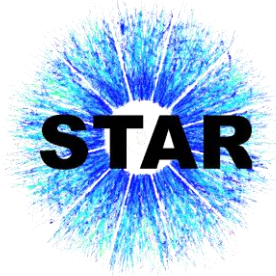
Recent heavy-flavor measurements from STAR

DIS 2024

Veronika Prozorova ***(for the STAR Collaboration)***

Czech Technical University in Prague



The 31st International Workshop on Deep Inelastic Scattering and Related Subjects
April 8 - 12, 2024, Grenoble, France

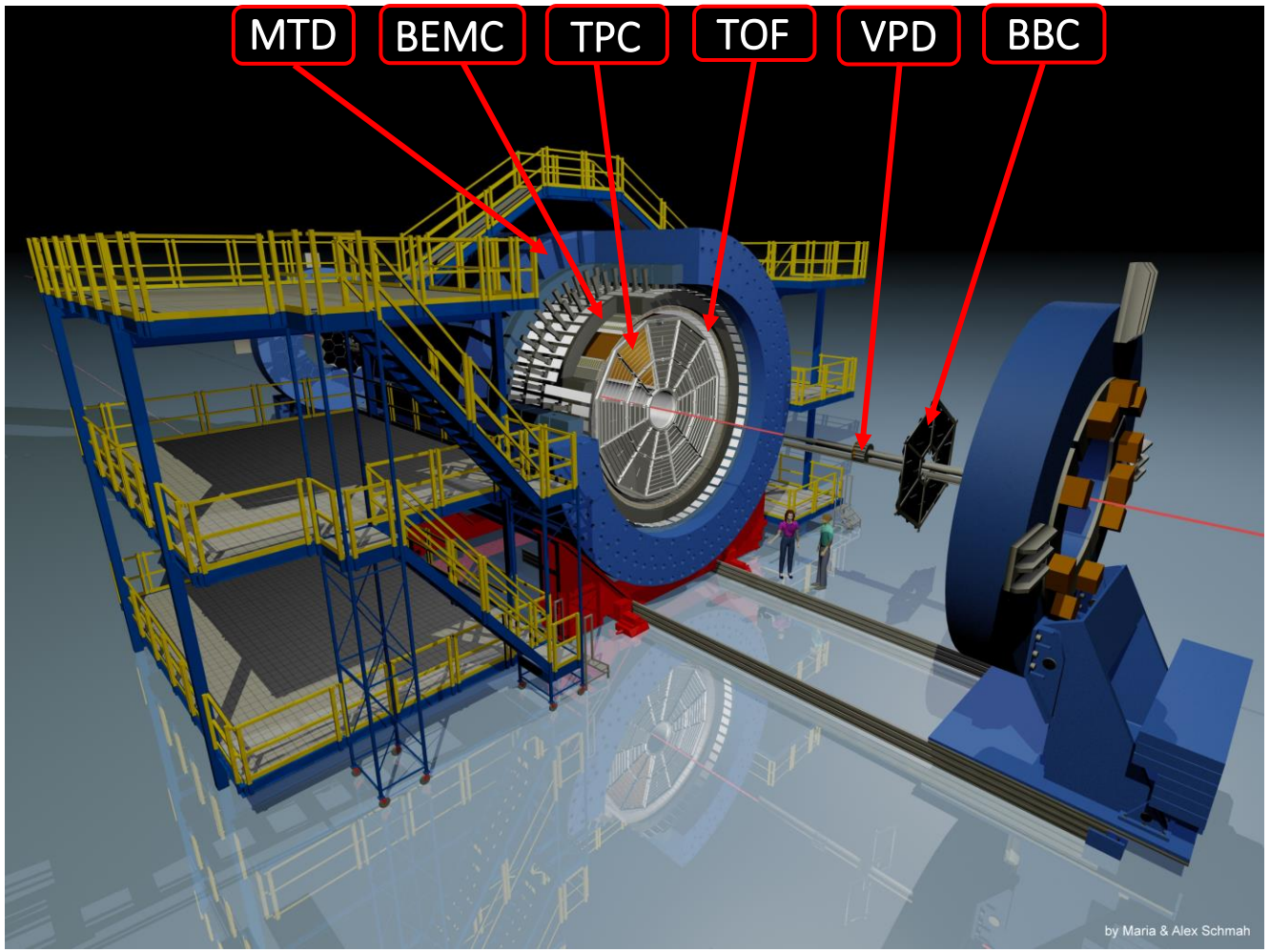
Supported in part by

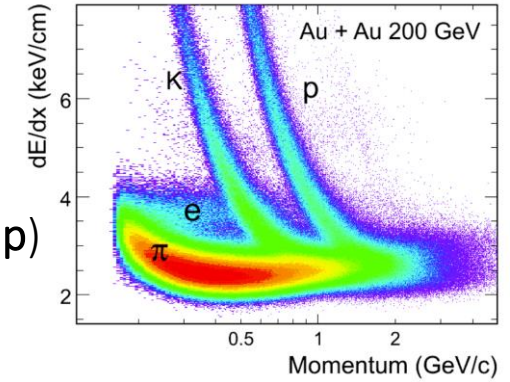
U.S. DEPARTMENT OF ENERGY | Office of Science

Outlook

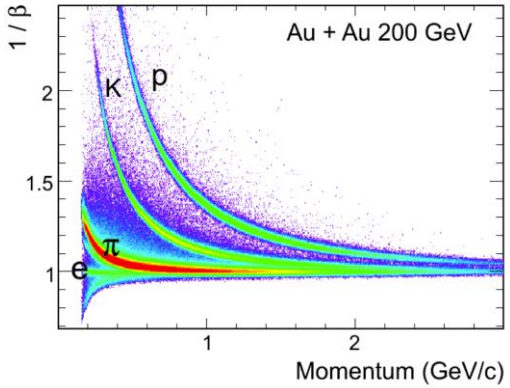
- STAR detector
- Introduction
- Recent open heavy-flavor results
- Recent quarkonia results
- Summary

The Solenoidal Tracker At RHIC (STAR)



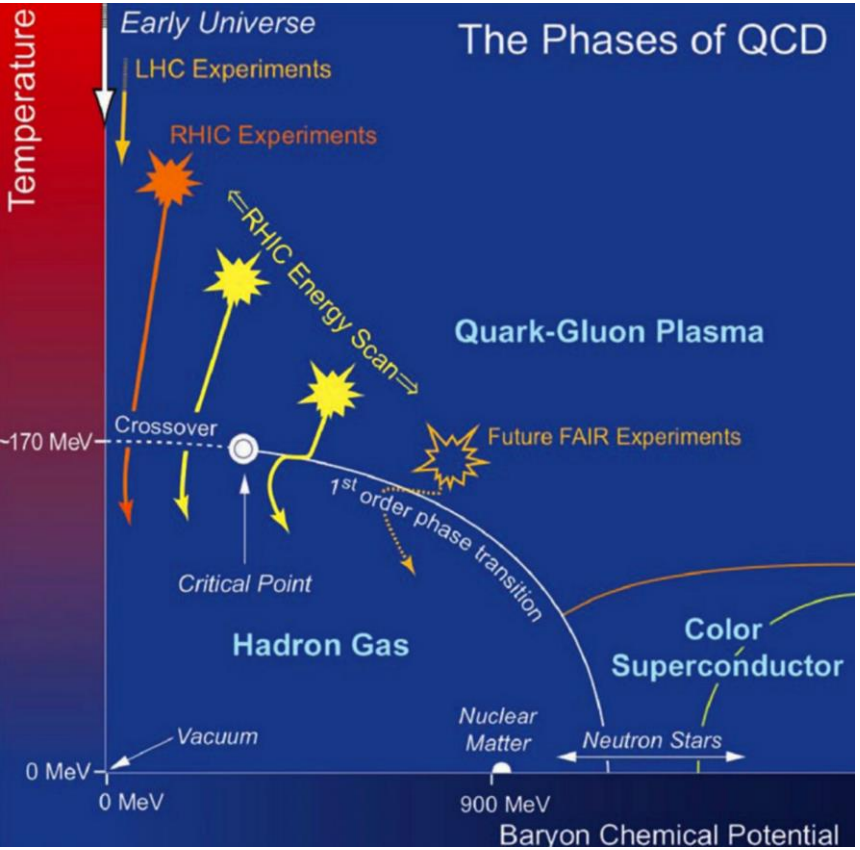


- TPC – tracking and PID (dE/dx, **p**)
  Acceptance: $|\eta| < 1$
- BEMC – high p_T electron identification and triggering
  Acceptance: $|\eta| < 1$



- TOF – PID (1/β)
  Acceptance: $|\eta| < 1$
- MTD – muon identification and triggering
  Acceptance: $|\eta| < 0.5$
- BBC & VPD – minimum bias trigger
  Acceptance: $3.9 < |\eta| < 5$ – BBC
  $|\eta| < 1$ – VPD

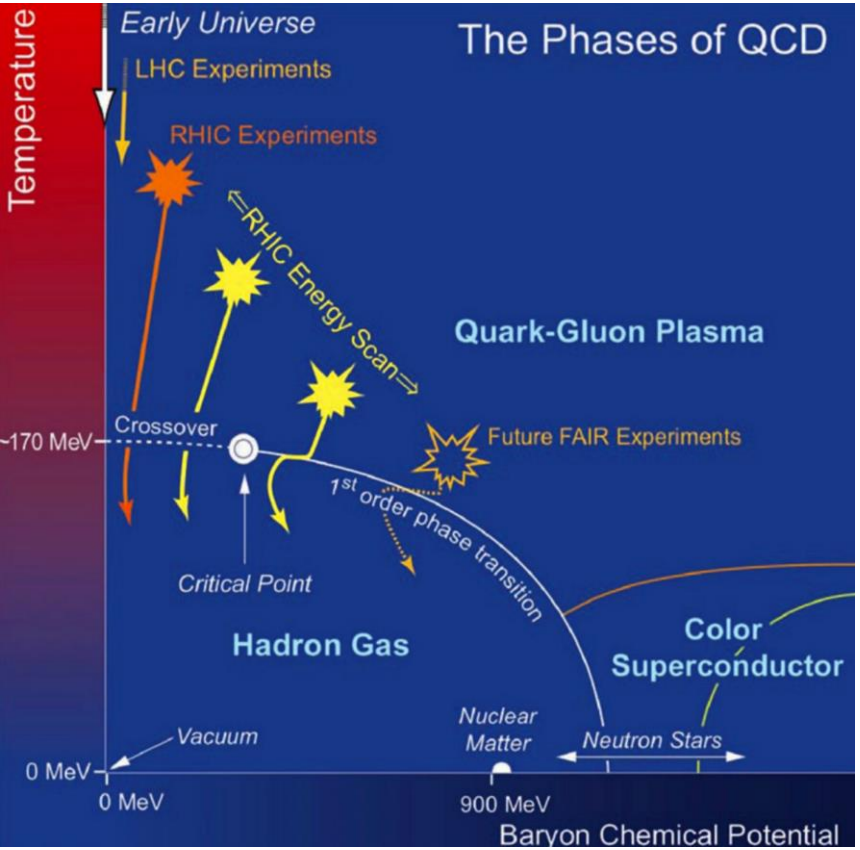
Introduction



Quark-Gluon Plasma (QGP) – strongly interacting matter at extreme temperature and/or density.

Heavy Ion Collisions are used to explore the phase diagram and QGP properties.

Introduction



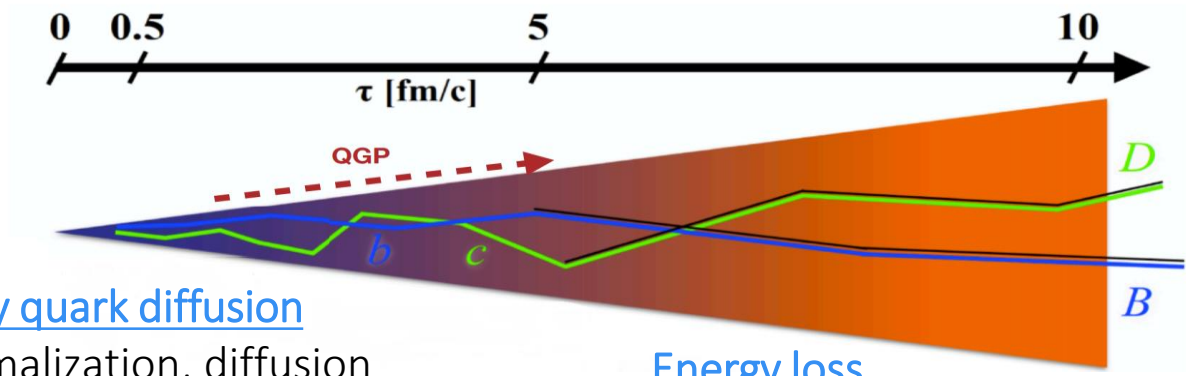
Quark-Gluon Plasma (QGP) – strongly interacting matter at extreme temperature and/or density.

Heavy Ion Collisions are used to explore the phase diagram and QGP properties.

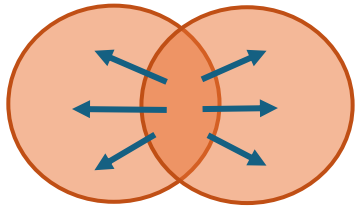
Heavy quarks
charm & bottom

- Heavy quarks: $m_Q >> \Lambda_{QCD}$, $m_Q >> T_{QGP}$
- Dominantly produced in initial hard scatterings
- Participate in the whole medium evolution
- Production cross-sections can be calculated in perturbative QCD

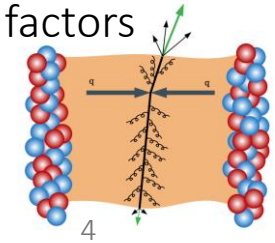
→ Ideal probes of QGP



Heavy quark diffusion
Thermalization, diffusion
→ Elliptic flow (v_2)



Energy loss
Nuclear modification factors



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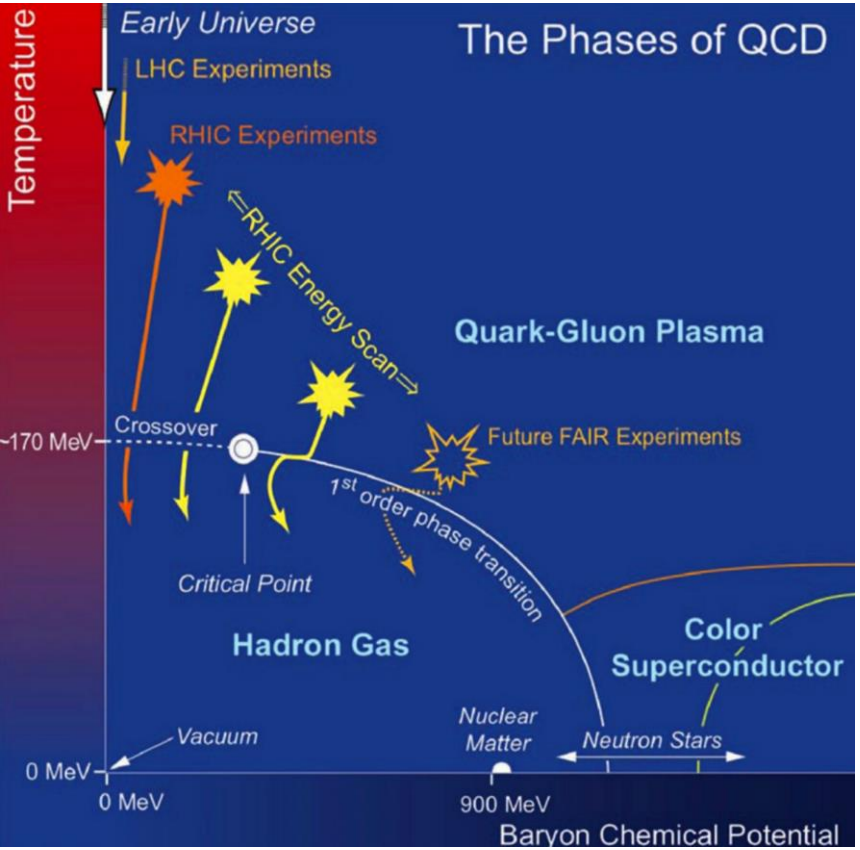

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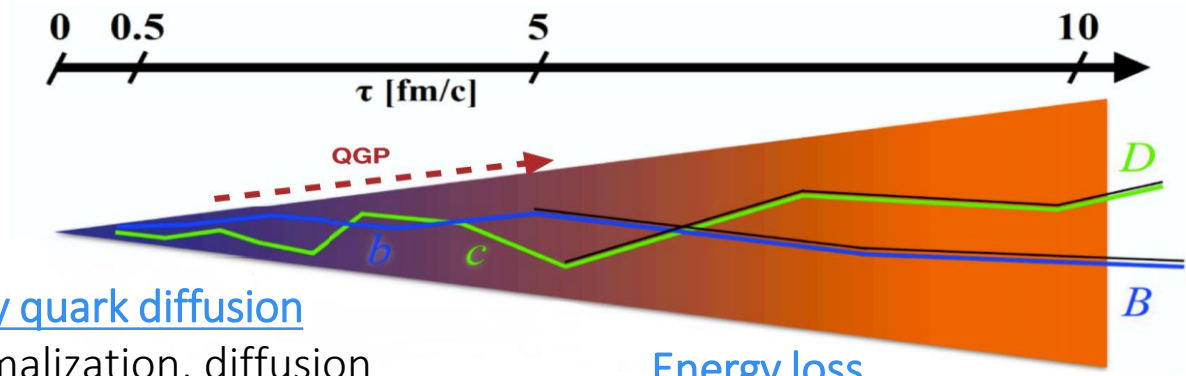


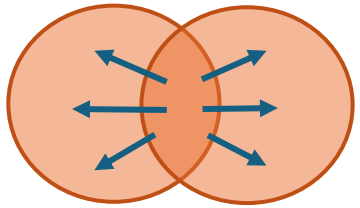
Heavy-flavor (HF) – hadrons carrying charm or bottom quarks

- ➢ Open heavy-flavor – carry one c or b quark
- ➢ Quarkonia – $c\bar{c}$ or $b\bar{b}$

Heavy quark diffusion

Thermalization, diffusion

→ Elliptic flow (v_2)



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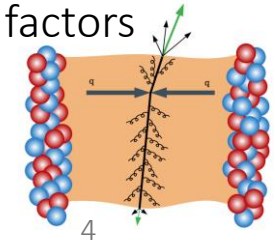
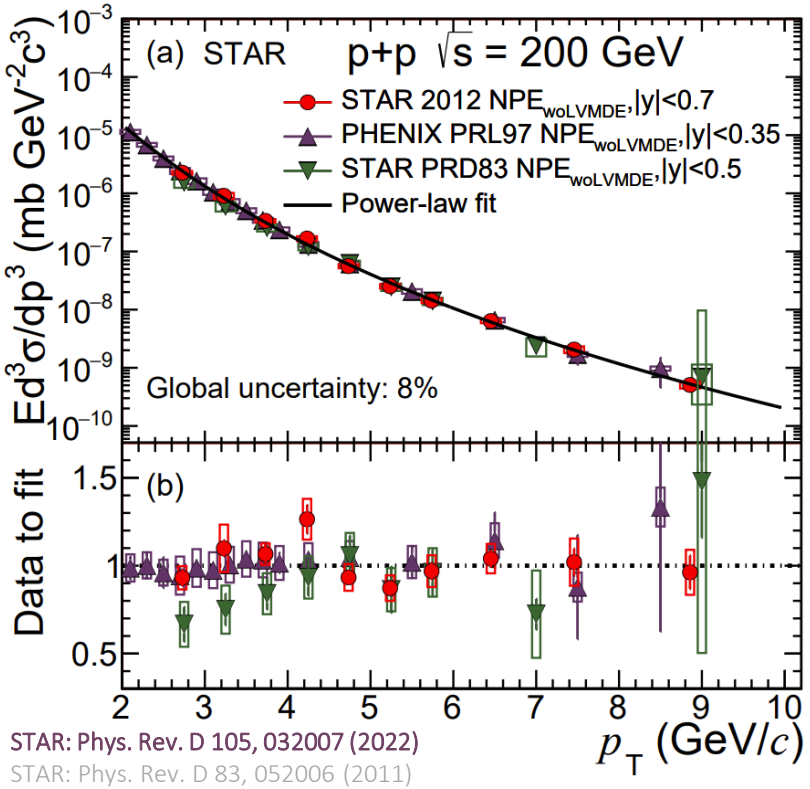


Inclusive $e^{\pm}$ from open HF hadron decays in p+p @ 200 GeV



STAR: Phys. Rev. D 105, 032007 (2022)
STAR: Phys. Rev. D 83, 052006 (2011)
PHENIX: Phys. Rev. Lett. 97, 252002 (2006)

- Good agreement among the results
- Precision improvement at p_T > 6 GeV/c

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{2}\frac{1}{L}\frac{N_{NPE}}{2\pi p_T \Delta p_T \Delta y} - E\frac{d^3\sigma}{dp^3}(\text{LVMDE or HDE})$$

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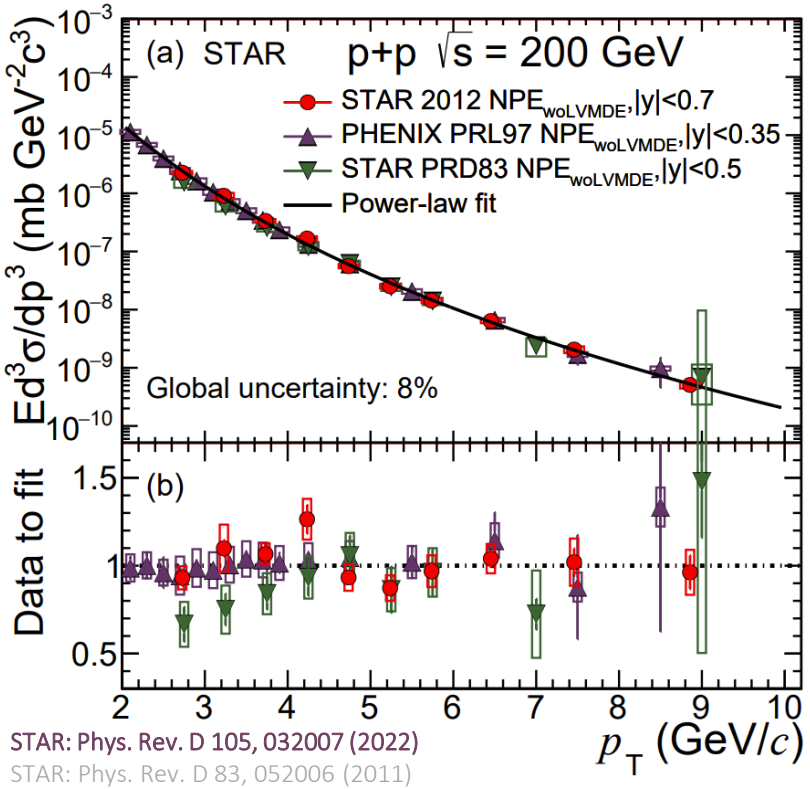

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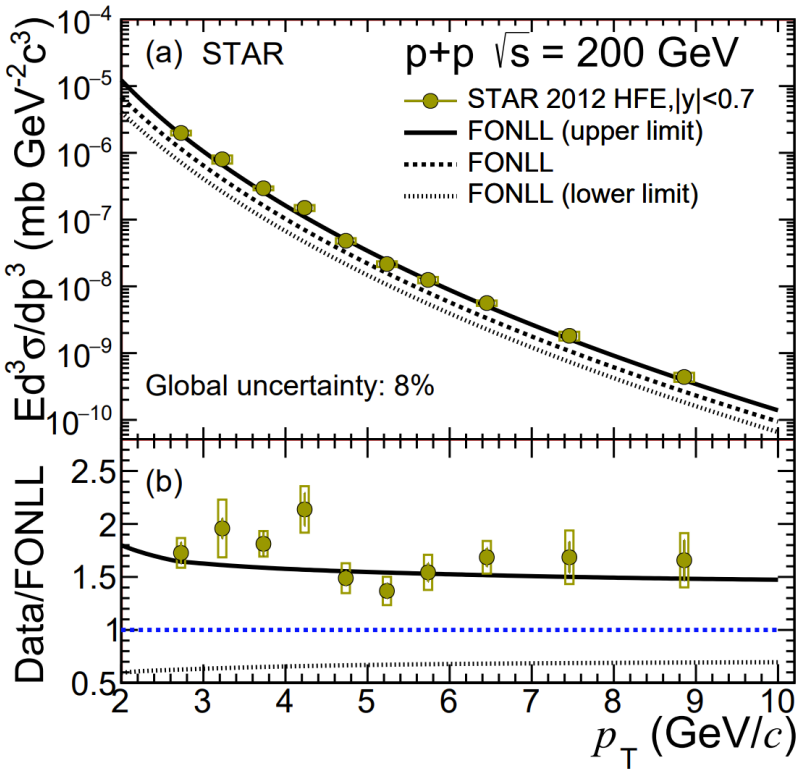

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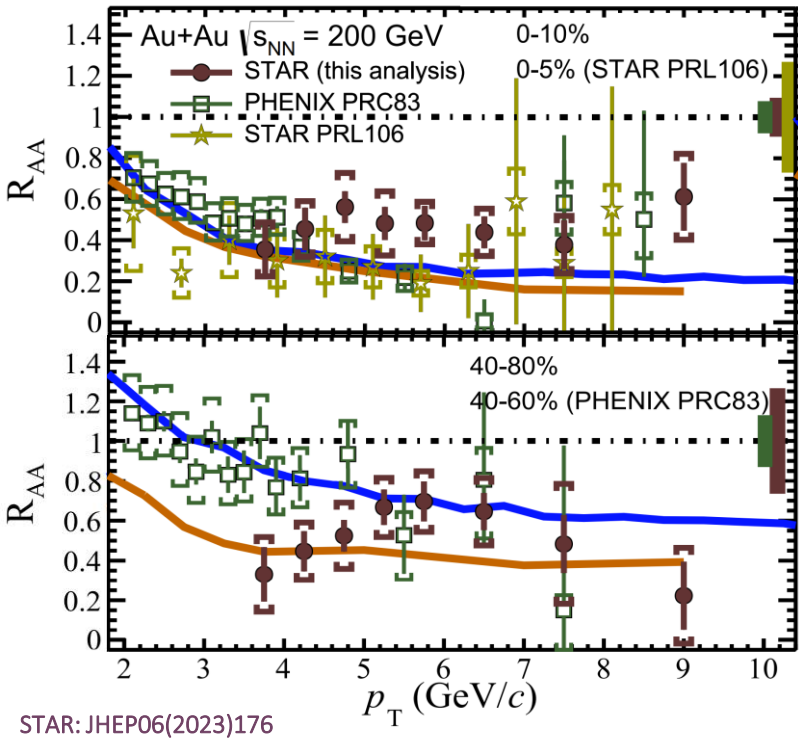
- Good agreement among the results
- Precision improvement at p_T > 6 GeV/c
- Consistency with the upper limit of the FONLL uncertainty

- Further constraints on theoretical calculations
- Precise reference for R_{AA} measurements for heavy-flavor decayed electrons

$e^{\pm}$ from open HF hadron decays in Au+Au @ 200 GeV

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}^2/\, dp_T\, dy}{dN_{pp}^2/\, dp_T\, dy}$$



STAR: JHEP06(2023)176

PHENIX: V, Phys. Rev. C 84 (2011) 044905

STAR: Phys. Rev. Lett. 98 (2007) 192301.

- Suppression by factor of 2 in central collisions within $3.5 < p_T < 8$ GeV/c

Significant energy loss of HQ in QGP

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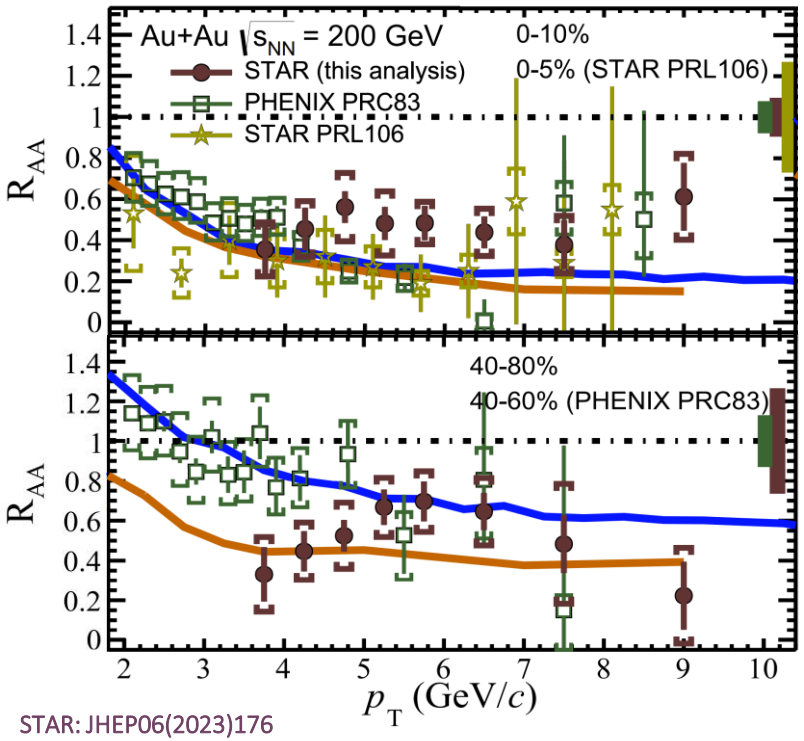

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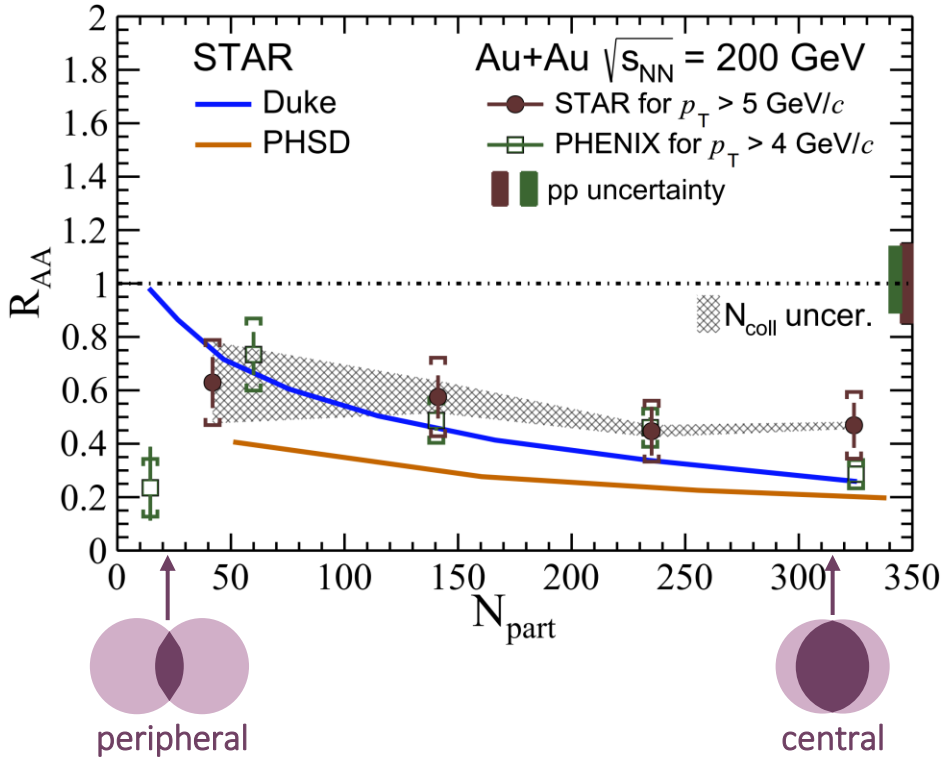
- Suppression by factor of 2 in central collisions within $3.5 < p_T < 8$ GeV/c

Significant energy loss of HQ in QGP

- A hint of HFE R_{AA} decreasing from peripheral to central collisions

Stronger parton energy loss in central collisions



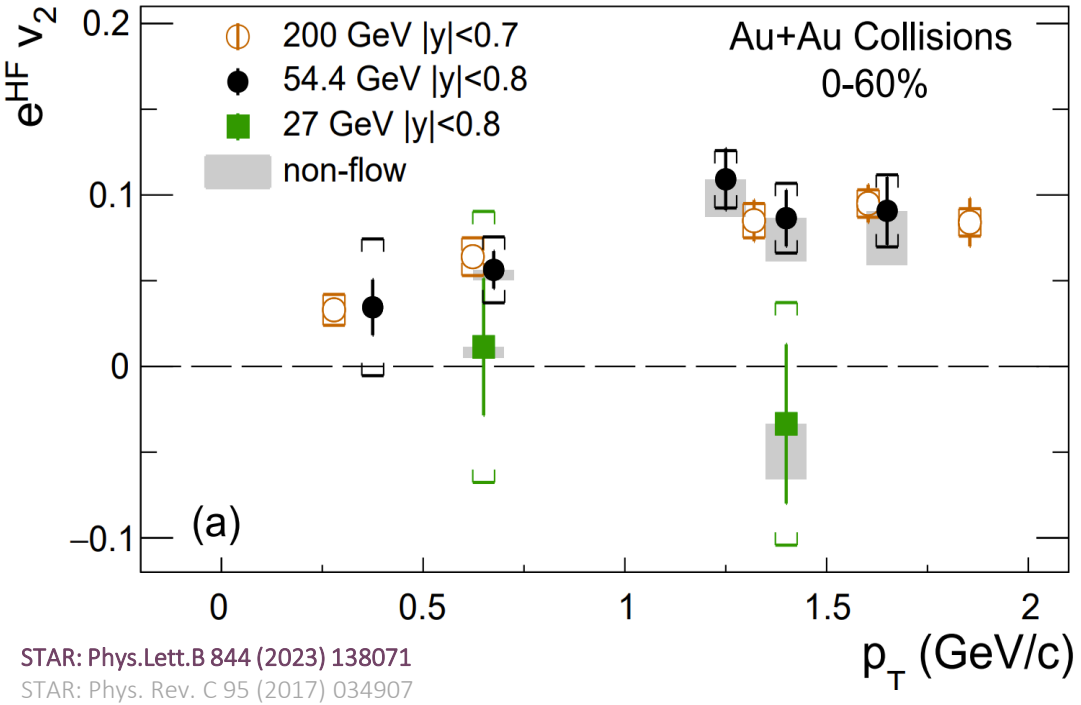
- Consistency with PHENIX results

- Qualitative description of data by Duke and PHSD models

Elliptic flow of HFE in Au+Au @ 27 & 54.4 GeV

e^{HF} (HFE) – heavy-flavor electrons

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



STAR: Phys.Lett.B 844 (2023) 138071

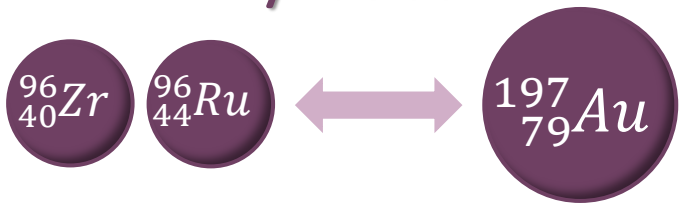
STAR: Phys. Rev. C 95 (2017) 034907

- 54.4 GeV : significant v_2 of e^{HF}
  - Strong interaction of *c* quarks with QGP
  - Hints of close to thermal equilibrium with the medium
- 27 GeV : v_2 is consistent with 0 within uncertainties
  - Hints of deviation of *c* quarks from local thermal equilibrium ?

D^0 R_{AA} in isobar collisions @ 200 GeV

STAR Preliminary

Why isobar?



Moderate size collision system, between Au+Au and Cu+Cu

Good for studying hot nuclear medium effects dependence on colliding system size

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STAR: Phys. Rev. C **99**, 034908 (2019)

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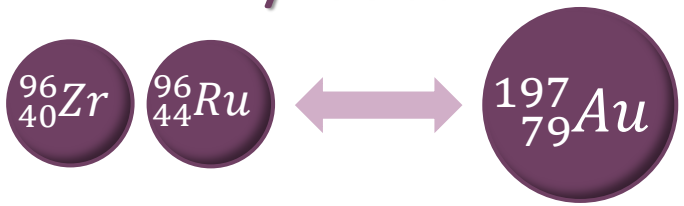

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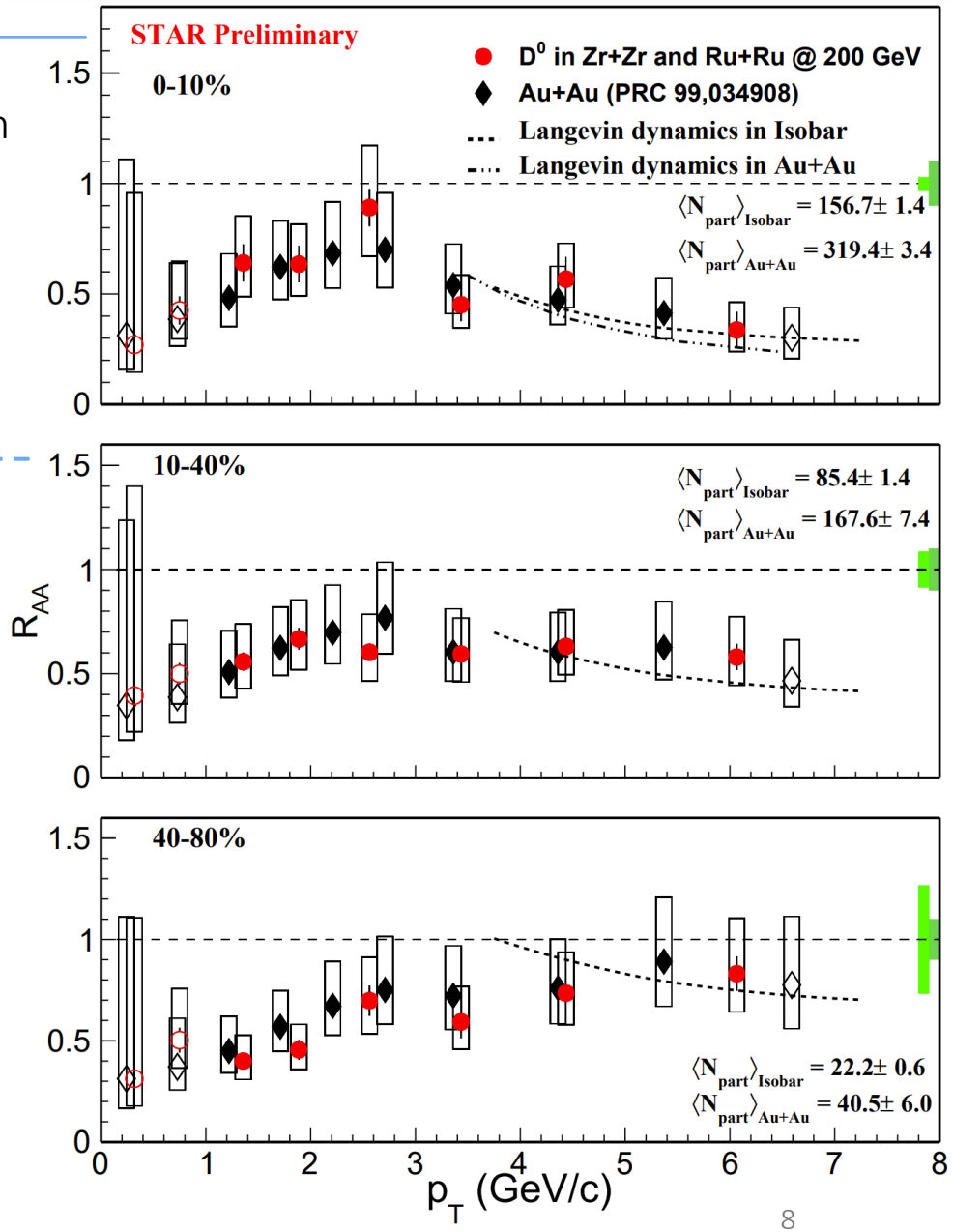
- No obvious centrality dependence for the low p_T suppression → Interplay of radial flow, the cold nuclear matter effects, and the charm hadrochemistry
- Suppression in central collisions at p_T > 3 GeV/c →
  - Significant energy loss of *c* quarks in the bulk QCD medium
  - Centrality dependence of the high p_T suppression



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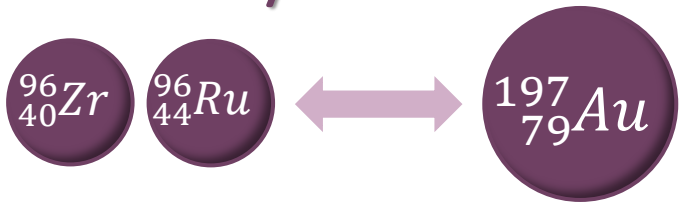

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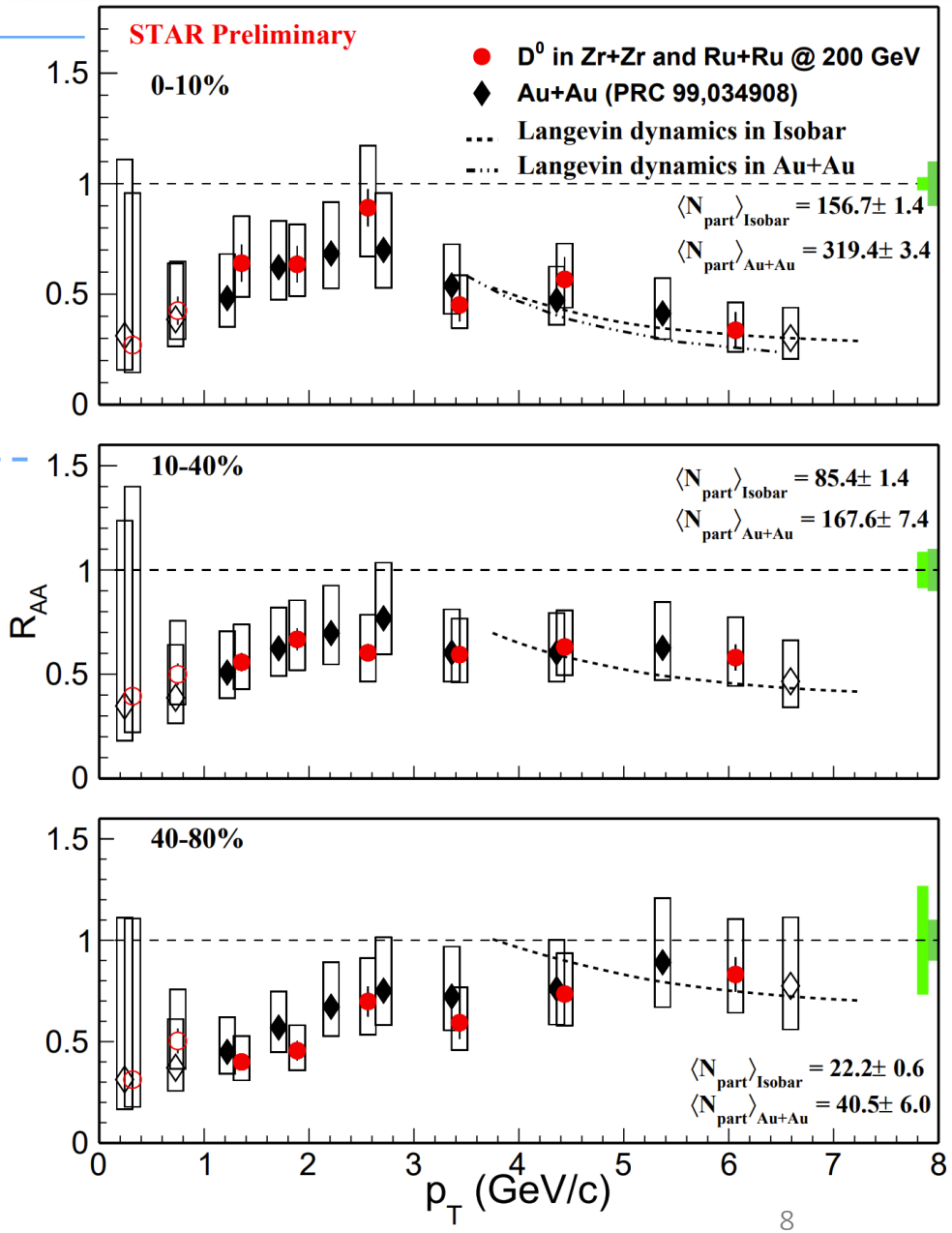
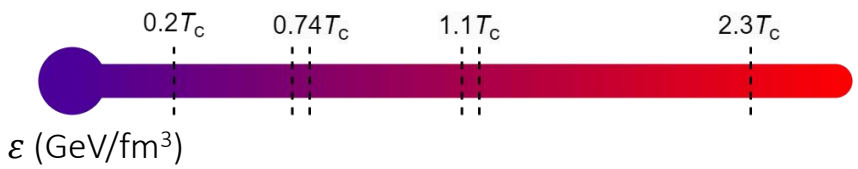
- Suppression in central collisions at p_T > 3 GeV/c →
  - Significant energy loss of *c* quarks in the bulk QCD medium
  - Centrality dependence of the high p_T suppression
  - Good description by a Langevin model from 3 GeV/c
  - Similar suppression in isobar and Au+Au collisions despite different <N_{part}> at a given energy

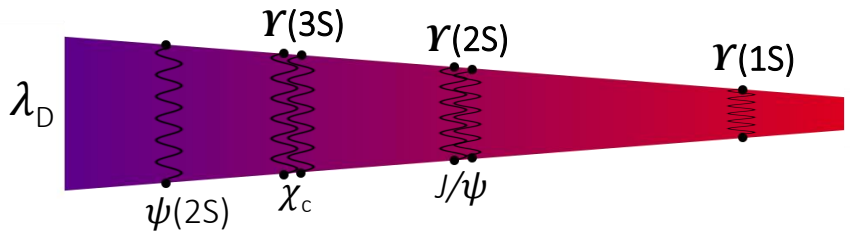


Quarkonia

- Observation of quarkonium suppression in HIC = strong evidence for QGP formation, important probes of the medium T
- Hot nuclear matter effects:
  - Dissociation due to color screening and regeneration

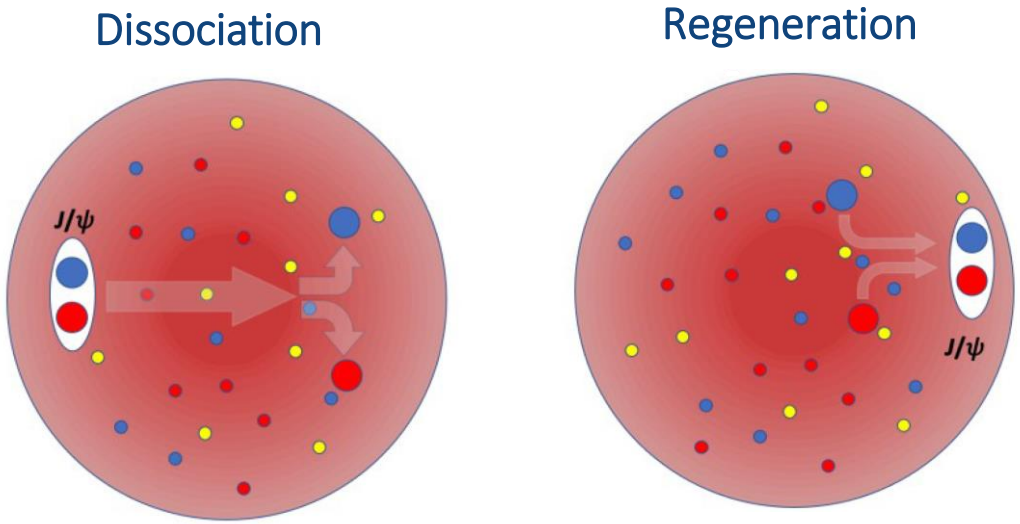
- Sequential quarkonium suppression due to different binding energies (quarkonium state size > $\lambda_D \sim 1/T_C$)

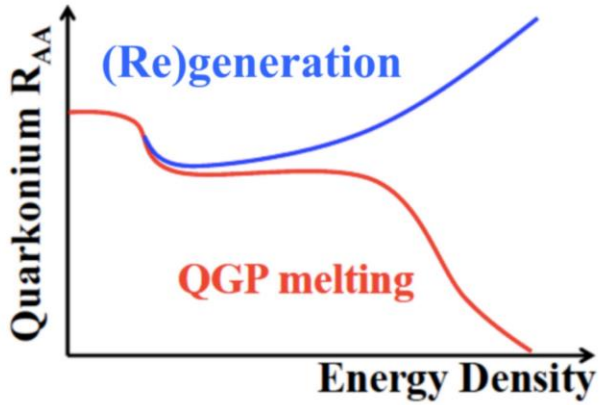




- Cold Nuclear Matter (CNM) effects:
  - Modification of PDFs, nuclear absorption, coherent energy loss, co-mover absorption, ... - study in p+A collisions

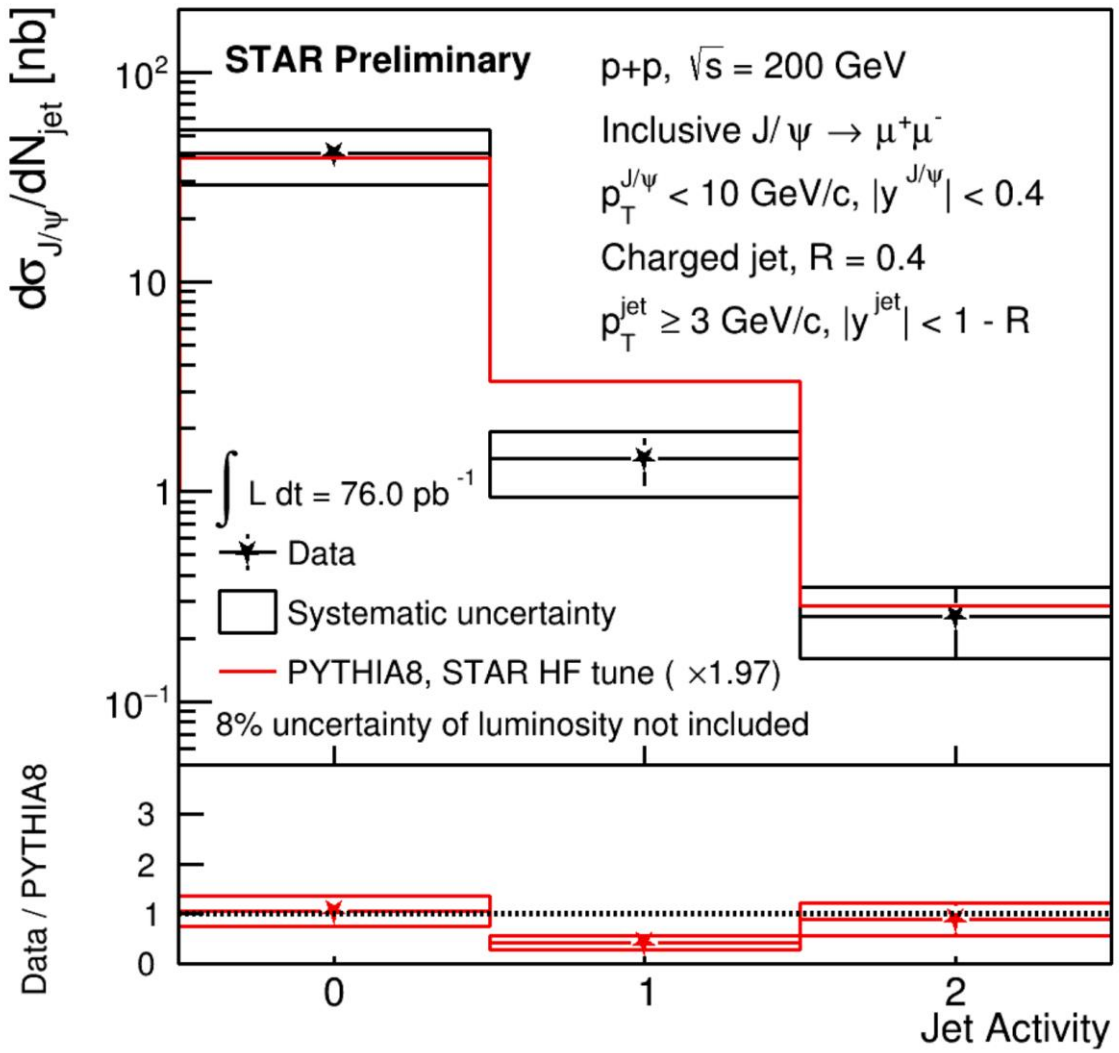
- Production mechanism - study in p+p collisions





J/ψ with jet activity in p+p collisions @200 GeV

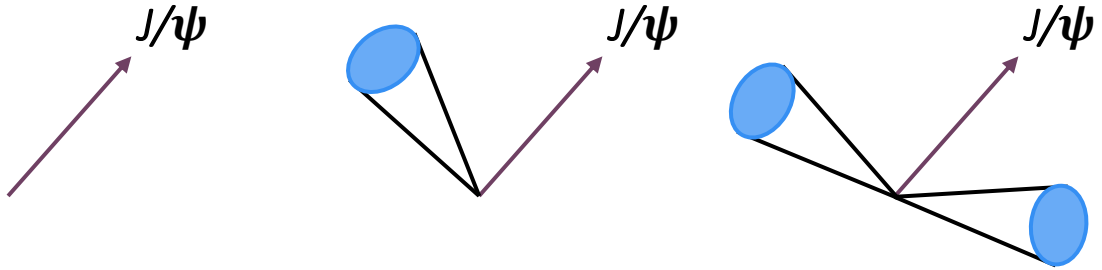
STAR Preliminary



Constraining J/ψ production mechanisms: comparing color singlet vs color octet states, which should result in differing jet activity.

Lansberg, Physics Reports, 889, 1 (2020)

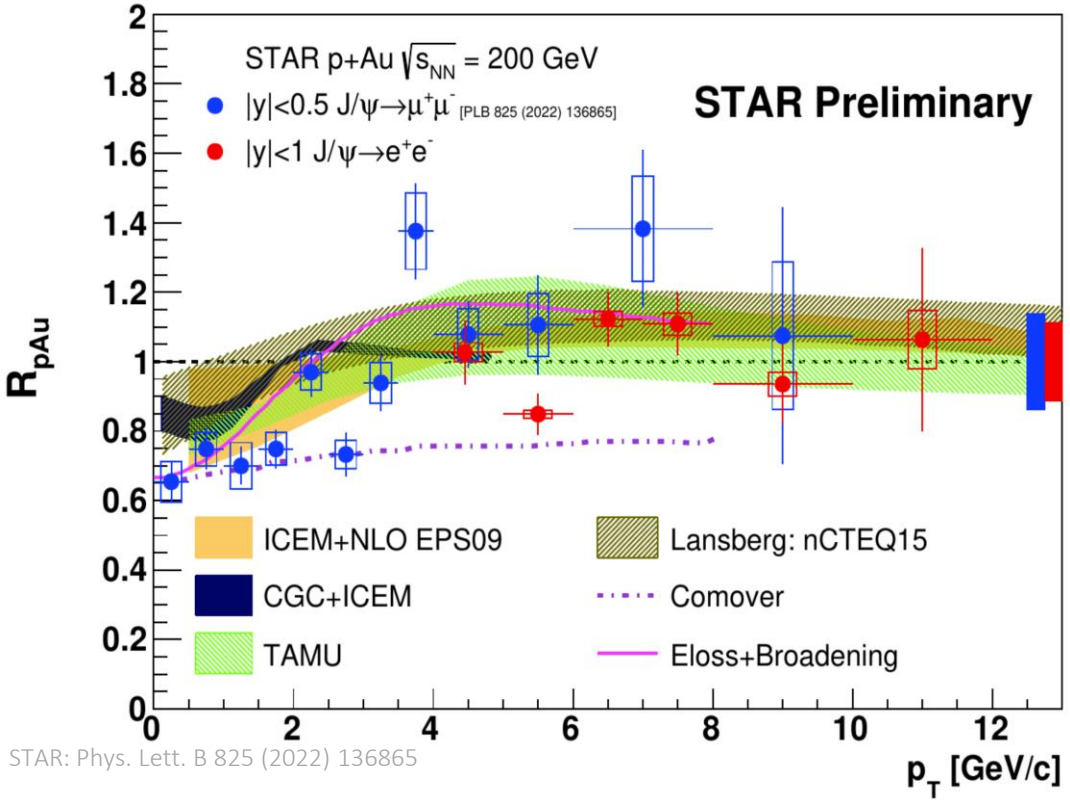
- Dependence of J/ψ production cross section on jet activity for charged jets
- Larger fraction of J/ψ produced associated with jet in Pythia than in data



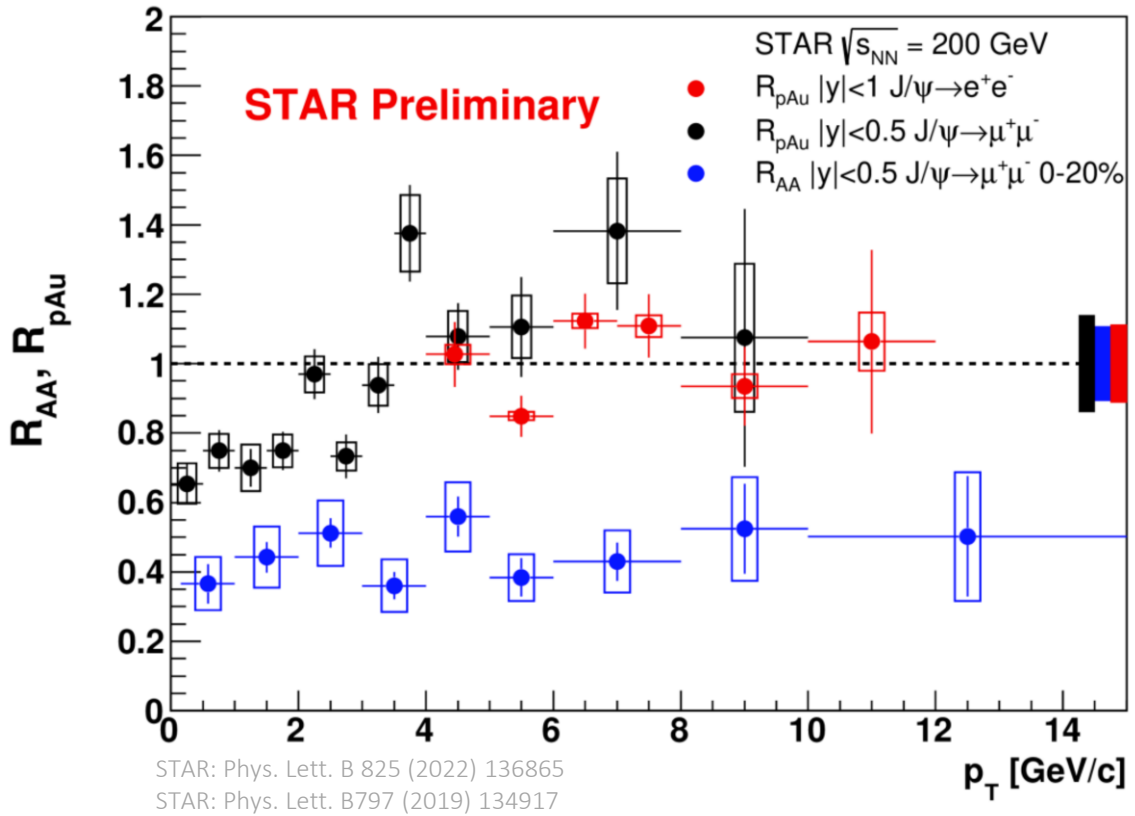
J/ψ with 0 jet | J/ψ with 1 jet | J/ψ with 2 jets

CNM effects on J/ψ in p+Au @ 200 GeV

STAR Preliminary



STAR: Phys. Lett. B 825 (2022) 136865



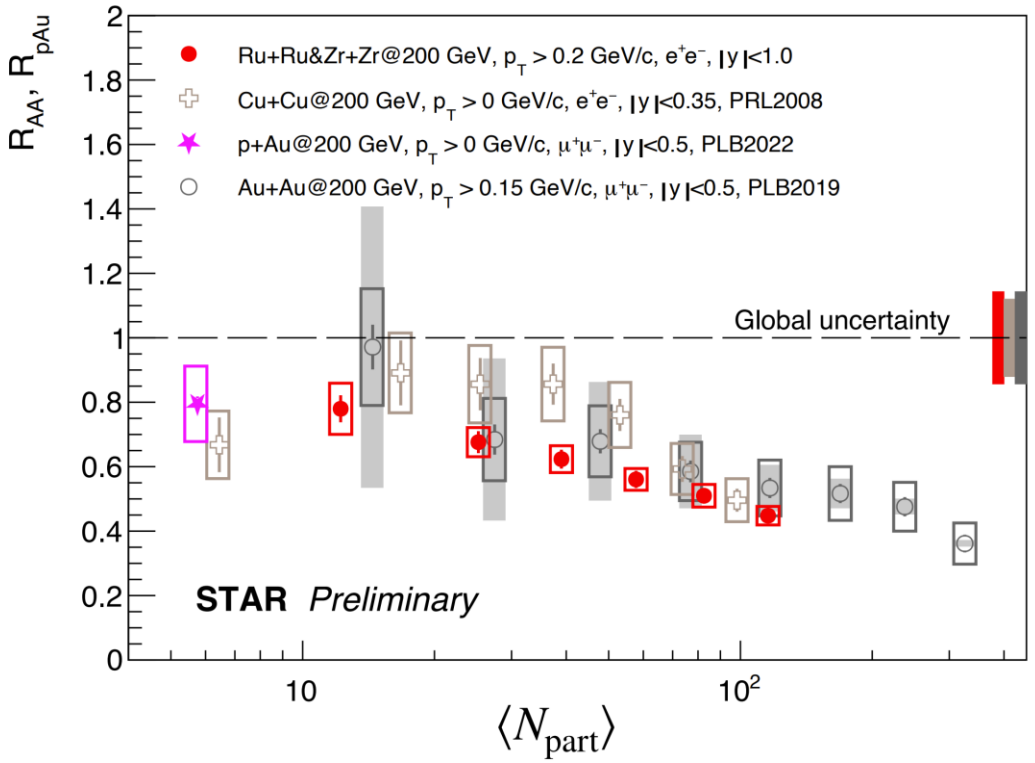
STAR: Phys. Lett. B 825 (2022) 136865
STAR: Phys. Lett. B797 (2019) 134917

- Significant CNM effects at low p_T
- Consistency with the model calculations within uncertainties
- Consistency with unity above 3 GeV/c → Little CNM effects on J/ψ production

- Au+Au: large suppression of J/ψ yield above 3 GeV/c due to hot medium effects

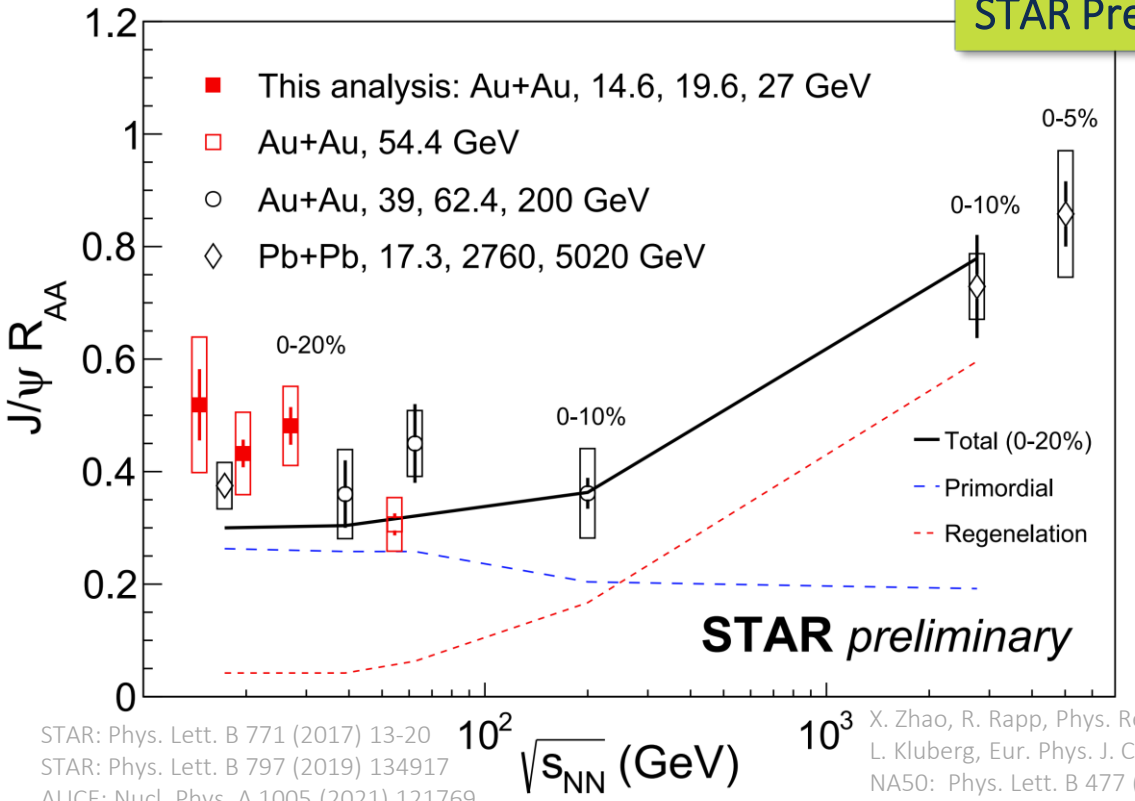
$$R_{pAu} = \frac{1}{< T_{AA} >} \times \frac{\left(\frac{d^2 N_{J/\psi}}{dp_T\, dy}\right)_{p+Au}}{\left(\frac{d^2 \sigma_{J/\psi}}{dp_T\, dy}\right)_{p+p}}$$

Collision energy and system size dependence of J/ψ suppression



No collision system size dependence

STAR Preliminary



STAR: Phys. Lett. B 771 (2017) 13-20
STAR: Phys. Lett. B 797 (2019) 134917
ALICE: Nucl. Phys. A 1005 (2021) 121769

X. Zhao, R. Rapp, Phys. Rev. C 82 (2010)
L. Kluberg, Eur. Phys. J. C 43 (2005) 145
NA50: Phys. Lett. B 477 (2000) 28
ALICE: Phys. Lett. B 734 (2014) 314

No significant energy dependence within uncertainties up to 200 GeV

↓

Interplay of dissociation, regeneration and cold nuclear matter effects

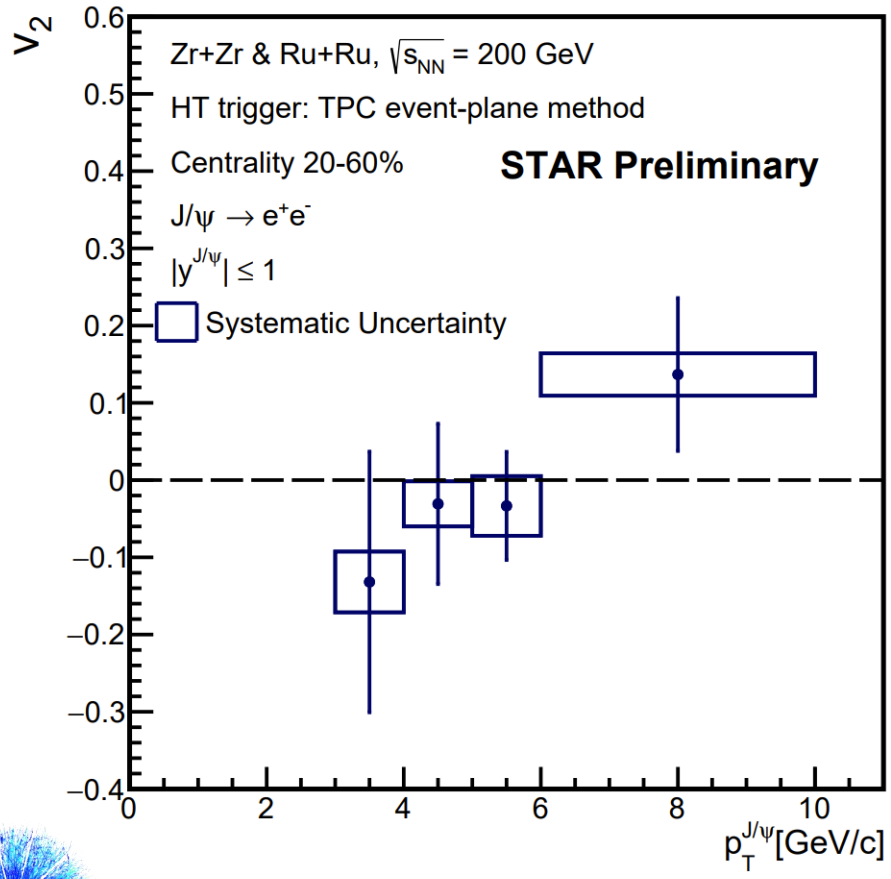
J/ψ elliptic flow in isobar collisions @ 200 GeV

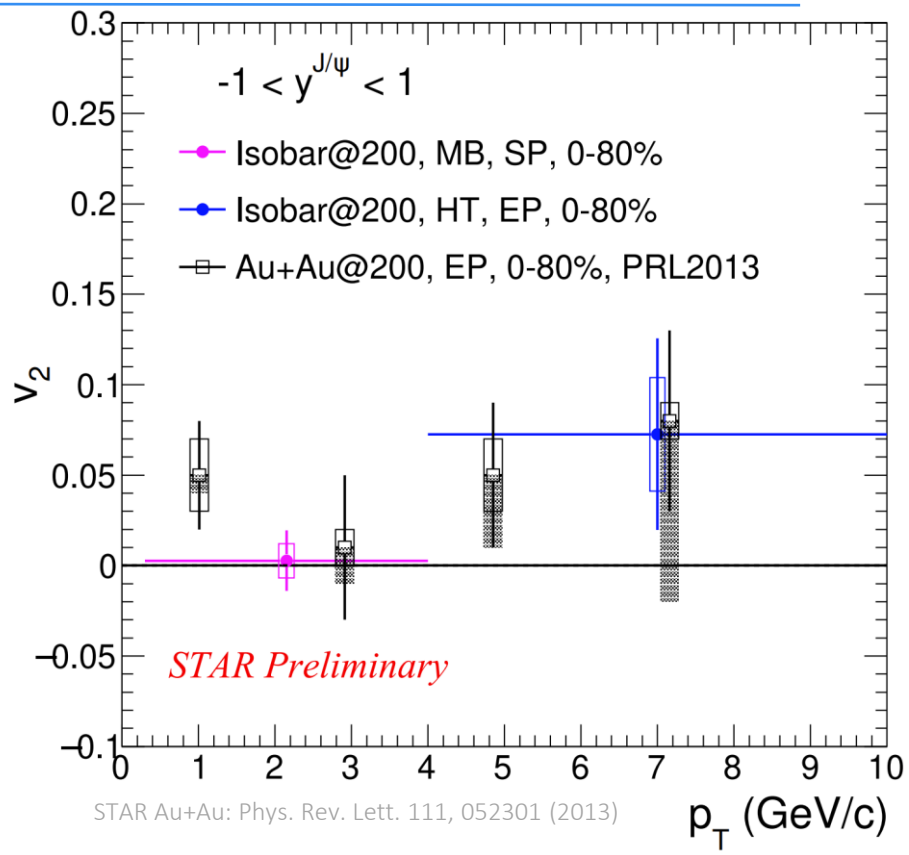
STAR Preliminary

Why J/ψ v_2 ?

↓

Distinguish J/ψ from dissociation or regeneration





STAR Au+Au: Phys. Rev. Lett. 111, 052301 (2013)

- J/ψ v_2 is consistent with 0 and with Au+Au results

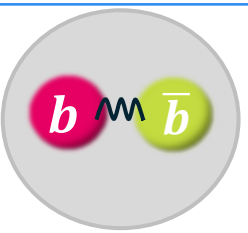
↓

Indication of small regeneration effects

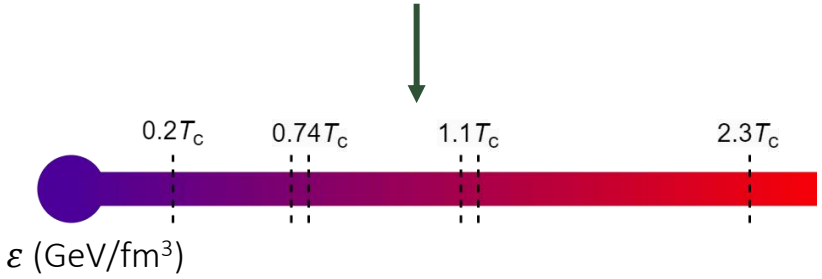
- Uncertainty is dominated by statistical error

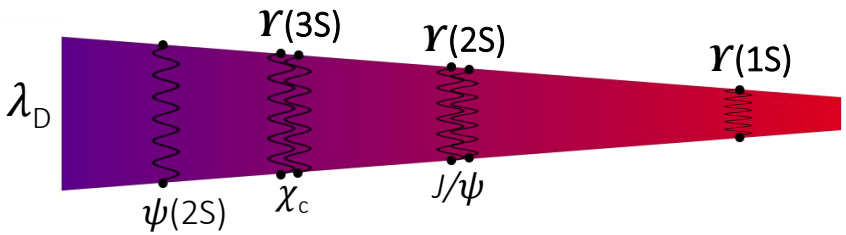
ϒ production in isobar collisions @ 200 GeV

STAR Preliminary



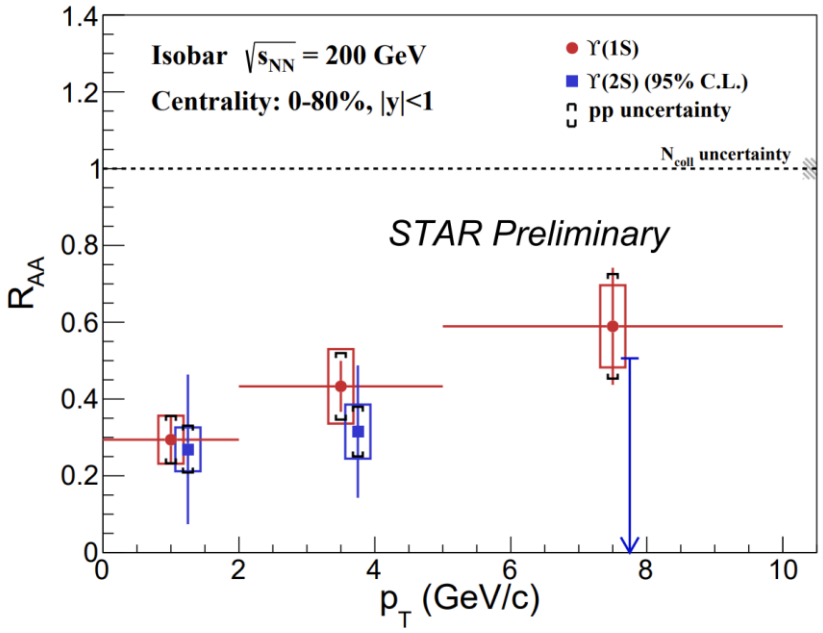
- Dissociation of quarkonium states (quarkonium state size > $\lambda_D \sim 1/T_C$)

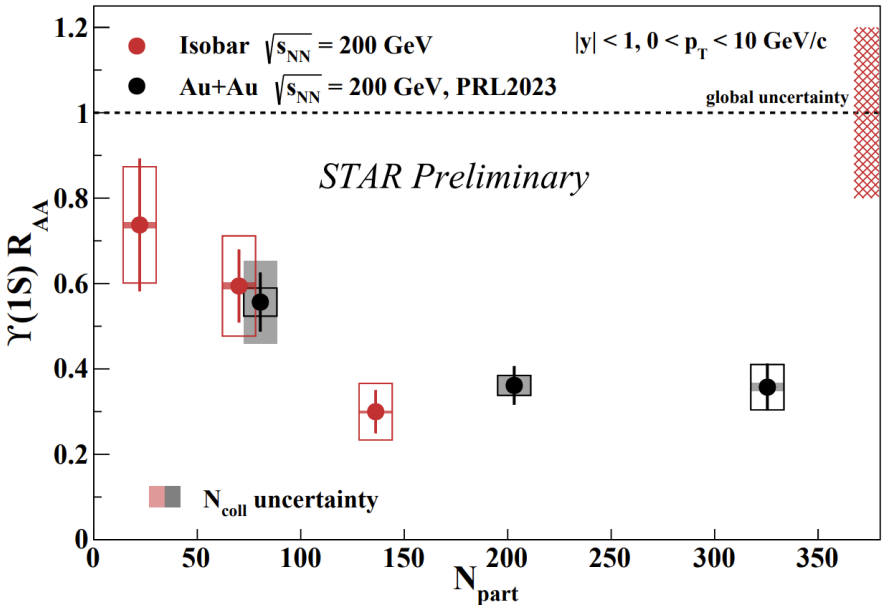




- Different levels of suppression of quarkonium states of different sizes

STAR: Phys. Rept. 858 (2020) 1–117





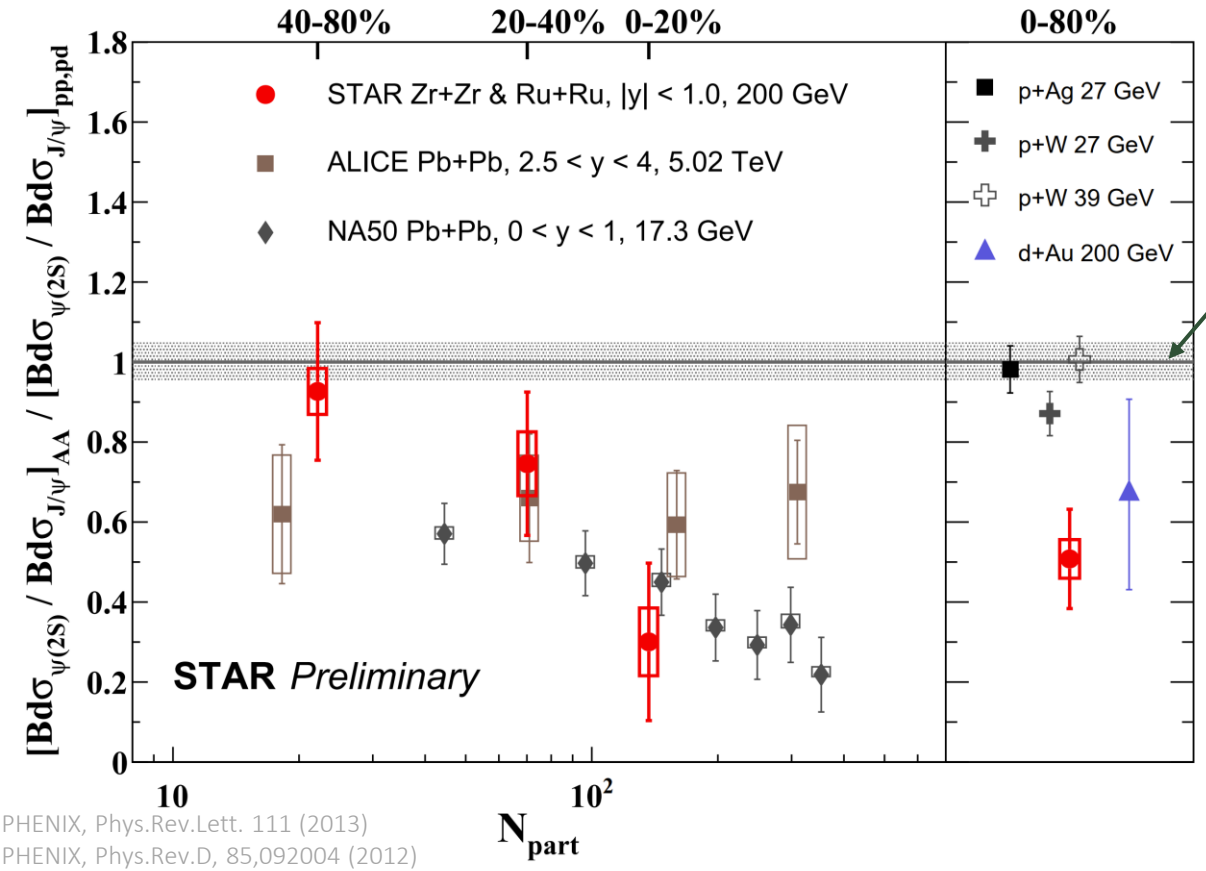
Sequential ϒ states suppression observed at RHIC energies in Au+Au

STAR: Phys. Rev. Lett. 130 (2023) 112301

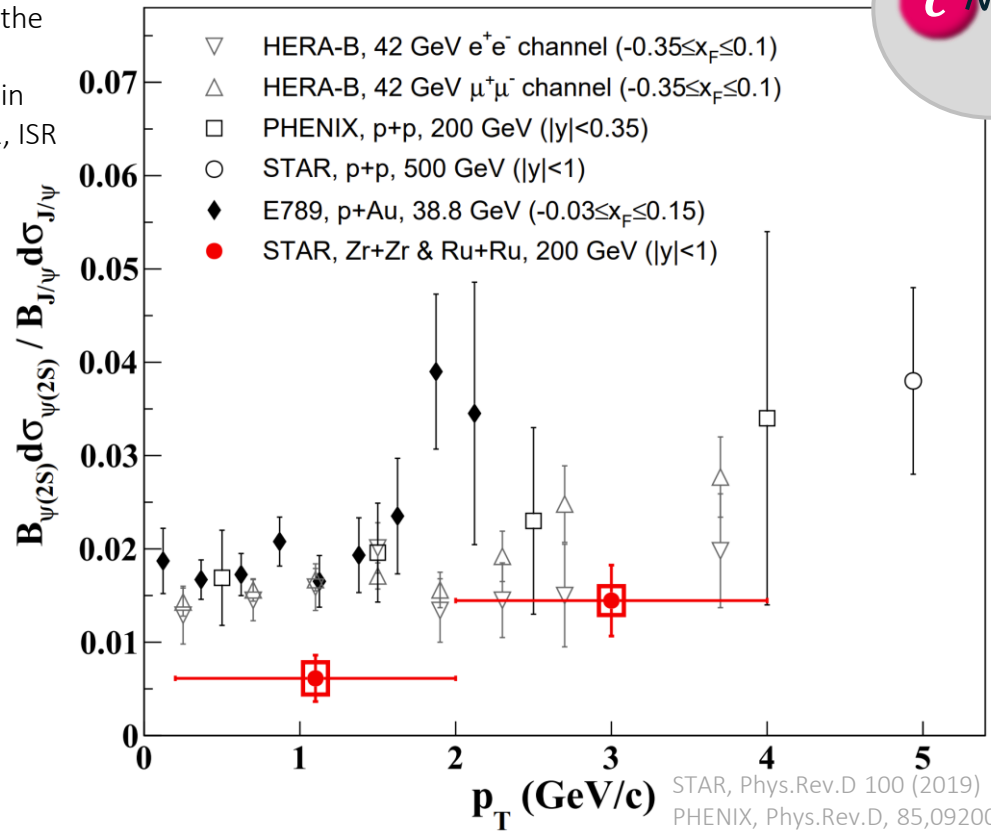
- No significant p_T dependence
- Indication of centrality dependence
- No significant species dependence at the same <N_{part}>

$\psi(2S)$ production in isobar collisions @ 200 GeV

STAR Preliminary



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



PHENIX, Phys.Rev.Lett. 111 (2013)
PHENIX, Phys.Rev.D, 85,092004 (2012)
NA50, Eur.Phys.J.C 48, (2006) E772
Phys.Rev.Lett. 66 (1991) 133-136

STAR, Phys.Rev.D 100 (2019)
PHENIX, Phys.Rev.D, 85,092004 (2012)
HERA-B, Eur.Phys.J.C 49 (2007)
E789, Phys.Rev.D 52 (1995) 1307, 1995

- First observation of charmonium sequential suppression in heavy-ion collisions at RHIC
- Ratio decreases towards central collisions
- Significantly lower than that in p+p and p+A collisions at p_T < 2 GeV/c

Summary

- Recent heavy-flavor results from PHENIX : by Dan Richford at RHIC AUM ’23
- Recent J/ψ results measured with PHENIX: by Tamas Novak at Rencontres de Moriond QCD 2023

Heavy quarks are good tool for studying QGP properties

Open heavy-flavor

Significant energy loss of heavy quarks for different energies: 200 GeV, 54.4 GeV

and for different system sizes: Au+Au and Ru+Ru, Zr+Zr

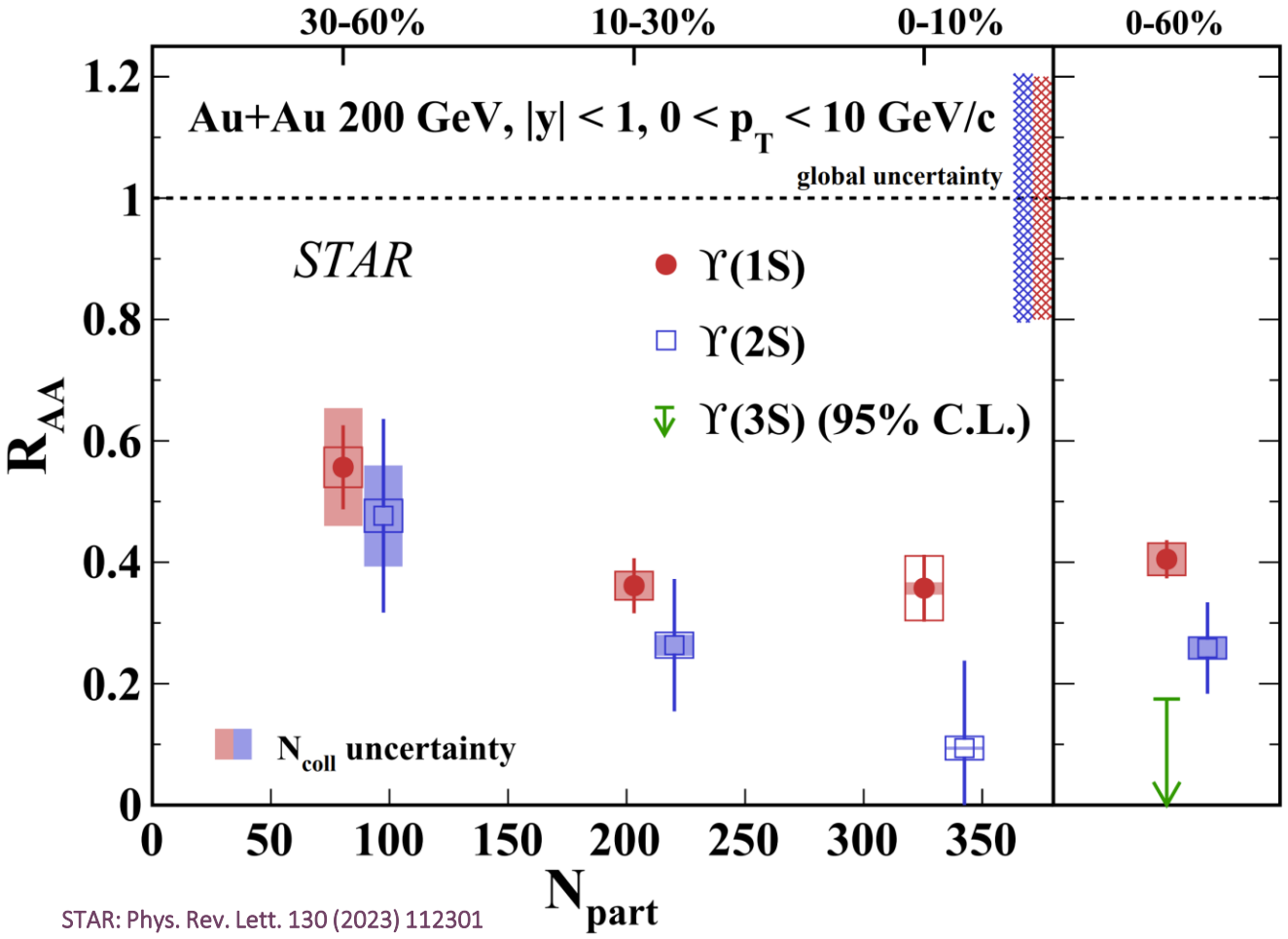
Quarkonia

- Observation of sequential suppression in both charmonium and bottomonium states at RHIC
- Neither collision energy nor system size dependence of J/ψ suppression at similar $\langle N_{part} \rangle$

Thank you for your attention!

BACKUP

Sequential ϒ states suppression in Au+Au @ 200 GeV



STAR: Phys. Rev. Lett. 130 (2023) 112301

- Suppression in all three centrality intervals
- Hint of increasing suppression from 30-60% to 0-10%

↓

Consistency with the expected increasing hot medium effect towards central collisions

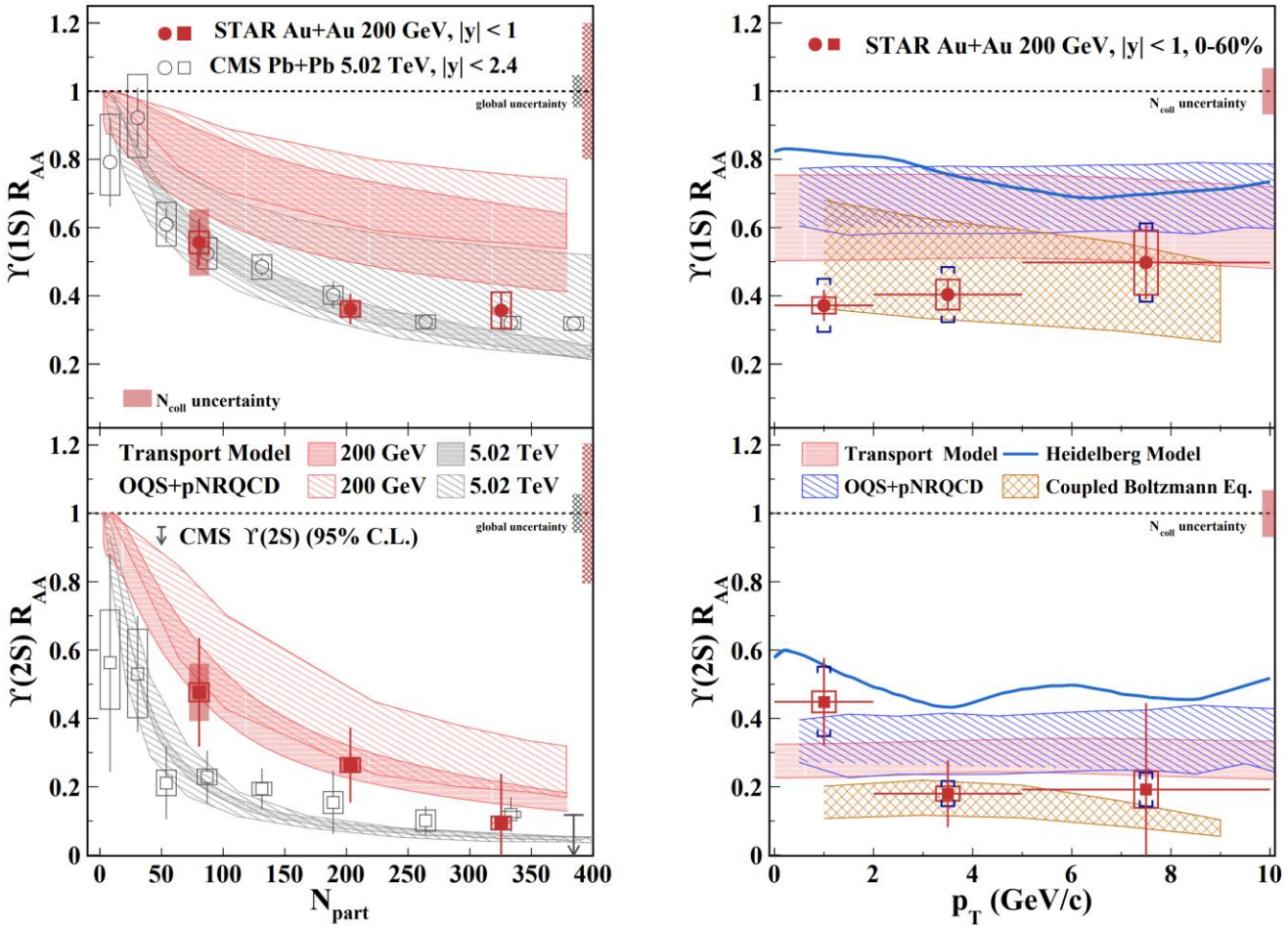
- Upper limit of ϒ(3S) is estimated to be 0.17
- Suppression level of ϒ(2S) (R_{AA} = 0.26) is between ϒ(1S) and ϒ(3S)

↓

Consistency with a sequential suppression pattern observed at LHC

Sequential Υ states suppression in Au+Au @ 200 GeV

- Υ(1S): consistency between the STAR and CMS data within uncertainties
- Υ(2S): hint of smaller suppression at RHIC energies in peripheral collisions
- No clear p_T dependence of the suppression for Υ(1S) and Υ(2S)
- Consistency between the model calculations and data within uncertainties
- Data overshooting by Heidelberg model due to the lack of CNM effects

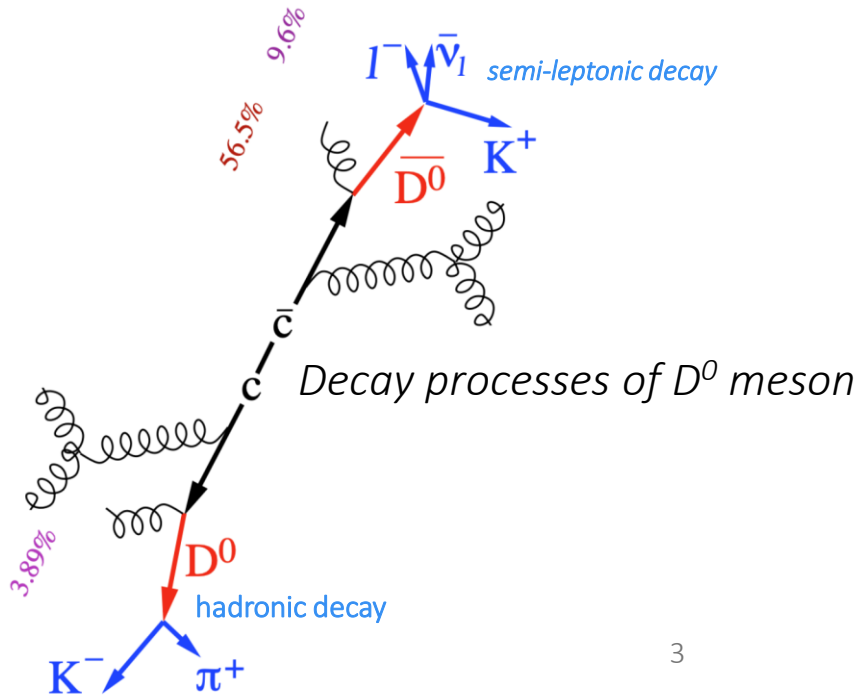


STAR: Phys. Rev. Lett. 130 (2023) 112301

Heavy-Flavor Electrons (HFE)

- Electrons from semi-leptonic decays of open heavy-flavor hadrons
- Relative contribution of ***D*** and ***B*** hadron decays depend on electron p_{T}
- Semi-leptonic decays branching ratio (BR) > hadronic decays BR

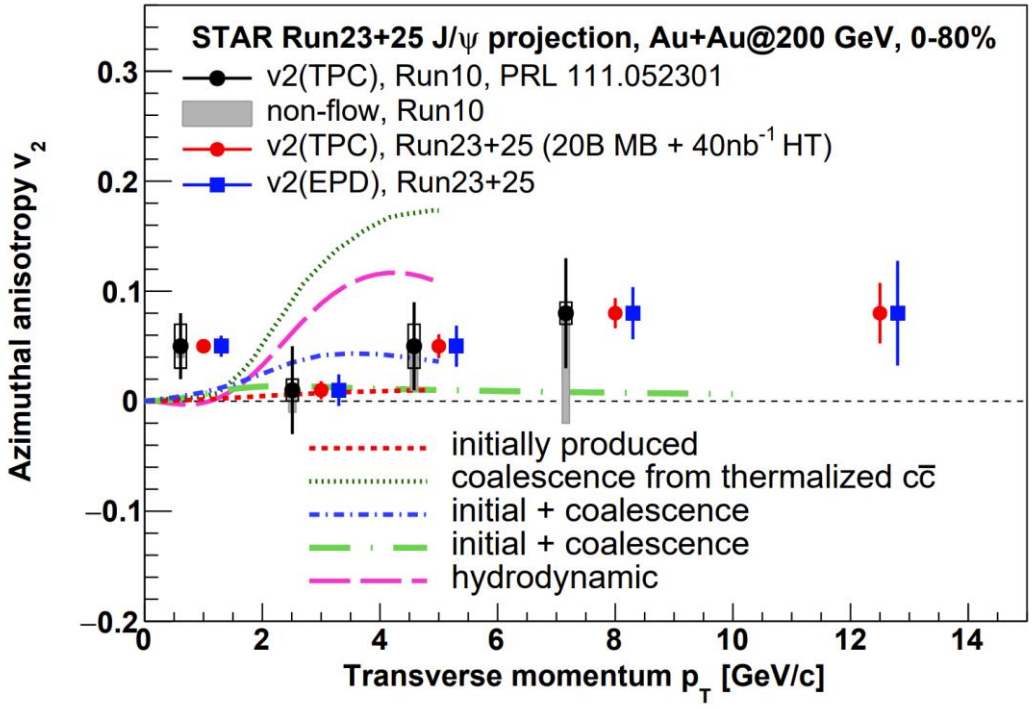
Widely used to study heavy quark (HQ) production



Decay processes of D^0 meson

STAR Heavy-flavor program for Runs 23-25

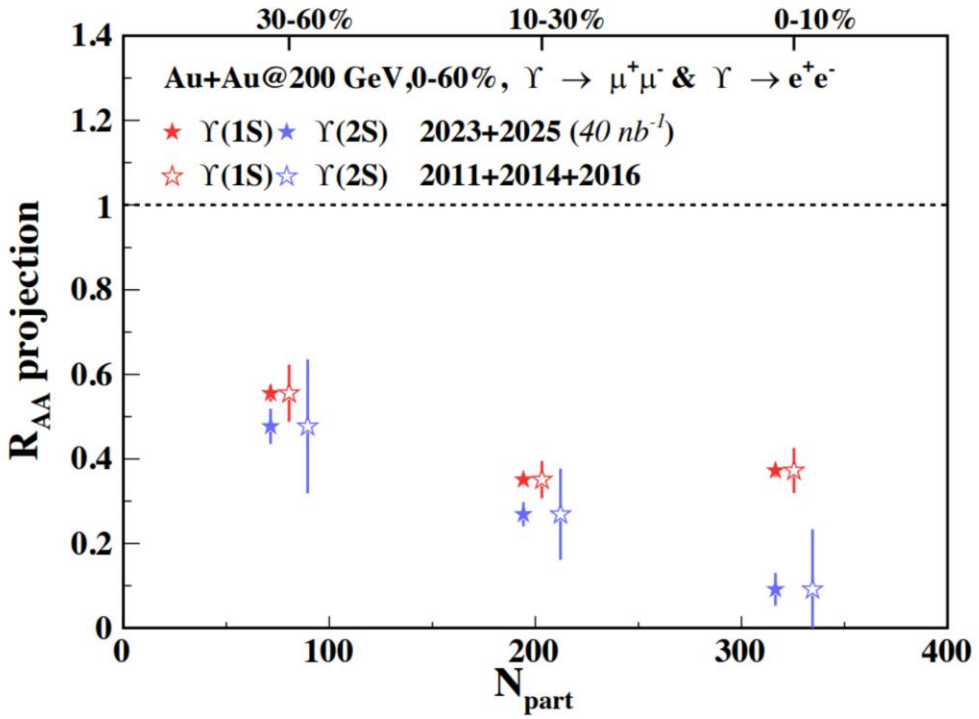
- Run 23 + 25 Au+Au at 200 GeV: 20B MB and 40nb^{-1} HT events projected
- Detector upgrades (EPD, ETOF, iTPC..)



- E.g. precise J/ψ v_2 measurement at RHIC energies
- EPD for event plane reconstruction ⟶ less non-flow effect contribution

- Run 24 p+Au: higher statistics than in Run 15

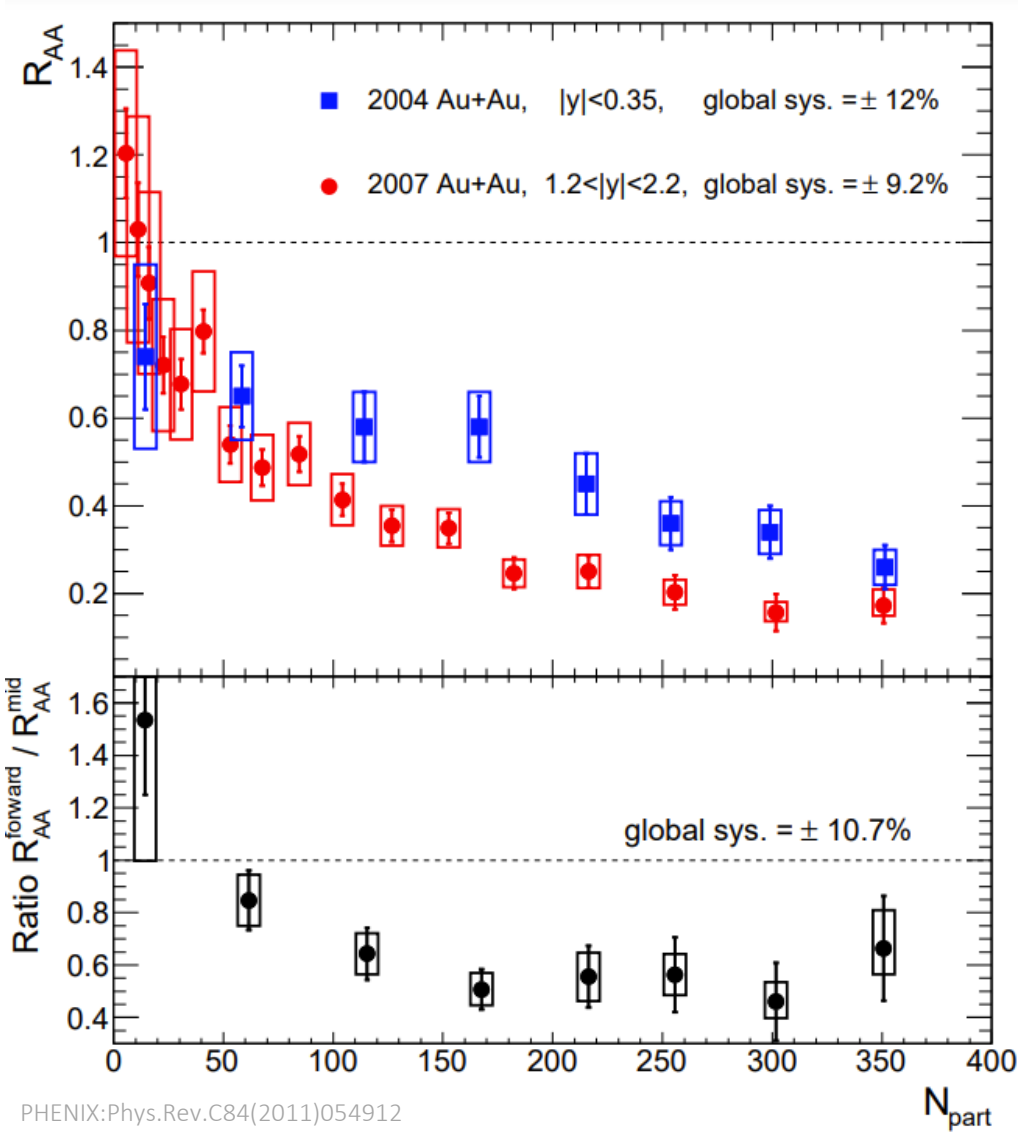
- Potential enhancement at high p_T for the STAR results



- Broader momentum coverage at RHIC
- Enlarge acceptance : η coverage from 1.0 to 1.5

J/ψ suppression at forward rapidity in Au+Au @ 200 GeV

PHENIX



PHENIX:Phys.Rev.C84(2011)054912

- Suppression due to hot nuclear matter effects
- $R_{AA}^{fwd} < R_{AA}^{mid}$, contrary to expectation

- Significant difference in J/ψ R_{AA} due to J/ψ regeneration of from $c\bar{c}$ pairs at midrapidity?