Measurement of transverse single-spin asymmetries for dijet production in polarized p+p collisions at √S= 200 GeV at STAR

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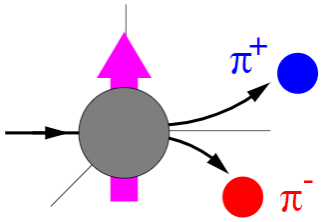
BNL Seminar

June 30 2020

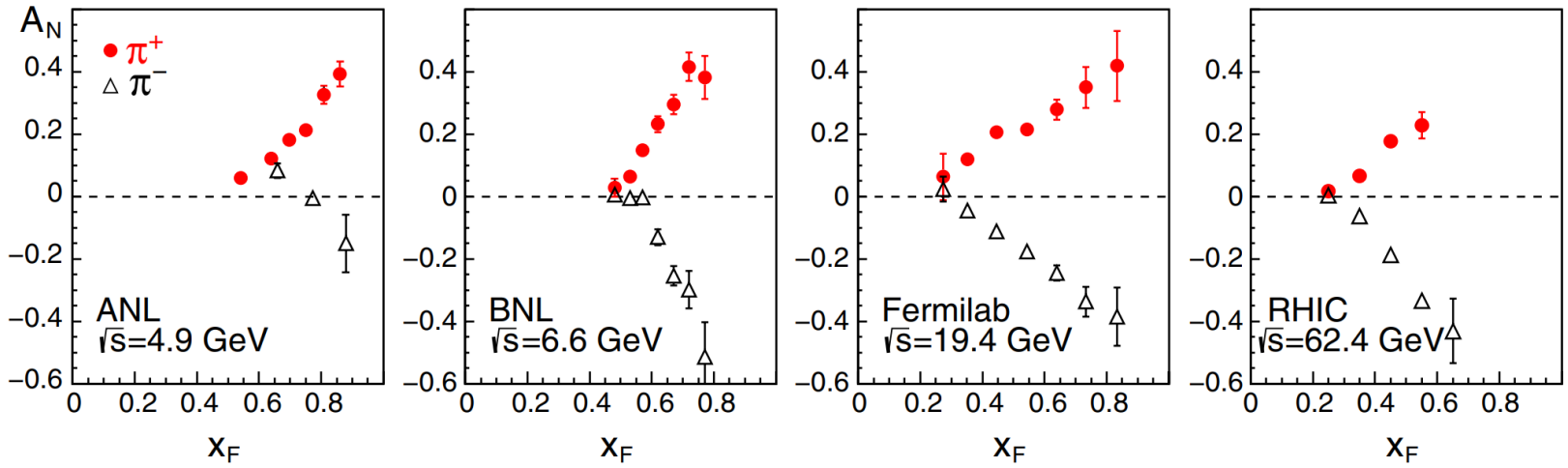
Transverse Single Spin Asymmetry (SSA)

$p\uparrow + p \rightarrow \pi X$



Analyzing power for SSA

$$A_N = \frac{1}{P_{beam}} \frac{N^{\pi}_{left} - N^{\pi}_{right}}{N^{\pi}_{left} + N^{\pi}_{right}}$$



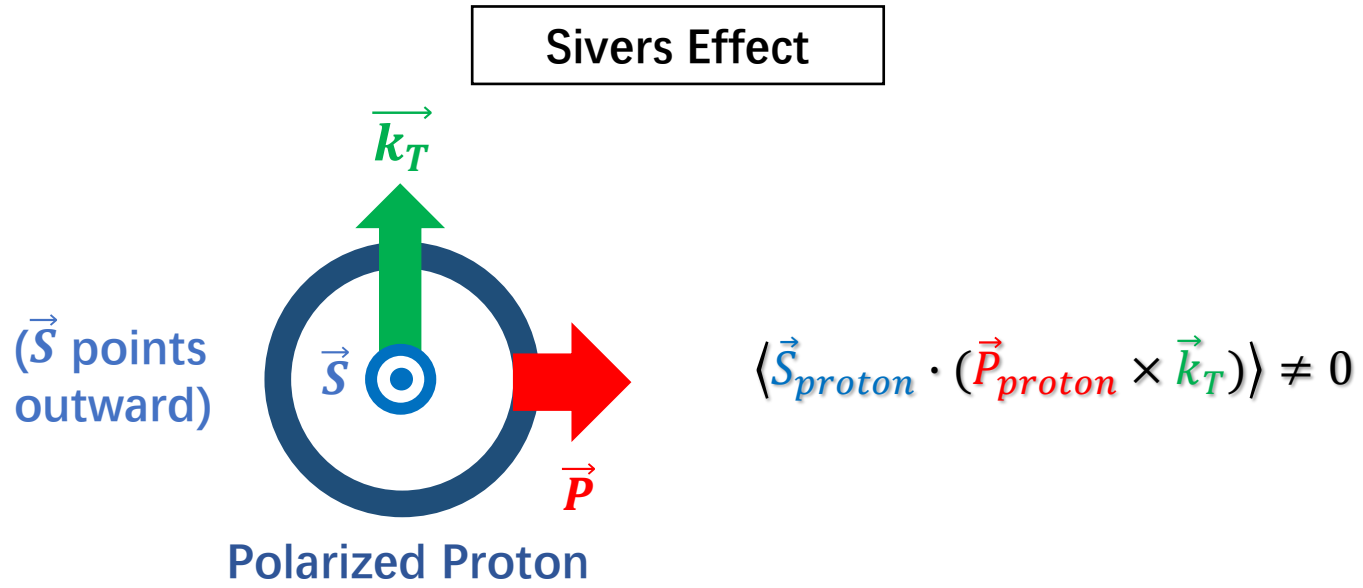
Aidala et al. Rev. Mod. Phys. 85, 655 (2013)

- Large single spin asymmetries have been observed in forward meson production in hadron collisions since 1970s.
- Two possible mechanisms (probably the most famous two among the eight TMD PDFs for the understanding of nucleon structure):
  - Sivers distribution function
  - Collins fragmentation function

Sivers Effect

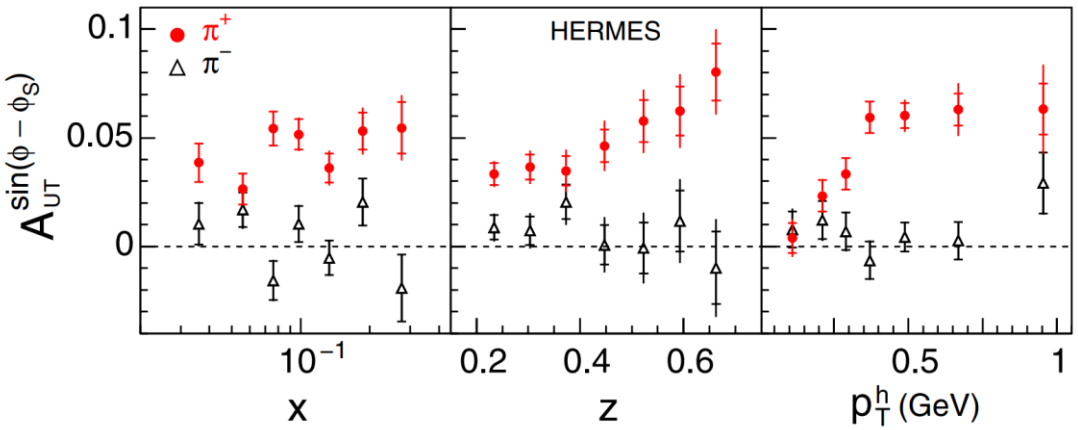
- **The Sivers function was first proposed by Sivers (1990) to explain the large hadron SSA.**
- A **transversely polarized proton** with spin $\vec{S}$ and momentum $\vec{P}$, is correlated with the **constituent partons** with a **transverse momentum** $\vec{k}_T$:

$$f_{q/p^\uparrow}(x, k_t) = f_1^q(x, k_t^2) - f_{1t}^{\perp q}(x, k_t)\frac{\mathbf{S}\cdot(\mathbf{k_t}\times\hat{\mathbf{p}})}{M}$$

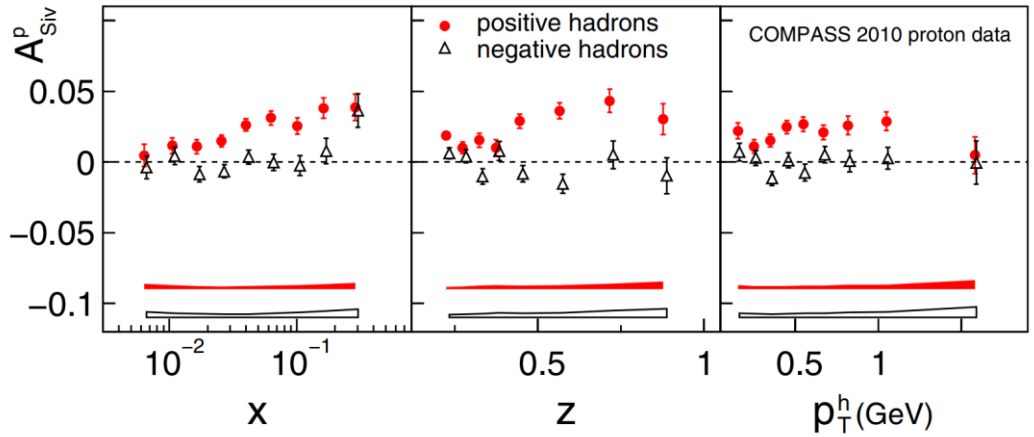


Measurements in SIDIS and W production

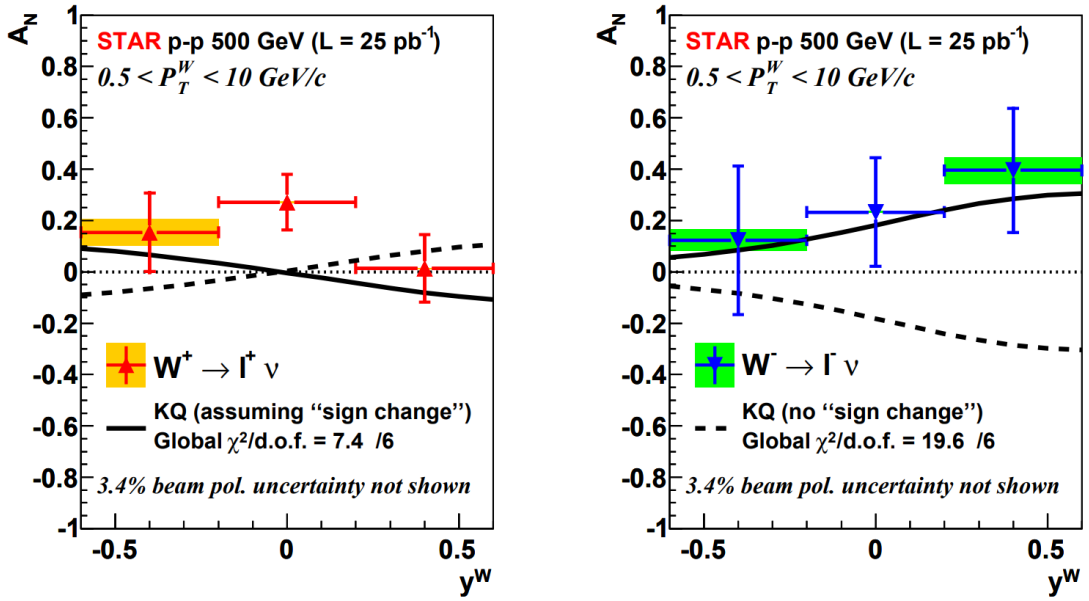
SIDIS @Hermes
Phys. Rev. Lett. 103, 152002 (2009)



SIDIS @Compass
Phys. Lett. B 717, 383 (2012)

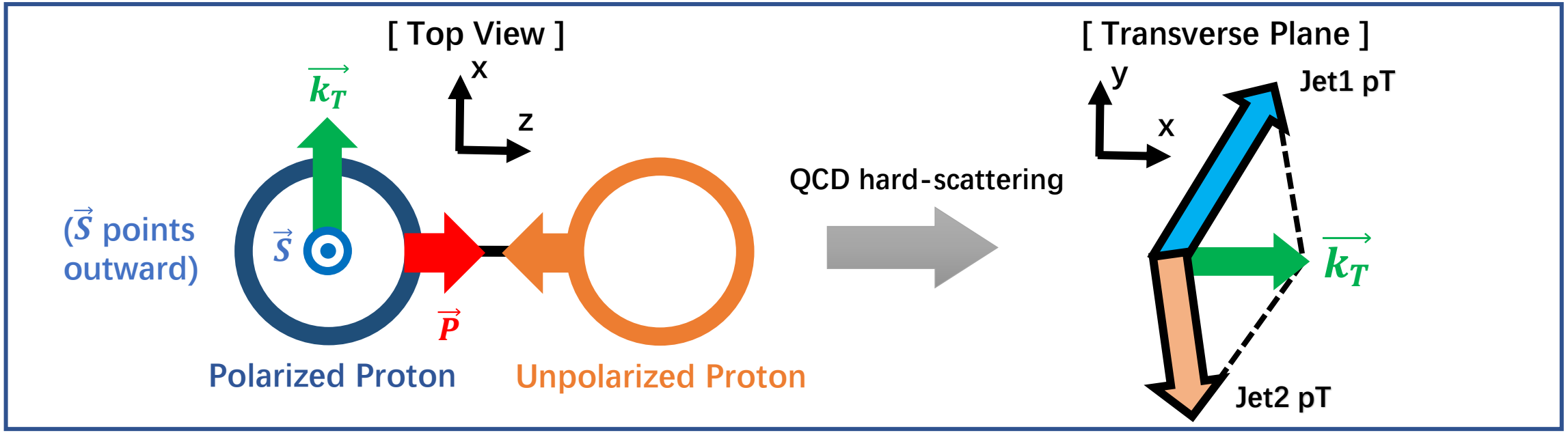


W measurement @STAR
Phys. Rev. Lett. 116, 132301 (2016)



- *u*-quark and *d*-quark are expected to have $\langle \boldsymbol{k_T} \rangle$ in opposite signs. (Observed in SIDIS @Hermes, Compass, JLab)
- The sign of $\langle \boldsymbol{k_T} \rangle$ is opposite between SIDIS and DY (hinted @STAR)

Sivers Effect in Proton-Proton Dijet Production

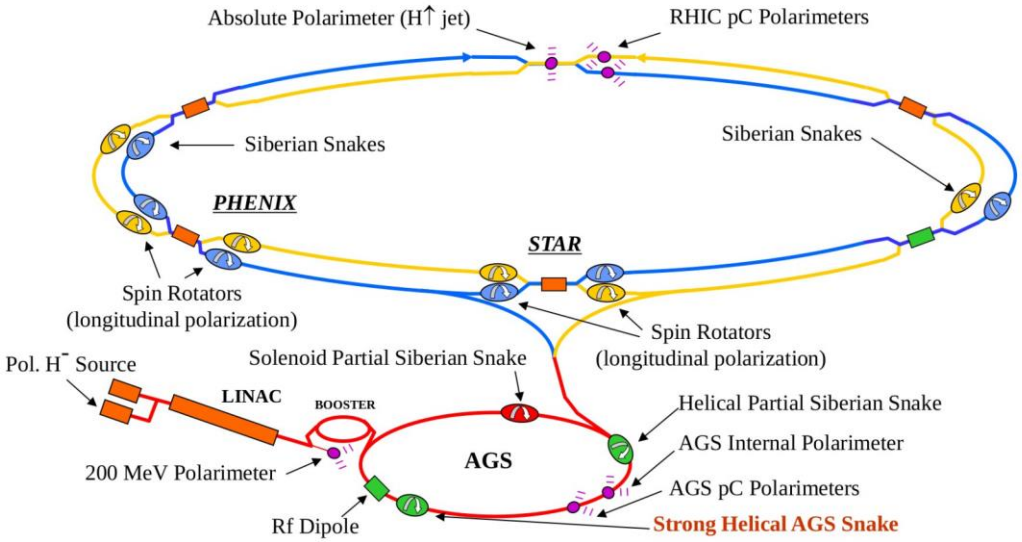


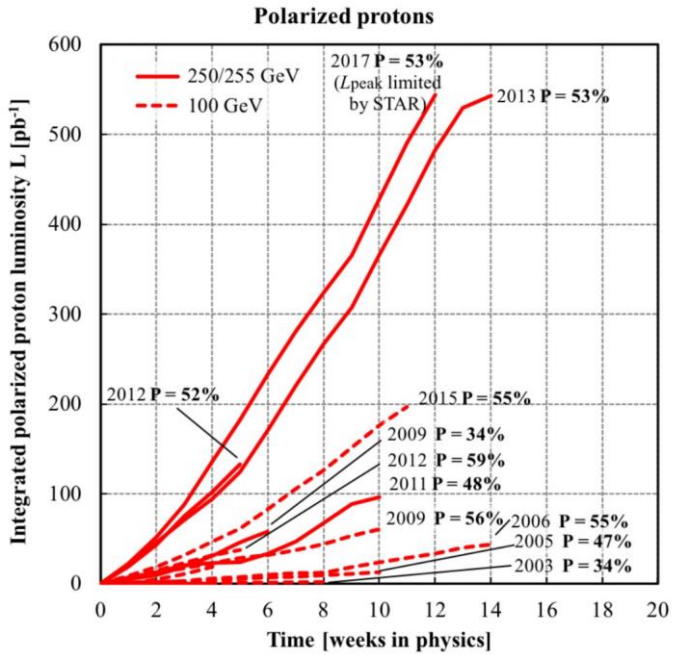
Measuring the Sivers effect in dijet production:

- Non-zero effects indicate possible **contributions from partonic angular momentum to the proton spin**.
- Since the net partonic kT must average to zero, **expect *u* and *d* contributions to be opposite in sign and different in magnitude**. Can test if this is true.
- Explore the the Sivers effect with a focus on much **larger Q^2 scale than SIDIS**

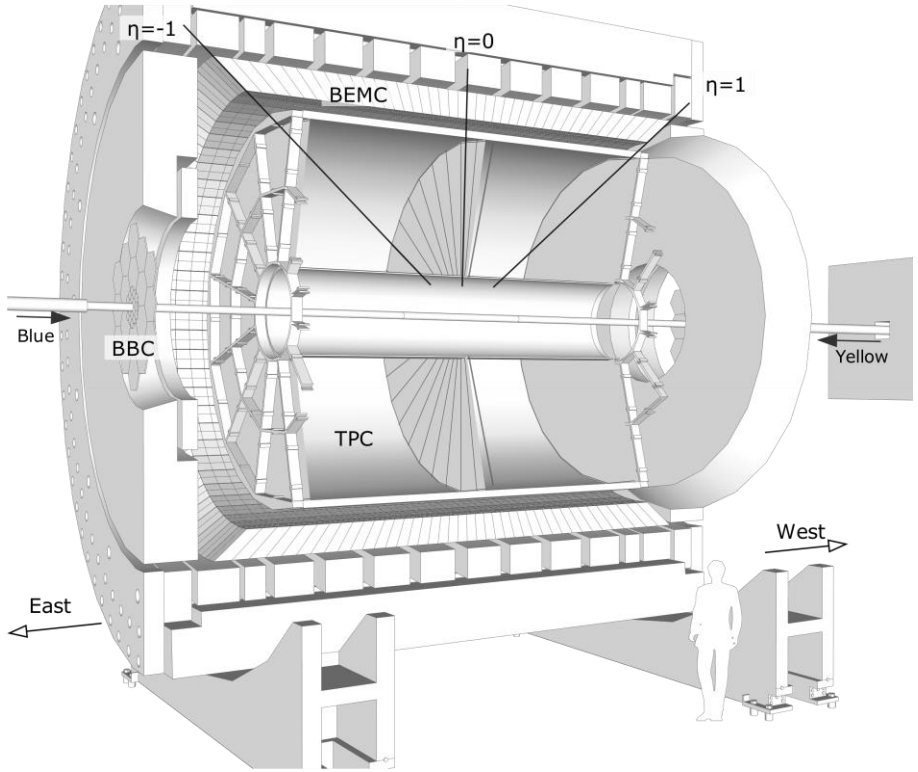
RHIC & STAR Detector

Relativistic **H**eavy **I**on **C**ollider





Solenoidal **T**racker **A**t **R**HIC



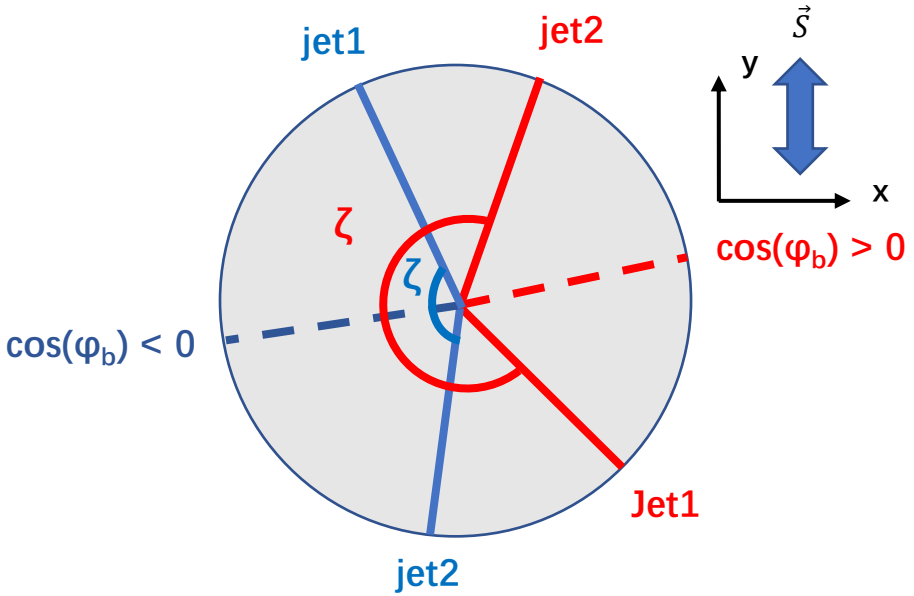
- RHIC – colliding transverse and longitudinal polarized pp at different energies (200, 500 GeV, etc).
- STAR detector is capable of reconstructing tracks, identifying charged particles in $|\eta|< 1.3$, and measuring EM particle energies in $-1< \eta <2$.

Observable for Probing the Sivers Effect

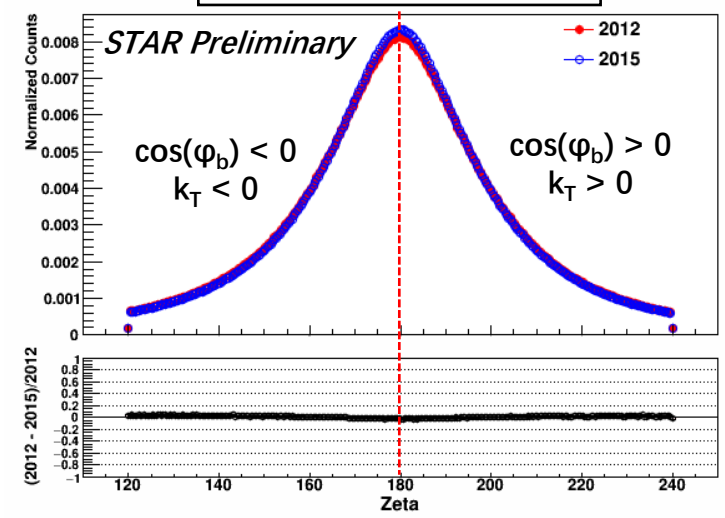
The Sivers asymmetry can be probed via the signed opening angle ζ .

Definition of ζ

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



Distribution of ζ



Extraction of asymmetry

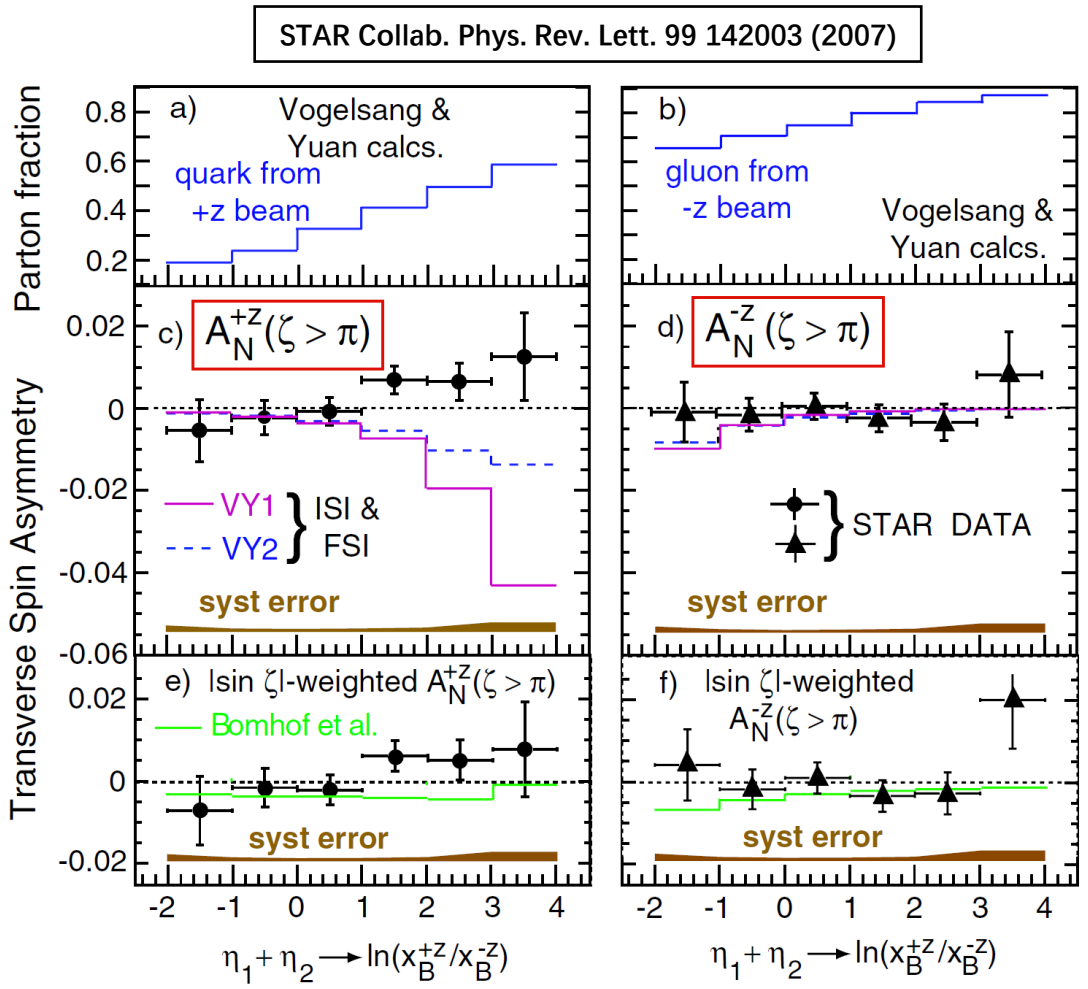
The sivers effect leads to a spin-dependent centroid shift of **ζ**, so we define the asymmetry as:

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

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

Improvements since 2006

- In the 2006 analysis, the result was found to be consistent with zero within dominant statistical uncertainties.
- In 2012 and 2015 data, we see:
  - ✓ **33 times larger data set**
  - ✓ **Fully reconstructed jets (no tracking for 2006 data) at higher average pT**
  - ✓ **Employ a charge-tagging method to enhance *u*-quark and *d*-quark signals**
- Simulation is based on Pythia6+Geant3

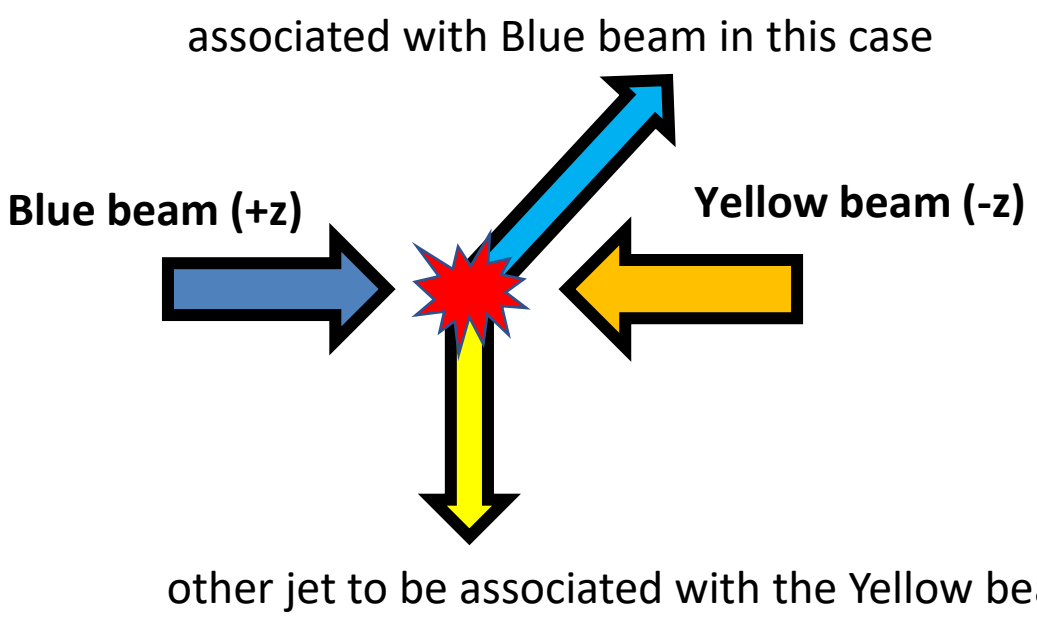


Asymmetry is plotted as a function of the sum of dijet pseudo-rapidities ($\eta 1 + \eta 2 \propto \ln(\frac{x1}{x2})$).

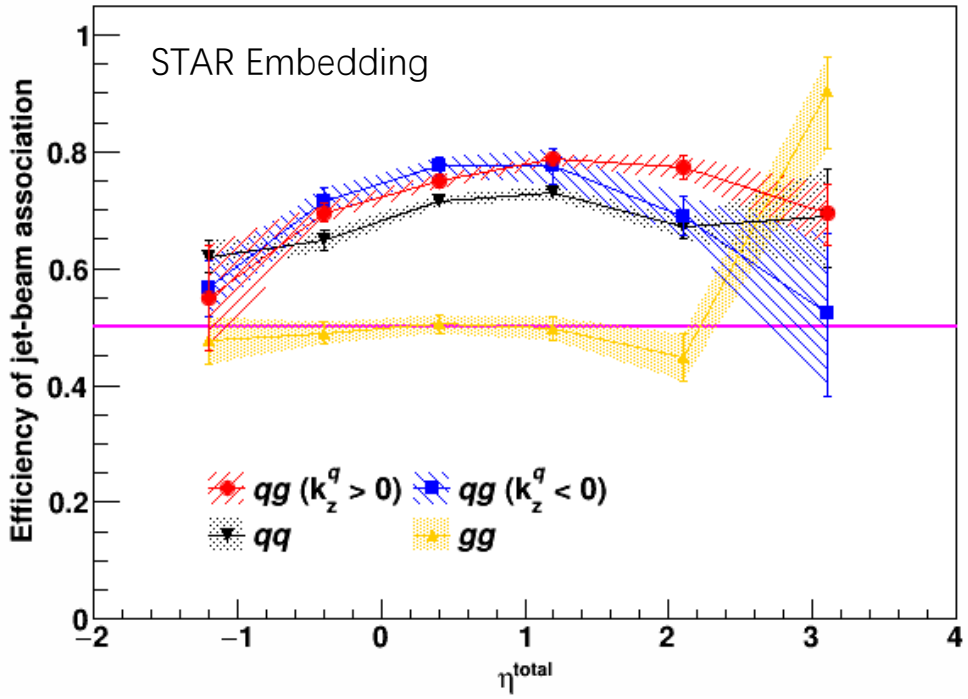
Beam-to-Jet Association

- 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



Association efficiency



$* \eta^{total} = \eta 1 + \eta 2$

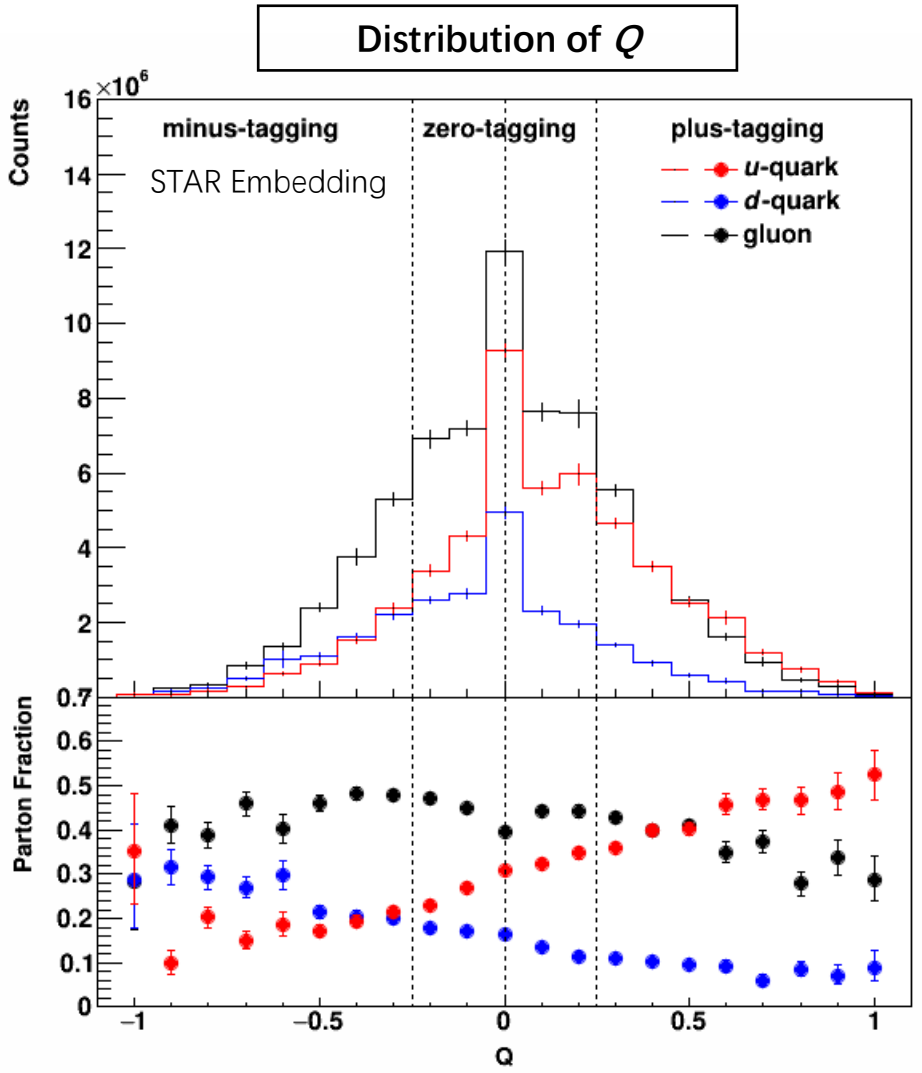
Charge Tagging

We employ **a weighted-charge tagging on the associated jets** to enhance the fraction of ***u*-quarks and *d*-quarks** separately.

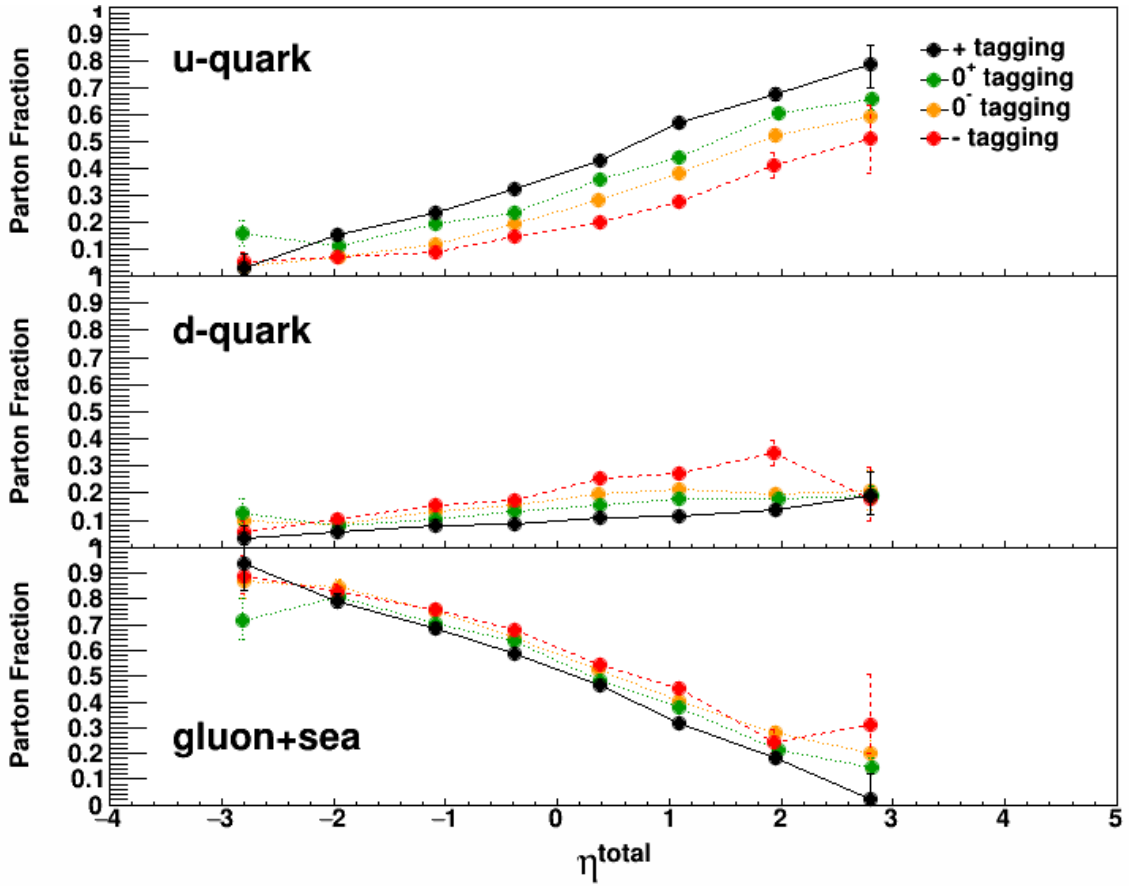
$$Q = \sum_{\substack{all\ the\ tracks \\ with\ pT>0.8GeV}} \frac{track\ pT}{jet\ pT} \cdot track\ charge$$

Data is divided into four bins:

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

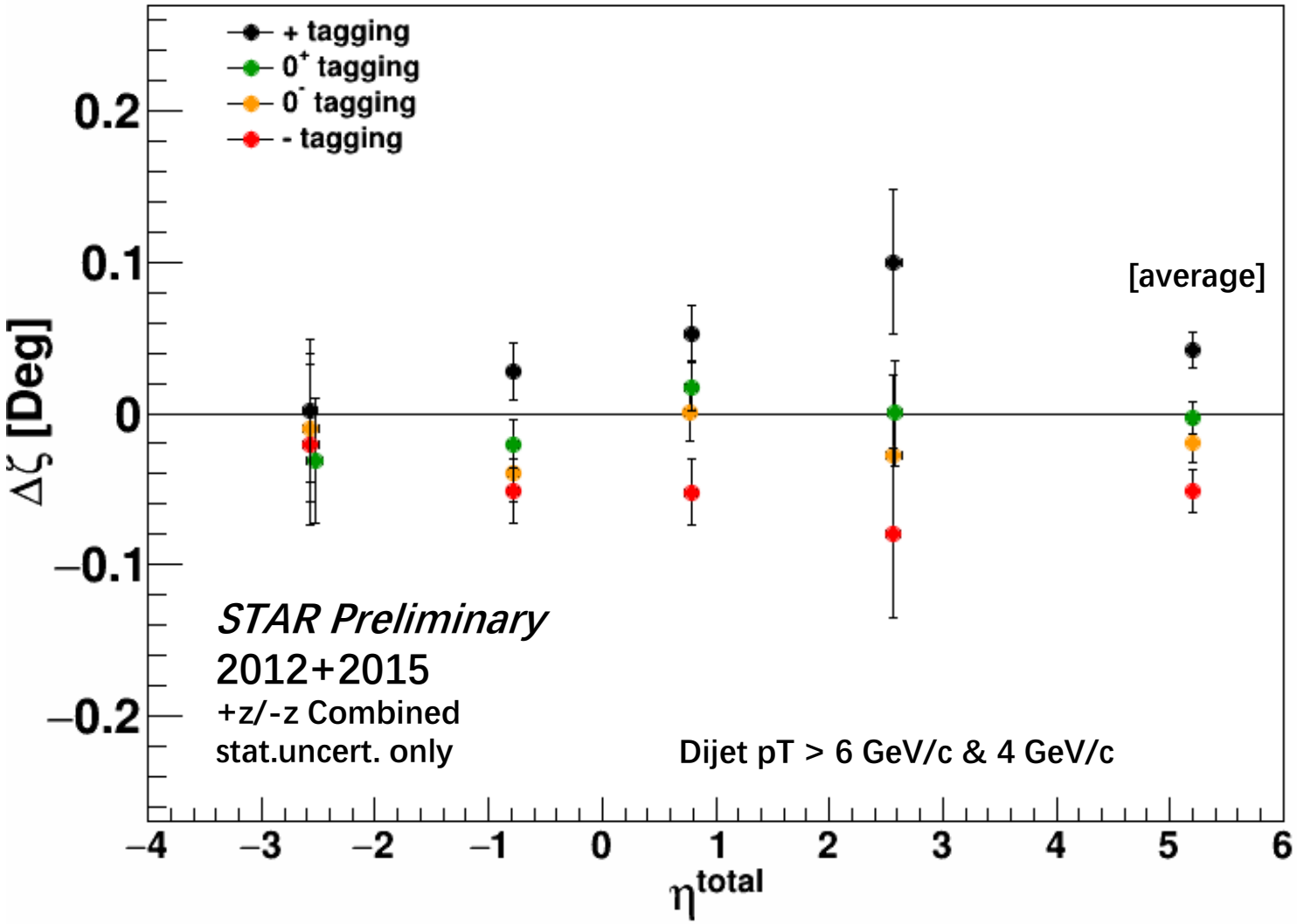


Parton Fractions



- Parton fractions are estimated from STAR embedding.
- $\eta^{total} = \eta 1+\eta 2$ is proportional to ln(x1/x2)
- More u-quarks at higher Q and higher η^{total}
- More d-quarks at lower Q, weak dependency on η^{total}
- More gluons at lower Q and lower η^{total}

The Δζ Asymmetry



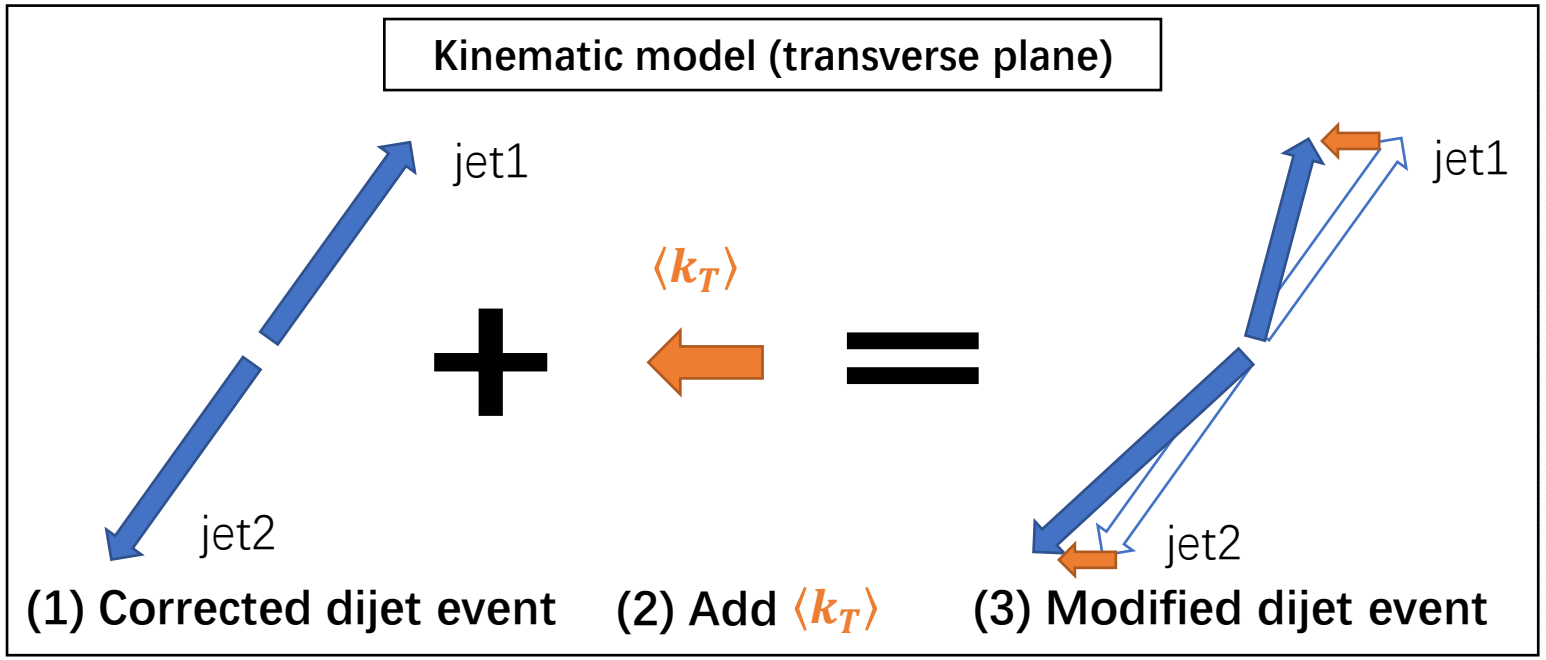
- Large separation (~5σ) between plus-tagging and minus-tagging.
- The untagged result is still consistent with zero even with 33X more data than the 2006 measurement.
- Asymmetry systematically shifting from "+" to "-" values when u quark fraction goes down and d quark fraction goes up.
- η^{total} dependency in plus and minus taggings

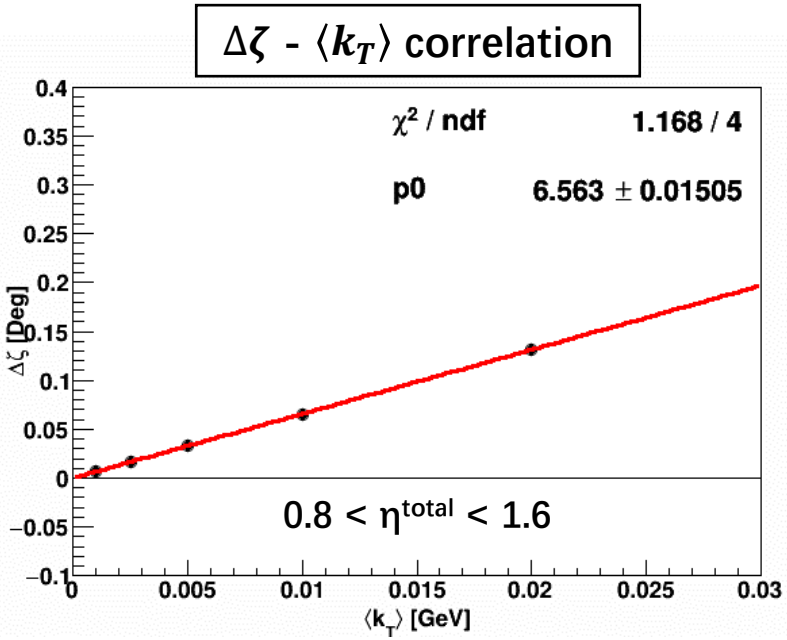
Converting the $\Delta\zeta$ asymmetry to $\langle k_T \rangle$

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

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

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

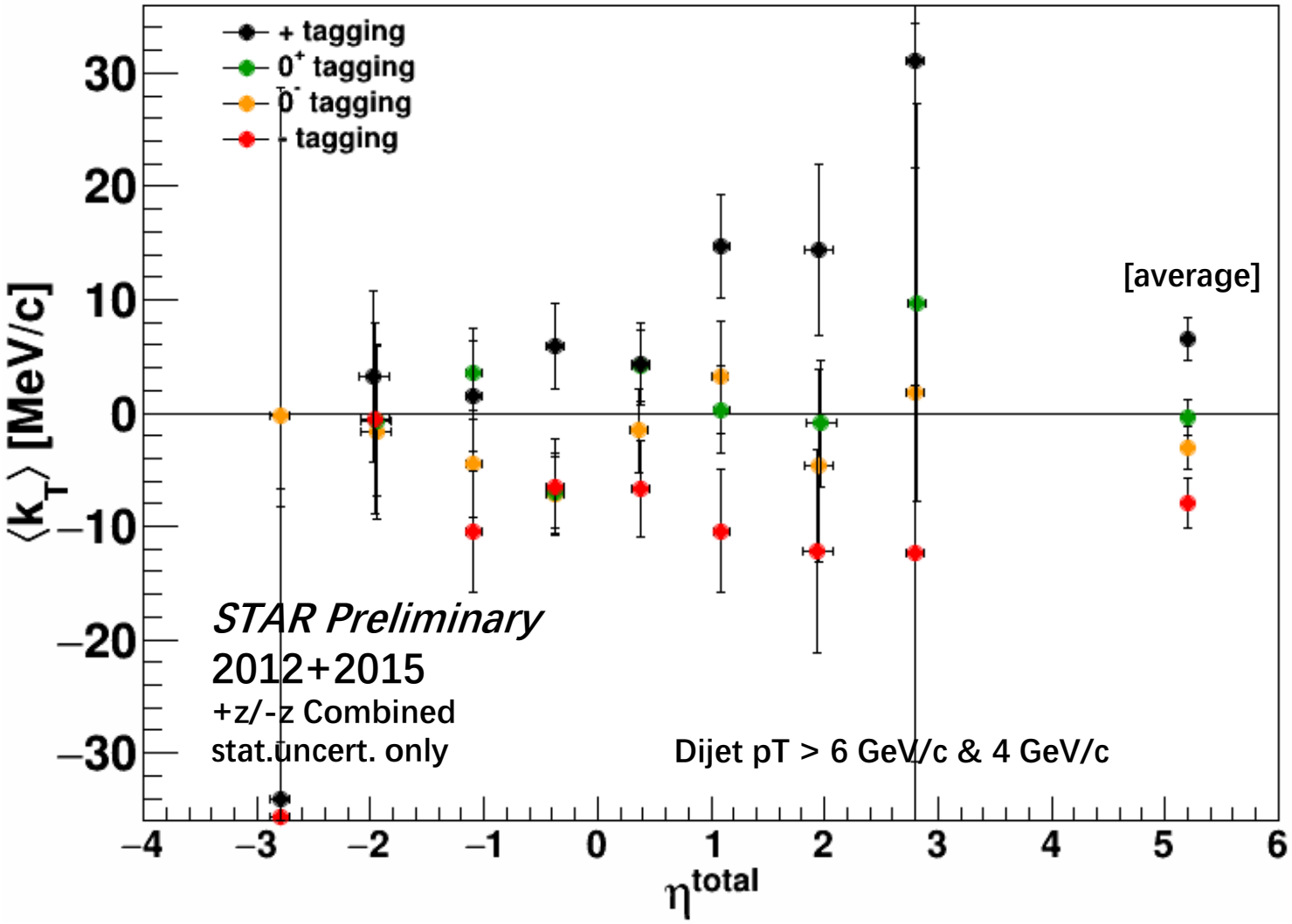




III. Convert the $\Delta\zeta$_vs_ η^{total} results to $\langle k_T \rangle$ _vs_ η^{total} results :

$$\langle k_T \rangle = \Delta\zeta \text{ / slope}$$

The Converted $\langle k_T \rangle$



- Using a finer binning (reason in next slide)
- Based on the simple kinematic model, we have :

$$\left\langle k_T^{+tagging} \right\rangle = +6.5\ \mathrm{MeV/c}$$

$$\left\langle k_T^{-tagging} \right\rangle = -7.9\ \mathrm{MeV/c}$$

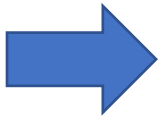
- Really tiny signal accessed through the STAR detector!

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

- **The tagged $\langle k_T \rangle$** results are parton mixtures, which can be **converted to the $\langle k_T \rangle$ of individual partons (*u*, *d*, *g*+sea)** through **solving system of equations**.
- 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} (see slide 11)
- The **over-constrained system** is solved through **Moore-Penrose inverse**.

$$f_1^u * u + f_1^d * d + f_1^g * g = \Delta_1$$
$$f_2^u * u + f_2^d * d + f_2^g * g = \Delta_2$$
$$\dots$$
$$f_8^u * u + f_8^d * d + f_8^g * g = \Delta_8$$

8 x 3 matrix

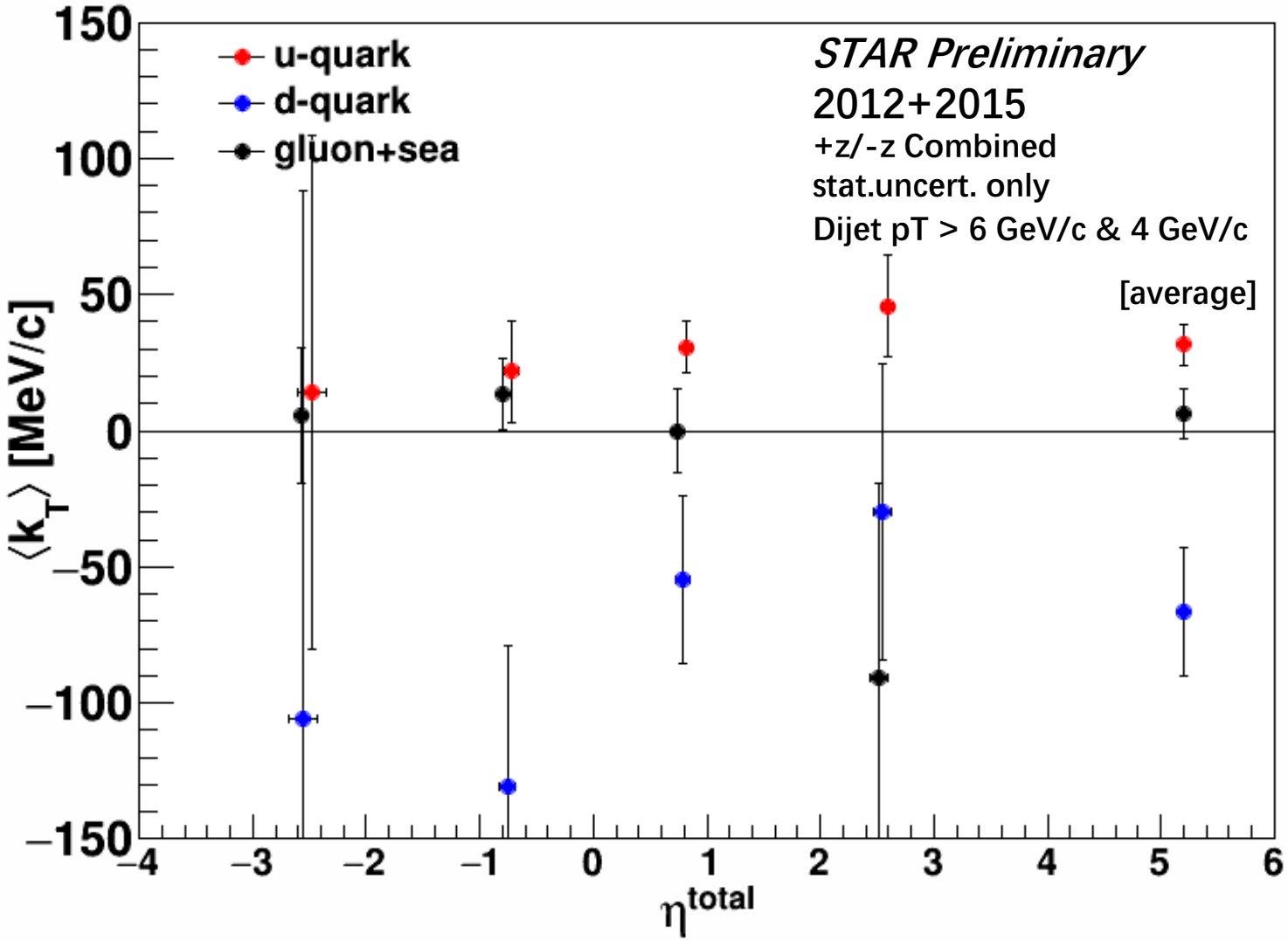


$$c_1^u * \Delta_1 + c_2^u * \Delta_2 + \dots + c_8^u * \Delta_8 = u$$
$$c_1^d * \Delta_1 + c_2^d * \Delta_2 + \dots + c_8^d * \Delta_8 = d$$
$$c_1^g * \Delta_1 + c_2^g * \Delta_2 + \dots + c_8^g * \Delta_8 = g$$

3 x 8 matrix

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

The Unfolded Parton $\langle k_T \rangle$



- $Q^2 > 160\ \mathrm{GeV}^2$
- $\langle k_T^u \rangle > 0, \langle k_T^d \rangle < 0, \langle k_T^{g+sea} \rangle \sim 0$
- $\left|\frac{\langle k_T^d \rangle}{\langle k_T^u \rangle}\right| \sim 2$
- No clear dependency on η^{total} at given statistics

Summary

- The preliminary dijet Sivers asymmetry using STAR 2012 and 2015 polarized pp data are presented.
- First observation of non-zero Sivers asymmetries in dijet production of polarized proton collisions!
- Individual parton <kT> is extracted:
  - $\langle k_T^u \rangle \approx$ 32 MeV/c, $\langle k_T^d \rangle \approx$ -67 MeV/c, $\langle k_T^{g+sea} \rangle$ is consistent with zero at given statistics.
  - These measurements will be important in theoretical investigation.
- Results are being finalized, publication is in preparation.

BACKUP

Event Selection and Yields

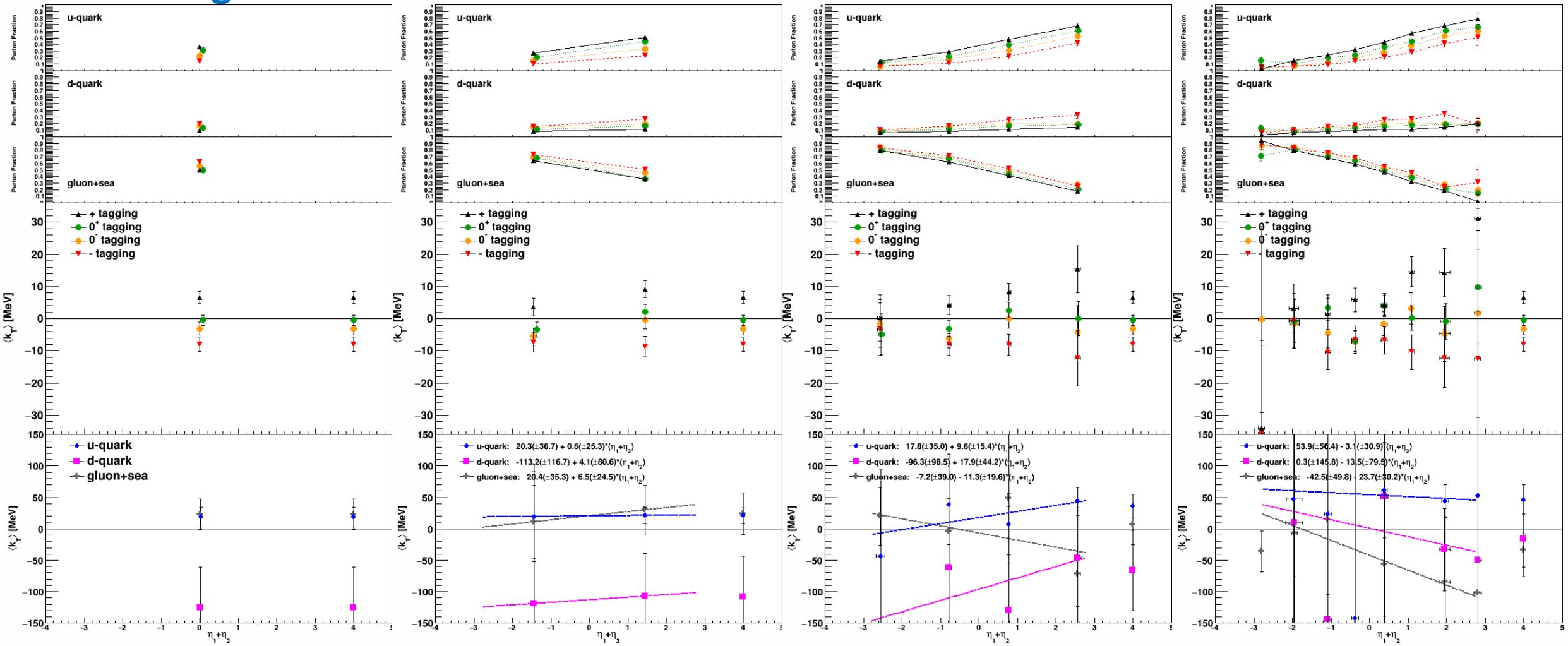
- Same selection criteria for 2012 and 2015
- Jet Reconstruction:
  - AntikT algorithm with R=0.6
  - jet pT > 4 GeV/c && -0.7 < $\eta^{detector}$ < 1.7 && -0.8 < η < 1.8
- Dijet Selection:
  - Number of jets = 2
  - ΔΦ > 120 deg
  - high pt > 6 GeV, low pt > 4 GeV

Event yields

2012	2015
24.9M	62.2M

The 2006 result has only 2.6M events. We have 33X statistics now.

Combining the eta1+eta2 bins



Doing 4X3 matrix inversion in combined eta1+eta2 bins:
(from left to right) 1 bin, 2 bins, 4 bins, 8 bins