

Quarkonium measurements at RHIC

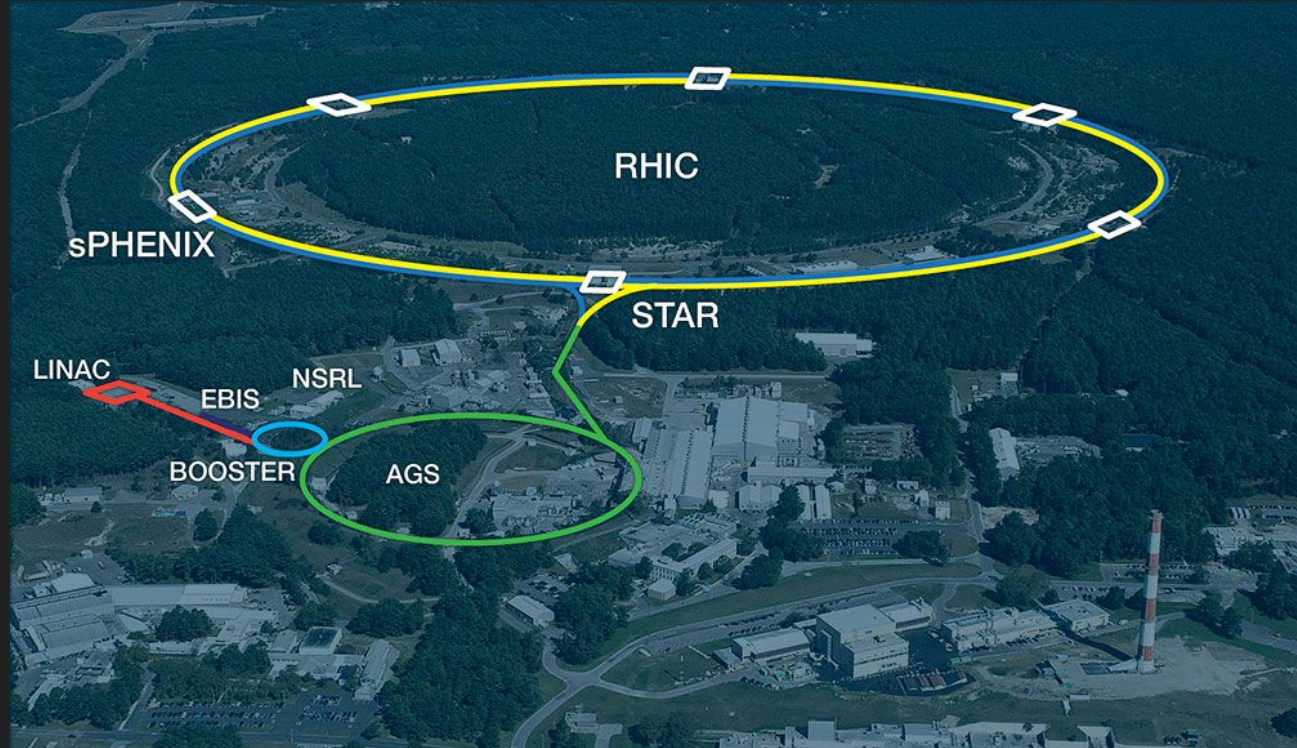
Jakub Češka (CTU in Prague)

Quarkonia as Tools 2025
Centre Paul Langevin, Aussois, France
5. - 11. 1. 2025

RHIC

Relativistic Heavy Ion Collider (RHIC)

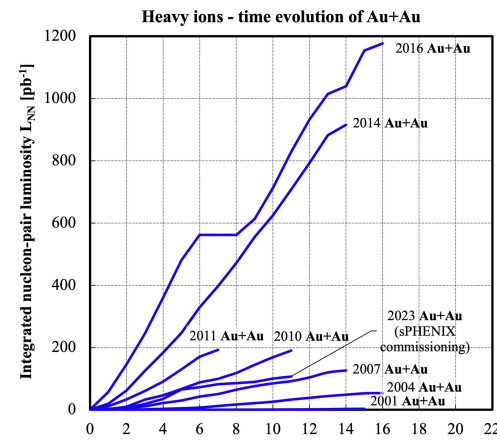
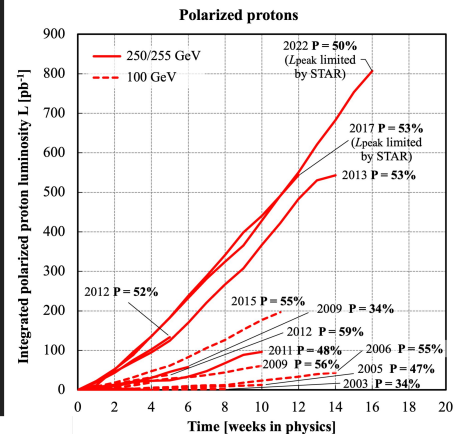
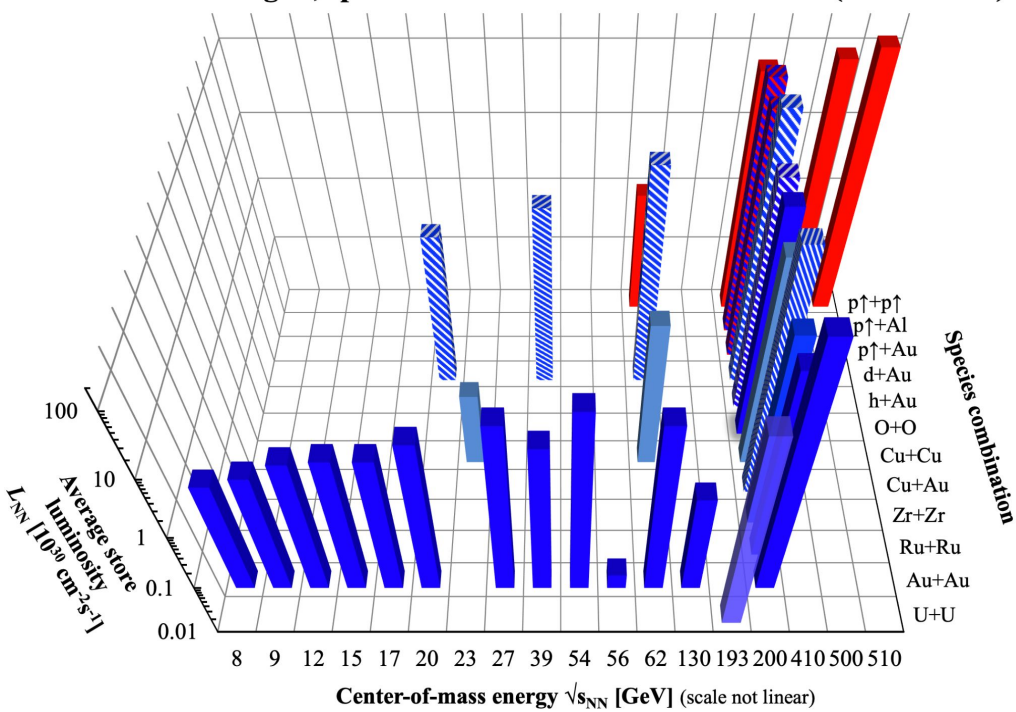
- Brookhaven National Laboratory (BNL), New York, USA
- World's only polarised hadron collider
- Future site of the EIC



RHIC collider

Run	species	total particle energy [GeV/nucleon]	calendar time in physics
Run-24 CY2024, FY2024/25 27.0 cryo-weeks	polarized p + p	100.2	21.9 weeks
	$^{197}\text{Au}^{79+} + ^{197}\text{Au}^{79+}$	100.0	2.6 weeks
Run-25 CY2025, FY2025 20.0 cryo-weeks planned	$^{197}\text{Au}^{79+} + ^{197}\text{Au}^{79+}$	100.0	— in preparation —

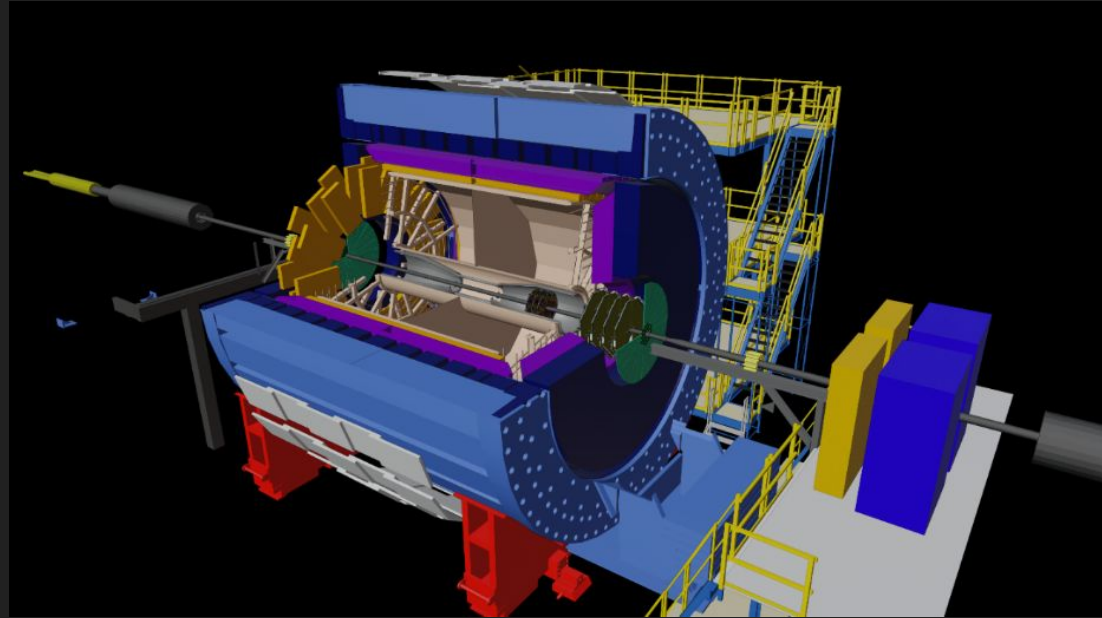
RHIC energies, species combinations and luminosities (Run-1 to 22)



Experiments

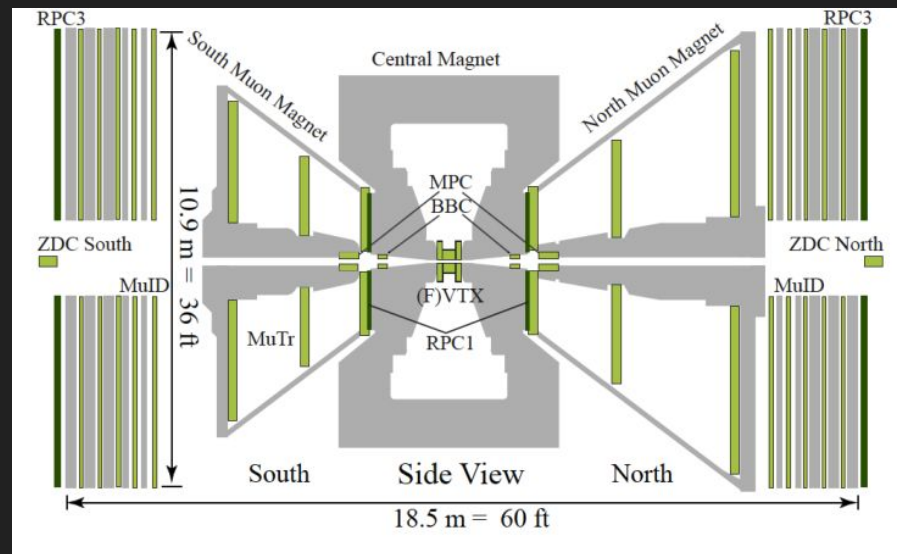
STAR

- Commissioned in 2000
- TPC: $|\eta| < 1$
 - iTPC: $|\eta| < 1.5$
- BEMC: $|\eta| < 1$
- MTD: $|\eta| < 0.5$
- Forward upgrade (2022 -):
 $2.4 < |\eta| < 4$
- TOF: $|\eta| < 0.9$
- HFT (2014-2016)



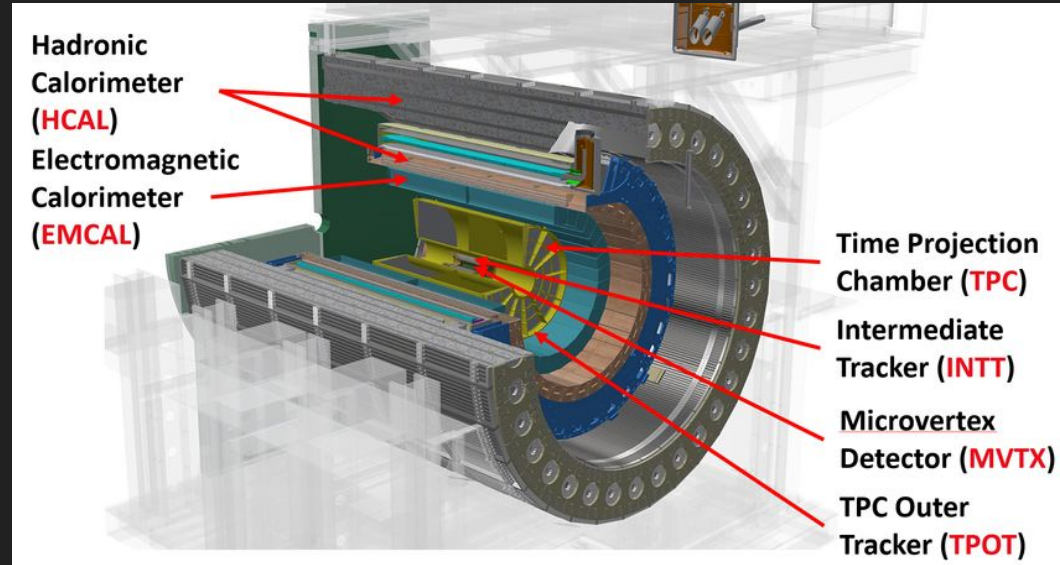
PHENIX

- Finished data-taking in 2016
- Central arm (electrons)
 - $|\eta| < 0.35$
 - $|\Delta\phi| < \pi$
 - tracking: DC, PC, VTX
 - ID: RICH, Emcal
- Forward arms (muons)
 - $1.2 < |\eta| < 2.2$
 - $|\Delta\phi| < 2\pi$
 - tracking: MuTr, FVTX
 - ID: MuID
- Event plane
 - FVTX, BBC, CNT



sPHENIX

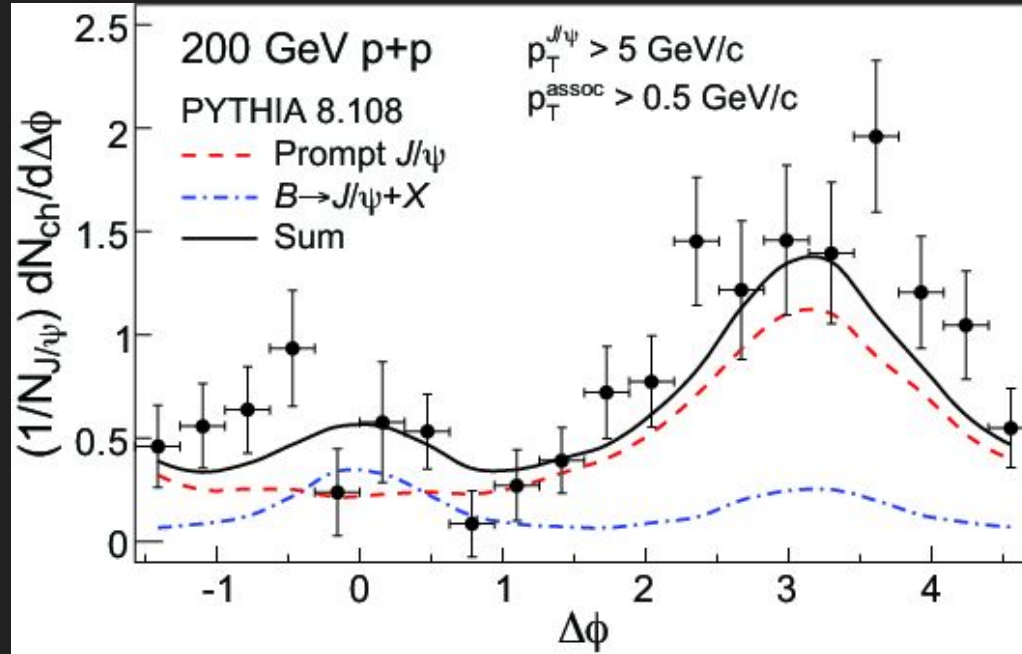
- Commissioned in 2023
- Hermetic coverage in $|\eta| < 1.1$
- >15 kHz data rate for all detectors
- Trigger capability and streaming readout
- MAPS vertexing via MVTX
- Precision tracking \rightarrow 3 Y state separation expected



Onium-hadron correlations

J/ ψ -hadron azimuthal correlations

[Phys.Rev.C 80 (2009) 041902]

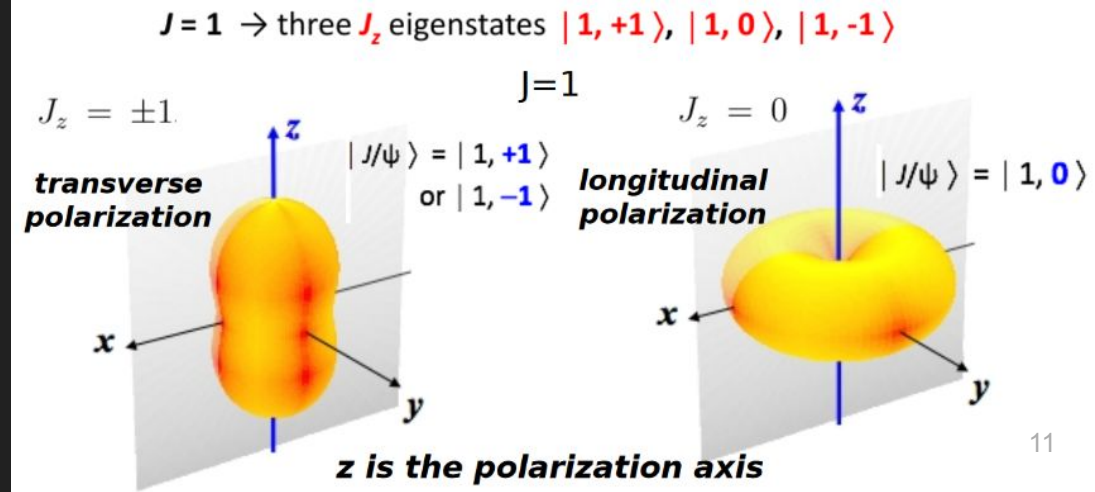
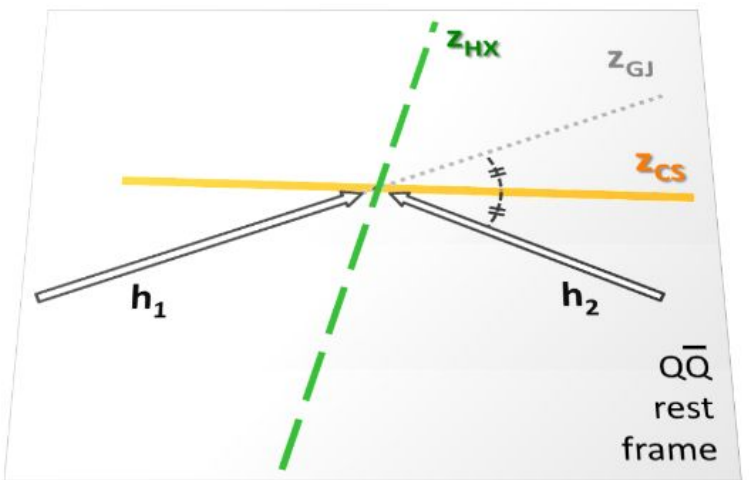
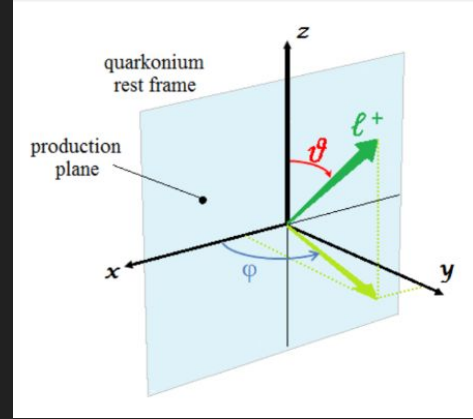


STAR measurements show **two peaks**, which consists of a single away-side peak contribution of prompt J/ψ and a double peak from B to J/ψ decays with the near-side peak having larger magnitude

$$\frac{d\sigma}{d\cos\vartheta d\varphi} \propto 1 + \lambda_\vartheta \cos^2\vartheta + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \dots$$

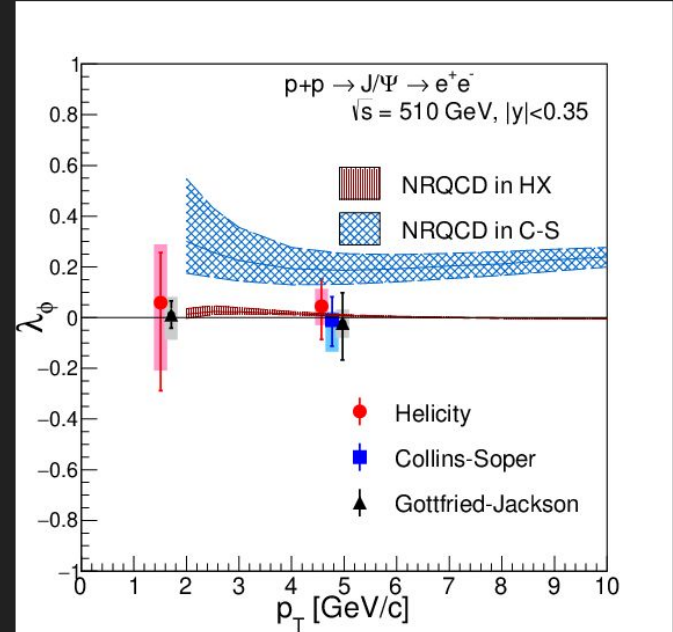
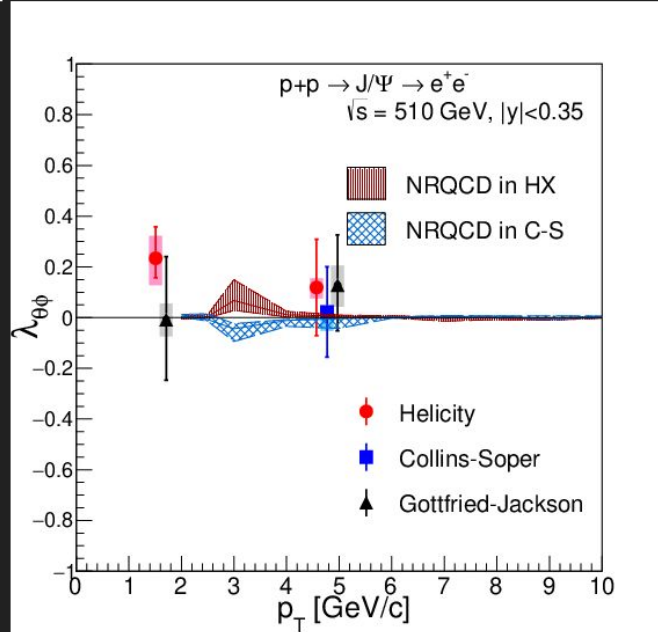
Polarisation

- Helicity (HX) - quarkonium momentum direction
- Collins-Soper (CS) - beam angle bisection
- Gottfried-Jackson (GJ) - beam direction



J/ ψ polarisation

[Phys.Rev.D 102 (2020) 7, 072008]

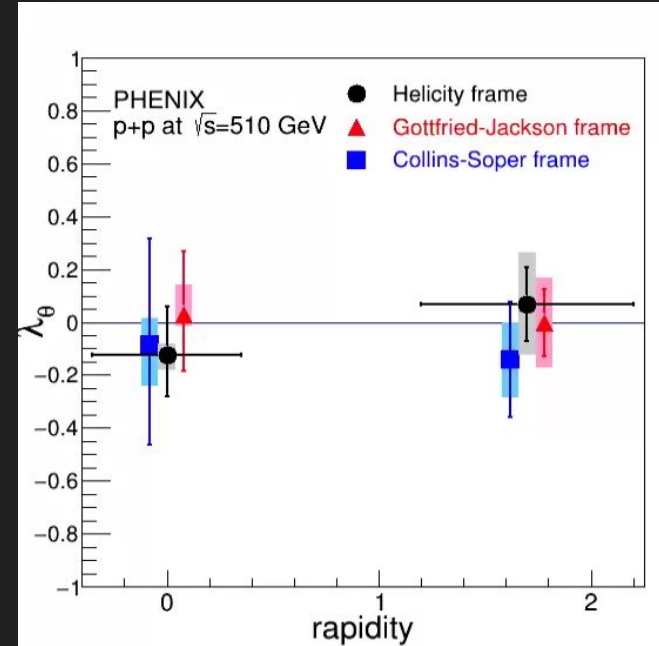
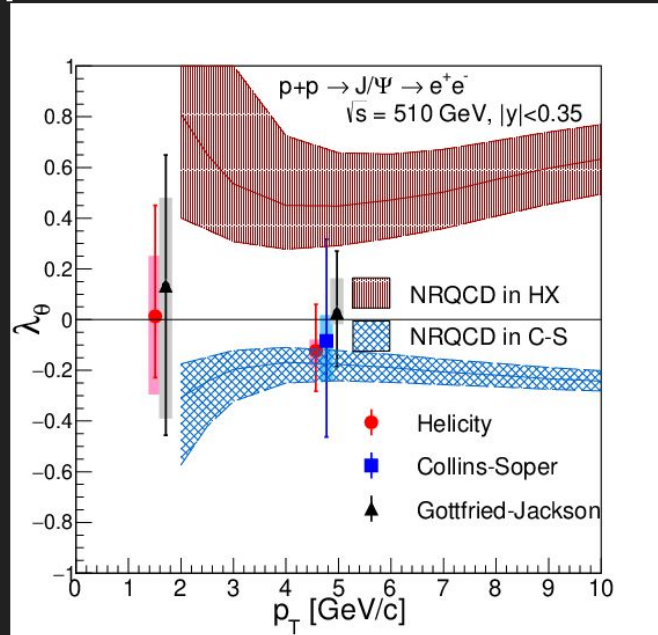


PHENIX measurements of $\lambda_{\theta\phi}$ are **consistent with 0 in C-S and G-J frames**, whereas **it is positive in HX at low p_T**

The data for λ_ϕ are **consistent with 0 in all frames**. The NRQCD prediction does not describe the **C-S data**, but the **HX data agree within errors**

J/ ψ polarisation

[Phys.Rev.D 102 (2020) 7, 072008]



PHENIX data for λ_θ are **consistent with 0 in all frames** in both p_T and rapidity dependent measurements

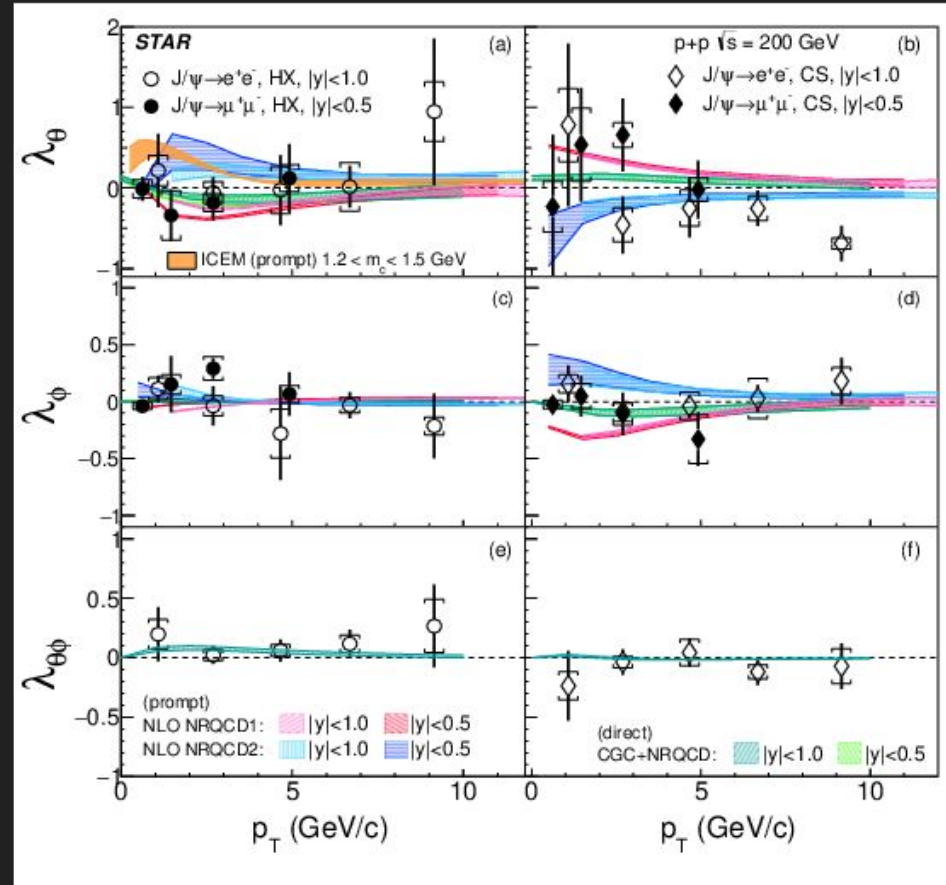
In p_T dependent measurements the **NRQCD model describes the C-S data** within errors, but the **HX data do not agree with the predictions**

J/ ψ polarisation

The STAR results for J/ ψ in two decay channels show differences in λ_θ and λ_ϕ between HX and C-S frames.

Data consistent with no polarisation and no strong p_T dependence except for λ_θ in C-S at high p_T

CGC+NRQCD offers best description, other models not ruled out due to large uncertainties



Multiplicity dependence

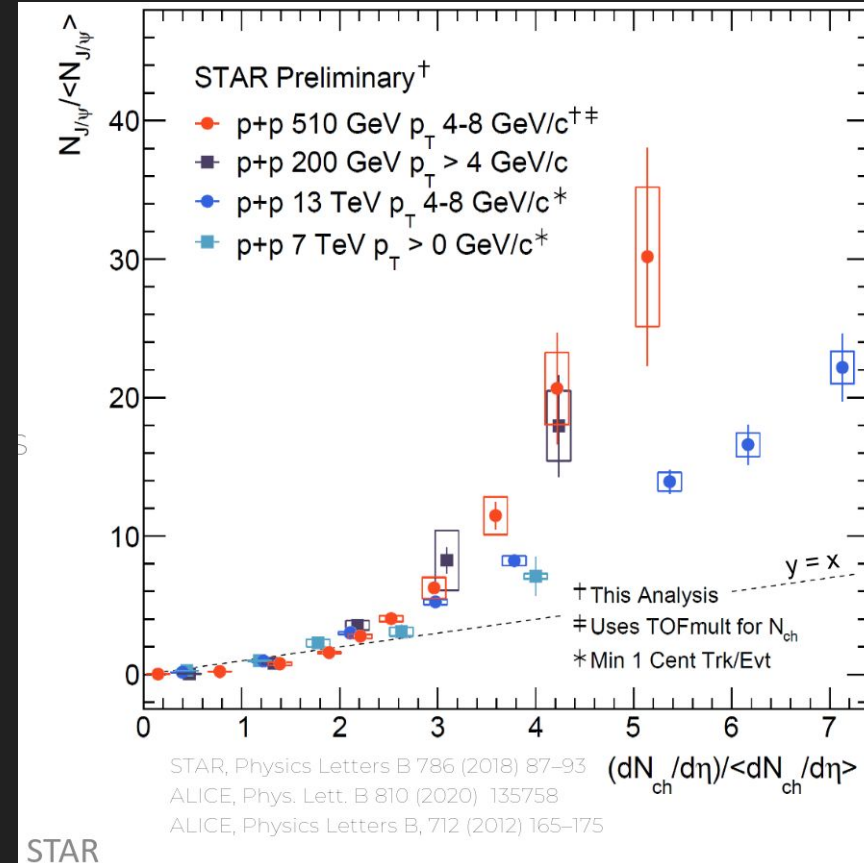
J/ψ multiplicity dependence

Newest measurement of J/ψ multiplicity dependence at 510 GeV in p+p by STAR

Improved multiplicity reach

Consistent with 200 GeV STAR data

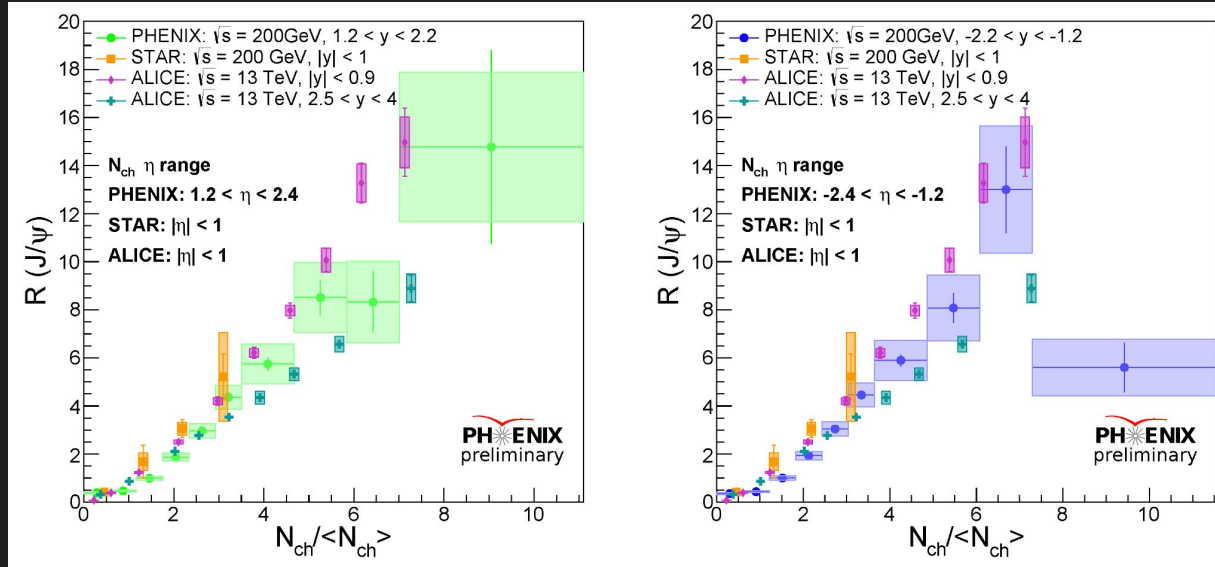
Hints of splitting between RHIC and LHC energies



STAR

J/ψ multiplicity dependence

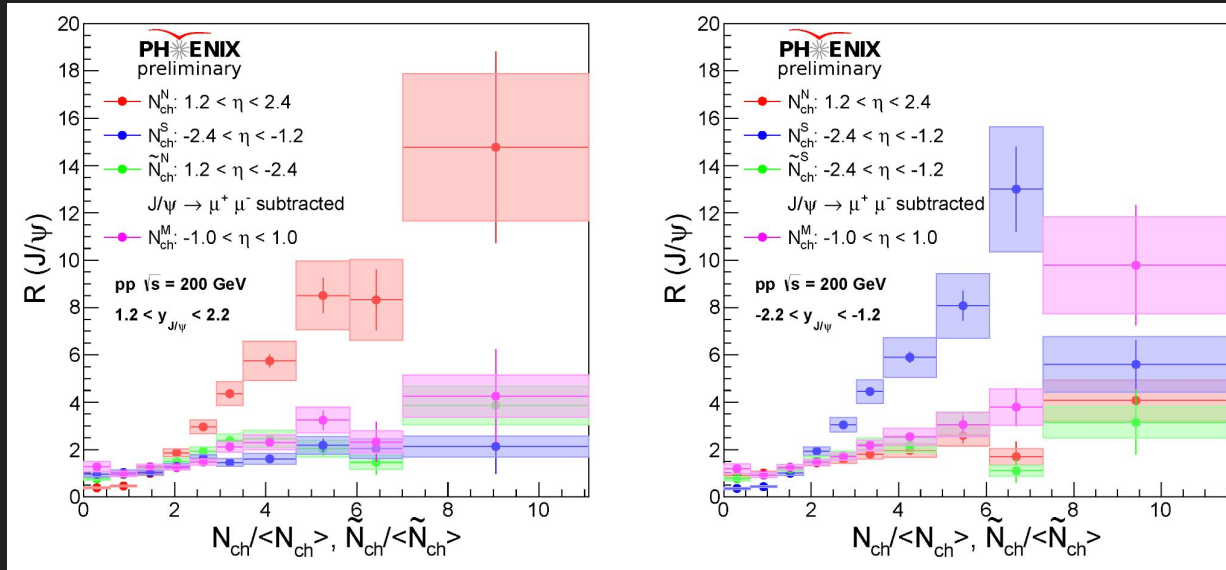
[Universe 2023, 9(7), 322]



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

J/ψ multiplicity dependence

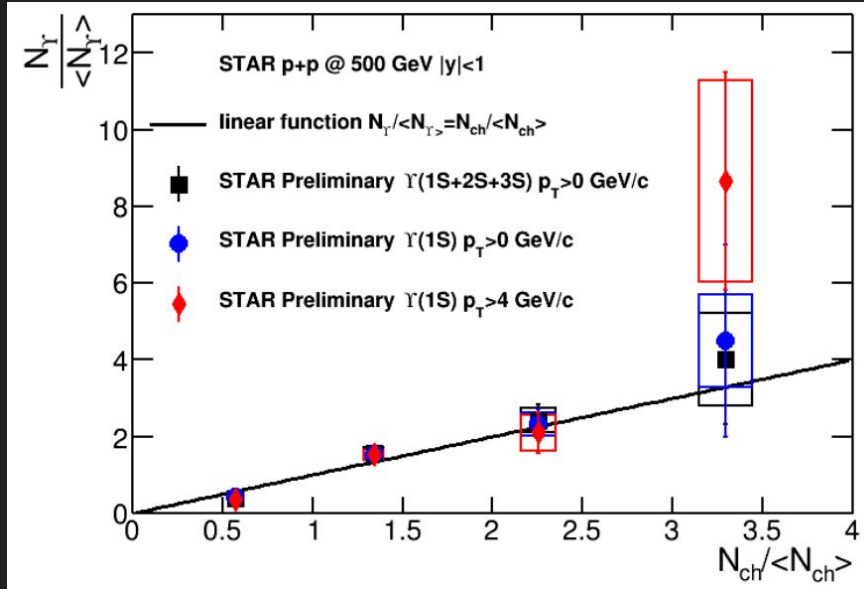
[Universe 2023, 9(7), 322]



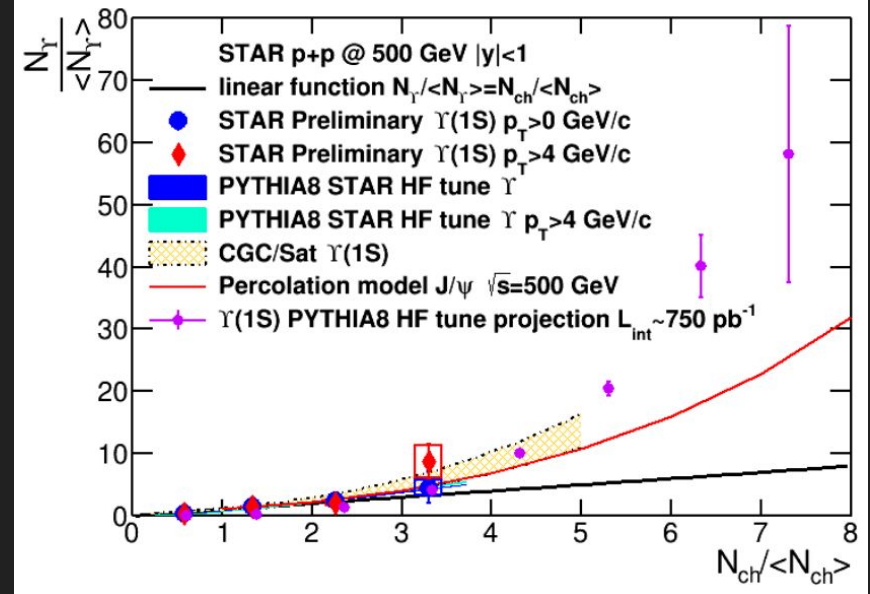
The analysis also highlights a **strong dependence of the rapidity window used for N_{ch} calculation**

Y multiplicity dependence

[Leszek Kosarzewski, MPI@LHC 2023]



[Leszek Kosarzewski, 20th Conference of Czech and Slovak Physicists]



The STAR measurements of Υ exhibit the same **stronger-than-linear increase** with high- p_T data having a larger magnitude than p_T -integrated ones

BES-II

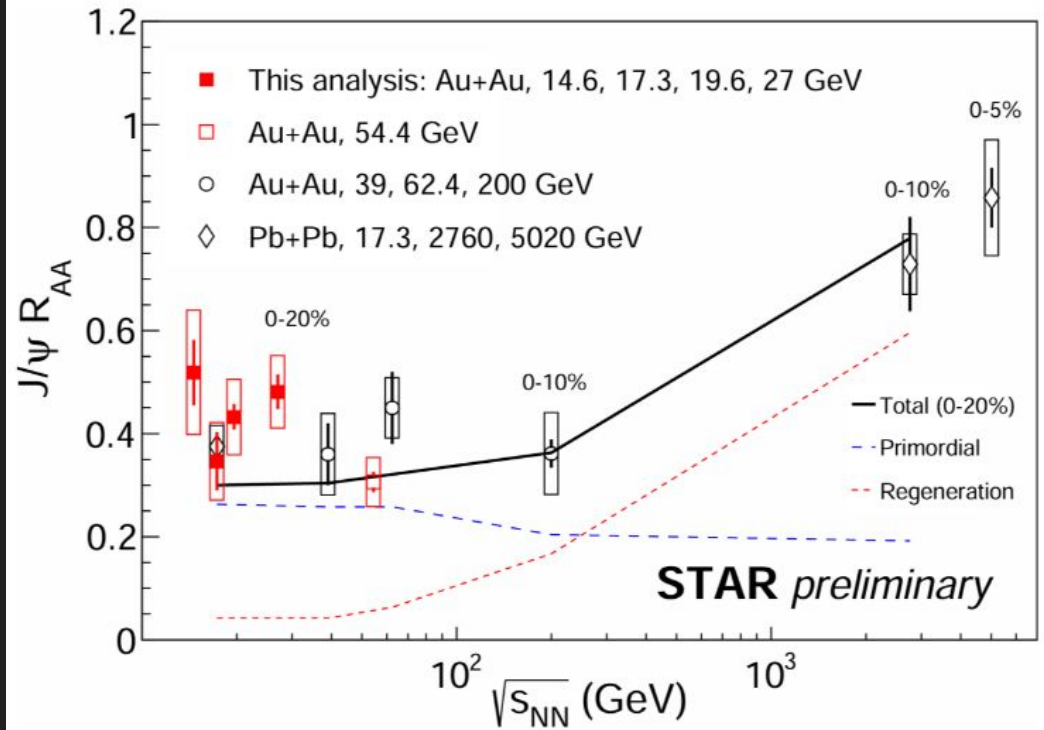
Inclusive J/ψ R_{AA}

STAR results from BES-II available for Au+Au collisions at 14.6, 17.3, 19.6, 27 GeV

Data follow global trend

No significant energy dependence observed up to 200 GeV with respect to uncertainties

Qualitatively described by transport model

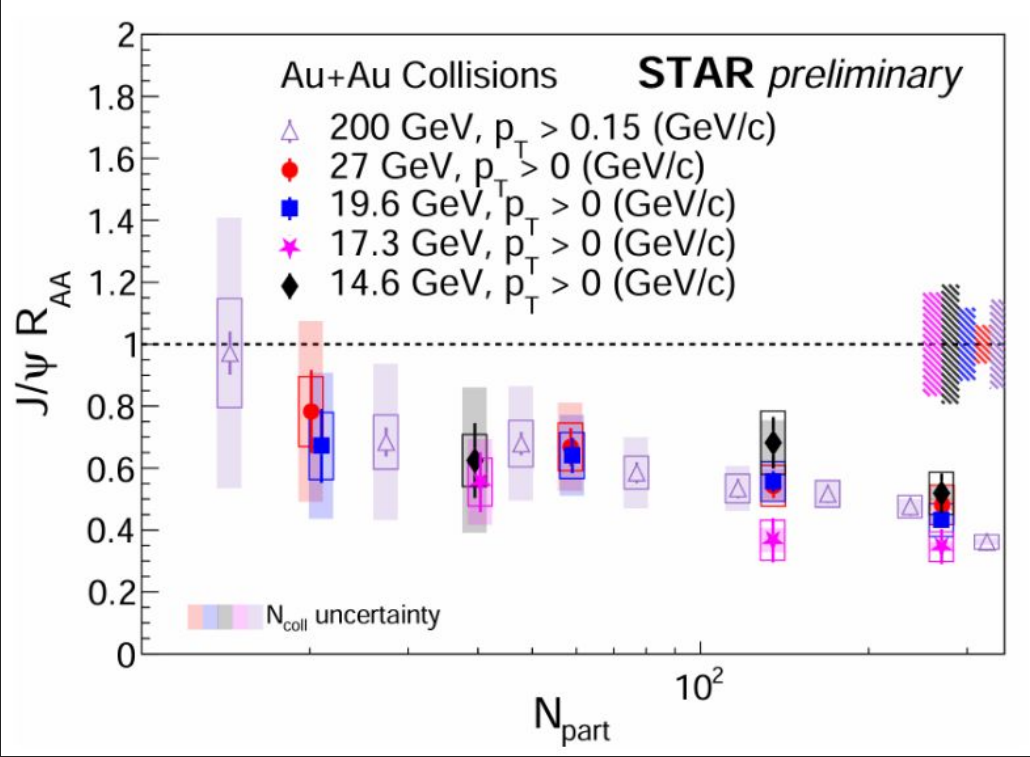


X. Zhao, R. Rapp, *Phys. Rev. C* 82 (2010) 064905 (private communication).
 L. Kluberg, *Eur. Phys. J. C* 43 (2005) 145.

Inclusive J/ψ R_{AA}

Hints of decreasing trend as a function of centrality

No significant dependence on energy at same $\langle N_{part} \rangle$

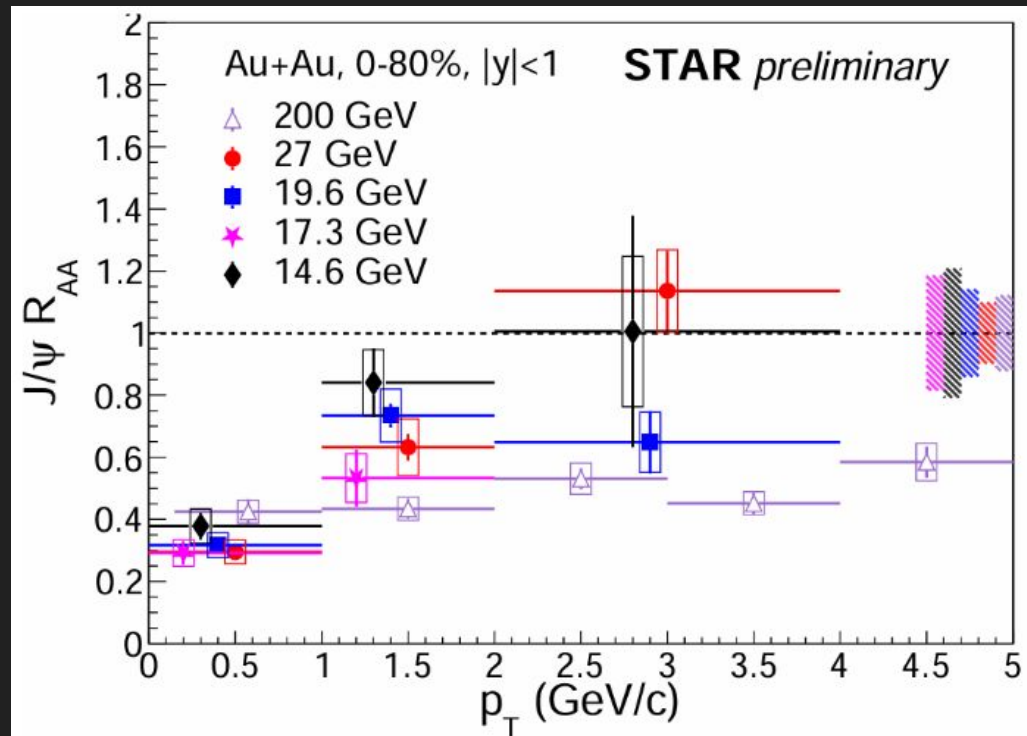


Inclusive J/ψ R_{AA}

[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



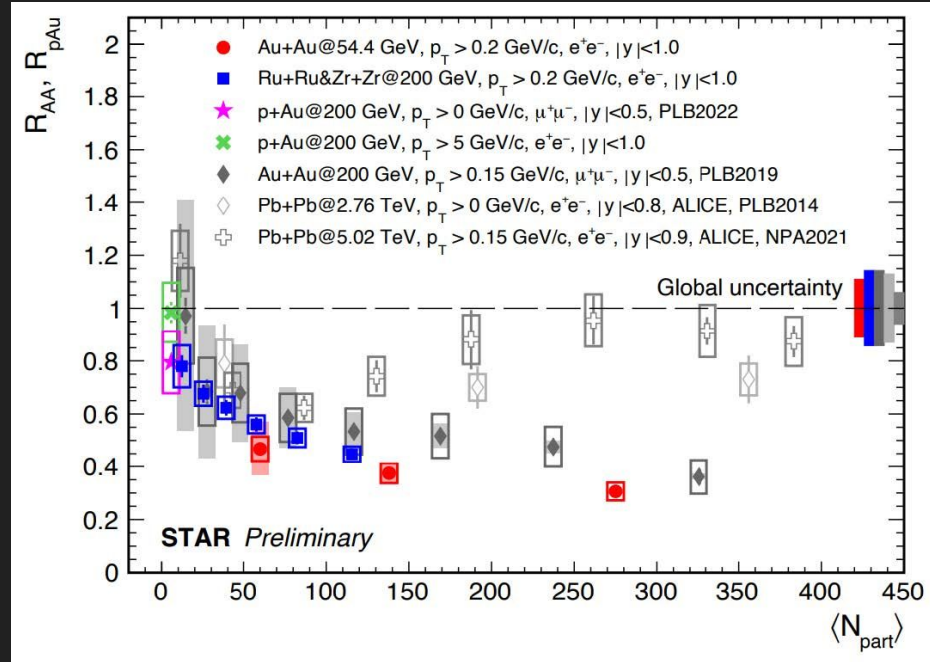
Isobar collisions

J/ ψ in isobar collisions

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

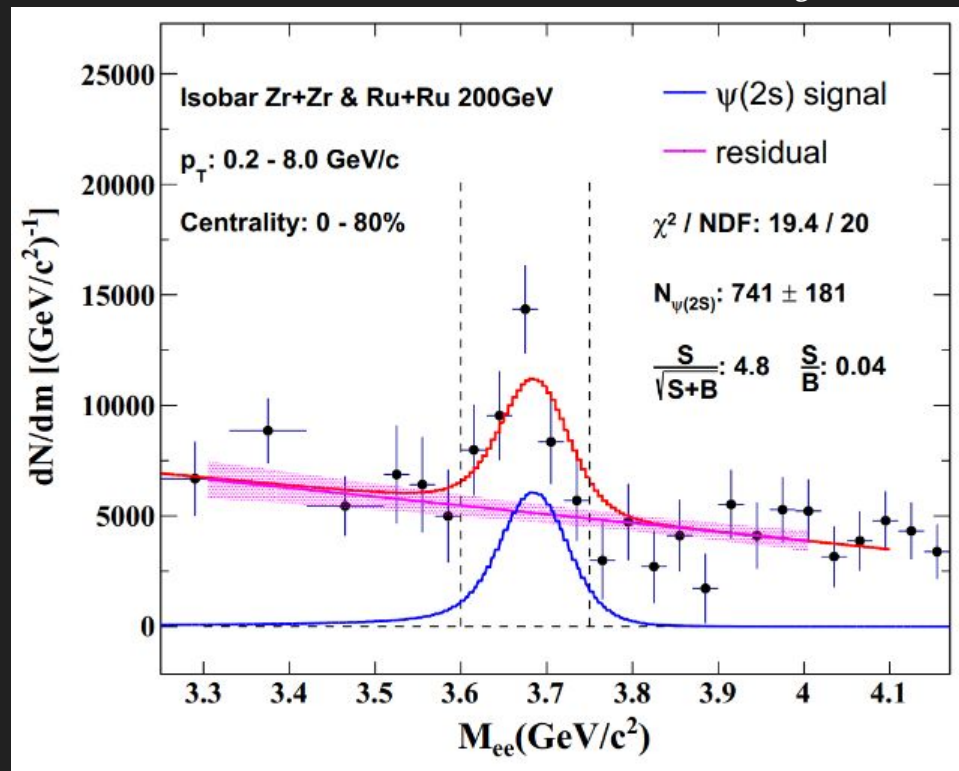
Stronger suppression at high p_T at RHIC than at LHC



J/ ψ and $\psi(2S)$ in isobar collisions

[Wei Zhang, HP2024]

First RHIC observation of $\psi(2S)$ in heavy ion collisions



J/ψ and ψ(2S) in isobar collisions

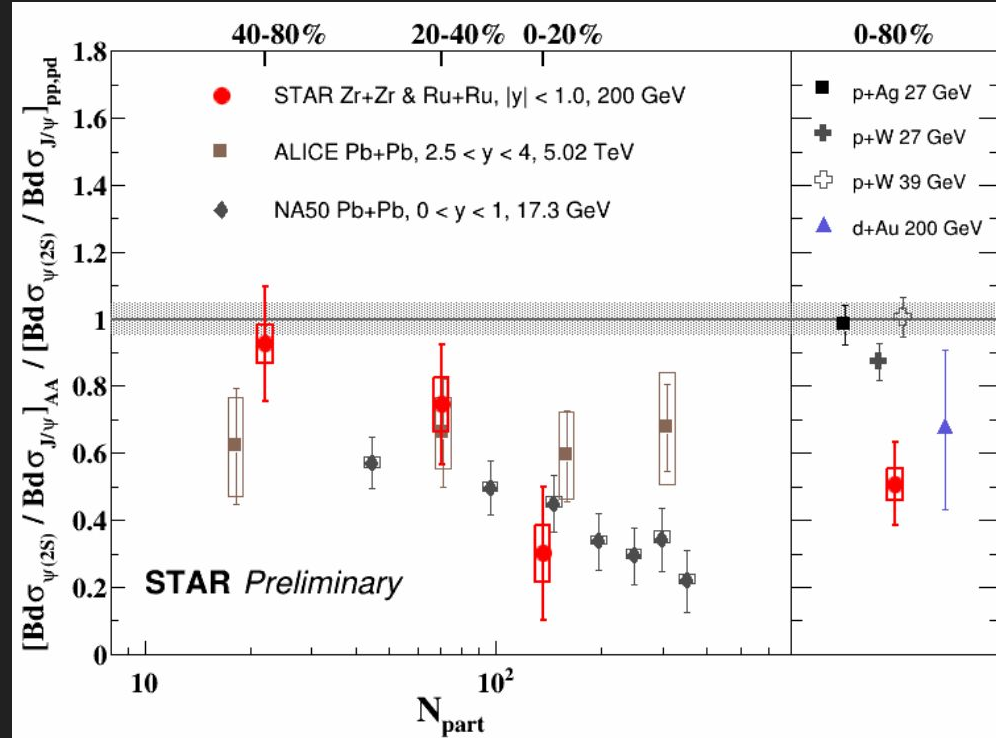
[Wei Zhang, HP2024]

First observation of **charmonium sequential suppression in heavy ion collisions** at RHIC (3.5σ)

Smaller than in p+Au collisions

Hint of decrease towards central collisions

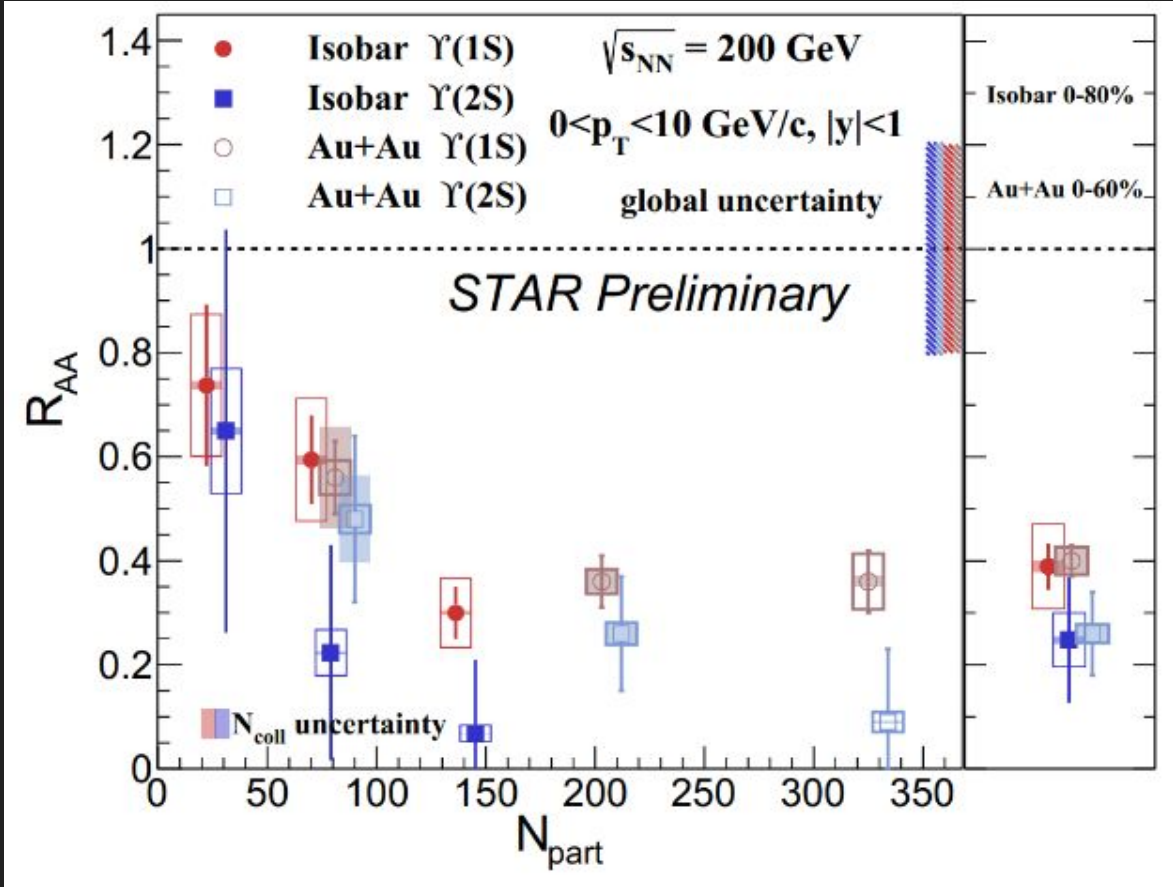
Centrality dependence trend seems more similar to SPS than to LHC



*p+p reference average of NA51, ISR and PHENIX

Y in isobar collisions

Hints of $Y(1S)$ and $Y(2S)$ suppression in isobar (Zr+Zr, Ru+Ru) and Au+Au collisions



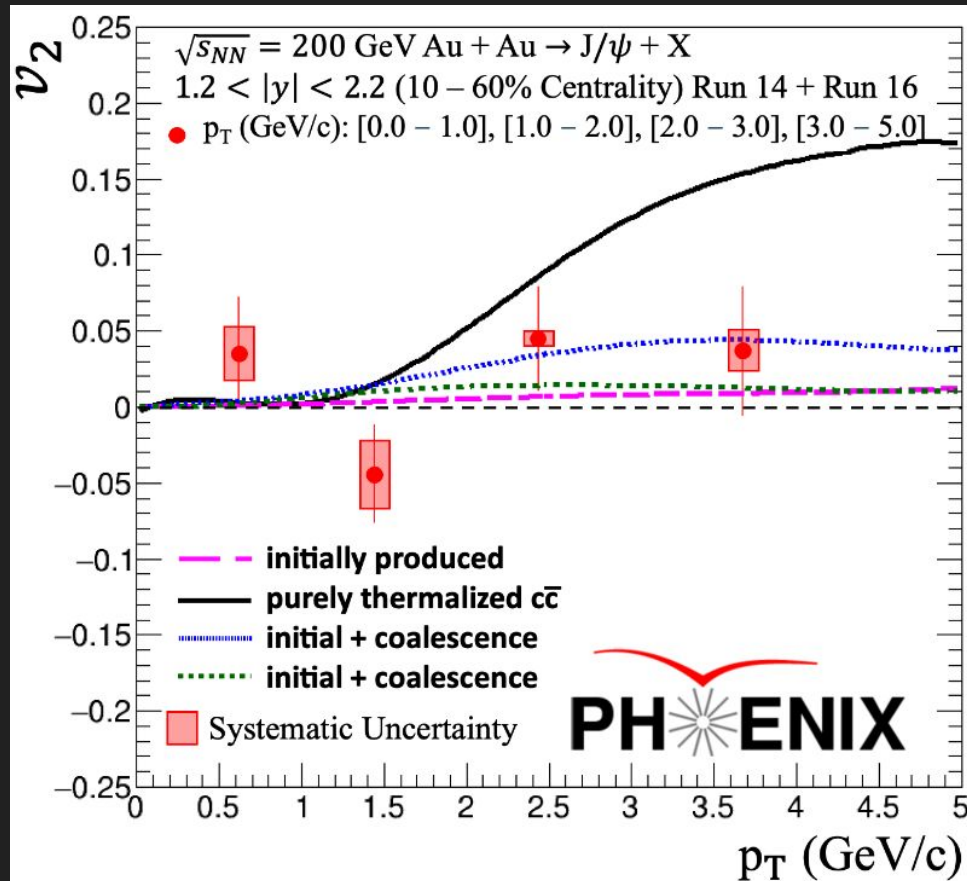
Flow

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

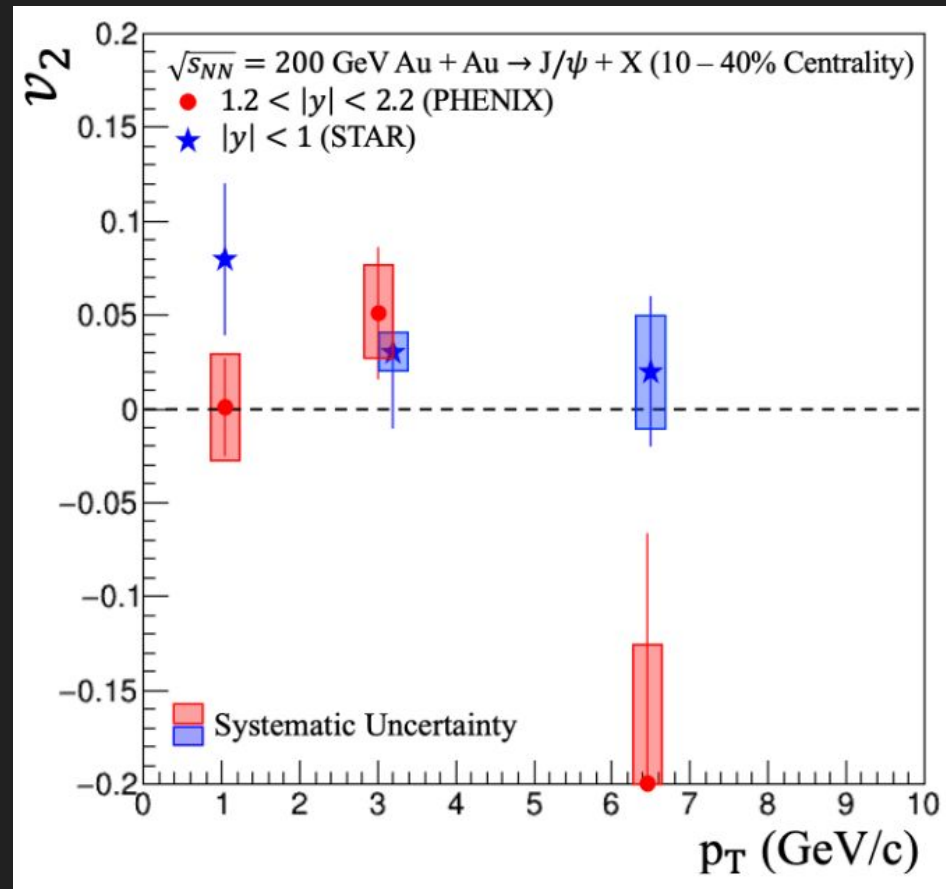


J/ ψ v_2 in Au+Au

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

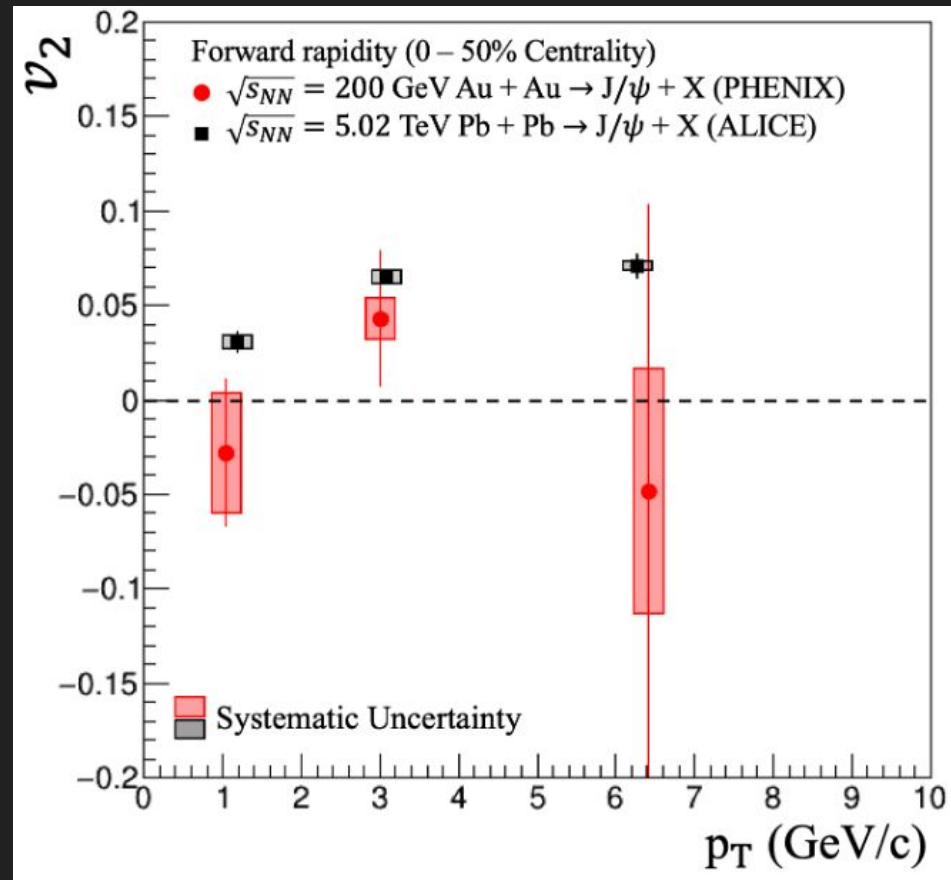


J/ψ v_2 in Au+Au

New PHENIX measurement of J/ψ v_2 consistent with unity, coalescence model predictions

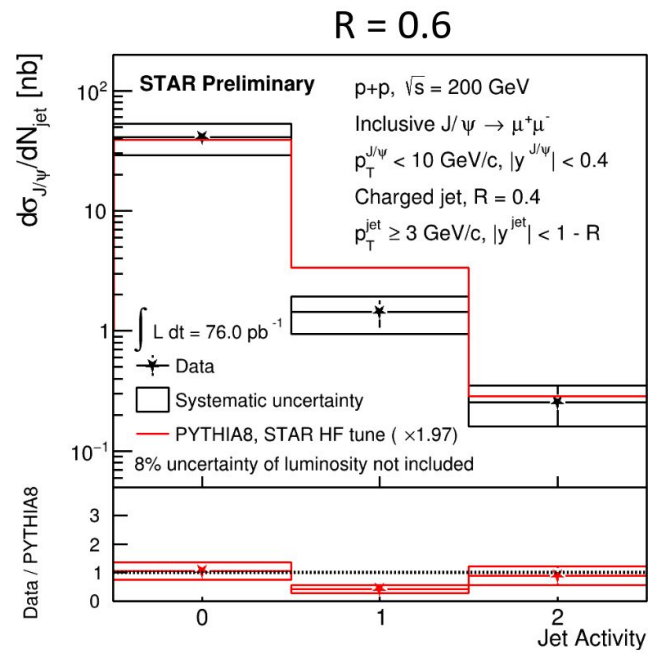
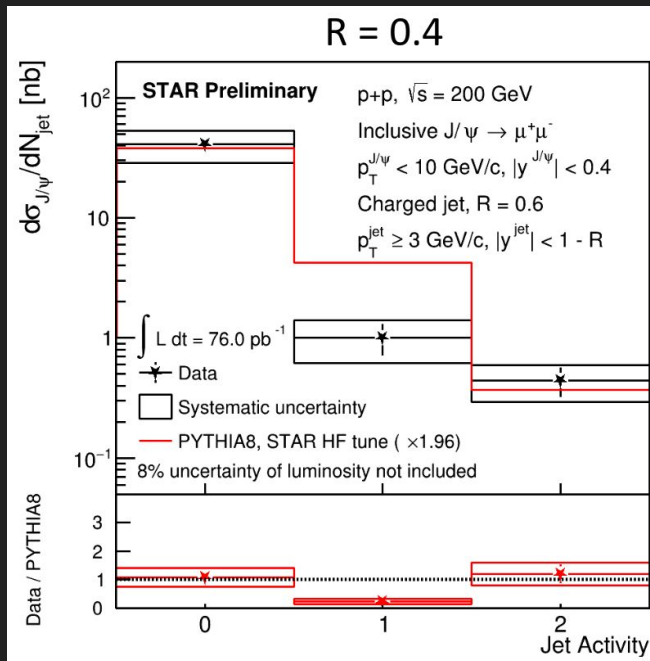
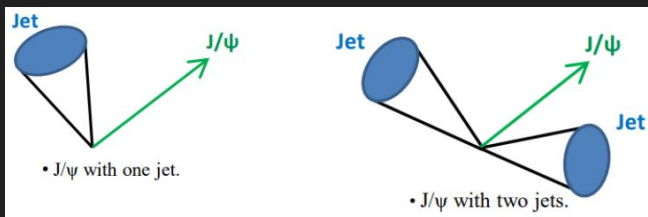
Forward- (PHENIX) and mid-rapidity (STAR) data at RHIC consistent

PHENIX measurements distinct from ALICE non-zero data



Quarkonia and jets

J/ψ production with jet activity

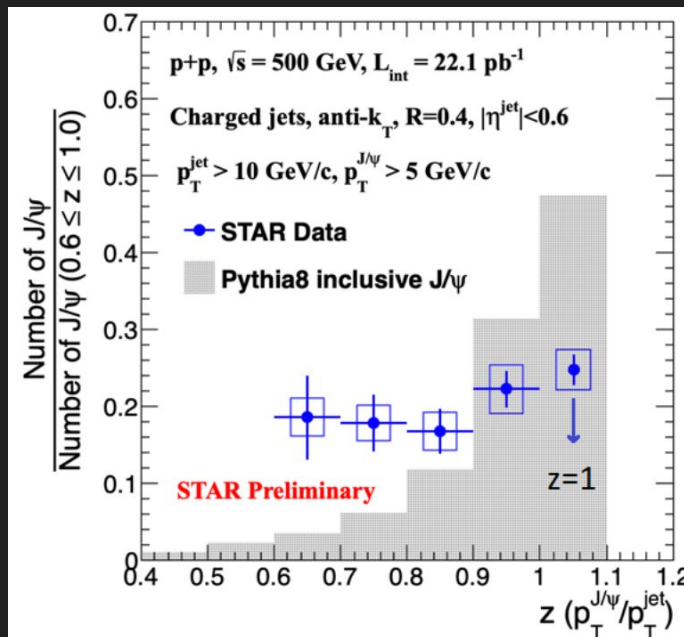


[Yi Yang, DIS23]

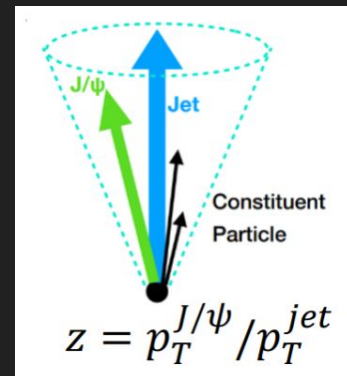
PYTHIA8 predicts a larger fraction of jet-associated J/ψ compared to STAR data

Theoretical model calculations needed

J/ ψ production within jets



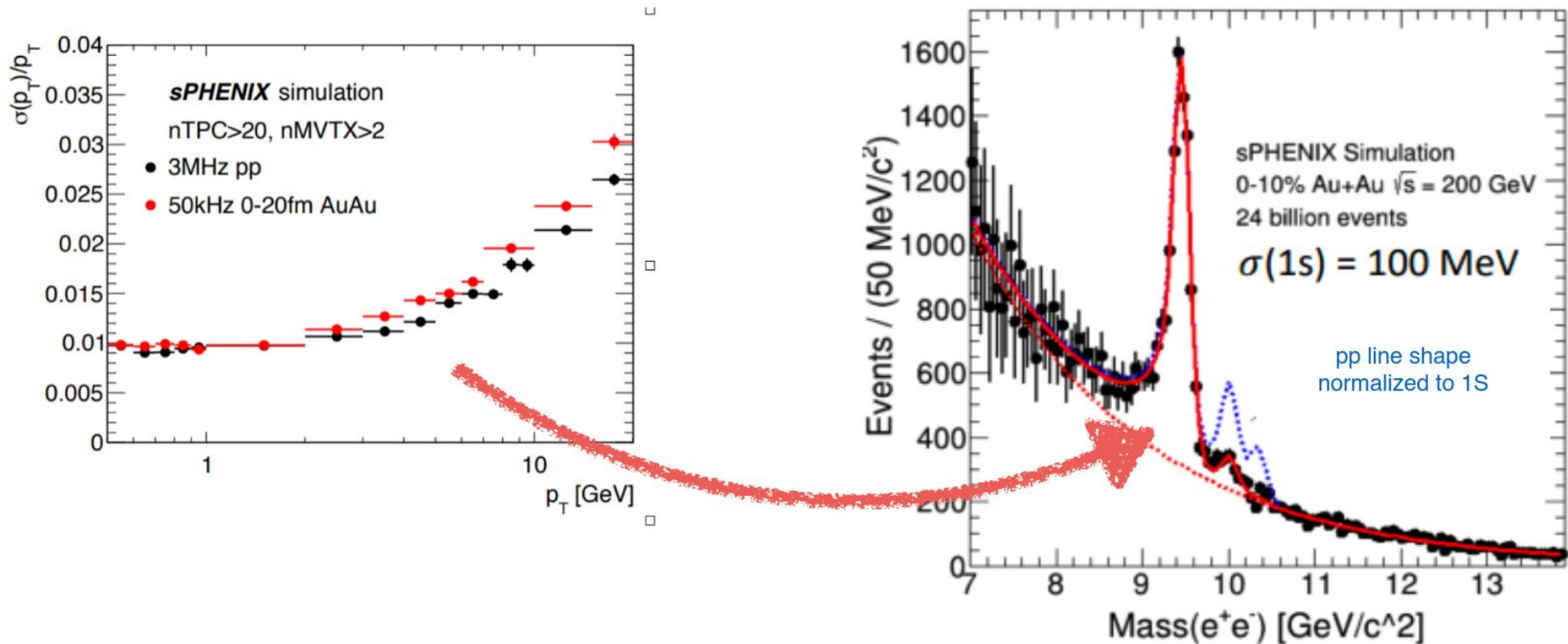
[Kaifeng Shen, SQM21]



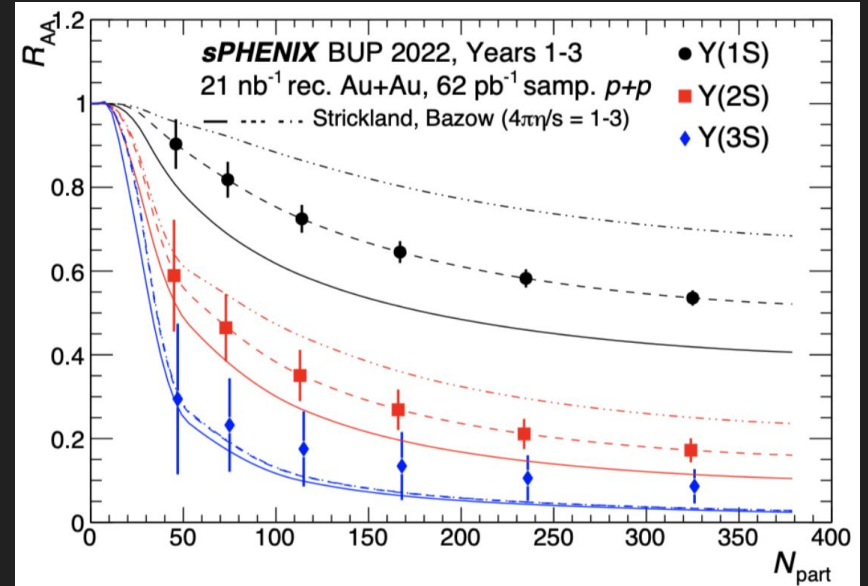
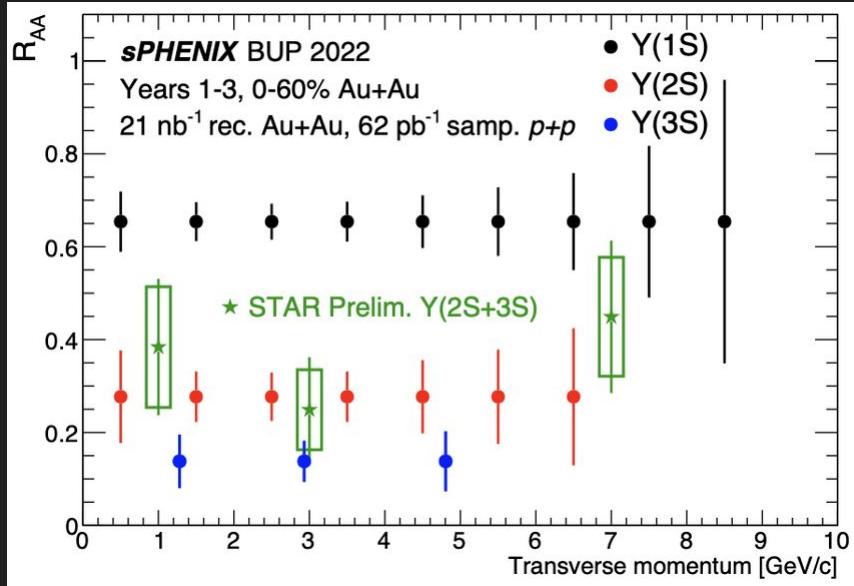
No significant z dependence in data observed

J/ ψ production less isolated in data compared to PYTHIA8 prediction

sPHENIX



precision tracking with mass resolution -> **expected first separation of Y states at RHIC**



projected statistical uncertainties for p_T and centrality dependent R_{AA} for Y(1S, 2S, 3S) offers **improvement compared to previous measurements**

Outlook and summary

- BES-II
 - $J/\psi R_{AA}$ not dependent on collision energy at similar $\langle N_{part} \rangle$
 - No significant $J/\psi R_{AA}$ energy dependence up to 200 GeV
 - Increasing $J/\psi R_{AA}$ trend with p_T at BES-II energies
- Isobar collisions
 - $J/\psi R_{AA}$ not dependent on collision system at similar $\langle N_{part} \rangle$
 - Charmonium sequential suppression
 - Hints of $Y(1S)$ and $Y(2S)$ suppression
- PHENIX $J/\psi v_2$ consistent with zero
- No significant z dependence of J/ψ in jets
- sPHENIX commissioned in 2023
- Upcoming Run25 (Au+Au)

Thank you for your attention!