J/ψ polarization at $\sqrt{s} = 13$ TeV p-p collisions in Run2 data using ALICE detector

Deekshit Kumar
Supervisor: Dr. Partha Pratim Bhaduri

Variable Energy Cyclotron Centre(VECC), Kolkata

ALICE-STAR Collaboration Meeting, 1-4 July 2025

- Motivation of study of particle polarizations.
- How we can measure J/ψ polarizations?
- Analysis strategy & plan of J/ψ polarizations measurement.
- Results
- Summary

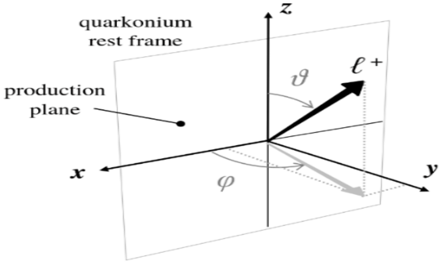
Analysis Note: https://alice-notes.web.cern.ch/node/1386

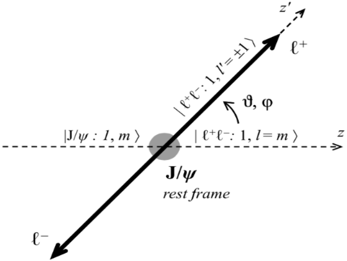
J/ψ as a useful probe in hadronic collisions

- Non-relativistic bound state of charm quark(c) and charm antiquark($\bar{c}$).
- In hadronic collisions, J/ψ production is believed to be a factorizable two step process:
  - c$\bar{c}$ pair production (calculable within pQCD)
  - c$\bar{c}$ pair hadronization (formation of physical resonance)
- Different models for color neutralization.
- Different predictions from different models on transverse spectra and angular distributions.
- No model can simulatneously explain measured J/ψ p_T spectra and polarization parameters.
- Need precise experimental measurements over a large kinematic domain, to constrain the theoretical model estimations of production cross section and polarization

What is polarization and how do we measure it in experiment?

- It is an observable which measures the alignment of particle spin with respect to a chosen quantisation axis.
- It can be measured through the angular distribution of decay products because of very small lifetime of quarkonia.





- Angular Distribution of Decay products is parameterised as:

$$W(cos\theta, \varphi) \propto \frac{1}{(3+\lambda_\theta)} \left(1 + \lambda_\theta \; cos^2\theta + \lambda_{\theta\varphi} \; sin2\theta cos\varphi + \lambda_\varphi \; sin^2\theta cos2\varphi \right)$$

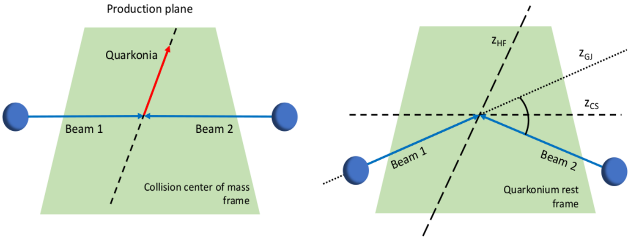
where, $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (1,0,0) \rightarrow$ Transverse polarization

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1,0,0) \rightarrow$ Longitudinal Polarization

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0,0,0) \rightarrow$ Unpolarized State

Polarization Frames

- Conventionally, three polarization frames are defined.
- Polarization frames are decided on the definition of quantization axis (say, z axis).
- Polarization parameters λ_θ , λ_φ, $\lambda_{\theta\varphi}$ are frame dependent.



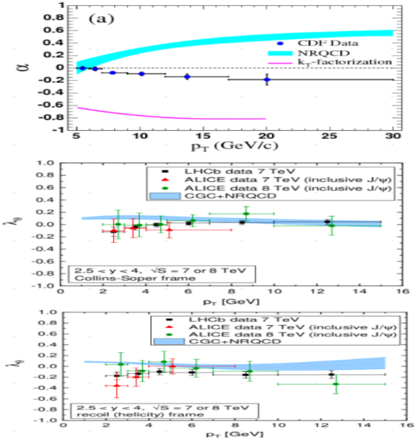
$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

[B. Sahoo, D. Sahu, S. Deb, C. R. Singh and R. Sahoo, Phys. Rev. C 109, 034910 (2024)]

- **Helicity reference frame (HE) :** In the direction of quarkonia momentum in the center of the mass frame of the colliding beams.
- **Collins-Soper reference frame (CS):** The bisector of the angle between the momentum of one beam and the opposite of the other beam.
- **GottFried-Jackson Frame (GJ):** The direction of the momentum of one of the colliding beams.

J/ψ polarization puzzle and why Quarkonium Polarization

- Experimental measurement of polarization parameters from CDF Run 2 Data → Very weak longitudinal polarization.
- LHC data show almost no J/ψ polarization in hadronic collisions.
- Theoretical predictions based on NRQCD model suggested Strong transverse polarization at high p_T [https://arxiv.org/pdf/1201.1872.pdf]
- k_T -Factorization → Strong longitudinal polarization.
- So called "J/ψ polarization puzzle"



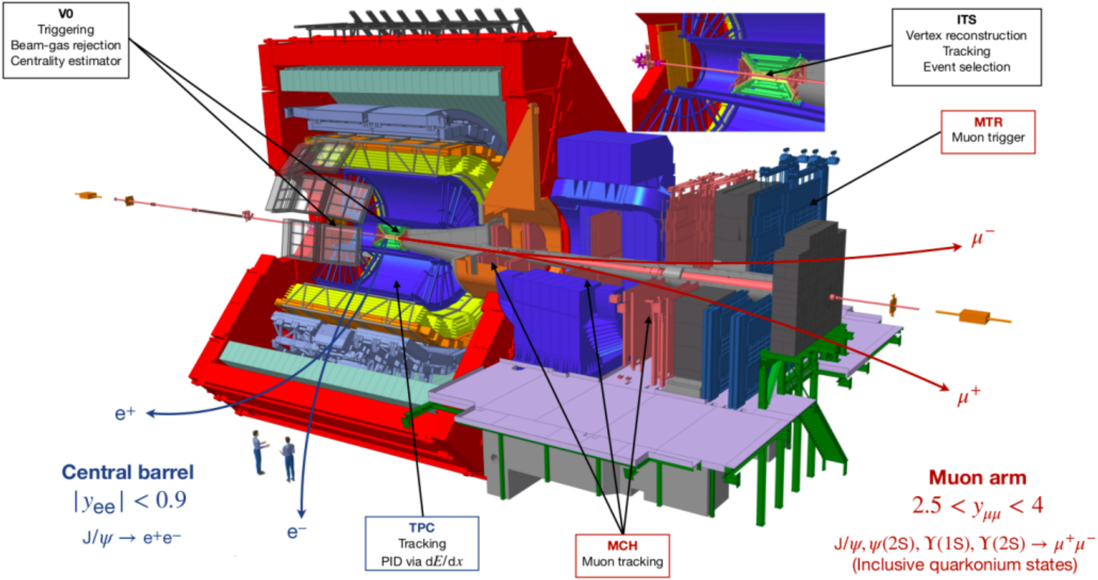
https://doi.org/10.1007/JHEP12(2018)057

- Polarization measurement are a test for different quarkonium production mechanism.
- Signature of medium anisotropy: probe of thermalisation of QGP [Maurice Coquet, et. al, Phys.Rev.Lett. 132, 232301 (2024)]

Motivations for J/ψ polarization studies in pp collisions at $\sqrt{s} = 13$ TeV

- No measurement so far in ALICE at 13 TeV energy, possibility to have first results and study energy dependence of polarization parameters.
- Largest dataset (from Run2) in pp collisions are available at $\sqrt{s}$ =13 TeV, allows one to measure J/ψ polarization with unprecedented precision and p_T up to 15 GeV/c.
- Possibility of extracting the polarization parameters down to zero p_T at 13 TeV.
- Possibility of comparing the results with the ones obtained by ALICE (Pb-Pb at $\sqrt{s} = 5.02$ TeV, pp at $\sqrt{s} = 8$ TeV) and LHCb (pp at $\sqrt{s} = 7$ TeV)
- Higher p_T reach, more stringent tests to QCD models.

ALICE Detector



Data Set And Analysis Goal

- Run2 Data sets: (Same as other quarkonia analysis in pp collision at 13 TeV)
  2016: LHC16f, g, h, i, j, k, o, p
  2017: LHC17h, i, k, l, m, o, r
  2018: LHC18b, c, d, e, f, g, h, i, j, l, m, o, p

- Files: AliAOD.Muons.root
- Muon trigger: CMUL7-B-NOPF-MUFAST
- All the good runs in these periods have the same low-p_T trigger threshold (0.5 GeV/c) .
- CMUL7 trigger event analyzed = 596.43 M

- Analysis goal: Studying J/ψ polarization both in helicity reference frame (HE) and Collins-Soper reference frame (CS) and extraction of polarization parameters.

Selection criteria:

- **Selection of muon track candidates:**
  - The track pseudo-rapidity must be in the range corresponding to the muon spectrometer acceptance,

    $$\mathbf{-4.0} < \eta < \mathbf{-2.5}$$

  - Transverse radius coordinate of the tracks at the end of the hadron absorber, must be in the range,

    $$\mathbf{17.6} < R_{abs} < \mathbf{89.5\ (cm)}$$

  - Each track reconstructed in the muon tracking system must match a track in the trigger system and additionally must pass the low- p_T trigger condition.
  - pDCA cut applied for each track.
- **Selection of di-muon track candidates:**
  - Opposite sign muon pair **(charge1 + charge2 = 0)**.
  - Each unlike-sign di-muon pair is required to be in the absolute rapidity range, $\mathbf{2.5} < |y| < \mathbf{4}$

Signal extraction:

- 2 signal functions: double CB (crystal ball) and NA60 for J/ψ and $\psi'(2S)$.
- VWG (variable width gaussian) and DE(double exponential), for background.

- **Details of fit procedure:**

  Fixed parameters:
  - Tail parameters(n_L ,α_L ,n_R and α_R) of J/ψ and $\psi'(2S)$ are same and fixed from MC data .
  - Mean(mass) and Sigma(width) of $\psi'(2S)$ signal are fixed by,
    $M_{\psi(2S)} = M_{J/\psi} + (M_{\psi(2S)}(\text{PDG}) - M_{J/\psi}(\text{PDG}))$
    $\sigma_{\psi(2S)} = \sigma_{J/\psi} \times (\frac{\sigma^{MC}_{\psi(2S)}}{\sigma^{MC}_{J/\psi}})$

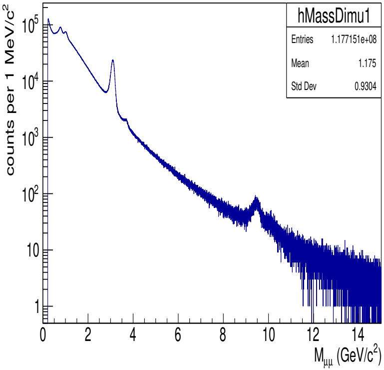
  Free parameters:
  - Mean and Sigma of J/ψ signal are free.
  - Normalization constants are free for both J/ψ and $\psi(2S)$.
  - Parameters of background function are also free.

Analysis procedure

- First we calculate the J/ψ raw yield ($N^{Raw}_{J/\psi}$) by fitting di-muon invariant mass spectra in inclusive, p_T and angular bins with different signal and background combinations:
  Case I: DCB + VWG (2.0 – 5.0 GeV/c^2)
  Case II: DCB + DoubExpo (2.0 – 5.0 GeV/c^2)
  Case III: NA60 + VWG (2.0 – 5.0 GeV/c^2)
  Case IV: NA60 + DoubExpo (2.0 – 5.0 GeV/c^2)
- MC analysis performed to calculate A x $\epsilon = \frac{N^{Rec}_{J/\psi}}{N^{Gen}_{J/\psi}}$
- Corrected yield calculated by $N^{Corr}_{J/\psi} = \frac{N^{Raw}_{J/\psi}}{Ax\epsilon}$
- For systamatic uncertaintiy calculation change the fitting range:
  Case V: DCB + VWG (1.8 -4.8 GeV/c^2)
  Case VI: DCB + DoubExpo (1.8 -4.8 GeV/c^2)
  Case VII: NA60 + VWG (1.8 -4.8 GeV/c^2)
  Case VIII: NA60 + DoubExpo (1.8 -4.8 GeV/c^2)

Fitting function:

- **Signal:** CB2
- **Background:** VWG
- **Fitting Range:** [2.0, 5.0]



- **Bin width of invariant mass =** 1 MeV/c^2

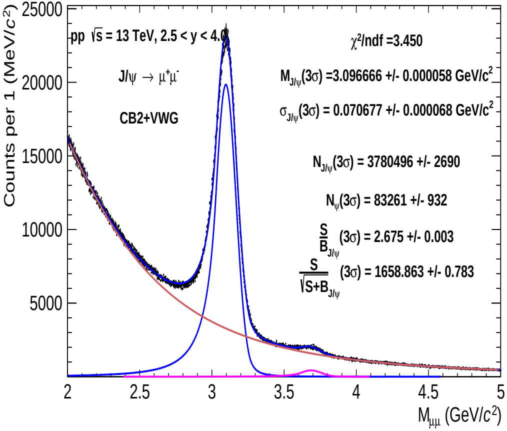


Figure: DCB+VWG

Signal extraction from inclusive invariant mass spectra:

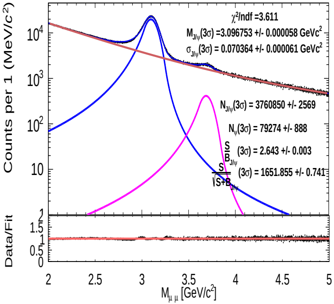


Figure: DCB+DE

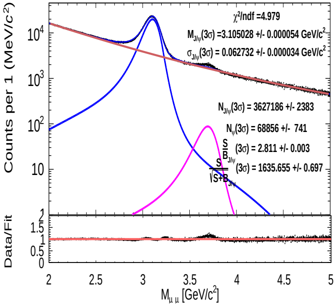


Figure: NA60+VWG

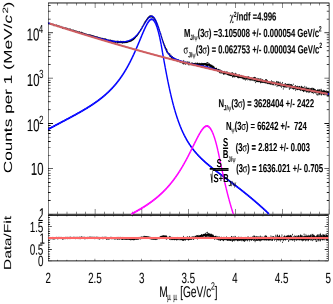


Figure: NA60+DE

	Function	$N_{J/\psi}$	$N_{\psi(2S)}$
Case I	DCB+VWG	3780496 ± 2690	83261 ± 932
Case II	DCB+DE	3760850 ± 2569	79274 ± 888
Case III	NA60+VWG	3627186 ± 2383	68856 ± 741
Case IV	NA60+DE	3628404 ± 2397	66242 ± 724

Signal extraction in differential p_T bin:

p_T bin (GeV/c)	$(N_{J/\psi})$ case I DCB+VWG	$(N_{J/\psi})$ case II DCB+DE	$(N_{J/\psi})$ case III NA60+VWG	$(N_{J/\psi})$ case IV NA60+DE
0 - 2	1423770 ± 1699	1411290 ± 1616	1365200 ± 1683	1360810 ± 1525
2 - 4	1351870 ± 1504	1347210 ± 1506	1295780 ± 1456	1291770 ± 1418
4 - 6	596248 ± 951	596644 ± 914	570353 ± 884	573284 ± 989
6 - 8	231805 ± 501	232034 ± 506	220080 ± 598	222079 ± 524
8 - 10	90255 ± 378	90252 ± 377	85372 ± 371	85982 ± 329
10 - 15	58481 ± 287	56115 ± 267	54538 ± 302	55053 ± 262

Differential analysis in p_T bins: Raw Yield

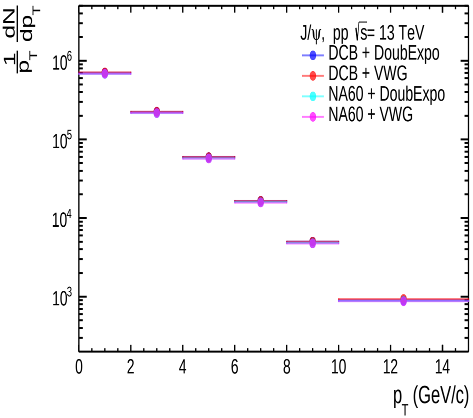


Figure: Uncorrected p_T spectra:

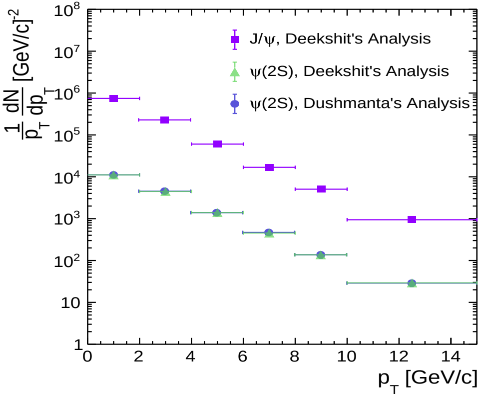


Figure: Comparision spectra:

- Consistent results for different combinations of signal and background fitting functions.

$$A \times \epsilon = \frac{N^{Rec}_{J/\psi}}{N^{Gen}_{J/\psi}}$$

$$N^{Corr}_{J/\psi} = \frac{N^{Raw}_{J/\psi}}{A x \epsilon}$$

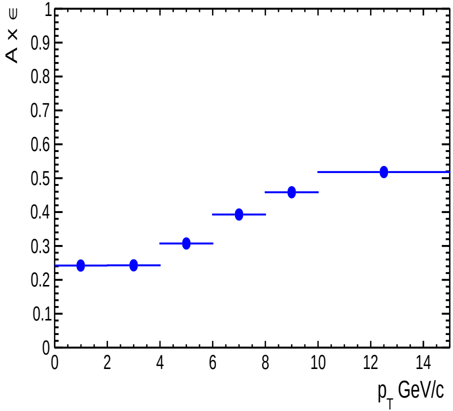


Figure: A x ϵ correction

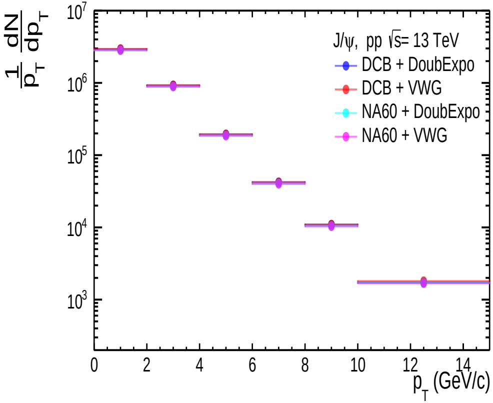
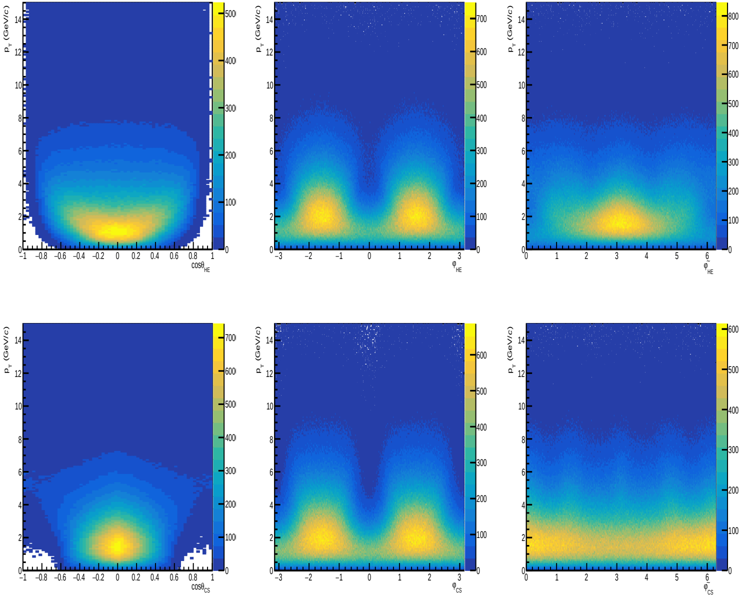


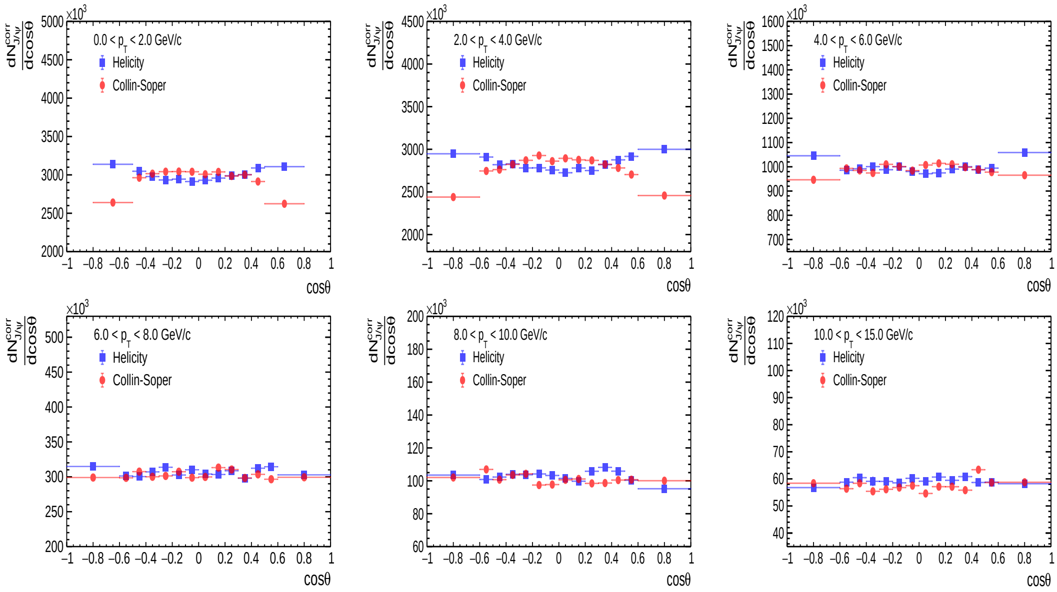
Figure: Corrected p_T Spectra

Acceptance-efficiency map:

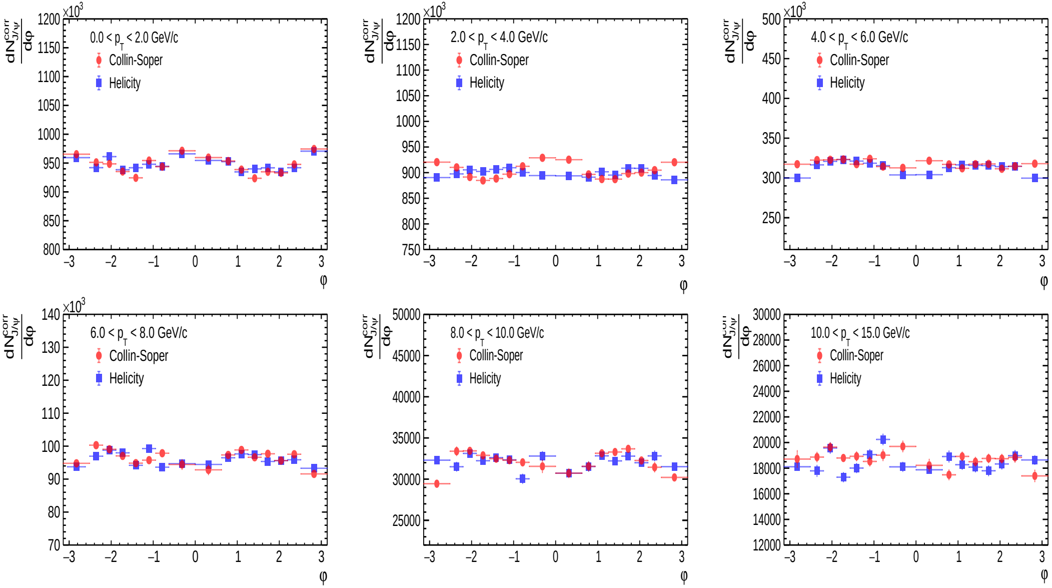
- In particular, for $p_T < 2$ GeV/c, its value is close to zero in the range $0.6 < |cos\theta| < 1$ (in both CS and HE frame).
- Acceptance - efficiency is dependent of the polar and azimuthal angle distributions



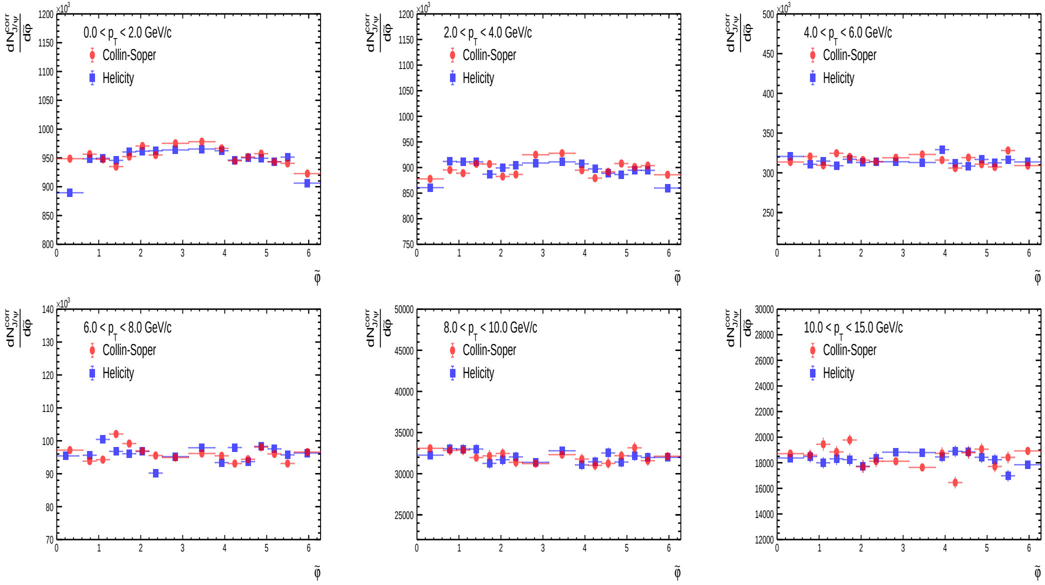
Corrected J/ψ as a function of cosθ: Case I (DCB+VWG)



Corrected J/ψ as a function of φ: Case I (DCB+VWG)



Corrected J/ψ as a function of $\tilde{\varphi}$: Case I (DCB+VWG)



Polarization parameter extraction

Polarization can be measured through the study of the angular distribution of the leptons produced in the dimuon channel;

$$W(\cos\vartheta, \varphi|\vec{\lambda}) \propto \frac{1}{3+\lambda_\vartheta}(1+\lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi)$$

for $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) = (0,0,0)$, no polarization

for $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) = (-1,0,0)$, pure longitudinal polarization

for $(\lambda_\vartheta, \lambda_\varphi, \lambda_{\vartheta\varphi}) = (+1,0,0)$, pure transverse polarization

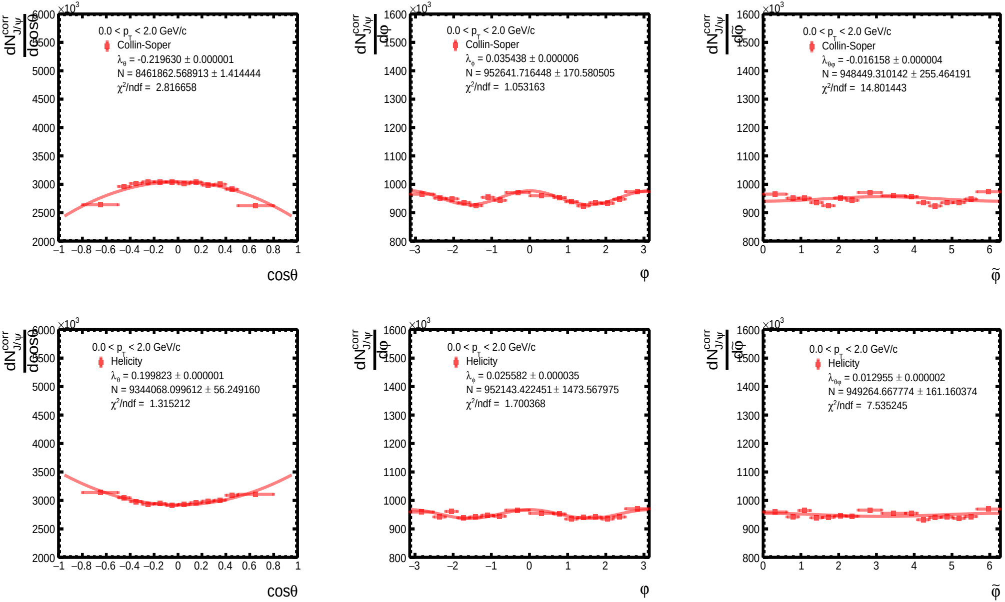
One can also fit the distribution integrated over $cos\theta$ and ϕ taking a 1D fitting approach:

$$W(\cos\vartheta|\lambda_\vartheta) \propto \frac{1}{3+\lambda_\vartheta}(1+\lambda_\vartheta \cos^2\vartheta)$$

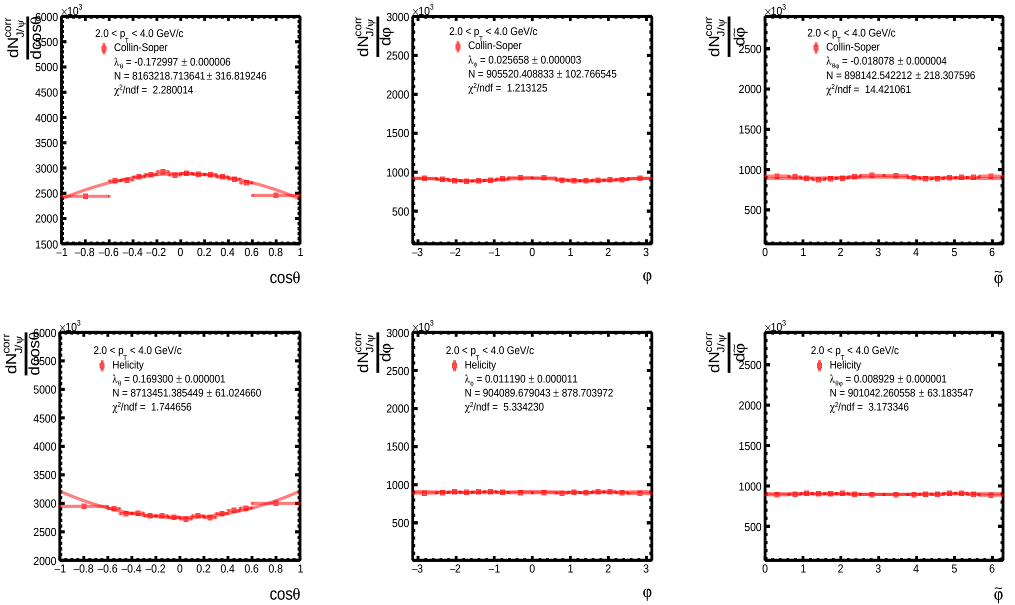
$$W(\varphi|\lambda_\vartheta, \lambda_\varphi) \propto 1 + \frac{2\lambda_\varphi}{3+\lambda_\vartheta}\cos 2\varphi$$

$$W(\tilde{\varphi}|\lambda_\vartheta, \lambda_{\vartheta\varphi}) \propto 1 + \frac{\sqrt{2}\lambda_{\vartheta\varphi}}{3+\lambda_\vartheta}\cos\tilde{\varphi}$$

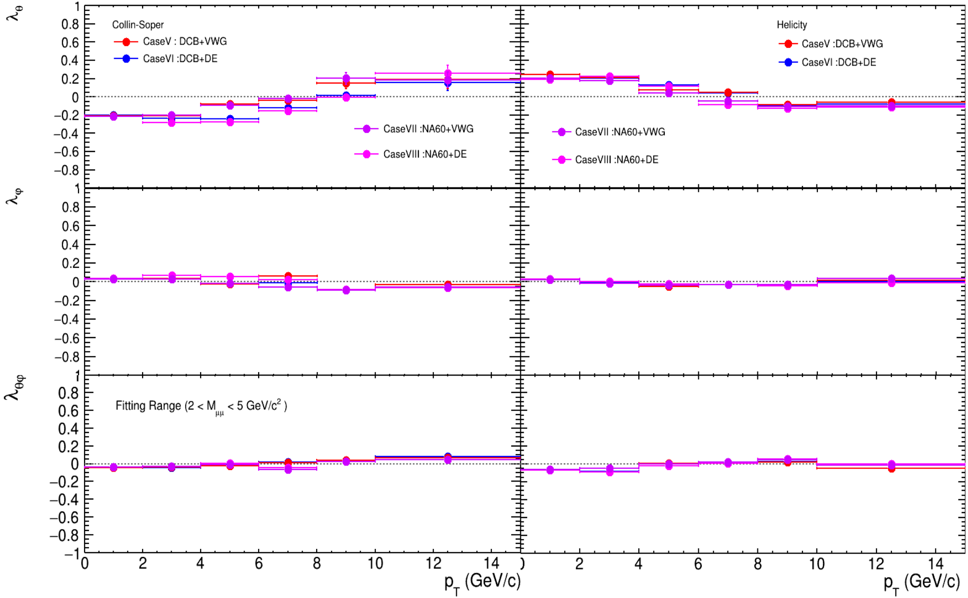
Fit the angular distribution($0 < p_T < 2$ GeV/c): Case I



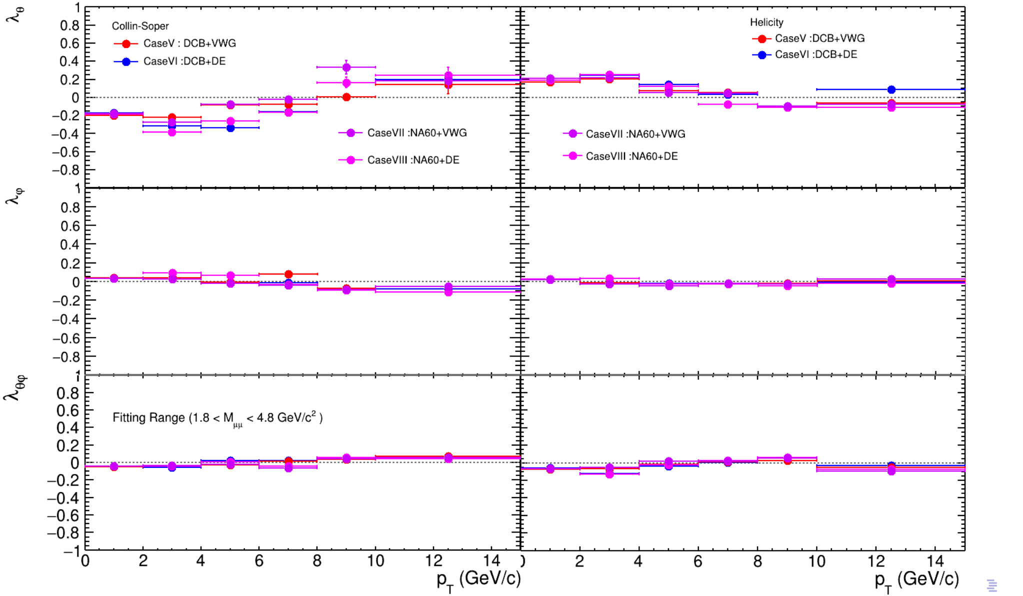
Fit the angular distribution($2<p_T<4$ GeV/c): Case I



Polarization Parameters: Signal + Background Fit (2.0–5.0 GeV/c^2) - Systematic Evaluation



Polarization Parameters: Signal + Background Fit (1.8-4.8 GeV/c^2) - Systematic Evaluation



Trigger Response function systematic

- A source of systematic uncertainty is related to the evaluation of the trigger efficiency and can be estimated via the calculation of the trigger response function.

- It is computed as the ratio between the number of muons passing the low-p_T threshold ($p_T > 1$ GeV/c) divided by the number of muons passing the all-p_T threshold ($p_T > 0.5$ GeV/c).

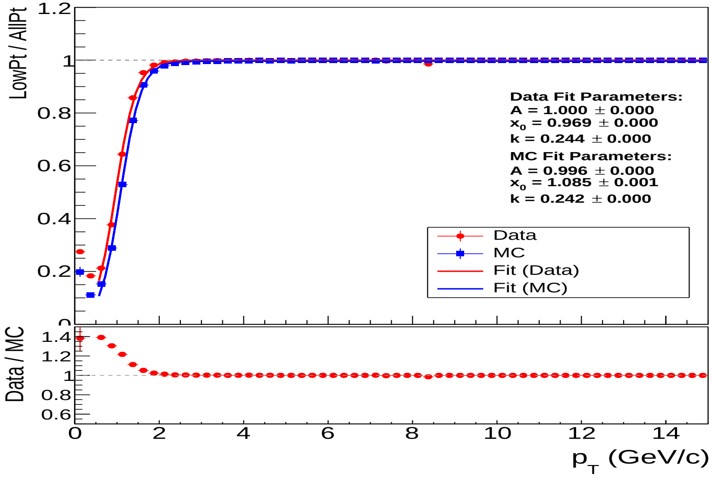
- The resulting shape as a function of single muon p_T is parametrized with a smeared step function

$$f(p_T) = \frac{N}{(1 + e^{-b(p_T - x_0)})} \tag{1}$$

where b is related to the curvature of the function, while x_0 to the inflection point.

- In the comparison among the trigger response functions evaluated in the data and in the Monte Carlo, a small shift is observed for $p_T < 2$ GeV/c and this can have an effect on the polarization parameter estimation.

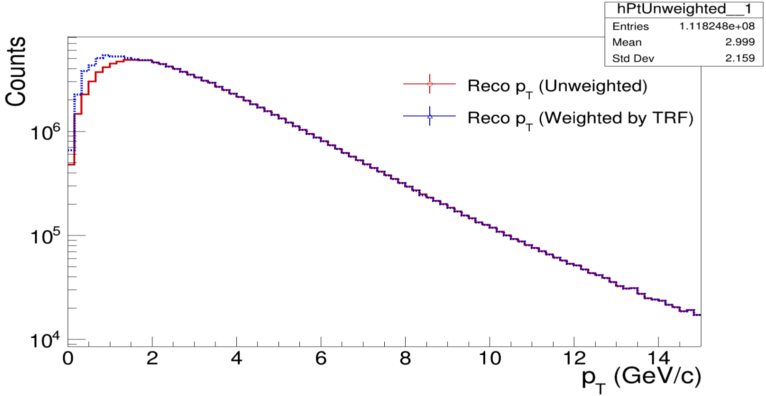
Trigger Responce function (RF) $= \frac{low-p_T}{all-p_T}$



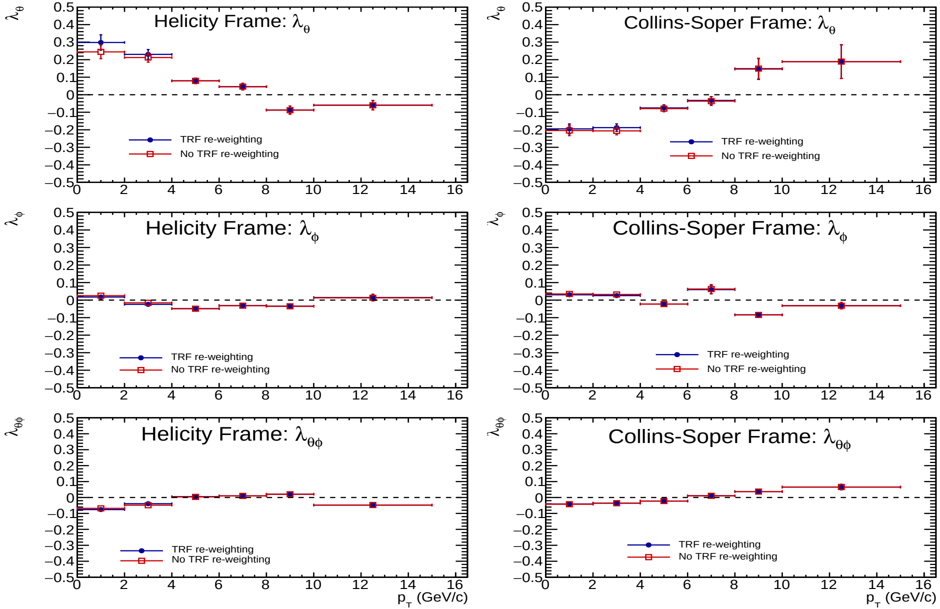
- Every single muon in the Monte Carlo is weighted in the following way:

$$w(p_T) = \frac{\epsilon_{Data}^{Low/All}}{\epsilon_{MC}^{Low/All}}(p_T) \tag{2}$$

where ϵ indicates the trigger efficiency obtained for a certain muon p_T.



Polarization Results from TRF Systematic



Systematic Uncertainty via Iterative Method

Motivation

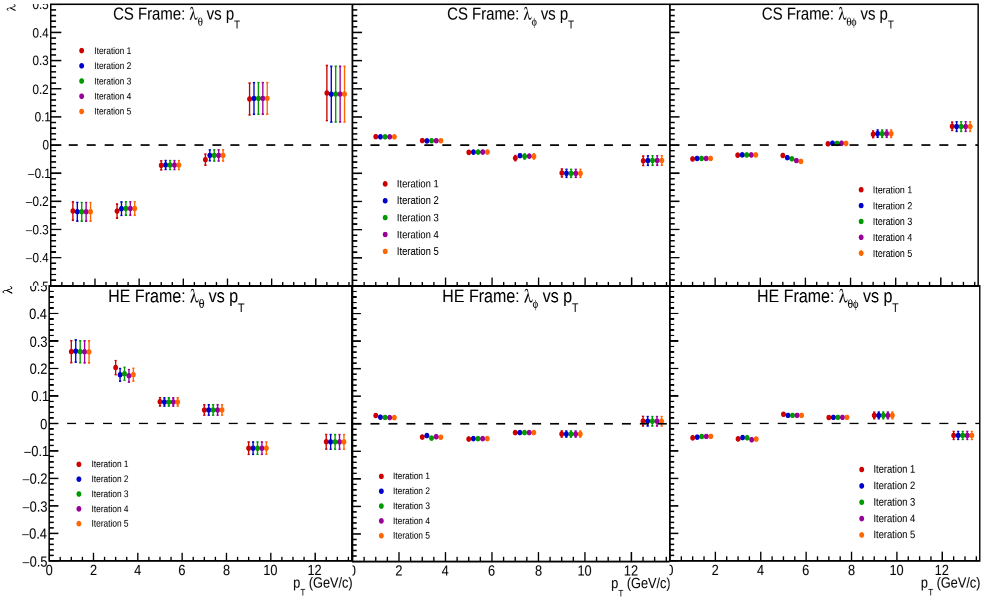
- In data analysis, the observed angular distributions of decay muons are significantly affected by the detector's non-uniform acceptance and efficiency.
- To recover the true angular distributions and extract unbiased polarization parameters (λ_θ, λ_ϕ, $\lambda_{\theta\phi}$), these detector effects must be corrected using Monte Carlo (MC) simulations through the acceptance $\times$ efficiency (A$\times\epsilon$) approach.
- Applying acceptance $\times$ efficiency (A$\times\epsilon$) corrections based on an unpolarized MC sample (λ_θ, λ_ϕ, $\lambda_{\theta\phi} = 0$) can introduce systematic biases in the extracted polarization parameters.

Why the Iterative Method Is Needed ?

- Accounts for polarization-dependent acceptance effects.
- Enables unbiased extraction of angular parameters.
- Crucial for accurate determination of λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$.

1. **Start with Unpolarized MC**
   Simulate $J/\psi \to \mu^+\mu^-$ with no polarization.
   Calculate acceptance × efficiency $(A \times \varepsilon)$ in $(\cos\theta, \phi)$ bins.
2. **Fit Experimental Data**
   Fit observed angular distribution:
   $$\frac{d^2N}{d\cos\theta\, d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$
3. **Reweight MC with Fitted Parameters**
   Apply weights to MC:
   $$w(\cos\theta, \phi) = 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$
4. **Recalculate Efficiency** $(A \times \varepsilon)$
   Use reweighted MC to compute updated efficiency.
5. **Repeat Fit and Iterate**
   Use new efficiency to re-fit data.
   Repeat steps until λ values converge.

Iterative Method:Results



Systematic uncertainties calculation:

- The central value ($\bar{\lambda}_i$) of the polarization parameters and the corresponding statistical uncertainty (σ_i^{stat}) for each polarization parameter are defined as:

$$\bar{\lambda}_i = \frac{\Sigma_j \lambda_i^j}{N} \ \& \ \sigma_{\bar{\lambda}_i}^{stat} = \frac{\Sigma_j \sigma_i^j}{N}$$

- The resulting systematic uncertainty is computed by adding in quadrature the N different tests with respect to the central value:

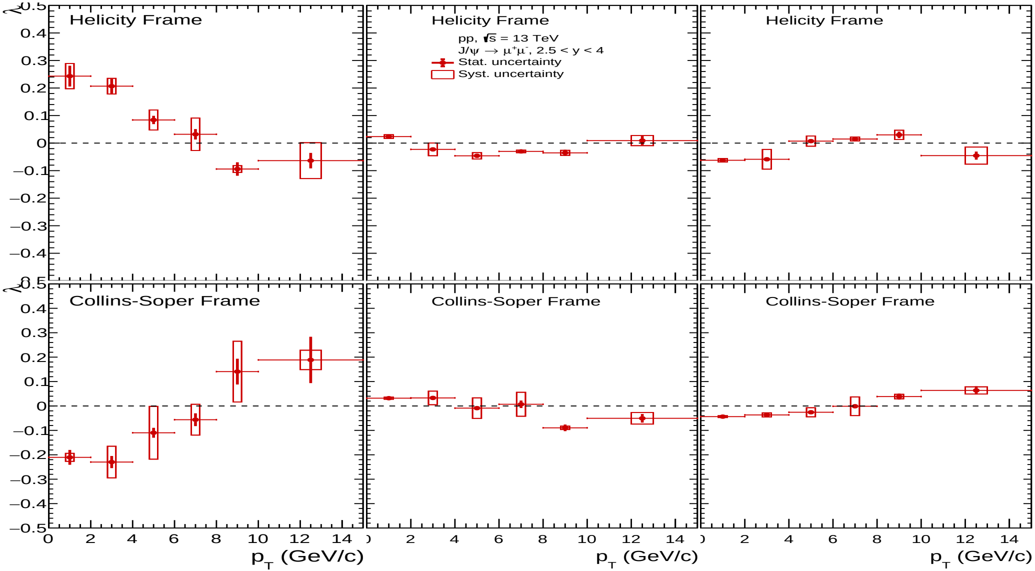
$$\sigma_{\bar{\lambda}_i}^{syst} = \sqrt{\frac{\Sigma_j [\lambda_i^j - \bar{\lambda}_i]^2}{N-1}}$$

where i = 0, 1 and 2 corresponds to the cosθ, ϕ and $\tilde{\phi}$ respectively. While j = 1, 2, ..., N refers to the j^{th} signal extraction test.

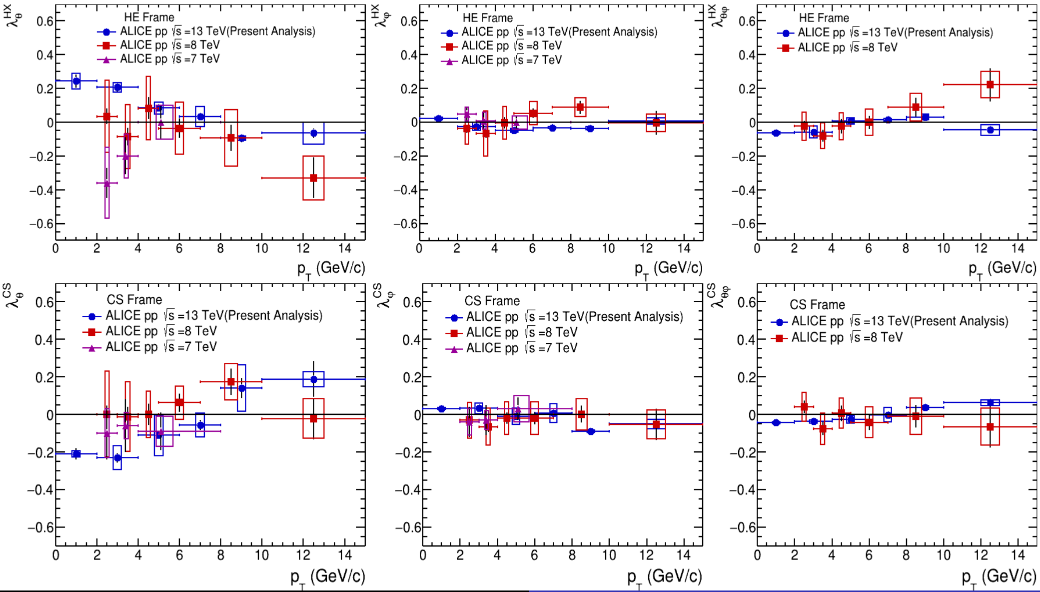
- The final total systematic uncertainty is obtained by adding all individual sources in quadrature:

$$\sigma_{\bar{\lambda}_i}^{\text{syst, total}} = \sqrt{\left(\sigma_{\bar{\lambda}_i,\text{trig}}^{\text{syst}}\right)^2 + \left(\sigma_{\bar{\lambda}_i,\text{iter}}^{\text{syst}}\right)^2 + \left(\sigma_{\bar{\lambda}_i,\text{sig+bg}}^{\text{syst}}\right)^2}$$

Polarization :Results



Comparison plot



Summary of Polarization Analysis

- Raw yields have been extracted in differential p_{T} and angular bins.
- Monte Carlo (MC) analysis has been performed to correct the raw J/ψ yields for acceptance and efficiency in each p_{T} and angular bin.
- A one-dimensional (1D) fit of angular distributions is carried out to extract polarization parameters: λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$.
- **Systematic due to signal and background extraction**: Estimated by varying signal and background functions, mass fit ranges.
- **Systematic due to the trigger response function:** Study of Low-p_T and All-p_T triggers efficiency as a function of muon and dimuon p_T to correct for trigger bias.
- **Systematic from the iterative method:** Used to refine polarization parameters (λ_θ, λ_ϕ, $\lambda_{\theta\phi}$) by reweighting MC and recalculating A$\times\epsilon$.

To do:

- Update the analysis note.
- Submit the paper proposal.

Thank you