Exploring the Proton Spin

Werner Vogelsang

RBRC & BNL Nuclear Theory

LBNL Berkeley, 12/01/2004

Spin

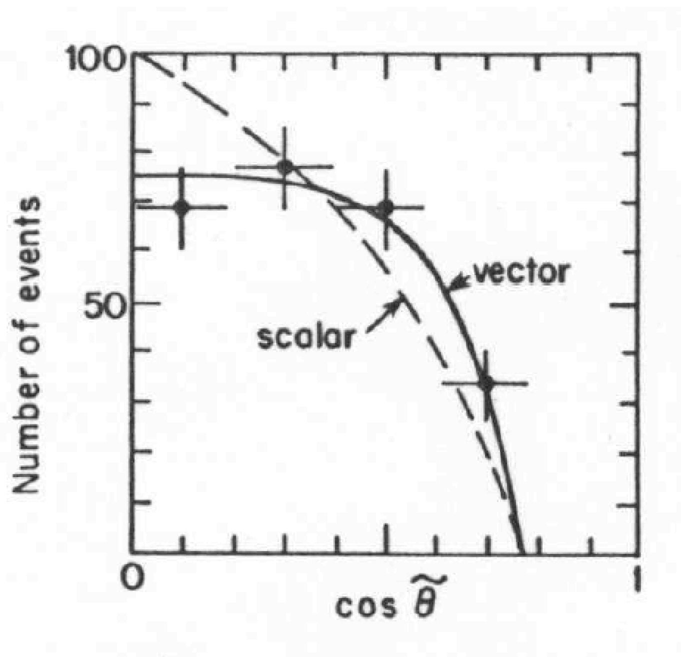
- invariants of Poincare group

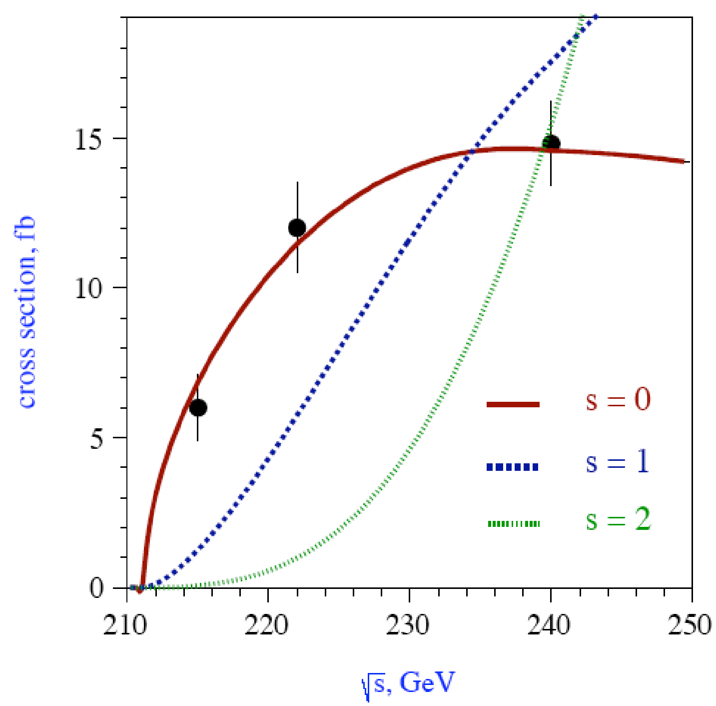
$$\mathcal{P}_\mu \, \mathcal{P}^\mu = m^2$$
$$\mathcal{W}_\mu \, \mathcal{W}^\mu = -m^2 \, S\,(S+1)$$

$$\mathcal{W}^\mu \sim \epsilon^{\mu\nu\rho\sigma} \, \mathcal{M}_{\nu\rho} \mathcal{P}_\sigma$$

- all particles that we believe to be elementary have Spin !
- gauge fields (W, Z, γ, g) : spin-1
- quarks and leptons : spin-1/2
- Higgs ?

- spin $\leftrightarrow$ many phenomena in particle physics
  - $*$ magnetic moments
  - $*$ electric dipole moments
  - $*$ angular (& other) distributions in particle reactions



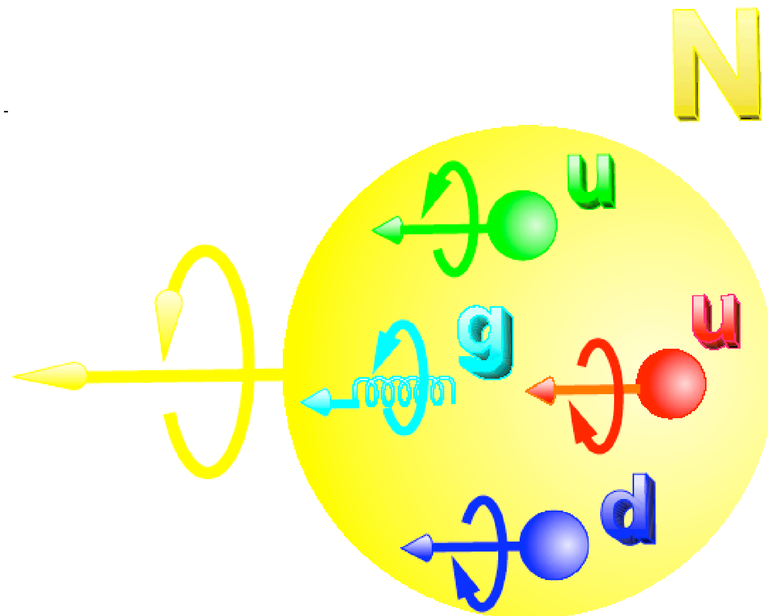


$e^+e^- \to q\bar{q}g$ TASSO

$e^+e^- \to H\,Z$ LC

- Today : let's look at spin in QCD

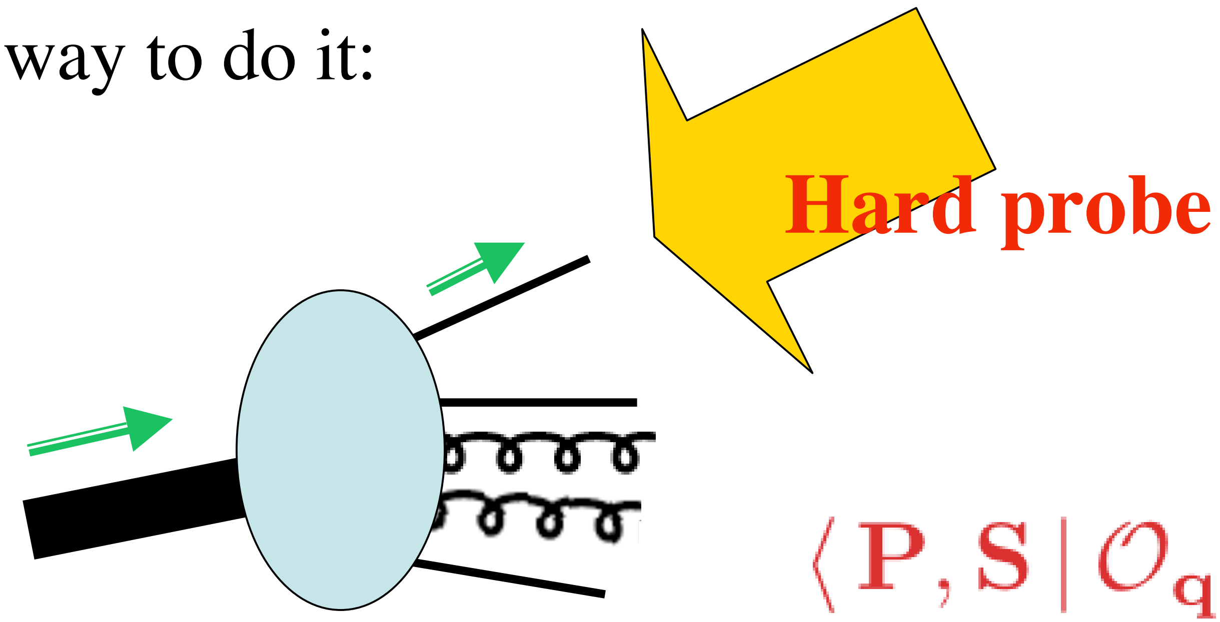
$\boxed{\text{The nucleon, a composite particle with spin}}$



- Main goal of QCD spin physics:

To understand the spin structure of hadrons in terms of quarks and gluons

- The way to do it:



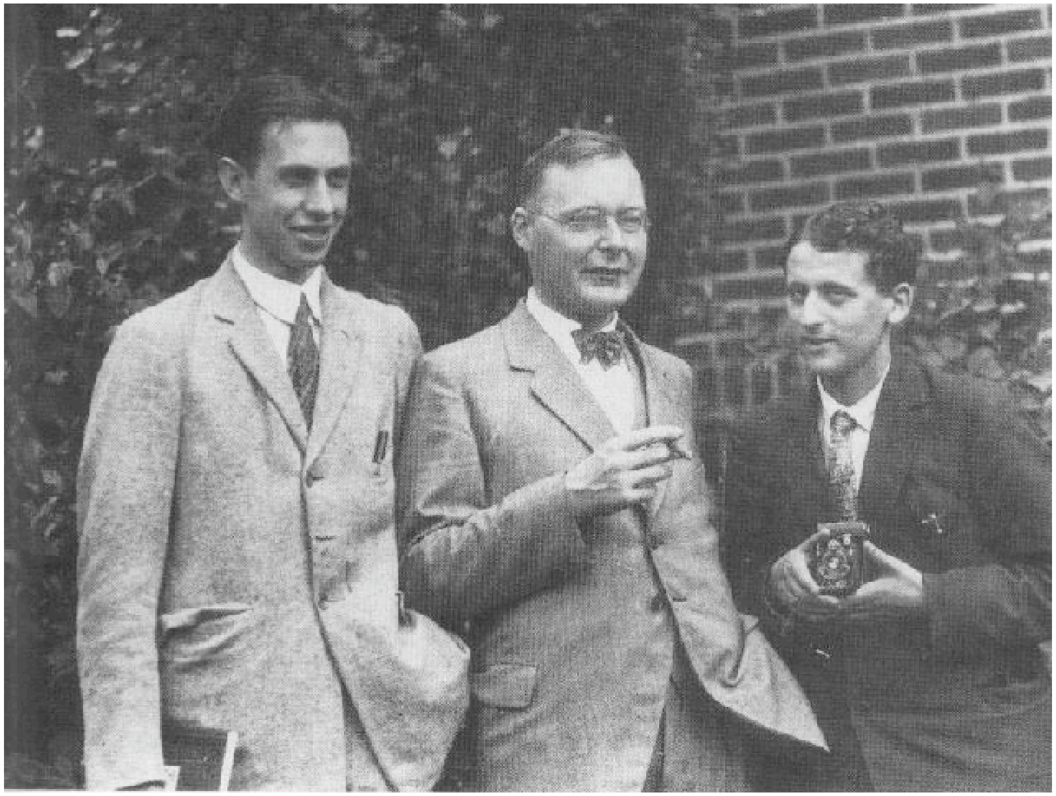
$$\langle \mathbf{P}, \mathbf{S} \,|\, \mathcal{O}_{\mathbf{q},\mathbf{g}} \,|\, \mathbf{P}, \mathbf{S} \rangle$$

Outline:

- Early history of spin
- Early nucleon structure
- Deeply-inelastic scattering
- Polarized DIS
- Current goals in QCD spin physics
    - quark & gluon polarization
    - parton orbital angular momentum
    - transverse polarization
- Conclusions & outlook

Early history of spin

Goudsmit & Uhlenbeck 1925: propose "self-rotating" electron



"This is a good idea. Your idea may be wrong,
but since both of you are so young without any
reputation, you would not lose anything by making
a stupid mistake." (Ehrenfest)

1927: the proton spin is 1/2

- Hund, Hori & Dennison's conclusion

A Note on the Specific Heat of the Hydrogen Molecule.

By DAVID M. DENNISON, Ph.D., University of Michigan.

(Communicated by R. H. Fowler, F.R.S.—Received June 3, 1927.)

In a recent article F. Hund* has treated the problem of the specific heat of the hydrogen molecule on the basis of the wave mechanics. The total number of rotational states are divided due to the homopolar character of the molecule into two groups, to the one of which belong wave functions symmetrical in the two nuclei, and to the other wave functions which are antisymmetrical in the nuclei. Hund has suggested that the presence of both groups in hydrogen may be accounted for by assuming that the nuclei possess a spin, in which case transitions between symmetrical or between antisymmetrical states will have their usual intensity but transitions between symmetrical and antisymmetrical states

a time long compared with the time of the experiment, we obtain a specific heat curve which follows the observed curve to within the errors of observation, and that moreover the constants ρ and I are in good agreement with the values of these constants as found in the band spectrum of H_2.

[*Added June* 16, 1927.—It may be pointed out that the ratio of 3 to 1 of the antisymmetrical and symmetrical modifications of hydrogen, as regards the rotation of the molecule, is just what is to be expected from a consideration of the equilibrium at ordinary temperatures if the nuclear spin is taken equal to that of the electron, and only the complete antisymmetrical solution of the Schrödinger wave equation allowed.*

I wish to express my thanks to Mr. R. H. Fowler for much helpful criticism and to Prof. T. Hori for the opportunity of seeing the results of his work before their publication. I wish also to acknowledge with gratitude a stipend from the University of Michigan.

* W. Heisenberg, 'Z. f. Physik,' vol. 41, p. 239 (1927), in particular see p. 264.

- Heisenberg had previously entertained this idea

Early structure of the Nucleon

Structure of the nucleon in 1933:

$$\vec{\mu}_p = \frac{e\hbar}{mc}\, 2.79\, \vec{s}_p$$

Magnetic Moment of the Proton

THE spin of the electron has the value $\frac{1}{2} \cdot \frac{h}{2\pi}$, and its magnetic moment has the value $2 \frac{e}{m_e c} \cdot \frac{1}{2} \cdot \frac{h}{2\pi}$, or 1 Bohr magneton. The spin of the proton has the same value, $\frac{1}{2} \cdot \frac{h}{2\pi}$, as that of the electron. Thus for the magnetic moment of the proton the value $2 \frac{e}{m_p c} \cdot \frac{1}{2} \cdot \frac{h}{2\pi}$ = 1/1840 Bohr magneton = 1 nuclear magneton is to be expected.

So far as we know, the only method at present available for the determination of this moment is the deflection of a beam of hydrogen molecules in an inhomogeneous magnetic field (Stern-Gerlach experiment). In the hydrogen molecule, the spins of the two electrons are anti-parallel and cancel out. Thus the magnetic moment of the molecule has two sources: (1) the rotation of the molecule as a whole, which is equivalent to the rotation of charged particles, and leads therefore to a magnetic moment as arising from a circular current; and (2) the magnetic moments of the two protons.

fore, even at the lowest temperatures, the rotational magnetic moment is superimposed on that due to the two protons with parallel spin. Since, however, the rotational moment is known from the experiments with pure para-hydrogen, the moment of the protons can be determined from deflection experiments with ortho-hydrogen, or with ordinary hydrogen consisting of 75 per cent ortho- and 25 per cent para-hydrogen. The value obtained is 5 nuclear magnetons for the two protons in the ortho-hydrogen molecule, that is, 2·5 (and not 1) nuclear magnetons for the proton.

This is a very striking result, but further experiments carried out with increased accuracy and over a wide range of experimental conditions (such as temperature, width of beam, etc.) have shown that it is correct within a limit of less than 10 per cent.

A more detailed account of these experiments will appear in the *Zeitschrift für Physik*.

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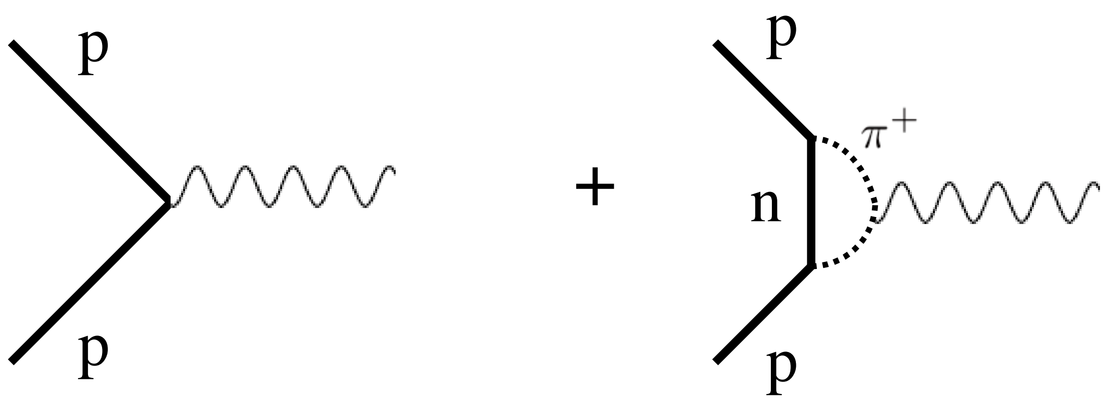
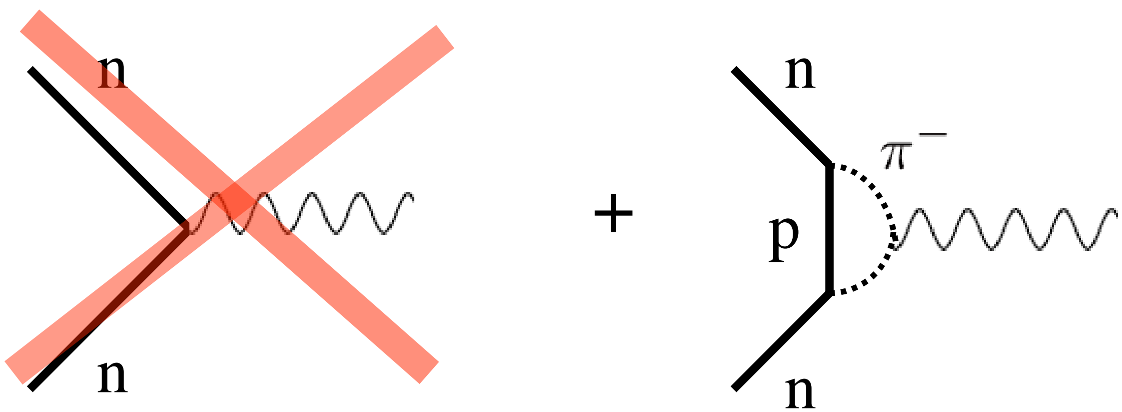
Hamburgischer Universität.
June 10.

- early attempts by Yukawa's theory:



$= 1 + \delta$



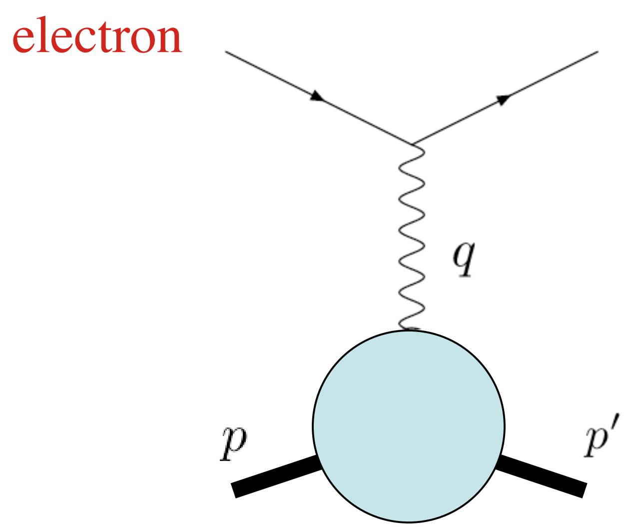
$= 0 - \delta$

$$2.79 = 1 + 1.79 \qquad -1.91 = 0 - 1.91$$

- heavier mesons ?   divergencies ?

How to get deeper insight ?

- Basic idea: scatter off nucleon with simple probe



$$Q \equiv \sqrt{-q^2}$$

$$\boxed{\frac{\hbar}{Q} = \frac{2\times 10^{-16}\,\mathrm{m}}{Q/\mathrm{GeV}}}$$

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{point}} |F(q)|^2$$

$$F(\vec{q}) = \int d^3x\,\rho(\vec{r})\,\mathrm{e}^{i\vec{q}\cdot\vec{r}}$$

form factor

- for spin-1/2 proton:

$$\bar{u}(p', s')\,\Gamma^{\mu}\,u(p, s) \;=\; \chi^{\dagger}_{s'}\left(G_E(Q^2)\;,\;\; \frac{i\vec{\sigma}\times\vec{q}}{2m_p}\,G_M(Q^2)\right)\chi_s$$

where $\quad G_E(0) \;=\; 1 \qquad G_M(0) \;=\; 2.79$

- cross section: $\qquad \tau \;\equiv\; Q^2/4M^2$

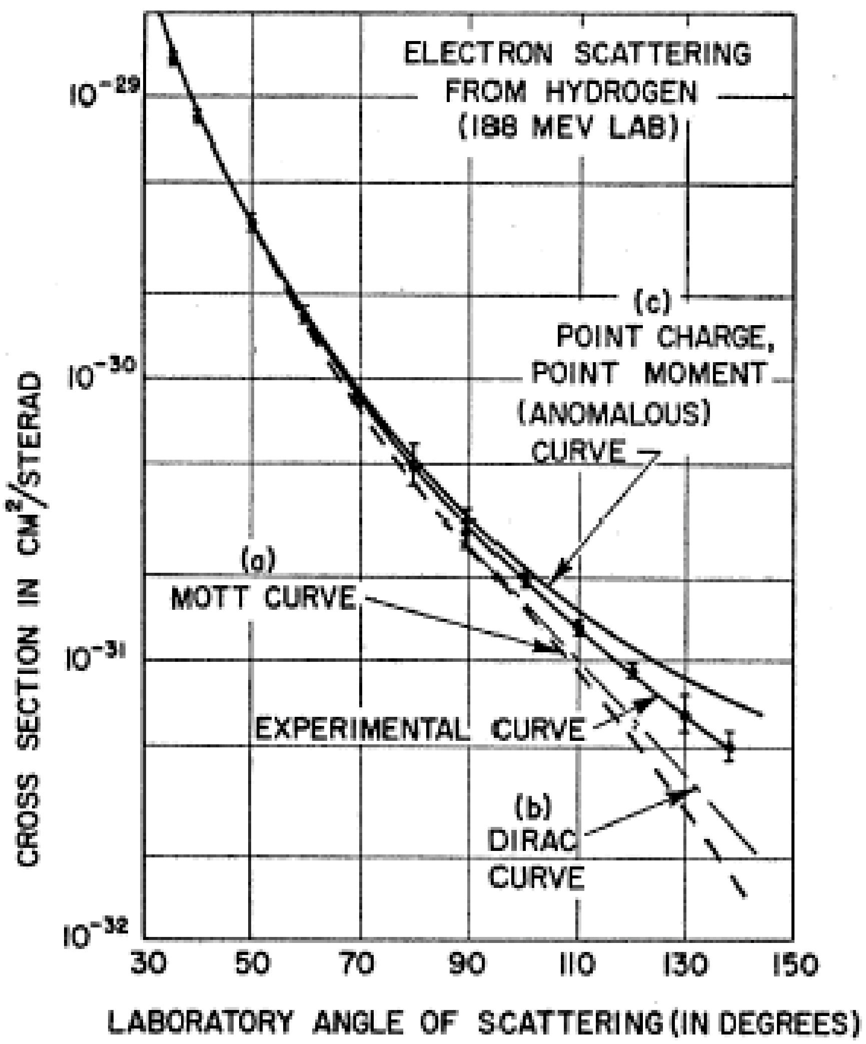
$$\frac{d\sigma}{d\Omega} \;=\; \frac{\alpha^2}{4E^2\sin^4\left(\frac{\theta}{2}\right)}\,\frac{E'}{E}\left[\frac{G_E^2 + \tau\,G_M^2}{1+\tau}\;\cos^2\left(\frac{\theta}{2}\right) \;+\; 2\tau\,G_M^2\;\sin^2\left(\frac{\theta}{2}\right)\right]$$

- compare point-like, but with anomalous magnetic moment:

$$\frac{d\sigma}{d\Omega} \;=\; \frac{\alpha^2}{4E^2\sin^4\left(\frac{\theta}{2}\right)}\,\frac{E'}{E}\left[\frac{1 + 7.78\,\tau}{1+\tau}\;\cos^2\left(\frac{\theta}{2}\right) \;+\; 5.58\,\tau\;\sin^2\left(\frac{\theta}{2}\right)\right]$$

Structure of the nucleon in the ‘50s

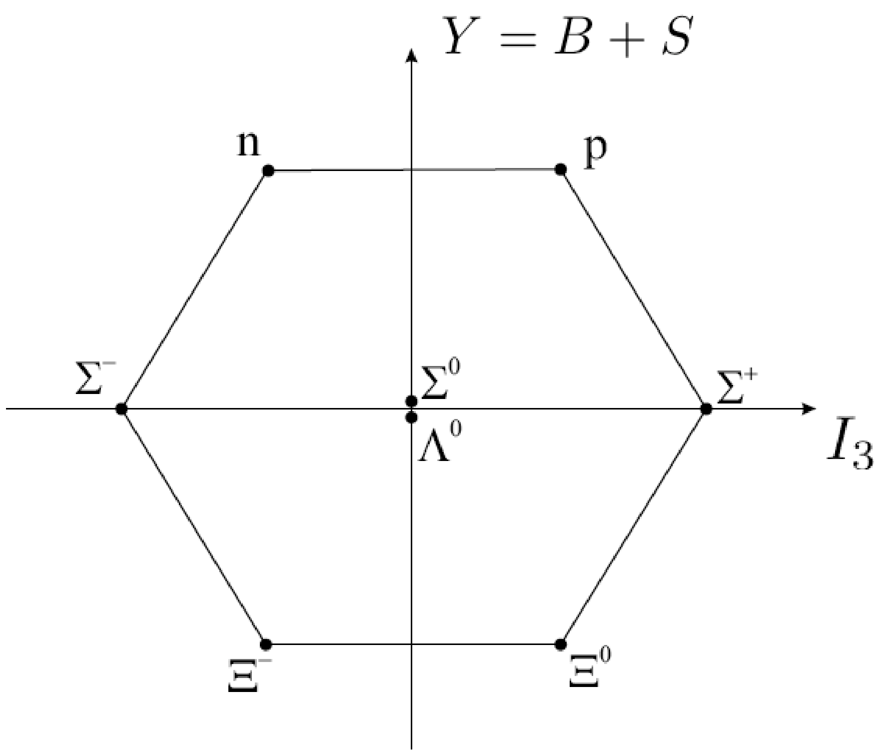
McAllister, Hofstadter



$$\Rightarrow \langle r^2 \rangle \sim 10^{-15} \mathrm{m}$$

- fit hadrons with similar properties into SU(3) multiplets:

Gell-Mann; Ne'eman; Nishijima



- fundamental representation of SU(3): triplet $\rightarrow$ u d s quarks

Gell-Mann; Zweig

$$|\text{baryon}\rangle = |qqq\rangle \qquad |\text{meson}\rangle = |q\bar{q}\rangle$$

- the proton wave function is:

$$|P,\uparrow\rangle = \frac{1}{\sqrt{18}}\left[2u^{\uparrow}u^{\uparrow}d^{\downarrow} - u^{\uparrow}u^{\downarrow}d^{\uparrow} - u^{\downarrow}u^{\uparrow}d^{\uparrow} + \text{perm.}\right]$$

- from this, magnetic moments: $\sim \langle P,\uparrow | \mu_i (\sigma_3)_i | P,\uparrow\rangle$

$$\mu_p = \frac{1}{3}\left[4\mu_u - \mu_d\right] \qquad \mu_n = \frac{1}{3}\left[4\mu_d - \mu_u\right] \qquad \mu_i = \frac{e_i\hbar}{2m_i c}$$

$$\frac{\mu_n}{\mu_p} = -\frac{2}{3} \qquad \text{exp.} = -0.685 \qquad ✔$$

- quarks carry the proton spin - entirely:

$$\mathcal{N}(u^{\uparrow}) - \mathcal{N}(u^{\downarrow}) = \frac{4}{3} \qquad \mathcal{N}(d^{\uparrow}) - \mathcal{N}(d^{\downarrow}) = -\frac{1}{3}$$

$$\frac{1}{2}\left(\frac{4}{3} - \frac{1}{3}\right) = \frac{1}{2}$$

- from now on:

$$\mathcal{N}(u^{\uparrow}) - \mathcal{N}(u^{\downarrow}) \equiv \Delta U$$

- $\mathbf{q}^{\dagger}\,\sigma_{\mathbf{k}}\,\mathbf{q}$ becomes $\bar{\mathbf{q}}\,\gamma^{\mu}\gamma^{\mathbf{5}}\,\mathbf{q}$ in rel. theory

- simple quark model has limitations: predicts

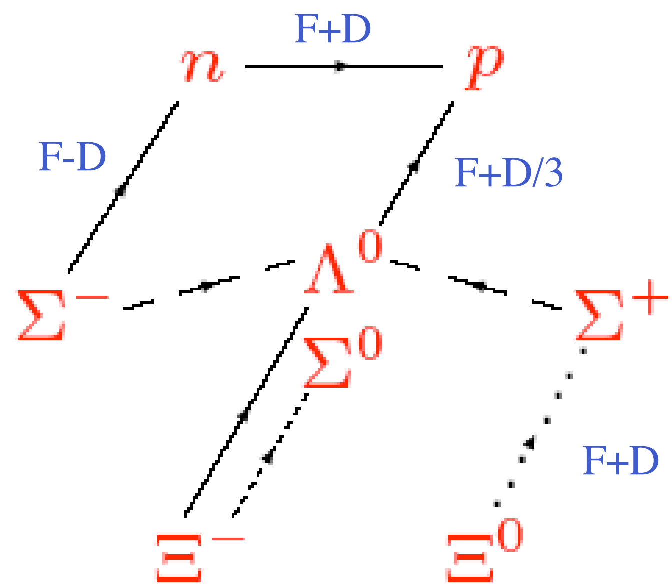
$$g_A = \Delta U - \Delta D = \frac{5}{3} \qquad \text{exp.} = 1.257 \qquad ✘$$

β decay $n \to p\, e^{-}\, \bar{\nu}_e$

- also, expect higher Fock states in nucleon:

$$|\,u, u, d\,\rangle + |\,u, u, d, (u\bar{u})\,\rangle + |\,u, u, d, (s\bar{s})\,\rangle + \ldots$$

- what can be said in terms of SU(3) symmetry alone?



- find:

Bjorken; Ellis, Jaffe

$$\Delta U + \Delta\bar{U} - \left(\Delta D + \Delta\bar{D}\right) = F + D = 1.257 \pm 0.003$$

$$\Delta U + \Delta\bar{U} + \Delta D + \Delta\bar{D} - 2\left(\Delta S + \Delta\bar{S}\right) = 3F - D = 0.575 \pm 0.05$$

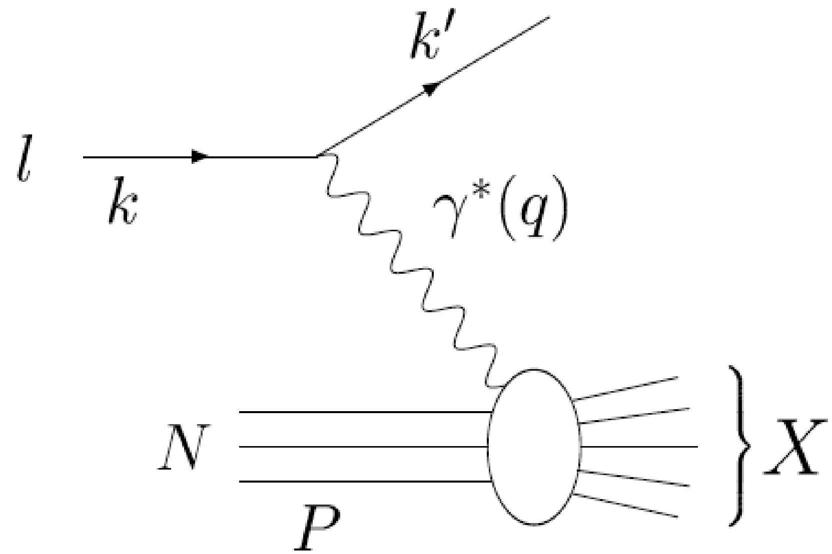
- no prediction for total quark spin contribution:

$$\Delta\Sigma = \Delta U + \Delta\bar{U} + \Delta D + \Delta\bar{D} + \Delta S + \Delta\bar{S} = ?$$

Measure in deeply-inelastic processes!

Structure of the Nucleon from the late '60s: the inelastic era

- Deeply-inelastic scattering : $e\,p \to e\,X$



$$Q^2 = -q^2 \gg m_N^2$$

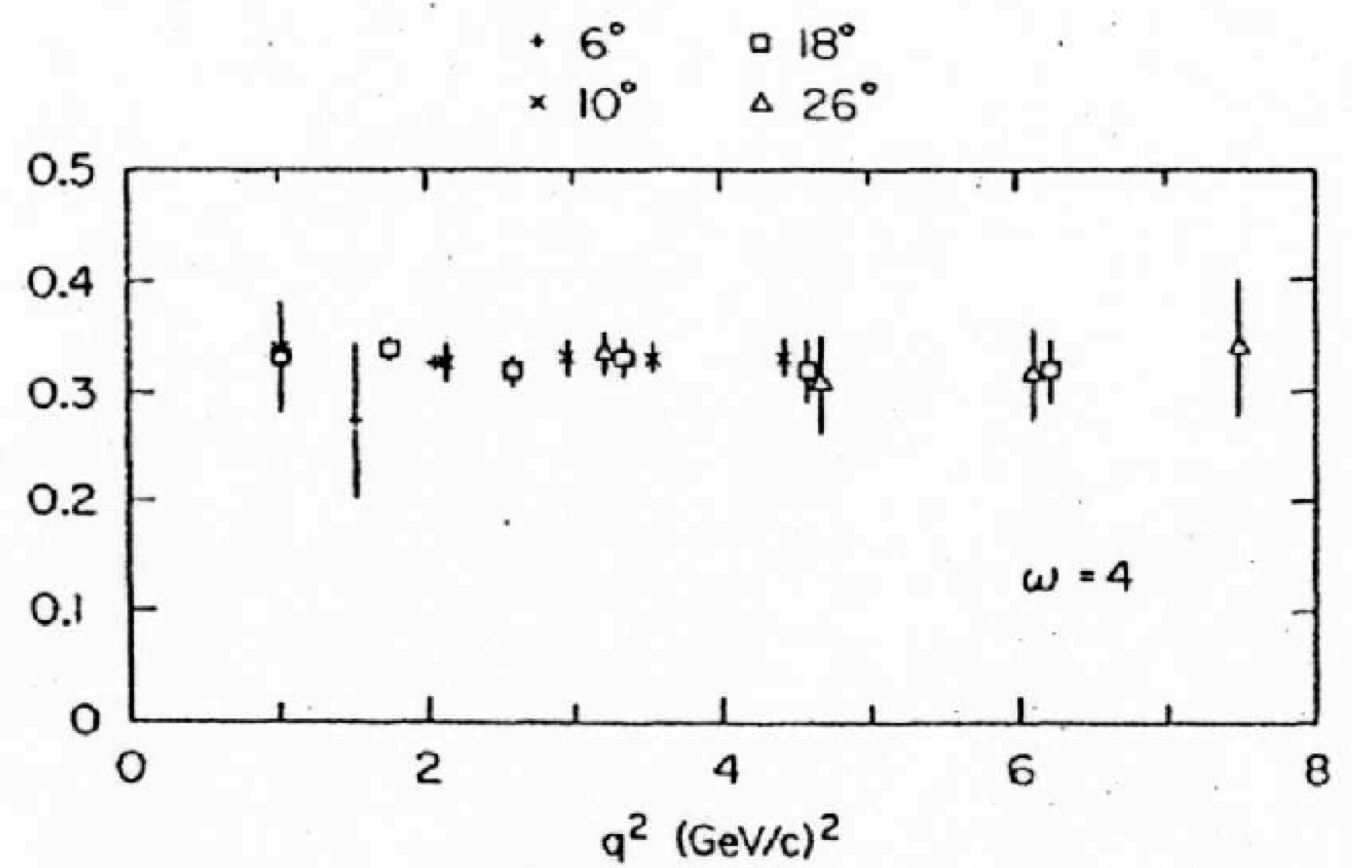
"inelasticity" $$\boxed{x \equiv \frac{Q^2}{2P\cdot q} = \frac{Q^2}{Q^2 + M_X^2 - m_N^2}}$$ Bjorken var.

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

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

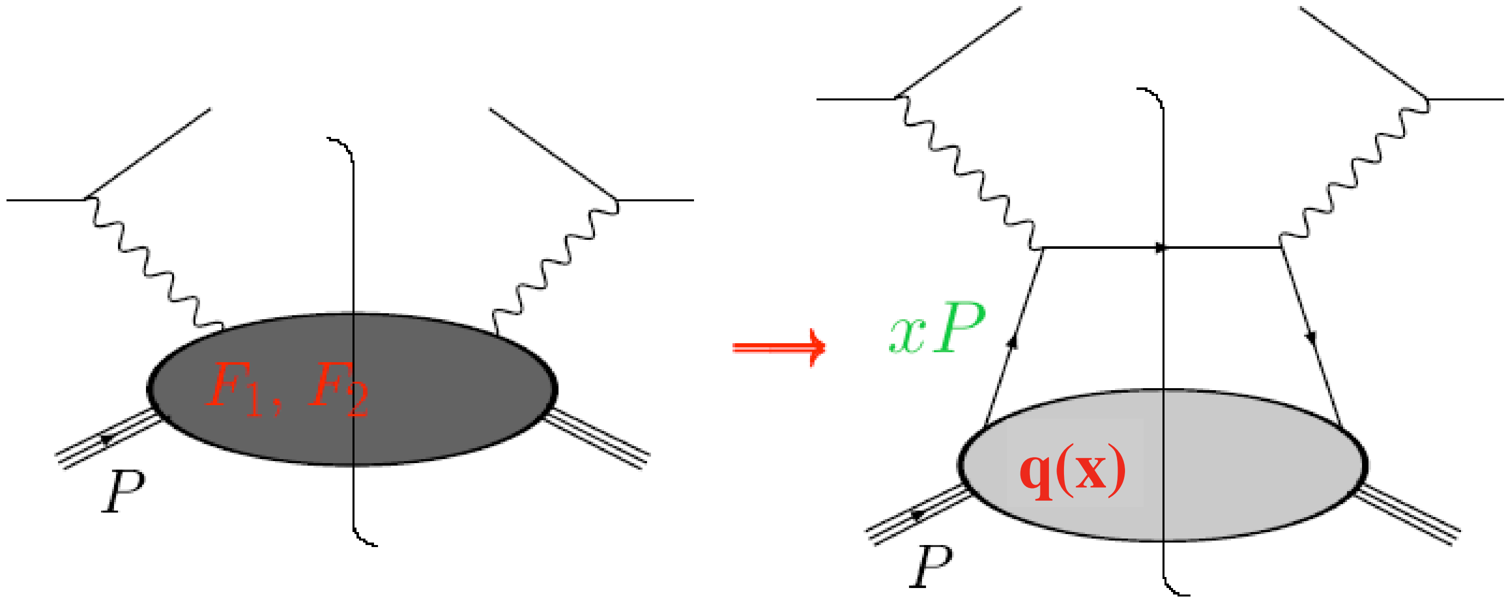
- early results from SLAC : "scaling"

$F_2 = \nu W_2$



Parton Model :

Feynman; Bjorken, Paschos



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

$$F_2(x) \ = \ 2xF_1(x)$$

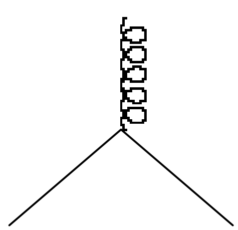
(spin 1/2 !)

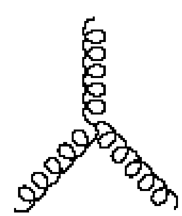
- this opened the door to the development of a comprehensive theory of quarks and gluons and their interactions: Quantum Chromo-Dynamics (QCD)

  - quarks come in 3 colors

$$u = \begin{pmatrix} u \\ u \\ u \end{pmatrix}$$

  - $\mathcal{L}_{\mathrm{QCD}}$ invariant under local SU(3) phase transformations
  - color charge couples to 8 generalized “photons”: gluons
  - non-abelian gauge group $\Rightarrow$ gluons carry color





Ultraviolet Behavior of Non-Abelian Gauge Theories*

David J. Gross† and Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 27 April 1973)

It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field–theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Non-Abelian gauge theories have received much attention recently as a means of constructing unified and renormalizable theories of the weak and electromagnetic interactions.[1] In this note we report on an investigation of the ultraviolet (UV) asymptotic behavior of such theories. We have found that they possess the remarkable feature, perhaps unique among renormalizable theories, of asymptotically approaching free-field theory. Such asymptotically free theories will exhibit, for matrix elements of currents between on-mass-shell states, Bjorken scaling. We therefore suggest that one should look to a non-Abelian gauge theory of the strong interactions to provide the explanation for Bjorken scaling, which has so far eluded field-theoretic understanding.

VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

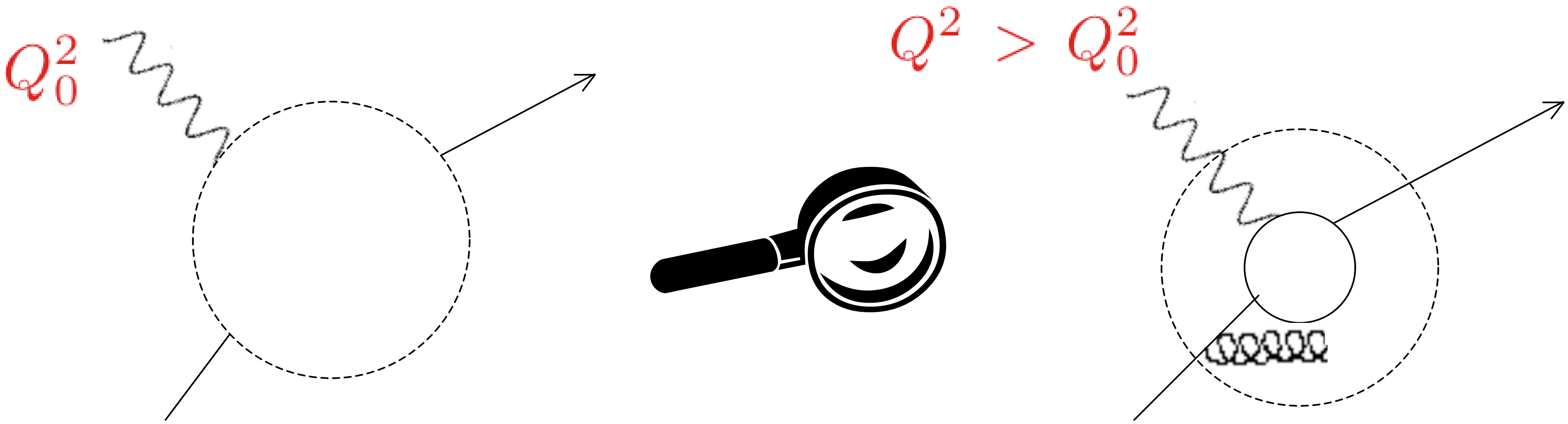
An explicit calculation shows perturbation theory to be arbitrarily good for the deep

- crucial success for QCD : Christ,Hasslacher,Mueller; Georgi,Politzer; DGLAP

  quantitative prediction of scaling violations in DIS

- why dependence on Q^2 after all ?

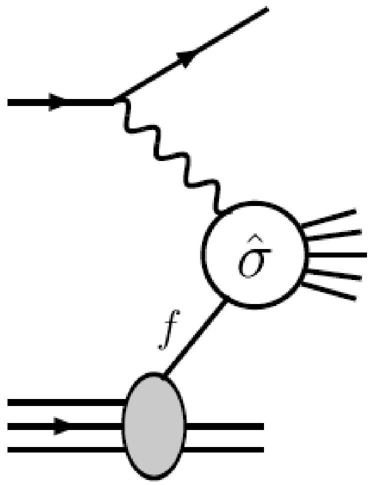
  Parton states not truly frozen. Some fluctuate on scales $\sim 1/Q$



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

"DGLAP" evolution

The essence: DIS "factorizes"

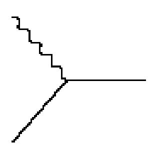
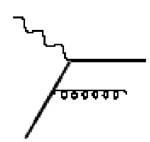
$$\Bigg|$$  $$\Bigg|^2$$

$$\sigma = \sum_f f(x,Q) \times \hat{\sigma}^{\gamma^* f}(x, \alpha_s(Q)) + \underbrace{\mathcal{O}\left(\frac{\lambda^2}{Q^2}\right)}_{\text{"small"}}$$

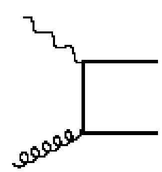
parton distrib.

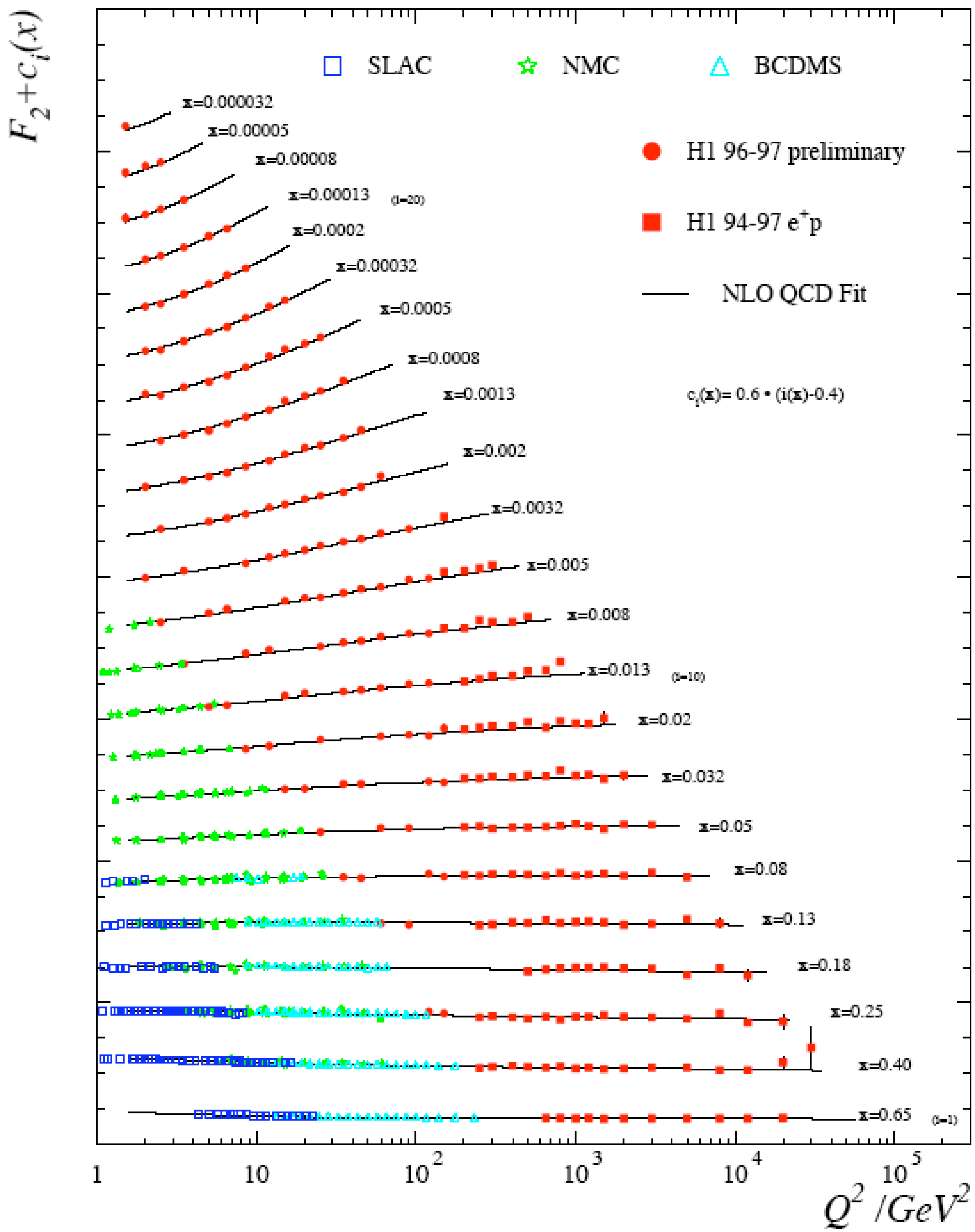
$$\langle P \,|\, \mathcal{O}_q \,|\, P \rangle$$

parton-γ^*
cross sec.
perturbative

$\hat{\sigma}^{\gamma^* q} \sim \Big|$  $\Big|^2 + \Big|$  $+ \ldots \Big|^2 + \ldots$

LO **NLO**

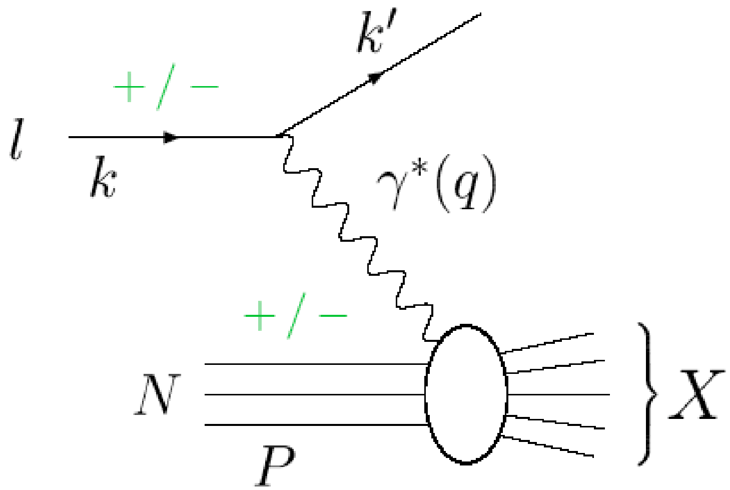
$\hat{\sigma}^{\gamma^* g} \sim \Big|$  $+ \ldots \Big|^2 + \ldots$



SLAC
NMC
BCDMS
H1 96-97 preliminary
H1 94-97 e+p
NLO QCD Fit
x=0.000032
x=0.00005
x=0.00008
x=0.00013 (i=20)
x=0.0002
x=0.00032
x=0.0005
x=0.0008
x=0.0013
x=0.002
x=0.0032
x=0.005
x=0.008
x=0.013 (i=10)
x=0.02
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.40
x=0.65 (i=1)
c_i(x)= 0.6 • (i(x)-0.4)
F_2+c_i(x)
Q^2 /GeV^2
1
10
10^2
10^3
10^4
10^5

Polarized deeply-inelastic scattering

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

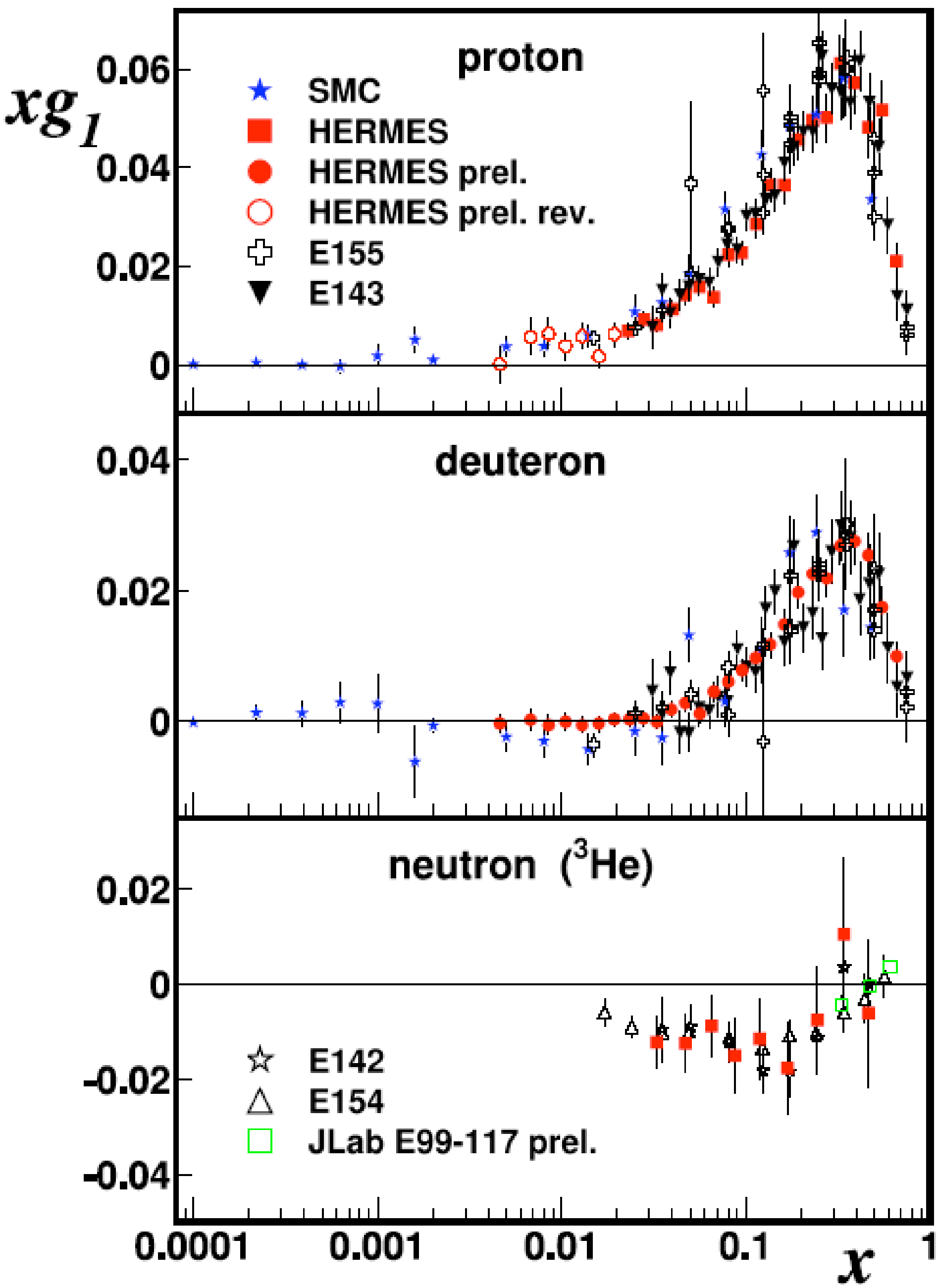


$$\frac{d^2\sigma}{dx\,dy} \approx \frac{4\pi\alpha^2}{Q^2}\left[y\,F_1(x,Q^2) + \frac{1-y}{yx}F_2(x,Q^2) \;+\; \lambda_l\,\lambda_N\;(2-y)\;g_1(x,Q^2)\right]$$

$\sigma(++) \;-\; \sigma(+-)$ gives $g_1(x,Q^2)$

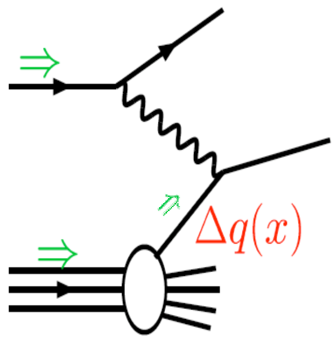
- so far "fixed-target" experiments (p,n,d)

SLAC (E80,130,142,143,155), CERN (EMC,SMC), DESY (HERMES)



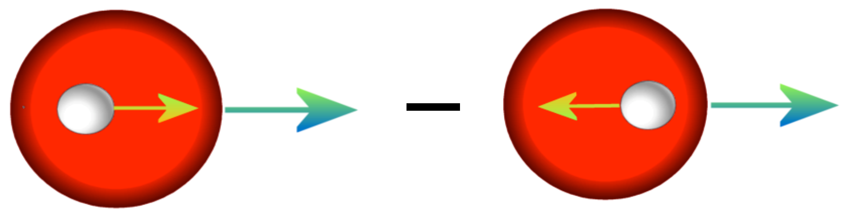
(U. Stösslein / HERMES)

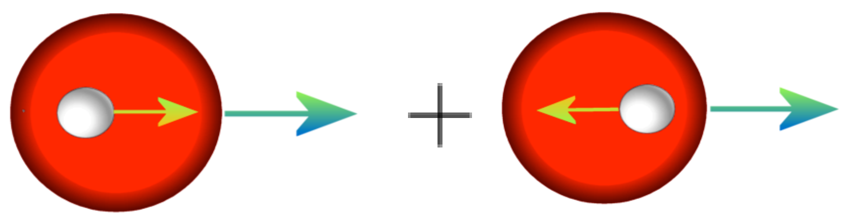
in the parton model :



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

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

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

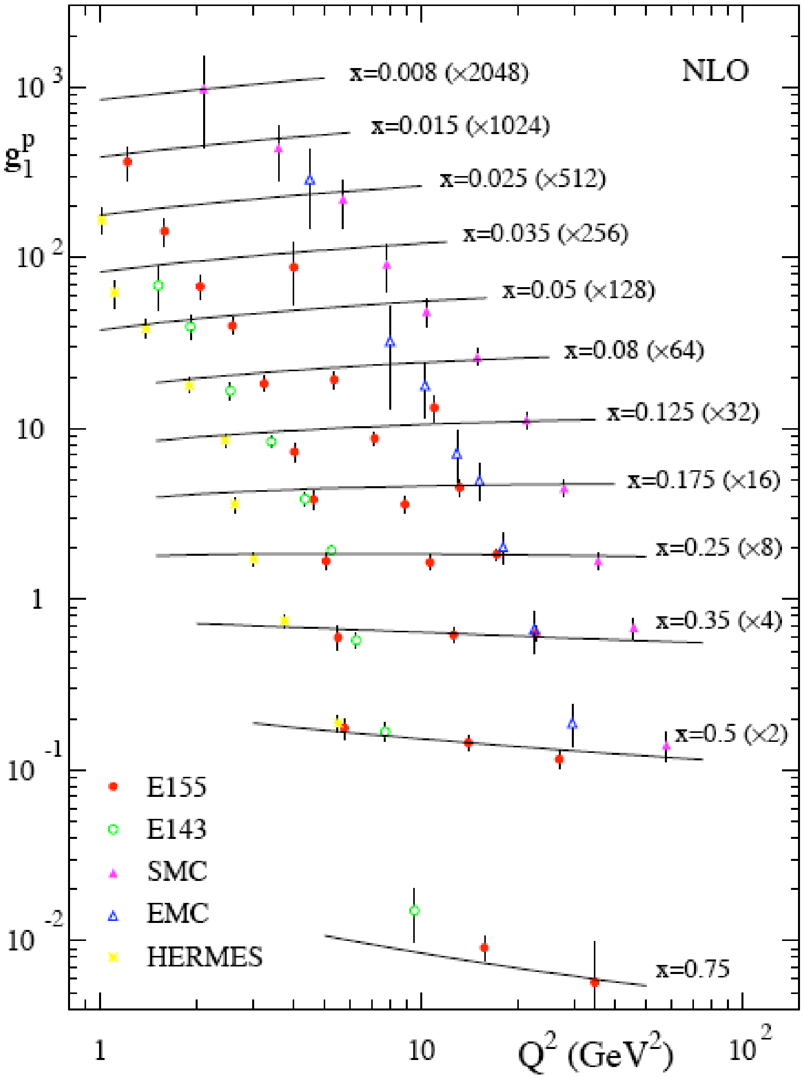
$\mathbf{q(x)} =$ 

- also for g_1 scaling violations predicted in QCD:

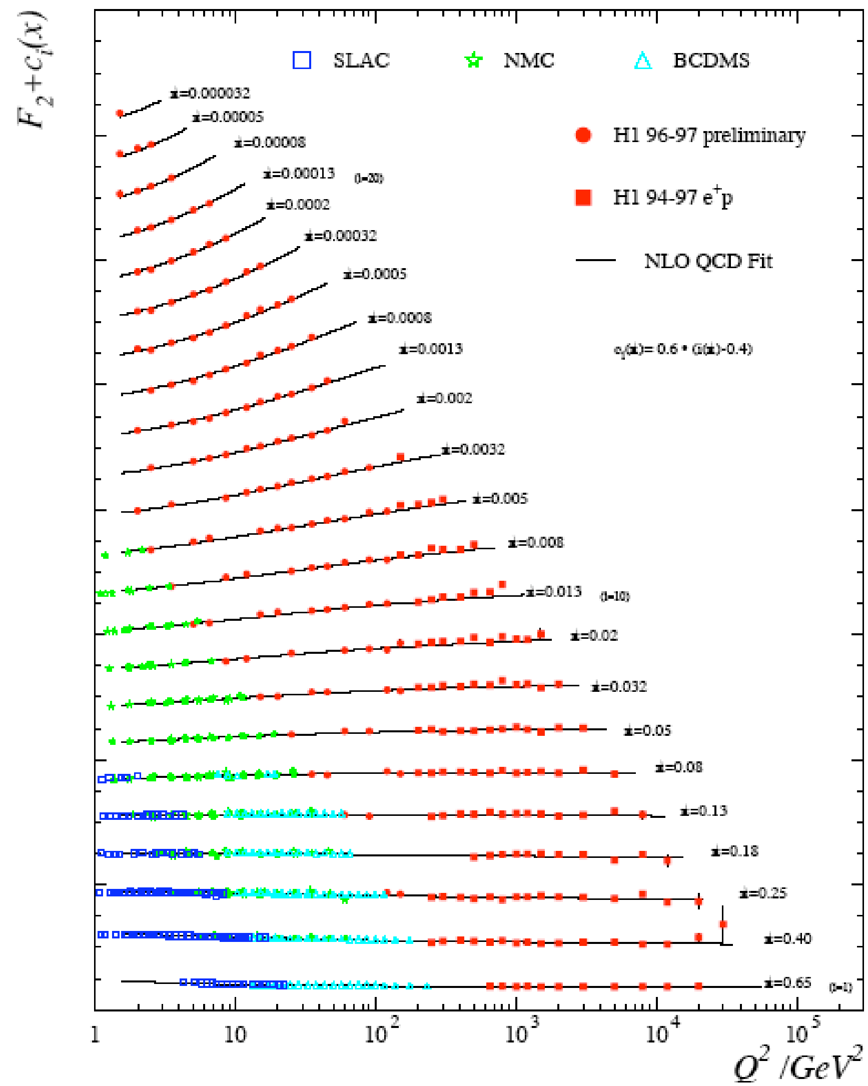
$$g_1(x) \longrightarrow g_1(x, Q^2)$$

World data on pol. and unpol. deep-inelastic scattering

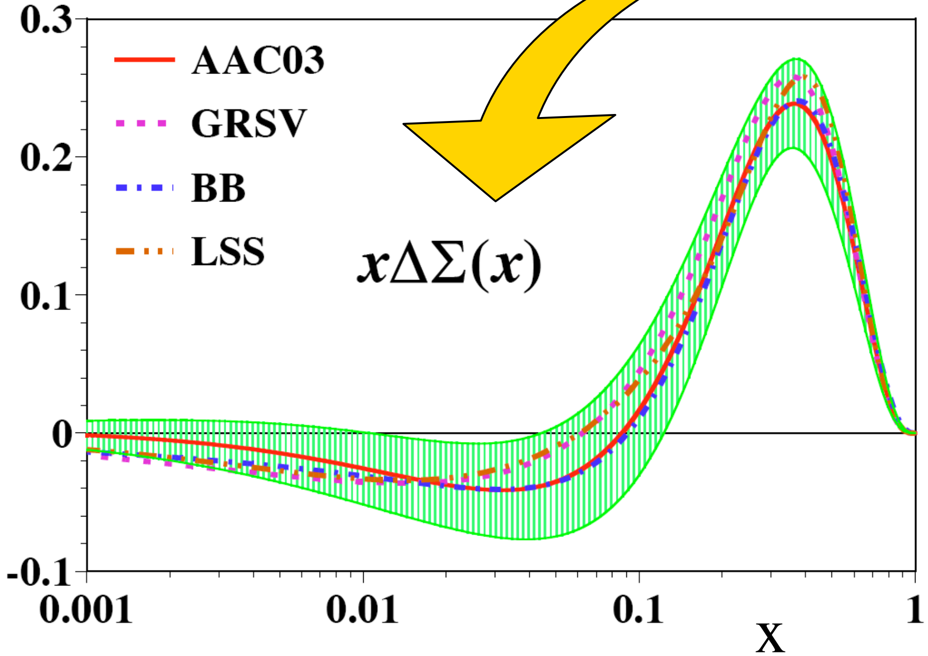
polarized



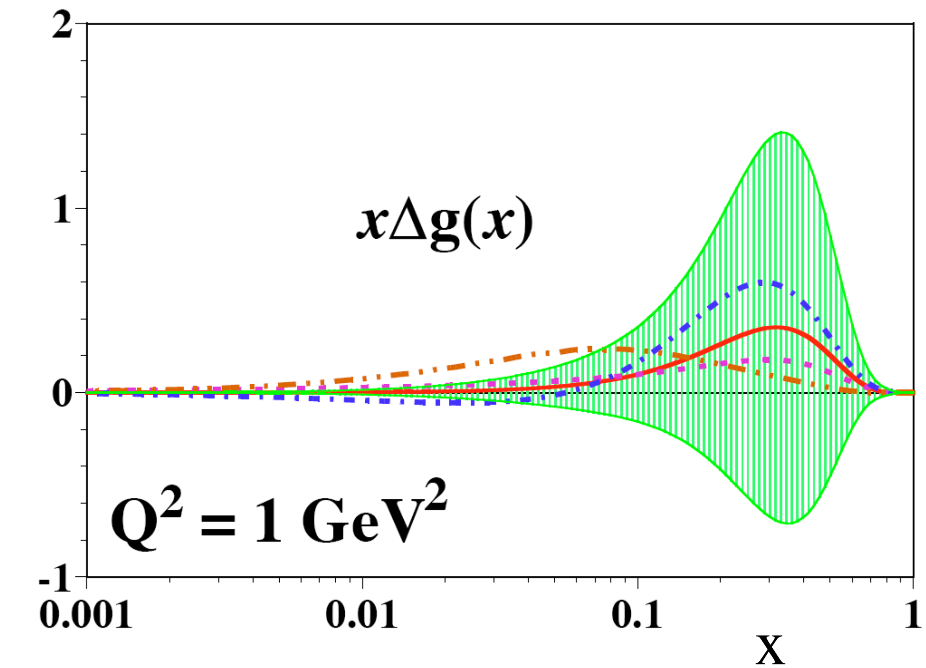
unpolarized



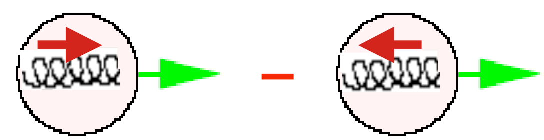
Hirai, Kumano, Saito



$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$



gluon polarization ?

$\Delta g(x) =$ 

very weak constraint from scaling violations

- experiments have determined

$$\Gamma_1(Q^2) \equiv \int_0^1 dx\, g_1(x, Q^2)$$

- have

$$2\,\Gamma_1 = \frac{4}{9}\left(\Delta U + \Delta\bar{U}\right) + \frac{1}{9}\left(\Delta D + \Delta\bar{D}\right) + \frac{1}{9}\left(\Delta S + \Delta\bar{S}\right)$$

- recall

$$\Delta U + \Delta\bar{U} - \left(\Delta D + \Delta\bar{D}\right) = F + D$$

$$\Delta U + \Delta\bar{U} + \Delta D + \Delta\bar{D} - 2\left(\Delta S + \Delta\bar{S}\right) = 3F - D$$

$$\boxed{\Delta\Sigma \equiv \Delta U + \Delta\bar{U} + \Delta D + \Delta\bar{D} + \Delta S + \Delta\bar{S} \approx 0.2 \ll 1}$$

So, what carries the proton spin ?

$$\mathbf{\frac{1}{2} = \langle P, \frac{1}{2} | \, J_3 \, | p, \frac{1}{2} \rangle}$$

$$\mathbf{J_i = -\frac{1}{2} \epsilon_{ijk} \, M^{jk} = \int d^3x \left[\vec{x} \times \vec{T}_{QCD} \right]_i}$$

In QCD:

$$J_3 = \int d^3x \left[\underbrace{\bar{\psi} \, \gamma^3 \gamma_5 \, \psi}_{\sim \text{ quark spin}} + \underbrace{\psi^\dagger \left(\vec{x} \times \left(-i\vec{D} \right) \right)_3 \psi}_{\sim \text{ quark OAM}} + \underbrace{\left[\vec{x} \times \left(\vec{E}(\vec{x}) \times \vec{B}(\vec{x}) \right) \right]_3}_{\sim \text{ total gluon ang. mom.}} \right]$$

spin + OAM

- spin sum rule :

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

where

$*$ $\Delta G(Q^2) = \int_0^1 dx\, \Delta g(x, Q^2)$

$$\Delta g(x) =$$

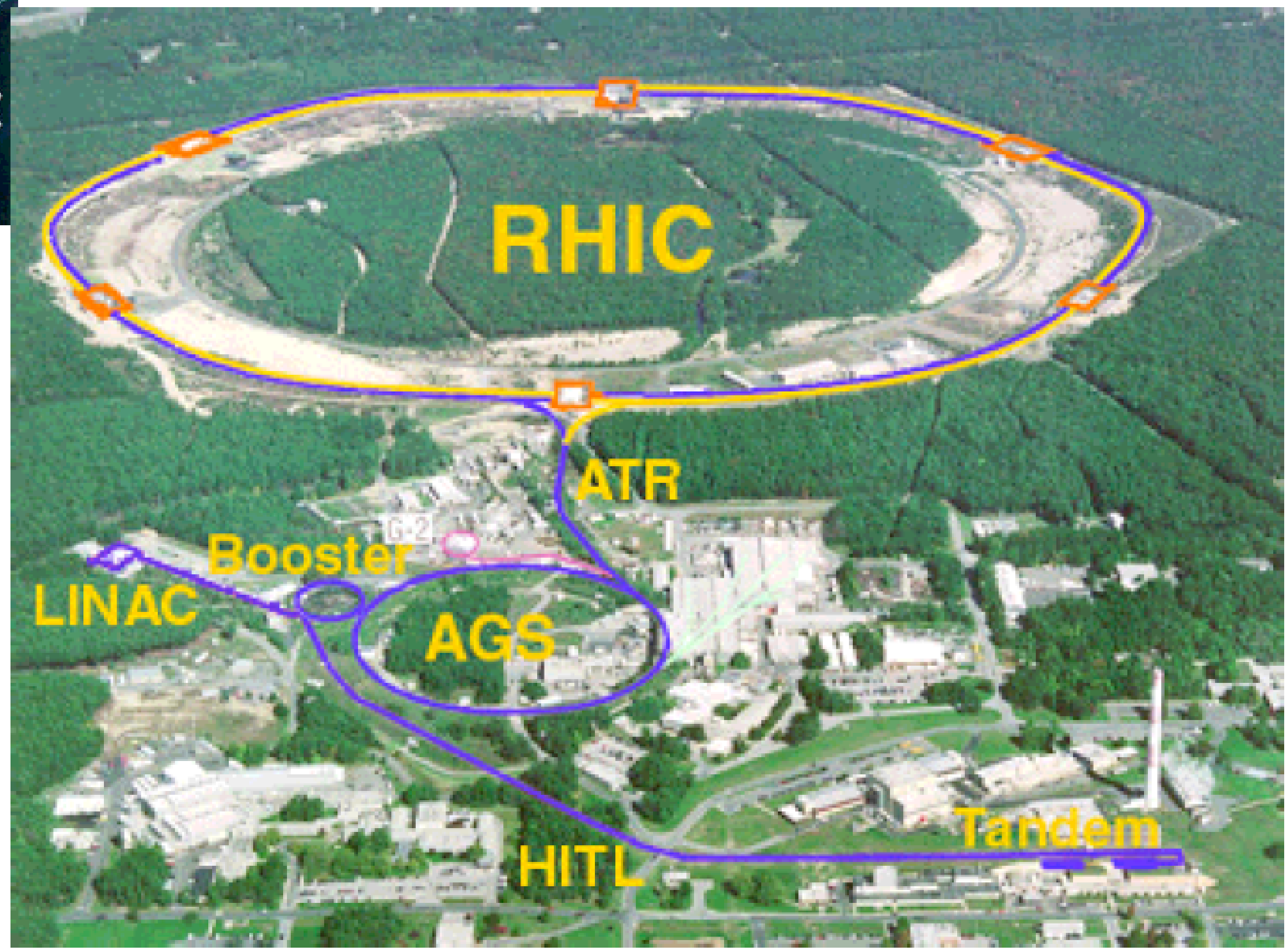
$*$ $L_{q,g}$ quark, gluon orbital angular momenta

$\longrightarrow$ How to measure ?

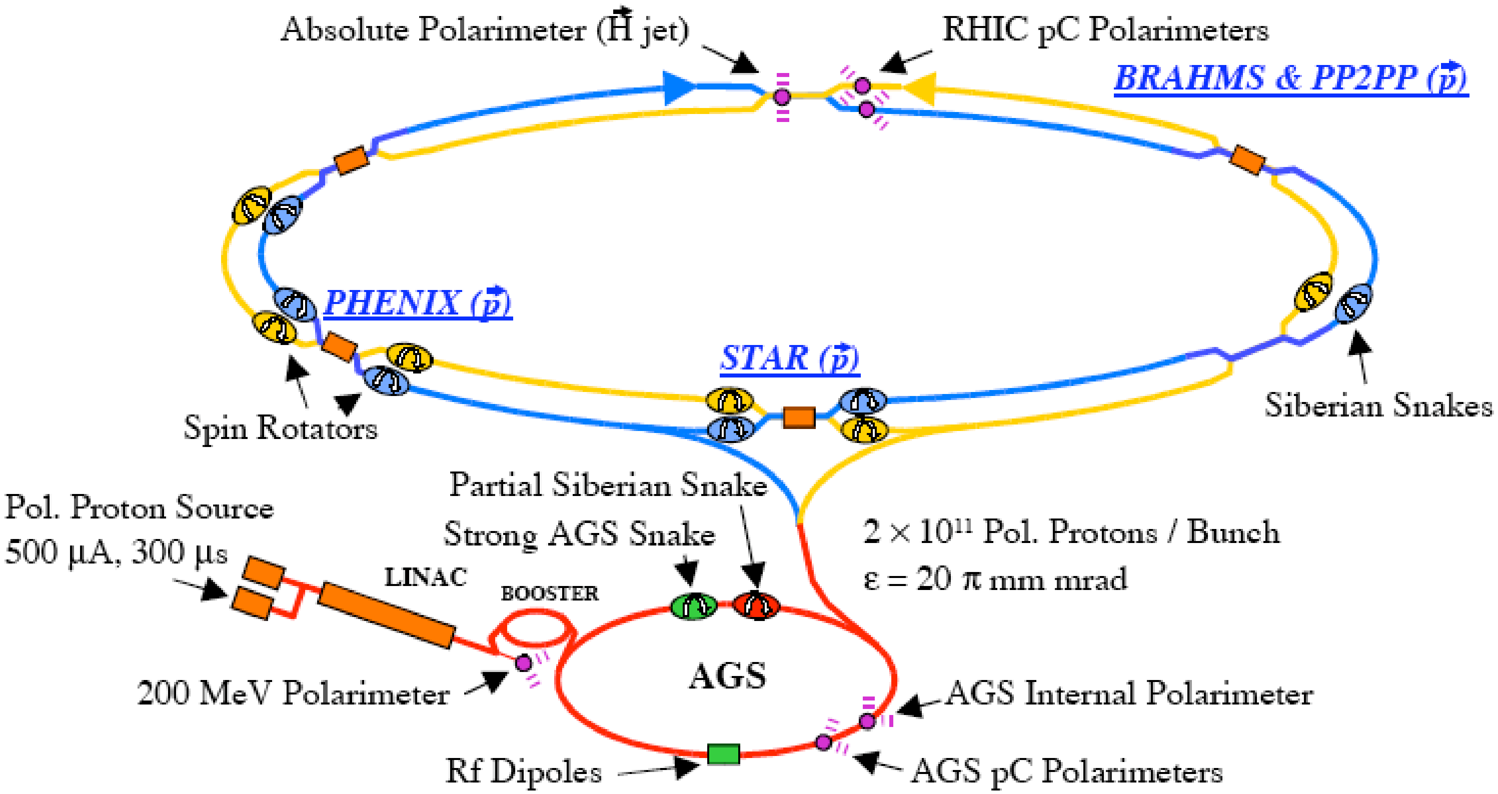
Current goals in QCD spin physics

- results from polarized DIS have motivated
  - new generation of facilities to explore the nucleon spin structure
  - large theoretical activity
- today, have a number of new experiments / facilities
  - lepton-nucleon scattering HERMES, COMPASS, JLab
  - polarized proton-proton collisions at RHIC
- key goals :
  - gluon polarization Δg in nucleon
  - more information on Δq, $\Delta \bar{q}$ (e.g., by flavor)
  - orbital angular momentum
  - phenomena in QCD with transverse polarization

A new milestone : polarized pp collider RHIC



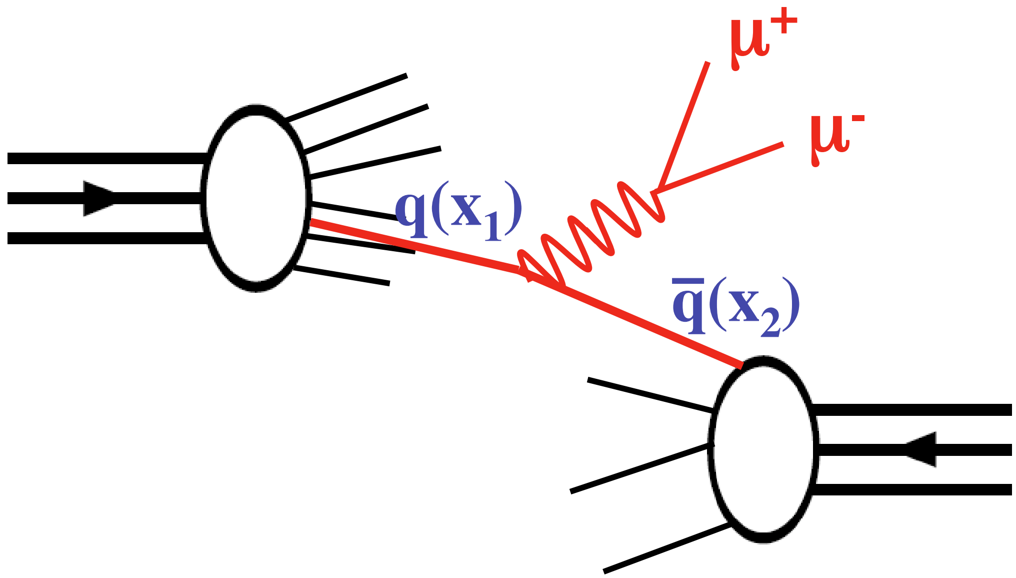
Polarized Proton Collisions in RHIC



BROOKHAVEN
NATIONAL LABORATORY

Soon after DIS & parton model :

Drell, Yan



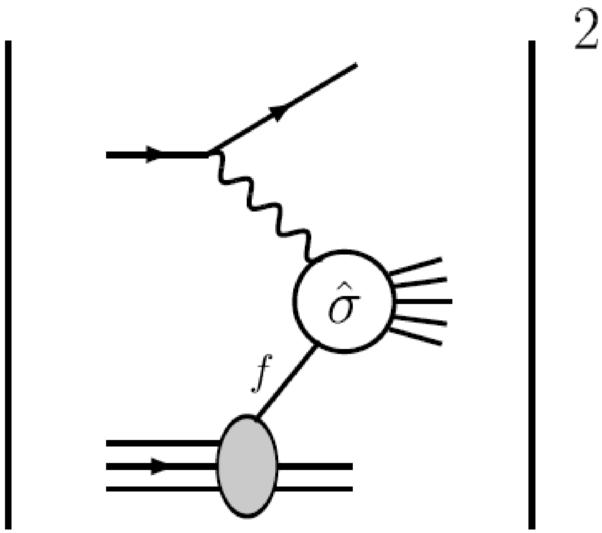
Then extension to many other reactions :

$pp \to$ jet X, $pp \to \pi X$, $pp \to \gamma X$, $pp \to Q\bar{Q} X$, …

Feynman; Berman,Jacob; Berman,Bjorken,Kogut; Feynman,Field,Fox; . . .

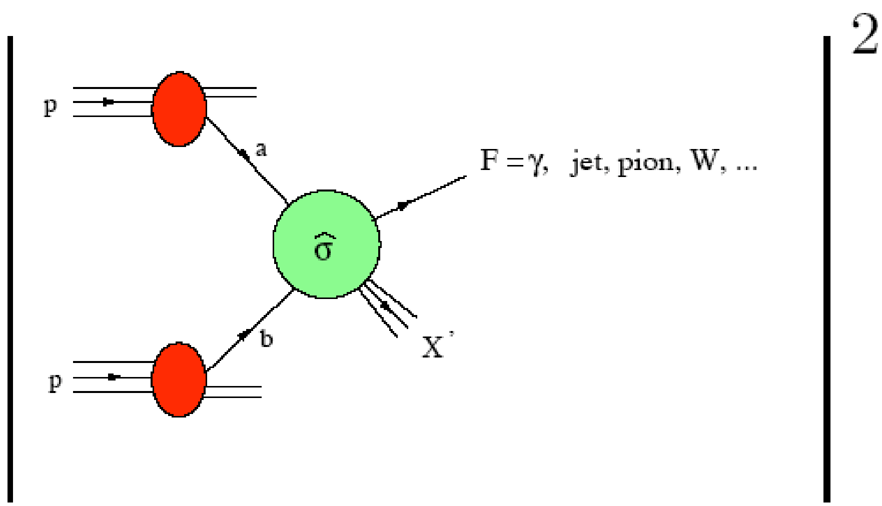
- this is formalized in “factorization theorems”

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



$$\sigma = \sum_f f(x,Q) \;\times\; \hat{\sigma}^{\gamma^* f}(x,\alpha_s(Q)) + \mathcal{O}\left(\frac{\lambda^2}{Q^2}\right)$$

universal pdf’s



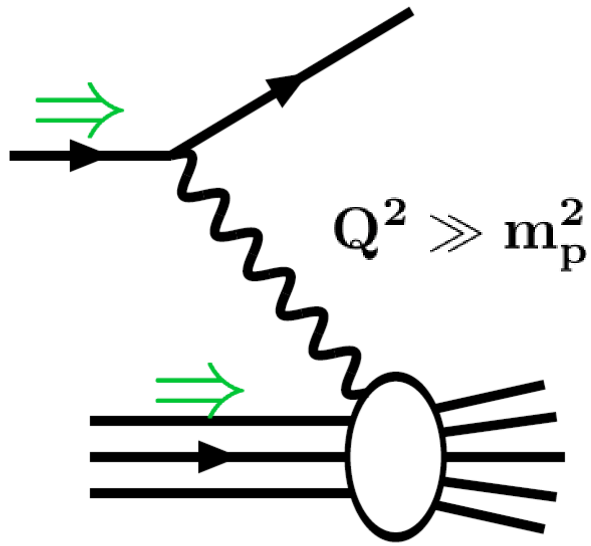
$$\sigma = \sum_{a,b} f_a(x_a,p_T) \;\times\; f_b(x_b,p_T) \;\times\; \hat{\sigma}^{ab\to F}(x_a,x_b,\alpha_s(p_T)) + \mathcal{O}\left(\frac{\lambda}{p_T}\right)$$

perturbation theory

$$\hat{\sigma} = \underbrace{\hat{\sigma}^0}_{\text{LO}} + \underbrace{\alpha_s\hat{\sigma}^1}_{\text{NLO}} + \ldots$$

Compare the probes :

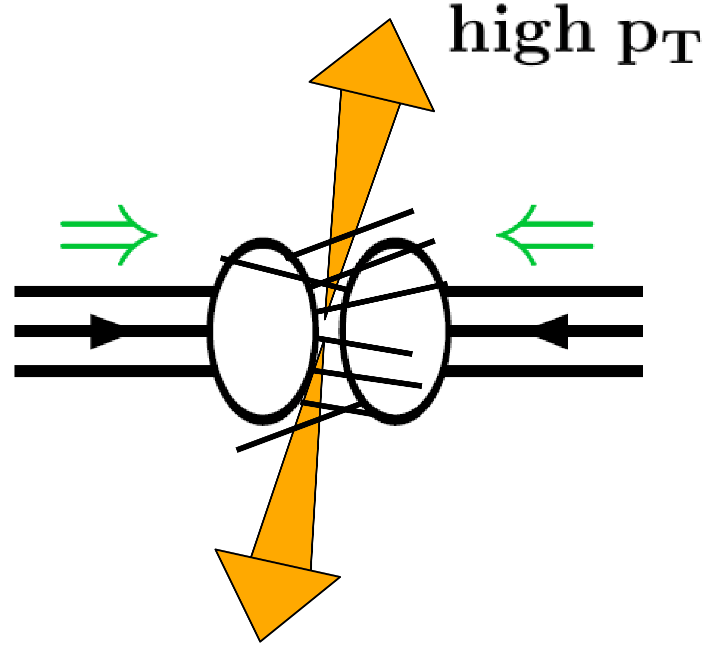
Polarized DIS



SLAC, CERN, DESY, Jlab, eRHIC

a powerful probe of quarks
(but sees gluons, too!)

pp scattering

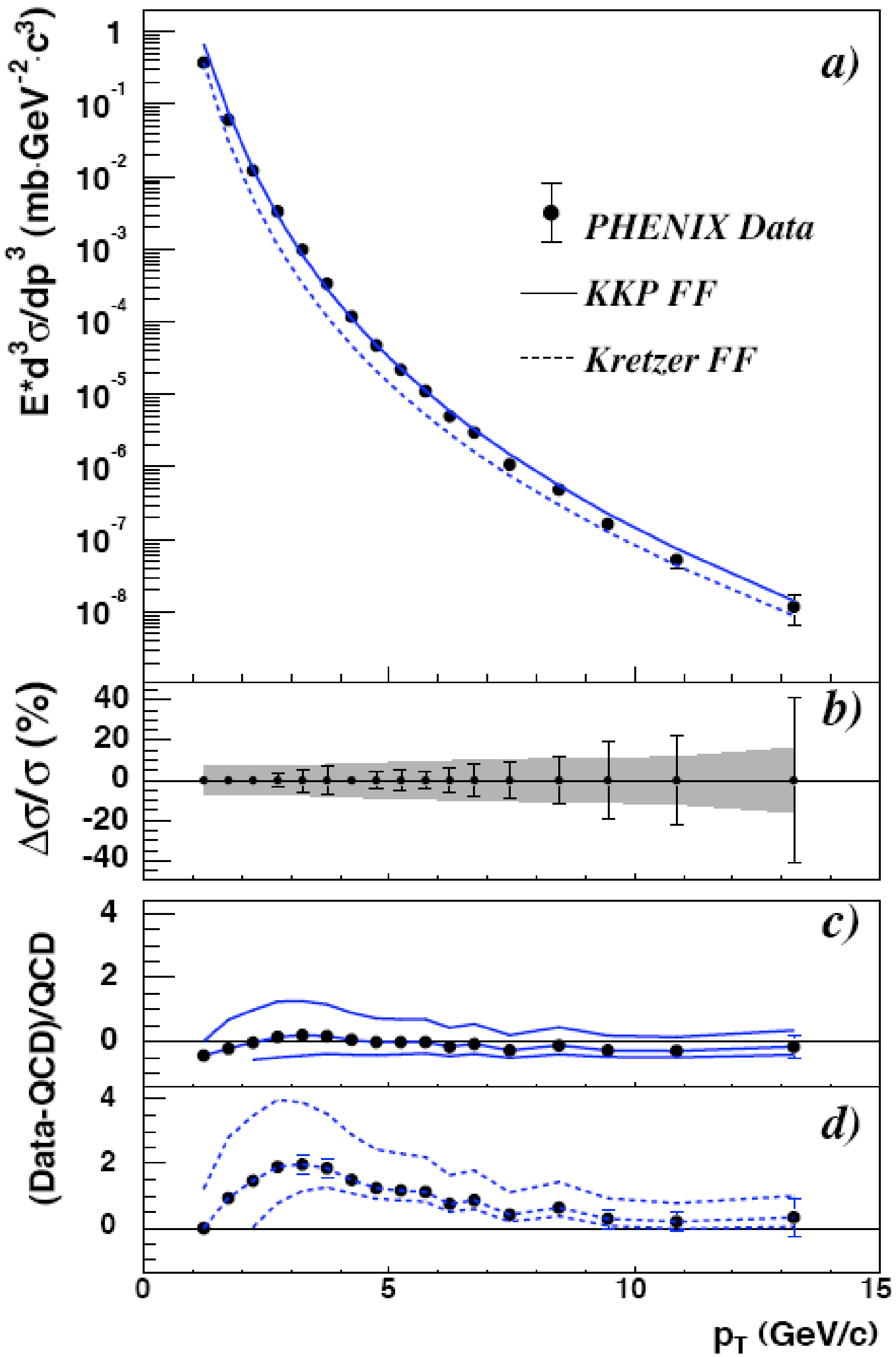


RHIC

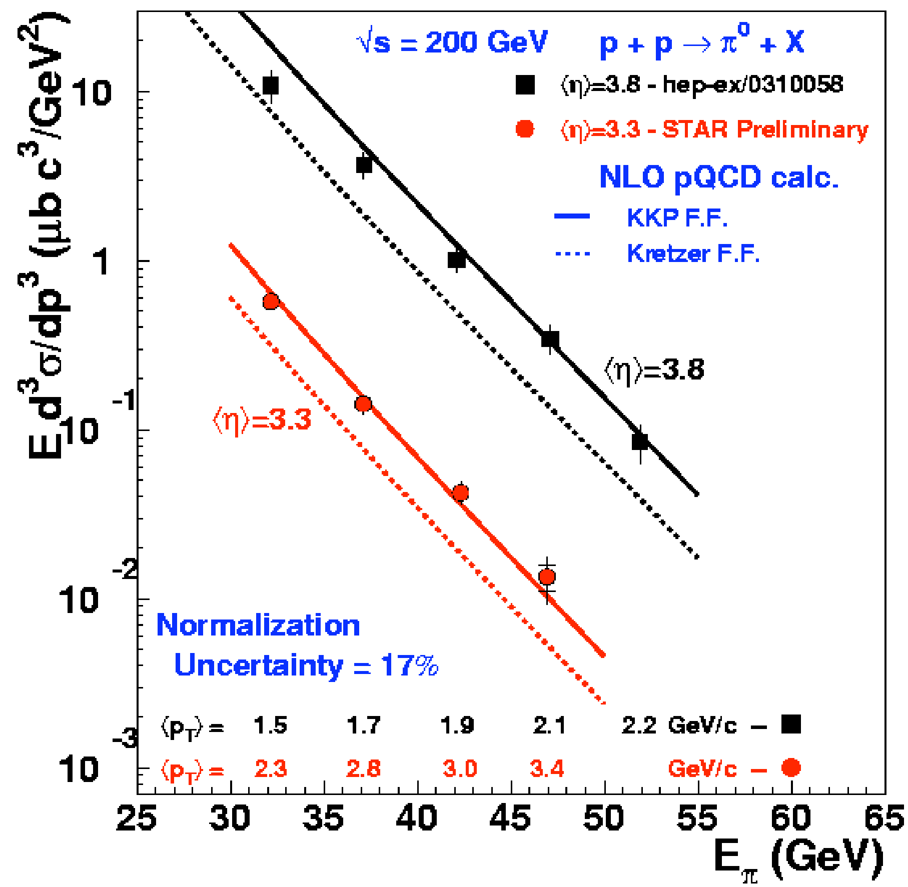
a powerful probe of gluons
(but sees quarks, too!)


LONG ISLAND

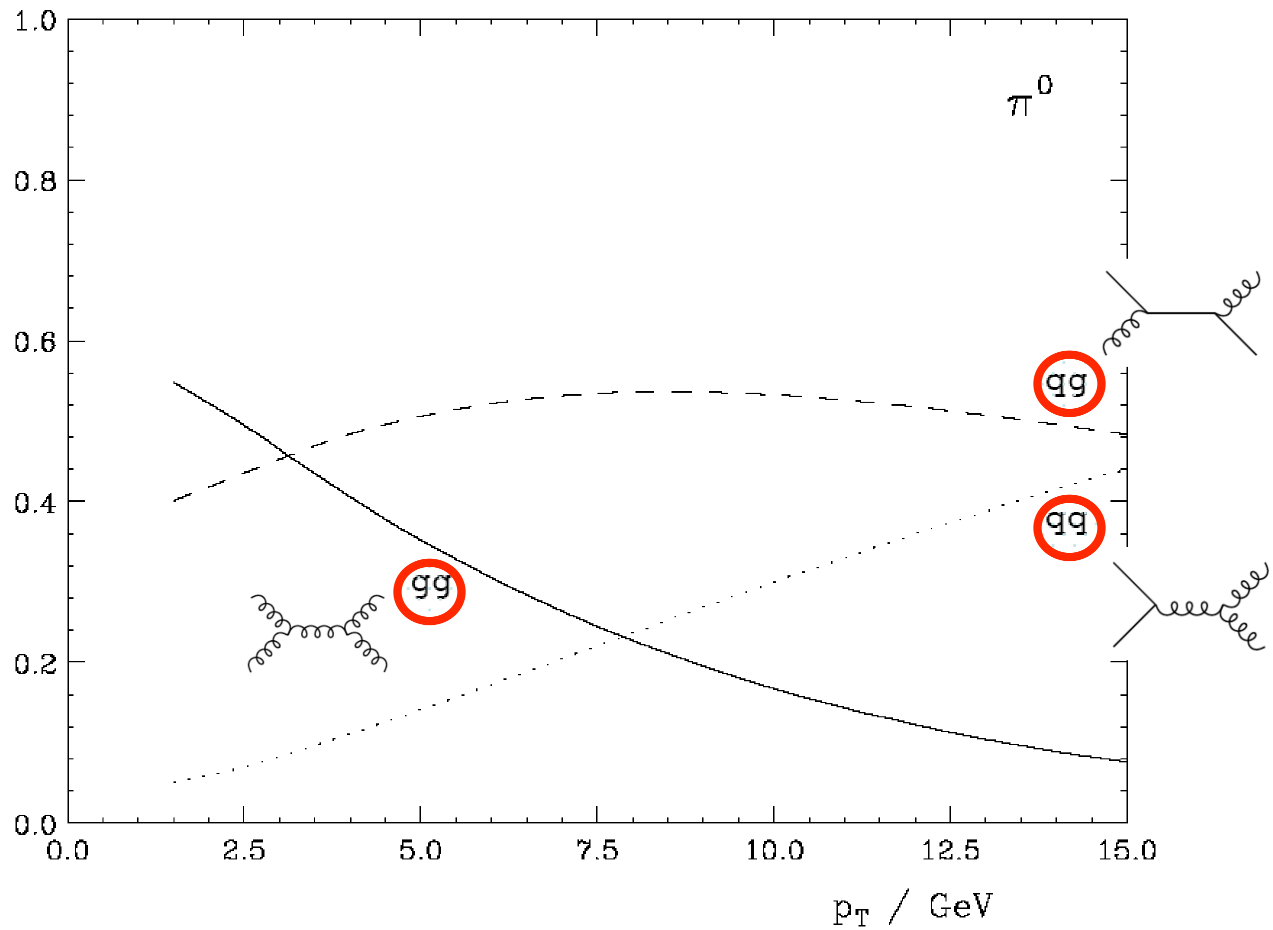
Probing gluon polarization Δg



$pp \to \pi^0 X$ at RHIC

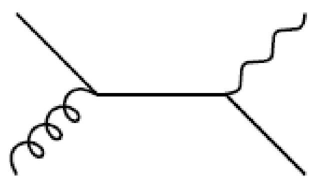


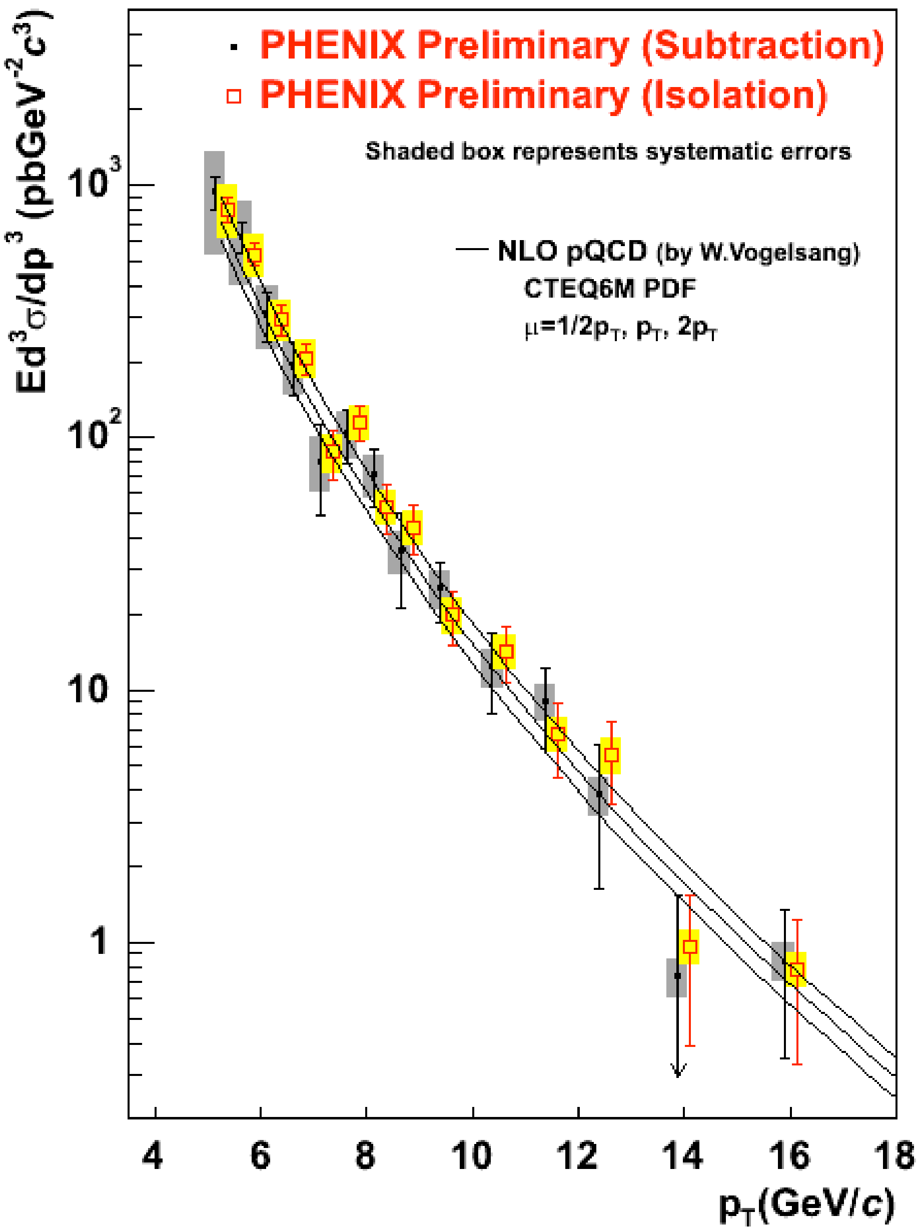
- contributions by partonic scatterings :



→ **A good probe of gluons !**

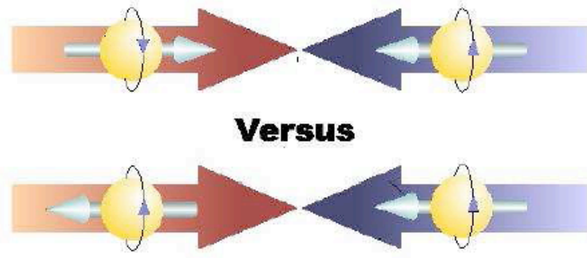
$$pp \to \gamma X$$





PHENIX Preliminary (Subtraction)
PHENIX Preliminary (Isolation)
Shaded box represents systematic errors
NLO pQCD (by W.Vogelsang)
CTEQ6M PDF
μ=1/2p_T, p_T, 2p_T
Ed^3σ/dp^3 (pbGeV^-2c^3)
p_T(GeV/c)

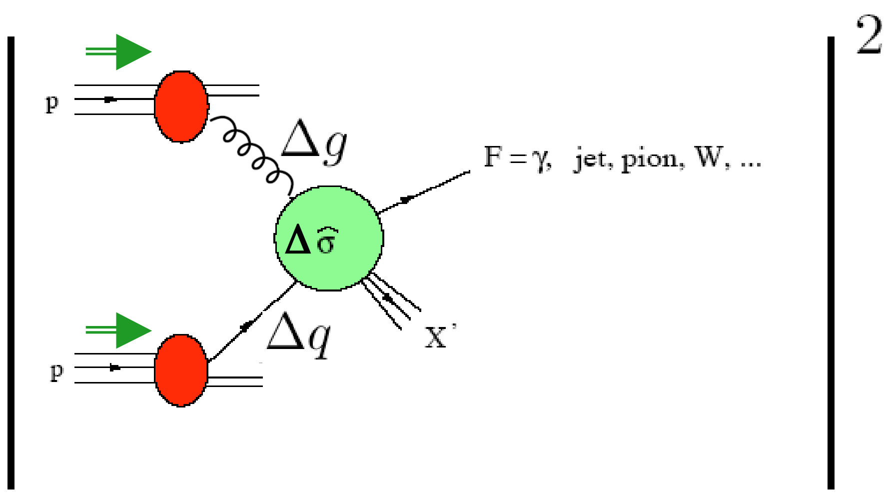
Polarized hadron collisions



Spin asymmetry

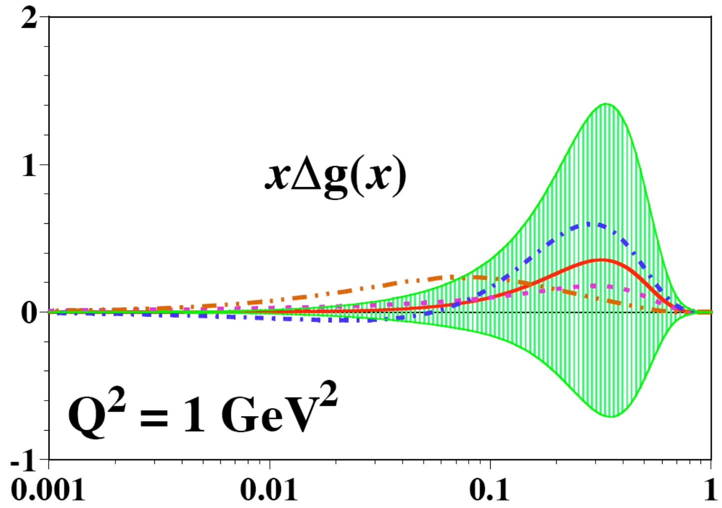
$$\boxed{A_{\mathrm{LL}} \equiv \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \equiv \frac{\Delta\sigma}{\sigma}}$$

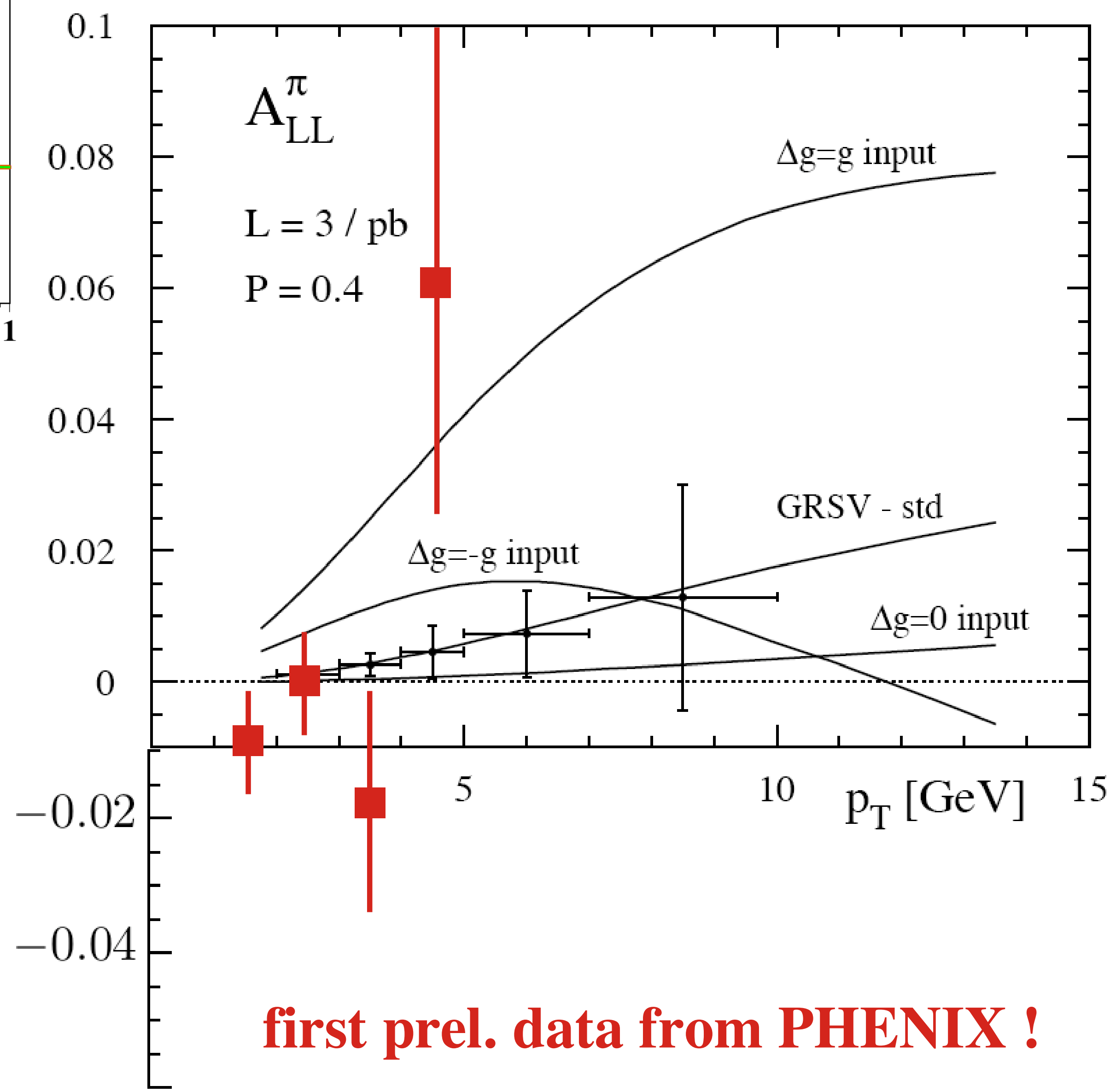
$\Delta\sigma \sim$



Jäger, Schäfer, Stratmann, WV

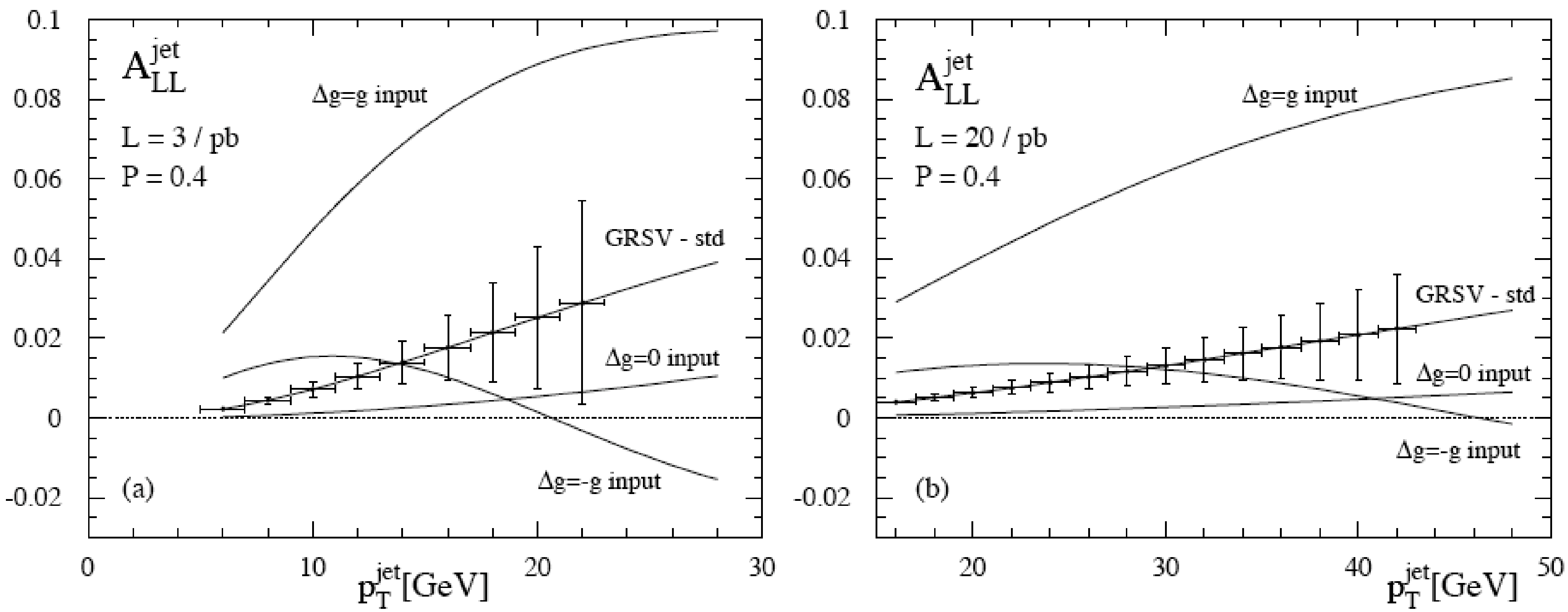
Example : $pp \longrightarrow \pi^0 X$





first prel. data from PHENIX !

Spin asymmetry for jet production at STAR:



Jäger, Stratmann, WV

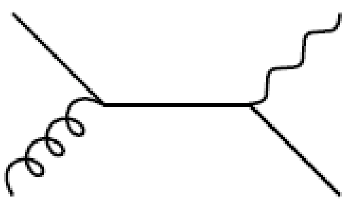
(de Florian, Frixione, Signer, WV)

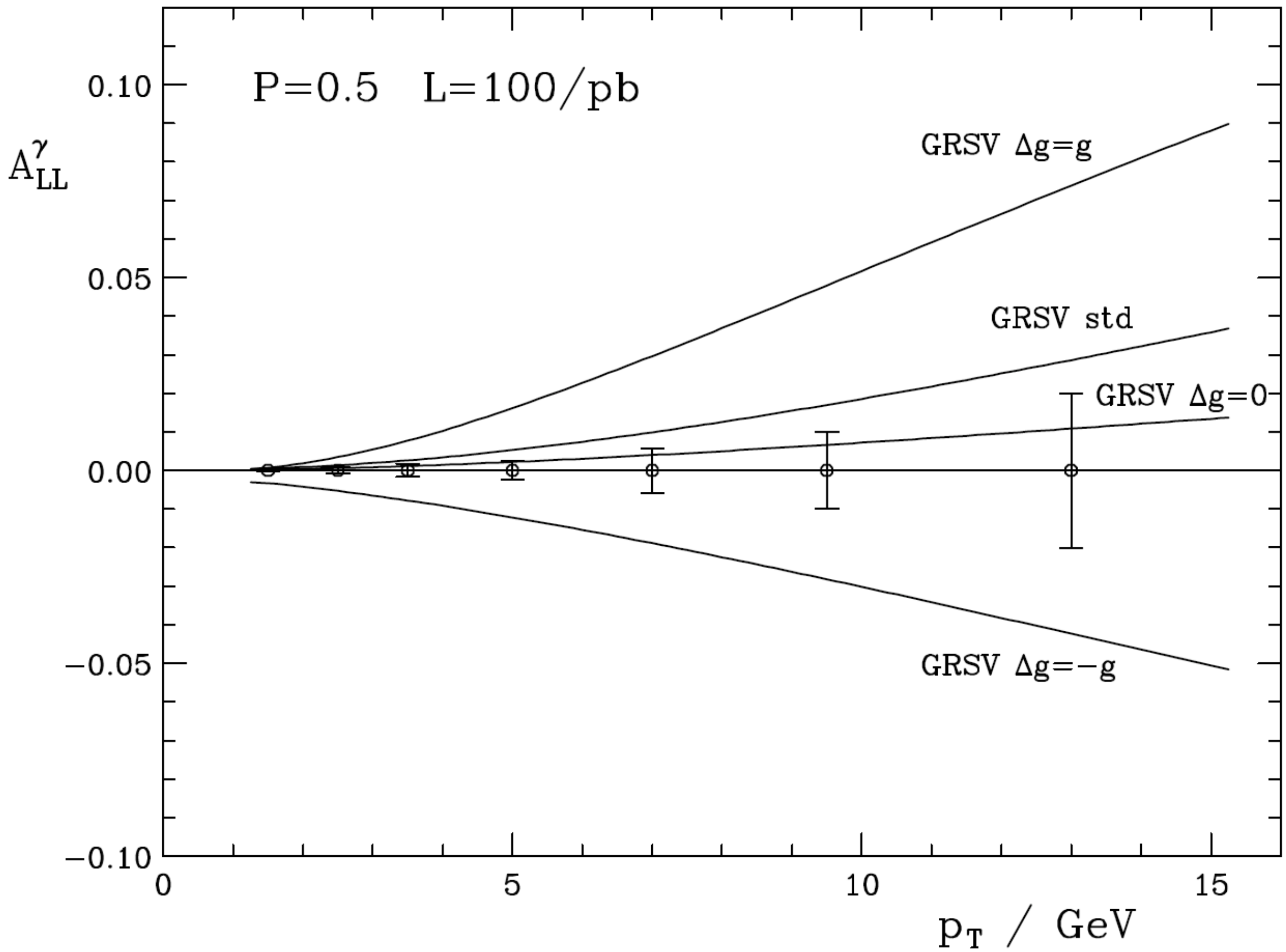
Mid / long-term at RHIC: "rare probes"

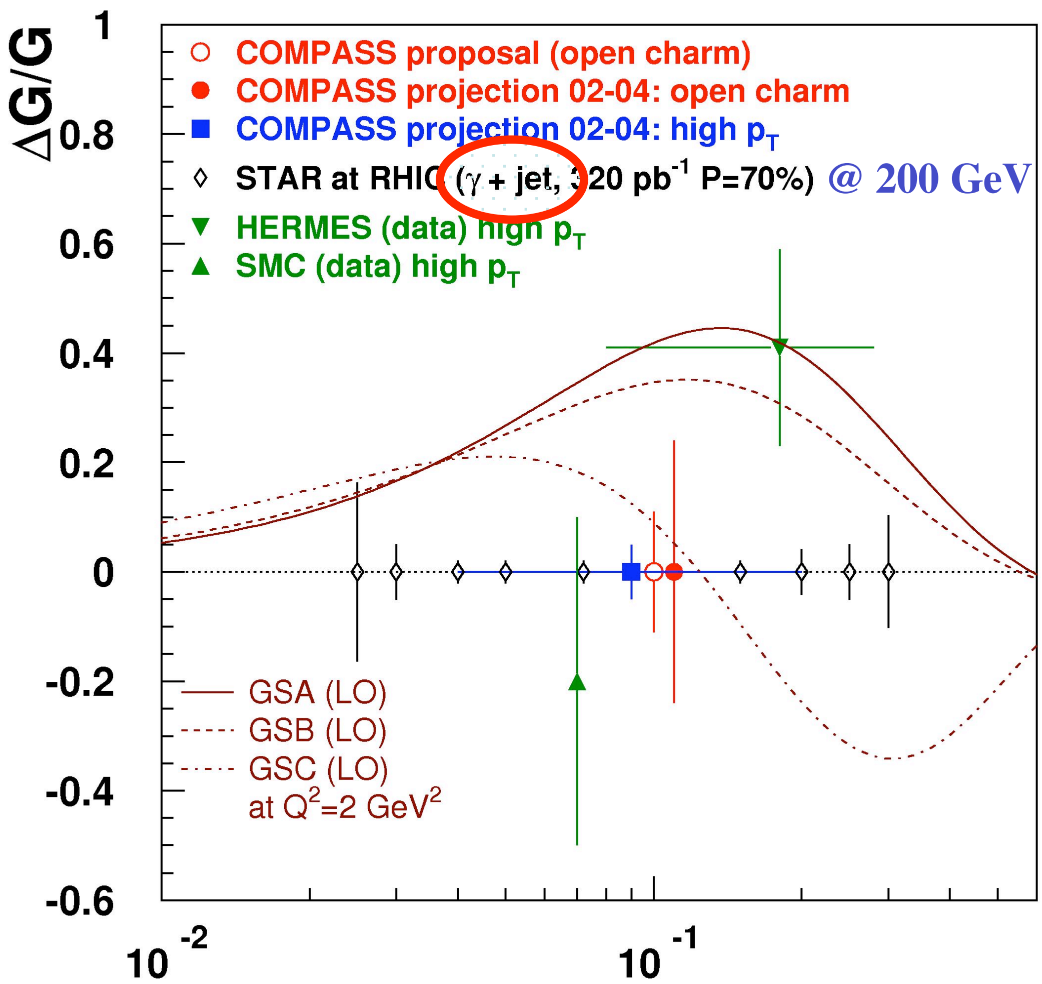
- gluon polarization from **pp → γ X**

L=100/pb

Frixione,WV







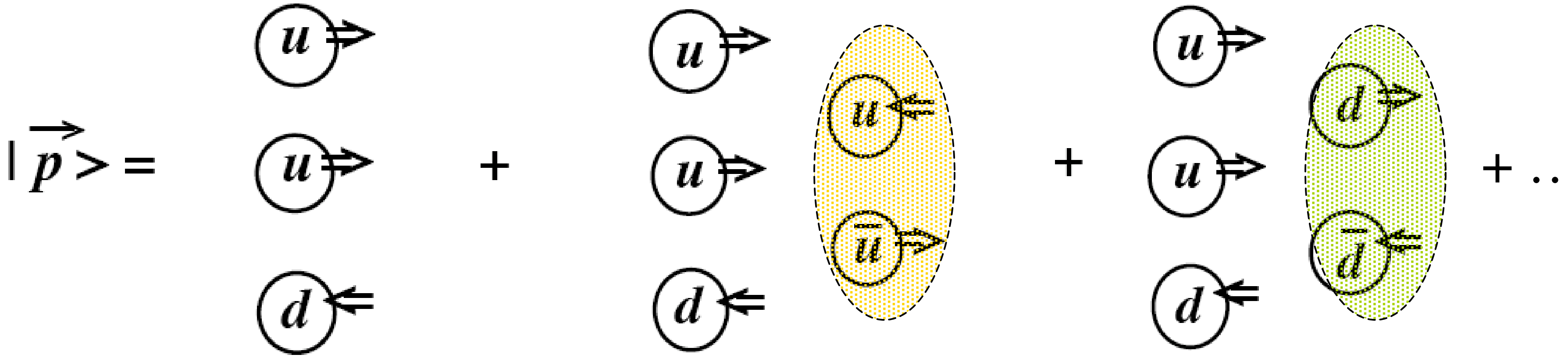
$$x_g \sim 2p_T/\sqrt{s}$$

typically, $0.025 < x_g < 0.3$ @ $\sqrt{s} = 200$ GeV

$0.01 < x_g < 0.1$ @ $\sqrt{s} = 500$ GeV

Further information

on quark distributions



most models predict $\quad \Delta\bar{\mathrm{u}} > 0 \quad \Delta\bar{\mathrm{d}} < 0$

$$\Delta\bar{\mathrm{u}} - \Delta\bar{\mathrm{d}} \;\; \substack{> \\ < \\ =} \;\; 0 \;\; ?$$

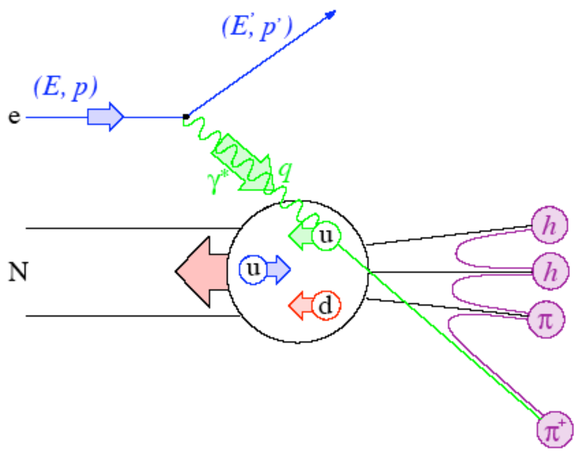
- considerable interest :

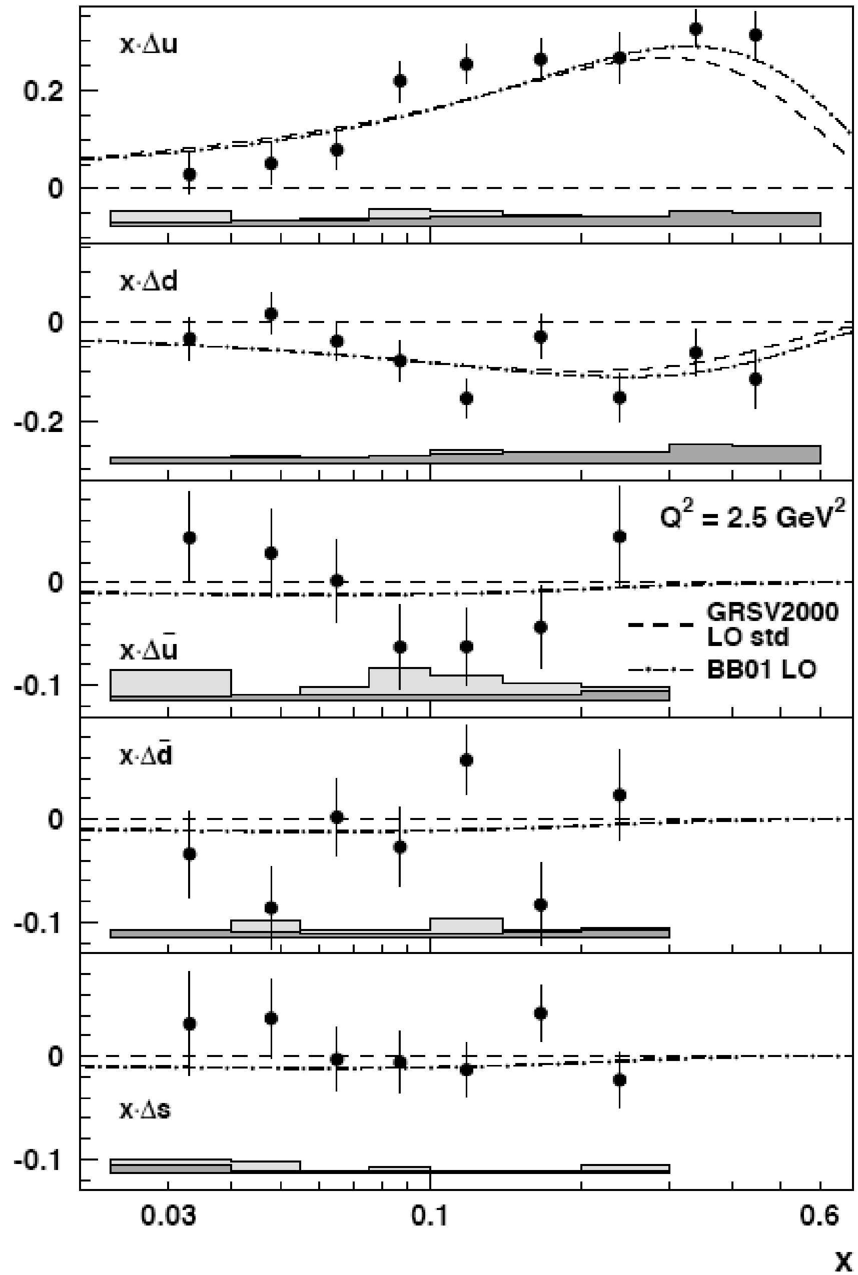
  ∗ SU(2) breaking in sea (meson cloud models, Pauli exclusion, . . .)

  (Thomas,Signal,Cao; Diakonov,Goeke,Polyakov,Weiss; Glück,Reya; Schäfer,Fries; Kumano; Wakamatsu)

  ∗ strange quark polarization

  (Ellis,Karliner et al.; Brodsky,Ma Bo-Qiang et al; . . .)

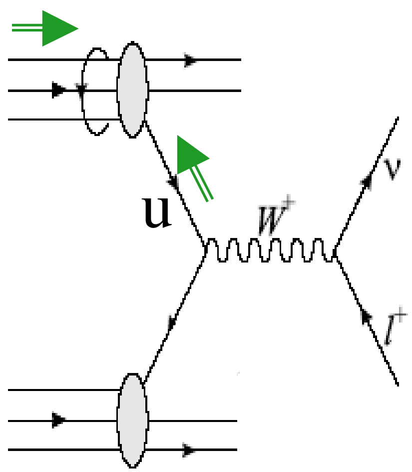

(E', p')
(E, p)
e
γ*
q
N
u
u
d
h
h
π
π+


x·Δu
0.2
0
x·Δd
0
-0.2
Q² = 2.5 GeV²
0
GRSV2000
LO std
BB01 LO
x·Δū
-0.1
x·Δd̄
0
-0.1
0
x·Δs
-0.1
0.03
0.1
0.6
x

HERMES

at RHIC:

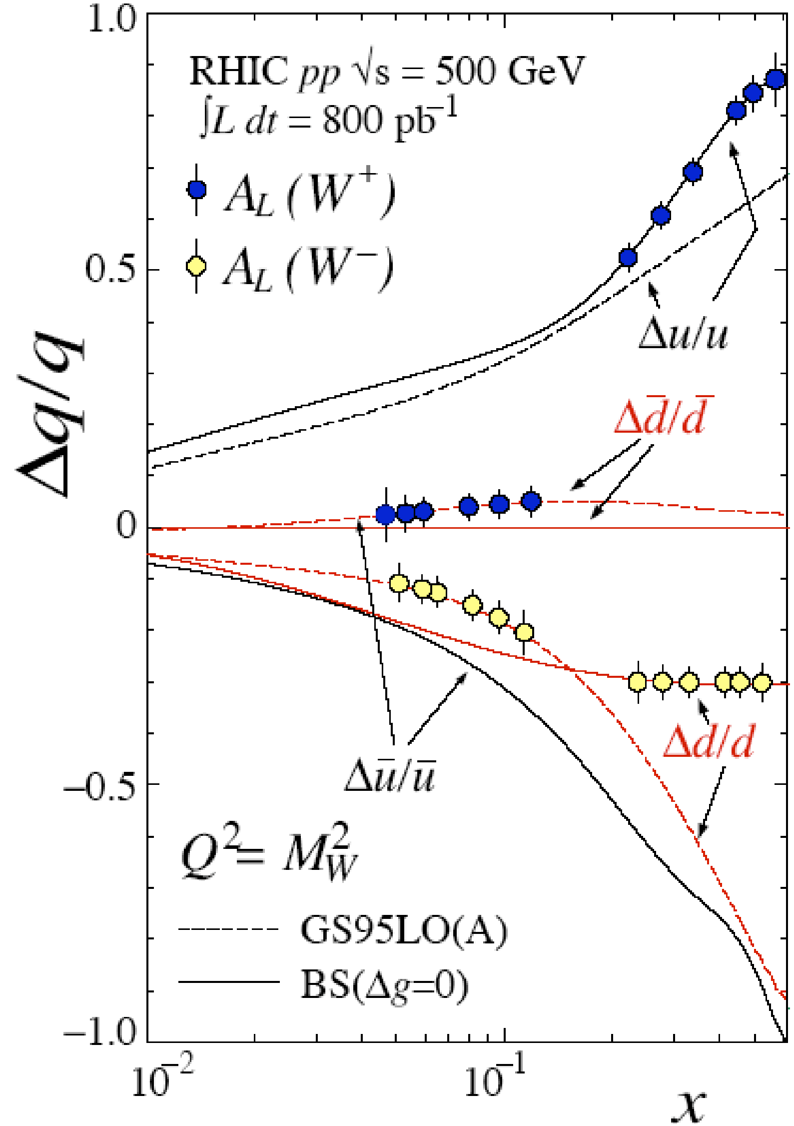
W boson production



unpol.

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

parity violating



Access to orbital angular momentum ?

- recall, in elastic scattering we had

$$\langle P' \,|\, J^{\mu} \,|\, P \rangle \;\sim\; \chi^{\dagger}_{s'} \left(G_E(Q^2) \;,\; \frac{i\vec{\sigma} \times \vec{q}}{2m_p} G_M(Q^2) \right) \chi_s$$

where $\quad G_E(0) \,=\, 1 \qquad G_M(0) \,=\, 2.79$

- measurement of $G_M(0)$ requires non-zero momentum transfer
- on the other hand, magnetic moment is

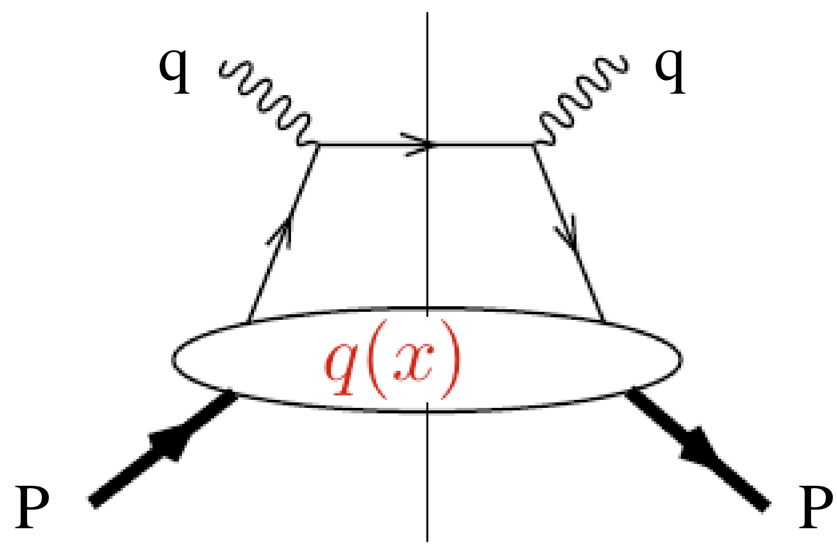
$$G_M(0) \;\sim\; \int d^3x \; \langle P \,|\, \frac{1}{2}\, \vec{x} \times \vec{J} \,|\, P \rangle$$

- operators for angular momentum involve explicit factor $\vec{x}$

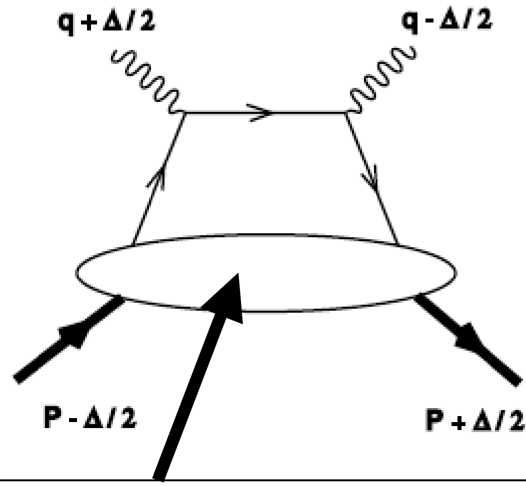
$$L_q = \int d^3x \, \langle P, \frac{1}{2} \,|\, \psi_q^\dagger \left[\vec{x} \times \left(-i\vec{\nabla} \right) \right]_3 \psi_q \,|\, P, \frac{1}{2} \rangle$$

- $\rightarrow$ need an off-forward process!

- DIS isn't like that:



- X. Ji: "Deeply-virtual Compton scattering"



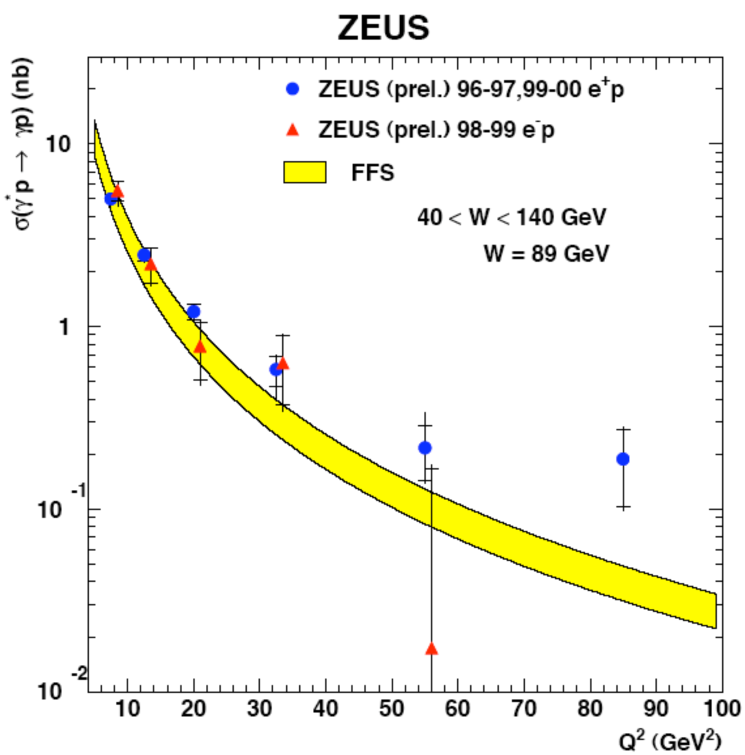
$$\boxed{H_q(x,\xi,\Delta^2),\ E_q(x,\xi,\Delta^2)}$$

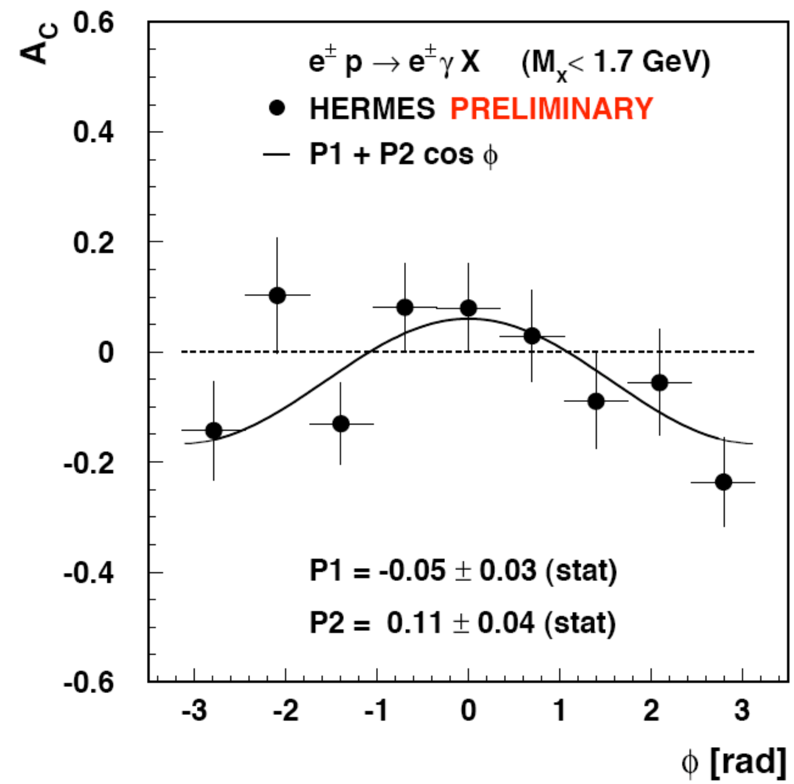
- $H_q(x,\xi,\Delta^2)$ and $E_q(x,\xi,\Delta^2)$ are related to both ordinary pdf's and to form factors:

"Generalized parton distributions"

$$J_q = \frac{1}{2} \lim_{\Delta^2\to 0} \int dx\, x\, \left[H_q(x,\xi,\Delta^2) + E_q(x,\xi,\Delta^2)\right]$$

- measurements have begun: HERMES, H1, ZEUS, CLAS



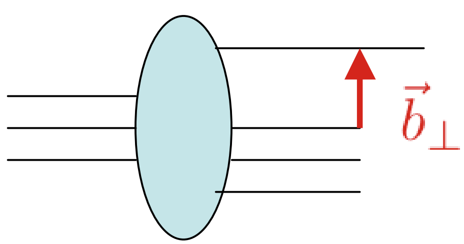


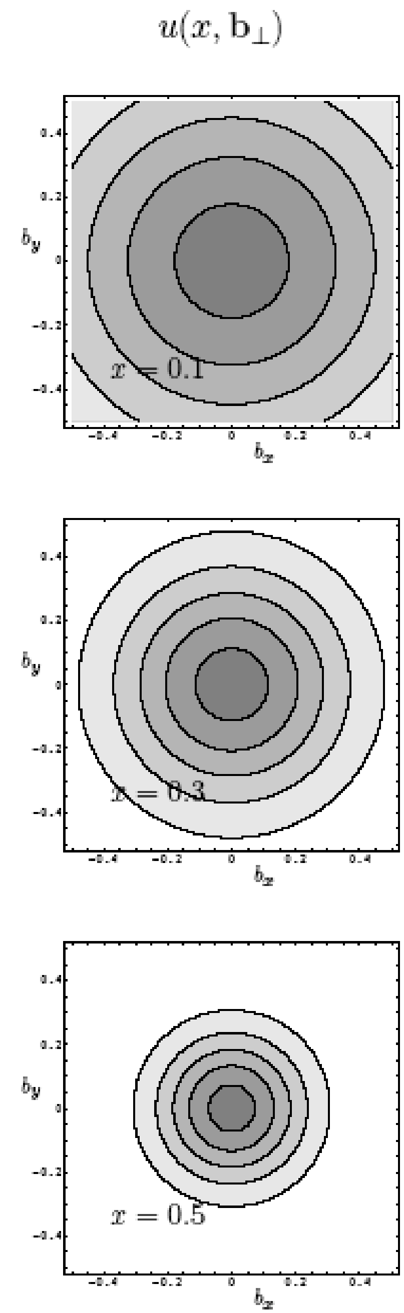
- theory: Belitsky,Müller; Frankfurt,Freund,Strikman; Ji,Osborne …

- orbital angular momentum
- exclusive processes in QCD
- spatial distributions of partons in proton

$$q(x, \vec{b}_\perp) \; = \; \int d^2\Delta_\perp \, \mathrm{e}^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} \, H_q(x, 0, -\Delta_\perp^2)$$

Burkardt; Ralston,Pire; Diehl; Belitsky,Ji,Yuan

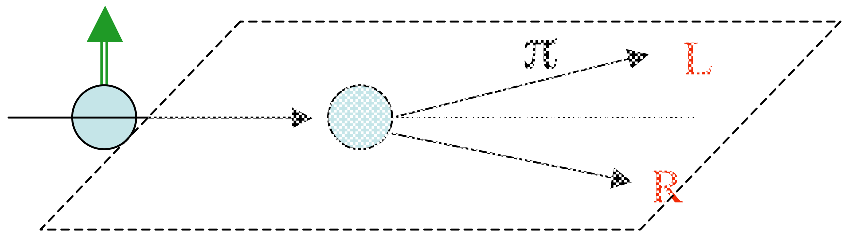




Transverse polarization

- hadronic single-spin asymmetries, e.g. in $\vec{p}p \to \pi X$

$$\boxed{A_{\mathrm{L}} \equiv \frac{\sigma_{+}-\sigma_{-}}{\sigma_{+}+\sigma_{-}} = 0 \quad \text{in QCD}} \qquad \boxed{A_{\mathrm{N}} \equiv \frac{\sigma_{\uparrow}-\sigma_{\downarrow}}{\sigma_{\uparrow}+\sigma_{\downarrow}} \neq 0 \quad \text{allowed}}$$

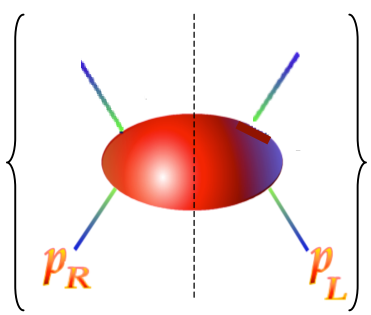


$$A_N = \frac{L-R}{L+R}$$

- in helicity basis :

$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\Big(|+\rangle + i\,|-\rangle\Big) \qquad |\downarrow\rangle = \frac{1}{\sqrt{2}}\Big(|+\rangle - i\,|-\rangle\Big)$$

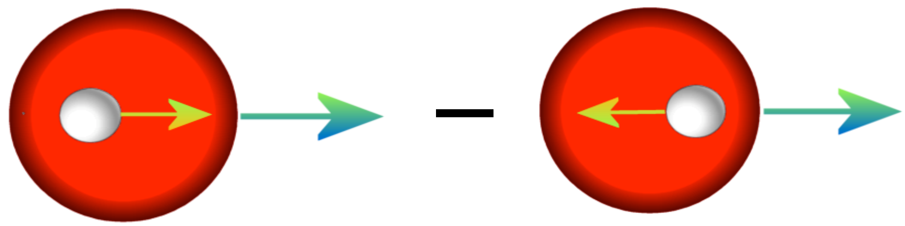
A_{N} **~ Im**



- the simplest idea: transverse nucleon polarization carried by quark

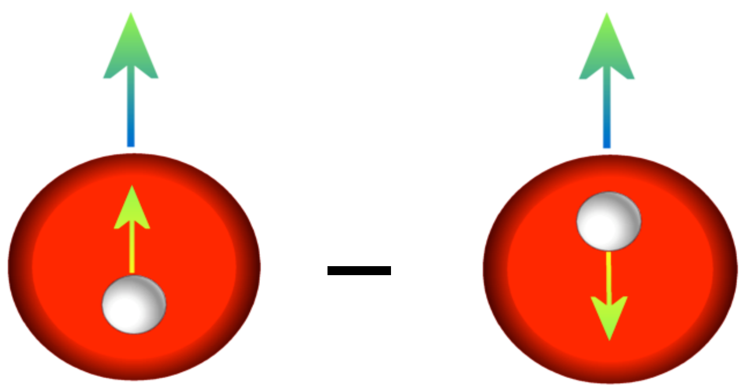
Helicity :

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



Transversity :

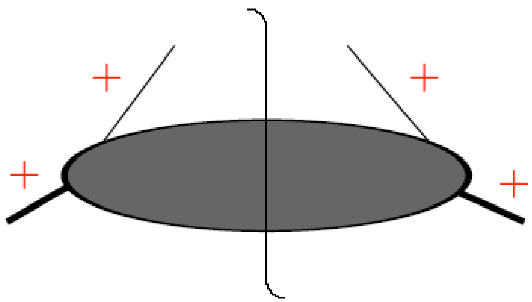
$$\delta \mathbf{q}(\mathbf{x}) =$$



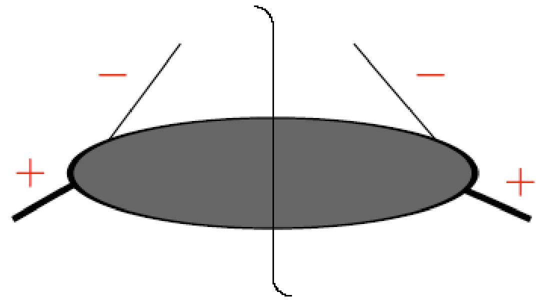
Ralston,Soper; Jaffe,Ji; …

- a little more precisely …

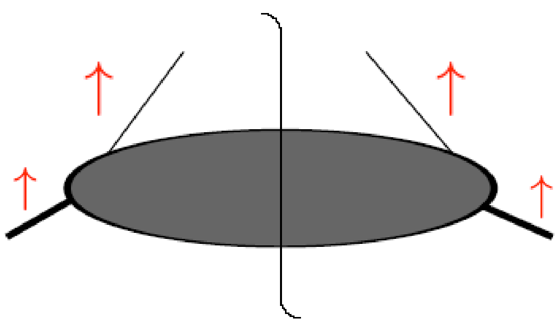
$$\Delta q(x) \ =$$



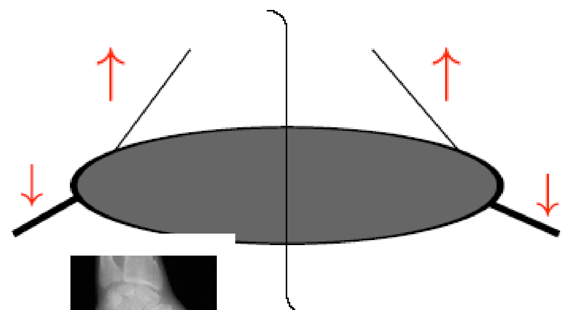
$$-$$



$$\delta q(x) \ =$$

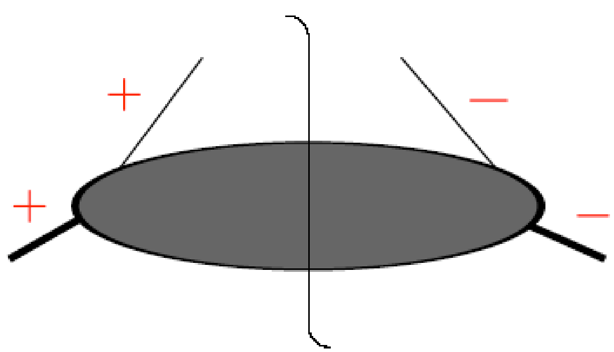


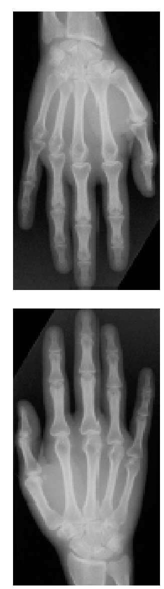
$$-$$



- in helicity basis:

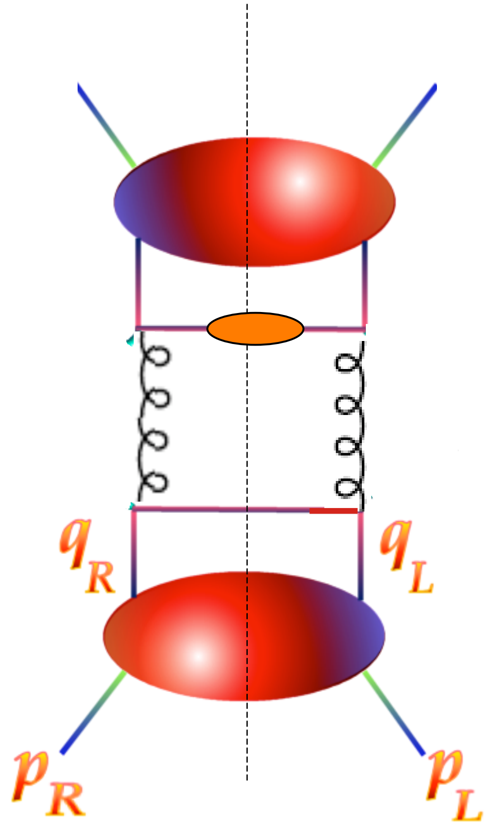
$$\delta q(x) \ \sim$$





helicity-flip,
χSB, …

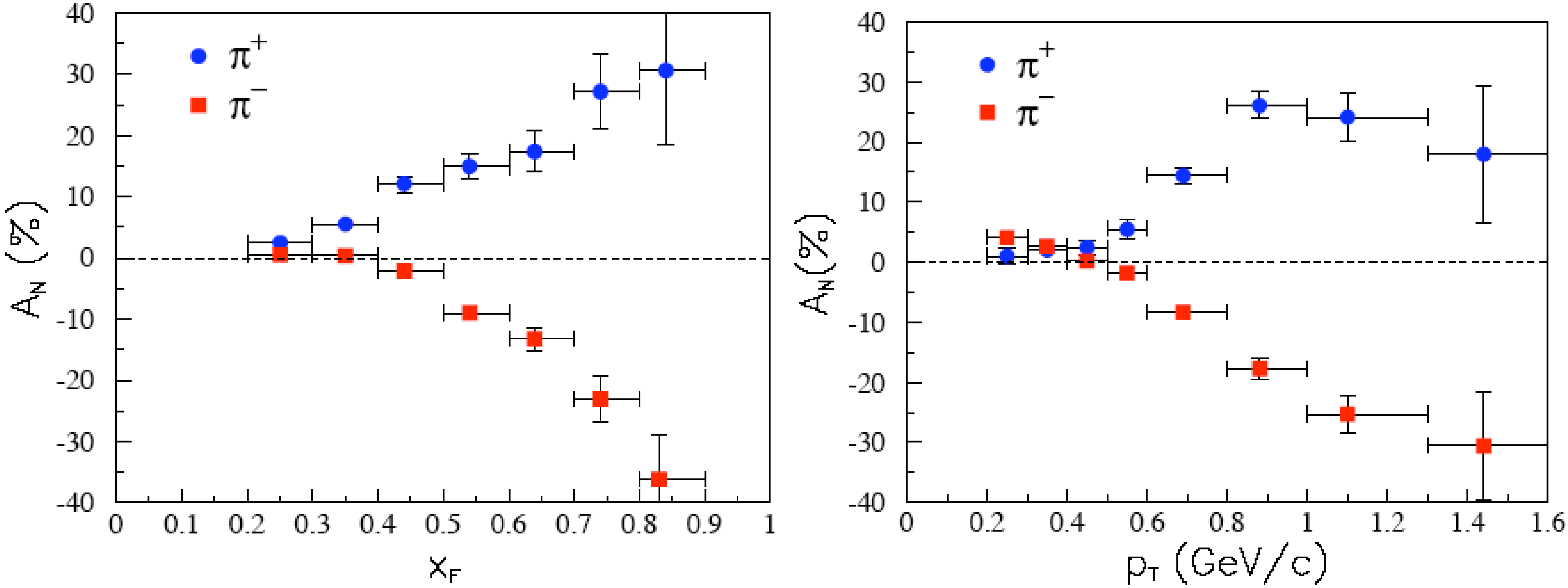
- back to single-spin asymmetry:



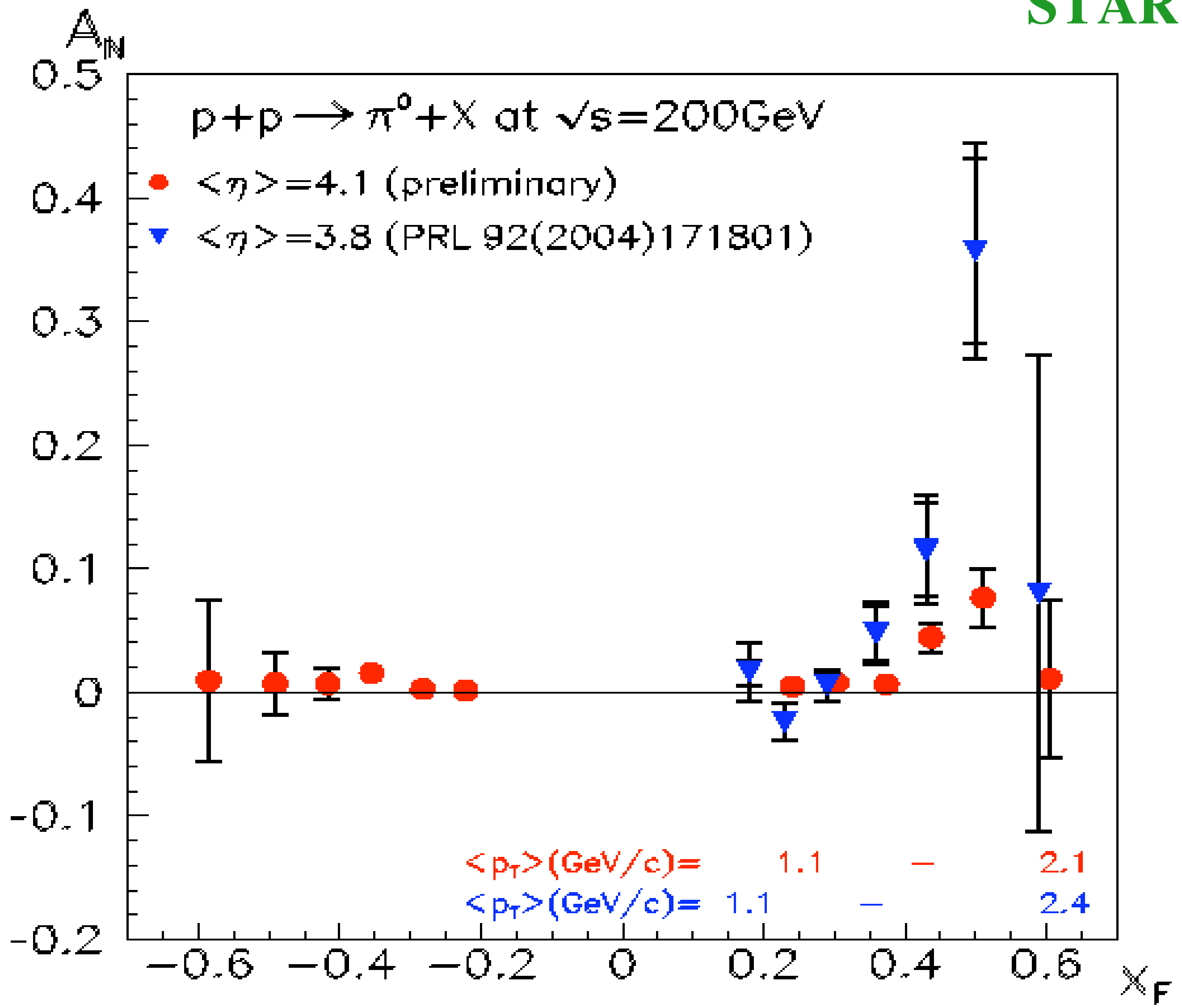
transversity

- may arise only as $\boxed{\frac{m_q}{p_T}\alpha_s \ll 1}$ (Kane,Pumplin,Repko)
- the lesson : $A_{\rm N}$ is power-suppressed as $1/p_T$ . . .
- . . . and is therefore small ?

- in striking contrast :
  - ∗ large A_N seen in fixed-target experiments at BNL,ANL,Fermilab,Serpukhov
  - ∗ E704 ('96) :



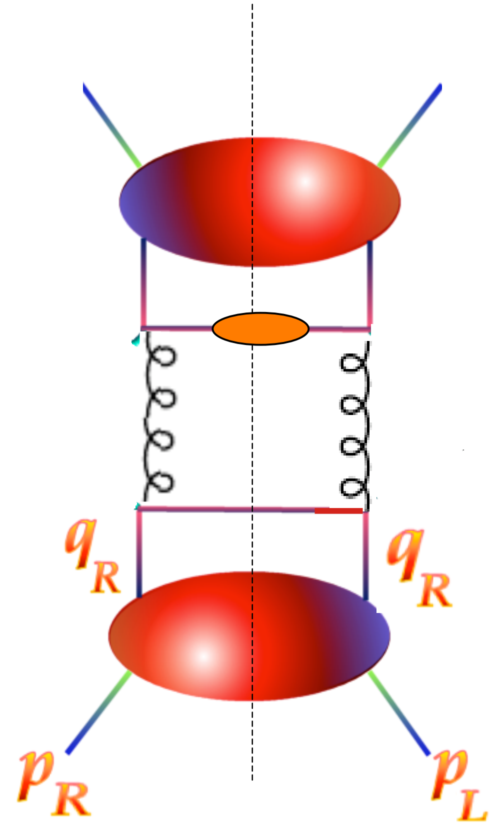
STAR



A_N
p+p → π^0+X at √s=200GeV
<η>=4.1 (preliminary)
<η>=3.8 (PRL 92(2004)171801)
<p_T>(GeV/c)= 1.1 – 2.1
<p_T>(GeV/c)= 1.1 – 2.4
x_F

Much theoretical activity:

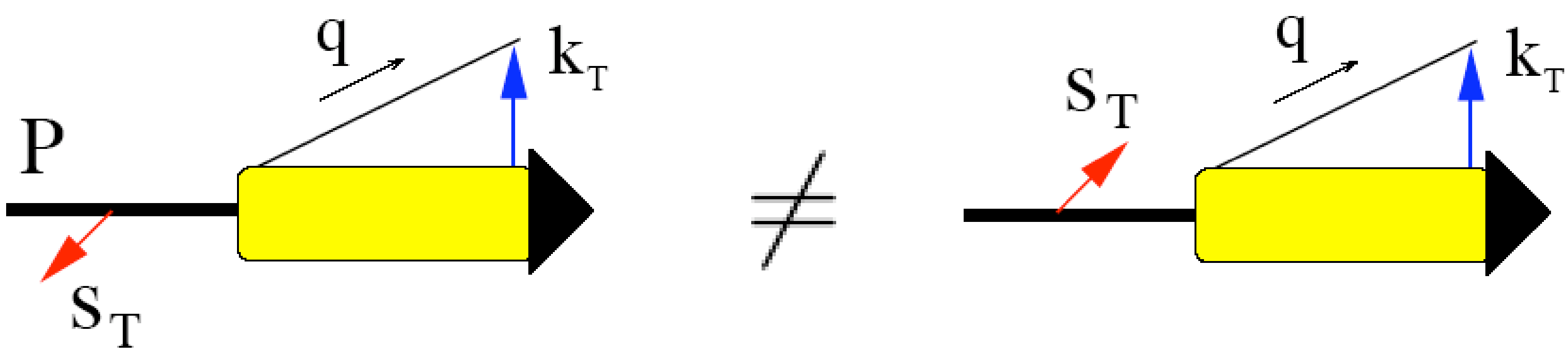
- how to avoid quark helicity flip ?



- requires transverse momentum k_T for quark
- interference of $J_z^p = +\frac{1}{2}$ and $J_z^p = -\frac{1}{2}$ amplitudes
- involves quark orbital angular momentum

“Sivers effect”

- realized if Sivers '90

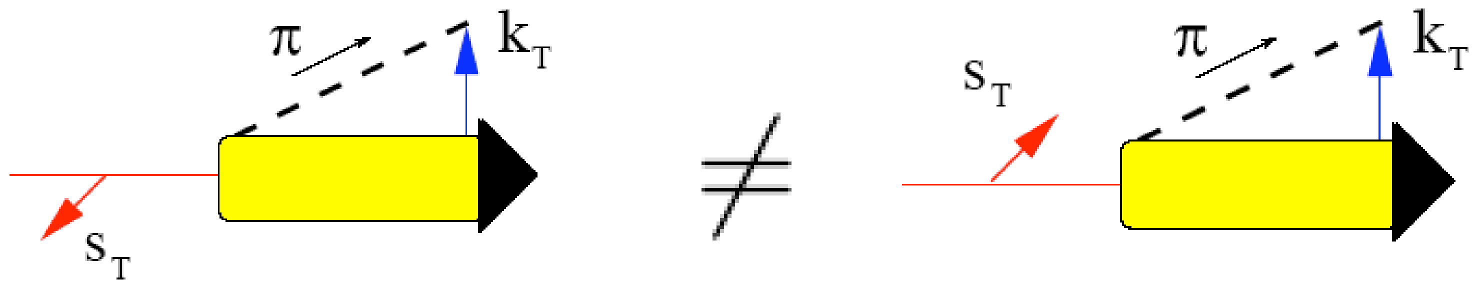


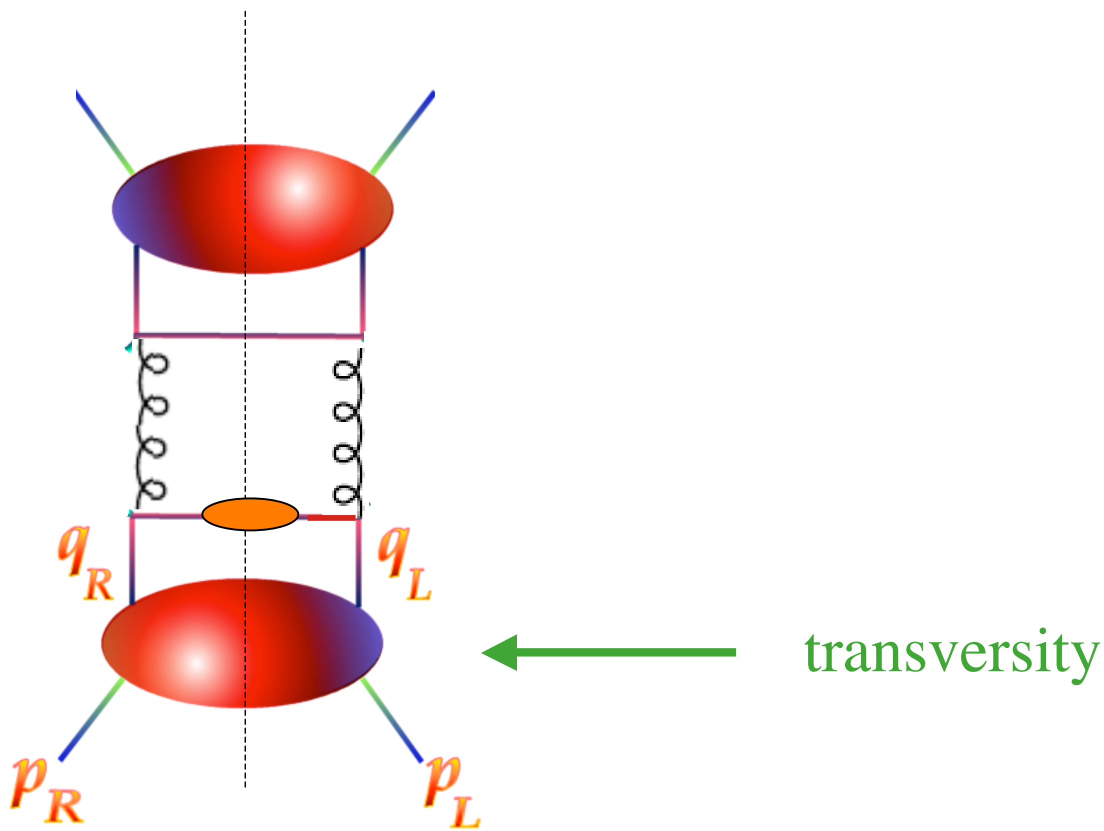
- correlation $\sim \vec{S}_T \cdot \left(\vec{P} \times \vec{k}_T \right)$

- thought of as arising from interaction of struck quark with gluon field (Brodsky,Hwang,Schmidt; Collins; Belitsky,Ji,Yuan; Boer,Mulders,Pijlman)

- steeply falling cross sections $\longrightarrow$ large effects possible

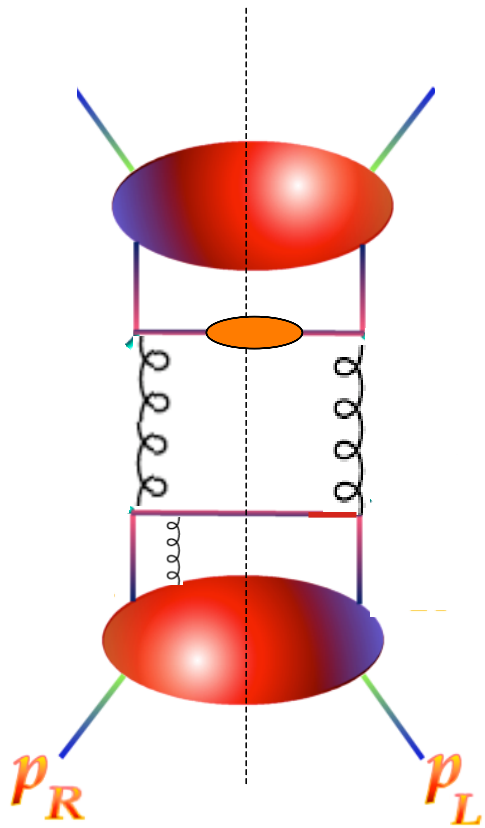
- Collins '93 : related effect in fragmentation





- yet another possibility :
  "quark-gluon correlation functions"

Qiu, Sterman; Efremov, Teryaev; Koike …



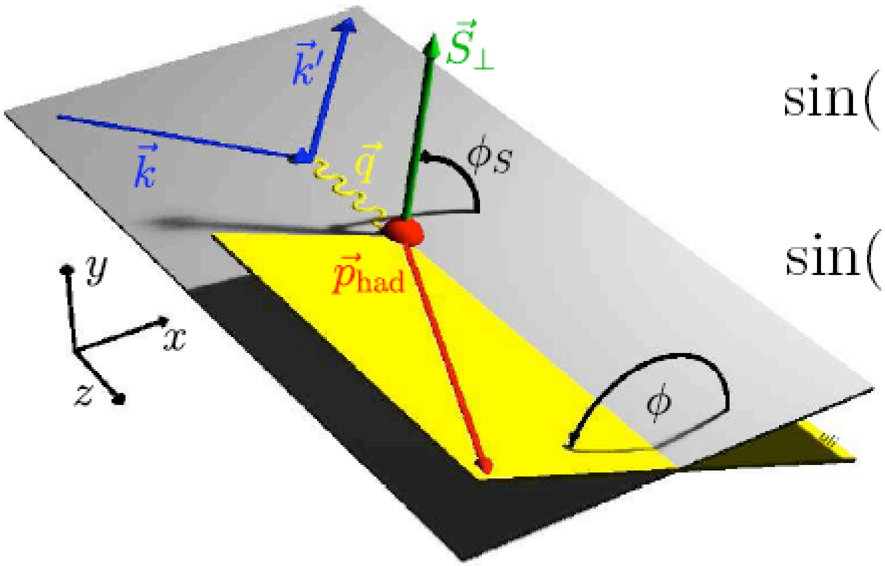
- nonperturbative models :   Boros, Liang, Meng; Ostrovsky, Shuryak; …

- still a lot to learn about the origins of single-spin asymmetries !

Some observables are directly sensitive to $\vec{k}_T$:

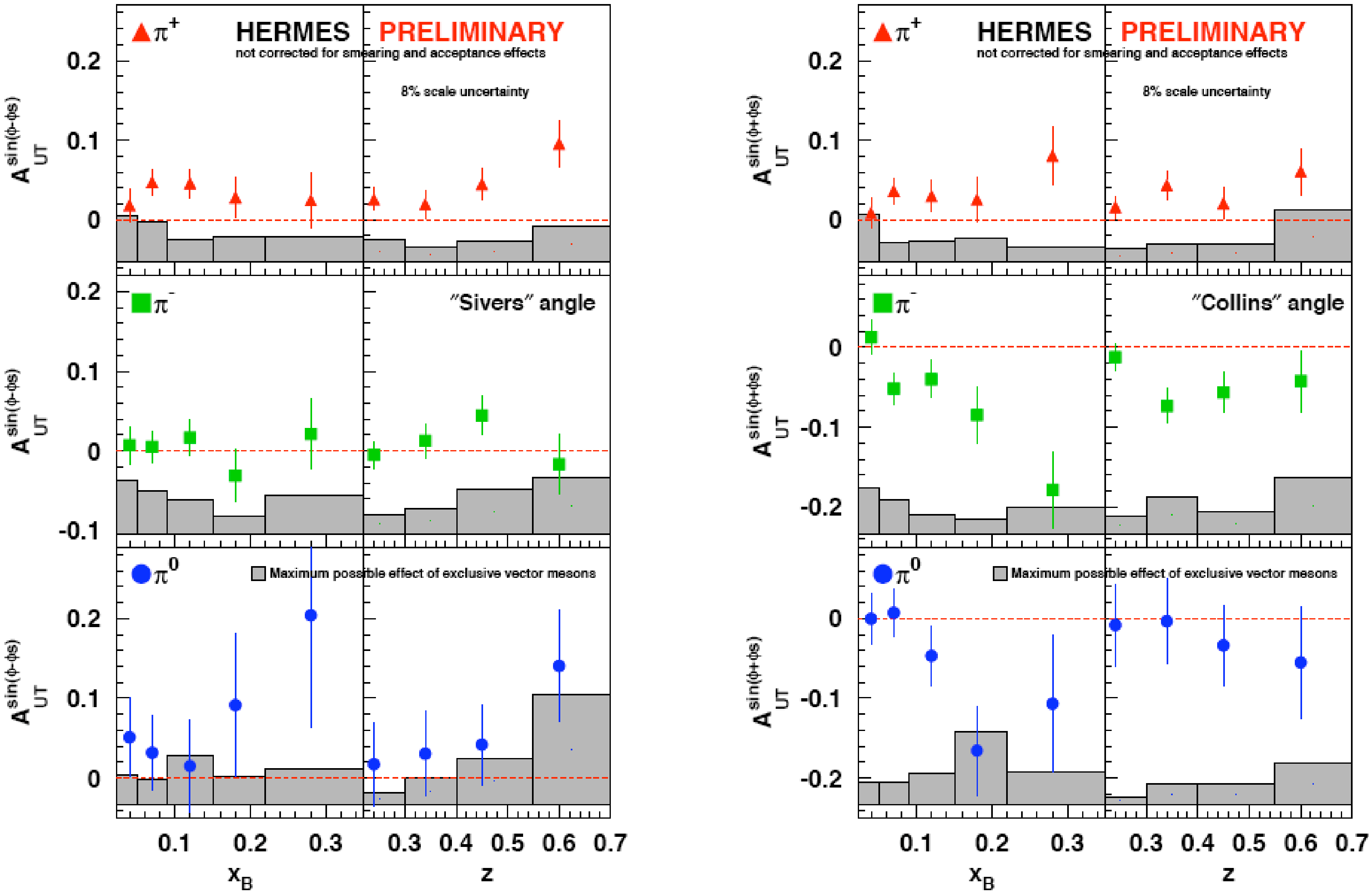
- example : $ep^{\uparrow} \to e\pi X$

Collins



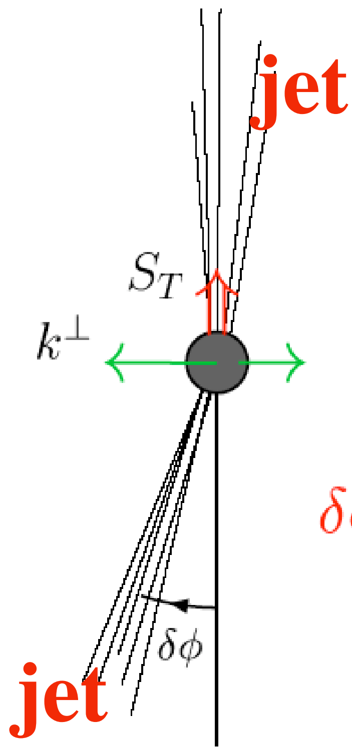
$$\sin(\phi - \phi_S)\ \sum_q e_q^2\ f_{1T}^{\perp,q}(x)\ D_q(z)$$

$$\sin(\phi + \phi_S)\ \sum_q e_q^2\ \delta q(x)\ H_1^{\perp,q}(z)$$


HERMES
PRELIMINARY
not corrected for smearing and acceptance effects
8% scale uncertainty
π+
π-
π0
"Sivers" angle
"Collins" angle
Maximum possible effect of exclusive vector mesons
A_UT^sin(φ-φs)
A_UT^sin(φ+φs)
x_B
z

at RHIC:

- consider $p^{\uparrow} p \rightarrow$ jet jet X



$$\delta\phi = \phi_2 - \phi_1 - \pi$$

Conclusions & Outlook:

- one can address & answer the question "What carries the proton spin?"

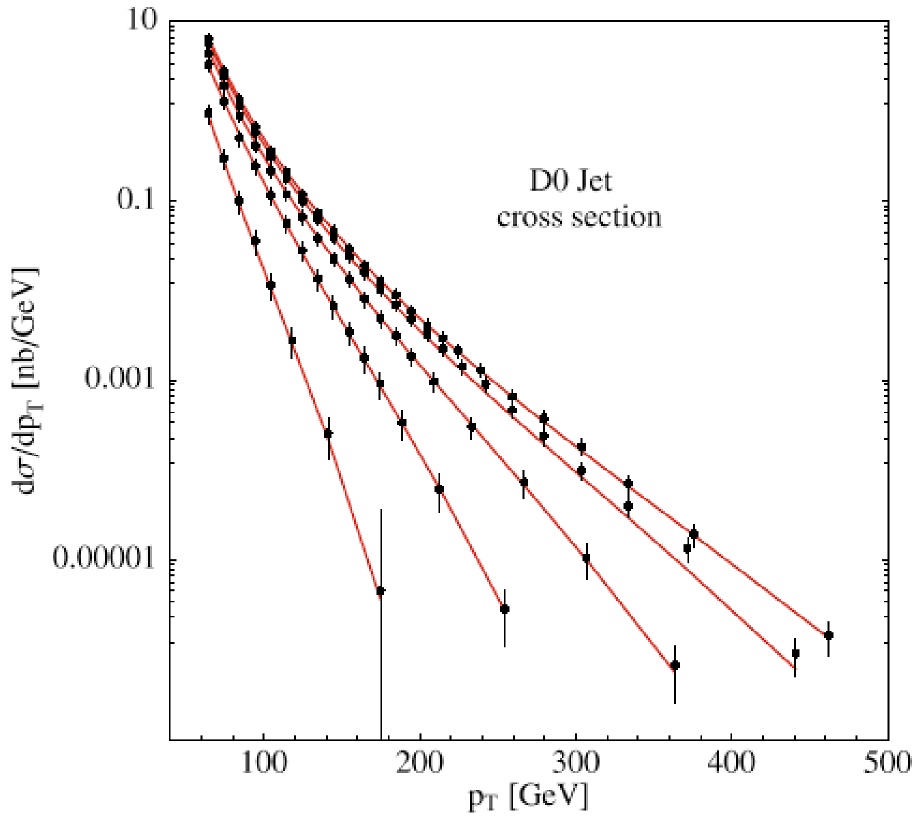
- future promises to be as exciting as past was:

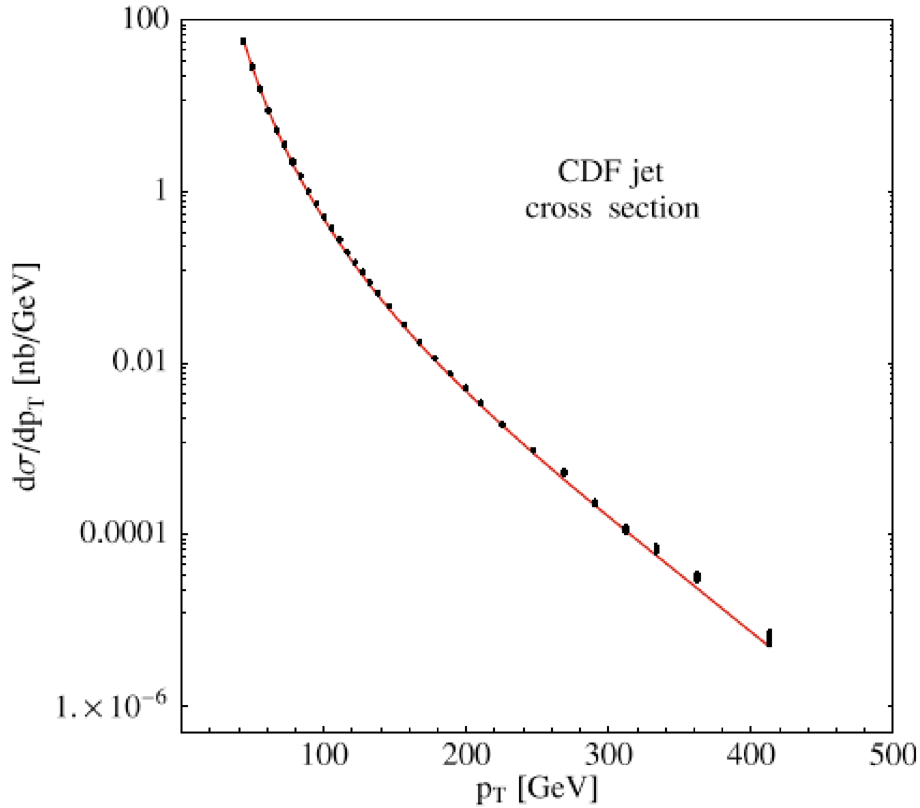
  lepton-nucleon expt. and RHIC provide a wealth of information

  * gluon polarization
  * single-spin asymmetries
  * quark polarizations by flavor
  * orbital angular momenta
  * . . .

- spin will continue to provide challenges to theory and experiment

High-p_T jets at the Tevatron :





Gluon polarization

- a key contributor to the proton spin ?
- $\langle \mathbf{S_g} \rangle = \int_0^1 \mathbf{dx}\, \boldsymbol{\Delta}\mathbf{g}(\mathbf{x}, \mathbf{Q^2}) \propto \frac{\mathbf{1}}{\alpha_\mathbf{s}(\mathbf{Q^2})}$ in QCD
- some model predictions (Q ≈ 0.5 GeV) :

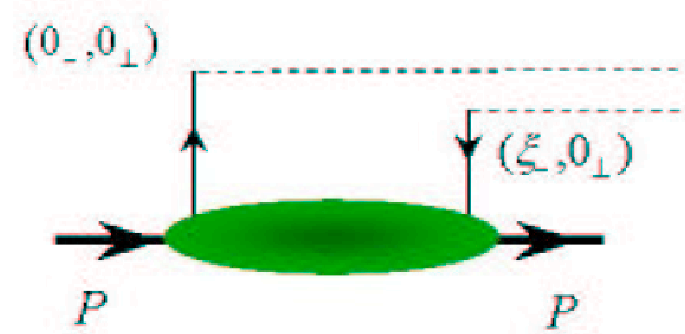
$$\langle \mathbf{S_g} \rangle = -0.4 \quad \text{(Jaffe, bag model)}$$

$$\langle \mathbf{S_g} \rangle = +0.25 \quad \text{(Barone et al., Isgur – Karl)}$$

$$\langle \mathbf{S_g} \rangle = +0.3 \quad \text{(Rho et al., chiral bag)}$$

...

- gauge-invariant parton distributions :



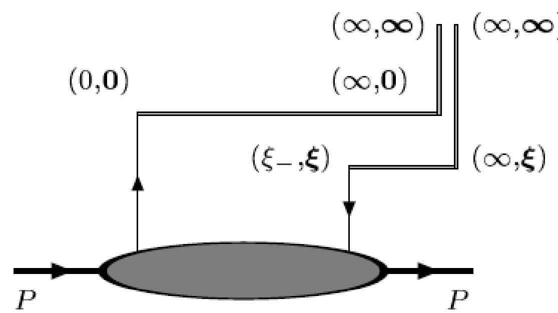
$$q(x) \sim \int d\xi^- \, e^{i\xi^- x} \, \langle P \,|\, \overline{\psi}_+(\xi^-) \, U_{[\infty,\xi^-]} \, U_{[0,\infty]} \, \psi_+(0) \; |\, P \rangle$$

$$U_{[a,\xi^-]} \equiv \mathcal{P} \exp\left(-ig \int_a^{\xi^-} d\lambda \, A^+(\lambda) \right)$$

- with k_T dependence

$$q(x, \vec{k}_T) \sim \int d\xi^- \, d^2\xi_T \, e^{i\xi^- x + i\vec{k}_T \cdot \vec{\xi}_T}$$

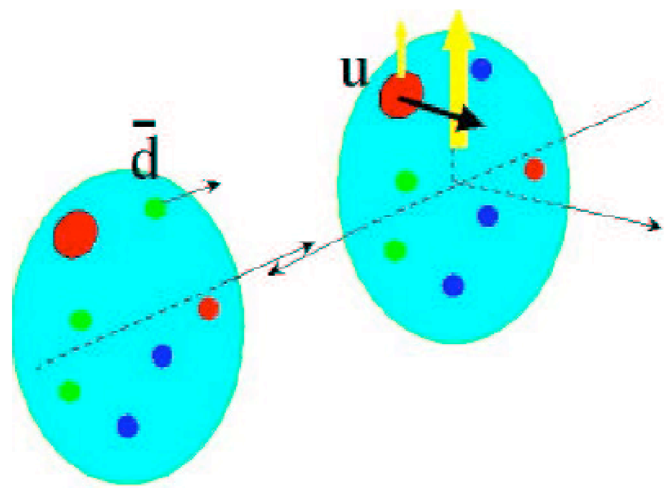
$$\times \langle P \,|\, \overline{\psi}_+(\xi^-, \vec{\xi}_T) \, \tilde{U}_{[\infty,\xi^-]} \, \tilde{U}_{[0,\infty]} \, \psi_+(0) \; |\, P \rangle$$



- gauge link survives even in $A^+ = 0$ gauge

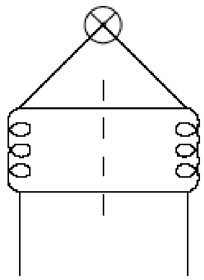
(Belitsky,Ji,Yuan; Boer,Mulders,Pijlman)

- a caveat :
  - data on $A_{\rm N}$ in "borderline pQCD" regime $p_T \sim \mathcal{O}(1)$ GeV
- in "soft regime", description for $A_{\rm N}$ could be different : (Boros,Liang,Meng)
- quark-antiquark fusion "on front surface"



- a crucial feature of the quark singlet :

$$s^\mu \, \Delta\Sigma \;=\; \langle P, S \,|\; \underbrace{\bar{\psi}\,\gamma^\mu\,\gamma^5\,\frac{\mathbb{1}}{2}\,\psi}_{\text{singlet axial current } j_5^{\mu,0}} \;|\, P, S\rangle$$



- connection to axial anomaly :

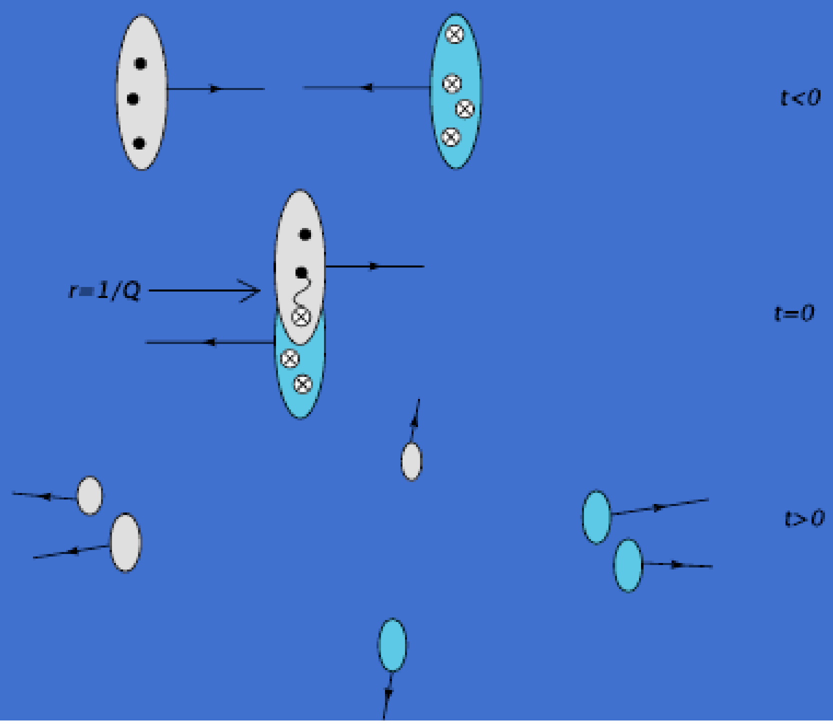
$$\partial_\mu\, j_5^{\mu,0} \equiv \partial_\mu \left[\bar{\psi}\,\gamma^\mu\,\gamma^5\,\psi\right] = n_f\,\frac{\alpha_s}{2\pi}\,\mathrm{Tr}\left[G_{\mu\nu}\,\tilde{G}^{\mu\nu}\right]$$

- a consequence (in $\overline{\mathrm{MS}}$ scheme) :

$$\Delta\Sigma(Q^2) \;=\; \left(1 \;+\; \frac{6n_f}{(33-2n_f)\,\pi}\;\left[\,\alpha_s(Q^2)\;-\;\alpha_s(\mu_0^2)\,\right]\right)\;\Delta\Sigma(\mu_0^2)$$

$\Rightarrow$ moderate decrease in perturbative region (Jaffe)

Recall the essence of the parton model:



$$\sigma_{AB\to X}(Q) = \sum_{ab}\int d\xi_1 \int d\xi_2 \times \phi_{a/A}(\xi_1)\,\phi_{b/B}(\xi_2)\hat{\sigma}_{ab\to X}(\xi_1,\xi_2,Q)$$

Key notions:

i) Lorentz contraction of protons

ii) Time dilations of dynamics

$\rightarrow$ protons are static disks that only "see" eachother when they overlap.

Hadronic cross section is weighted sum ($\int d\xi_1 d\xi_2$, ξ_i are momentum fractions) of partonic cross sections.

The parton distributions $\phi_{a/A}(\xi)$

Do classical fields behave like the parton model?

Scalar field at rest, and boosted ($\beta \simeq 1, \gamma \gg 1$)

$$\phi(x) = \frac{q}{|\vec{x}|}, \quad \phi'(x') = \frac{q}{\sqrt{x_T^2 + \gamma^2 (t' - z')^2}},$$

Field lines also take pan-cake form!

Gauge field at rest, and boosted ($\beta \simeq 1, \gamma \gg 1$)

$$A^\mu(x) = \frac{q\delta_{\mu 0}}{|\vec{x}|}, \quad {A'}^0(x') = -{A'}^3(x') = \frac{q\gamma}{\sqrt{x_T^2 + \gamma^2 (t' - z')^2}}$$

Gauge field does *not* die off, but for $\gamma \to \infty$ takes the form

$${A'}^\mu(x') \to q\partial^\mu \ln(t' - z')$$

But this is gauge tranformation of $A^\mu = 0$, so there is no physics in this!