Indiana University

STAR

# 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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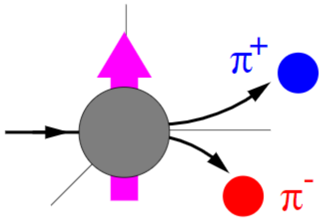
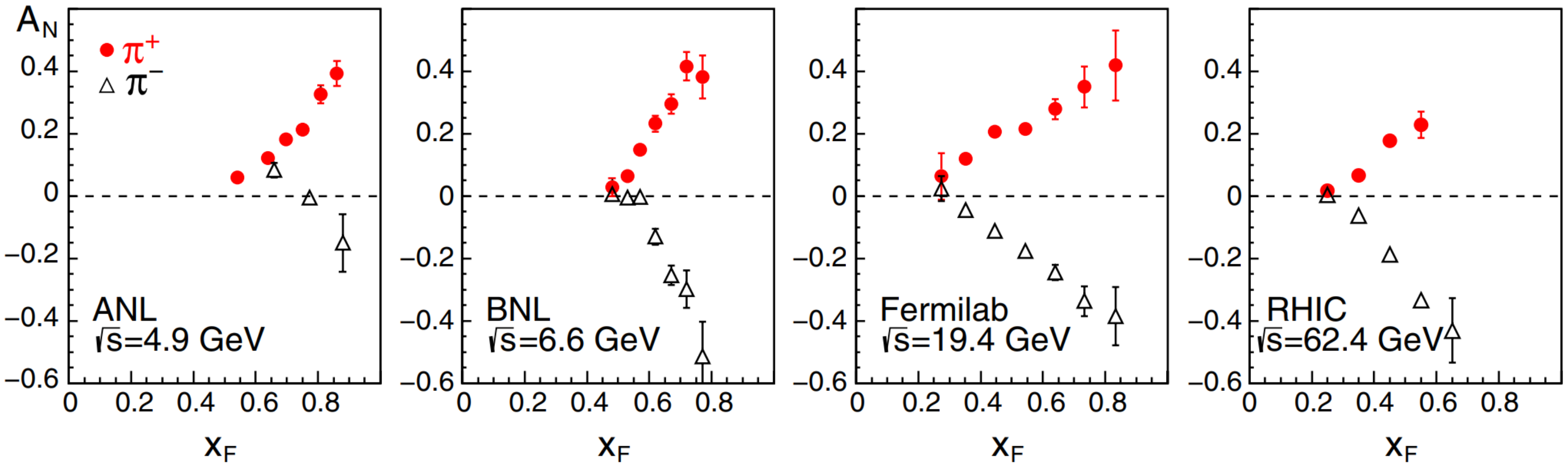
# Transverse Single-Spin Asymmetries: A Puzzle

$p\uparrow + p \to \pi X$

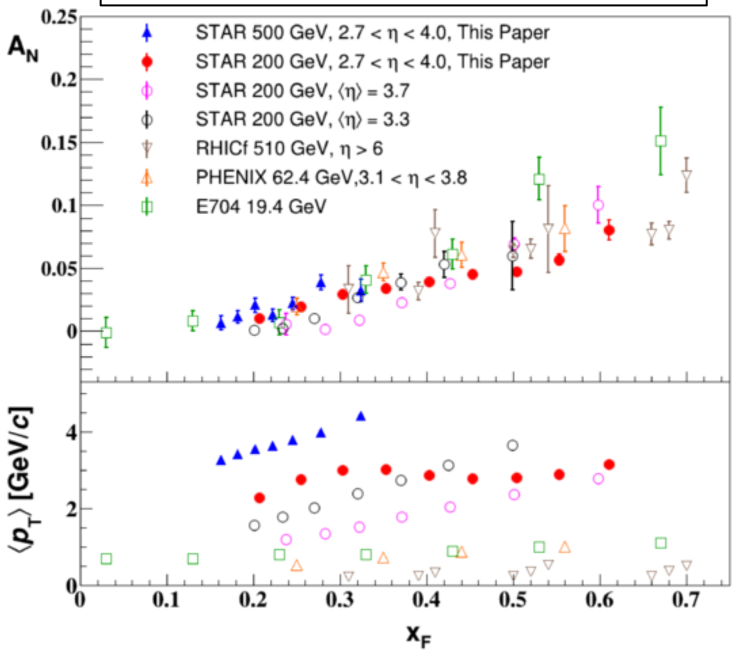



$$A_N = \frac{1}{P_{beam}} \frac{N^{\pi}_{left} - N^{\pi}_{right}}{N^{\pi}_{left} + N^{\pi}_{right}}$$

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




Adam *et al.*, Phys. Rev. D **103**, 92009 (2021)



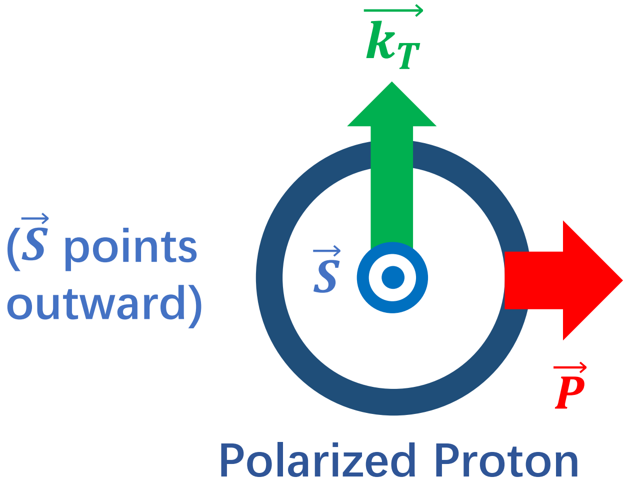

- Surprisingly large transverse single-spin asymmetries (TSSA's) have been observed in forward meson production from hadronic collisions since the 1970's, for $\sqrt{s}$ ranging from ~5 to 500 GeV
- Several possible mechanisms have been proposed, most involving partonic transverse motion within the proton
- Two particularly strong candidates lend themselves to experimental investigation at RHIC:
  - Sivers distribution function
  - Collins fragmentation function

# Partonic $k_T$ in the Initial State: the Sivers Effect

- A mechanism proposed by Sivers (1990) to explain the large hadron TSSA.
- Introduces a correlation (triple product) within a transversely polarized proton among the proton's spin $\vec{S}$ and momentum $\vec{P}$ with the transverse momenta $\vec{k}_T$ of its constituent partons:

Sivers Effect

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

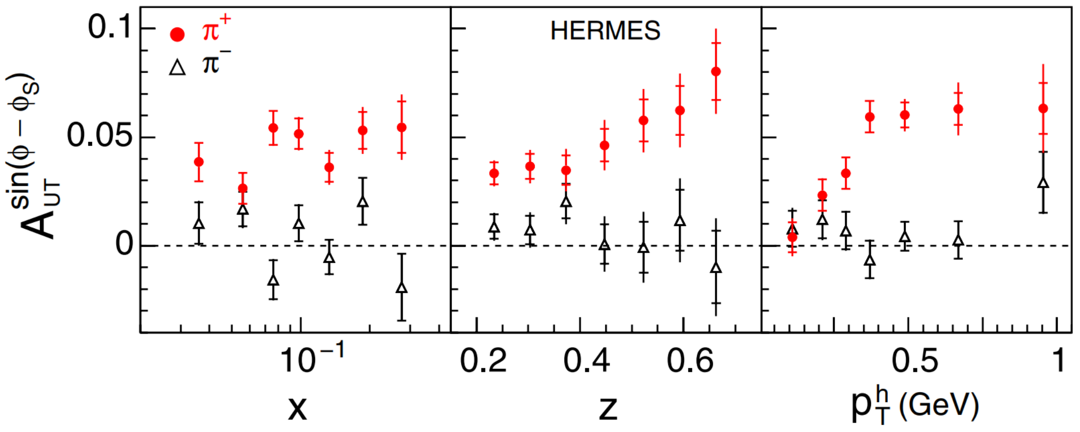



$$\langle \vec{S}_{proton}\cdot(\vec{k}_T\times\vec{P}_{proton})\rangle \neq 0$$

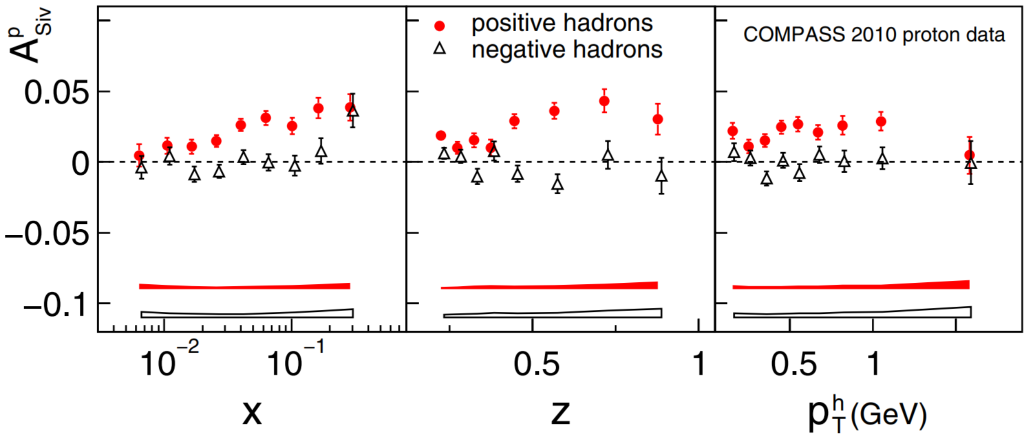
- The Sivers function $f_{1t}^{\perp}$ encodes the correlation between partonic orbital motion and the proton spin
- Related to the twist-3 Qiu-Sterman matrix element (multi-parton correlation) in a collinear framework

# Measurements in SIDIS and W production

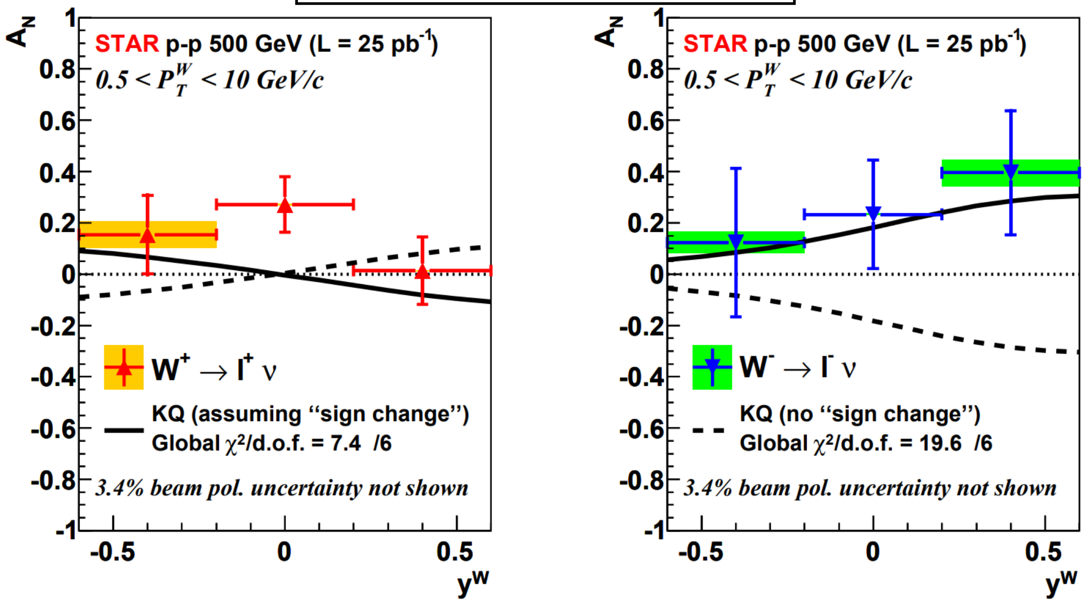
**SIDIS @Hermes**
Phys. Rev. Lett. 103, 152002 (2009)




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



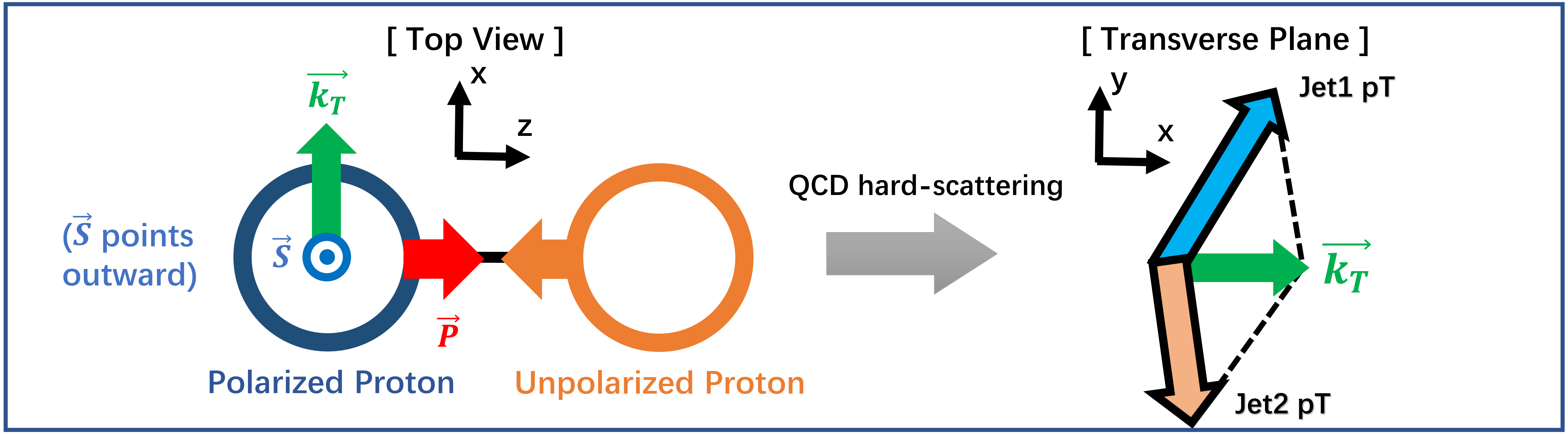

**W measurement @STAR**
Phys. Rev. Lett. 116, 132301 (2016)




- ✓ *u* and *d* quarks are expected to have $\langle k_T \rangle$ of opposite sign – observed in SIDIS @Hermes, Compass, JLab
- ✓ The sign of $A_N$ is predicted to reverse between SIDIS and DY / W production in pp – hints in STAR data

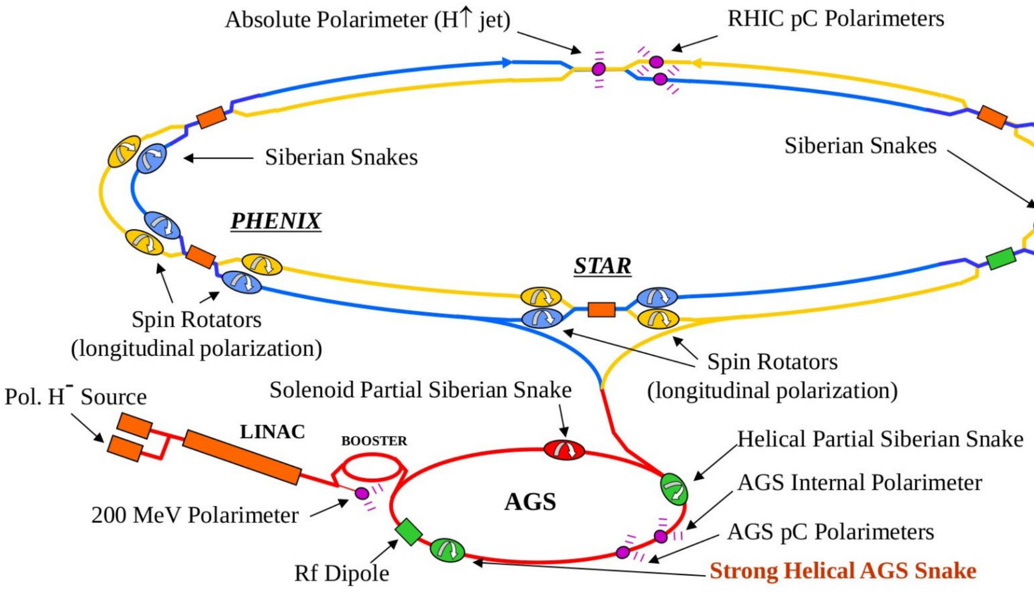
Scott Wissink – SPIN2021, Oct. 2021

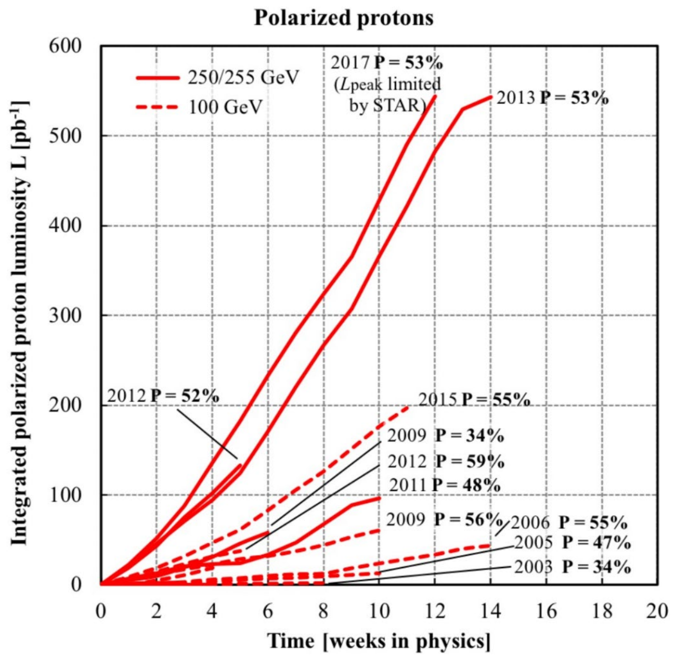
# Observing Sivers Effect in $\vec{p} + p$ Dijet Production

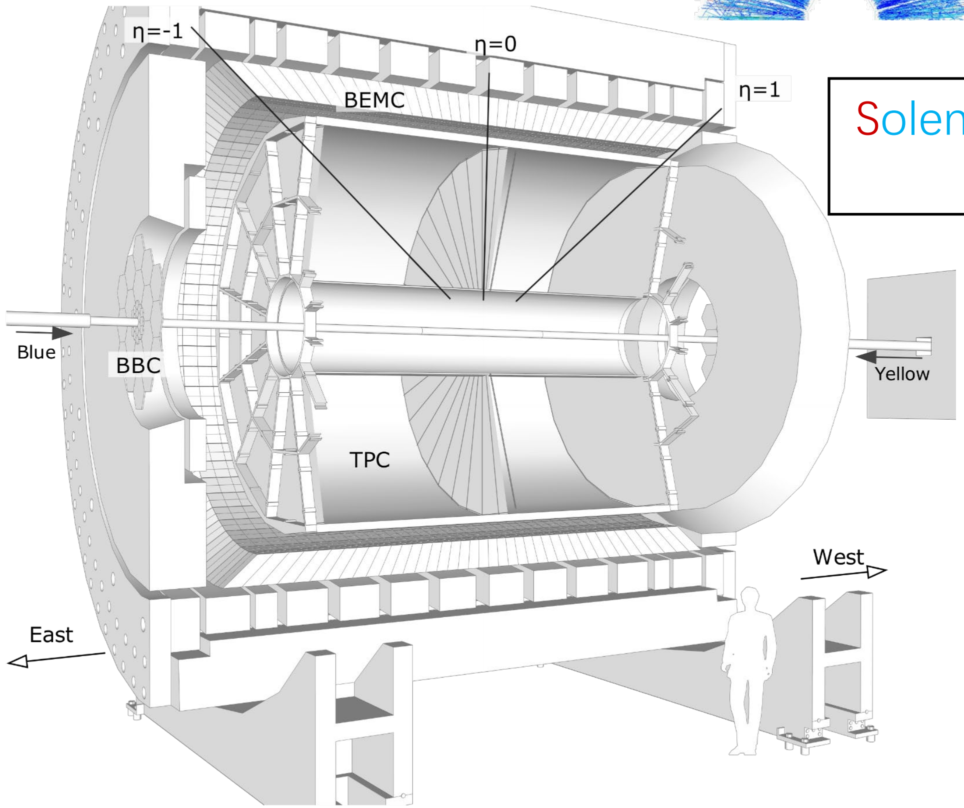



- Allows for a kinematic detection of a non-zero spin-dependent $k_T$, rather than a yield asymmetry
- Non-zero results would suggest contributions from partonic angular momentum to the proton spin
- Because the net partonic $k_T$ must average to zero for a proton moving longitudinally, expect $u$ and $d$ contributions to be opposite in sign and different in magnitude
- Probing the Sivers effect via dijet production at RHIC explores physics at a much higher $Q^2$ than is possible via SIDIS at current and previous facilities

# Facilities: RHIC & STAR at BNL




Solenoidal Tracker At RHIC

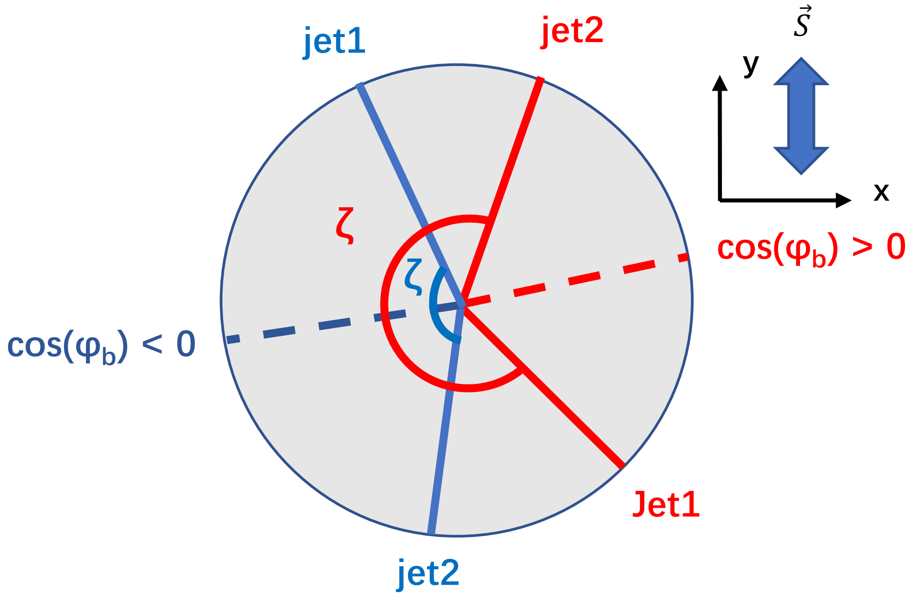
- RHIC: provides collisions of transversely or longitudinally polarized protons at energies up to $\sqrt{s}$ = 510 GeV
- STAR: allows for charged-particle track reconstruction for |η|< 1.3, and measures EM particle energies for -1< η <2, both over the full azimuthal range of 2π

# New Observable for Probing the Sivers Effect

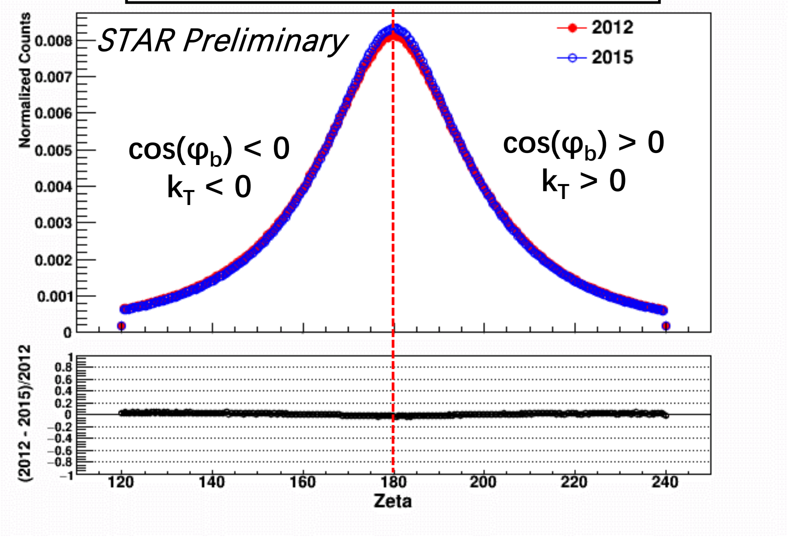
The Sivers asymmetry can be probed via the signed opening angle ζ .

**Definition of ζ**

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




**Distribution of ζ in data**




**Key idea:** A non-zero Sivers function will lead to a *spin-dependent shift* of the ζ distribution. Thus, we seek to extract the spin-dependent asymmetry

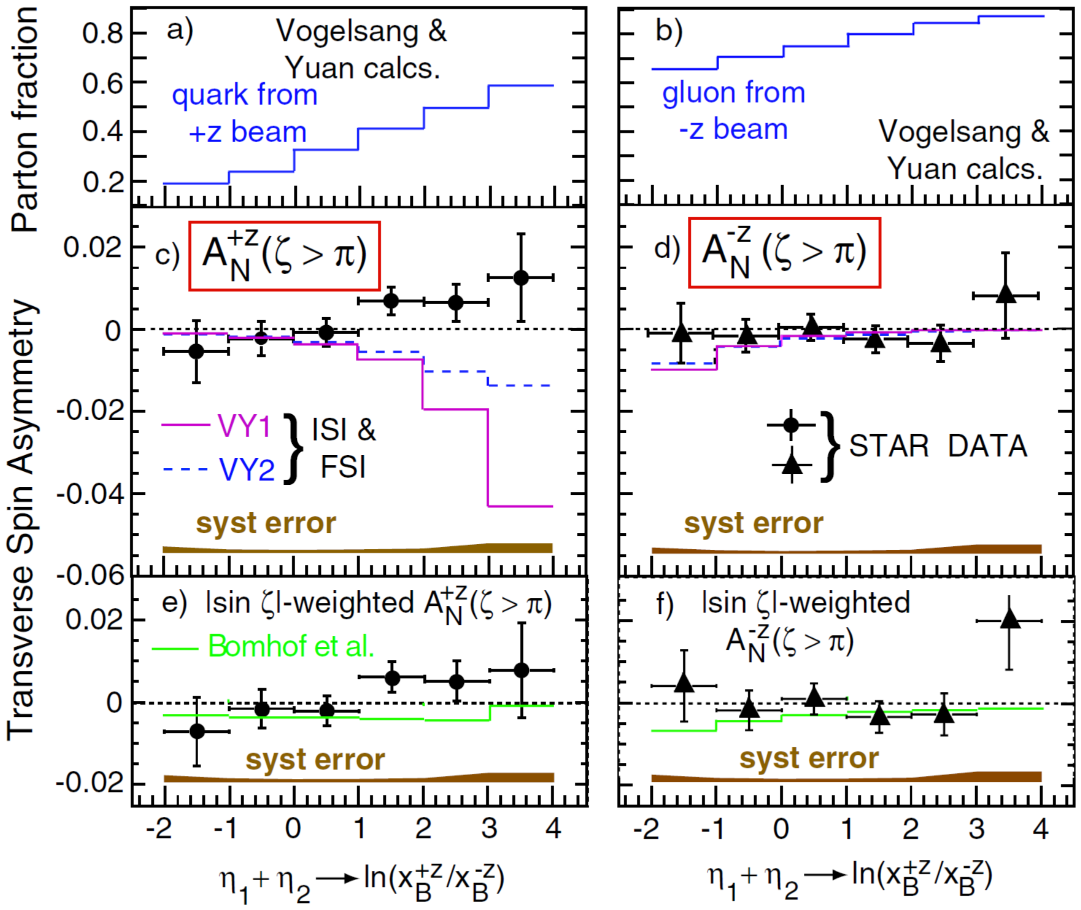
$$\Delta\zeta = \frac{\langle\zeta\rangle^{+} - \langle\zeta\rangle^{-}}{P}$$

where $\langle\zeta\rangle^{+/-}$ is the centroid of the ζ distribution for spin-up / spin-down proton beams, respectively, and $P$ is the magnitude of the beam polarization.

# Improving on the 2006 Analysis

- A previous analysis of STAR data from 2006 yielded spin asymmetries consistent with zero, though with large statistical uncertainties
- This analysis is based on combined STAR data from 2012 and 2015, and differs by having:
  - ✓ 33 times larger integrated luminosity
  - ✓ Fully reconstructed jets (no tracking for 2006 data) at a higher average $p_T$
  - ✓ Use of a charge-tagging method to enhance separately the $u$-quark and $d$-quark signals
- Simulations for the current analysis are based on Pythia6+Geant3, embedded in real zero-bias events for all data/MC comparisons

STAR, Phys. Rev. Lett. **99** 142003 (2007)




Asymmetries are plotted versus the sum of the dijet pseudo-rapidities. For 2→2 scattering, note that

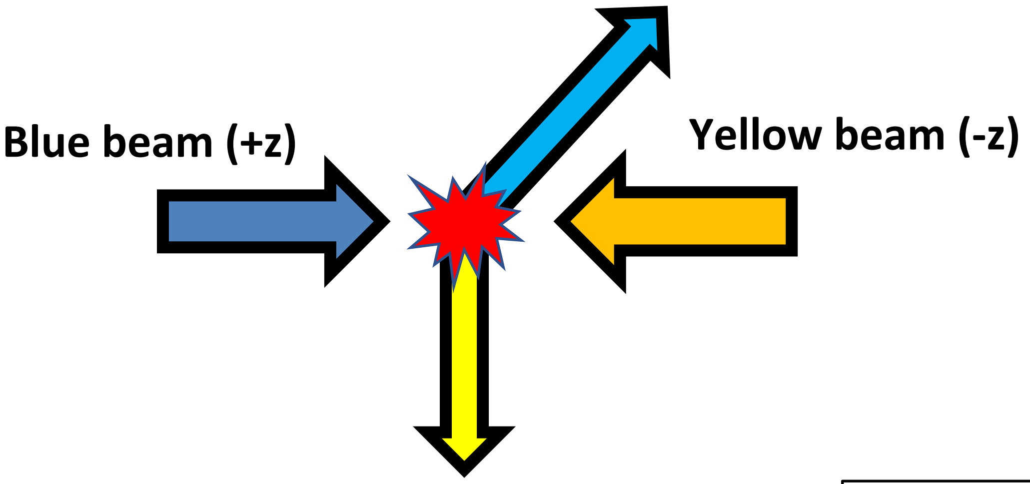
$$\eta_3 + \eta_4 = \ln\left(\frac{x_1}{x_2}\right)$$

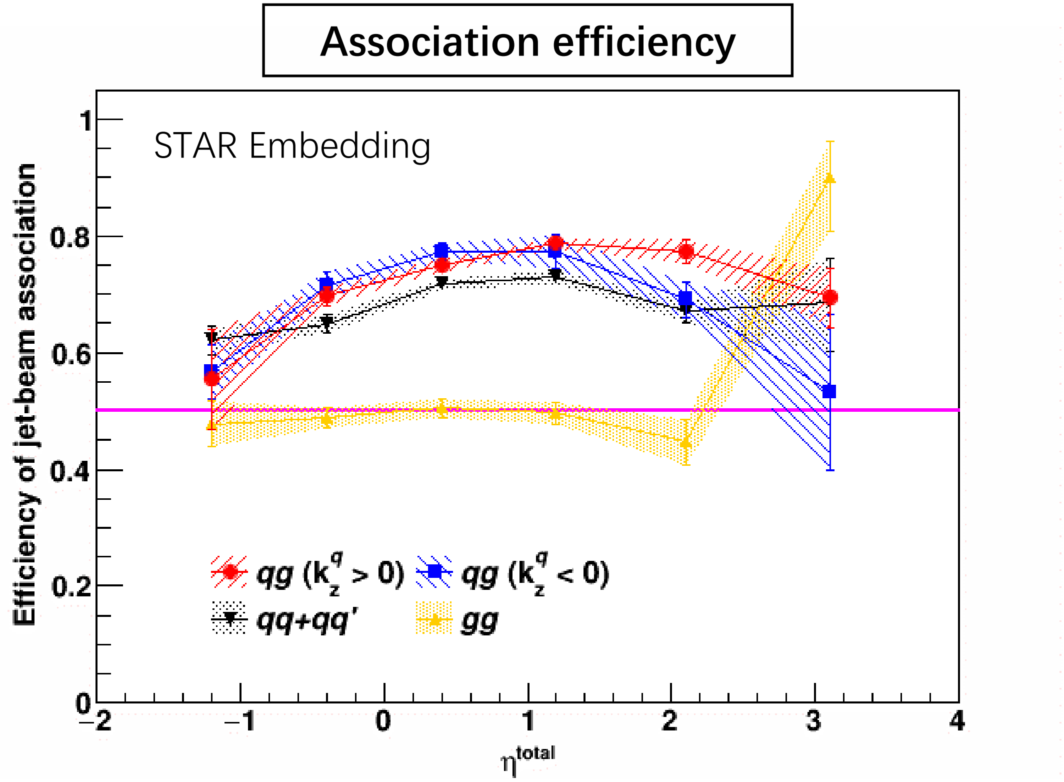
# First step: Beam → Jet Association

- To follow the “parton flow” during the scattering, one must first decide which of the reconstructed jets arises from fragmentation of a parton contained initially in the polarized proton beam.
- To do so, we assume the more forward of the two jets (largest |η|) is associated with a fragmenting parton from the beam moving in that direction.

Example: in the event below, |η| for the blue jet is greater than |η| for the yellow jet, so we assume the blue (yellow) jet originates from the parton scattered from a proton in the blue (yellow) beam.

Simulations indicate this association is correct about 70-80% of the time.




$$\eta^{total} \equiv \eta_3 + \eta_4$$

# Next: Sort All Jets by Net Charge

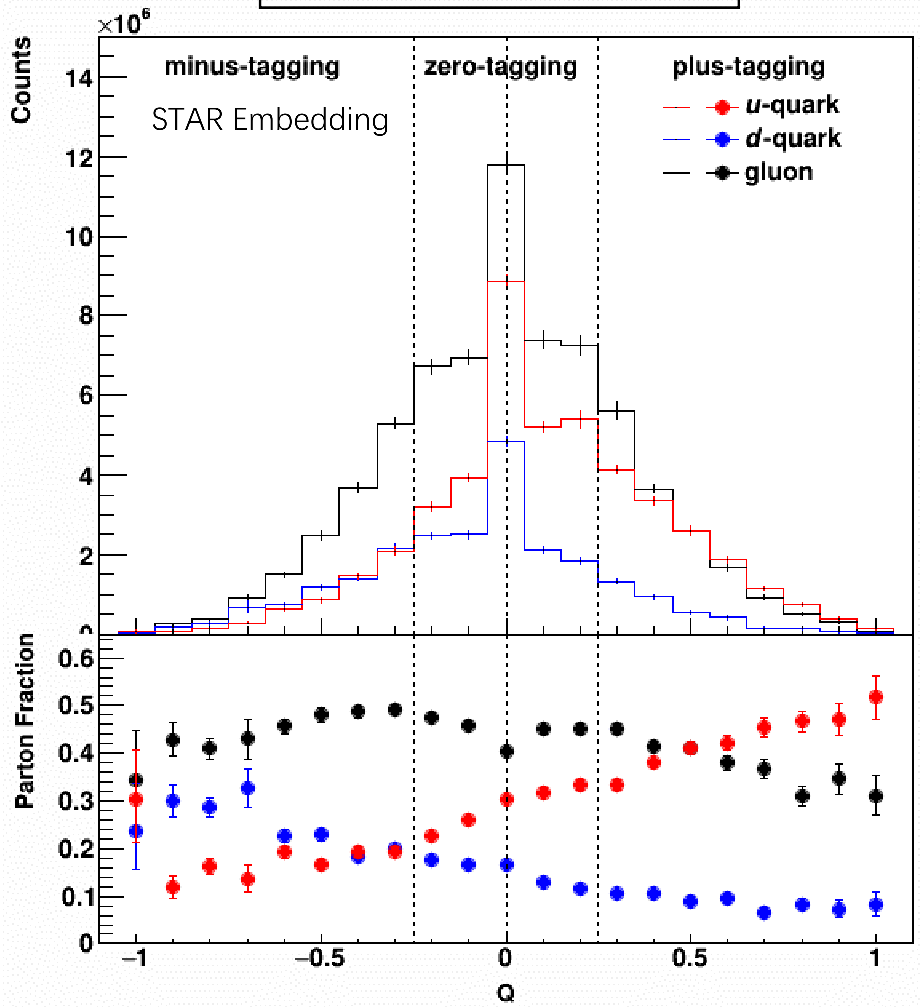
We calculate a momentum-weighted charge sum for each jet, to yield samples enhanced to different extents in *u*-quarks and *d*-quarks

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

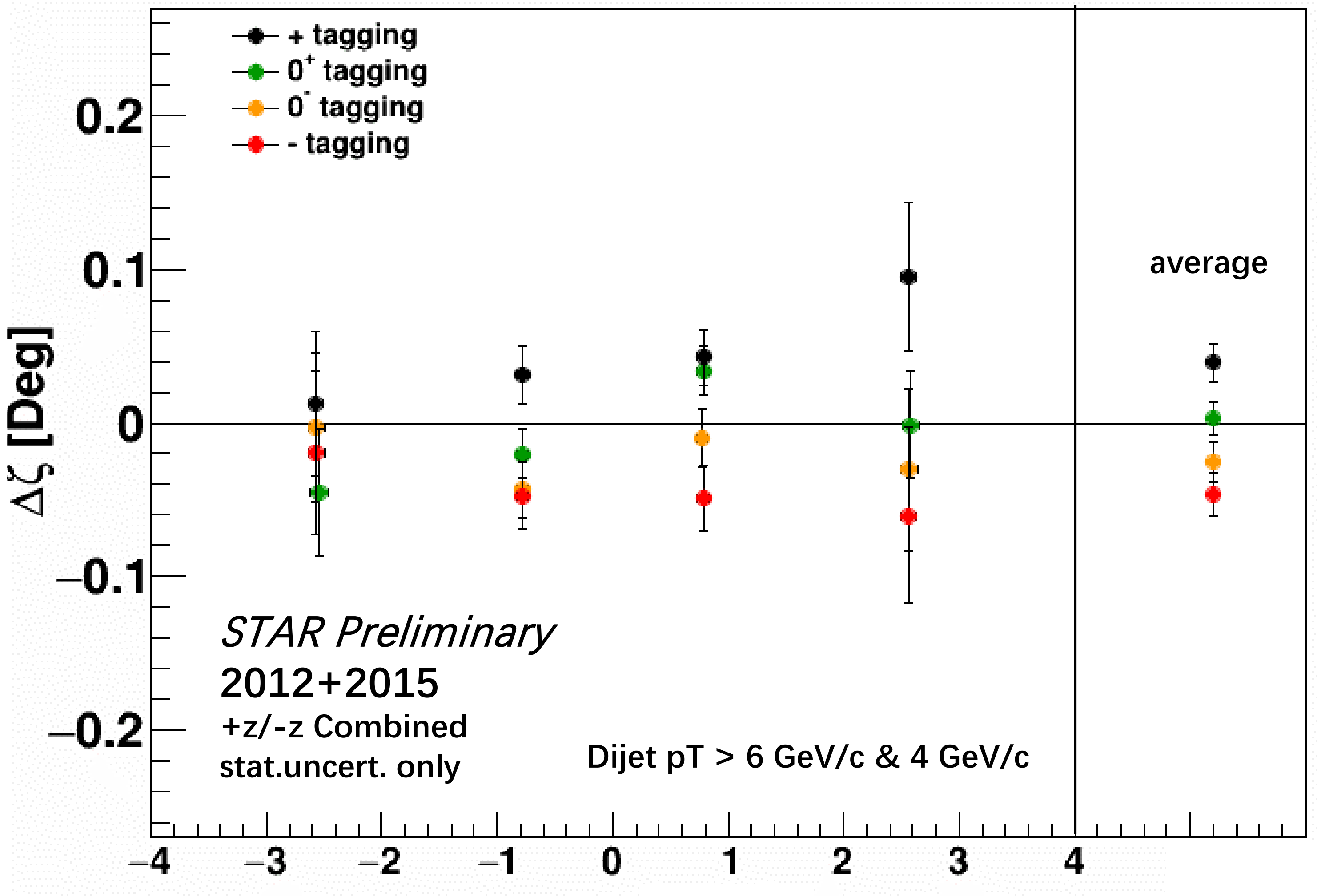
Jets are then sorted into four categories:

1. Plus tagging ($Q \geq 0.25$): highest *u* content, lowest *d*
2. Zero+ tagging ($0 \leq Q < 0.25$): more *u* than *d*
3. Zero- tagging ($-0.25 < Q < 0$): about equal *u* and *d*
4. Minus tagging ($Q \leq -0.25$): highest *d* content, lowest *u*

Distribution of $Q$



# Extract Δζ Asymmetry for each Tagged Sample




$\eta^{total} = \eta_3 + \eta_4$

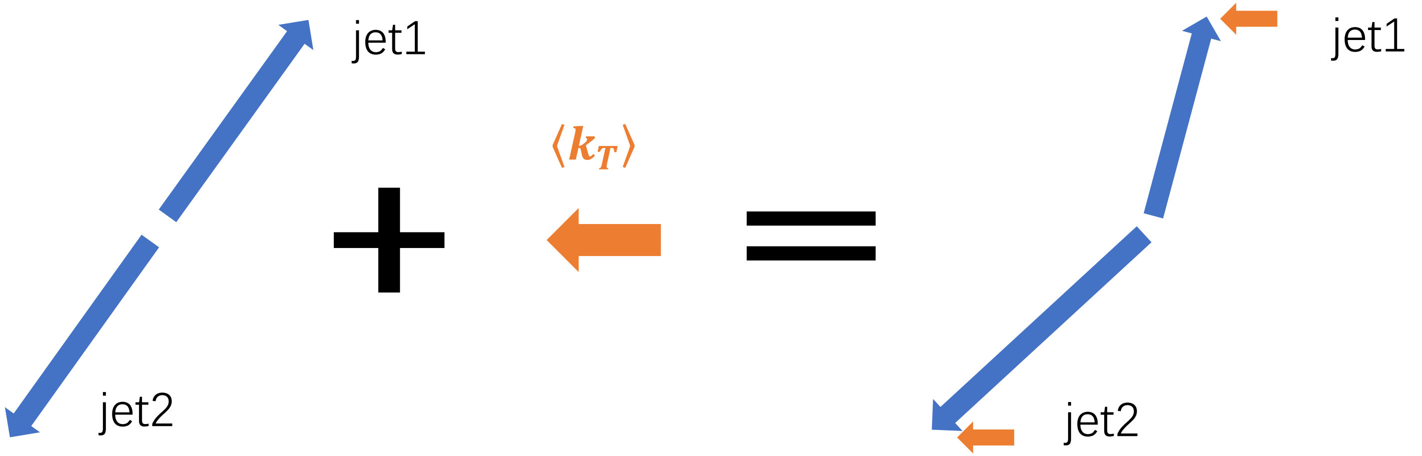
- Combine results for blue and yellow beams by 'flipping' signs of both $\eta$ and asymmetry for yellow beam
- Clear increase with $\eta^{total}$ seen for plus-tagging and minus-tagging
- Average asymmetry systematically shifts from + to – as sampled data moves from *u*-quark to *d*-quark dominated, ~5σ separation between plus-tagging and minus-tagging
- Asymmetries are consistent with zero when averaged over tagging samples, even with 33x more data than the 2006 measurement.

# Physics: Convert the $\Delta\zeta$ Asymmetry to a $\langle k_T \rangle$

Converting the measured $\Delta\zeta$ asymmetries to $\langle k_T \rangle$ values involves 3 steps:

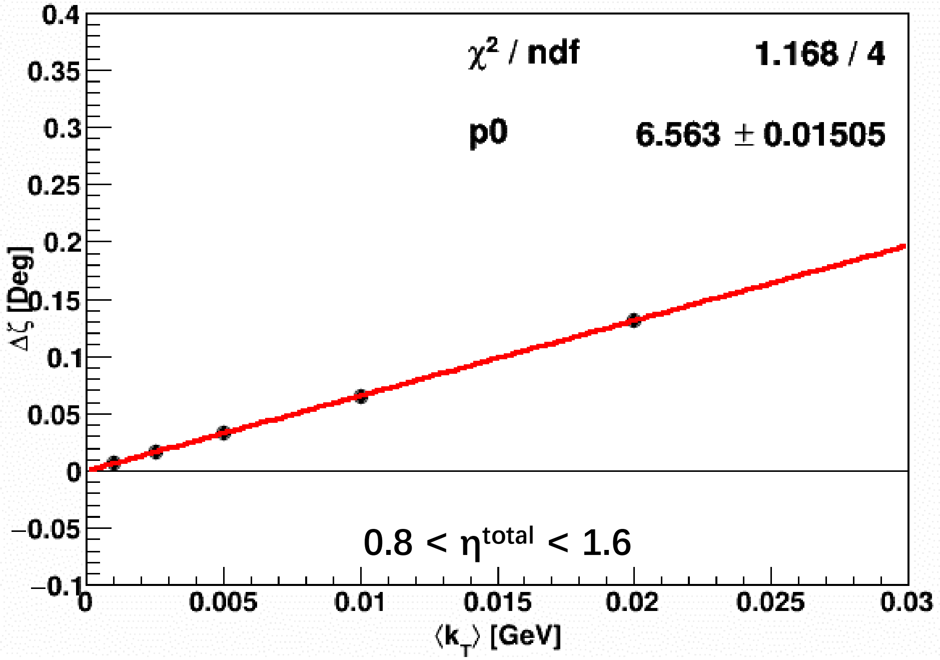
1. First correct detector-level jet $p_T$ to parton-level $p_T$ using machine learning
2. Assuming a constant $k_T$, calculate $\Delta\zeta$ for the corrected jet $p_T$ distribution in each $\eta^{total}$ bin and extract the needed $\Delta\zeta$-$\langle k_T \rangle$ correlation, as shown below
3. Convert $\Delta\zeta$ vs $\eta^{total}$ results to $\langle k_T \rangle$ vs $\eta^{total}$ results, using $\langle k_T \rangle = \Delta\zeta$ / slope

Kinematic model (transverse plane)

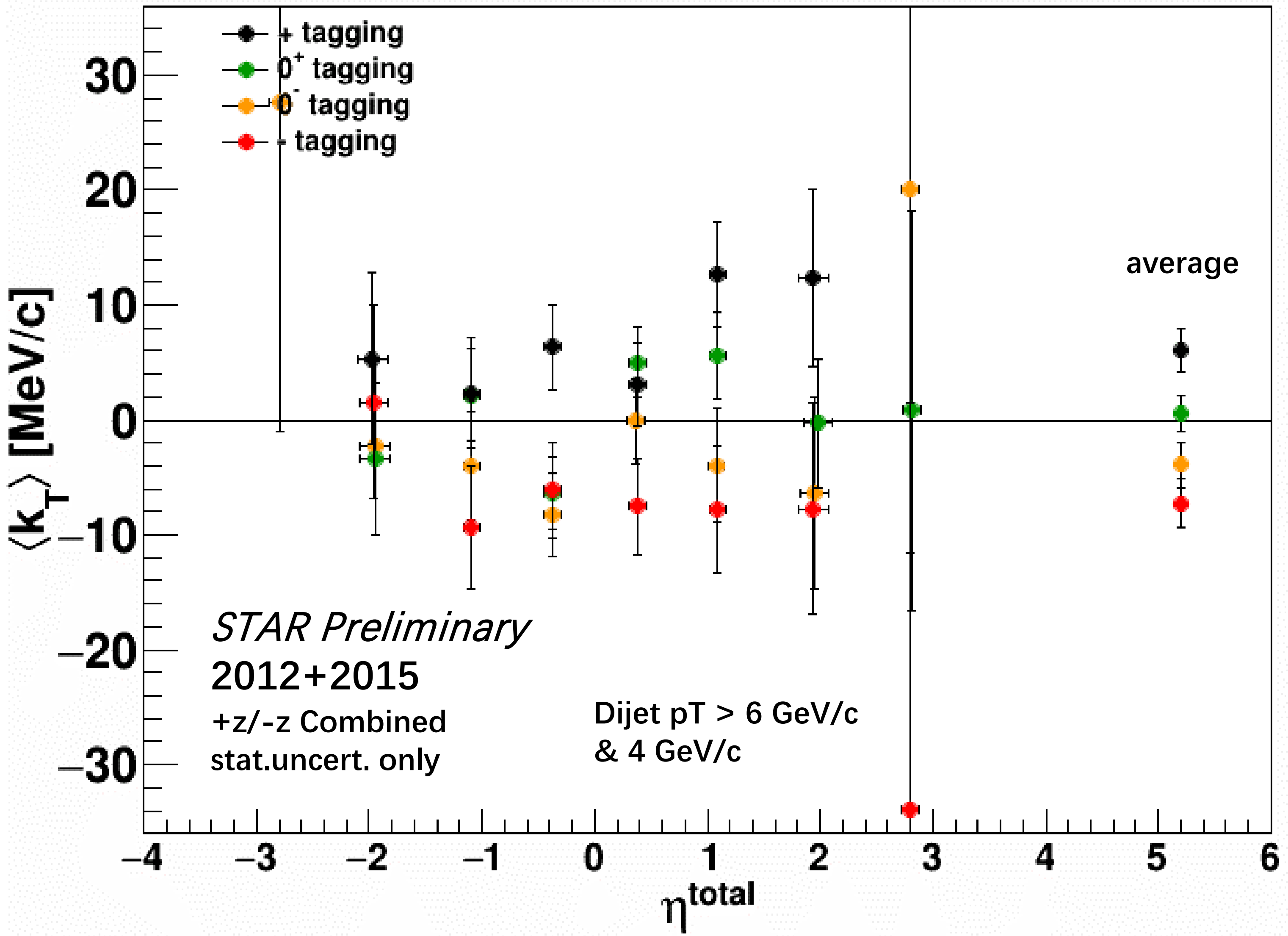



(1) Corrected dijet event (2) Add $\langle k_T \rangle$ (3) Modified dijet event

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



# Sivers $\langle k_T \rangle$ Values for Tagged Dijet Samples




- Qualitatively very similar to Δζ plot, though we used finer binning in $\eta^{tot}$
- Scale of effect is small, on the order of ~10 MeV/*c*. In particular, we note
  - $\left\langle k_T^{+tagging} \right\rangle = +6.1\ \mathrm{MeV/c}$
  - $\left\langle k_T^{-tagging} \right\rangle = -7.3\ \mathrm{MeV/c}$
- Hierarchy of decreasing charge sum correlated with more negative $\langle k_T \rangle$ is preserved
- Without jet sorting by charge sum, average $\langle k_T \rangle$ statistically consistent with zero

# Convert Tagged $\langle k_T \rangle$ to Parton $\langle k_T \rangle$ in $\eta^{total}$ bins

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- Tagged $\langle k_T \rangle$ results represent different parton mixtures. Using simulations, these can be converted to the $\langle k_T \rangle$ of individual partons (*u*, *d*, *g*+sea) using inversion techniques
- We construct the following set of equations, yielding an 8 x 3 matrix:
  - 4 charge-taggings: differentiate among the various parton species
  - Each inversion uses results from a pair of adjacent $\eta^{total}$ bins: because the parton fraction is dependent on $\eta^{total}$ as shown previously, this leads to more stability in the inversion process
- The over-constrained system is solved using the Moore-Penrose inversion:

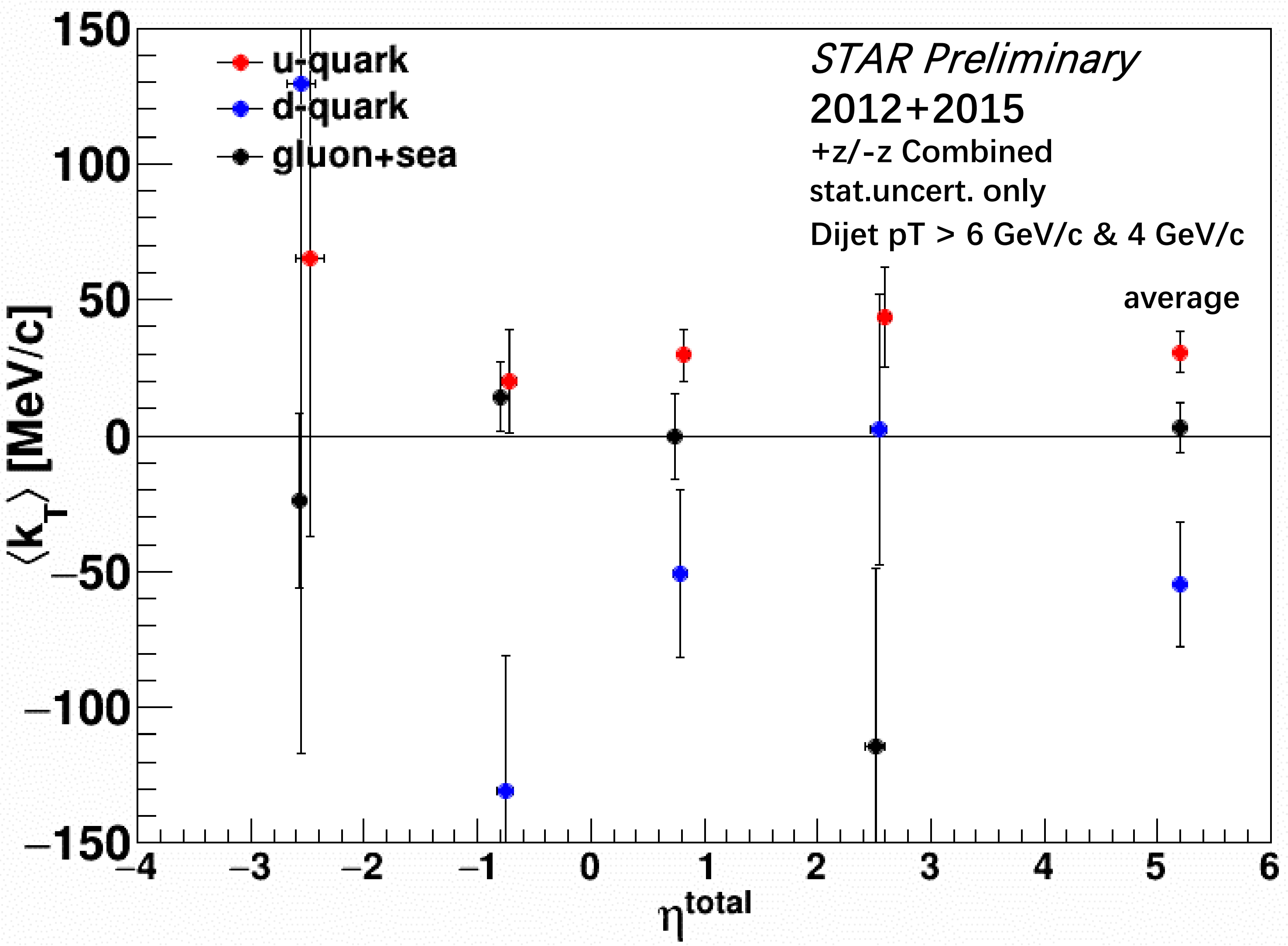
$$\begin{bmatrix} f_1^u * u + f_1^d * d + f_1^g * g = \Delta_1 \\ f_2^u * u + f_2^d * d + f_2^g * g = \Delta_2 \\ \ldots \\ f_8^u * u + f_8^d * d + f_8^g * g = \Delta_8 \end{bmatrix} \Rightarrow \begin{bmatrix} c_1^u * \Delta_1 + c_2^u * \Delta_2 + \cdots + c_8^u * \Delta_8 = u \\ c_1^d * \Delta_1 + c_2^d * \Delta_2 + \cdots + c_8^d * \Delta_8 = d \\ c_1^g * \Delta_1 + c_2^g * \Delta_2 + \cdots + c_8^g * \Delta_8 = g \end{bmatrix}$$

8 x 3 matrix

3 x 8 matrix

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

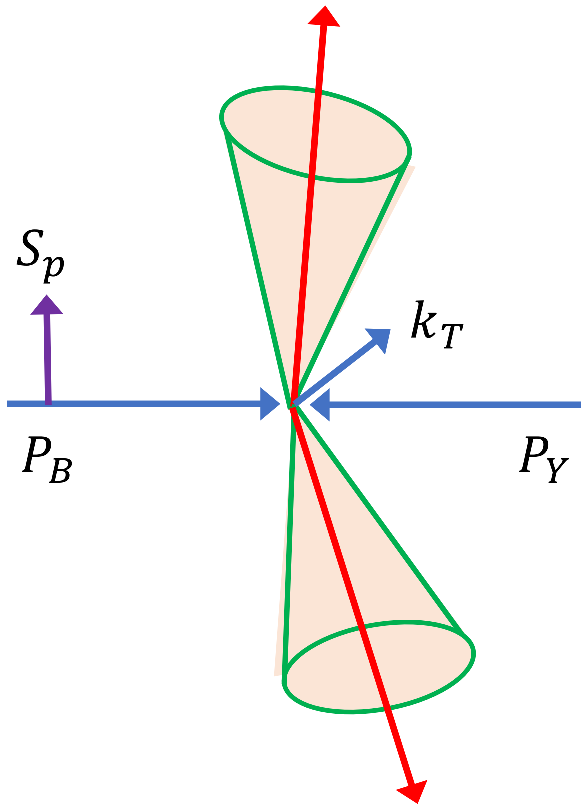
# Results: The Unfolded Parton $\langle k_T \rangle$




- First direct evidence for a non-zero Sivers effect in dijet production!
- Averaged over $\eta^{total}$, parton results follow general expectations:
  - ✓ $\langle k_T^u \rangle > 0$
  - ✓ $\langle k_T^d \rangle < 0$
  - ✓ $\langle k_T^{g+sea} \rangle \sim 0$
- Note $\langle k_T^d \rangle$ / $\langle k_T^u \rangle$ ~ -2, as needed to bring proton total $\langle k_T \rangle$ close to 0
- No clear dependency of partonic $\langle k_T \rangle$'s on $\eta^{total}$ within our statistical precision, suggesting a weaker than expected $x$-dependence for the Sivers functions

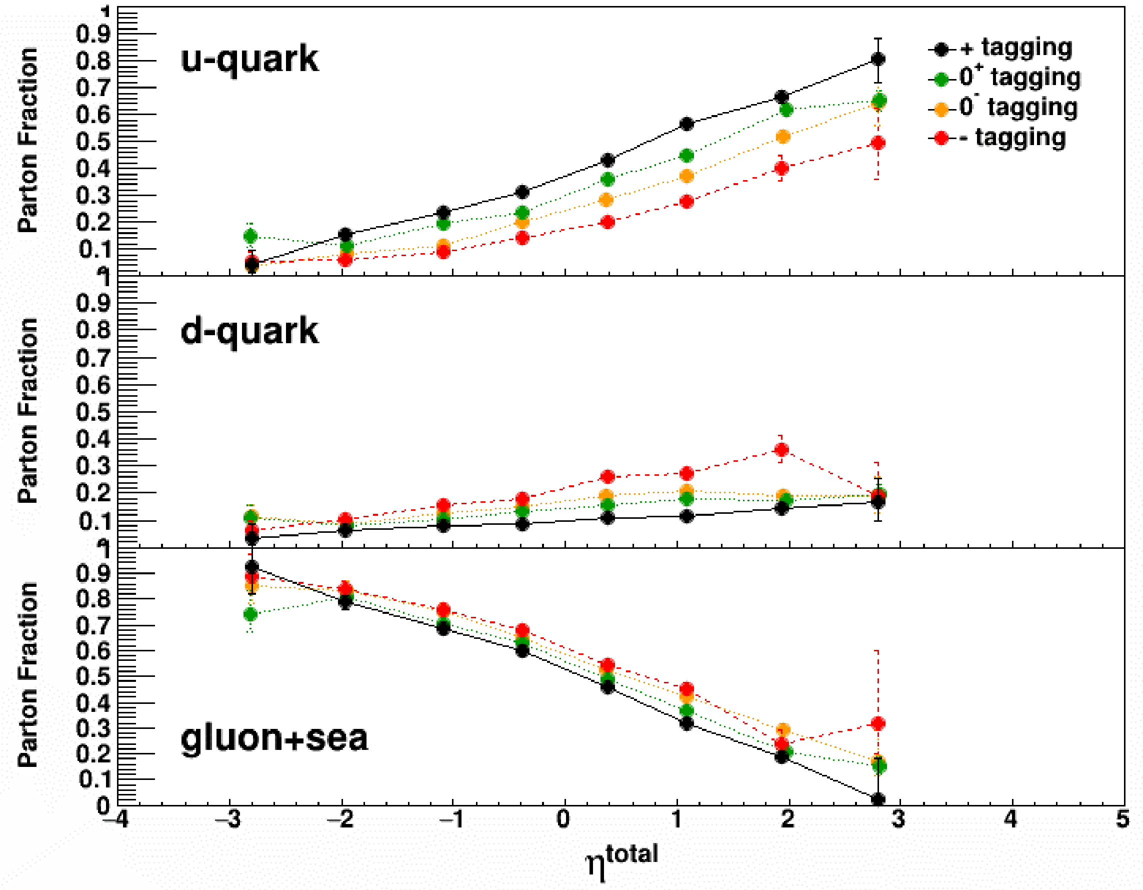
# Summary and Future Work

- Preliminary results for Sivers asymmetries from dijet production in high-energy p+p collisions at STAR (2012 and 2015 data sets) are presented
- First observation of non-zero Sivers asymmetries in a purely hadronic reaction channel
- Using simulations, $\langle \boldsymbol{k_T} \rangle$ for individual partons have been extracted, yielding $\langle \boldsymbol{k_T^u} \rangle$ ≈ 30 MeV/c, $\langle \boldsymbol{k_T^d} \rangle$ ≈ -55 MeV/c, and $\langle \boldsymbol{k_T^{g+sea}} \rangle$ is statistically consistent with zero
- No strong dependence on $\eta^{total}$ is observed, which suggests a fairly weak $x$ dependence in $\boldsymbol{f_{1t}^{\perp}}$
- Results have been finalized, systematic uncertainties have been evaluated, and a publication is in preparation.



# Back-up material

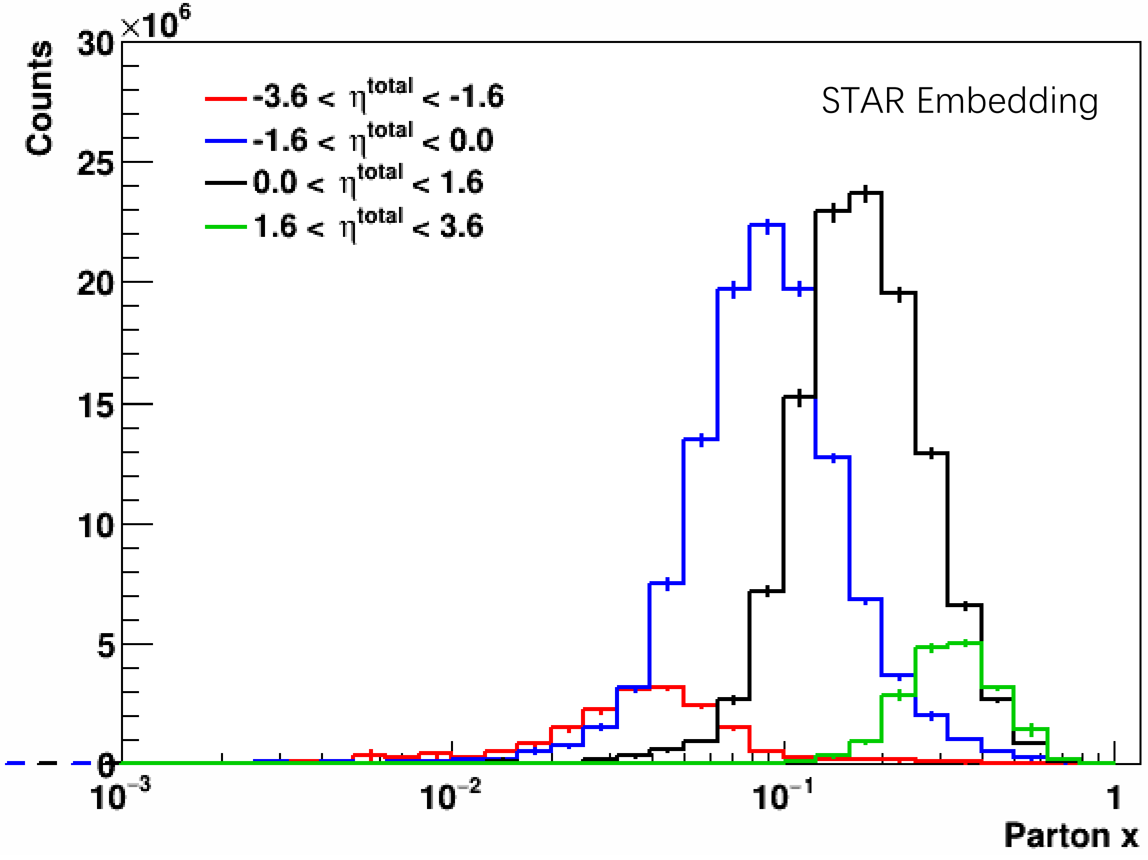
# Parton Fractions




- Parton fractions are estimated from STAR embedding.
- $\eta^{total} = \eta1+\eta2$ is proportional to ln(x1/x2)
- More u-quarks at higher Q and higher $\eta^{total}$
- More d-quarks at lower Q, weak dependency on $\eta^{total}$
- More gluons at lower Q and lower $\eta^{total}$

# Parton $x$ Distributions

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

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