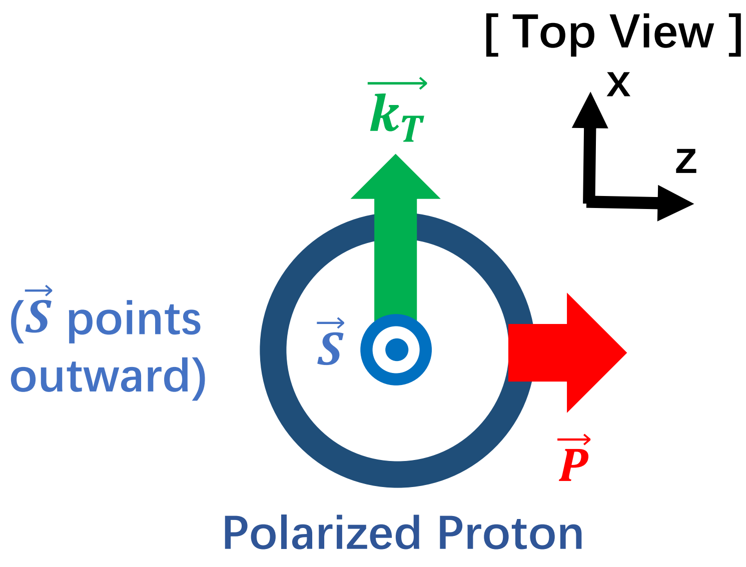
Measurement of transverse single-spin asymmetries for di-jet production in polarized p+p collisions at $\sqrt{S}$= 200 GeV at STAR

Huanzhao Liu, for the STAR Collaboration

Center for Exploration of Energy and Matter, Indiana University

DNP 2019, Crystal City, VA

Sivers Effect in pp Dijet Production



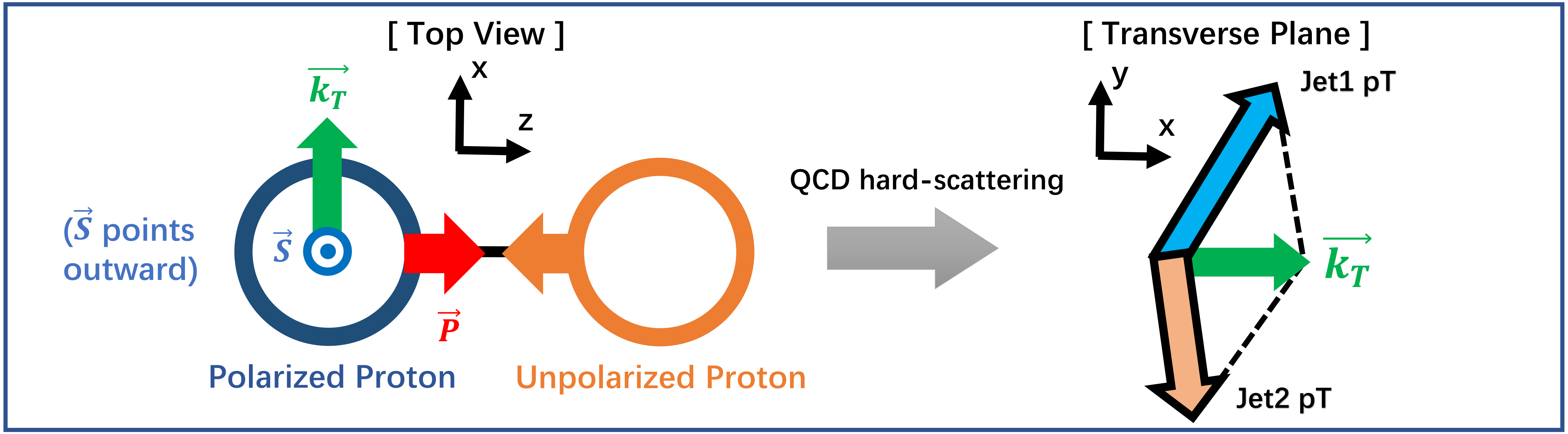
Sivers Effect: For a **transversely polarized proton** with spin $\vec{S}$ and momentum $\vec{P}$, the **constituent partons** have a **flavor-dependent momentum preference** $\vec{k}_T$ that follows:

$$\left\langle \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T) \right\rangle \neq 0$$

Measuring the Sivers effect in dijet production:

- Non-zero effects indicate possible **contributions from partonic angular momentum to the proton spin**.
- Important to our understanding of **QCD factorization.**
- Test if ***u*-quark and *d*-quark contributions are opposite in sign and different in magnitude.**

Sivers Effect in pp Dijet Production



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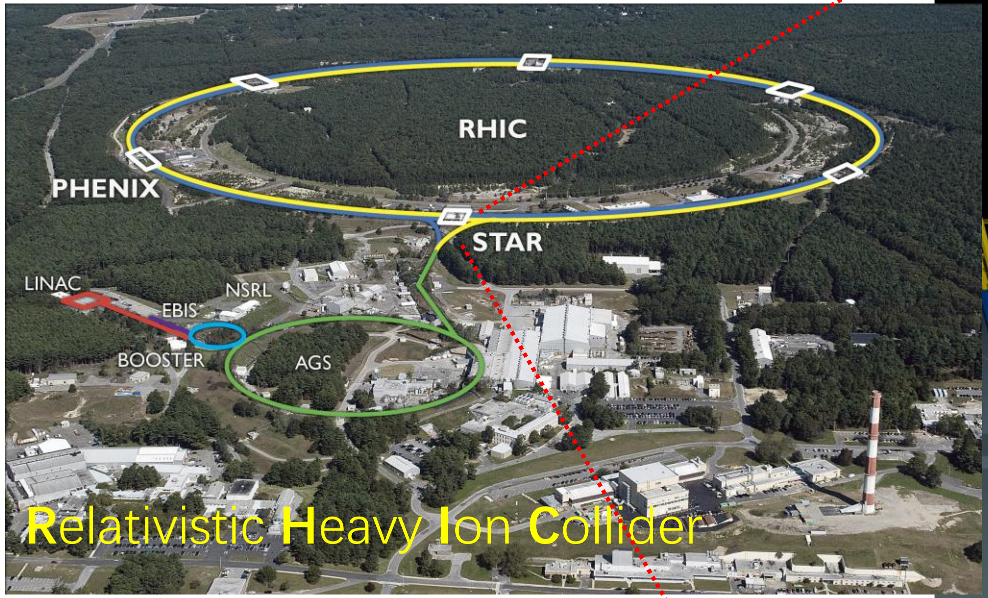
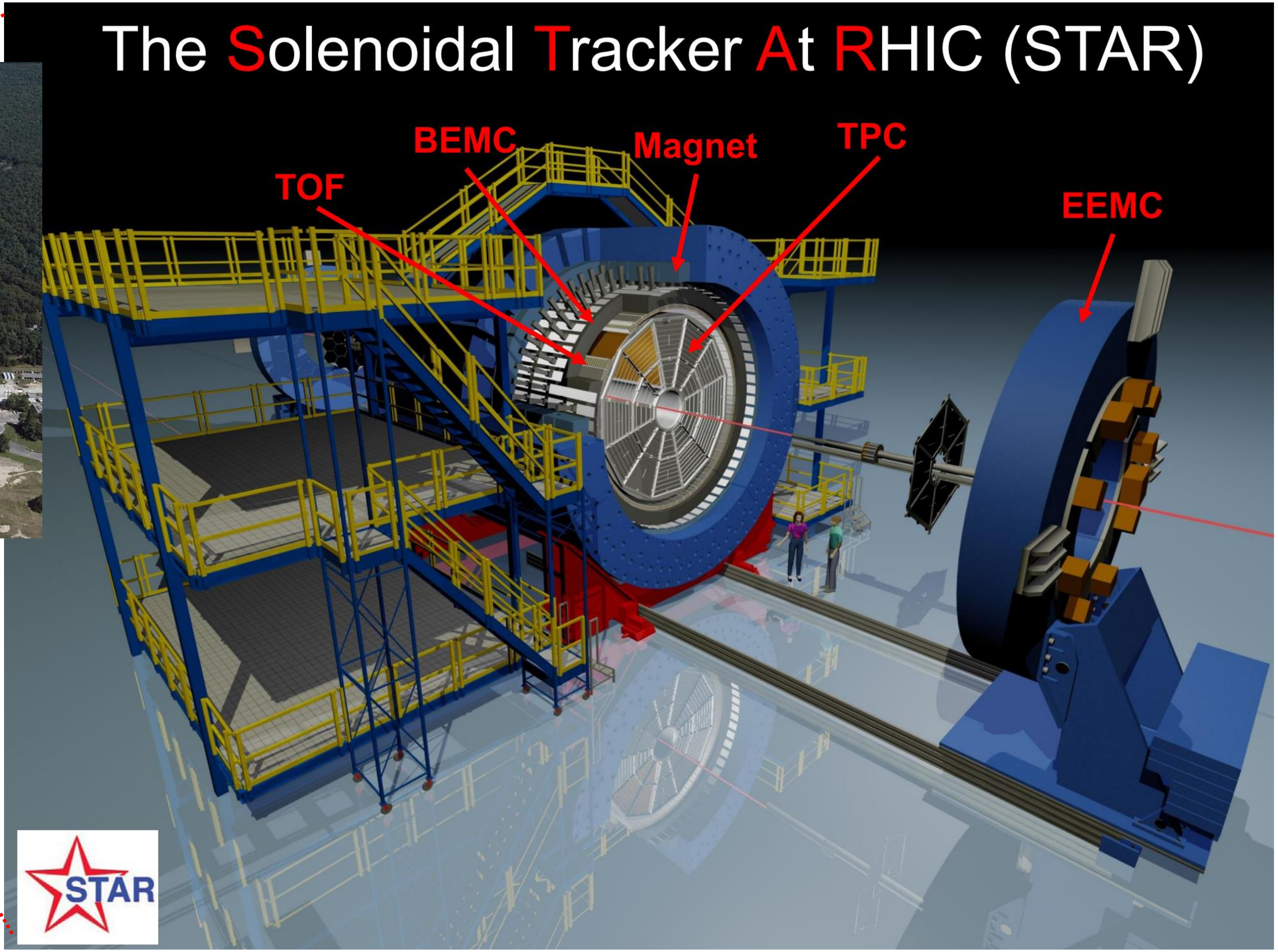
RHIC & STAR Detector





- STAR detector is capable of **reconstructing tracks and identifying charged particles in $|\eta|<1.3$**, and **measuring EM particle energies in $-1< \eta <2$**.
- Jets are reconstructed using standard STAR anti-Kt method.

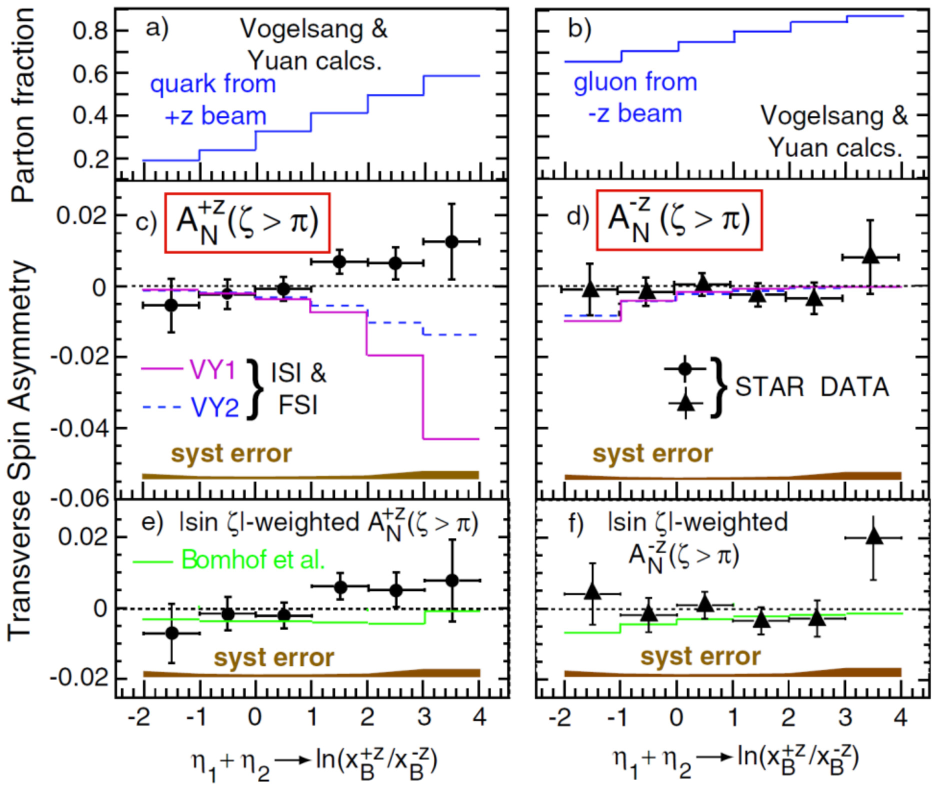
STAR 2006 Analysis Result & New 2012+2015 Improvements

In the 2006 analysis, the result was found to be consistent with zero within dominant statistical uncertainties.

With data taken in 2012 and 2015, the current analysis sees:

- **33 times larger data set**
- **Fully reconstructed jets (no tracking for 2006 data)**
- **Employ a tagging method to enhance *u*-quark and *d*-quark signals**

STAR Collab. PhysRevLett 99 142003



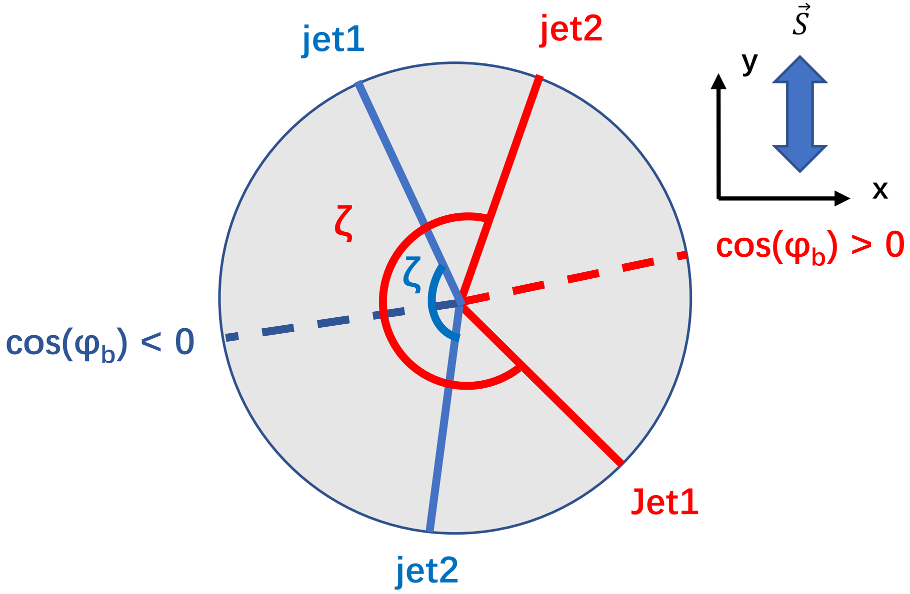
Asymmetry is plotted as a function of the sum of dijet pseudo-rapidities ($\eta1 + \eta2 \propto \ln(\frac{x1}{x2})$) since Sivers effect is expected to be dependent on parton *x*.

Observable for Probing the Sivers Effect

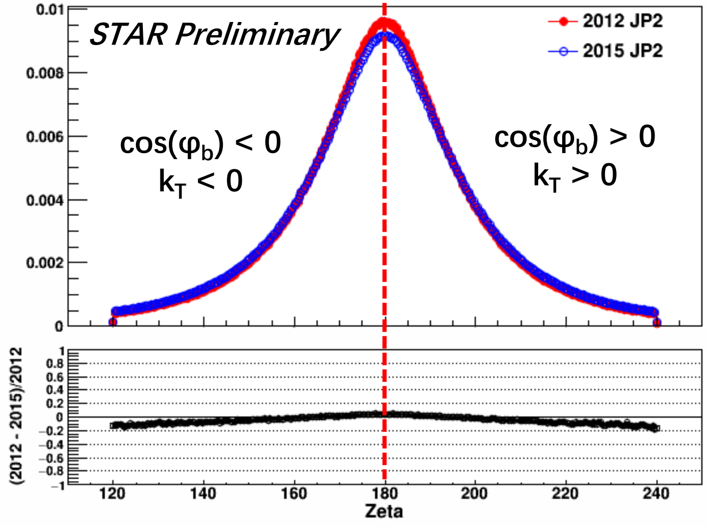
The Sivers asymmetry can be probed via the signed opening angle ζ . This observable is also used in the previous 2006 measurement.

- φ_b is di-jet bisector angle (the ray points to the tilt direction of the two jets)
- ζ is the opening angle of dijet in the transverse plane, and

$$\zeta > \pi \text{ when } \cos(\varphi_b) > 0$$
$$\zeta < \pi \text{ when } \cos(\varphi_b) < 0$$



Distribution of ζ [deg] in 2012 and 2015 data taken by JetPatch2 Trigger*



Asymmetry is directly extracted as a **centroid shift of ζ between spin up and spin down states** to avoid various systematic uncertainties.

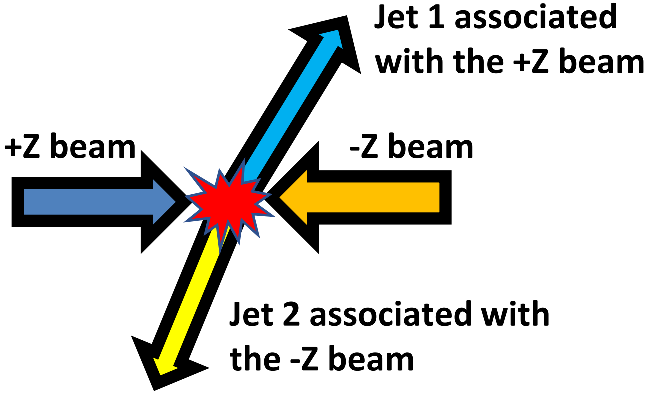
The **centroid shift** will be corrected for an average of 59% Polarization.

* J**e**tPatch**2**(**1**) trigger:
jet energy in $\Delta\eta \times \Delta\varphi = 1 \times 1$ "jet patch" > 7.3 (5.4)GeV

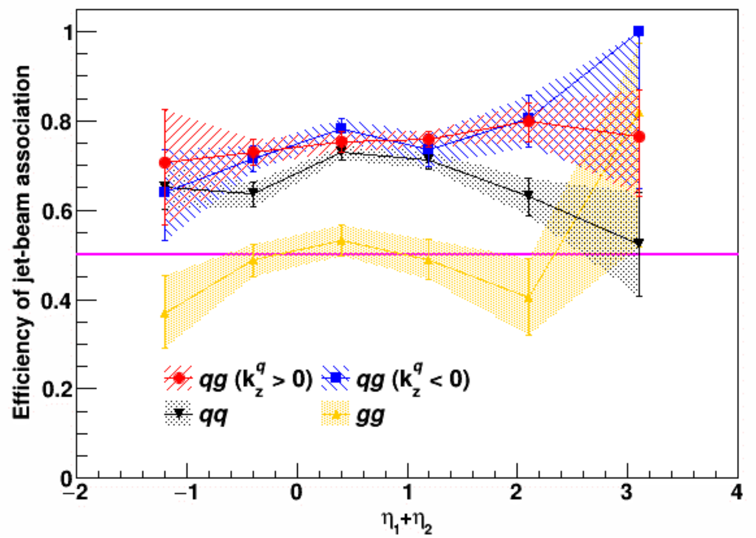
Jet-Beam Association

To figure out the "parton flow" from beam to jets, a jet-beam association is performed.

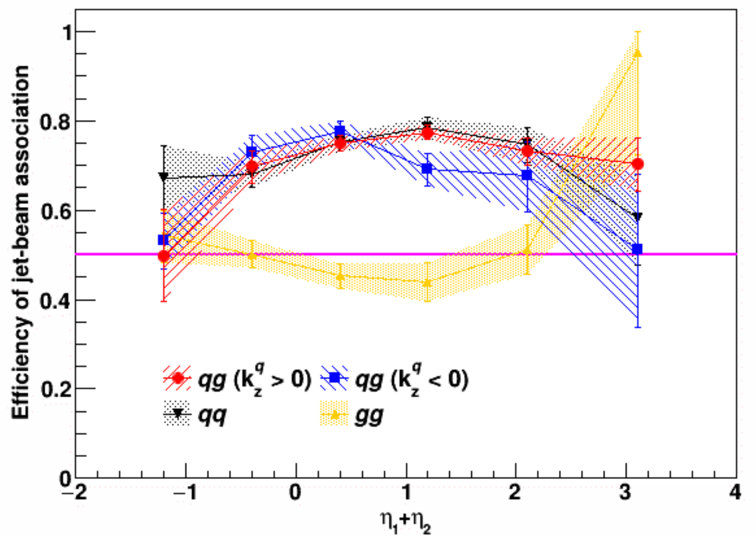
We assume the forward (backward) jet is more likely fragmented from the parton that comes out of +z (-z) beam.



Association efficiency for Events taken by JetPatch2 Trigger (2012 embedding with Pythia6)



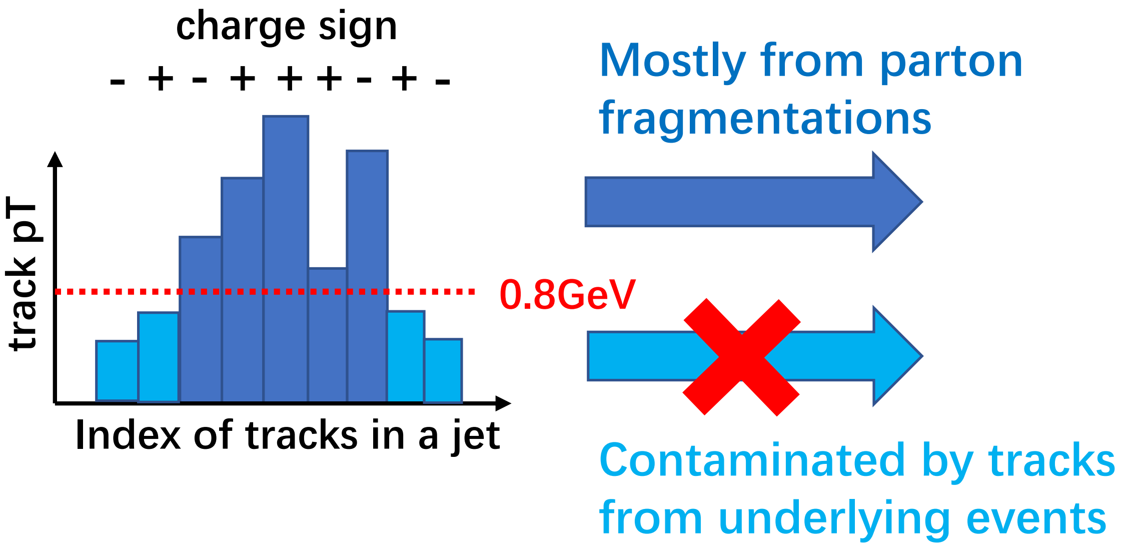
Association efficiency for Events taken by JetPatch1 Trigger (2012 embedding with Pythia6)



⋆ The efficiency represents how often we get the association right.
⋆ The error bar/band represents the statistical error.

Flavor Tagging

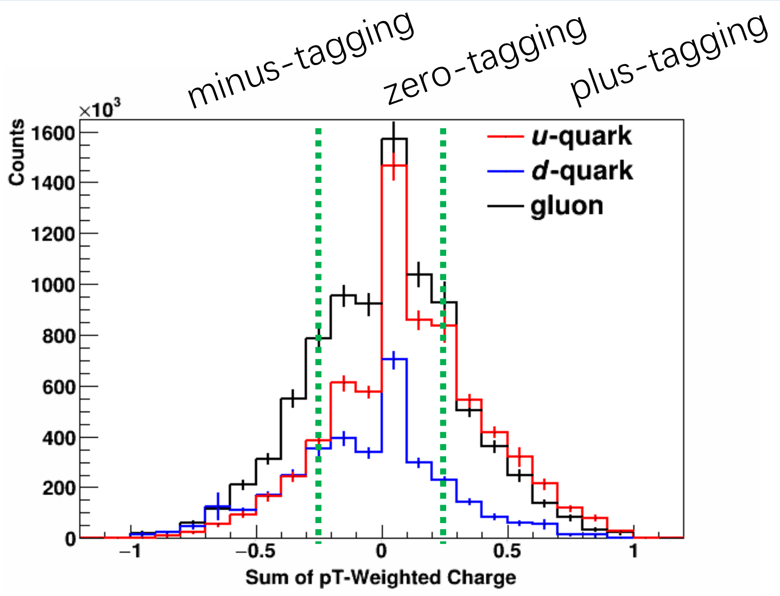
We employ **a method of tagging on the associated jets** to enhance the purities of ***u*-quarks and *d*-quarks** separately.



$$Q = \sum_{\substack{all\ the\ tracks \\ with\ pT>0.8GeV}} \frac{track\ pT}{jet\ pT} \cdot track\ charge$$

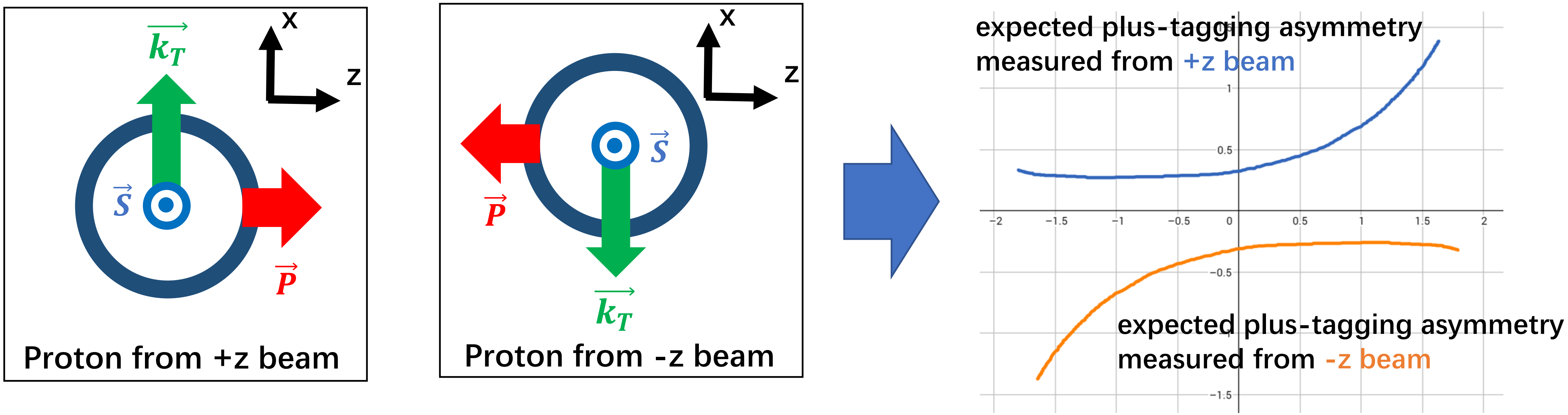
Data is divided into three groups:

1. **Plus-tagging** ($Q > 0.25$) : enhances the u-quark purity.
2. **Minus-tagging** ($Q < -0.25$) : enhances the d-quark purity.
3. **Zero-tagging** ($-0.25 < Q < 0.25$) : u / d fractions are more balanced than the other two taggings.



Distribution of Q for Events taken by JetPatch2 Trigger (2012 embedding with Pythia6)

STAR Coordinate System & the Patterns of Signals



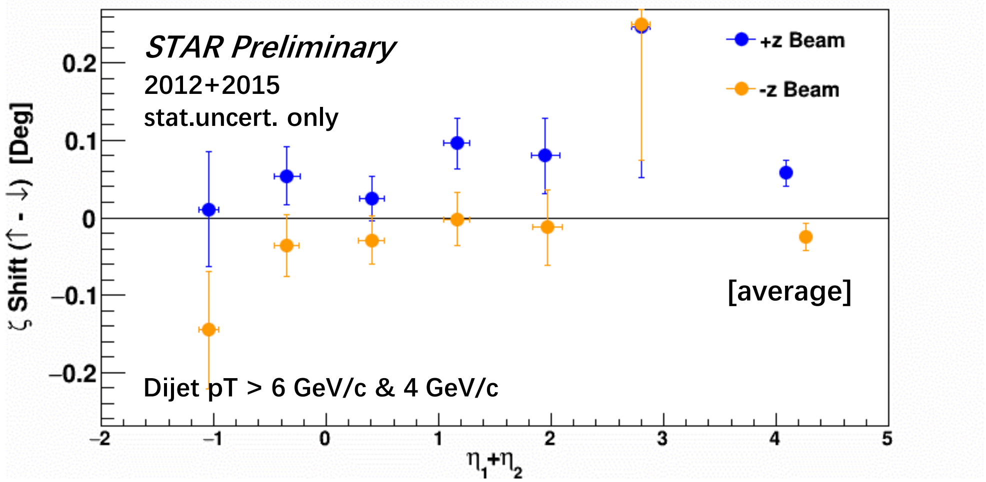
In STAR's geometric frame:

- If one expects the asymmetry in **plus-tagging** to be **"positive" for the +z Beam**, it will be **"negative" for the -z Beam**. Respectively, the **minus-tagging** will be expected to be **"negative" for the +z Beam** and **"positive" for the -z Beam**.
- The data for the +z Beam and the -z Beam should **look the same** if one **flips the sign of ζ shift** and **flips the sign of η1+ η2**

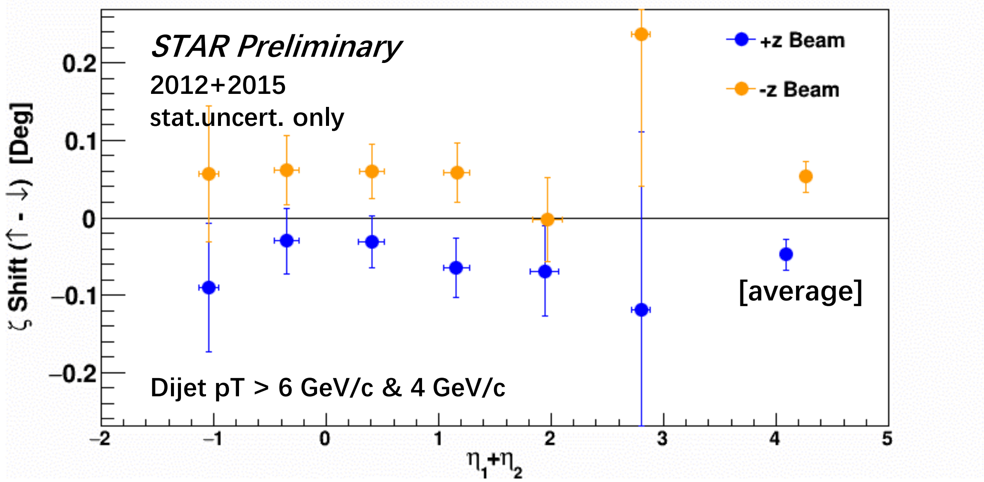
2012+2015 Data — Dijet Sivers Asymmetry

- **Asymmetries** with **associated statistical uncertainties** measured **in STAR coordinate system**.
- The points in the far right ([4,5] bin) represent the average.

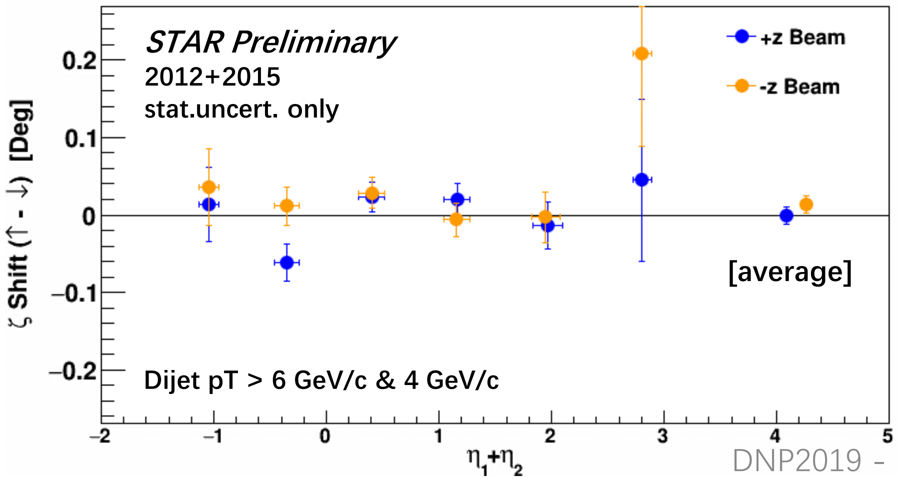
plus-tagging



minus-tagging



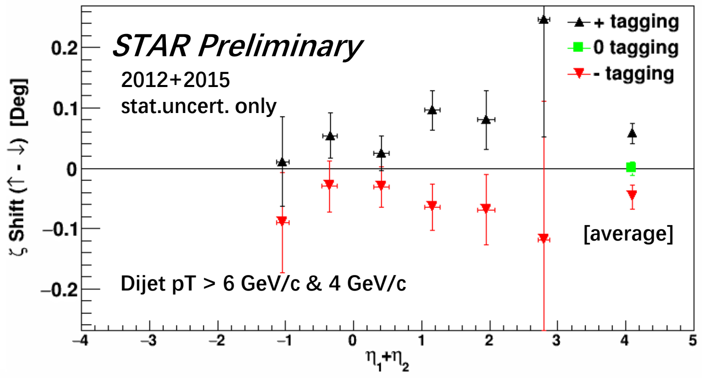
zero-tagging



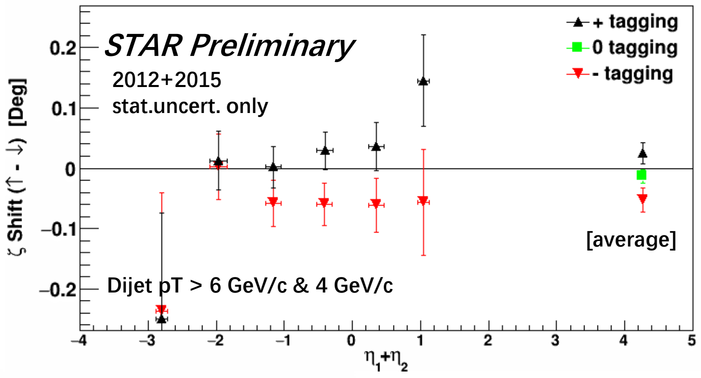
- **Some expected features of the signals are reflected in the Data !**
  - ✓ Separation between +z Beam and –z Beam
  - ✓ +z Beam and –z Beam measurements are symmetric about (0, 0), e.g., for plus vs. minus tagging.
- **Data points are mostly one-sided from the x-axis for plus-tagging and minus-tagging.**
- **Zero-tagging is consistent with zero.**

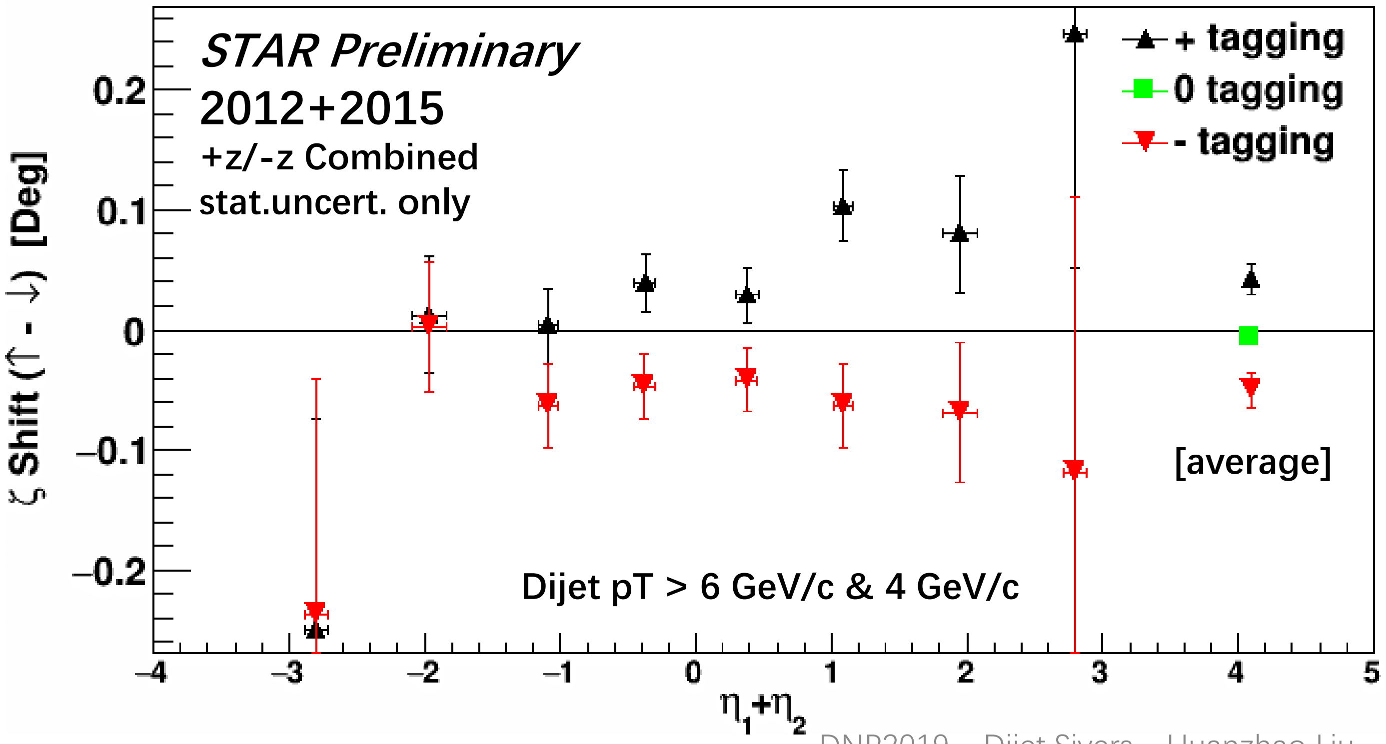
2012+2015 Data — Dijet Sivers Asymmetry

+z Beam



-z Beam (flipped to be along +z)





- Nice separation between plus-tagging and minus-tagging.
- There appears to be an η1+ η2 dependency: an enhanced kinematical selection of qg events is expected at larger η1+ η2.
- zero-tagging is consistent with zero.

Systematic Uncertainties – work in progress

Main Systematic Uncertainties

- Selection cut uncertainties
- Trigger & Reconstruction Bias
- Jet-Beam Association
- Polarization

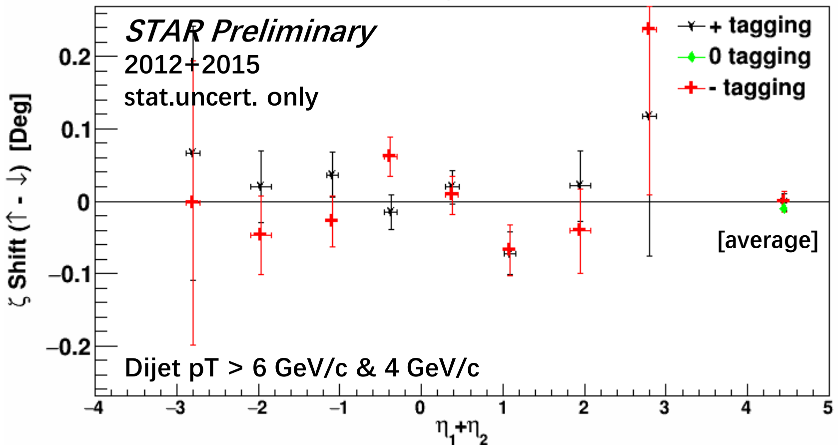
The data and null-tests suggest that we have the systematic uncertainties under control.

A class of systematic uncertainties relates to how well we understand the fraction of quarks and gluons in the data.

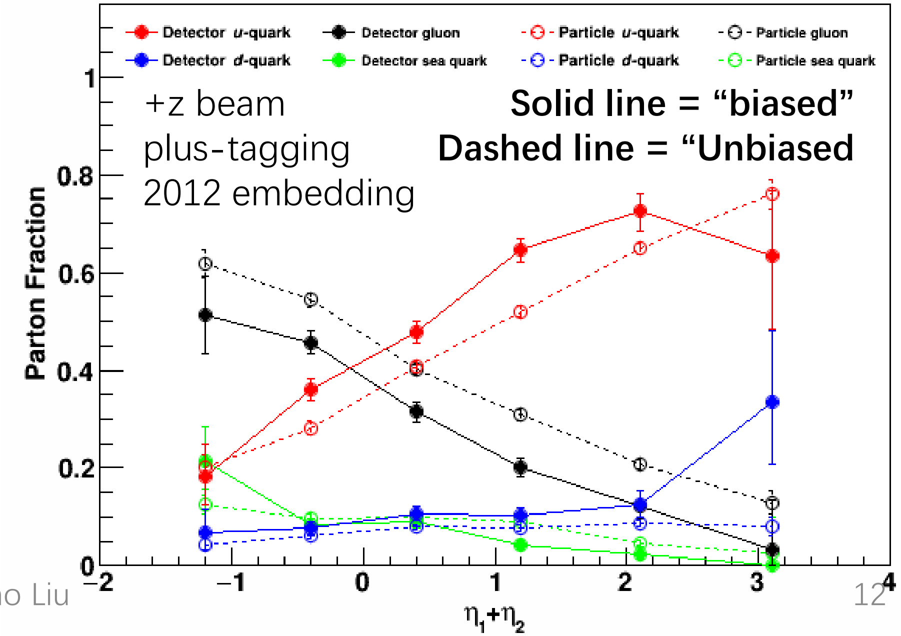
$$\Delta^{det,+/-/0}(\eta_1+\eta_2) = f_u^{det,+/-/0} * \Delta_u + f_d^{det,+/-/0} * \Delta_d + f_g^{det,+/-/0} * \Delta_g$$

- $+/-/0$ represent different taggings
- f_u , f_d , and f_g are the fractions of u/d/g, which can be estimated using simulation
- Δ_u, Δ_u, and Δ_u are the signals from u/d/g, which we don't know
- $\Delta^{det}(\eta_1+\eta_2)$ is what we measure in the data

Null-test by measuring asymmetries in the orthogonal direction



An example of shift of parton fractions due to Trigger & Reconstruction bias and association.



Conclusions

- The central value and statistical uncertainty of a Dijet Sivers Asymmetry using 2012 and 2015 polarized pp data using the STAR detector are presented.
- First observation of non-zero Sivers asymmetries in polarized proton collisions!
- Estimation of the systematic uncertainties is a work in progress, although results from the data themselves suggest these are relatively small and statistical uncertainties dominate.
- Correlation studies between <kT> and the ζ shift are currently under way using MC and toy models.

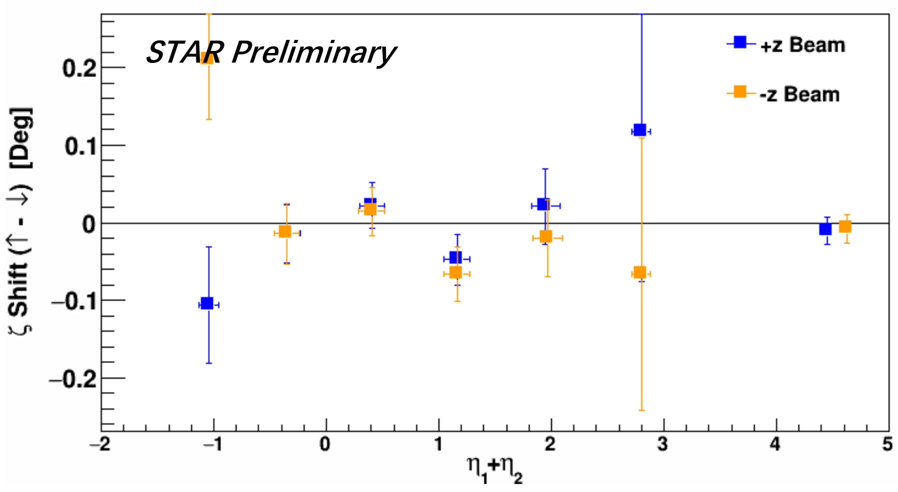
Thank you !

BACKUP

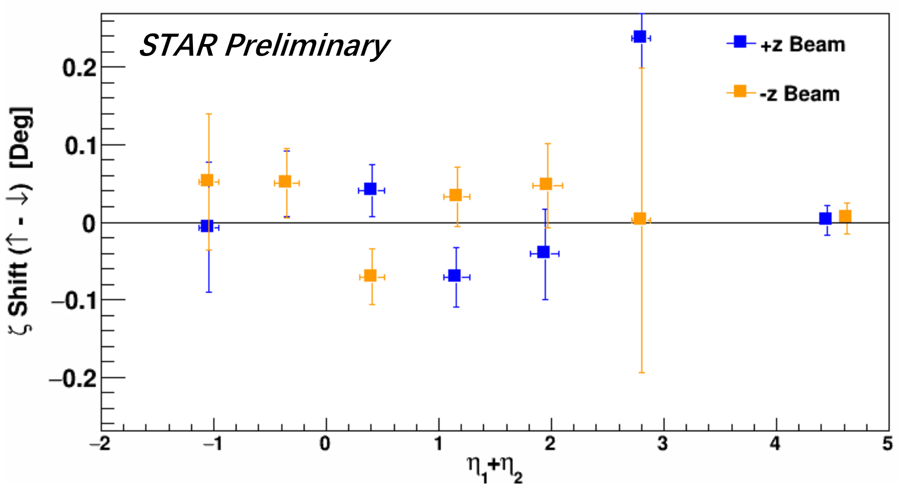
2012+2015 Data — Null-Test

The null-test looks at the up-down asymmetry of dijet opening angle.
The two points in the far right ([4,5] bin) represent the average for +z and -z beams.

plus-tagging



minus-tagging



zero-tagging