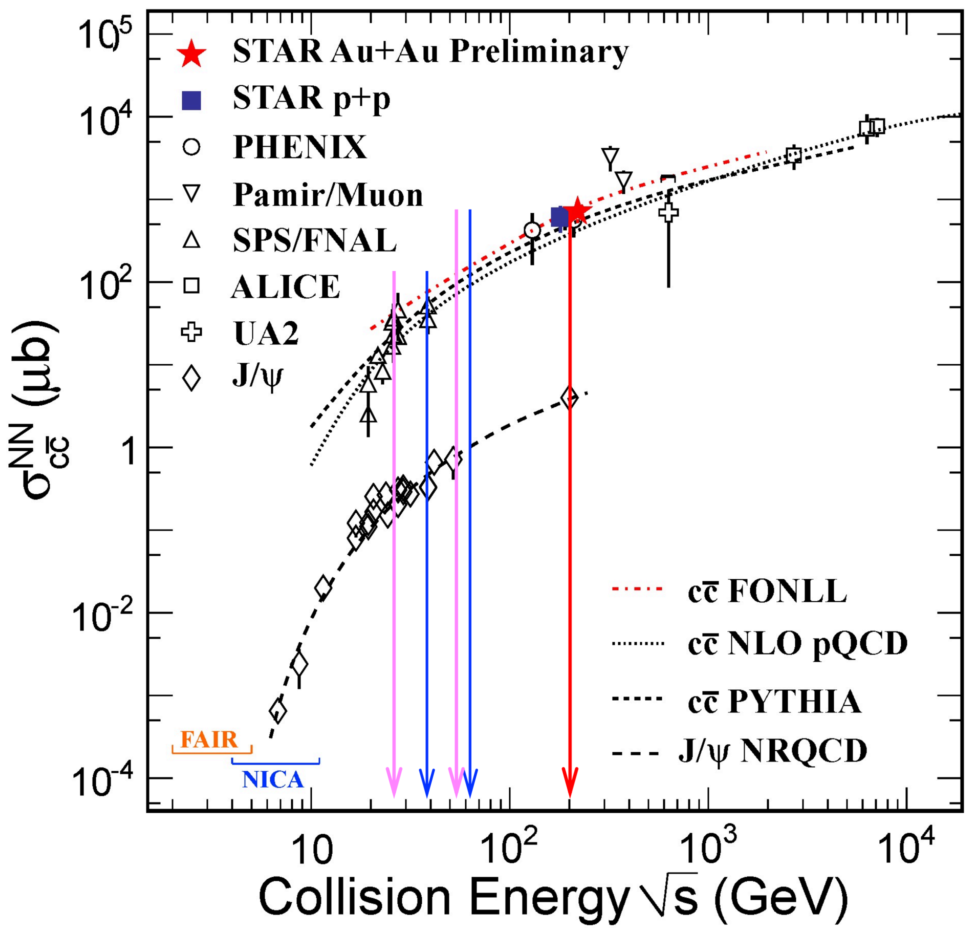
Dong X, et al. 2019.
Annu. Rev. Nucl. Part. Sci. 69:417–45

Different trajectory in the phase diagram with different collision energy

Adding another dimension to (hopefully) provide more information

Datasets for Energy Dependence Study

$\sqrt{s_{NN}}$	MB Events	Year	μ_B MeV
200	~1000 ~1800	2010+2011 2014+2016	25
62.4	46	2010	73
54.4	1200	2017	83
39	86	2010	112
27	560/30	2018/2011	156
19.6	538/15	2019/2011	206
17.3	250	2021	230
14.5	325/13	2019/2014	264
11.5	230/7	2020/2010	315
9.2	160/0.3	2020/2008	355
7.7	100/3	2021/2020	420



X. Luo et al., Particles 2020, 3, 278

PHENIX decommissioned in 2017

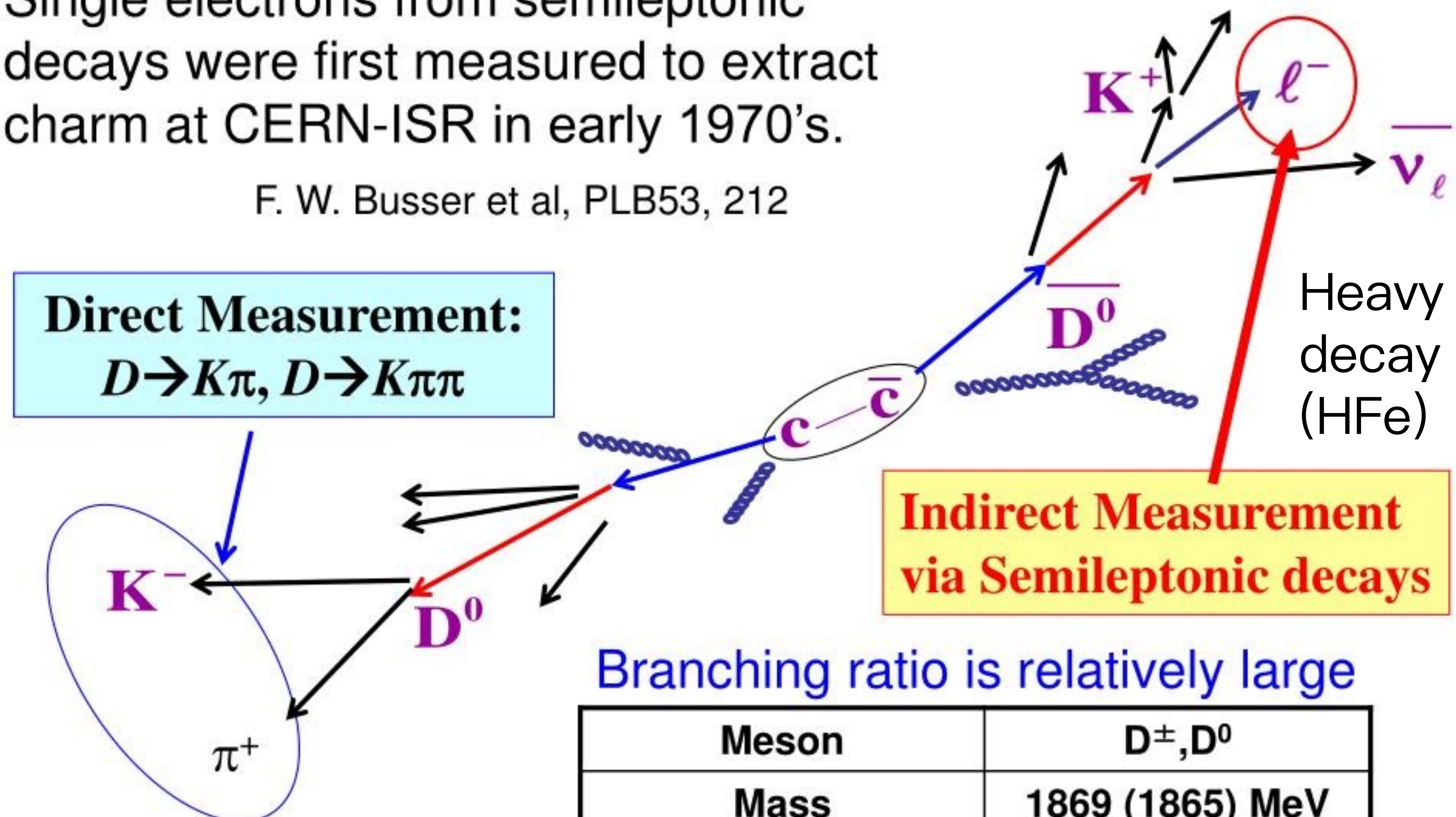
X–section decreases dramatically
~5x from 200 to 54 GeV

Open Heavy Flavor

Methods: Direct and Indirect

Single electrons from semileptonic decays were first measured to extract charm at CERN-ISR in early 1970's.

F. W. Busser et al, PLB53, 212



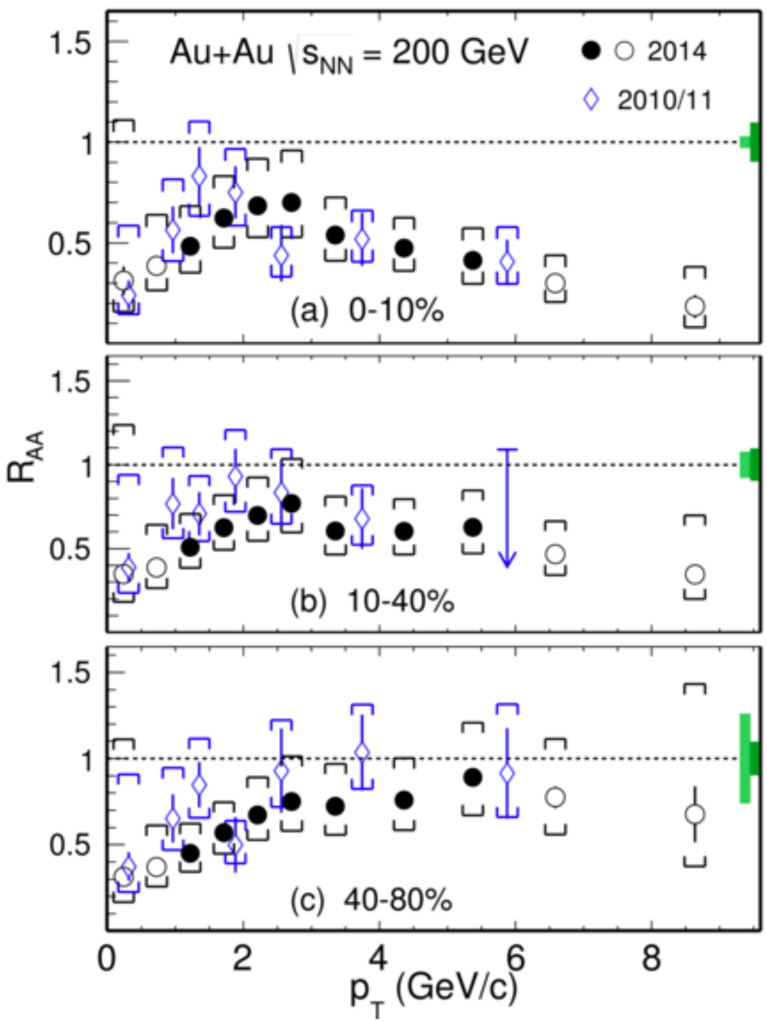
Branching ratio is relatively large

Meson	$D^{\pm}$,D^0
Mass	1869 (1865) MeV
BR: $D^0 \rightarrow K\pi$	(3.85 ± 0.10) %
BR: $D \rightarrow e + X$	$D^{\pm}$: 17.2, D^0: 6.7 %

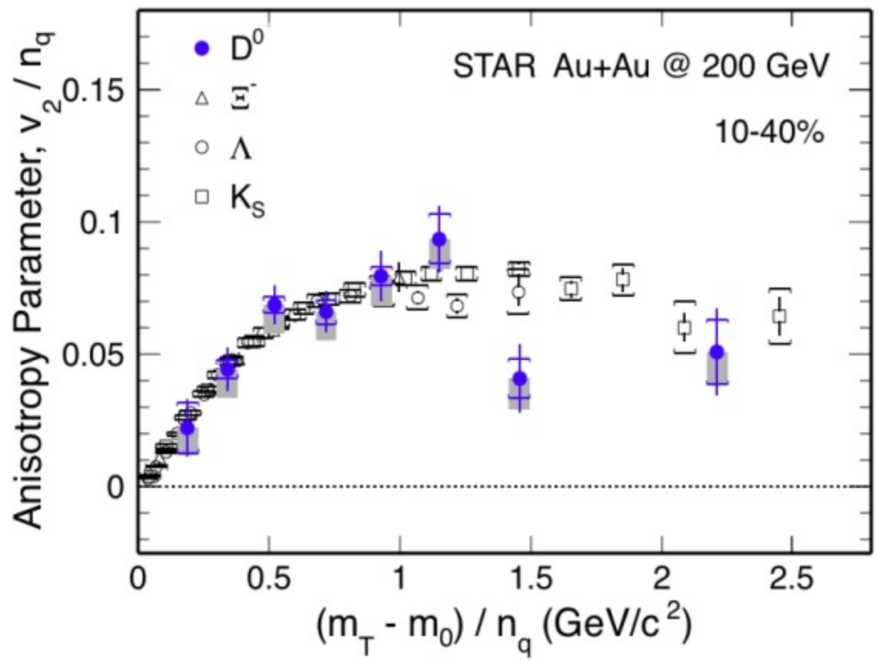
Slide of Fukutaro Kajihara

D^0 in Au+Au at 200 GeV

STAR, PRC99, 034908 (2019)



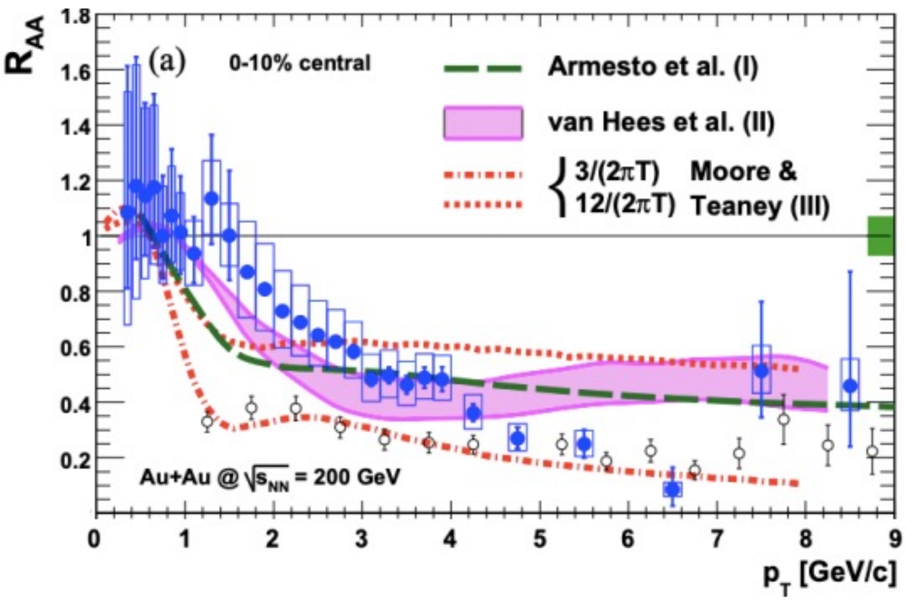
STAR, PRL118, 212301 (2017)

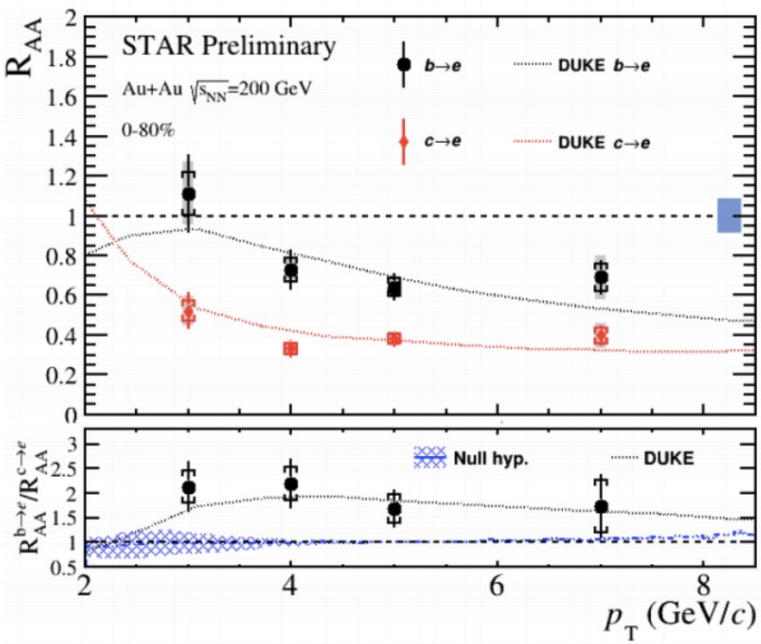


- Significant suppression in central collisions in all p_T bins
- v_2 follows NCQ scaling with light hadrons

HFe Suppression in Au+Au at 200 GeV

PHENIX, PRL98, 172301 (2007)

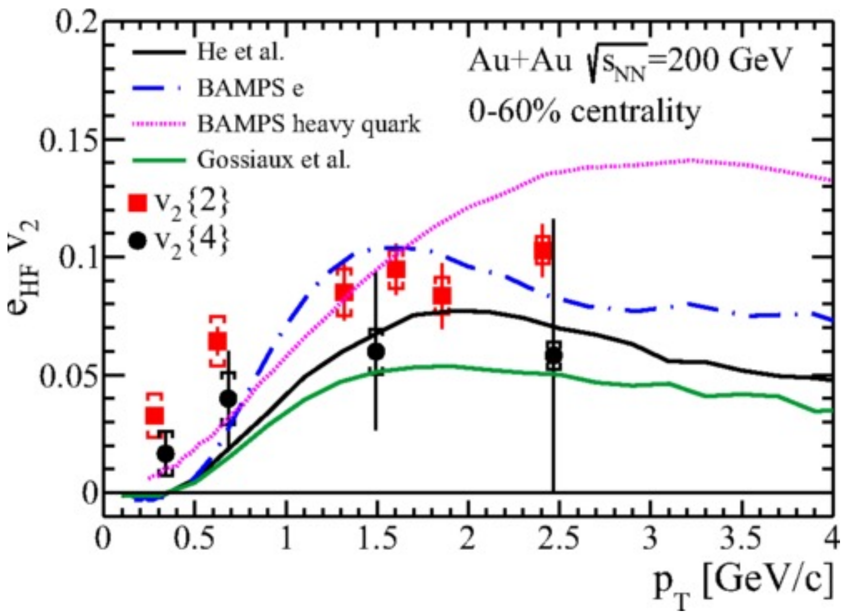


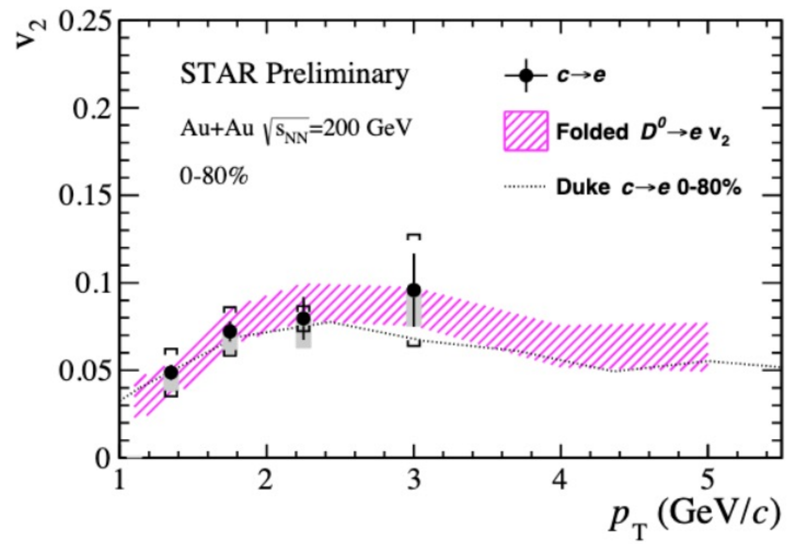


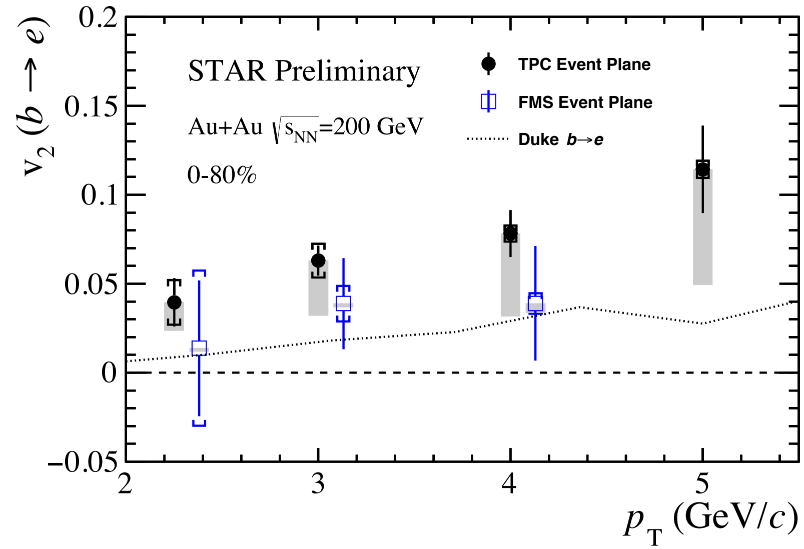
- Strong suppression of HFe at high p_T
- Less suppression of b→e than c→e

HFe Flow in Au+Au at 200 GeV

STAR, PRC95, 034907 (2017)

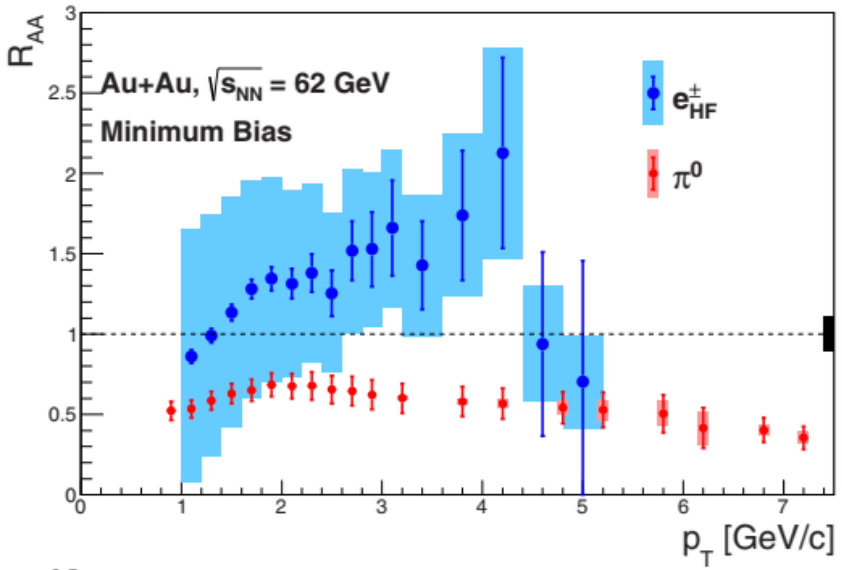


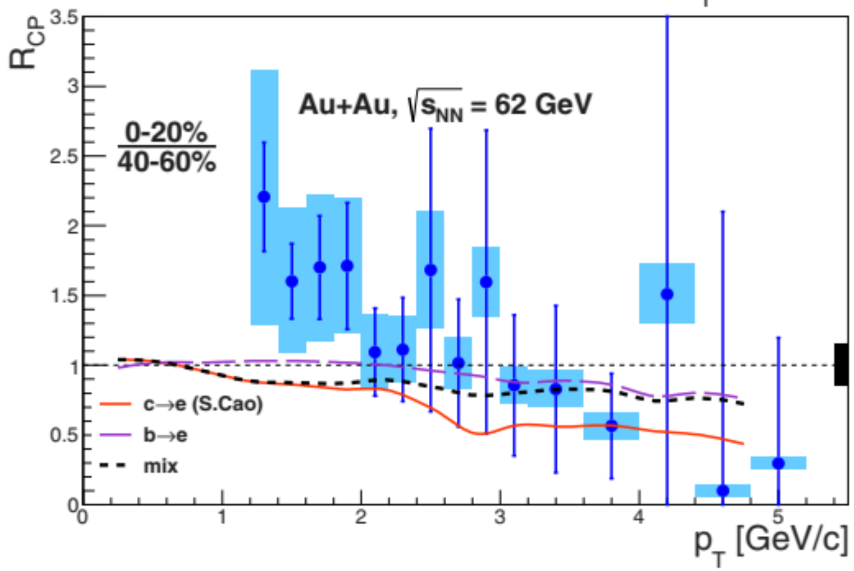




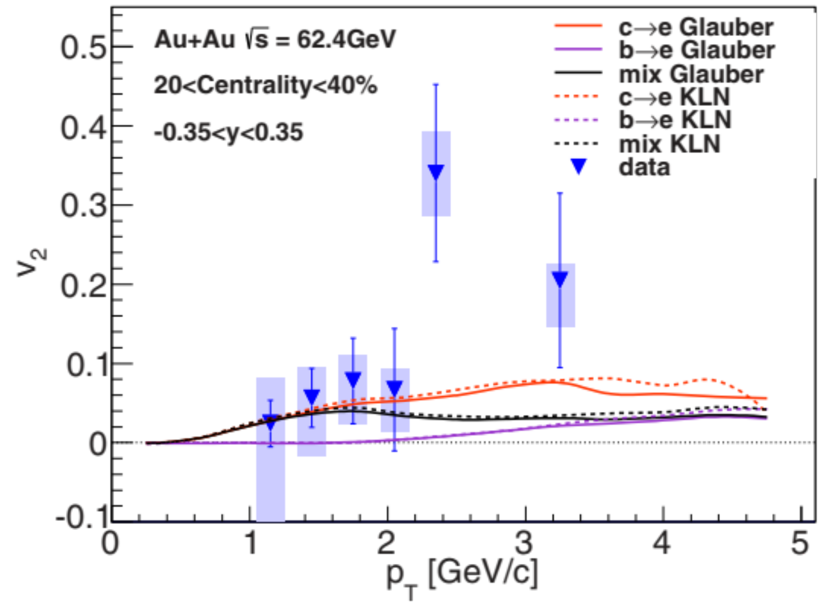
- Significant v_2 for HFe
- c→e v_2 consistent with D^0 v_2
- Non zero b→e v_2 observed

HFe Production in Au+Au at 62 GeV





PHENIX, PRC91, 044907 (2015)



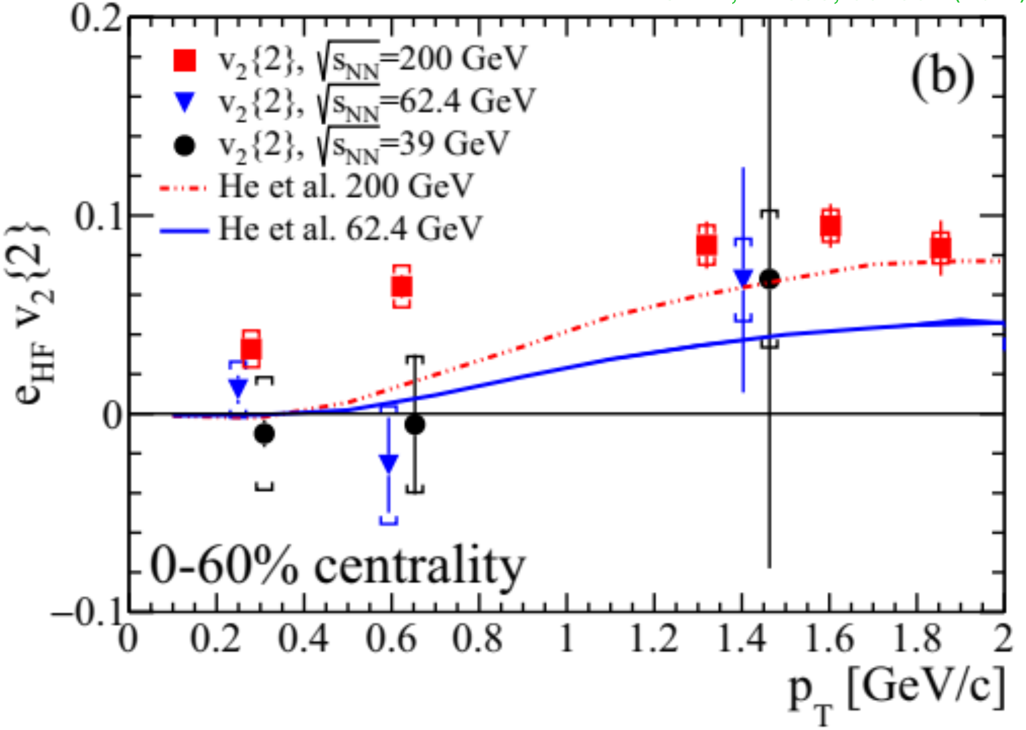
- Enhancement of yield
  Cronin effect play a role?

- But sizable v_2

HFe Flow in Au+Au at 62 and 39 GeV

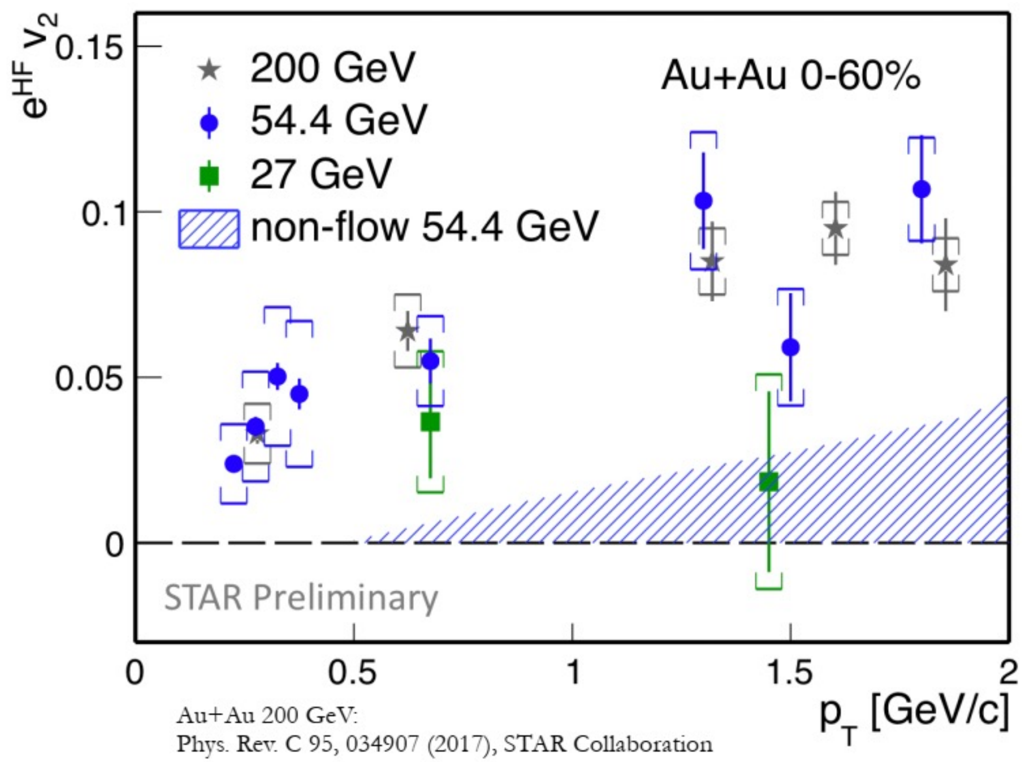
First attempt to lower energy at STAR

STAR, PRC95, 034907 (2017)



- v_2 at 62 and 39 GeV consistent with zero within uncertainties
- Systematically smaller than that at 200 GeV for p_T <1 GeV/c though uncertainties are large

HFe Flow in Au+Au at 54.4 and 27 GeV

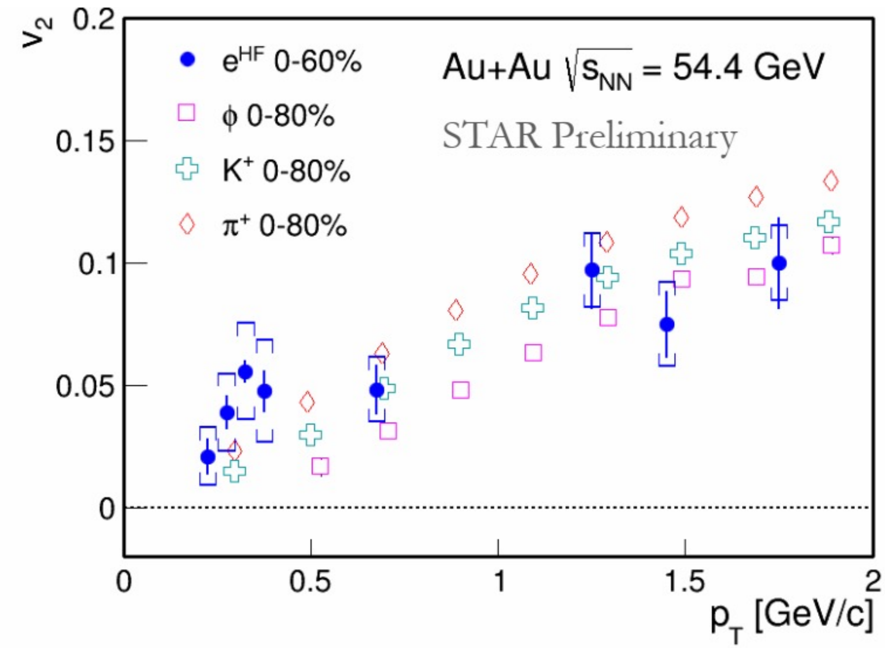


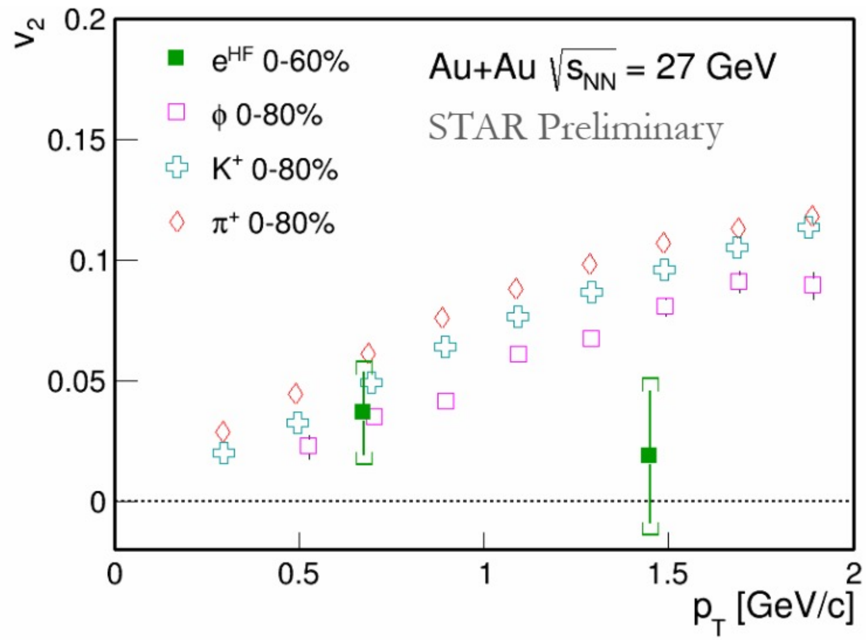
- Significant v_2 for HFe observed at 54.4 GeV and comparable to that at 200 GeV

  ➔ Charm quark interact strongly with the medium at 54.4 GeV

- v_2 at 27 GeV seems smaller than that at higher energies

Comparison to Light Hadrons





54.4 GeV:

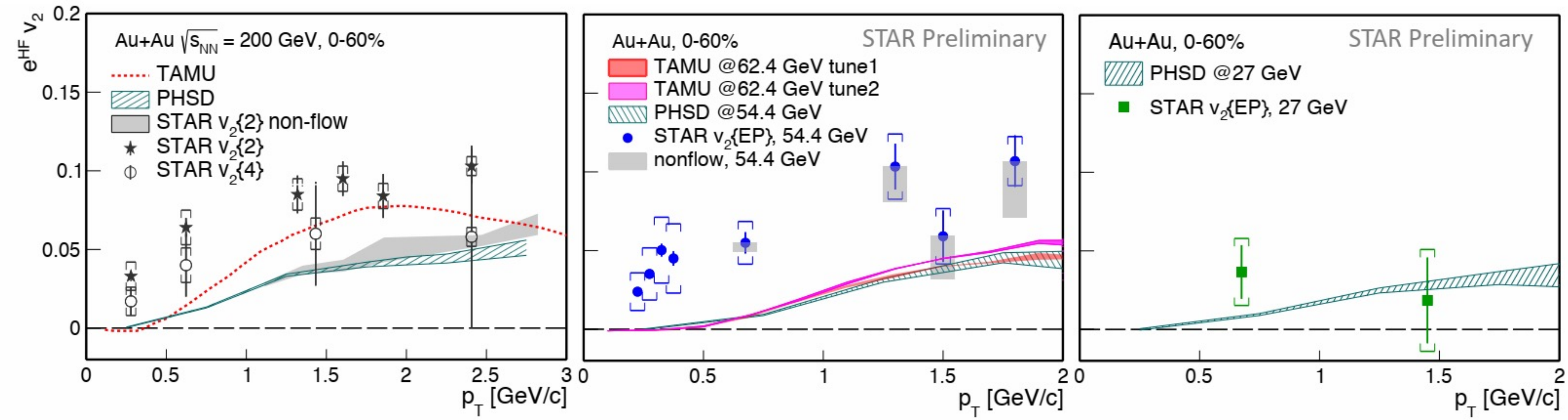
v_2 of HFe is comparable to those of light hadrons

27 GeV:

Hint of HFe v_2 at p_T>1 GeV/c lower than those of light hadrons

Comparison to Theory

M. He et al. PRC 91,024904 (2015)
T. Song et al. PRC 92, 014910 (2015)
T. Song et al. PRC 96, 014905 (2017)



- TAMU and PHSD calculations are comparable to data at p_T>1.4 GeV/c considering the upper limit of estimated non–flow and uncertainties
- The calculations are lower than data at p_T < 1 GeV/c

Summary of Open Heavy Flavor

See Xin Dong's talk

200 GeV:
- Yield consistent with flavor–dependent parton energy loss
- Significant flow for charm and non–zero flow for bottom

➔ Charm strongly interact with medium and reach local equilibrium

62 & 54 GeV:
- Enhancement of yield for HFe at 62 GeV
- Significant of v_2 for HFe at 54 GeV and comparable to 200 GeV
- Flow described by transport models

➔ Charm strongly interact with medium but CNM may also play a role

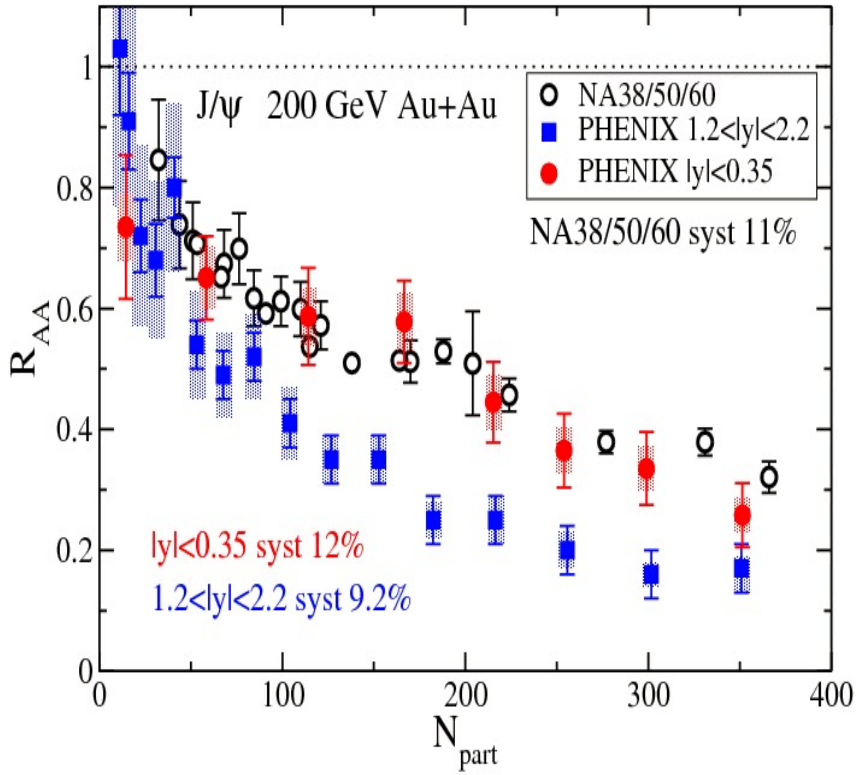
27 GeV:
- No yield measurement
- v_2 for HFe seems have different behaviors than those at higher energies and light hadrons

➔ No enough precision to draw firm conclusion

Quarkonium

RHIC J/ψ Puzzles (History)

See Enrico Scomparin's talk



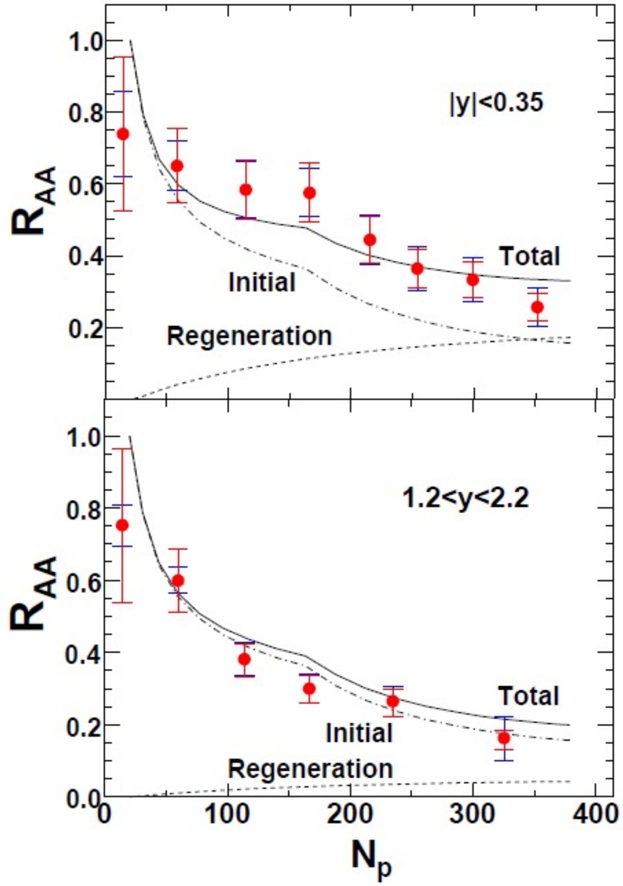
Mid-rapidity:
Similar suppression as SPS

Forward rapidity:
More suppression than in mid-rapidity

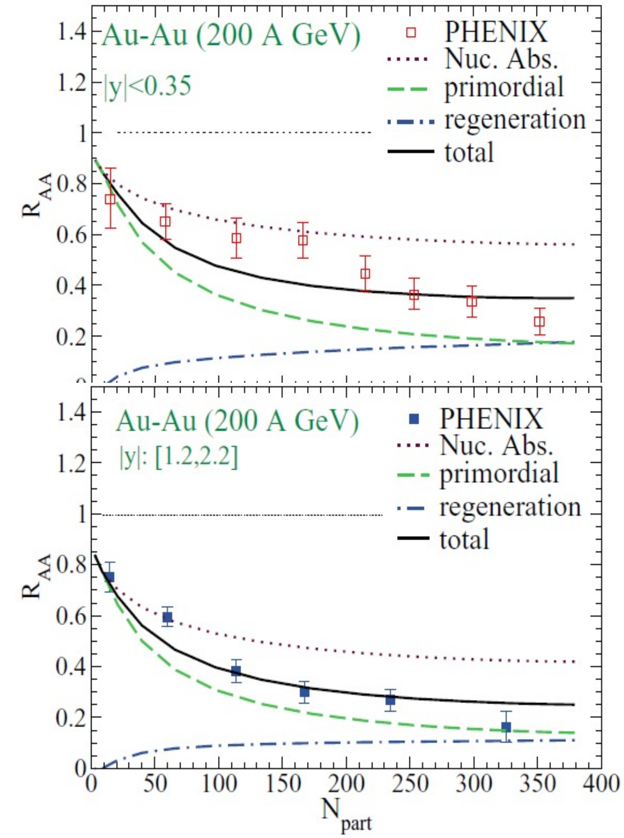
Two Puzzles!!

QGP Melting, Regeneration and CNM

Z. Qu, Y. Liu, N. Xu, P. Zhuang, NPA830, 335c (2009)



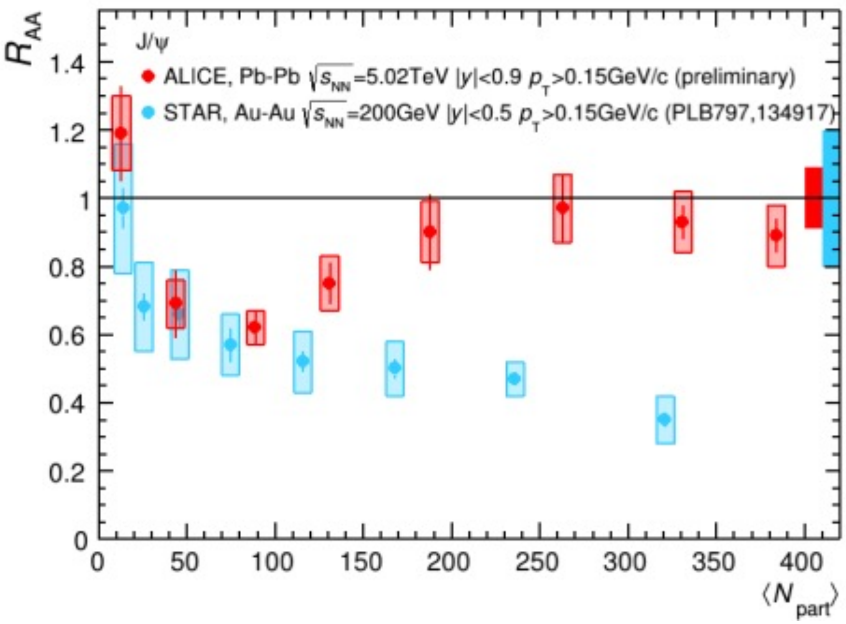
X. Zhao, R. Rapp, PRC82, 064905 (2010)

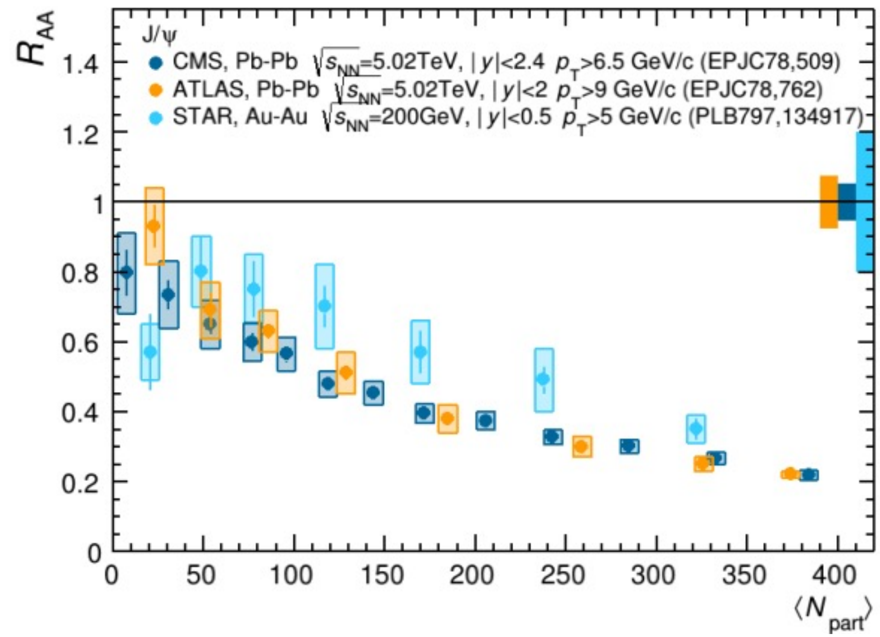


Interplay of QGP melting, regeneration and CNM effects

From RHIC to LHC

See Roberta Arnaldi's talk





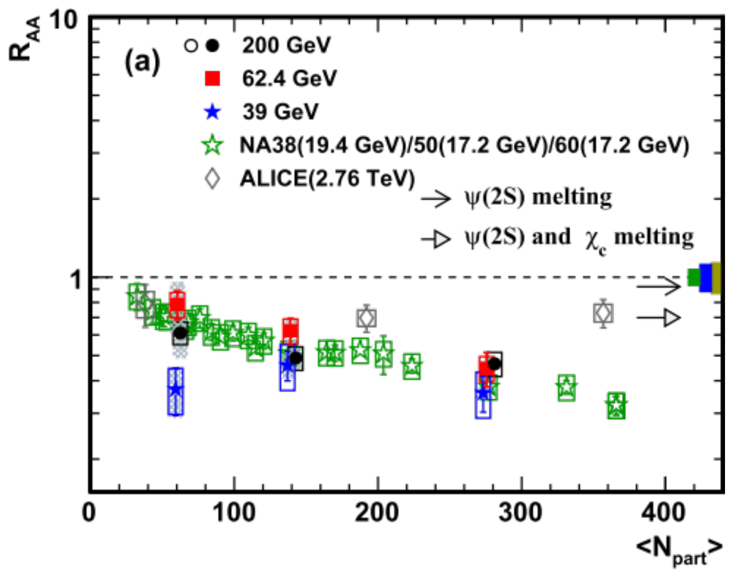
- Increase of R_{AA} in (semi-)central collisions

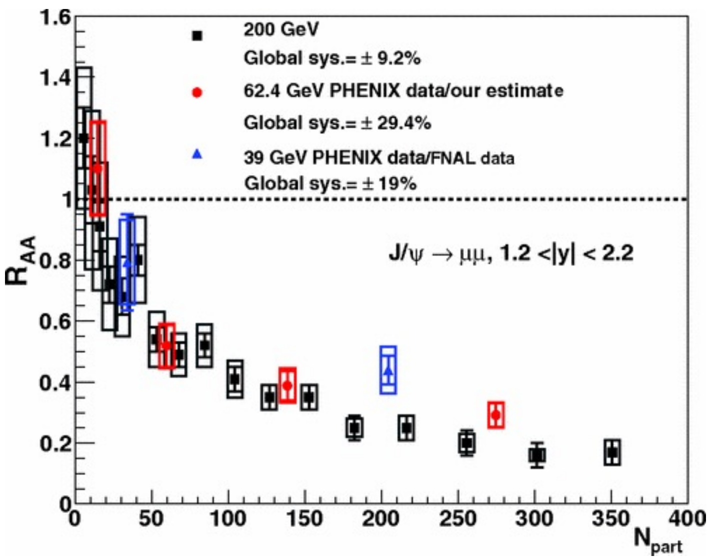
➔ Evidence of regeneration

- Strong suppression at high-p_T
- Stronger at LHC than at RHIC

➔ Evidence of QGP melting

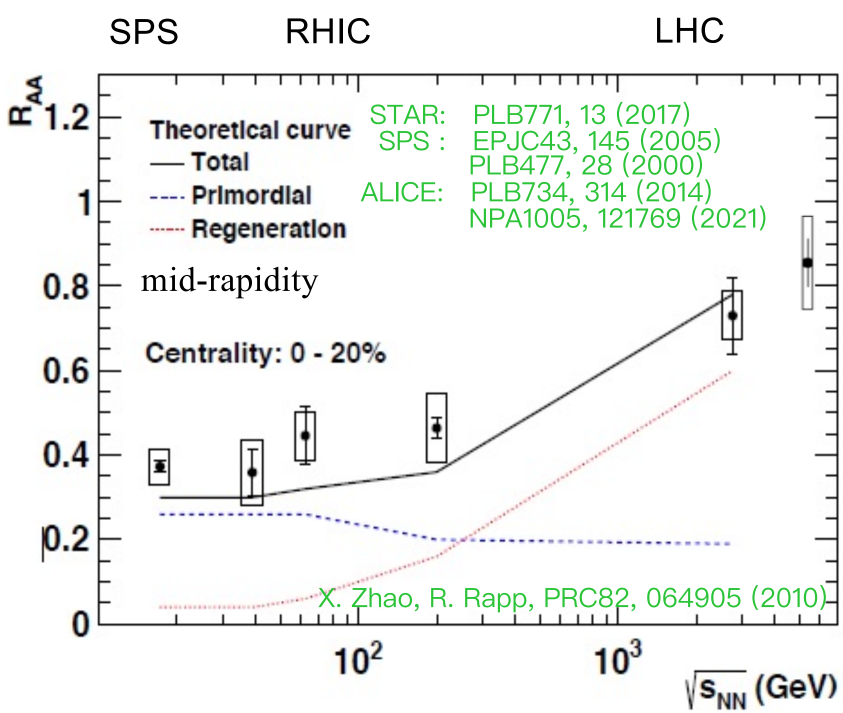
Towards SPS Energy





R_{AA} in Au+Au at 62 and 39 GeV consistent with those at 200 GeV at both mid– and forward rapidity within uncertainties

Energy Dependence at Mid–rapidity



Nuclear absorption: ↗

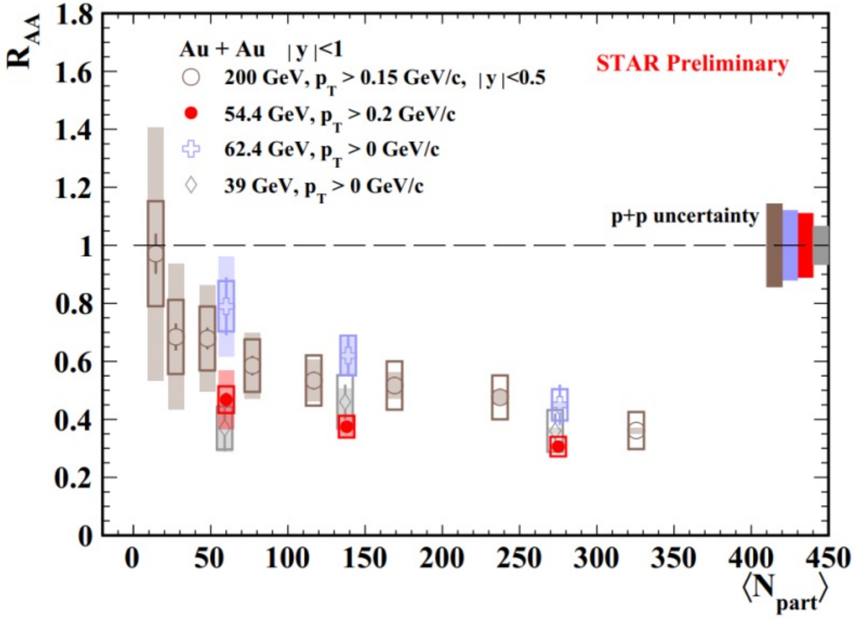
QGP melting: ↘

Regeneration: ↗

- No significant energy dependence from top SPS to RHIC energy
- Significant increase from RHIC to LHC
- Described by transport model calculation over broad energy range
  - Require careful treatment of all the three effects

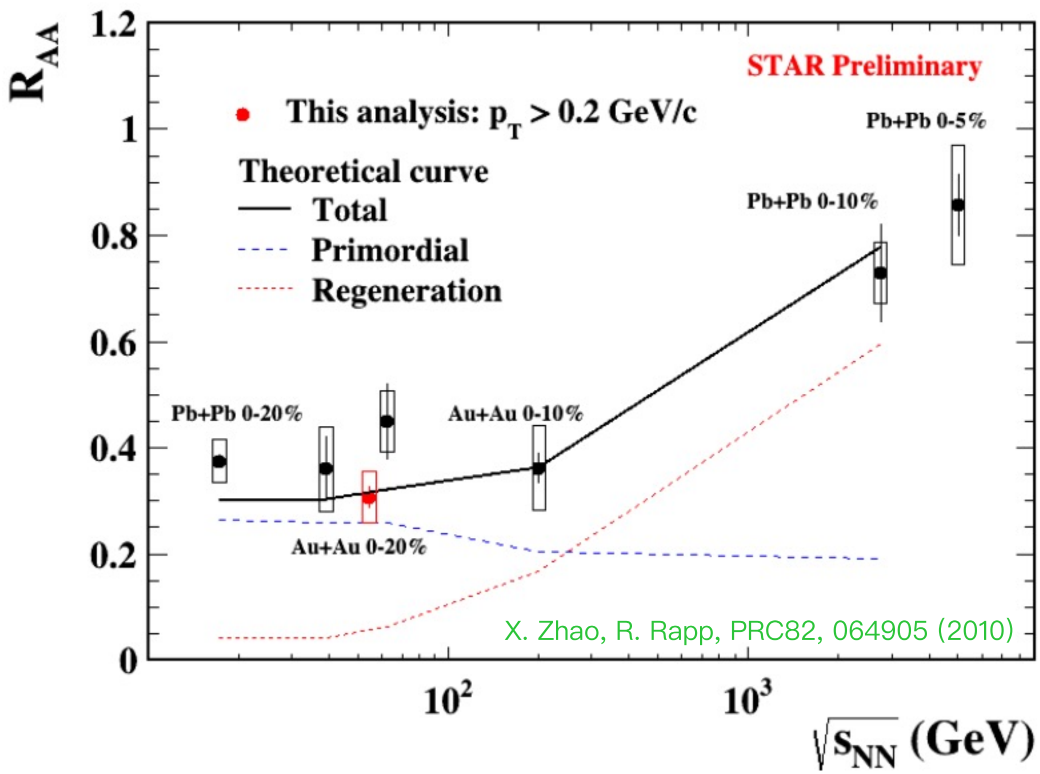
J/ψ Suppression in Au+Au at 54.4 GeV

STAR, PLB771, 13 (2017)



- Significant suppression observed at 54.4 GeV with improved precision
- No significant difference among 200, 62.4 and 54.4 and 39 GeV

R_{AA} vs. Energy

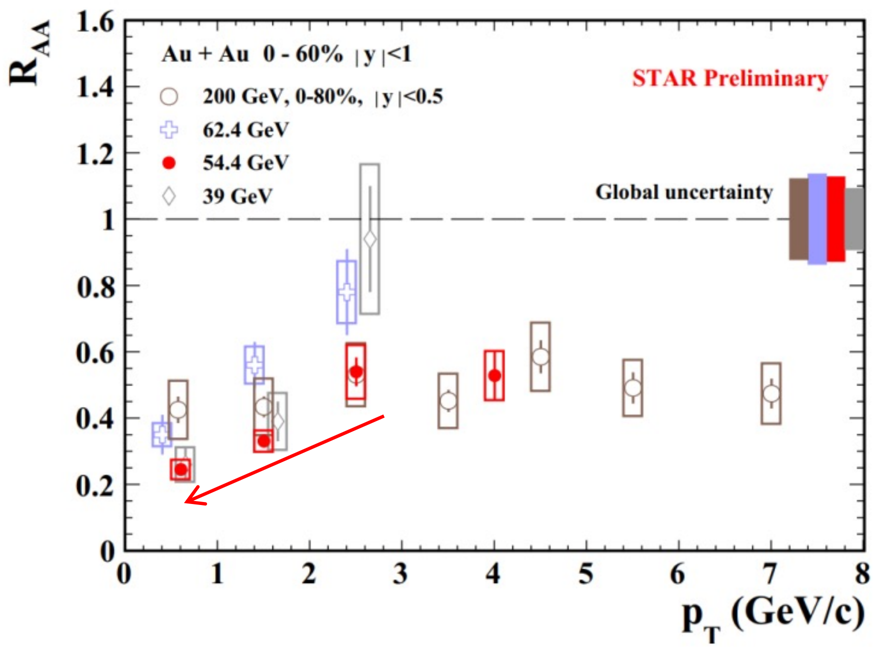


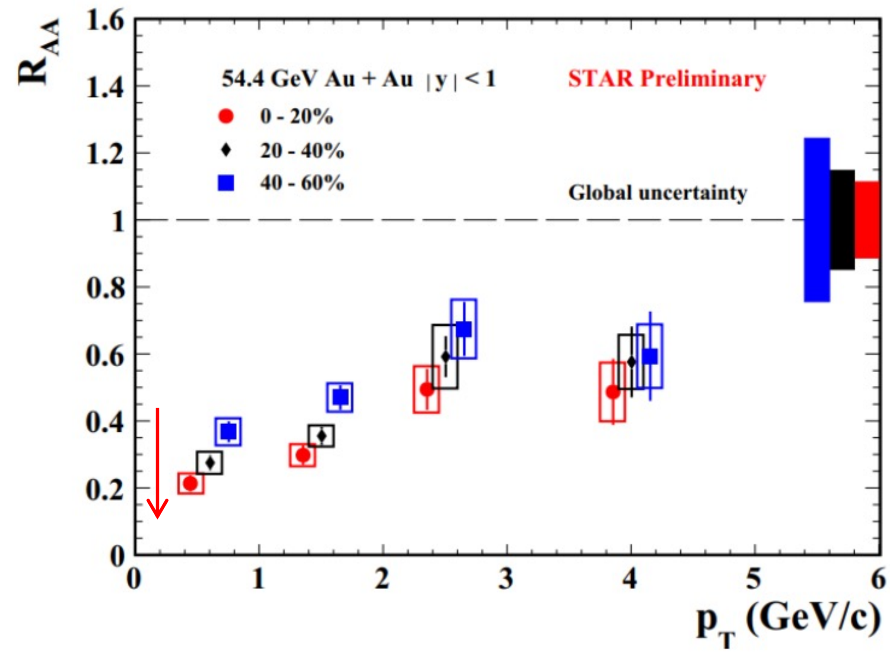
STAR: PLB771, 13 (2017)
SPS : EPJC43, 145 (2005)
PLB477, 28 (2000)
ALICE: PLB734, 314 (2014)
NPA1005, 121769 (2021)

Data at 54.4 GeV fit the world data trend

and transport model prediction

p_T Dependence





- p_T dependence measured in different centralities with good precision
- Stroger suppression towards low-p_T and central collisions
- To be compared to theory

Summary of Quarkonium

200 GeV:

- Significant suppression at low and high p_T
- Described by transport models

➔ Evidence of QGP melting and regeneration

62 & 54 & 39 GeV:

- Suppression shows no significant energy dependence from SPS to RHIC
- Increasing p_T trend at 54.4 GeV

➔ Provide constraints of the hot and cold nuclear matter effects

27 & 19.6 GeV:

- 6x #events of 39 GeV, 2x and 5x smaller cross–section
- One step closer to SPS

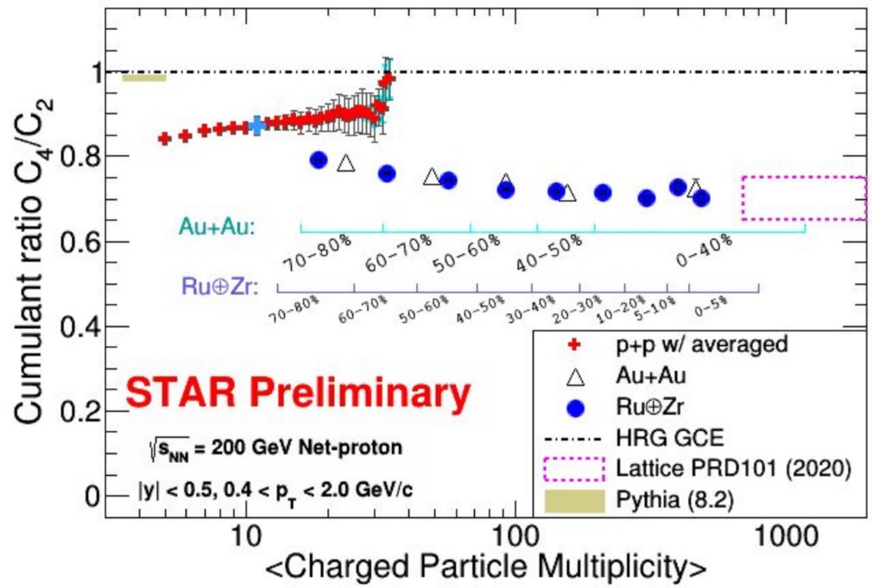
Opportunities with Isobaric Collisions

STAR took large data samples in

$${}^{96}_{44}Ru + {}^{96}_{44}Ru, \quad {}^{96}_{40}Zr + {}^{96}_{40}Zr$$

collisions in 2018

- ~3B MB events in each species
- Unblinded recently



Excellent signals of J/ψ→ee and D→Kπ observed

- Analysis in progress

Thanks!

High statistics allows the studies in fine centrality and p_T bins

- $\langle N_{part} \rangle$ in 0–5% Ru/Zr collisions similar to that in 20–30% Au+Au
- System size spans from p+Au to (semi–)central Au+Au