Heavy flavour physics at RHIC

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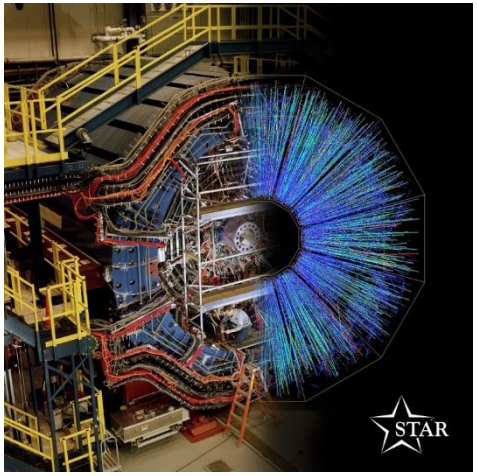
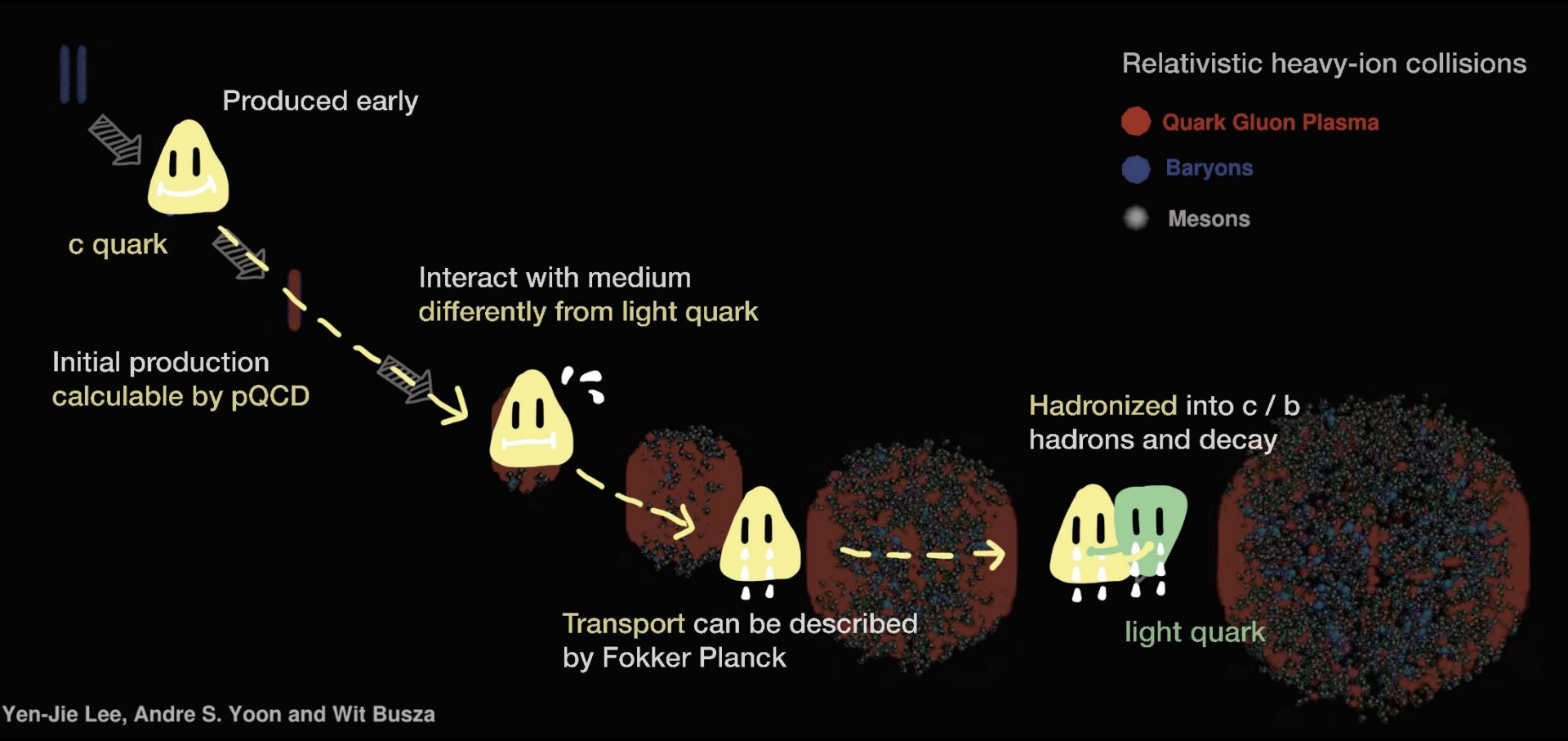


Triggering Discoveries in High Energy Physics III, 9.-13.12. 2024, High Tatras, Slovakia

Life of heavy quark open heavy flavors



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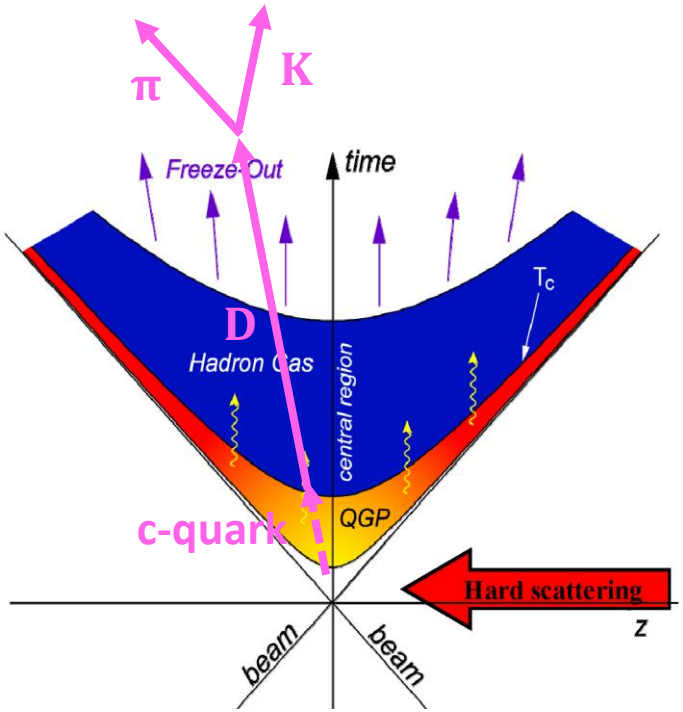
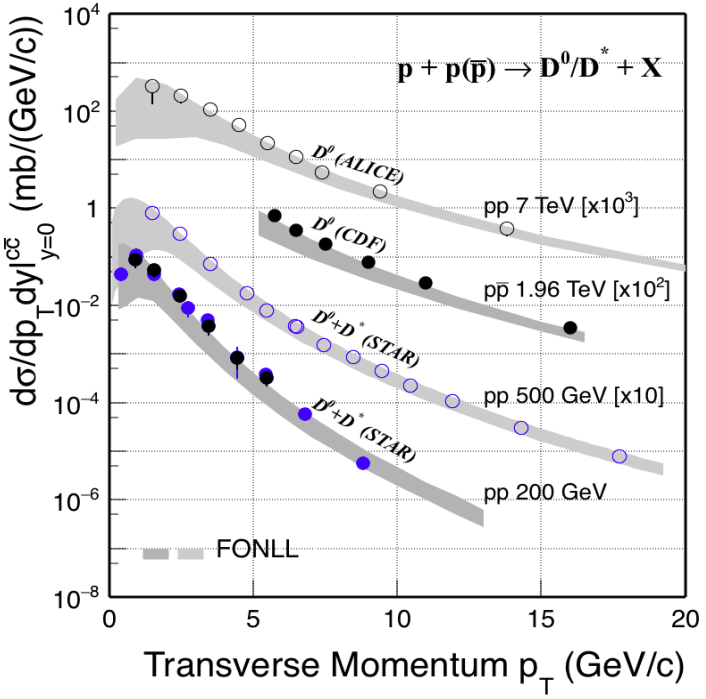
Probing Quark Gluon Plasma with charm quark





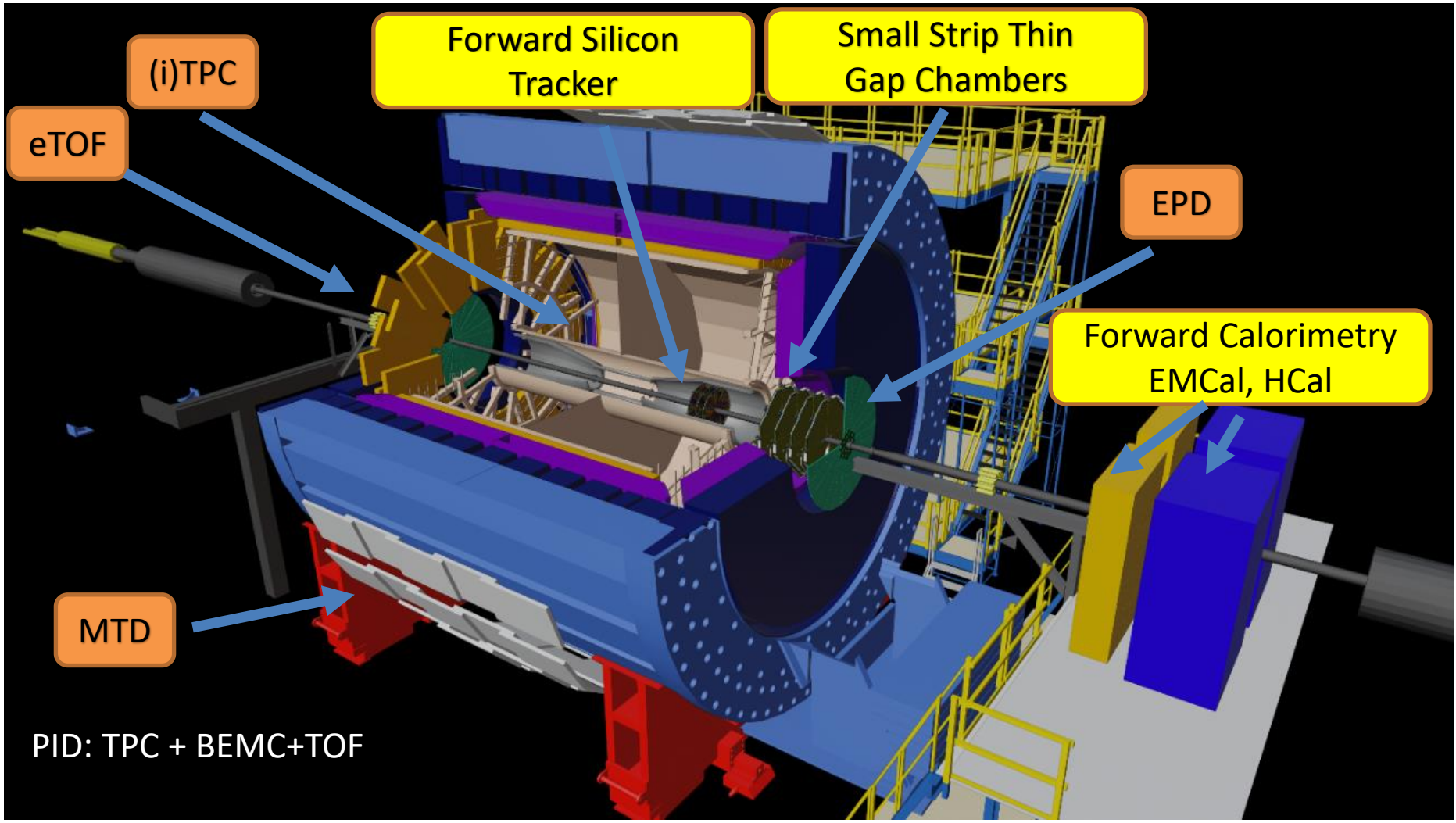
STAR: PRD 86 (2012) 072013, NPA 931 (2014) 520
CDF: PRL 91 (2003) 241804; ALICE: JHEP01 (2012) 128
FONLL: PRL 95 (2005) 122001

- **Charm quark: $m_c >> T_{QGP}, \Lambda_{QCD}$**
- Produced in hard scatterings at the early stage of nuclear collisions → experience the entire evolution of medium
- We aim to understand charm quark energy loss in the medium, charm quark transport and hadronization

- Its production rates are well described by pQCD in elementary collisions

STAR experiment

- 2023-2025: Au+Au 200 GeV, p+p 200 GeV, p+Au 200 GeV



Forward upgrade: $2.5 < \eta < 4$

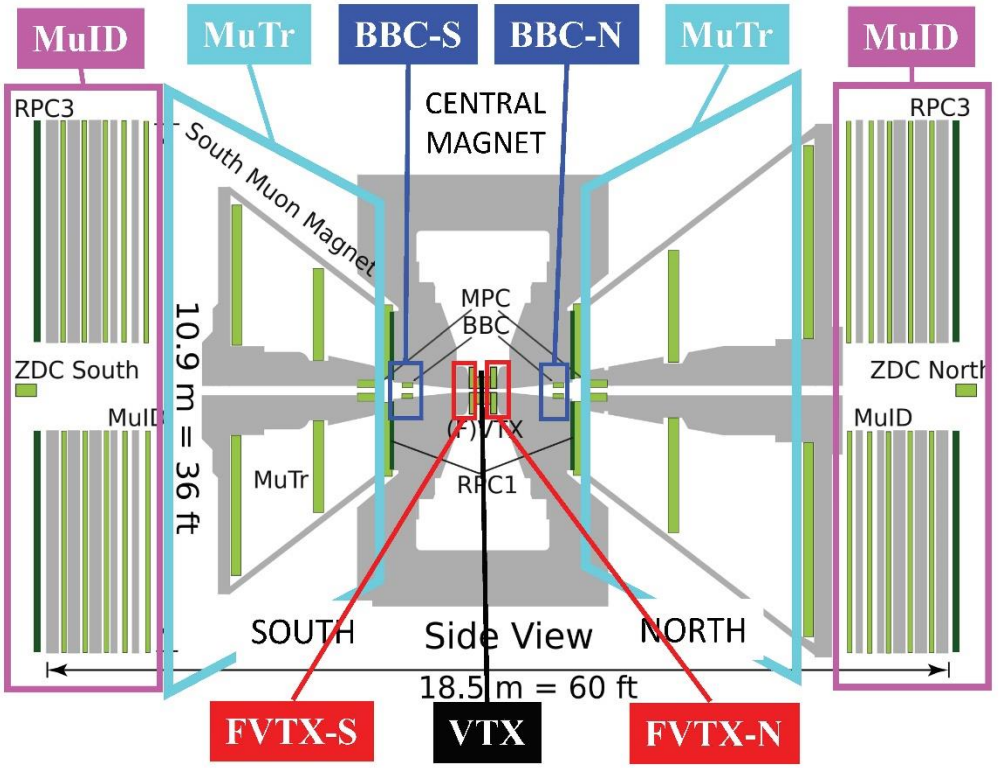
Heavy flavor tracker: 2014-2016

PHENIX experiment

CENTRAL ARM (Electrons)
- $|\eta| < 0.35$
- $\Delta\phi = \pi$
- Tracking: DC, PC, **VTX**
- eID: RICH, Emcal

BBC (Event Characterization)
- $3.1 < |\eta| < 3.9$
- Centrality, z-vertex and EP determination

FORWARD ARMS (Muons)
- $1.2 < |\eta| < 2.2$
- $\Delta\phi = 2\pi$
- Tracking: MuTr, FVTX
- MuID: Muon Identification detector



Run 14 Au+Au 200 GeV (19B MB events)
Run 16 Au+Au 200 GeV (15B MB events)

- Data taking is completed in 2016
- Collaboration is actively working for data analysis

Open charm hadron reconstruction

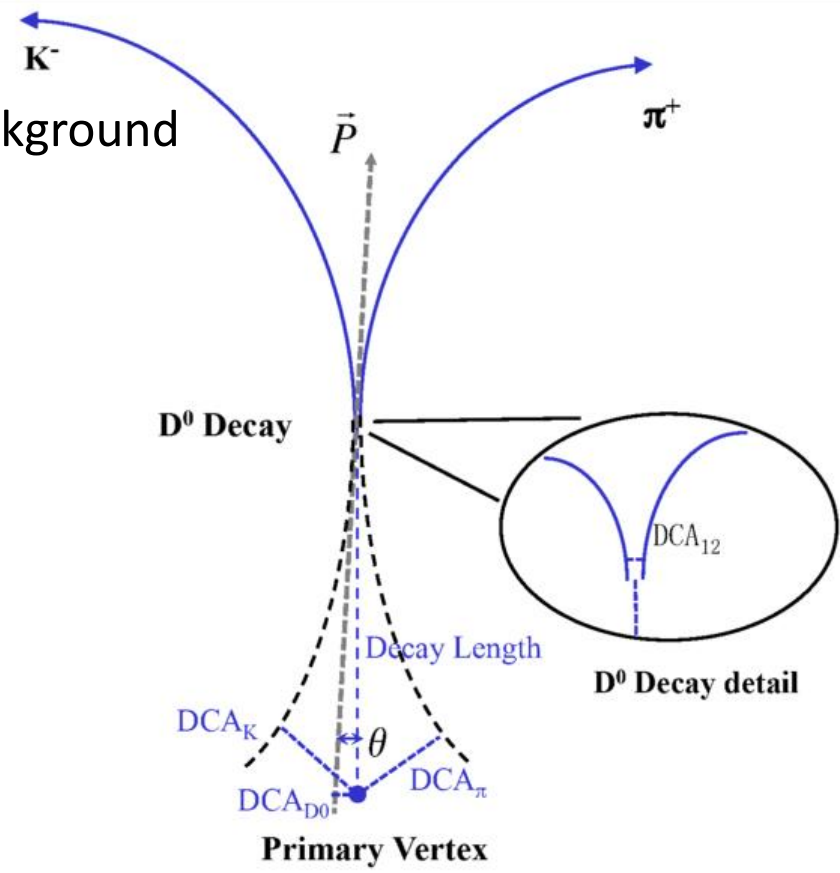
- Data from Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV STAR collected with Heavy flavor tracker in years 2014 and 2016
- HFT allows direct **topological reconstruction** of open-charm hadrons via their hadronic decays
- Significant suppression of combinatorial background
- Decay channels used:
  - $D^+ \rightarrow K^-\pi^+\pi^+$, $c\tau$ = (311.8 ± 2.1) **μm**

    BR = (8.98 ± 0.28) %
  - $D^0 \rightarrow K^-\pi^+$, $c\tau$ = (122.9 ± 0.4) **μm**

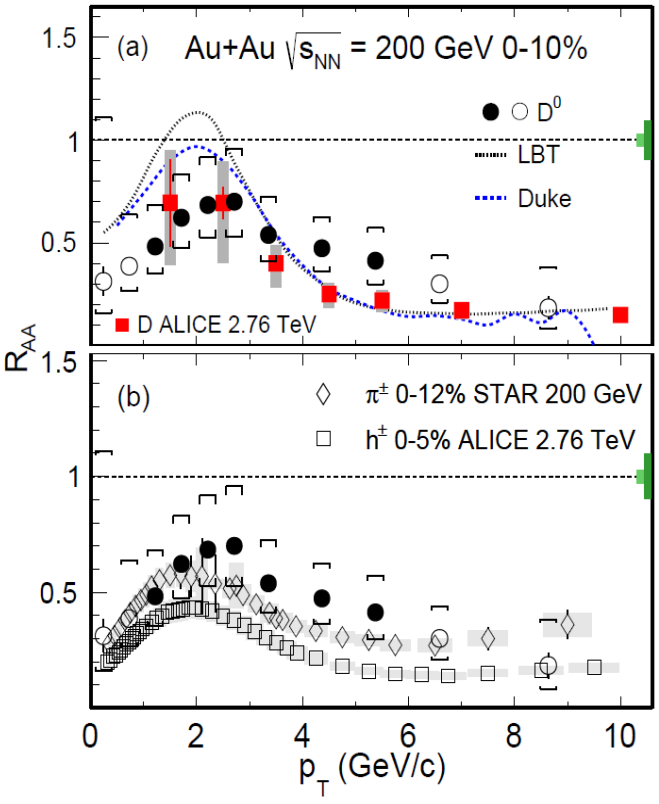
    BR = (3.93 ± 0.04) %
  - $D_s \rightarrow \pi^+\phi$, $\phi \rightarrow K^-K^+$, $c\tau$ = (149.9 ± 2.1) **μm**

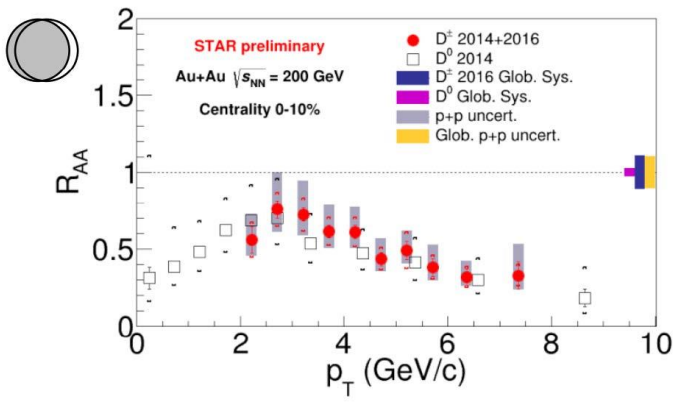
    BR = (2.27 ± 0.08) %
  - $\Lambda_c \rightarrow K^-\pi^+p$, $c\tau$ = (59.9 ± 1.8) **μm**

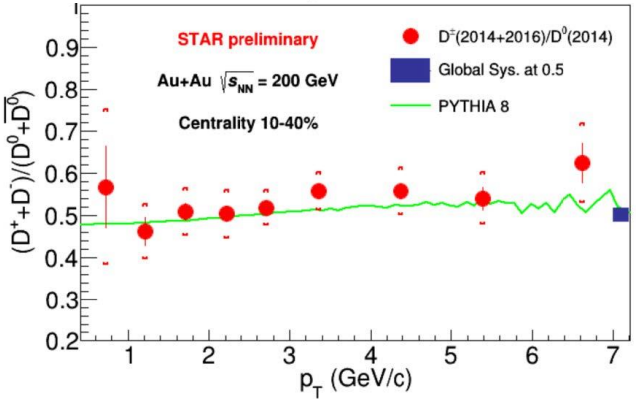
    BR = (6.35 ± 0.33) %



Nuclear modification factor R_{AA} of D^0 and $D^{\pm}$







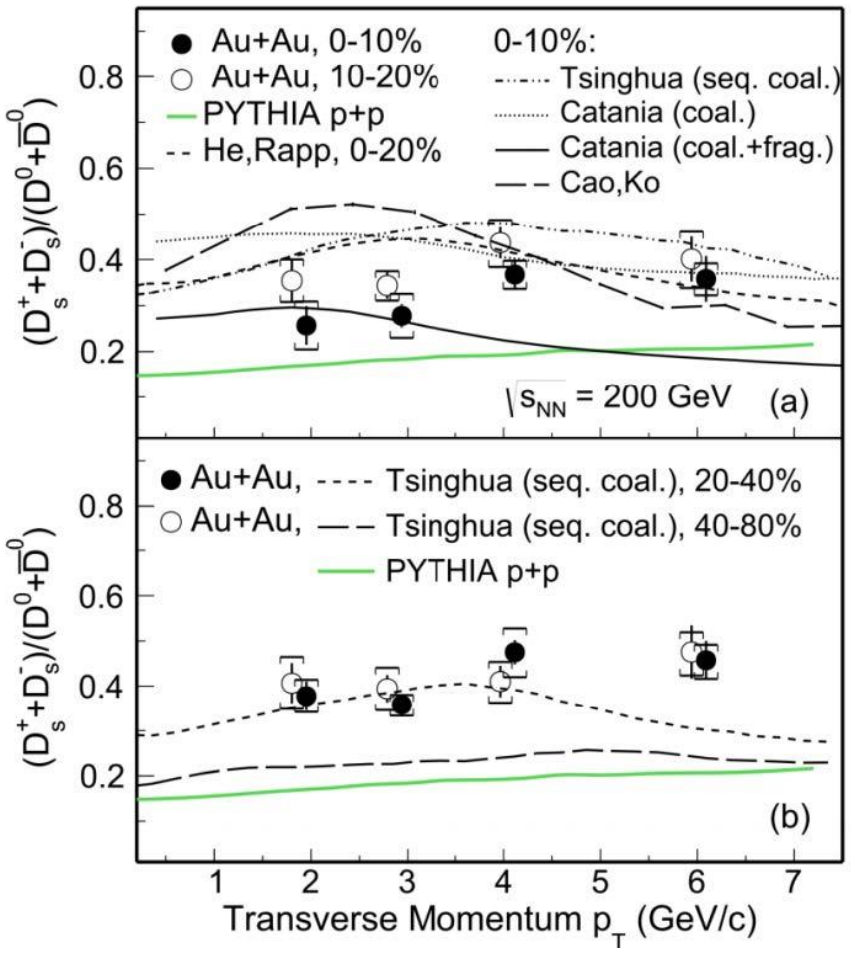
$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{D}}^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle\, \mathrm{d}N_{\mathrm{D}}^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

D^0 (STAR): Phys. Rev. C 99, 034908, (2019).
$\pi^{\pm}$ (STAR): Phys. Lett. B 655, 104 (2007).
D (ALICE): JHEP 03, 081 (2016).
$h^{\pm}$ (ALICE): Phys. Lett. B 720, 52 (2013).
LBT: Phys. Rev. C 94, 014909, (2016).
Duke: Phys. Rev. C 97, 014907, (2018).

Strong interaction between charm quarks and medium

- Suppression of D^0 and D$^{\pm}$ mesons at high p_T comparable to light-flavor hadrons at RHIC and D mesons at LHC
- It is reproduced by models incorporating both **radiative and collisional energy loss**
- D$^{+/-}$/D^0 yield ratio in Au+Au is consistent with PYTHIA8.

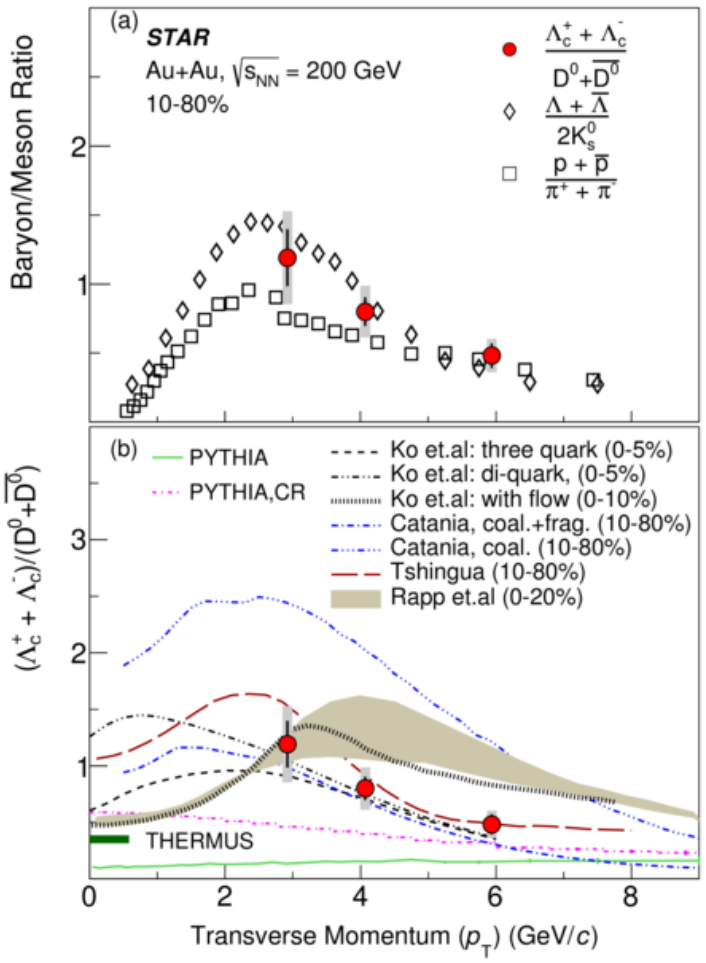
D_s/D^0 yield ratio enhancement



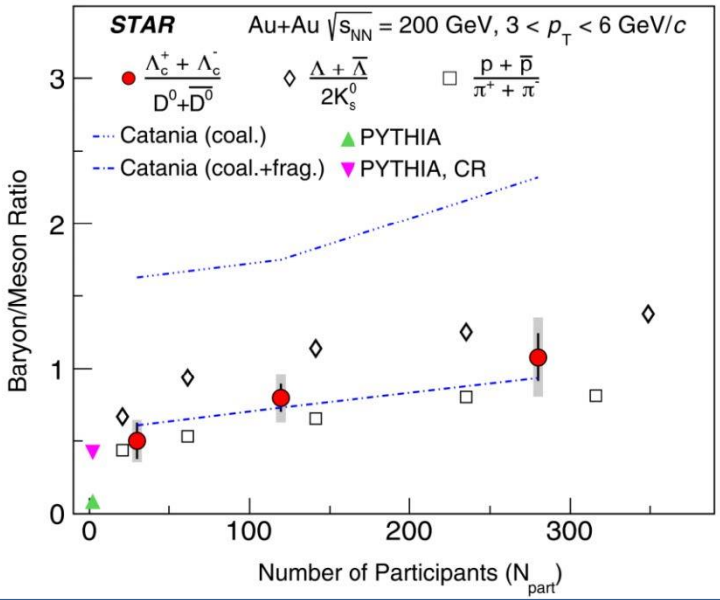
- Observed strong enhancement of the D_s/D^0 yield ratio compared to PYTHIA version 6.4 p+p baseline
- The enhancement can be qualitatively described by model calculations incorporating thermal abundance of strange quarks in the QGP and coalescence hadronization
- **Recombination** of charm quarks with strange quarks in the QGP plays an important role

STAR, Phys. Rev. Lett. 127 (2021) 092301

Λ_c/D^0 yield ratio



STAR, Phys. Rev. Lett. 124 (2020) 172301



- Λ_c/D^0 ratio is comparable to baryon-to-meson ratios of light-flavor hadrons
- Clear enhancement observed compared to PYTHIA 8.24
- Models incorporating charm quark hadronization via coalescence are consistent with data
- Enhancement of ratio increases in central collision

Importance of coalescence of charm quarks

Charm production 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 2014STAR, Phys. Rev. Lett. 127 (2021) 092301
Ds (STAR): Phys. Rev. C 99, 034908, (2019)
Lc STAR, Phys. Rev. Lett. 124 (2020) 172301
p+p (STAR): Phys. Rev. D 86 072013, (2012).

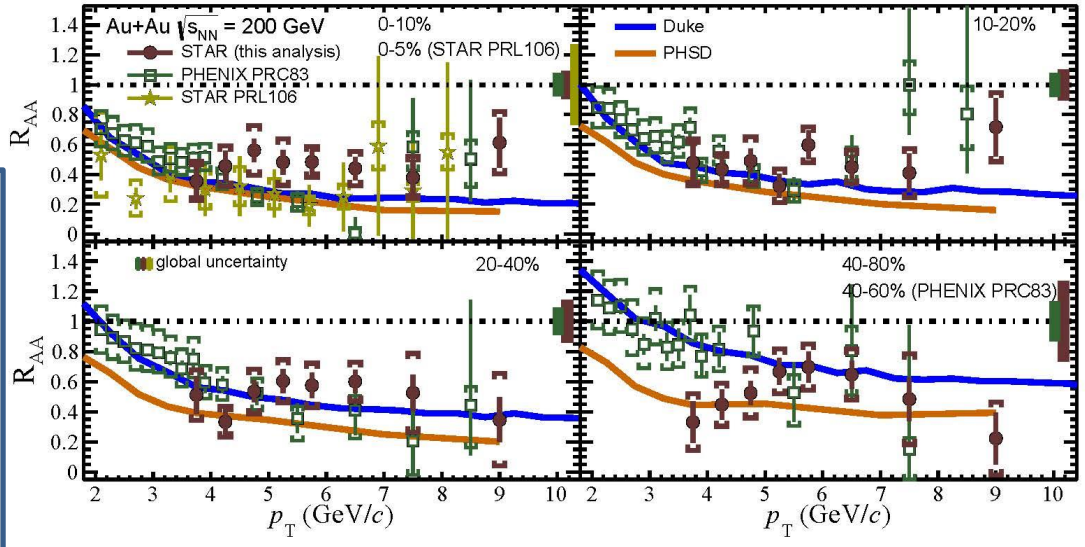
*Λ_c cross-section was derived using Λ_c/D^0 yield ratio

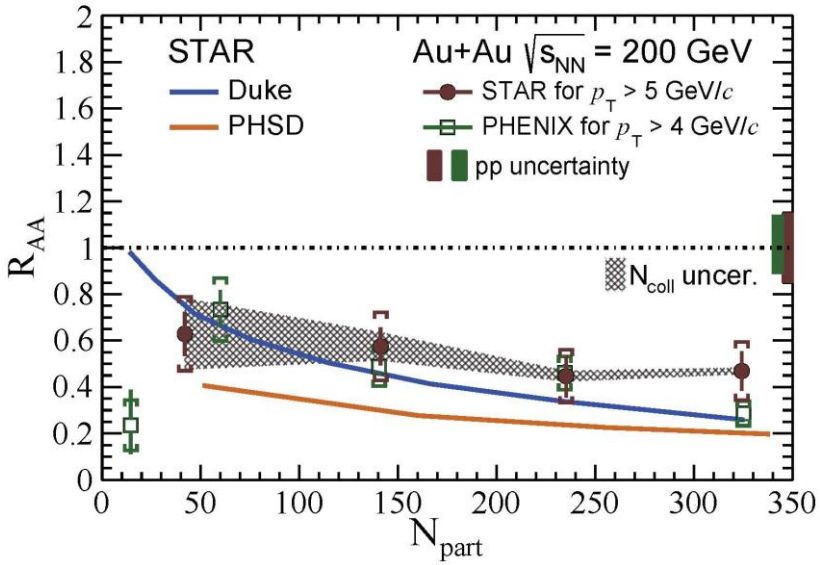
- p_T integrated total D^0 cross-section per binary collision is smaller in Au+Au than p+p
- Total charm production **cross-section per binary collision** in Au+Au
  - Au+Au result is consistent with that measured in p+p collisions within uncertainties
  - **Redistribution** of charm quarks among open-charm hadron species

Electrons from HF@ Au+Au 200GeV

D,B->e

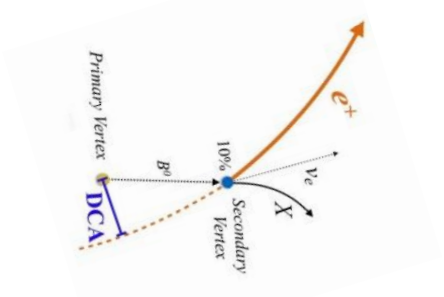
- Precise high-p_T measurement $3.5 < p_T < 9$ GeV/c
- A suppression by about a factor of 2 is observed in central and semi-central collisions
- No p_T dependence observed
- A hint of R_{AA} decreasing from peripheral to central collisions
- Models describe the data well
- Indication of substantial energy loss of heavy quarks in the QGP

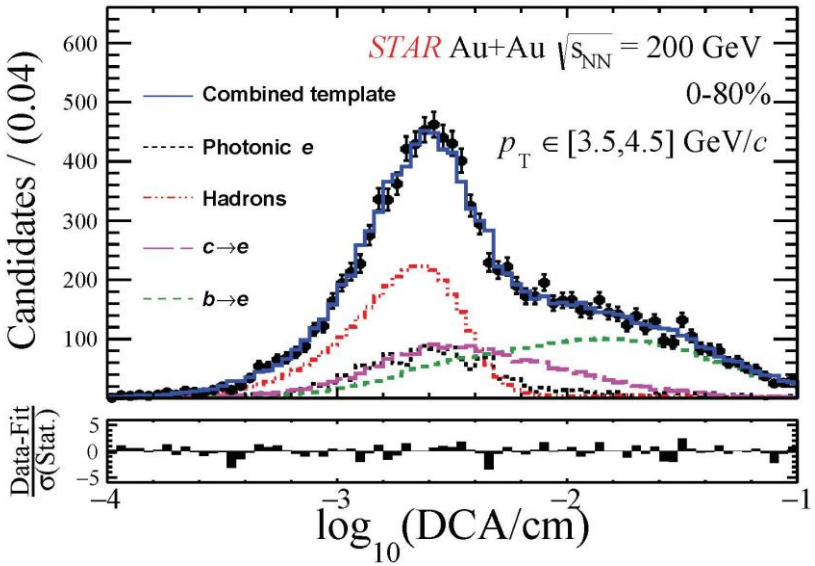




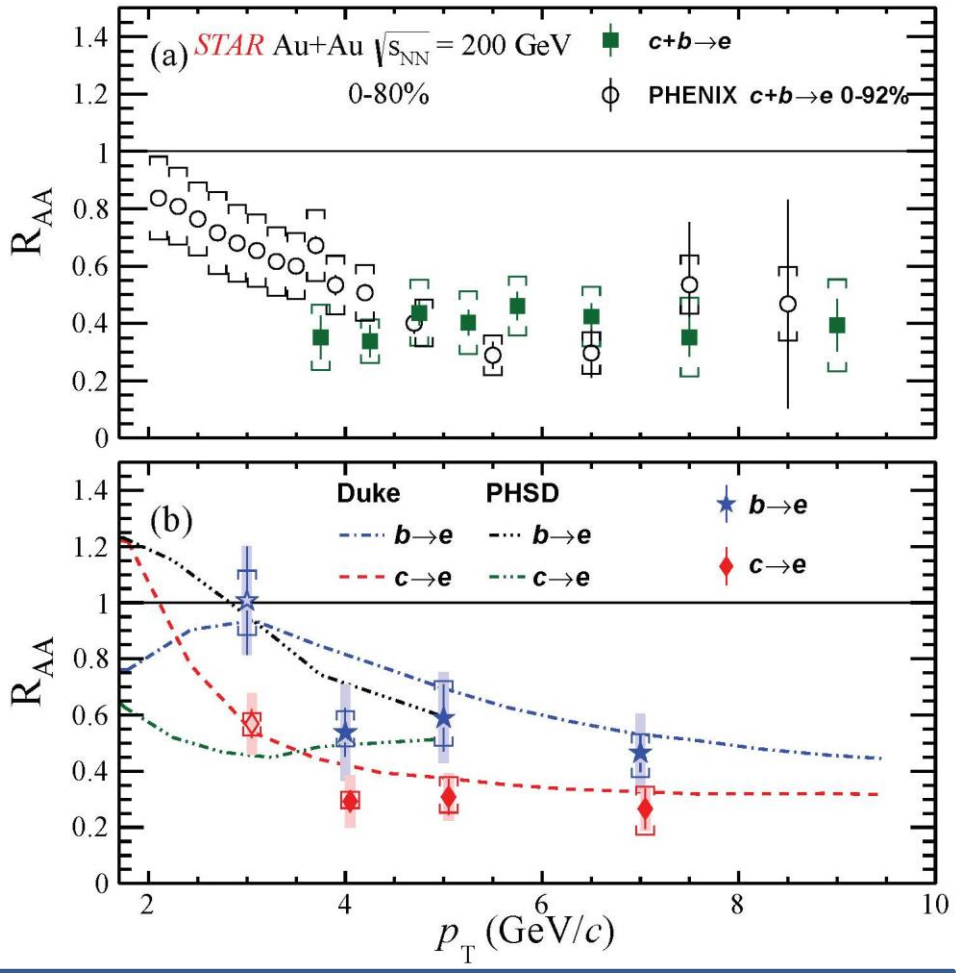
STAR: JHEP 06 (2023) 176

Mass ordering of heavy quarks energy loss





STAR Eur. Phys. J. C 82, 1150 (2022)

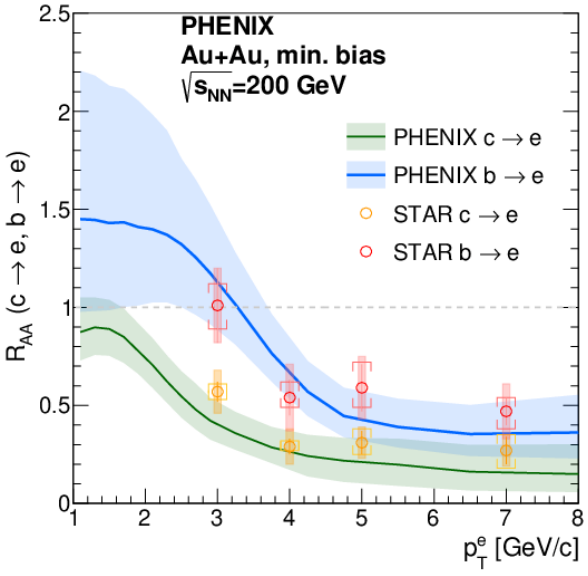


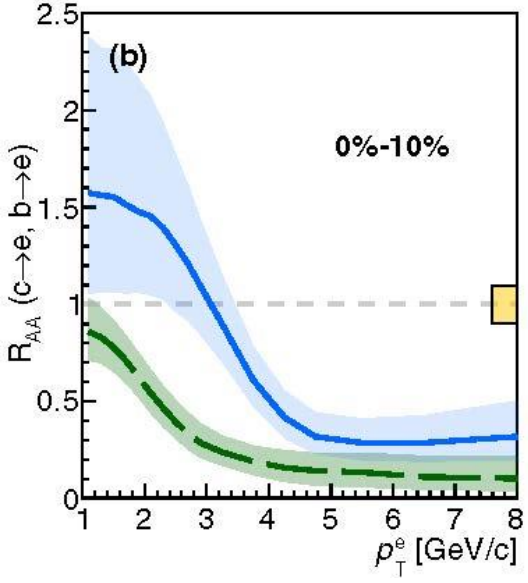
Heavy-flavor hadron decayed electrons: c → e and b → e separation **in 200 GeV Au+Au collisions** thanks to HFT

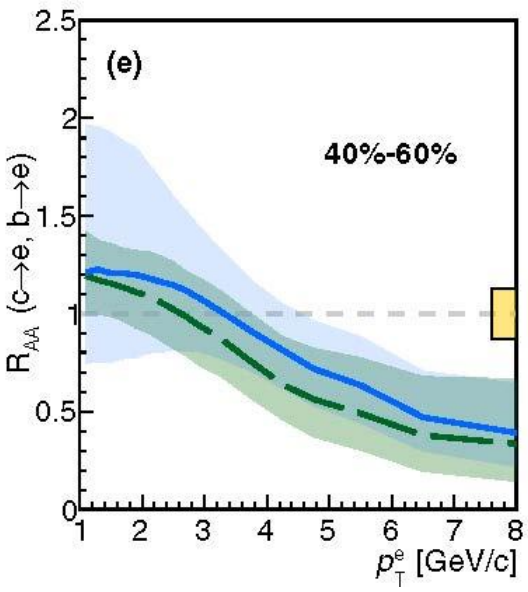
- Observation of less suppression for *B→e* than *D→e*
- Consistent with expected mass hierarchy for parton energy loss $\Delta E_c > \Delta E_b$

R_{AA} c->e, b->e

PHENIX, PRC 109, 044907 (2024)



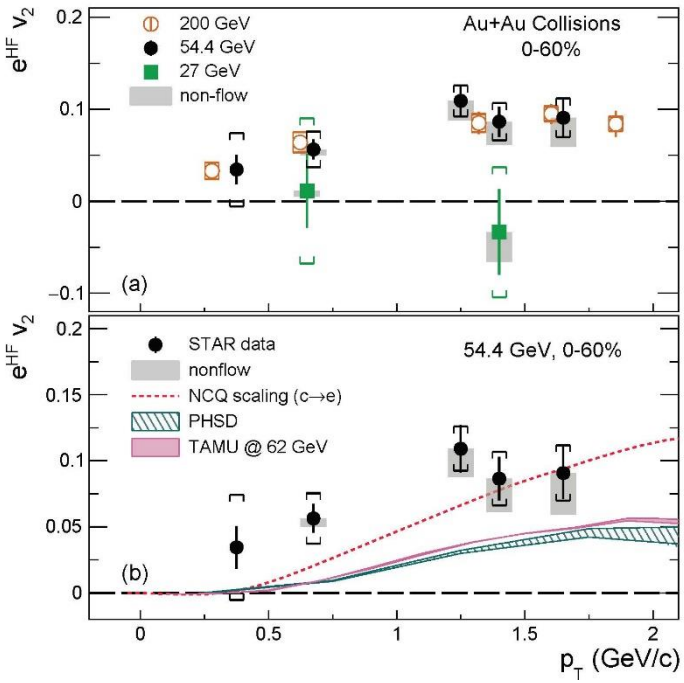


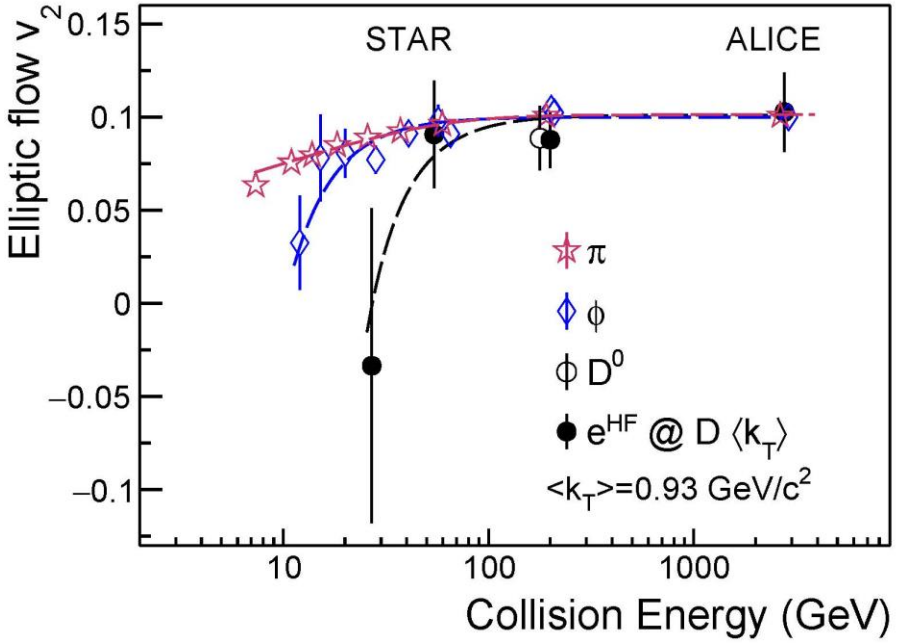


- MB results are consistent between PHENIX and STAR in Au+Au 200 GeV
- In **0-10%** suppression of **c->e** and **b->e** observed
- In **40-60%** are bottom and charm similarly suppressed and less then at 0-10%
- Centrality dependence of suppression is clearly seen

Energy dependence of HFE eliptic flow

$$v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$$



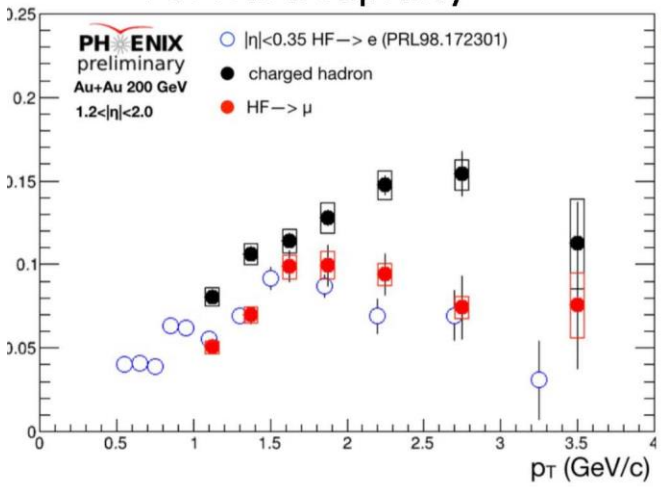


STAR: Physics Letters B (2023) 844:138071

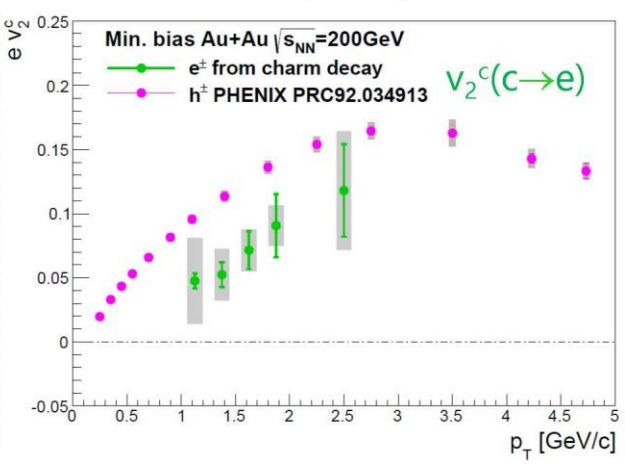
- v_2 vs coll. energy → temperature dependence of charm quark diffusion coefficient
- At 27 GeV v_2 of c,b → e consistent with zero
- Significant non-zero v_2 of c,b → e at 54.4 – 200 GeV
- At low p_T models underestimate data
- **HF quarks interact strongly with the medium at 54.4 – 200 GeV**
- A hint of mass hierarchy is observed where the v_2 of heavier particles drops faster than lighter ones with decreasing collision energy

Rapidity dependence of HFE elliptic flow

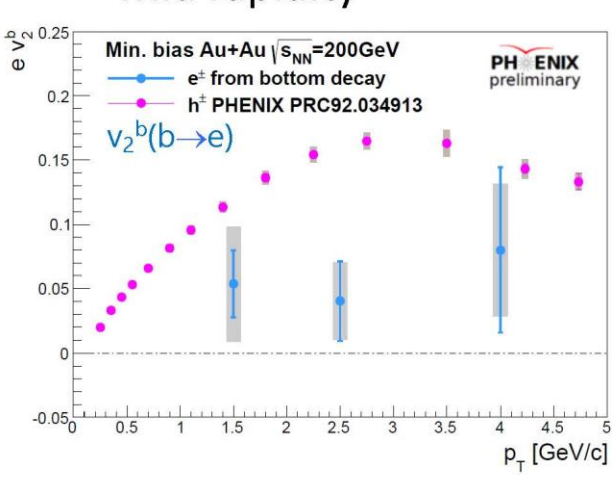
Forward rapidity



Mid rapidity



Mid rapidity

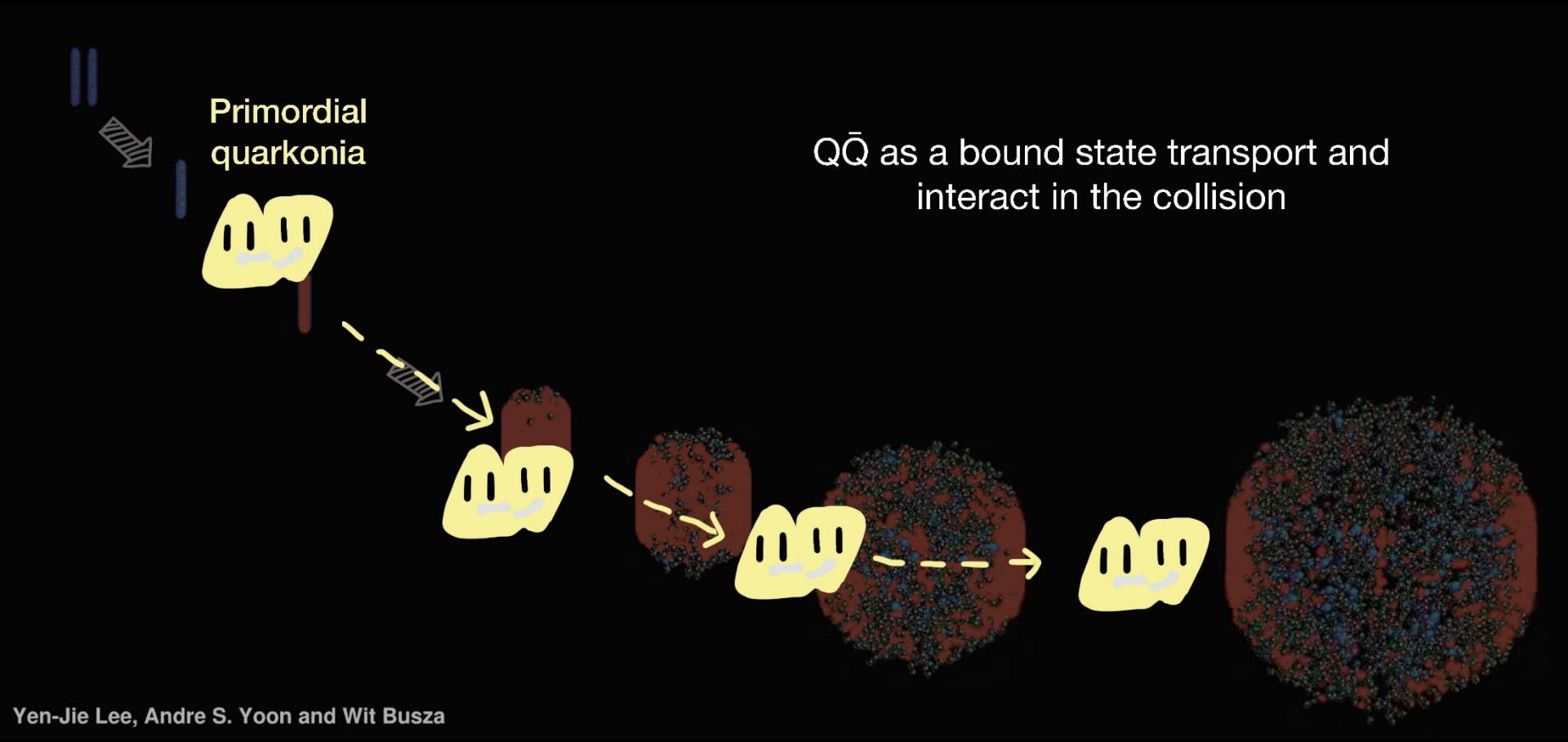


- HF v_2 is positive both at forward and mid rapidity and mostly consistent
- Hadron v_2 > HF v_2 and $v_{2c} > v_{2b}$,
- Heavier quarks have less flow - as expected

PHENIX SQM 2024

Quarkonia

Life of heavy quark - quarkonium



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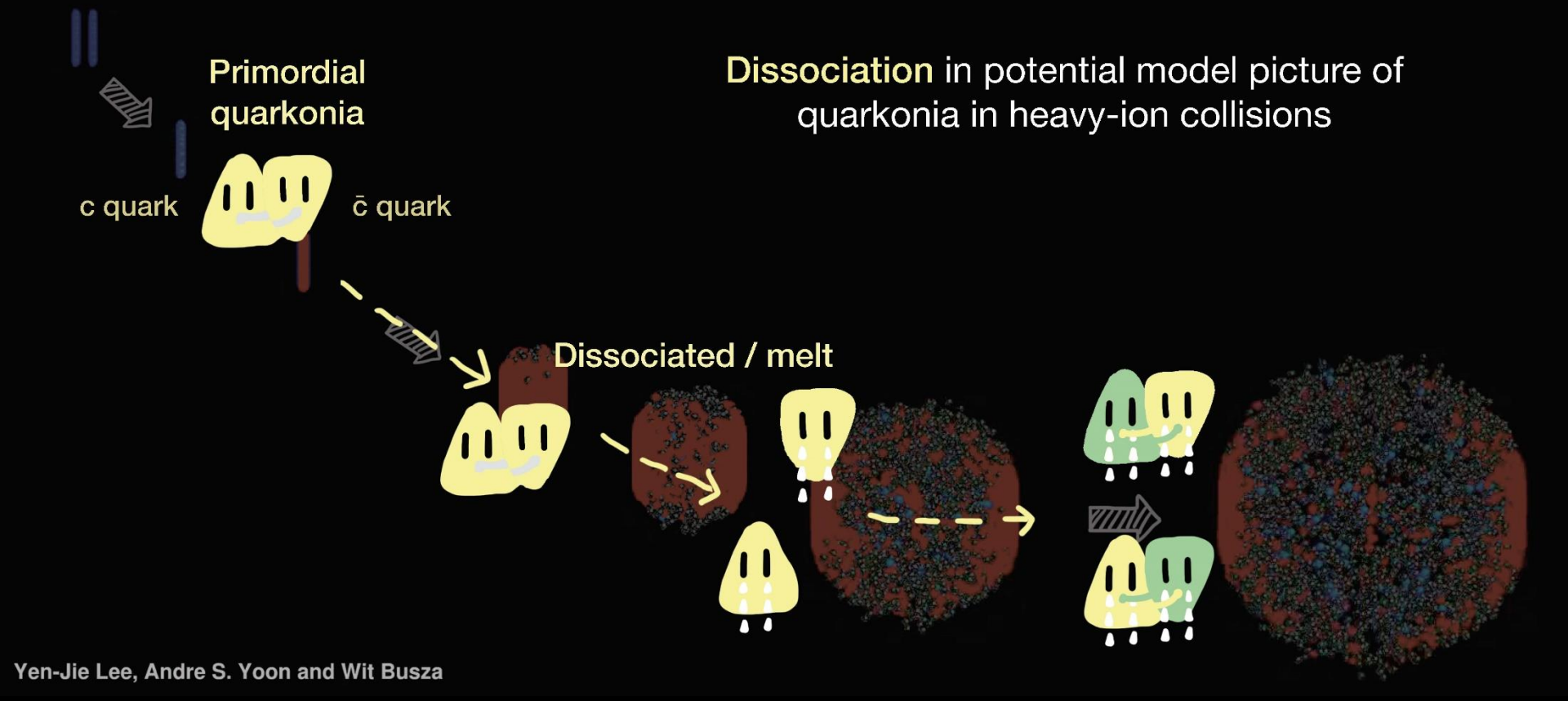
Life of heavy quark - quarkonium



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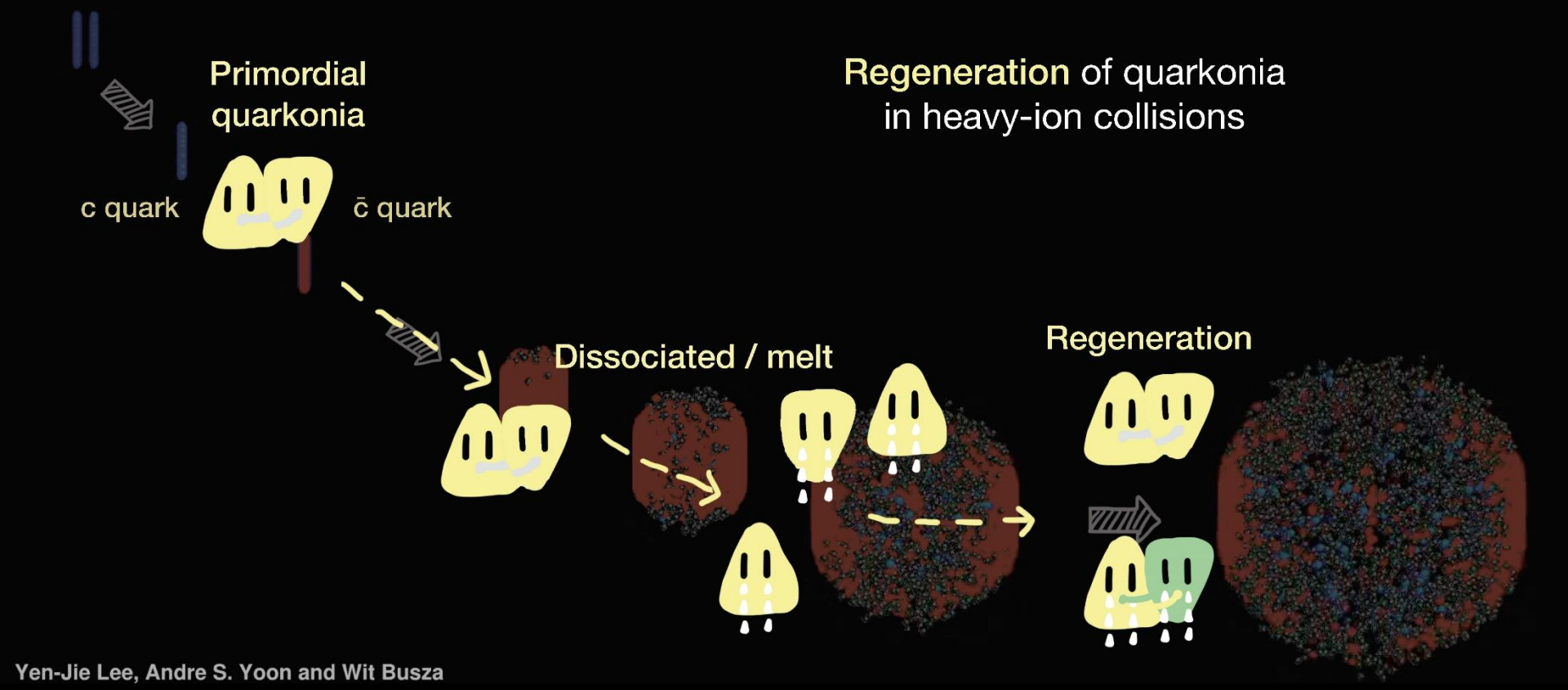
Life of heavy quark - quarkonium



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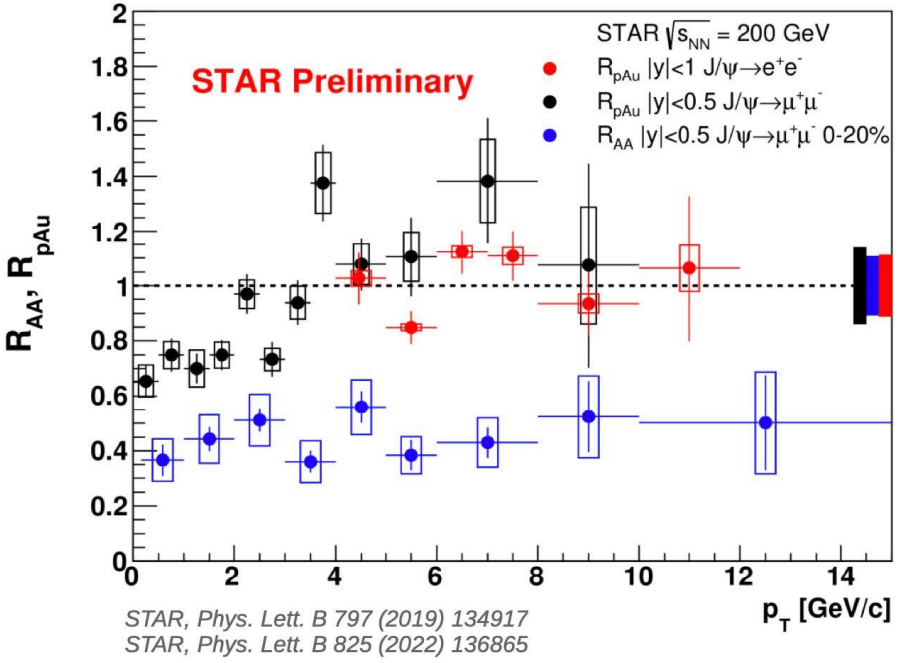
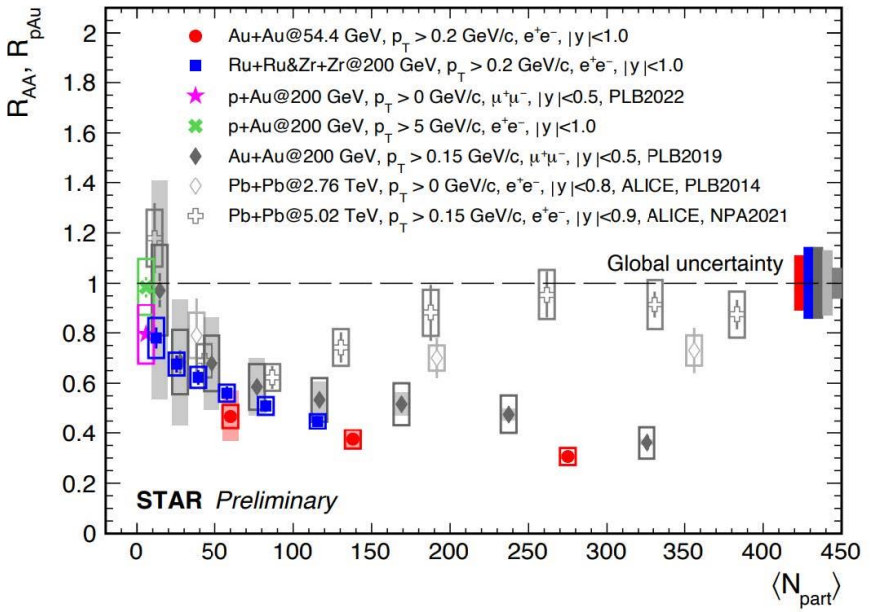
J/ψ production in heavy-ion collisions



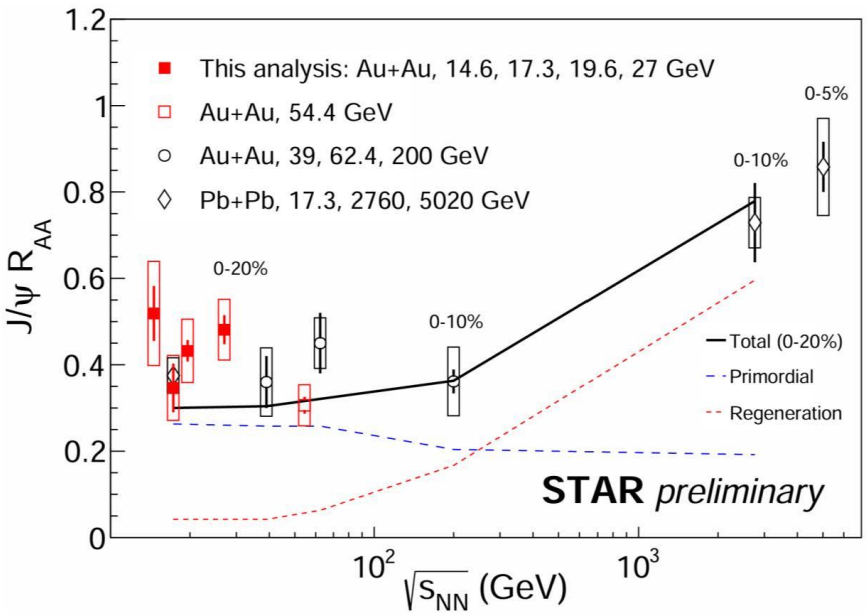
STAR, Phys. Lett. B 797 (2019) 134917
STAR, Phys. Lett. B 825 (2022) 136865

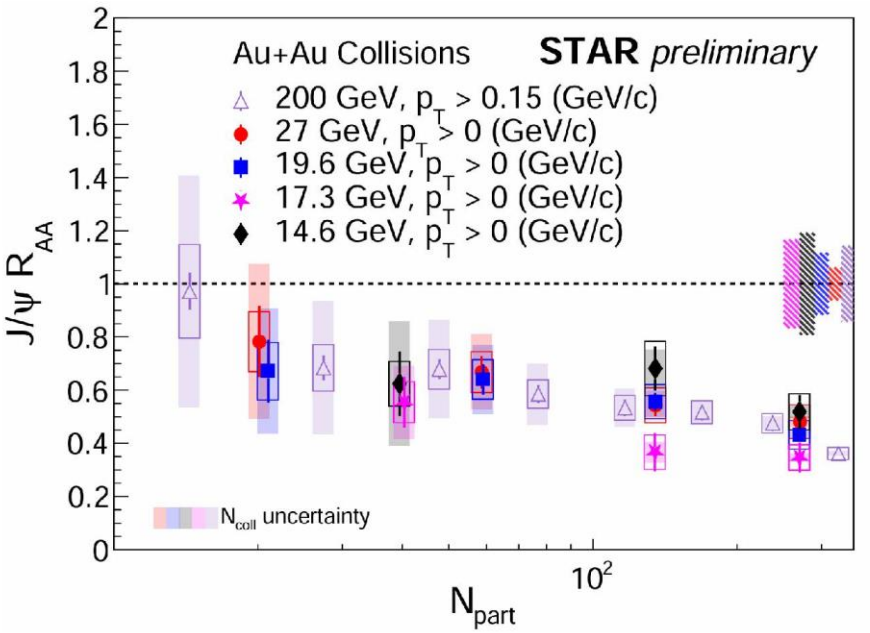


- Low p_T < 2 GeV/c: Cold nuclear matter effect
- High p_T: suppression in Au+Au due to QGP

- No significant collision system dependence of the J/ψ suppression at similar <N_{part}>
- Suppression driven by system size <N_{part}> not collision geometry
- At high p_T: Strong suppression at RHIC and regeneration at LHC

J/ψ R_{AA} 14,6-27 GeV

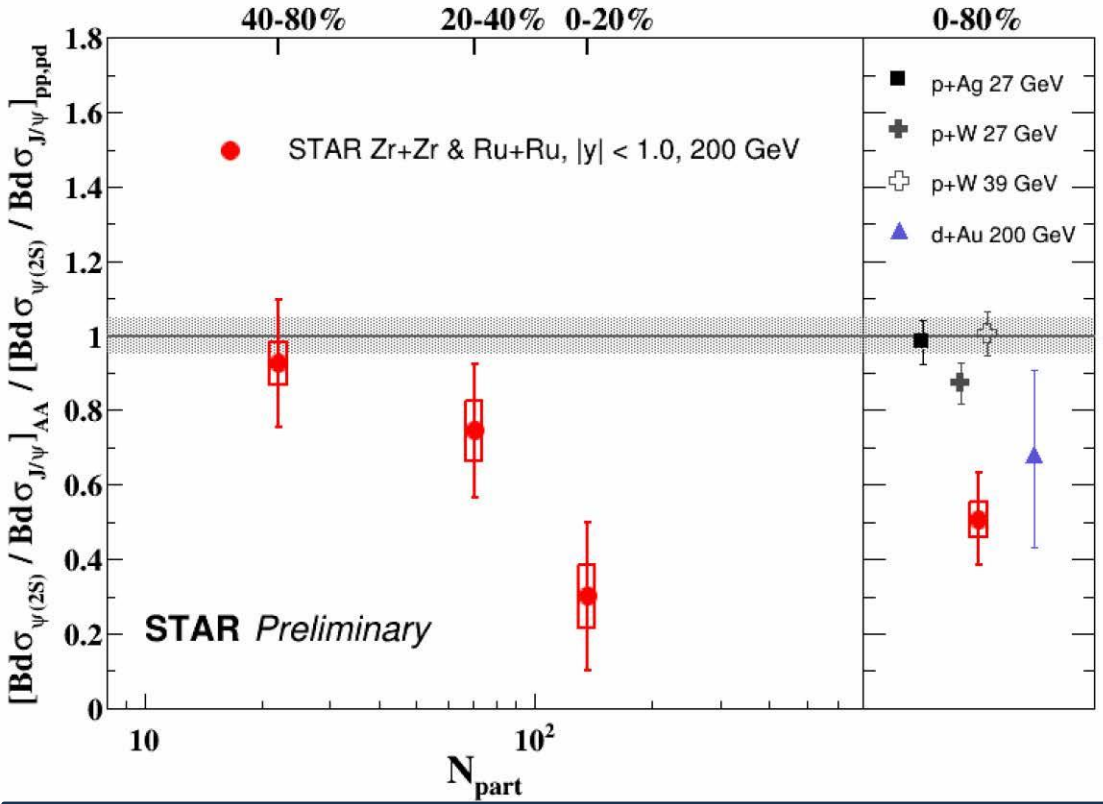




X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
L. Kluberg, Eur. Phys. J. C 43 (2005) 145.

- No significant energy dependence of J/ψ R_{AA} in central collisions up to 200 GeV
- No significant energy dependence at RHIC for similar $\langle N_{part} \rangle$
- Hint of decreasing trend as a function of centrality

ψ(2S) to J/ψ in Zr+Zr& Ru+Ru 200 GeV

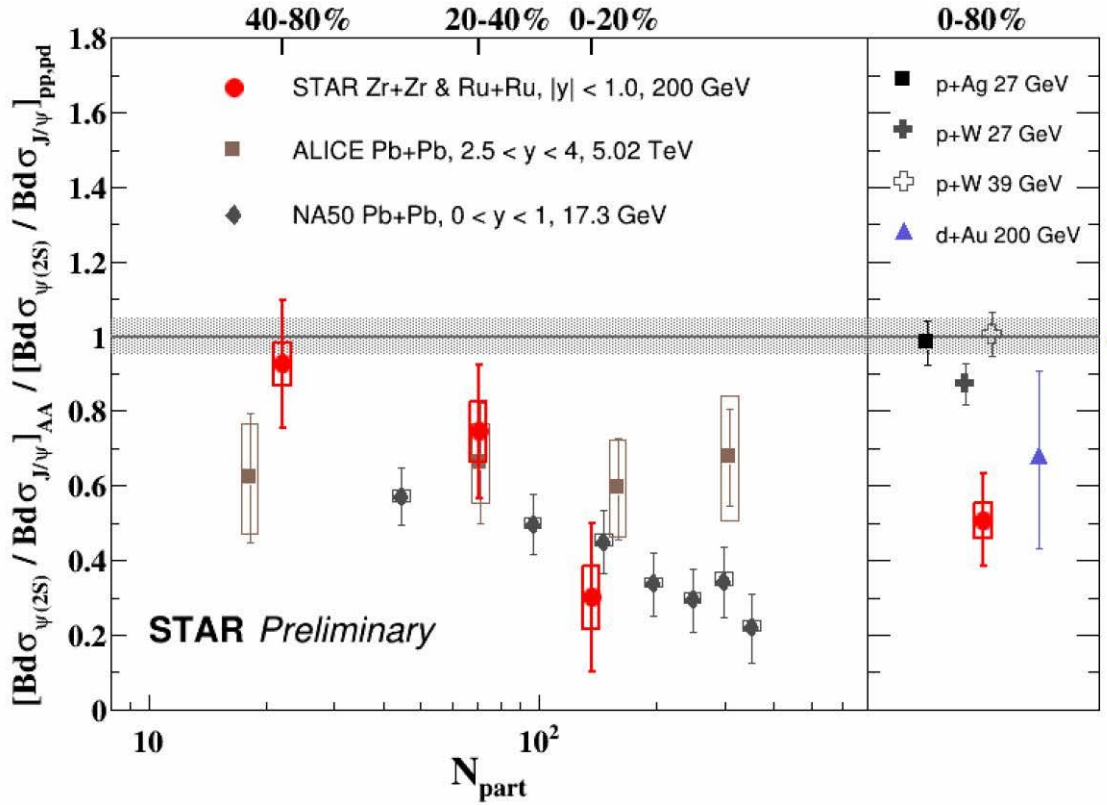


pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

PHENIX, Phys.Rev.D, 85,092004 (2012)
NA51, Phys.Lett.B 438 (1998) 35-40
ISR, Nucl.Phys.B 142 (1978) 29

- First observation of charmonium **sequential suppression** in heavy-ion collisions at RHIC
- ψ(2S) over J/ψ double ratio is smaller than that in p+A collisions

ψ(2S) to J/ψ in Zr+Zr& Ru+Ru 200 GeV



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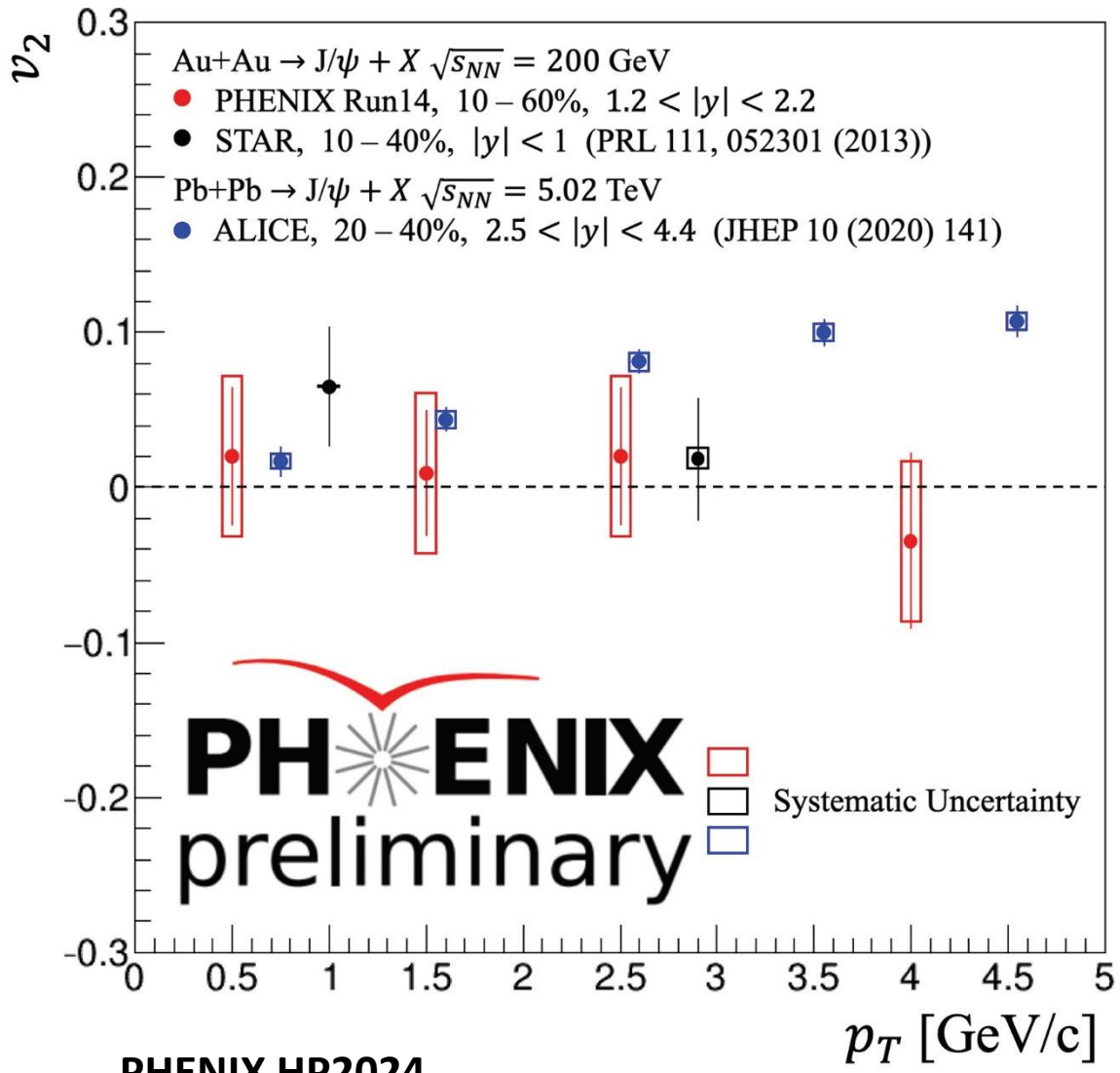
PHENIX, Phys.Rev.D, 85,092004 (2012)
NA51, Phys.Lett.B 438 (1998) 35-40
ISR, Nucl.Phys.B 142 (1978) 29

- First observation of charmonium **sequential suppression** in heavy-ion collisions at RHIC
- ψ(2S) over J/ψ double ratio is smaller than that in p+A collisions
- Centrality dependence trend seems to be more similar to that at SPS than at LHC

J/ψ eliptic flow



- PHENIX Run 2014
  J/ψ -> $\mu^+ + \mu^-$
- J/ψ v_2 at forward rapidity is consistent with 0
- Forward and mid-rapidity results at RHIC are consistent
- The ALICE nonzero result is different from RHIC

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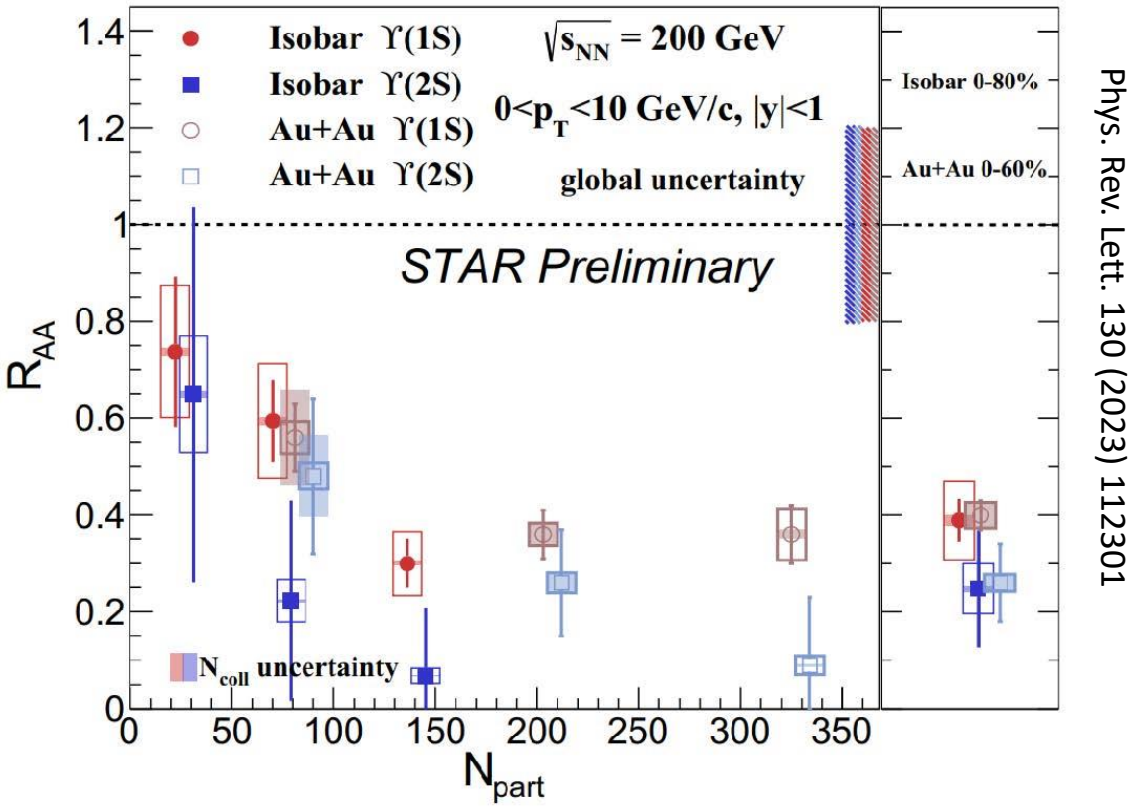
Υ(nS) suppression in heavy-ion collisions



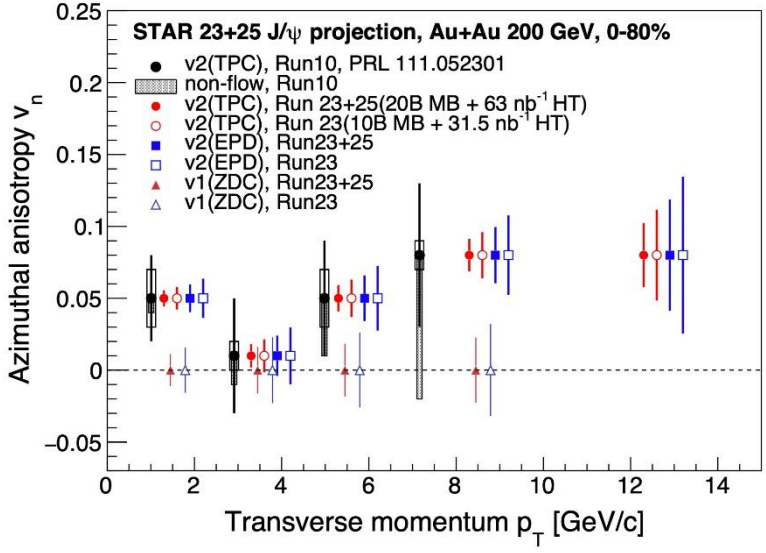
Phys. Rev. Lett. 130 (2023) 112301

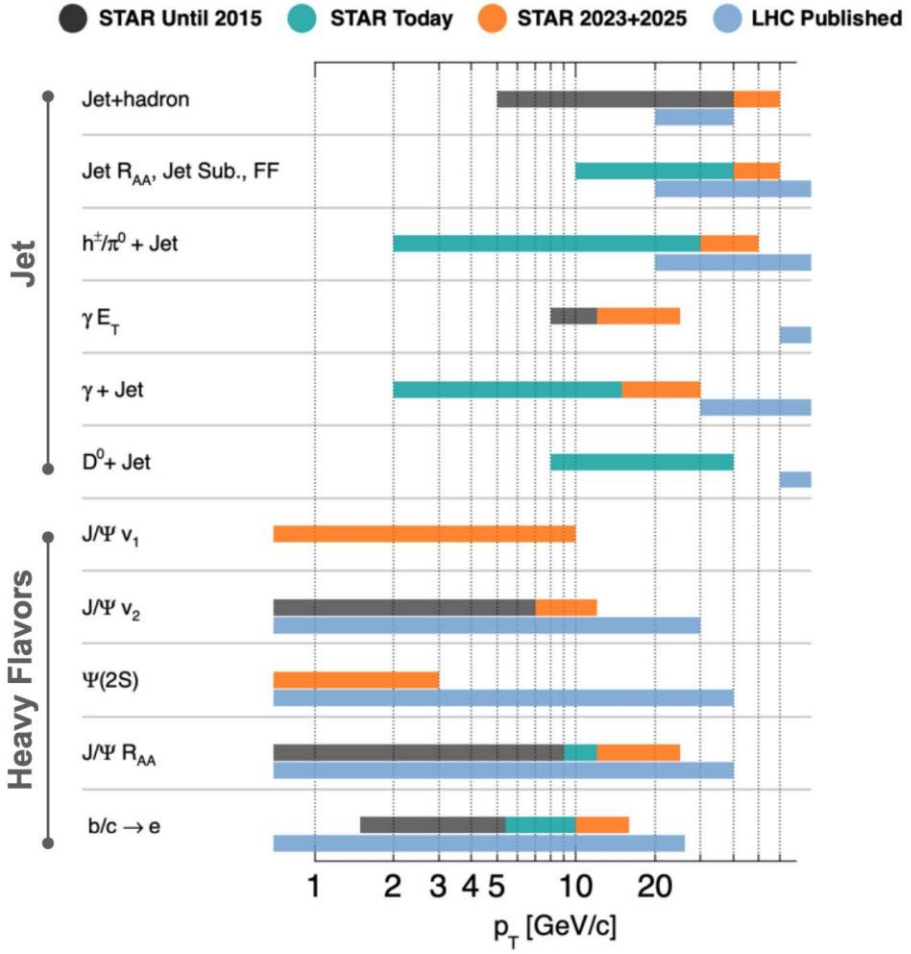
- Isobars: Zr+Zr& Ru+Ru 200 GeV
- Observed sequential suppression of different Υ(nS) states: R_{AA}[Υ(1S) > Υ(2S)]
- Consistent results in isobar and Au+Au at 200 GeV collisions at similar N_{part}

Outlook of 2023-2025

STAR BUR-2022:

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	20B / 40 nb^{-1}	2023+2025
200	p+p	235 pb^{-1}	2024
200	p+Au	1.3 pb^{-1}	2024





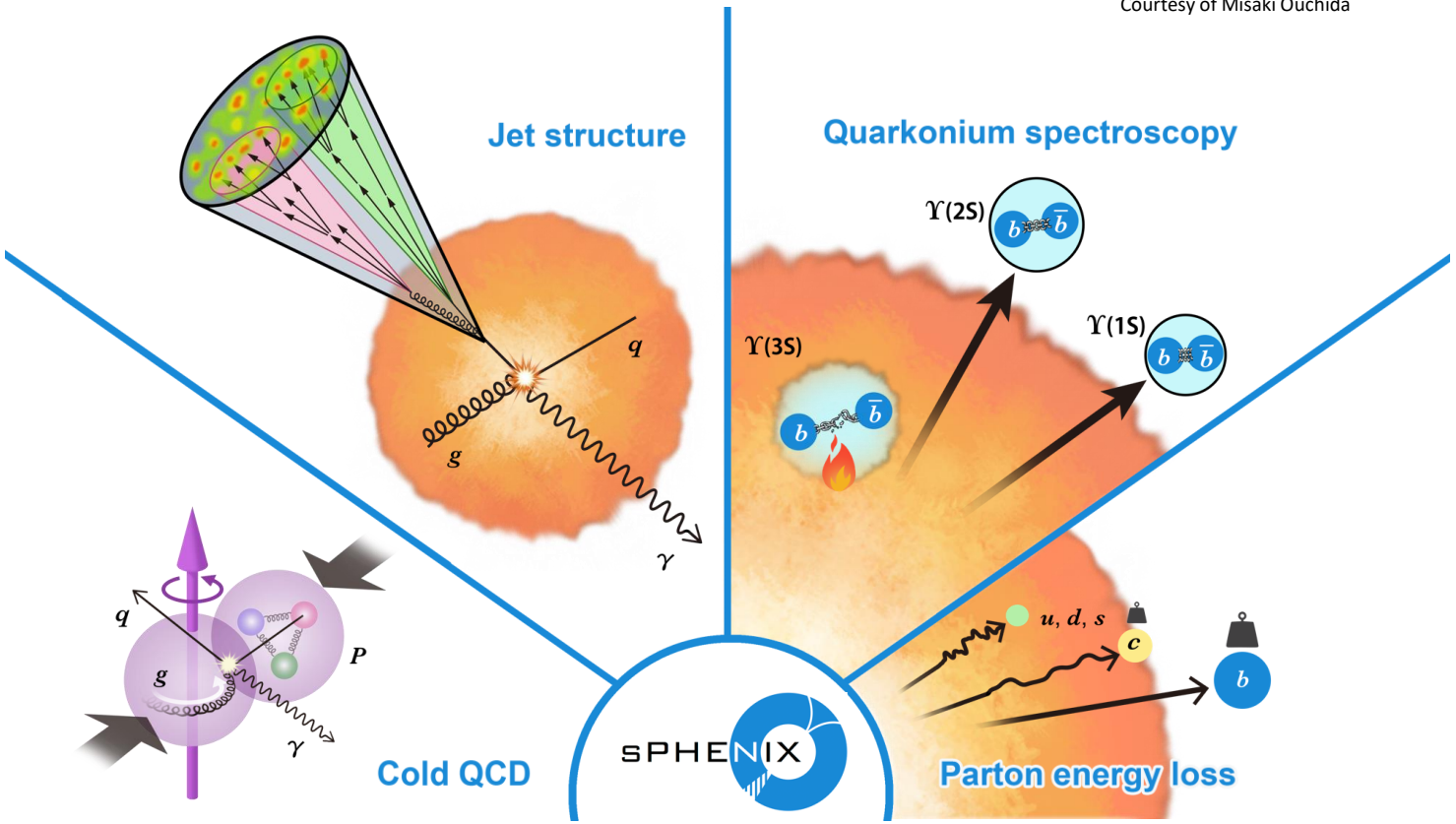
- Broader momentum coverage at RHIC
- Complementary between RHIC and LHC

https://indico.bnl.gov/event/15148/attachments/40846/68609/STAR_BUR_Runs23_25___2022 (1).pdf

sPHENIX Scientific Program

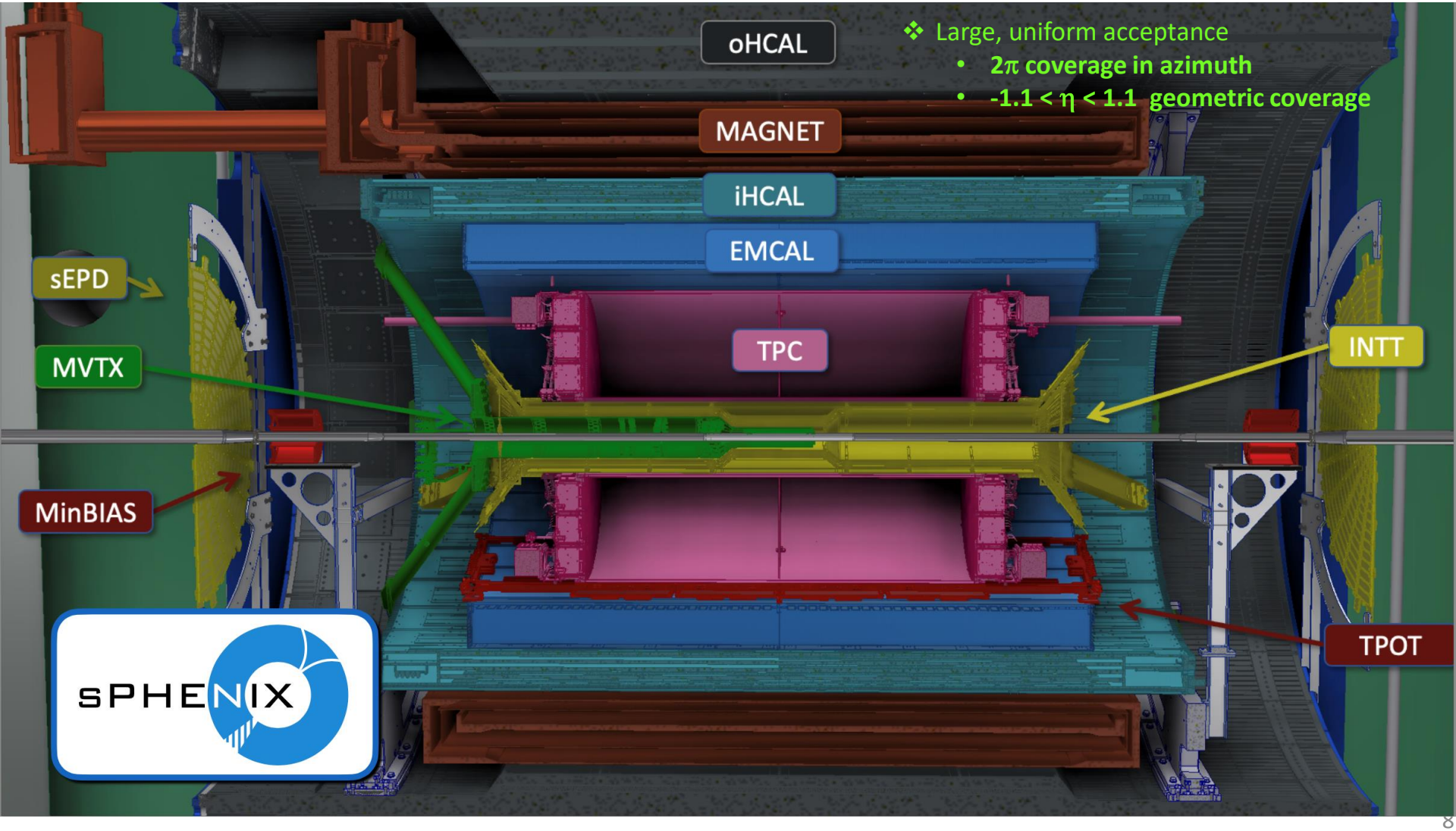
- **sPHENIX is a new state-of-the-art detector constructed 2015/2023 at BNL/RHIC.**

Courtesy of Misaki Ouchida

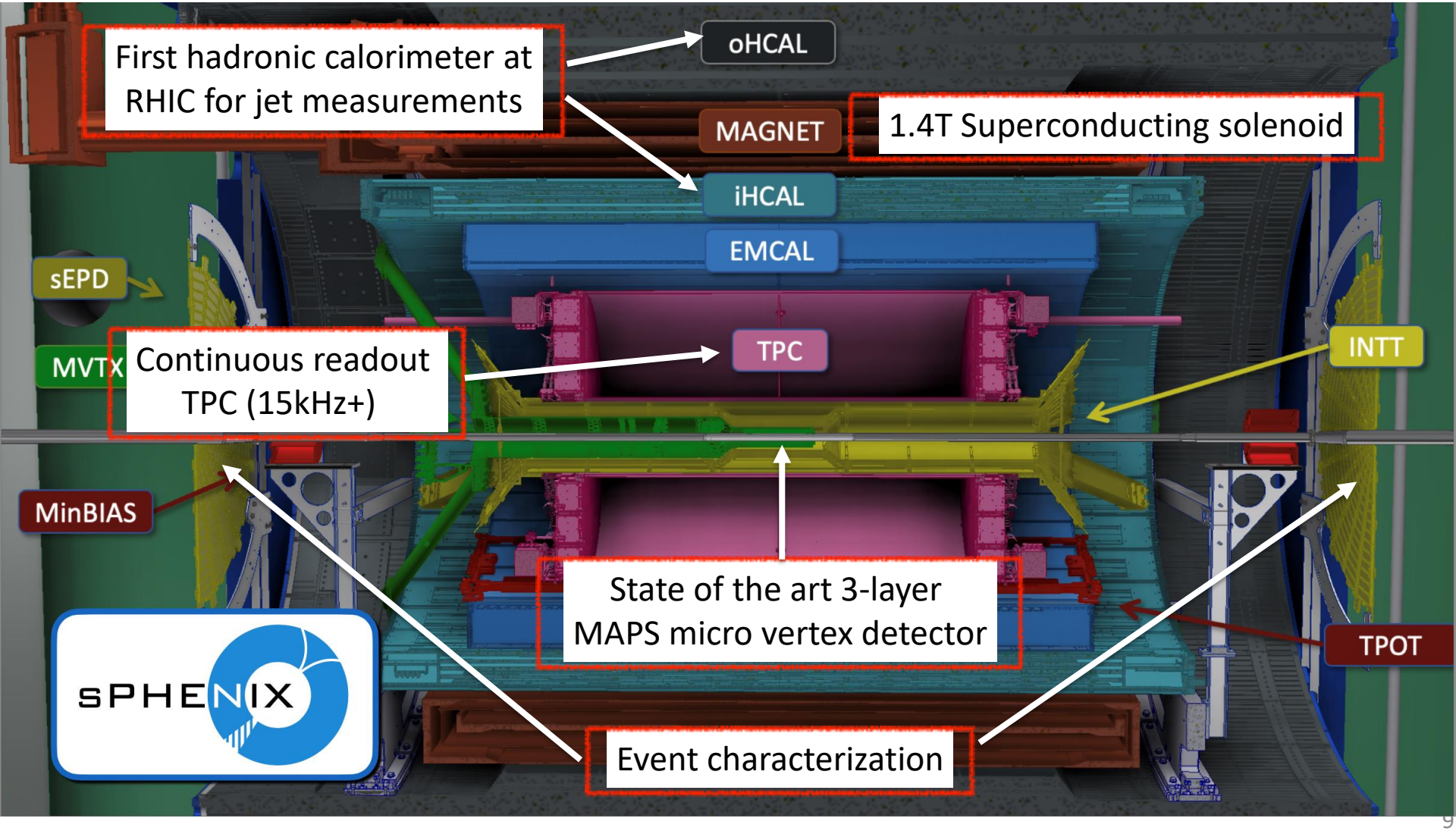


Detector design, computing effort and run schedule focused on these physics goals

sPHENIX detector



sPHENIX detector



Prospects for Heavy Flavor Physics in sPHENIX

Expectations from sPHENIX Beam Use Request (BUP)

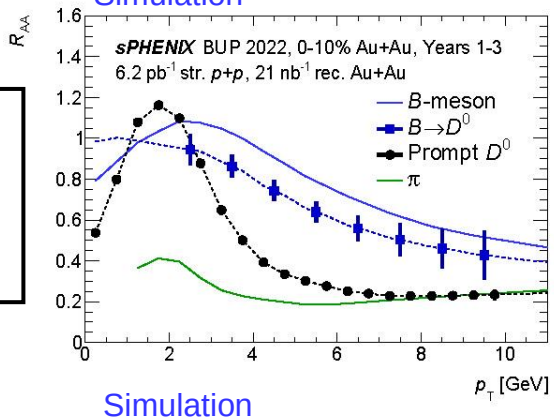
p+p running right now is key for HF program — streaming readout boost HF statistics which is needed for R_{AA}, Λ_C / D^0, …

The sPHENIX tracking detectors are taking p+p data with stream readout TOGETHER at a rate ~ 15 kHz

The HF physics requires 10's micron vertex resolution –
the collaboration is working intensively on alignment/calibration to achieve this goal !

Nuclear modification factor

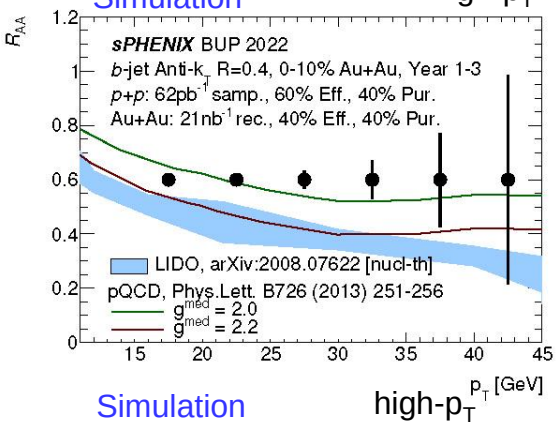
Simulation



Simulation

high-p_T

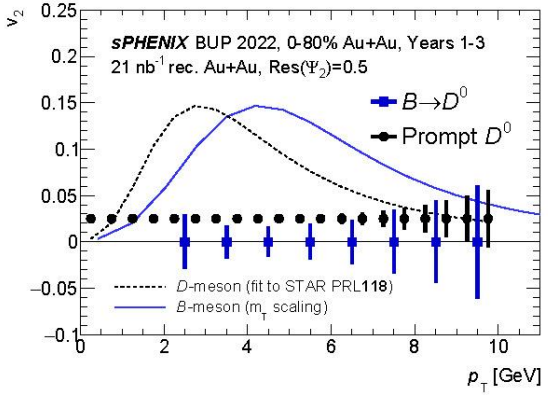
Simulation

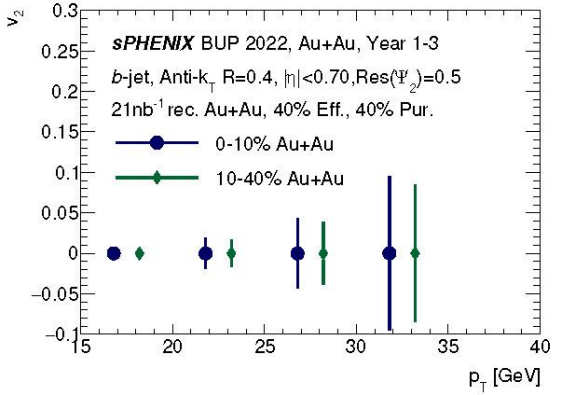


Simulation

high-p_T

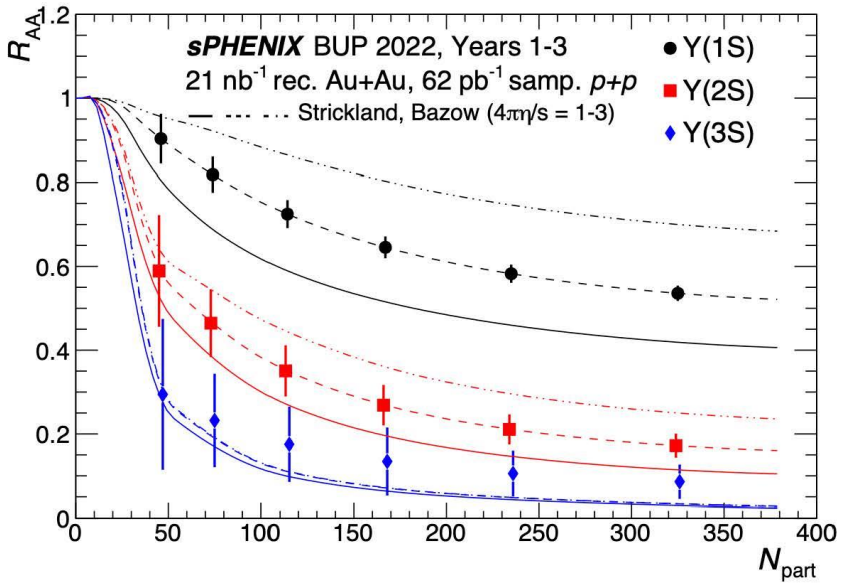
Elliptic Flow



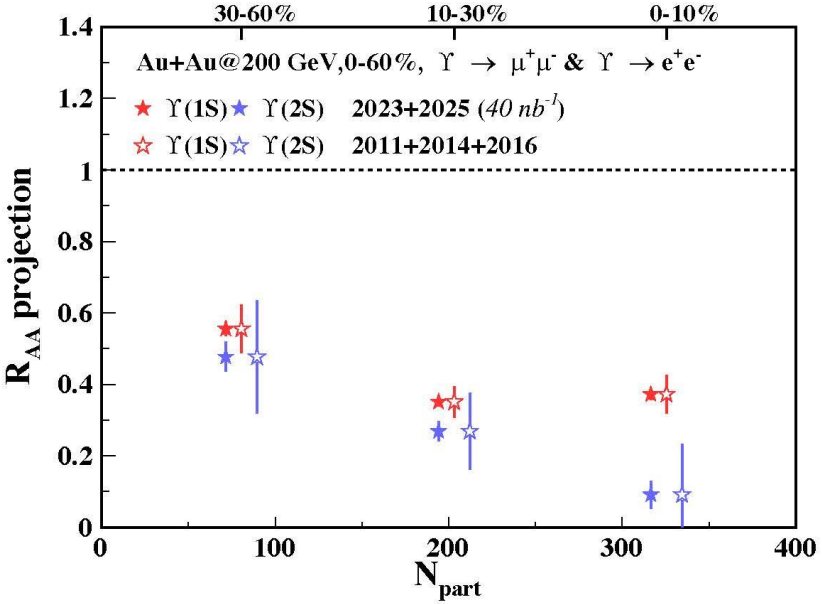


Upsilon sPHENIX/STAR outlook

sPHENIX Beam Use Proposal



STAR Beam Use Request



STAR BUR & sPHENIX BUR

2023+2024+2025 data:

- Enable first Upsilon(3S) R_{AA} measurement in Au+Au at RHIC
- Improve Upsilon(1S) and Upsilon(2S) measurement significantly

Summary

- STAR and PHENIX extensively studied production of heavy flavor hadrons in hadronic and electron channels
- **D^0, $D^{\pm}$ meson R_{AA}** in Au+Au collisions:
  - Indicate strong charm-medium interactions
- **Λ_c/D^0 and D_s/D^0** yield ratios are enhanced in Au+Au collisions with respect to p+p collisions
  - Coalescence plays an important role in charm quark hadronization
- Indication of less suppression for ***B→e* than *D→e***
  - Consistent with expected mass hierarchy of parton energy loss
- Observation of **non-zero flow** of HFE 54-200 GeV
- **J/ψ suppression**: no significant collision system and energy dependence
  - Interplay of dissociation and regeneration effects
- **Sequential** Υ suppression at RHIC
  - Thermodynamic properties of the medium
- **More results expected from STAR and sPHENIX after 2025 run**

sPHENIX Science Mission

sPHENIX Science Mission

- sPHENIX is a new state-of-the-art detector constructed 2015/2023 at BNL/RHIC.
- It was commissioned and took first Au+Au collisions data in the RHIC Run-2023:
  → First full calorimeter jets observation at RHIC
- Fundamental questions on the nature of the QGP, including its coupling strength and temperature dependence, by using precision jet and upsilon measurements probing different length scales of QGP.
- With the increased RHIC's luminosity, sPHENIX will perform high statistics measurements extending the kinematic reach at RHIC to overlap the LHC's.