Angular Distribution of J/ψ

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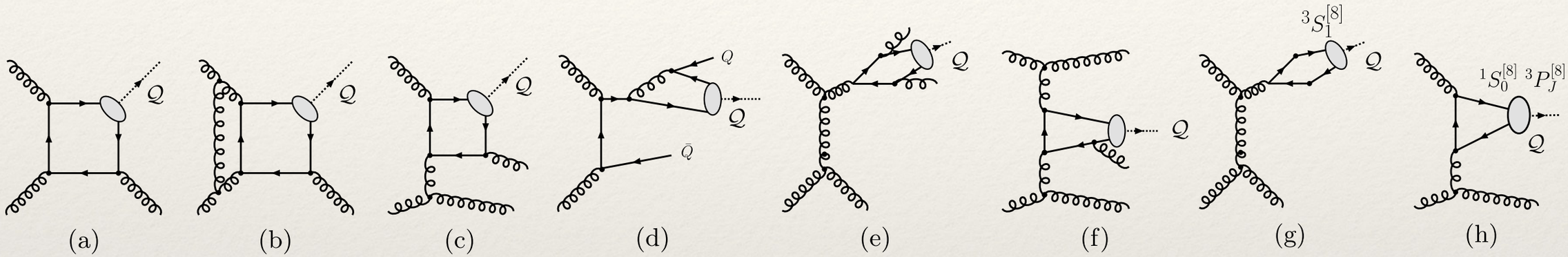
Non-Relativistic QCD (NRQCD)

- Introduce the charmonium hadroproduction via **color-singlet** channels (a-f) and **color-octet** channels (g-h)



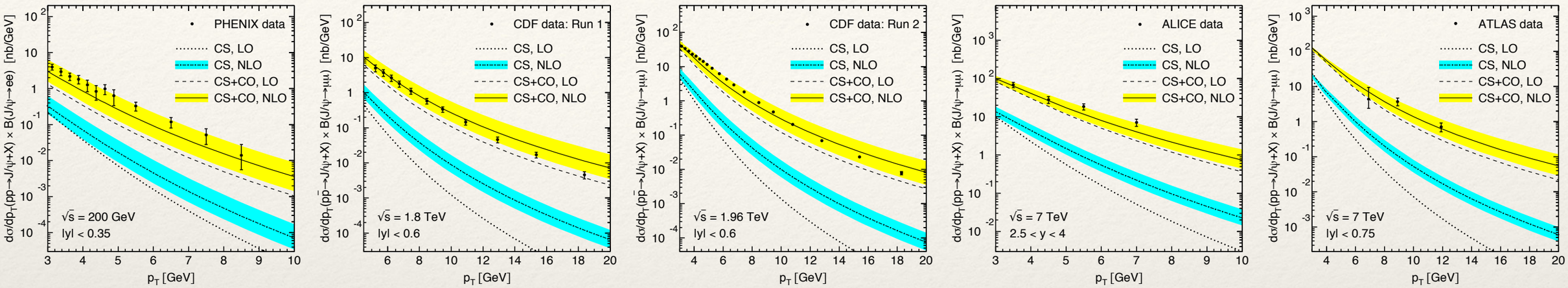
- The cross-section of quarkonium production rely on the extraction of short-distance coefficients (SDCs) and long-distance matrix elements (LDMEs)

$$\sigma(pp \to \mathcal{Q} + X) = \sum_n \underbrace{\hat{\sigma}(pp \to Q\bar{Q}[n] + X)}_{\text{SDCs}} \times \underbrace{\langle \mathcal{O}^{\mathcal{Q}}(n) \rangle}_{\text{LDMEs}}$$

  - ➡ SDCs can calculated by pQCD ⟶ $\hat{\sigma}(pp \to Q\bar{Q}[n] + X) = \sum_{a,b} \int dx_1 dx_2 d\mathrm{LIPS} f_{\mathrm{a/p}}(\mathrm{x}_1) f_{\mathrm{b/p}}(\mathrm{x}_2) \times |M(ab \to Q\bar{Q}[n] + X)|^2$
  - ➡ LDMEs estimation rely on experimental measurement (non-perturbative QCD)
    - ⤷ might affect the final prediction of polarization because of feed-down components

The Comparison of J/ψ Differential Cross-Section

Modern Physics Letters A Vol.28, No.9 (2013) 1350027



Polarization of J/ψ

- The **J/ψ** production mechanism described by QCD, but…
  - **Inconsistent p_T distribution** between theoretical prediction and experimental data
  - **Inconsistent polarization** between theoretical prediction and experimental data

- Several models are being considered:
  - **Color Evaporation Model (CEM)** ➟ predicts **unpolarized J/ψ ($\lambda = 0$)**
  - **Color Singlet Model (CSM)** ➟ predicts **longitudinal polarized J/ψ ($\lambda < 0$)**
  - **Non-Relativistic QCD (NRQCD)** ➟ predicts **transversely polarized J/ψ ($\lambda > 0$)**

- The **J/ψ** polarization from experimental measurement ➟ still puzzle at low-p_T !

Polarization of J/ψ

- The polarization of **J/ψ** can be accessed by the decay angular distribution of dimuon pairs. This is the way to explore the production mechanism of quarkonium.

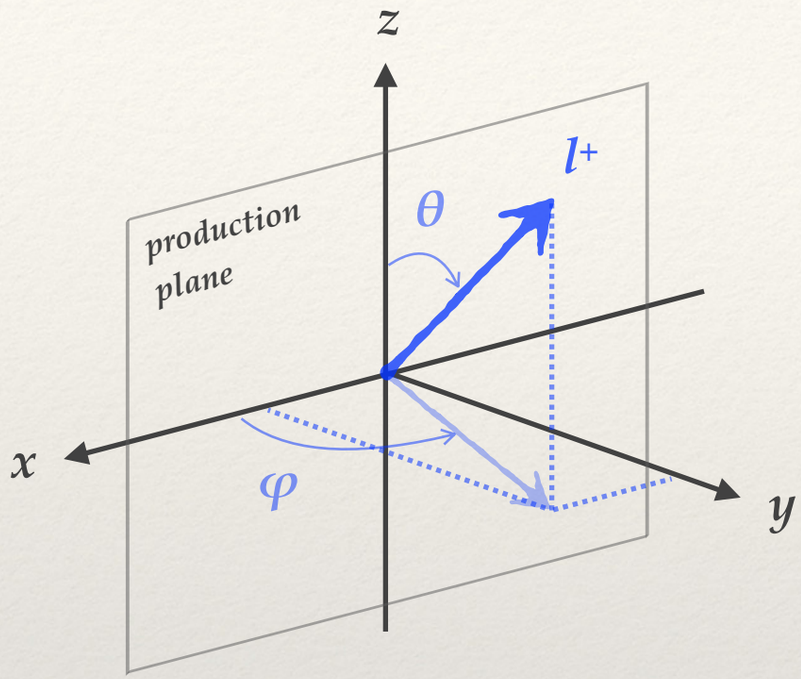
- The general expression of angular distribution of **J/ψ** (decay into dilepton):

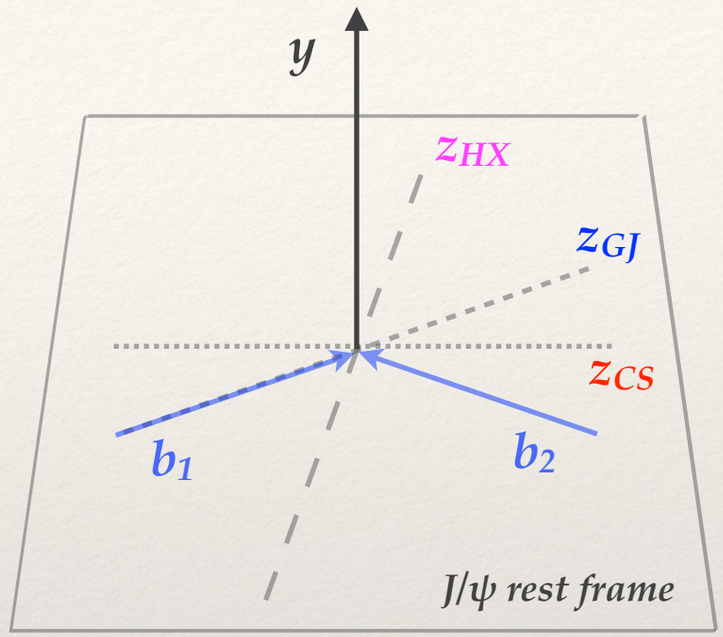
$$d\sigma/d\Omega \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\varphi + (\nu/2) \sin^2\theta \cos 2\varphi$$

  - where θ and φ refer to polar and azimuthal angle of $lepton^+$ in the **J/ψ** rest frame.
  - The **angular parameter λ** refers to the **polarization parameter.**

- The measurement of angle rely on the definition of **characteristic quantization axis** (e.g. *Helicity axis, Gottfried-Jackson axis, Collins-Soper axis …*).

The Choice of Reference Frame

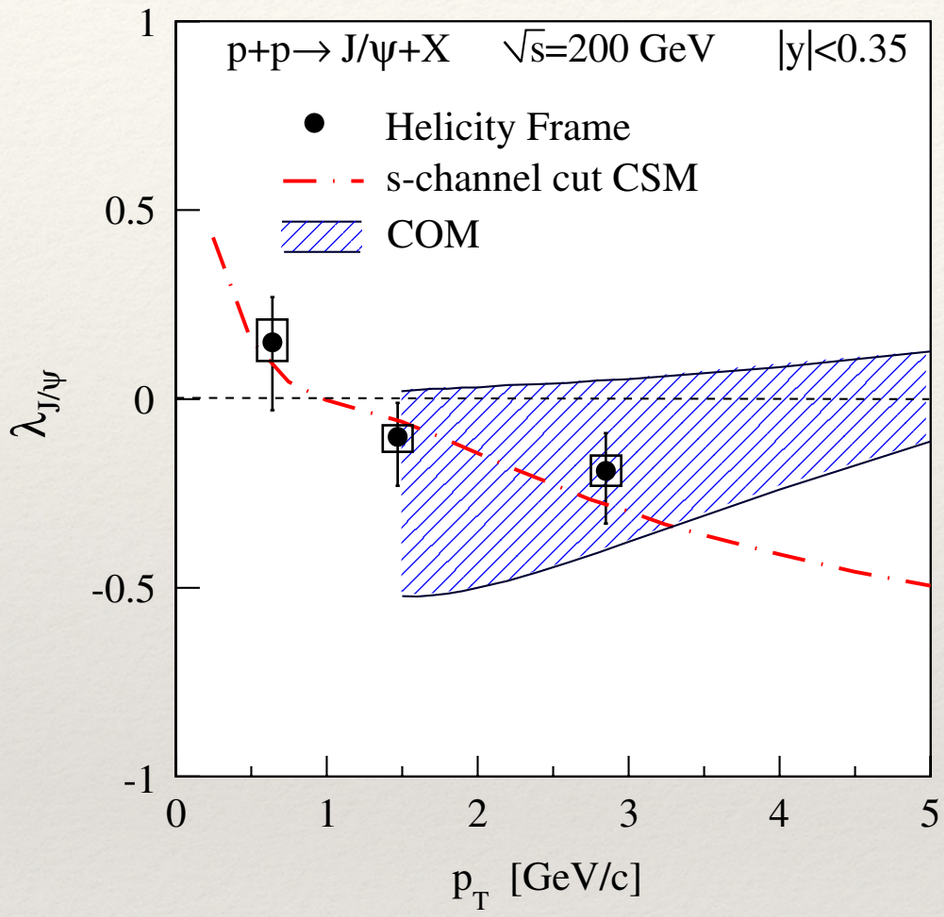


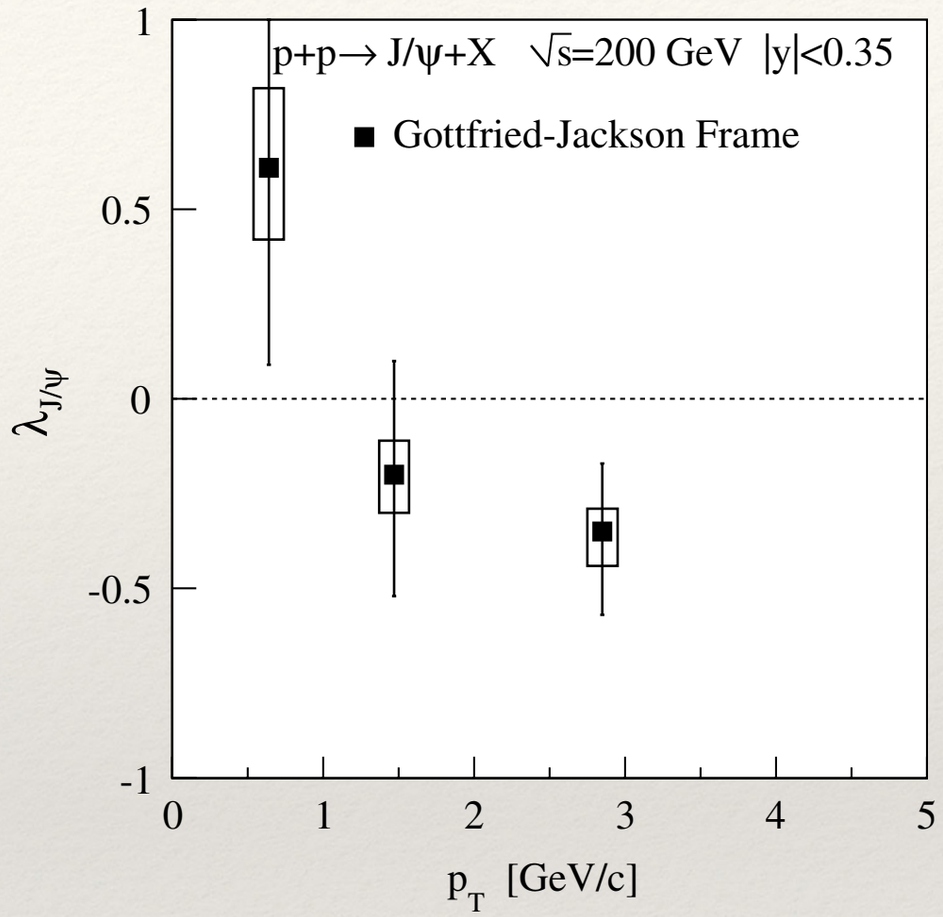


- The main difference of reference frame is the definition of ***polar axis*** (z axis):
  - ***Helicity*** (HX): direction of momentum sum of colliding beams ($\hat{b}_1 + \hat{b}_2$).
  - ***Gottfried-Jackson*** (GJ): direction of momentum of one of beams ($\hat{b}_1$).
  - ***Collins-Soper*** (CS): direction of momentum difference of colliding beams ($\hat{b}_1 - \hat{b}_2$).

PHENIX Experimental Result of J/ψ Polarization

PRD 82, 012001 (2010)



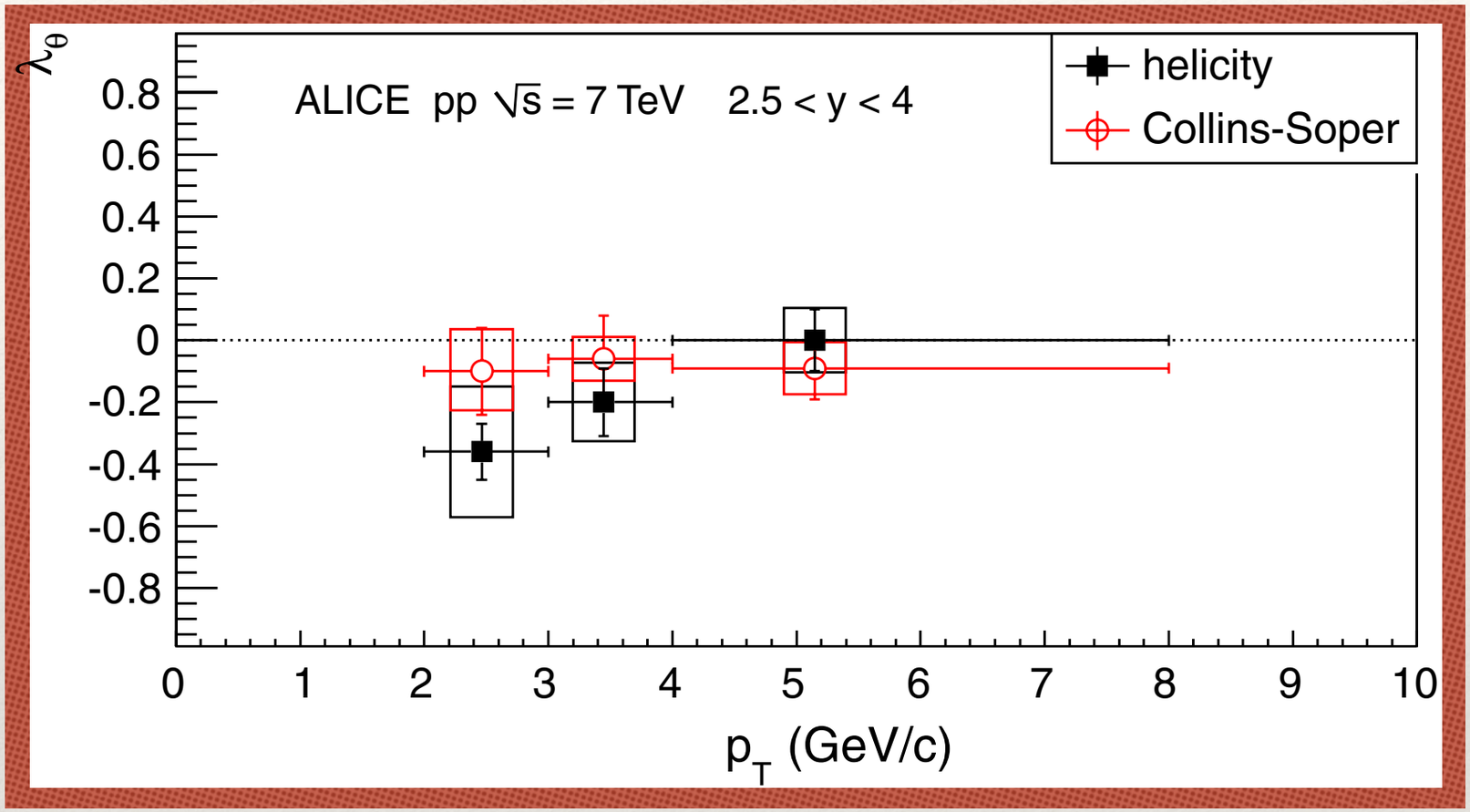


- Including the prompt **J/ψ** and feed-down **J/ψ** (33 ± 5%) from **χ_c**, **ψ′** (and *b*-hadron?).
- Obtain angular parameters with **1D fitting**.
- Present in ***Helicity*** and ***Gottfried-Jackson*** frame.

ALICE

Experimental Result of J/ψ Polarization

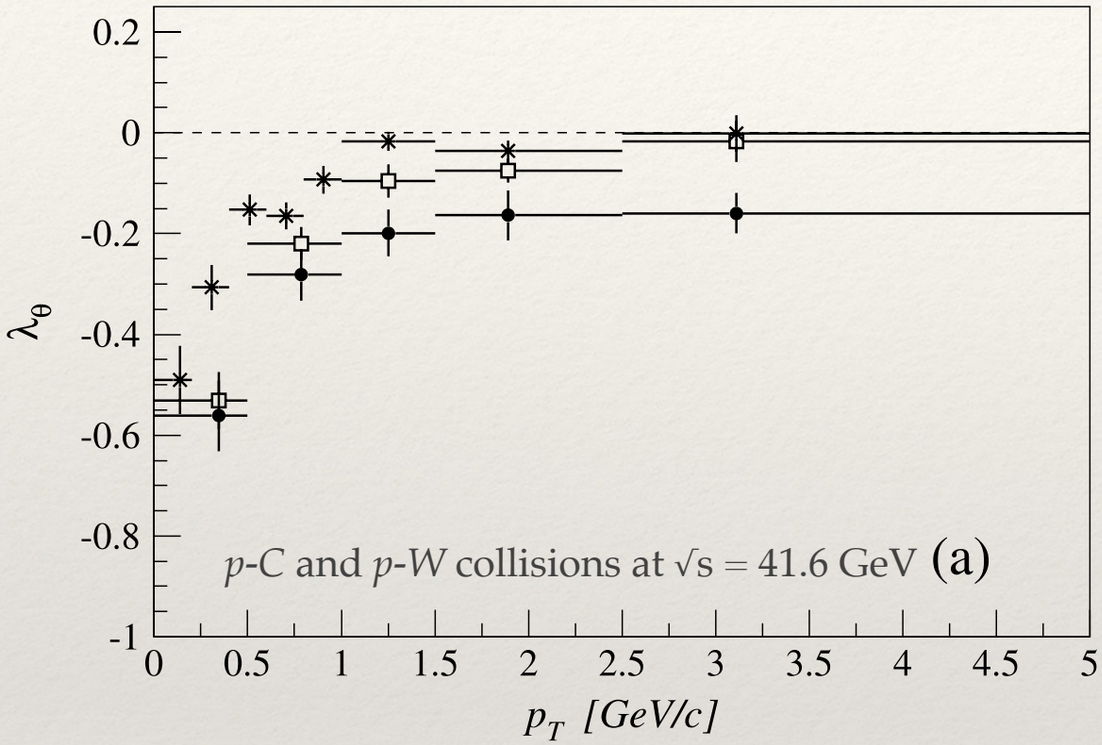
PRL 108, 082001 (2012)

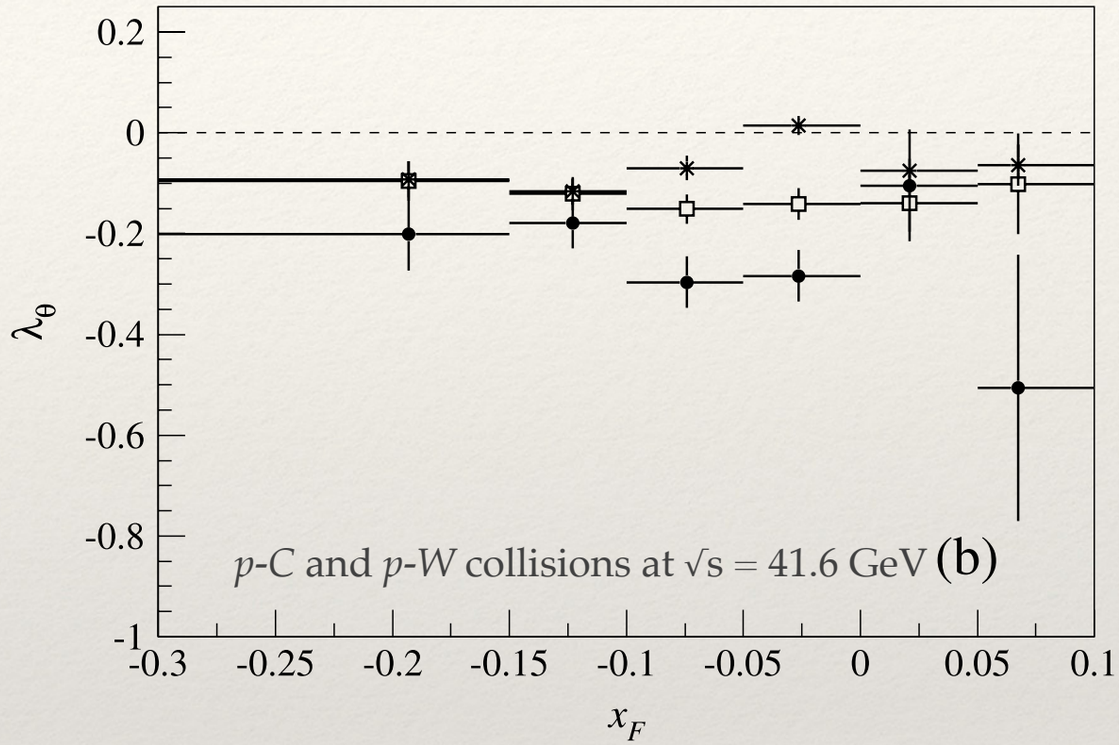


- Including the prompt **J/ψ** and feed-down **J/ψ** from χ_c, ψ' and *b*-hadron.
- Obtain angular parameters with **1D fitting**.
- Present in ***Helicity*** and ***Collins-Soper*** frame.

HERA-B Experimental Result of J/ψ Polarization

EPJC 60, 517-524 (2009)



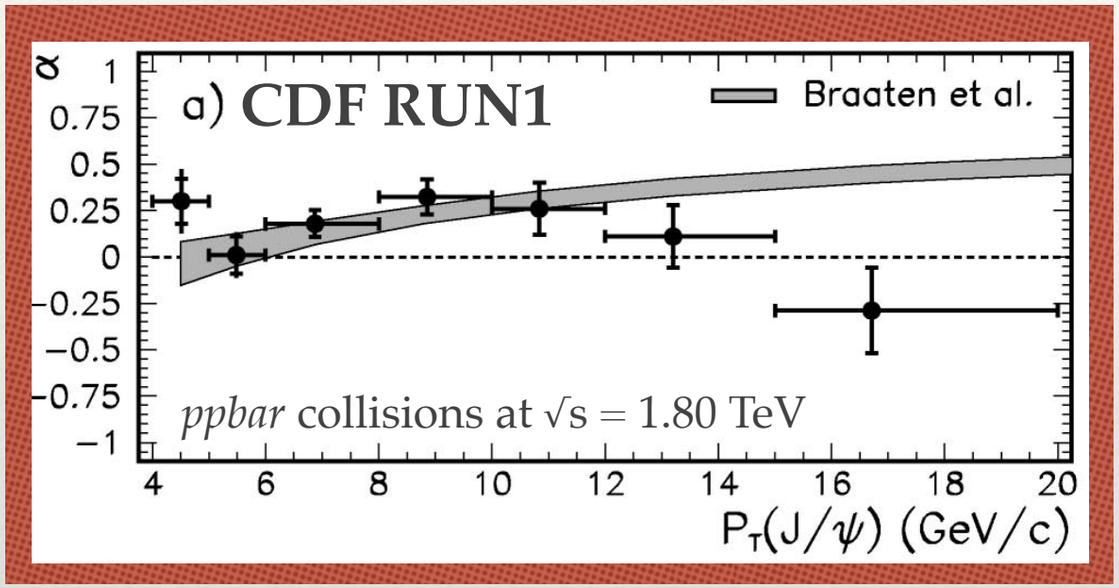


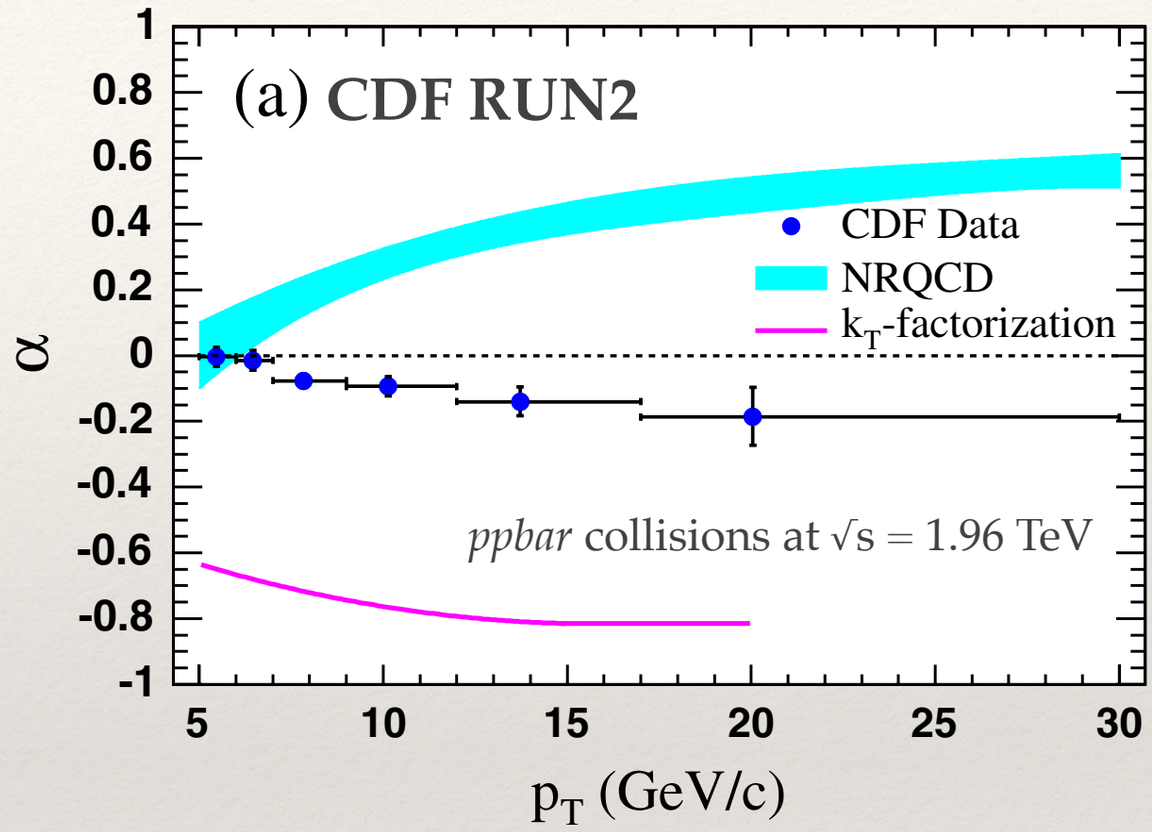
- Including the prompt **J/ψ** and feed-down **J/ψ** from χ_c, ψ' (~27%) (and *b*-hadron?).
- Obtain angular parameters with **1D fitting**.
- Present in ***Gottfried-Jackson***(□), ***Helicity***(✳) and ***Collins-Soper*** frame(•).

CDF

Experimental Result of J/ψ Polarization

PRL 85, 2886 (2000) | PRL 99, 132001 (2007)



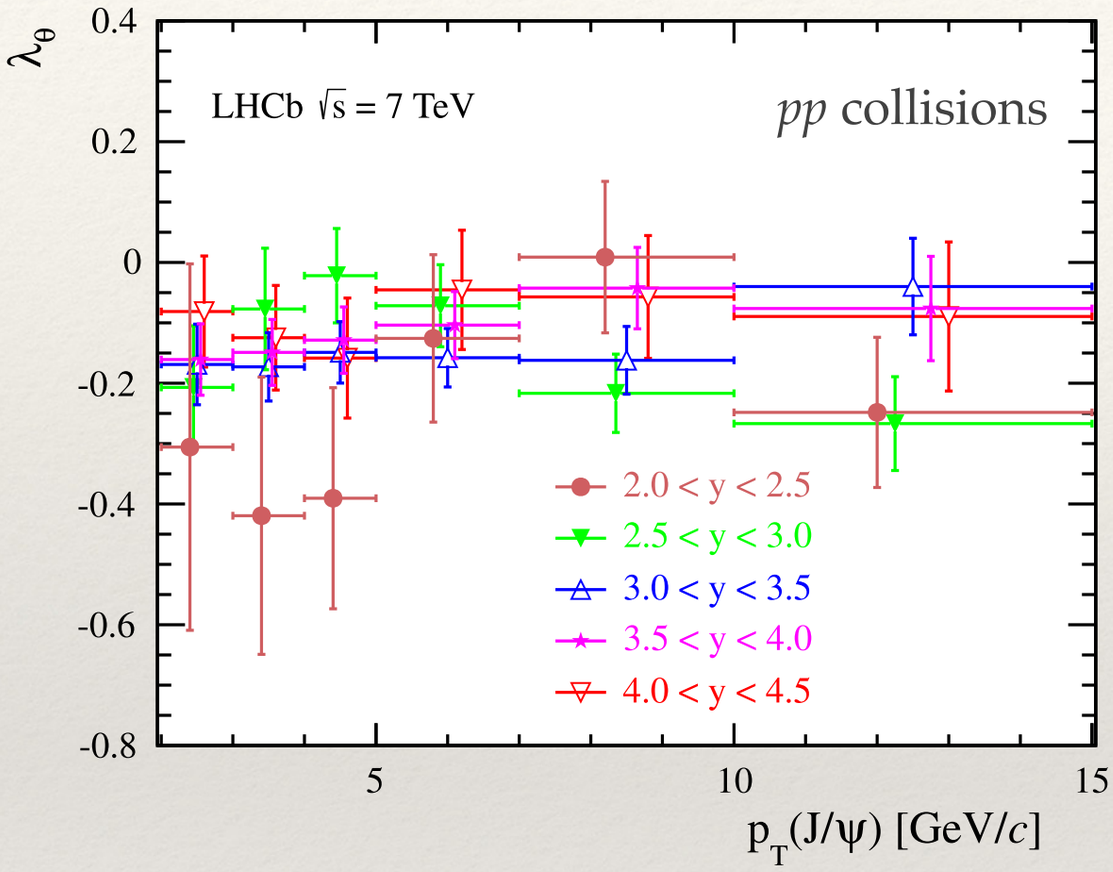


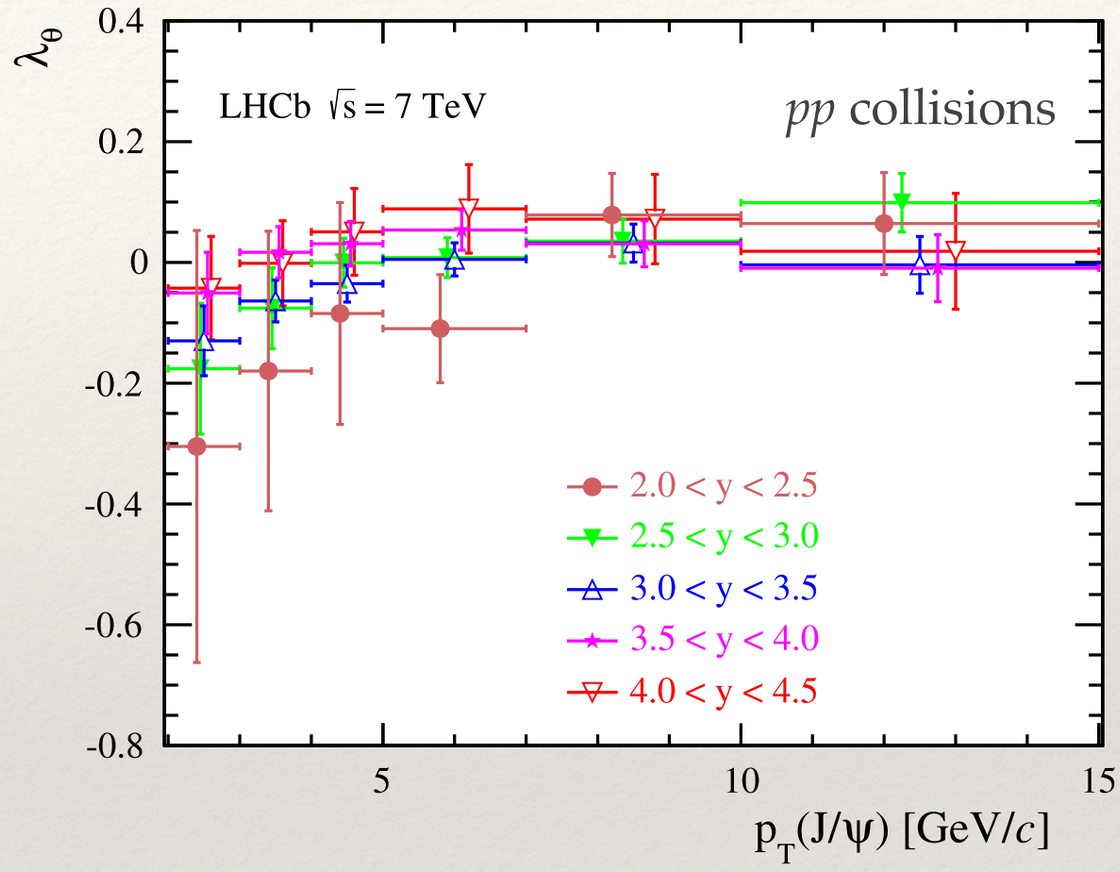
- Including the prompt **J/ψ** (32 ± 6%) and feed-down **J/ψ** from **χc**, **ψ′**
- Obtain angular parameters with **1D fitting**.
- Present in ***Helicity*** frame only.

LHCb

Experimental Result of J/ψ Polarization

EPJC 73, 2631 (2013)

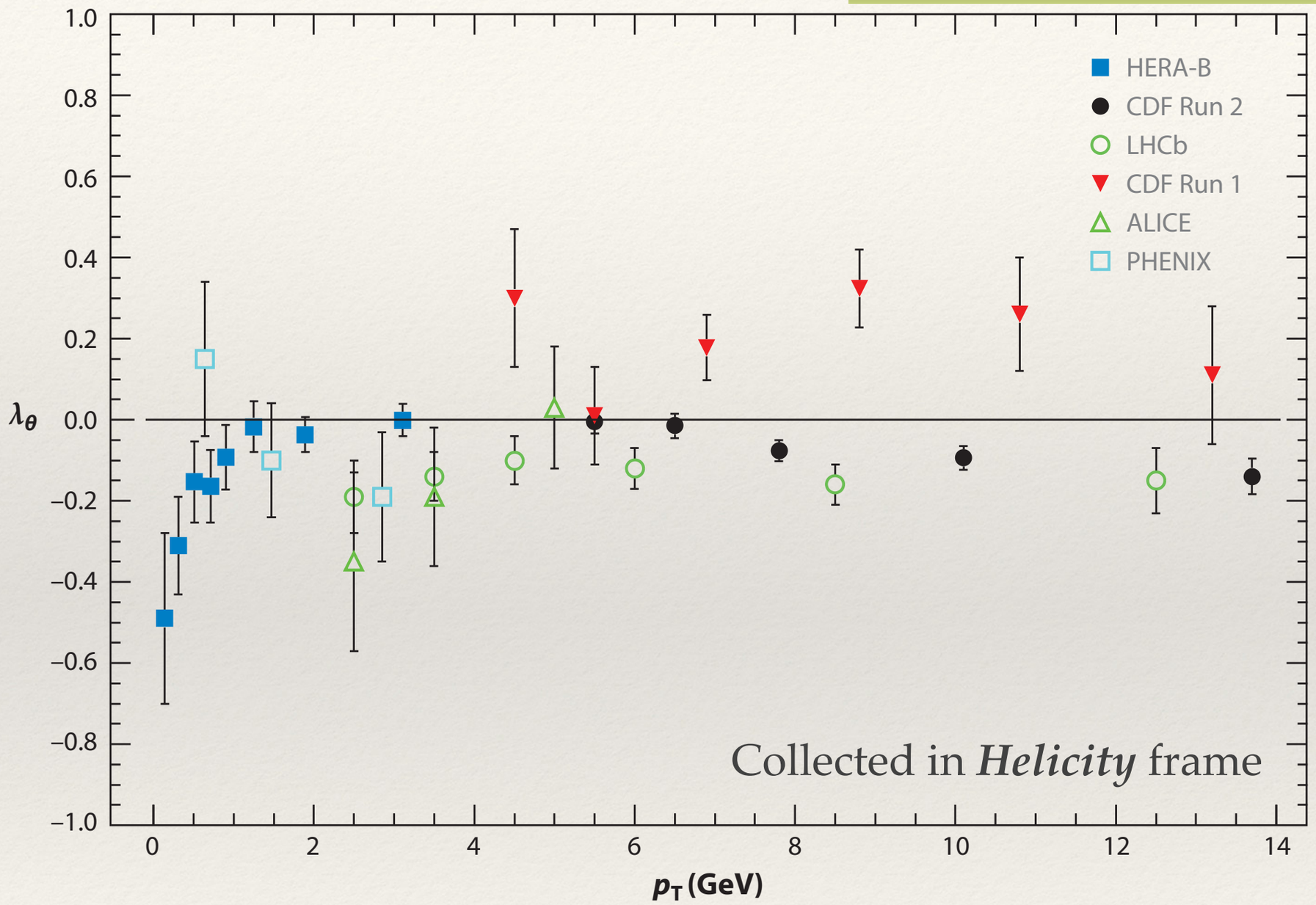




- Including the prompt **J/ψ** and feed-down **J/ψ** from **χ_c, ψ'**.
- Obtain angular parameters with **2D fitting**.
- Present in ***Helicity*** and ***Collins-Soper*** frame.

Comparison of J/ψ Polarization with Different Experiments

Annu. Rev. Nucl. Part. Sci. 2014.64:221-246



- What cause the inconsistency of the J/ψ polarization between each experiments?

Experimental Ambiguity

- 1D extraction *v.s.* 2D extraction:
  - The approach of 1D extraction rely on the perfectly understanding of azimuthal angle and μ, ν angular parameters.
  - Better to use 2D approach in order to minimize the bias.
- Frame dependence of angular parameters:
  - The results from each experiment show very strong frame dependence.
  - Need a **frame-independent** approach.
- Feed down component from χ_c states:
  - No good solution to separate ➟ requiring the global analysis.

Frame-Independent Approach

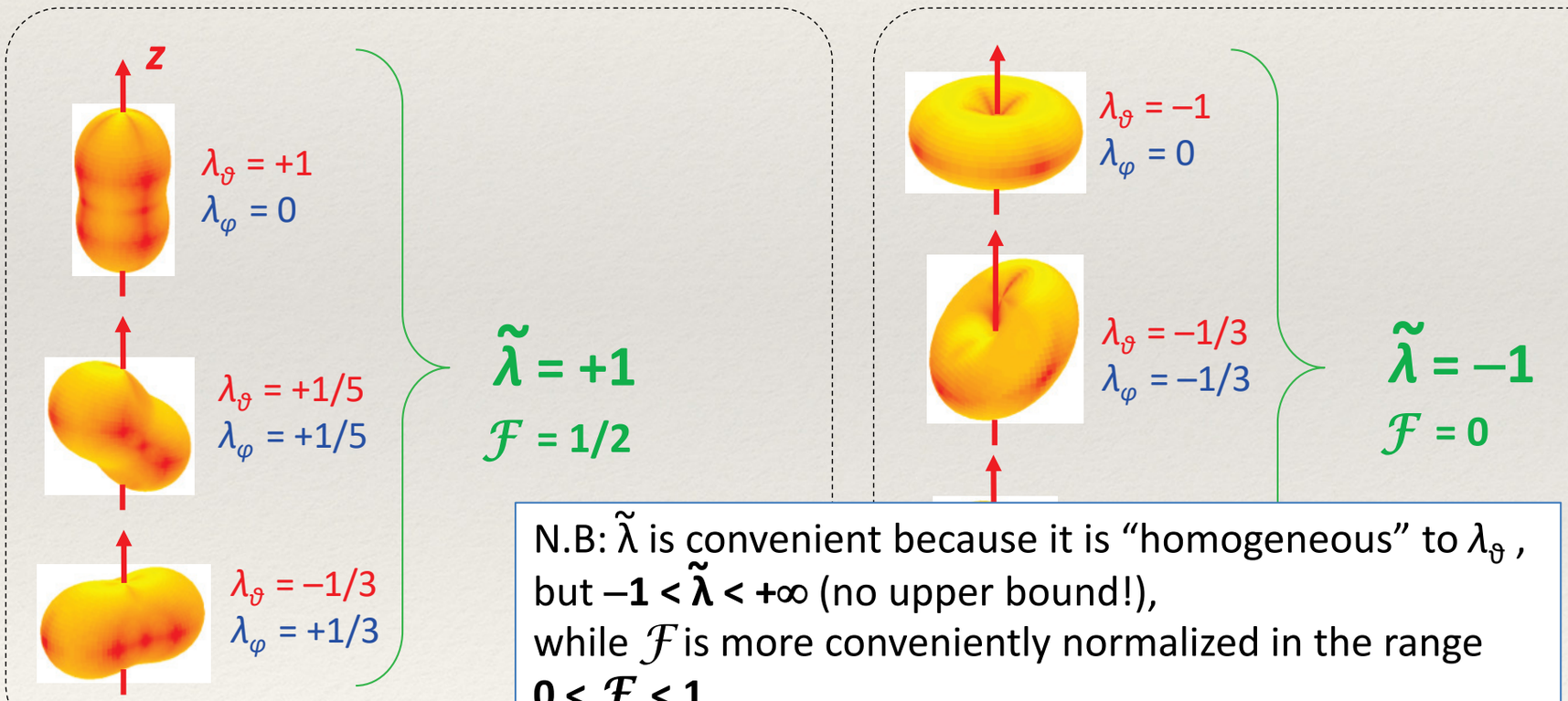
A complementary approach: frame-independent polarization

Pietro Faccioli

The *shape* of the distribution is (obviously) frame-invariant (= invariant by rotation)

→ it can be characterized by a frame-independent parameter, writeable e.g. as

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi} \qquad \text{or} \qquad \mathcal{F} = \frac{1 + \lambda_\vartheta + 2\lambda_\varphi}{3 + \lambda_\vartheta} \qquad \left(\mathcal{F} = \frac{1 + \tilde{\lambda}}{3 + \tilde{\lambda}} \right)$$



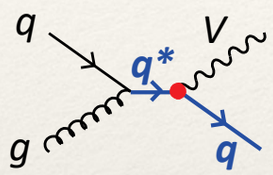
N.B: $\tilde{\lambda}$ is convenient because it is "homogeneous" to λ_ϑ , but $-1 < \tilde{\lambda} < +\infty$ (no upper bound!), while $\mathcal{F}$ is more conveniently normalized in the range $0 < \mathcal{F} < 1$

rotations *in the production plane!*

Frame-Independent Approach

"Optimal" frames for Drell-Yan, *Z* and *W* polarizations

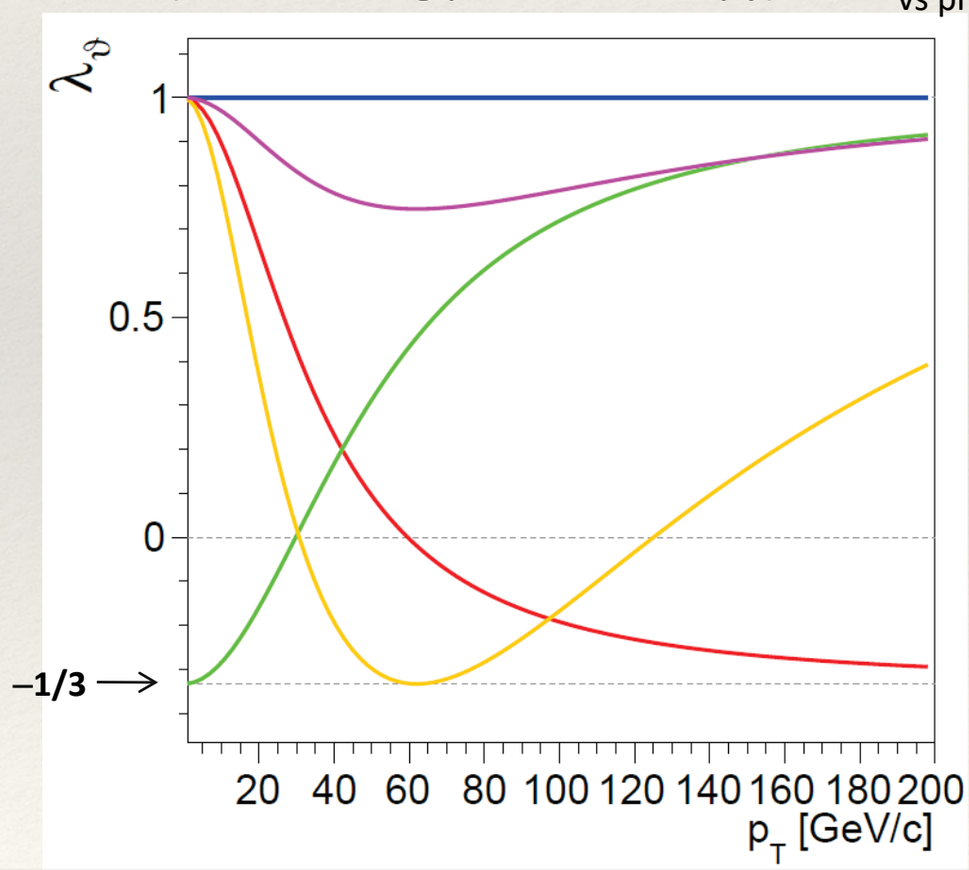
Different subprocesses have different "natural" quantization axes



For ***s*-channel processes** the natural axis is
the direction of the outgoing quark
(= direction of dilepton momentum)

→ optimal frame (= maximizing polar anisotropy): **HX**

(neglecting parton-parton-cms
vs proton-proton-cms difference!)



HX
CS
PX
GJ1 (negative beam)
GJ2 (positive beam)

example: Z
y = +0.5

Pietro Faccioli

Frame-Independent Approach

Pietro Faccioli et al. — Eur. Phys. J. C (2010) 69, 657-673

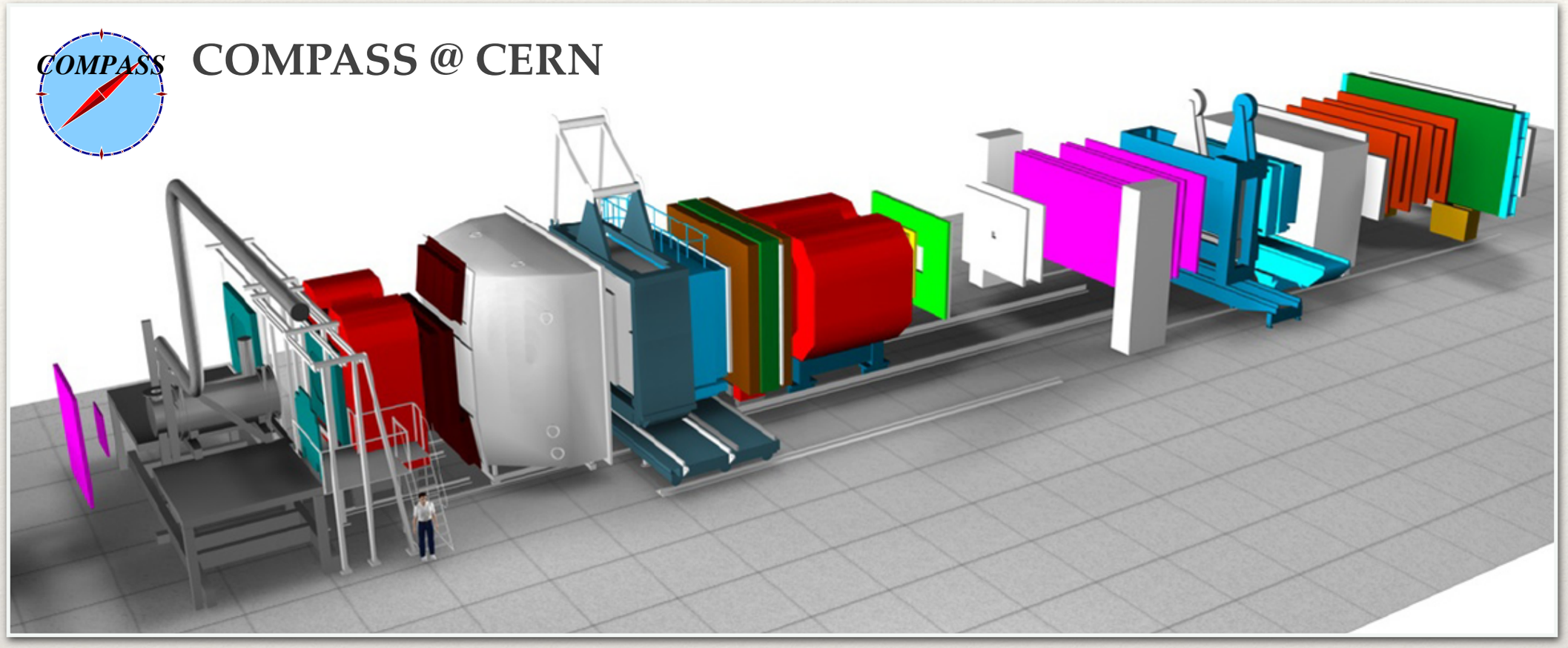
- Propose a new quantity which is independent of the choice of reference frame:

$$\tilde{\lambda} = \frac{\lambda_\theta + 3\nu_\varphi}{1 - \nu_\varphi} = \frac{2\lambda + 3\nu}{2 - \nu}$$

- Once we obtain the angular parameter λ and ν, we can determine the invariant parameter which suppose to be frame-independent.

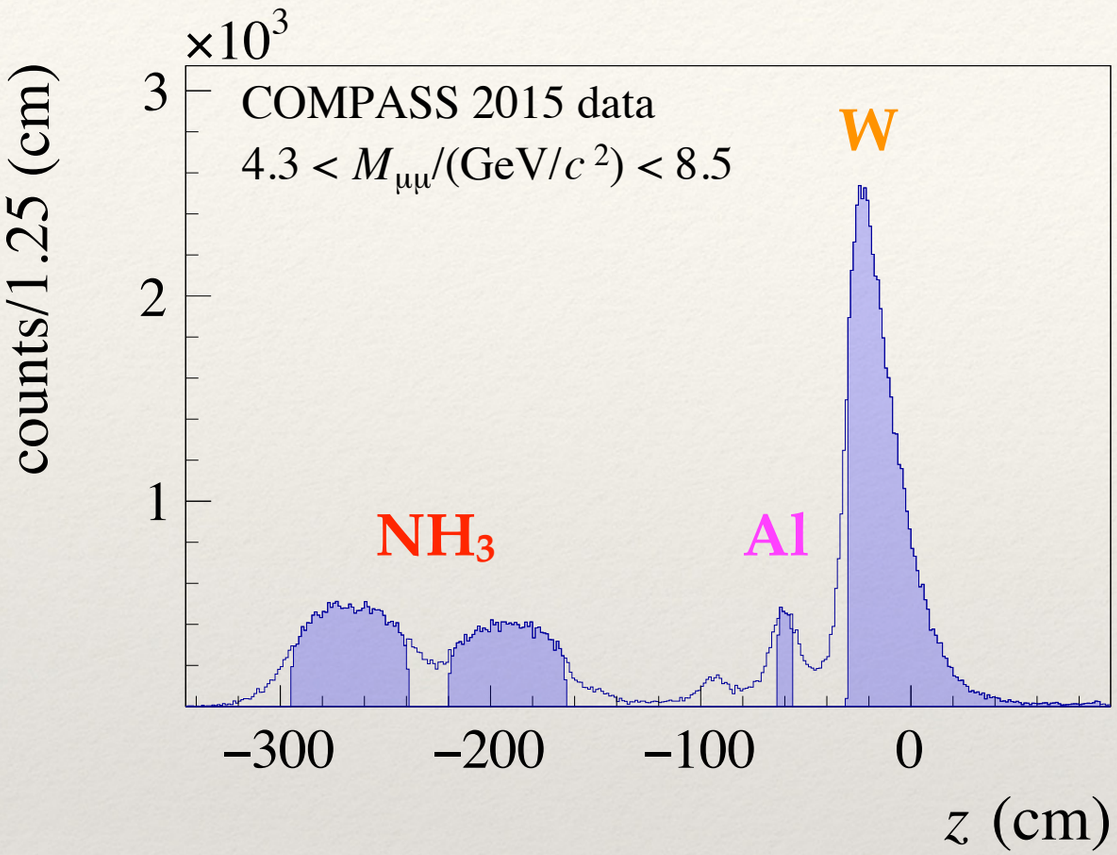
- On the other hand, determine the invariant parameter could be also **a systematic uncertainty test for angular analysis framework**.

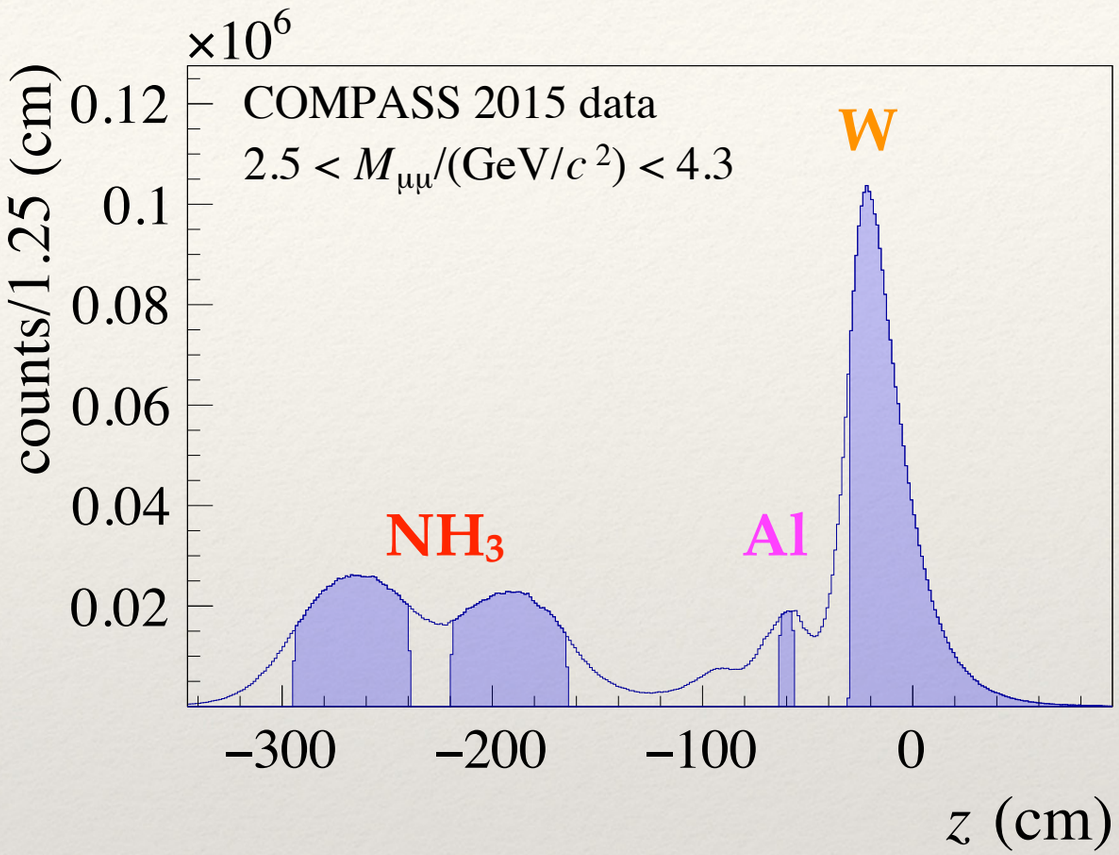
COMPASS/CERN Drell-Yan Experiment in 2015



- COMPASS has took DY data in **2015**, and continue to take DY data in **2018**
- π^- beam at **190 GeV/c** with average beam intensity **6×10^7 s^{-1}** from **CERN SPS**
- **Transversely polarized NH_3 targets** (110 cm) + **Al target** (7 cm) + **W target** (120 cm)

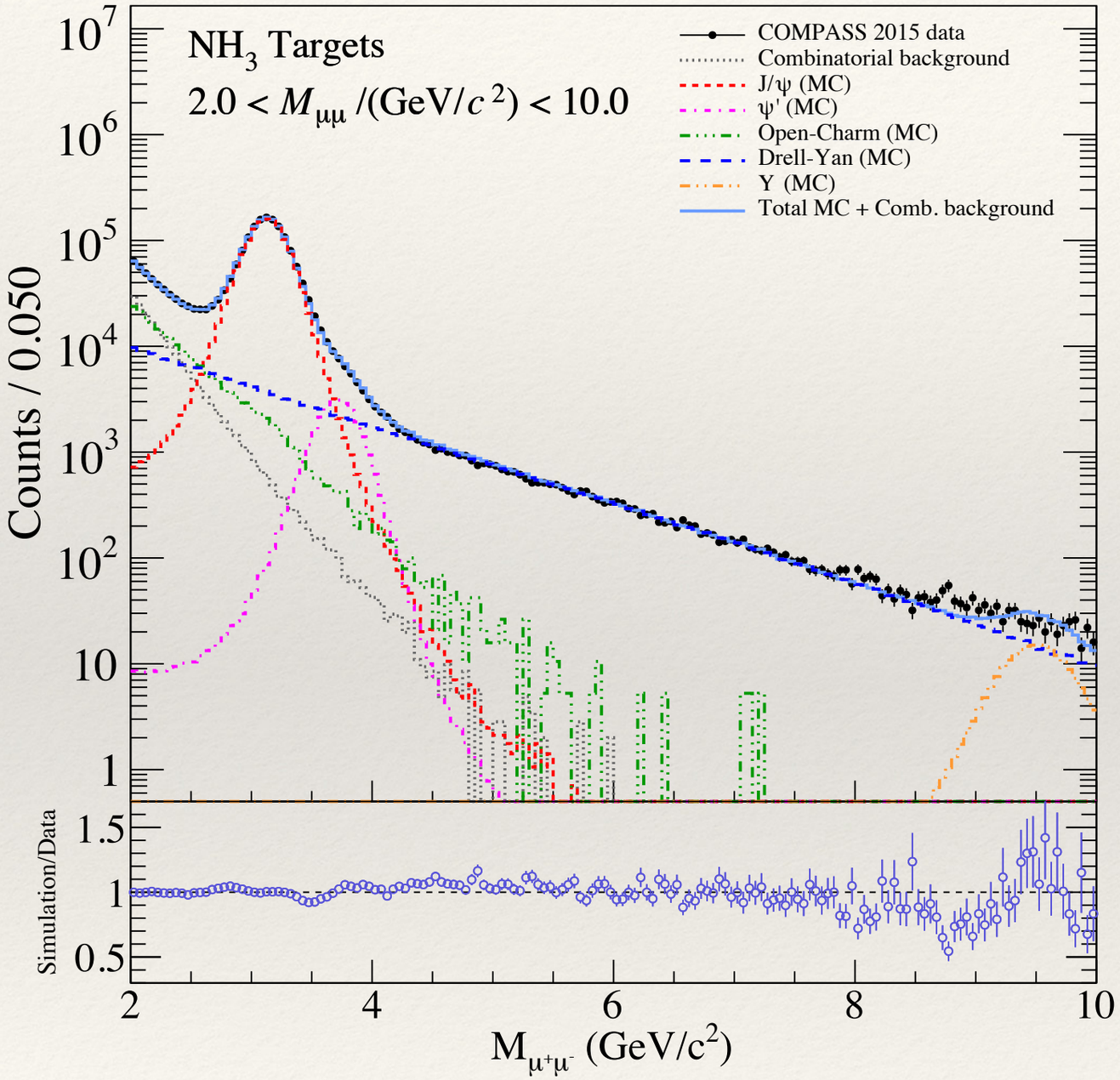
Z Vertex Distribution Selecting Dimuon





- In COMPASS 2015 setup, the **NH_3 targets**, **Al target** and **W target** are distinguishable. (with Z vertex resolution $\sigma_z \sim 11$ cm)
- The analysis of the angular distribution of events from **NH_3 targets** will be presented in this talk.

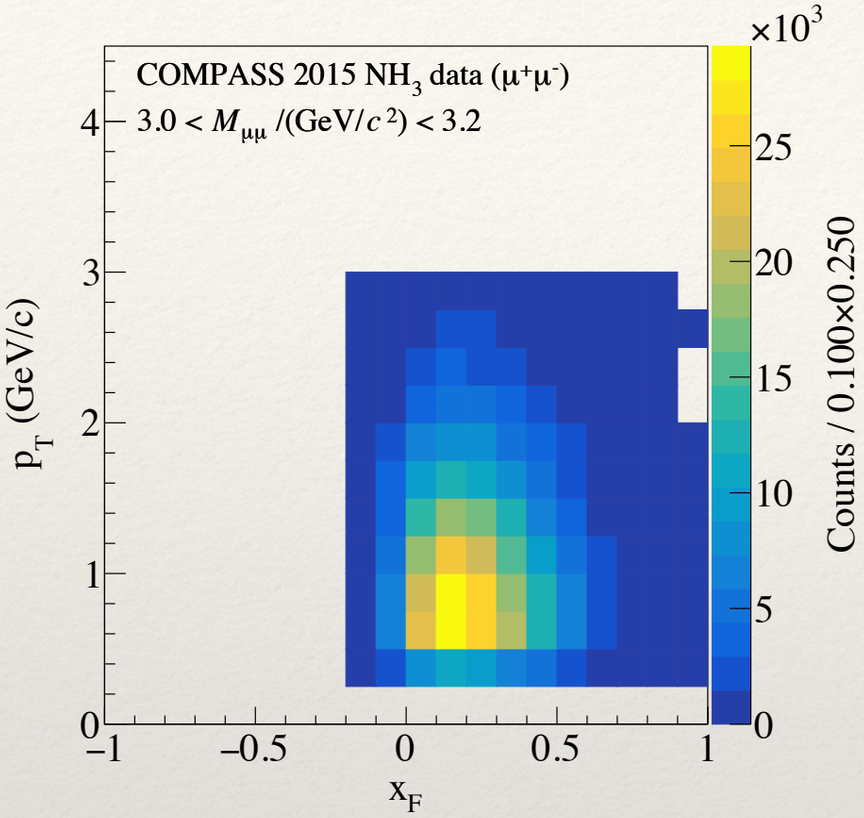
COMPASS/CERN Drell-Yan Experiment in 2015



- Several sources of dimuons have been considered:
  - **Drell-Yan process**
  - **Resonance: J/ψ, ψ', Upsilon**
  - **Open-Charm**
  - **Combinatorial background**
- Using the MC framework, we can well describe the **level of contamination** in mass region that we are interested:
  - **J/ψ** dominate region: **3.0 – 3.2 GeV/c²**

Mass region	Statistics	Contamination
3.0 – 3.2 GeV/c²	751,229 pairs	4.3 ± 0.1%

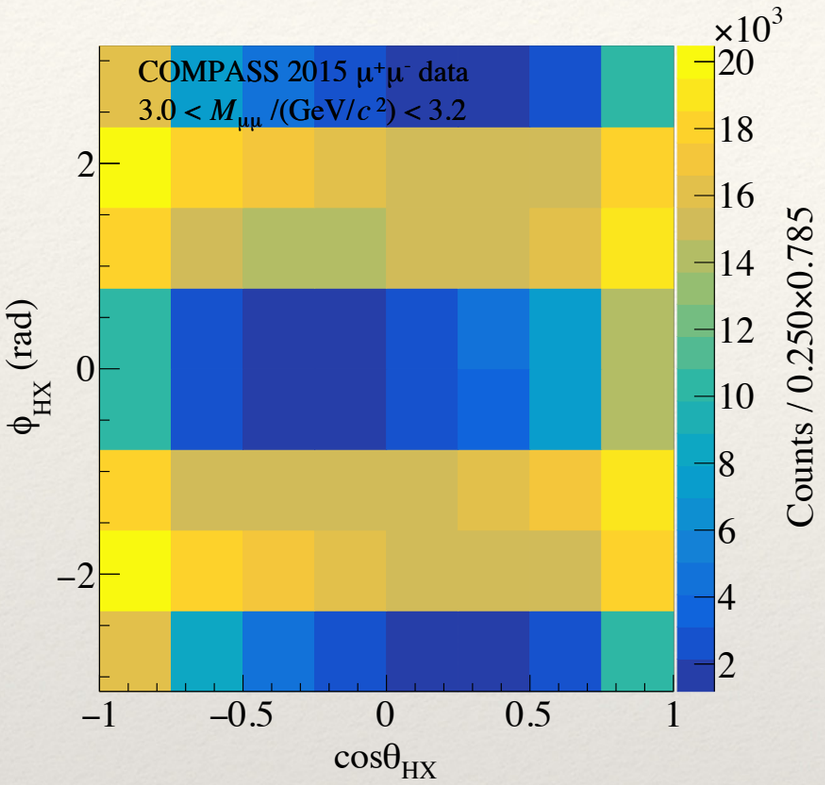
Kinematics Coverage of Dimuon

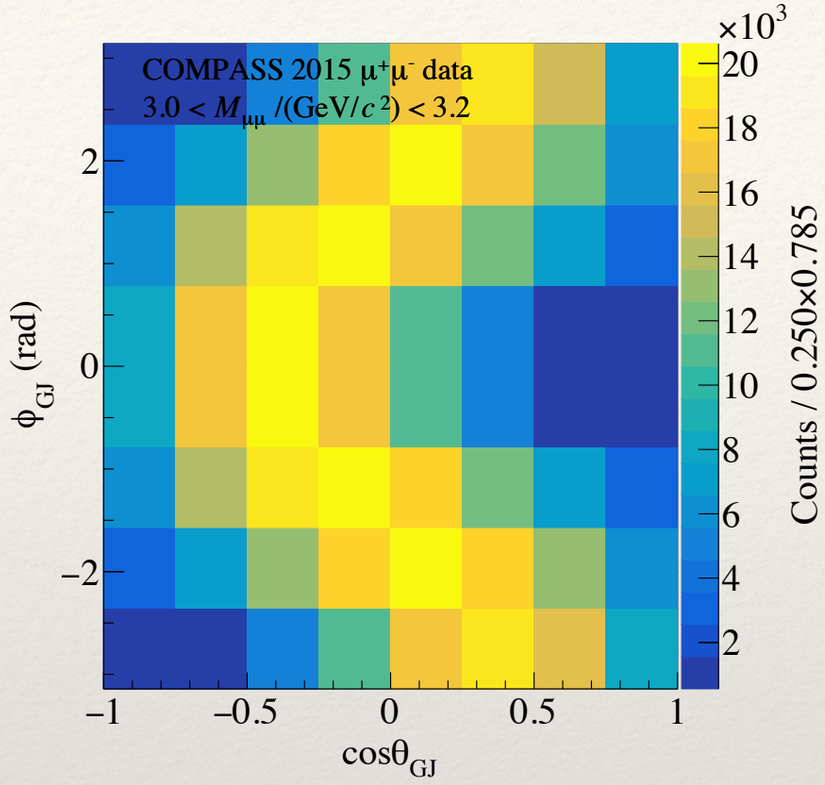


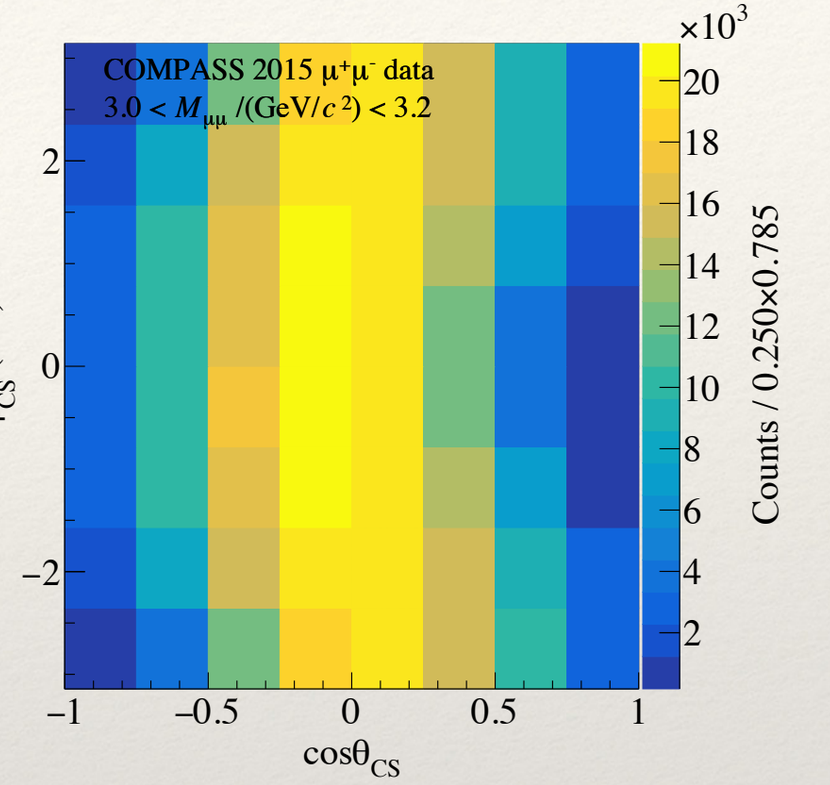
Mass region	$\langle M_{\mu\mu} \rangle$	$\langle p_T \rangle$	$\langle x_\pi \rangle$	$\langle x_N \rangle$	$\langle x_F \rangle$
3.0 – 3.2 GeV/c²	3.10	1.14	0.33	0.10	0.24

- The distributions of Feynman variable x_F versus transverse momentum p_T are presented in the top.
- The cut of transverse momentum is applied due to low resolution in angular variable (lower cut) and also due to very low statistics (upper cut): **$0.4 < p_T < 3.0$ GeV/c**
- The angular parameters extraction is evaluated in kinematics bins of p_T, x_π, x_N and x_F.

Angular Parameter Extraction

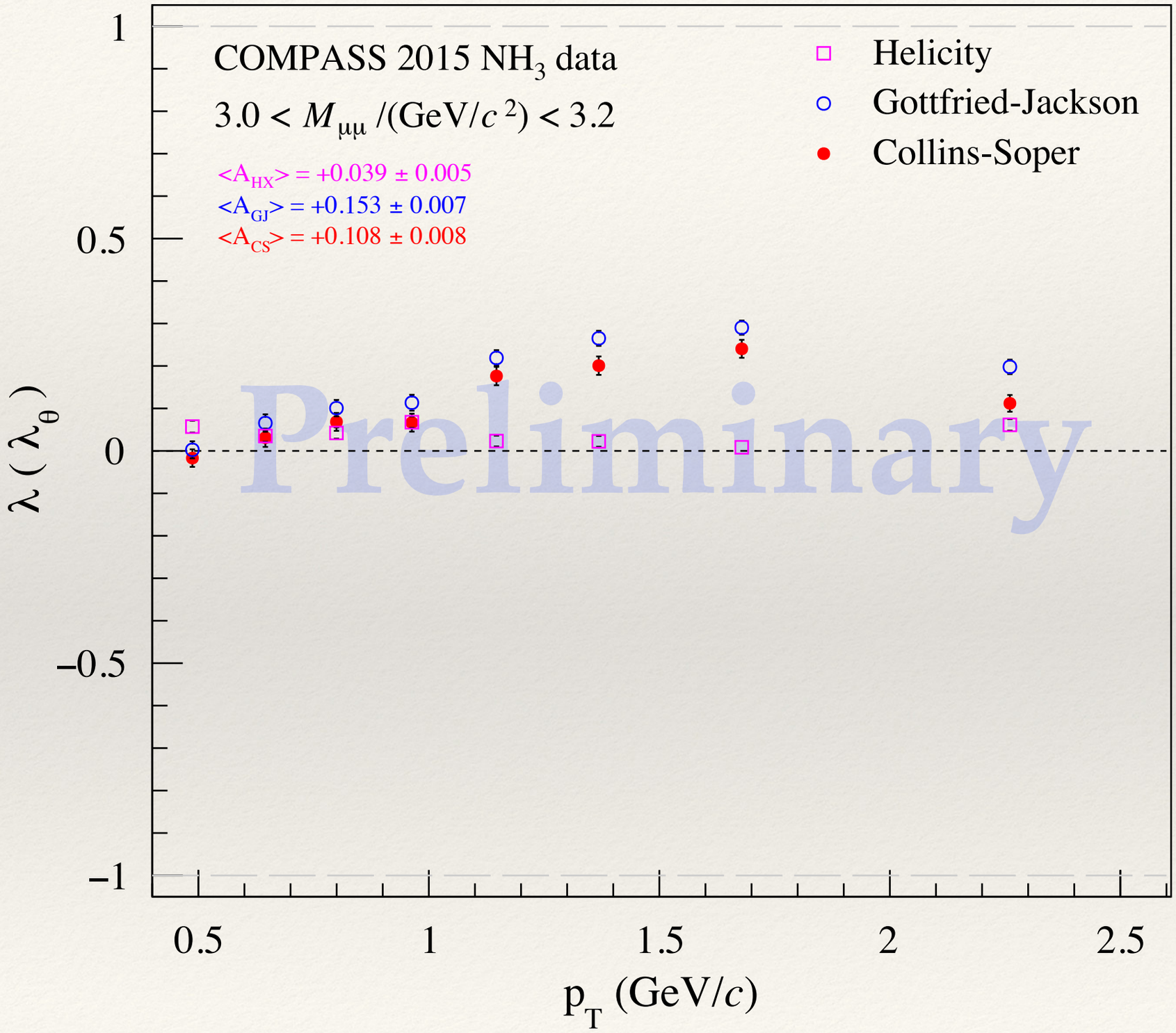


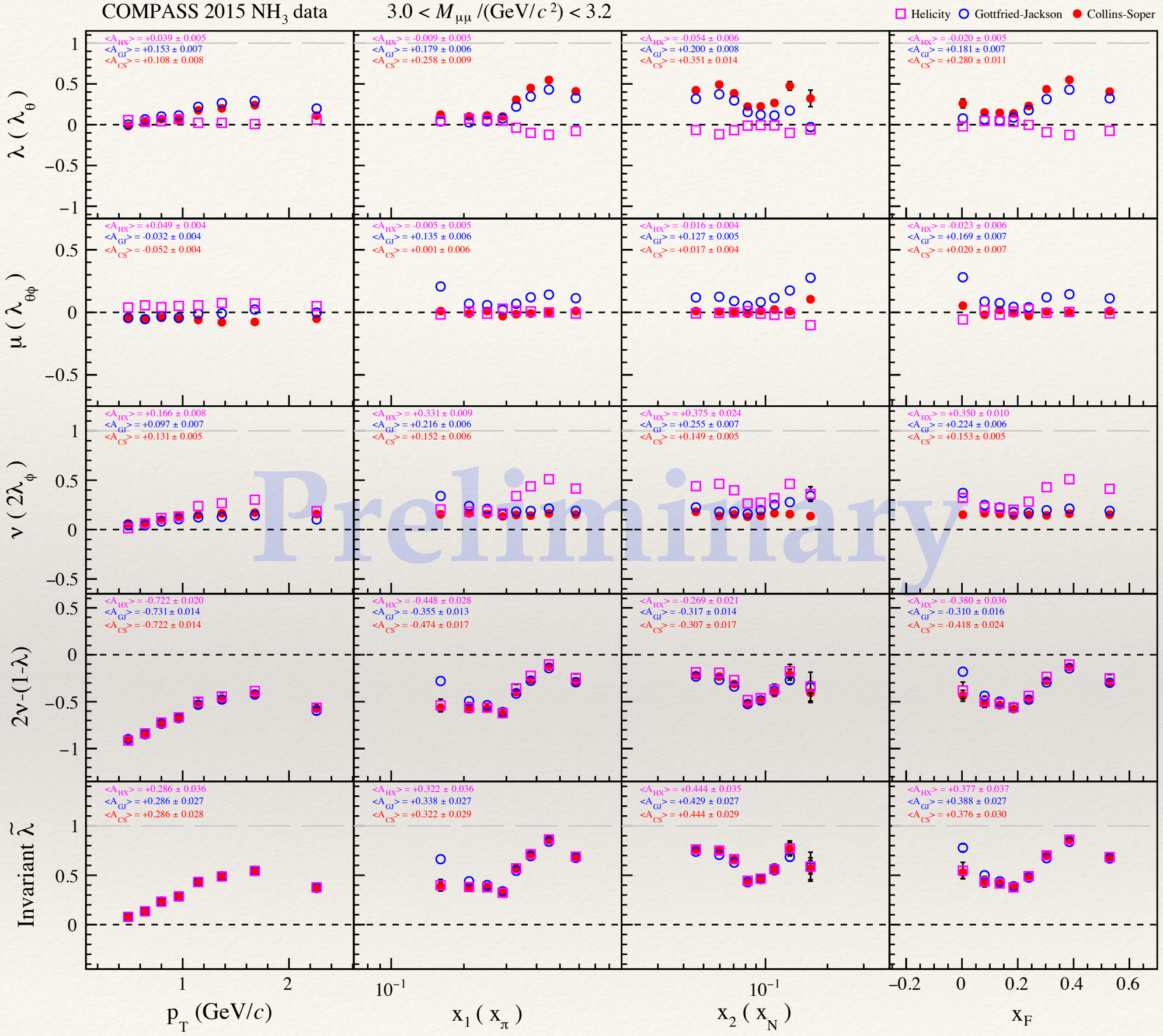


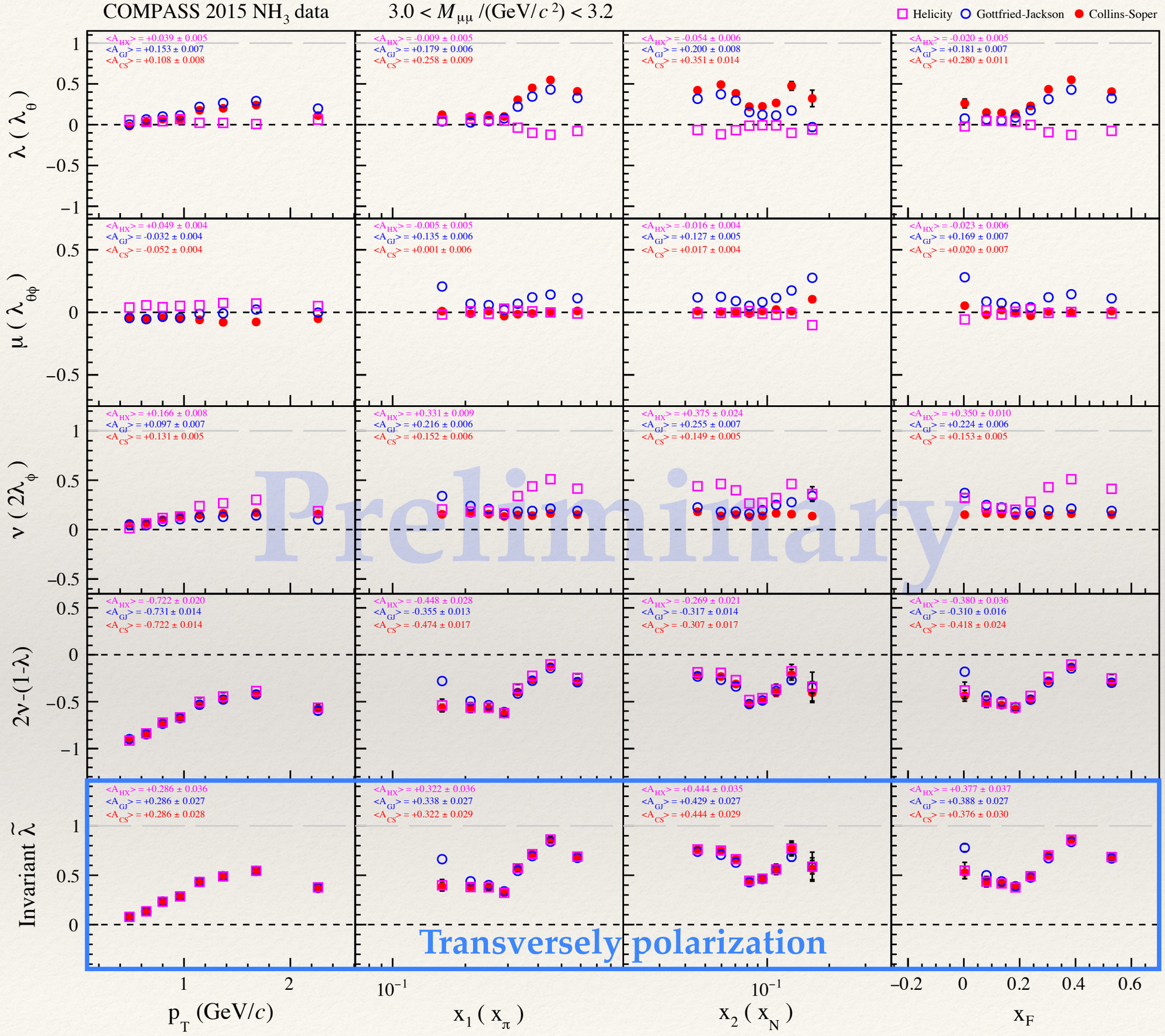


- Select events at fixed p_T (x_π, x_N or x_F) bin.
- Construct angular variables in **HX**, **GJ** and **CS** frames.
- Perform un-binned maximum likelihood fitting(UBML) with PDF.
- The acceptance are estimated by MC sample and applied during UBML fitting.

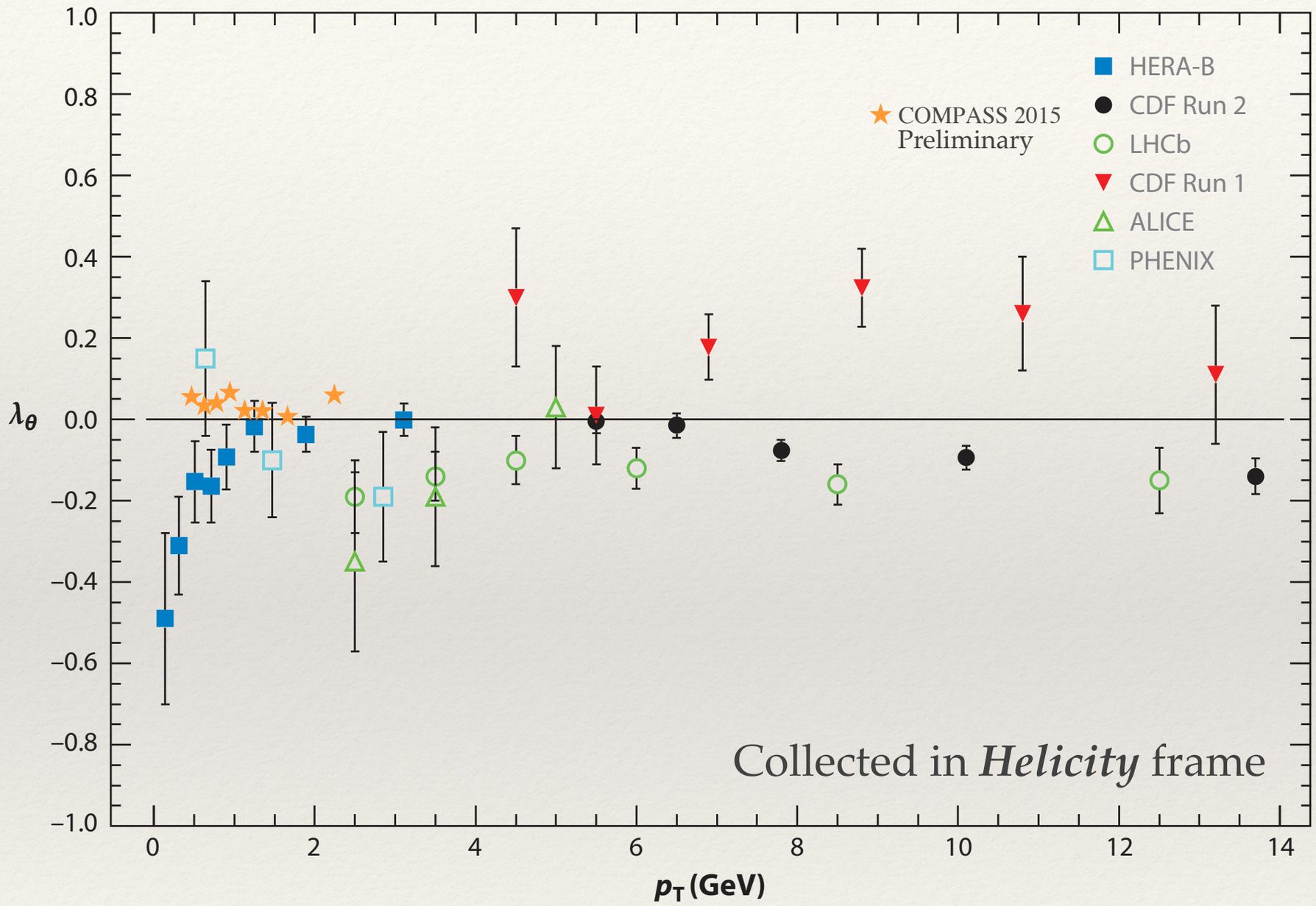
Result of J/ψ Polarization from COMPASS







The Polarization of J/ψ from each Experiments



Summary

- In order to extract unbiased **J/ψ** polarization, we should…
  - ➡ Extracting result from the 2D angular distribution (three-parameter function).
  - ➡ Presenting polarization parameters in at least two frames.

- Polarization of **J/ψ** is sizable from COMPASS 2015 preliminary result
  - ➡ Transversely polarized **J/ψ** (base on invariant parameters result)