A Discussion on the beauty of spin

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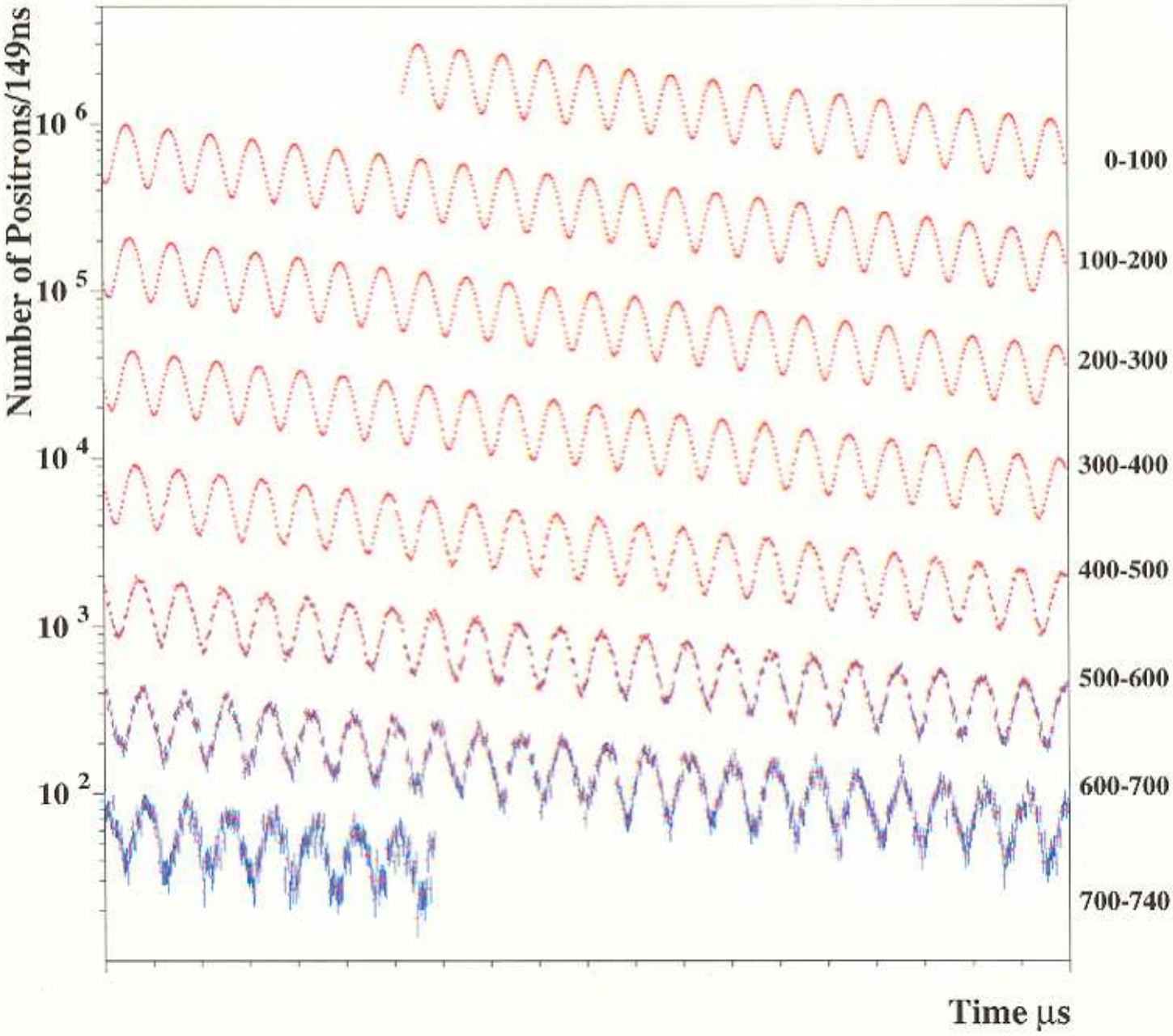
- Why spin?
- $p\uparrow + p\uparrow$ and RHIC
- Siberian Snakes
- How do we measure the polarization of the beams?
- First (surprising) results from $\overrightarrow{\text{RHIC}}$
- Where are we going?

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
  - $\vec{p} = \underbrace{\vec{q} + \vec{\bar{q}}}_{\sim 1/4 \text{ of proton spin!}} + \vec{g} + L_{orbital}$

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 <u>never</u> 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 $\rightarrow$ $\vec{p}$ 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

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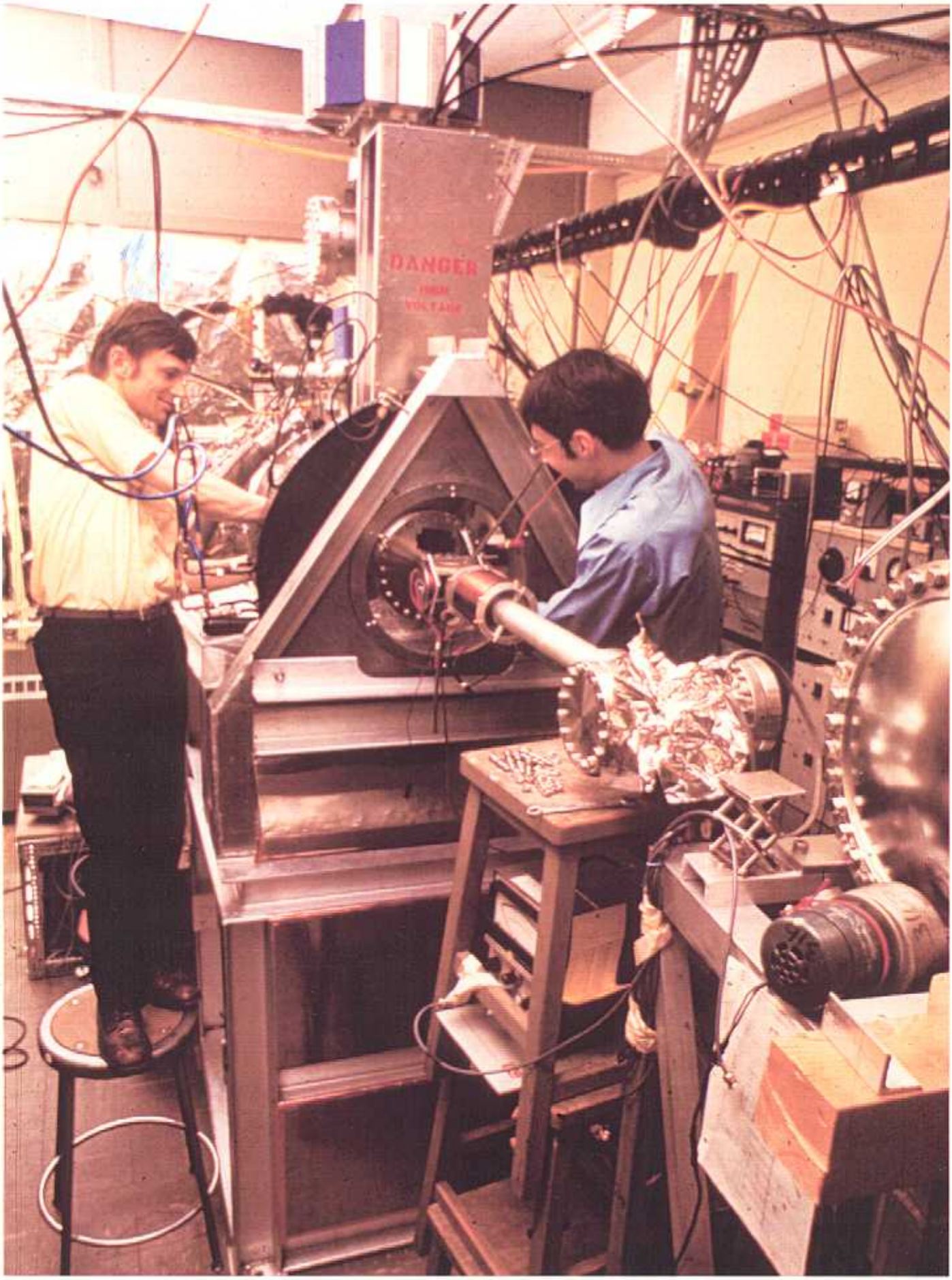
③ Quark model for spin of proton

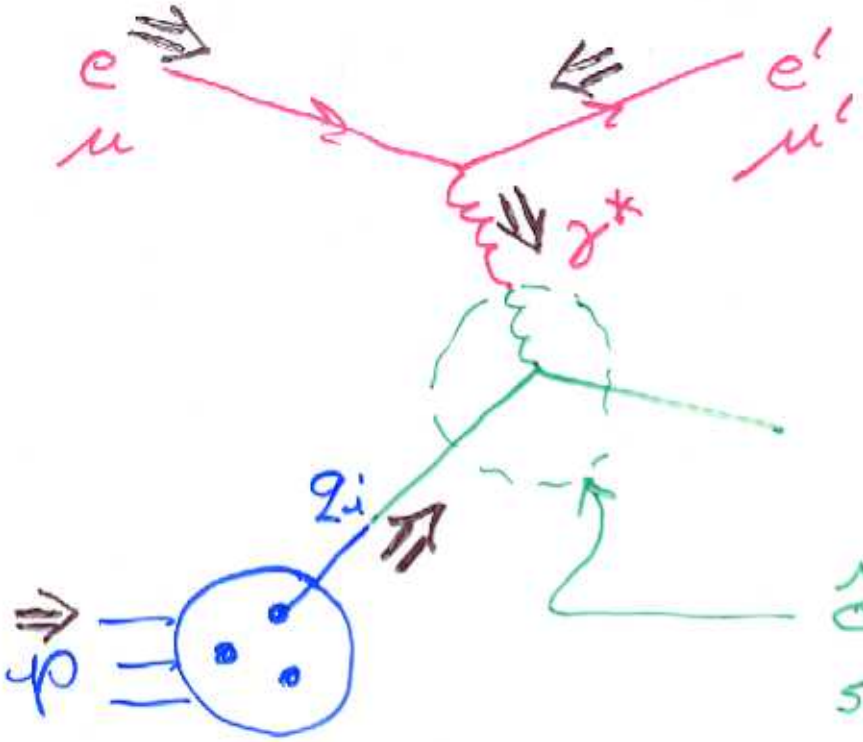
p spin $\frac{1}{2}$, from valence quarks

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:

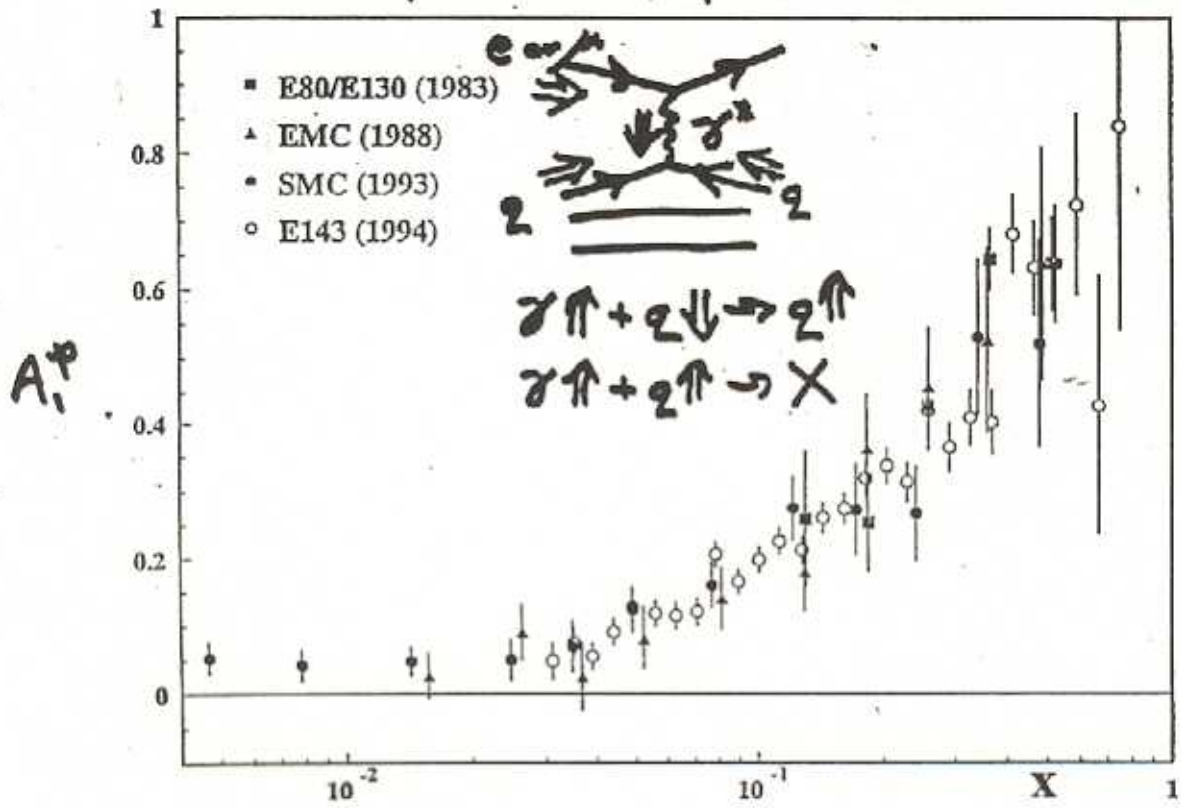
$$\underbrace{\vec{\gamma} + \vec{q}_i}_{\text{spin } 3/2} \rightarrow X$$

$$\underbrace{\vec{\gamma} + \overleftarrow{q}_i}_{\text{spin } +1/2} \rightarrow \underbrace{\vec{q}_i}_{+1/2}$$

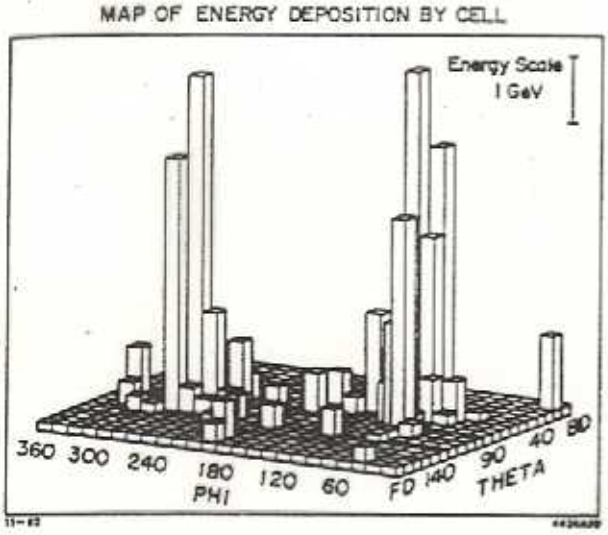
The electron helicity selects the <u>opposite</u> helicity quark in proton.

→ tool to probe proton spin structure!

At large X, quarks <u>do</u> 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:

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

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 <u>unknown</u>

RHIC: polarized quarks in one $\vec{p}$
probe polarisation 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: $p\Uparrow + p\Uparrow$ and RHIC

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

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

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

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

④ RHIC: collide $p\Uparrow + p\Uparrow$
- effective energy $\boxed{\sqrt{s} = 200 - 500 \text{ GeV}}$

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

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

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

$$\boxed{\frac{\sigma_{\Uparrow\Uparrow}}{\sigma_{\Uparrow\Downarrow}} = 4}$$

$p_T = 2.3$ GeV/c

② at Fermilab, $p + A \to \Lambda\Uparrow + X$

$$\boxed{\frac{N(\Lambda\Uparrow)}{N(\Lambda\Downarrow)} = 2}$$

$p_{protons} = 300$ GeV

$p_T(\Lambda) \gtrsim 1$ 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, $p\Uparrow + p \to \pi^{\pm} + X$

$$\boxed{\frac{N(\pi^{+}\text{ left}, p\Uparrow)}{N(\pi^{+}\text{ left}, p\Downarrow)} = 2.3}$$

$p_{protons} = 200$ GeV

$p_{\perp}(\pi) \simeq 1.5$ GeV/c

$x_F(\pi) = 0.8$

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

→ <u>spin effects are large at high energy.</u>

pp elastic scattering ~1976

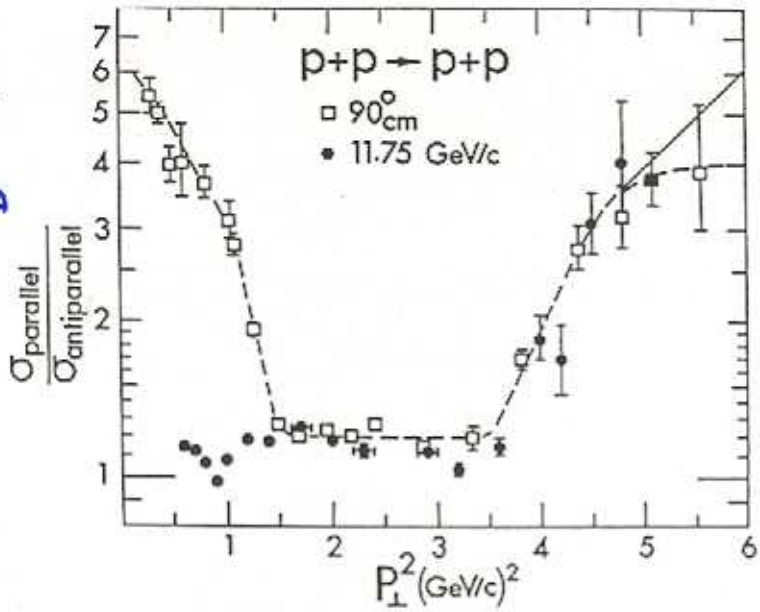


Fig. 3. Ratio of spin-parallel to spin-antiparallel p-p elastic cross-sections plotted against $P_\perp^2$ for fixed energy and fixed angle experiments.

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

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

N_{left} / N_{Right}

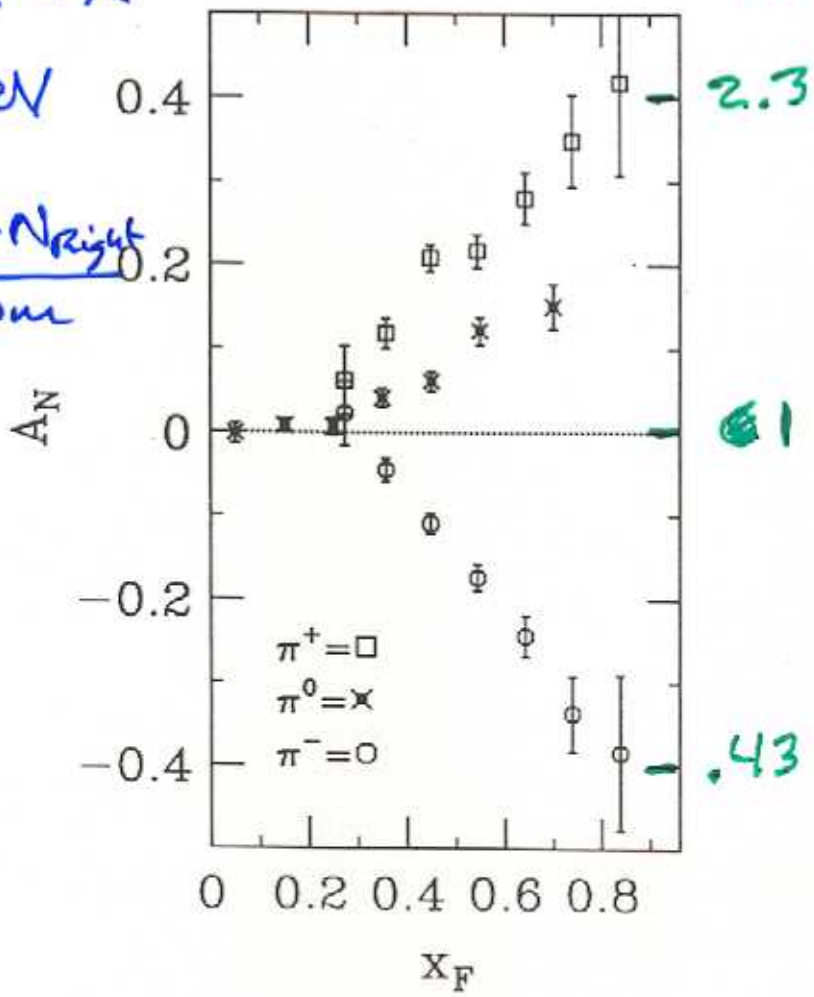


Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.

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

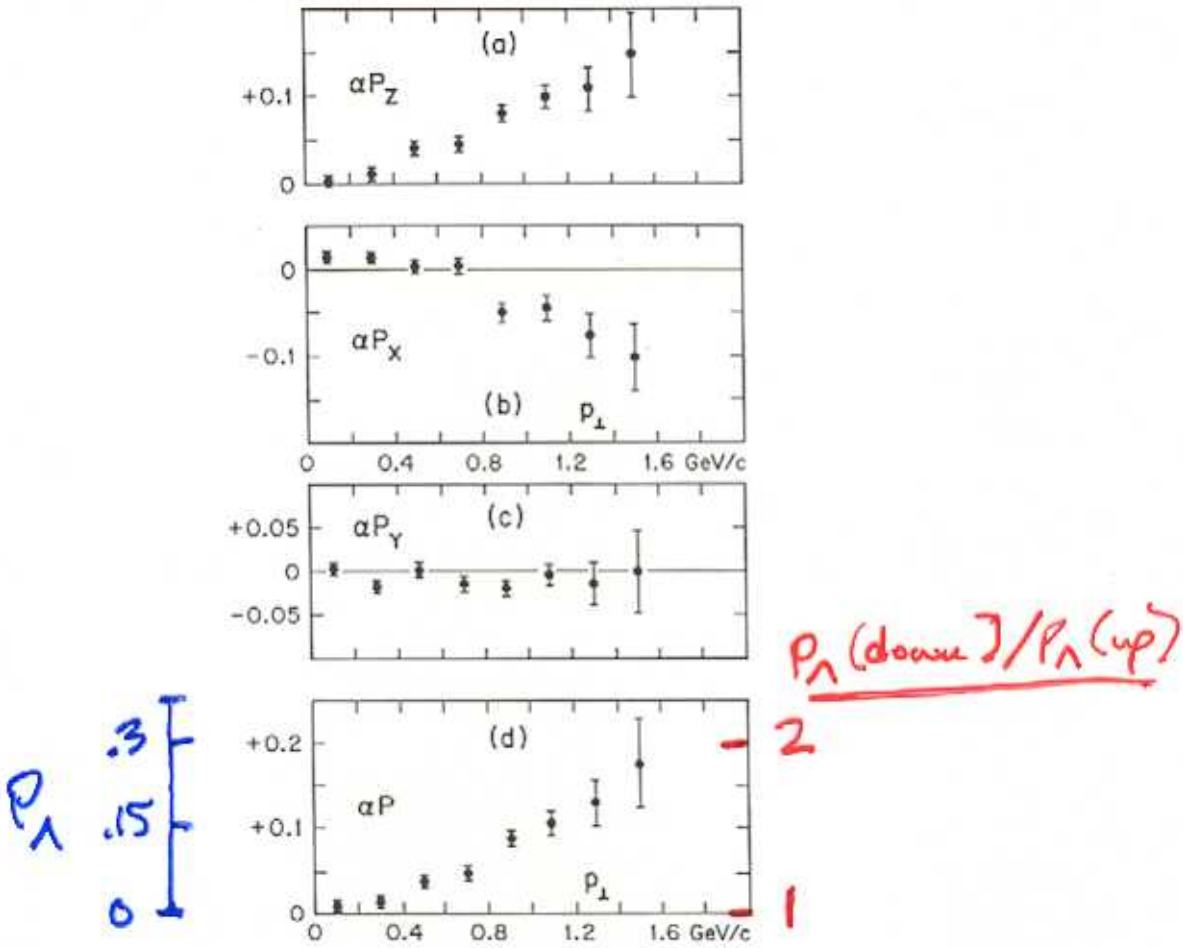
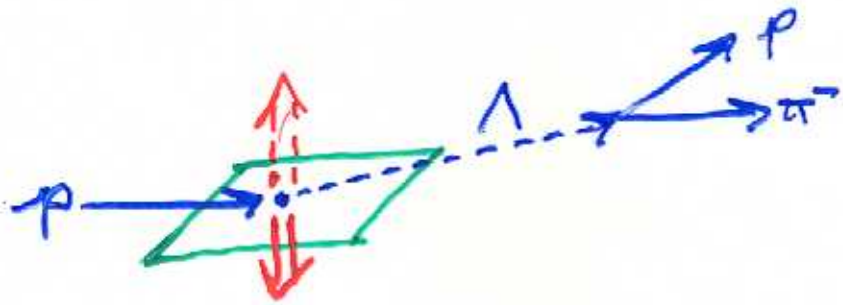


FIG. 3. Three components and magnitude of the $\Lambda^0 \to p + \pi^-$ asymmetry as a function of Λ^0 transverse momentum.



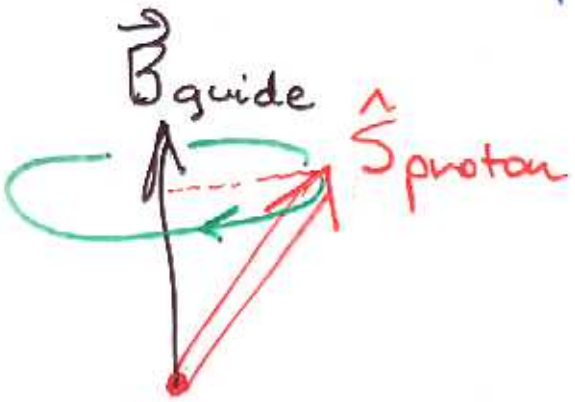
Siberian Snakes

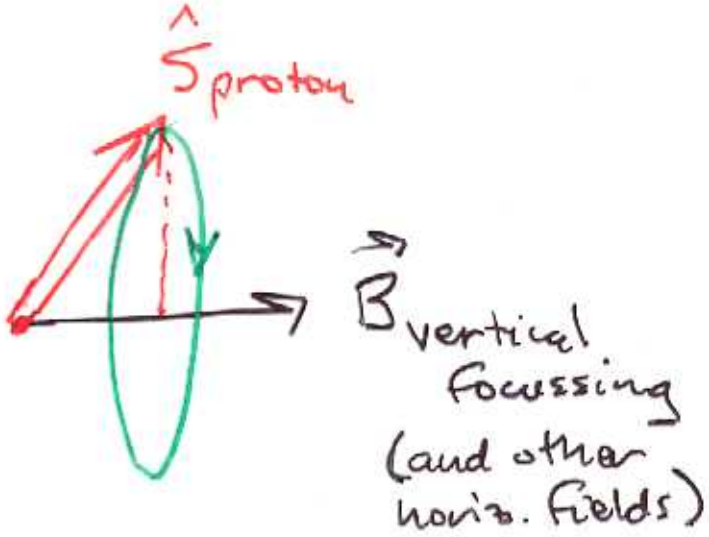
$$\left.\frac{g-2}{2}\right|_{e,\mu} \approx .001 \qquad \left.\frac{g-2}{2}\right|_{\text{proton}} \approx 2$$

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 <u>200 x</u> per turn!

What are spin resonances?





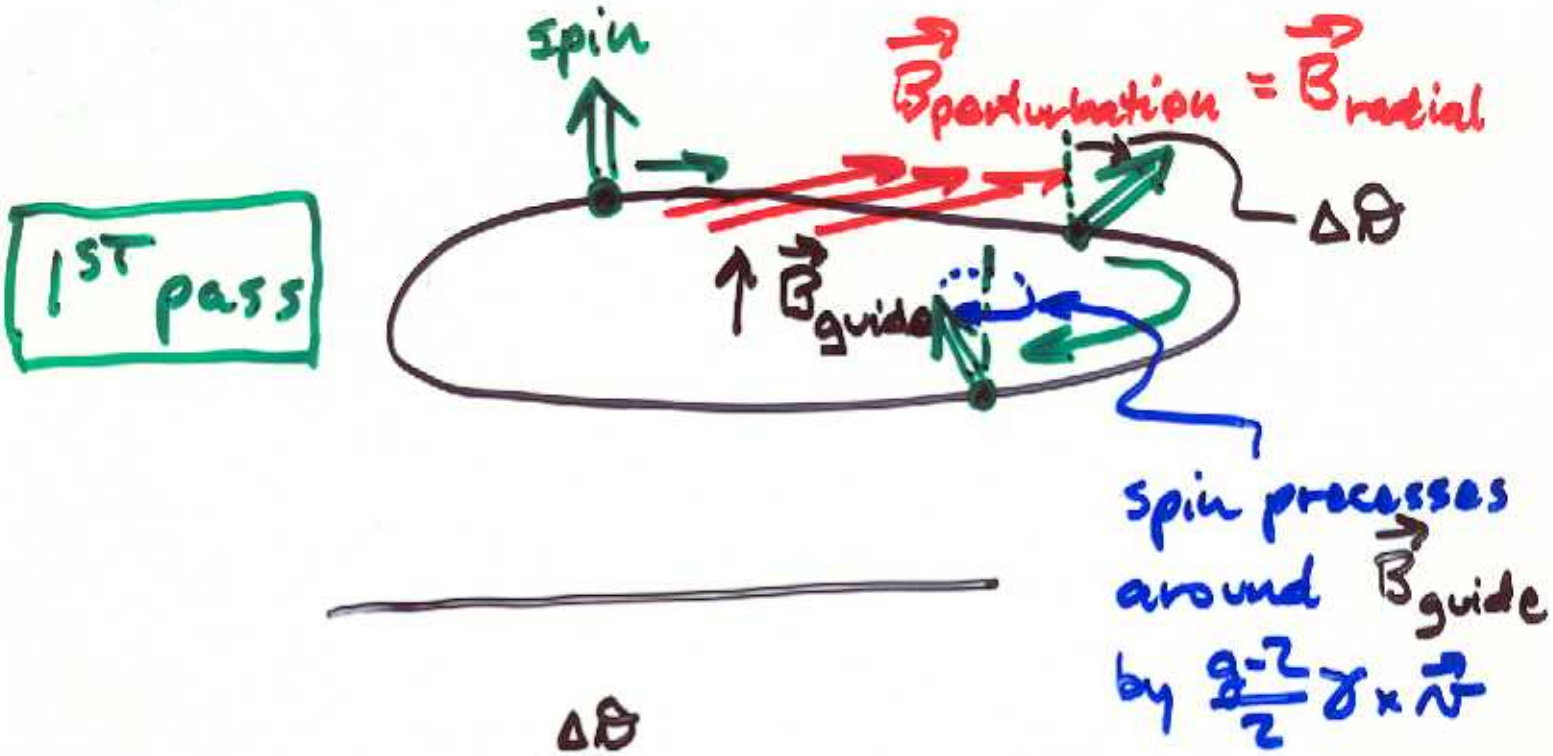
When the two are in phase → spin resonance.

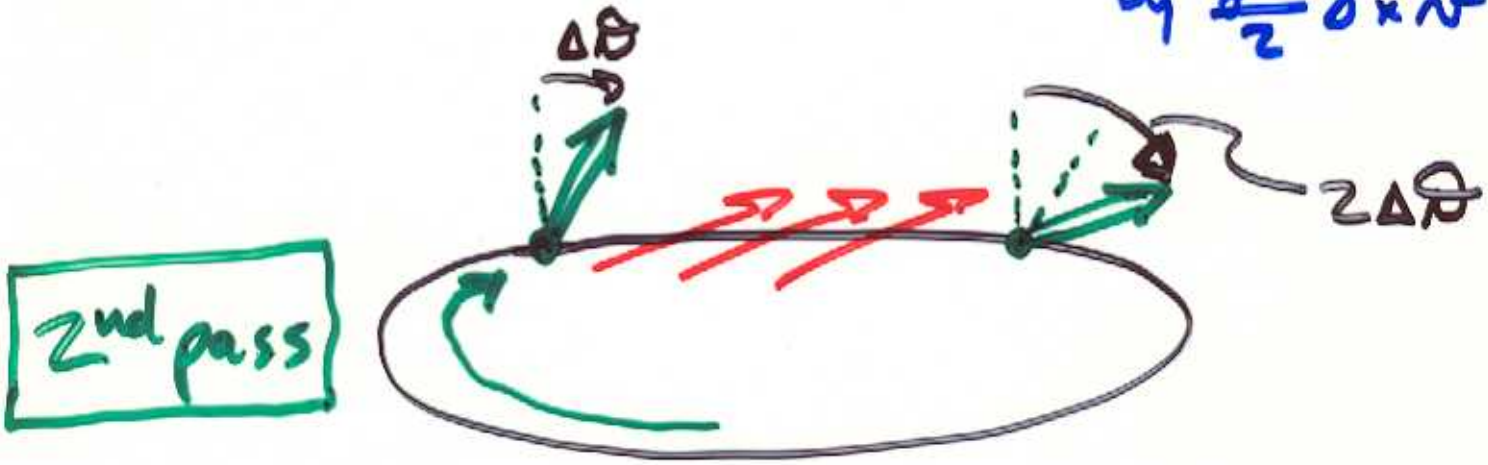
Several solutions:

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

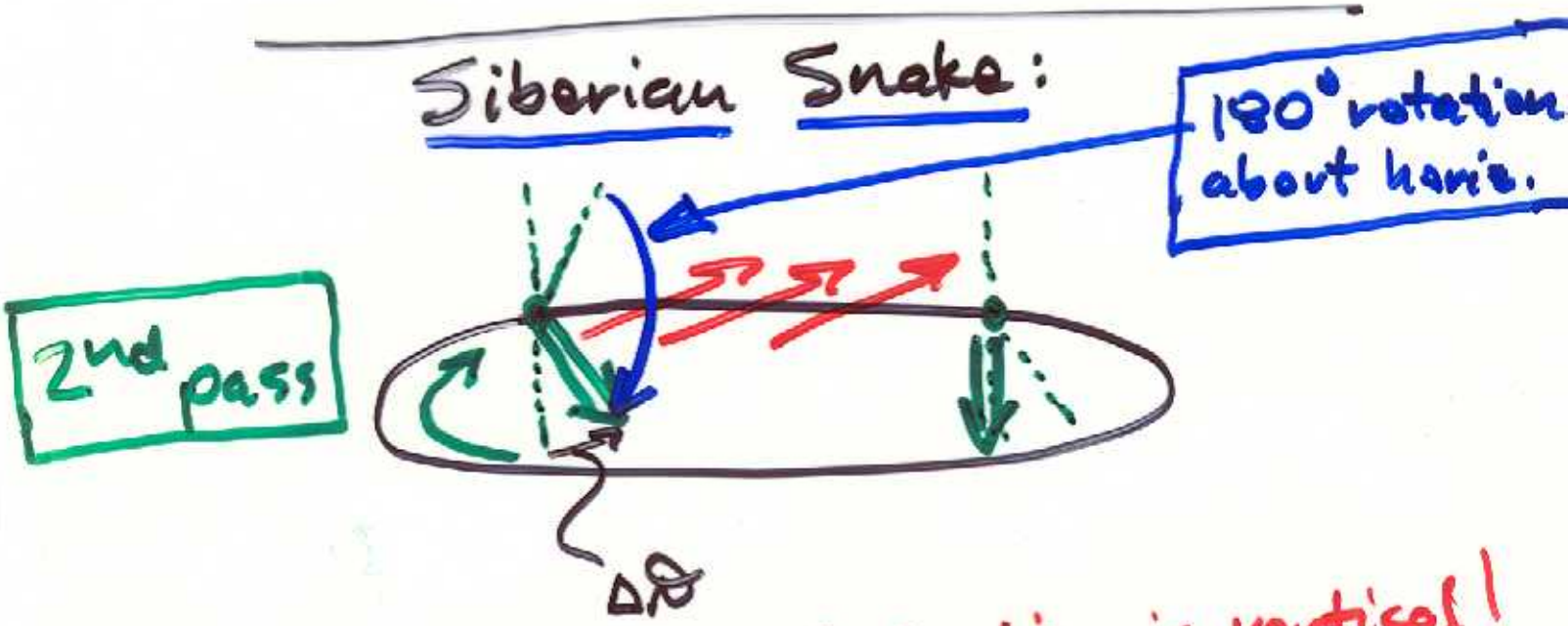
→ - for a strong resonance, spin flips but polarization is not lost if all the beam sees the resonance

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



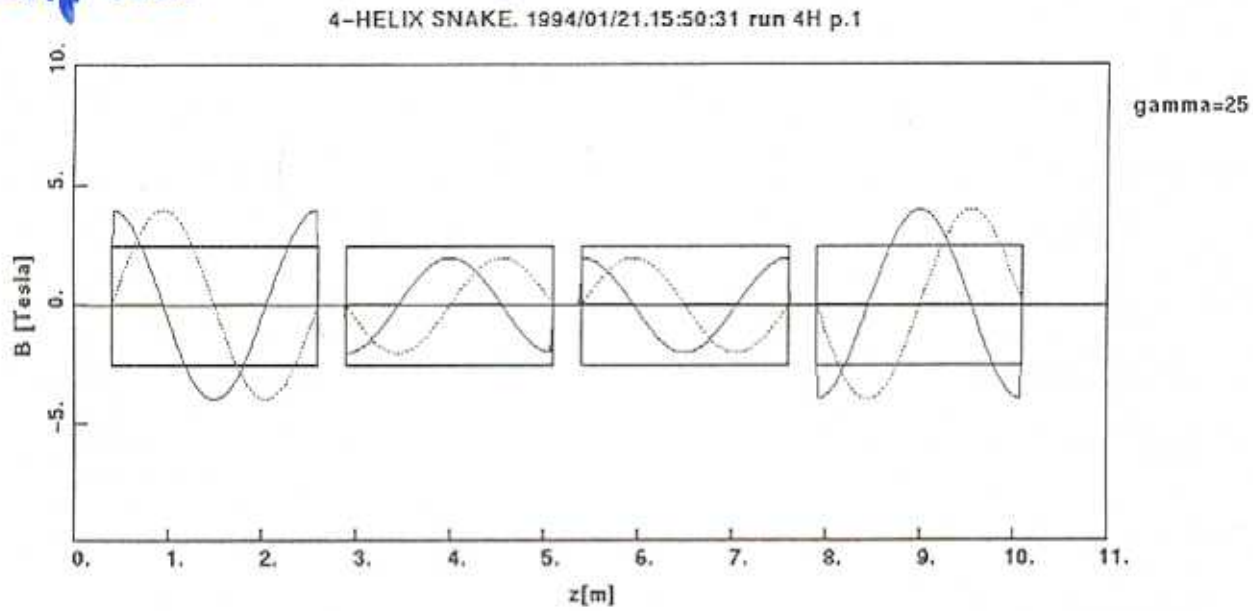


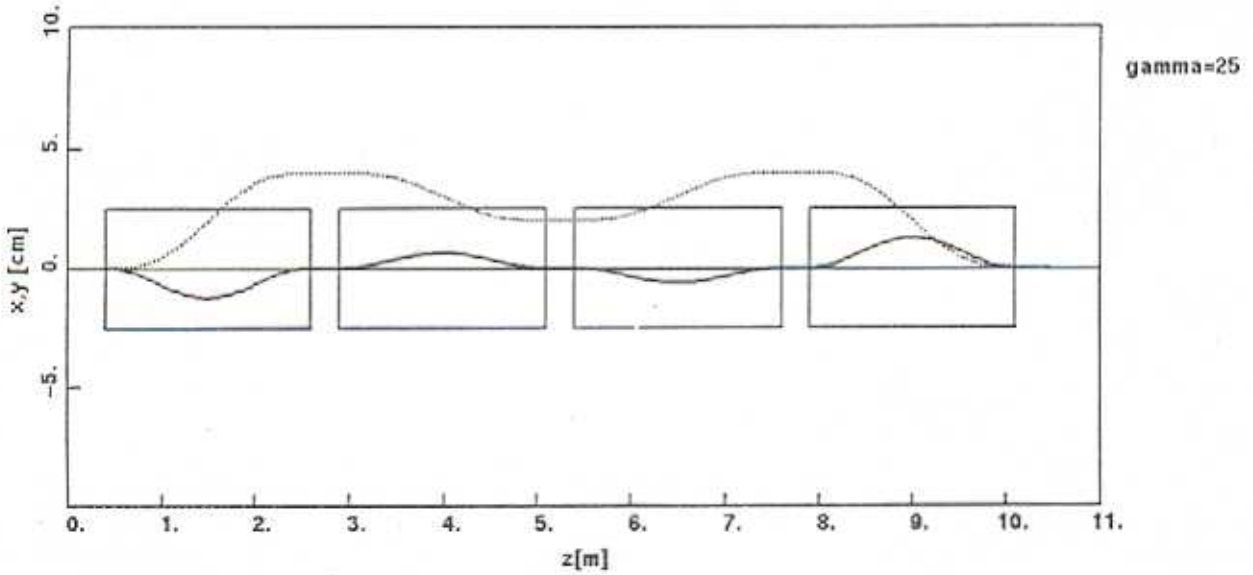
Siberian Snake:

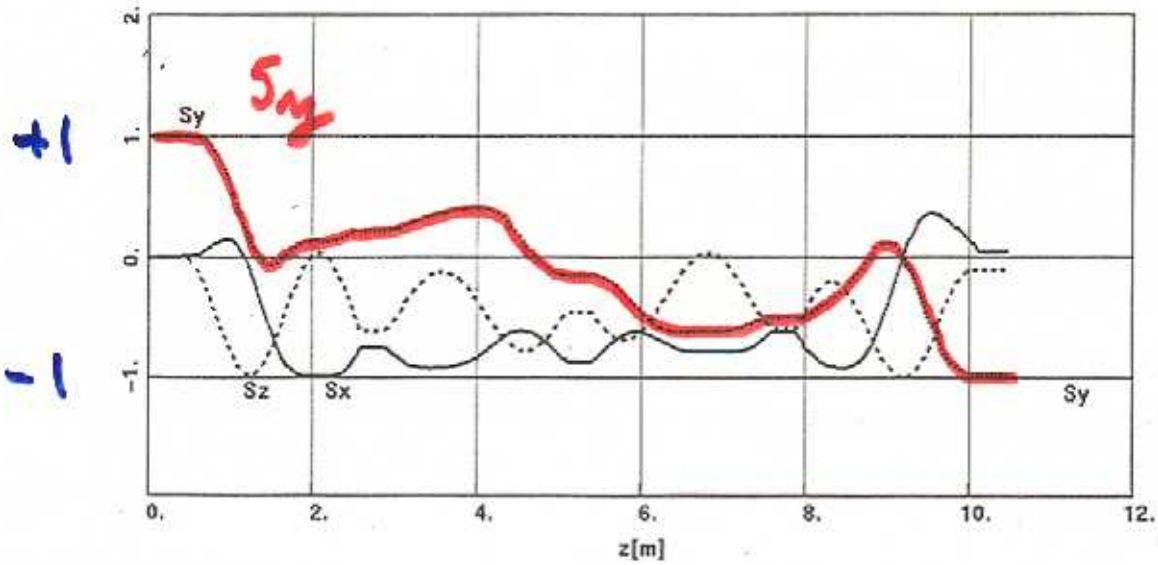


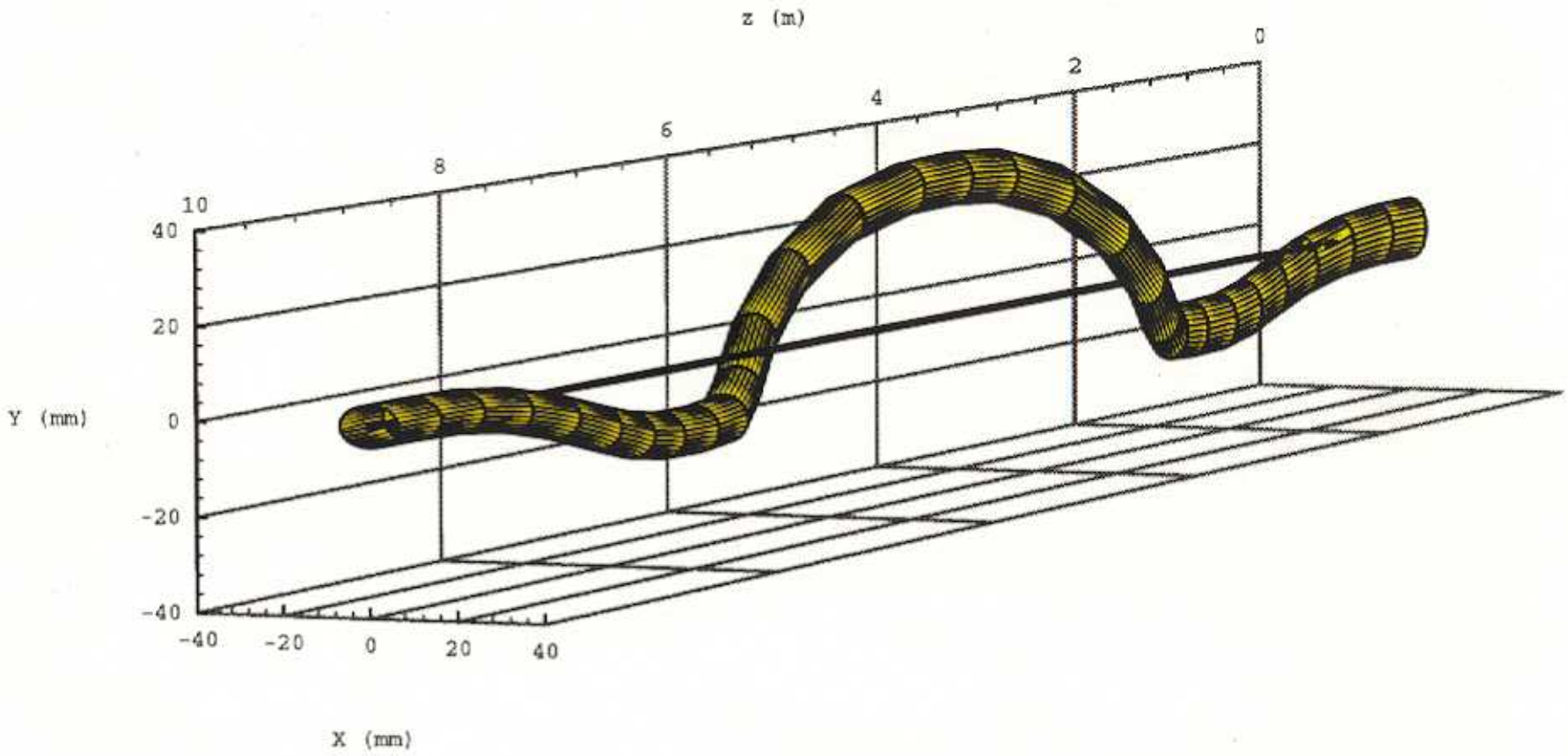
After 2 turns, polarization is vertical!

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

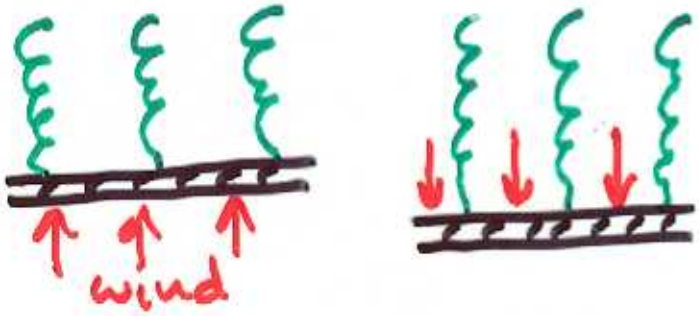


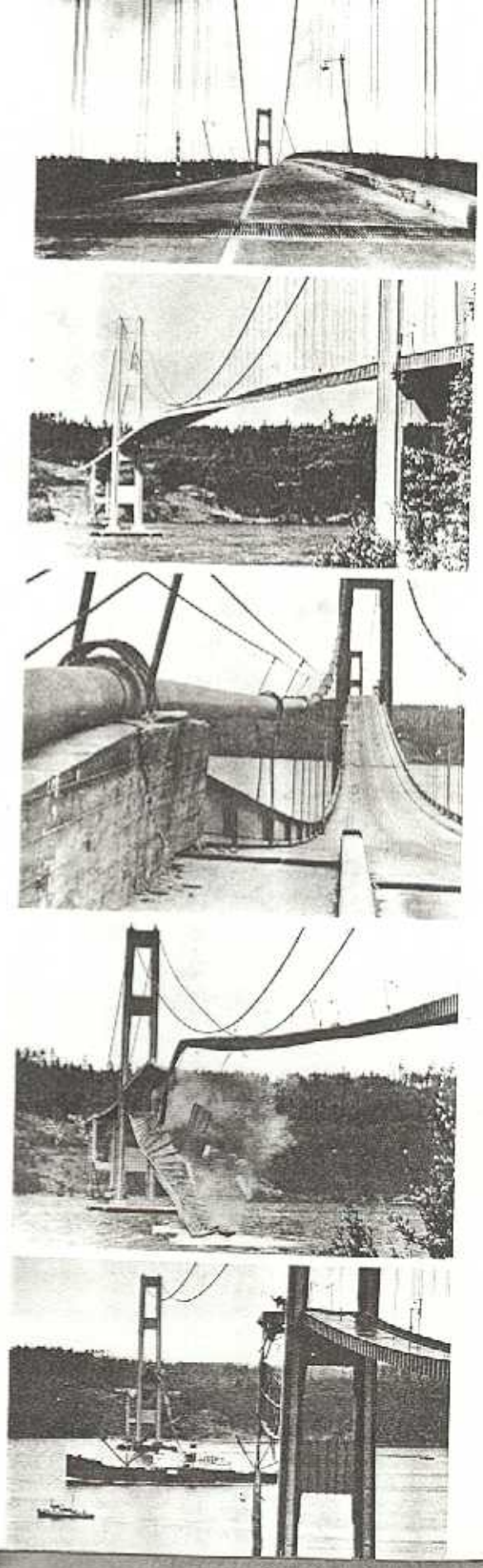





z (m)
0
2
4
6
8
10
40
20
0
-20
-40
Y (mm)
-40
-20
0
20
40
X (mm)

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

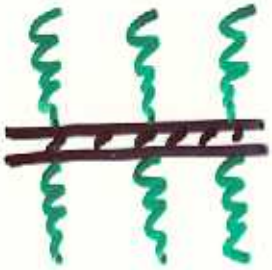


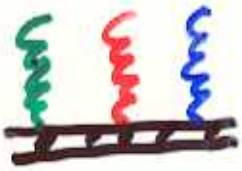


There are many solutions...

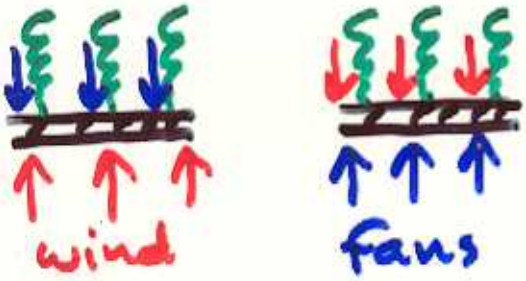
Bridge

Polarized protons

① 

② 

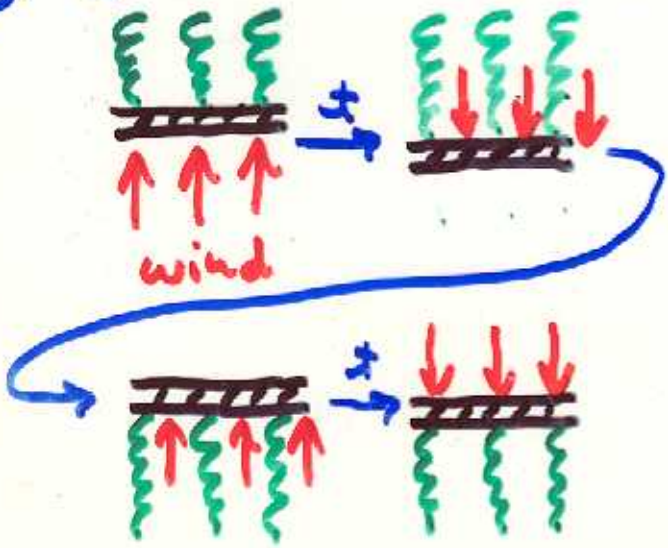
use particles with different g-2 values

③ 

add in correction magnetic field

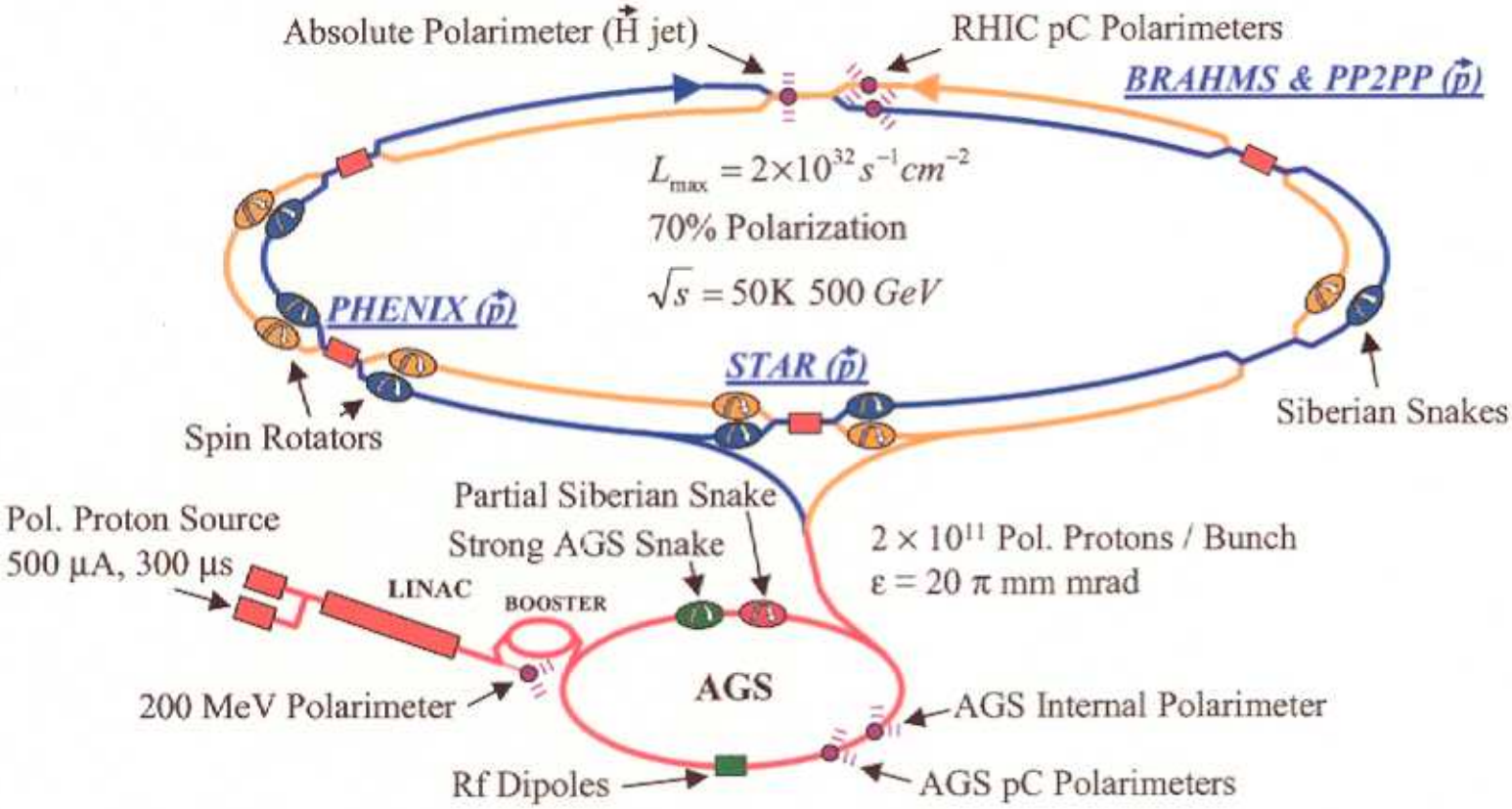
(AGS: 45 resonances × 96 correction dipoles → 1990)

④ (the Siberian solution)



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

Polarized Proton Collisions in RHIC



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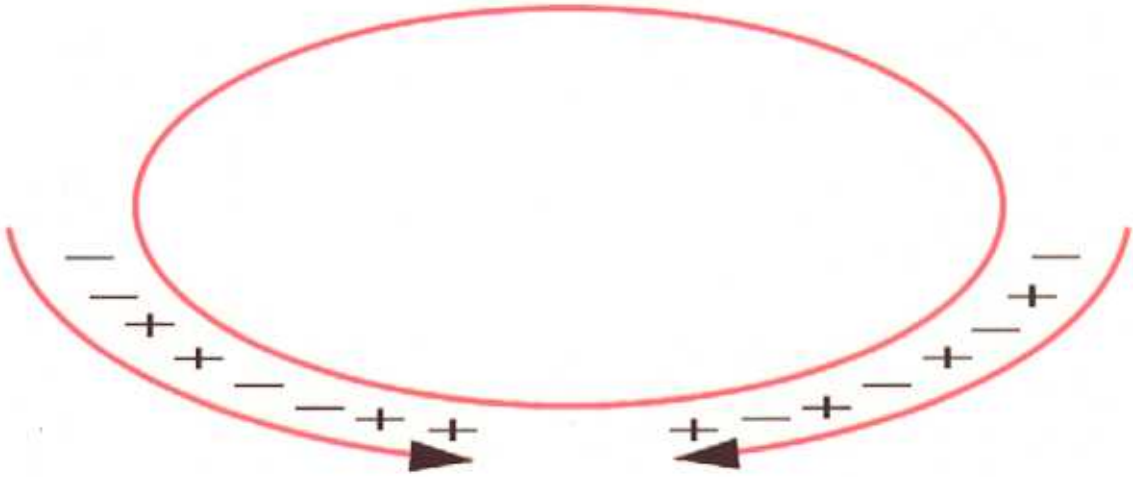
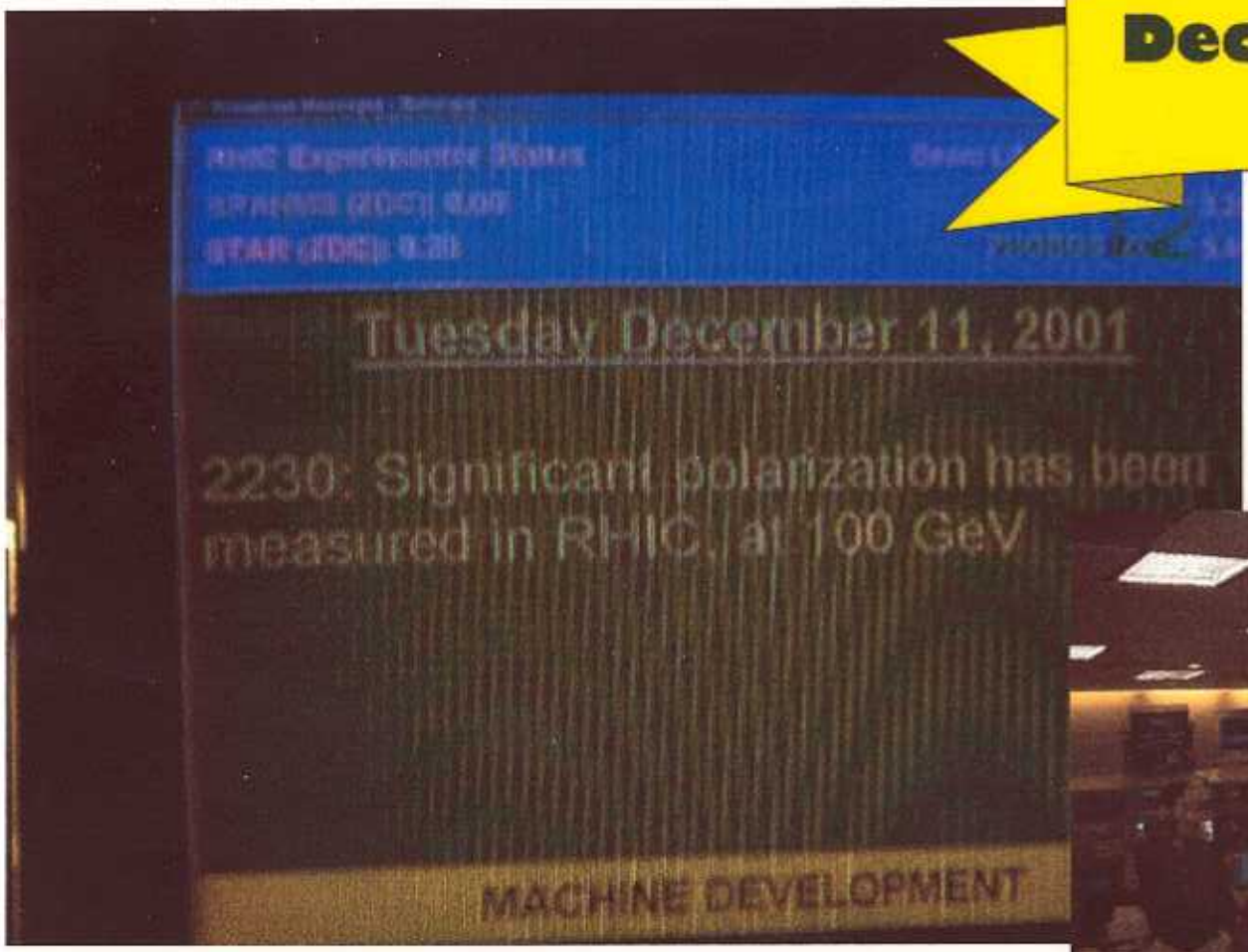
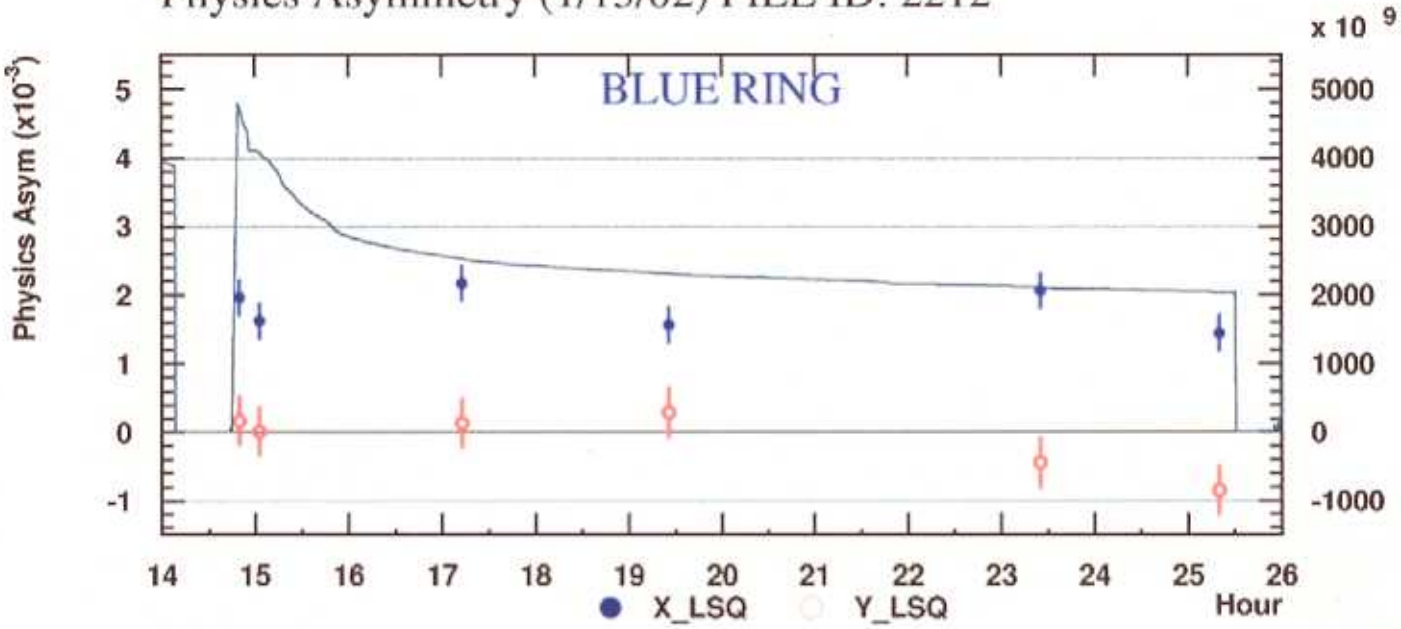


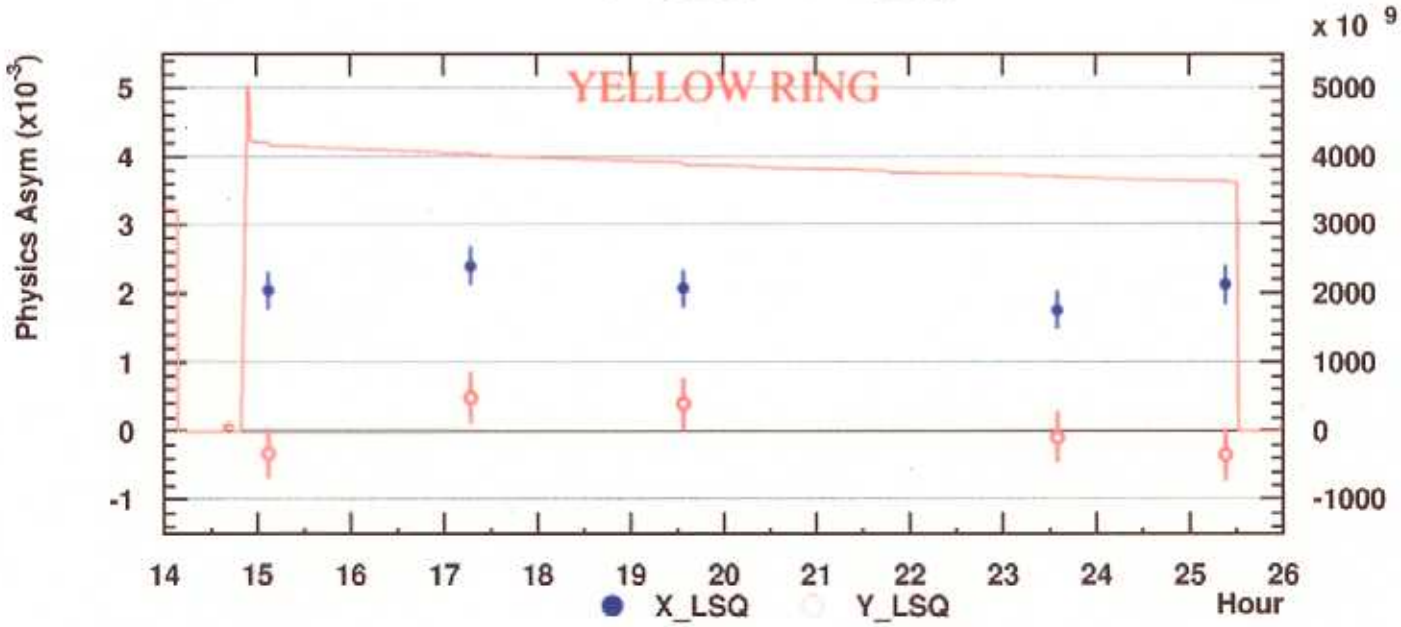
First polarized proton collisions

December 11th 2001

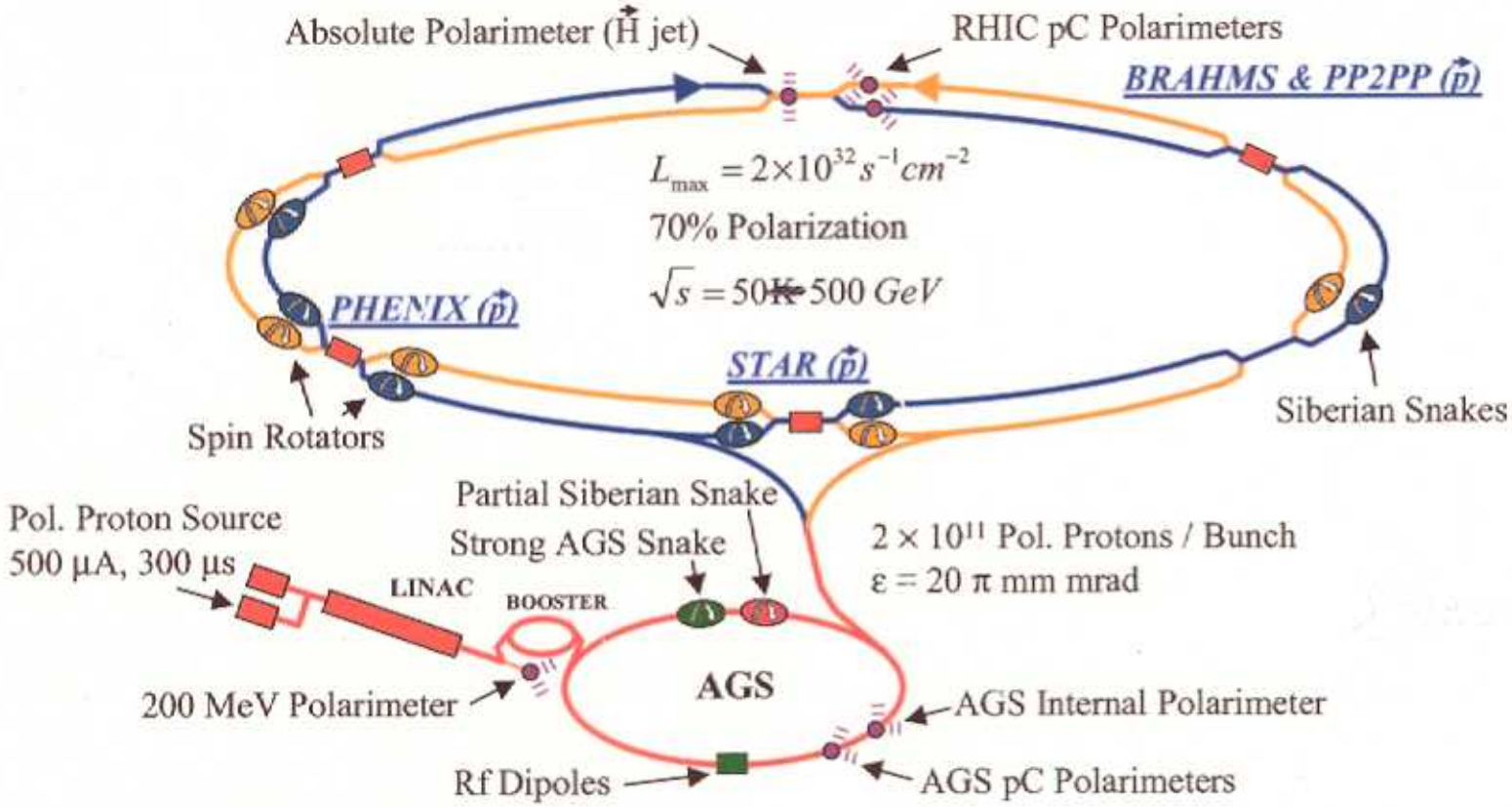


Physics Asymmetry (1/13/02) FILL ID: 2212





Polarized Proton Collisions in RHIC



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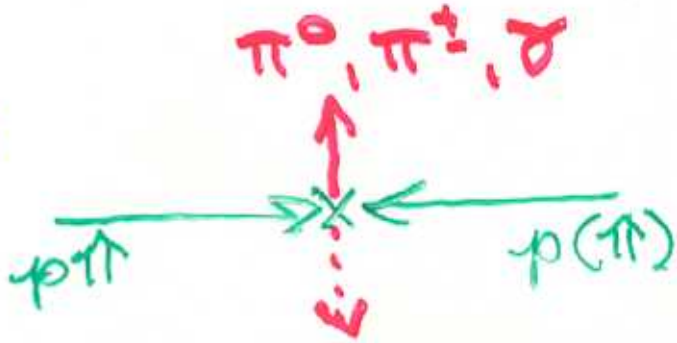
The First RHIC Spin Run

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

$$\boxed{\sqrt{s} = 200}$$

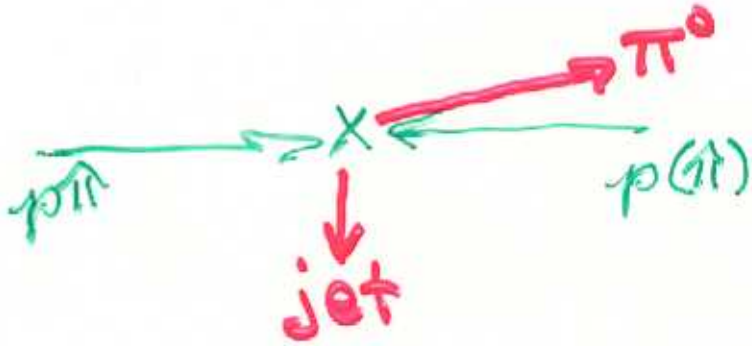
$p + p$

① mid-rapidity:



PHENIX, STAR

② forward:



STAR

③ very forward:

Local Pol
(12 o'clock)

④ elastic:

pp2pp

$-t \approx .005$

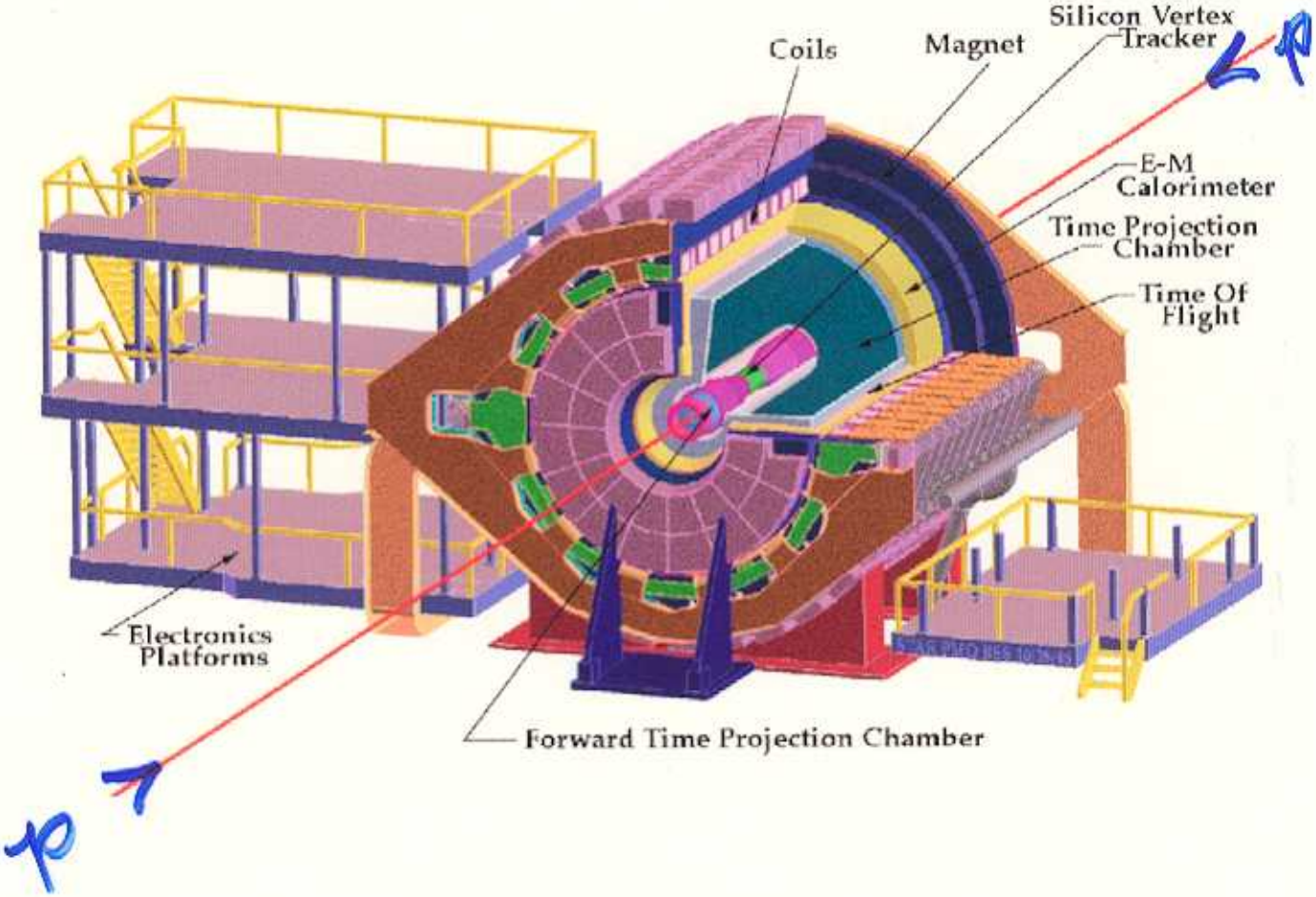
Yellow beam
polarized
(vertical) ⇑

Blue beam
<u>un</u>polarized

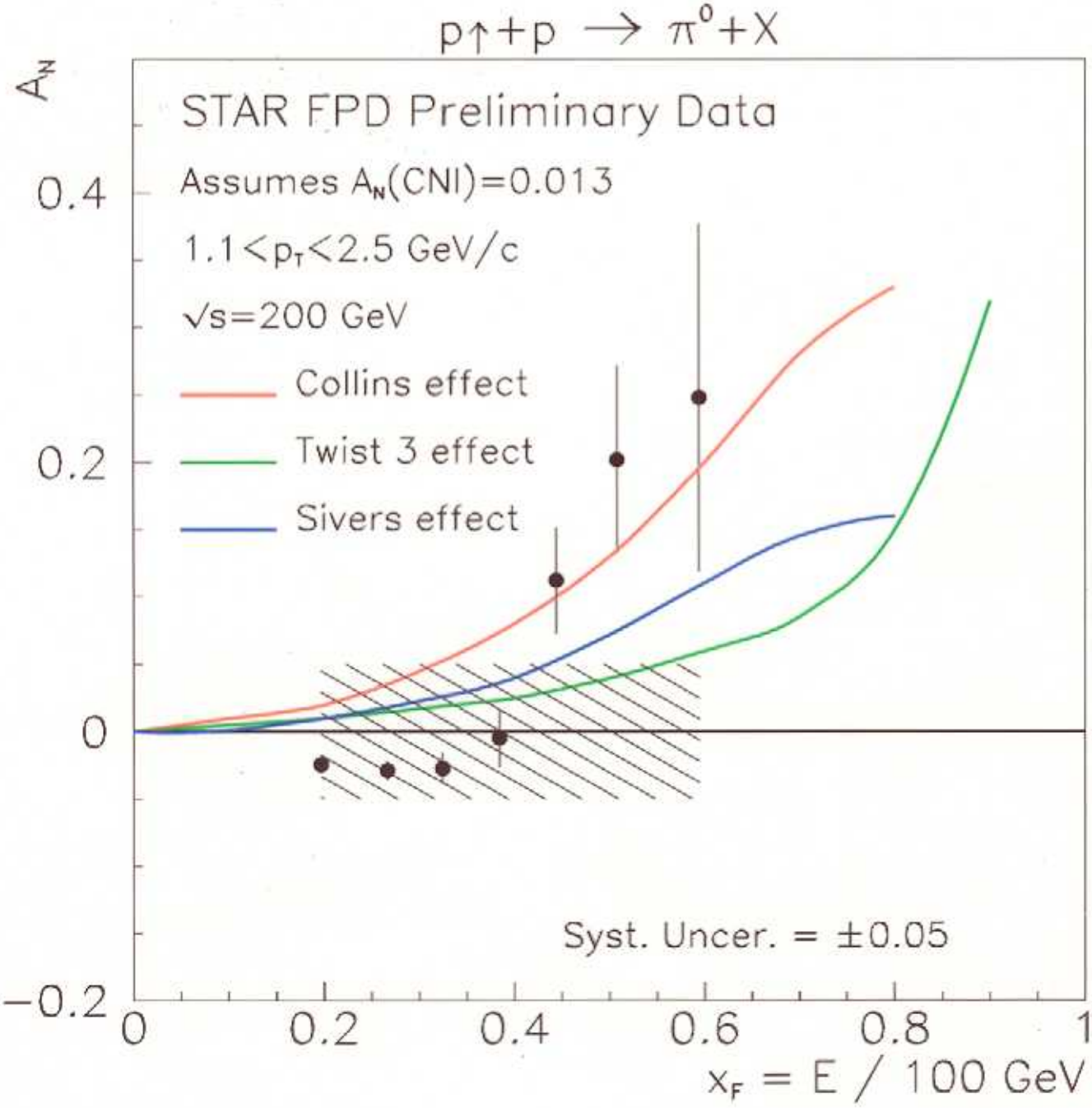
Forward "π^0" detector

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

STAR Detector



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



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?)
      - $\hookrightarrow n + \pi$
    - (any small asymmetry is also seen in the beam-beam counters at STAR — π?)

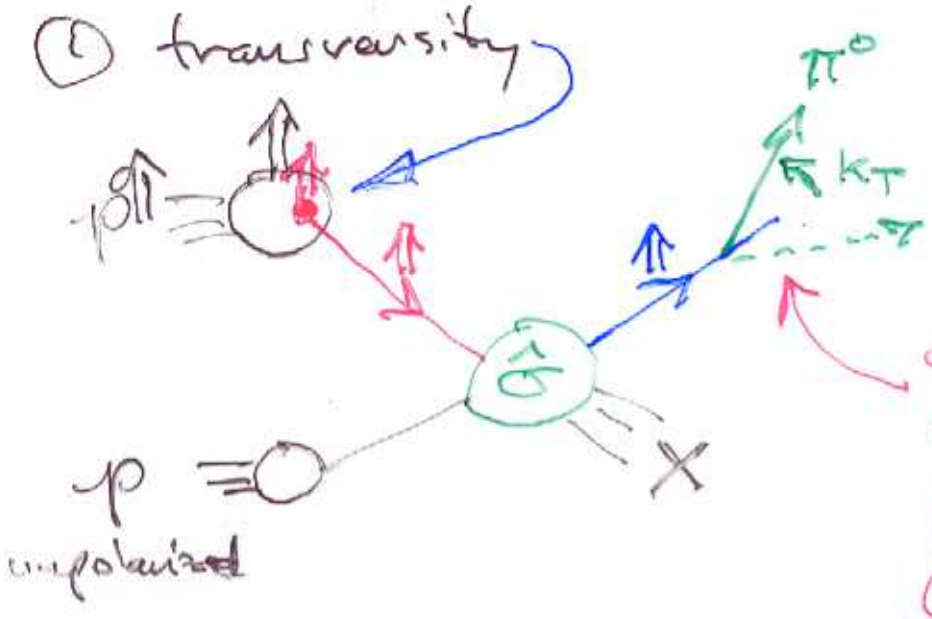
π^0 asymmetry:

- 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 $\to$ correct σ

π^0 asymmetry (cont.)

Models:

① transversity



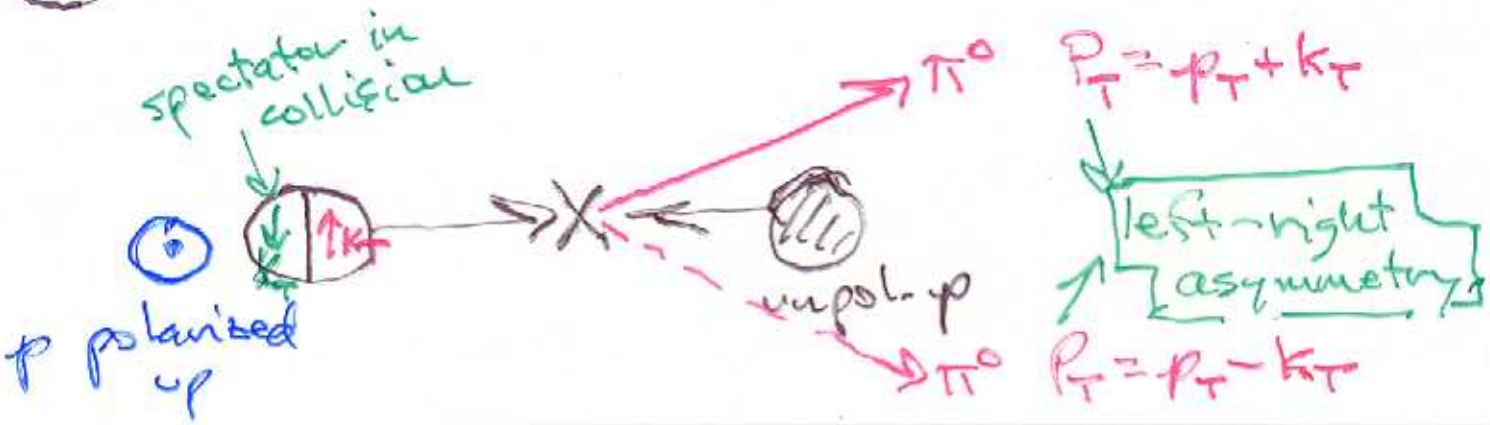
analysing power of π^0 from polarized quark (Heppelmann-Collins)

- many "buts"
- $e^+e^- \to q^{\Uparrow}\bar{q}^{\Uparrow}$, $q \to \pi$, $\bar{q} \to \pi$ } correlation

to be done at Belle

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

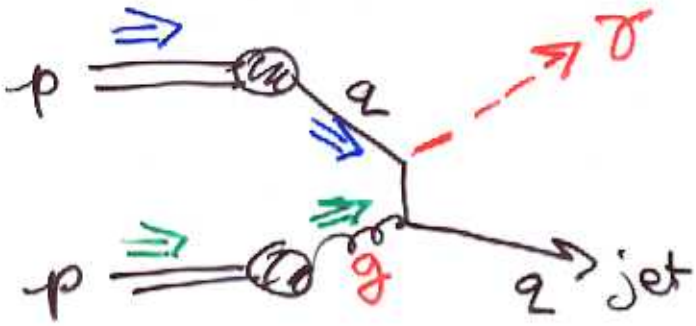
② initial state effect from k_T



RHIC Spin Probes

Gluon polarization:

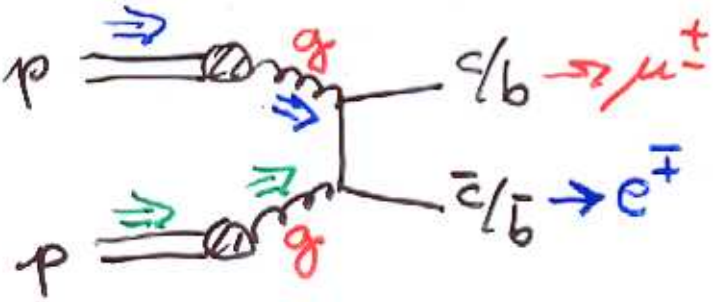
$$A_{LL} = \frac{1}{P^2}\frac{N_{++}(\theta)-N_{+-}(\theta)}{N_{++}+N_{+-}}$$



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

(.3) (.6)

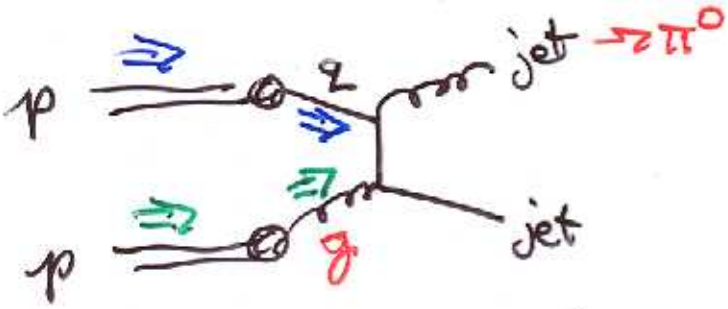
$$\simeq \frac{1}{5}\frac{\Delta G}{G}(x_g)$$



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

(.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)

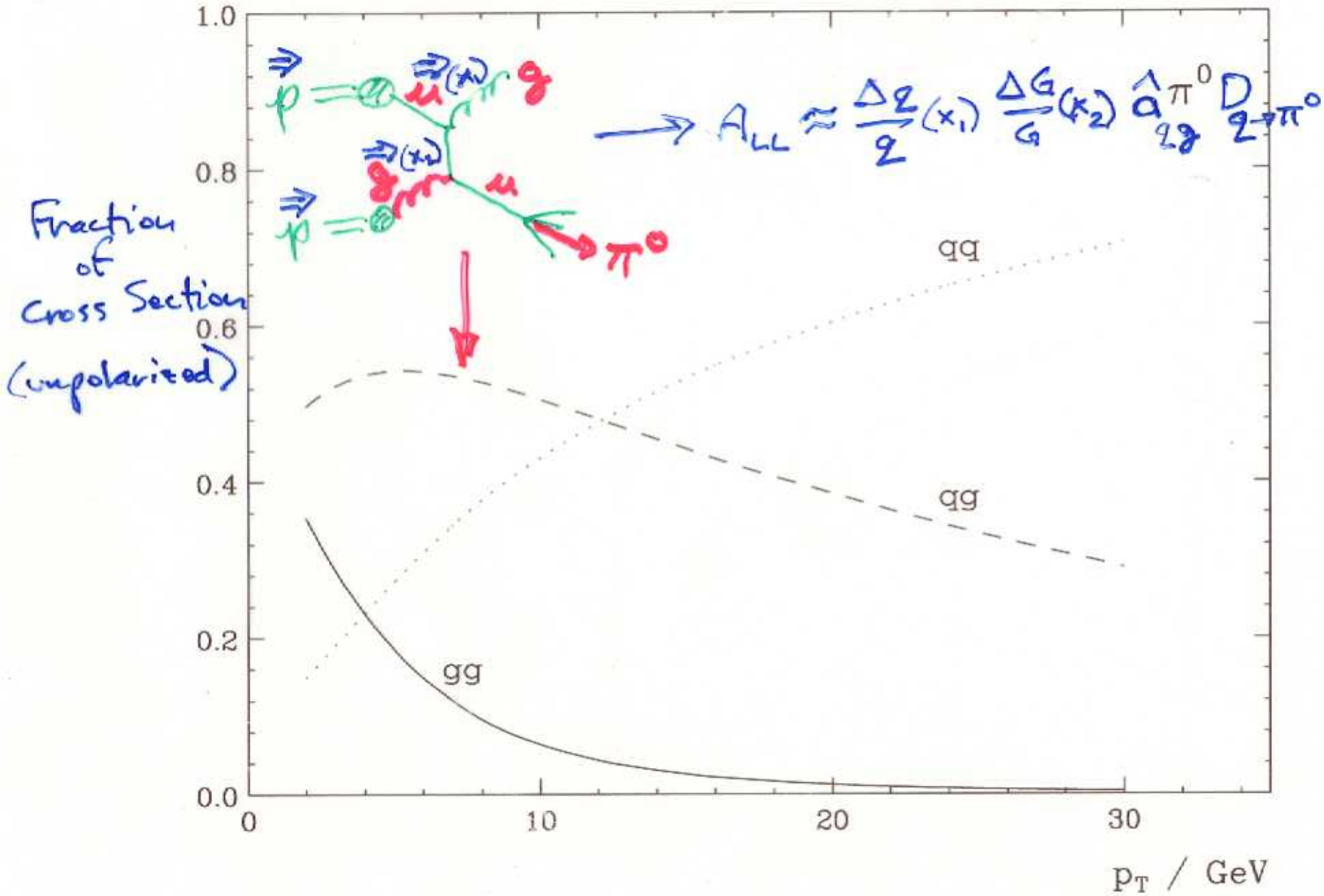
$$\simeq \frac{1}{4}\frac{\Delta G}{G}(x_1)$$

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

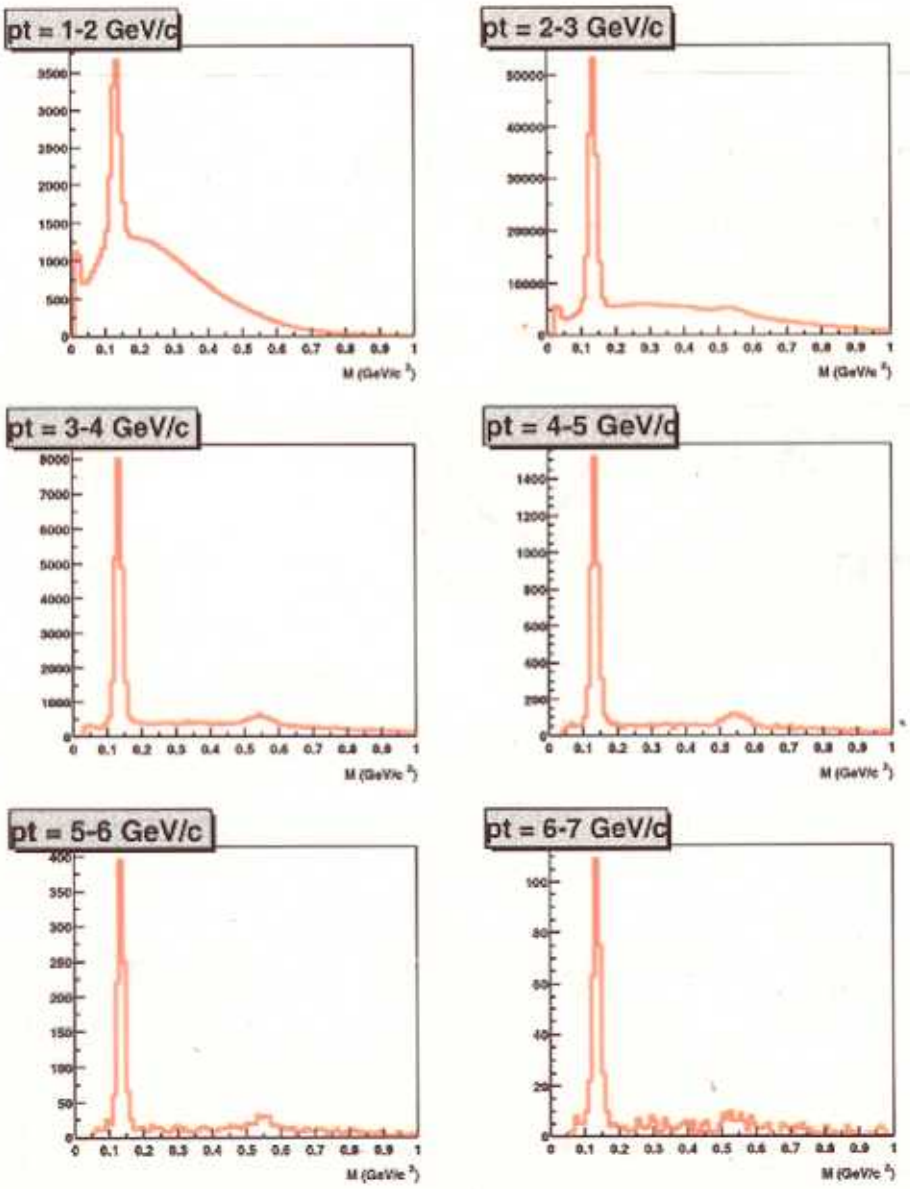
also J/ψ (but production mechanism)

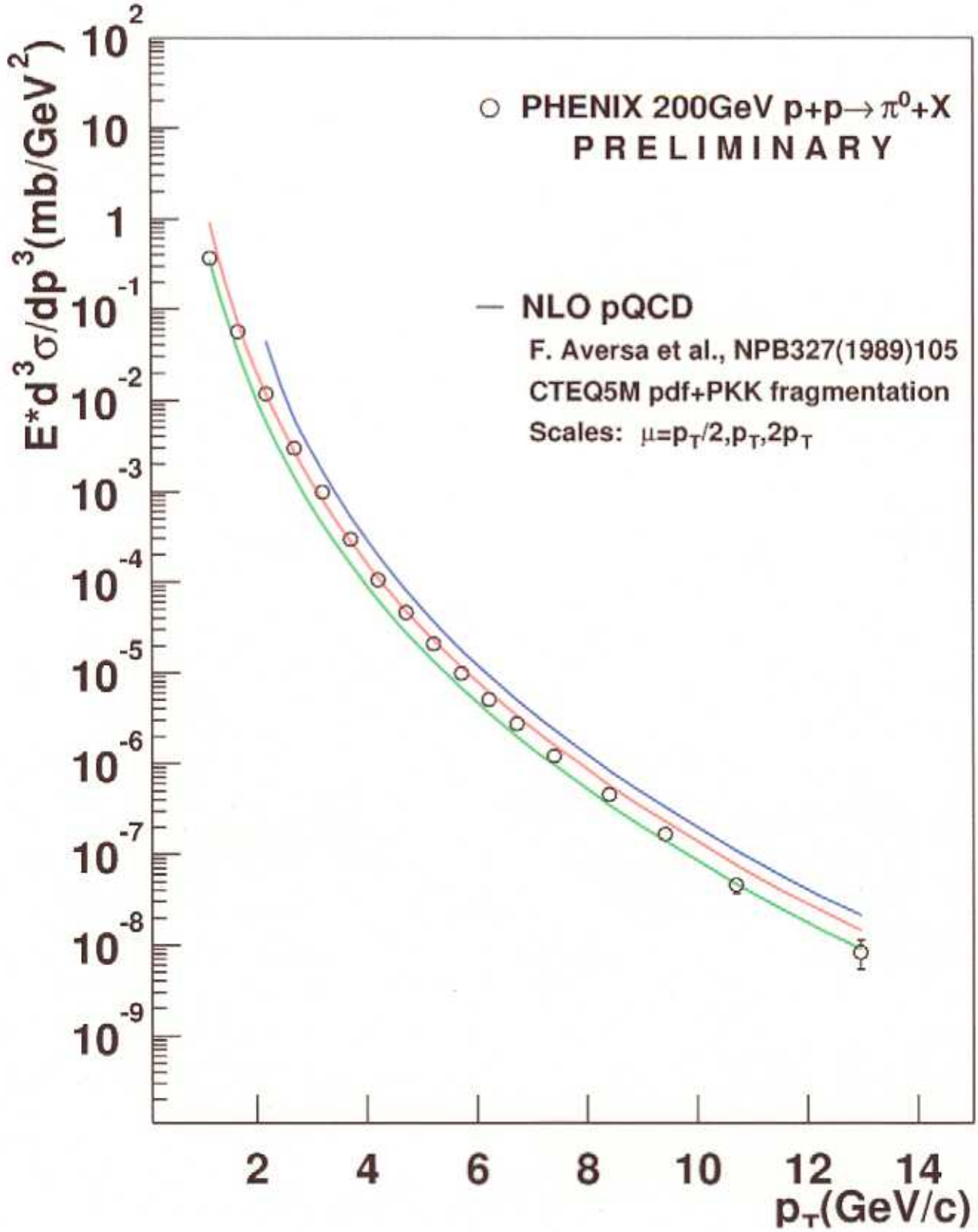
2003: π^0 as a jet surrogate to observe/measure/constrain gluon polarization.

$\sqrt{s} = 200$

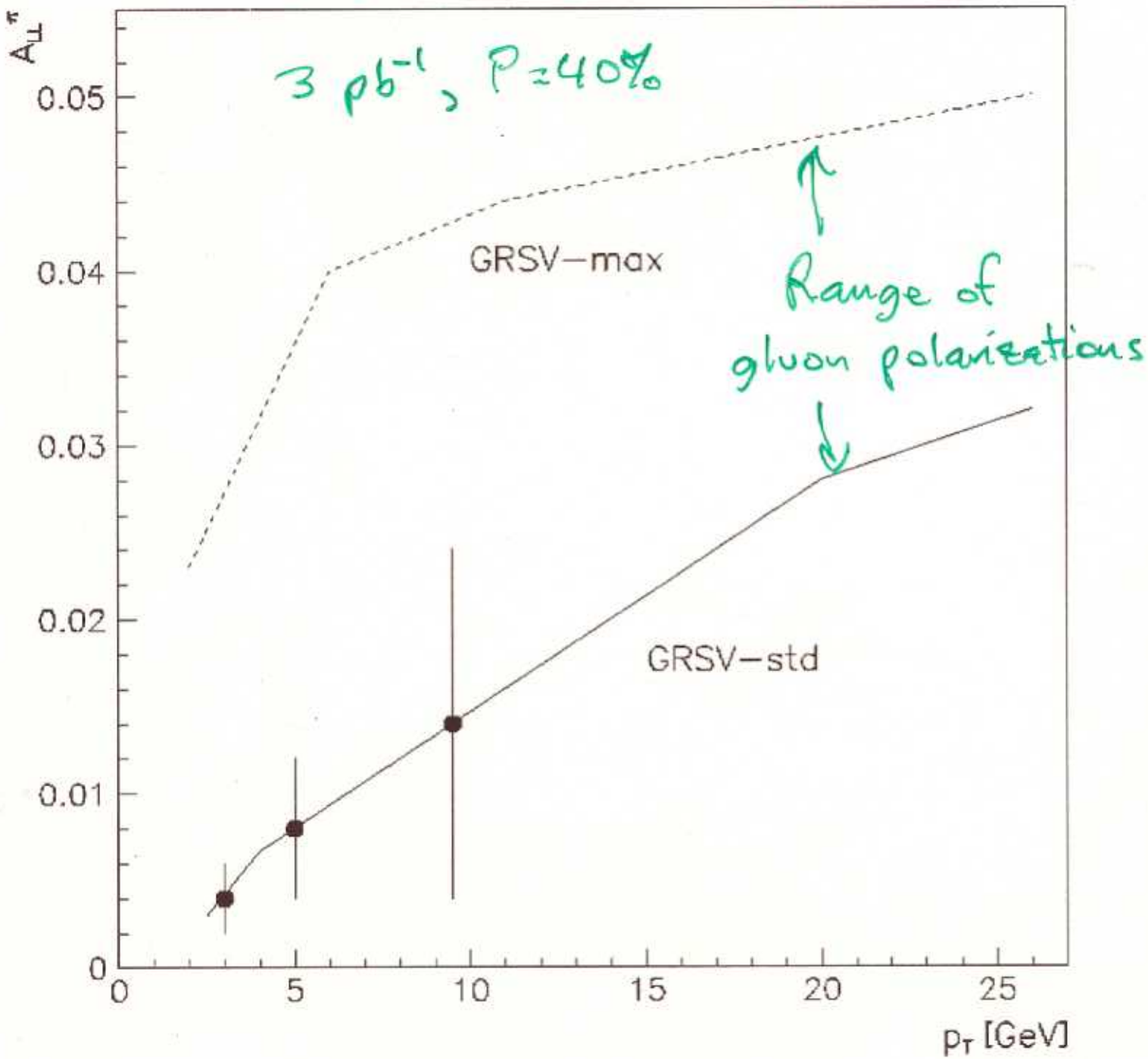


PHENIX π0 Reconstruction



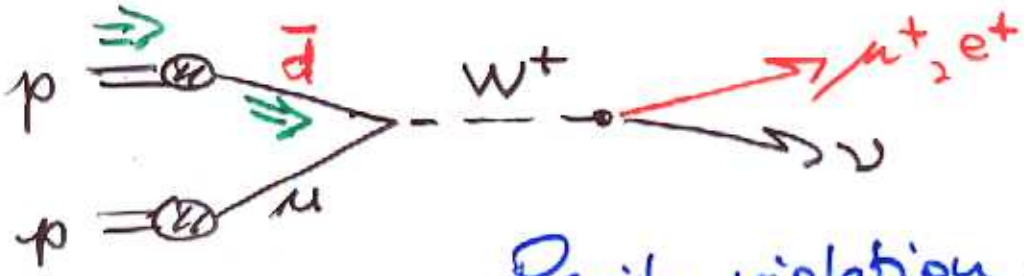

PHENIX 200GeV p+p→π⁰+X
PRELIMINARY
NLO pQCD
F. Aversa et al., NPB327(1989)105
CTEQ5M pdf+PKK fragmentation
Scales: μ=p_T/2,p_T,2p_T
E*d³σ/dp³(mb/GeV²)
p_T(GeV/c)

Phenix π^0 for 2003



Probes (cont.)

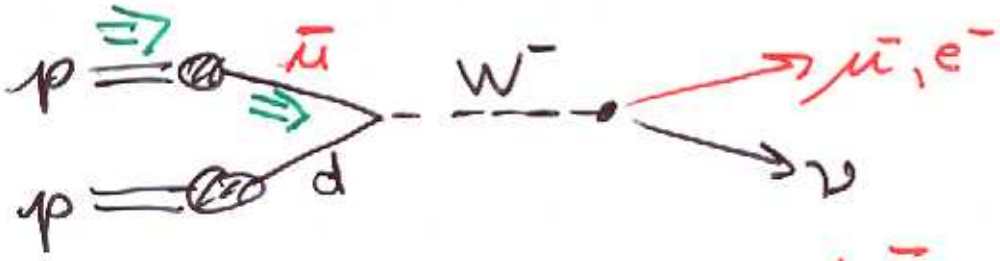
Quark polarization by flavor



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.D. 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, ...