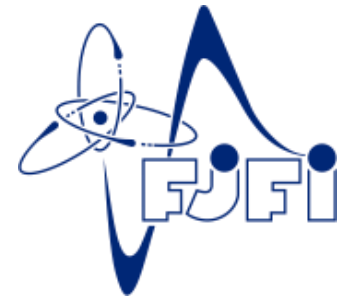
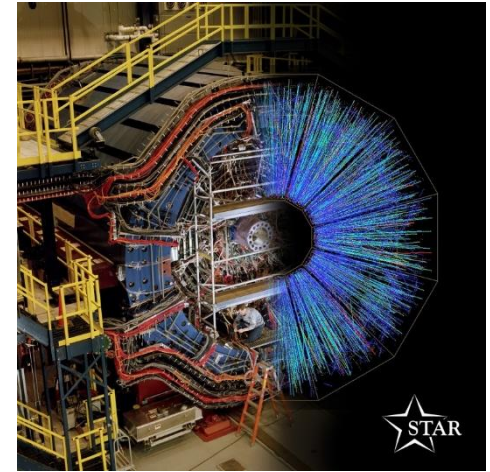


Quarkonium studies at RHIC



Jaroslav Bielicik

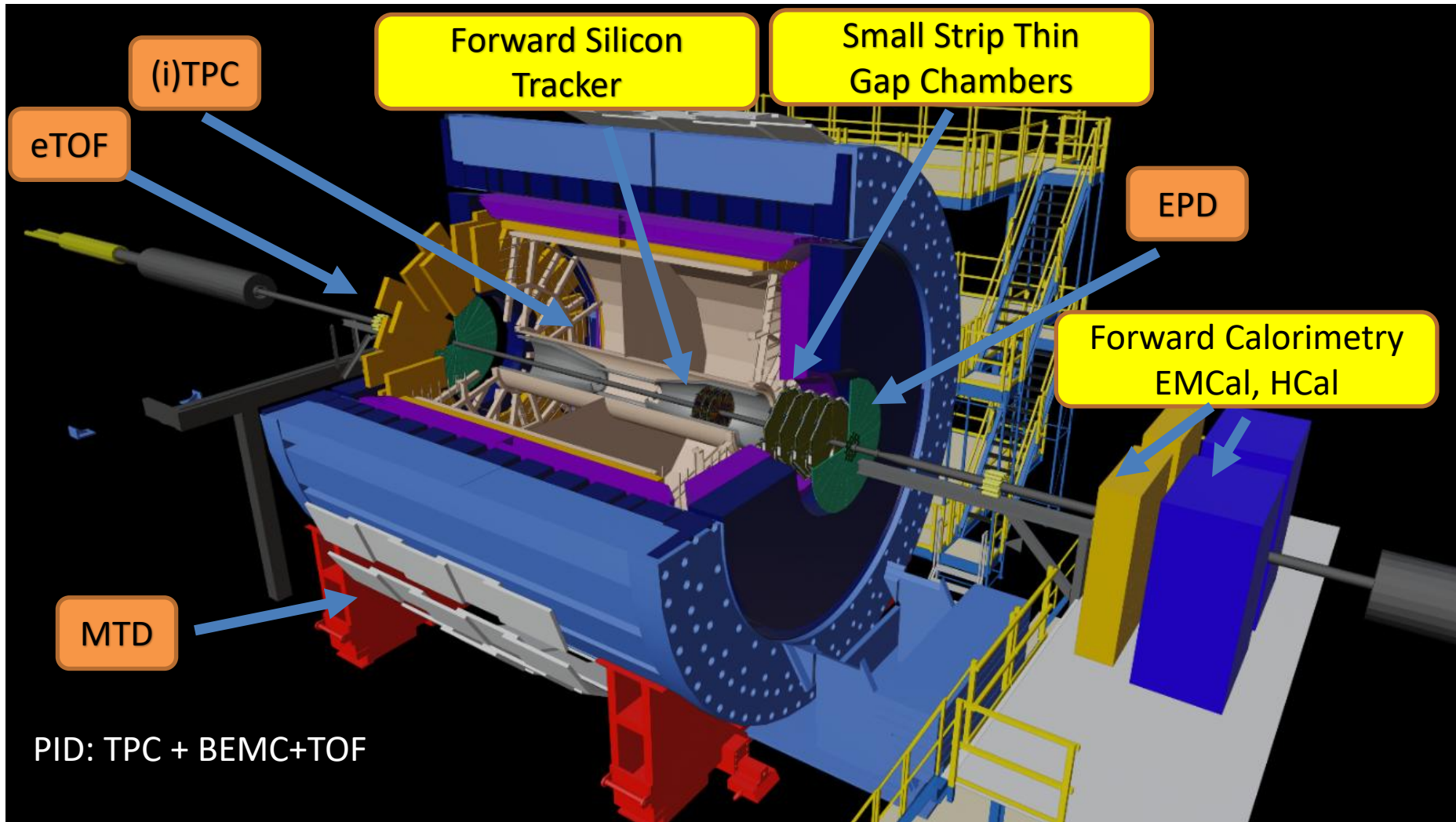
Czech Technical University in Prague



XIV International Conference on New Frontiers in Physics,
17.-31. 7. 2025, OAC, Kolymbari, Creete, Greece

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)

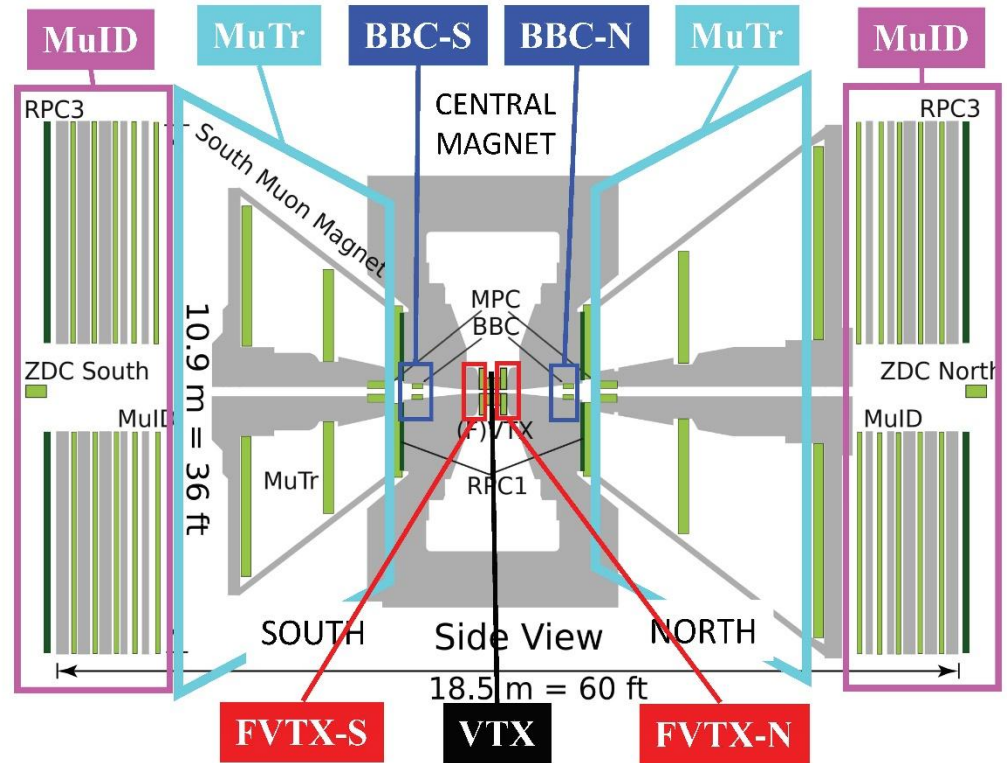
- $|\eta| < 0.35$
- $\Delta\phi = \pi$
- Tracking: DC, PC, VTX
- eID: RICH, Emcal

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

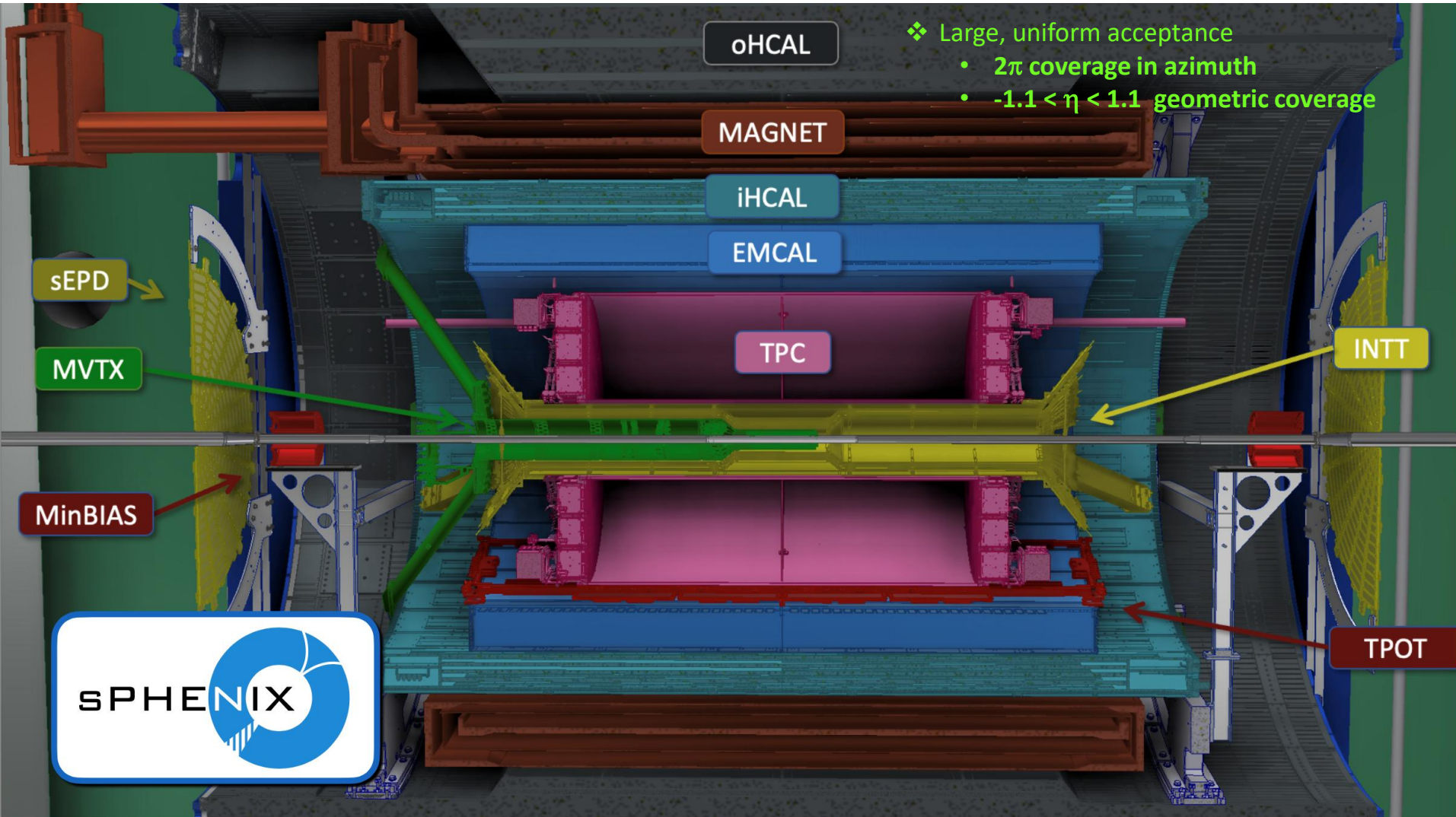


Run 14 Au+Au 200 GeV (19B MB events)

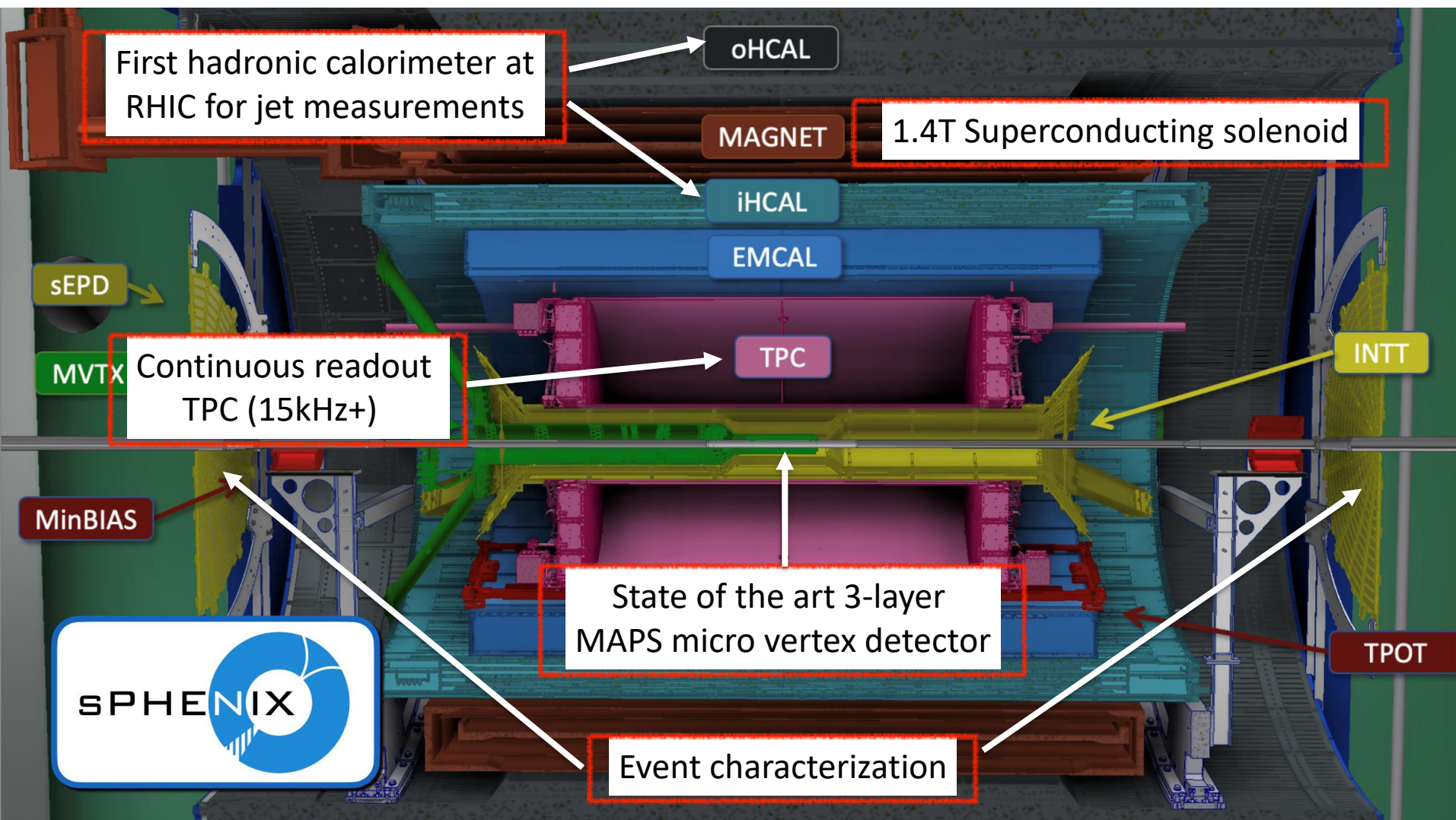
Run 16 Au+Au 200 GeV (15B MB events)

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

sPHENIX experiment

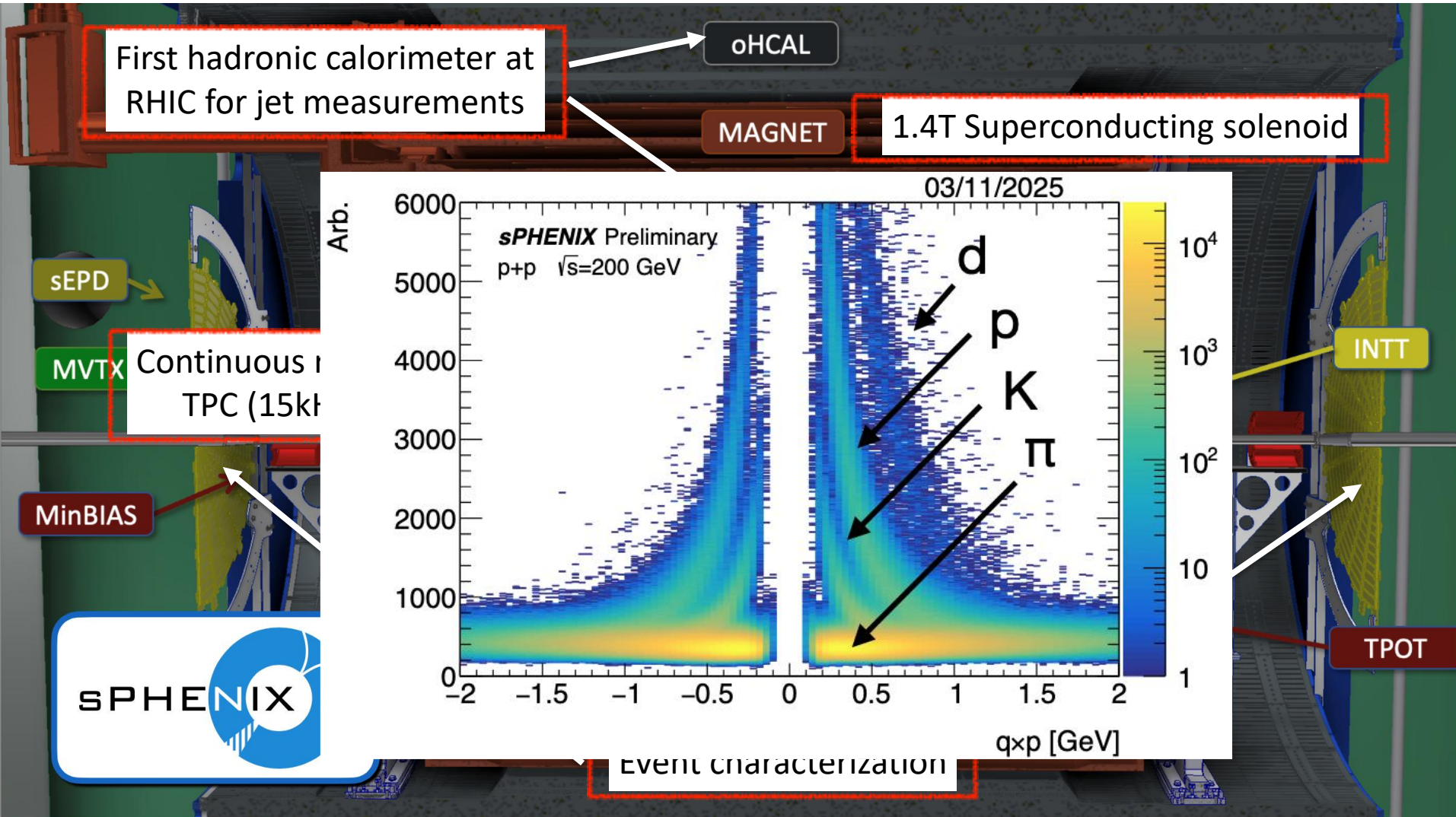


sPHENIX detector



- sPHENIX is fully commissioned and producing physics

sPHENIX detector



- sPHENIX is fully commissioned and producing physics

Probe QGP with quarkonium

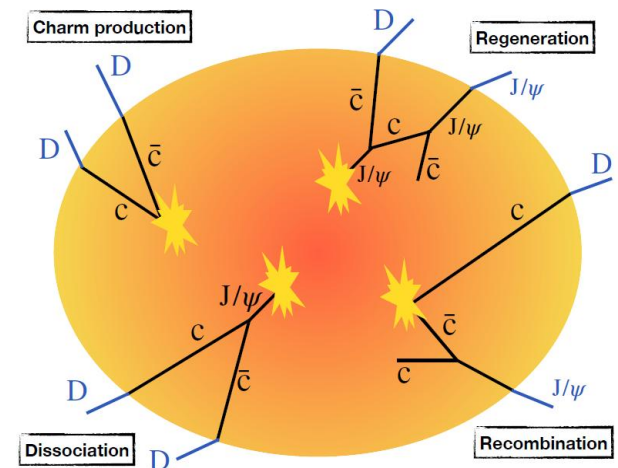
- **Quarkonia** are bound states of charm-anticharm or a bottom-antibottom quark pair
- Heavy quarks are created early in the collisions and can live longer than the QGP
→ Experience full evolution of the medium
- **Color-screening**: quarkonium dissociates in the medium



- Quarkonia states were initially proposed as QGP thermometer
- **Hot nuclear matter effects**
 - Dissociation
 - Regeneration from uncorrelated quarks
- **Cold nuclear matter effects**
- **Feed-down of excited quarkonium states**

J/ψ suppression was proposed as a direct proof of QGP formation

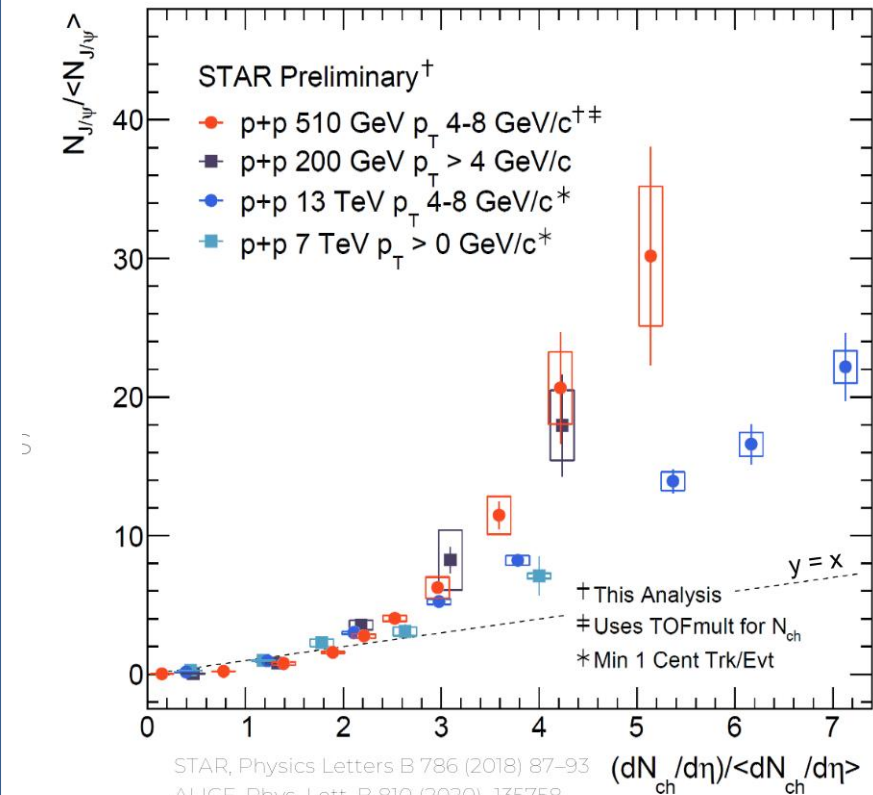
T. Matsui and H. Satz PLB 178 (1986) 416



J/ψ multiplicity dependence

- At RHIC and LHC energies, **J/ψ production** has been found to rise with respect to event **multiplicity**, at rates that are **faster than linear**
- More numerous **multi-parton interactions** are more likely to feature small impact parameters -> enhanced hard scattering processes such as J/ψ production
(S. Weber et al. Eur. Phys. J. C (2019) 79:36)
- **Percolation** of color strings may similarly contribute to the faster than linear increase
(E. G. Ferreiro, C. Pajares, Phys.Rev.C86(2012)034903)
- Newest measurement of J/ψ multiplicity dependence at 510 GeV in p+p by STAR
 - **Consistent with 200 GeV STAR data**
 - Hints of splitting between RHIC and LHC energies

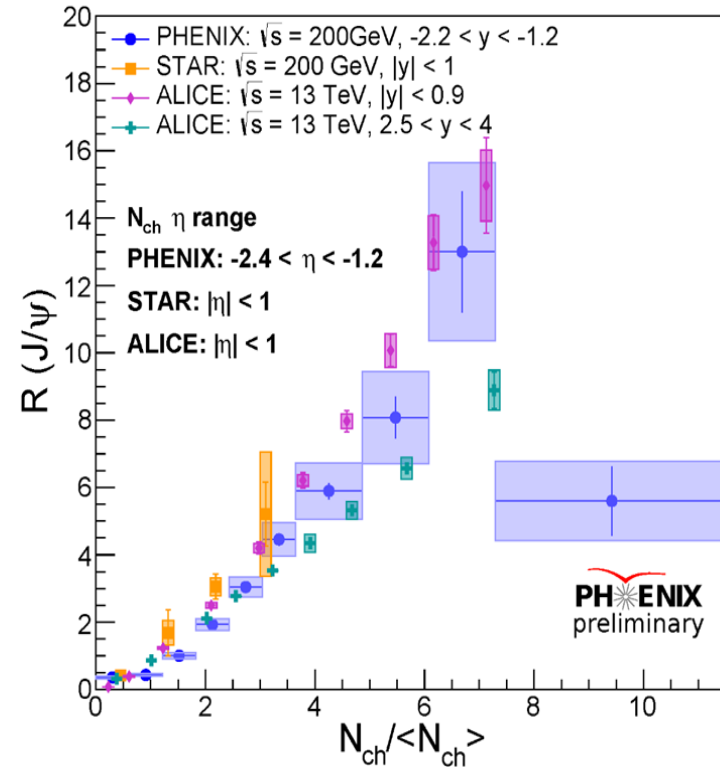
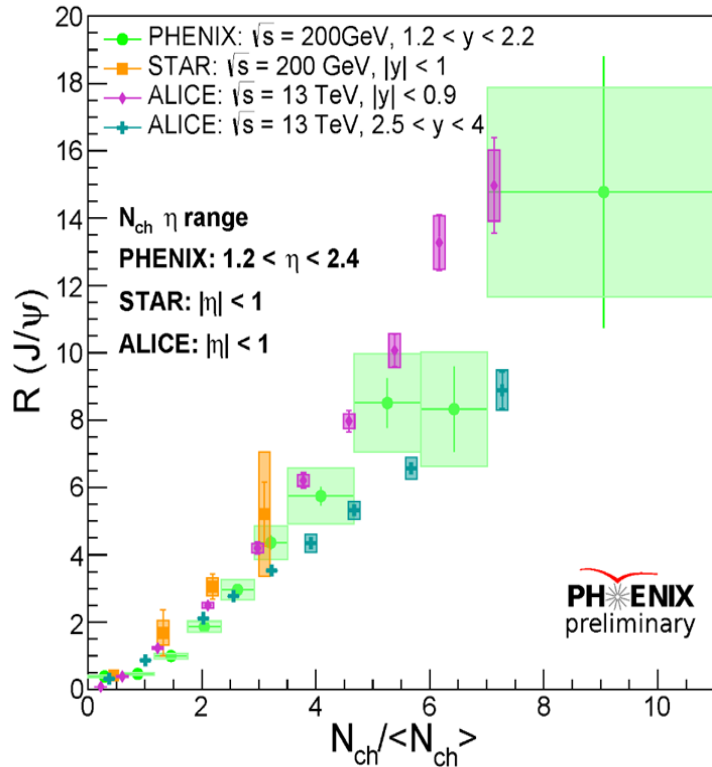
[Brennan Schaefer, HP2024]



STAR

J/ψ multiplicity dependence

[Universe 2023, 9(7), 322]

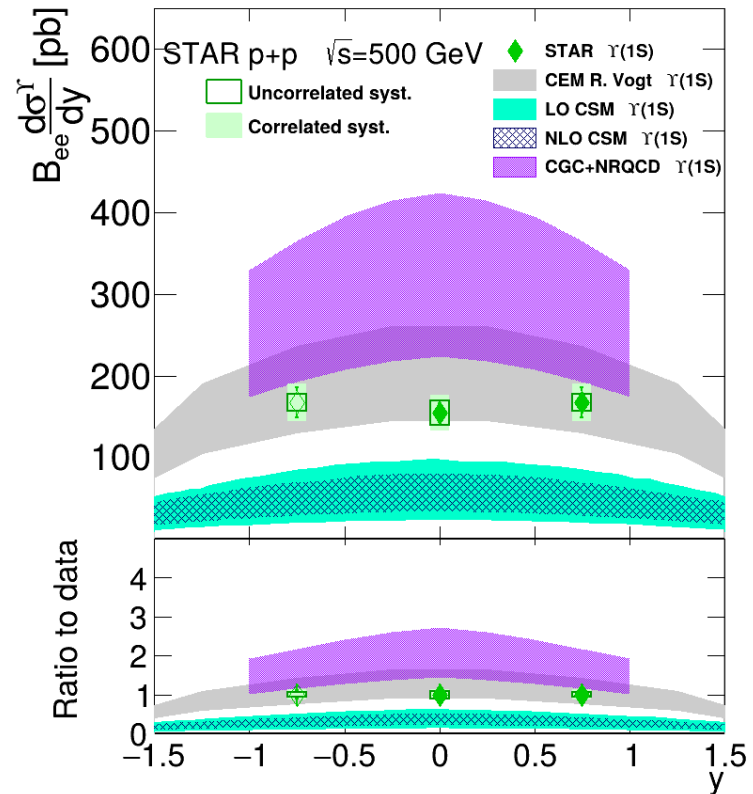
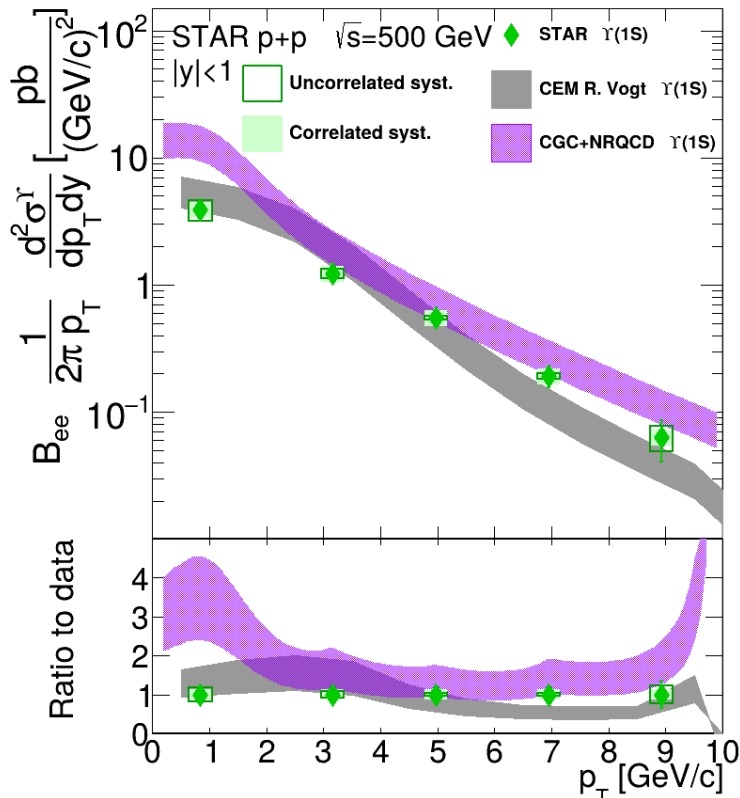


10

- The PHENIX measurements allow for measuring forward- and backward-rapidity J/ψ, which are mostly **consistent with world data** with the exception of the last bin in the backwards produced J/ψ

Upsilon production in p+p 500 GeV

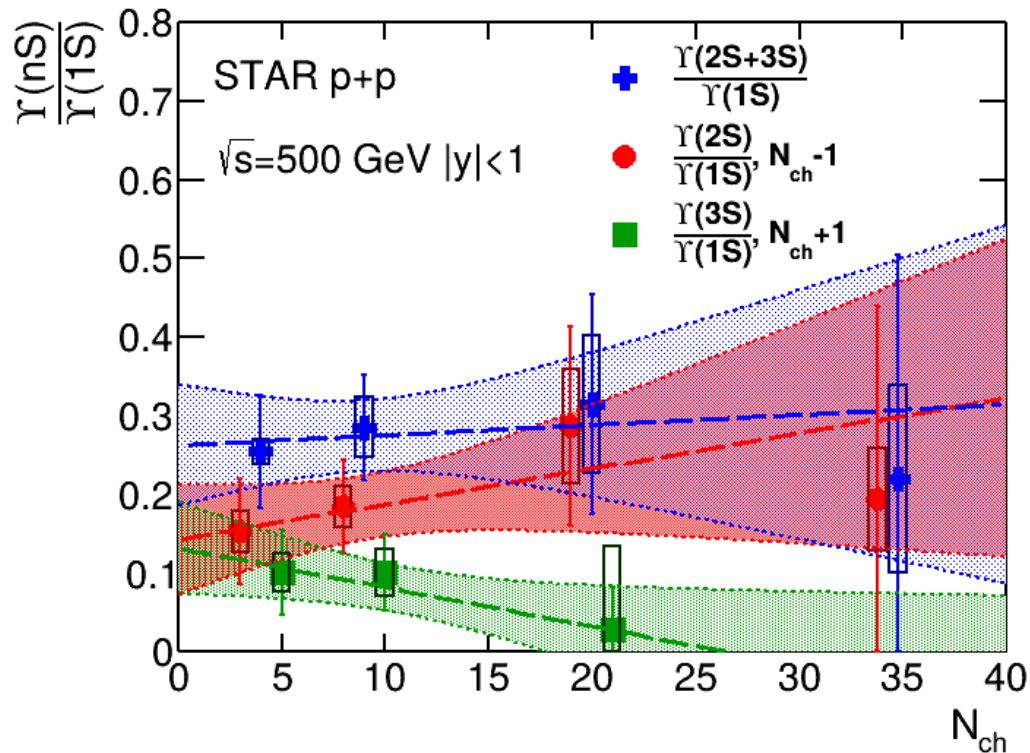
STAR arXiv:2502.03769v1



- Data are best consistent with CEM calculations

Charged multiplicity measurement

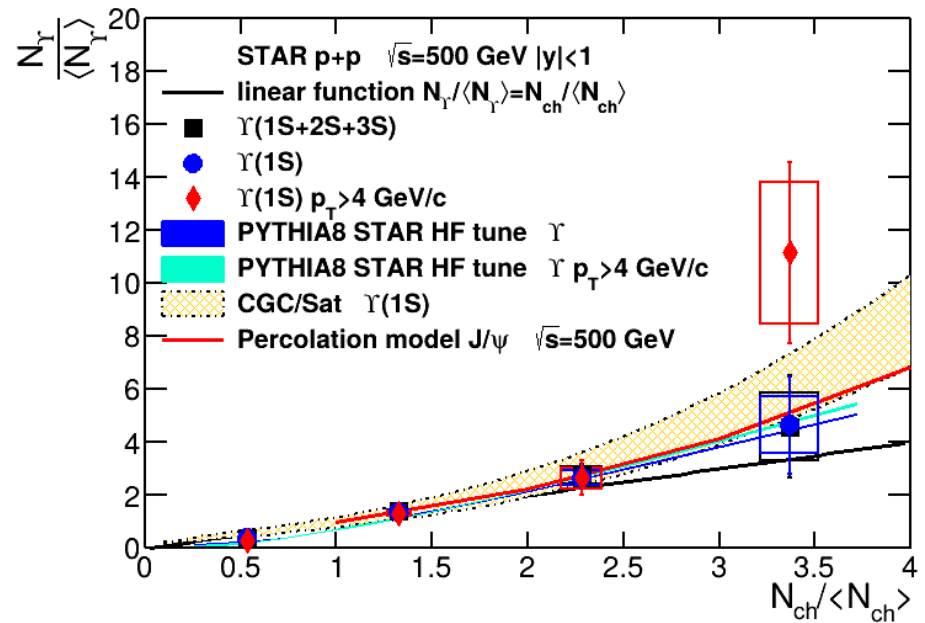
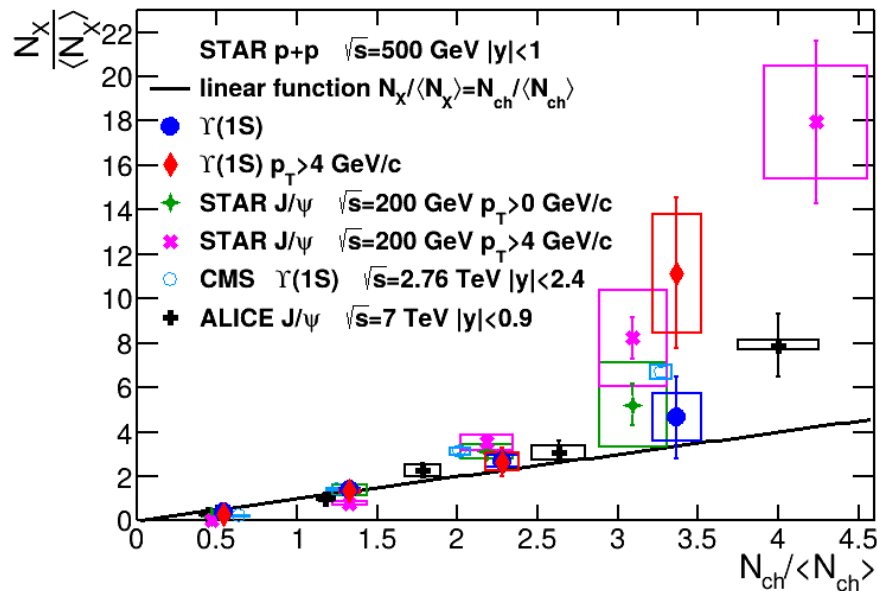
STAR arXiv:2502.03769v1



- $\langle N_{ch} \rangle = 8.078 \pm 0.007$ 0 – 1, 1 – 2, 2 – 3, 3 – 8 $\langle N_{ch} \rangle$
- Comover interactions are expected to decrease the $Y(nS)/Y(1S)$
- Decrease is not visible within the uncertainties

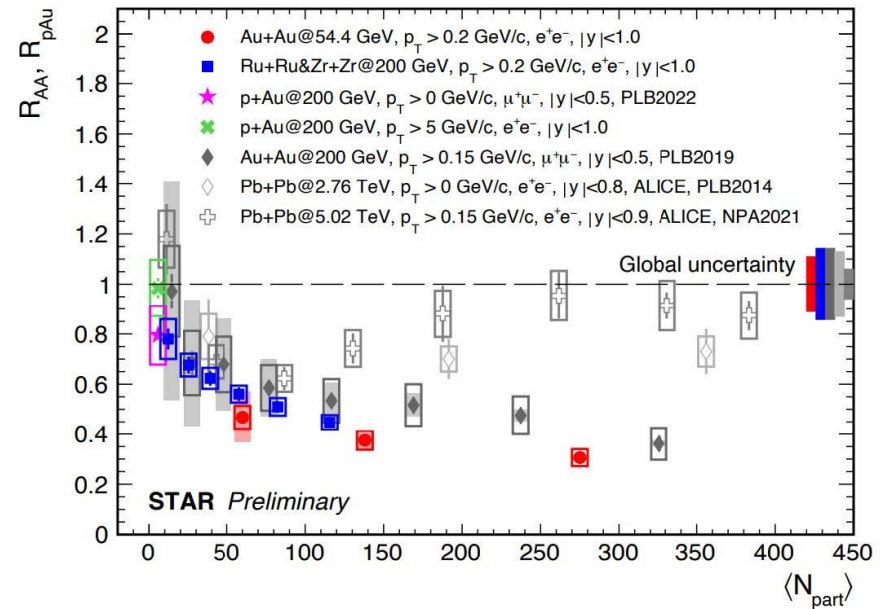
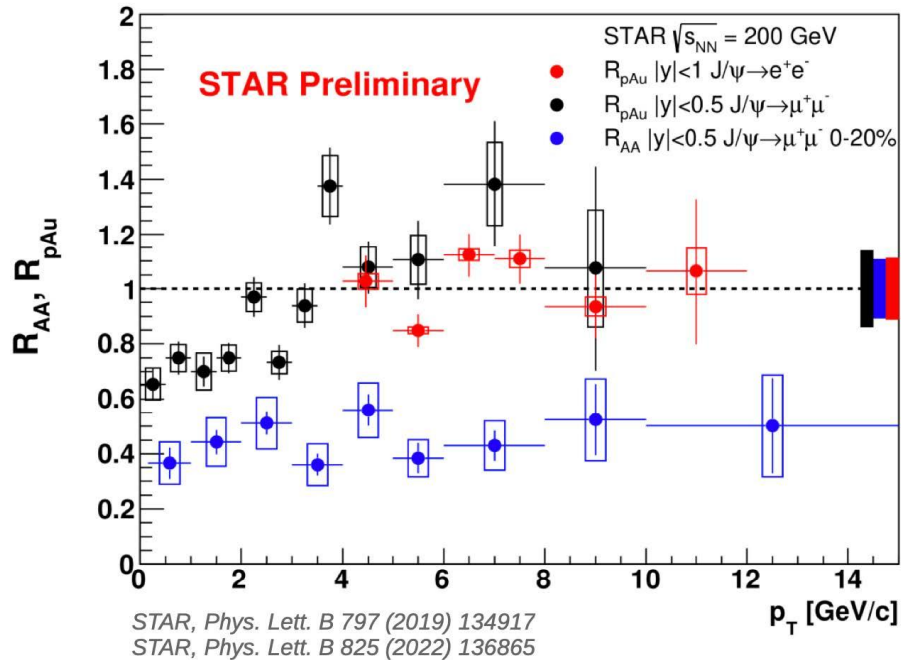
Charged multiplicity measurement

STAR arXiv:2502.03769v1



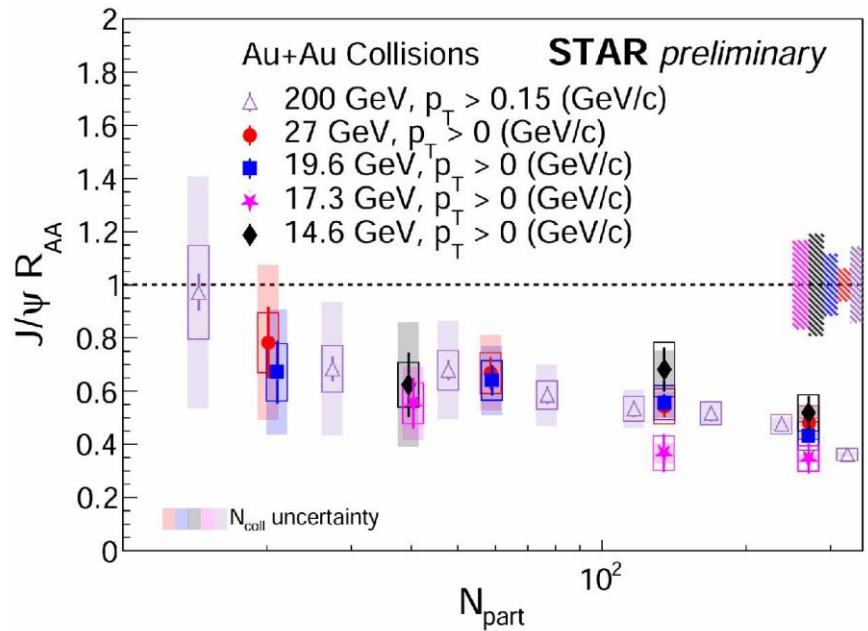
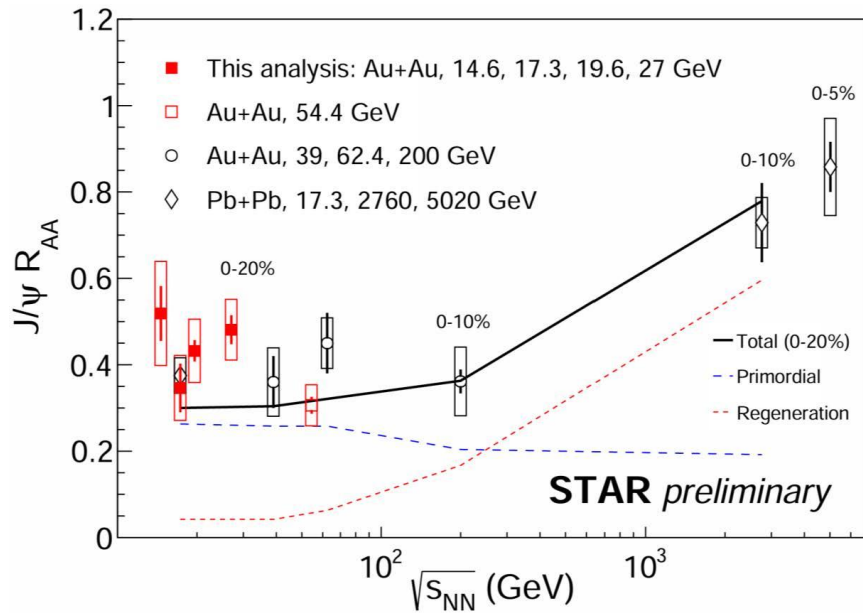
- Follows the same trend as J/ ψ at RHIC and LHC
- Qualitatively described by PYTHIA8 and models CGC/Sat and Percolation model

J/ψ production in heavy-ion collisions



- 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 $\langle N_{part} \rangle$
- Suppression driven by system size $\langle N_{part} \rangle$ not collision geometry
- At high p_T : Strong suppression at RHIC and regeneration at LHC

J/ψ R_{AA} 14,6-27 GeV



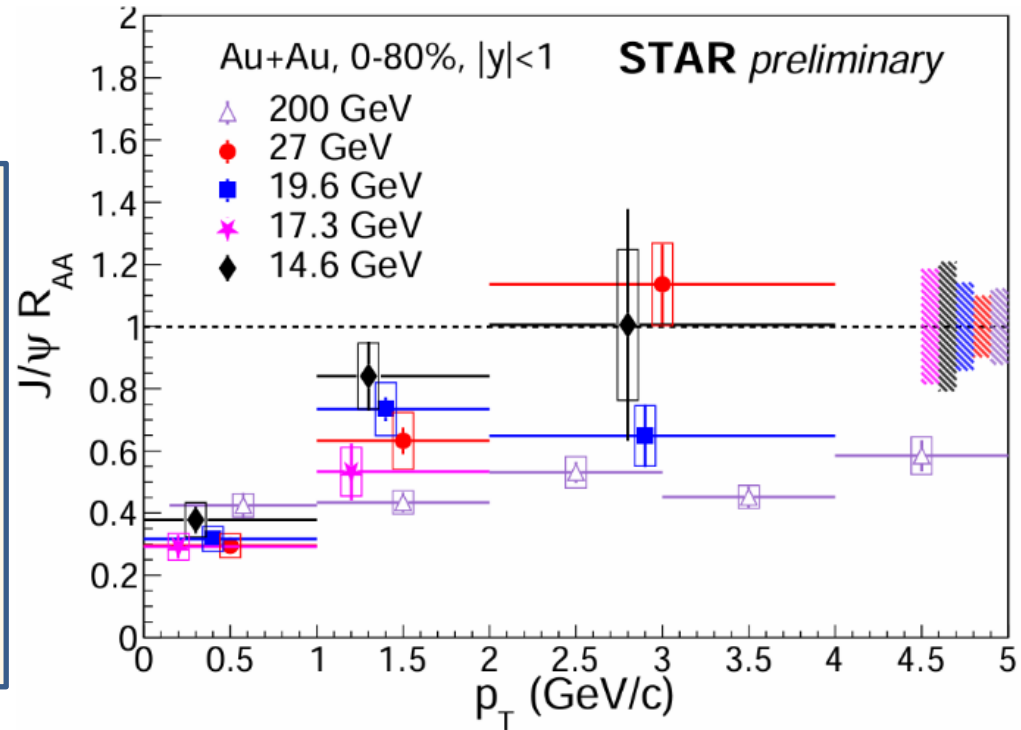
X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905 (private communication).
 L. Kluberg, Eur. Phys. J. C 43 (2005) 145.

- No significant energy dependence of $J/\psi R_{AA}$ 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

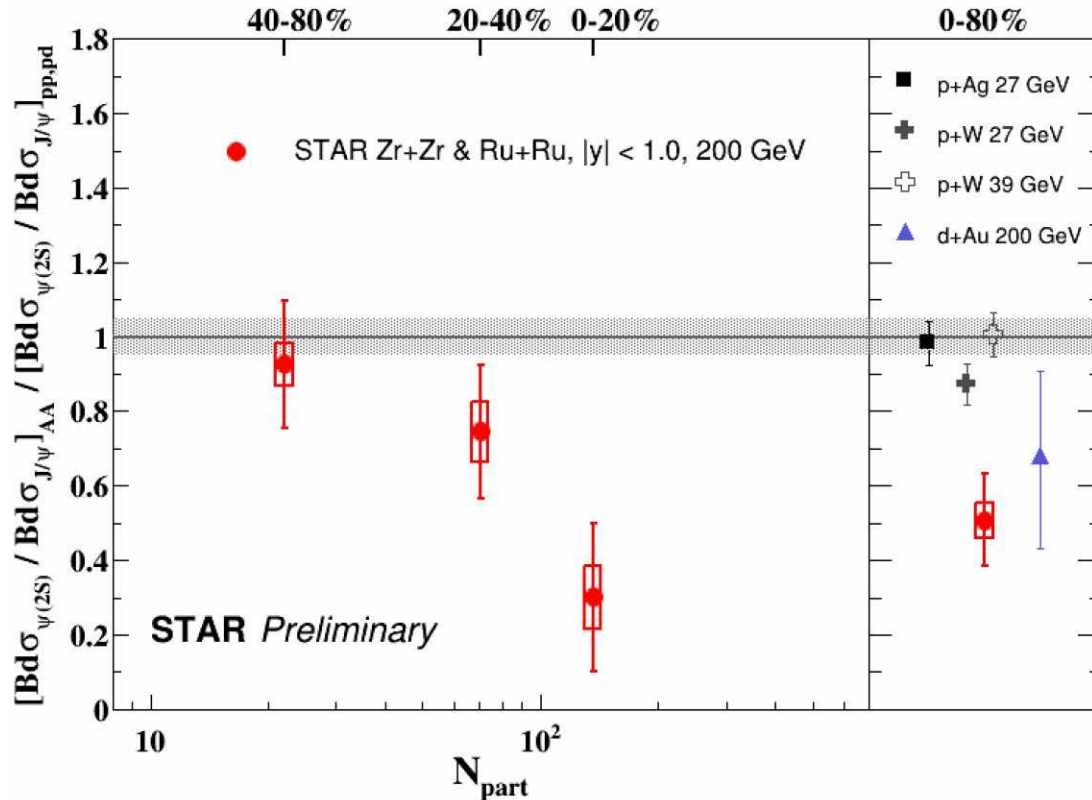
Inclusive J/ψ R_{AA}

[Wei Zhang, HP2024]

- Increasing trend with p_T for 14.6, 17.3, 19.6, 27 GeV
- **No significant p_T dependence for 200 GeV**



$\psi(2S)$ to J/ψ in Zr+Zr & Ru+Ru 200 GeV

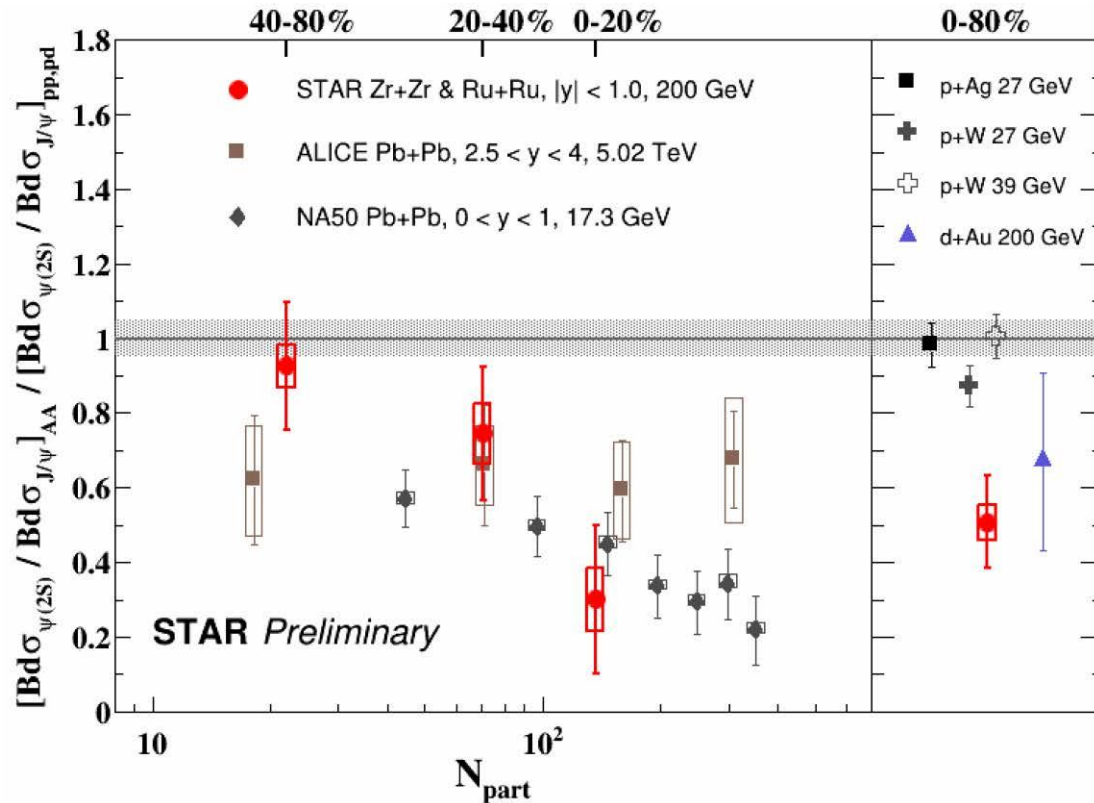


pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

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
- $\psi(2S)$ over J/ψ double ratio is smaller than that in p+A collisions

$\psi(2S)$ 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

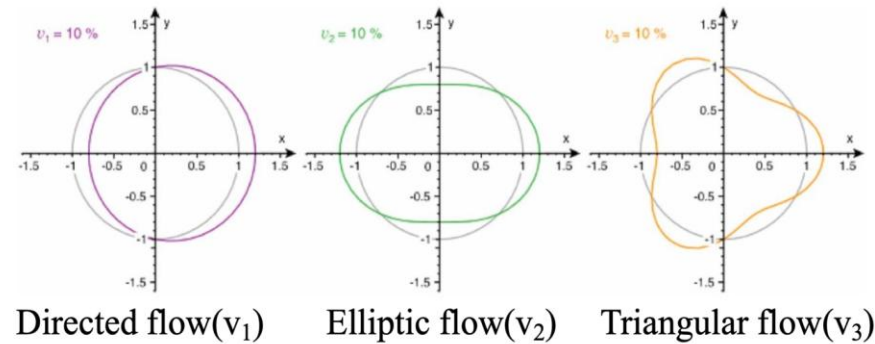
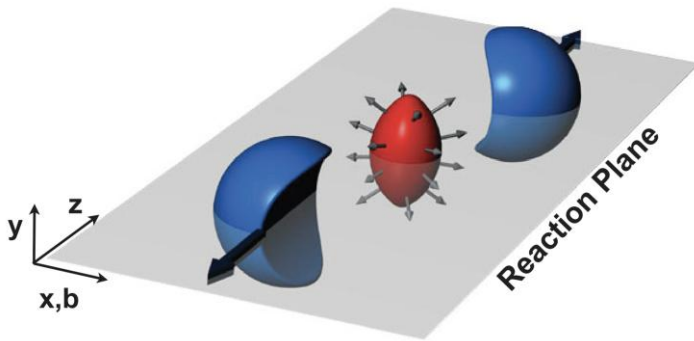
- First observation of charmonium **sequential suppression** in heavy-ion collisions at RHIC
- $\psi(2S)$ over J/ψ double ratio is smaller than that in p+A collisions
- Centrality dependence trend seems to be more similar to that at SPS than at LHC

Anisotropic Flow

- ❖ **Flow** is the measure of azimuthal anisotropy of particles
- ❖ **Azimuthal distribution of particles**

$$E \frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy} \left\{ 1 + \sum_{n \geq 1} 2v_n \cos[n(\phi - \Psi_n)] \right\}$$

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



Directed flow

$$v_1 = \langle \cos(\phi - \Psi_1) \rangle$$

Sideward motion of emitted hadrons with respect to collision reaction plane

Elliptic flow

$$v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle$$

Driven by the initial spatial asymmetry of the overlap region

Triangular flow

$$v_3 = \langle \cos 3(\phi - \Psi_1) \rangle$$

Driven by the shape of the initial collision geometry at low collision energies

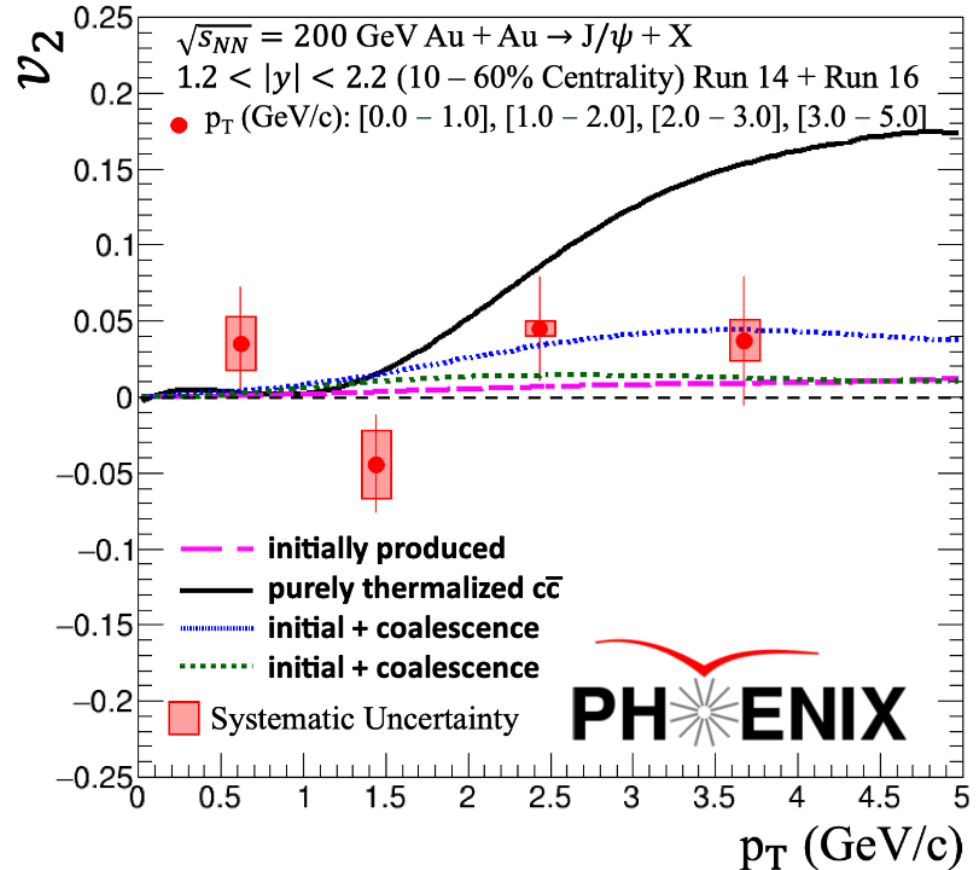
Why is v_n an important observable?

- ❖ Sensitive to the equation of state
- ❖ Sensitive to early times in the evolution of the system

J/ψ v₂ in Au+Au

PHENIX: Phys.Rev.C 112 (2025) 1, 014904

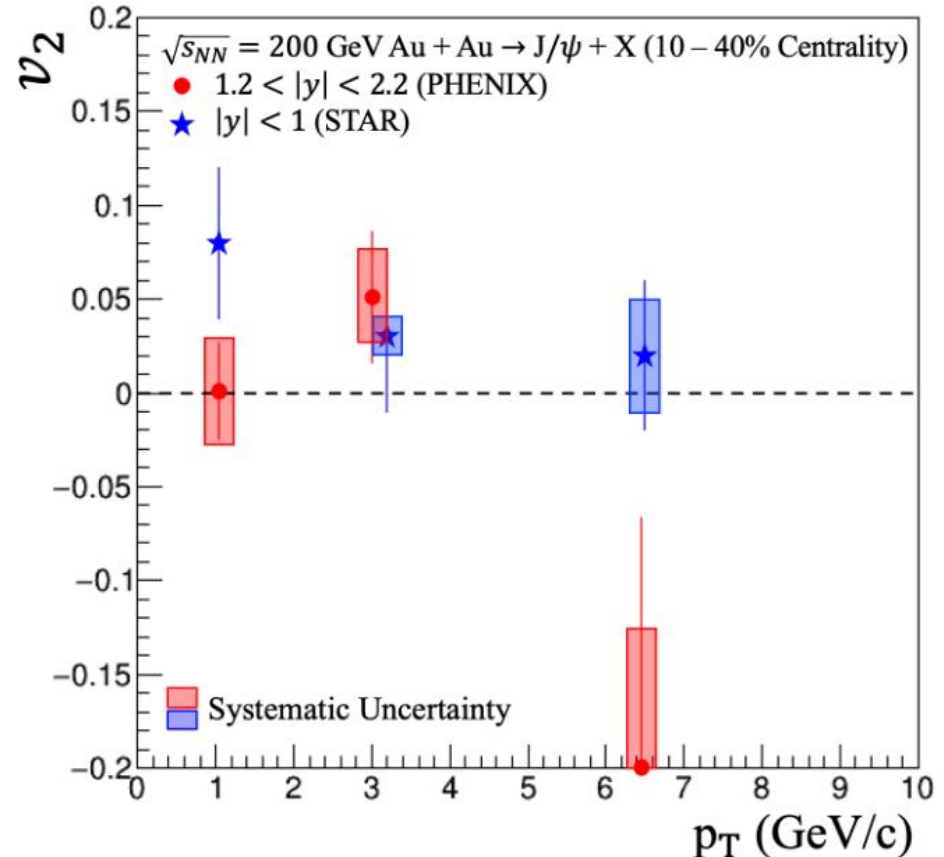
- New PHENIX measurement of J/ψ v₂ consistent with zero, coalescence model predictions
- Forward- (PHENIX) and mid-rapidity (STAR) data at RHIC consistent
- PHENIX measurements distinct from ALICE non-zero data



J/ψ v_2 in Au+Au

PHENIX: Phys.Rev.C 112 (2025) 1, 014904

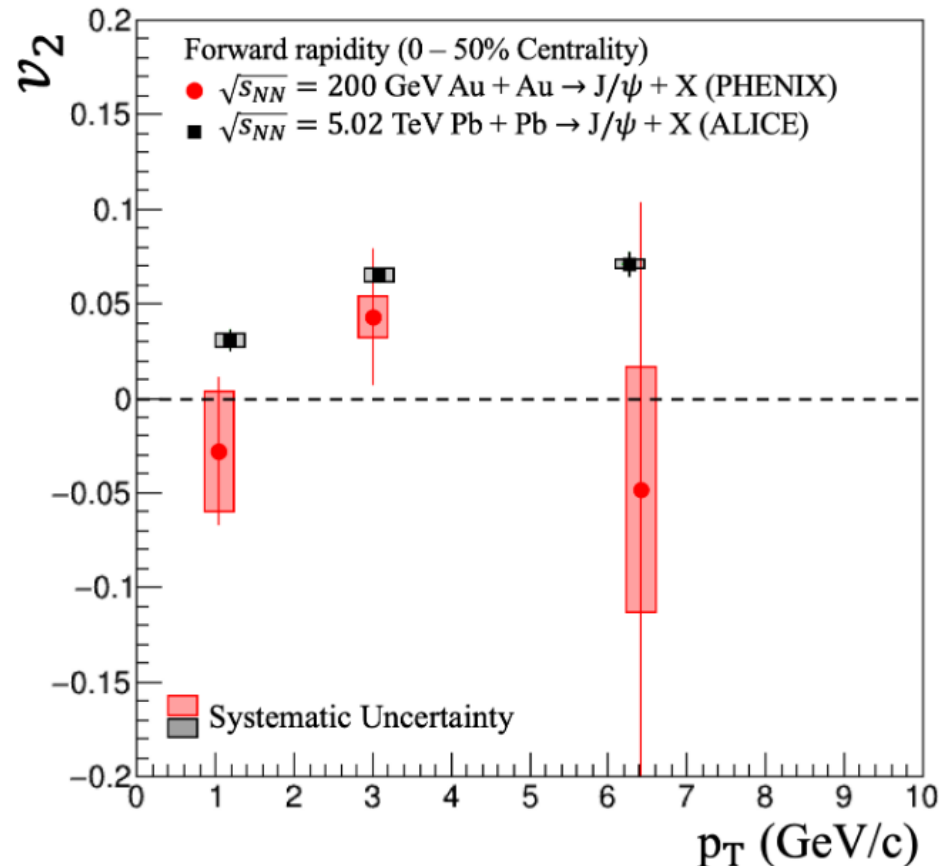
- New PHENIX measurement of J/ψ v_2 **consistent with zero**, coalescence model predictions
- **Forward-** (PHENIX) **and mid-rapidity** (STAR) data at **RHIC consistent**
- PHENIX measurements distinct from ALICE non-zero data



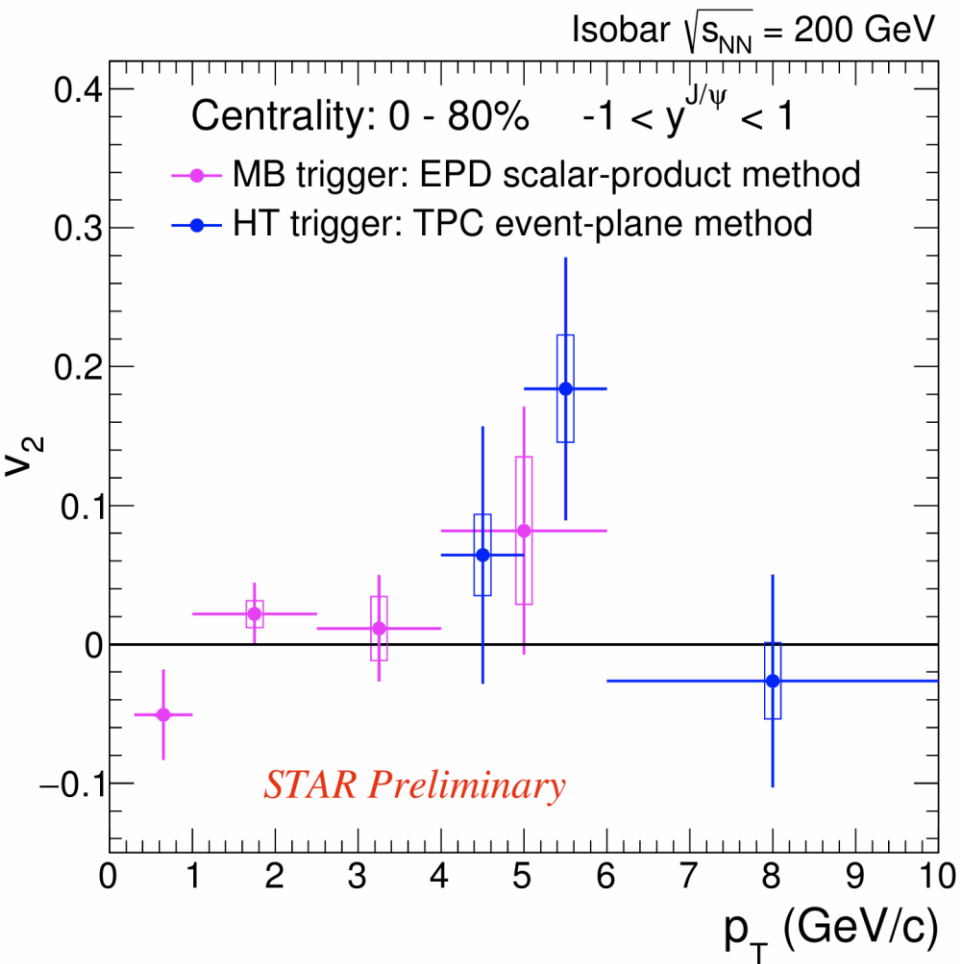
J/ψ v_2 in Au+Au

- New PHENIX measurement of J/ψ v_2 consistent with unity, coalescence model predictions
- Forward- (PHENIX) and mid-rapidity (STAR) data at RHIC consistent
- **PHENIX measurements distinct from ALICE non-zero data**

PHENIX: Phys.Rev.C 112 (2025) 1, 014904

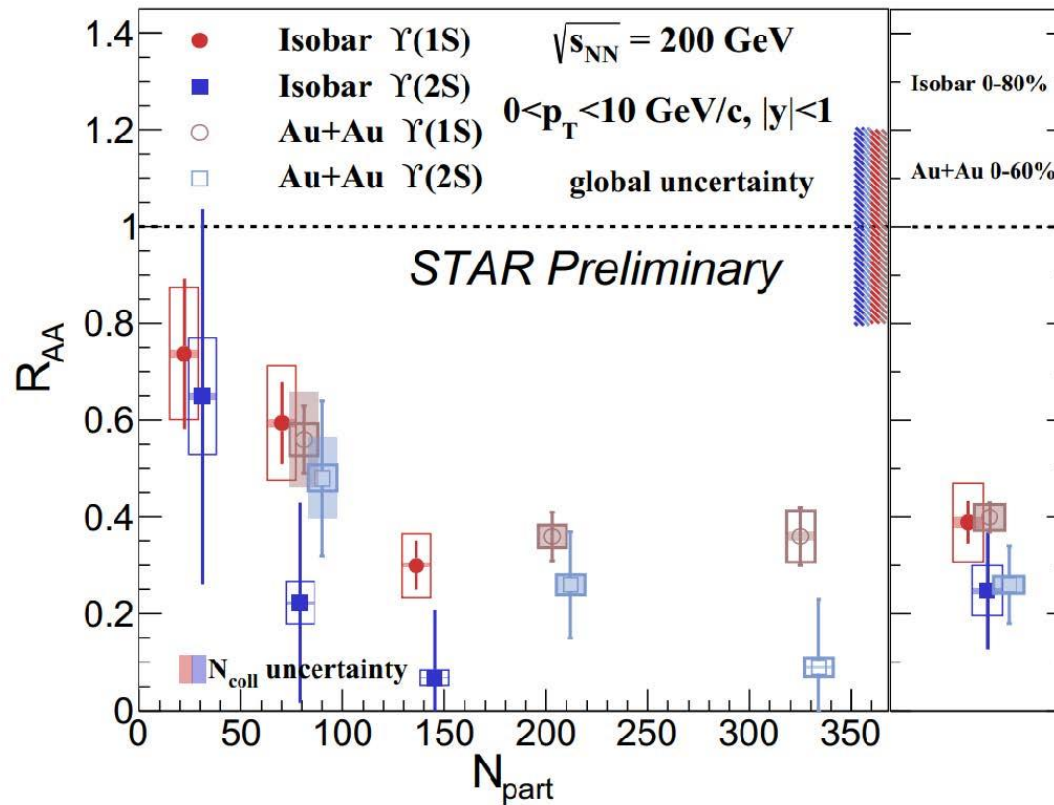


J/ψ v₂ in Zr+Zr & Ru+Ru 200 GeV



- No significant J/ψ v₂ signal is observed within uncertainties in isobaric collisions
- Smaller regeneration effect at RHIC compared to that at LHC ?

Y(nS) suppression in heavy-ion collisions



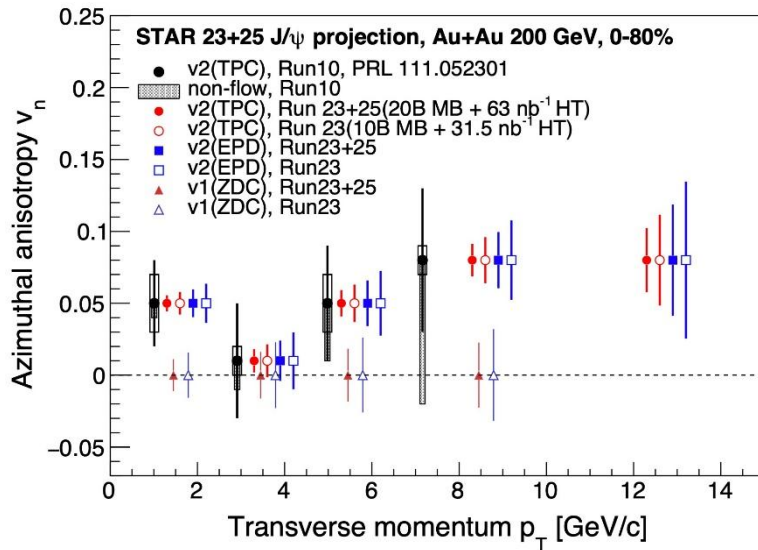
Phys. Rev. Lett. 130 (2023) 112301

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

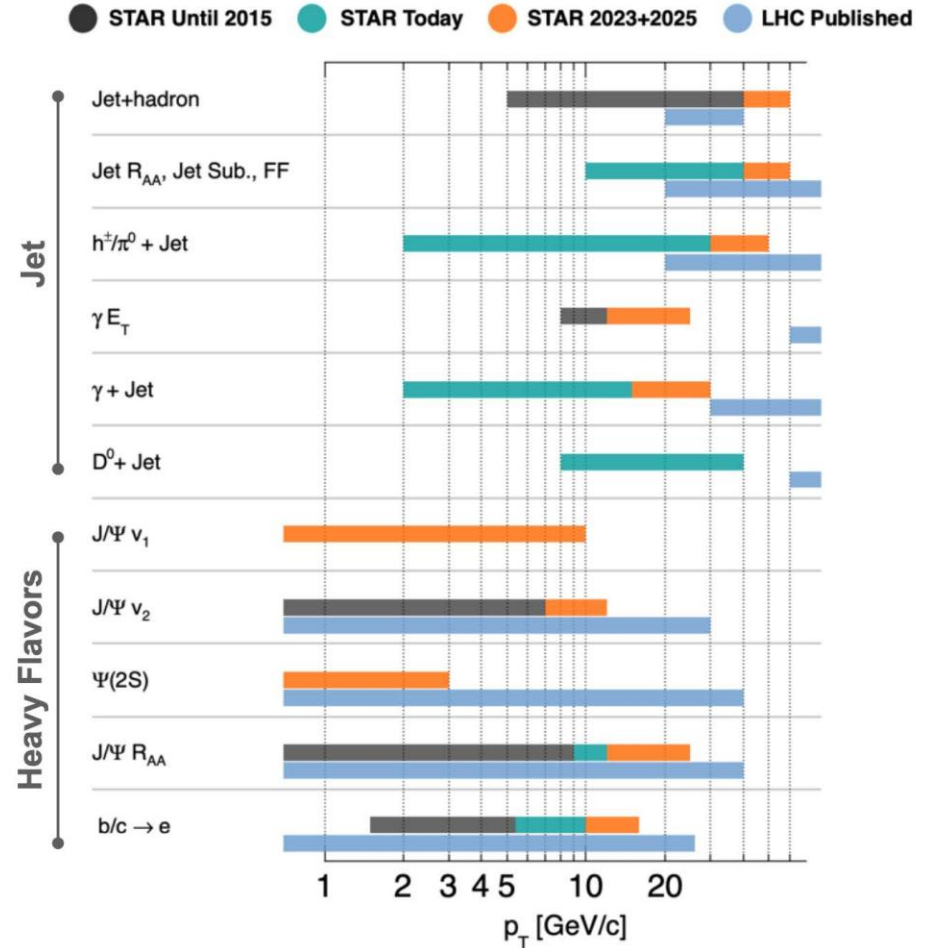
Outlook of 2023-2025

STAR BUR-2022:

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



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



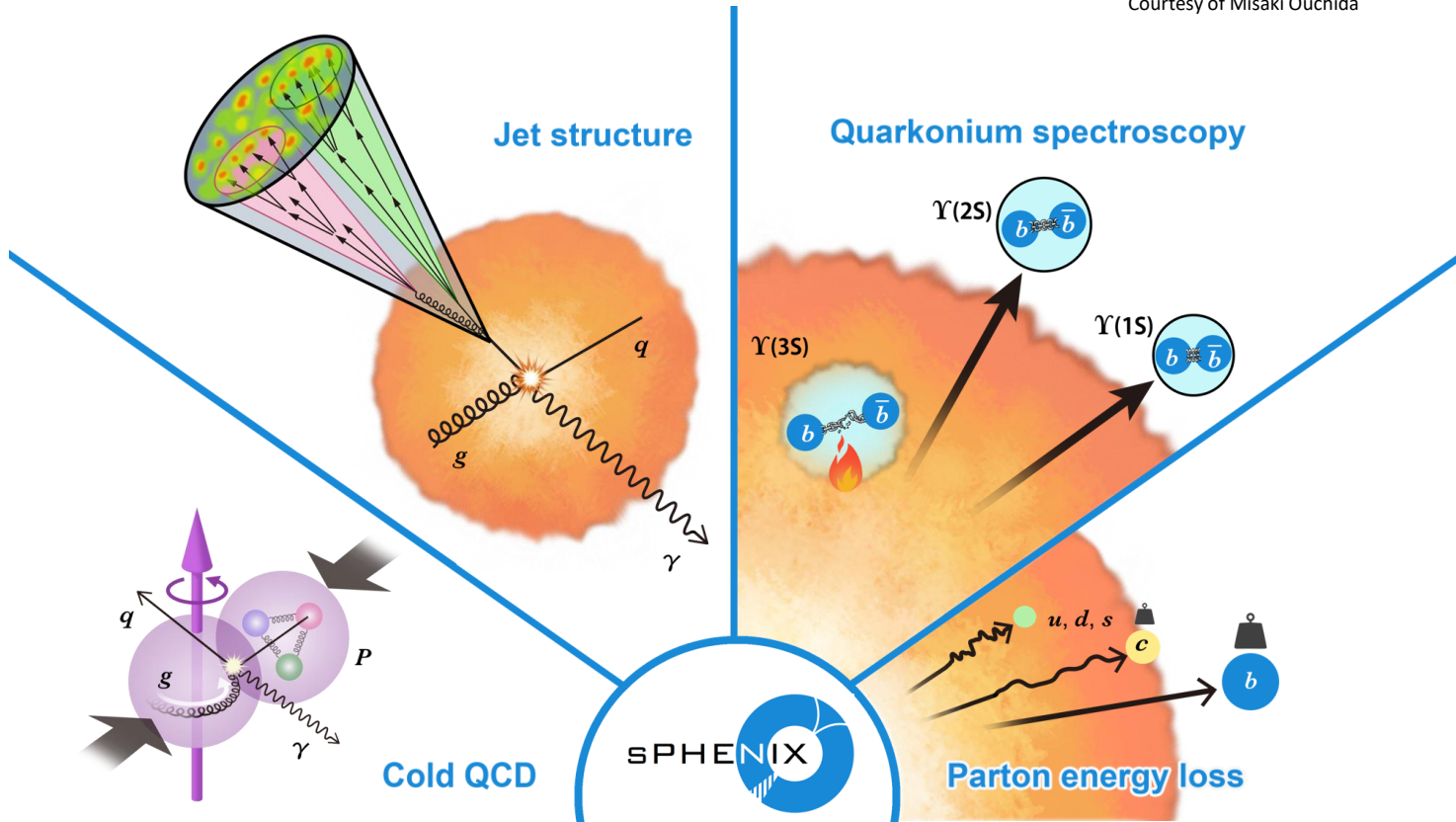
[https://indico.bnl.gov/event/15148/attachments/40846/68609/STAR_BUR_Runs23_25___2022\(1\).pdf](https://indico.bnl.gov/event/15148/attachments/40846/68609/STAR_BUR_Runs23_25___2022(1).pdf)

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

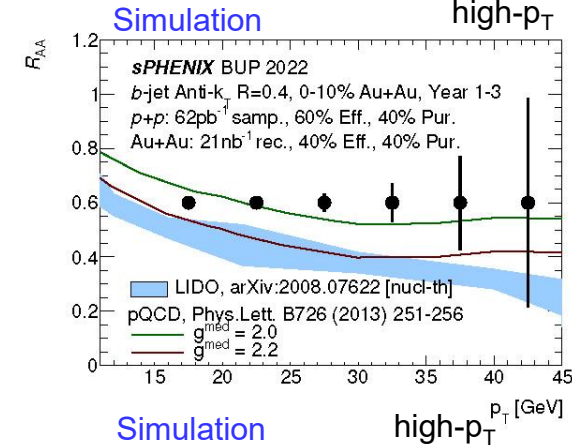
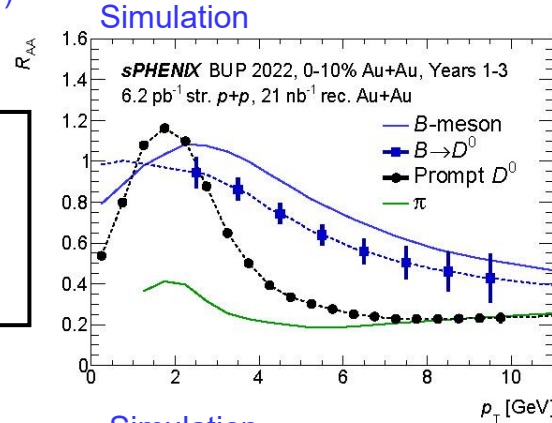
Prospects for Heavy Flavor Physics in sPHENIX



Expectations from sPHENIX Beam Use Request (BUR)

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 , ...

Nuclear modification factor



Simulation

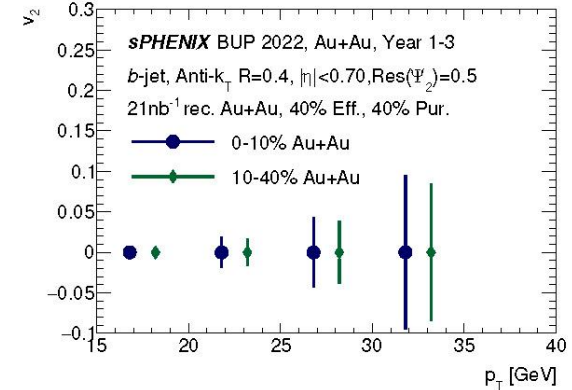
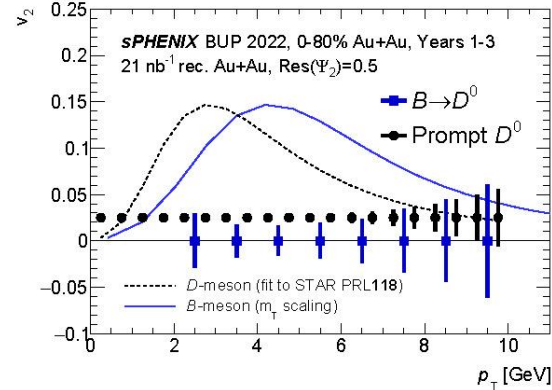
Simulation

high- p_T

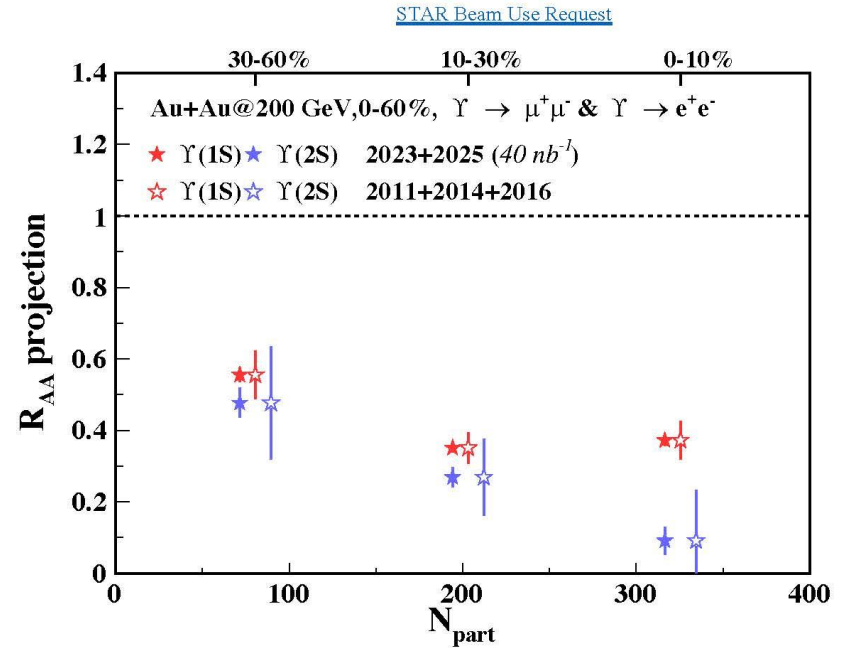
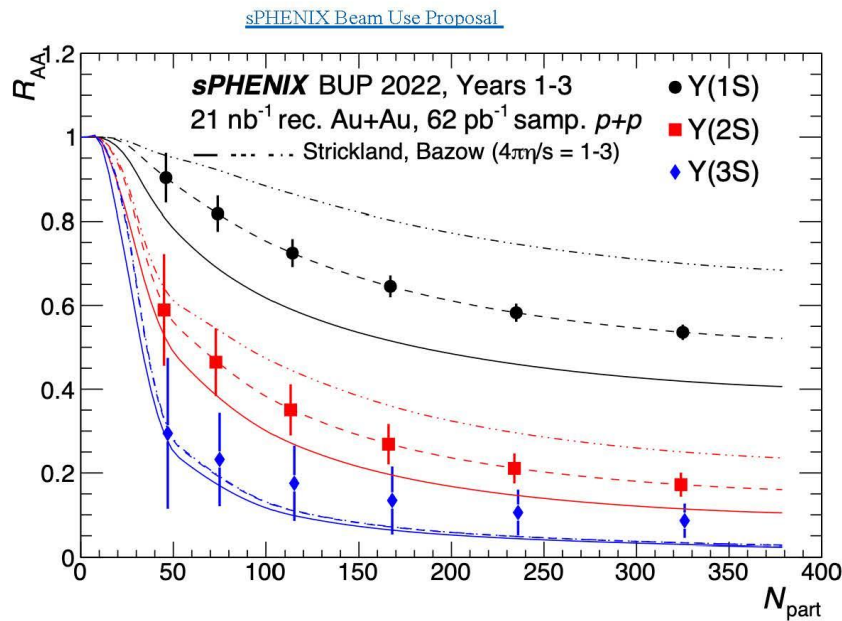
The sPHENIX tracking detectors are taking p+p data with stream readout TOGETHER at a rate ~ 15 kHz

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

Elliptic Flow



Upsilon sPHENIX/STAR outlook



[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 charmonium and bottomonium production
- **J/ψ and Upsilon production in p+p collisions:** faster than linear rise
 - Multiparton interactions and percolation models
- **J/ψ suppression:** no significant collision system and energy dependence
 - Interplay of dissociation and regeneration effects
- **Ψ(2S)/J/ψ ratio in isobars:** first charmonium sequential suppression
- **J/ψ flow:** zero flow observed in forward and central rapidity at RHIC
- **Sequential Y suppression at RHIC**
 - Thermodynamic properties of the medium
- **RUN 2025 – Au+Au 200 GeV (FY 25 – 18 weeks + FY26 -12 weeks no summer break)**
- **More results expected from STAR and sPHENIX in near future**