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

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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.[P. A. Zyla *et al.*, *PTEP* **2020**, 083C01 (2020)]

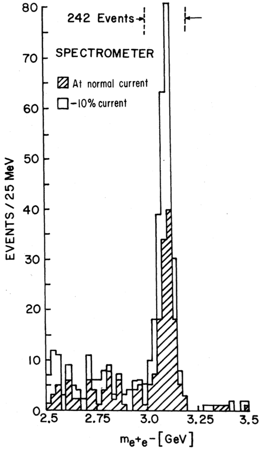


Figure 1: Mass spectrum showing the existence of J/ψ .[J. J. Aubert *et al.*, *Adv. Exp. Phys.* **5**, 128 (1976)]

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 there models attempt to factorize the J/ψ production into a non 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 [T. Kempel, PhD thesis, Iowa State U., 2011, arXiv: 1107.1293 (nucl-ex)].

- 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.

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

J/ψ Production

- CSM : In this model, the $c\bar{c}$ pair emerging from the relativistic scattering diagram is 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.

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

  Technique of non-relativistic QCD is apply to calculate the $\left\langle \mathcal{O}_{[n]}^{J/\psi} \right\rangle$ parameters in power of v, relativistic velocity between c and $\bar{c}$.

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[1]:

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

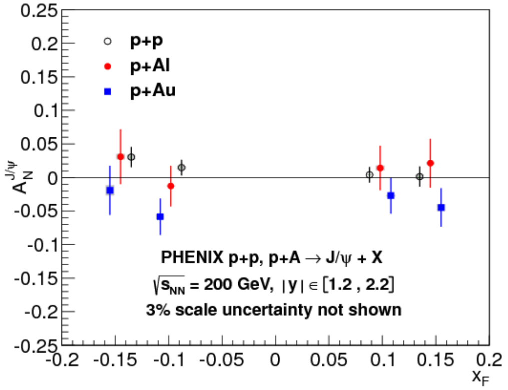


Figure 3: PHENIX results for $A_N^{J/\psi}$ vs. x_F. [C. Aidala *et al.*, *Phys. Rev. D* **98**, 012006, arXiv: 1805.01491 (hep-ex) (2018)]

- Using this equation we can remove the detector acceptance dependency from the A_N.

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

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.
- 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.

Anticipated Precision of J/ψ TSSA

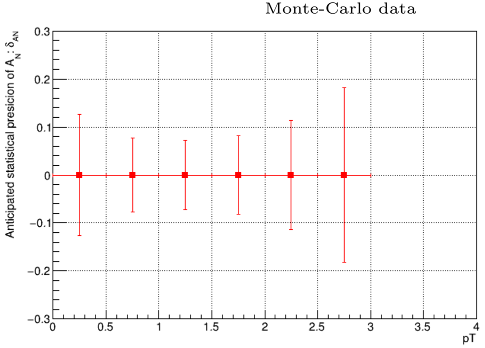


Figure 4: Anticipated Precision of J/ψ TSSA for p_T bins.

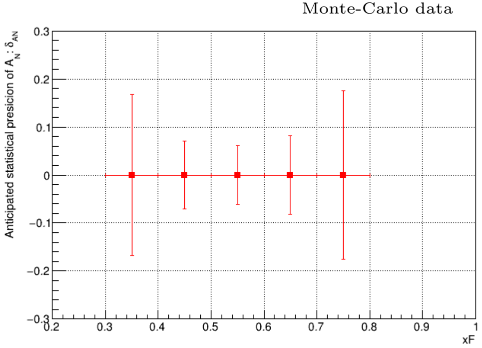


Figure 5: Anticipated Precision of J/ψ TSSA for x_F bins.

- For one week of dedicated data taking, a precision of ~ 0.1 is expected.

  [K. Nakano, DocDB: 9460-v1 (SEAQUEST) (July 2021)]

SpinQuest Spectrometer

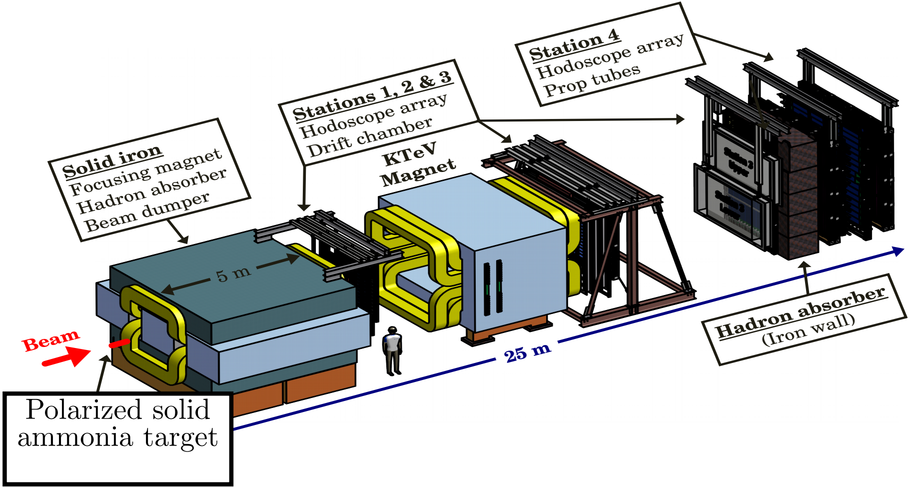


Figure 6: SpinQuest spectrometer. [A. Chen *et al.*, *PoS* **SPIN2018**, ed. by P. Lenisa *et al.*, 164, arXiv: 1901.09994 (nucl-ex) (2019)]

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]`
- Asymmetry was introduced by weighting the data [2] :

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

- 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.

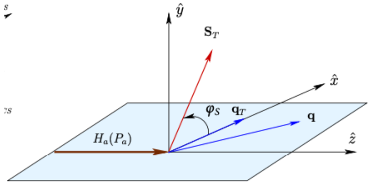
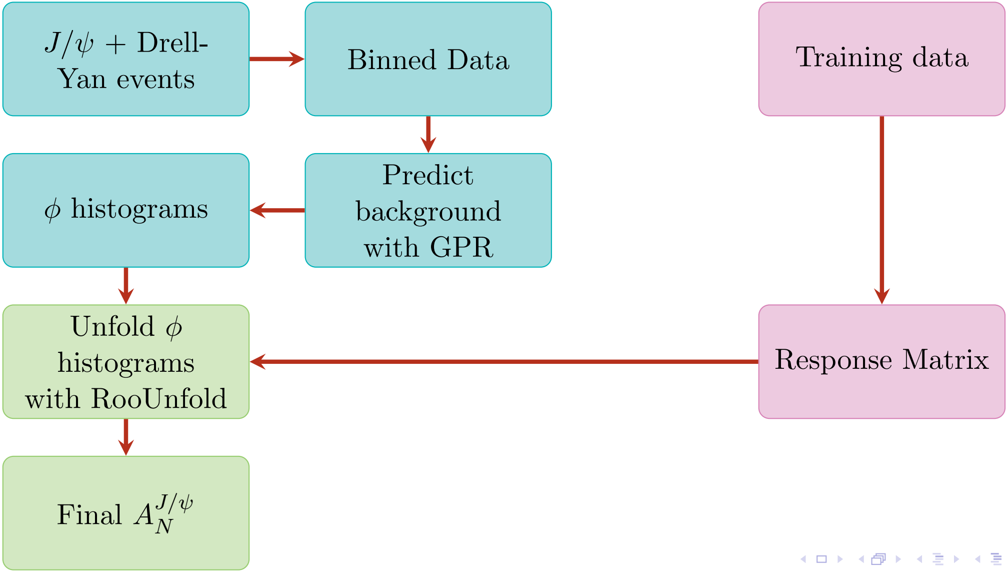


Figure 7: ϕ_S definition in the target rest frame.[R. Longo, *EPJ Web Conf.* **137**, ed. by Y. Foka *et al.*, 05013 (2017)]

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

Analysis Procedure



Gaussian Process Regression (GPR)

- Definition: A Gaussian Process is a collection of random variables, any finite number of which have (consistent) joint Gaussian distributions.
- 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 $X = x_1, ..., x_n$ 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.[F. Pedregosa *et al.*, *the Journal of machine Learning research* **12**, 2825–2830 (2011)]
- 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.

Predicted Background

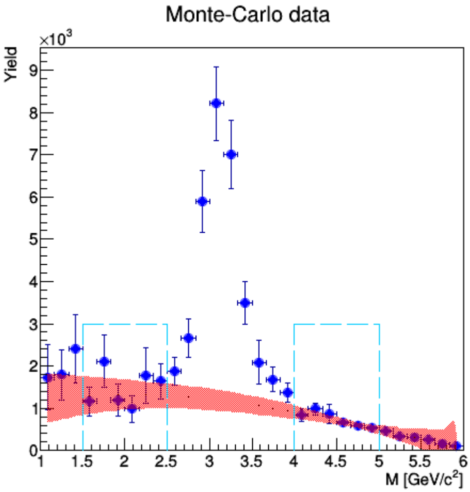


Figure 9: Mass histogram for 1st p_T bin and 1st ϕ bin. Predicted background is given in shaded red region. Side-bands are indicated in dashed blue lines.

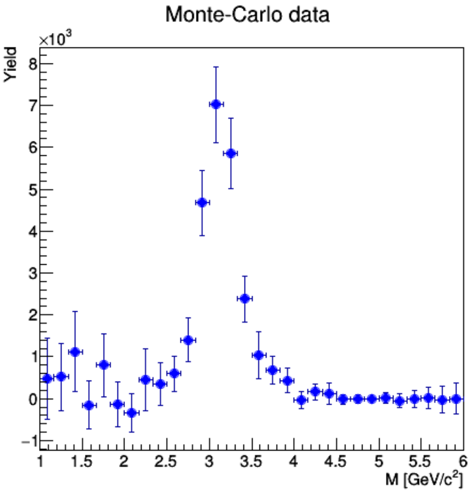


Figure 10: J/ψ signal after subtracting the background.

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.
- We used the `RooUnfold` package in the analysis. Some default algorithms are:
  - Iterative Bayesian
  - Singular value decomposition
  - Bin-by-bin (simple correction factors)
- We trained the response matrix with Drell-Yan events without any asymmetry included.
- We used the iterative Bayesian method to unfold the ϕ distributions. [B. Wynne, arXiv: 1203.4981 (physics.data-an) (Mar. 2012)]
- By using the unfolding method we will correct the bin-by-bin migration.

Response Matrix for p_T Bins

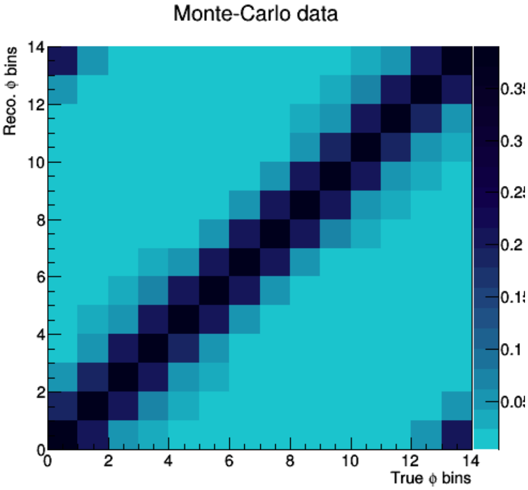


Figure 11: Reco. ϕ vs. true ϕ for $0.0 < p_T < 1.0$.

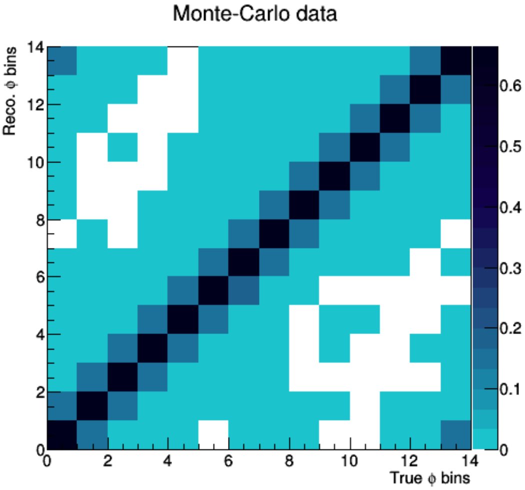


Figure 12: Reco. ϕ vs. true ϕ for $1.0 < p_T < 2.0$.

Response Matrix for x_F Bins

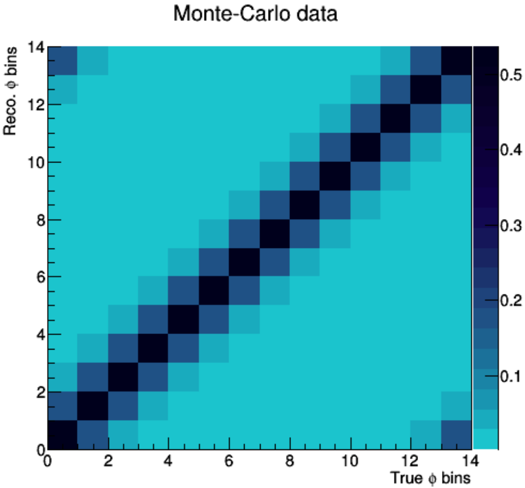


Figure 13: Reco. ϕ vs. true ϕ for $0.4 < x_F < 0.6$.

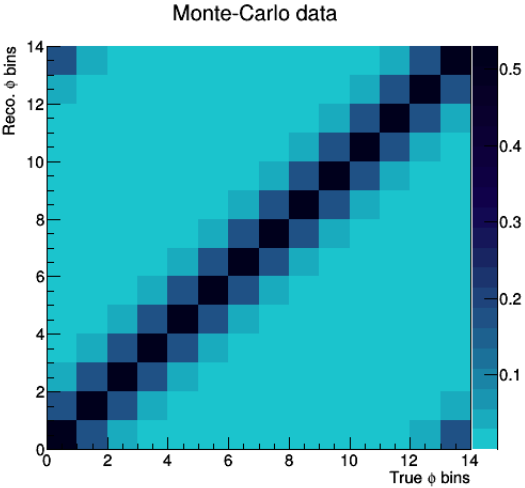


Figure 14: Reco. ϕ vs. true ϕ for $0.6 < x_F < 0.8$.

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

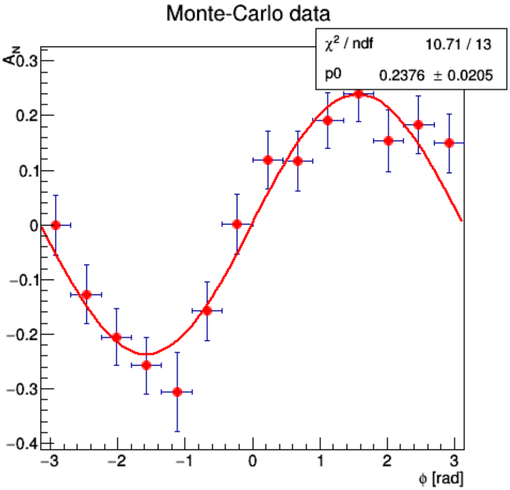


Figure 15: Unfolded asymmetry in $0.0 < p_T < 1.0$.

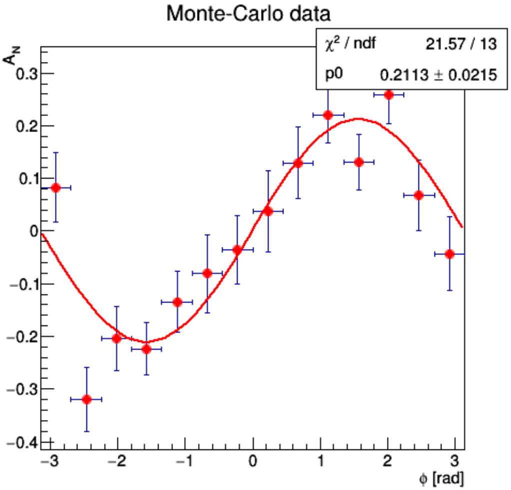


Figure 16: Unfolded asymmetry in $1.0 < p_T < 2.0$.

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

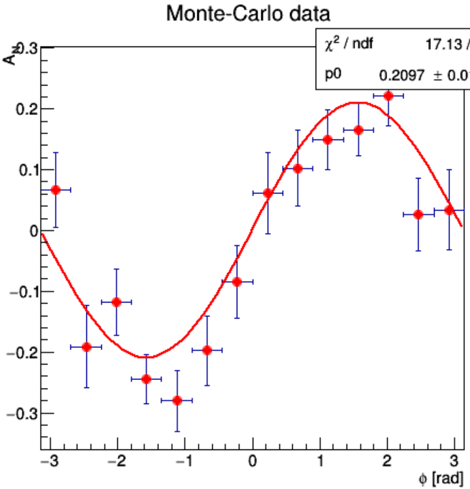


Figure 17: Unfolded asymmetry in $0.4 < x_F < 0.6$.

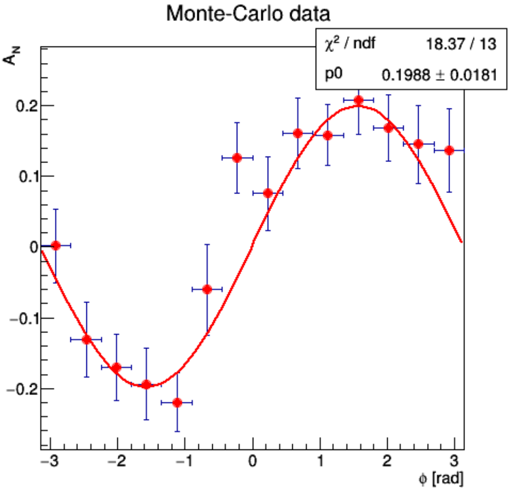


Figure 18: Unfolded asymmetry in $0.6 < x_F < 0.8$.

Extracted A_N

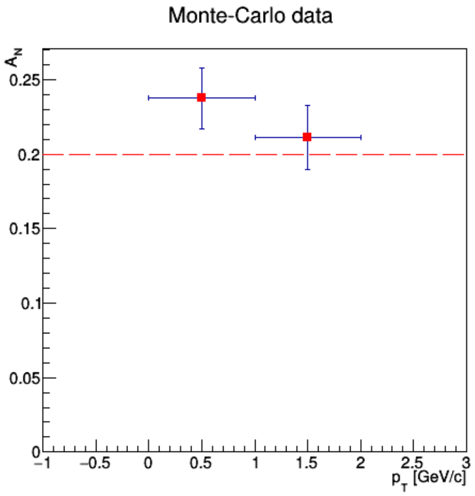


Figure 19: Extracted asymmetry for p_T bins. Generated asymmetry is shown in red dashed line.

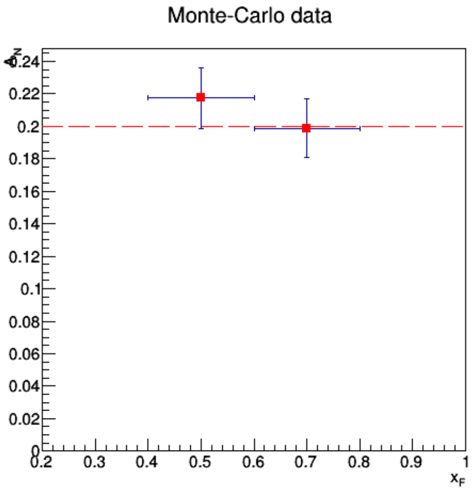


Figure 20: Extracted asymmetry for x_F bins. Generated asymmetry is shown in red dashed line.

Summary

- Gaussian process regression can be used as a good method to predict the background under the J/ψ peak.
- 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.