20 September 2003
Dubna Spin2003
G. Bunce

The RHIC Spin Program

Where are we?

Where are we going?

Goals of the RHIC Spin Program

Ref.: "Prospects for Spin Physics at RHIC",
Ann. Rev. Nuclear Part. Sci. 2000, 50:525-75
G. Bunce, N. Saito, J. Soffer, W. Vogelsang

Proton spin sum rule:

$\frac{1}{2} = \frac{1}{2}\Sigma(\Delta q + \Delta\bar{q}) + \Delta G + L$: 1980s-present: $\Sigma(\Delta q + \Delta\bar{q}) \approx \frac{1}{4}$

$\Delta q = q_+ - q_-$, $q = u, d, s, \ldots$; $\Delta G = g_+ - g_-$; $\int_0^1 dx$ assumed

Probe the spin structure of the proton using pQCD

---using polarized quarks (and gluons ?)

===> gluon polarization (γ, jets, c, b)

===> transversity/orbital ang. momentum/
quark-gluon correlations in proton

---using parity-violating $W^{+/-}$ production

===> u, dbar, d, ubar polarization in proton

Searches for surprises using parity violation

---sensitivity to right-handed Zs; quark substructure; ...

Study elastic p+p for first time to $\sqrt{s} = 500$ with spin

— σ, A_N, A_{NN} from coulomb-nuclear interference to medium t

Spin-RHIC At a Glance

$\sqrt{s} = 500$
$L = 2 \times 10^{32}$ } high p_T

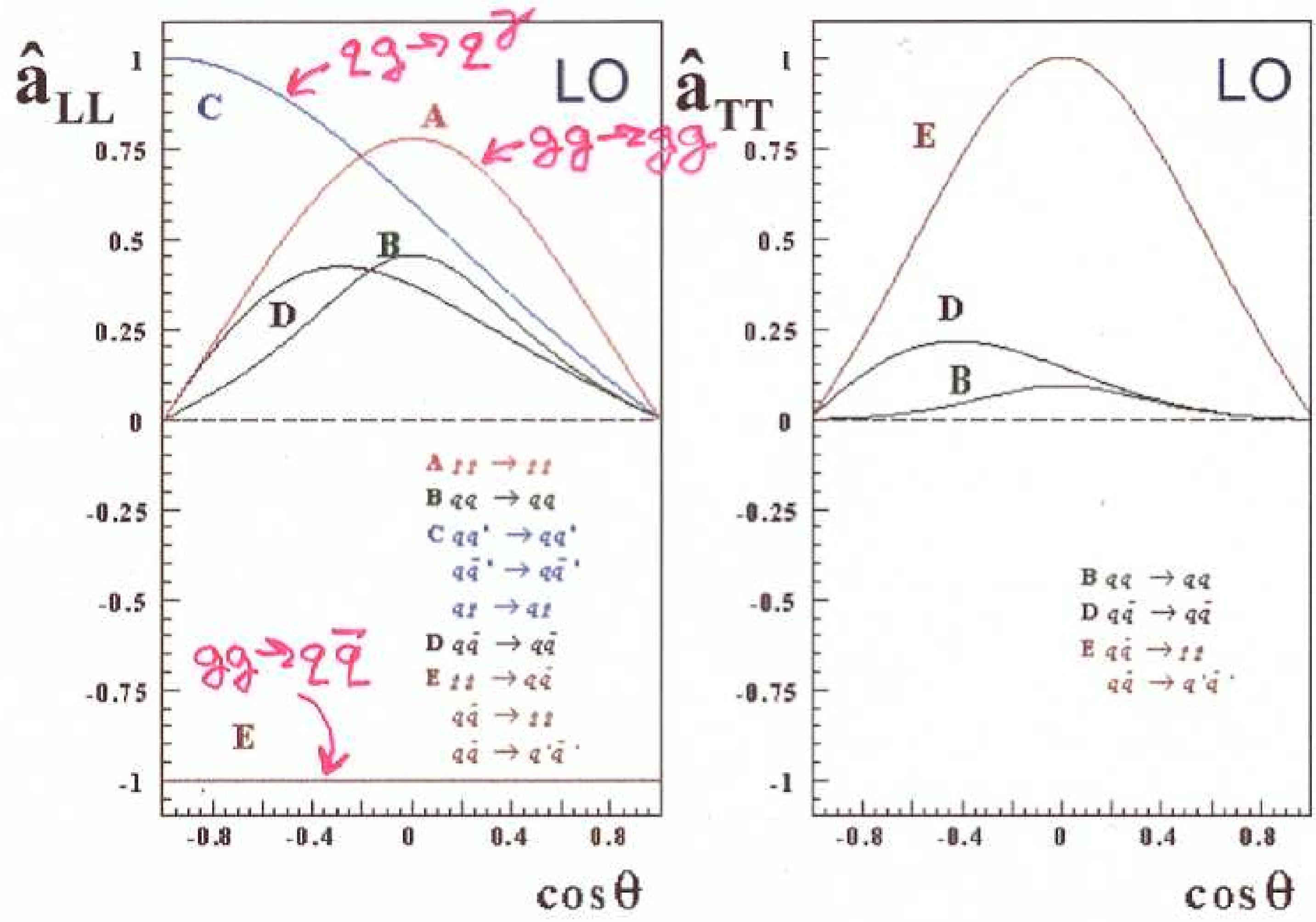
Pol. = 70% each beam
Yale / SLAC / EMC DIS } beams of polarized quarks ($x \gtrsim .1$)

Factorization ⇒ $A_{LL} \sim \frac{\Delta a}{a} \frac{\Delta b}{b} \hat{a}(a+b \to c+d)$

pQCD, helicity conservation } subprocess analyzing power ($\hat{a}$) often large

∴ We can measure parton asymmetries in a polarized proton. Different processes will give different combinations of partons ⇒ we can separate the factors, giving $\Delta a/a$, $\Delta b/b$, $\hat{a}$ and self-consistency checks.

LO pQCD partonic level asymmetries

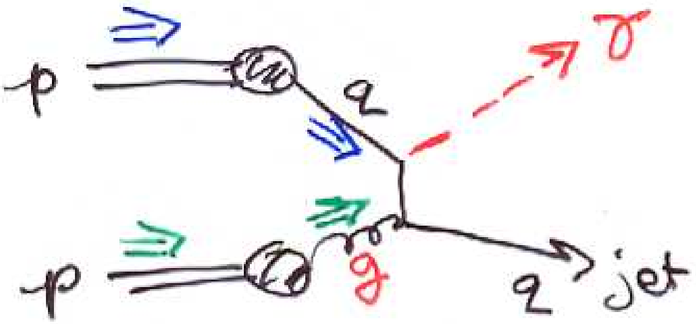


NLO corrections are now known for all relevant reactions

RHIC Spin Probes

Gluon polarization:

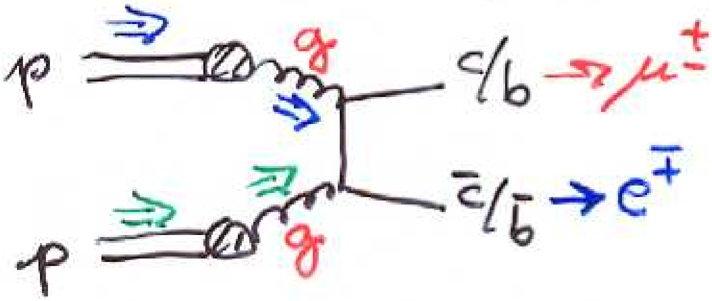
$$A_{LL} = \frac{1}{P^2} \frac{N_{++}(\gamma) - N_{+-}(\gamma)}{N_{++} + N_{+-}}$$



$$A_{LL} = \frac{\Delta G}{G}(x_g)\, A_1^p(x_q)\, \hat{a}_{LL}$$

(.3) (.6)

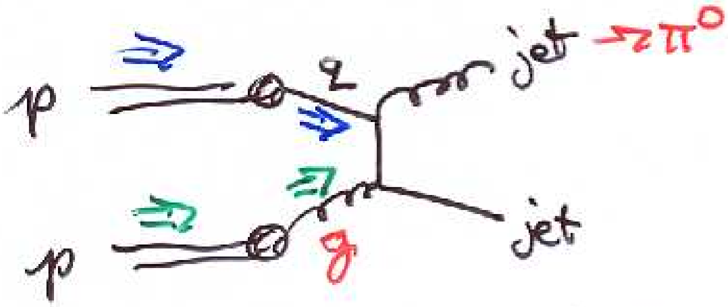
$$\simeq \frac{1}{5} \frac{\Delta G}{G}(x_g)$$



$$A_{LL} = \frac{\Delta G}{G}(x_1) \frac{\Delta G}{G}(x_2)\, \hat{a}_{LL}$$

(.5?) (.15)

$$\overset{?}{\simeq} \frac{1}{12} \frac{\Delta G}{G}(x_1)$$



$$A_{LL} = \frac{\Delta G}{G}(x_1) \frac{\Delta u}{u}(x_2)\, \hat{a}_{LL}$$

(.4) (.6)

$$\simeq \frac{1}{4} \frac{\Delta G}{G}(x_1)$$

$+\, gg \to gg / q\bar{q}$

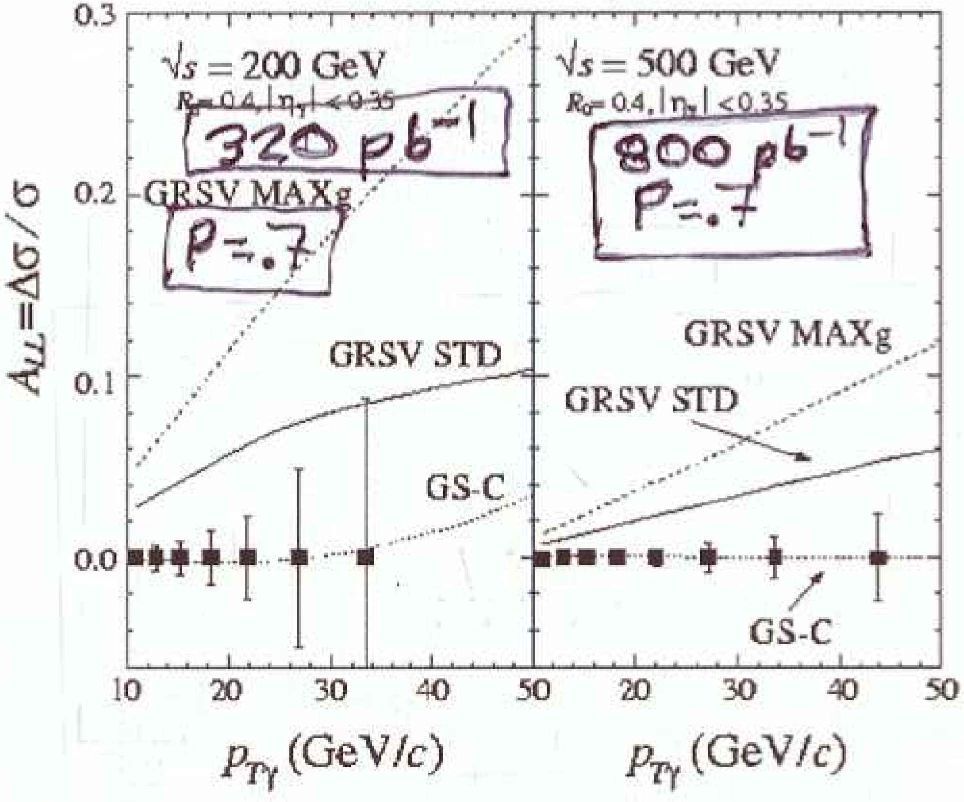
also J/Ψ (but production mechanism)

Prompt photon measurement

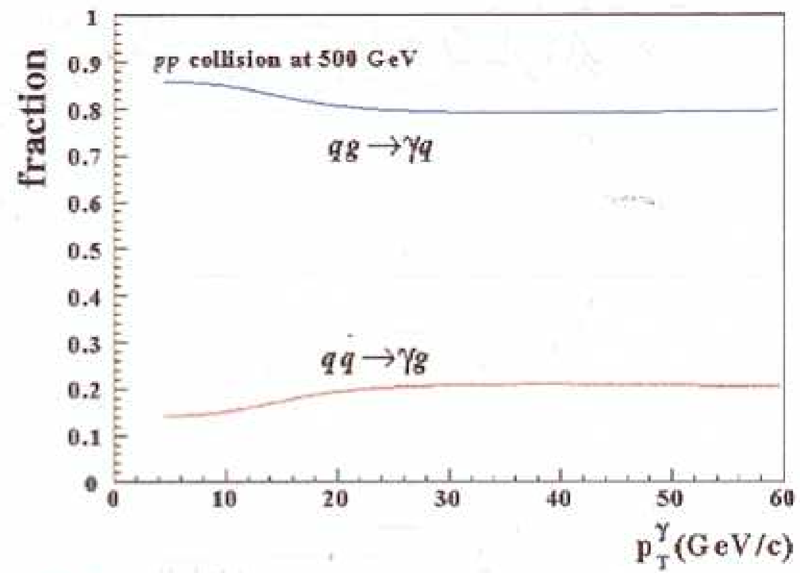
Prompt photon

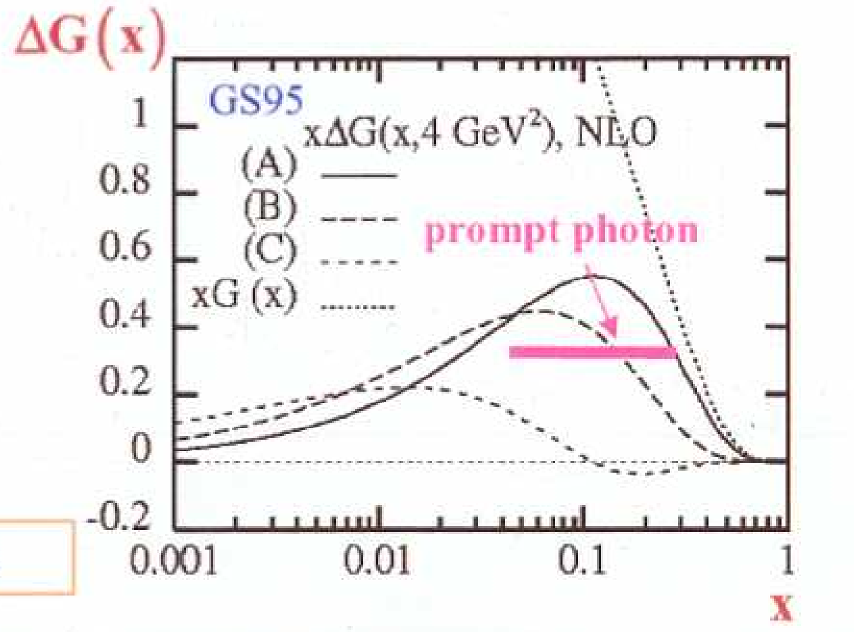
» clear interpretation

- gluon Compton process dominant



statistics with full design luminosity and polarization

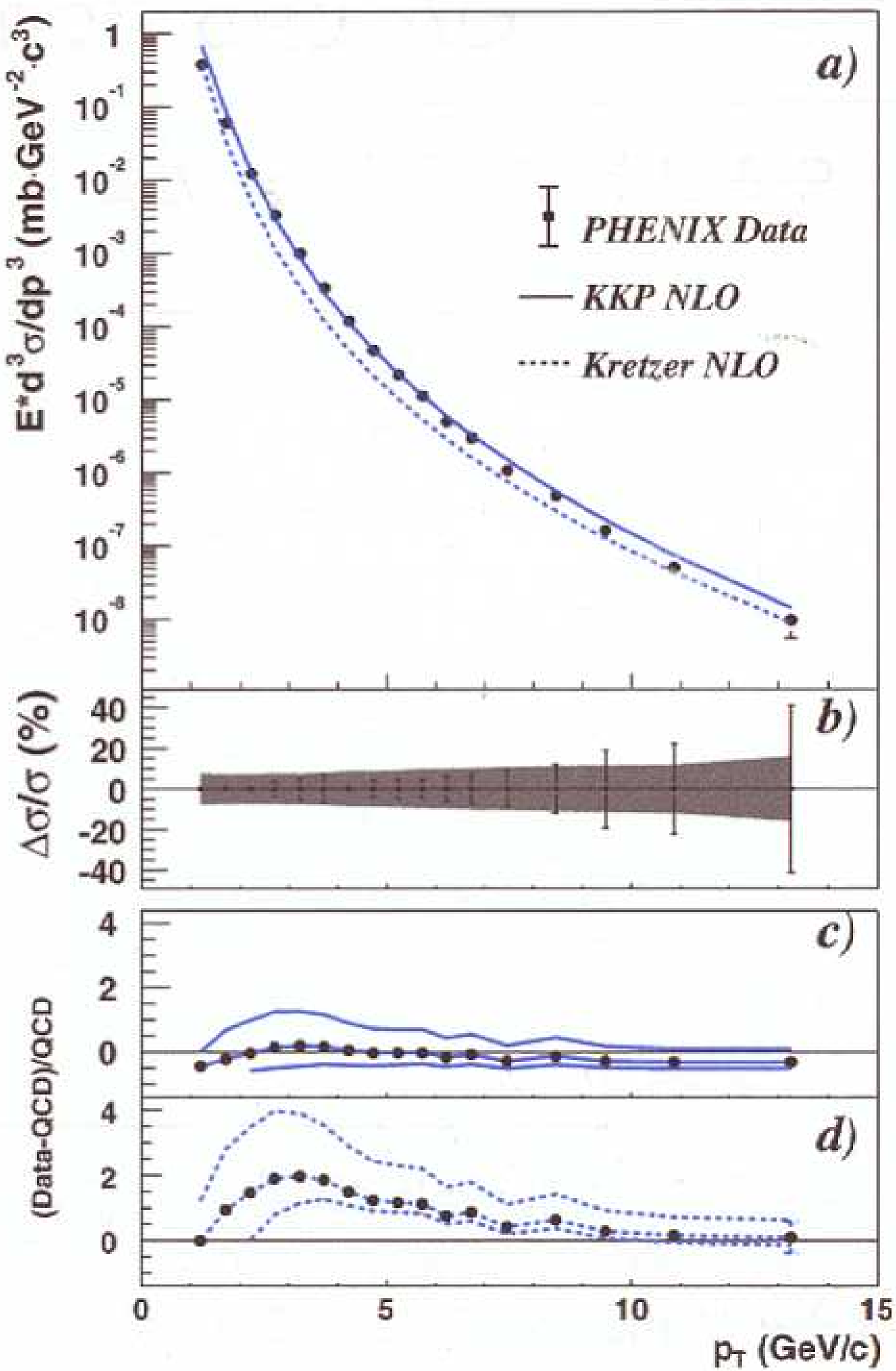




PHENIX

π^0 Cross Section

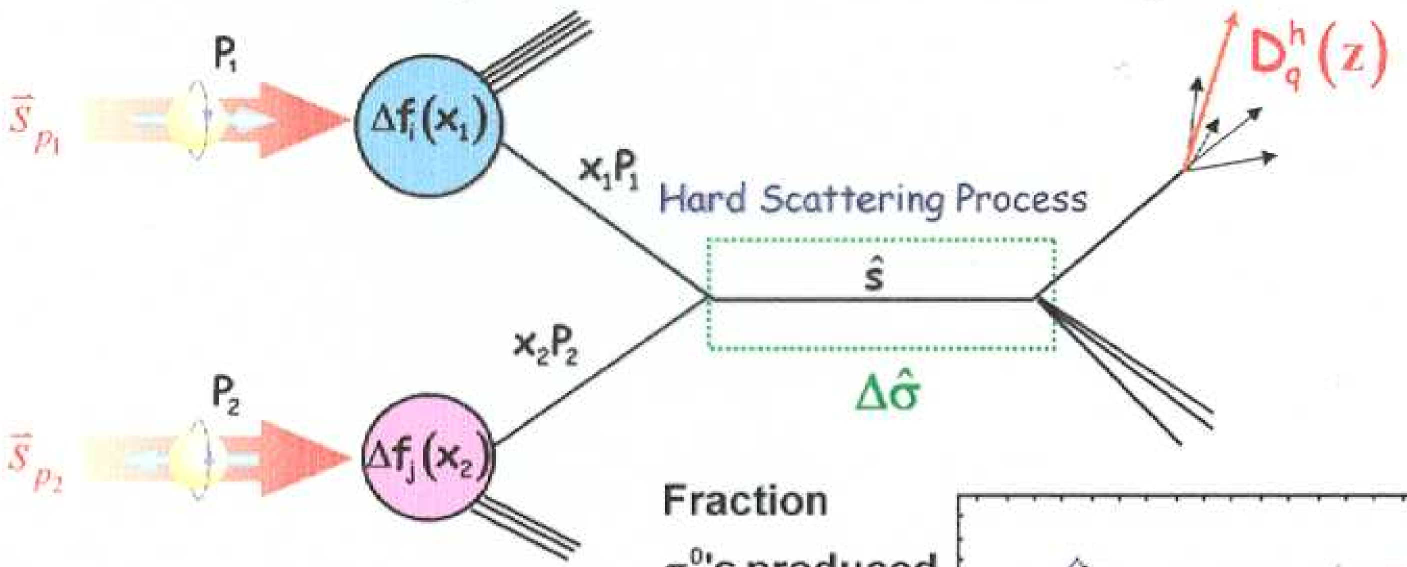
- The data covers over 8 order of magnitude
  - by combining minimum bias trigger and EMCal trigger data
- NLO pQCD calculation is consistent with data
  - CTEQ5M PDF + KKP FF



H. Torii, Kyoto University
B. Fox (BNL), SPIN 2002

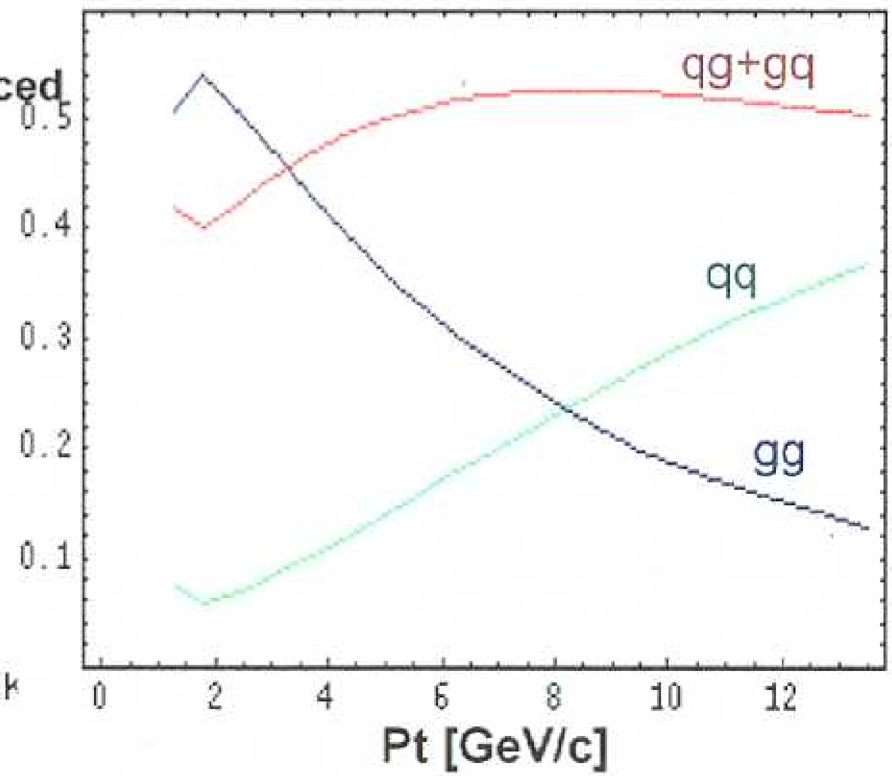
submitted to PRL, hep-ex/0304038

Leading hadrons as jet tags



$gg \to gg$ $\quad$ $gq \to gq$ $\quad$ $qq \to qq$

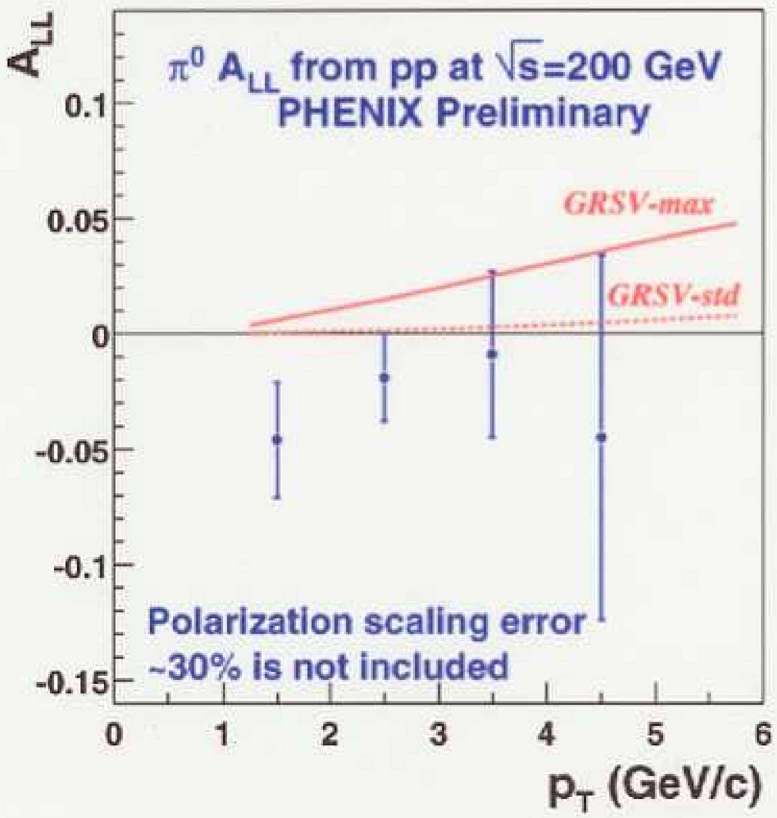
$\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$ $\quad$ $\propto \frac{\Delta q}{q}\frac{\Delta G}{G}$ $\quad$ $\propto \frac{\Delta q}{q}\frac{\Delta q}{q}$



2003/09/17 SPIN03 $\quad$ Atsushi Taketani RIk

A_{LL}: PHENIX vs theory

B.Jäger e al., PRD67, 054005 (2003)



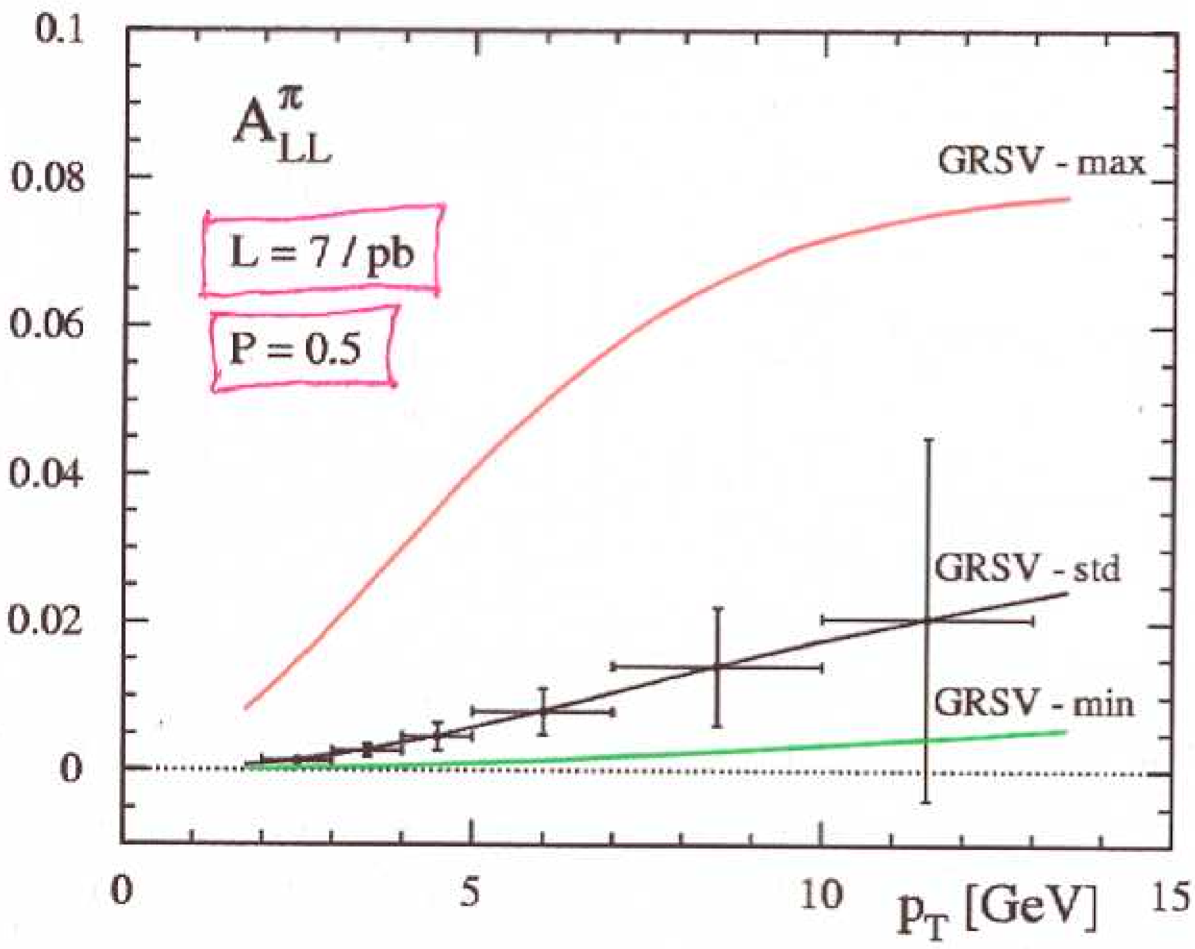
$P = .26$

$\int L\,dt = .2\ pb^{-1}$

PHENIX

π^0 Production and ΔG

π^0 can be used to determine ΔG with limited L & P



Jager, Schafer, Stratmann, Vogelsang

Parity Violation in W^+ Production

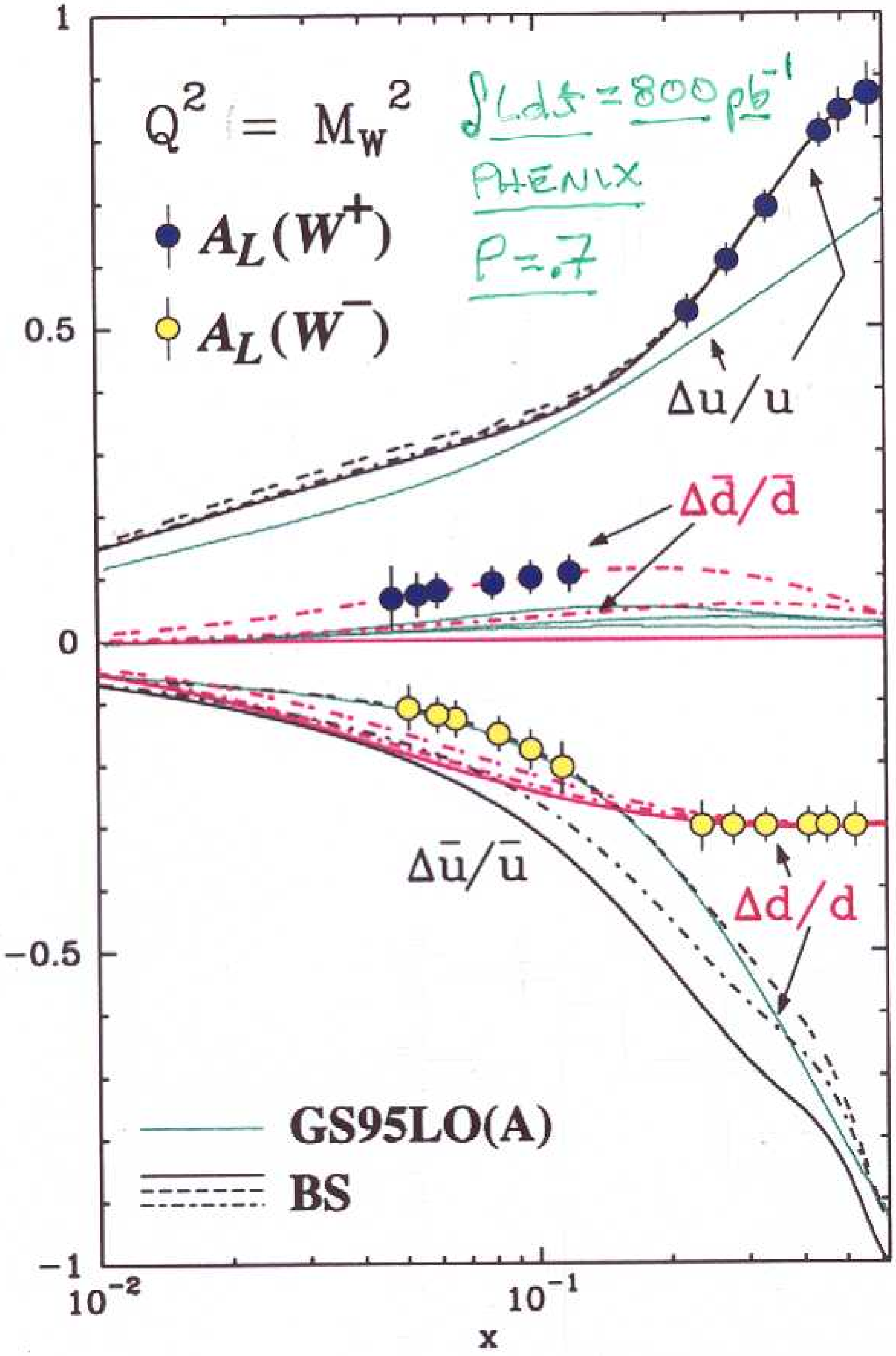
One beam is longitudinally polarized : $A_L = \frac{1}{Pol.} \frac{N_+ - N_-}{N_+ + N_-}$

- if W^+ is produced to $+y \Rightarrow$ large x_1, small x_2
  u $\bar{d}$

- but proton 1 is polarized $\Rightarrow$
  u quark is polarized and
  $A_L(+y) = \frac{\Delta u}{u}$

- if W^+ is produced to $-y \Rightarrow$ small x_1, large x_2
  $\bar{d}$ u

- proton 1 is polarized $\Rightarrow$
  $\bar{d}$ is polarized and
  $A_L(-y) = \frac{\Delta \bar{d}}{\bar{d}}$



courtesy of Jacques Soffer & Claude Bourrely

Physics and Requirements

$\Delta G/G(x)$:

- with π/jets → **1–10 pb^{-1}, $P \geq .4$**
  - → π/jets are the most sensitive probe of $\Delta G/G(x)$, measurements come early in RHIC spin program
  - for non-zero result → measure $A_{TT}(\pi/\text{jets})$
    - → if $A_{LL} \neq 0$ due to gluons, then $A_{TT} << A_{LL}$
- with direct γ → **300 pb^{-1}, $P = .7$**
  - $\dfrac{\text{signal}}{\text{background}} = \dfrac{qg \to \gamma q}{q\bar{q} \to \gamma g} \approx 4$
  - → γ is the most precise probe of $\Delta G/G(x)$, measurements come later in RHIC spin program

$\Delta\bar{u}/\bar{u}$, $\Delta\bar{d}/\bar{d}$:

- $W^{\pm}$: **$\sqrt{s} = 500$ GeV, 800 pb^{-1}, $P > .5$**
  - → later in RHIC spin program

Where are we <u>now</u>?

$\sqrt{s} = 200$ GeV, $P = .2$ to $.3$,

$L = 4 \times 10^{30}\ cm^{-2} s^{-1}$

$\int L\,dt \approx .5\ pb^{-1}$

A long way to go:

$\sqrt{s} = 200$ GeV, $P = .7$ (×3)

$L = 8 \times 10^{31}\ cm^{-2} s^{-1}$ (×20)

$\int L\,dt = 300\ pb^{-1}$ (×600)

$\sqrt{s} = 500$ GeV, $P = .7$ (not tried yet)

$L = 2 \times 10^{32}\ cm^{-2} s^{-1}$

$\int L\,dt = 800\ pb^{-1}$

Figure of merit:

$$\Delta A_{LL} = \pm \frac{1}{P^2 \sqrt{\int L\,dt} \times \left(\frac{\text{expt. yield}}{\int L\,dt}\right)^{1/2}}$$

$$F.O.M. = P^2 \sqrt{\int L\,dt}$$ → need × 250 for direct γ probe of $\Delta G / G$

However: even with low L and low P, from the short runs in 2002 and 2003:

- first acceleration to high energy (100 GeV) using Siberian Snakes
- routine measurement of polarization to ±3% with newly invented proton-carbon polarimeters (measurements in 1 minute)
- and the physics:

---

at $\sqrt{s}=200$

- very forward neutron $A_N = -.1$
- forward charged particles $A_N = +.006$
- forward π^0 $A_N = +.2$ (!)
- first measurement of $A_{LL}(\pi^0)$, $\eta = 0$ presented here
- measurements of $A_{LL}(\pi^0)$, forward rapidity and A_{LL}(jets), mid-rapidity still to come from 2003 data

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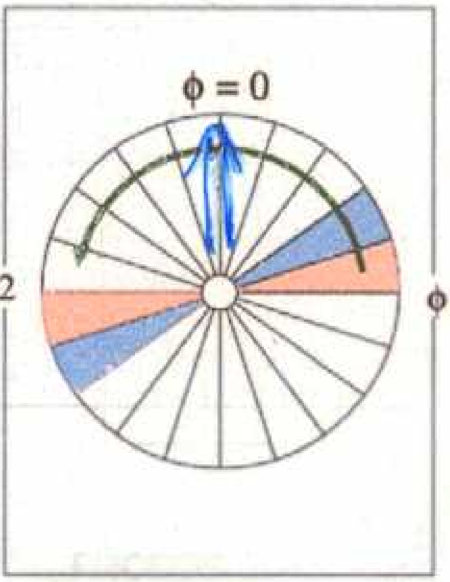
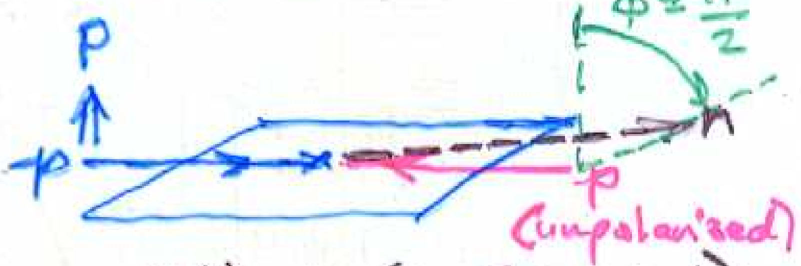
⇒ the signals point to a rich physics harvest at high energy using protons as probes

Neutron Asymmetry
φ distribution

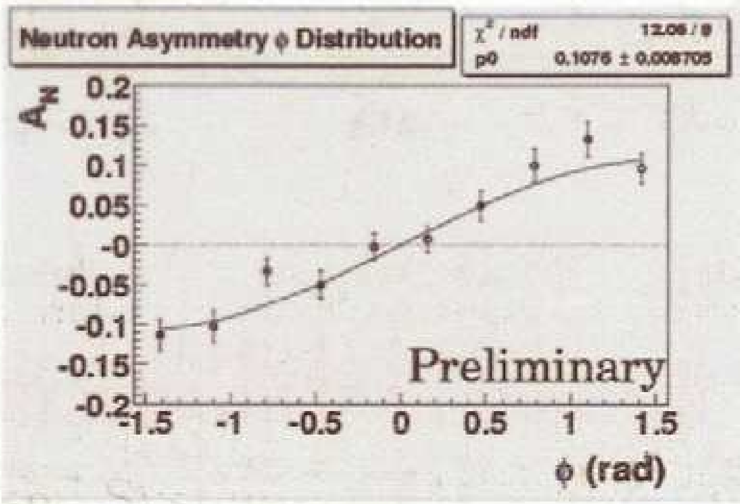




$$N(\phi) = N_0 (1 + P A_N \sin\phi)$$

square root formula is used for φ dependent asymmetry (for example red area, blue area)

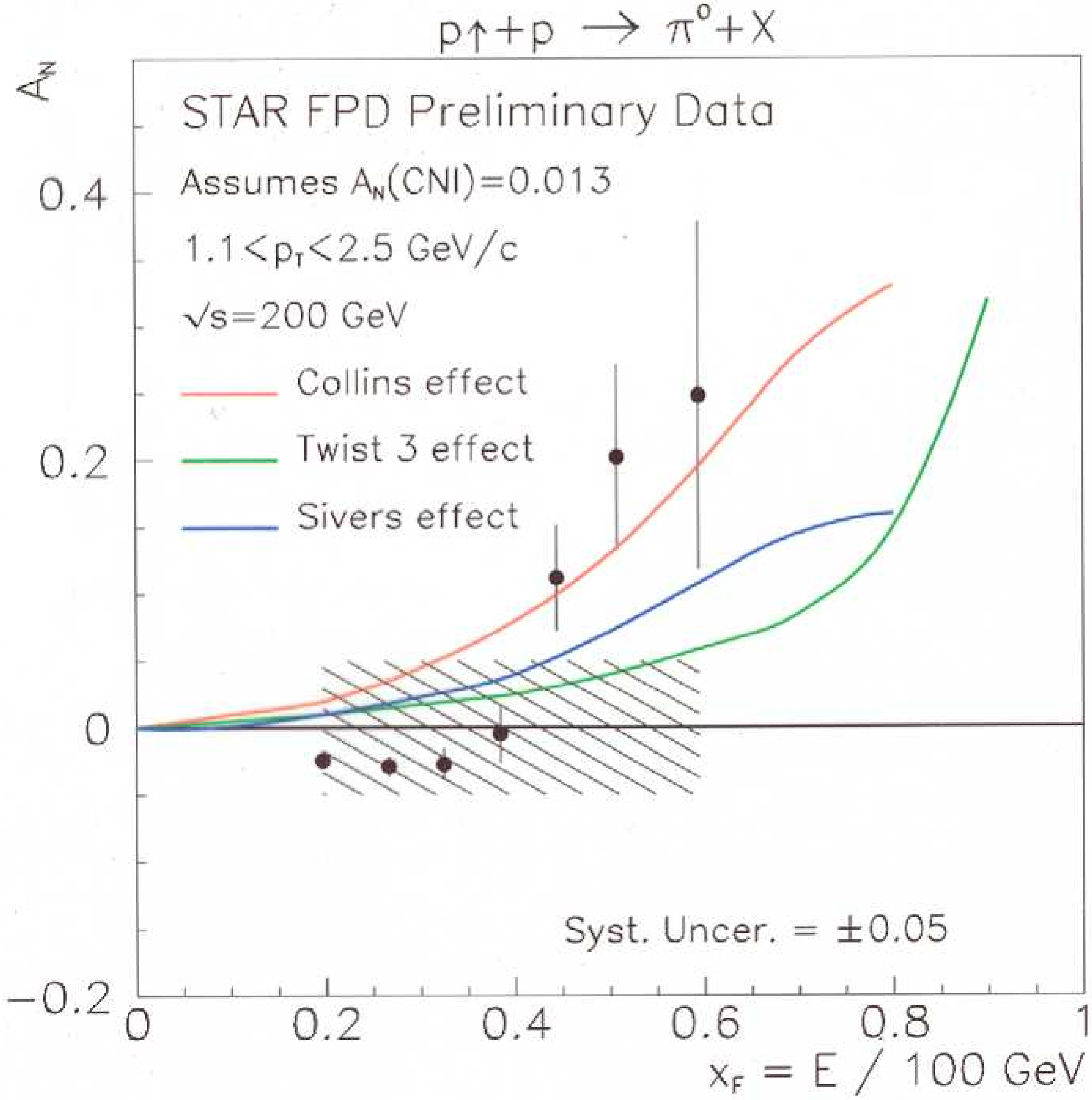
EM Calorimeter



$\langle A_N \rangle = -0.108 \pm 0.0087$
additional scale-error

φ-dependence is consistent with sin φ

$$A_N = \frac{1}{P_{Yellow}} \times \frac{N_{\Uparrow}(\pi^0, \text{left})/L_{\Uparrow} - N_{\Downarrow}(\pi^0, \text{left})/L_{\Downarrow}}{N_{\Uparrow}(\pi^0, \text{left})/L_{\Uparrow} + N_{\Downarrow}(\pi^0, \text{left})/L_{\Downarrow}}$$



How do we get there (full L, P) and when?

1. $P = .25 \rightarrow P = .7$, $\sqrt{s} = 200$ GeV
2. $L = 4 \times 10^{30} \rightarrow L = 8 \times 10^{31}\ cm^{-2}s^{-1}$
3. $\sqrt{s} = 500$ GeV, $P = .7$

Polarization program: $P_{AGS}\Big|_{2003} = .4$

2004: – new helical snake for AGS
→ remove coupling resonances
→ $P_{AGS} \cong .5$

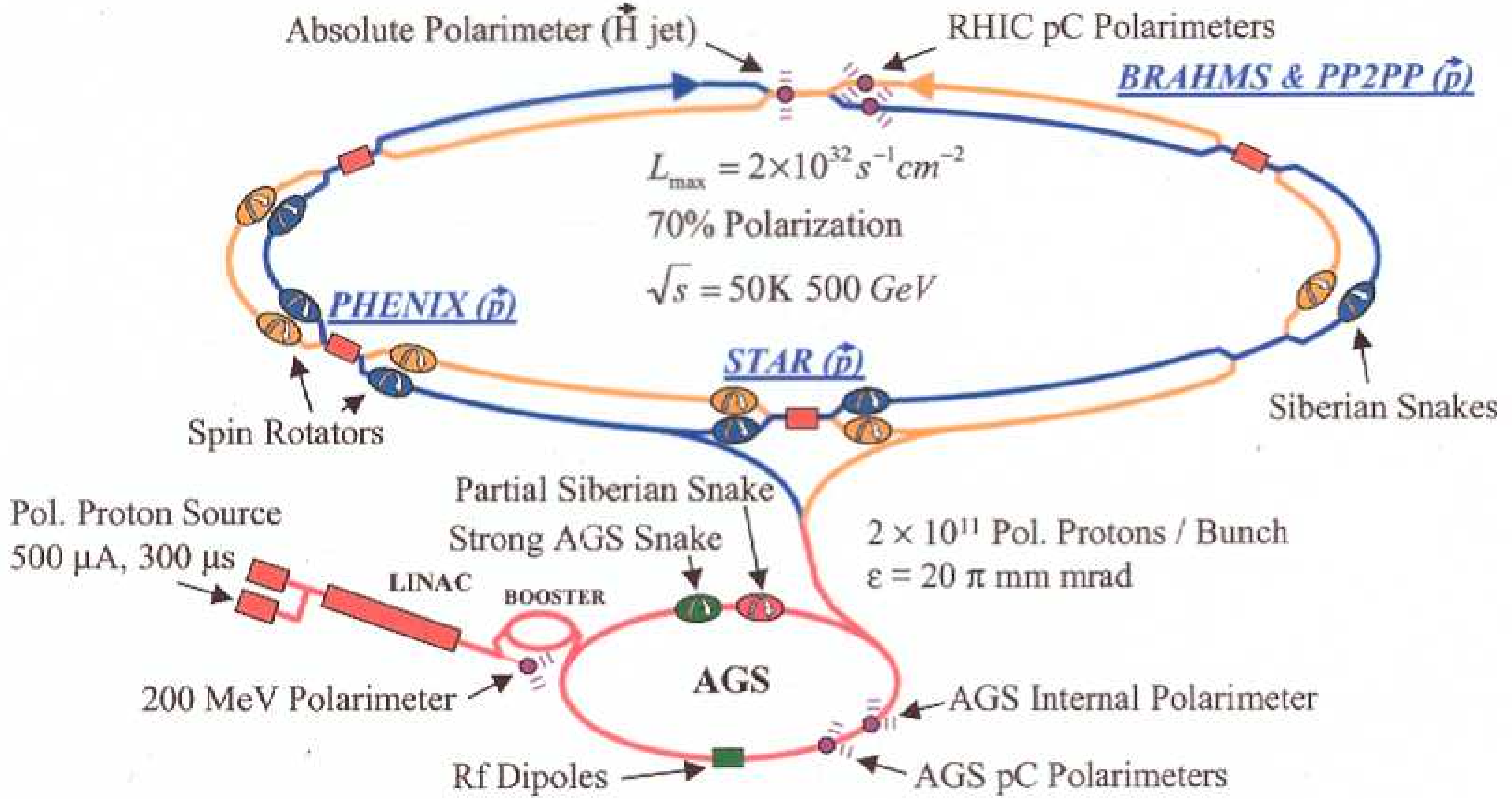
– control betatron tune in RHIC
→ $P_{RHIC} = .5$

2005: – high field snake for AGS
(also spin matching for AGS lattice)
→ development (with ramp measurements with polarimeters)

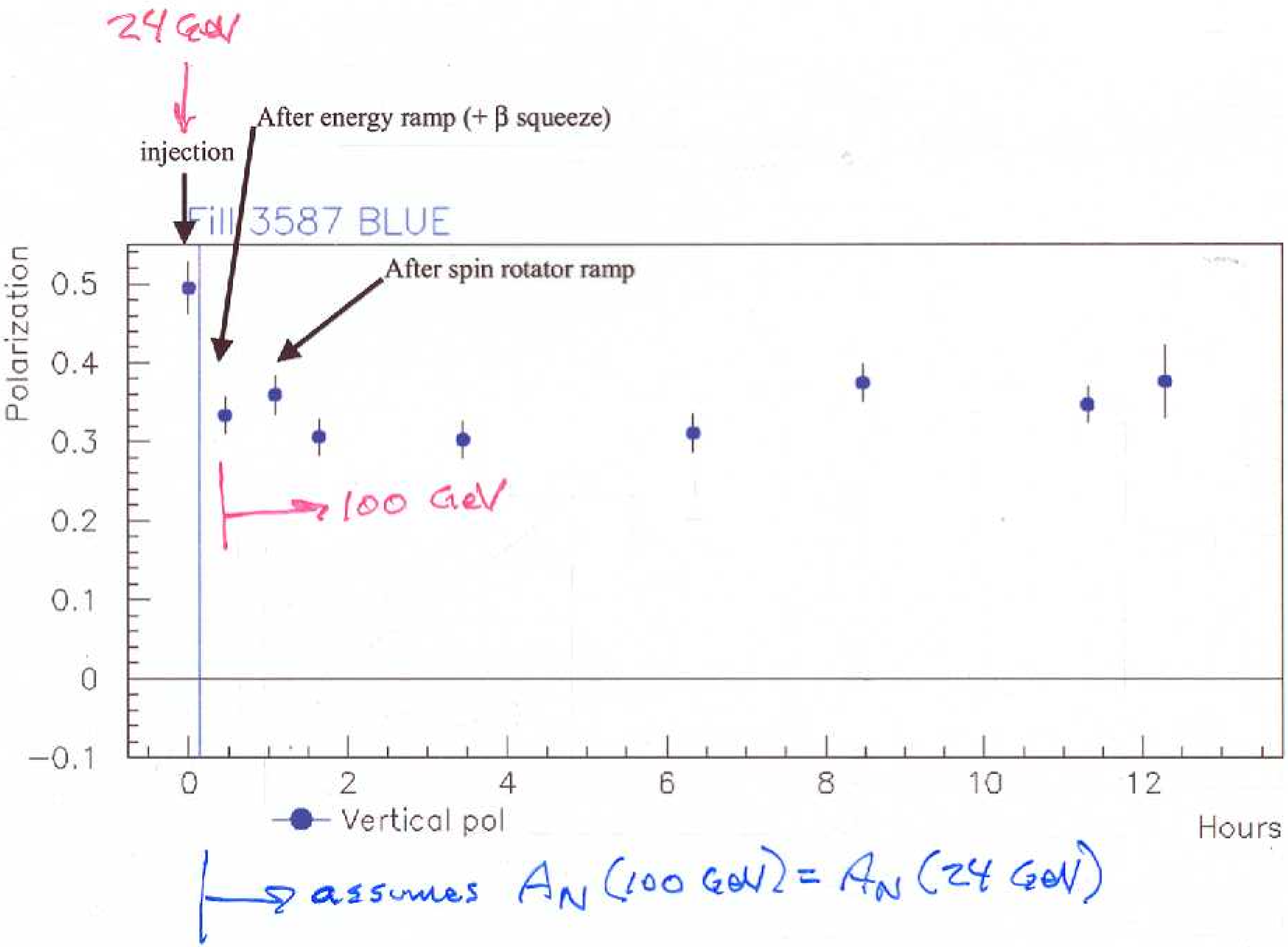
2006: **$P_{RHIC} = .7$ at $\sqrt{s} = 200$ GeV**

– also: $|P|$ to $\pm 5\%$ from new polarized jet in RHIC (2004-6)

Polarized Proton Collisions in RHIC



BROOKHAVEN NATIONAL LABORATORY


24 GeV
injection
After energy ramp (+ β squeeze)
Fill 3587 BLUE
After spin rotator ramp
Polarization
0.5
0.4
0.3
0.2
0.1
0
−0.1
100 GeV
0
2
4
6
8
10
12
Hours
Vertical pol
assumes A_N (100 GeV) = A_N (24 GeV)

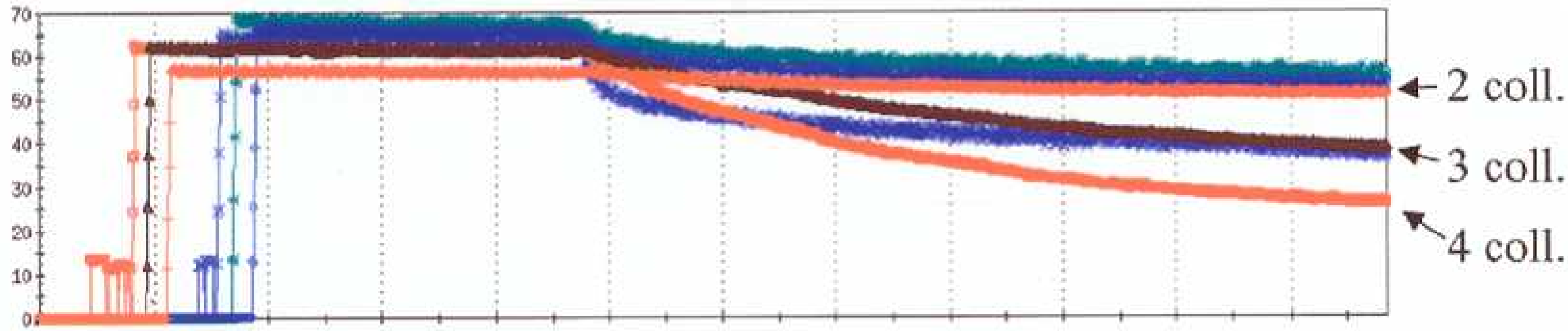
How do we get there and when?

Luminosity program: $L\big|_{2003} = 4 \times 10^{30}\ cm^{-2}s^{-1}$

- luminosity lifetime worse in 2003 for more collision locations (IRs)
  - ⇒ luminosity was limited by <u>beam-beam</u> electromagnetic interactions at IRs
  - ⇒ beam loss from betatron tune shift and tune spread (hit beam resonance)
    - → find new "working point"
      - betatron tune where we don't hit beam resonances from beam-beam tune shift <u>and</u> we don't hit spin resonances
    - → 2 candidates for new working points
    - → <u>develop</u> <u>in</u> <u>2004</u>

Luminosity Limitations (2)

- Electron multipacting (electron cloud)
  - Total charge per ring < 10^{13} e
    - Solenoids, scrubbing, NEG coating
- Beam-beam tune shift and spread
  - First strong-strong hadron collider (after ISR)
  - Limits high luminosity pp operation to two IRs
    - Non-linear corrections, better working point



- Intra-Beam Scattering (IBS)
  - Transverse and longitudinal emittance growth
  - Eventually will need electron cooling (see below)

Luminosity program (continue):

	now	goal	factor (L)
I/bunch	$.5 \times 10^{11}$	2×10^{11}	x16
N bunches	55	110	x2
efficiency RHIC	.2	.6	x3
$\int L\,dt$ /week	.5 pb^{-1}	20 pb^{-1}	x40
L $cm^{-2}s^{-1}$	4×10^{30}	8×10^{31}	x20
$\int L\,dt$ (200 GeV $\sqrt{s}$)	.5 pb^{-1}	300 pb^{-1}	x600

2002: first acceleration of pol. protons to 100 GeV → snakes work
$P = .15$ to $.2$, $L = 1.5 \times 10^{30}\,cm^{-2}s^{-1}$

2003: first collisions of longitudinally polarized protons → spin rotators ✓
$P = .25$ to $.3$, $L = 4 \times 10^{30}$

2004/5: new AGS snake, new β tune
$P \overset{?}{=} .5$, $L \overset{?}{=} 1.5 \times 10^{31}$ ($\sqrt{s} = 200$)

2006/7: high field AGS snake, new vacuum pumping in RHIC
→ $P = .7$, $L = 8 \times 10^{31}\,cm^{-2}s^{-1}$

The biggest hurdle:

<u>Running</u> <u>time</u>!

- for <u>both</u> heavy ions + spin
- presently RHIC scheduled for <u>27</u> <u>cryo</u> weeks/year

$\Rightarrow \sim 19$ physics weeks.

That said, our physics goals:

2004/5: with $P = .25 \rightarrow .5$

$L = 4 \times 10^{30} \rightarrow 1.5 \times 10^{31}$

$$\Delta A_{LL}\Big|_{2004} \Big/ \Delta A_{LL}\Big|_{2003} \approx \frac{1}{8}$$

- for π^0/jets: (note: ΔA_N improves by factor 4)

A_{LL}, A_N (also $\pi^{+/-}$), A_{TT}

2006/7:

- direct γ physics (+ jets)
- develop acceleration to 250 GeV with $P = .7$

2008/9: $W^{\pm}$ parity violating production

- $\Delta\bar{u}/u$, $\Delta\bar{d}/d$

What might we learn from all of this?

1. $(\Delta q + \Delta \bar{q})$ small – DIS ✓
2. A_N at $\sqrt{s} = 200$ large – transversity?
   – orbital ang. mom.?
3. $\frac{\Delta G}{G}$ small → $L_g + L_q$ large (why?)
   large → why? (T.D. Lee: connection to confinement from violation of chirality)
4. $\Delta \bar{q}$ small – expected naively
   large → why? (Chiral quark soliton model?) (CQSM)
5. $\Delta \bar{u} = \Delta \bar{d}$ – naively expected
   $\gg \Delta \bar{d}$ – CQSM? Why?
   $\ll \Delta \bar{d}$ → why?
6. unexpected parity violation?
   → quark substructure, Z', ...
7. DIS + RHIC + eRHIC
   → comprehensive tests of factorization, universality of structure functions, scales, ...