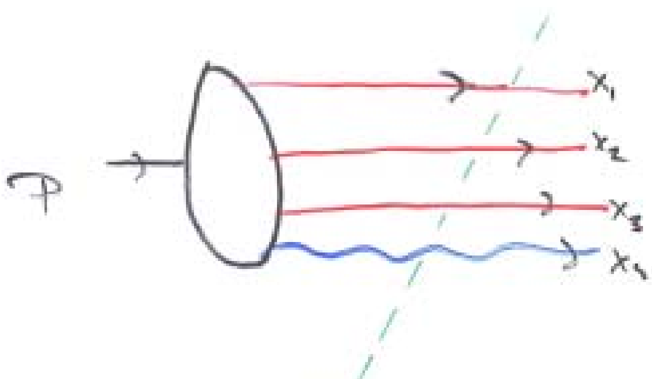
New QCD Phenomena and QCD Light-Front Wavefunctions

S. Brodsky

SLAC

Light-Cone 2002 LANL

August 4, 2002



$\Psi_{qqqg/p}(x_i, \vec{k}_{\perp i}, \lambda_i)$

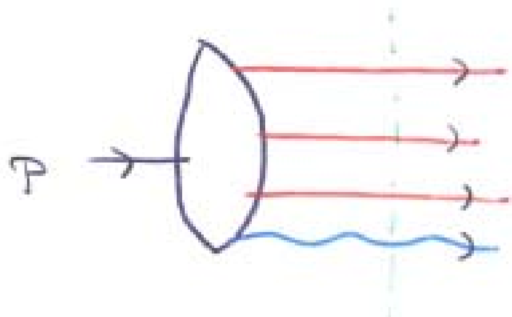
$\tau = t + z/c$

$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{p^0 + p^z}$, $\Sigma x_i = 1.$

Light-Cone Wavefunctions and QCD Phenomena

Non-Perturbative QCD

$\{\psi_n\}$: translation: hadrons $\Rightarrow$ q, g



$x_1, \vec{k}_{\perp 1}, \lambda_1$

$$x_i = \frac{k_i^+}{P^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

fixed $\tau = t + z/c$ Dirac

$$|\Psi\rangle = \sum_n |n\rangle \, \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

free q, g basis

$$\sum_{i=1}^{n} x_i = 1 \, , \quad \sum_{i=1}^{n} \vec{k}_{\perp i} = 0$$

"Light-cone Fock expansion"

boost invariant Frame-indep.

$*$ Given $\{\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\}$

wavefunction known for <u>all</u> P^μ !

relative coordinates

$$|P^+, \vec{P}_\perp\rangle = \sum_n \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \prod_j \frac{1}{\sqrt{x_j}}$$

$$|x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i\rangle$$

absolute coordinates

In equal-time theory (instant form)

boost's mix with interactions

changing $\vec{P} \to \vec{P}'$ as complicated

as solving $H|\Psi\rangle = E|\Psi\rangle$

L.C. wfns — rest frame, $P \to \infty$, Frame-independent!

Dirac
Bjorken, Kogut, Soper
Lepage + SJB
Pauli + SJB

$$\tau = t + z/c$$

Equation of motion

$$i\frac{\partial}{\partial\tau}|\Psi_H\rangle = P^-|\Psi_H\rangle = \frac{M_H^2 + \vec{P}_\perp^2}{P^+}|\Psi_H\rangle$$

$$H_{LC} = P^- P^+ - P_\perp^2 \qquad P^+,\ P_\perp$$

kinematical

$$\boxed{H_{LC}|\Psi_H\rangle = M_H^2|\Psi_H\rangle}$$

⇒ eigenvalue problem for LC Hamiltonian

Insert complete set of H^0_{LC} color-singlet eigenstate

$$\sum_n |n\rangle\langle n| = I$$

$$\sum_n \langle m|H_{LC}|n\rangle\langle n|\Psi_H\rangle = M_H^2\langle m|\Psi_H\rangle$$

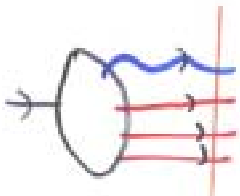
DLCQ

⇒ Heisenberg matrix form of eigenvalue problem

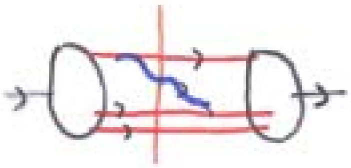
$$|\Psi_H\rangle = \sum_n |n\rangle\langle n|\Psi_H\rangle = \sum_n |n\rangle\,\psi_{n/H}(x_i, \vec{k}_{\perp i}, \lambda$$

⇒ LC Fock expansion of eigenstate $|\Psi_H\rangle$

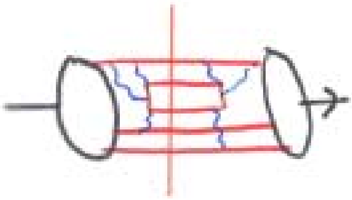
Hadrons: complex relativistic systems



fluctuations in particle no., size, spin, color

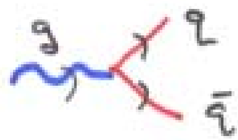


gluons intrinsic to hadron structure

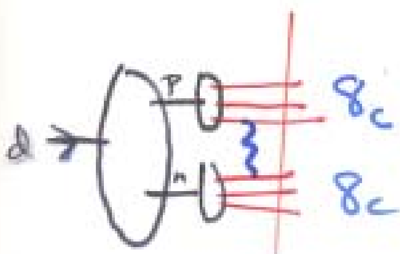


$$\left\{ \begin{array}{l} \bar{u}(x) \neq \bar{d}(x) \Rightarrow \text{correlations} \\ \\ s(x) \neq \bar{s}(x) \ ? \end{array} \right.$$

∴ sea not from $\overset{\text{PQCD}}{\text{gluon}}$ splitting



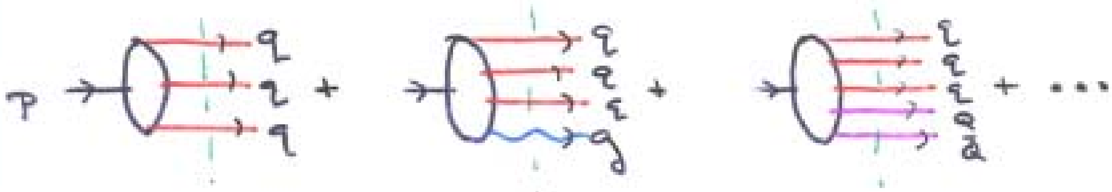
$q(x) = \bar{q}(x)$
$\bar{u}(x) = \bar{d}(x)$



"Hidden color" in nuclei

$$\Psi_d \neq \Psi_n \otimes \Psi_p$$

Light-Cone Fock Representation of Hadrons



$$|p\rangle = \sum_n |n\rangle \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum x_i = 1$, $\sum \vec{k}_{\perp i} = 0$

- Explicit solutions using "DLCQ" — QCD(1+1), "collinear" QCD
  SJB, Pauli, Hornbostel
  Antonuccio, Dalley

- Calculate structure functions modulo FSI — $q(x)$, $g(x)$, $Q(x)$
  Spin-dependence

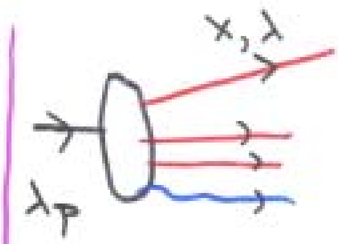
- Calculate Regge behavior using "ladder relations" — $x \to 0$, BFKL
  Spin-dependence
  Mueller, SJB, Antonuccio, Dalley

- $x \to 1$ constraints — Lepage, SJB, Burkardt, Schm

- Properties of heavy quark sea — $s(x) \neq \bar{s}(x)$
  extrinsic vs intrinsic
  physics of $\Delta\Sigma$, anomaly
  Pauli
  Kogan, Ma, Schmidt, SJB, Schlumpf

Light-Cone Wavefunctions

encode all helicity, transversity distributions

$$q_{\lambda/\lambda_p} = \sum_f \Bigg|$$  $$\Bigg|^2$$

$q_{\lambda/\lambda_p}(x, \Lambda)$ $\Bigg\{$ transversity: density matrix; light-cone helicity

$$= \sum_{n,q} \int \left| \psi^{(\Lambda)}_{n,\lambda_p}(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2 \prod_{j=1} dx_j \prod_{j=1} d^2 k_{\perp j}$$

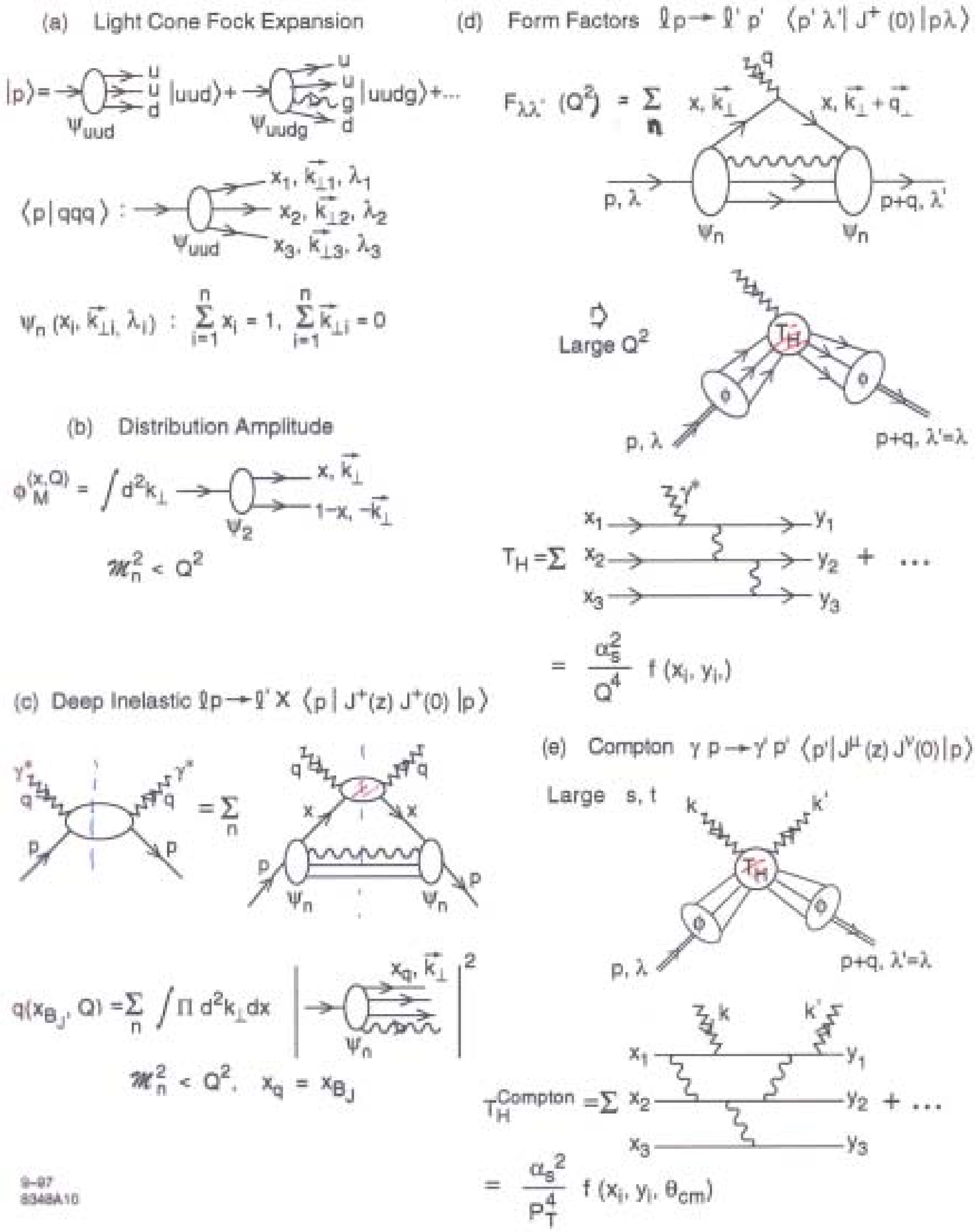
$$\delta\Big(\sum_i x_i - 1\Big)\, \delta\Big(\sum_i \vec{k}_{\perp i}\Big)$$

$$\delta(x - x_q)\, \delta_{\lambda, \lambda_q}$$

Factorization

Light-cone Scheme

$$\Theta(\Lambda^2 - \mathcal{M}_n^2)$$


(a) Light Cone Fock Expansion
|p⟩ = Ψuud |uud⟩ + Ψuudg |uudg⟩ + ...
⟨p|qqq⟩ : Ψuud x1, k⊥1, λ1 x2, k⊥2, λ2 x3, k⊥3, λ3
ψn (xi, k⊥i, λi) : Σ xi = 1, Σ k⊥i = 0
(b) Distribution Amplitude
φM(x,Q) = ∫ d2k⊥ Ψ2 x, k⊥ 1−x, −k⊥
Mn2 < Q2
(c) Deep Inelastic ℓp → ℓ' X ⟨p | J+(z) J+(0) |p⟩
γ* q p = Σn x ψn
q(xBj, Q) = Σn ∫ Π d2k⊥dx xq, k⊥ ψn
Mn2 < Q2, xq = xBj
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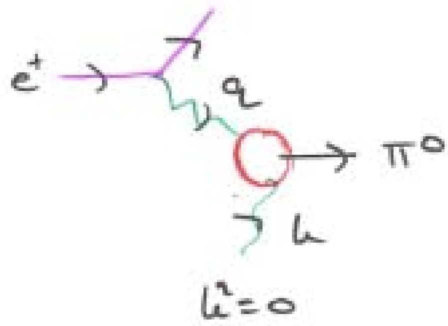
(d) Form Factors ℓp → ℓ' p' ⟨p' λ'| J+ (0) |pλ⟩
Fλλ' (Q2) = Σn x, k⊥ x, k⊥ + q⊥ p, λ p+q, λ' ψn ψn
Large Q2
TH φ p, λ p+q, λ'=λ
TH = Σ x1 x2 x3 y1 y2 y3 + ...
= αs2/Q4 f (xi, yi)
(e) Compton γ p → γ' p' ⟨p'| Jμ (z) Jν(0)|p⟩
Large s, t
k k' TH φ p, λ p+q, λ'=λ
THCompton = Σ x1 x2 x3 y1 y2 y3 + ...
= αs2/PT4 f (xi, yi, θcm)

$\gamma^*\gamma \to \pi^0, \eta, \eta', \eta_c \cdots$

Simplest example of exclusive process

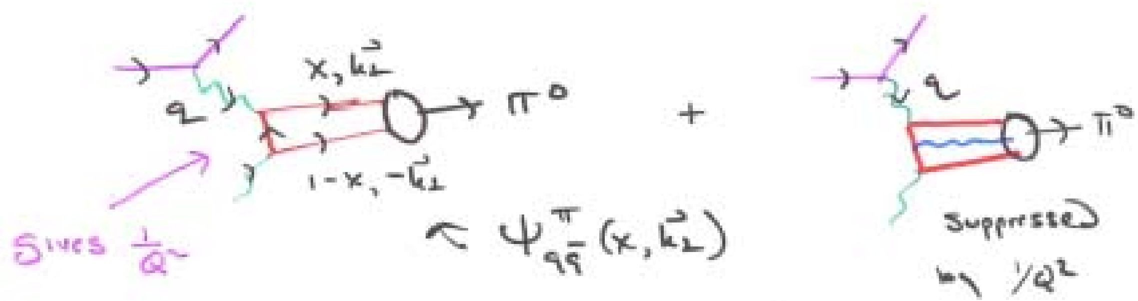


$F_{\gamma\pi^0}(q^2)$

$\pi^0 \to \gamma\gamma$ at $q^2=0$.

Lepage SJB

For $Q^2 \gg \Lambda^2_{QCD}$ analyse in PQCD

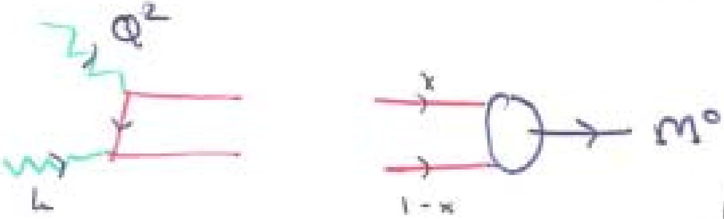


$$\star \quad F_{\gamma\pi^0}(Q^2) = \frac{1}{Q^2}\, 2\sqrt{n_c}\,(e_u^2 - e_d^2) \int_0^1 dx \left(\frac{1}{x} + \frac{1}{1-x}\right) \phi_\pi(x,Q)$$

$$\star \quad \phi_\pi(x,Q) = \int^{Q} \frac{d^2k_\perp}{16\pi^3}\, \psi_{q\bar{q}}(x, \vec{k}_\perp)$$

pion distribution amplitude

PQCD : $\boxed{F_{\gamma \to M^0}(Q^2) \sim \frac{1}{Q^2}\int_0^1 \frac{dx}{1-x}\, \phi_M(x, \tilde{Q})}$



T_H

$$\phi_M(x,Q) = \int^{k_\perp^2 < \tilde{Q}^2} d^2k_\perp\, \psi_{q\bar{q}}(x, k_\perp)$$

* $T_H(\gamma^* \gamma \to \underbrace{q\bar{q}}_{\text{collinear}}) \sim \frac{1}{Q^2(1-x)}$

$\mathcal{O}(Q)$

* Higher Fock states : $\frac{1}{Q^4}$

Other diagrams $\mathcal{O}(\alpha_s(Q^2))$!

* $\phi_M(x,Q) = \sum_{n=0}^{\infty} a_n P_n(x) \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n}$

log evolution

* $\lambda_M = \lambda_q + \lambda_{\bar{q}} = 0.$ HHC

test in ρ^0

** Small part of Fock state dominates

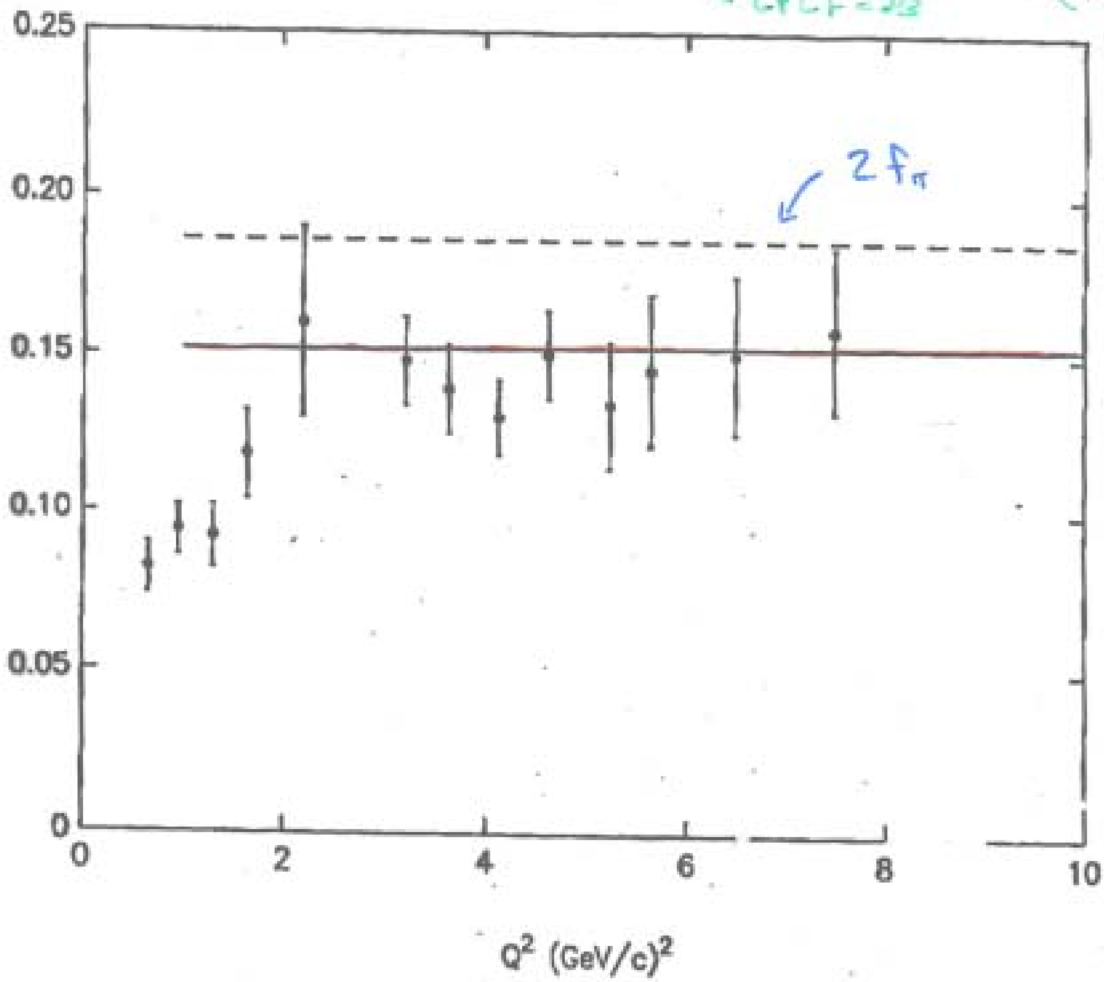
$$\phi_M \sim \psi(x, b_\perp \sim \tfrac{1}{Q})$$

$$* \quad \phi = \phi_{asympt} = \sqrt{3}\, x(1-x)\, f_\pi$$

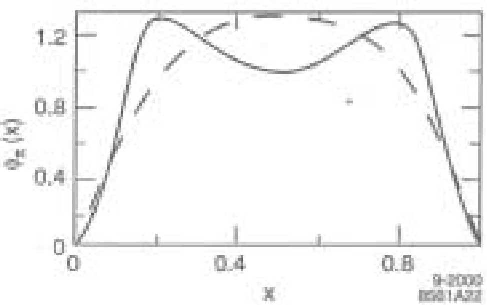
$$Q^2 F_{\pi\gamma}(Q^2) = 2 f_\pi \left[1 - \frac{5}{3\pi} \alpha_V (e^{-3} Q^2) \right]$$

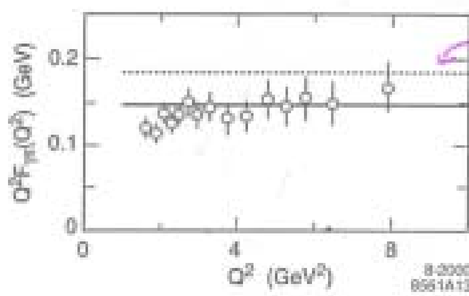
← GPLH=2B

← [illegible]



CLEO (Savinov et al)





asympt

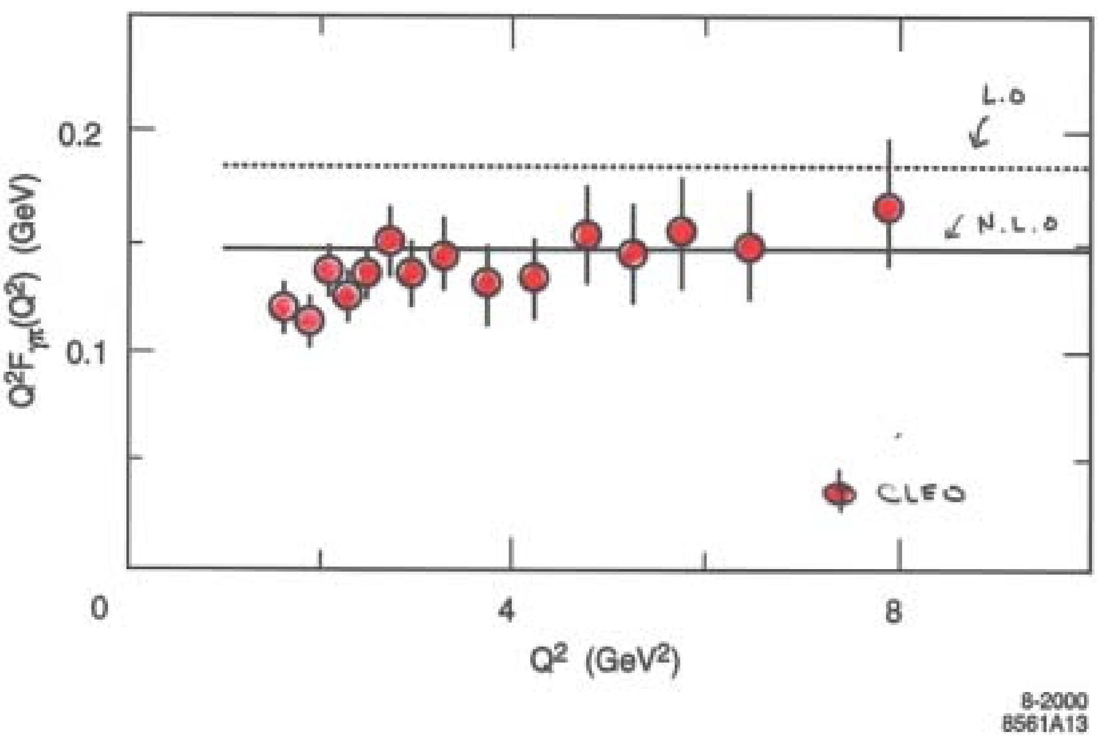
NLO

— transverse lattice / DLCQ

Dalley

- - - Asymptotic dist. ampl.

Burkardt



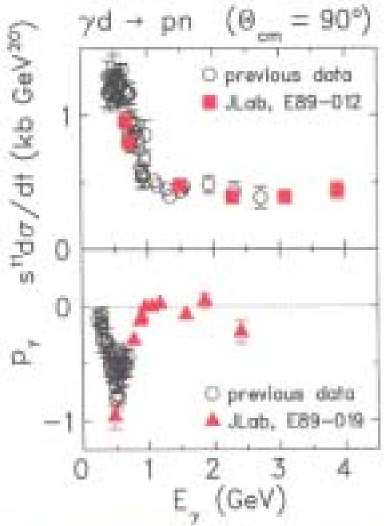
assumes $\phi_\pi(x) = \phi_{asympt}(x)$

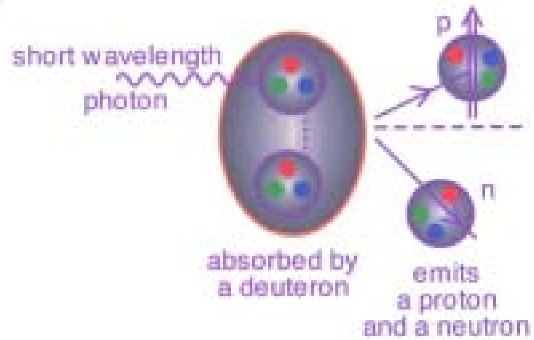
$= \sqrt{3} f_\pi \, x(1-x)$

SHORT-DISTANCE STRUCTURE of the DEUTERON

Jefferson Lab (E89 - 012, E89 - 019)

Do we see the effects of quarks and gluons in a nuclear reaction ?





- **Reaction probability is consistent with quark counting rules at high photon energy.**
- **Polarization vanishes at same photon energy that reaction probability begins scaling.**
- **First glimpse of the transition region.**

High Energy Photodisintegration of the Deuteron

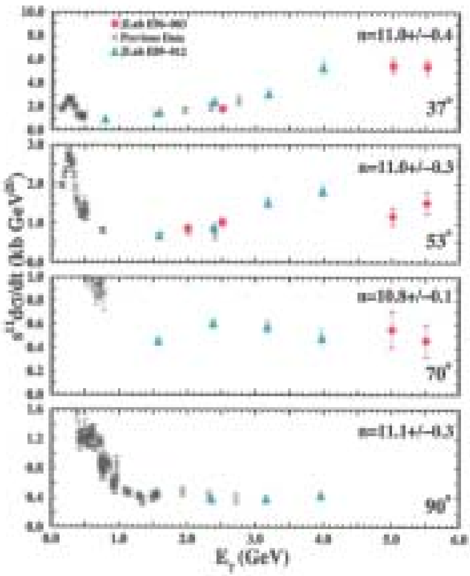
Jefferson Lab (E96 - 003)

> Is there a threshold for scaling for the $\gamma d \rightarrow pn$ reaction ?

Quark counting rules $\Rightarrow \frac{d\sigma}{dt} \sim \frac{1}{s^{11}}$

- Evidence for scaling observed for the first time at forward angles ($\theta_{c.m.}$= 37°, 53°).

- A scaling threshold in transverse momentum of P_T= 1.3 ± 0.1 GeV/c is consistent with all existing data.



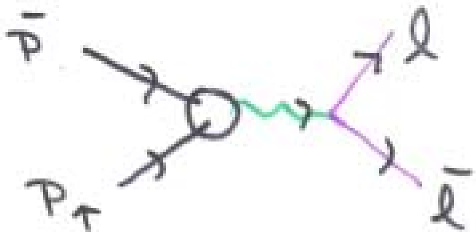
E.C. Schulte et al., Phys. Rev. Lett. 87, 102302 (2001)

Christ, Wille, Ji, SJB
Lepage

* New results for $ep_\uparrow \to ep_\uparrow$ from JLAB

$$\frac{G_E(t)}{G_M(t)} \text{ decreasing} \Rightarrow \sqrt{-t}\,\frac{F_2(t)}{F_1(t)} \sim \text{const}$$

Need higher t, timelike $p\bar{p} \to \ell\bar{\ell}$, $\ell\bar{\ell} \to p\bar{p}$
data!



measure pol. of final-state μ
?

$$\frac{d\sigma}{d\Omega} \propto |G_M(s)|^2(1+\cos^2\theta_{cm}) + \frac{4m^2}{s}|G_E(s)|^2\sin^2\theta$$

SSA $$P_y = \frac{-\sin 2\theta_{cm}\ \mathrm{Im}\, G_E^* G_M \frac{2M}{\sqrt{s}}}{|G_M|^2(1+\cos^2\theta) + \frac{4m^2}{s}|G_E|^2\sin^2\theta}$$

Pol transfer
$$P_x = P_\ell\,\frac{2\sin\theta_{cm}\ \mathrm{Re}\, G_E^* G_M \frac{2M}{\sqrt{s}}}{|G_M|^2(1+\cos^2\theta) + \frac{4m^2}{s}|G_E|^2\sin^2\theta}$$

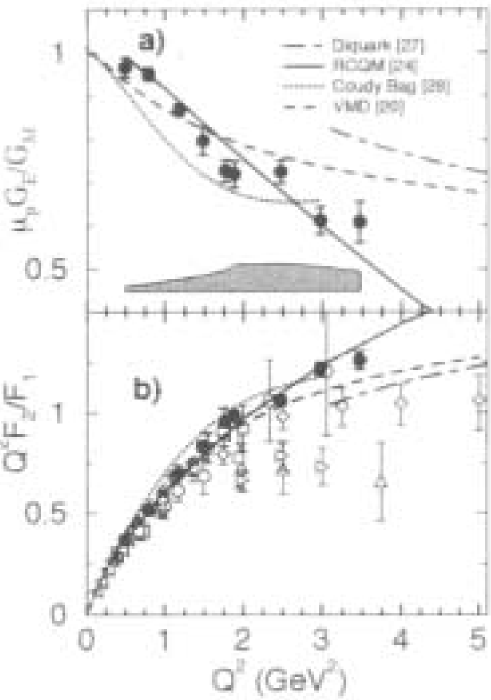
does G_E change sign?

does $\frac{d\sigma}{d\Omega} \sim (1+\cos^2\theta)$ PQCD HHC.

JLab uses polarization transfer to recoil proton

$$\frac{P_x}{P_y} = \frac{G_E}{G_M}\,\frac{2M}{(E+E')\tan\frac{\theta}{2}}$$

$\ell^\mu \langle P', \lambda' | J_\mu | P, \lambda \rangle \propto G_E, G_M$



Jefferson Lab

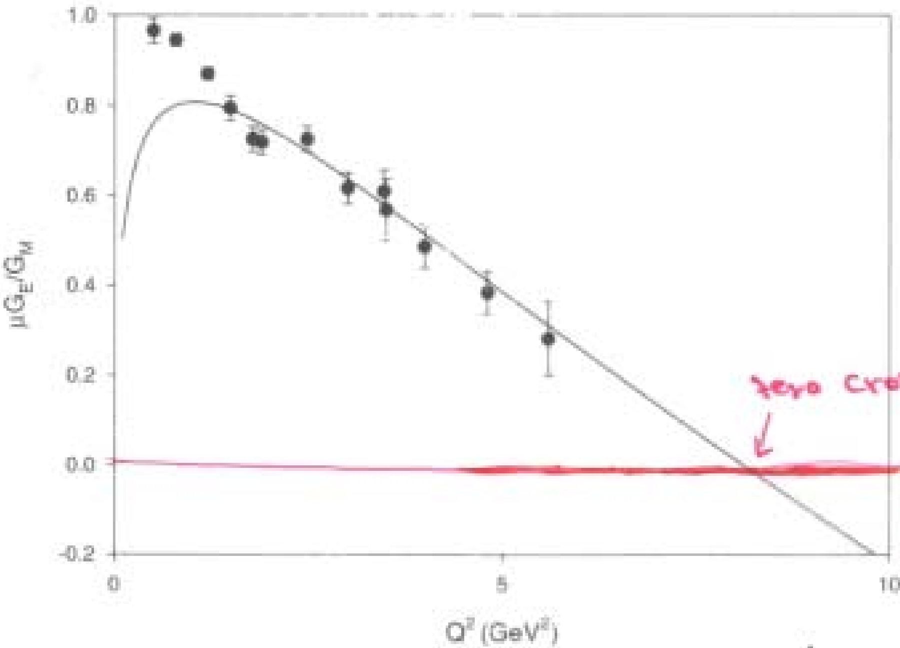
PQCD $\quad \frac{F_2}{F_1} \sim \frac{1}{Q^2}$

diquark model?

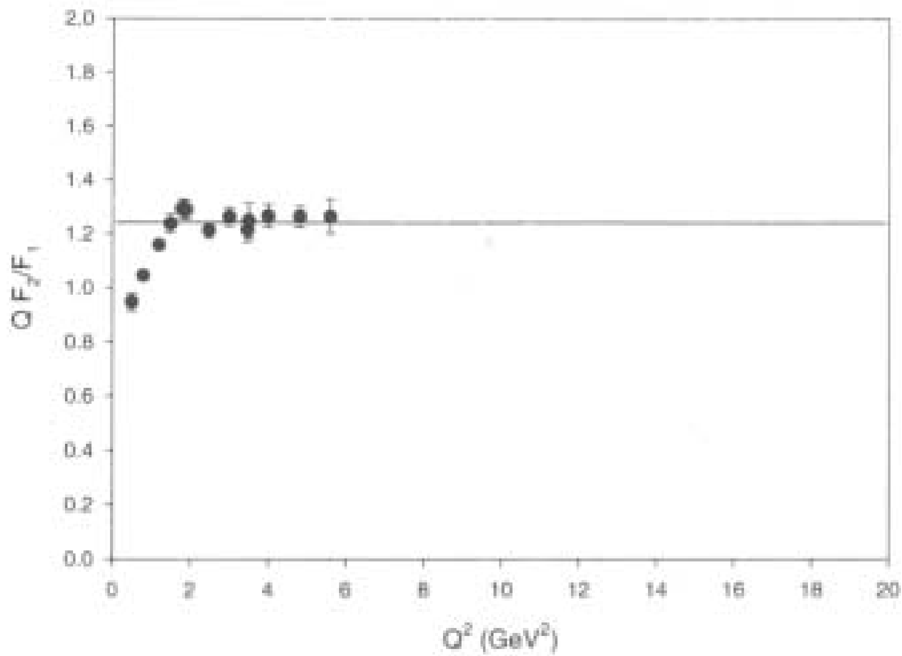
$F_2/F_1 = 0.66/\mathrm{sqrt}[\tau]$

$\tau = Q^2/4m^2$

J. Miller



Not negative value



See Miller & Frank

J. Miller
D.S. Hwang
SJB

$\boxed{\text{PQCD - motivated fit to JLab data}}$

$$\boxed{\frac{F_2(Q^2)}{F_1(Q^2)} = \frac{\mu_A}{1 + \frac{Q^2}{.96\,\mathrm{GeV}^2} \log^b\left(1 + \frac{Q^2}{4 m_\pi^2}\right)}}$$

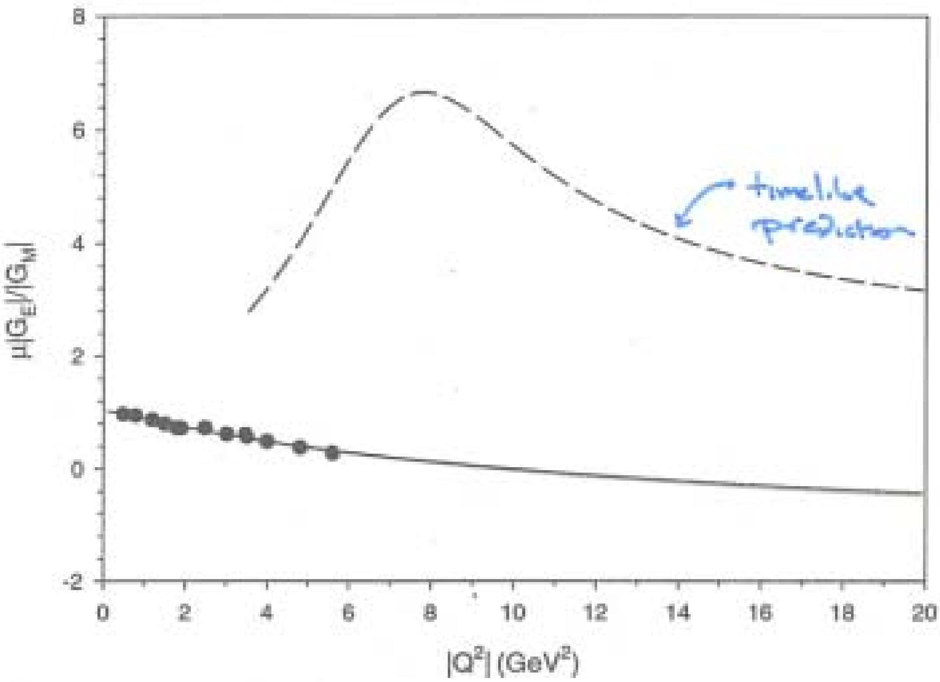
$\mu_A = 1.79$ $\qquad\qquad$ $Q^2 = -q^2 = -t$

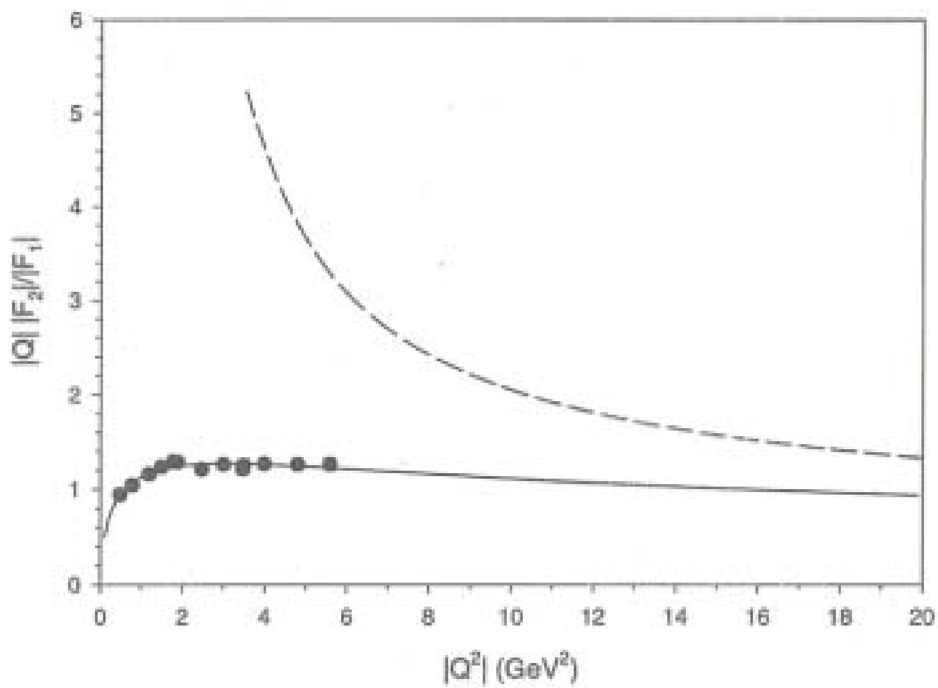
$b = -0.6$

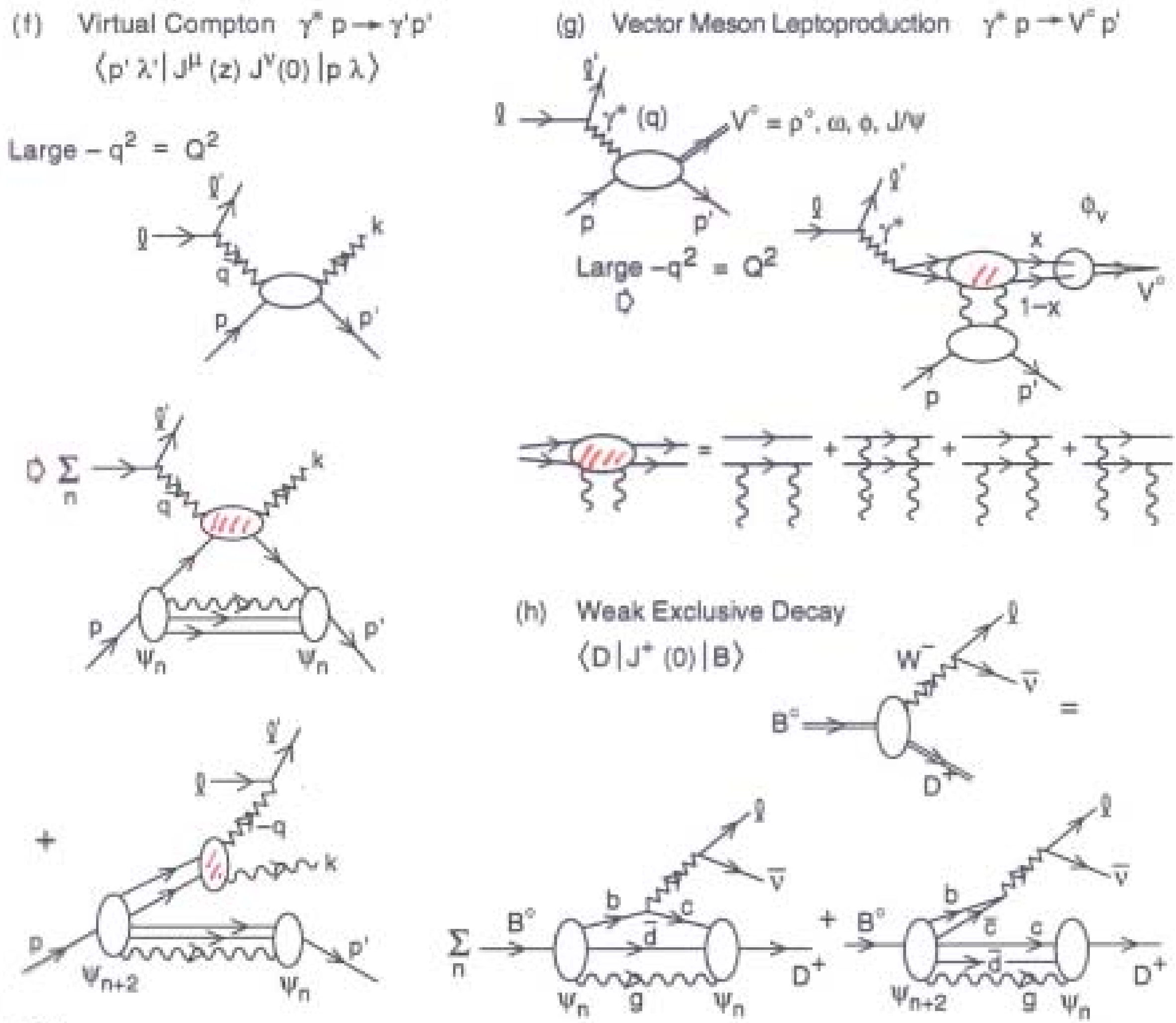
$$\Rightarrow \quad \frac{Q^2 F_2(Q^2)}{F_1(Q^2)} \sim \log^{.6} Q^2 \qquad Q^2 \to \infty$$

HHC maintained

$$\frac{F_2(Q^2)}{F_1(Q^2)} = \frac{\mu_A}{1 + \frac{Q^2}{.96\,\mathrm{GeV}^2} \log^{-.6}\left(1 + Q^2/4m_\pi^2\right)}$$






(f) Virtual Compton $\gamma^* p \to \gamma' p'$
$\langle p' \lambda' | J^{\mu}(z) J^{\nu}(0) | p \lambda \rangle$
Large $-q^2 = Q^2$
(g) Vector Meson Leptoproduction $\gamma^* p \to V^\circ p'$
$V^\circ = \rho^\circ, \omega, \phi, J/\psi$
Large $-q^2 = Q^2$
ϕ_V
x
1−x
(h) Weak Exclusive Decay
$\langle D | J^+(0) | B \rangle$
W^-
B°
D^+
ψ_n
ψ_{n+2}

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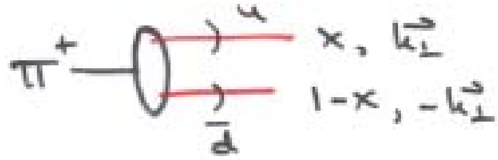
G. P. Lepage
SJB

Pion Distribution Amplitude

$$\phi_\pi(x, Q^2) = \int \frac{d^2k_\perp}{16\pi^3}\, \psi^{(Q)}_{q\bar{q}/\pi}(x, \vec{k}_\perp)$$



$$\sim\ \psi_{q\bar{q}/\pi}\left(x, b_\perp \sim O\left(\tfrac{1}{Q}\right)\right)$$

$$\phi_\pi(x, Q) = \int \frac{dz^-\, P_\pi^+}{4\pi}\, e^{ix P_\pi^+ z^-/2}$$

$$\left.\langle 0|\,\bar{\psi}(0)\,\frac{\gamma^+\gamma^5}{2\sqrt{2n_c}}\,\psi(z)\,|\pi\rangle^{(Q)}\right|_{z^+ = \vec{z}_\perp = 0}$$

$$P\exp\int_0^1 ds\ i g\, A(sz)\cdot z = 1 \quad \text{in } A^+=0 \text{ gauge}$$

$$= \int \frac{dk^-}{2\pi}\, \psi_{BS}(k, p)$$

obeys: OPE, RGE, Evolution Eq.