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

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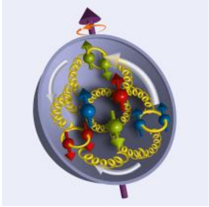
The Sivers Effect in pp Dijet Production

Proton Spin



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \left(\sum_q \mathcal{L}_q + \mathcal{L}_g\right)$$

Quark polarization : ~30% contribution

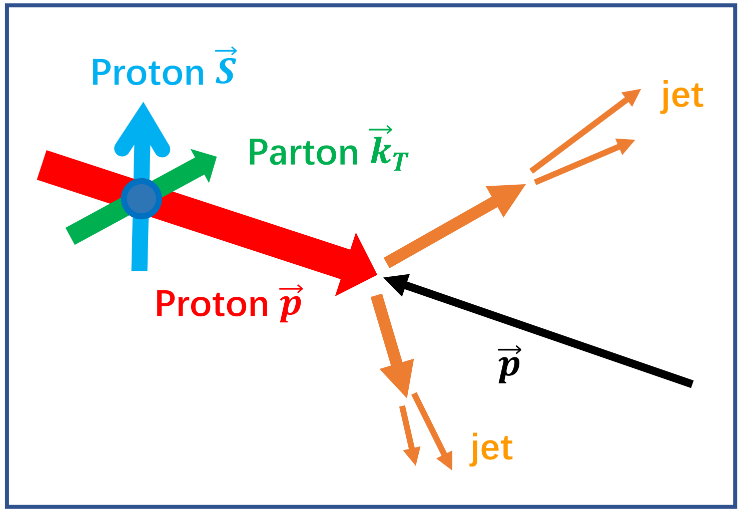
Gluon polarization : comparable to $\Delta\Sigma$, less well constrained

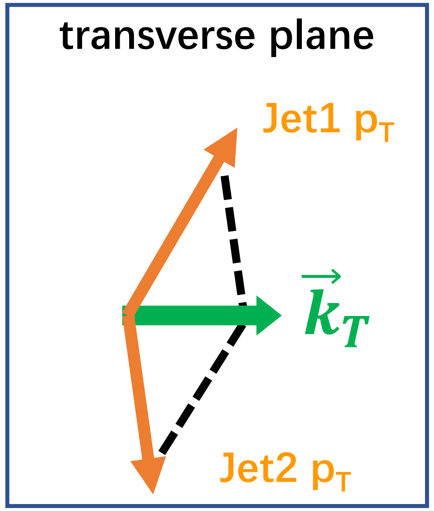
Orbital angular momentum (OAM) : largely unconstrained

- The parton OAM can be manifested via the *Sivers Effect*, a spin-dependent average transverse momentum:

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

- The *u*-quark $\vec{k}_T$ and the *d*-quark $\vec{k}_T$ are expected to be opposite in sign and different in magnitude.
- The Sivers effect can be measured in dijet production by examining the tilt in the back-to-back dijet opening angle.

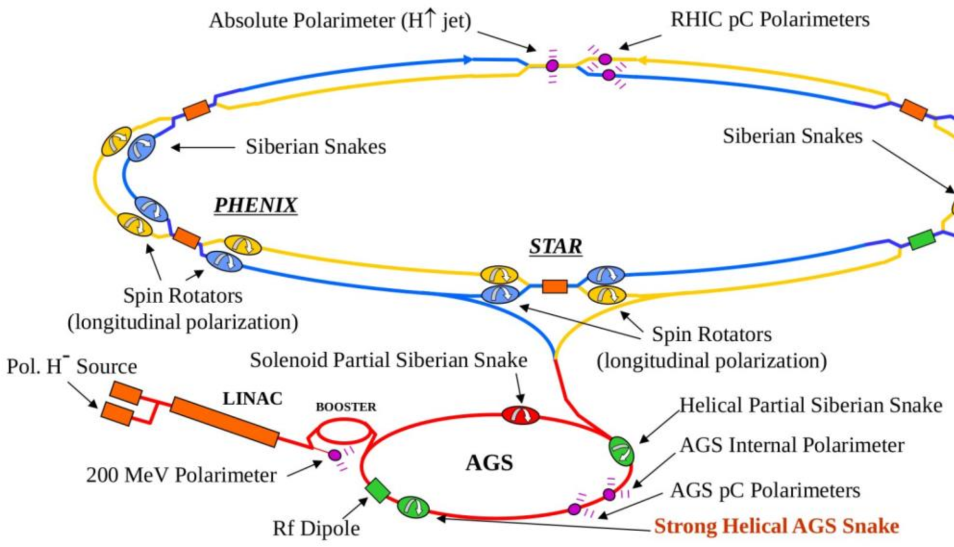


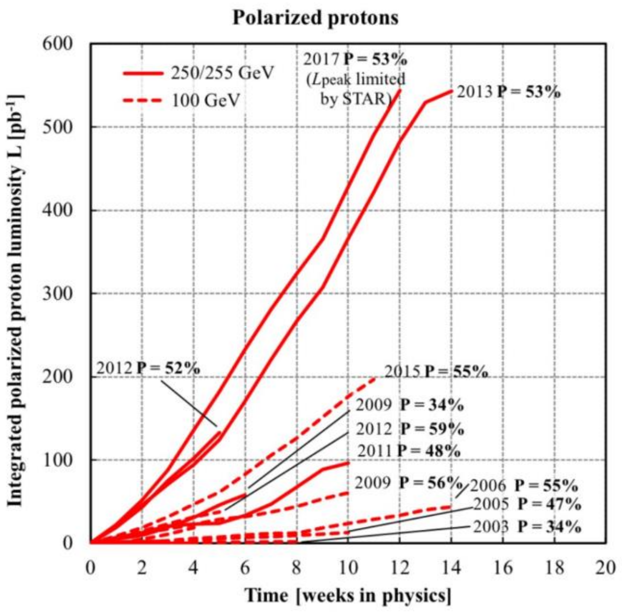


- Measuring the Sivers effect in dijet production :
  - Non-zero effects indicate possible contributions from partonic angular momentum to the proton spin.
  - Test the expected features of the Sivers effect (sign, magnitude) for flavor-separated partons
  - Help constraining the Sivers function, and explore the Sivers effect at a larger Q^2 scale than SIDIS

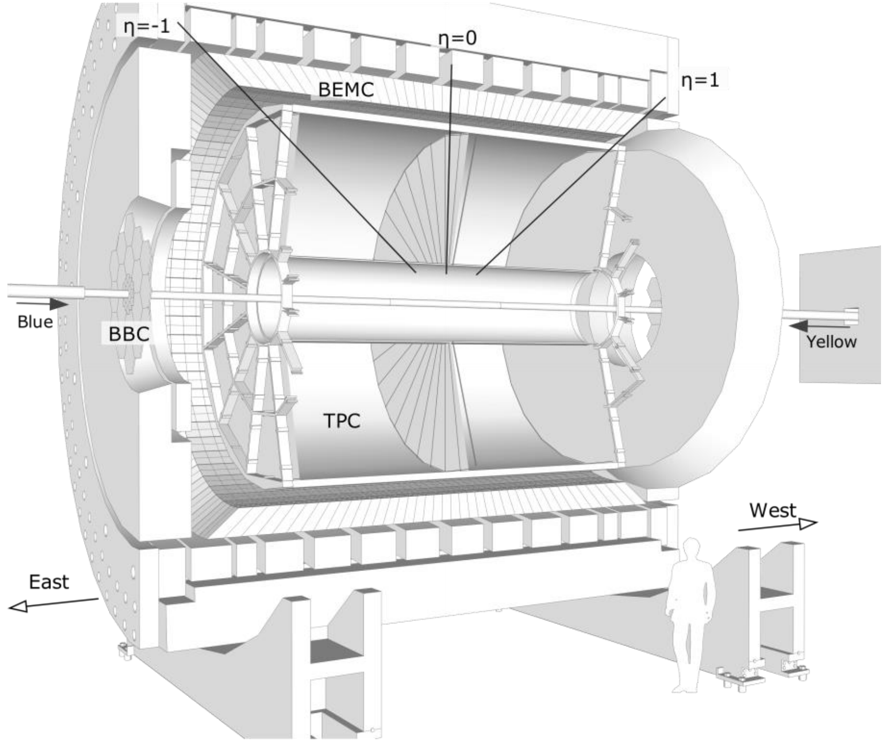
RHIC & STAR Detector

Relativistic Heavy Ion Collider





Solenoidal Tracker At RHIC



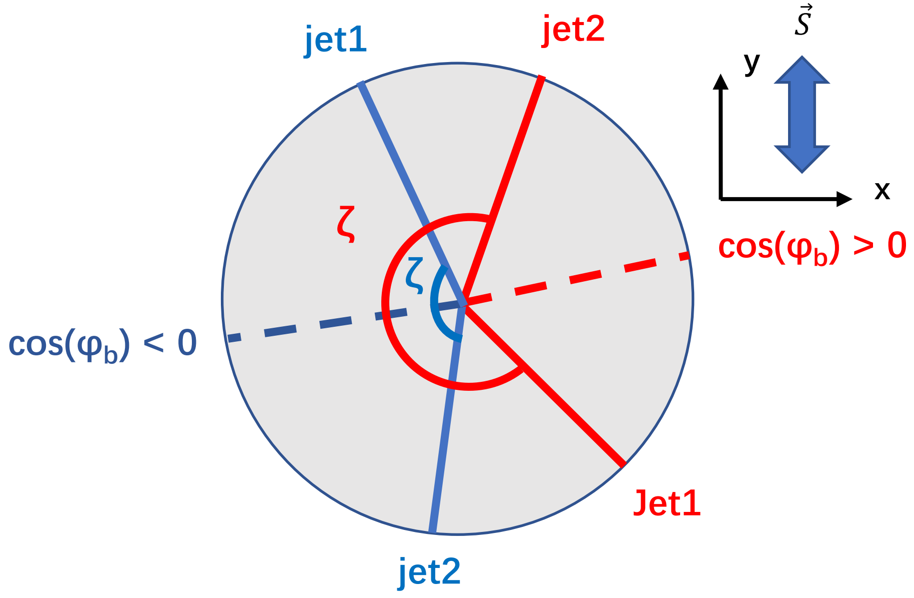
- **RHIC** – colliding transversely and longitudinally polarized *pp* at different energies (200, 500, 510 GeV, etc).
- **STAR detector** is capable of reconstructing tracks, identifying charged particles in |η|< 1.3, and measuring EM particle energies in -1< η <2.

Observable for Probing the Sivers Effect in Dijet Event

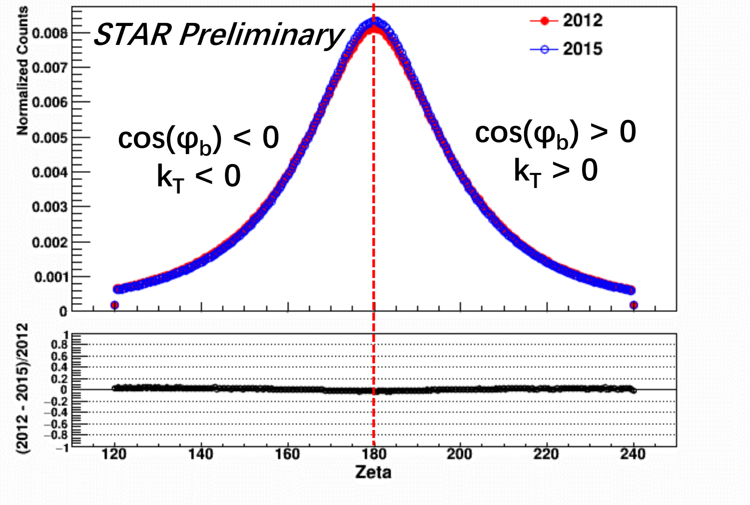
The Sivers asymmetry can be probed via the signed opening angle ζ .

Definition of ζ

$\zeta > \pi$ when $\cos(\varphi_b) > 0$
$\zeta < \pi$ when $\cos(\varphi_b) < 0$
where φ_b is dijet bisector angle



Distribution of ζ



Extraction of asymmetry

The Sivers effect leads to a spin-dependent centroid shift of **ζ**, so we define the asymmetry as:

$$\Delta\zeta = \frac{\langle\zeta\rangle^{+} - \langle\zeta\rangle^{-}}{P}$$

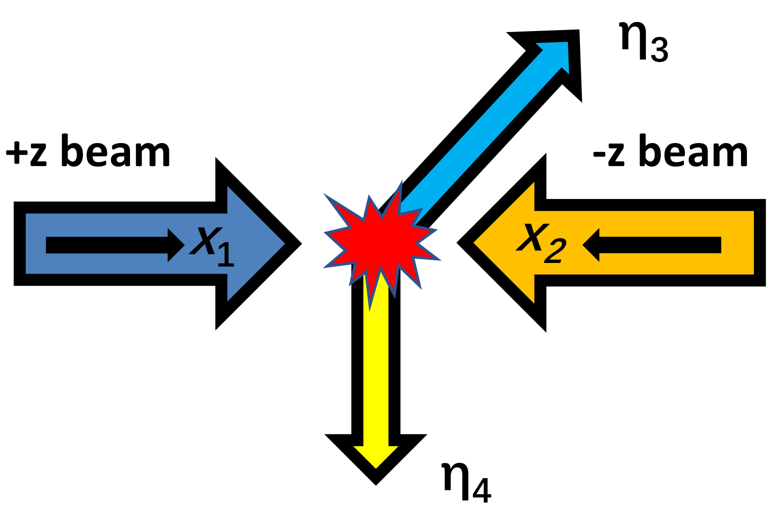
where $\langle\zeta\rangle^{+/-}$ is the centroid of **ζ** for spin-up and spin-down states, and **P** is the beam polarization.

Beam-to-Jet Association

- To figure out the "parton flow" from beam to jets, a beam-jet association is performed.
- We assume the more forward jet (largest |η|) is associated with a fragmenting parton from the beam moving in that direction.

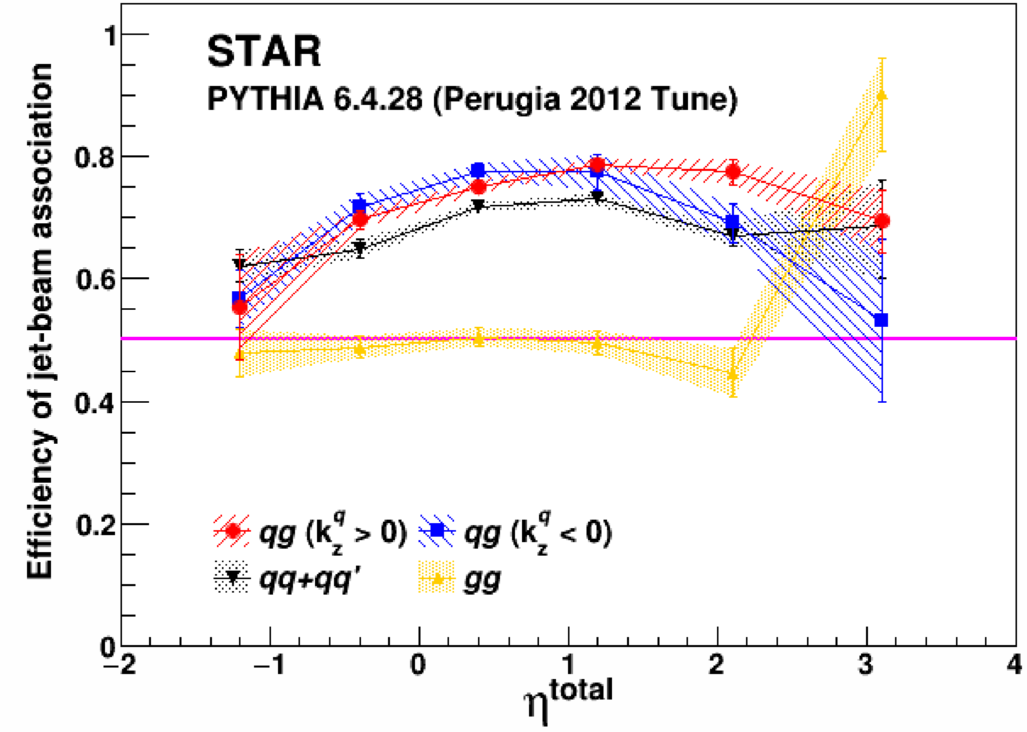
Beam-jet Association

associated with +z beam in this case



other jet to be associated with the -z beam

Association efficiency



$* \; \eta^{total} = \eta_3 + \eta_4 \propto \log(\frac{x_1}{x_2})$

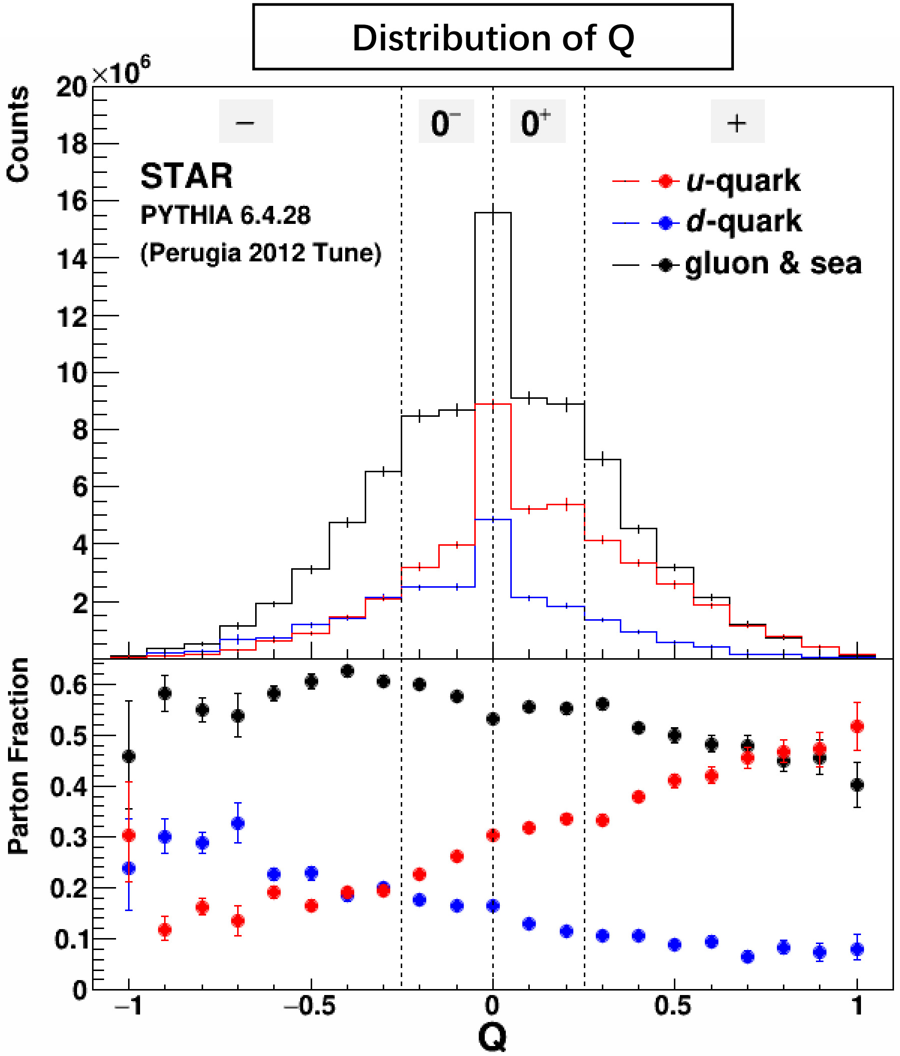
Jet Charge Tagging

We use the **Jet Charge (Q) of the associated jets** to enhance the fraction of ***u*-quarks and *d*-quarks** separately.

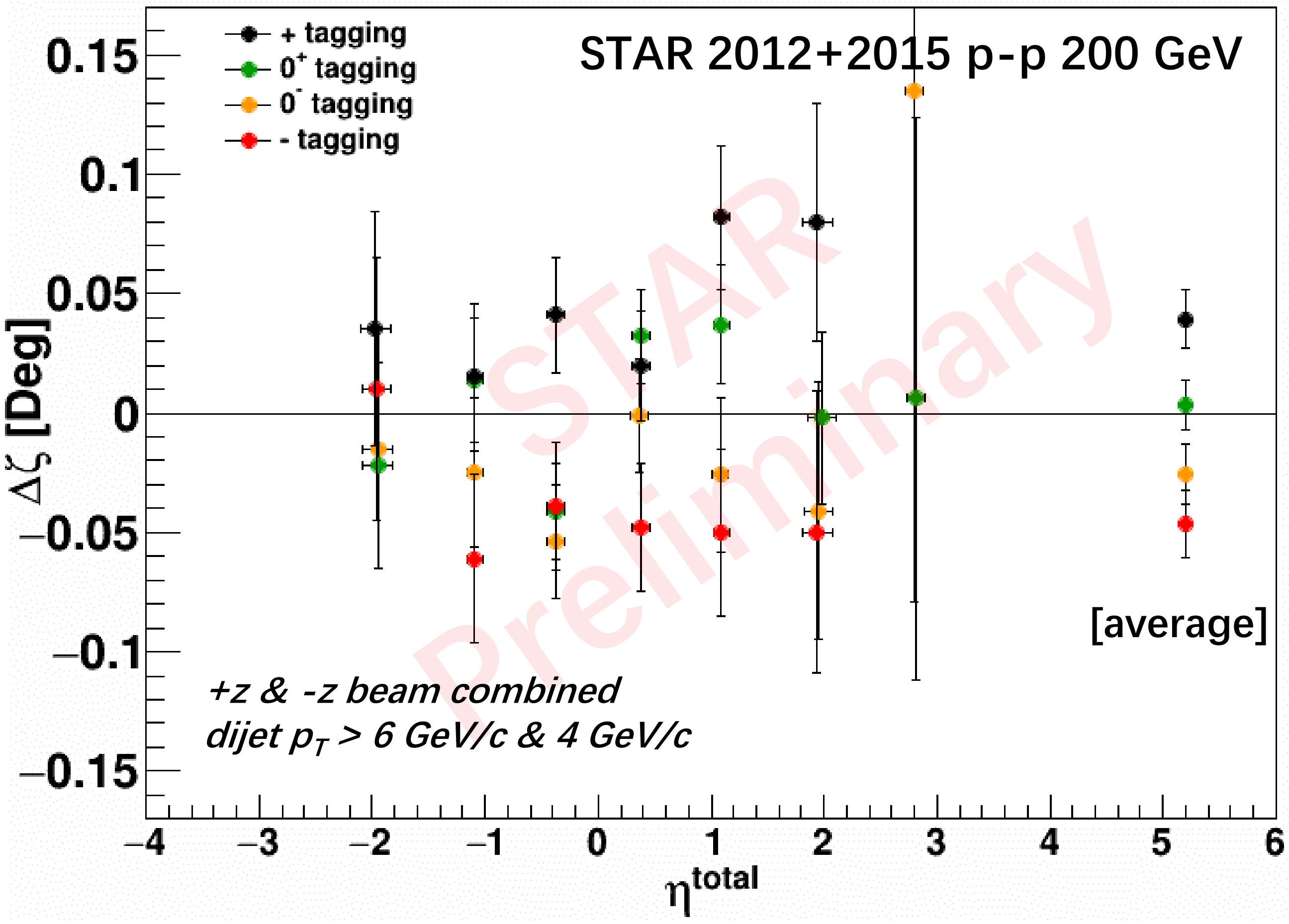
$$Q = \sum_{\substack{\text{all the tracks} \\ \text{with } p_T > 0.8\ GeV/c}} \frac{track\ |p|}{jet\ |p|} \cdot track\ charge$$

Data is divided into four bins:

1. **Plus tagging ($Q \geq 0.25$)** : enhances *u*
2. **Zero+ tagging ($0 \leq Q < 0.25$)** : less enhancement to *u*
3. **Zero- tagging ($-0.25 < Q < 0$)** : less enhancement to *d*
4. **Minus tagging ($Q \leq -0.25$)** : enhances *d*



The Δζ asymmetry



- Large separation (~5σ) between plus-tagging and minus-tagging.
- First observation of non-zero Sivers asymmetries in dijet production of polarized proton collisions!
- Comparison of asymmetries for the two beams show that the systematic uncertainty is well under control.
- Asymmetry systematically shifting from "+" to "-" values when *u* quark fraction goes down and *d* quark fraction goes up.
- η^{total} dependency in plus-tagging, possibly due to :
  - x-dependency in PDFs
  - potential x-dependency in Sivers $\langle k_T \rangle$

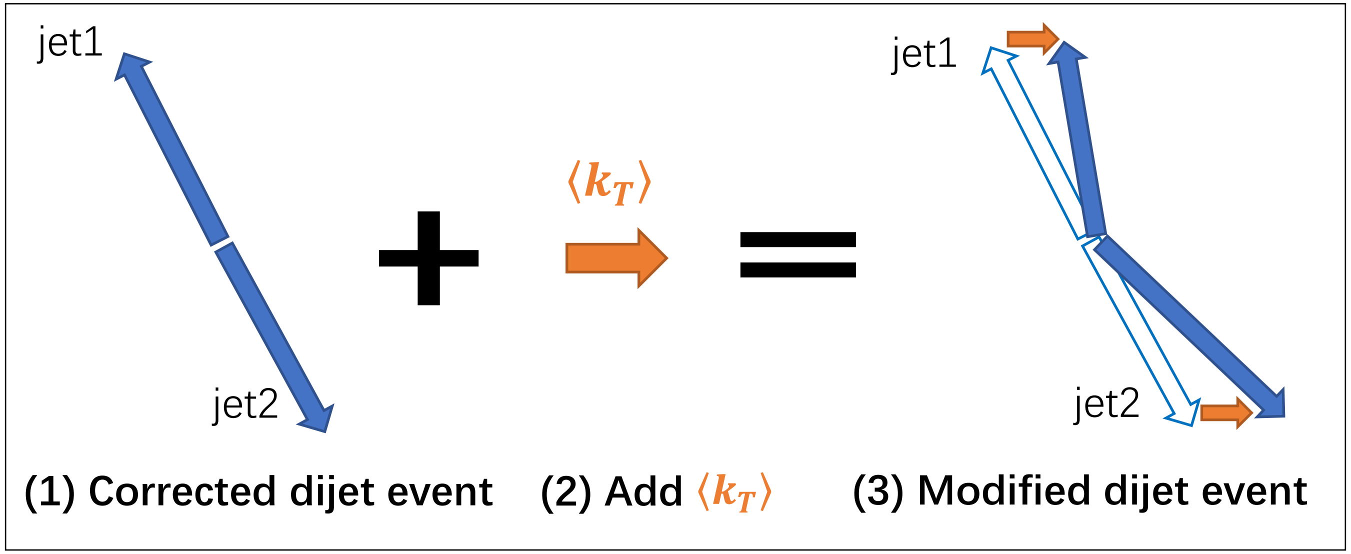
Converting the $\Delta\zeta$ asymmetry to $\langle k_T \rangle$

Three steps are taken to convert the $\Delta\zeta$ asymmetry to $\langle k_T \rangle$:

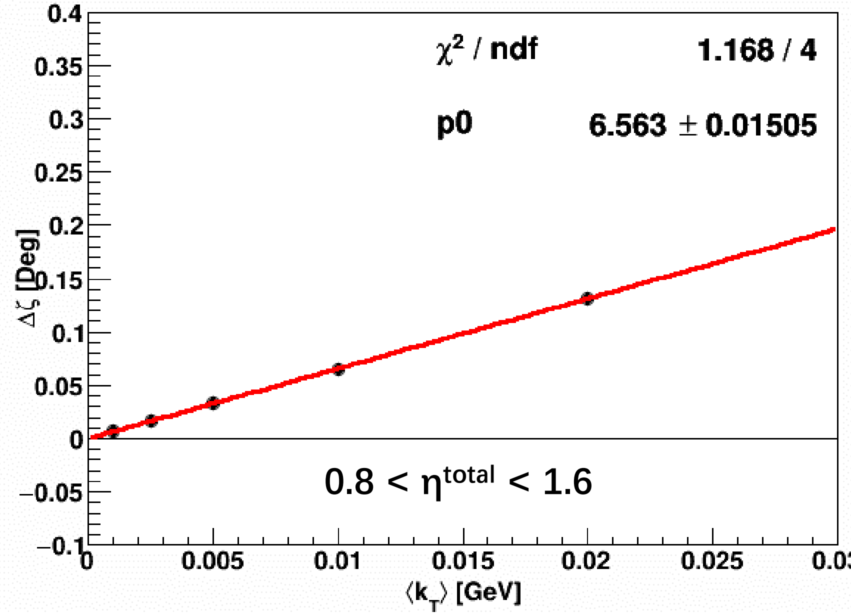
I. Correct detector jet p_T to parton p_T with machine learning.

II. Use simple kinematic modeling of $\langle k_T \rangle$, calculate $\Delta\zeta$ with corrected p_T, and get $\Delta\zeta$-$\langle k_T \rangle$ correlation.

Kinematic model (transverse plane)



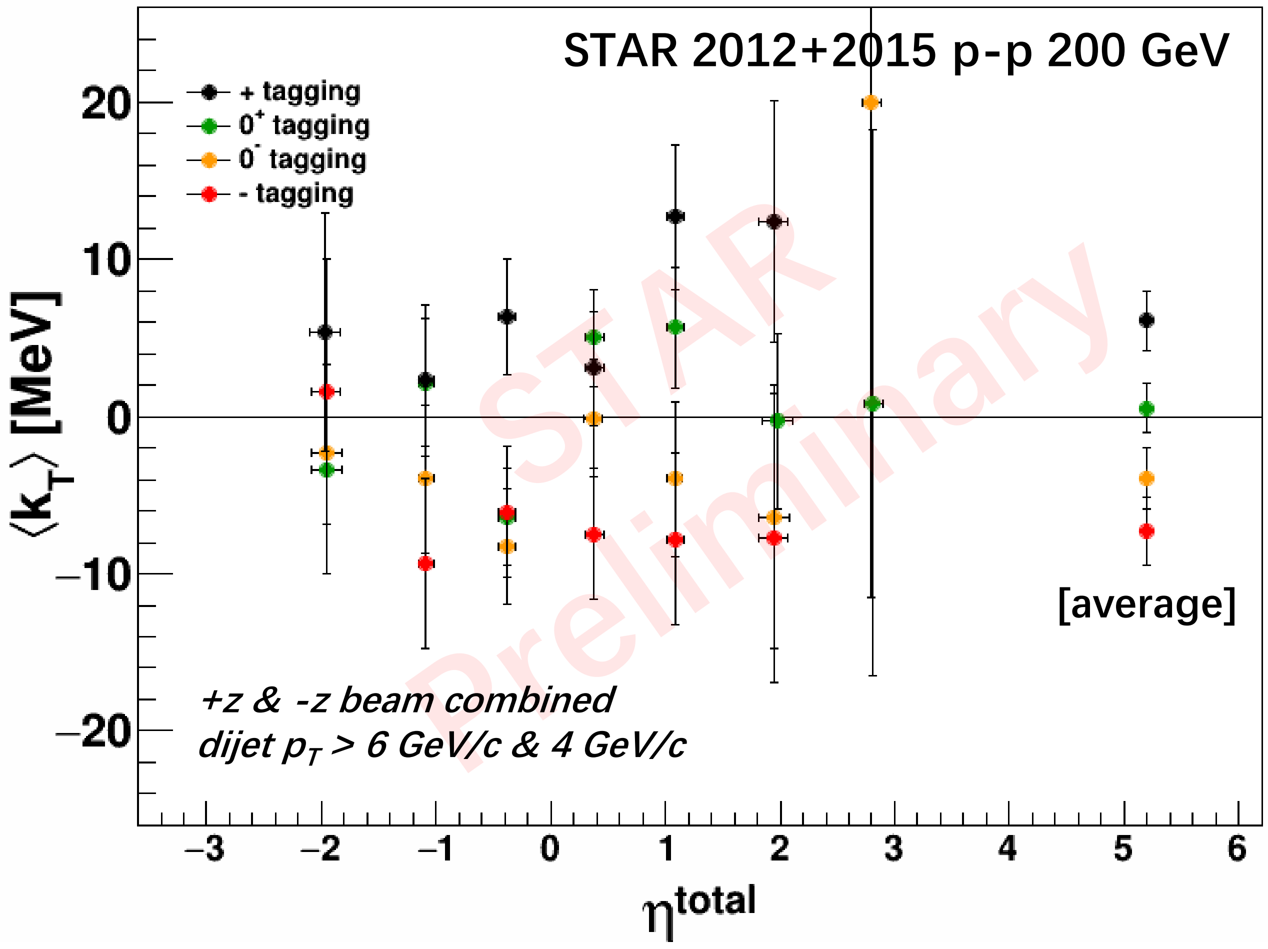
$\Delta\zeta$ - $\langle k_T \rangle$ correlation



III. Convert the $\Delta\zeta$ vs. η^{total} results to $\langle k_T \rangle$ vs. η^{total} results :

$$\langle k_T \rangle = \Delta\zeta \,/\, slope$$

The Converted $\langle k_T \rangle$ Results



- Based on the simple kinematic model, we have :

$$\left\langle k_T^{+tagging} \right\rangle = +6.1 \pm 1.9 \text{ MeV/c}$$

$$\left\langle k_T^{-tagging} \right\rangle = -7.3 \pm 2.2 \text{ MeV/c}$$

- Very small signals successfully accessed with STAR detector!
- In fact, each tagged measurement can be considered as a mixture of 3 different partonic contributions (*u*, *d*, *g*+sea). The 4 tagged measurements provide enough constraints to solve for the $\langle k_T \rangle$ for each parton.

Inverting the Tagged $\langle k_T \rangle$ to Individual Parton $\langle k_T \rangle$

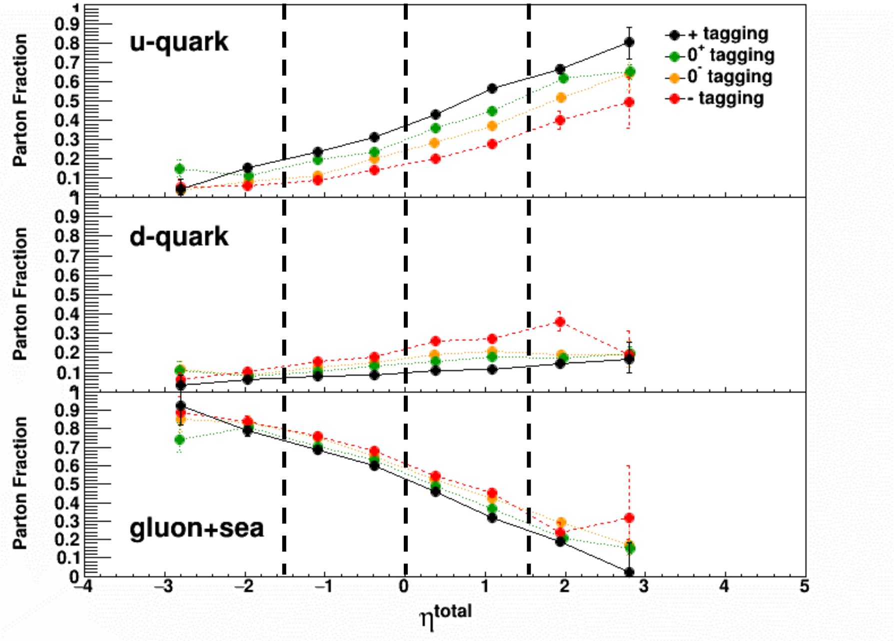
- The parton fraction is estimated in simulation for each tagged measurement.

- Constructing the system of equations (**8X3 matrix**):

  - **4 charge-taggings :** differentiation between u and d quarks

  - **Each inversion involves the data from a pair of adjacent η^{total} bins :** parton fraction is dependent on η^{total}

Parton fraction from simulation



- The **over-constrained system** is solved through **Moore-Penrose inverse**.

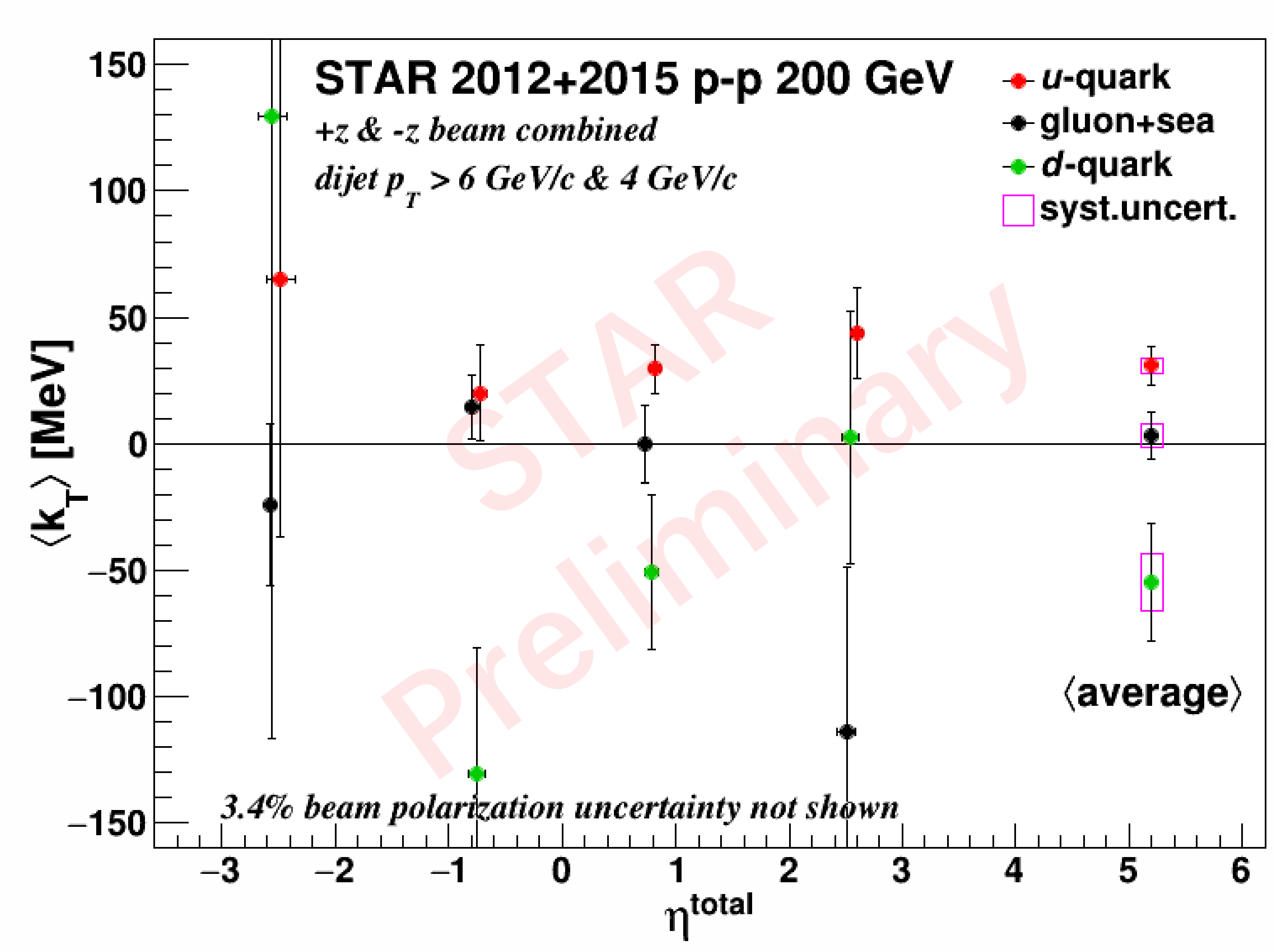
$$\begin{bmatrix} f_1^u & f_1^d & f_1^{gsea} \\ f_2^u & f_2^d & f_2^{gsea} \\ \vdots & \vdots & \vdots \\ f_8^u & f_8^d & f_8^{gsea} \end{bmatrix} \begin{bmatrix} u \\ d \\ gsea \end{bmatrix} = \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \vdots \\ \Delta_8 \end{bmatrix} \xrightarrow{\text{Moore-Penrose inverse}} \begin{bmatrix} c_1^u & c_2^u & \cdots & c_8^u \\ c_1^d & c_2^d & \cdots & c_8^d \\ c_1^{gsea} & c_2^{gsea} & \cdots & c_8^{gsea} \end{bmatrix} \begin{bmatrix} \Delta_1 \\ \Delta_2 \\ \vdots \\ \Delta_8 \end{bmatrix} = \begin{bmatrix} u \\ d \\ gsea \end{bmatrix}$$

8 x 3 matrix

3 x 8 matrix

f = parton fraction
u, d, gsea = parton <kT>
Δ = tagged <kT>

The Unfolded Parton $\langle k_T \rangle$



- $\langle k_T^u \rangle > 0$, $\langle k_T^d \rangle < 0$, $\langle k_T^{g+sea} \rangle \sim 0$
- $\left|\frac{\langle k_T^d \rangle}{\langle k_T^u \rangle}\right| \sim 2$
- The systematic uncertainty is dominated by the uncertainty of the estimated parton fraction.
- No clear η^{total}-dependency for given statistics, suggesting a relatively weak x-dependency.

Conclusions

- The Sivers effect has been studied in dijets measured with the STAR detector, using data taken in 2012 and 2015.
- First observation of non-zero Sivers asymmetries in polarized proton collisions!
- A conversion of the asymmetry to the $\langle k_T \rangle$ results is provided based on purely kinematic model. The results are further unfolded for the $\langle k_T \rangle$ of individual partons.
- The features of the unfolded parton $\langle k_T \rangle$ are consistent with expectation:
  - $\langle \boldsymbol{k_T^u} \rangle$ and $\langle \boldsymbol{k_T^d} \rangle$ have different signs
  - $\left| \langle \boldsymbol{k_T^d} \rangle / \langle \boldsymbol{k_T^u} \rangle \right| \sim \mathbf{2}$
- Results provide constraints for the Sivers function at a high Q^2 scale (Q^2 > 160 GeV^2).
- Several theoretical efforts are underway to make comparisons to these data.

Thank you !

BACKUP

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**

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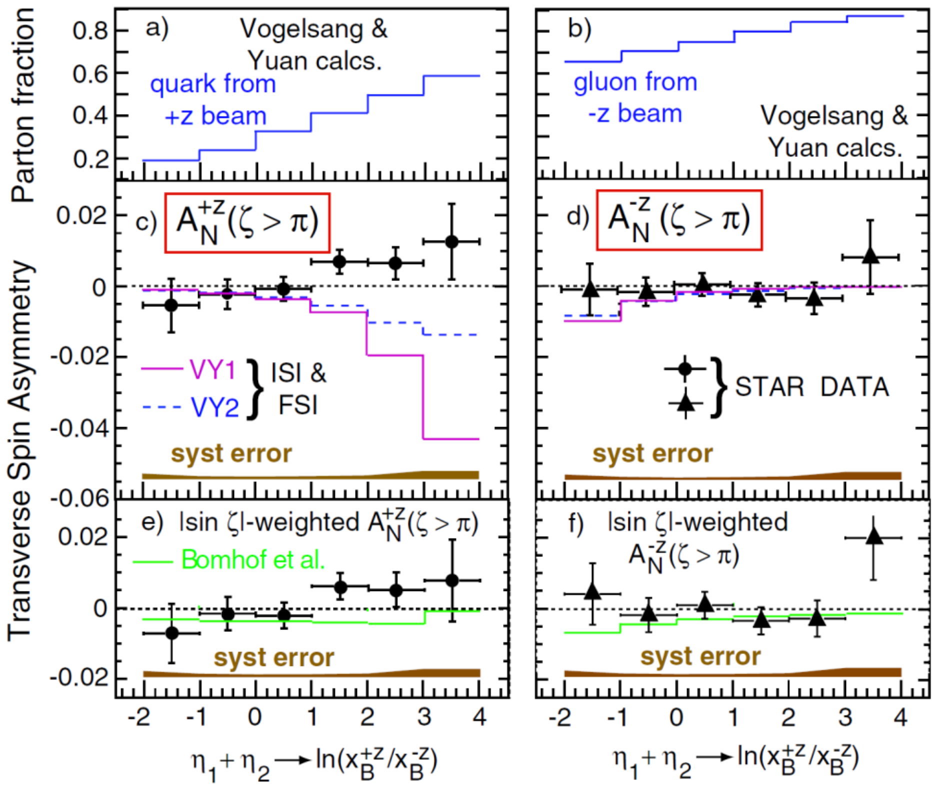

Asymmetry is plotted as a function of the sum of dijet pseudo-rapidities (η1+ η2 ∝ $\ln(\frac{x1}{x2})$) since Sivers effect is expected to be dependent on parton *x*.

Parton x

- $\mathrm{Q}^2 > 160\ \mathrm{GeV}^2$
- Parton x increases along with η^{total} , a possible x-dependence of $\langle k_T \rangle$ should manifest in the inverted results if strong enough.