Υ(nS) polarization measurements in pp collisions at $\sqrt{s}$ = 13.6 TeV with ALICE

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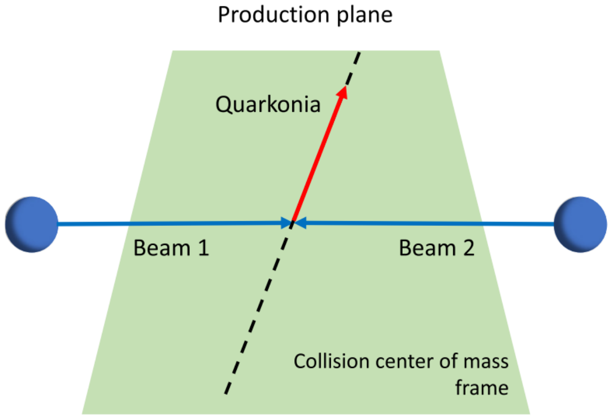
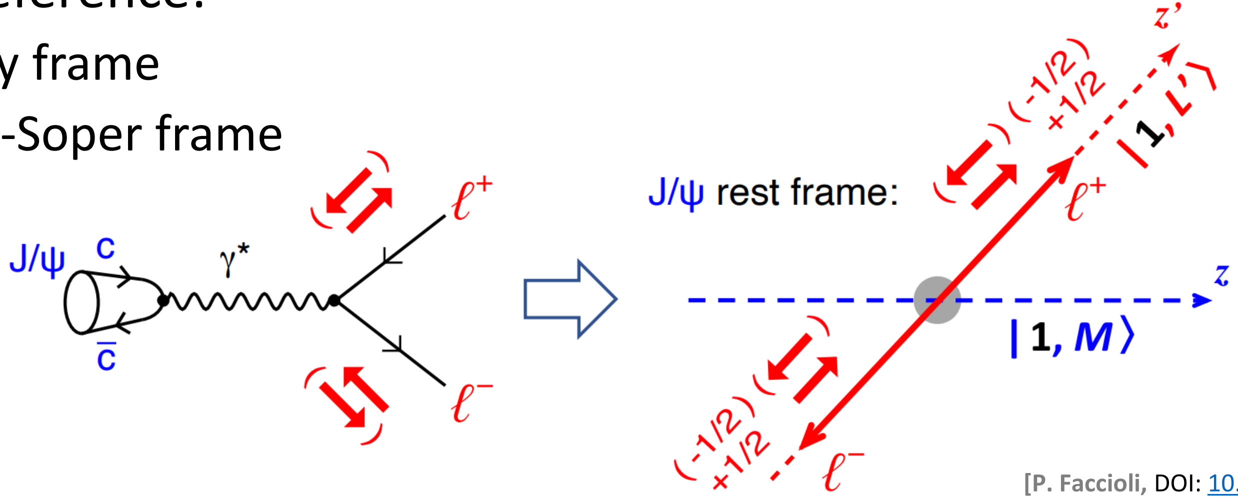
Outline

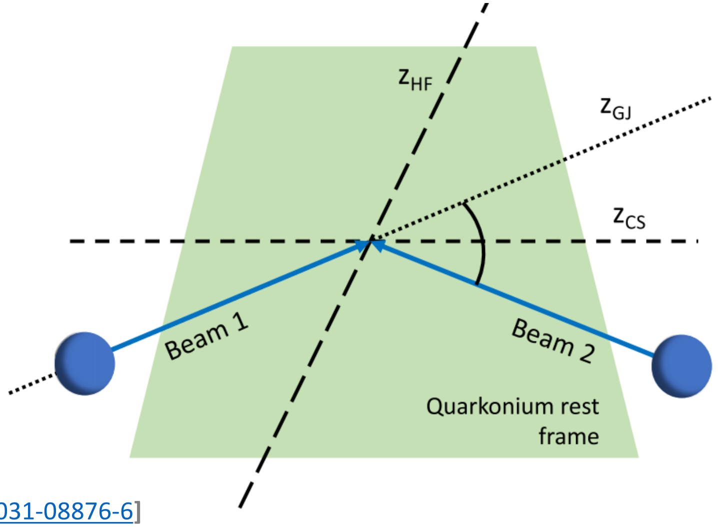
- Quarkonium polarization
- Physics motivation
- Analysis
- Summary

Introduction

- Polarization can be defined as the alignment of particle spin to a given quantization axis
- Polarization measurements can help to understand the particle production mechanisms
- It can be measured by analyzing the angular distribution of the decay products
- Frames of reference:
    1. Helicity frame
    2. Collins-Soper frame







[P. Faccioli, DOI: 10.1007/978-3-031-08876-6]

[Phys. Rev. C. 109, 034910 (2024)]

Introduction

- The angular distribution can be parametrized as:

$$\frac{d^2N}{dcos\theta\ d\phi} = \frac{3}{4\pi(3+\lambda_\theta)}(1+\lambda_\theta\ cos^2\theta + \lambda_\phi\ sin^2\theta\ cos2\phi + \lambda_{\theta\phi}\ sin2\theta\ cos\phi)$$

- As an alternative to a multi-parameter fit to the above relation, the one-dimensional angular distributions are used:

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

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

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

where

$$\tilde{\varphi} = \begin{cases} \varphi - \frac{3}{4}\pi & \text{for } \cos\vartheta < 0, \\ \varphi - \frac{\pi}{4} & \text{for } \cos\vartheta > 0 \end{cases}$$

With the polarization parameters,

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (1,0,0)$ ⟶ Transverse polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1,0,0)$ ⟶ Longitudinal polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0,0,0)$ ⟶ Unpolarized state

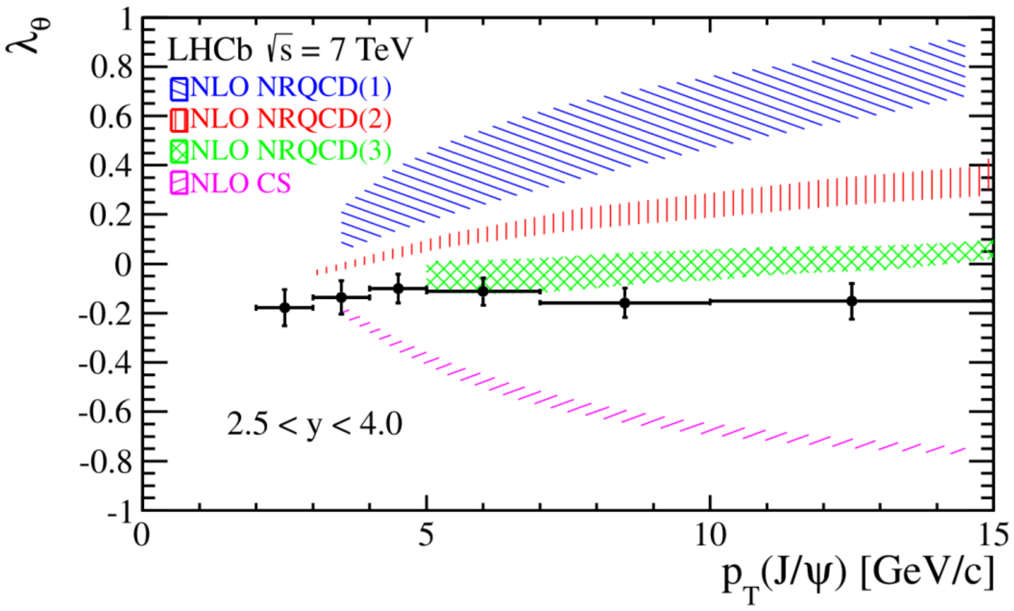
Frame Invariant variable:

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

[Eur. Phys. J. C. 69, 657 (2010)]

Introduction

- The production mechanism of heavy Quarkonium (like J/ψ) helps to study the QCD dynamics in vacuum and in medium
- Theoretical models like non-relativistic QCD (NRQCD) are developed in an attempt to explain their production
- Calculations based on color-octet model show good agreement with experimental data on production cross sections for charmonium states

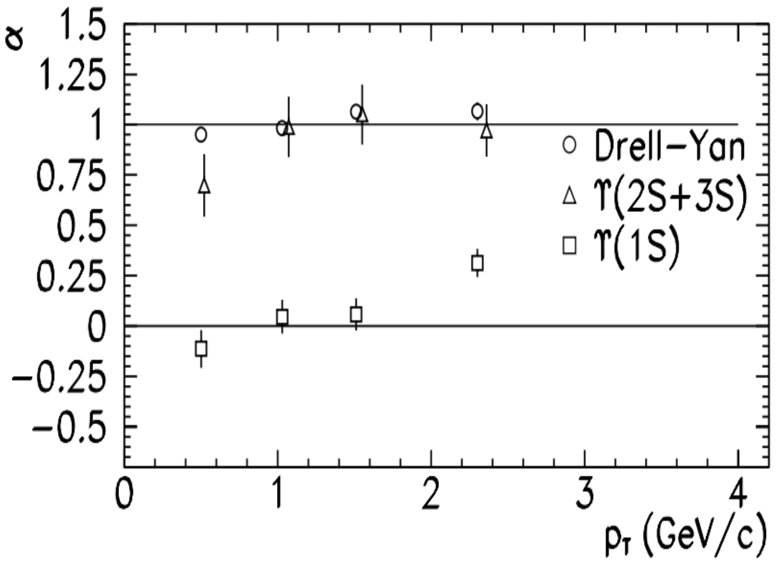


[Eur. Phys. J. C. 73, 2631 (2013)]

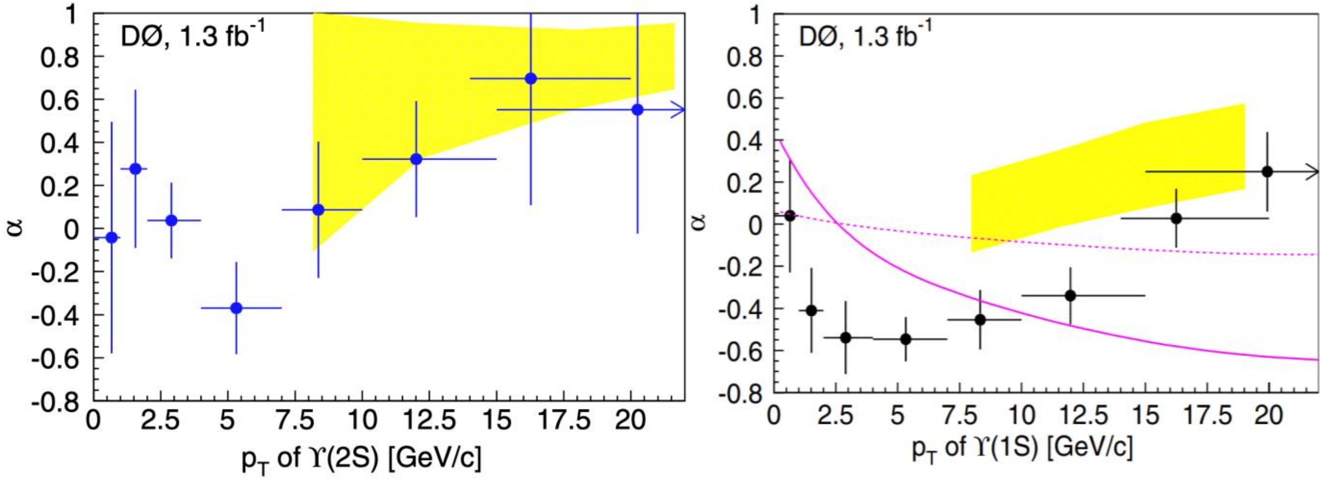
- However, it fails to describe the spin-alignment
- NRQCD calculations based on color-octet components predict transverse polarization for J/ψ, while next-to-leading order color-singlet calculations predicts a longitudinal polarization
- Experimental results are also far from a single conclusive idea

Upsilon Polarization

- Being massive the $b\bar{b}$ system should satisfy the non-relativistic approach much better than the charmonium states
- However, there are wide ranges of experimental results
- $\Upsilon(1S)$ polarization data from Tevatron shows either no polarization (CDF) or longitudinal polarization (DØ)
- At low energy and p_T (E866 Expt.), $\Upsilon(2S)$ and $\Upsilon(3S)$ states have maximal transverse polarization
- However, $\Upsilon(1S)$ is found to be weakly polarized



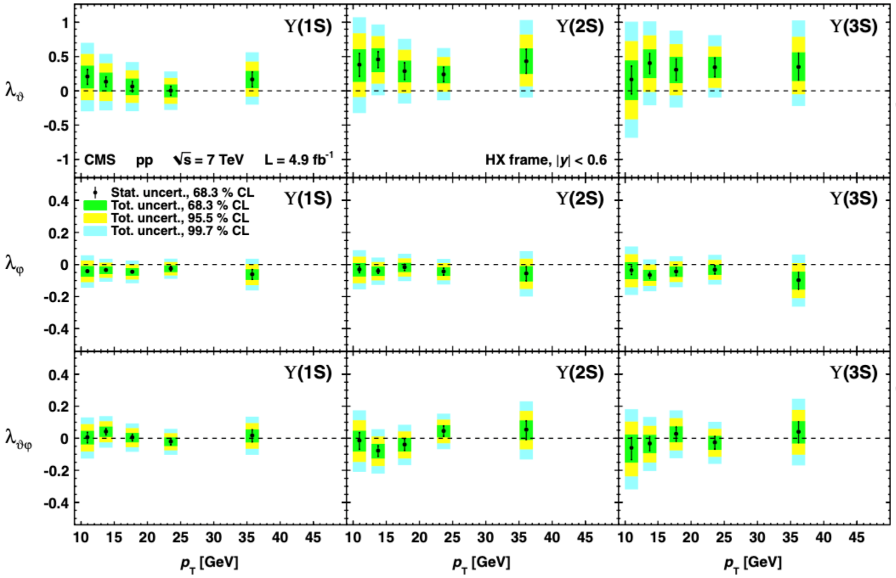
[Phys. Rev. Lett. 86, 2529 (2001)]



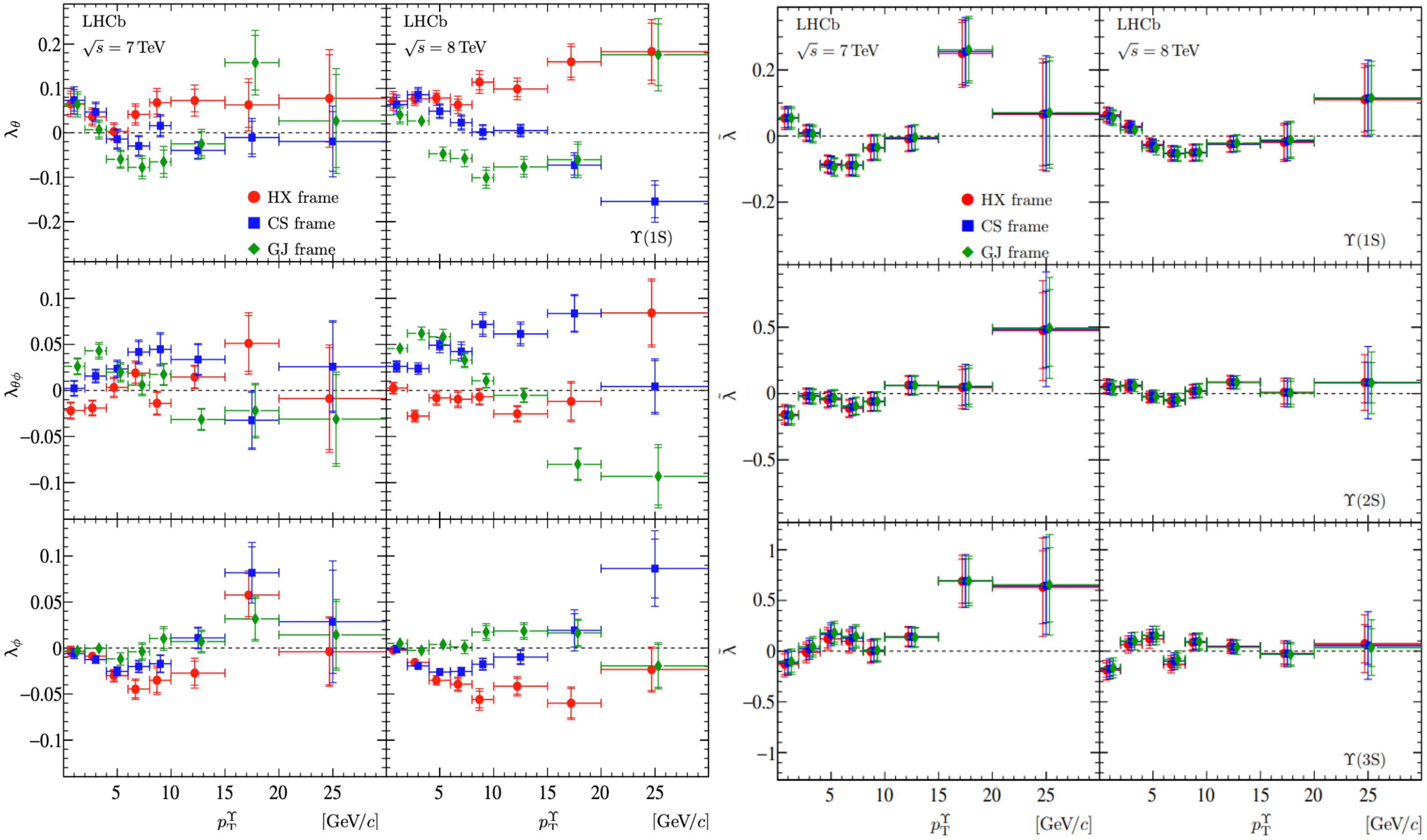
[Phys. Rev. Lett. 101, 182004 (2008)]

Upsilon Polarization

- The polarization of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ measured in LHCb and CMS experiments observed no significant polarization



[PRL 110, 081802 (2013)]

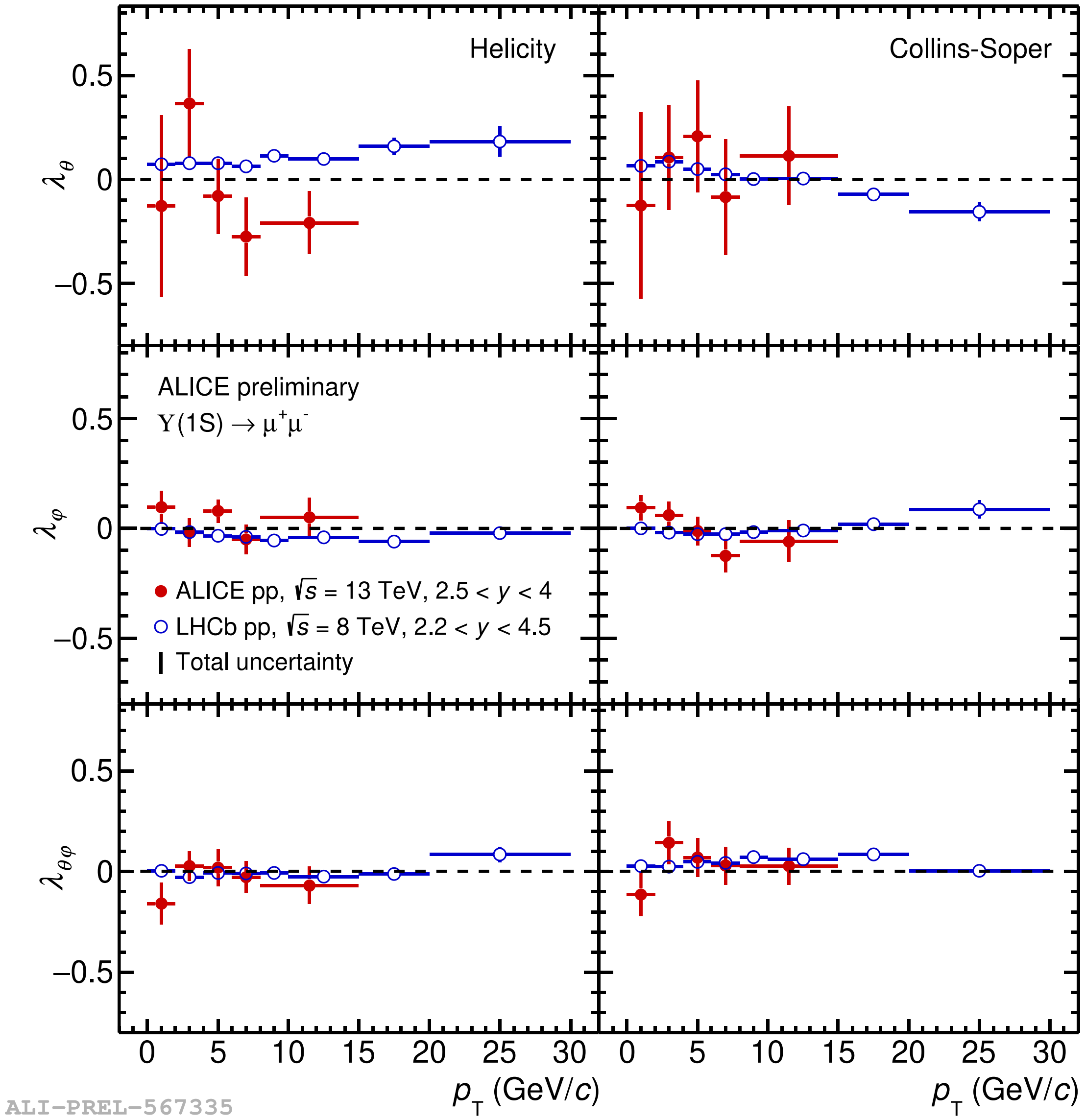


[JHEP 12, 110 (2017)]

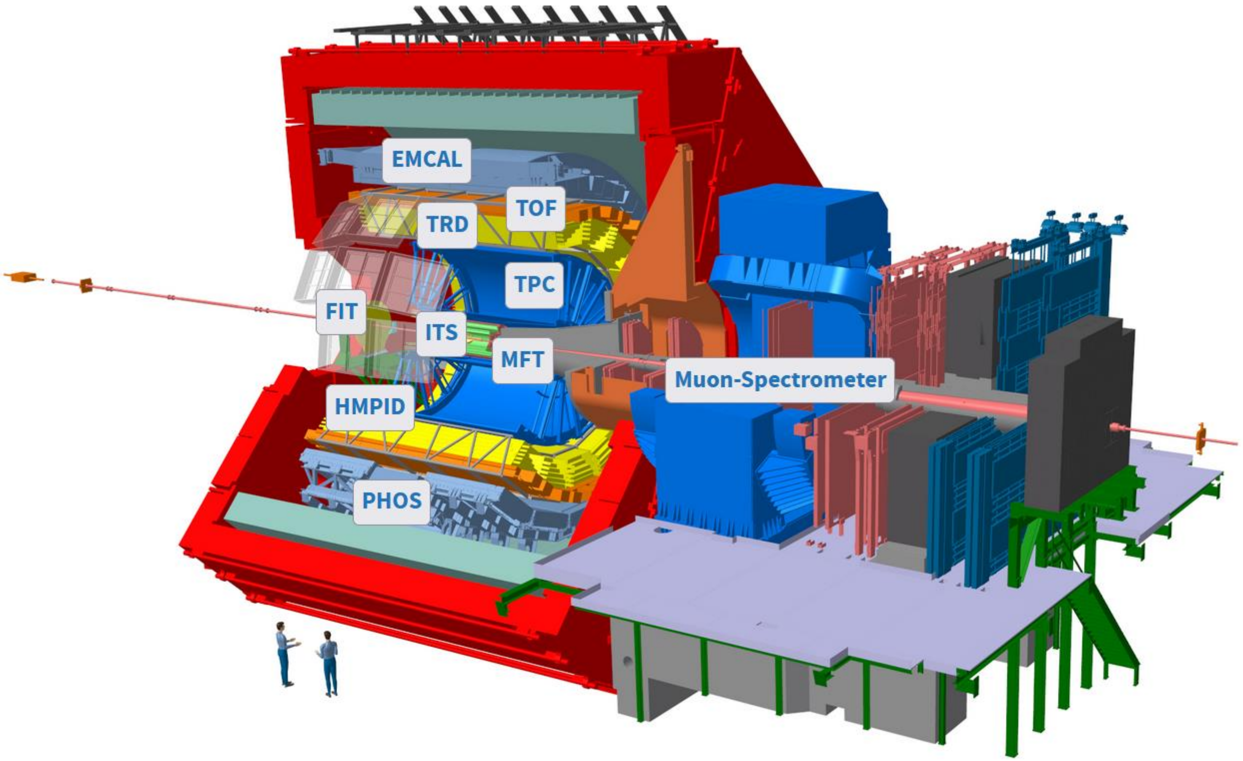
Upsilon Polarization

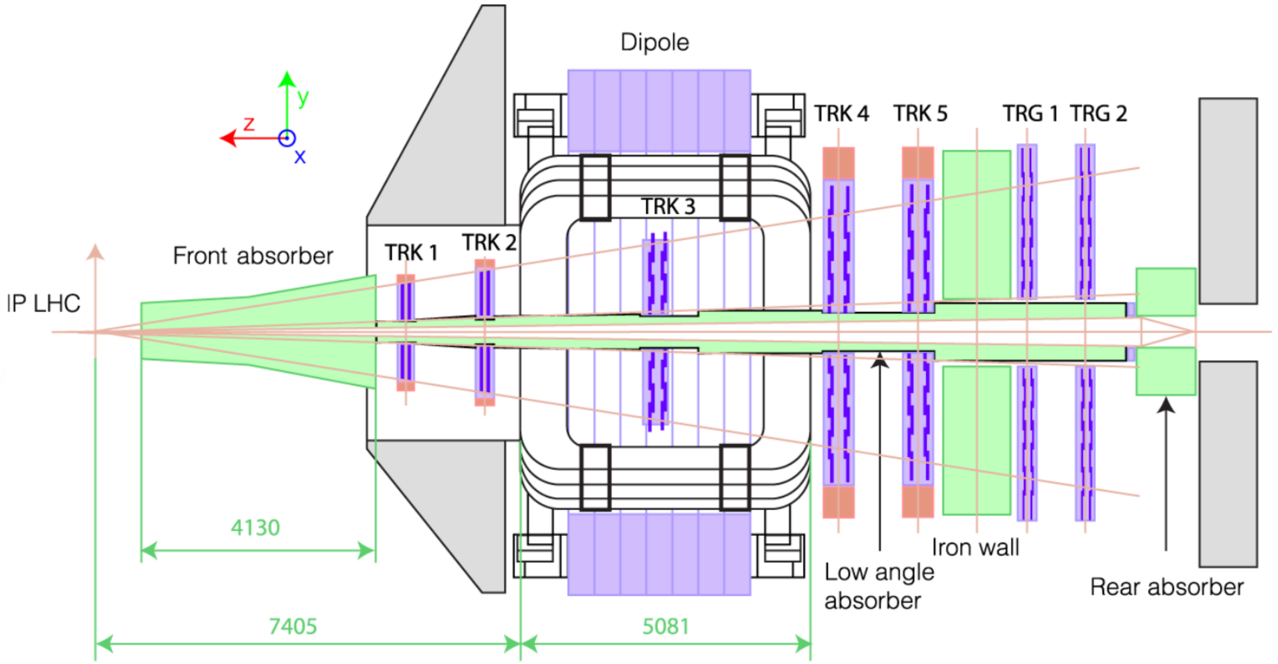
Motivation:

- The polarization analysis for all the three states of Υ(nS) will be first in ALICE for available statistics in Run3 data
- This can testify the NRQCD prediction if feed-down effect can dilute the polarization of lower states
- A comparison with the existing LHCb results



Detector-Muon Spectrometer





- To study the quarkonium decaying to dimuons
- Acceptance $-4.0 < \eta < -2.5$

[ALICE Muon Spectrometer]

Analysis

Plan of action:

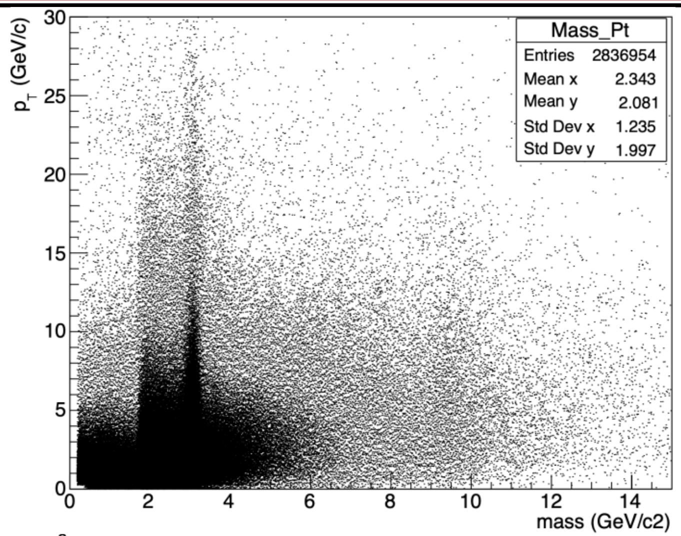
- Selection of the muon track candidates by using the task table-maker
- Then further selection on muon pairs by using table-reader task to build dimuon observables
- Extract the opposite sign dimuon ($\mu^+\mu^-$) invariant mass spectra
- Perform the same in different p_T bins
- Extract the cosθ and ϕ distributions in the selected p_T bins
- Perform the fitting of angular distribution to obtain polarization parameters
- Study these polarization parameter as a function of p_T

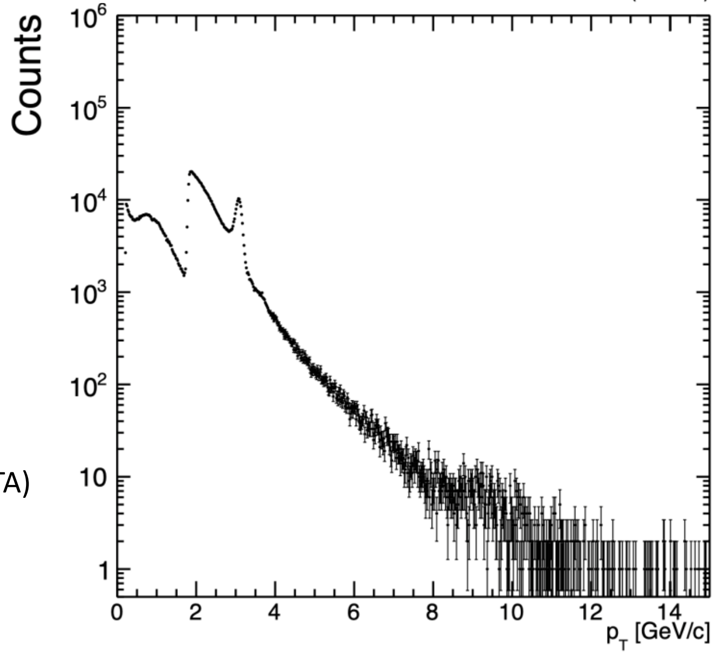
Analysis

- Dataset: LHC23_pass4_skimmed_QC1 (Data)
- Event Selection: $|Vtx_z|$ < 10 cm (eventStandardNoINT7)
- Muon track selection criteria:

  muonQualityCuts

  - Track within the muon spectrometer acceptance, rapidity cuts: $-4.0 < y <$ -2.5
  - Dimuon pairs within the pseudo-rapidity -4.0 $< \eta_{\mu\mu} <$ -2.5
  - Total charge of the pair = 0
  - To reduce the contamination by tracks crossing the thicker part of the absorber, cuts on the radial transverse position of muon tracks: 17.6 < R_{abs} < 89.5 cm





LHC23_pass4_skimmed_QC1 (DATA)
Entries: 1.18182e+06
Hyperloop link

Fitting Function

To fit the signal:

- The standard signal function is a double Crystal Ball (CB2) defined as

$$f(x;\mu,\sigma,\alpha_L,n_L,\alpha_R,n_R,N) = N \times \begin{cases} \exp(-0.5v^2), & \text{if } v > -\alpha_L \;\&\; v < \alpha_R \\ A \times (B-v)^{-n_L}, & \text{if } v \le -\alpha_L \\ C \times (D+v)^{-n_R}, & \text{if } v \ge \alpha_R \end{cases}$$

where,

$$v = (x-\mu)/\sigma$$

$$A = \left(\frac{n_L}{|\alpha_L|}\right)^{n_L} \times \exp(-0.5\alpha_L^2)$$

$$B = \frac{n_L}{|\alpha_L|} - |\alpha_L|$$

$$C = \left(\frac{n_R}{|\alpha_R|}\right)^{n_R} \times \exp(-0.5\alpha_R^2)$$

$$D = \frac{n_R}{|\alpha_R|} - |\alpha_R|$$

To fit the Background:

- The background is fitted with a variable width Gaussian function

$$f_{\text{bkg}}(x;N_B,\alpha,\beta,\gamma) = N_B \exp\left[-\frac{1}{2}\left(\frac{x-\alpha}{\sigma}\right)^2\right] \quad \text{with} \quad \sigma = \beta + \gamma\frac{x-\alpha}{\alpha}$$

Fitting Function

- Signal fitting function: Double Crystal function
- Background: Variable Width Gaussian function

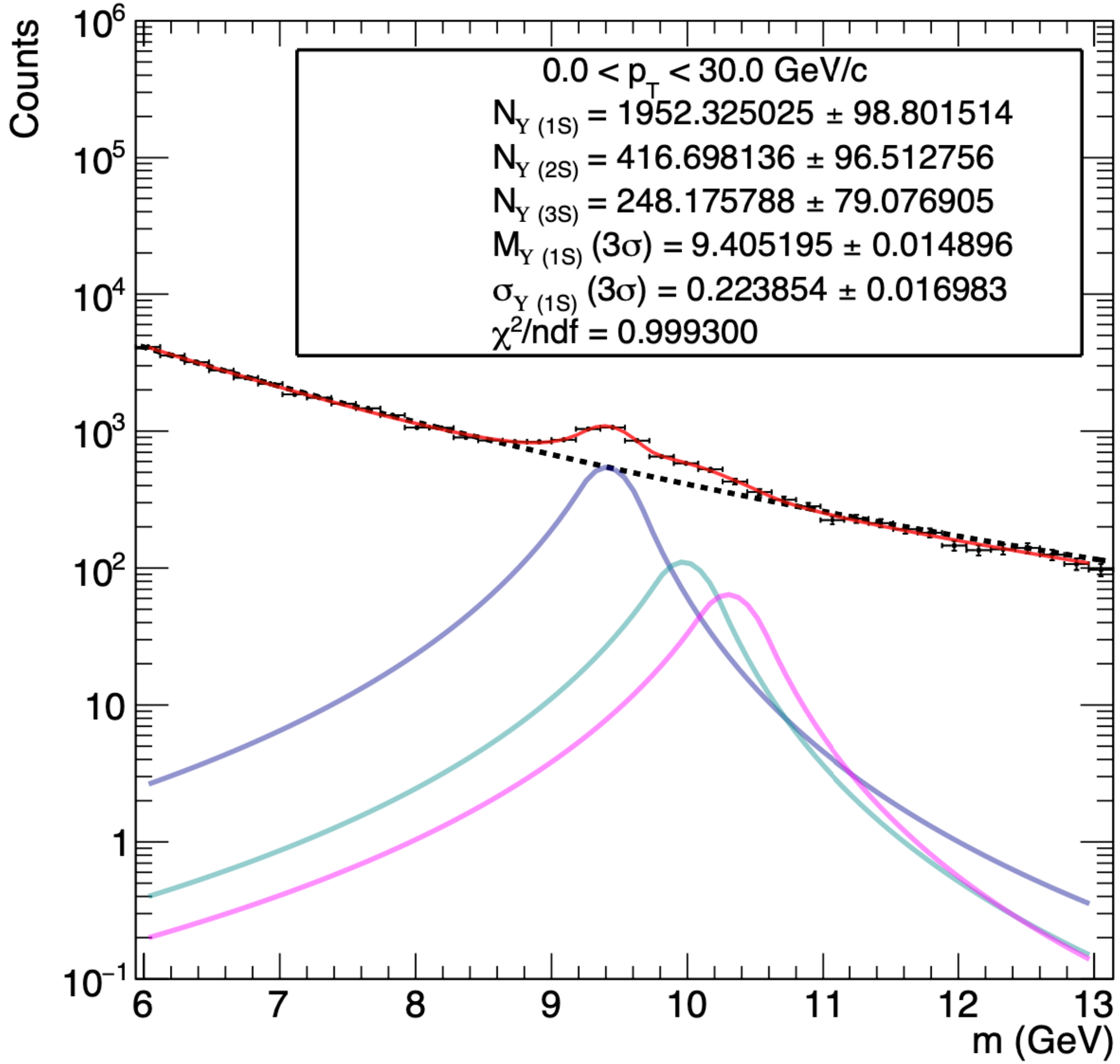
- Fitting procedure
  - For now, the tail parameters ($n_L, \alpha_L, n_R, \alpha_R$) are fixed from MC data at $\sqrt{s}$=13 TeV
  - Three Double Crystal functions for each Υ state
  - Mass of Υ(1S) is kept free
  - Sigma of Υ(1S) is kept free
  - Fitting Range:
    - $M_{\mu^+\mu^-} = 6.0 - 13.0\ GeV/c^2$

$$\mathbf{m_{\Upsilon(nS)} = m_{\Upsilon(1S)} + (m^{PDG}_{\Upsilon(nS)} - m^{PDG}_{\Upsilon(1S)})}$$

$$\boldsymbol{\sigma}_{\mathbf{\Upsilon(nS)}} = \boldsymbol{\sigma}_{\mathbf{\Upsilon(1S)}} \times \frac{\boldsymbol{\sigma}^{\mathbf{MC}}_{\mathbf{\Upsilon(nS)}}}{\boldsymbol{\sigma}^{\mathbf{MC}}_{\mathbf{\Upsilon(1S)}}}$$

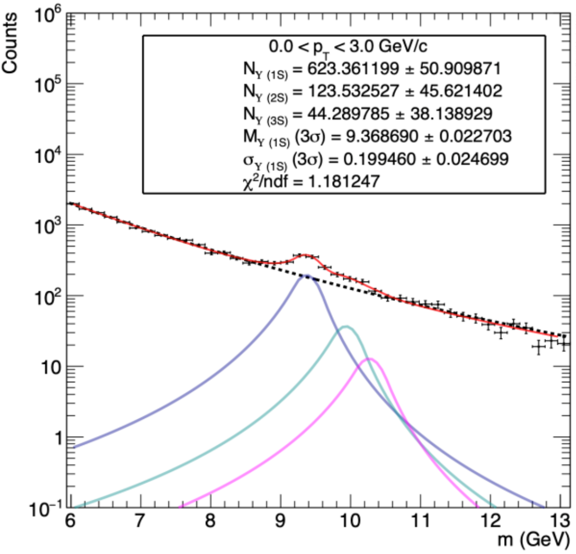
	Simulations at 13 TeV
α_L	1.0242
n_L	2.0000
α_R	2.0711
n_R	2.2565

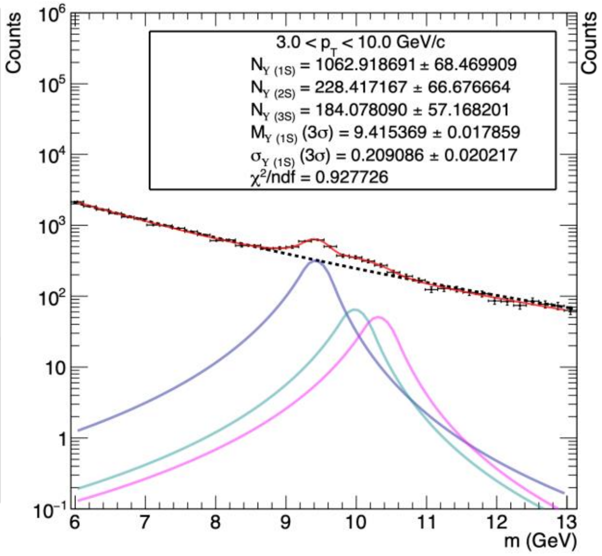
Signal

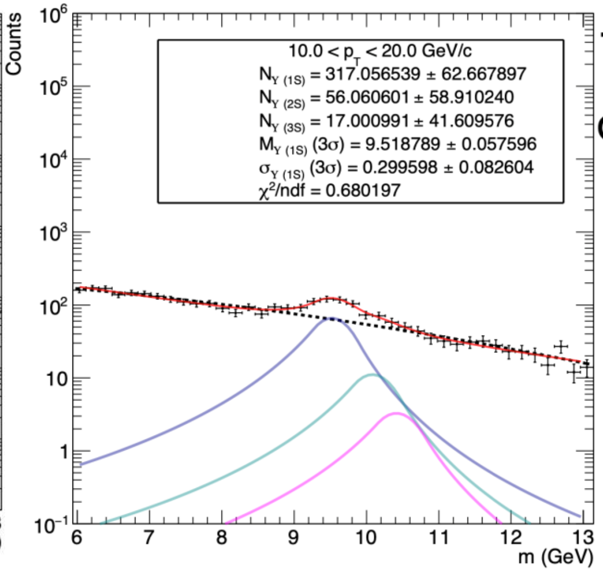


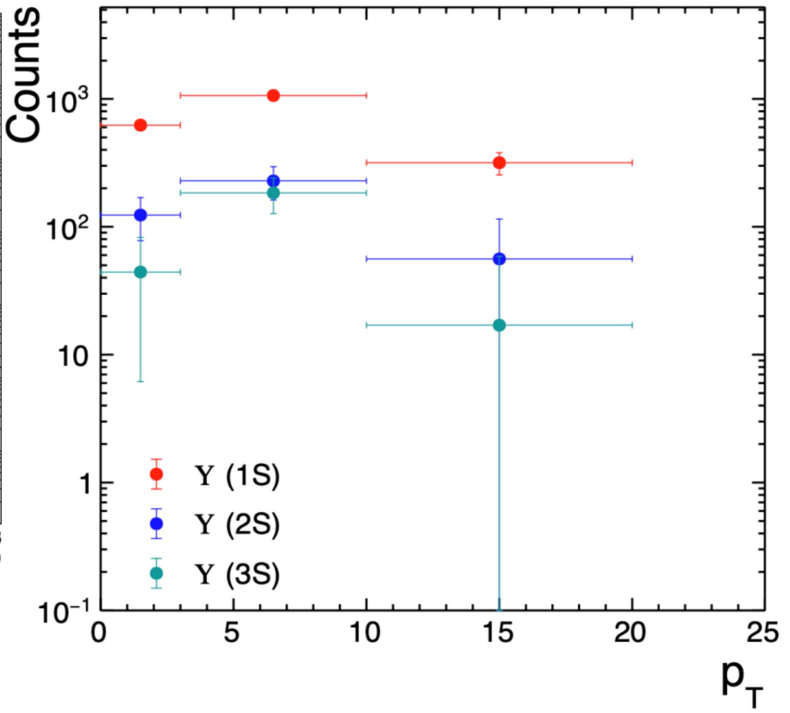
- Dataset used: LHC23_pass4_skimmed_QC1
- In the whole p_T range: 0.0 < p_T <30.0 GeV/c
- The fitting is converged and $\chi^2/\mathrm{N_{dof}}$ is good

Signal









p_T bins (GeV/c)	No. of $\Upsilon(1S)$	No. of $\Upsilon(2S)$	No. of $\Upsilon(3S)$
0-3	623.36$\pm$50.9	123.53$\pm$45.62	44.29$\pm$38.14
3-10	1062.92$\pm$68.45	228.42$\pm$66.68	184.08$\pm$57.17
10-20	317.06$\pm$62.67	56.06$\pm$58.91	17.00$\pm$41.61

- Need more statistics to have a good signal for all the states and to have angular distributions
- Looking for more datasets

Summary & Outlook

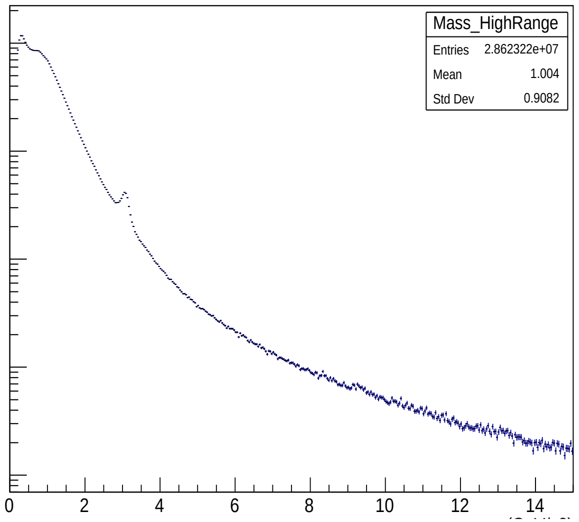
- The polarization analysis can improve our understanding of the production mechanism of heavy quarkonium
- Polarization of $\Upsilon(\mathrm{nS})$ can possibly explain the feed-down effect of the production/polarization if any
- To test more datasets to gather more statistics for all the Υ states
- Then to study the polarization parameters from the cosθ and ϕ distributions

THANK YOU

Backup

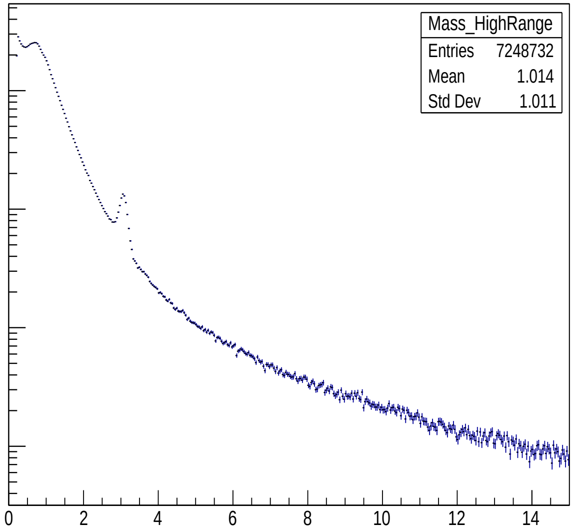
Analysis

- **Dataset**: LHC22o_pass4_minBias_medium



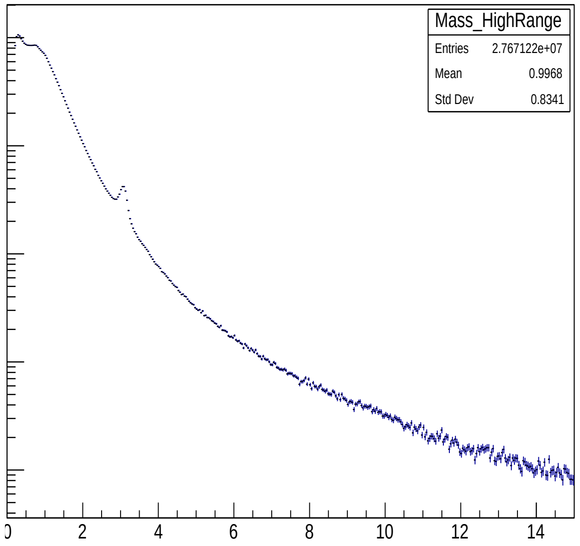
Maker
-processMuonOnlyWithCov
-cfgEventCuts: eventStandardNoINT7
-cfgMuonCuts: muonQualityCuts
-cfgPropMuon: 1

Reader
-cfgMuonCuts: muonQualityCuts
(hyperloop-link)



Maker
-processMuonOnlyWithCov
-cfgEventCuts: eventStandardNoINT7
-cfgMuonCuts: muonQualityCuts
-cfgPropMuon: 1

Reader
-cfgMuonCuts: MatchedMchid
(hyperloop-link)



Maker
-processMuonOnlyWithMult
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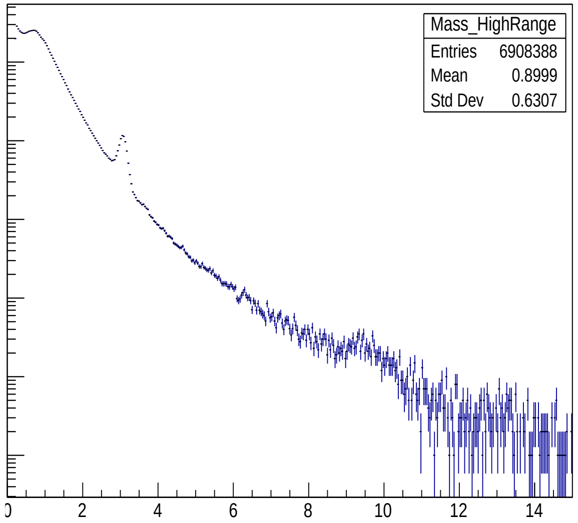
-cfgMuonCuts: muonQualityCuts
-cfgPropMuon: 1

Reader
-cfgMuonCuts: muonQualityCuts
(hyperloop-link)



Maker
-processMuonOnlyWithMult
-cfgEventCuts: eventStandardNoINT7
-cfgMuonCuts: muonQualityCuts
-cfgPropMuon: 0

Reader
-cfgMuonCuts: MatchedMchid
(hyperloop-link)