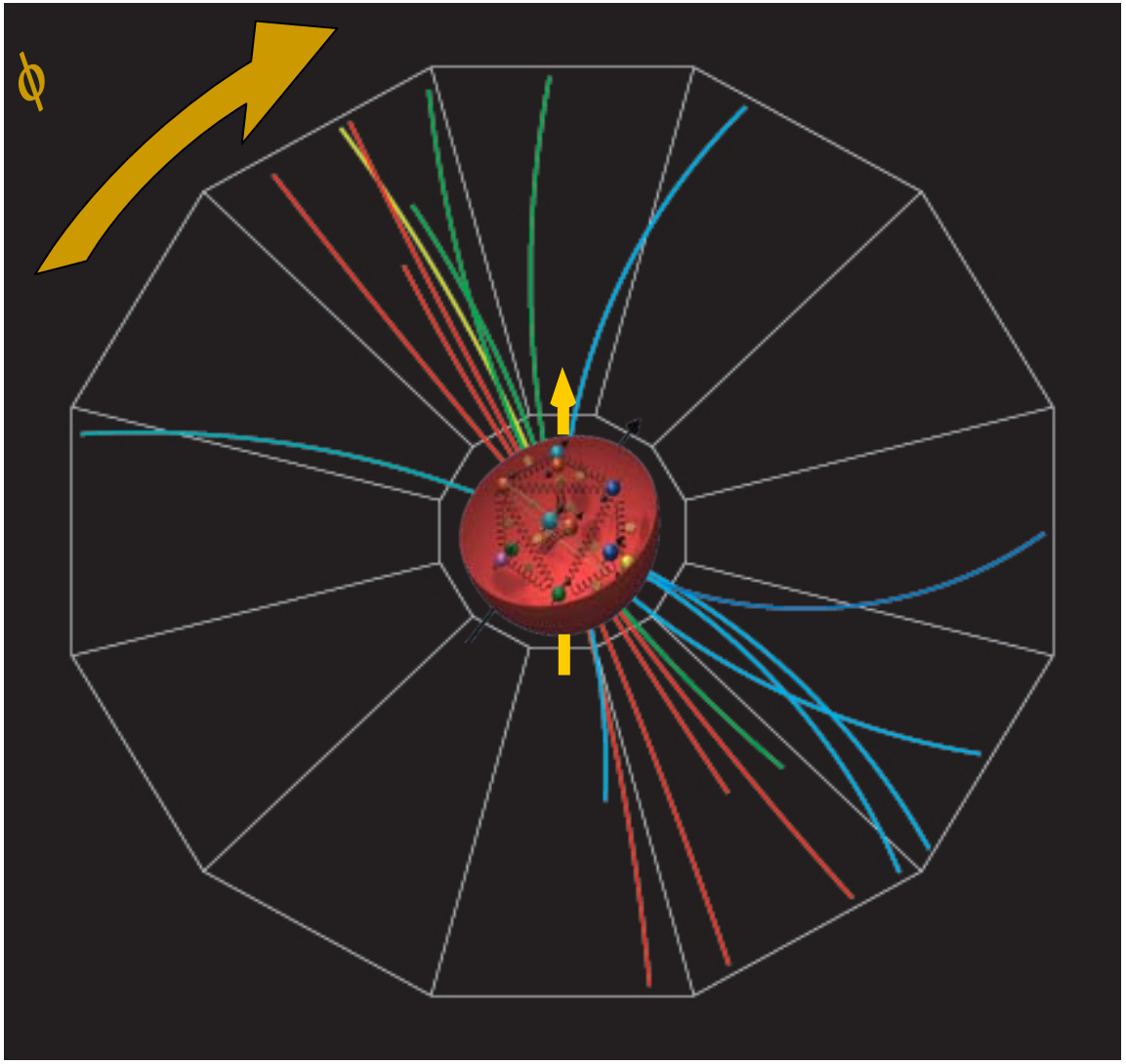
Di-Jet Asymmetry Measurements with STAR

S. Vigdor for STAR Collaboration, RHIC/AGS Users Meeting, June 2007



Search for Sivers asymmetry in azimuthal opening angle distribution between jet pairs

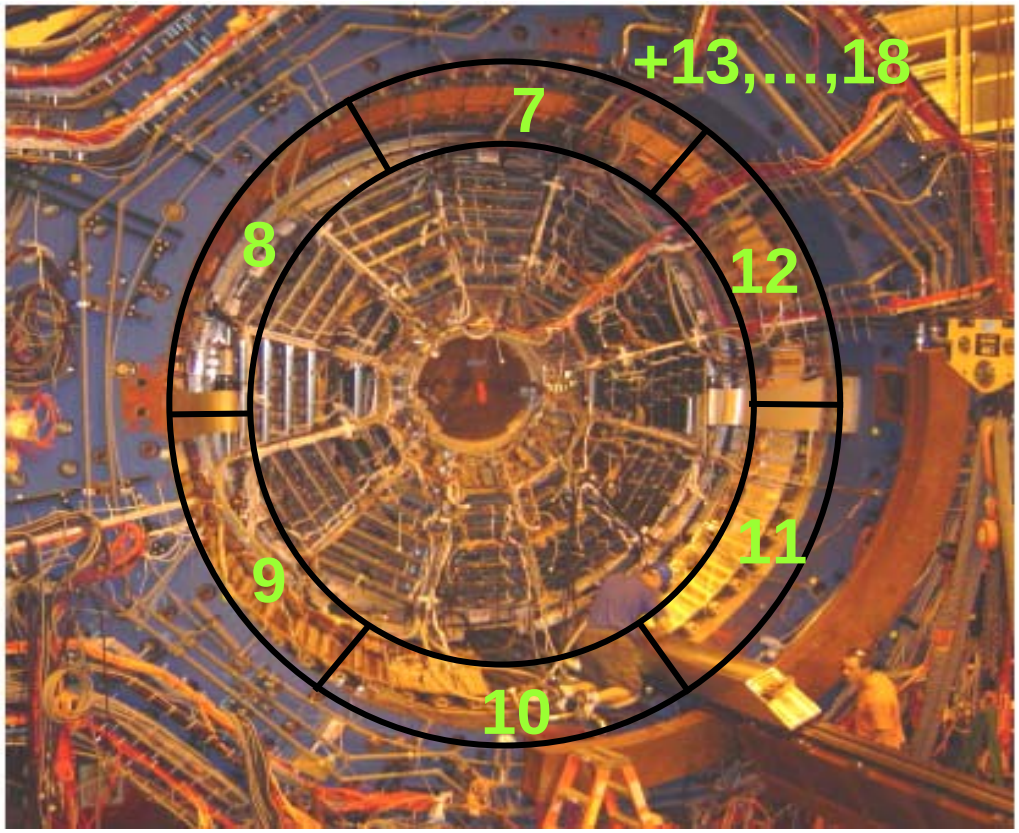
2006 $\vec{p}+\vec{p}$ run at RHIC (special thanks to Renaissance Technologies!)

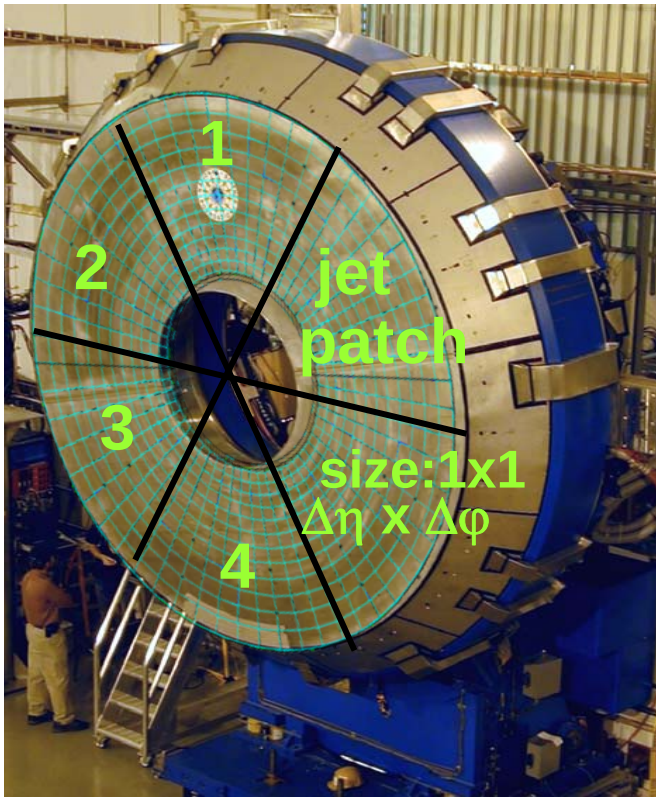
3 weeks of data with transverse spin orientations at STAR

EMCal-based analysis using dedicated Level 2 di-jet trigger

⇒ arXiv:0705.4629 (hep-ex), submitted to PRL

Level 0 Jet Triggering in STAR





Trigger either on

HT: ≥1 (of 4800 BEMC or 720 EEMC) tower E_T > thresh.

Or

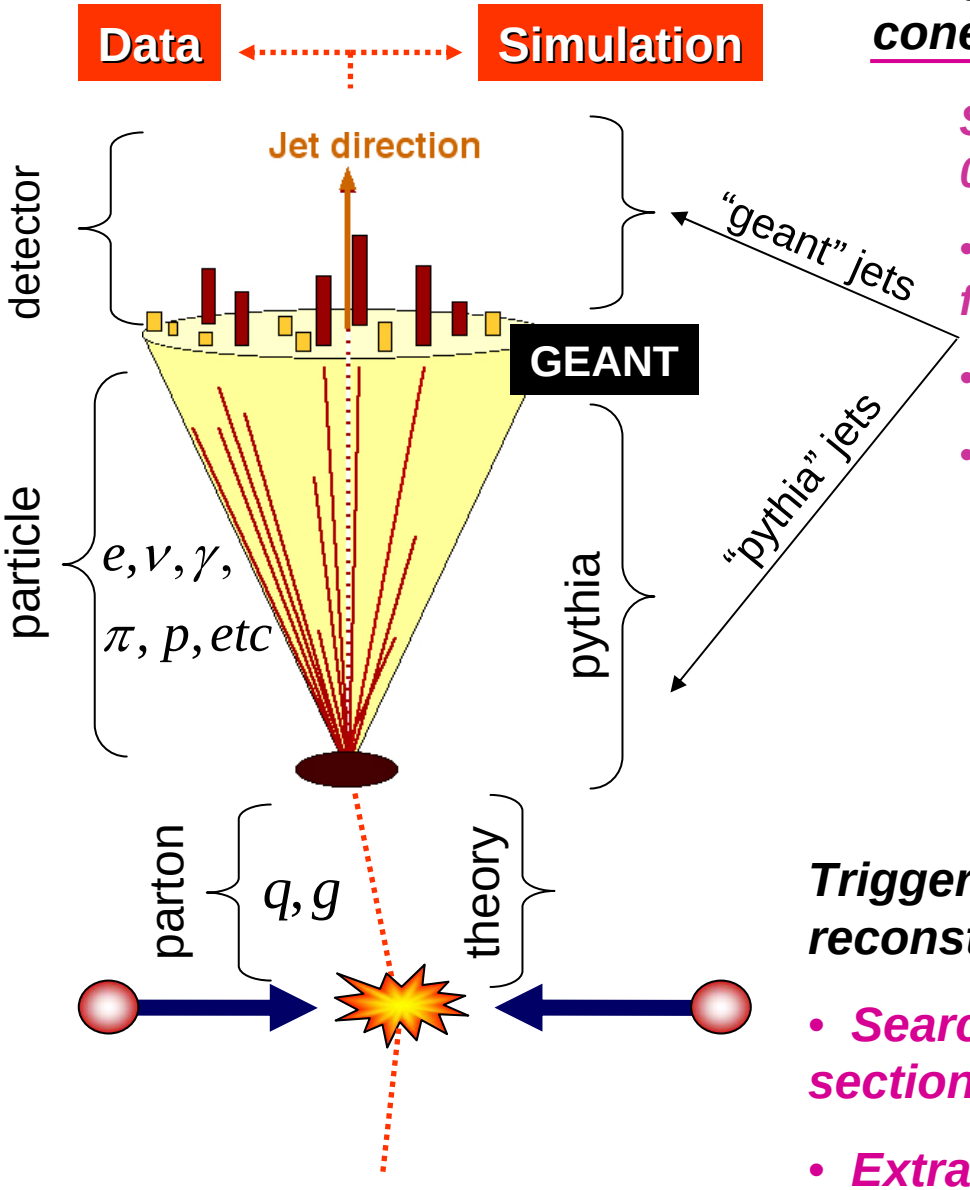
JP: ≥1 (of 12 BEMC or 6 EEMC) hard-wired jet patch $\sum E_T$ > thresh.

2006 rate ~ 150 Hz, combine with L2 trigger to fit in limited bandwidth

2006 rate ~ 2.5 Hz, sent to tape without prescaling

Allocated Jet Rate to tape: ~15 Hz

Jet Reconstruction in STAR



Full jet reconstruction uses "midpoint-cone" algorithm (hep-ex/0005012):

- ***Search over all possible seeds (p_T^{seed} > 0.5 GeV) for stable groupings***
- ***Check midpoints between jet-jet pairs for stable groupings***
- ***Split/merge jets based on $E_{overlap}$***
- ***Add all track/tower 4-momenta***

Use cone radius:

$$R_{cone} \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

- ***= 0.4 for half-BEMC 2003-5***
- ***= 0.6-0.7 for full B+EEMC 2006***

Trigger-level EMC-only L2 partial jet reconstruction:

- ***Search for any EMC $\Delta\eta \times \Delta\phi = 0.6 \times 0.6$ section with summed EMC E_T > threshold***
- ***Extract (η,ϕ) of jet axis from E_T-weighted EMC centroid locations***

Transverse Spin Measurements Have Stimulated Rapid Development of Theory

Factorization (valid?):

Non-pert. pQCD Non-pert.

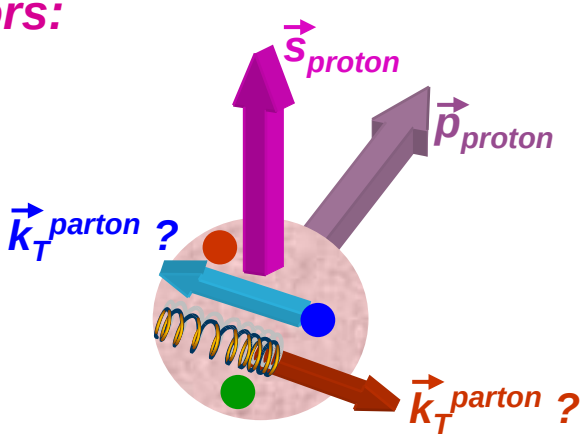
$$\text{Hard hadronic } d\sigma = \text{PDF's} \otimes \text{hard partonic } d\hat{\sigma} \otimes \text{fragment'n fcn.}$$

- ***Observed A_N values orders of magnitude too large to arise from explicit chiral-symmetry breaking quark mass terms in QCD Lagrangian.***

- ***Steep p_T -dependence of $d\sigma \Rightarrow$ sensitivity to spin-correlated transverse momentum preferences in non-perturbative factors:***

a) Partons in the initial state -- Sivers effect:

$$\left\langle \vec{s}_{proton} \cdot \left(\vec{p}_{proton} \times \vec{k}_T^{\,parton} \right) \right\rangle_{observed\ \ process} \neq 0$$



Sensitive to parton orbital components in proton wave function, but also needs initial- and/or final-state interactions to evade TRV.

b) Hadrons emerging off-axis in quark $\rightarrow$ jet fragmentation --

Collins effect: $\left\langle \vec{s}_{quark} \cdot \left(\vec{p}_{quark} \times \vec{k}_T^{\,fragment} \right) \right\rangle_{jet\ \ formation} \neq 0$

Requires quark transverse spin orientation preference in transversely polarized proton ("transversity") + spin transfer to outgoing quark in pQCD scattering.

Origin of Transverse Spin SSA, continued

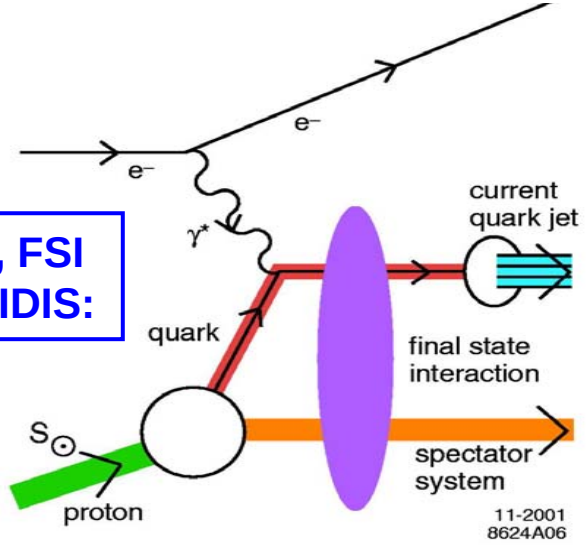
c) Boer-Mulders effect in the UNpolarized proton:

$$\left\langle \vec{s}_{quark} \cdot \left(\vec{p}_{proton} \times \vec{k}_T^{\,quark} \right) \right\rangle_{observed \quad process} \neq 0$$

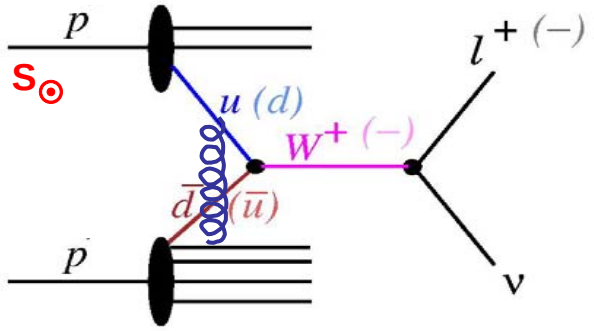
Can contribute to A_N in combination with transversity in polarized proton, via pQCD transverse spin correlation $A_{TT} \neq 0$ in quark-quark scattering contributions.

k_T factorization: ISI/FSI needed to evade TRV subsumed in gauge-invariant, but process-dependent, k_T-dependent (TMD) parton distribution (e.g., Sivers, Boer-Mulders) functions:

e.g., FSI in SIDIS:



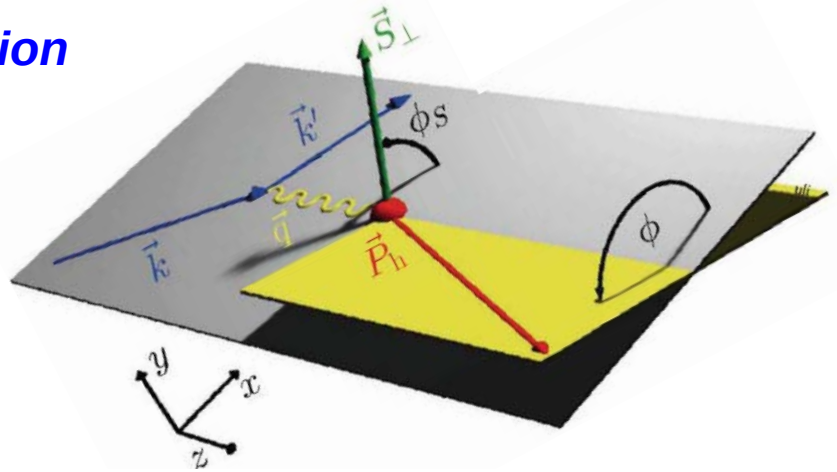
e.g., ISI in W-prod'n or Drell-Yan:



ISI and FSI tend to enter with opposite phase ⇒ predicted sign change of Sivers fcn. between SIDIS and Drell-Yan: non-universality! Hadron, jet production in p+p have both ISI and FSI QCD effects.

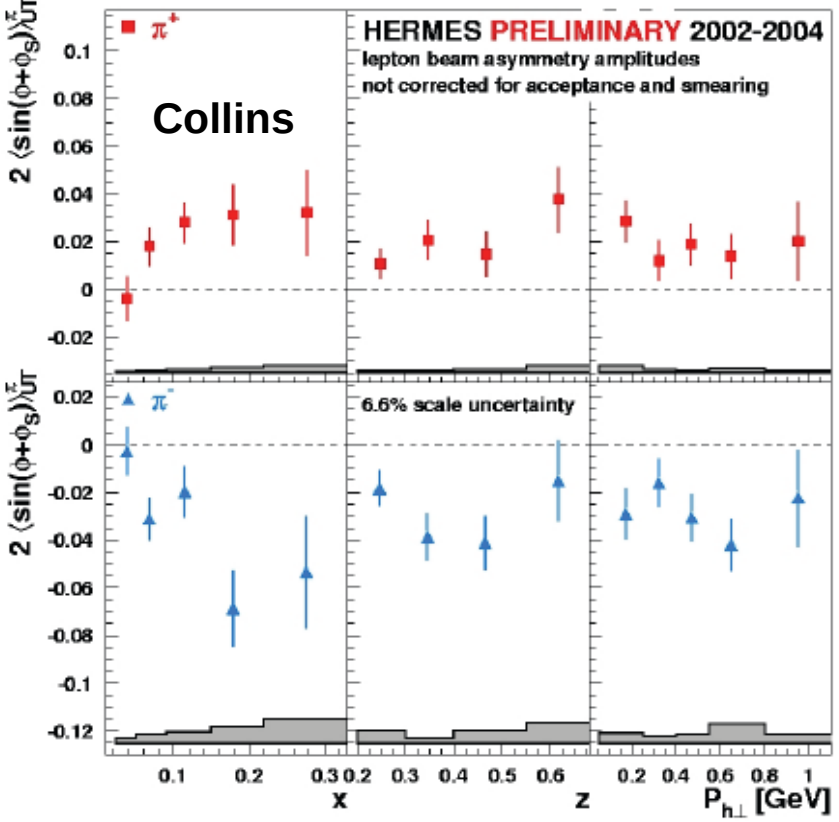
Distinguishing Sivers from Collins Asymmetries

In SIDIS, can distinguish transverse motion preferences in PDF's (Sivers) vs. in fragmentation fcns. (Collins) via asym. dependence on 2 azimuthal angles:

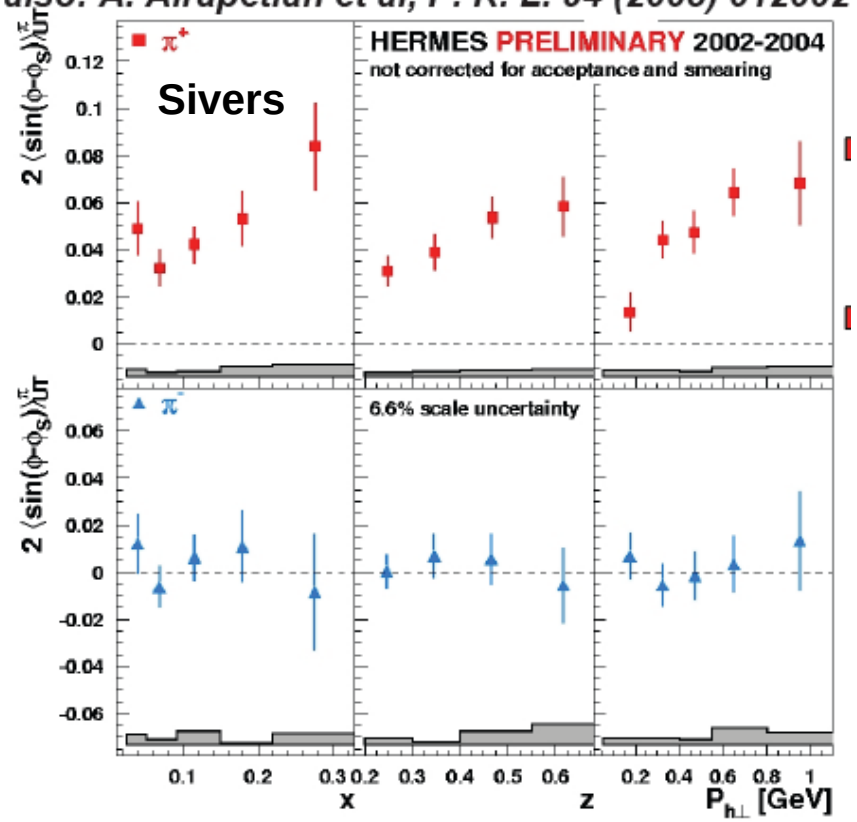


HERMES results $\Rightarrow$ both non-zero, but π^+ vs. π^- difference suggests Sivers functions opposite for u and d quarks.

also: A. Airapetian et al, P. R. L. 94 (2005) 012002

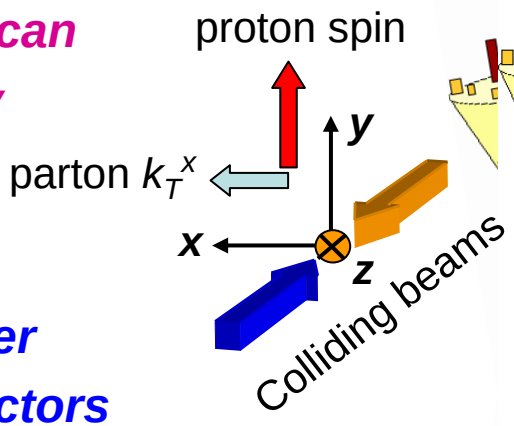


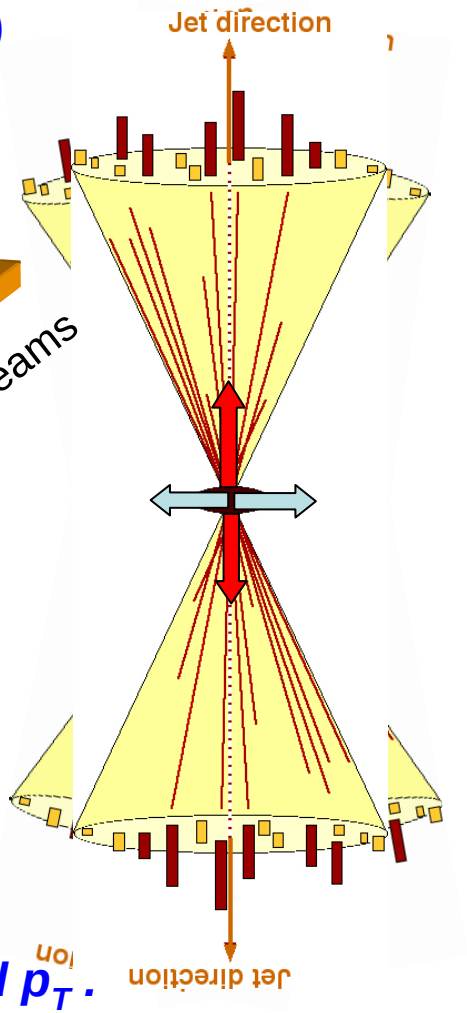
also: A. Airapetian et al, P. R. L. 94 (2005) 012002



Motivation for pp → Di-Jet Measurement

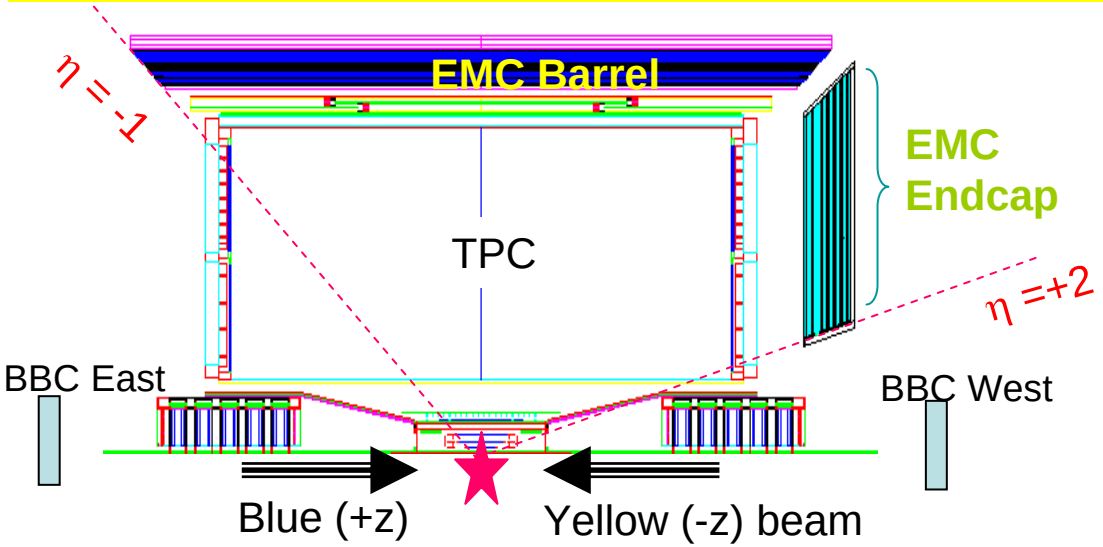
- *HERMES transverse spin SIDIS asymmetries ⇒ u and d quark Sivers functions of opposite sign, different magnitude.*
- *Sivers effect in $\vec{p}\vec{p}$ ⇒ spin-dependent sideways boost to di-jets, suggested by Boer & Vogelsang (PRD 69, 094025 (2004))*
- *Both beams polarized, $x^{+z} \neq x^{-z}$ ⇒ can distinguish high-x vs. low-x (primarily gluon) Sivers effects.*





- *Do we observe q Sivers consistent with HERMES, after inclusion of proper pQCD-calculable ISI/FSI gauge link factors for pp → jets? Tests limited TMD "universality".*
- *First direct measurement of gluon Sivers effects.*
- *Collins and Boer-Mulders asymmetry contributions expected to be very small, due to absence of charge-sign bias in hadrons omitted from EMC-only jet reconstruction and small role of q-q scattering at probed p_T .*

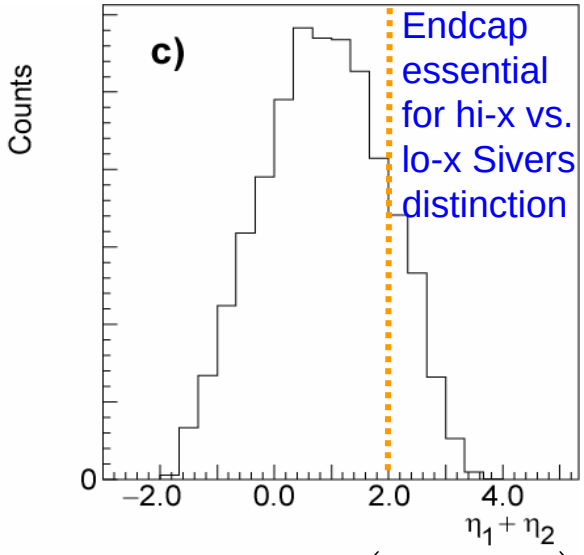
STAR EMC-Based (Level 0 + 2) Di-Jet Trigger in 2006



- *2006 $\vec{p}$+p run, 1.1 pb^{-1}*
- *2.6M di-jet triggered events*
- *2 localized clusters, with $E_T^{EMC} > 3.5$ GeV, $|\Delta\phi| > 60°$*

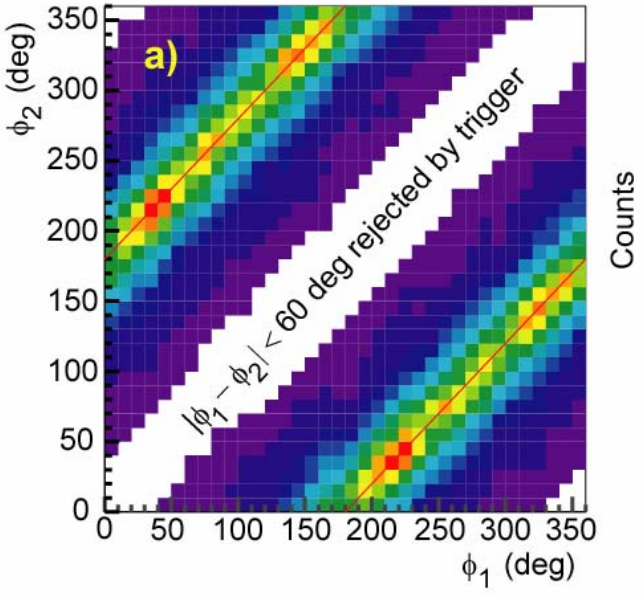
Reco cos($\varphi_{bisector}$) measures sign of net k_T^x for event

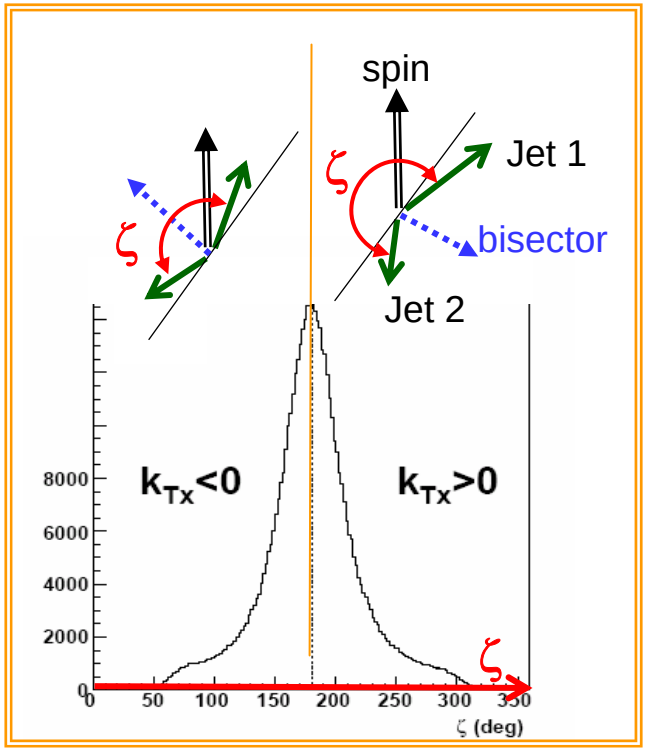
Broad $\eta_{1,2}$ coverage



$$\eta_1 + \eta_2 = \ln\left(x^{+z} / x^{-z}\right)$$

Full, symmetric $\phi_{1,2}$ coverage

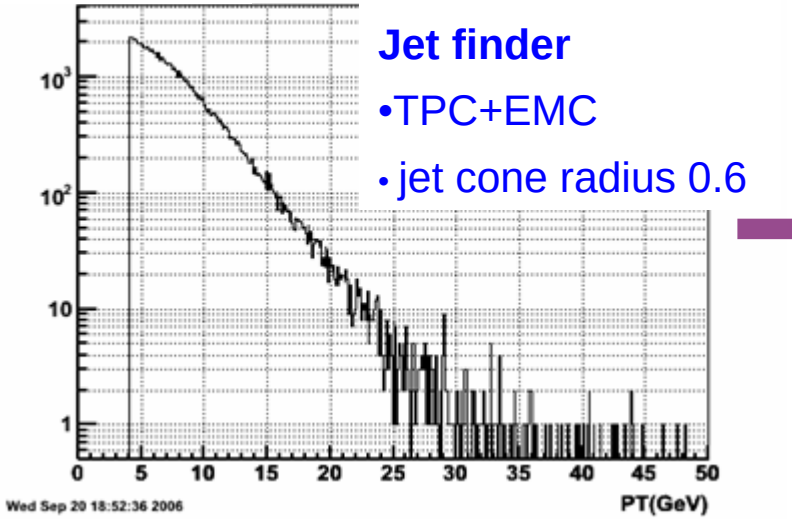




Signed azimuthal opening angle ζ

EMC-Only Information OK For 1st Dijet Sivers Asymmetry

Full offline di-jet reconstruction for ~2% of all runs shows triggered jet p_T spectrum:

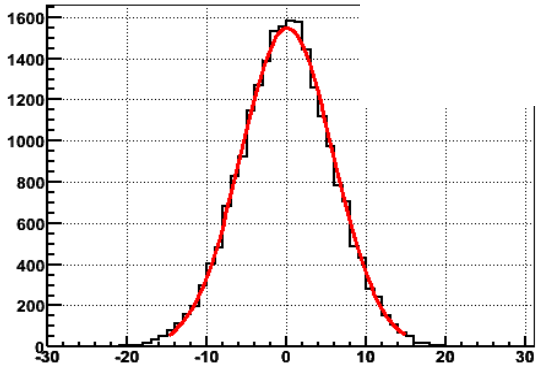


Typical x_T ~ 0.05 - 0.10;

$\eta_1+\eta_2$ range $\Rightarrow$ $0.01 < x_{Bj} < 0.4$

and $\Rightarrow$ angle resolution loss @ L2 OK:

$[\sigma(\phi)=3.9°, \sigma(\zeta)=5.8°]_{\text{L2 vs. full jet}} << \sigma_{\text{observed}}(\zeta) \approx 20°$, mostly from k_T



ζ (full reco) – ζ (L2) [deg]

PYTHIA+GEANT $\Rightarrow$ full jet reconstruction vs. parton-level resolution:

$[\sigma(\phi)=5.0°, \sigma(\eta)=0.10]_{\text{full reco. jet vs. parton angles}}$

Net L2-to-parton $\sigma(\phi_{jet}) = 6.3°$, $\sigma(\zeta_{di\text{-}jet}) = 9.0°$

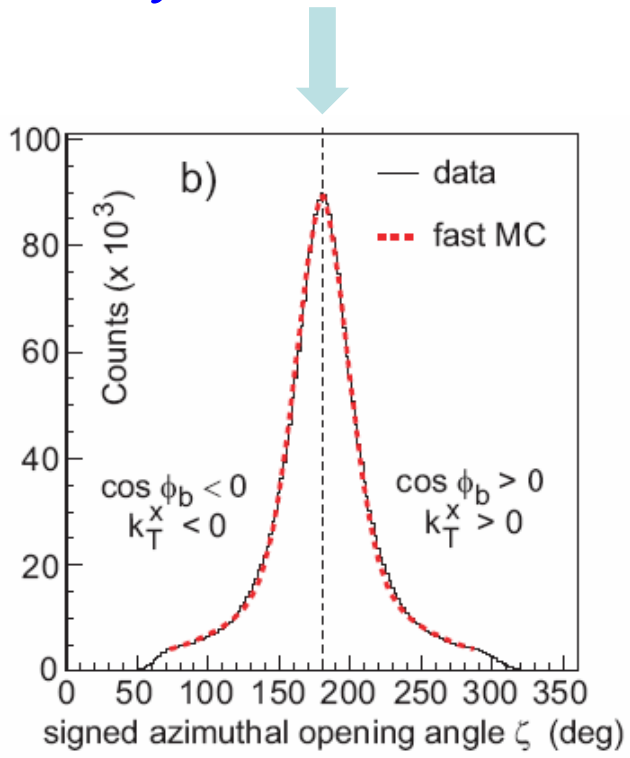
Fast MC Simulations Illustrate Di-Jet Sivers Effects

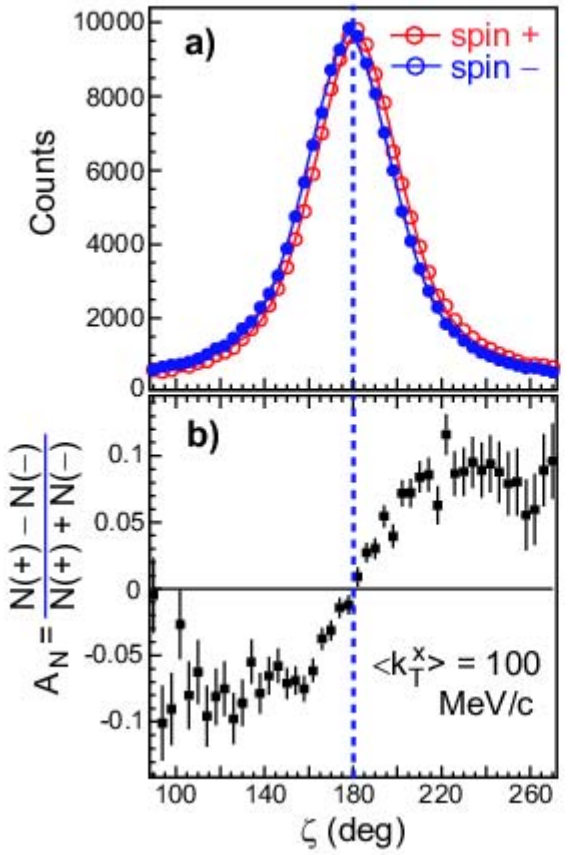
- *2-parton events, transverse plane*
- *match full jet reco. p_T distribution*
- *Gaussian + exp'l tail k_T distribution fits ζ distribution*

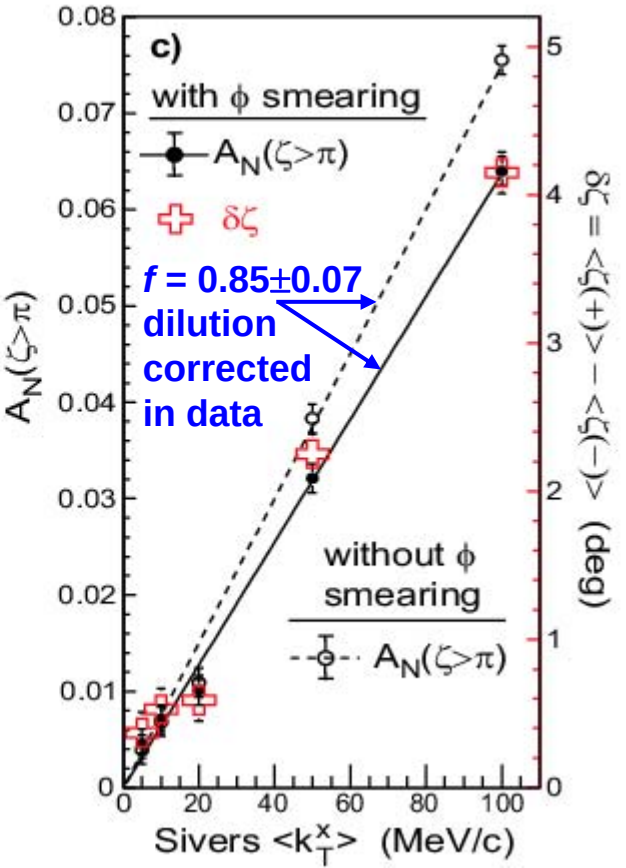
- *random $k_T^{x,y}$ (rms = 1.27 GeV/c) for each parton*
- *Sivers spin-dep. k_T^x offset $\Rightarrow$ ζ shift, L-R di-jet bisector asym.*
- *1-spin effects vary linearly with k_T^x offset*

$$f\,P_{\pm z}\,|\cos\phi_b\,|\,A_N^{\pm z}(\varsigma>\pi) = \left[r_{\pm z}(\phi_b)-1\right]/\left[r_{\pm z}(\phi_b)+1\right] \text{ with}$$

$$r_{+z}(\phi_b) \equiv \sqrt{\frac{\sum N_{+j}(\varsigma>\pi,\phi_b)}{\sum N_{-j}(\varsigma>\pi,\phi_b)}} \bullet \sqrt{\frac{\sum N_{-j}(\varsigma<\pi,\phi_b)}{\sum N_{+j}(\varsigma<\pi,\phi_b)}}, \text{ etc.}$$



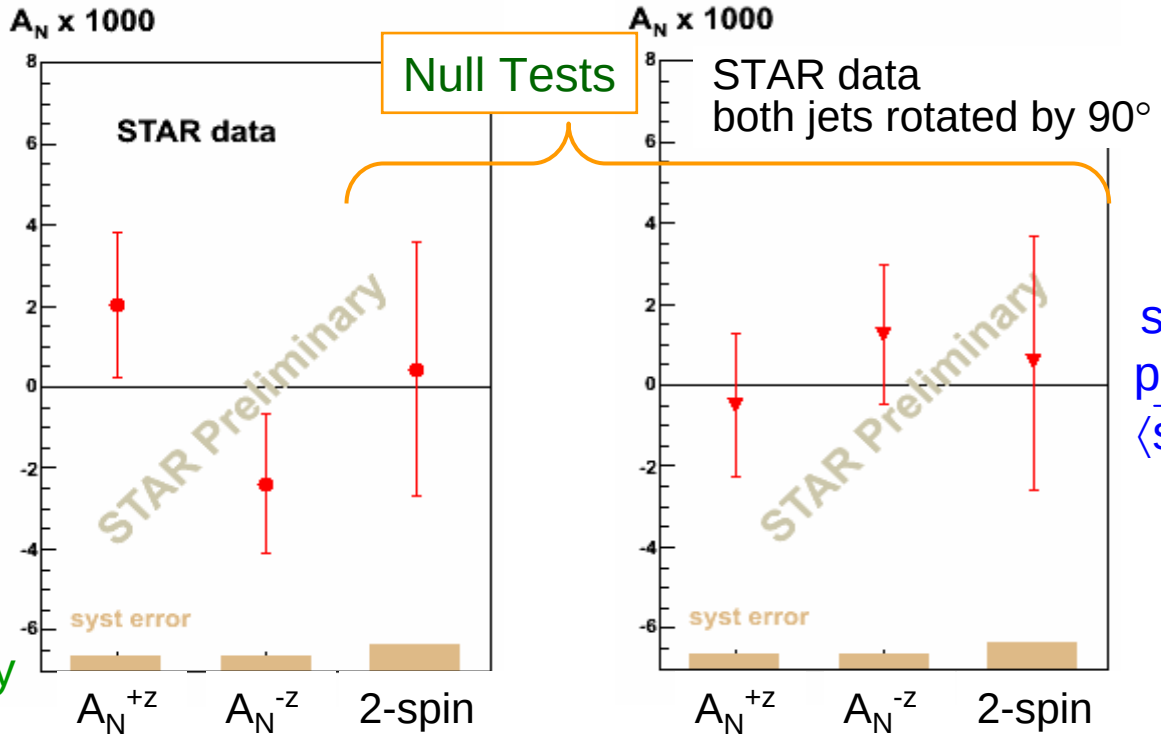




STAR Results Integrated Over Pseudorapidity

Error-weighted avg. of 16 independent $A_N(\zeta>\pi)$ values for $|\cos(\phi_{bisector})|$ slices, with effective $\perp$ beam polarization for each = $P_{beam}\times|\cos(\phi_{bisector})|$

P_{beam} from online CNI analysis, with ±20% calib. uncert'y



ϕ rotation samples $\langle k_T^y \rangle$, parity-violating $\langle \vec{s}_p \cdot \vec{k}_T \rangle$ correl'n

- ***Sivers asymmetries consistent with zero with stat. unc. = ±0.002***
- ***Fast MC ⇒ sensitivity to Sivers $\langle k_T^x \rangle$ offset ≈ few MeV/c ≈ 0.002 $\langle (k_T^x)^2 \rangle^{1/2}$***
- ***Systematic uncertainties smaller than statistics***
- ***All null tests, including forbidden 2-spin asym. ∝ $\cos(\phi_{bisector})$, consistent with zero, as are physics asymmetries for all polarization fill patterns***
- ***Validity of spin-sorting confirmed by reproducing known non-zero A_N for inclusive forward charged-particle production (STAR BBC's)***

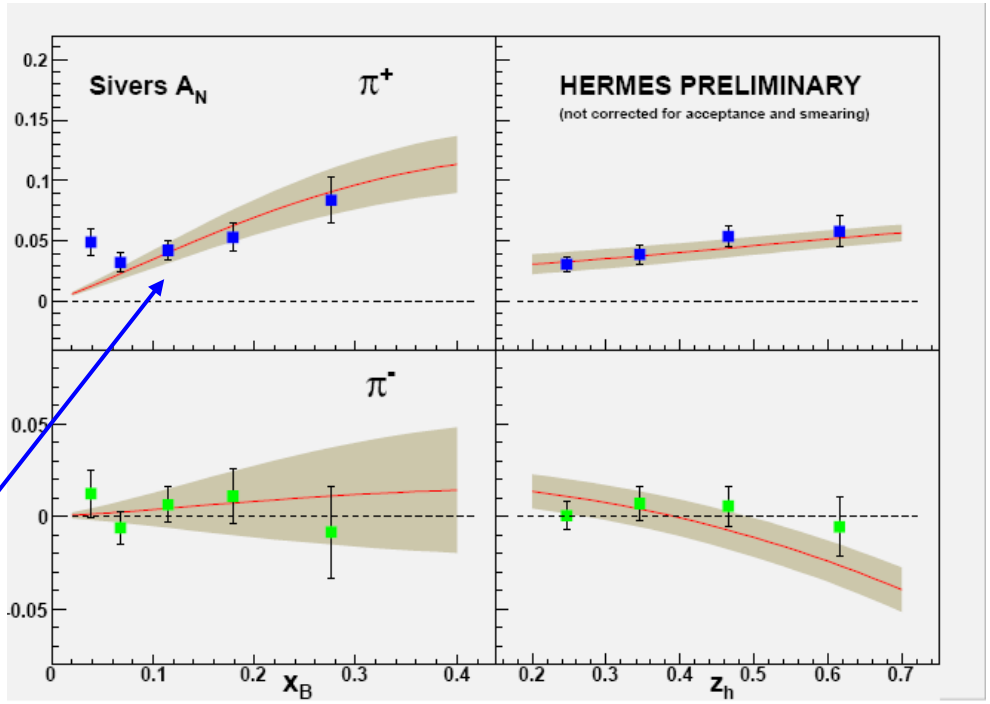
What Did We Expect? Constraints from SIDIS Results

Fits to HERMES SIDIS Sivers asymmetries constrain u and d quark Sivers functions, for use in $\vec{p}p \rightarrow$ dijet + X predictions.

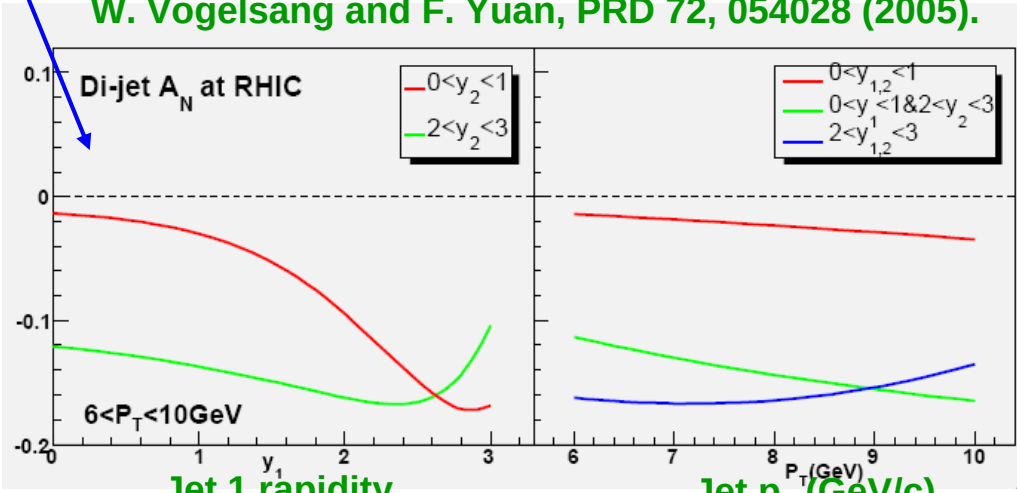
E.g., Vogelsang & Yuan use two different models of Sivers fcn. x-dependence:

$$VY\ 1: \quad u_T^{(1/2)}(x)/u(x) = -0.81\,x(1-x)$$
$$d_T^{(1/2)}(x)/u(x) = 1.86\,x(1-x)$$

$$VY\ 2: \quad u_T^{(1/2)}(x)/u(x) = -0.75\,x(1-x)$$
$$d_T^{(1/2)}(x)/d(x) = 2.76\,x(1-x)$$



W. Vogelsang and F. Yuan, PRD 72, 054028 (2005).



Jet 1 rapidity

Jet p_T (GeV/c)

Dijet calcs. include:

- ***no hadronization***
- ***no gluon Sivers fcns.***
- ***$5 < p_T^{parton} < 10$ GeV/c***
- ***Initial-state interactions only (à la Drell-Yan)***
- ***Trento sign convention (opposite Madison)***

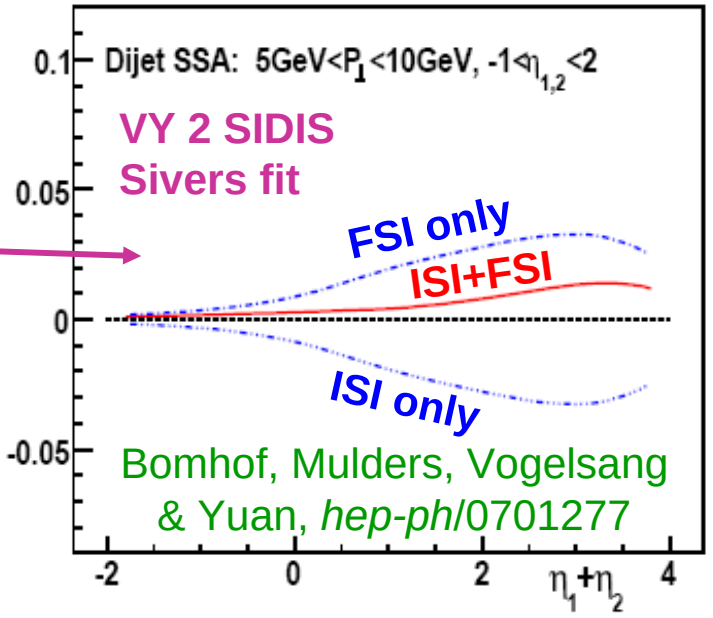
≥1 jet forward, expected $|A_N| \sim 0.1$, little p_T - dep.

Theory of Transverse SSA Developing Very Rapidly!

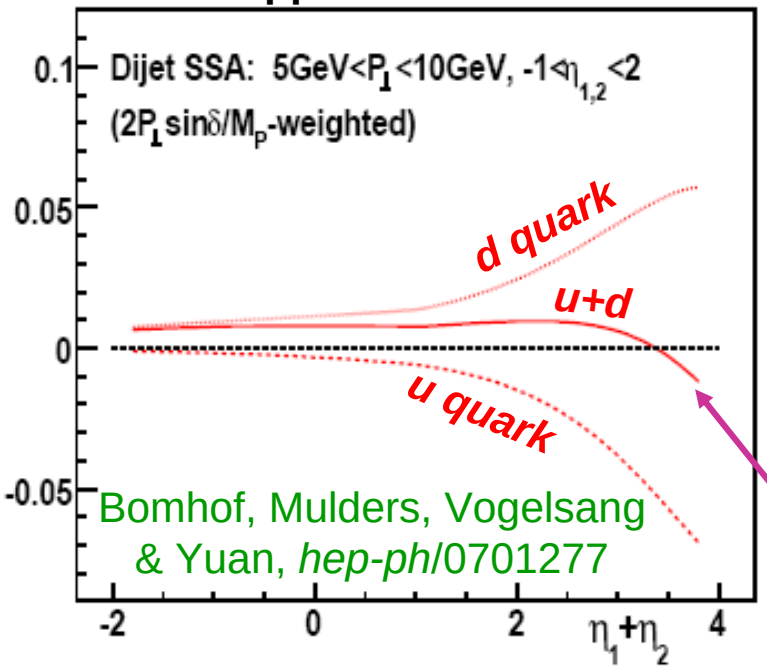
Bacchetta, Bomhof, Mulders & Pijlman* [PRD 72, 034030 (2005)] *deduce gauge link structure for pp → jets, hadrons:

$\Rightarrow A_N(\text{ISI+FSI}) \approx -0.5\, A_N(\text{ISI})$

⇒ Gauge links more robust for SSA weighted by $\sum p_T$ or $|\sin\zeta|$, due to k_T - factorization breakdown (Collins & Qiu, arXiv:0705.2141)



Sivers fcns. from twist-3 qg correl'n fits to $\vec{p}p \rightarrow$ forward hadron

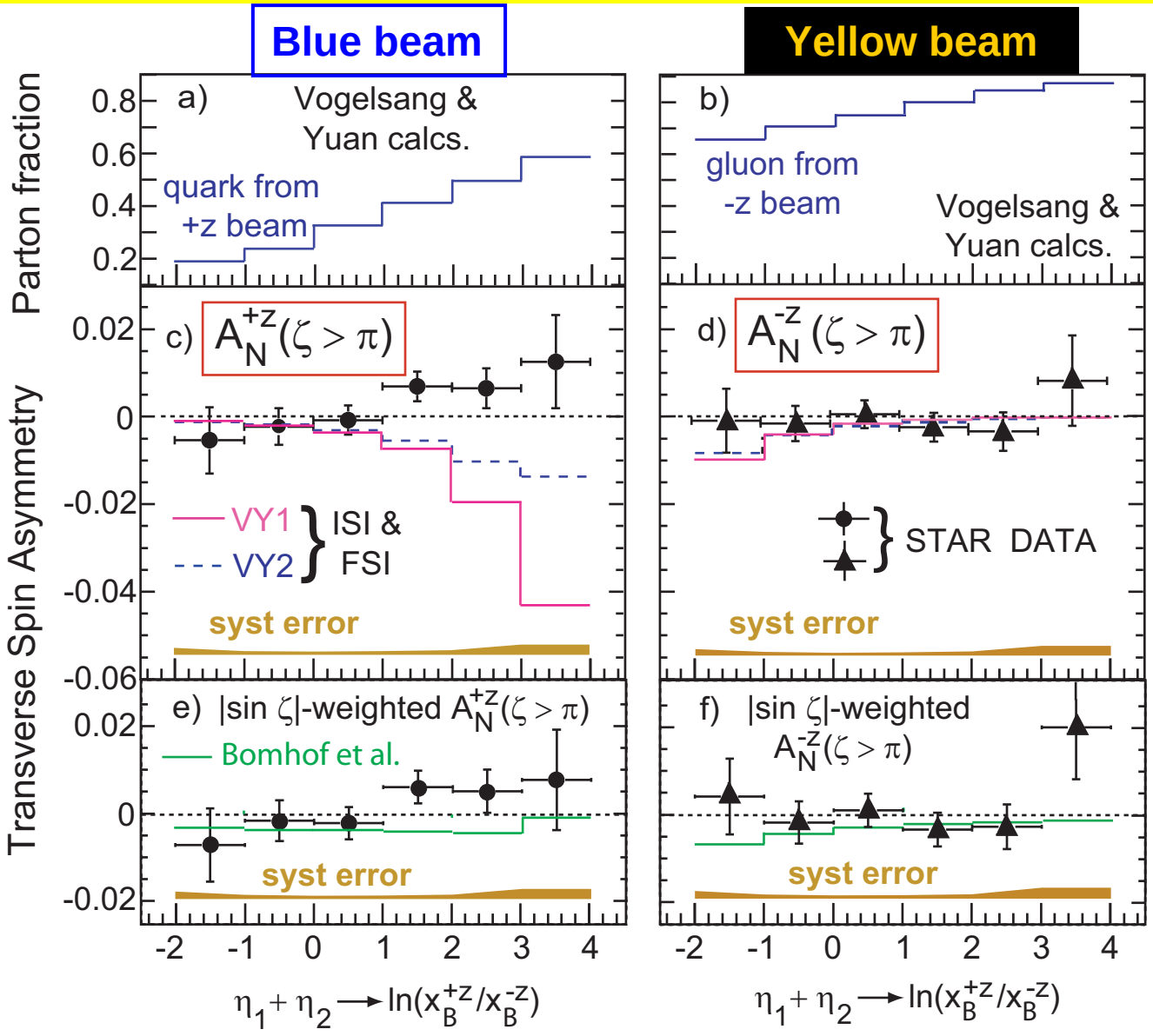


Ji, Qiu, Vogelsang & Yuan* [PRL 97, 082002 (2006)] *show strong overlap between Sivers effects & twist-3 quark-gluon (Qiu-Sterman) correlations:

⇒ twist-3 fits to $A_N(\vec{p}+p \rightarrow$ fwd. h) can constrain Sivers fcn. moment relevant to weighted di-jet SSA

⇒ Kouvaris et al. [PRD 74, 114013 (2006)] *fits give nearly complete u vs. d cancellation in weighted di-jet SSA*

STAR Di-Jet Sivers Results vs. Jet Pseudorapidity Sum



- ***All calcs. for STAR η acceptance***
- ***Reverse calc. A_N signs for Madison convention***
- ***Scale Bomhof calcs by $1/\langle|\sin\zeta|\rangle \approx 3.0$ to get A_N of unit max. magnitude***
- ***u vs d and FSI vs ISI cancellations ⇒ sizable SSA in inclusive fwd. h prod'n and SIDIS (weighted SSA) compatible with small weighted di-jet SSA -- test via LCP flavor select***

STAR A_N all consistent with zero ⇒ both net high-*x* parton and low-*x* gluon Sivers effects ~10x smaller in $\vec{p}p \rightarrow$ di-jets than SIDIS quark Sivers asym.!

Summary and Ongoing Analysis

- ***First measurement of spin asymmetries for di-jet production in pp collisions $\Rightarrow$ Sivers asymmetries consistent with zero, whether dominated by partons in the valence or sea regions.***

- ***pQCD calculations reconcile small observed asymmetries with larger effects seen in SIDIS and in pp $\rightarrow$ forward hadron, via cancelling ISI vs. FSI and u vs. d contributions.***

- ***Ongoing analysis incorporates more triggers + TPC tracks for full jet reconstruction $\Rightarrow$ allowance for cuts on jet p_T , u vs. d filtering via leading hadron charge sign, etc. Without adding cuts or events, full reconstruction results consistent with EMC-only analysis.***

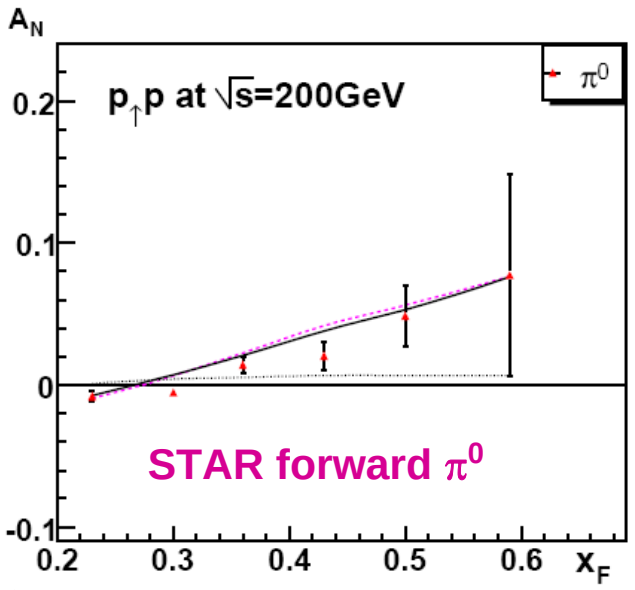
- ***Results constrain unified theoretical accounts for transverse SSA in hard pQCD processes, and connection to parton orbital momentum.***

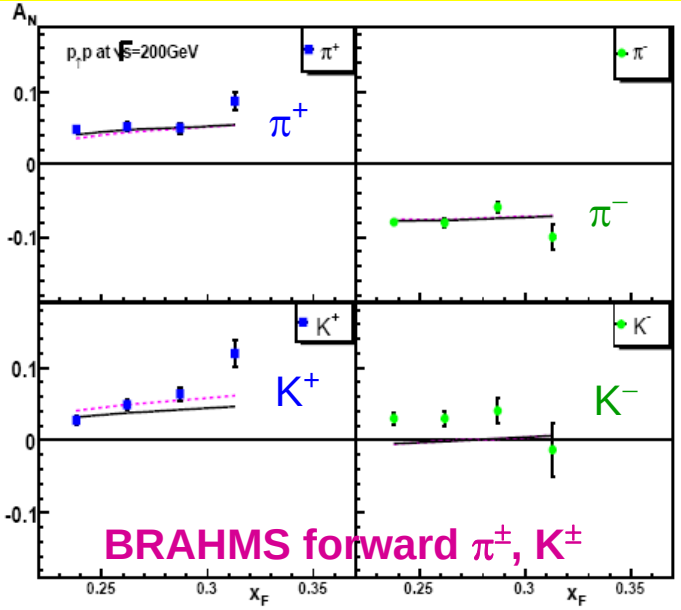
- ***STAR plans to make heavy use of di-jets as well in upcoming A_{LL} analyses to begin constraining $\Delta g(x)$. Also, use FMS to extend transverse asymmetry measurements to di-jets at large rapidity, where inclusive A_N is sizable.***

Backup Slides

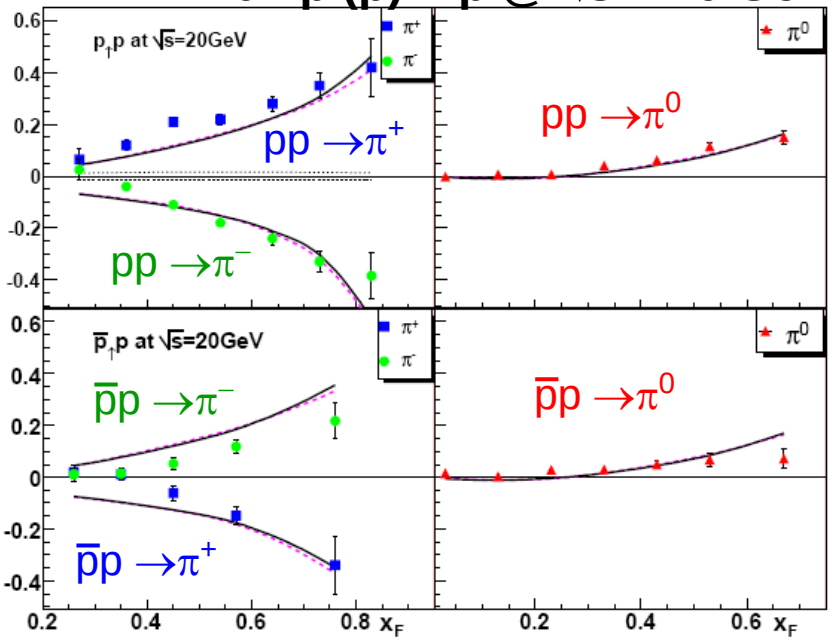
Kouvaris et al. q-g Twist-3 Fits to $\vec{p}$+p → Fwd. Hadron

RHIC $\vec{p}$ + p @ √s = 200 GeV

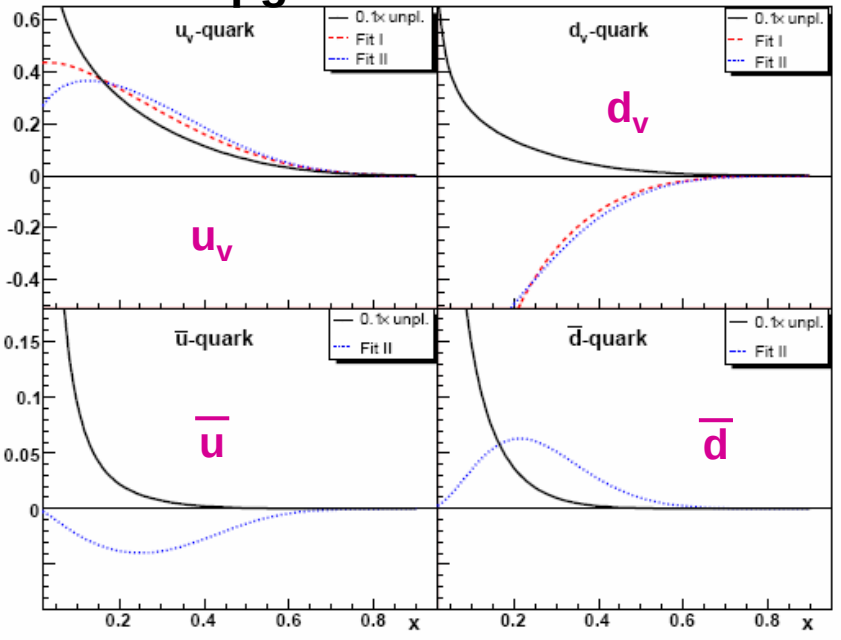




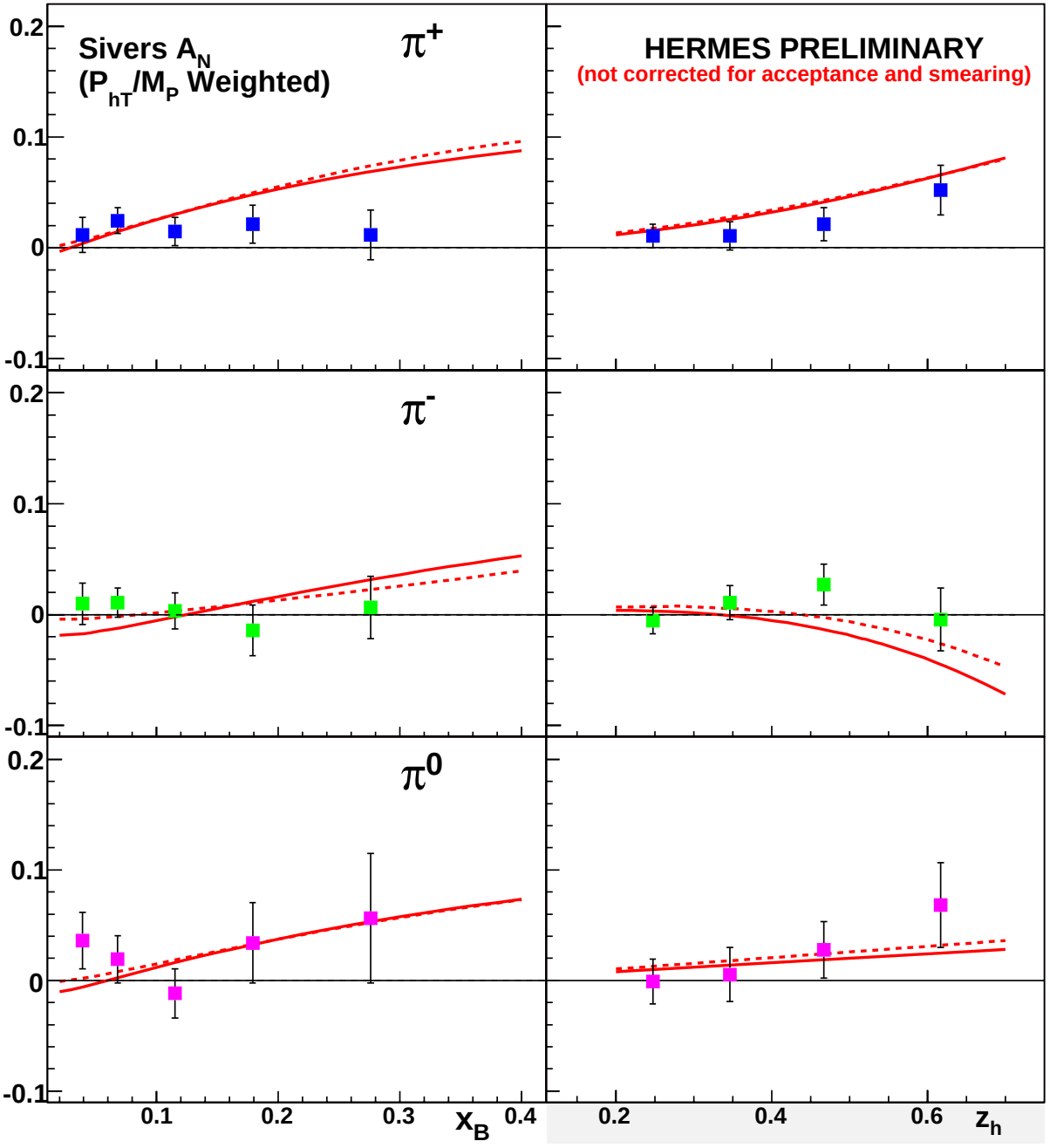
FNAL E704 $\vec{p}$ ($\vec{\bar{p}}$) + p @ √s = 20 GeV



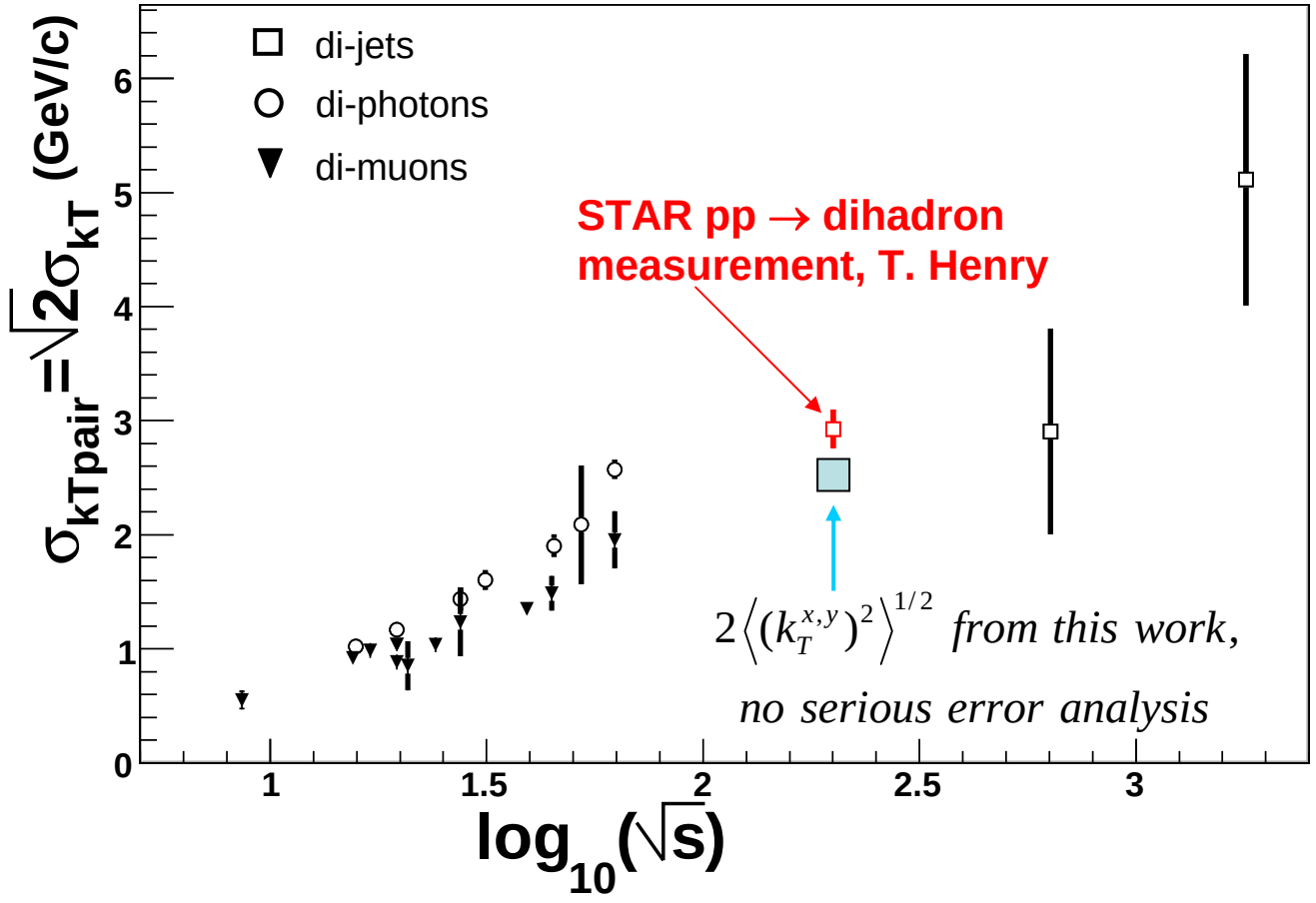
Fitted q-g correlation functions



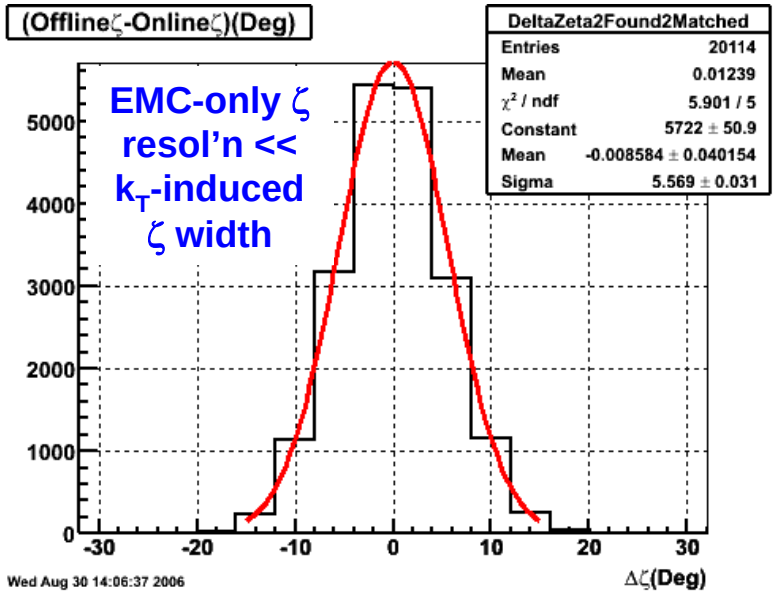
HERMES p_T - Weighted Sivers SSA, Compared To Vogelsang & Yuan Predictions Based on Twist-3 Fits to A_N for $\vec{p}p \to \pi^0 X$

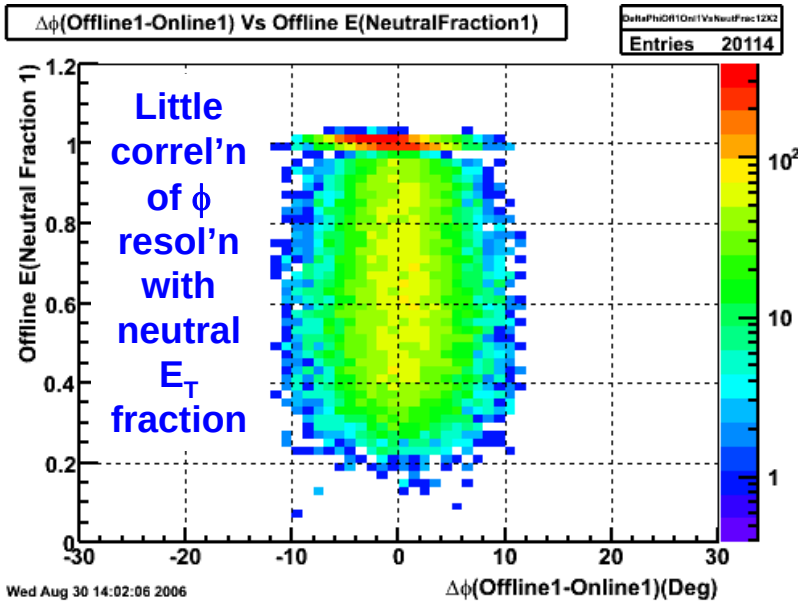


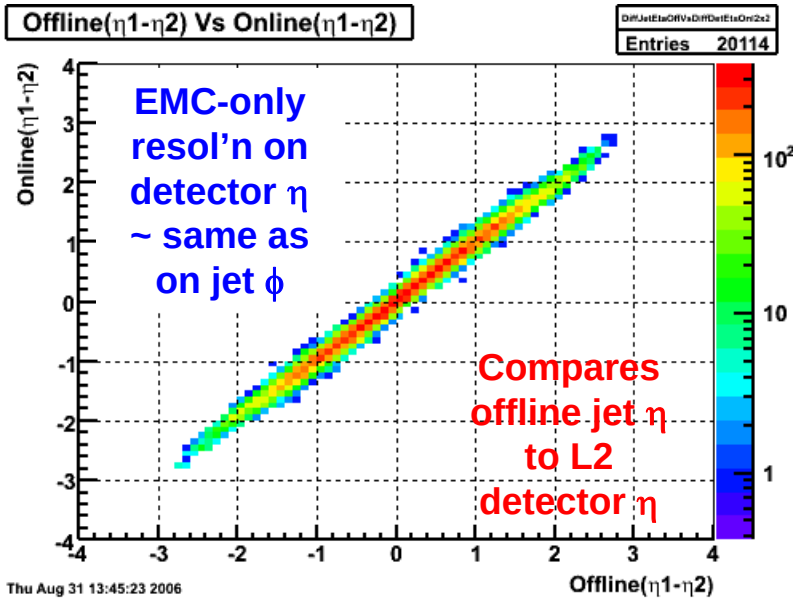
Inferred k_T Distribution Width ~Consistent with World Data for pp Collisions

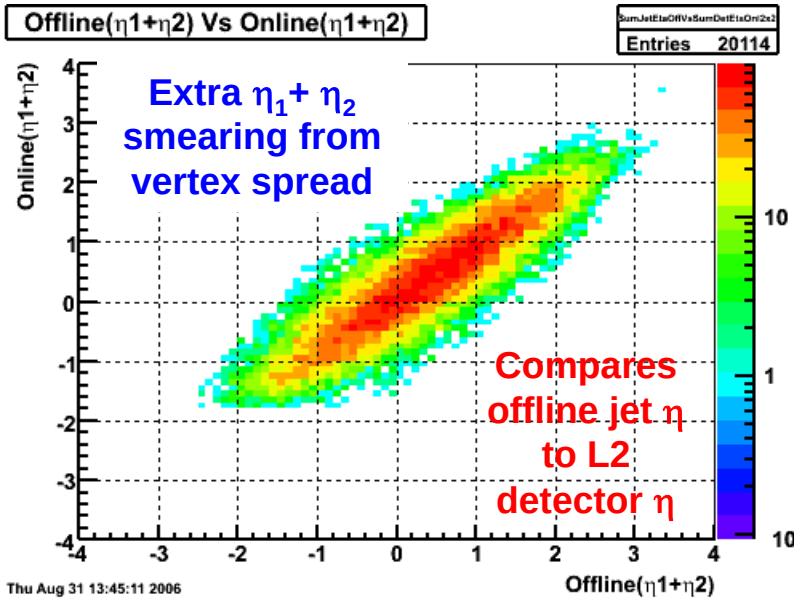


Comparison of Jet Properties from L2 vs. Full Offline Reconstruction: Angle Information

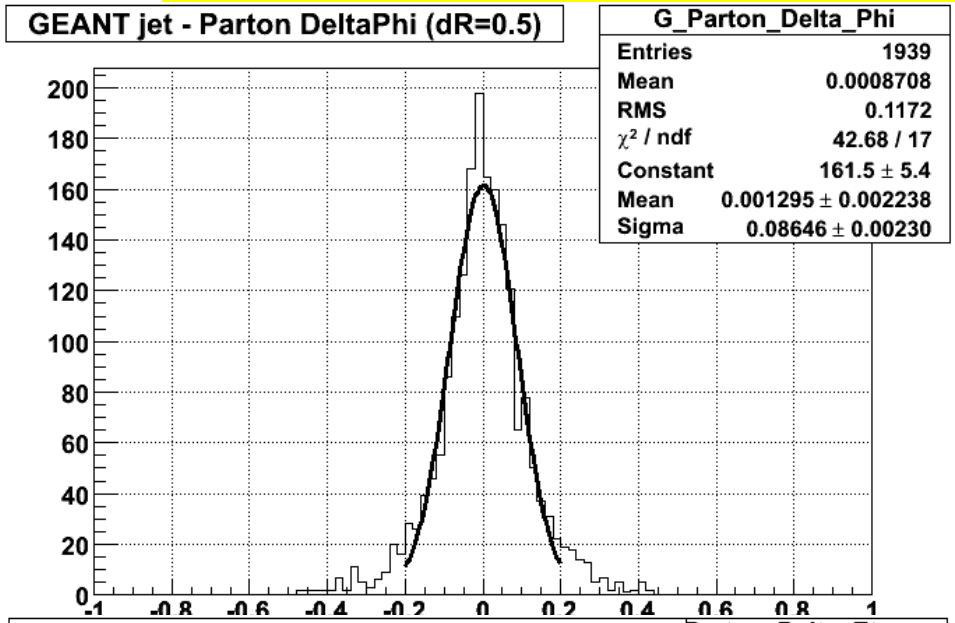


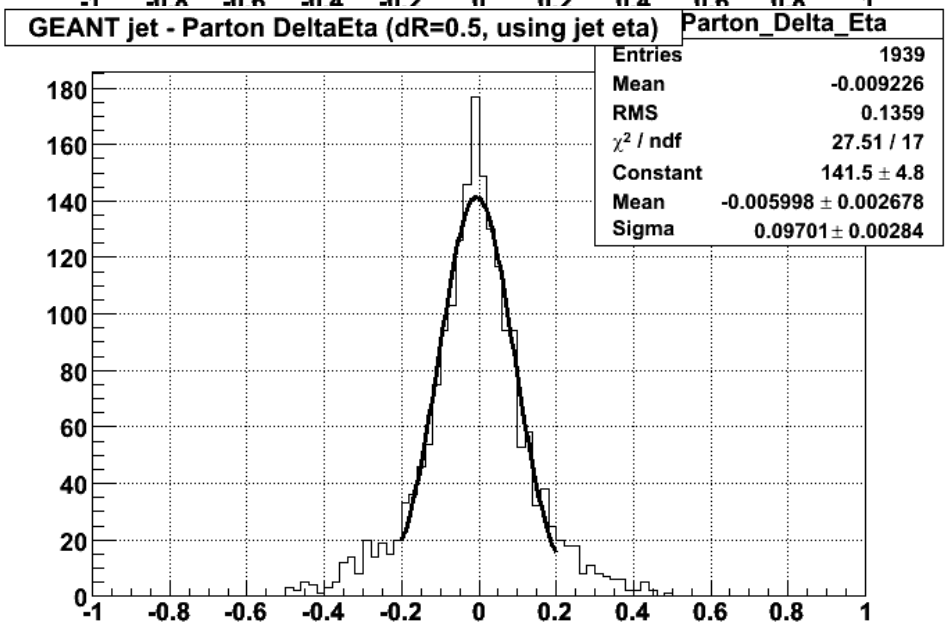






Comparison of Reconstructed Jet Angles to PYTHIA-Generated Parton Angles





- ***Full reconstruction of simulated jets (2005 JP2 trigger and status tables) ⇒ jet angle resolutions, with respect to PYTHIA partons:***

$$\sigma_{1\ jet}^{full\ vs\ parton}(\phi) = 5.0^{\circ};$$

$$\sigma_{1\ jet}^{full\ vs\ parton}(\eta) = 0.10$$

- ***These resolutions should be added in quadrature to those for the difference between full and L2 EMC-only reconstructions:***

$$\sigma_{1\ jet}^{L2\ vs\ full}(\phi) = 3.9^{\circ};$$

$$\sigma_{1\ jet}^{L2\ vs\ full}(\det.\ \eta) = 0.06$$

- ***Net di-jet ζ resolution vs. parton level is then $\sigma(\zeta) \cong 9.0^{\circ}$, compared to intrinsic ζ width ~ 20° from k_T distribution. Measurement resolution may be a bit better in 2006 with fewer EMC "holes".***

2006 p+p run ⇒ STAR measurement of Sivers transverse single-spin asymmetry for di-jets -- shows smaller effects than predicted for observable sensitive to orbital components of parton motion in proton.