Machine Learning Approach To Determine The Transverse Single Spin Asymmetry In J/ψ Production

Chatura Kuruppu

(SpinQuest Collaboration)

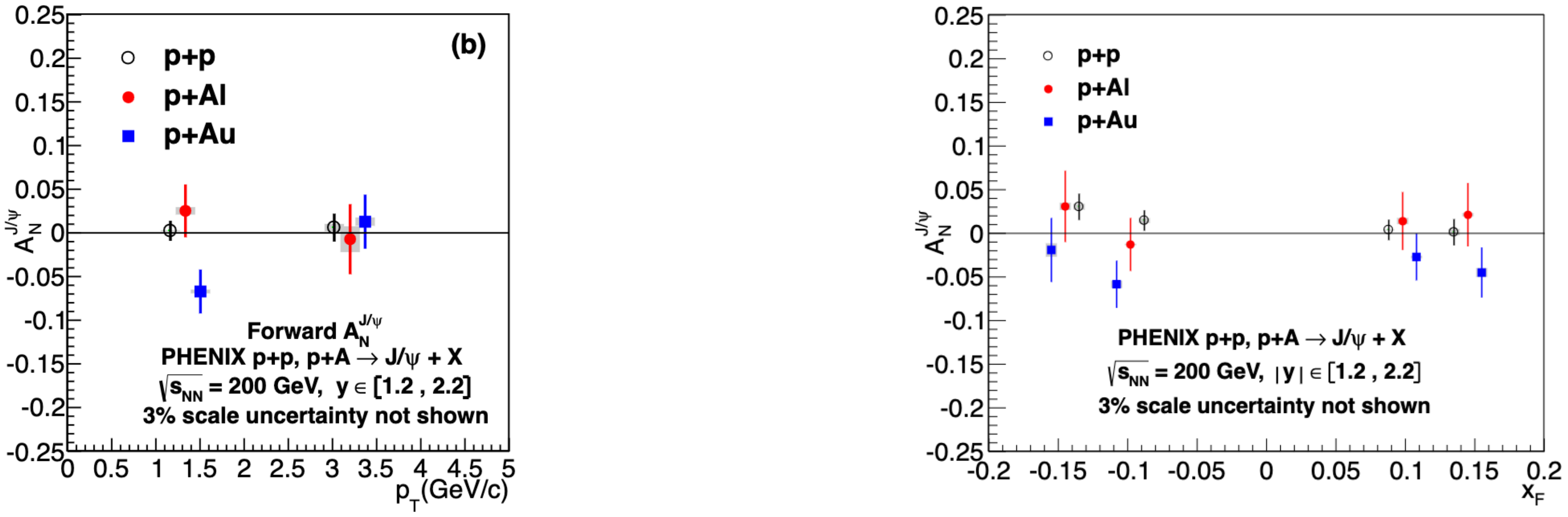
Topical Group on Hadronic Physics
GHP

Outline

- Introduction
- SpinQuest Experiment
- Analysis Procedure
- Results Based On Commisioning Data (statistically limitted)
- Conclusions
- Next Steps and Discussion

Transverse Single Spin Asymmetry in J/ψ Production

- In proton-proton interactions, the Transverse Single Spin Asymmetry (TSSA), denoted as A_N, characterizes the extent of azimuthal modulation in the scattering cross-section of outgoing particles relative to the transverse spin orientation of the polarized proton.
- The asymmetry is defined as a function of ϕ_S: $A(\phi_S) = \frac{N^{\uparrow}(\phi_S) - N^{\downarrow}(\phi_S)}{N^{\uparrow}(\phi_S) + N^{\downarrow}(\phi_S)} = A_N Sin(\phi_S)$, Here, $\phi_S = \phi_{spin} - \phi_{J/\psi}$
- TSSA is relates to Siver's function and helpful to understand spin momentum correlation
- PHENIX results demonstrates $A_N^{J/\psi}$ as a function of P_T *and* x_F



Aidala et al., Phys. Rev. D 98, 012006, arXiv: 1805.01491 (hep-ex) (2018)

Motivation

- **Theoretical Interests:**

TSSA for direct J/ψ production Sensitive to both the Sivers effect and J/ψ production mechanisms

Role of gluons in creating A_N is not well understood, while quarks relatively well understood

- **Experimental Interests:**

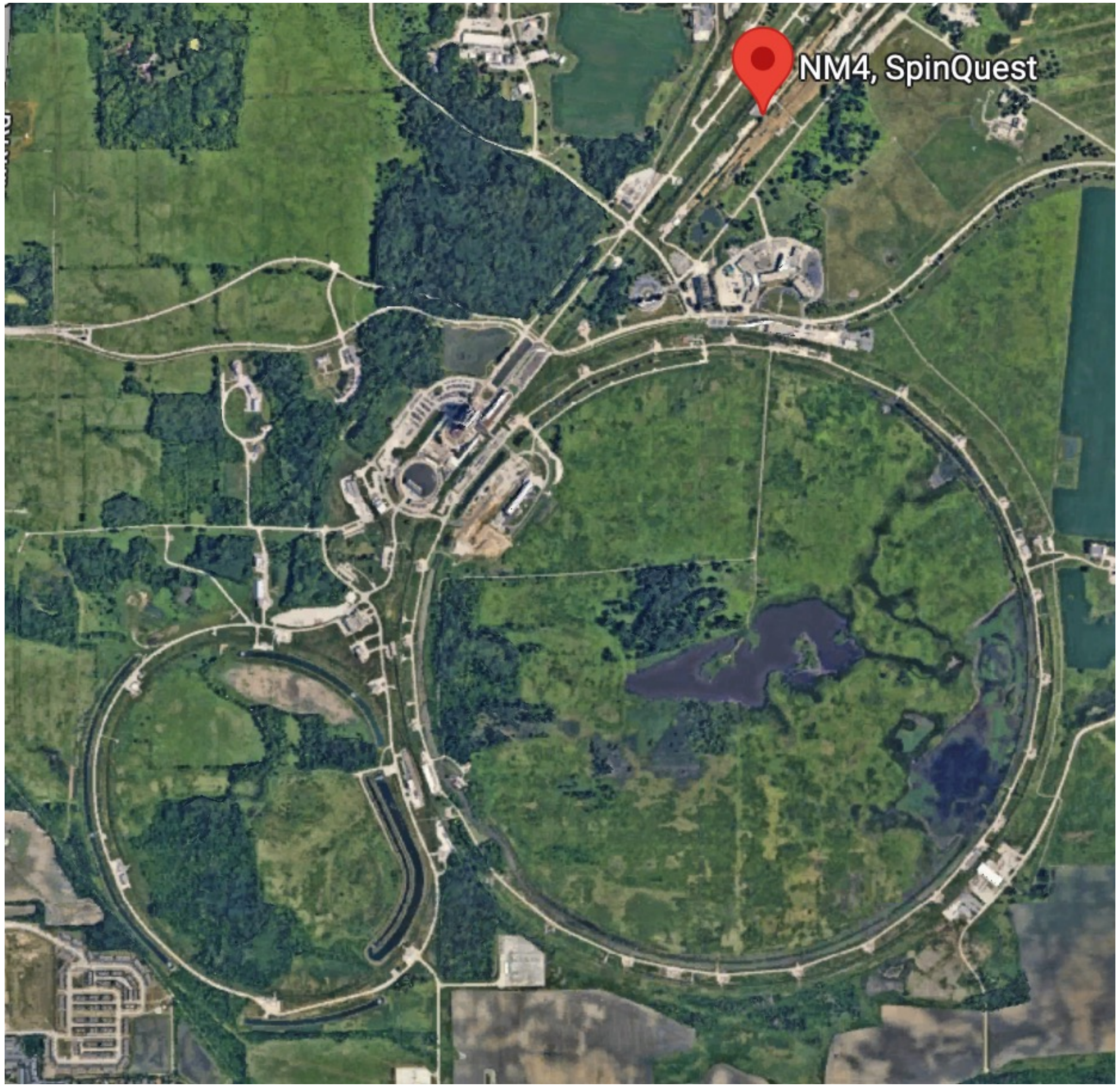
TSSA asymmetry in J/ψ production complementary to PHENIX measurement in unique kinematic region (i.e. $X_F > 0.4$)

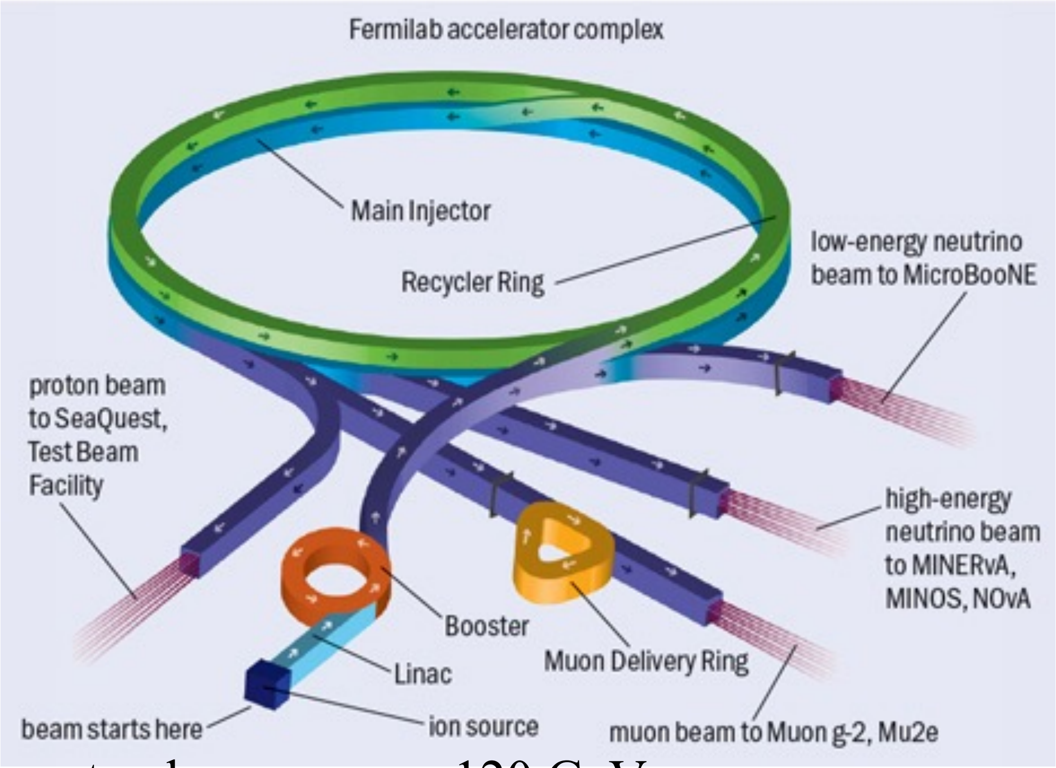
Spectrometer is well tested and calibrated to detect physics events with final-state di-muons

J/ψ results will be relevant for future experiments like EIC

Higher statistics achievable due to the large production cross section compared to DY

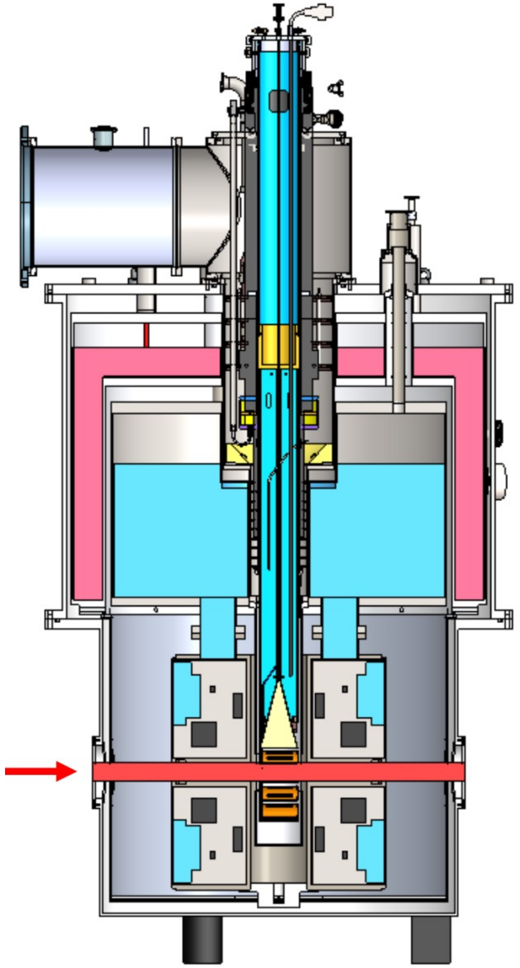
SpinQuest Experiment (Beamline)

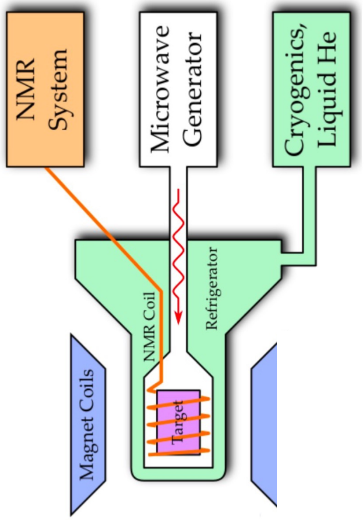




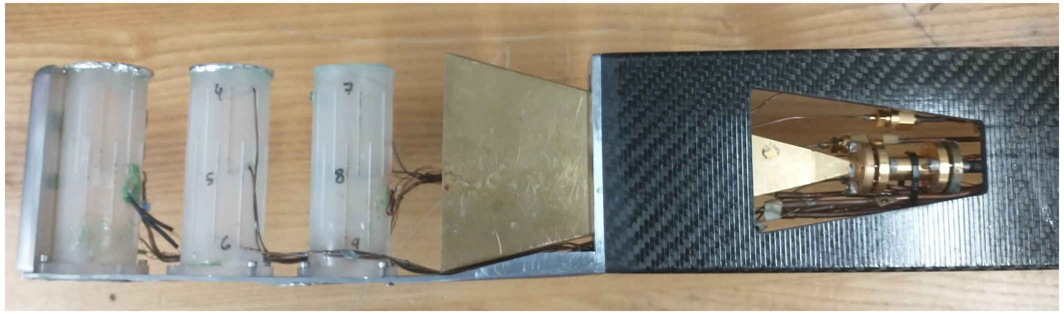
- proton beam energy 120 GeV
- $\sqrt{s} = 15$ GeV (fixed-target)
- Consisting of $2.67\times10^{12} protons/spill$
- Beam spill $\approx 4.4s/min$
- Expect $7.7\times10^{17}\ POT/Year$
- **High luminosity, polarized DY experiment!**

SpinQuest Experiment (Cryogenic Polarized Target)



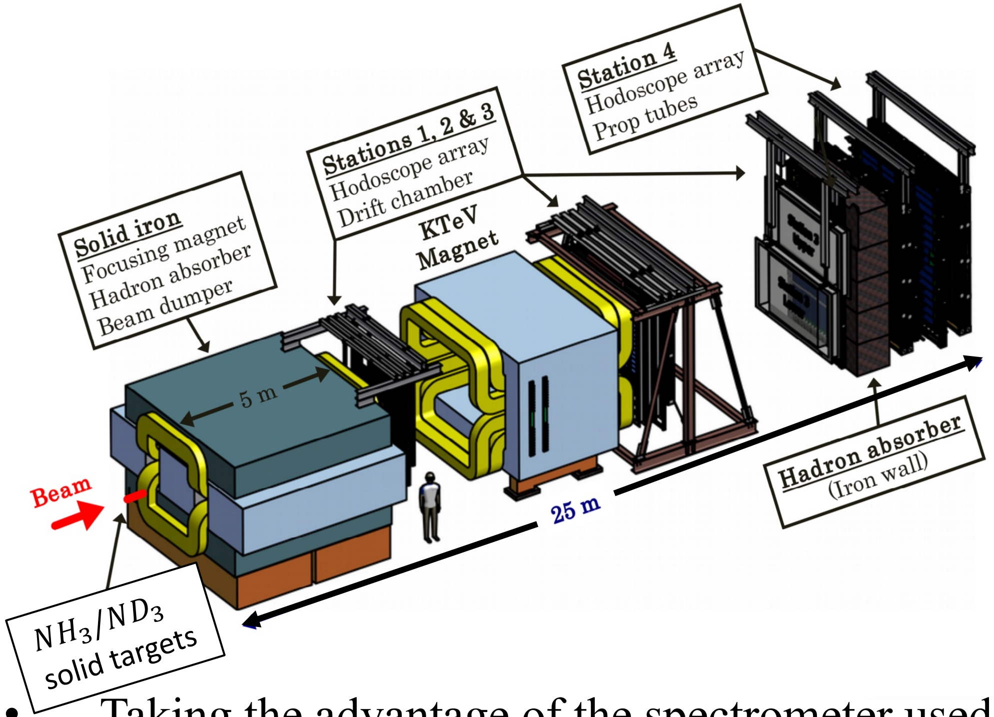


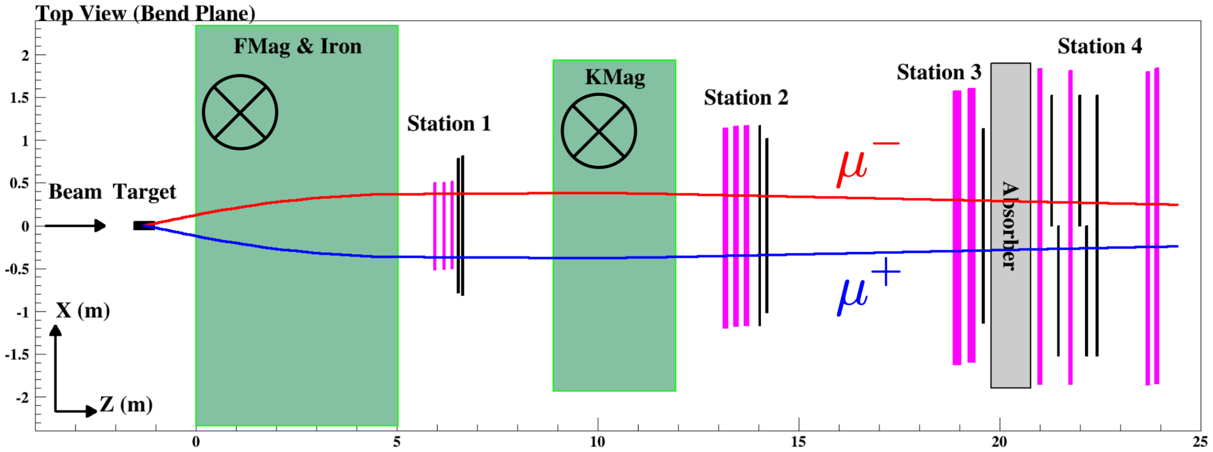
- 8 cm long solid NH_3 and ND_3 target cells
- Magnetic Field: B = 5 T with uniformity $dB/B < 10^{-4}$ T over 8 cm
- Maintaining the target at 1.1K using ^{4}He evaporation refrigerator
- Expected polarizations:
  - NH_3: 80%
  - ND_3: 32%

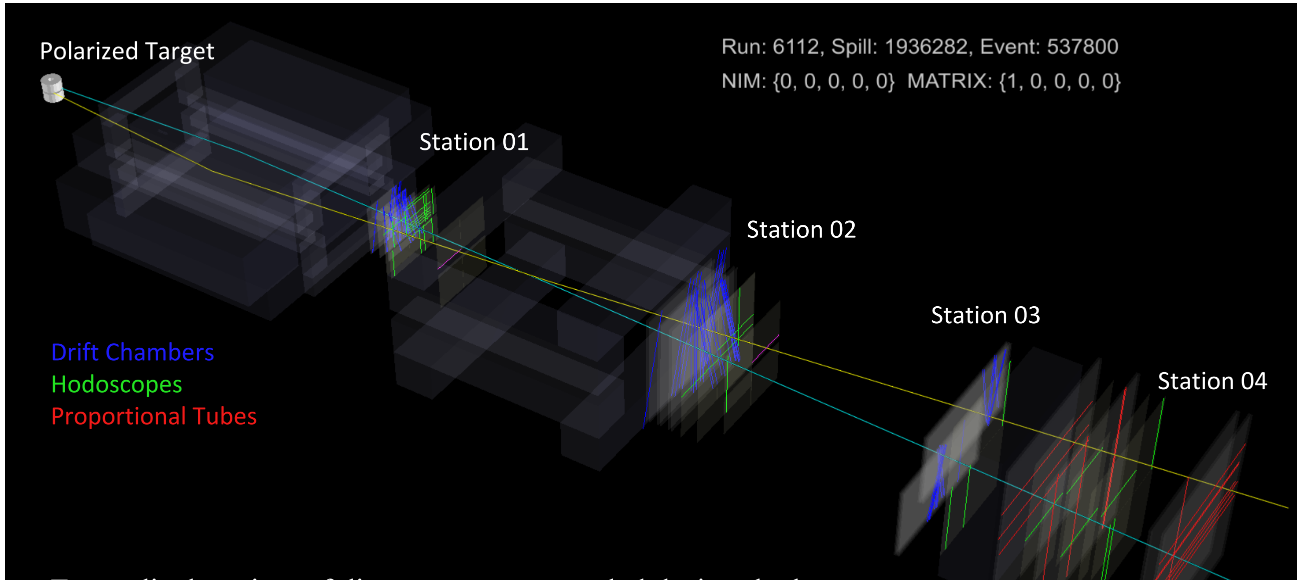


Material	Density	Dilution factor	Packing fraction	Polarization	Interaction length
NH_3	0.867 g/cm^3	0.176	0.60	80%	5.3%
ND_3	1.007 g/cm^3	0.300	0.60	32%	5.7%

SpinQuest Experiment (Spectrometer Setup)







Event display view of di-muon event recorded during the beam commissioning period

- Taking the advantage of the spectrometer used by SeaQuest experiment
- Made by 24 wire chamber planes, 16 hodoscope planes and 8 planes with proportional tubes
- FMag generates magnetic field of 1.8T to select muons in appropriate momentum region
- KMag generates magnetic field of 0.4T and useful to evaluate momenta of muon candidates

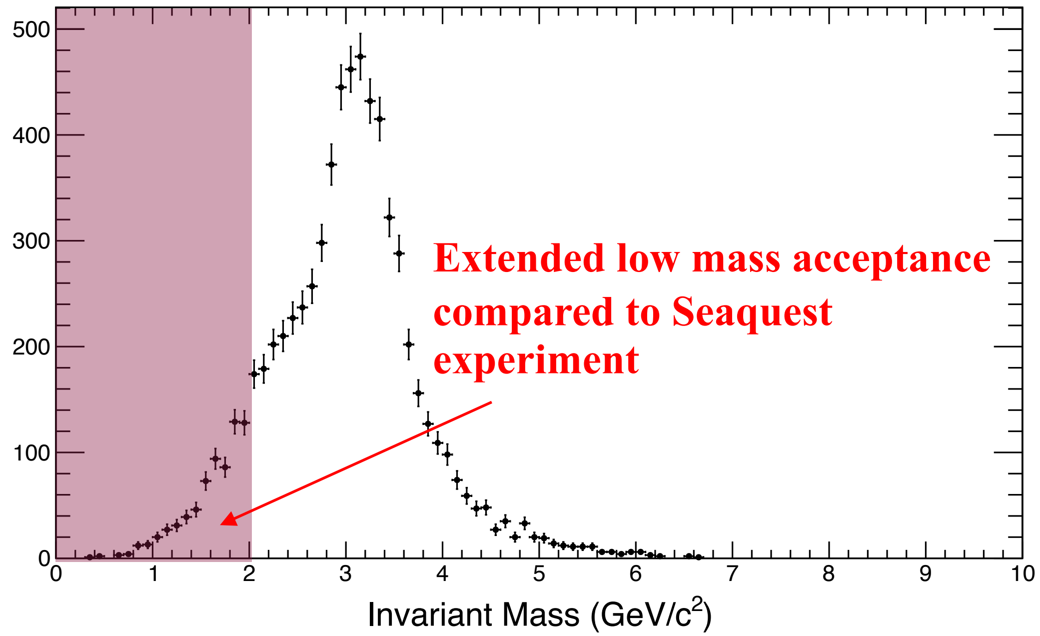
Objectives Of The Commissioning Run

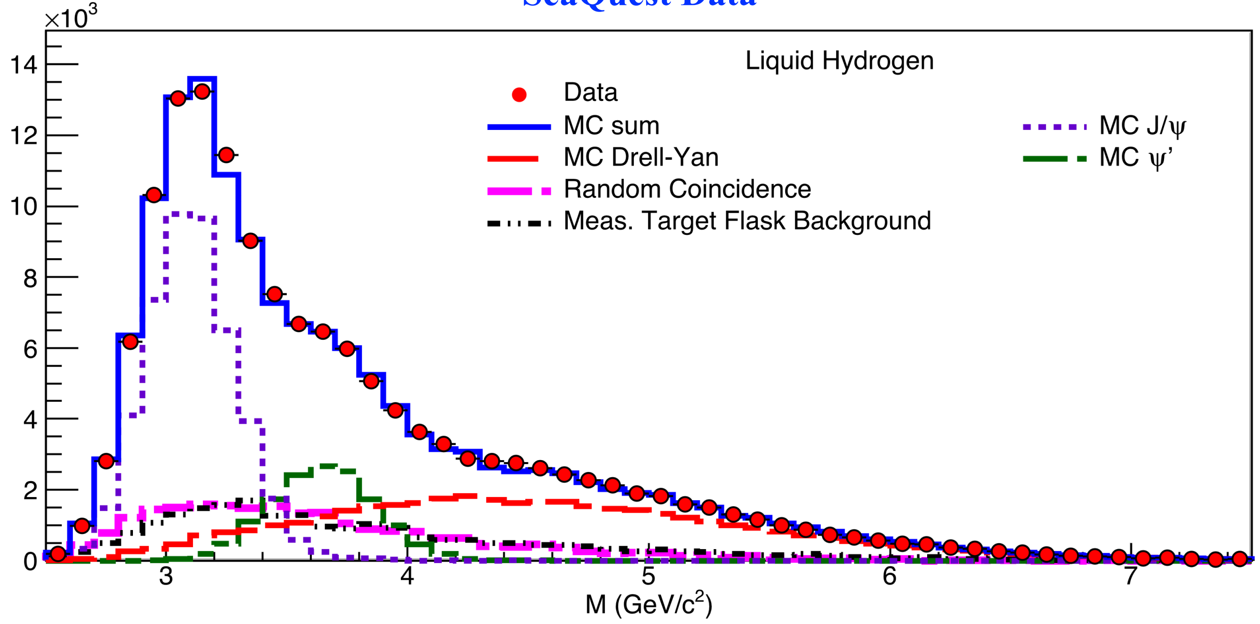
Timeline: May 24th - July 24th 2024

- **Polarized Target System:**
    - Achieve precise beam alignment with target cells
    - Conduct polarized runs using CH2 and NH3, testing both target polarities
    - Validate procedures for extracting and shipping irradiated ammonia
    - Evaluate the target annealing process
    - Determine the optimal beam intensity through quench testing
    - Establish stable liquid helium production and consumption

- **Spectrometer and Data Acquisition:**
    - Confirm operational readiness for production runs
    - Optimize timing for trigger and tracking detectors
    - Synchronize beam intensity monitors and provide real-time feedback to the Main Control Room (MCR)
    - Assess trigger performance across varying beam intensities and magnet configurations

Commissioning Status



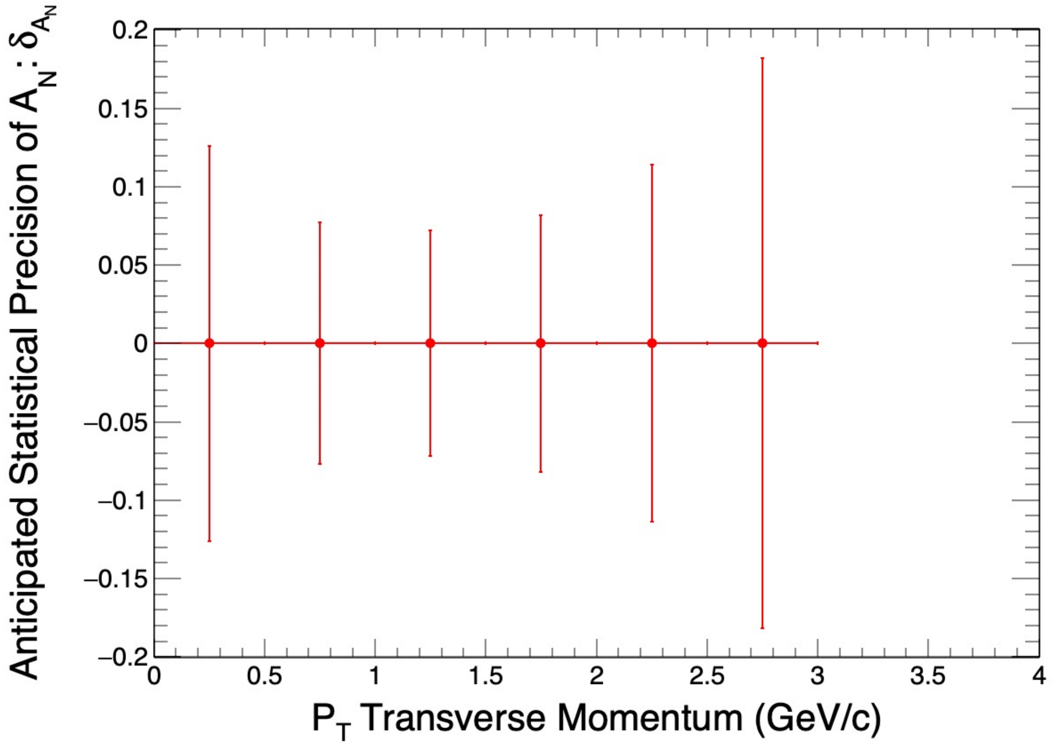


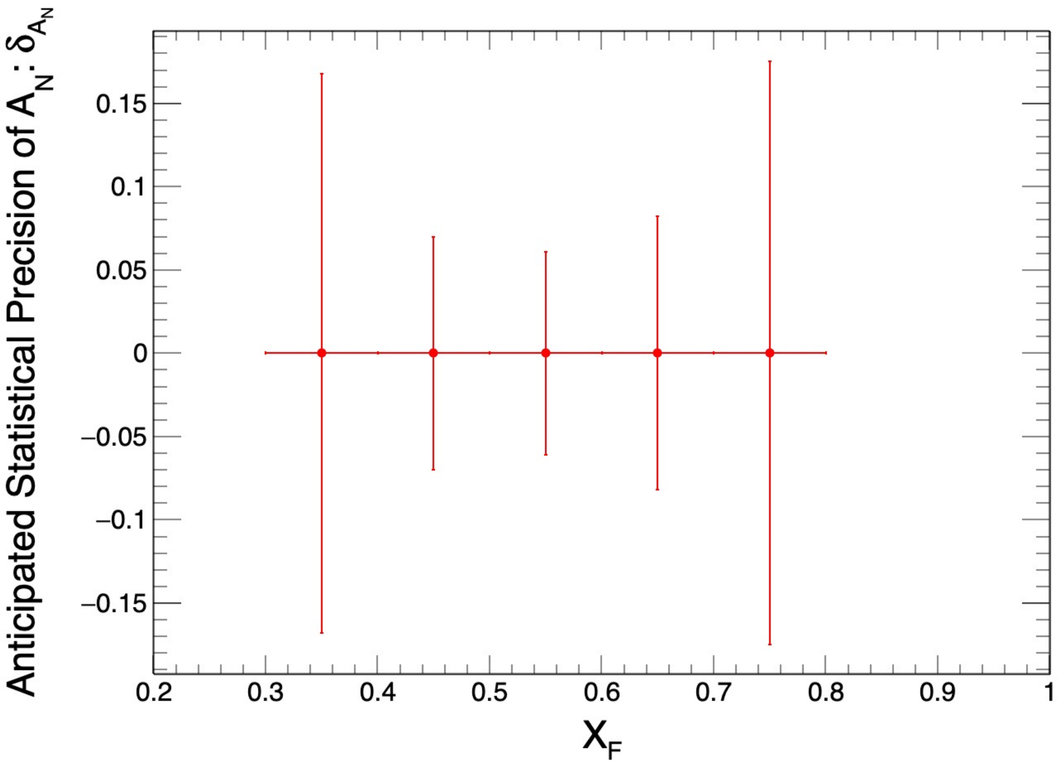
Nature 590, 561–565 (2021)

- Wider acceptance range (compared to SeaQuest) below 2 GeV to better understand backgrounds with sideband studies
- Projected event selection/reconstruction is expected to be the same for SpinQuest from SeaQuest

- $\delta\sigma_M(J/\psi) \sim 220$ MeV
- Already collected data during the beam commissioning and analyzed invariant mass spectrum with the limited data collected for online reconstruction (not a full reconstruction)
- We expect better efficiency and resolution from offline analysis

Projected Precision of J/ψ TSSA

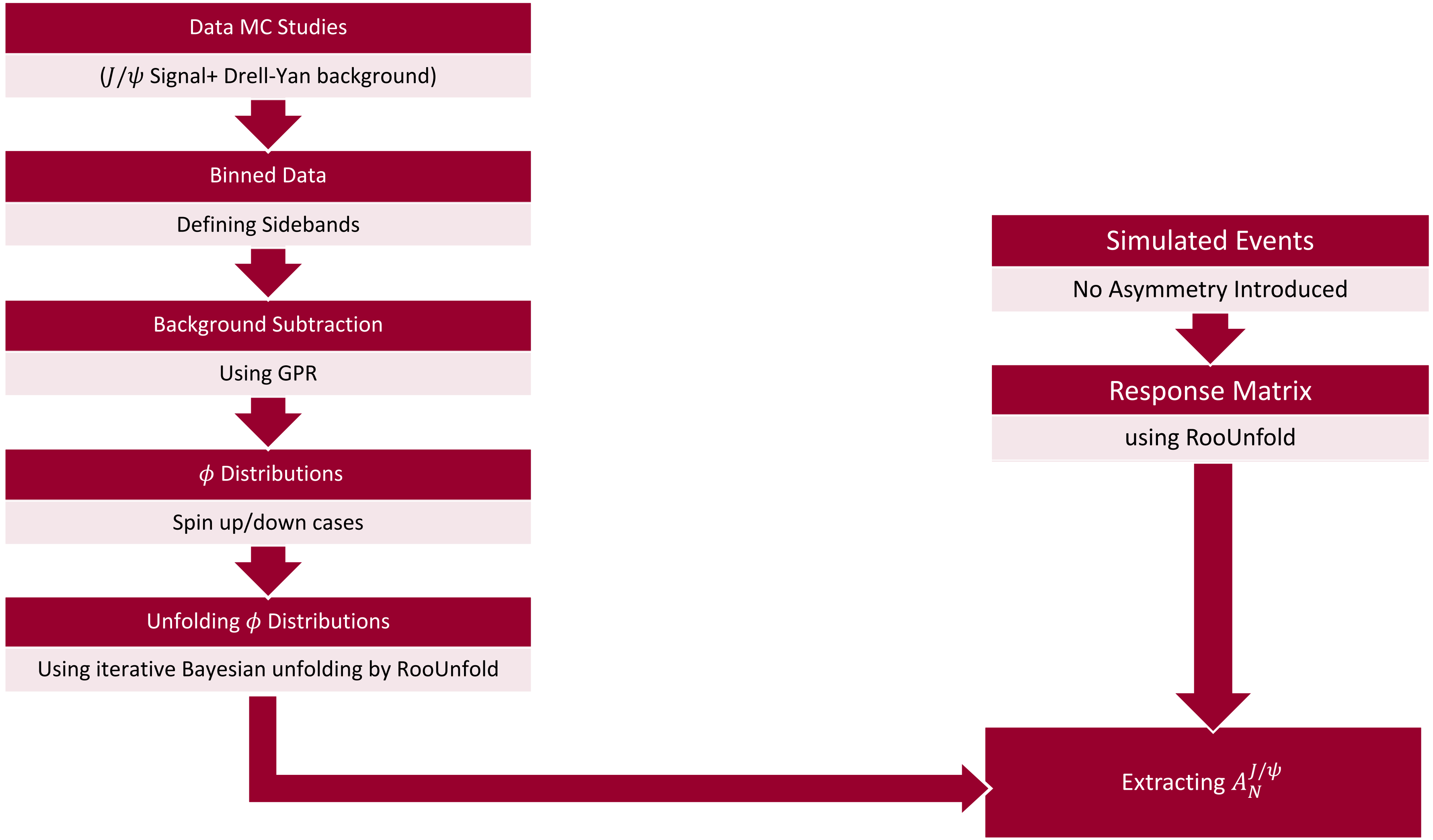




- In order to scale easily, one week of dedicated data taking is assumed
- $\delta_{AN} = 1/(f_{dil} \times P_{pol} \times \sqrt{R_{dim} \times \mathcal{L}^{1w}})$

- precision of ~0.1 is expected
- A longer data-taking period is needed to achieve the target precision, 0.015

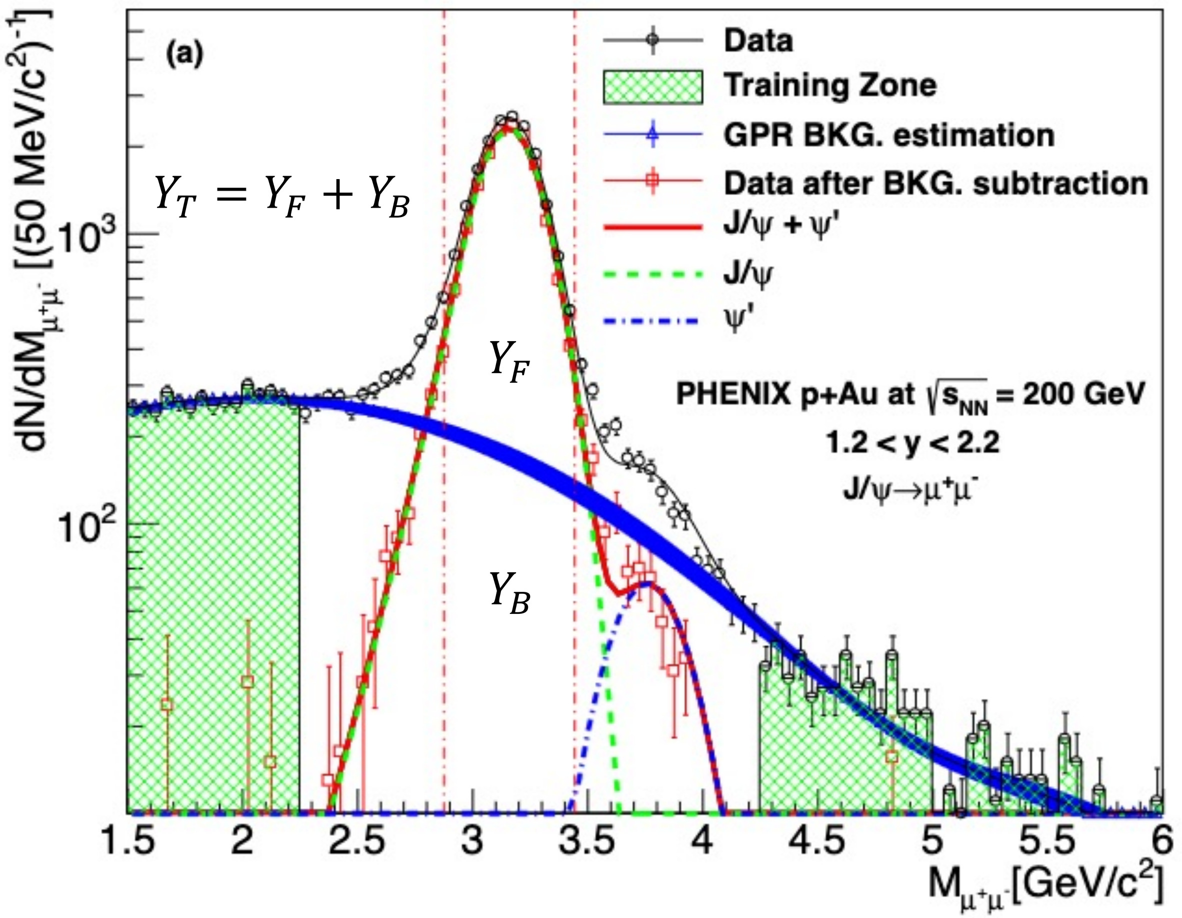
Analysis Strategy



Simulation Studies for $A_N^{J/\psi}$ Determination

- SpinQuest commissioning data is statistically limited
- Currently using SeaQuest data to benchmark the background subtraction
- Already generated Monte-Carlo events for:
  - J/ψ signal events
  - Drell-Yan events + backgrounds
- Everything scaled down to 2.873×10^{17} POT
- Asymmetry was introduced by weighting MC events (Initially we set A_N = 0.2 for simulation):
  - $w_{A_N} = 1 + A_N \times P \times Sin(\phi_{spin} - \phi_{J/\psi})$; $where\ \phi_{spin} = \pm\frac{\pi}{2}$; $P = 1.0$
  - $w_{total} = w_{A_N} \times w_{event}(mass, x_F)$

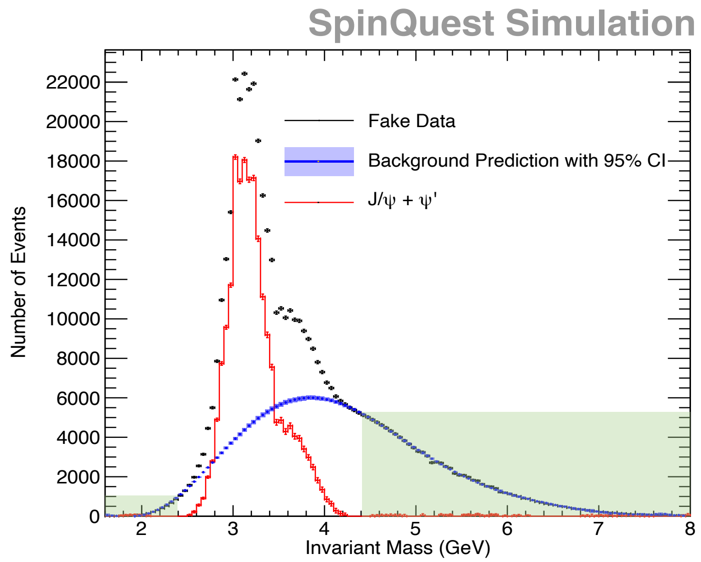
Background Subtraction using GPR

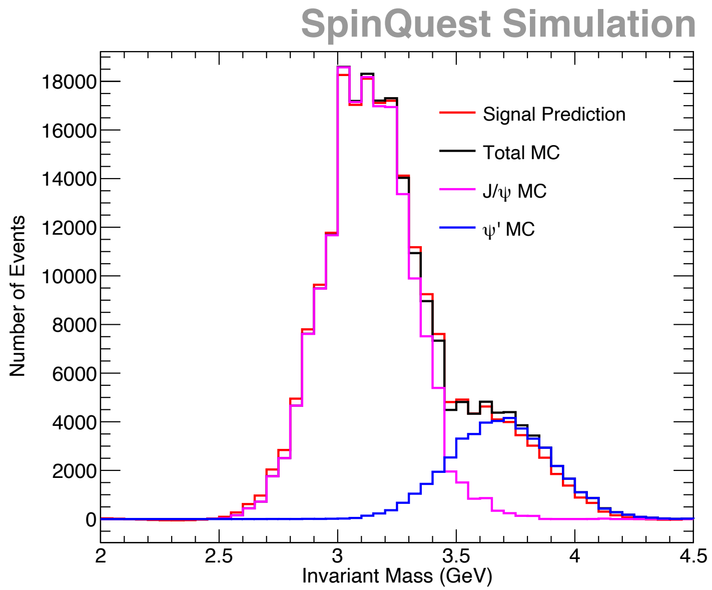


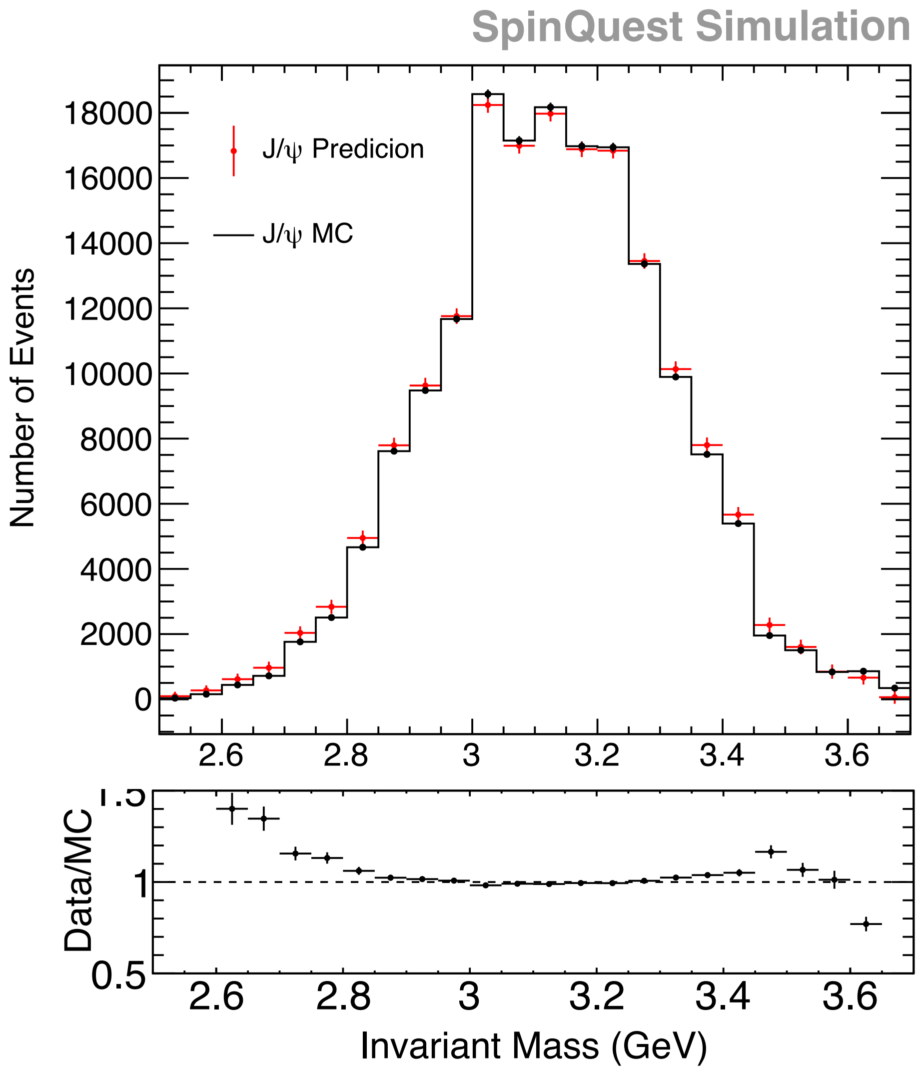
Aidala et al., Phys. Rev. D 98, 012006, arXiv: 1805.01491 (hep-ex) (2018)

- Background dominated regions were chosen for sideband study
- We selected GPR (Matern Kernel) among other regression techniques
- Multiple Gaussian Process Regression models were trained by optimizing hyper parameters
- This background subtraction needs to be done in each ϕ bin to extract J/ψ yields (Y_F) for both spin up/down cases

Comparing Background-Subtracted Spectrum to Monte-Carlo

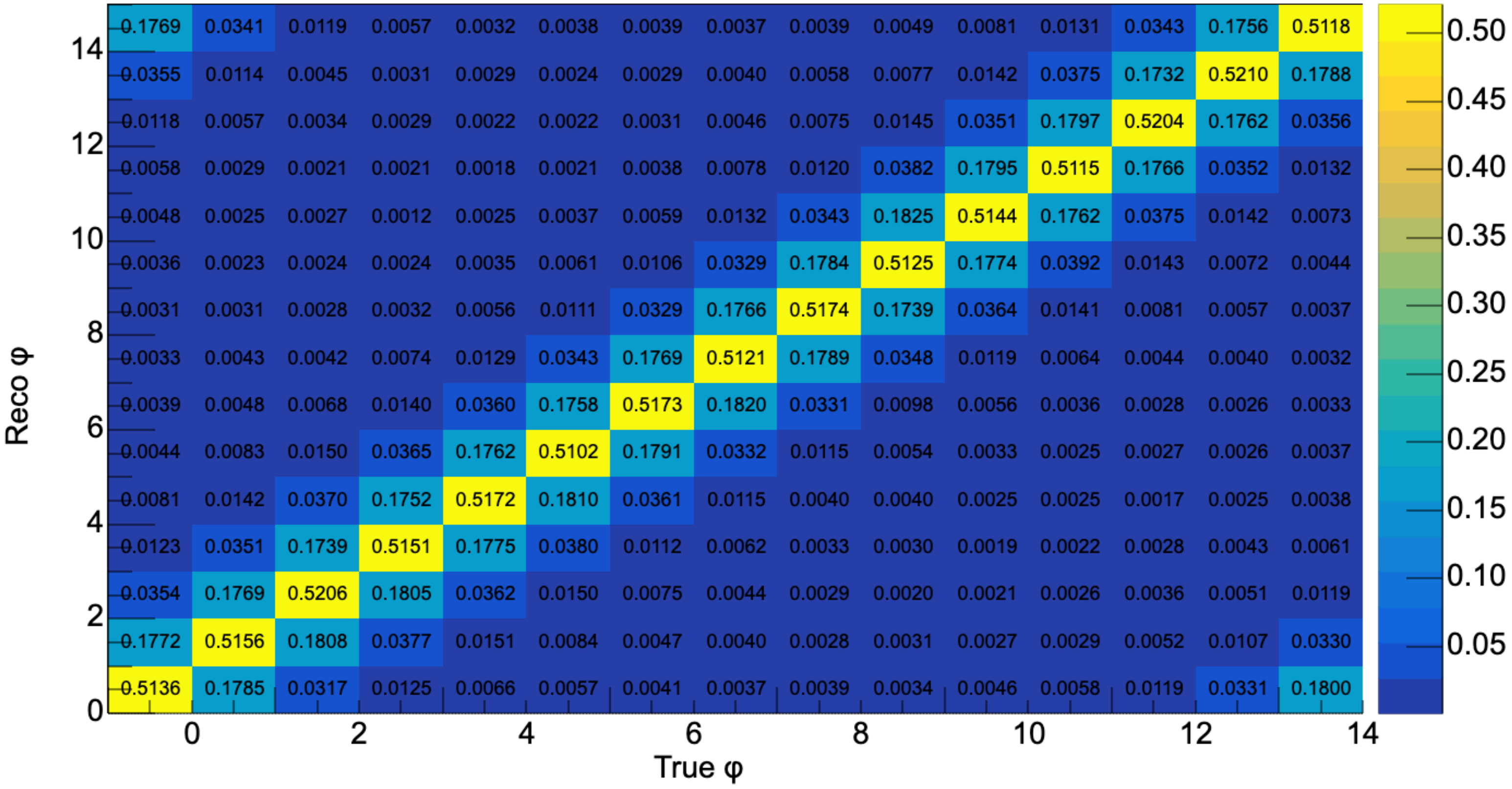






- Applied template fit to remove the tail due to ψ' background events
- Obtained a good agreement between data-based prediction and MC

Iterative Bayesian Unfolding using RooUnfold

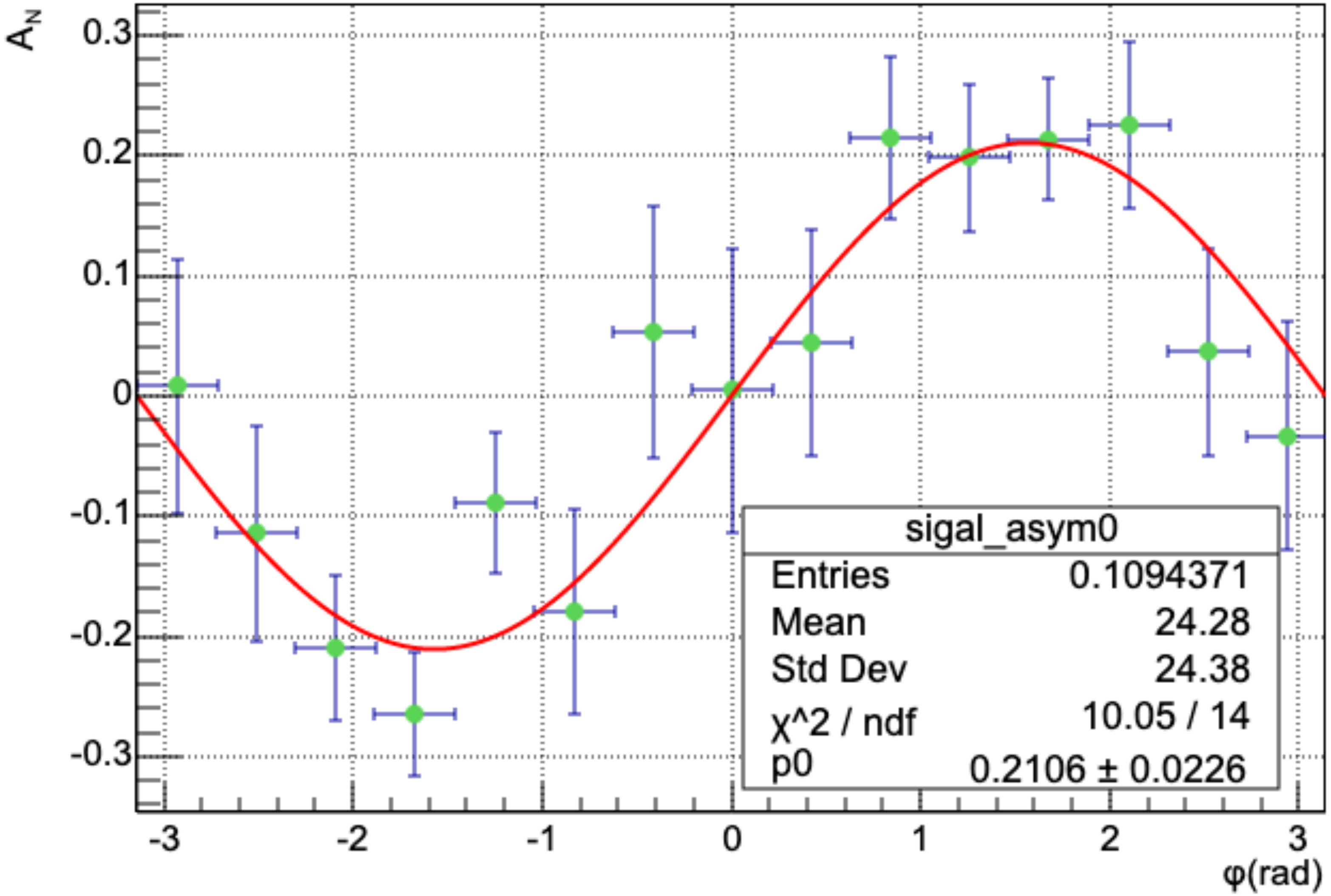


- Initially defined 15 bins between: $\{-\pi, \pi\}$
- Selected Kinematic region:

$$0 < P_T < 6 \text{ GeV}$$

- Response matrix will be used to calculate unfolded ϕ distributions
- Use unfolded yields for each ϕ bin to calculate asymmetry per ϕ bin

Unfolded $A_N^{J/\psi}$ for selected P_T bin



- Trigonometric function can be used to extract asymmetry
- Measured $A_N^{J/\psi} = 0.21 \pm 0.02$
- Injected $A_N^{J/\psi} = 0.2$
- $0 < P_T < 6$ GeV
- Same procedure can be conducted for X_F bins

Generating Combinatoric Backgrounds (Event Mixing)

- Developed a method to estimate combinatoric background for di-lepton experiments that works when:
  - Signal pair density in data stream is sufficiently low
  - Events can be sorted into classes with same track distributions

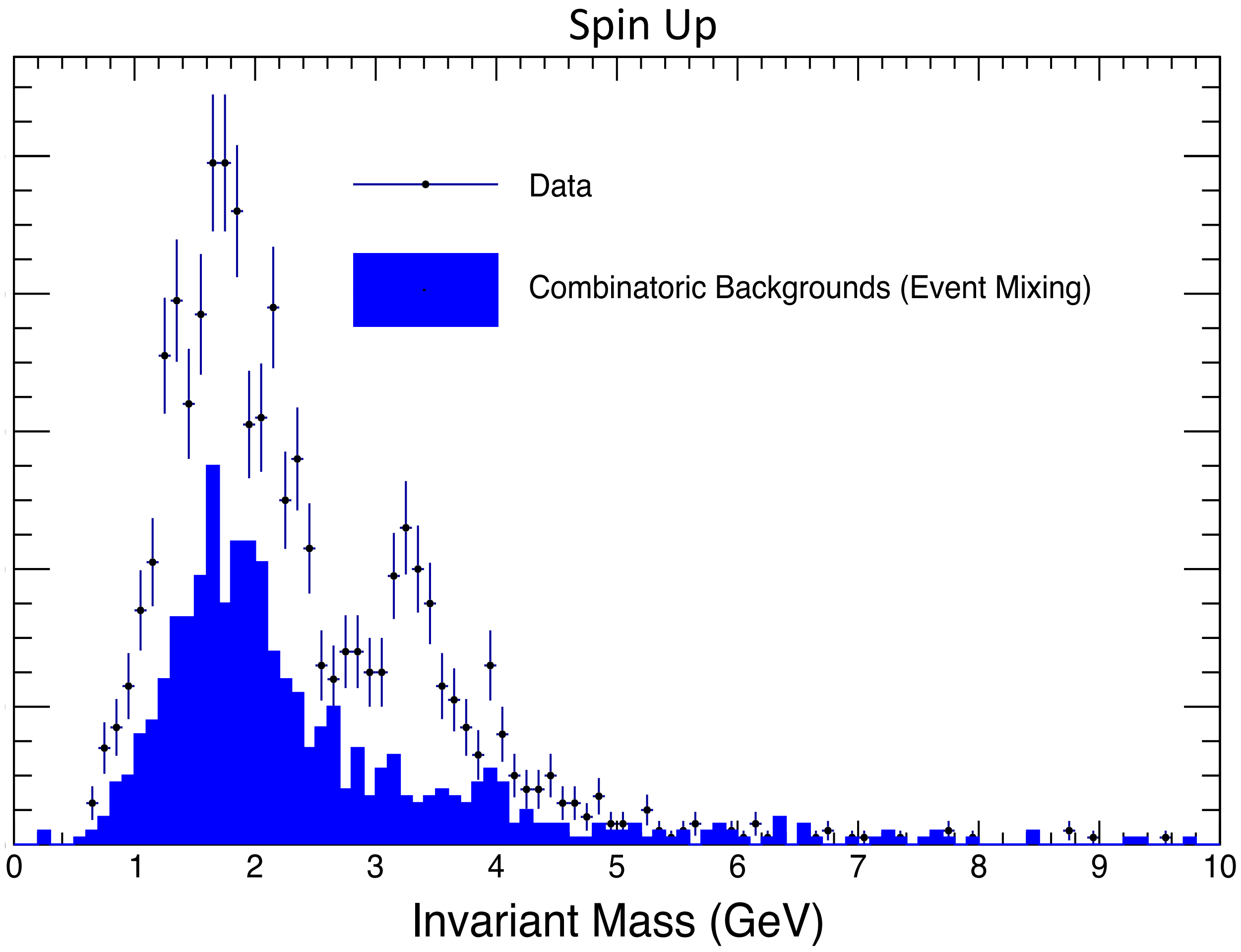
- Method benefits:
  - Has correct normalization
  - Computed distribution can be directly subtracted from total yields to recover signal yields

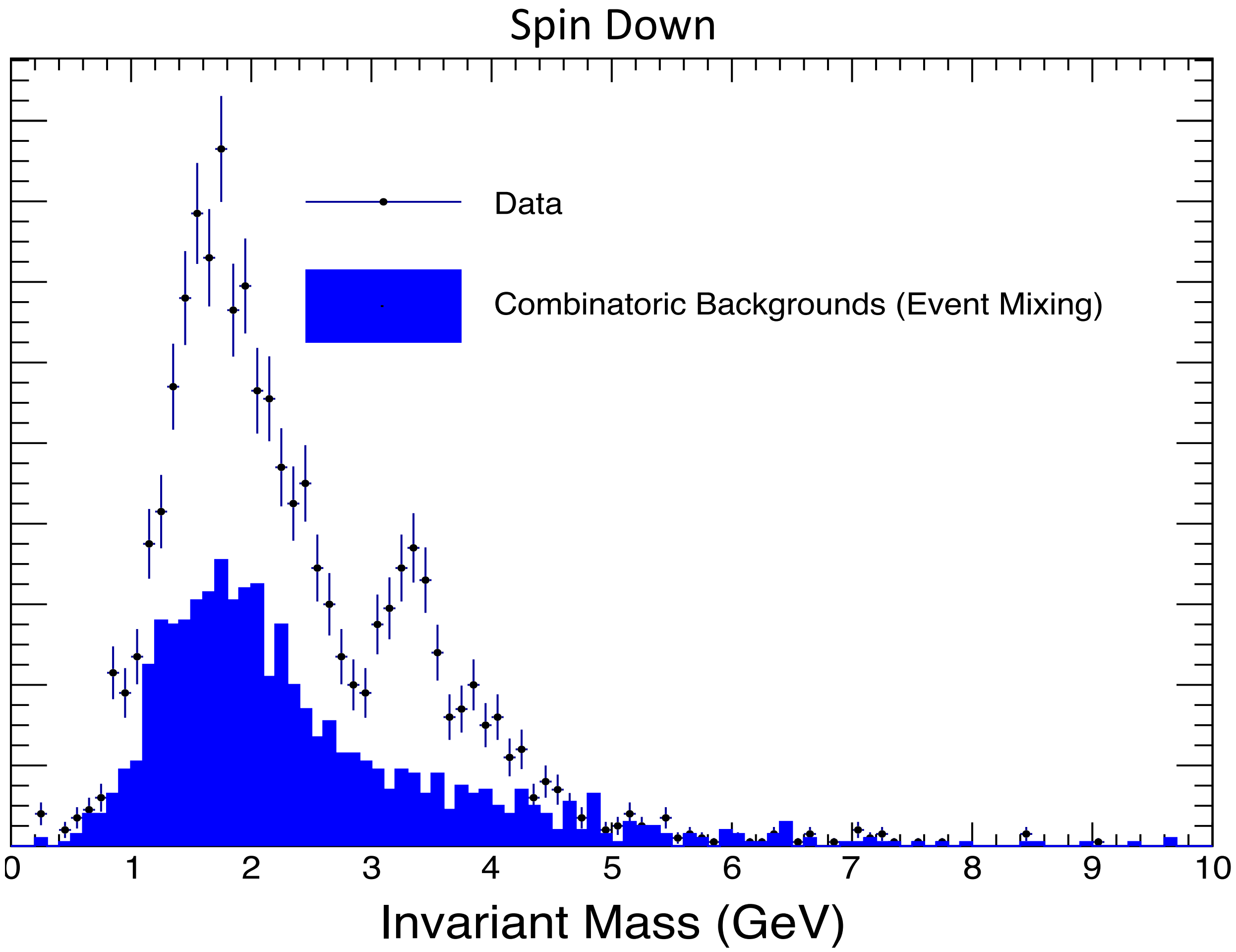
- For high statistical significance experiments:
  - Signal pairs in adjacent events can perturb results
  - Demonstrated technique to quantify and correct for this effect

- For low statistics experiments:
  - Possible to improve statistical significance of background estimate
  - Could double statistics by combining positive tracks from event i with negative tracks from events i+1 and i+2
  - Correct normalization maintained by dividing by 2

Reference: S.F. Pate et al 2023 JINST 18 P10032

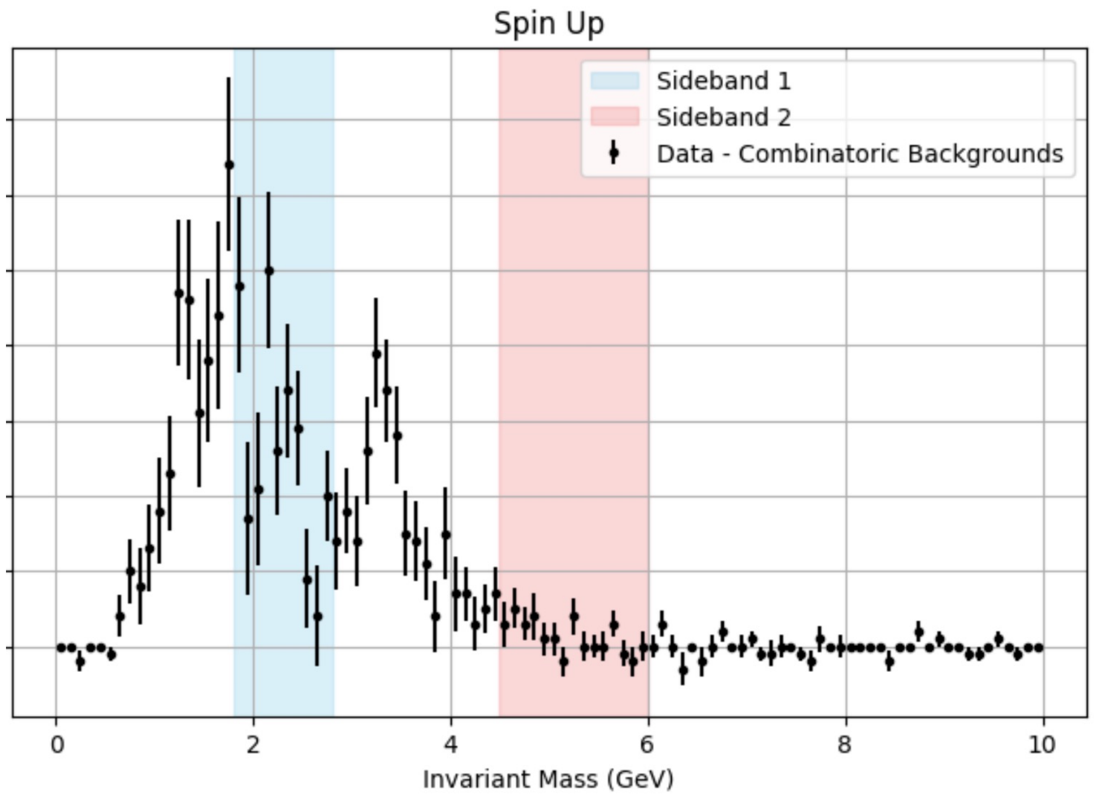
Background Subtraction (Combinatoric Backgrounds)

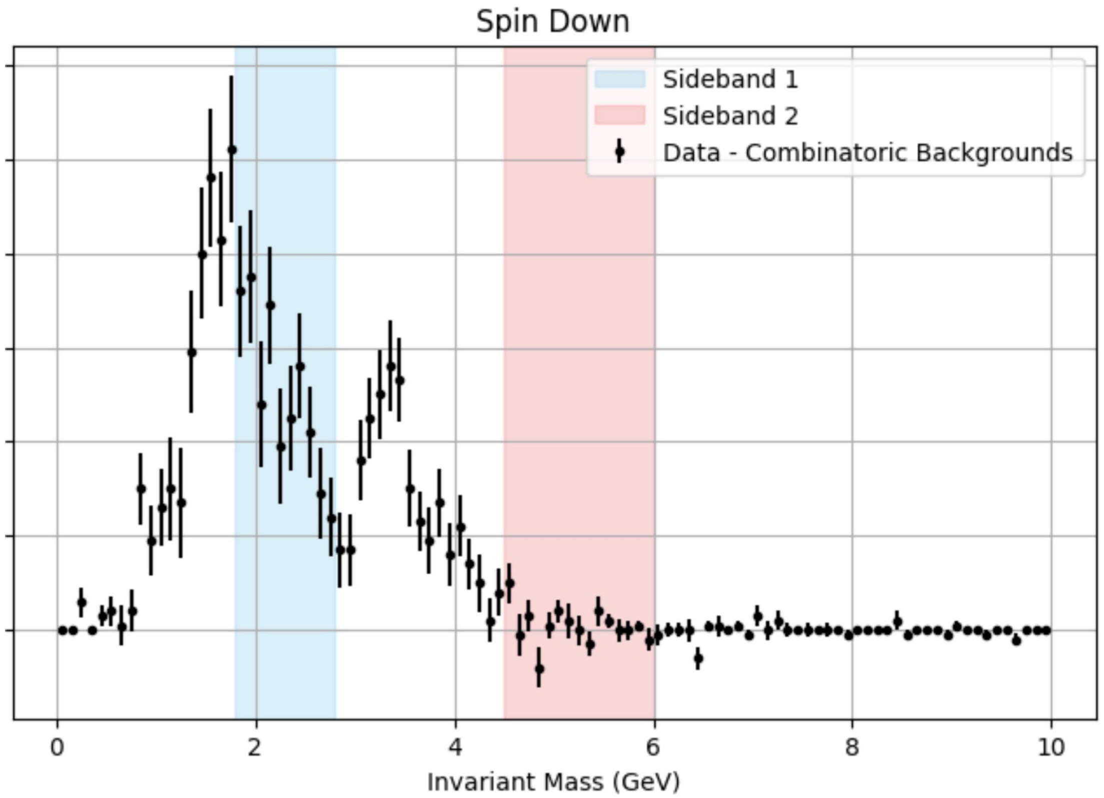




Reference: S.F. Pate et al 2023 JINST 18 P10032

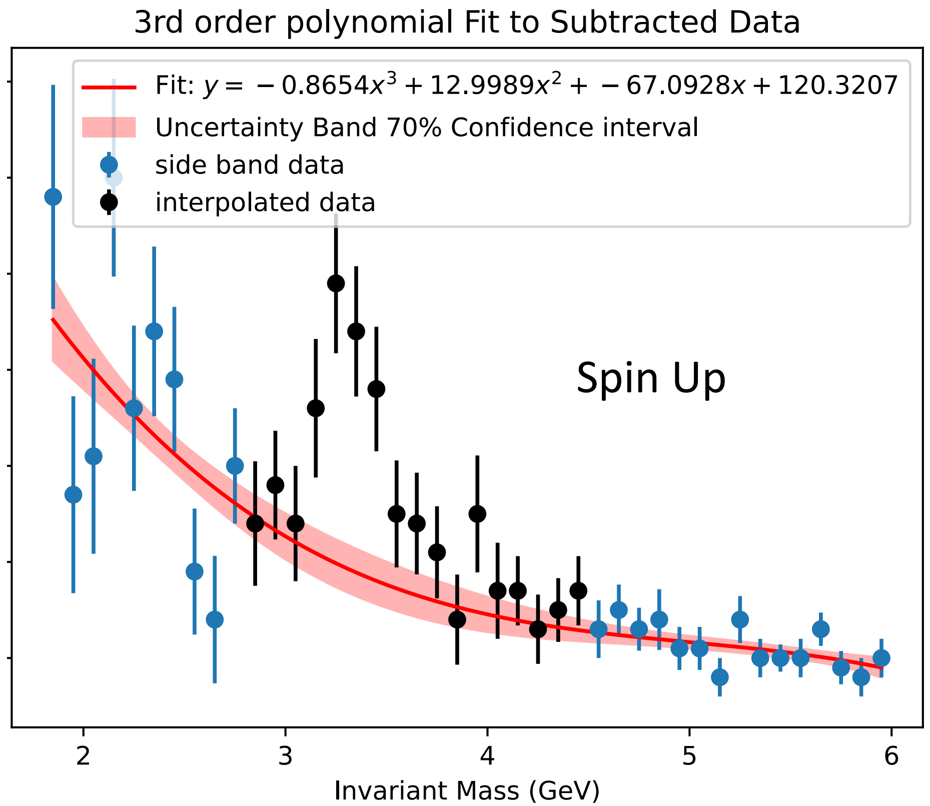
Background Modeling (Sideband Study)

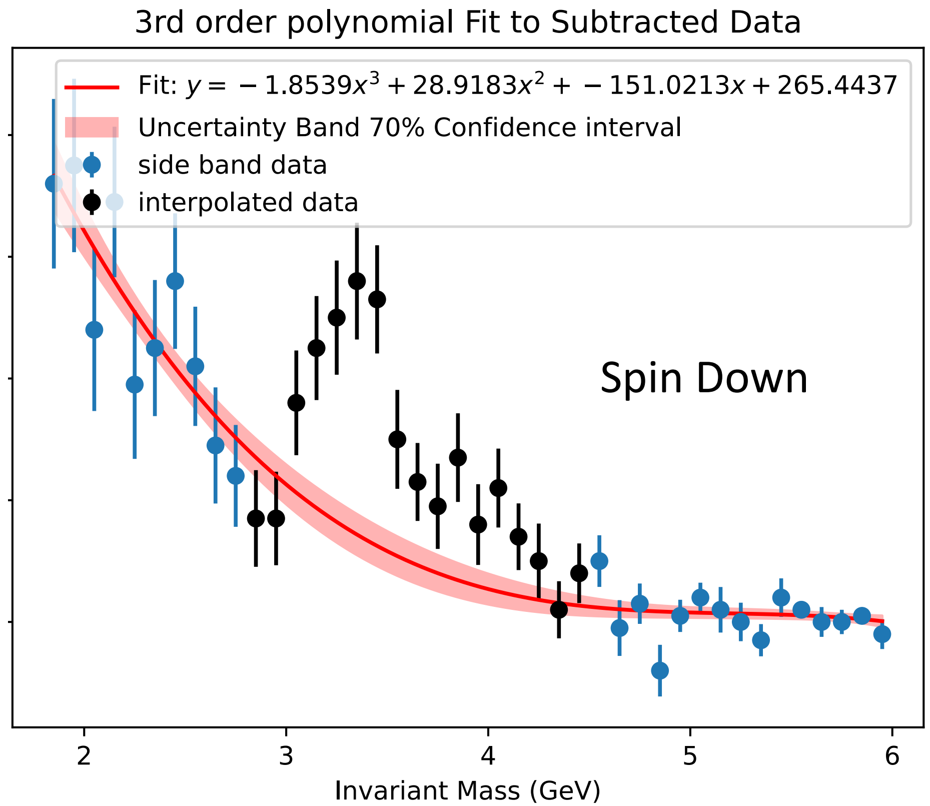




Side Band	Left Boundary (GeV)	Right Boundary (GeV)
SideBand 1	1.8	2.8
SideBand 2	4.5	6.0

Background Predictions: (3^{rd} Order Polynomials)

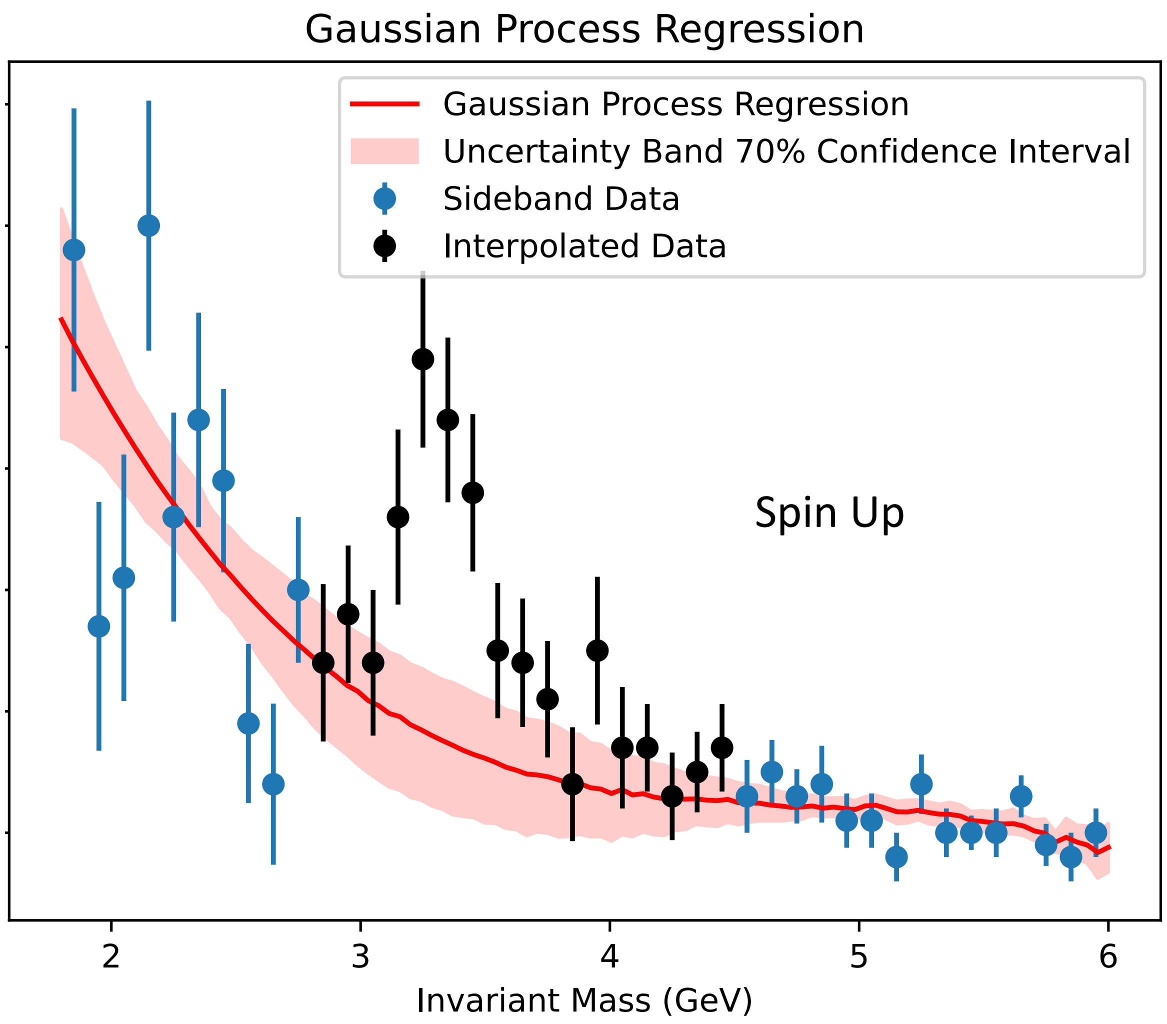




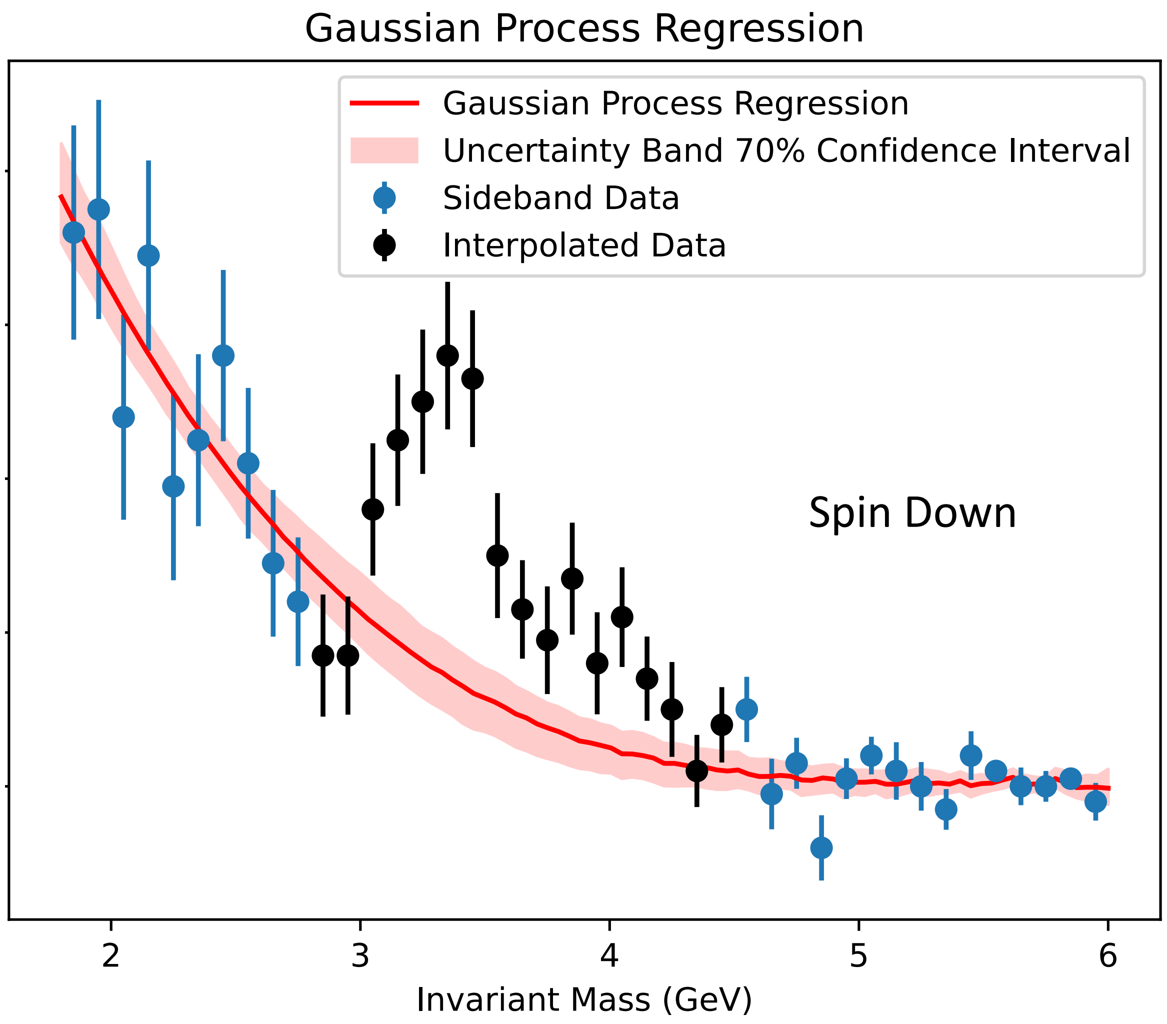
Fitted parameters:
a = −0.8654 ± 0.7822
b = 12.9989 ± 10.1355
c = −67.0928 ± 41.5035
d = 120.3207 ± 52.0398
χ^2/ndf=1.38

Fitted parameters:
a = −1.8539 ± 0.9979
b = 28.9183 ± 13.0304
c = −151.0213 ± 53.6237
d = 265.4437 ± 67.2432
χ^2/ndf=1.03

Background Predictions: (Gaussian Process Regression)

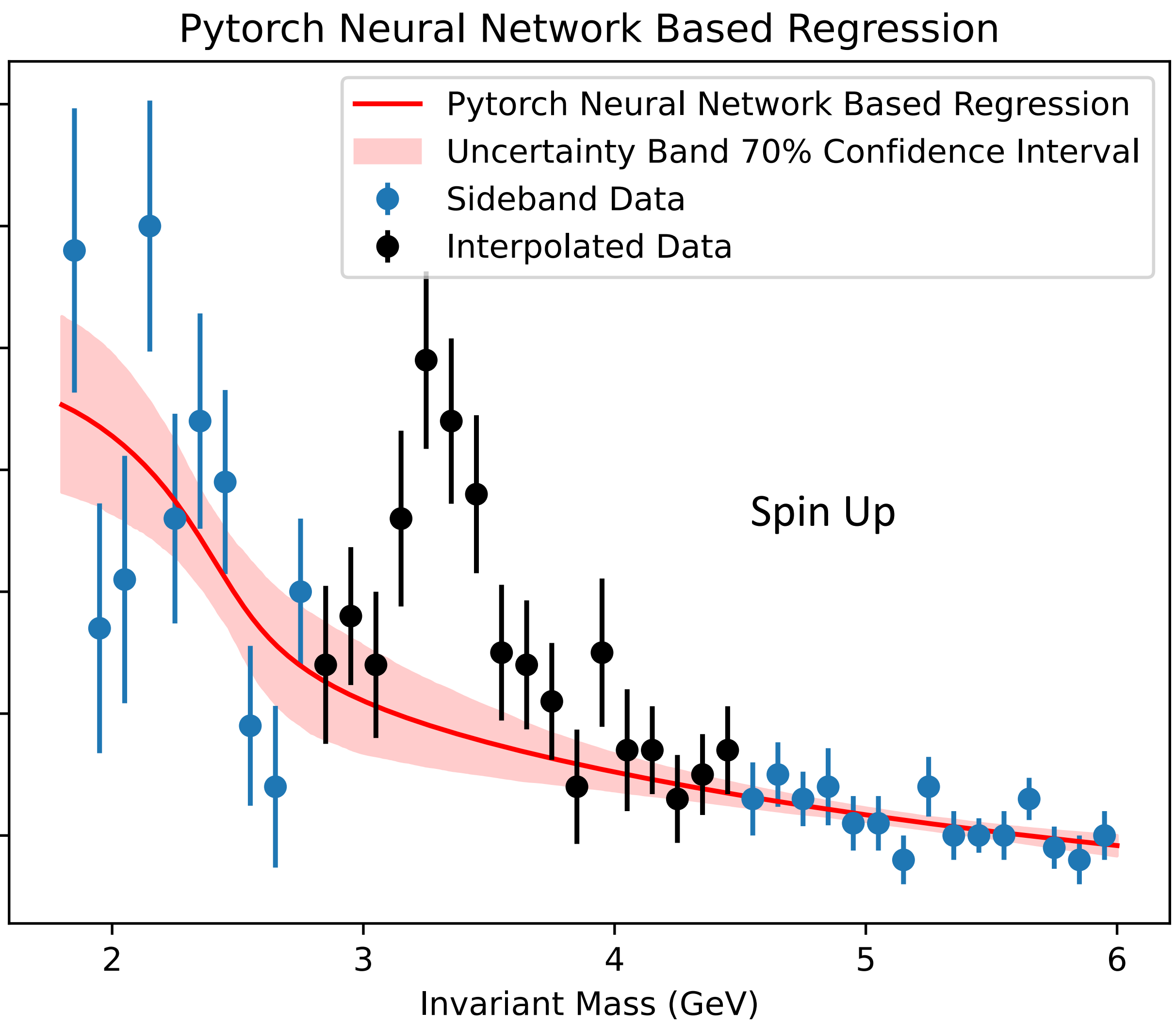


χ^2/ndf=1.44

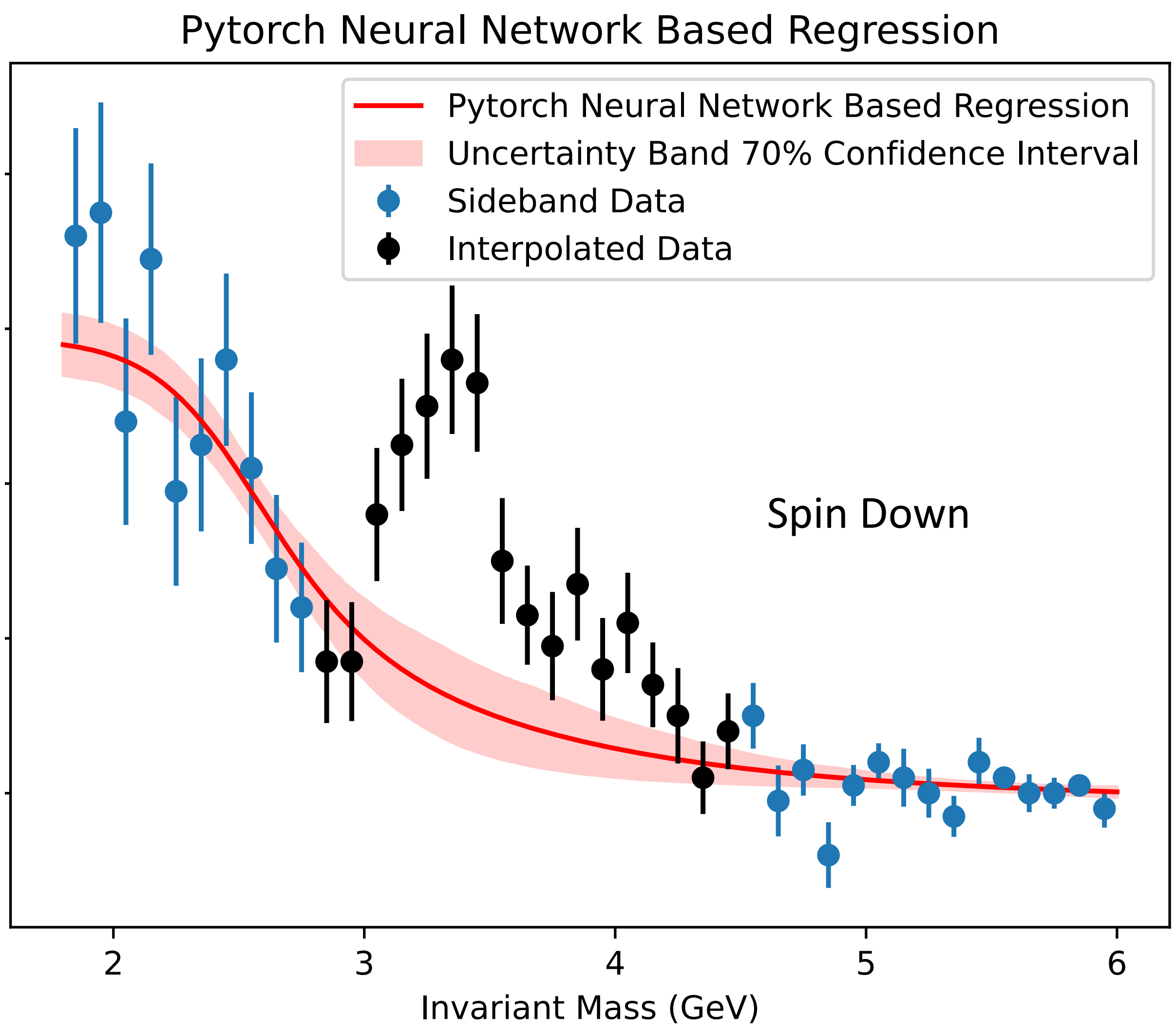


χ^2/ndf=1.12

Background Prediction: (PyTorch NN Regression)



χ^2/ndf=1.11



χ^2/ndf=1.08

Conclusions

- The SpinQuest commissioning run achieved its objectives, demonstrating the readiness of the experimental setup for physics data collection

- We have a robust tool (GPR) to extract J/ψ peak and using GPR method with Matern 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

- $A_N^{J/\psi}$ can be determined for different P_T and X_F bins

- $A_N^{J/\psi}$ is sensitive to both the Sivers effect in the nucleon and J/ψ production mechanisms

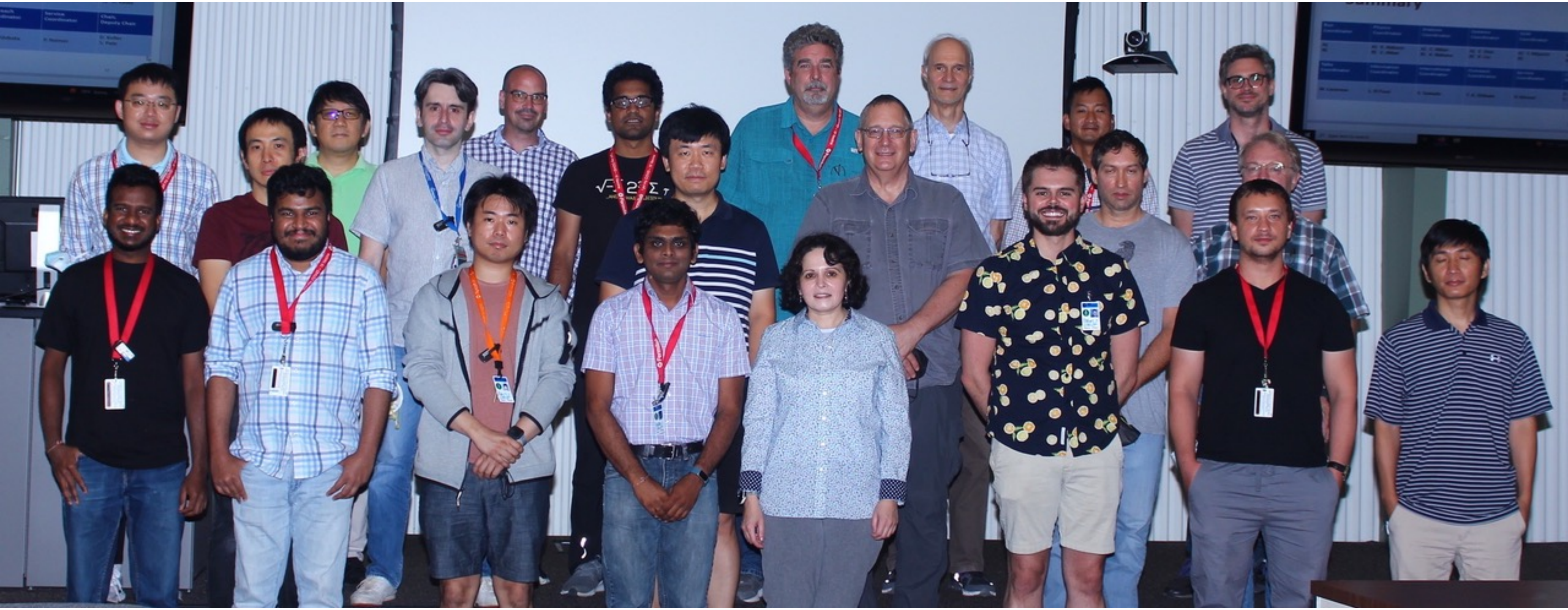
- Projected timeline to receive long term beam for SpinQuest experiment: 2026 calendar year

Next Steps

- Benchmark GPR with new regression models to further improve background subtraction
- SpinQuest experiment is now fully commissioned and ready to start taking physics data in the 2025/2026 beam period at Fermilab.
- Applying a template fit for DY tail above 4.5 GeV before sideband study
- Fully assess complete set of systematics
- We are excited to produce statistically significant publishable result after next production run, stay tuned with the latest updates!

This work is supported in part by the U.S. DOE award #: DE-FG02-94ER40847

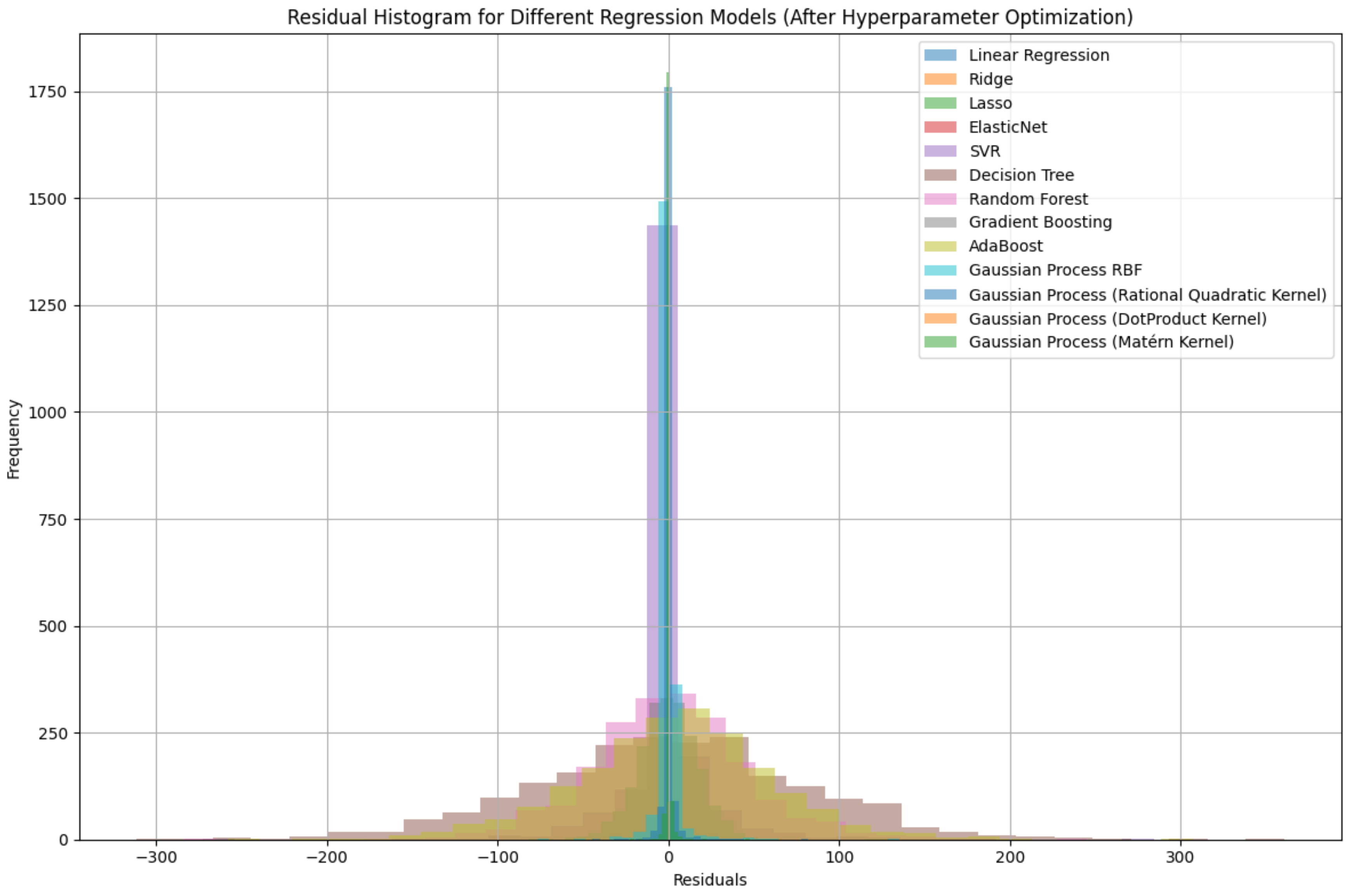
Thank you.!



Please Join The Effort

Dustin Keller [UVA] (dustin@virginia.edu)[Spokesperson] Kun Liu [LANL] (liuk.pku@gmail.com) ([Spokesperson])

Benchmarking Regression Models



Event selection criteria

- Only used Good-spills defined in Kenichi’s slides (docdb: **10854-v2, 11058 and 11048**)
- FPGA-1 Trigger requirement
- Only target-like dimuons selected
- Track separation cut applied ($|Z_{\mu+} - Z_{\mu-}| < 200$)
- Using the default occupancy
- used the latest alignment file (alignment/align_mille_v10_a.txt)
- Reconstruction configuration:

Attribute	**Reconstruction Parameter**
Geometry file	geom_run005433.root
Kalman Filter	True
"HIT_MASK_MODE", "X"	Added
RejectWinDC0	Default: 0.30
RejectWinDC1	Default: 0.50
RejectWinDC2	Default: 0.35
RejectWinDC3p	Default: 0.24
RejectWinDC3m	Default: 0.24
SQVertexFitting	True

Calculating Confidence Intervals

- Fit the data and find best values for the fitting parameters, their errors and their covariance matrix C
- In order to find an error band for a 70% confidence level. You have four parameters. According to the James manual says the deviation from the minimum χ^2 should be 4.88 (This is the S value in the equation below).
- Try a grid search over the values of the a_i in the vicinity of the to find the points that satisfy the inequality by introducing additional constraints within for each parameter $\pm 3\sigma$, covering all of those regions in a grid, that should get them all
- Finally, calculate the fitting functions f(x : ai) for each point found within that confidence region. Keep track of the largest and smallest value of f for each value of x. (The values of x will depend on the bins in x.) Those extremum values are the limits of the error band

$$\left[\ \theta_i - \hat{\theta}_i \quad \theta_j - \hat{\theta}_j\ \right] C^{-1} \left[\begin{array}{c} \theta_i - \hat{\theta}_i \\ \theta_j - \hat{\theta}_j \end{array} \right] = S.$$