Transverse polarization results

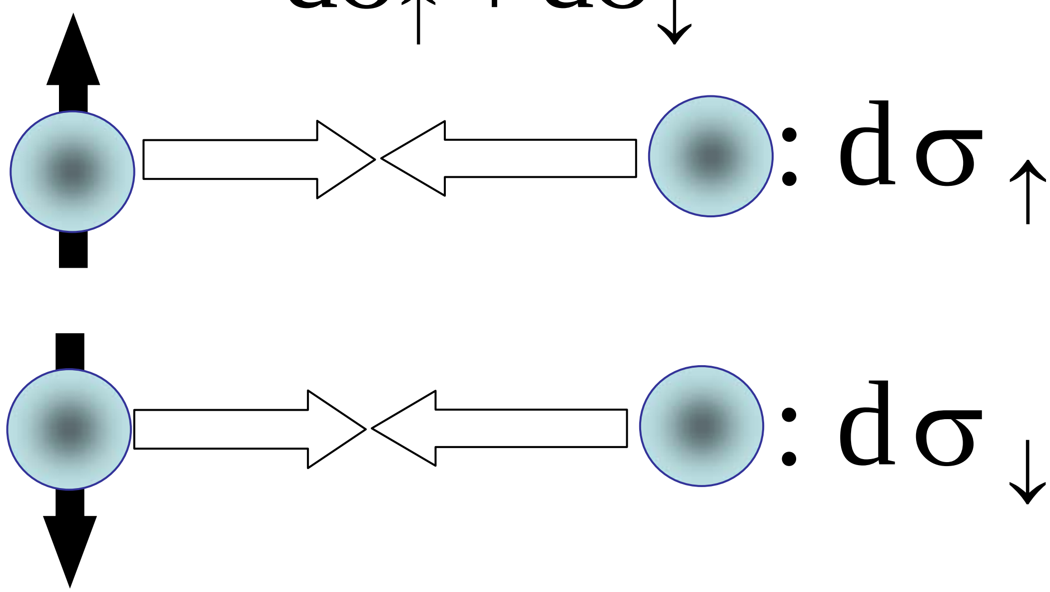
Hiromi Okada (BNL)

1. Introduction
   - What is Single Spin Asymmetry (SSA) ?
   - Why SSA is interesting ?
   - Why SSA at RHIC
2. Experimental SSA results at RHIC
   - STAR (Inclusive π^0 and di-jet)
   - PHENIX (Inclusive π^0, $h^\pm$, J/ψ)
   - BRAHMS (inclusive $\pi^\pm$, $K^\pm$, p, pbar)
3. Summary and next

What is **SSA** (Single-transverse-Spin Asymmetry) ?

Definition: The ratio of the difference and the sum of the transverse **spin-dependent** differential cross-sections of **a certain interaction.**

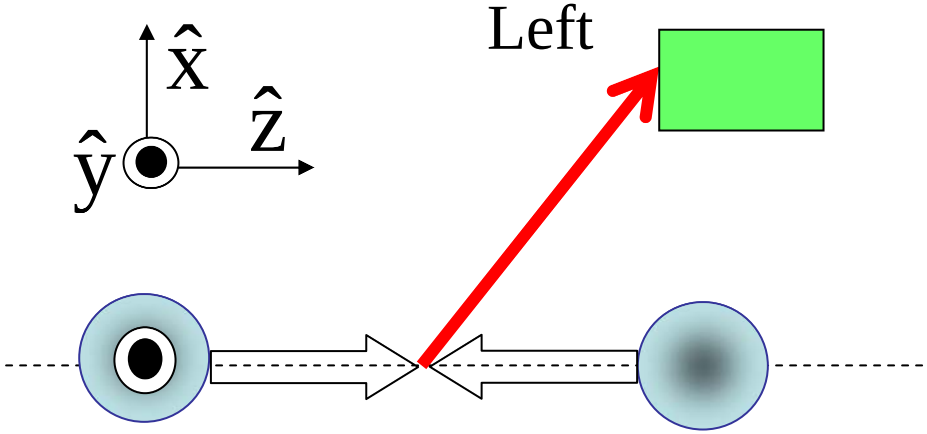
$$SSA = \frac{d\sigma_\uparrow - d\sigma_\downarrow}{d\sigma_\uparrow + d\sigma_\downarrow}$$



A certain interaction: elastic, hard scatter processes etc.

How to measure SSA?

Top view



A certain interaction is detected by:

Single arm detector (Left)

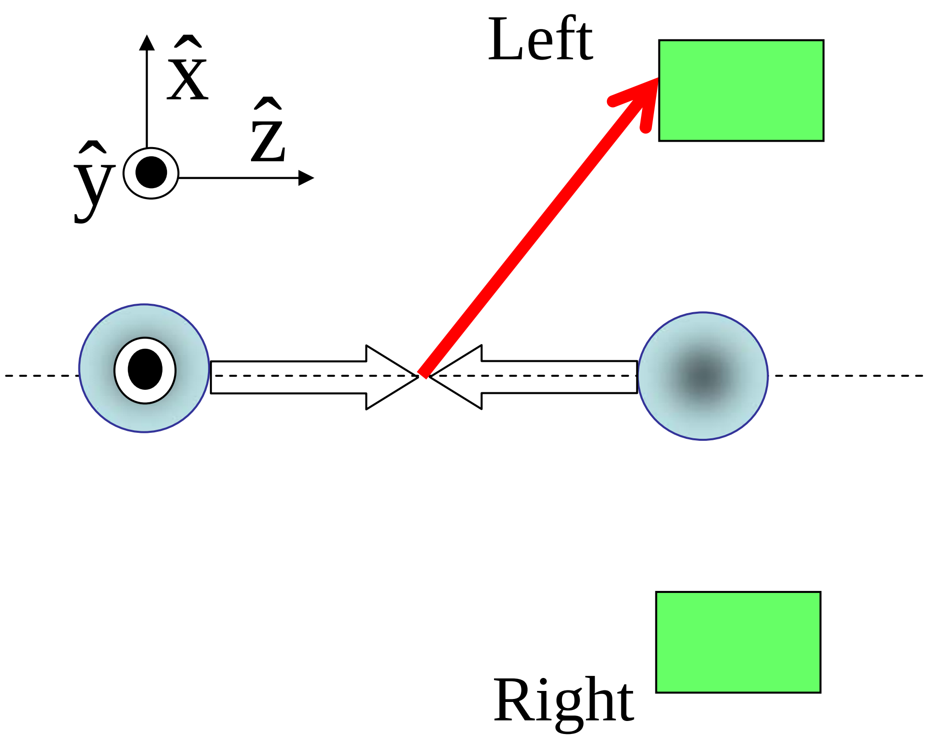
$$\mathrm{SSA} = \frac{1}{\mathrm{pol.}} \frac{N_L^{\uparrow} - R N_L^{\downarrow}}{N_L^{\uparrow} + R N_L^{\downarrow}}$$

R: Relative luminosity

- Normalization by relative luminosity is crucial.
- Normalization by beam polarization is crucial.

How to measure SSA?

Top view



A certain interaction is detected by:

Double arms detector (Left-Right)

$$SSA = \frac{1}{pol.} \frac{\sqrt{N_{\uparrow}^{L} N_{\downarrow}^{R}} - \sqrt{N_{\uparrow}^{R} N_{\downarrow}^{L}}}{\sqrt{N_{\uparrow}^{L} N_{\downarrow}^{R}} + \sqrt{N_{\uparrow}^{R} N_{\downarrow}^{L}}}$$

Square-root-formula

- Normalization by beam polarization is crucial.

SSA of elastic process is ideal tool to measure beam pol.

$$\text{pol.} = \frac{1}{\text{SSA}} \frac{\sqrt{N_{\uparrow}^{L} N_{\downarrow}^{R}} - \sqrt{N_{\uparrow}^{R} N_{\downarrow}^{L}}}{\sqrt{N_{\uparrow}^{L} N_{\downarrow}^{R}} + \sqrt{N_{\uparrow}^{R} N_{\downarrow}^{L}}}$$

Non-zero and **known SSA**

→ we can measure beam polarization

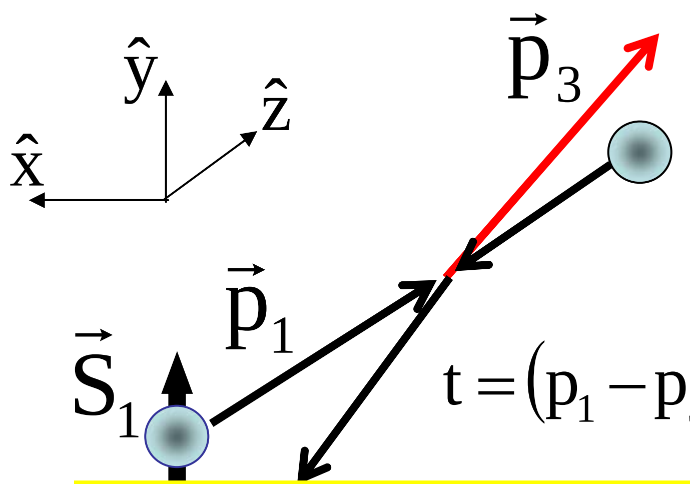
SSA of elastic process is ideal tool to measure beam pol.

$$\mathrm{pol.} = \frac{1}{\mathrm{SSA}} \frac{\sqrt{N_\uparrow^L N_\downarrow^R} - \sqrt{N_\uparrow^R N_\downarrow^L}}{\sqrt{N_\uparrow^L N_\downarrow^R} + \sqrt{N_\uparrow^R N_\downarrow^L}}$$

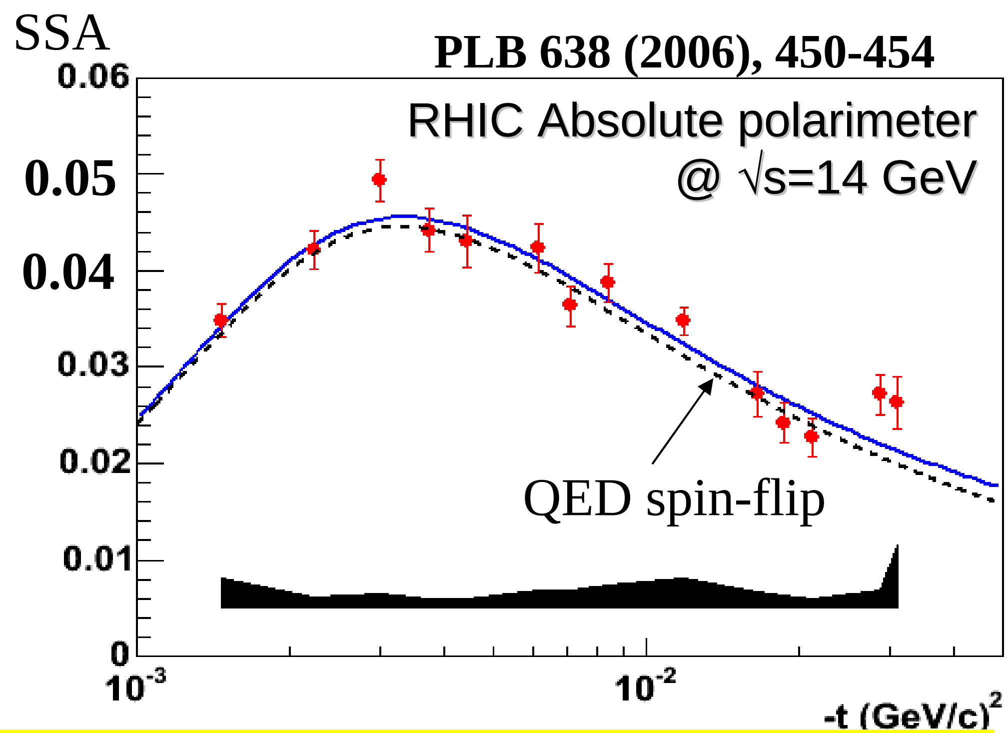
Non-zero and **known SSA**
→ we can measure beam polarization

$$p^\uparrow + p \rightarrow p + p$$

Very forward scattering



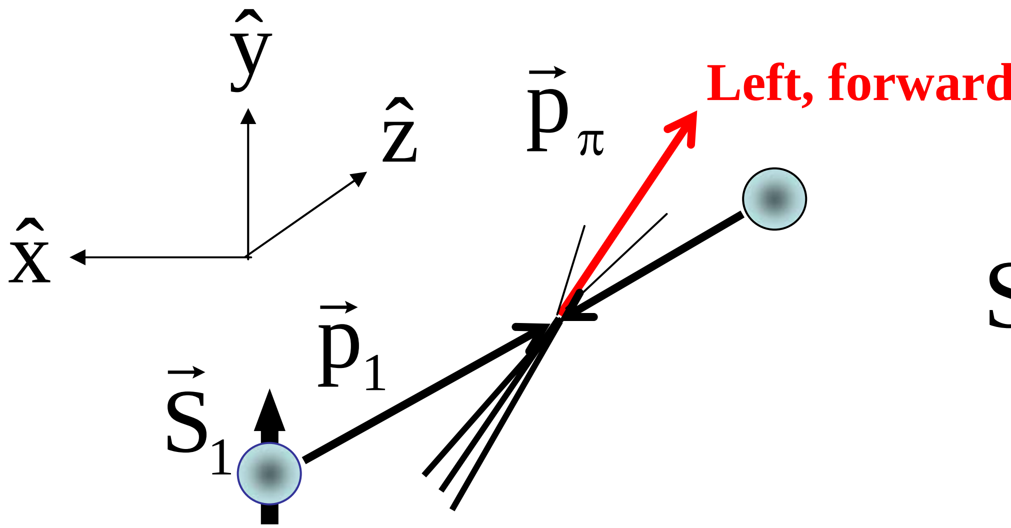
$$t = (p_1 - p_3)^2 <$$



For more details….
Please visit the poster session!

How about SSA of hard scattering?

For example: $p^{\uparrow} + p \rightarrow \pi + X$ **Azimuthal asymmetry in singly polarized *pp* collisions**



$$\mathrm{SSA} \propto \vec{S}_1 \cdot (\vec{p}_1 \times \vec{p}_{\pi})$$

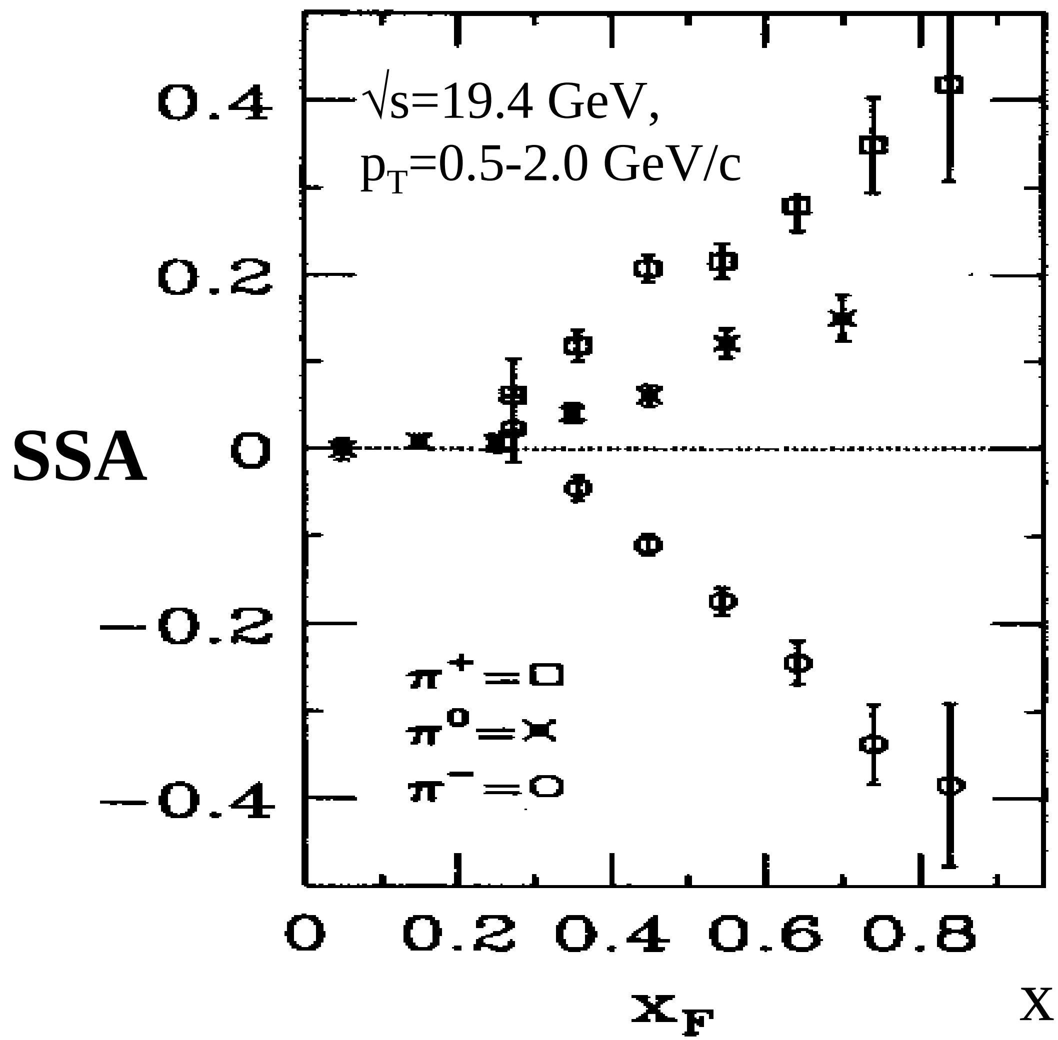
Prediction: $\mathrm{SSA} \sim \frac{m_q \alpha_s}{p_T} \sim 0.001$ Kane, Pumplin and Repko PRL 41 1689 (1978)

SSA of hard scattering is expected to be very **small** by the **leading twist collinear**, $p_T \geq 4\sim5$ GeV/*c*.

Measurements?

Huge SSAs have been measured at E704-FNAL!

$p^{\uparrow} + p \rightarrow \pi + X$ **azimuthal asymmetry in singly polarized pp collisions**



π^0 – E704, PLB261 (1991) 201.
$\pi^{+/-}$ - E704, PLB264 (1991) 462.
Citation amount: 258 !

- Increase linearly with Feynman x (x_F).
- Extremely bigger than expectation!
- **What is the p_T dependence?**

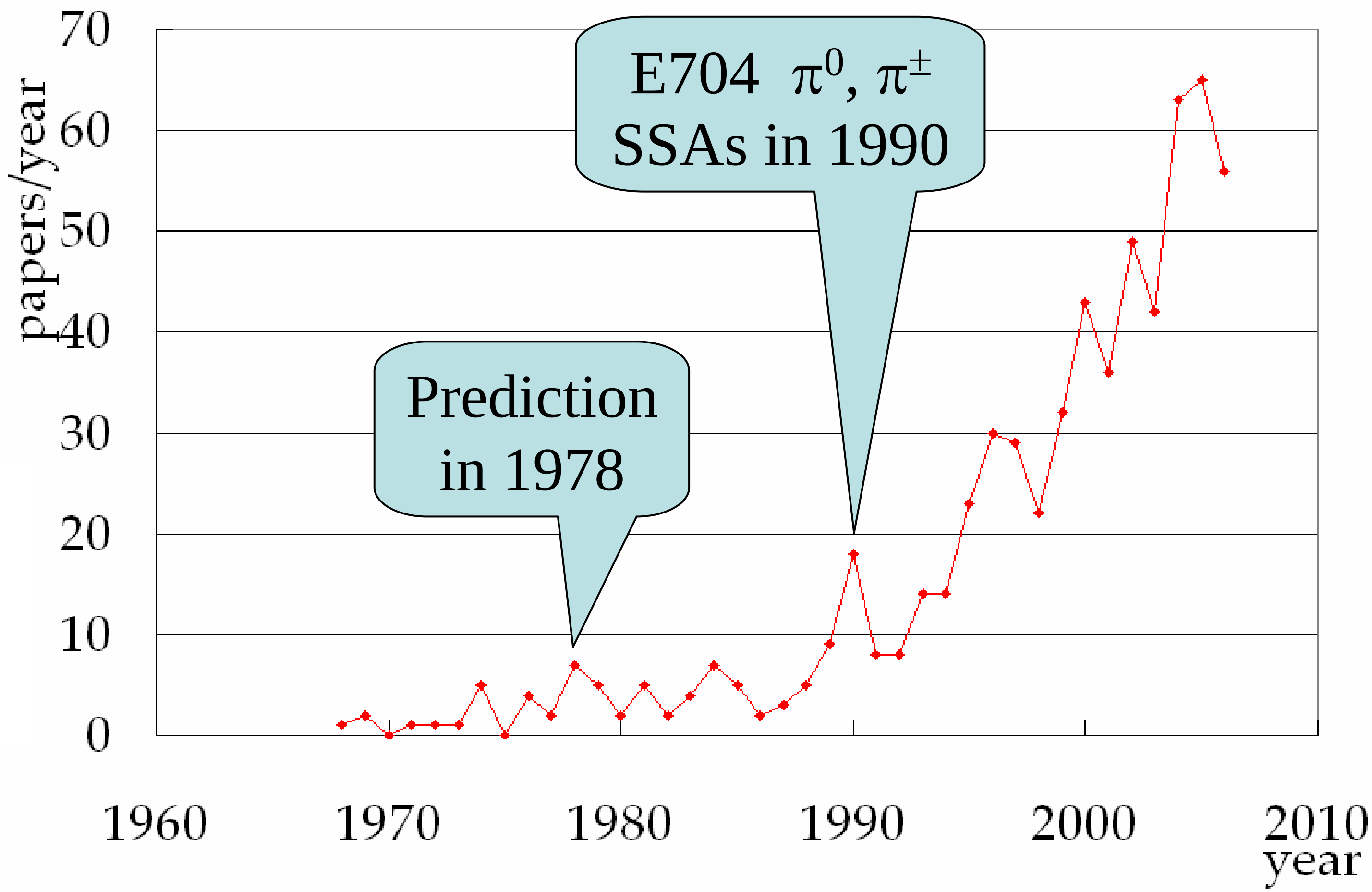
$$x_F = \frac{p_{z,\pi}}{p_{z,1}} \approx \frac{2E_\pi}{\sqrt{s}}$$

How people excited about huge SSAs!

SPIRES-HEP: search title including:
“Transverse spin, Transversity, single spin”.

Total number: 625
(1968~2006)

Experimental results
~14%



… SSAs!

Theoretical approaches for huge SSA beyond the **leading twist collinear;**

A) Higher-twist collinear QCD

→ Twist3 quark-gluon correlations for both initial and final state interactions.

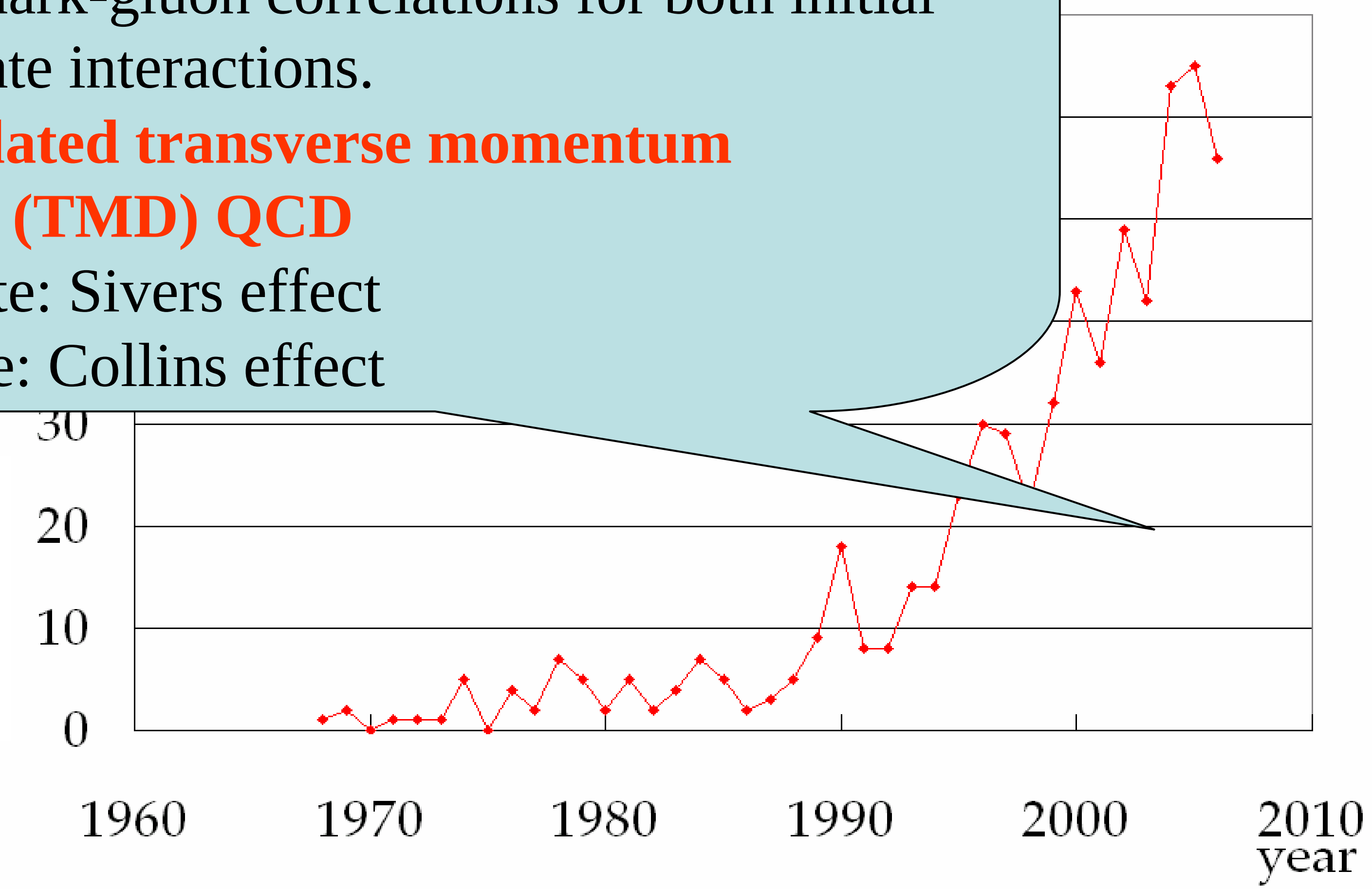
B) Spin-correlated transverse momentum dependent (TMD) QCD

→ Initial state: Sivers effect

→ Final state: Collins effect

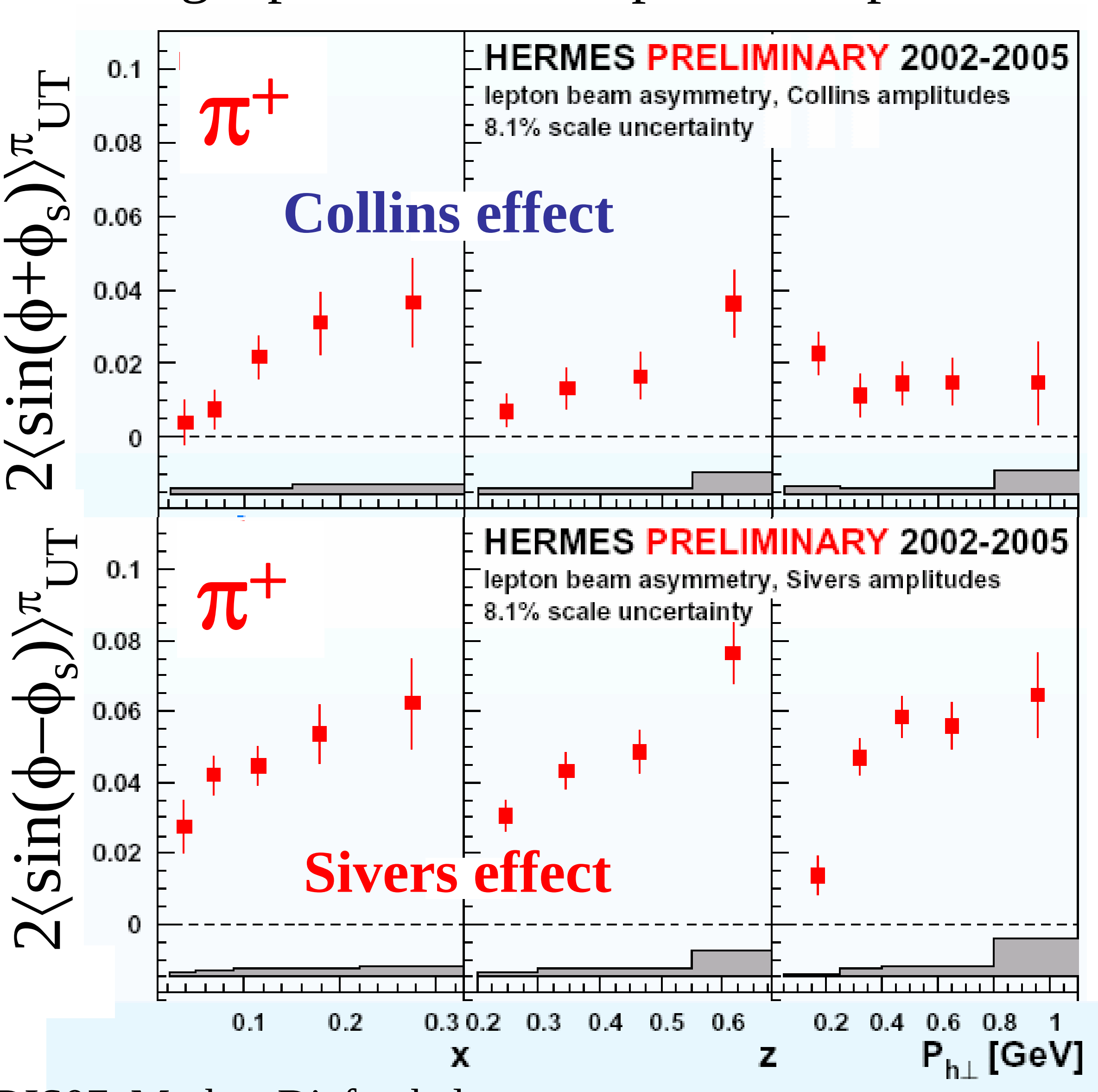
Total number: 625 (1968~2006)

Experimental results ~14%



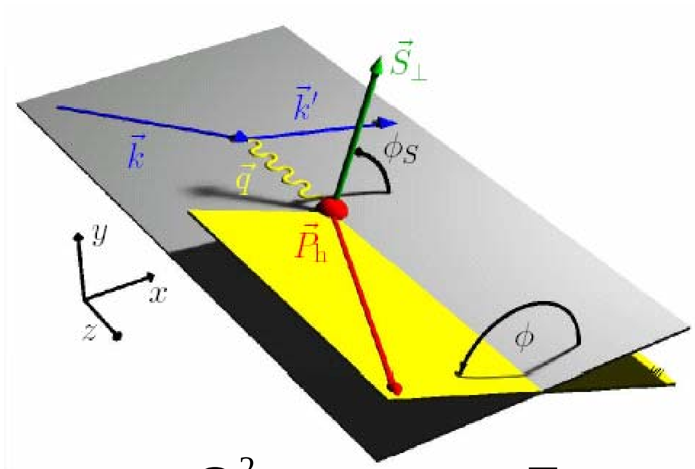
SSAs have been measured in **D**eep **I**nelastic **S**cattering, too.

Using lepton beam and polarized proton target.



$$k = (E, \vec{k}),\quad k' = (E', \vec{k}')$$

$$-Q^2 = (k - k')^2 < 0$$



$$x = \frac{Q^2}{2M(E - E')},\quad z = \frac{E_h}{E - E'}$$

$P_{h\perp}$: Transverse momentum of π^+

Ongoing experiments at **DESY**, **CERN etc.**

New program at **JLAB** 12GeV upgrade.

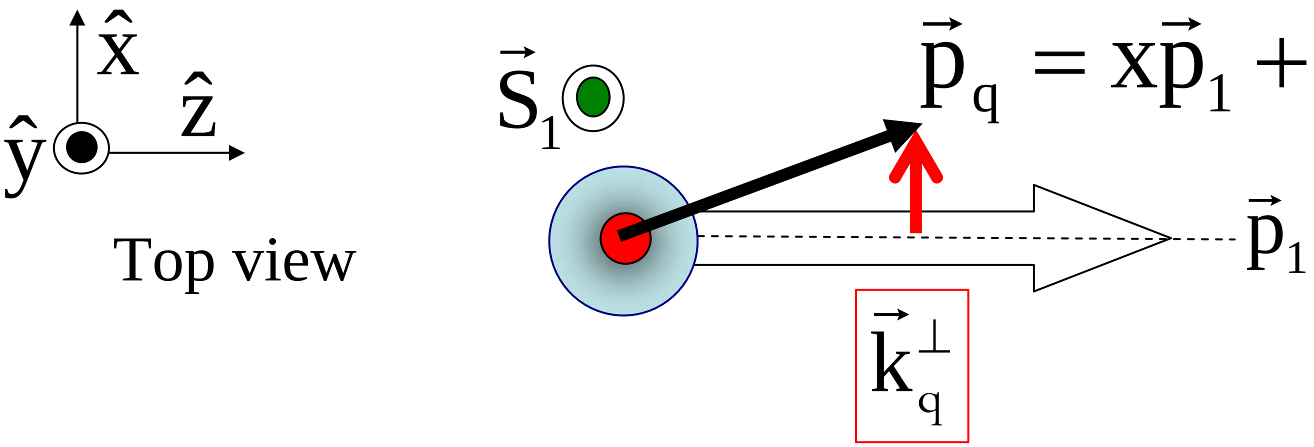
DIS07, Markus Diefenthaler

Sivers effect: **Initial state** of the polarized nucleon

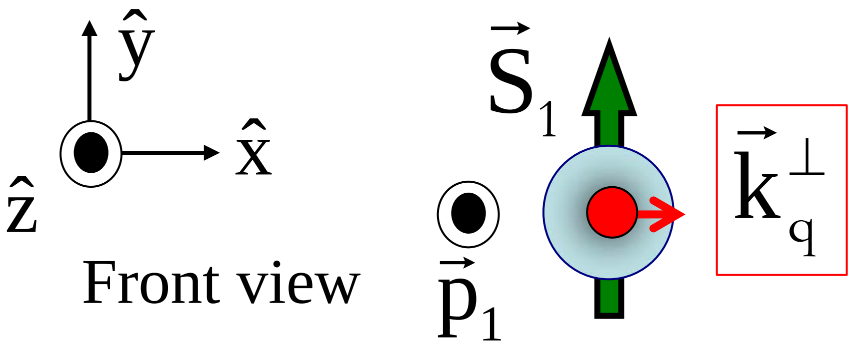
Phys Rev D41 (1990) 83; Phys Rev D43 (1991) 261

$$SSA_{Sivers} \propto \vec{S}_1 \cdot (\vec{p}_1 \times \vec{k}_q^{\perp})$$

$$\vec{p}_q = x\vec{p}_1 + \vec{k}_q^{\perp}$$



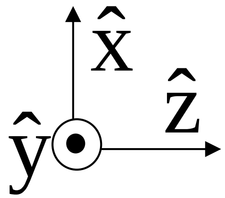
x is longitudinal momentum fraction.



Quark transverse momentum in transversely polarized proton.

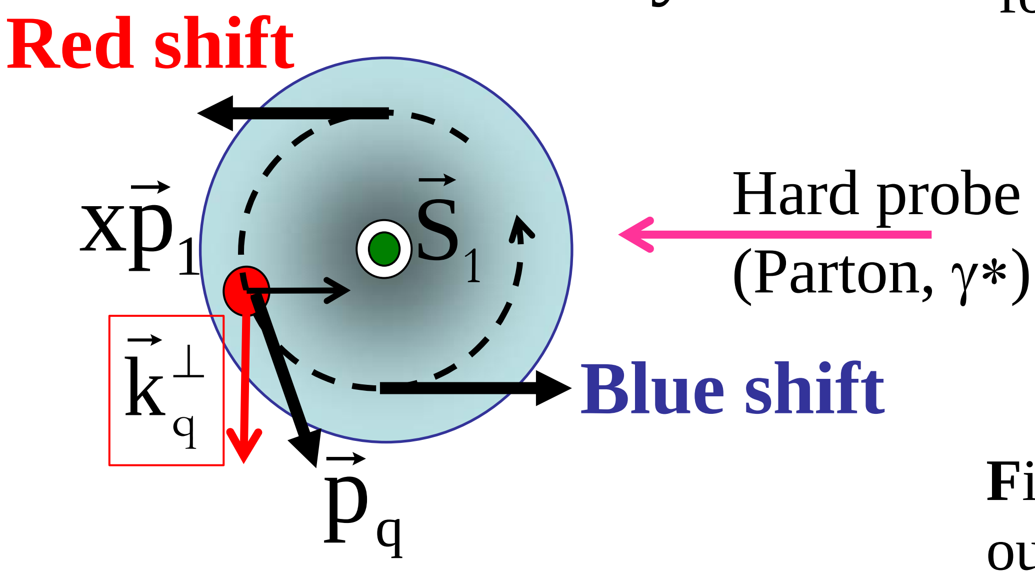
What does Sivers effect probe?

Top view, Breit frame



Quarks orbital motion adds/ subtracts longitudinal momentum for negative/positive $\hat{x}$.

PRD66 (2002) 114005



Parton **D**istribution **F**unctions rapidly fall in longitudinal momentum fraction x.

Final **S**tate **I**nteraction between outgoing quark and target spectator.

Sivers function

$$f_{1T}^{\perp}\left(x, \vec{k}_q^{\perp}\right)$$

hep-ph/ 0703176

Quark Orbital angular momentum

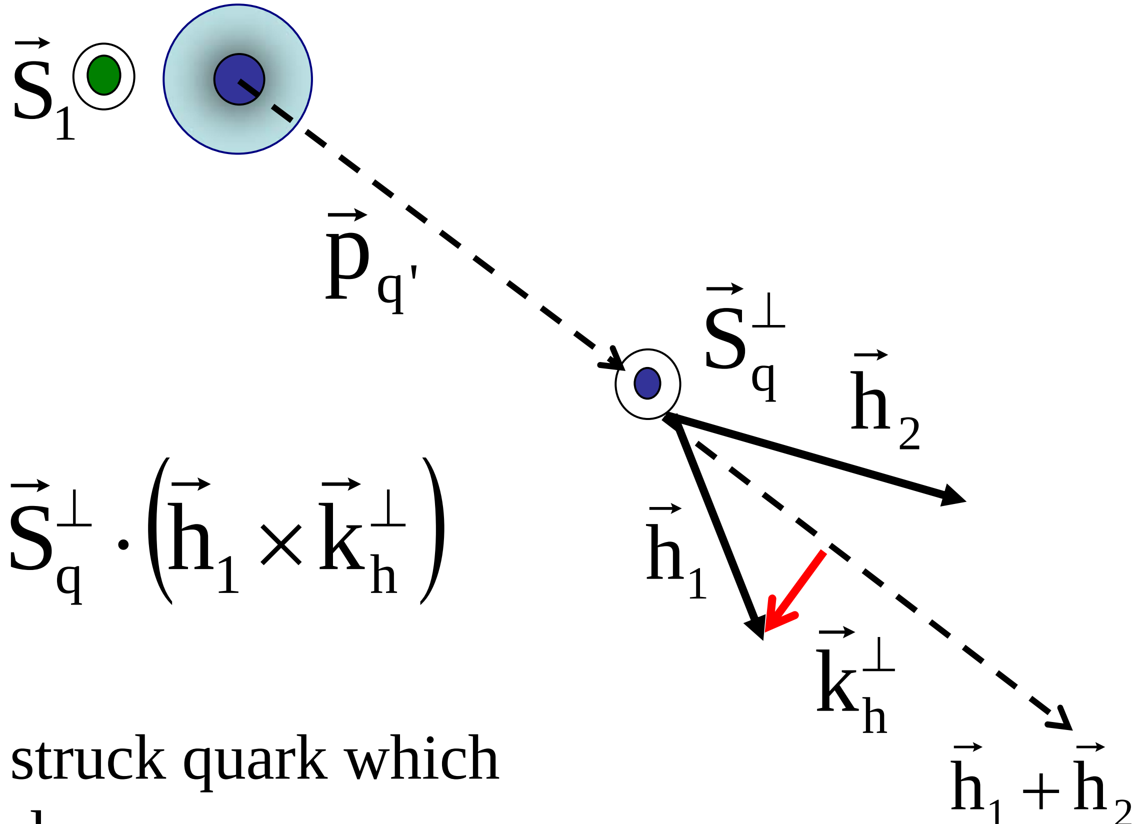
Generalized **P**arton **D**istribution Functions

PRD59 (1999) 014013

Collins Heppelmann effect: **Final state** of fragmentation hadrons

Nucl Phys B396 (1993) 161,
Nucl Phys B420 (1994) 565

Example: $p^{\uparrow} + p \rightarrow h_1 + h_2 + X$

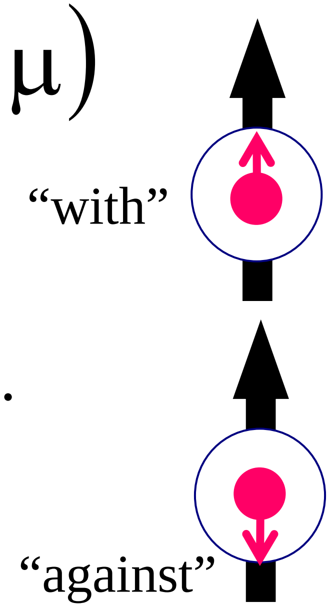


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot \left(\vec{h}_1 \times \vec{k}_h^{\perp}\right)$$

Polarization of struck quark which fragments to hadrons.

Collins function: analyzer of **“Transversity”**

Transversity: $\delta q(x,\mu) = q_{\uparrow}^{\uparrow}(x,\mu) - q_{\uparrow}^{\downarrow}(x,\mu)$



$q_{\uparrow}^{(\uparrow)\downarrow}(x,\mu)$: Probability to observe **parton** whose pol. vector is “with” or “against” the proton pol. vector with the renormalization scale μ.

- ✓ δq(x,μ) has not been measured experimentally.
- ✓ Lattice QCD calculates the first moments of δq(x,μ) for u,d, s quarks and the sum at μ^2=2 GeV^2.

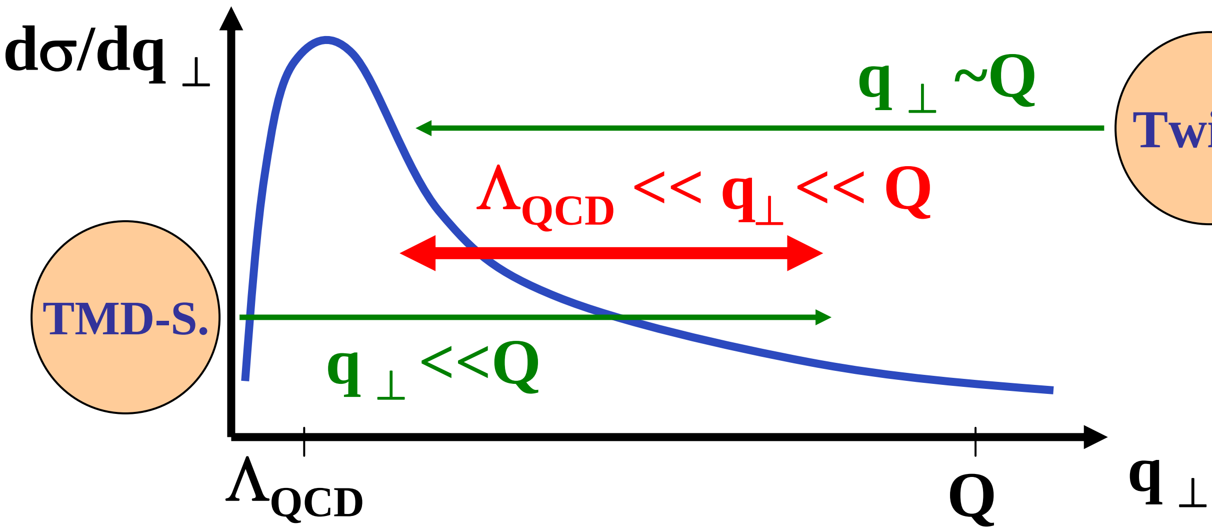
$$\delta q(\mu) = \int_0^1 dx \left[\delta q(x,\mu) - \delta \overline{q}(x,\mu)\right]$$

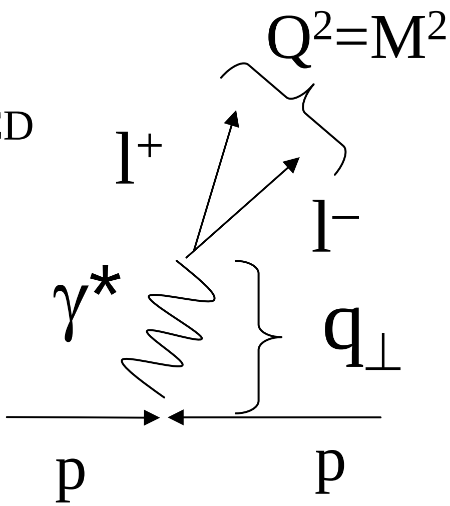
$$\delta\Sigma(\mu) = \delta u(\mu) + \delta d(\mu) + \delta s(\mu)$$

Relevance of Twist3 and Spin-correlated TMD

Lepton-pair (Drell-Yan) production is examined:

- Twist3 (Higher-twist Collinear QCD): $q_\perp \sim Q >> \Lambda_{QCD}$
- TMD-Sivers QCD: $q_\perp << Q$





PRL97, 082002 (2006)

PRD73, 094017 (2006)

Twist3 and TMD-Sivers are related at $\Lambda_{QCD} << q_\perp << Q$

Towards consistency of phenomenological studies of SSA!

Similar study in SIDIS: PLB638, 178 (2006)

Current understanding of SSA

1. SSA of hard scattering is expected to be very small and have p_T dependence by the **leading twist collinear**.
2. **Huge SSAs** have been measured in ***pp* collision** and **SIDIS** (semi-inclusive deep inelastic scattering).
3. Theoretical approaches to explain huge SSAs:
   - **Sivers** effect ($\vec{k}_q^{\perp}$ is connected to quark orbital angular momentum).
   - **Collins** effect (Analyzer of transversity δq).
   - **Twist3** effect which is related to both initial and final states. Relation of Twist3 to Sivers effect is introduced.

Issues

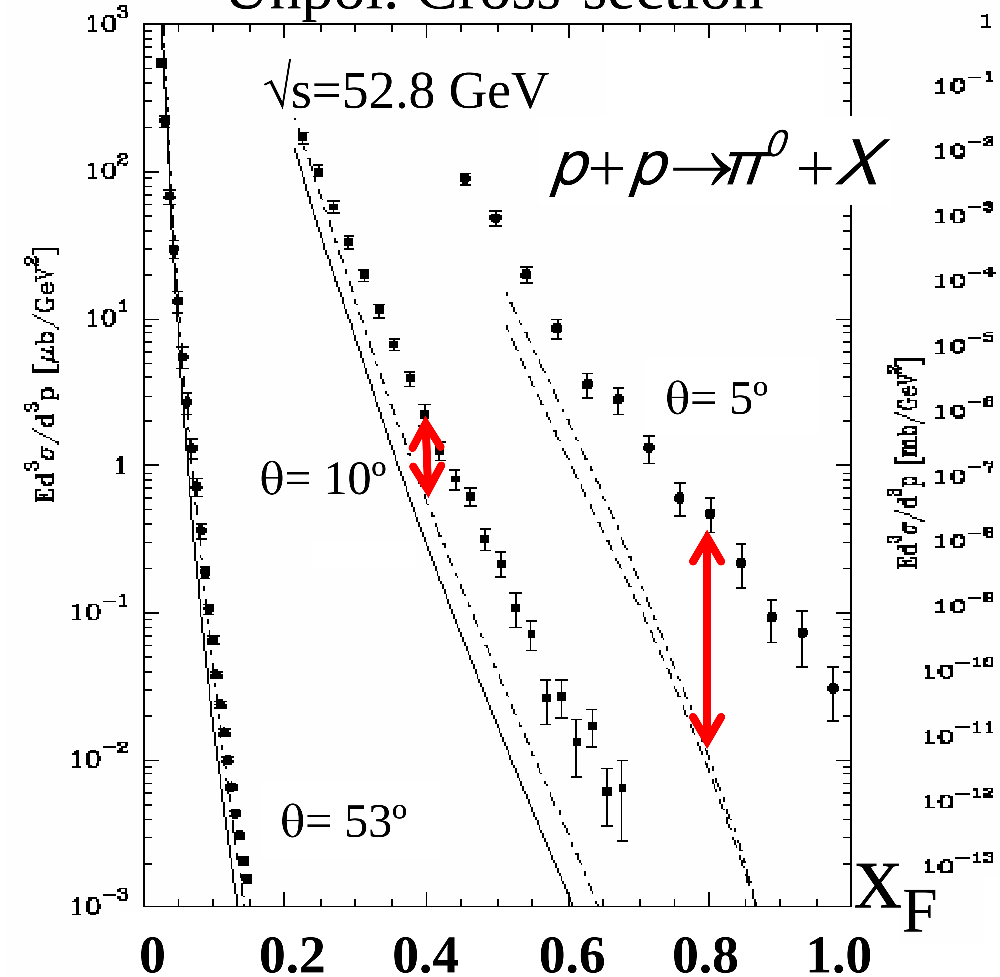
1. Applicability of pQCD?
2. Relationship of SSAs between SIDIS and *pp* collision?

Is pQCD applicable for √s ≤ 50 GeV ?

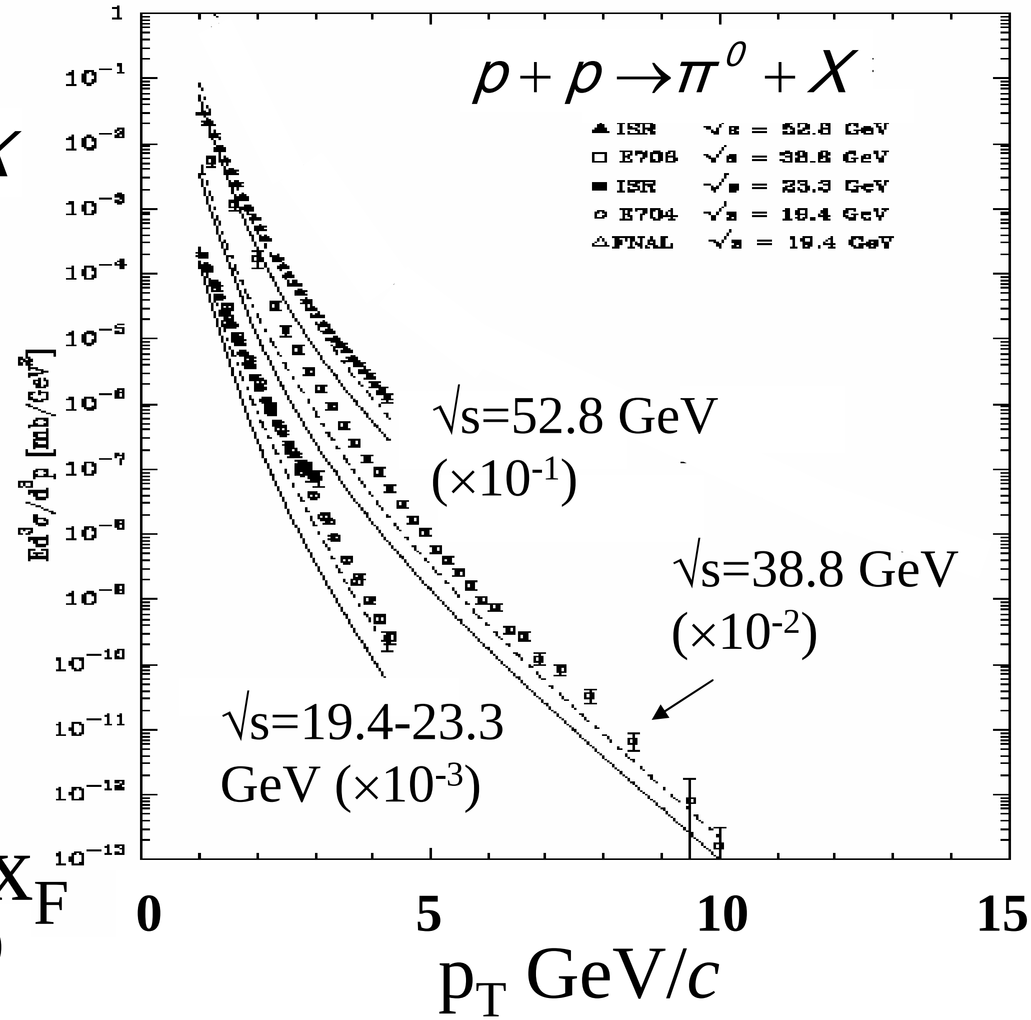
Eur.Phys.J.C36:371-374,2004. ,
Data references therein.

2 NLO calculations with different scales p_T and $p_T/2$

Unpol. Cross-section



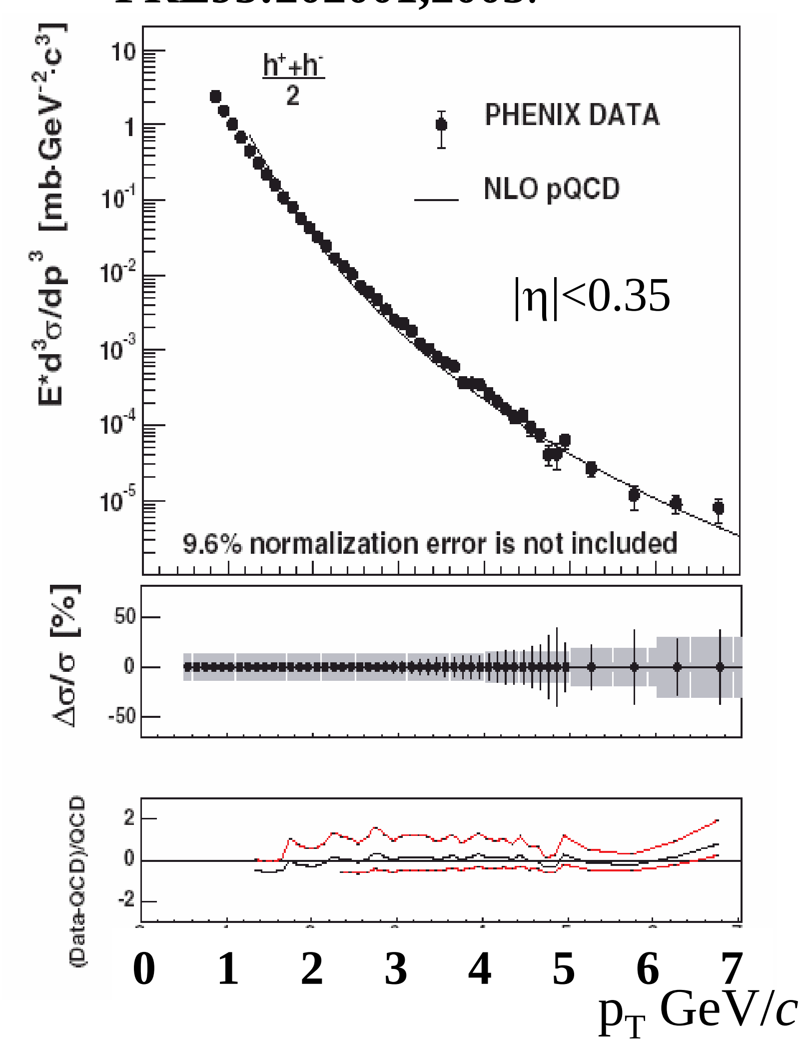
Unpol. Cross-sections at θ=90º



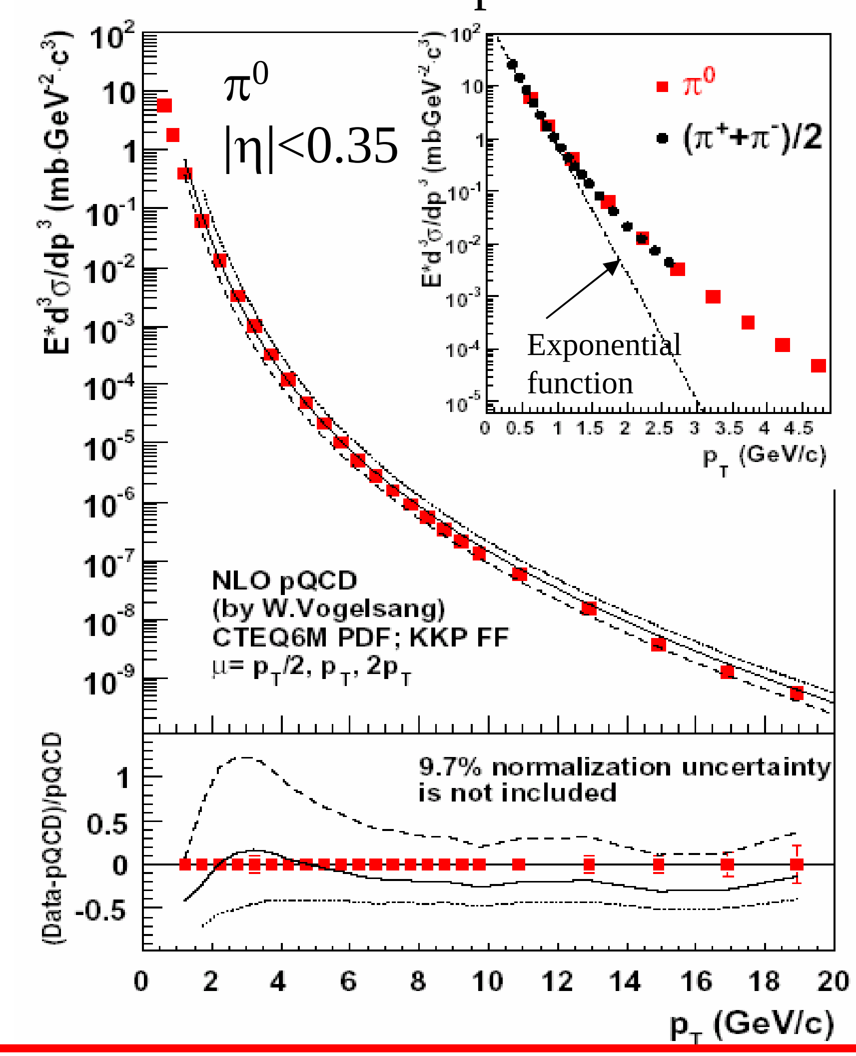
Require more than NLO pQCD…

pp collision at √s=200GeV (1)

PRL95:202001,2005.



hep-ex/0704.3599



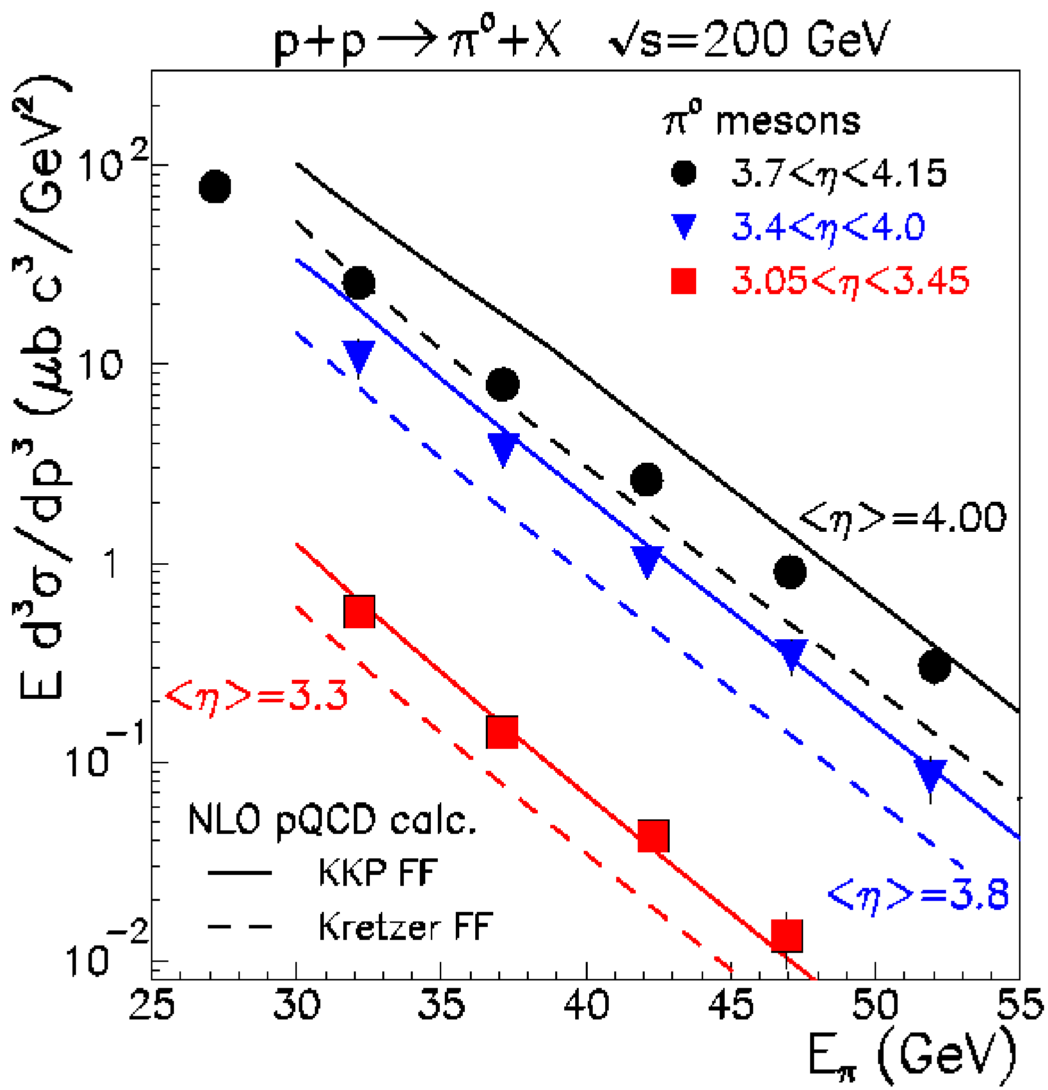
Cross-sections at |η|<0.35 are consistent with NLO pQCD.

W. Vogelsang, M. Stratmann *et al.*

pp collision at √s=200GeV (2)

STAR

PRL97:152302, 2006.



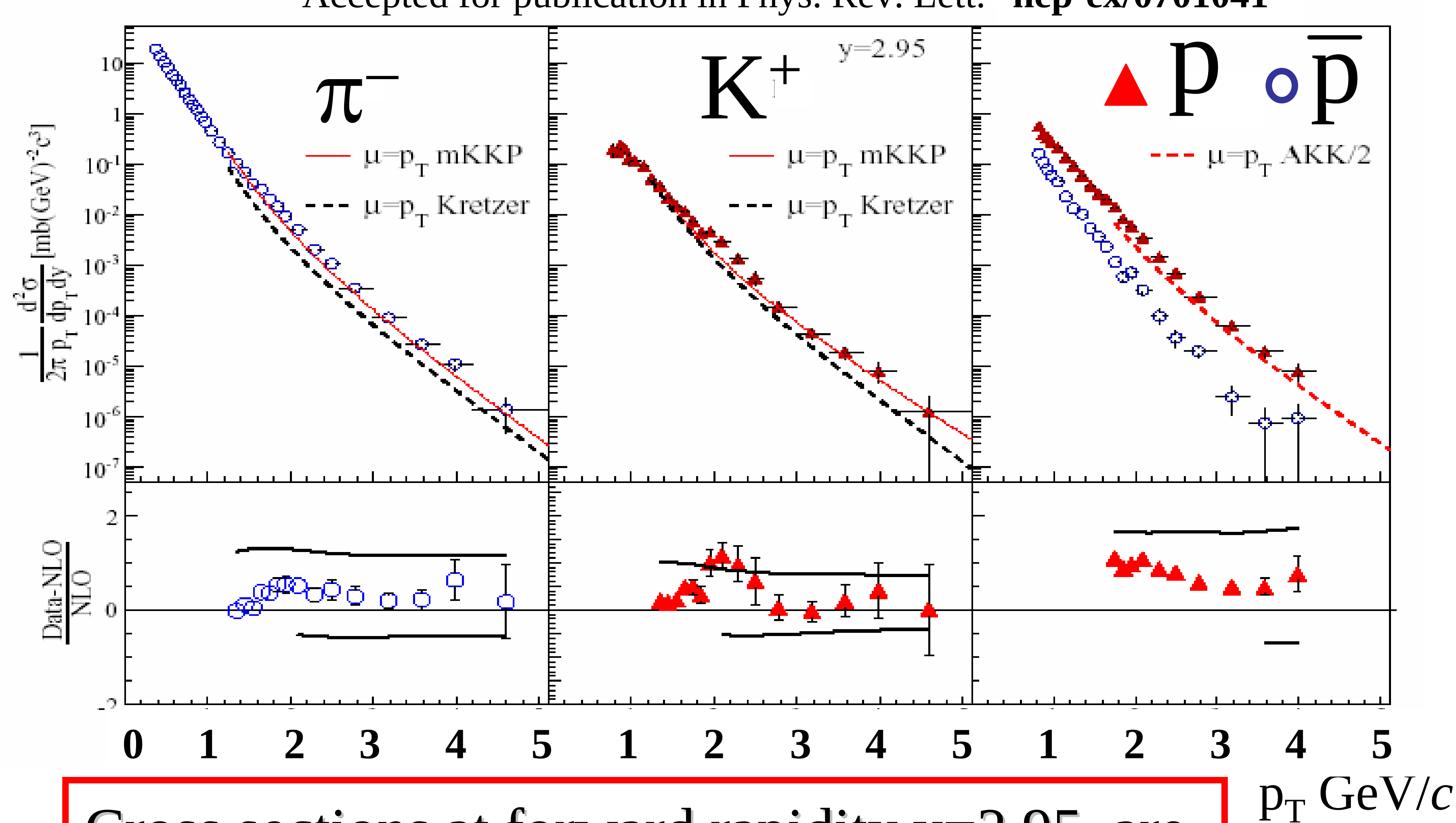
Cross-sections at the forward region, <η>=3.3, 3.8 and 4.0 are mostly consistent with NLO pQCD calculations.

KKP FF : Nucl. Phys. B597, 337 (2001)
Kretzer FF: Phys. Rev. D62, 054001 (2000).

pp collision at √s=200GeV (3)

BRAHMS

Accepted for publication in Phys. Rev. Lett. **hep-ex/0701041**



Cross sections at forward rapidity y=2.95 are consistent with NLO pQCD.

mKKP: Nucl. Phys. B597, 337 (2001); Kretzer: Eur. Phys. J.C22, 269 (2001); AKK: Nucl. Phys. B725, 181 (2005)

- **RHIC provides $\sqrt{s}$ =200 GeV polarized *pp* collision.**
- **Hard process, pQCD is applicable.**

⇒Advantage of SSA investigation at RHIC!

Establish Universality of SSA

hadron-hadron high energy collision for Sivers/Collins at RHIC

Intercomparison via pQCD

Semi-inclusive deep inelastic scattering for Sivers/Collins. (HERMES, COMPASS, ..)

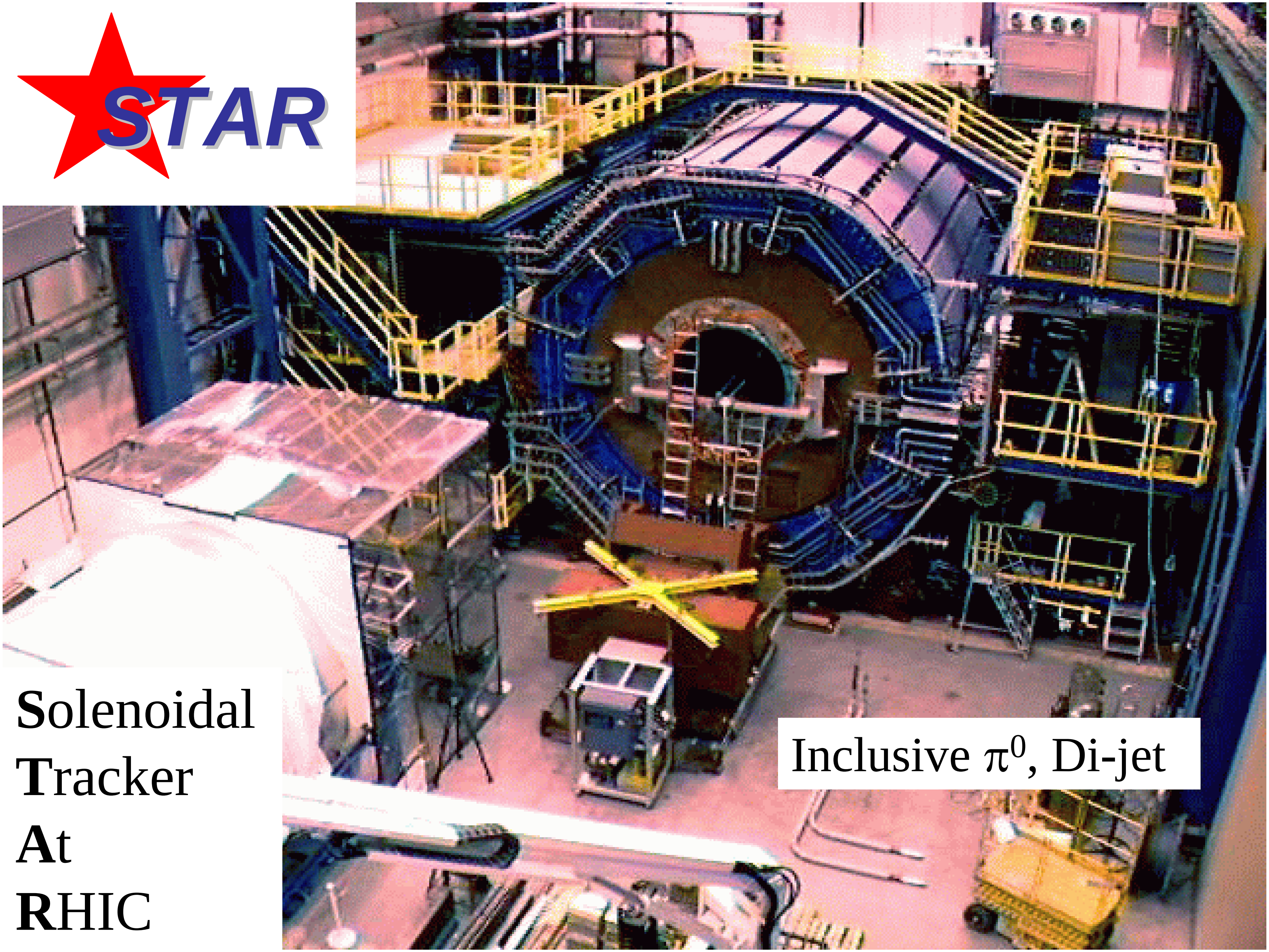
e^+e^- collision for Collins. (BELLE)

	Available Probes at RHIC	
1	**$p^{\uparrow}$+p→h+X**	Both mix
2	**$p^{\uparrow}$+p→di-jet+X**	Sivers?
3	$p^{\uparrow}$+p→h+h+X (far side)	Separate?
4	$p^{\uparrow}$+p→h+h+X (near side) $p^{\uparrow}$+p→jet+X	Collins Sivers
5	$p^{\uparrow}$+p→direct γ+X	Sivers
6	$p^{\uparrow}$+p→l^+l^- (Drell-Yan)	Sivers

I am going to show!

Probe **"color charge"** by comparing with SIDIS process. I will come back this topic, later.

STAR



Solenoidal
Tracker
At
RHIC

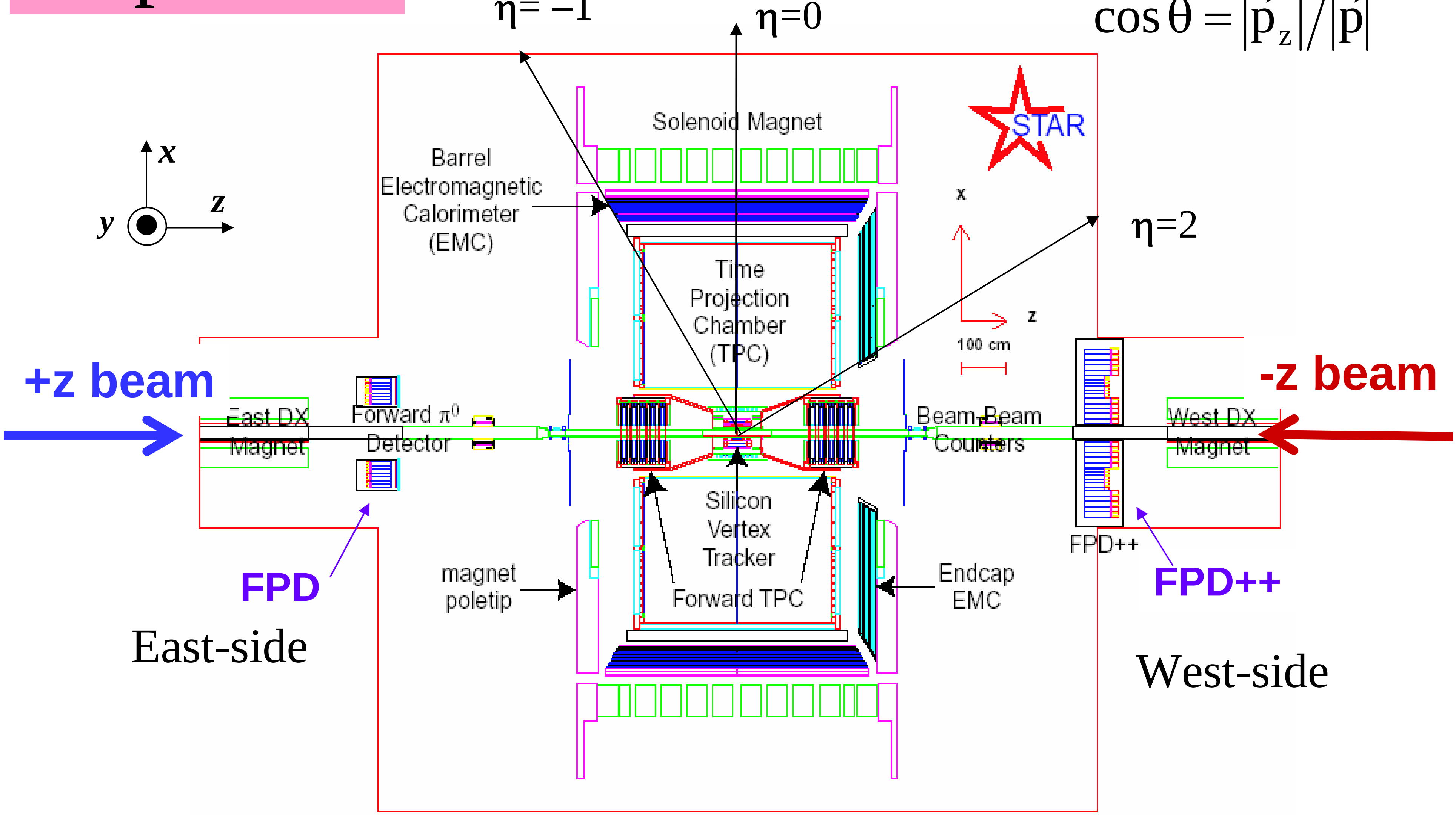
Inclusive π^0, Di-jet

Top-view

RUN6 configuration

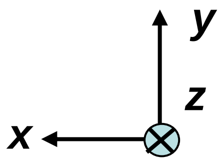
$$\eta = -\ln\{\tan(\theta/2)\}$$

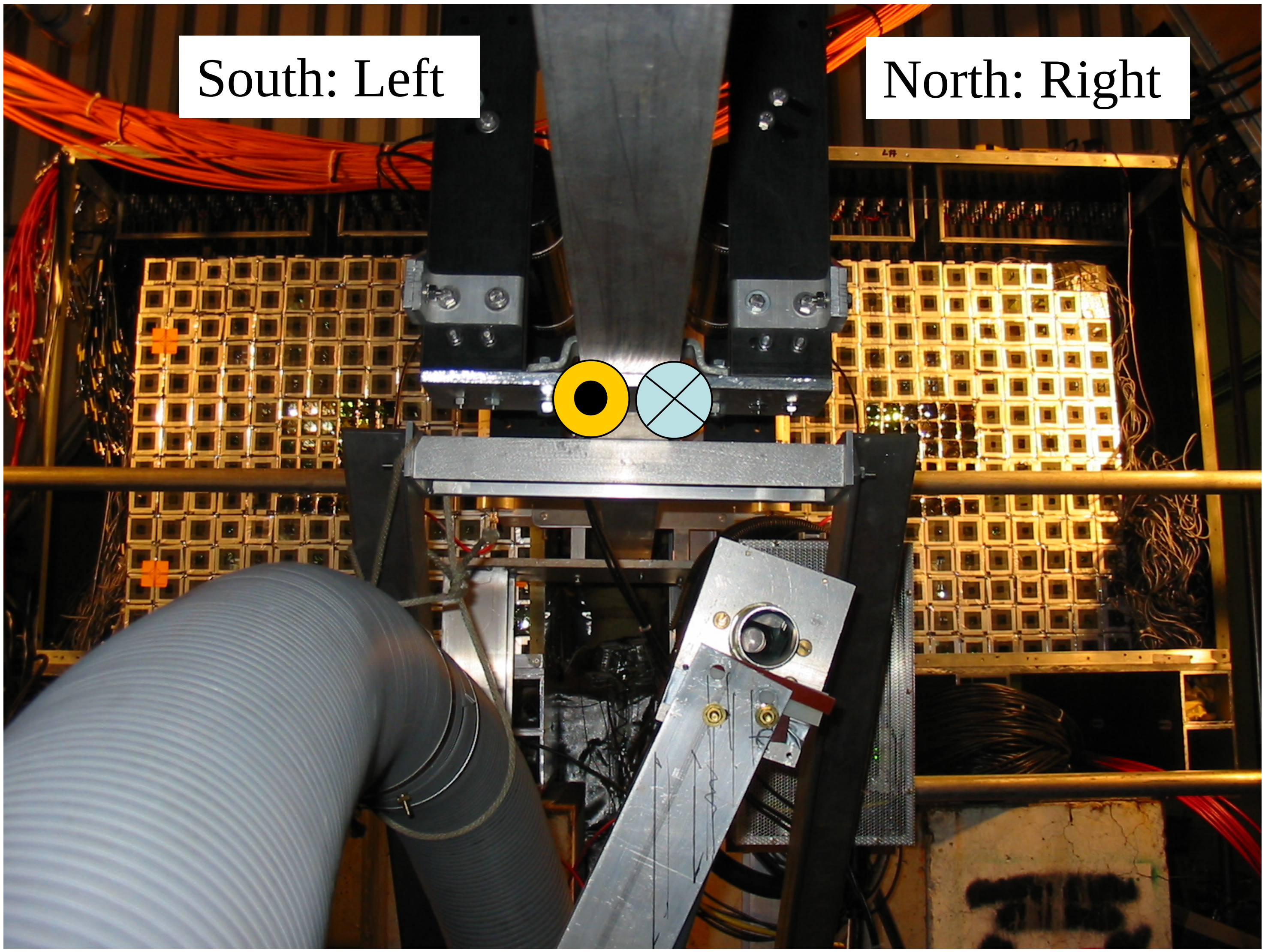
$$\cos\theta = |\vec{p}_z| / |\vec{p}|$$



- Inclusive π^0 in forward region: $-4<\eta<-3$ (FPD), $2.5<\eta<4$ (FPD++)
- Di-jet results: $-1<\eta<2$ (Barrel EMC, Endcap EMC, 2π)

FPD++ (Forward Pion Detector) , West side





Inclusive π^0

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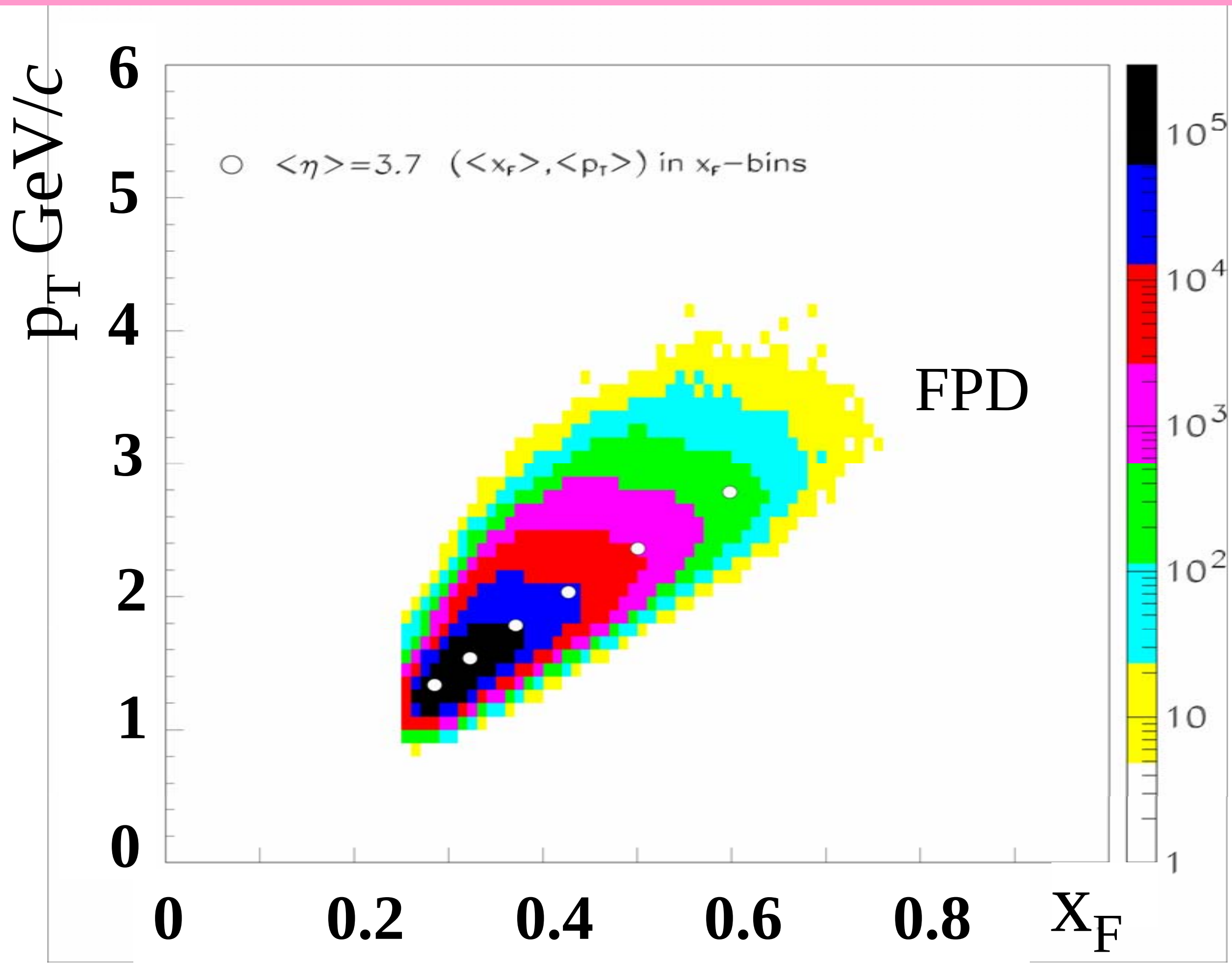
Acceptance of FPD

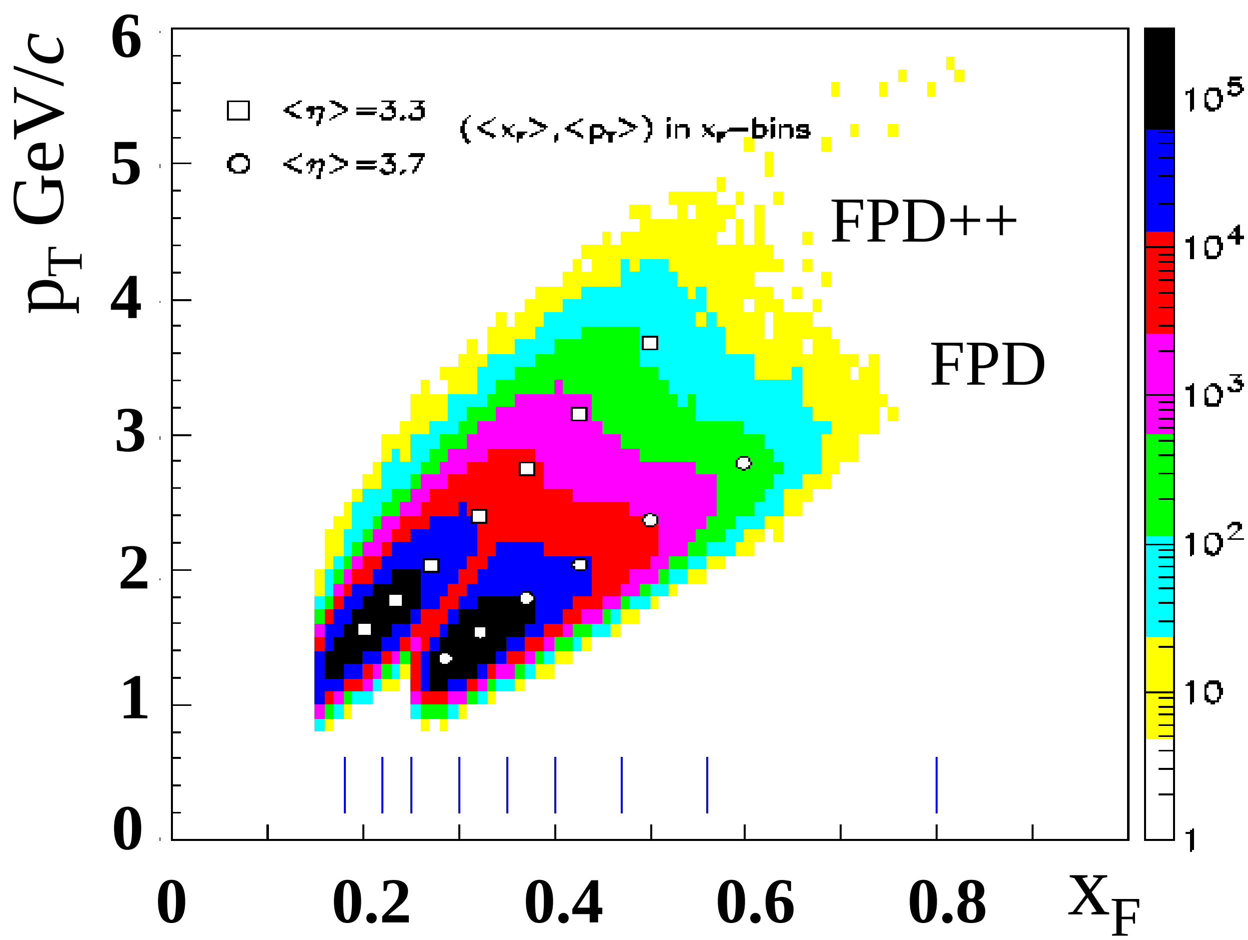
Inclusive π^0



Strong x_F and p_T correlation because of limited acceptance.

Acceptance of FPD and FPD++

Inclusive π^0



Study of the p_T dependence needs large acceptance.

Overview of transverse spin runs at STAR with forward calorimetry: 2001→2006

	Run2	Run3	Run5	**Run6 (2006)**
detector	EEMC and FPD prototypes	6 matrices of FPD	full FPD (8 matrices)	**East FPD West FPD++**
$P_{BEAM}^{sampled}$, %	~15	~30	~45	**~60**
$\int Ldt,\ pb^{-1}$	0.15	0.25	0.1	**6.8**
$< \eta >$	3.8	±3.3/±4.0	±3.7/±4.0	**-3.7/3.3**

FOM (P^2L) in Run 6 is ~50 times larger than from all the previous STAR runs, and ~ 725 times larger than for Run 2

SSA of inclusive π^0 production with FPD and FPD++

$p^{\uparrow} + p \rightarrow \pi^0 + X$

Inclusive π^0

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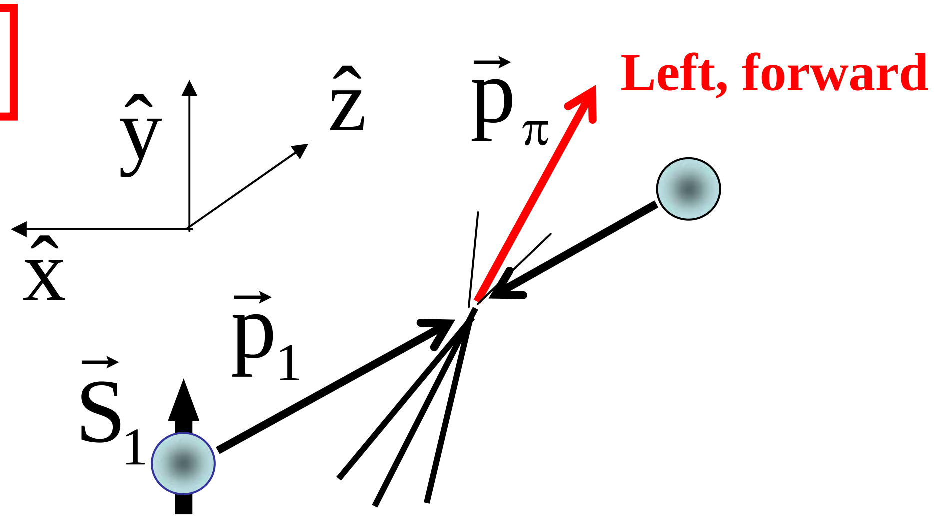
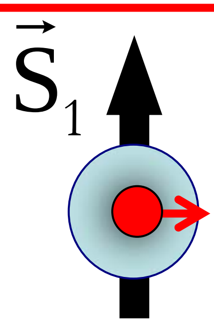


Measure;

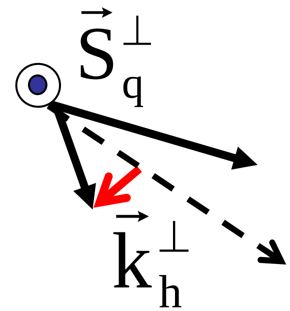
$$\vec{S}_1 \cdot \left(\vec{p}_1 \times \vec{p}_\pi\right) \Rightarrow A \cdot \left[\vec{S}_1 \cdot (\vec{p}_1 \times \vec{k}_q^{\perp})\right] + B \cdot \left[\vec{S}_q \cdot \left(\vec{h}_1 \times \vec{k}_h^{\perp}\right)\right]$$

Sivers



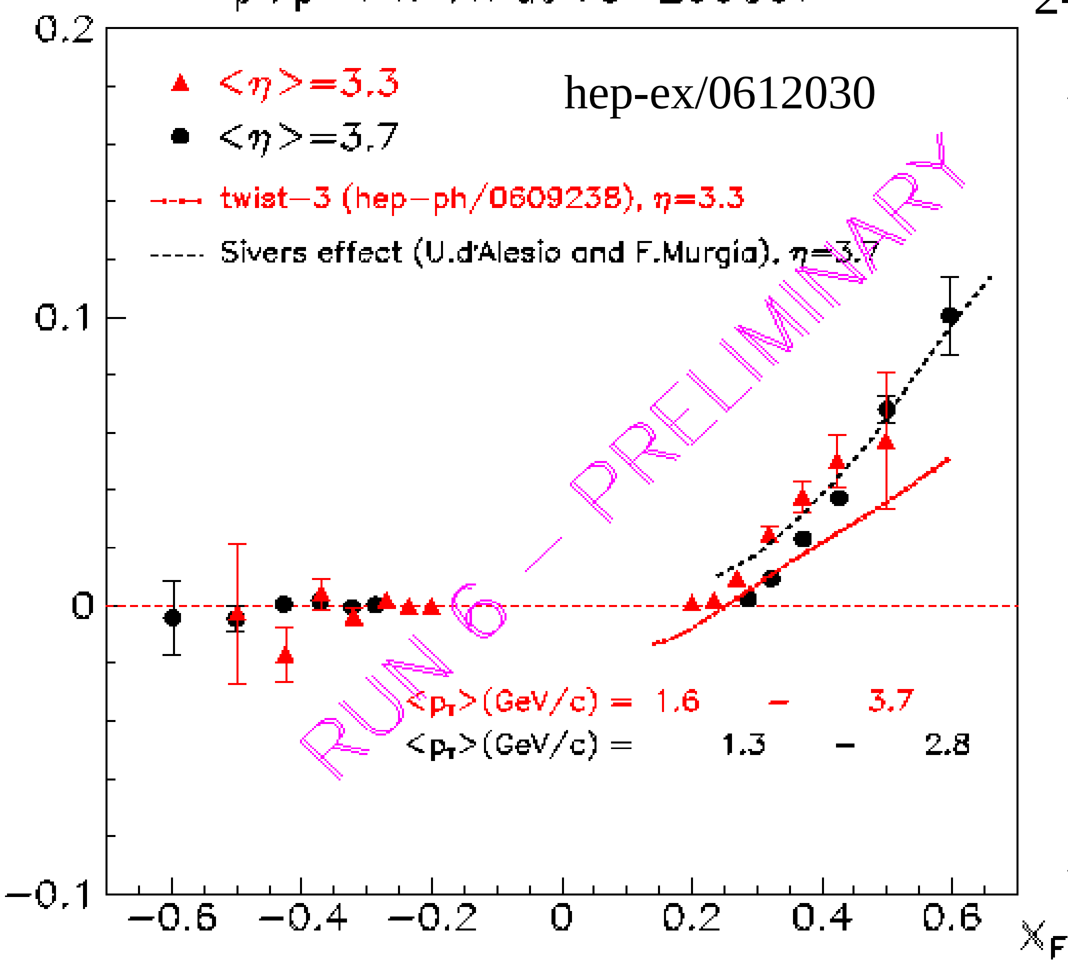
$\vec{k}_q^{\perp}$

Collins



Does SSA survive in pQCD region?

SSA (π^0) at $\sqrt{s}$=200 GeV SURVIVES !

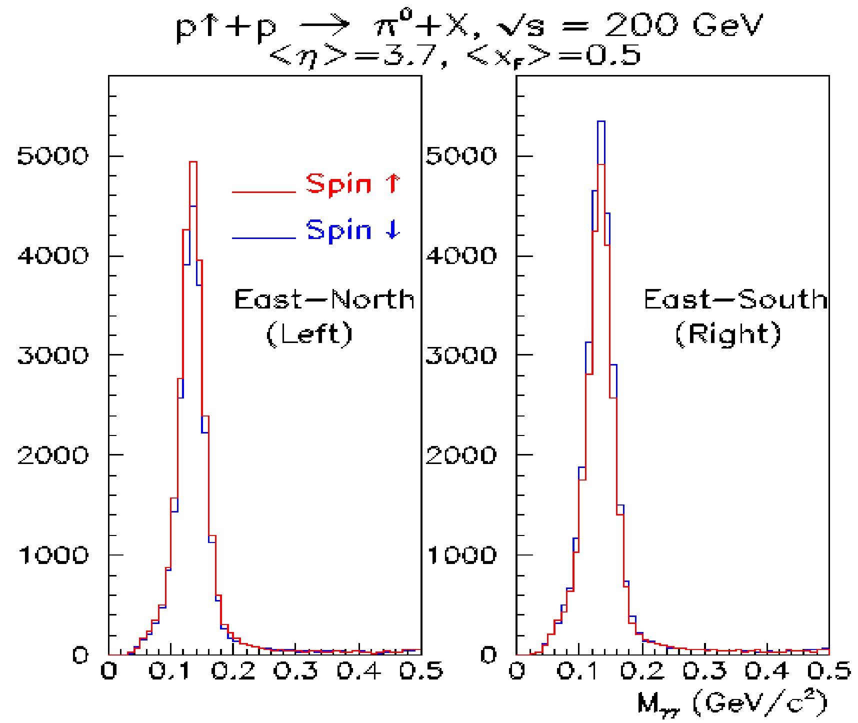


2-γ inv.-mass spectra

47 <= E_π < 56 GeV

Inclusive π^0

STAR



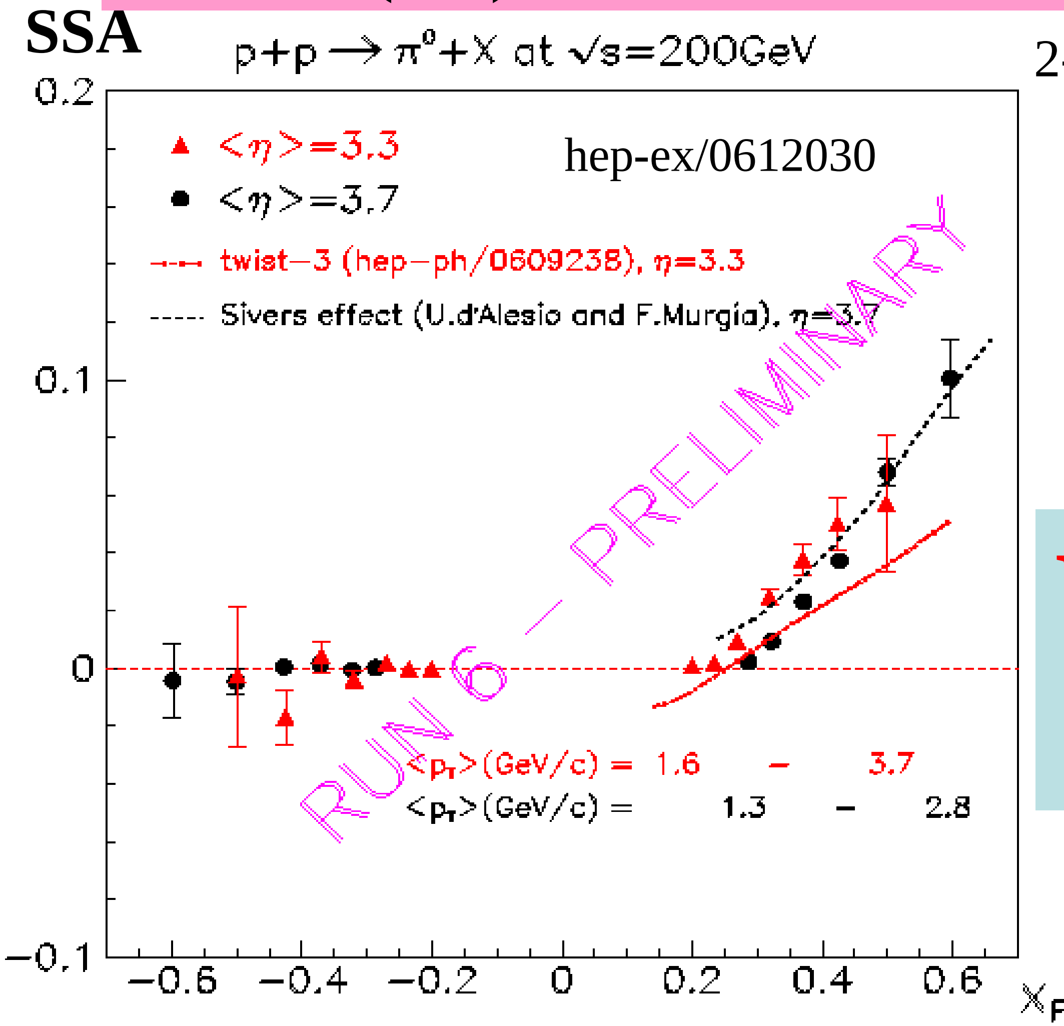
Double arms

Left arm only

$$x_F = \frac{p_{z,\pi}}{p^{unpol}_{z,1}} < 0, \qquad x_F = \frac{p_{z,\pi}}{p^{pol}_{z,1}} > 0$$

$$SSA = \frac{1}{pol.}\frac{\sqrt{N^L_\uparrow N^R_\downarrow} - \sqrt{N^R_\uparrow N^L_\downarrow}}{\sqrt{N^L_\uparrow N^R_\downarrow} + \sqrt{N^R_\uparrow N^L_\downarrow}}$$

SSA (π^0) at $\sqrt{s}$=200 GeV SURVIVES !

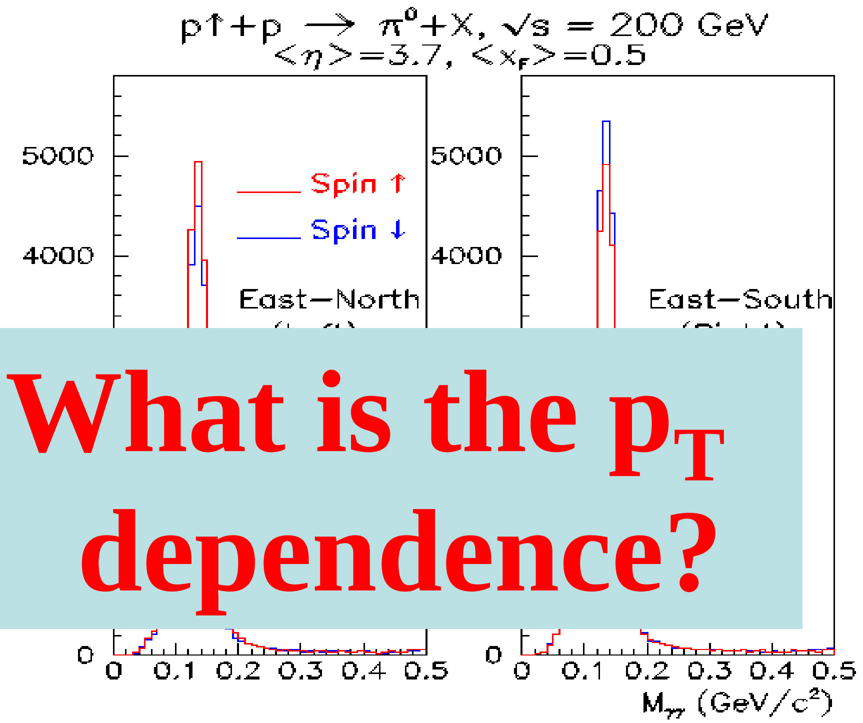


2-γ inv.-mass spectra

Inclusive π^0

STAR

$47 <= E_\pi < 56$ GeV



What is the p_T dependence?

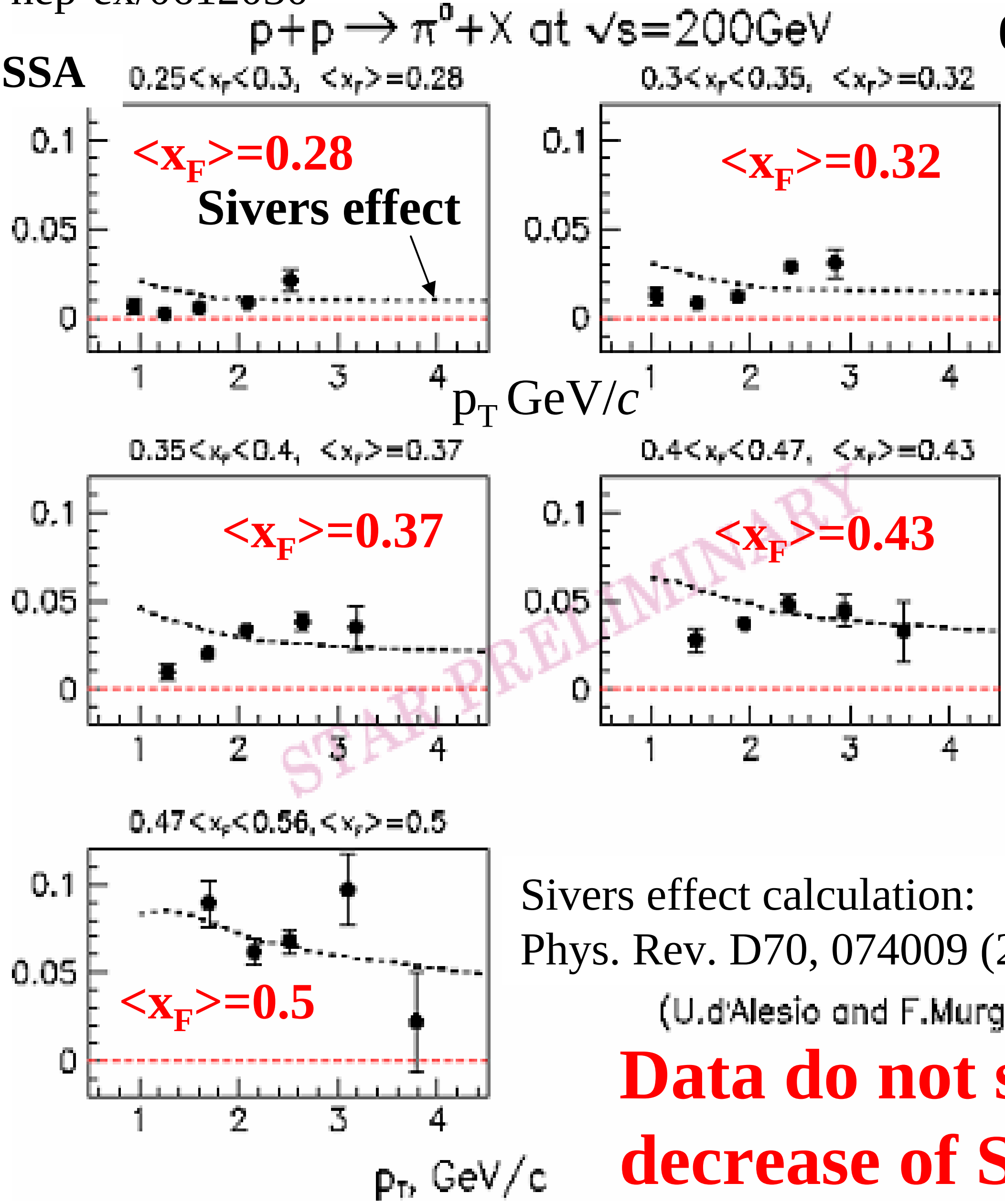
$$x_F = \frac{p_{z,\pi}}{p_{z,1}^{unpol.}} < 0, \qquad x_F = \frac{p_{z,\pi}}{p_{z,1}^{pol.}} > 0$$

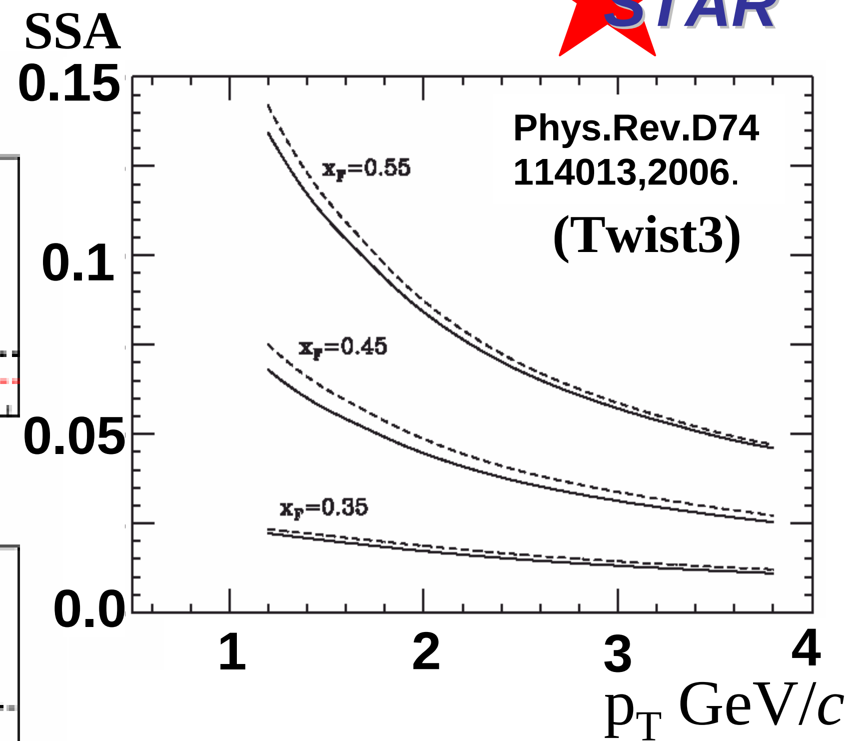
- SSA is measured by square-root formula with double-arms (left-right) detector:
- SSAs at different $<\eta>$ do not change much.

SSA as a function of p_T in x_F slice

Inclusive π^0 STAR

hep-ex/0612030





Sivers effect calculation:
Phys. Rev. D70, 074009 (2004)

(U.d'Alesio and F.Murgia)

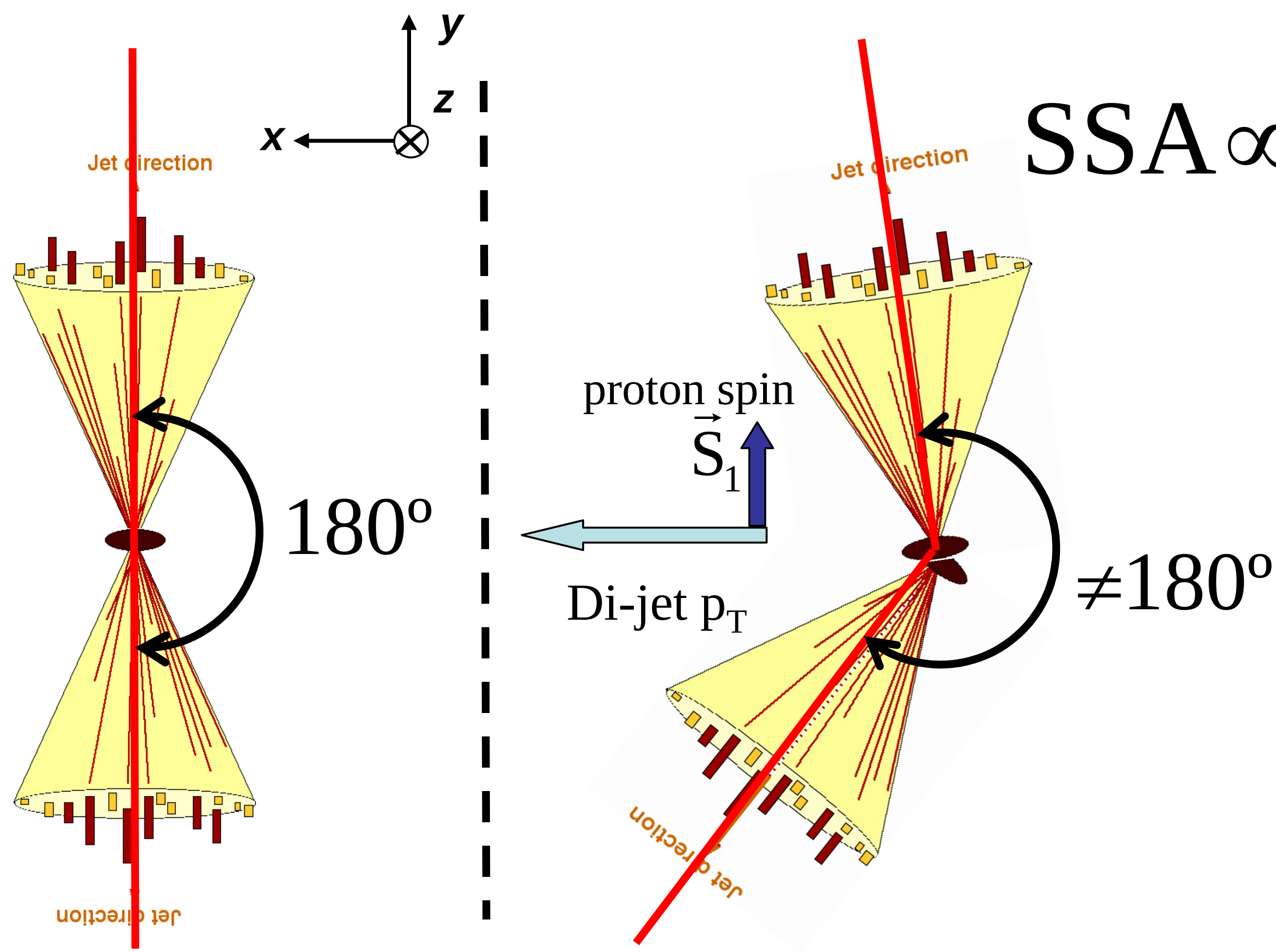
- Combined data from three runs at <η>=3.3, 3.7 and 4.0.
- Within each x_F bin, $\langle x_F \rangle$ does not significantly change with p_T.

Data do not show a simply monotonic decrease of SSA with increasing p_T.

SSA in di-jet production

Di-jet STAR

Boer & Vogelsang, PRD 69, 094025 (2004)



$$SSA \propto \vec{S}_1 \cdot \left(\vec{p}_1 \times \vec{k}^{\perp}\right)$$

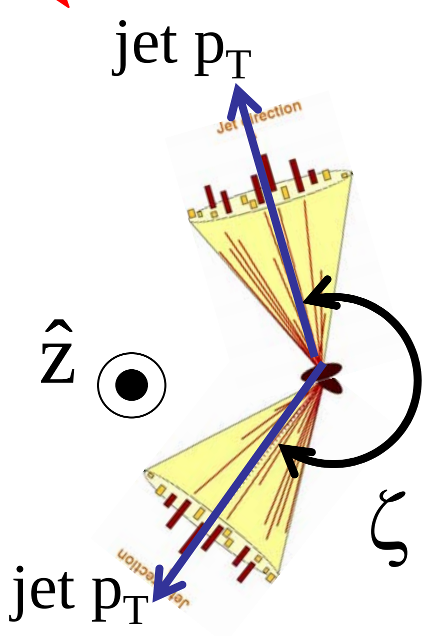
Di-jet p_T

$$\vec{K}^{\perp} + \vec{k}^{\perp}$$

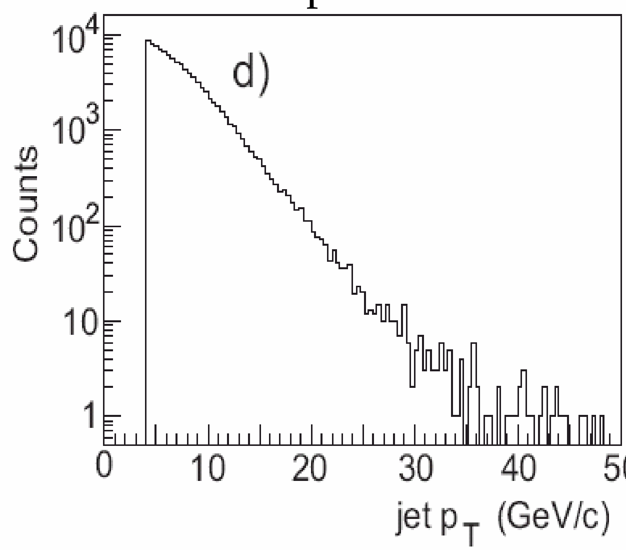
Gluon radiation parton

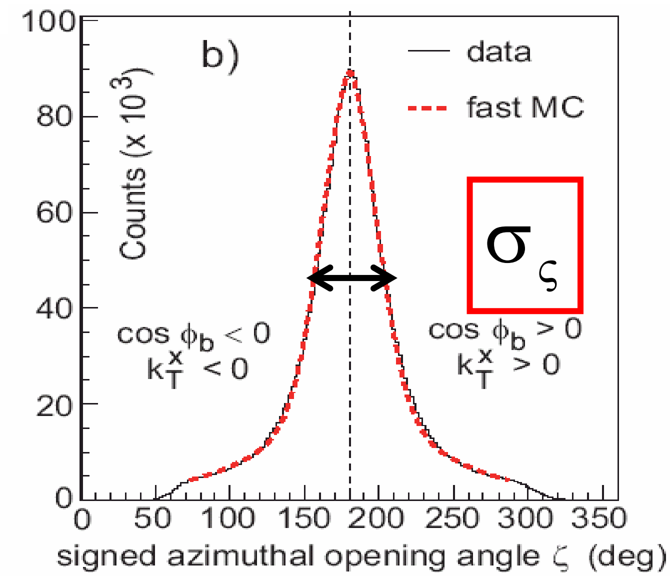
What is dominance of di-jet p_T ?

Di-jet event measurements



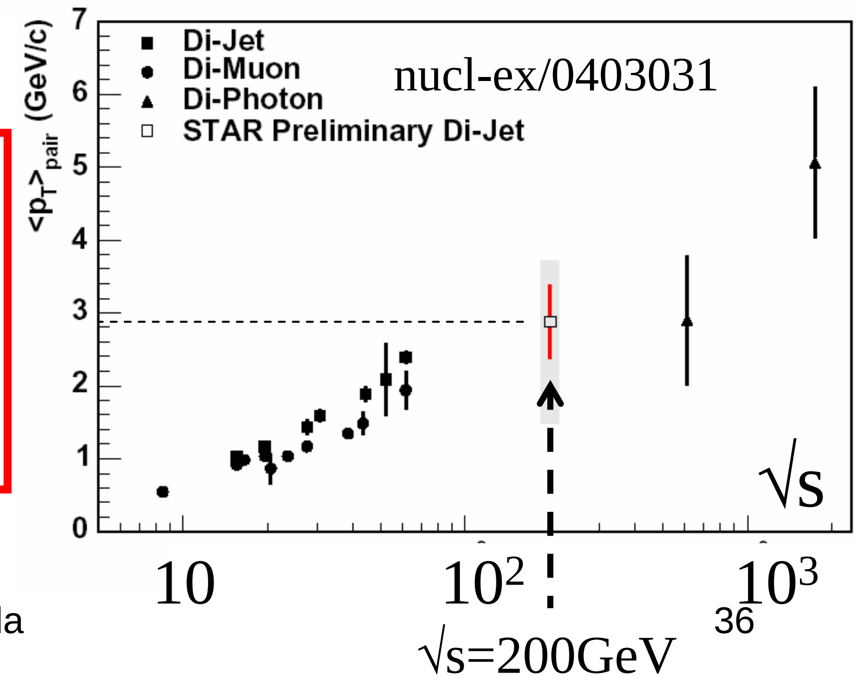
hep-ex/0705.4629



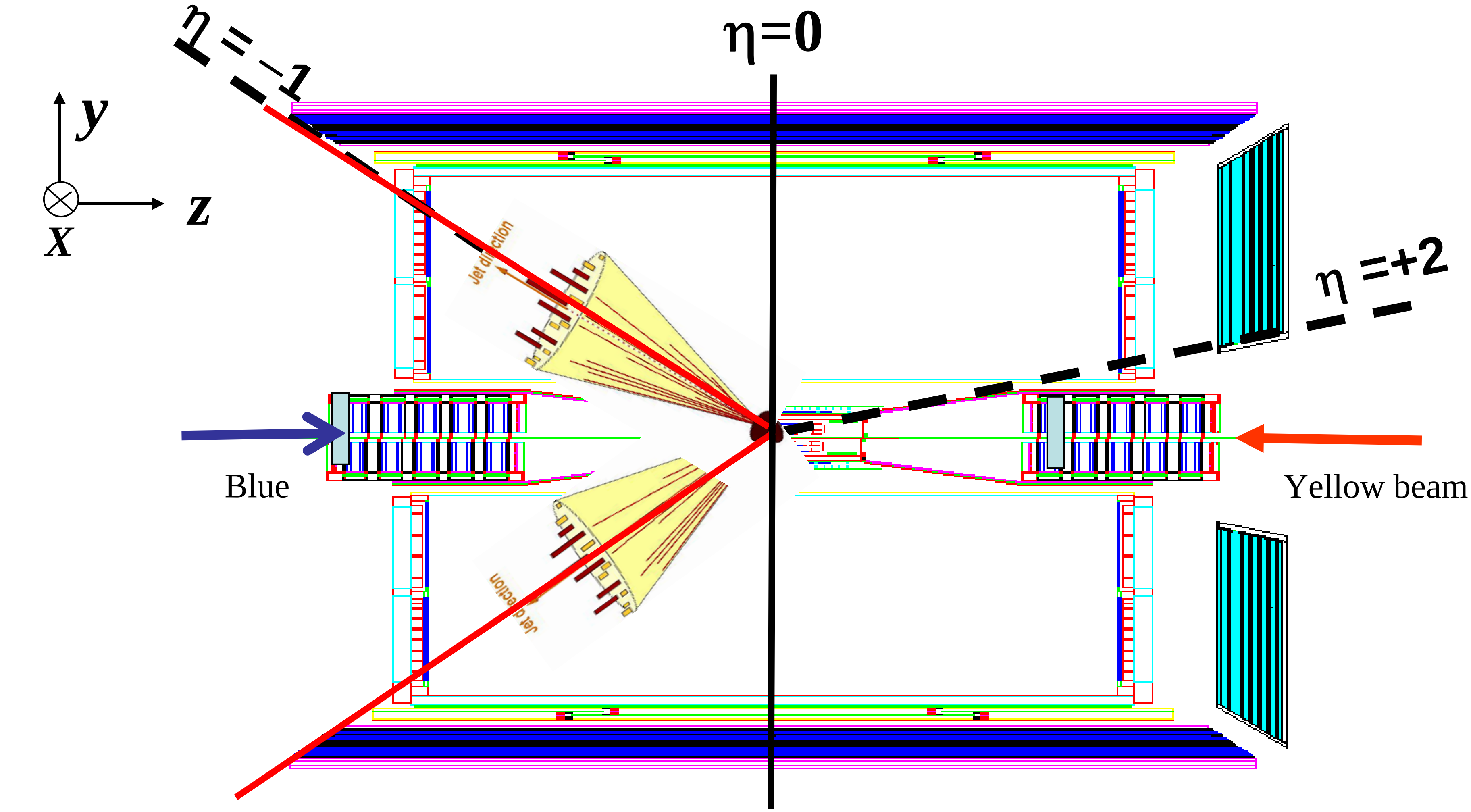


$$\langle \text{Di-jet } p_T \rangle = \frac{\pi}{2} \langle E_T \rangle \sin \sigma_\varsigma \sim 2.8\,\text{GeV}/c$$

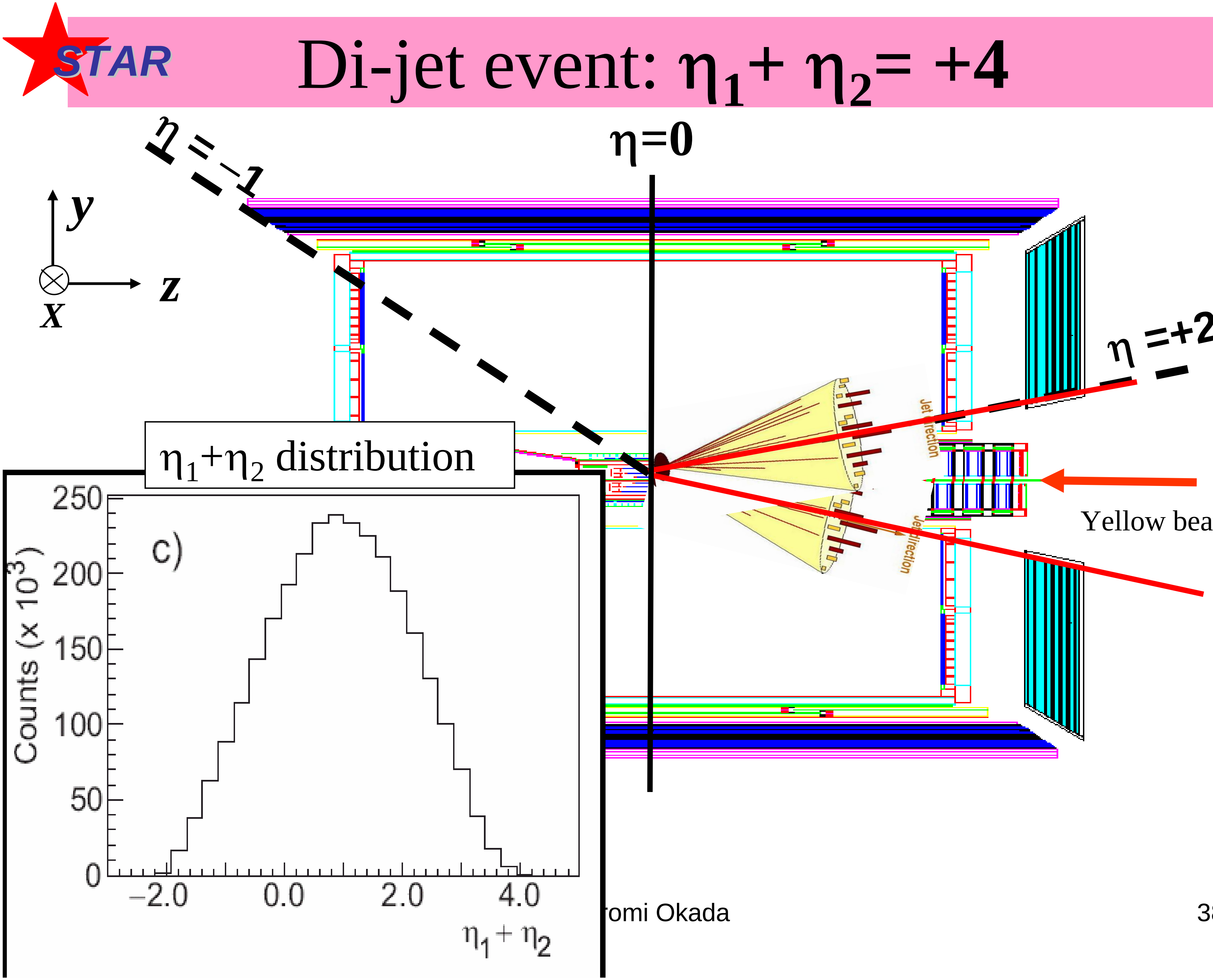
$$\text{parton} \quad \left|\vec{k}^\perp\right| \sim \frac{\hbar c}{r_p} \sim 0.2\,\text{GeV}/c$$



Di-jet event: $\eta_1 + \eta_2 = -2$

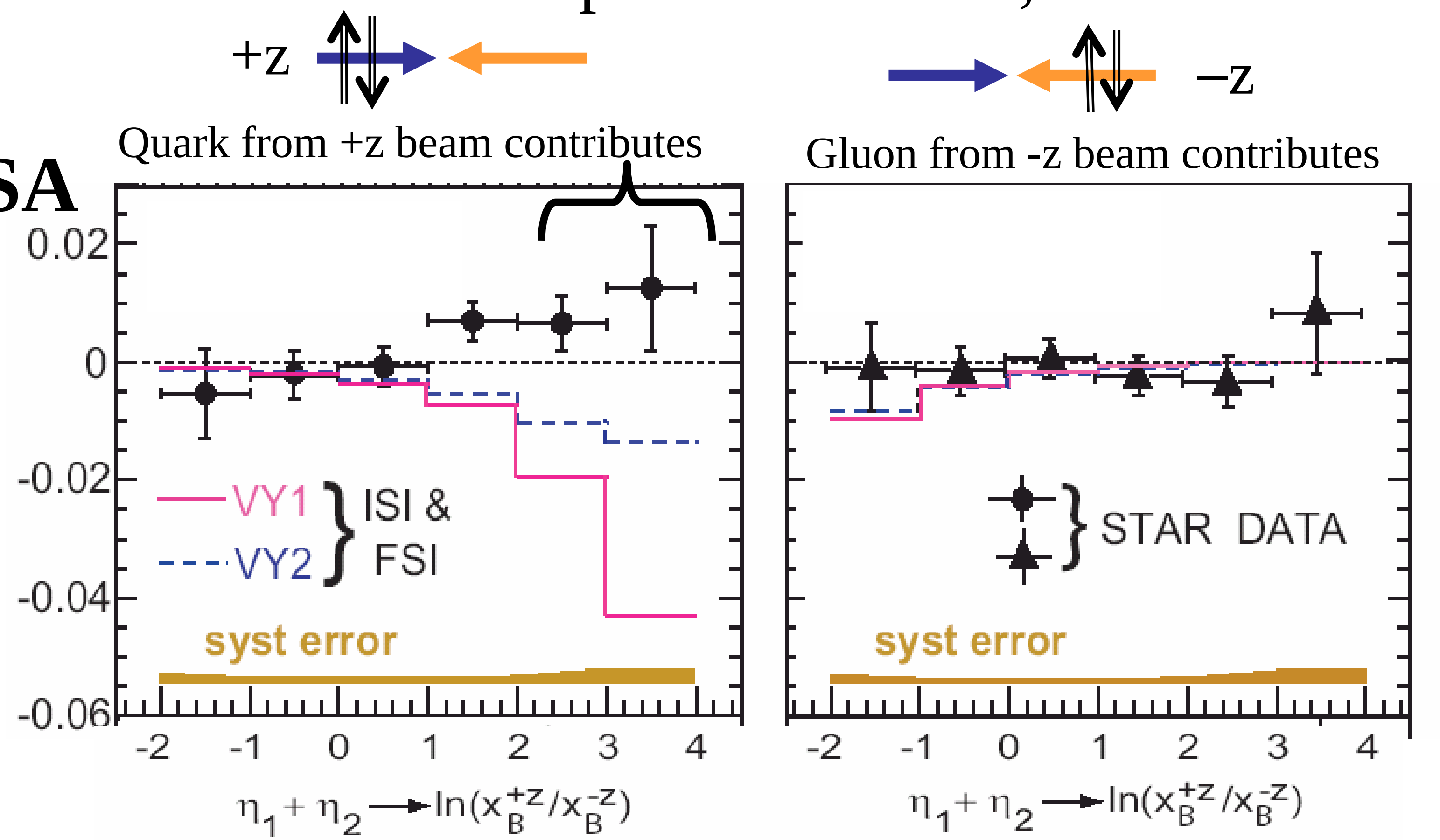


Di-jet event: $\eta_1 + \eta_2 = +4$



STAR Results vs. Di-jet Pseudorapidity Sum

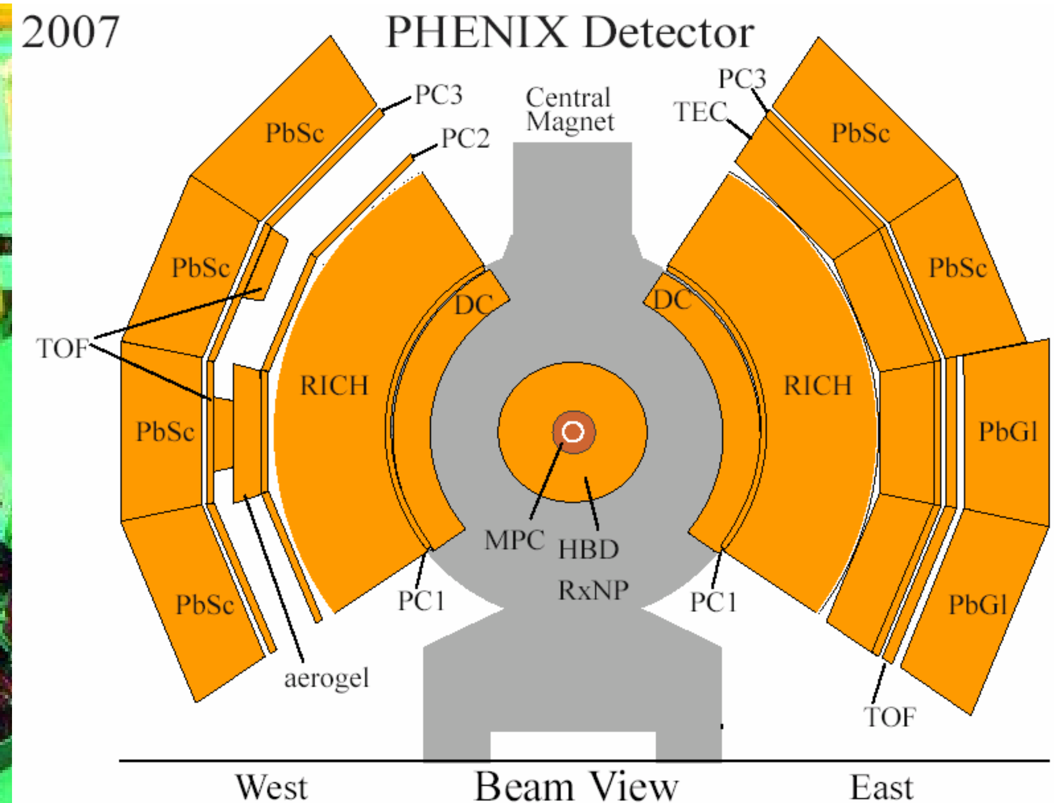
hep-ex/0705.4629, submitted to PRL.

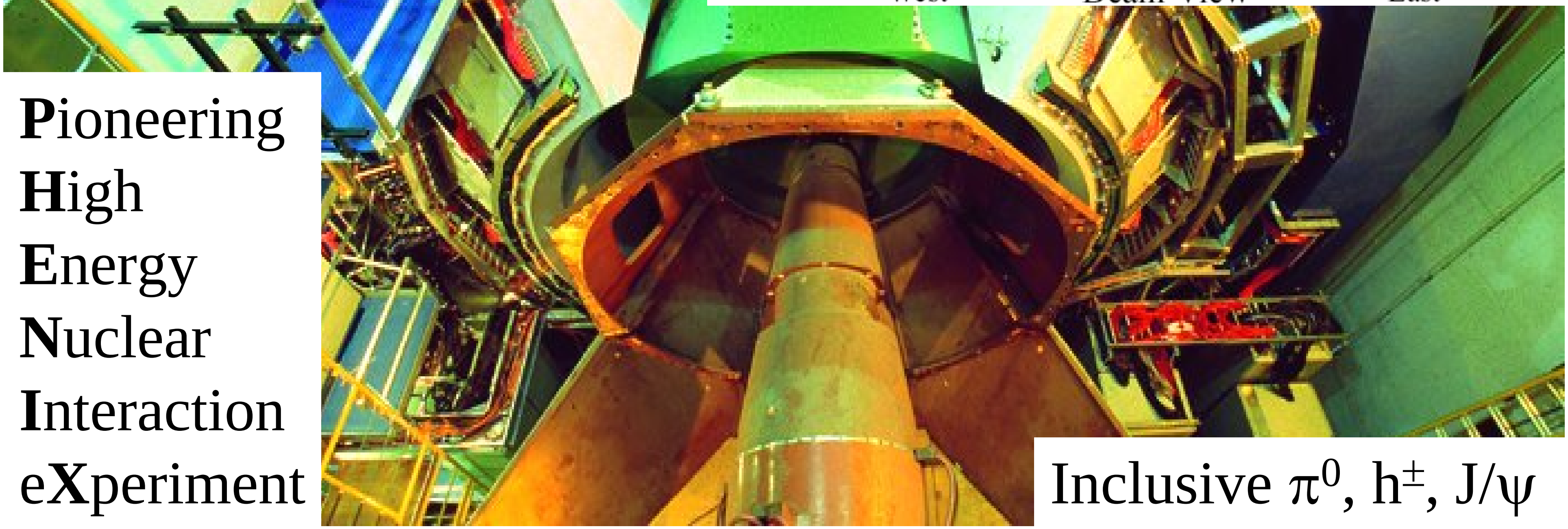


Measured di-jet SSAs are consistent with zero.

VY 1, VY 2 are calculations by Vogelsang & Yuan using HERMES-fitted quark Sivers function. PRD **72** (2005) 054028.

PHENIX

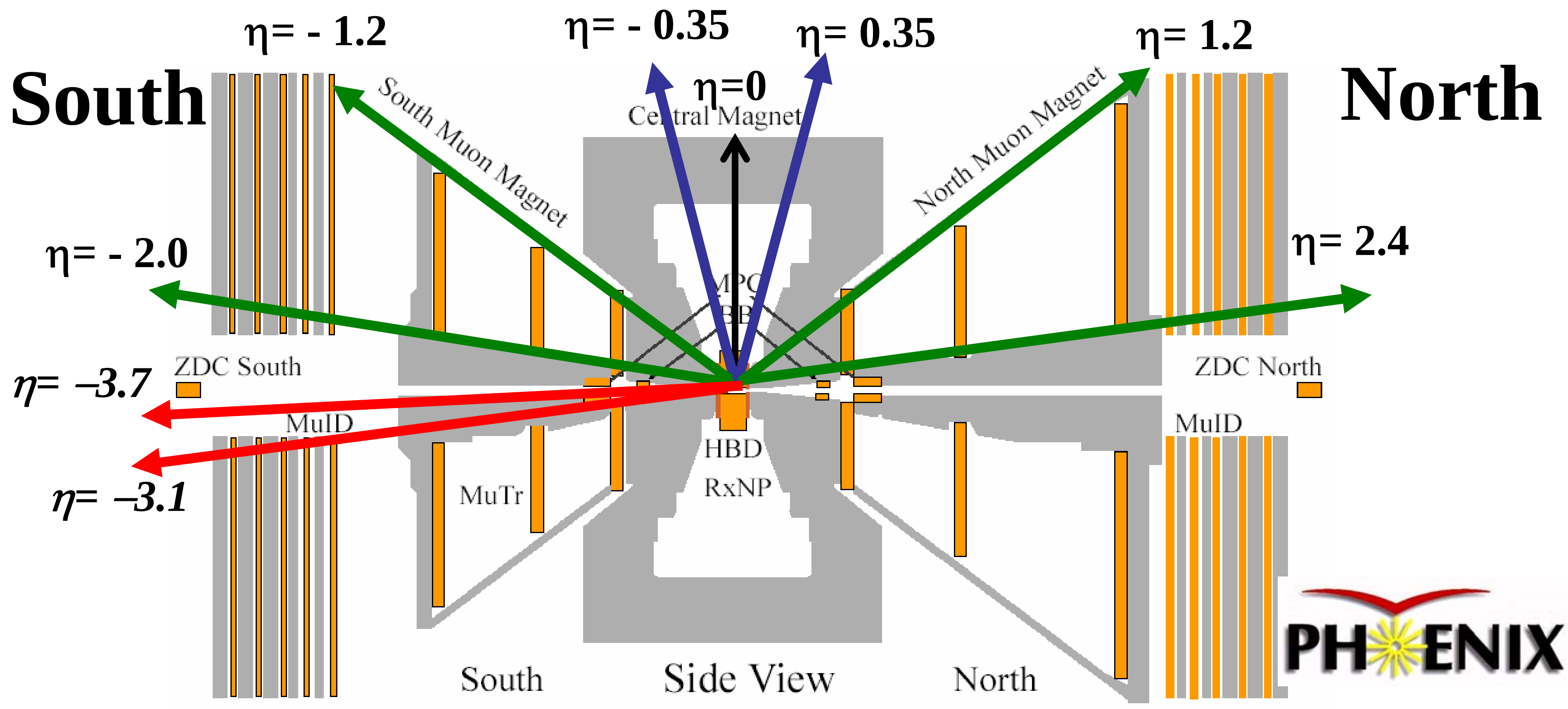




Pioneering
High
Energy
Nuclear
Interaction
e**X**periment

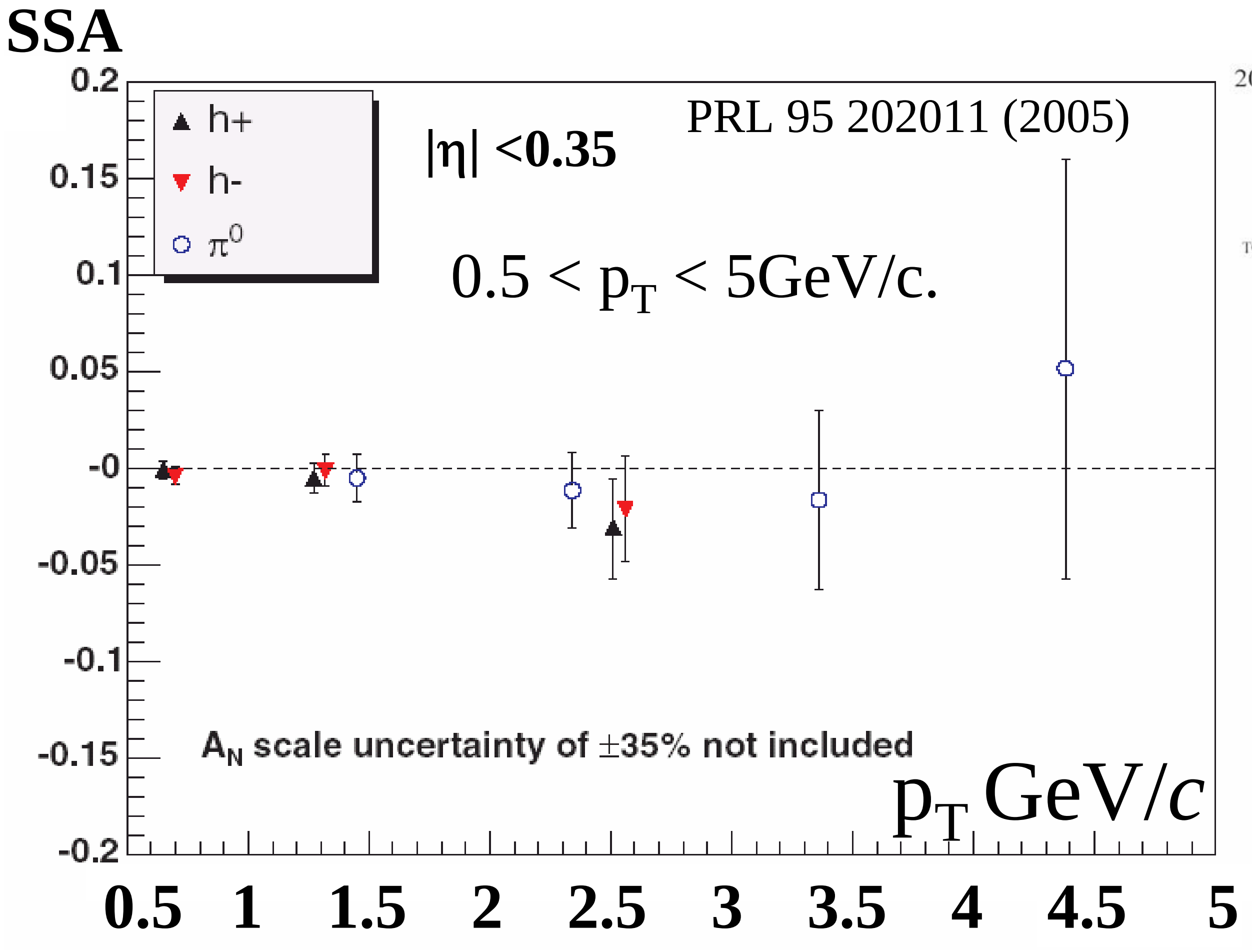
Inclusive π^0, $h^\pm$, J/ψ

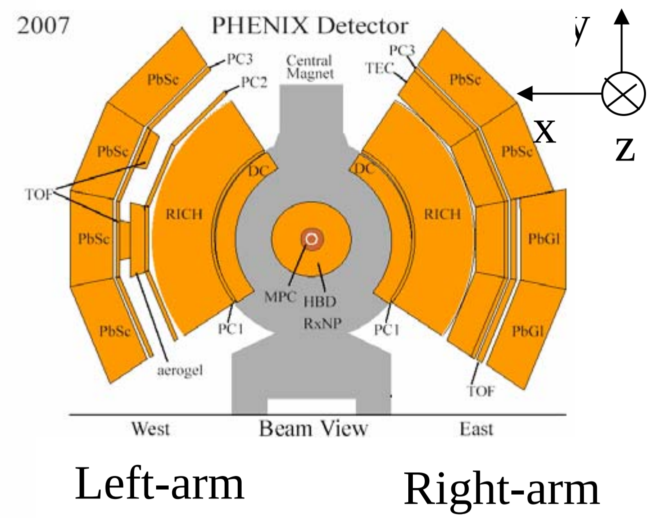
Kinematical coverage at PHENIX (Side View)



- Central-Arms: $\pi^0/h^\pm$ at $\sqrt{s}$=200GeV, $|\eta|<0.35$
- μ-Arms: J/ψ at $\sqrt{s}$=200GeV, $-2.0<\eta<-1.2$ & $1.2<\eta<2.4$
- *MPC: Inclusive π^0 at $\sqrt{s}$= 62GeV, $-3.7<\eta<-3.1$*

SSA of π^0 and $h^{\pm}$ from central-arms at $\sqrt{s}$=200GeV

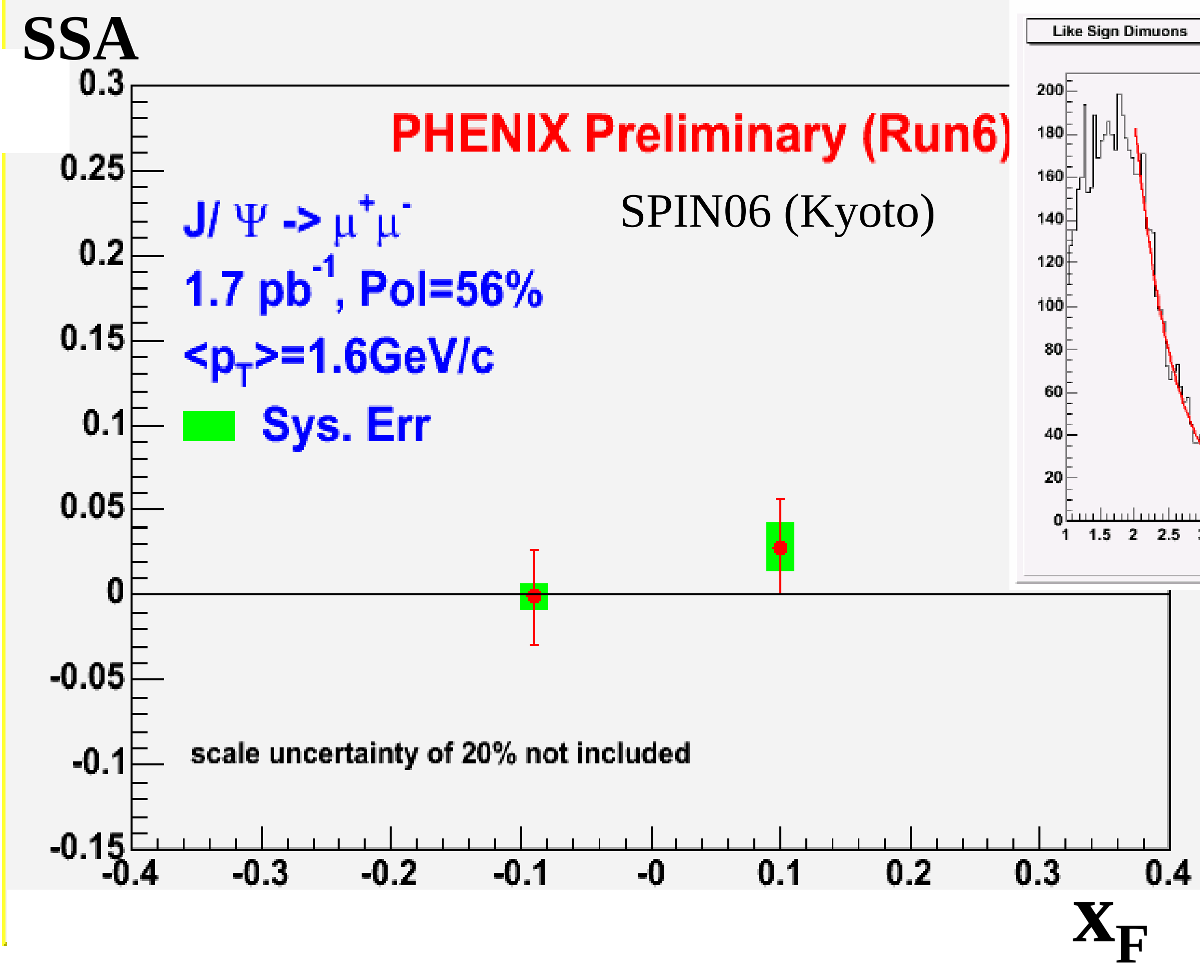


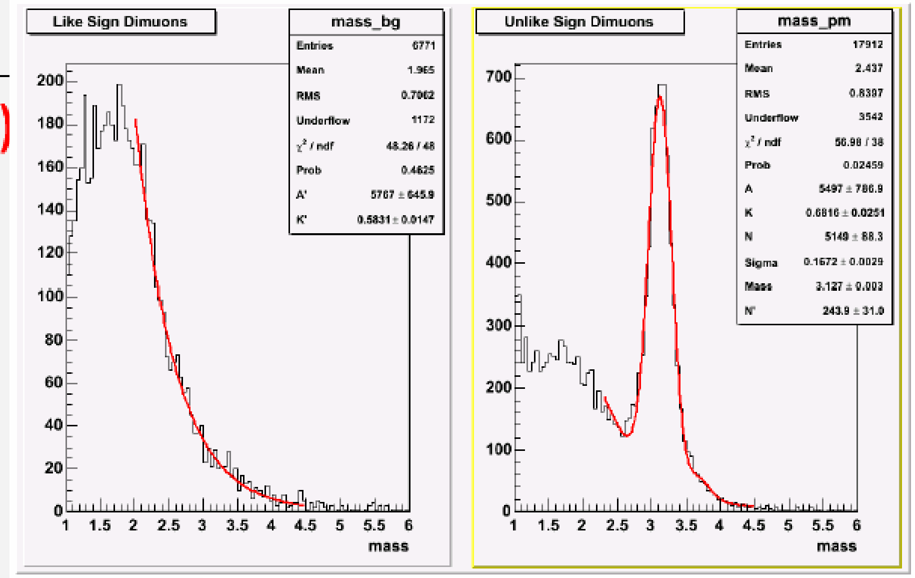


SSAs are measured by square-root-formula with two-arms (left-right) detector for either beam polarization.

- ✓ Mid-rapidity $<x_F>\sim 0$ → See "pure" p_T dependence of SSAs.
- ✓ **SSAs for mid-rapidity production of both π^0 and $h^{\pm}$ are consistent with zero.**

SSA of J/ψ from μ-arms at √s=200GeV



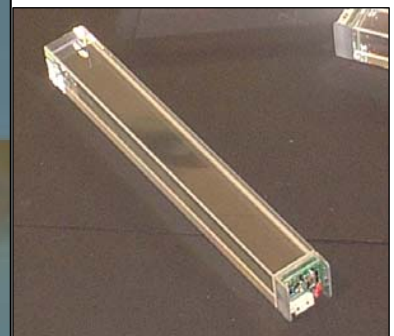


- SSAs are measured by "cross-ratio" method for either beam polarization.
- Sensitive to gluon Sivers as produced through g-g fusion

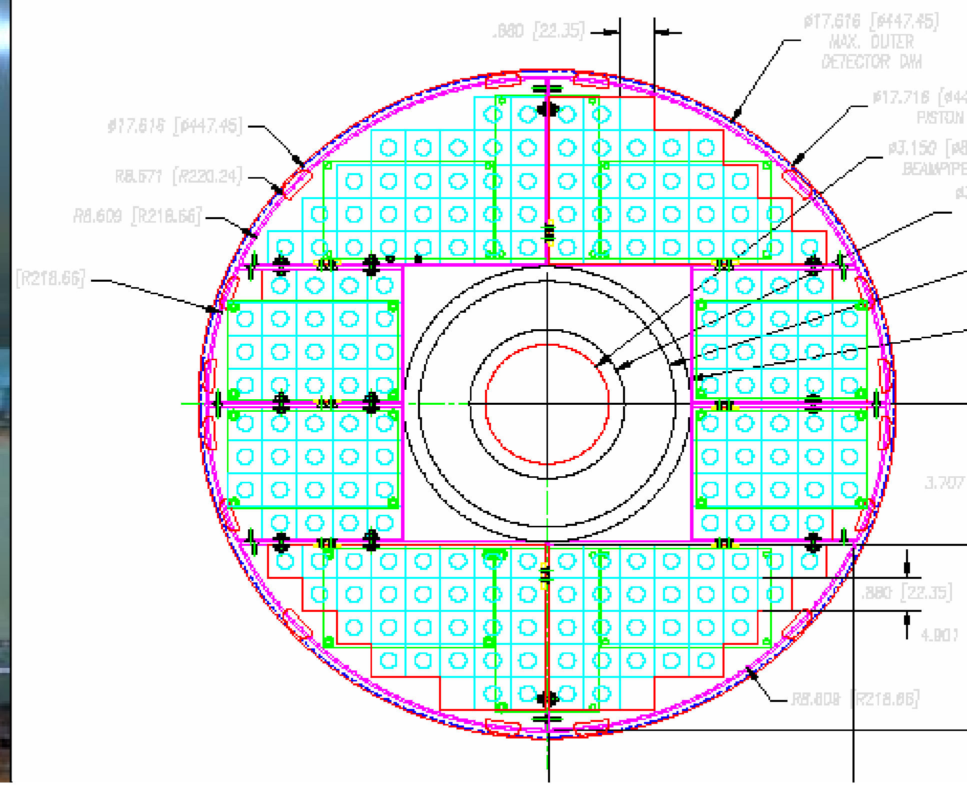
SSAs at 1.2<|η|<2.4 of J/ψ production are consistent with zero.

PHENIX Muon Piston Calorimeter

2.2×2.2 ×18 cm³

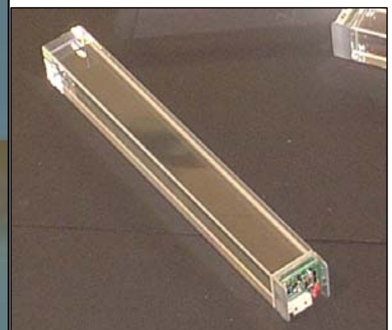


- 192 $PbWO_4$ crystals with APD readout
- Better than 80% of the acceptance is okay

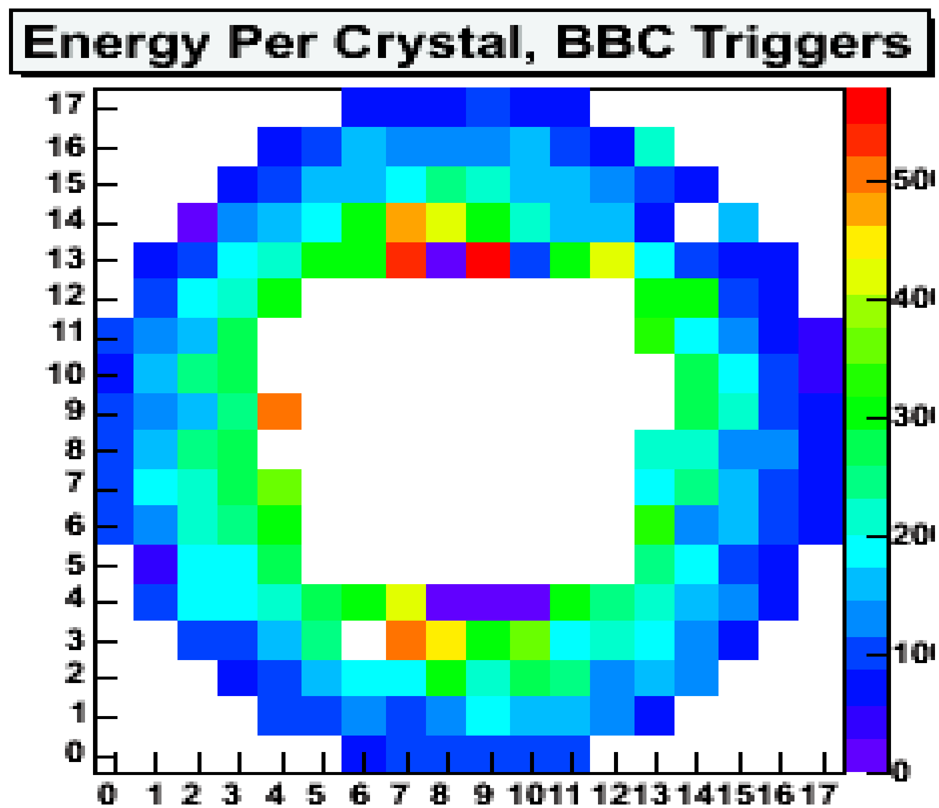


PHENIX Muon Piston Calorimeter

2.2×2.2 ×18 cm^3



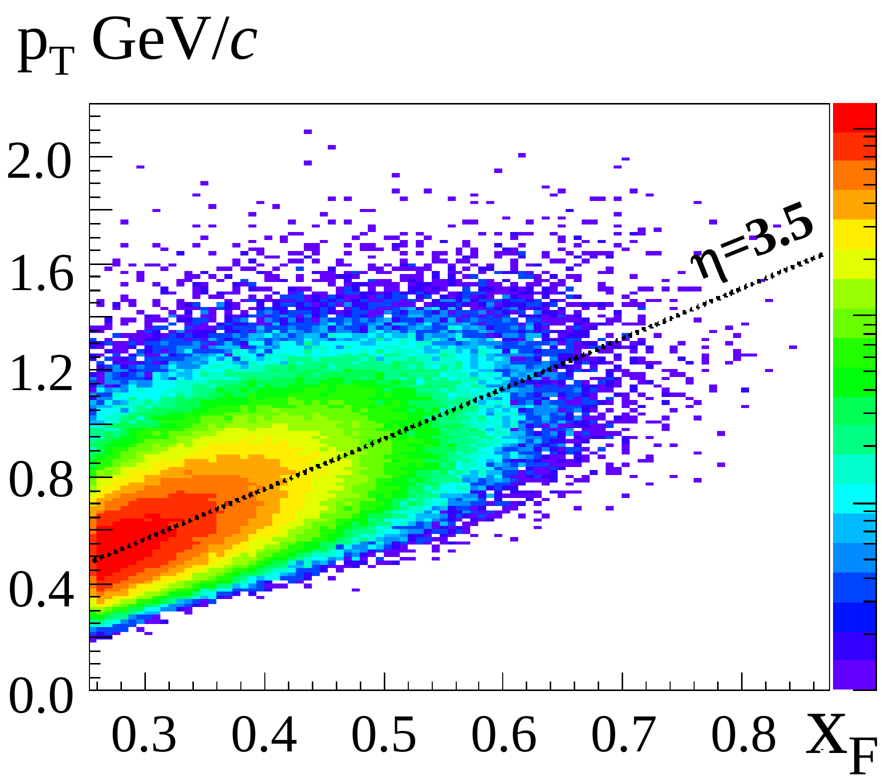
- 192 $PbWO_4$ crystals with APD readout
- Better than 80% of the acceptance is okay

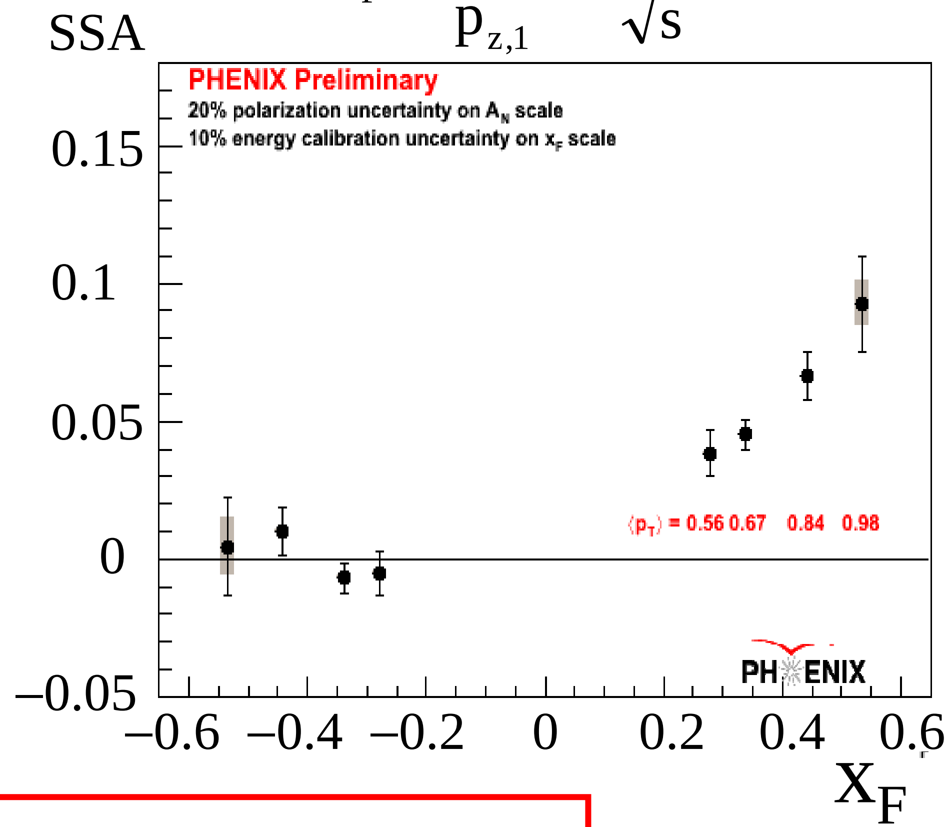


SSA at √s=62.4 GeV from Muon Piston Calorimeter (MPC)

- π^0 detection in forward direction; $3.1 < |\eta| < 3.7$
- Achieve higher x_F by decreasing √s.

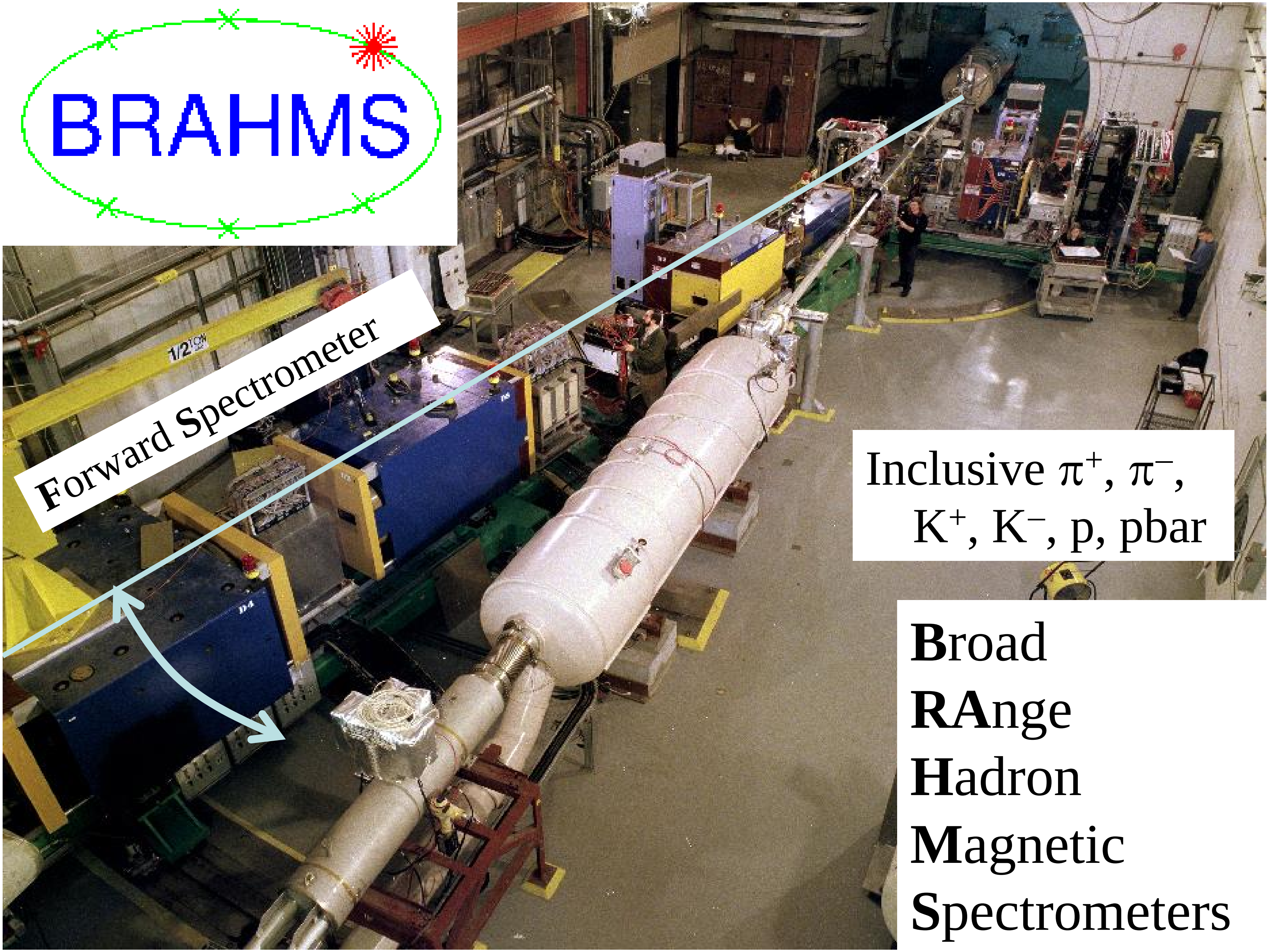
$$x_F = \frac{p_{z,\pi}}{p_{z,1}} \approx \frac{2E_\pi}{\sqrt{s}}$$





SSA survives and has similar characteristics over a broad √s region 20~ 200 GeV.

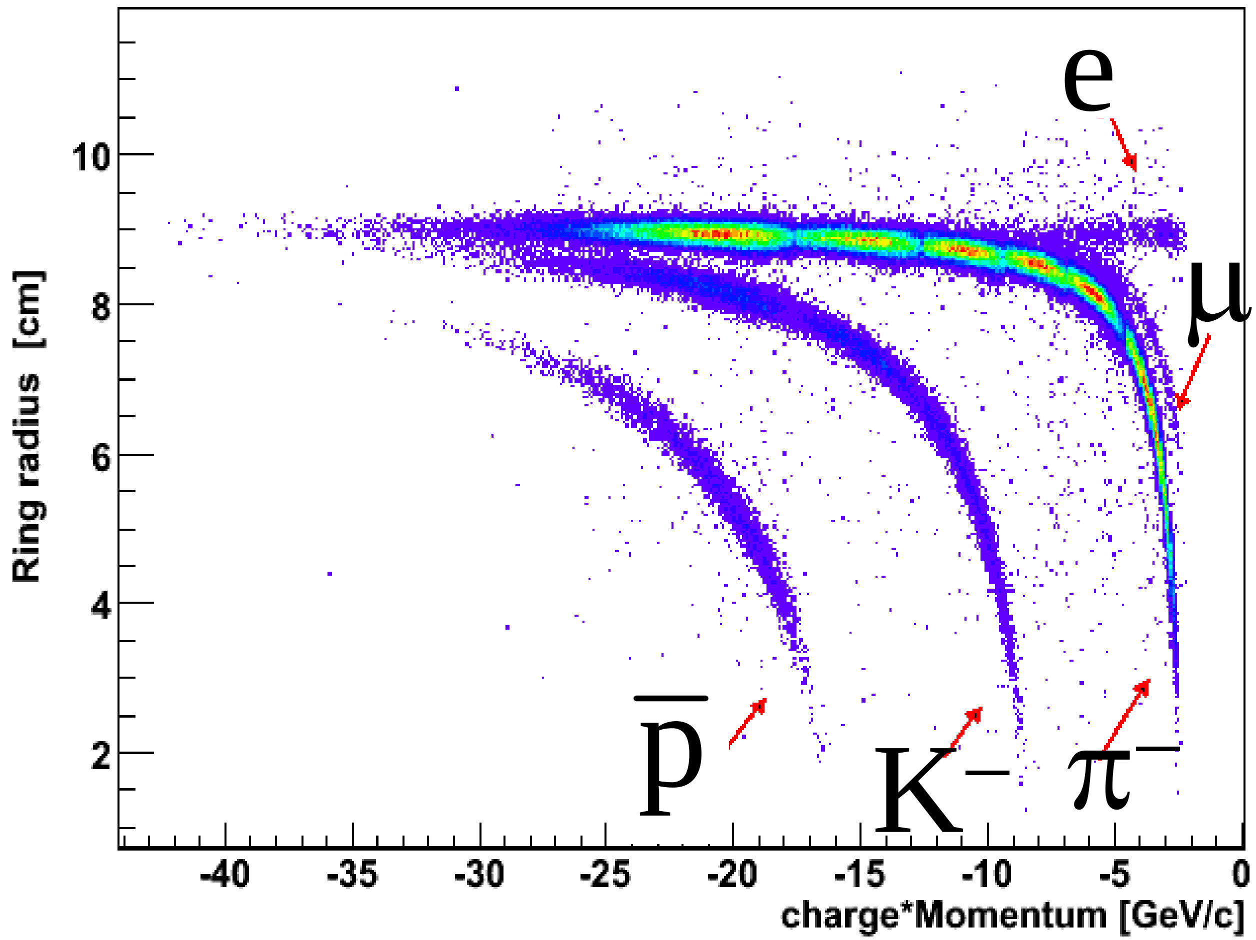
BRAHMS



Inclusive π^+, π^-, K^+, K^-, p, pbar

Broad
RAnge
Hadron
Magnetic
Spectrometers

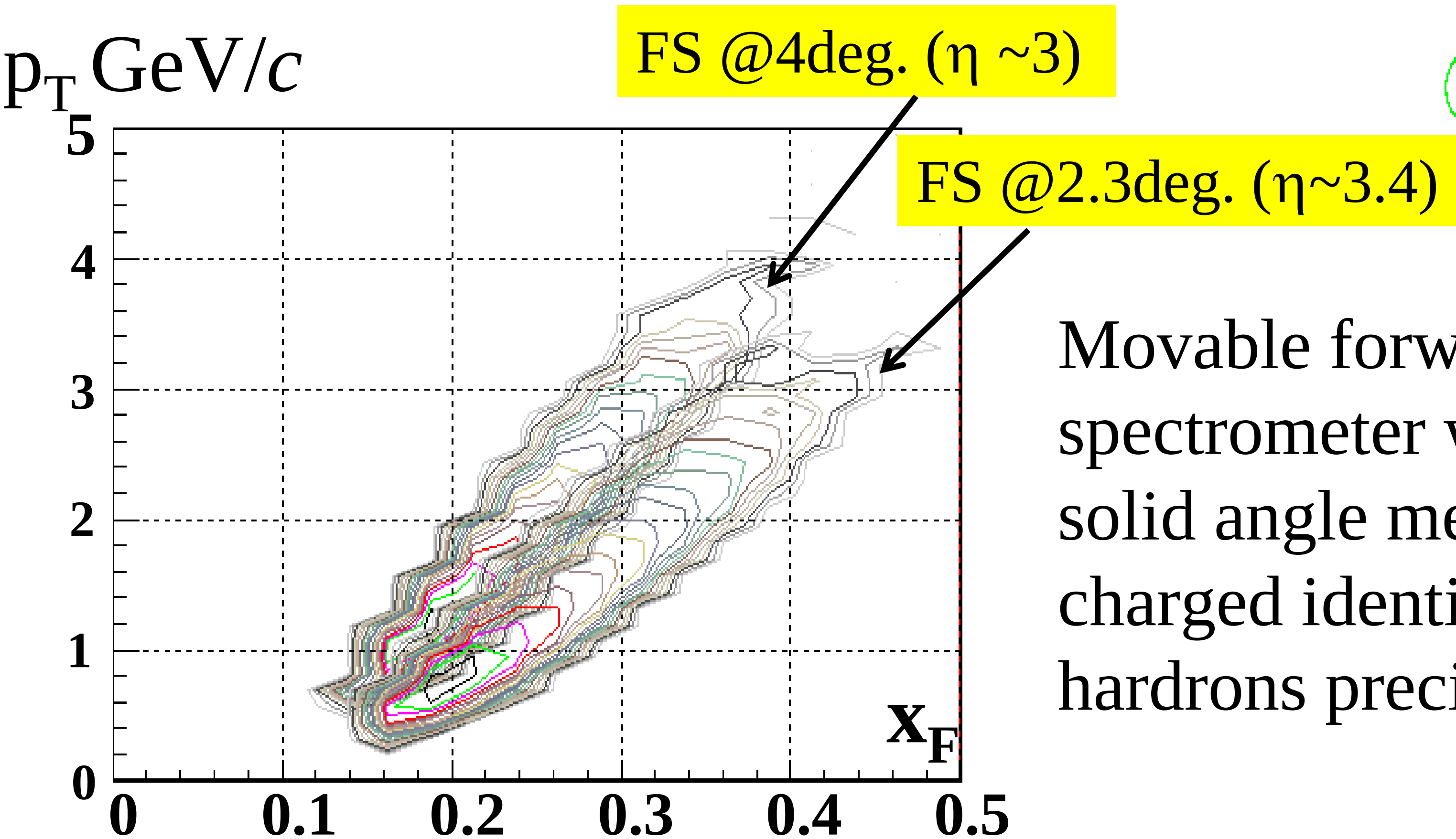
Particle Identification using RICH



p,K identification < 30 GeV/*c*, $\bar{p}$ > 17 GeV/*c* with efficiency ~ 97%

BRAHMS FS Acceptance at 2.3 deg. and 4 deg.

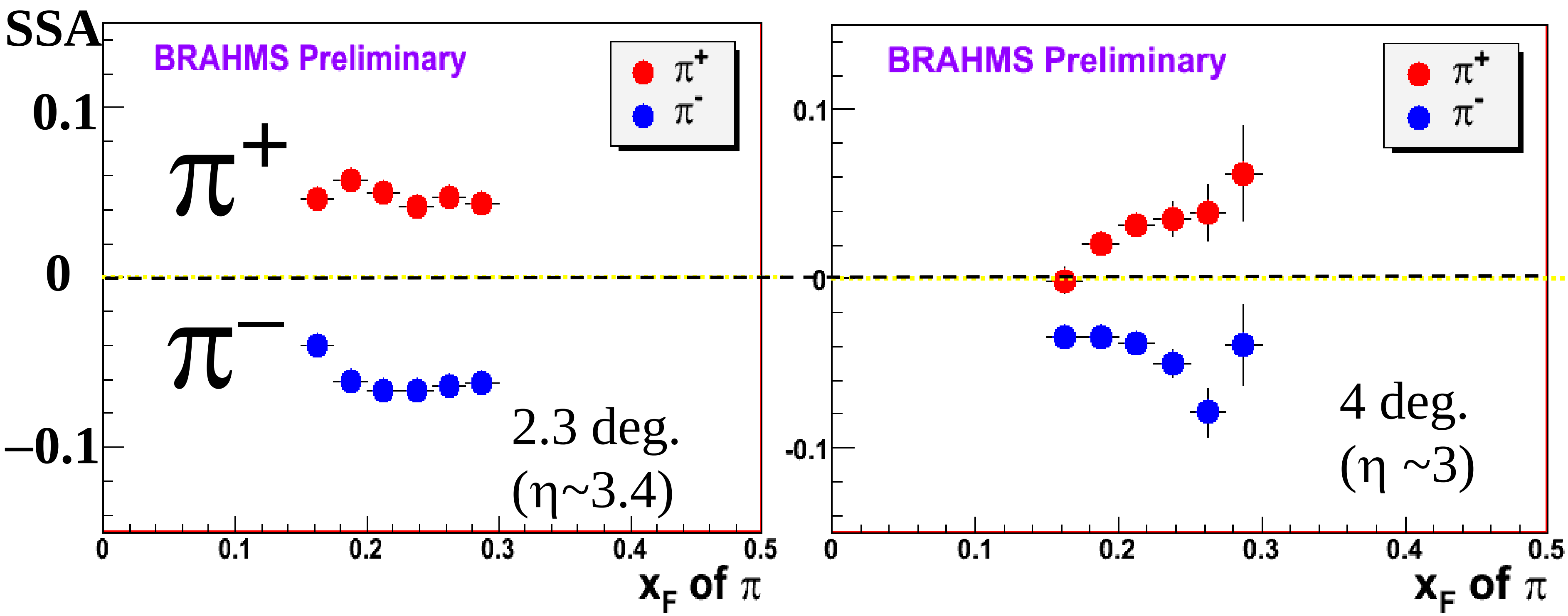
Full Field (7.2 Tm) at √s = 200 GeV



Movable forward spectrometer with small solid angle measuring charged identified hardrons precisely

- Strong x_F-p_T correlation due to limited spectrometer solid angle acceptance

$\pi^{\pm}$ SSAs at **2.3 and 4 deg.** at $\sqrt{s}$ = 200 GeV

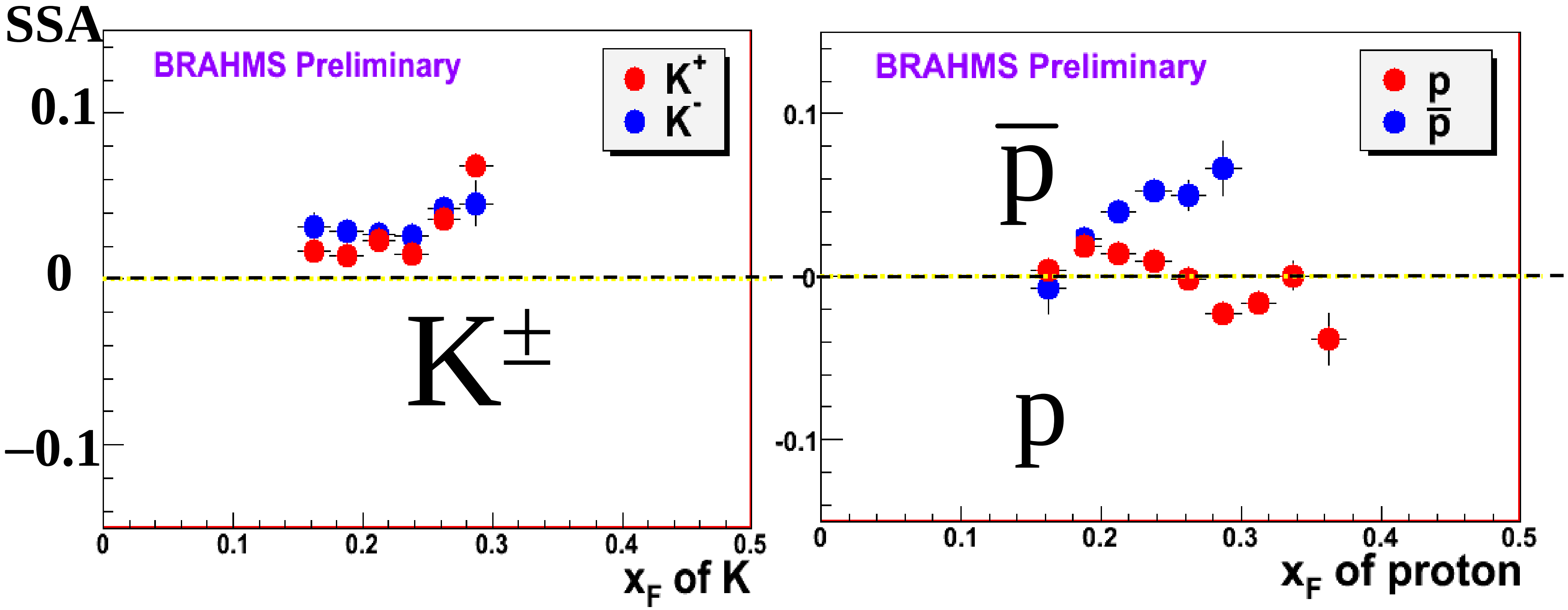


- SSA(π^+): positive
  SSA(π^-): negative

  4-6% in 0.15 <x_F< 0.3.

- SSA ($\pi^{\pm}$) survive.

SSAs at **2.3 deg.** at √s = 200 GeV

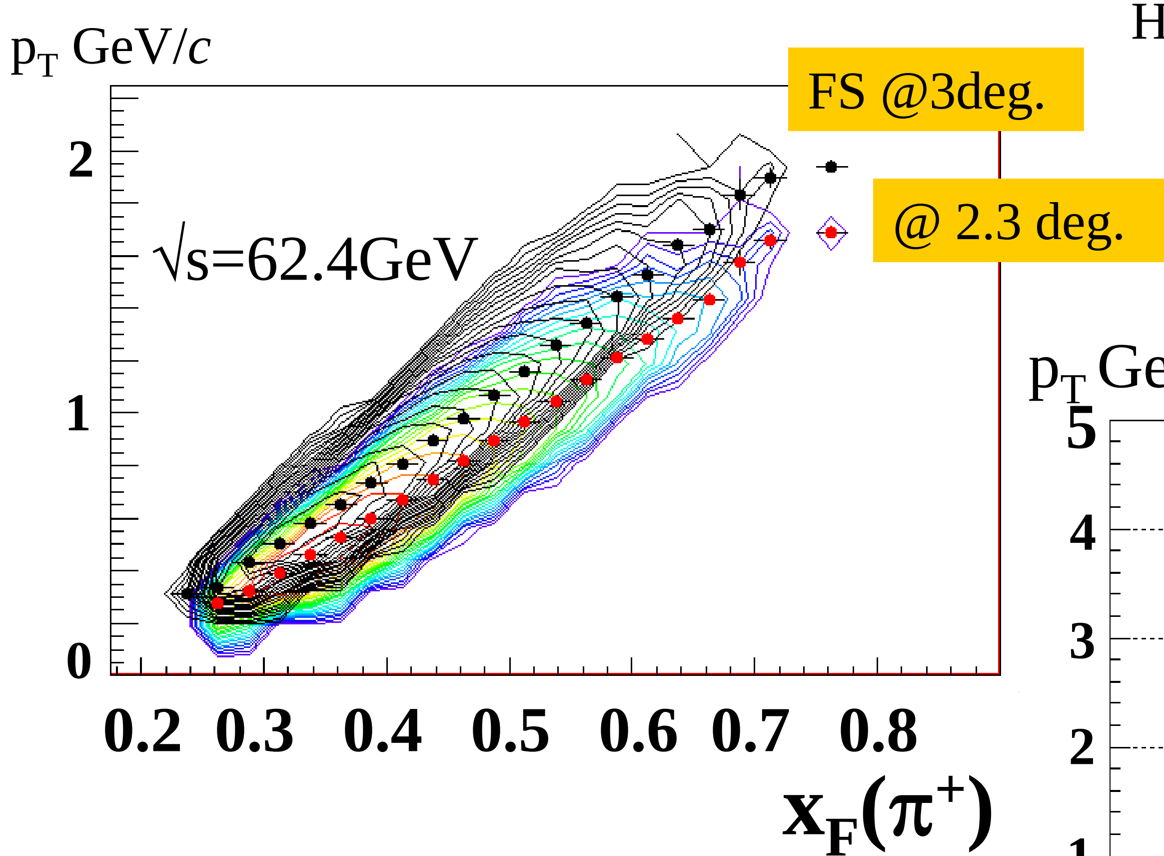


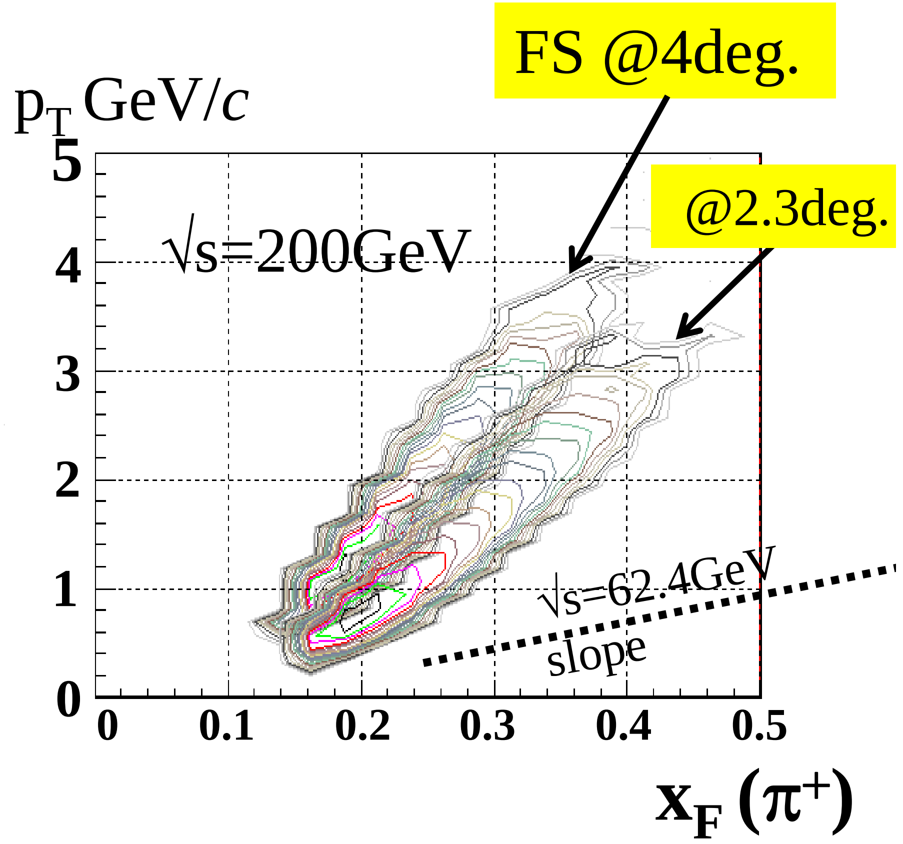
- SSA(K^+), SSA(K^-): positive 2-5% for $0.15 < x_F < 0.3$.
- SSA($\bar{p}$), SSA(K^-) > 0: Contribution from sea-quarks.
  Or Accidental?
- SSA(p) ~ 0: Significant fraction of proton can be mostly from polarized beam proton, but only ones showing SSA~0.

SSA results at $\sqrt{s}$=62.4 GeV at higher x_F

BRAHMS

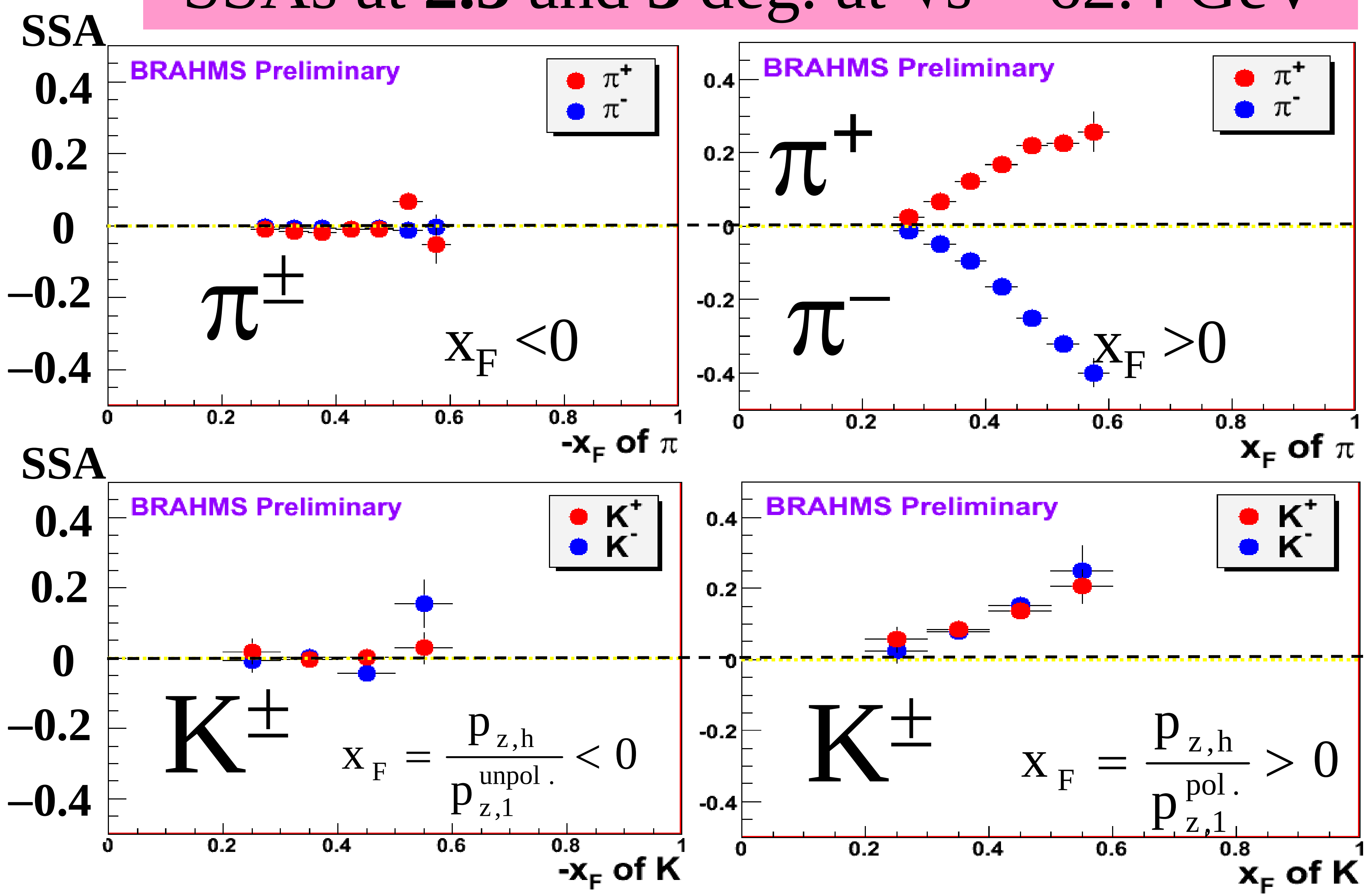
Half Field (3.6 Tm)





$$x_F = \frac{p_{z,\pi}}{p_{z,1}} \approx \frac{2E_\pi}{\sqrt{s}}$$

SSAs at **2.3** and **3** deg. at $\sqrt{s}$ = 62.4 GeV



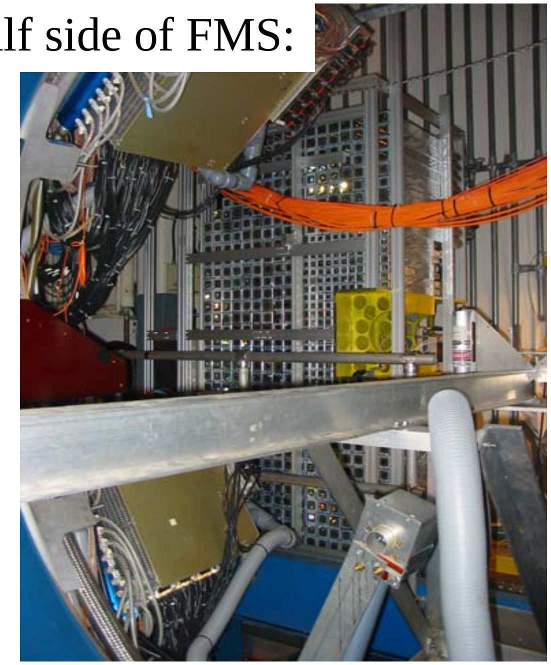
Summary from the RHIC results

1. Study of SSA in polarized *pp* collisions has begun at RHIC, where cross sections are consistent with pQCD.
2. SSAs in the mid-rapidity region are consistent with zero.
3. Sizable SSAs are measured in the forward region only.
4. First observation of p_T dependence of SSA is performed in pQCD region.
   - An increase of SSA with increasing p_T is observed.
   - This is contrary to the theoretical expectation.
5. Interaction between experiment and theory is ongoing and critical.

Forward physics is very exciting !

Outlook

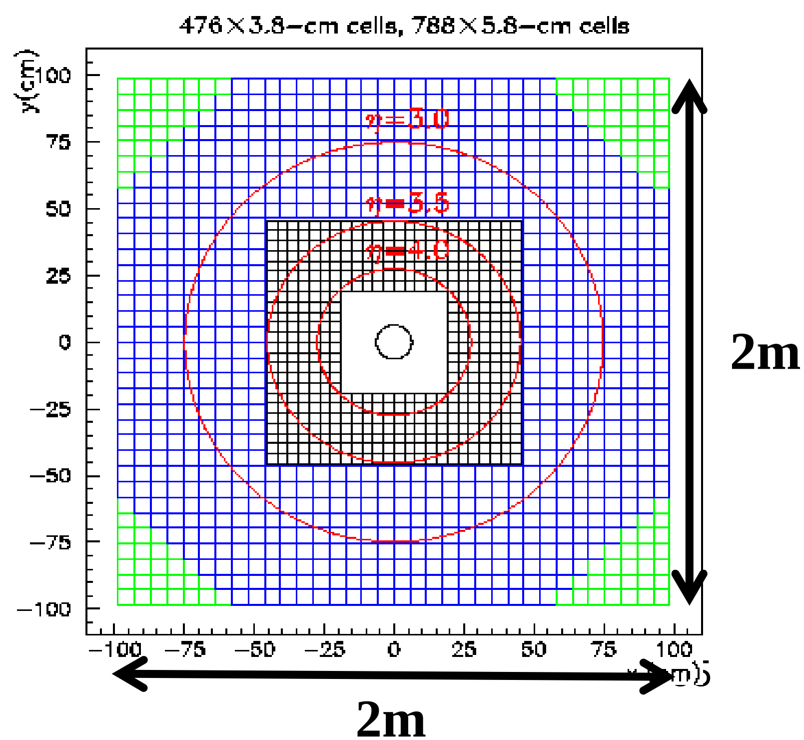
Half side of FMS:



A) Continue study of p_T dependence of SSA using **F**orward **M**eson **S**pecrometer at the STAR in RUN8. → more than factor 25 increase of acceptance for triggered events !

B) Sivers/Collins separation by choosing proper process.
- Orbital motion via Sivers mechanism.
- Transversity via Collins mechanism.

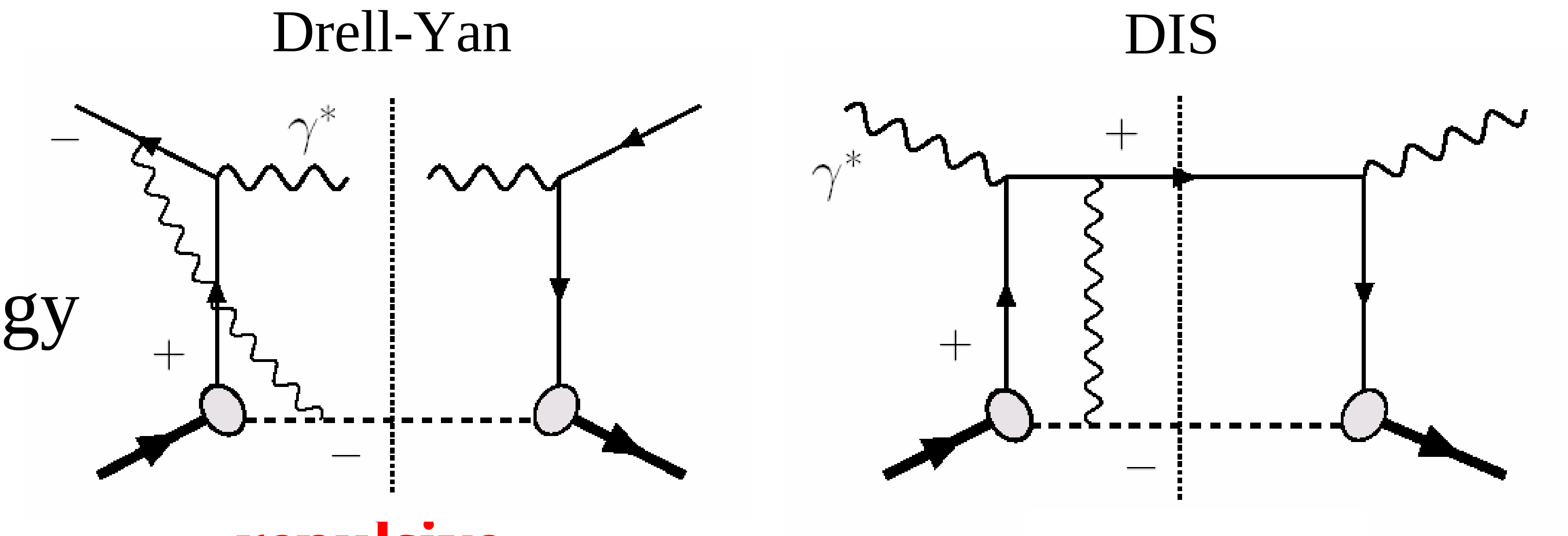
C) Confirm **"color charge"** via SSA-Sivers effect in Drell-Yan process. (Needs tracking)



C) Confirm color charge via SSA-Sivers effect.

http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

QED analogy



repulsive **attractive**

$$f_{1T}^{\perp}\left(x,\vec{k}_q^{\perp}\right)\Big|_{DY} = -f_{1T}^{\perp}\left(x,\vec{k}_q^{\perp}\right)\Big|_{DIS}$$

The non-universality of the Sivers functions expects opposite sign between DY and DIS processes.

Forward physics is very very exciting !

Thank you!!