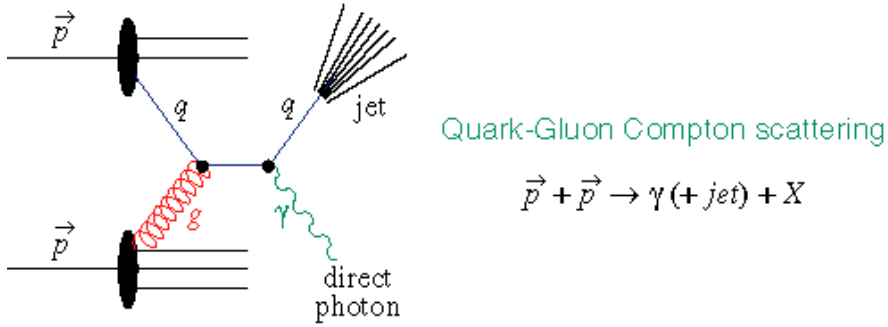
The (Present and) Future of STAR Spin



hard-scattering (Þ pQCD) with spin

- Motivation and goals of spin physics
- Required measurements with polarized beams
- Polarized protons at RHIC in FY02 and beyond
- A path from the present to the future

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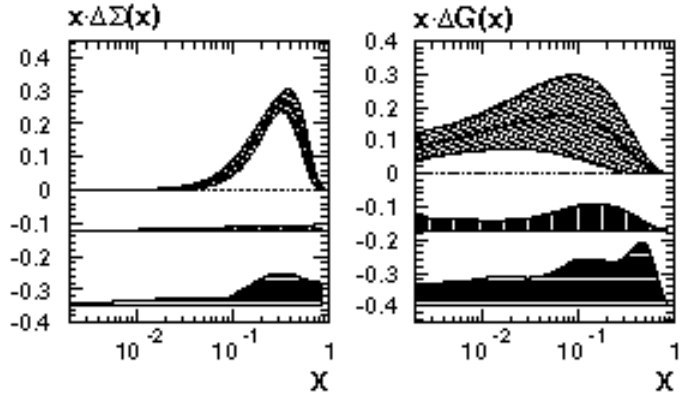
Brookhaven National Lab

Where is the spin of the proton?

Global analyses of polarized deep inelastic scattering (pDIS) observe only a small fraction of the proton's spin carried by quarks.



First moments at $Q_0^2 = 1\ \mathrm{GeV}^2$:

SMC , PRD 58 (1998) 112002

$$\Delta\Sigma_{(AB)} = 0.38\ ^{+0.03}_{-0.03}\ ^{+0.03}_{-0.02}\ ^{+0.03}_{-0.05}$$

$$\Delta G_{(AB)} = 0.99\ ^{+1.17}_{-0.31}\ ^{+0.42}_{-0.22}\ ^{+1.43}_{-0.45}$$

q($\bar{q}$) contribution — gluon contribution

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \underbrace{L_z^q + L_z^g}_{\text{orbital angular momentum}}.$$

At present, the gluon contribution to the proton spin (ΔG) is known only poorly from scaling violations in polarized deep inelastic scattering, spanning a small range of Q^2.

$\Rightarrow$ Require a NEW GENERATION of experiments to determine ΔG.

$\Rightarrow$ RHIC Spin

- determine the *gluon contribution* to the proton's spin
- determine the *flavor decomposition* of the *quark* (*antiquark*) *polarization*
- probe *transversity*: the unknown, remaining leading-twist structure function

Spin Measurements at STAR

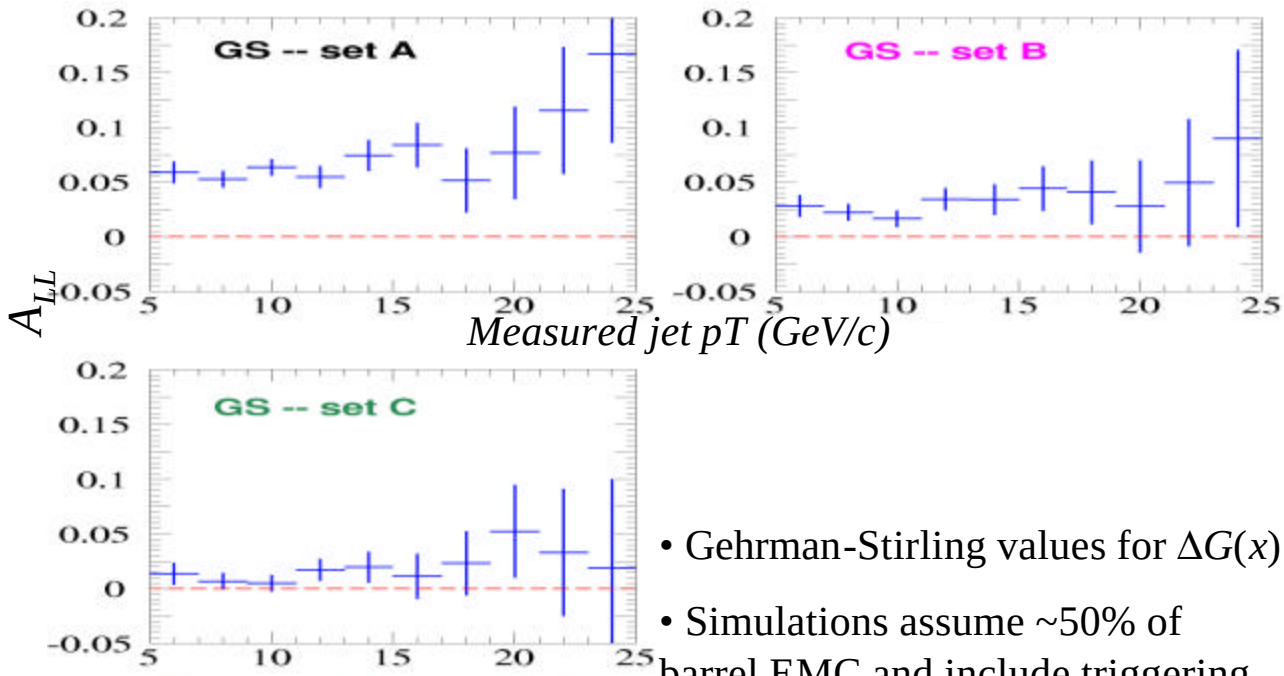
- Determining the polarization of the proton's glue
  - o A_{LL} for $\vec{p} + \vec{p} \rightarrow \text{jets} + X$, inclusive jets (proposed first attempt in FY03 run)
  - o A_{LL} for $\vec{p} + \vec{p} \rightarrow \gamma + X, \gamma + \text{jet} + X$, inclusive γ and γ+jet (first attempt in FY04 run)
  - o other possibilities: di-jet production, heavy flavor production

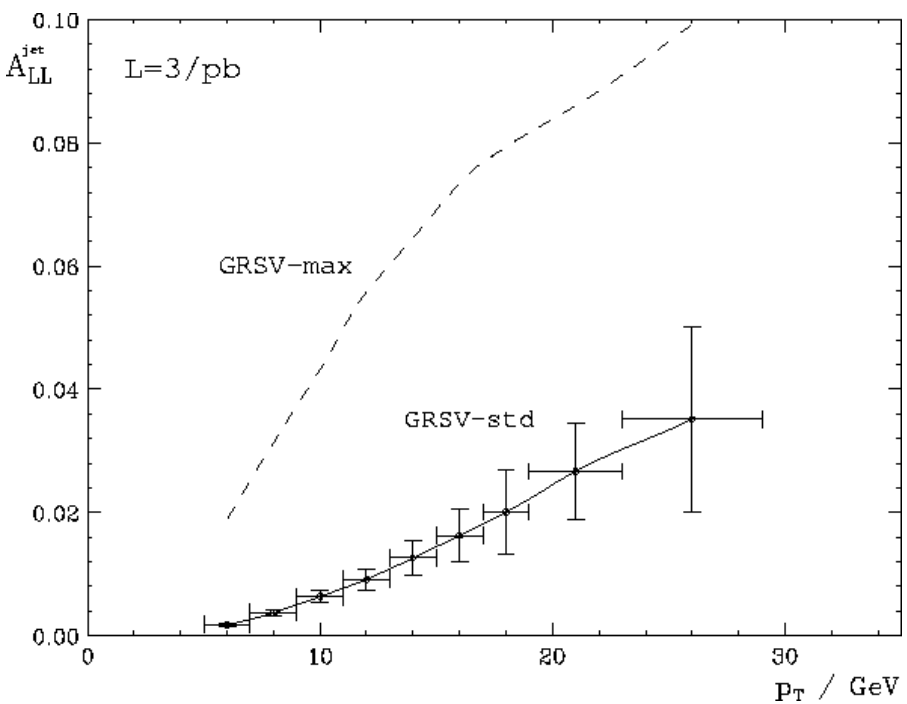
- Flavor decomposition of proton's spin
  - o A_L for $\vec{p} + p \rightarrow W^{\pm} + X$, electroweak probe of flavor contribution to spin
  - o other possibilities: two-spin asymmetries for Drell-Yan

- Probes of the transversity structure function

- Spin dependent tests of Standard Model (see, e.g. Hardtke's talk on CP violation)

Predictions for sensitivity to $\Delta G(x)$ from A_{LL} measurement for inclusive jets near mid-rapidity





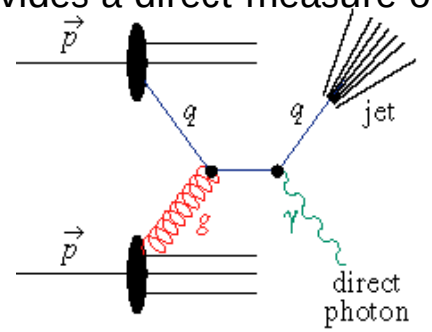
- Gehrman-Stirling values for $\Delta G(x)$
- Simulations assume ~50% of barrel EMC and include triggering and jet reconstruction efficiencies.
- admixture of partonic scattering, from PYTHIA

  ~60% qg + ~25% qq' + ~15% gg
- $\int \mathbf{L}\, dt = 1\ pb^{-1}$ (expect 3x more in FY03 run)

Similar predictions for sensitivity in calculation by W. Vogelsang.

Gluon Contribution to the proton's spin

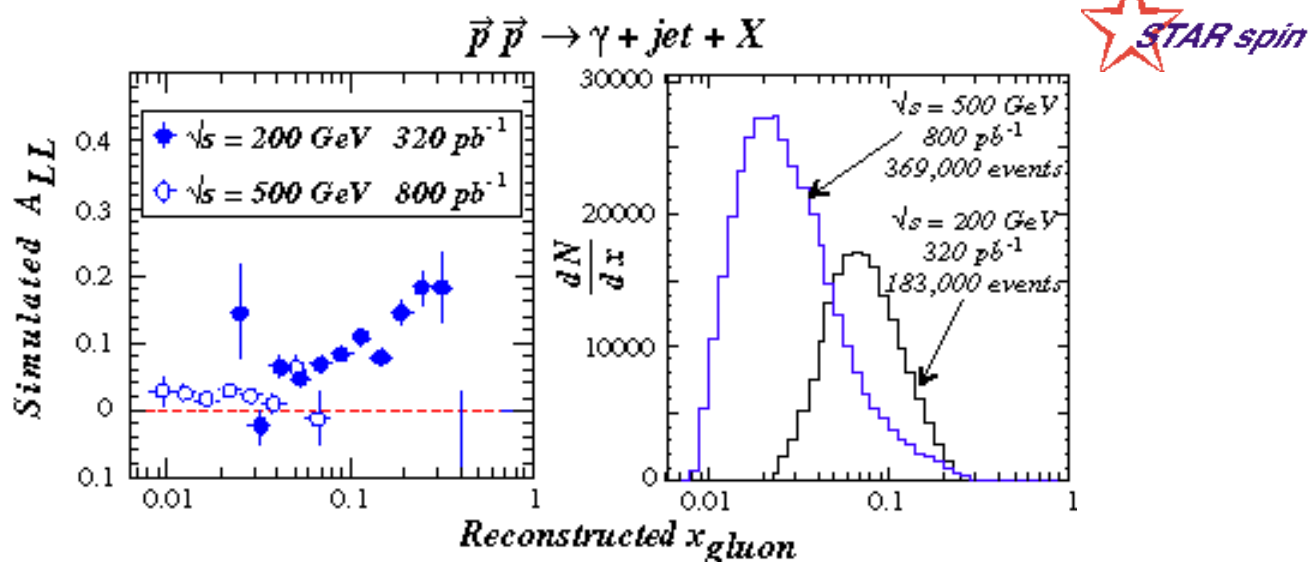
qg Compton scattering with polarized protons provides a direct measure of gluon polarization.



Quark-Gluon Compton scattering

$$\vec{p} + \vec{p} \rightarrow \gamma\,(+\,jet) + X$$

Coincident detection of γ and away-side jet $\Rightarrow$ event determination of initial-state partonic kinematics.



Interpret measured asymmetry within leading-order pQCD

$$A_{LL} = \overbrace{P_{part.\,1}\,P_{part.\,2}}^{parton\ pol'ns.}\ \hat{a}_{LL} = \overbrace{\frac{\Delta f_1}{\underbrace{f_1}_{unpol\ struct\ fncs.}}\,\frac{\Delta f_2}{f_2}}^{pol\ struct\ fncs.}\ \hat{a}_{LL}(\hat{s},\hat{t},\hat{u}) \xrightarrow{QCD\ Compton} \boxed{\frac{\Delta G(x_g)}{G(x_g)}}\,A_1^p(x_q)\,\hat{a}_{LL}$$

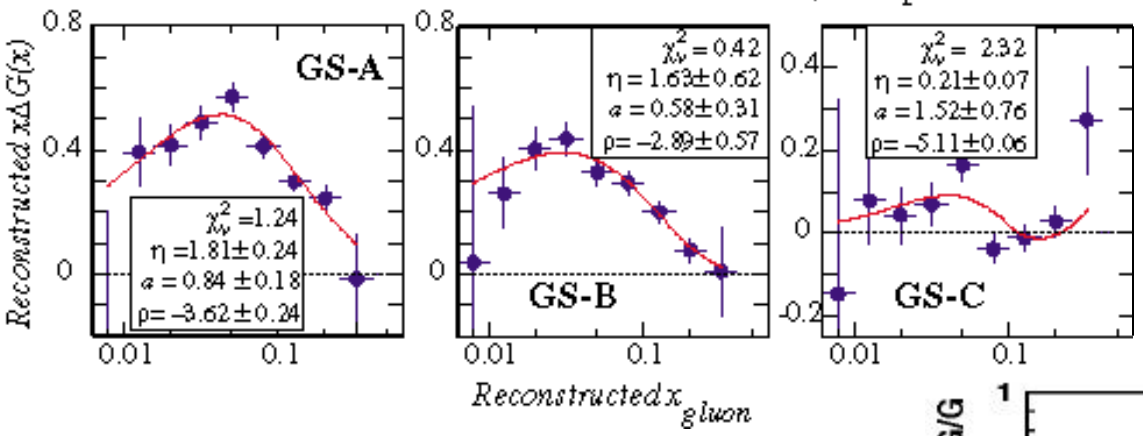
pQCD result for specific process

gluon polarization

Measured in polarized deep-inelastic scattering

Sensitivity to Gluon Polarization at RHIC

$\vec{p} + \vec{p} \rightarrow \gamma + jet + X$ $\sqrt{s} = 200$ GeV, 320 pb^{-1} $\sqrt{s} = 500$ GeV, 800 pb^{-1}



RHIC spans a broad range of x_{gluon}

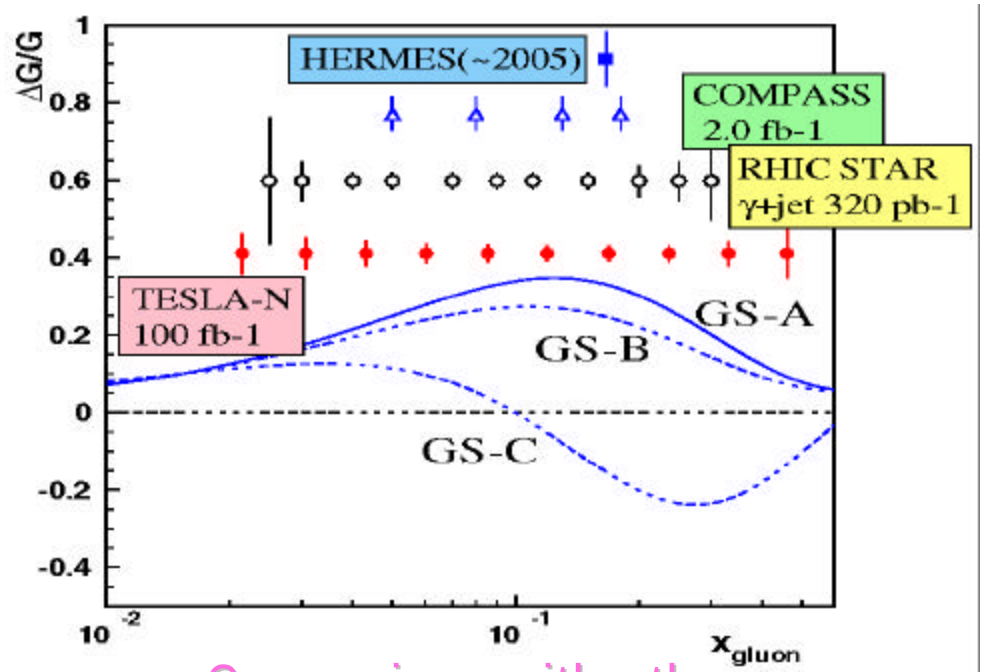
$\Rightarrow$ determine integral ΔG

$\Rightarrow$ gluon contribution to proton spin.

PHENIX and STAR will also be sensitive to ΔG through many different channels:

inclusive γ, inclusive jets, J/ψ production, heavy flavor production, etc.

$\Rightarrow$ check consistency of results.



Comparison with other experiments

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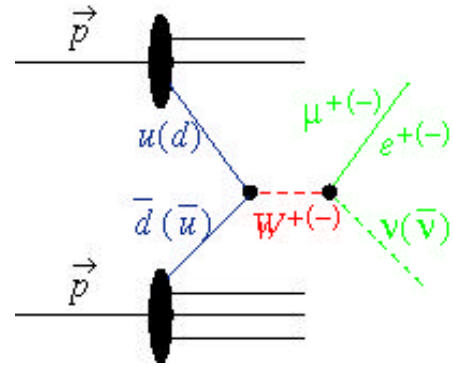
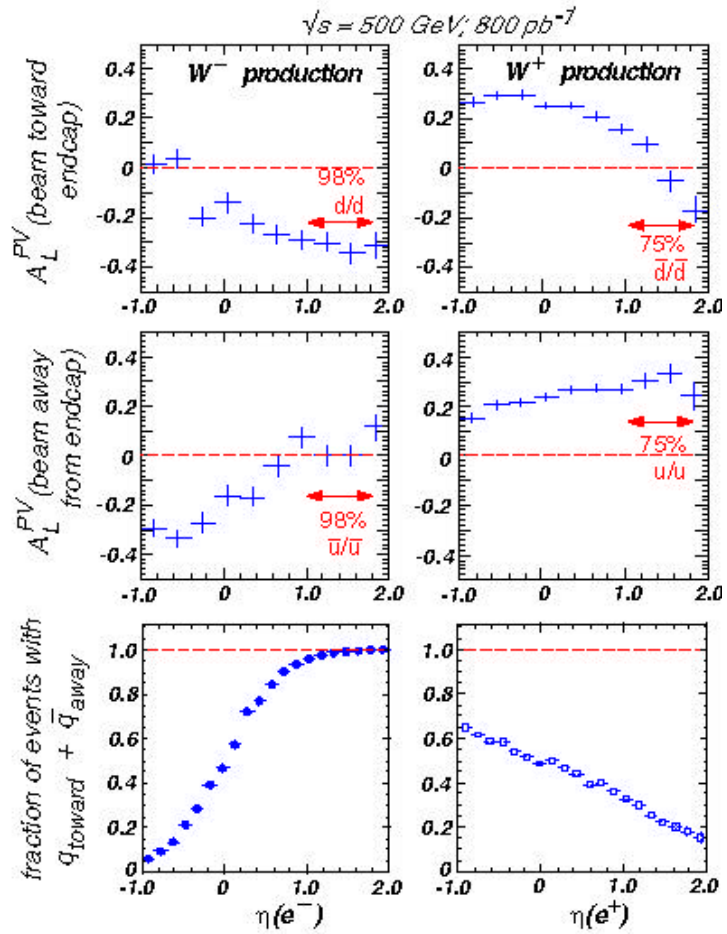
Flavor Decomposition of the proton's spin



- $W^{\pm}$ production probes flavor structure analogous to ν deep inelastic scattering.
- Polarized proton beams allows the measurement of (the expected large) parity violation in $W^{\pm}$ production.
- Forward μ,e detection (dominated by production of W's with large longitudinal momentum) gives direct probe of quark (antiquark) polarization:

$$A_L \xrightarrow[x_1 >> x_2]{} \begin{cases} \dfrac{\Delta q(x_1)}{q(x_1)}, & \textit{when lepton is mostly parallel to the polarized proton} \\[2ex] \dfrac{\Delta \bar{q}(x_2)}{\bar{q}(x_2)}, & \textit{when lepton is mostly antiparallel to the polarized proton} \end{cases}$$



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Transversity

General Remarks

Leading twist quark distribution functions $F = \frac{q}{2} I \times I + \frac{\Delta q}{2} s_3 \times s_3 + \frac{dq}{2}(s_+ \times s_- + s_- \times s_+)$

Longitudinal Spin Distribution $p^{\rightarrow} \Rightarrow \; : \; \Delta q = q^{\rightarrow} - q^{\leftarrow}$

Transversity $p^{\uparrow} \Rightarrow \; : \; dq = q^{\uparrow} - q^{\downarrow}$

cannot be probed in DIS because of *helicity conservation* (δq is **chiral odd**)

- requires pair of **chiral odd** effects $\Rightarrow$ e.g.,

  $k_\perp$ dependent Collins fragmentation $\otimes$ transversity

- difference between $\delta q(x)$ and $\Delta q(x)$ is expected for *relativistic quarks* because boosts & rotations don't commute.

- gluons cannot contribute to transversity $\Rightarrow$ more robust determination of fraction of proton's spin carried by quarks??

- the only real knowledge about transversity is the so-called Soffer bound

$$| \delta q(x) | < \tfrac{1}{2} | q(x) + \Delta q(x) |$$

Spin Asymmetry Measurments
General Comments

- Systematic errors for *transverse* spin asymmetries are minimized using ϕ dependence of scattering rates.

  $\Rightarrow$ *Polarimeters* employ ϕ symmetric detection systems.

- *Longitudinal* spin asymmetry measurements require the accurate determination of + and – relative luminosities.

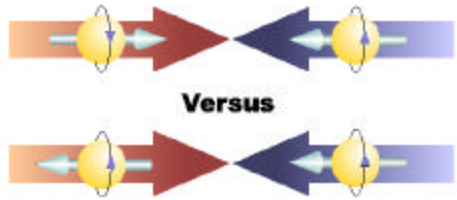
- The *statistical significance* of spin asymmetries is given by the *figure of merit* (FOM):

  Single spin asymmetries: FOM ~ $P^2(\mathbf{L}t)$

  Double spin asymmetries: FOM ~ $P^4(\mathbf{L}t)$

- *Systematic errors* for spin asymmetries are increasingly important as $\varepsilon \rightarrow 0$ ($\Rightarrow$ either small polarization, or small A, or both).

Spin Asymmetry Measurements



$$A_{LL} = \frac{(s_{++} + s_{--}) - (s_{+-} + s_{-+})}{(s_{++} + s_{--}) + (s_{+-} + s_{-+})}$$

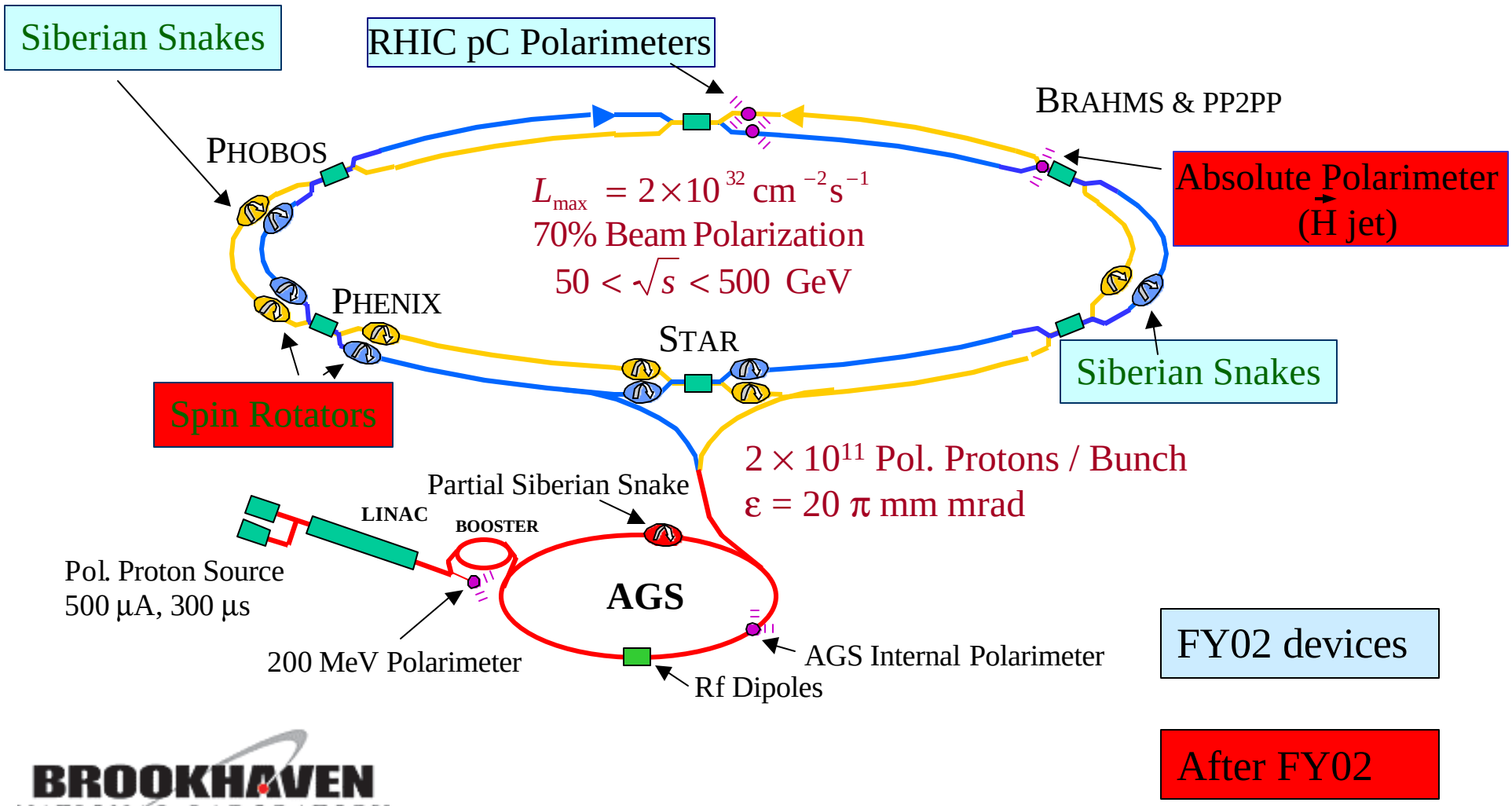
Measure spin-correlation parameter (A_{LL}) with longitudinally polarized protons

$$P_{b1} P_{b2} A_{LL} = \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

Require concurrent measurements:

- magnitude of beam polarization, $P_{b1(2)}$
- direction of polarization vector at STAR interaction point (after spin rotator)
- relative luminosity for bunch crossings of different luminosity (R=$\mathbf{L}_{++}$ / $\mathbf{L}_{+-}$)
- spin dependence of process of interest (N_{++},N_{+-})

Polarized Proton Acceleration at RHIC



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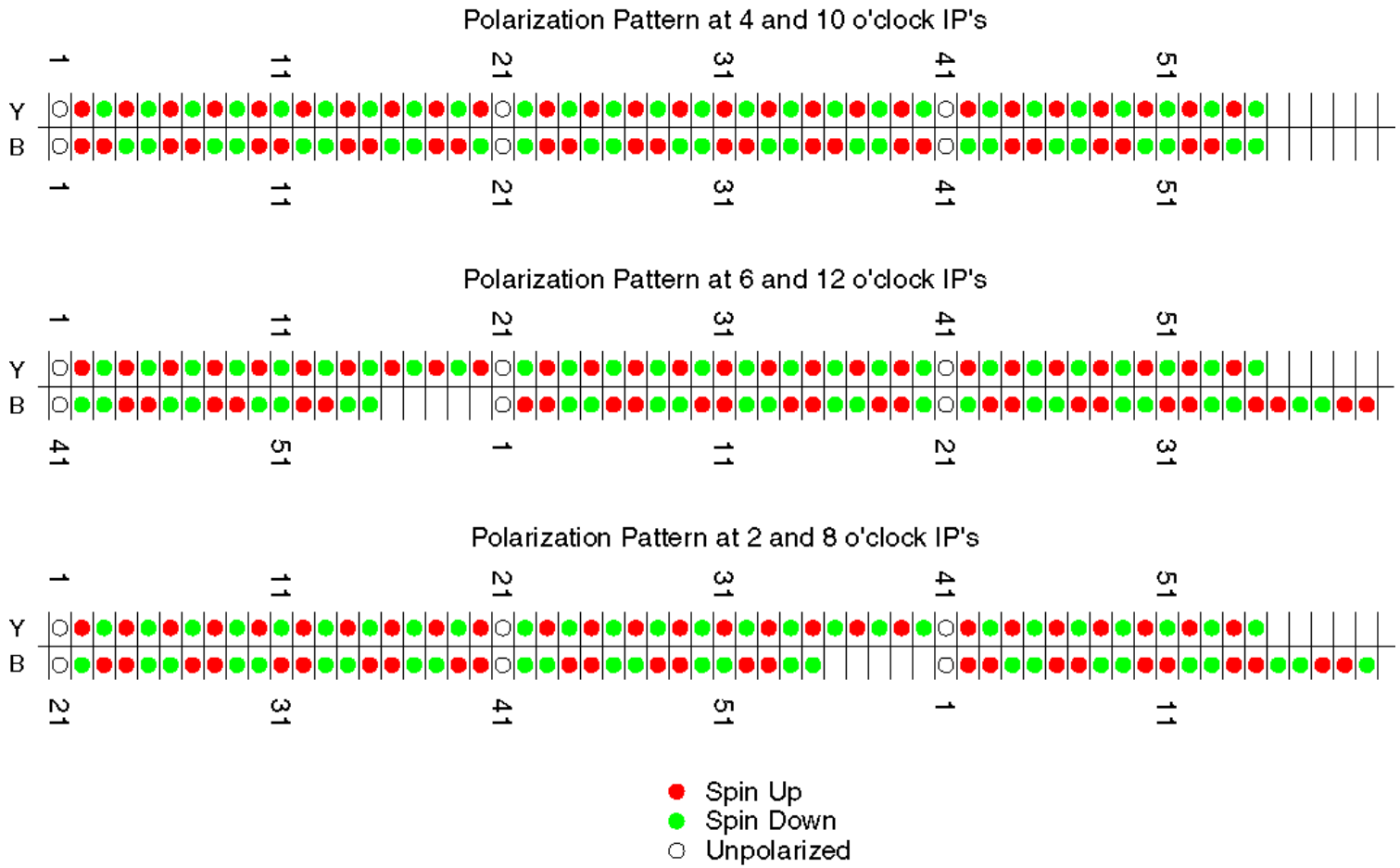
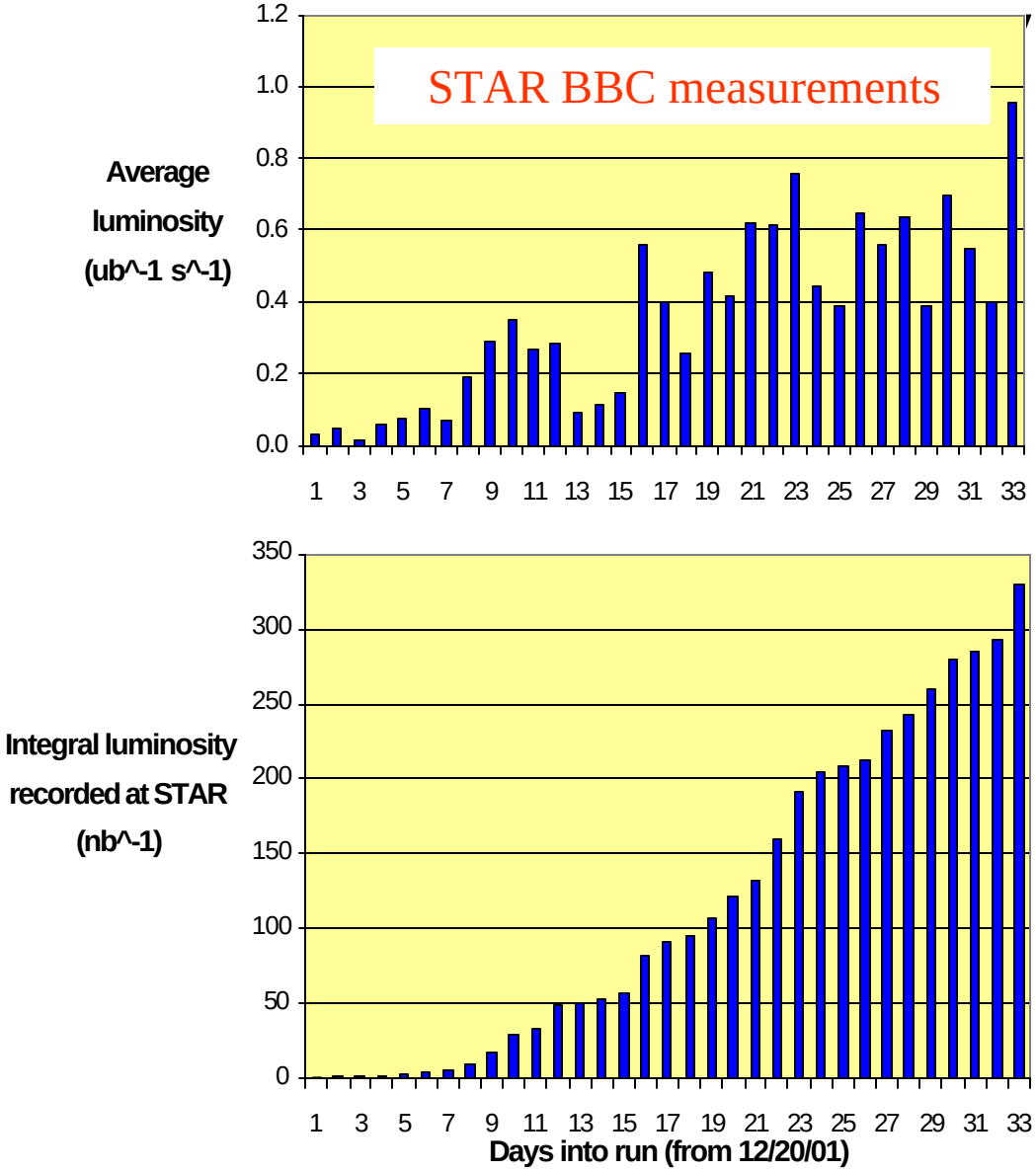
Polarization Pattern/Timing in FY02 Run



- 55 bunches in FY02 $\Rightarrow$ 214 ns between bunches (future runs, 110 bunches with δt = 107 ns)
- measured fill-dependent luminosity asymmetries averaged between 2 and 8% (but large bunch-to-bunch variations).
- AC-dipole in RHIC for FY03 and beyond provides means of reversing polarization of stored bunches.

RHIC Luminosity for FY02 Polarized pp Run



Good News…

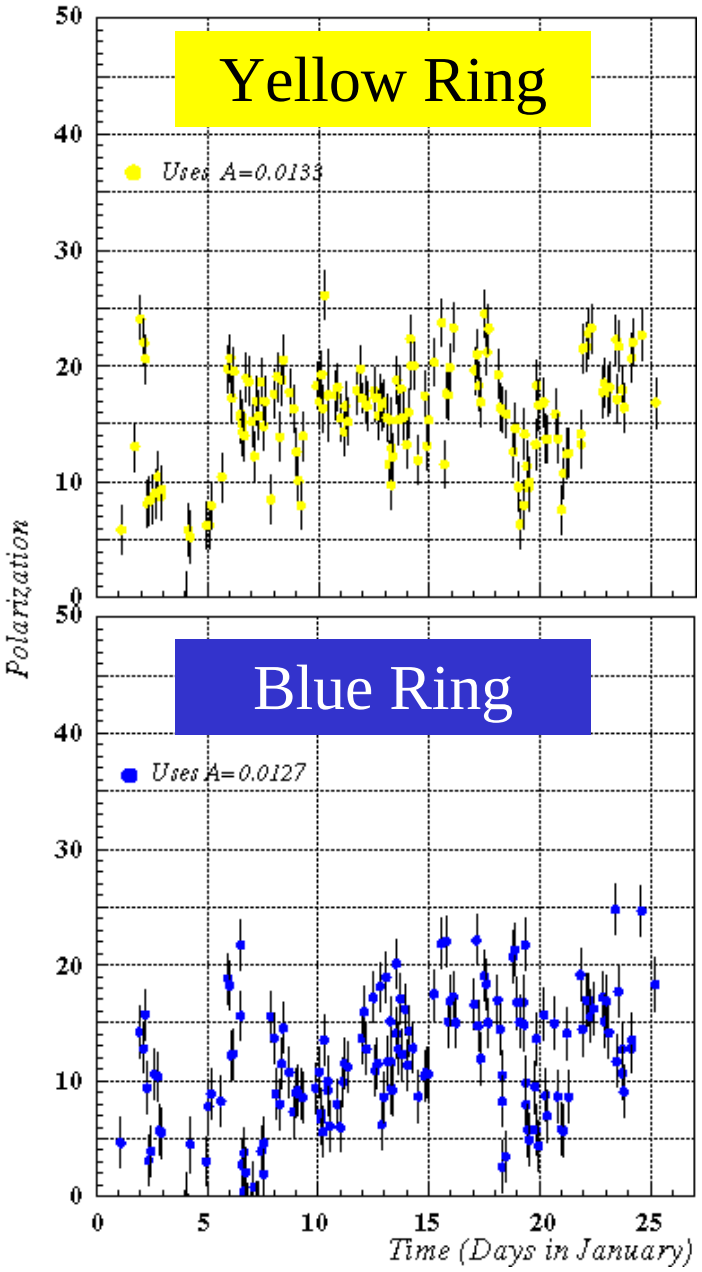
- RHIC can deliver 10^{30} $cm^{-2}s^{-1}$.
- 110 bunches and β^*=1m possible.

$\Rightarrow$ order of magnitude increase

Not so good news…

- Maximum luminosity in FY02 is ~80x smaller than needed for γ+jet probe of ΔG.
- Up time averaged over FY02 run only ~30%.

RHIC Polarization at 100 GeV/c in FY02



Good News…

- First polarized beams at high energy.
- First polarized collider.

Not so good news…

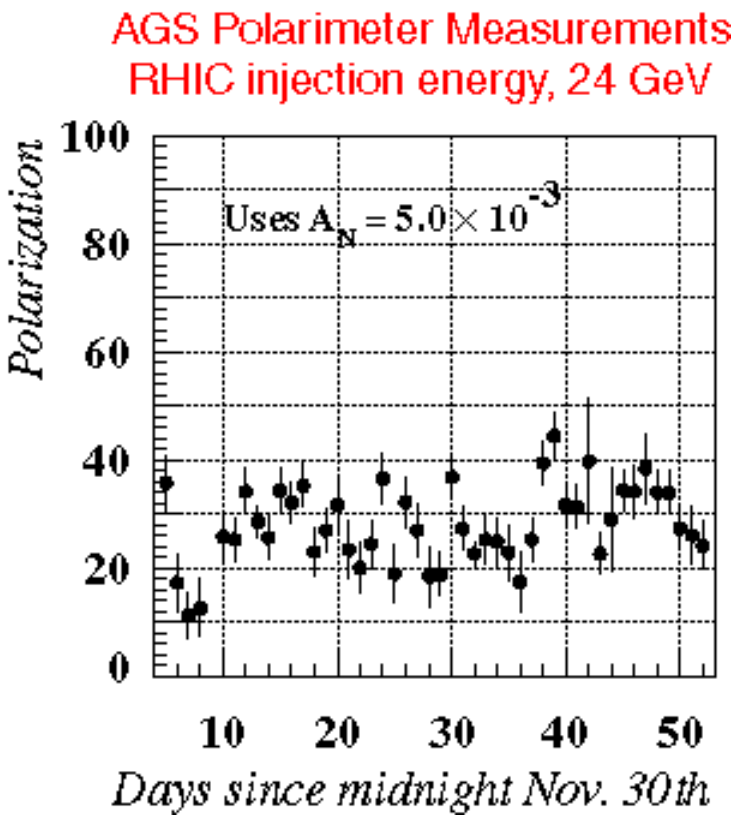
- Beam polarization lower than expected.

  ⇒ increased sensitivity to systematic errors
- Polarization magnitude not measured.

  ⇒ deceleration ramp required.
- Evidence for systematic errors in polarimeter.

Data compilation: R. Cadman (ANL), B. Surrow (BNL)

Why was the polarization so small?



- AGS dedicated to polarization tuning from the mid-November.
- Failure of Siemens motor generator for AGS reduced ramp rate by $\times$ 2, increasing depolarizing resonance strengths by $\times$2.

Data compilation: H. Spinka (ANL), R. Cadman (ANL), B. Surrow (BNL)

Future Expectations of RHIC for Spin

- FY03: luminosity **L** ~ 10^{31} cm^{-2} s^{-1} at $\sqrt{s}$ = 200 GeV, polarization P ~ 40%

  New equipment: spin rotator magnets at STAR and PHENIX

- FY04: further increase in luminosity contingent on understanding

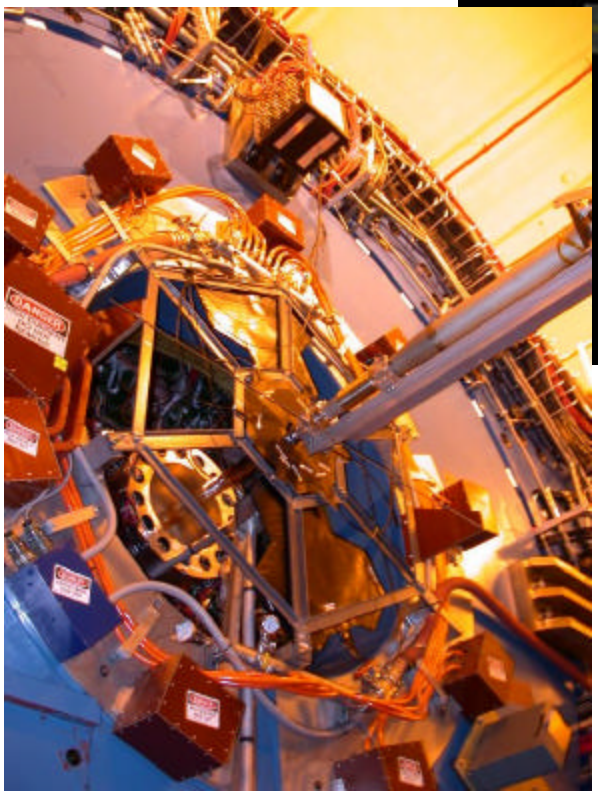
  New equipment: polarized gas jet target / begin polarimeter calibration

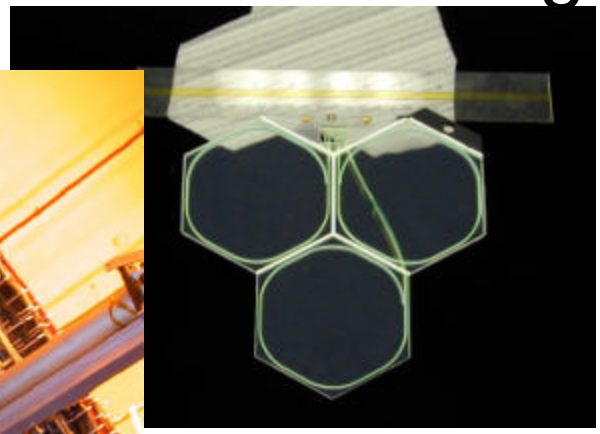
- FY05: luminosity **L** ~ 8×10^{31} cm^{-2} s^{-1} at $\sqrt{s}$ = 200 GeV, polarization P ~ 70%

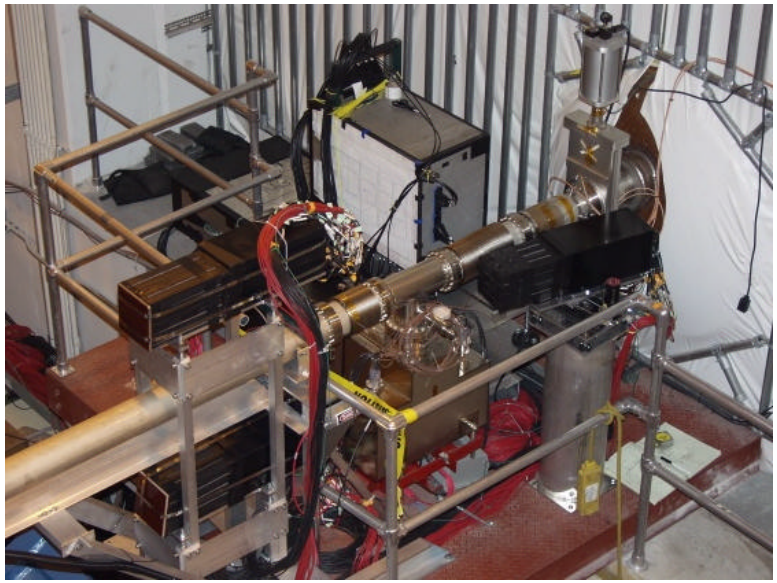
  New equipment: strong snake for AGS / final polarimeter calibration

- and beyond: luminosity **L** ~ 2×10^{32} cm^{-2} s^{-1} at $\sqrt{s}$ = 500 GeV, polarization P ~ 70%

STAR Commissioning for Spin in FY02







STAR Forward π^0 Detector (FPD)

STAR Beam-Beam Counters (BBC)

- trigger
- relative luminosity monitor

- Commission new detector systems

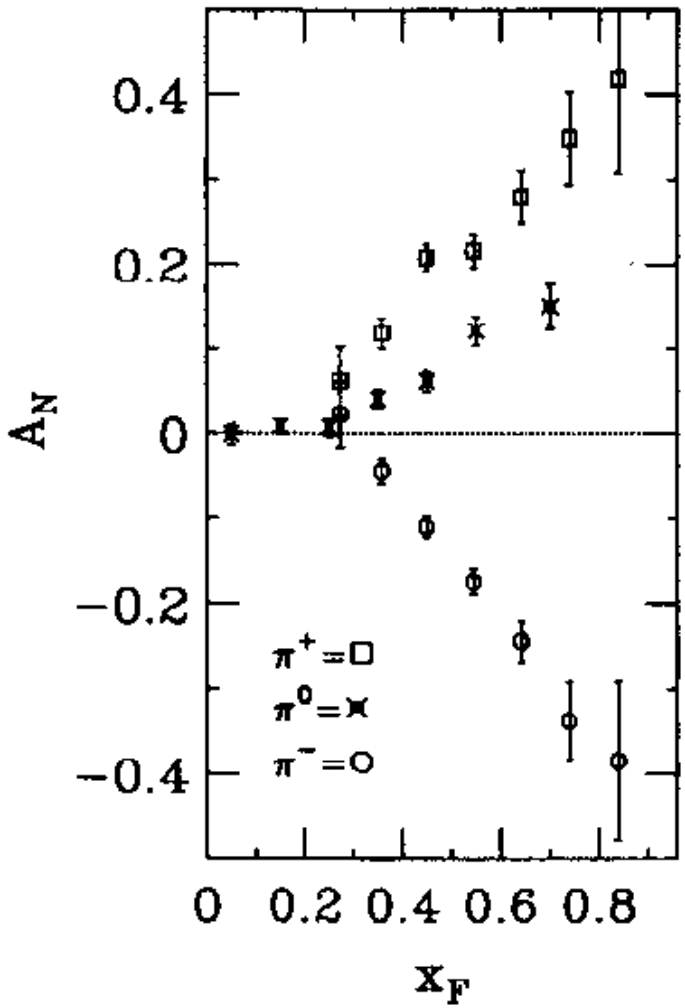
  BBC, barrel EMC, prototype FPD, …
- Commission triggers and high-rate DAQ
- Commission spin timing/bunch counters
- Commission scaler board system

STAR Run Summary / STAR Score Card

Polarized pp collision run at $\sqrt{s}$=200 GeV
12/20/01 – 1/24/02

Trigger type/physics	Goal	Achieved
• minimum bias triggers (Heavy-ion reference data, spin effects at mid-rapidity)	20M events	16M events
• Forward Pi0 Detector triggers (spin effects at x_F>0.2, p_T~1-4 GeV/c)	>0.5M events with P_{yellow}>30%	3.5M events with $<P_{yellow}>$~15%
• Barrel EMC high-tower triggers (Heavy-ion high-p_T reference data, spin effects at mid-rapidity)	2M events	0.8M events

Why Forward Pions?



π^0 - D.L. Adams, et al. Phys. Lett. B261 (1991) 201.

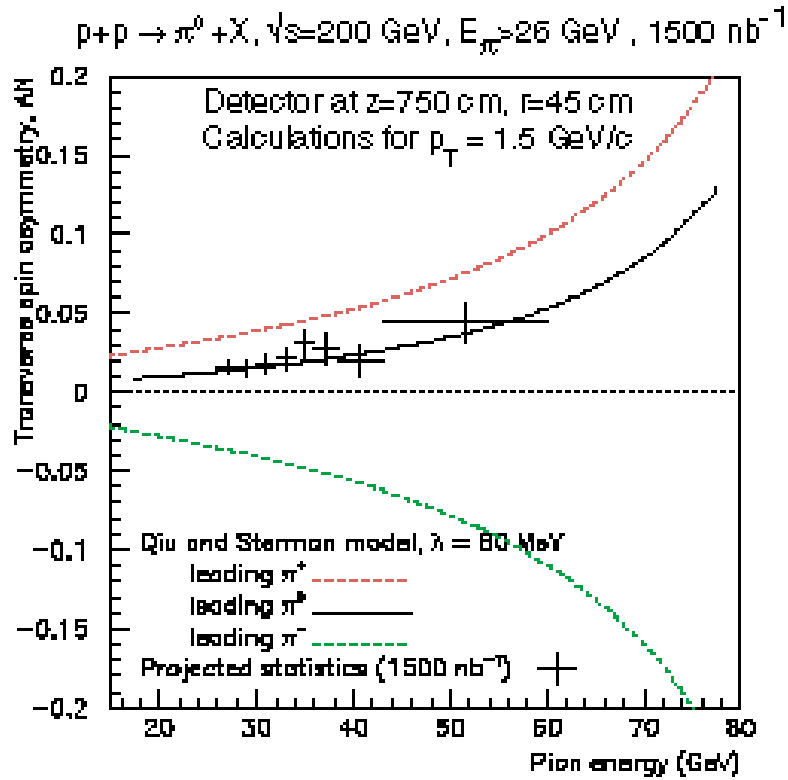
$\pi^\pm$ - D.L. Adams, et al. Phys. Lett. B264 (1991) 462

Non-zero values of A_N have been observed in FNAL E704…

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

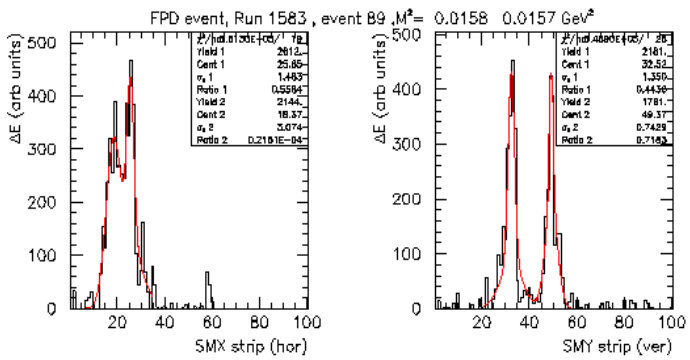
$$\sqrt{s} = 20 \text{ GeV}, \; 0.5 < p_T < 2.0 \text{ GeV/c}$$

Theoretical models that explain the E704 data also predict non-zero A_N for pion production at RHIC at $\sqrt{s}$ = 200 GeV (and may be related to transversity).



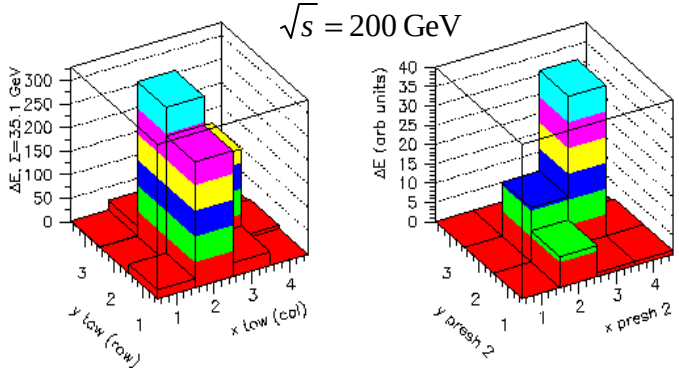
π^0-signal in Forward-Pion Detector (FPD)

- Transverse shower profile response of shower maximum detector:

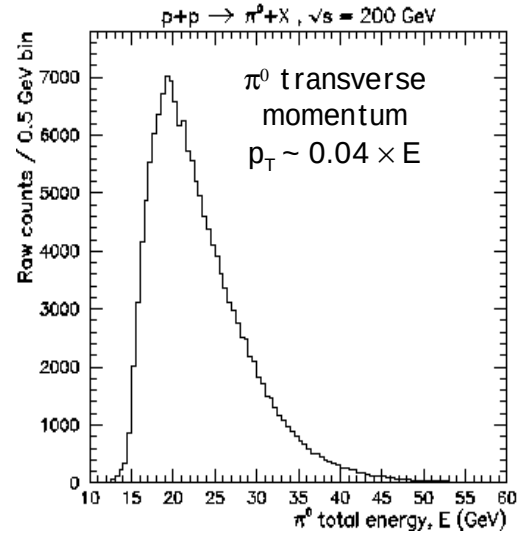


$\sqrt{s} = 200$ GeV

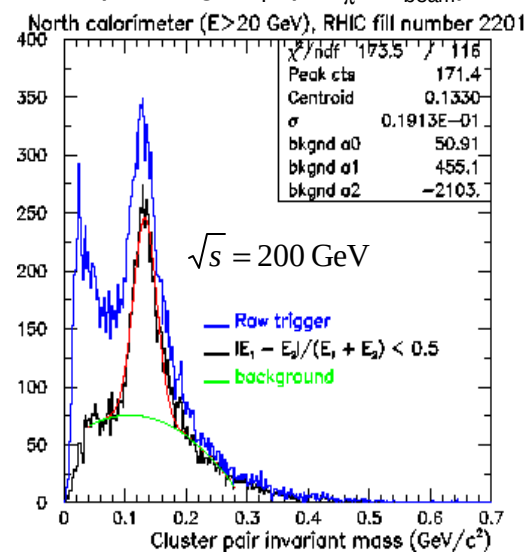
- Calorimeter and pre-shower detector response:



- Cluster separation in shower maximum detector and measured calorimeter energy serves as input to the π^0 mass determination!



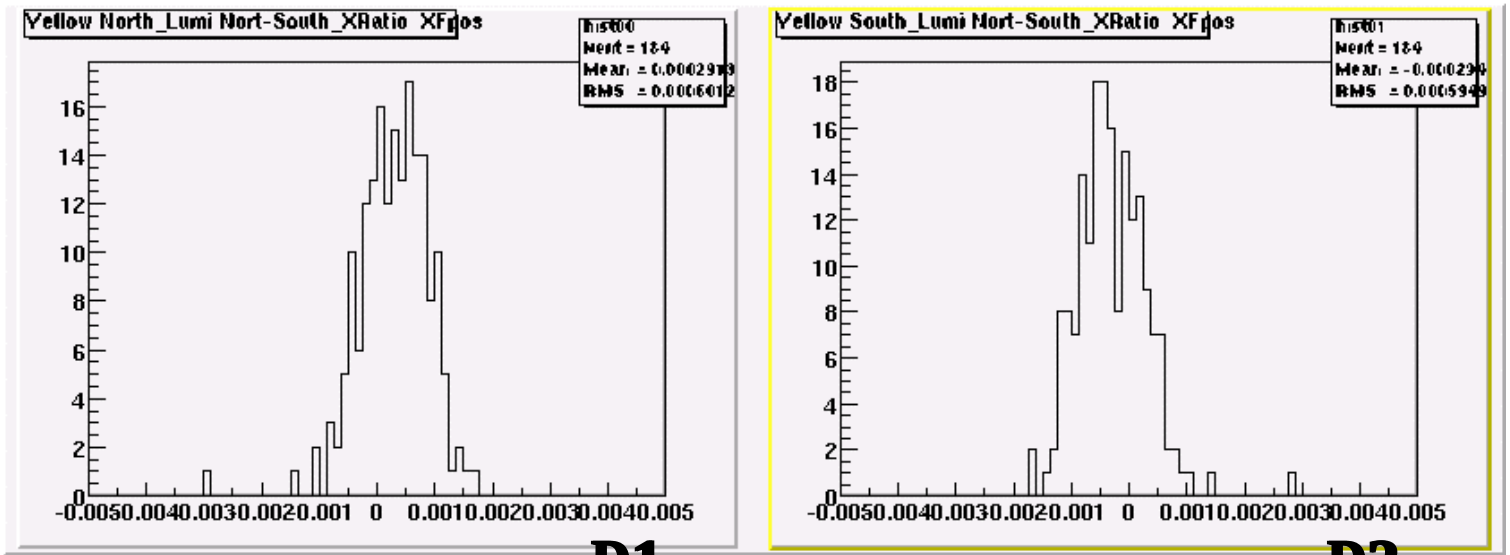
- π^0 mass determination up to 60 GeV ($\Rightarrow$ Large x_F ($\approx E_{\pi^0}/E_{beam}$)!



- Clearly identified π^0 mass peak!

- Single spin asymmetry calculated using counts from North/South BBC East detector,

- Comparison of 2 methods of single spin asymmetry calculation : ε_1 and ε_2 (North/South)



D1

$$\Delta 1 = \frac{\sqrt{N^{\uparrow}S^{\downarrow}} - \sqrt{N^{\downarrow}S^{\uparrow}}}{\sqrt{N^{\uparrow}S^{\downarrow}} + \sqrt{N^{\downarrow}S^{\uparrow}}} - \left(\frac{N^{\uparrow}/L^{\uparrow} - N^{\downarrow}/L^{\downarrow}}{N^{\uparrow}/L^{\uparrow} + N^{\downarrow}/L^{\downarrow}} \right)$$

D2

$$\Delta 2 = \frac{\sqrt{N^{\uparrow}S^{\downarrow}} - \sqrt{N^{\downarrow}S^{\uparrow}}}{\sqrt{N^{\uparrow}S^{\downarrow}} + \sqrt{N^{\downarrow}S^{\uparrow}}} - \left(\frac{S^{\uparrow}/L^{\uparrow} - S^{\downarrow}/L^{\downarrow}}{S^{\uparrow}/L^{\uparrow} + S^{\downarrow}/L^{\downarrow}} \right)$$

Conclusion: Relative luminosity known up to 10^{-3}

Results from the leading charged particle analysis (midrapidity, TPC) supports this conclusion.

J. Kiryluk, RSC 5/02

STAR Subsystems for Spin

- barrel electromagnetic calorimeter + shower maximum detector + preshower detector

  $\Rightarrow$ trigger and energy measurement for high p_T π^0 (η^0), jets, γ, $e^{\pm}$ at mid-rapidity

  – 50% completed by FY03 run; fully completed by FY05 run

- endcap EMC + shower maximum detector + pre/post shower detectors

  $\Rightarrow$ see above, but for $1<\eta<2$ $\Rightarrow$ asymmetric partonic collisions ($\Rightarrow$ ΔG at small x)

  – 4/12 sector commissioning in FY03 run; fully completed by FY05 run

- beam-beam counter

  $\Rightarrow$ required for discriminating beam-gas background from collisions + relative **L** monitor

  – complete for FY03 run

- Forward π^0 detector

  $\Rightarrow$ study E-704 effect at RHIC energies + low-x gluons in Au + local polarimeter

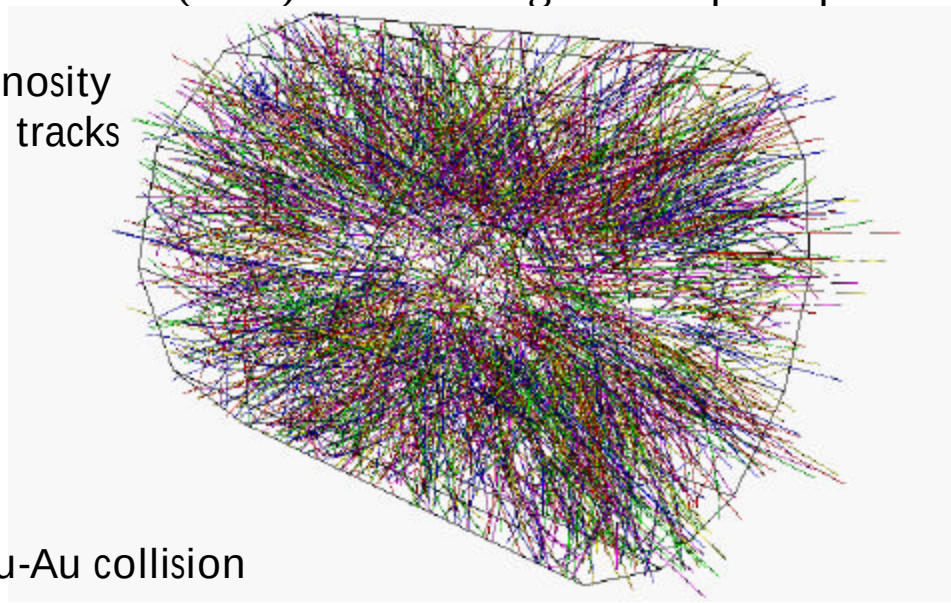
  – partial implementation for FY03 run?

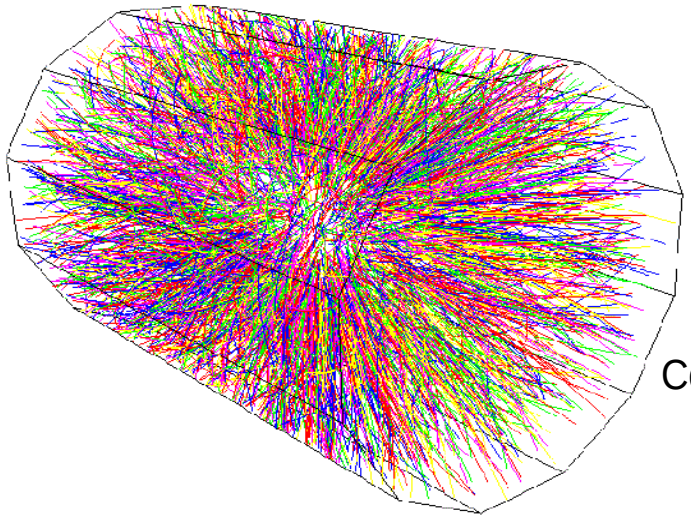
  – complete for FY04 run?

Challenges for STAR spin

- Slow drift of electrons in Time Projection Chamber (TPC) results in significant pile up.

pp collision at highest luminosity
with pile up events ~4000 tracks





Central Au-Au collision

- Can the TPC discriminate charged lepton daughters from $W^{\pm}$ decay (e^{+} from e^{-}) at p_T~40 GeV/c, particularly in the region of the endcap EMC ($\eta > 1$)?

$\Rightarrow$ stronger magnetic field to help mid-rapidity tracking

$\Rightarrow$ supplement STAR with forward tracking

Summary
(STAR spin in the future)

- FY2003 RHIC run (as proposed by STAR spin PWG for beam-use request)
  - study E-704 effect at RHIC energies (prelude to spin rotator tuning)
  - first attempt at A_{LL} via mid-rapidity inclusive jet production
- FY2004 RHIC run
  - first probes of ΔG with γ and γ+jet
- FY2005 RHIC run
  - study $\Delta G(x)$ via γ+jet at $\sqrt{s}$=200 GeV
- FY2006, and beyond
  - probing flavor contributions to spin via $W^{\pm}$ production at $\sqrt{s}$=500 GeV
  - study small x gluons via γ+jet at $\sqrt{s}$=500 GeV