The 35th Winter Workshop on Nuclear Dynamics

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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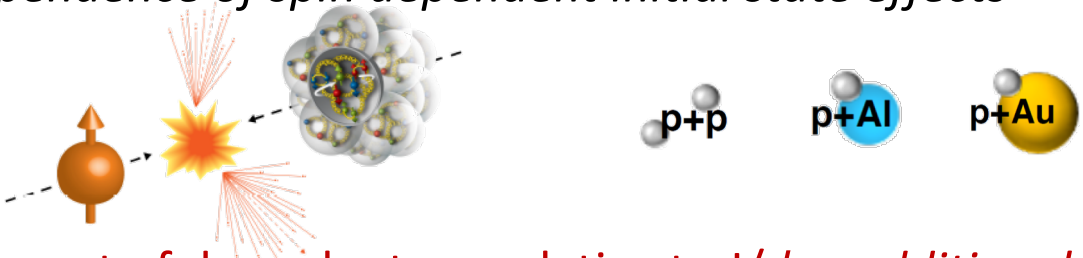
PHENIX

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.

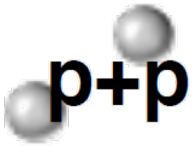
- Nuclear modification in small to large systems : *Effects of QGP (suppression and flow) and Cold Nuclear Matter effects (rapidity, centrality and pT dependent modification) on J/ψ production.*
- Correlation with initial proton spin in different collision systems: *path-length dependence of spin dependent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

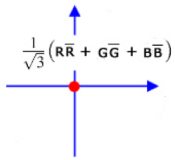


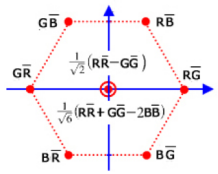
- Spin alignment of decay leptons relative to J/ψ : *additional handle on distinguishing production mechanisms.*

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.







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

J/ψ Production mechanisms

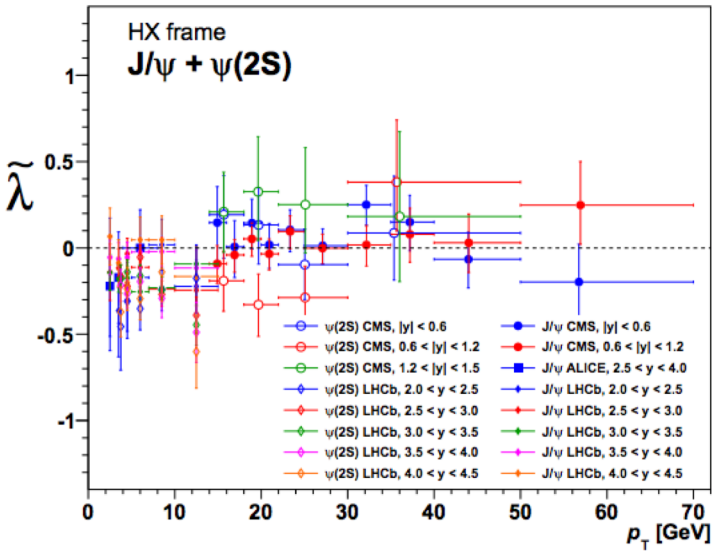
- In 90's, it was proposed that color singlet fragmentation was the dominant J/ψ production mechanism at high p_T.
- Prediction based on this idea fell more than an order of magnitude below the inclusive ψ' cross section measurements by CDF – " CDF ψ' anomaly".
- NRQCD formalism was introduced as a solution that included an intermediate color octet state binding into a color singlet state. It was later supported by the CDF data.
- Inclusive production cross-section measurements of S wave charmonium states became available by other experiments and all reasonably support the NRQCD calculation.

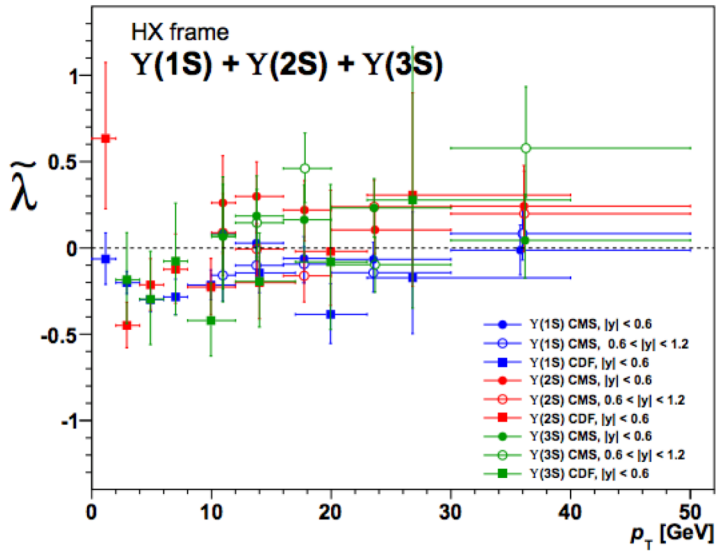
J/ψ Production mechanisms

- Polarization measurements have been proposed as an independent test on the NRQCD approach.
- Global analysis of various data sets has shown that color octet state is the dominant mechanism for hadro- and photo-production of j/ψ and well describe polarization data.

Previous quakonium polarization measurements

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

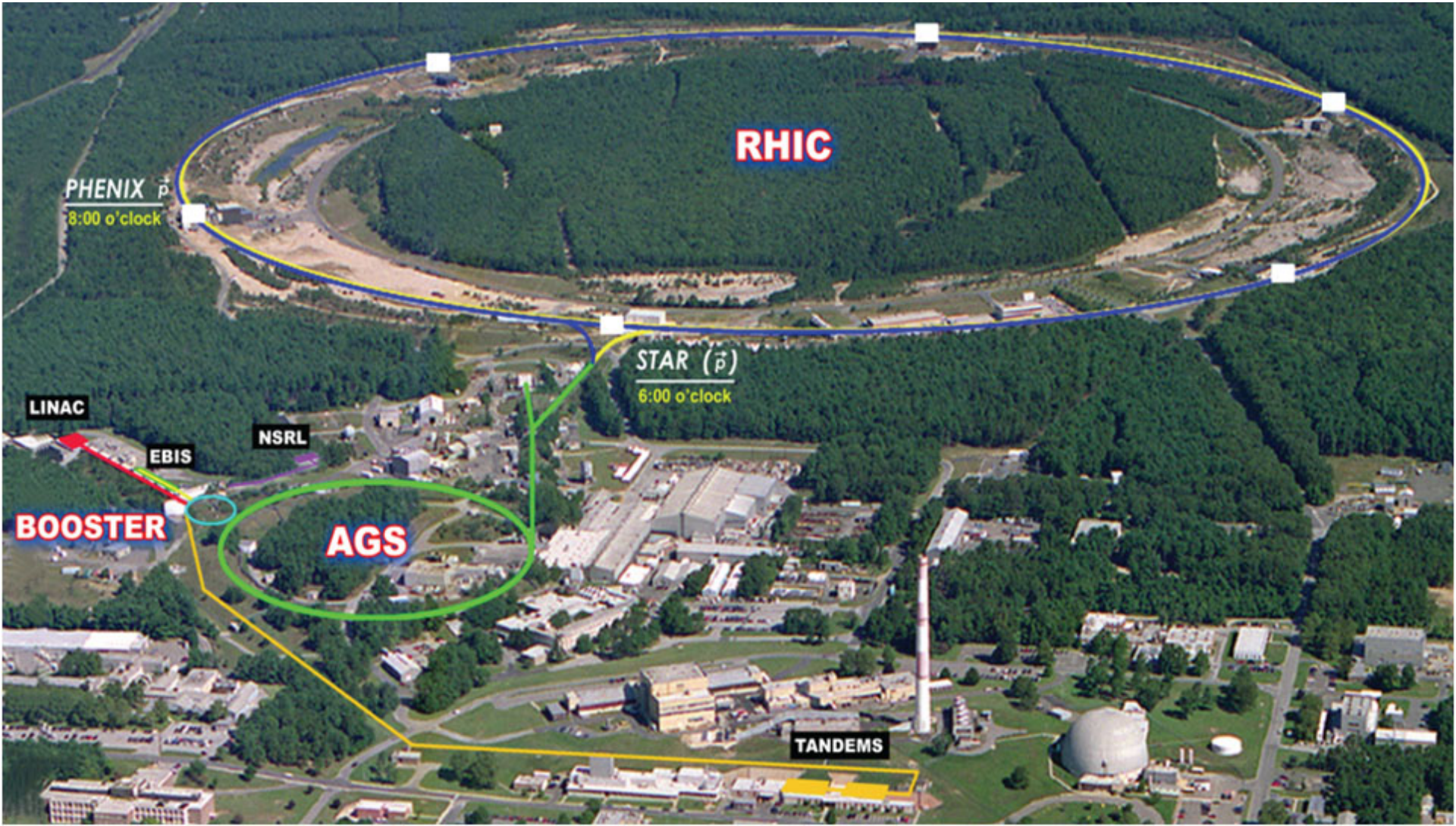




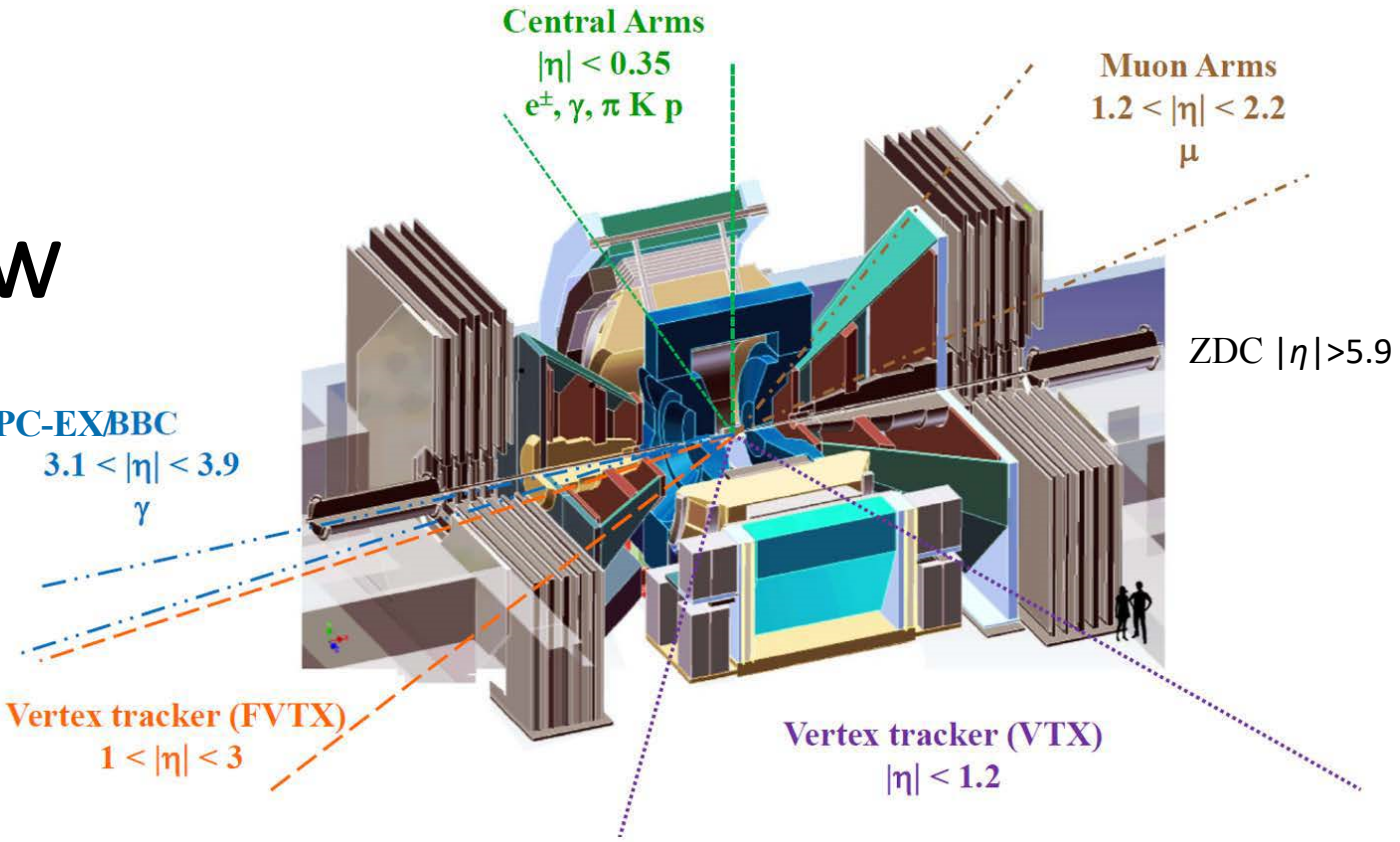
[10.22323/1.216.0012]

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								✓	

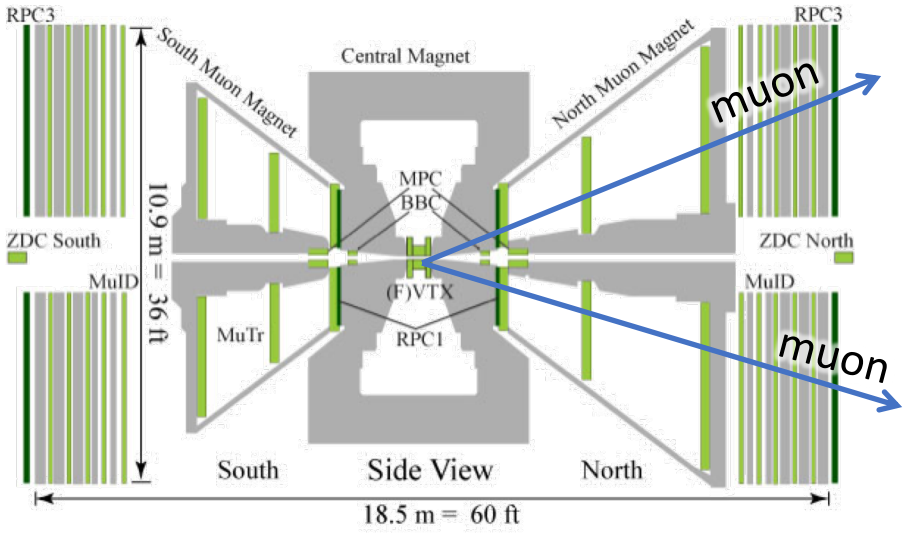
- Multiple golden data sets (●) at various collision energies.
- This talk will cover recent results and ongoing analysis that utilize data sets from p+p at √s = 200 and 510 GeV.

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

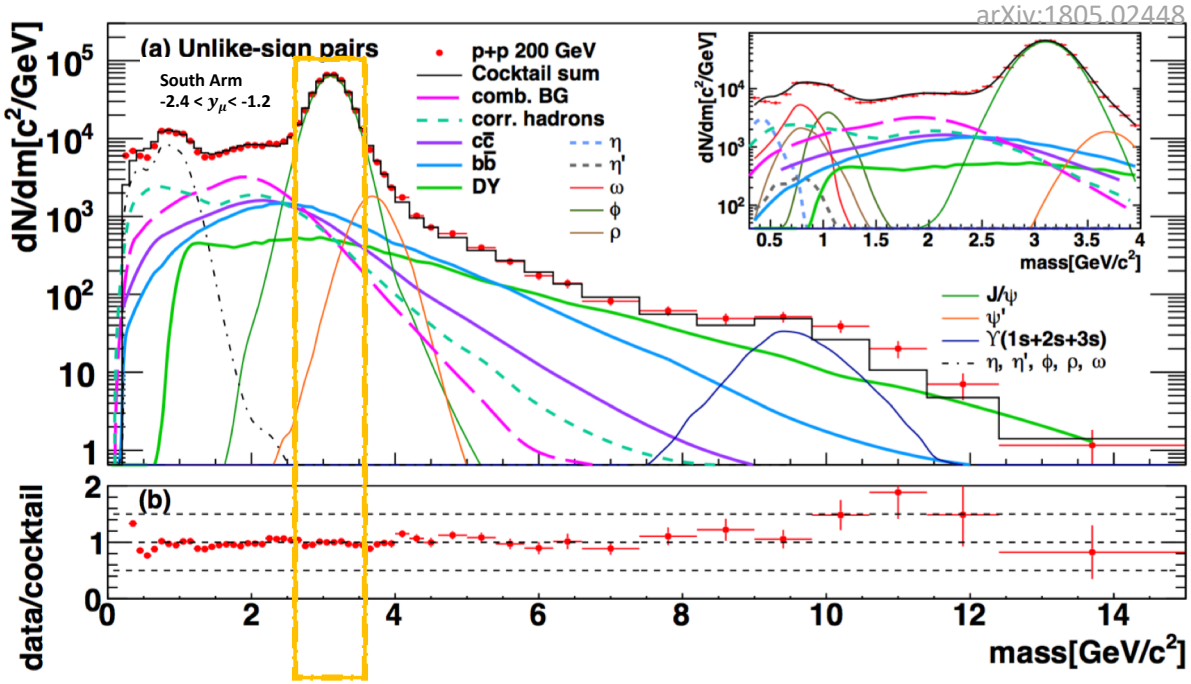
- Forward arm covers full azimuth and $1.2<|y|<2.4$
- Theoretical prediction accessible by NRQCD.

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



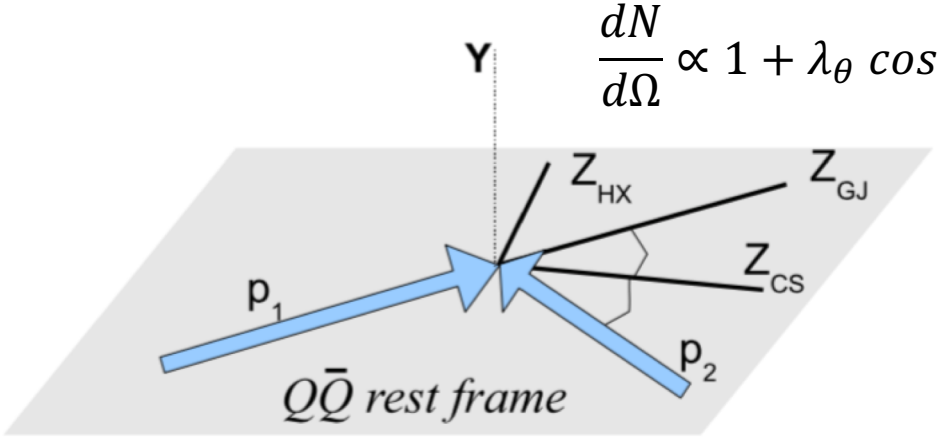
J/ψ in di-muon mass spectra



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

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.



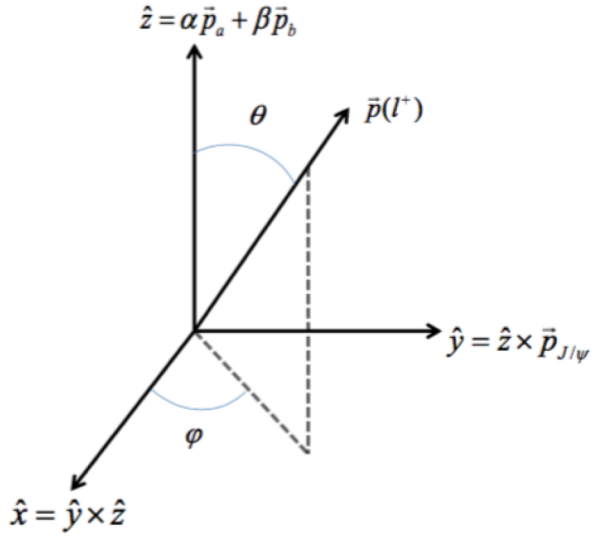
$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_{\theta\varphi} \sin^2\theta \cos 2\phi + \lambda_\varphi \sin 2\theta \cos\phi$$

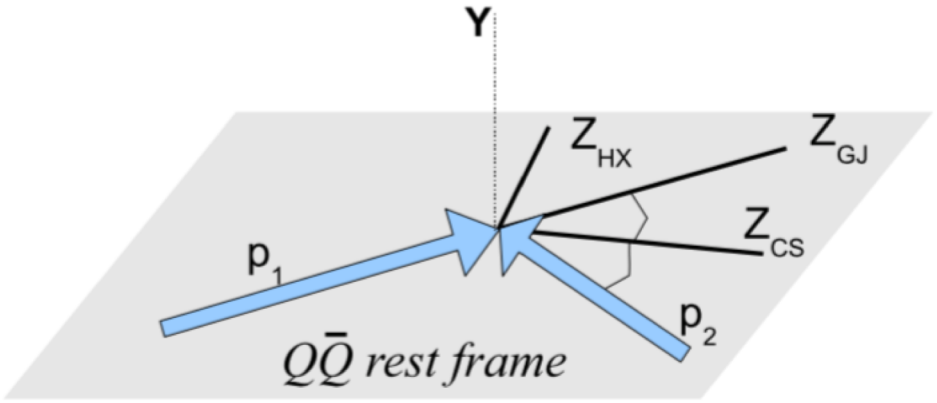
$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

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

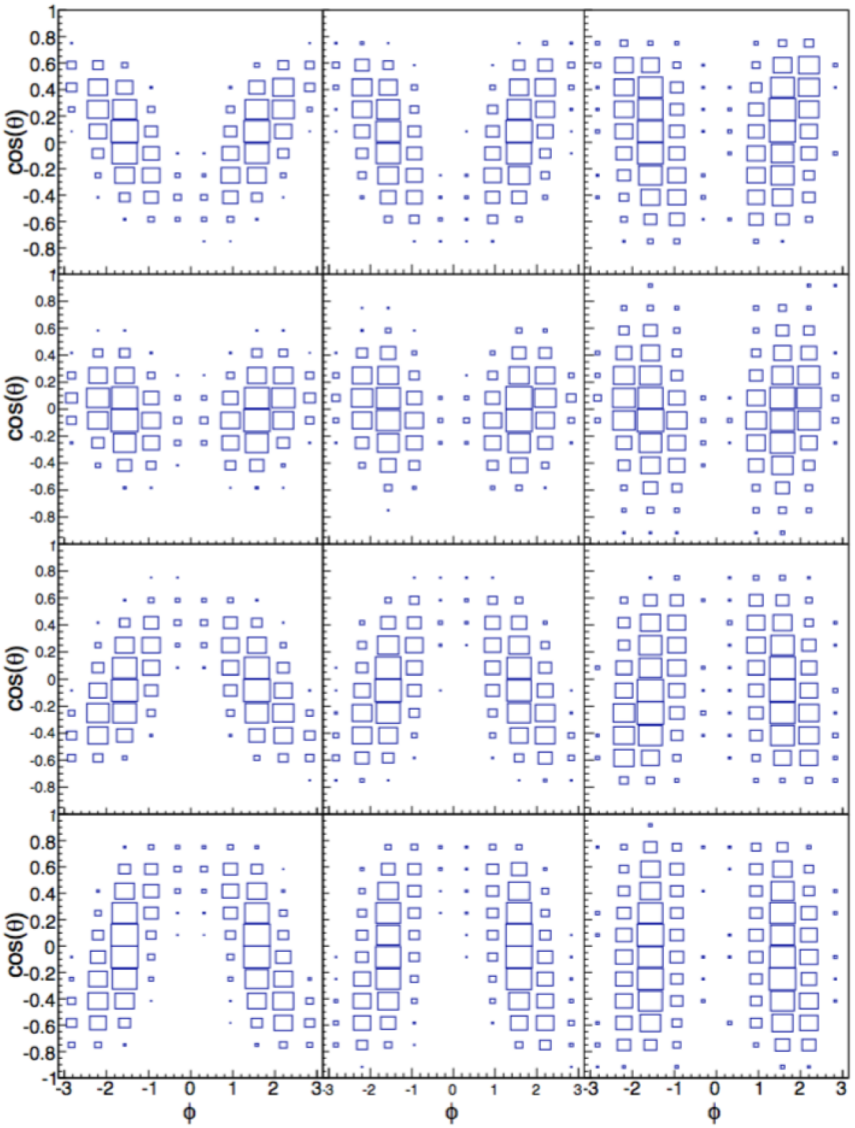
Polarization measurement frames

- 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

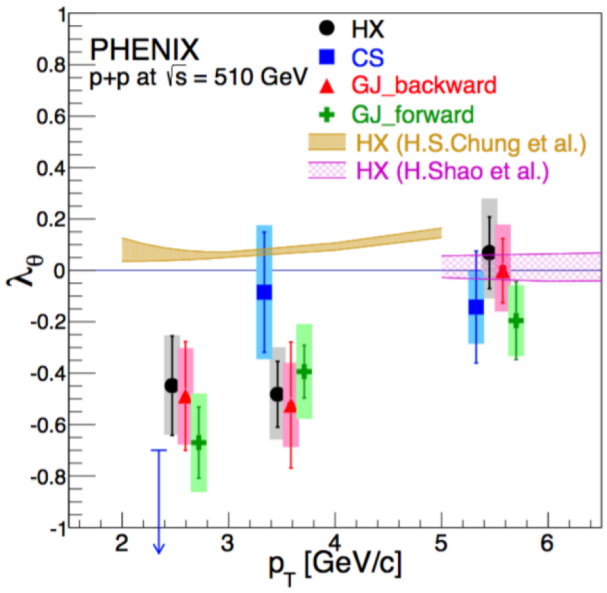


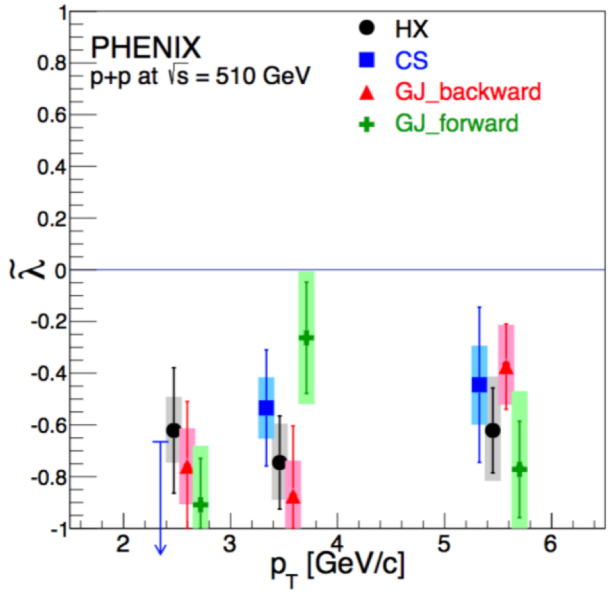
Simultaneously fit all angular coefficients to angular distributions shown here.

- (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 by H.Shao et al. [10.1103/PhysRevD.83.037501, arXiv:1012.1954],[JHEP05 (2015) 103, arXiv:1411.3300]
- Frame invariant variable $\tilde{\lambda}$ consistent in different frames.





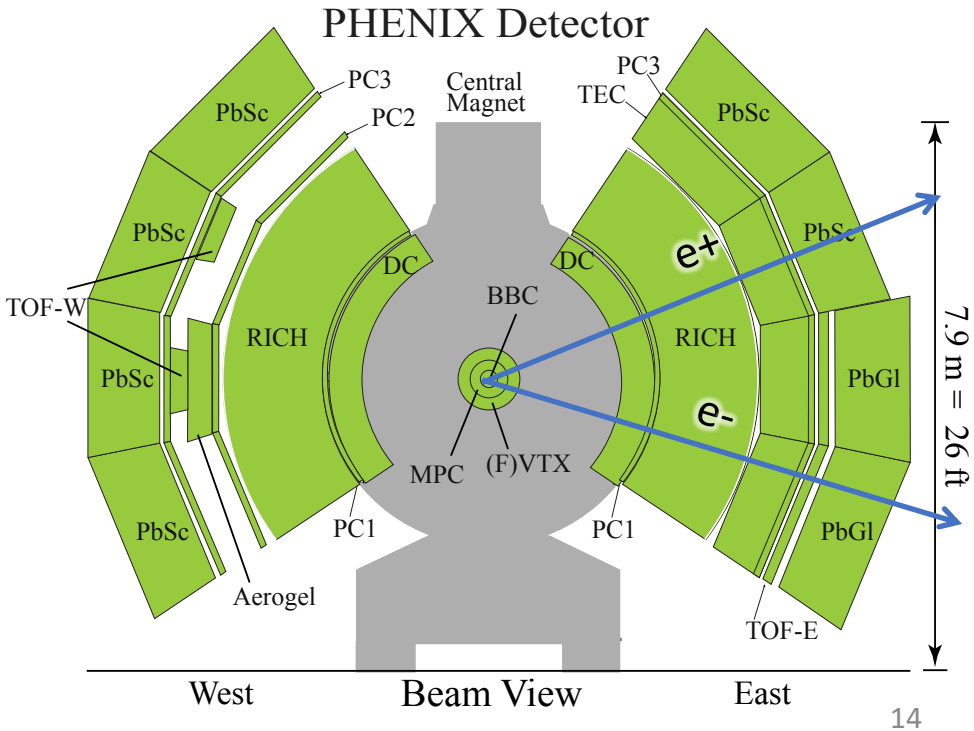
PRD 95 (2017) 092003

Heavy flavor 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

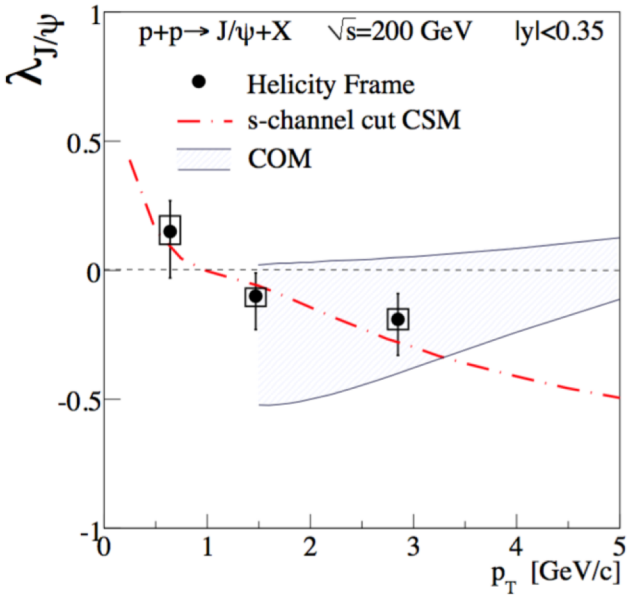
- RICH : Ring Imaging Cherenkov detector, > 99% efficient for electrons $p_T > 0.5$ GeV/c
- EMCal : 2 different types of Electro-magnetic Calorimeters. PbGl and PbSc.
- DC : Drift Chamber, gas proportional wire chamber.

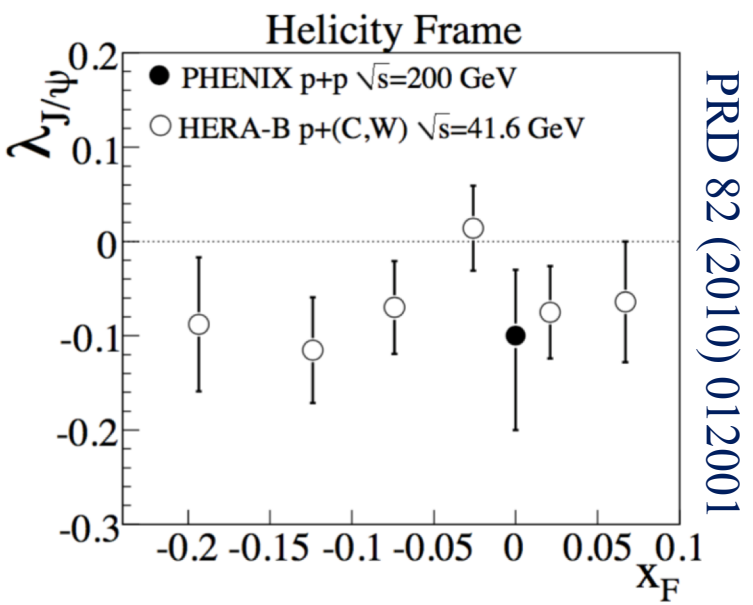


J/ψ to di-electron spin alignment in PHENIX central arm

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

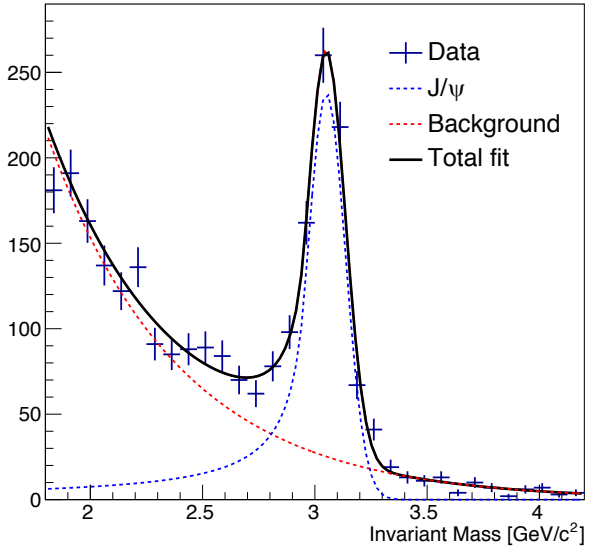
- Results of 1-dimensional analysis.
- λ_θ measurement shows agreement with NRQCD based Color Octet Model (COM) prediction. [10.1103/PhysRevD.81.014020, arXiv:0911.2113]
- Full 3-dimensional analysis needed in order to draw physics interpretation.

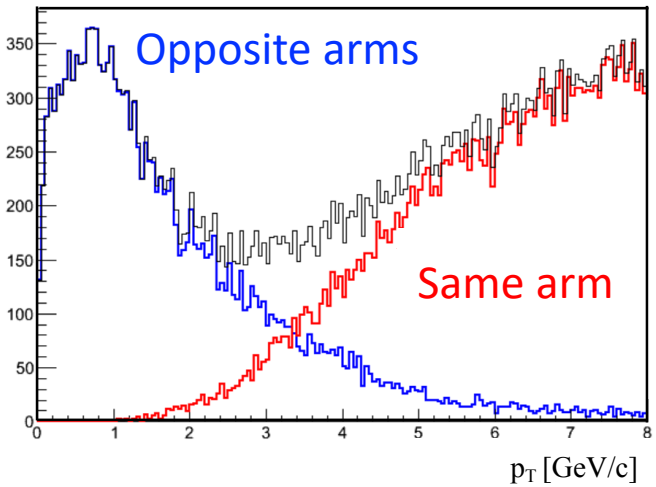




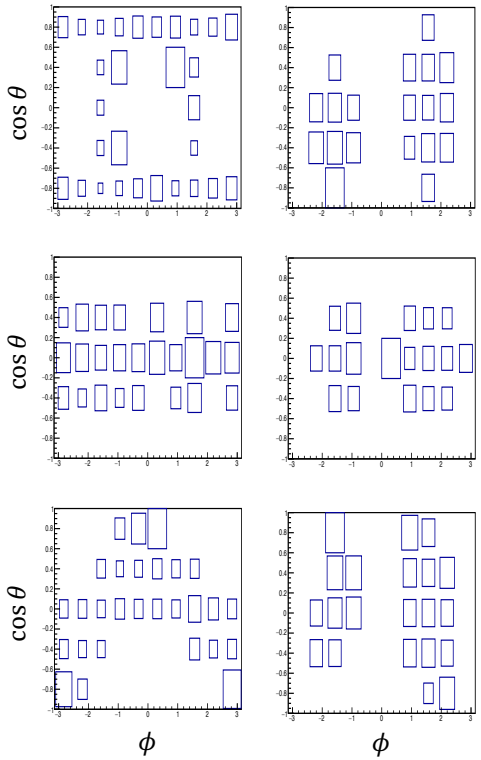
Full 3-dimensional analysis of J/ψ polarization at midrapidity

- Full 3-dimensional analysis in progress 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.





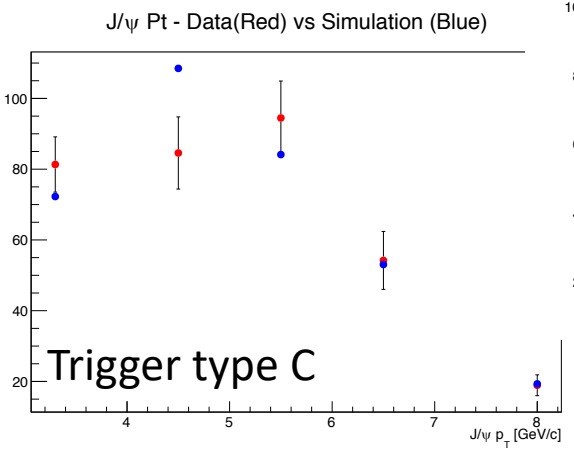
Decay angular distributions

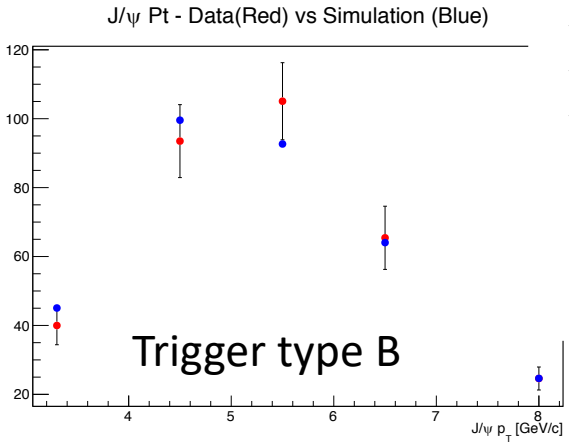


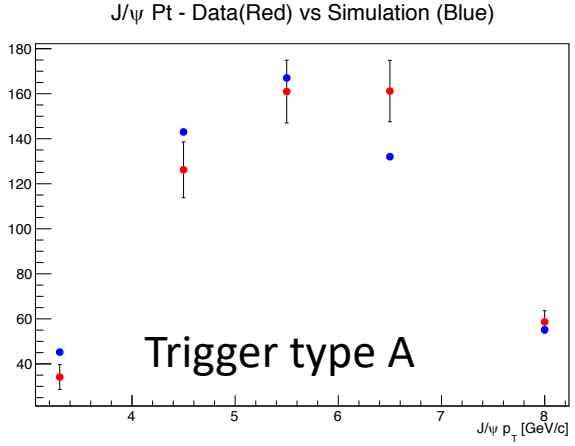
- (Top to bottom) Frame : HX, CS, GJF
- (Left to right) pT : 0.-2.5, 2.5-10 GeV/c

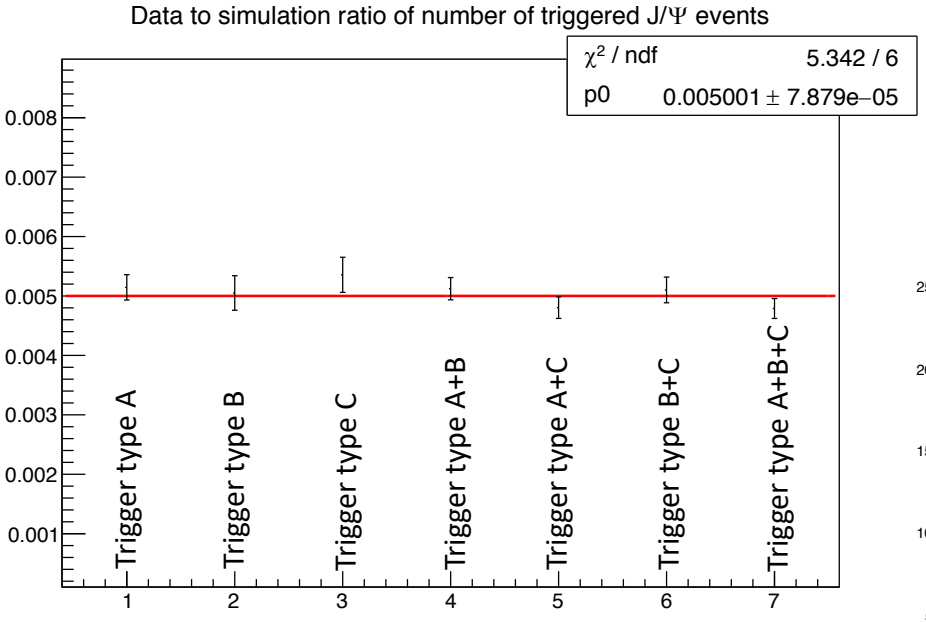
Analysis method (i)

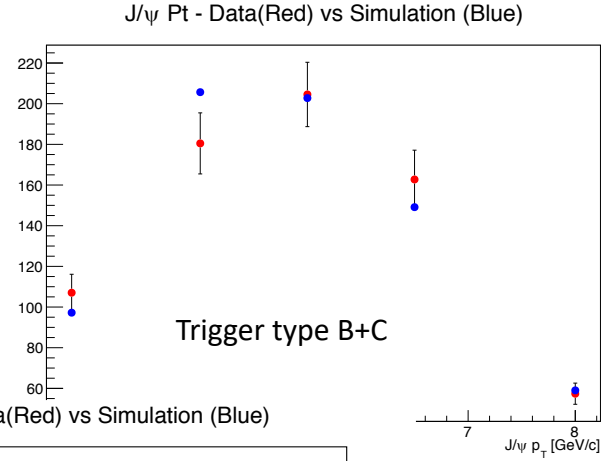
- Monte Carlo simulation developed in order to generate data for acceptance*efficiency corrections.
- Simulator emulates data acquisition system and mixes triggers with different energy thresholds and pre-scale factors.
- Tested with data being analyzed, well describes all possible combinations of mixed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

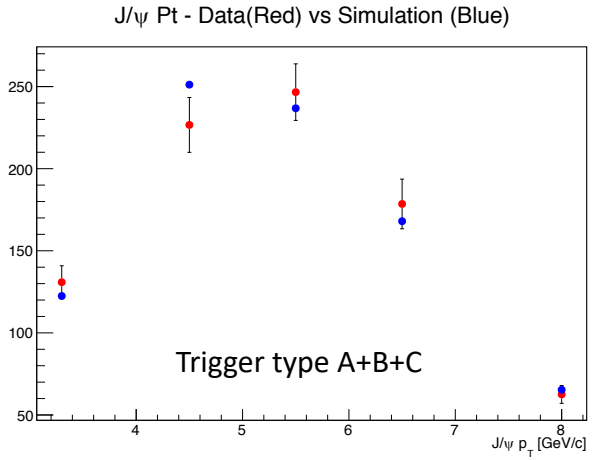

J/ψ Pt - Data(Red) vs Simulation (Blue)
Trigger type C
J/ψ p_T [GeV/c]


J/ψ Pt - Data(Red) vs Simulation (Blue)
Trigger type B
J/ψ p_T [GeV/c]


J/ψ Pt - Data(Red) vs Simulation (Blue)
Trigger type A
J/ψ p_T [GeV/c]


Data to simulation ratio of number of triggered J/Ψ events
χ² / ndf 5.342 / 6
p0 0.005001 ± 7.879e−05
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

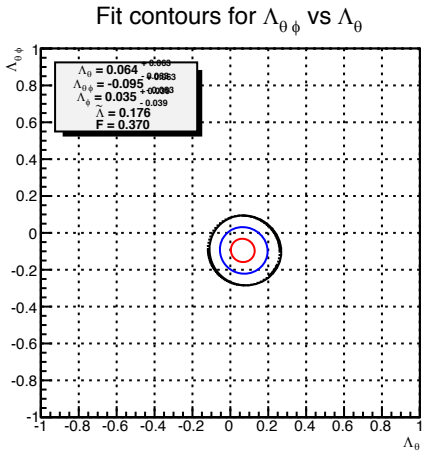

J/ψ Pt - Data(Red) vs Simulation (Blue)
Trigger type B+C
J/ψ p_T [GeV/c]

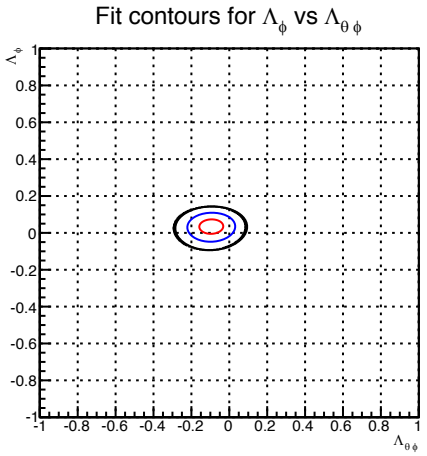

J/ψ Pt - Data(Red) vs Simulation (Blue)
Trigger type A+B+C
J/ψ p_T [GeV/c]

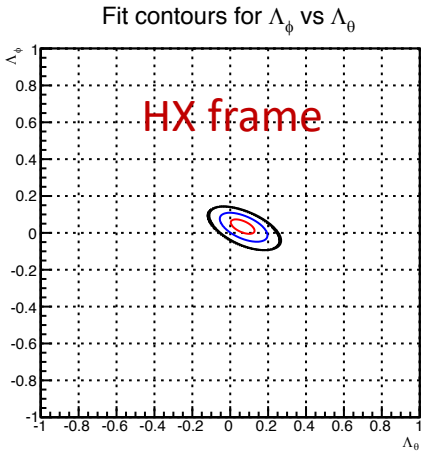
Analysis method (ii)

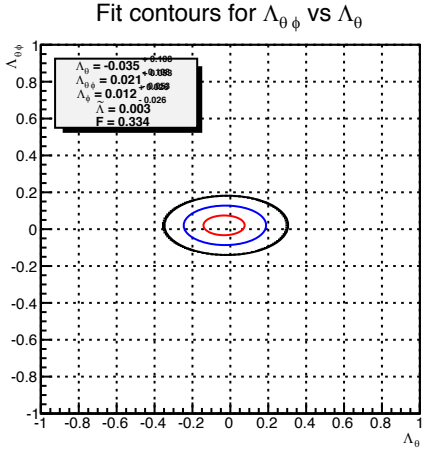
- 3 different approaches to determine decay angular coefficients and their uncertainties.
  - χ^2 minimization
  - Maximum log likelihood method : Poisson statistics better treats low statistics measurements.
  - Sampling method : randomize central value of each measurement according to Gaussian distribution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

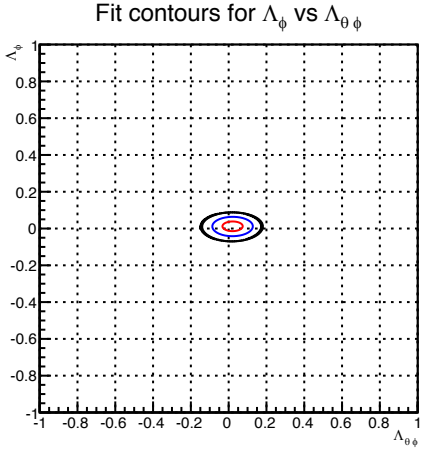
- Tested with fake data with no polarization

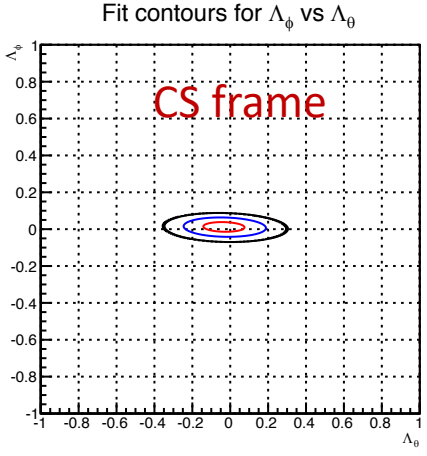


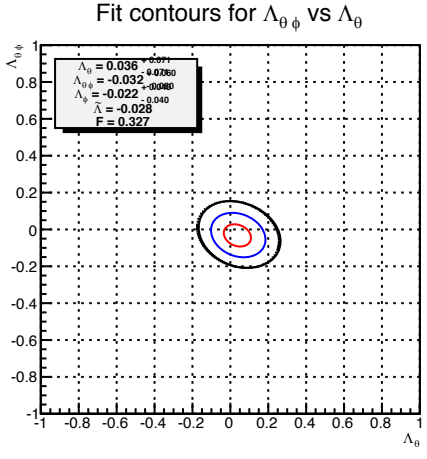


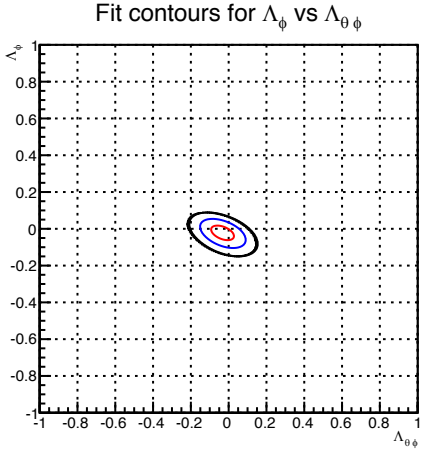


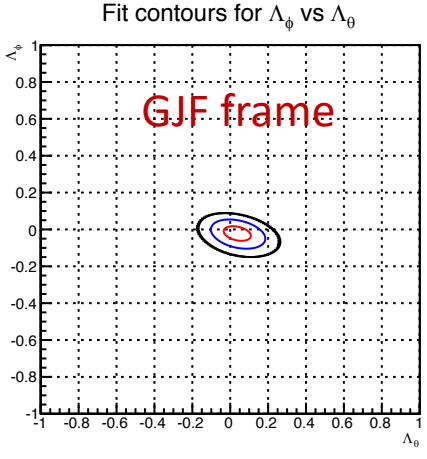










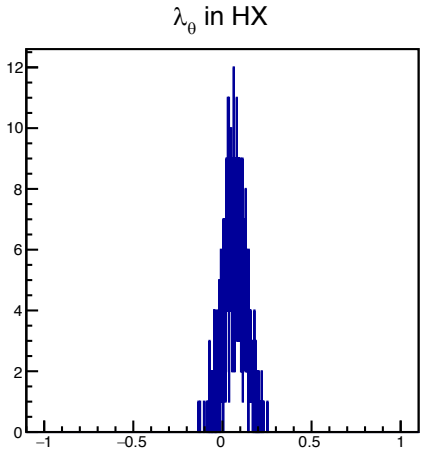


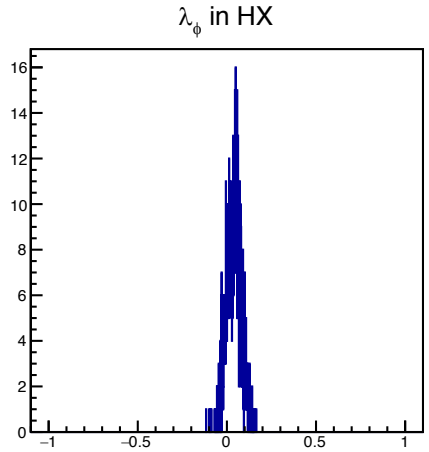
Maximum log -likelihood Method

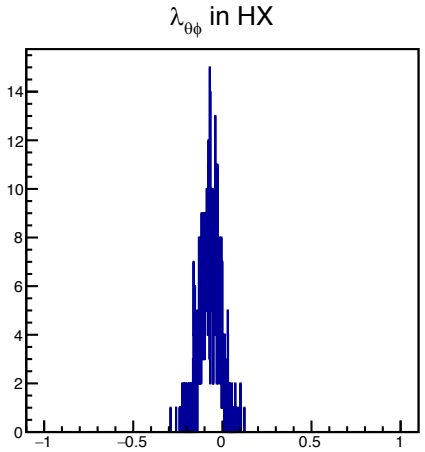
NOT from real data!

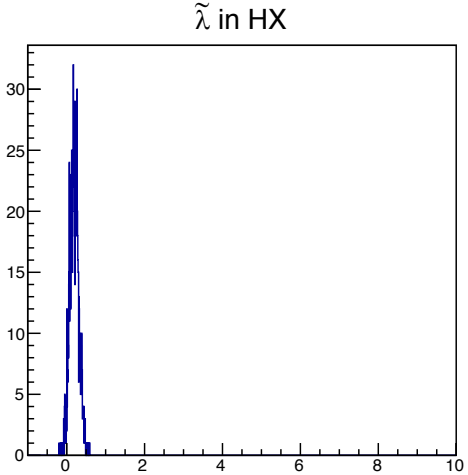
Sampling method

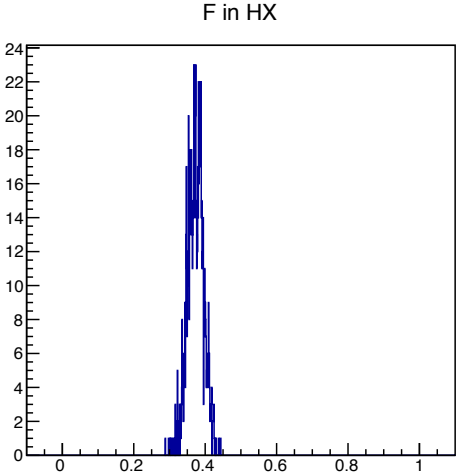
NOT from real data!



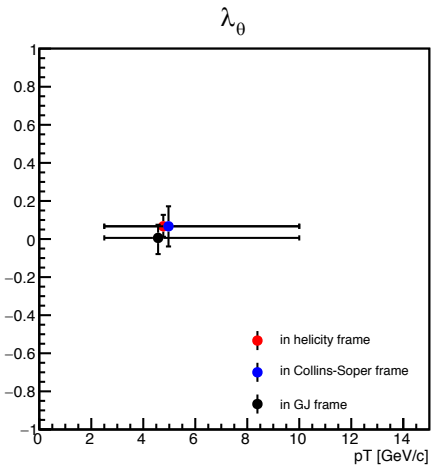


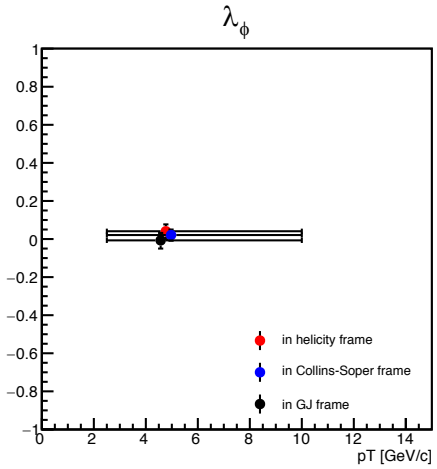


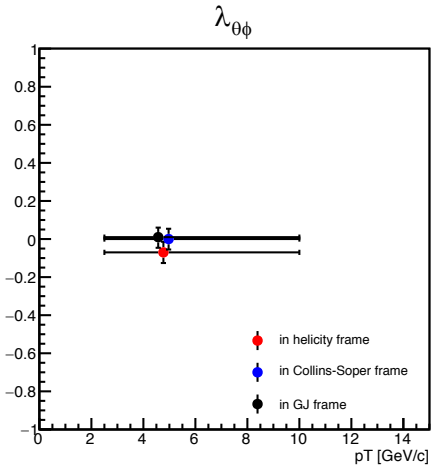


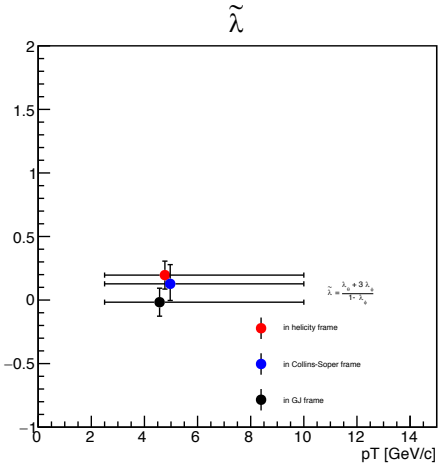


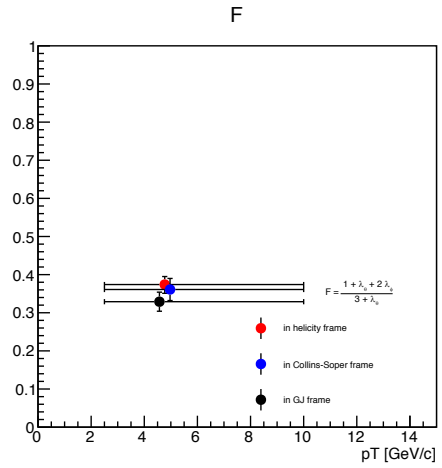
Comparison between 3 frames
NOT from real data!











J/ψ dN/pT spectra at midrapidity

- Work in progress
- Data at at $\sqrt{s}$ = 510 GeV indicates significant hardening of J/psi production in comparison with $\sqrt{s}$ = 200 GeV.
- Shape of pT spectra a determining factor on decay angular coefficients.
- Uncertainties on pT spectra expected to be a major source of systematic uncertainties.
- J/ψ cross section provides information on dominant production mechanism in its own right.

Outlook

- At 200 GeV, it has been known from cross section measurements that color octet hadronization is dominant mechanism in PHENIX acceptance.
- Full NRQCD calculations for J/ψ production and polarization at midrapidity $\sqrt{s}$= 510 GeV are not available at the moment.
- Yield as well as rapidity dependent polarization measurements can shed light on discrepancy between data and theory seen at low J/ψ p_T at forward rapidity.
- When included in global analysis, universality of LDME can be tested for NRQCD.

Summary

- Negative $\tilde{\lambda}$ seen in data taken from p+p collisions at 510 GeV with its value increasing with pT in J/ψ to di-muon decay into forward rapidity.
- λ_θ measured in midrapidity at 200 GeV shows agreement with COM prediction at 1.5 < pT < 5 GeV/c.
- Full 3-d analysis using higher p_T enhanced data sample from 510 GeV p+p collisions is in progress for complete interpretation on polarization.
- Polarization of J/ψ measured at mid rapidity as well as forward rapidity will provide additional handle on mapping out its production mechanisms.
- J/ψ dN/dp_T measurement under way and cross section measurement will be an excellent cross check on theory predictions.