Inclusive onium measurements in p+p collisions at RHIC

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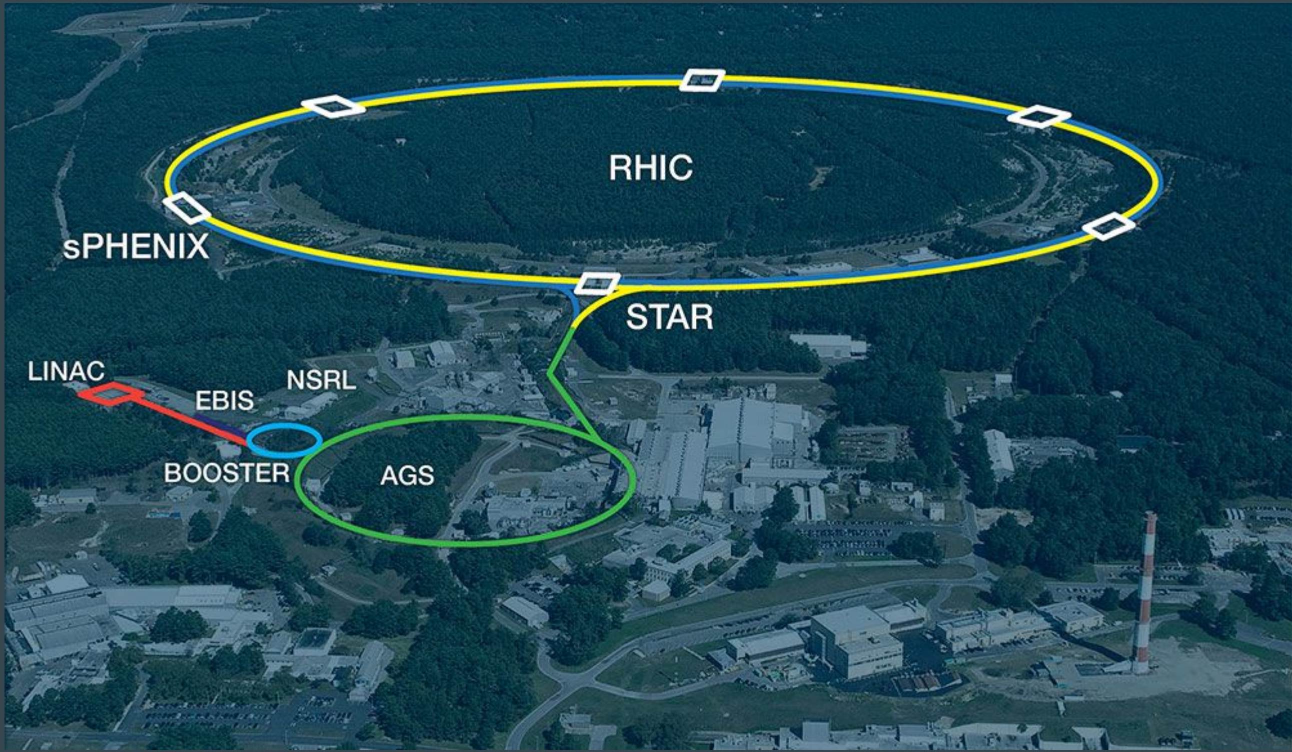
Quarkonia as Tools 2024
Centre Paul Langevin, Aussois, France
7. - 13. 1. 2024

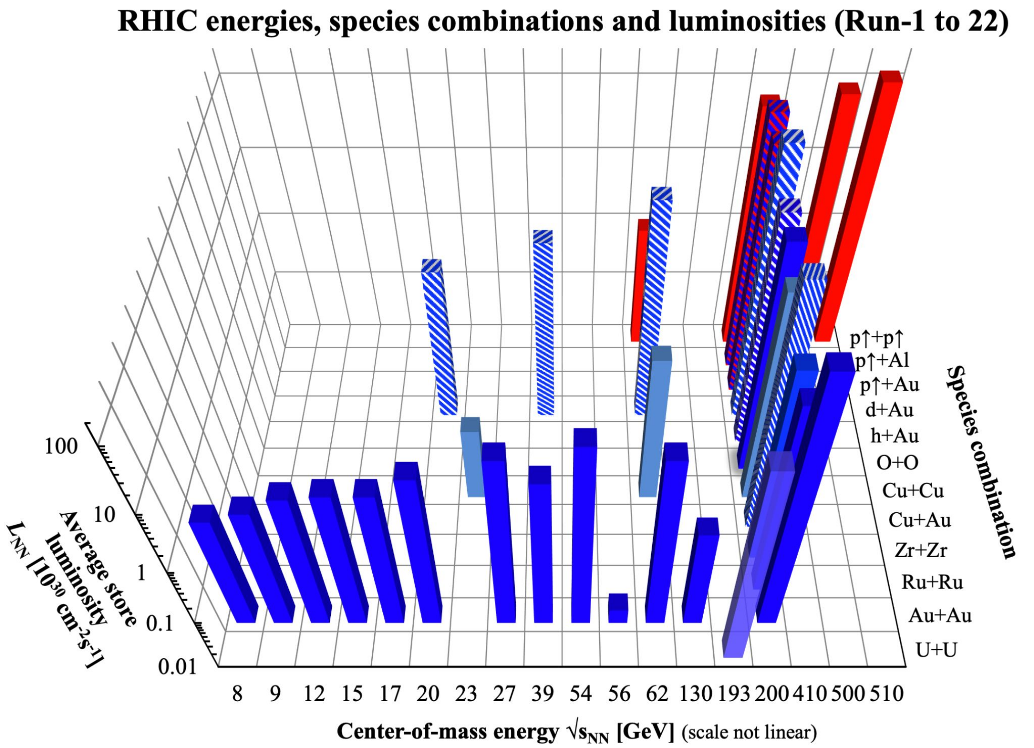
Relativistic Heavy Ion Collider (RHIC)

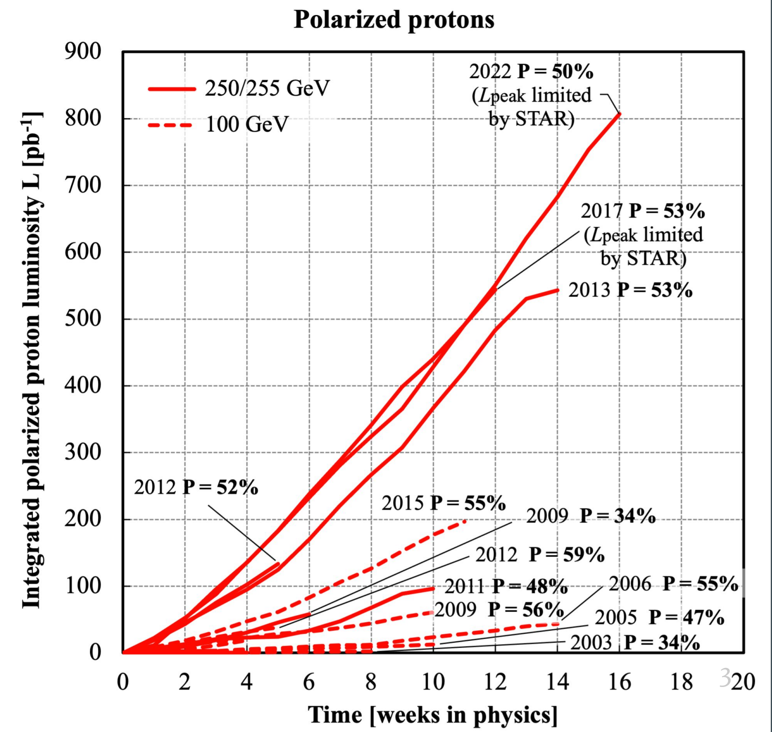
- Located in Brookhaven National Laboratory (BNL), NY, USA
- World's only polarised hadron collider



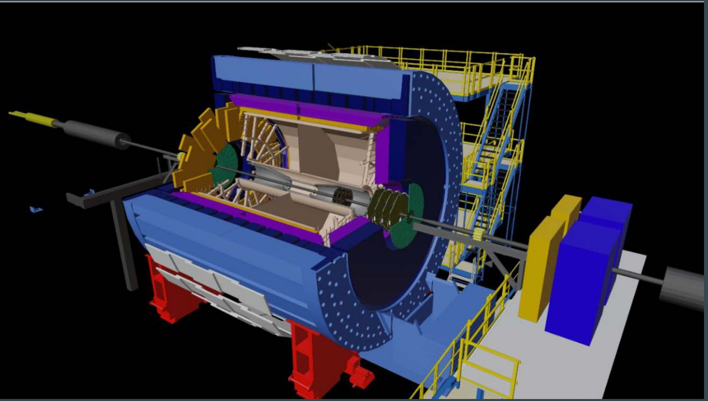
RHIC collider

$\sqrt{s_{NN}}$ (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





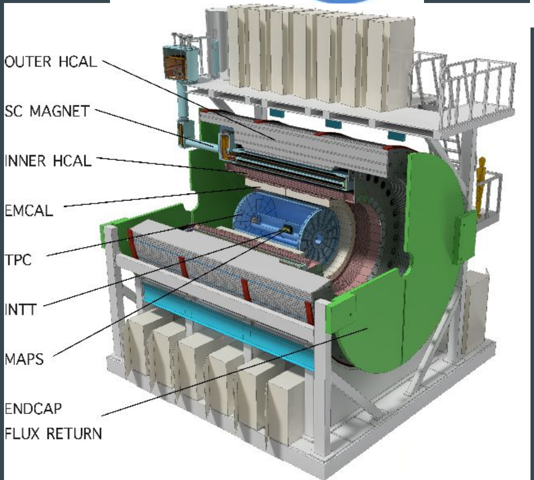
Experiments at RHIC

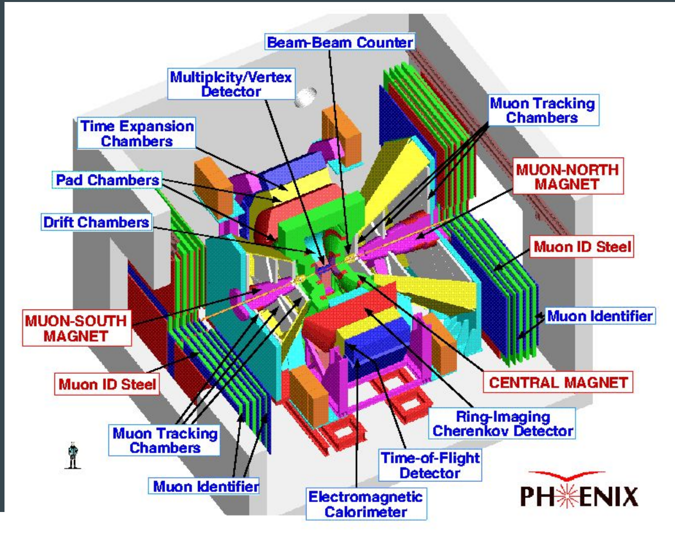


STAR

Commissioned in 2023

sPHENIX



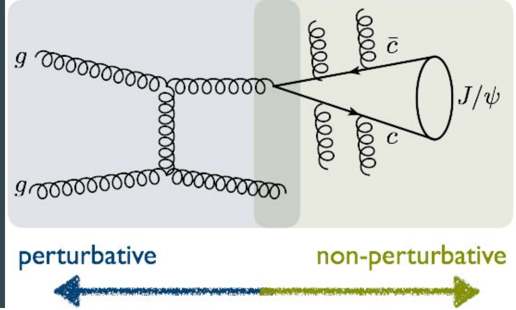


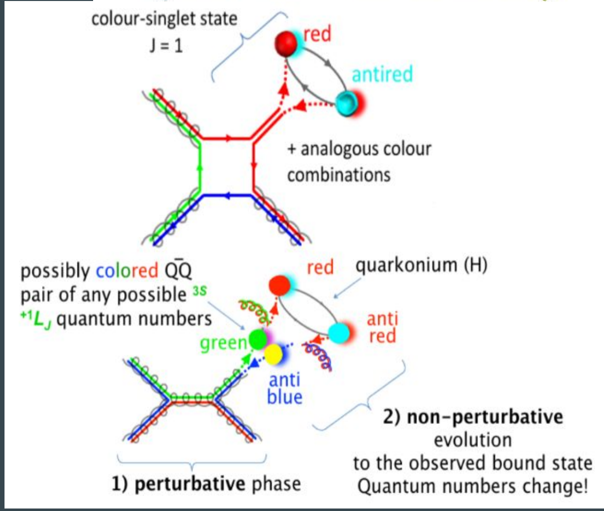
PHENIX

Finished data-taking in 2016

Production models

- **Color Singlet Model**
  - pair produced directly in same state as quarkonium, associated with a gluon
- **Color Octet Model**
  - pair produced in any state
  - long distance matrix elements (LDMEs) - bound state probability
- **(Improved) Color Evaporation Model**
  - quantum numbers neglected, fixed production probability
- **Color Dipole Model**
  - projectile radiates gluon in target rest frame
  - gluon fluctuates into $Q\bar{Q}$ dipole
  - dipole interacts with target producing quarkonium via CS channel



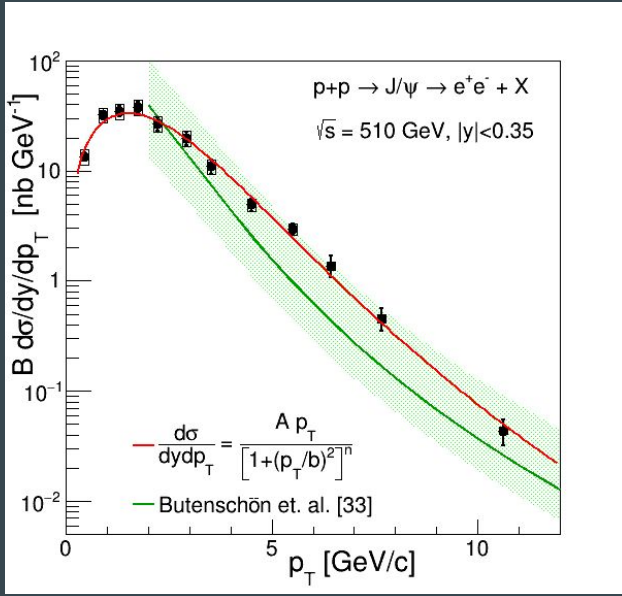


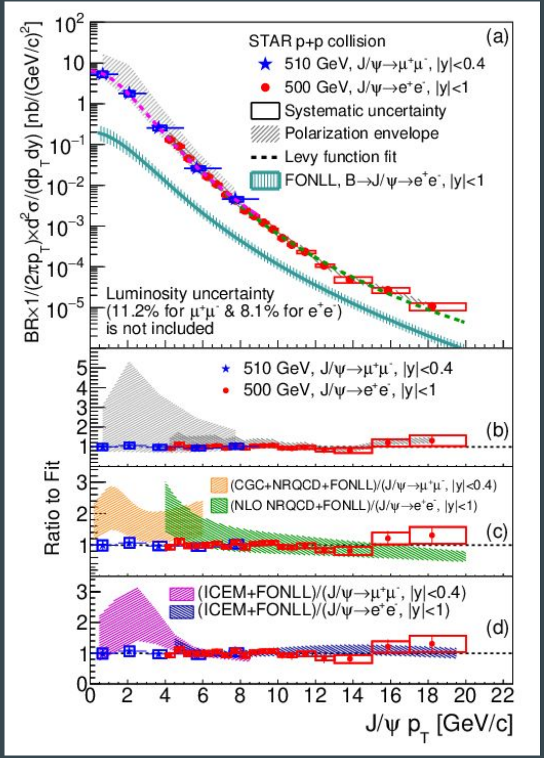
Spectra

[Phys.Rev.D 100 (2019) 5, 052009]

J/Ψ p_T spectra

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



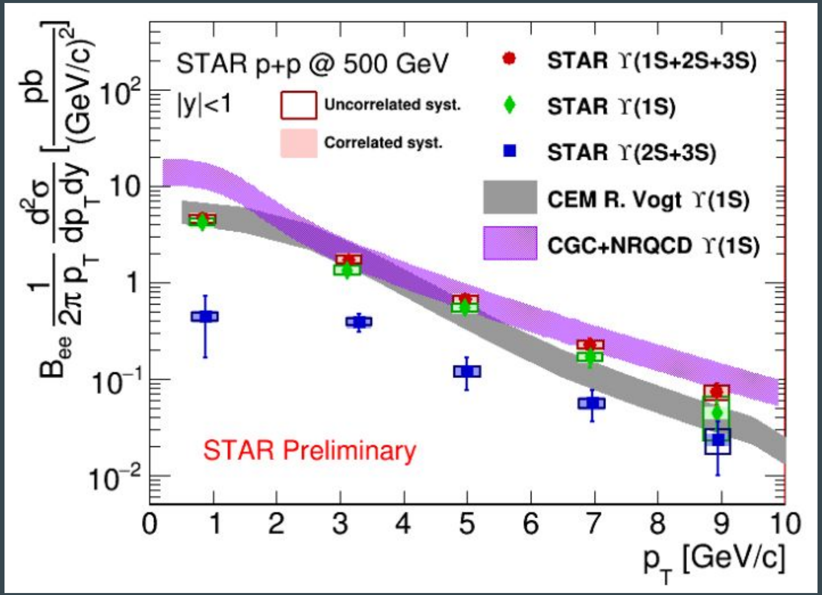


PHENIX J/Ψ **data (left) follow the** $Ap_T/[1+(p_T/b)^2]^n$ **lineshape and agree with NLO NRQCD predictions..**

STAR measured J/Ψ p_T spectrum up to 20 GeV/c (right), with both **NRQCD+FONLL and ICEM+FONLL predictions overestimating the data at lower transverse momenta. NLO NRQCD+FONLL also underestimates at high** p_T**.**

Υ p_T spectra

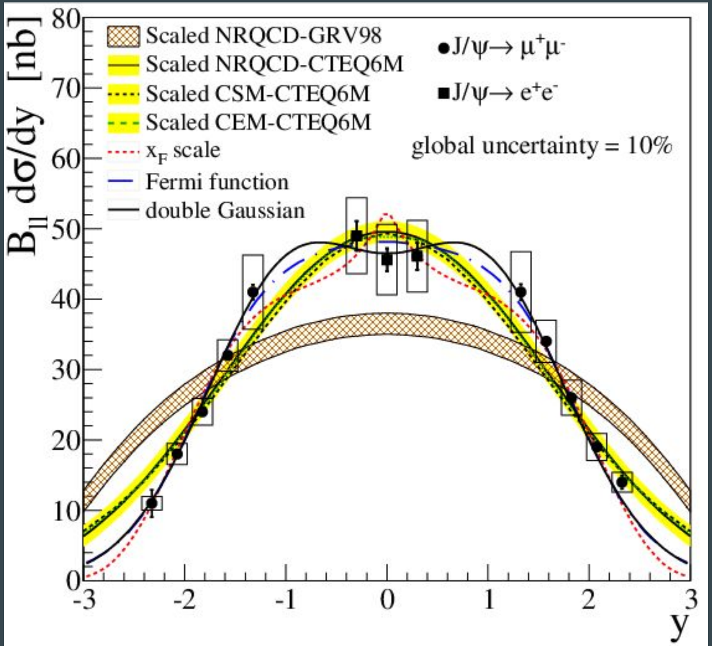
[J. Phys.: Conf. Ser., 1667(1), 012022]



The **CGC+NRQCD model overestimates the STAR data** at low and high p_T. The **CEM model predictions are consistent with the measurements**.

J/Ψ rapidity spectra

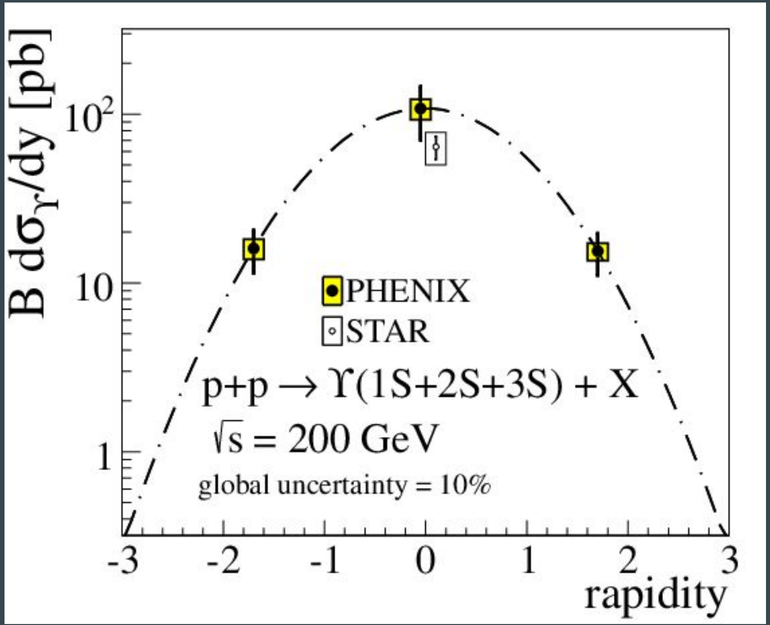
[Phys.Rev.D 85 (2012) 092004]



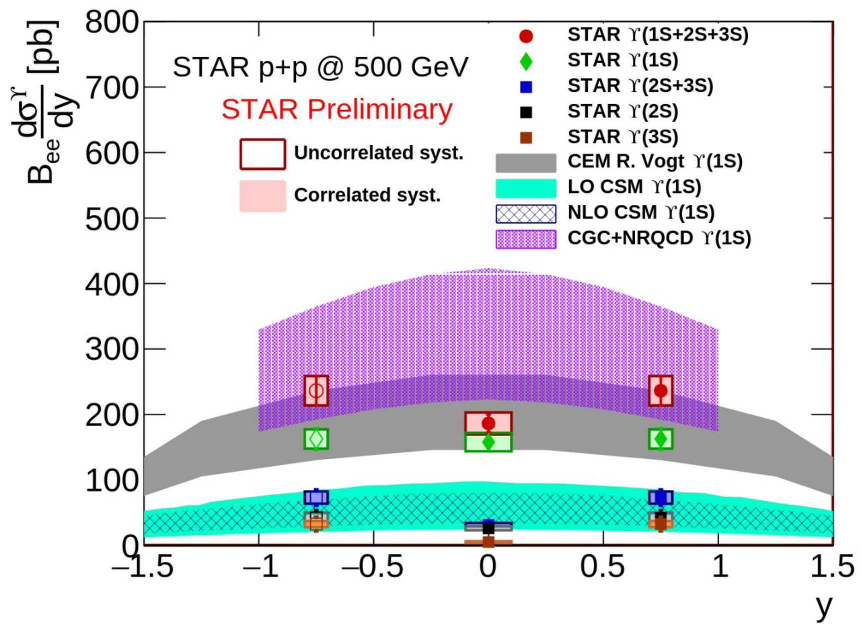
The **PHENIX data is best described by the scaled CTEQ6M model**, with GRV98 not reproducing the data trend.

Υ rapidity spectra

[Phys.Rev.C 91 (2015) 2, 024913]



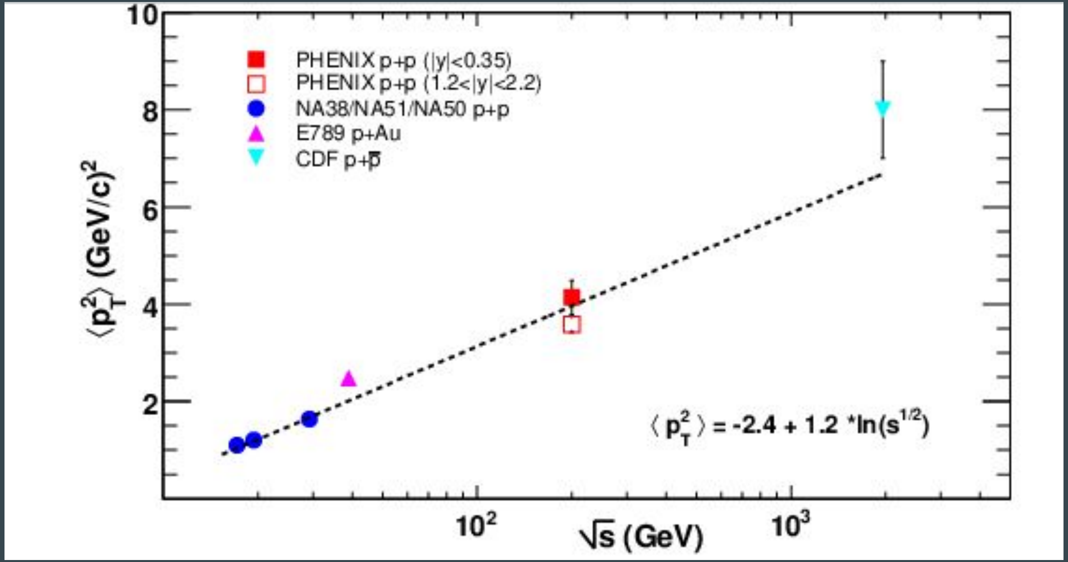
[L. Kosarzewski, QM22]



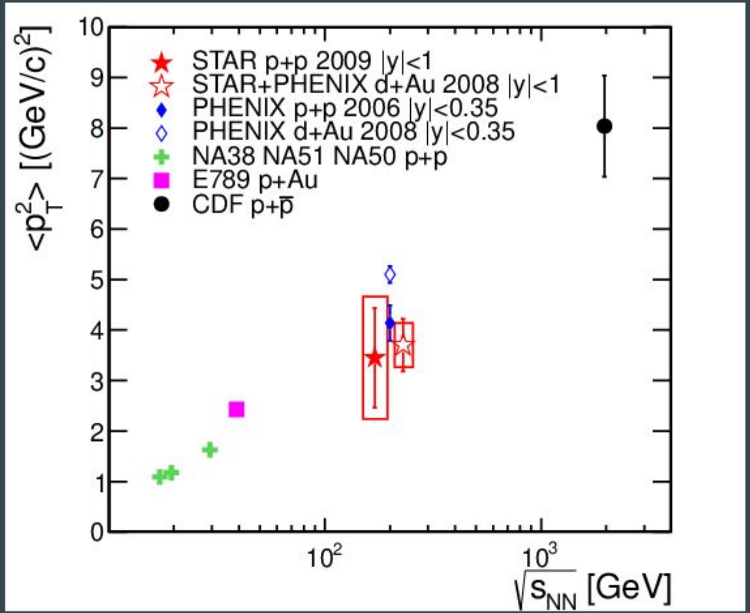
The **STAR** Υ->e^+e^- **data is best described by the CEM model**, whereas **the other models do not describe the data** well.

J/Ψ mean $<p_T^2>$

[Phys.Rev.Lett. 98 (2007) 232002]



[Phys.Rev.C 93 (2016) 6, 064904]



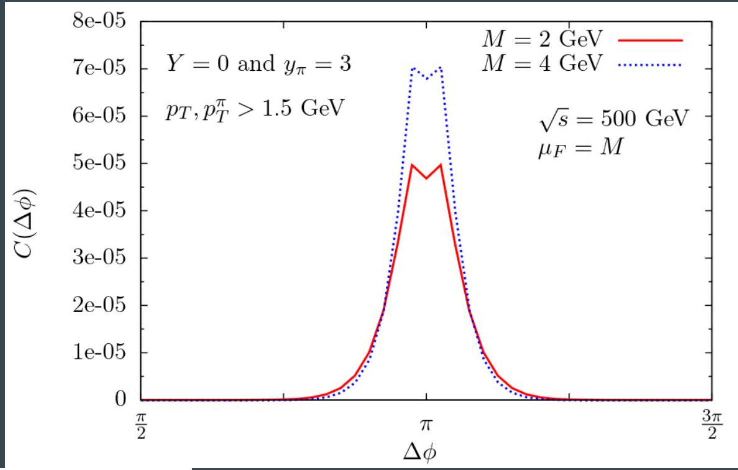
Broadening of the spectra due to **Cronin effect.**

PHENIX and STAR measurements of mean J/Ψ mean p_T are **consistent with world's data**.

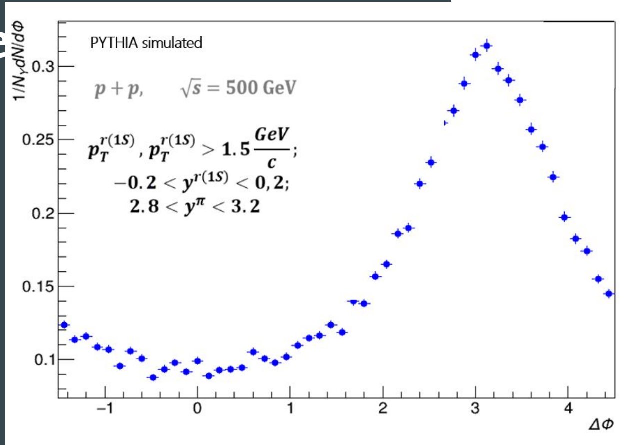
Onium-hadron correlations

Onium-hadron azimuthal correlations

[E. Basso et al., PoS, EPS-HEP2015, 191 (2016)]



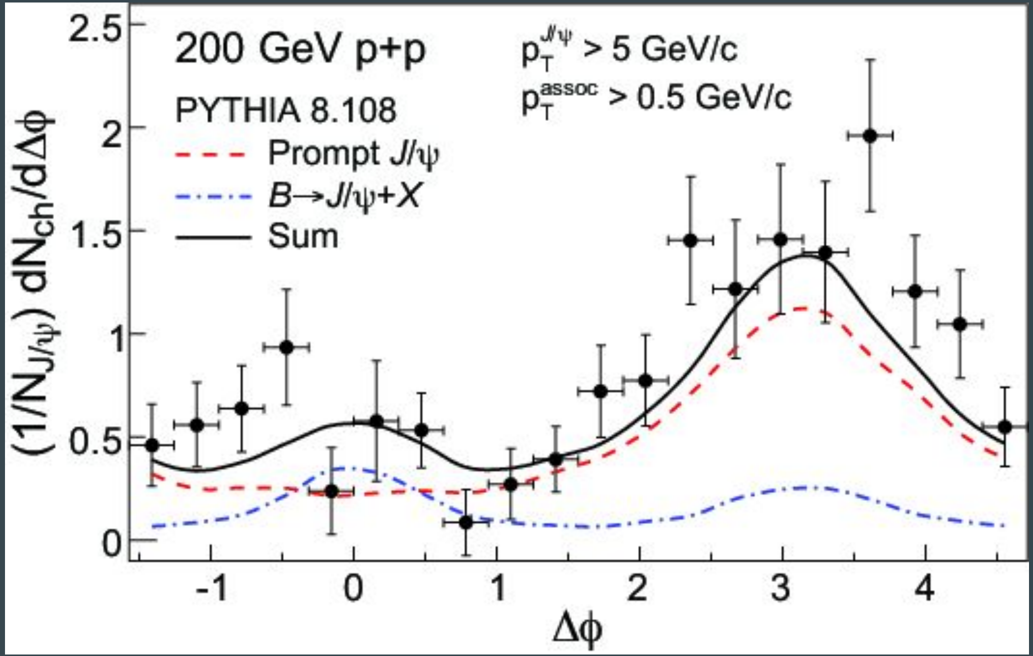
- GBW model predicts a **double-peak structure** for central Drell-Yan dileptons and associated forward pions
- This should hold true for **quarkonia in colour dipole approach**
- **PYTHIA8 does not reproduce the double-peak structure**



[O. Mezhenska, Zimanyi 23]

J/Ψ-hadron azimuthal correlations

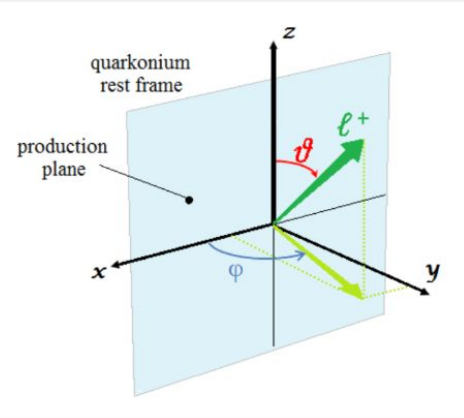
[Phys.Rev.C 80 (2009) 041902]



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.

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

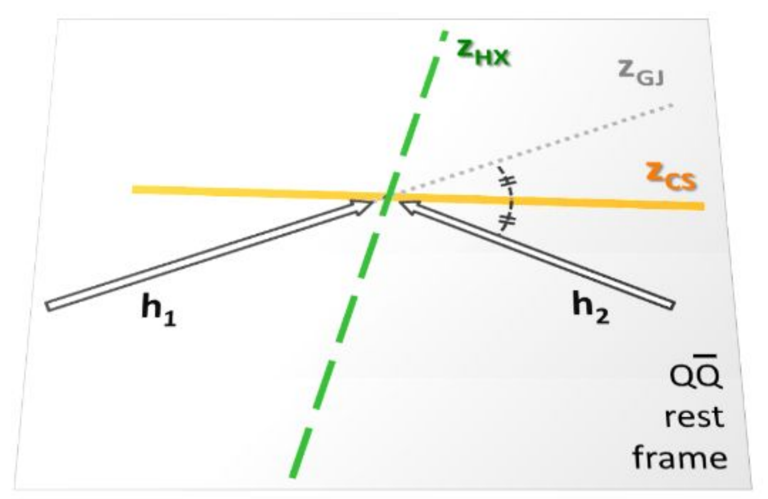
Polarisation

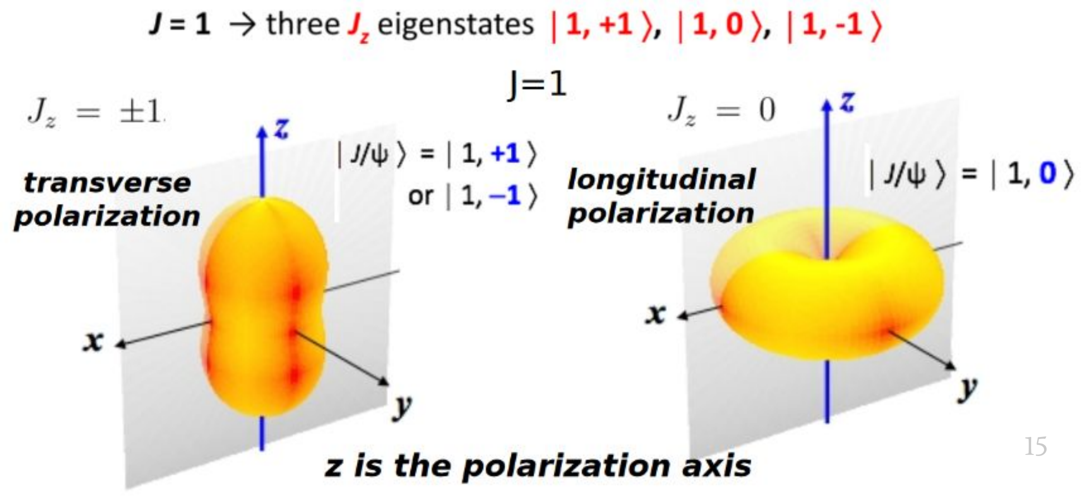


Helicity (HX) - quarkonium momentum direction

Collins-Soper (CS) - beam angle bisection

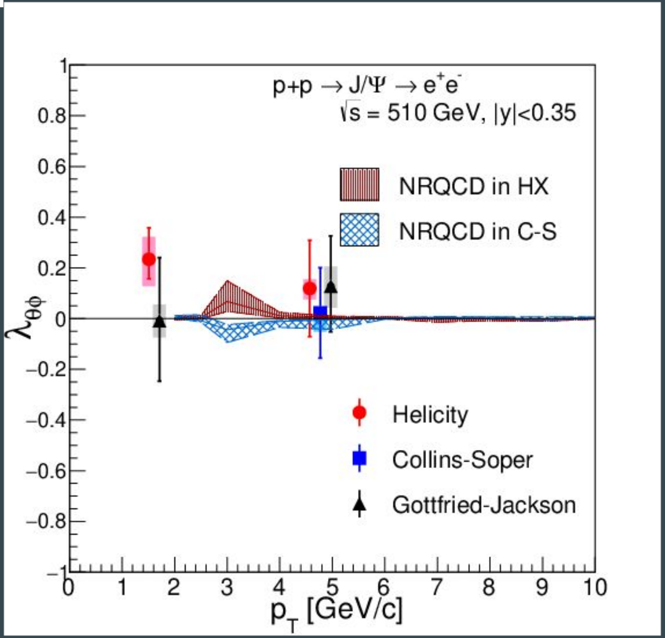
Gottfried-Jackson (GJ) - beam direction

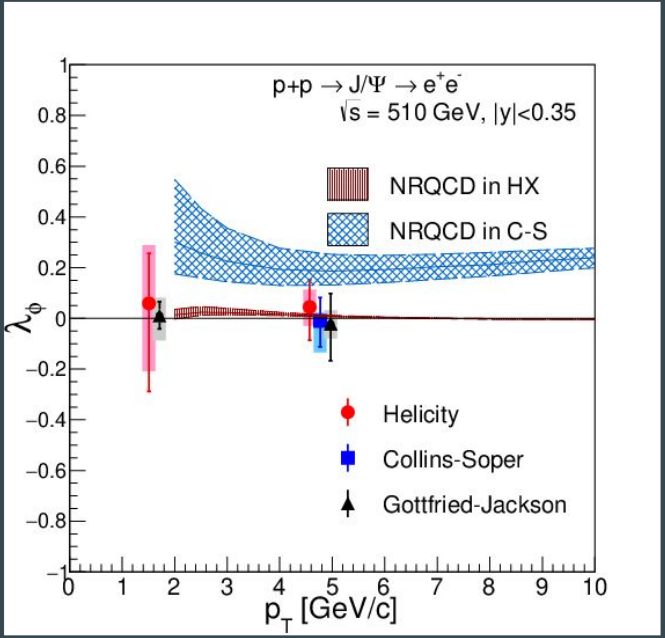




J/Ψ polarisation

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



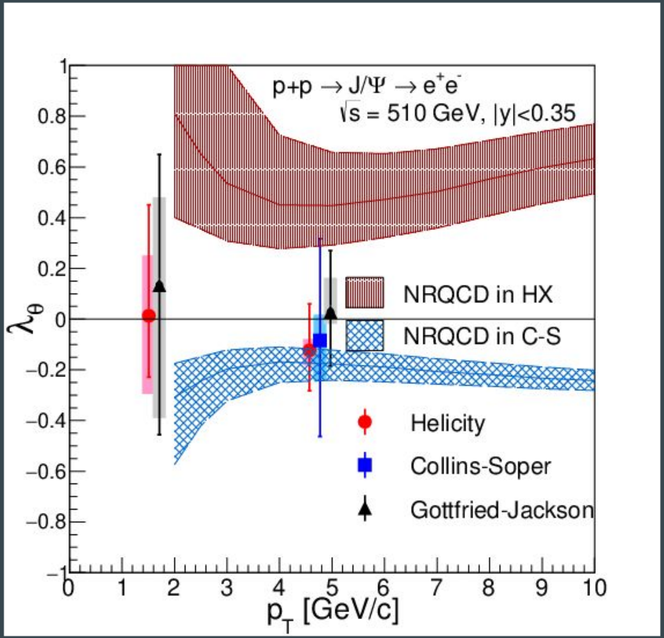


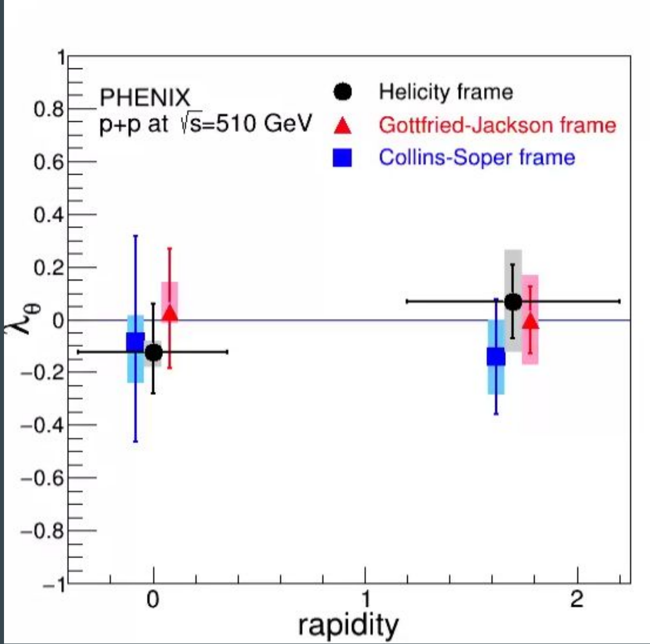
PHENIX measurements of $\lambda_{\theta\varphi}$ are **consistent with 0 in C-S and G-J frames**, whereas **it is positive in HX at low p_T.**

The data for λ_{φ} are **consistent with 0 in all frames. The C-S data does not match NRQCD prediction**, 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 **he C-S data match NRQCD prediction** within errors, but the **HX data do not agree with the predictions.**

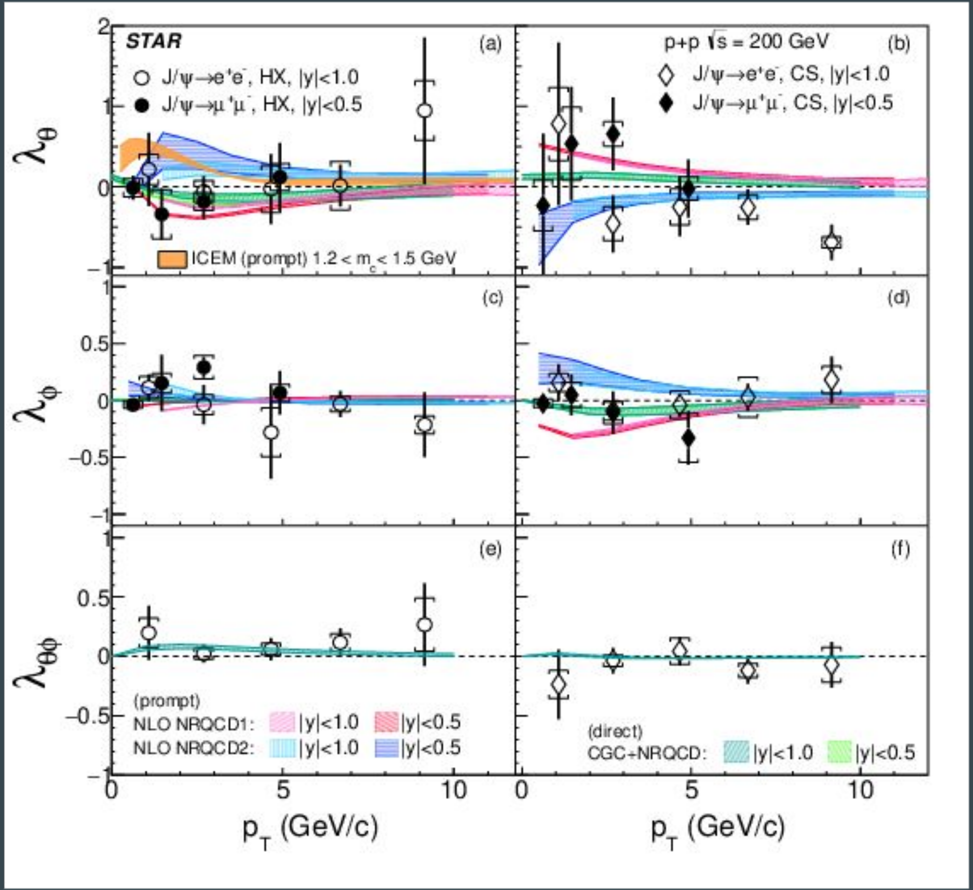
[Phys.Rev.D 102 (2020) 9, 092009]

J/Ψ polarisation

The STAR results for J/Ψ in two decay channels show differences in λ_θ and λ_φ between HX and CS frames.

Data consistent with no polarisation except for λ_θ for $|y| < 0.5$ dimuon data at high p_T

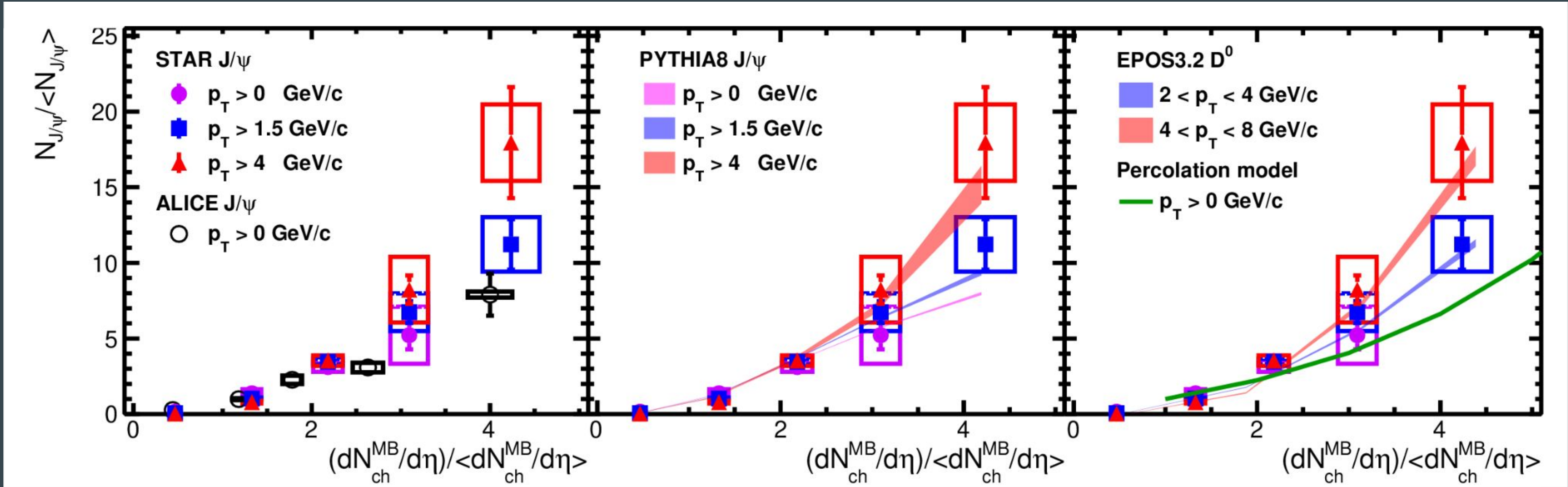
CGC+NRQCD offers best description, other models not ruled out due to large uncertainties



Multiplicity dependence

J/Ψ multiplicity dependence

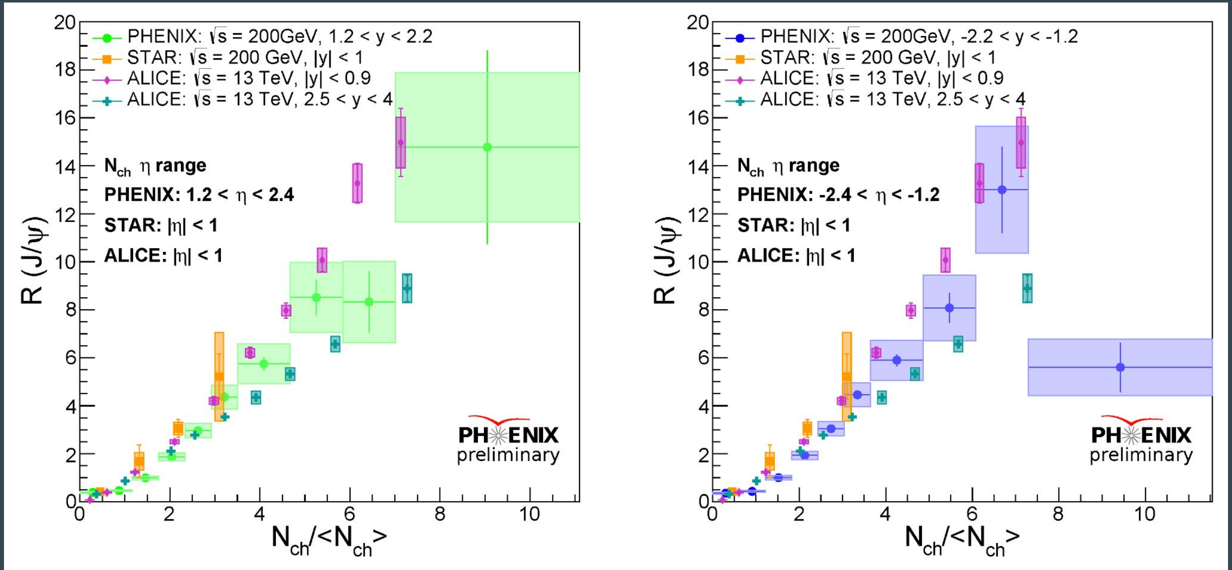
[Phys.Lett.B 786 (2018) 87-93]



The STAR data for mid-rapidity J/Ψ show a stronger than linear increase consistent with world data. The data is **described well via PYTHIA8 and EPOS3.2, whereas the percolation model underestimates the data at large multiplicities.**

J/Ψ multiplicity dependence

[Universe 2023, 9(7), 322]

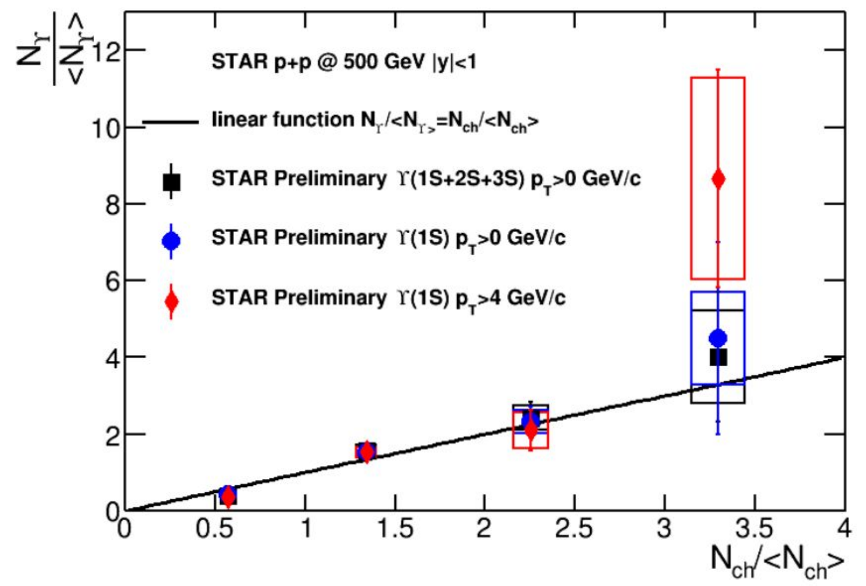


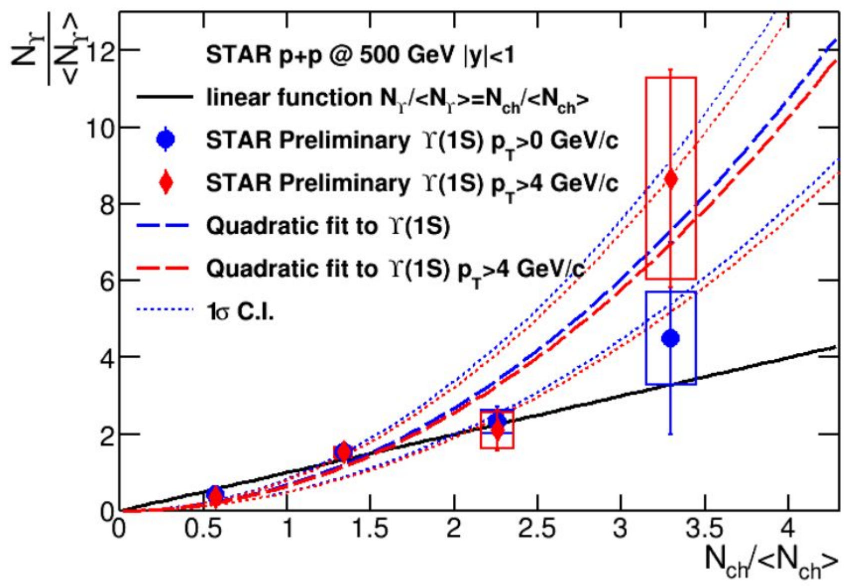
The PHENIX measurements allow for measuring forward- and backward-rapidity J/Ψ, which are mostly **consistent with world data** with the exception of the last bin in the backwards produced J/Ψ.

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

Υ multiplicity dependence

[L. Kosarzewski, MPI@LHC 2023]



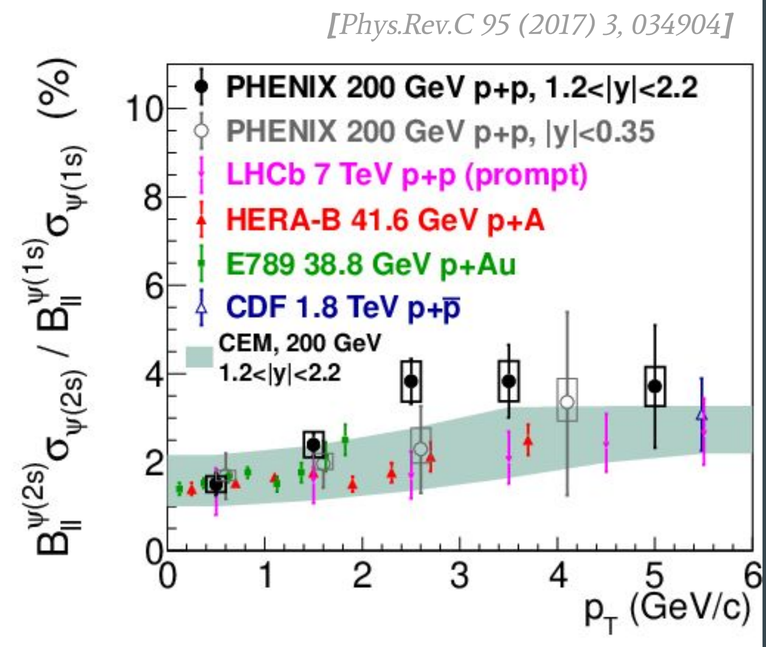


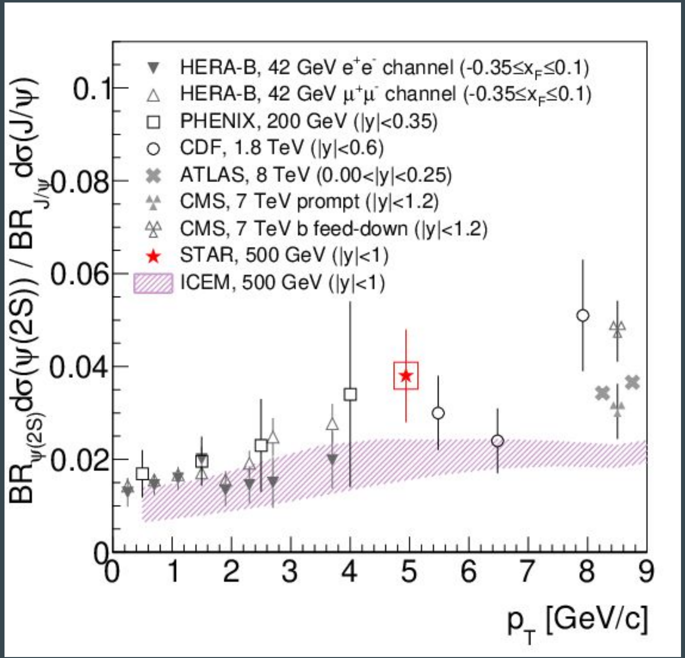
The STAR measurements of Υ exhibit the same **stronger-than-linear increase with high-p_T data having a larger magnitude than p_T-integrated ones**.

Feed-down and ratio measurements

Ψ(2S) and J/Ψ ratio

[Phys.Rev.D 100 (2019) 5, 052009]



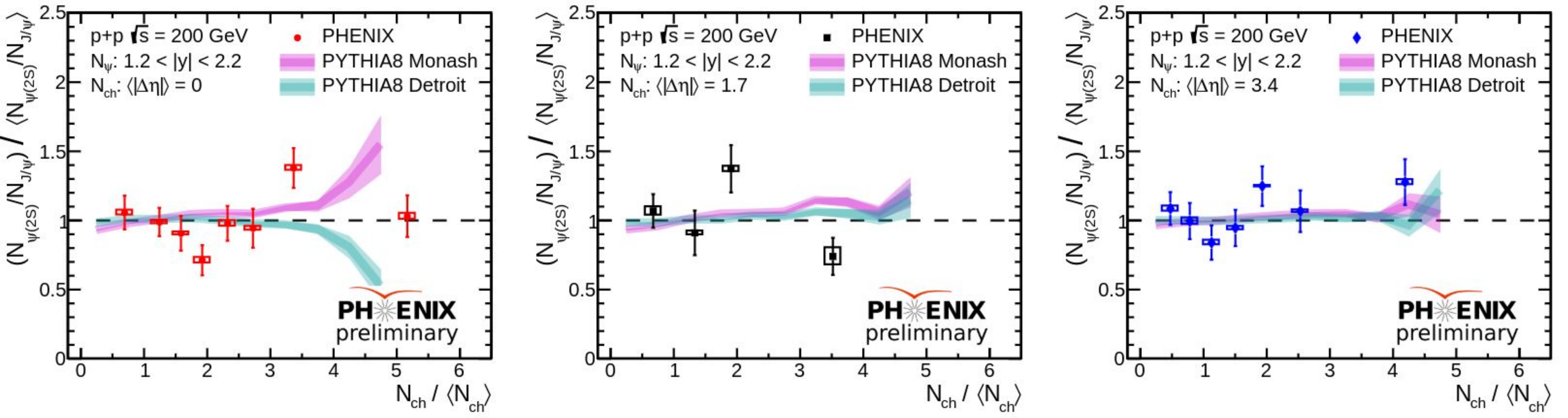


The **CEM prediction underestimates the PHENIX data at intermediate p_T.**

The **ICEM model underestimates the STAR data** point.

Ψ(2S) and J/Ψ ratio

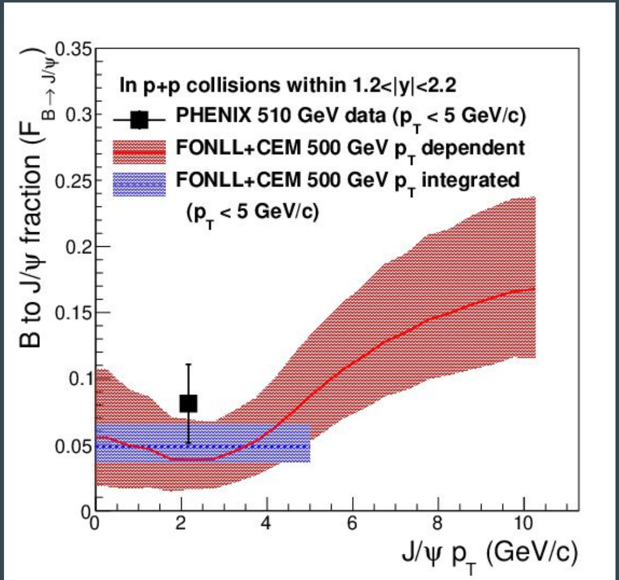
[JongHo Oh, QM23]



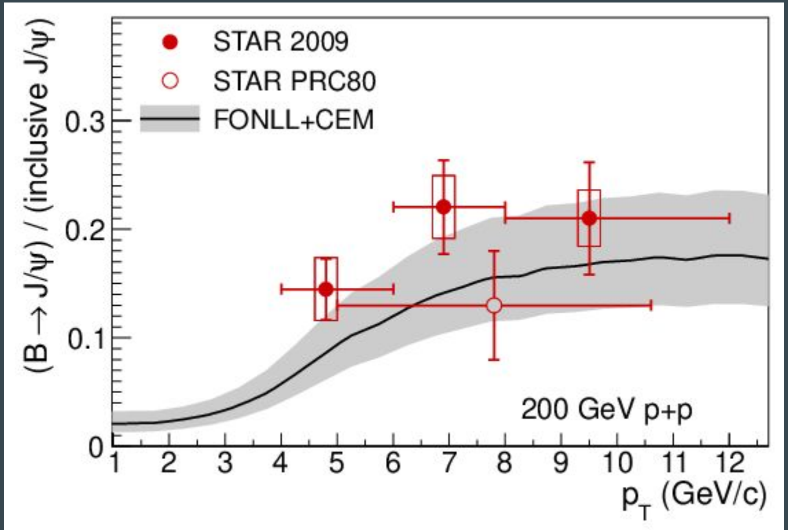
PHENIX analysis show measurements in different |Δη| intervals. In all, **the ratio changes minimally with multiplicity**. PYTHIA8 Monash and Detroit tune describe the data well at lower multiplicities.

B → J/Ψ fraction

[*Phys.Rev.D* 95 (2017) 9, 092002]

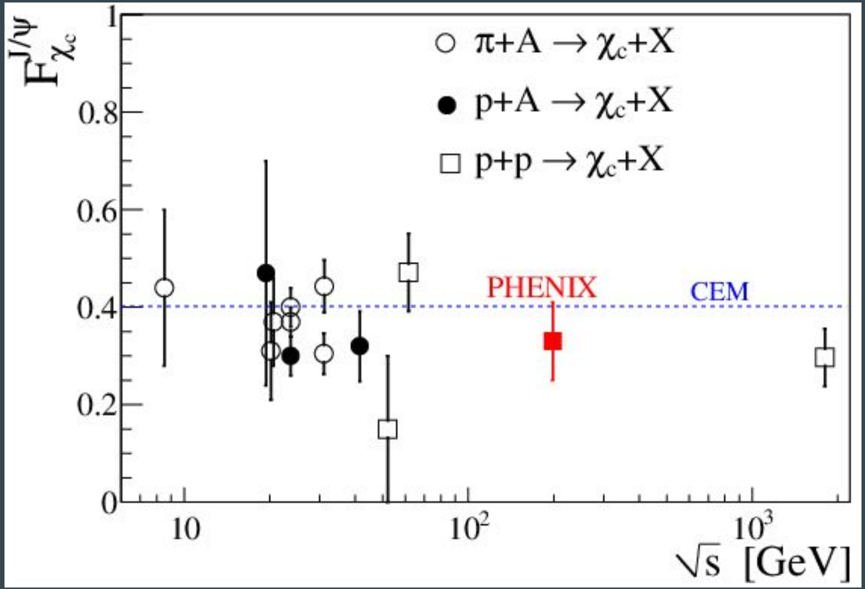


[*Phys.Lett.B* 722 (2013) 55-62]



STAR 200 GeV data at central rapidity and PHENIX 500 GeV data at forward/backward rapidity **consistent with FONLL+CEM calculations** within errors

$\chi_c \rightarrow J/\Psi$ branching ratio

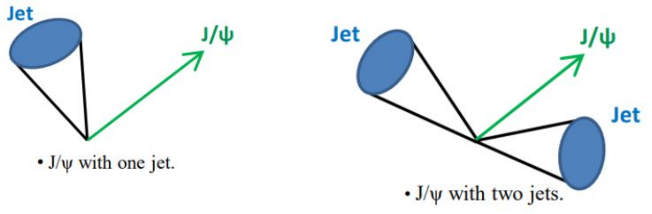


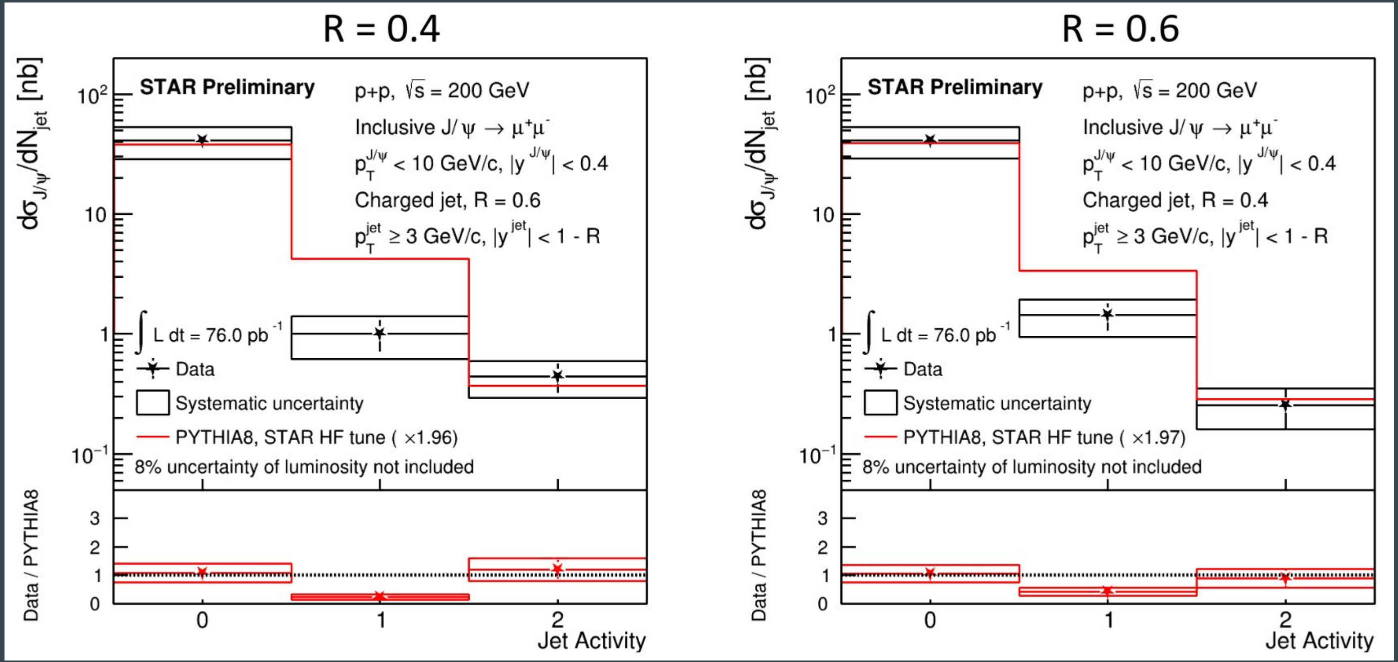
[*Phys.Rev.D* 85 (2012) 092004]

PHENIX measurements of χ_c to J/Ψ feed-down fraction consistent with CEM predictions.

Quarkonia and jets

J/Ψ production with jet activity



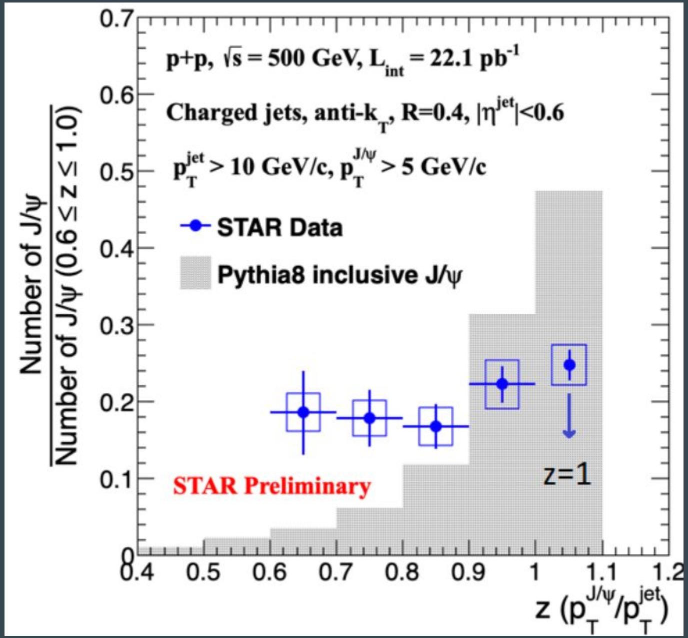


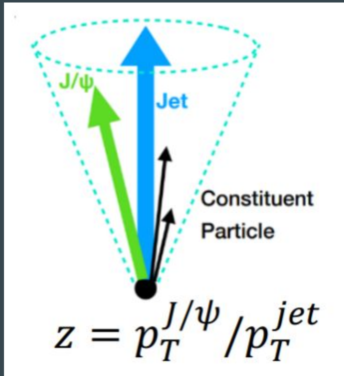
[Yi Yang, DIS23]

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

Theoretical model calculations needed.

J/Ψ production within jets





Should provide constraints to LDMEs.

No significant z dependence in data observed. **J/Ψ production less isolated in data compared to PYTHIA8 prediction.**

Outlook

- STAR:
  - Forward upgrade installed
    - $2.5 < y < 4$ (FST and sTGC tracking, EM and h calorimetry)
    - High integrated luminosity at mid and forward rapidity
  - Better precision J/Ψ and Υ dependence on N_{ch} with 2017 and 2022 datasets
    - Higher integrated luminosities sampled (up to a factor of 10 in 2017 data compared to 2011)
    - 2017 dataset analyses ongoing *[J. Ceska, A. Knospe, QM23]*
    - Better model discrimination
- sPHENIX:
  - Quarkonia are an essential part of the physics program
- RHIC
  - 200 GeV polarised p+p collisions planned for Run24

Summary

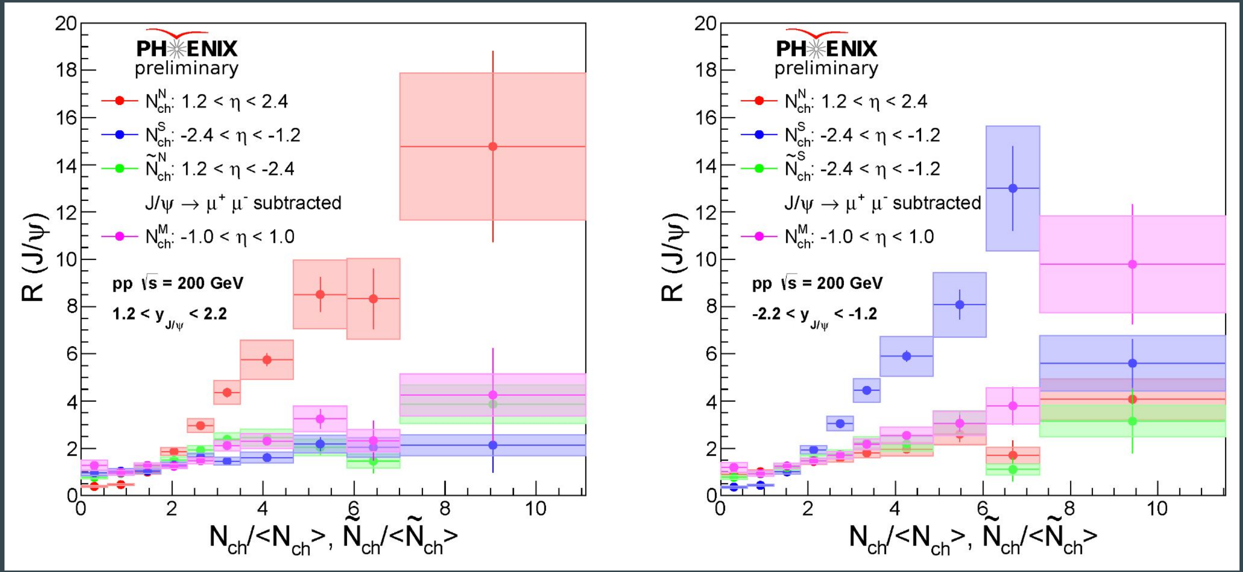
- RHIC and its experiments have a rich quarkonium programme
  - Spectra
  - Onium-hadron correlations
  - Polarisation
  - Multiplicity dependent measurements
  - Feed-down and ratio measurements
  - Quarkonia and jets
  - Single-spin asymmetry, ...
- Exciting new results
- Data taking still ongoing
- Plenty of data yet to be analysed

Thank you for your attention!

Backup

Multiplicity dependence

[*Universe 2023, 9(7), 322*]



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

Single-spin asymmetry

https://inspirehep.net/literature/870935

Taken from erratum

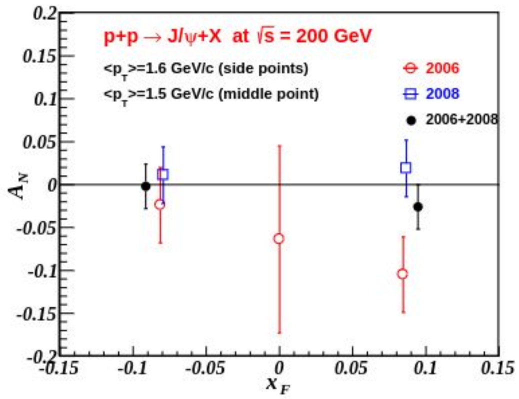


FIG. 1: (color online) Transverse single-spin asymmetry in J/ψ production as a function of x_F for 2006 and 2008 data sets separately, and the combined result; the points for the combined result have been offset by 0.01 in x_F for visibility. The error bars shown are statistical and type A systematic uncertainties, added in quadrature. Type B systematic uncertainties are not included but are 0.003 or less in absolute magnitude and can be found in Table III. Not shown is an additional uncertainty in the scale of the ordinate due to correlated polarization uncertainties of 3.4%, 3.0%, and 2.4% for the 2006, 2008, and combined 2006 + 2008 data sets, respectively.

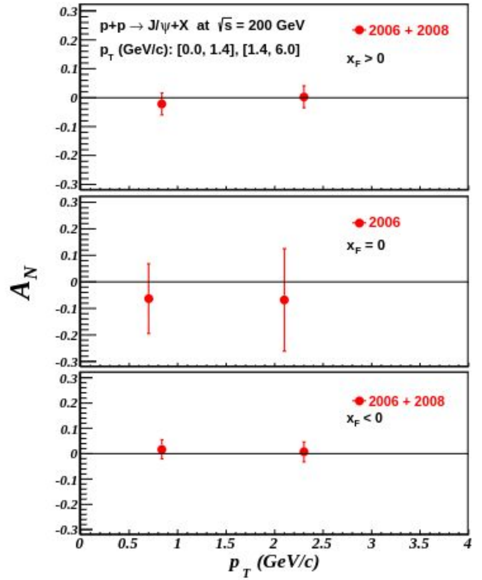


FIG. 2: (color online) Transverse single-spin asymmetry of J/ψ mesons plotted against J/ψ transverse momentum. See Table III for mean x_F values for each point. The error bars shown are statistical and type A systematic uncertainties, added in quadrature. Type B systematic uncertainties are not included but are 0.002 or less in absolute magnitude and can be found in Table III. An additional uncertainty in the scale of the ordinate due to correlated polarization uncertainties is 2.4% (3.4%) for the points with $|x_f| > 0$. ($x_F = 0$ is not shown.)

https://inspirehep.net/literature/1467456

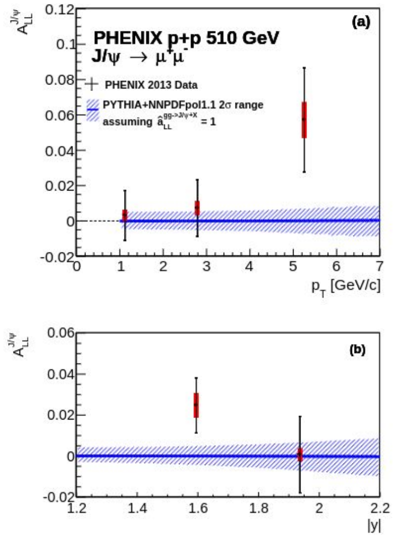


FIG. 3. $A_{LL}^{J/\psi}$ as a function of p_T (top panel) and $|y|$ (bottom panel). The black error bars show the statistical uncertainty. The red boxes show only the Type A systematic uncertainties. There are additionally a 4×10^{-4} global systematic uncertainty from the relative luminosity determination and a 6.5 % global scaling systematic uncertainty from the polarization magnitude determination for all p_T or $|y|$ bins. The blue curve with shaded band is our $A_{LL}^{J/\psi}$ estimation using PYTHIA6 [29] simulation with NNPDF data sets under the assumption of $\hat{a}_{LL}^{gg\to J/\psi+X} = 1$. The solid blue curve is the central value and the blue shaded band is the $\pm\, 2\,\sigma$ uncertainty range. See details in the text.

https://inspirehep.net/literature/1671782

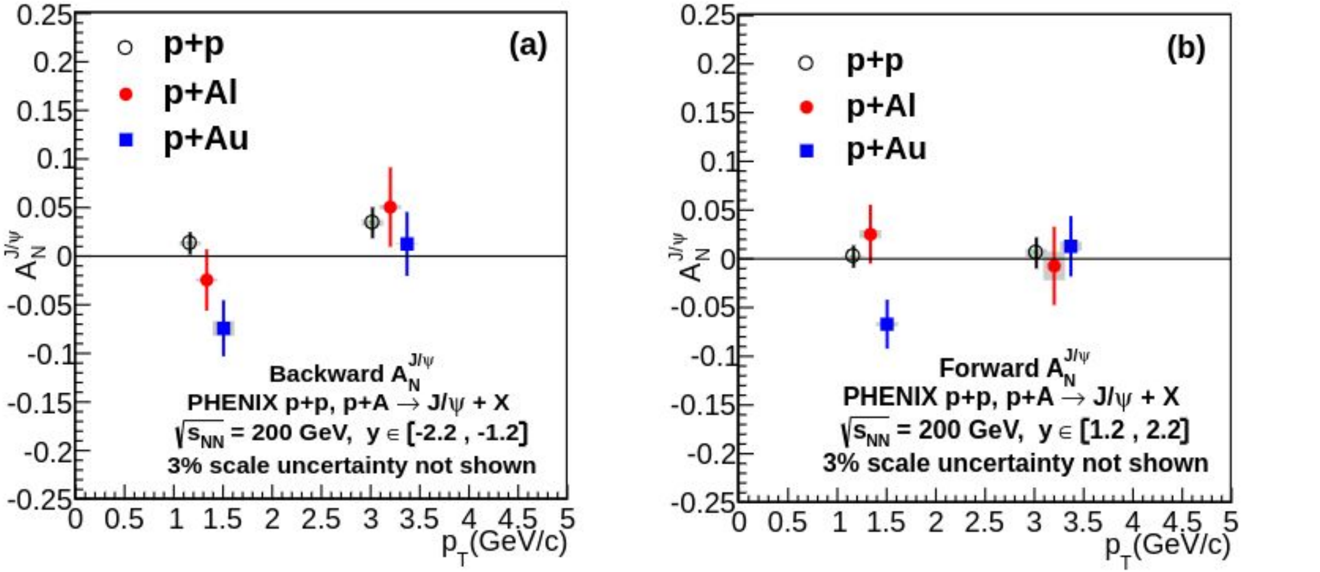


FIG. 4. (a) Backward $[x_F < 0]$ and (b) forward $[x_F > 0]$ $A_N^{J/\psi}$ vs p_T for open [black] circles p+p, closed [red] circles p+Al, and closed [blue] boxes p+Au collisions. The shaded [gray] boxes show the systematic uncertainty. The data points for p+Al and p+Au collisions have been shifted in p_T for clarity.