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DIS 2019 TORINO 8-12 April

J/ψ production and polarization at forward and mid-rapidity in p + p Collisions at RHIC

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for the PHENIX collaboration

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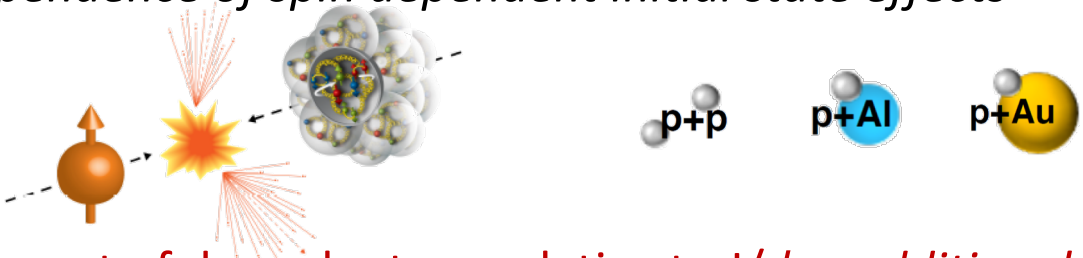
PHENIX

STATE

Charmonium production in hadron collisions

- Charmonium is dominantly produced by gluon fusion in p+p collisions at RHIC energy.
- J/ψ meson is a bound state of a $c\bar{c}$ pair with spin 1.
- Decays into $\mu^+\mu^-$ or e^+e^- with a large branching ratio.

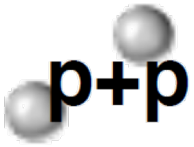
- Nuclear modification in small to large systems : *Effects of QGP (suppression and flow) and Cold Nuclear Matter effects (rapidity, centrality and pT dependent modification) on J/ψ production.*
- Correlation with initial proton spin in different collision systems: *path-length dependence of spin dependent initial state effects*

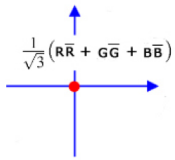


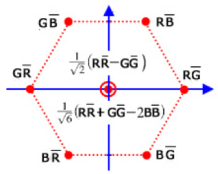
- Spin alignment of decay leptons relative to J/ψ : *additional handle on distinguishing production mechanisms.*

J/ψ polarization in p+p collisions

- Unpolarized p+p collisions.
- Hadronization of charmonium in unpolarized p+p collisions accessible in Non-relativistic QCD formalism.
- Predominantly prompt J/ψ production in p+p collisions will help map out color singlet and octet production mechanisms.



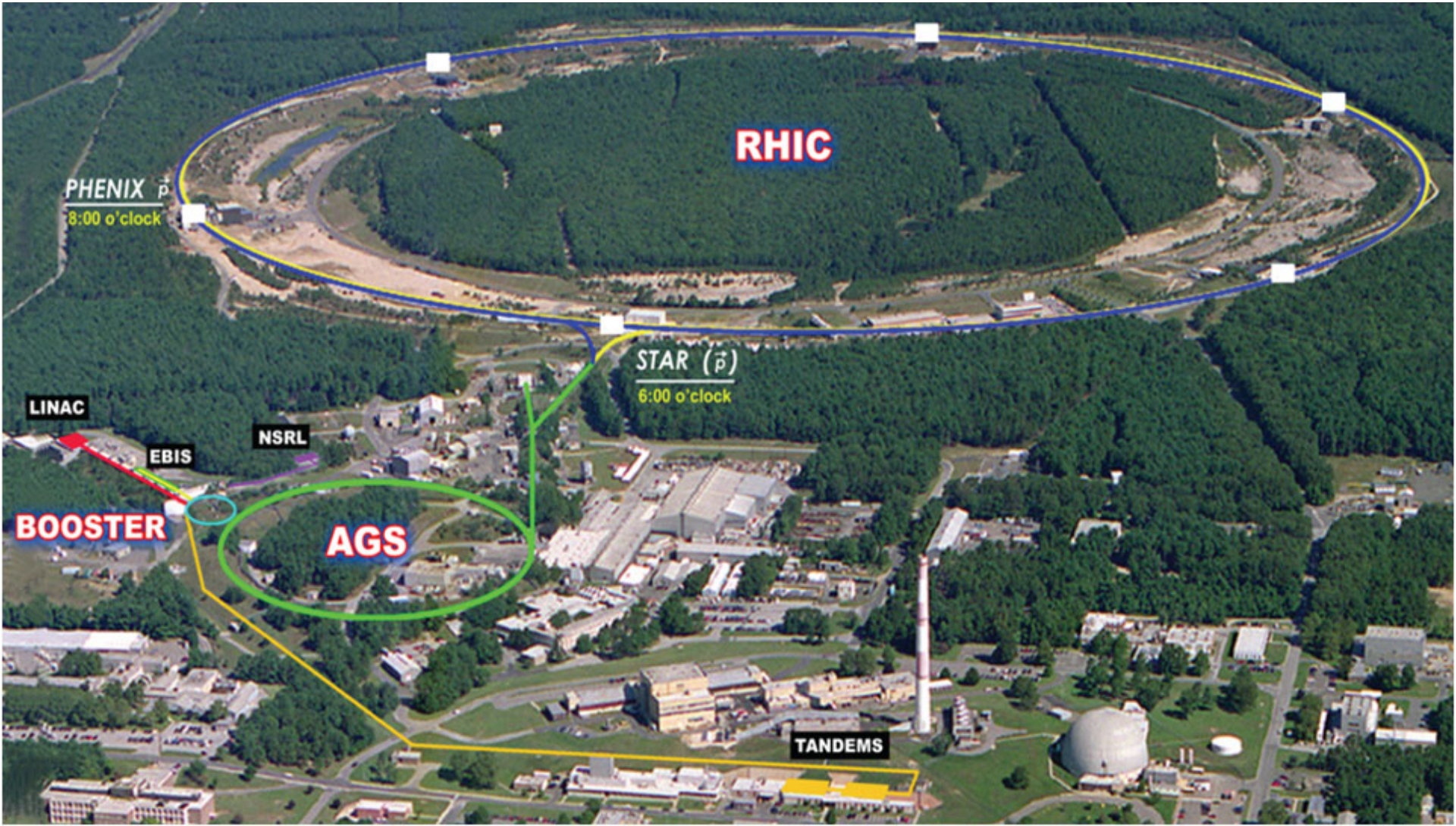




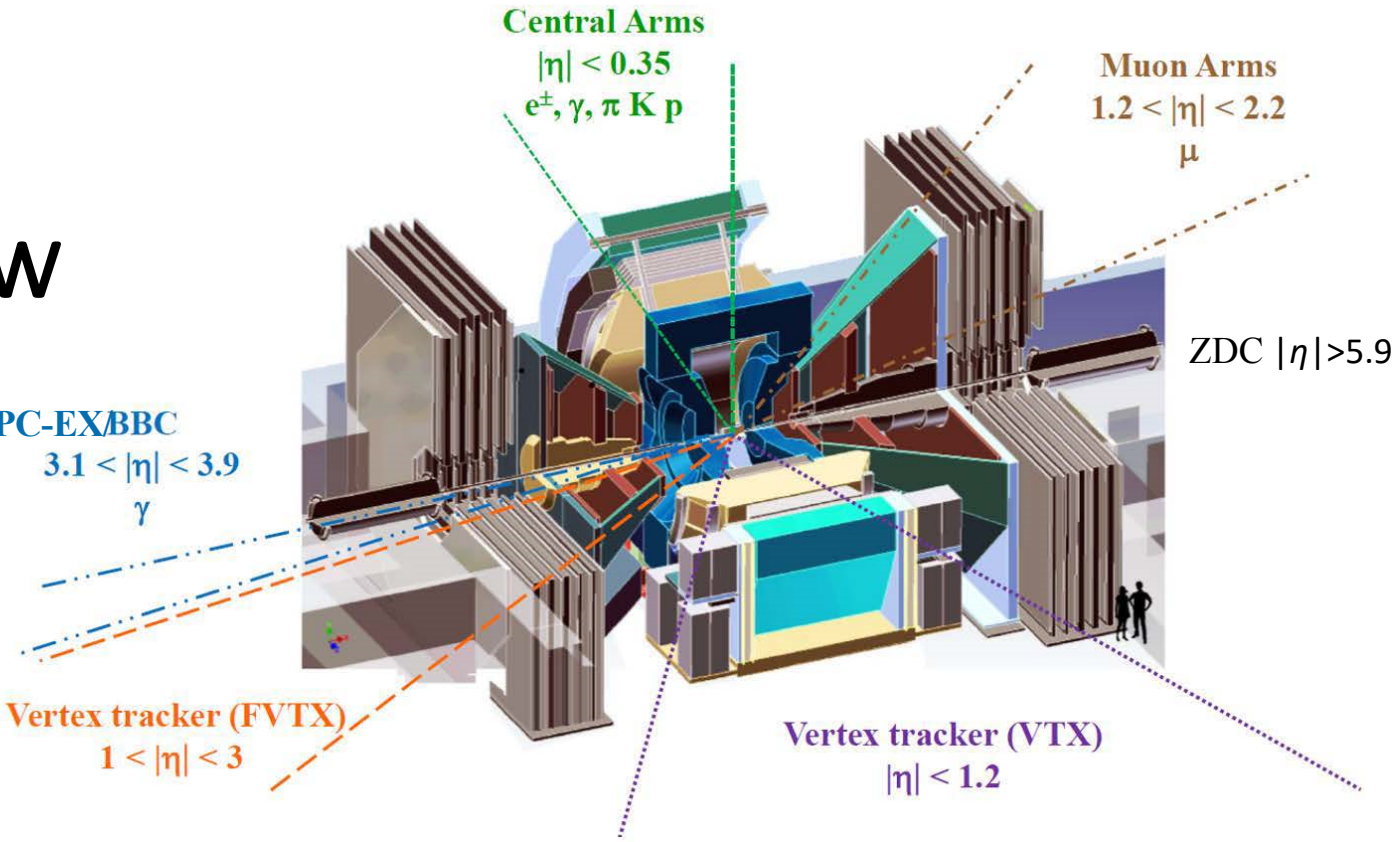
$$|\psi_Q\rangle = \mathcal{O}(1)\left|{}^3S_1^{(1)}\right\rangle + \mathcal{O}(v)\left|{}^3P_J^{(8)}g\right\rangle + \mathcal{O}\left(v^2\right)\left|{}^3S_1^{(8)}gg\right\rangle + \mathcal{O}\left(v^2\right)\left|{}^1S_0^{(8)}g\right\rangle + \cdots$$

Relativistic Heavy Ion Collider

- Located in Long Island, New York USA
- World's only polarized proton collider



PHENIX overview

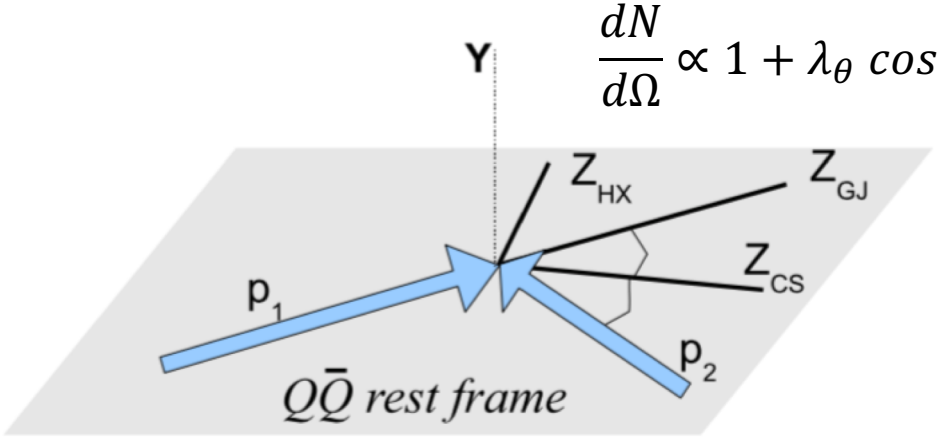


√s [GeV]	p+p	p+Al	p+Au	d+Au	³He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	●								
200	●	●	●	●	●	✓	✓	●	✓
130								✓	
62.4	✓			●		✓		✓	
39				●				✓	
27								✓	
20				●		✓		✓	
14.5								✓	
7.7								✓	

- Multiple golden data sets (●) at various collision energies.
- This talk will cover recent results and ongoing analysis that utilize data sets from p+p at √s = 200 and 510 GeV.

J/ψ polarization measurement

- Spin alignment of decay lepton with respect to J/ψ.
- Measured via angular distribution of a decay lepton in J/ψ rest frame.
- Freedom in choice of z-axis.
- Invariant variables thanks to rotational invariance.



$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin^2\theta \cos 2\phi + \lambda_\varphi \sin 2\theta \cos\phi$$

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

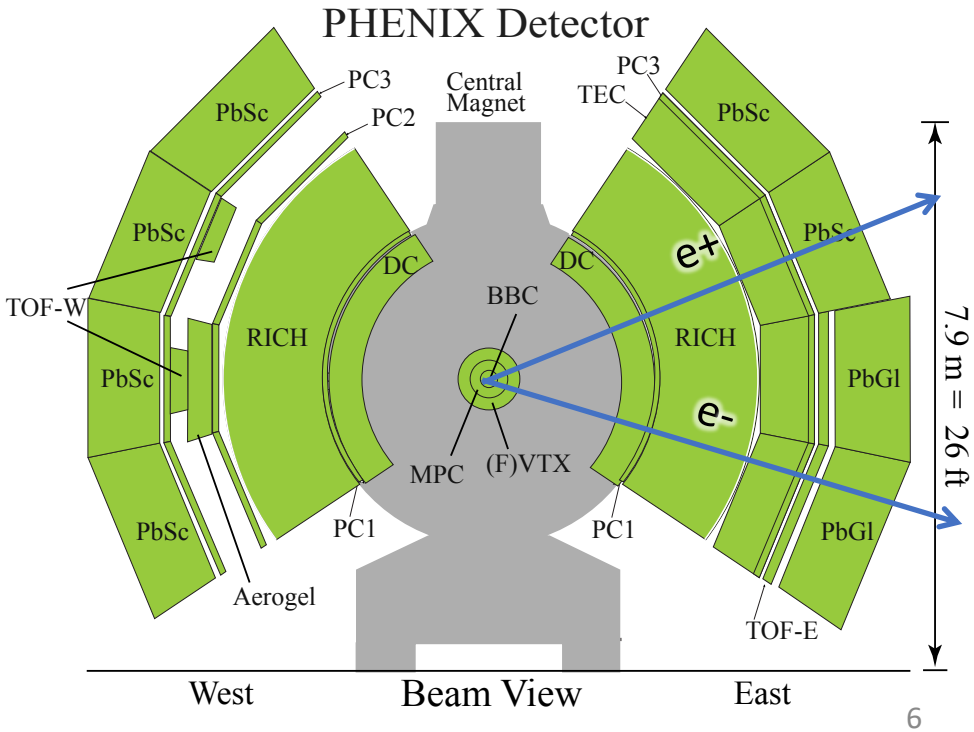
$$F = \frac{1 + \lambda_\theta + 2\lambda_\phi}{3 - \lambda_\theta}$$

Charmonium measurements via di-electron pairs in PHENIX central arm

- Central arm covers half azimuth and $|y| < 0.35$.
- Different arm combination can access different p_T range.

Electron Identification

- RICH : Ring Imaging Cherenkov detector, > 99% efficient for electrons $p_T > 0.5$ GeV/c
- EMCal : 2 different types of Electro-magnetic Calorimeters. PbGl and PbSc.
- DC : Drift Chamber, gas proportional wire chamber.



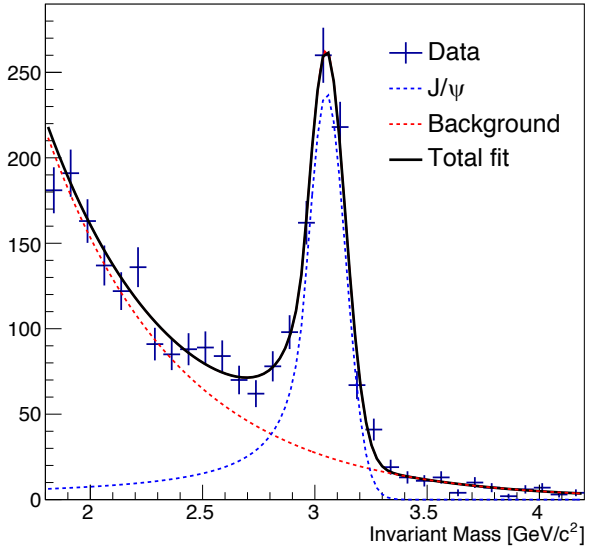
J/ψ polarization at midrapidity

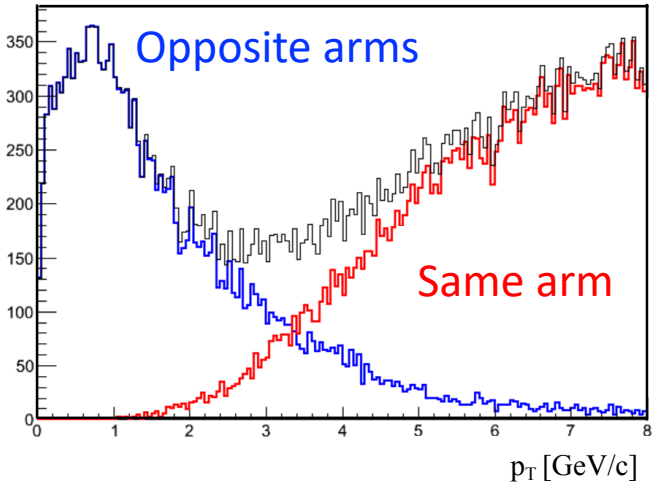
- PHENIX previously measured λ_θ by 1 dimensional analysis at $\sqrt{s}$ = 200 GeV at p_T < 5 GeV/c.

$$\frac{d\sigma}{dcos\theta} = A(1 + \lambda_\theta \, cos^2\theta)$$

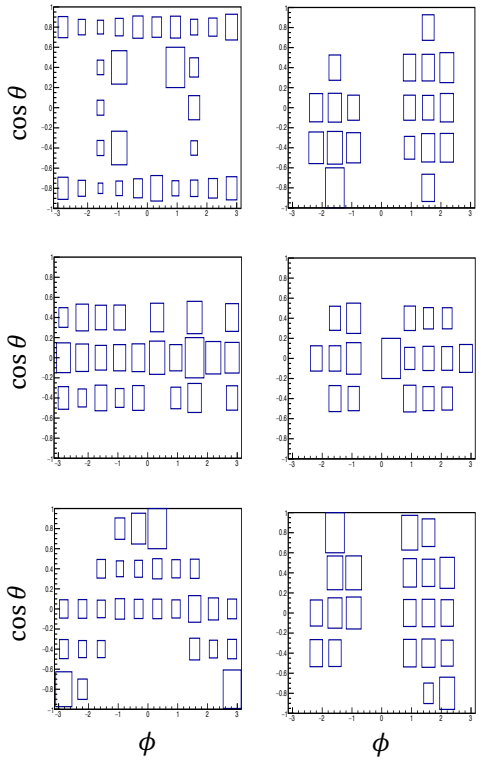
- Full 2-dimensional analysis has been done at $\sqrt{s}$ = 510 GeV with high p_T enhanced data sample for this talk.

- Full 2-d polarization measurements at same energy & forward rapidity also exist to compare with.





Decay angular distributions



- Decay lepton with different p_T populates different angular space in different frames.

- (Top to bottom)

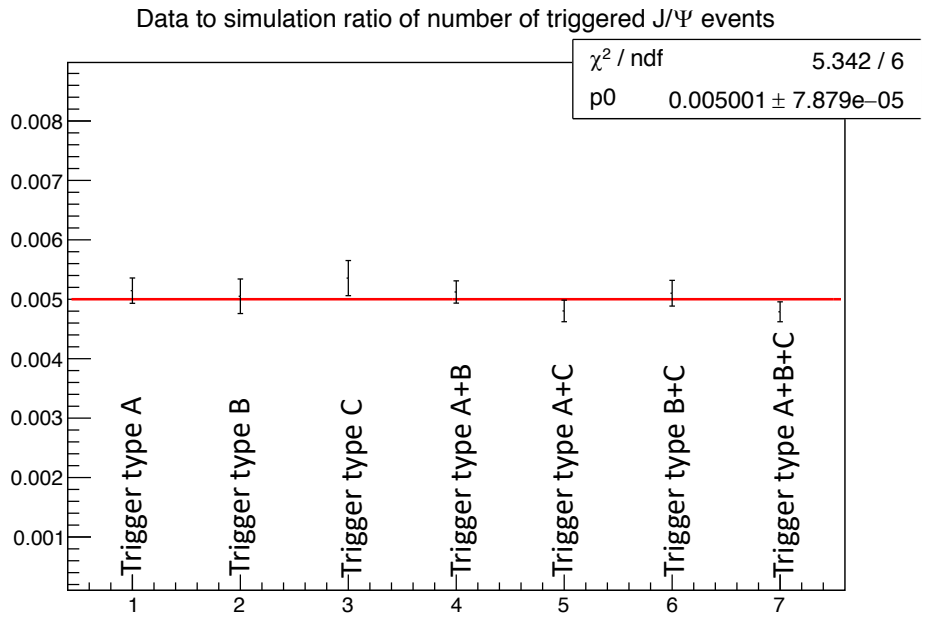
  Frame : HX, CS, GJF

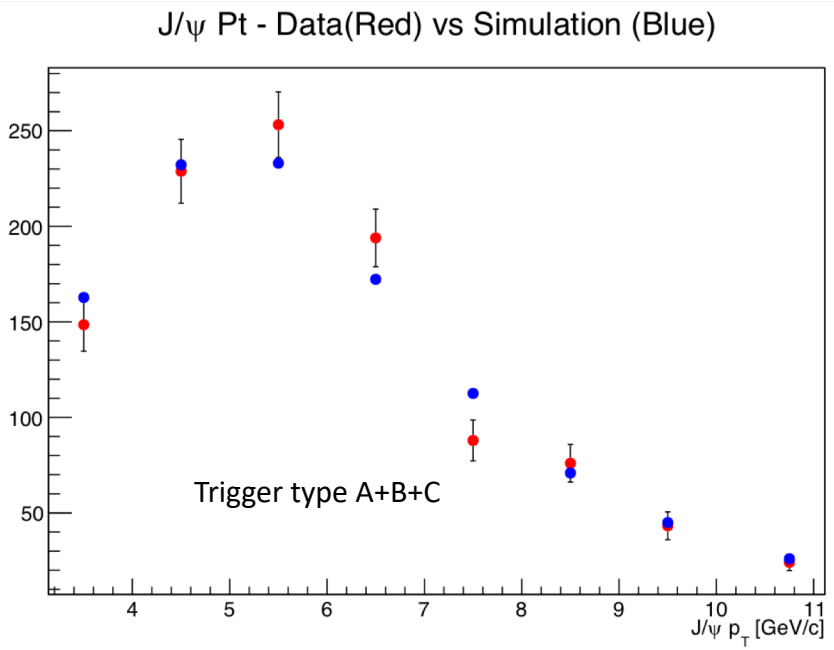
- (Left to right)

  pT : 0.-2.5, 2.5-10 GeV/c

Analysis method (i)

- Monte Carlo simulation developed in order to generate data for acceptance*efficiency corrections.
- Simulator emulates data acquisition system and mixes triggers with different energy thresholds and pre-scale factors.
- Tested with data being analyzed, well describes all possible combinations of mixed triggered data.

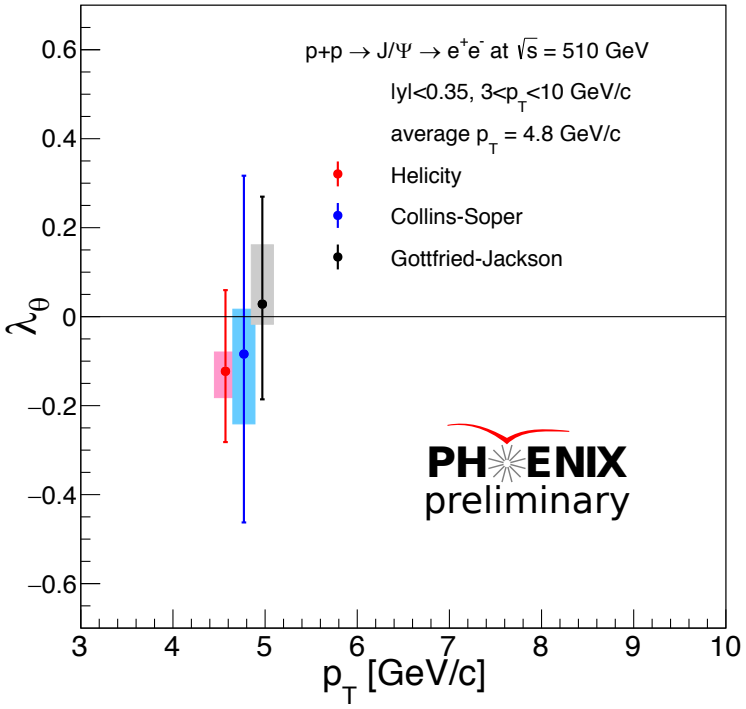

Data to simulation ratio of number of triggered J/Ψ events
χ² / ndf 5.342 / 6
p0 0.005001 ± 7.879e−05
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
Trigger type A
Trigger type B
Trigger type C
Trigger type A+B
Trigger type A+C
Trigger type B+C
Trigger type A+B+C
1
2
3
4
5
6
7

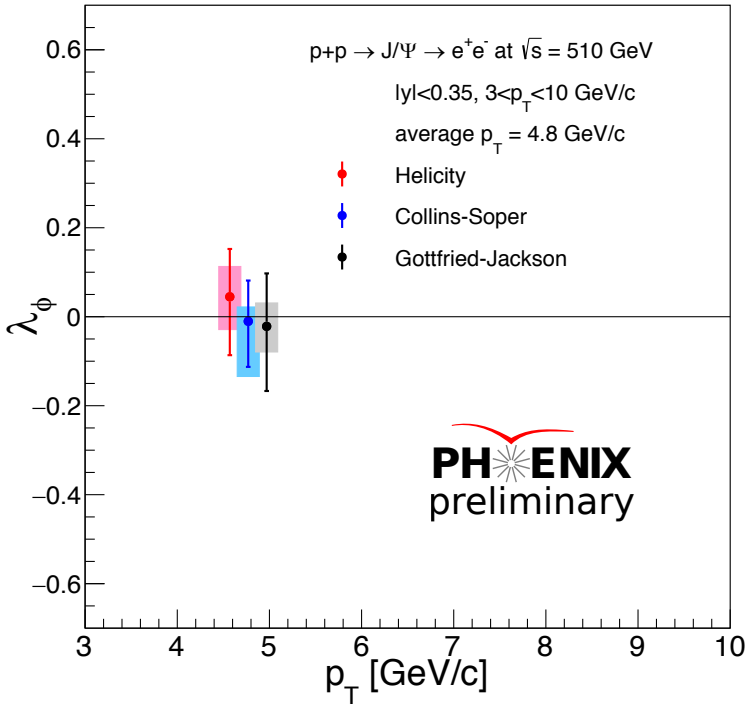

J/ψ Pt - Data(Red) vs Simulation (Blue)
250
200
150
100
50
Trigger type A+B+C
4
5
6
7
8
9
10
11
J/ψ p_T [GeV/c]

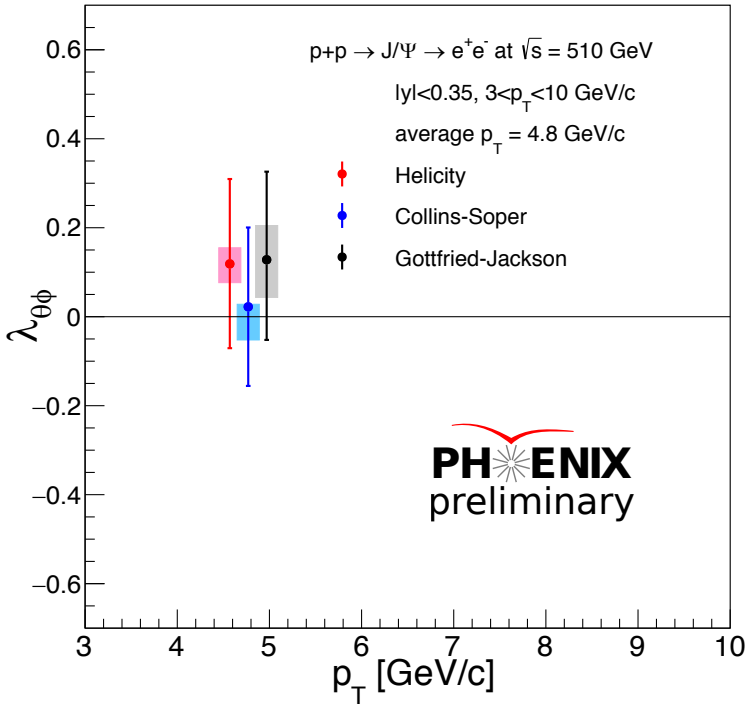
Analysis method (ii)

- 3 different approaches to determine decay angular coefficients and their uncertainties.
  - χ^2 minimization
  - Maximum log likelihood method : Poisson statistics better treats low statistics measurements.
  - Sampling method : randomize central value of each measurement according to Gaussian distribution and fit either by minimizing χ^2 or maximizing log likelihood function.

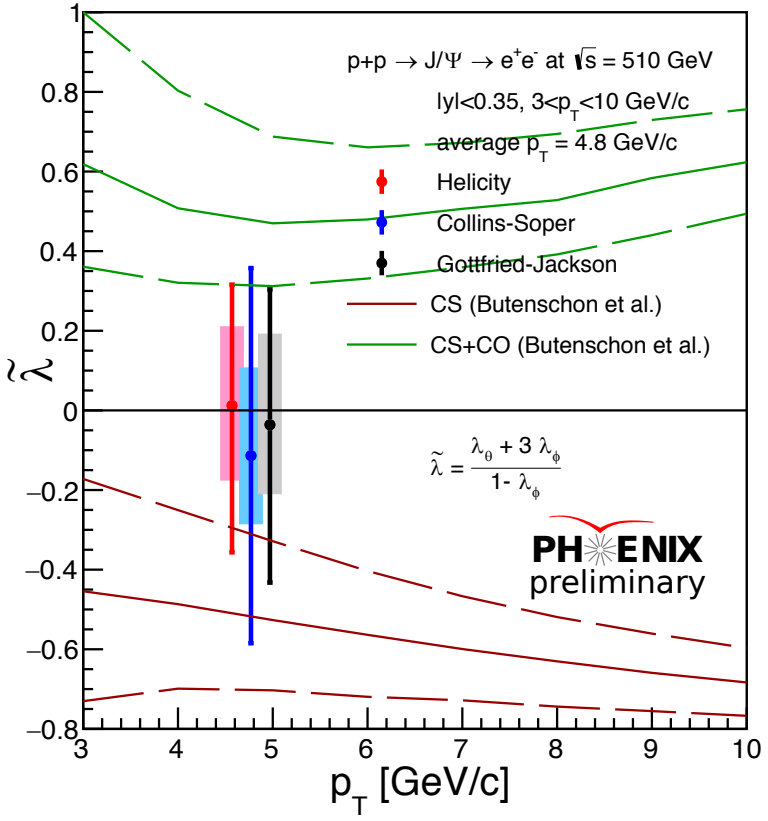
Angular decay coefficients

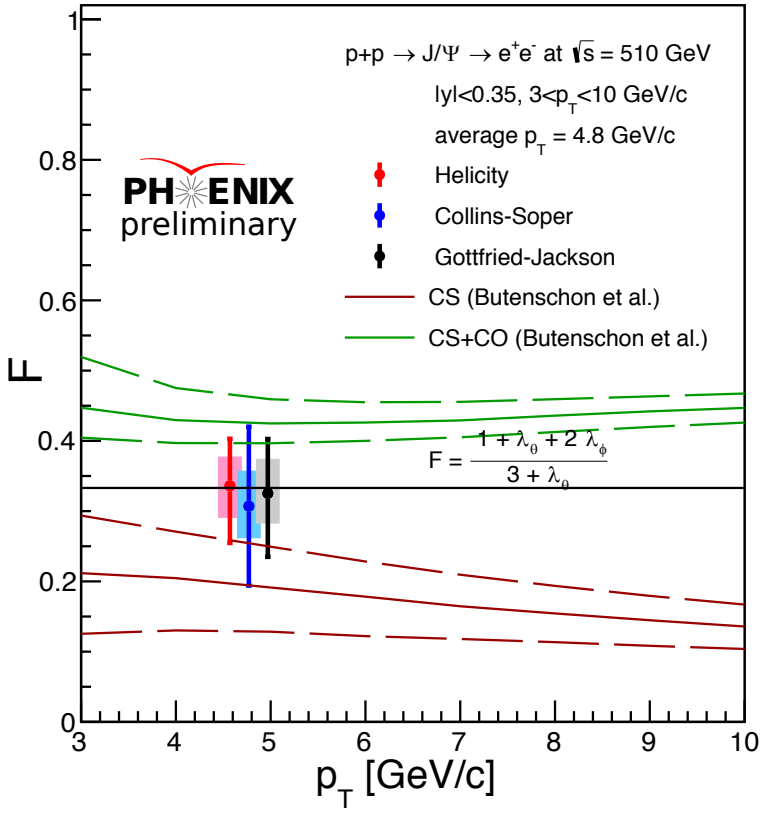






Invariants


p+p → J/Ψ → e+e- at √s = 510 GeV
|y|<0.35, 3<p_T<10 GeV/c
average p_T = 4.8 GeV/c
Helicity
Collins-Soper
Gottfried-Jackson
CS (Butenschon et al.)
CS+CO (Butenschon et al.)
λ̃ = (λ_θ + 3 λ_φ) / (1 - λ_φ)
PHENIX
preliminary
λ̃
p_T [GeV/c]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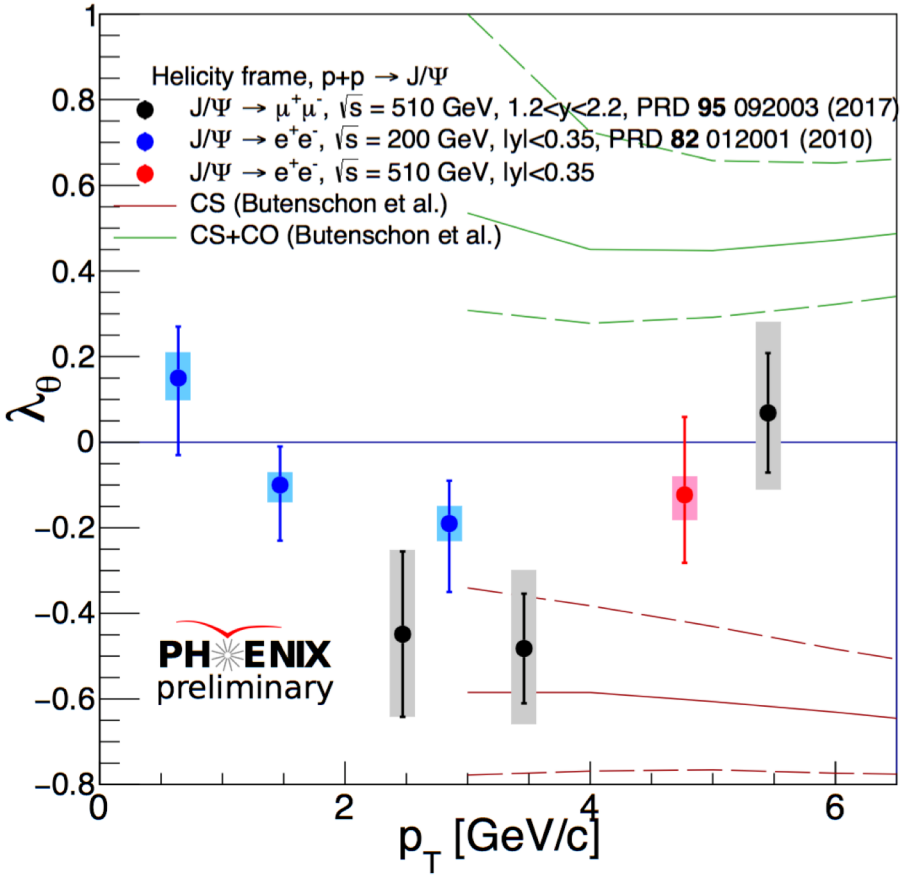
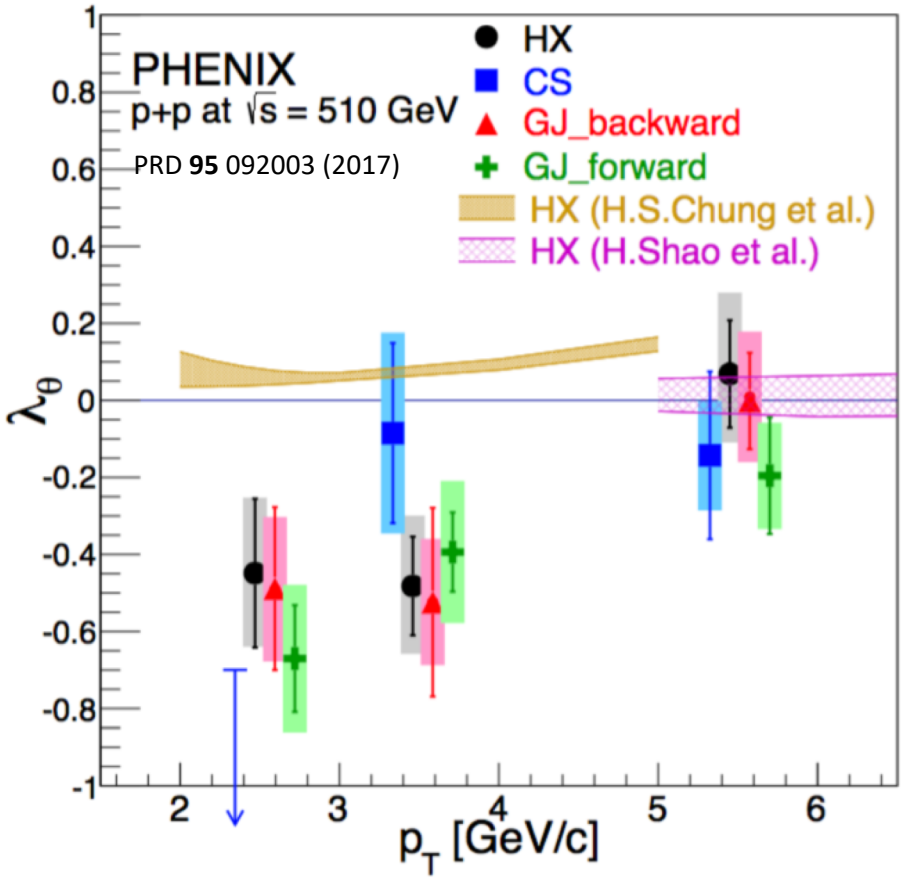
average p_T = 4.8 GeV/c
Helicity
Collins-Soper
Gottfried-Jackson
CS (Butenschon et al.)
CS+CO (Butenschon et al.)
F = (1 + λ_θ + 2 λ_φ) / (3 + λ_θ)
PHENIX
preliminary
F
p_T [GeV/c]

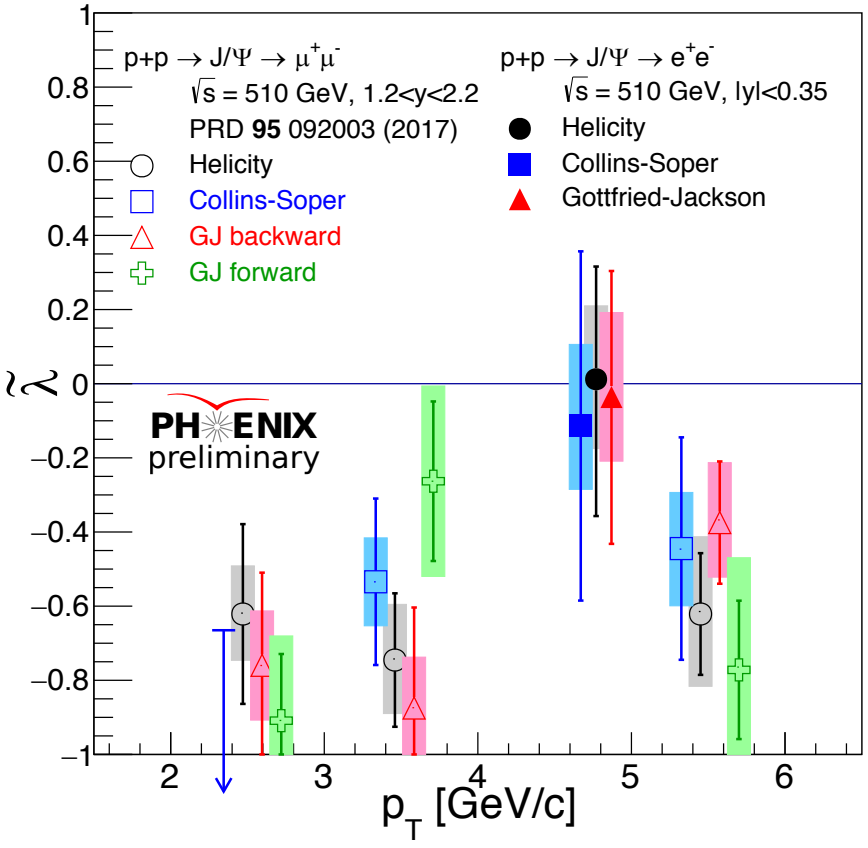
λ_θ

H.S.Chung at al. [10.1103/PhysRevD.83.037501, arXiv:1012.1954],
H.Shao et al. [JHEP05 (2015) 103, arXiv:1411.3300]



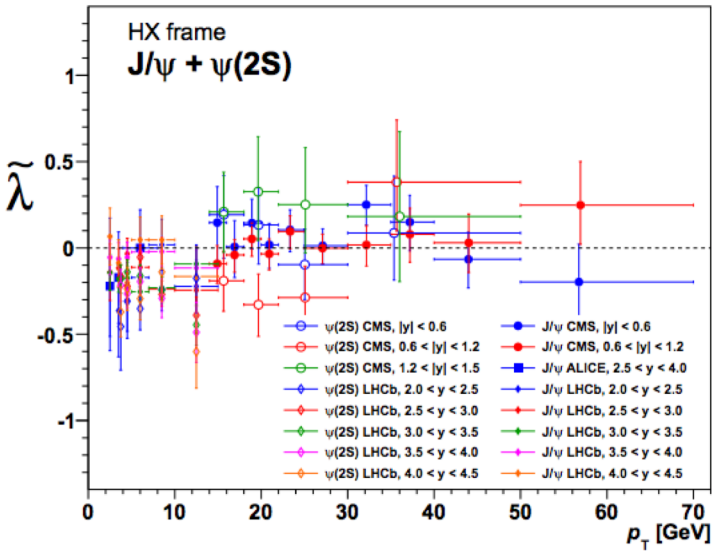


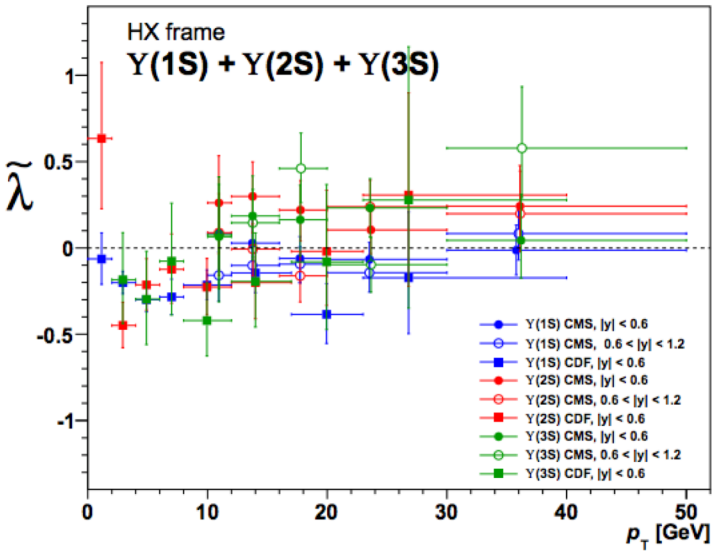
$\tilde{\lambda}$



Other quarkonia polarization measurements

- CMS/LHCb/ALICE at LHC, CDF at Tevatron have seen no strong preference to large a net polarization in all 5 S wave quakonium states.





[10.22323/1.216.0012]

Summary and Outlook

- At 200 GeV, it has been known from cross section measurements that color octet hadronization is dominant mechanism in PHENIX acceptance.
- Polarization measurements at $\sqrt{s}$= 510 GeV mid-rapidity does not reject neither NRQCD (CO+CS) nor CS predictions.
- Similar discrepancy between data and NRQCD prediction by a different group was seen at forward rapidity.
- Yield as well as rapidity dependent polarization measurements with precision can shed light on discrepancy between data and theory seen at low J/ψ p_T.
- Additional lower p_T polatization measurements at mid-rapidity is essential in this regard.
- When included in global analysis, universality of LDME can be tested for NRQCD.