Faculty of Physics
WARSAW UNIVERSITY OF TECHNOLOGY

Quarkonium production at RHIC

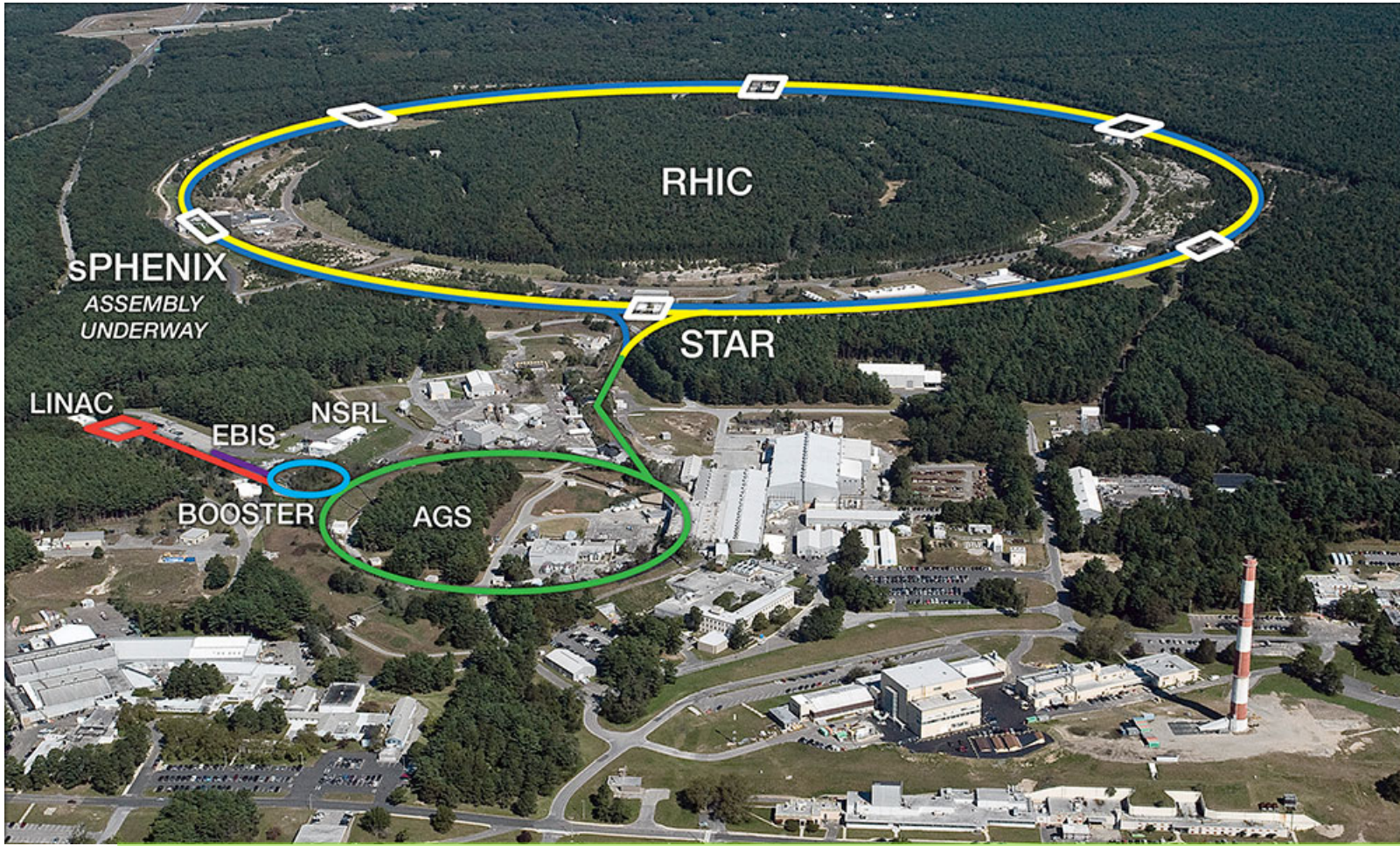
Recent results and plans for near future

Daniel Kikoła
Quarkoniua as Tools 2023

Outline

- RHIC, and STAR and PHENIX detectors
- Recent results on nuclear effects in pA collisions
- Quarkonium production in A+A reactions
- J/ψ photoproduction in d+Au ultra-peripheral collisions
- J/ψ production with jet activity in STAR
- Recent upgrades and plans for near future

Reltivistic Heavy Ion Collider at Brookhaven National Laboratory



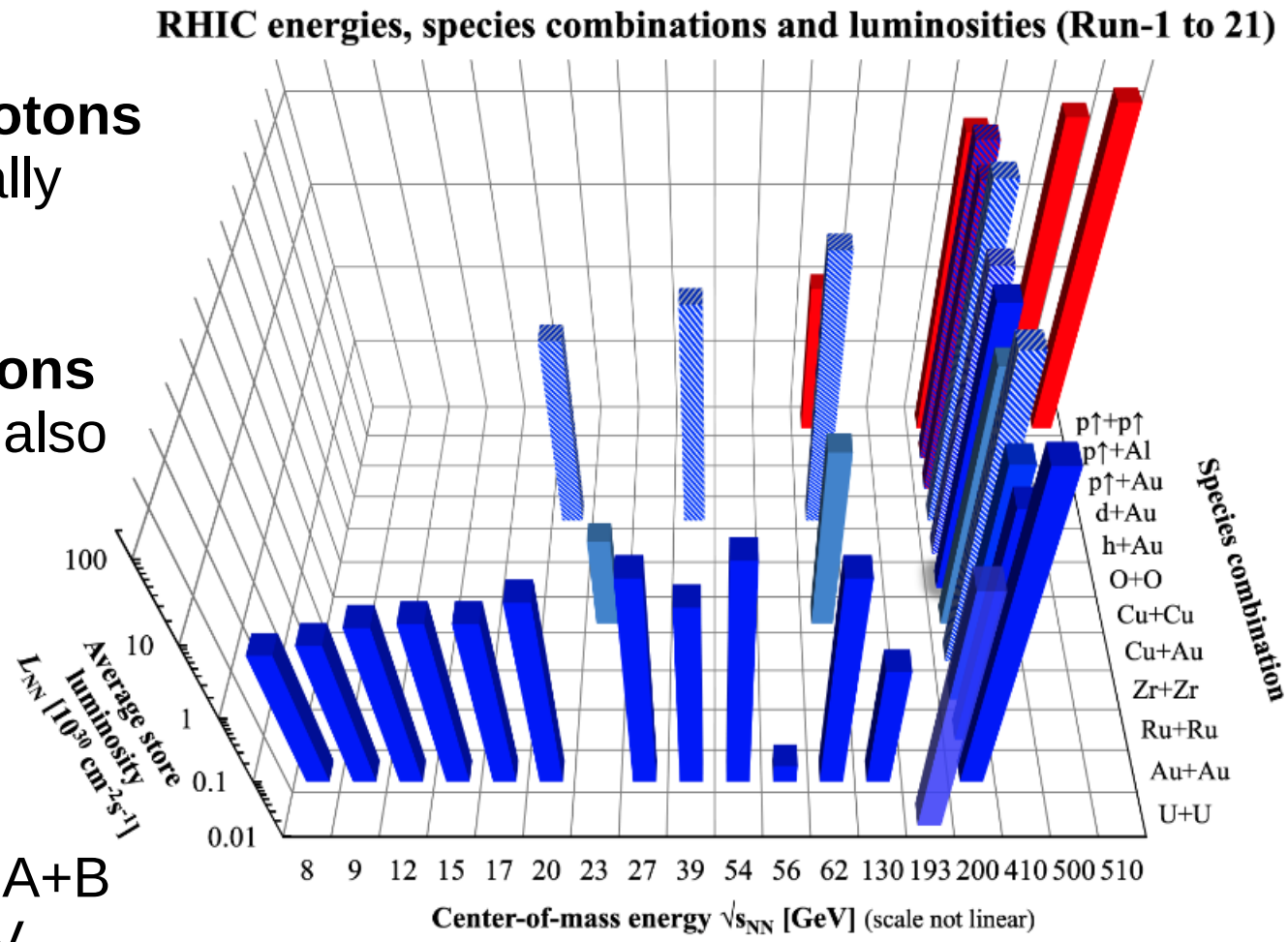
https://www.bnl.gov/newsroom/news.php?a=119262

RHIC → versatile machine

Collisions of polarized protons
(transversal and longitudinally polarization possible)

Large variety of collided ions
- from **proton** to **Uranium**, also asymmetric reaction

Broad energy range
- $\sqrt{s_{NN}}$ = 7.7 to 200 GeV for A+B
- p+p with $\sqrt{s}$ up to 510 GeV



Physics program

Study of Quark-Gluon Plasma properties

Beam Energy Scan program
Au+Au $\sqrt{s_{NN}}$ = 3.85 GeV to 62.4 GeV

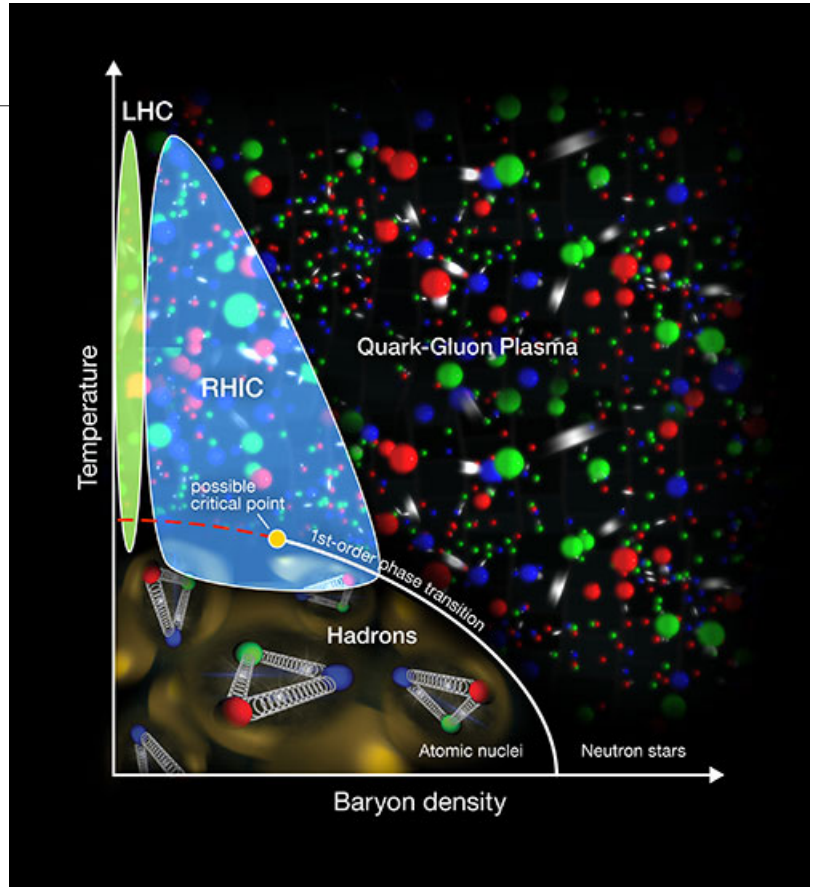


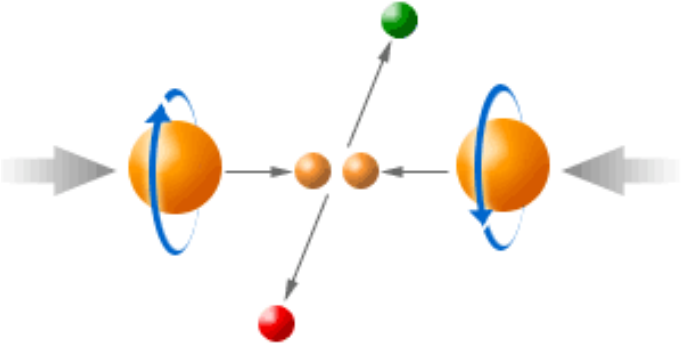
Image courtesy of BNL.

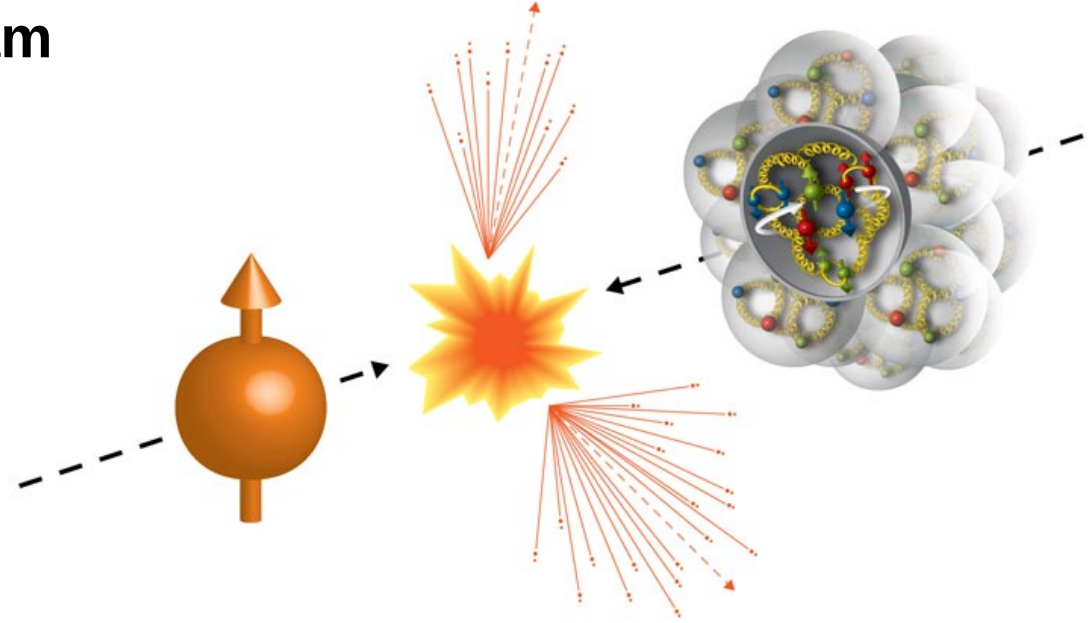
Physics program

Study of Quark-Gluon Plasma properties

Beam Energy Scan program
Au+Au $\sqrt{s_{NN}}$ = 3.85 GeV to 62.4 GeV

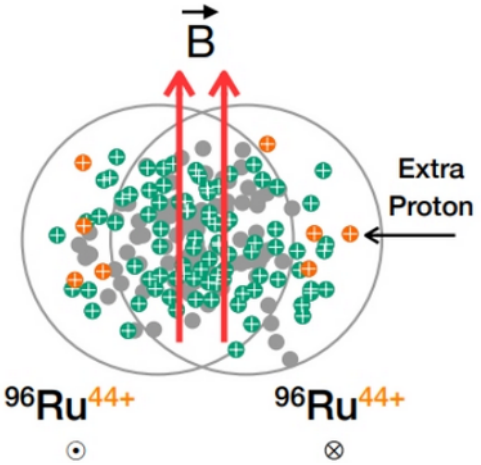
Cold QCD and spin physics program
p+A and polarized p+p collisions

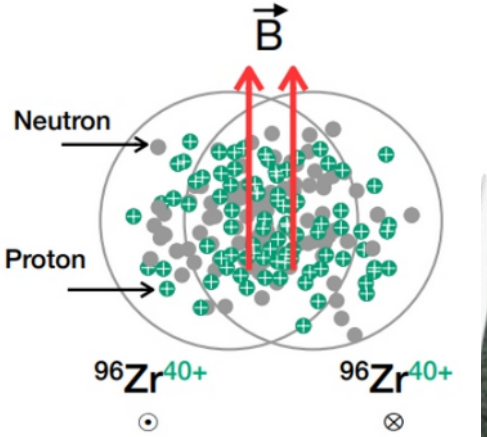




Images courtesy of BNL.

Isobar collisions (run for search for Chiral Magnetic Effect)





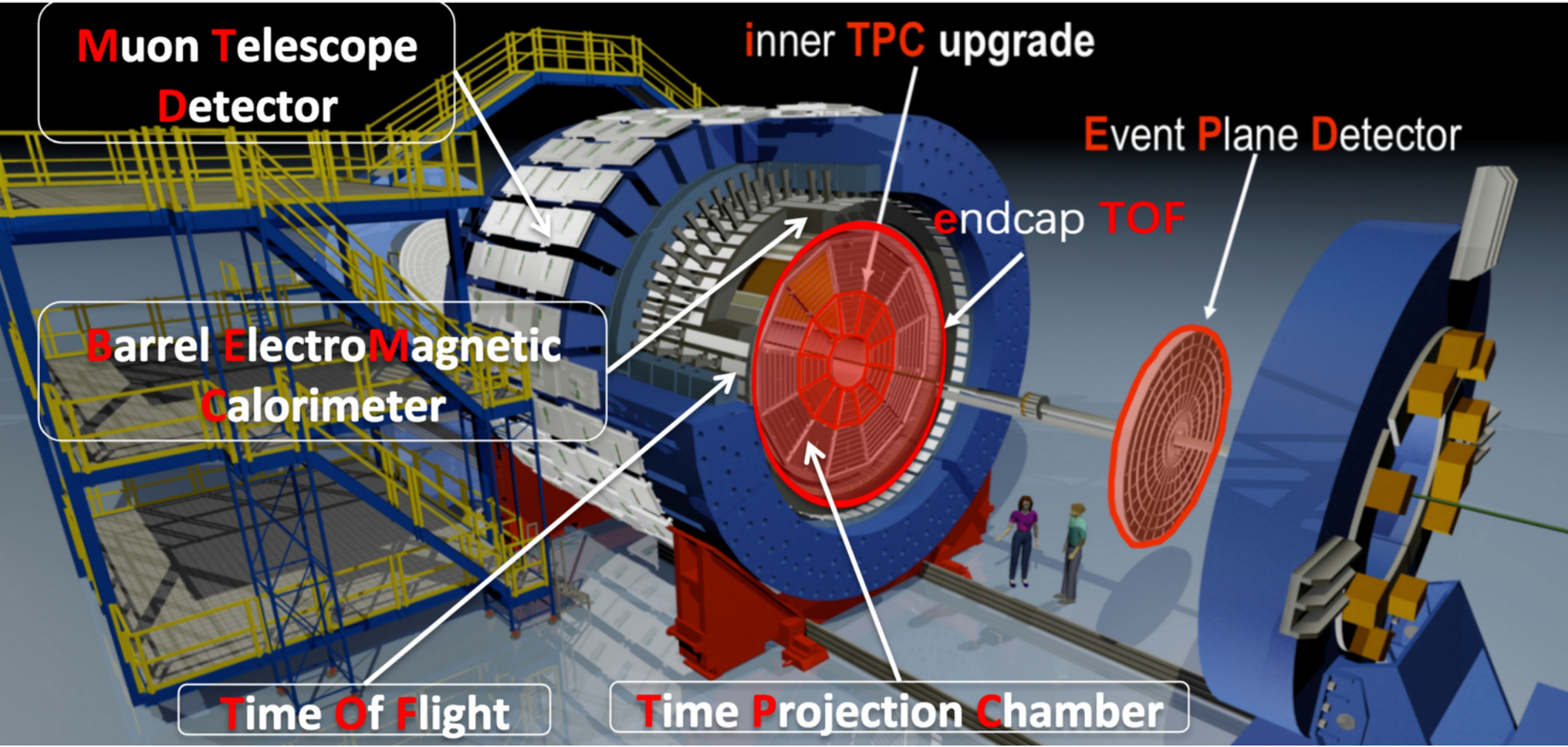
B-field² in Ru+Ru ~15% larger than in Zr+Zr

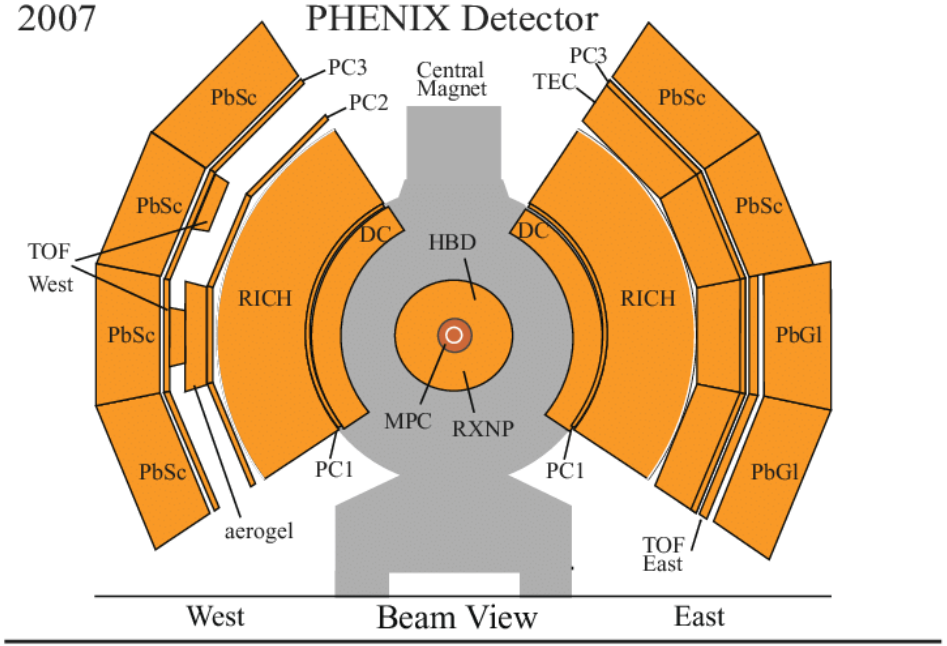
4B events

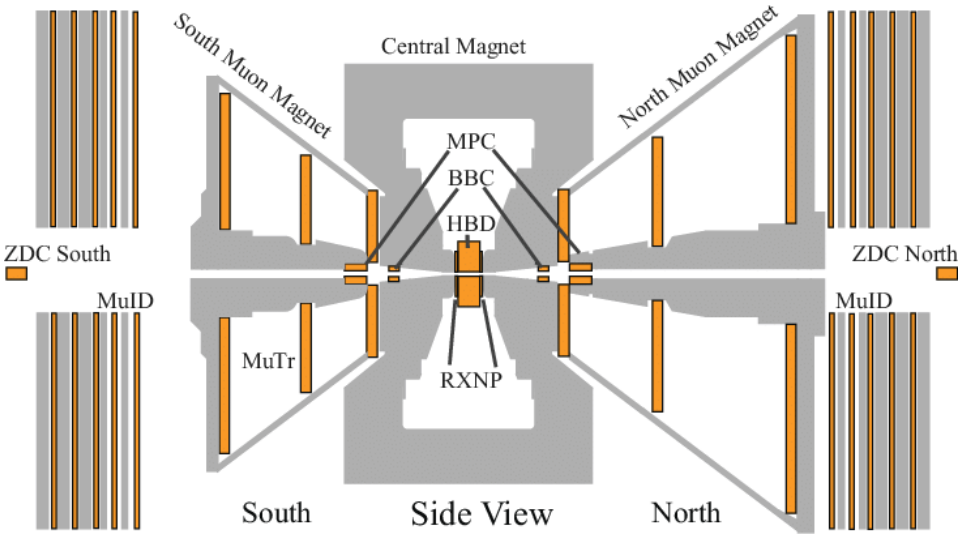
Useful for UPC / peripheral collision studies?

$\sqrt{s_{NN}}$ = 200 GeV

The STAR detector







https://www.phenix.bnl.gov/

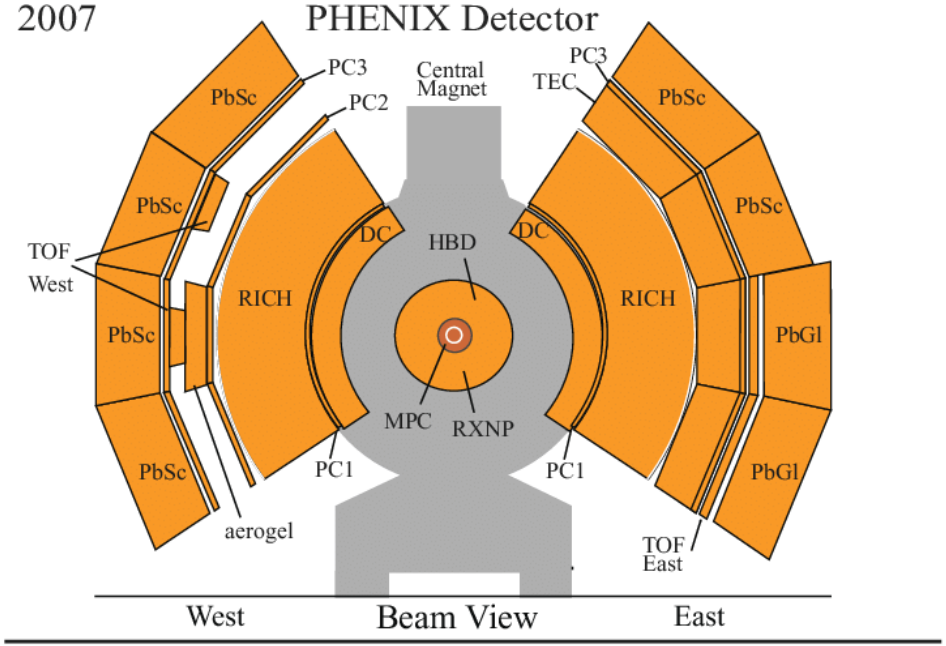
Acceptance

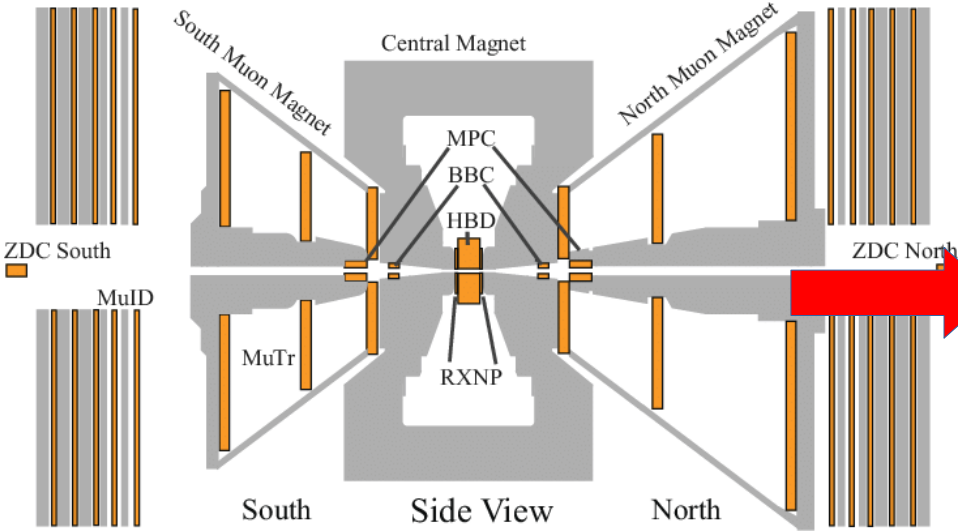
$|y| < 0.35$

$1.2 < |y| < 2.2$

PHENIX

https://www.phenix.bnl.gov/





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$|y| < 0.35$

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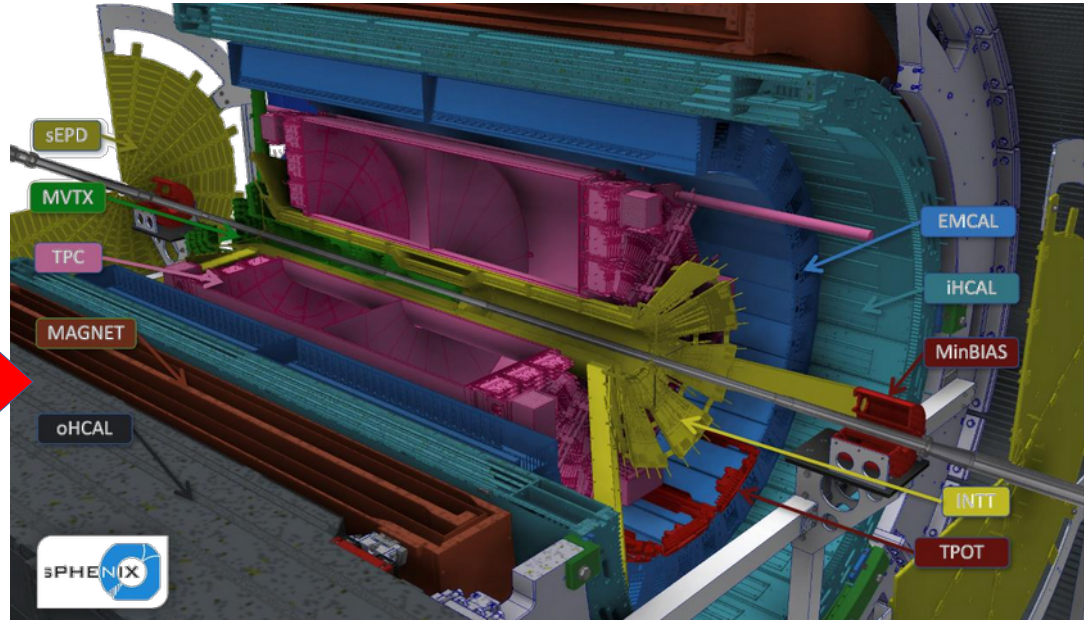
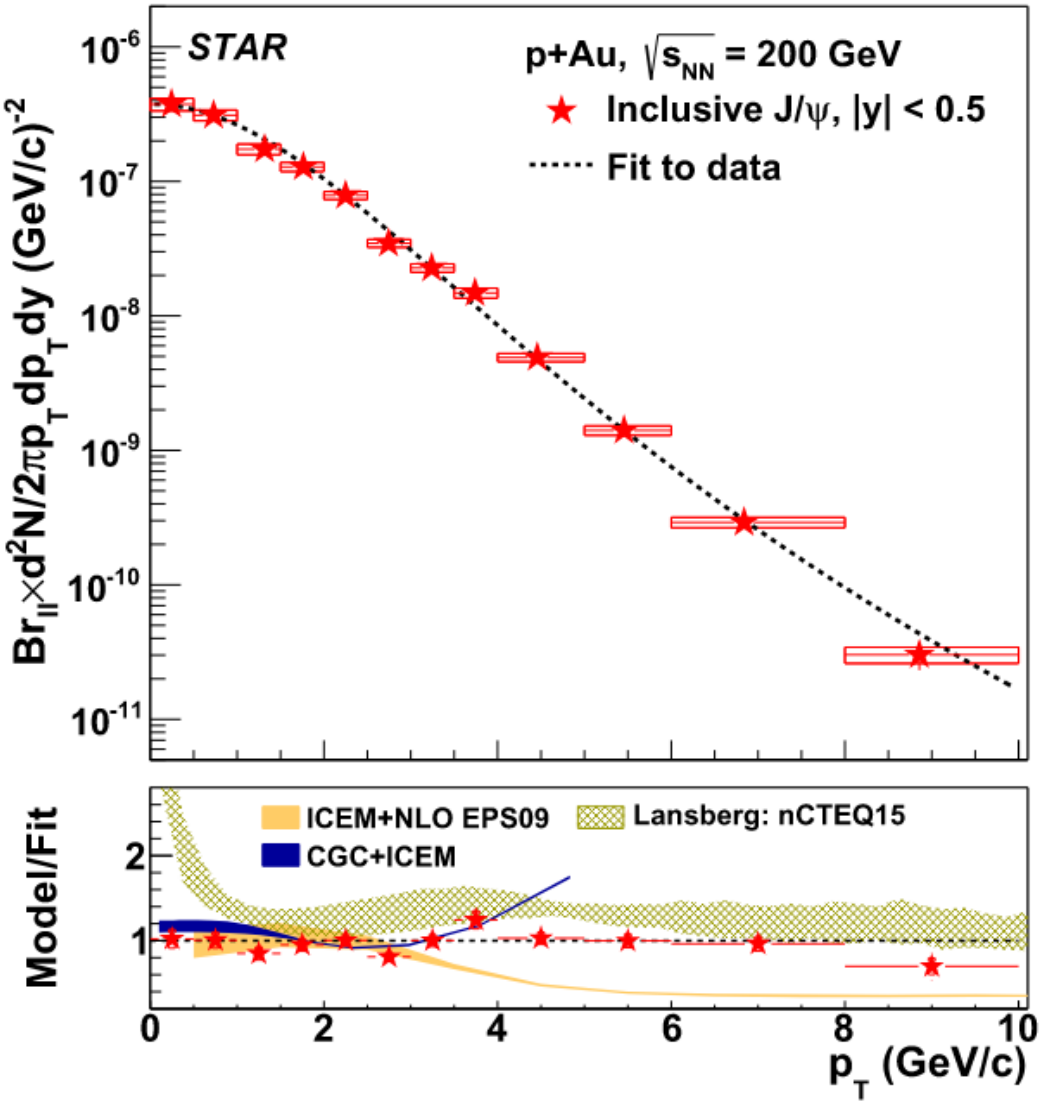
Dismounted in 2016 → **sPHENIX**



p+A collisions

J/ψ in p+Au at $\sqrt{s_{NN}}$ = 200 GeV

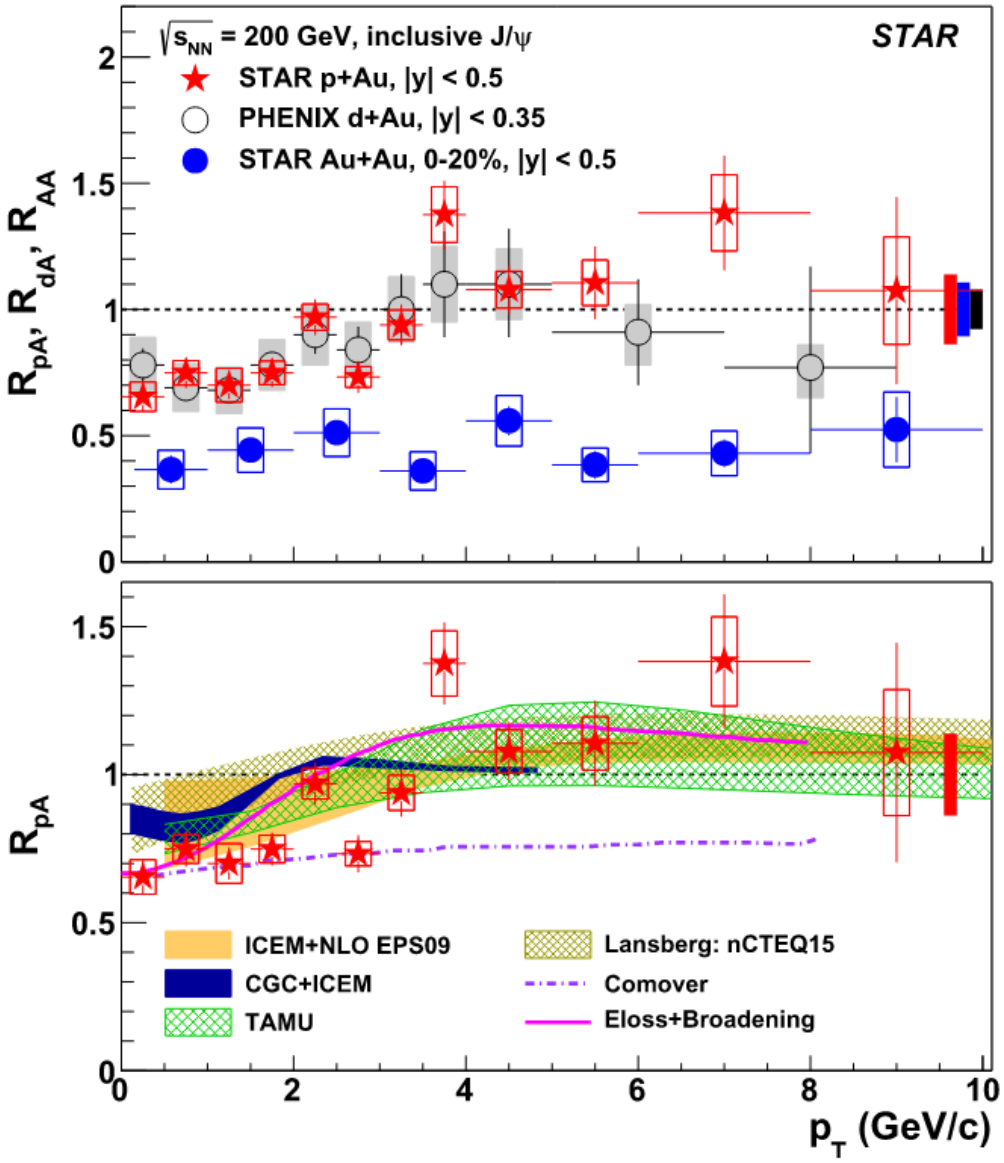
Physics Letters B 825 (2022) 136865



Reasonable description of the p_T spectrum with nPDF only

J/ψ in p+Au at $\sqrt{s_{NN}}$ = 200 GeV

Physics Letters B 825 (2022) 136865



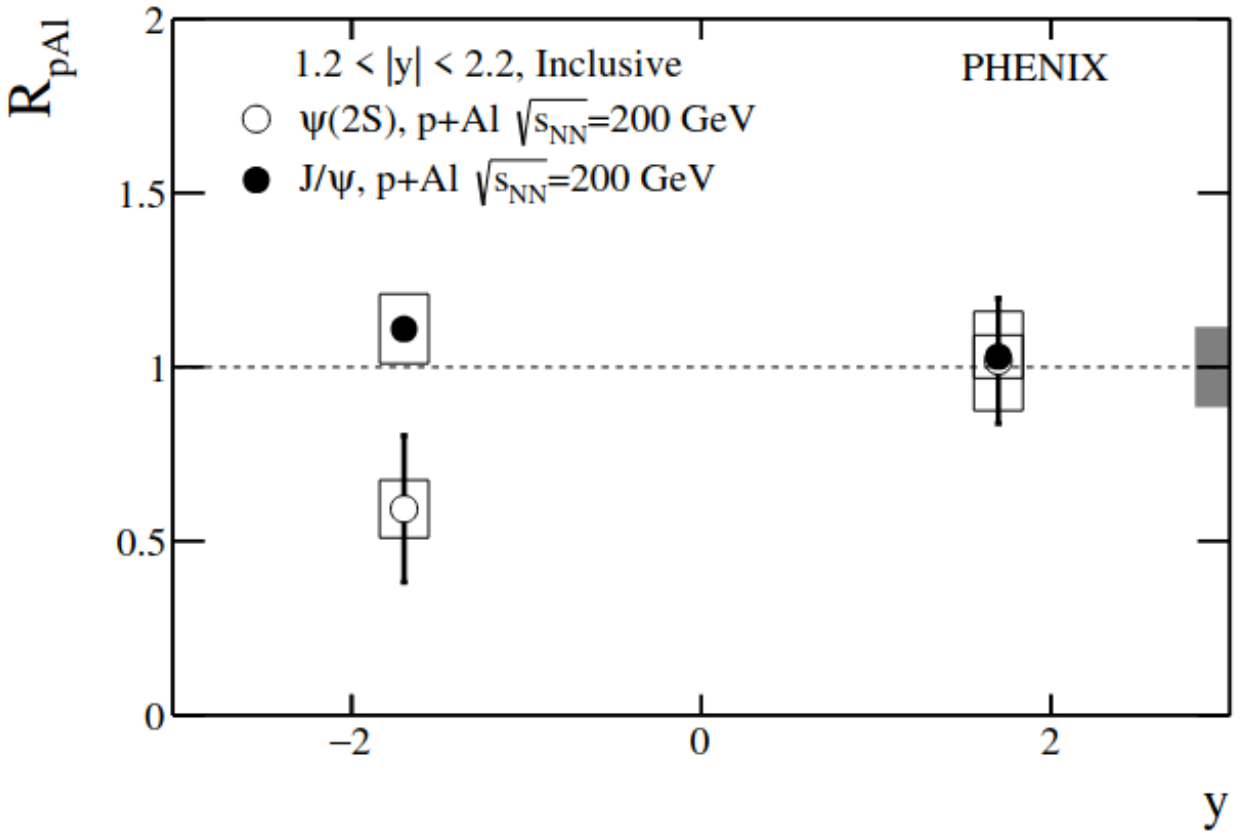
Reasonable description of the p_T spectrum with nPDF only

Similar modification as in d+Au

$$R_{AB} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{d^2N^{AB}/dydp_T}{d^2N^{pp}/dydp_T}$$

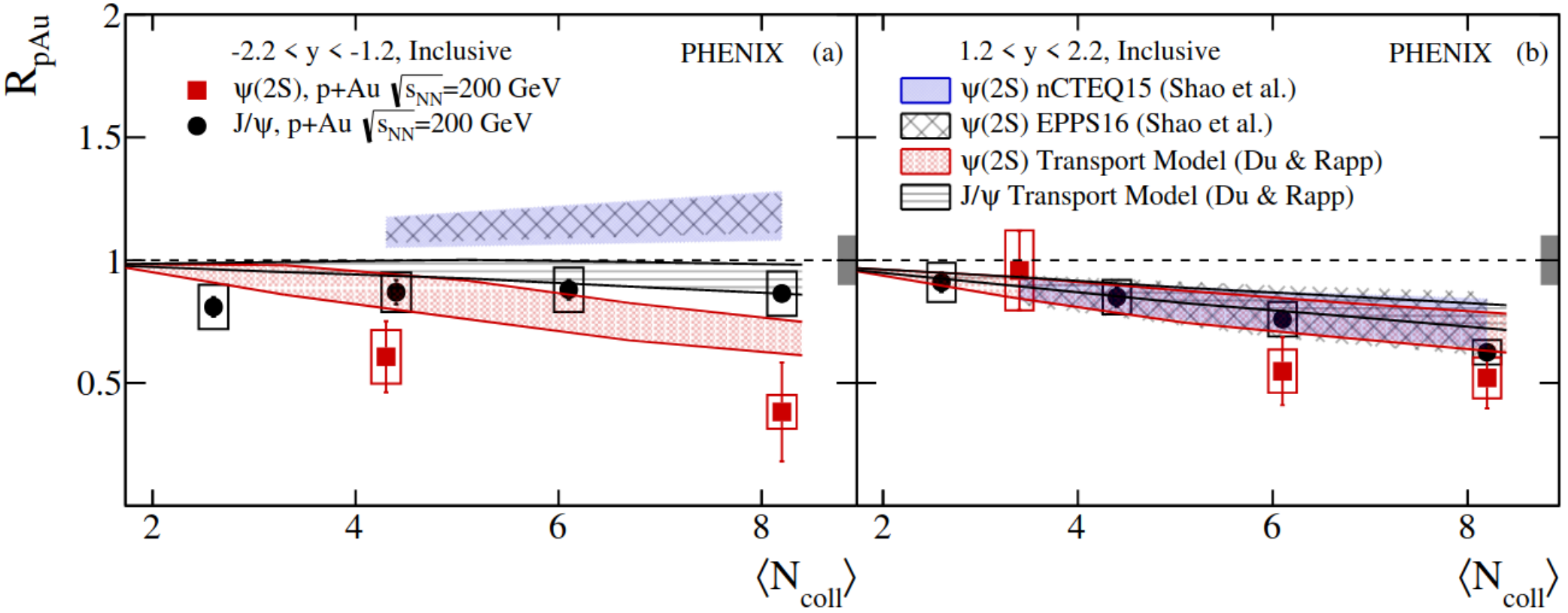
ψ(2S) in p+Al and p+Au $\sqrt{s_{NN}}$ = 200 GeV

Phys.Rev.C 105 (2022) 6, 064912
[arXiv:2202.03863]



ψ(2S) in p+Al and p+Au $\sqrt{s_{NN}}$ = 200 GeV

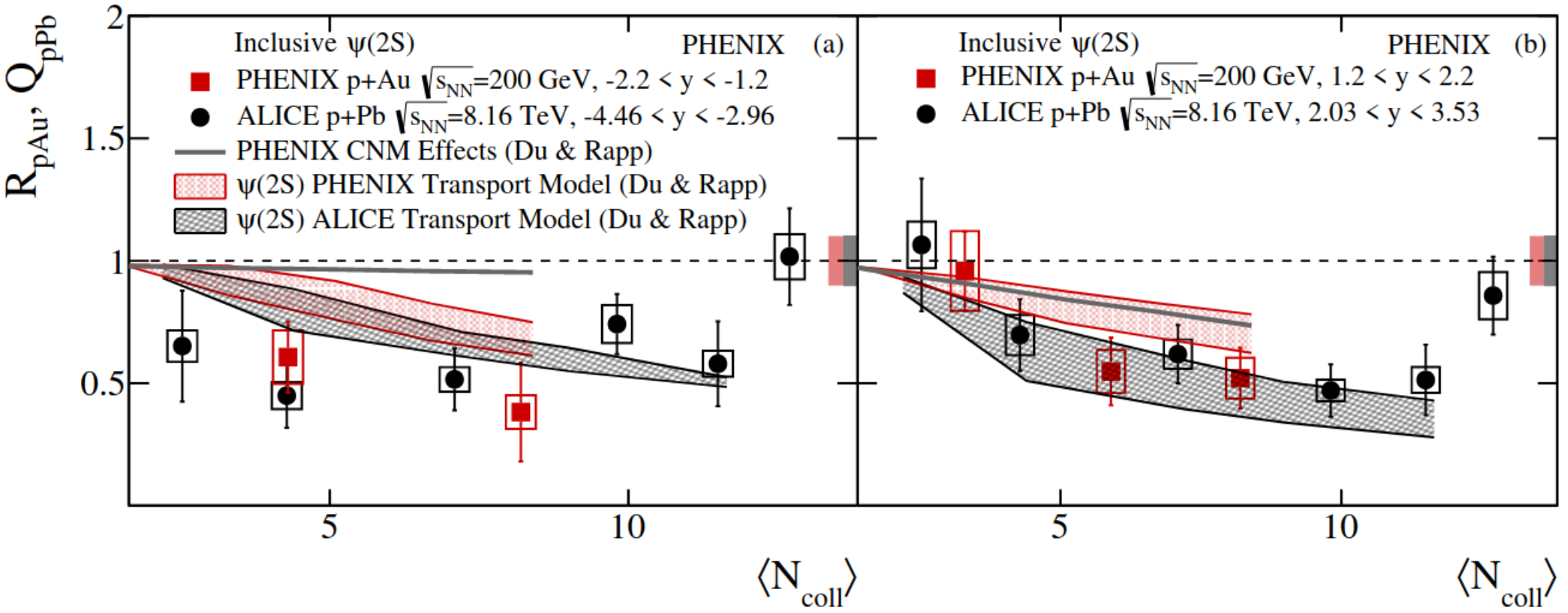
Phys.Rev.C 105 (2022) 6, 064912
[arXiv:2202.03863]



- Similar modification of J/ψ and ψ(2S) in p-direction
- Stronger ψ(2S) suppression in Au-direct.
- nPDF only can not describe the ψ(2S) data

ψ(2S) in p+Al and p+Au $\sqrt{s_{NN}}$ = 200 GeV

Phys.Rev.C 105 (2022) 6, 064912
[arXiv:2202.03863]

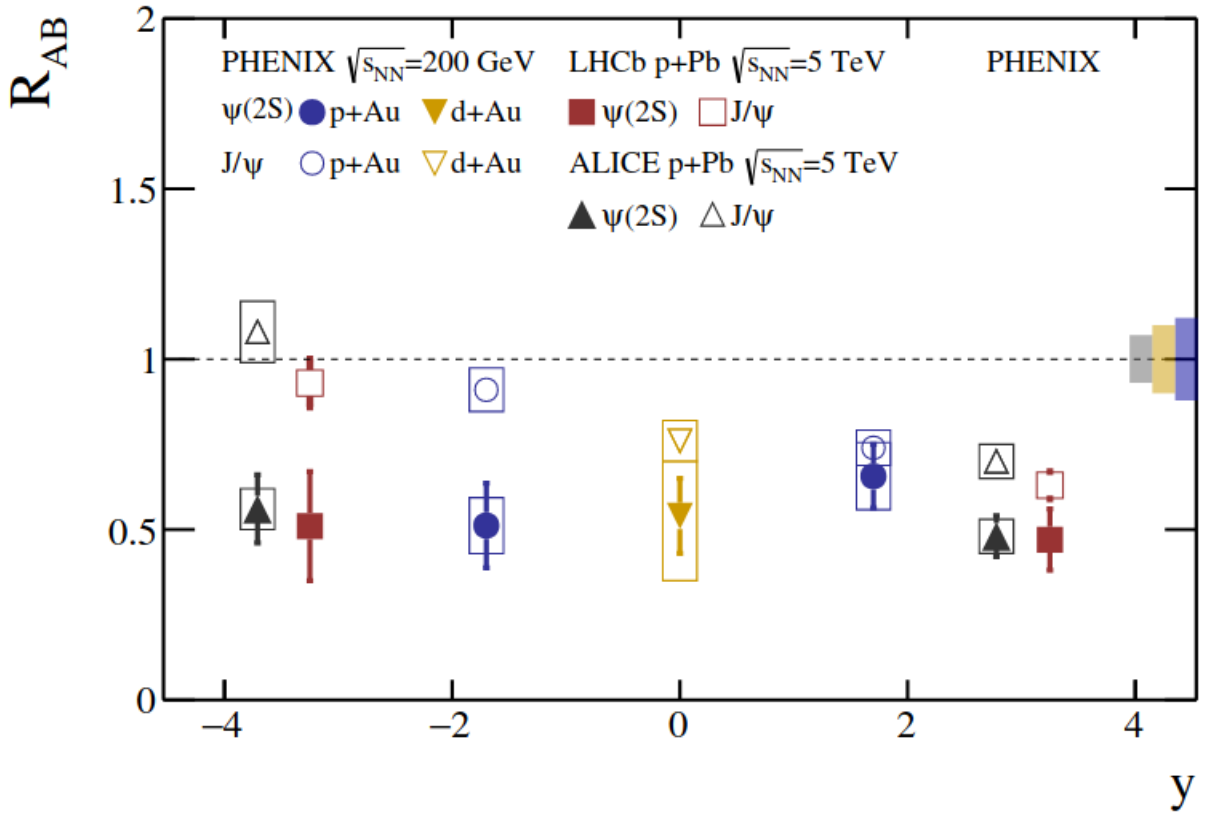


Similar modification of ψ(2S) at RHIC and LHC

ψ(2S) in p+Al and p+Au $\sqrt{s_{NN}}$ = 200 GeV

Phys.Rev.C 105 (2022) 6, 064912
[arXiv:2202.03863]

- Similar modification of J/ψ and ψ(2S) in forward direction
- Stronger ψ(2S) suppression at backward rapidity
- Similar results at RHIC and the LHC

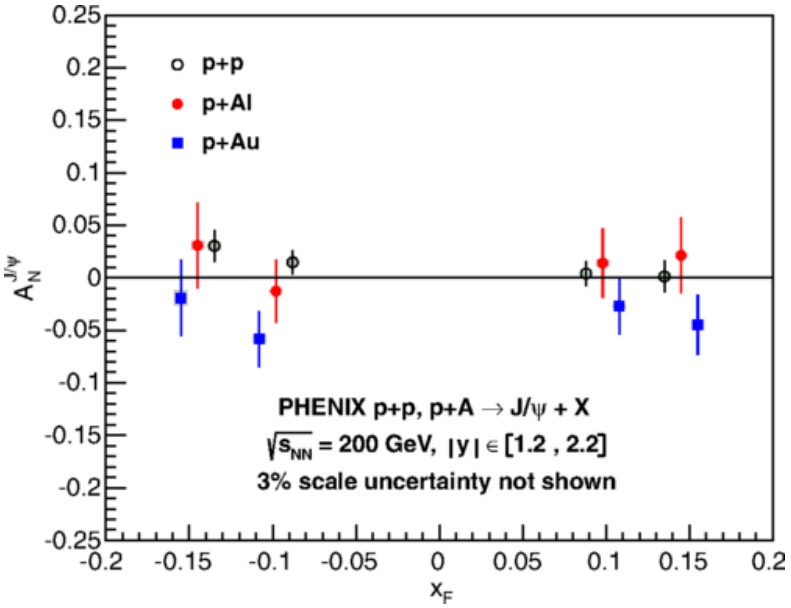


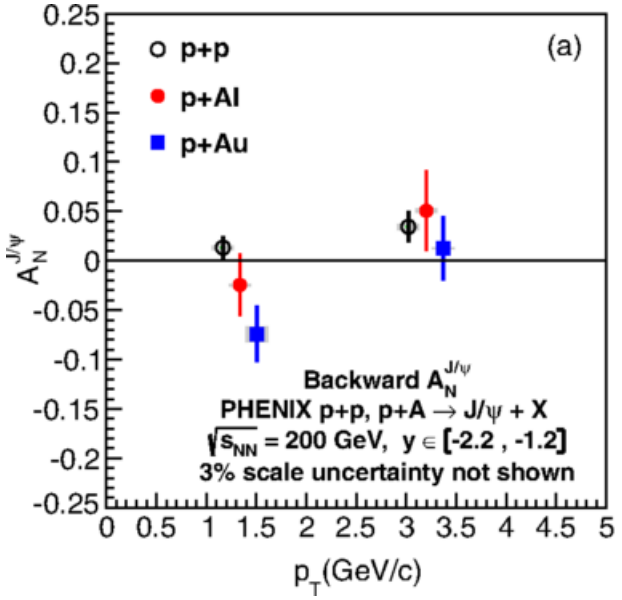
Spin-dependence of nuclear effects ?

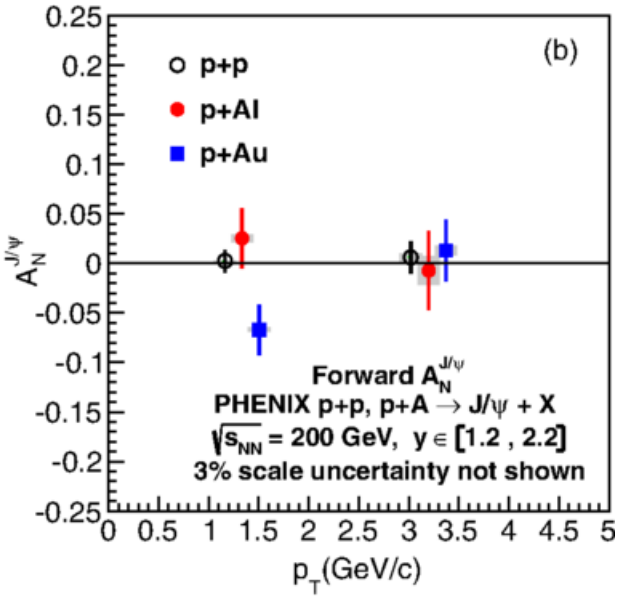
Transversely polarized proton beam:

$p^{\uparrow}$+p, $p^{\uparrow}$+Al, and $p^{\uparrow}$+Au collisions at $\sqrt{s_{NN}}$=200 GeV

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$







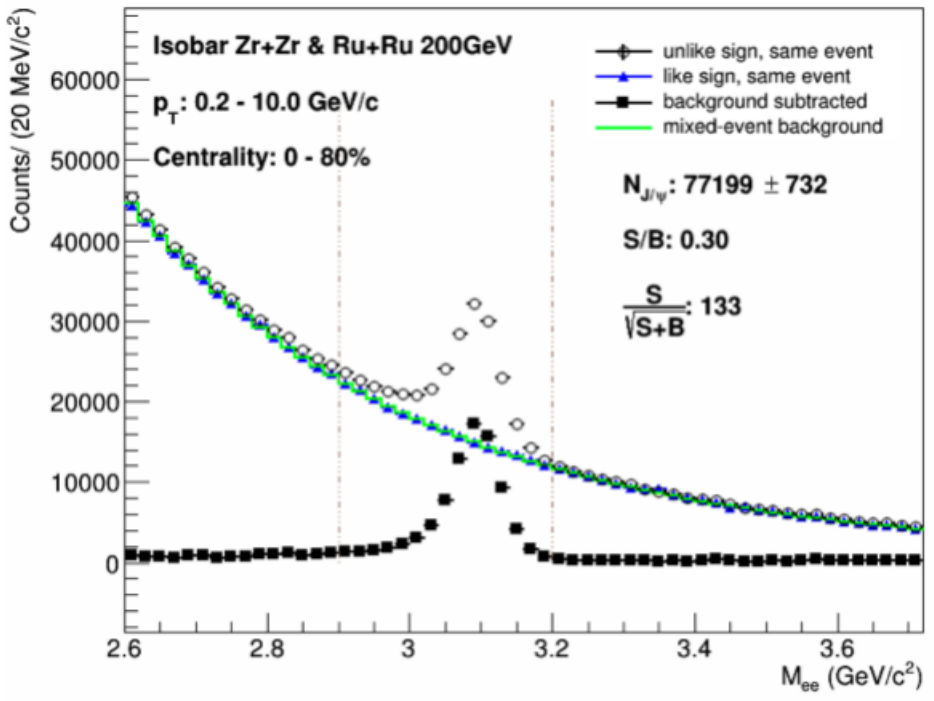
nonzero A_N at the 2σ level in the lower-p_T bins

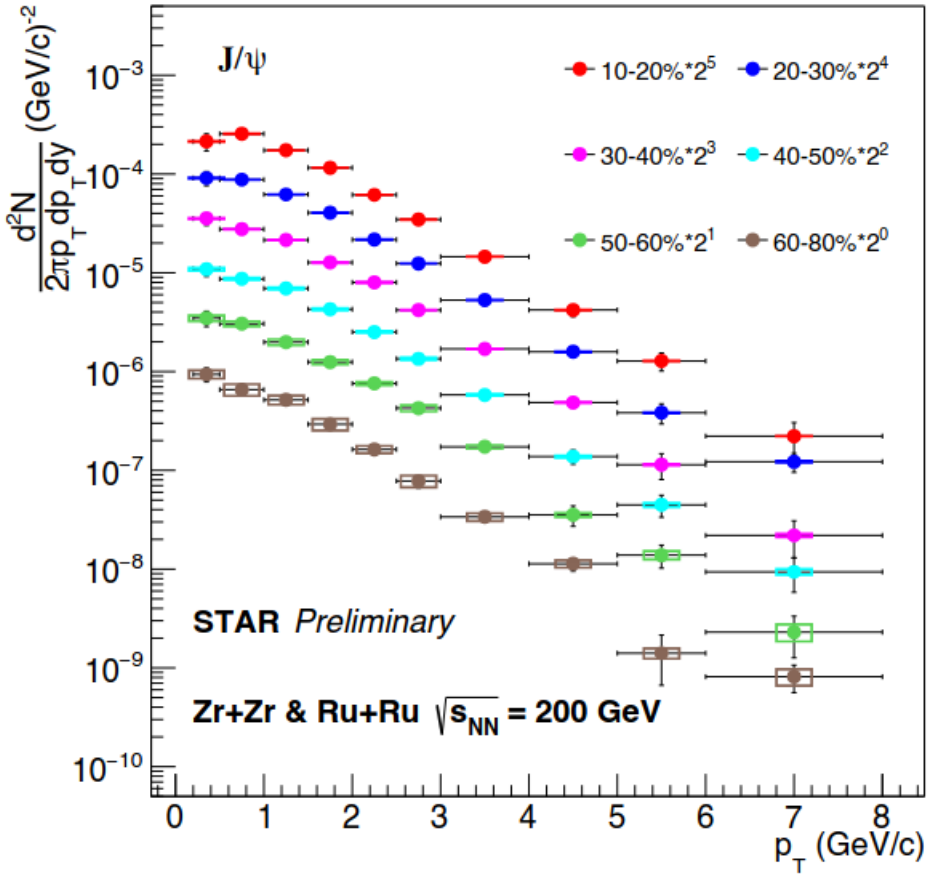
Phys.Rev.D 98 (2018) 1, 012006

Heavy-ion collisions

J/ψ isobar collisions (Ru+Ru and Zr+Zr) at STAR

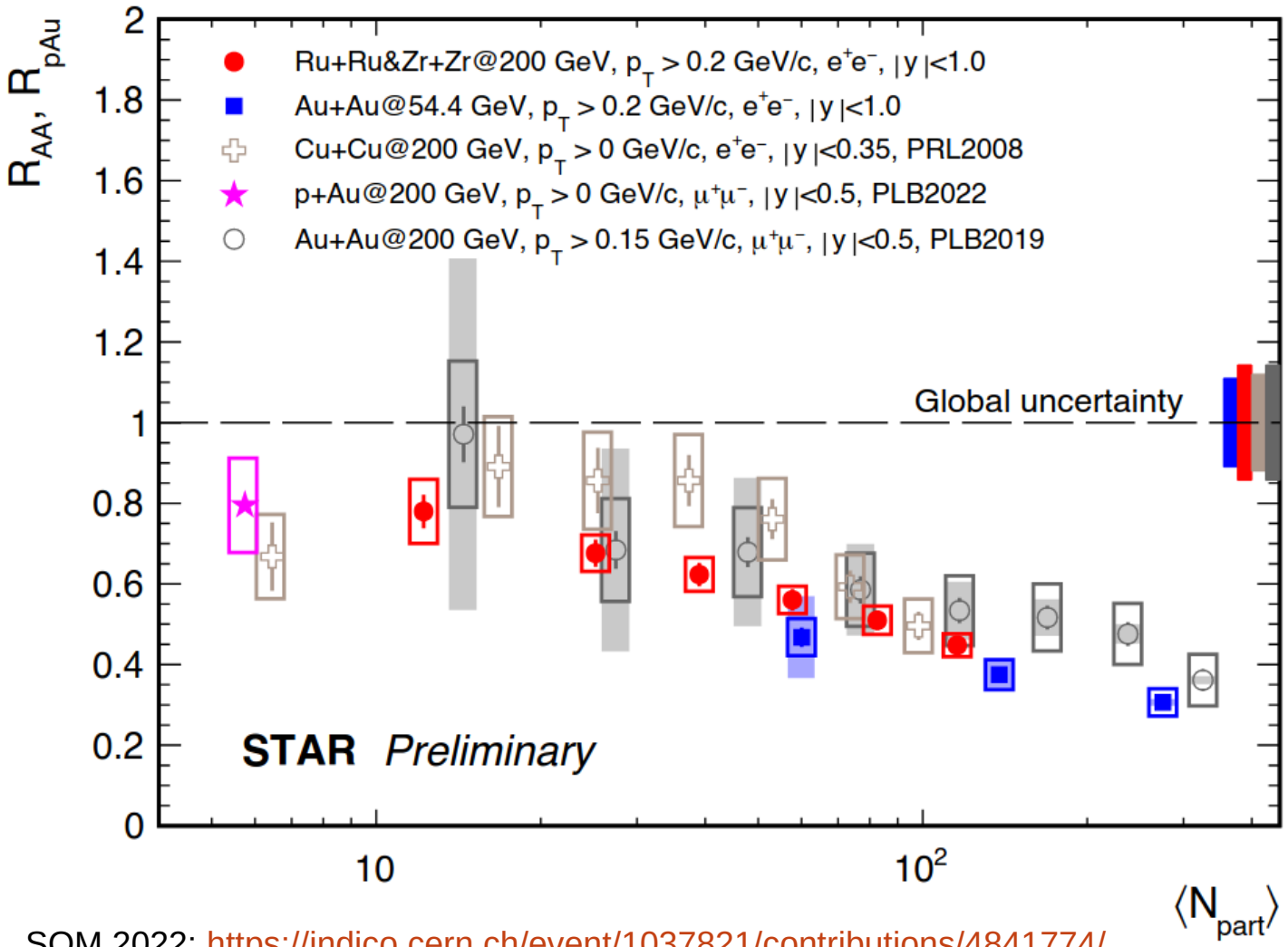
A moderate size collision system between Au+Au and Cu+Cu, large data set (4B events)





SQM 2022: https://indico.cern.ch/event/1037821/contributions/4841774/

System-size and energu dependence of nuclear modification



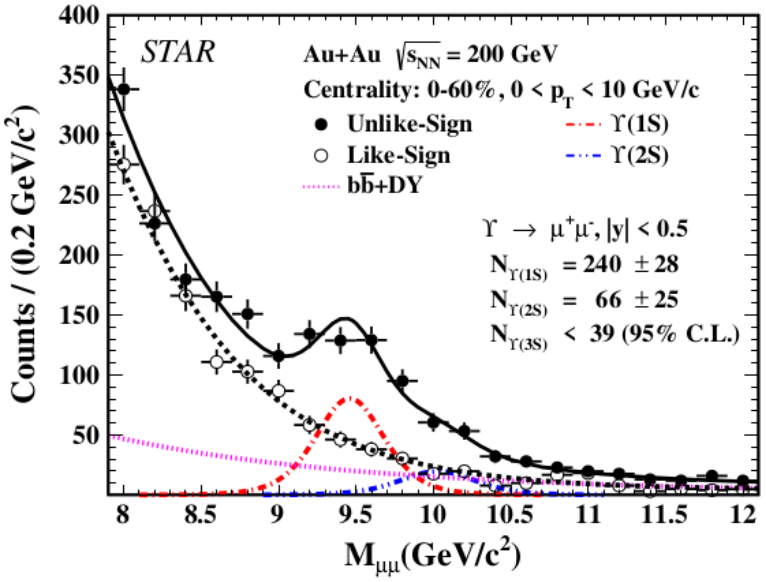
High-quality new data

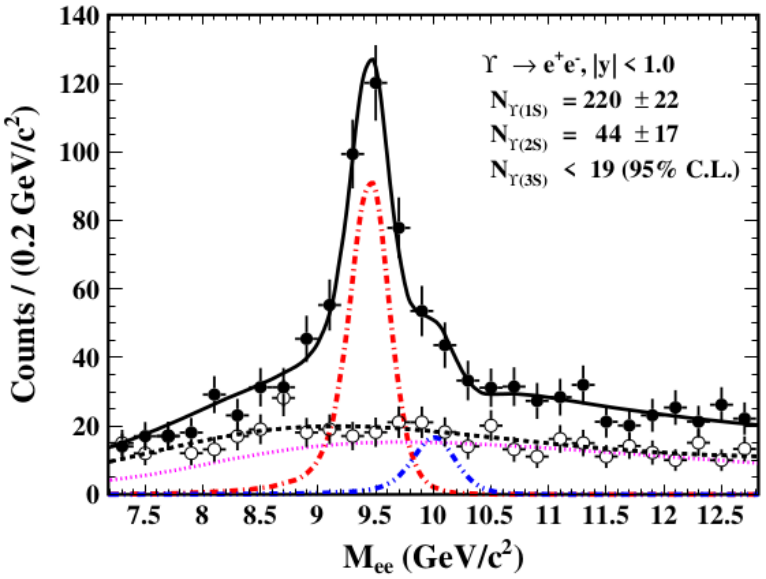
Similar suppression

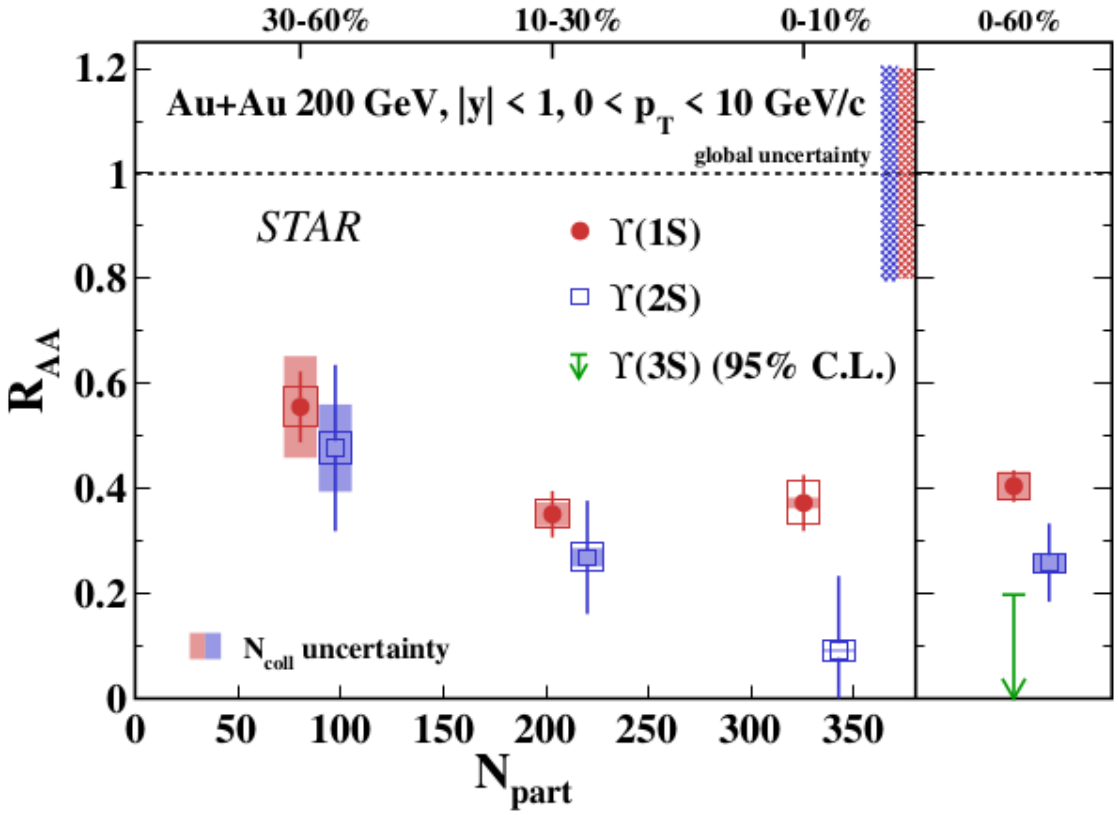
SQM 2022: https://indico.cern.ch/event/1037821/contributions/4841774/

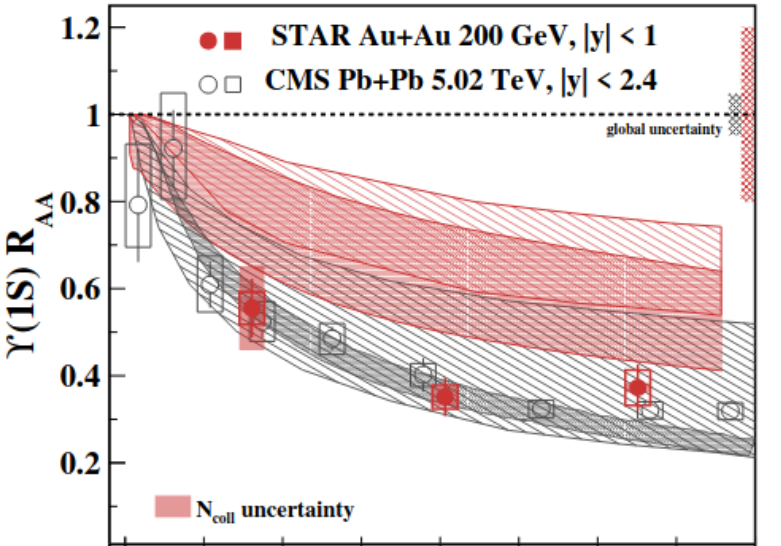
ϒ suppression in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

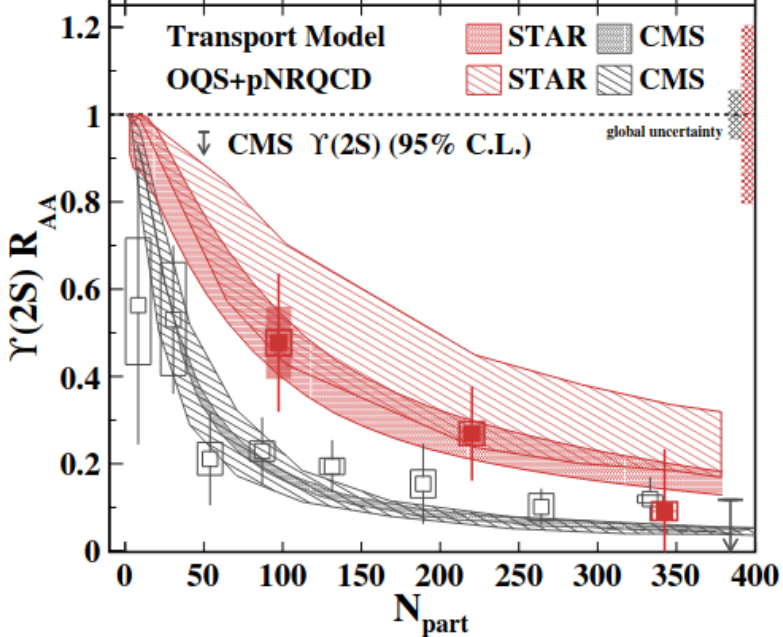
arXiv:2207.06568

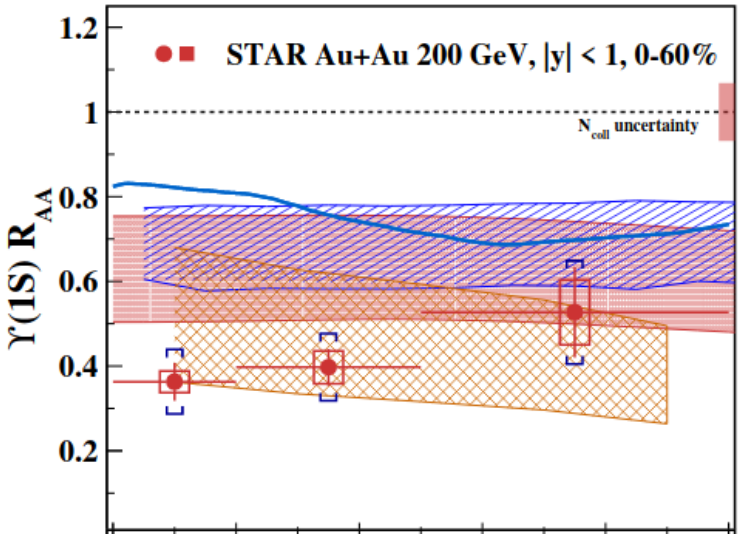


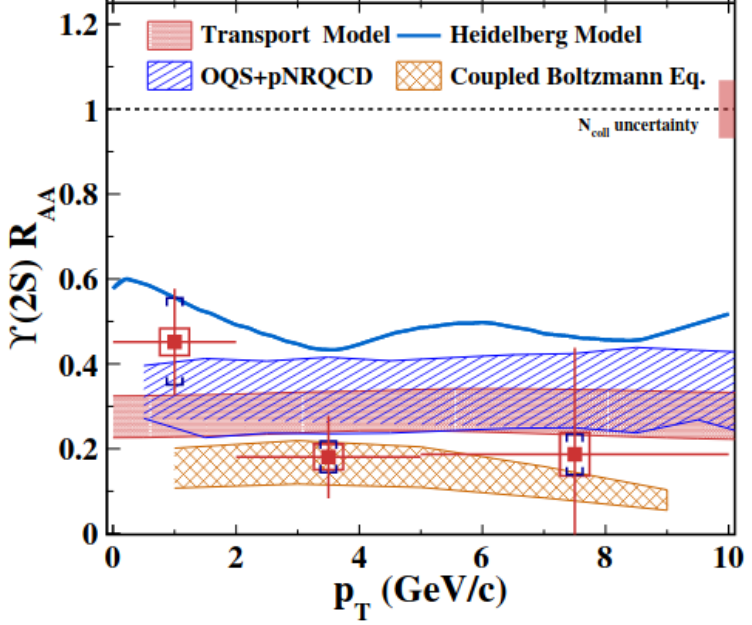












Υ suppression in Au+Au $\sqrt{s_{NN}}$ = 200 GeV

arXiv:2207.06568

Probing the gluonic structure of the deuteron with J/ψ photoproduction in d+Au ultra-peripheral collisions

Phys. Rev. Lett. 128, 122303

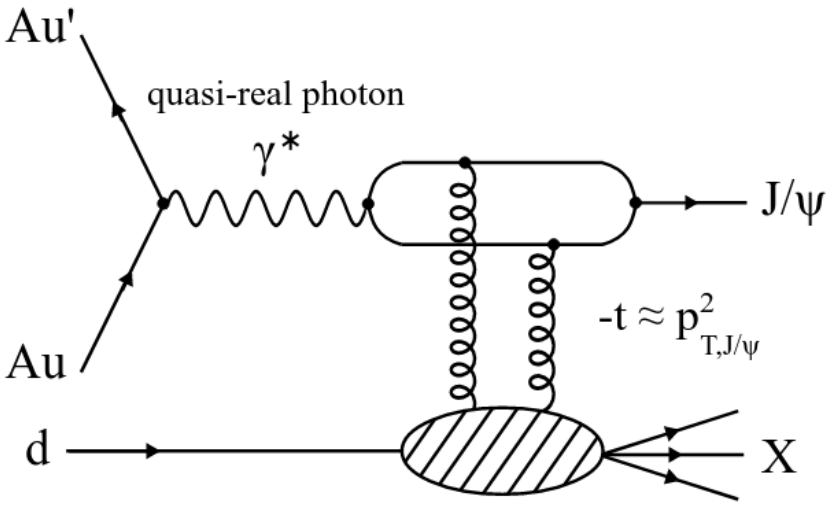
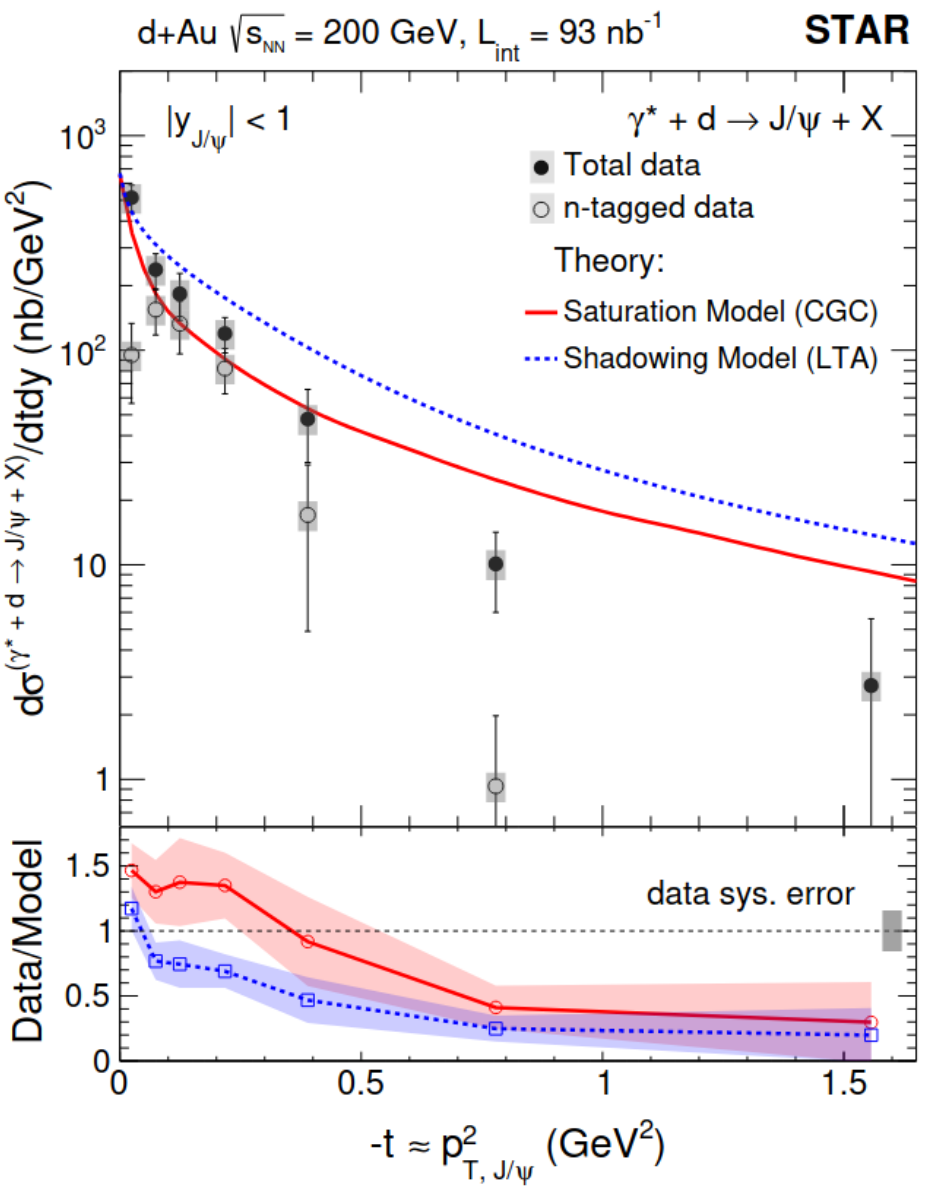
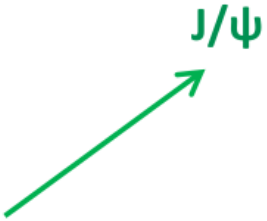


FIG. 1. Photoproduction of J/ψ in d+Au UPCs, where X represents the deuteron (coherent) or deuteron-dissociative (incoherent) system.

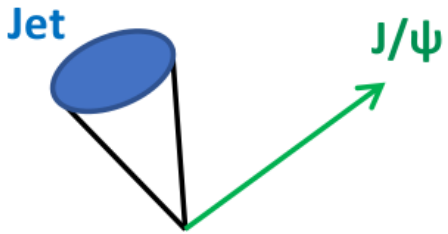


Study of J/ψ production with jet activity in STAR

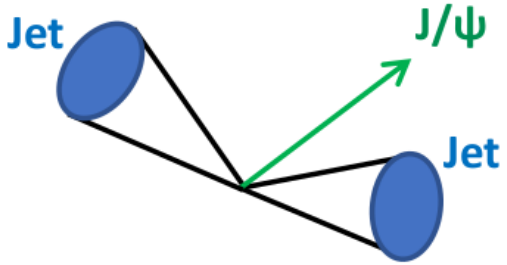
Motivation: Quarkonium production from the **Color Singlet Model should result in a larger jet activity** (number of jets per event) than that from the Color Octet Mechanism (J.P. Lansberg, Physics Reports, 889, 1 (2020))



• J/ψ with 0 jet



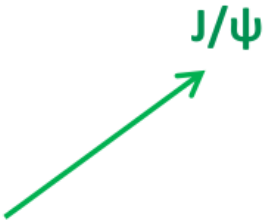
• J/ψ with one jet



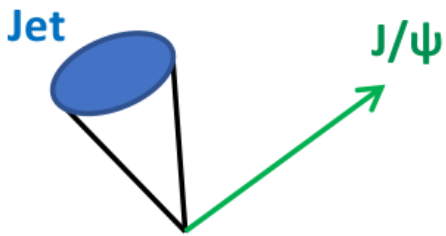
• J/ψ with two jets

Study of J/ψ production with jet activity in STAR

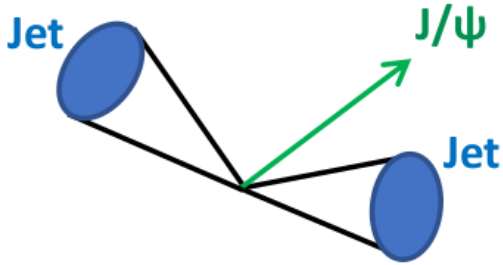
Signal for jet radii are considered: R = 0.4



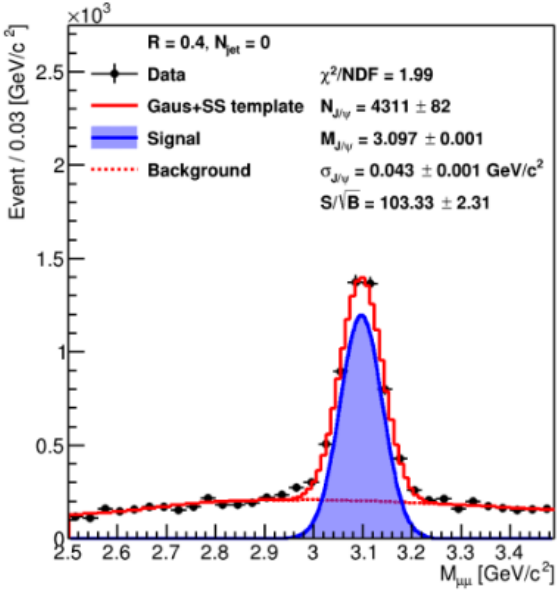
• J/ψ with 0 jet

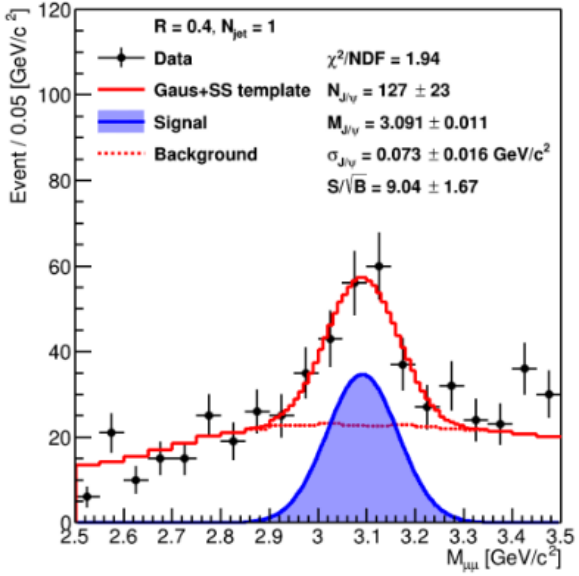


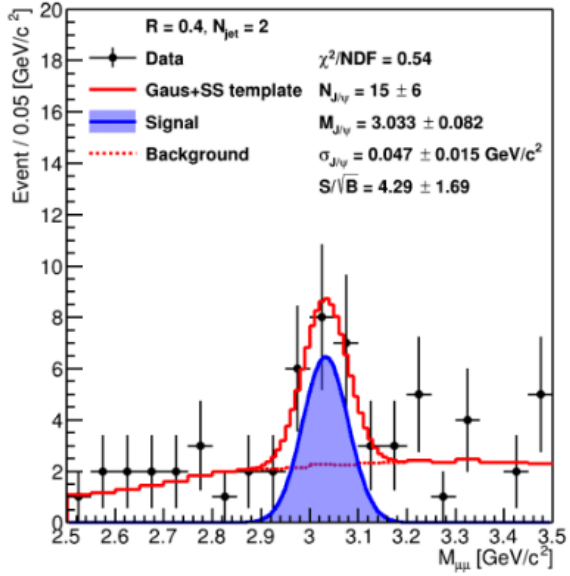
• J/ψ with one jet



• J/ψ with two jets



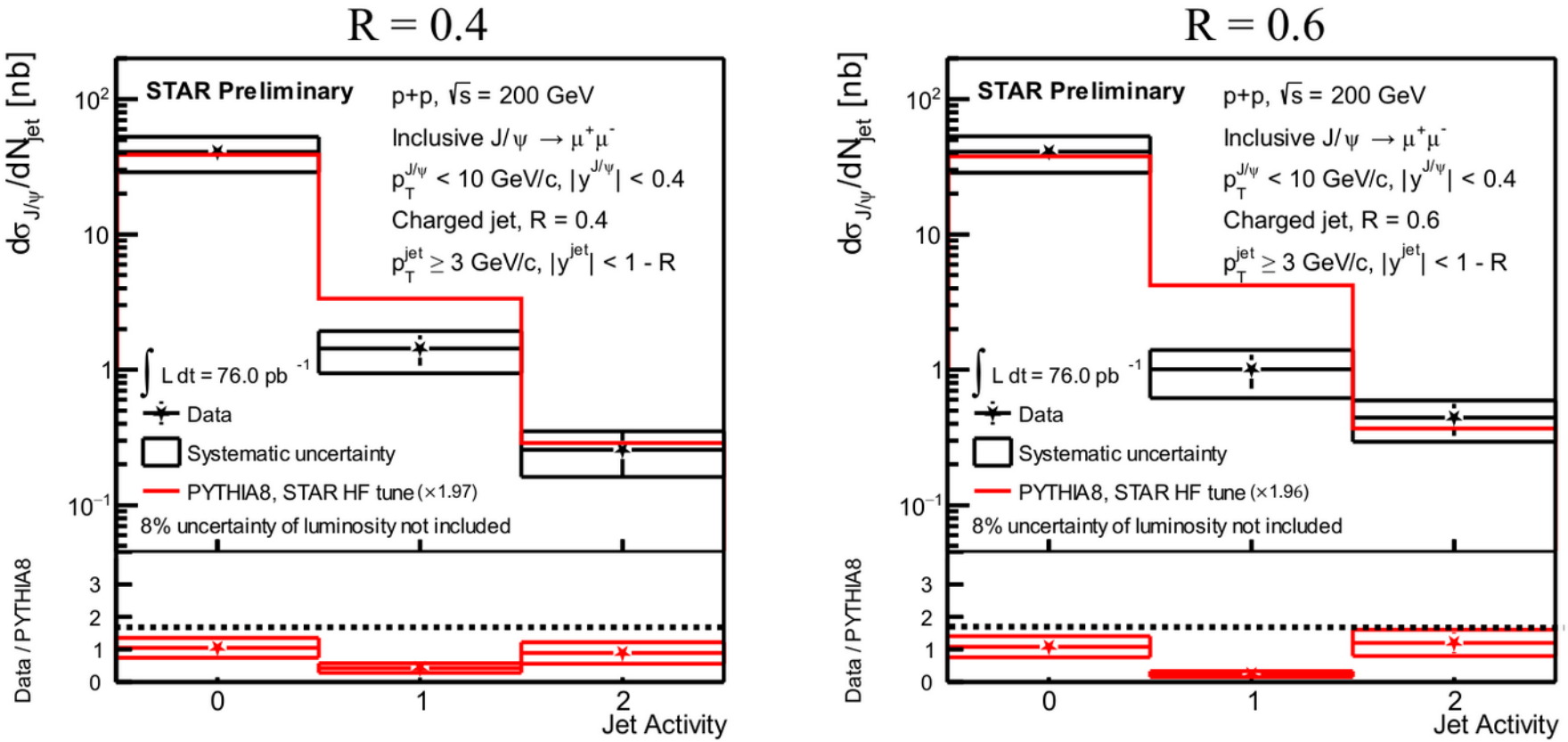




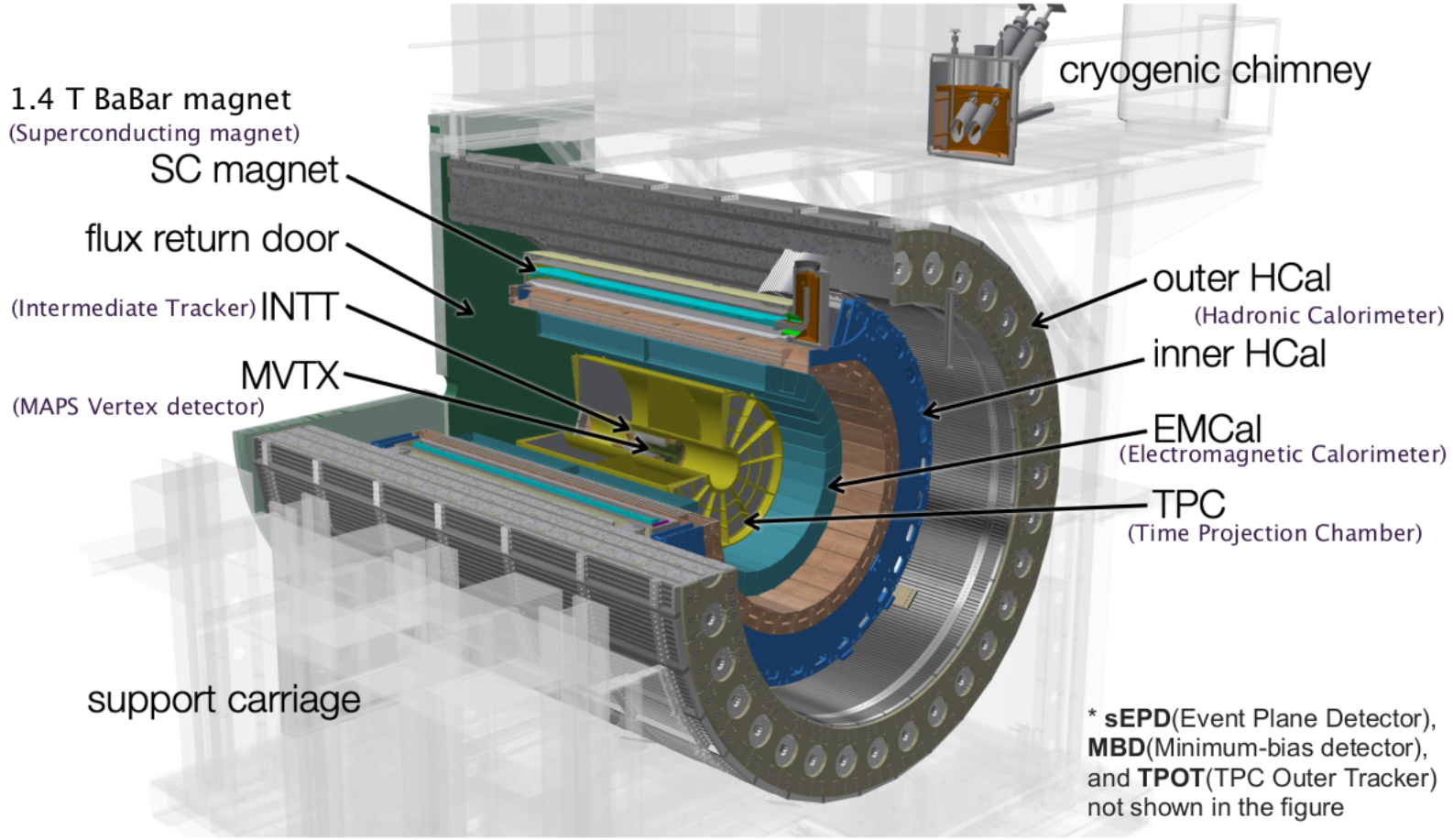
Study of J/ψ production with jet activity in STAR

Differences between data and the PYTHIA8 predictions:

- Inconsistent shape (p-value = 0.01) with jet R = 0.6
- Larger fraction of J/ψ are produced associated with jets in PYTHIA8 than data



sPHENIX Detector



* **sEPD**(Event Plane Detector), **MBD**(Minimum-bias detector), and **TPOT**(TPC Outer Tracker) not shown in the figure

➡ **High data readout rate** of 15 kHz for all subdetectors

Focus on
- Υ suppression
- jets
- open heavy flavor

RHIC run plan for 2023 - 2025

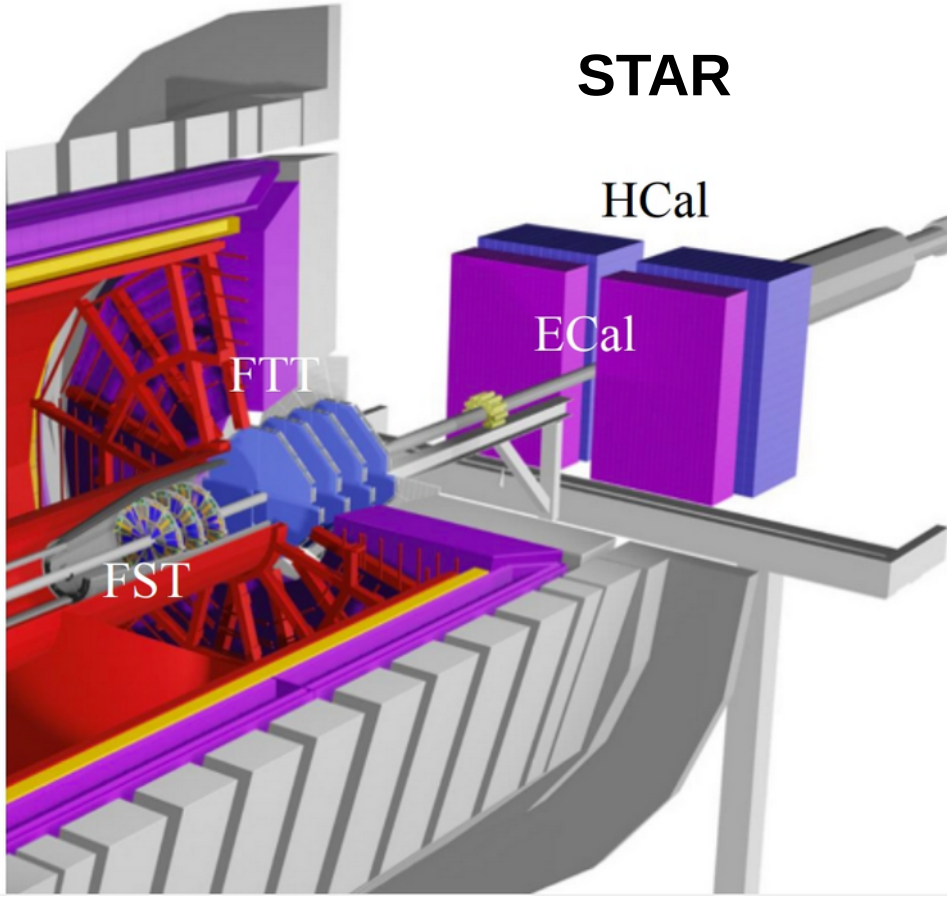
sPHENIX and STAR will take data in parallel

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\lvert z\rvert$ <10 cm	Samp. Lum. $\lvert z\rvert$ <10 cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Yeonju Go, Quark Matter 2022, April 4-10

Summary and outlook

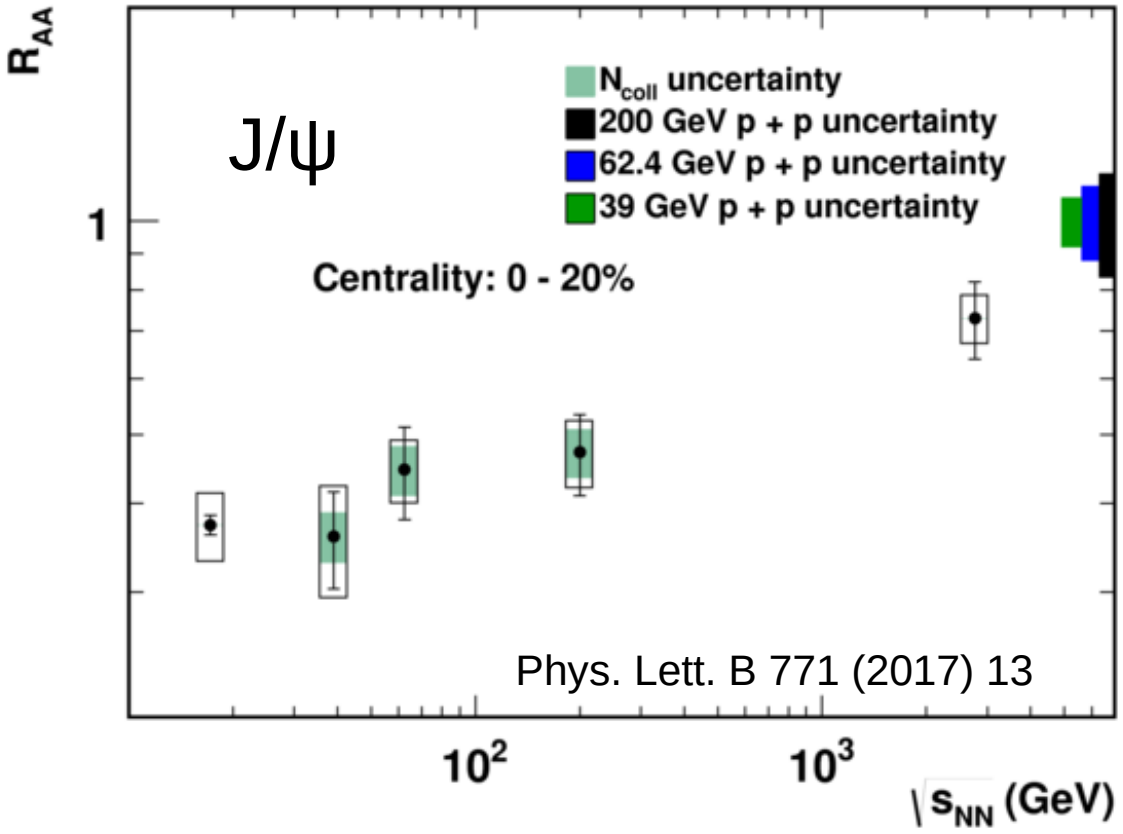
- **RHIC is a versatile machine and facilitates broad physics program**
- **Recently completed forward upgrades**
  - **sPHENIX**
  - **STAR**:
    - Forward Tracking System
    - Forward Colorimeter System (EM and Hadronic)
    - $2.5 < \eta < 4$



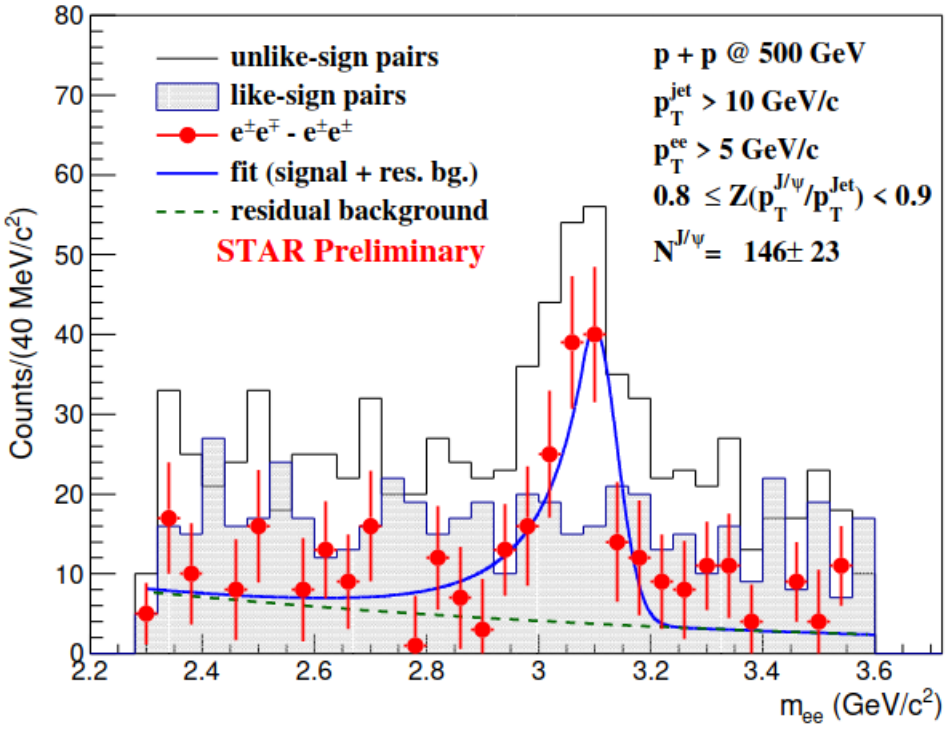
- **Rich heavy-ion physics program at RHIC**
  - More cold and hot QCD studies with high-statistics 200 GeV p+p, p+Au and Au+Au data to be collected in 2023-2025

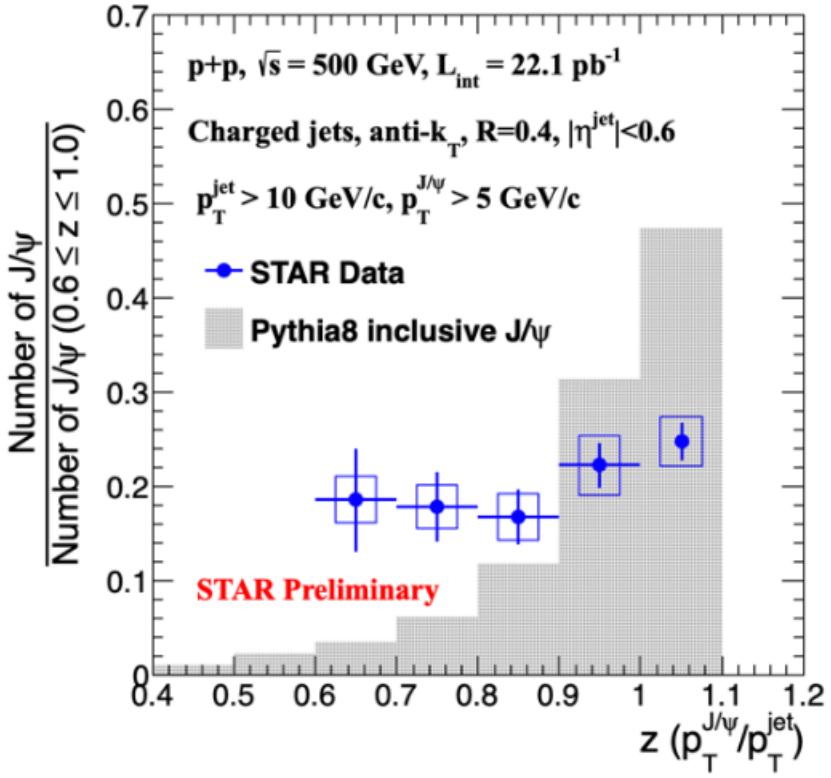
Backup

System-size and energy dependence of nuclear modification



J/psi in jets: p+p 500 GeV





PoS(HardProbes2020)072, https://pos.sissa.it/387/072/

J/ψ in p+Al, p+Au, and ^{3}He+Au at $\sqrt{s_{NN}}$ = 200 GeV

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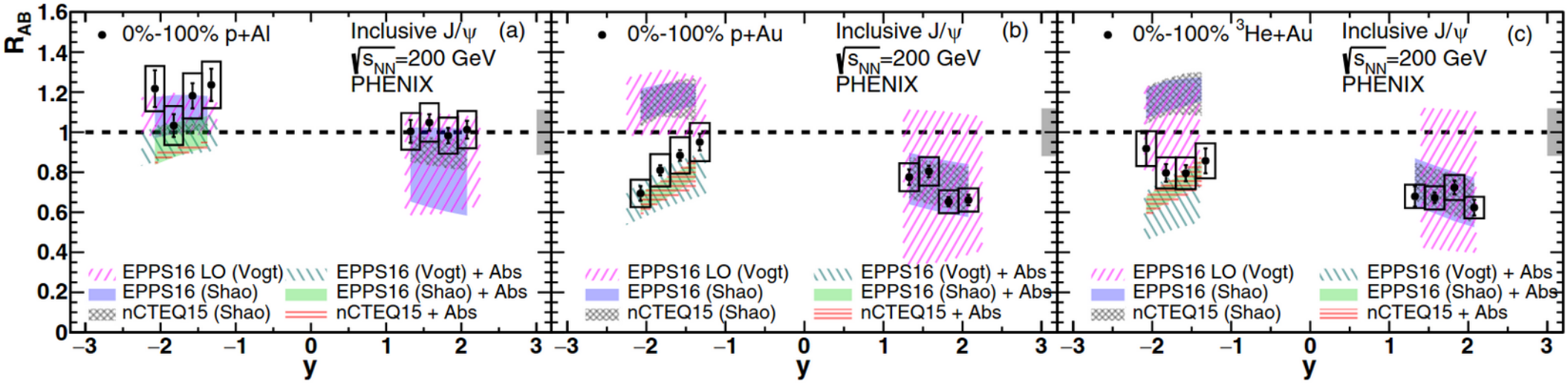
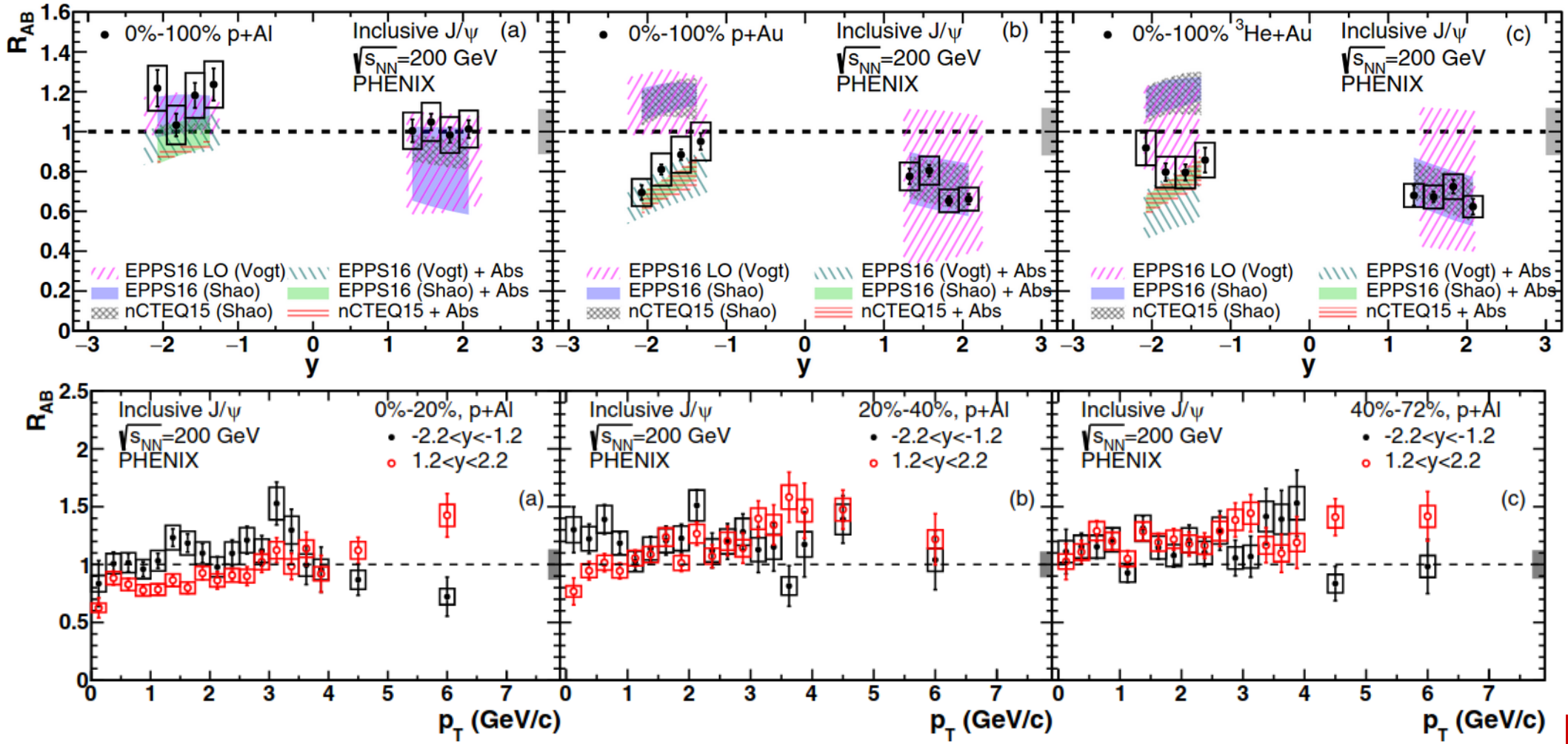


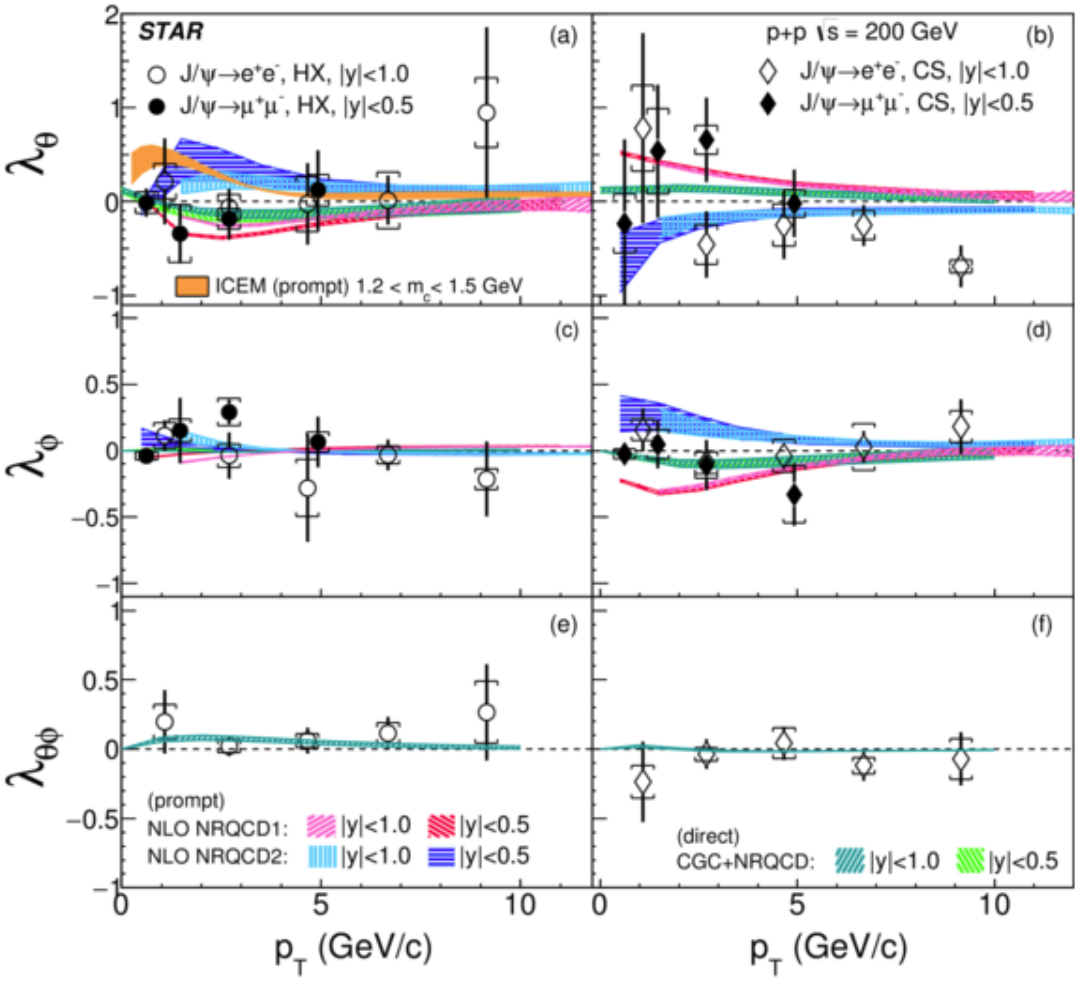
$$R_{AB} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2N^{AB}/dy dp_T}{d^2N^{pp}/dy dp_T}$$

J/ψ in p+Al, p+Au, and ^{3}He+Au at $\sqrt{s_{NN}}$ = 200 GeV

PHYSICAL REVIEW C102, 014902 (2020)

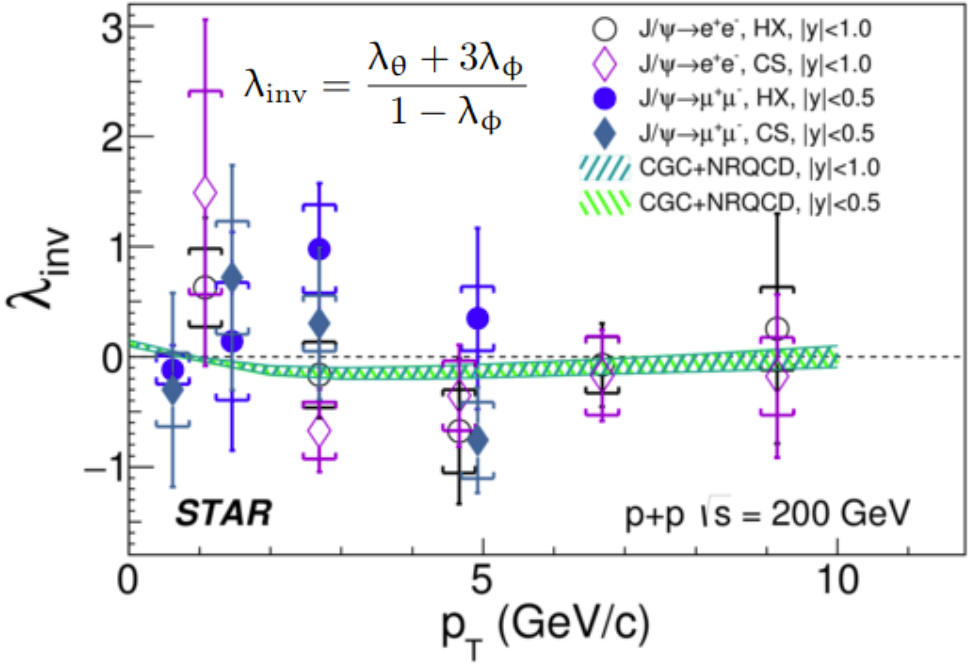


J/ψ polarization in p+p 200 GeV



$$W(\cos\theta,\phi) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi + \lambda_{\theta\phi}\sin 2\theta\cos\phi),$$

p+p 200 GeV: data consistent with **no polarization** within (sizeable) uncertainties



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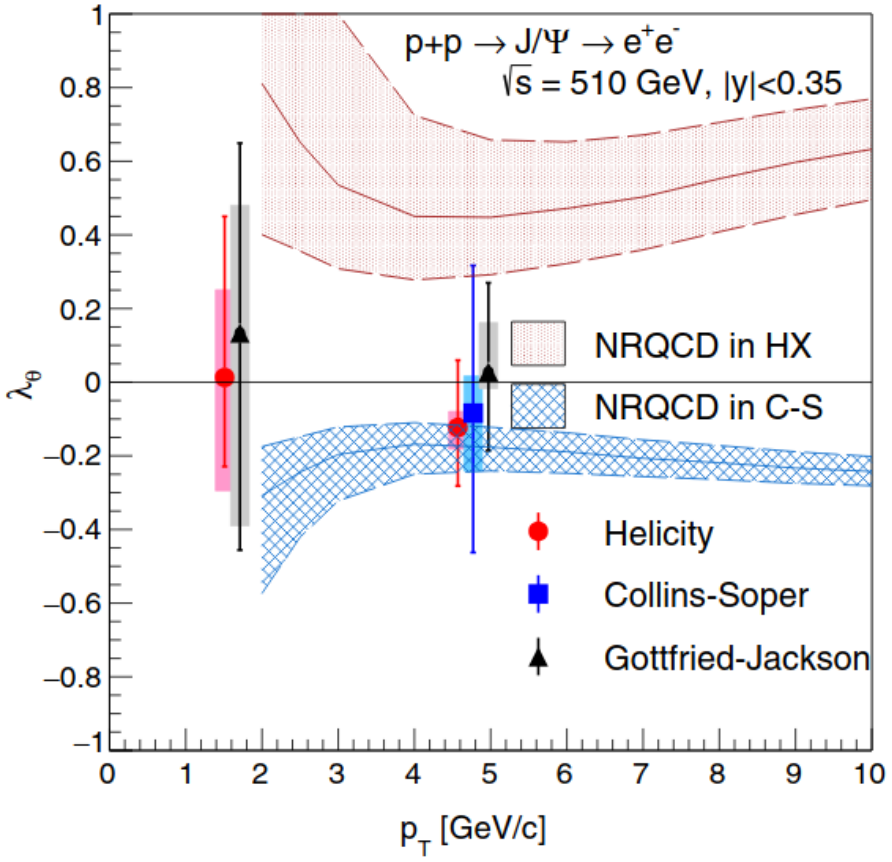

FIG. 8. λ_θ measured in J/ψ transverse momentum bins of $0.0 < p_T < 3.0$ GeV/c and $3.0 \leq p_T < 10.0$ GeV/c overlaid with NRQCD predictions in the helicity and Collins-Soper frames. The points for different frames are shifted for visual clarity.

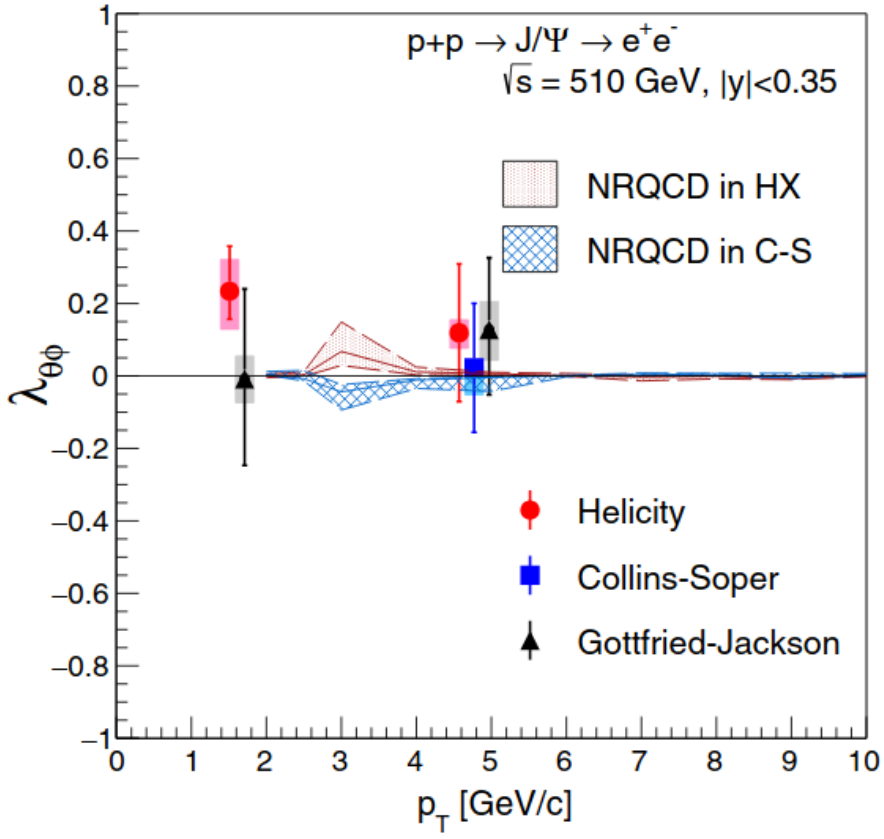

FIG. 10. Angular coefficient $\lambda_{\theta\phi}$ measured in J/ψ transverse momentum bins of $0.0 < p_T < 3.0$ GeV/c and $3.0 \leq p_T < 10.0$ GeV/c overlaid with NRQCD predictions in the helicity and Collins-Soper frames. The points for different frames are shifted for visual clarity.

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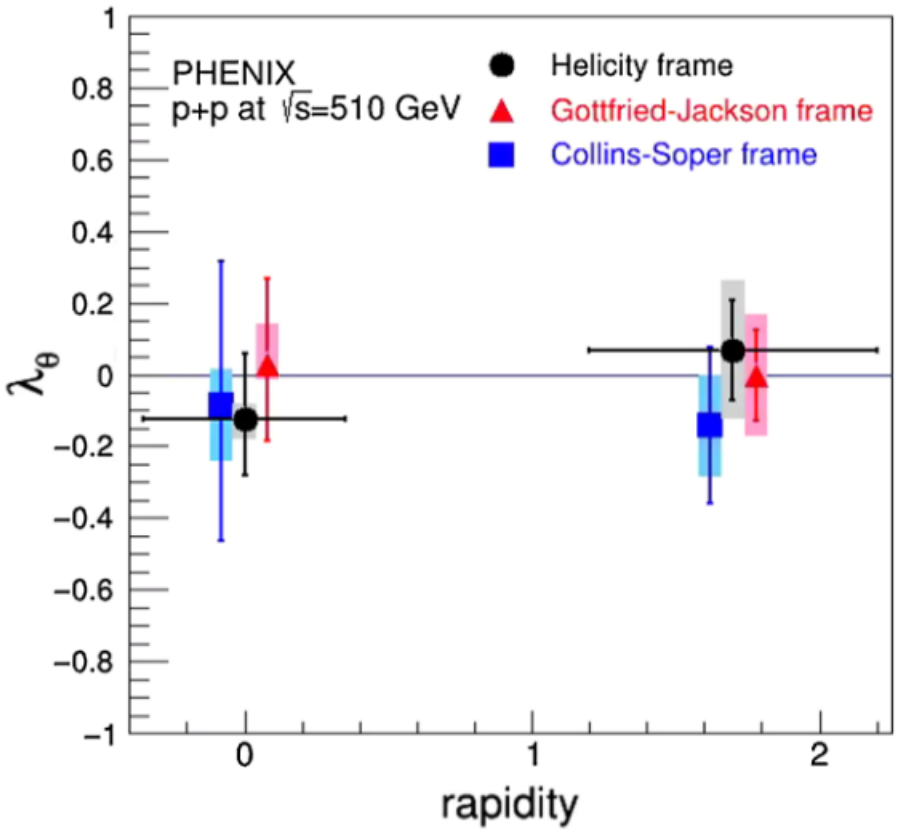

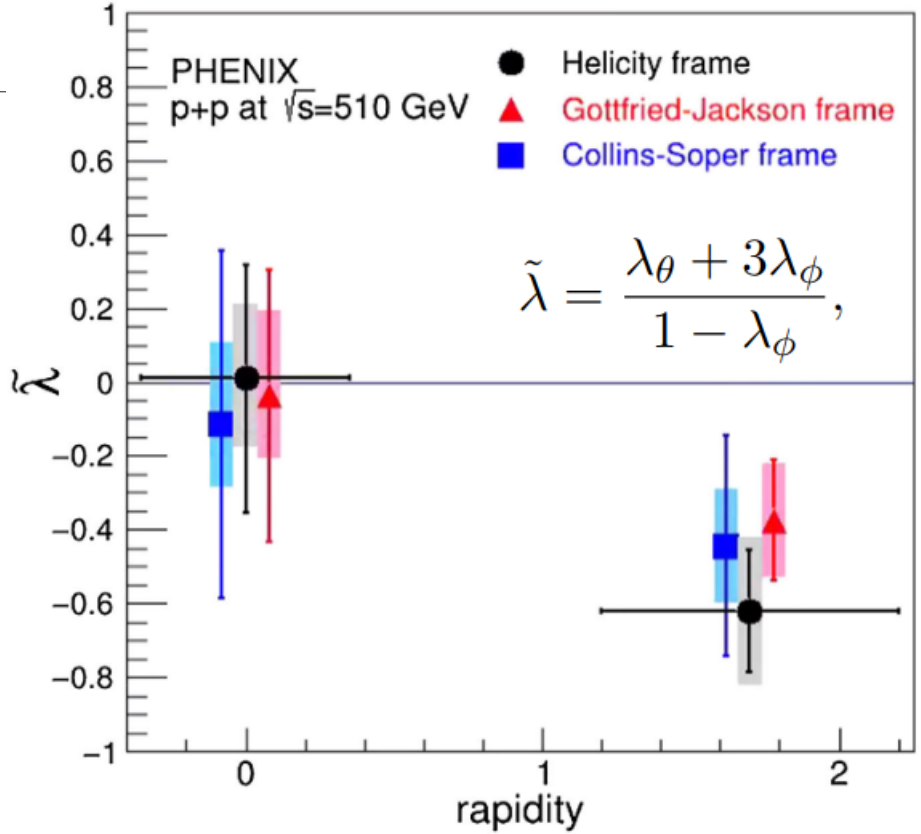

Results consistent with no polarization at mid-rapidity

A hint of negative polarization at forward rapidity

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