Ideas on probing TMDs and spin entanglement via double Λ polarizations

Kong Tu

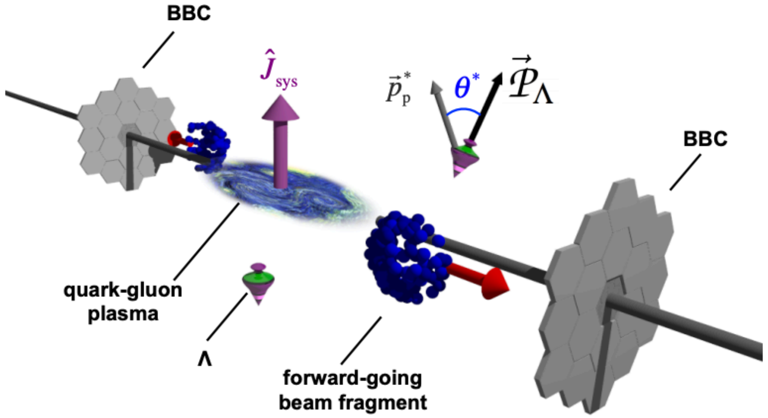
BNL

08.06.2020

Ideas are inspired from discussions with Raju, Dima, Elke, Thomas, et al…

Lambda polarization

STAR (nature, 2018)



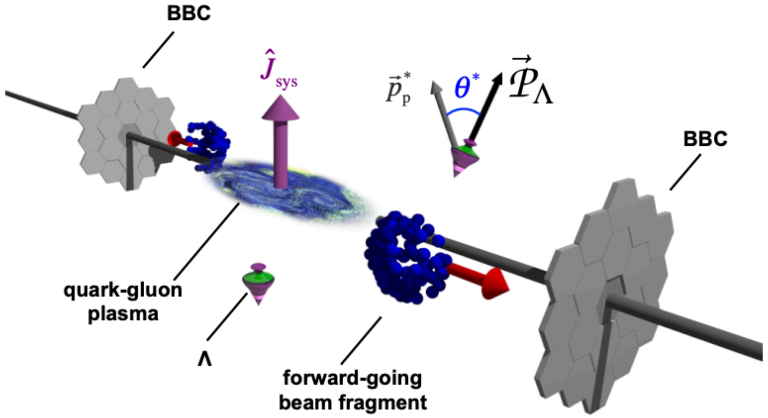
- Lambda hyperon - parity-violating nature of its weak decay – results in *angular distribution* of the decay proton preferentially emitting along the lambda direction

- Great tool for studying spin and polarization effects.
  - Lambda polarization was observed in ee. (BELLE)
  - Lambda polarization was observed in ep unpolarized DIS. (HERMES)
  - Global Lambda polarization in heavy ion collisions – vorticity (STAR)
  - Lambda polarization with respect to transversely polarized axis in polarized DIS (COMPASS), Null result

$$\frac{dN}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$$

Lambda polarization

STAR (nature, 2018)



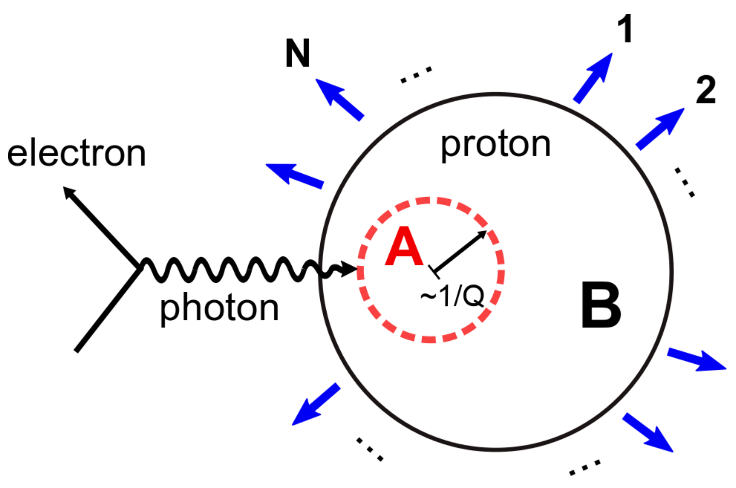
- Lambda hyperon - parity-violating nature of its weak decay – results in *angular distribution* of the decay proton preferentially emitting along the lambda direction

- Great tool for studying spin and polarization effects.
  - Lambda polarization was observed in ee. (BELLE)
  - Lambda polarization was observed in ep unpolarized DIS. (HERMES)
  - Global Lambda polarization in heavy ion collisions – vorticity (STAR)
  - Lambda polarization with respect to transversely polarized axis in polarized DIS (COMPASS), Null result

$$\frac{dN}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$$

These topics are deeply related to TMD physics, e.g., TMD PDFs, TMD FFs, which are in line with the EIC physics.

Questions



- Can I use lambda polarization to study entanglement? From two distinct regions that are casually disconnected, e.g., Region A & B. (***Ideas from Dima, Thomas, and our paper***)

- Are quarks/gluons entangled in polarized and/or unpolarized proton?

- What's their dynamical picture from high-x to low-x? Is there a quantum to classical transition? (***saturations? Raju's novel idea for entanglement***)

- What can we learn from their (not) entanglement/correlations? Do these measurements constrain TMDs PDF or FFs? (***questions inspired by Elke's comments***)

- Or turn the question around, can TMDs predict such correlations?

Questions

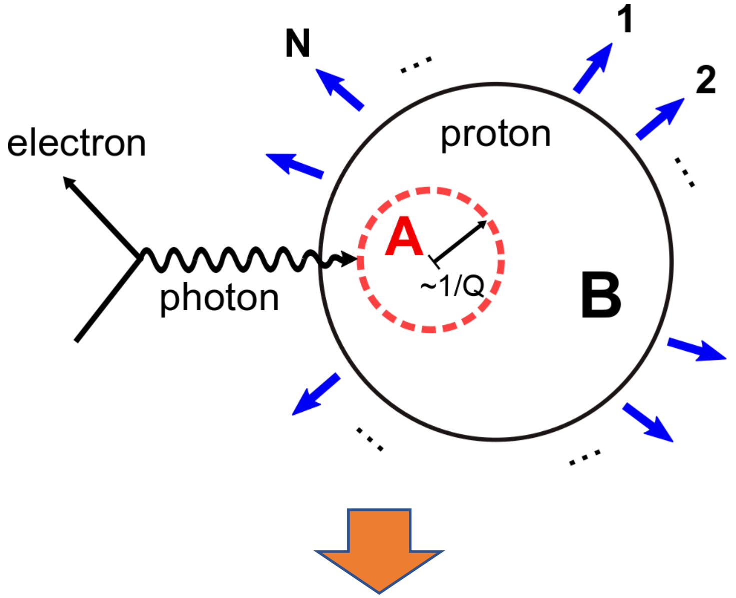
- Can I use lambda polarization to study entanglement? From two distinct regions that are casually disconnected, e.g., Region A & B. (***Ideas from Dima, Thomas, and our paper***)

- Are quarks/gluons entangled in polarized and/or unpolarized proton?

- What's their dynamical picture from high-x to low-x? Is there a quantum to classical transition? (***saturations? Raju's novel idea for entanglement***)

- What can we learn from their (not) entanglement/correlations? Do these measurements constrain TMDs PDF or FFs? (***questions inspired by Elke's comments***)

- Or turn the question around, can TMDs predict such correlations?



Generally, I would like to build a correlation measurement:

1. Lambda from current region
2. Lambda from target region
3. Their correlation as a function of rapidity gap.

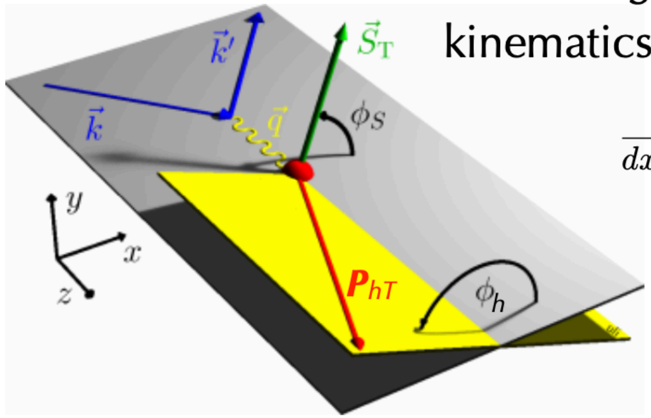
*Correlations can be with respect to each other or a common quantization axis.

Established measurements

– focus on current fragmentations

SIDIS

kinematics & cross section



$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{hT}^2} \sim \quad A(y)\,F_U \quad + \quad B(y)\,\cos 2\phi_h\,F_U^{\cos 2\phi_h}$$
$$+\,C(y)\,F_{LL} \quad + \quad B(y)\,\sin 2\phi_h\,F_L^{\sin 2\phi_h}$$
$$+\;A(y)\,\sin(\phi_h-\phi_S)\,F_T^{\sin(\phi_h-\phi_S)}$$
$$+\;B(y)\,\sin(\phi_h+\phi_S)\,F_T^{\sin(\phi_h+\phi_S)}$$
$$+\;B(y)\,\sin(3\phi_h-\phi_S)\,F_T^{\sin(3\phi_h-\phi_S)}$$
$$+\;C(y)\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}$$

- build $\dfrac{d\sigma^{\uparrow}(\phi_h,\phi_S)-d\sigma^{\downarrow}(\phi_h,\phi_S+\pi)}{d\sigma^{\uparrow}(\phi_h,\phi_S)+d\sigma^{\downarrow}(\phi_h,\phi_S+\pi)}$ (or similar when electron is polarized)

- isolate specific azimuthal component, coefficient ~ $\dfrac{F_X^{xxx}(x,z,P_{hT}^2;Q^2)}{F_U(x,z,P_{hT}^2;Q^2)}$

Azimuthal Spin Asymmetry $\equiv A_X^{xxx}(x,z,P_{hT}^2;Q^2)$

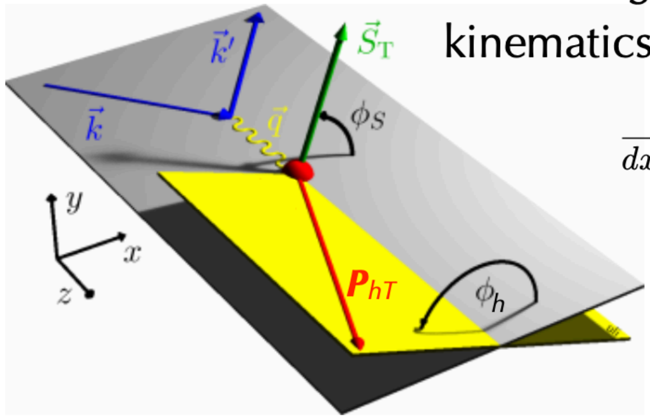
(Nice summary by Marco Redici's slides, https://indico.cern.ch/event/797767/contributions/3682622/attachments/1965784/3268756/6_radici.pdf)

Established measurements

– focus on current fragmentations

SIDIS

kinematics & cross section



$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{hT}^2} \sim \quad A(y)\,F_U \;+\; B(y)\,\cos 2\phi_h\,F_U^{\cos 2\phi_h}$$
$$+\,C(y)\,F_{LL} \;+\; B(y)\,\sin 2\phi_h\,F_L^{\sin 2\phi_h}$$
$$+\;A(y)\,\sin(\phi_h-\phi_S)\,F_T^{\sin(\phi_h-\phi_S)}$$
$$+ \dots$$
$$+ \dots$$
$$+ \dots$$

All 8 asymmetries have been measured (plus more at subleading twist..)

- build $\dfrac{d\sigma^{\uparrow}(\phi_h,\phi_S) - d\sigma^{\downarrow}(\phi_h,\phi_S+\pi)}{d\sigma^{\uparrow}(\phi_h,\phi_S) + d\sigma^{\downarrow}(\phi_h,\phi_S+\pi)}$ (or similar w

- isolate specific azimuthal component, coefficier

Azimuthal Spin Asymmetry

hermes

$A_U^{\cos 2\phi_h}$ on p & D targets *arXiv:1204.4161*

$A_L^{\sin 2\phi_h}$ on p→ *hep-ph/0608048*

$A_T^{\sin(\phi_h-\phi_S)}$ on p↑ *arXiv:0906.3918*

$A_T^{\sin(\phi_h+\phi_S)}$ on p↑ *arXiv:1006.4221*

COMPASS

$A_U^{\cos 2\phi_h}$ on D targets *arXiv:1401.6284*

A_{LL} on p→ *arXiv:1509.03526*

A_{LL} & $A_L^{\sin 2\phi_h}$ on p→ *arXiv:1509.03526* on D→ *arXiv:1609.06062*

$A_T^{\sin(\phi_h-\phi_S)}$ on p↑ { *arXiv:1205.5122*, *arXiv:1609.07374* }

$A_T^{\sin(\phi_h+\phi_S)}$ on p↑ *arXiv:1205.5121*

} *arXiv:1005.5609*, *arXiv:1408.4405*

$A_T^{\sin(\phi_h\pm\phi_S)}$ on D↑ *arXiv:0802.2160*

$A_T^{\sin(\phi_h\pm\phi_S)}$ & $A_{LT}^{\cos(\phi_h-\phi_S)}$ & $A_T^{\sin(3\phi_h-\phi_S)}$ on p↑ *arXiv:1512.06590*

Jefferson Lab

Hall A $A_T^{\sin(\phi_h\pm\phi_S)}$ on ³He↑ with π *arXiv:1106.0363* with K *arXiv:1404.7204*

$A_T^{\sin(\phi_h-\phi_S)}$ on ³He↑ with π *arXiv:1311.1866*

$A_{LT}^{\cos(\phi_h-\phi_S)}$ on ³He↑ *arXiv:1108.0489*

$A_T^{\sin(3\phi_h-\phi_S)}$ on ³He↑ *arXiv:1312.3047*

Hall B A_{LL} & $A_L^{\sin 2\phi_h}$ on p→ *arXiv:1003.4549*

(Nice summary by Marco Redici's slides, https://indico.cern.ch/event/797767/contributions/3682622/attachments/1965784/3268756/6_radici.pdf)

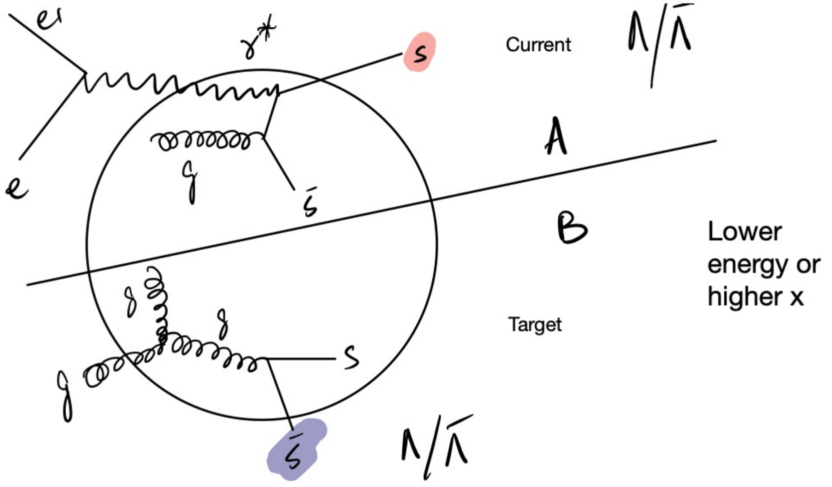
Proposing new measurements

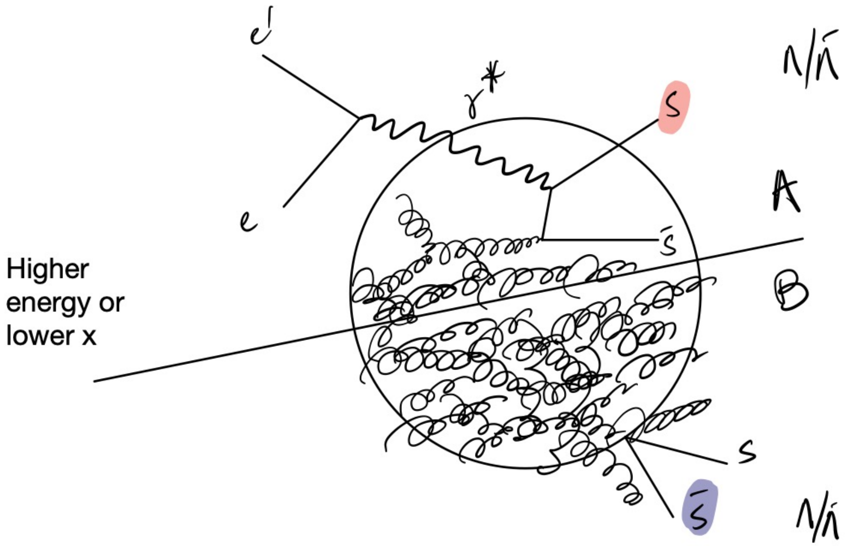
- Correlations between two lambdas, can be studied with Same-sign (SS) or Opposite-sign (OS), namely lambda-lambda or lambda-anti-lambda.

- Correlations between current and target regions or large rapidity gap.

- Correlations with respect to each other, or simultaneously with respect to a common axis, e.g., nucleon polarization axis.

- Current vs Target correlations. Entanglement?





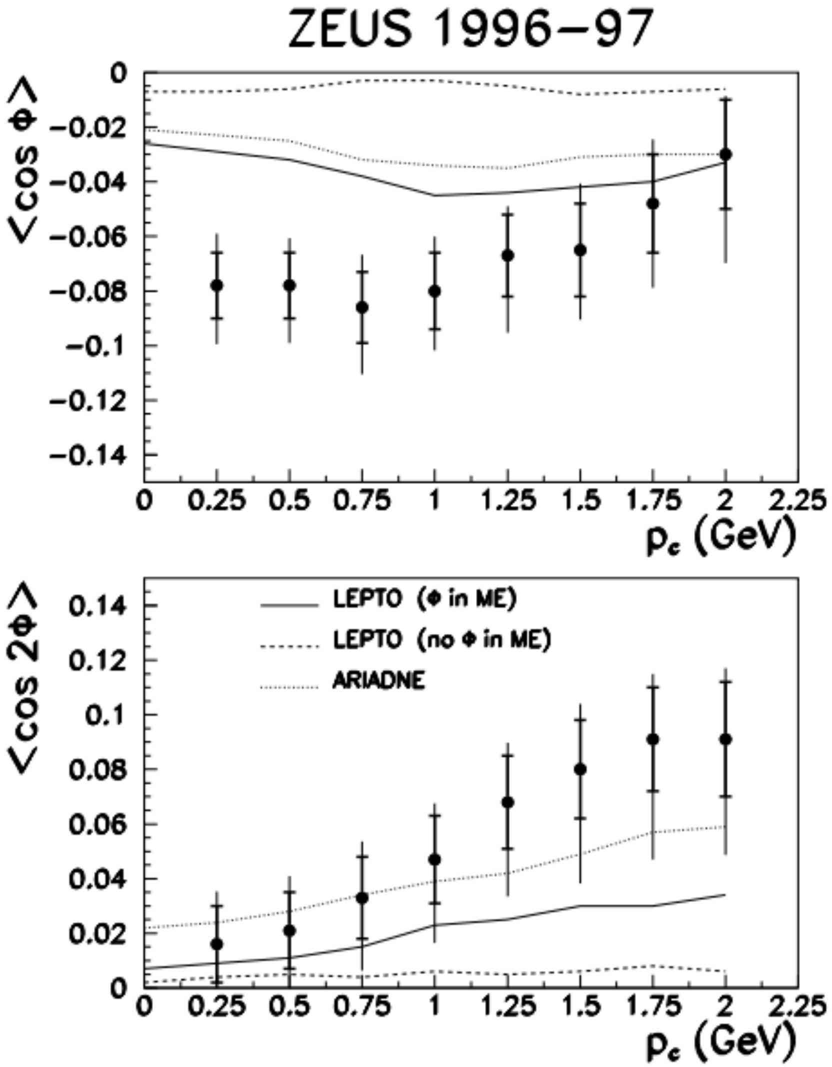
Tool

- Monte Carlo generator, PYTHIA 8, to establish baseline. No spin or nontrivial effect should be expected.
- DIS process at EIC top energy. (18 x 275 GeV^2 ep)
- $Q^2 > 1$ and $0.05<y<0.95$
- Generated 2 billions events with Q2 > 1.
- With EIC detector coverage in mind.

- First to establish the observables and correlators.

HCM – charged pion asymmetry

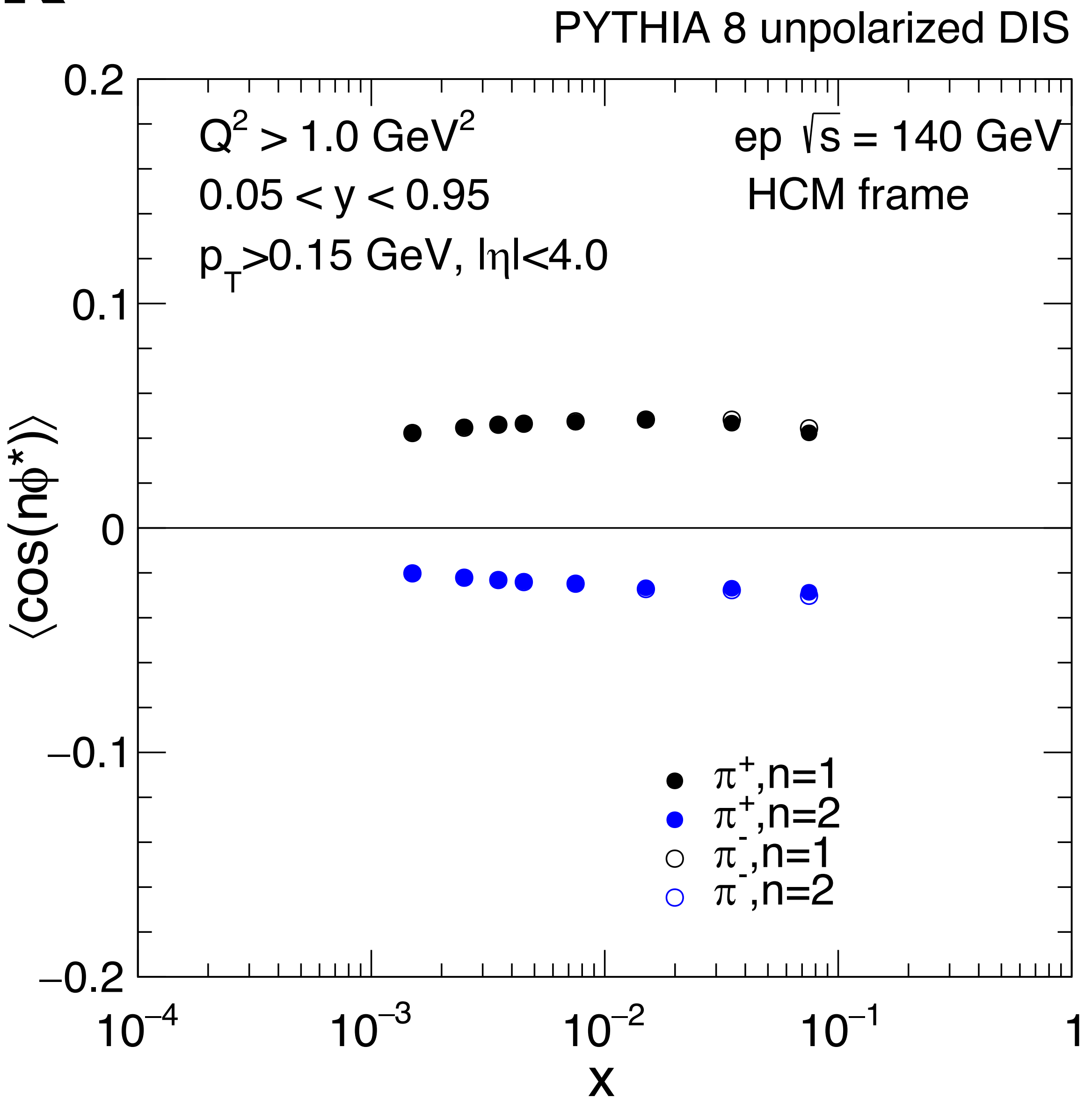
- Boer-Molders distribution uses unpolarized DIS ep and look at <cos(phi*)> and <cos(2phi*)>, have been measured at ZEUS, HERMES, COMPASS.
- MC does have nonzero correlations, seen by ZEUS using Ariadne and LEPTO
- (I don’t find much explanations why nonzero in MCs, yet)



https://arxiv.org/pdf/hep-ex/0003017.pdf

Pythia 8 – first look

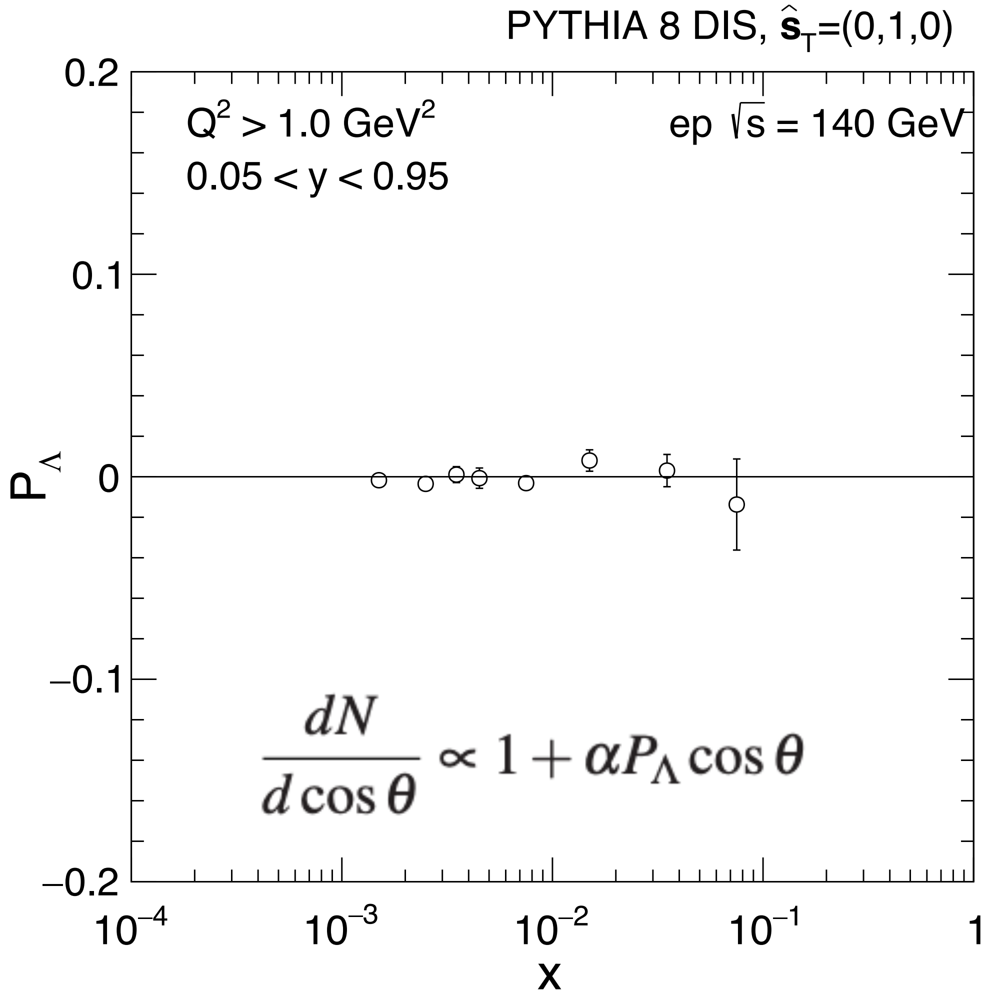
- Used charged pions and both cos(phi*) and cos(2phi*)
- Observations are very similar to what ZEUS showed.
- No charge separations are seen. Same for pi+ and pi-
- Good baseline.



Pythia 8
– artificial transversely polarized proton

- To establish the observable, I used (0,1,0) as transversely polarized nucleon direction, similar to HERMES or COMPASS. Of course, the underlying physics is still unpolarized DIS.

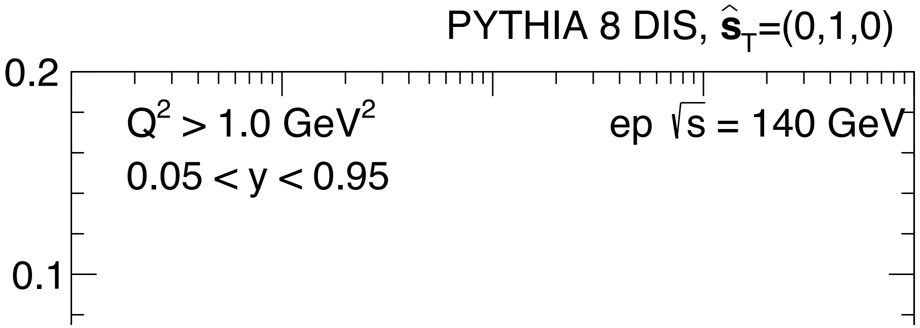
- Inclusive lambda polarizations, including lambda and lambda-bar.

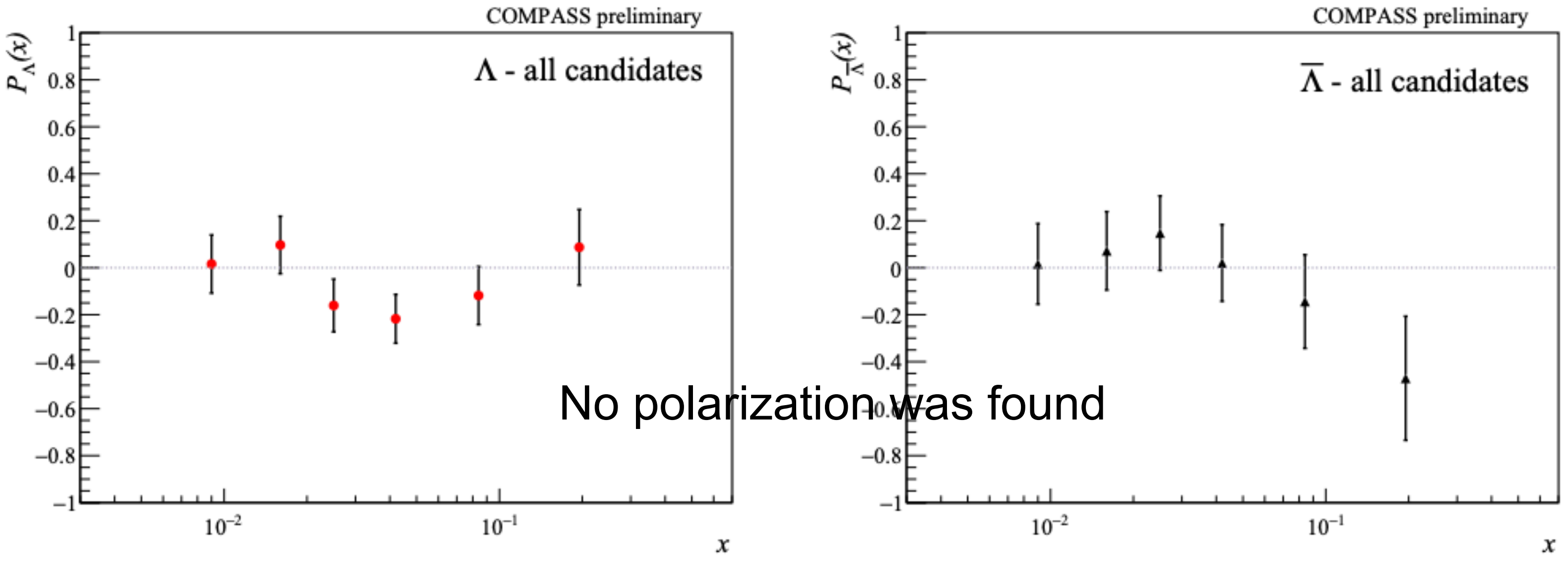


Pythia 8
– artificial transversely polarized proton

- To establish the observable, I used (0,1,0) as transversely polarized nucleon direction, similar to HERMES or COMPASS. Of course, the underlying physics is still unpola

- Inclusive lambda pola lambda and lambda-



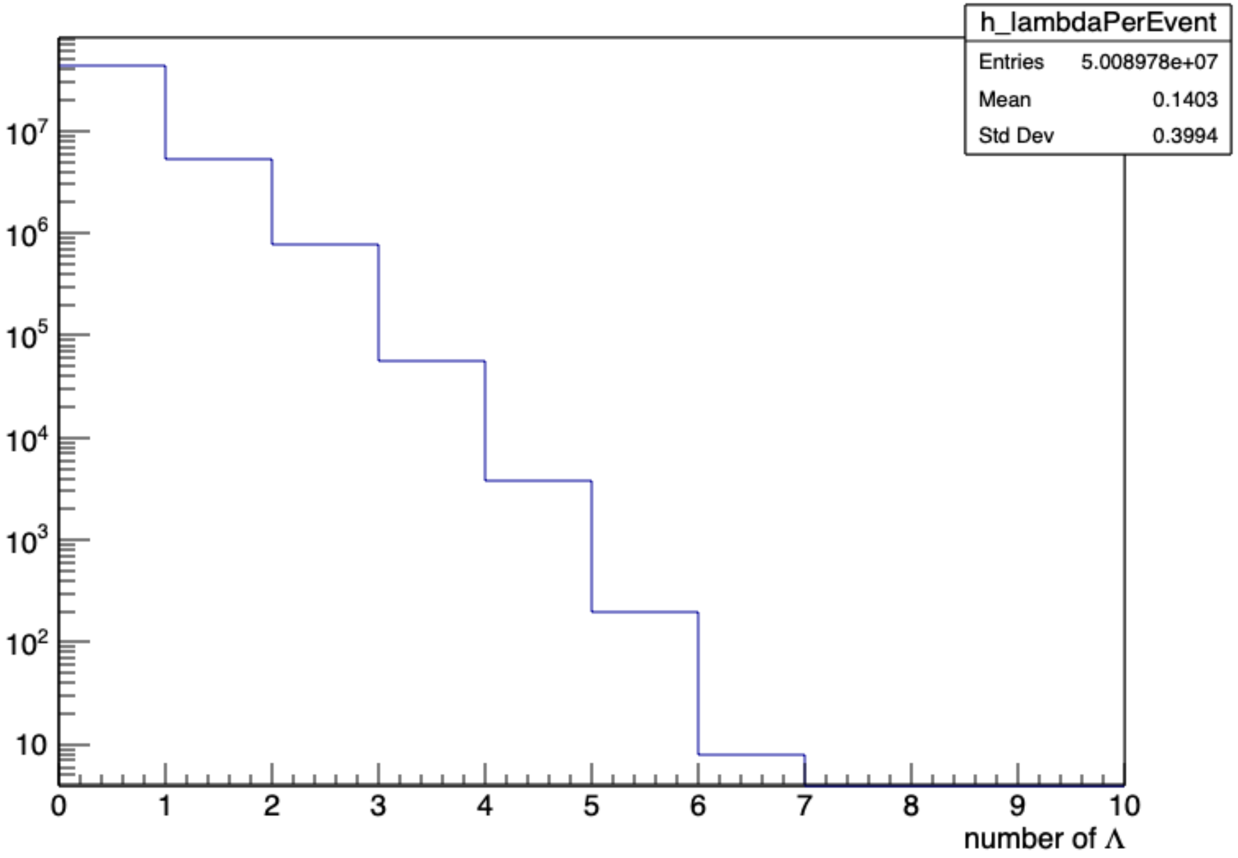


No polarization was found

Exact same measurement at COMPASS, https://arxiv.org/pdf/1901.01735.pdf

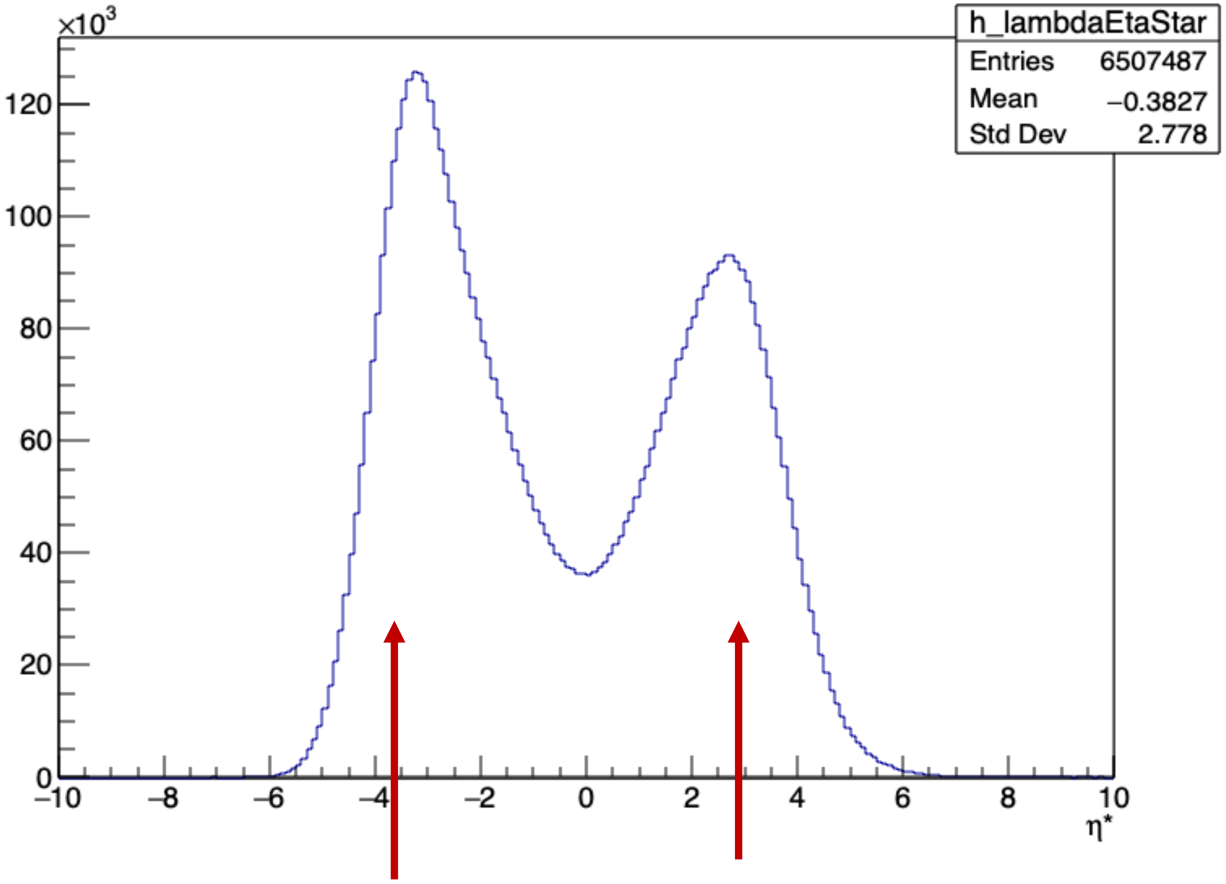
Pythia 8 – double lambdas

2B events of DIS



Number of lambdas per event distribution

HCM frame lambda eta* distribution



Target lambdas

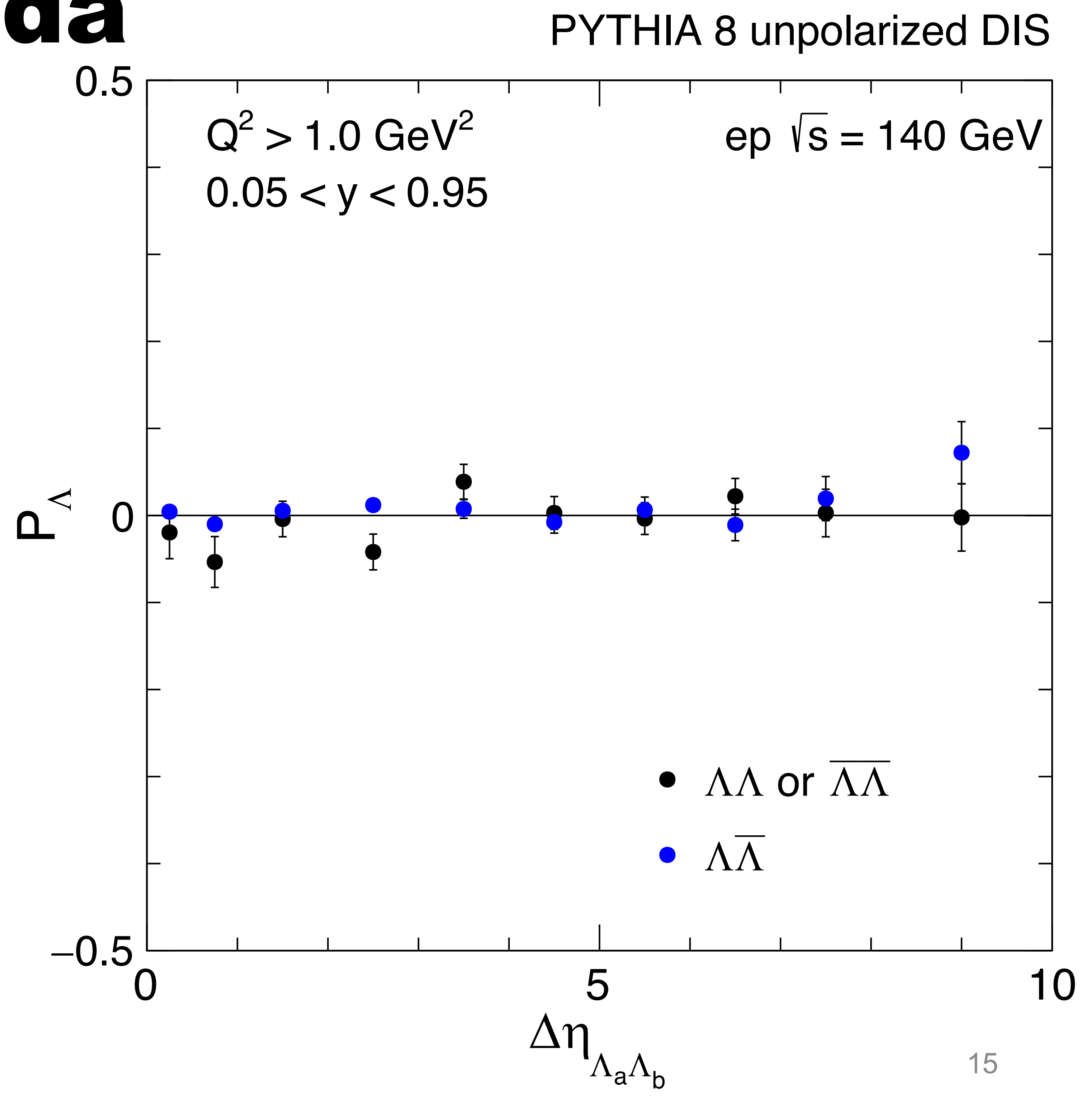
Current lambdas

Lambda polarization w.r.t another lambda

- Lambda 1, use its proton daughter in lambda 1's rest frame, with respect to the Lambda 2 momentum direction.

$$\frac{dN}{d\cos\theta} \propto 1 + \alpha P_\Lambda \cos\theta$$

- As a function of two lambdas' rapidity gap
- SS and OS are separated.
- At large rapidity gap, if strange quarks are entangled, will there be correlation? In either polarized or unpolarized target

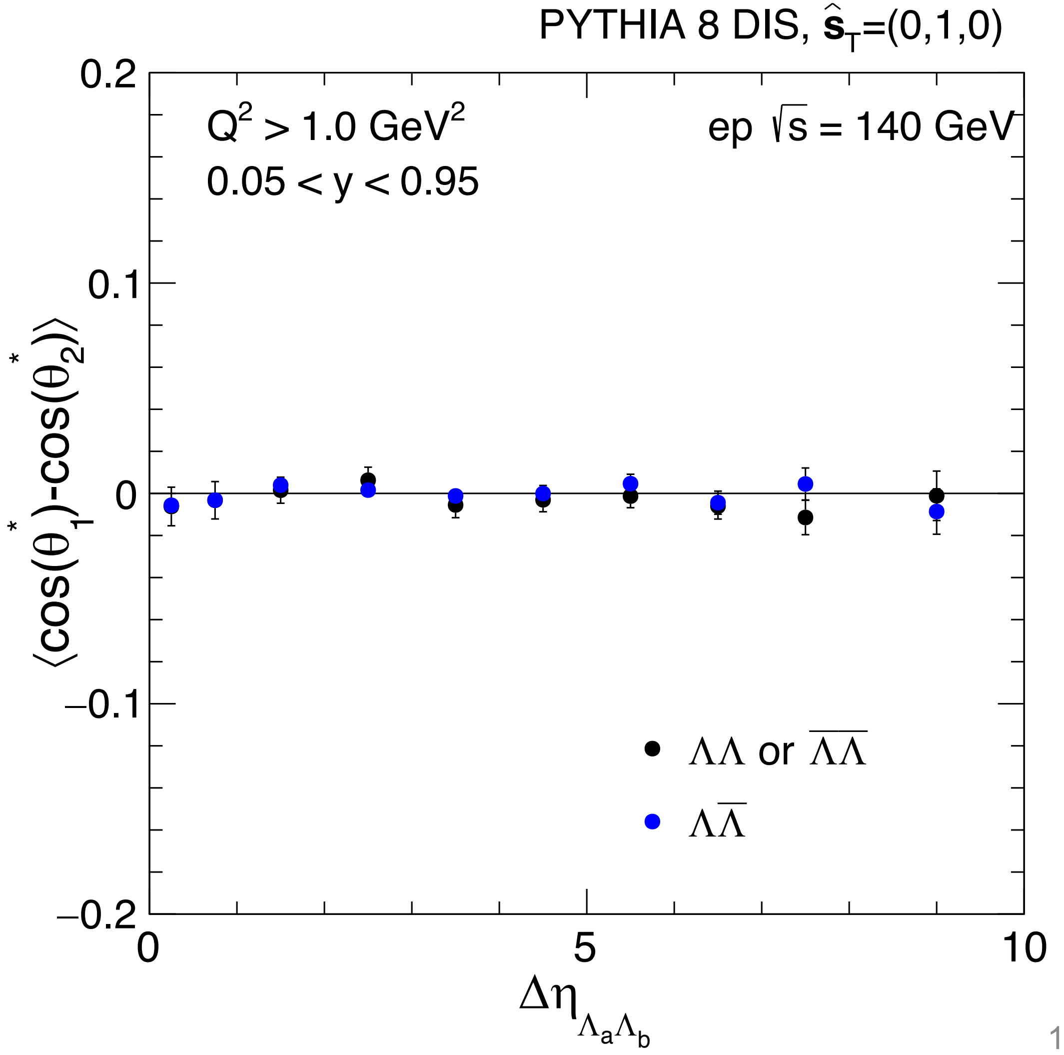


Double lambda polarization with respect to nucleon spin

- Theta*1 is the lambda 1's proton daughter in lambda 1's rest frame with respect to (0,1,0). Similar for lambda 2.

- Alternative observable can be <cos(theta*1-theta*2)>

- Analogy to CME observable for charge separations. Should expect an OS and SS separation?



Summary and next step

- Pythia 8 has been looked at and baselines are established for these new observables.
- MC has no signal, meaning no trivial kinematics or acceptance can give any signal.
- Working on CHSH inequality test (Bell's inequality test) using two lambdas. (some progress has been made but not finish yet)
- Similar (~exact) observables can be built in pp collisions? Test at the LHC and RHIC? STAR forward upgrades with single polarized proton beam?