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J/ψ Transverse Single Spin Asymmetries (TSSA) and Spin Alignment to Decay Leptons in p + p Collisions at RHIC

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for the PHENIX collaboration

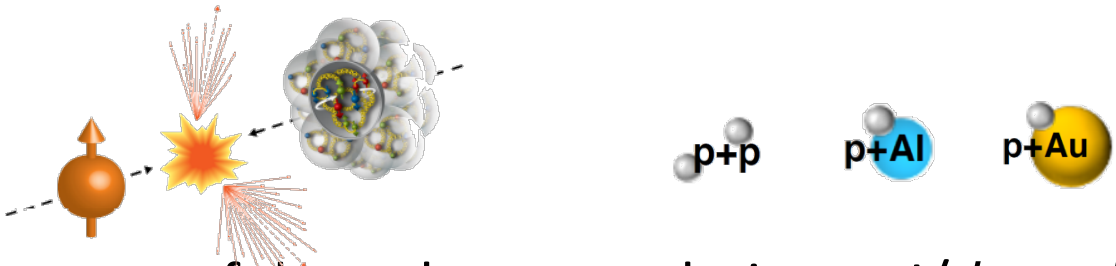
PHENIX

STATE

Charmonium production in hadron collisions

- 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.
- Dominantly produced by gluon+gluon interactions in p+p collisions at RHIC energy.

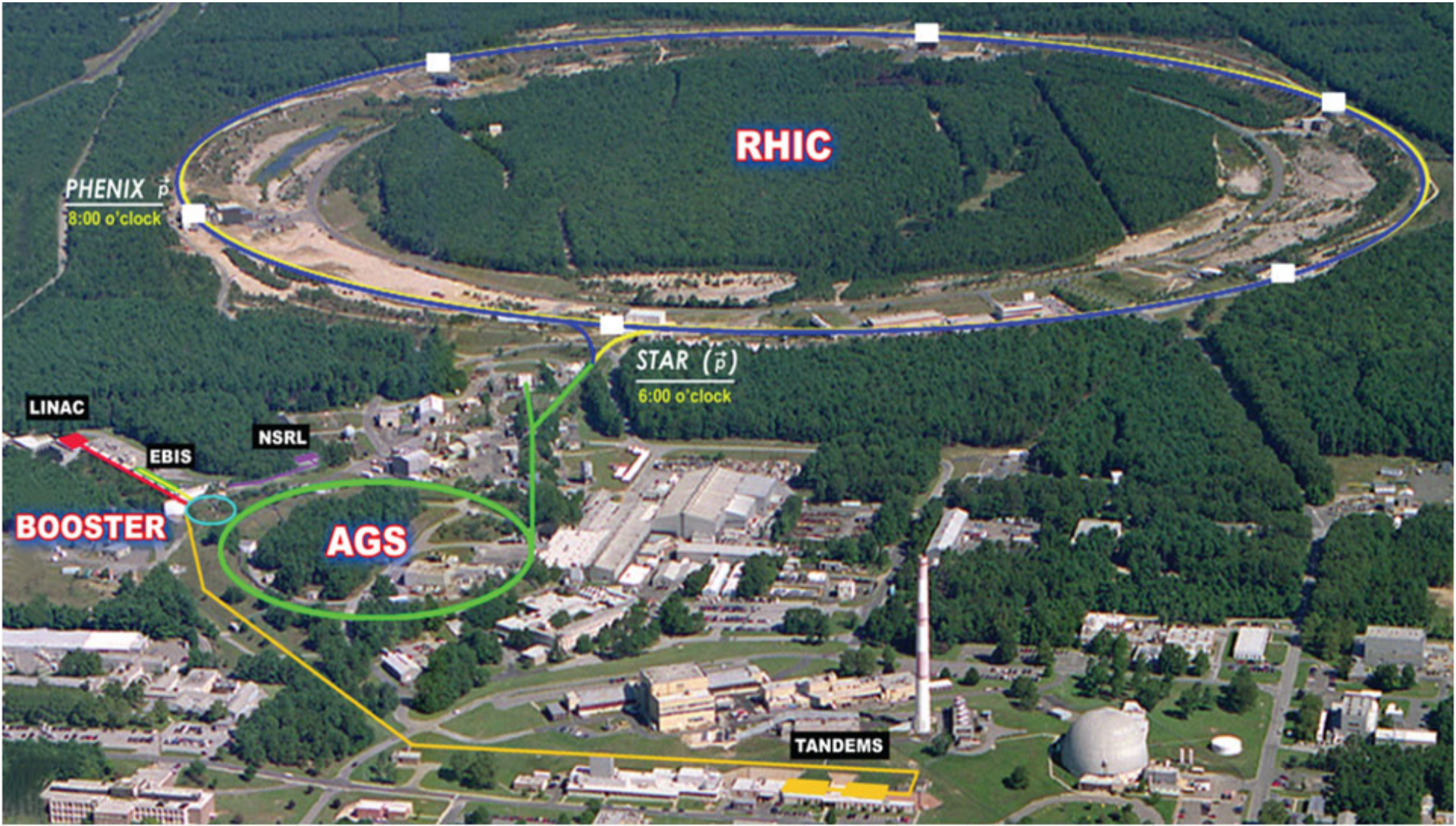
- Correlation with initial proton spin in different collision systems: *path-length dependence of initial state effects*



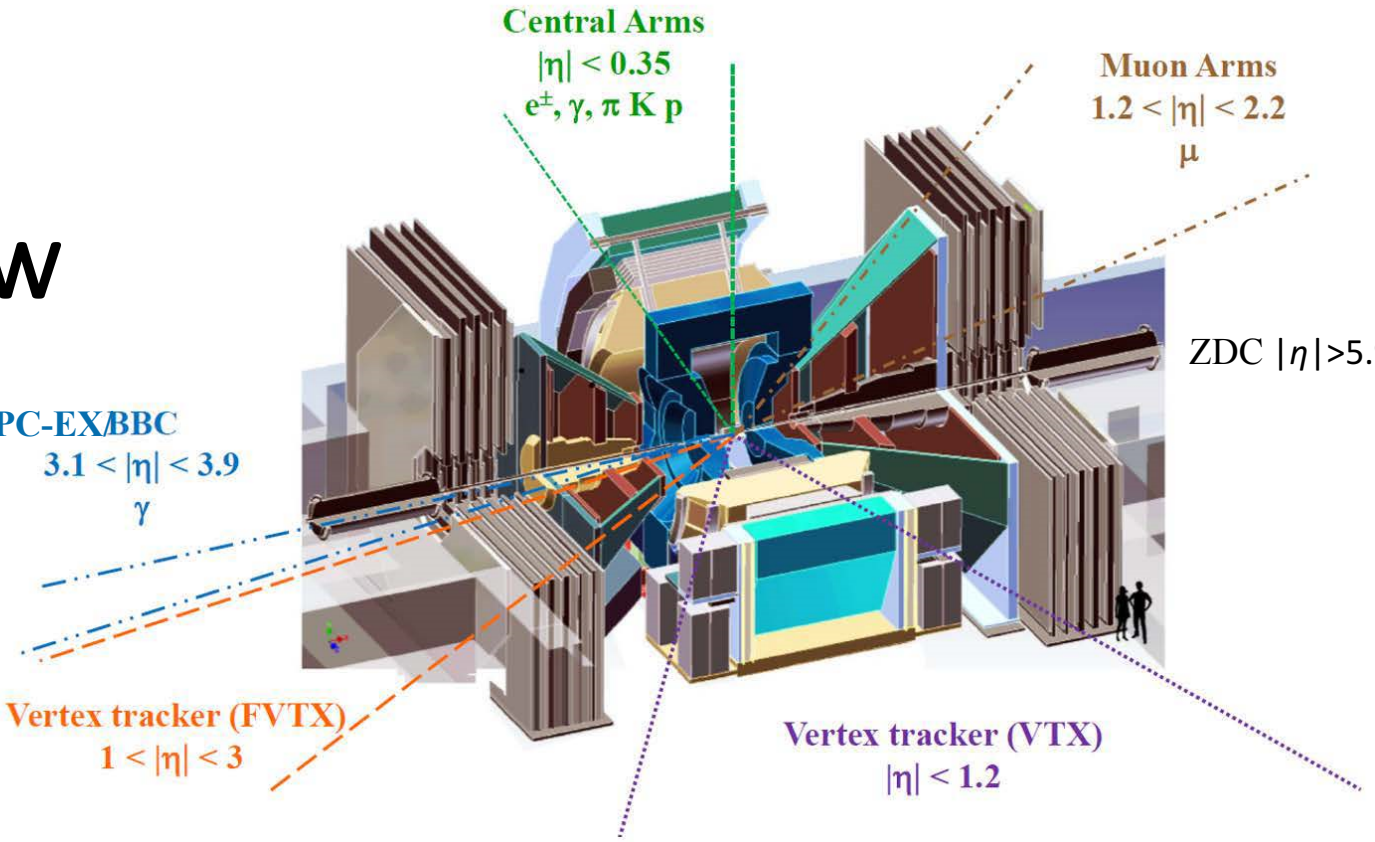
- Spin alignment of decay leptons relative to J/ψ : *additional handle on distinguishing production mechanisms.*

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								✓	

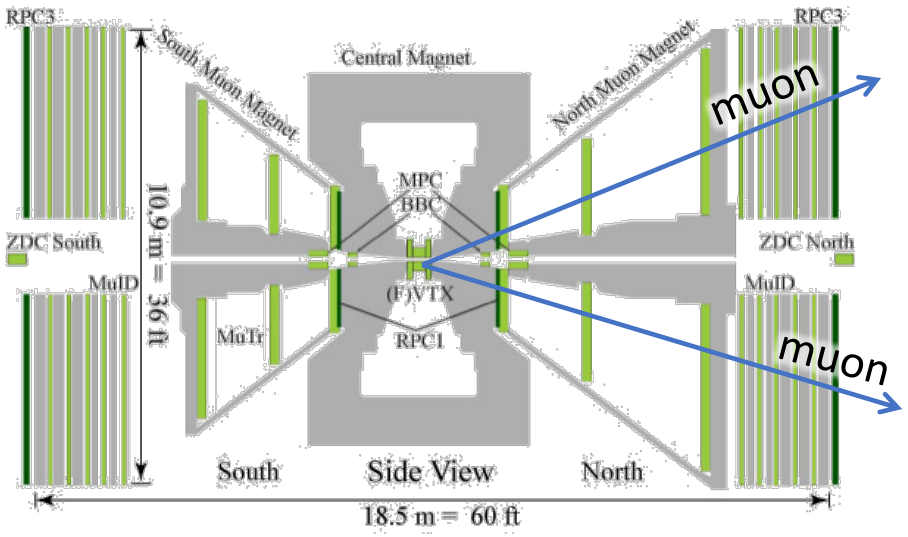
- Multiple golden data sets (●) at various collision energies.
- This talk will cover recent results and ongoing analysis that utilize data sets from p+p, p+Al and p+Au at √s = 200 and 510 GeV.

Heavy flavor measurements via di-muon pairs in PHENIX forward arm

- Forward arm covers full azimuth and $1.2<|y|<2.4$
- Theoretical prediction accessible by NRQCD.

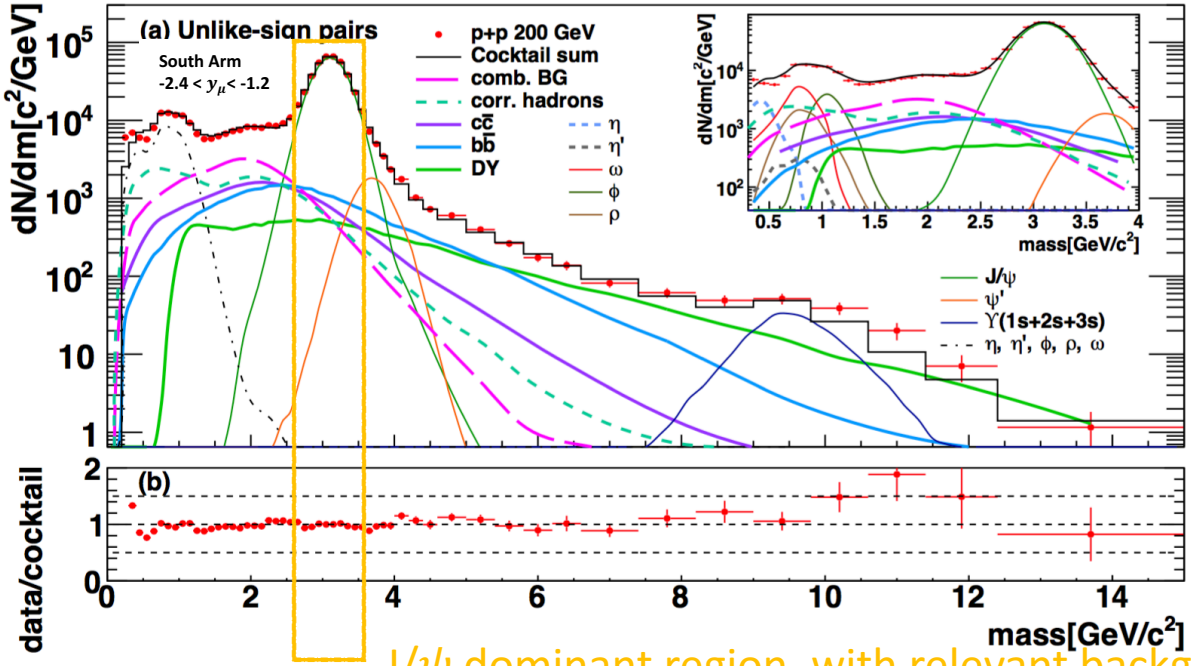
Muon Identification

- MuTr : 3 stations of cathode-strip tracking chambers inside a radial magnetic field → momentum reconstruction
- MuID : 5 sensitive layers, each with 1 vertical + 1 horizontal Iarocci tubes interweaved with steel absorber plate. → hadron rejection



J/ψ in di-muon mass spectra

arXiv:1805.02448

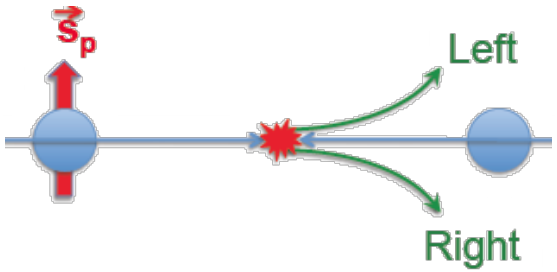


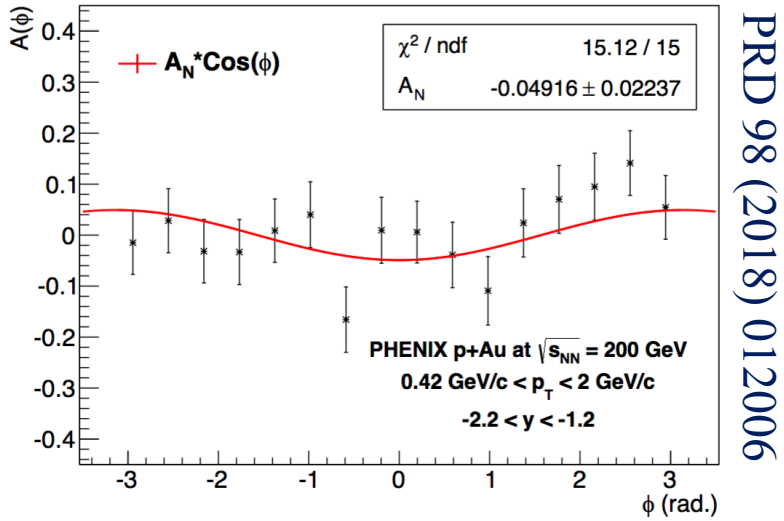
J/ψ dominant region, with relevant background sources : c$\bar{c}$ b$\bar{b}$ DY and ψ' (physical) and combinatorial background.

- Look in other ways :
  - Spin asymmetries in polarized p+p collisions, can be also looked at in p+Al and p+Au for nuclear effects.
  - Angular distributions of a decay lepton in J/ψ rest frame in unpolarized p+p collisions for mapping out production mechanisms.

TSSA A_N in hadron collisions

- Role of *gluons* in creating A_N is not well understood, while quarks relatively well understood.
- *Asymmetric collisions* offer a control over gluon density that might affect creation of A_N.



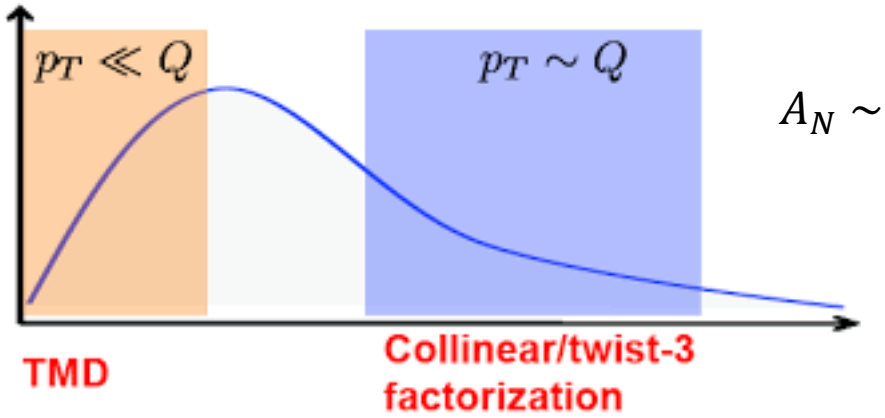


PRD 98 (2018) 012006

Initial state effects at RHIC PHENIX

- At RHIC, A_N is sensitive to initial state effects such as *Qui-Sterman or trigluon correlation* in collinear factorization framework and *gluon Sivers function* in TMD formalism.
- Uniquely, Large mass of **J/ψ** allows accessing p_T << Q where TMD factorization is valid.

$f_{1T}^{\perp}$ Sivers fn

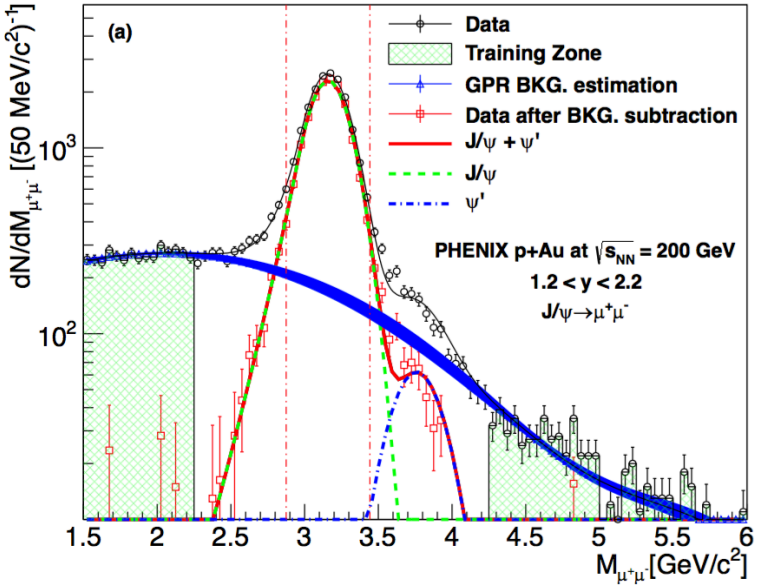


Twist 3 correlation fn

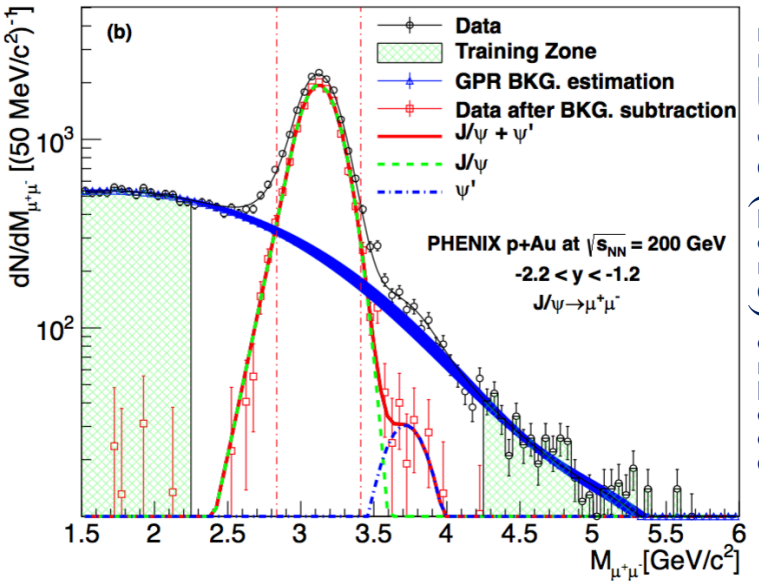
$$A_N \sim H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes f_{b/B(2)} \otimes D_{c/C(2)} + \cdots + \cdots$$

J/ψ mass fits in p+Au collisions

Forward, p going direction



Backward, Au going direction



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- Combinatorial Background shape determined by Gaussian Process Regression method, with its training sample outside J/ψ and ψ ' region.
- BG asymmetries measured in mass range of 1.5 ~ 2.4 GeV/c^2 and subtracted.
- J/ψ and ψ ' are fit separately.

A_N for J/ψ as a function of x_F

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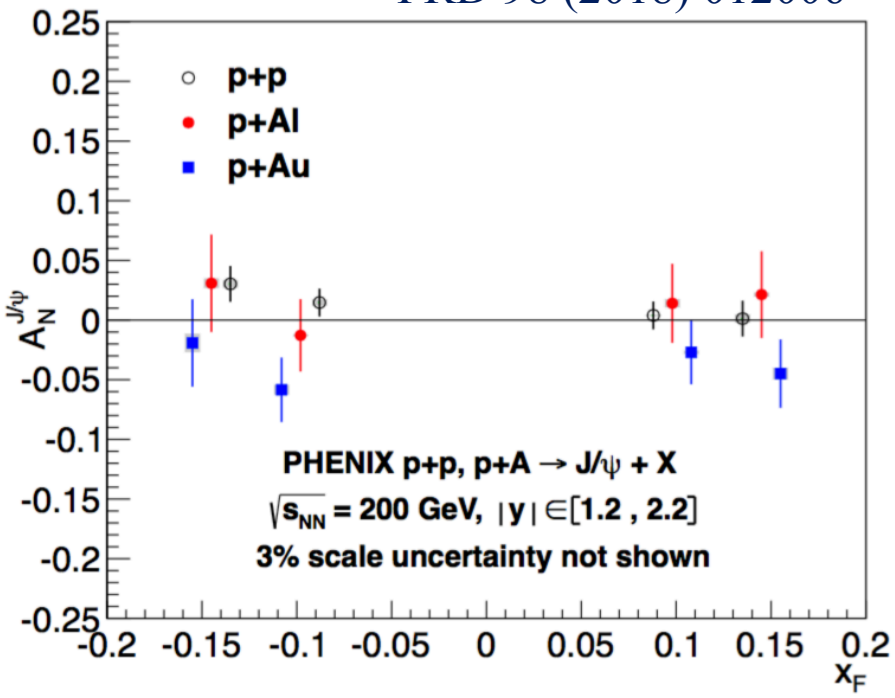

- Negative A_N seen in p+Au collisions both in forward and backward rapidity.

A_N for J/ψ as a function of x_F

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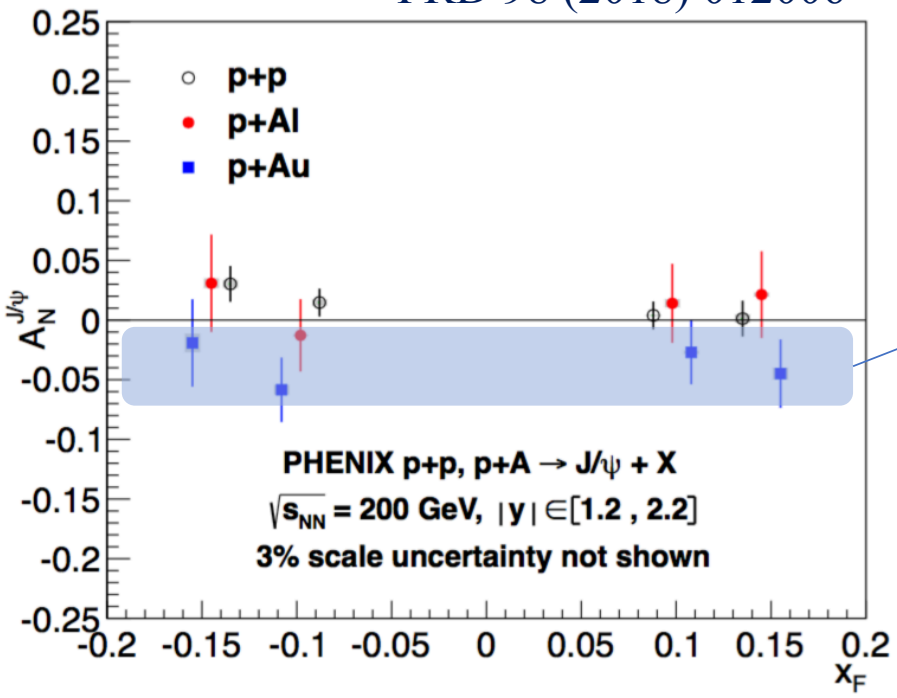
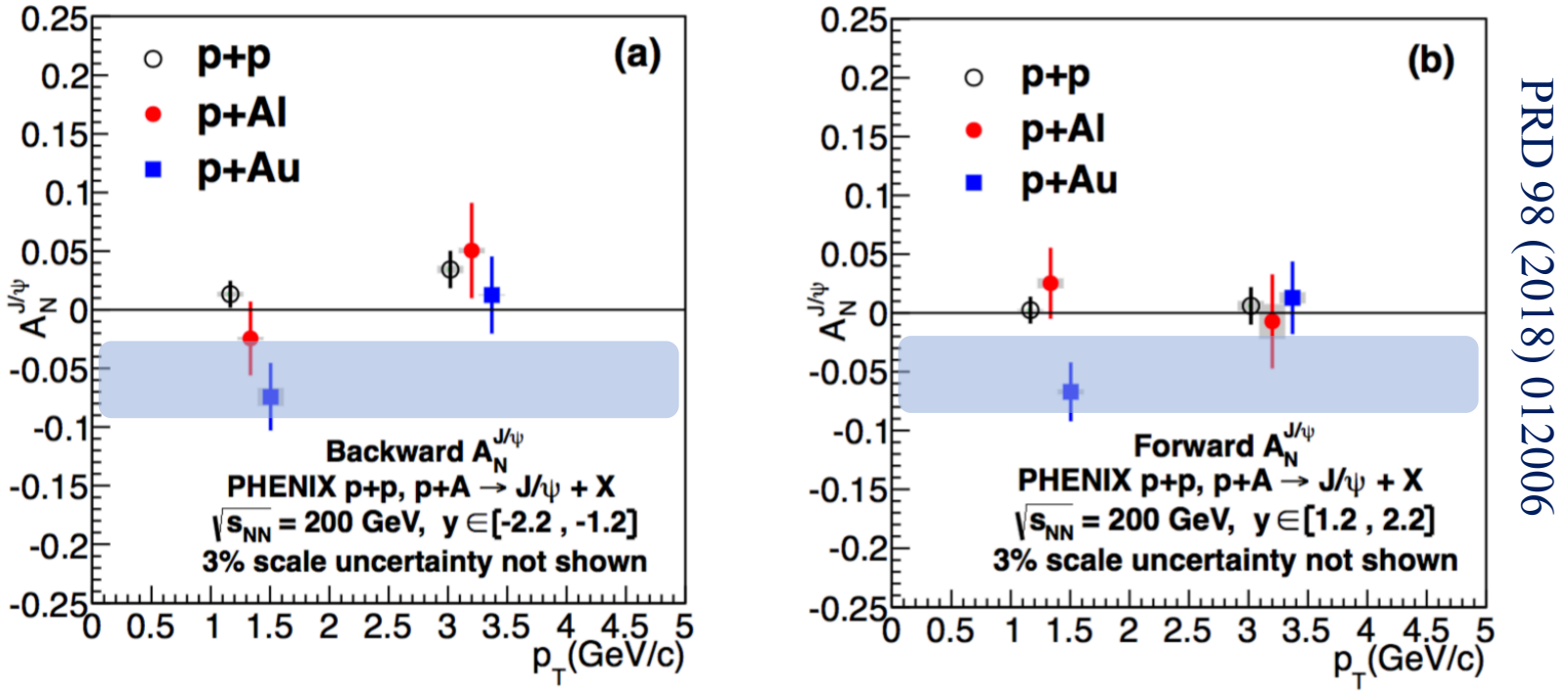


- Negative A_N seen in p+Au collisions both in forward and backward rapidity.

A_N for J/ψ as a function of p_T



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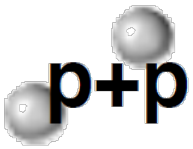
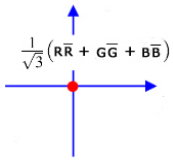
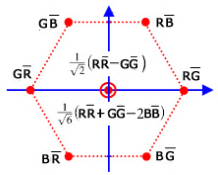
- Negative A_N seen in p+Au collisions both in forward and backward production for $0.42 < p_T. < 2$ GeV/c.
- Indication that nuclear environment played a role in creating non-zero asymmetries.

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.
- Prompt J/ψ dominant production in hadron collisions will help map out color singlet and octet production mechanisms.



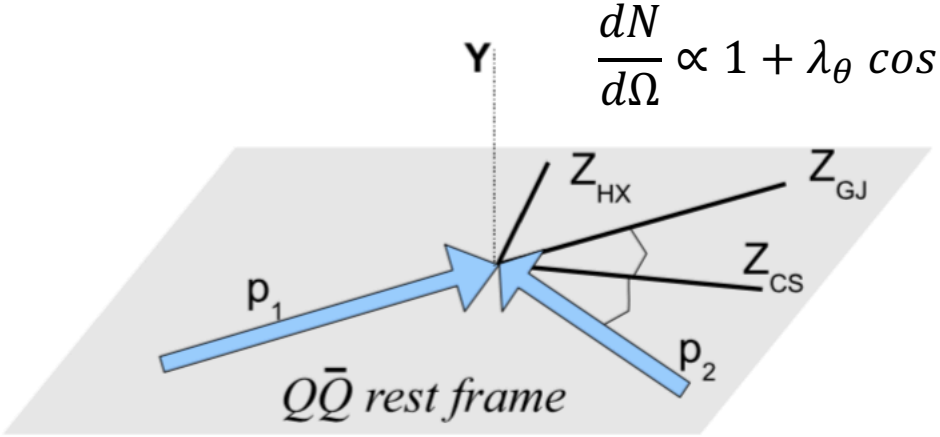




$$|\psi_Q\rangle = \mathcal{O}(1)\left|{}^3S_1^{(1)}\right\rangle + \mathcal{O}(\nu)\left|{}^3P_J^{(8)}g\right\rangle + \mathcal{O}\left(\nu^2\right)\left|{}^3S_1^{(8)}gg\right\rangle + \mathcal{O}\left(\nu^2\right)\left|{}^3S_0^{(8)}g\right\rangle + \cdots$$

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.

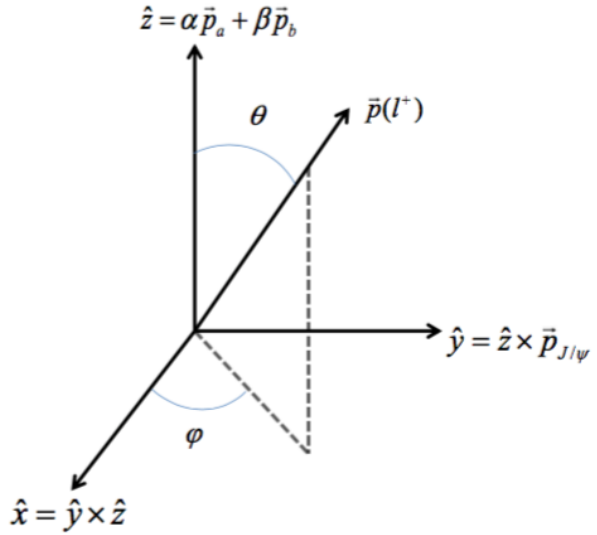


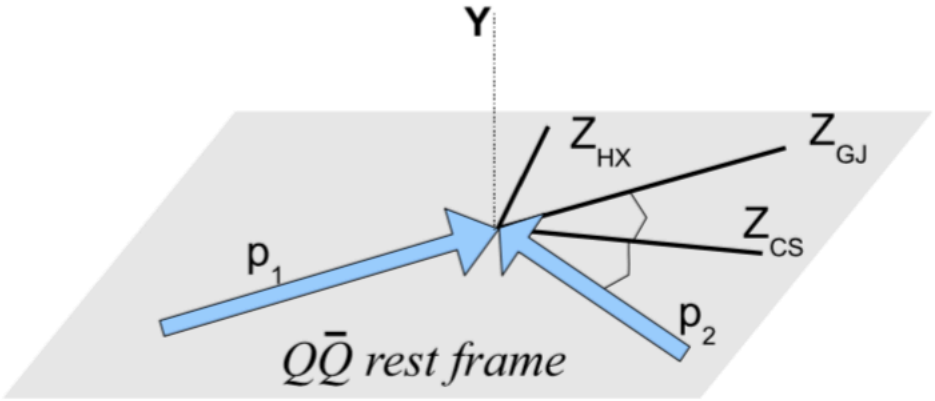
$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \, cos^2\theta + \lambda_{\theta\varphi} \, sin^2\theta \, cos2\phi \; + \lambda_\varphi \, sin2\theta \, cos\phi$$

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

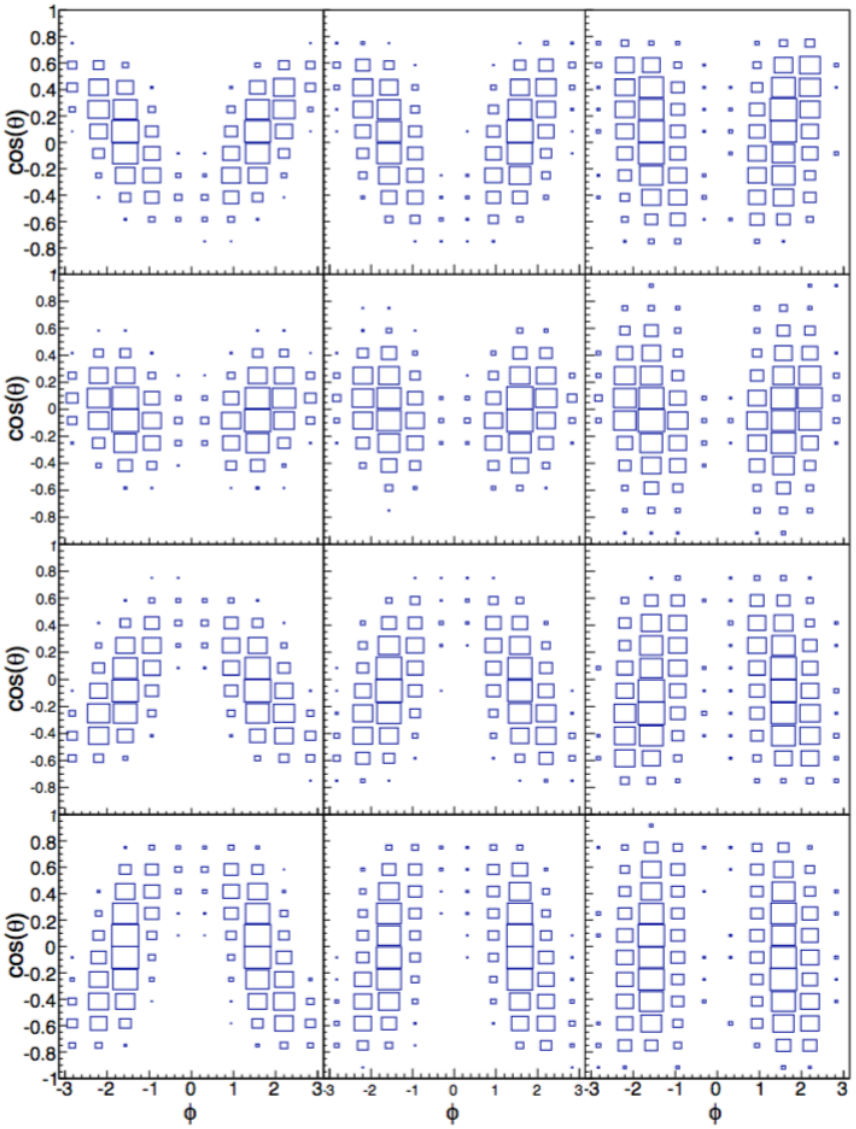
Polarization measurement frames

- Helicity frame:
  - $\hat{z} \parallel$ momentum of J/ψ.
- Collins-Soper frame:
  - $\hat{z} \parallel (\mathbf{k}_1 - \mathbf{k}_2)$.
- Gottfried Jackson frame:
  - $\hat{z} \parallel \boldsymbol{P}_1$





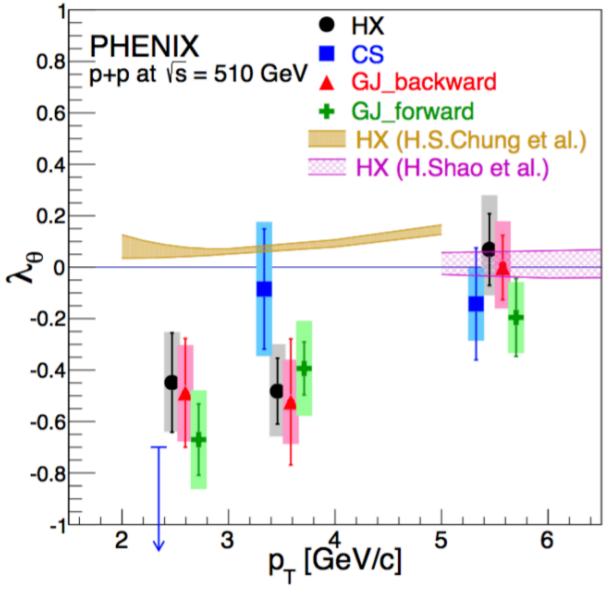
Angular decay distributions

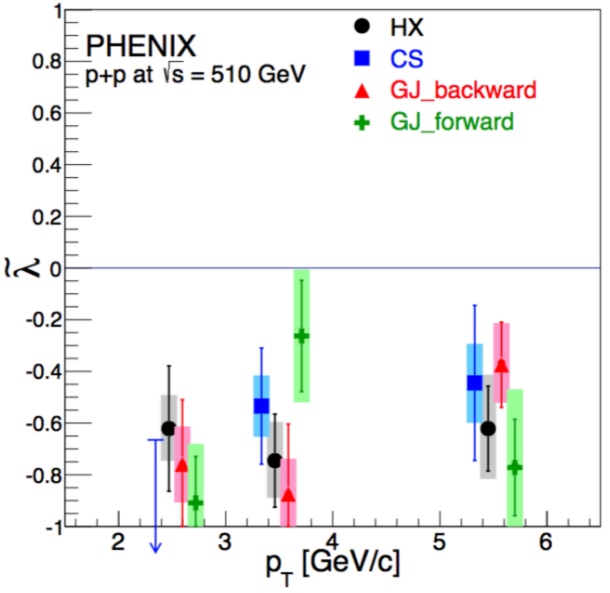


- (Top to bottom) Frame : HX, CS, GJF and GJB
- (Left to right) pT : 2-3, 3-4 and 4-10 GeV/c

J/ψ to di-muon spin alignment in PHENIX Forward Arm

- Results for λ_ϑ and $\tilde{\lambda}$.
- Better agreement at higher pT with NRQCD calculations.
  [10.1103/PhysRevD.83.037501, arXiv:1012.1954],[JHEP05 (2015) 103, arXiv:1411.3300]
- Frame invariant variable $\tilde{\lambda}$ consistent in different frames.





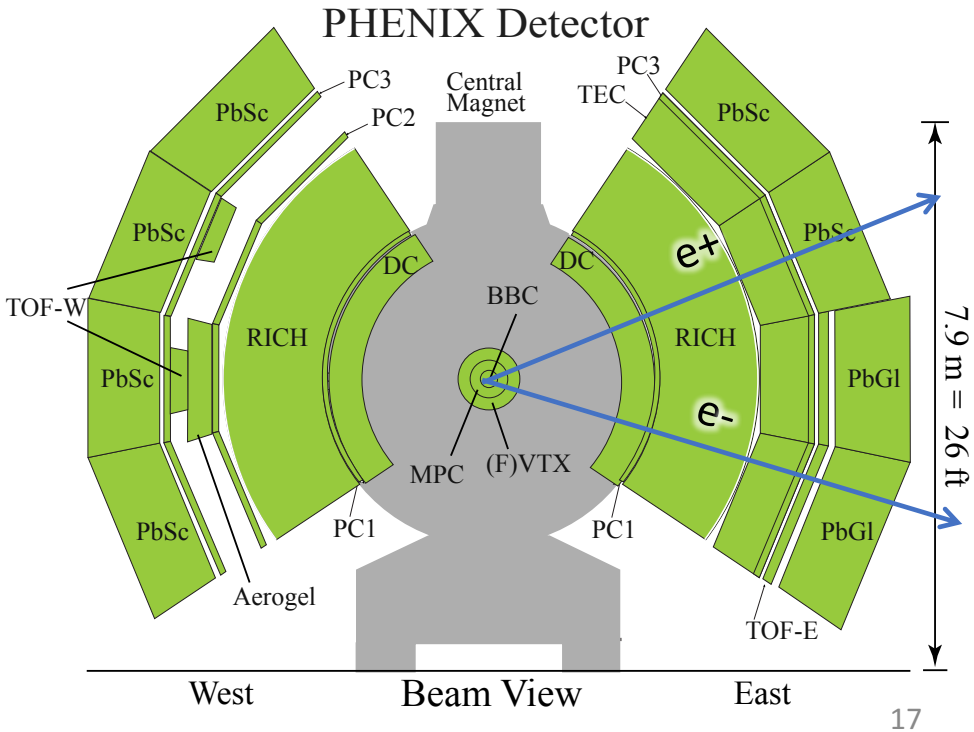
PRD 95 (2017) 092003

J/ψ to di-electron spin alignment in PHENIX central arm

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

Electron Identification

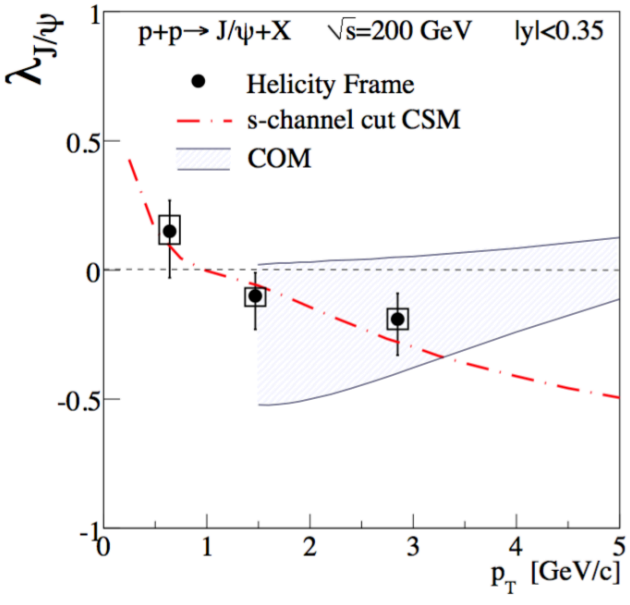
- RICH : Ring Imaging Cherenkov detector, > 99% efficient for electrons p_T > 0.5 GeV/c
- EMCal : 2 different types of Electro-magnetic Calorimeters. PbGl and PbSc.
- DC : Drift Chamber, gas proportional wire chamber.

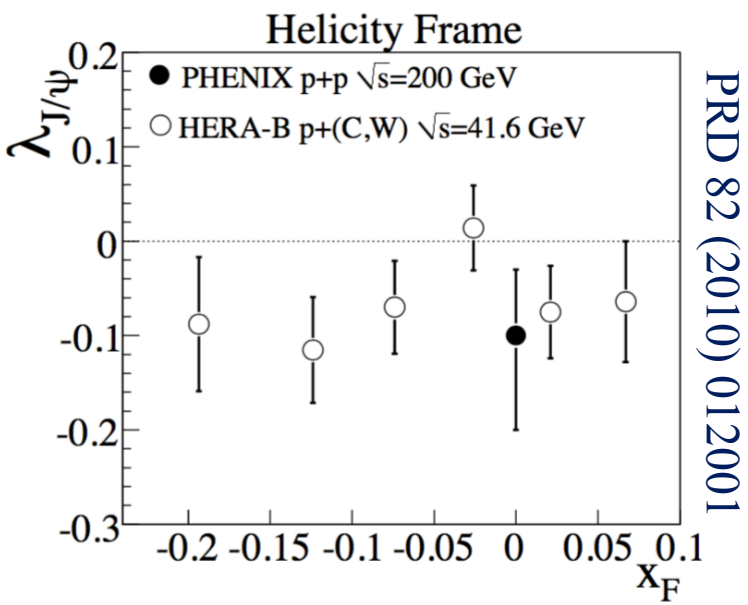


J/ψ to di-electron spin alignment in PHENIX central arm

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

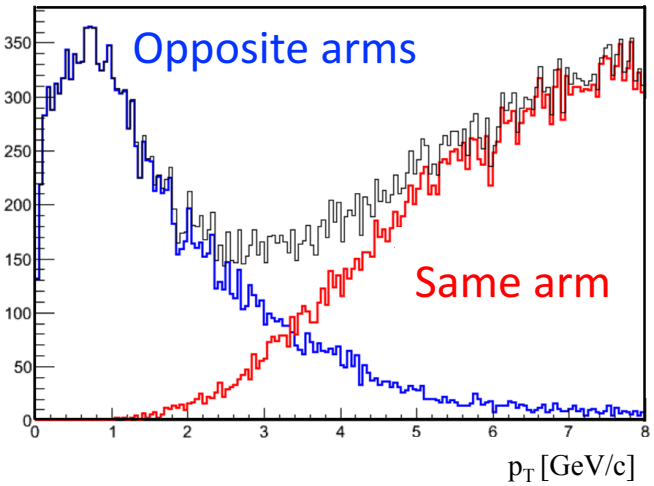
- Results of 1-dimensional analysis.
- λ_θ measurement shows agreement with NRQCD based Color Octet Model (COM) prediction. [10.1103/PhysRevD.81.014020, arXiv:0911.2113]
- Full 3-dimensional analysis needed in order to draw physics interpretation.

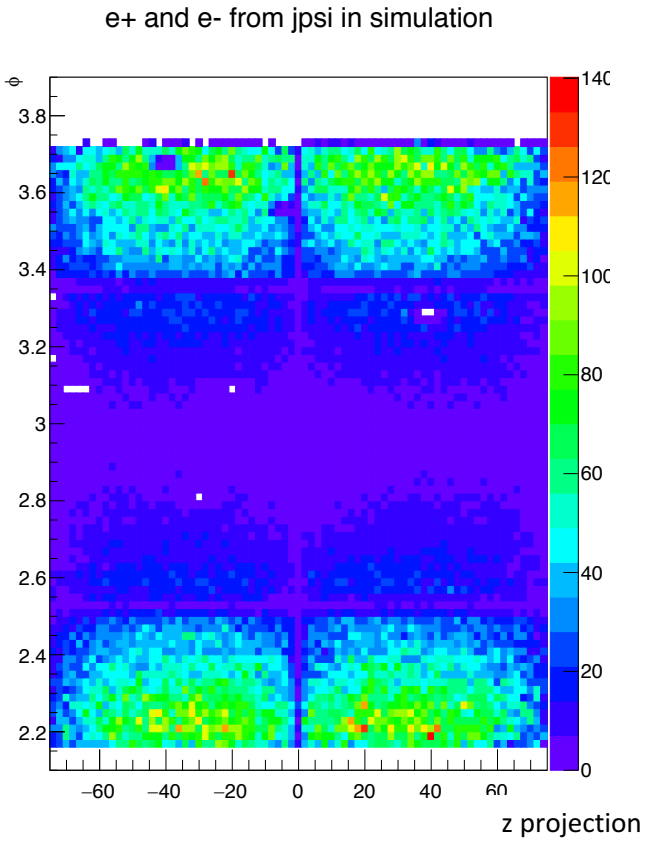




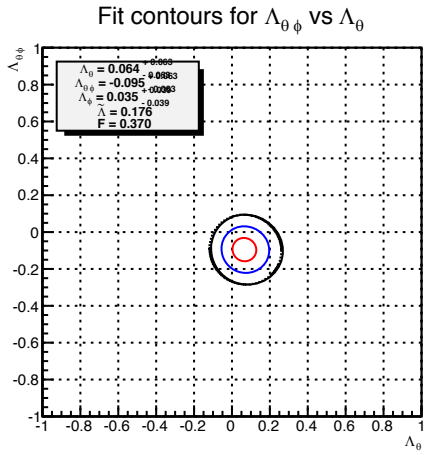
J/ψ to di-electron spin alignment in PHENIX central arm

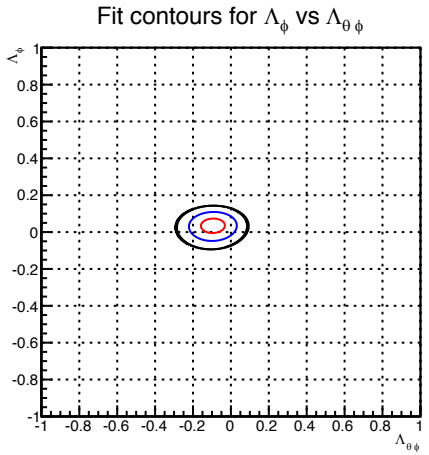
- Full 3-dimensional analysis under way with $\sqrt{s}$ = 510 GeV high p_T enhanced data sample.
- Localized statistics due to limited azimuthal coverage : systematic effects need to be addressed with great care.

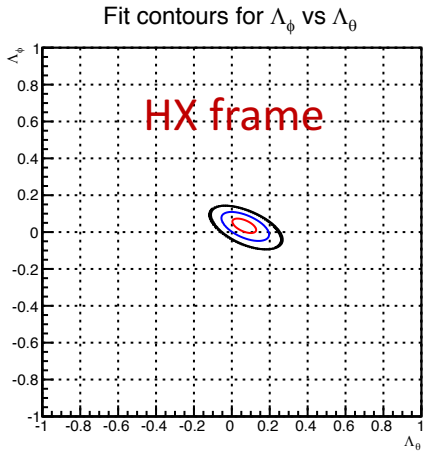


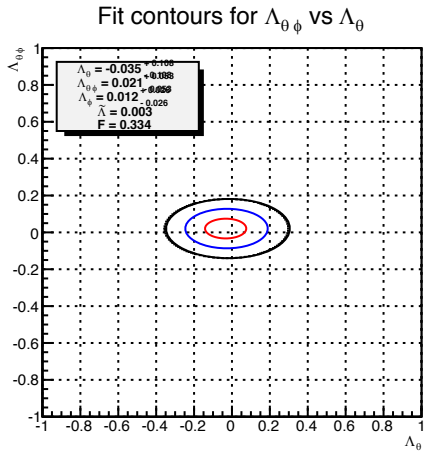


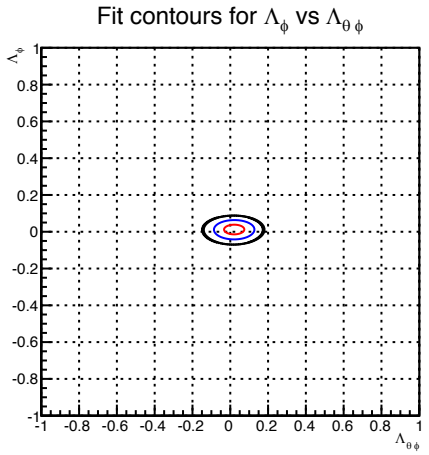
Test fit with simulated data w/ no polarization + acceptance corrected

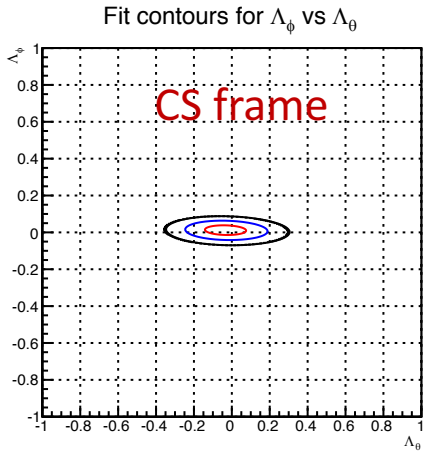




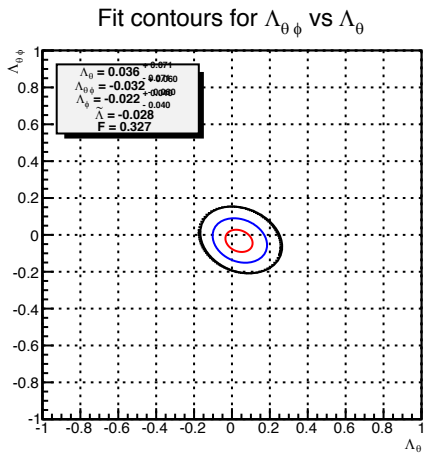


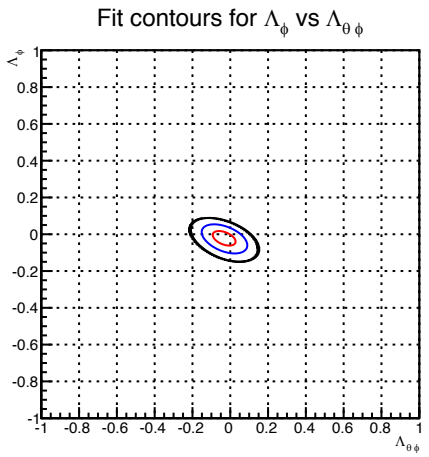


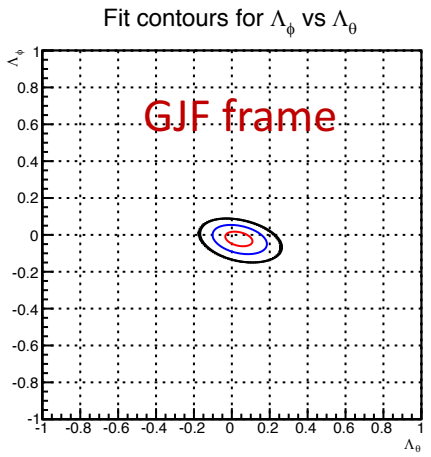




Test fit with simulated data w/ no polarization + acceptance corrected



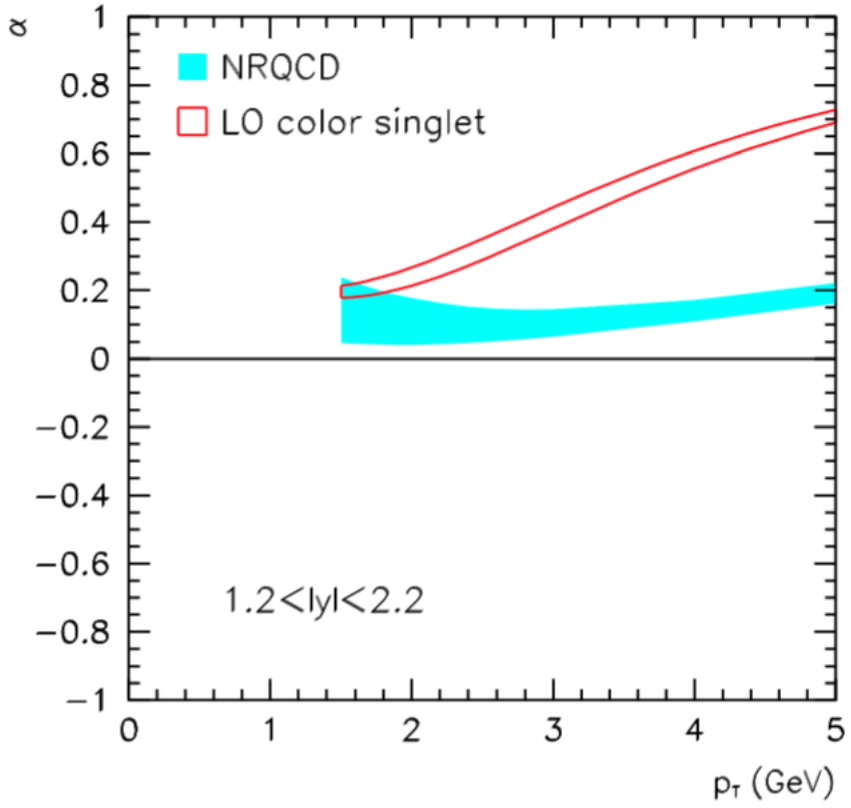




Summary

- Observed negative A_N for backward and forward J/ψ productions in p+Au collisions where gluon density in initial state is enhanced.
- Negative $\tilde{\lambda}$ seen with increasing value with pT in J/ψ to di-muon decay into forward rapidity.
- λ_θ measured in central rapidity and shows agreement with COM prediction at 1.5 < pT < 5 GeV/c.
- Interpretation is limited and 3-d analysis in higher p_T enhanced data sample is under way.
- J/ψ polarization as well as A_N will provide additional handle on distinguishing production mechanisms.

extra


α
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
NRQCD
LO color singlet
1.2<|y|<2.2
0
1
2
3
4
5
p_T (GeV)