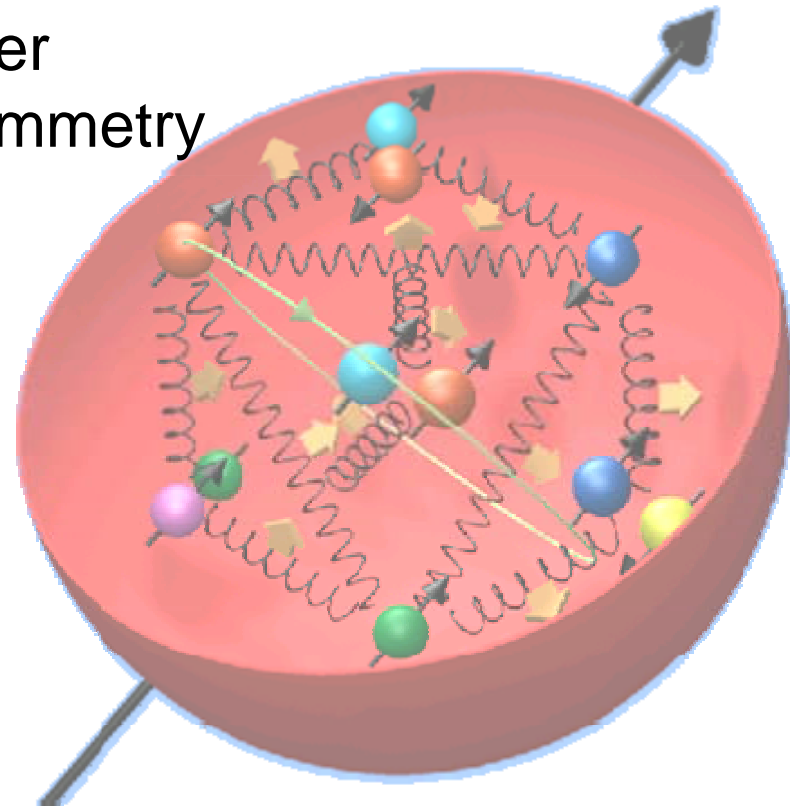# Measurement of Sivers asymmetry
for di-jets at STAR
in polarized p+p collisions at 200GeV

Outline

- Motivation
- Theory predictions
- Principle of measurement, L2 trigger
- Fast M-C model of Sivers spin asymmetry
- Measured SSA
- Conclusions

Jan Balewski, IUCF
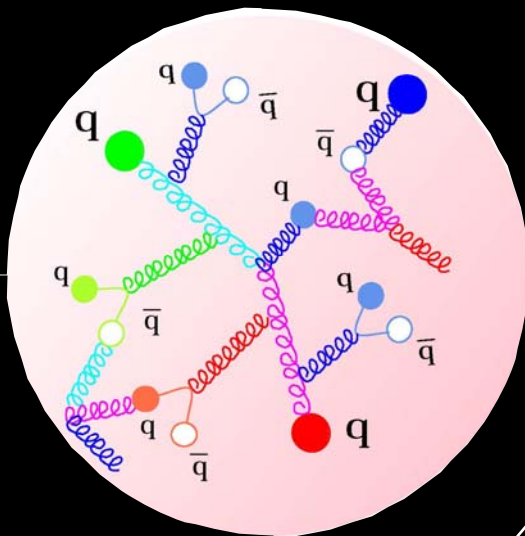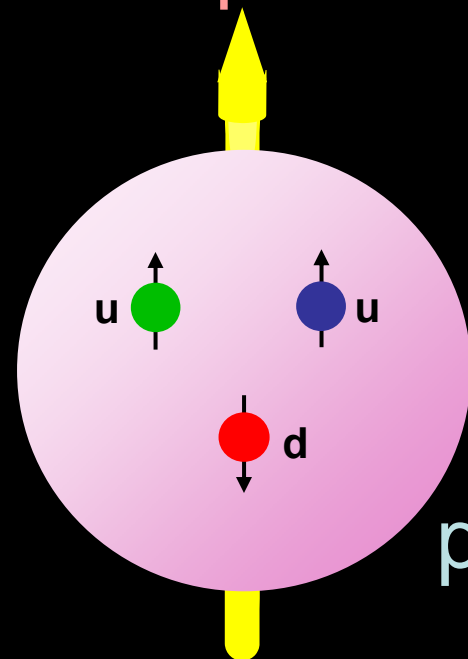**DIS 2007**

April 16-20, 2007
Munich, Germany

Where does the proton's spin come from?

p is made of 2 u and 1d quark

$$S = \tfrac{1}{2} = \Sigma \, S_q$$

Explains magnetic moment
of baryon octet

p

BUT partons have an x distribution and
there are sea quarks and gluons

Check via electron scattering and find
quarks carry only ~1/3 of the proton's spin!

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Jets,pions,A_{LL}
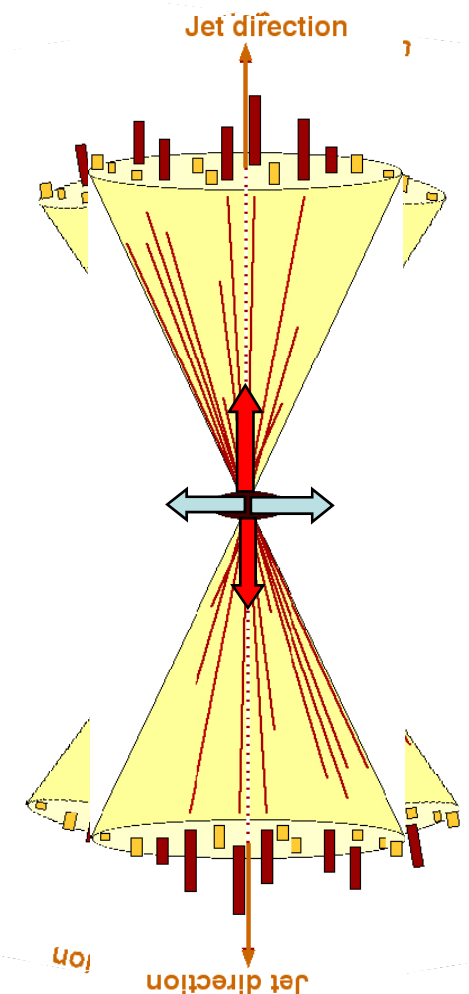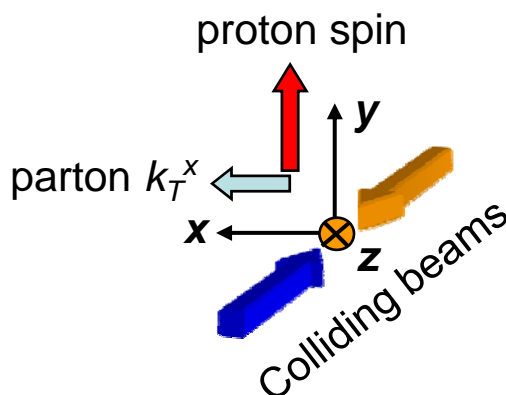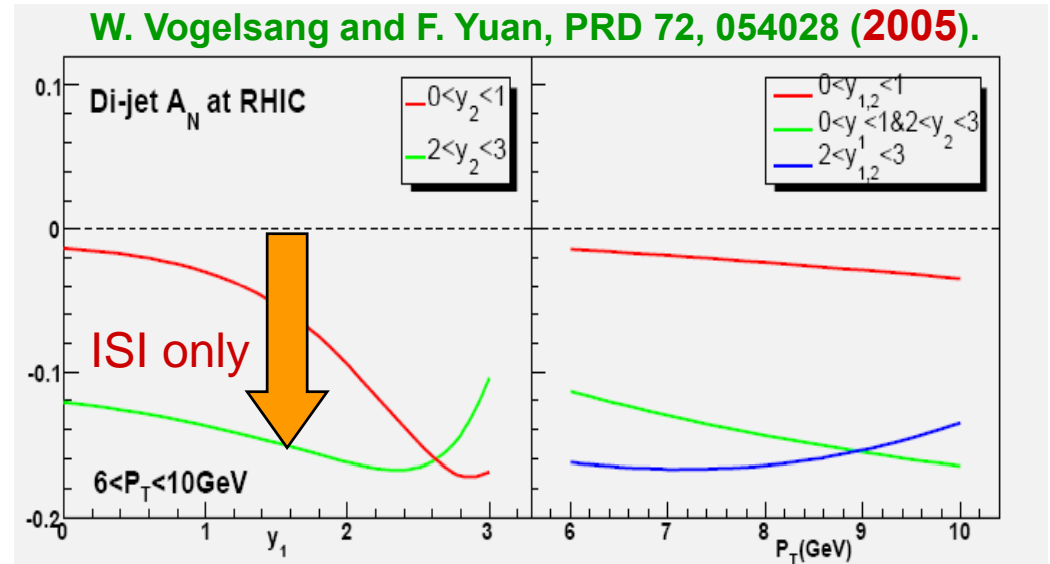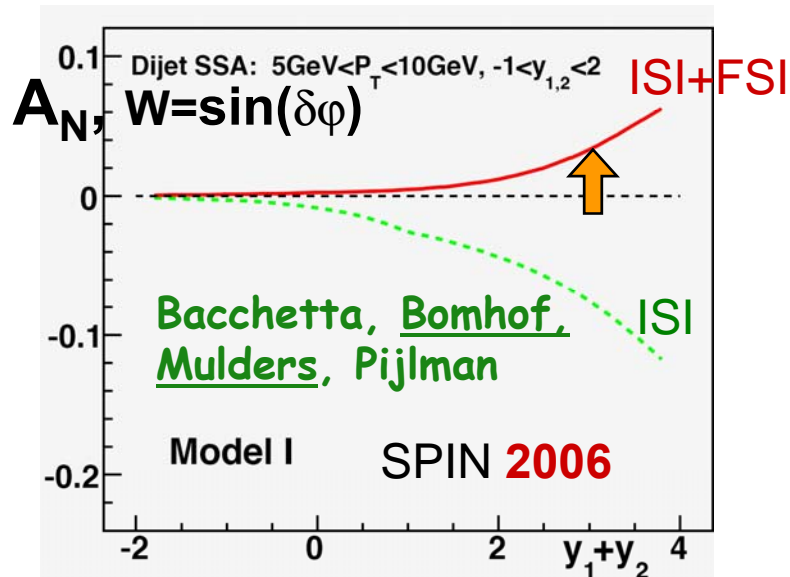
Di-jets, Sivers A_N

➢ **HERMES transverse spin SIDIS asymmetries ⇒ u and d quark Sivers functions of opposite sign, different magnitude.**

➢ **Sivers effect in pp ⇒ spin-dependent sideways boost to di-jets, suggested by Boer & Vogelsang (PRD 69, 094025 (2004))**

➢ **Both beams polarized, $x^{+z} \neq x^{-z} \Rightarrow$ can distinguish q vs. g Sivers effects.**

➢ **Do we observe q Sivers consistent with HERMES? Tests universality.**

➢ **First direct measurement of gluon Sivers effects.**

$$A_N \propto \vec{p} \cdot \left(\vec{k}^{\perp} \times \vec{S}_T \right)$$

proton spin

parton k_T^x

Jet direction

Colliding beams

Jet direction

History of Predictions of Sivers A_N for Di-jets @ STAR

pp → dijet + X
√s = 200 GeV
8 ≤ $p_T(1,2)$ ≤ 12 GeV
|η(1,2)| ≤ 1.0

D. Boer & W. Vogelsang, PRD 69, 094025 (2004) – various models

HERMES SIDIS

A_N, W=sin(δφ)

ISI+FSI

Bacchetta, Bomhof, Mulders, Pijlman

ISI

Model I   SPIN **2006**

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

Di-jet A_N at RHIC

ISI only

6<P_T<10GeV

Triggering Barrel EM Calorimeter $-1 < \eta < 1$

⭐ *STAR* Detector

Lum. Monitor Local Polarim. Beam-Beam Counters $2 < |\eta| < 5$

$\eta = -\ln(\tan(\theta/2))$

$\eta = -1$

$\eta = 0$

$\eta = 2$

+z beam

-z beam

Time Projection Chamber $-2 < \eta < 2$

Triggering Endcap EM Calorimeter $1 < \eta < 2$

Tracking Solenoidal Magnetic Field 5kG

Di-jets at STAR

Jan Balewski (IUCF)

L0 Jet Trigger

+13,…,18

7

8

12

11

9

10

1

2

3

4

jet patch

size: 1x1
$\Delta\eta \times \Delta\phi$

18 Hardwired
1x1 Jet patches →

10^3

10^2

10

1

4   8
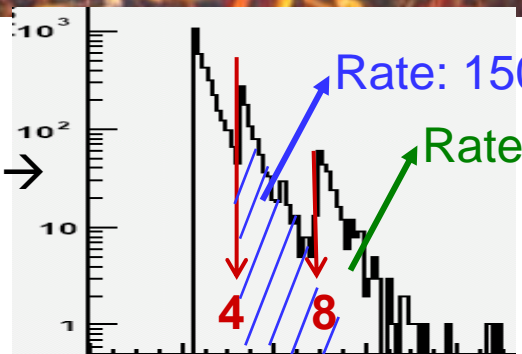
1x1 Jet patch E_T/GeV
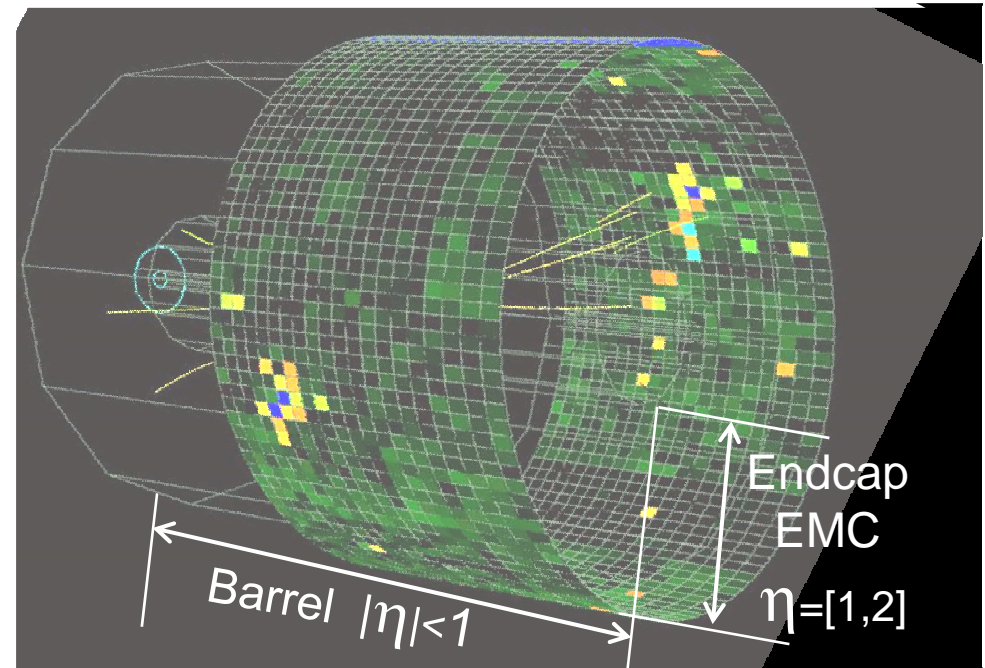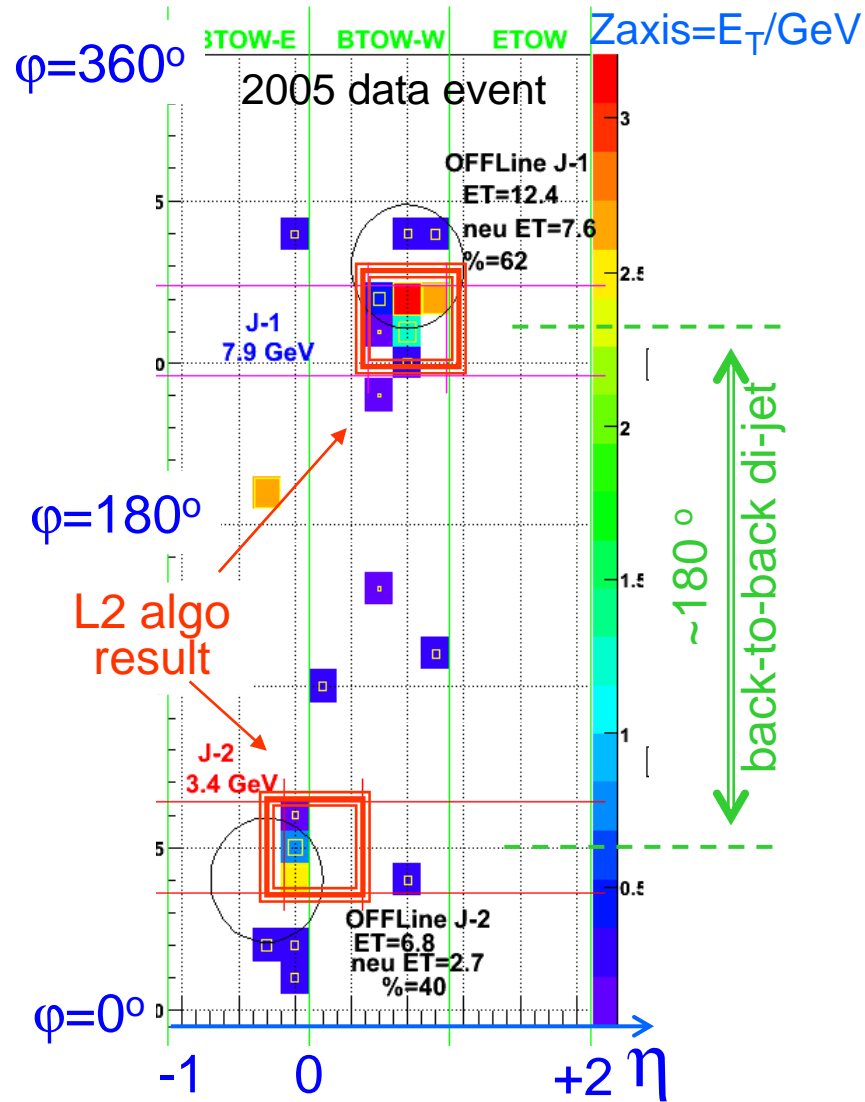
Rate: 150 Hz, needs prescale by 20 or…smarter trigger

Rate: 3 Hz, sent to tape

Luminosity $3*10^{31}$/cm^2/s
Allocated Jet Rate
to tape only 15 Hz

STAR Di-Jet Software Trigger (developed in 2006)

Comparison with off-line → similar

2005 data event

$Zaxis=E_T/GeV$

$\varphi=360^\circ$

BTOW-E   BTOW-W   ETOW

OFFLine J-1
ET=12.4
neu ET=7.6
%=62

J-1
7.9 GeV

$\varphi=180^\circ$

L2 algo
result

~180° back-to-back di-jet

J-2
3.4 GeV

OFFLine J-2
ET=6.8
neu ET=2.7
%=40

$\varphi=0^\circ$

-1   0   +2 η

Endcap
EMC
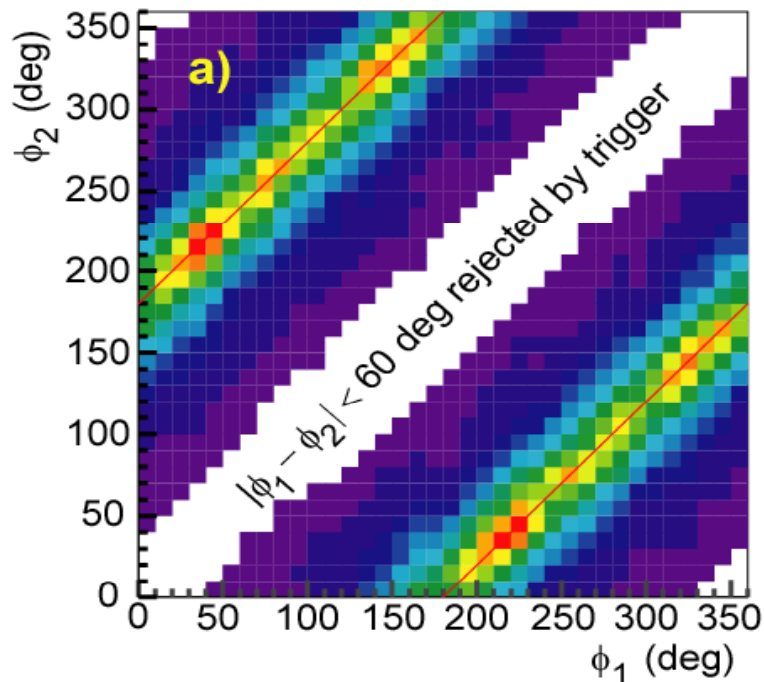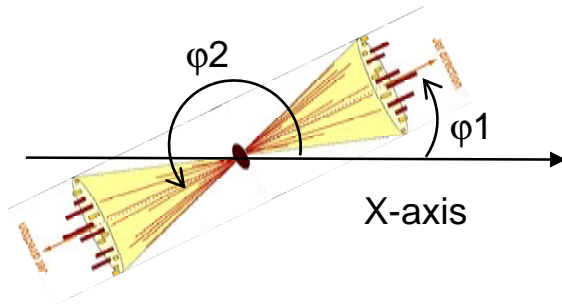η=[1,2]

Barrel $|\eta|<1$

Rates @ STAR
- 9.4 MHz : RHIC bunches collide
- 300 kHz : min-bias collisions trigger BBCs
- 150 Hz : L0 single jet exceeds 4 GeV E_T
  in a **hardwired 1x1** ($\Delta\eta$ x $\Delta\varphi$) EMC patch
- **10 Hz : L2 di-jet** trigger with $E_T > 3.5$ GeV
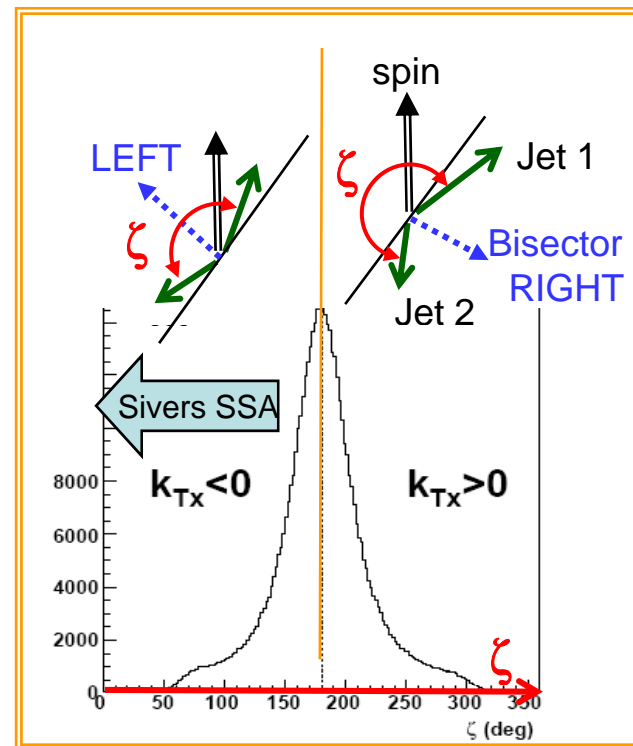 for a pair of back-to-back **sliding 0.6x0.6** patches
  ~80 muSec decision time

Di-jets at STAR   *Jan Balewski (IUCF)*

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

φ2

φ1

X-axis

- **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($\phi_{bisector}$) measures sign of net k_T^x for event

a)

$|\phi_1 - \phi_2| < 60$ deg rejected by trigger

spin

LEFT   ζ   Jet 1
ζ
Bisector
RIGHT
Jet 2
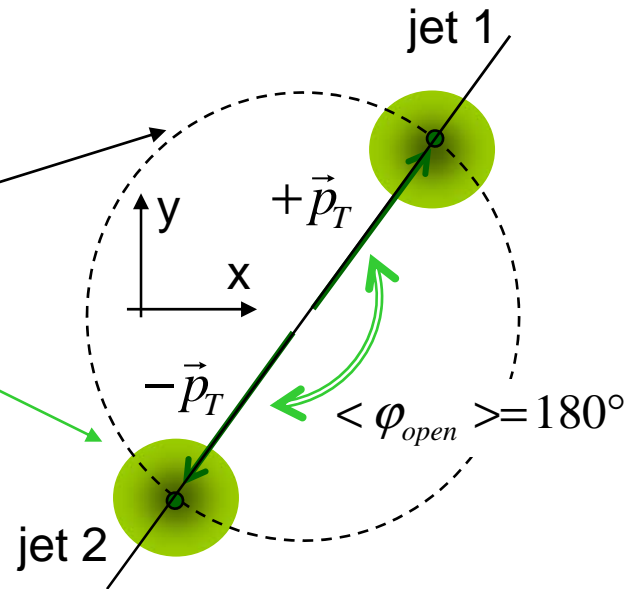
Sivers SSA

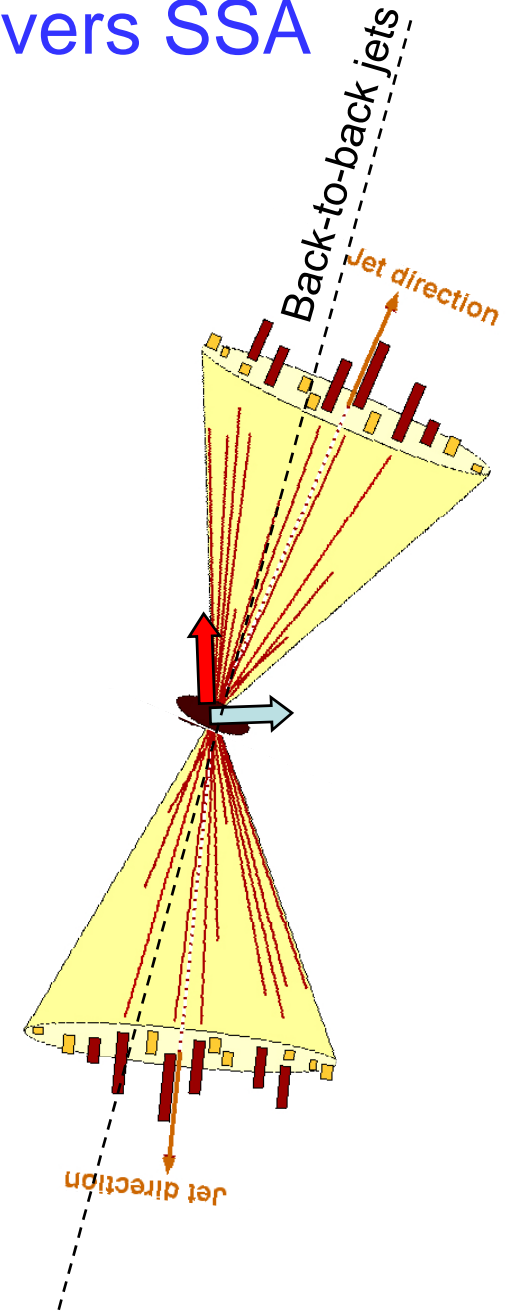$k_{Tx} < 0$ $k_{Tx} > 0$

ζ

ζ (deg)
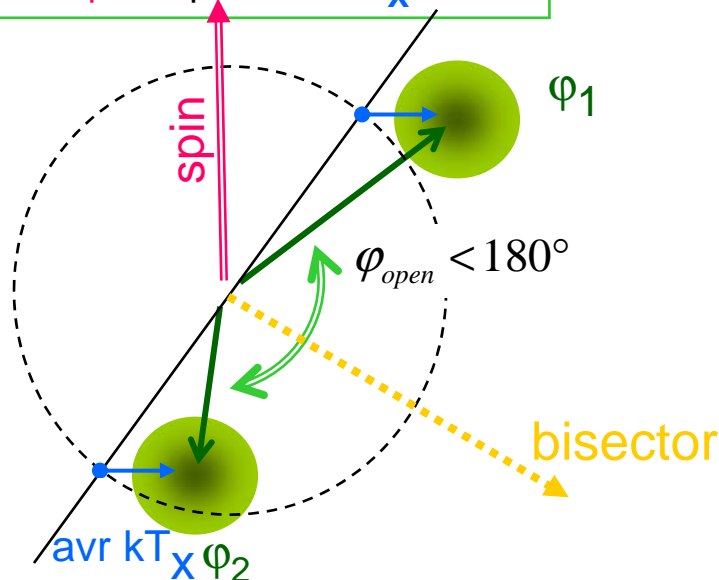
Signed azimuthal opening angle ζ

Fast M-C Captures Essence of Sivers SSA

Model Generator:

- Back-to-back partonic collision yields a di-jet
- intrinsic kT1,2↑ smearing 2D *Gauss*(0,σkTx, σkTy)
- sum kT↑ from both IS
  kT↑=kT1↑+kT2↑
- sum:
  partonic pT↑ + intrinsic kT↑

jet 1

$+\vec{p}_T$

y

x

$-\vec{p}_T$

$<\varphi_{open}>=180°$

jet 2

Add Spin dependent kT$_\mathbf{X}$ offsets

spin

φ_1

$\varphi_{open} <180°$

bisector

avr kT$_\mathbf{X}$ φ_2

Back-to-back jets

Jet direction

Jet direction

Fast M-C Tuned to Real Di-jets

Di-jets at STAR   *Jan Balewski (IUCF)*
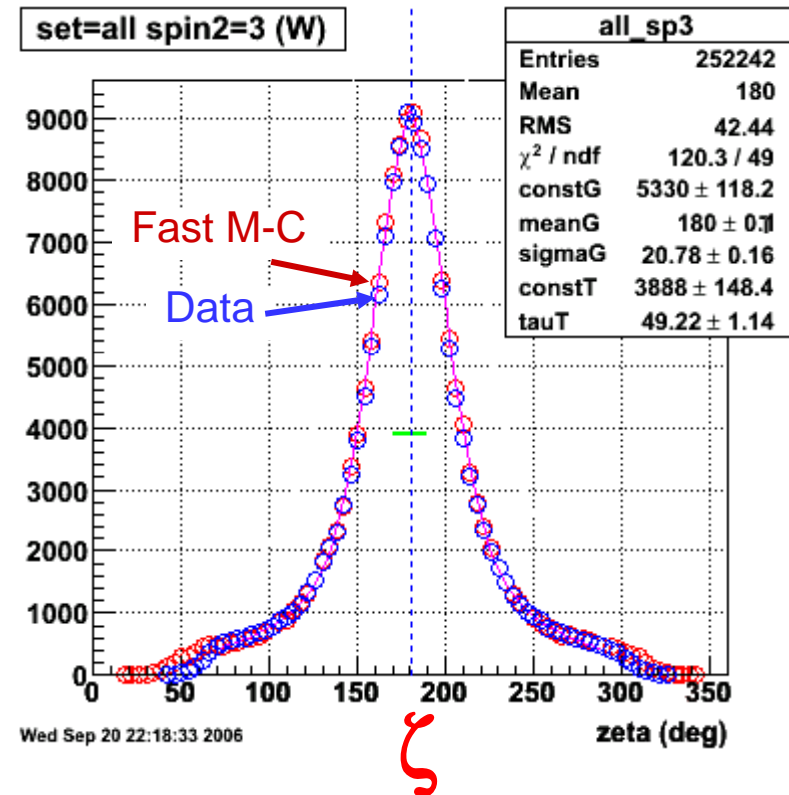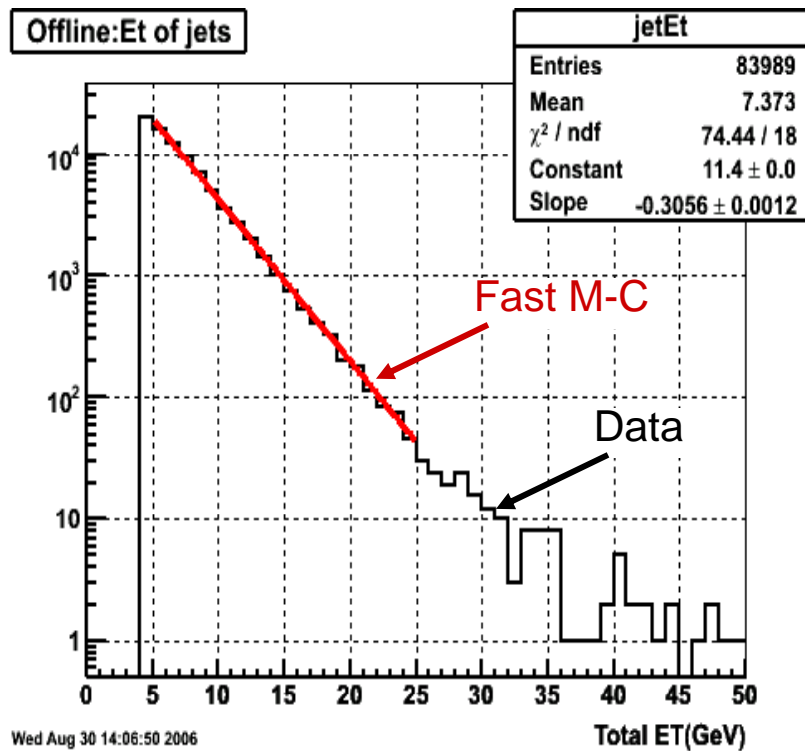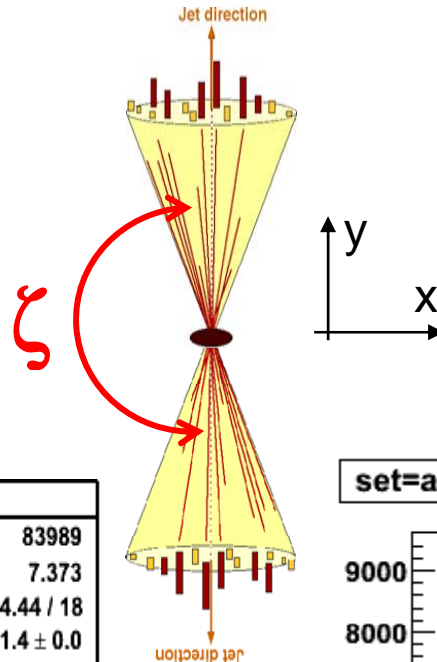
Fast M-C: shift in ζ equivalent to Sivers A_N

Assume non-zero Sivers $<k_T^X> = 100$ MeV/c

'Calibration' of A_N
vs.
amplitude Sivers $<k_T^X>$

Displaced ζ peak
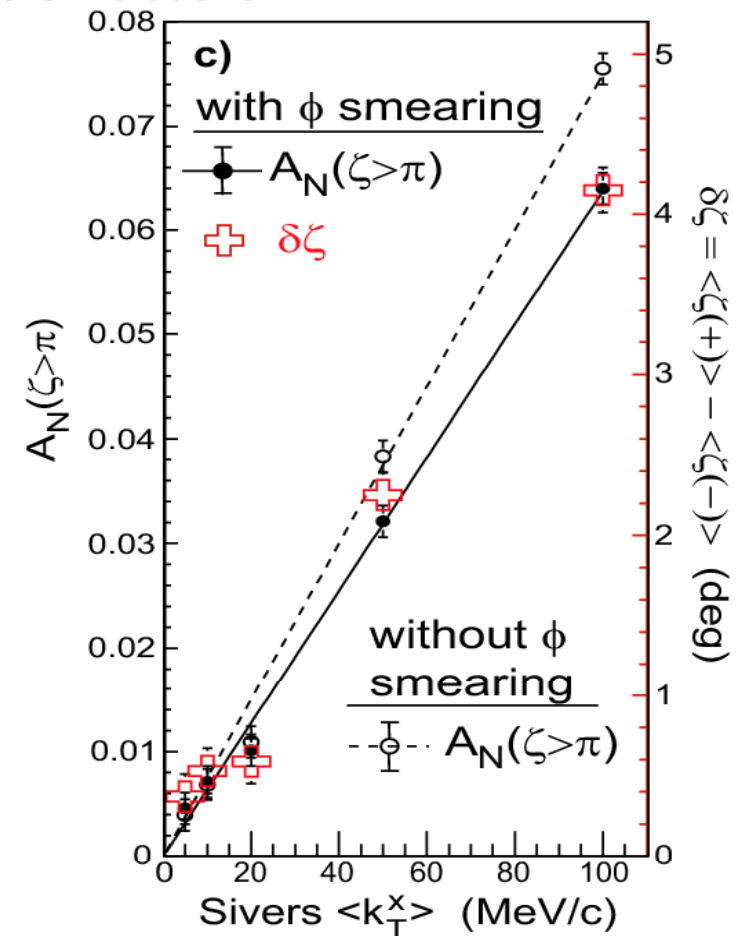for pol=+ and -

SSA A_N results
naturally as
the difference

a) spin +, spin −

b) $A_N(\zeta) = \dfrac{N(+) - N(-)}{N(+) + N(-)}$, $<k_T^X> = 100$ MeV/c

c) with φ smearing, $A_N(\zeta>\pi)$, $\delta\zeta$; without φ smearing, $A_N(\zeta>\pi)$

$A_N(\zeta>\pi)$

ζ (deg)

Sivers $<k_T^X>$ (MeV/c)

$<\zeta(-)-\zeta(+)> = \delta\zeta$ (deg)

Di-jets at STAR   *Jan Balewski (IUCF)*
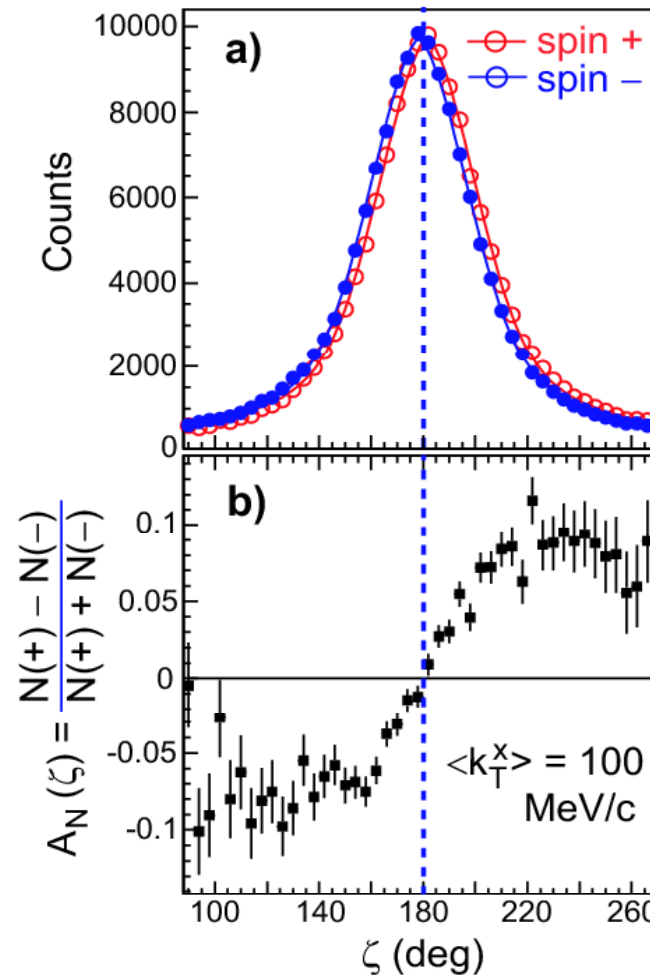
STAR Di-Jet Results Integrated Over Pseudorapidity

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

A_N x 1000 (left plot)

STAR data

Null Tests

STAR data both jets rotated by 90°
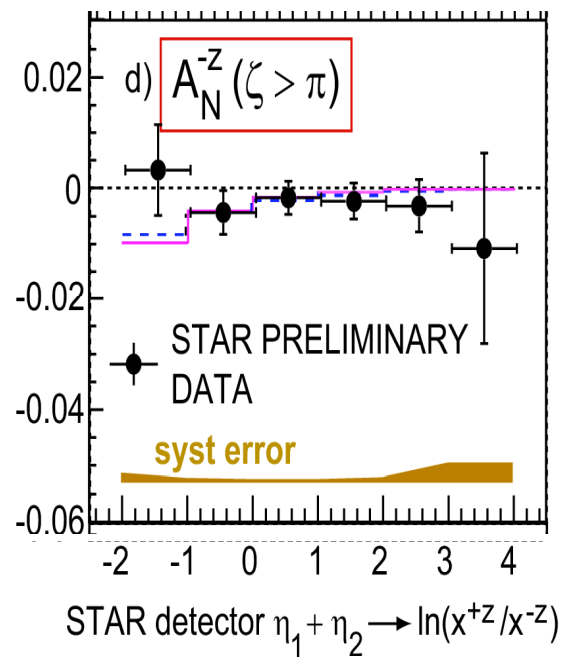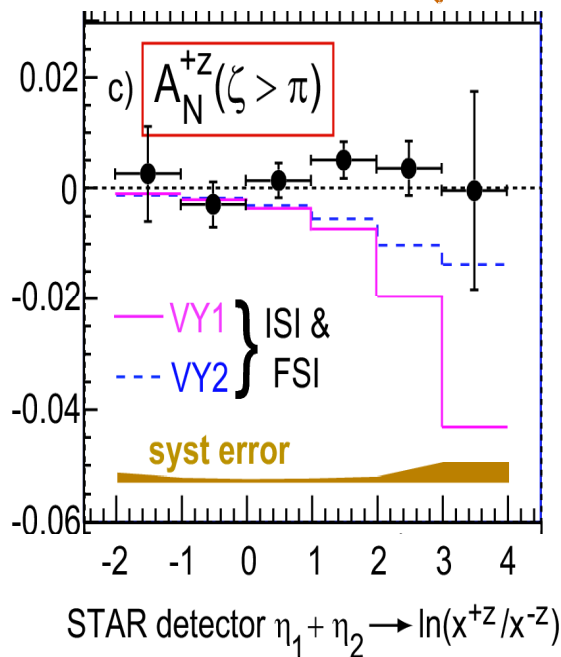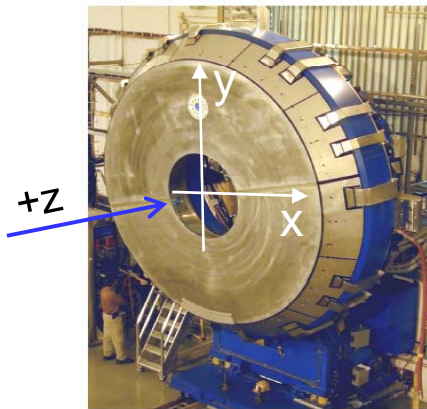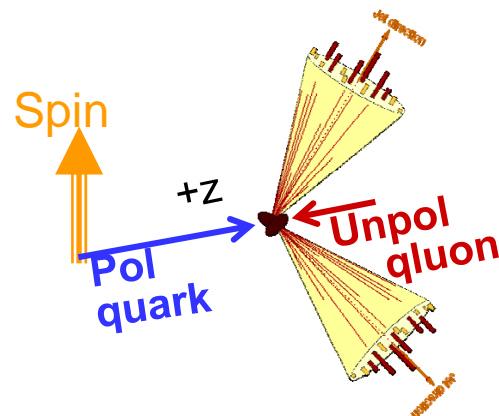
A_N x 1000 (right plot)

A_N^{+z} A_N^{-z} 2-spin

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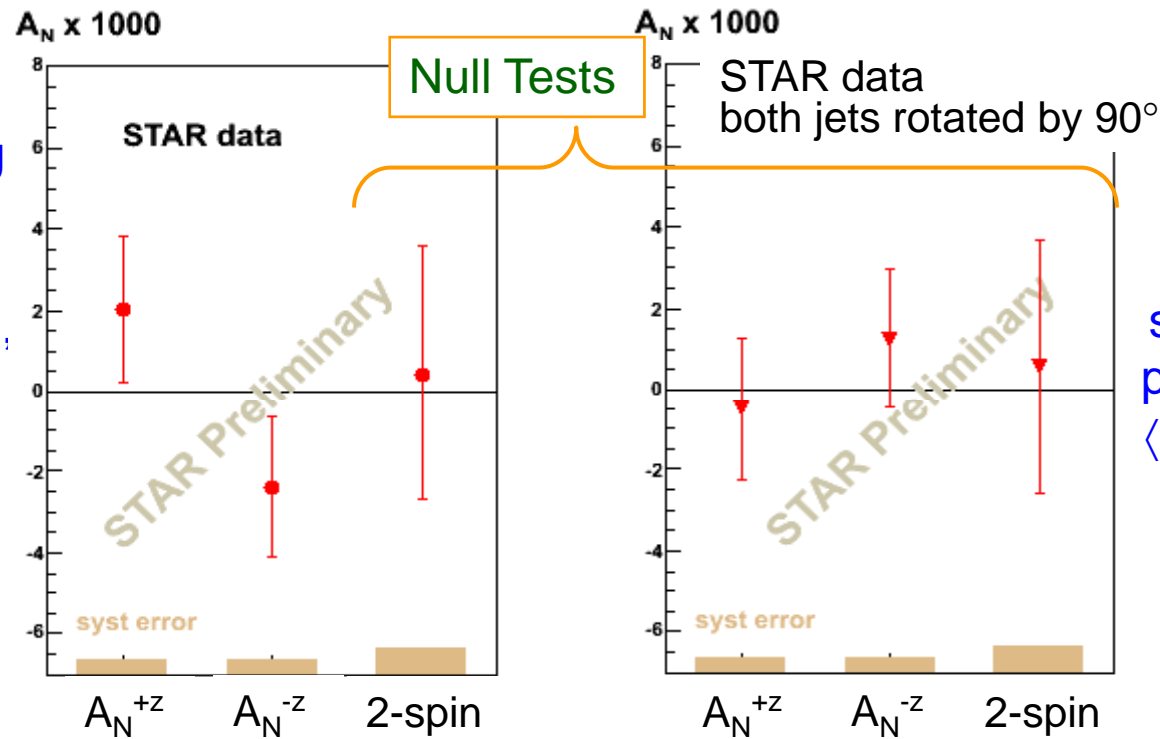
ϕ rotation samples $\langle k_T^y \rangle$, parity-violating $\langle \vec{s}_p \cdot \vec{k}_T \rangle$ correl'n

STAR Preliminary

> *Sivers asymmetries consistent with zero with stat. unc. $= \pm 0.002$*

> *Fast M-C model $\Rightarrow$ sensitivity to Sivers $\langle k_T^x \rangle$ offset $\approx$ few MeV/c $\approx 0.004\ \sigma(k_T^x)$*

> *Systematic uncertainties smaller than statistics*

> *All null tests, including forbidden 2-spin asym. $\propto \cos(\phi_{bisector})$, consistent with zero*

> *Validity of spin-sorting confirmed by reproducing known non-zero A_N for inclusive forward charged-particle production (STAR BBC's)*

Di-jets at STAR   *Jan Balewski (IUCF)*

STAR Results vs. Di-Jet Pseudorapidity Sum

Spin

+z

Pol quark

Unpol gluon

+z

y

x

c) $A_N^{+z}(\zeta > \pi)$

0.02

0

-0.02

-0.04

-0.06

— VY1 } ISI &
--- VY2 } FSI

syst error

-2 -1 0 1 2 3 4

STAR detector $\eta_1 + \eta_2 \longrightarrow \ln(x^{+z}/x^{-z})$

d) $A_N^{-z}(\zeta > \pi)$

0.02

0

-0.02

-0.04

-0.06

STAR PRELIMINARY DATA

syst error

-2 -1 0 1 2 3 4

STAR detector $\eta_1 + \eta_2 \longrightarrow \ln(x^{+z}/x^{-z})$

V&Y calcs. include:

- no hadronization

- $5 < p_T^{parton} < 10$ GeV/c

- STAR η acceptance

- HERMES-fitted q Sivers

- no gluon Sivers fcns.

They predict:
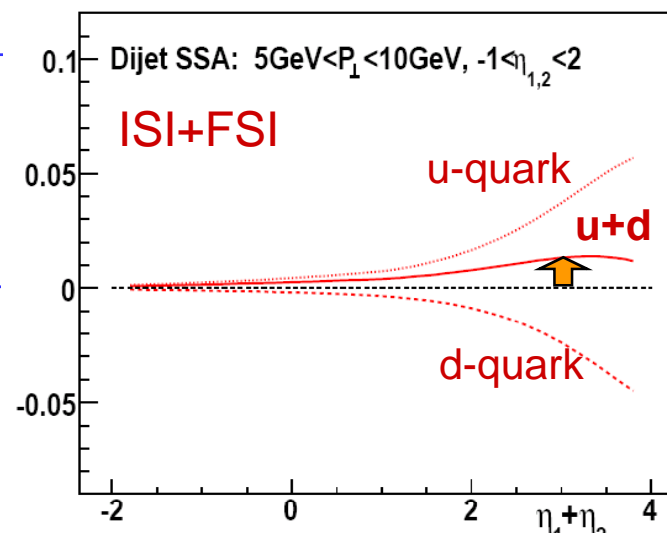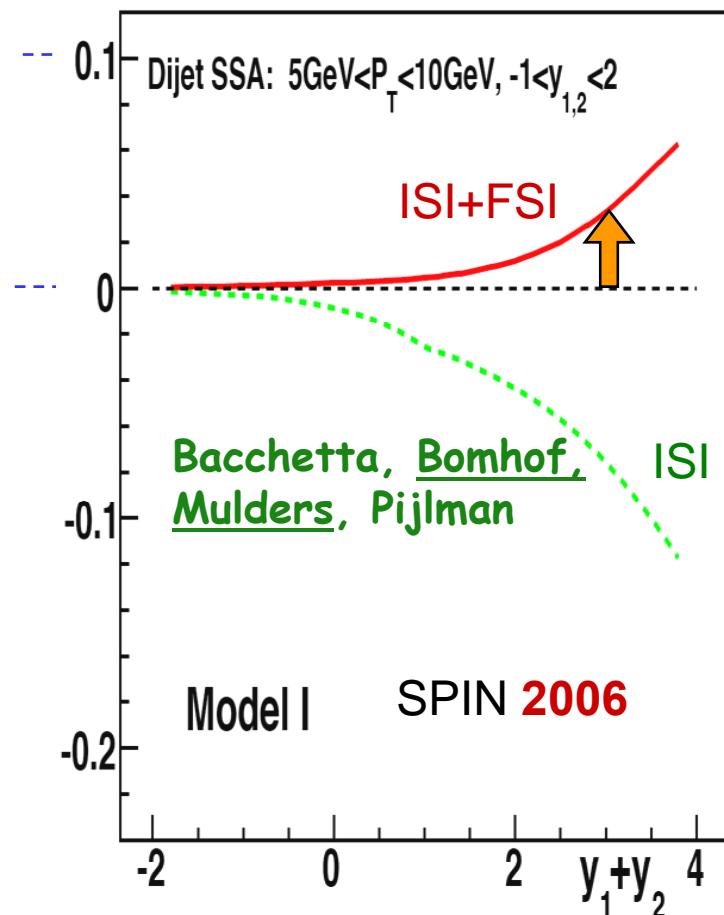
- $A_N \sim A_N^{HERMES}$ where q dominates, if only ISI included (à la Drell-Yan)

- A_N sign reversal, factor ~2 reduction when gauge links include FSI as well

Reverse V&Y signs here to obey Madison convention!

STAR A_N all consistent with zero ⇒ both quark and gluon Sivers effects ~order of magnitude smaller in $\vec{p}p \to$ di-jets than SIDIS quark Sivers asym.!

Theory Few Months Later

A_N , yields weighted w/ $|\sin(\zeta)|$

Left plot:
Dijet SSA: 5GeV<P_T<10GeV, -1<$y_{1,2}$<2
- ISI+FSI
- ISI
- Bacchetta, Bomhof, Mulders, Pijlman
- Model I
- SPIN **2006**
- axes: y_1+y_2

Right plot:
Dijet SSA: 5GeV<$P_\perp$<10GeV, -1<$\eta_{1,2}$<2
- ISI+FSI
- u-quark
- **u+d**
- d-quark
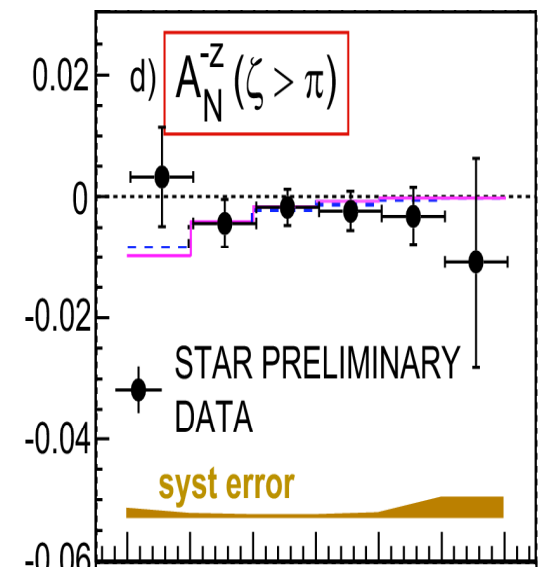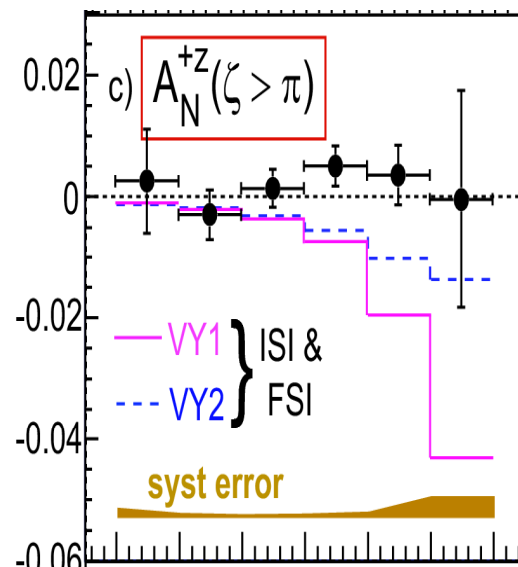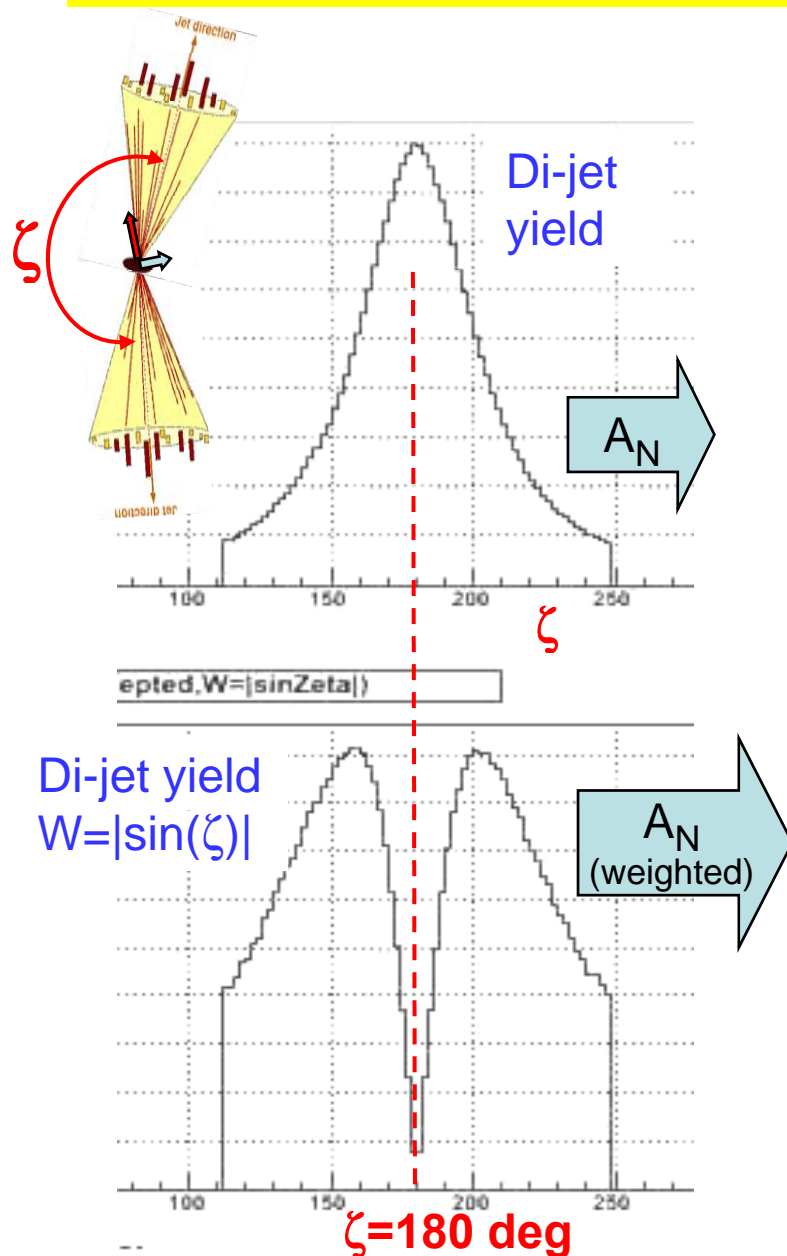- Bomhof, Mulders, Vogelsang, Yuan, hep-ph/0701277
- 31 Jan **2007**
- axes: $\eta_1+\eta_2$

Delicate cancellations of Sivers fcn for:
- u and d quarks and
- ISI and FSI

reconciles theory & experiment

Di-jet yield

A_N

ζ

epted,W=|sinZeta|)

Di-jet yield
W=|sin(ζ)|

A_N
(weighted)

ζ=180 deg

c) $A_N^{+z}(\zeta > \pi)$

— VY1 } ISI &
--- VY2 } FSI

syst error

d) $A_N^{-z}(\zeta > \pi)$

STAR PRELIMINARY DATA

syst error

Theory calculation for A_N more robust,
better characterization of initial state k_T.
Describes forward inclusive pi0's and
analogous k_T-weighted
SIDIS asymmetries moderately well

STAR detector $\eta_1 + \eta_2 \rightarrow \ln(x^{+z}/x^{-z})$

STAR detector $\eta_1 + \eta_2 \rightarrow \ln(x^{+z}/x^{-z})$

Summary & Outlook

• STAR acquired 2.6M di-jet events w/ transversely polarized proton beams at sqrt(s)=200 GeV

•Experimental values of Sivers SSA for quarks & gluons is consistent w/ zero +/-0.002

•Early large predictions tuned to non-zero HERMES quark Sivers SSA has been reduced due to accounting for cancellation between ISI & FSI and u- and d-quarks Sivers fcns.
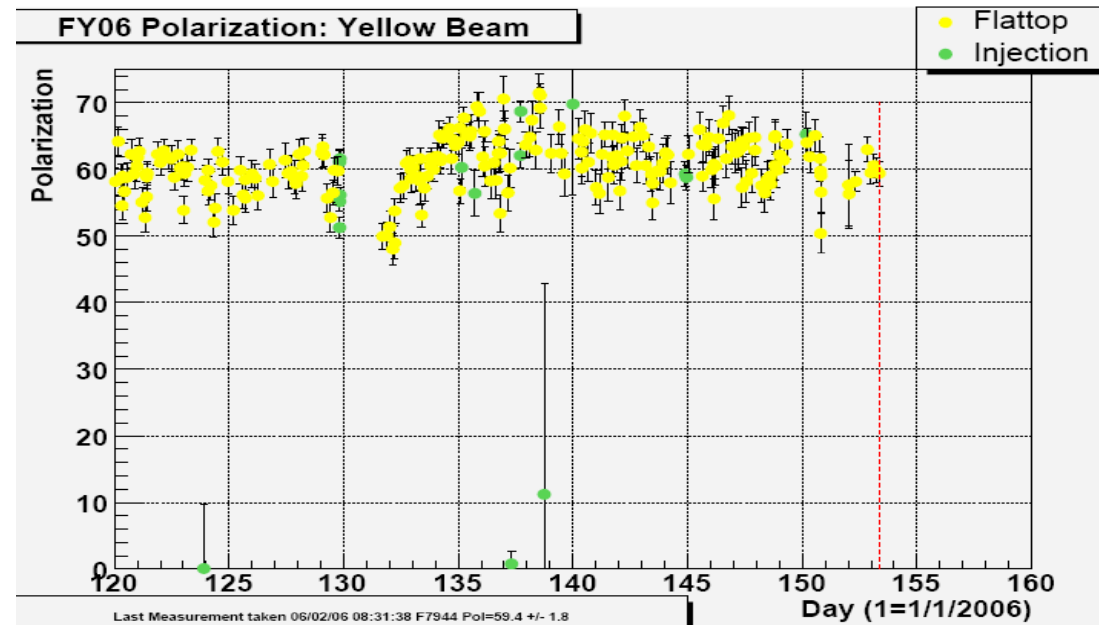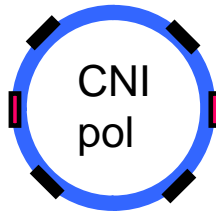
•More detailed analysis is ongoing ….

Full jet reco : charge tracks & EM
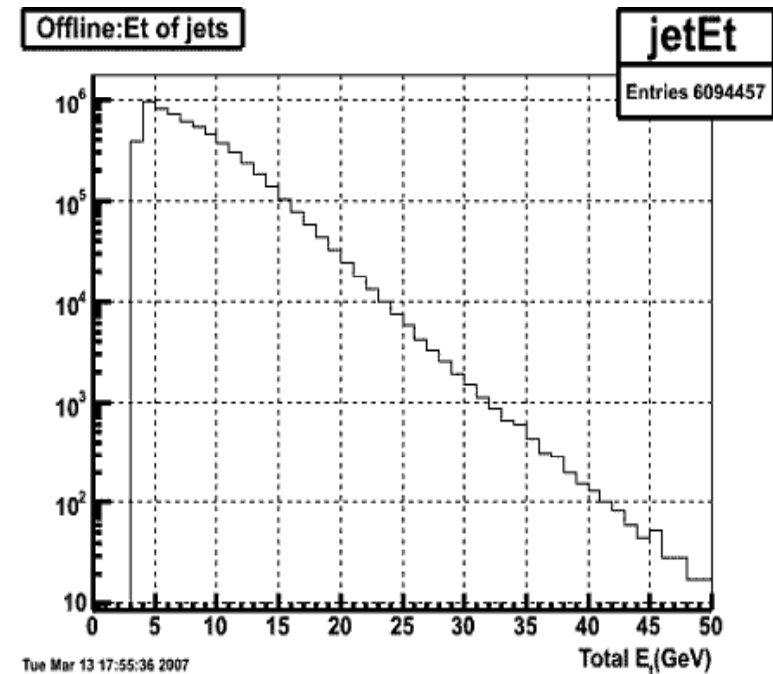
•2x larger statistics
    Include HT & JP1 triggers
• energy dependence
• quark/gluon enhancement
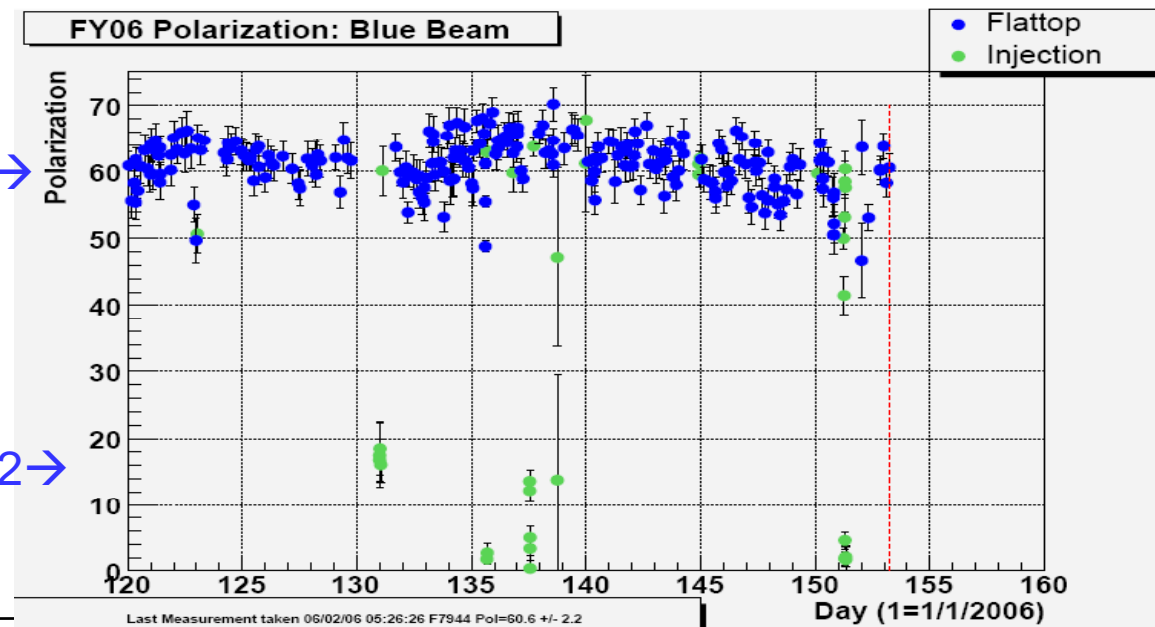• u-,d-quark flavored jets

Di-jets at STAR   *Jan Balewski (IUCF)*

Backup Slides

Di-jets at STAR *Jan Balewski (IUCF)*

CNI Measured On-line 60%+ Polarization at RHIC in 2006

☺ Year 2006→

☹ Year 2002→

2006 pp200 Transverse Run @ RHIC

April 6

May 9

WCM intensity

`./wrk/data/blue-wcm-wcmbeam.dat" using 2:3`
`./wrk/data/yell-wcm-wcmbeam.dat" using 2:3`

STAR magnet incident (~10 days)

spin Info problem

good data

good STAR data

days in 2006

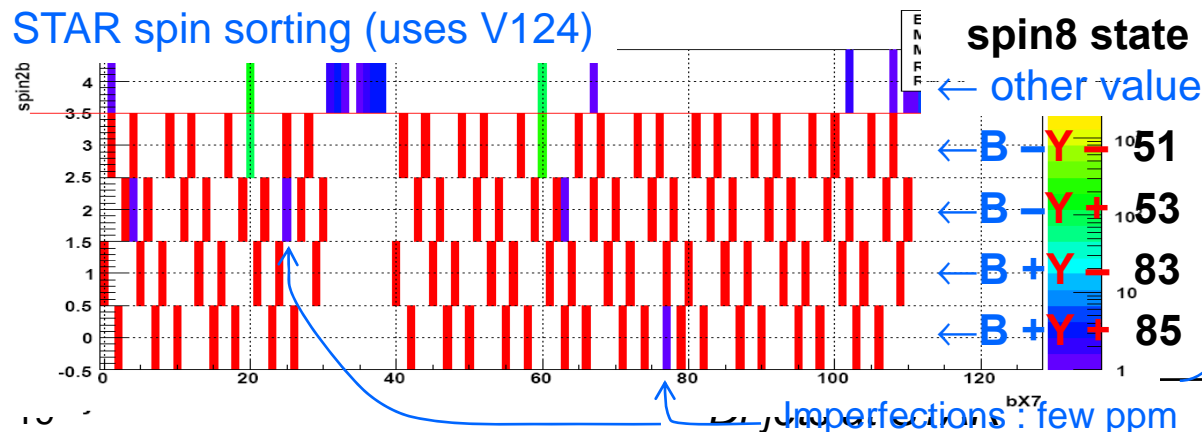
STAR event count

Entries 871588
Integral 5.574e+05

Blue Abort gap

Yellow Abort gap

Yellow bXing (uses revTick)
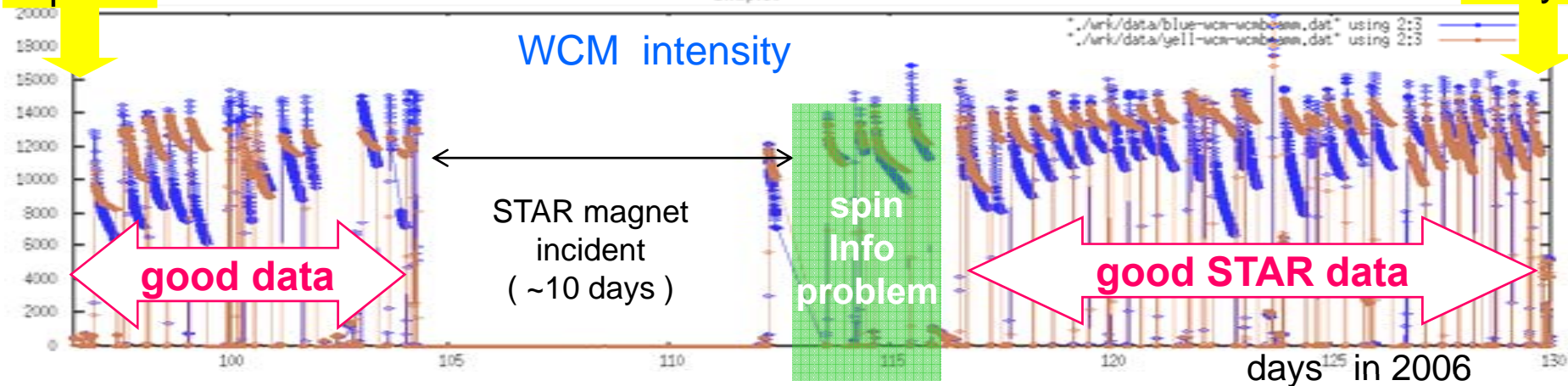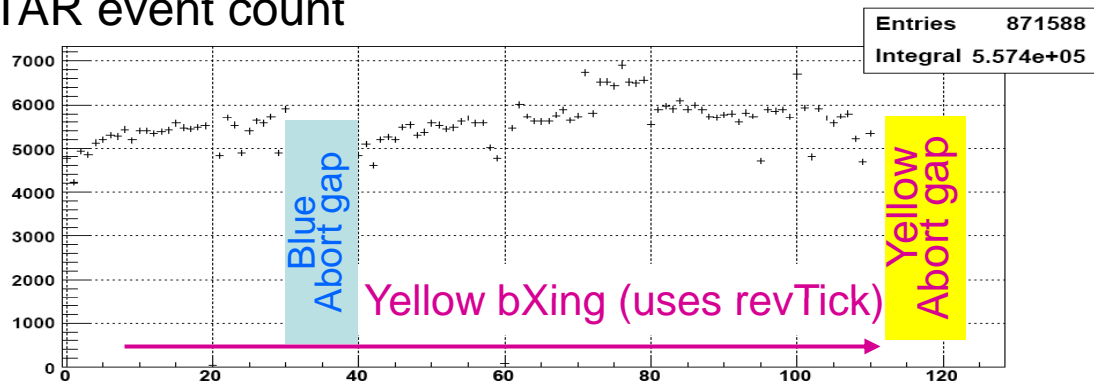
Available STAR events:
- both TPC & EMC active
- few M 1-jet trig, $E_T > 8.0$ GeV
- 3M di-jet trig, $2 \times E_T > 3.7$ GeV
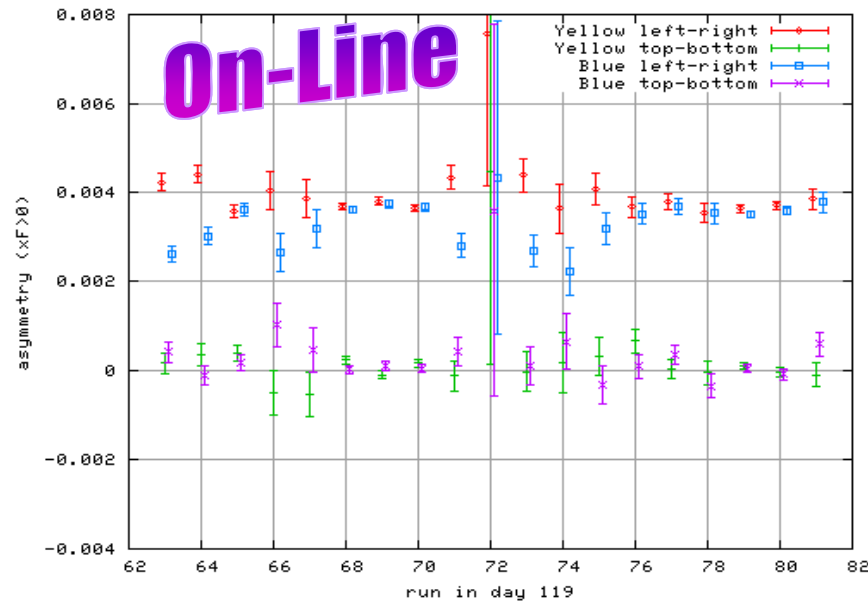- few M di-jet w/o TPC
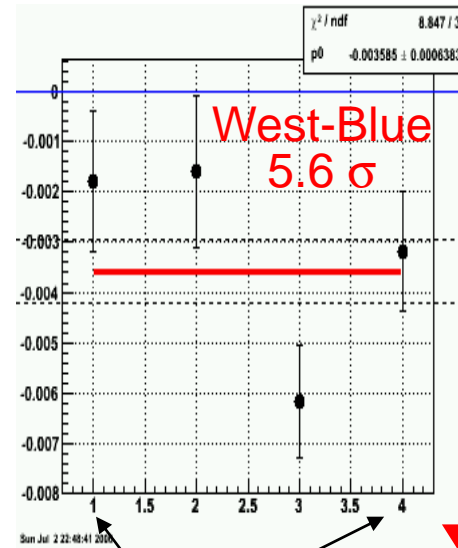 (crude run QA)

STAR spin sorting (uses V124)

spin2b

spin8 state

← other value

← B − Y − 51
← B − Y + 53
← B + Y − 83
← B + Y + 85

bX7

Example of di-jet events for one of 4 RHIC fill polarization patterns { \\ , \\+1, // , //+1 }

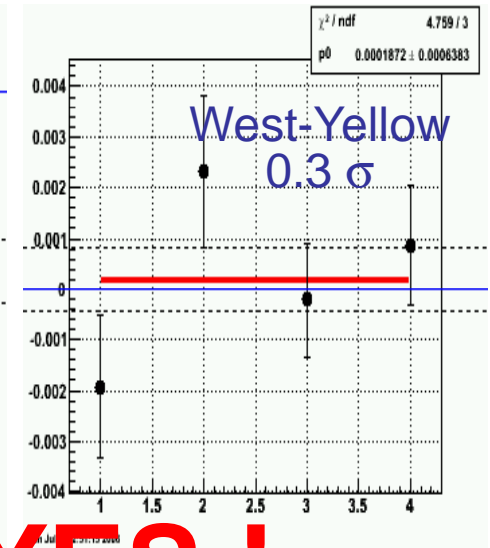D. Imperfections : few ppm

Jan Balewski (IUCF)

Is the Di-jet Spin Sorting Correct?
(Find MinB BBC SSA)

12M MinB evens

Off-Line

On-Line

Pol patt 1,2,3,4

West-Blue
5.6 σ

West-Yellow
0.3 σ

East-Blue
0.1 σ

East-Yellow
5.8 σ

YES !

Top view

East BBC   **West** BBC

Blue beam

6   **2**

2   **6**

Blue-**Left**

Yellow-**Left**

Yellow beam

X

Y

+Z

Di-jets at STAR

Jan Balewski (IUCF)
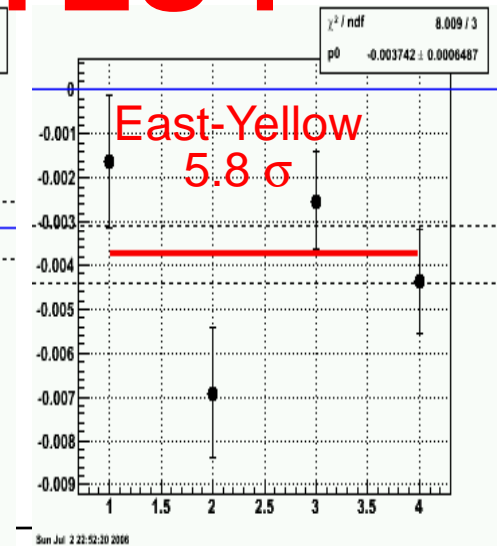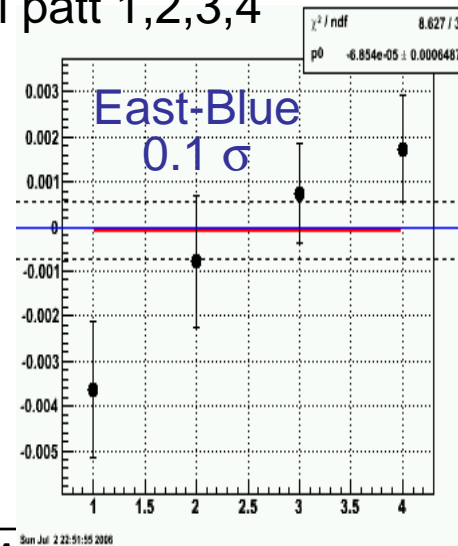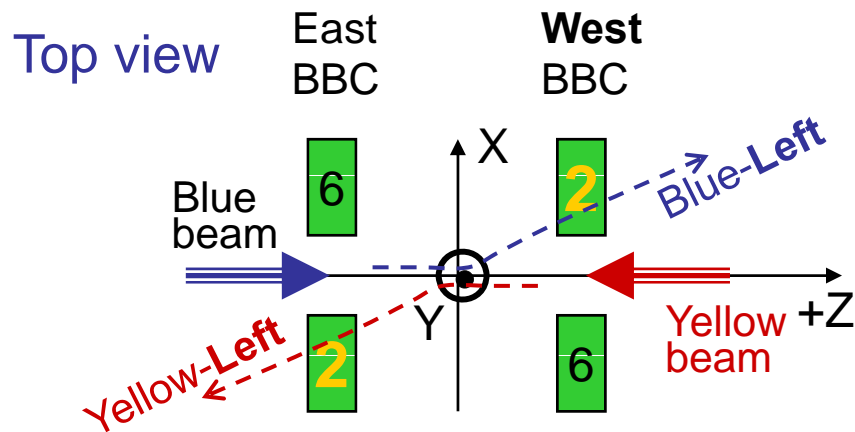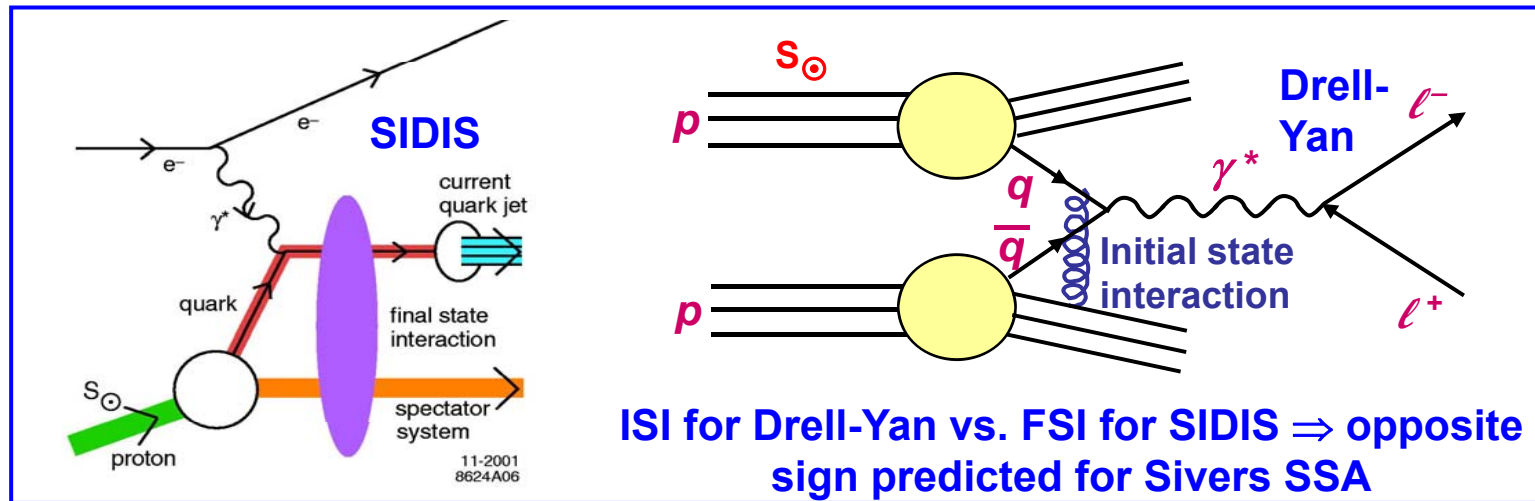
Theory - exp't discrepancy raises questions!

Are observed di-jet Sivers SSA much smaller than predictions because:

➢ *ISI & FSI both important in $\vec{p}p \rightarrow$ jets and tend to cancel?*

SIDIS

current quark jet

final state interaction

spectator system

quark

proton

$S_\odot$

11-2001
8624A06

$S_\odot$

p

p

q $\bar{q}$

Initial state interaction

γ^*

Drell-Yan

ℓ^-

ℓ^+

ISI for Drell-Yan vs. FSI for SIDIS ⇒ opposite sign predicted for Sivers SSA

➢ *Need $\bar{q}$ Sivers or different q Sivers x, k_T - shapes in HERMES fits?*

➢ *Contributions from Collins fragmentation asymmetries in incompletely reconstructed jets conspire to cancel Sivers asymmetries for quarks, while gluon Sivers functions naturally small?*

➢ *If ISI / FSI cancel at mid-rapidity, does their balance change at high η to yield sizable Sivers contribution to observed $\vec{p}p \rightarrow \pi^0 X$ SSA?*