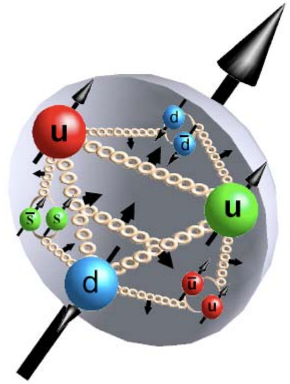
Transverse Spin program at STAR

involving possible Collins and Sivers effects



Mirko Planinić

University of Zagreb

Prague, July 20 - July 26, 2008

RHIC Spin Goals - I

How is the proton built from its known quark and gluon constituents?

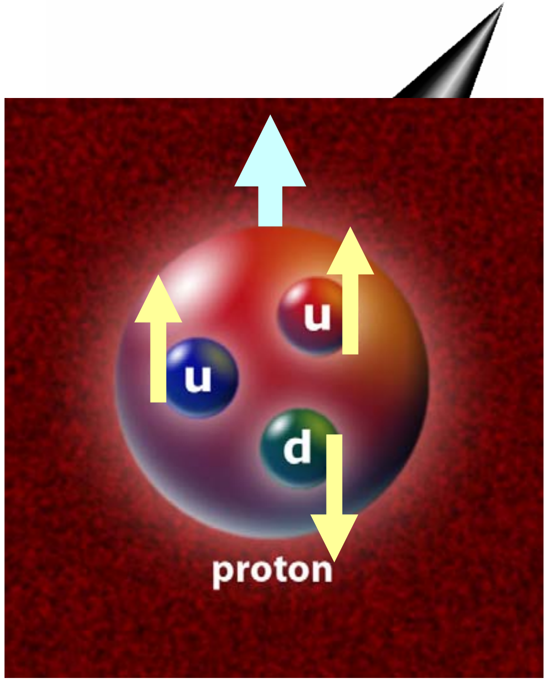
As with atomic and nuclear structure, this is an evolving understanding

In QCD: proton is not

just 3 quarks !

Recall:

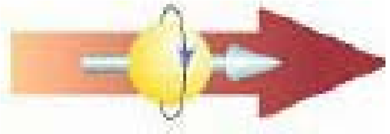
simple quark model



Rich structure of quarks

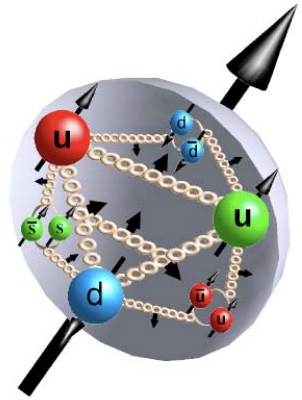
anti-quarks, gluons

RHIC Spin Goals II



Longitudinal Spin

$$J = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^g$$

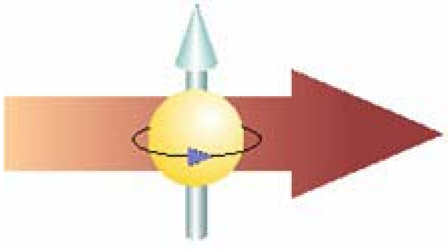


- $\Delta\Sigma = \Delta u + \Delta d + \Delta s + \ldots$, Quark Contribution
- ΔG, Gluon Contribution
- L_z^q, Quarks orbital angular momentum
- L_z^g, Gluons orbital angular momentum

Frank Simon talk

RHIC Spin Goals III

Transverse Spin



PRD 70 (2004) 114001

For a proton with transverse spin vector $\vec{S}_T$

$$\frac{1}{2} = \frac{1}{2}\sum_{q,\bar{q}}\int dx \Delta_T q^a(x) + \sum_{q,\bar{q},G}\left\langle L_{\vec{S}_T}\right\rangle^a$$

$L_{\vec{S}_T}$ Component of partonic orbital angular momentum *L* along $\vec{S}_T$

$\Delta_T q^a(x)$ quark transverse spin distribution in the nucleon

Understanding the origin of proton spin helps to understand its structure.

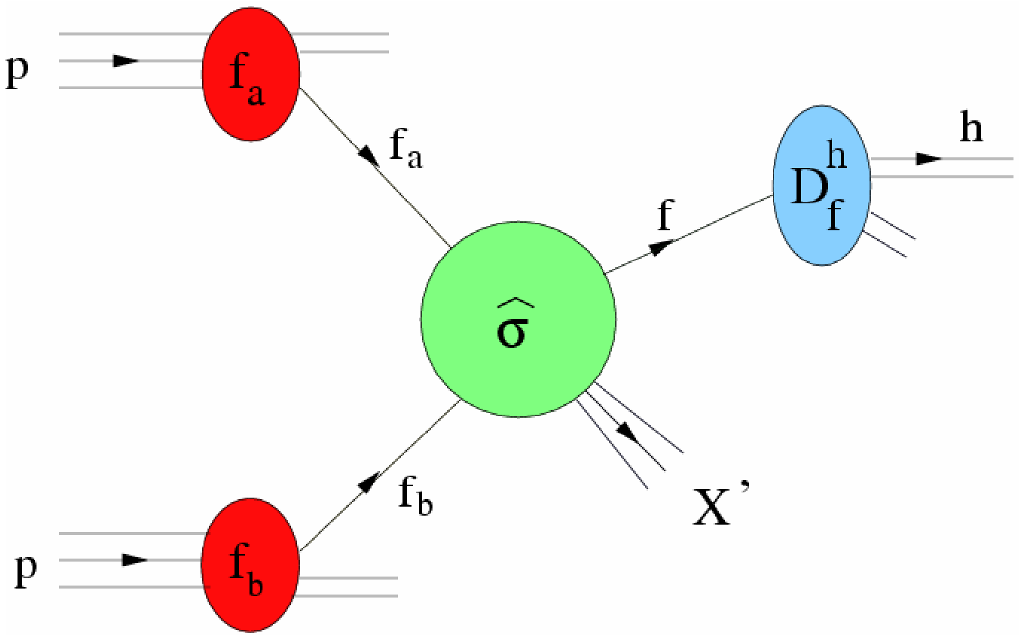
RHIC Spin Goals - IV

- Direct measurement of flavor identified *anti-quark polarization* using *parity violating production of* $W^{\pm}$

This talk

- *Transverse spin:* connections to partonic orbital angular momentum **L** and transversity Δ_T

Hard scattering of protons



π

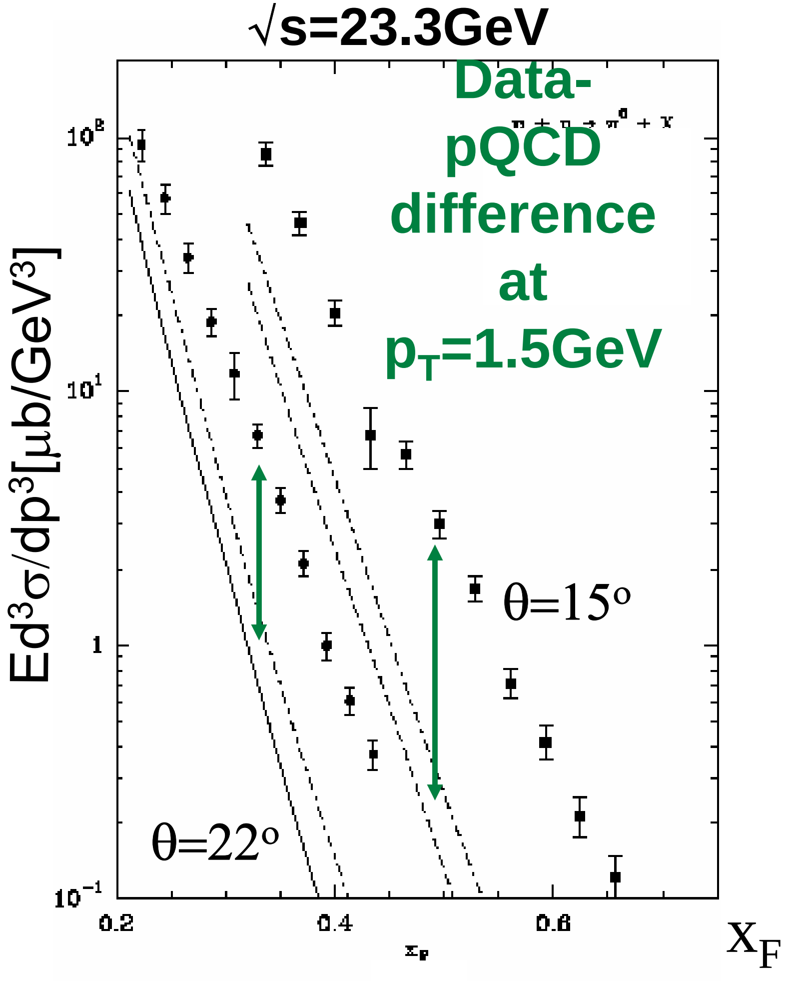
or Jet

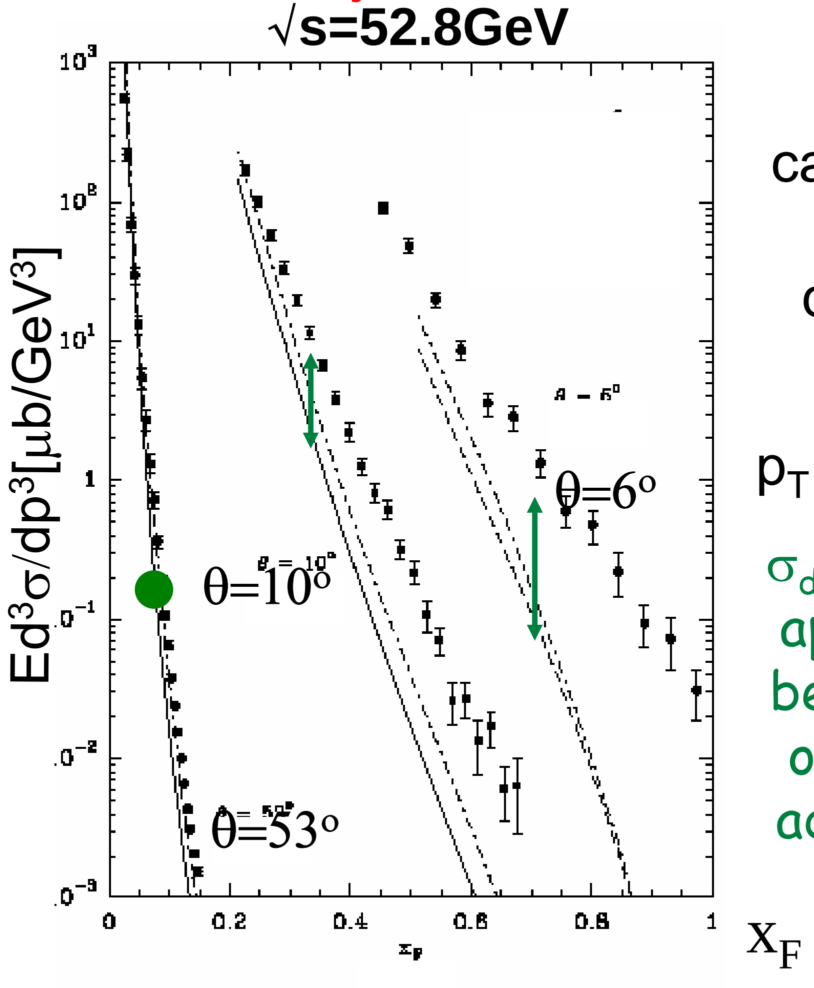
$$d\sigma = \sum_{a,b,c} \int dx_a \int dx_b \int dz_c f_a(x_a,\mu) f_b(x_b,\mu) D_c^{\pi}(z_c,\mu) \times d\hat{\sigma}_{ab}^{c}(x_a P_A, x_b P_B, P_\pi / z_c, \mu)$$

Using perturbative QCD at NLO and *universal* parton distribution functions and fragmentation functions. RHIC energy $\sqrt{s} = 200$ GeV.

But, do we understand forward π^0 production in p + p?

At $\sqrt{s}$ << 200 GeV, not really….





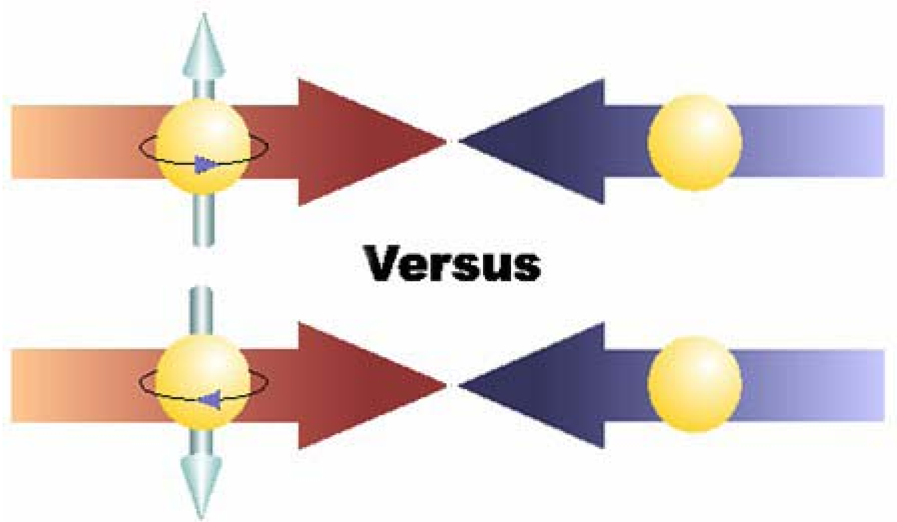
2 NLO calculation with different scale:

p_T and $p_T/2$

$\sigma_{data}/\sigma_{pQCD}$ appears to be function of θ, $\sqrt{s}$ in addition to p_T

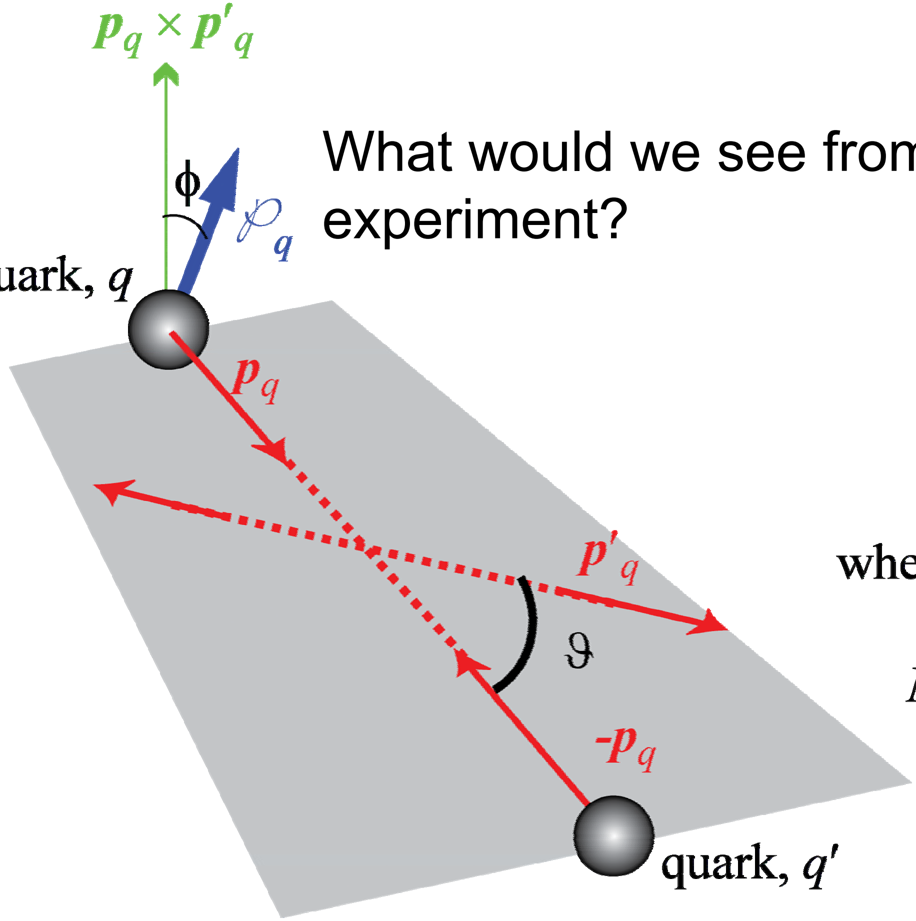
Bourrely and Soffer (Eur. Phys. J C36 (2004) 371):
NLO pQCD calculations underpredict the data at low $\sqrt{s}$

Transverse Single-Spin Asymmetries (A_N)



$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

Expectations from Theory



What would we see from this gedanken experiment?

$$N(\vartheta,\phi) = N_0(\vartheta)\,[1 + \wp_q A_N \cos\phi]$$

$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

where, $\wp_q$ is quark transverse polarization;
$A_N \propto \mathrm{Im}(NF^*)$;
N is the non-*helicity*-flip amplitude;
and F is the *helicity*-flip amplitude

$F \to 0$ as $m_q \to 0$ in vector gauge theories, so $A_N \sim m_q/p_T$

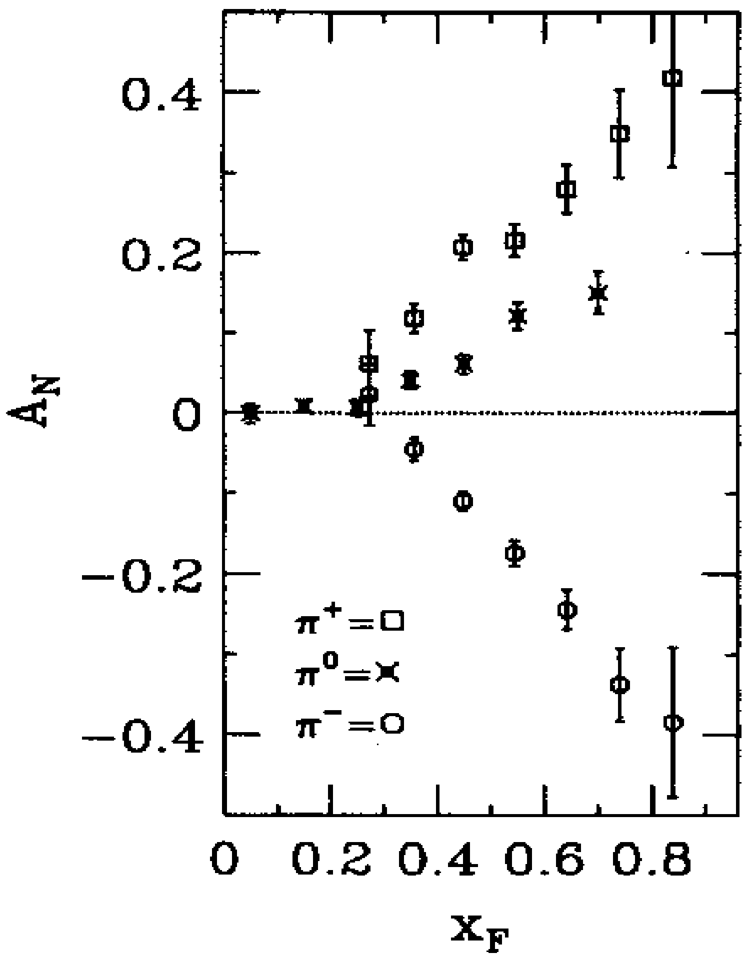
or, $A_N \sim 0.001$ for $p_T \sim 2$ GeV/c

Kane, Pumplin and Repko PRL **41** (1978) 1689

History

$p_{\uparrow} + p \rightarrow \pi + X$

√s=20 GeV, p_T=0.5-2.0 GeV/c



•QCD theory expects small $A_N \sim 0.001$ transverse single spin asymmetries

•E-704 (Fermilab) – fixed target

Remember from slide 7 that:

Cross-section is NOT consistent with NLO pQCD calculations

π^0 – E704, PLB261 (1991) 201.

$\pi^{+/-}$ - E704, PLB264 (1991) 462.

Transverse Single-Spin Asymmetries

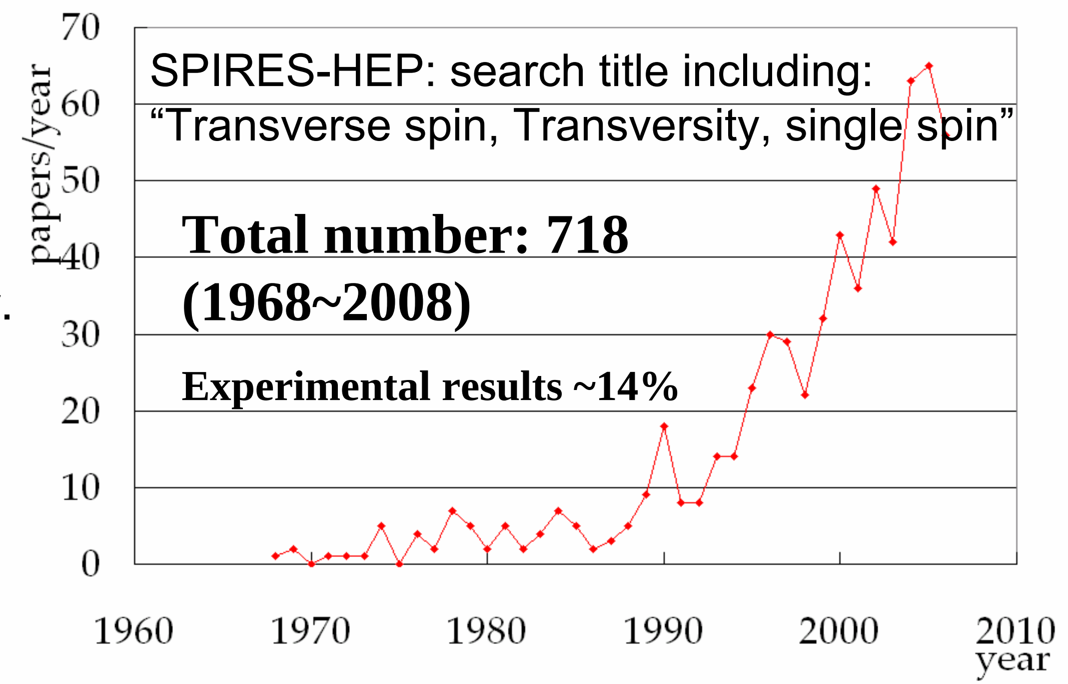
World-wide experimental and theoretical efforts

- Transverse single-spin asymmetries are observed in semi-inclusive deep inelastic scattering with transversely polarized proton targets

  ⇒ HERMES (e); COMPASS (μ); and planned at JLab

- Intense theory activity underway

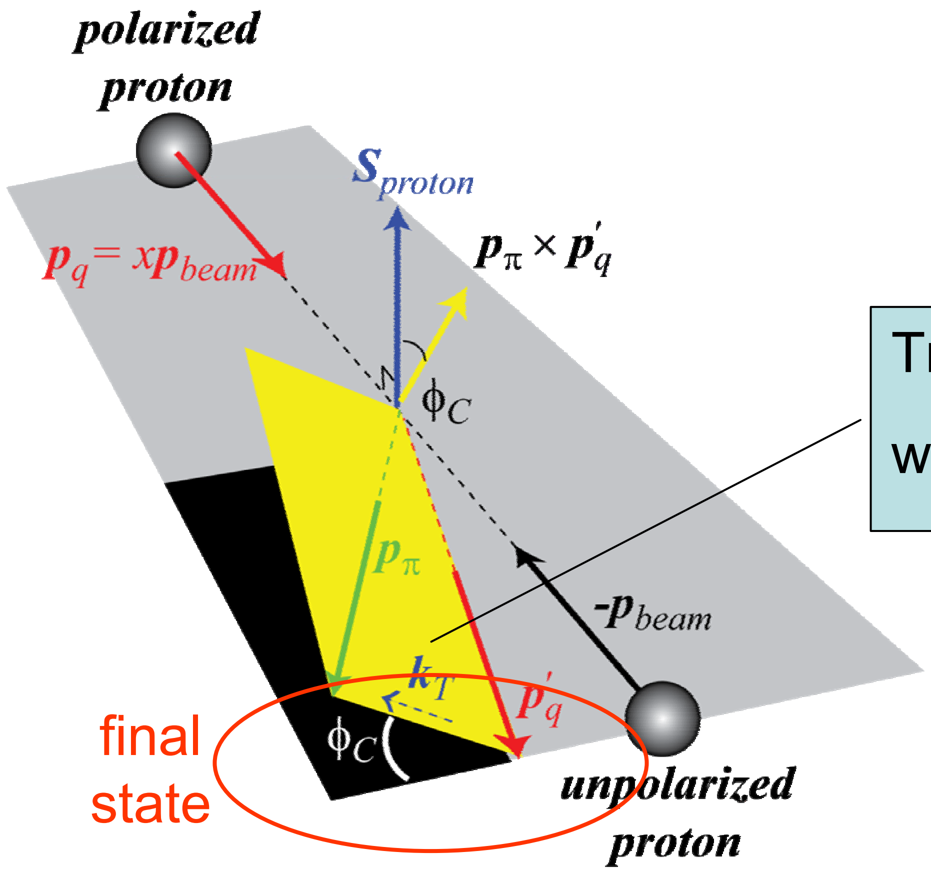
•Four theory hires in "permanent" positions in the US within the past year. All four were transverse spin theorists.



Possible explanations for Large Transverse SSA

Collins/Hepplemann mechanism [Nucl. Phys. B396, 161 (1993)]:

requires *transverse quark polarization* and *spin-dependent fragmentation*



asymmetry in the forward jet fragmentation

Sensitive to **transversity**

Transverse momentum of the hadron with respect to the fragmenting quark

quark momentum

quark spin

$$D_{\pi/q}(z, \mathbf{k}_\pi^\perp, \mathbf{s}_q) = \hat{D}_{\pi/q}(z, k_\pi^\perp) + \frac{1}{2}\Delta^N D_{\pi/q}(z, k_\pi^\perp)\frac{\mathbf{s}_q \cdot (\mathbf{p}_q \times \mathbf{k}_\pi^\perp)}{\left|\mathbf{p}_q \times \mathbf{k}_\pi^\perp\right|}$$

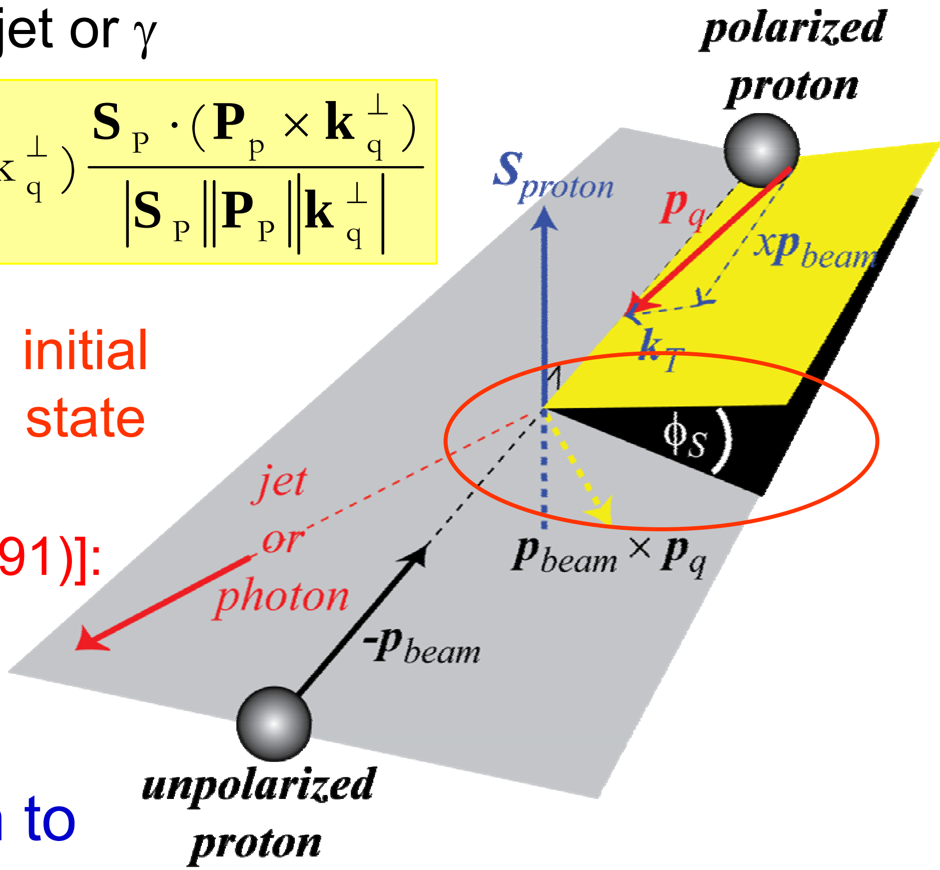
Sivers mechanism

requires *spin-correlated transverse momentum* in the proton (orbital motion).

SSA is present for jet or γ

$$f_q(x, \mathbf{k}_q^{\perp}, \mathbf{S}_P) = f_q(x, k_q^{\perp}) + \frac{1}{2}\Delta_q^N f_q(x, k_q^{\perp}) \frac{\mathbf{S}_P \cdot (\mathbf{P}_p \times \mathbf{k}_q^{\perp})}{|\mathbf{S}_P||\mathbf{P}_P||\mathbf{k}_q^{\perp}|}$$

initial state



[Phys. Rev. D 41, 83 (1990); 43, 261 (1991)]:

Sensitive to **proton spin** – parton **transverse motion** correlations

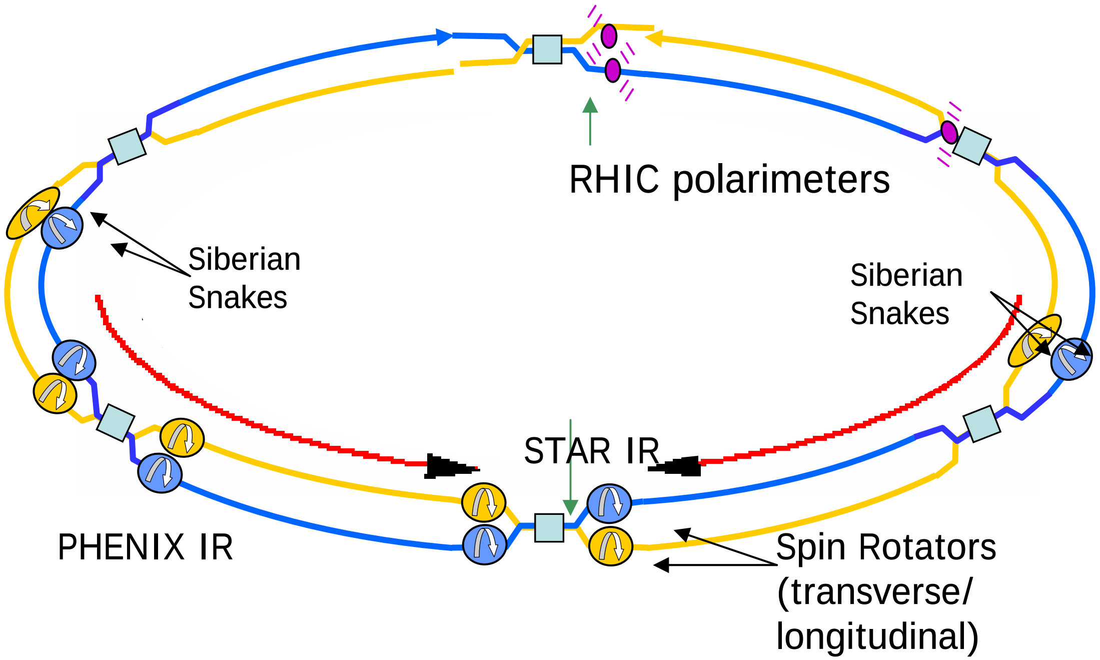
Need to go beyond π^0 detection to

jets and **direct photons**

Require experimental separation of Collins and Sivers contributions

Relativistic Heavy Ion Collider

…worlds 1st $\vec{p}\vec{p}$ Collider



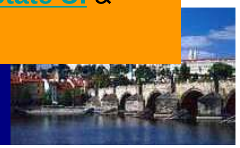
- 100 GeV beam proton beams
- Each bunch filled with a distinct polarization state
- Spin Rotators at STAR IR allow for transverse and longitudinal spin orientation
- Bunch Xings every 100-200ns
- CNI polarimeters + Hydrogen Jet target provide run by run & absolute polarization

pp Run Year FOM=P^2L	2002	2003	2004	2005	2006
< Polarization> %	15	30	40-45	45-50	60
L_{max} [10^{30} $s^{-1}cm^{-2}$]	2	6	6	16	20
L_{int} [pb^{-1}] at STAR (T)	0 .15	0.25	0	0.1	6.8

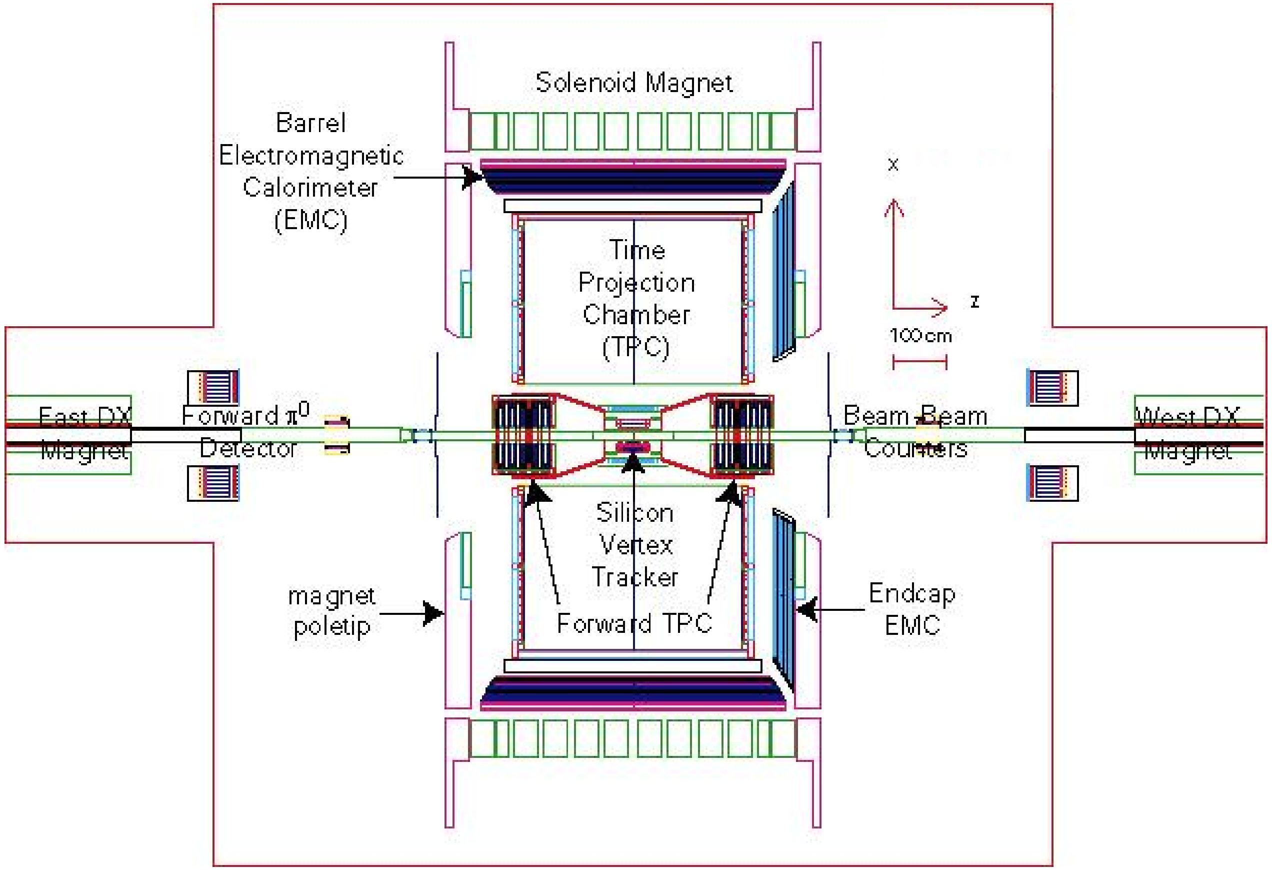
STAR Collaboration

B.I. Abelev, M.M. Aggarwal, Z. Ahammed, B.D. Anderson, D. Arkhipkin, G.S. Averichev, Y. Bai, J. Balewski, O. Barannikova, L.S. Barnby, J. Baudot, S. Baumgart, V.V. Belaga, A. Bellingeri-Laurikainen, R. Bellwied, F. Benedosso, R.R. Betts, S. Bhardwaj, A. Bhasin, A.K. Bhati, H. Bichsel, J. Bielcik, J. Bielcikova, L.C. Bland, S.-L. Blyth, M. Bombara, B.E. Bonner, M. Botje, J. Bouchet, A.V. Brandin, A. Bravar, T.P. Burton, M. Bystersky, X.Z. Cai, H. Caines, M. Calder, M. Calderon de la Barca Sanchez, J. Callner, O. Catu, D.A. Cebra, M.C. Cervantes, Z. Chajecki, P. Chaloupka, S. Chattopadhyay, H.F. Chen, J.H. Chen, J.Y. Chen, J. Cheng, M. Cherney, A. Chikanian, W. Christie, S.U. Chung, R.F. Clarke, M.J.M. Codrington, J.P. Coffin, T.M. Cormier, M.R. Cosentino, J.G. Cramer, H.J. Crawford, D. Das, S. Dash, M. Daugherity, M.M. de Moura, T.G. Dedovich, M. DePhillips, A.A. Derevschikov, L. Didenko, T. Dietel, P. Djawotho, S.M. Dogra, X. Dong, J.L. Drachenberg, J.E. Draper, F. Du, V.B. Dunin, J.C. Dunlop, M.R. Dutta Mazumdar, V. Eckardt, W.R. Edwards, L.G. Efimov, V. Emelianov, J. Engelage, G. Eppley, B. Erazmus, M. Estienne, P. Fachini, R. Fatemi, J. Fedorisin, A. Feng, P. Filip, E. Finch, V. Fine, Y. Fisyak, J. Fu, C.A. Gagliardi, L. Gaillard, M.S. Ganti, E. Garcia-Solis, V. Ghazikhanian, P. Ghosh, Y.N. Gorbunov, H. Gos, O. Grebenyuk, D. Grosnick, B. Grube, S.M. Guertin, K.S.F.F. Guimaraes, N. Gupta, B. Haag, T.J. Hallman, A. Hamed, J.W. Harris, W. He, M. Heinz, T.W. Henry, S. Heppelmann, B. Hippolyte, A. Hirsch, E. Hjort, A.M. Hoffman, G.W. Hoffmann, D.J. Hofman, R.S. Hollis, M.J. Horner, H.Z. Huang, E.W. Hughes, T.J. Humanic, G. Igo, A. Iordanova, P. Jacobs, W.W. Jacobs, P. Jakl, F. Jia, P.G. Jones, E.G. Judd, S. Kabana, K. Kang, J. Kapitan, M. Kaplan, D. Keane, A. Kechechyan, D. Kettler, V.Yu. Khodyrev, J. Kiryluk, A. Kisiel, E.M. Kislov, S.R. Klein, A.G. Knospe, A. Kocoloski, D.D. Koetke, T. Kollegger, M. Kopytine, L. Kotchenda, V. Kouchpil, K.L. Kowalik, P. Kravtsov, V.I. Kravtsov, K. Krueger, C. Kuhn, A.I. Kulikov, A. Kumar, P. Kurnadi, A.A. Kuznetsov, M.A.C. Lamont, J.M. Landgraf, S. Lange, S. LaPointe, F. Laue, J. Lauret, A. Lebedev, R. Lednicky, C-H. Lee, S. Lehocka, Micheal J. LeVine, C. Li, Q. Li, Y. Li, G. Lin, X. Lin, S.J. Lindenbaum, M.A. Lisa, F. Liu, H. Liu, J. Liu, L. Liu, T. Ljubicic, W.J. Llope, R.S. Longacre, W.A. Love, Y. Lu, T. Ludlam, D. Lynn, G.L. Ma, J.G. Ma, Y.G. Ma, D.P. Mahapatra, R. Majka, L.K. Mangotra, R. Manweiler, S. Margetis, C. Markert, L. Martin, H.S. Matis, Yu.A. Matulenko, C.J. McClain, T.S. McShane, Yu. Melnick, A. Meschanin, J. Millane, M.L. Miller, N.G. Minaev, S. Mioduszewski, A. Mischke, J. Mitchell, B. Mohanty, D.A. Morozov, M.G. Munhoz, B.K. Nandi, C. Nattrass, T.K. Nayak, J.M. Nelson, C. Nepali, P.K. Netrakanti, L.V. Nogach, S.B. Nurushev, G. Odyniec, A. Ogawa, V. Okorokov, M. Oldenburg, D. Olson, M. Pachr, S.K. Pal, Y. Panebratsev, A.I. Pavlinov, T. Pawlak, T. Peitzmann, V. Perevoztchikov, C. Perkins, W. Peryt, S.C. Phatak, M. Planinic, J. Pluta, N. Poljak, N. Porile, A.M. Poskanzer, M. Potekhin, E. Potrebenikova, B.V.K.S. Potukuchi, D. Prindle, C. Pruneau, N.K. Pruthi, J. Putschke, I.A. Qattan, R. Raniwala, S. Raniwala, R.L. Ray, D. Relyea, A. Ridiger, H.G. Ritter, J.B. Roberts, O.V. Rogachevskiy, J.L. Romero, A. Rose, C. Roy, L. Ruan, M.J. Russcher, R. Sahoo, I. Sakrejda, T. Sakuma, S. Salur, J. Sandweiss, M. Sarsour, P.S. Sazhin, J. Schambach, R.P. Scharenberg, N. Schmitz, J. Seger, I. Selyuzhenkov, P. Seyboth, A. Shabetai, E. Shahaliev, M. Shao, M. Sharma, W.Q. Shen, S.S. Shimanskiy, E.P. Sichtermann, F. Simon, R.N. Singaraju, N. Smirnov, R. Snellings, P. Sorensen, J. Sowinski, J. Speltz, H.M. Spinka, B. Srivastava, A. Stadnik, T.D.S. Stanislaus, D. Staszak, R. Stock, M. Strikhanov, B. Stringfellow, A.A.P. Suaide, M.C. Suarez, N.L. Subba, M. Sumbera, X.M. Sun, Z. Sun, B. Surrow, T.J.M. Symons, A. Szanto de Toledo, J. Takahashi, A.H. Tang, T. Tarnowsky, J.H. Thomas, A.R. Timmins, S. Timoshenko, M. Tokarev, T.A. Trainor, S. Trentalange, R.E. Tribble, O.D. Tsai, J. Ulery, T. Ullrich, D.G. Underwood, G. Van Buren, N. van der Kolk, M. van Leeuwen, A.M. Vander Molen, R. Varma, I.M. Vasilevski, A.N. Vasiliev, R. Vernet, S.E. Vigdor, Y.P. Viyogi, S. Vokal, S.A. Voloshin, M. Wada, W.T. Waggoner, F. Wang, G. Wang, J.S. Wang, X.L. Wang, Y. Wang, J.C. Webb, G.D. Westfall, C. Whitten,, Jr., H. Wieman, S.W. Wissink, R. Witt, J. Wu, Y. Wu, N. Xu, Q.H. Xu, Z. Xu, P. Yepes, I.-K. Yoo, Q. Yue, V.I. Yurevich, M. Zawisza, W. Zhan, H. Zhang, W.M. Zhang, Y. Zhang, Z.P. Zhang, Y. Zhao, C. Zhong, J. Zhou, R. Zoulkarneev, Y. Zoulkarneeva, A.N. Zubarev, J.X. Zuo

Argonne & **Birmingham U.** & **Brookhaven** & **Caltech** & **UC, Berkeley** & **UC, Davis** & **UCLA** & **Carnegie Mellon U.** & **Illinois U., Chicago** & **Creighton U.** & **Rez, Nucl. Phys. Inst.** & **Dubna, JINR** & **Frankfurt U.** & **Bhubaneswar, Inst. Phys.** & **Indian Inst. Tech., Mumbai** & **Indiana U.** & **Strasbourg, IReS** & **Jammu U.** & **Kent State U.** & **Lanzhou, Inst. Modern Phys.** & **LBL, Berkeley** & **MIT, LNS** & **Munich, Max Planck Inst.** & **Michigan State U.** & **Moscow Phys. Eng. Inst.** & **City Coll., N.Y.** & **NIKHEF, Amsterdam** & **Utrecht U.** & **Ohio State U.** & **Panjab U.** & **Penn State U.** & **Serpukhov, IHEP** & **Purdue U.** & **Pusan Natl. U.** & **Rajasthan U.** & **Rice U.** & **Sao Paulo U.** & **Hefei, CUST** & **SINAP, Shanghai** & **SUBATECH, Nantes** & **Texas A-M** & **Texas U.** & **Tsinghua U., Beijing** & **Valparaiso U., Indiana** & **Calcutta, VECC** & **Warsaw U. of Tech.** & **Washington U., Seattle** & **Wayne State U.** & **Hua-Zhong Normal U.** & **Yale U.** & **Zagreb U.**

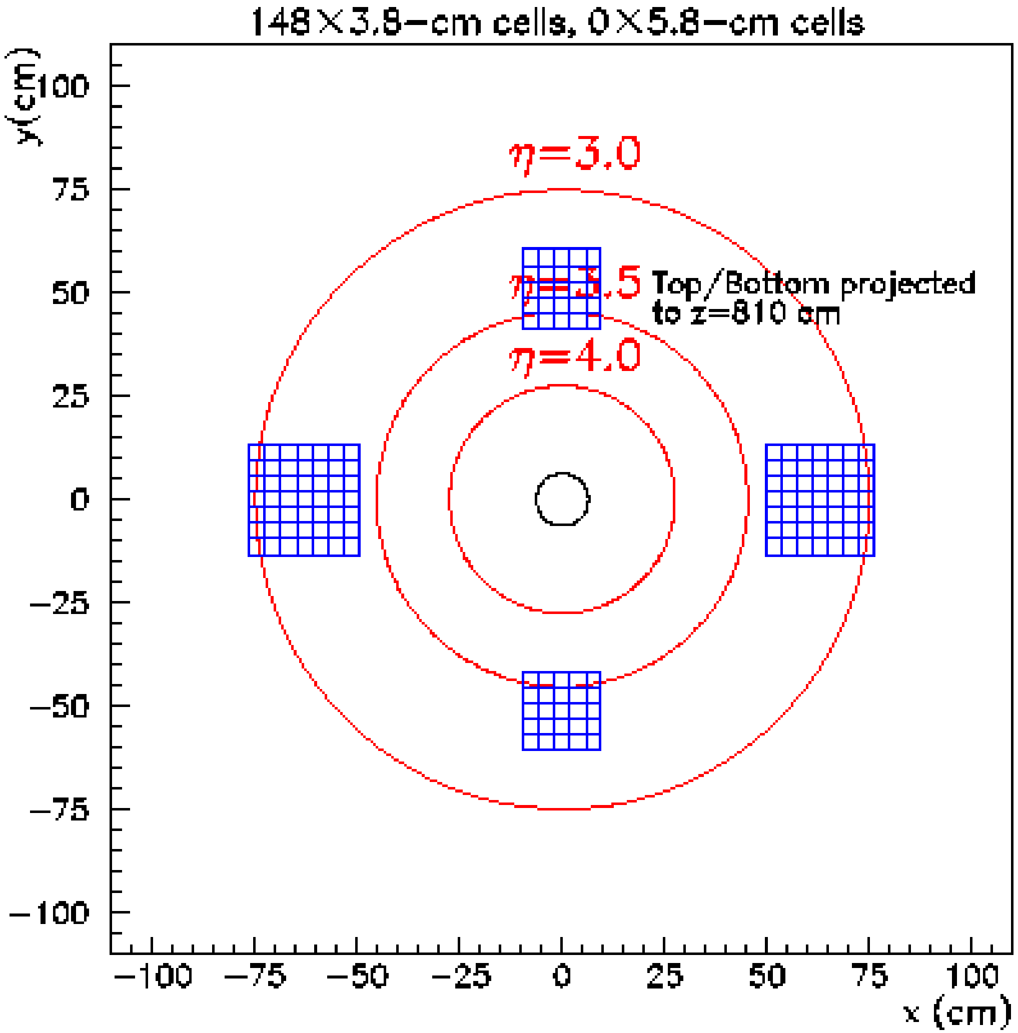


STAR detector layout



- **TPC: $-1.0 < \eta < 1.0$**
- **FTPC: $2.8 < |\eta| < 3.8$**
- **BBC : $2.2 < |\eta| < 5.0$**
- **EEMC:$1 < \eta < 2$**
- **BEMC:$0 < \eta < 1$**
- **FPD: $|\eta| \sim 4.0$ & ~ 3.7**

FPD-Forward Pion Detector

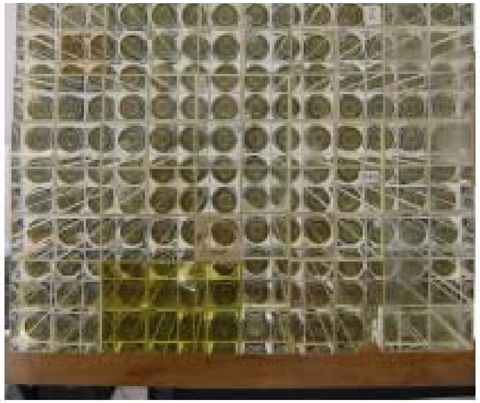


(3.8cm)[2] x 45 cm lead glass

18 radiation lengths

FEU84 + XP2972 photomultipliers

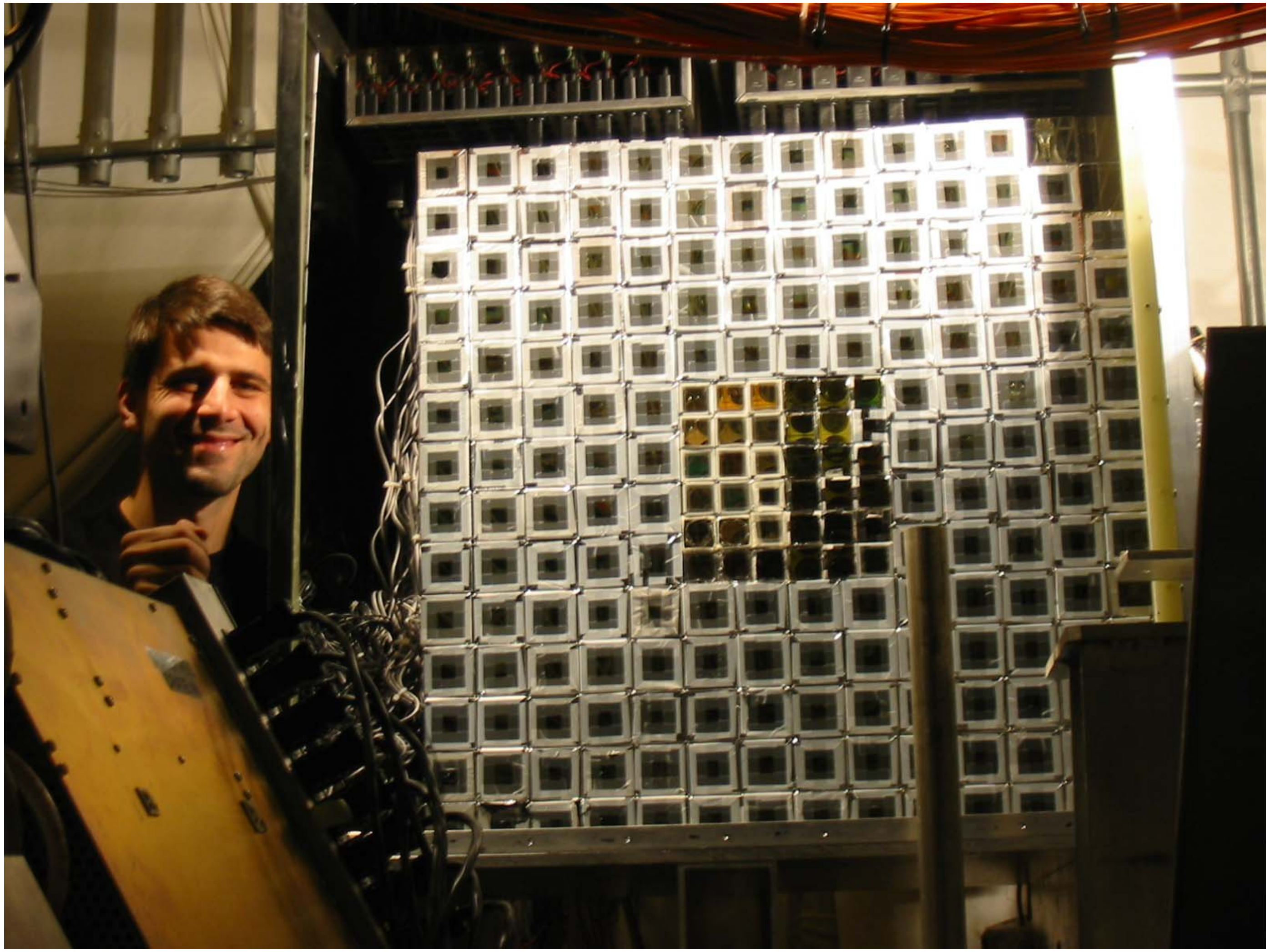
17



170 small cells prior to wrapping

Run 5 FPD

Run 6 – FPD++



TPC: $-1.0 < \eta < 1.0$

FTPC: $2.8 < |\eta| < 3.8$

BBC : $2.2 < |\eta| < 5.0$

EEMC: $1 < \eta < 2$

BEMC: $-1 < \eta < 1$

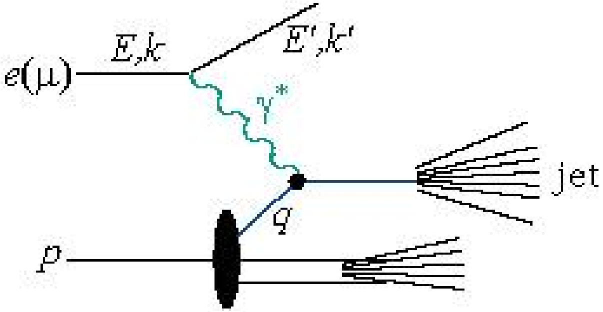
FPD++/FPD:

$\eta \sim 3.3/-3.7$

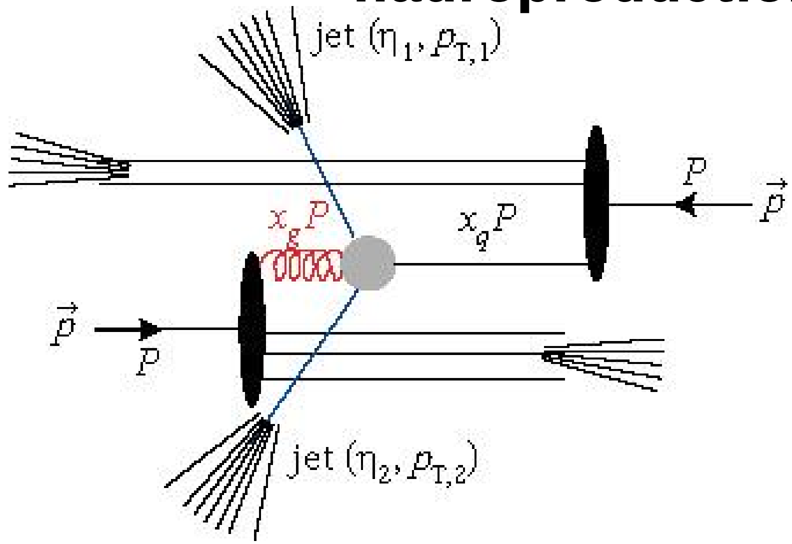
12/30/2005

Why Consider Forward Physics at a Collider?

Deep inelastic scattering — **Kinematics** — **Hard scattering hadroproduction**



$$Q^2 = 2(EE' - \vec{k} \cdot \vec{k}')$$
$$\nu = E - E'$$
$$x = Q^2 / 2M\nu$$



How can Bjorken x values be selected in hard scattering?

Assume:

1. Initial partons are collinear
2. Partonic int. is elastic $\Rightarrow p_{T,1} \approx p_{T,2}$

$$\Rightarrow \quad x_q \approx p_T/\sqrt{s}\,(e^{+\eta_1} + e^{+\eta_2})$$
$$x_g \approx p_T/\sqrt{s}\,(e^{-\eta_1} + e^{-\eta_2})$$

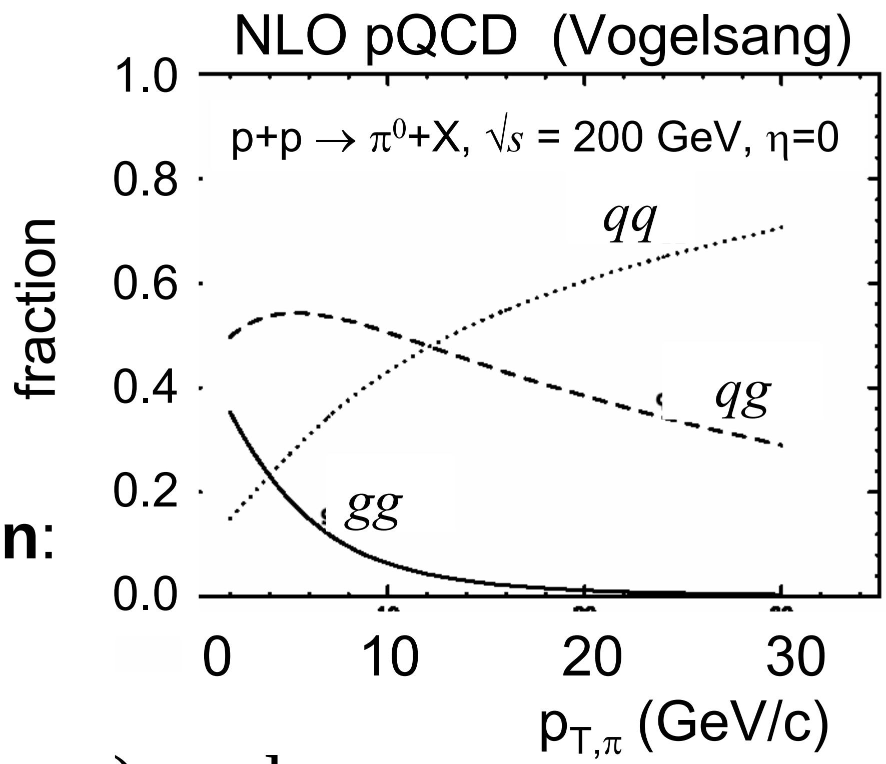
Studying pseudorapidity, η=-ln(tanθ/2), dependence of particle production probes parton distributions at different Bjorken x values and involves different admixtures of gg, qg and qq' subprocesses.

Simple Kinematic Limits

Mid-rapidity particle detection:

$\eta_1 \approx 0$ and $<\eta_2> \approx 0$

$$\Rightarrow x_q \approx x_g \approx x_T = 2\, p_T / \sqrt{s}$$



Large-rapidity particle detection:

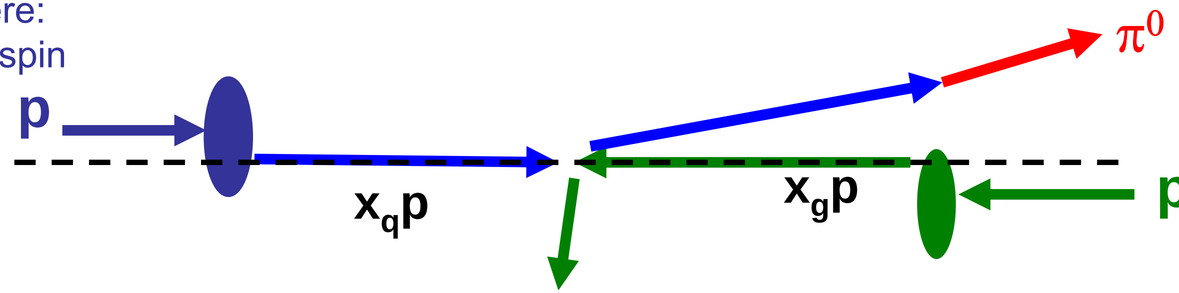
$\eta_1 >> \eta_2$

$$\Rightarrow x_q \approx x_T\, e^{\eta_1} \approx x_F \text{ (Feynman } x\text{), and}$$

$$x_g \approx x_F\, e^{-(\eta_1+\eta_2)}$$

⇒ Large rapidity particle production and correlations involving large rapidity particle probes low-x parton distributions using valence quarks

Recent asymmetry measurements at STAR



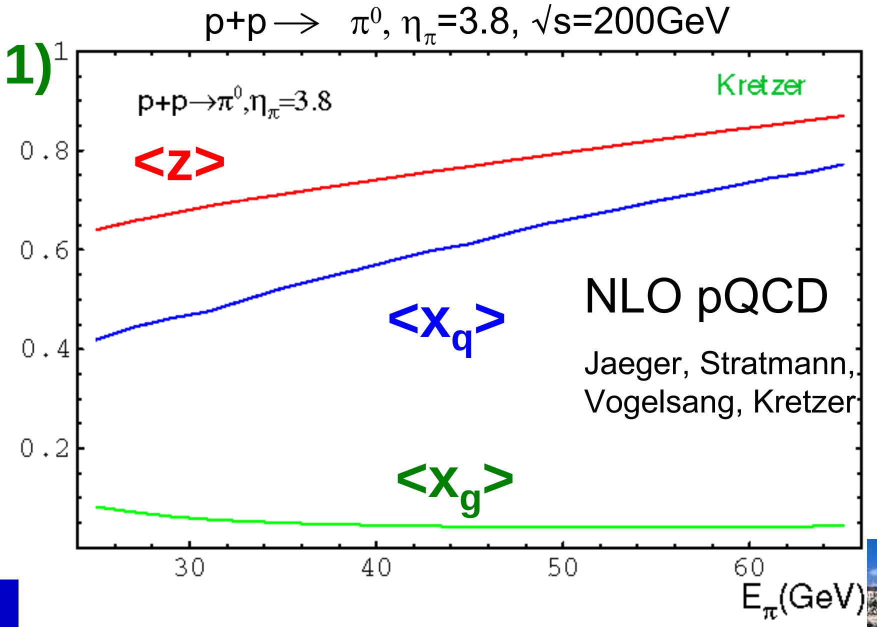
High rapidity π's (η_π~4) from asymmetric partonic collisions

Mostly high-x valence quark on low-x gluon

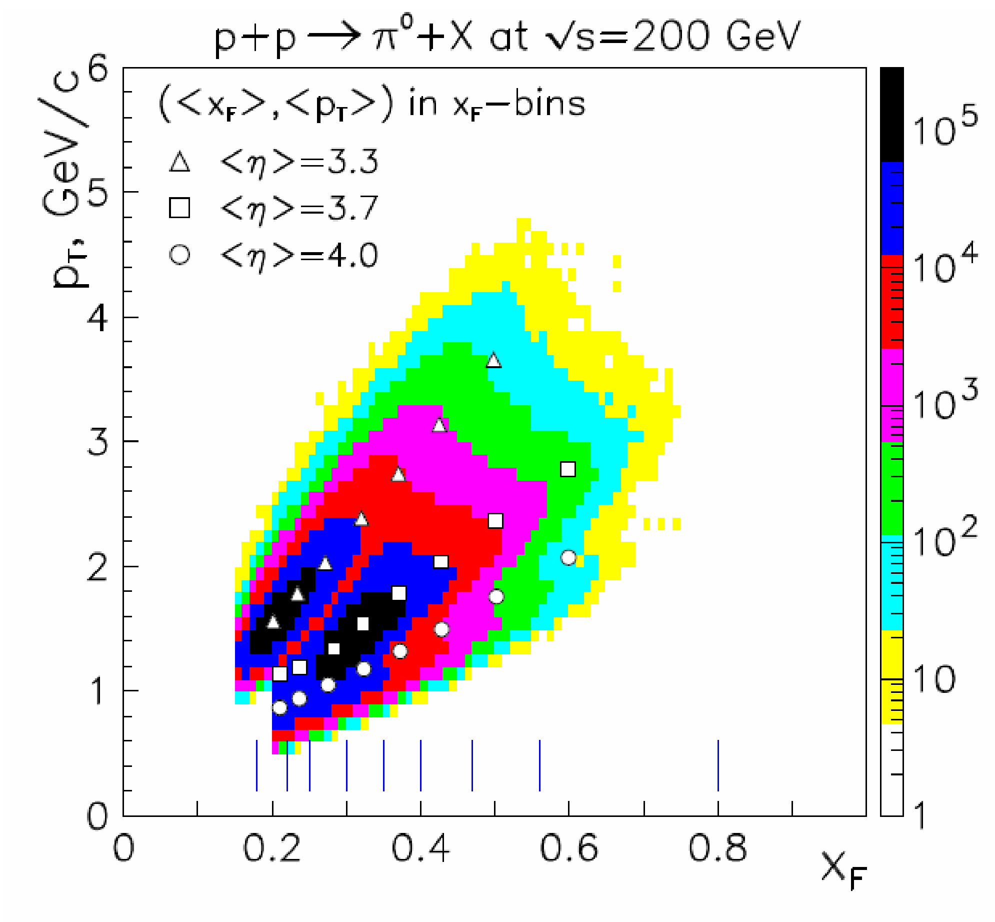
($0.3 < x_q < 0.7$, $0.001 < x_g < 0.1$)

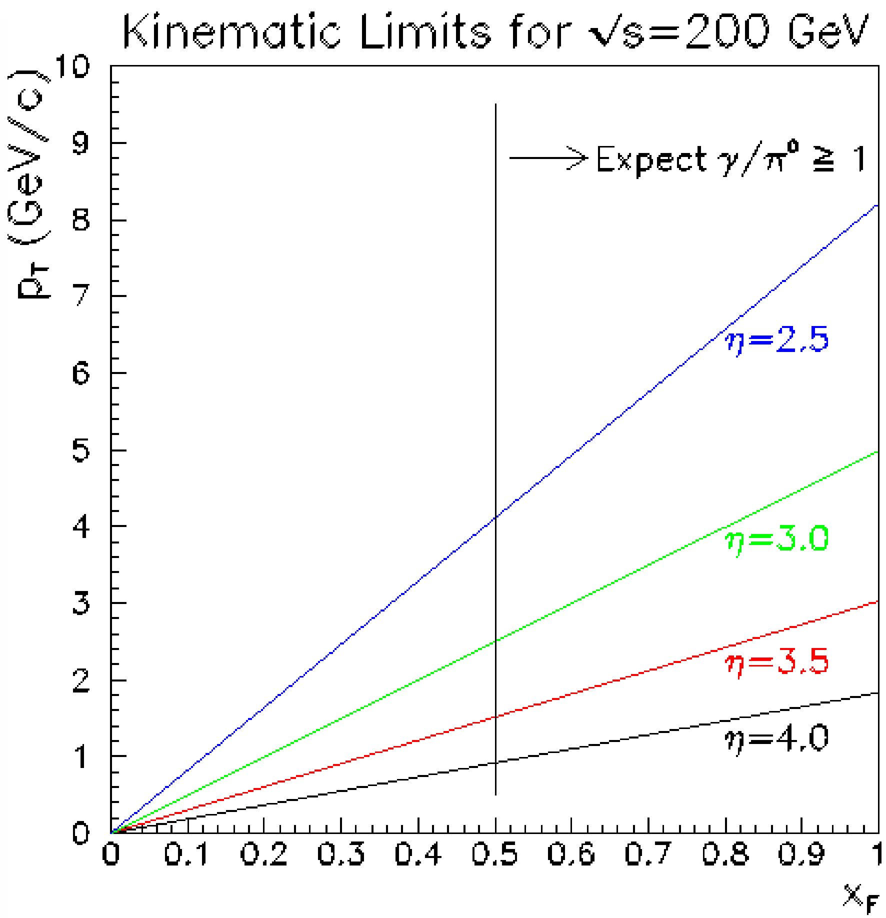
Fragmentation z nearly constant and high 0.7 ~ 0.8

- **Large-x quark polarization is known to be large from DIS**
- **Directly couple to gluons = A probe of low x gluons**



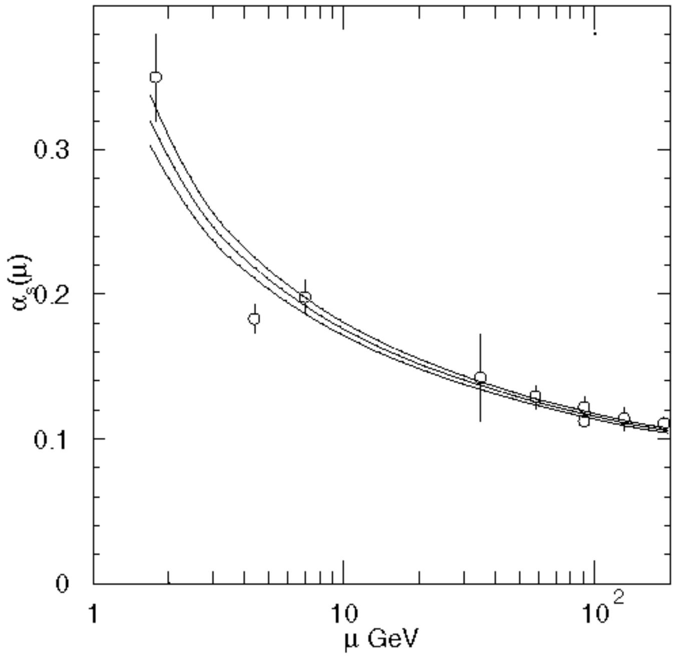
x_F and p_T range of FPD data





Possible Problems at Forward Angles

• Is it possible to access large enough p_T where NLO pQCD is applicable?



Although α_S does not vary much over accessible scales at RHIC, large η will primarily probe small p_T $\Rightarrow$ need to understand scale dependence of fixed order pQCD calculations.

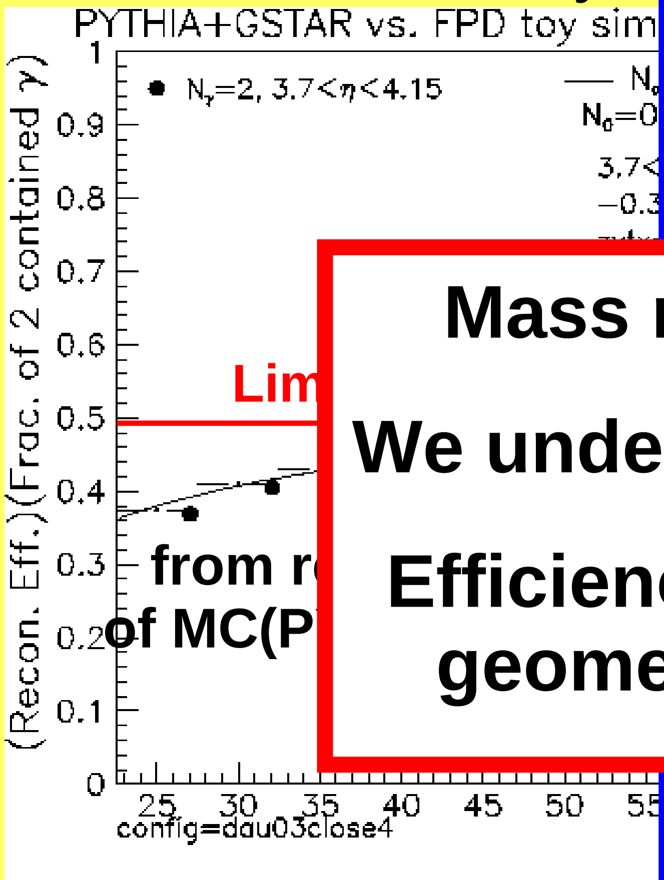
• Large x_F means high energy particles. Detection is best accomplished using electromagnetic + hadronic calorimetry + charge-sign determination from tracking through a magnetic field.

• For increasing p_T at large x_F, faced with increasingly steep falloff of $dN/d\eta$ distributions.

Di-photon Mass Reconstruction and calibration

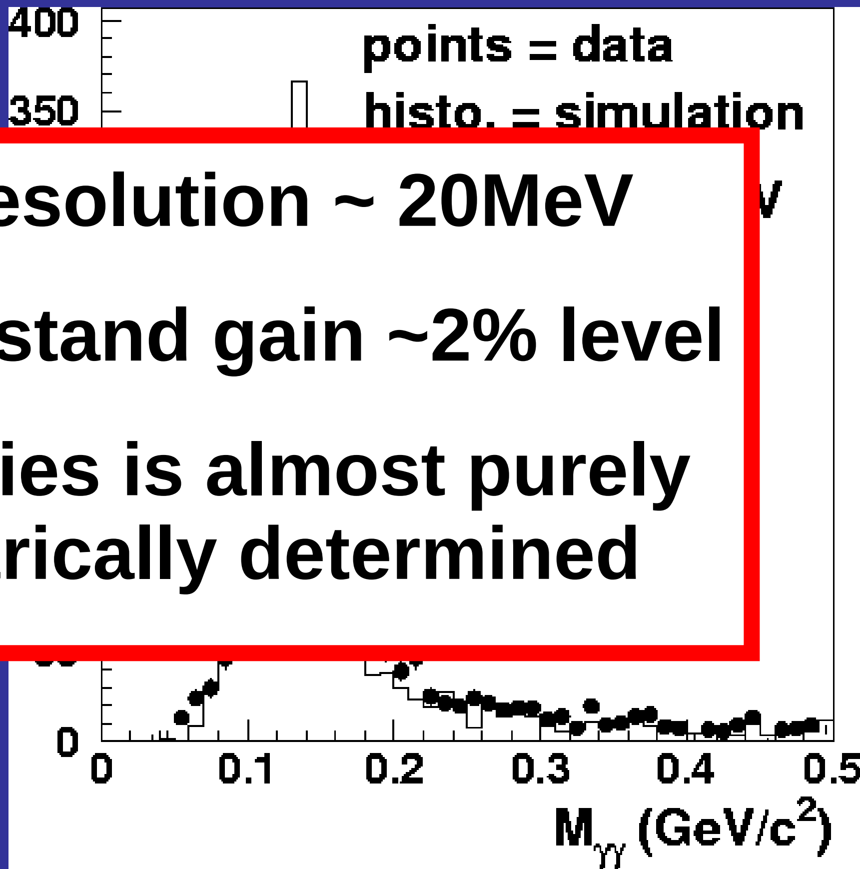
Pb-glass reconstruction (no SMD)

π^0 reconstruction efficiency



tegorization

MC & Data comparison



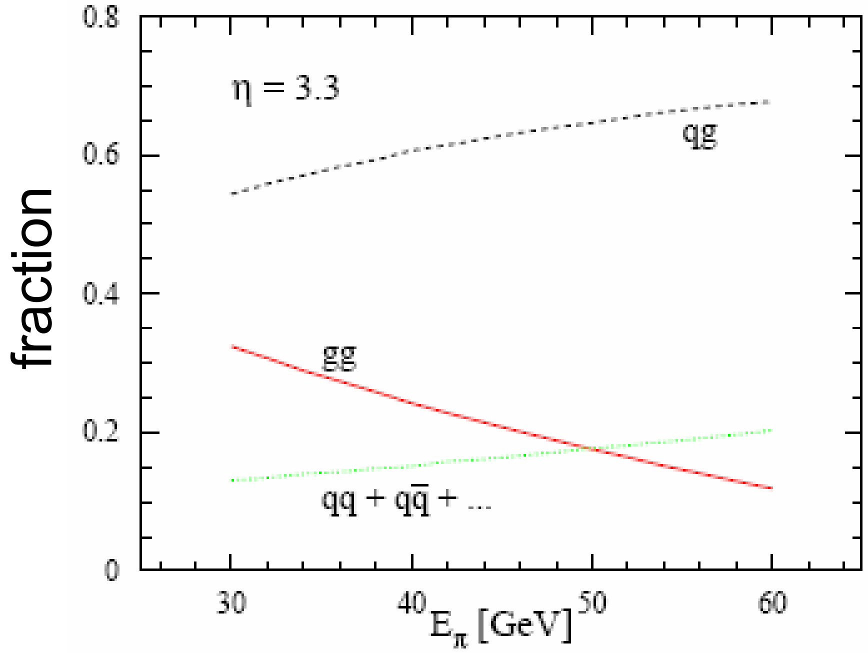
Mass resolution ~ 20MeV

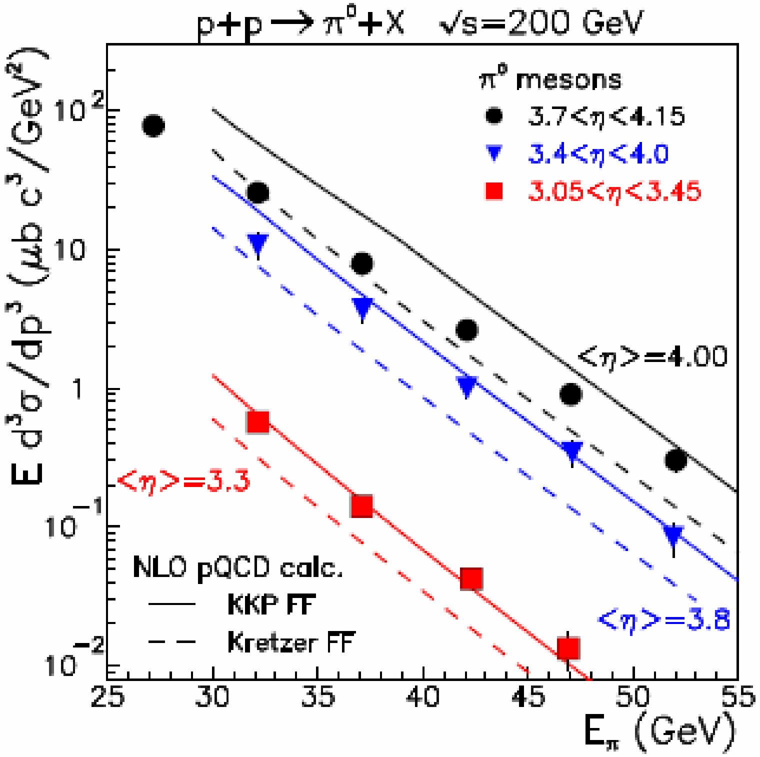
We understand gain ~2% level

Efficiencies is almost purely geometrically determined

Cross section measurements: Forward pion production

Phys. Lett. B603 (2004) 173





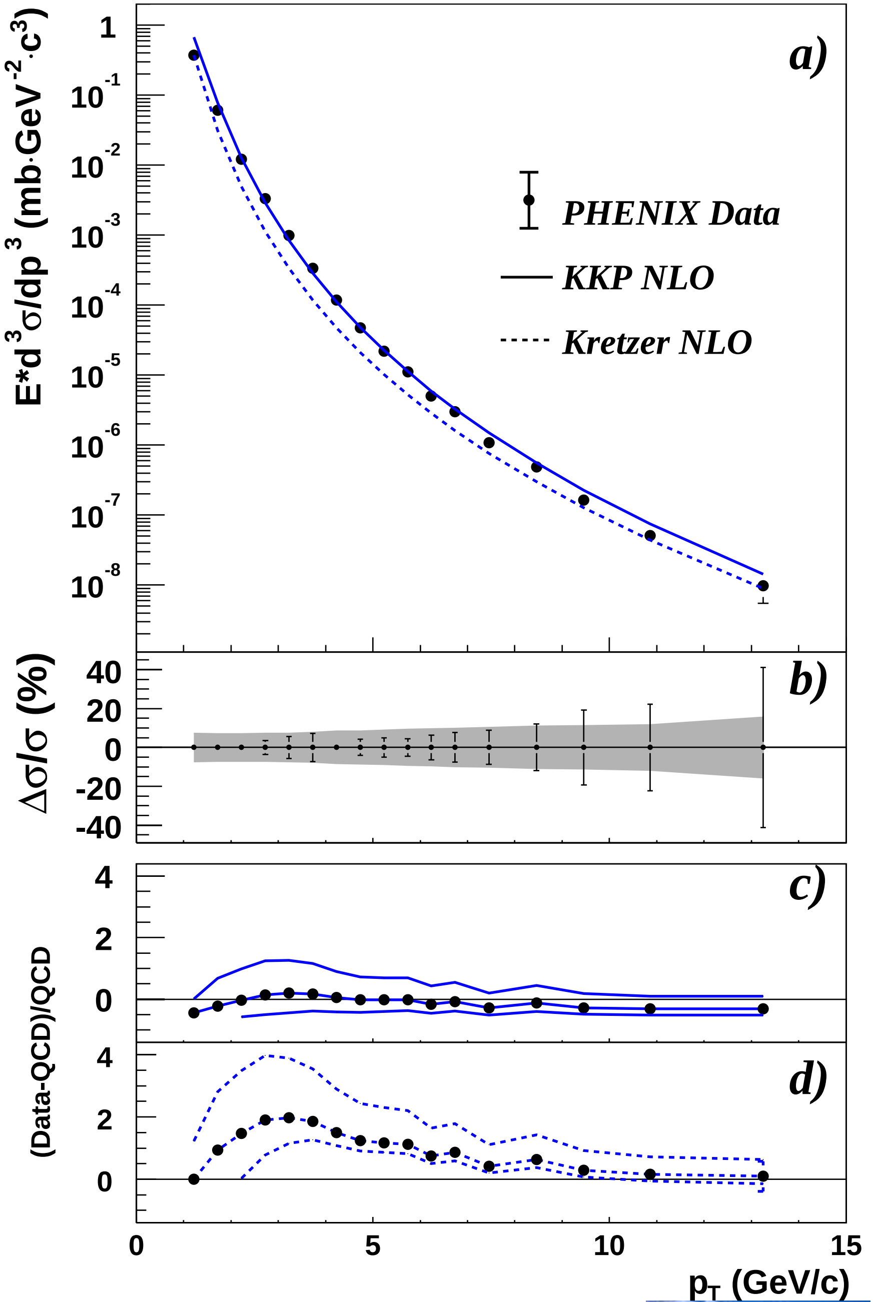
Forward production is dominated by asymmetric qg collisions

Data compares favorably to NLO pQCD at $\sqrt{s} = 200$ GeV in contrast to fixed-target or ISR energies

π^0 production at midrapidity

$p + p \rightarrow \pi^0 + X$, $\sqrt{s}$=200 GeV

S.S. Adler *et al*. (PHENIX), PRL **91**, 241803 (2003).

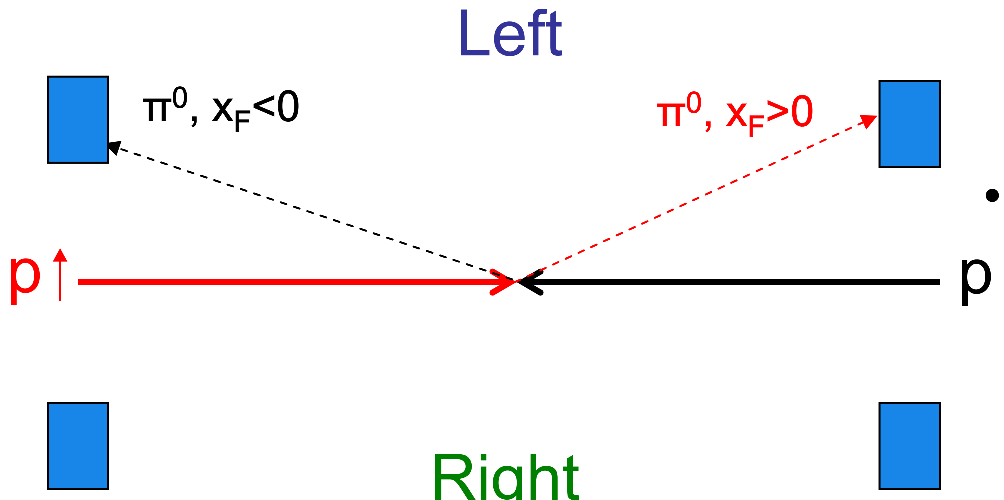


NLO pQCD calculation, using CTEQ5M PDF and KKP fragmentation functions is found to be consistent with data down to surprisingly low p_T.

Universality tests at collider energies yield comparable results.

Single Spin Asymmetry

- Definition: $A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$
- $d\sigma^{\uparrow(\downarrow)}$ – differential cross section of π^0 when incoming proton has spin up(down)



positive A_N: more π^0 going left to polarized beam

Two methods of measurements:

- Single arm calorimeter:

$$A_N = \frac{1}{P_{beam}} \cdot \left(\frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}} \right) \qquad R = \frac{L^{\uparrow}}{L^{\downarrow}}$$

R – relative luminosity (by BBC)

P_{beam} – beam polarization

- Two arm (left-right) calorimeter:

$$A_N = \frac{1}{P_{Beam}} \cdot \left(\frac{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_R^{\uparrow} \cdot N_L^{\downarrow}}}{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_R^{\uparrow} \cdot N_L^{\downarrow}}} \right)$$

No relative luminosity needed

Transverse spin runs at STAR with forward calorimetry: 2001→2006

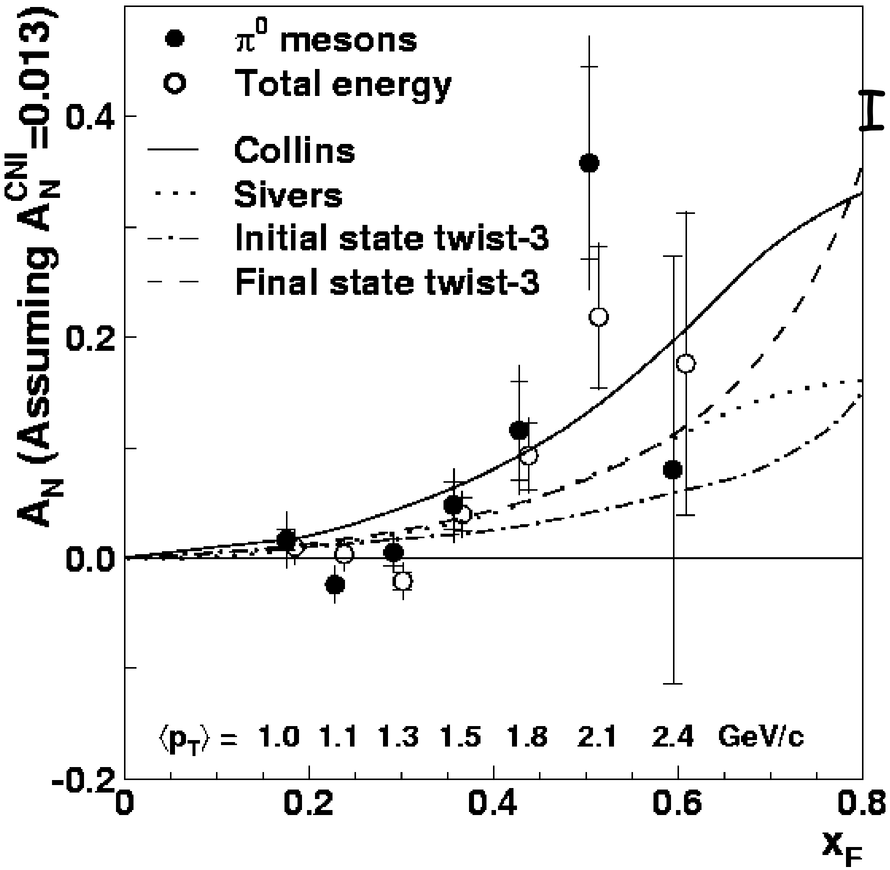
	Run2	Run3	Run5	**Run6**
detector	EEMC and FPD prototypes	6 matrices of FPD	full FPD (8 matrices)	**East FPD West FPD++**
P_{BEAM}, %	~15	~30	~45	**~60**
$\int^{\text{sampled}} Ldt,\ pb^{-1}$	0.15	0.25	0.1	**6.8**
$< \eta >$	3.8	±3.3/±4.0	±3.7/±4.0	**-3.7/3.3**

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

Large Analyzing Powers at RHIC

First measurement of A_N for forward π^0 production at $\sqrt{s}$=200GeV

STAR collaboration, hep-ex/0310058,
Phys. Rev. Lett. **92** (2004) 171801



Similar to FNAL E704 result at $\sqrt{s}$ = 20 GeV

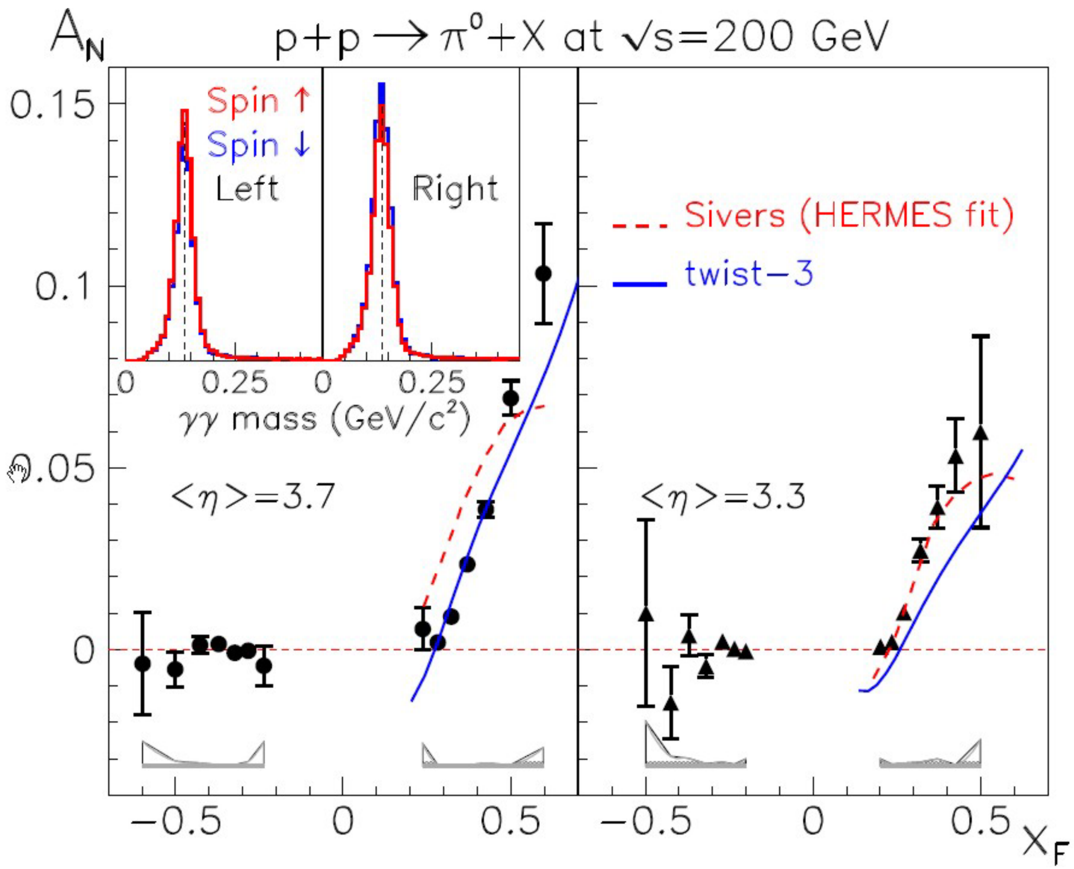
In agreement with several models including different dynamics:

- Sivers: spin and $k_\perp$ correlation in initial state (related to orbital angular momentum?)
- Collins: Transversity distribution function & spin-dependent fragmentation function
- Qiu and Sterman (initial-state) / Koike (final-state) twist-3 pQCD calculations

High Precision Analyzing Powers

(red line) M. Boglione, U. D'Alesio, F. Murgia, PRD 77 (2008) 051502

(blue line) C. Kourvaris, J. Qiu, W. Vogelsang, F. Yuan, PRD 74 (2006)



(2003 – 2006)

B.I. Abelev, *et al*, hep-ex/0801.2990

Null at xF<0 is natural since gluon Sivers function is probed where unp. gluon distribution is large.

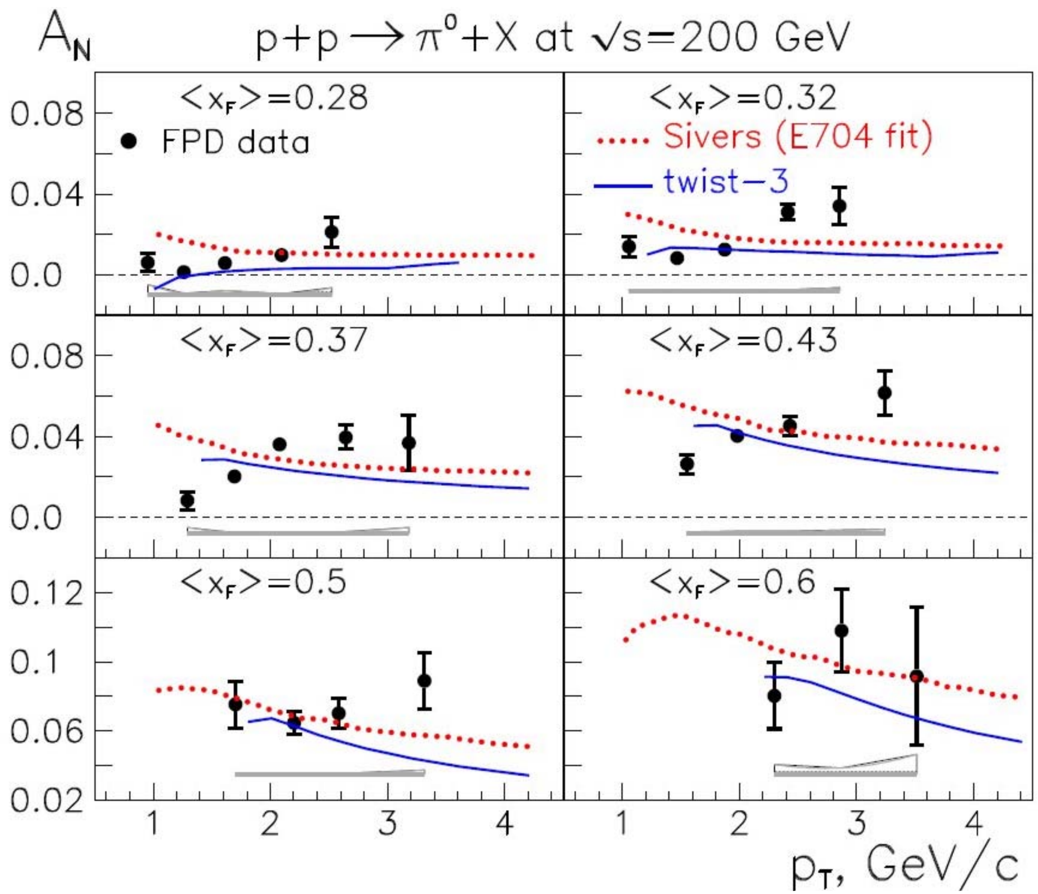
⇒ Precision measurements at √s = 200 GeV provide stringent contraints on the models…

High Precision Analyzing Powers

(2003 – 2006)

B.I. Abelev, *et al*, hep-ex/0801.2990

Data broken out in X_F bins



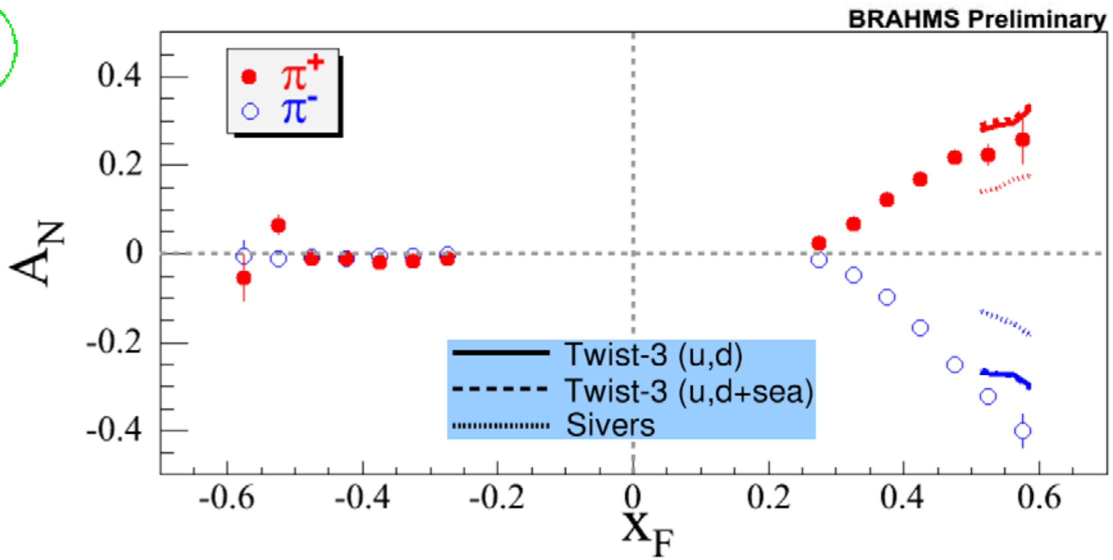
…but rising P_T dependence is not predicted by the same fits

→ No model fully describes the precision data

More experimental (and theoretical) work needed…

SSA of $\pi^{\pm}$ at $\sqrt{s} = 62.4$ GeV

BRAHMS



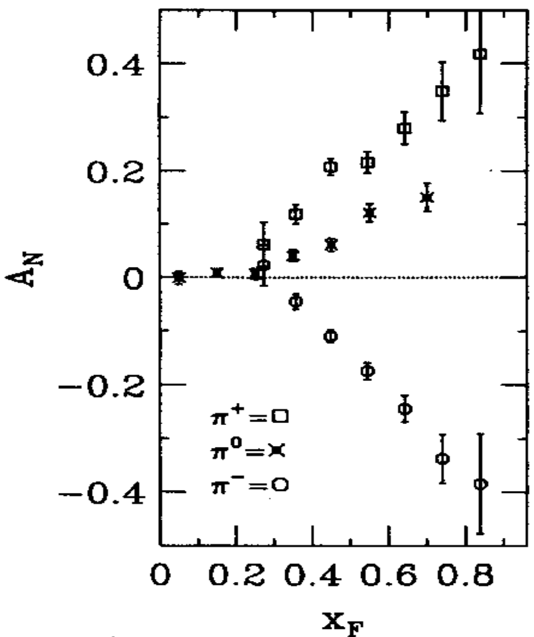
- Large $A_N(\pi^-)$: 40% at $x_F \sim 0.6$, $p_T \sim 1.3$ GeV$/c$, $A_N(-x_F) \sim 0$.
- Strong x_F-dependence
- $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with x_F
- Sivers and Twist-3 calculations are compared with the data: Twist-3 calculations are in a better agreement with data.

Large asymmetries persist at high √s

Examples:

√s = 20 GeV

$p_\uparrow + p \rightarrow \pi + X$, $\sqrt{s}$ = 20 GeV
p_T=0.5-2.0 GeV/c

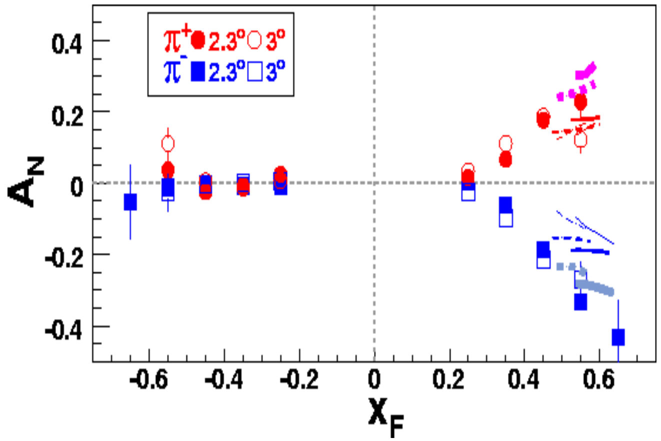


π^0: E704, Phys.Lett. B261 (1991) 201.
$\pi^{+/-}$: E704, Phys.Lett. B264 (1991) 462.

Fermilab, Fixed target, E704, 1991

√s = 62 GeV

$p_\uparrow + p \rightarrow \pi^\pm + X$, $\sqrt{s}$ = 62 GeV

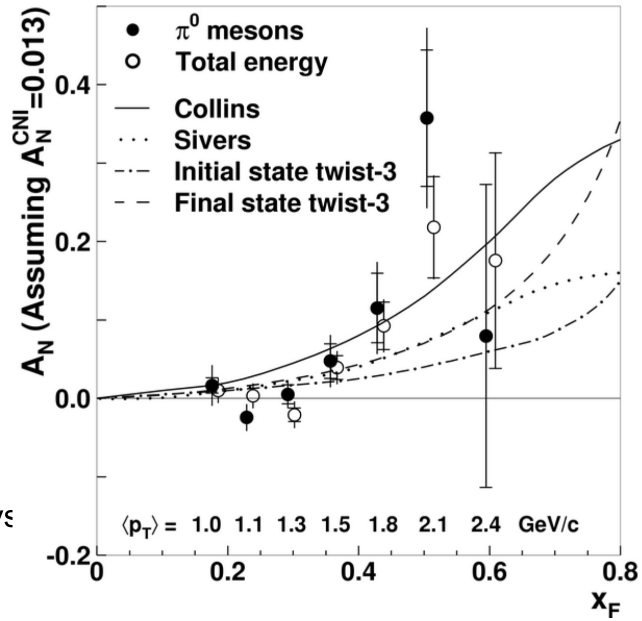


Arsene et al. (BRAHMS), submitted to Phys Rev. Lett. [arXiv:nucl-ex/0801.1078]

RHIC, Brahms, 2007

√s = 200 GeV

$p_\uparrow + p \rightarrow \pi^0 + X$, $\sqrt{s}$ = 200 GeV

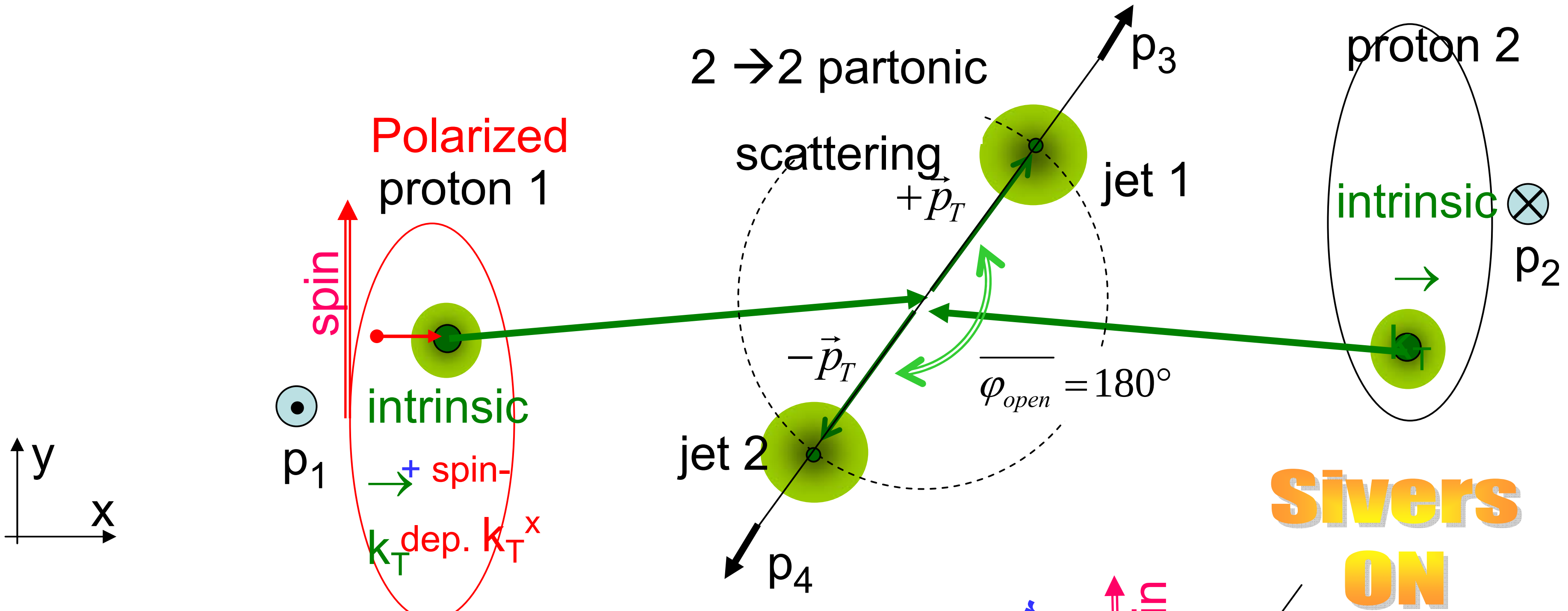


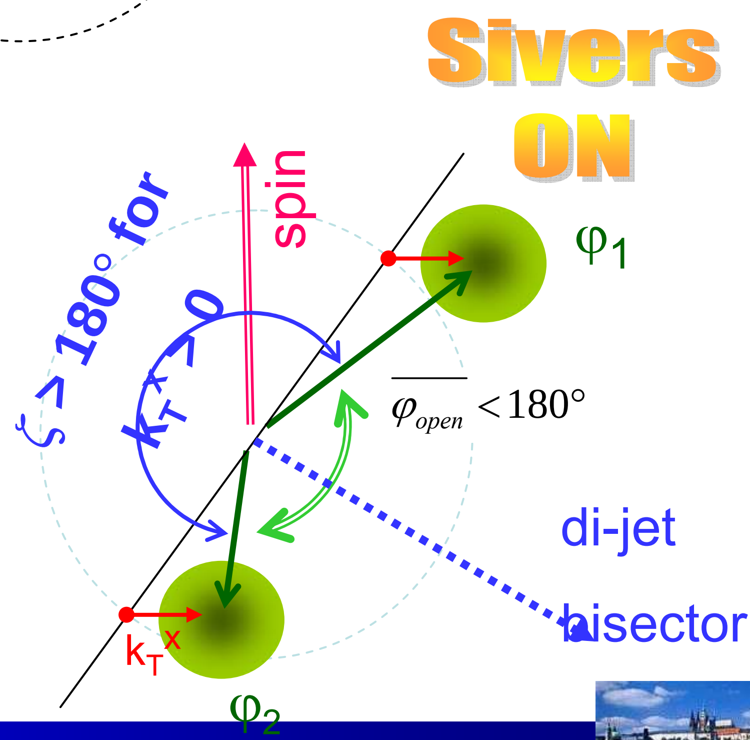
(STAR) Phys. Rev. Lett. **92** (2004) 171801

RHIC, STAR, 2004

Non-Perturbative cross section → Perturbative cross section

Sivers Mechanism of SSA





Spin dependent k_T^x offset

- deflects both jets in the same direction
- reduces average di-jet opening angle

STAR Results vs. Di-Jet Pseudorapidity Sum

Run-6 Result

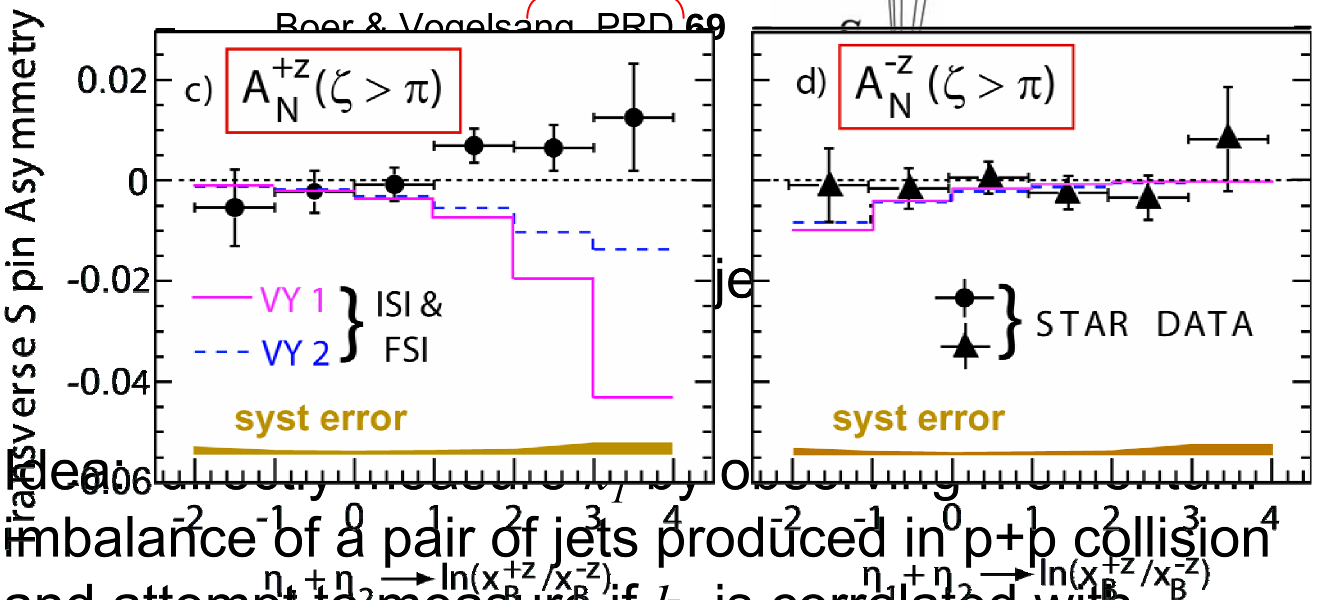
VY 1, VY 2 are calculations by

Vogelsang & Yuan, PRD **72** (2005) 054028

$A_N \propto \vec{p}_{beam} \bullet (\vec{k}_T \times \vec{S}_T)$ jet

Emphasizes (50%+) quark Sivers

Boer & Vogelsang, PRD **69**



Idea: directly measure k_T by observing momentum imbalance of a pair of jets produced in p+p collision and attempt to measure if k_T is correlated with incoming proton spin

A_N consistent with zero

⇒~order of magnitude smaller in pp → di-jets than in semi-inclusive DIS quark Sivers asymmetry!

arXiv:0705.4629

Summary I

Transverse Single Spin Asymmetry (SSA) Measurements

- Feynman-x dependence of large-rapidity pion production shows large transverse SSA at RHIC energies, where cross sections are described by NLO pQCD

- Feynman-x dependence of large-rapidity transverse SSA are consistent with theoretical models (Sivers effect $\Rightarrow$ orbital motion / twist-3 calculations)

- The p_T dependence of large-rapidity π^0 transverse SSA does not follow theoretical expectations

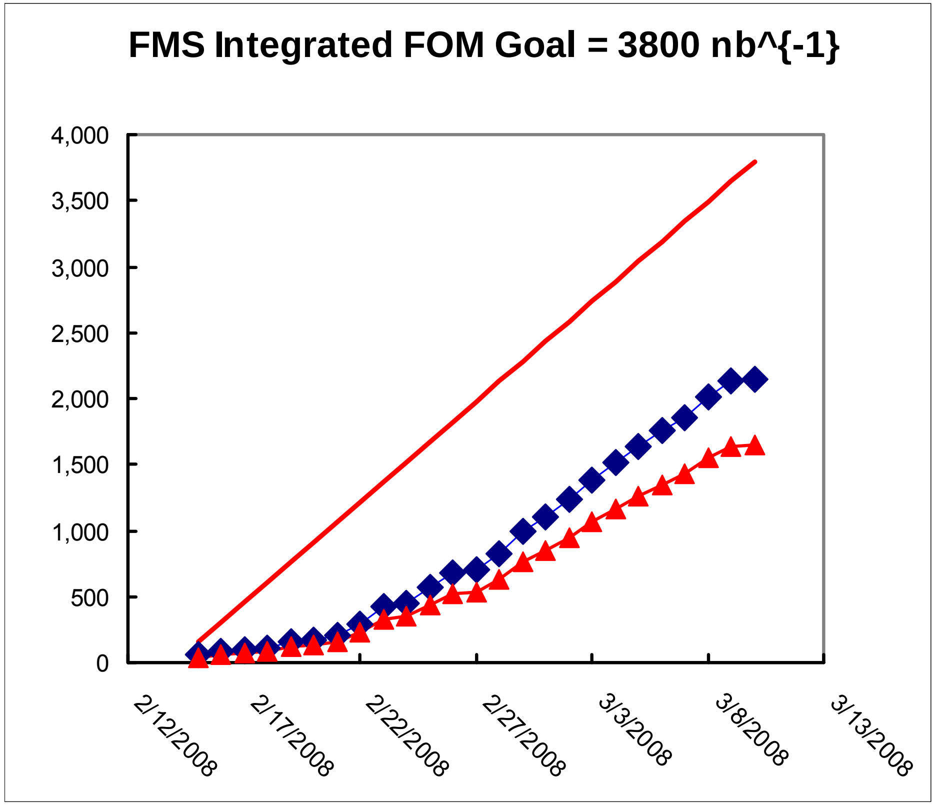
Summary II
Transverse Single Spin Asymmetry (SSA) Measurements

- Direct measurement of spin-correlated k_T (Sivers effect) via midrapidity di-jet spin asymmetries completed in RHIC run 6 and found consistent with zero.

- Cancellations found in theory calculations subsequent to measurements also expect small di-jet spin asymmetries at midrapidity.

Run 8 data

Because of lower polarization than expected, figure of Merit (P^2L) fell short by roughly a factor of two.

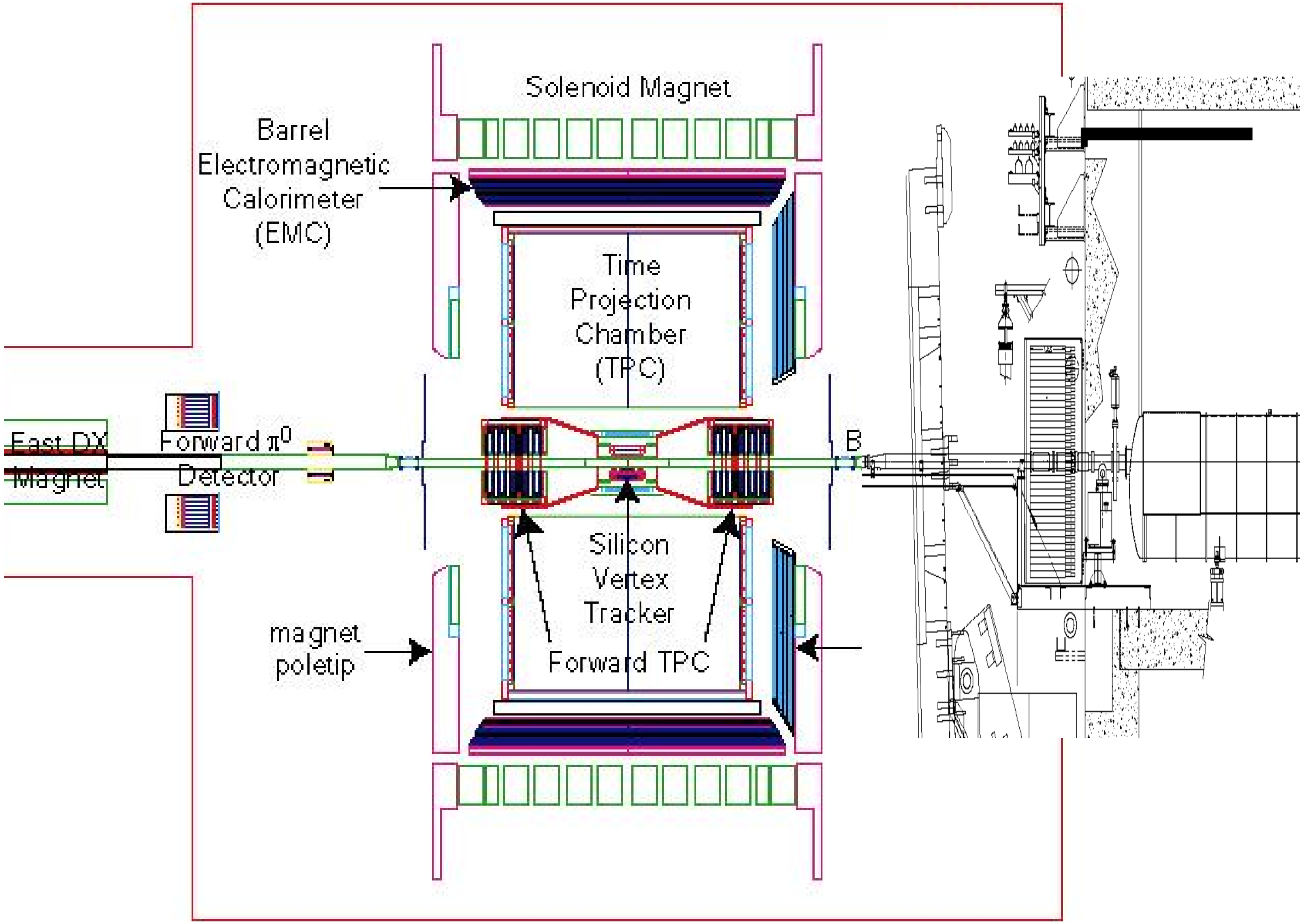


Run 8 Integrated FMS transverse figure-of-merit.

Only 43% of goal, after calibration from jet

However, the FMS provides roughly 20 times the coverage of previous runs in the forward region.

STAR detector layout with FMS



TPC: $-1.0 < \eta < 1.0$

FTPC: $2.8 < |\eta| < 3.8$

BBC : $2.2 < |\eta| < 5.0$

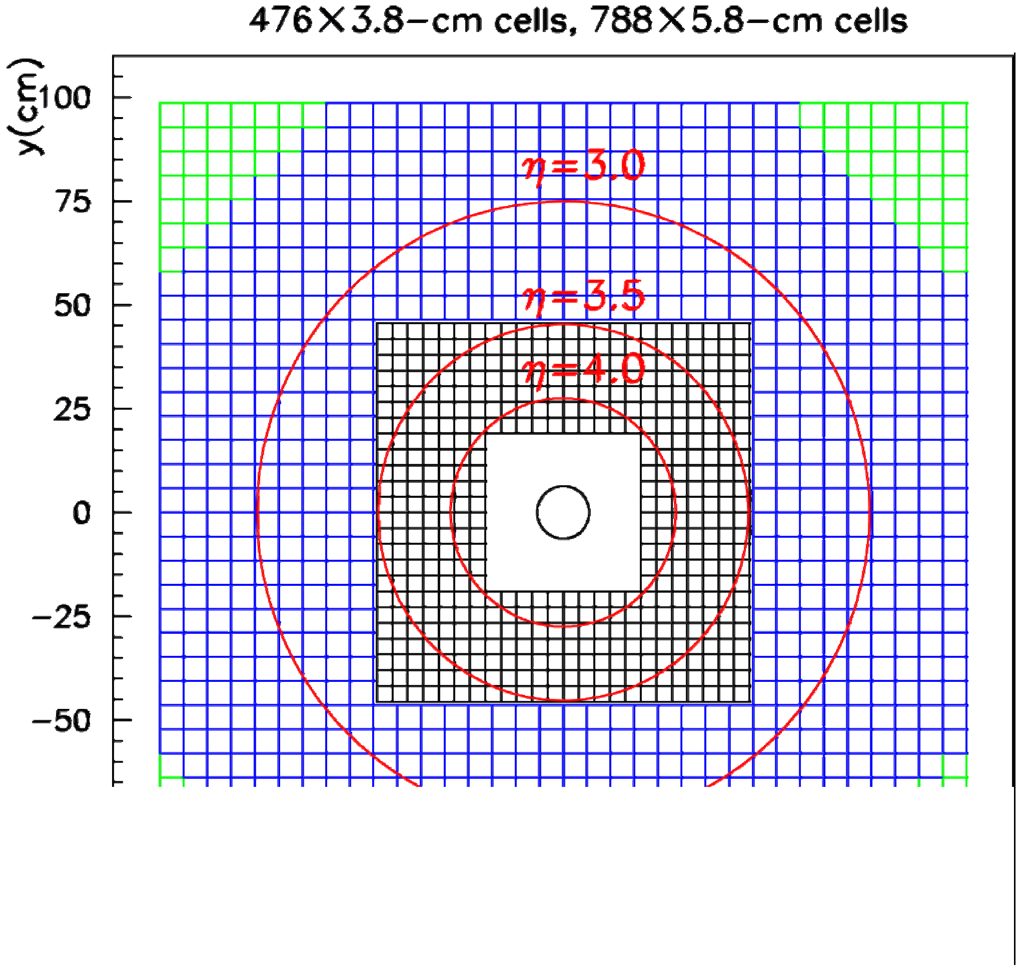
EEMC: $1 < \eta < 2$

BEMC: $-1 < \eta < 1$

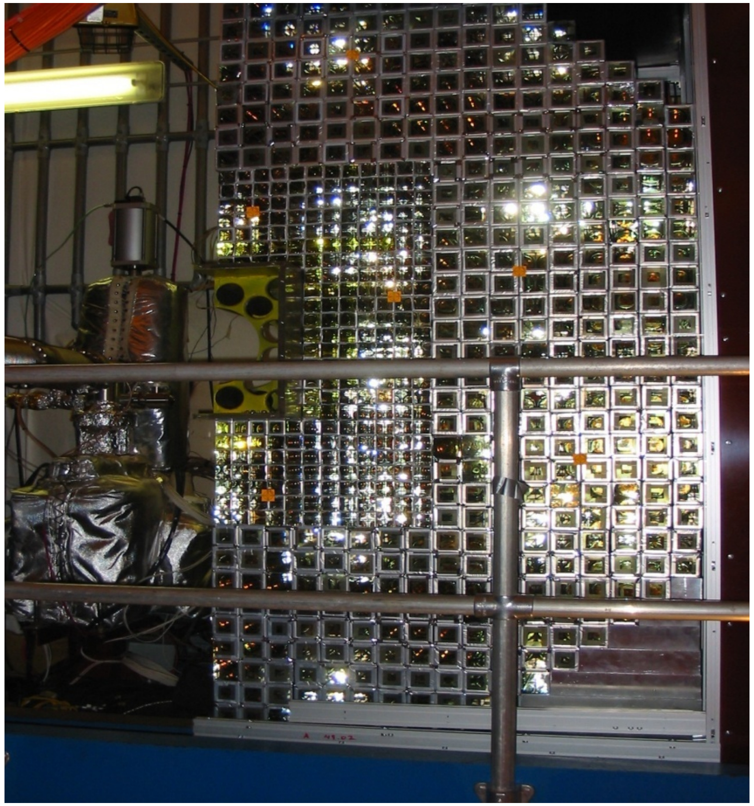
FMS: $2.5 < \eta < 4.0$

New forward detector for Run 8: FMS

FMS provides nearly 20x the coverage of previous forward detectors



North-half, view from the hall



Nearly contiguous coverage for $2.5<\eta<4.0$.

Run 5 FPD