Recent Transverse Spin Results from pp Collisions at STAR

Transversity2022, Pavia
23-27 May, 2022

W.W. Jacobs
CEEM / Indiana University
for the STAR Collaboration

Supported in part by:

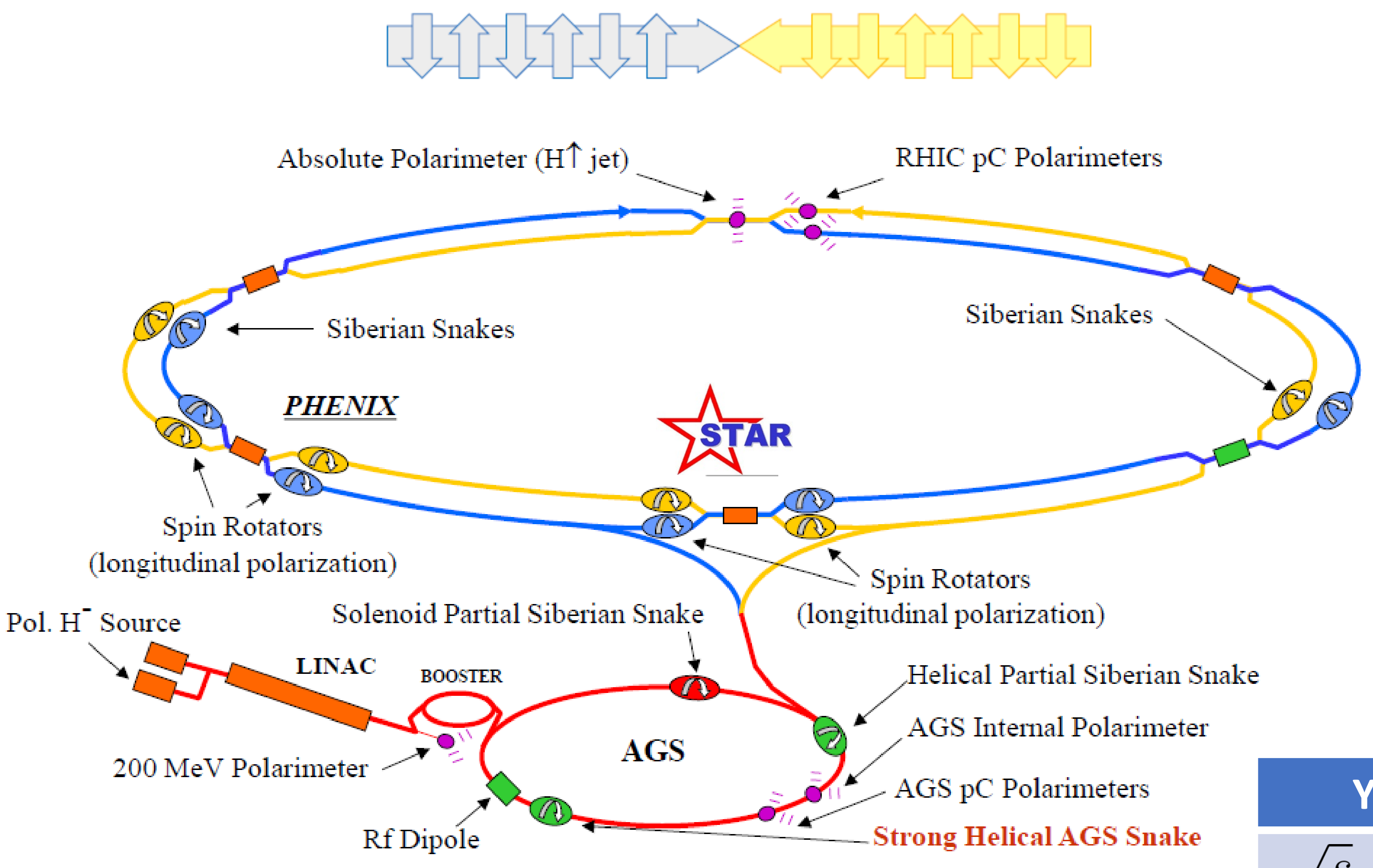
Talk Topics:

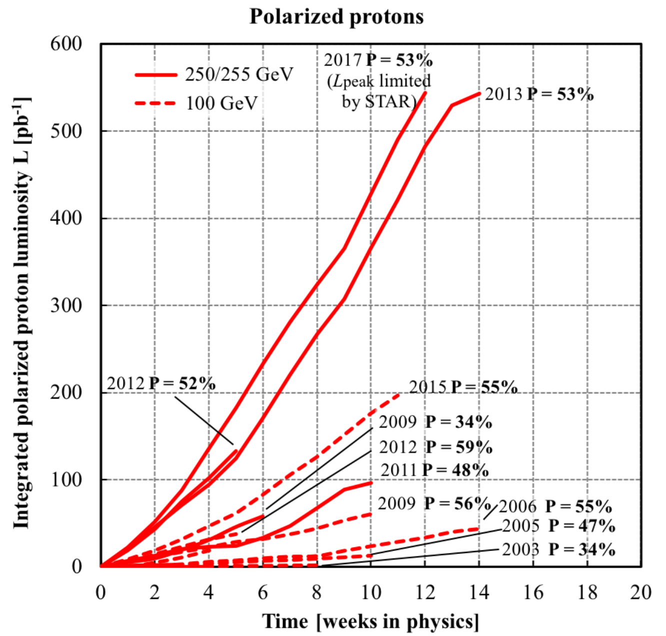
- Intro / TSSA
- Dijet Sivers
- $W^{\pm}, Z$ and Sivers
- Di-hadons & Transversity
- Collins asymmetry results
- A_N: fwd π° and EM jets
- Future / Prospects

- A rich environment for transverse spin studies at STAR.
- Many relevant recent results and ongoing analyses.
- Focus here on dijet / Sivers and recent results relevant to workshop themes.

RHIC (World's First & Only) Polarized Proton Collider

$\vec{p} + \vec{p} \,/\, \vec{p} + A \qquad \sqrt{s_{NN}} = 200 - 510$ GeV





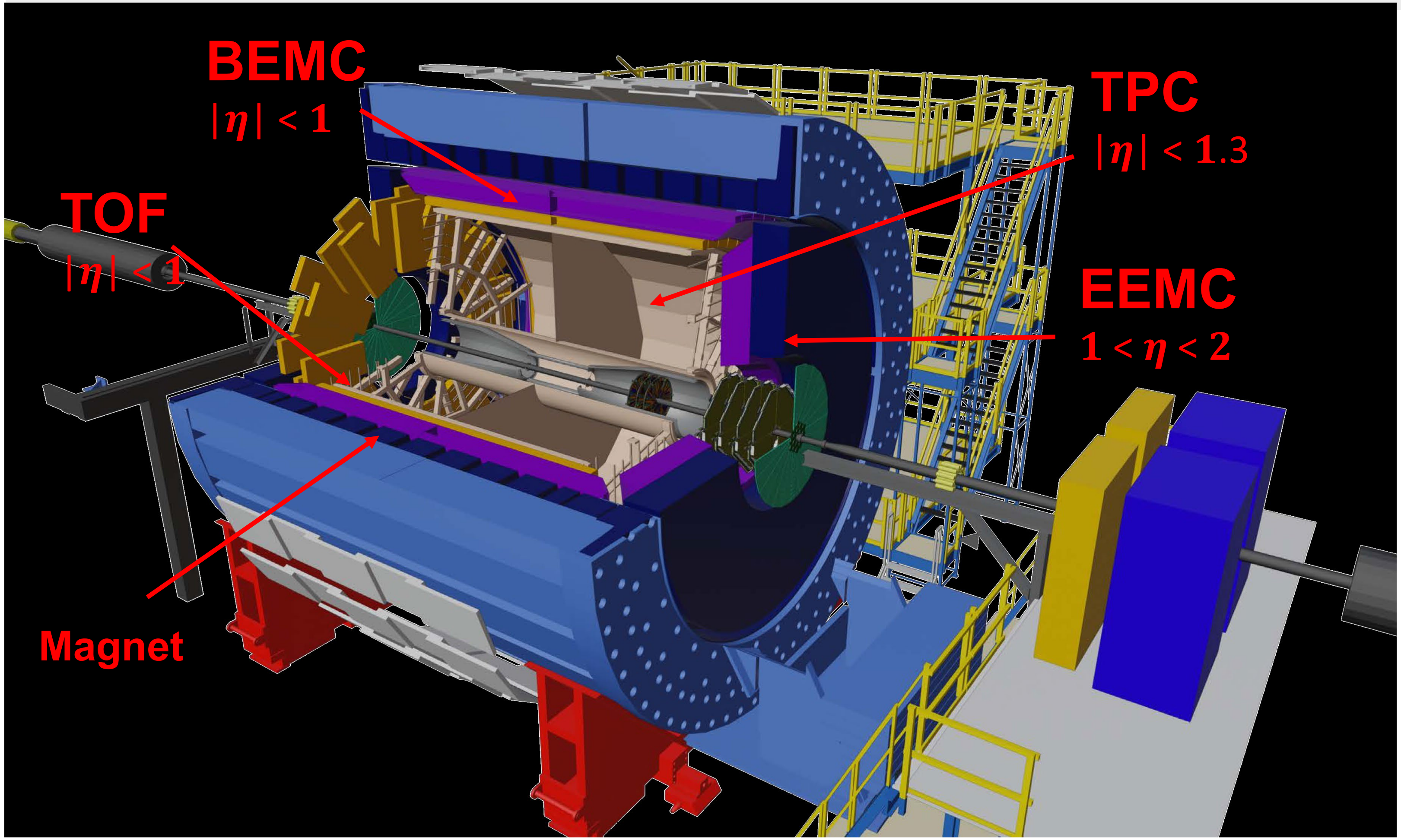
- Spin pattern is changed from fill to fill
- Siberian snakes preserve the polarization
- Spin rotators select spin orientation

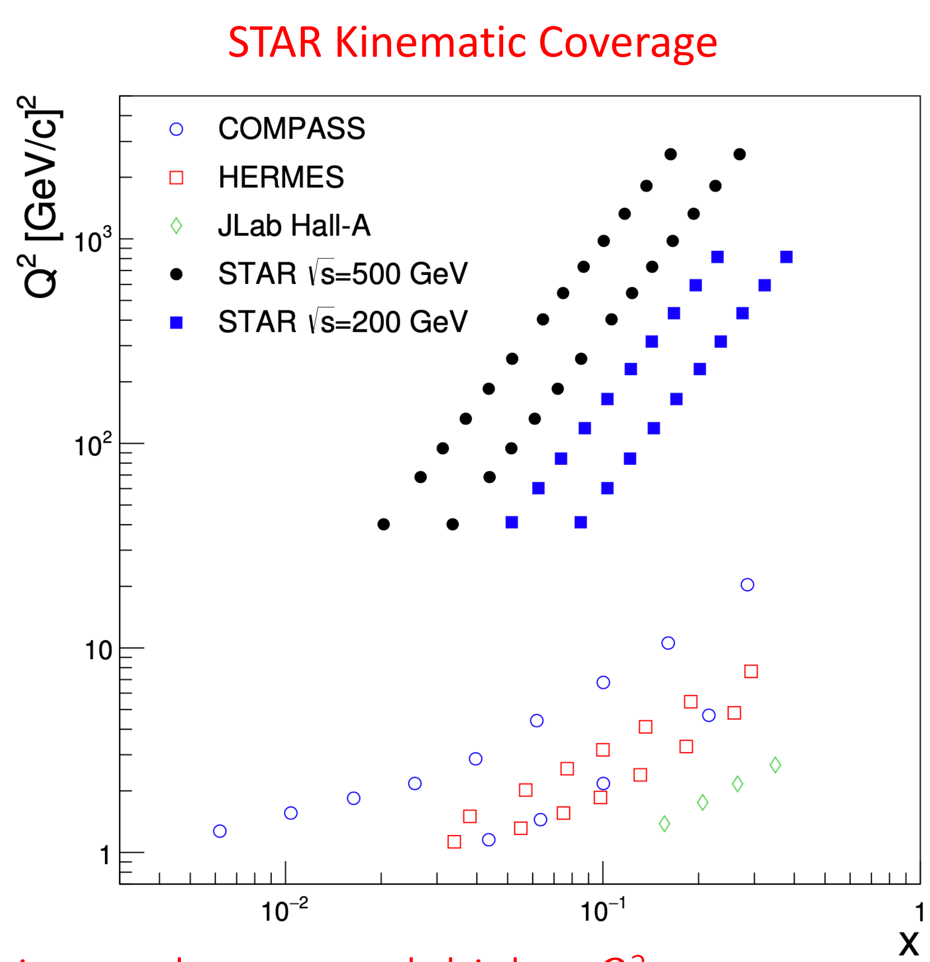
Summary: recent transversely polarized beams

Year	2011	2012	2015	2017	2022
$\sqrt{s}$ (GeV)	500	200	200	510	508
$L_{int}(pb^{-1})$	25	22	52	350	400
Polarization	53%	57%	57%	58%	50%

- proton-Carbon (pC) polarimeters and hydrogen gas jet (H-Jet) measure the polarization.

Solenoidal Tracker At RHIC (STAR): JETS, Hadron ID

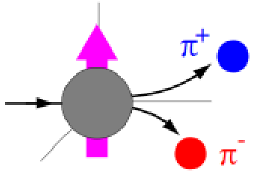




- ➢ STAR covers a similar range in momentum fraction to that of SIDIS experiments but at much higher Q^2
- ➢ 200 GeV results provide better statistical precision at larger momentum fraction regions; 500 GeV results probe lower values.
- ➢ The two different energies provide experimental constraints on evolution effects and insights into the magnitude and nature of TMD observables that will be measured at the EIC.

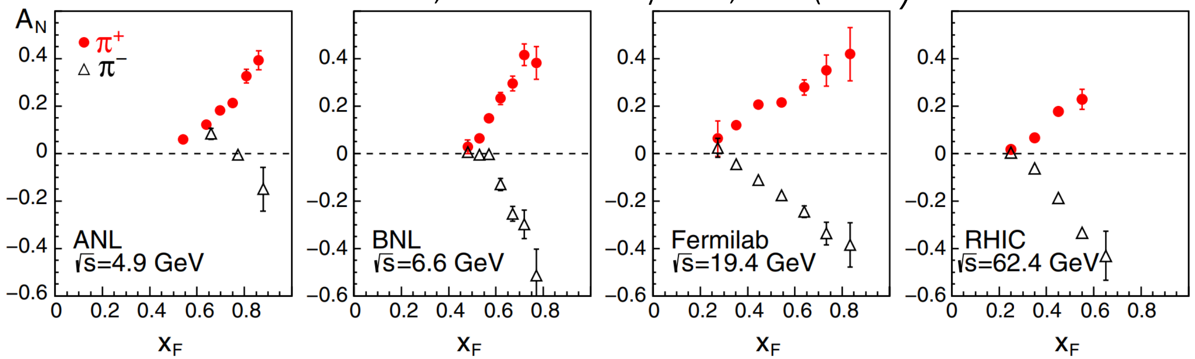
Old Puzzle: Transverse Single-Spin Asymmetries

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



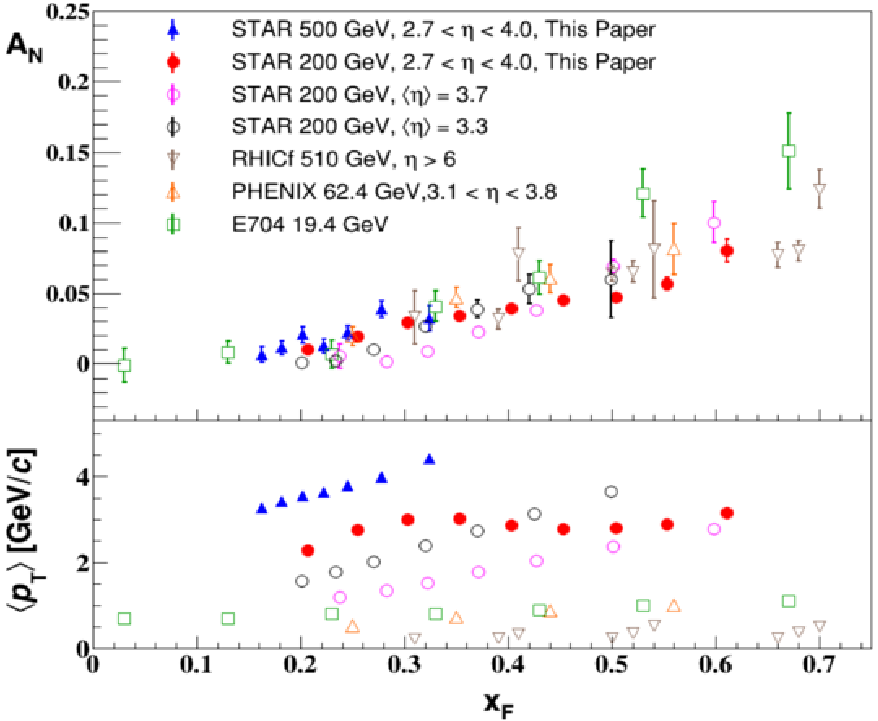
$$A_N = \frac{1}{P_{beam}} \frac{N^{\pi}_{left} - N^{\pi}_{right}}{N^{\pi}_{left} + N^{\pi}_{right}}$$

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



- **Surprisingly large transverse single-spin asymmetries (TSSA's) observed in forward meson production from hadronic collisions since the 1970's => <u>impetus for introducing the Sivers function!</u>**

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

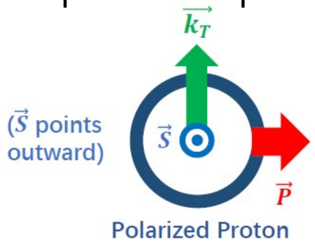


- The most recent results for STAR show the persistence of TSSA to the highest energies; the current interpretation includes terms from twist-3 parton correlations among others …
- Among the contributing mechanisms proposed, most involve partonic transverse motion within the proton. Two particularly interesting candidates lend themselves to experimental investigation at RHIC:
  - Sivers distribution function => next discussion
  - Collins fragmentation function => further below

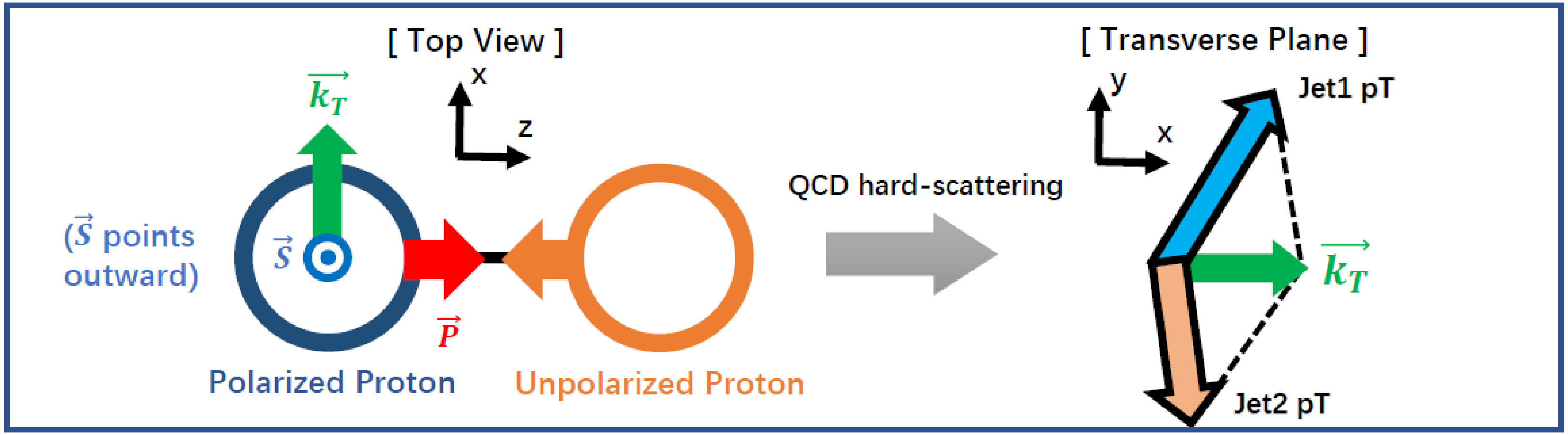
Partonic k_T in the Initial State: the Sivers Effect

The Sivers function introduces a triple product among a proton's spin and momentum with the transverse momenta of its constituent partons, encoding the correlation between partonic orbital motion and the proton spin.

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



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



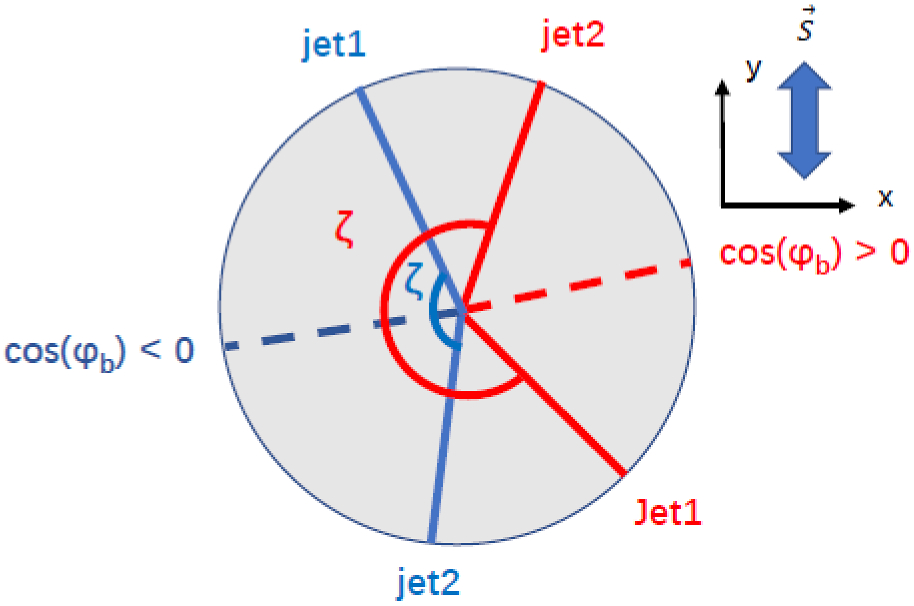
- Allows for the kinematic detection of a non-zero spin-dependent k_T, rather than a yield asymmetry
- Expect u and d contributions to be different in sign/magnitude; average k_T zero for a longitudinally moving proton.
- Sivers dijet production at RHIC explores physics at a much higher Q^2 than currently possible via SIDIS.
- Non-zero results would suggest contributions from partonic angular momentum to the proton spin.

(New) Observable to Probe the Sivers Effect with Dijets

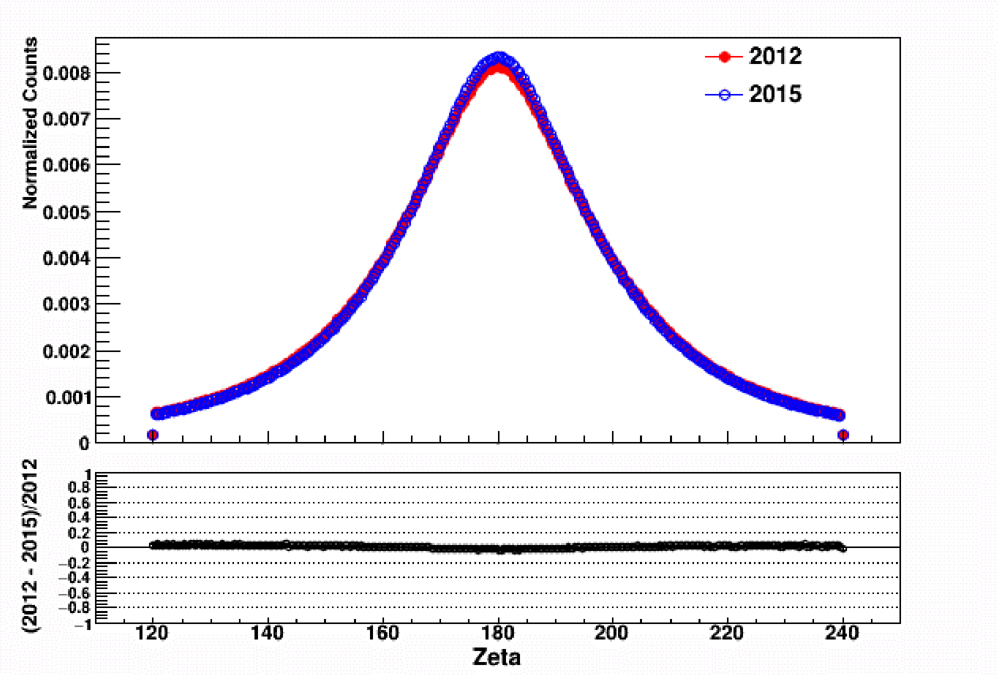
The Sivers asymmetry can be probed via the signed opening angle ζ

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



NOTE: definition similar to STAR analysis of 2006 data, which yielded spin asymmetries consistent with zero, though with large statistical uncertainties: Phys. Rev. Lett **99**, 142003 (2007)



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

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

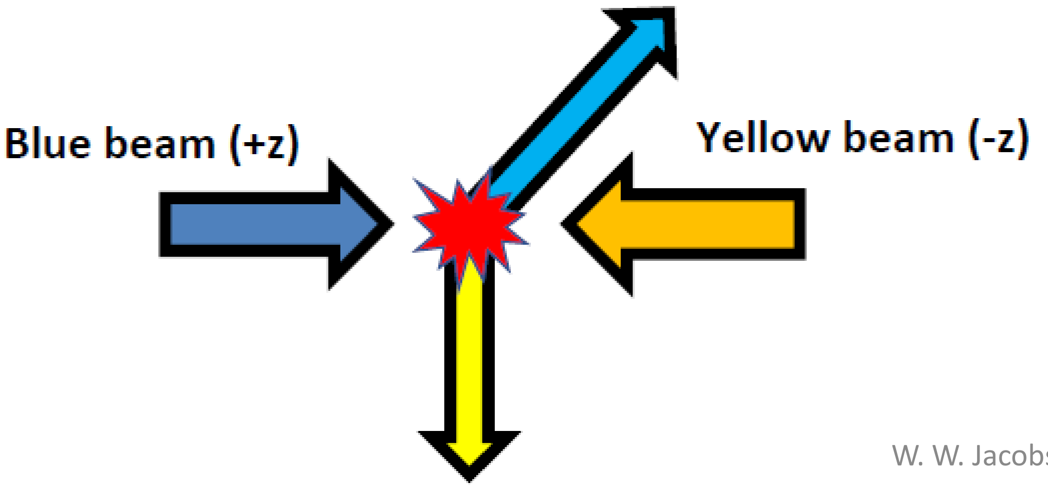
where $\langle\zeta\rangle^{\pm}$ is the centroid of the ζ distribution for spin-up / spin-down proton beams, respectively, and P the magnitude of the beam polarization.

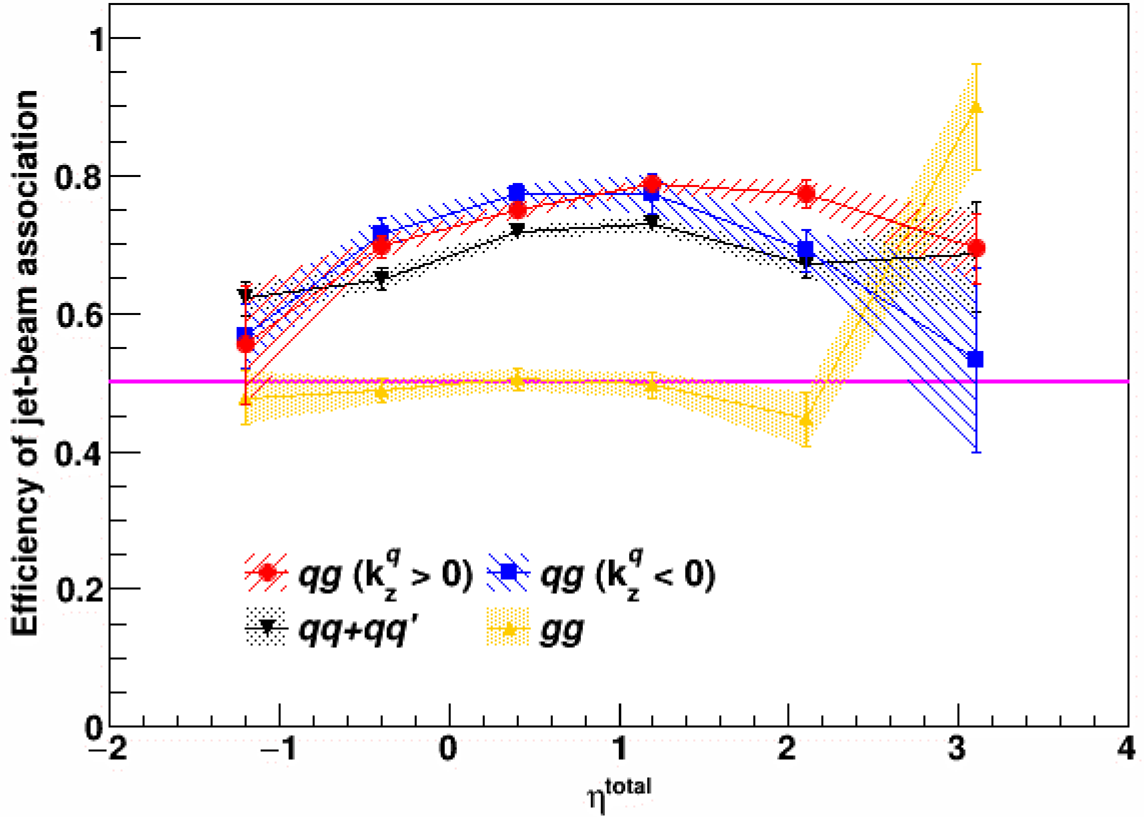
First Step: Establish Beam -> Jet Association

- 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 $|\eta|$) 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.





Note: η^{total} is the sum of the individual jet η .

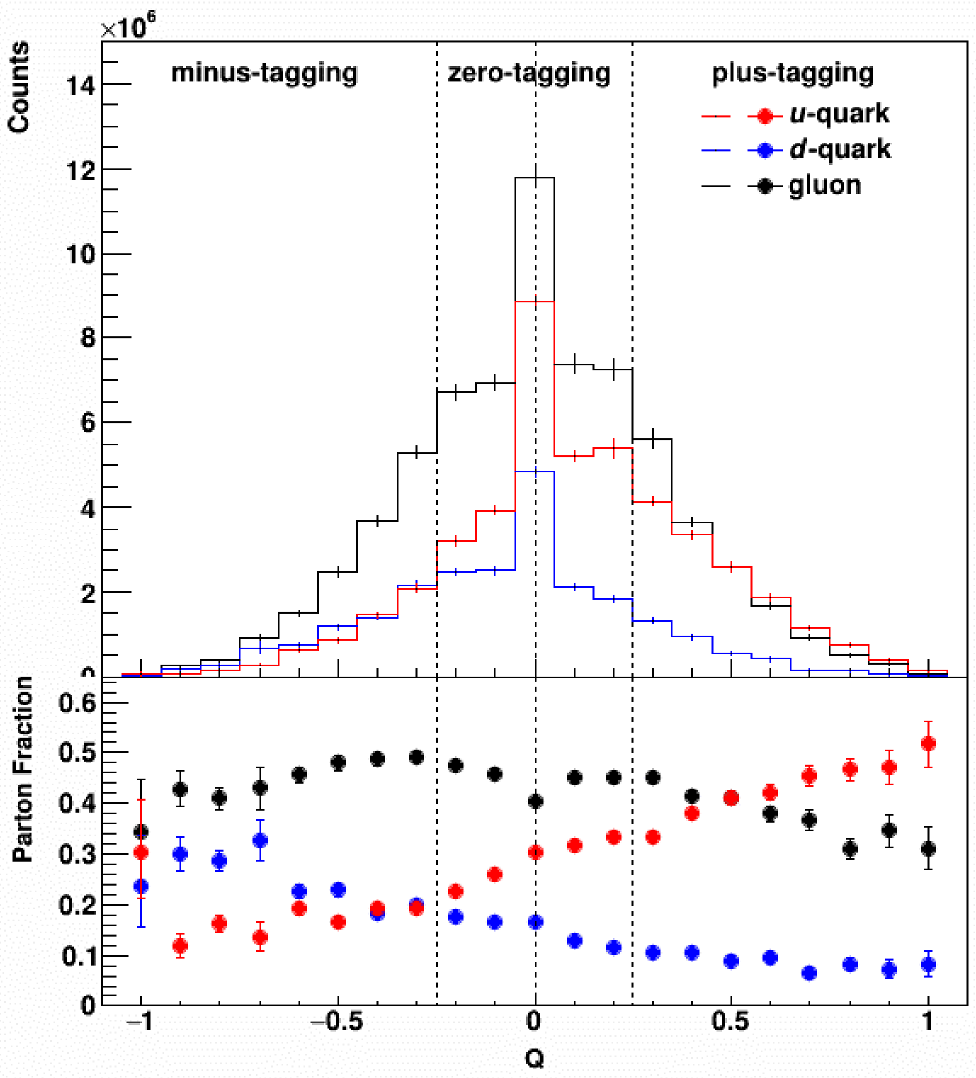
Next Step: Sort the Dijet Events by Net Charge

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

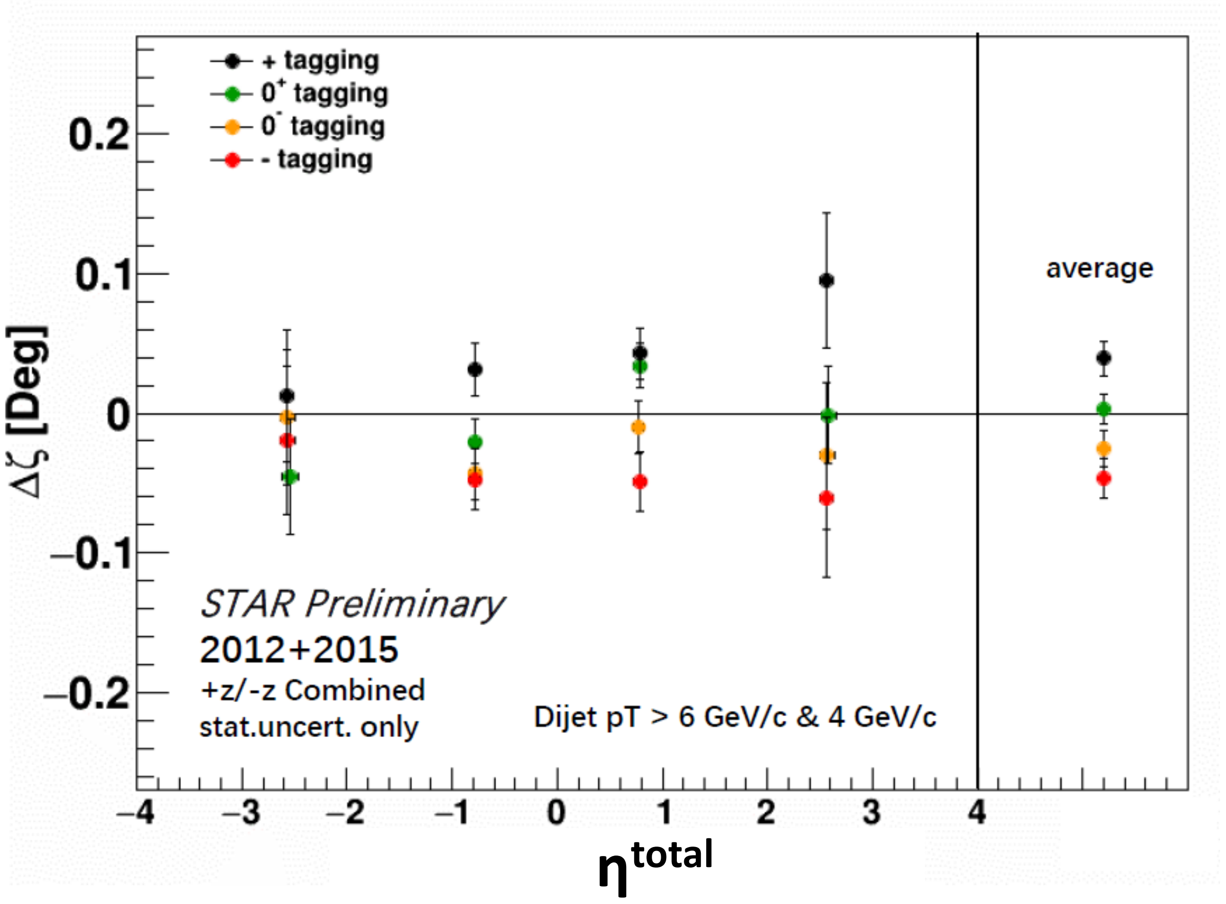
$$Q = \sum_{\substack{\text{all the tracks} \\ \text{with } pT>0.8GeV/c}} \frac{track\ |p|}{jet\ |p|} \cdot track\ charge$$

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*



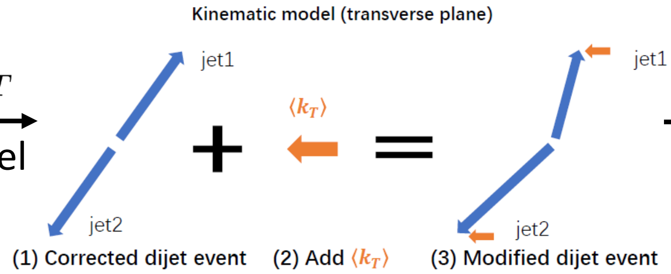
Extract the Δζ Asymmetry for each Tagged Sample



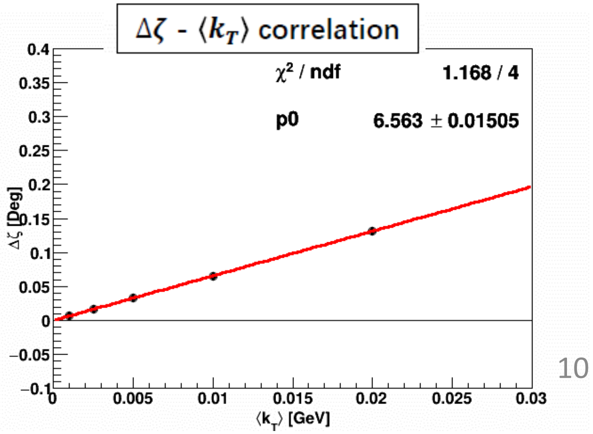
- Combine results for blue and yellow beams by 'flipping' signs of both η and asymmetry for the yellow beam.
- Average asymmetry systematically shifts from + to – as sampled data moves from u-quark to d-quark dominated, ~ 5σ separation between plus-tagging and minus-tagging.
- A hint of an increase with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

Use a simple kinematic model to convert $\Delta\zeta$ asymmetry to $\langle k_T \rangle$

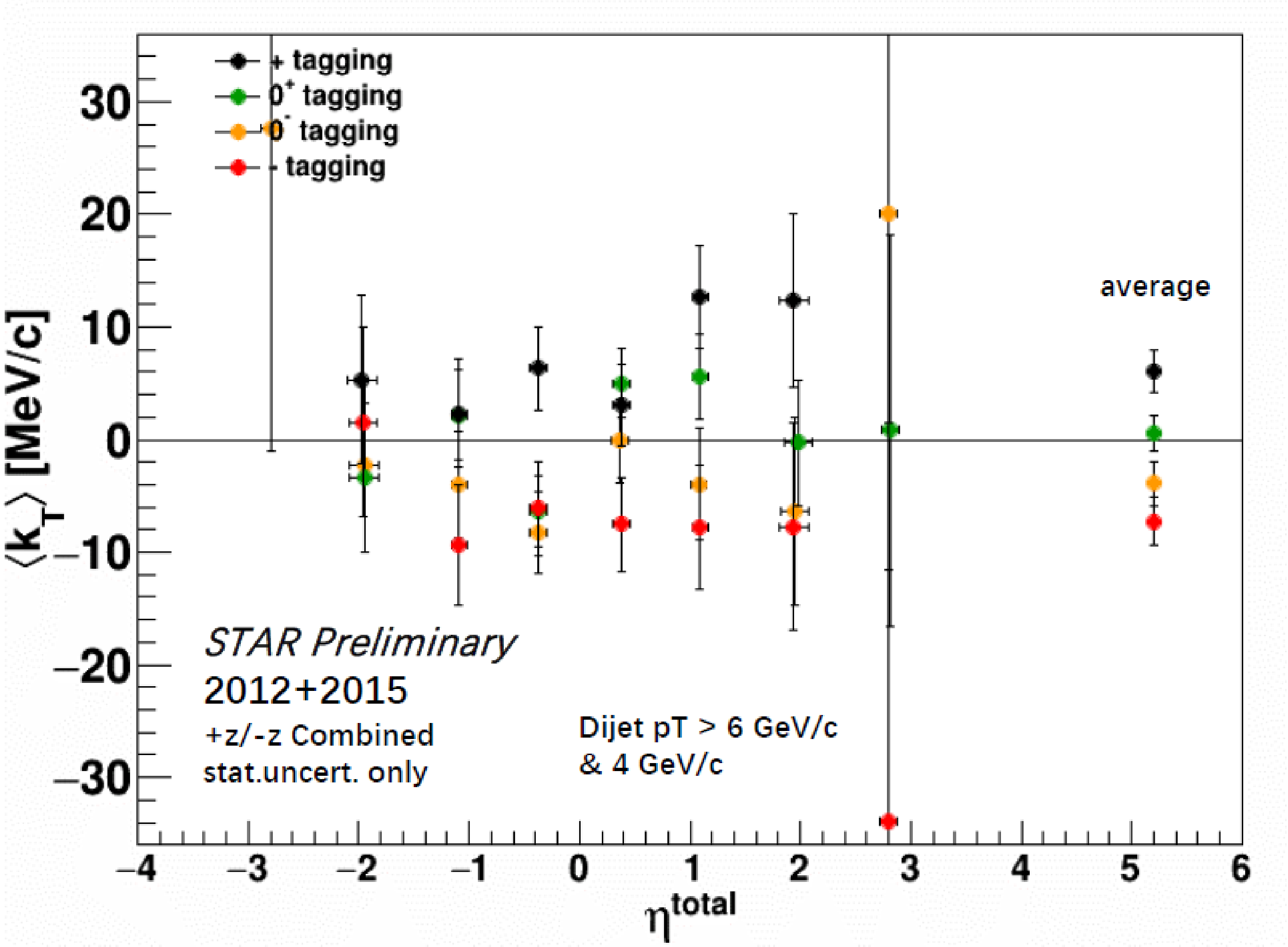
correct jet p_T → to parton level



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



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



- Note: asymmetries are plotted versus the sum of the dijet pseudo-rapidities. For 2 → 2 scattering kinematics, recall that $\eta_3 + \eta_4 = ln(x_1/x_2)$

- Qualitatively very similar to Δζ plot, although a finer binning in η^{total} is used.
- **Scale of effect is small, of the order ~ 10 MeV/c**. In particular:
  - $\langle k_T^{+tagging} \rangle = +6.1\ \mathrm{MeV/c}$
  - $\langle k_T^{-tagging} \rangle = -7.3\ \mathrm{MeV/c}$
- Hierarchy of **decreasing charge sum correlated with more negative $\langle k_T \rangle$ is preserved.**
- Again, **without jet sorting by charge sum, average $\langle k_T \rangle$ statistically consistent with zero**

Convert Tagged $\langle \mathrm{k_T} \rangle$ to Parton $\langle \mathrm{k_T} \rangle$ in η^{total} bins

- 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 η^{total} bins: because the parton fraction is dependent on η^{total}, this leads to more stability in the inversion process.
  - The over-constrained system is solved using the Moore-Penrose inversion:

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

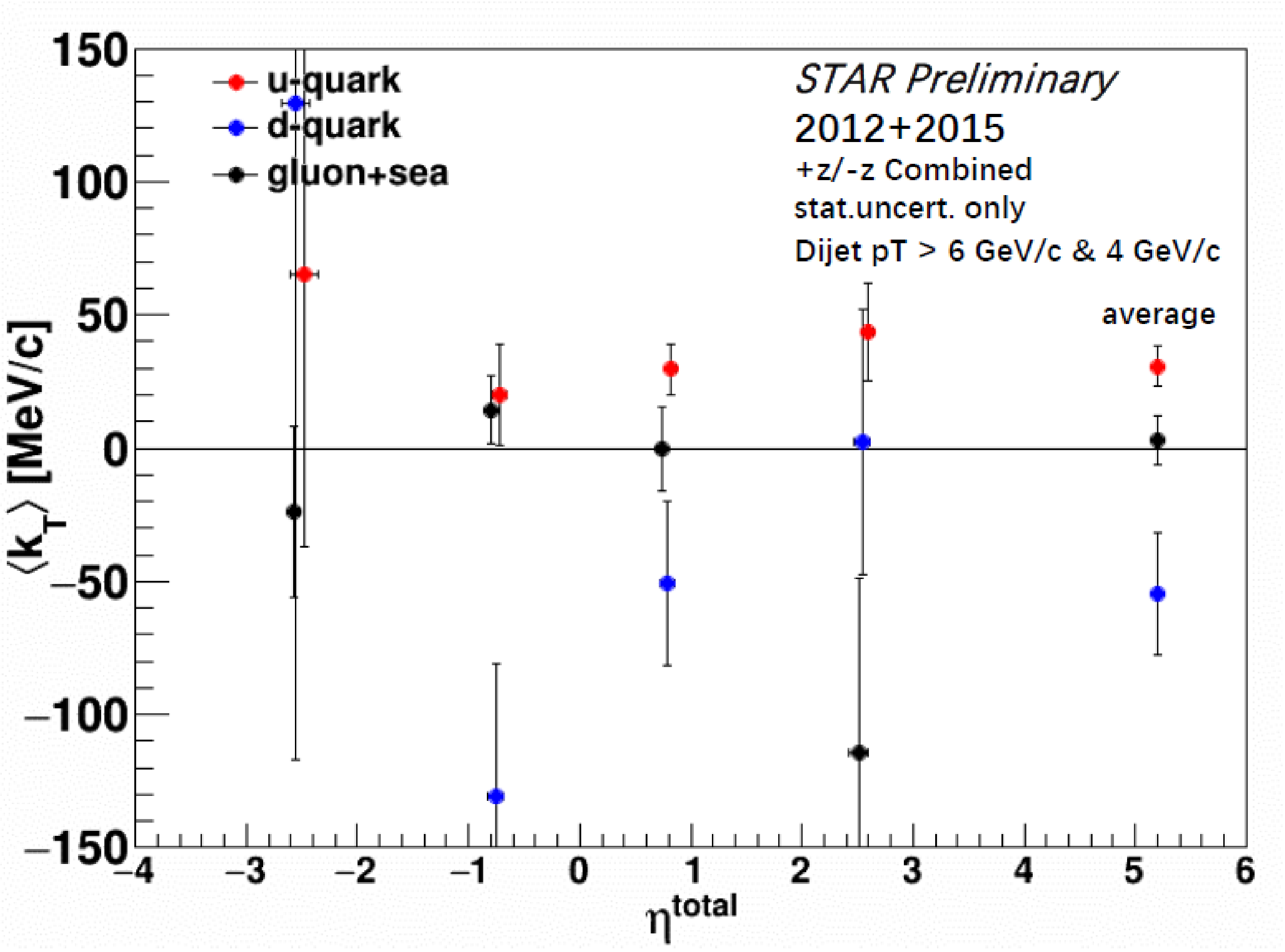
8 x 3 matrix

3 x 8 matrix

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

Results: The Unfolded Parton $\langle \mathbf{k_T} \rangle$ vs. η^{total}

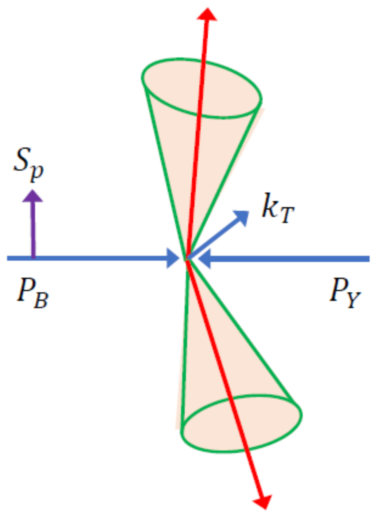
STAR



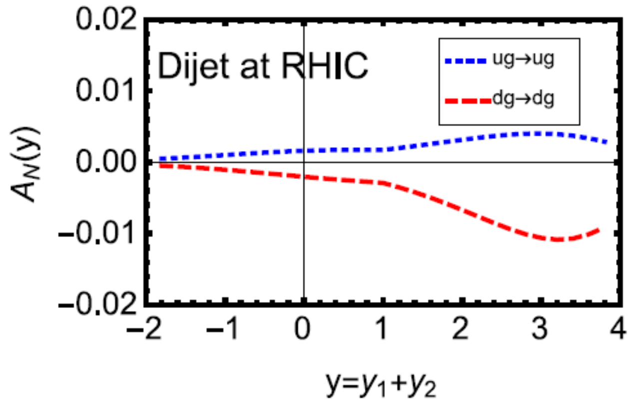
- First direct evidence for **a non-zero Sivers effect in dijet production**!
- Averaged over η^{total}, parton results follow general expectations:
  - ✓ $\langle k_T^u \rangle > 0$
  - ✓ $\langle k_T^d \rangle < 0$
  - ✓ $\langle k_T^{g+sea} \rangle \sim 0$
- Note $\langle k_T^d \rangle / \langle k_T^u \rangle \sim -2$, as needed to bring **proton total $\langle \mathbf{k_T} \rangle$ close to 0.**
- **No clear dependency** of partonic $\langle k_T \rangle$'s on η^{total} within our statistical precision, suggesting a weak x-dependence at scale order $Q^2 \sim 160\ \mathrm{GeV}^2$

- **For comparison**: the first Mellin moments of the Sivers function derived from SIDIS data for u and d partons are: $\langle k_{\perp u} \rangle = 96^{+60}_{-28}$ MeV and $\langle k_{\perp d} \rangle = -113^{+45}_{-51}$ MeV at much lower scale [D. Boer *et al.*, Adv. HEP **2015,** 371396 (32015)]

Summary/Status and Future Directions for Dijet Sivers

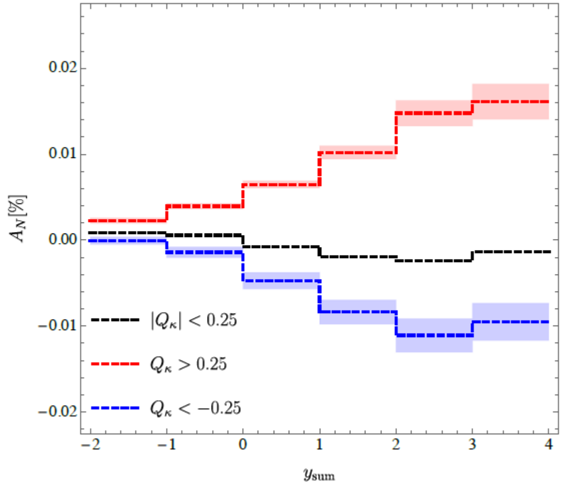


- First observation of non-zero Sivers asymmetries in a purely hadronic reaction channel.
- Final results being prepared for publication.
- Preliminary results have generated theoretical interest; at issue is approach/treatment of large logarithmic integrals associated with (breaking) factorization.



Xiaohui Liu, Felix Ringer, Werner Vogelsang, and Feng Yuan, Phys. Rev. D **102**, 114012. (2020)

- Further STAR data sets, also at different $\sqrt{s}$, will enable results with higher precision, with further tests of kinematic sensitivity.
- With the STAR forward upgrade, 2022 (508 GeV in hand) and projected 2024 data at 200 GeV, can further probe the kinematical behavior of $\langle k_T \rangle$.
  - Charged particle tracking 2.5 < η < 4, also Ecal and Hcal.
  - Measure distributions over nearly full 0.005 < x < 0.5 range.



Zhong-Bo Kang, Kyle Lee, Ding Yu Shao and John Terry , *J. High Energ. Phys.* **2021,** 66 (2021).

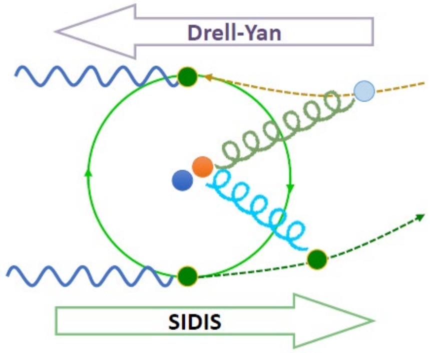
W-Boson production in pp

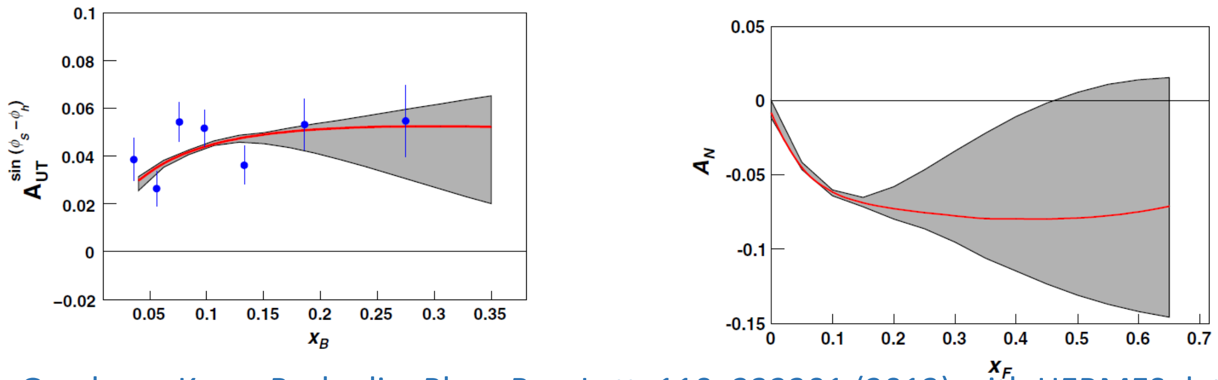
- Updated analyzing power
- Z-boson analyzing power and cross section

QCD, Universality, and the Proton Structure

Spin-orbit correlation Sivers effect: proton spin and transverse momentum of parton correlation

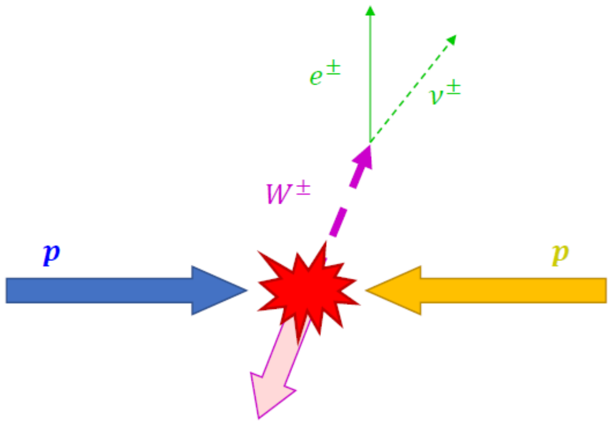
Non-universality exhibits the process dependence
Attractive color force in SIDIS turns into repulsive force in p+p





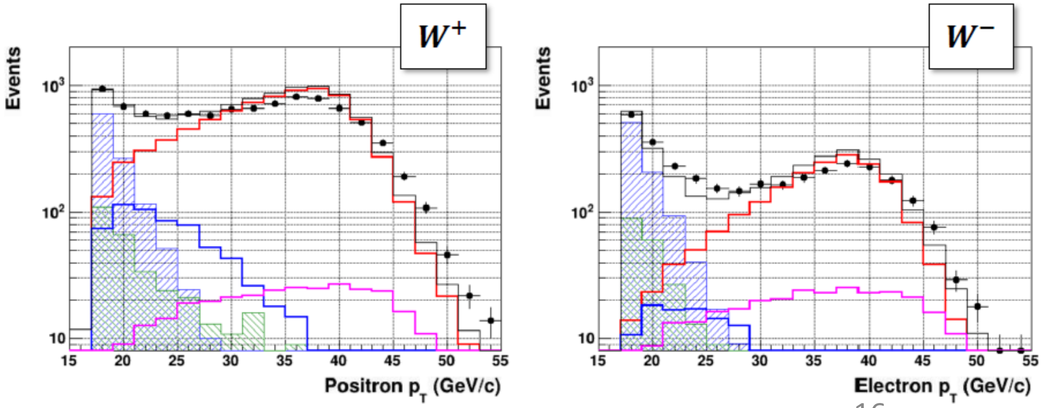
Gamberg, Kang, Prokudin, Phys. Rev. Lett. 110, 232301 (2013) with HERMES data

W Boson production in RHIC Run 2017: $p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$



Lepton candidate selection using well established methods

- Data driven QCD background normalized at low p_T-range
- Includes Z^0 and τ decays
- Missing EEMC impact estimated
- Jacobian peak: Lepton candidate $p_T > 25 \mathrm{GeV}/c$



Recent STAR W-boson results: PRD 103 (2021) 012001; 99 (2019) 051102

W-Boson Reconstruction $p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$

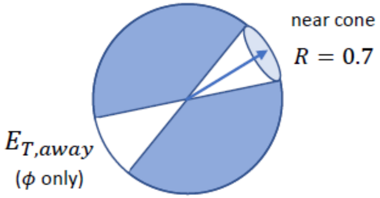
STAR

Measure recoil from the collision

(use TPC tracks and the EMC)

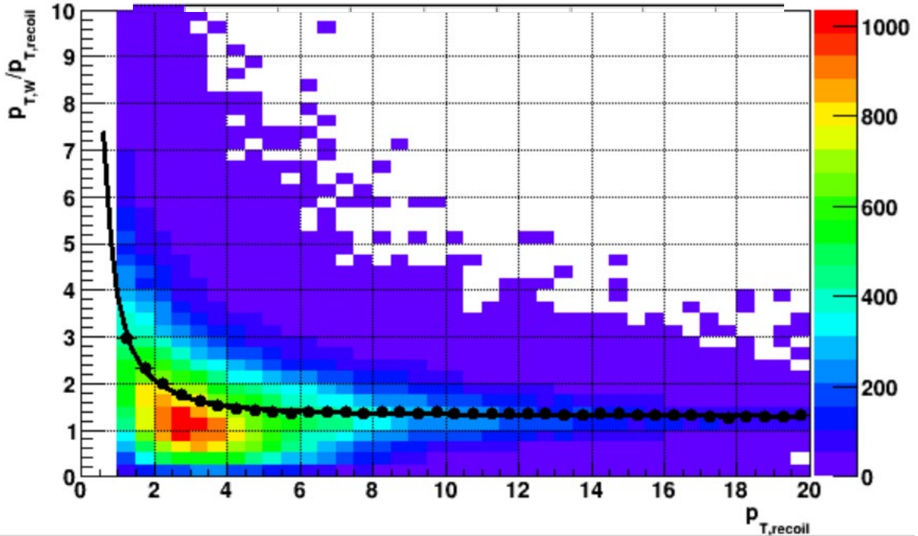
$$p_{T,W} = p_{T,e} + p_{T,\nu} = p_{T,recoil}$$

$$p_{T,recoil} = \sum (p_{T,TPC} + E_{T,EMC})$$



- Limited barrel acceptance
- Comparison with simulation
- Recoil p_T correction

$$p_{T,W} = f(p_{T,meas}) = A + \frac{b}{(p_{T,meas})^c}$$



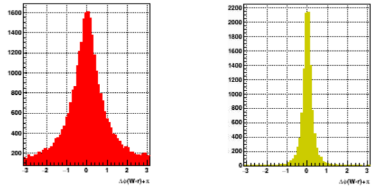
Azimuthal Angle Smearing

Transverse spin asymmetries are measured through azimuthal modulations:

$$d\sigma(\phi) = \sigma_0[1 + PA_N \cos(\phi)]$$

$$A_N = \frac{d\sigma(\phi) - d\sigma(\phi + \pi)}{d\sigma(\phi) + d\sigma(\phi + \pi)} \qquad A_N = \frac{1}{P}\frac{N_\phi - N_{\phi+\pi}}{N_\phi + N_{\phi+\pi}}$$

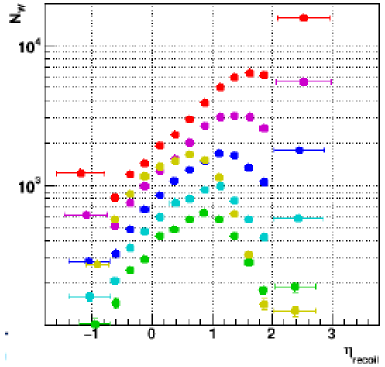
Toy Monte Carlo study →determine asymmetry dilution.

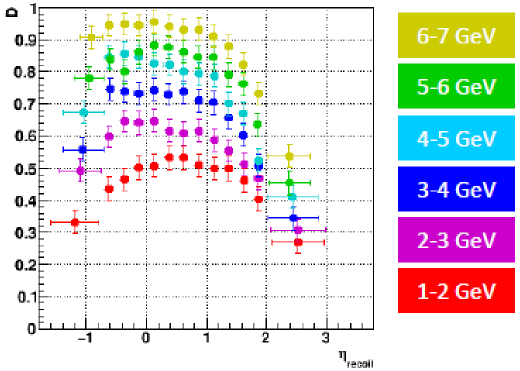


$$\Delta\phi = \phi_W - \phi_{recoil}$$

$$D = A_{N,meas}/A_{N,input}$$

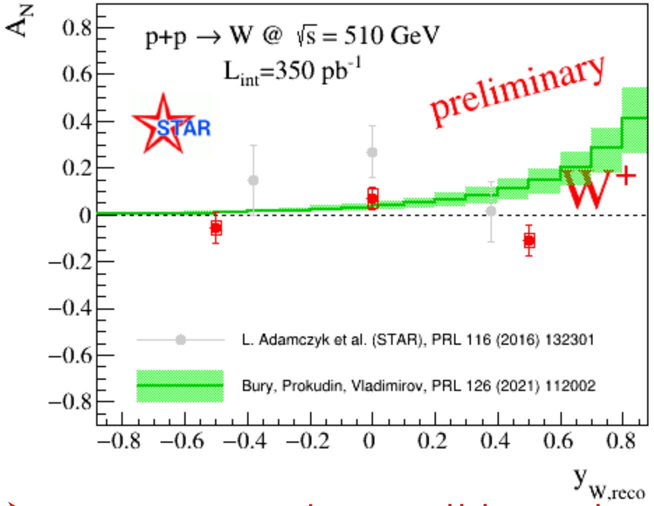
$$\sigma_{A_N} \propto \frac{1}{\sqrt{ND}}$$

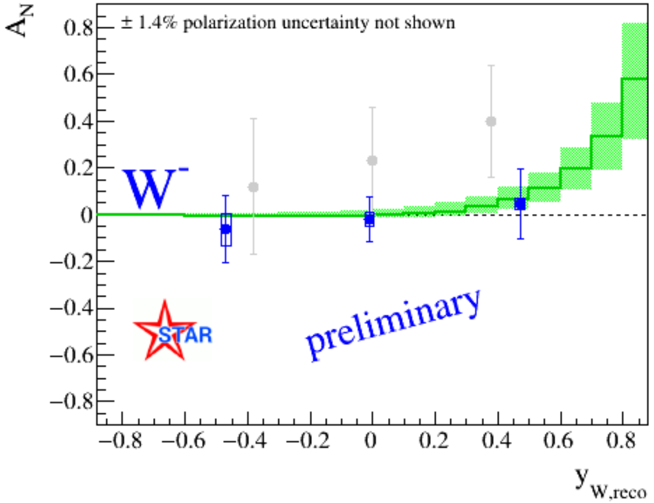




Asymmetry correction: $A_N = A_{N,meas}/D$

Preliminary 2017 Data Results for A_N in $W^{\pm}$ Production



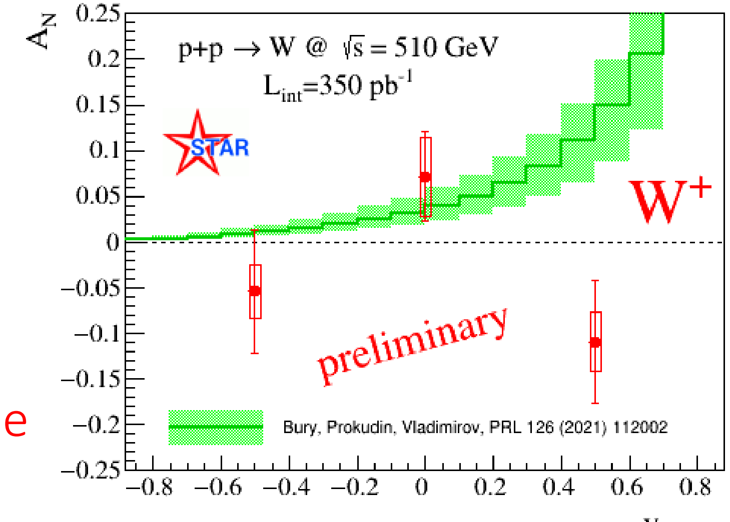


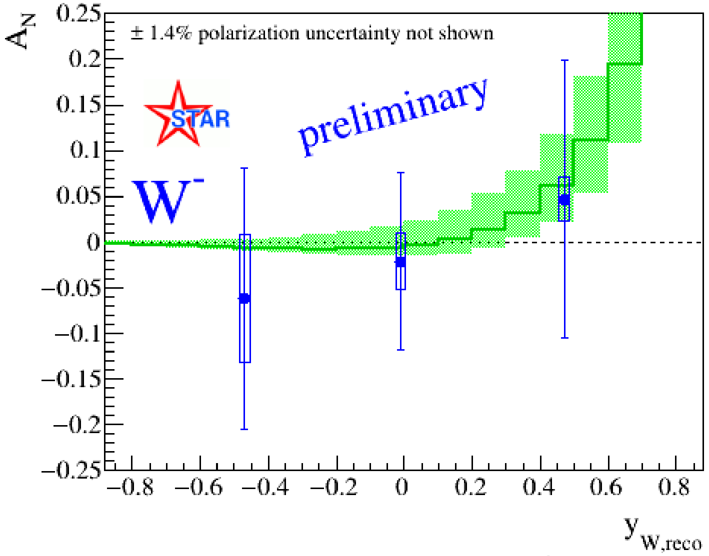
- 2017 results have much improved precision over those from the initial measurement PRL **116**, 132301 (2106).
- Corrected for smeared reconstruction of the recoil.
- Contribution from transversal helicity function, g_{1T}, estimated via simultaneous (sin/cos) fit with A_N. Measured A_S consistent with zero.

- New STAR data will have biggest impact on high-x region of the quark Sivers function.
- Comparison with new theory prediction (N^3LO), M. Bury, A. Prokudin, A. Vladimirov, PRL 126 (2021) 112002.
- Updated for STAR kinematics w/ 1st global fit to world data, PRD 102 (2020) 054002.
- Analysis of the new '22 dataset will increase precision of asymmetry measurements;

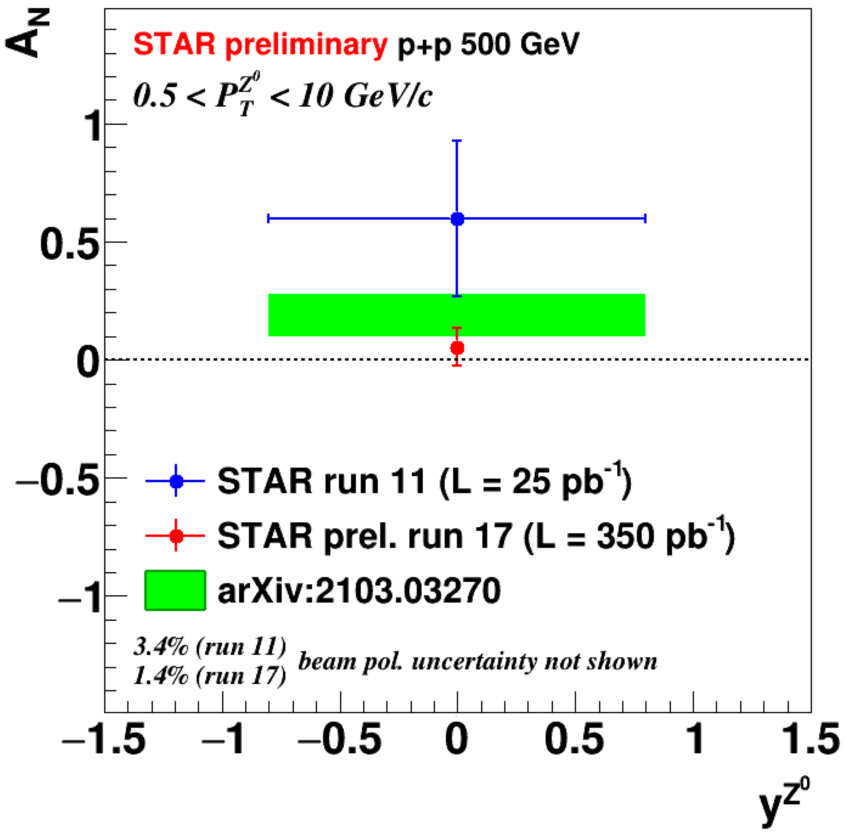
forward detectors of the STAR upgrade will improve the reconstruction.

Zoom in

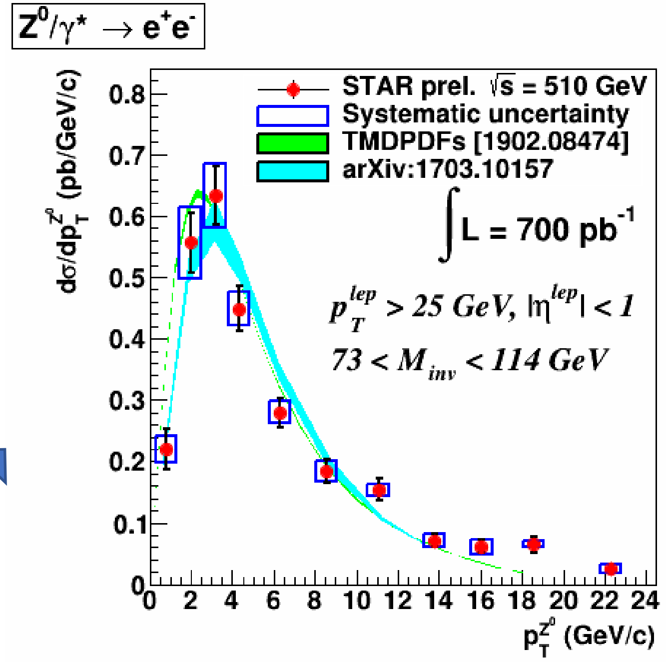




New Results for Z^0 : $p + p \to Z^0 \to e^+ + e^-$



- Experimentally very clean; two high-p_T electrons (e^+, e^-) from the same vertex.
- Leading systematic uncertainty from energy resolution.
- Comparison with PRL 126 (2021) 112002 global analysis, folding in data on the sea-quark Sivers.



- Differential cross section of high interest for TMD-PDF fits. Pavia group, *JHEP* 07 (2020) 1172017.
- Data doubles the previous statistics; unfolded p_T spectrum
- Systematics from energy resolution and electron selection.

Transversity

- Di-hadron correlations $A_{UT}^{\sin(\phi_S - \phi_R)}$
- Collins fragmentation and other modulations.

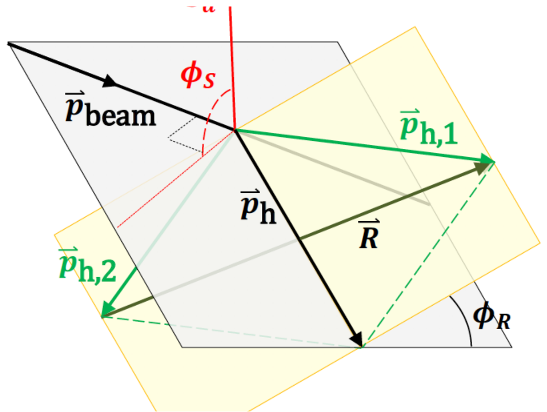
Di-hadron Transverse Spin Correlations I

- Di-hadron spin correlations in transversely polarized pp => extract transversity $h_1^q(x)$
- Chiral odd $h_1^q(x)$ transversity is coupled with chiral odd spin-dependent Interference FF.
- Integral over quark transversity => tensor charge: data can be compared to lattice calcs.

Measure di-hadron azimuthal correlation asymmetry:

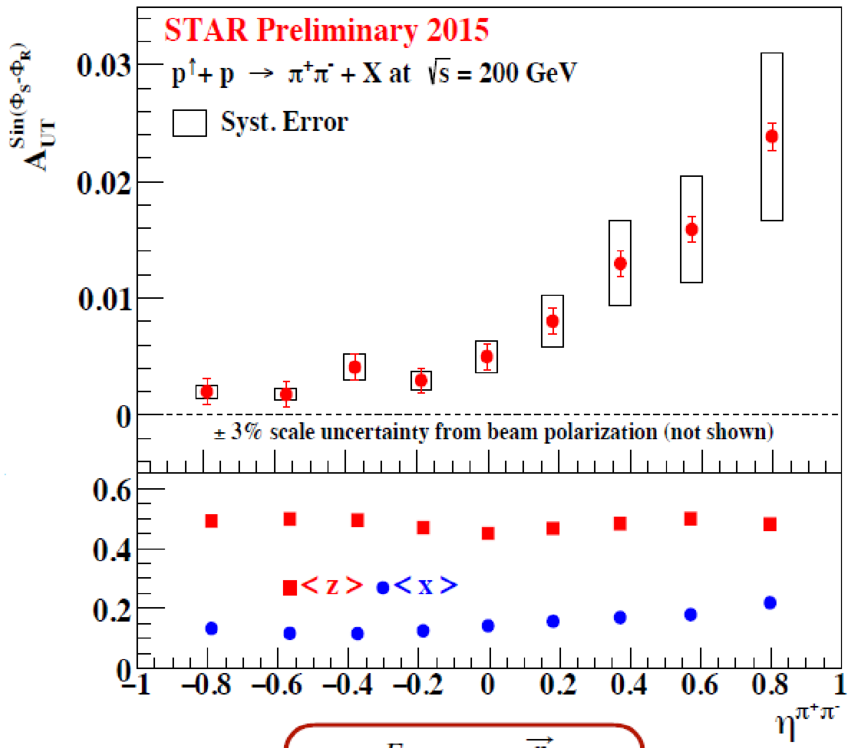
$$d\sigma_{UT} \propto \sin(\phi_S - \phi_R) \int dx_a\, dx_b\, f_1(x_a)\, h_1(x_b) \frac{d\Delta\hat{\sigma}}{d\hat{t}} H_1^{\sphericalangle}(z, M)$$

transverity IFF



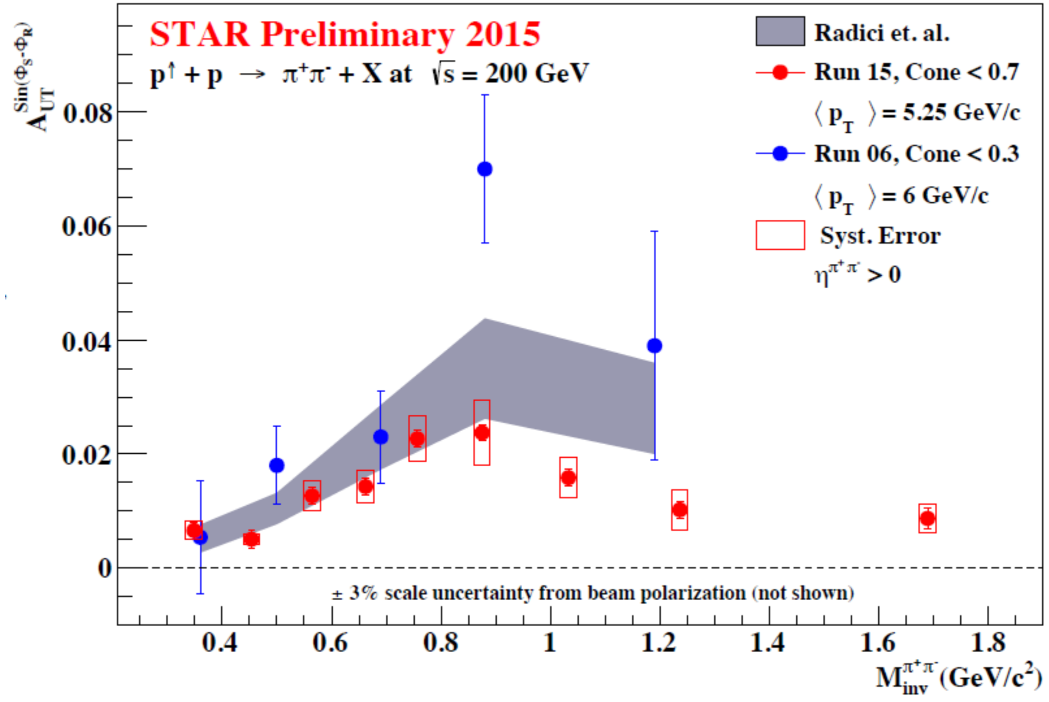
$$A_{UT} \cdot \sin(\phi_{RS}) = \frac{1}{P} \cdot \frac{\sqrt{N^{\uparrow}(\phi_{RS})N^{\downarrow}(\phi_{RS}+\pi)} - \sqrt{N^{\downarrow}(\phi_{RS})N^{\uparrow}(\phi_{RS}+\pi)}}{\sqrt{N^{\uparrow}(\phi_{RS})N^{\downarrow}(\phi_{RS}+\pi)} + \sqrt{N^{\downarrow}(\phi_{RS})N^{\uparrow}(\phi_{RS}+\pi)}}$$

$A_{UT}^{\sin(\phi_s-\phi_R)}$ vs $\eta^{\pi^+\pi^-}$



$$z \rightarrow \frac{E_{\pi^+\pi^-}}{E_{quark}},\; x = \frac{\vec{p}_{quark}}{\vec{p}_{proton}}$$

Di-hadron Transverse Spin Correlations II



- The **statistical precision** of the new 2015 results is **significantly improved** compared to the previous STAR measurements at 200 GeV.
- Further improvements in PID systematic uncertainties expected with improved PID method based on TOF (in progress).
- Theory comparison is based on analysis from original/first 2006 data.
- These results can be used to **test the universality** in comparison to SIDIS, especially at the high *x* (> 0.1) region.

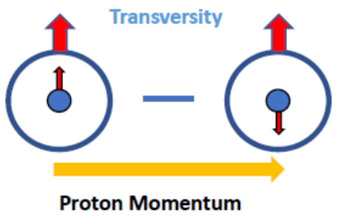
Further Developments

- Ongoing IFF analysis using the 2017 dataset at √s = 510 GeV (L_{int} ~ 350 pb^{-1}) with ~ 14 times more statistics than 2015 (allowing multidimensional analysis).
- Planned unpolarized di-hadron cross-section measurement, combined with these high precision asymmetry results, expected to help constrain transversity.

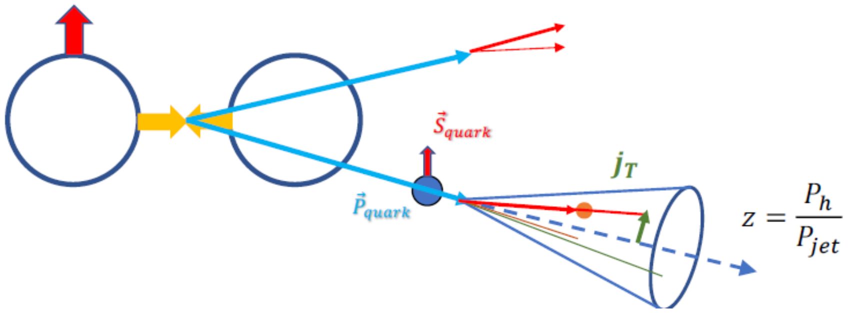
Collins Effect: π+/- Azimuthal Distribution in Jets

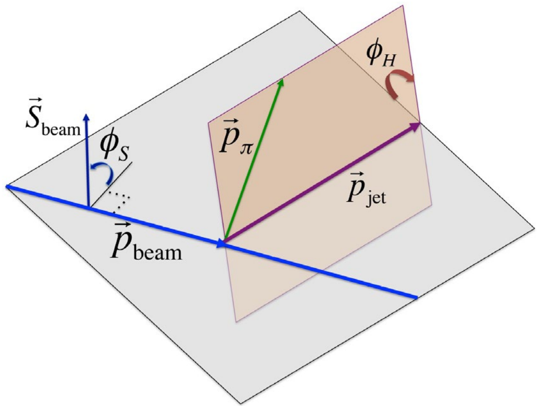
Correlation between the polarization of a scattered quark and the momentum of a hadron fragment transverse to the scattered quark direction

Transversity



Collins fragmentation



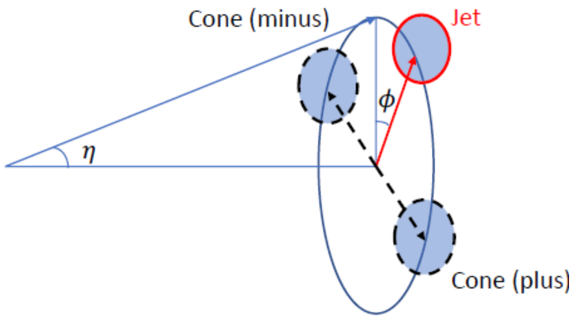


$$d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)$$

$$\sim d\Delta\sigma_0 \sin(\phi_S) + d\Delta\sigma_1^- \sin(\phi_S - \phi_H) + d\Delta\sigma_1^+ \sin(\phi_S + \phi_H) + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_H)$$

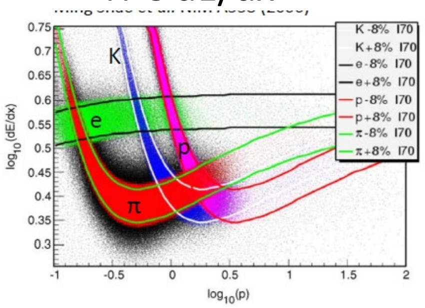
$$A_{UT}^{\sin(\phi)} \sin(\phi) \xrightarrow[\phi=\phi_S-\phi_H]{} \frac{\sum_{a,b,c} h_1^a(x_1,\mu)\ f_b(x_2,\mu)\ \sigma_{ab\to c}^{\rm Collins}\ H_{1,h/c}^{\perp}(z_h, j_T; Q)}{\sum_{a,b,c} f_a(x_1,\mu)\ f_b(x_2,\mu)\ \sigma_{ab\to c}^{\rm unpol}\ D_{h/c}(z_h, j_T; Q)}$$

Underlying Event Correction and Particle Identification

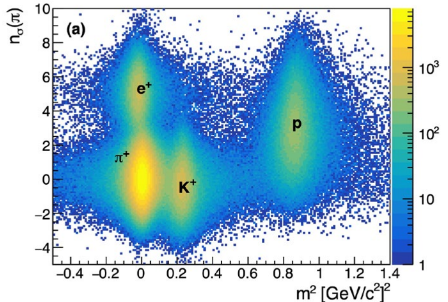


- Underlying event from off-axis cone method;
- Correct particle jet p_T values and spin asymmetries for dilution

TPC dE/dx

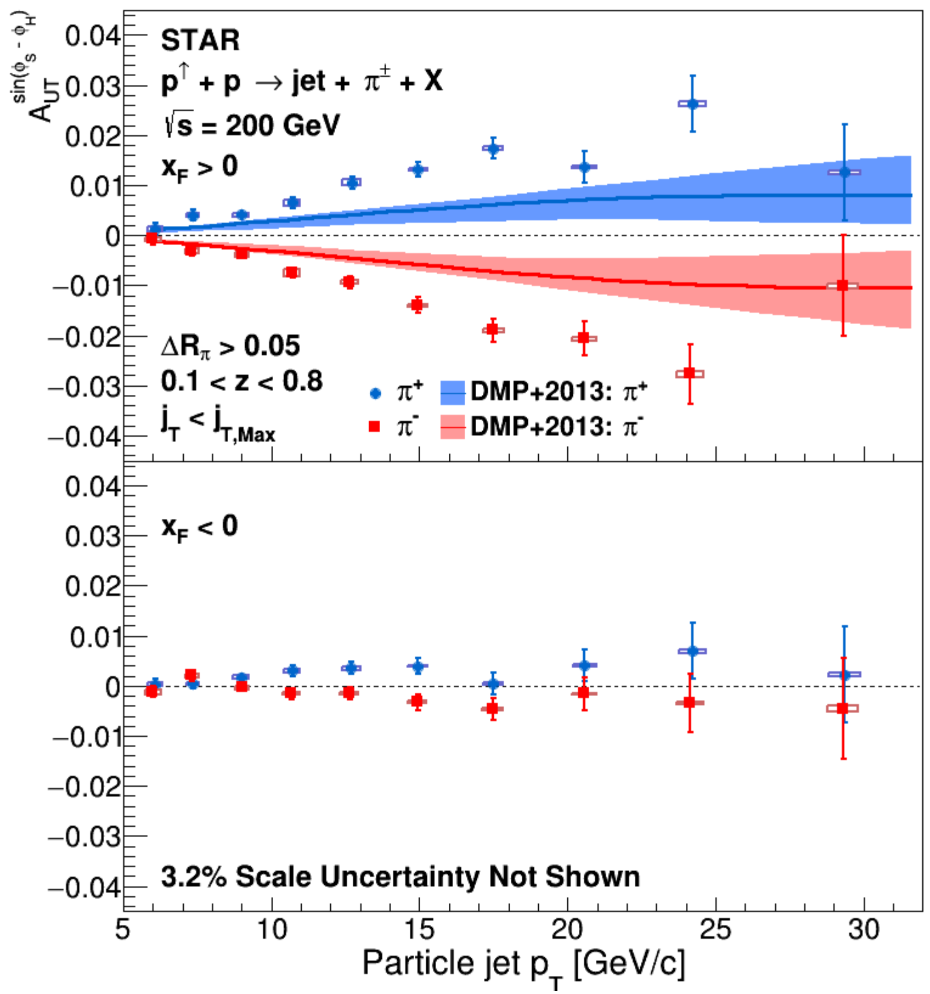


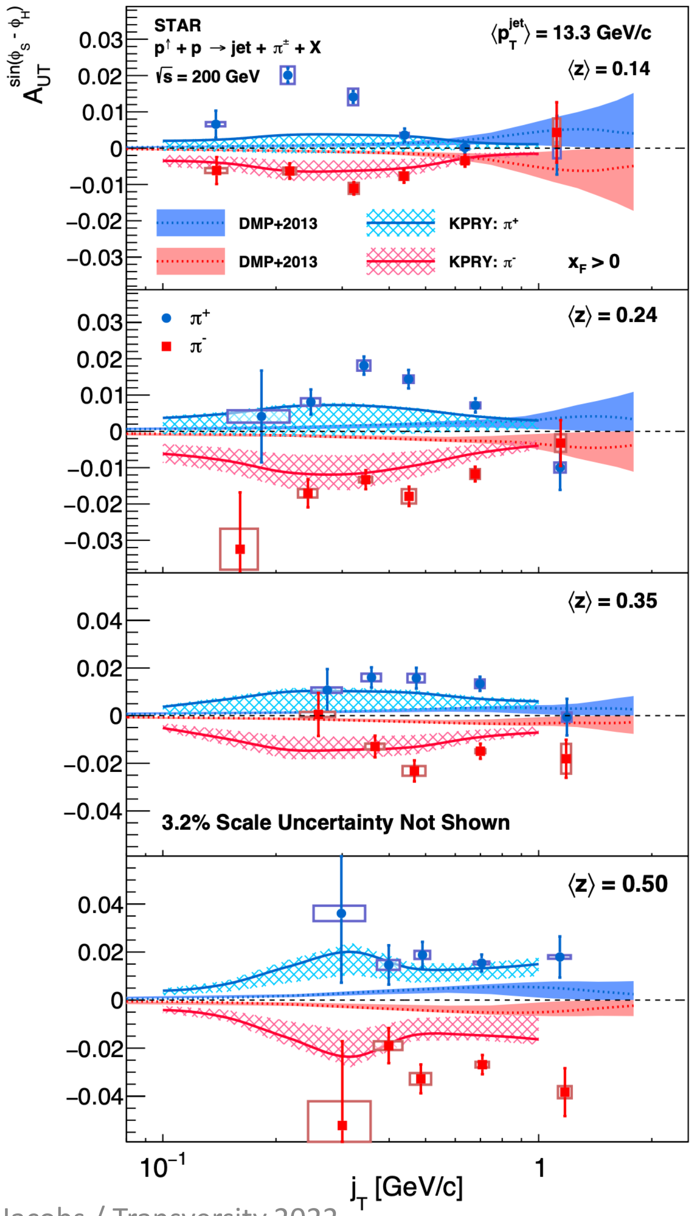
Time-of-flight



$\pi^{\pm}$ Azimuthal Distributions in Jets (200 GeV)

Submitted to arXiv May '22





- Collins TMD FF is sensitive to the (j_T, z) dependence.
- The results slightly favor the KPRY model than DMP+2013.
- Sizable differences between data and both theoretical calculations.

DMP+2013 model: Umberto D'Alesio *et.al.*, PLB 773, 300 (2017)
KPRY model: Zhong-Bo Kang *et. al.*, PLB 774, 635 (2017)
Both assume universality and factorization.

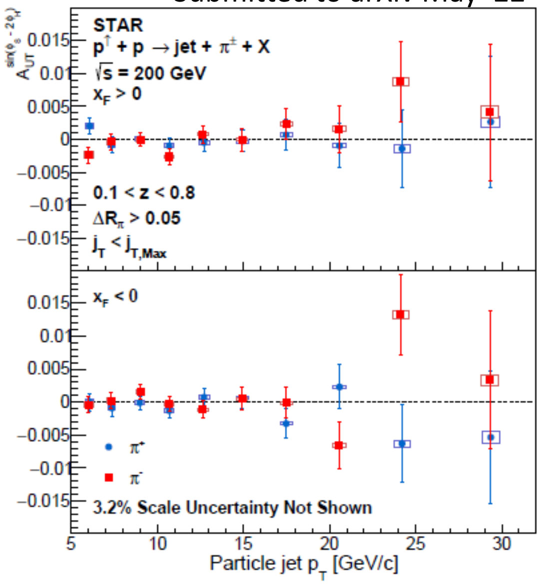
- Theoretical expectations: DMP+2013 model combines quark transversity from SIDIS with the Collins FF from $e^+ + e^-$ collisions.

Additional Modulations: 2015 Final 200 GeV Results

STAR

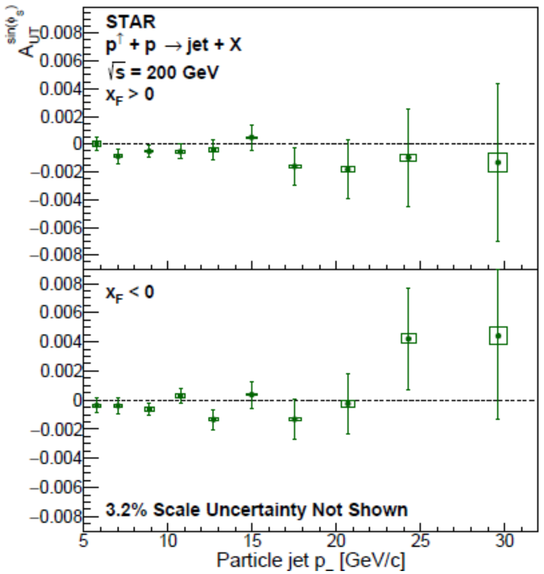
Collins-like asymmetry

Submitted to arXiv May '22



- Constraints on linearly polarized gluons in a polarized proton.
- New data will provide stronger limits than previous 500 GeV work PRD 97, 032004 (2018).

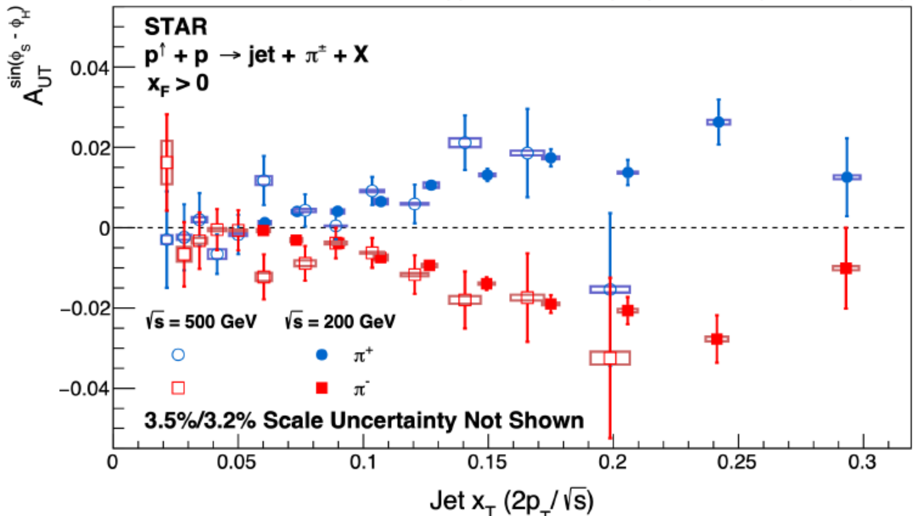
Inclusive jet A_N



- Sensitive to gluon Sivers vis Twist-3 relationship
- Asymmetries consistent with zero, but x 10 (x 4) smaller uncertainties than previous 200 (500) GeV pp results.

Comparison of Collins 200 GeV with Previous 500 GeV

pp500 from: STAR, Phys. Rev. D 97, 032004 (2018)



- The asymmetries agree at $0.06 < x_T < 0.2$, Q^2 differ by a factor of 6.
- Collins asymmetry has a weak energy dependence in hadronic collisions.

Current/Future

Year	2011	2012	2015	2017	2022
$\sqrt{s}$ (GeV)	500	200	200	510	508
$L_{int}(pb^{-1})$	25	22	52	350	400
Polarization	53%	57%	57%	58%	50%

- Still a large 500 GeV data set
- In 2024 plan more 200 GeV
- '22-24 data w/ Fwd. Upgrade

Future Directions

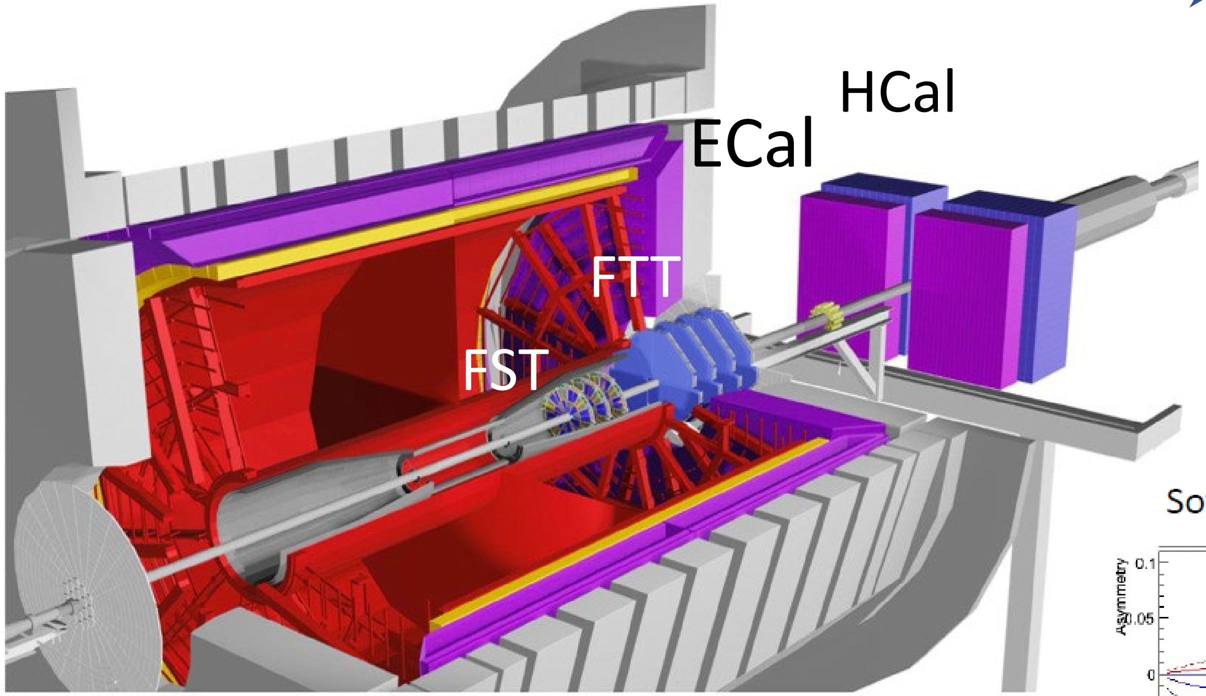
- Data sets with additional statistics/energy
  - Several analyses currently underway

- Exploit new kinematical regime and capabilities of STAR Forward Upgrade with ‘22 and ‘24 data sets

STAR Fwd Upgrade: '22 & '24 Transverse Spin Physics

Rapidity coverage:
2.5 < η < 4 (similar to EIC hadron endcap)

Goal: Charge separation; e, γ and π^0 identification



Components:

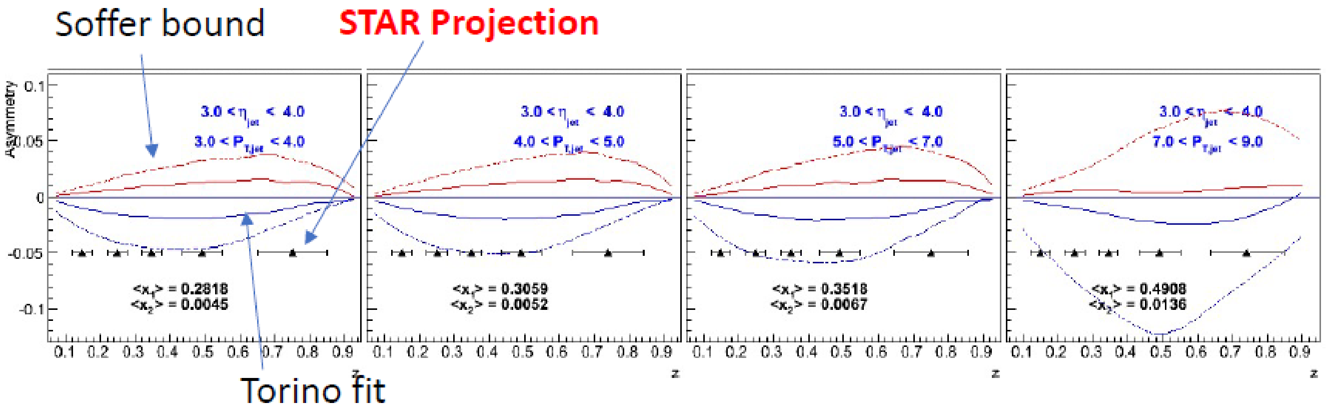
- Forward Silicon Tracker (**FST**)
- Forward sTGC Tracker (**FTT**)
- EM Calorimeter (**ECal**)
- Hadronic Calorimeter (**HCal**)

p+p @508 GeV (2022), p+p/Au @200 GeV (2024)

- Sivers asymmetries for hadrons, (tagged) jets
- Gluon PDFs in nuclei: R_{pA} for direct photon and DY
- Gluon saturation: di-hadron, γ+jets, …

In particular (re: topics presented in this talk);

- Dijet Sivers asymmetries over extended range
- IFF measurements for +/- hadrons out to $\eta = 4$.
- iTPC coverage (η < 1.6): IFF w/ $\pi^{\pm}$ and π^0 in EEMC
- Similarly, extended range of W, Z analyses
- Collins for forward charged hadrons, as per the below:



- Transversity at small & large x and the tensor charge will be better constrained with the STAR forward upgrade and transverse spin data sets '22, '24.

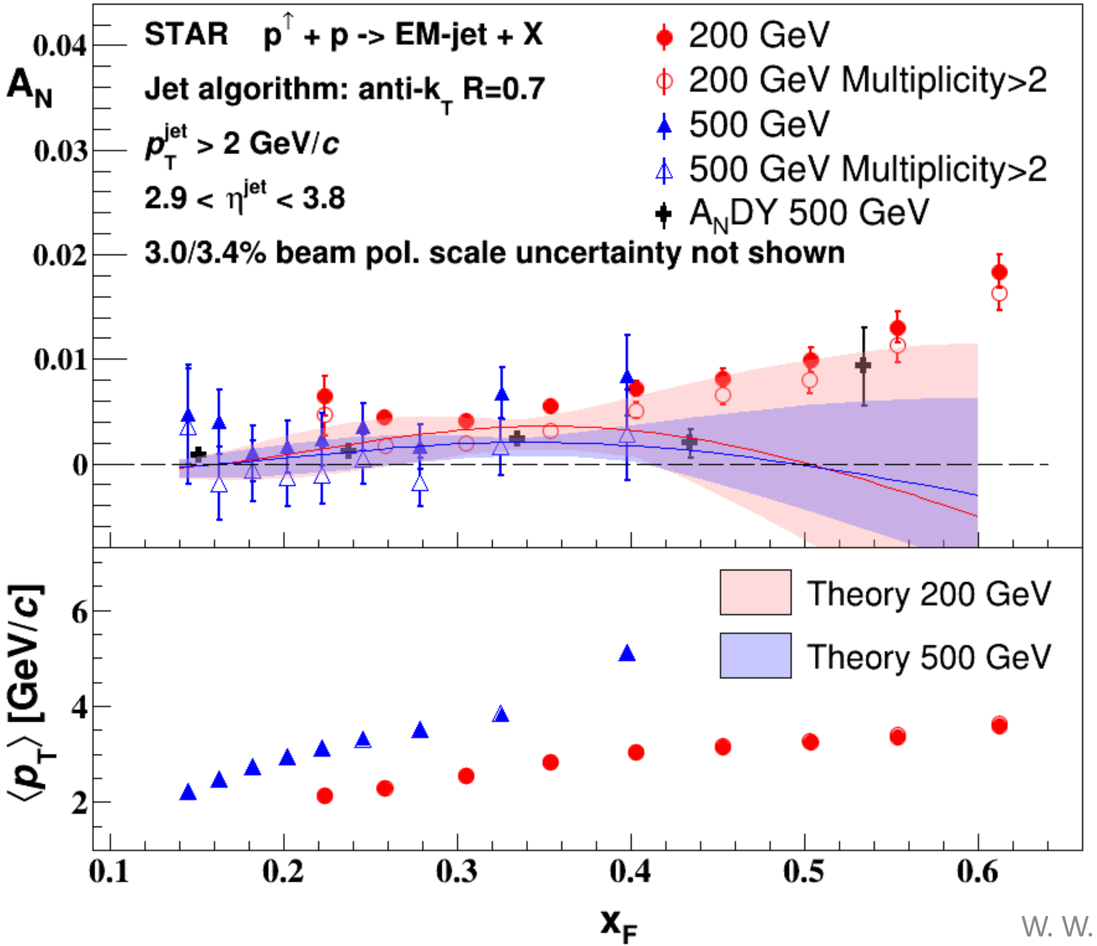
TSSA for Forward EM Jets

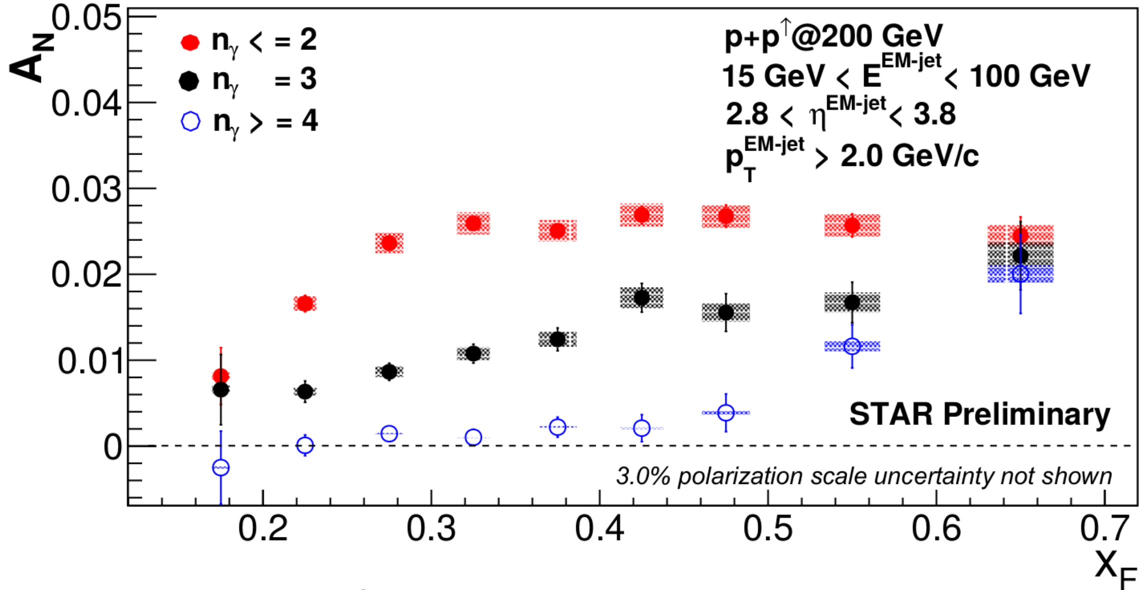
STAR

As Prelude to the Forward Upgrade:

- Additional A_N for π^0 in different topologies,
- <u>Also for EM-jets</u> in the Fwd. Meson Spectr. (FMS) and Endcap EMC (EEMC) at 200 GeV

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





- A_N for isolated π^0 is significantly larger than A_N of non-isolated π^0.
  - Collins π^0 asymmetries found small (not pictured here) .
- For EM-jets of different substructures in FMS and EEMC, A_N decreases with increasing photon multiplicity (e.g., increasing jettiness).
- Expect these, other and future results to provide rich input towards understanding the physics mechanism of large A_N in hadron collisions

Summary and Conclusions

Talk Topics:

- Intro / TSSA
- Dijet Sivers
- $W^{\pm}, Z$ and Sivers
- Di-hadons & Transversity
- Collins asymmetry results
- A_N: fwd π° and EM jets
- Future / Prospects

- A rich environment for transverse spin studies at STAR.
- Many relevant recent results and ongoing analyses.
- <u>Much more to come!</u>

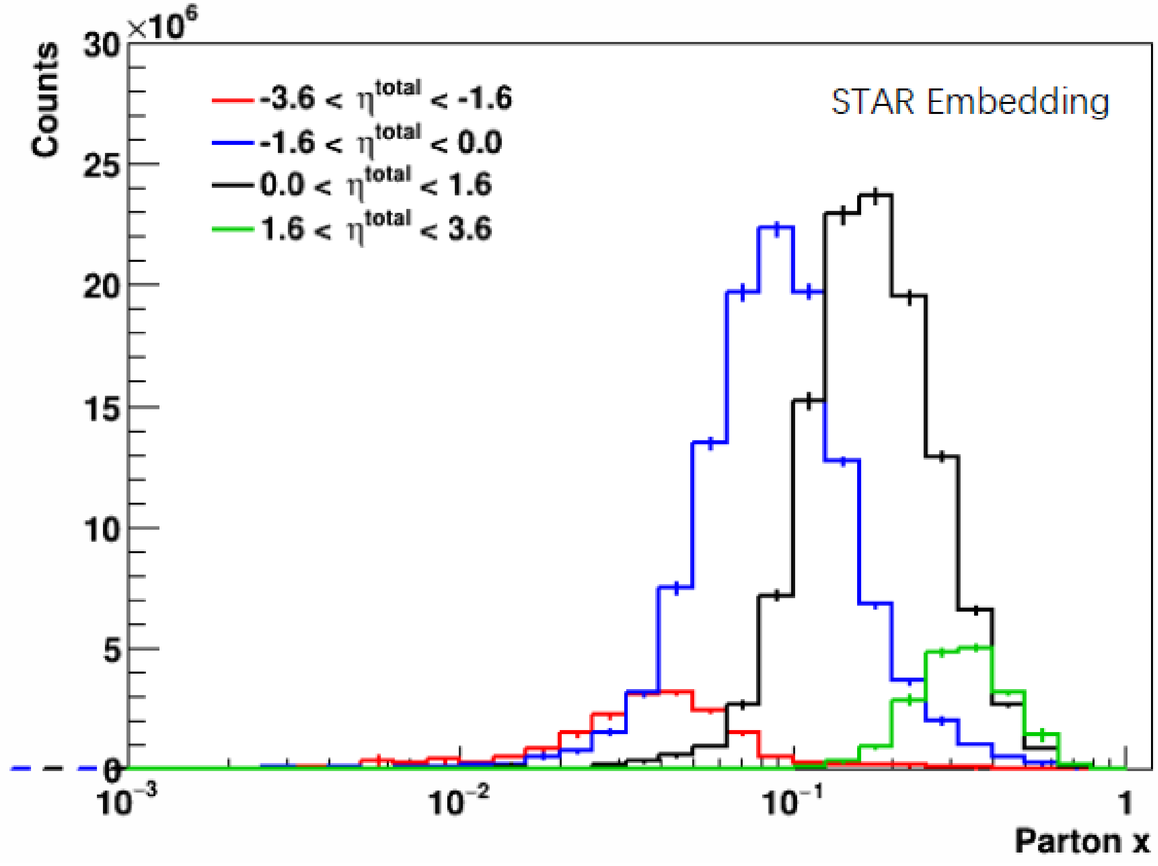
Big **<u>thanks</u>** to STAR collaborators as well as colleagues in the field for discussions, etc.!

Thank you!

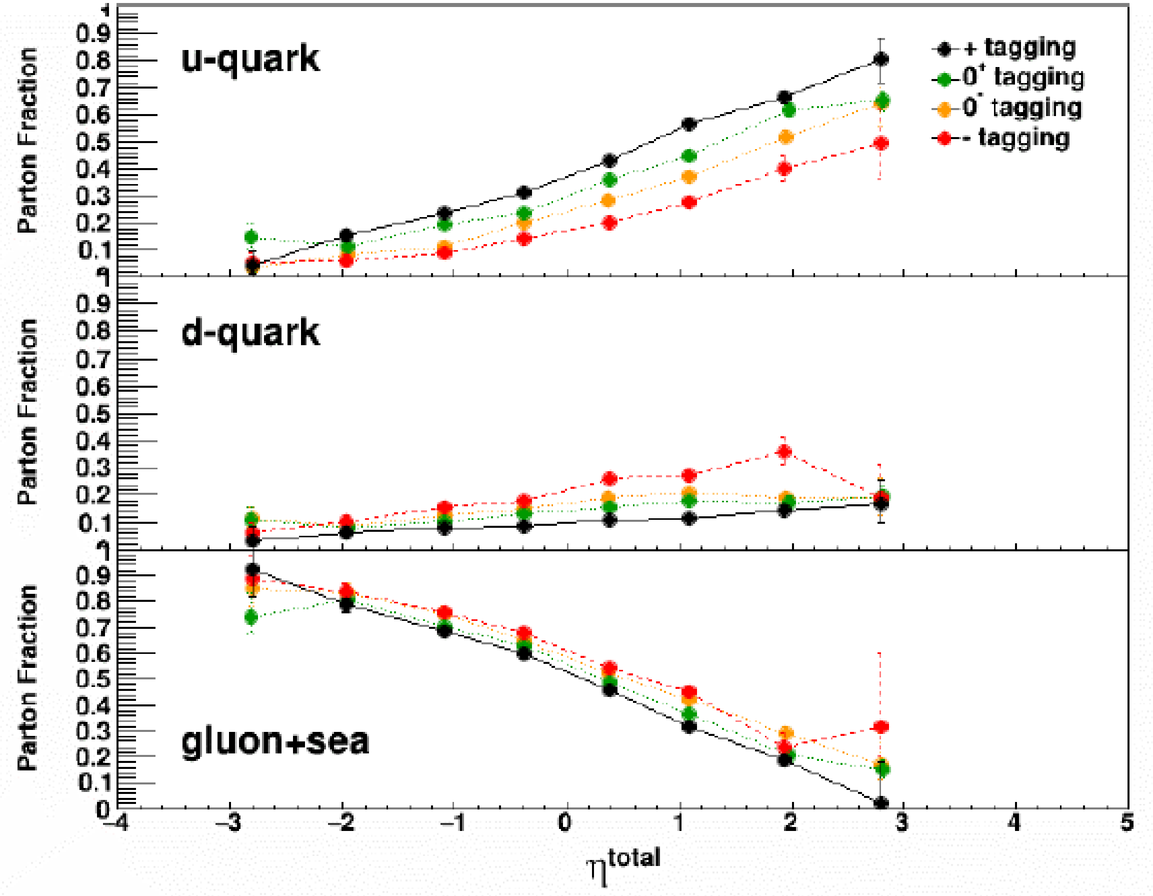
Backup Slides

Parton x Distributions

- $Q^2 > 160$ 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.



Parton Fractions

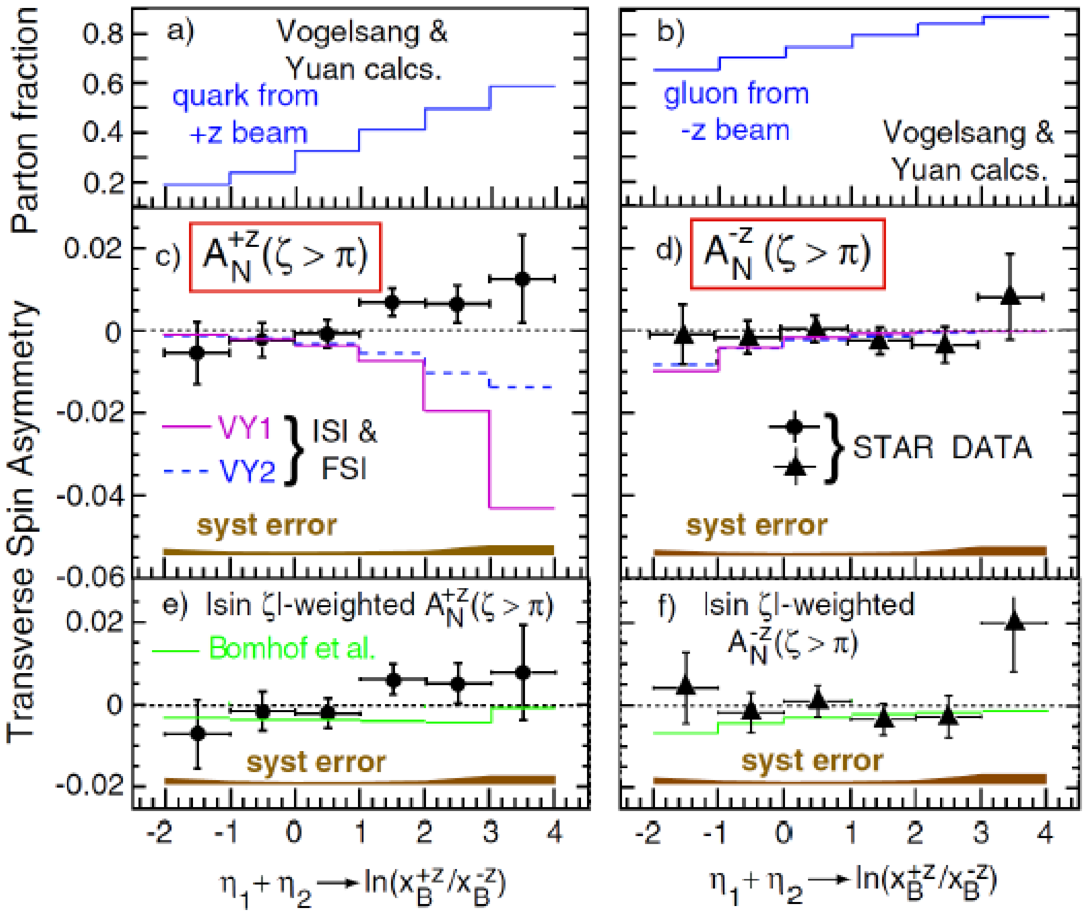


- Parton fractions are estimated from STAR embedding.
- $\eta^{total} = \eta 1 + \eta 2$ is proportional to ln(x1/x2)
- More u-quarks at higher Q and higher η^{total}
- More d-quarks at lower Q, weak dependency on η^{total}
- More gluons at lower Q and lower η^{total}

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

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

W-Boson Reconstruction

$$p + p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

- W-boson decay
  - $p_{T,W}$ is lost
  - Almost no azimuthal angle correlation
- Measure recoil from the collision (tracks and EMC)

$$p_{T,W} = p_{T,e} + p_{T,\nu} = p_{T,recoil}$$
$$p_{T,recoil} = \sum(p_{T,TPC} + E_{T,EMC})$$

- Limited barrel acceptance
  - Comparison with simulation
  - Recoil p_T correction
  - $p_{z,\nu}$ is more problematic

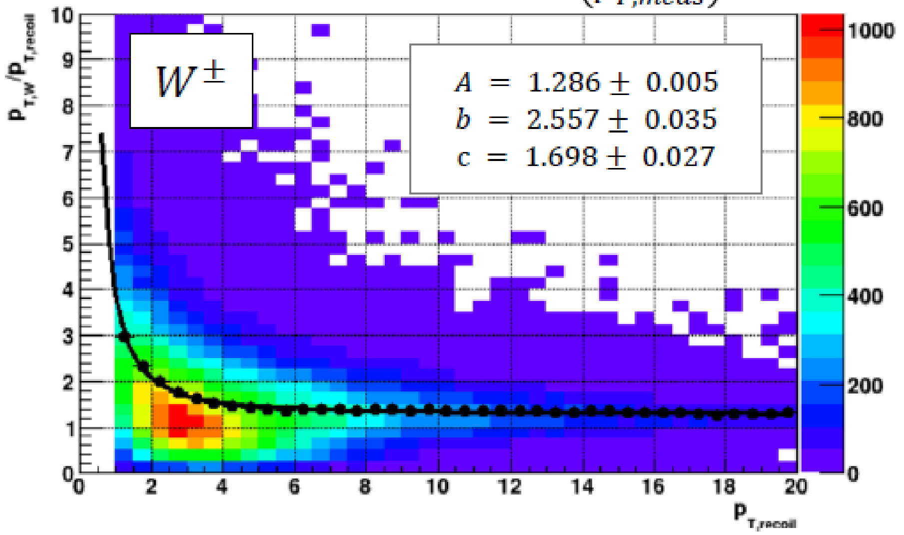
$$M_W^2 = (E_e + E_\nu)^2 - (\vec{p}_e + \vec{p}_\nu)^2$$

$$p_{\nu,z} = \frac{A}{p_{e,T}^2}\left[p_{e,z} \pm p_e \cdot \sqrt{1 - \frac{p_{e,T}^2 \cdot p_{\nu,T}^2}{A^2}}\right]$$

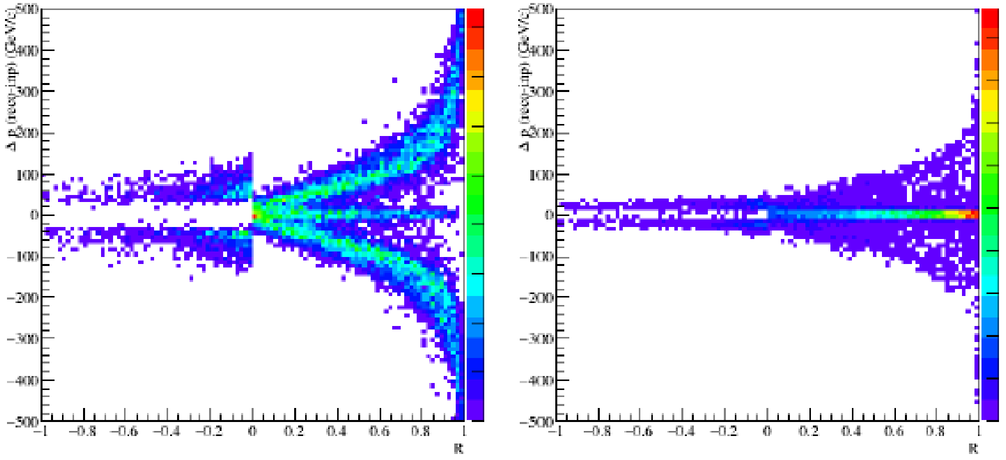
$$A = M_W^2 + \vec{p}_{e,T} \cdot \vec{p}_{\nu,T}$$

$$R = 1 - \frac{p_{e,T}^2 \cdot p_{\nu,T}^2}{A^2}$$

$$p_{T,W} = f(p_{T,meas}) = A + \frac{b}{(p_{T,meas})^c}$$

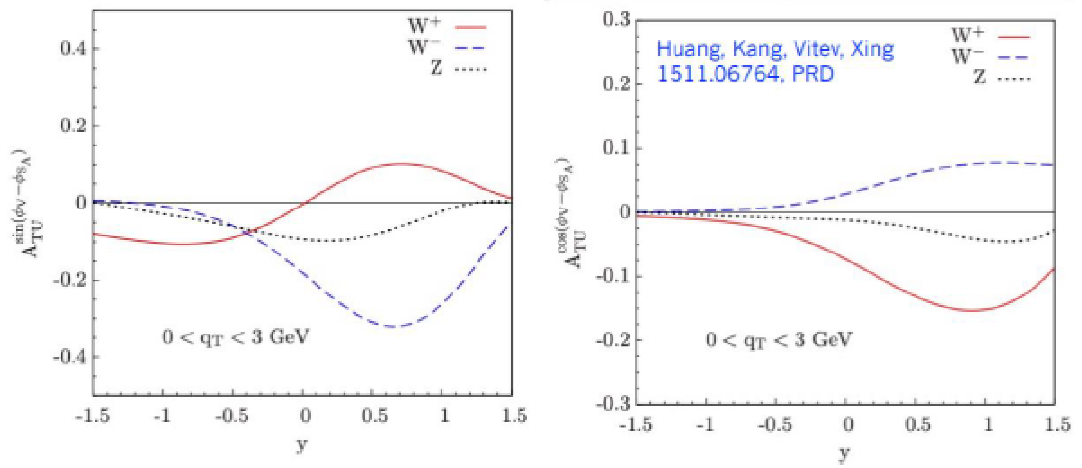


W^-



Transversal Helicity Function g_{1T}

- Transversal helicity can also be measured in W-production
- χ^2 of fit is improved
- Uncertainties in A_S are similar to A_N
- Measured A_S consistent with 0
- Cross talk in A_N is very small
  - W^-: $\Delta A_N/\sigma_{A_N} < 20\%$
  - Included in $\sigma_{syst}(A_N)$



$\phi_V - \phi_{S_A} = \phi - \pi/2$

A_N: $\sin(\phi_V - \phi_{S_A}) = -\cos\phi$

A_S: $\cos(\phi_V - \phi_{S_A}) = \sin\phi$

$$\begin{aligned}\frac{d\sigma^W}{dy\,d^2\vec{q}_T} = \sigma_0^W \Big\{ & F_{UU} + S_{AL}F_{LU} + S_{BL}F_{UL} + S_{AL}S_{BL}F_{LL} \\ & + |\vec{S}_{AT}|\left[\sin(\phi_V-\phi_{S_A})F_{TU}^{\sin(\phi_V-\phi_{S_A})} + \cos(\phi_V-\phi_{S_A})F_{TU}^{\cos(\phi_V-\phi_{S_A})}\right] \\ & + |\vec{S}_{BT}|\left[\sin(\phi_V-\phi_{S_B})F_{UT}^{\sin(\phi_V-\phi_{S_B})} + \cos(\phi_V-\phi_{S_B})F_{UT}^{(\cos\phi_V-\phi_{S_B})}\right] \\ & + |\vec{S}_{AT}|S_{BL}\left[\sin(\phi_V-\phi_{S_A})F_{TL}^{\sin(\phi_V-\phi_{S_A})} + \cos(\phi_V-\phi_{S_A})F_{TL}^{\cos(\phi_V-\phi_{S_A})}\right] \\ & + S_{AL}|\vec{S}_{BT}|\left[\sin(\phi_V-\phi_{S_B})F_{LT}^{\sin(\phi_V-\phi_{S_B})} + \cos(\phi_V-\phi_{S_B})F_{LT}^{\cos(\phi_V-\phi_{S_B})}\right] \\ & + |\vec{S}_{AT}||\vec{S}_{BT}|\Big[\cos(2\phi_V-\phi_{S_A}-\phi_{S_B})F_{TT}^{\cos(2\phi_V-\phi_{S_A}-\phi_{S_B})} + \cos(\phi_{S_A}-\phi_{S_B})F_{TT}^{1} \\ & \quad + \sin(2\phi_V-\phi_{S_A}-\phi_{S_B})F_{TT}^{\sin(2\phi_V-\phi_{S_A}-\phi_{S_B})} + \sin(\phi_{S_A}-\phi_{S_B})F_{TT}^{2}\Big]\Big\}.\end{aligned}$$

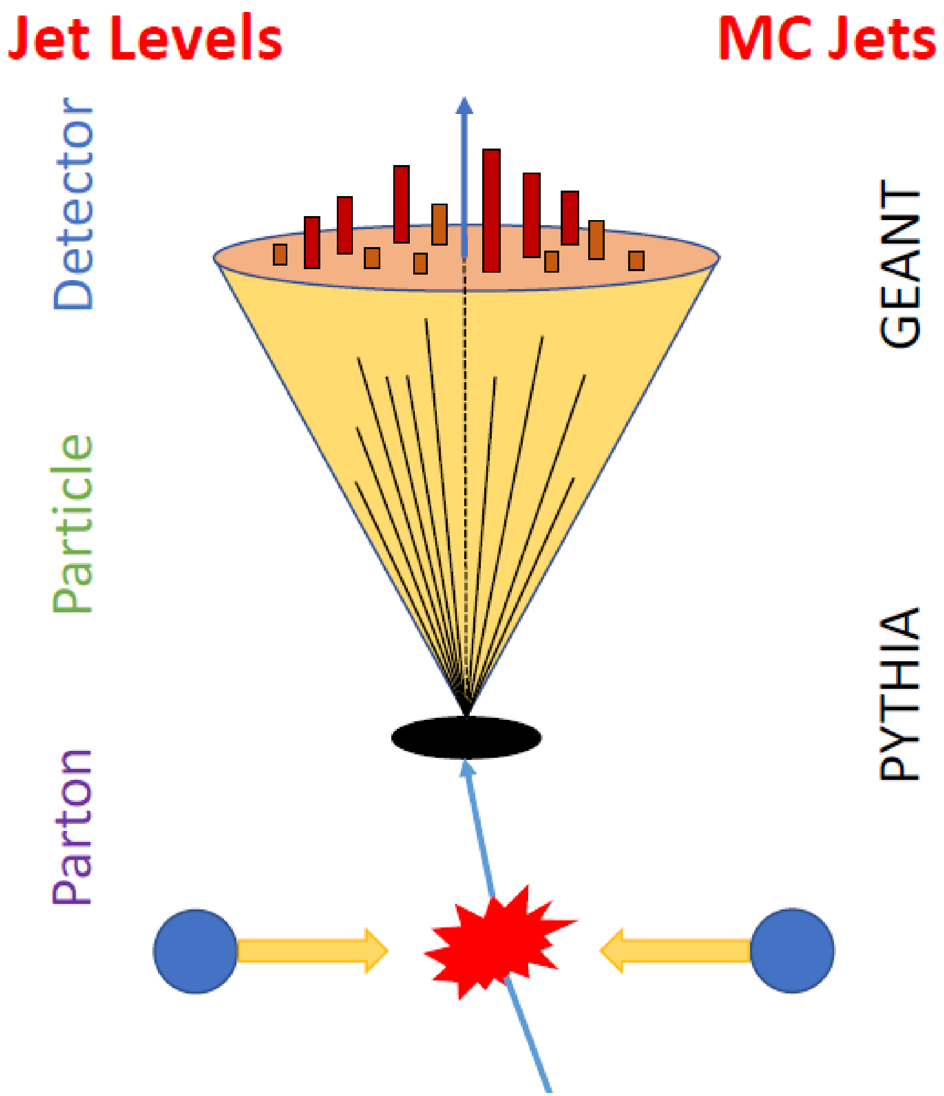
$$F_{TU}^{\sin(\phi_V-\phi_{S_A})} = \mathcal{C}^W\left[(v_q^2+a_q^2)\frac{\hat{q}_T\cdot\vec{k}_{aT}}{M_A}f_{1T}^{\perp}\bar{f}_1\right],$$

$$F_{TU}^{\cos(\phi_V-\phi_{S_A})} = -\mathcal{C}^W\left[2v_q a_q\frac{\hat{q}_T\cdot\vec{k}_{aT}}{M_A}g_{1T}\bar{f}_1\right],$$

Z. Kang, CFNS Workshop on RHIC physics for EIC, May 2021

O. Eyser / SPIN 2021

Jet Reconstruction



Anti-k_T Algorithm:

- Radius = 0.6;
- Less sensitive to underlying event and pile-up effects;
- Used in both data and simulation;

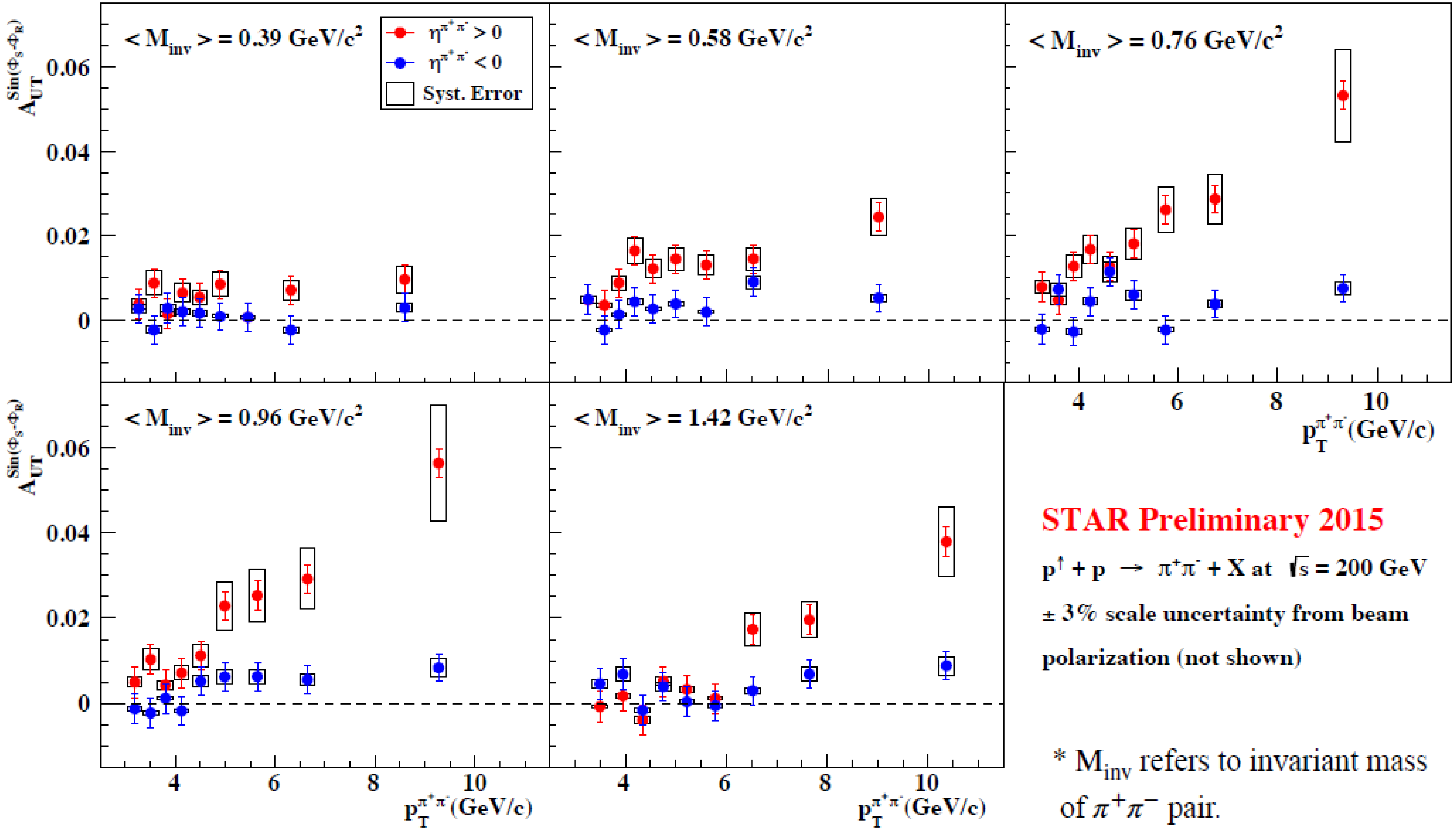
Simulation: PYTHIA 6.4 Perugia 2012 with additional tuning to STAR data;

Three Simulation Levels :

- Parton – hard scattered partons involved in 2->2 hard scatterings from PYTHIA;
- Particle – partons propagate and hadronize into stable and color-neutral particles;
- Detector – detector response to the stable particles.

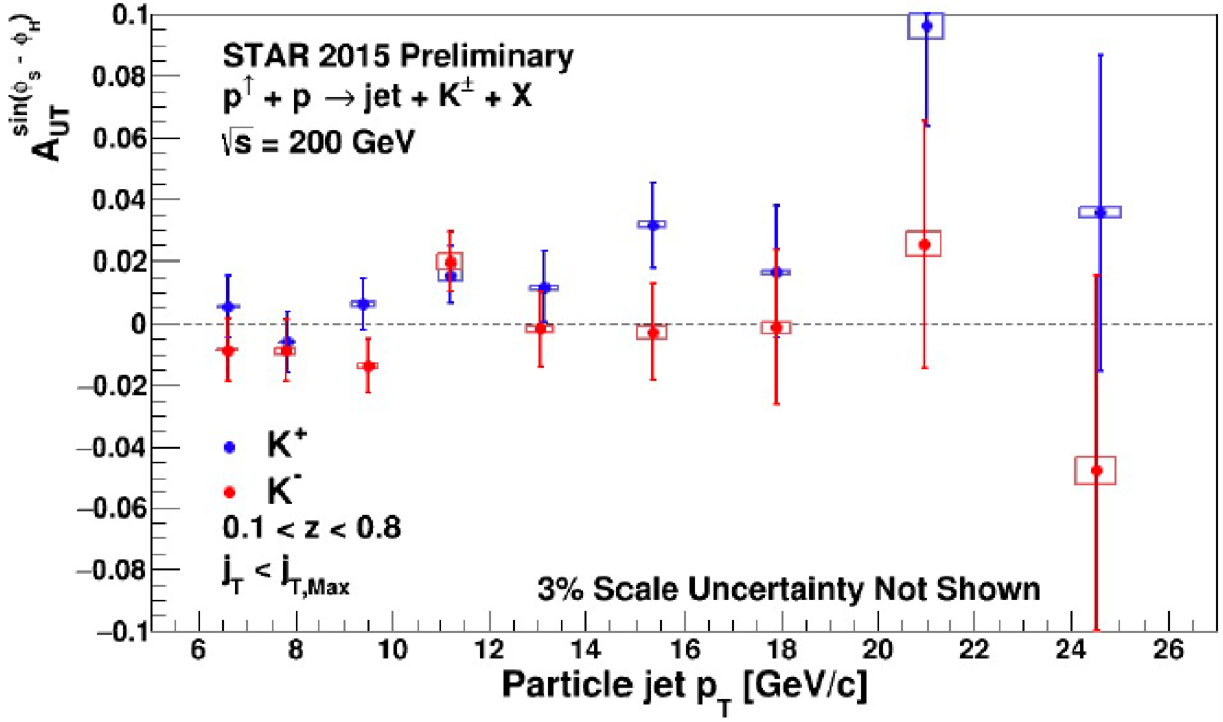
STAR Preliminary: $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $p_T^{\pi^+\pi^-}$

- $A_{UT}^{sin(\phi_s-\phi_R)}$ vs $p_T^{\pi^+\pi^-}$ in different M_{inv} and $\eta^{\pi^+\pi^-}$ bins.
  - Large asymmetry signal at higher p_T in forward $\eta^{\pi^+\pi^-}$ region. Stronger signal when $< M_{inv} > \sim M_\rho$.
  - Backward $\eta^{\pi^+\pi^-}$ signal is small, mainly from low x quarks from polarized beam.
- Systematic uncertainty includes effects related to PID and trigger bias.



* M_{inv} refers to invariant mass of $\pi^+\pi^-$ pair.

$K^{\pm}$ Azimuthal Distribution in Jets



- K^+, which can be produced through favored fragmentation of a valence u quark, has asymmetries that are consistent with the π^+ asymmetries within statistical uncertainties;
- K^-, which is produced by unfavored fragmentation, has asymmetries that are consistent with zero at the current precision.