Single Transverse Spin Asymmetries at RHIC

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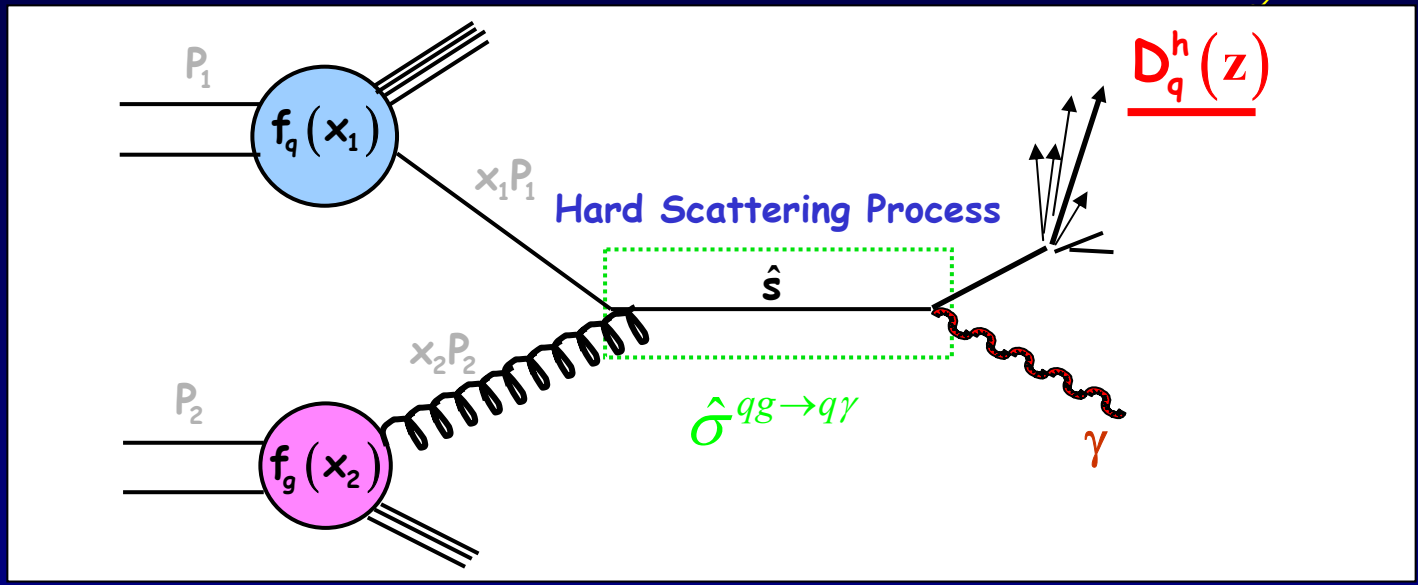
RHIC Physics

Broadest possible study of QCD in A-A, p-A, p-p collisions

- *Heavy ion physics*
  - Investigate nuclear matter under extreme conditions
  - Examine systematic variations with species and energy
- ***Explore the spin of the proton***
  - In particular, contributions from
    - Gluon polarization (ΔG)
    - Sea-quark polarization $\left(\Delta\bar{u}, \Delta\bar{d}\right)$
    - Transversity distributions (δq)
- *Nucleon structure in a nuclear environment*
  - Nuclear dependence of pdf's
  - Saturation physics

Continue to explore in eRHIC

Hard Scattering Processes in p+p: Factorization and Universality



$$\sigma(pp \to \gamma X) \propto f_q(x_1) \otimes f_g(x_2) \otimes \hat{\sigma}^{qg\to q\gamma}(\hat{s})$$

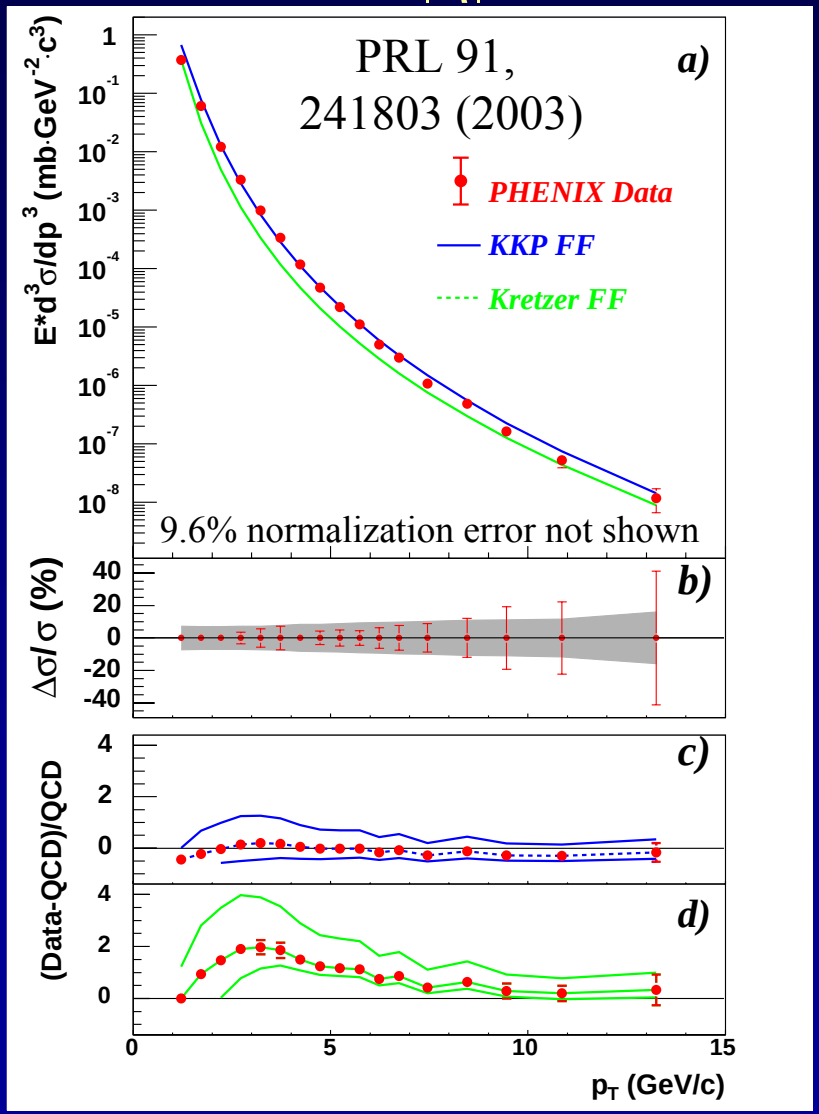
"Hard" probes have predictable rates given:

- Parton distribution functions (need experimental **input**)
- **pQCD hard scattering rates (calculable in pQCD)**
- **Fragmentation functions (need experimental input)**

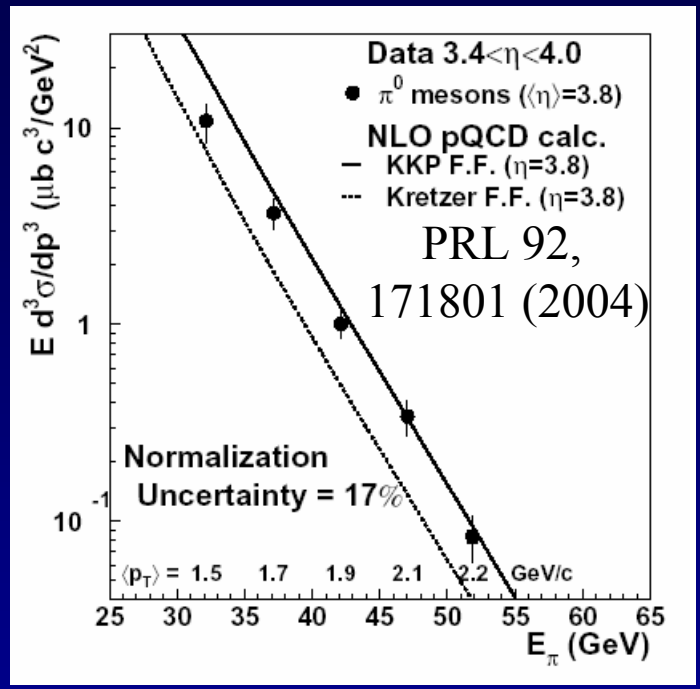
Universality

π^0 Cross Section from 2001-2 Run

PHENIX, $|\eta| < 0.35$

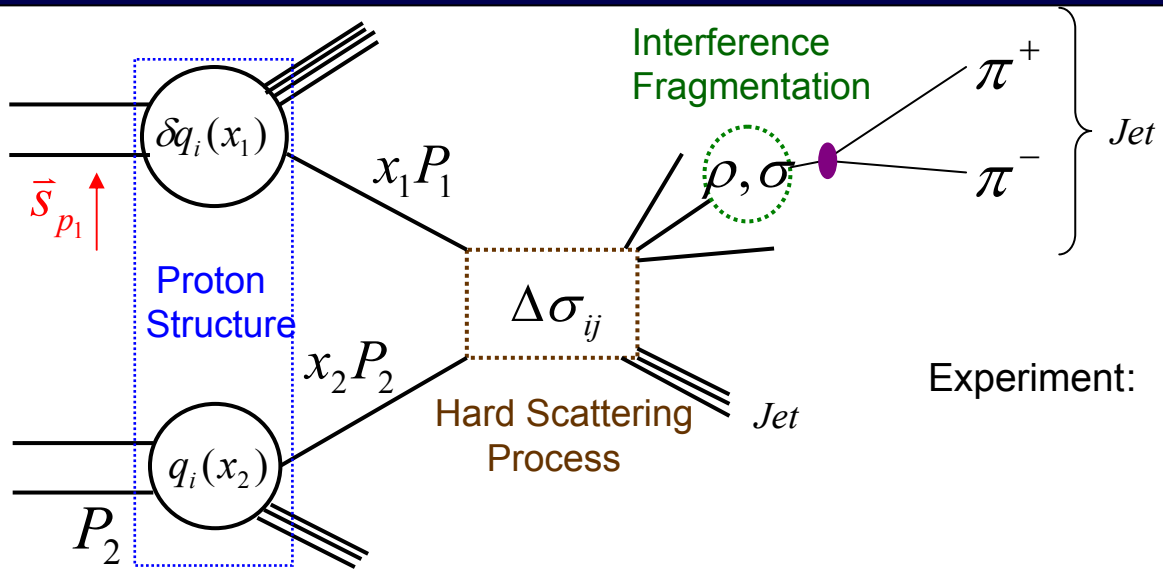


STAR, $3.4 < \eta < 4.0$



- Good agreement between NLO pQCD calculations and experiment
  - ➢ Can use NLO pQCD analysis to extract spin-dependent pdf's

Nucleon Transversity and Factorization at RHIC



Jian Tang , Thesis MIT, June 1999

R. Jaffe, X.Jin, J. Tang Phys. Rev. D57 (1999)5920

X. Ji, Phys. Rev. D49 (1994)114

J. Collins, S. Heppelmann, G. Ladinsky, Nucl.Phys. B420 (1994)565

A. Bianconi, S. Boffi, R. Jakob, M. Radici, Phys. Rev. D62 (2000) 034009

Experiment: $A_\perp = \frac{1}{P_{beam}} \frac{N^\rightarrow - N^\leftarrow}{N^\rightarrow + N^\leftarrow}$

Currently unknown: b-Factories,LEP

measured parton dis.

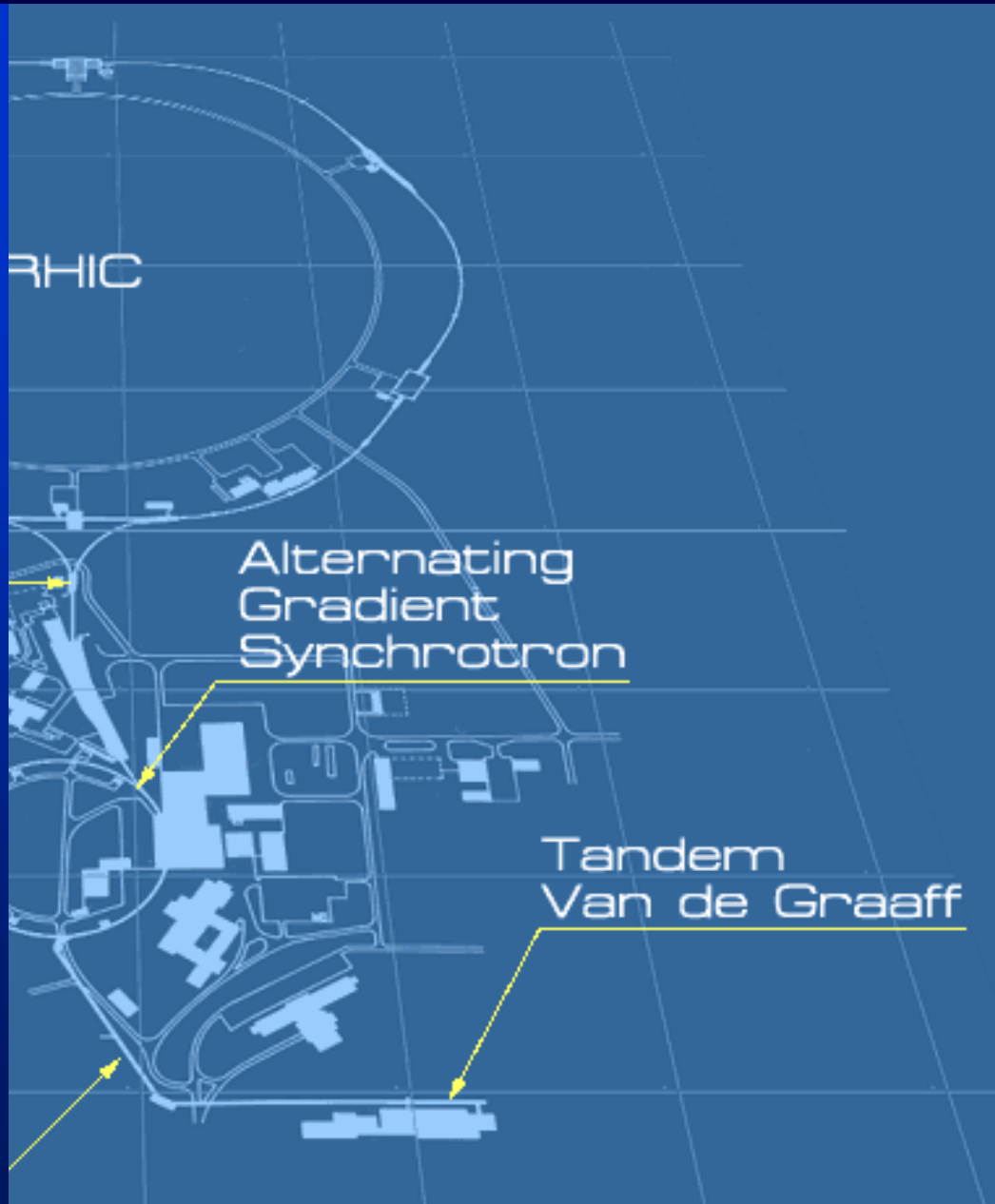
pQCD

$$\frac{d^7\sigma_{\pi^+,\pi^-},\left(pp^\uparrow \to \pi^+\pi^- X\right)}{dx_1 dx_2 dt dz dm^2 d\cos\theta d\varphi} \propto \delta q(x_1)\cdot q(x_2) \times \frac{d^3\sigma(q_1 q_2 \to q_3 q_4)}{dx_1 dx_2 dt} \times \frac{d^2 M}{dz dm^2 d\cos\theta d\varphi}$$

Model Calculations

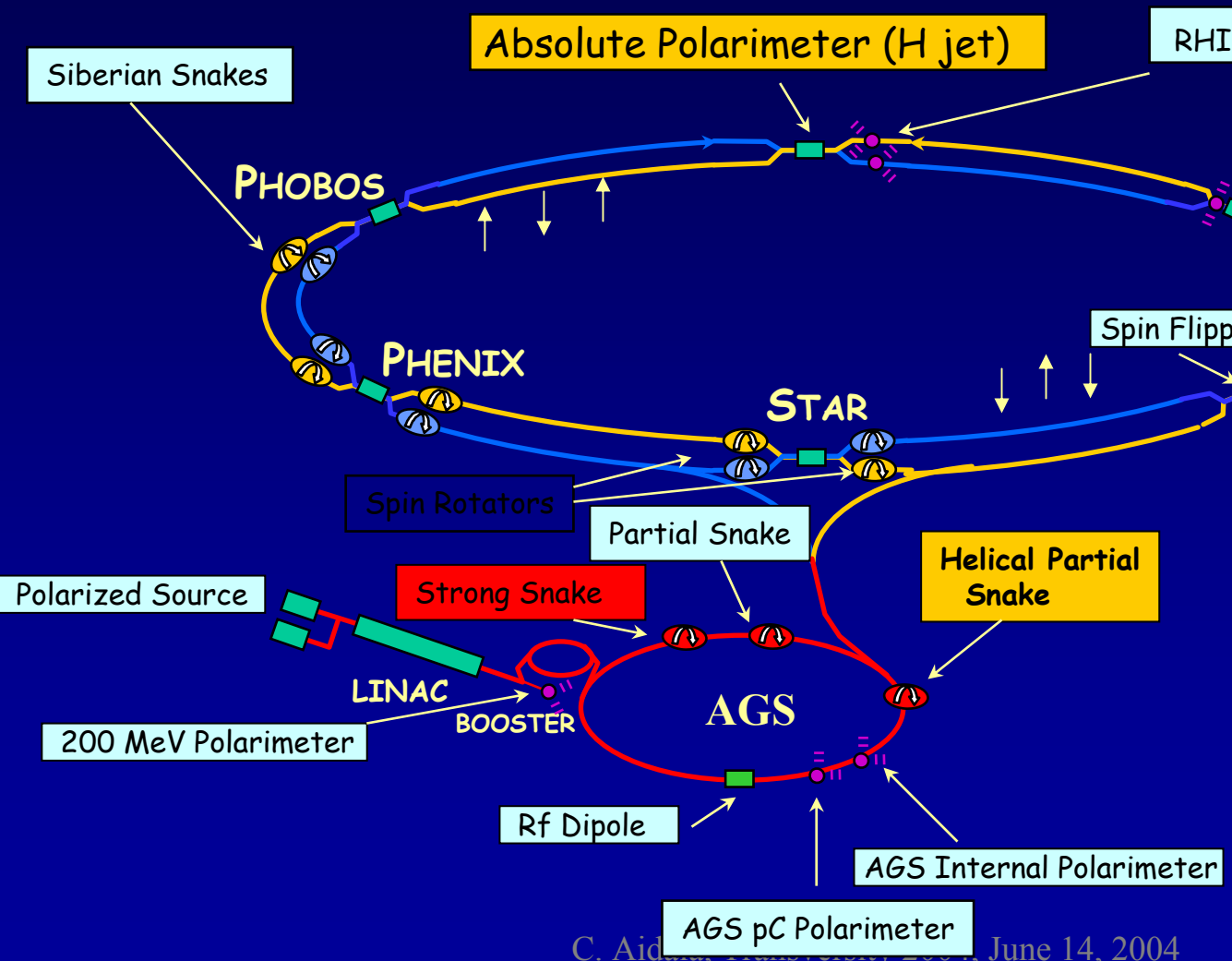
RHIC Specifications

- 3.83 km circumference
- Two independent rings
  - Up to 120 bunches/ring
  - 106 ns crossing time
- Energy:
  - ➔Up to 500 GeV for p-p
  - ➔Up to 200 GeV for Au-Au (per N-N collision)
- Luminosity
  - Au-Au: 2×10^{26} cm^{-2} s^{-1}
  - p-p : 2×10^{32} cm^{-2} s^{-1} (*polarized*)



RHIC as a Polarized p-p Collider

source: Thomas Roser, BNL



Run 04 achieved:

$\sqrt{s} = 200\text{GeV}$, $L_{peak} \sim 6 \times 10^{30}\ \text{cm}^{-2}\ \text{s}^{-1}$

P_b~45% , 55 bunches
New working point with long beam and polarization lifetimes

Run 05 planned:

Time to tune accelerator complex
Measure: A_{LL}(jets), $A_{LL}(\pi^0)$
Commission strong superconducting AGS snake

Absolute Polarimetry for RHIC: Polarized H Jet Target

Courtesy Sandro Bravar, STAR and Yousef Makdisi, CAD

Polarized Hydrogen Gas Jet Target

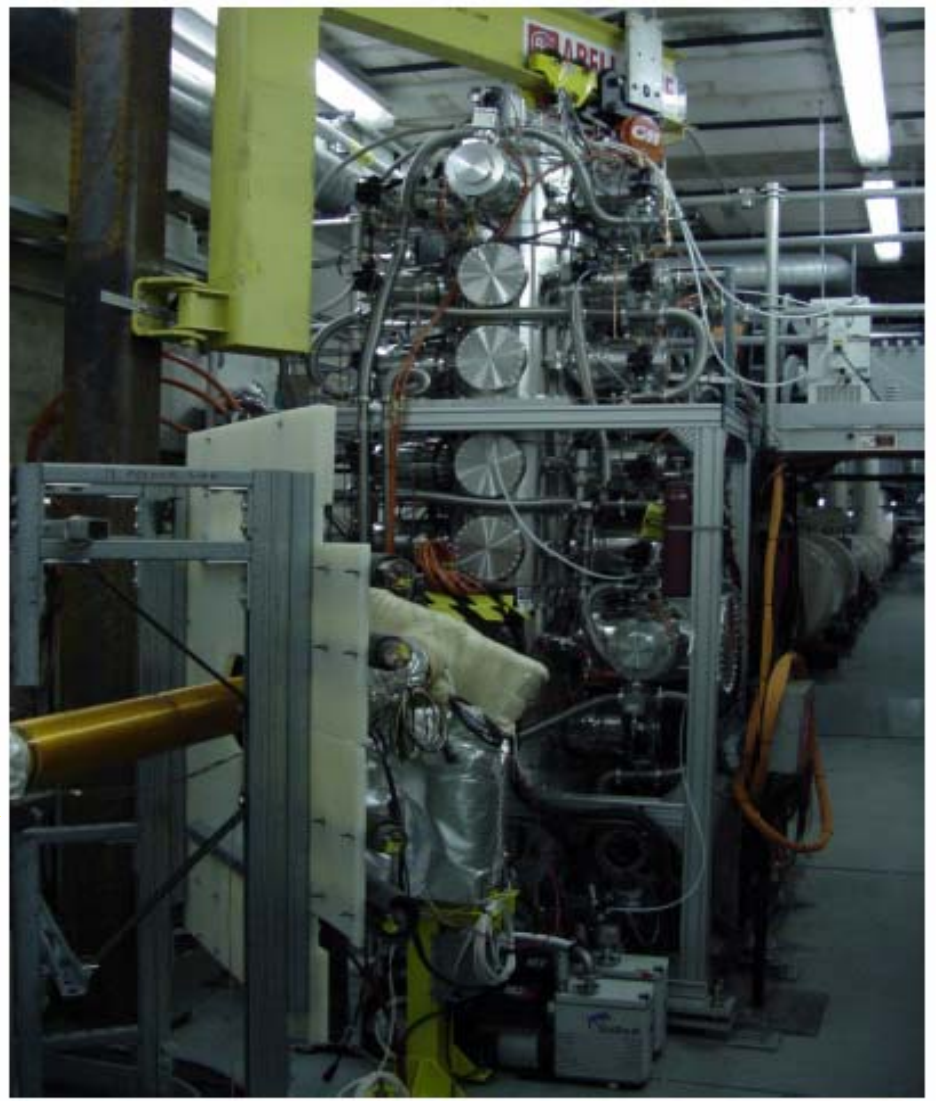
thickness of $> 10^{12}$ p/cm^2

polarization = 93% (+1 −2)%!

no depolarization from beam wake fields

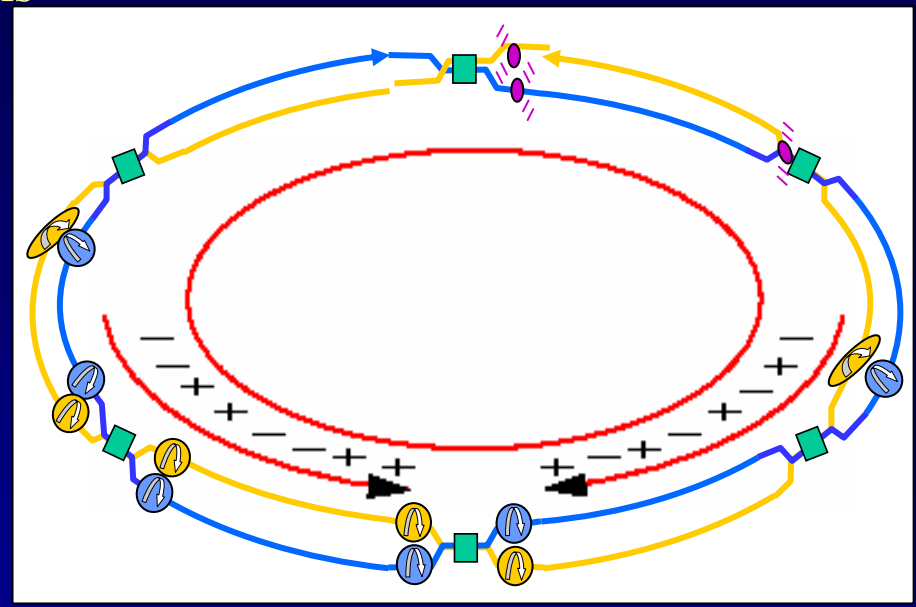
Silicon recoil spectrometer to measure

- The left-right asymmetry A_N in pp elastic scattering in the CNI region to $\Delta A_N < 10^{-3}$ accuracy.
- Calibrate the p-Carbon polarimeters
- Two large data samples at 24 and 100 GeV
- Expect results on P_{Beam} to 10% in the near future



Spin Running at RHIC So Far

- 2001-2
  - ***Transversely*** polarized p+p collisions
  - Average polarization of ~15%
  - Integrated luminosity 0.15 pb^{-1}
- 2003
  - ***Longitudinally*** polarized p+p collisions achieved
  - Average polarization of ~27%
  - Integrated luminosity 0.35 pb^{-1}
- 2004
  - 5 weeks polarized p+p commissioning
    - Specifically to work on spin tune and AGS polarization
    - Commission hydrogen jet polarimeter
  - 1 week data-taking
  - Average polarization ~45%



Flipping spin of bunches every ~100 or 200 ns aids in eliminating systematic errors

Possible Schedule for Future Runs

example: STAR 32 week scenario → all schedules subject to further advances in RHIC operations!

L= $6x10^{30}cm^{-2}s^{-1}$ ……. $8x10^{31}cm^{-2}s^{-1}$

P= 0.45 0.5 0.7 ……

√s= …… 200 GeV ……

	2004	2005	2006	2007	2008	2009 ….
pp	5+1	5+10	5+11	0	5+9 → 156pb^{-1}	

Inclusive hadrons + Jets

Transverse Physics

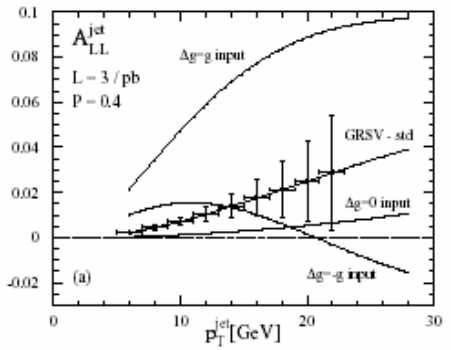
Charm Physics

direct photons

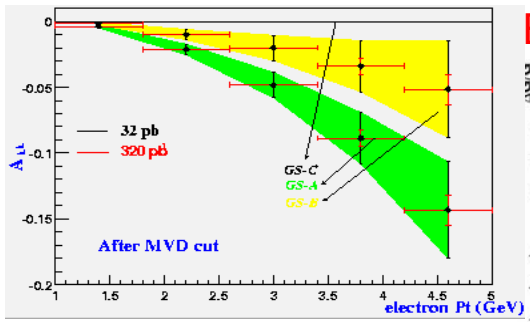
Bottom physics

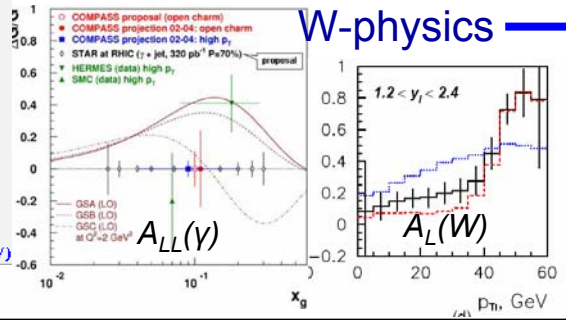
W-physics

A_{LL}(hadrons, Jets)

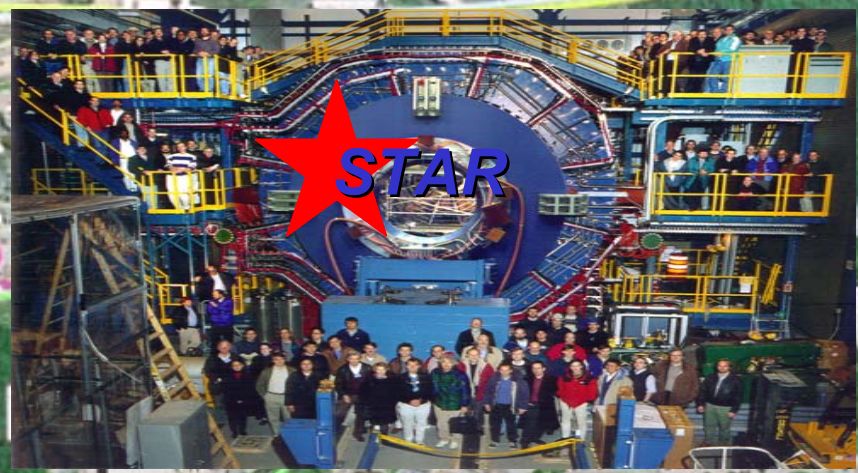


A_{LL}(charm)





RHIC's Experiments



The PHENIX Detector

2 central spectrometers

- Track charged particles and detect electromagnetic processes

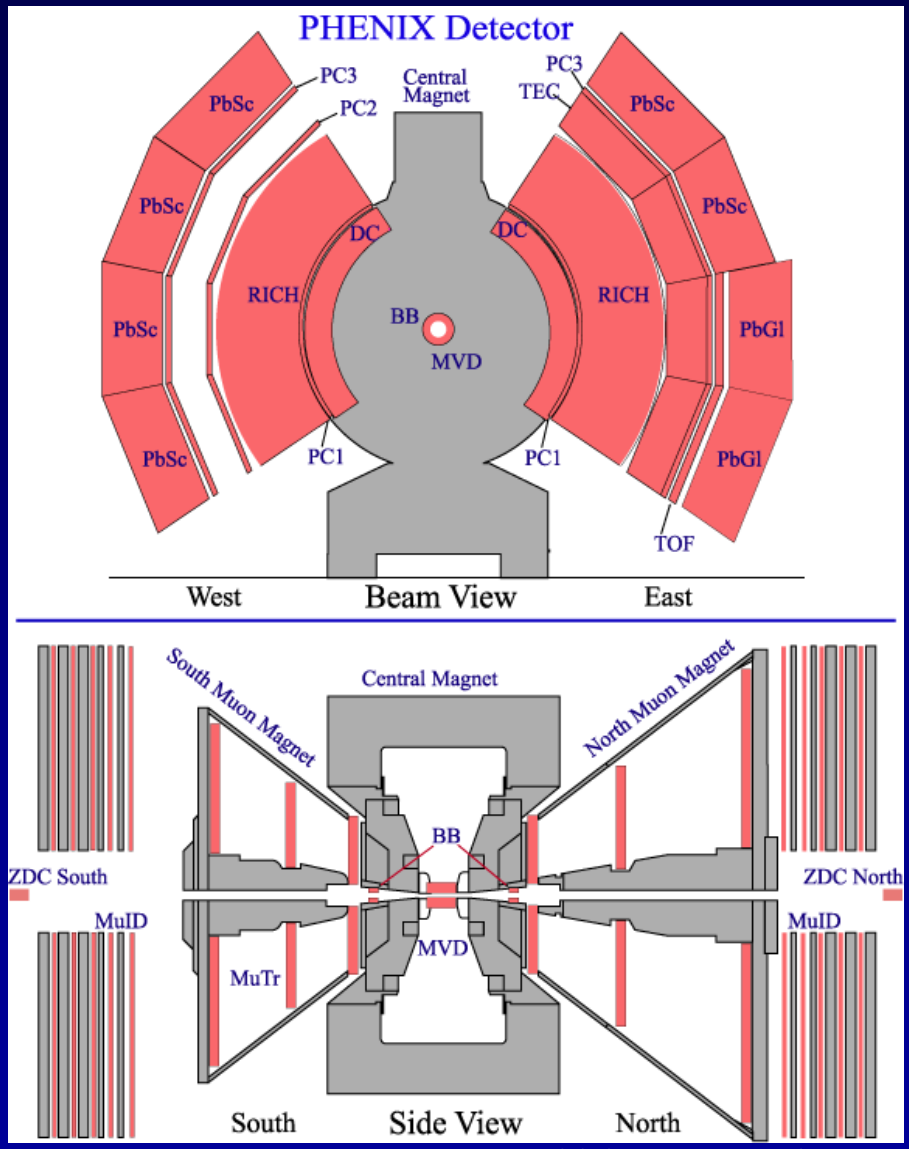
2 forward spectrometers

- Identify and track muons

3 global detectors

- Determine when there's a collision

PHENIX Detector Overview



Central arms

Photons, electrons, identified charged hadrons

$|\eta| < 0.35$

$\Delta\phi = 180$ degrees

Forward muon arms

Track and identify muons

$1.2 < |\eta| < 2.4$

$\Delta\phi = 2\pi$

Detector fully operational for intermediate luminosities. Upgrades planned for high-luminosity running.

Measurement of Proton Spin Structure at RHIC

Gluon polarization

$$\Delta G(x)/G(x)$$

Inclusive jets, hadrons, photons, and heavy flavor in STAR and PHENIX

Flavor separation of quark polarizations

$$\Delta q(x)/q(x), \quad \Delta\bar{q}(x)/\bar{q}(x)$$

Single lepton asymmetries $A_L(e,\mu)$ in W-production in STAR and PHENIX

Transverse spin structure of the nucleon

$$\delta q(x)/q(x)$$

A_T in Collins- and Interference-fragmentation and A_N in STAR, PHENIX, and BRAHMS, A_{TT} in jets and Drell-Yan

Avenues to Transversity at RHIC

Present and Near Future		Upgrades	
$\int Ldt = 320\text{pb}^{-1}, \sqrt{s} = 200\text{GeV}$		$\int Ldt = 8\text{fb}^{-1}$ at RHIC, eRHIC	
• Precision measurement of A_N	BRAHMS, PHENIX, STAR	• Direct Photon : Collins in Jets, Interference Fragmentation	PHENIX, STAR
• Collins Effect in Jets: $A_T(pp_\perp \to \pi + Jet + X)$ J.C. Collins, Nucl. Phys. B396, 161(1993)		• Drell Yan: $A_{TT}(p_\perp p_\perp \to ll) \Leftrightarrow \delta q \cdot \delta \bar{q}$ J.Ralston and D.E. Soper, Nucl. Phys. B152, 109(1979)	
• π^+, π^- Interference Fragmentation : $A_T\left(p_\perp p \to (\pi^+, \pi^-) + X\right)$ J. Collins, S. Heppelmann, G. Ladinsky, Nucl.Phys. B420 (1994)565 R. Jaffe, X.Jin, J. Tang Phys. Rev. D57 (1999)5920 A. Bianconi, S. Boffi, R. Jakob, M. Radici, Phys. Rev. D62 (2000) 034009		• Collins Effect in Jets • Interference Fragmentation	eRHIC
• Inclusive jet production $5 \cdot 10^{-4} \le A_{TT} \le 3 \cdot 10^{-3}$ W. Vogelsang and M. Stratmann, RBRC Wrkshp on Transversity (2000)			

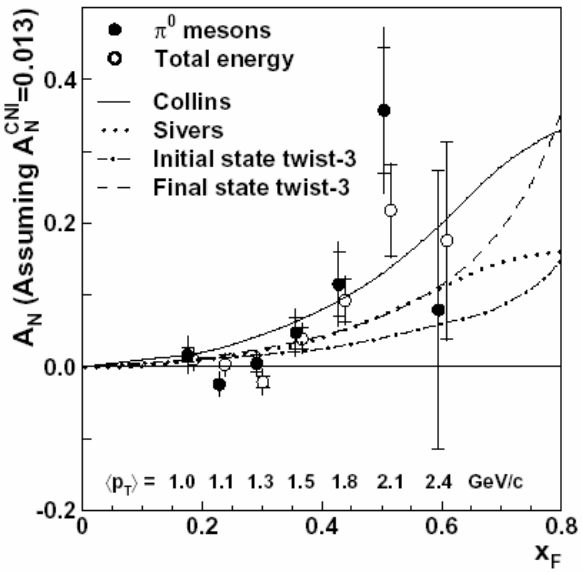
Transverse Spin at RHIC: Present

$$\int Ldt = 1-10\ \mathrm{pb}^{-1}, \sqrt{s} = 200\ \mathrm{GeV}$$

Precision measurement at BRAHMS, also PHENIX, STAR

(I) Measure A_N : $A_N(pp_\perp \to h + X)$

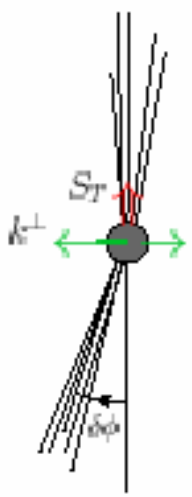
STAR Phys. Rev. Lett. 92:171801, 2004



Separation of transversity and Sivers with high-precision and large p_T range?

STAR and PHENIX

(II) Boer and Vogelsang (hep-ph/0312320): azimuthal back to back correlation between hadrons in opposite hemisphere jets:



Clean channel for Sivers effect!

Interference Fragmentation: Near-Term and Long-Term Projections

$\int Ldt = 32\,pb^{-1}$

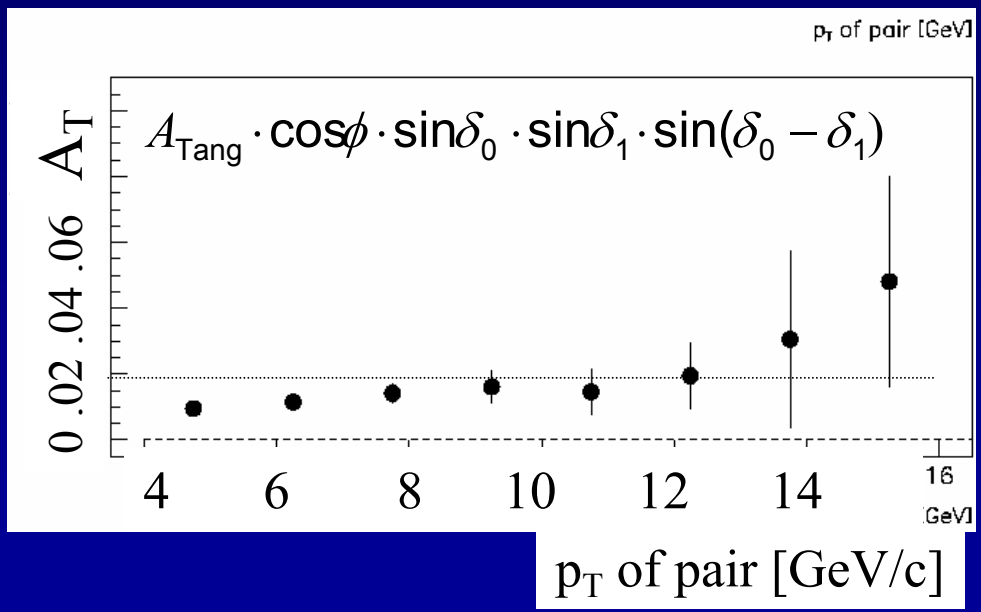
$E_{\pi_1,\pi_2} > 4\,\mathrm{GeV}$

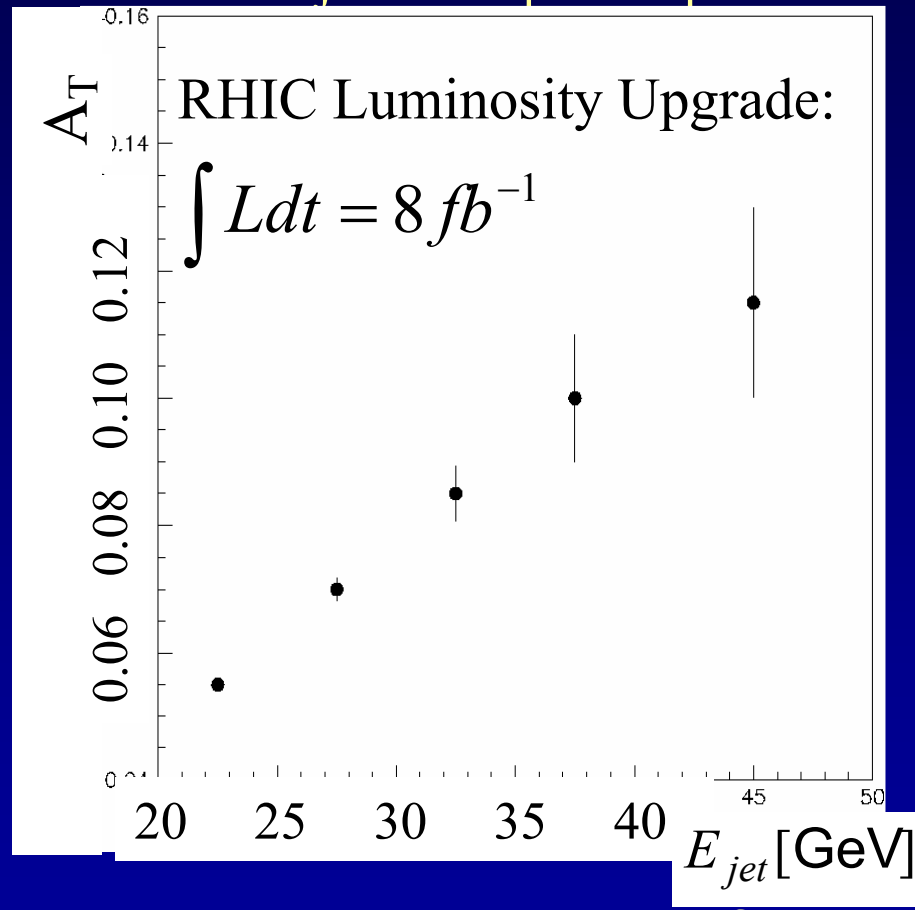
$\sqrt{p_{1T}^2 + p_{2T}^2} > 4\,\mathrm{GeV}$

$800\,\mathrm{MeV} < m_{\pi_1,\pi_2} < 950\,\mathrm{MeV}$

PHENIX

Interference FF in jet-direct photon production





Small aymmetry—below 5%—but good rate!

Large aymmetry, but lots of luminosity required!

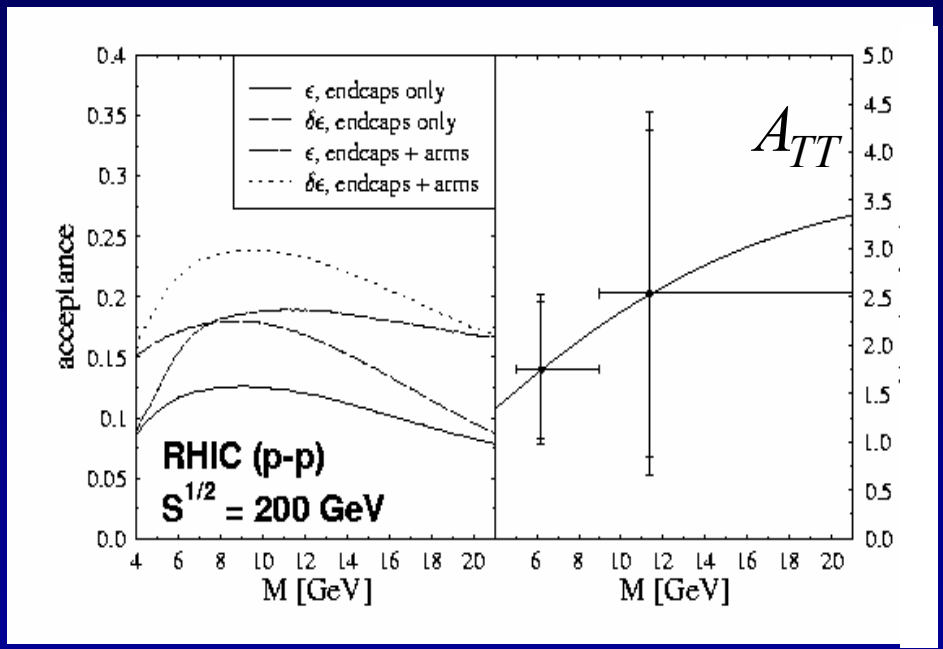
Drell-Yan Physics at RHIC

J.Ralston and D.E. Soper, Nucl. Phys. B152, 109(1979)

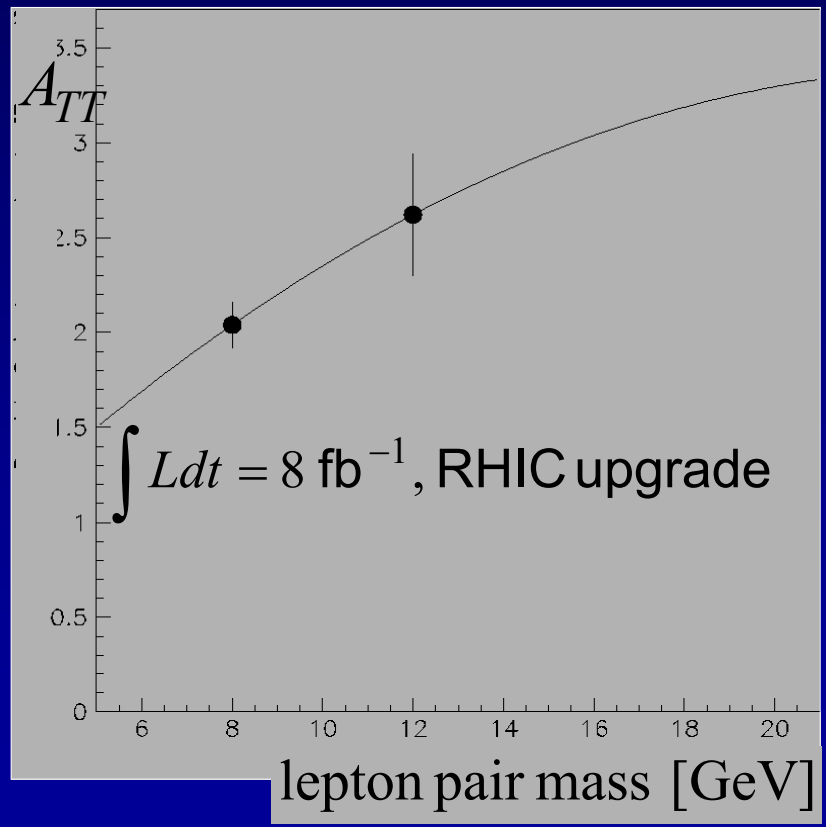
Drell-Yan: $A_{TT}(p_\perp p_\perp \to ll) \Leftrightarrow \delta q \cdot \delta \bar{q}$

Observable $\propto \delta q \cdot \delta \bar{q}$

$\int Ldt = 320\ \text{pb}^{-1}$, at PHENIX



O.Martin, A. Schaefer, M. Stratmann, W. Vogelsang Phys.Rev. D60, 117502(1999)

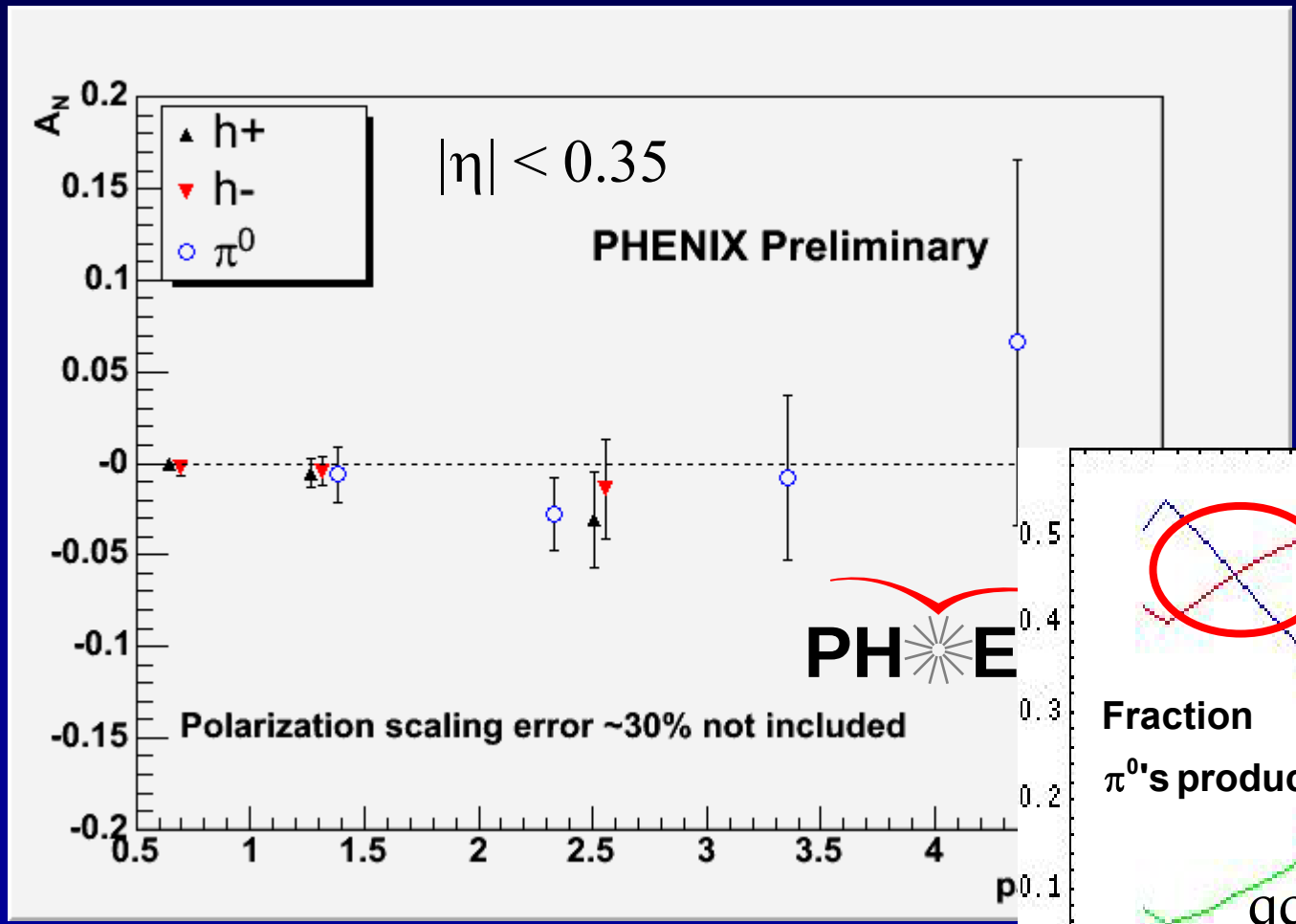


Components of the Transversity Program at RHIC

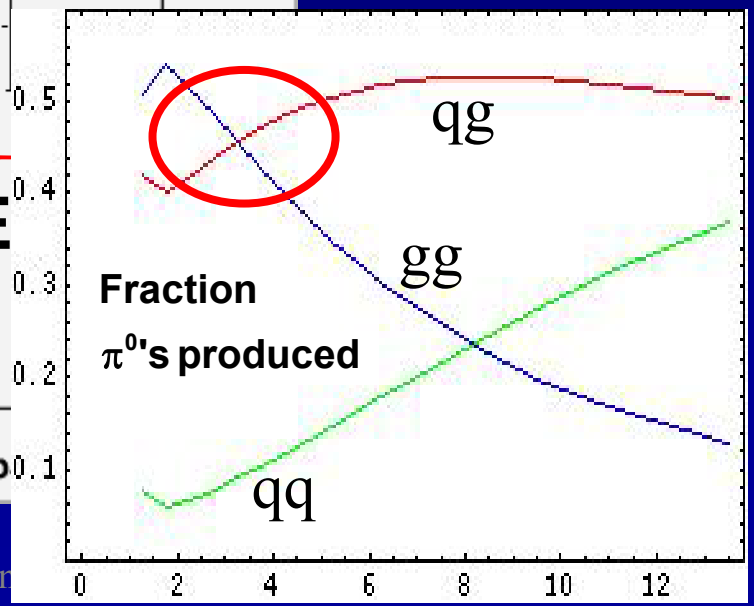
- $\delta\tilde{q}_I, H_1^\perp$ in e+e- using b-factory data (2005)
  - RBRC active in Belle
- Precision measurement of A_N at BRAHMS (2005)
- Tensor charge lattice calculation at RBRC (2005?)
  - 10 Tflops!
  - T. Blum, S. Sasaki, S. Ohta
- $\delta q \cdot \delta\tilde{q}_I$ at STAR, PHENIX
- $\delta q \cdot H_1^\perp$ at STAR
- $\delta q \cdot \delta\bar{q}$ at PHENIX (after luminosity upgrade)

} (2006-8)

A_N of Neutral Pions and Non-Identified Charged Hadrons at Midrapidity



A_N for both charged hadrons and neutral pions consistent with zero.



A_N of Neutral Pions at Forward Rapidity

Large asymmetry seen

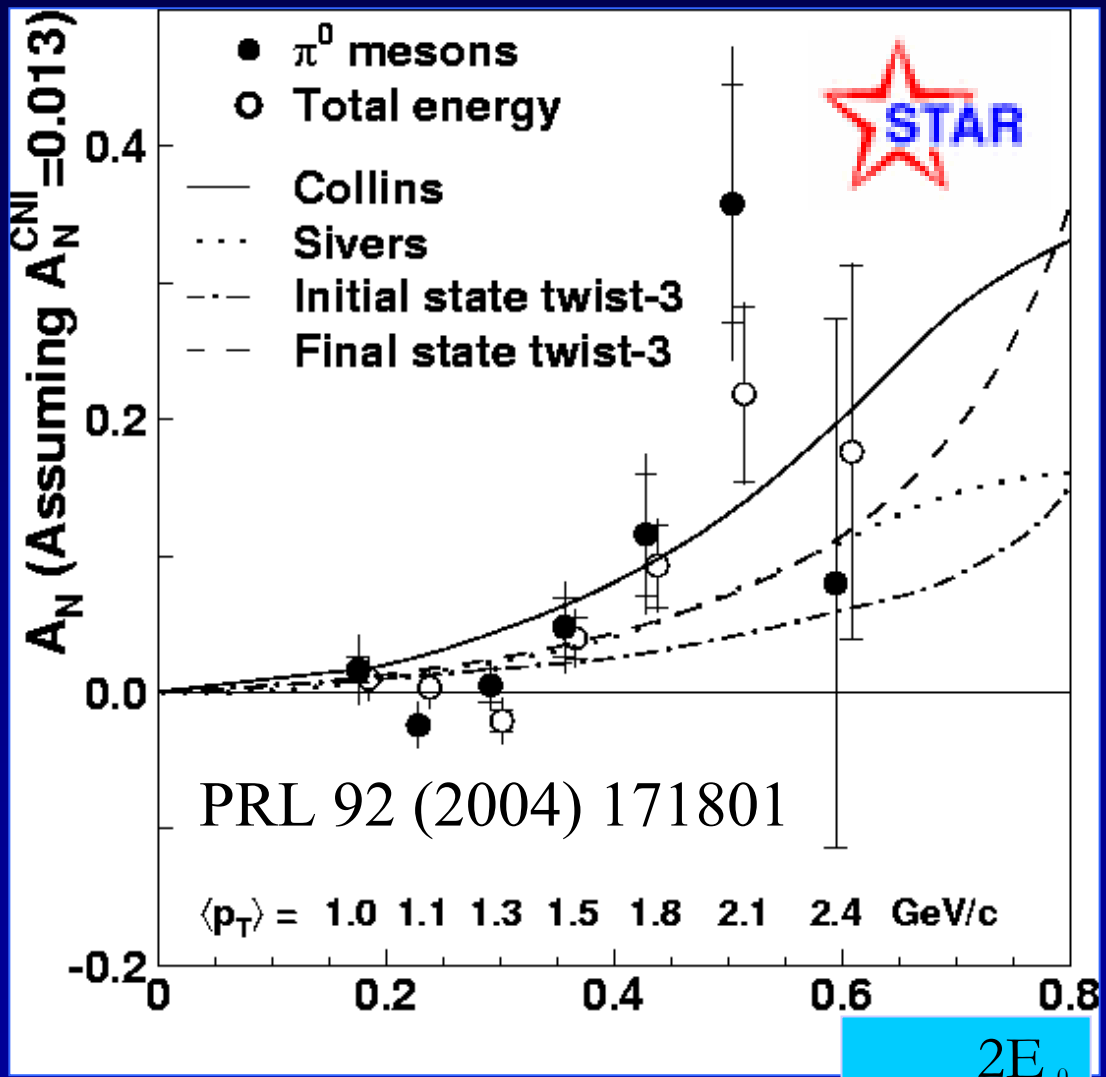
For $\langle\eta\rangle = 3.7$ possible contributions to A_N are:

Sivers Effect – Spin dependent initial partonic transverse momentum

Collins Effect – Spin dependent transverse momentum kick in fragmentation

Sterman and Qiu – Initial-state twist 3

Koike – Final-state twist 3

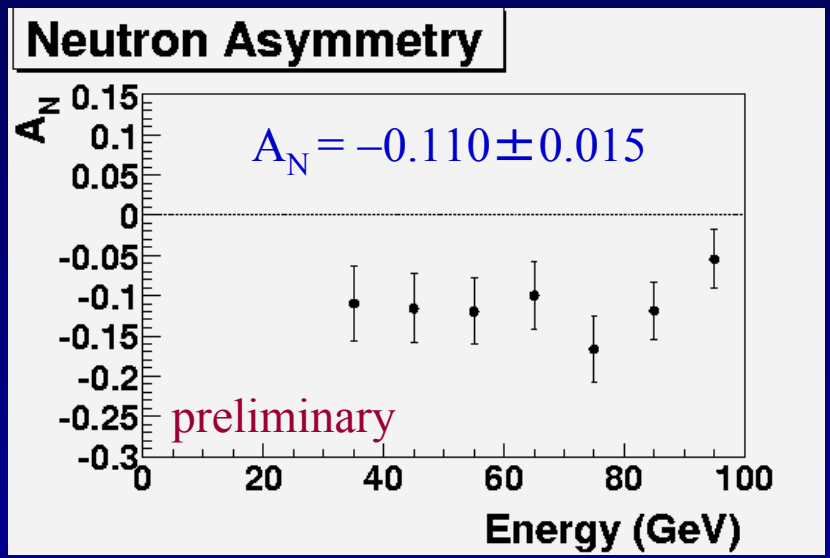


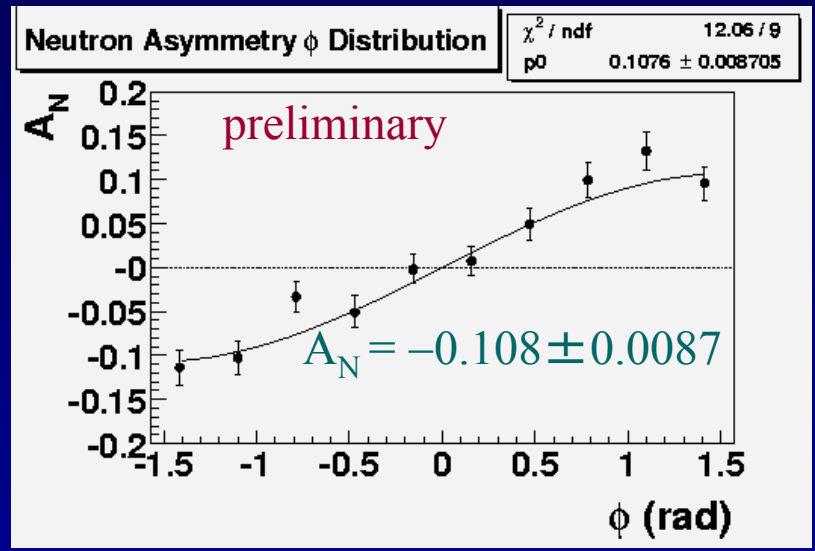
$$X_F = \frac{2E_{\pi^0}}{\sqrt{s}}$$

Neutron A_N at IP12

- A_N measurement at IP12
  - large neutron A_N was discovered

Y. Fukao



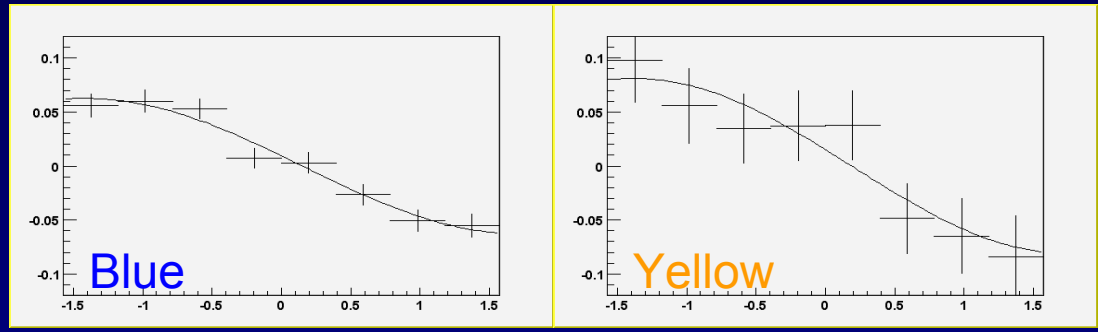


➔ Local polarimeter at PHENIX

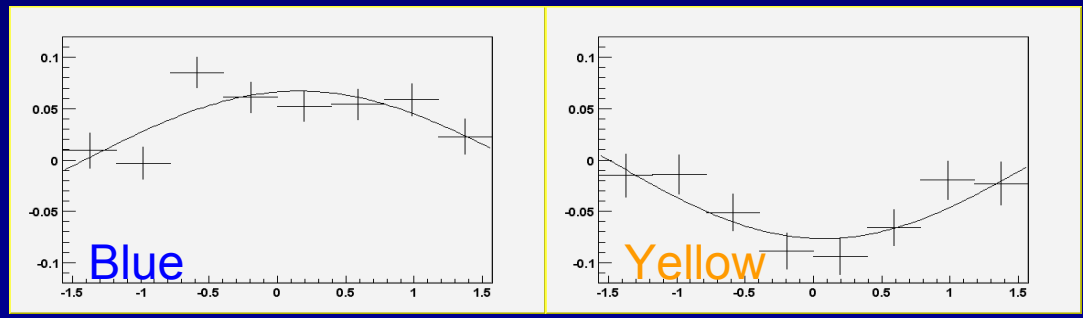
- ZDC + position sensitive counters to measure the neutron A_N

Single-Spin Asymmetries for Local Polarimetry: Confirmation of Longitudinal Polarization

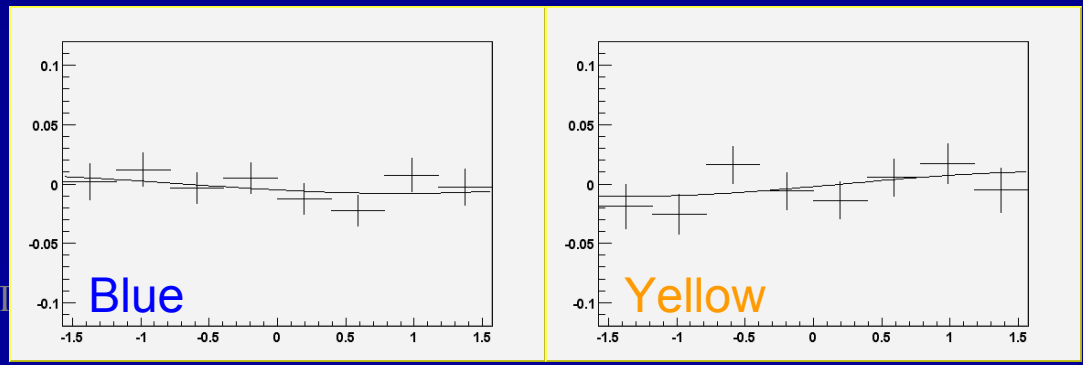
Spin Rotators OFF
Vertical polarization



Spin Rotators ON
Current Reversed!
Radial polarization

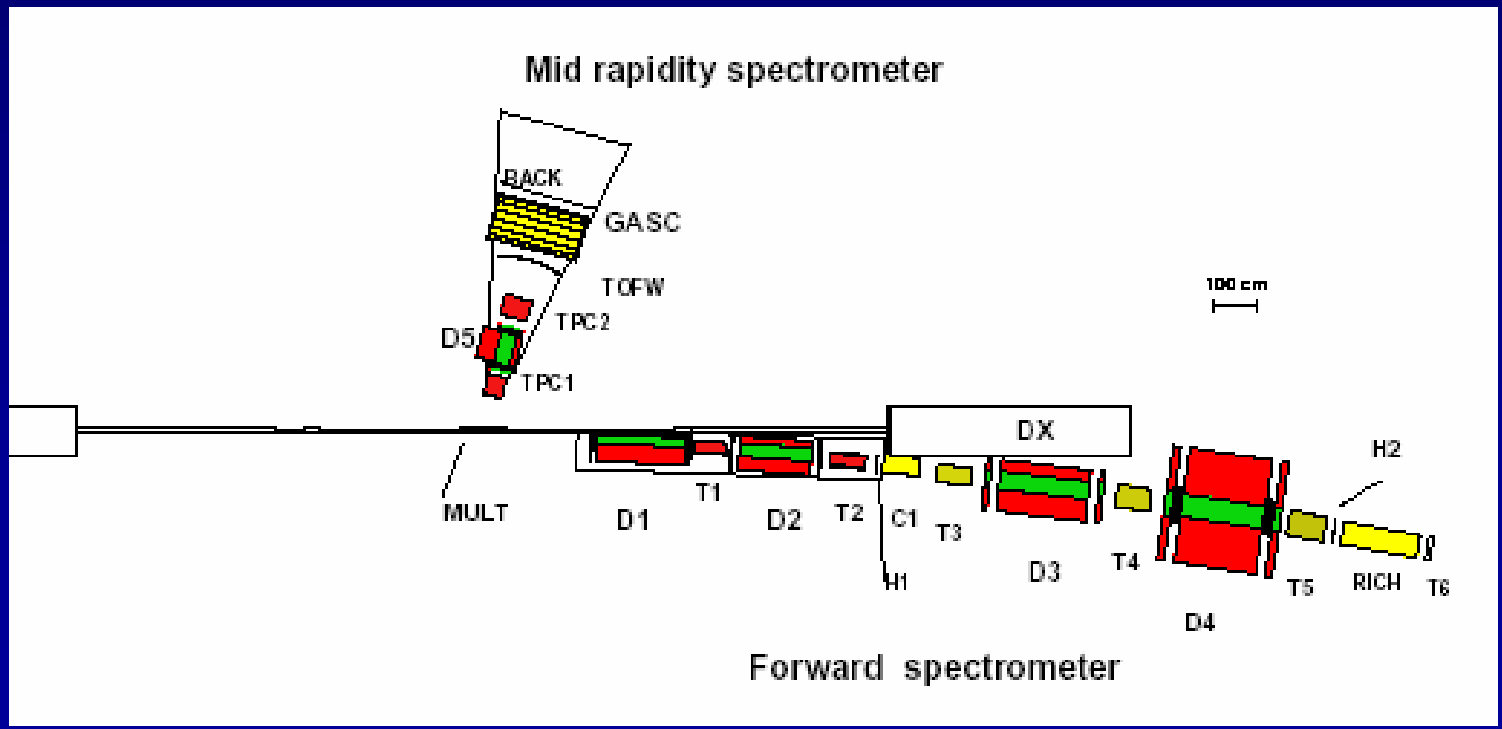


Spin Rotators ON
Correct Current
Longitudinal polarization!

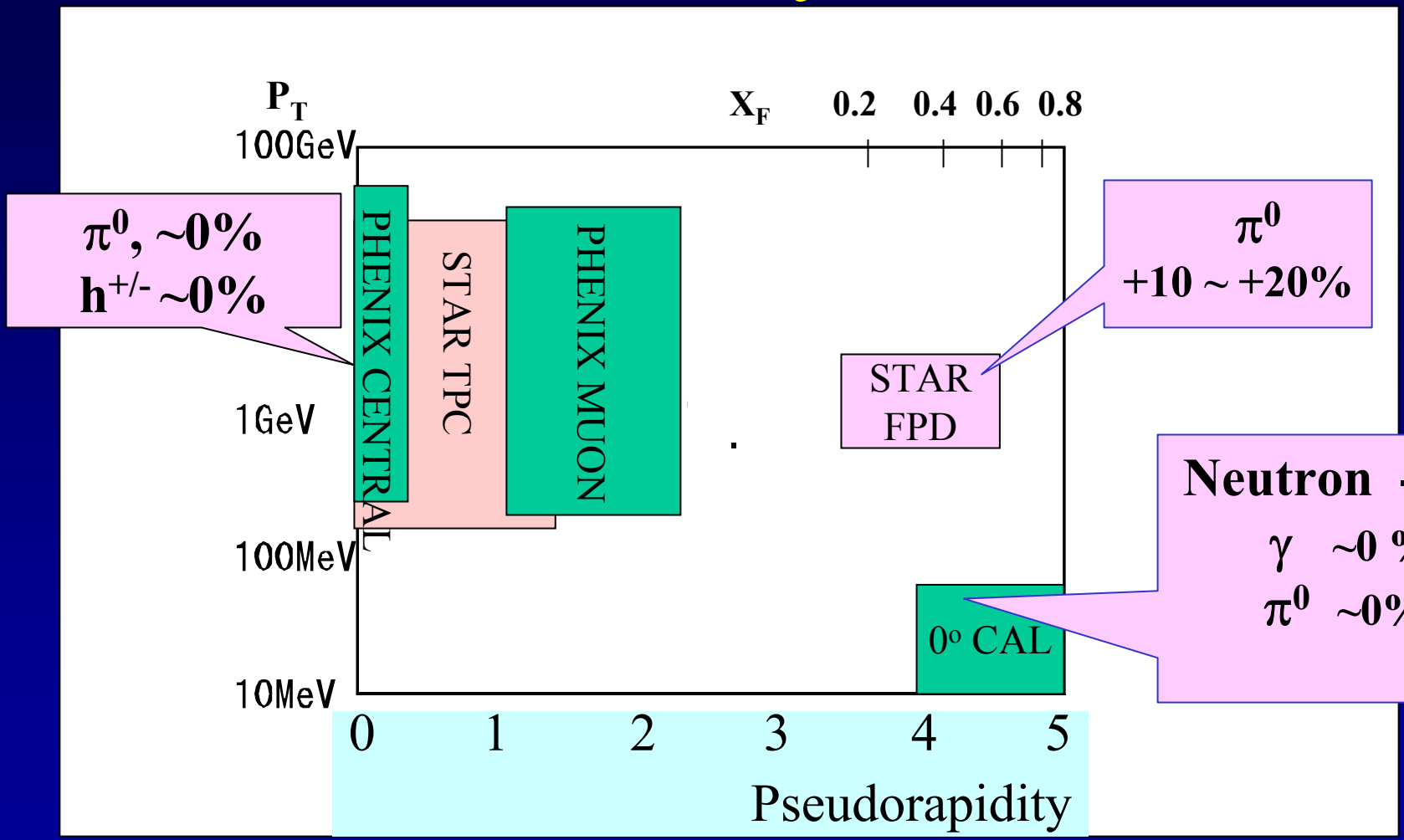


A_N of Charged Hadrons at BRAHMS (2005)

- Dedicated transverse spin measurements (no spin rotators)
- $p^{\pm}, K^{\pm}, \pi^{\pm}$ identified from $0 < |y| < 4$,
  $0.2 < p_T < 3$ GeV/c at forward rapidity
- High-precision measurement of A_N



Single-spin asymmetries seen at RHIC so far…



Summary

- RHIC has been successful as the world's first polarized proton collider, opening up new kinematic regions for investigating the spin of the proton

- The first transverse spin results are out, and non-zero asymmetries have been observed at RHIC energies
  - A_N of forward neutral pions (~+10-20%)
  - A_N of forward neutrons (~-10%)
  - A_N of neutral pions and non-identified charged hadrons at midrapidity (~0%)

- An extensive program planned for the near- and long-term future

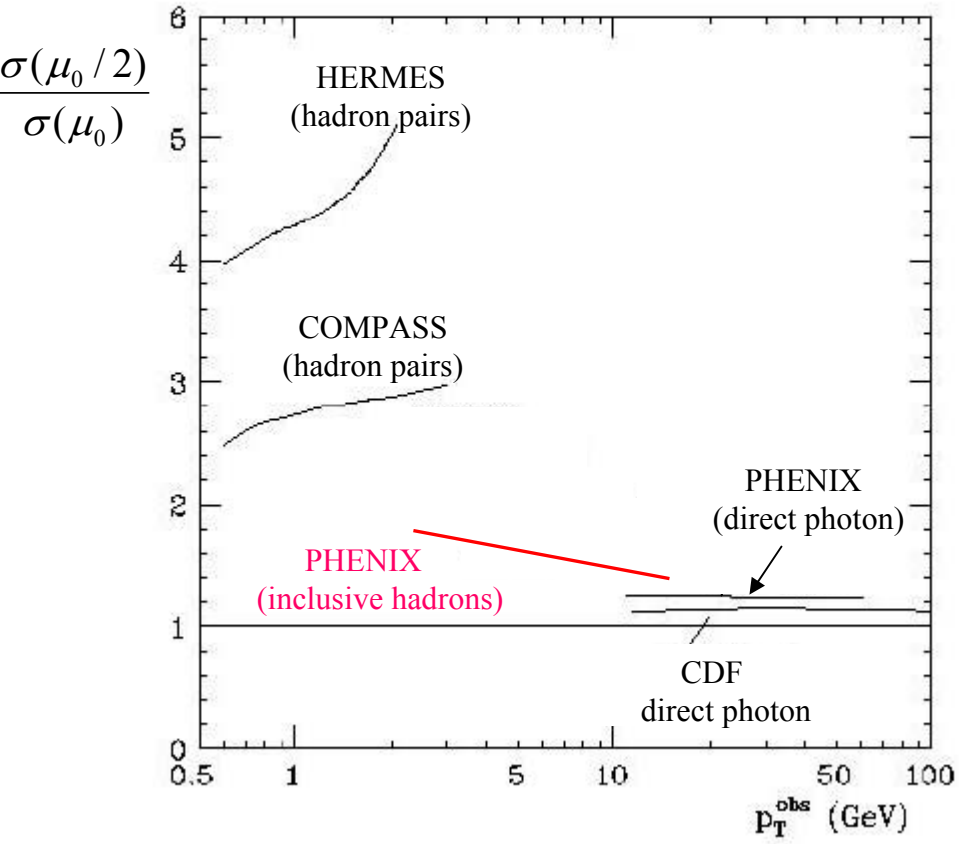
Many more years of exciting data and results to look forward to!

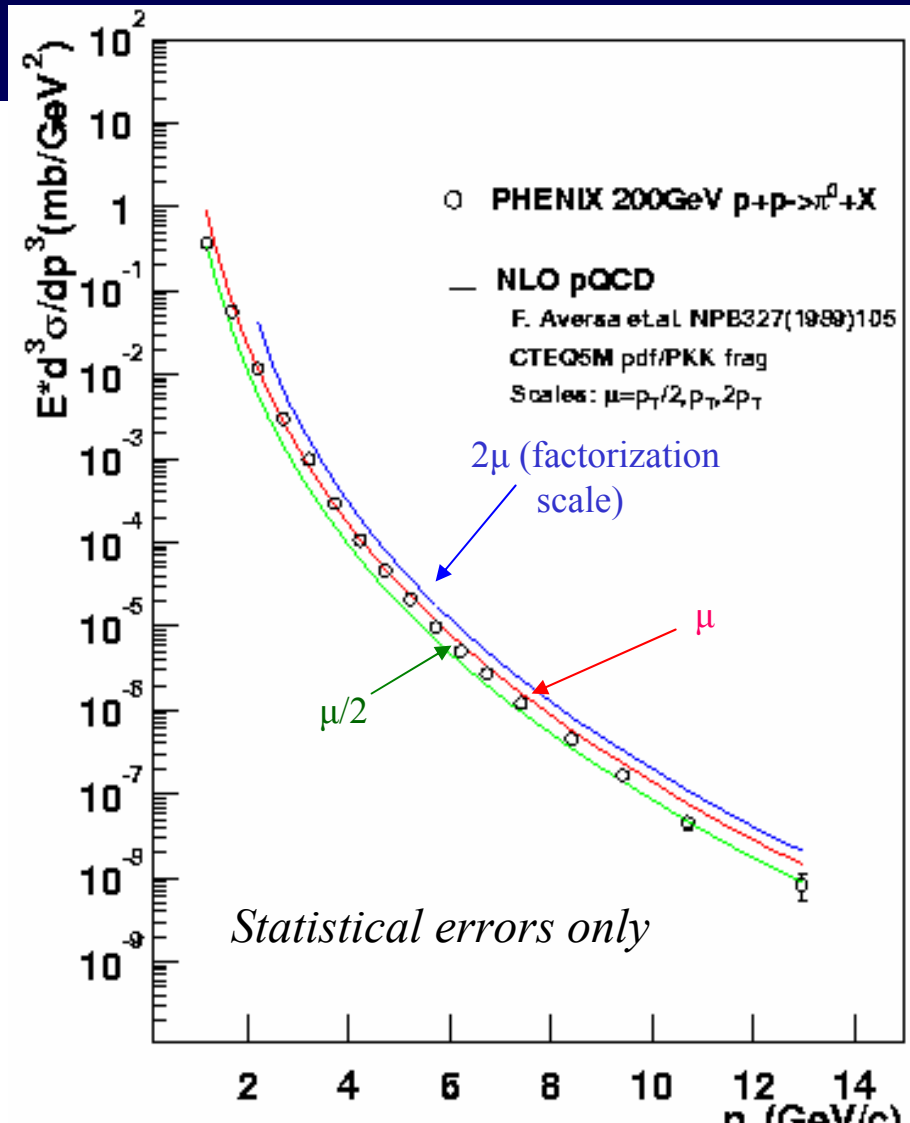
Extra Slides

pQCD Scale Dependence at RHIC

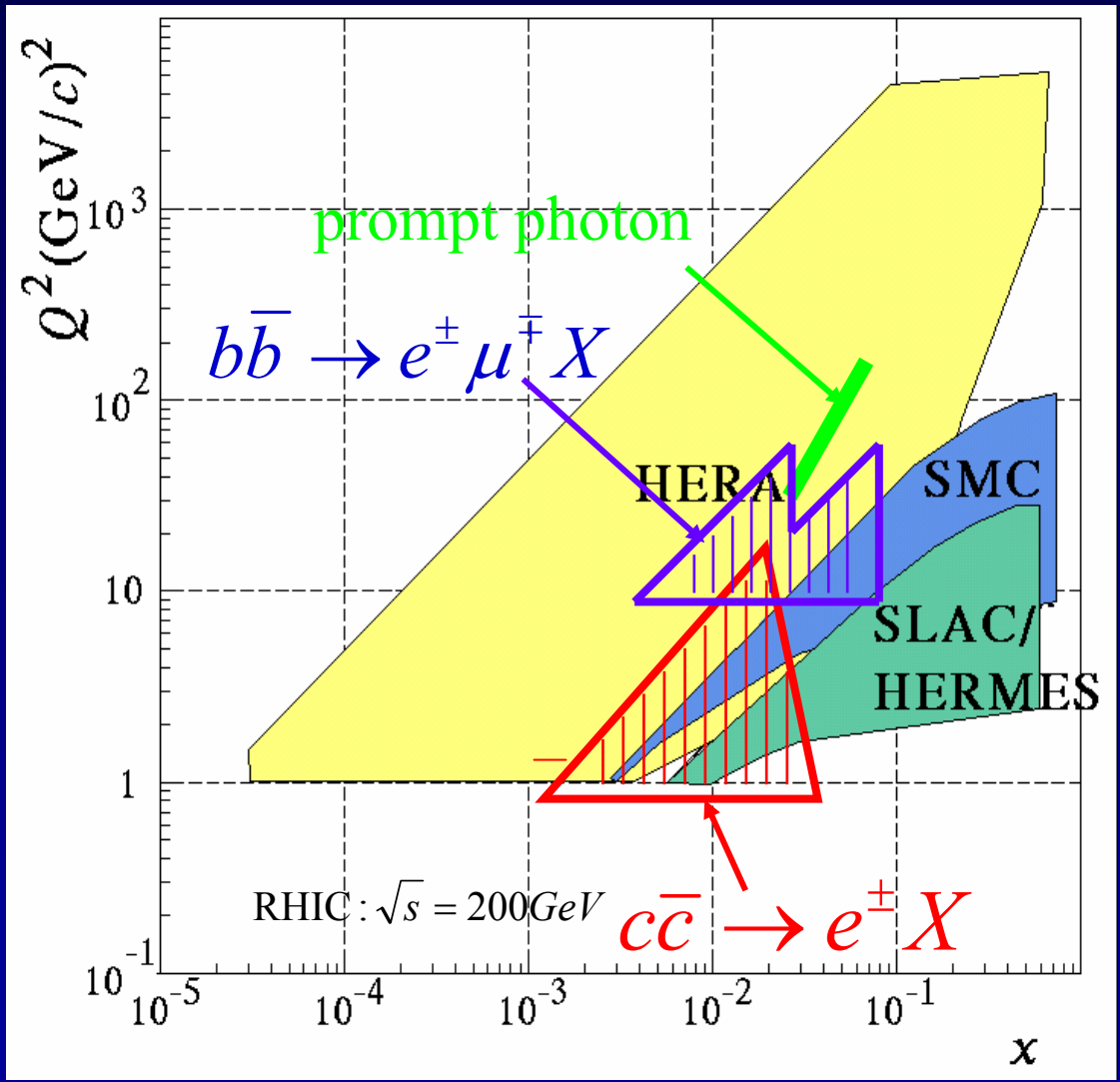
Theoretical uncertainty of pQCD calculations in channels relevant for gluon polarization measurements:

π^0 data vs pQCD with different factorization scales:



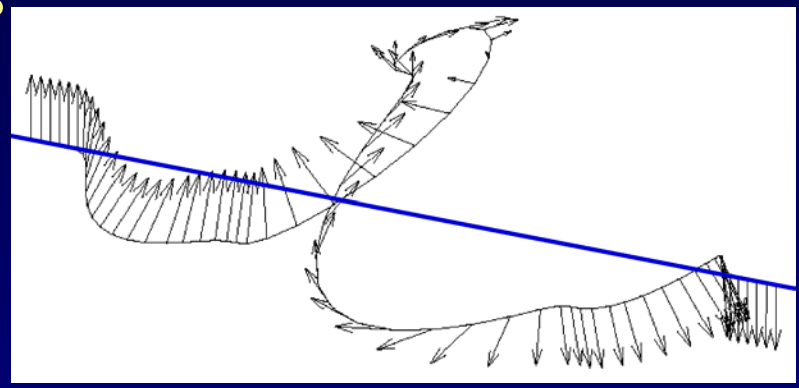


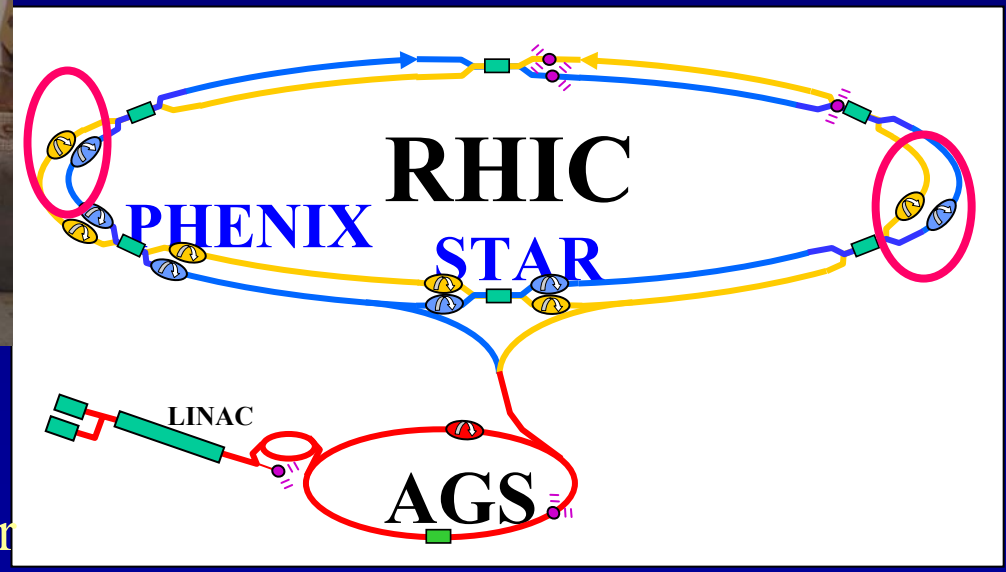
RHIC vs. DIS Kinematic Coverage



Siberian Snakes

Effect of depolarizing resonances averaged out by rotating spin by 180 degrees on each turn





- 4 helical dipoles ➔ S. snake
- 2 snakes in each ring
  - axes orthogonal to each other

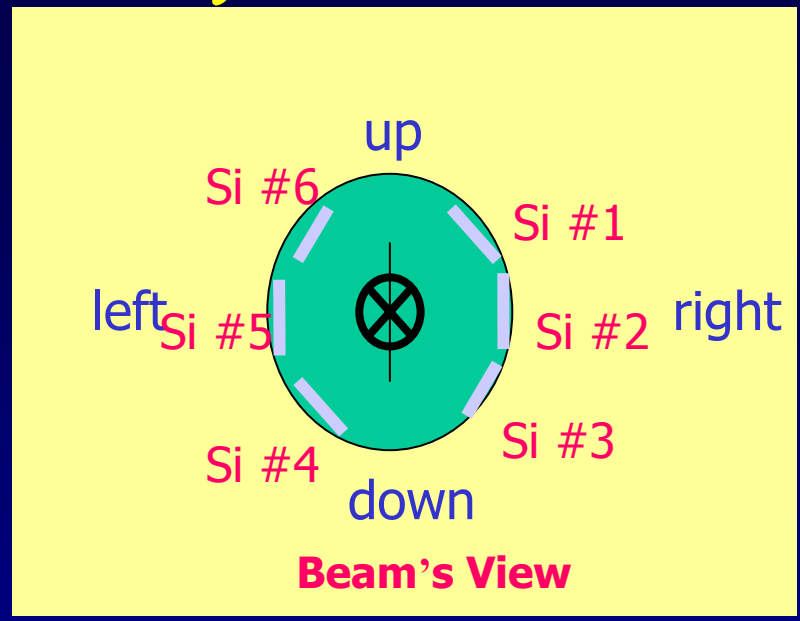
RHIC Polarimetry

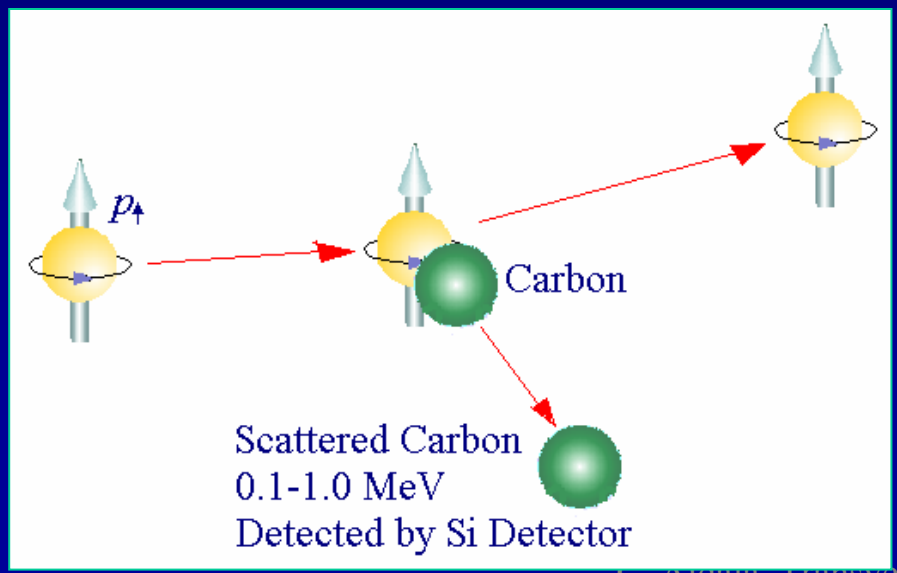
Carbon filament target ($5\mu g/cm^2$) in the RHIC beam

Measure recoil carbon ions at $\theta \sim 90^\circ$

$100\ keV < E_{carbon} < 1\ MeV$

E950 Experiment at AGS (1999)
→→→ RHIC polarimetry now

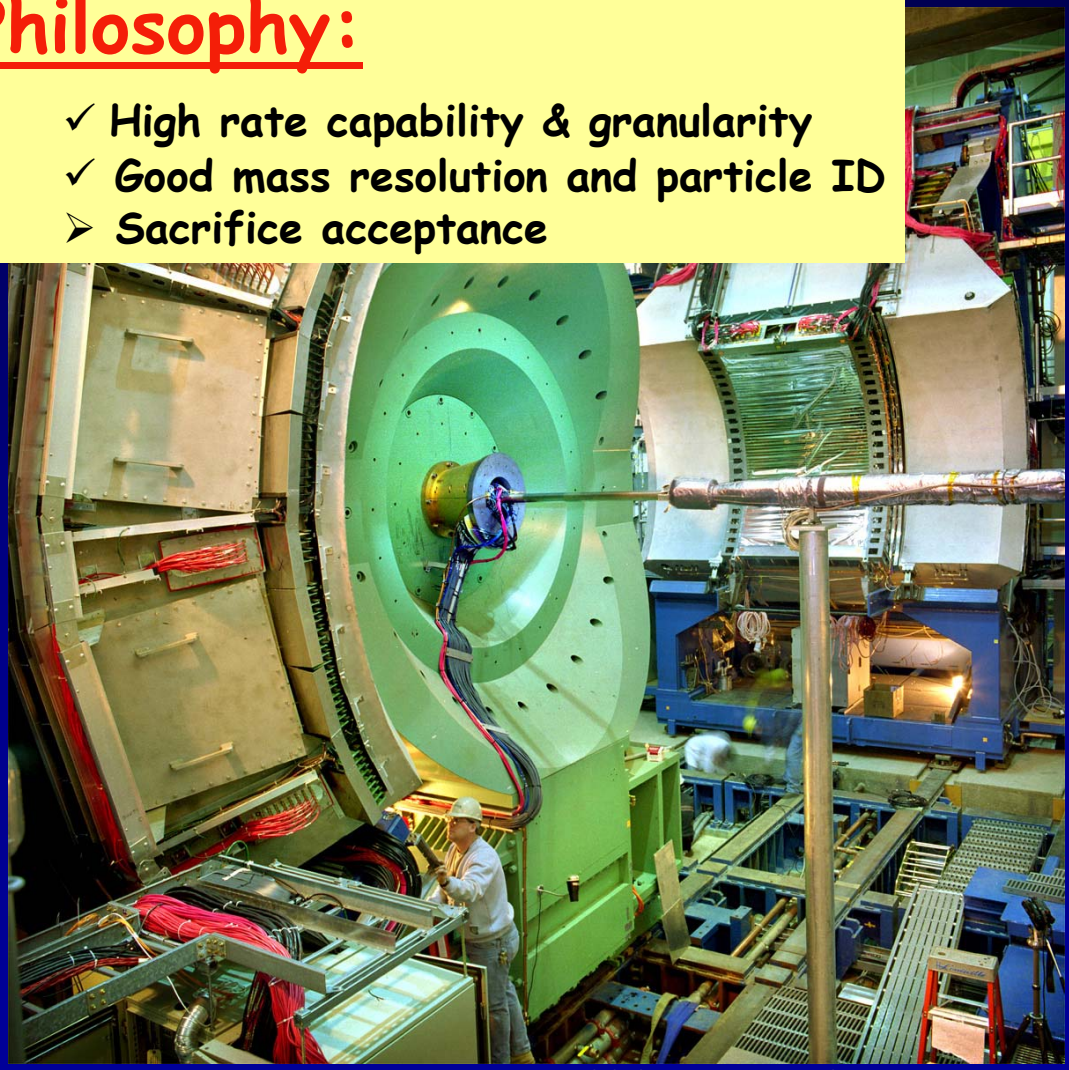




The PHENIX Detector

Philosophy:

- ✓ High rate capability & granularity
- ✓ Good mass resolution and particle ID
- ➢ Sacrifice acceptance



2 central spectrometers

- Track charged particles and detect electromagnetic processes

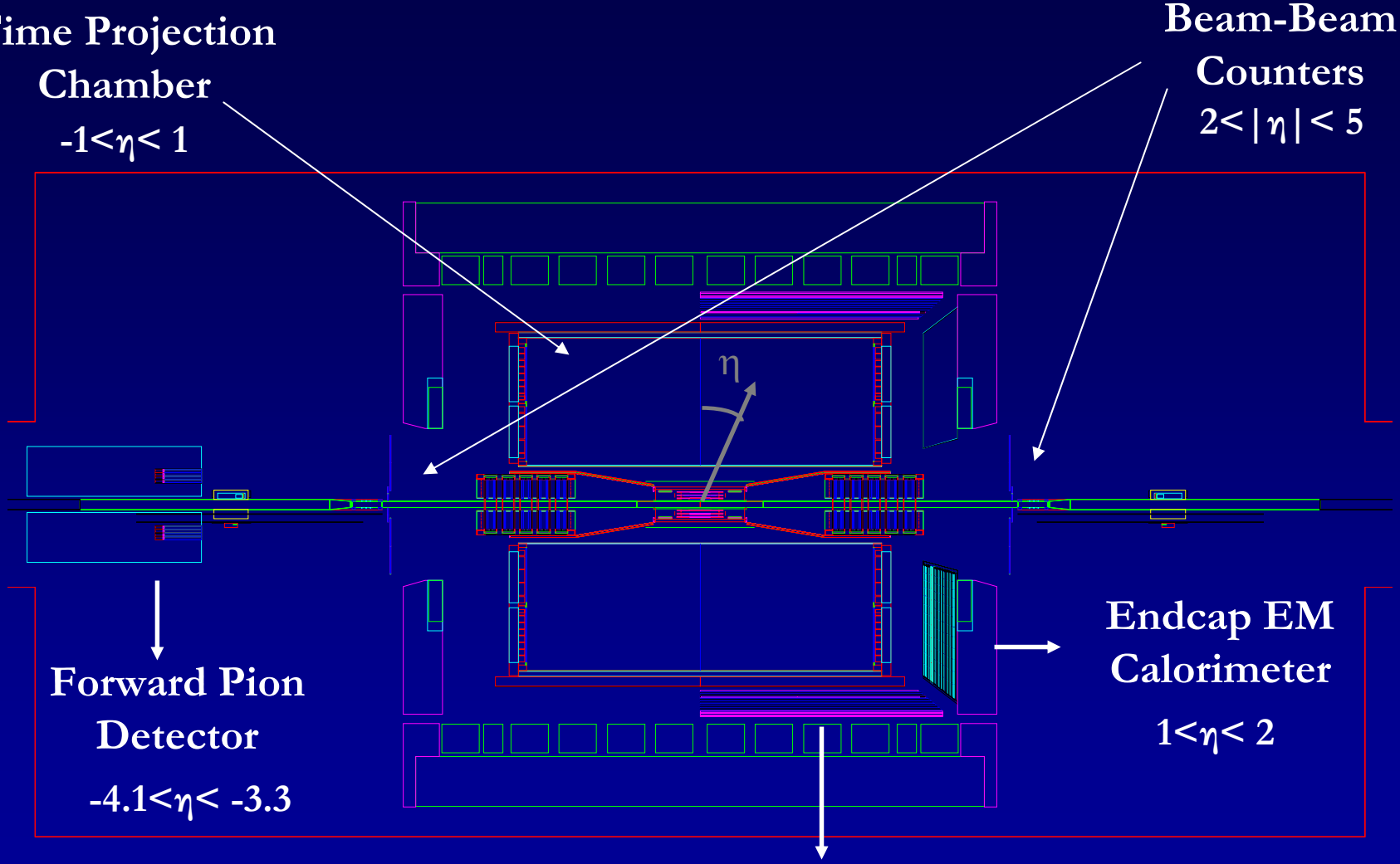
2 forward spectrometers

- Identify and track muons

3 global detectors

- Determine when there's a collision

The STAR Detector



Access to Sivers Functions in STAR

- High-rapidity π^0 Production

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

- Mid-rapidity Leading Charged Particle Analysis

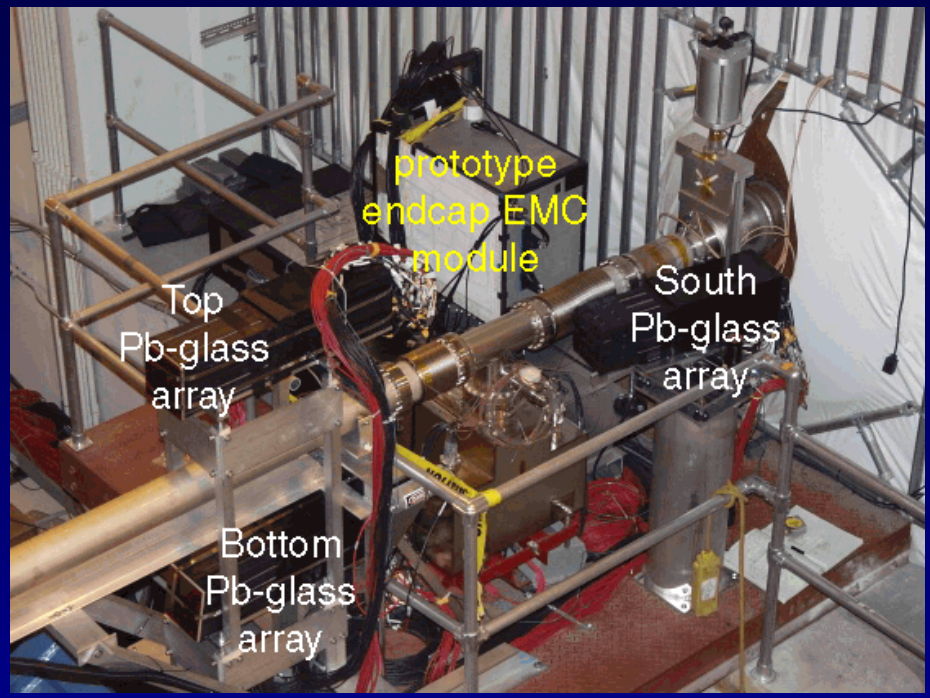
  $\mathbf{p\uparrow p \rightarrow h^{+/-} + X}$

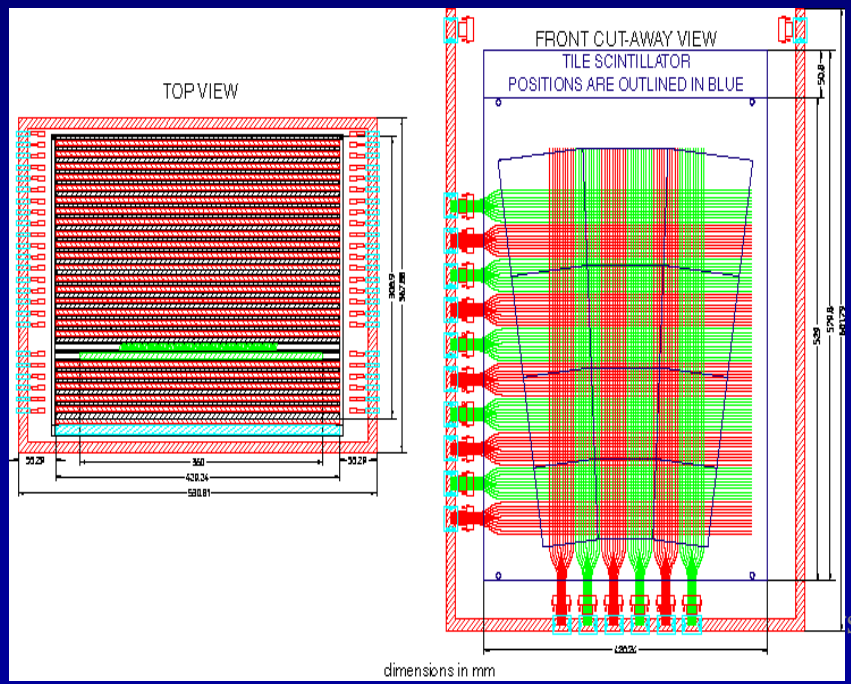
- $\Delta\phi$ Di-jet production

  $\mathbf{p\uparrow p \rightarrow jet + jet + X}$

Forward Pion Detector at STAR

- 24 layer Pb-Scintillator Sampling Calorimeter
- 12 towers
- Shower-Maximum Detector - 2 orthogonal layers of 100 x 60 strips
- 2 Preshower Layers





Top-Bottom-South Detectors

- 4x4 array of Lead-Glass
- No Shower Max
- Used for systematic error studies

TRIGGER $E_{DEP} > 15$ GeV

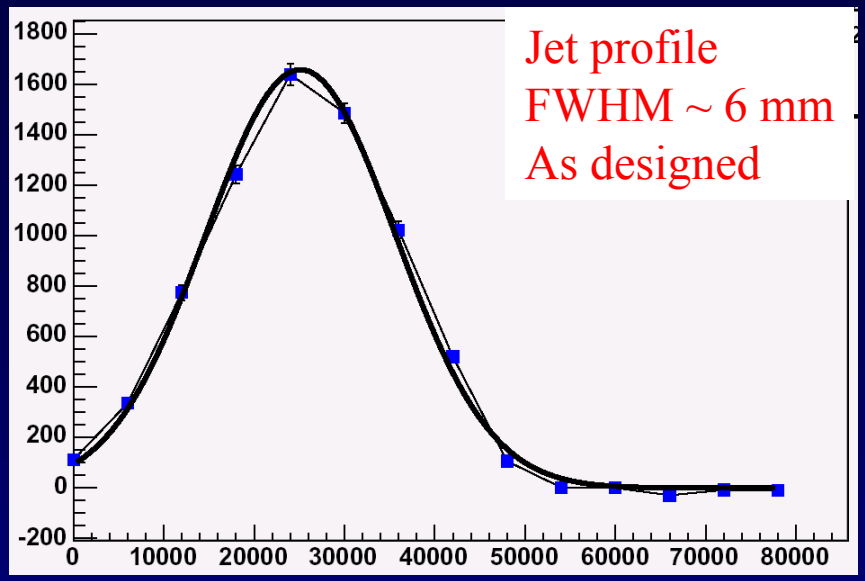
An Example: High Energy Proton Polarimeters for p=20-250 *GeV/c*

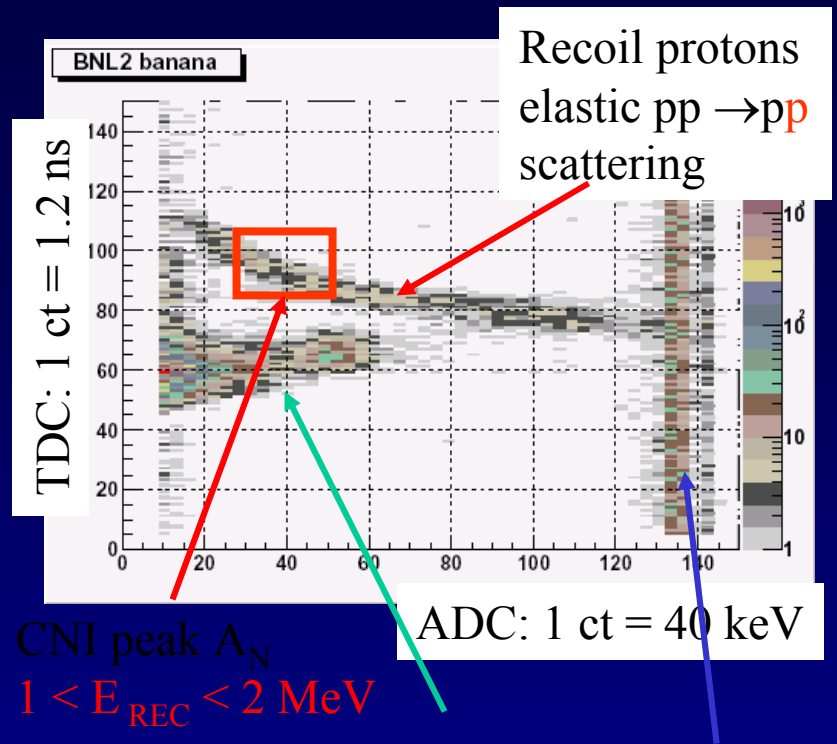
High Energy Polarimeter Requirement for RHIC Spin

- ❑ Absolute RHIC polarimeter
- ❑ Fast relative RHIC and AGS polarimeters for monitoring and tuning
- ❑ Local Polarimeters to confirm spin orientation at collision point

RHIC polarimetery relies on newly observed spin asymmetries:

- o Sizeable elastic proton-Carbon spin asymmetries at high energies
  - → J. Tojo et al. Phys. Rev. Lett. 89:052302, 2002
- o Very forward neutron asymmetries
  - → A. Bazilevsky et al. AIP Conf. Proc. 675: 584-588, 2003
- o Spin asymmetries in forward multiplicity production as seen by beam-beam counters in STAR
  - → J. Kiryluk, AIP Conf. Proc. 675, 424 (2003)





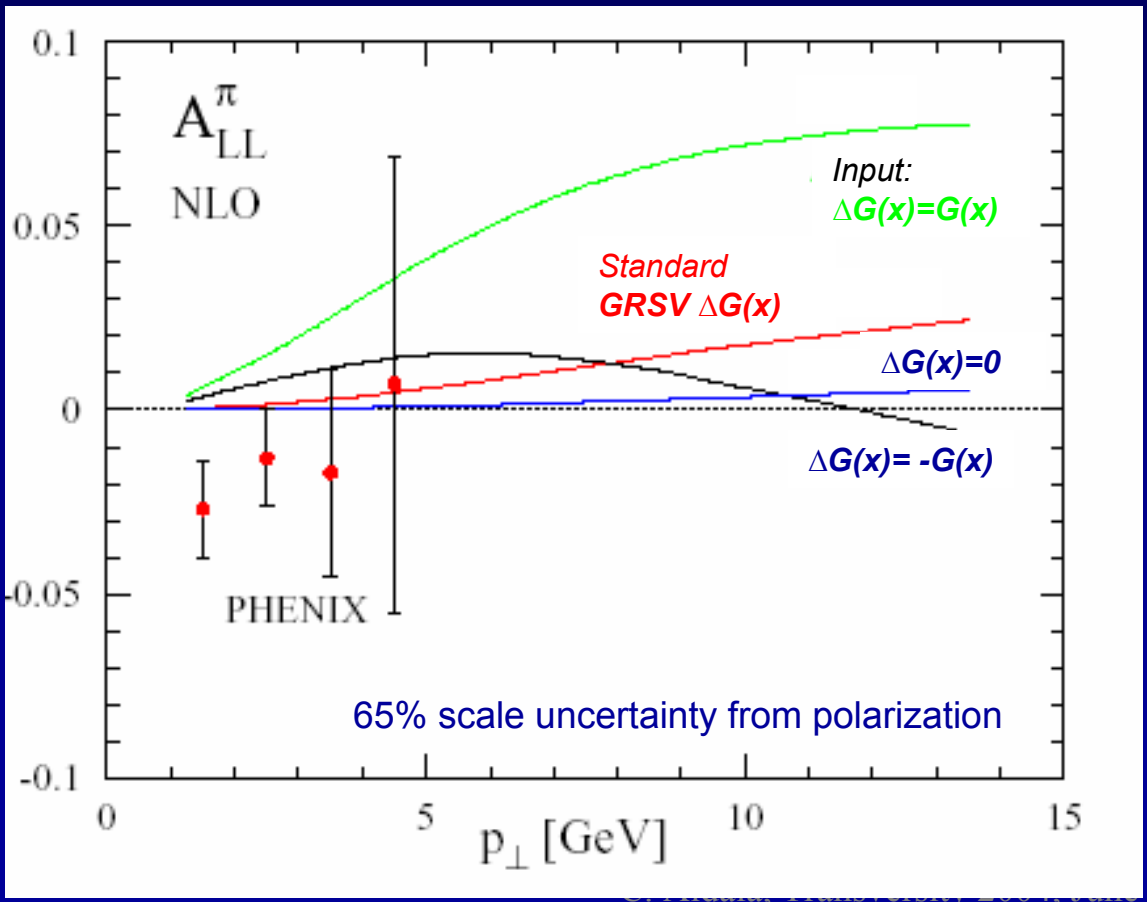
Data collected so far in this run:

- 100 GeV ~ 700,000 events at the peak of the analyzing power (~ 3 x 10^6 total useful *pp* elastic events)
- 24 GeV ~ 120,000 events at the peak of the analyzing power (~ 5 x 10^5 total useful *pp* elastic events)

First Results: A_{LL}

PHENIX $A_{LL}(\pi^0)$ at $|\eta|<0.35$, hep-ex/0404027
plot from Vogelsang hep-ph/0405069

Run 03, $\int Ldt \sim 0.2 pb^{-1}$, P~0.27



First results on longitudinal double spin asymmetries from RHIC

→consistent with DIS sample
→result disfavors large ΔG
→eg $\int Ldt = 3pb^{-1}$ and P-0.4 (2005) errors will reduce by factor 8

Experiments are ready for spin measurements at low to moderate luminosities!

→ relative luminosity ~5×10^{-4}
→ trigger
→ polarization analysis
→ data analysis

Transverse Spin at RHIC

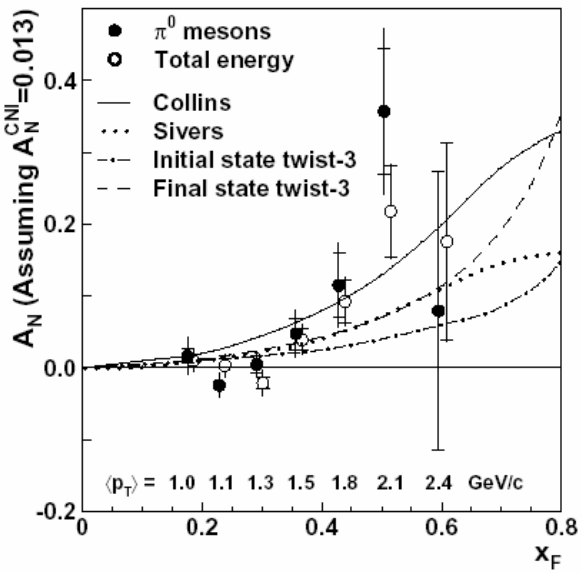
(A) Physics Channels for Low Luminosity

$$\int Ldt = 1-10\ \mathrm{pb}^{-1}, \sqrt{s} = 200\ \mathrm{GeV}$$

STAR, PHENIX and BRAHMS

(I) Measure A_N : $A_N(pp_\perp \to h + X)$

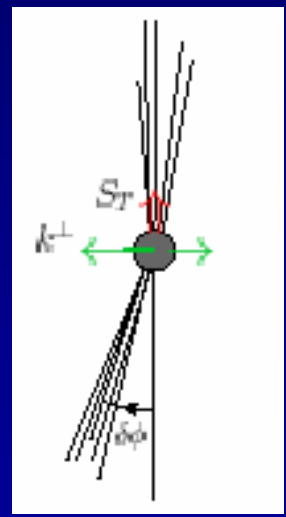
STAR Phys. Rev. Lett. 92:171801, 2004



Separation of intrinsic transverse quark spin (transversity) from transverse momentum effects (Sivers)?

STAR and PHENIX

(II) Boer and Vogelsang (hep-ph/0312320): azimuthal back to back correlation between hadrons in opposite hemisphere jets:



Clean channel for Sivers effect!