Study of angular distributions for $J/\psi \rightarrow \mu^+ + \mu^-$ decays in p+p collisions at $\sqrt{s}$ = 510 GeV by the PHENIX Collaboration at RHIC.

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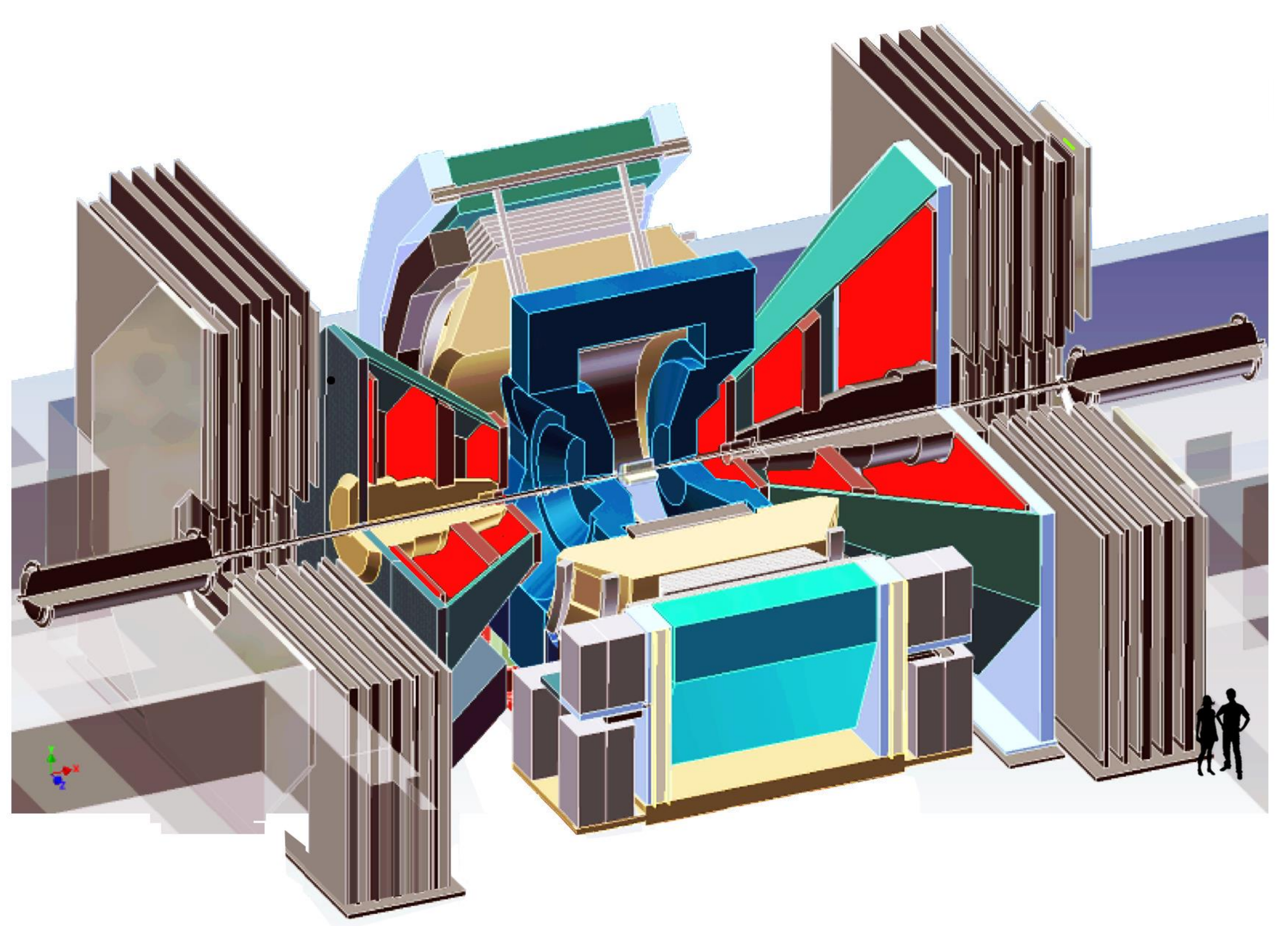
2015 KOBE JAPAN

Motivation

Measurements of heavy quark bound states, like J/ψ meson, provide a unique opportunity to access basic QCD properties.
One of the observables important for understanding J/ψ production and dynamics is angular distribution of decay products, sometimes also called "polarization". J/ψ polarization measurements can help to differentiate between various models of J/ψ production.

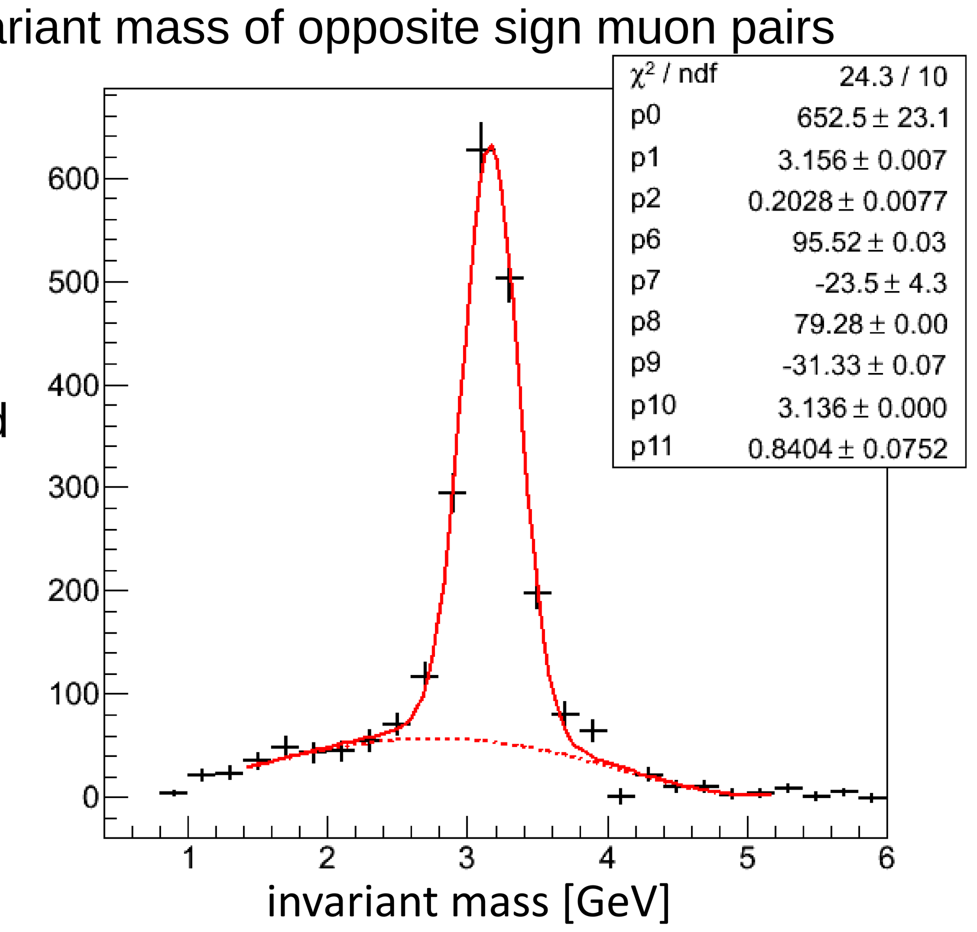
The PHENIX Experiment

The PHENIX experiment is one of the two large experiments at the Relativistic Heavy Ion Collider (RHIC) located at the Brookhaven National Laboratory (BNL) on Long Island, New York.



The two PHENIX muon spectrometers, located at forward and backward rapidity, are shielded by absorbers composed of 19 cm of copper and 60 cm of iron. Each spectrometer consists of the muon tracker (MuTr) immersed in a radial magnetic field of integrated bending power of 0.8 T·m, and backed by the muon identifier (MuID). The muon spectrometers subtend 1.2 < |η| < 2.2 and the full azimuth. The momentum resolution, δp/p, of particles in the analyzed momentum range is about 5%. The minimum momentum of a muon to reach the last MuID plane is ~2 GeV/c.

J/ψ are identified via invariant mass of opposite sign muon pairs in $J/\psi \rightarrow \mu^+\mu^-$ decay channel. An example of di-muon invariant mass distribution is shown in the plot to the right. Combinatorial background is subtracted by first subtracting the same sign background, and then fitting the result with a Gaussian and a polynomial for the remaining physical background.

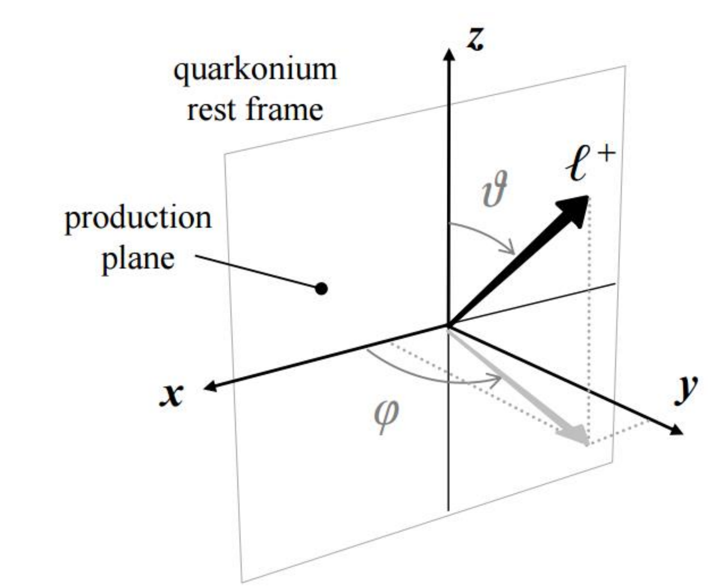


Introduction

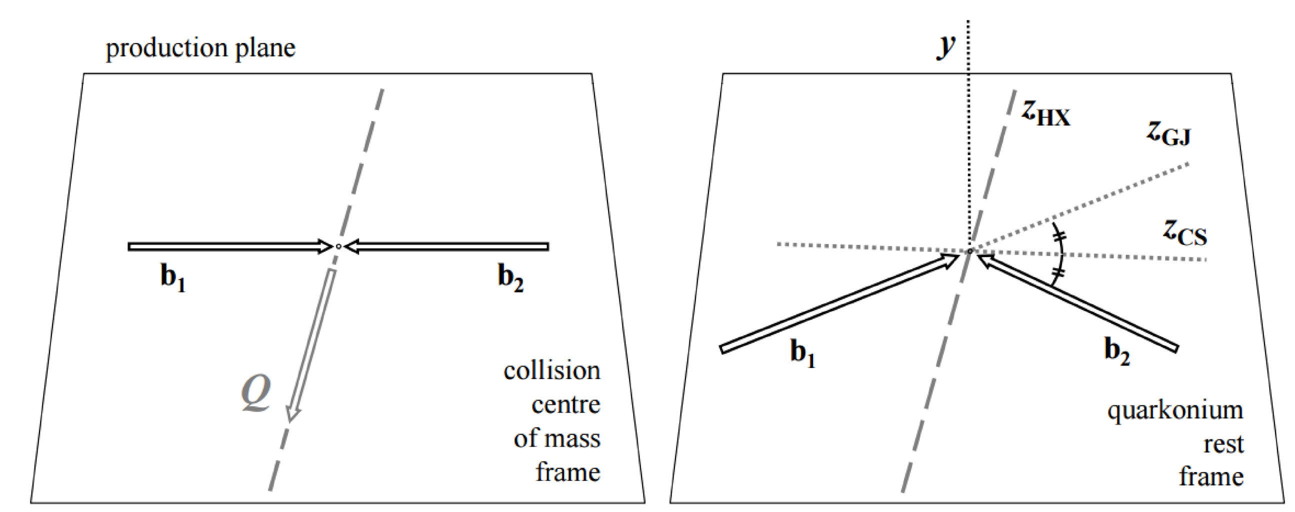
The angular decay coefficients for J/ψ meson decays to leptons along with the cross-section for those decays are the two major predictions made by the leading J/ψ meson production mechanism models. The full angular decay distribution for the decay of any spin-1 particle with < J_z >= 0 into two spin-1/2 particles can be written as [4]:

$$\frac{d\sigma}{d(\cos\vartheta)d\varphi} \propto 1+\lambda_\vartheta\cos^2\vartheta+\lambda_{\vartheta\varphi}\sin(2\vartheta)\cos\varphi+\lambda_\phi sin^2\vartheta\cos 2\varphi \qquad (1)$$

where θ is the angle of the positively charged particle relative to the Z axis of an arbitrarily chosen reference frame with X and Z axes lying in the production plane, and ϕ is the angle relative to the X axis. The coefficients of the distribution are related to density matrix elements which determine the alignment of the particle's spin along some axis.

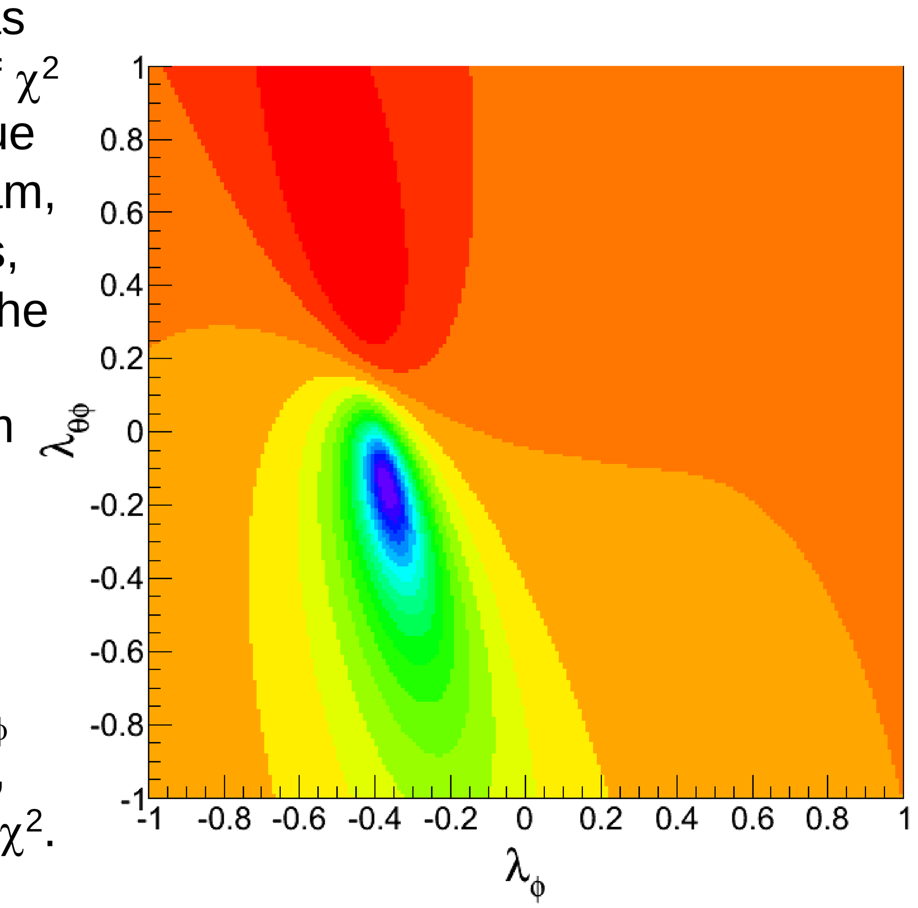


We will consider four reference frames:
Helicity (Jacob-Wick) frame [1], Collins-Soper frame [2], Gottfried-Jackson Forward [3] and Gottfried-Jackson Backward [3] frames. The definitions of the Z axis are shown in the plot below [4].



The method.

Many previous J/ψ polarization measurements assumed that λ_ϕ and $\lambda_{\theta\phi}$ are zero, and integrated over ϕ, reducing Eq.1 to a simple 1+λcos(θ) formula. However, this is correct only if reference frame is properly selected.
In our study we made no assumptions about values of λ_ϕ and $\lambda_{\theta\phi}$ Instead, we searched for a global minimum of a 3D fit in λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ space.
After appropriate acceptance correction, two-dimensional histogram of cos(θ) vs. ϕ were filled. Instead of directly fitting this histogram with Eq.1 we use different approach. Values of all 3 λs are changed from -1 to 1 with a step size of 0.01. At each step, λs are fixed, a fit with Eq.1 is performed with only overall normalization as free parameter, and the value of χ^2 at this step is obtained. The value of χ^2 is then put into 3D histogram, which has λ_θ, $\lambda_{\theta\phi}$ and λ_ϕ as axes, and the value of each bin χ_2 of the fit. After scan of all λ values is finished, a search for a minimum χ^2 in 3D histogram is done.
An example of 2D projection of 3D histogram is shown in the figure on the right. The plot is a projection of 3D histogram to $\lambda_{\theta\phi}$ vs. λ_ϕ plane. Red shows high χ^2, blue color corresponds to small χ^2.



Simulation Test

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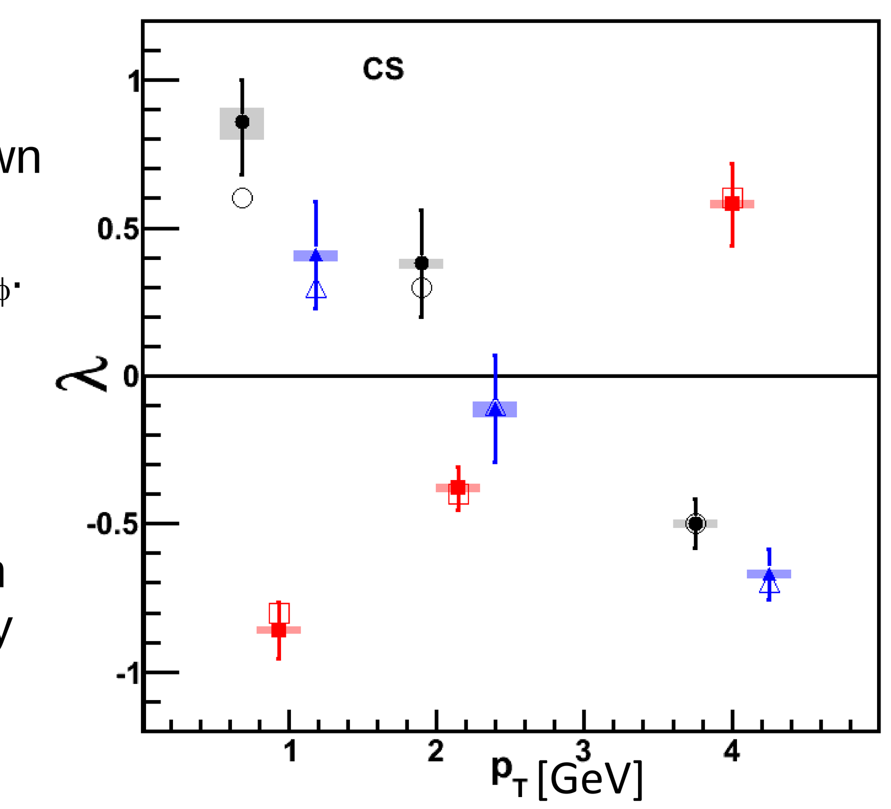
In order to test the procedure, we created a fake data sample from a part of the single J/ψ simulation used for acceptance calculation. The fake data sample was weighted with Eq. 1, and had approximately the same statistics as the actual data sample.
We used non-zero values for all three λ's in the weighting of fake data, and tried to extract the input values of λ in this test.

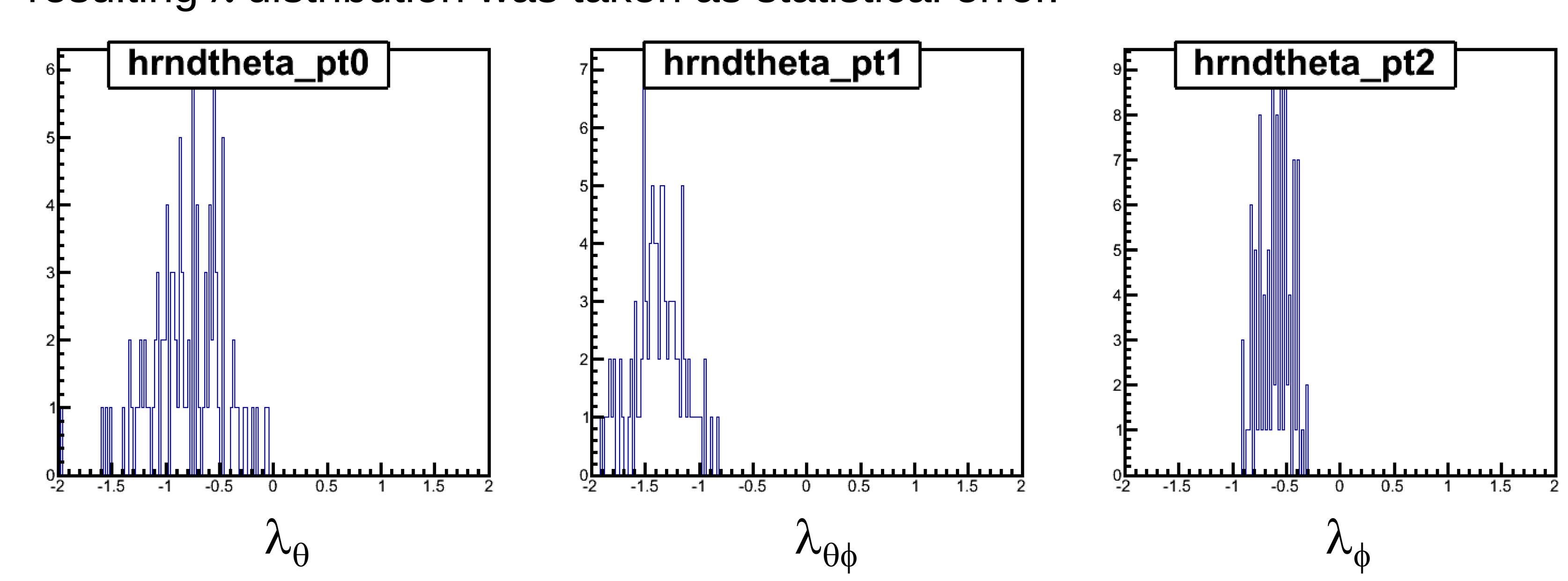
The results of the simulation test are shown in the plot to the left, Reconstructed λ values are shown for 3 p_T bins for Collins-Soper frame. Black: λ_θ; red: λ_ϕ; blue: $\lambda_{\theta\phi}$. The points are shifted for clarity. Open symbols indicate the input (true) polarization.

As one can see, within statistical uncertainty, the input polarization can be correctly reconstructed by this method.



Uncertainty calculations.

Uncertainty due to how well we know J/ψ p_T and rapidity distribution is shown in the plot above by colored boxes. It was calculated by modifying input p_T and rapidity distribution parameters obtained by fitting the data, modifying these parameters by ±1σ and taking the largest deviation as the systematic error. The statistical errors shown as error bars was calculated by randomization. Each data point was randomly smeared with a Gaussian distribution with s equal to the statistical uncertainty at this point, and re-fitting the resulting distribution again. After many such re-fits, RMS of the resulting λ distribution was taken as statistical error.



Conclusions and Outlook

As one can see, the procedure works well, and we are able to extract correctly the input polarization parameters after a single iteration.
After establishing that the polarization parameter extraction procedure works well, we started working on real data analysis, and expect to get preliminary results soon.

References

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[2] John C. Collins and Davison E. Soper. *"Angular Distribution of Dileptons in High-Energy Hadron Collisions"*. Phys. Rev., D16:2219, 1977.
[3] K. Gottfried and J. D. Jackson. *"On the connection between production mechanism and decay of resonances at high energies"*. Nuovo Cimento, 33:309.330, 1964.
[4] Pietro Faccioli et al., *"Towards the experimental clarifcation of quarkonium polarization"* Eur.Phys.J.C69:657-673,2010