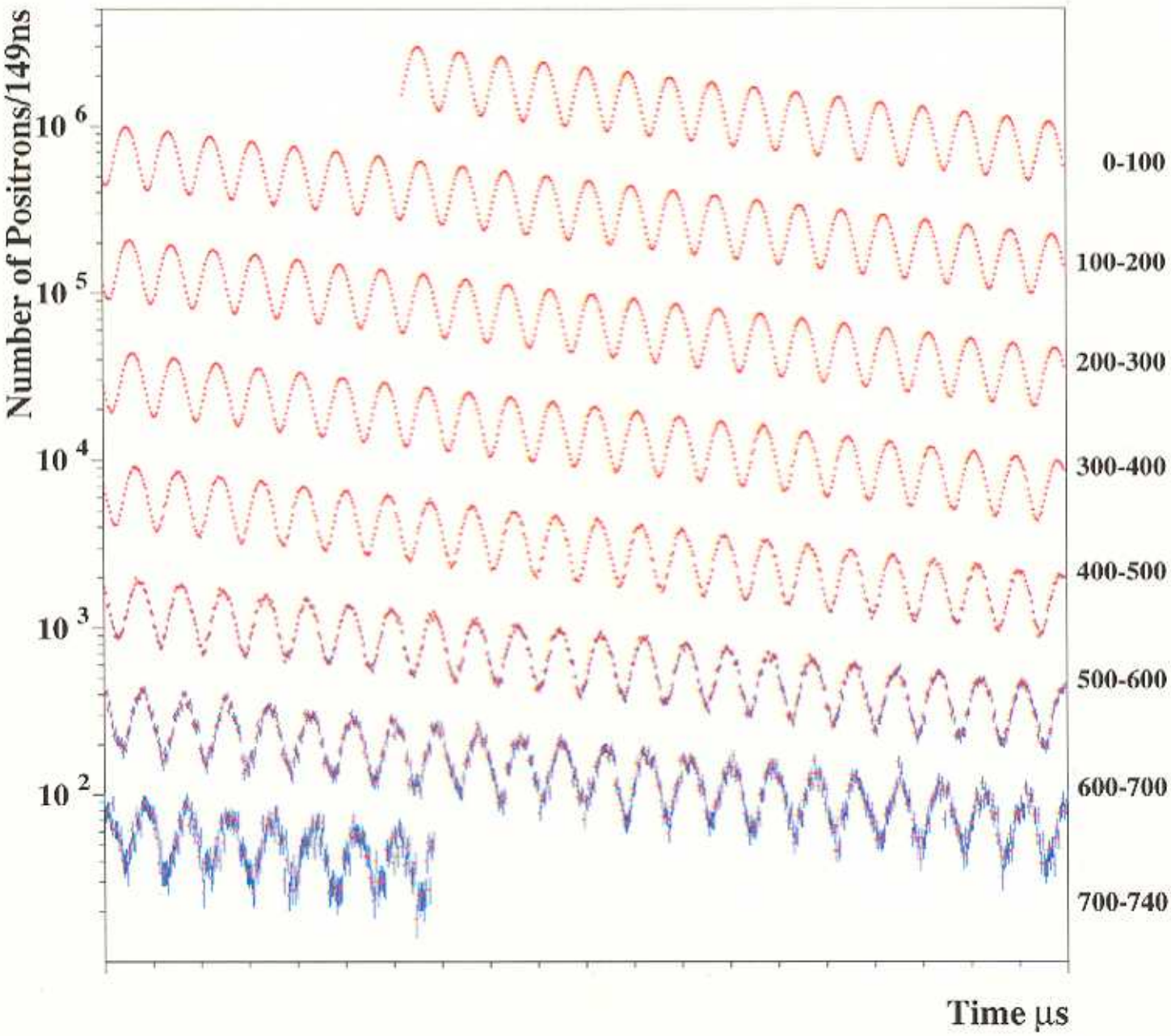
A Discussion on the beauty of Λ spin

G. Bunce, RBRC

- Why spin?
- $p\uparrow + p\uparrow$ and RHIC
- Siberian Snakes
- How do we measure the polarization of the beams?
- First (surprising) results from RHIC
- Where are we going?

CCAST Symposium
Beijing
7 April 2003

Muon g-2 Spin Precession at BNL



A prelude: Why spin?

Physics: a search for the unexpected, non-intuitive in nature

- Intrinsic spin
  - point-like particles with quanta of angular momentum!
- proton spin
  - $\vec{p} = \vec{q} + \vec{\bar{q}} + \vec{g} + L_{orbital}$
    - $\vec{q} + \vec{\bar{q}}$: ~1/4 of proton spin!

Elegance: spin → access to mirror symmetry of physics

Powerful: deeper tests of theoretical understanding with spin

Unexpected order: large spin effects ⇒ coherance and order ⇒ underlying simplicity

Beauty: spin signals are direct quantum phenomena ⇒ amplitudes (not probabilities) ⇒ seem to defy intuition

A touch more philosophy...

Spin is often seen as an added complication (and as too complicated!)

- historically: expectations from spin-averaged data are never correct!

Spin experiments have a strong coupling between the accelerator and the experiment

- this is very attractive to many of us
  - many elegant solutions for accelerating polarized particles
- spin experimenters are usually involved in both their experiment and accelerator issues
  - it is fun!

1. p structure → $\vec{p}$ structure

A brief history of proton structure

(1) Quark model of proton

u quark: charge $+2/3$

d $-1/3$

SLAC (~1966): quarks real

color force (3 color charges)

(2) Gluons:

QCD

half of proton momentum is carried by gluons, anti-quarks

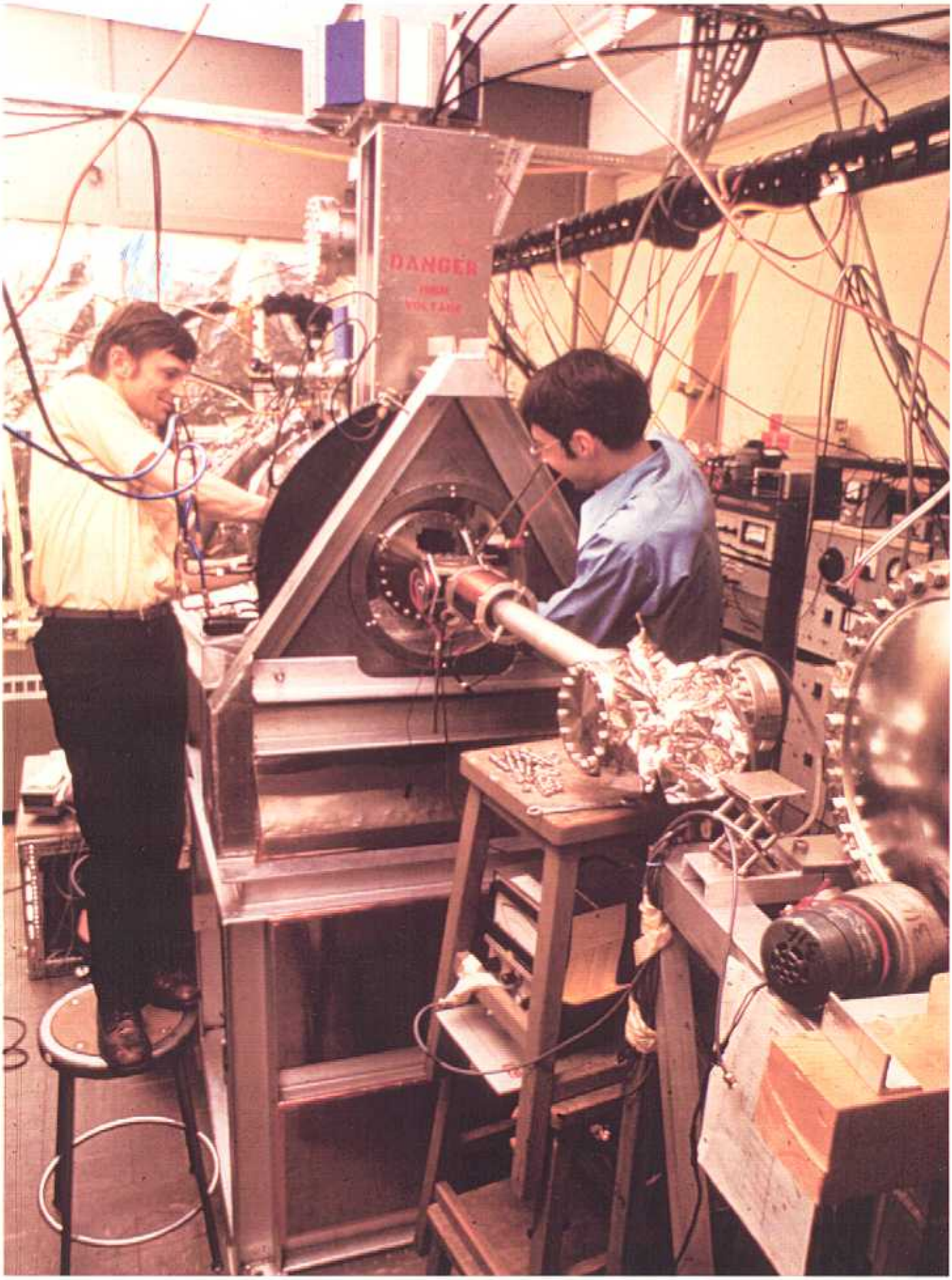
---

(3) Quark model for spin of proton

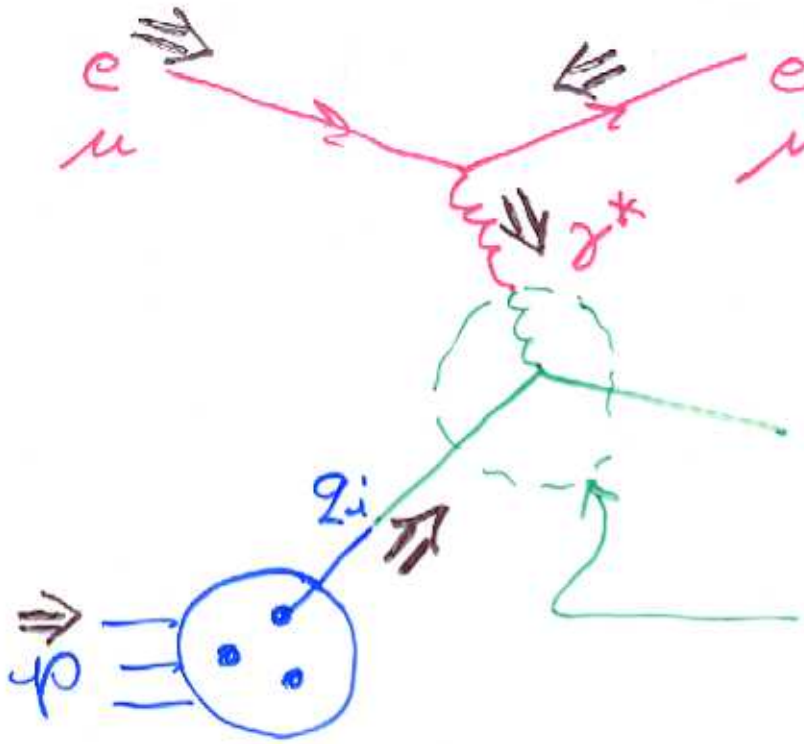
p spin $\frac{1}{2}$, from valence quarks

(4) $\vec{e} + \vec{p}$ at SLAC, CERN:

$(q + \bar{q})$ carry $20\% \pm 5\%$ of p spin


DANGER

Polarized deep inelastic scattering



$\hat{\sigma}$ angular momentum selection rules:

$\vec{\gamma} + \vec{q}_i \rightarrow X$

spin 3/2

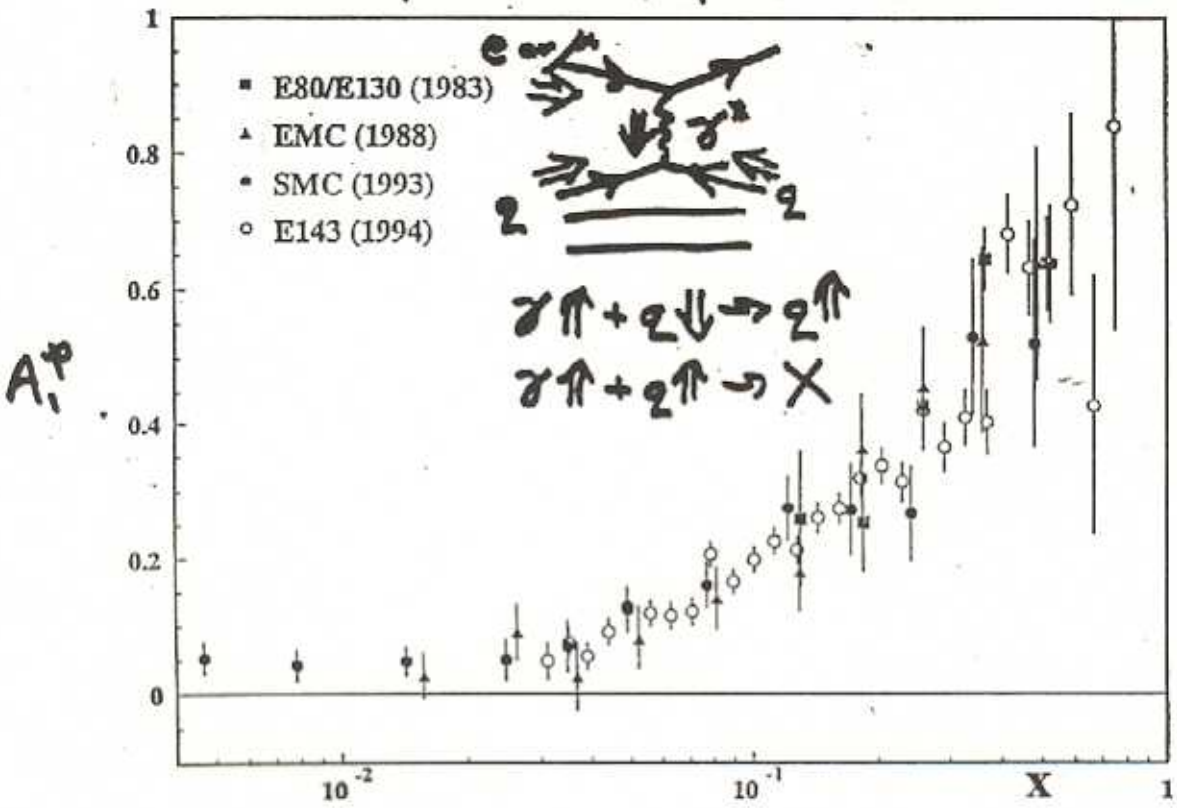
$\vec{\gamma} + \overleftarrow{q}_i \rightarrow \vec{q}_i$

spin +1/2 → +1/2

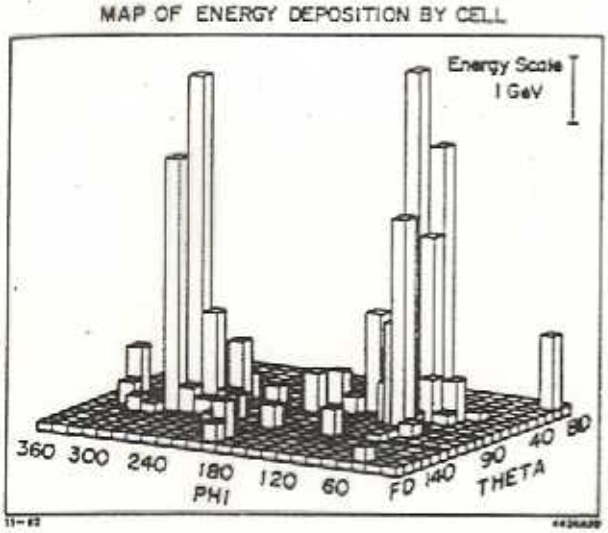
The electron helicity selects the opposite helicity quarks in proton.

→ tool to probe proton spin structure!

At large X, quarks do carry proton spin.



At high p_T, proton beam is a beam of quarks and gluons.



UA2, Paris Conf. 1982

At high p_T, polarized proton beam is a beam of polarized quarks.

The power of RHIC

Proton spin sum rule:

$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta q + \Delta \bar{q})}_{\sim 1/4} + \Delta g + L_{orbital}$$

SLAC $(\vec{e} + \vec{p})$, CERN $(\vec{\mu} + \vec{p})$:

- probe proton only via electric charge
- do not distinguish $\vec{q}$, $\vec{\bar{q}}$
- Δgluon is unknown

RHIC: polarized quarks in one $\vec{p}$
probe polarization of gluons in other $\vec{p}$

$\vec{p} \longrightarrow \quad \longleftarrow \vec{p}$

- direct measurement of Δgluon
- direct measurement of $\vec{q}$, $\vec{\bar{q}}$ by flavor

Discussion 2: $p\uparrow\uparrow + p\uparrow\uparrow$ and RHIC

A very short history of $p\uparrow\uparrow + p\uparrow\uparrow$:

(1) very difficult to accelerate $p\uparrow\uparrow$
due to large g-2 of proton (actually $\frac{g-2}{m_p}$)

(2) ZGS (Argonne) $p\uparrow\uparrow$ to 12 GeV
AGS $p\uparrow\uparrow$ to 22 GeV
- fixed target → effective energy
$\sqrt{s} = 7$ GeV

(3) Fermilab $p + A \rightarrow \Lambda$
$\hookrightarrow p\uparrow\uparrow$ (200 GeV)
- effective energy $\sqrt{s} = 20$ GeV
- low intensity

(4) RHIC: collide $p\uparrow\uparrow + p\uparrow\uparrow$
- effective energy $\sqrt{s} = 200 - 500$ GeV

→ completely new laboratory to study $p\uparrow\uparrow$
→ new domain: many surprises likely

What did these earlier $p\uparrow$ experiments find?

(1) at ZGS, $p\uparrow + p\uparrow \to p + p$ (90°)

$$\frac{\sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow}} = 4$$

$p_T = 2.3$ GeV/c

(2) at Fermilab, $p + A \to \Lambda\uparrow + X$

$$\frac{N(\Lambda\uparrow)}{N(\Lambda\downarrow)} = 2$$

$p_{protons} = 300$ GeV

$p_T(\Lambda) \geq 1$ GeV/c

(measured to 4 GeV/c)

Also: $\Xi^{0}\uparrow$, $\Sigma^{+,-,0}\uparrow$, $\Lambda + A \to \Omega^{-}\uparrow$

Also: ISR with $\sqrt{s} = 60$.

(3) at Fermilab, $p\uparrow + p \to \pi^{\pm} + X$

$$\frac{N(\pi^{+}\text{ left}, p\uparrow)}{N(\pi^{+}\text{ left}, p\downarrow)} = 2.3$$

$p_{protons} = 200$ GeV

$p_\perp(\pi) \approx 1.5$ GeV/c

$x_F(\pi) = 0.8$

$R(\pi^{-}) = .43$

→ spin effects are large at high energy.

pp elastic scattering ~1976

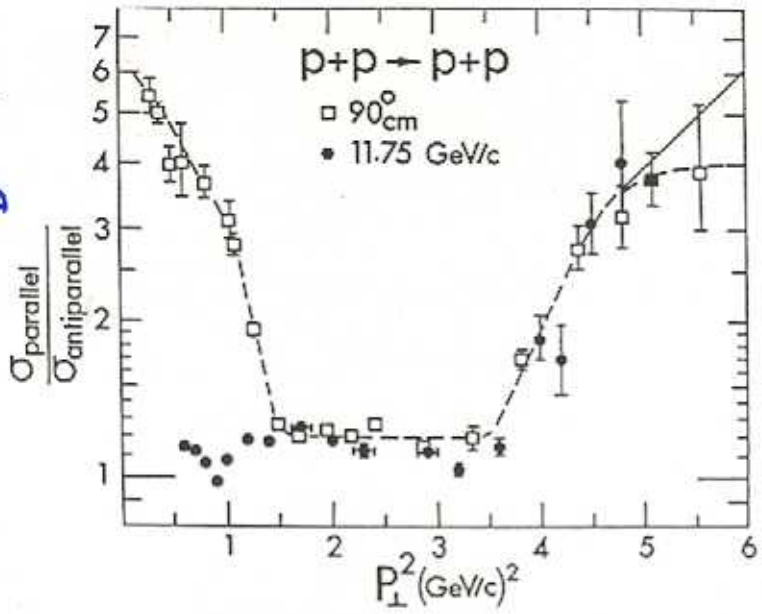


Fig. 3. Ratio of spin-parallel to spin-antiparallel p-p elastic cross-sections plotted against $P_\perp^2$ for fixed energy and fixed angle experiments.

$p^{\uparrow} + p \to \pi + X$ at 200 GeV

N_{left} / N_{Right}

$$A_N = \frac{1}{P_{beam}} \frac{N_{left} - N_{Right}}{sum}$$

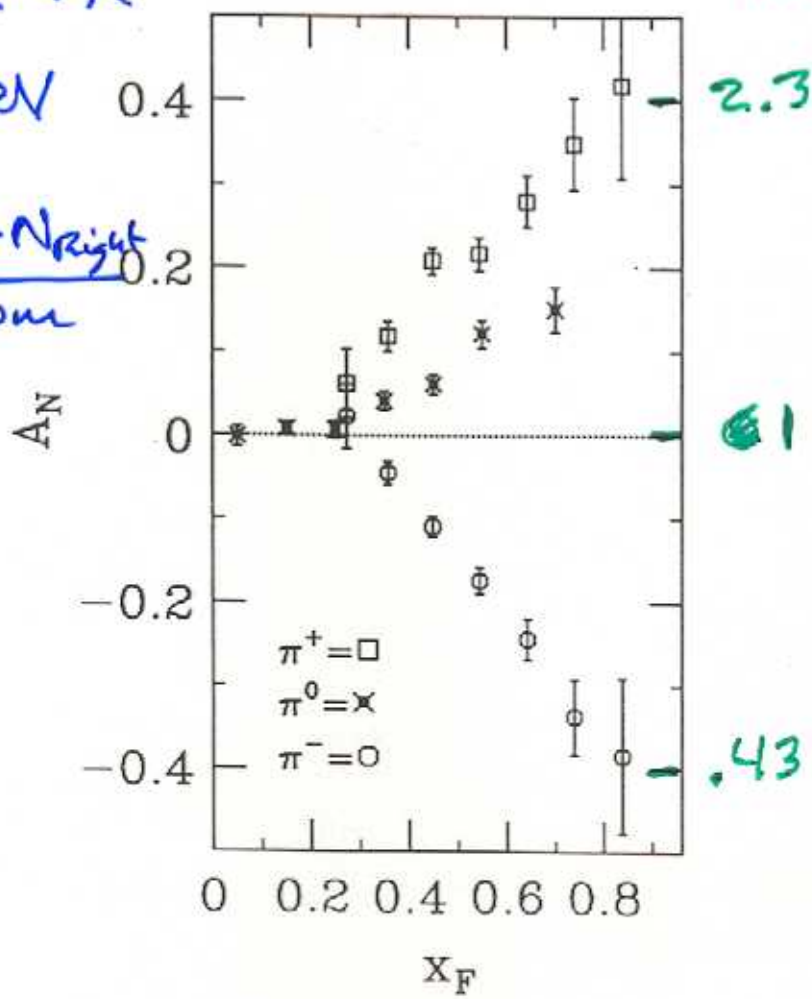
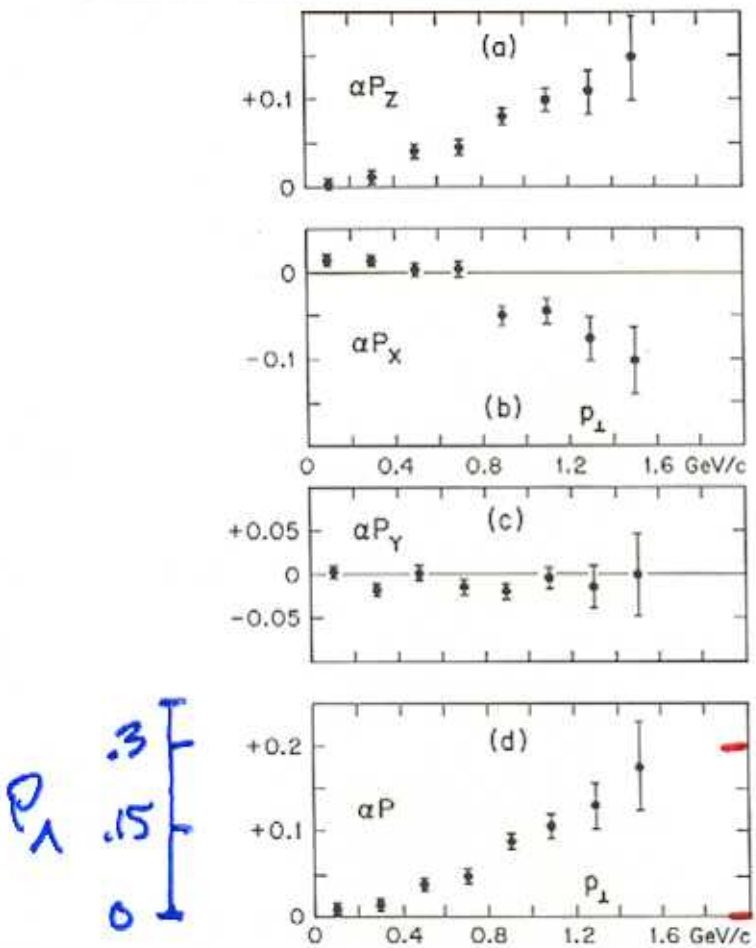


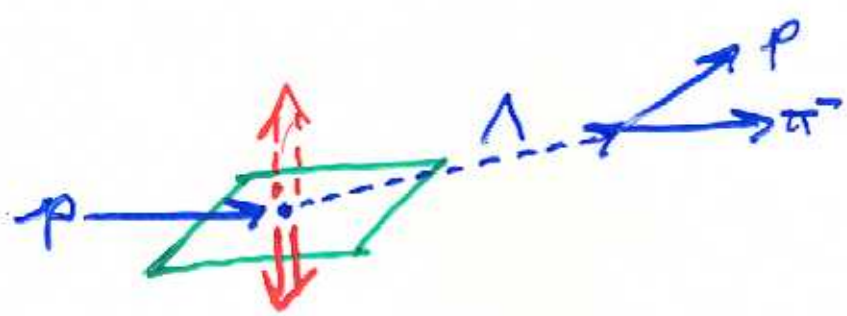
Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.

$p + Be \rightarrow \Lambda + X$ at 300 GeV



P_Λ (down)/P_Λ (up)

FIG. 3. Three components and magnitude of the $\Lambda^0 \rightarrow p + \pi^-$ asymmetry as a function of Λ^0 transverse momentum.



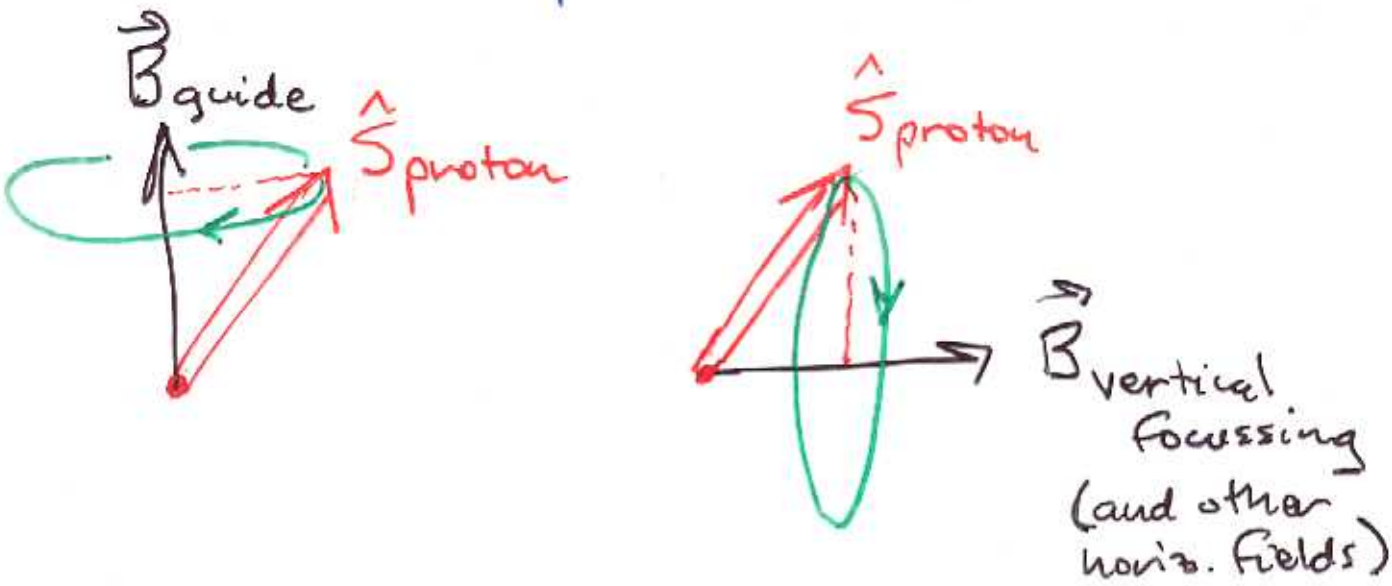
Siberian Snakes

$\left|\frac{g-2}{2}\right| \approx .001$ e, μ $\qquad$ $\left|\frac{g-2}{2}\right| \approx 2$ proton

In a circular accelerator/storage ring the spin in the horizontal plane precesses $\boxed{\frac{g-2}{2} \times \gamma}$ full revolutions per turn:

For $\gamma = 100$, $\vec{S}$ precesses 200 x per turn!

What are spin resonances?



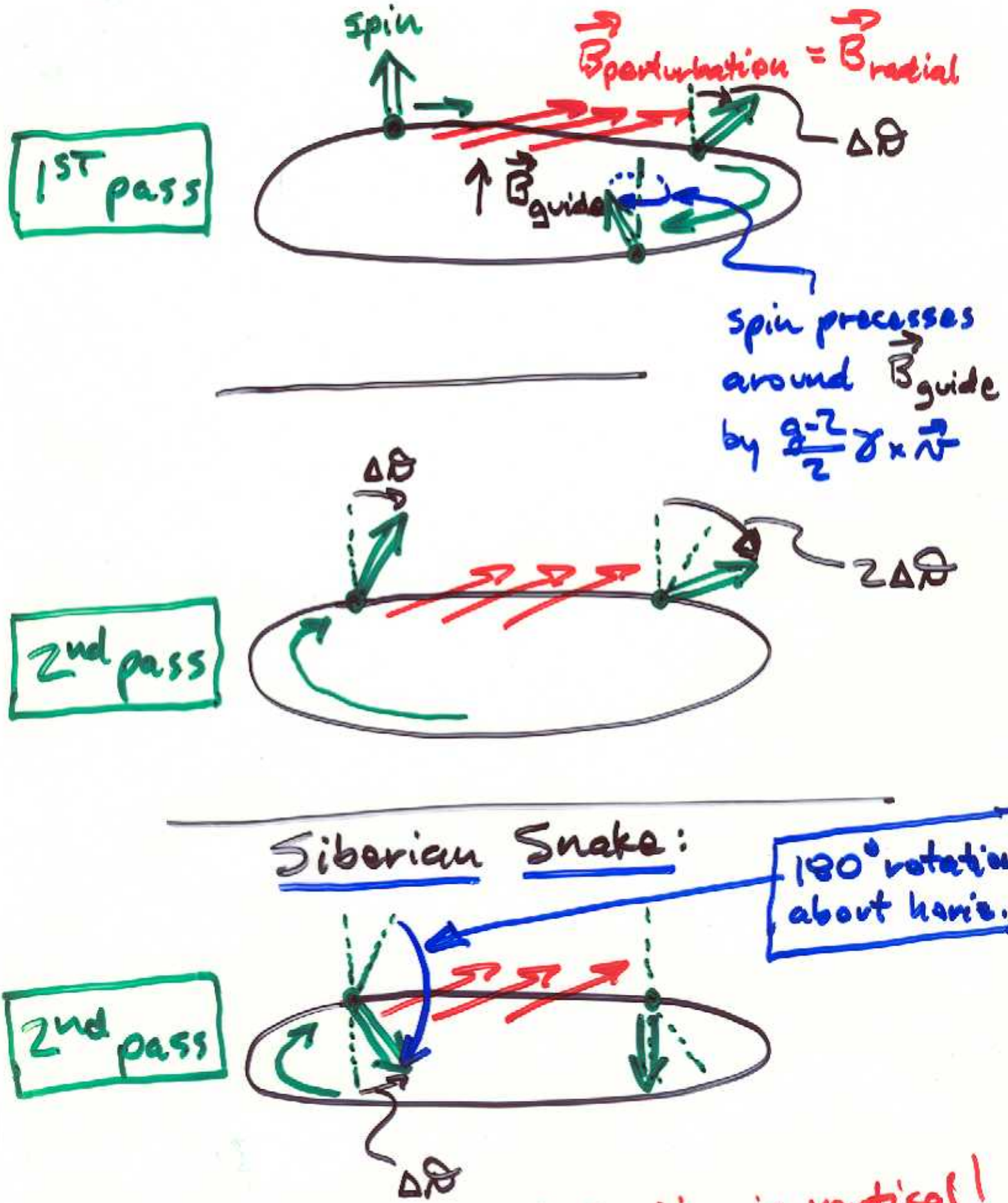
When the two are in phase → spin resonance.

Several solutions:

- jump past energies of spin resonances
  → non-adiabatic, blows up beam size

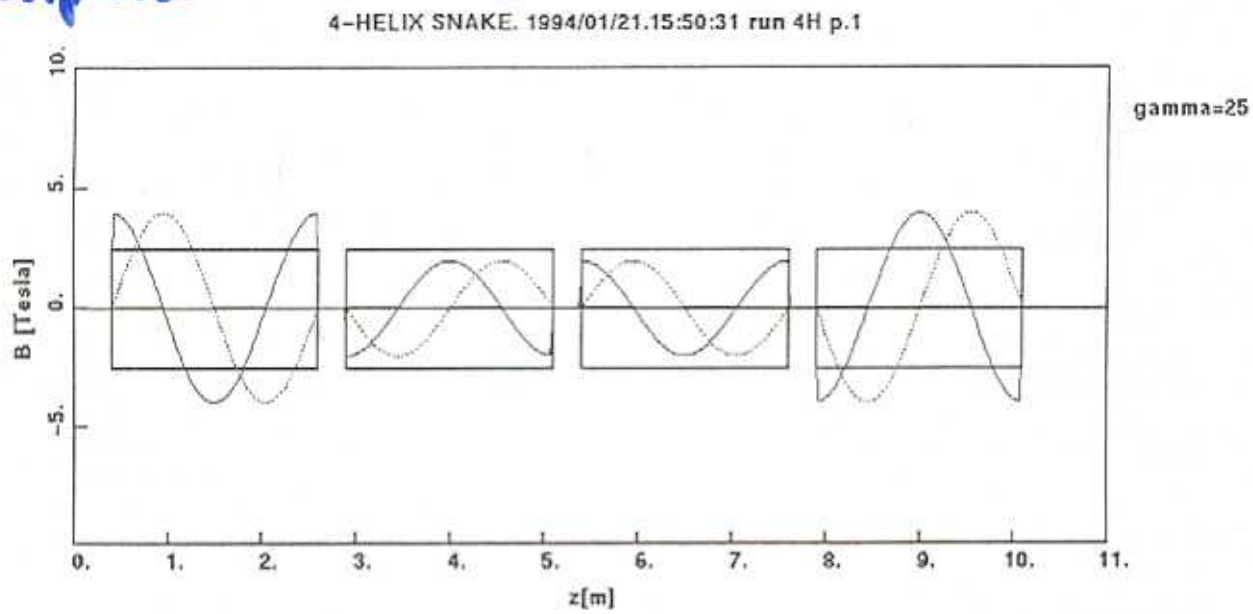
→ - for a strong resonance, spin flips but polarization is not lost if all the beam sees the resonance

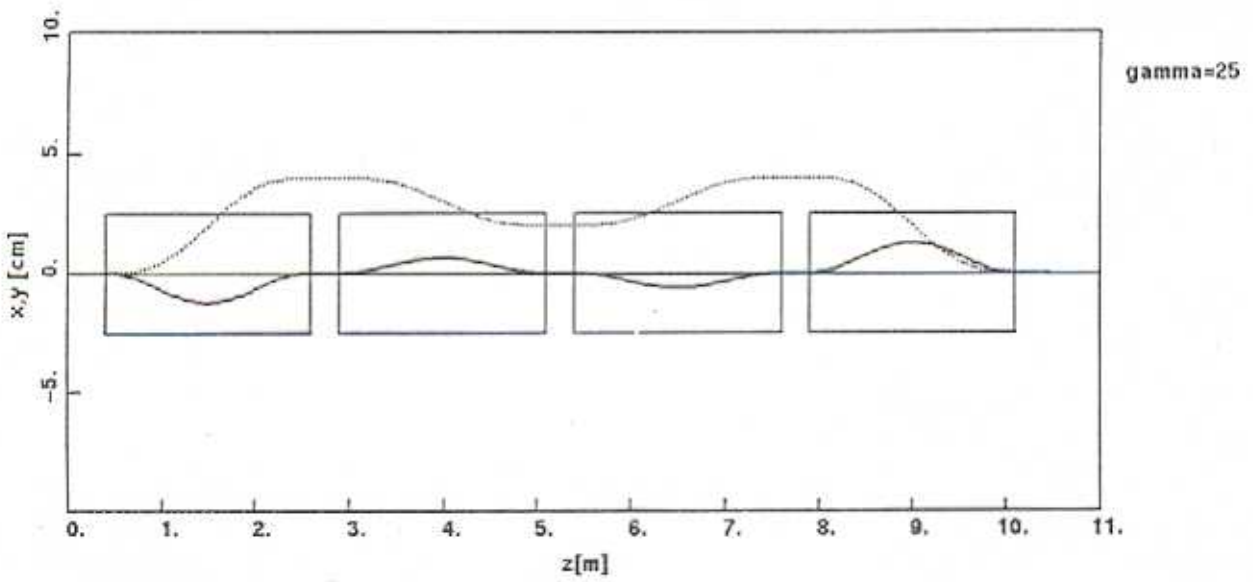
→ - Siberian Snakes
  - a set of magnets which rotates spin 180° around a horizontal axis

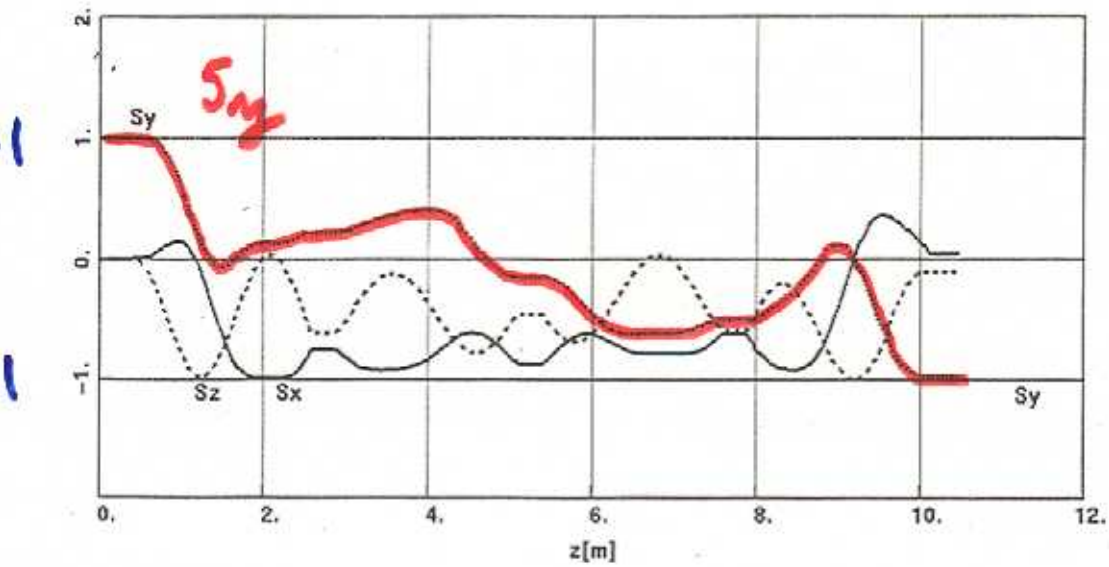


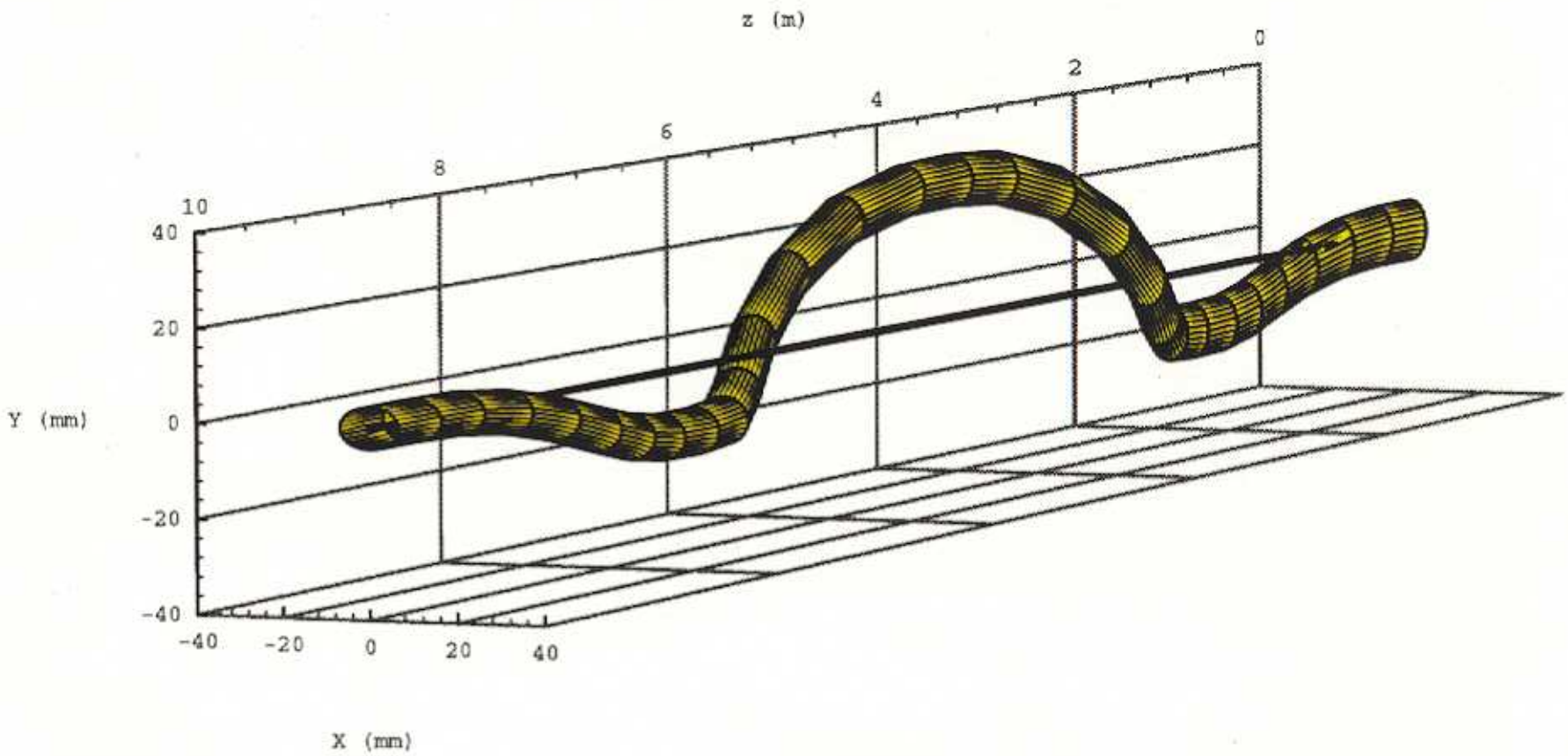
After 2 turns, polarisation is vertical!

Shatunov, Ptitsin (1993): use 4 helical dipoles → snake.

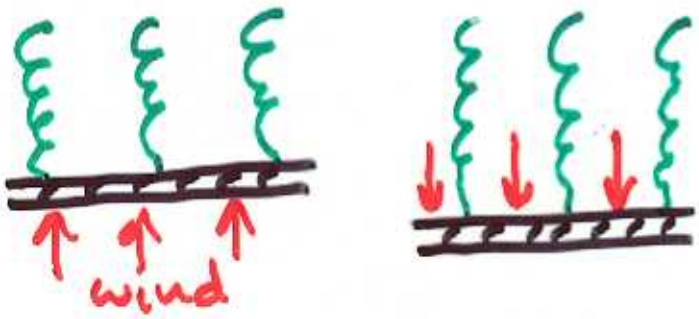


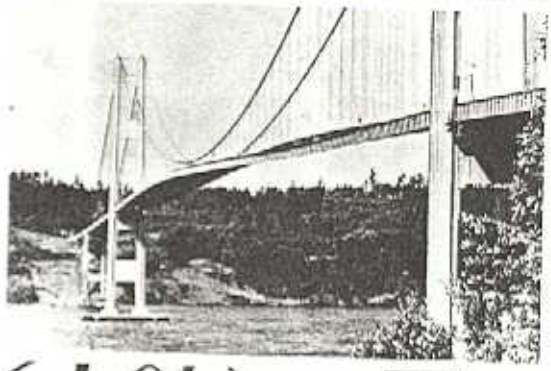


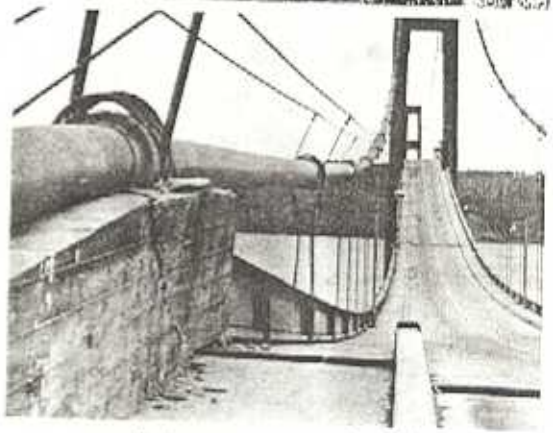


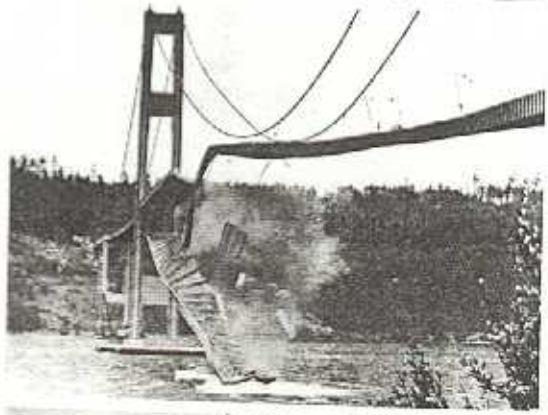

z (m)
0
2
4
6
8
10
40
20
0
-20
-40
Y (mm)
-40
-20
0
20
40
X (mm)

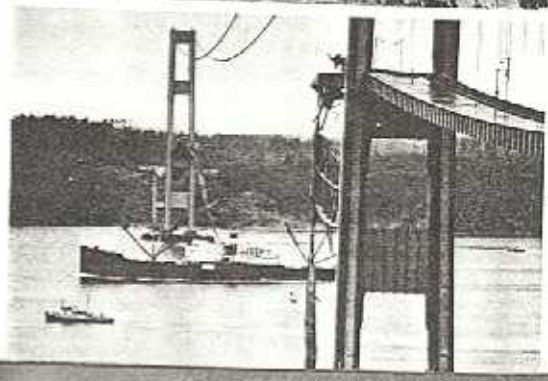
Consider another well-known resonance: the Tacoma Rapids Bridge in 1940:







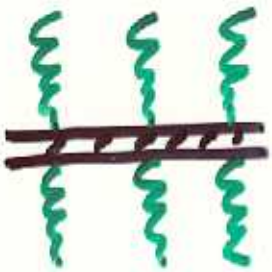


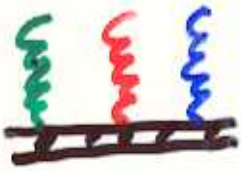


There are many solutions...

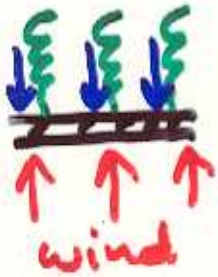
Bridge

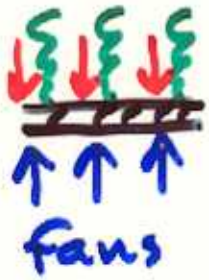
Polarized protons

① 

② 

use particles with different g-2 values

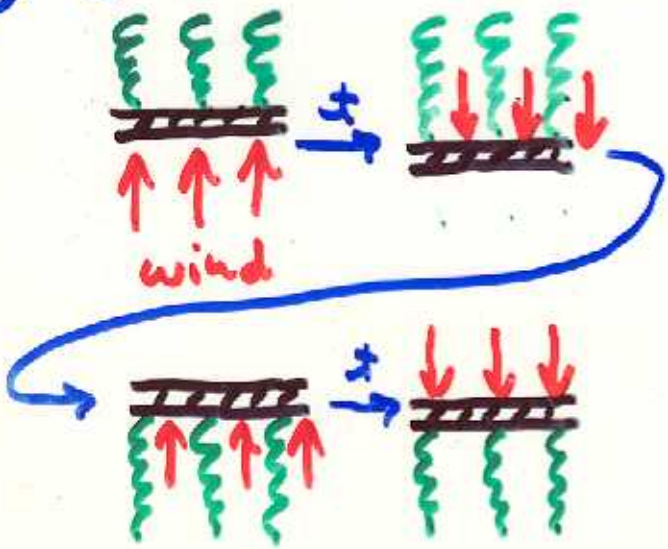
③ 



add in correction magnetic field

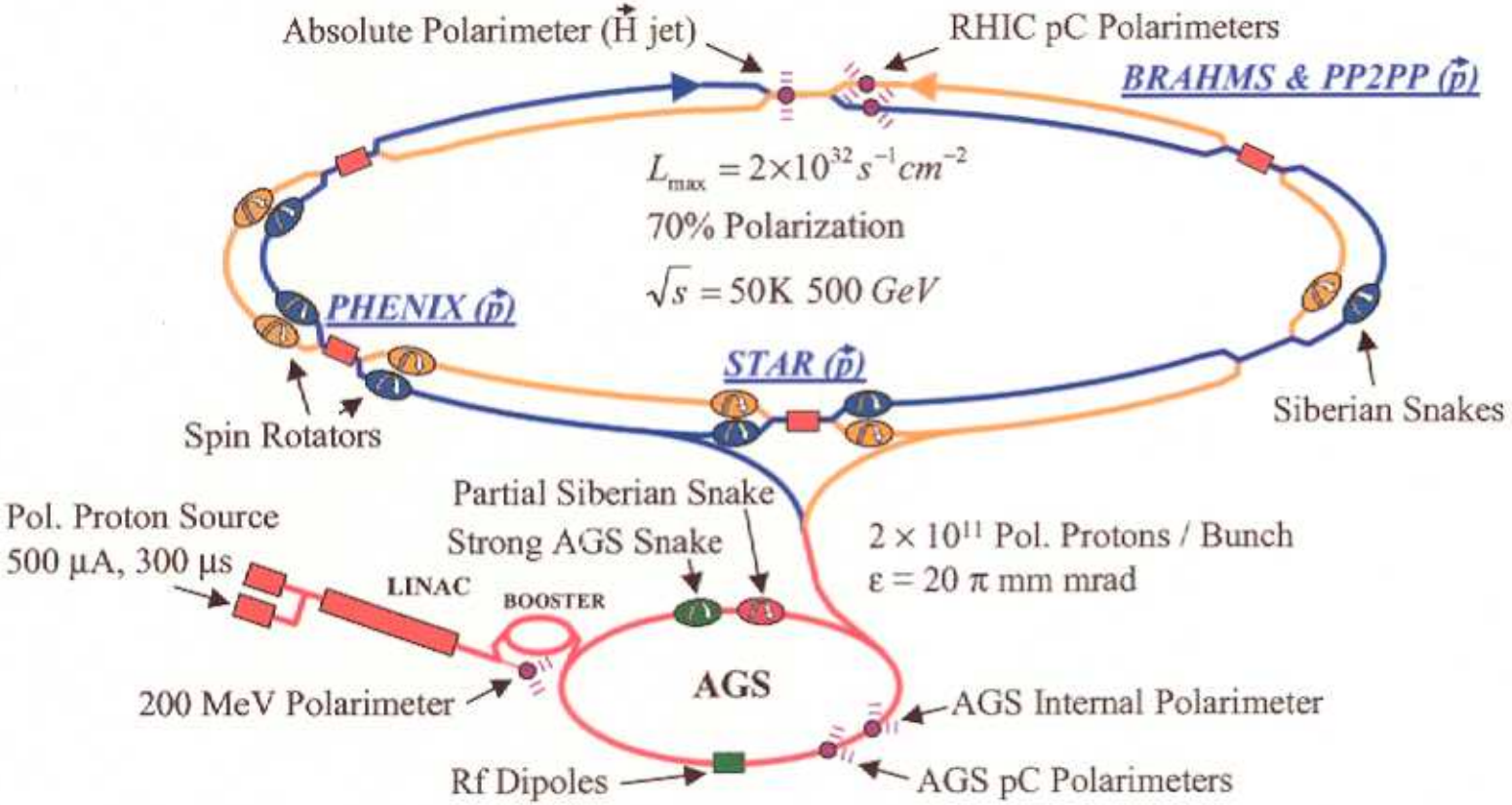
(AGS: 45 resonances × 96 correction dipoles → 1990)

④ (the Siberian solution)

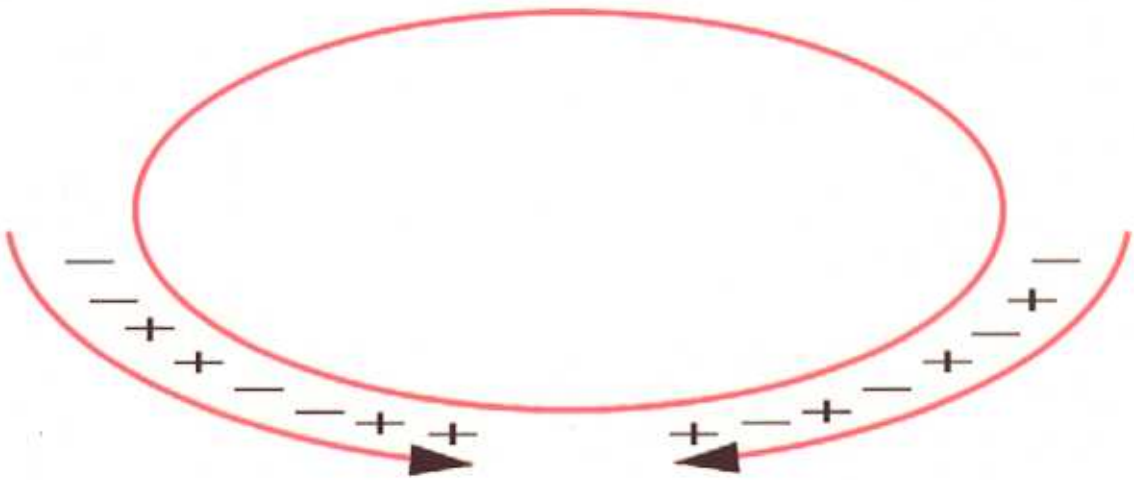


reverse the s_y component of the spin each pass around the accelerator

Polarized Proton Collisions in RHIC

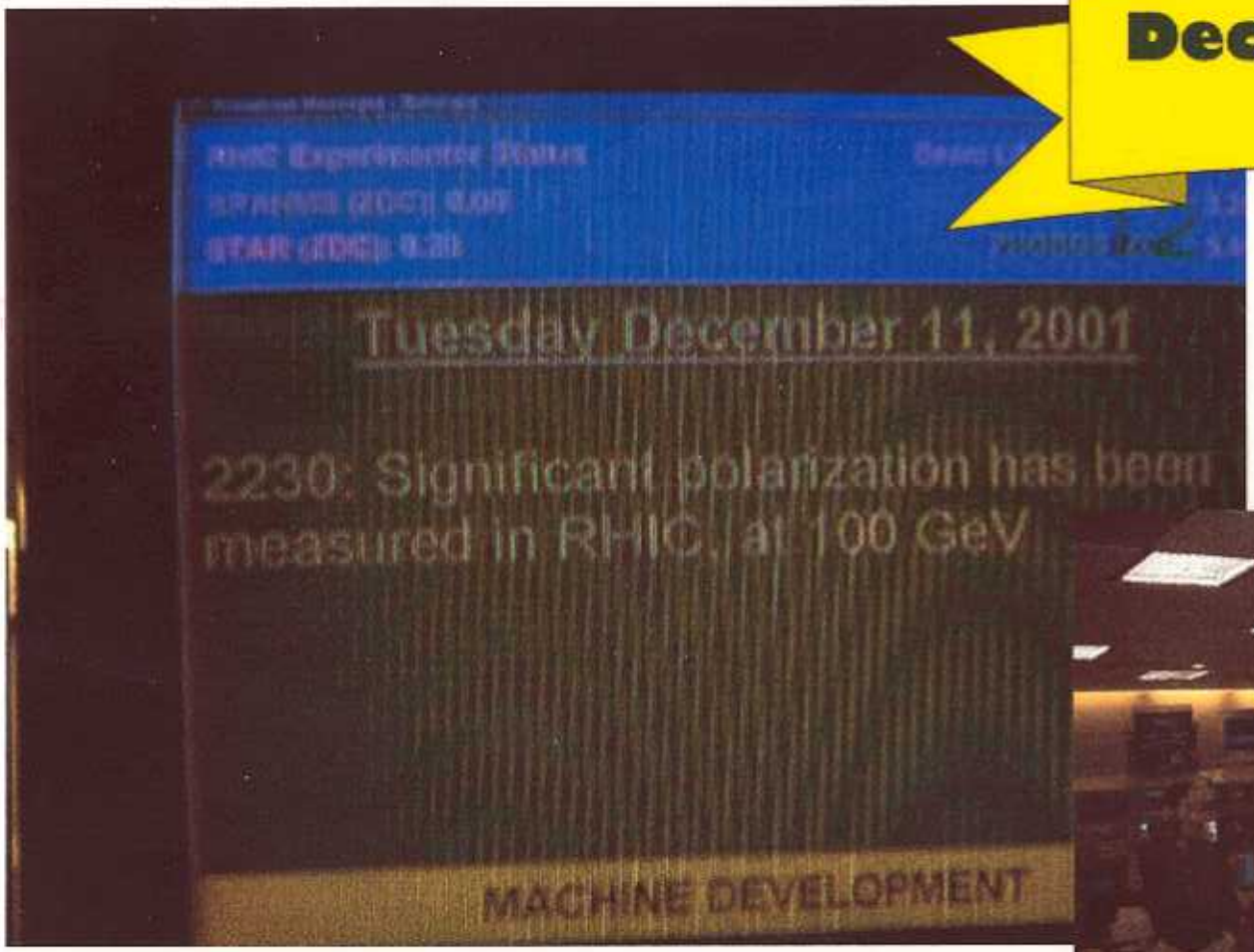


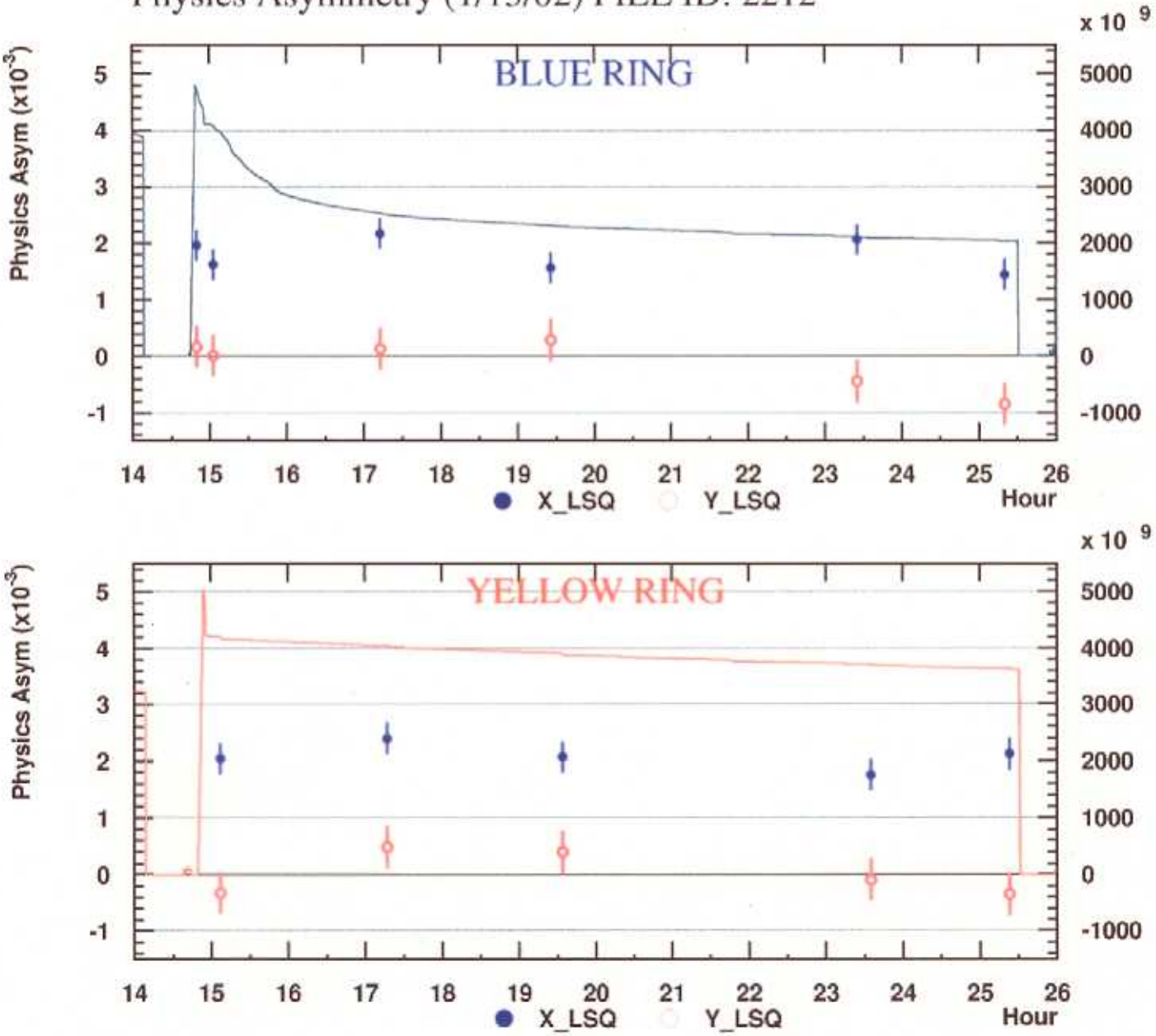
BROOKHAVEN
NATIONAL LABORATORY



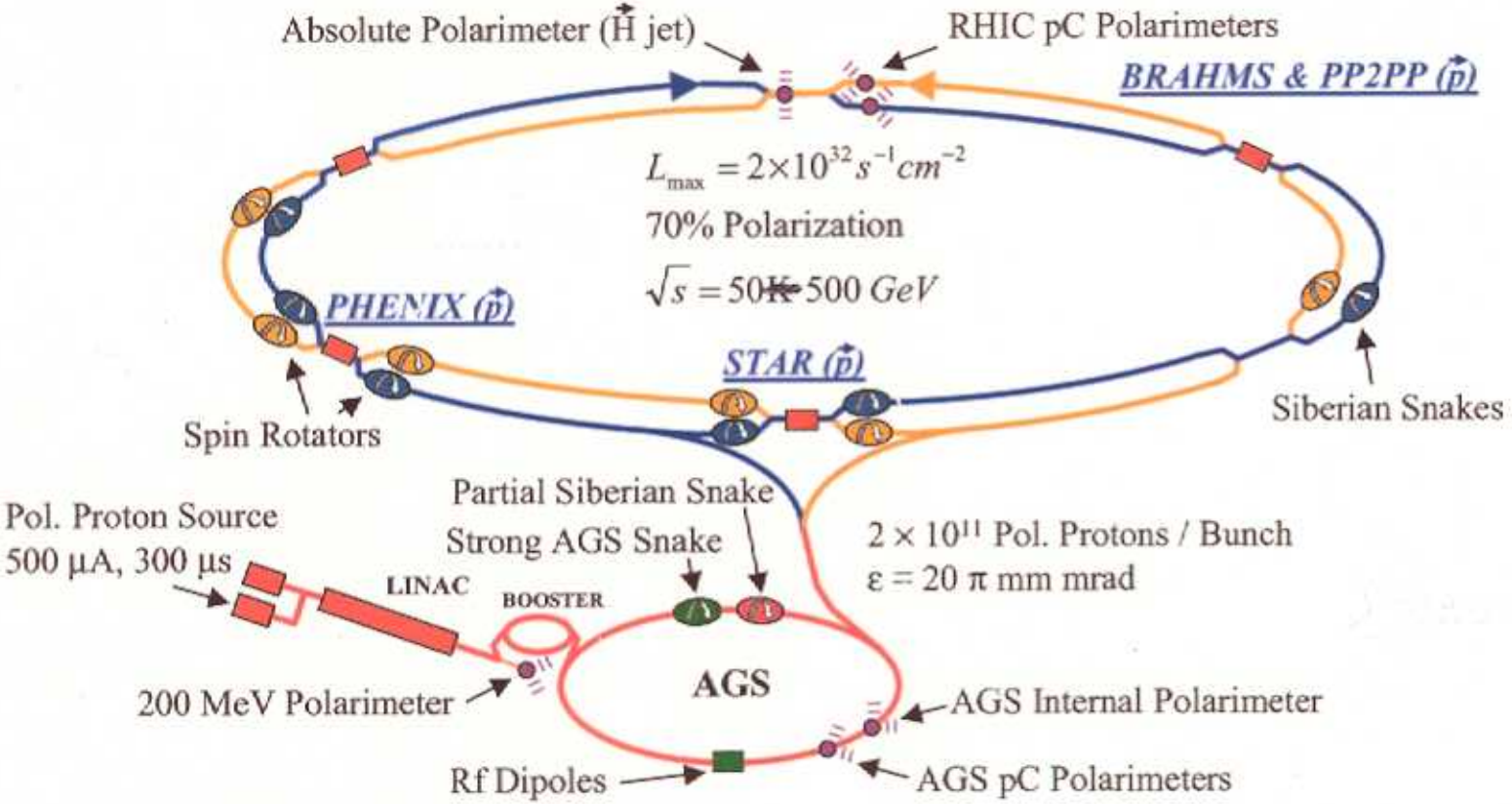
First polarized proton collisions

December 11th 2001




Physics Asymmetry (1/13/02) FILL ID: 2212
BLUE RING
YELLOW RING
Physics Asym (x10^{-3})
x 10 ^{9}
5
4
3
2
1
0
-1
5000
4000
3000
2000
1000
0
-1000
14
15
16
17
18
19
20
21
22
23
24
25
26
Hour
X_LSQ
Y_LSQ

Polarized Proton Collisions in RHIC



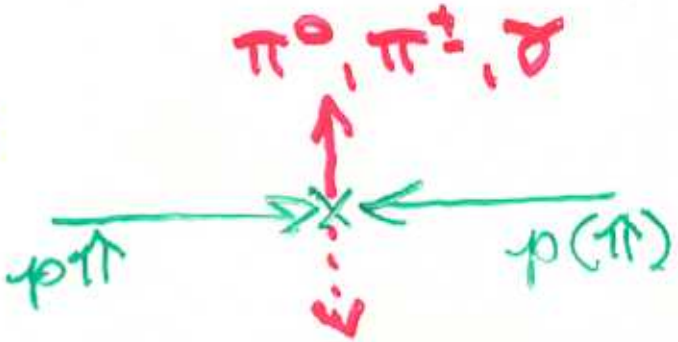
BROOKHAVEN
NATIONAL LABORATORY

The First RHIC Spin Run

$p\uparrow + p\uparrow \rightarrow \left.\begin{matrix}\pi^0 \\ \pi^{\pm} \\ n \\ p+p\end{matrix}\right\} + X$

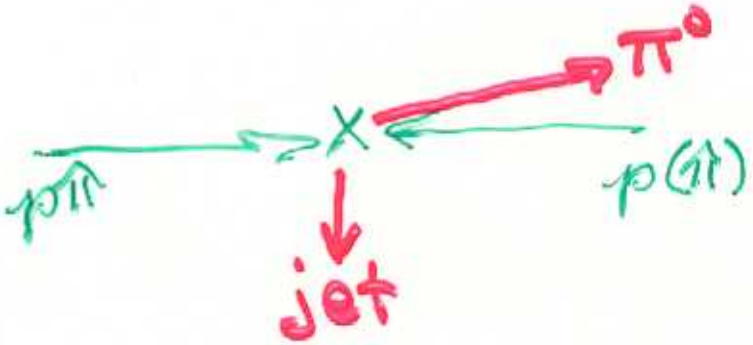
$\sqrt{s} = 200$

(1) mid-rapidity:



PHENIX, STAR

(2) forward:



STAR

(3) very forward:

Local Pol. (12 o'clock)

(4) elastic:

pp2pp

$-t \approx .005$

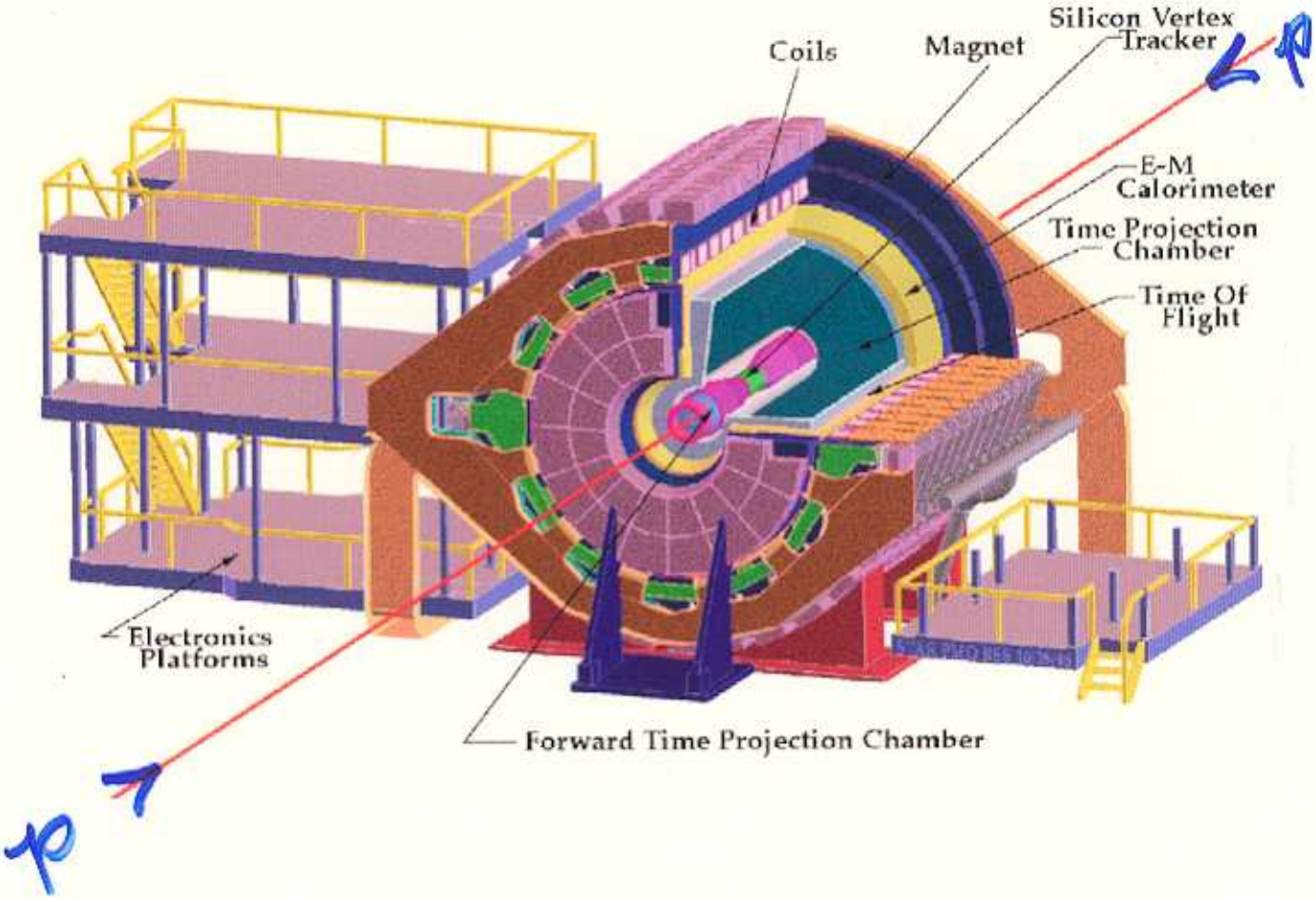
Yellow beam
polarized
(vertical)

Blue beam
unpolarized

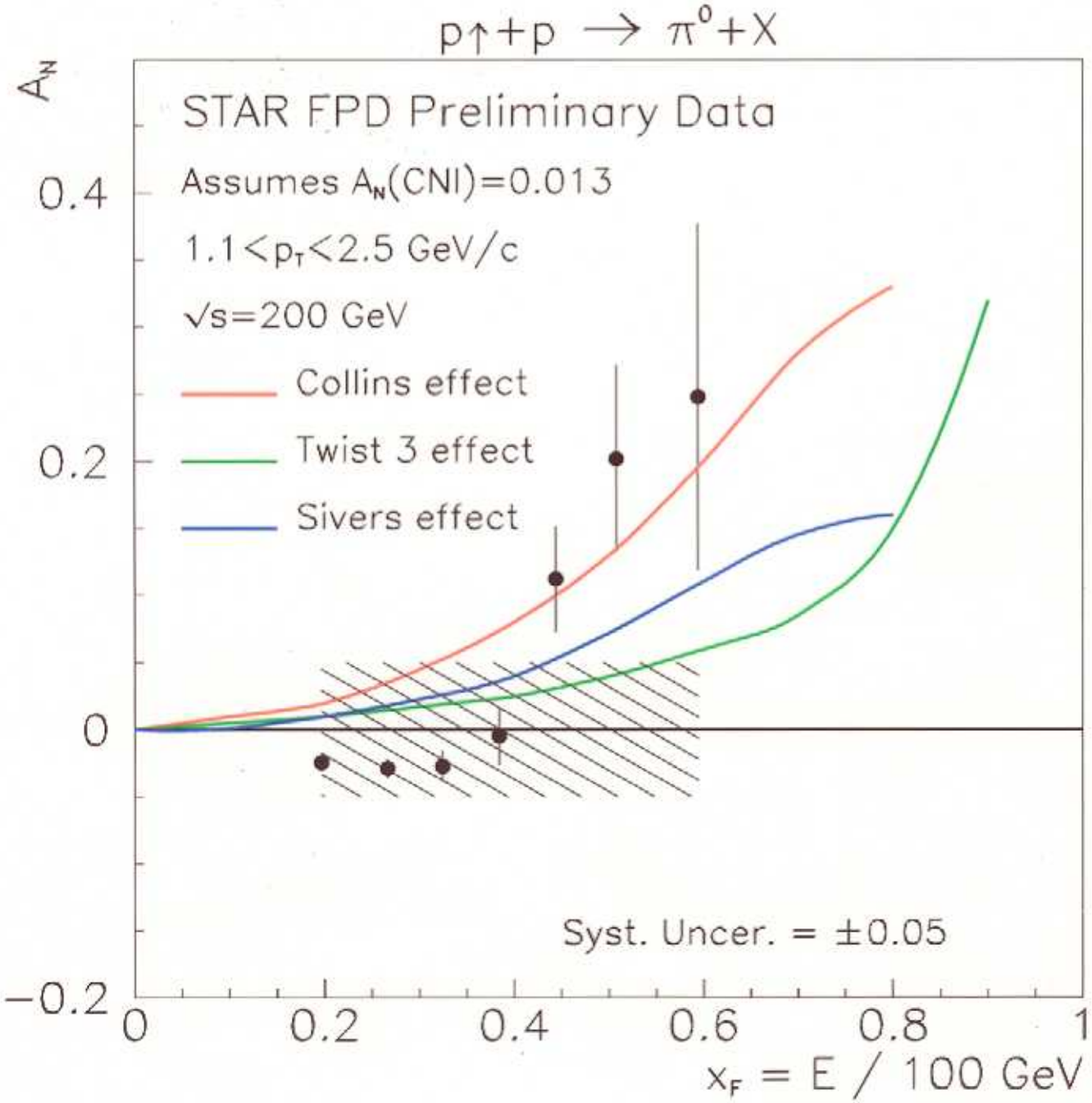
Forward "π^0" detector

$p\uparrow + p\uparrow \rightarrow \pi^0 X$
$\hookrightarrow \gamma + \gamma$

STAR Detector



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



Interesting! What is the physics?

neutron asymmetry:

- very forward, $p_T < .5$ GeV/c

$\Rightarrow$ definitely soft physics

$p\uparrow + p \to \Delta + X$ (or basically exclusive (?))

$\hookrightarrow n + \pi$

(small asymmetry is also seen in the beam-beam counters at STAR — ?)

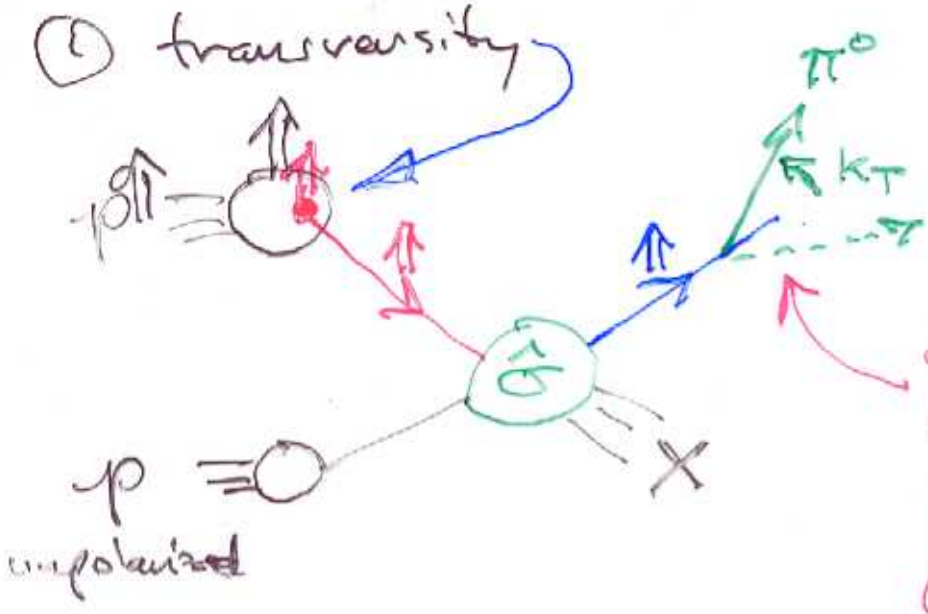
π^0 asymmetry:

- p_T 1.5-3 GeV/c, large x_F
  - just like $\sqrt{s} = 20$ GeV
  - but $\left.\frac{N_{jets}(\pi^0)}{N(\pi^0)}\right|_{\sqrt{s}=200} = 5 \times \left.\frac{N_{jets}(\pi^0)}{N(\pi^0)}\right|_{\sqrt{s}=20}$
    - just from Pythia
      - real model of hard physics
      - hand-tweaked model of soft physics $\Rightarrow$ correct σ

π^0 asymmetry (cont.)

Models:

(1) transversity

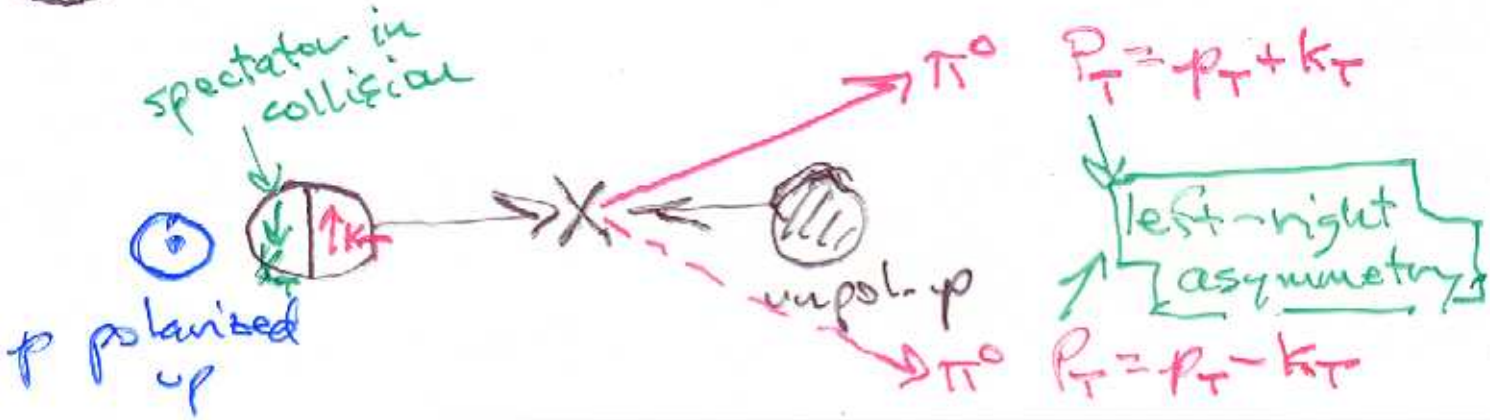


analysing power of π^0 from polarized quarks (Heppelmann-Collins)

- many "buts"
- $e^+e^- \to q\uparrow \bar{q}\uparrow$ → π, π } correlation ← to be done at Belle

(earlier study $A_N \sim .05$, but kinematics?)

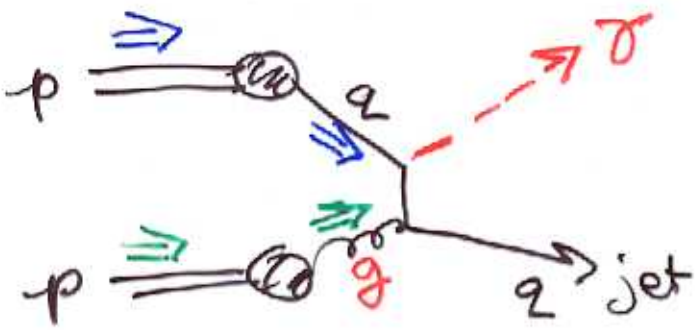
(2) initial state effect from k_T



RHIC Spin Probes

Gluon polarization:

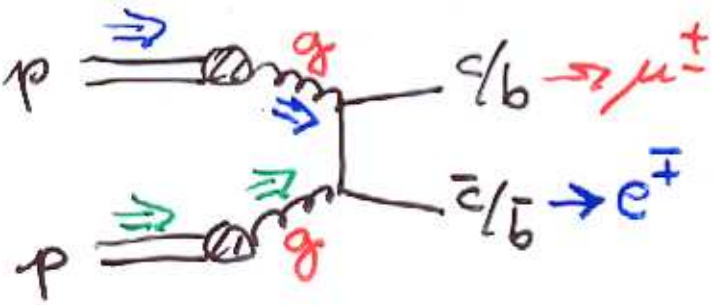
$$A_{LL} = \frac{1}{P^2}\frac{N_{++}(\phi) - N_{+-}(\phi)}{N_{++} + N_{+-}}$$



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

(.3) (.6)

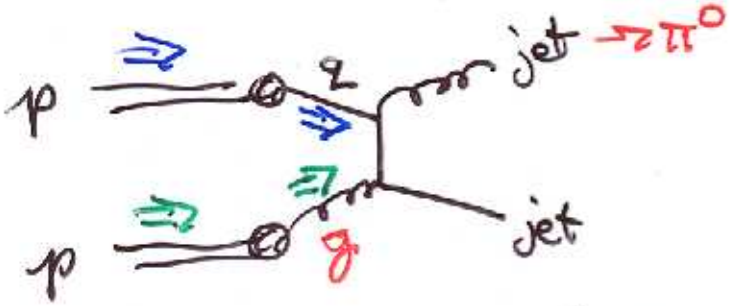
$$\simeq \frac{1}{5}\frac{\Delta G}{G}(x_g)$$



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

(.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)

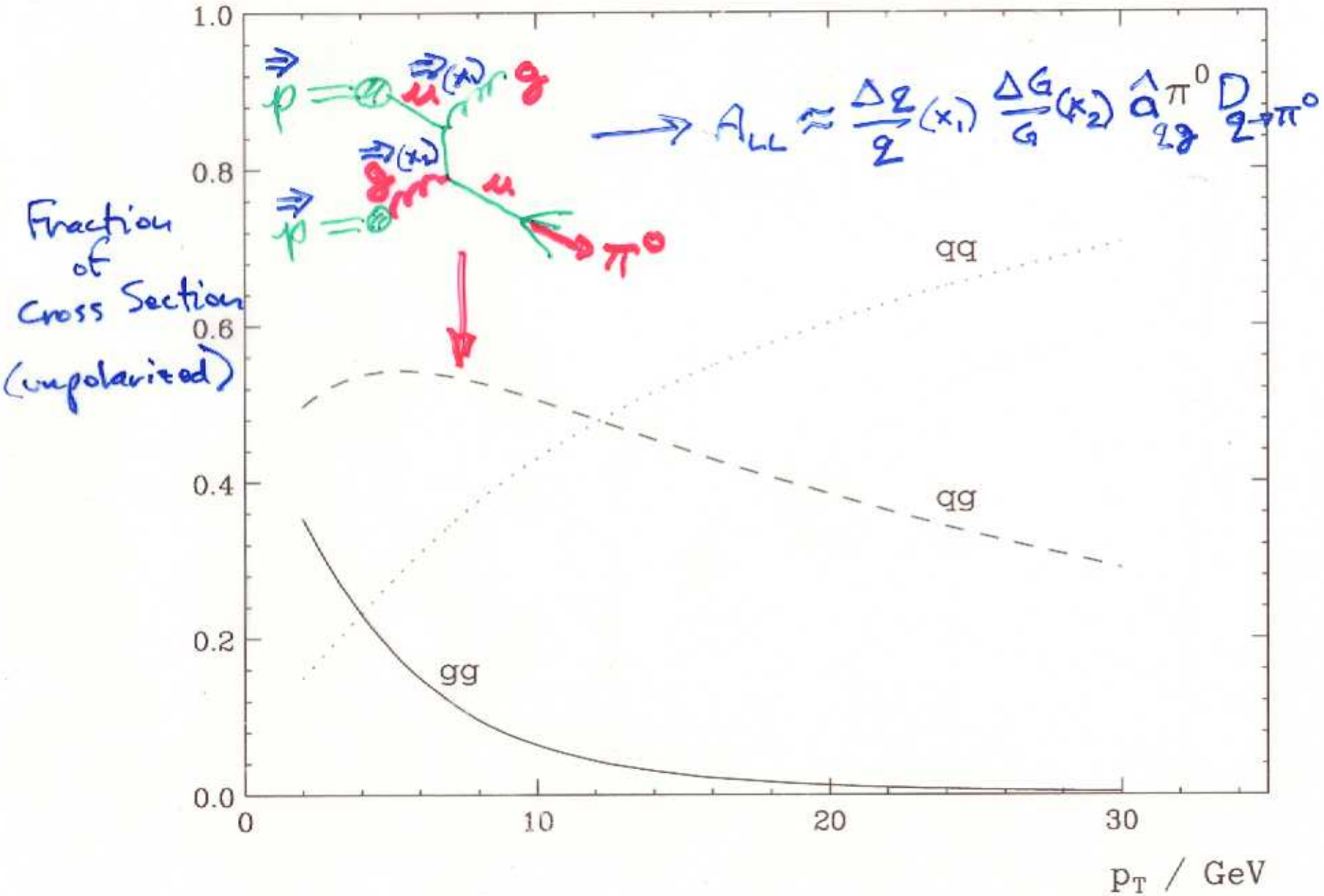
$$\simeq \frac{1}{4}\frac{\Delta G}{G}(x_1)$$

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

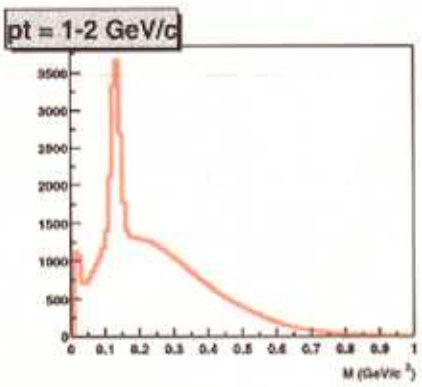
also J/ψ (but production mechanism)

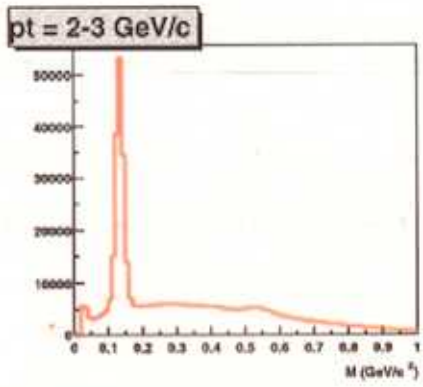
2003: π^0 as a jet surrogate to observe/measure/constrain gluon polarization.

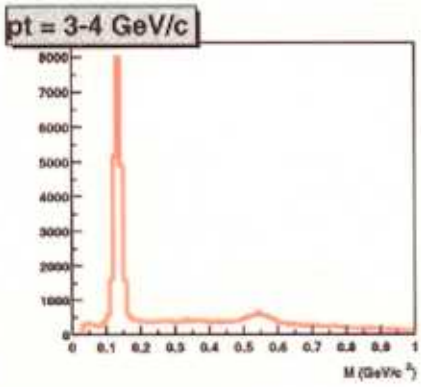
$\sqrt{s} = 200$

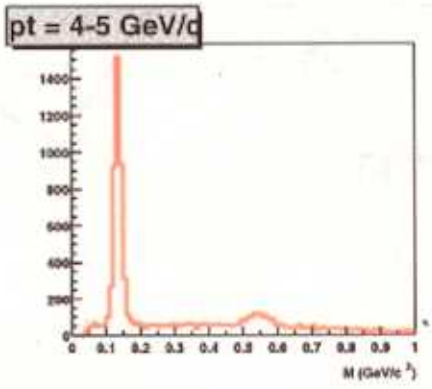


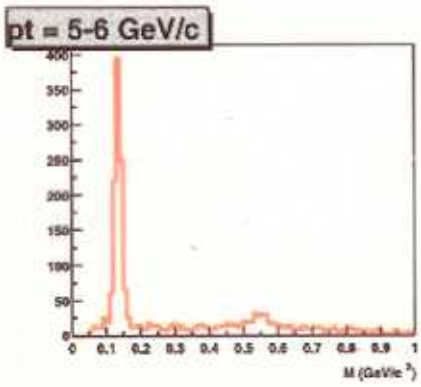
PHENIX π0 Reconstruction

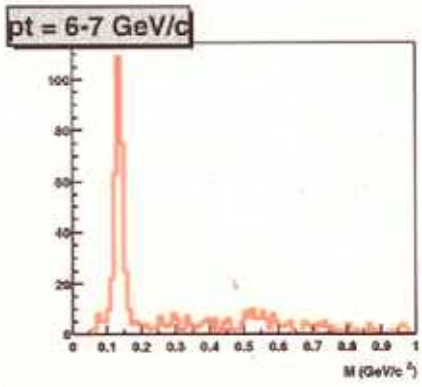


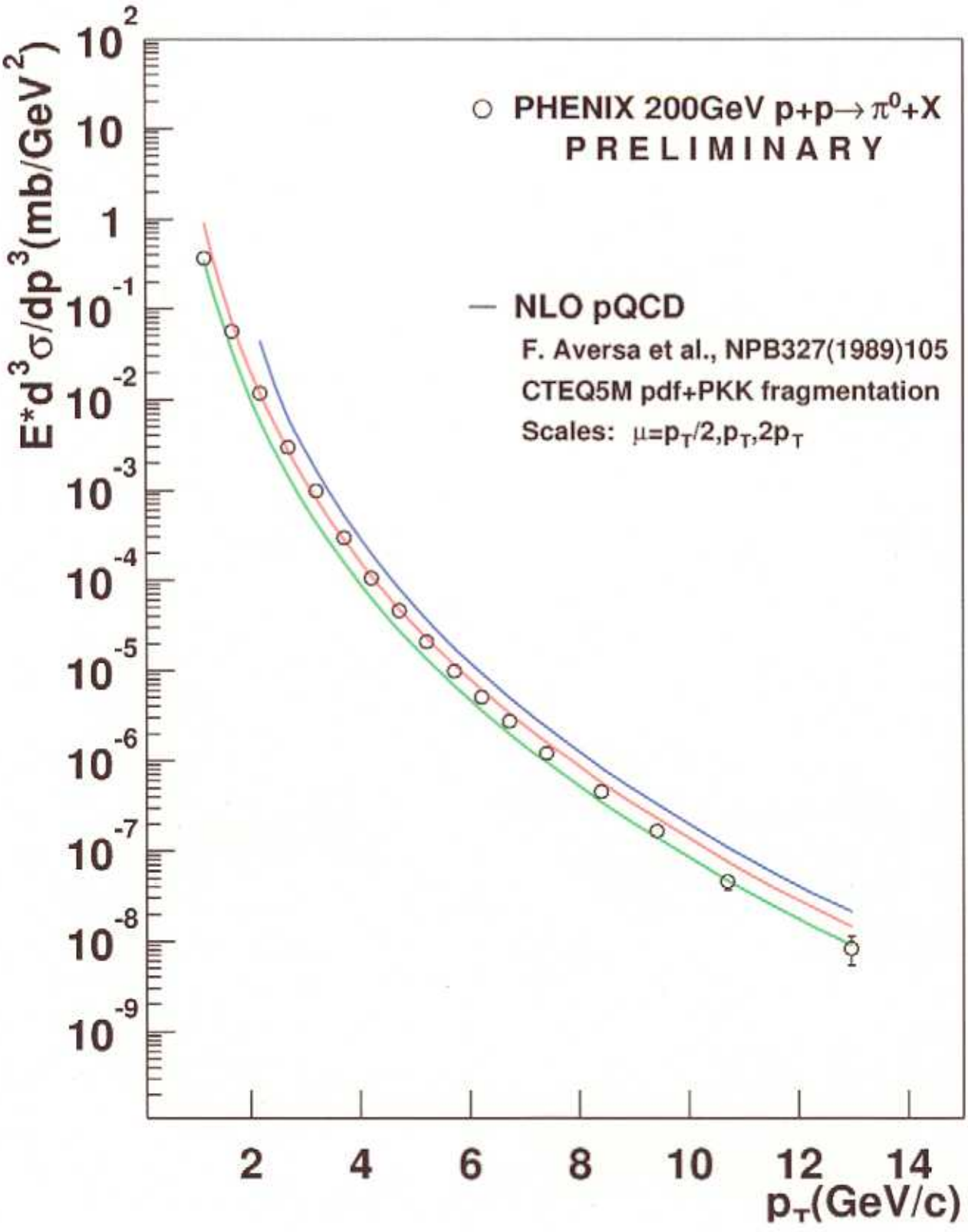




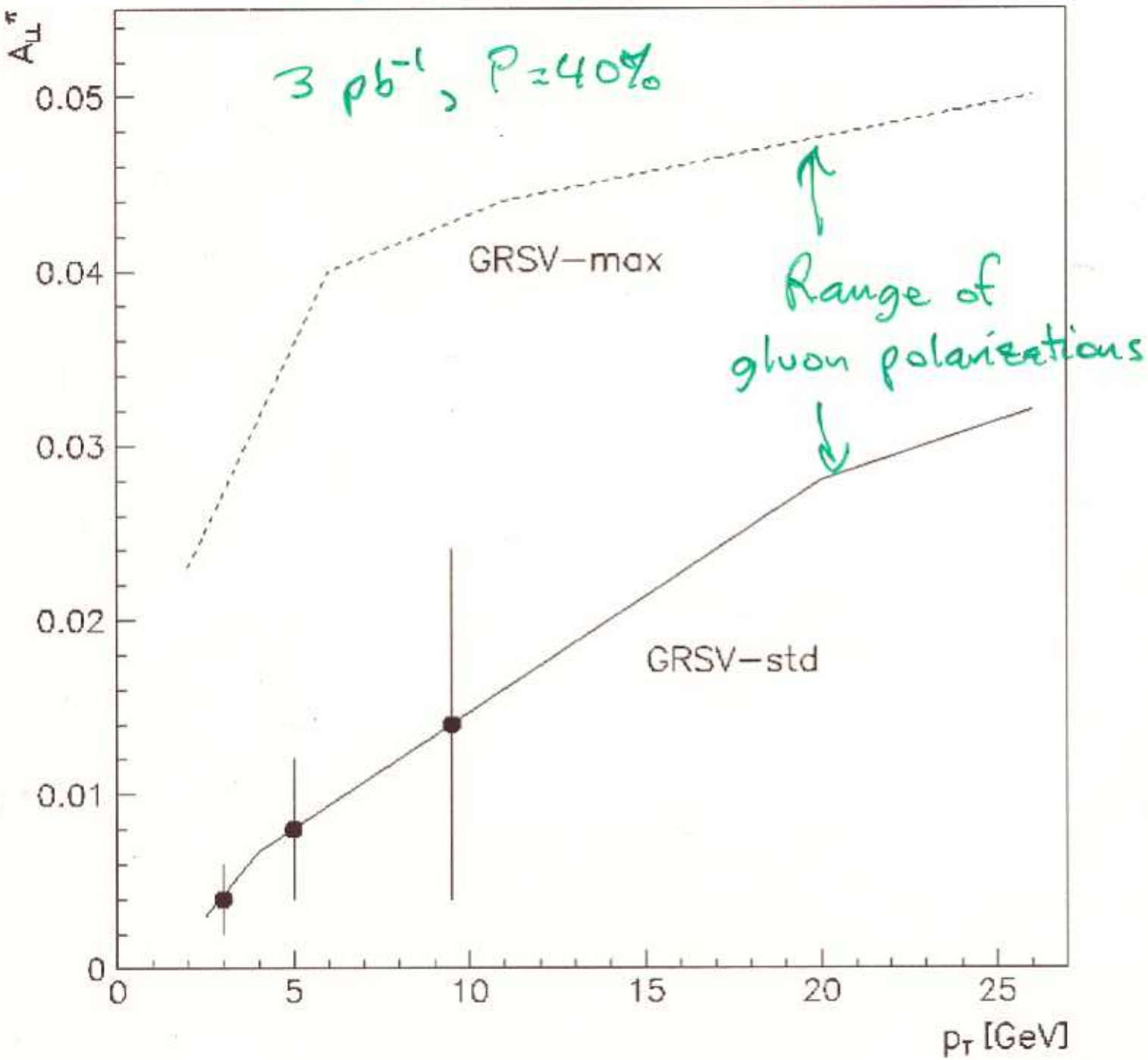






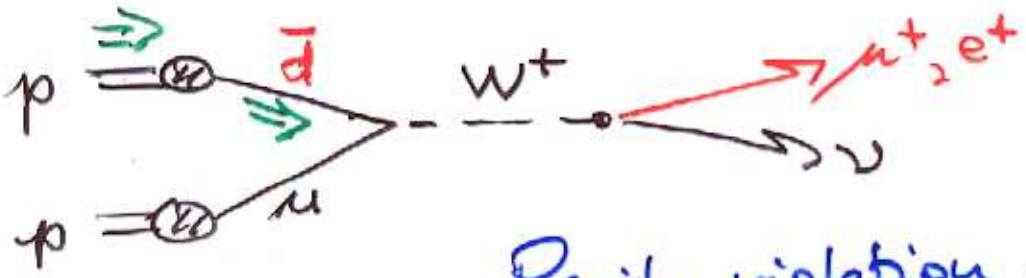

○ PHENIX 200GeV p+p→ π⁰+X
PRELIMINARY
— NLO pQCD
F. Aversa et al., NPB327(1989)105
CTEQ5M pdf+PKK fragmentation
Scales: μ=p_T/2,p_T,2p_T
E*d³σ/dp³(mb/GeV²)
p_T(GeV/c)

Phenix π^0 for 2003



Probes (cont.)

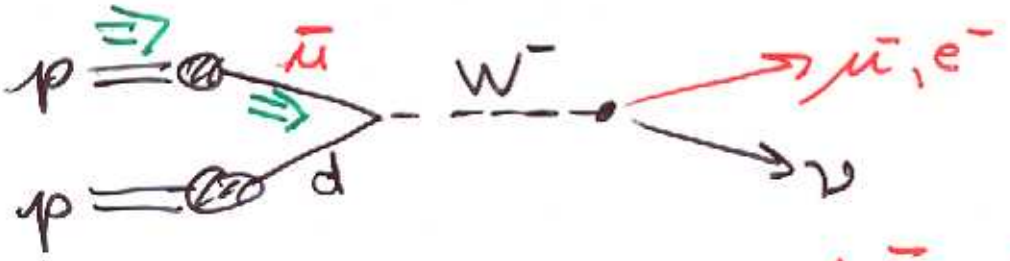
Quark polarization by flavor



Parity violation of W production

$A_L \approx \frac{\Delta \bar{d}}{\bar{d}}$ for W^+ backward from polarized p

$A_L \approx \frac{\Delta u}{u}$ for forward W^+



$A_L \approx \frac{\Delta \bar{u}}{\bar{u}}$ for W^- backward.

$A_L \approx \frac{\Delta d}{d}$ for W^- forward.

Search for new physics using parity violation

From M. Tannenbaum:

Criteria for The Maximum Discovery Potential:

- Look where most theorists predict that nothing will be found.
- Look in a channel where the known rates from conventional processes are small, since low background implies high sensitivity for something new.
- Be the first to explore a new domain—something that has never been measured by anybody else.

Almost any model for new physics violates parity since any new mass scale $\Lambda > M_W$.

Example: CDF search for quark substructure in high p_T jet production...

What will we learn from all of this?

(1) $\Delta q + \Delta \bar{q}$ small – DIS ✓

(2) $\frac{\Delta G}{G}$ small → L_{orbit} large (!?)

large → why? (T.P. Lee: connection to confinement → violates chirality)

(3) $\Delta \bar{q}$ small – expected naively

large → why? (Chiral quark soliton model?)

(4) $\Delta \bar{u} = \Delta \bar{d}$ – naively expected

$\gg \Delta \bar{d}$ – CQSM? why?

$\ll \Delta \bar{d}$ → why?

} $\bar{d} \gg \bar{u}$ known why?

(5) beyond standard model (quark substructure, Z', ...)

(6) DIS + RHIC (+ EIC)

→ comprehensive tests of factorization, universality of structure functions, scales, ...