Extraction of Transverse Single Spin Asymmetry in J/ψ Production in $p\bar{p}$ Interactions at 120 GeV Beam Energy

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Overview

J/ψ Particle

- J/ψ is a vector meson which is a $c\bar{c}$ bound state.
- Discovered by Burton Richter and Samuel Ting in 1974. Awarded Nobel price for the discovery in 1976.
- In $p\bar{p}$ collisions, J/ψ particles are primarily produced by $q\bar{q}$ annihilation and gg fusion.

$J/\psi(1S)$ $\qquad I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 3096.900 \pm 0.006$ MeV
Full width $\Gamma = 92.9 \pm 2.8$ keV $\quad$ (S = 1.1)
$\Gamma_{ee} = 5.53 \pm 0.10$ keV
$\Gamma_{ee} < 5.4$ eV, CL = 90%

$J/\psi(1S)$ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
hadrons		(87.7 ± 0.5) %		–
virtual $\gamma \to$ hadrons		(13.50 ± 0.30) %		–
ggg		(64.1 ± 1.0) %		–
γgg		(8.8 ± 1.1) %		–
e^+e^-		(5.971 ± 0.032) %		1548
$e^+e^-\gamma$	[a]	$(8.8 \pm 1.4) \times 10^{-3}$		1548
$\mu^+\mu^-$		(5.961 ± 0.033) %		1545

Figure 2: J/ψ properties.[2]

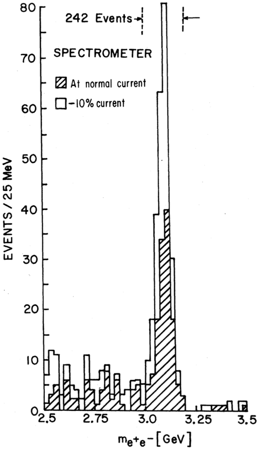

Figure 1: Mass spectrum showing the existence of J/ψ .[1]

[1] J. J. Aubert *et al.*, *Adv. Exp. Phys.* **5**, 128 (1976).
[2] P. A. Zyla *et al.*, *PTEP* **2020**, 083C01 (2020).

J/ψ Production

Color evaporation model (CEM), Color Singlet model (CSM) and Color Octet model (COM) are three most prominent models developed to understand the production of J/ψ particle. All three models attempt to factorize the J/ψ production into a relativistic part describing the production of $c\bar{c}$ $d\sigma_{c\bar{c}[n]}$, and a non-relativistic part describing the bound state of two quarks $F_{c\bar{c}[n]}(\Lambda)$;

$$d\sigma(J/\psi + X) = \Sigma_n \int d\Lambda \frac{d\sigma_{c\bar{c}[n]+X}}{d\Lambda} F_{c\bar{c}[n](\Lambda)}$$

where $[n]$ is the quantum state of the $c\bar{c}$ pair and Λ is the energy scale[3].

- CEM : The non-relativistic part is assumed to be non-zero and constant between $4m_c^2$ and $4m_D^2$ and zero for all other energies, where m_c is the mass of the charm quark and m_D is the mass of D meson.

$$d\sigma(J/\psi + X) = \frac{F_{c\bar{c}[J/\psi]}}{9} \Sigma_n \int_{2mc_c}^{2m_D} dM \frac{d\sigma_{c\bar{c}[n]+X}}{dM}$$

[3] T. Kempel, PhD thesis, Iowa State U., 2011, arXiv: 1107.1293 (nucl-ex).

J/ψ Production

- CSM : In this model, the $c\bar{c}$ pair emerging from the relativistic scattering diagram is assumed to be in the same quantum state as the produced J/ψ , and the non-relativistic amplitude is the real-space J/ψ wave function evaluated at the origin;

$$d\sigma(J/\psi + X) = \int_0^\infty dM \frac{d\sigma_{c\bar{c}[^3S_1]+X}}{dM} \psi_{J/\psi}(r=0)$$

- COM: This model attempts to formalize the factorization of relativistic and non-relativistic effects. The model use a generic expansion;

$$d\sigma(J/\psi + X) = \Sigma_n \int_0^\infty dM \frac{d\sigma_{c\bar{c}[^3S_1]+X}}{dM} \left\langle \mathcal{O}_{[n]}^{J/\psi} \right\rangle$$

with parameters $\left\langle \mathcal{O}_{[n]}^{J/\psi} \right\rangle$, non-relativistic matrix elements associated with the amplitude for producing a J/ψ from a $c\bar{c}$ pair in state $[n]$.Technique of non-relativistic QCD is apply to calculate the $\left\langle \mathcal{O}_{[n]}^{J/\psi} \right\rangle$ parameters in power of v, relative velocity between c and $\bar{c}$. The model is thus a double expansion, about v^2 and α_S.

Transverse Single Spin Asymmetry

- In $p\bar{p}$ collisions, the transverse single spin asymmetry (TSSA), A_N, is defined as the amplitude of the azimuthal angular modulation of the outgoing particle's scattering cross section with respect to the transverse spin direction of the polarized proton.
- The asymmetry can be written as function of azimuthal angle ϕ_S[4]:

$$A(\phi_S) = \frac{N^{\uparrow}(\phi_S) - N^{\downarrow}(\phi_S)}{N^{\uparrow}(\phi_S) + N^{\downarrow}(\phi_S)} = A_N \sin(\phi_S)$$

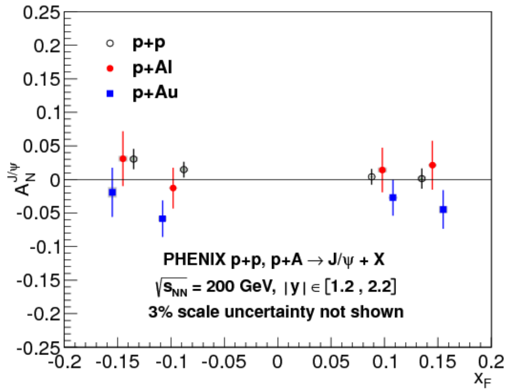

Figure 3: PHENIX results for $A_N^{J/\psi}$ vs. x_F.[5]

- Figure 3 shows the $A_N^{J/\psi}$ as a function of x_F. In the $p+p$ data a $\sim 2\sigma$ positive A_N in the backward higher x_F bins. The results for other x_F bins are consistent with zero.

[4] ϕ_S is the angle between $\vec{S}_{\text{target}}$ and $\vec{p}_{T\,J/\psi}$.

[5] C. Aidala *et al.*, *Phys. Rev. D* **98**, 012006, arXiv: 1805.01491 (hep-ex) (2018).

SpinQuest Experiment

- SpinQuest is a fixed-target Dimuon experiment at Fermilab, using an unpolarized 120 GeV proton beam incident on a polarized solid ammonia target.
- SpinQuest measurements will allow us to test models for the internal transverse momentum and angular momentum structure of the nucleon.
- In the SpinQuest experiment J/ψ production should be dominated by the $q\bar{q}$ annihilation[6].
- Our goal is to measure A_N with an absolute error $\mathcal{O}(10^{-2})$ for a few p_T and/or x_F bins.
- In this presentation, we demonstrate the analysis procedure and extraction of single spin asymmetry (A_N) for a few p_T and x_F bins.

[6] M. Abdallah *et al.*, *Phys. Rev. D* **105**, 032007, arXiv: 2109.13191 (nucl-ex) (2022).

SpinQuest Spectrometer

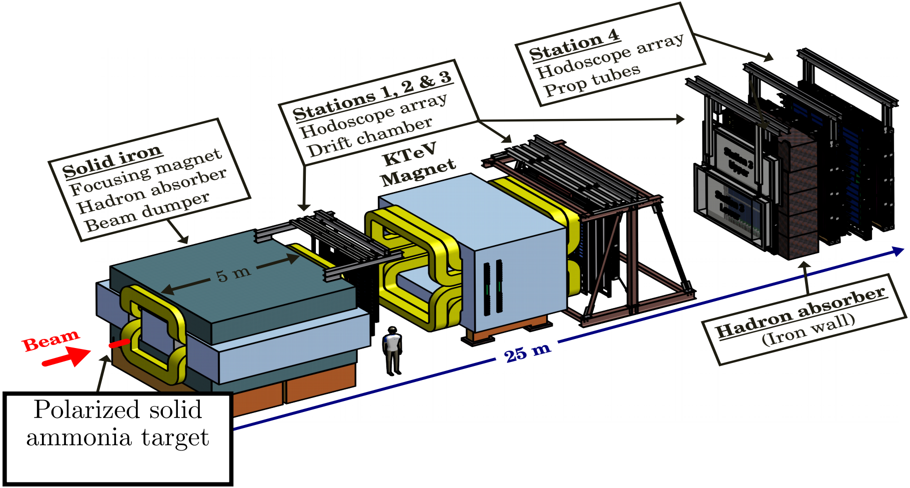

Figure 4: SpinQuest spectrometer.[7]

[7] A. Chen *et al.*, *PoS* **SPIN2018**, ed. by P. Lenisa *et al.*, 164, arXiv: 1901.09994 (nucl-ex) (2019).

Data Generation

- Simulated data were generated with kinematics:
  - J/ψ events were considered as signal events.

    `xF = [-0.2, 1.0]`

    where x_F is the the Feynman x.
  - Drell-Yan events were considered as background events.

    `xF = [-0.2, 1.0]`
    `mass = [1.0, 6.0]`

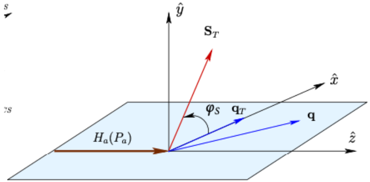

Figure 5: ϕ_S definition in the target rest frame.[9]

- Asymmetry was introduced by weighting the data [8] ;

$$w_{A_N} = 1 + A_N \sin(\phi_S - \phi_{\text{phase}})$$
$$w_{\text{Total}} = w_{\text{Gen.}}(mass, x_F) \times w_{A_N}$$

- Asymmetry values are set as $A_N^{J/\psi} = 0.2$ for J/ψ events and $A_N^{BG} = 0.1$ for Drell-Yan events.

[8] $\phi_{\text{phase}} = 0.$ for spin up and $\phi_{\text{phase}} = \pi$ for spin down.

[9] R. Longo, *EPJ Web Conf.* **137**, ed. by Y. Foka *et al.*, 05013 (2017).

Analysis Procedure

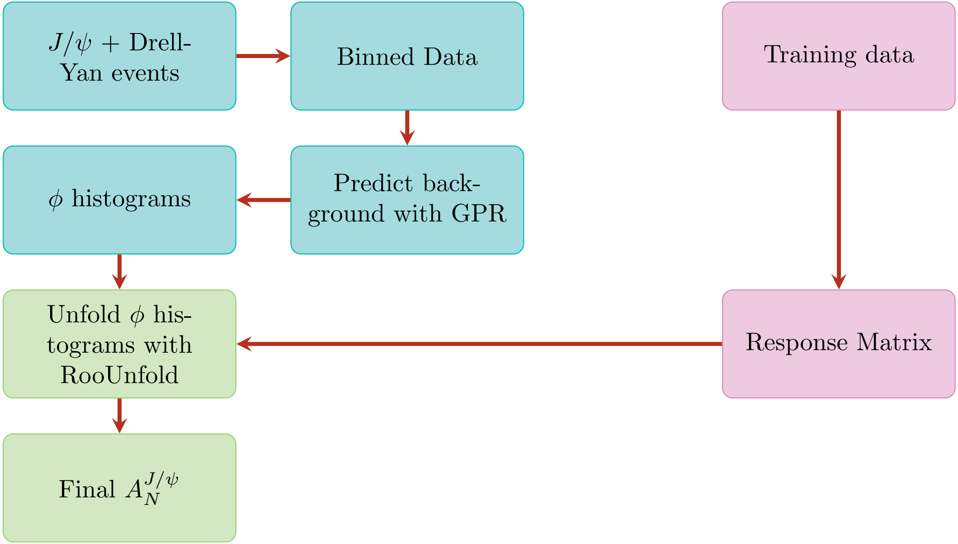

Figure 6: Analysis procedure.

Gaussian Process Regression (GPR)

- Probability density function (PDF) of a multivariate normal distribution (MVN) with dimension D is;

$$\mathcal{N}(x|\mu,\Sigma) = \frac{1}{(2\pi)^{D/2}|\Sigma^{1/2}|}\exp\left[-\frac{1}{2}(x-\mu)^T\sigma^{-1}(x-\mu)\right]$$

  where D is the number of dimensions, x is the variable, μ is the mean vector and Σ is the covariance matrix.

- Gaussian processes are distributions over functions $f(x)$ of which the distribution is defined by a mean function $m(x)$ and positive definite covariance function $k(x, x')$, with x the function values and x, x' all possible pairs in the input domain;

$$f(x) \sim \mathcal{GP}(m(x), k(x, x'))$$

  where for any finite subset $X = x_1, \ldots\ldots, x_n$ of the domain of x, the marginal distribution is a multivariate Gaussian distribution;

$$f(X) \sim \mathcal{N}(m(X), k(X, X))$$

  with mean vector $\mu = m(X)$ and covariance matrix $\Sigma = k(X, X)$.

Gaussian Process Regression (GPR)

- In this analysis, the Radial-Basis Function (RBF) kernel was used as the kernel function in GPR.

$$k(x_i, x_j) = \exp\left[-\frac{d^2(x_i, x_j)}{2l^2}\right]$$

where l is the length scale of the kernel and $d(\cdot,\cdot)$ is the Euclidean distance.[10]

- We fit this kernel in side-band regions on either side of the J/ψ invariant mass peak. Then we used the trained kernel to predict the background in the J/ψ peak region.

[10] F. Pedregosa *et al.*, *the Journal of machine Learning research* **12**, 2825–2830 (2011).

Predicted Background

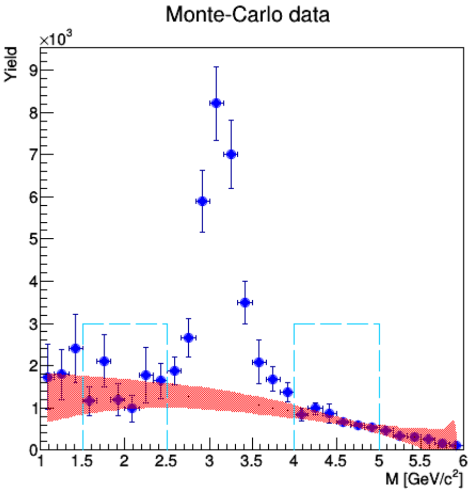

Figure 7: Mass histogram for 1st p_T bin and 1st ϕ bin. Predicted background is given in shaded red region. Side-bands are indicated in dashed blue lines.

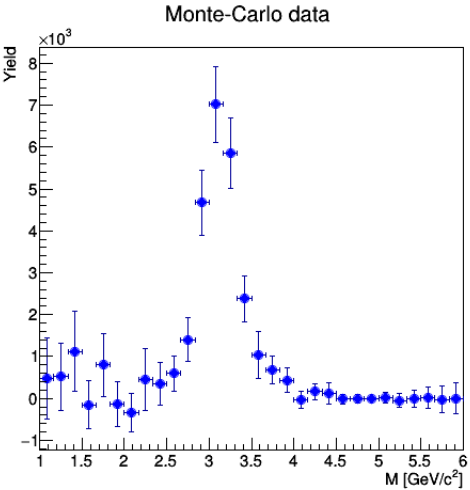

Figure 8: J/ψ signal after subtracting the background.

Sanity Check

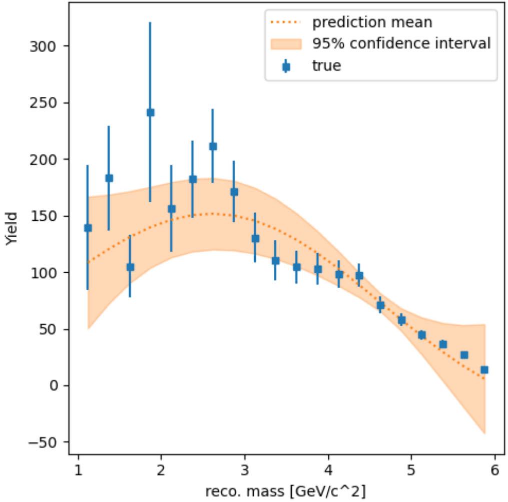

Figure 9: GPR prediction for background.

- We used the Drell-Yan mass distribution in different p_T and x_F bins to check the GPR prediction.background
- As shown in figure 9, the prediction from GPR method agrees with the Drell-Yan events with 95% confidence interval in the J/ψ mass region.

RooUnfold

- Unfolding in high energy physics represents the correction of measured spectra in data for the finite detector efficiency, acceptance, and resolution from the detector to particle level.
- The equation of unfolding[11];

$$p = \frac{1}{\epsilon} M^{-1} \eta (D - B)$$

where D is the data spectrum, B is the background spectrum, η acceptance correction, M^{-1} is the migration matrix and ϵ is the detector efficiency.
- We trained the response matrix with Drell-Yan events without any asymmetry included.
- We used the iterative Bayesian method to unfold the ϕ distributions.[12] By using the unfolding method we will correct the bin-by-bin migration.

[11] P. Baron, *Acta Phys. Polon. B* **52**, 863, arXiv: 2104.03036 (hep-ex) (2021).

[12] B. Wynne, arXiv: 1203.4981 (physics.data-an) (Mar. 2012).

Response Matrix for p_T Bins

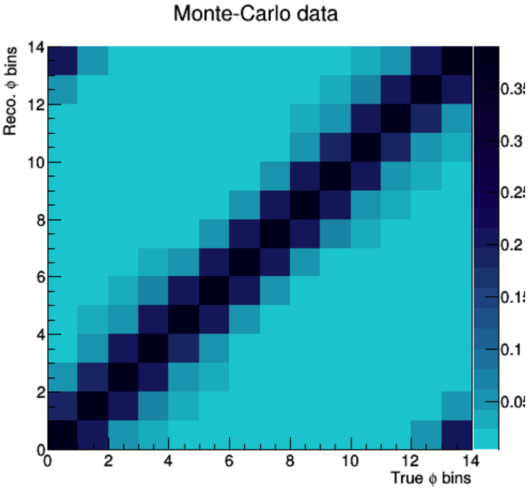

Figure 10: Reco. ϕ vs. true ϕ for $0.0 < p_T < 1.0$.

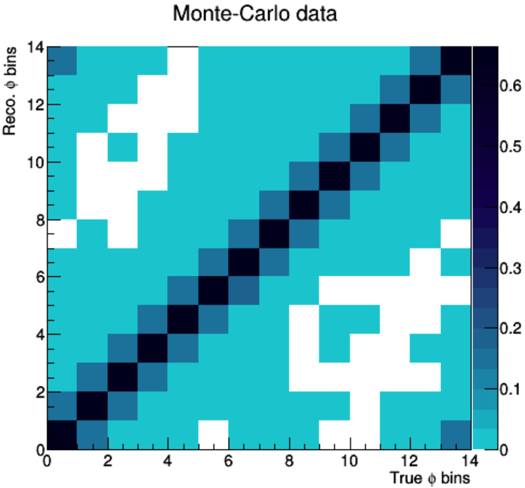

Figure 11: Reco. ϕ vs. true ϕ for $1.0 < p_T < 2.0$.

Response Matrix for x_F Bins

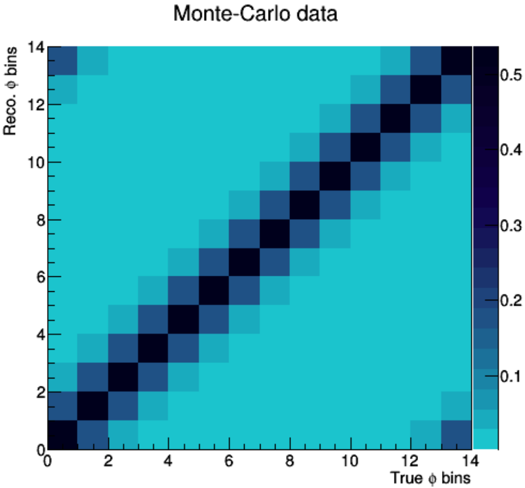

Figure 12: Reco. ϕ vs. true ϕ for $0.4 < x_F < 0.6$.

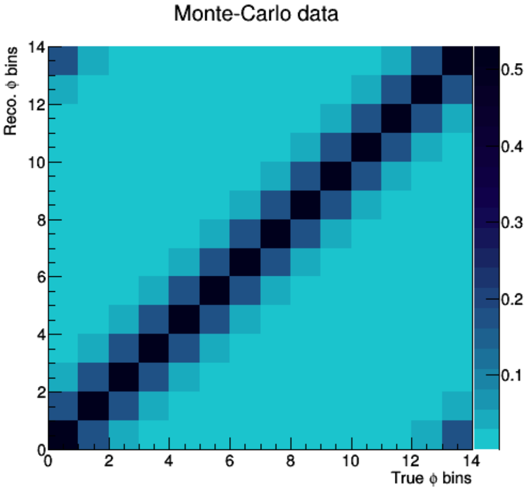

Figure 13: Reco. ϕ vs. true ϕ for $0.6 < x_F < 0.8$.

Unfolded $A_N^{J/\psi}$ in p_T Bins

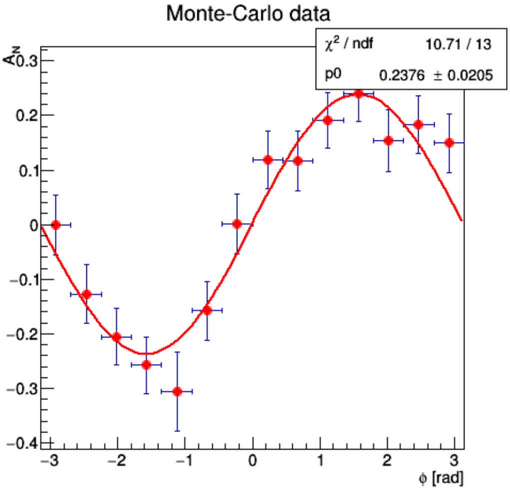

Figure 14: Unfolded asymmetry in $0.0 < p_T < 1.0$.

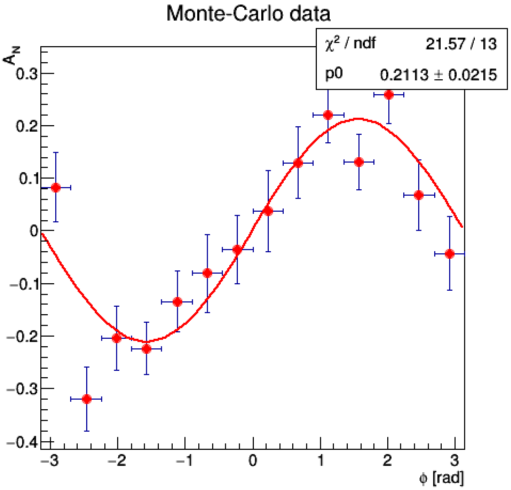

Figure 15: Unfolded asymmetry in $1.0 < p_T < 2.0$.

Unfolded $A_N^{J/\psi}$ in x_F Bins

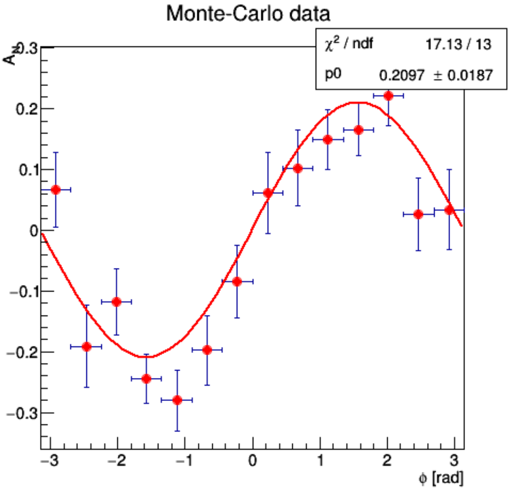

Figure 16: Unfolded asymmetry in $0.4 < x_F < 0.6$.

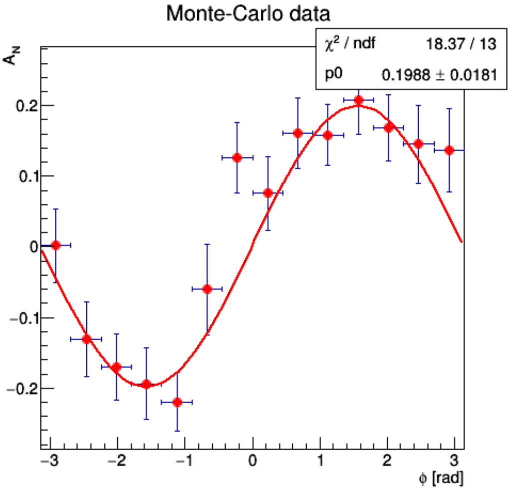

Figure 17: Unfolded asymmetry in $0.6 < x_F < 0.8$.

Extracted A_N

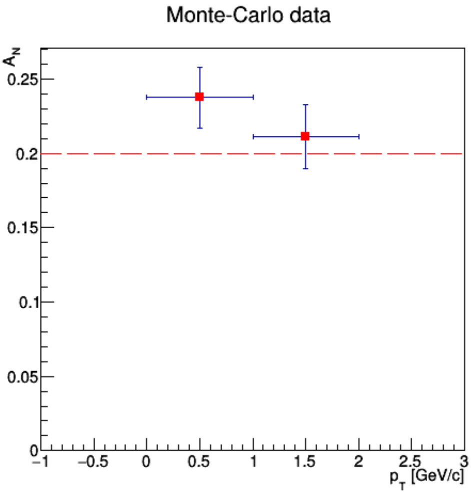

Figure 18: Extracted asymmetry for p_T bins. Generated asymmetry is shown in red dashed line.

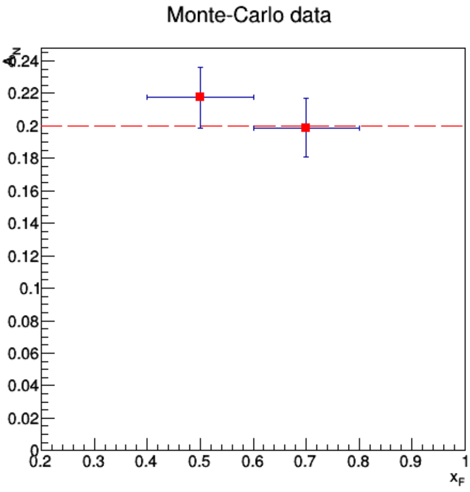

Figure 19: Extracted asymmetry for x_F bins. Generated asymmetry is shown in red dashed line.

Summary

- GPR is a supervised machine learning method can be to predict the background under the J/ψ peak.
- Using GPR method with the RBF kernel, background of the J/ψ mass can be predicted with 95% confidence interval.
- Using iterative Bayesian unfolding, the extracted asymmetry reproduces the generated asymmetry within 1-σ confidence interval.
- Acknowledgement:

  - This work is supported by the US Department of Energy, Office of Science, Medium Energy Nuclear Physics Program.