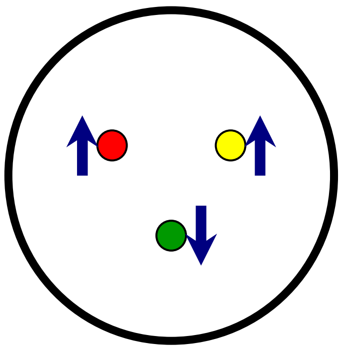
SLAC Summer Institute
21 July 2006
G. Bunce

RHIC Spin

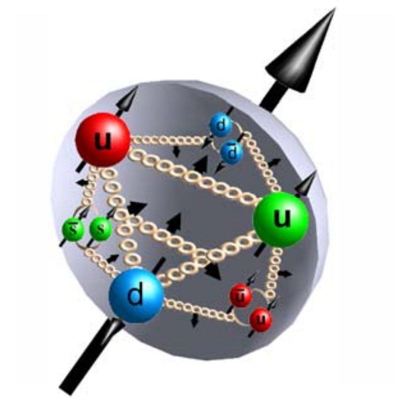
…to study the spin structure of the proton

- a history—from quarks to spin structure
- Deeply Inelastic Scattering and RHIC
- Siberian Snakes and accelerating polarized protons
- Our plans and some results
- Future directions

Quark Model



QCD



a history of the strong interaction:

1964: "quarks" …to understand the zoo of strongly interacting particles; "color" quantum number …to describe the Ω- (sss, S=3/2)

1967: quarks are real! …from hard inelastic scattering of electrons from protons at SLAC

1973: the theory of QCD …quarks and "gluons" and color; *perturbative* QCD

1980s to present: e-p and pbar-p colliders …beautiful precision tests of pQCD, *unpolarized*

…………………………………………………………………

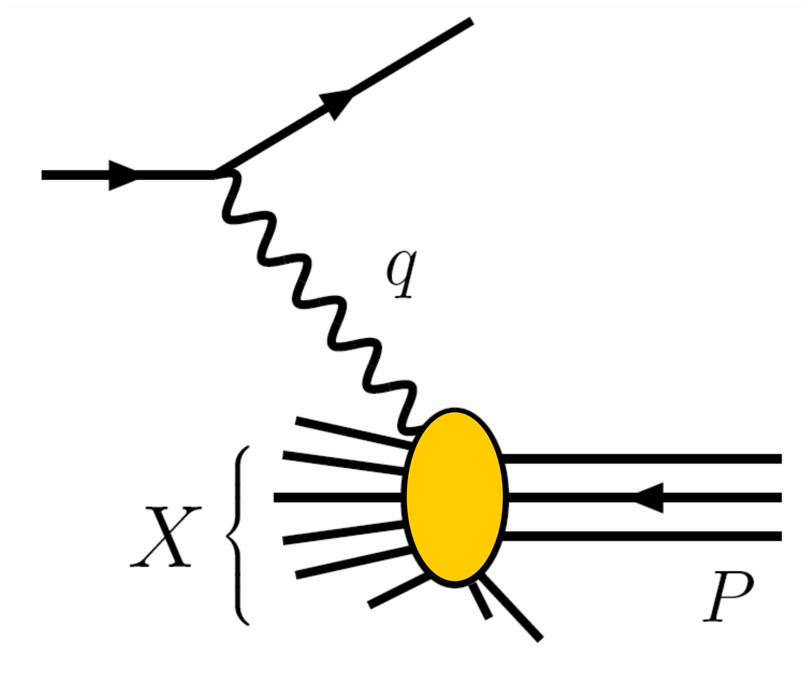
1970s: *polarized* beams and targets

1988: the spin of the proton is <u>not</u> carried by its quarks!

1990s to present: <u>confirmed</u> in "DIS" fixed target experiments using electrons and muons to probe the spin structure of the proton

2001 to present: probe the spin structure of the proton using quarks and gluons *(strongly interacting probes see both the gluons and quarks in the proton):* <u>RHIC</u>

Deeply-inelastic scattering ep → e X :



$$Q^2 = -q^2$$

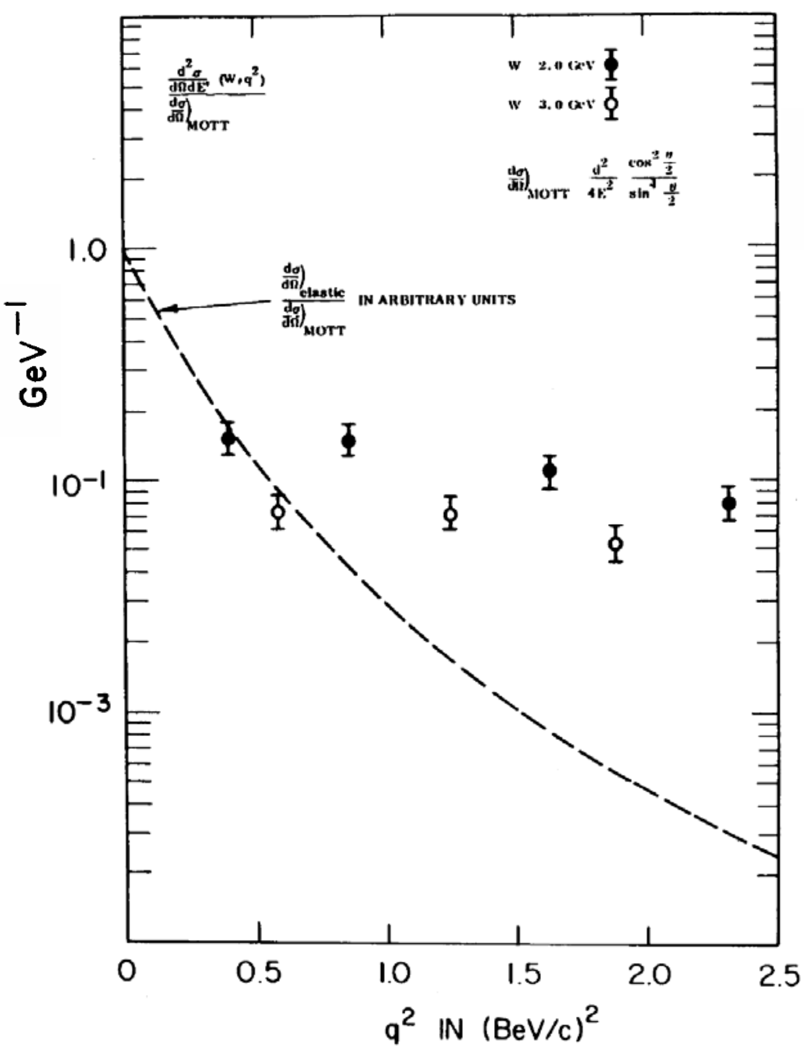
"inelasticity"

$$x \equiv \frac{Q^2}{2P \cdot q} = \frac{Q^2}{Q^2 + M_X^2 - m_N^2}$$

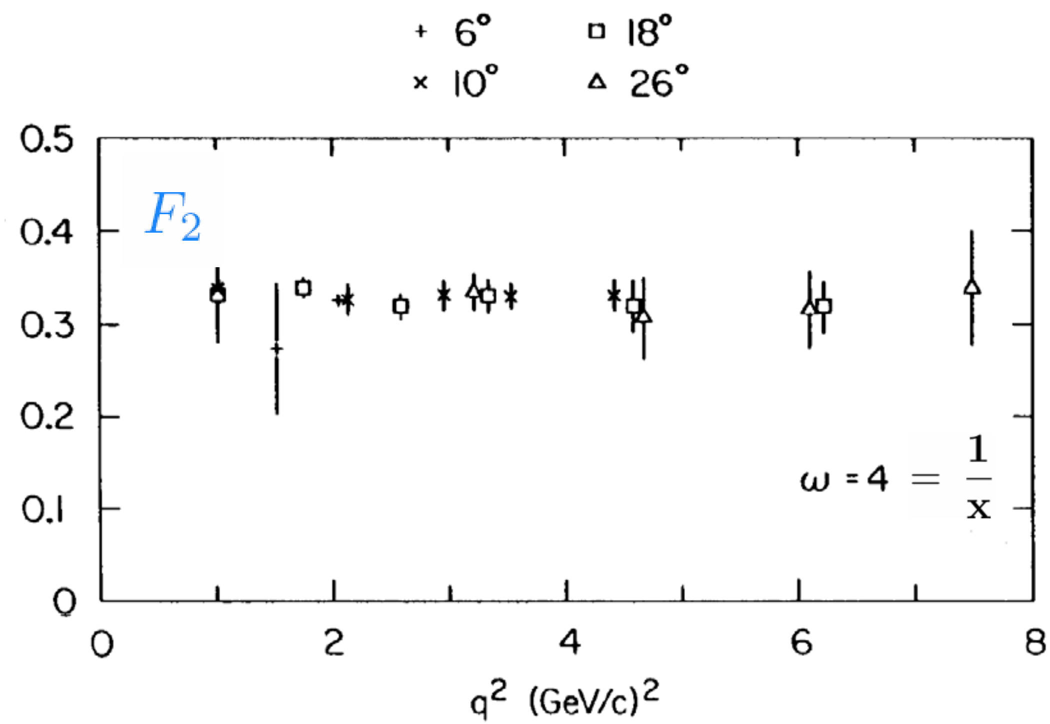
Bjorken var.

- spin-averaged cross section : $\left(y = 1 - \frac{P \cdot k'}{P \cdot k} \right)$

$$\frac{d^2\sigma}{dx\, dQ^2} = \frac{4\pi\alpha^2}{Q^4 x} \left[x y^2\, F_1(x, Q^2) + (1-y)\, F_2(x, Q^2) \right]$$

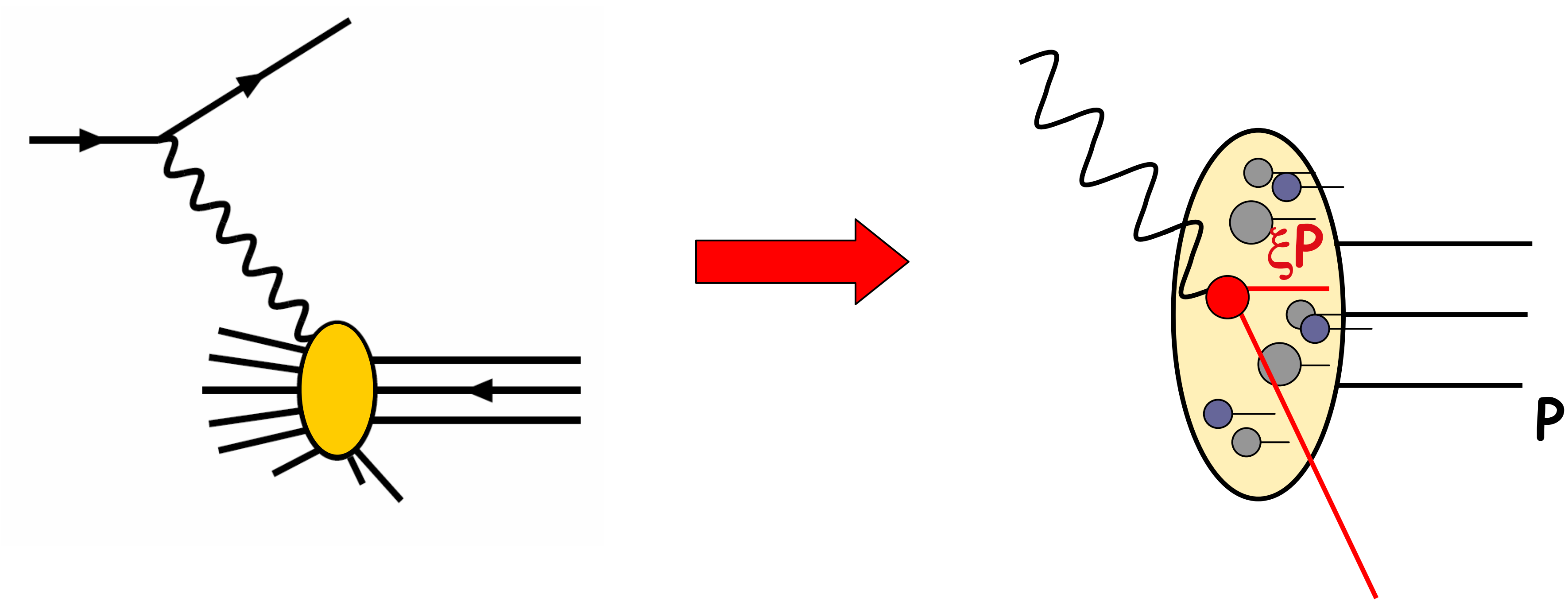


early results from SLAC : "scaling"



Parton Model :

Feynman; Bjorken, Paschos



Assume: struck parton carries momentum ξP

Find: $\xi \equiv x$

$$F_1(x) = \frac{1}{2} \sum_q e_q^2 \left[q(x) + \bar{q}(x) \right]$$

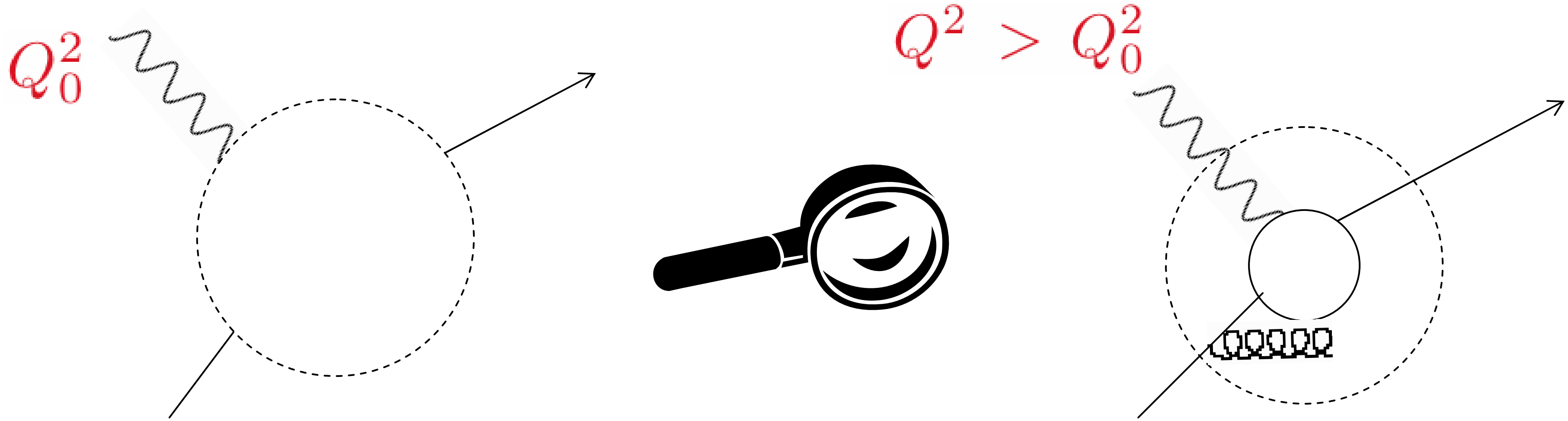
$$F_2(x) = 2x F_1(x)$$

(spin 1/2 !)

- crucial success for QCD :

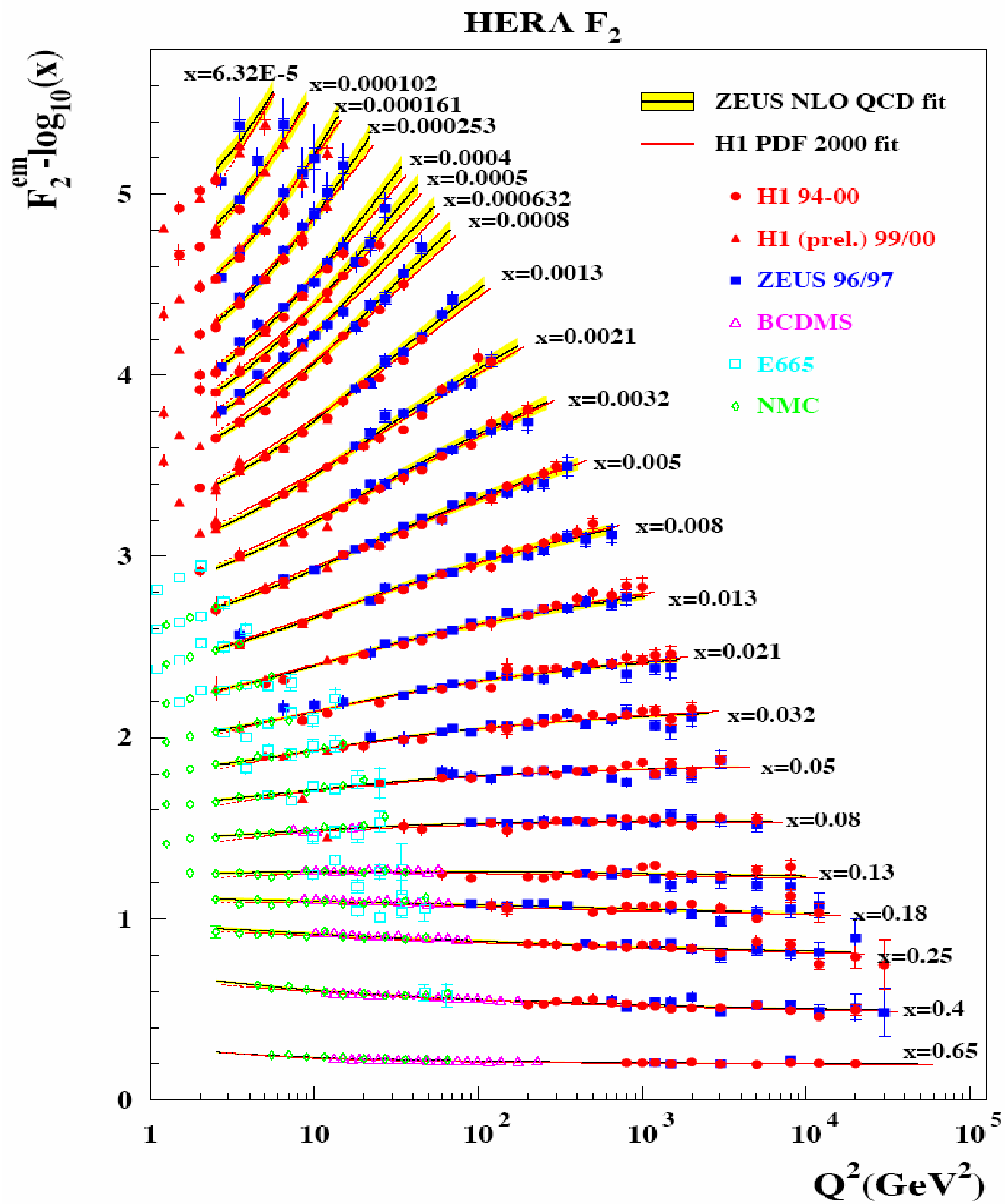
  quantitative prediction of scaling violations in DIS

Christ,Hasslacher,Mueller; Georgi,Politzer; DGLAP



$$Q^2 \frac{\mathrm{d}}{\mathrm{d}Q^2} \begin{pmatrix} q(x, Q^2) \\ g(x, Q^2) \end{pmatrix} = \int_x^1 \frac{dz}{z} \begin{pmatrix} \mathcal{P}_{qq} & \mathcal{P}_{qg} \\ \mathcal{P}_{gq} & \mathcal{P}_{gg} \end{pmatrix}_{(z, \alpha_s(Q^2))} \cdot \begin{pmatrix} q \\ g \end{pmatrix} \left(\frac{x}{z}, Q^2\right)$$

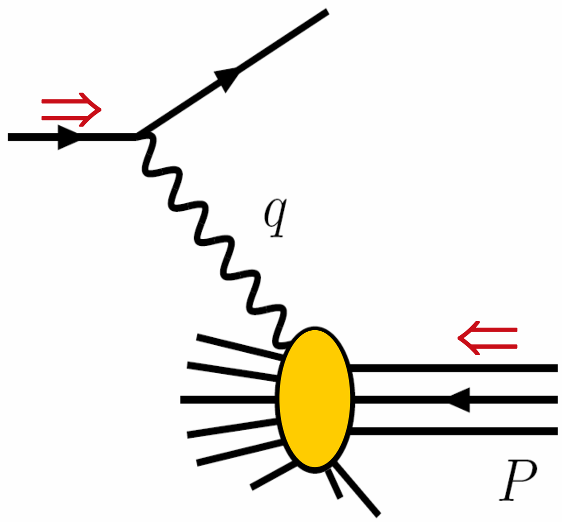
"DGLAP" evolution



HERA F$_2$
F_2^{em}-$\log_{10}(x)$
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
ZEUS NLO QCD fit
H1 PDF 2000 fit
H1 94-00
H1 (prel.) 99/00
ZEUS 96/97
BCDMS
E665
NMC
Q^2(GeV^2)

Polarized Deeply Inelastic Scattering

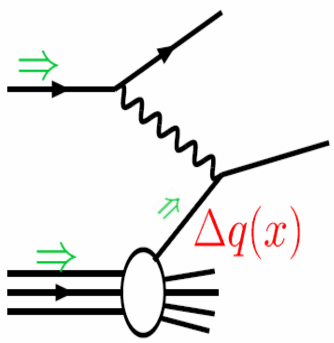
- advent of polarized electron beams 1972
- first polarized DIS (SLAC E-80) 1976



$$\sigma(\Rightarrow,\Leftarrow) - \sigma(\Rightarrow,\Rightarrow) \sim \mathbf{g_1(x, Q^2)}$$

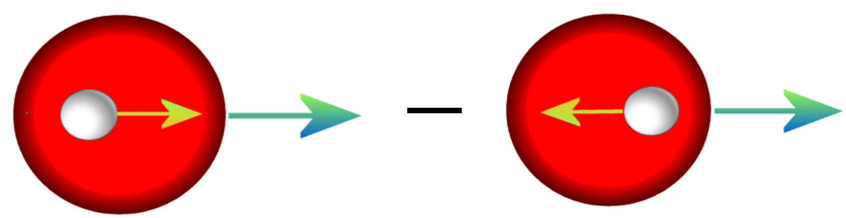
SLAC (E80,130,…), CERN (EMC, SMC, COMPASS), DESY (HERMES), JLab

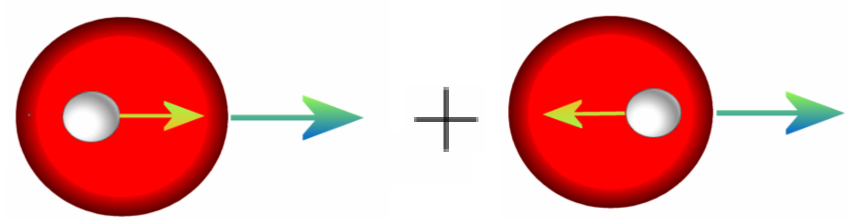
in the parton model :



$$F_1(x) = \frac{1}{2} \sum_q e_q^2 \left[q(x) + \bar{q}(x) \right]$$

$$g_1(x) = \frac{1}{2} \sum_q e_q^2 \left[\Delta q(x) + \Delta \bar{q}(x) \right]$$

$\mathbf{\Delta q(x)} =$ 

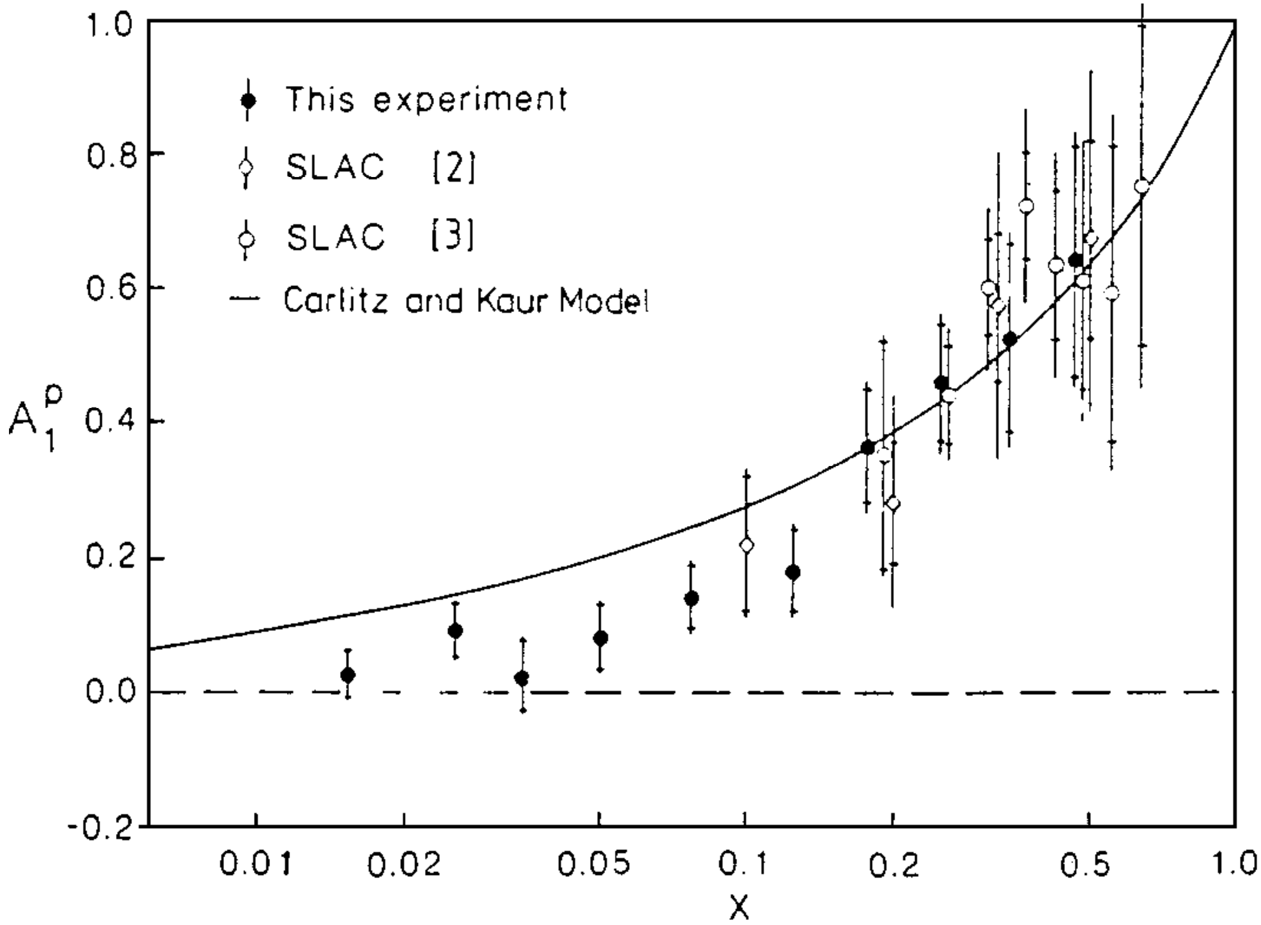
$\mathbf{q(x)} =$ 

- also for g_1 scaling violations predicted in QCD:

$$g_1(x) \longrightarrow g_1(x, Q^2)$$

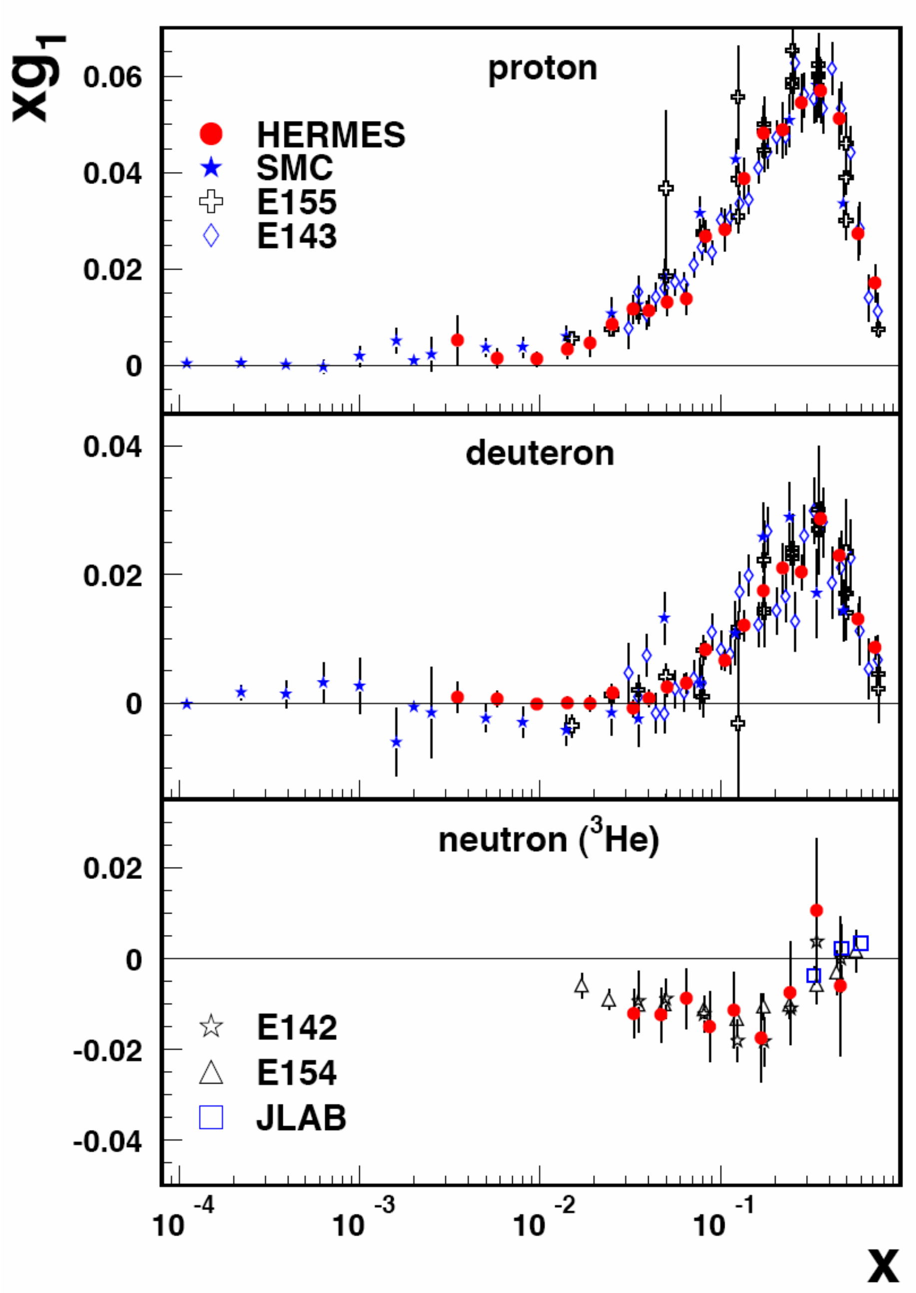
EMC at CERN: J. Ashman et al., NPB 328, 1 (1989):

polarized muons probing polarized protons



$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

"proton spin crisis"



L. De Nardo (HERMES)

2006:
Delta Sigma = 0.2

Quarks and anti-quarks carry 20% of proton spin

(doesn't yet include new COMPASS results)

- **What else carries the proton spin ?**

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$\rightarrow$ **How are gluons polarized ?**
$\rightarrow$ **How large are parton orbital angular mom. ?**

- **What are the detailed patterns of quark & antiquark polarizations ?**

  $\rightarrow$ **Flavor asymmetries in sea ? Strangeness ?**

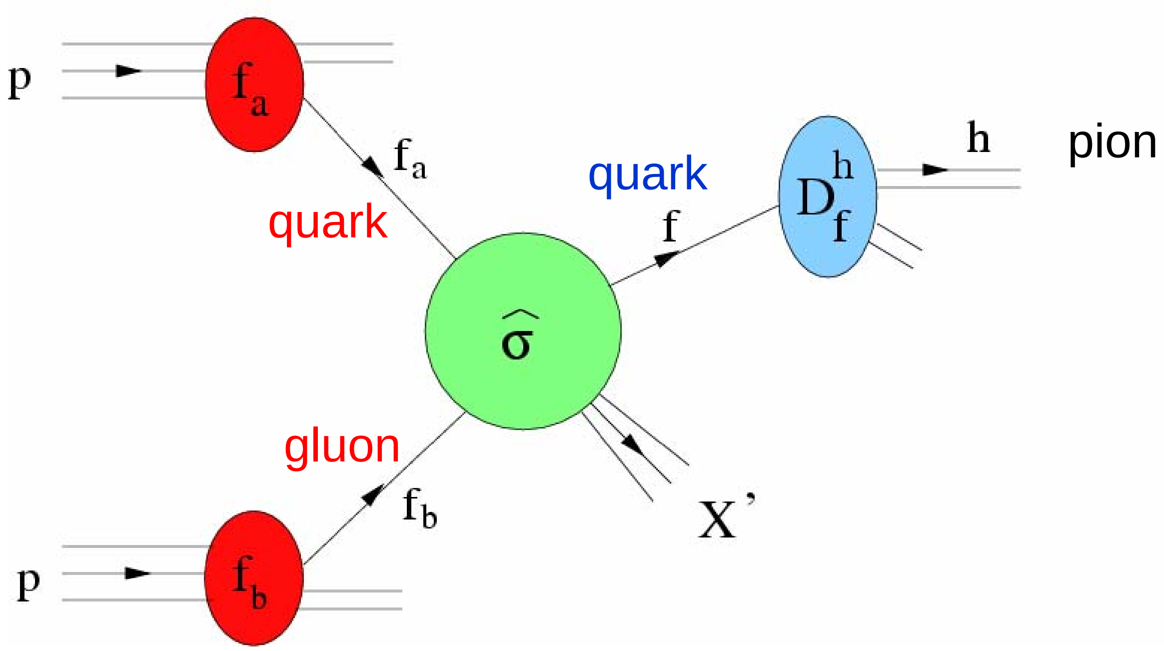
- **What are the origins of large observed single-transverse-spin asymmetries ? What do they tell us about the nucleon ?**

  $\rightarrow$ **Transverse quark pol.? Correlations spin / parton k_T ? Orbital angular momentum? Spatial distributions?**

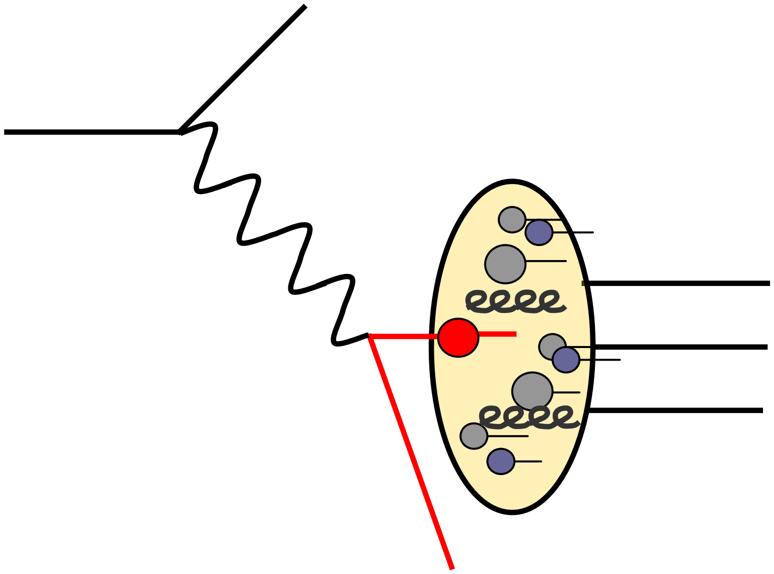
Measuring the proton spin structure with polarized proton probes

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

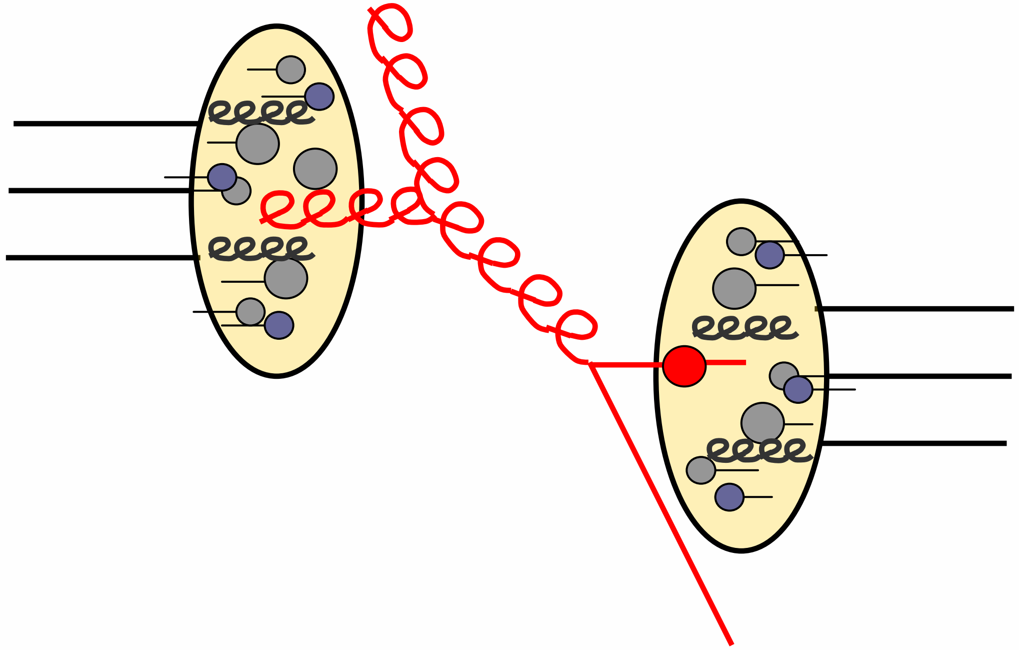
Quarks contribute only 20%!



DIS

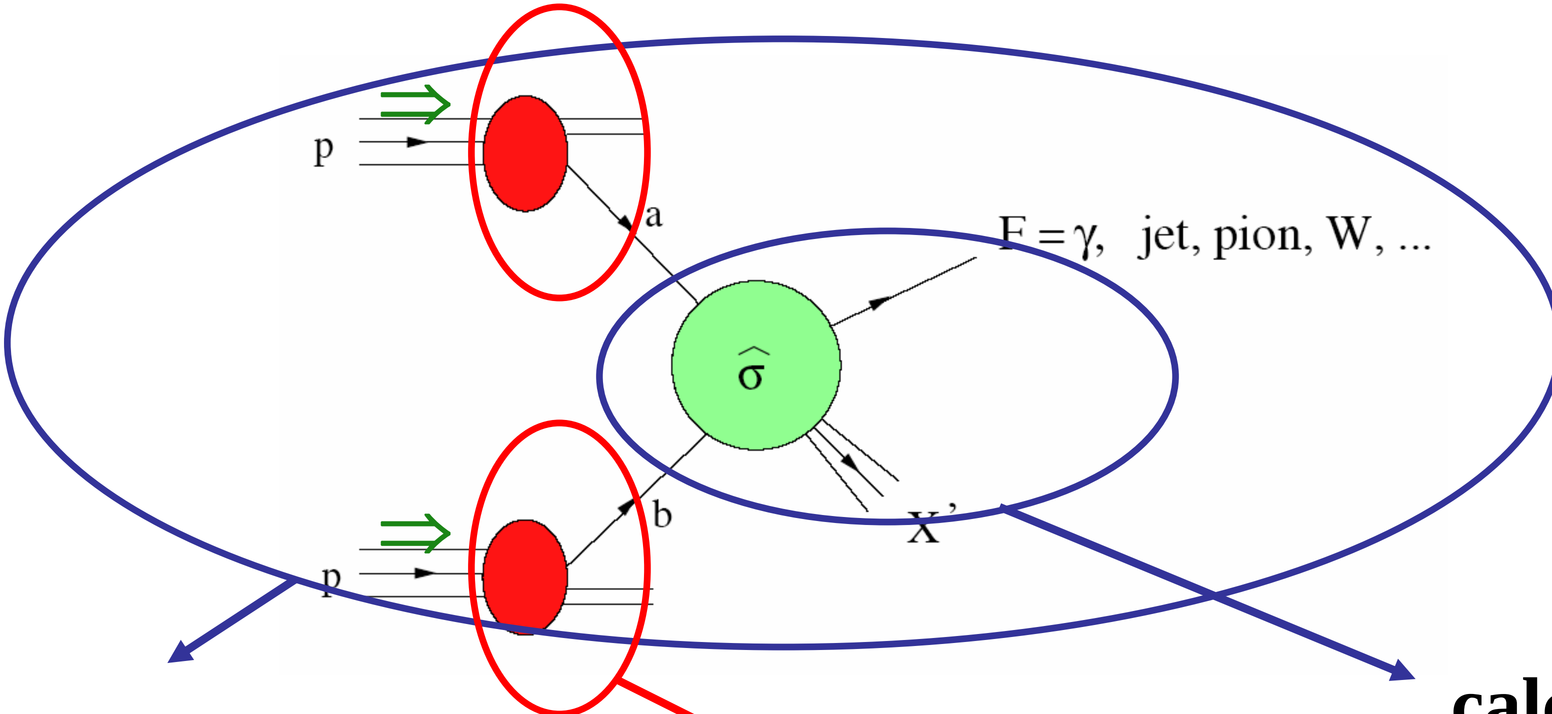


pp



- this is formalized through "factorization theorems"

Sterman, Libby; Ellis et al.; Collins, Soper, Sterman



measure

calculate

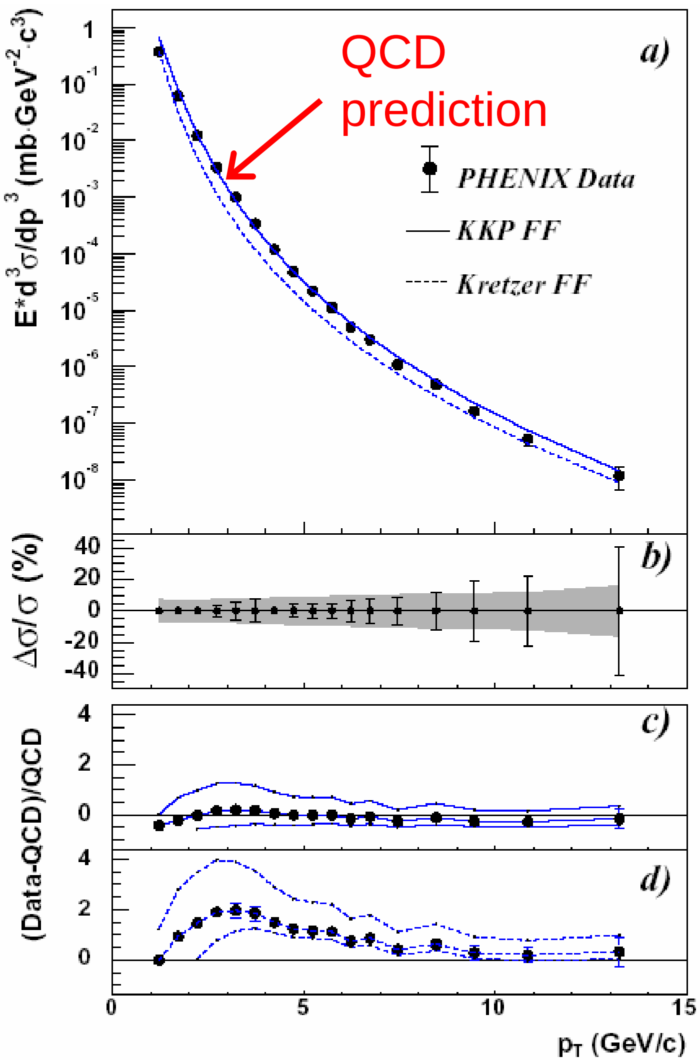
→ learn about !

$$\frac{d\sigma^{\Rightarrow\Leftarrow} - d\sigma^{\Rightarrow\Rightarrow}}{dp_T\, d\eta} = \sum_{ab} \int dx_a \int dx_b\, \Delta f_a(x_a, p_T)\, \Delta f_b(x_b, p_T)\, \frac{d\hat{\sigma}_{ab}^{\Rightarrow\Leftarrow} - d\hat{\sigma}_{ab}^{\Rightarrow\Rightarrow}}{dp_T\, d\eta}$$

universal

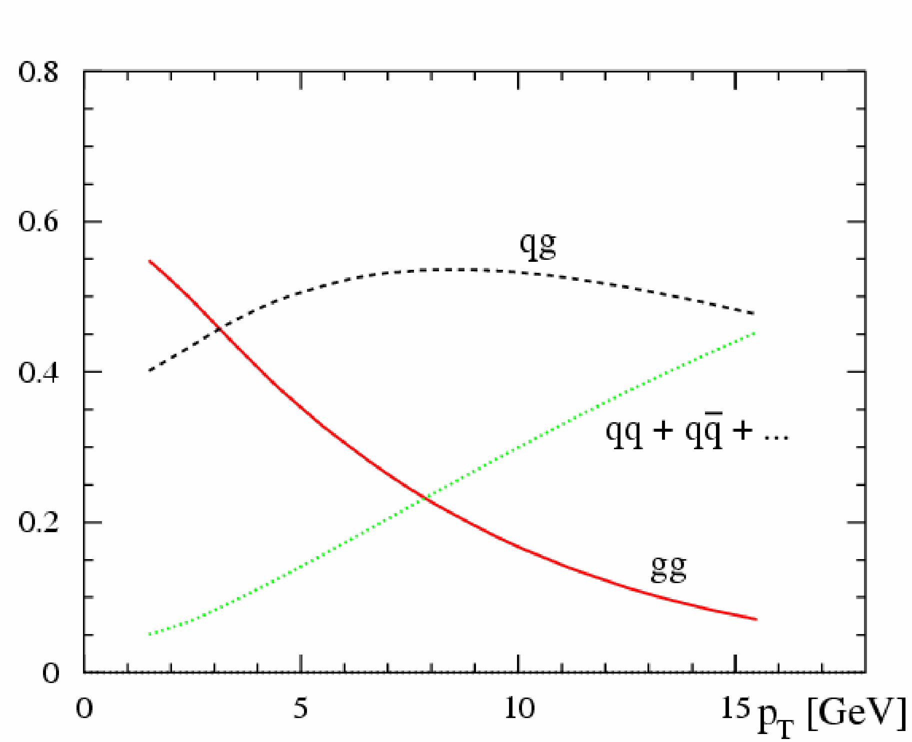
parton scatt.
perturbative QCD

Cornerstones to the RHIC Spin program



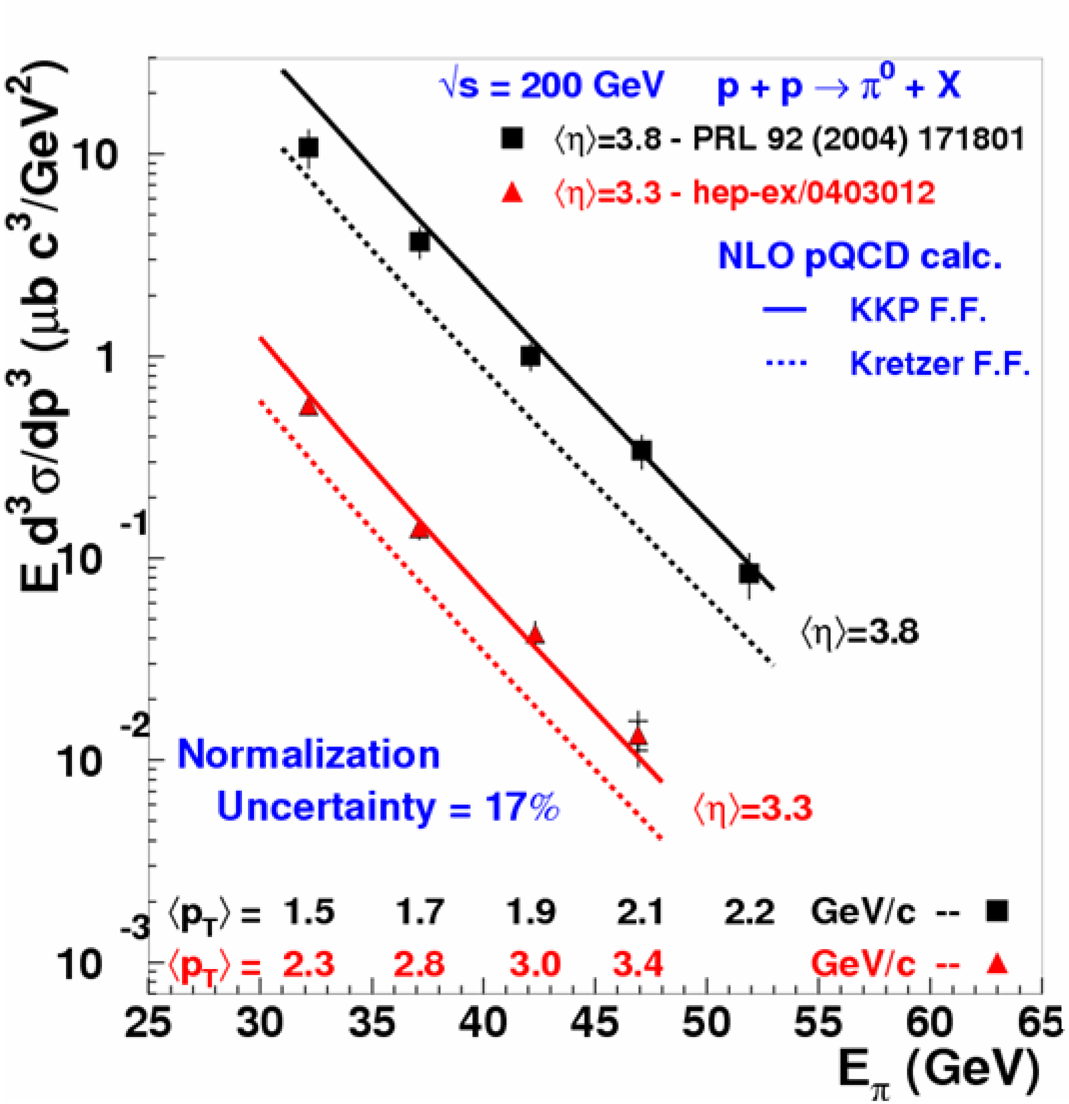
$pp \rightarrow \pi^0 X$

Mid-rapidity: PHENIX



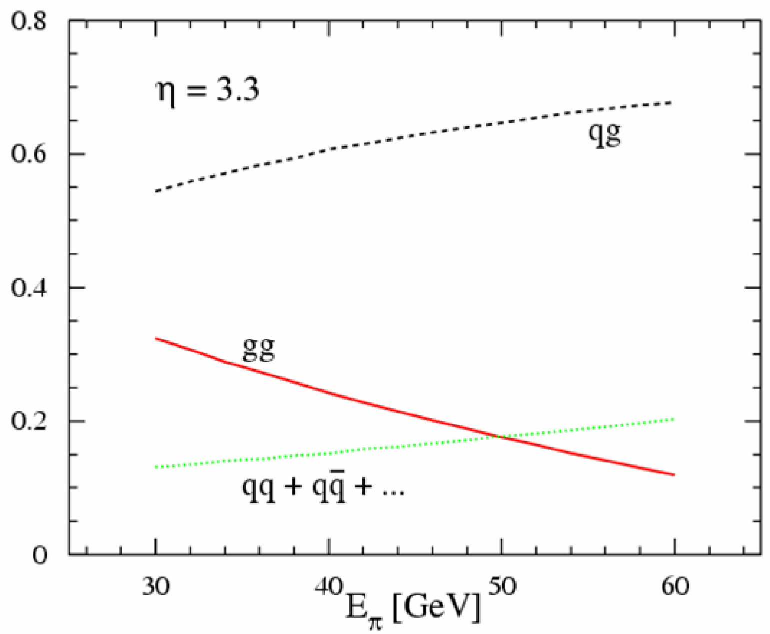
Physical Review Letters **91**, 241803 (2003)

Cornerstones (continued)



$pp \rightarrow \pi^0 X$

Forward rapidity: STAR



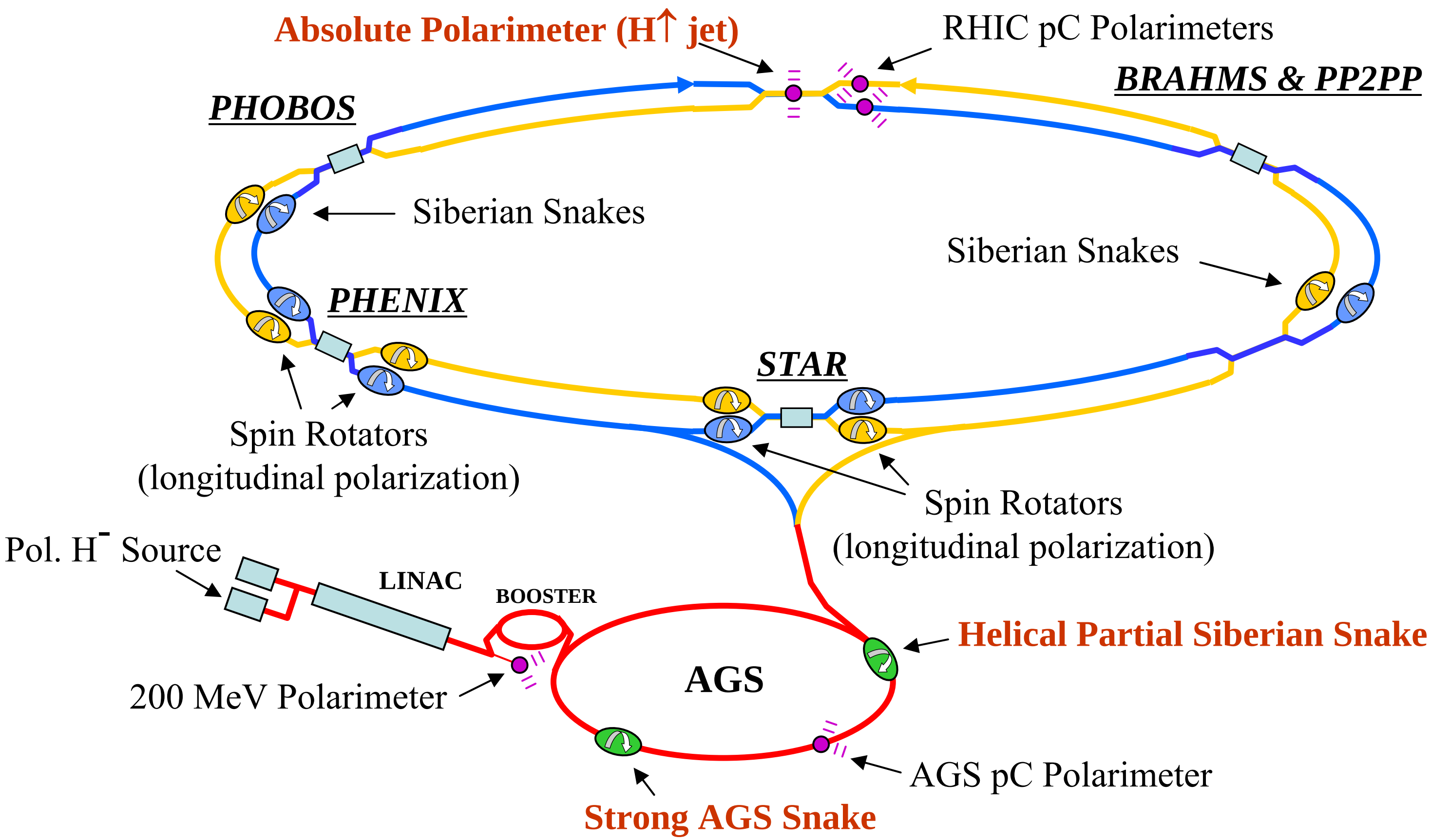
RHIC Spin Physics Program

- *Direct measurement* of polarized gluon distribution *using multiple probes*

- Direct measurement of *anti-quark polarization* using parity violating production of $W^{+/-}$

- Transverse spin: Transversity & transverse spin effects: possible connections to orbital angular momentum?

RHIC Polarized Collider



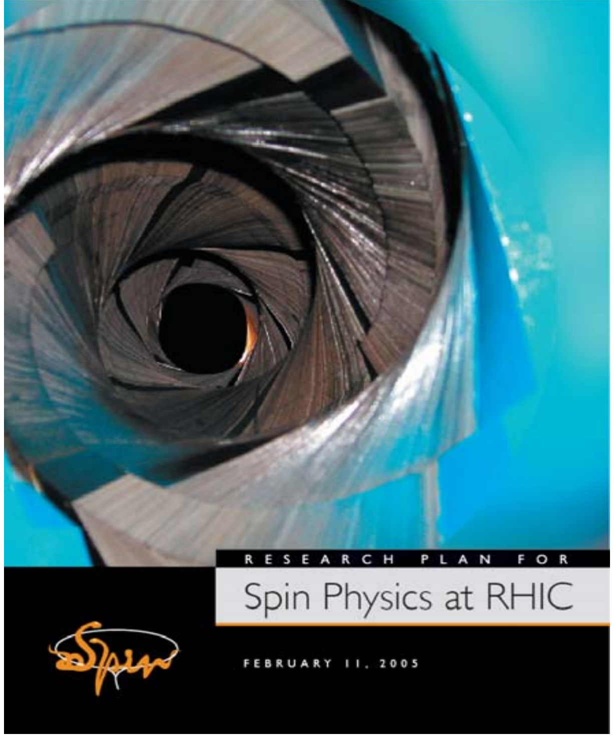
2006: 1 MHz collision rate; P=0.6

The Problem of Spin Resonances

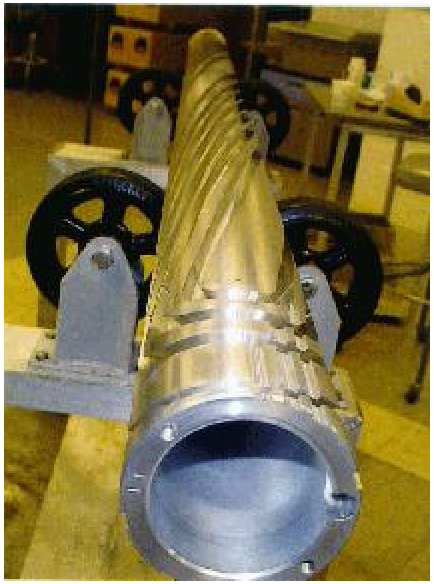
- Spin precesses about guide field (proton: 200 precessions in one turn at RHIC, 100 GeV)
- Spin precesses about horizontal magnetic fields (for example, focusing fields)
- When the 2 precessions beat, resonance condition: every 500 MeV of acceleration!

- Solution: Siberian Snakes

Siberian Snakes



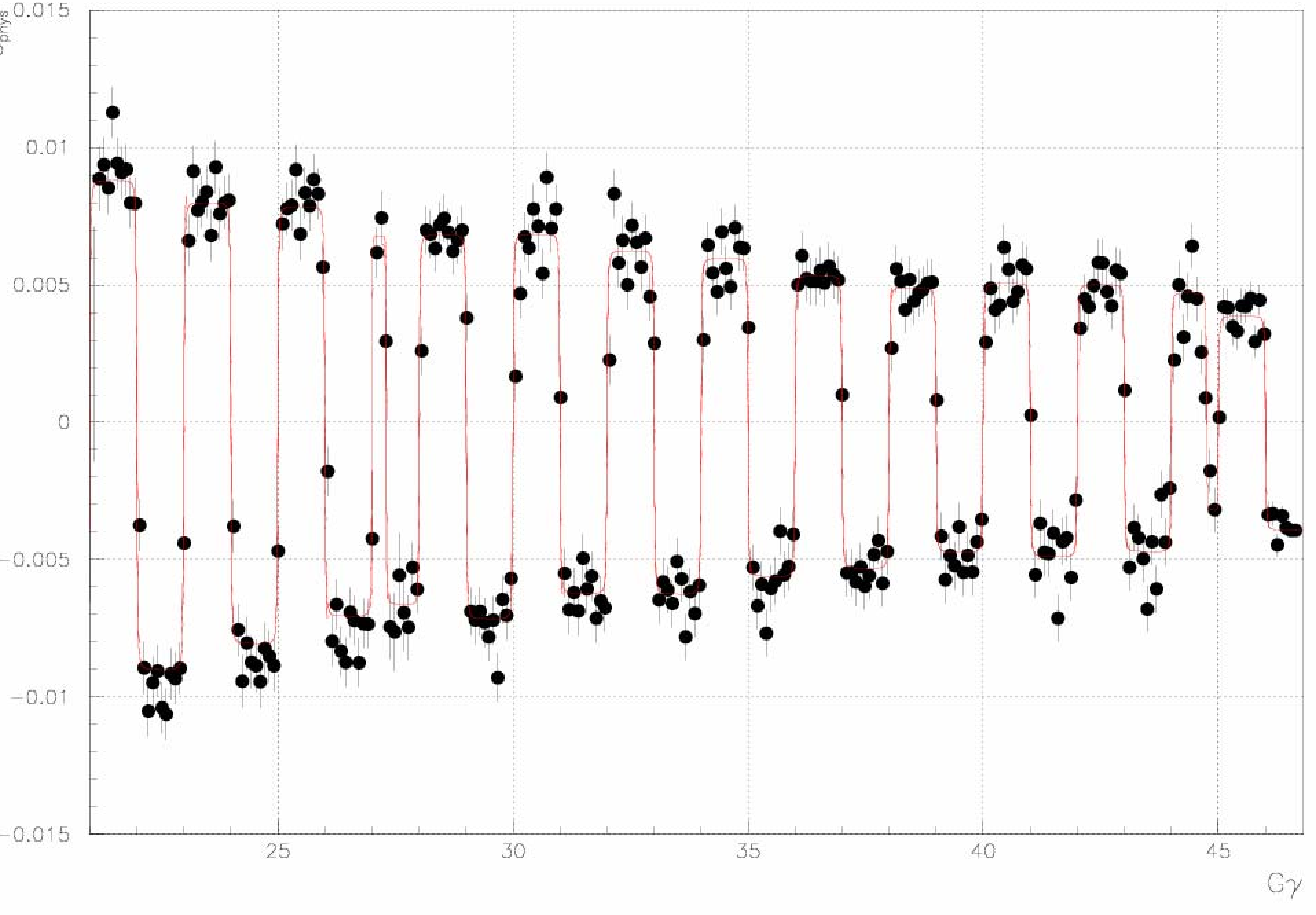
2003-4: Warm AGS Snake



1996-2001: Siberian Snakes

Snake: precess spin, leaving beam direction unchanged at exit of snake

Asymmetry during AGS ramp



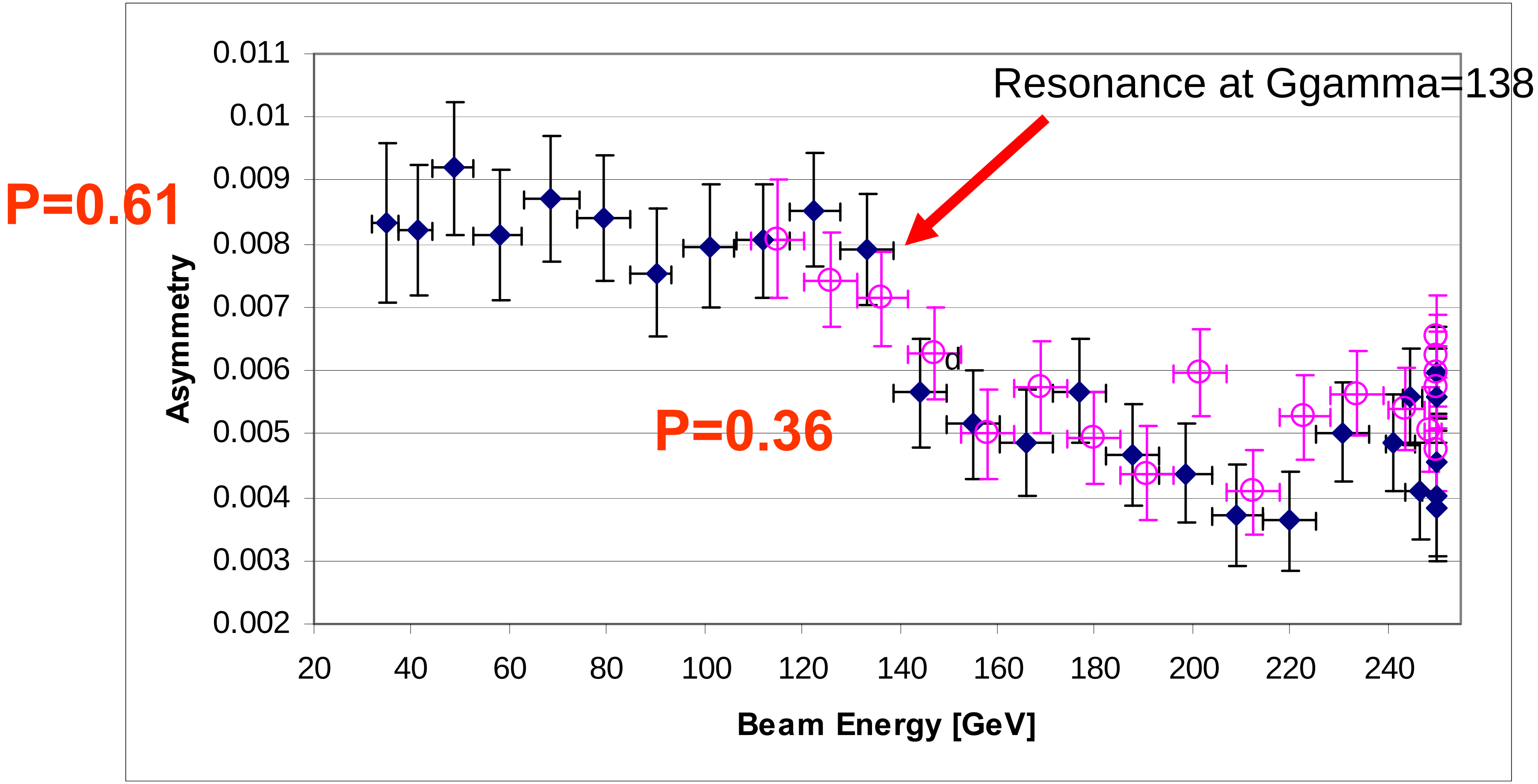
Siberian Snakes—how they work

- Spin resonance: spin axis is no longer vertical

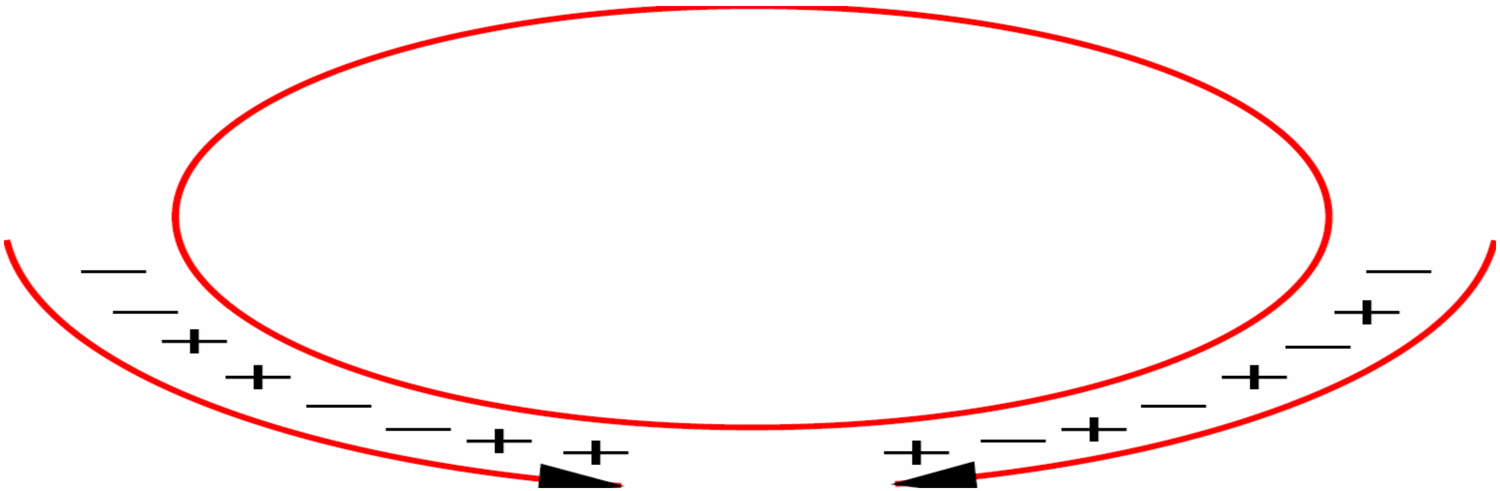
- Snake 1: precess spin 180 deg. about +45 deg. in horizontal plane
  - +45 deg. spin component unchanged, vert. and -45 deg. spin components flipped
- Snake 2: precess spin 180 deg. about -45 deg.
  - -45 deg. spin component unchanged, vert. and +45 deg. spin components flipped

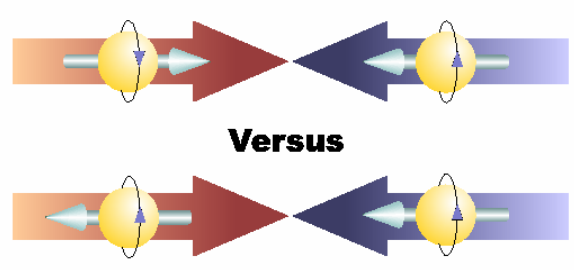
Two snakes: vertical spin is unchanged, horizontal spin components flip each turn.

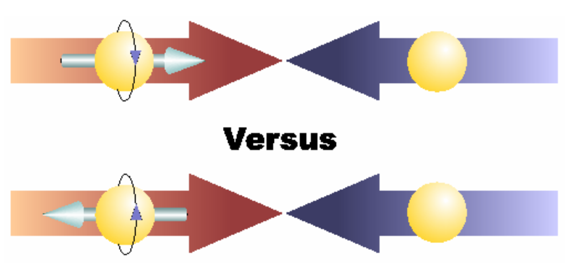
Polarization measurement on RHIC acceleration ramp, June 2006

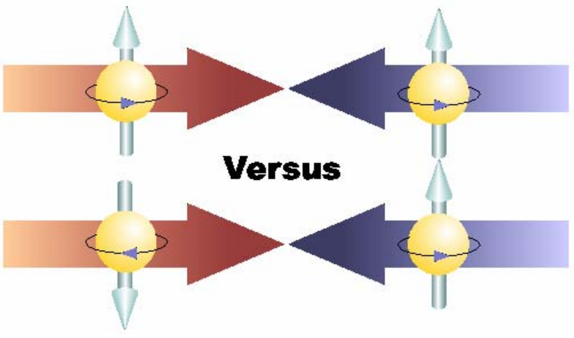


Exquisite Control of Systematics



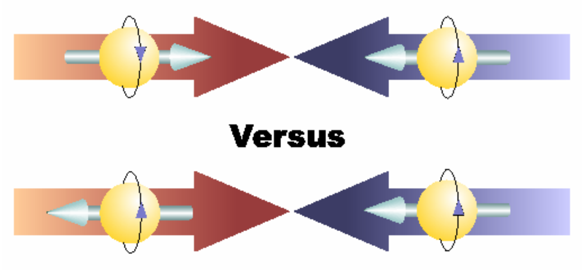






A_{LL}

“Yellow” beam “Blue” beam

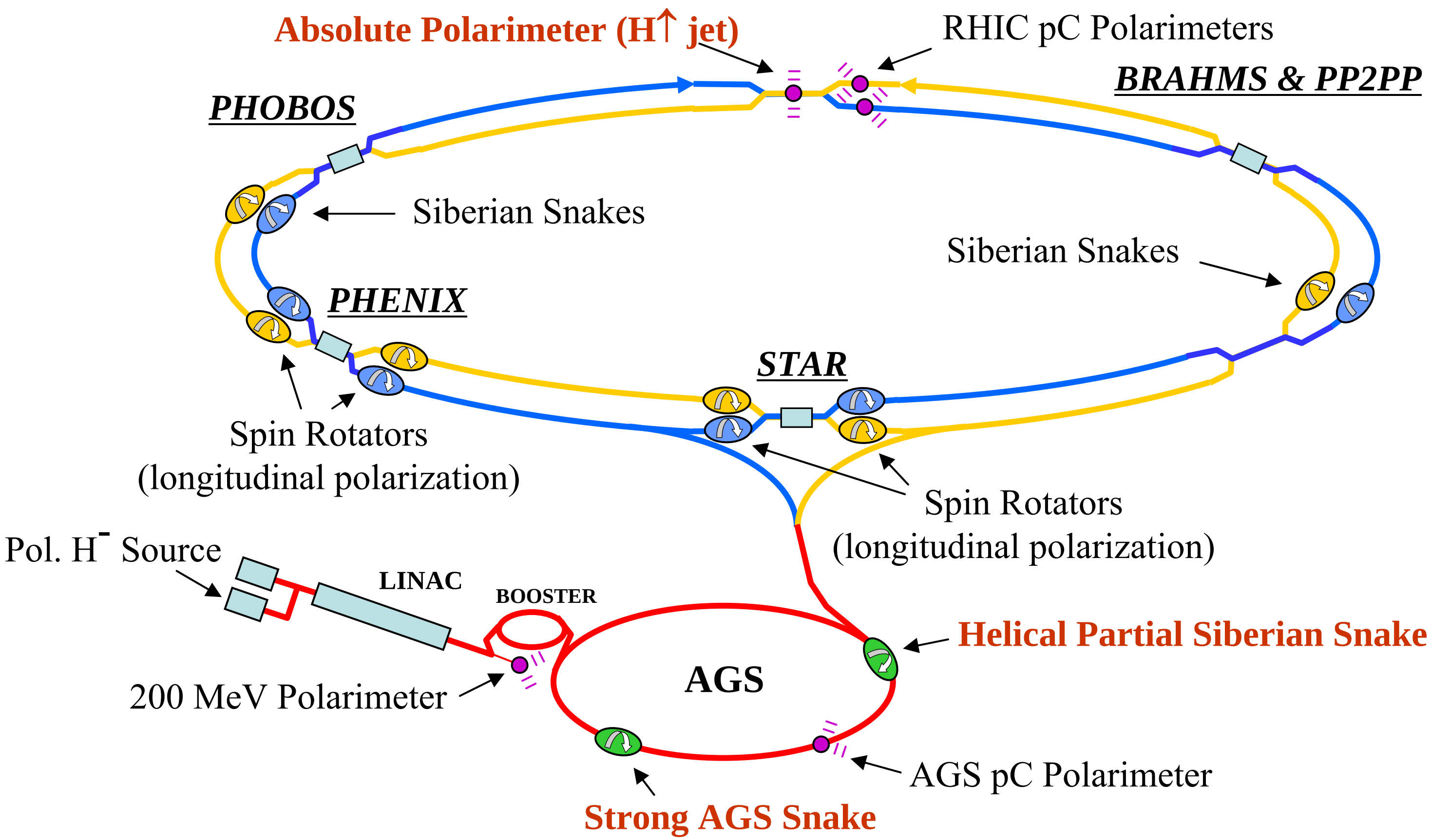


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{|P_B P_Y|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

++ same helicity
+– opposite helicity

(P) Polarization
(L) Relative Luminosity
(N) Number of pi0s

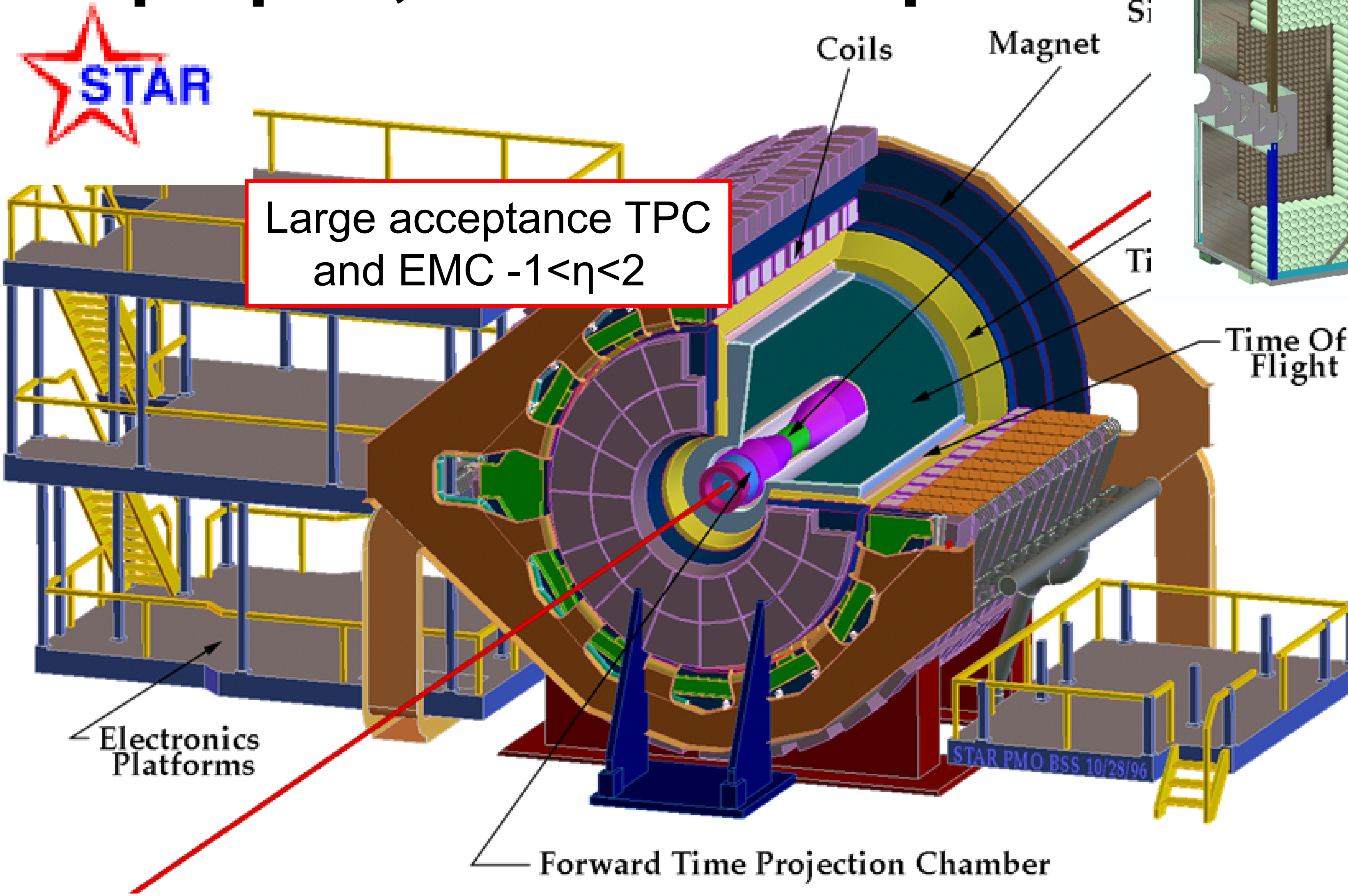
RHIC Polarized Collider



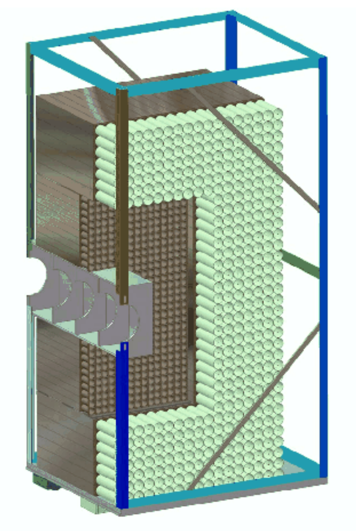
2006: 1 MHz collision rate; P=0.6

STAR spin physics program: ΔG, $\Delta q/\Delta \bar{q}$, transverse spin

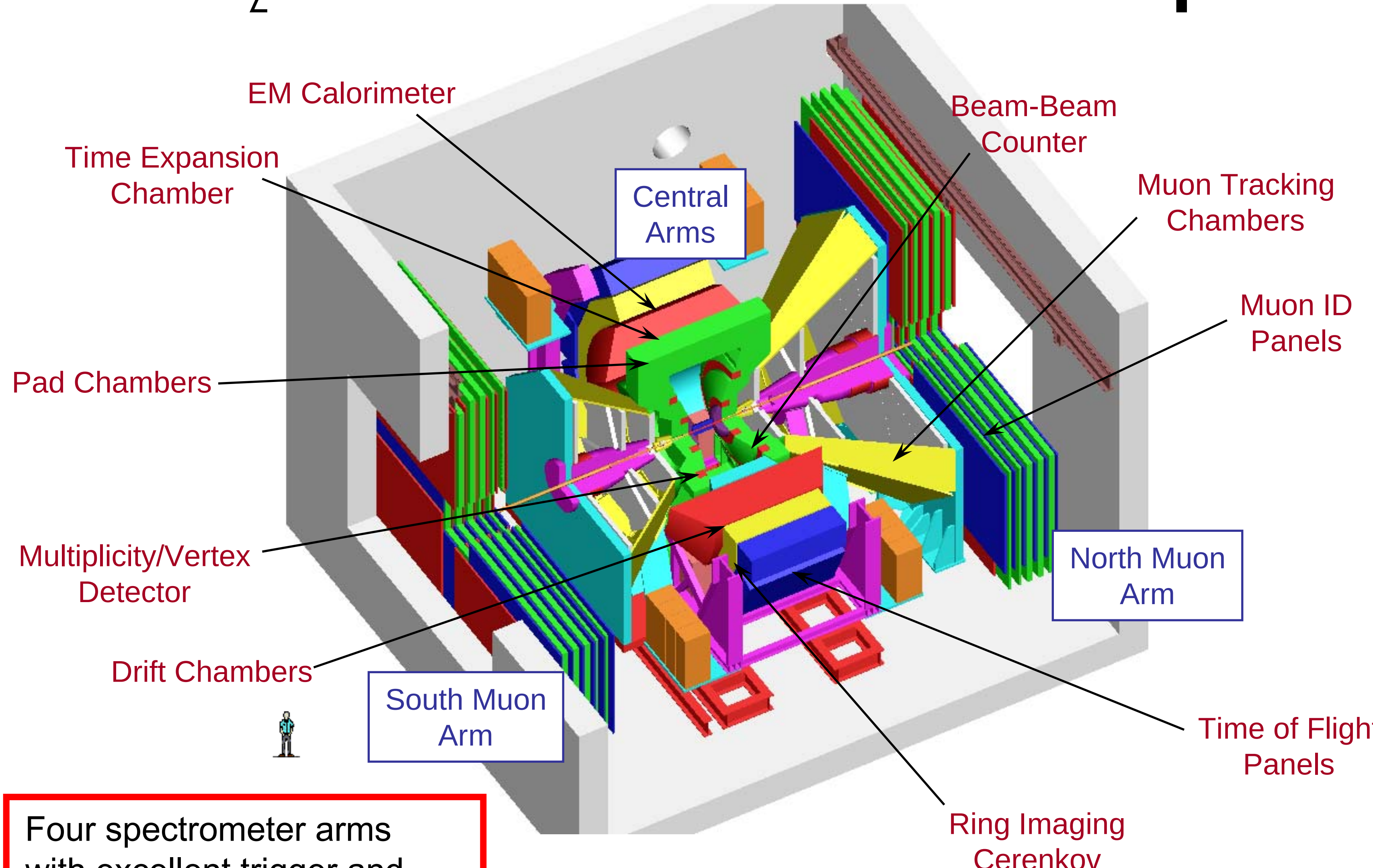
Large acceptance TPC and EMC $-1<\eta<2$



FMS

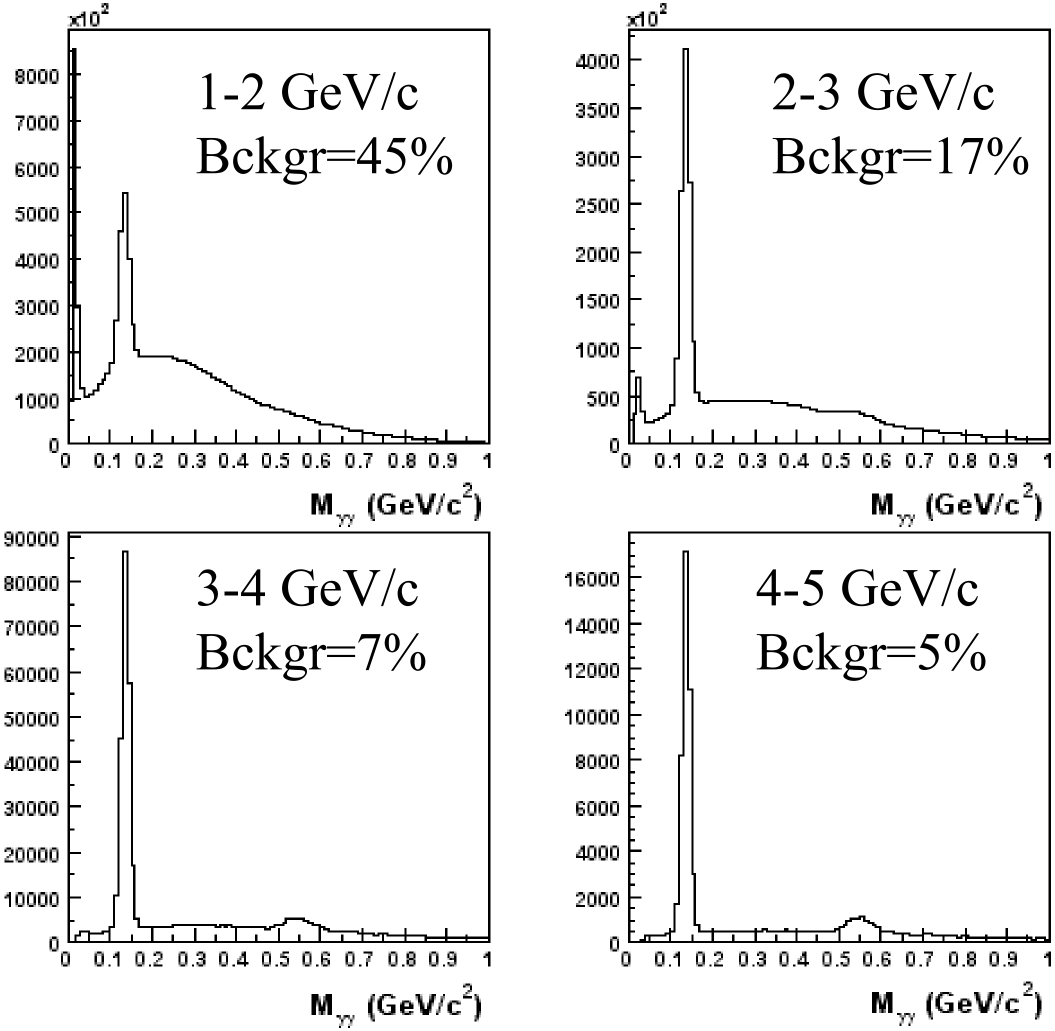


PHENIX spin physics program: ΔG, $\Delta q/\Delta \bar{q}$, transverse spin



Four spectrometer arms with excellent trigger and DAQ capabilities.

Pi0 reconstruction for A_{LL}

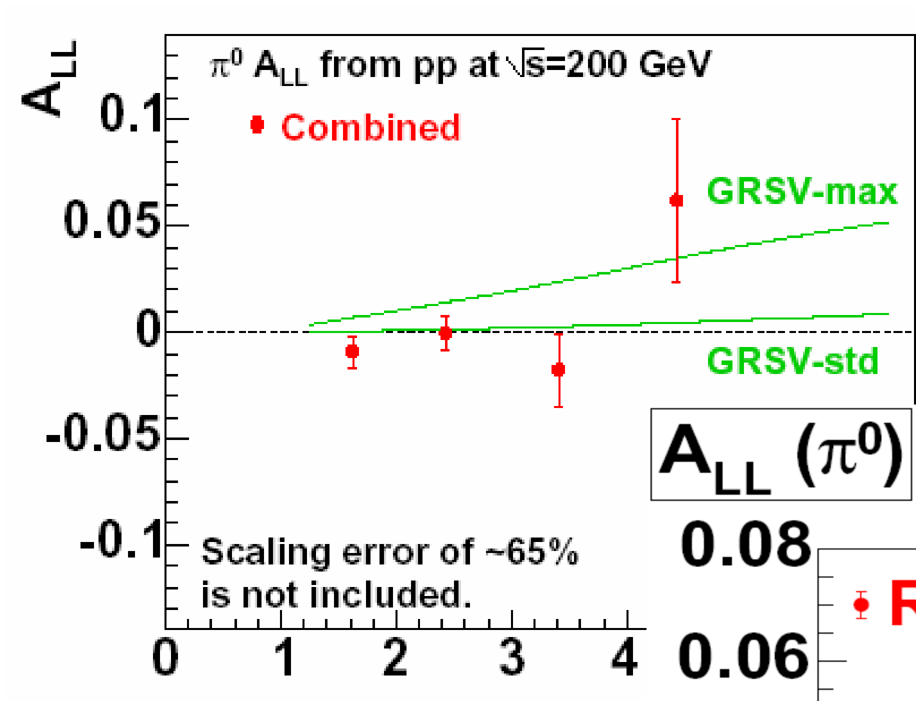


Results obtained for four pt bins from 1 to 5 GeV/c

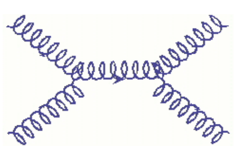
Pi0 peak width varies from 12 to 9.5 MeV/c^2 from lowest to highest pt bins

Background contribution under pi0 peak for ±25 MeV/c^2 mass cut varies from 45% to 5% from lowest to highest pt bins

2003+2004 Data

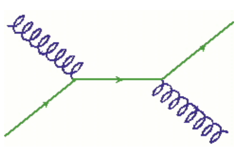


2005 Data:
Y. Fukao and K. Boyle
PANIC Oct. 2005



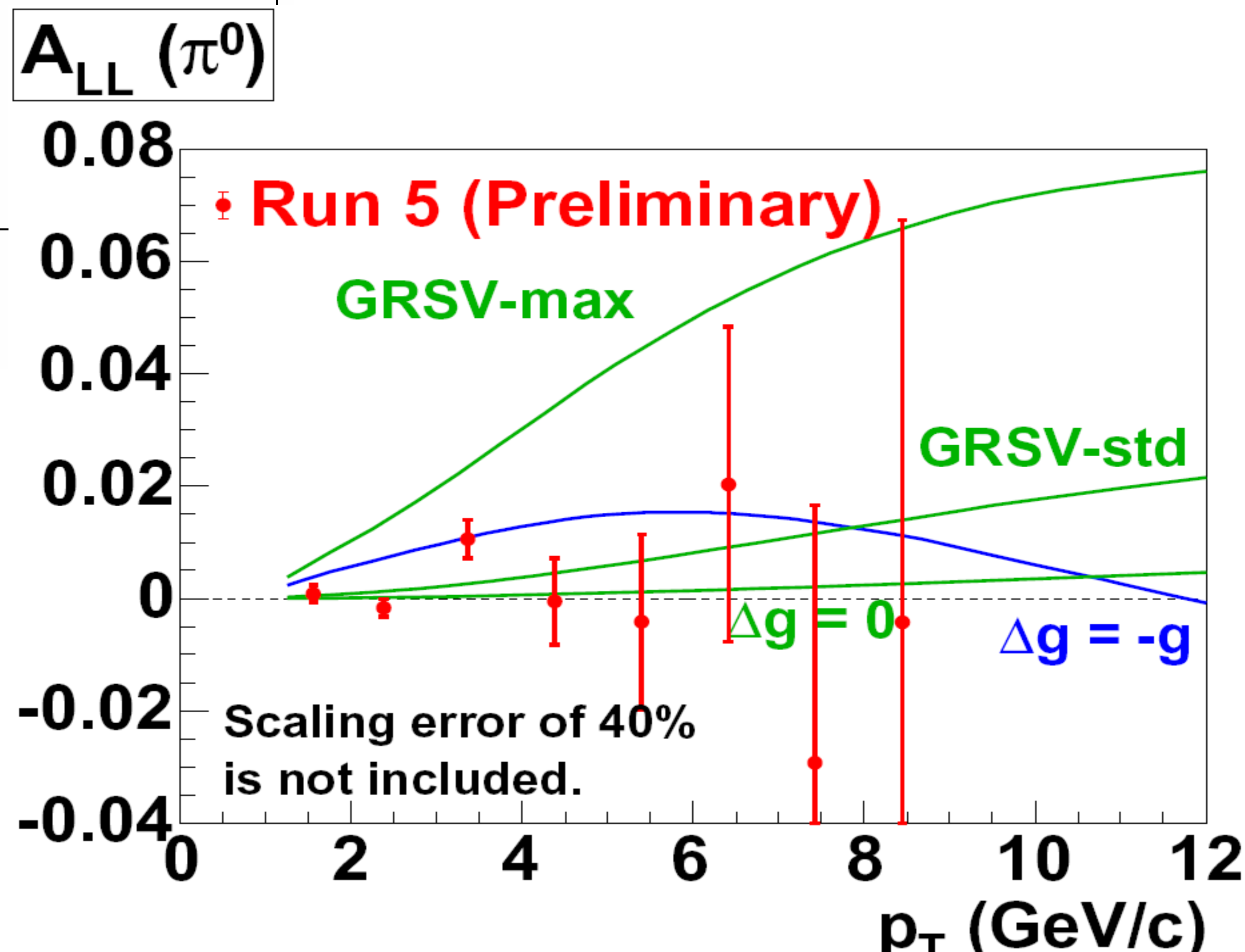
$gg \rightarrow gg$

$$A_{LL} \propto \frac{\Delta G}{G}\frac{\Delta G}{G}$$



$gq \rightarrow gq$

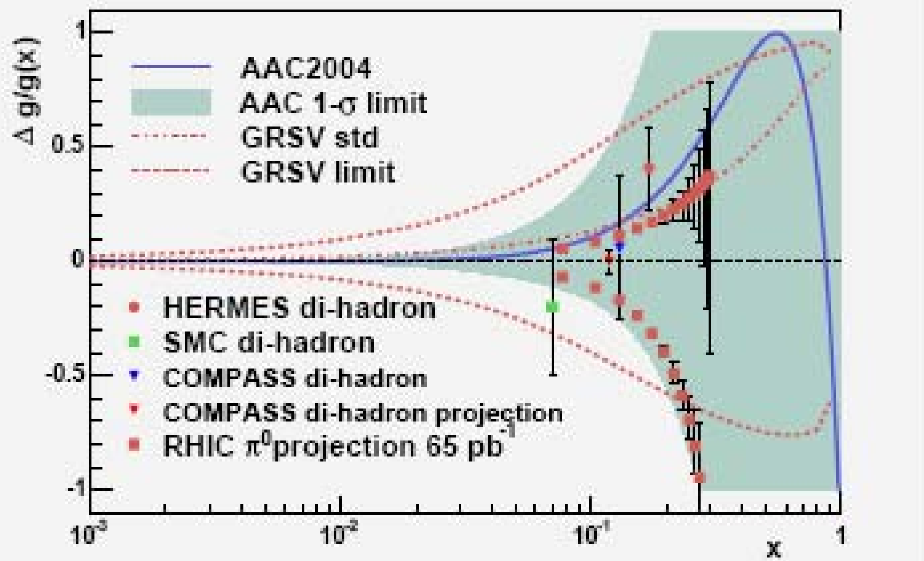
$$A_{LL} \propto \frac{\Delta q}{q}\frac{\Delta G}{G}$$



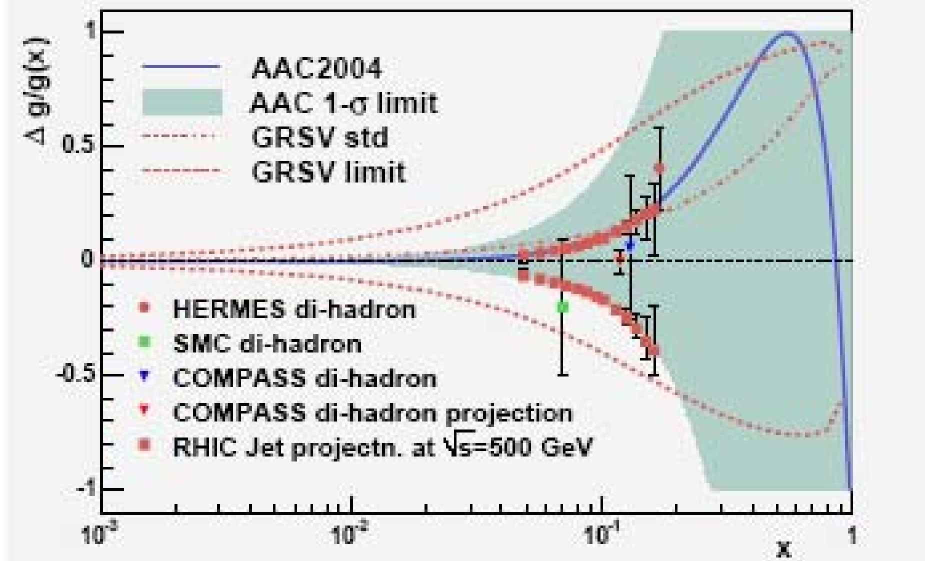
ΔG Measurements by 2012

see Spin report to DOE http://spin.riken.bnl.gov/rsc/

$\sqrt{s}$=200 GeV incl. π^0 prod'n

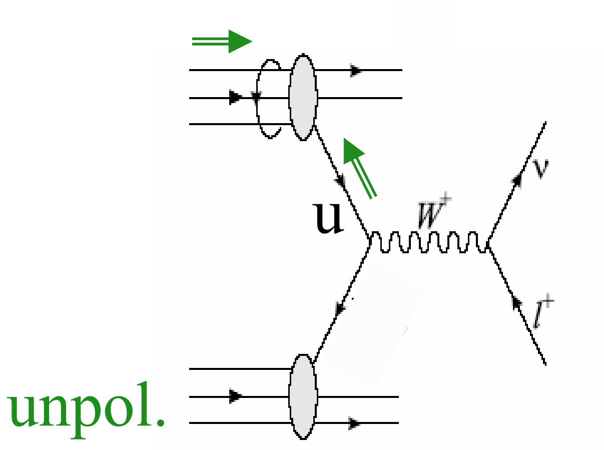


$\sqrt{s}$=500 GeV incl. jet prod'n



- Final results on ΔG will come from combined NLO analysis of all channels at RHIC and in DIS
- RHIC measurements will span broad range in x with good precision. multiple channels with independent theo. and exp. uncertainties.
- Uncertainty through extrapolation to small x

Δq-$\Delta\bar{q}$ at RHIC via W production



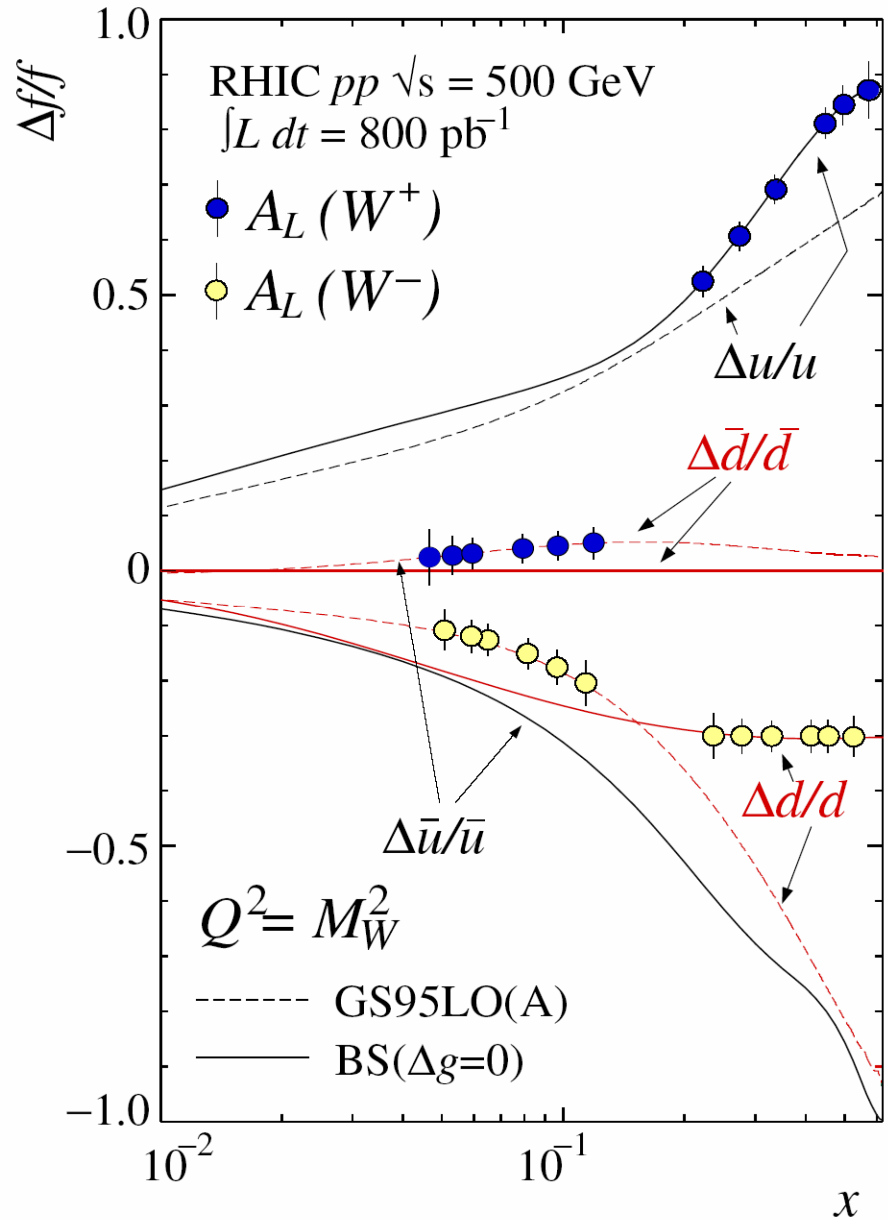
$$\Delta d + \bar{u} \rightarrow W^-$$

$$\Delta\bar{u} + d \rightarrow W^-$$

$$\Delta\bar{d} + u \rightarrow W^+$$

$$\Delta u + \bar{d} \rightarrow W^+$$

$$\mathbf{A_L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



Expected start: 2009

Transverse Spin

The RHIC (STAR and BRAHMS) results at forward rapidity demonstrate that large spin effects exist in the perturbative QCD regime.

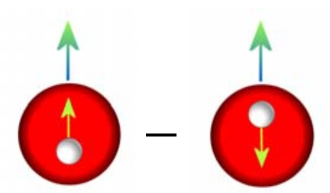
There are new results from Belle showing large fragmentation asymmetry for polarized quarks.

New HERMES results show large asymmetries for orbital angular momentum effects in polarized proton.

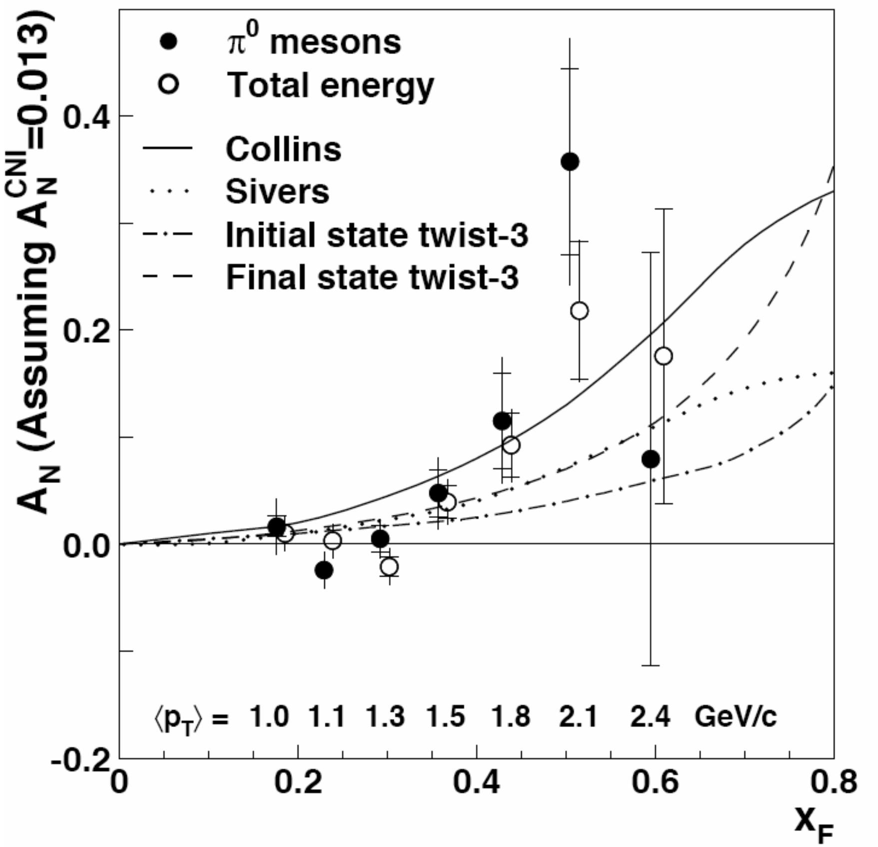
Physics with transverse spin at RHIC

$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

$\delta \mathbf{q}(\mathbf{x}) =$



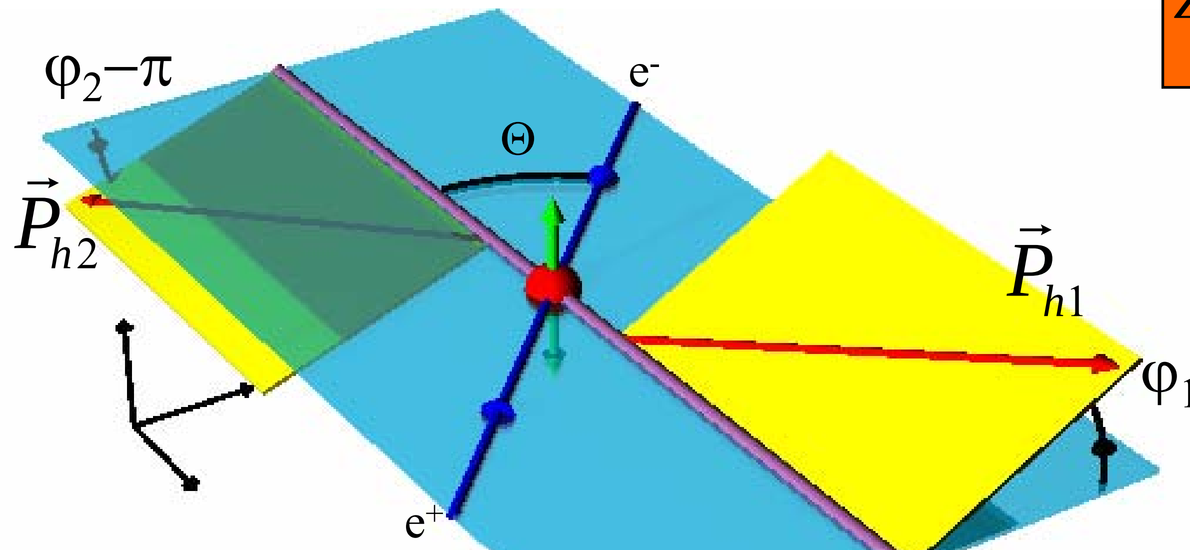
STAR data



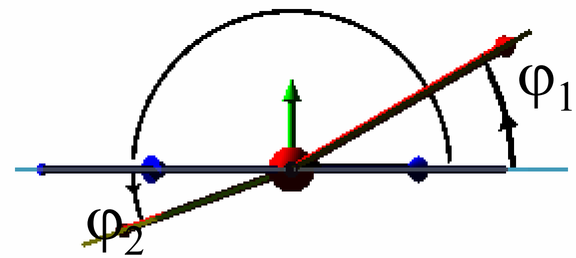
- **Transverse Physics: Measurement of transversity and study of other transverse spin effects with possible connections to orbital angular momentum**

Quark Analyzing Power at Belle

e^+e^- CMS frame:



$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\,\boldsymbol{GeV}$$



[D.Boer: PhD thesis(1998)]

2-hadron inclusive transverse momentum dependent cross section:

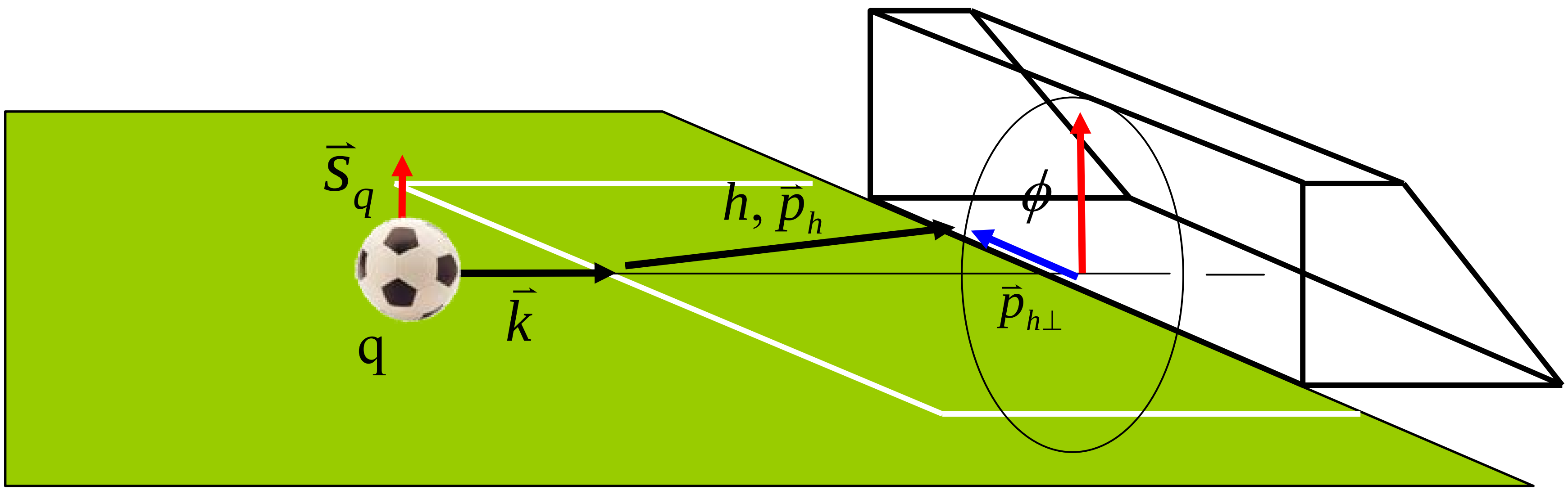
$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \cdots B(y)\, cos(\varphi_1 + \varphi_2) H_1^{\perp[1]}(z_1) \overline{H}_1^{\perp[1]}(z_2)$$

$$B(y) = y(1-y) \stackrel{cm}{=} \frac{1}{4} sin^2 \Theta$$

Net (anti-)alignment of transverse quark spins

Quark Analyzing Power

J.C. Collins, Nucl. Phys. B396, 161(1993)



$\vec{k}$: quark momentum

$\vec{s}_q$: quark spin

$\vec{p}_h$: hadron momentum

$\vec{p}_{h\perp}$: transverse hadron momentum

$$z_h = E_h / E_q$$
$$= 2E_h/\sqrt{s}$$: relative hadron momentum

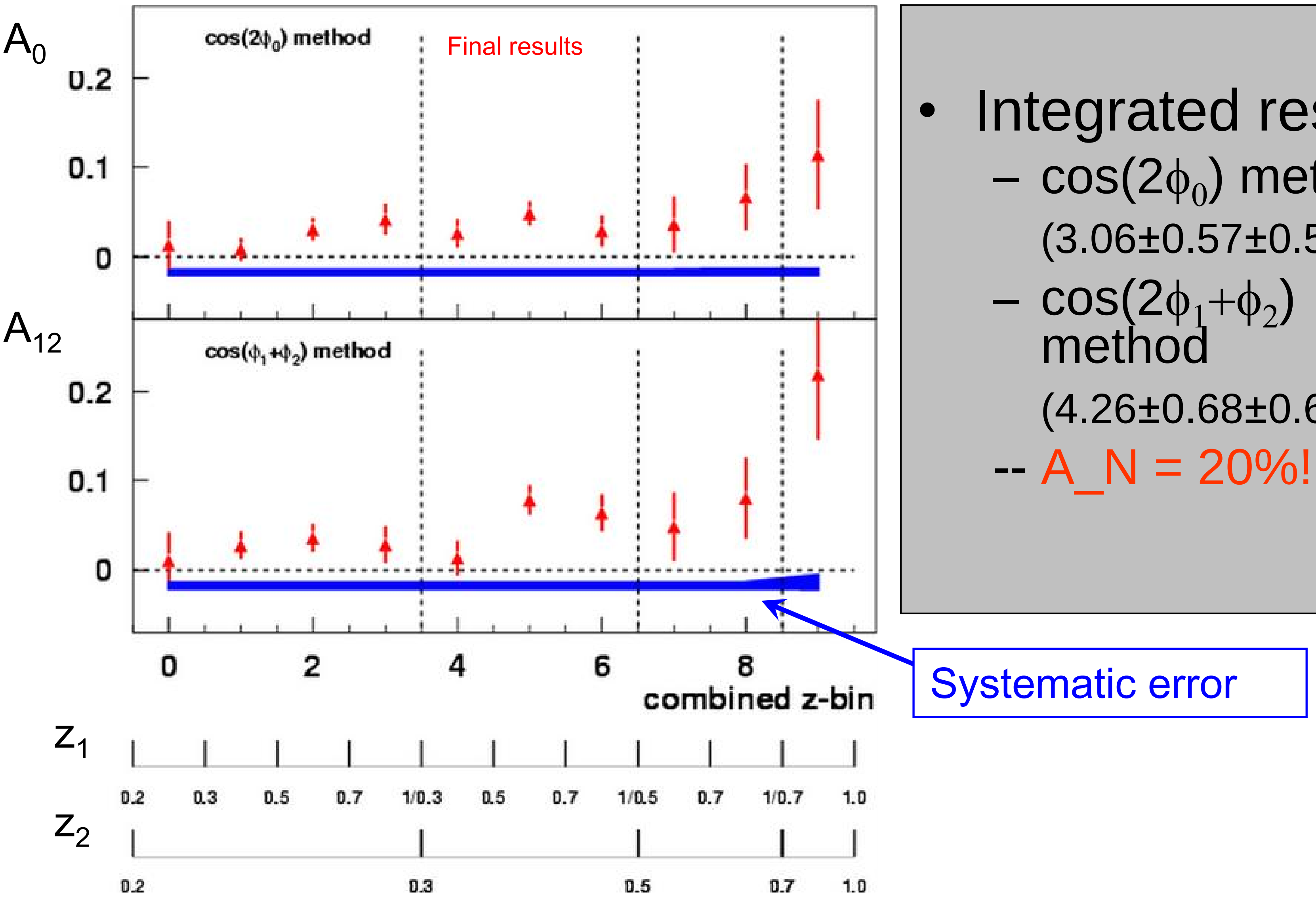
Collins Effect:
Fragmentation with of a quark *q* with spin s_q into a spinless hadron *h* carries an azimuthal dependence:

$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$

$$\propto \sin\phi$$

Results for $e^+ e^- \rightarrow \pi \pi X$ for $29 fb^{-1}$

R. Seidl et al. (Belle), PRL 96, 232002 (2006)



- Integrated results:
  - $\cos(2\phi_0)$ method
    $(3.06\pm0.57\pm0.55)\%$
  - $\cos(2\phi_1+\phi_2)$ method
    $(4.26\pm0.68\pm0.68)\%$
  -- A_N = 20%!

Plans

- **Longitudinal spin**

  ---gluon polarization at root(s)=200 GeV to 2009

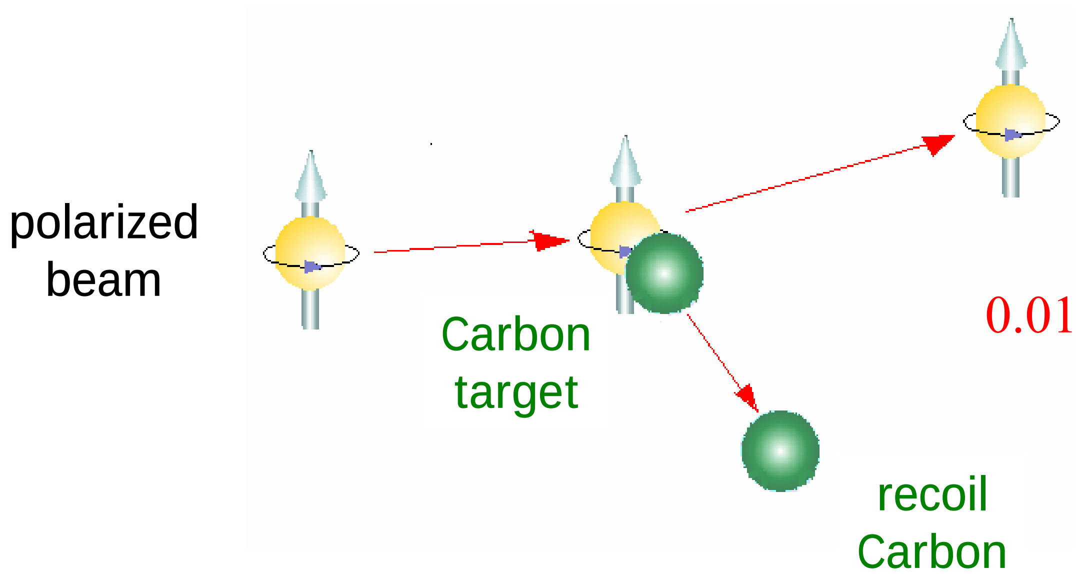
  ---W parity violating production: anti-quark polarizations by flavor---2009-2012, 500 GeV
- **Transverse spin**

  ---study quark transversity, quark analyzing power, orbital angular momentum of quarks and gluons in proton
- **New detectors:** forward spectrometers (2007), micro vertex detectors (2010), endcap cal. (2012)
- **Polarized ep and eA Collider:** **start 2012?**

Spin is one of the most fundamental concepts in physics, deeply rooted in Poincare invariance and hence in the structure of space-time itself. All elementary particles we know today carry spin, among them the particles that are subject to the strong interactions, the spin ½ quarks and the spin 1 gluons. Spin, therefore, plays a central role also in our theory of the strong interactions, QCD, and to understand spin phenomena in QCD will help to understand QCD itself.

To contribute to this understanding is the primary goal of the spin physics program at RHIC.

Polarimetry



$0.01 < |t| < 0.02\ (\mathrm{GeV}/c)^2$

$$P_B = -\frac{1}{A_N} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$

Raw asymmetries from carbon polarimeter by bunch (2005)