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

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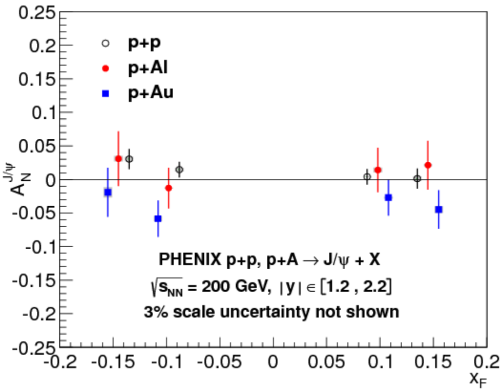
Overview

Transverse Single Spin Asymmetry

- In $p\vec{p}$ 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]:

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



- PHENIX results[2] shows $A_N^{J/\psi}$ [3] 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.

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

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

[3] PHENIX convention: x_F is measured w.r.t p, SpinQuest convention: x_F is measured w.r.t. $\vec{p}$.

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 $p\vec{p}$ collisions, J/ψ particles are primarily produced by strong interaction with $q\bar{q}$ annihilation and gg fusion.
- 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.

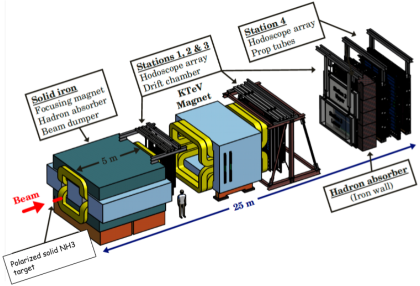


Figure 1: SpinQuest spectrometer.[4]

- In this presentation, we demonstrate the analysis procedure and extraction of single spin asymmetry (A_N) with kinematics $0.0\mathrm{GeV/c} < p_T < 2.0\mathrm{GeV/c}$ and $0.4 < x_F < 0.8$.

[4] 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;

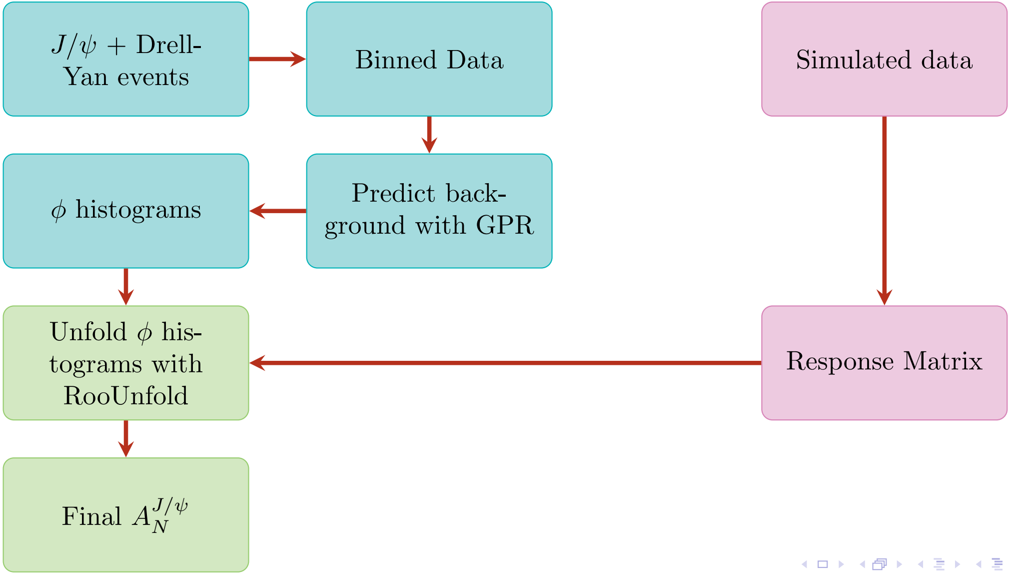
$$
\begin{aligned}
w_{A_N} &= 1 + A_N \sin(\phi_S + \phi_{\text{phase}}) \\
w_{\text{Total}} &= w_{\text{Gen.}}(mass, x_F) \times w_{A_N}
\end{aligned}
$$

  where ϕ_S is the angle between $\vec{S}_{\text{target}}$ and $\vec{p}_{T\,J/\psi}$ and $\phi_{\text{phase}} = 0.$ for spin up and $\phi_{\text{phase}} = \pi$ for spin down.

- 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.[5]

[5] Dilution factor of the NH3 was not considered in this study.

Analysis Procedure



Gaussian Process Regression (GPR)

- The Gaussian process model is a probabilistic supervised machine learning technique used in classification and regression tasks. A Gaussian process regression (GPR) model can make predictions incorporating prior knowledge (kernels) and provide uncertainties of the predictions.[6]
- In this analysis, the Radial-Basis Function (RBF) kernel was used as the kernel function in GPR class in `sklearn` library.

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

  where l is the length scale of the kernel and $d(\cdot, \cdot)$ is the Euclidean distance.[7]
- 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.
- **Our first goal is to extract the background under the J/ψ peak using the GPR method with good statistical precision.**

[6] C. E. Rasmussen, C. K. I. Williams, *Gaussian Processes for Machine Learning*, (The MIT Press, Nov. 2005), ISBN: 9780262256834, (https://doi.org/10.7551/mitpress/3206.001.0001).

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

Sanity Check

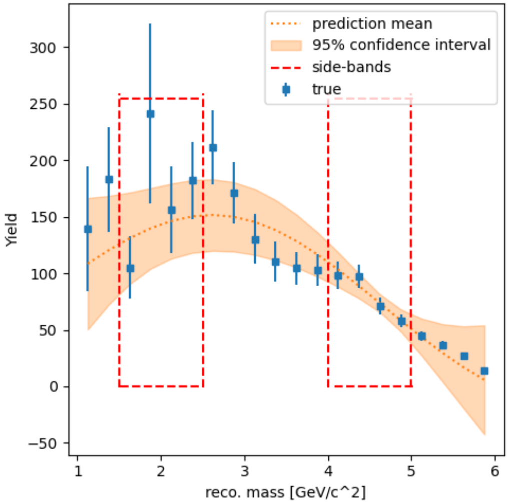


Figure 2: GPR prediction for background. The side-bands are given in the red dashed lines.

- 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.**

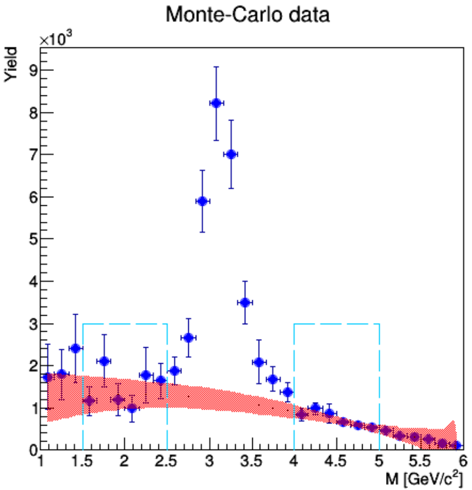


Figure 3: Mass histogram for 1st p_T bin and 1st ϕ bin. Predicted background is given in shaded red region. Side-bands are indicated in dashed blue lines.

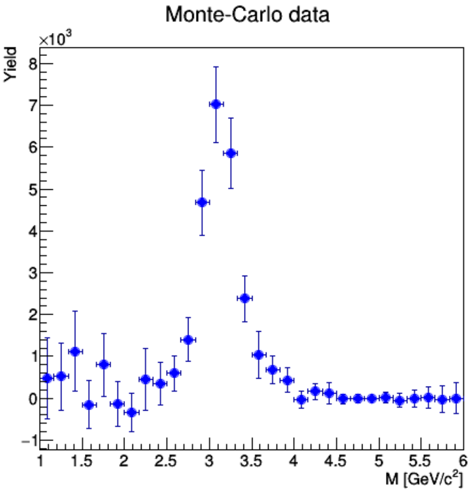


Figure 4: J/ψ signal after subtracting the background.

Unfolding ϕ Distributions

- 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[8];

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

  where $\vec{D}$ is the data spectrum, $\vec{B}$ is the background spectrum, η acceptance correction, M^{-1} is the migration matrix, ϵ is the detector efficiency and $\vec{P}$ is the unfolded spectrum.
- We trained the response matrix with Drell-Yan events without any asymmetry included. We used the iterative Bayesian method in `ROOUnfold` library to unfold the ϕ distributions.[9]
- **Our second goal is to correct the bin-by-bin migration using the iterative Bayesian unfolding.**

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

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

Response Matrix for p_T Bins

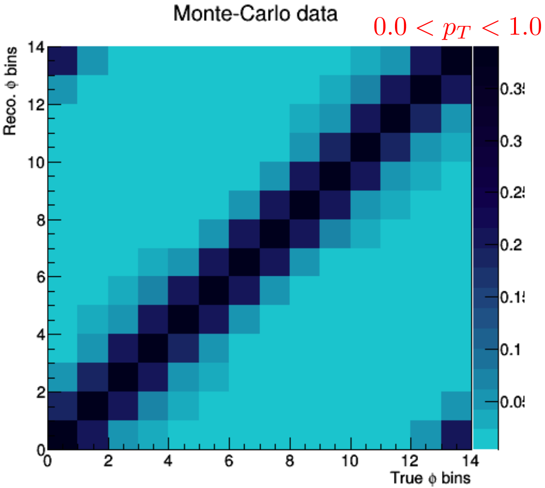


Figure 5: Reco. ϕ vs. true ϕ.

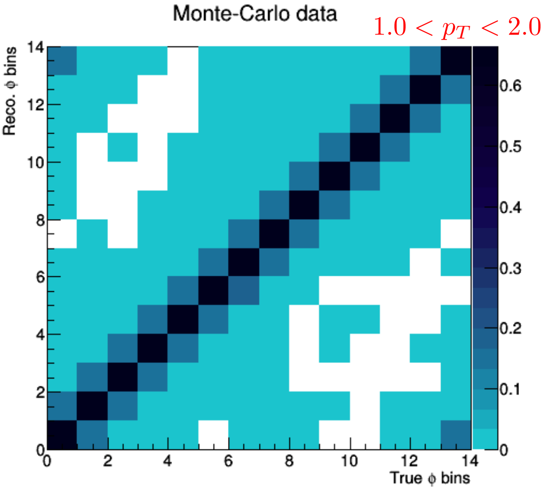


Figure 6: Reco. ϕ vs. true ϕ.

Response Matrix for x_F Bins

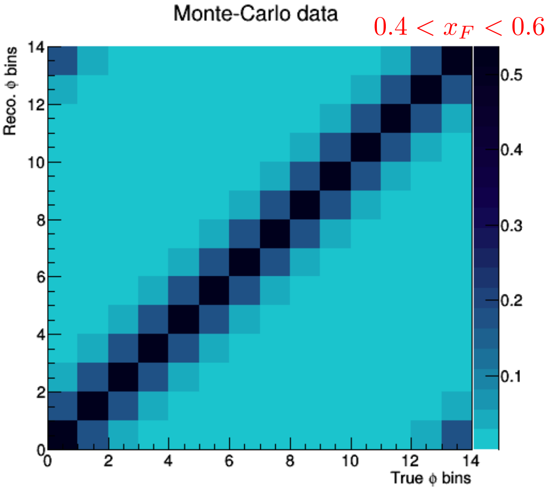


Figure 7: Reco. ϕ vs. true ϕ.

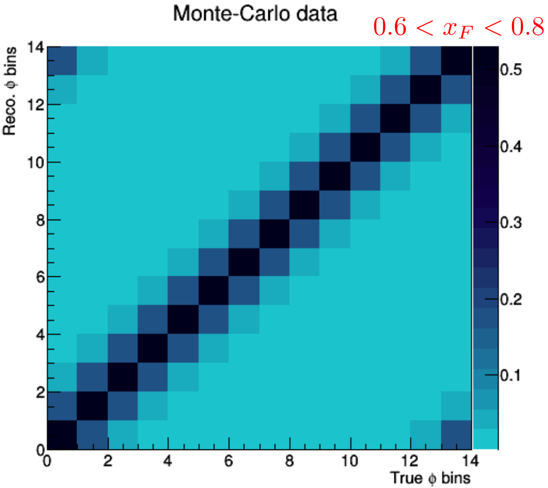


Figure 8: Reco. ϕ vs. true ϕ.

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

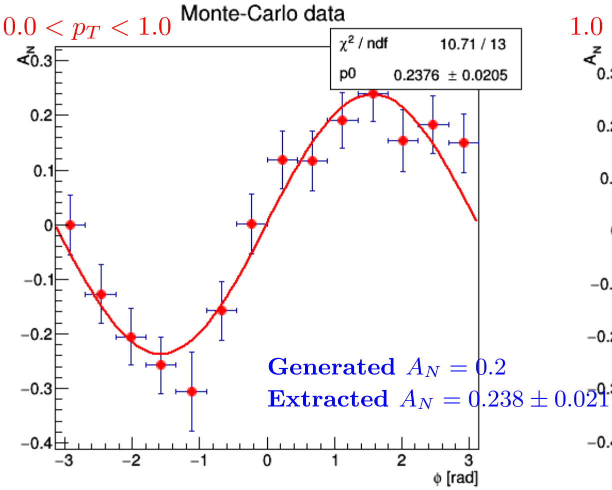


Figure 9: Unfolded asymmetry.

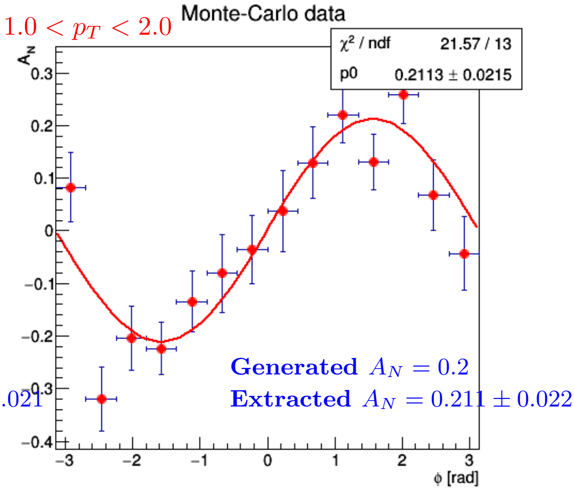


Figure 10: Unfolded asymmetry.

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

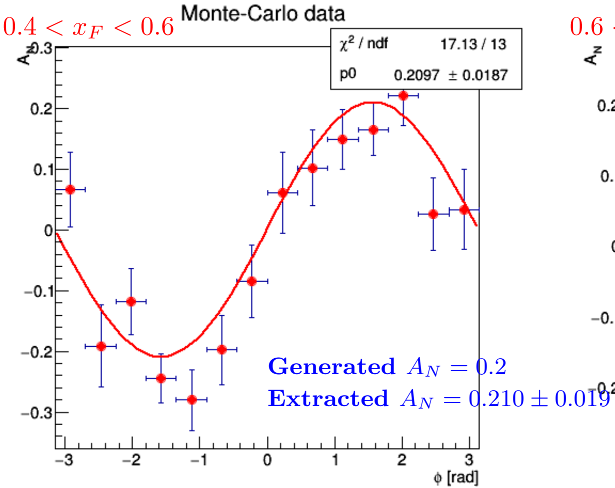


Figure 11: Unfolded asymmetry.

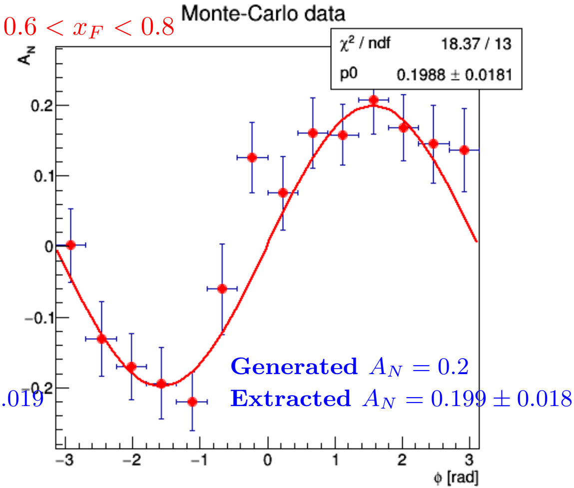


Figure 12: Unfolded asymmetry.

Extracted A_N

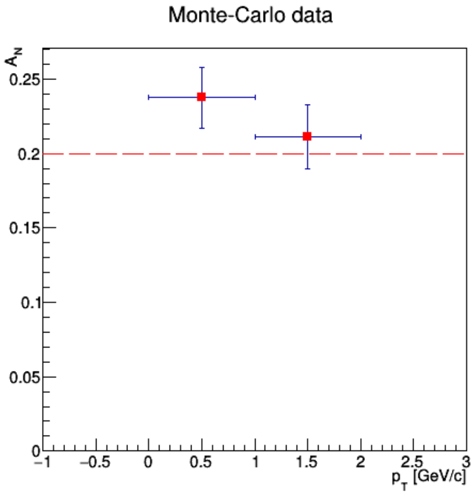
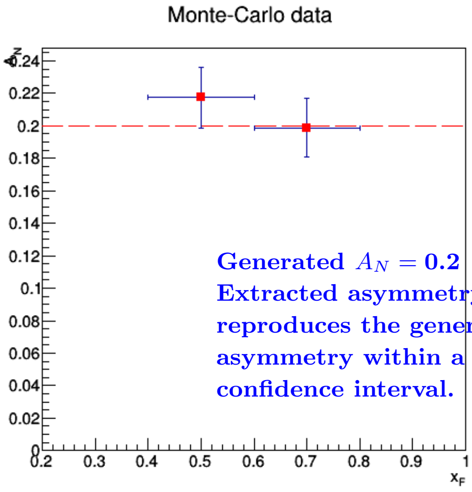


Figure 13: Extracted asymmetry for p_T bins. Generated asymmetry is shown in red dashed line.



Generated $A_N = 0.2$ Extracted asymmetry reproduces the generated asymmetry within a $\sim \sigma$ confidence interval.

Figure 14: Extracted asymmetry for x_F bins. Generated asymmetry is shown in red dashed line.

Summary

- Gaussian process regression (GPR) is a supervised machine learning method that can be used 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 we can correct the bin-by-bin migration.
- Using these techniques (GPR+Unfolding), the extracted asymmetry reproduces the generated asymmetry within a $\sim \sigma$ confidence interval.
- SpinQuest does not overlap with PHENIX kinematics.
  - In PHENIX $|x_F| < 0.3$
  - In SpinQuest $|x_F| > 0.4$

  SpinQuest will explore a new region of kinematics. Measurement for J/ψ transverse single spin asymmetry can be extracted in a few weeks of data taking with good statistical precision.
- Acknowledgement:
  - This work is supported by the US Department of Energy, Office of Science, Medium Energy Nuclear Physics Program.

Backup Slides

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 $p\vec{p}$ collisions, J/ψ particles are primarily produced by strong interaction with $q\bar{q}$ 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 16: J/ψ properties.[11]

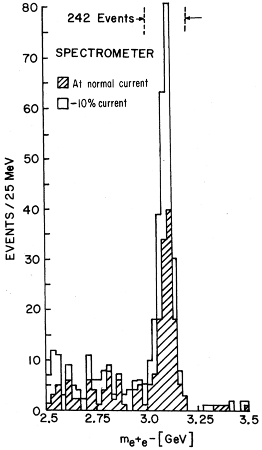


Figure 15: Mass spectrum showing the existence of J/ψ .[10]

[10] J. J. Aubert *et al.*, *Adv. Exp. Phys.* **5**, 128 (1976).
[11] 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[12].

- 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.

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

[12] 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.

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 $X = x_1, ..., x_n$ 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 $\Sigma = k(X,X)$.

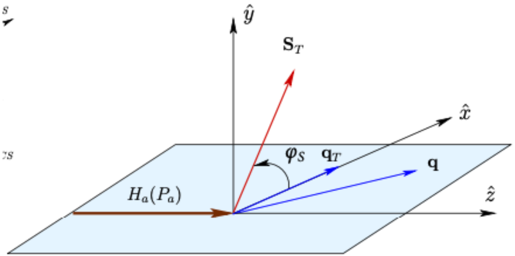


Figure 17: ϕ_S definition in the target rest frame.[13]

$$\sigma(\phi_S) \propto 1 + PA_N \sin(\phi_S + \phi)$$

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

where P is the target polarization, ϕ_S is the angle between q_T & S_T, ϕ is the spin alignment of the target.
We can extract the A_N using $\sin \phi_S$ modulations.

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