

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

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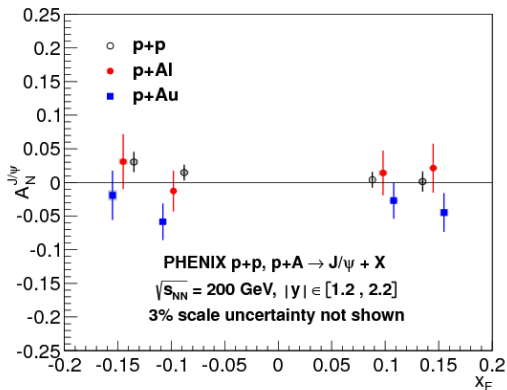
- 1 Transverse Single Spin Asymmetry in  $J/\psi$  Production
- 2 SpinQuest Experiment
- 3 Analysis Procedure
  - Data Generation
  - Gaussian Process Regression (GPR)
  - RooUnfold
- 4 Results and Discussion
- 5 Summary

# Transverse Single Spin Asymmetry in $J/\psi$ Production

- 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  $\phi_S$ <sup>1</sup>:

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

- PHENIX results<sup>2</sup> shows  $A_N^{J/\psi}$ <sup>3</sup> 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.



<sup>1</sup> $\phi_S$  is the angle between  $\vec{S}_{\text{target}}$  and  $\vec{p}_{TJ/\psi}$ .

<sup>2</sup>C. Aidala *et al.*, *Phys. Rev. D* **98**, 012006, arXiv: 1805.01491 (hep-ex) (2018).

<sup>3</sup>PHENIX convention:  $x_F$  is measured w.r.t  $p$ , SpinQuest convention:  $x_F$  is measured w.r.t.  $\vec{p}_\perp$ .

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

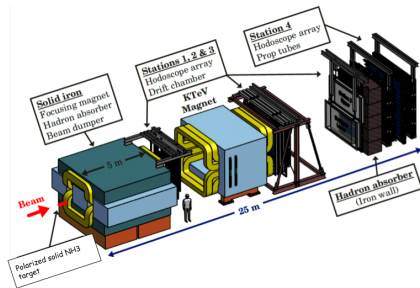


Figure 1: SpinQuest spectrometer.<sup>4</sup>

<sup>4</sup>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:
  - $J/\psi$  events were considered as signal events.  
 $x_F = [-0.2, 1.0]$   
where  $x_F$  is the the Feynman x.
  - Drell-Yan events were considered as background events.  
 $x_F = [-0.2, 1.0]$   
 $mass = [1.0, 6.0]$
- Asymmetry was introduced by weighting the data;

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

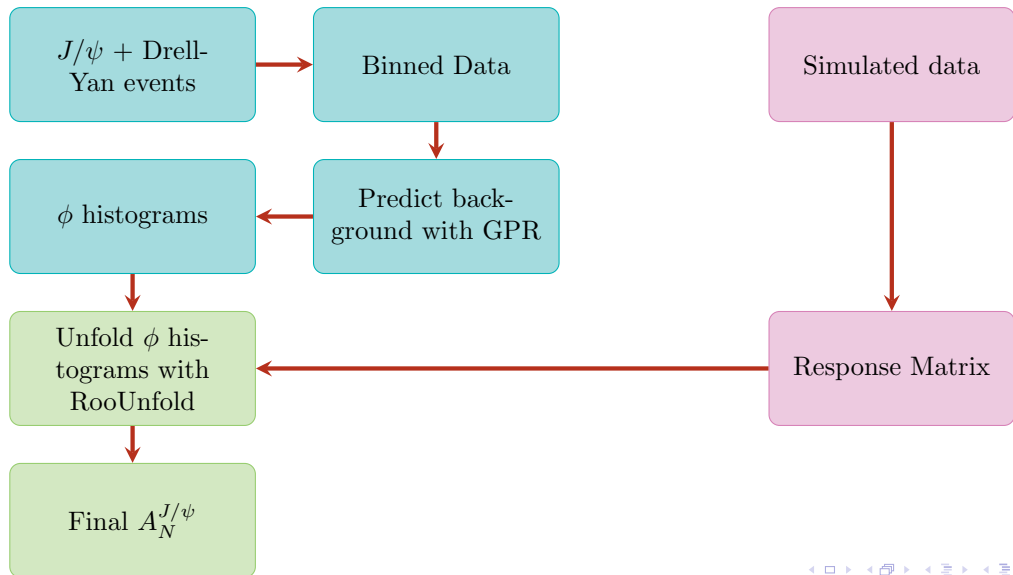
where  $\phi_S$  is the angle between  $\vec{S}_{\text{target}}$  and  $\vec{p}_{TJ/\psi}$  and  $\phi_{\text{phase}} = 0$ . for spin up and  $\phi_{\text{phase}} = \pi$  for spin down.

- Asymmetry values are set as  $A_N^{J/\psi} = 0.2$  for  $J/\psi$  events and  $A_N^{BG} = 0.1$  for Drell-Yan events.<sup>5</sup>

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<sup>5</sup>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.<sup>6</sup>
- 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.<sup>7</sup>

- We fit this kernel in side-band regions on either side of the  $J/\psi$  invariant mass peak. Then we used the trained kernel to predict the background in the  $J/\psi$  peak region.
- **Our first goal is to extract the background under the  $J/\psi$  peak using the GPR method with good statistical precision.**

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<sup>6</sup>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>).

<sup>7</sup>F. Pedregosa *et al.*, *the Journal of machine Learning research* **12**, 2825–2830 (2011).

# Sanity Check

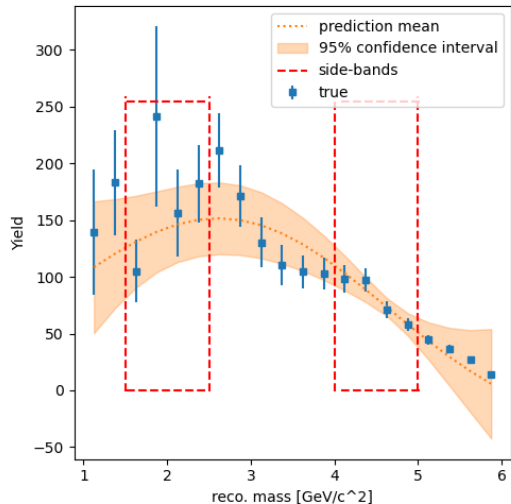


Figure 2: GPR prediction for background. The side-bands are given in the red dashed lines.

- 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  $J/\psi$  mass region.



# Predicted Background

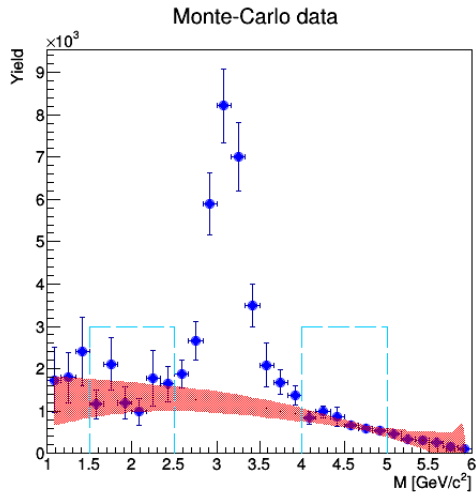


Figure 3: Mass histogram for 1st  $p_T$  bin and 1st  $\phi$  bin. Predicted background is given in shaded red region. Side-bands are indicated in dashed blue lines.

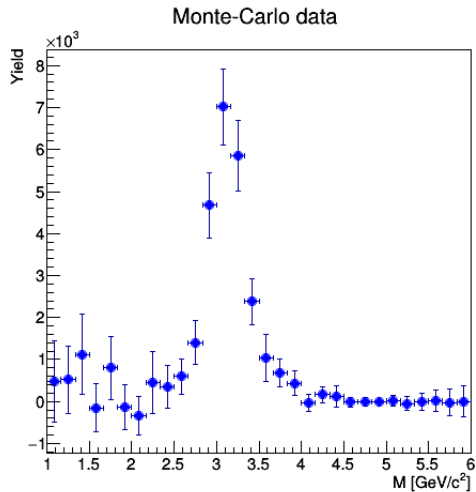


Figure 4:  $J/\psi$  signal after subtracting the background.

# Unfolding $\phi$ 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<sup>8</sup>;

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

where  $\vec{D}$  is the data spectrum,  $\vec{B}$  is the background spectrum,  $\eta$  acceptance correction,  $M^{-1}$  is the migration matrix,  $\epsilon$  is the detector efficiency and  $\vec{P}$  is the unfolded spectrum.

- We calculate the response matrix with Drell-Yan events without any asymmetry included. We used the iterative Bayesian method in `ROOUnfold` library to unfold the  $\phi$  distributions.<sup>9</sup>
- **Our second goal is to correct the bin-by-bin migration using the iterative Bayesian unfolding.**

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<sup>8</sup>P. Baron, *Acta Phys. Polon. B* **52**, 863, arXiv: 2104.03036 (hep-ex) (2021).

<sup>9</sup>B. Wynne, arXiv: 1203.4981 (physics.data-an) (Mar. 2012).

# Response Matrix for $p_T$ Bins

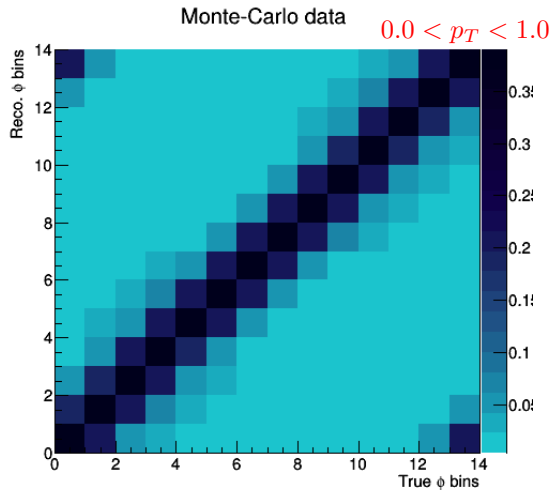


Figure 5: Reco.  $\phi$  vs. true  $\phi$ .

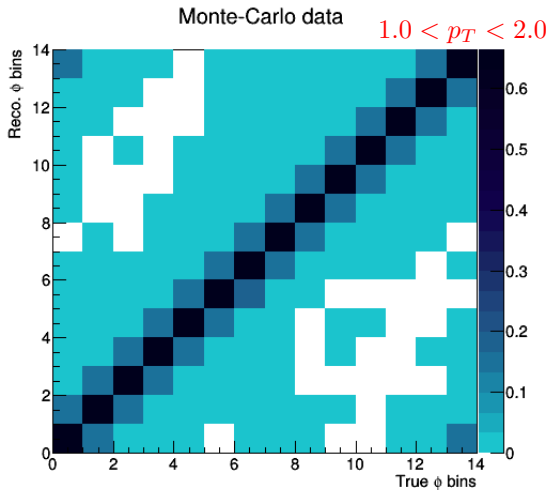


Figure 6: Reco.  $\phi$  vs. true  $\phi$ .

# Response Matrix for $x_F$ Bins

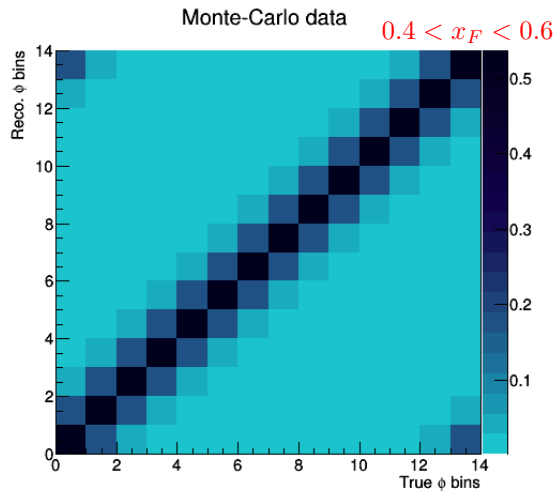


Figure 7: Reco.  $\phi$  vs. true  $\phi$ .

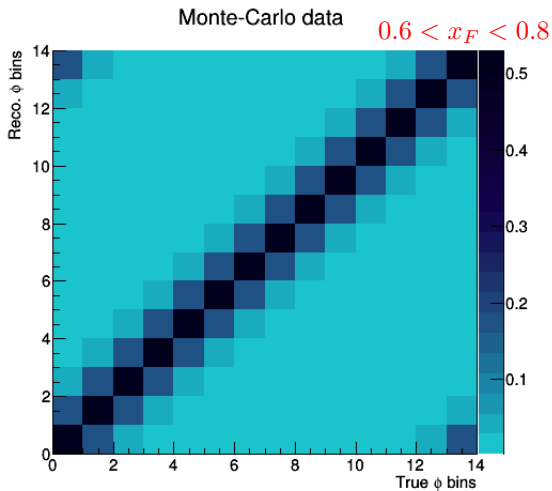


Figure 8: Reco.  $\phi$  vs. true  $\phi$ .

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

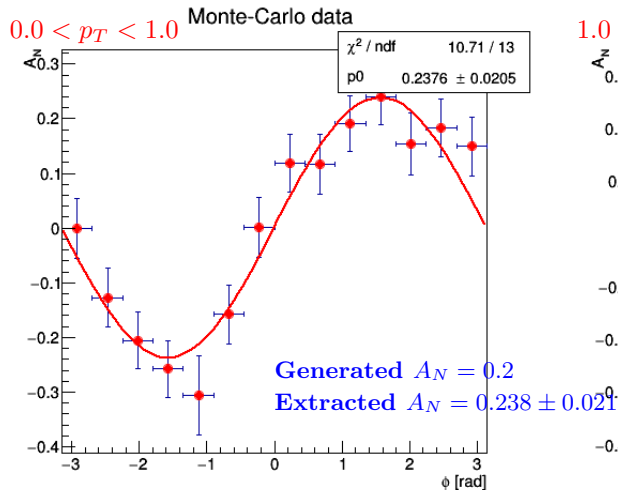


Figure 9: Unfolded asymmetry.

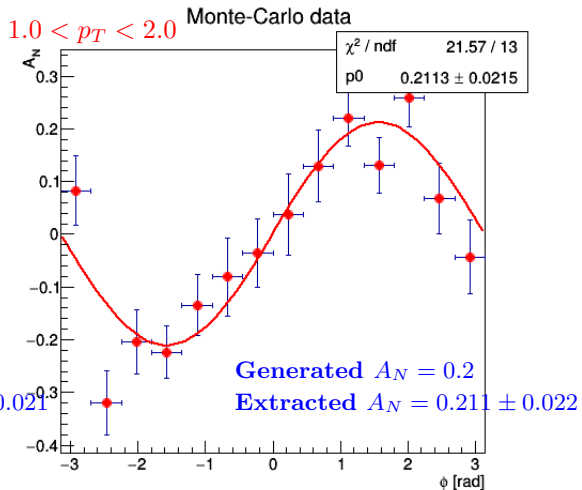


Figure 10: Unfolded asymmetry.

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

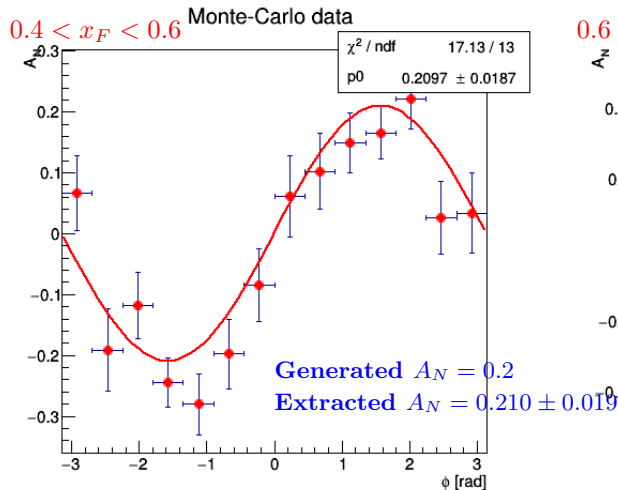


Figure 11: Unfolded asymmetry.

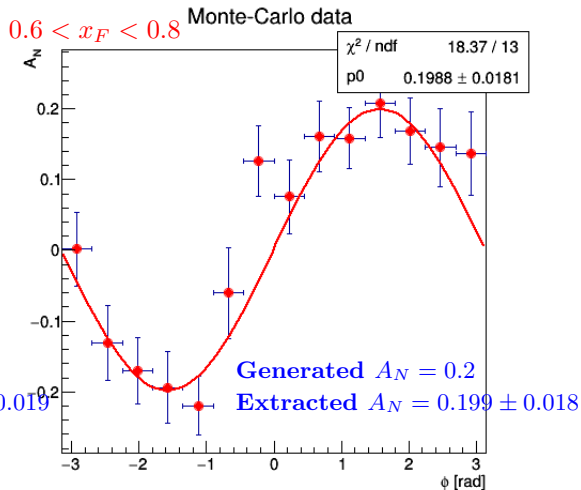


Figure 12: Unfolded asymmetry.

# Extracted $A_N$

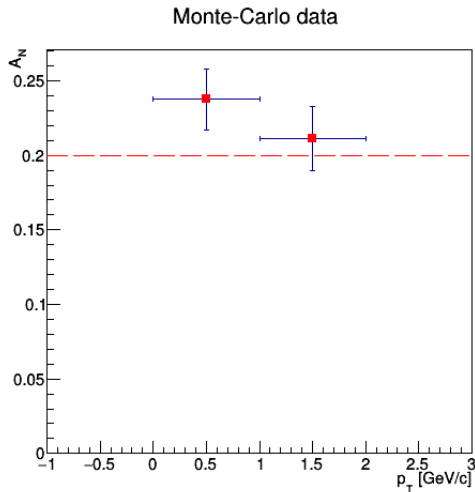


Figure 13: Extracted asymmetry for  $p_T$  bins. Generated asymmetry is shown in red dashed line.

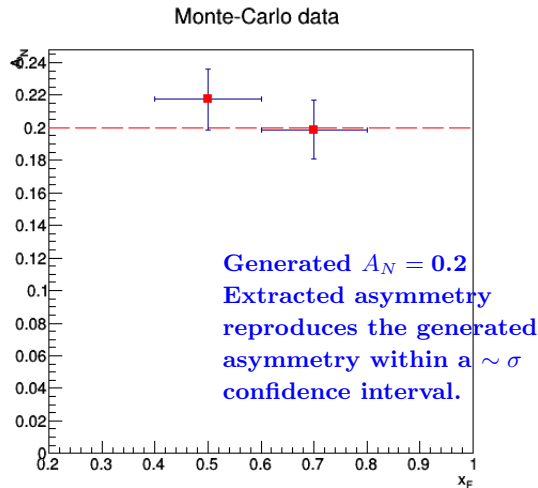


Figure 14: Extracted asymmetry for  $x_F$  bins. Generated asymmetry is shown in red dashed line.

# Summary

- Gaussian process regression (GPR) is a supervised machine learning method that can be used to predict the background under the  $J/\psi$  peak.
- Using GPR method with the RBF kernel, background of the  $J/\psi$  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  $J/\psi$  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

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# $J/\psi$ Particle

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

$J/\psi(1S)$		
$J^G(J^{PC}) = 0^-(1^{--})$		
Mass $m = 3096.900 \pm 0.006$ MeV		
Full width $\Gamma = 92.9 \pm 2.8$ keV ( $S = 1.1$ )		
$\Gamma_{ee} = 5.53 \pm 0.10$ keV		
$\Gamma_{ee} < 5.4$ eV, CL = 90%		
$J/\psi(1S)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level (MeV/c)
hadrons	$(87.7 \pm 0.5) \%$	—
virtual $\gamma \rightarrow$ hadrons	$(13.50 \pm 0.30) \%$	—
$ggg$	$(64.1 \pm 1.0) \%$	—
$\gamma gg$	$(8.8 \pm 1.1) \%$	—
$e^+e^-$	$(5.971 \pm 0.032) \%$	1548
$e^+e^-\gamma$	[a] $(8.8 \pm 1.4) \times 10^{-3}$	1548
$\mu^+\mu^-$	$(5.961 \pm 0.033) \%$	1545

Figure 16:  $J/\psi$  properties.<sup>11</sup>

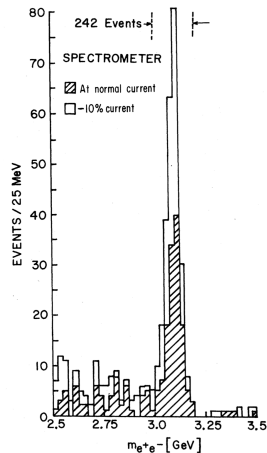


Figure 15: Mass spectrum showing the existence of  $J/\psi$ .<sup>10</sup>

<sup>10</sup>J. J. Aubert *et al.*, *Adv. Exp. Phys.* **5**, 128 (1976).

<sup>11</sup>P. A. Zyla *et al.*, *PTEP* **2020**, 083C01 (2020).

# $J/\psi$ 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  $J/\psi$  particle. All three models attempt to factorize the  $J/\psi$  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  $\Lambda$  is the energy scale<sup>12</sup>.

- 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.

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

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<sup>12</sup>T. Kempel, PhD thesis, Iowa State U., 2011, arXiv: 1107.1293 (nucl-ex).

# $J/\psi$ 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  $J/\psi$ , and the non-relativistic amplitude is the real-space  $J/\psi$  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;

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

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

# 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,  $\mu$  is the mean vector and  $\Sigma$  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  $X = x_1, \dots, x_n$  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  $\Sigma = k(X, X)$ .

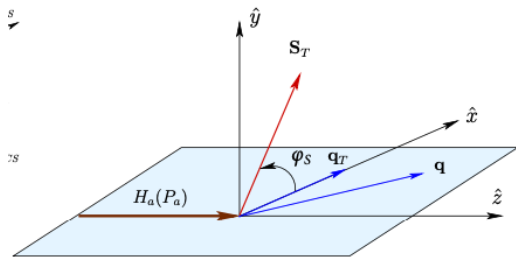


Figure 17:  $\phi_S$  definition in the target rest frame.<sup>13</sup>

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

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

where  $P$  is the target polarization,  $\phi_S$  is the angle between  $q_T$  &  $S_T$ ,  $\phi$  is the spin alignment of the target.

We can extract the  $A_N$  using  $\sin \phi_S$  modulations.

<sup>13</sup>R. Longo, *EPJ Web Conf.* **137**, ed. by Y. Foka *et al.*, 05013 (2017).