HF Quarkonium Physics in PHENIX

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for the PHENIX Collaboration

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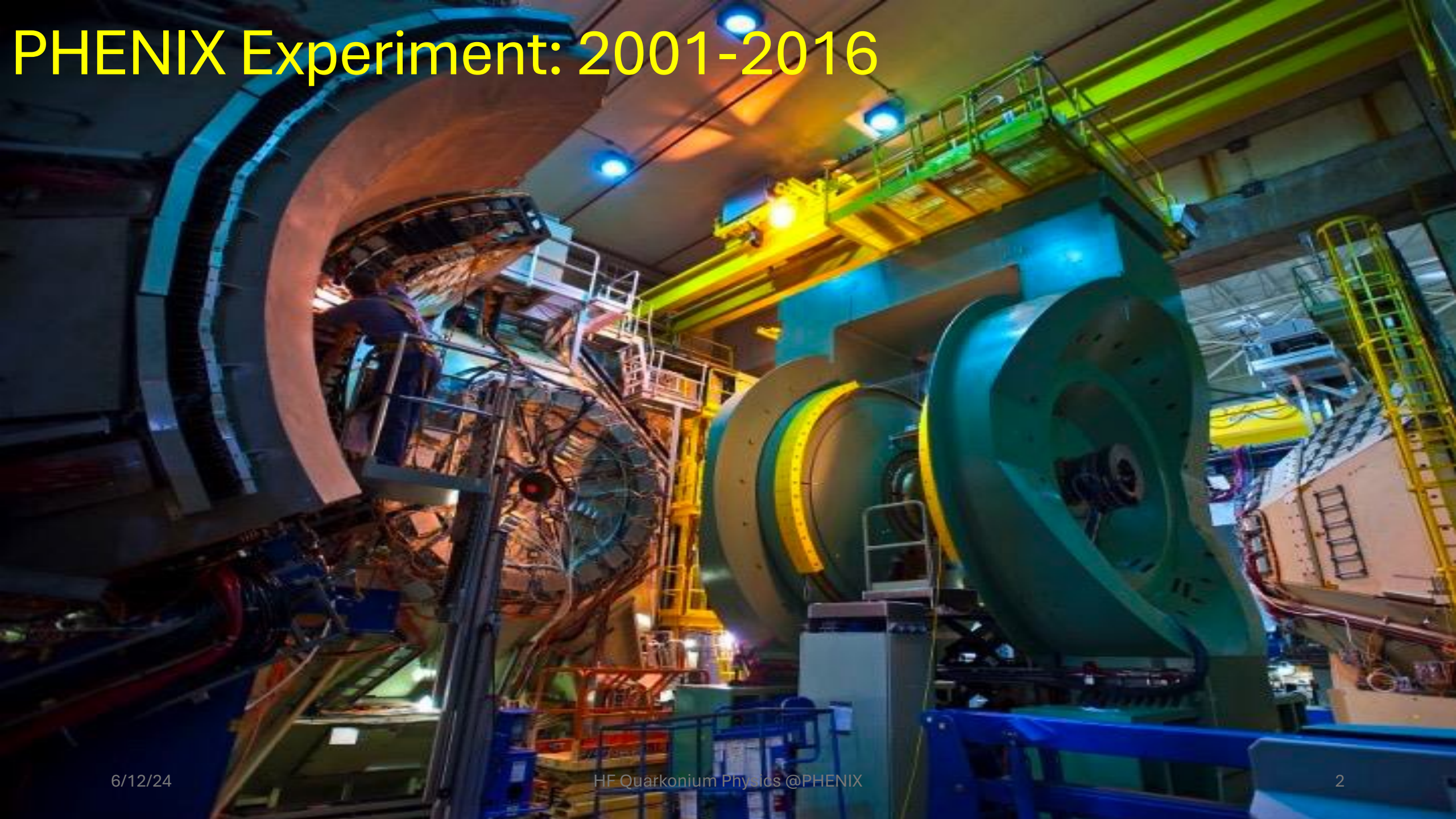
06/12/2024

RHIC/AGS Annual Users' Meeting

PHENIX Experiment: 2001-2016



Broad Physics Topics being explored: HI, Spin to BSM

- continue producing high impact physics beyond 2016

PHYSICAL REVIEW C **105**, 064912 (2022)

Editors' Suggestion

Measurement of $\psi(2S)$ nuclear modification at backward and forward rapidity in $p+p$, p+Al, and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

PHYSICAL REVIEW C **109**, 044912 (2024)

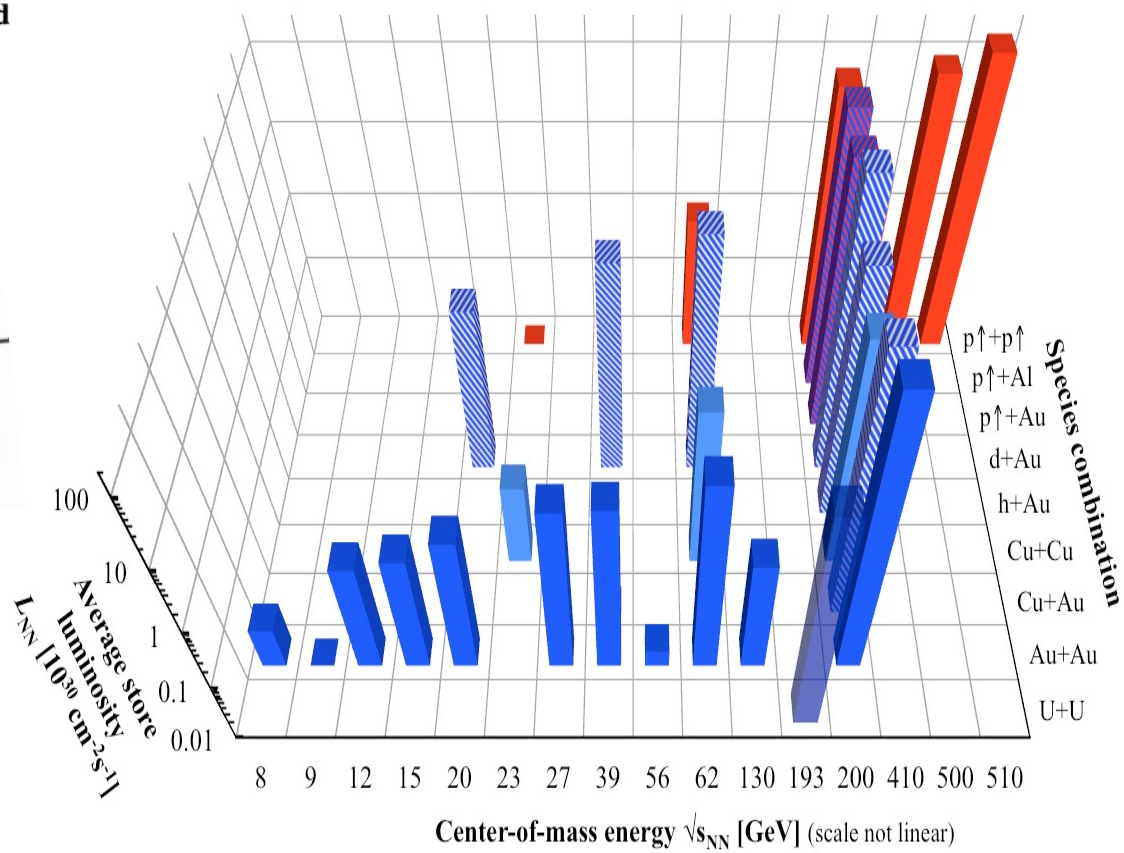
Nonprompt direct-photon production in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

PHYSICAL REVIEW LETTERS **130**, 251901 (2023)

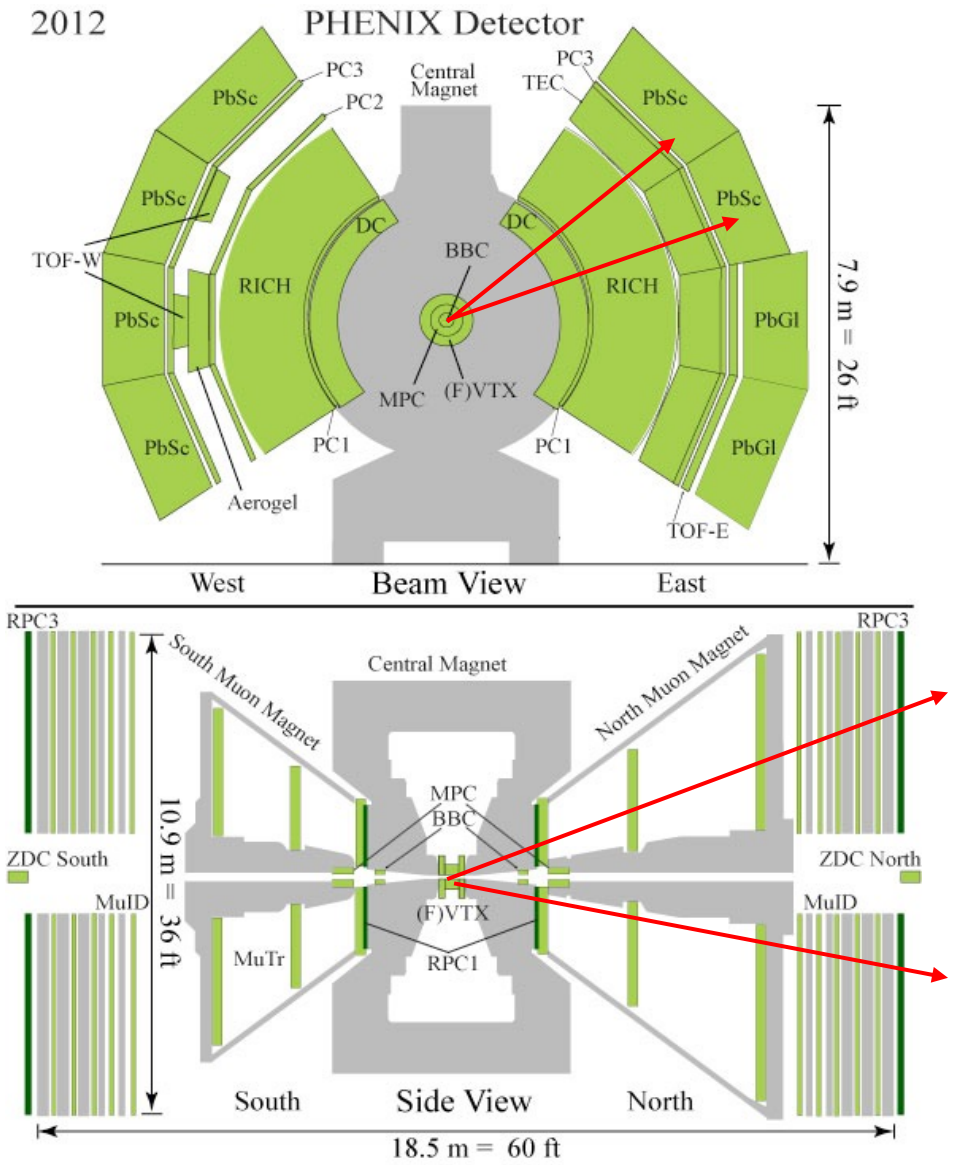
Measurement of Direct-Photon Cross Section and Double-Helicity Asymmetry at $\sqrt{s} = 510$ GeV in $\vec{p}+\vec{p}$ Collisions

"Study of charged hadron production in p+Al, 3He+Au, Cu+Au collisions at sqrt(sNN) = 200 GeV and in U+U collisions at sqrt(sNN) = 193 GeV"
Preprint: arXiv:2312.09827 inSPIRE, Citations
Submitted: 2023-12-14

RHIC energies, species combinations and luminosities (Run-1 to 16)



PHENIX Detector: J/ψ ->di-lepton



Central Arms $|\eta| < 0.35$
- Identified charged hadrons
- Neutral Pions/Etas
- Direct Photon
- J/ψ
- Heavy Flavor (VTX)

Muon Arms $1.2 < |\eta| < 2.4$
- J/ψ
- Unidentified charged hadrons
- Heavy Flavor (FVTX)

BBC/MPC $3.1 < |\eta| < 3.9$
- Neutral Pion's, Eta's
- Charged particles

ZDC $|\eta| \sim 5.9$
- Neutrons

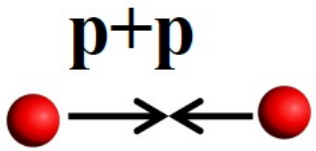
J/Psi & Psi(2S) Measurements:

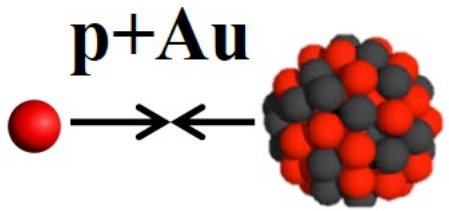
$J/\psi \rightarrow e^+ + e^-;$

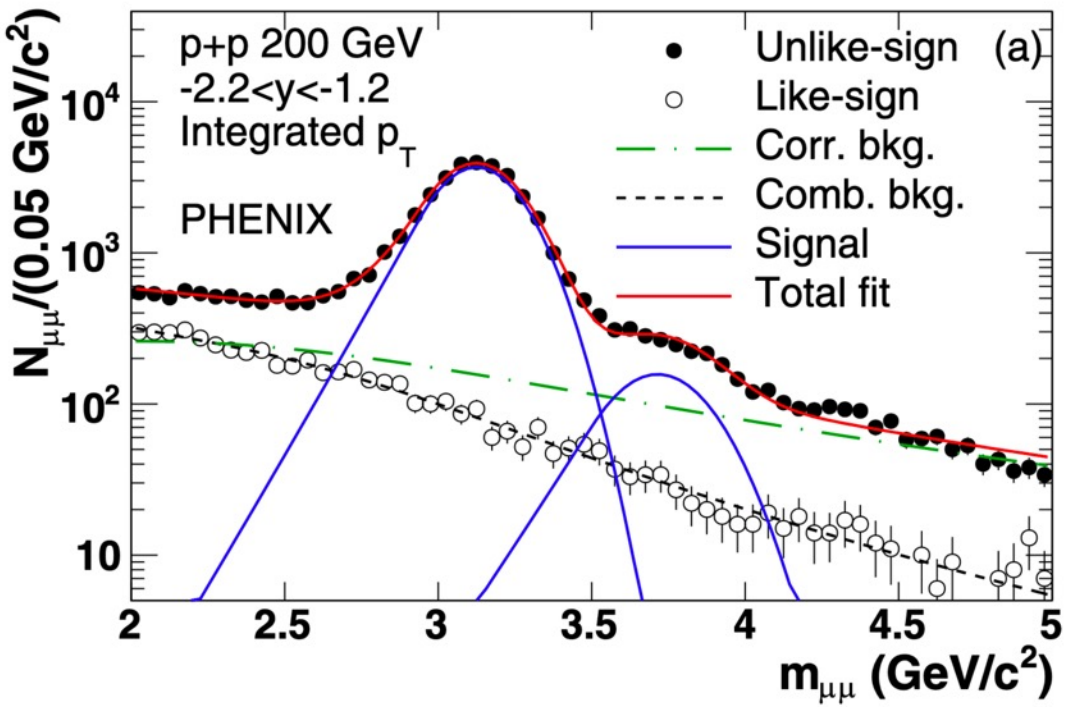
$\mu^+ + \mu^-;$

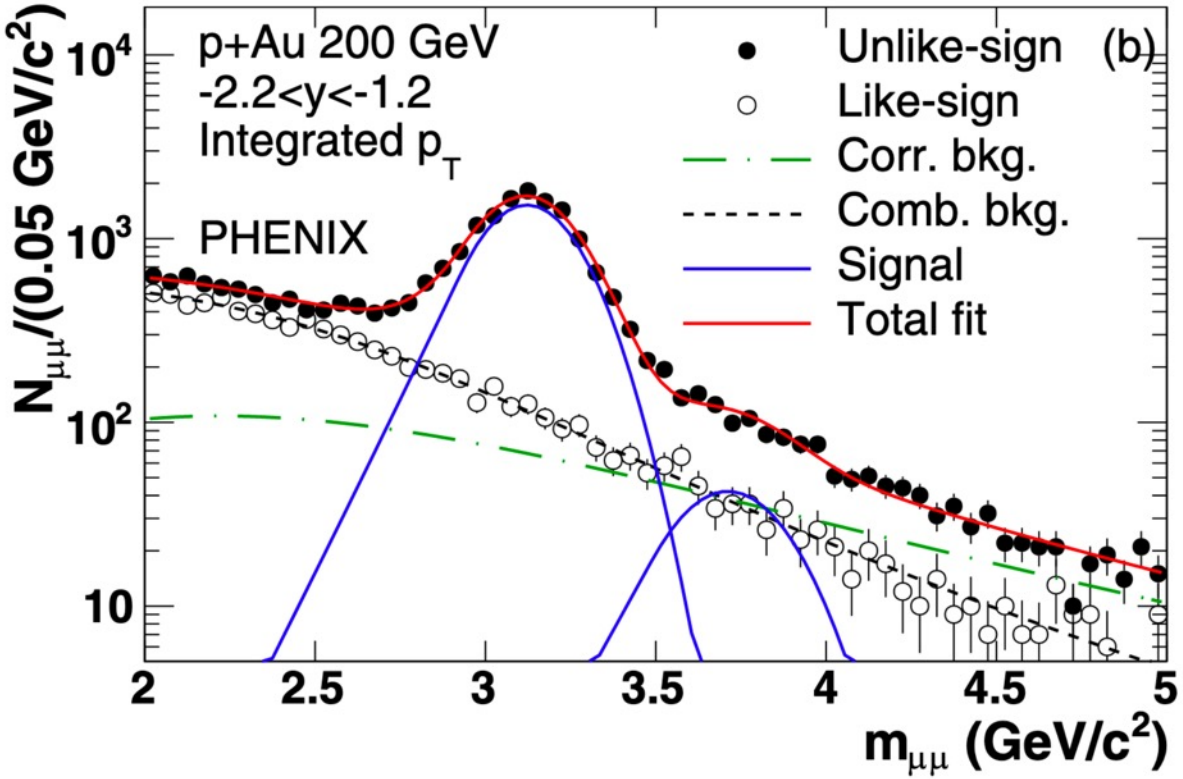
BR = 6%,
Good statistics;
Good triggers;

J/ψ, Psi(2S) Measurements in Dimuon Channel









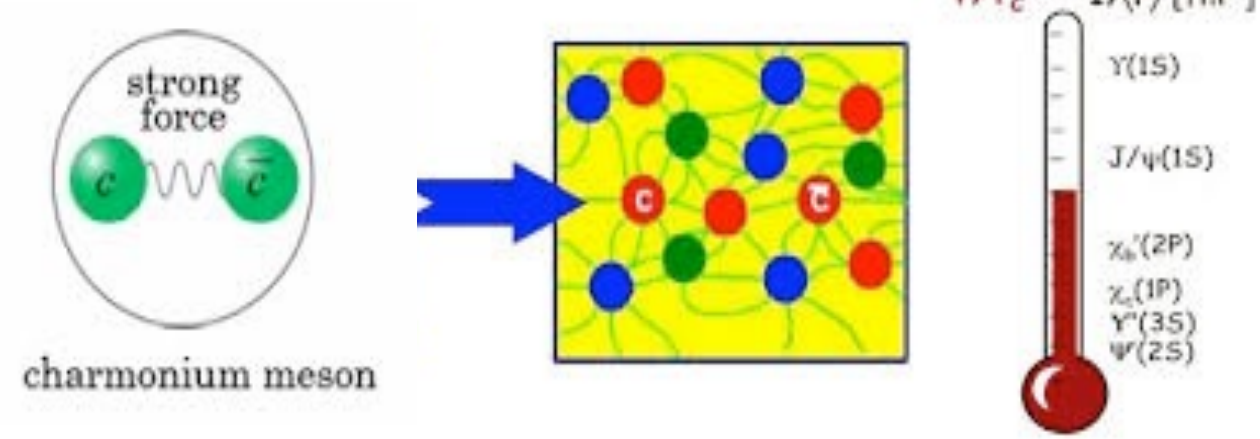
Selected Recent Highlights

- J/Psi flow in Au+Au collisions
- J/Psi, Psi(2S) and CNM in p+A (Al, Au)
- J/Psi and Psi(2S) productions vs event multiplicity (p+p)

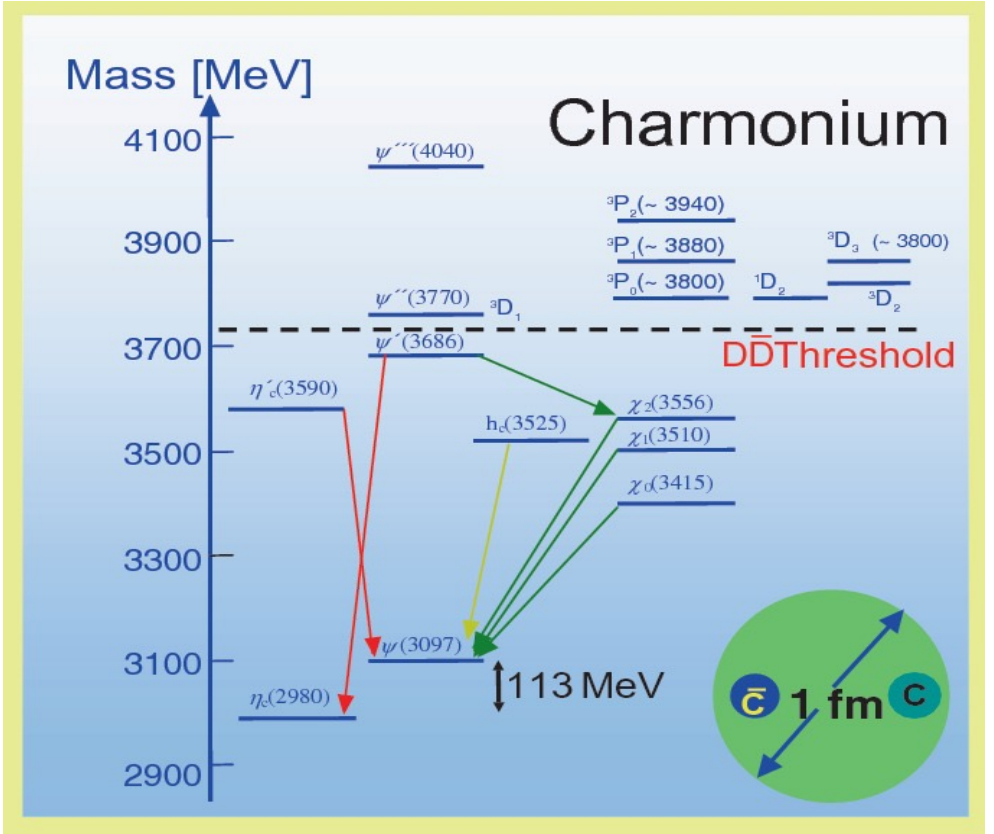
Run/Spec	p+p	Au+Au	d+Au	Cu+Cu	Cu+Au	U+U	He3+Au	p+Au	p+Al
Run-16		☐ 200GeV	☐ 200GeV ☐ 62GeV ☐ 39GeV ☐ 20GeV						
Run-15	☑ 200GeV							☑ 200GeV	☑ 200GeV
Run-14		☑ 200GeV ☐ 14.6GeV					☑ 200GeV		
Run-13	☐ 510GeV								
Run-12	☐ 510GeV ☐ 200GeV				☐ 200GeV	☐ 193GeV			
Run-11	☐ 500GeV	☐ 200GeV ☐ 27GeV ☐ 19.6GeV							
Run-10		☐ 200GeV ☐ 62.4GeV ☐ 39GeV ☐ 7.7GeV							
Run-9	☐ 500GeV ☐ 200GeV								
Run-8	☐ 200GeV	☐ 9.2GeV	☐ 200GeV						
Run-7		☐ 200GeV							
Run-6	☐ 200GeV ☐ 62.4GeV								
Run-5	☐ 410GeV ☐ 200GeV			☐ 200GeV ☐ 62.4GeV ☐ 22.4GeV					
Run-4	☐ 200GeV	☐ 200GeV ☐ 62.4GeV							
Run-3	☐ 200GeV		☐ 200GeV						
Run-2	☐ 200GeV	☐ 200GeV ☐ 19.2GeV							
Run-1		☐ 130GeV							

Why HF Quarkonium?

Matsui & Satz, Phys. Lett. B178 (1986)
- first quantitative predictions



https://link.springer.com/chapter/10.1007/978-3-030-79489-7_2/figures/1



Binding energy ~ O(10²) MeV ~ QGP Temperatures

Quarkonium dissociation by string breaking

S. Digal et al. / Physics Letters B 514 (2001) 57–62

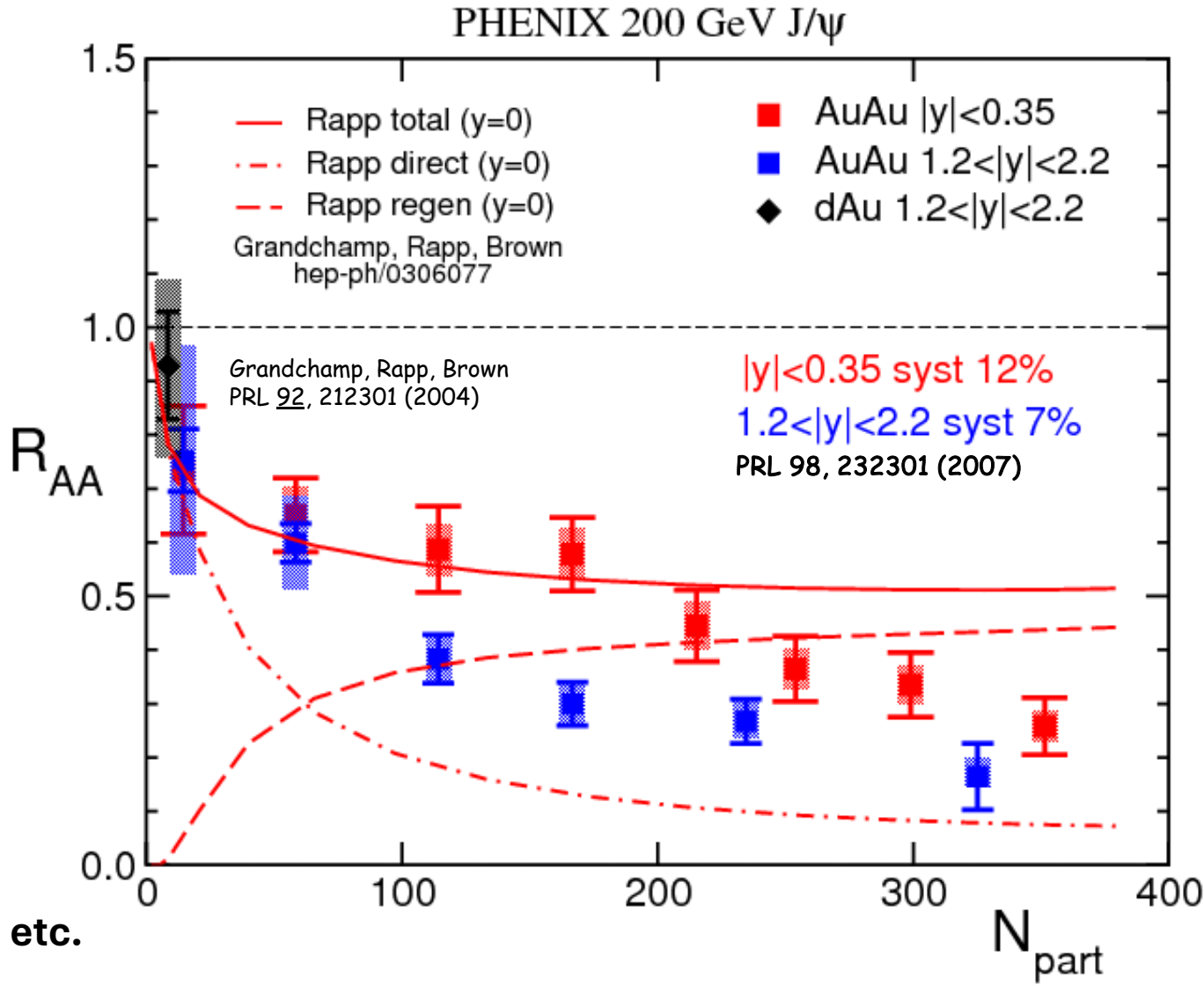
State	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
E_s^i (GeV)	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
T_d/T_c	–	0.74	0.1–0.2	–	–	$\gtrsim 0.93$	0.83	0.74

Suprises from the frist J/Psi Measurements in Au+Au

- New phenomena, regeneration compensating for screening!

- Larger gluon density at RHIC expected to give stronger suppression than SPS
- But larger charm production at RHIC gives higher probability of regeneration, <c-cbar> ~20 in central Au+Au at top energy
- Forward rapidity lower than mid due to smaller open-charm density there for recombination

- Sensitive to open-charm production
  - Expect inherited flow from open charm;
  - Expect regeneration would be HUGE at the LHC! Confirmed many years later!

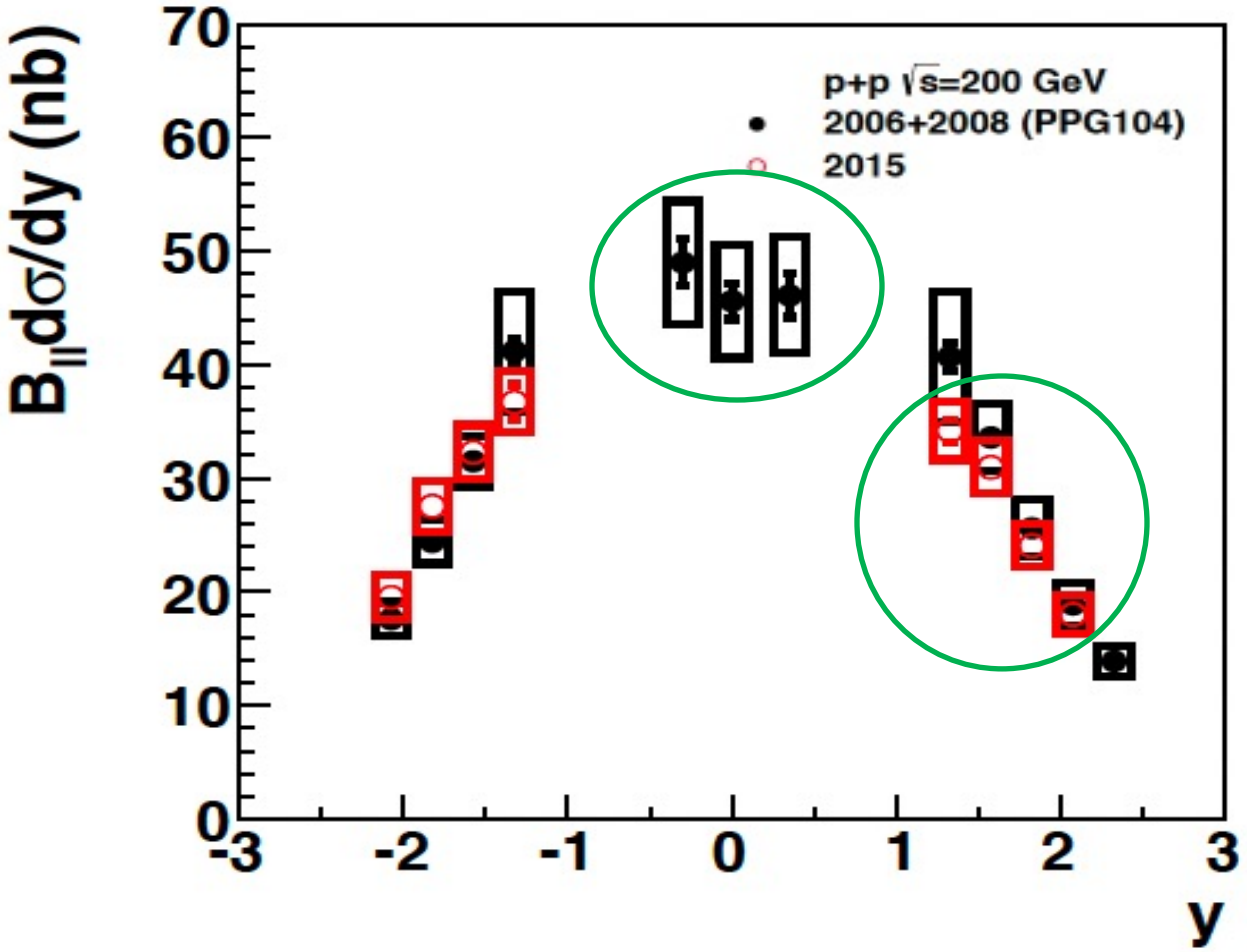


Need to go beyond a simple "color screening" model,
- check other observables/effects: flow, particle ratios etc.

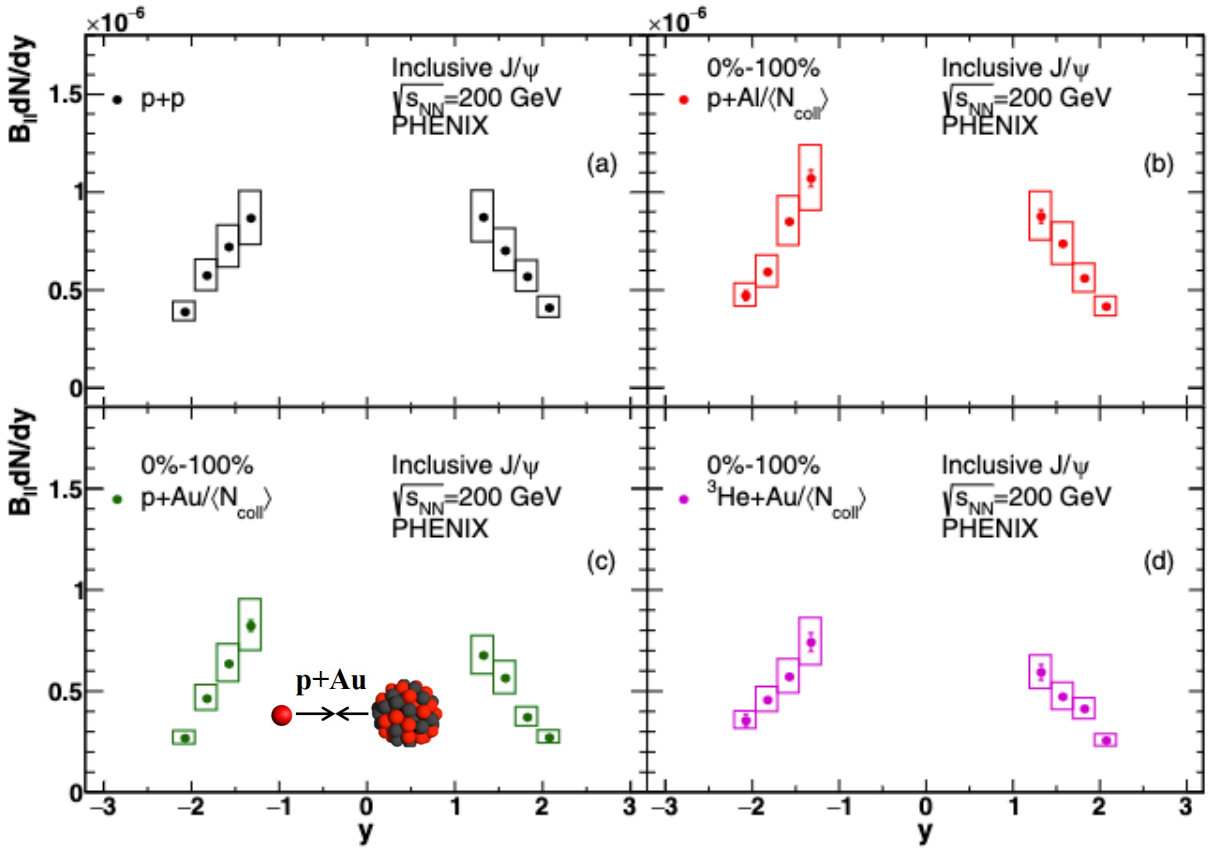
J/Psi Production vs Rapidity

- p+p, p+Al, p+Au, ^{3}He+Au

PHENIX, PRC 102, 014902 (2020)

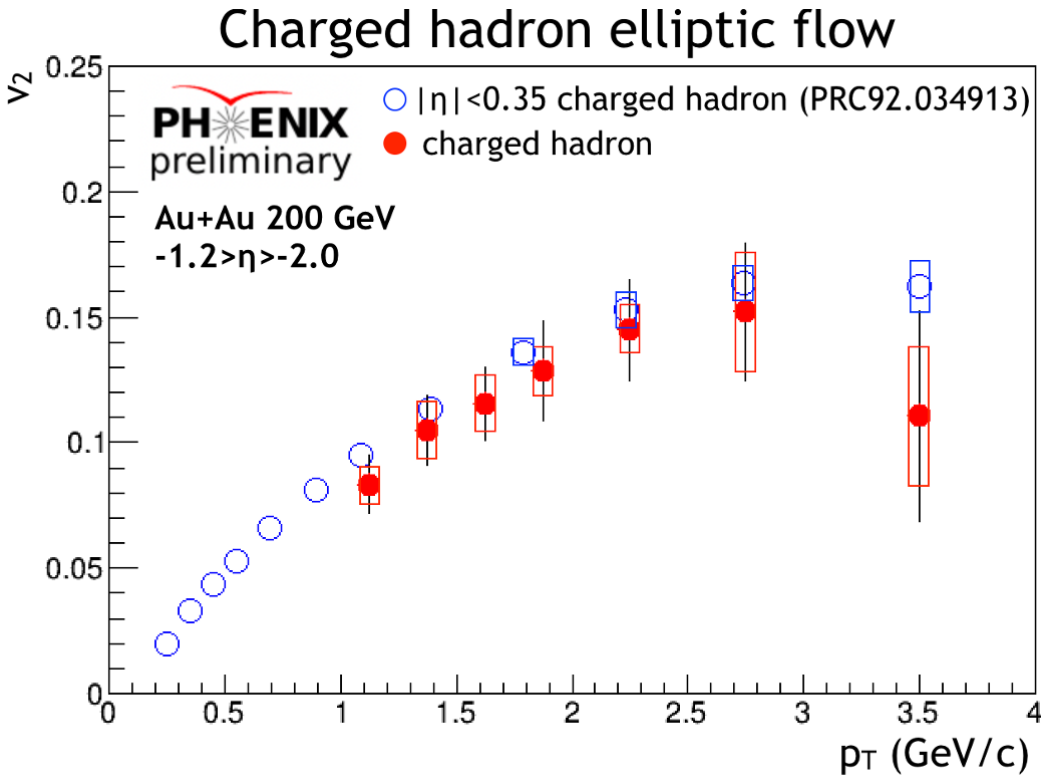


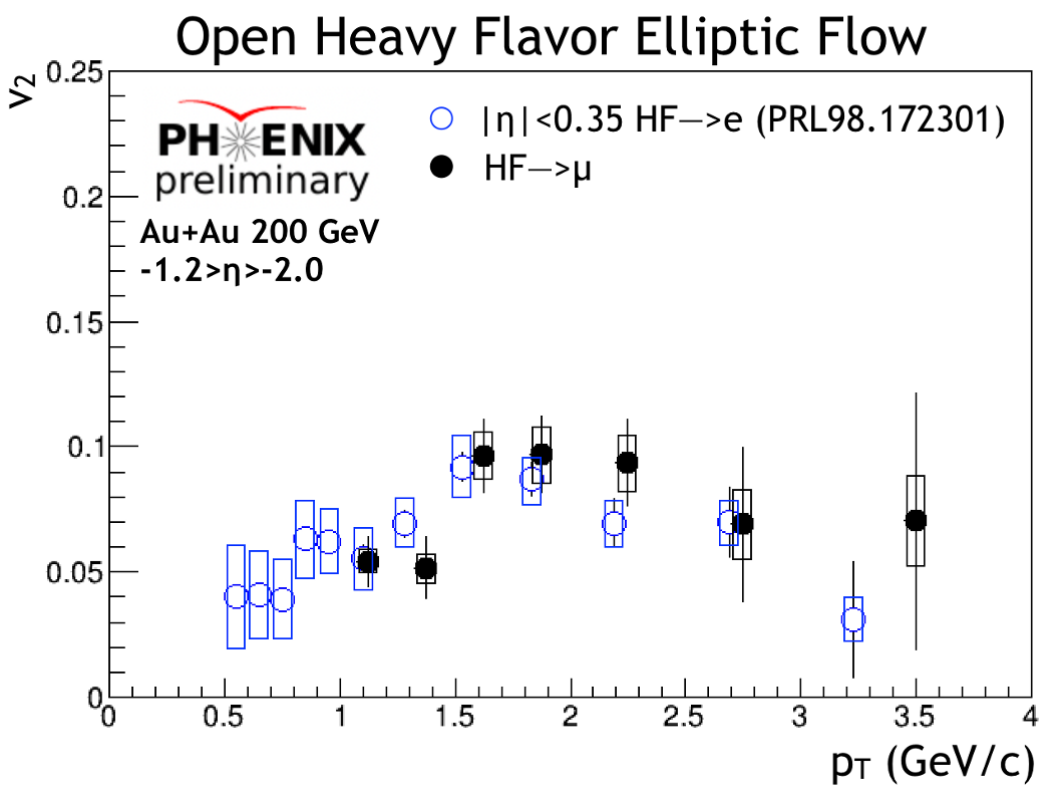
Forward/Backward J/Psi measured in dimuon channel in p+p/Al/Au & ^{3}He+Au



None-zero Open HF v_2 Observed:

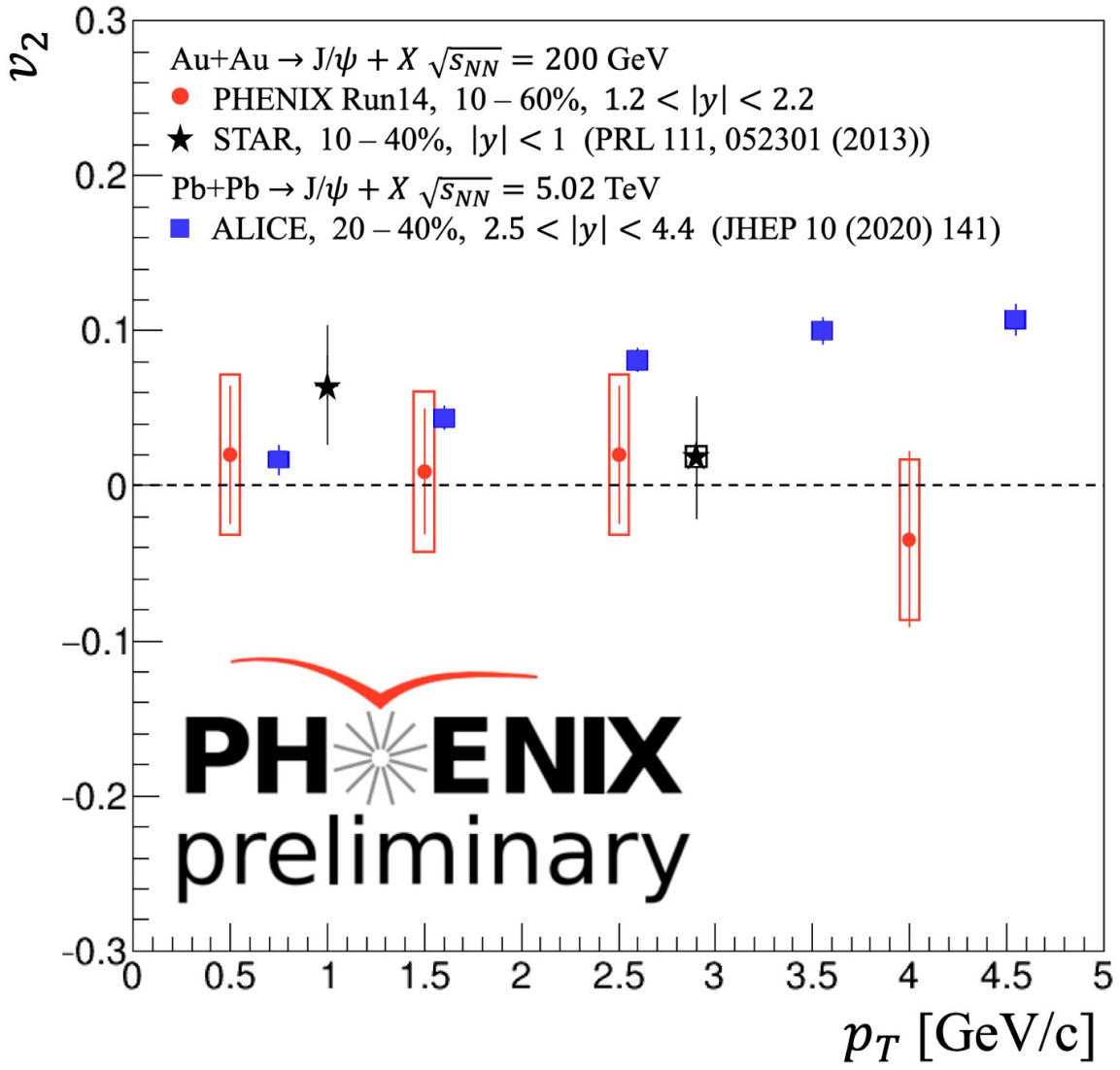
- at both central & forward rapidity





- First observation of none-zero open heavy flavor v2 at the forward rapidity
  - Consistent with mid-rapidity HF results
  - Smaller than light hadron v2
  - **Similar magnitude in central and forward rapidity**

First J/Psi v2 in the forward rapidity



- Compared with STAR (central) and ALICE (forward) none-zero v2, much smaller v2 in the forward rapidity, consistent with zero
  - ➢ Open charm, none-zero v2!
  - ➢ Final State Interactions(FSI)
    - Breakup?
  - ➢ J/Psi formation
    - lack of “recombination” in the forward rapidity?
- Run2016 Au+Au, in progress
  - 4x more stat!

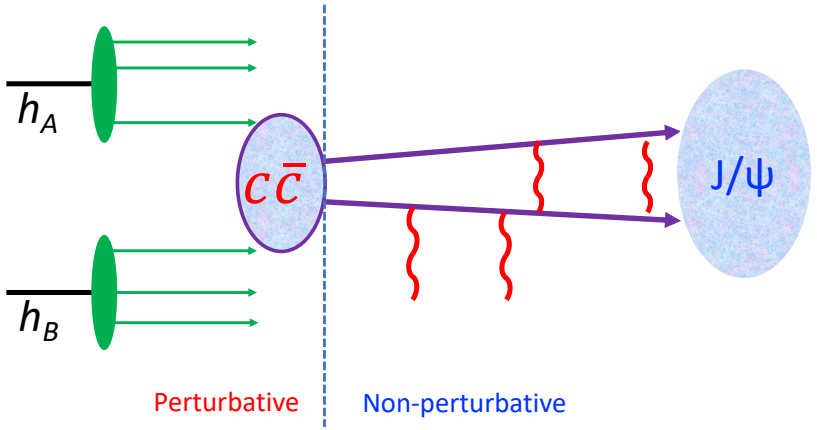
J/ψ Production

Perturbative + **Non-perturbative**

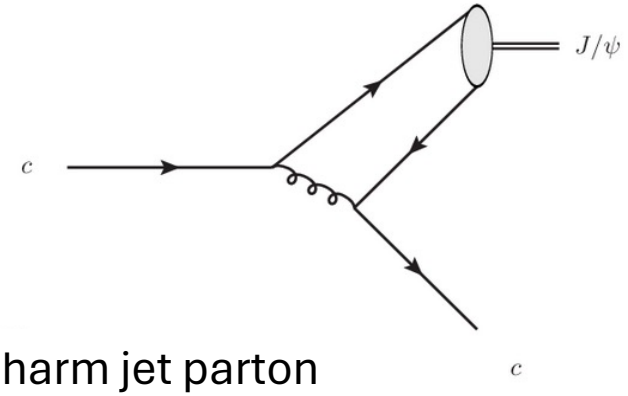
- J/ψ ($c\bar{c}$), a simplest QCD system

- "$c\bar{c}$" pair from hard processes
  - Low pT:
    - Traditional "single" hard scattering process in "p+p"
    - Multiple semi-hard parton interactions (MPI), important at high energy
  - High pT:
    - Jet fragmentation and parton shower, important at high pT

- "$c\bar{c}$" hadronization to J/ψ
  - Color neutralization
    - NRQCD
    - Color evaporation
  - Interactions with QCD medium in HI
  - Recombination if multiple < $c\bar{c}$ > pairs created in HI



I. Belyaev et al, Mod. Phy. Lett. A, (2017)



Charm jet parton shower..

Charmonia in p+p, p+Al, p+Au

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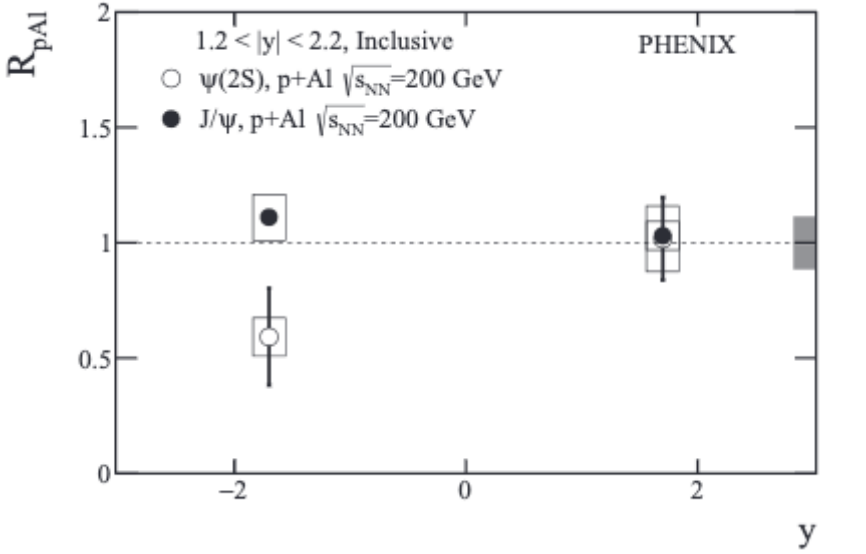
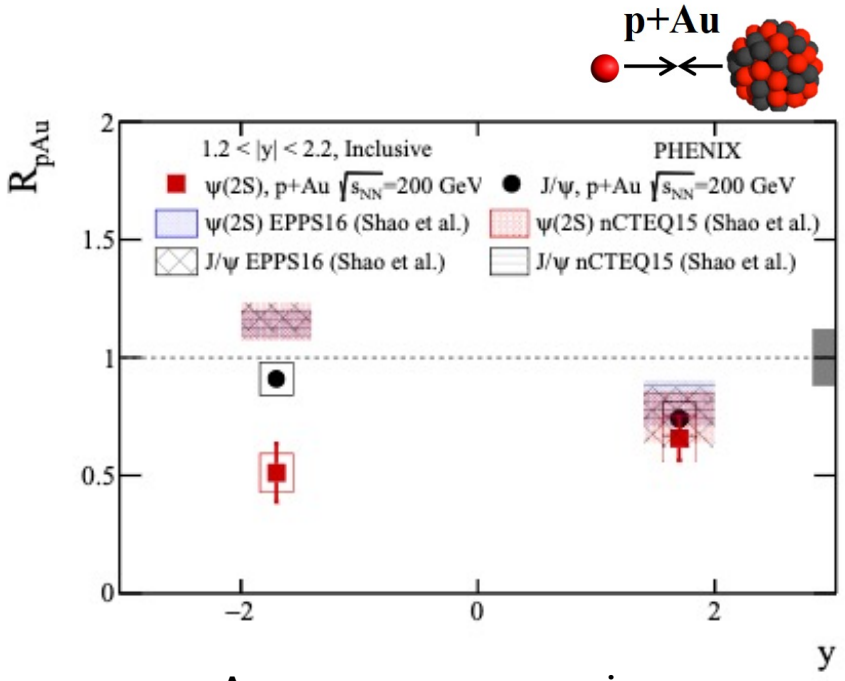
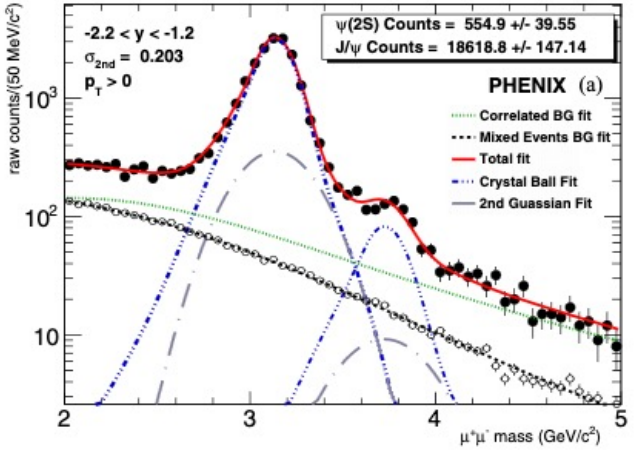
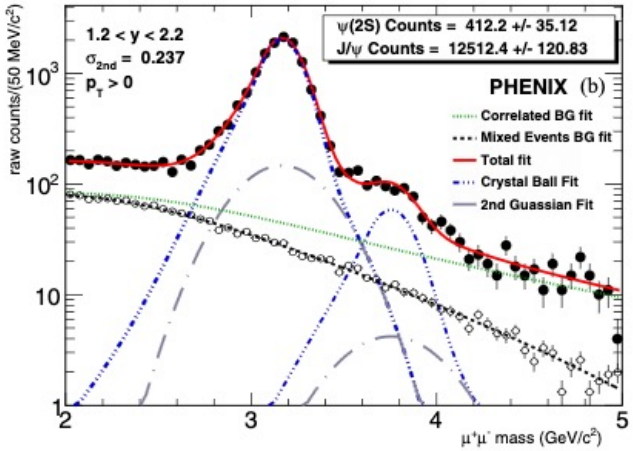


- p+Al: more suppression in Psi(2S) in the backward rapidity

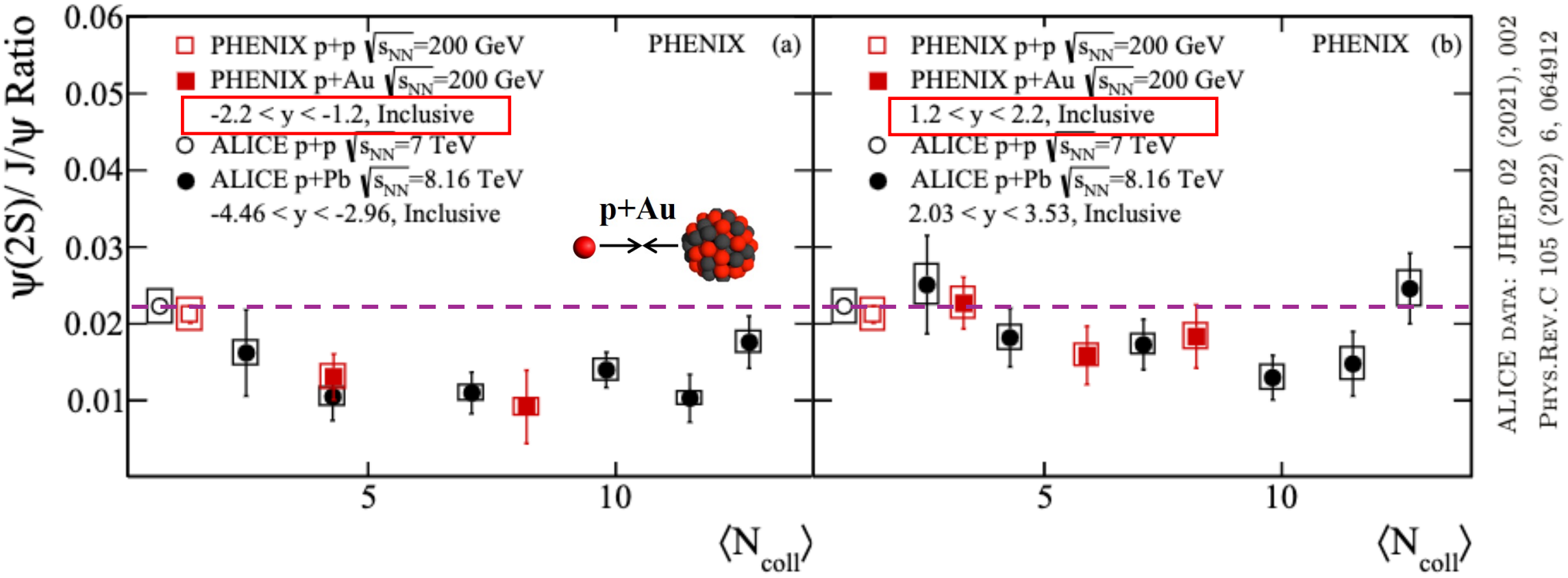


- p+Au: more suppression, in both F & B rapidity



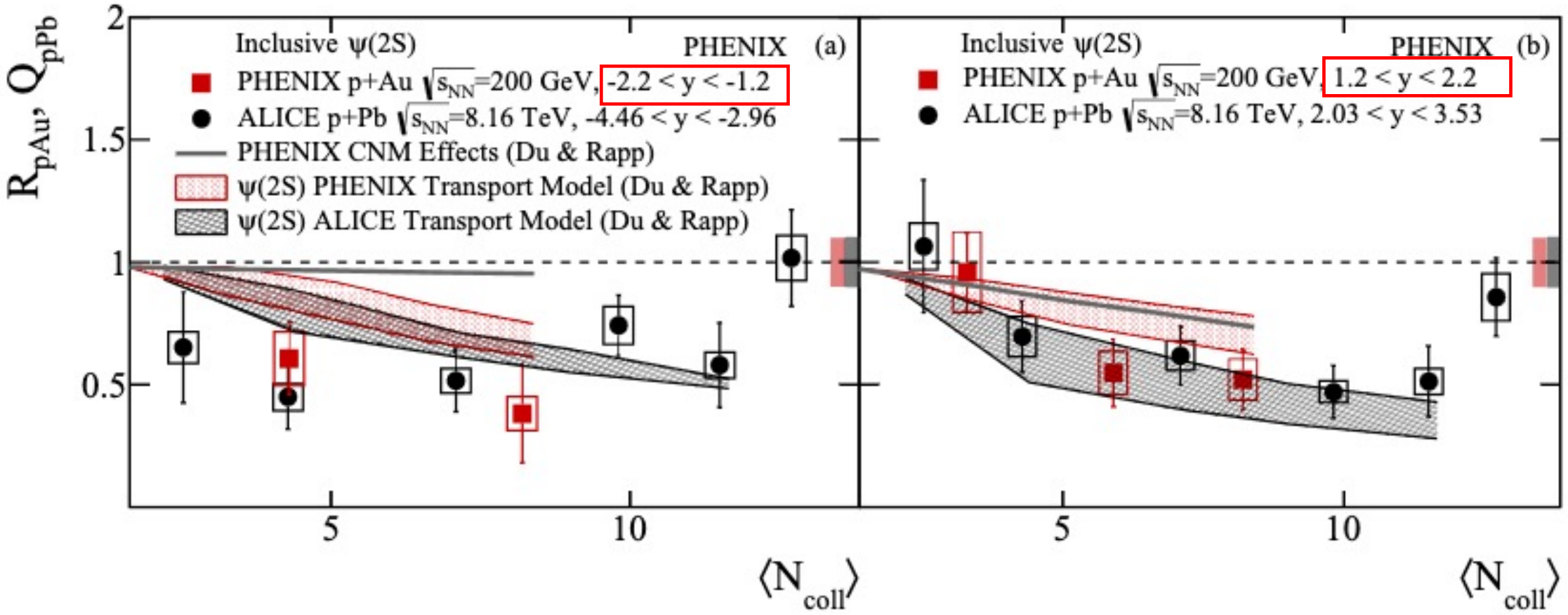


Psi(2S) to J/Psi Ratios in p+A at RHIC and LHC



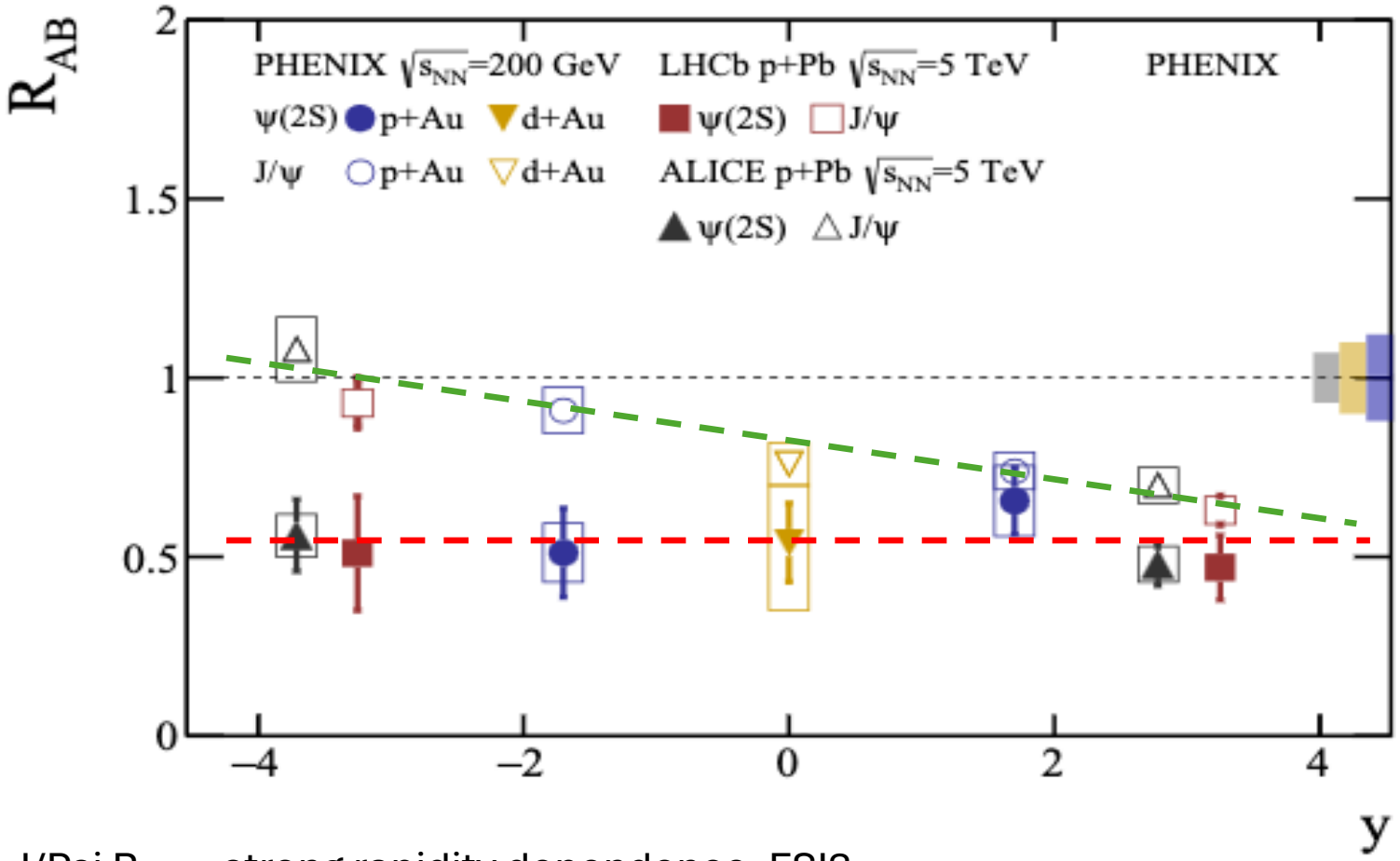
- Similar suppression pattern, weak energy dependence
- Final stat effect is significant, and larger in the backward rapidity where multiplicity is higher

Compared with Models



- stronger suppression in the backward rapidity, more final state effects not accounted for?

RHIC vs LHC R_{AB} : Put them all together

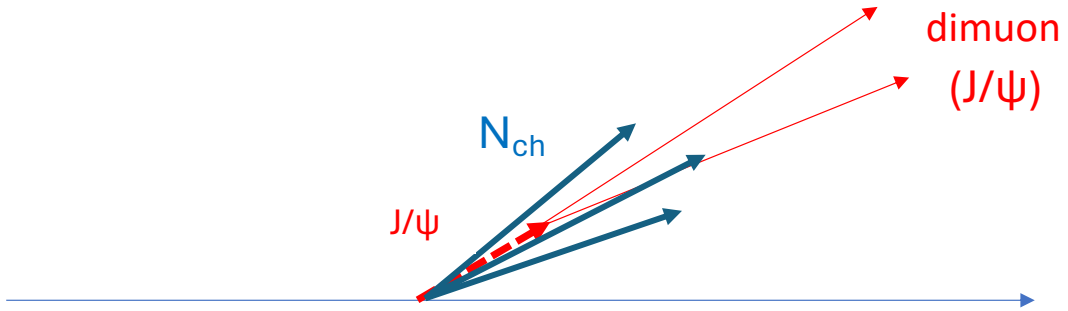


- J/Psi R_{AB} ~ strong rapidity dependence, FSI?
- Psi(2S) R_{AB} remain ~flat vs rapidity, also independent of collision energy, suppression already saturated?

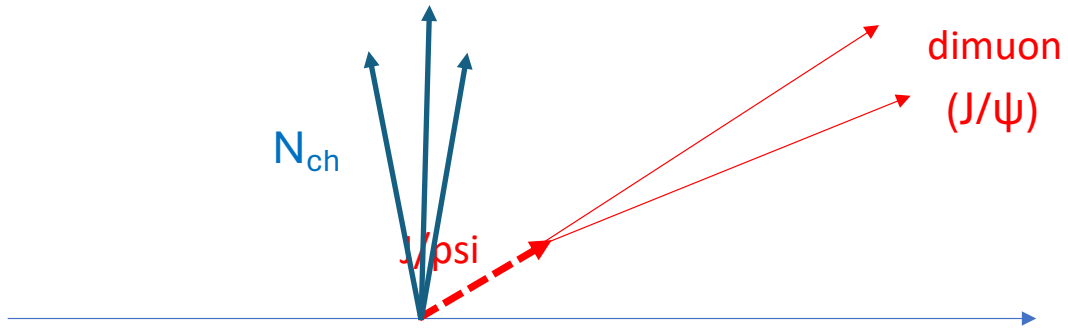
Study J/ψ Yields vs Event Multiplicity at Different Rapidity

- **Final State Interactions (FSI)**
- **Local event multiplicity: N_{ch}**
- **Multi-Parton Interactions (MPI)**

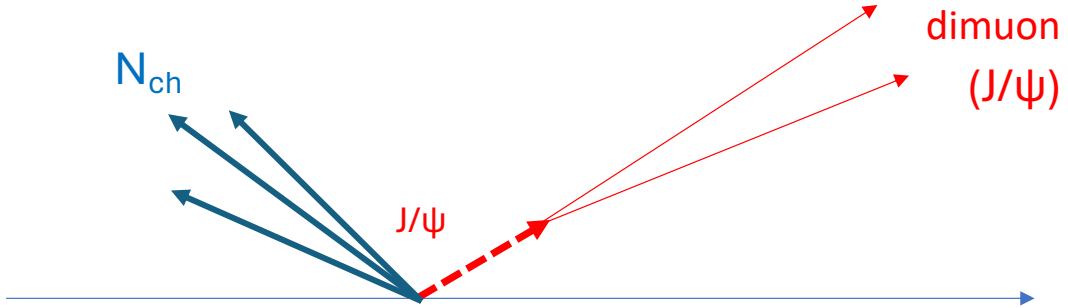
$J/\psi \rightarrow \mu^+ + \mu^-$



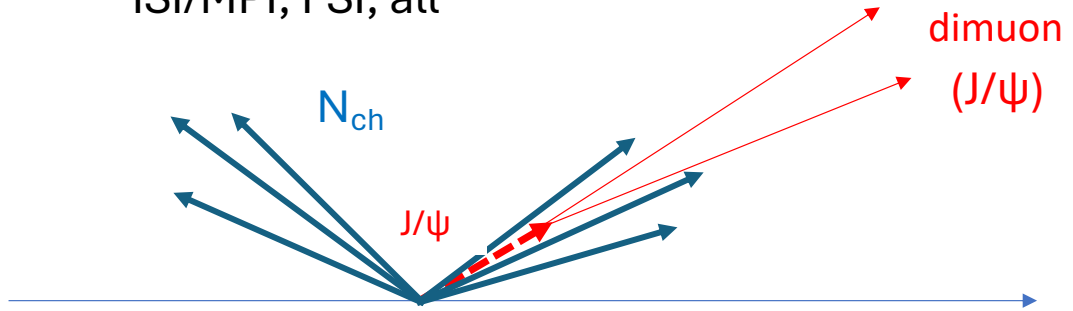
MPI, local energy density?



MPI, local energy density?



ISI/MPI, FSI, all

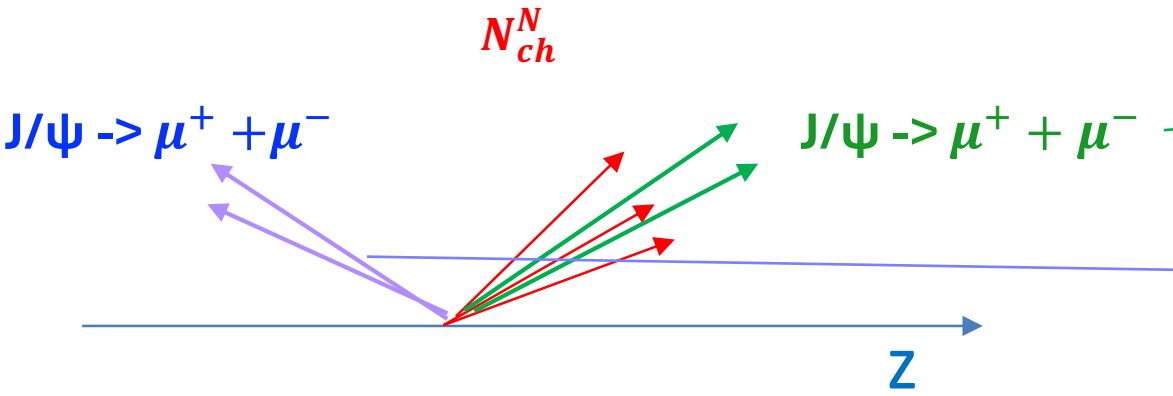


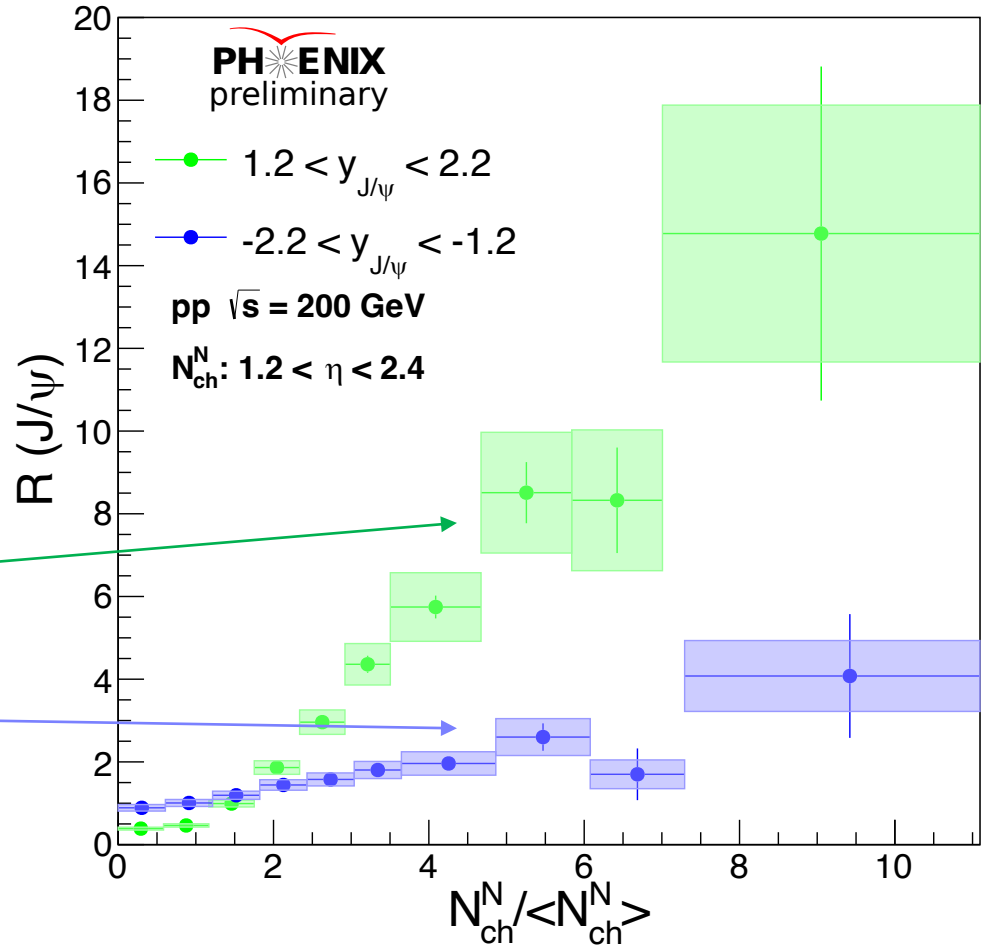
J/ψ Yields vs Event Multiplicity

RED = Tracklets N_{ch}^{N} ($1.2 < \eta < 2.4$)

Green = J/ψ ($1.2 < y < 2.2$)

Blue = J/ψ ($-2.2 < y < -1.2$)



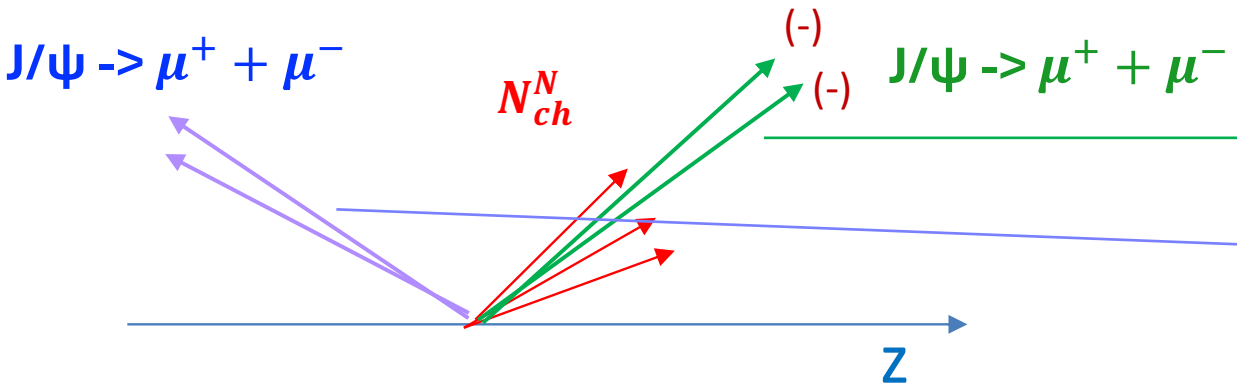


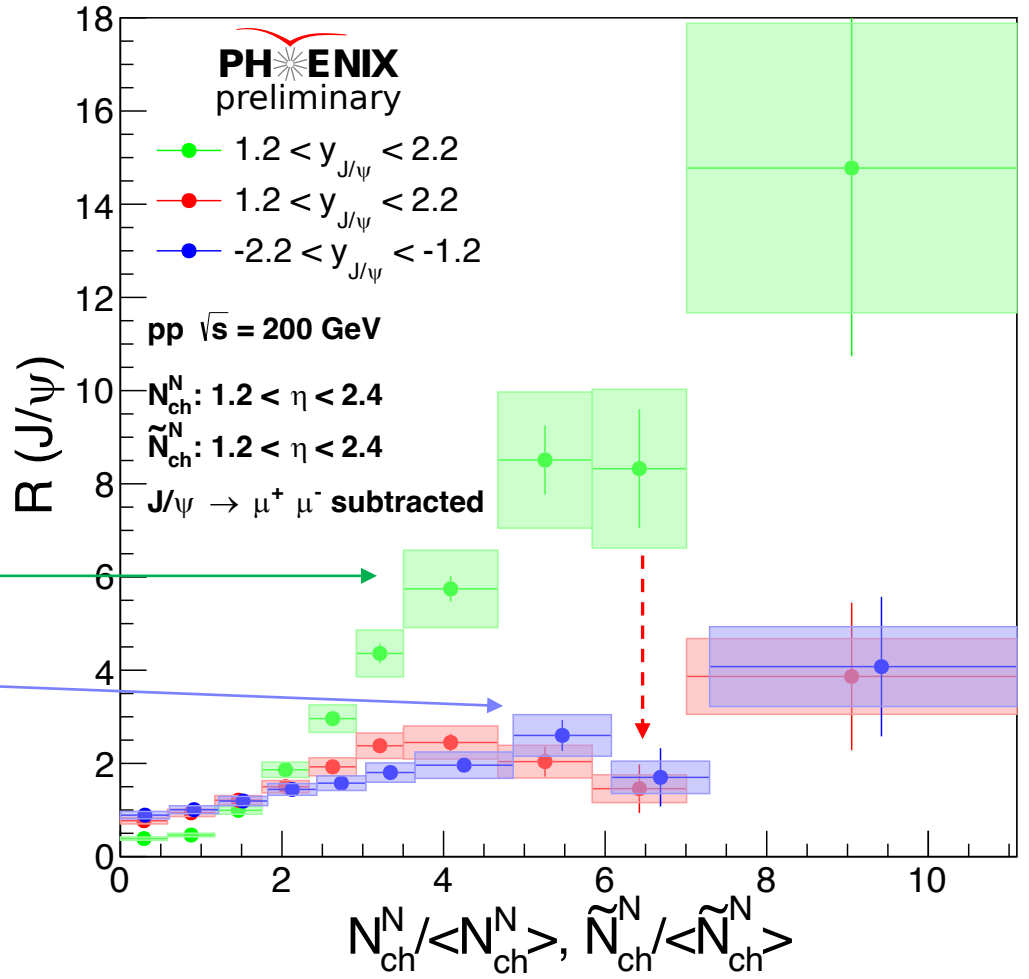
J/ψ Yields vs Event Multiplicity: All Together

RED = Tracklets $N_{ch}^{N}(1.2 < \eta < 2.4)$ [inclusive, dimuon subtracted]

Green = J/ψ (1.2 < y < 2.2)

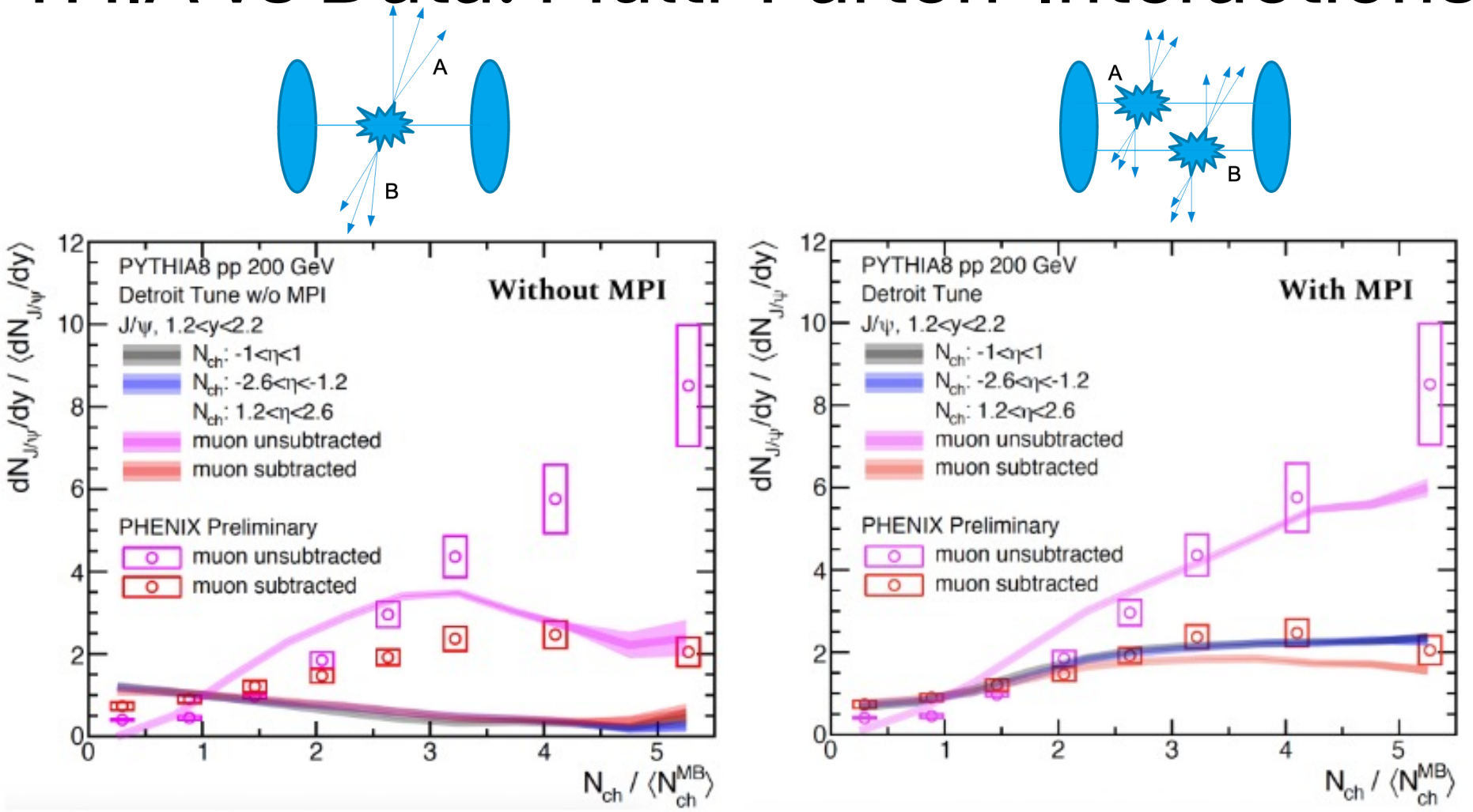
Blue = J/ψ (-2.2 < y < -1.2)





- Less MPI contribution to the forward **J/ψ** production?

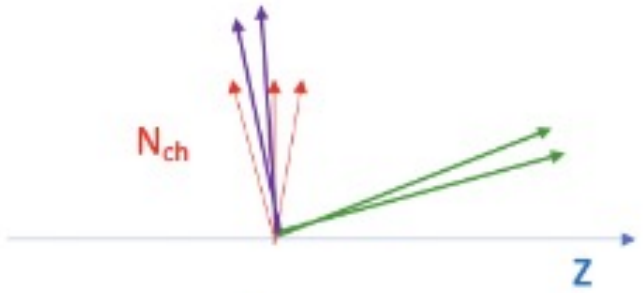
PYTHIA vs Data: Multi-Parton-Interactions



- PYTHIA8 Detroit tune reasonably agree with PHENIX data, with MPI
  - ➢ w/o MPI, fit failed badly
- Proper understanding of the Underline Events is important

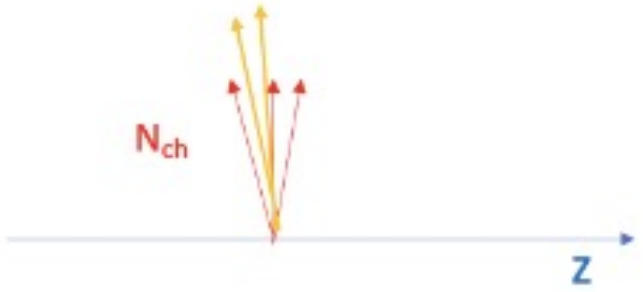
J/Psi Multiplicity Dependence: RHIC vs LHC

ALICE:



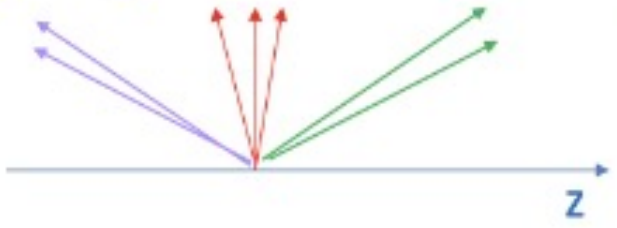
Dileptons not subtracted in ALICE, STAR "N_{ch}"

STAR:

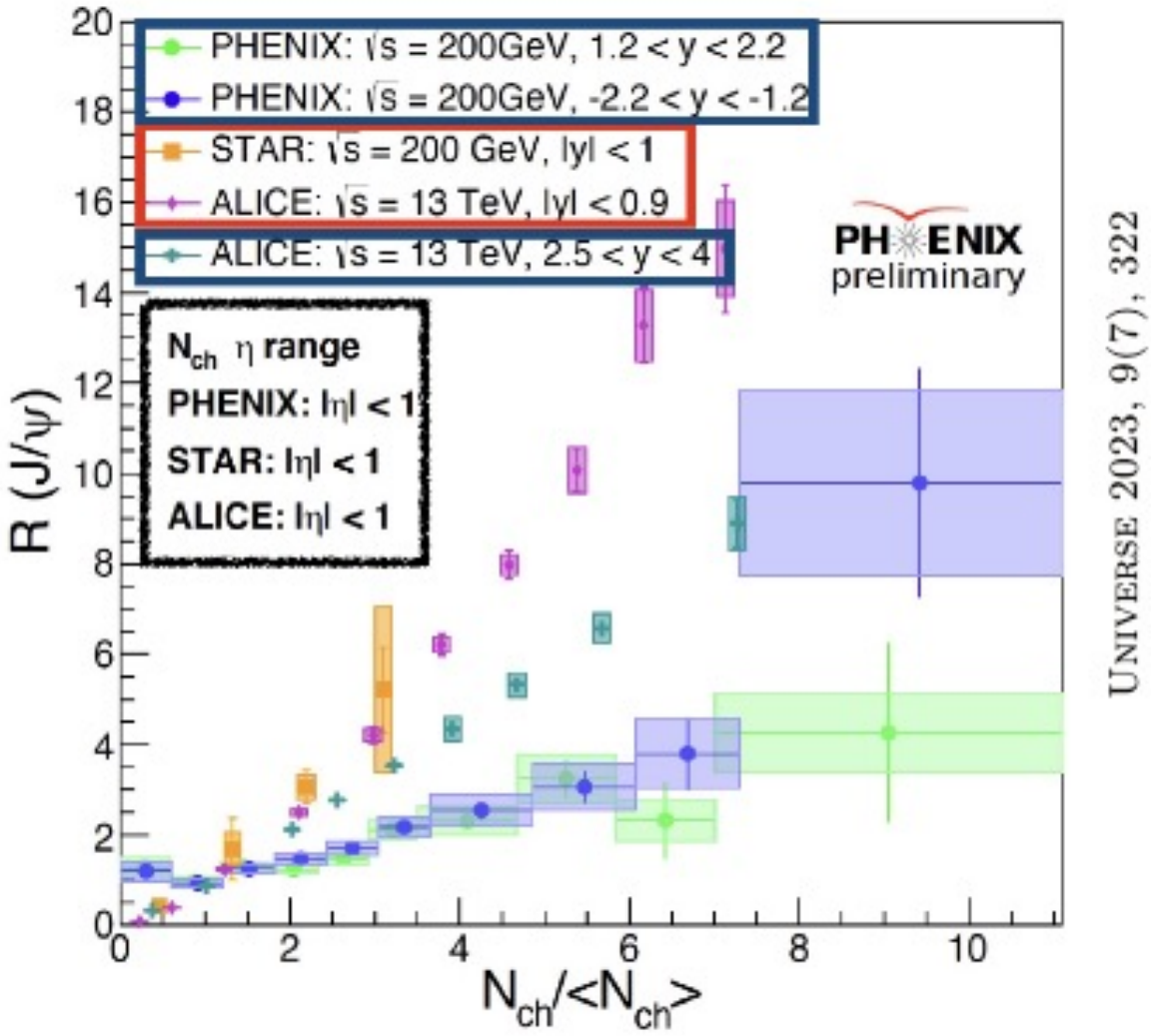


$J/\psi \rightarrow \mu^+ + \mu^-$ N_{ch}^N $J/\psi \rightarrow \mu^+$

PHENIX:

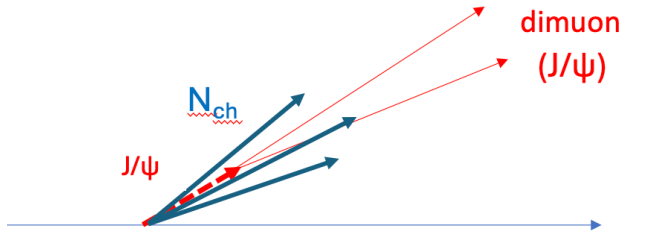


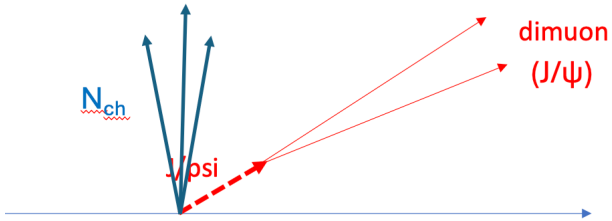
$dN_{J/\psi} / dy \; / \; < dN_{J/\psi} / dy >$

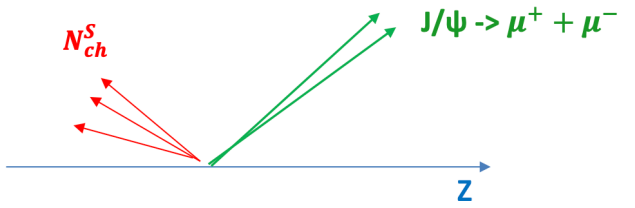


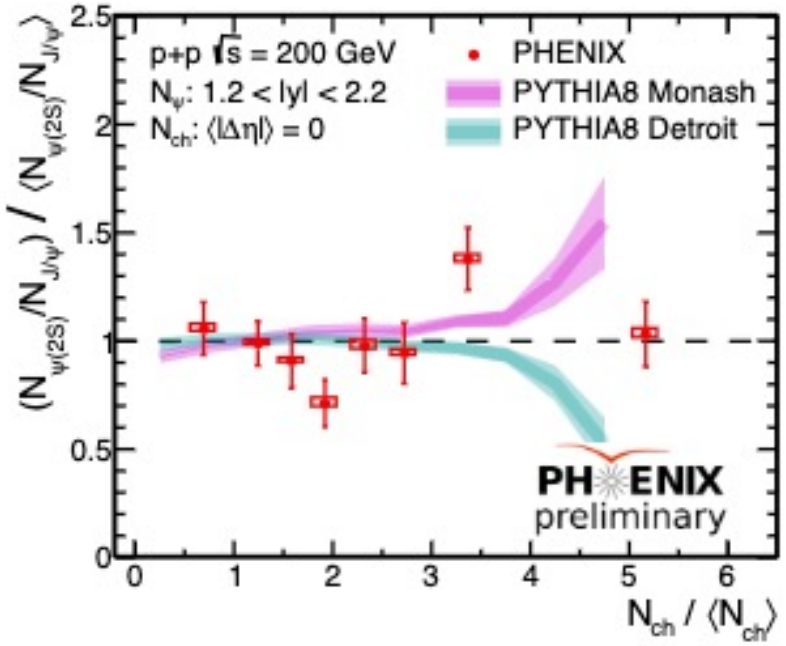
Universe 2023, 9(7), 322

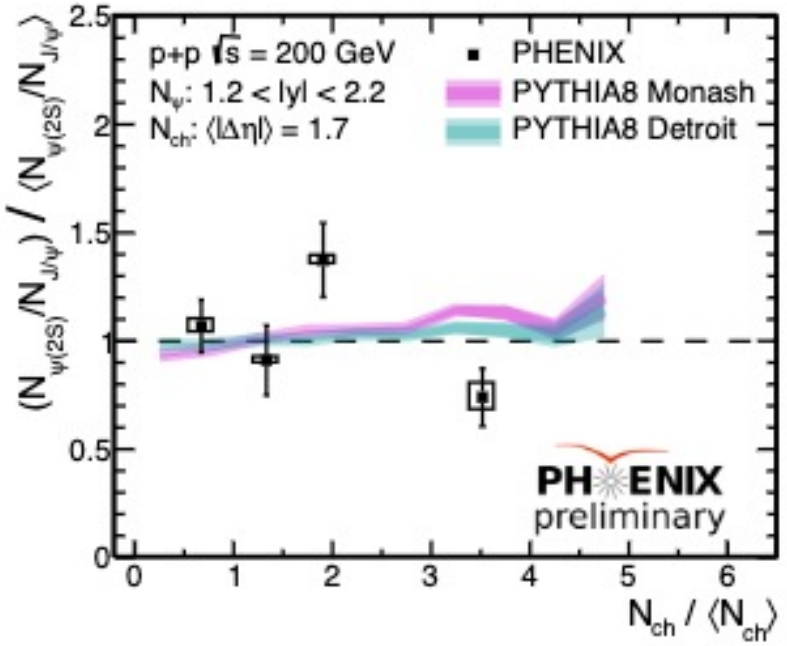
More about FSI: Psi(2S) to J/Psi Ratios

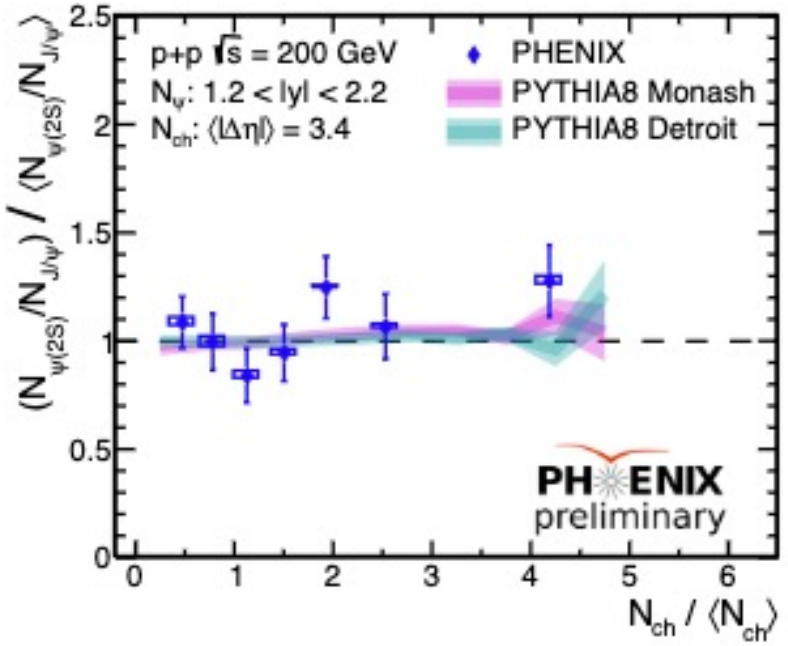






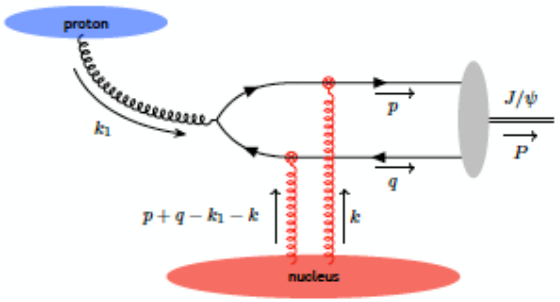


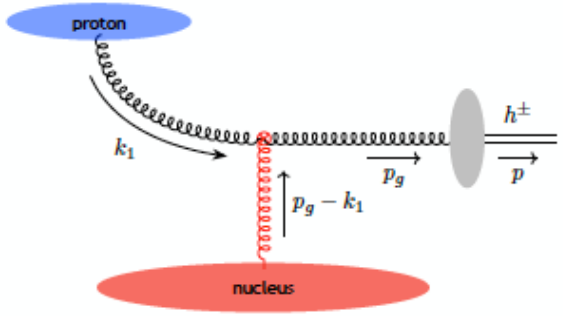


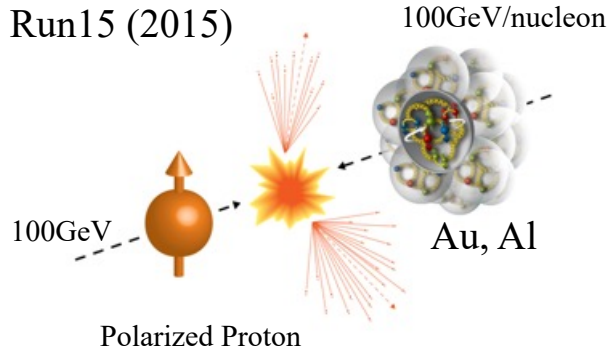


- FSI co-mover interaction effect seems similar to J/Psi and Psi(2S), interesting!
- Weak dependance to underline event multiplicity determined in different rapidity

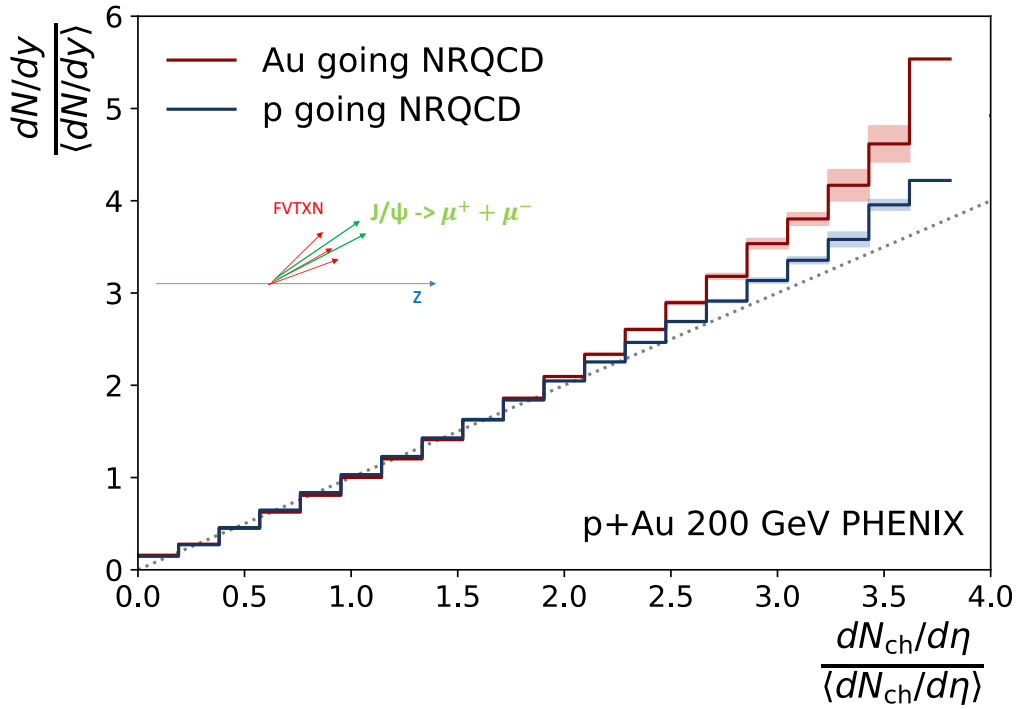
Probe CGC in p+Au?

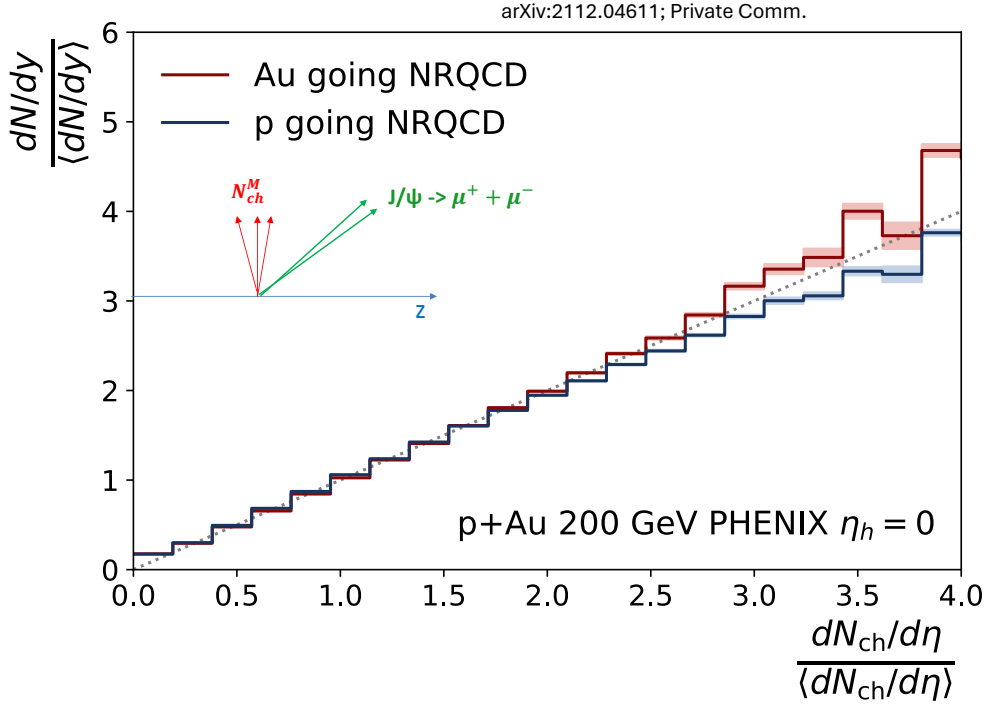






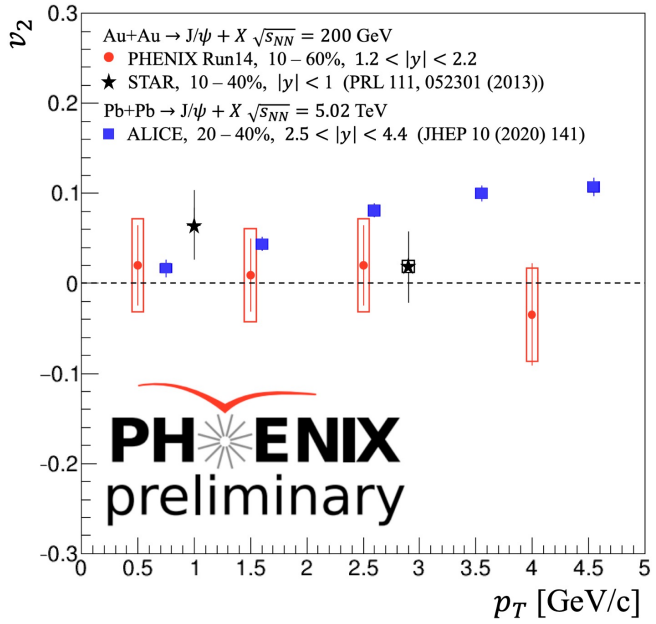
Farid Salazer, Bjorn Schenke and Alba Soto-Ontoso
arXiv:2112.04611; Private Comm.

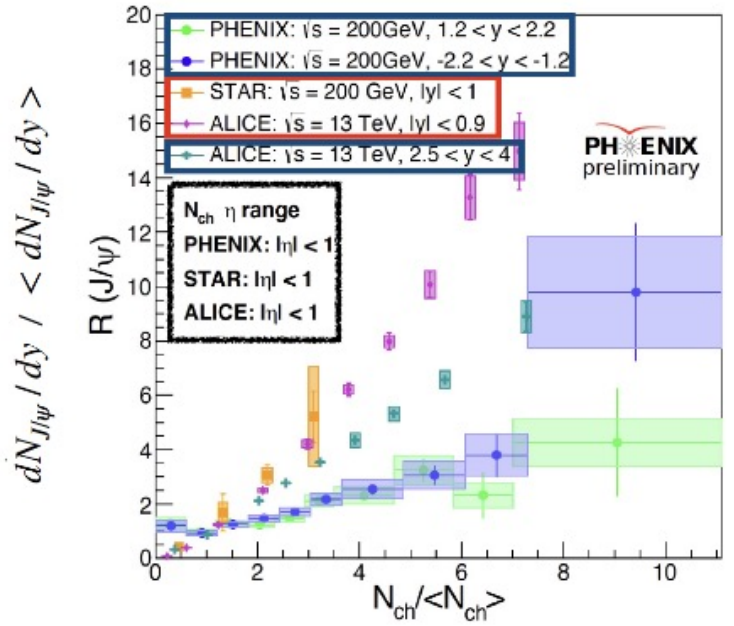




Summary and Outlook

- First J/Psi v2 measured in the forward rapidity in Au+Au, small, consistent with zero
  - ➢Shed new light on J/Psi production at RHIC
  - ➢Run16 data analysis, in progress
- Very rich QCD physics beyond QGP screening
  - ➢Initial state effects, geometry, nPDF
  - ➢Final state effects, co-mover, recombination
- Strong none-trivial correlation observed between J/Psi yield and UE activity at different rapidity
  - ➢Global vs local density?
  - ➢p+Au data analysis, in progress

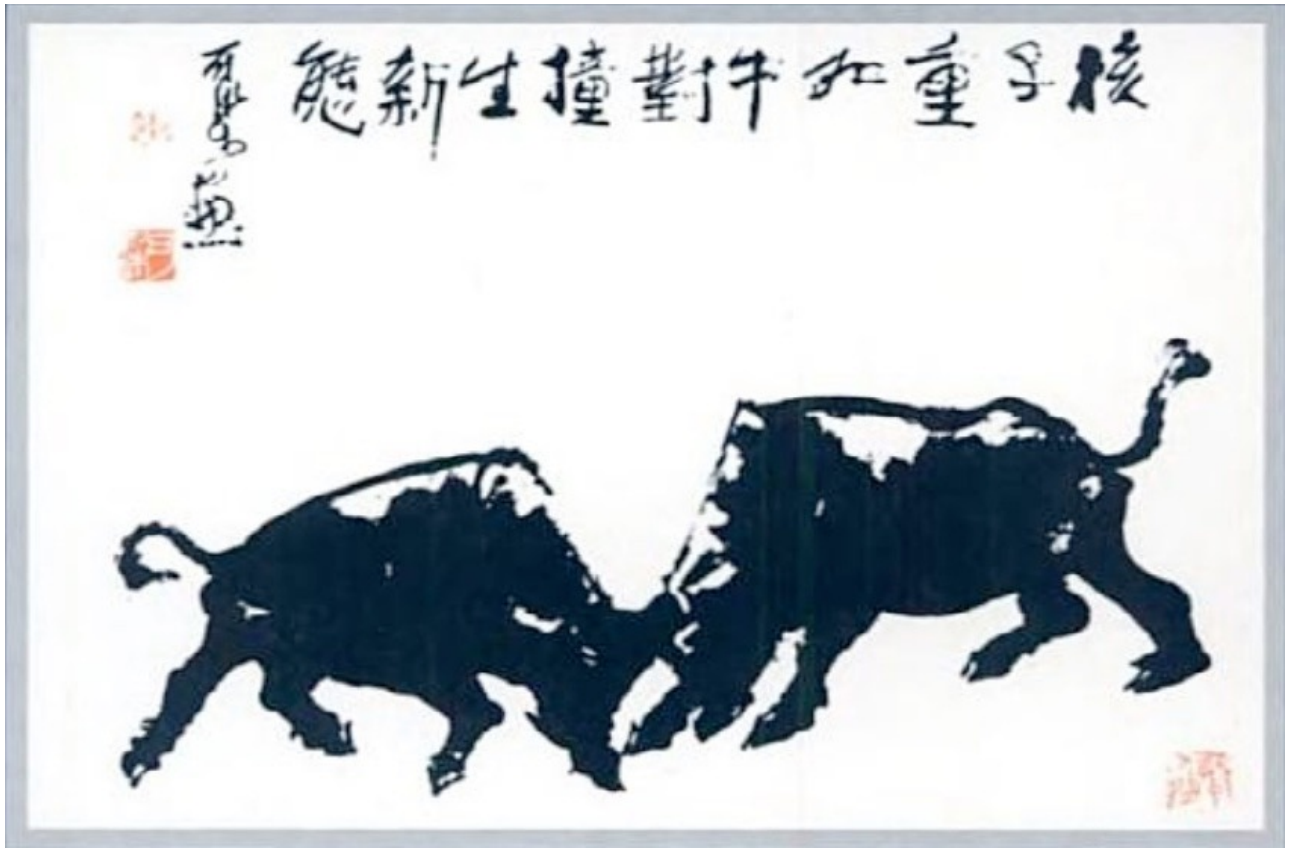


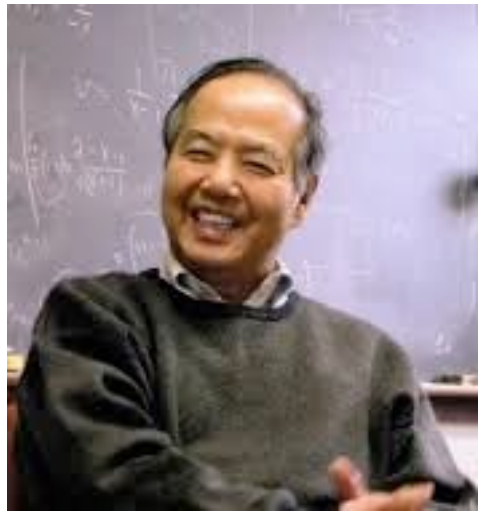


Heavy Ion Collisions

- an exciting playground for QCD physics

Birth of Relativistic Heavy Ion Collider (RHIC) at BNL, 1983

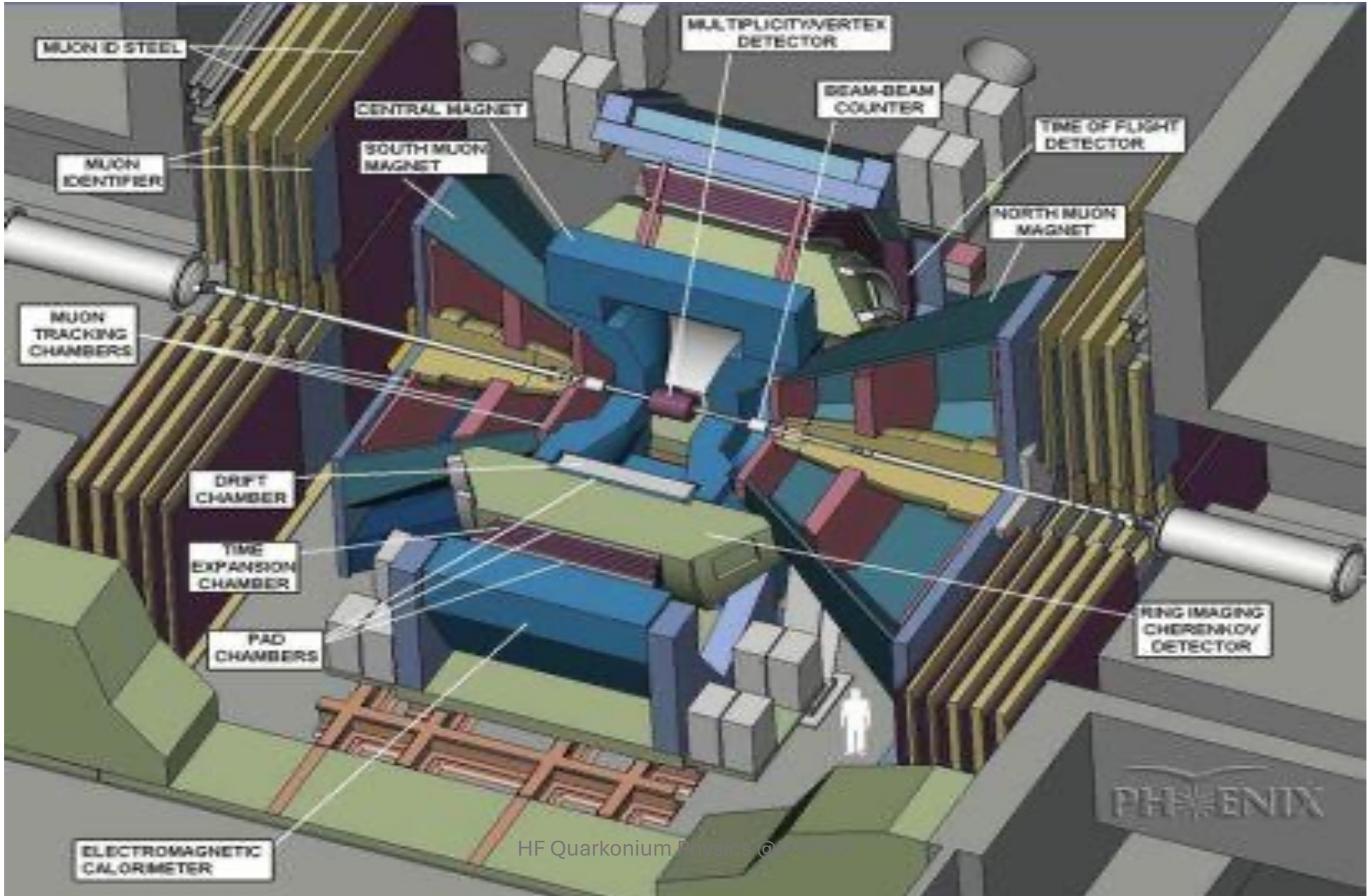




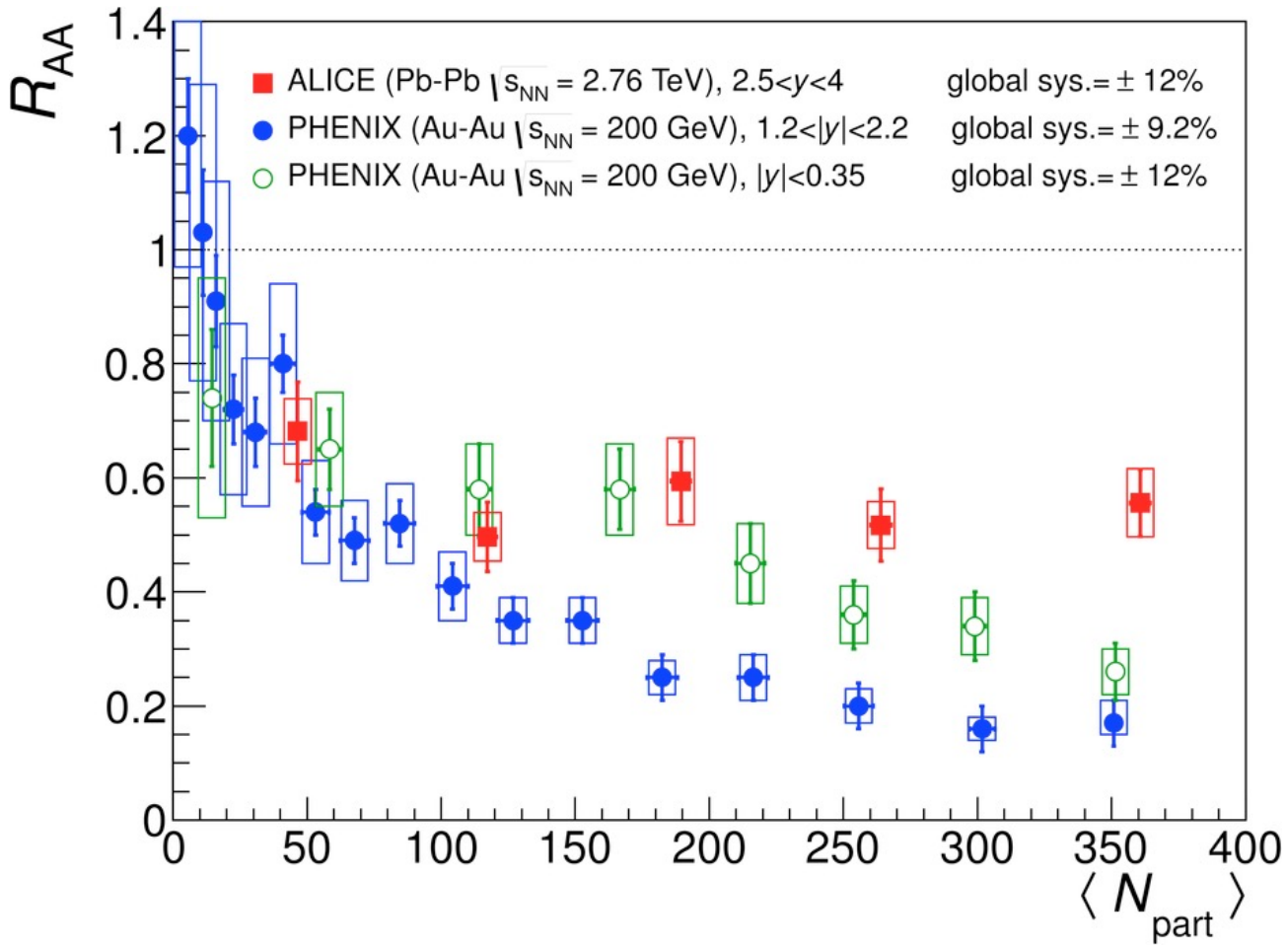
T. D. Lee
Nobel Prize, 1957

Backup

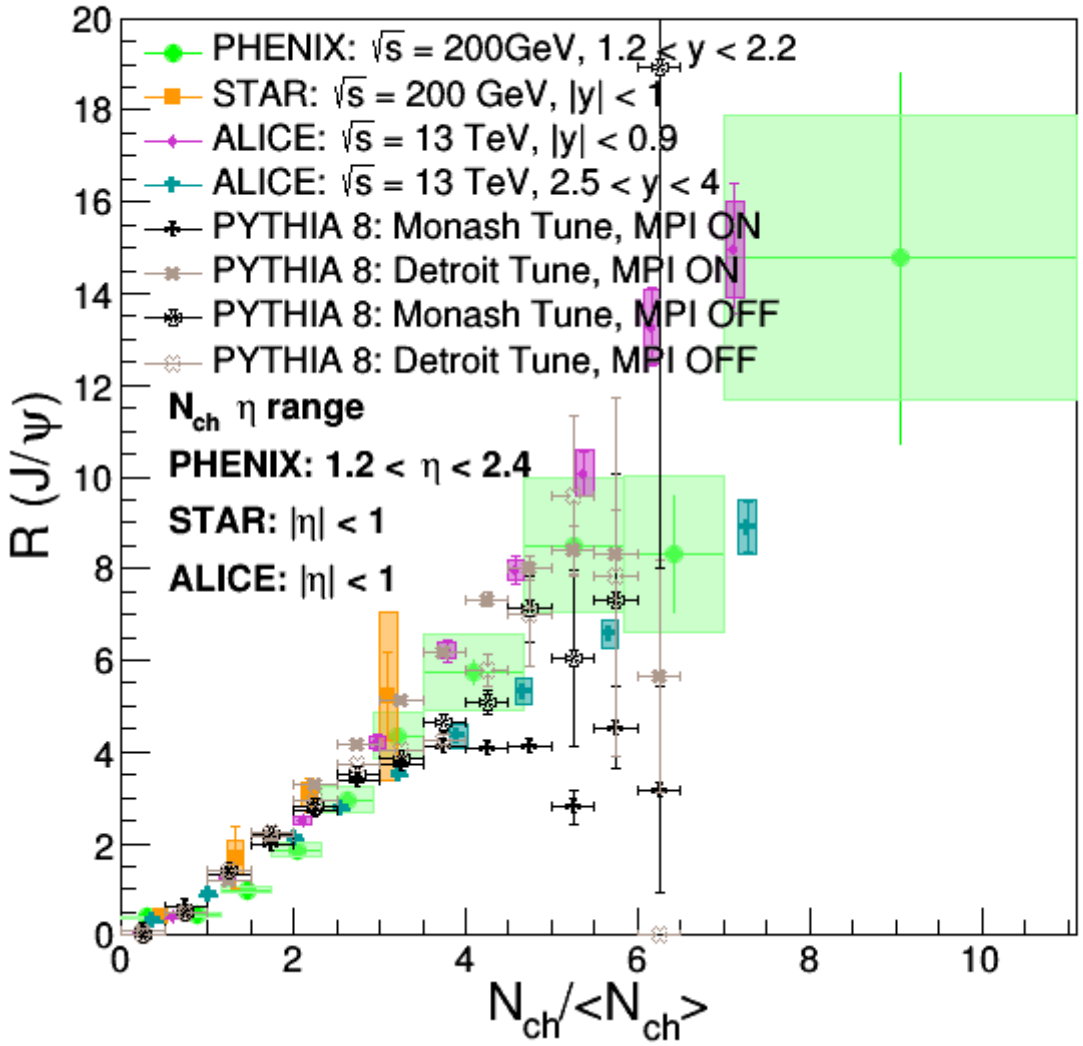
PHENIX: a State of the Art Particle Detector

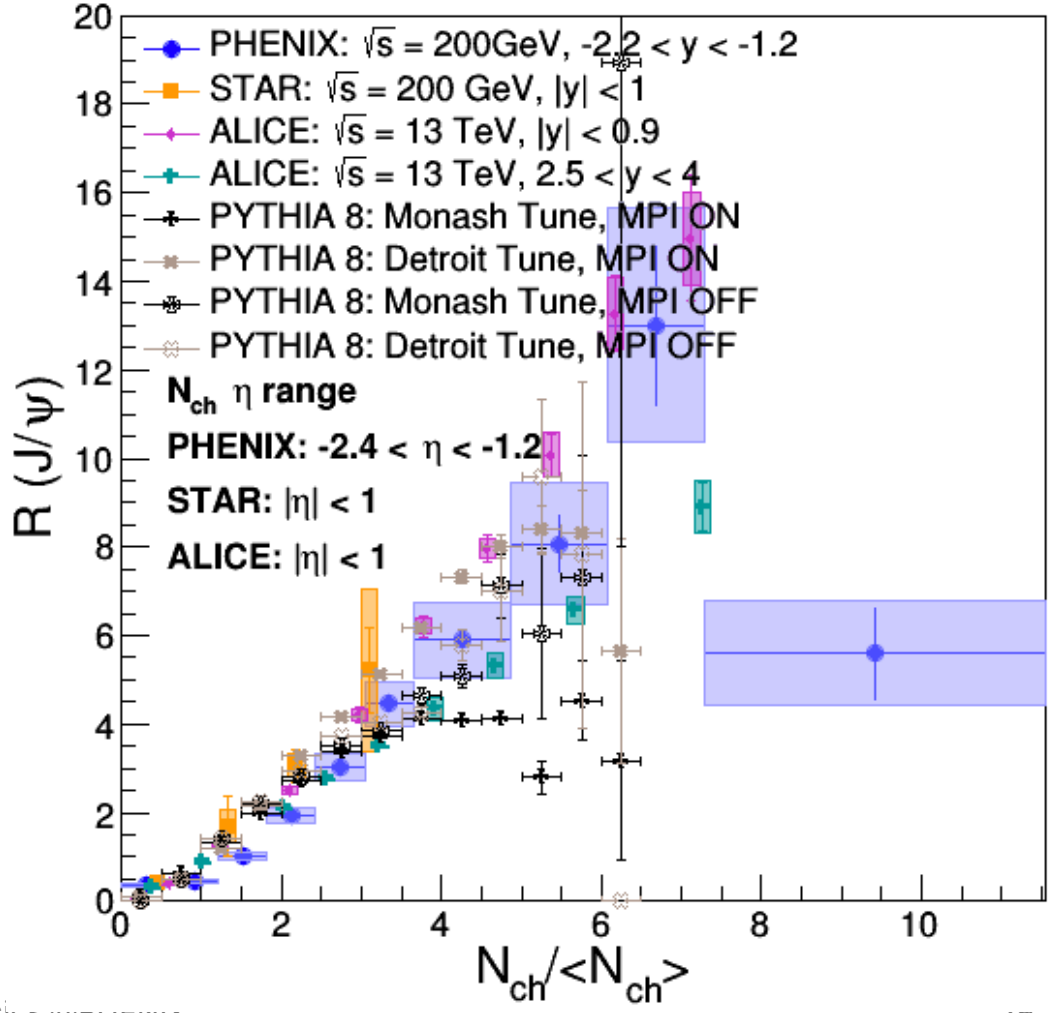


J/Psi Suppression: RHIC vs LHC

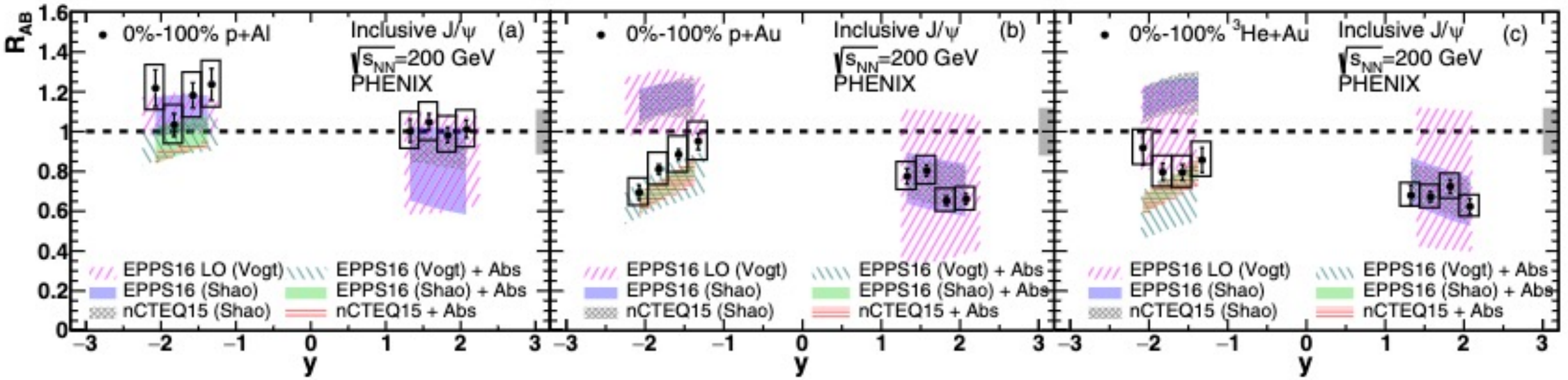


Data and PYTHIA – Same Arms

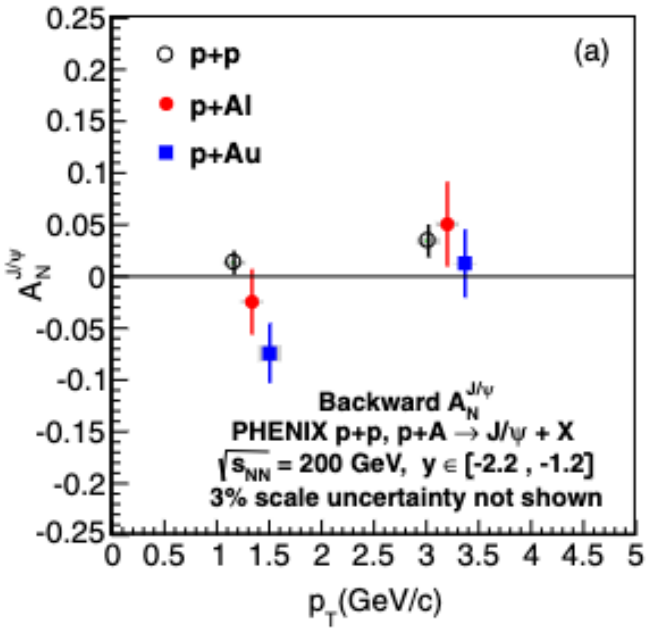


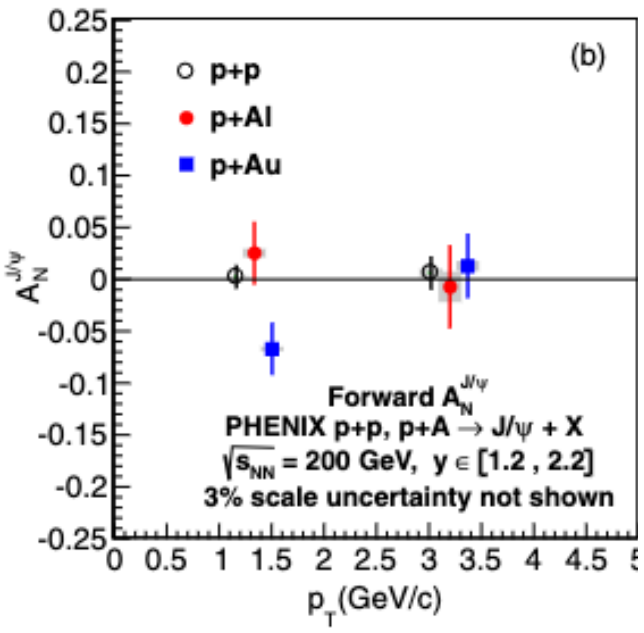


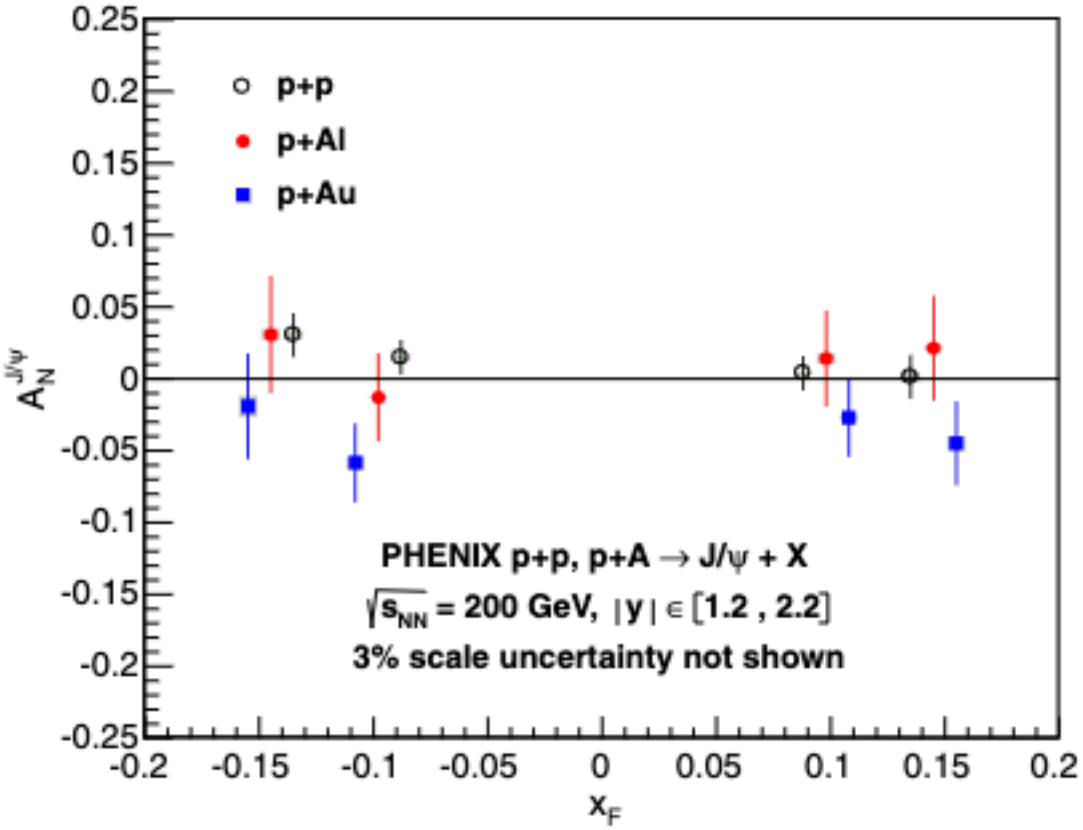
Measurement of J/ψ at forward and backward rapidity in $p+p$, $p+\mathrm{Al}$, $p+\mathrm{Au}$, and $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV



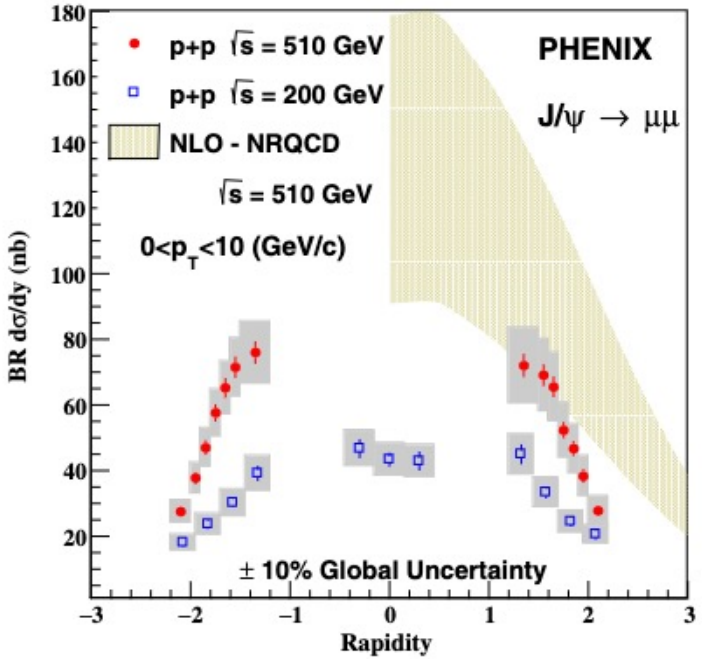
Single-spin asymmetry of J/ψ production in $p+p$, $p+\mathrm{Al}$, and $p+\mathrm{Au}$ collisions with transversely polarized proton beams at $\sqrt{s_{NN}}=200$ GeV

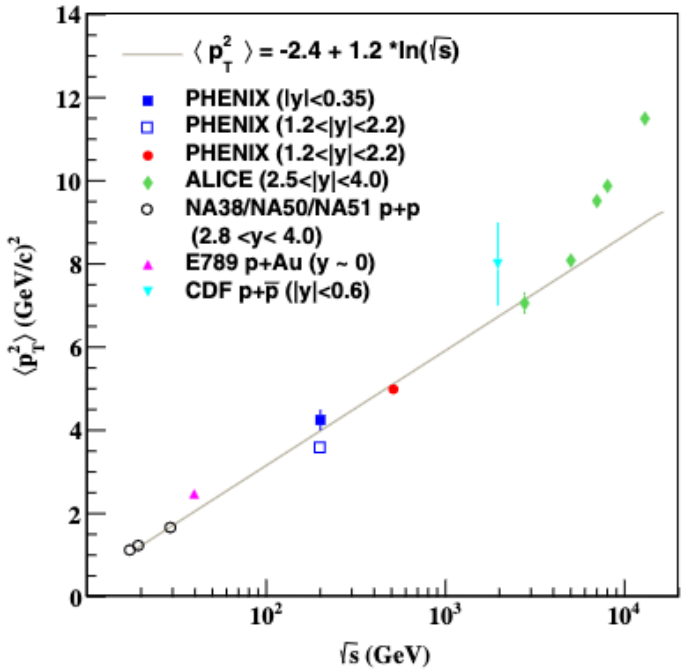


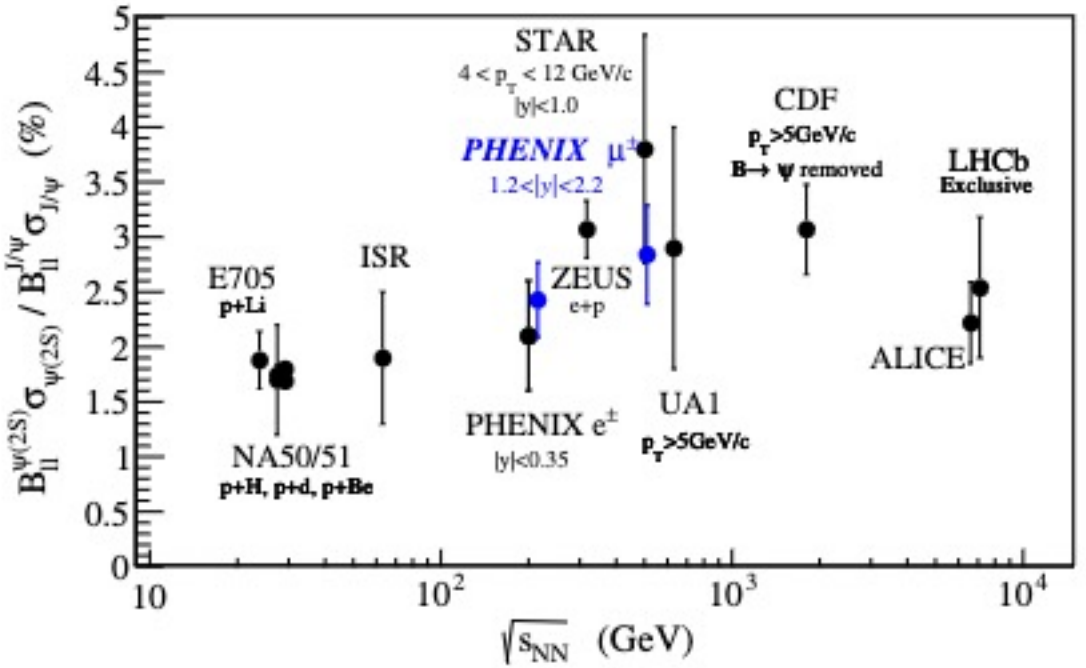




J/ψ and $\psi(2S)$ production at forward rapidity in $p+p$ collisions at $\sqrt{s}=510$ GeV

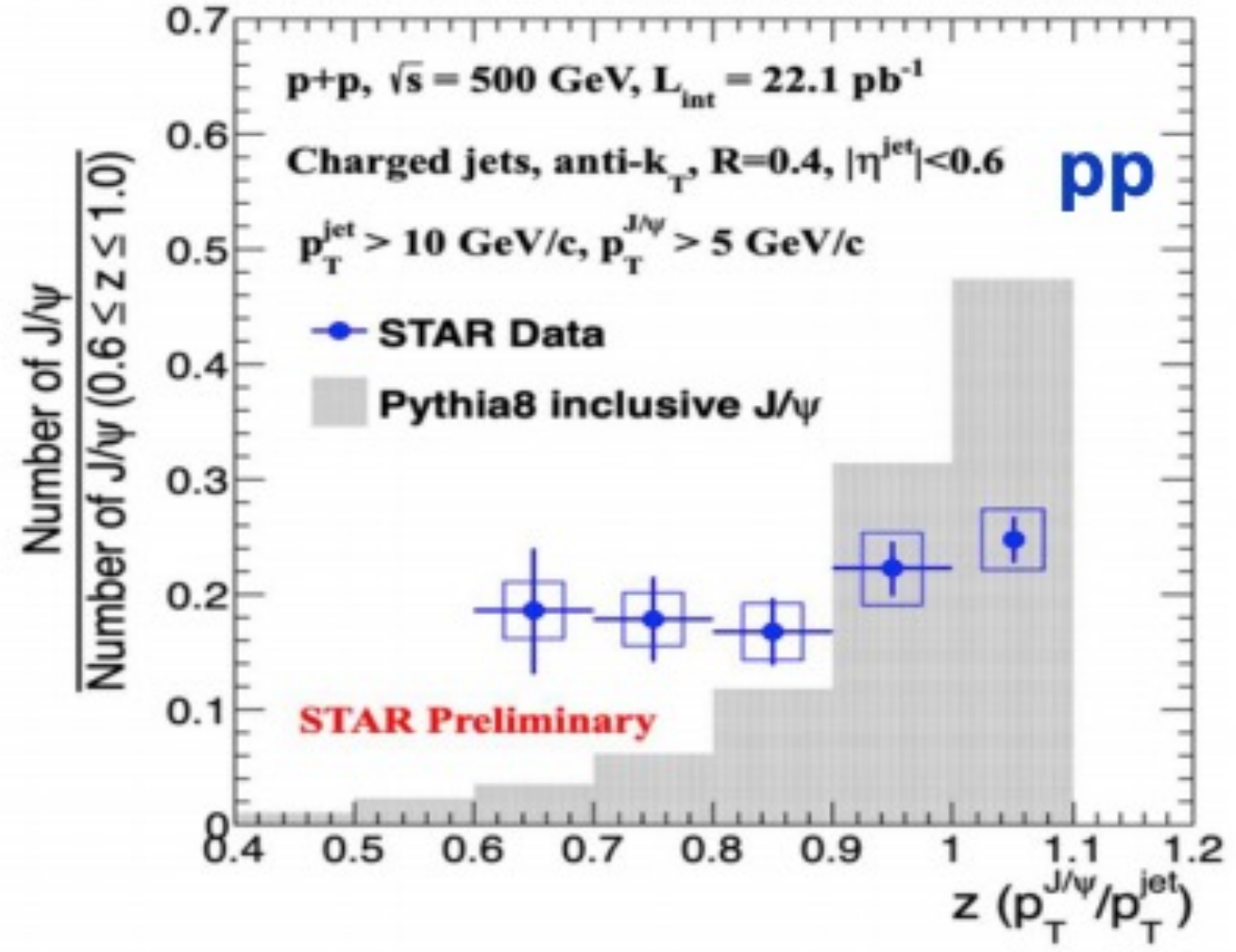






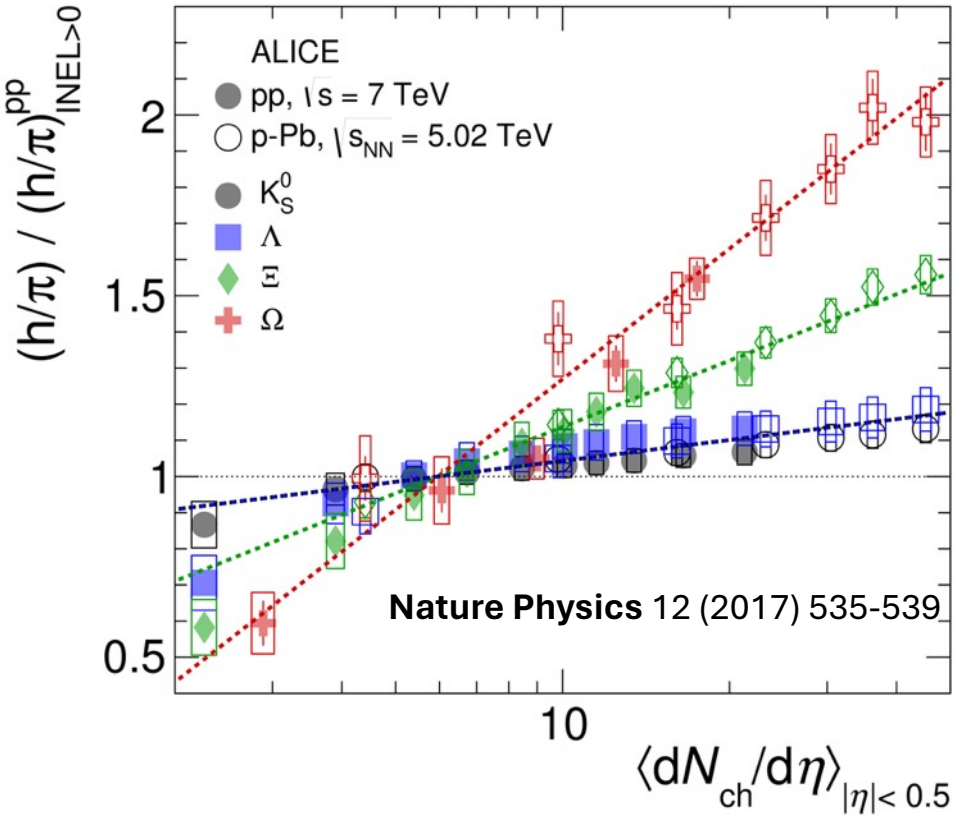
J/Psi-Jets in pp
- flat distribution?

- **Quite different from expectation**
- **J/Psi production mechanisms**
  - CEM
  - NRQCD
  - Jet fragmentation
  - …



Event multiplicity dependence

Strangeness enhancement in high multiplicity pp



From PHENIX to sPHENIX