SPIN EFFECTS IN THE STRONGLY CORRELATED QUARK MODEL

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DSPIN-07

Introduction

Where does the Proton Spin come from?

Spin "Crisis“:

DIS experiments: $\Delta\Sigma=\Delta u+\Delta d+\Delta s$ □ 1

SU(6) $\longrightarrow$ 1

Sum rule for the nucleon spin:

$$1/2 = (1/2)\Delta\Sigma(Q^2)+\Delta g(Q^2)+L(Q^2)_{q+g}$$

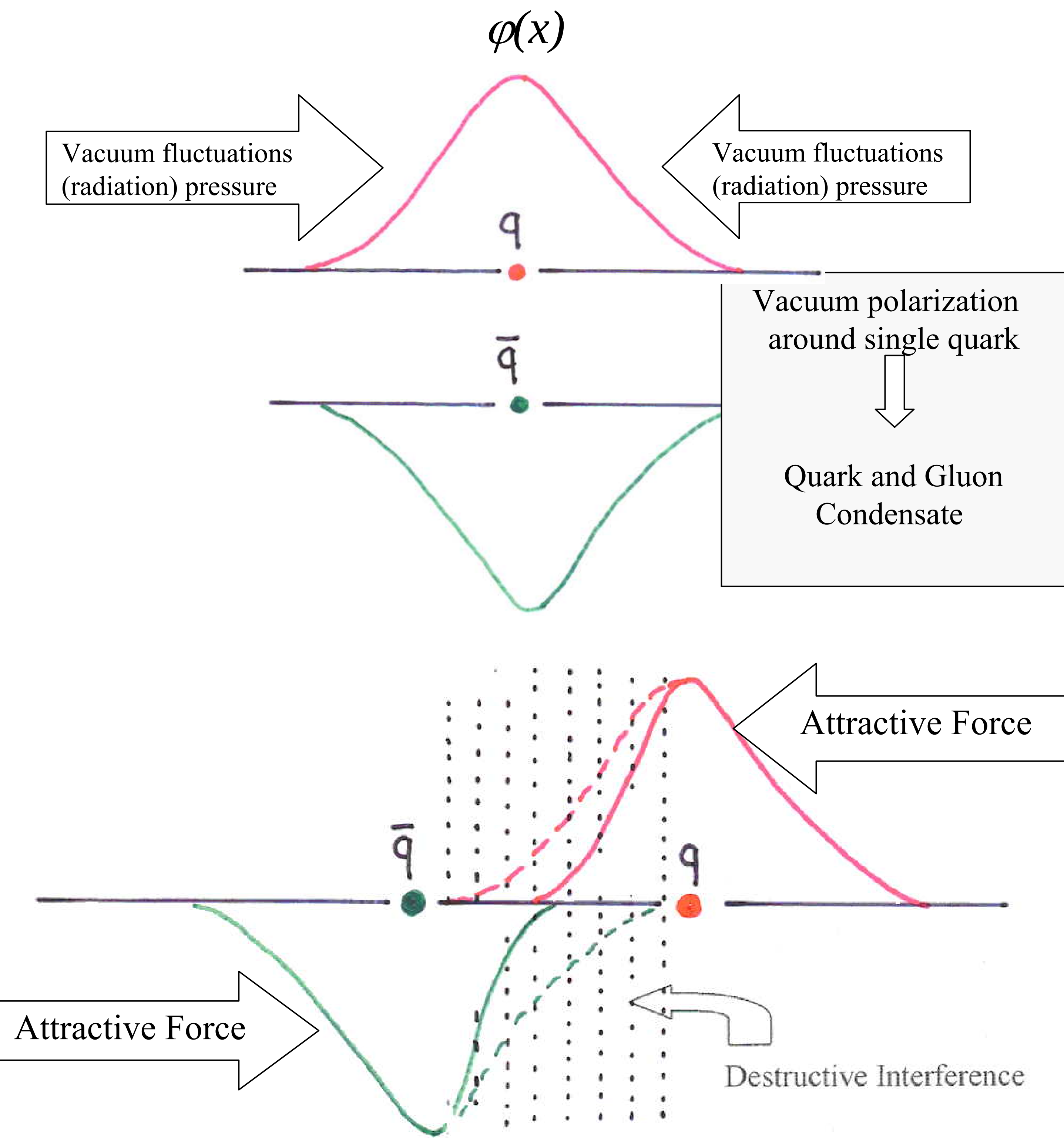
SCQM:

Total nucleon spin comes from circulating around each of three valence quarks gluon and quark-antiquark condensate.

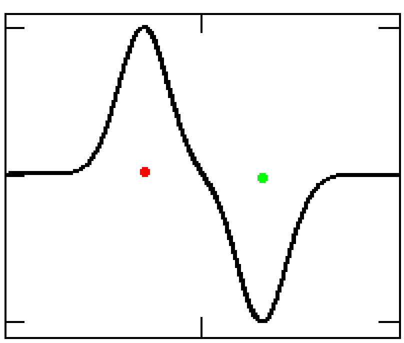
$$s = L_{q\bar{q}+g}$$

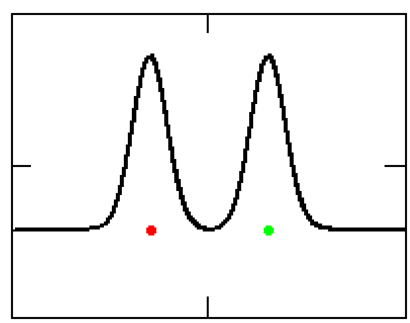
Strongly Correlated Quark Model

(SCQM)



Quark – antiQuark Oscillations





Constituent Quarks – Solitons

Sine- Gordon (SG) equation

$$\partial_\mu \partial^\mu \phi(x,t) + \sin\phi(x,t) = 0$$

Breather – oscillating soliton-antisoliton pair, the periodic solution of SG:

$$\phi(x,t)_{s-as} = 4\tan^{-1}\left[\frac{\sinh\left(ut/\sqrt{1-u^2}\right)}{u\cosh\left(x/\sqrt{1-u^2}\right)}\right]$$

The density profile of the breather:

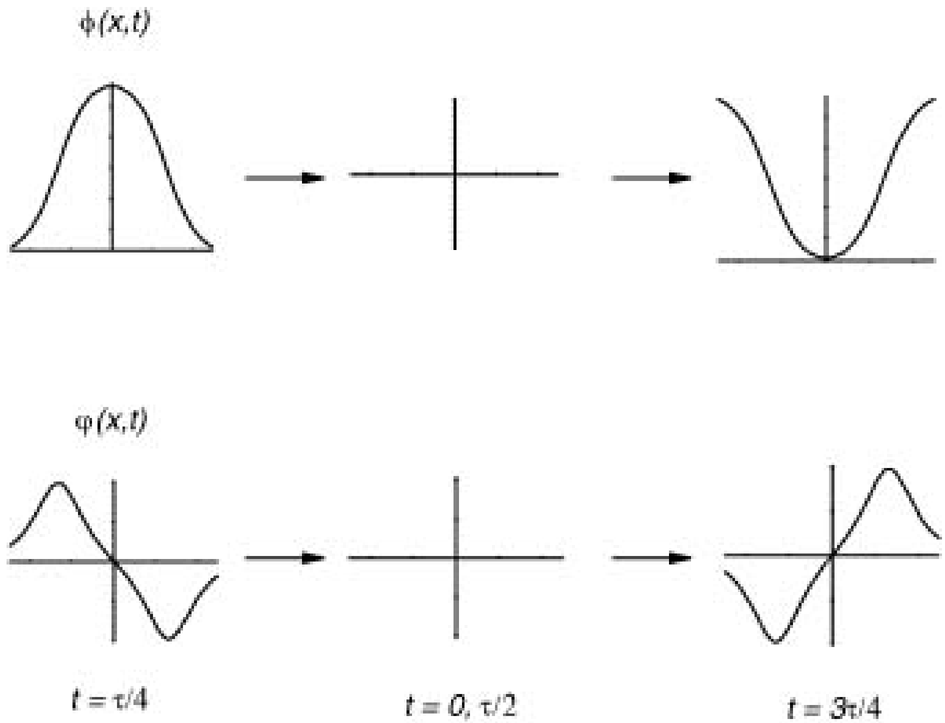
$$\varphi(x,t)_{s-as} = \frac{\partial\phi(x,t)_{s-as}}{\partial x}$$

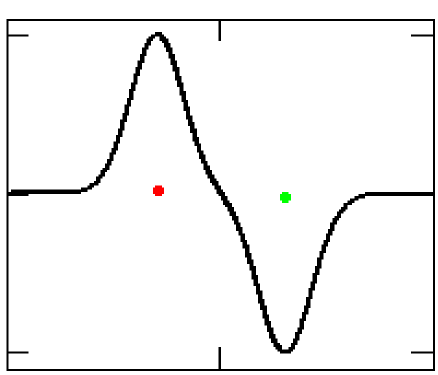
Breather solution of SG is Lorenz – invariant.

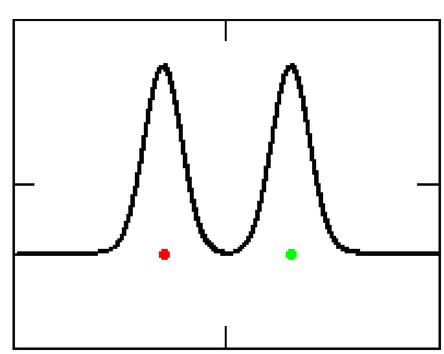
Effective soliton – antisoliton potential

$$U(x) = 2M\tanh^2(mx)$$

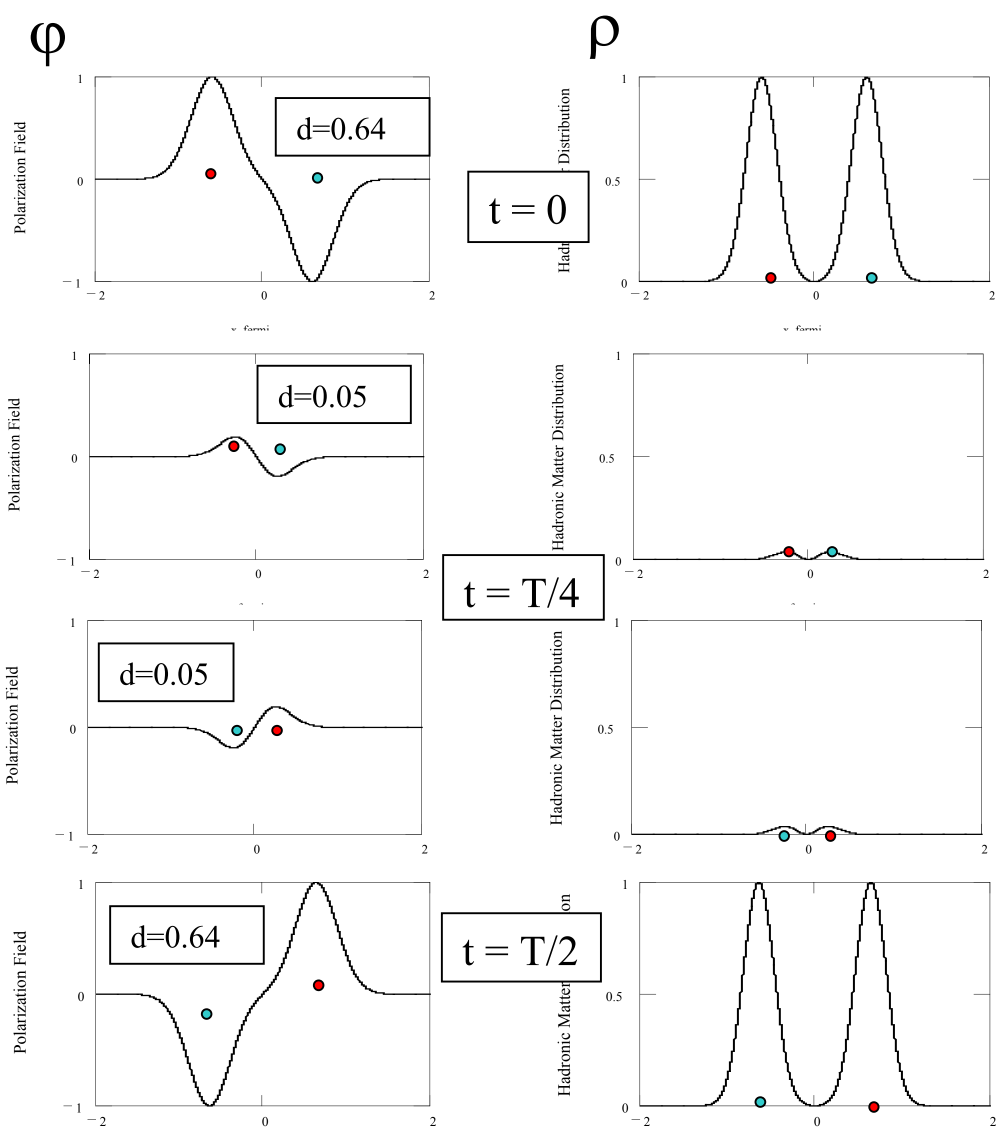
Breather (soliton –antisoliton) solution of SG equation







Interplay Between Current and Constituent Quarks ≡ Chiral Symmetry Breaking and Restoration ≡ Dynamical Constituent Mass Generation



Hamiltonian of the Quark – AntiQuark System

$$H = \frac{m_{\bar{q}}}{(1-\beta_{\bar{q}}^{\ 2})^{1/2}} + \frac{m_q}{(1-\beta_q^{\ 2})^{1/2}} + V_{\bar{q}q}(2x)$$

$m_{\bar{q}}$, m_q are the current masses of quarks,
$\beta = \beta(x)$ – the velocity of the quark (antiquark),
$V_{\bar{q}q}$ is the quark–antiquark potential.

$$H = \left[\frac{m_{\bar{q}}}{(1-\beta_{\bar{q}}^{\ 2})^{1/2}} + U(x)\right] + \left[\frac{m_q}{(1-\beta_q^{\ 2})^{1/2}} + U(x)\right]$$

$U(x) = \frac{1}{2} V_{\bar{q}q}(2x)$ is the potential energy of the quark.

Conjecture:

$$2U(x) = \int_{-\infty}^{\infty} dz' \int_{-\infty}^{\infty} dy' \int_{-\infty}^{\infty} dx' \rho(x, \vec{r}\,') \approx 2M_Q(x),$$

where $M_{Q(\bar{Q})}(x)$ is the dynamical mass of the constituent quark and

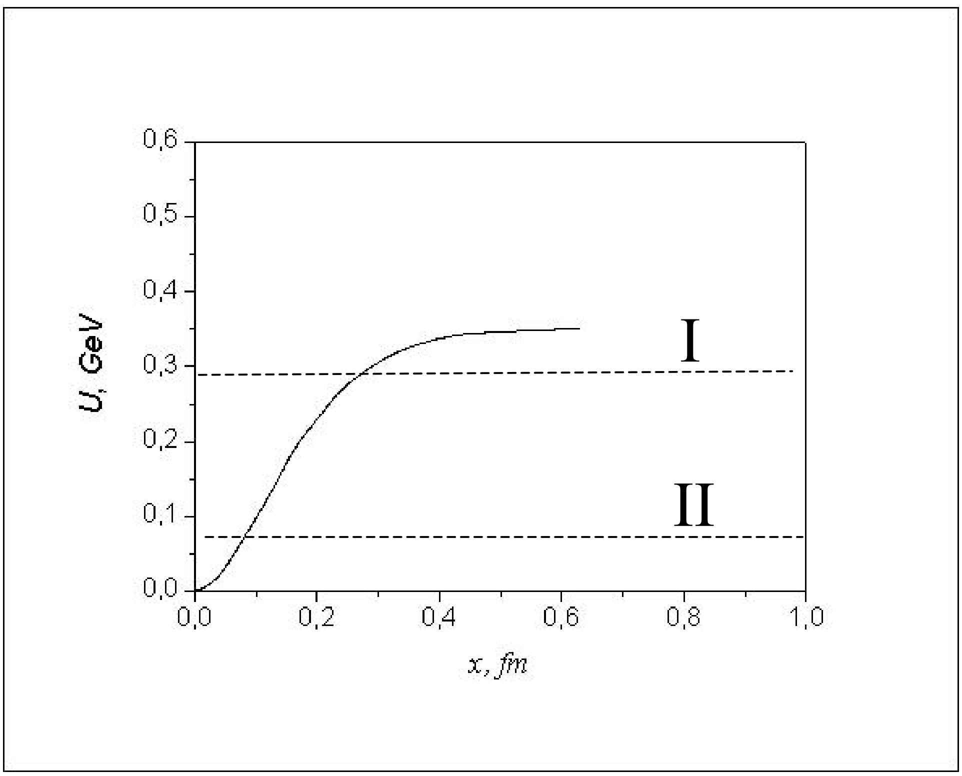
$$\rho(x, \vec{r}\,') = C \left| \varphi_{Q\bar{Q}}(x, \vec{r}\,') \right| =$$

$$C \left| \varphi_Q(x' + x, y', z') - \varphi_{\bar{Q}}(x' - x, y', z') \right|$$

For simplicity

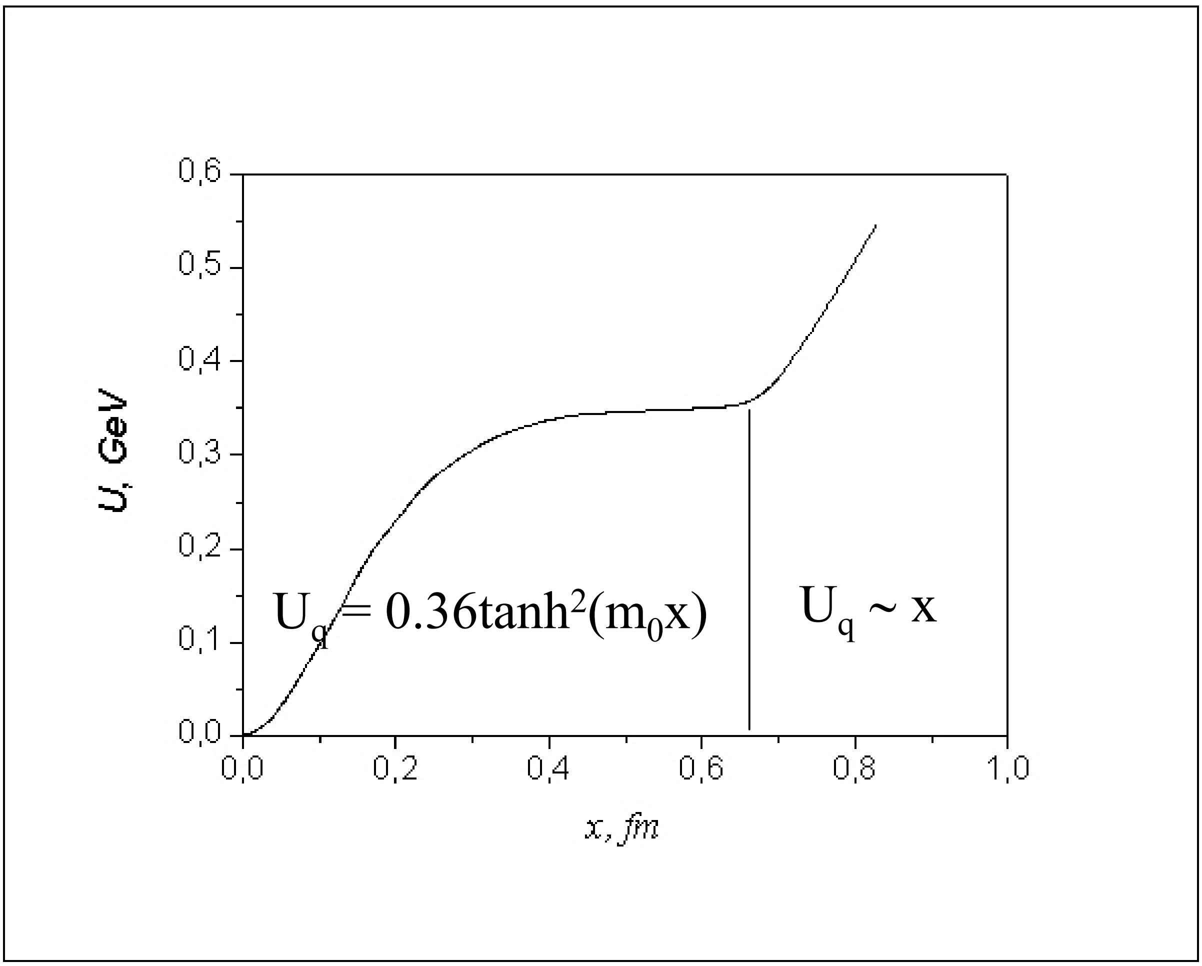
$$\varphi(\vec{r}) = \frac{(\det \hat{A})^{1/2}}{\pi^{3/2}} \exp\left(- \vec{X}^T \hat{A} \vec{X} \right)$$

Quark Potential inside Light Hadrons



U(x) > I – constituent quarks
U(x) < II – current(relativistic) quarks

Quark Potential inside Light Hadrons

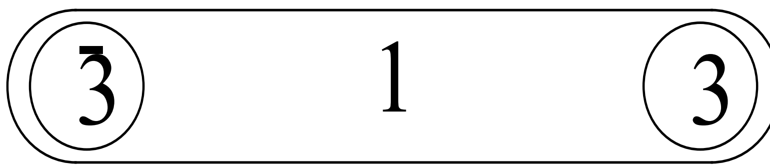


Generalization to the 3 – quark system (baryons)

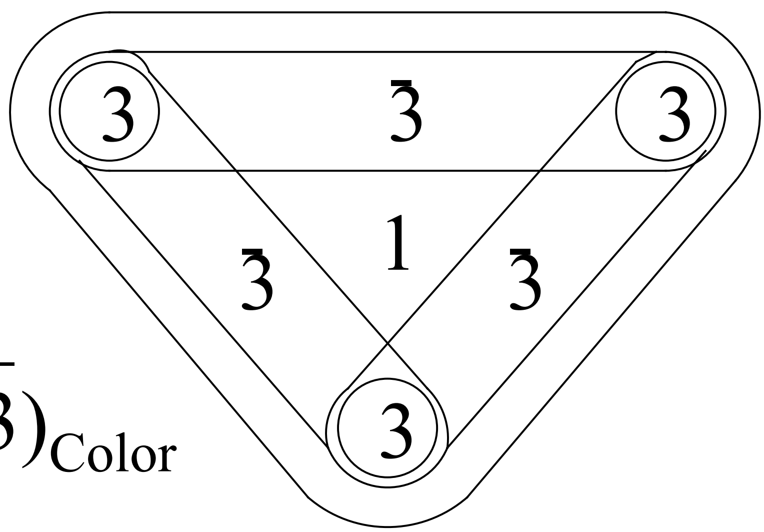
$SU(3)_{Color}$

$3 \Leftrightarrow$ RGB, $\quad \bar{3} \Leftrightarrow$ CMY

$\bar{q}q \Rightarrow$

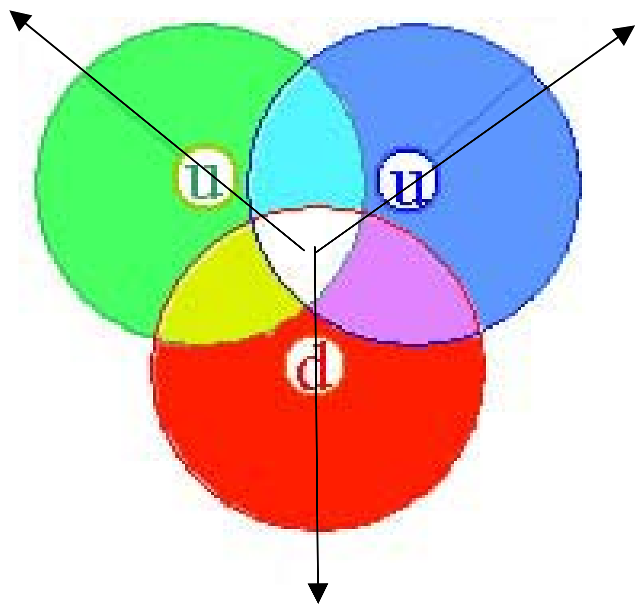


$qqq \Rightarrow$



$\bar{q} \Rightarrow qq \quad (\bar{3})_{Color}$

The Proton



One–Quark color wave function

$$\psi(x)_{Color} = \sum_{i=1}^{3} a_i(x)\left|c_i\right\rangle$$

Where $\left|c_i\right\rangle$ are orthonormal states with i = R,G,B

$$\left\langle c_i \middle| c_j \right\rangle = \delta_{ij}$$

Nucleon color wave function

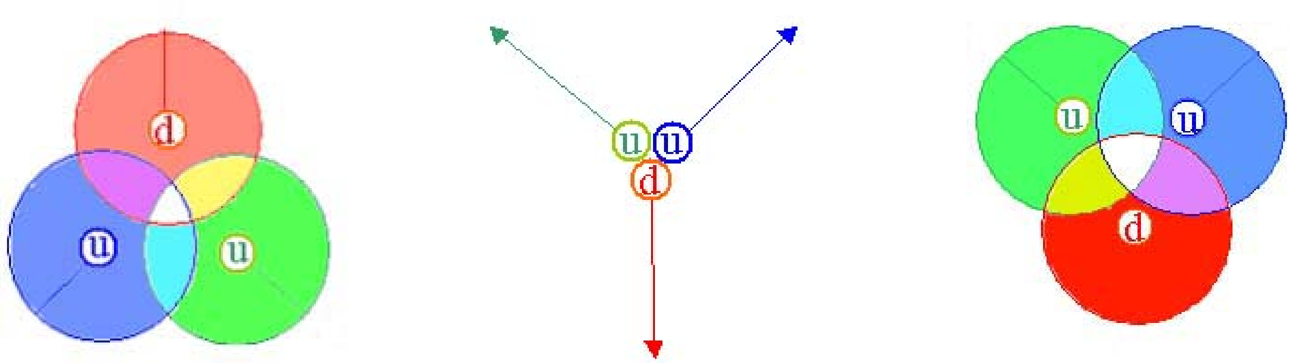
$$\psi(x) \rightarrow \frac{1}{\sqrt{6}} \sum_{ijk} e_{ijk} \left|c_i\right\rangle \left|c_j\right\rangle \left|c_k\right\rangle$$

Chiral Symmetry Breaking and its Restoration

t = 0
$x = x_{max}$

t = T/4
$x = 0$

t = T/2
$x = x_{max}$



Consituent Quarks

Current Quarks
Asymptotic Freedom

Consituent Quarks

During the valence quarks oscillations:

$$|B\rangle = c_1|q_1q_2q_3\rangle + c_1|q_1q_2q_3\bar{q}q\rangle + c_1|q_1q_2q_3g\rangle + \ldots$$

Local gauge invariance in SCQM

Considering each quark separately

$$SU(3)_{Color} \Longrightarrow U(1)$$

During valence quarks oscillation destructive interference of their color fields leads to the phase rotation of each quark w.f. in color space:

$$\psi(x)_{Color} \rightarrow e^{ig\theta(x)}\psi(x)_{Color}$$

Phase rotation in color space ➡ dressing (undressing) of the quark ≡ the gauge transformation ≡ chiral symmetry breaking (restoration)

$$A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu \theta(x);$$

here

$$A_\mu = (\varphi, 0, 0, 0)$$

Spin in SCQM

1. Now we accept that

$$A_\mu = \{\varphi, \mathbf{A}\}$$

and intersecting $\mathbf{E_{ch}}$ and $\mathbf{B_{ch}}$ create around VQ circulating flow of energy, color analog of the Pointing's vector

$$\mathbf{S_{ch}} = c^2\mathbf{E_{ch}} \times \mathbf{B_{ch}} \, .$$

Classical analog of electron spin

– F.Belinfante 1939; R. Feynman 1964; H.Ohanian 1986; J. Higbie 1988.

2. Circulating flow of energy carrying along with it hadronic matter is associated with hadronic matter current.

3. Total angular momentum created by this Pointing's vector

$$\mathbf{s_Q} = \mathbf{L_g} = (\ldots)\int_a^\infty d^3r\left[\mathbf{r} \times (\mathbf{E_{ch}} \times \mathbf{B_{ch}})\right]$$

is associated with the total spin angular momentum of the constituent quark.

4. Quark oscillations lead to changing of the values of **E_{ch}** and **B_{ch} :** at the origin of oscillations they are concentrated in a small space region around VQ. As a result hadronic current is concentrated on a narrow shell with small radius.

5. Quark spins are perpendicular to the plane of oscillation.

6. Analogue from hydrodynamics:

Helmholtz laws for velocity field

$$((\partial \xi)/(\partial t)) + \Box \times (\xi \times \mathbf{v}) = 0,$$

$$\xi = \Box \times \mathbf{v},$$

$$\Box\,\Box\,\mathbf{v} = 0,$$

lead to

$$\cdot \quad = \oint_{\sigma} \mathbf{v} \cdot d\mathbf{r} = \mathrm{s} = \mathrm{const}.$$

$$\boxed{\mathrm{v} \propto 1/r}$$

The velocity field of the hadronic matter around the valence quarks is irrotational.

Parameters of SCQM

1.Mass of Consituent Quark

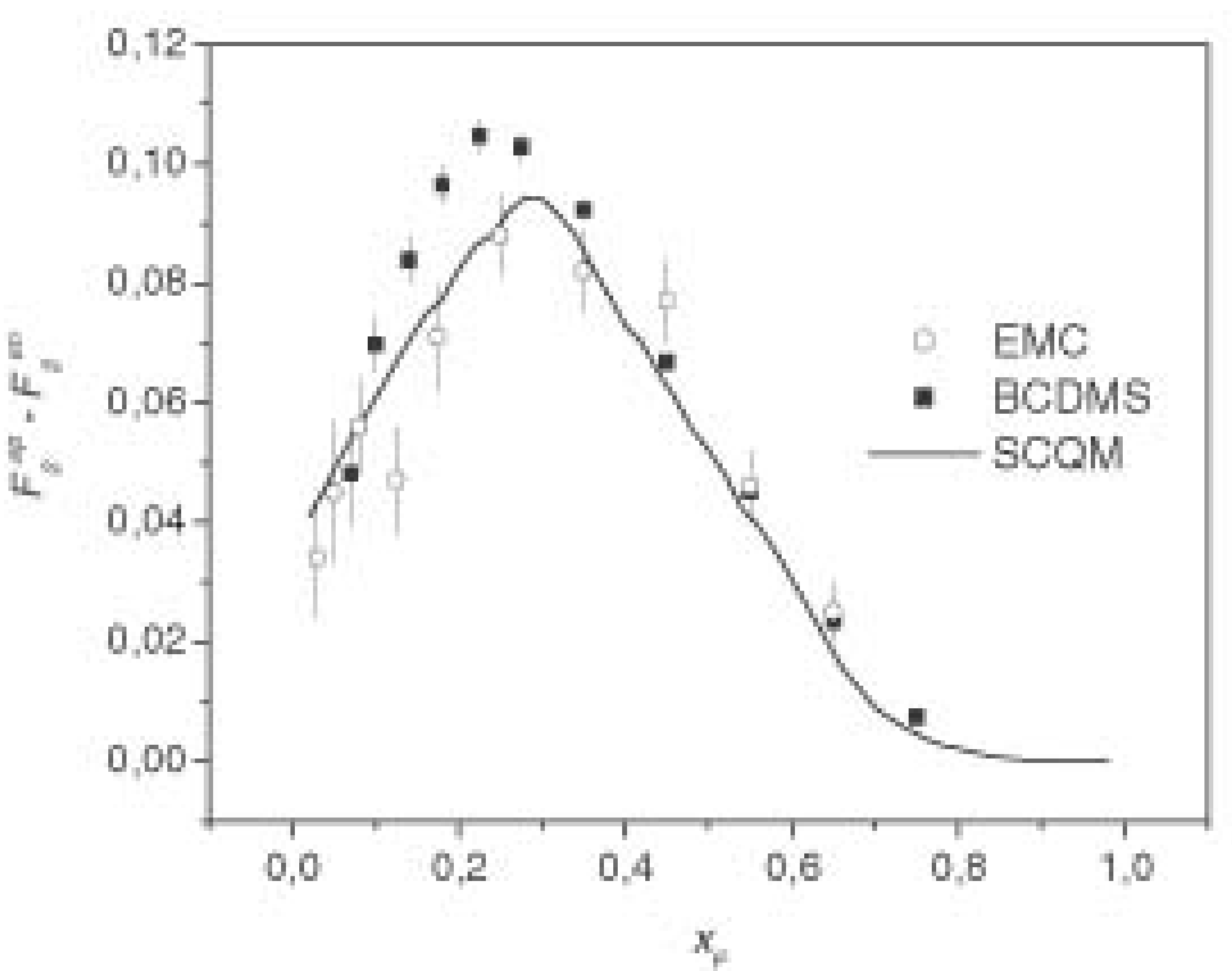
$$M_{Q(\overline{Q})}(x_{\max}) = \frac{1}{3}\left(\frac{m_\Delta + m_N}{2}\right) \approx 360 MeV,$$

2.Maximal Displacement of Quarks: ***x_{max}=0.64 fm,***

3.Constituent quark sizes (parameters of gaussian distribution): ***$\sigma_{x,y}$=0.24 fm, σ_z =0.12 fm***

Parameters 2 and 3 are derived from the calculations of Inelastic Overlap Function (IOF) and σ_{in} in $\bar{p}\,p$ and *pp* – collisions.

Structure Function of Valence Quarks in Proton



Summary on SCQM

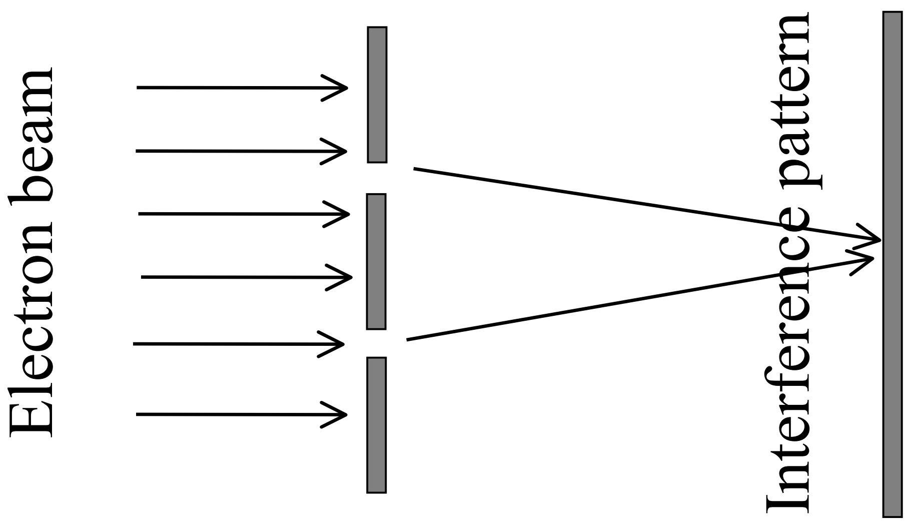
- Quarks and gluons inside hadrons are strongly correlated;
- Valence quarks do not orbit inside nucleons
- Constituent quarks are identical to vortical solitons.
- Hadronic matter distribution inside hadrons is fluctuating quantity resulting in interplay between constituent and current quarks.
- **Hadronic matter distribution inside the nucleon is deformed; it is oblate in relation to the spin direction.**

What is "Spin crisis"

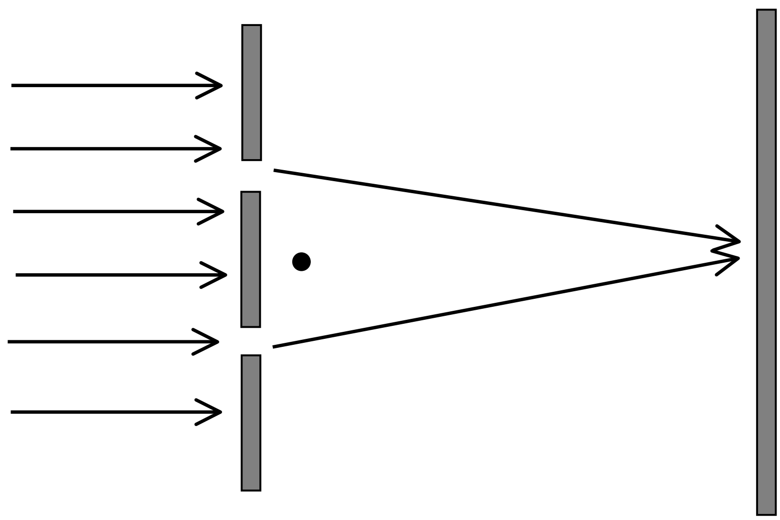
- Quark-vortex is singularity (hole) in vacuum that means nonsimple-connectedness of vacuum structure.
- In DIS the transverse size of virtual photon emitted by incident lepton is given by d^2 □ $1/Q^2$.
- $s_q = \oint_\sigma \mathbf{v} \cdot d\mathbf{r}\,, \qquad v \propto \frac{1}{r}$
- If the wavelength of the virtual photon in DIS is large enough to cover the center of the vortex then the circulation integral is nonzero and equal to $s_q = 1/2$; otherwise $s_q = 0$.

Aaronov-Bohm effect

Double-slit experiment



Double-slit experiment with thin solenoid



Dirac phase $$\varphi_{\mathrm{D}} = \frac{e}{\hbar c} \int \mathscr{A}^{\alpha}\, \mathrm{d}r_{\alpha}.$$

is dependent on the transport path. Phase transfer along the closed contour is determined by the field flux Φ though this contour:

$$\varphi_{\mathrm{D}} = \frac{e}{\hbar c} \oint \mathscr{A}\, \mathrm{d}\mathbf{r} = \frac{e}{\hbar c} \int \mathscr{B}\, \mathrm{d}\mathbf{s} = \frac{e}{\hbar c} \Phi.$$

According to SCQM

- In DIS

$Q^2 \longrightarrow 0 \quad s_q \longrightarrow 1/2$

$Q^2 \longrightarrow \infty \quad s_q \longrightarrow 0$

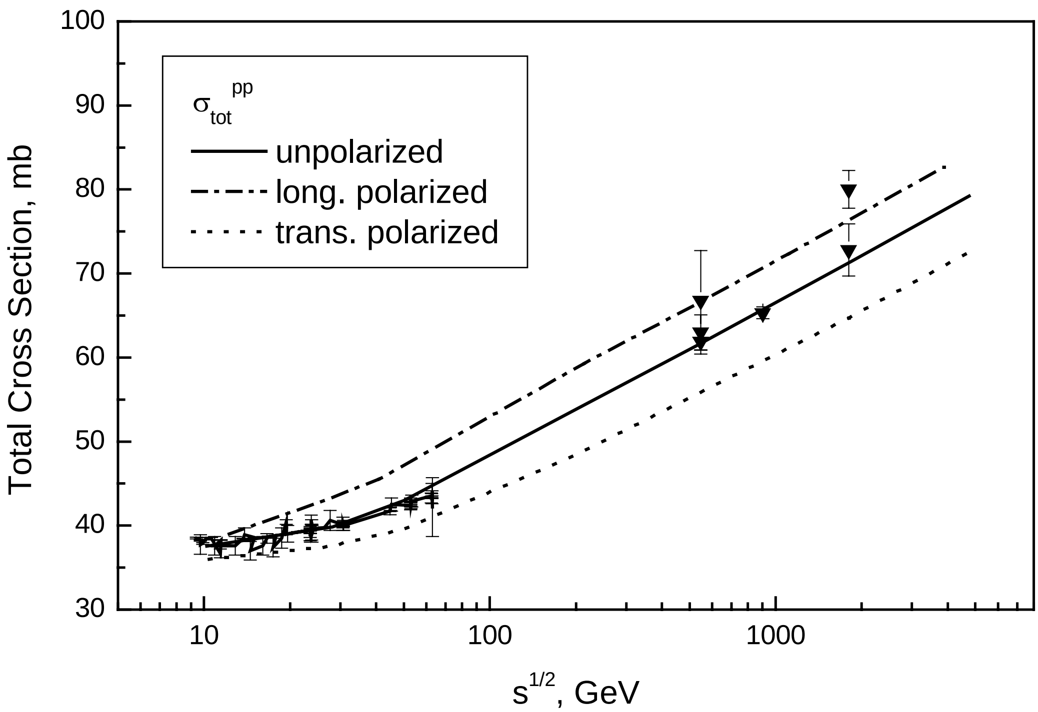
Our calculations

At $Q^2 = 3(\mathrm{GeV}/c)^2 \quad \Delta\Sigma = 0.18$

Spin Effect in Soft process

Proposal for forward elastic pp-scattering on RHIC

$$\sigma_T^{tot} < \sigma_L^{tot}$$



Single Spin Asymmetry in proton – proton collisions

$$p^{\uparrow} + p \rightarrow \pi^{\pm,0} + X$$

- In the factorized parton model

$$\sigma_{\pi/p} \approx f_q \otimes \sigma_{q \rightarrow q'} \otimes D_{\pi/q'}$$

$$\frac{d\sigma_{\uparrow}}{d^3\bar{p}} = \int dx \cdot d^2k_{\perp} f_{q/p}(x, \bar{k}_{\perp}) \int dy \cdot f_{r/p}(y) \times$$

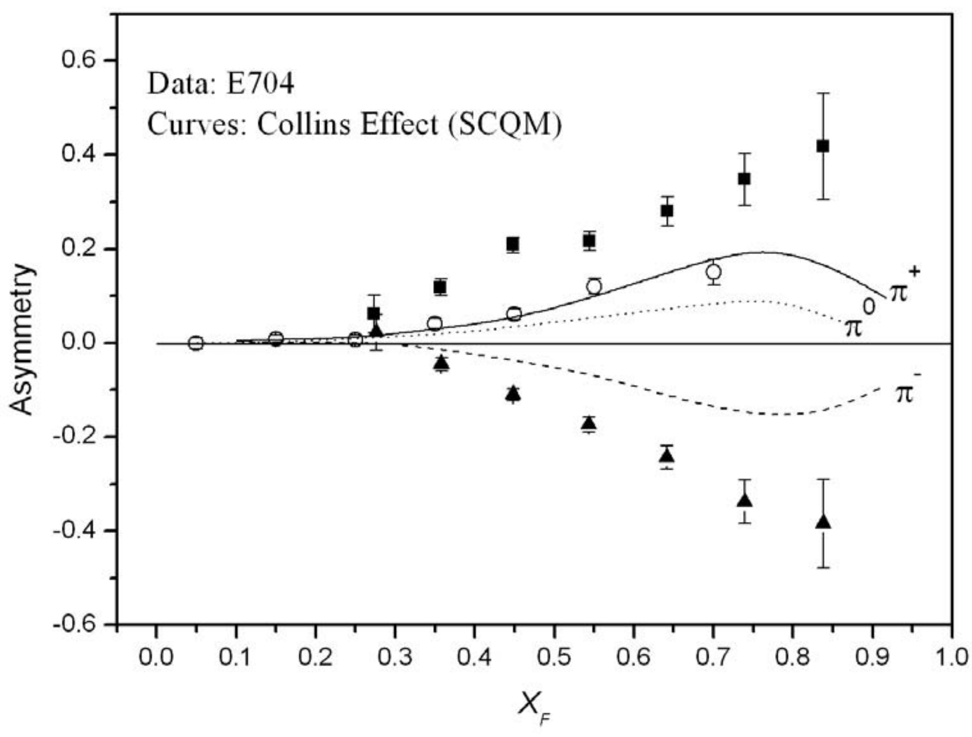
$$\int d\cos\theta \cdot d\varphi \frac{d\sigma(\bar{P}_q, \theta, \varphi)}{d\Omega} \times$$

$$\int dz \cdot d^2\bar{h}_{\perp} D_{h/q'}(\bar{P}_{q'}, z, \bar{h}_{\perp}) \cdot \delta^3(\bar{p} - zk' - \bar{h}_{\perp})$$

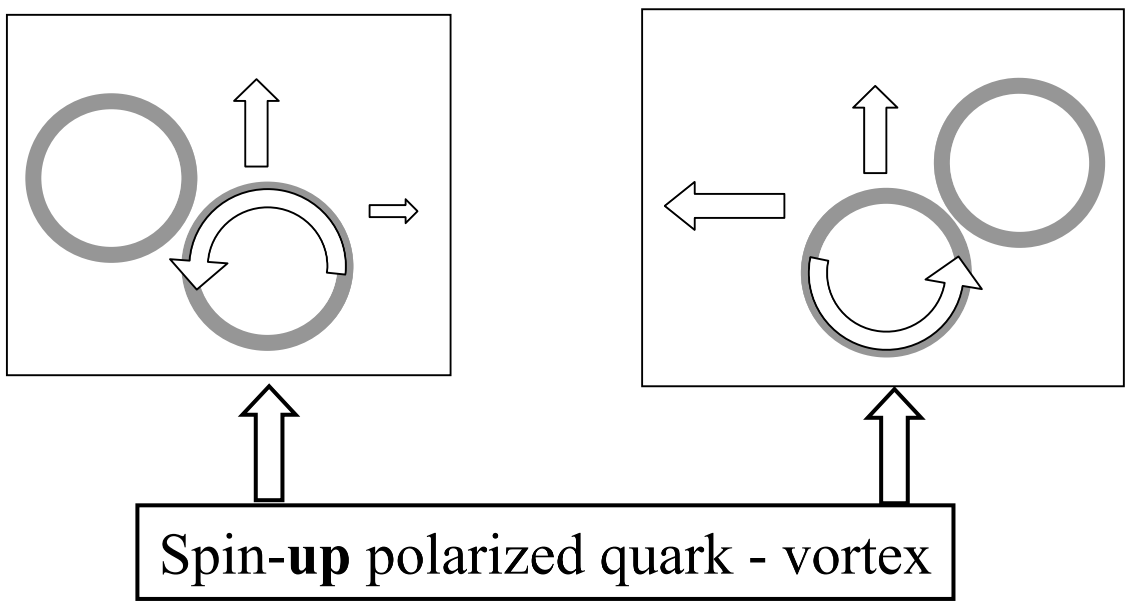
where

$$\vec{P}_q = \frac{\Delta_{\perp} f_{q\uparrow/p\uparrow}}{f_{q/p}} = \frac{f_{q\uparrow/p\uparrow} - f_{q\downarrow/p\uparrow}}{f_{q/p}}$$

Collins Effect in SSA



Orbital Angular Momentum in SSA



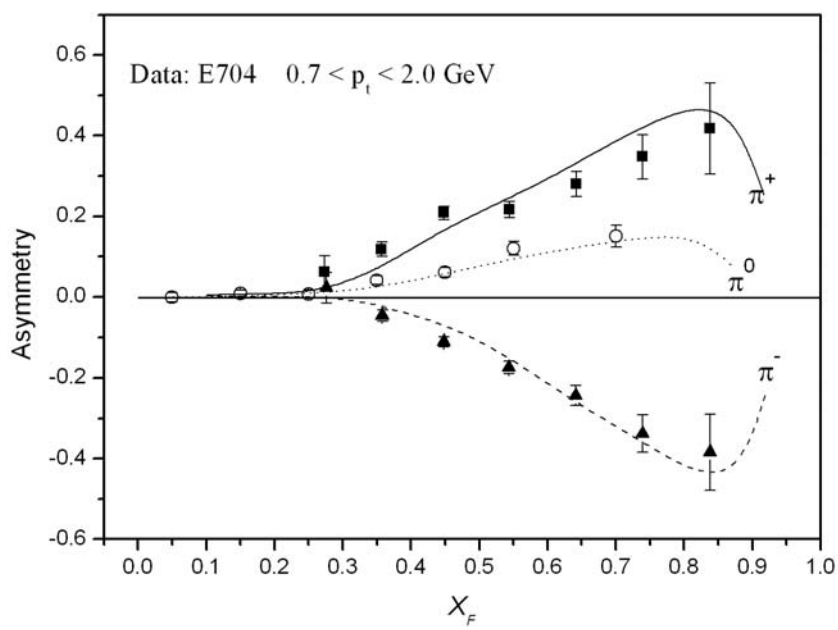
Chou & Yang 1976

Hadronic matter current distributions inside polarized hadrons and nuclei

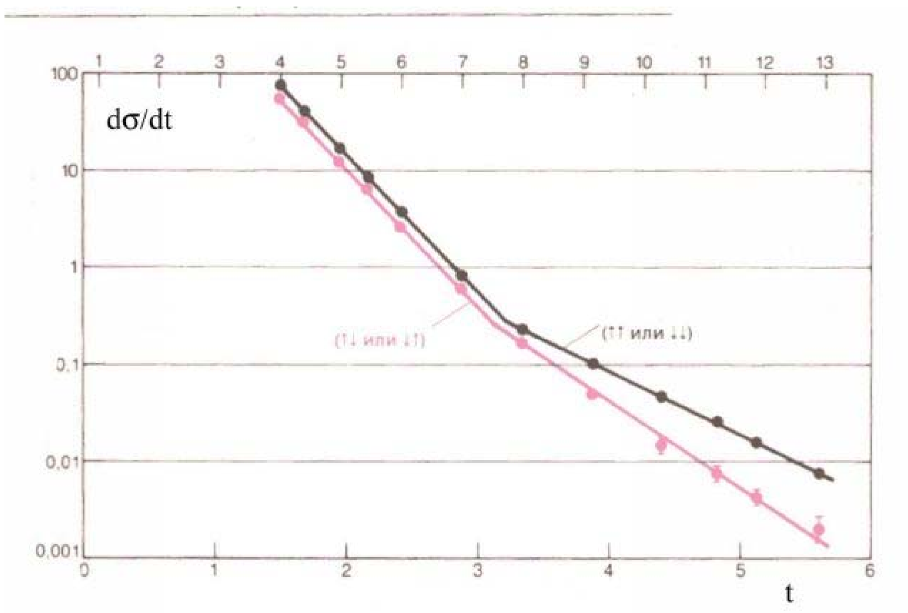
$$Opaqueness \propto P_{eff}^{\alpha}\,\rho(b_x, b_y, b_z)$$

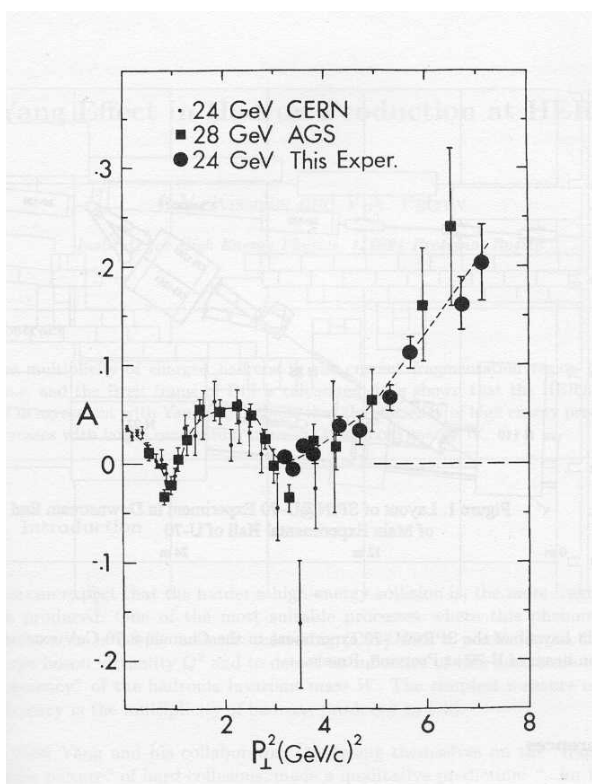
$$P_{eff}^{\alpha} \cong P_{in}^{\alpha}(1-\alpha v_z)$$

Collins & Orbital Angular Momentum in SSA



Experiments with Polarized Protons





Visualization of Hadron Structure and Scattering Processes

- Pion
- rho – meson
- Nucleon
- Soft scattering of polarized protons (proposal for RHIC)
- Role of the orbital angular momentum of chiral (quark-antiquark and gluon) condensate in SSA and Double Spin Asymmetry.