G. Bunce
APS, April 2008

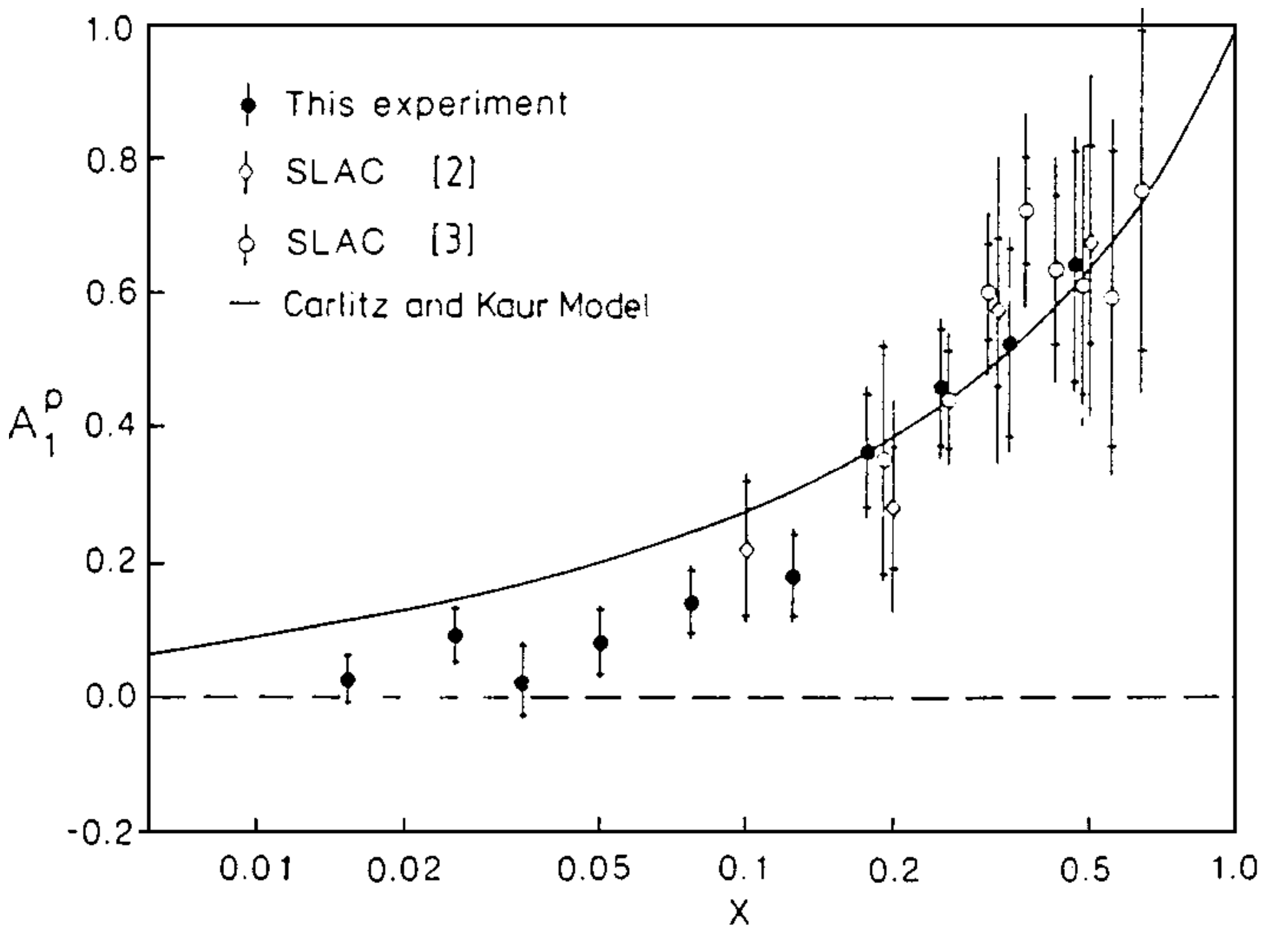
The Gluon's spin contribution to the proton's spin ---as seen at RHIC*

I would like to thank Les Bland, Werner Vogelsang, Abhay Deshpande, Sasha Bazilevsky, Matthias Grosse Perdekamp, Bernd Surrow, for their advice and many plots; also, importantly, the members of the RHIC Spin Collaboration, including the RHIC accelerator staff, the STAR, PHENIX, and BRAHMS experiments, and crucial work by many theoretical colleagues.

*** Support: DOE, NSF, RIKEN, Renaissance (2006)**

EMC at CERN: J. Ashman et al., NPB 328, 1 (1989):

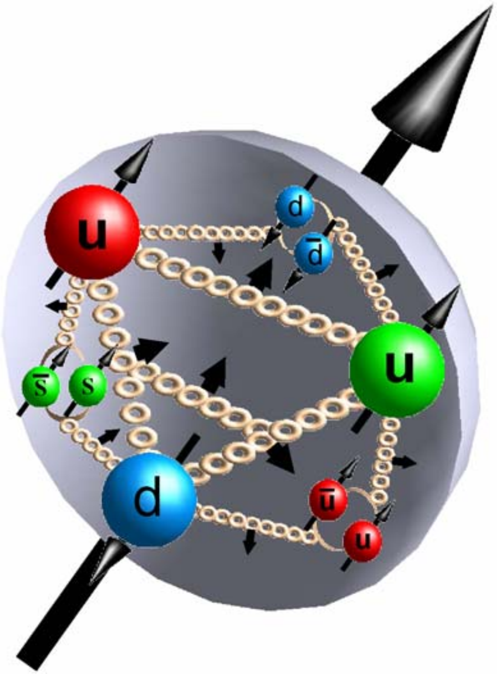
polarized muons probing polarized protons



$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

"proton spin crisis"

- What else carries the proton spin ?
  Central question for the field.



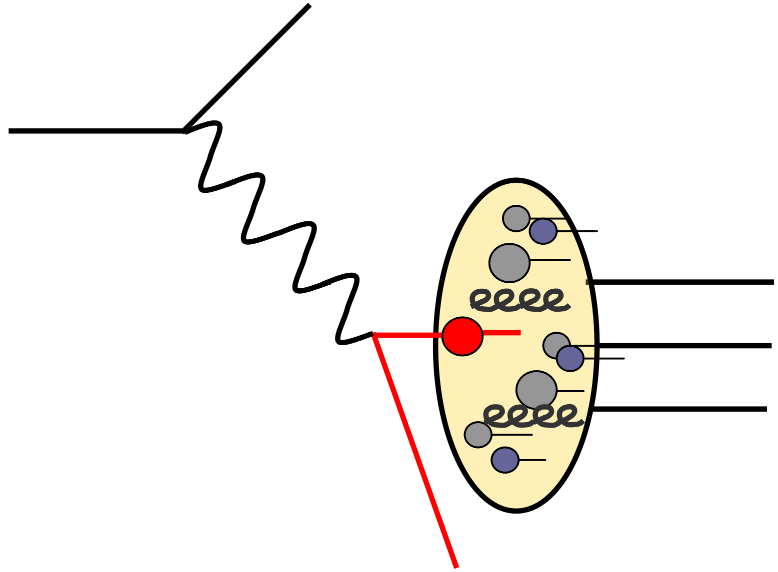
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Quark spin ≈ 0.1

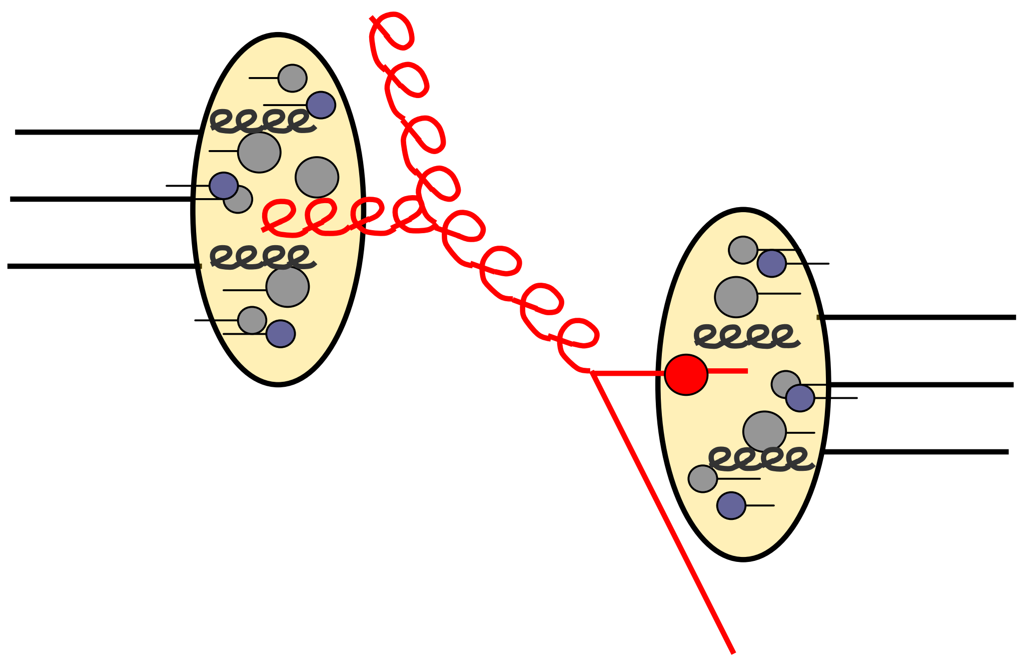
Gluon spin contrib.

Orbital ang. momenta

DIS

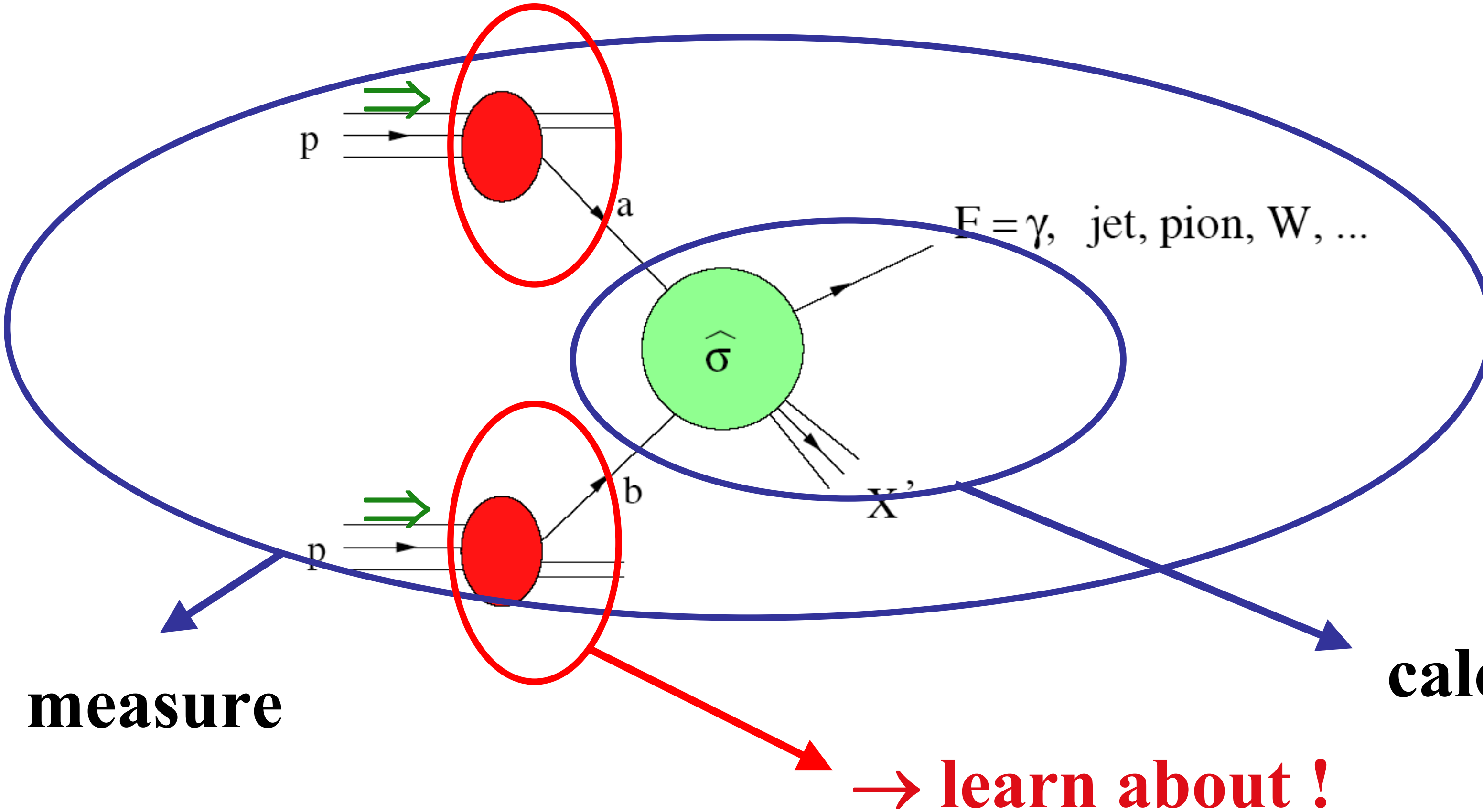


pp



- perturbative QCD and factorization:

Sterman,Libby; Ellis et al.; Collins,Soper,Sterman

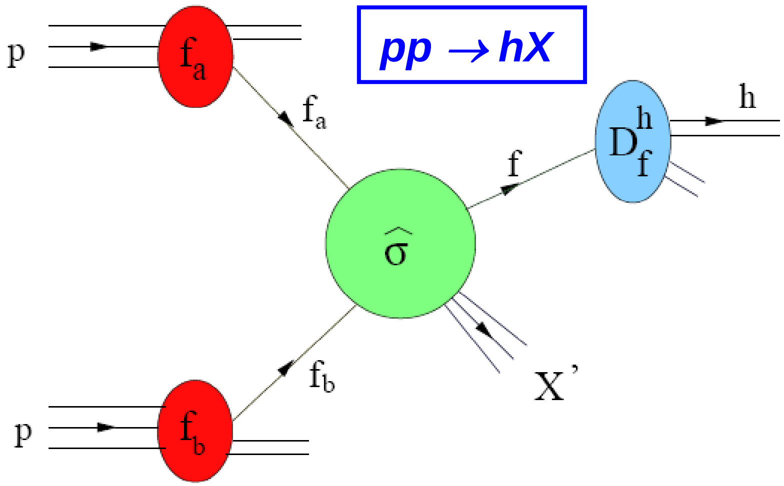


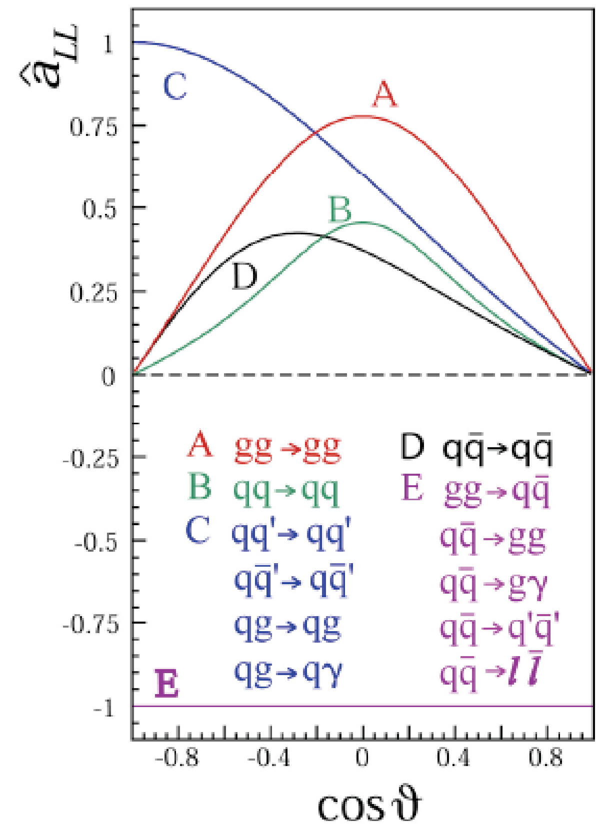
$$\frac{d\sigma^{\Rightarrow\Leftarrow} - d\sigma^{\Rightarrow\Rightarrow}}{dp_T\, d\eta} = \sum_{ab}\int dx_a \int dx_b\, \Delta f_a(x_a, p_T)\, \Delta f_b(x_b, p_T)\, \frac{d\hat{\sigma}_{ab}^{\Rightarrow\Leftarrow} - d\hat{\sigma}_{ab}^{\Rightarrow\Rightarrow}}{dp_T\, d\eta}$$

universal

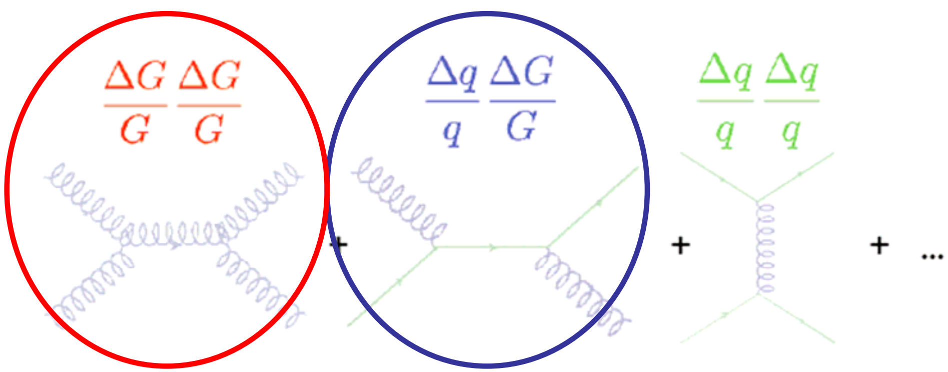
parton scatt.
perturbative QCD

Probing ΔG in pp Collisions





$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \cdot \hat{a}_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \otimes D_f^h}$$



Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

- **How:**

---collide beams of protons in the world’s only polarized proton collider

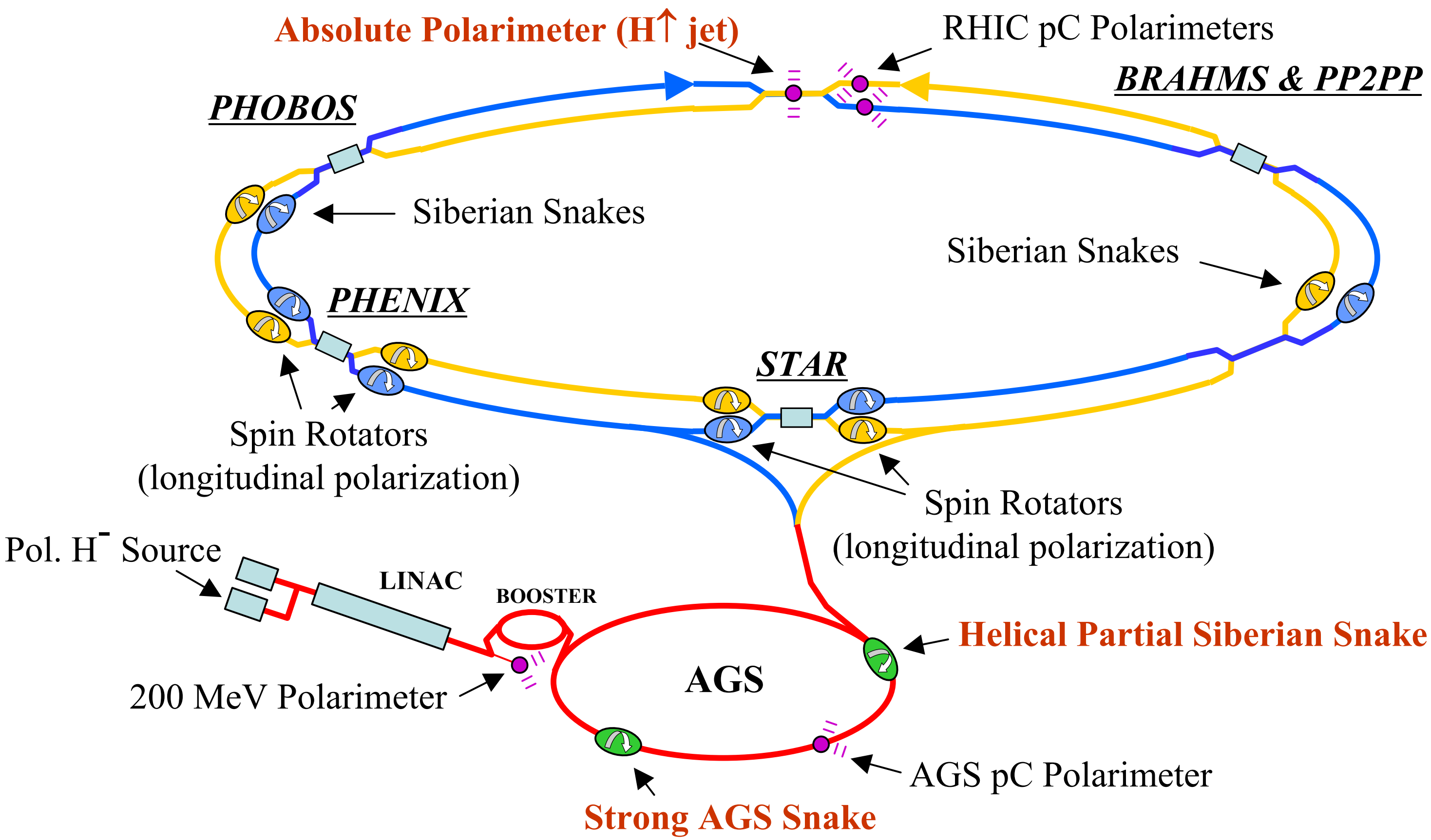
---polarized H^- : 1 mA, 85% polarized

---”Siberian Snakes” to maintain the spin directions of the protons as we accelerate

---polarized H ABS in RHIC to obtain absolute RHIC beam polarization

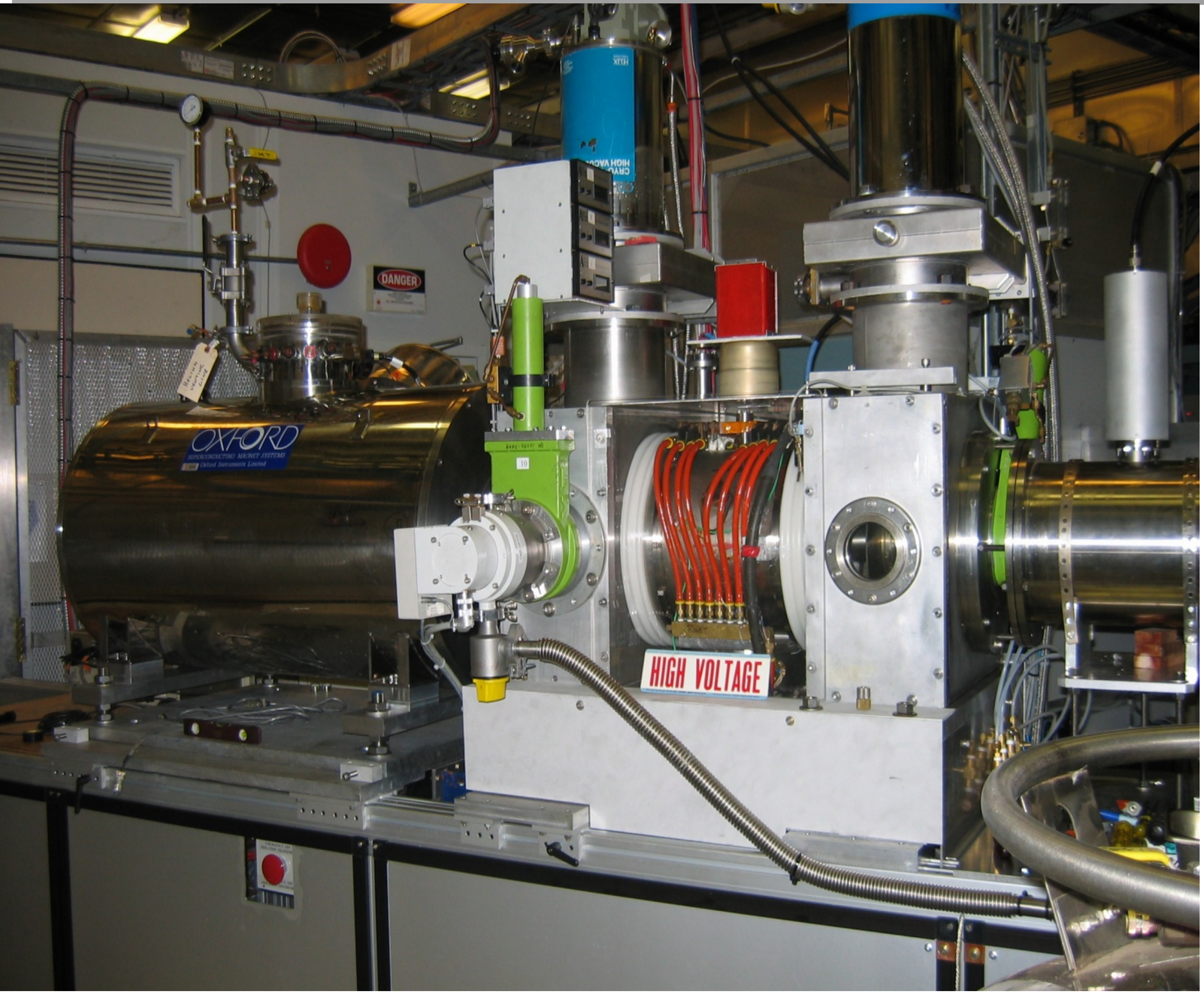
---STAR, PHENIX, and BRAHMS (transverse spin only) experiments

RHIC Polarized Collider



2006: 1 MHz collision rate; P=0.6

Optically-Pumped Polarized H^- Ion Source at RHIC.



RHIC OPPIS produces reliably 0.5-1.0mA (maximum 1.6 mA) polarized H^- ion current.

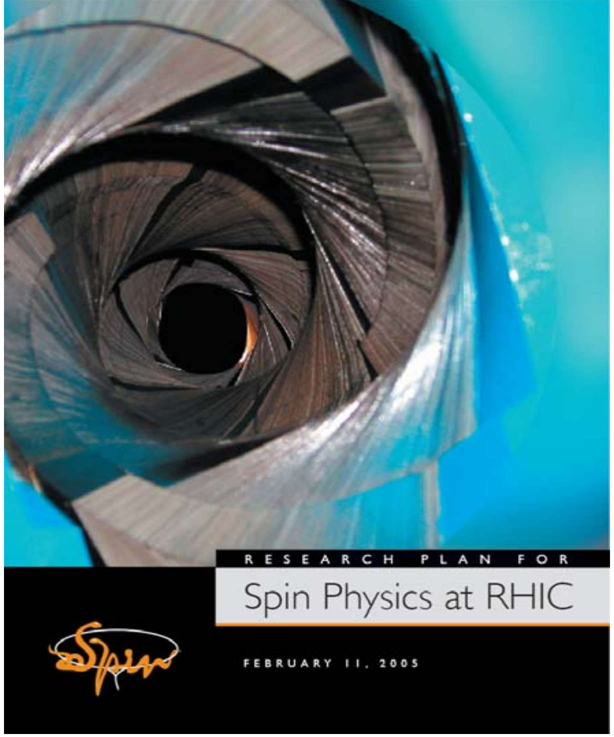
Pulse duration 400 us.

Polarization at 200 MeV P = 85 %.

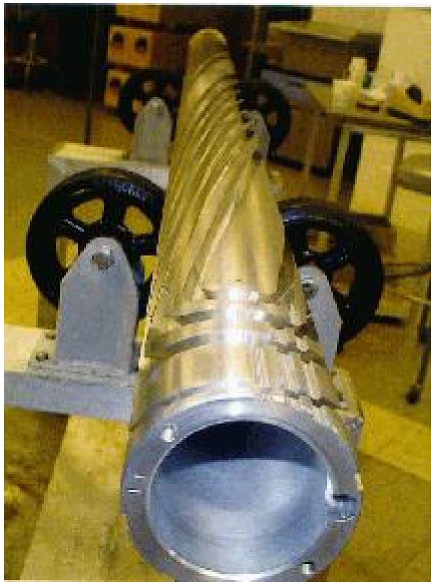
Beam intensity (ion/pulse) routine operation:

Source	- 10^{12} H^-/pulse
Linac (200MeV)	- $5\text{-}6\cdot10^{11}$
Booster	- $2\text{-}3\cdot10^{11}$
AGS	- $1.7\text{-}2.2\cdot10^{11}$
RHIC	- $1.5\text{-}1.8\cdot10^{11}$ (p/bunch).

The RHIC OPPIS was developed in collaboration with TRIUMF and INR, Moscow.



Siberian Snakes

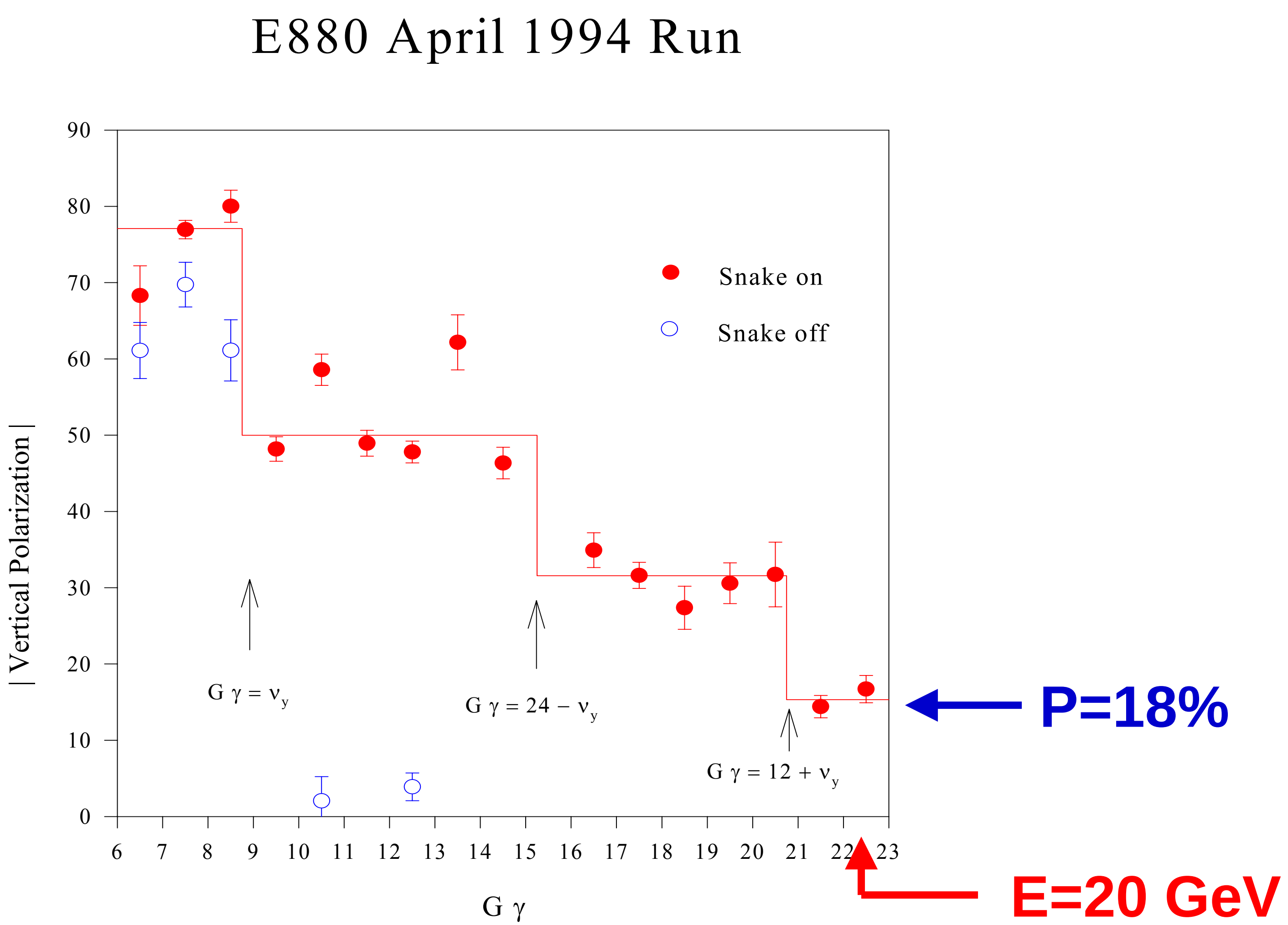


2003-4: Warm AGS Snake

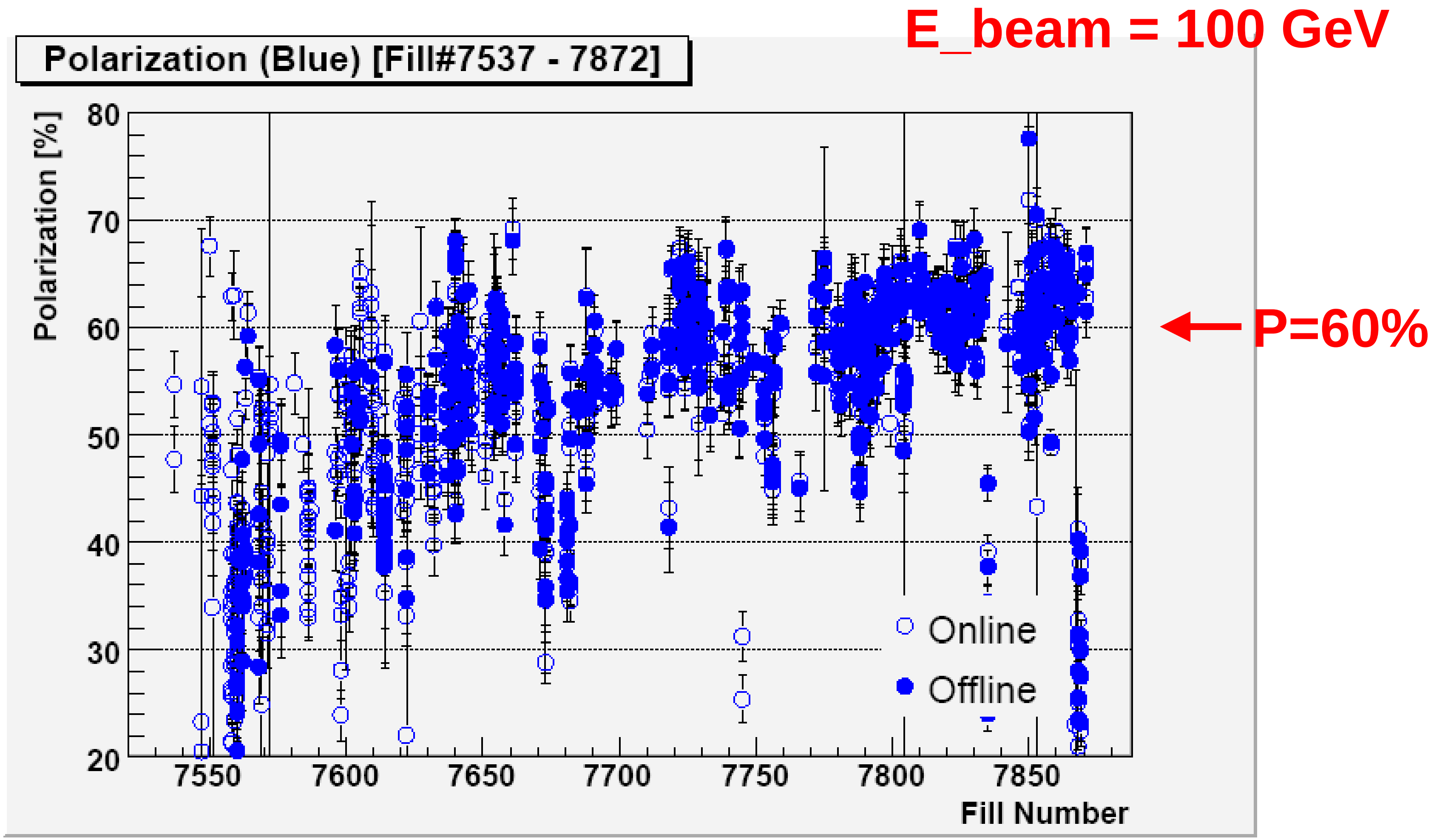
1996-2001:
Siberian Snakes

Snake: precess spin, leaving beam direction unchanged at exit of snake

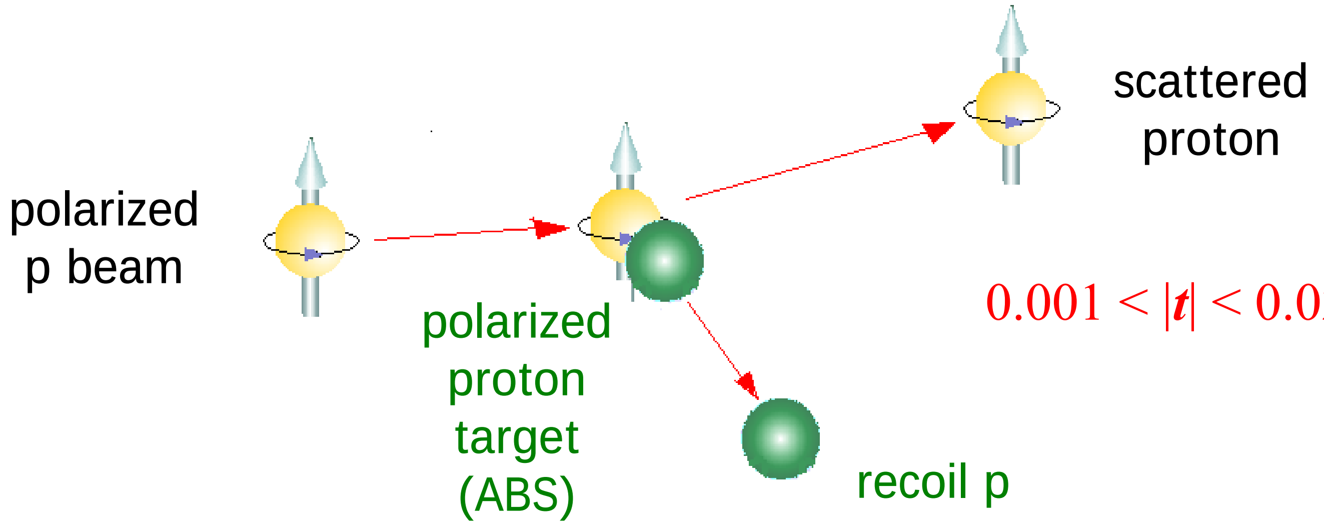
The First Siberian Snake at BNL
---in the AGS



Polarization Measurements
2006 Run



Polarimetry



$0.001 < |t| < 0.02\ (\text{GeV}/c)^2$

For p-p elastic scattering only:

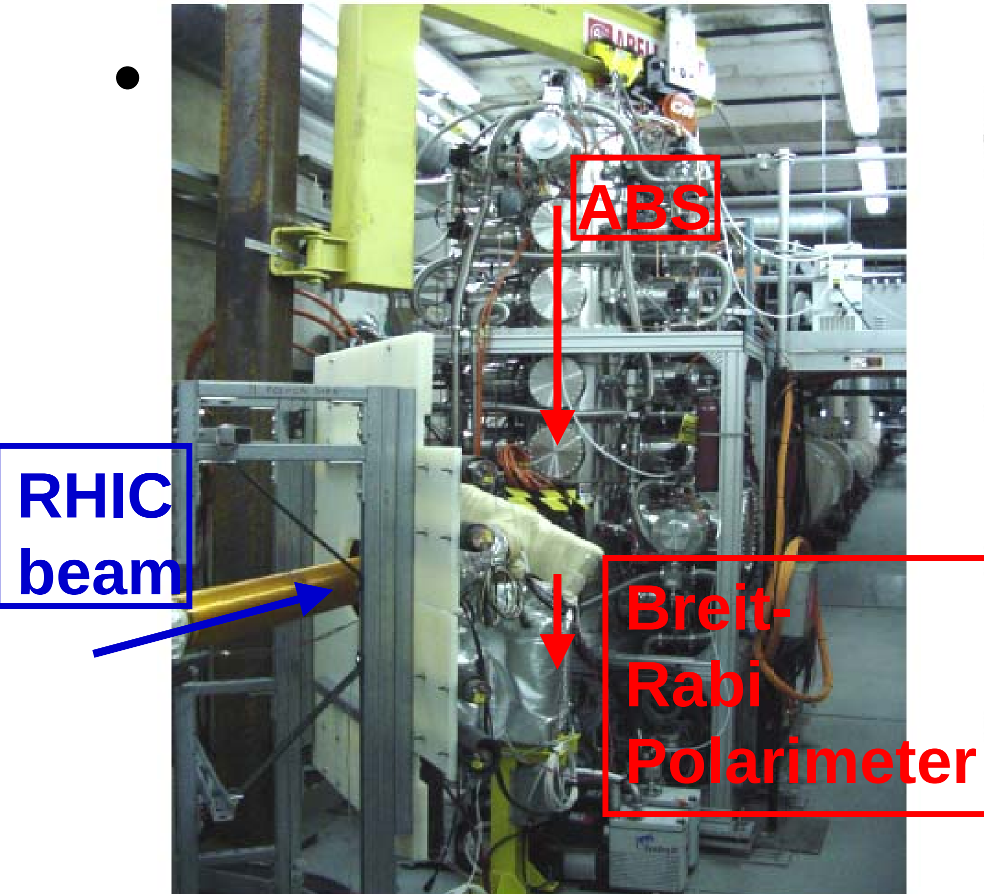
$$\varepsilon = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

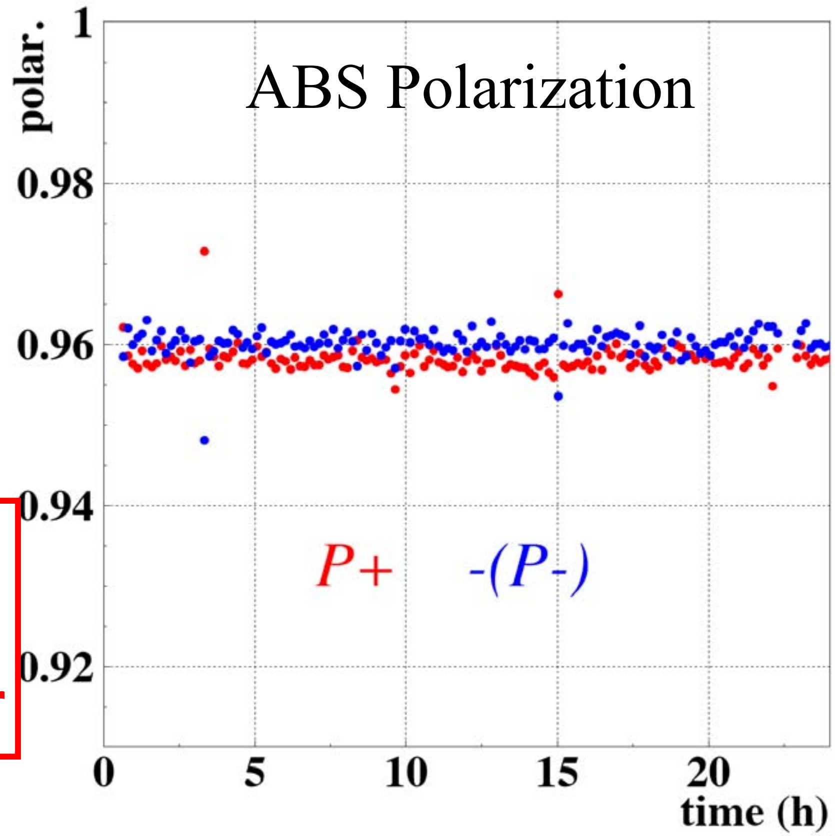
$$\varepsilon_{beam} = A_N \cdot P_{beam}$$

$$\varepsilon_{target} = -A_N \cdot P_{target}$$

$$\boxed{P_{beam} = -\frac{\varepsilon_{beam}}{\varepsilon_{target}} \cdot P_{target}}$$

H↑ Atomic Beam Source in RHIC

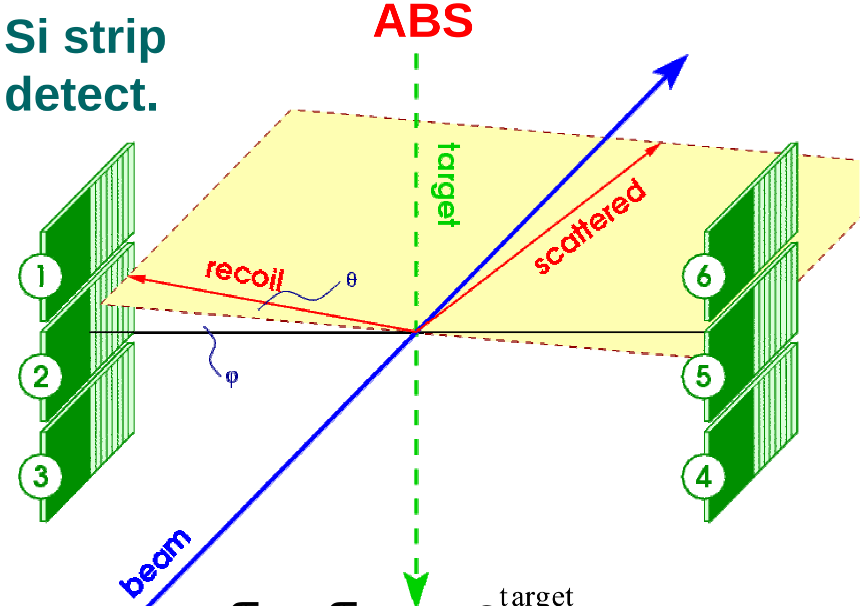
- 



A_N & Coulomb Nuclear Interference:

$$A_N = C_1 \,\mathrm{Im}(\phi^{em}_{flip}{}^* \phi^{had}_{non-flip}) + C_2 \,\mathrm{Im}(\phi^{had}_{flip}{}^* \phi^{had}_{non-flip})$$

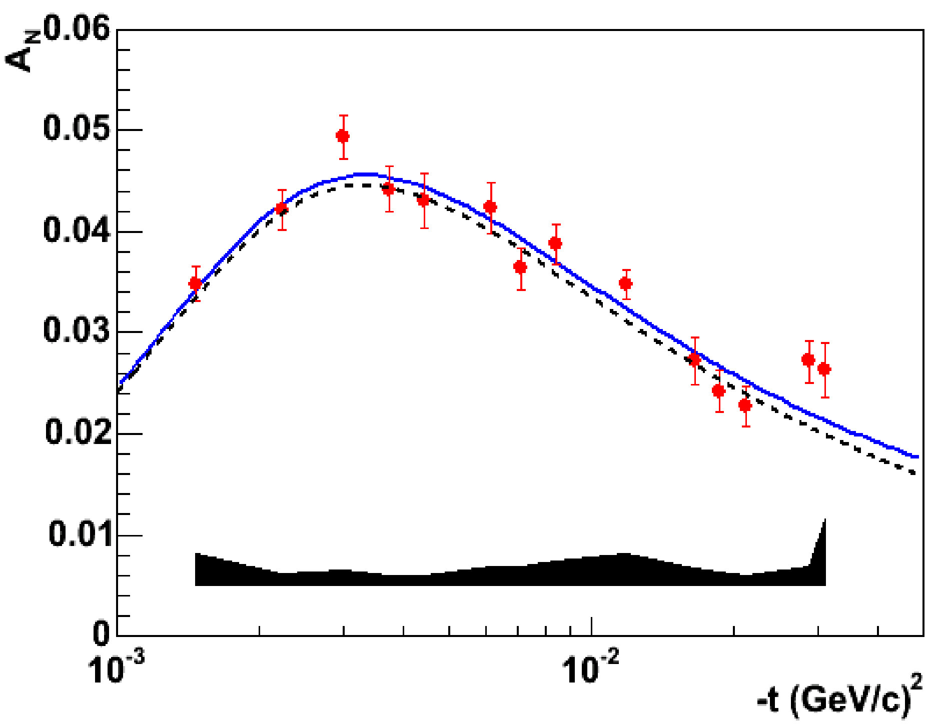
$\propto(\mu-1)_p$ $\propto\sqrt{\sigma^{pp}_{had}}$



$$A_N(-t) = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = -\frac{\varepsilon_N^{target}}{P_{target}}, \ (\langle P_{beam}\rangle = 0)$$

$$= \frac{\varepsilon_N^{beam}}{P_{beam}}, \ (\langle P_{target}\rangle = 0)$$

H. Okada et al., PLB 638 (2006), 450-454



Obtaining the beam polarization

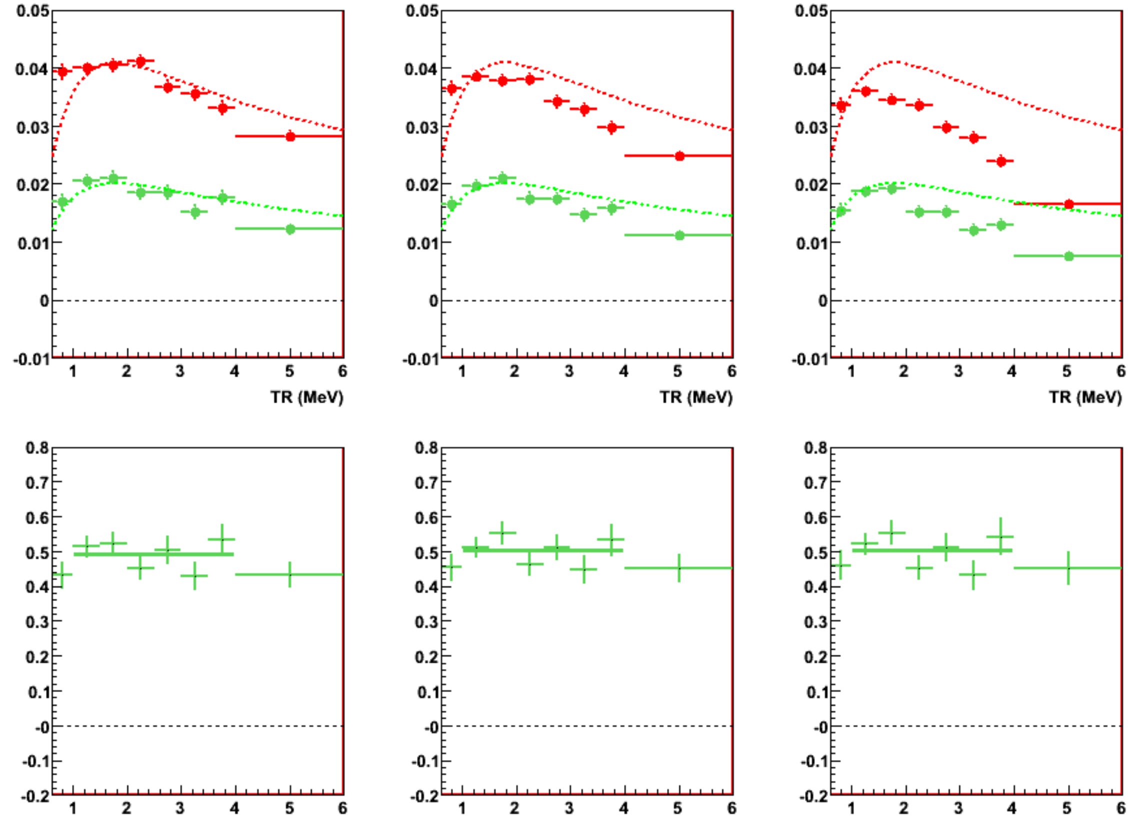
2005 Data

background: 1x 2x 4x

ε(target)

ε(beam)

ε(beam)/ ε(target)



$$P_{beam} = -\frac{\varepsilon_{beam}}{\varepsilon_{target}} \cdot P_{target}$$

E(recoil) MeV

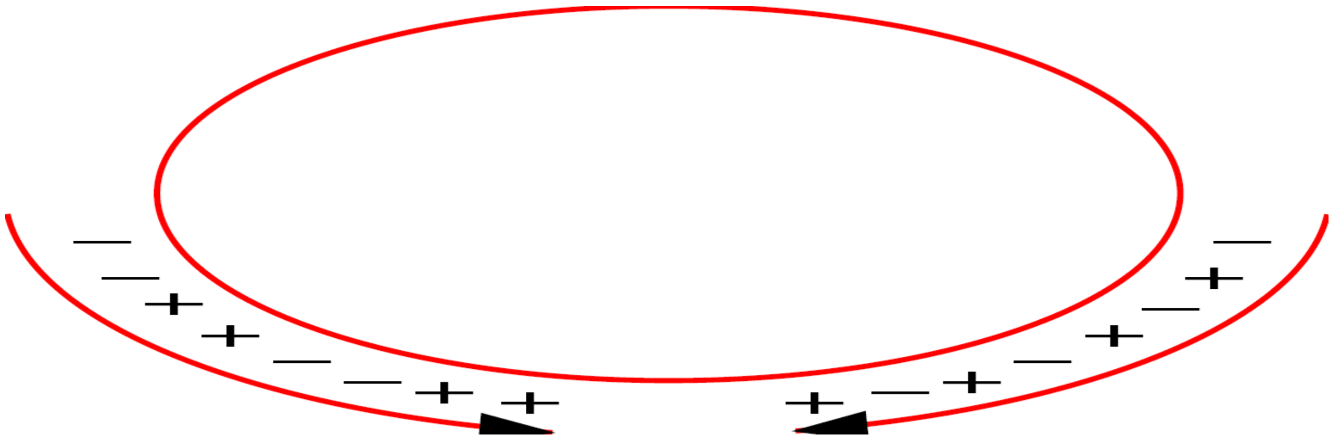
P(target)=92.4% +/- 1.8%

P(blue beam)=49.3% +/- 1.5% +/- 1.4%
P(yellow beam)=44.3% +/- 1.3% +/- 1.3%

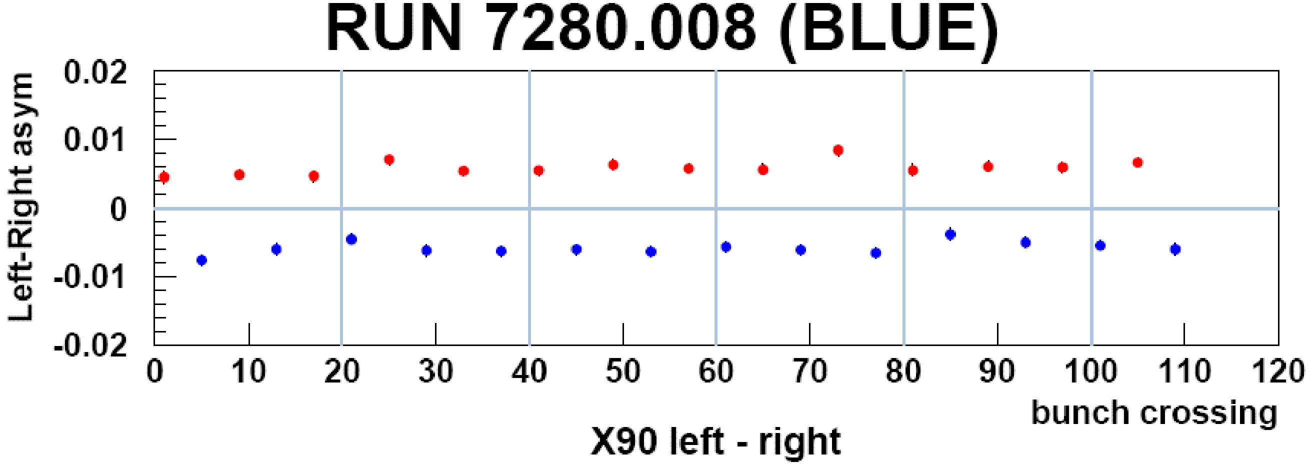
Delta P/P = 4.2%

Goal: 5%

Exquisite Control of Systematics



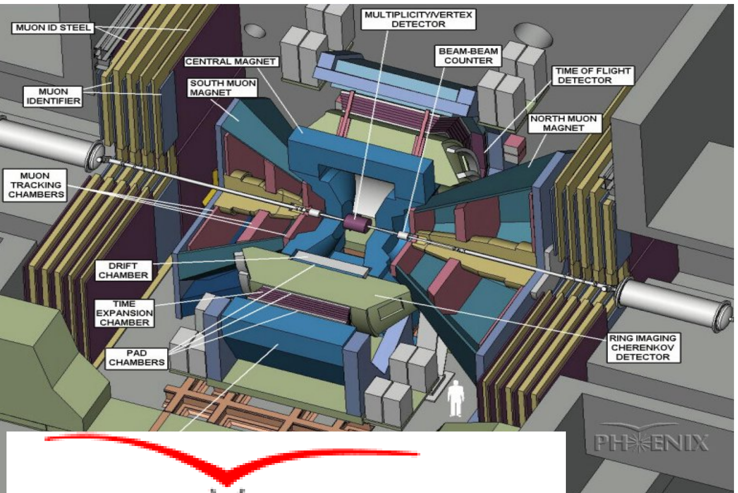
Raw asymmetries from carbon polarimeter by bunch:



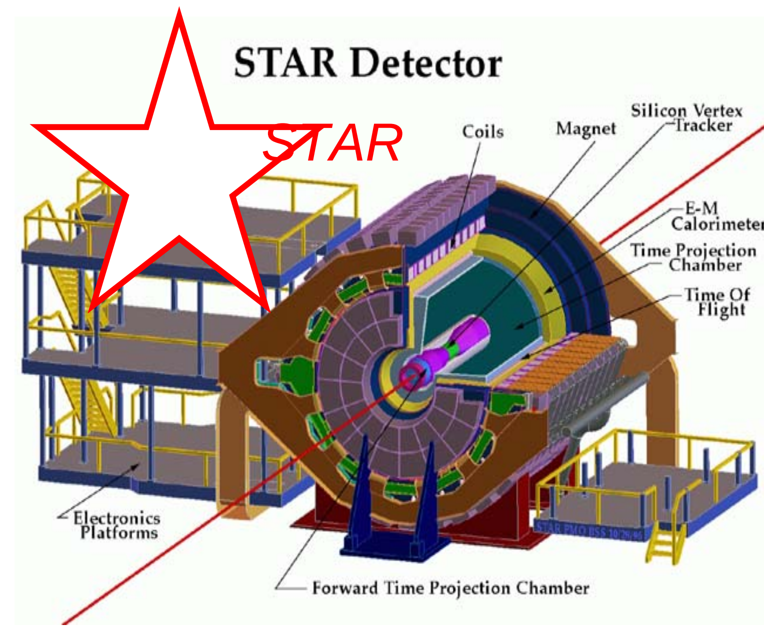
RHIC Spin Runs

	P	L(pb^-1)	Results
2002	15%	0.15	first pol. pp collisions!
2003	30%	1.6	pi^0, photon cross section, A_LL(pi^0)
2004	40%	3.0	absolute beam polarization with polarized H jet
2005	50% (P^4 x L = 0.8)	13	large gluon pol. ruled out
2006	60% (P^4 x L = 6)	46	first long spin run
2007			no spin running
2008	50%		(short) run

PHENIX and STAR



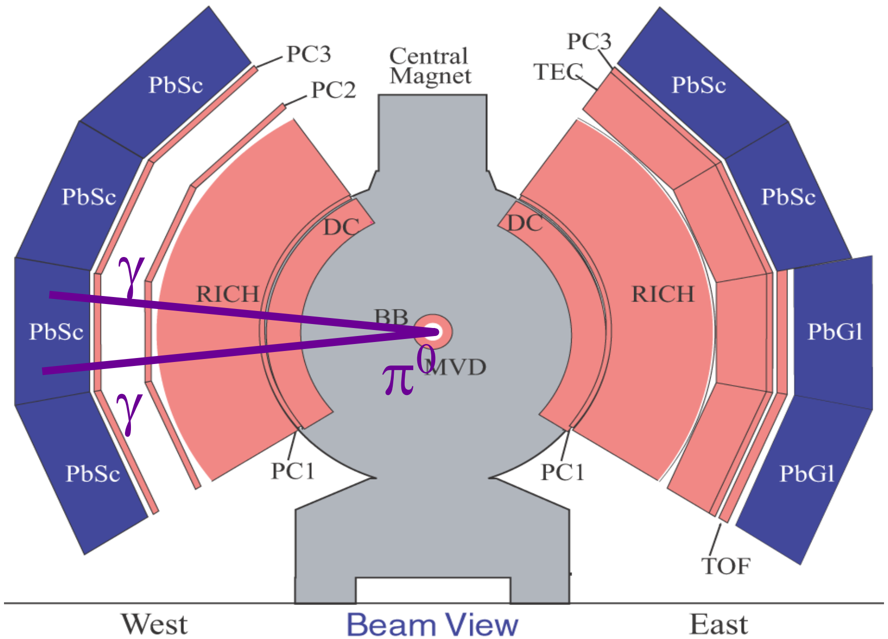
PHENIX:
High rate capability
High granularity
Good mass resolution and PID
Limited acceptance



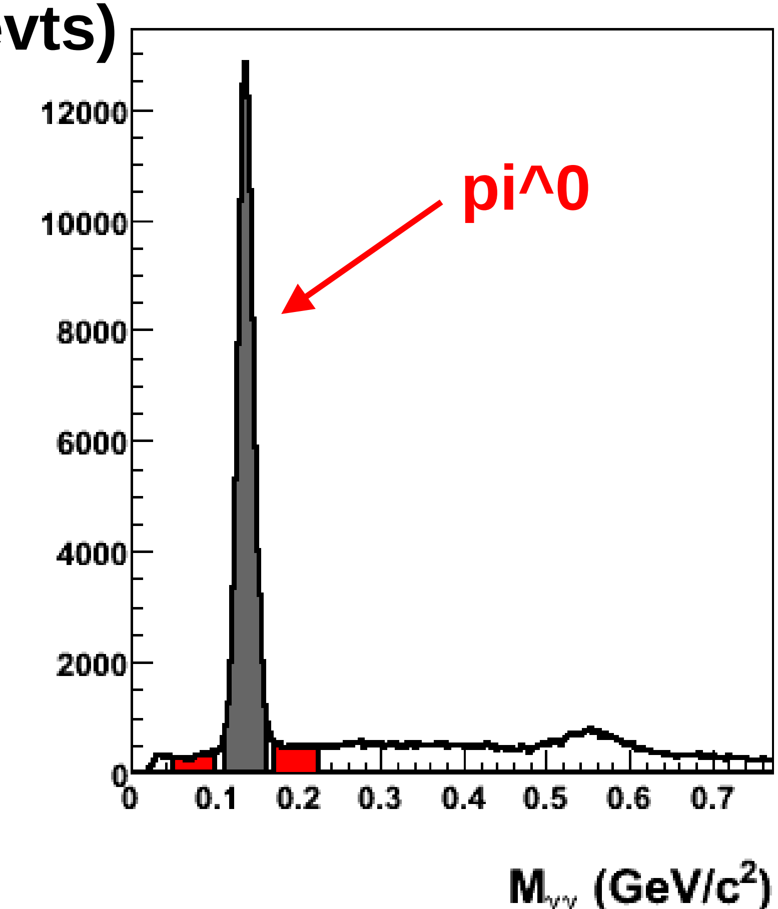
STAR:
Large acceptance with azimuthal symmetry
Good tracking and PID
Central and forward calorimetry

Observing the pi^0 (PHENIX)

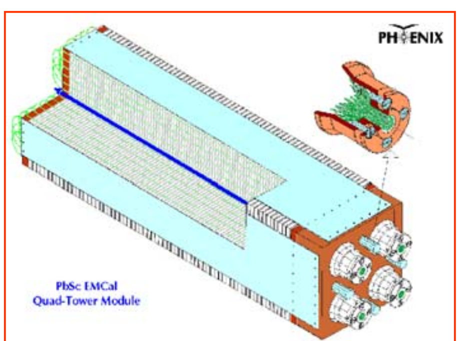
1. **proton + proton → pi^0 + X**



3. **reconstruct pi^0**



2. **pi^0 → 2 photons,**
calorimeter observes photons

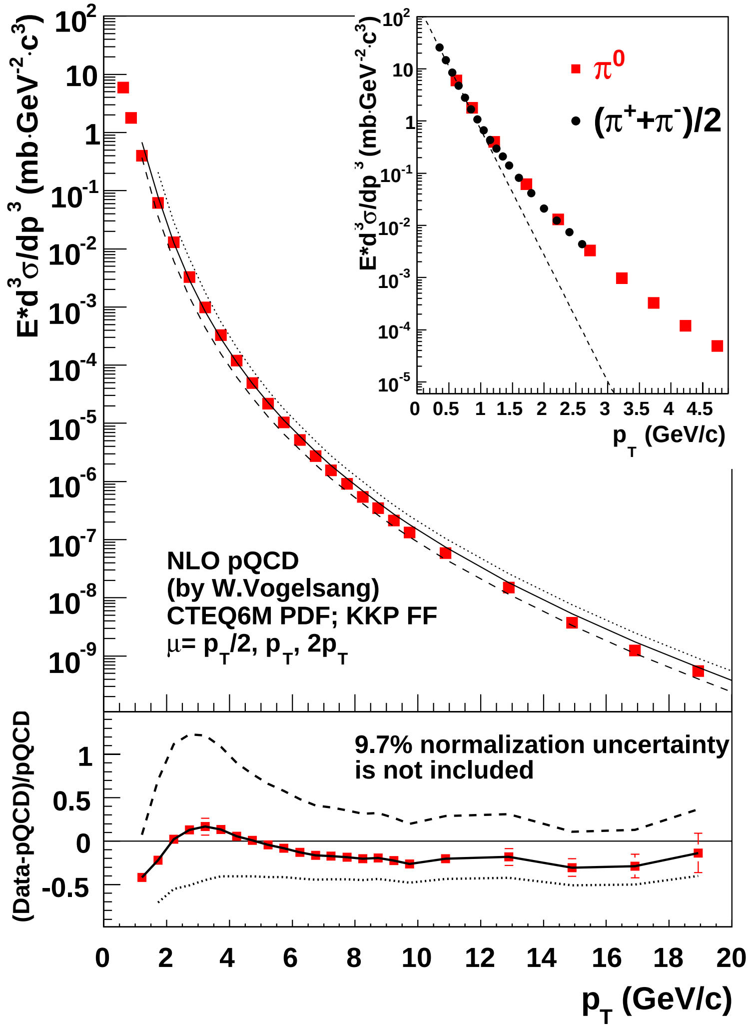


24768 cells!

Cornerstones to the RHIC Spin program

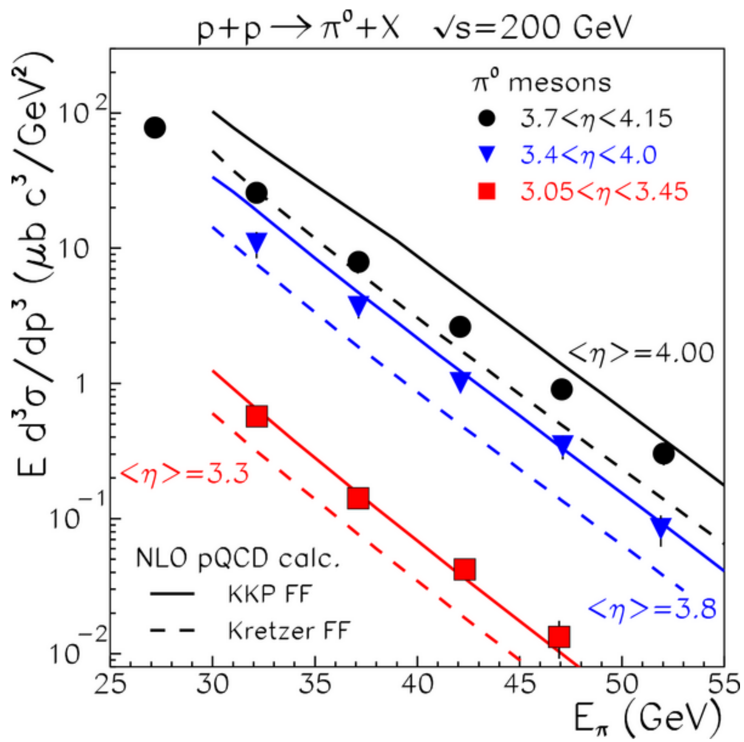
$pp \rightarrow \pi^0 X$

Mid-rapidity: PHENIX



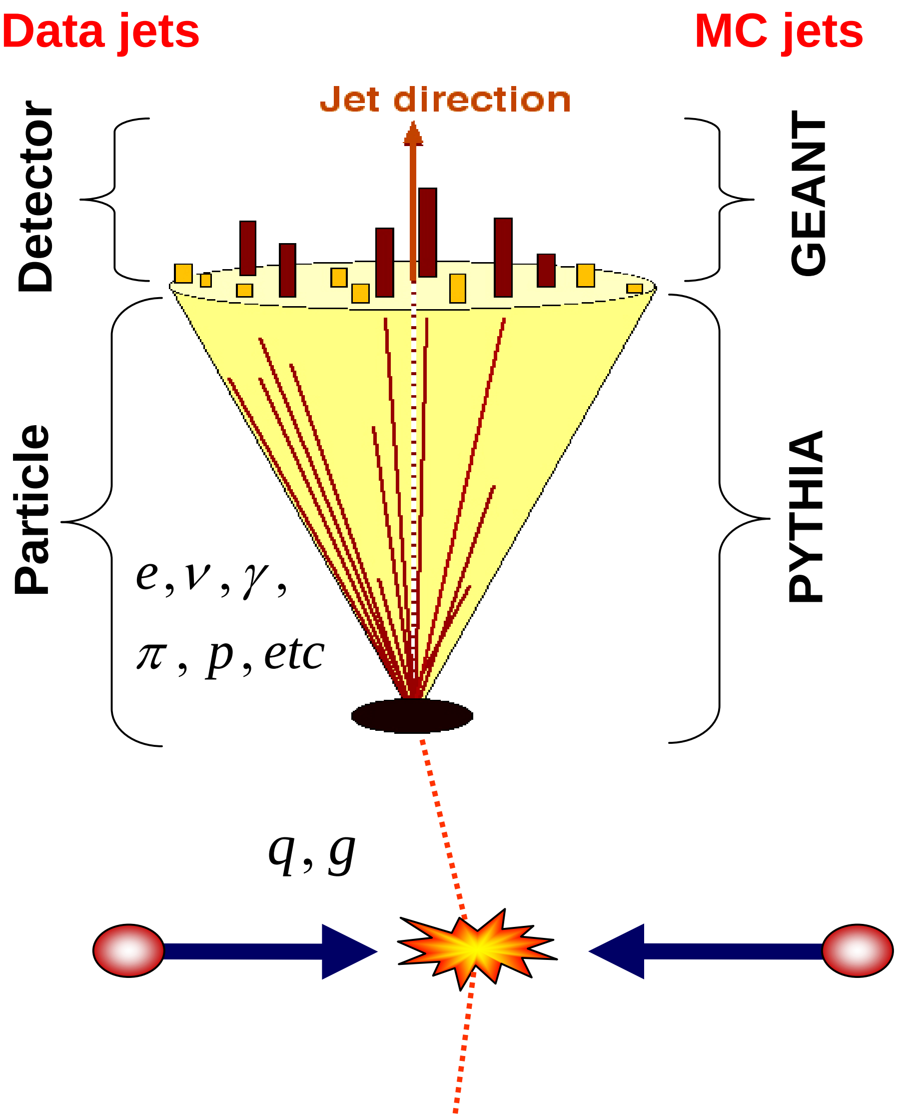
PR **D76**, 051106 (2007)

Forward: STAR



PRL **97**, 152302 (2006)

Jet reconstruction in *STAR*



Midpoint cone algorithm

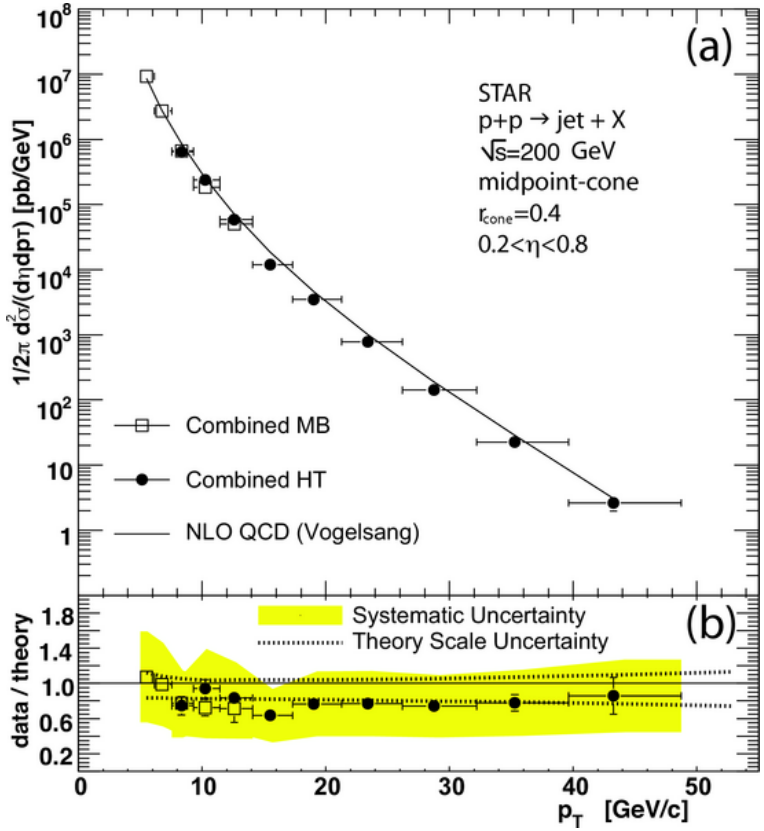
(Adapted from Tevatron II - hep-ex/0005012)

- Seed energy = 0.5 GeV
- Cone radius in η-ϕ
  - R=0.4 with 0.2 < η < 0.8 (2005)
  - R=0.7 with -0.7 < η < 0.9 (2006)
- Splitting/merging fraction f=0.5

Use **PYTHIA** + **GEANT** to quantify detector response

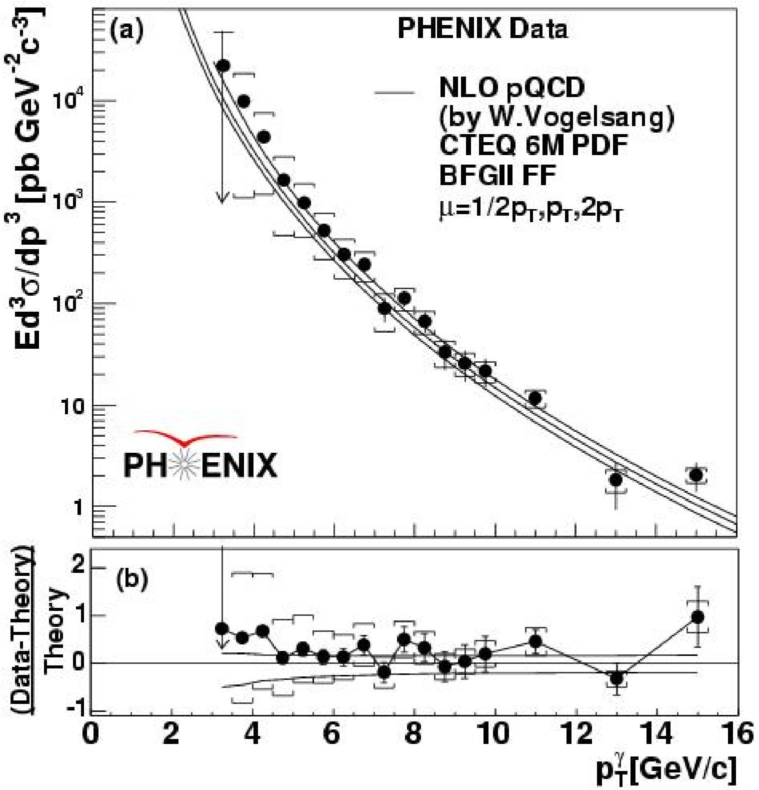
And Jets and Direct γ

pp → jet X : STAR



PRL 97, 252001 (2006)

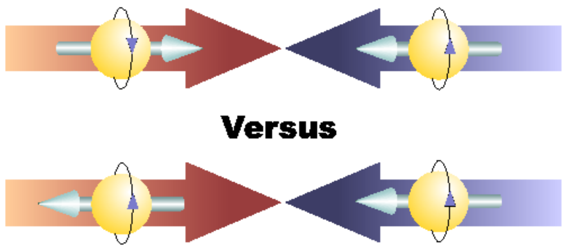
pp → γ X : PHENIX



PRL 98, 012002 (2007)

A_{LL}

“Yellow” beam “Blue” beam



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{|P_B P_Y|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

++ same helicity
+– opposite helicity

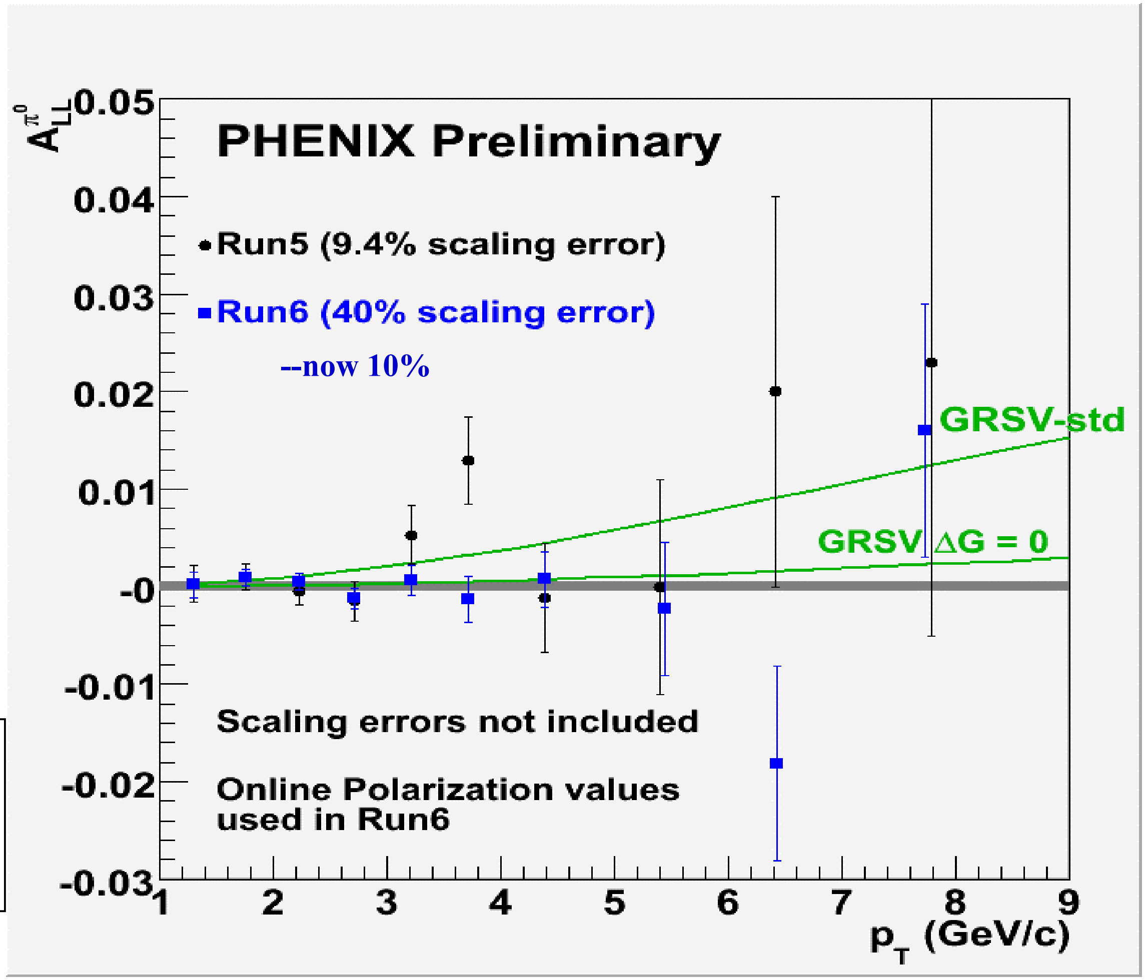
(P) Polarization
(L) Relative Luminosity
(N) Number of pi0s

Calculate beam spin asymmetry of N(pions) :

A_LL = (N(pi0,++) – N(pi0,+-))/sum/P^2

beam spin directions

π^0 A_{LL}



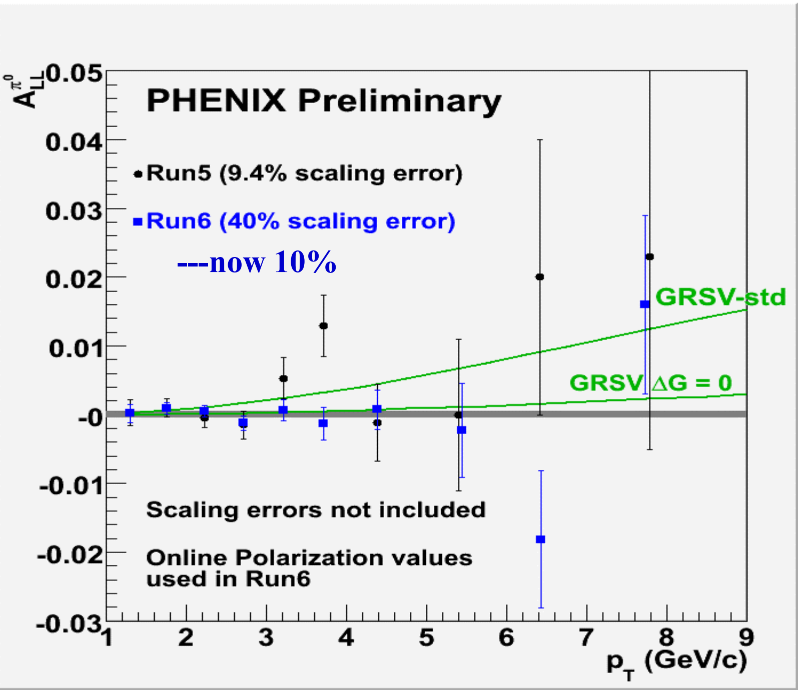
Green:
models of gluon polarization

GRSV model:

"ΔG = 0": ΔG(Q^2=1GeV^2)=0.1

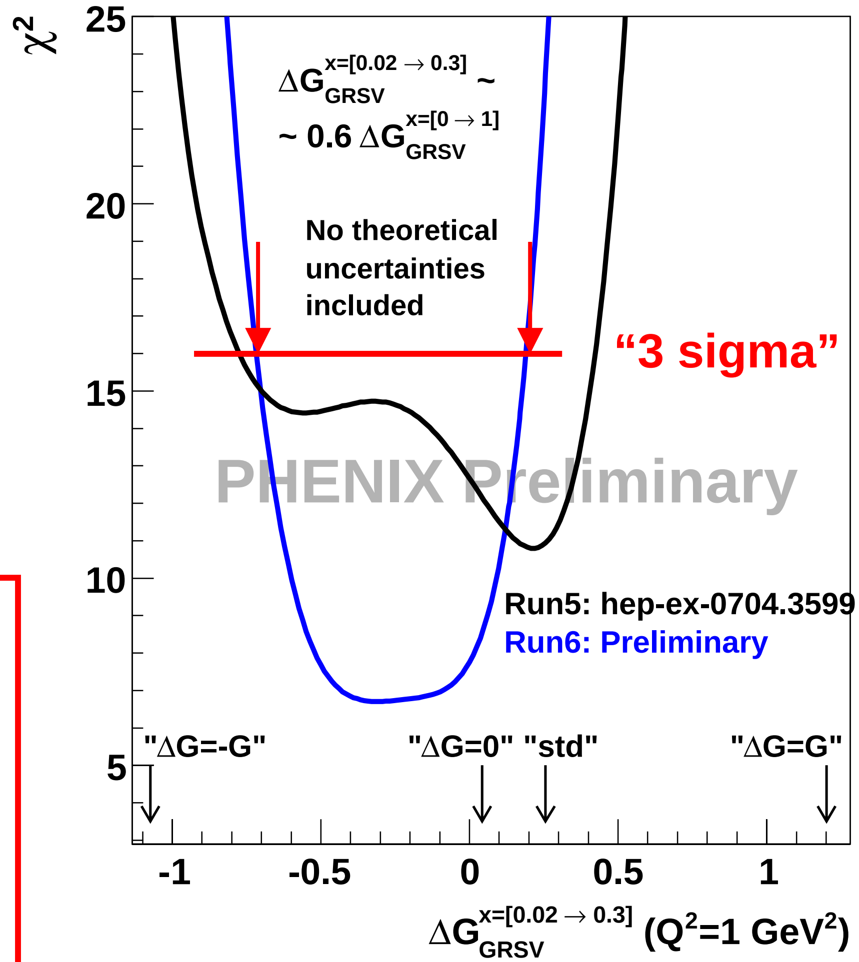
"ΔG = std": ΔG(Q^2=1GeV^2)=0.4

From A_{LL} to ΔG (with GRSV)



⇒

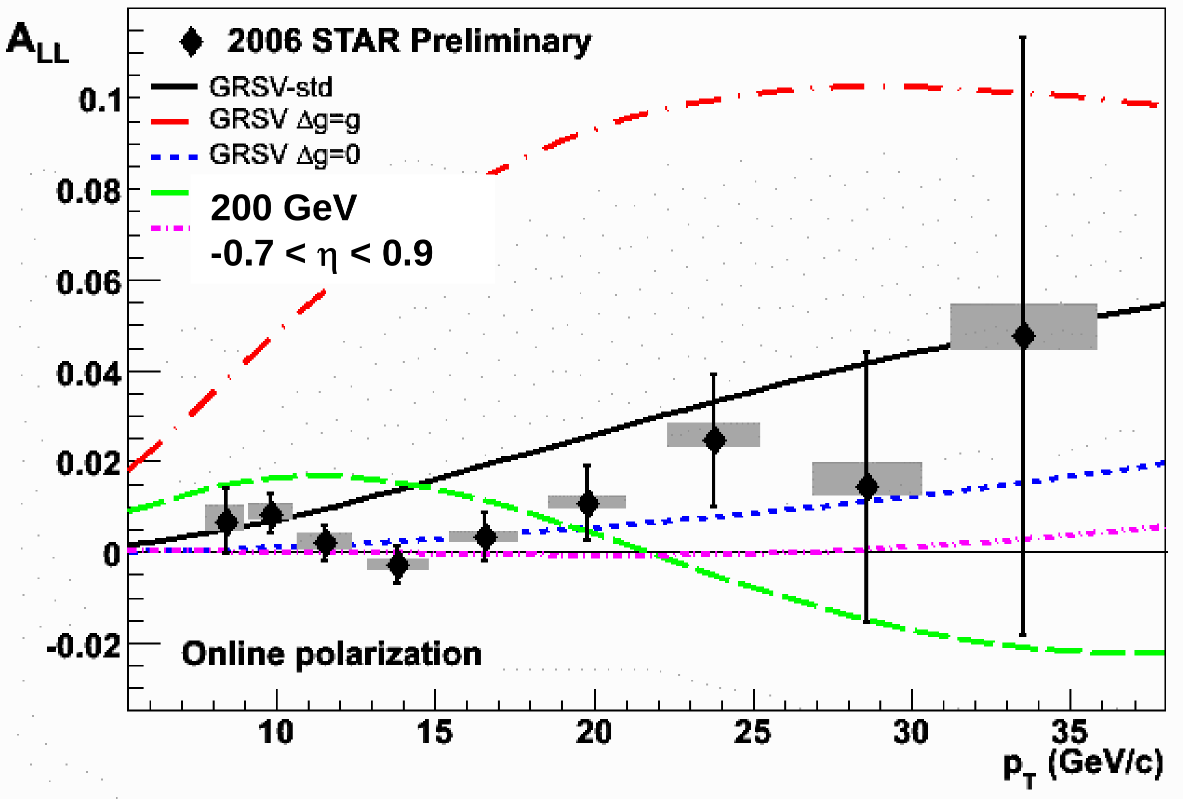
Calc. by W.Vogelsang and M.Stratmann



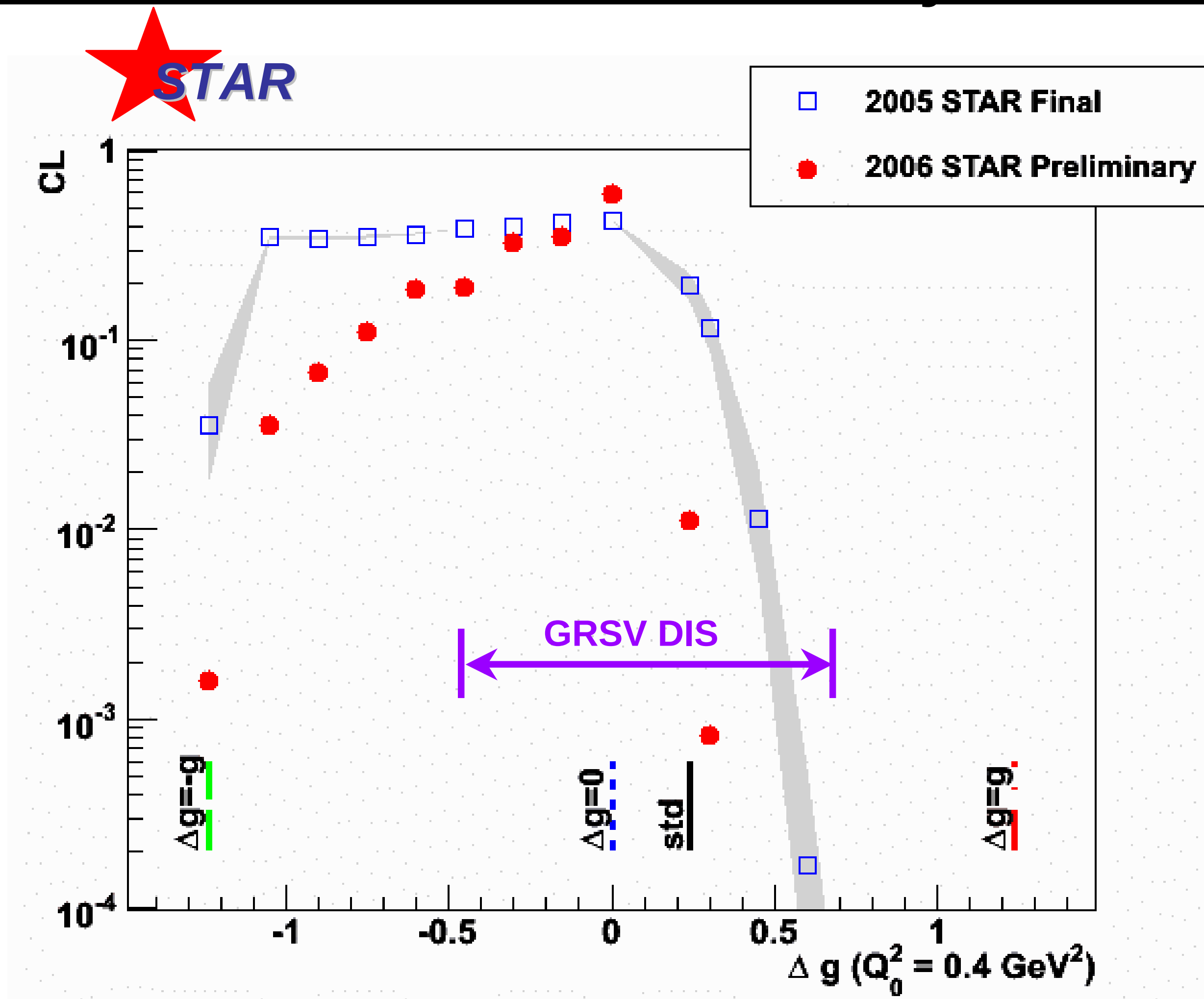
"std" scenario, $\Delta G(Q^2=1\text{GeV}^2)=0.4$, is excluded by data on >3 sigma level: $\chi^2(\text{std})-\chi^2_{min}>9$

- ✓ Only exp. stat. uncertainties are included (the effect of syst. uncertainties is expected to be small in the final results)
- ✓ Theoretical uncertainties are not included

2006 inclusive jets A_{LL}



Limits on ΔG from 2006 jet results



- Within the GRSV framework:
  - GRSV-std excluded with 99% CL
  - ΔG < -0.7 excluded with 90% CL

Delta G at RHIC

---present and future

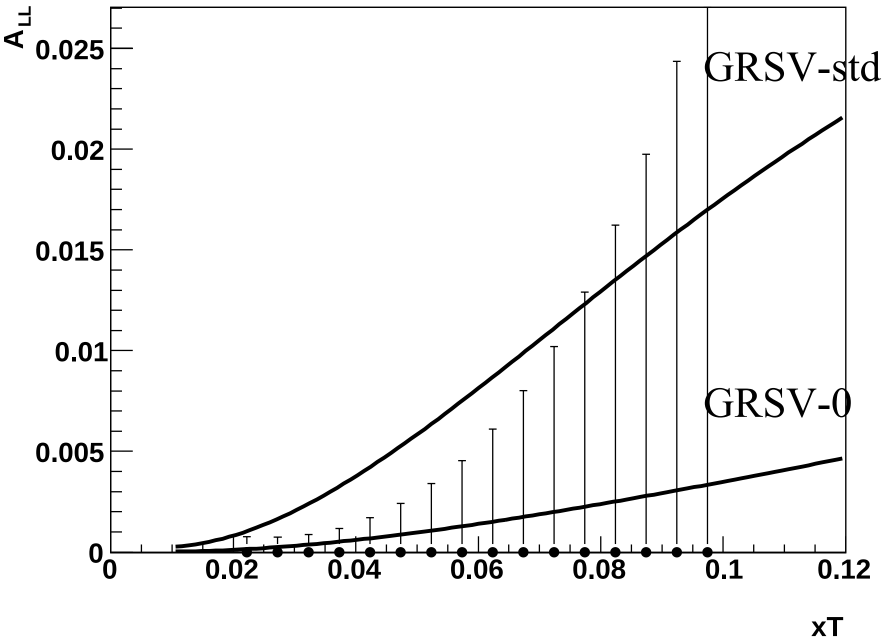
- from pi^0 and jets, 2006: **the gluon contribution to the proton spin is not large!***
- more probes: pi^+, pi^-, pi^0 (STAR), eta
- more luminosity and P: **pi^0**, jets, direct photon; **dijets**, photon + jet

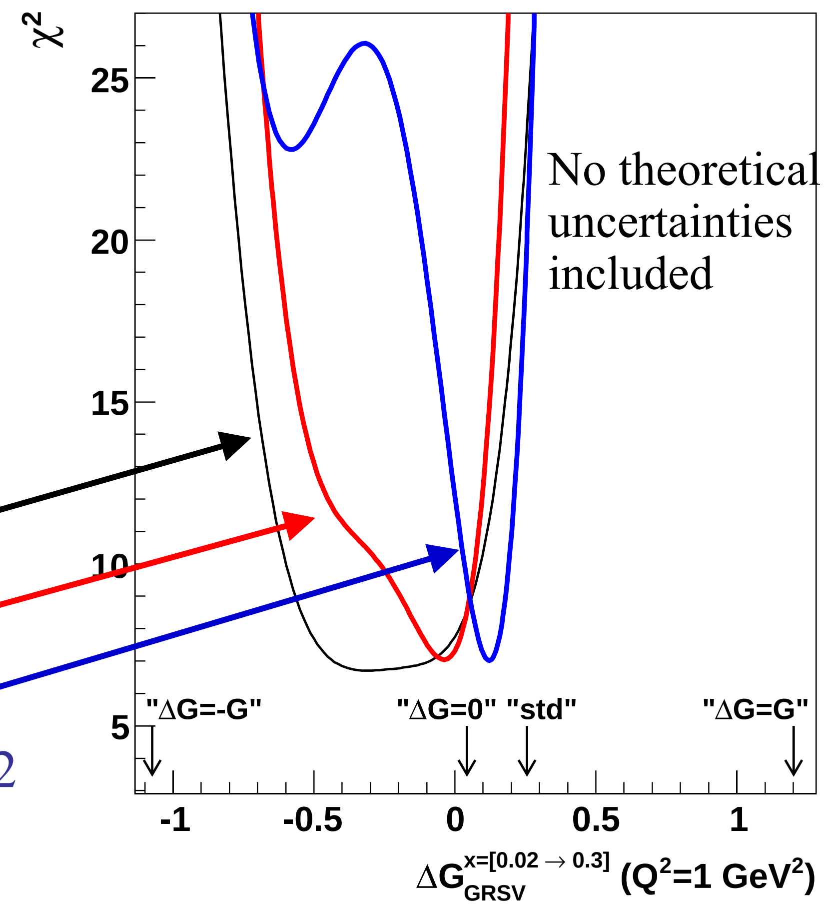
---both experiments requesting long p-p run in 2009 to obtain significant increase in sensitivity to Delta G (root(s)=200 GeV)

*** in range 0.02 < x_gluon < 0.3 ; using GRSV framework**

$\pi 0\ A_{LL}$

L=25 pb^{-1} P=60%





Run6 Preliminary

Run9 proj: “GRSV-0”

Run9 proj: (“GRSV-0”+ “GRSV-std”)/2

(still consistent with Run6 within 2σ)

The next few years: di-jets and $\Delta g(x)$

STAR

2005 preliminary di-jet distributions

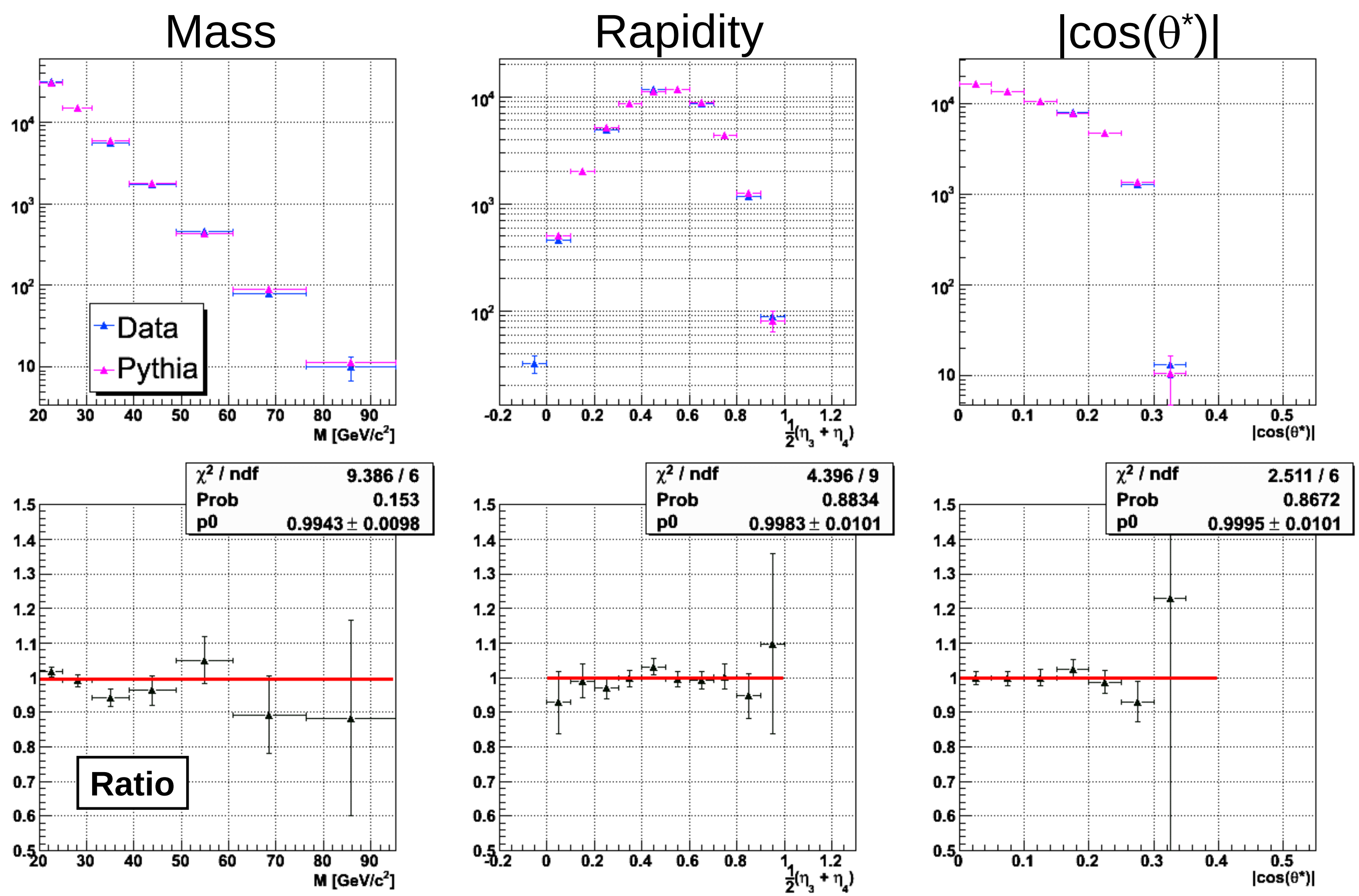
$$x_1 = \frac{1}{\sqrt{s}}\left(p_3 e^{\eta_3} + p_4 e^{\eta_4}\right)$$

$$x_2 = \frac{1}{\sqrt{s}}\left(p_3 e^{-\eta_3} + p_4 e^{-\eta_4}\right)$$

$$M = \sqrt{x_1 x_2 s}$$

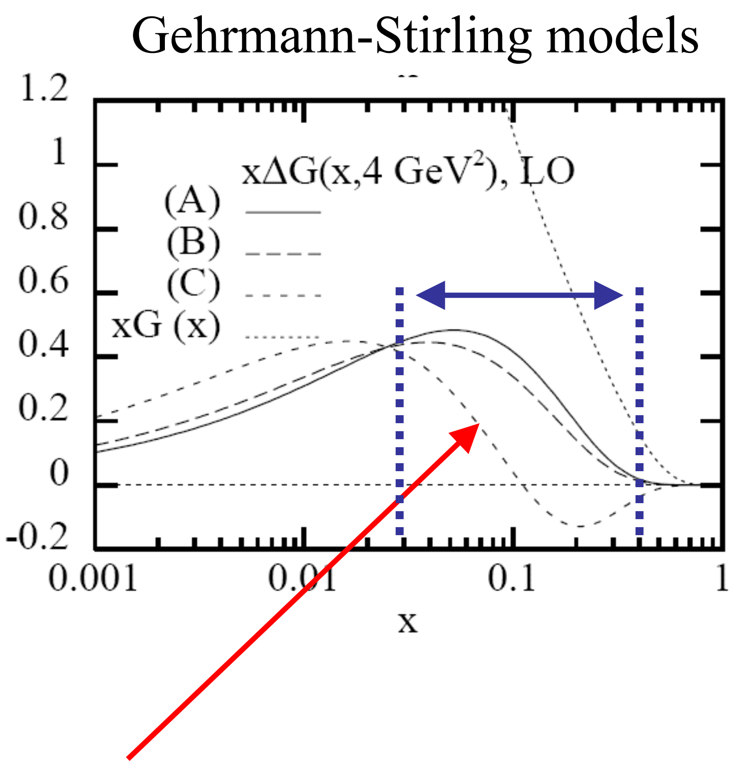
$$y = \frac{1}{2}\ln\frac{x_1}{x_2} = \frac{\eta_3 + \eta_4}{2}$$

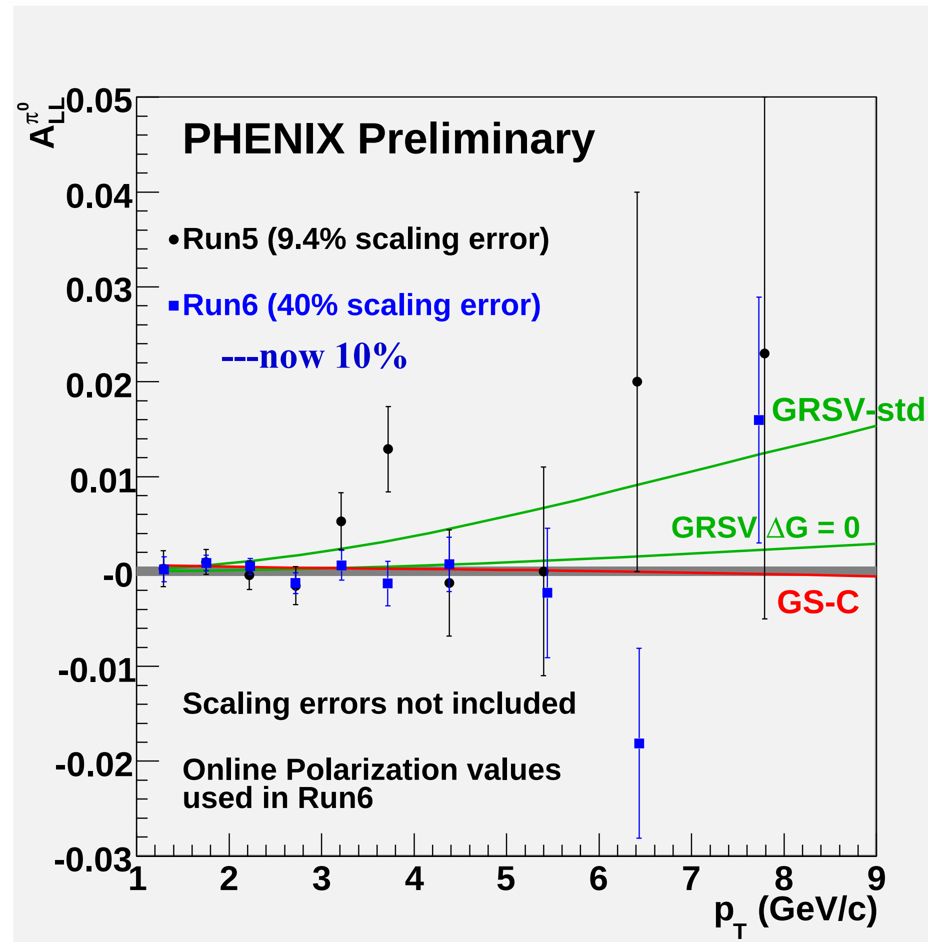
$$|\cos\theta^*| = \tanh\frac{|\eta_3 - \eta_4|}{2}$$



- Di-jets provide direct access to parton kinematics at LO
- *STAR* will also obtain complementary information about **$\Delta g(x)$ from γ + jet**

Also: Extending x range is crucial!





GSC: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 1$

$\boldsymbol{\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0}$

GRSV-0: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 0$

$\boldsymbol{\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0}$

GRSV-std: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 0.4$

$\boldsymbol{\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0.25}$

Current data is sensitive to ΔG for $x_{gluon} = 0.02 \rightarrow 0.3$

Beyond the Delta G Program:
W bosons at RHIC

---100% parity violating in production

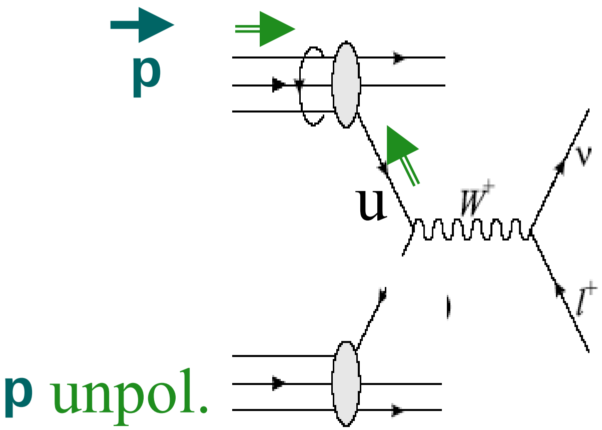
---observation of degree of parity violation of W→mu/e (+ neutrino) gives direct measurement of **quark** and **anti-quark** polarizations in the proton

---requires running at root(s)=500 GeV

---new detectors also required

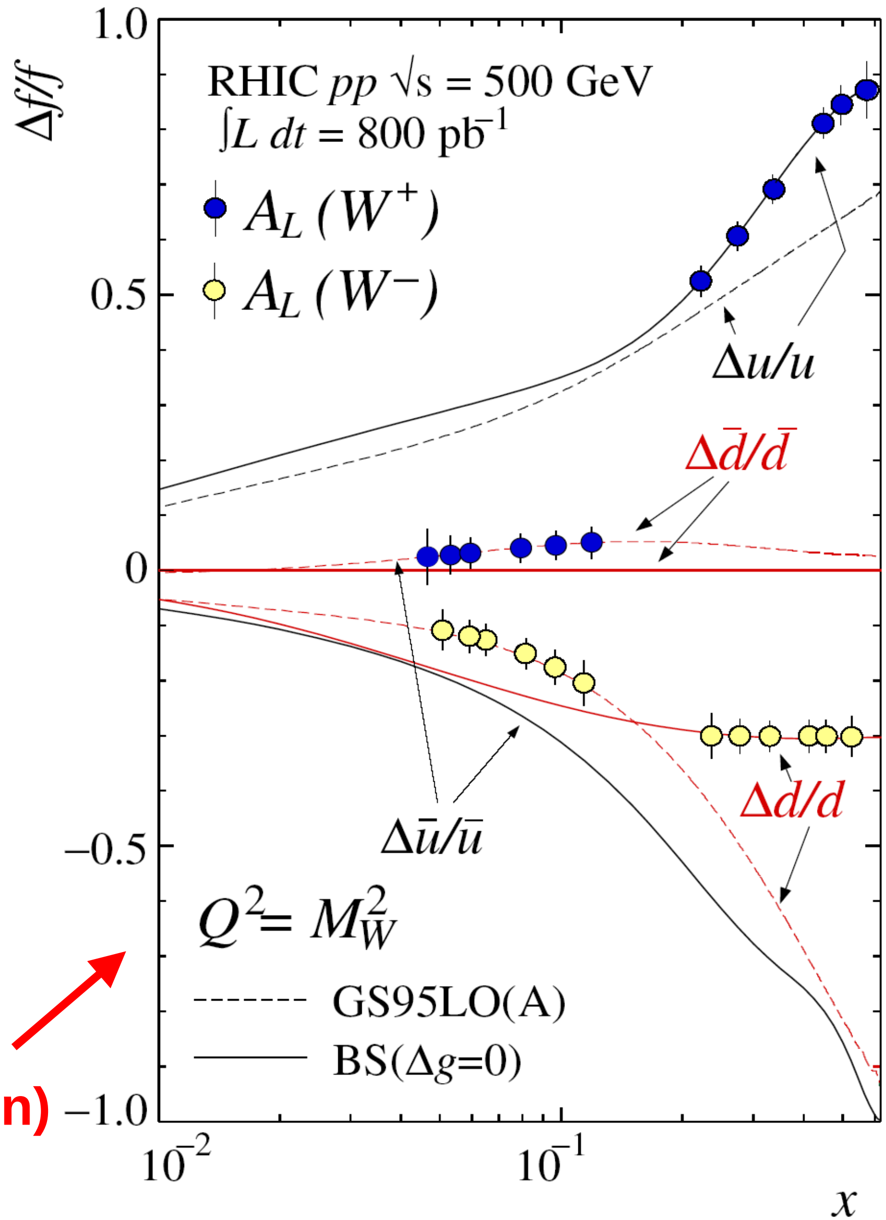
---expect first studies in **2009**, measurements in **2010-2012**

Δq-$\Delta\bar{q}$ at RHIC via $W^{+/-}$ production



$$\Delta d + \bar{u} \rightarrow W^-$$
$$\Delta \bar{u} + d \rightarrow W^-$$
$$\Delta \bar{d} + u \rightarrow W^+$$
$$\Delta u + \bar{d} \rightarrow W^+$$

$$\mathbf{A_L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



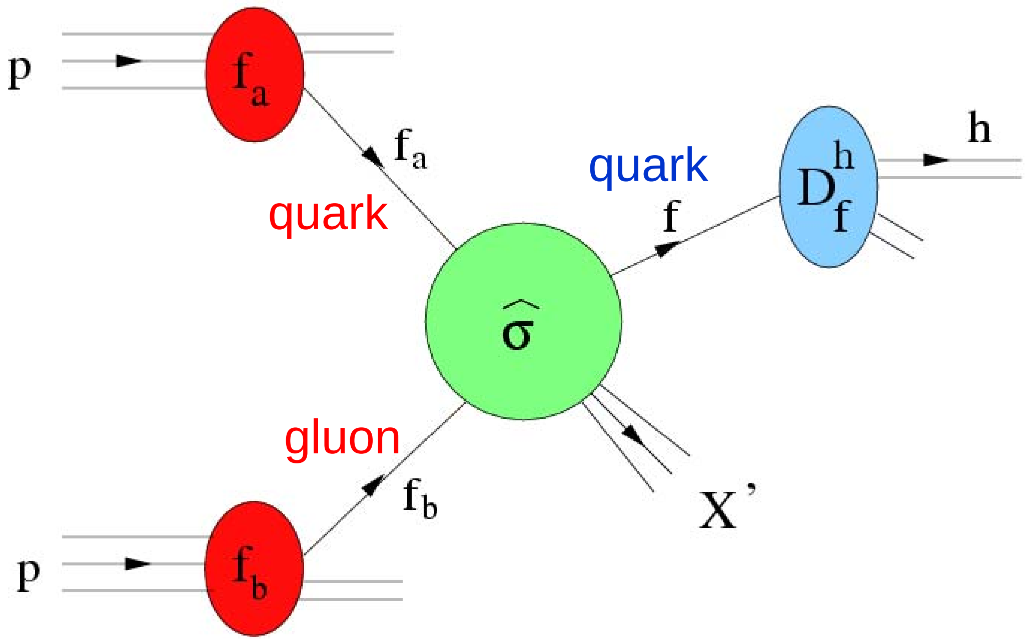
Note: measurements will be of lepton;
no missing E, results will be vs. y(lepton)

The proton spin structure:

And orbital angular momentum?

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

Quarks contribute only 20%!



pion or jet

Transverse Spin

---Collide beams of transversely spinning protons

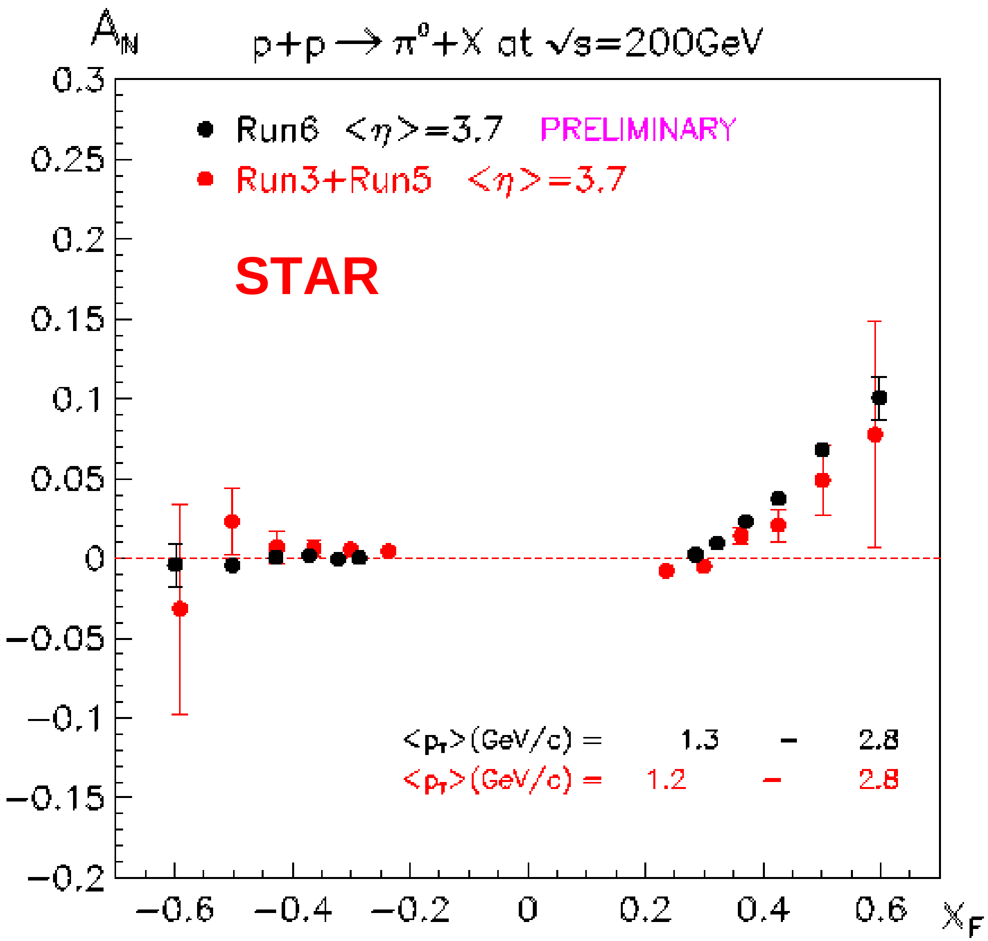
---measure left-right asymmetry of pions with vertically polarized beam (A_N)

---very large spin asymmetries observed!

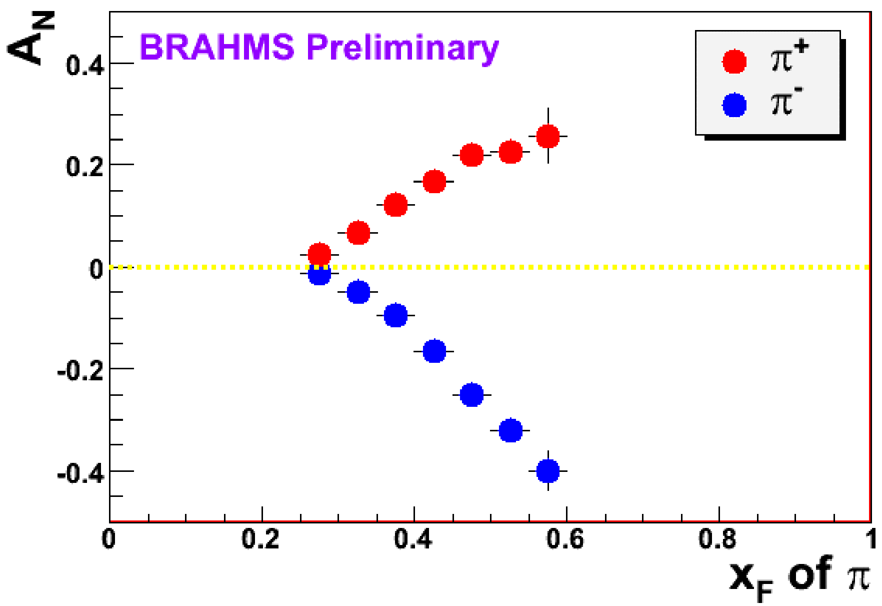
---the orbital angular momentum of the quarks in the proton may be an important source of the asymmetries

Charged and neutral pion:

p + p → pi + X (left-right asymmetry)



$A_N(\pi)$ at 62 GeV



Kyoto Spin2006

A huge asymmetry: twice as many pi^- are produced to the right of the beam as are produced to the left!

Concluding Remarks

- **High luminosity and high polarization achieved! But, still work to do.**

- **Delta G: global fits with RHIC, DIS; considerably more sensitivity to come.**

- **W boson parity violating production: ubar and dbar**

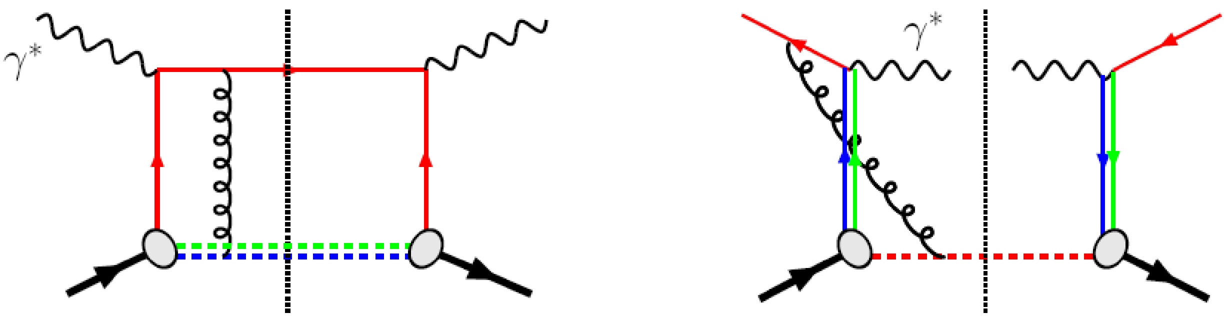
- **Very strong theoretical support**

- **Transverse spin renaissance→Drell Yan crucial test of our understanding of the underlying physics**

Attractive vs Repulsive "Sivers" Effects

Unique Prediction of Gauge Theory !

DIS: attractive **Drell-Yan: repulsive**



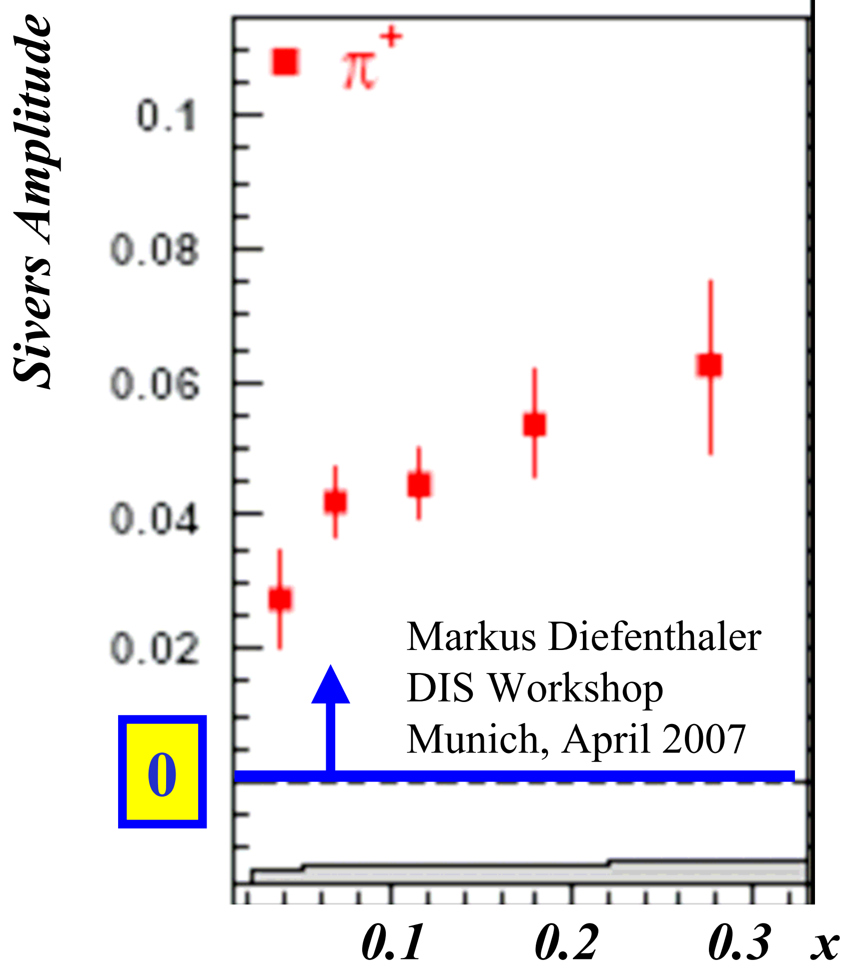
$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

Sivers = <u>Dennis Sivers</u> (predicted orbital angular momentum origin of transverse asymmetries)

Experiment SIDIS vs Drell Yan: $\text{Sivers}|_{DIS} = -\ \text{Sivers}|_{DY}$

*** Probes QCD attraction and QCD repulsion ***

HERMES Sivers Results



RHIC II Drell Yan Projections