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

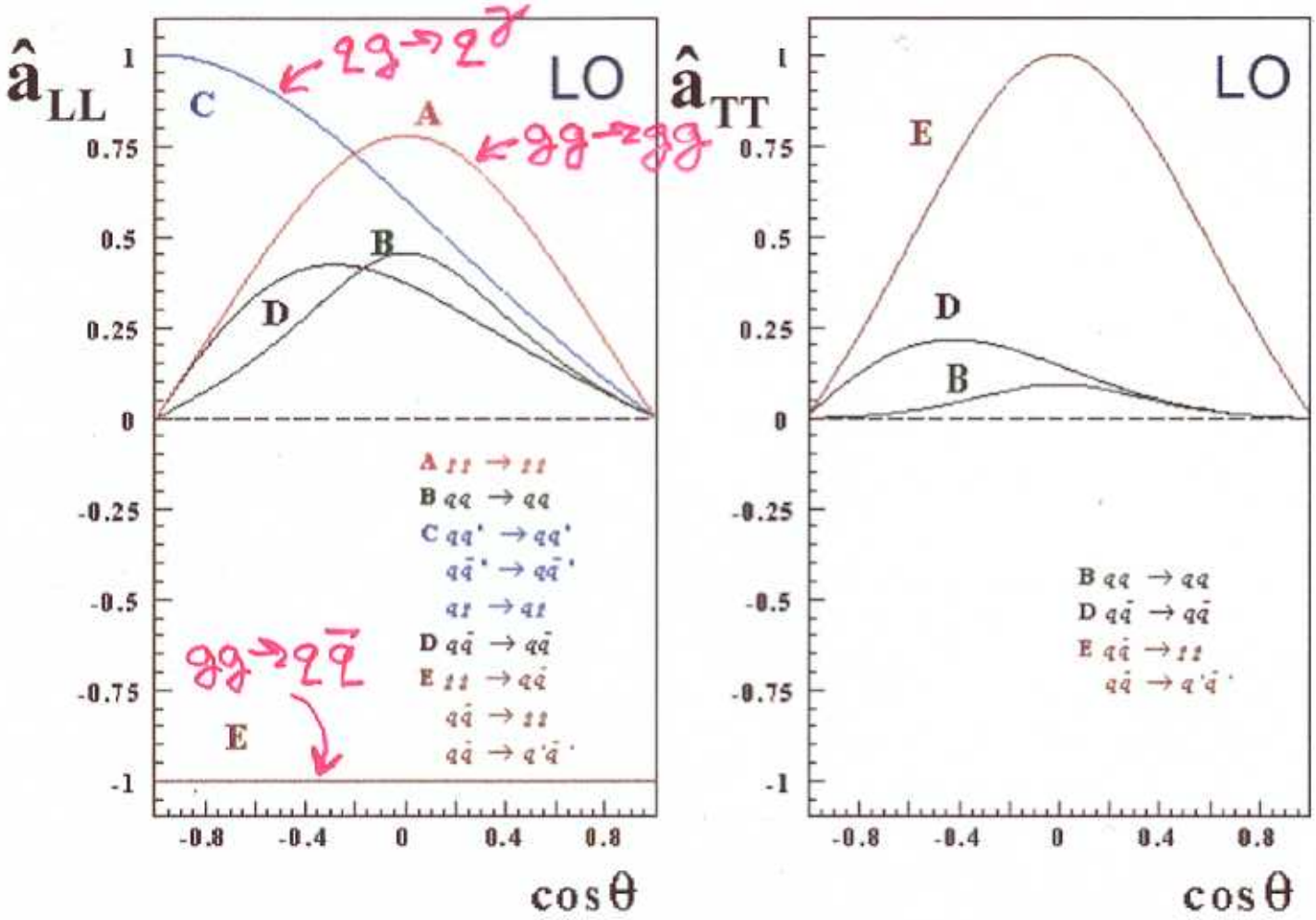
Pol. = 70% each beam
Yale / SLAC / EMC DIS } beams of polarized quarks ($x \gtrsim .1$)

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

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

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

LO pQCD partonic level asymmetries

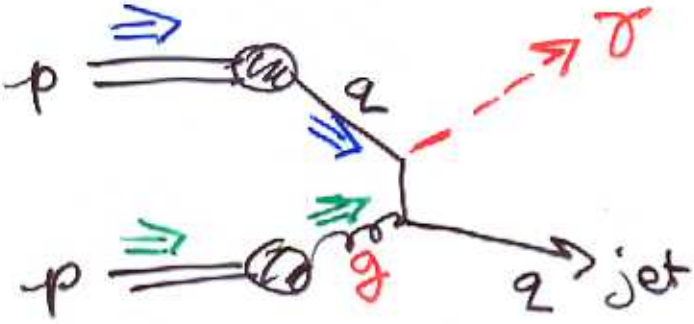


NLO corrections are now known for all relevant reactions

RHIC Spin Probes

Gluon polarization:

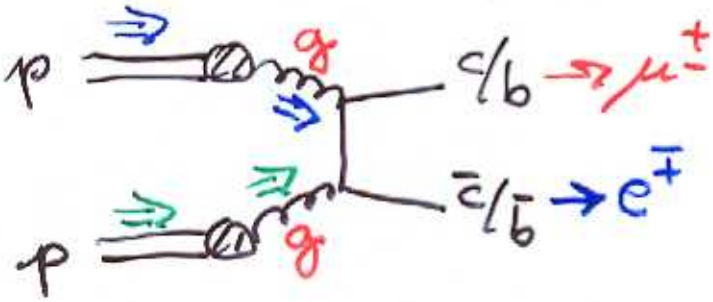
$$A_{LL} = \frac{1}{P^2}\frac{N_{++}(\vec{p}) - N_{+-}(\vec{p})}{N_{++} + N_{+-}}$$



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

(.3) (.6)

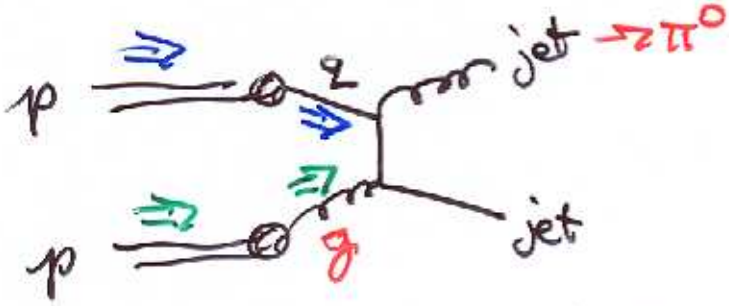
$$\simeq \frac{1}{5}\frac{\Delta G}{G}(x_g)$$



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

(.5?) (.15)

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



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

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

(.4) (.6)

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

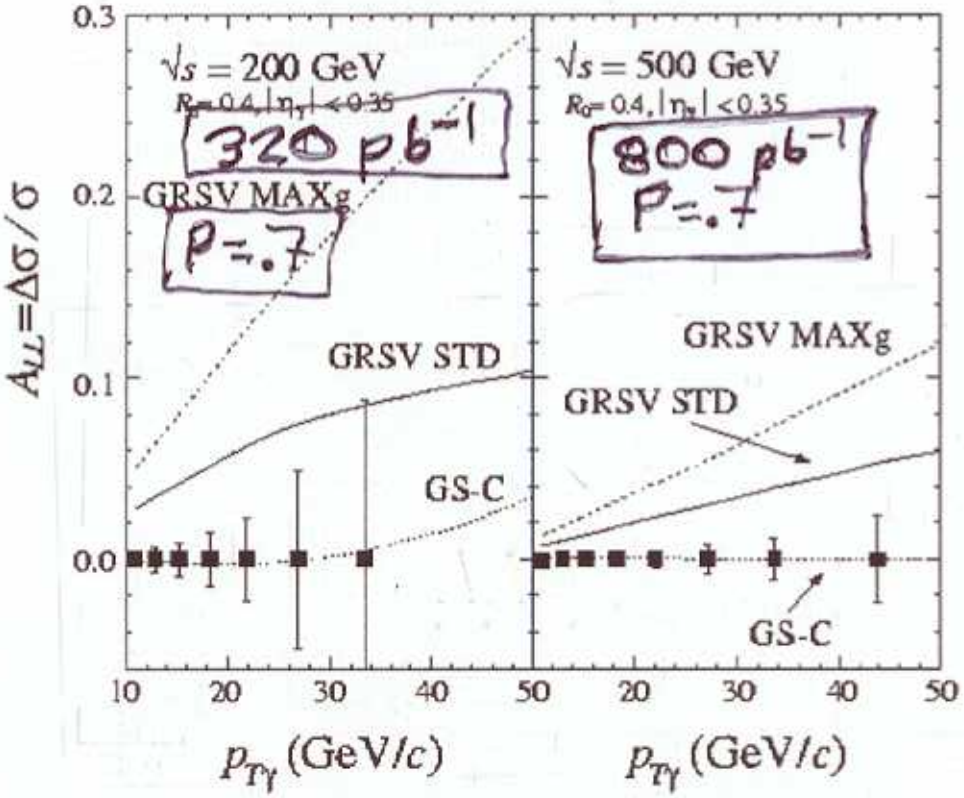
also J/ψ (but production mechanism)

Prompt photon measurement

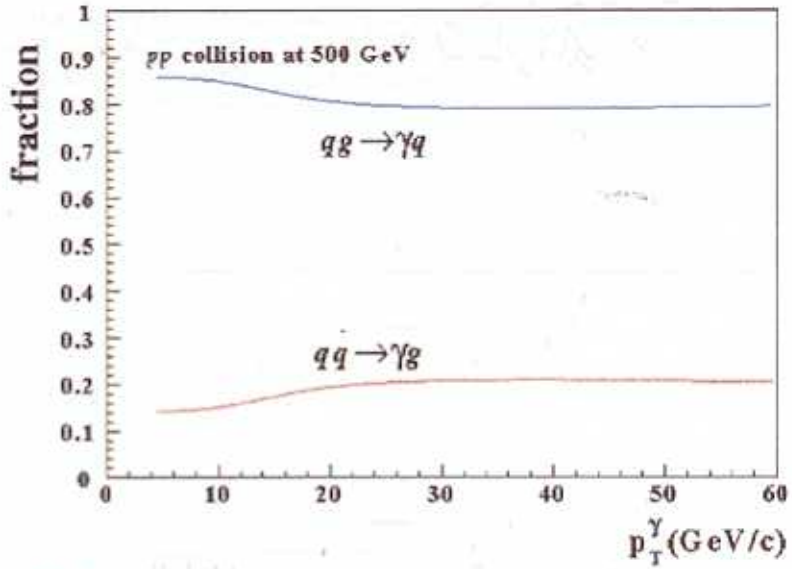
Prompt photon

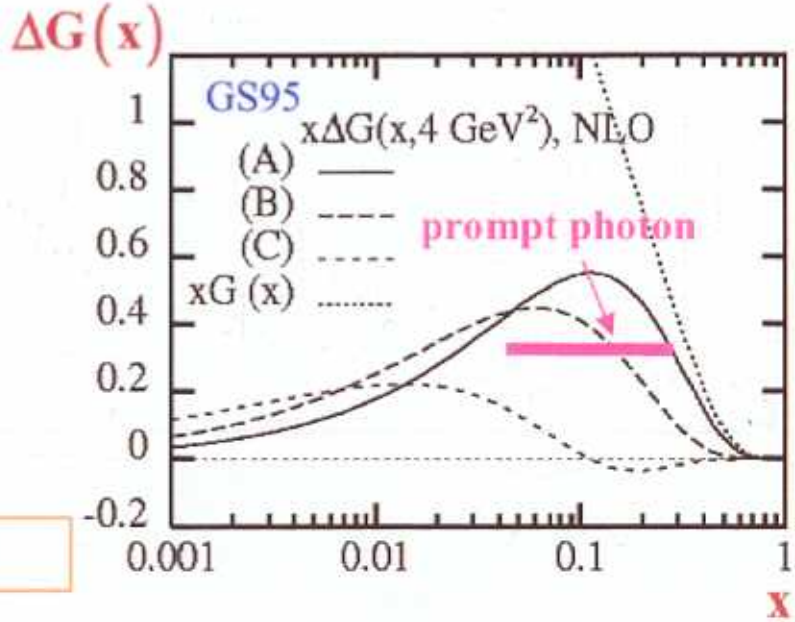
» clear interpretation

– gluon Compton process dominant



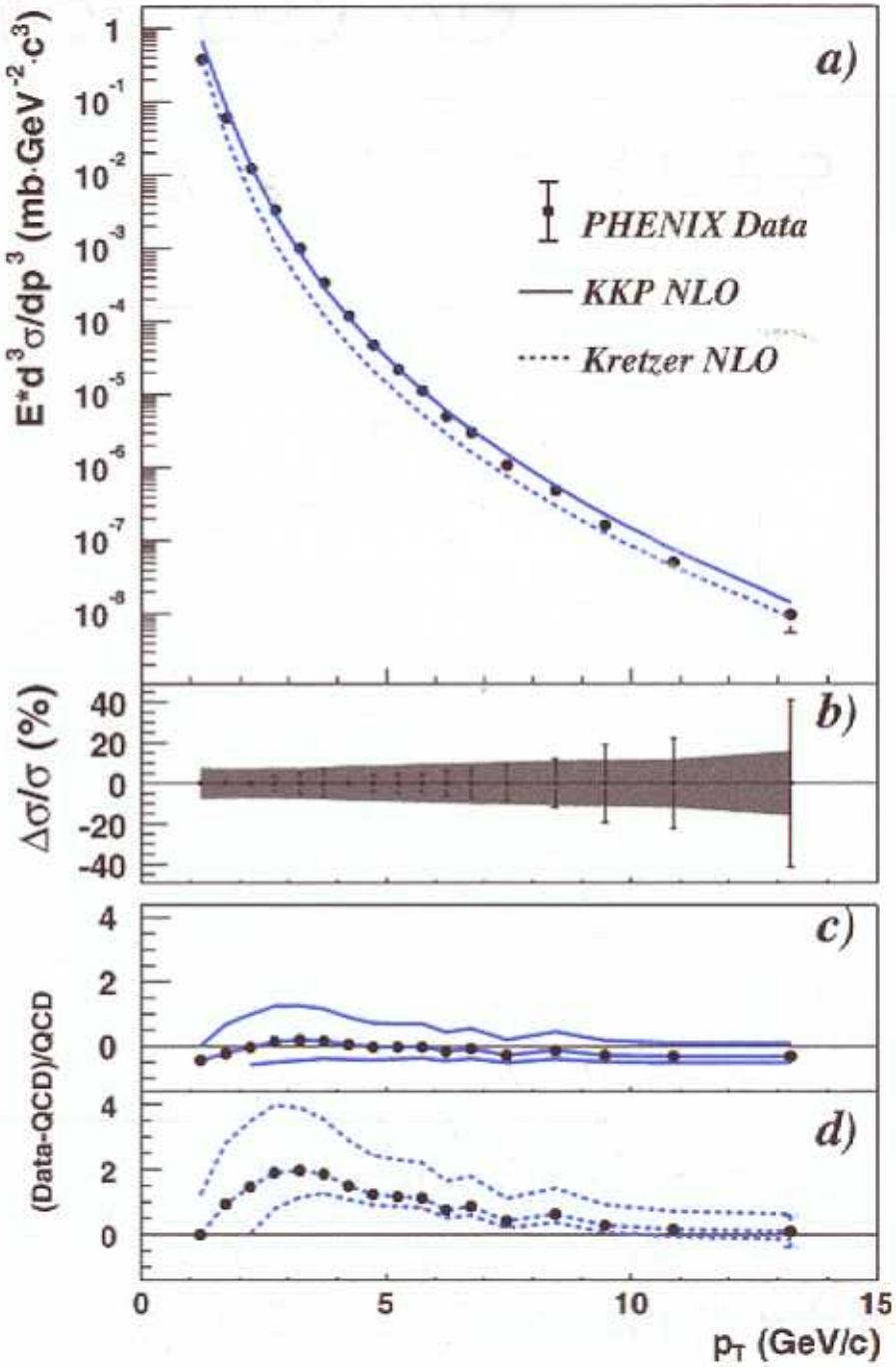
statistics with full design luminosity and polarization





π^0 Cross Section

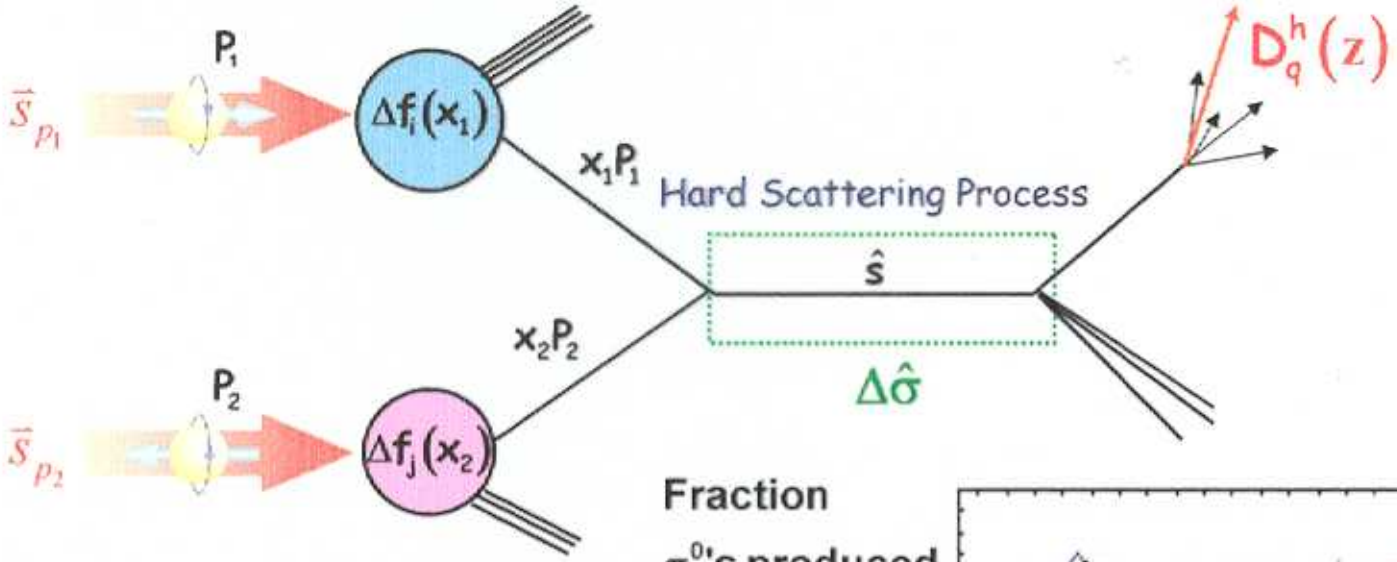
- The data covers over 8 order of magnitude
  - –by combining minimum bias trigger and EMCal trigger data
- NLO pQCD calculation is consistent with data
  - –CTEQ5M PDF + KKP FF

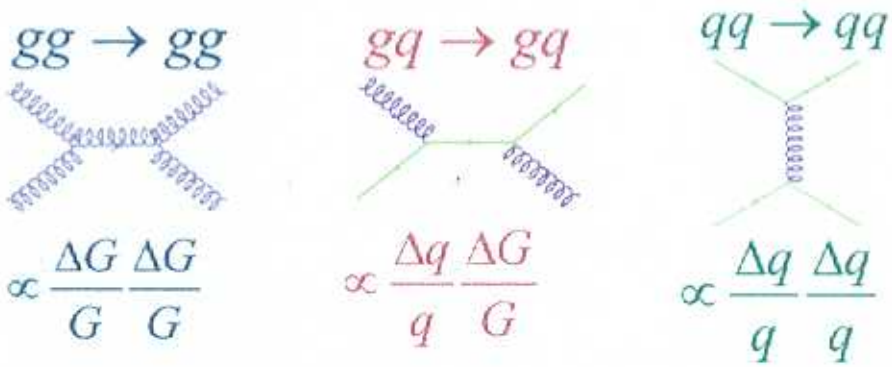


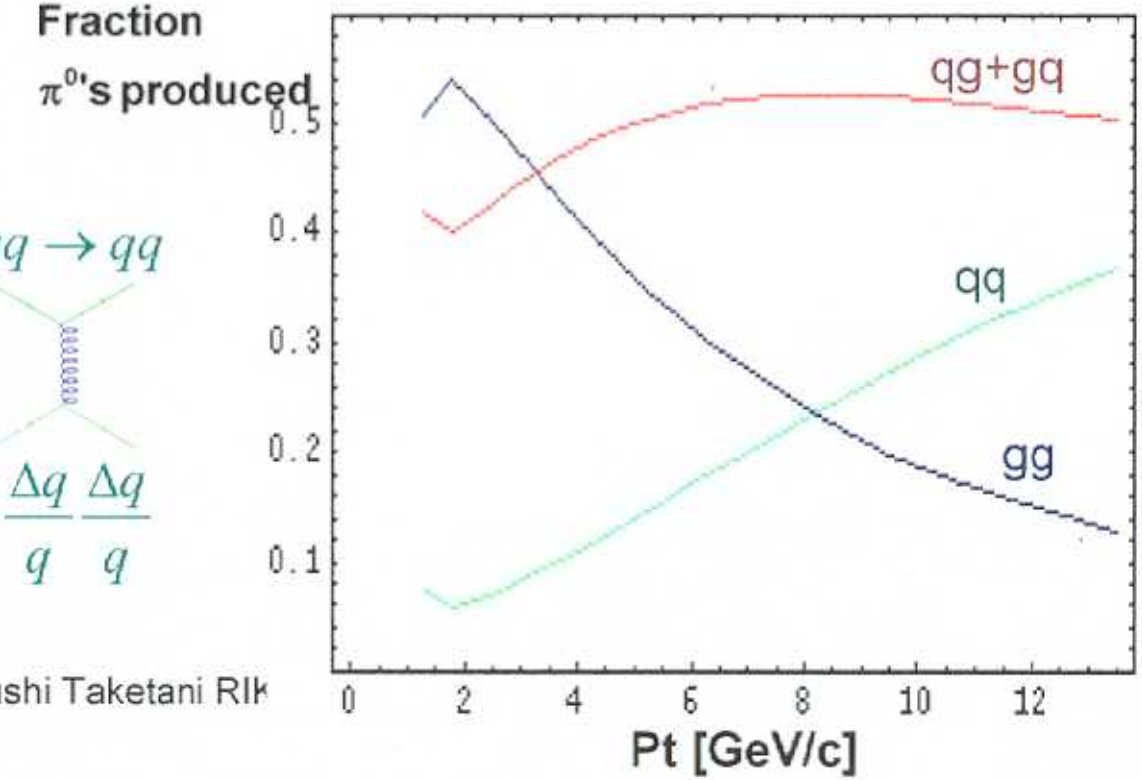
H. Torii, Kyoto University
B. Fox (BNL), SPIN 2002

submitted to PRL, hep-ex/0304038

Leading hadrons as jet tags

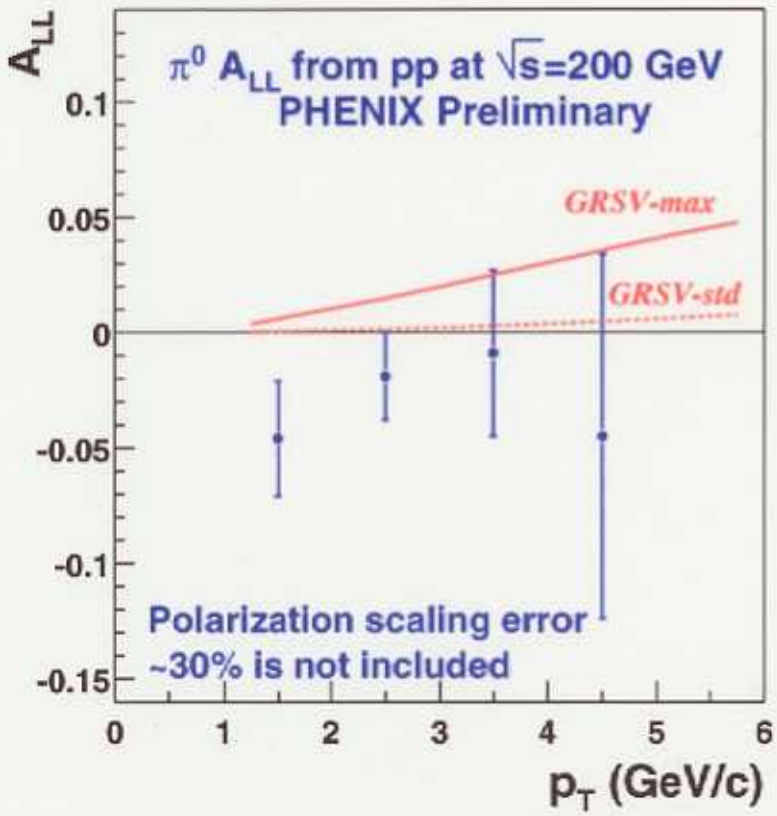






A_{LL}: PHENIX vs theory

B.Jäger e al., PRD67, 054005 (2003)



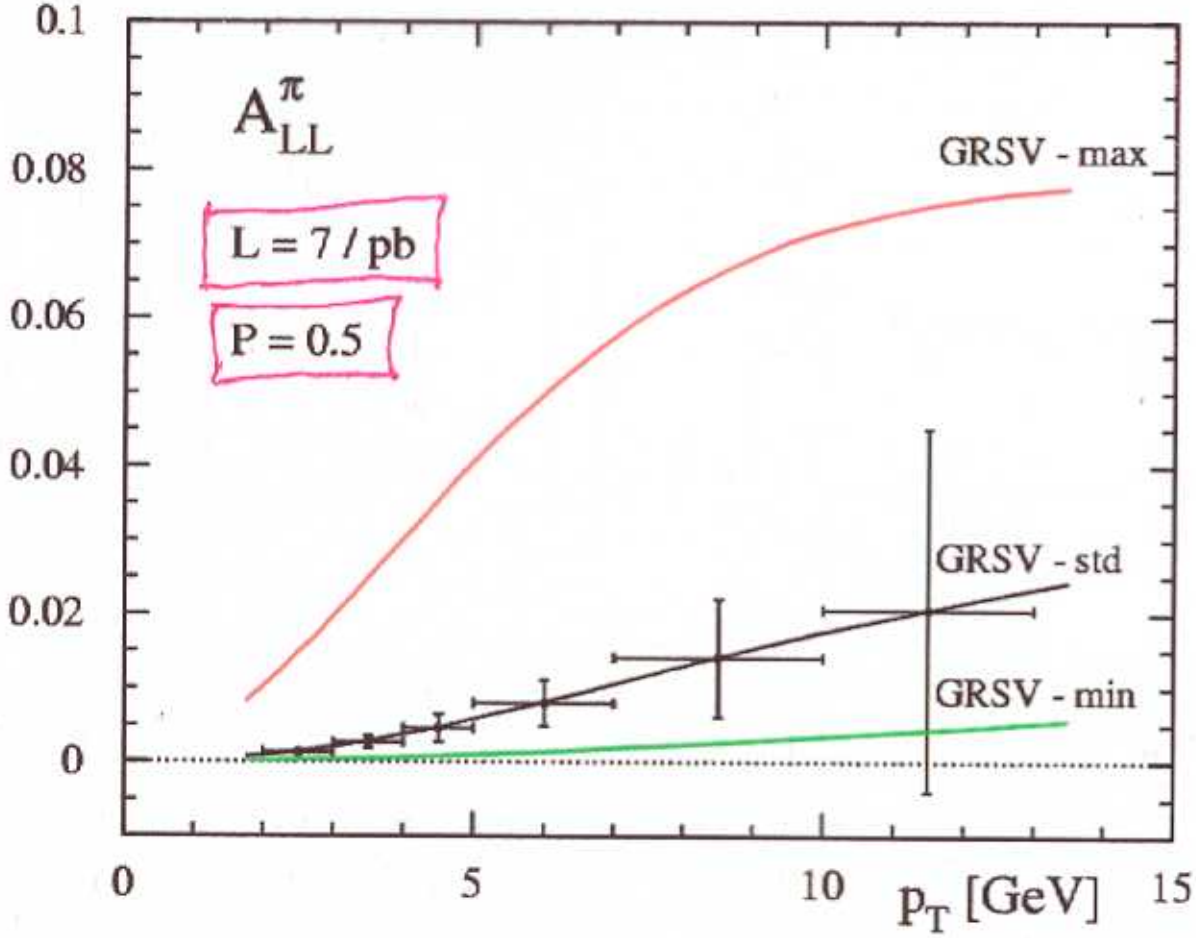
$P = .26$

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

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

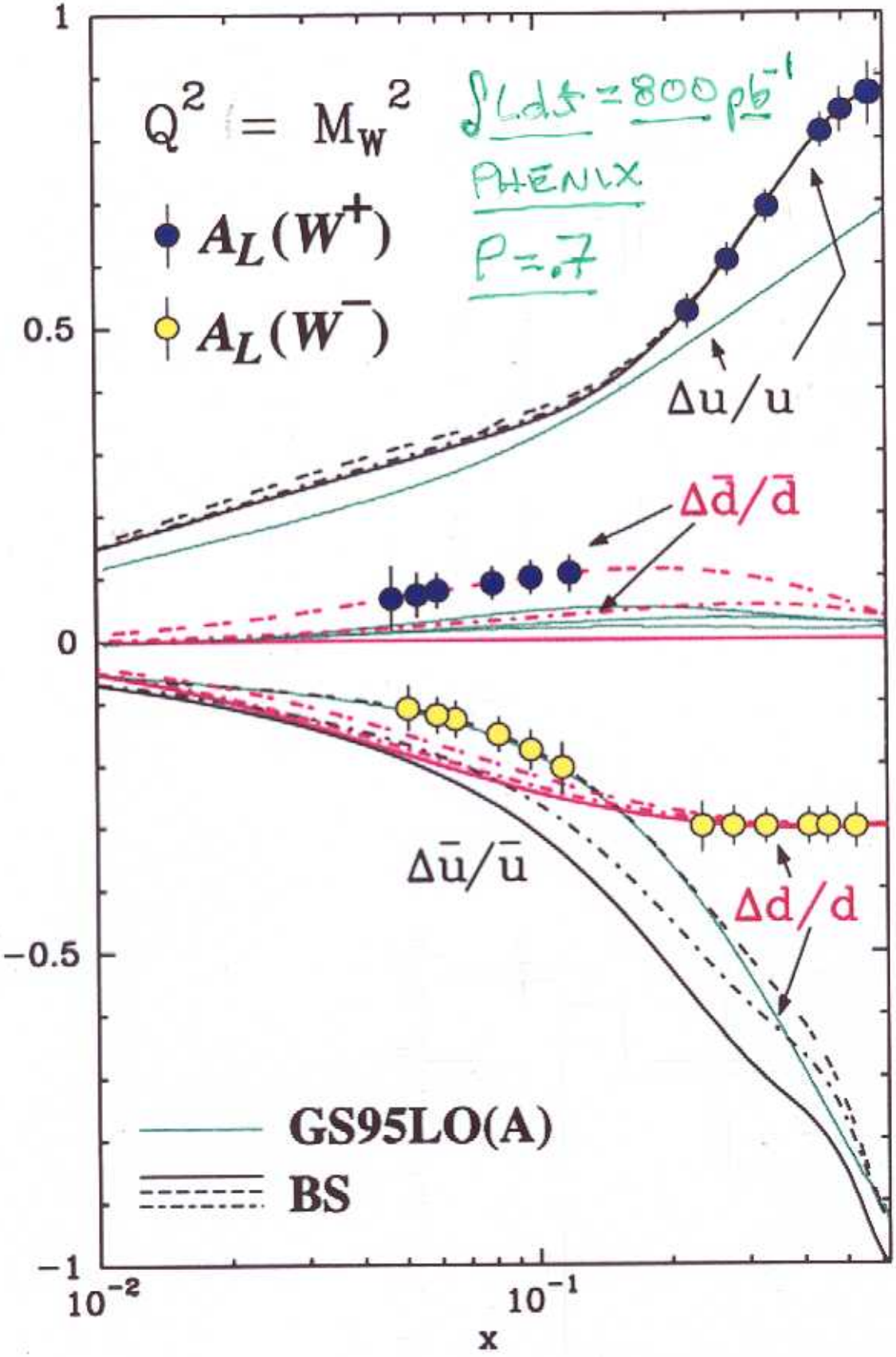
One beam is longitudinally polarized : $A_L = \frac{1}{Pol.} \frac{N_+ - N_-}{N_+ + N_-}$

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

  - but proton 1 is polarized $\Rightarrow$
    <u>u quark is polarized</u> 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 $\Rightarrow$
    <u>$\bar{d}$ is polarized</u> 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 → $\boxed{1\text{-}10\ pb^{-1},\ P \geq .4}$

  → 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 $A_{TT} \ll A_{LL}$

- with direct γ → $\boxed{300\ pb^{-1},\ P = .7}$

  - $\dfrac{\text{signal}}{\text{background}} = \dfrac{qg \to \gamma q}{q\bar{q} \to \gamma g} \approx 4$

  → γ is the most precise probe of $\Delta G/G(x)$, measurements come later in RHIC spin program

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

- $W^{\pm}$: $\boxed{\sqrt{s} = 500\ GeV,\ 800\ pb^{-1},\ P > .5}$

  → later in RHIC spin program

Where are we now?

$\sqrt{s} = 200$ 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, $P = .7$ (x 3)

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

$\int L dt = 300\ pb^{-1}$ (x 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 x 250 for direct γ probe of $\Delta G/G$

<u>However</u>: 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:

- very forward neutron $A_N = -.1$ $\boxed{\text{at } \sqrt{s} = 200}$
- 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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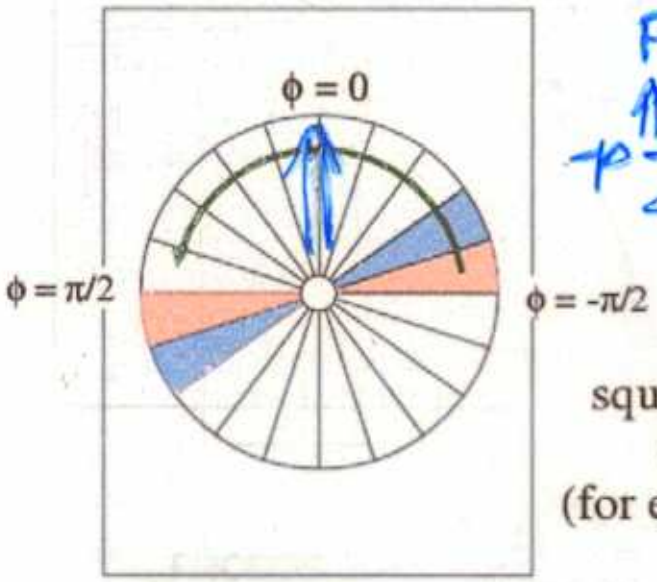
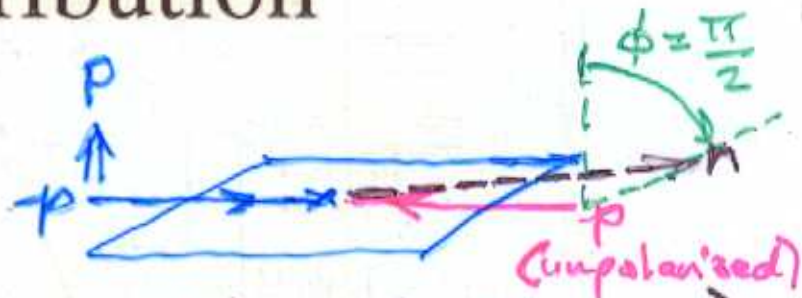
$\Rightarrow$ the signals point to a rich physics harvest at high energy using protons as probes

Neutron Asymmetry ϕ distribution

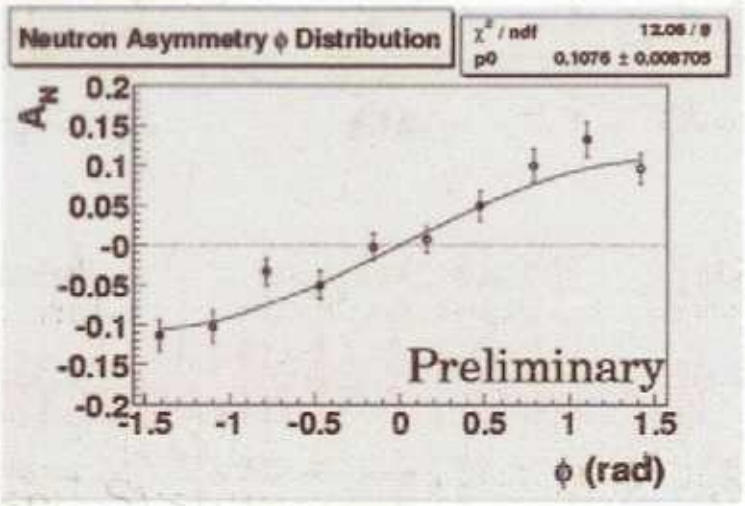




$$N(\phi) = N_0 (1 + P A_N \sin\phi)$$

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

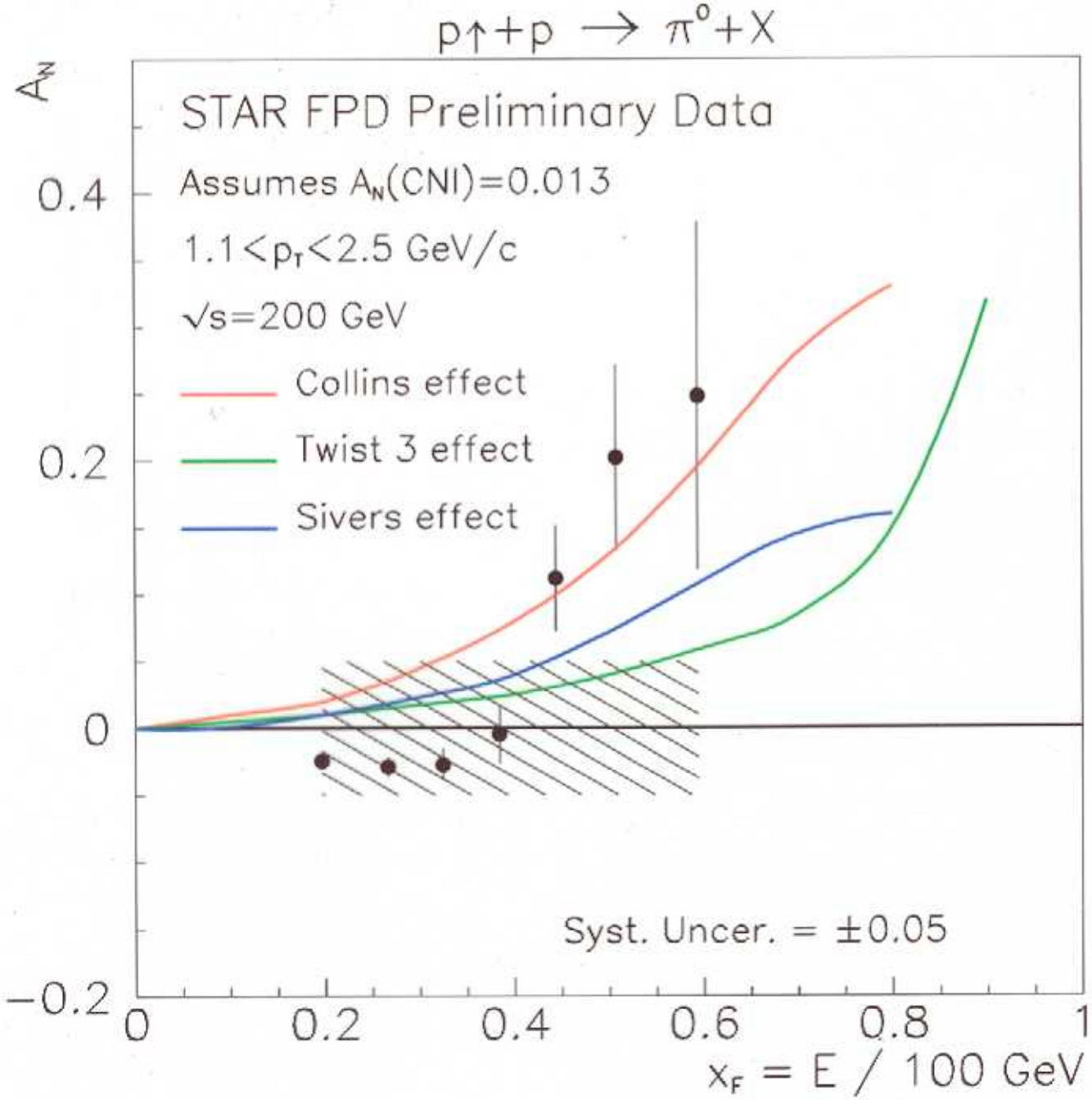
EM Calorimeter



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

ϕ-dependence is consistent with sin ϕ

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



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

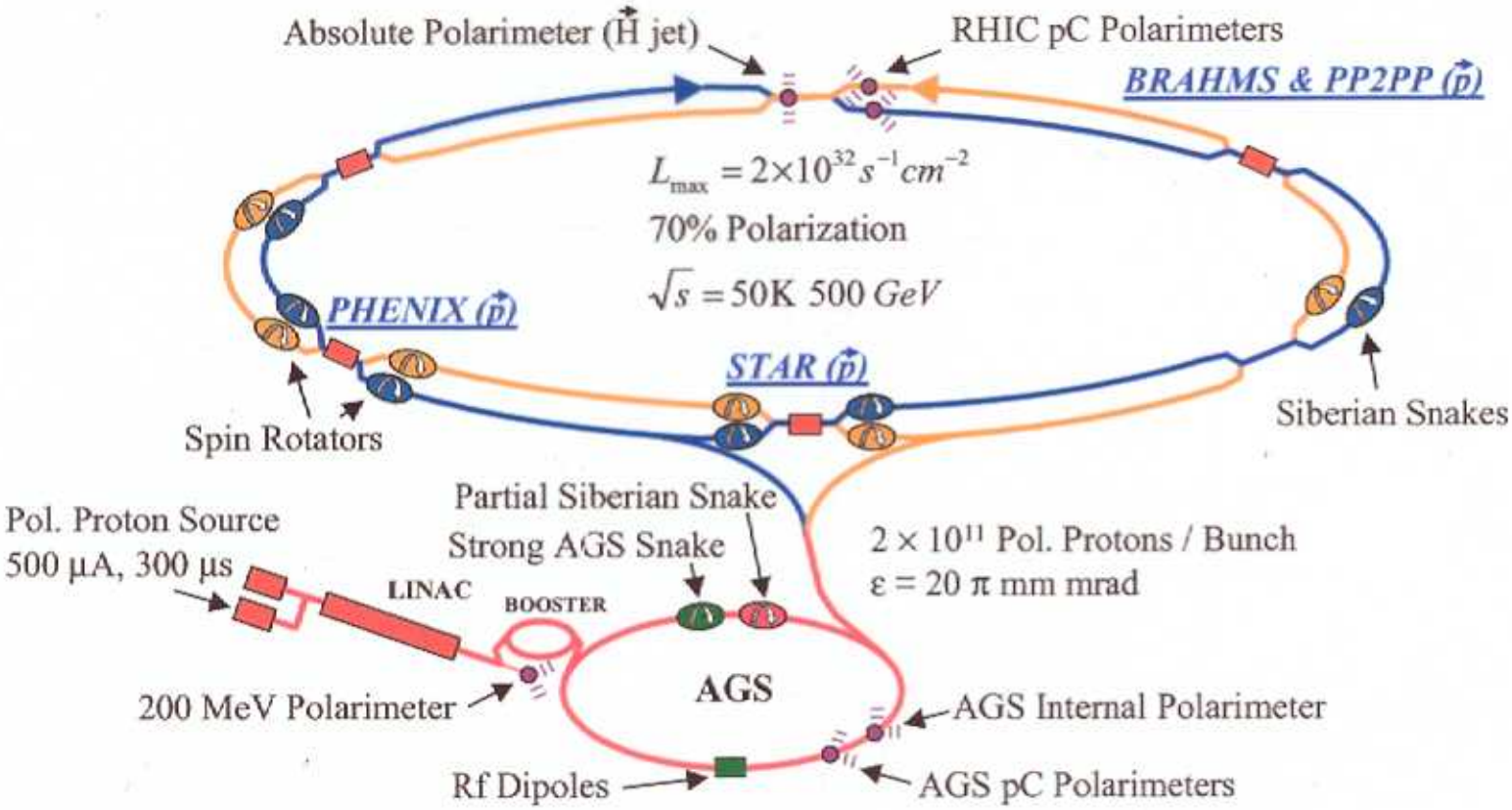
(also spin matching for AGS lattice)

→ development (with ramp measurements with polarimeters)

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

- also: |P| to ±50% from new polarized jet in RHIC (2004-6)

Polarized Proton Collisions in RHIC



BROOKHAVEN
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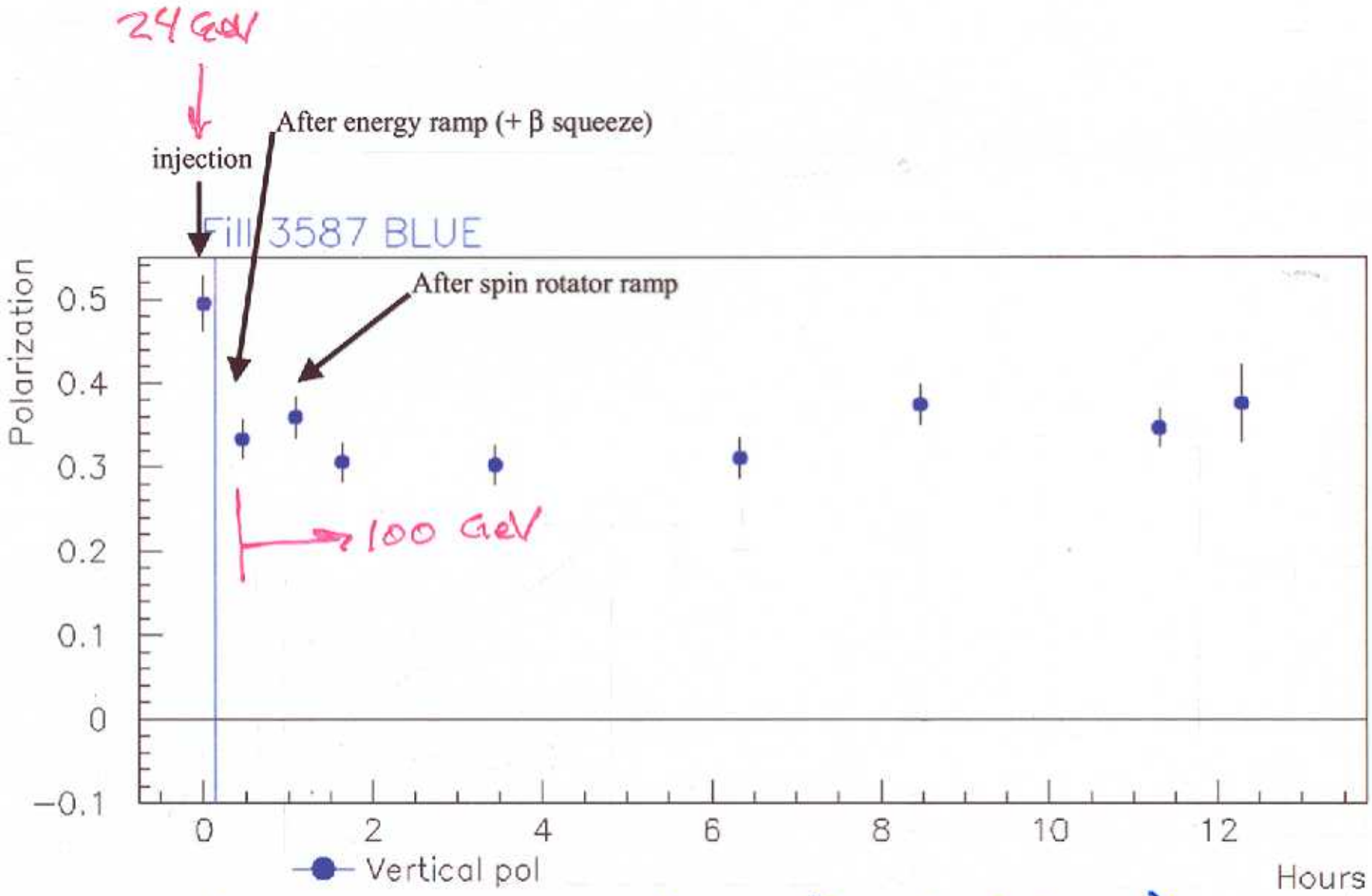


assumes $A_N(100\ \text{GeV}) = A_N(24\ \text{GeV})$

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 beam-beam electromagnetic interactions at IRs

  ⇒ beam loss from betatron tune shift and tune spread (hit beam resonance)

  → find new "working point"

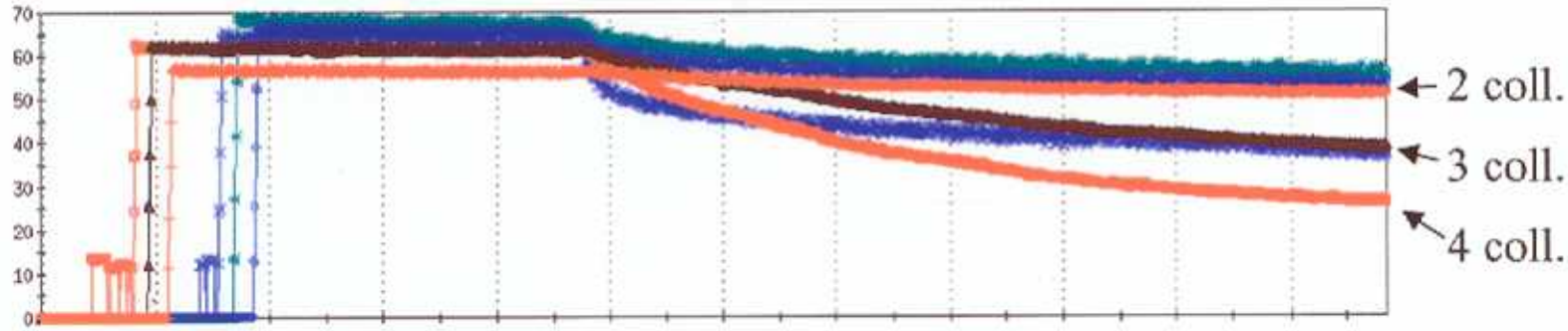
  - betatron tune where we don't hit beam resonances from beam-beam tune shift and we don't hit spin resonances

  → 2 candidates for new working points

  → develop in 2004

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}	$\times 16$
N bunches	55	110	$\times 2$
efficiency RHIC	.2	.6	$\times 3$
$\int L dt$ / week	$.5\ pb^{-1}$	$20\ pb^{-1}$	$\times 40$
$L\ cm^{-2}s^{-1}$	4×10^{30}	8×10^{31}	$\times 20$
$\int L dt$ (200 GeV $\sqrt{s}$)	$.5\ pb^{-1}$	$300\ pb^{-1}$	$\times 600$

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 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 $P = .25 \to .5$
$L = 4 \times 10^{30} \to 1.5 \times 10^{31}$

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

- 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, ...