QCD Phenomenology and Nucleon Structure

Stan Brodsky, SLAC

Lecture II

National Nuclear Physics Summer School

QCD Lagrangian

Generalization of QED

gluon dynamics

quark kinetic energy +
quark-gluon dynamics

mass term

$$L_{QCD} = -\frac{1}{4g^2} Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{nf} i \overline{\psi_f} D_\mu \gamma^\mu \psi_f + \sum_{f=1}^{nf} m_f \overline{\psi_f} \psi_f$$

QCD color charge

field strength tensor

covariant derivative

quark field

Yang Mills Gauge Principle:
Color Rotation and Phase
Invariance at Every Point of
Space and Time

Scale-Invariant Coupling
Renormalizable
Nearly-Conformal
Asymptotic Freedom
Color Confinement

Recent Lectures from the SLAC Theory Group

http://www.slac.stanford.edu/grp/th/lectures/

- The Impact of AdS/CFT on QCD, Part 1, Part 2, presented at the meeting: QCD and String Theory at the
  Benasque Center for Science 2006, July 2-July 14, Benasque, Spain
- Testing Novel Phenomena in QCD and AdS/CFT using Antiprotons, Part 1, Part 2, Part 3, Presented at the ECT* Workshop: Observables in Antiproton-Proton Interactions and their Relevance to QCD, 3-8 July 2006, Trento, Italy
- The Renormalization Scale Problem, LoopFest V, SLAC, June 21, 2006
- Novel Tests of QCD at Super B, Super B III, SLAC, June 15, 2006
- Hadron Spectroscopy and Structure from AdS/CFT, Part 1, Part 2, Part 3, QNP06, Madrid, Spain, June 8, 2006
- Insights from AdS/CFT for Light-Front Wavefunctions and QCD Phenomena at the Amplitude Level, Part 1, Part 2, LC2006, May 15, 2006
- Light-Front Wavefunctions, QCD Phenomena at the Amplitude Level, and Insights for QCD from AdS/CFT, Part 1, Part 2, CAQCD, May 12, 2006
- Insights for QCD from AdS/CFT, Part 1, Part 2, Newe Shalom Joint Seminar, May 9, 2006
- Novel Diffractive Phenomena and New Insights into QCD Wavefunctions, Ashery Colloquium, Part 1, Part 2, Tel Aviv, May 8, 2006
- Nuclear Chromodynamics and Hadron Dynamics at the Amplitude Level, Eisenberg Colloquium, Part 1, Part 2, Tel Aviv, May 7, 2006
- Insights for QCD from AdS/CFT, Part 1, Part 2, Technion, Israel, May 1, 2006
- The World of Quarks and Gluons: A Contemporary View of the Structure of Matter, Universidad de Costa Rica, April 6, 2006
- Novel Diffractive Phenomena and New Insights Into QCD from AdS/CFT, Part 1, Part 2, Part 3, University of Connecticut, March 27, 2006
- Orbital Angular Momentum in QCD, presented at the Joint UNM/RBRC Workshop on Parton Orbital Angular Momentum, Albuquerque, New Mexico, February 24, 2006

Light-front QCD.
Stanley J. Brodsky (**SLAC**) **. SLAC-PUB-10871, Nov 2004. 66pp.**
Invited lectures and talk presented at the 58th Scottish University Summer School in Physics: A NATO Advanced Study Institute and EU Hadronic Physics 13 Summer Institute (SUSSP58), St. Andrews, Scotland, 30 Aug - 1 Sep 2004.
e-Print Archive: hep-ph/0412101

Hadronic spectra and light-front wavefunctions in holographic QCD.
Stanley J. Brodsky (**SLAC**) **,** **Guy F. de Teramond** (**Costa Rica U.**) **. SLAC-PUB-11716, Feb 2006. 11pp.**
Published in Phys.Rev.Lett.96:201601,2006
e-Print Archive: **hep-ph/0602252**

Testing quantum chromodynamics with antiprotons.
Stanley J. Brodsky (**SLAC**) **. SLAC-PUB-10811, Oct 2004. 92pp.**
Published in *Varenna 2004, Hadron physics* 345-422
e-Print Archive: hep-ph/0411046

Exclusive Processes In Quantum Chromodynamics.
Stanley J. Brodsky (**SLAC**) **,** **G.Peter Lepage** (**Cornell U., LNS**) **. SLAC-PUB-4947, Mar 1989. 149pp.**
Contribution to 'Perturbative Quantum Chromodynamics', Ed. by A.H. Mueller, to be publ. by World Scientific Publ. Co.
Published in Adv.Ser.Direct.High Energy Phys.5:93-240,1989 Also in Perturbative Quantum Chromodynamics, 1989, p. 93-240 (QCD161:M83)

Physics Reports 301 (1998) 299–486

Quantum chromodynamics and other field theories on the light cone

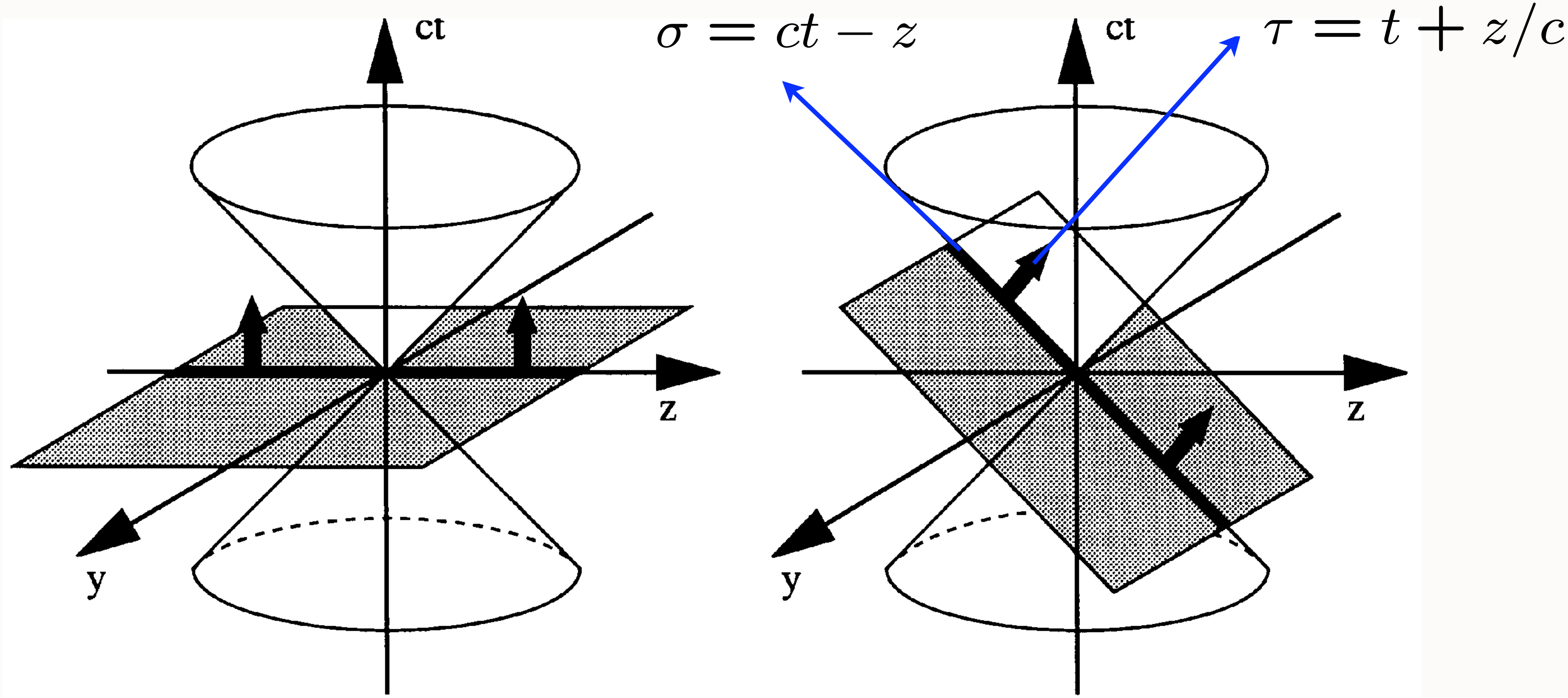
Stanley J. Brodsky[a], Hans-Christian Pauli[b], Stephen S. Pinsky[c]

Wavefunctions: Fundamental description of composite systems

- Basic quantum mechanical quantities in atomic and nuclear physics
- Physics at the amplitude level
- **Schrödinger** wavefunction in nonrelativistic theory
- Relativistic formulation: Bethe Salpeter amplitudes evaluated at fixed time t
- Problem: "Instant" form: Frame-dependent

Dirac's Amazing Idea: The "Front Form"

Evolve in light-cone time!



Instant Form

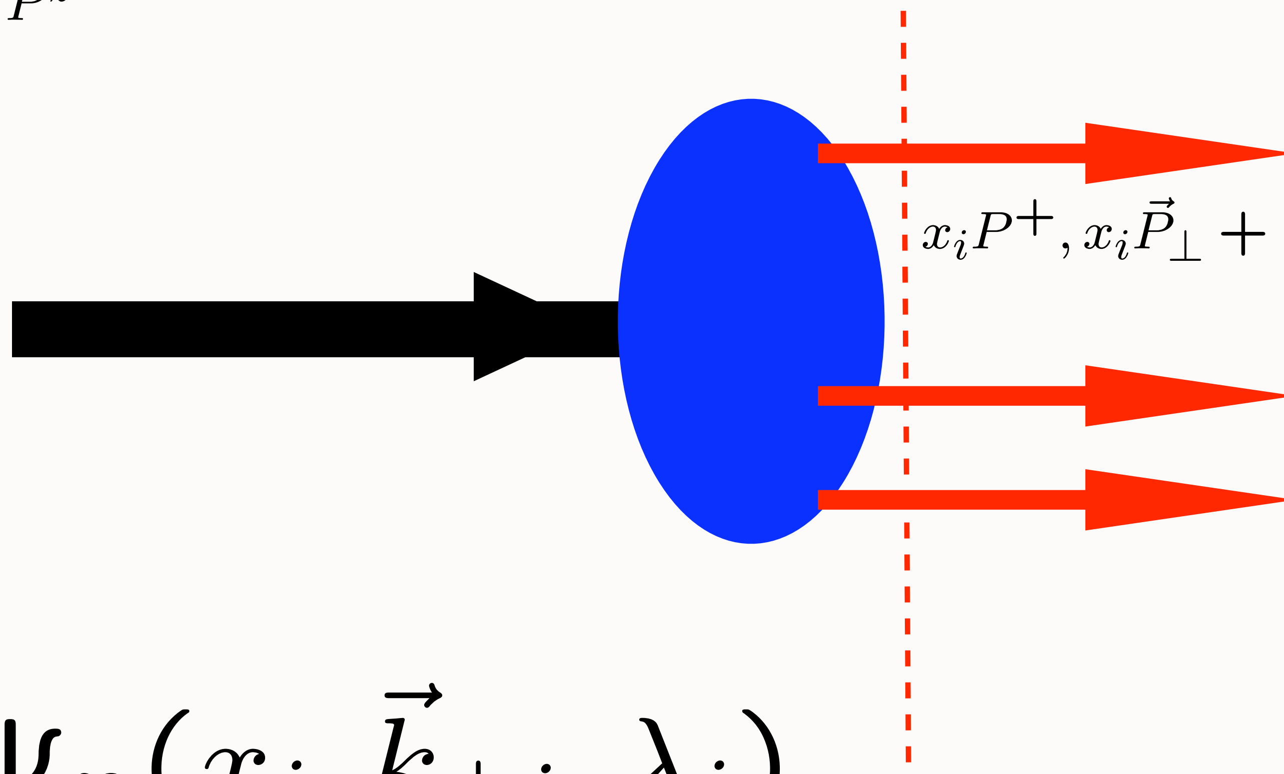
Front Form

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

$P^+ = P^0 + P^z$

$P^+, \vec{P}_\perp$



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$\sum_i^n x_i = 1$

$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions

Dirac's Front Form: Fixed $\tau = t + z/c$

$$\psi(x, k_\perp)$$

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

Invariant under boosts. Independent of P^μ

$$H_{LF}^{QCD}|\psi> = M^2|\psi>$$

Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp_i}, \lambda_i>$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

are boost invariant; they are independent of the hadron's energy and momentum P^μ.

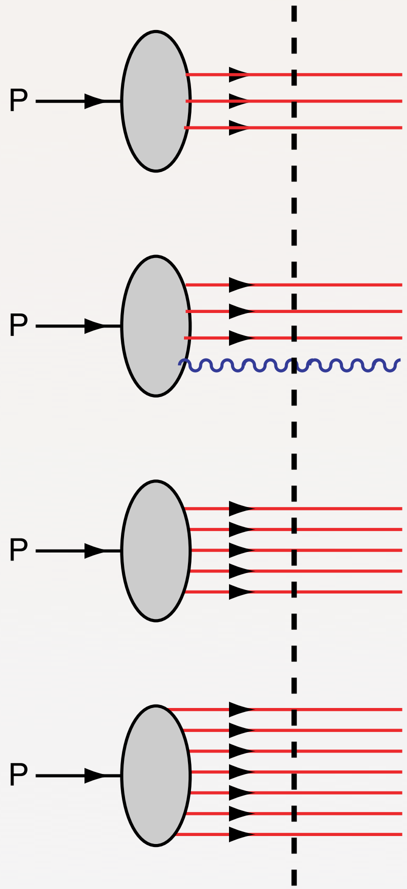
The light-cone momentum fraction

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

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \; \sum_i^n x_i = 1, \; \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$

Intrinsic glue, sea quarks, charm, bottom



Fixed LF time

Hadrons Fluctuate in Particle Number

- Proton Fock States

  $|uud>, |uudg>, |uuds\bar{s}>, |uudc\bar{c}>, |uudb\bar{b}> \cdots$

- Strange and Anti-Strange Quarks not Symmetric

  $s(x) \neq \bar{s}(x)$

- "Intrinsic Charm": High momentum heavy quarks
- "Hidden Color": Deuteron not always p + n
- Orbital Angular Momentum Fluctuations - Anomalous Magnetic Moment

Light-Front Quantization of Gauge Theory

Identify independent and constrained fields

Choose light-front gauge $A^+ = 0$

$$\Psi_\pm \equiv \Lambda_\pm \Psi = \tfrac{1}{2}(1 \pm \alpha^z)\Psi$$

Ψ_+ dynamical

constraint: $\Psi_- = \frac{1}{2i\partial^+}(m\beta - \vec{\alpha}_\perp \cdot T^a \vec{D}^a_\perp)\Psi_+$

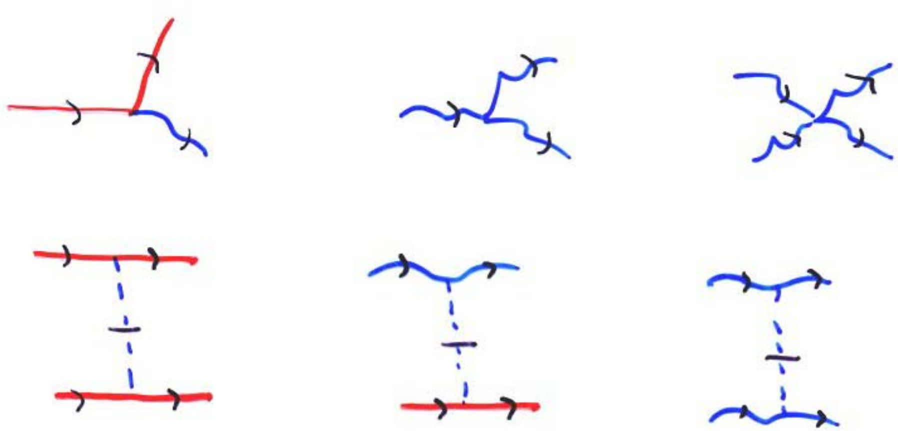
constraint: $A^-_a = \frac{g}{(i\partial^+)^2} J^+_a$

$$\frac{1}{i\partial^+} \to \frac{1}{k^+}$$

dynamical: $\vec{A}_\perp$

$$
\begin{aligned}
\mathcal{H}^{LF}_{int} = & -g\, \bar{\psi}^i \gamma^\mu A^{ij}_\mu \psi^j \\
& + \frac{g}{2} f^{abc} \left(\partial_\mu A^a_\nu - \partial_\nu A^a_\mu \right) A^{b\mu} A^{c\nu} \\
& + \frac{g^2}{4} f^{abc} f^{ade} A_{b\mu} A^{d\mu} A_{c\nu} A^{e\nu} \\
& - \frac{g^2}{2} \bar{\psi}^i \gamma^+ (\gamma^\perp A_\perp)^{ij} \frac{1}{i\partial_-} (\gamma^\perp A_\perp)^{jk} \psi^k \\
& - \frac{g^2}{2} J^+_a \frac{1}{(\partial_-)^2} J^+_a
\end{aligned}
$$

$$
J^+_a = \bar{\psi}^i \gamma^+ (t_a)^{ij} \psi^j + f_{abc} (\partial_- A_{b\mu}) A^{c\mu}
$$



$$\frac{1}{(k^+)^2}$$

$$\mathcal{L}_{QCD} \rightarrow \mathcal{H}_{QCD}^{LF}$$

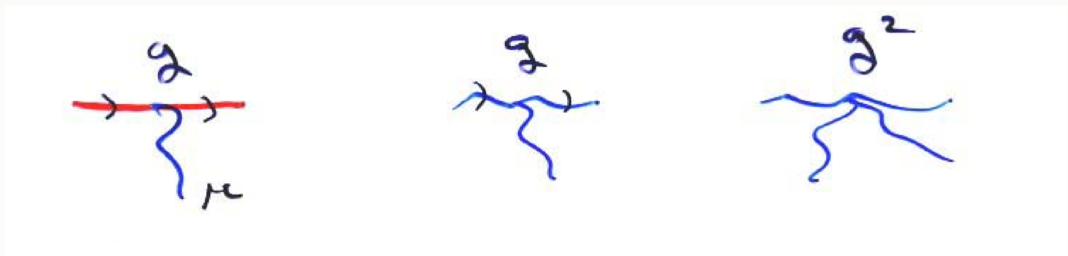
Canonical quantization in light-front gauge

$A^+ = 0$

spinors are eigenstates of $\Lambda_\pm = \frac{\gamma^0 \gamma^\pm}{2}$

QCD Interactions

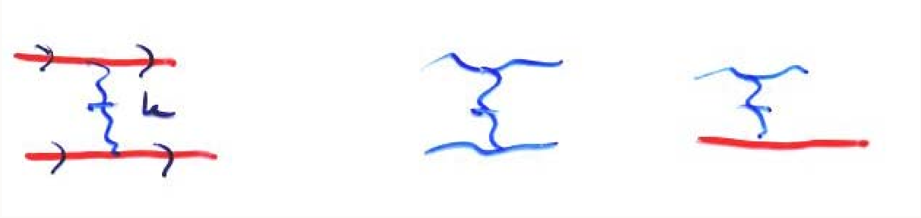
$\overline{u}\gamma^\mu u$



$\frac{\overline{u}\gamma^\nu\gamma^+\gamma^\mu u}{k^+}$

$\gamma^\pm = \gamma^+ \pm \gamma^z$

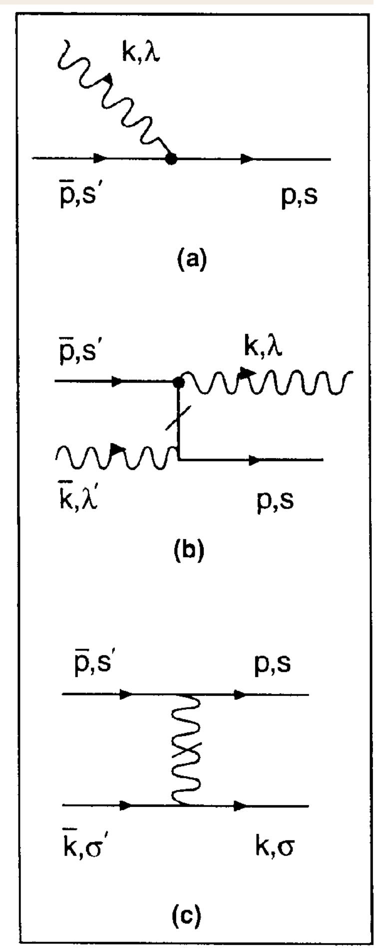
$\frac{\overline{u}\gamma^+ u \;\; \overline{u}\gamma^+ u}{{k^+}^2}$

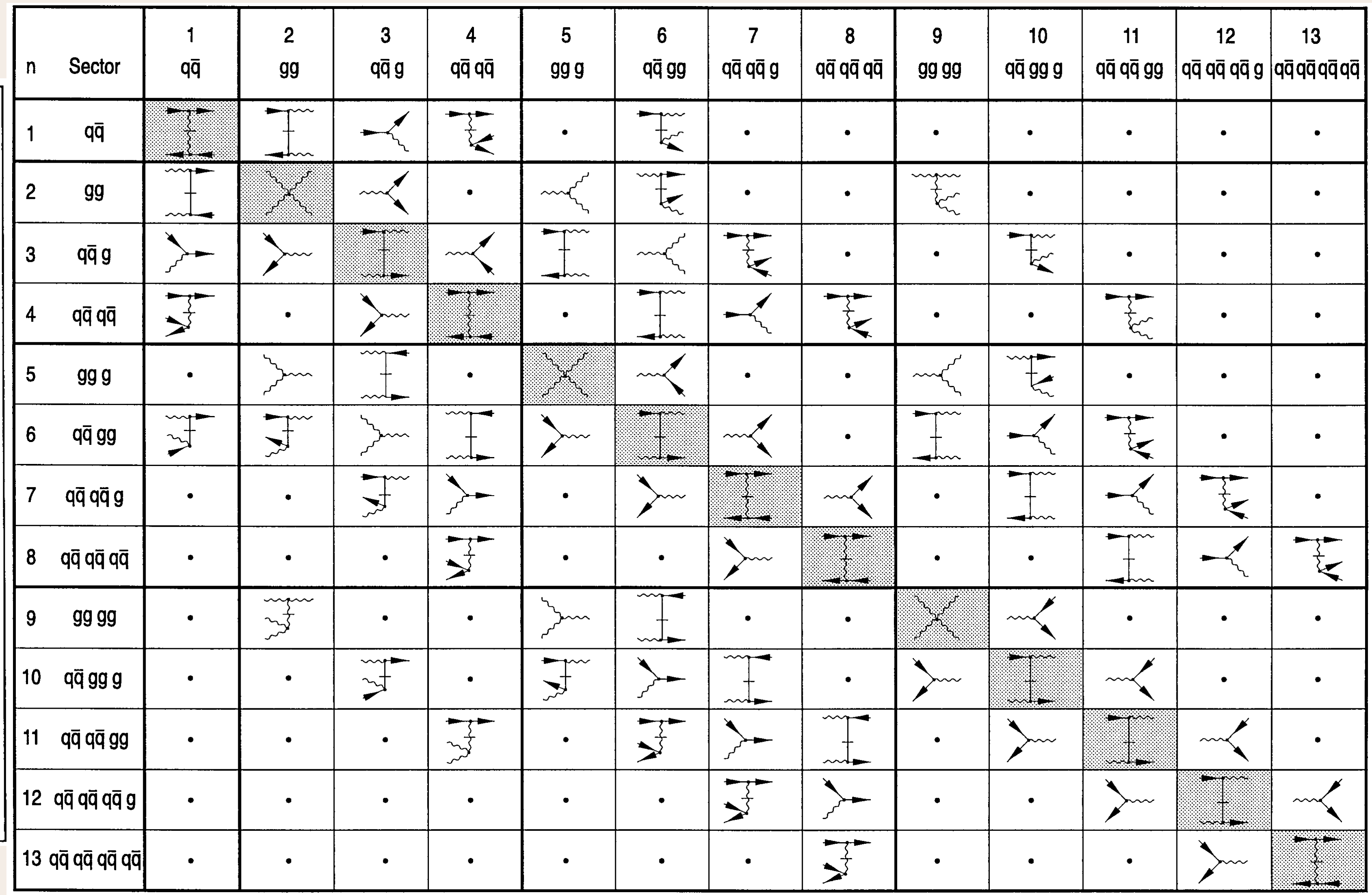


Light-Front QCD Heisenberg Equation

$$H_{LC}^{QCD} |\Psi_h\rangle = \mathcal{M}_h^2 \; |\Psi_h\rangle$$

DLCQ





Pauli, Pinsky, sjb

Solving the LF Heisenberg Equation

- Discretized Light-Cone Quantization (DLCQ) Pauli, sjb
  Minkowski space !
- Many 1+1 model field theories completely solved using DLCQ Hornbostel, Pauli, sjb; Klebanov
- UV Regularization: 3+ 1 Pauli Villars Hiller, McCartor, sjb
- Transverse Lattice Bardeen, Peterson,Rabinovici, Burkardt, Dalley
- Bethe-Salpeter/Dyson-Schwinger at fixed LF time
- Angular Structure of Solutions known Karmanov, Hwang, sjb
- Use AdS/CFT model solutions as starting point! Vary, sjb

Discrete Light-Front Quantization

program for solving quantum field theories

Diagonalize H_{LF}^{QCD} $\quad H_{LF}|\Psi>= M^2|\Psi>$

$$< n|H_{LF}|m >< m|\Psi >= M^2 < n|\Psi >$$

$|n >$: eigenstates of H^0_{LF}

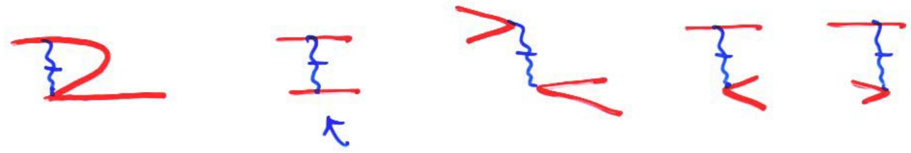
Periodic or antiperiodic boundary conditions

$k_i^+ = \frac{2\pi}{L} n_i$ $\quad P^+ = \frac{2\pi}{L} K$

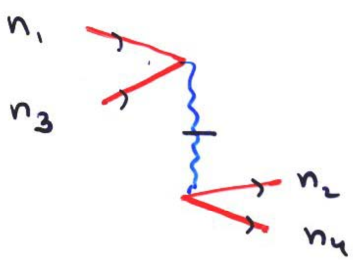
$\sum n_i = K$ $\quad n^i > 0$

Pauli, sjb

Interactions in QCD[1+1]



$$g^2 \, \bar{u} \gamma^+ u \, \frac{1}{(k^+)^2} \, \bar{u} \gamma^+ u$$



$$\frac{L}{2\pi} \frac{g^2}{\pi} \frac{1}{2} \left(\delta^{c_2}_{c_4} \delta^{c_3}_{c_1} - \delta^{c_3}_{c_4} \delta^{c_2}_{c_1} \right)$$

$$\sum_{n_i = \frac{1}{2}, \frac{3}{2} \ldots} \frac{\delta_{n_1+n_3, \, n_2+n_4}}{(n_1+n_3)^2} \, b^+_{\substack{n_4 \\ c_4}} \, b_{\substack{n_3 \\ c_3}} \, d^+_{\substack{n_2 \\ c_2}} \, d_{\substack{n_1 \\ c_1}}$$

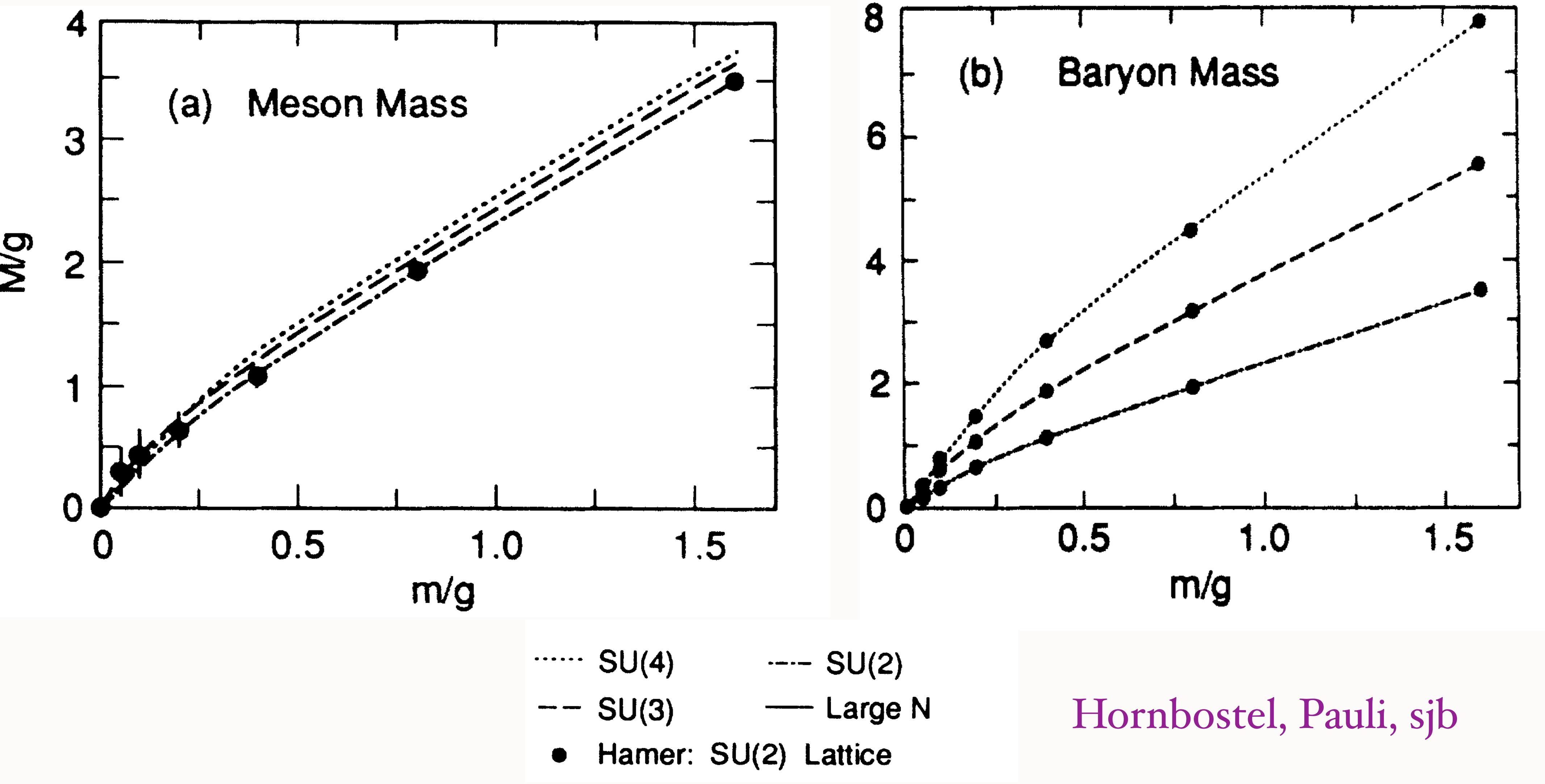
No dynamical gluon in 1+1

$\frac{g}{m}$ dimensionless

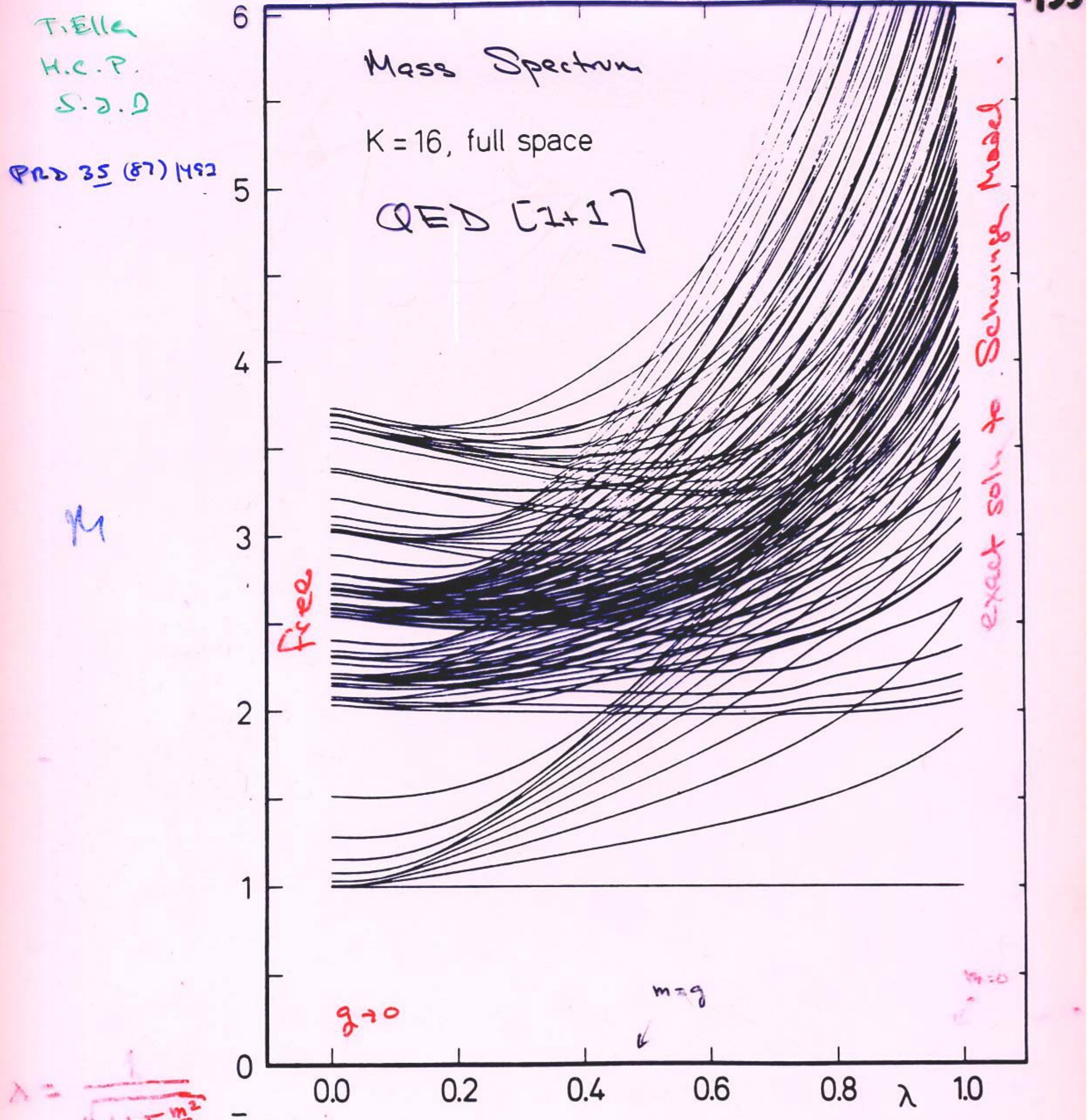
* QED[1+1] $\;\; \begin{matrix} m \to 0 \\ g \to \infty \end{matrix}$: Schwinger model

Free bosons! $\quad V \Rightarrow \sum_i \frac{m^2}{k^+} a^+ a \, , \quad m^2 = \frac{g^2}{2\pi}$

Light-cone-quantized QCD in 1 + 1 dimensions

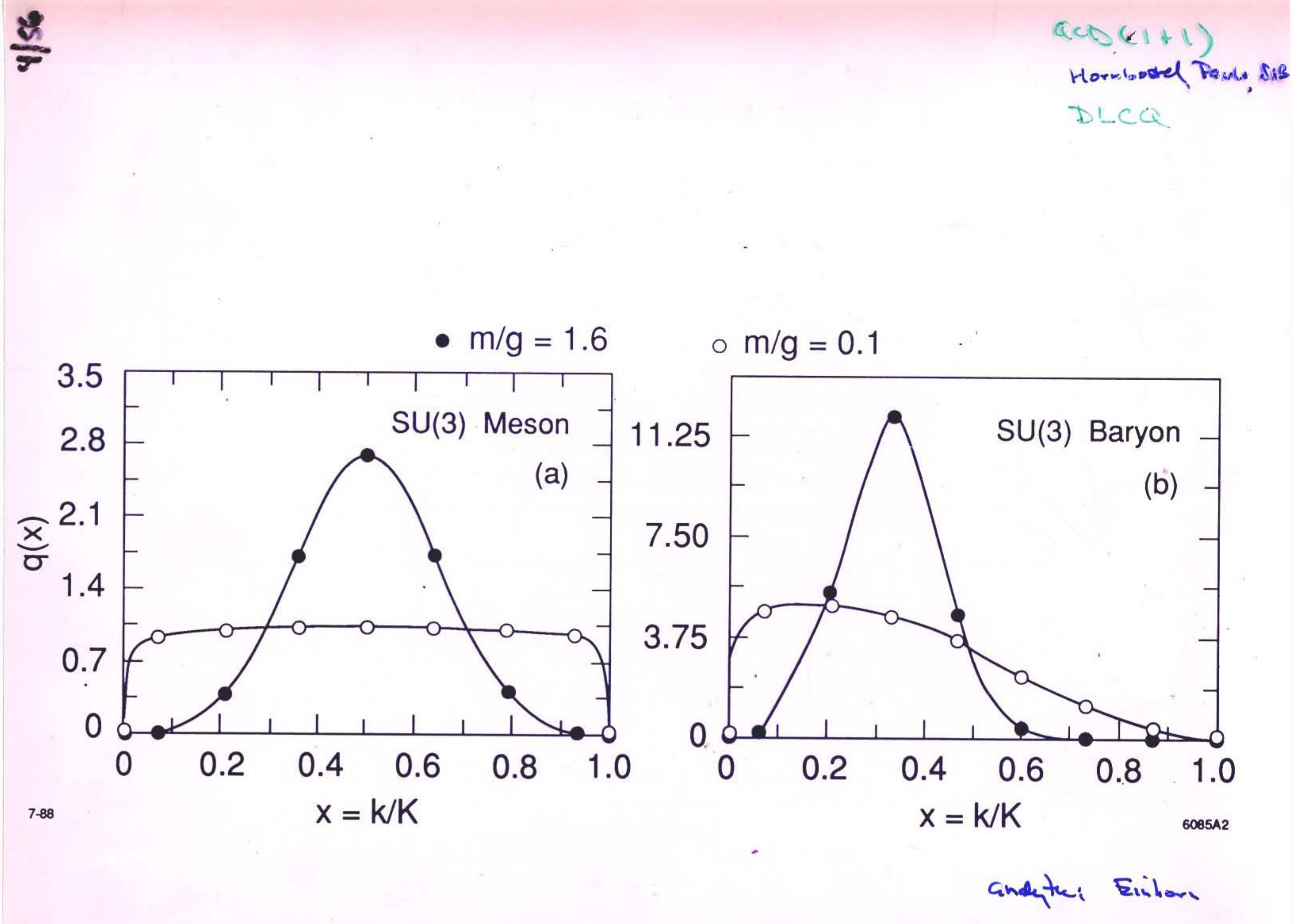


Hornbostel, Pauli, sjb



6. *The renormalized spectrum of invariant masses.* — The invariant masses M_i/M_1 as calculated with the full Fock space of the massive representation for $K = 16$ is plotted versus *all values* of the coupling constant λ. — Note the qualitatively different parts of the spectrum. Many quasi-crossings are not resolved graphically despite the small step in the calculation, $\Delta\lambda = 0.01$.

Prob $q\bar{q}q\bar{q} \lesssim 10^{-4}$


QCD(1+1)
Hornbostel, Pauli, SJB
DLCQ
● m/g = 1.6
○ m/g = 0.1
SU(3) Meson
(a)
SU(3) Baryon
(b)
q(x)
3.5
2.8
2.1
1.4
0.7
0
11.25
7.50
3.75
0
0.2
0.4
0.6
0.8
1.0
x = k/K
7-88
6085A2

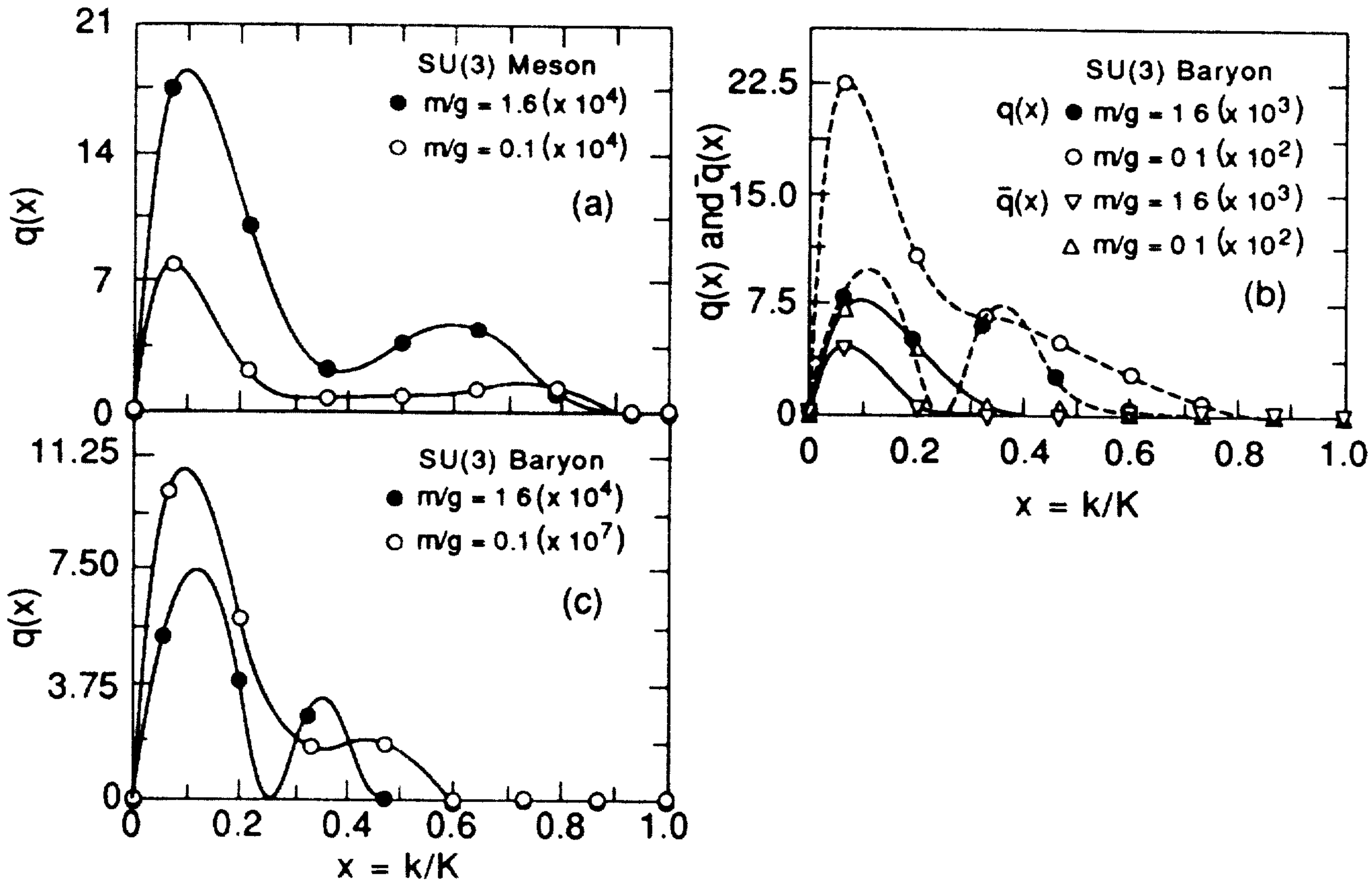
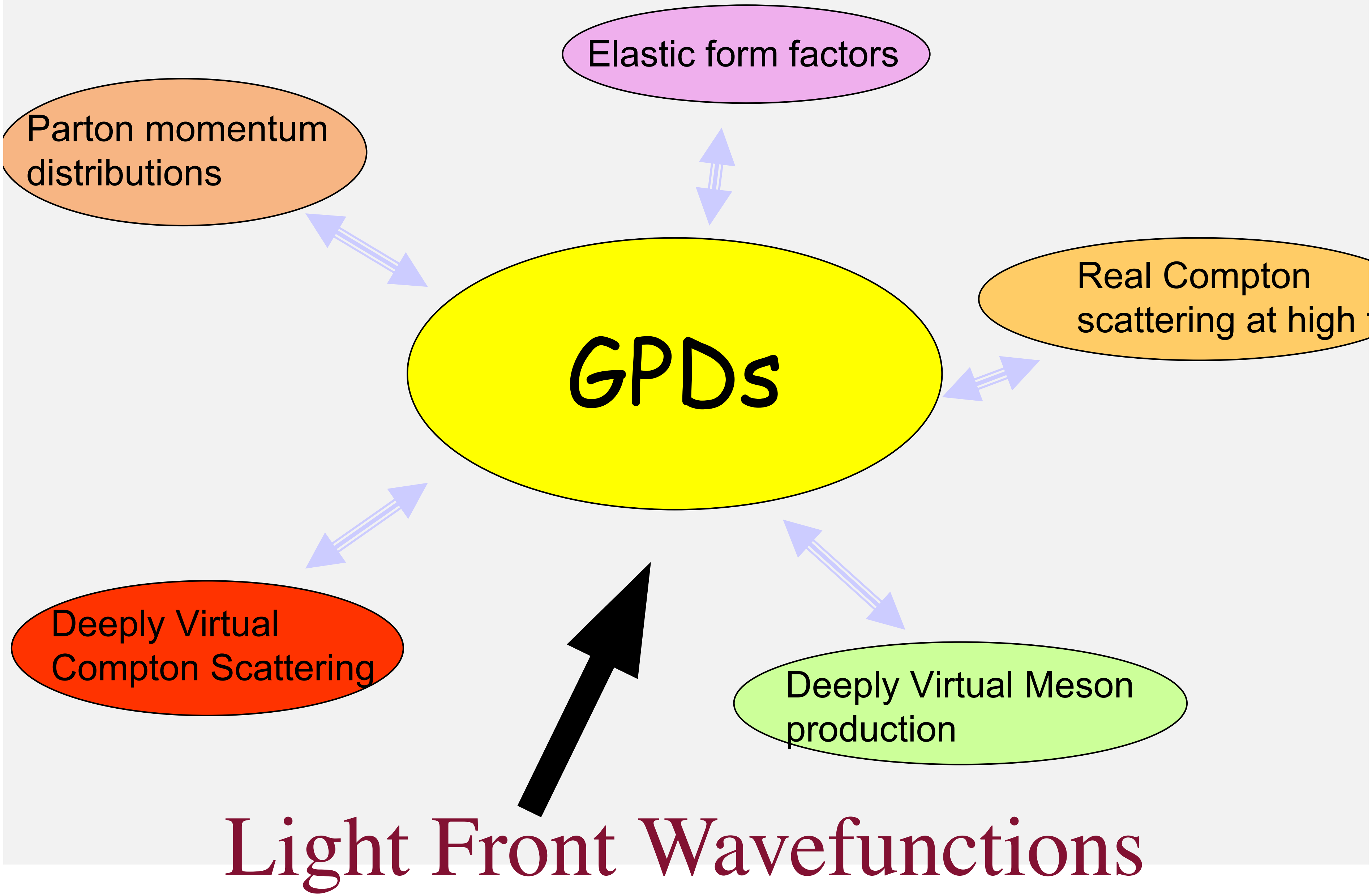


FIG. 4. Higher-Fock contributions to $N=3$ structure functions. (a) Lightest meson. (b) Lightest baryon, including antiquarks. (c) Baryon: contribution from two extra quark pairs. The curves are intended to guide the eye.

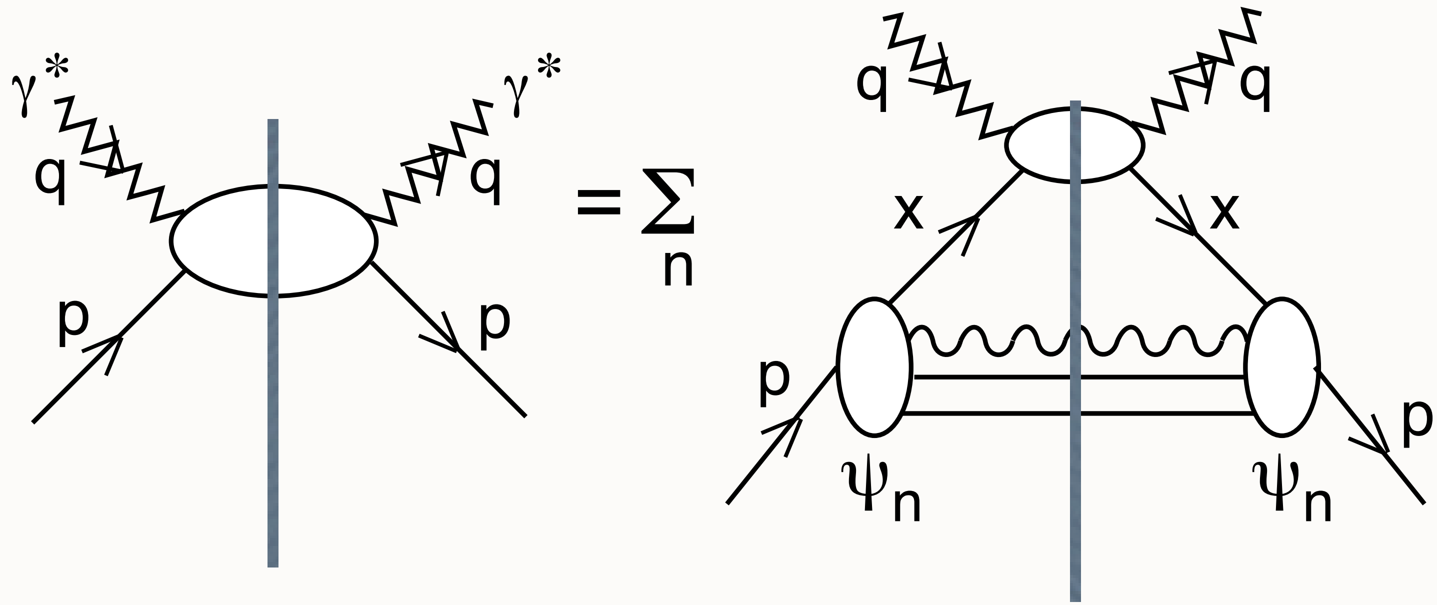
Advantages of Light-Front Quantization

- Frame independent; J_z kinematical
- Minkowski space; no fermion doubling
- Physical degrees of freedom; physical polarization
- Trivial vacuum; zero modes
- **B(0) =0**; Exact formula for current matrix elements
- DLCQ; covariant truncation of Fock space
- LFWFs, spectra, physics at the amplitude level, phases

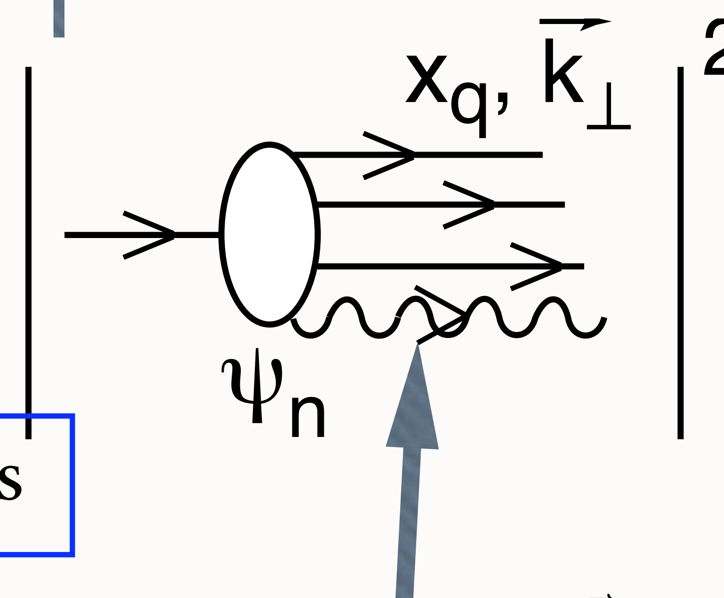
A Unified Description of Hadron Structure



Deep Inelastic Lepton Proton Scattering



Imaginary Part of
Forward Virtual Compton Amplitude



$q(x,Q^2) = \sum_n \int^{k_\perp^2 \leq Q^2 \perp} d^2k_\perp \, |\Psi_n(x,k_\perp)|^2$

$x = x_q$

All spin, flavor distributions

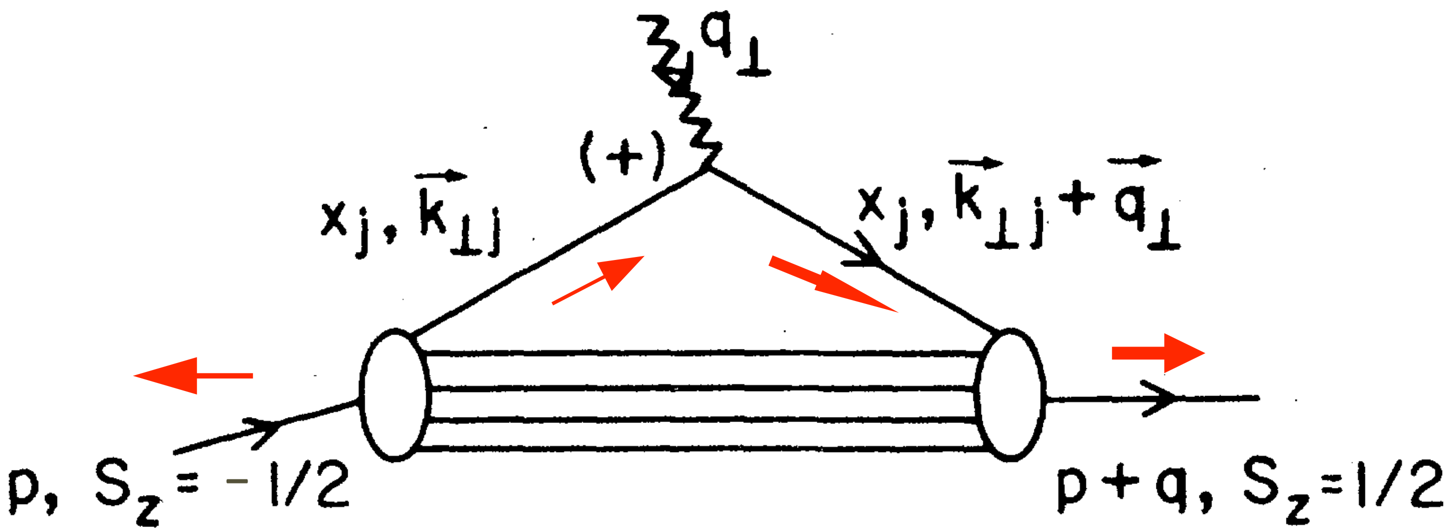
Light-Front Wave Functions $\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

$$\left[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \right]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$



Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

The form factors of the energy–momentum tensor for a spin-$\frac{1}{2}$ composite

$$\langle P'|T^{\mu\nu}(0)|P\rangle = \bar{u}(P')\Big[A(q^2)\gamma^{(\mu}\overline{P}^{\nu)} + B(q^2)\frac{i}{2M}\overline{P}^{(\mu}\sigma^{\nu)\alpha}q_\alpha + C(q^2)\frac{1}{M}(q^\mu q^\nu - g^{\mu\nu}q^2)\Big]u(P),$$

where $q^\mu = (P' - P)^\mu$, $\overline{P}^\mu = \frac{1}{2}(P' + P)^\mu$, $a^{(\mu}b^{\nu)} = \frac{1}{2}(a^\mu b^\nu + a^\nu b^\mu)$,

$$\left\langle P+q,\uparrow\left|\frac{T^{++}(0)}{2(P^+)^2}\right|P,\uparrow\right\rangle = A(q^2),$$

$$\left\langle P+q,\uparrow\left|\frac{T^{++}(0)}{2(P^+)^2}\right|P,\downarrow\right\rangle = -(q^1 - \mathrm{i}q^2)\frac{B(q^2)}{2M}.$$

The angular momentum projection of a state is given by

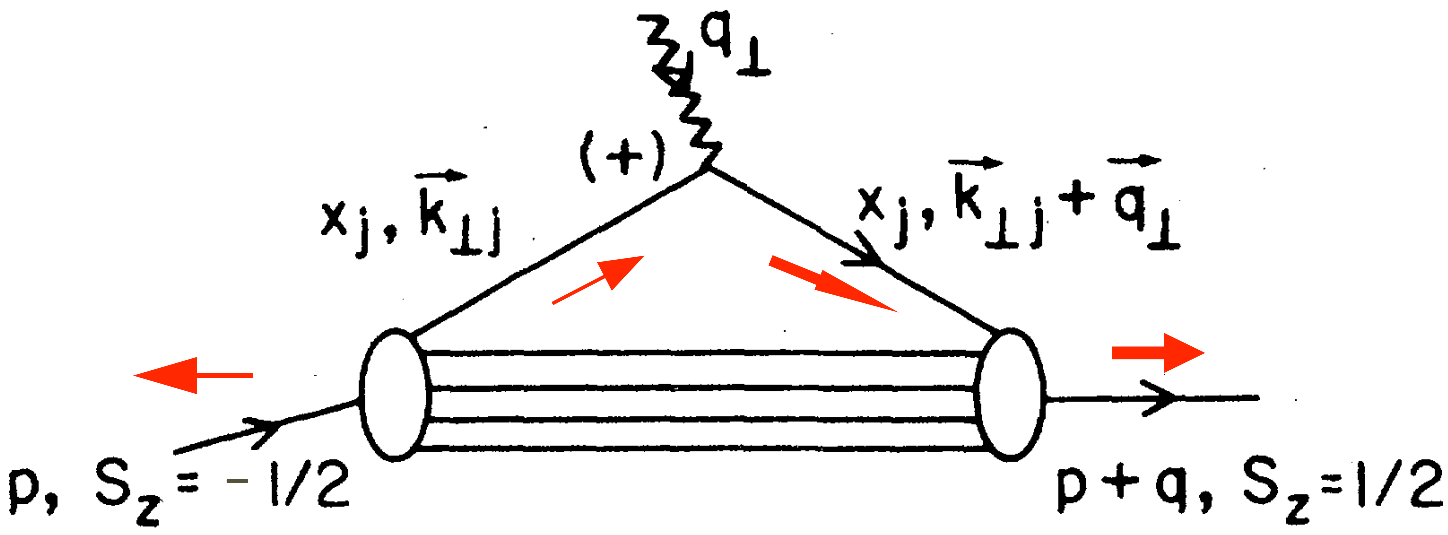
$$\langle J^i\rangle = \frac{1}{2}\epsilon^{ijk}\int \mathrm{d}^3x\,\langle T^{0k}x^j - T^{0j}x^k\rangle$$
$$= A(0)\langle L^i\rangle + [A(0) + B(0)]\bar{u}(P)\frac{1}{2}\sigma^i u(P).$$

$$\langle J^z\rangle = \left\langle\frac{1}{2}\sigma^z\right\rangle[A(0) + B(0)].$$

Anomalous gravitomagnetic moment B(0)

graviton

sum over constituents

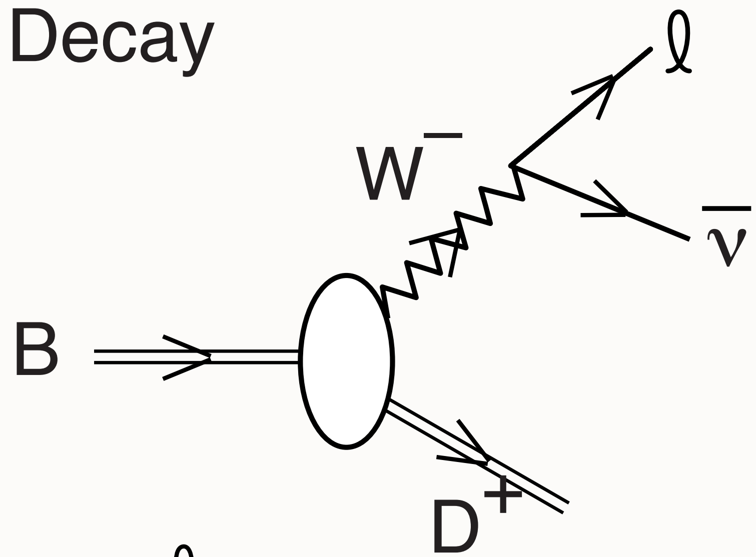


$B(0) = 0$

Each Fock State

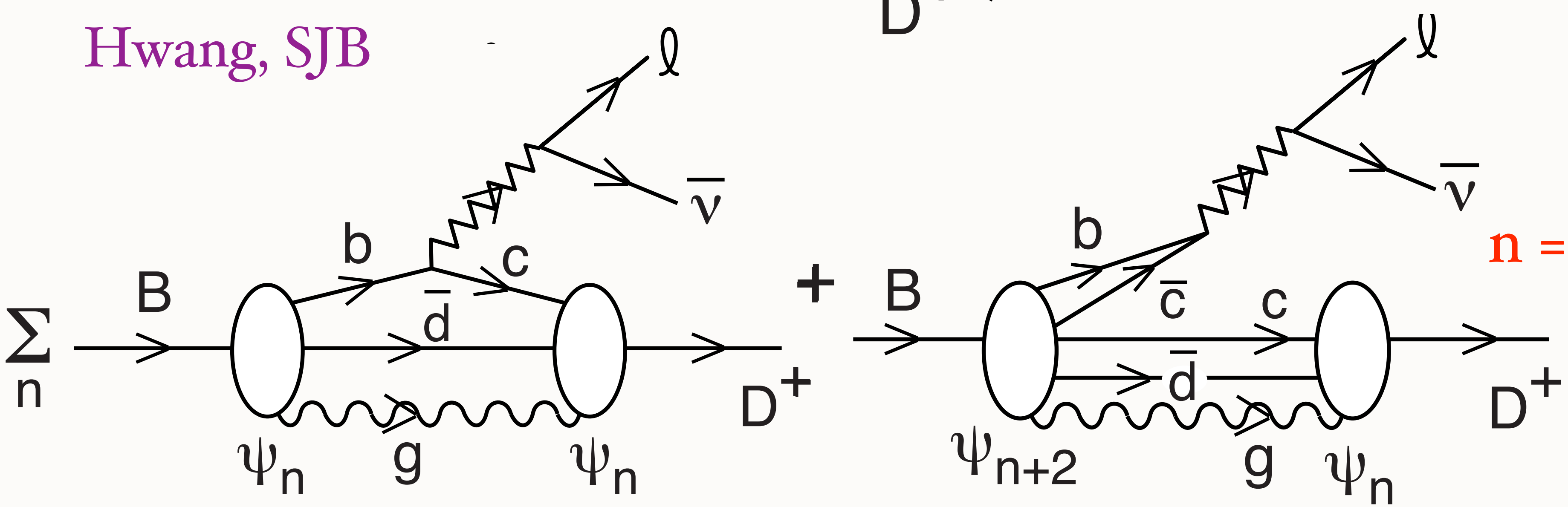
Weak Exclusive Decay

$\langle D \,|\, J^{+}(0) \,|\, B \rangle$



Exact Formula

Hwang, SJB



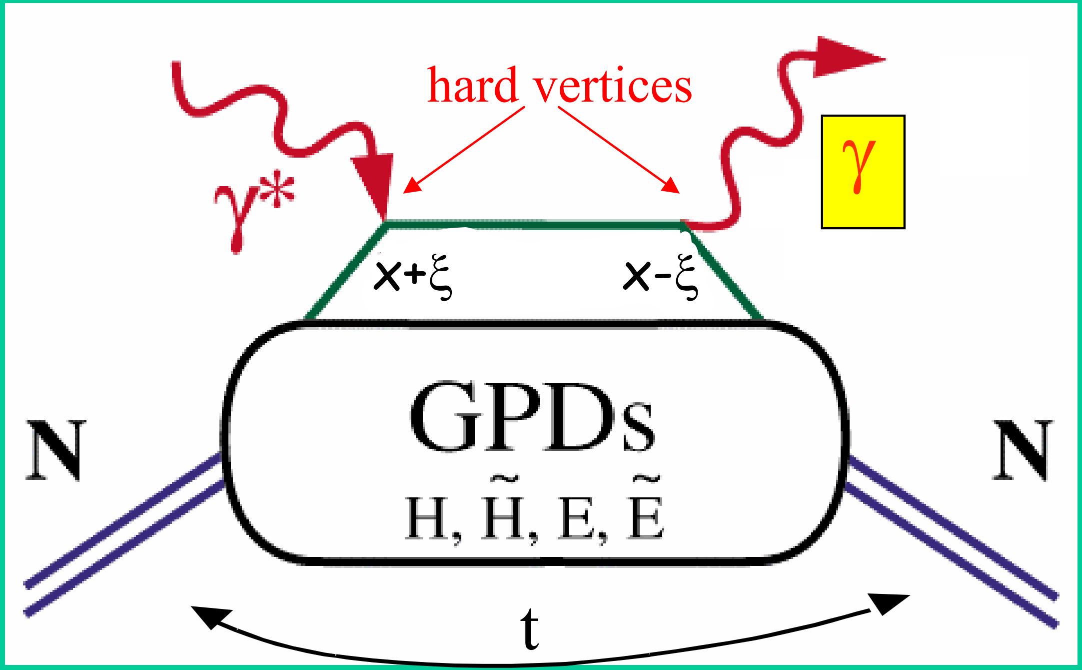
$n = n' + 2$

Annihilation amplitude needed for Lorentz Invariance

GPDs & Deeply Virtual Exclusive Processes

"handbag" mechanism

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

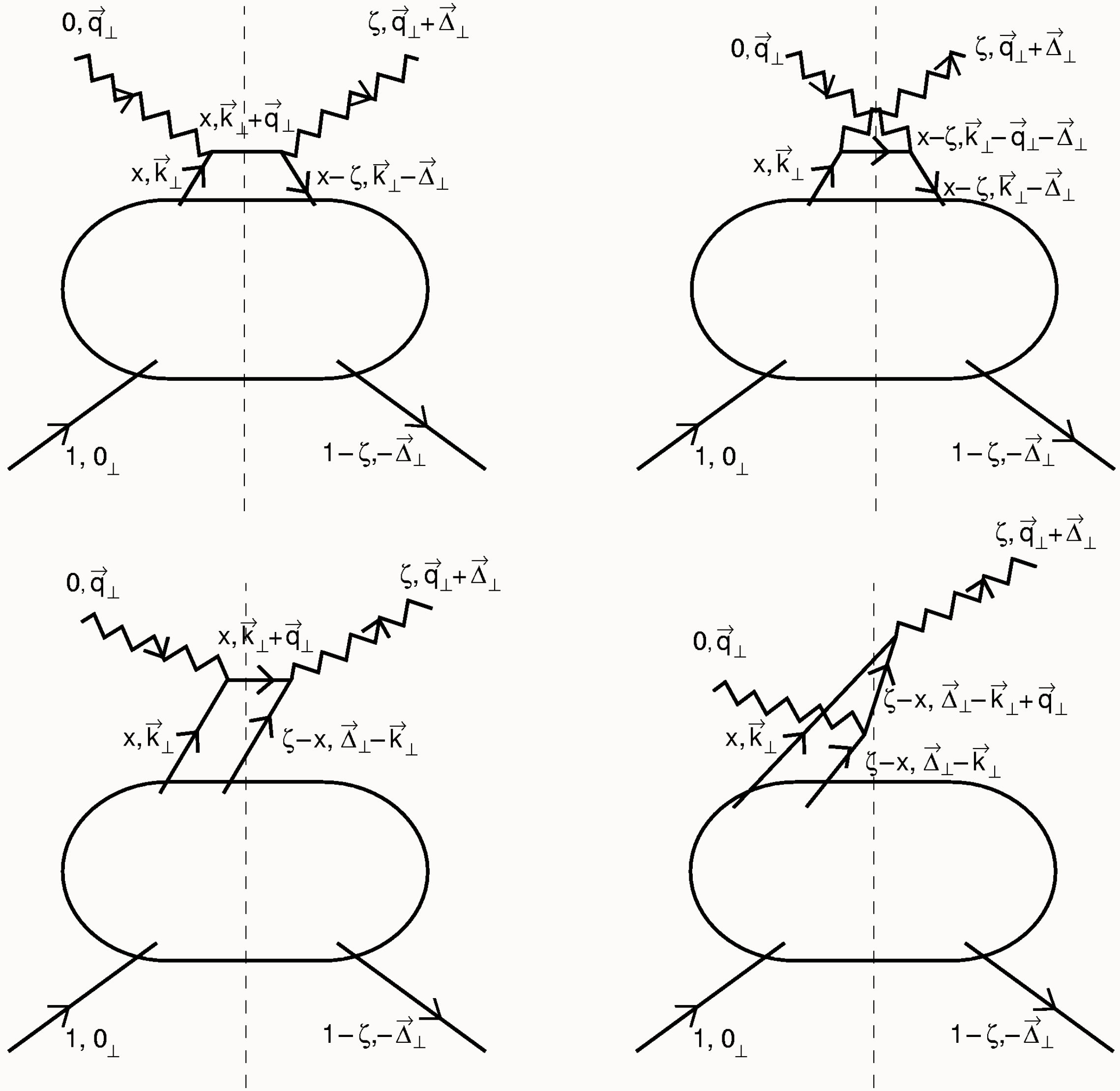
$H(x,\xi,t), E(x,\xi,t), . .$

Physics of DVCS

- Generalized Compton scattering $\gamma^*(q)p \to \gamma(k)p'$
- Interference with Bethe-Heitler gives real and imaginary parts of virtual Compton amplitude
- Local two-photon interaction produces J=0 fixed pole

$$M[\gamma^*(q)p \to \gamma(k)p'] \simeq \sum e_q^2 \; \epsilon \cdot \epsilon' \; s^0 F(t)$$

- Imaginary part of forward virtual Compton amplitude gives DIS structure functions
- Regge theory predicts energy dependence at fixed t, q^2
- Handbag approximation at large q^2



Light-cone wavefunction representation of deeply virtual Compton scattering ☆

Stanley J. Brodsky [a], Markus Diehl [a,1], Dae Sung Hwang [b]

Example of LFWF representation of GPDs (n => n)

Diehl,Hwang, sjb

$$\frac{1}{\sqrt{1-\zeta}}\frac{\Delta^1 - i\Delta^2}{2M} E_{(n\to n)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{2-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3}\, 16\pi^3 \delta\left(1-\sum_{j=1}^{n} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n} \vec{k}_{\perp j}\right)$$

$$\times\, \delta(x-x_1)\, \psi^{\uparrow *}_{(n)}(x'_i, \vec{k}'_{\perp i}, \lambda_i)\, \psi^{\downarrow}_{(n)}(x_i, \vec{k}_{\perp i}, \lambda_i),$$

where the arguments of the final-state wavefunction are given by

$$x'_1 = \frac{x_1-\zeta}{1-\zeta}, \qquad \vec{k}'_{\perp 1} = \vec{k}_{\perp 1} - \frac{1-x_1}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the struck quark,}$$

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp \quad \text{for the spectators } i = 2, \ldots, n.$$

Example of LFWF representation of GPDs (n+1 => n-1)

Diehl,Hwang, sjb

$$\frac{1}{\sqrt{1-\zeta}}\frac{\Delta^1 - i\Delta^2}{2M} E_{(n+1\to n-1)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{3-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n+1} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3} 16\pi^3 \delta\left(1-\sum_{j=1}^{n+1} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n+1} \vec{k}_{\perp j}\right)$$

$$\times 16\pi^3 \delta(x_{n+1}+x_1-\zeta)\delta^{(2)}(\vec{k}_{\perp n+1}+\vec{k}_{\perp 1}-\vec{\Delta}_\perp)$$

$$\times \delta(x-x_1)\psi^{\uparrow *}_{(n-1)}(x'_i,\vec{k}'_{\perp i},\lambda_i)\psi^{\downarrow}_{(n+1)}(x_i,\vec{k}_{\perp i},\lambda_i)\delta_{\lambda_1-\lambda_{n+1}},$$

where $i = 2, \ldots, n$ label the $n-1$ spectator partons which appear in the final-state hadron wavefunction with

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp.$$

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Form factors (sum rules)

$$\int^1 dx \sum_q \left[H^q(x,\xi,t)\right] = F_1(t) \text{ Dirac f.f.}$$

$$\int^1 dx \sum_q \left[E^q(x,\xi,t)\right] = F_2(t) \text{ Pauli f.f.}$$

$$\int_{-1}^1 dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^1 dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

Verified using LFWFs

Diehl, Hwang, sjb

Quark angular momentum (Ji's sum rule)

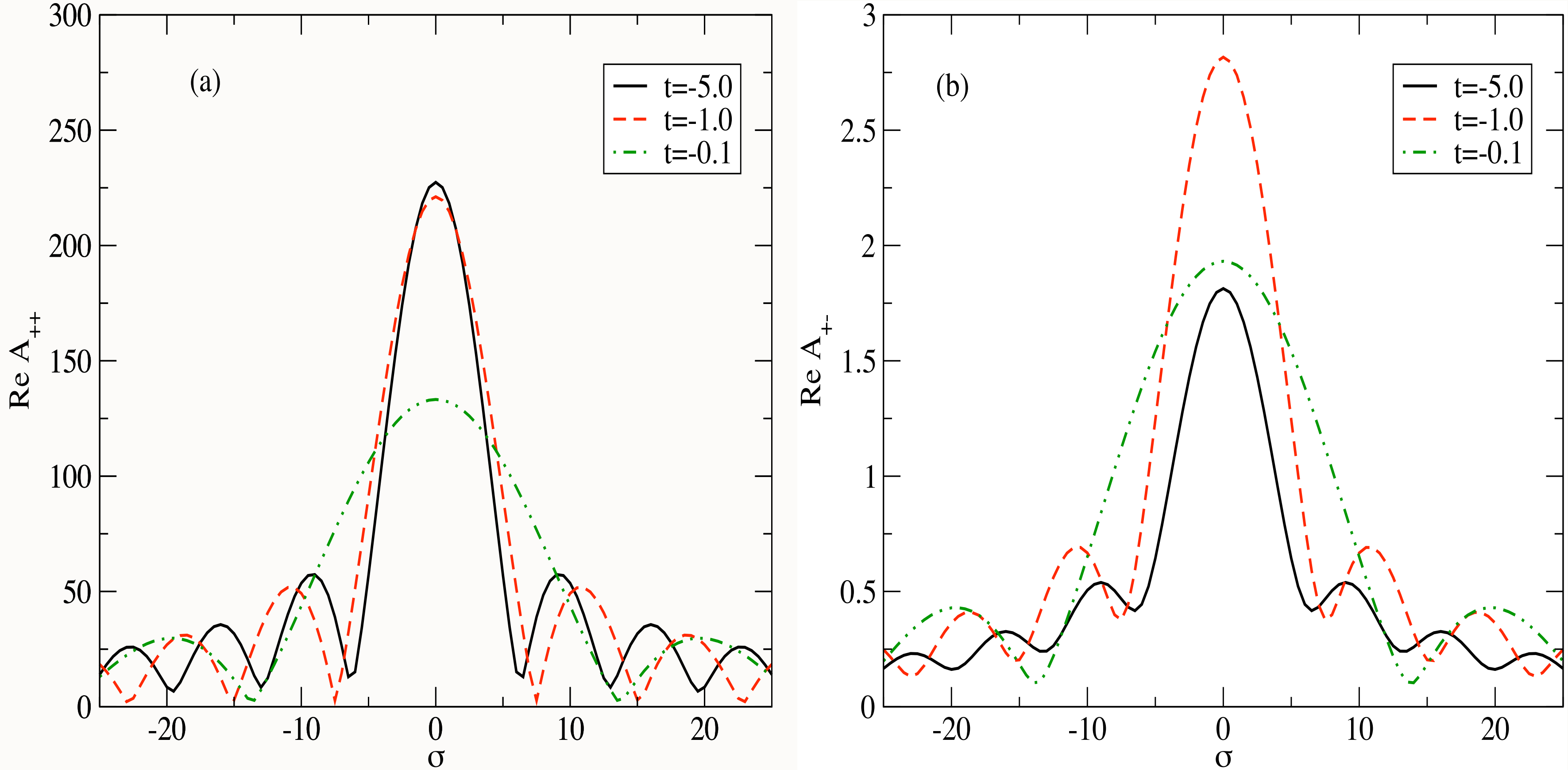
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^1 x\,dx\left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

LFWFS give a fundamental description of hadron observables

- LFWFS underly structure functions and generalized parton distributions.
- Parton number not conserved: n=n' & n=n'+2 at nonzero skewness
- GPDs are not densities or probability distributions
- Nonperturbative QCD: Lattice, DLCQ, Bethe-Salpeter, AdS/CFT

Hadron Optics from the Fourier Transform of DVCS amplitudes



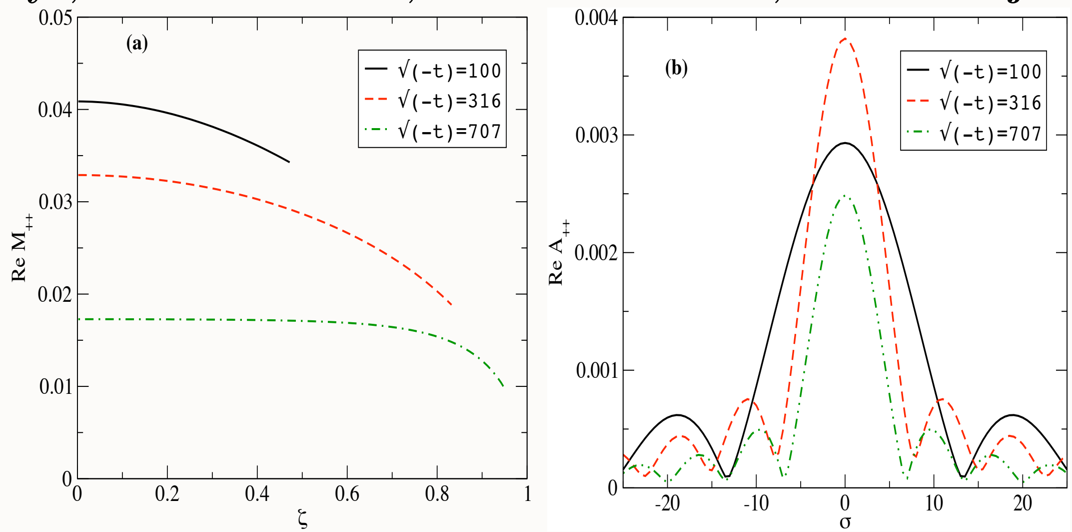
Fourier spectrum of the real part of the DVCS amplitude of an electron vs. σ for $M = 0.51$ MeV, $m = 0.5$ MeV, $\lambda = 0.02$ MeV, (a) when the electron helicity is not flipped; (b) when the helicity is flipped. The parameter t is in MeV^2.

S. J. Brodsky[a], **D. Chakrabarti**[b], **A. Harindranath**[c], **A. Mukherjee**[d], **J. P. Vary**[e,a,f]

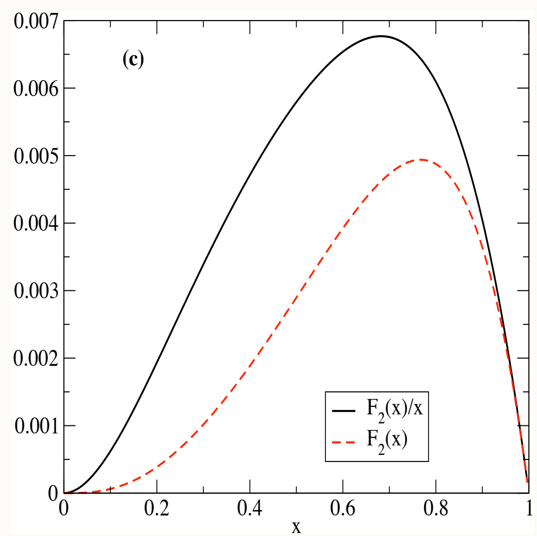
$$A(\sigma, \Delta_\perp) = \frac{1}{2\pi} \int d\zeta e^{\frac{i}{2}\sigma\zeta} M(\zeta, \Delta_\perp) \qquad \zeta = \frac{Q^2}{2p\cdot q}$$

S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

Hadron Optics from the Fourier Transform of DVCS amplitudes



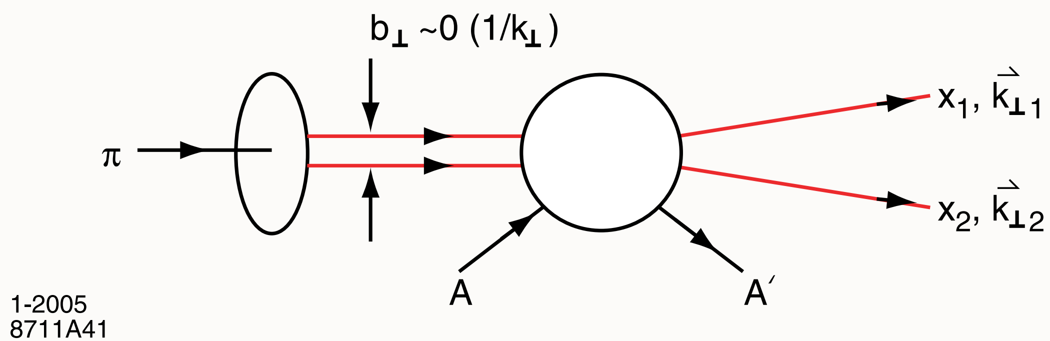
$$A(\sigma, \Delta_\perp) = \frac{1}{2\pi} \int d\zeta e^{\frac{i}{2}\sigma\zeta} M(\zeta, \Delta_\perp)$$



Real part of the DVCS amplitude for the simulated meson-like bound state. The parameters are $M = 150, m = \lambda = 300$ MeV. (a) Helicity non-flip amplitude vs. ζ, (b) Fourier spectrum of the same vs. σ, (c) Structure function vs. x. The parameter t is in MeV^2.

Diffractive Dissociation of Pion

E791 Ashery et al.

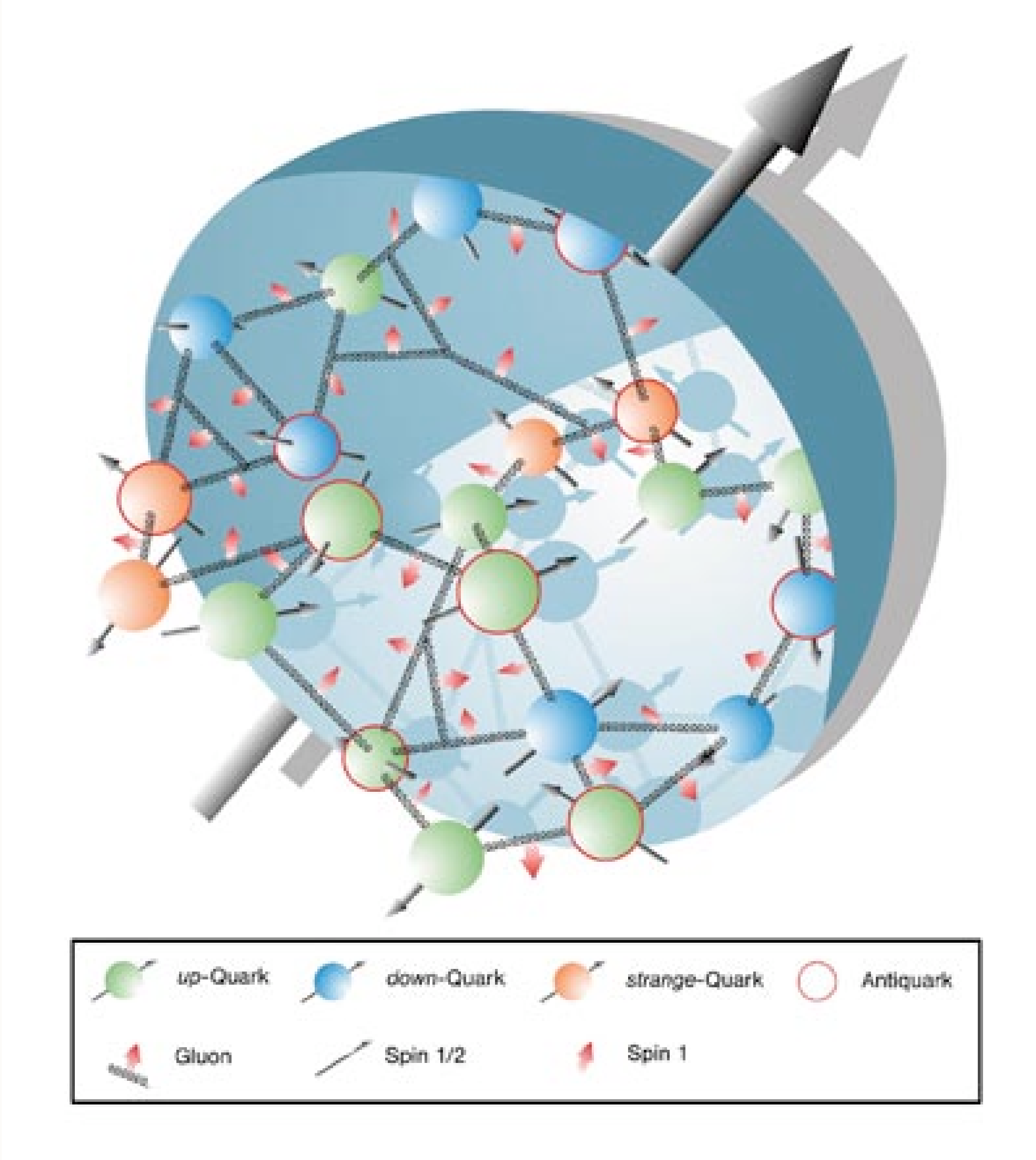


Measure Light-Front Wavefunction of Pion

Two-gluon Exchange

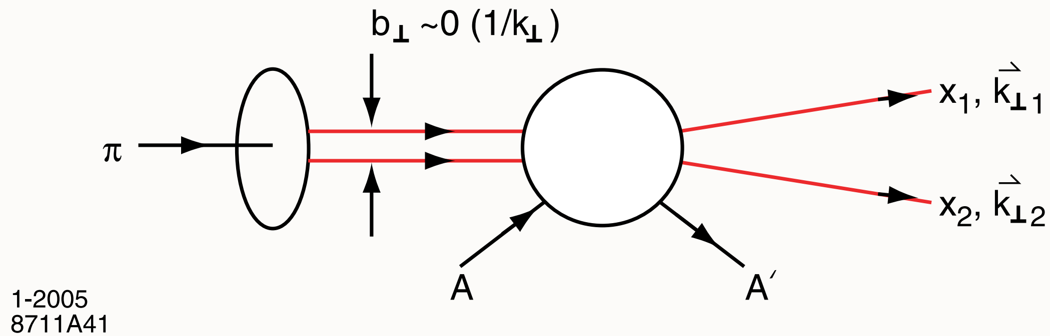
Minimal momentum transfer to nucleus

Nucleus left Intact



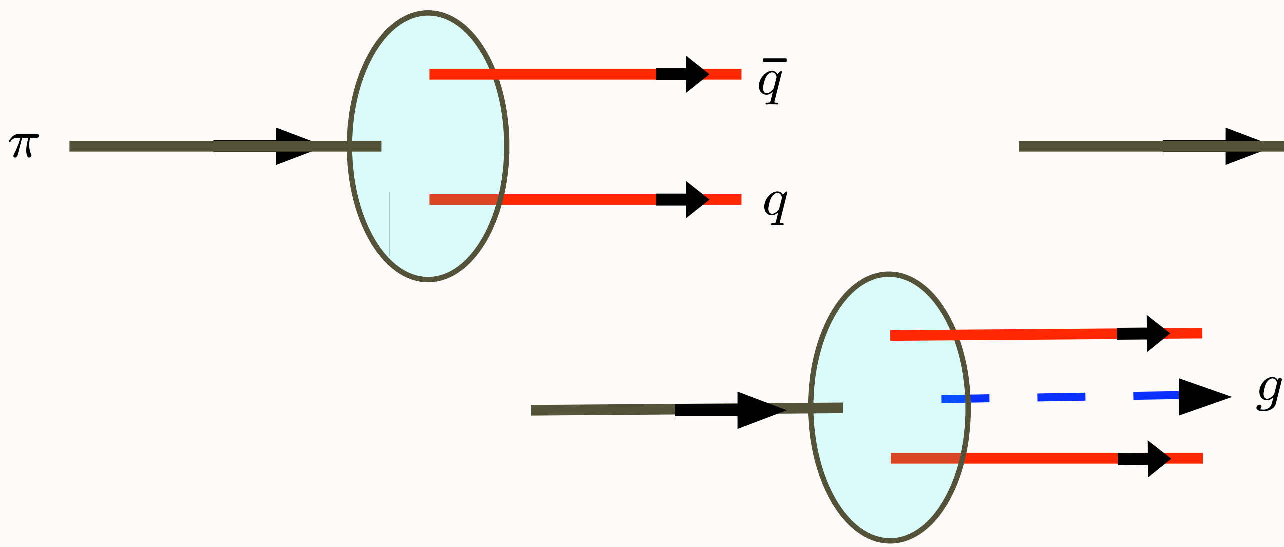
Fluctuations of extra gluons and quark-antiquark pairs

Key Ingredients in Ashery Experiment

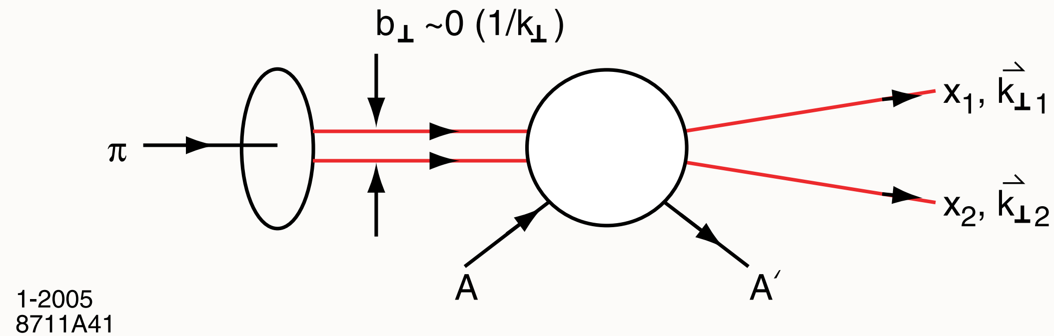


1. Quantum Fluctuations of a hadron wavefunction

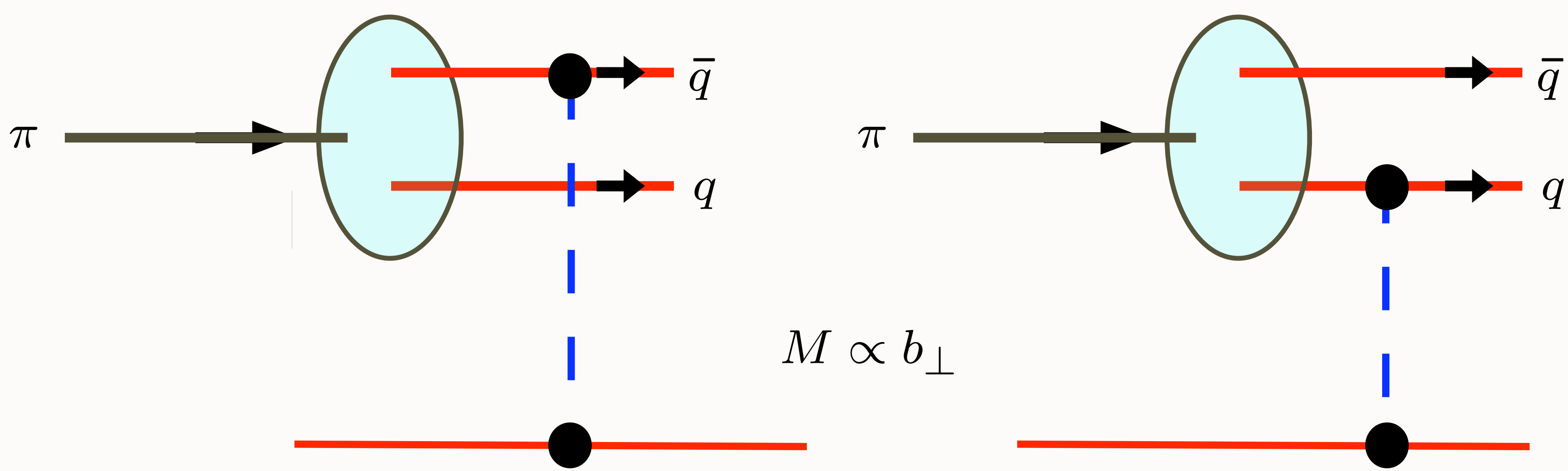
Pion wavefunction fluctuates not only in size, but also in particle number



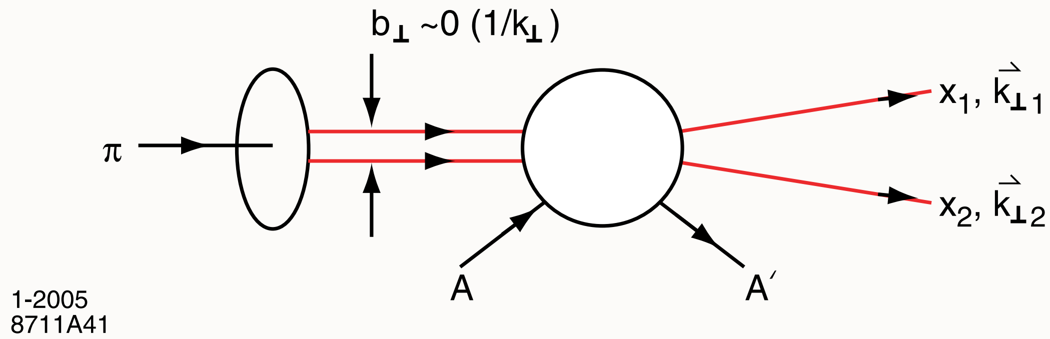
Key Ingredients in Ashery Experiment



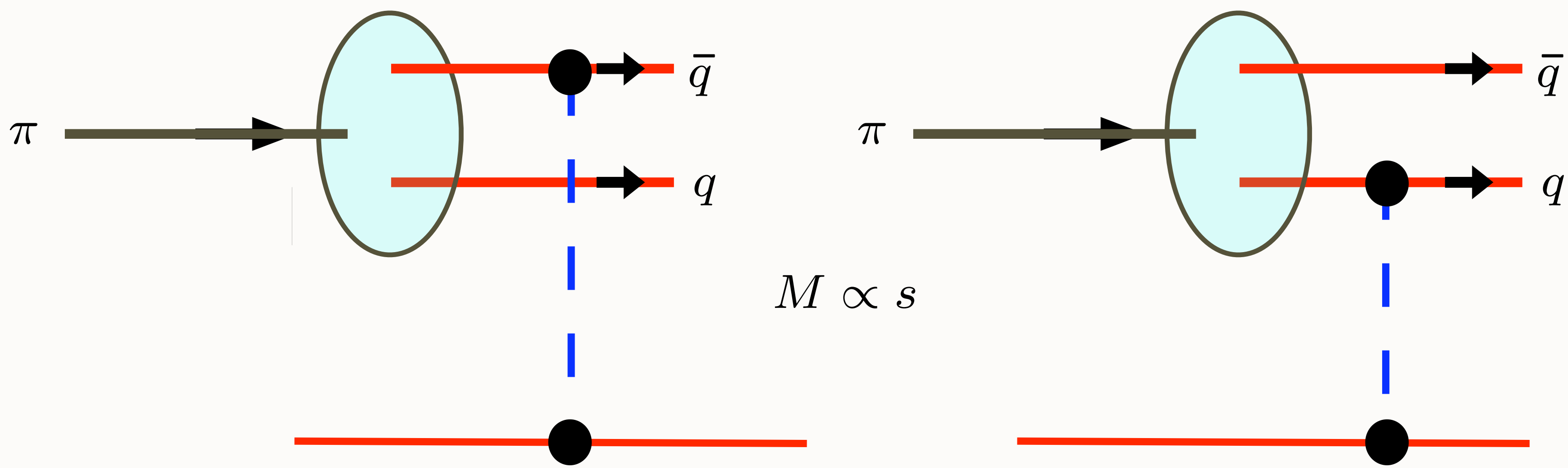
Local gauge-theory interactions
measure transverse size of color dipole



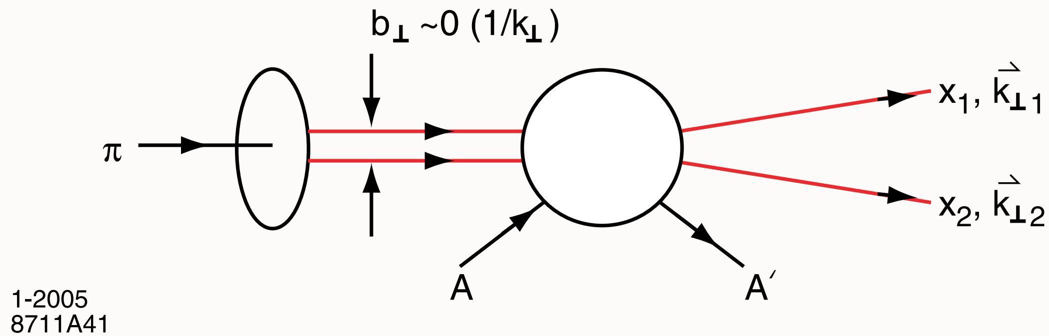
Key Ingredients in Ashery Experiment



Vector gluon exchange gives amplitudes proportional to energy, constant cross sections

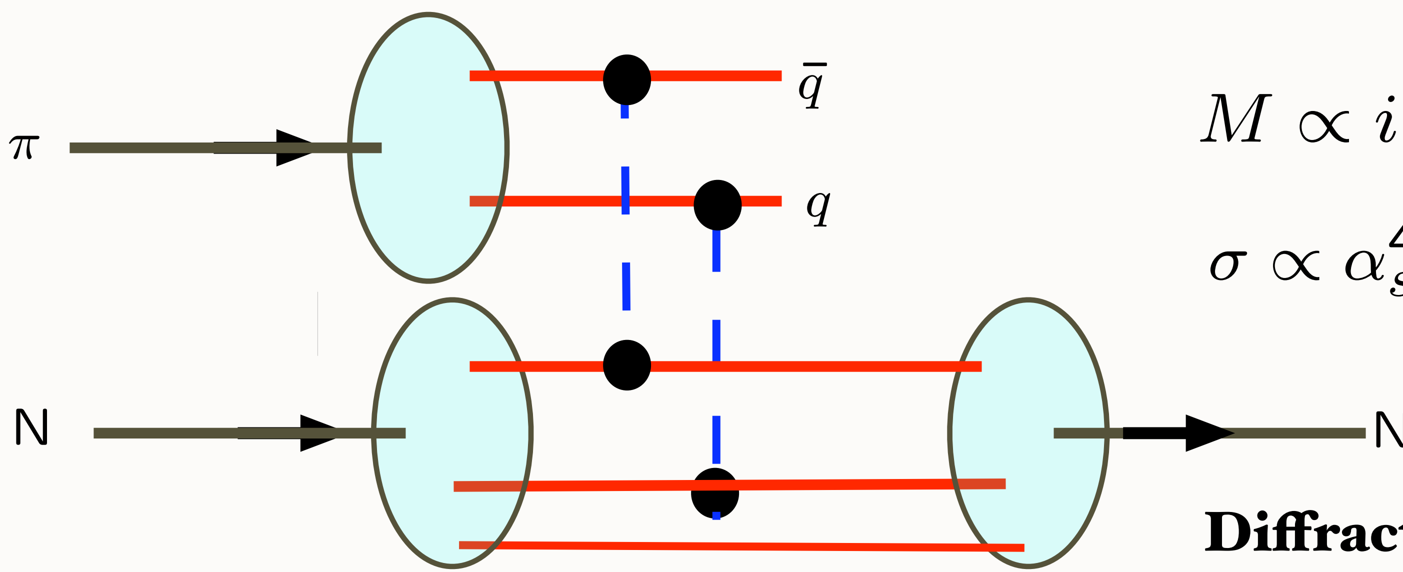


Key Ingredients in Ashery Experiment



Low Nussinov

Two-gluon exchange gives imaginary amplitude proportional to energy, constant diffractive cross sections



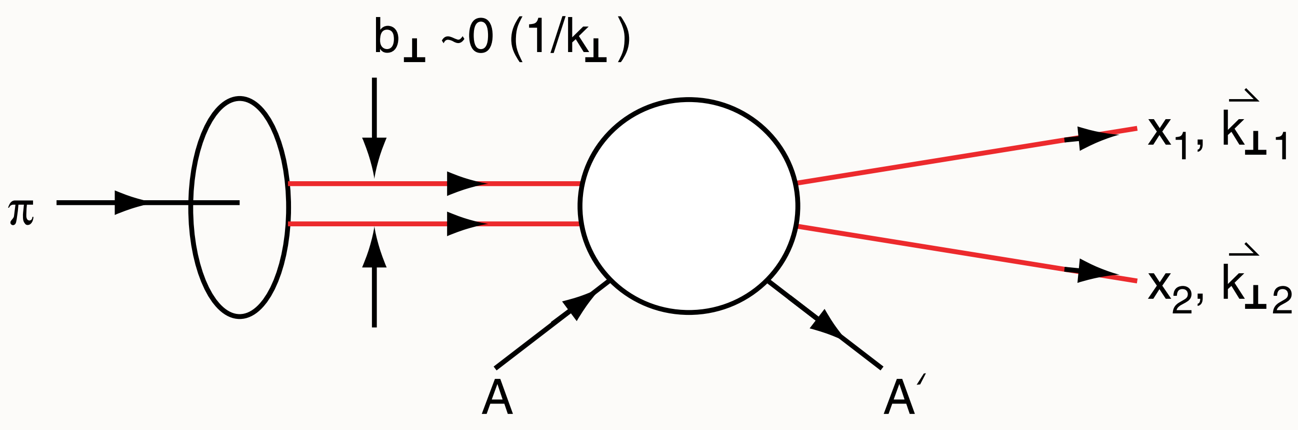
$$M \propto i\ s\ \alpha_s^2\ b_\perp^\pi\ b_\perp^N$$

$$\sigma \propto \alpha_s^4\ (b_\perp^\pi)^2\ (b_\perp^N)^2$$

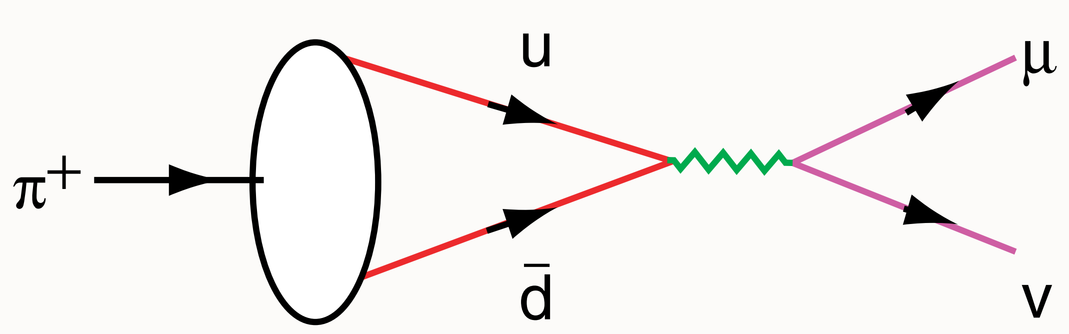
Target left intact

Diffraction, Rapidity gap

Fluctuation of a Pion to a Compact Color Dipole State

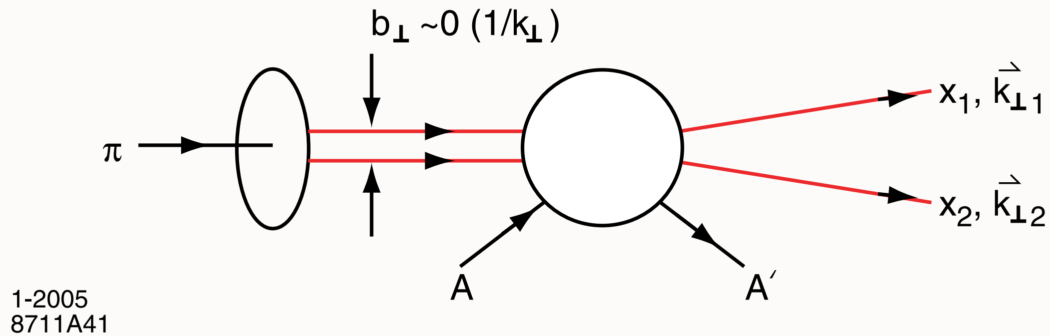


Color - Transparent Fock State Produces High Transverse Momentum Di-Jets



Same Fock State Determines Weak Decay

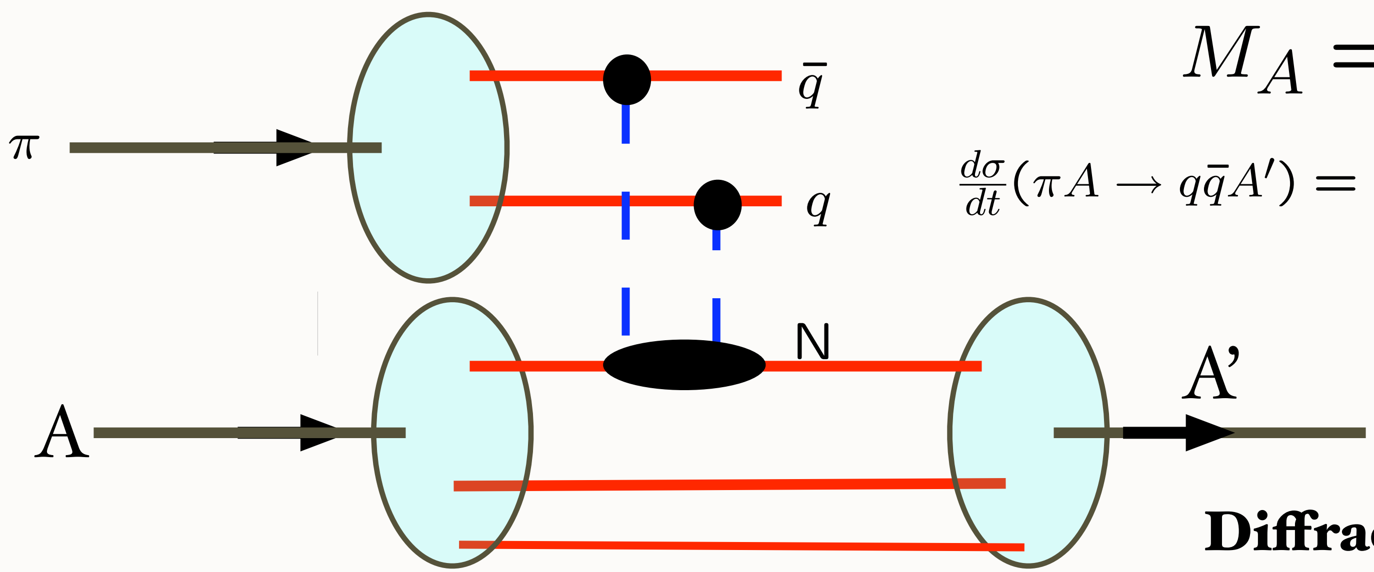
Key Ingredients in Ashery Experiment



Brodsky Mueller
Frankfurt Miller
Strikman

Small color-dipole moment pion not absorbed; interacts with each nucleon coherently

QCD COLOR Transparency



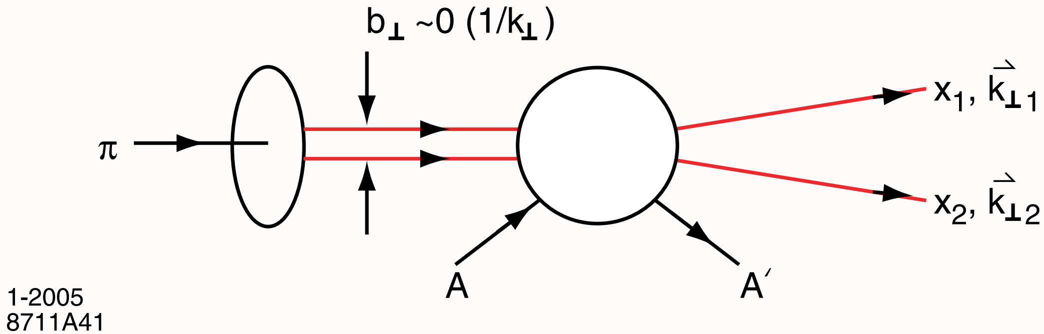
$$M_A = A\ M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2\ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N')\ F^2_A(t)$$

Target left intact

Diffraction, Rapidity gap

Key Ingredients in Ashery Experiment



$$\Delta P_z = \frac{M^2_{\text{final}} - M^2_{\text{initial}}}{2E_{\text{Lab}}}$$

Nuclear Coherence: Small color-dipole moment pion persists over long distances and time

Uncertainty principle: Small Longitudinal Momentum Transfer implies long coherence length

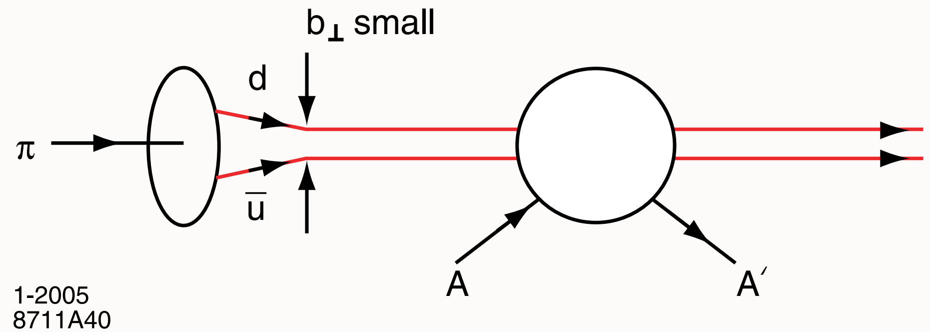
$$L_{\text{Ioffe}} = \frac{1}{\Delta P_z} \sim \frac{2E_{lab}}{\mathcal{M}^2_{q\bar{q}}}$$

For $E^{\pi}_{\text{Lab}} = 500\text{GeV}, \quad \mathcal{M}^2_{q\bar{q}} < 50\text{GeV}^2$

$$L_{\text{Ioffe}} > 4\text{fm} \sim R_A$$

Fluctuation of a Pion to a Compact Color Dipole State

Small Size Pion Can Interact Coherently on Each Nucleon of Nucleus



Diffractive Dijet Cross Section Color Transparent

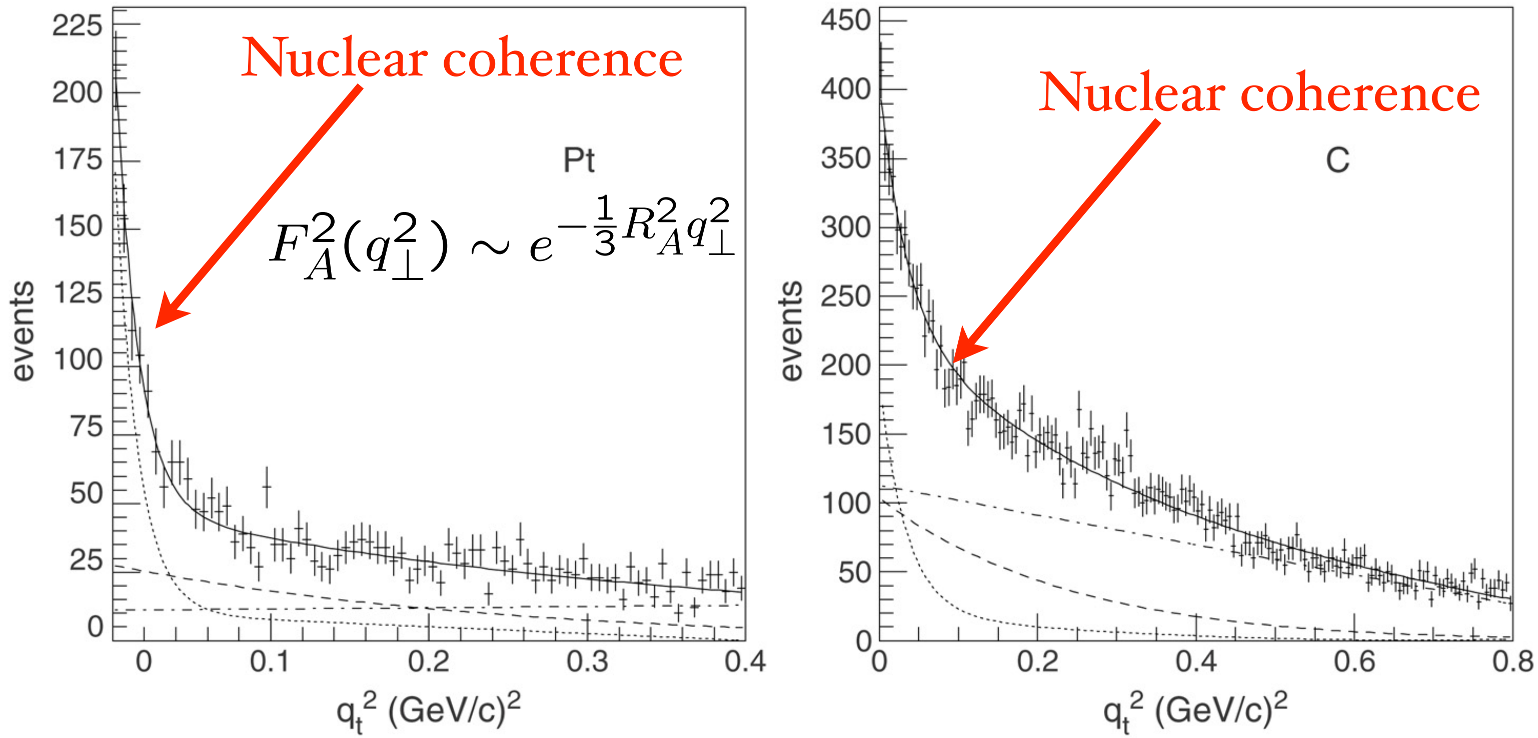
$$
\mathrm{M}(\pi A \to JetJetA') = A^1 M(\pi N \to JetJetN') F_A(t)
$$
$$
\mathrm{d}\sigma/dt(\pi A \to JetJetA') =
$$
$$
\mathrm{A}^2 d\sigma/dt(\pi N \to JetJetN')|F_A(t)|^2
$$
$$
\sigma \propto \frac{A^2}{R_A^2} \sim A^{4/3}
$$

- **Fully coherent interactions between pion and nucleons.**
- **Emerging Di-Jets do not interact with nucleus.**

$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

$$\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0$$

$$\sigma \propto A^{4/3}$$



Ashery E791:
Measure pion LFWF in diffractive dijet production
Confirms color transparency !

Mueller, sjb; Bertsch et al; Frankfurt, Miller, Strikman

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
$1.25 < k_t < 1.5$	1.64 +0.06 -0.12	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

α (Incoh.) = 0.70 ± 0.1

Conventional Glauber Theory Ruled Out !

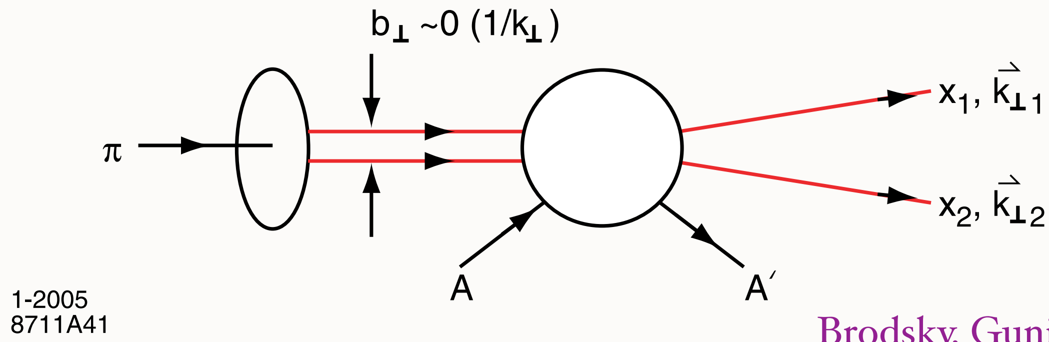
Factor of 7

FermiLab E791
Ashery et al

k_t bin (GeV/c)	α	$\Delta\alpha_{stat}$	$\Delta\alpha_{sys}$	$\Delta\alpha$	α(CT)
1.25–1.5	1.64	± 0.05	$+0.04$–0.11	$+0.06$–0.12	1.25
1.5–2.0	1.52	± 0.09	± 0.08	± 0.12	1.45
2.0–2.5	1.55	± 0.11	± 0.12	± 0.16	1.60

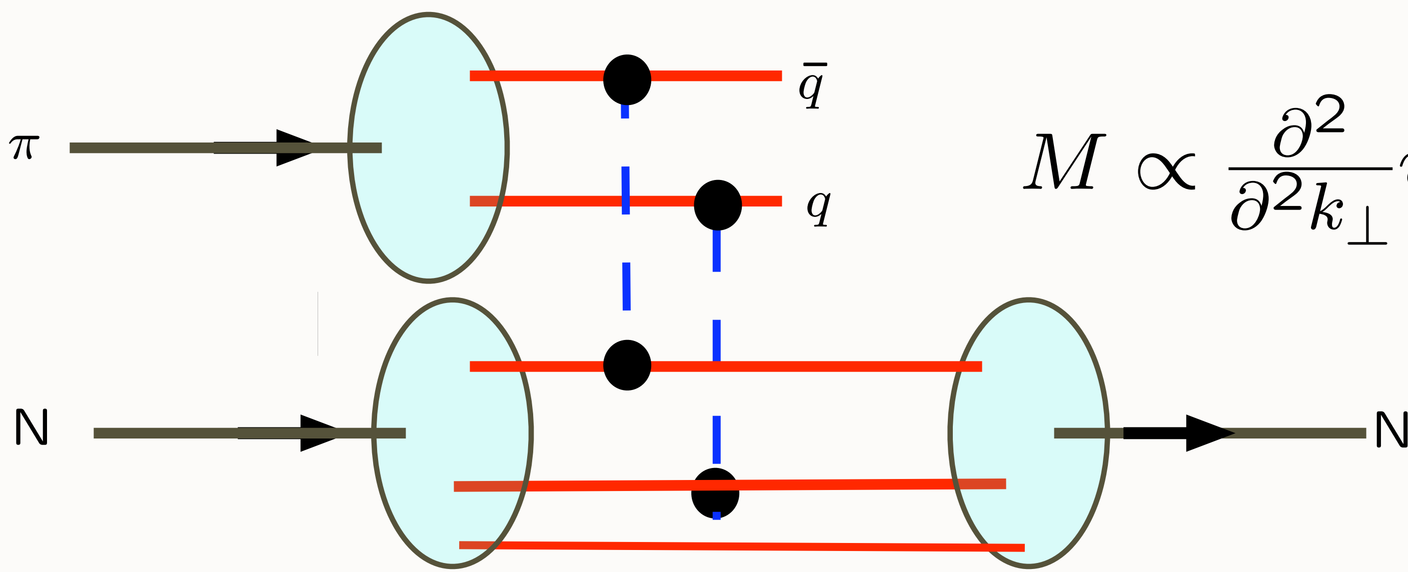
The exponent in $\sigma \propto A^{\alpha}$, experimental results for coherent dissociation and the color-transparency (CT) predictions [69]

Key Ingredients in Ashery Experiment

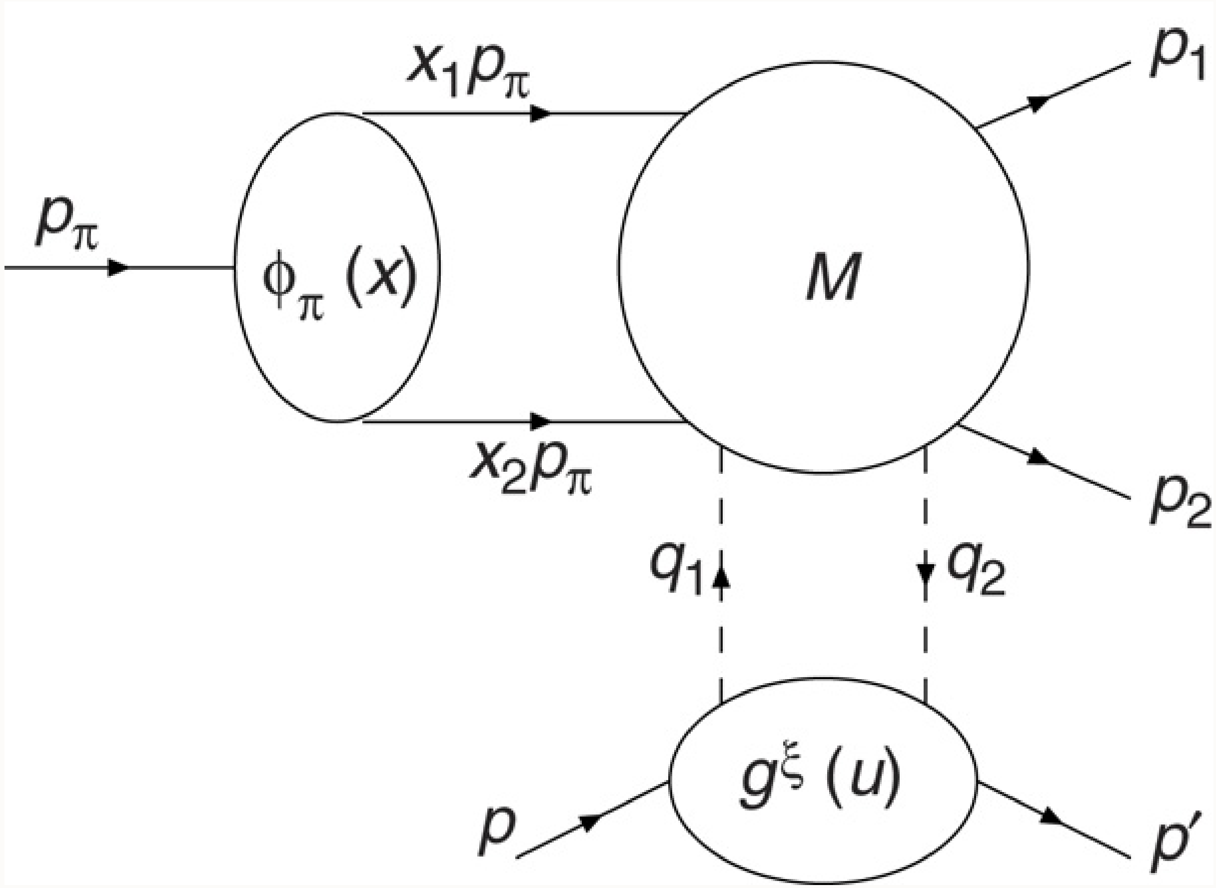


Brodsky, Gunion, Frankfurt, Mueller, Strikman
Frankfurt, Miller, Strikman

Two-gluon exchange measures the second derivative of the pion light-front wavefunction



$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$



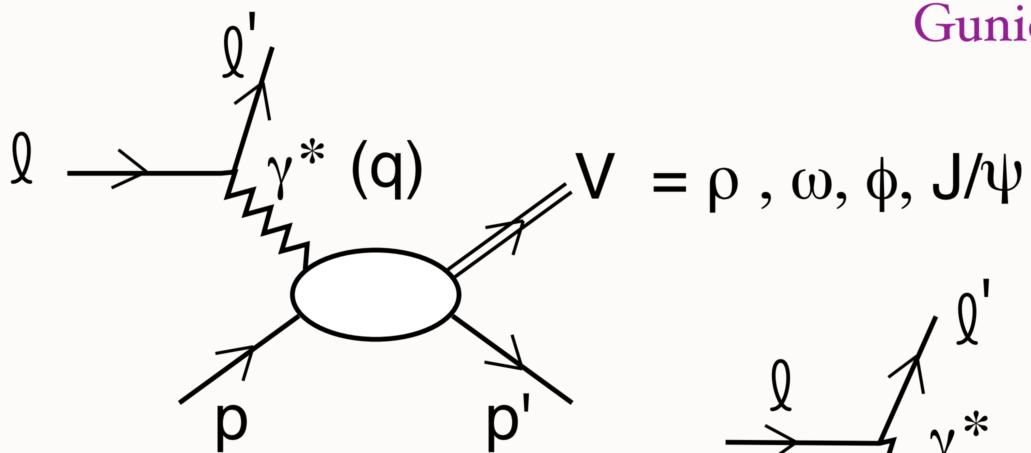
x

1-x

gluons measure size of color dipole

$$\frac{d\sigma}{dk_t^2} \propto |\alpha_s(k_t^2) x_N G(u, k_t^2)|^2 \left| \frac{\partial^2}{\partial k_t^2} \psi(x, k_t) \right|^2$$

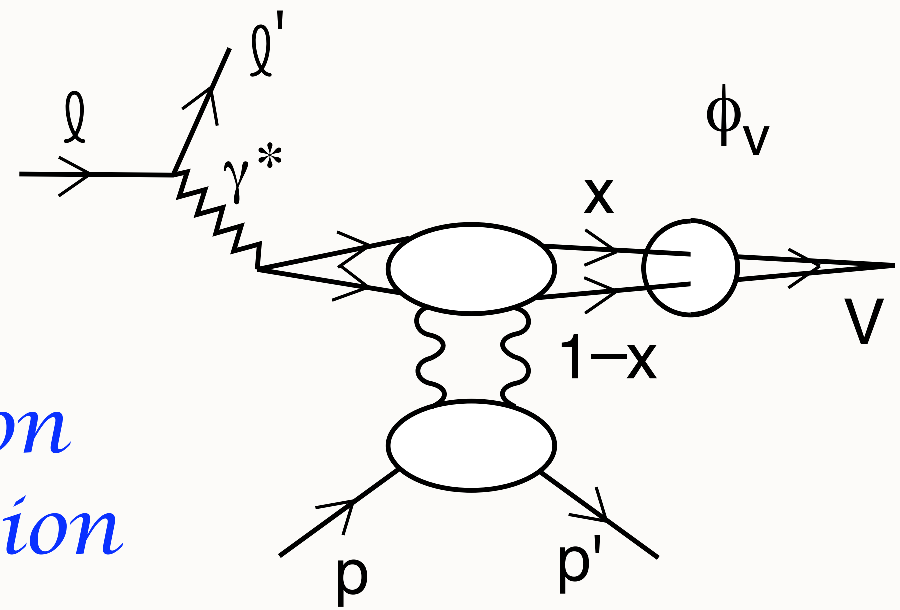
Gunion, Frankfurt, Mueller, Strikman, sjb

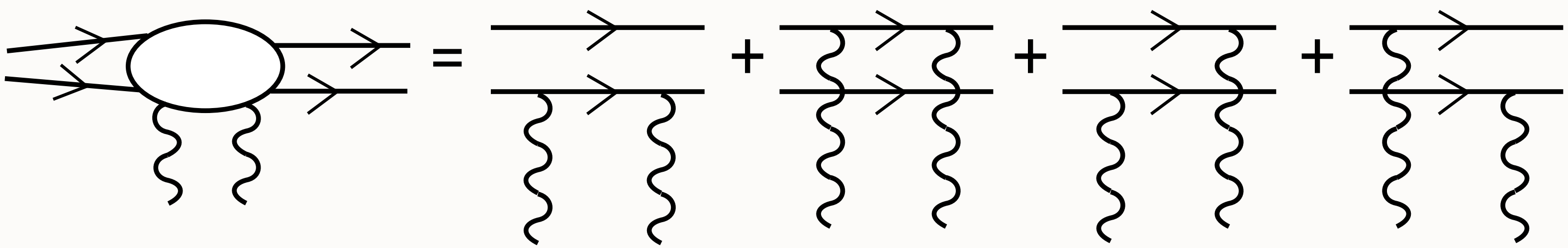


Large $-q^2 = Q^2$

⇨

Vector Meson Leptoproduction

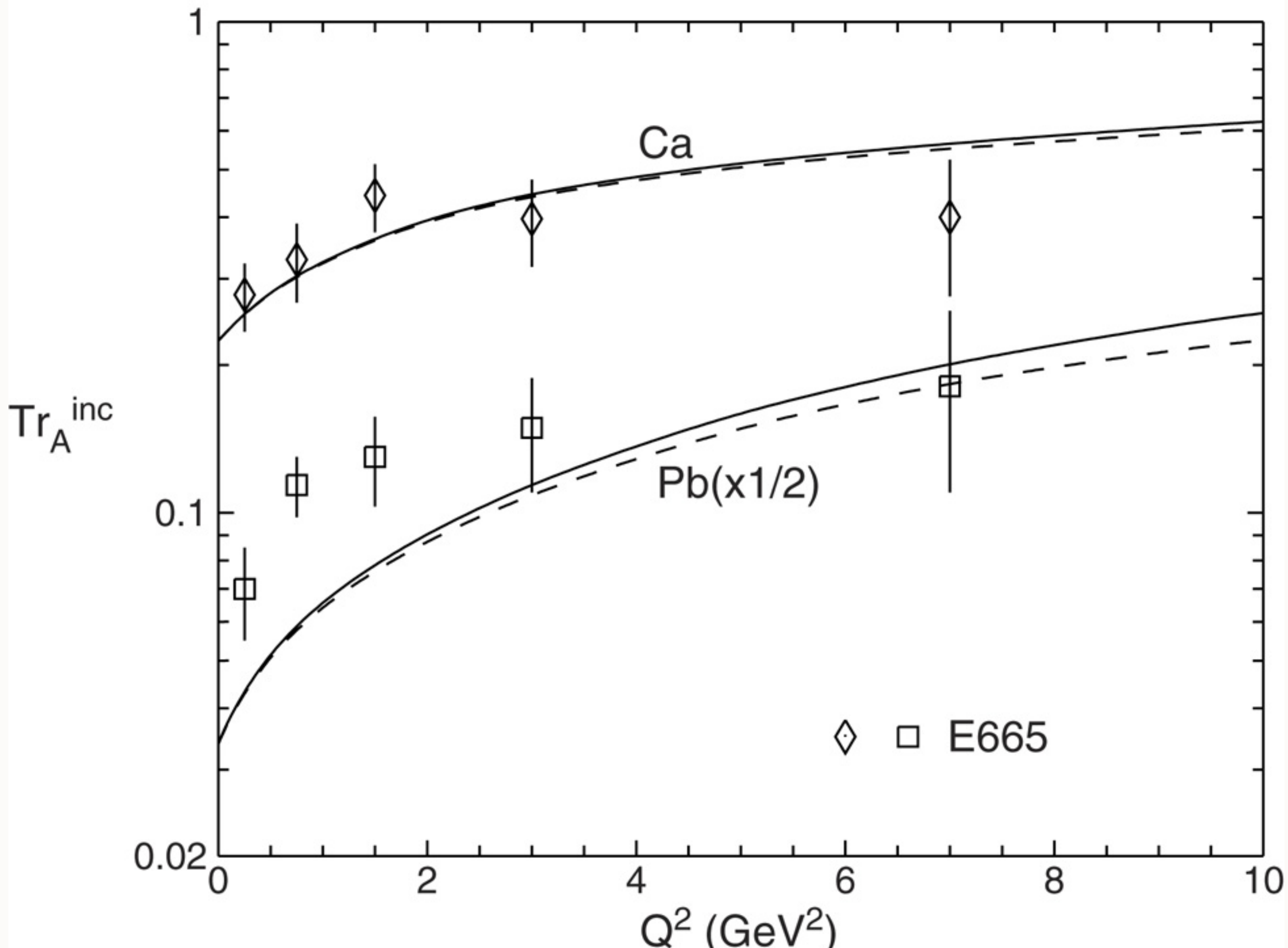




$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_{\gamma^*}(x, k_\perp)$$

Convolute with

$$\phi(x,Q) = \int d^2k_\perp \Psi_{q\bar{q}}(x, \vec{k}_\perp)$$



Verification of color transparency in incoherent vector meson electroproduction

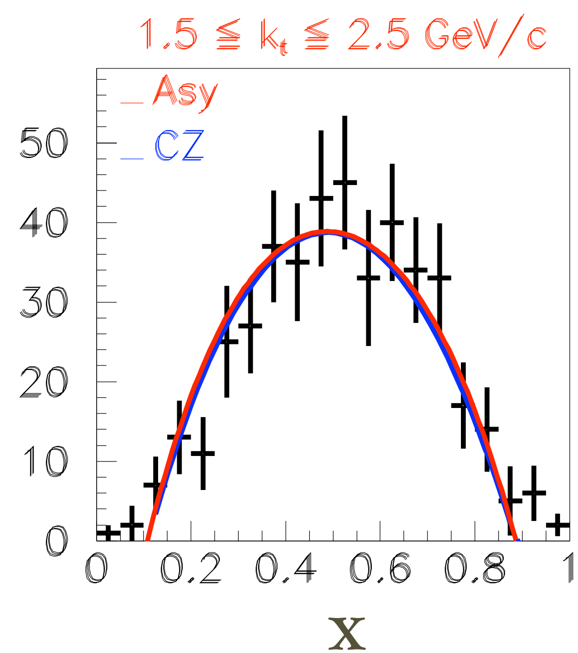
Fig. 6. Nuclear transparencies Tr_A^{inc} measured for incoherent ρ^0 production by Fermilab experiment E665 [61]. calculations are from [64]; solid line with full calculations, dashed lines with frozen approximation.

Diffractive Dissociation of a Pion into Dijets

$$\pi A \rightarrow Jet\, Jet\, A'$$

- E791 Fermilab Experiment Ashery et al
- 500 GeV pions collide on nuclei keeping it intact
- Measure momentum of two jets
- Study momentum distributions of pion LF wavefunction

$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_\perp)$$



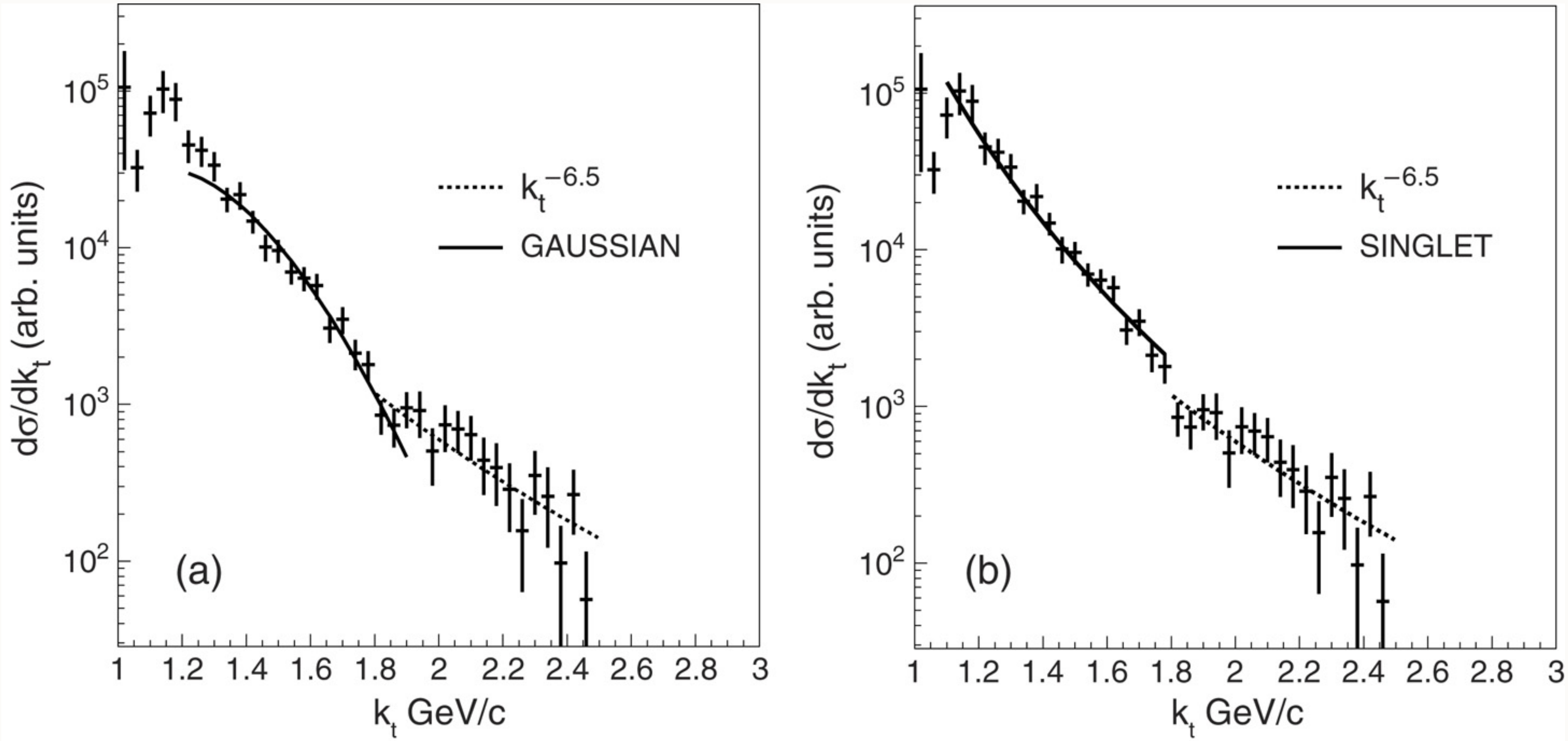


Fig. 24. Comparison of the experimental k_t distribution [96] with fits derived from: (a) Gaussian LCWF [98] for low and a power law dependence: $\frac{d\sigma}{dk_t} \propto k_t^n$, as expected from perturbative calculations, for high k_t; (b) Two-term Singl Model wave function [99] for low k_t and a power law for high k_t.

Diffractive Dissociation of Pion into Di-Jets

- Verify Color Transparency
- Pion Interacts coherently on each nucleon of nucleus!

$$M \propto A, \ \sigma \propto A^2$$

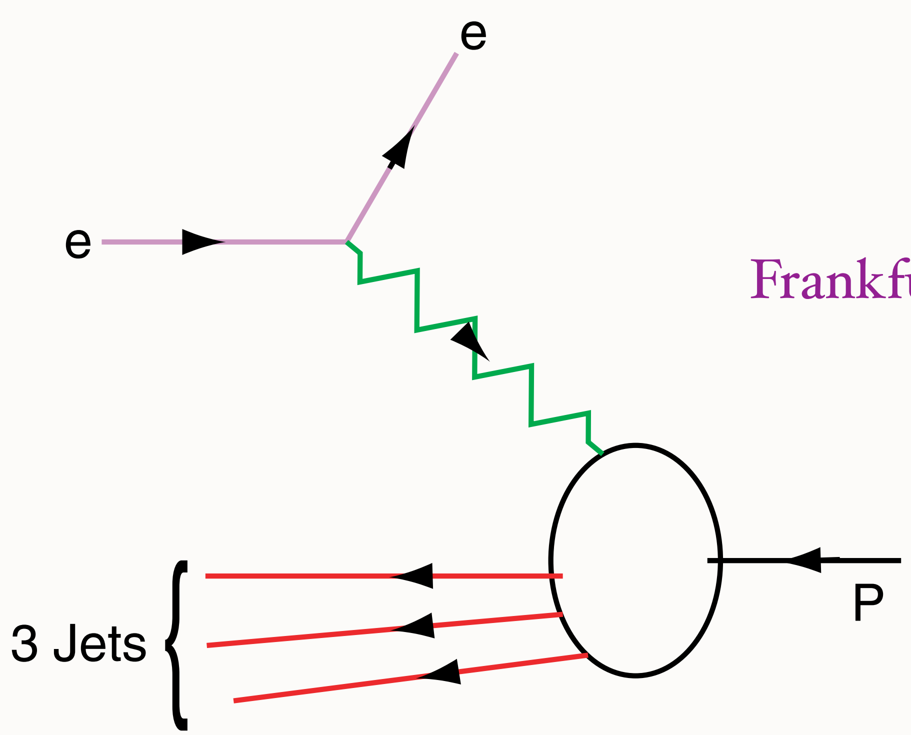
- Pion Distribution similar to Asymptotic Form

$$\psi(x, k_\perp) \propto x(1-x)$$

- Scaling in transverse momentum consistent with PQCD

Compare with AdS/CFT predictions

Coulomb Dissociate Proton to Three Jets at HERA



Frankfurt, Strikman, Miller;

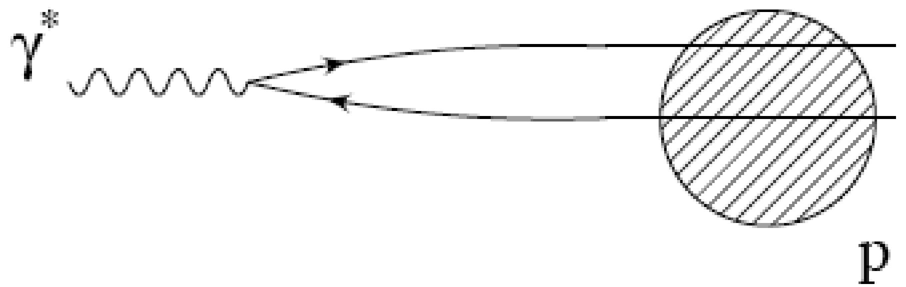
Measure $\Psi_{qqq}(x_i, \vec{k}_{\perp i})$ valence wavefunction of proton

Dipole models

Many models are based on using the dipole frame

→ Use proton's rest frame, or more generally, a frame where the photon has very large lightcone q^+ momentum

Then the photon fluctuates into a *color dipole* before hitting the proton



At small x_B the fluctuation is very long-lived and the $q\bar{q}$ pair of the dipole is transversely frozen during the interaction.

Very useful in small-x physics!

Measurement of the photon QED LFWF

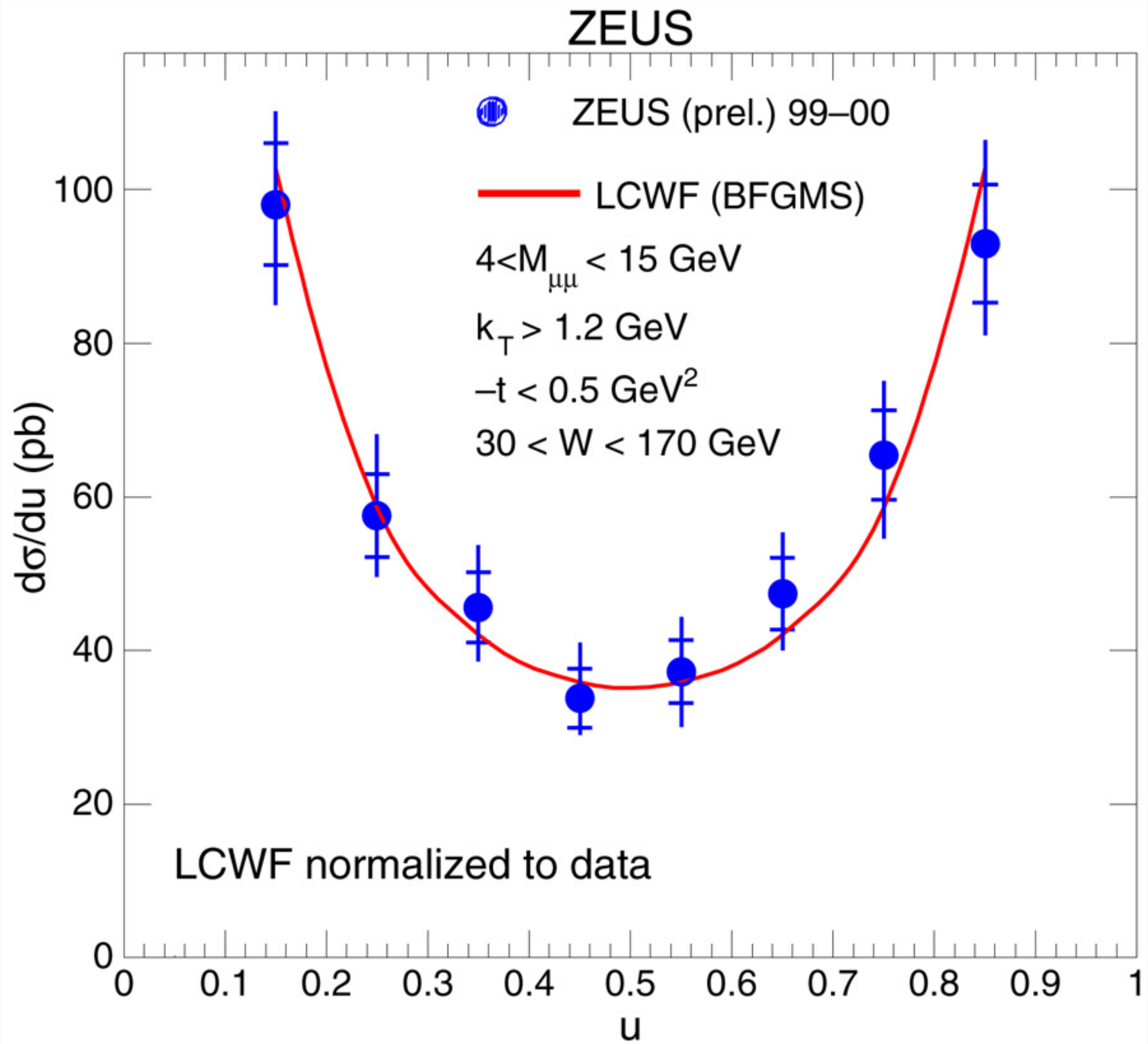


Fig. 39. Differential cross section $d\sigma/du$ for the $\gamma \rightarrow \mu^+\mu^-$ process measured for $30 < W < 170$ GeV, $4 < M_{\mu\mu} < 15$ GeV, $k_T > 1.2$ GeV$/c$ and $-t < 0.5$ (GeV$/c)^2$. The inner error bars show the statistical uncertainty; the outer error bars show the statistical and systematics added in quadrature. The data points are compared to the prediction of LCWF theory [16]. The theory is normalized to data.

Ashery

The remarkable anomalies of proton-proton scattering

- Double spin correlations
- Single spin correlations
- Color transparency

PQCD and Exclusive Processes

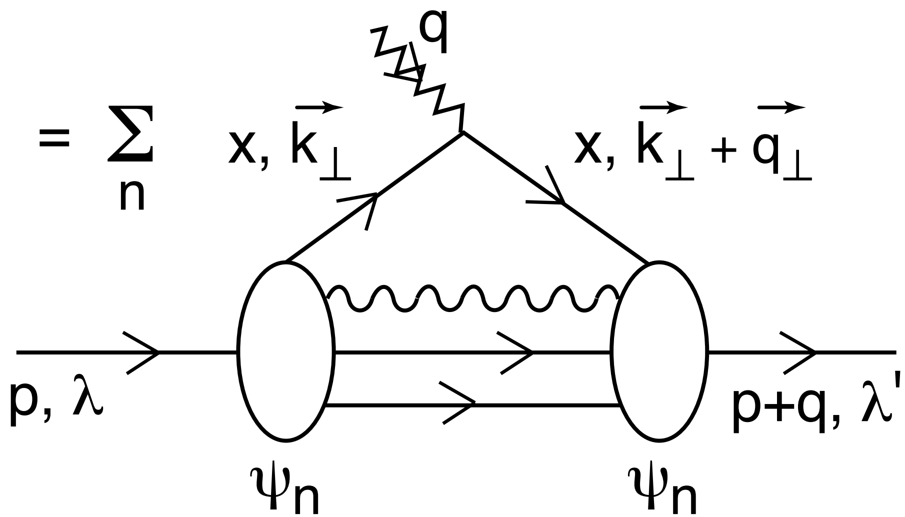
Lepage; SJB
Efremov, Radyuskin

$$M = \int \prod dx_i dy_i \phi_F(x, \tilde{Q}) \times T_H(x_i, y_i, \tilde{Q}) \phi_I(y_i, Q)$$

- Iterate kernel of LFWFs when at high virtuality; distribution amplitude contains all physics below factorization scale
- Rigorous Factorization Formulae: Leading twist
- Underly Exclusive B-decay analyses
- Distribution amplitude: gauge invariant, OPE, evolution equations, conformal expansions
- BLM scale setting: sum nonconformal contributions in scale of running coupling
- Derive Dimensional Counting Rules/ Conformal Scaling

Form Factors $\ell p \to \ell' p'$ $\langle p' \lambda' | J^+(0) | p \lambda \rangle$

$$F_{\lambda\lambda'}(Q^2) = \sum_n$$

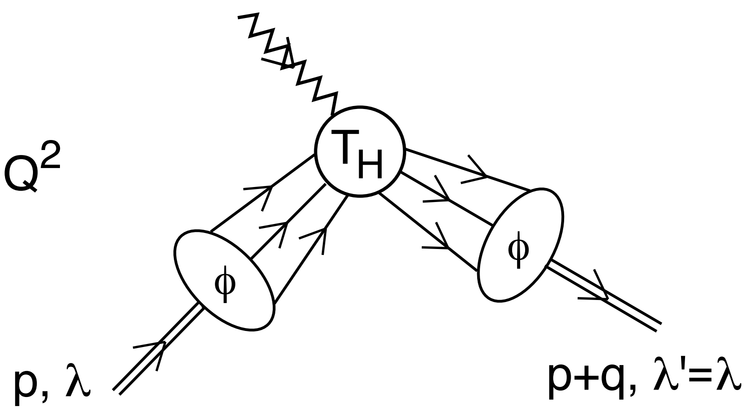


Lepage, Sjb
Efremov
Radyushkin

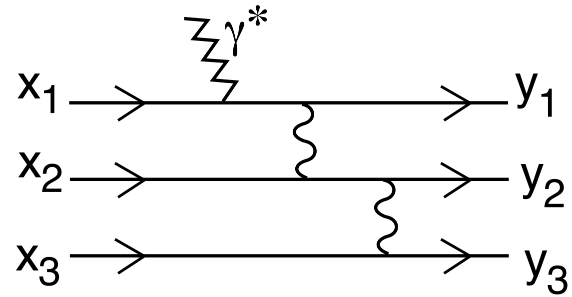
QCD Factorization

Scaling Laws from PQCD or AdS/CFT

⇨ Large Q^2



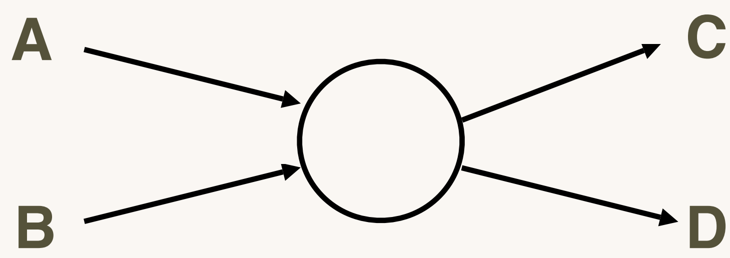
$T_H = \sum$



$+ \ \ldots$

$$= \frac{\alpha_s^2}{Q^4} f(x_i, y_i,)$$

Constituent Counting Rules



$$\frac{d\sigma}{dt}(s,t) = \frac{F(\theta_{\text{cm}})}{s^{[n_{\text{tot}}-2]}} \qquad s = E^2_{\text{cm}}$$

$$F_H(Q^2) \sim [\frac{1}{Q^2}]^{n_H - 1} \qquad -t = Q^2$$

- Point-like quark and gluon constituents plus scale-invariant interactions

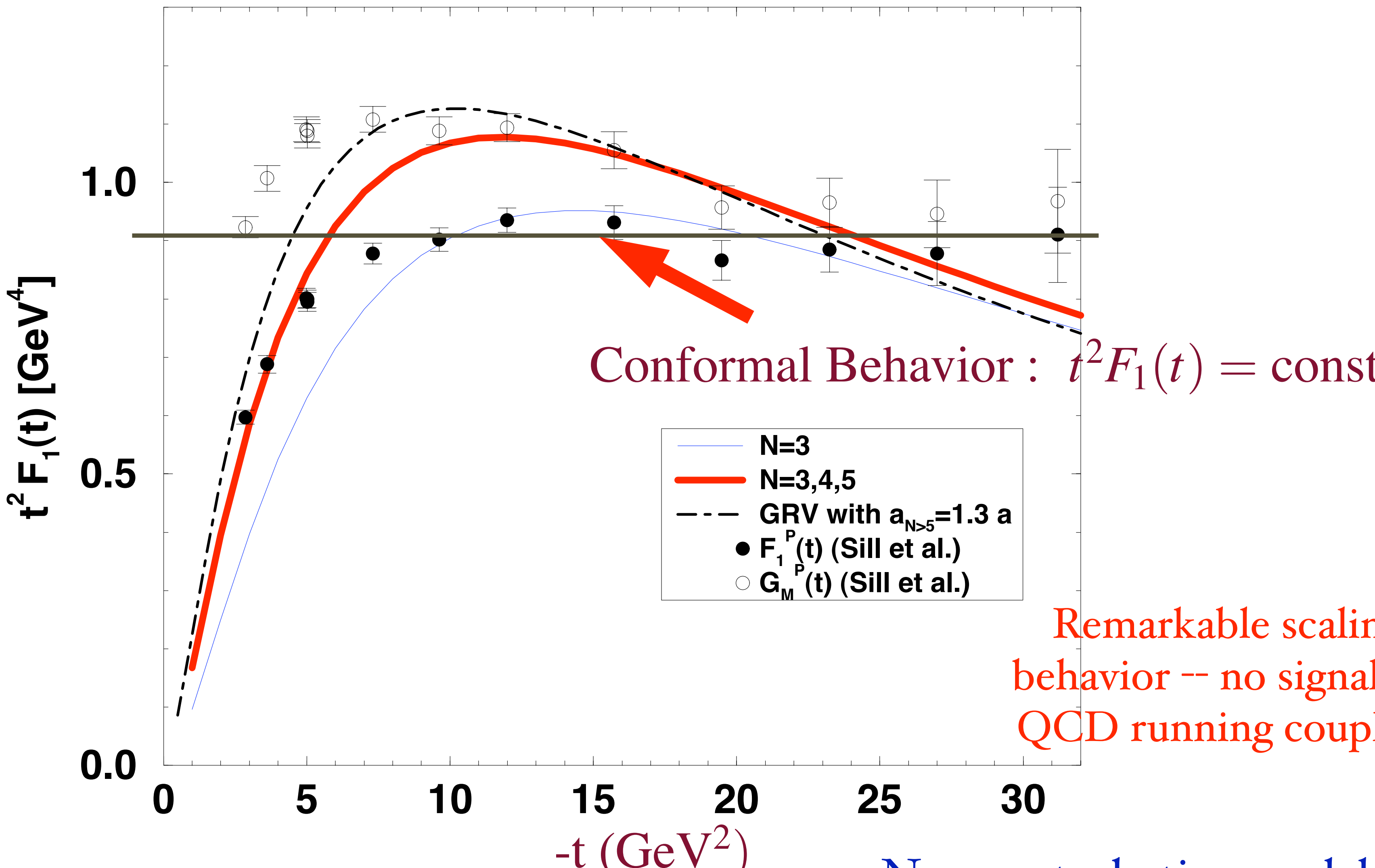
Farrar, sjb; Matveev et al

- Fall-off of Amplitude measures degree of compositeness (twist)
- Near-Conformal Invariance of QCD
- QCD: Logarithmic Modification by running coupling and Evolution Equations

Lepage, sjb; Efremov, Radyushkin

- Angular and Spin Dependence -- Fundamental Wavefunctions: Hadron Distribution Amplitudes $\phi_H(x_i, Q)$

Proton Form Factor



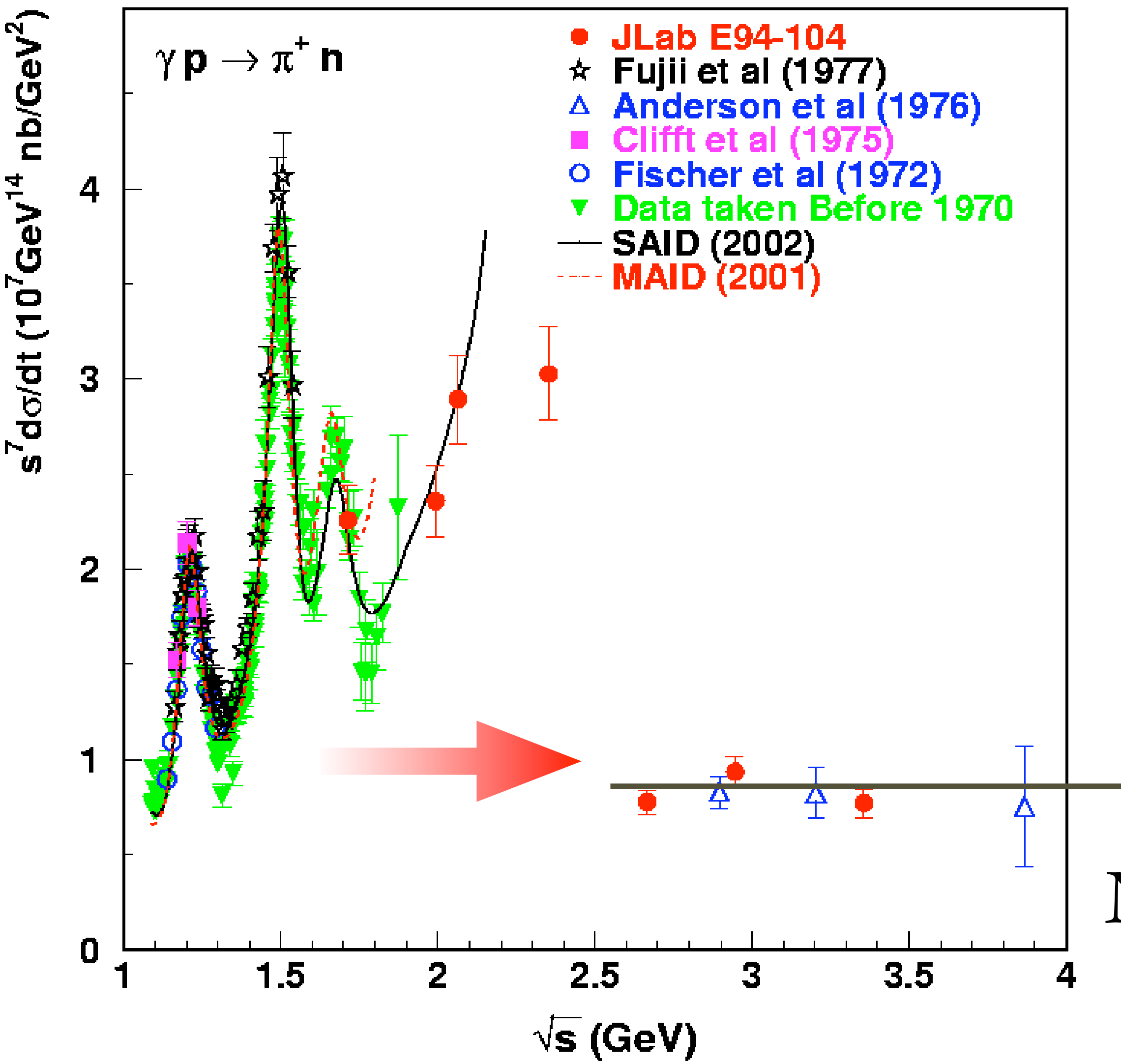
Remarkable scaling behavior -- no signal for QCD running coupling

Non-perturbative model: Diehl, Kroll

Test of PQCD Scaling

Constituent counting rules

Farrar, sjb; Muradyan, Matveev, Taveklidze



$s^7 d\sigma/dt(\gamma p \to \pi^+ n) \sim const$

fixed θ_{CM} scaling

PQCD and AdS/CFT:

$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B \to C+D) =$
$F_{A+B\to C+D}(\theta_{CM})$

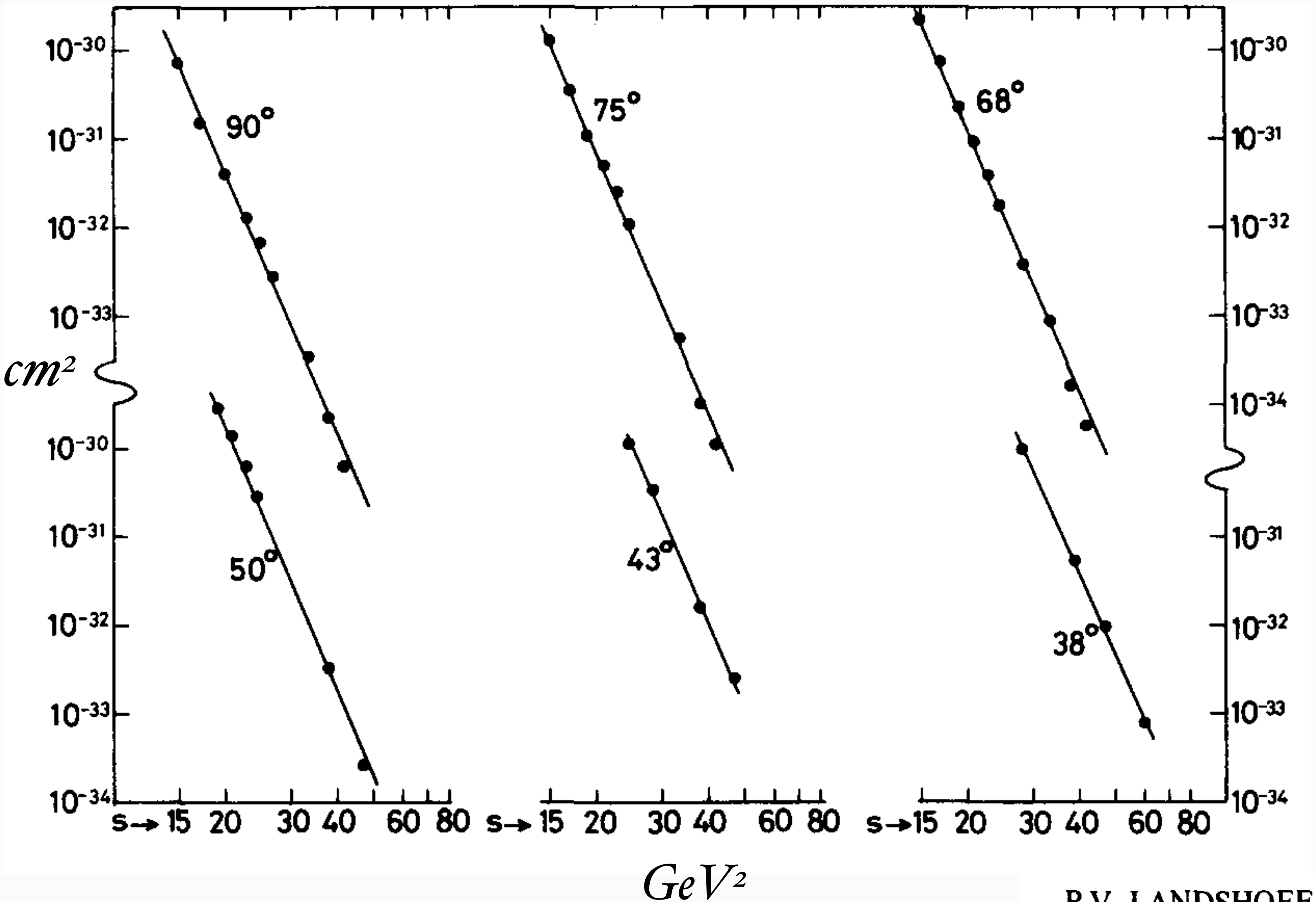
$s^7\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = F(\theta_{CM})$
$n_{tot} = 1+3+2+3 = 9$

No sign of running coupling

Conformal invariance at high momentum transfers!

Quark-Counting : $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$

$n = 4 \times 3 - 2 = 10$



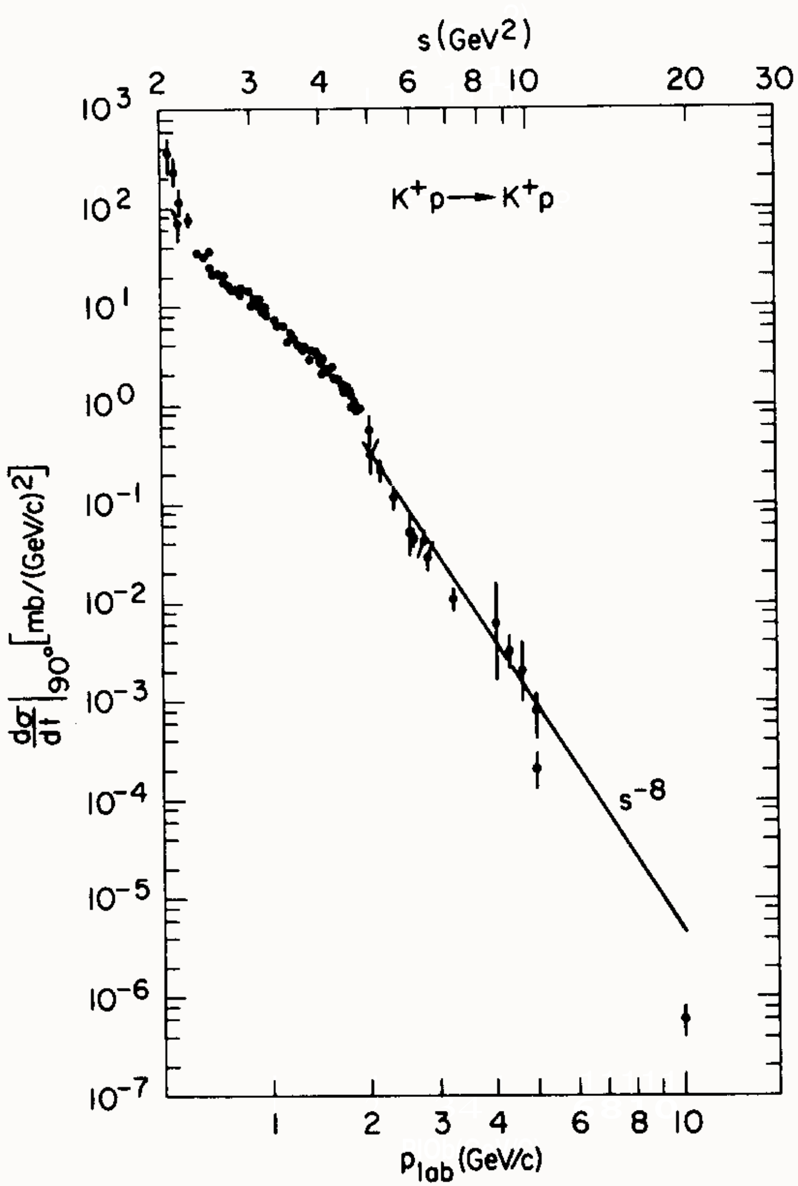
P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

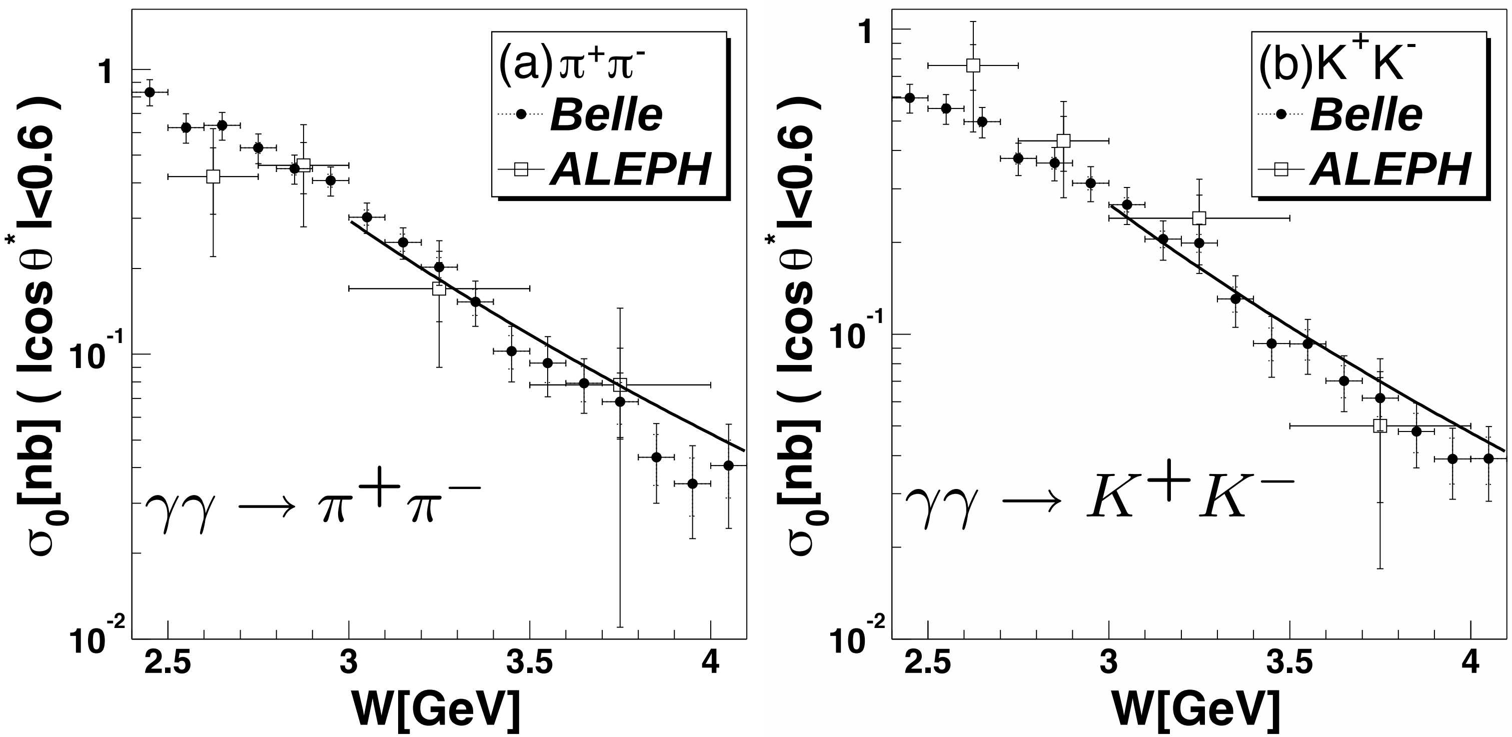
Reflects underlying conformal scale-free interactions

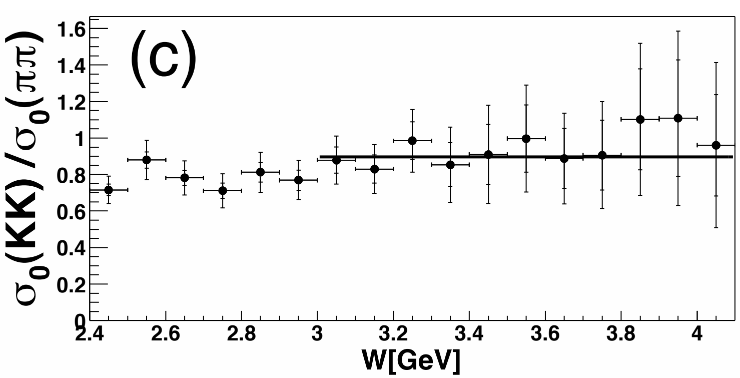
Quark-Counting



$$\frac{d\sigma}{dt}(K^+p \to K^+p) = \frac{F(\theta_{CM})}{s^8}$$

$$n = 2 \times 3 + 2 \times 2 - 2 = 8$$





$$s = E_{\rm cm}^2 = W^2 = Q^2$$

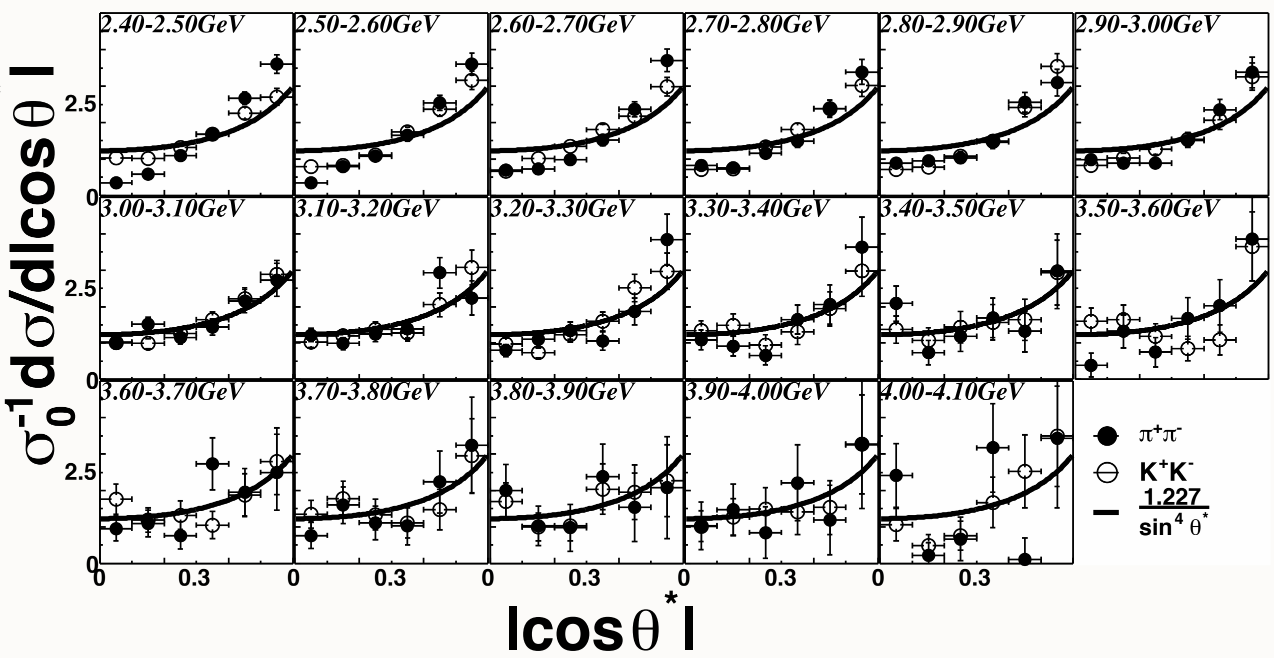
PQCD, AdS/CFT:

$$\Delta\sigma(\gamma\gamma \to \pi^+\pi^-, K^+, K^-) \sim 1/W^6$$

$$|\cos(\theta_{CM})| < 0.6$$

Fig. 5. Cross section for (a) $\gamma\gamma\to\pi^+\pi^-$, (b) $\gamma\gamma\to K^+K^-$ in the c.m. angular region $|\cos\theta^*| < 0.6$ together with a W^{-6} dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data above 3 GeV. The errors indicated by short ticks are statistical only.

$$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to M^+M^-) \approx \frac{16\pi\alpha^2}{s}\frac{|F_M(s)|^2}{\sin^4\theta^*},$$

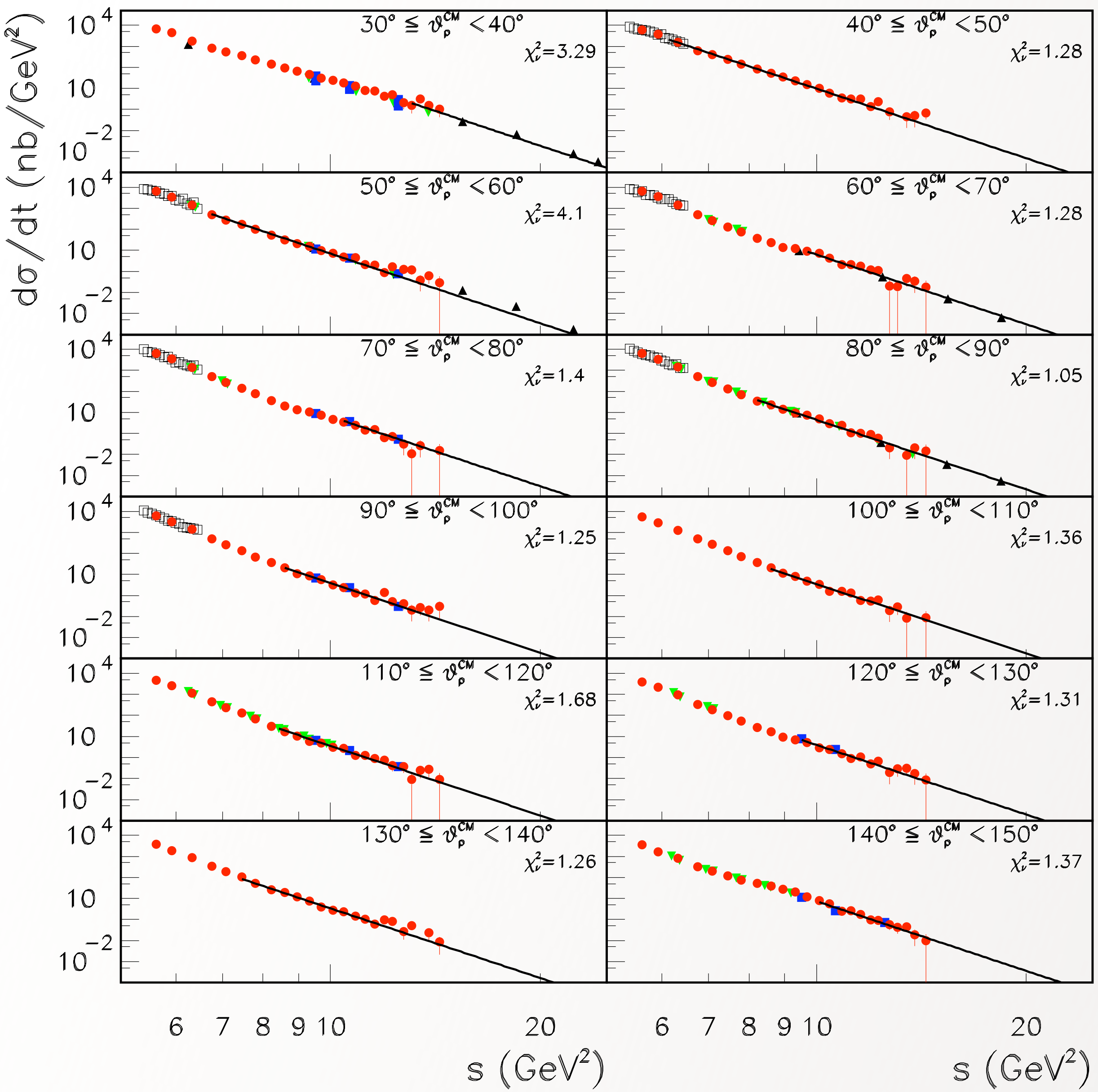


Measurement of the $\gamma\gamma \to \pi^+\pi^-$ and $\gamma\gamma \to K^+K^-$ processes at energies of 2.4–4.1 GeV

Belle Collaboration

Fig. 4. Angular dependence of the cross section, $\sigma_0^{-1} d\sigma/d|\cos\ \theta^*|$, for the $\pi^+\pi^-$(closed circles) and K^+K^-(open circles) processes. The curves are $1.227 \times \sin^{-4}\theta^*$. The errors are statistical only.

Deuteron Photodisintegration & Dimensional Counting Rules



PQCD and AdS/CFT:

$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B\to C+D) = \mathrm{F}_{A+B\to C+D}(\theta_{CM})$$

$$s^{11}\frac{d\sigma}{dt}(\gamma d\to np) = F(\theta_{CM})$$

$$n_{tot}-2 = (1+6+3+3)-2 = 11$$

Conformal invariance at high momentum transfers!

$$s^{11}\frac{d\sigma}{dt}(\gamma d \rightarrow np) = F(\theta_{CM})$$

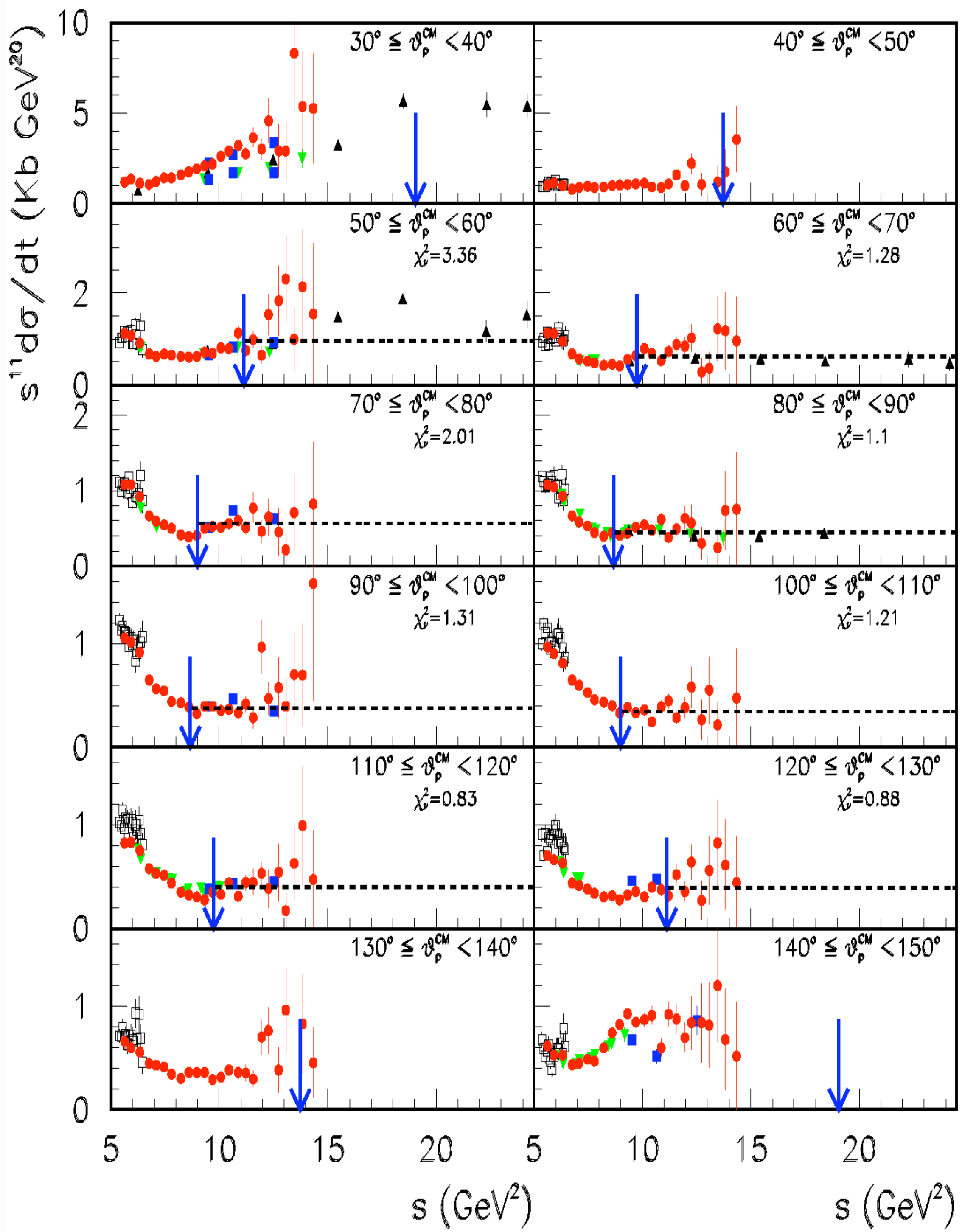
Fit of dσ/dt data for the central angles and $P_T \geq 1.1$ GeV/c with $A\ s^{-11}$

For all but two of the fits $\chi^2 \leq 1.34$

- Better χ^2 at 55° and 75° if different data sets are renormalized to each other
- No data at $P_T \geq 1.1$ GeV/c at forward and backward angles
- Clear s^{-11} behaviour for last 3 points at 35°

Data consistent with CCR

P.Rossi et al, P.R.L. 94, 012301 (2005)



Quantum Chromodynamic Predictions for the Deuteron Form Factor

$$F_d(Q^2) = \int_0^1 [dx][dy]\varphi_d^\dagger(y,Q) \times T_H^{6q+\gamma^*\to 6q}(x,y,Q)\varphi_d(x,Q), \qquad (1)$$

where the hard-scattering amplitude

$$T_H^{6q+\gamma^*\to 6q} = [\alpha_s(Q^2)/Q^2]^5 t(x,y) \times [1 + O(\alpha_s(Q^2))] \qquad (2)$$

gives the probability amplitude for scattering six quarks collinear with the initial to the final deuteron momentum and

$$\varphi_d(x_i,Q) \propto \int^{k_{\perp i}<Q} [d^2k_\perp]\psi_{qqq\,qqq}(x_i,\vec{k}_{\perp i}) \qquad (3)$$

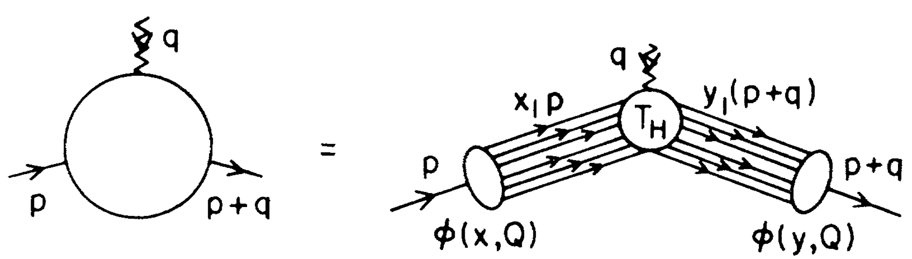


FIG. 1. The general structure of the deuteron form factor at large Q^2.

Ji, Lepage, sjb

QCD Prediction for Deuteron Form Factor

$$F_d(Q^2) = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n^d - \gamma_m^d} \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$

Define "Reduced" Form Factor

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_N^{\,2}(Q^2/4)}.$$

Same large momentum transfer behavior as pion form factor

$$f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-(2/5)\,C_F/\beta}$$

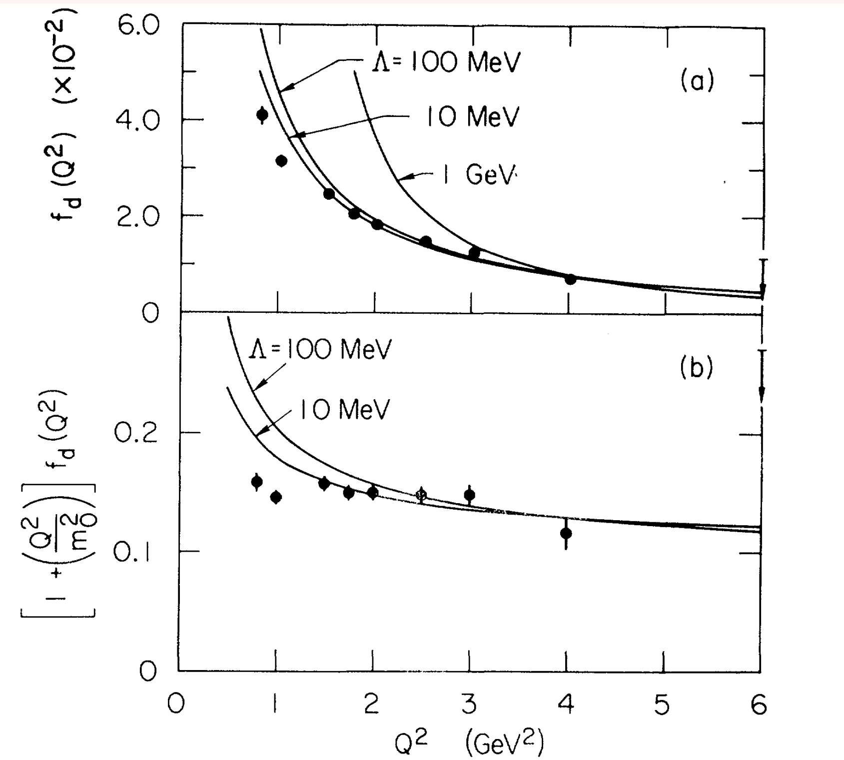
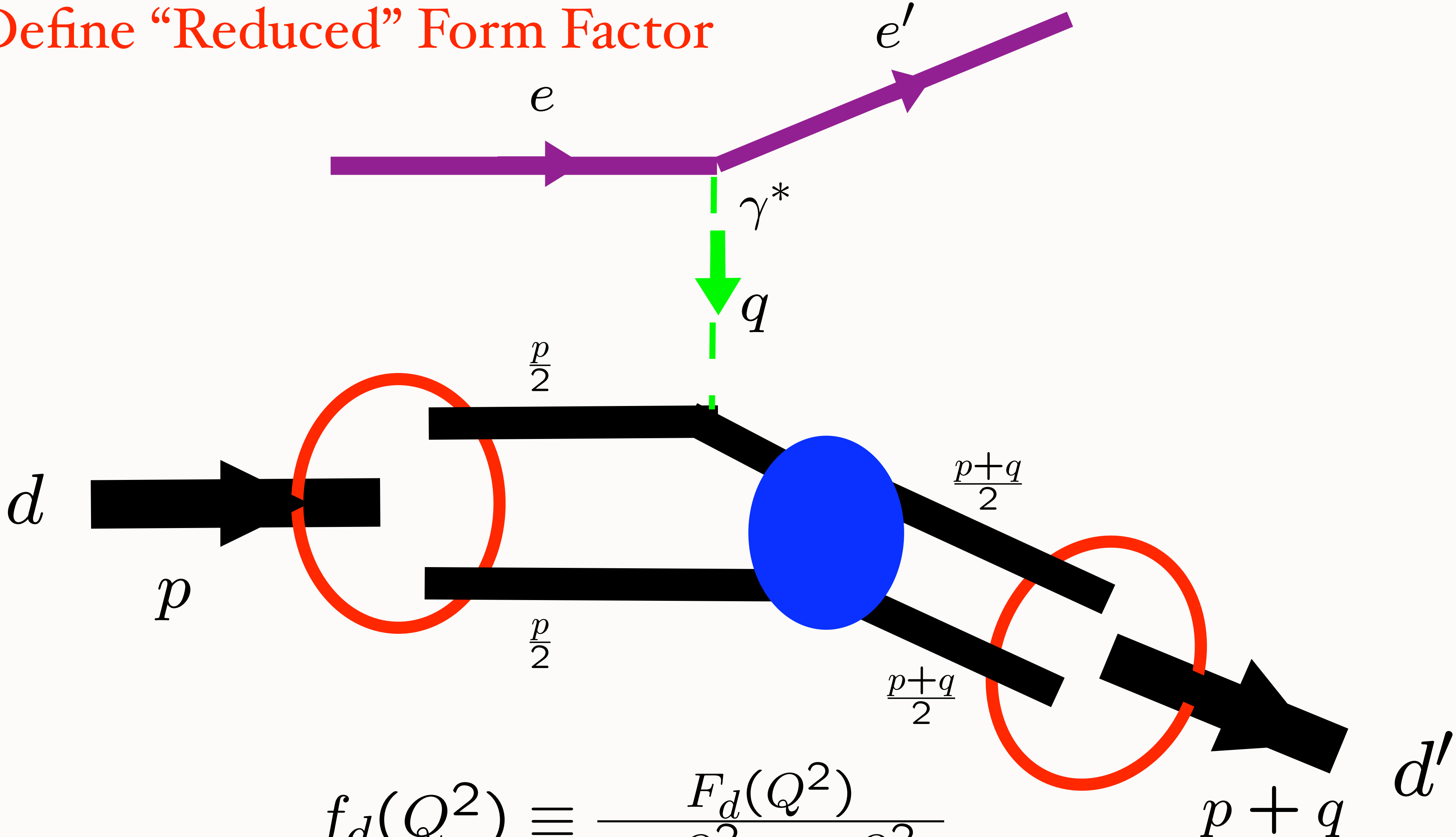


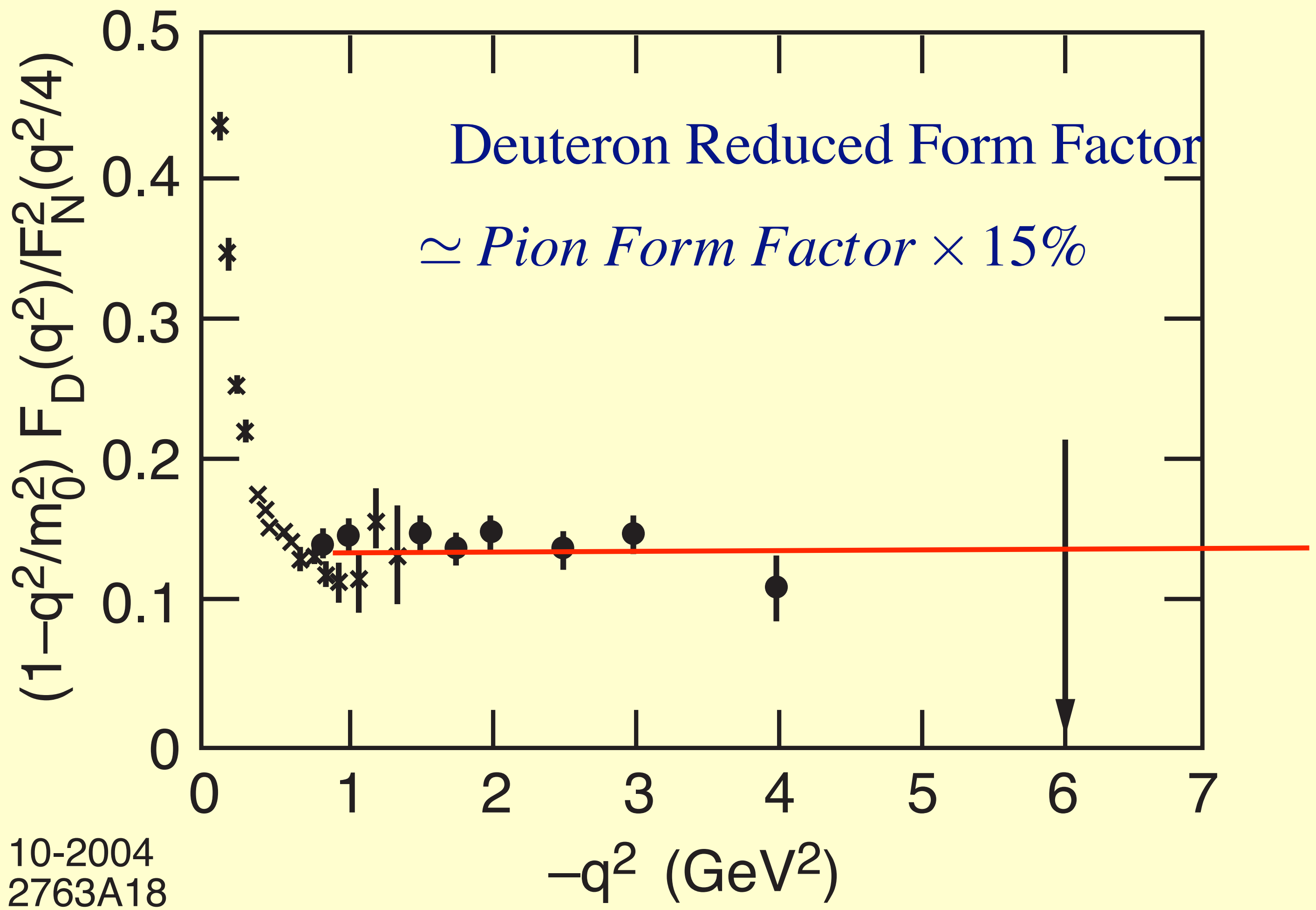
FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \text{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4$ GeV^2 data point. (b) Comparison of the prediction $[1 + (Q^2/m_0^2)] f_d(Q^2) \propto [\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with the above data. The value $m_0^2 = 0.28$ GeV^2 is used (Ref. 8).

Define "Reduced" Form Factor



$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_p(\frac{Q^2}{4})F_n(\frac{Q^2}{4})}$$

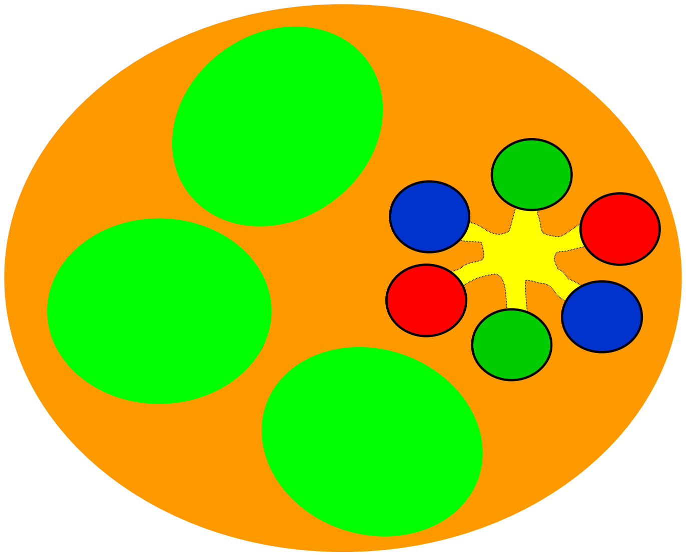
Elastic electron-deuteron scattering



- 15% Hidden Color in the Deuteron

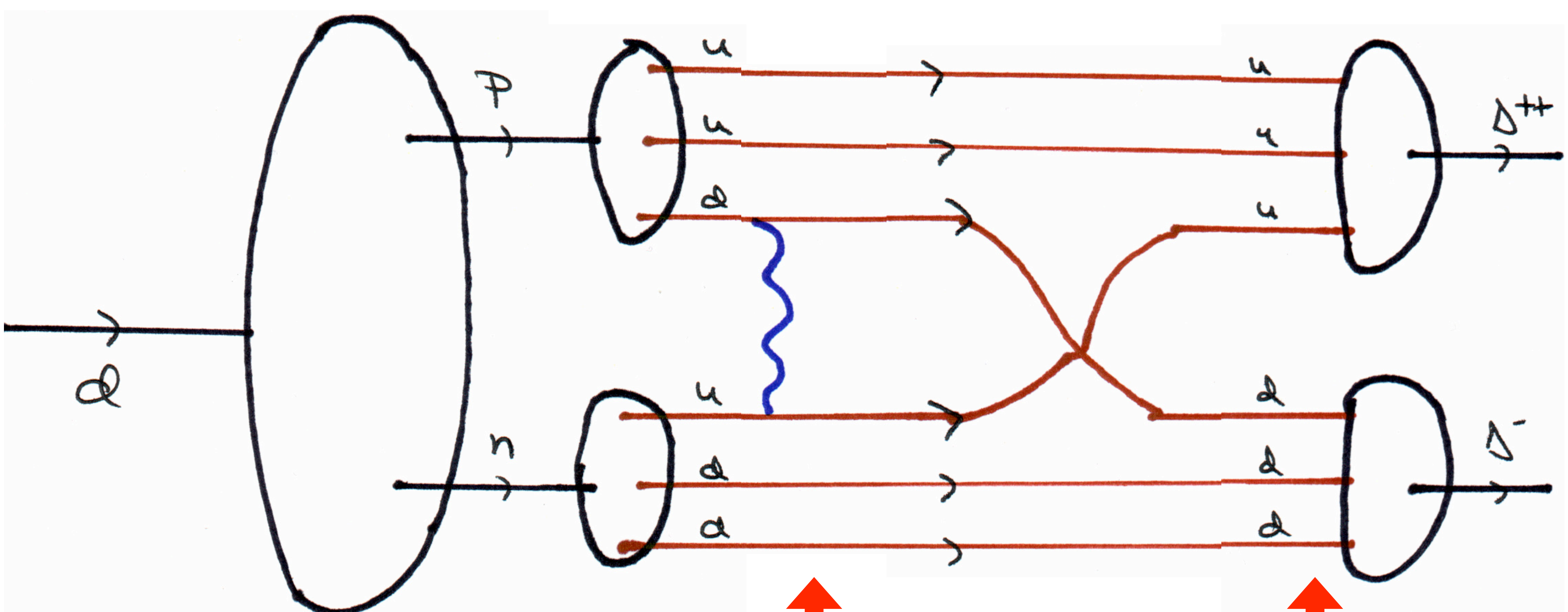
Do multi-quark clusters exist in the nuclear wavefunction?

Does the nucleus only consist of nucleons?



Hidden Color!

Structure of Deuteron in QCD



Hidden Color Fock State

Delta-Delta Fock State

Hidden Color

- Deuteron six quark wavefunction: Lepage, Ji, sjb

- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>

- Components evolve towards equality at short distances

- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer

- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Ratio = 2/5 for asymptotic wf

The evolution equation for six-quark systems in which the constituents have the light-cone longitudinal momentum fractions x_i $(i=1,2,\ldots,6)$ can be obtained from a generalization of the proton (three-quark) case.[2] A nontrivial extension is the calculation of the color factor, C_d, of six-quark systems[5] (see below). Since in leading order only pairwise interactions, with transverse momentum Q, occur between quarks, the evolution equation for the six-quark system becomes $\{[dy]=\delta(1-\sum_{i=1}^{6}y_i)\prod_{i=1}^{6}dy_i$, $C_F=(n_c^2-1)/2n_c=\frac{4}{3}$, $\beta=11-\frac{2}{3}n_f$, and n_f is the effective number of flavors$\}$

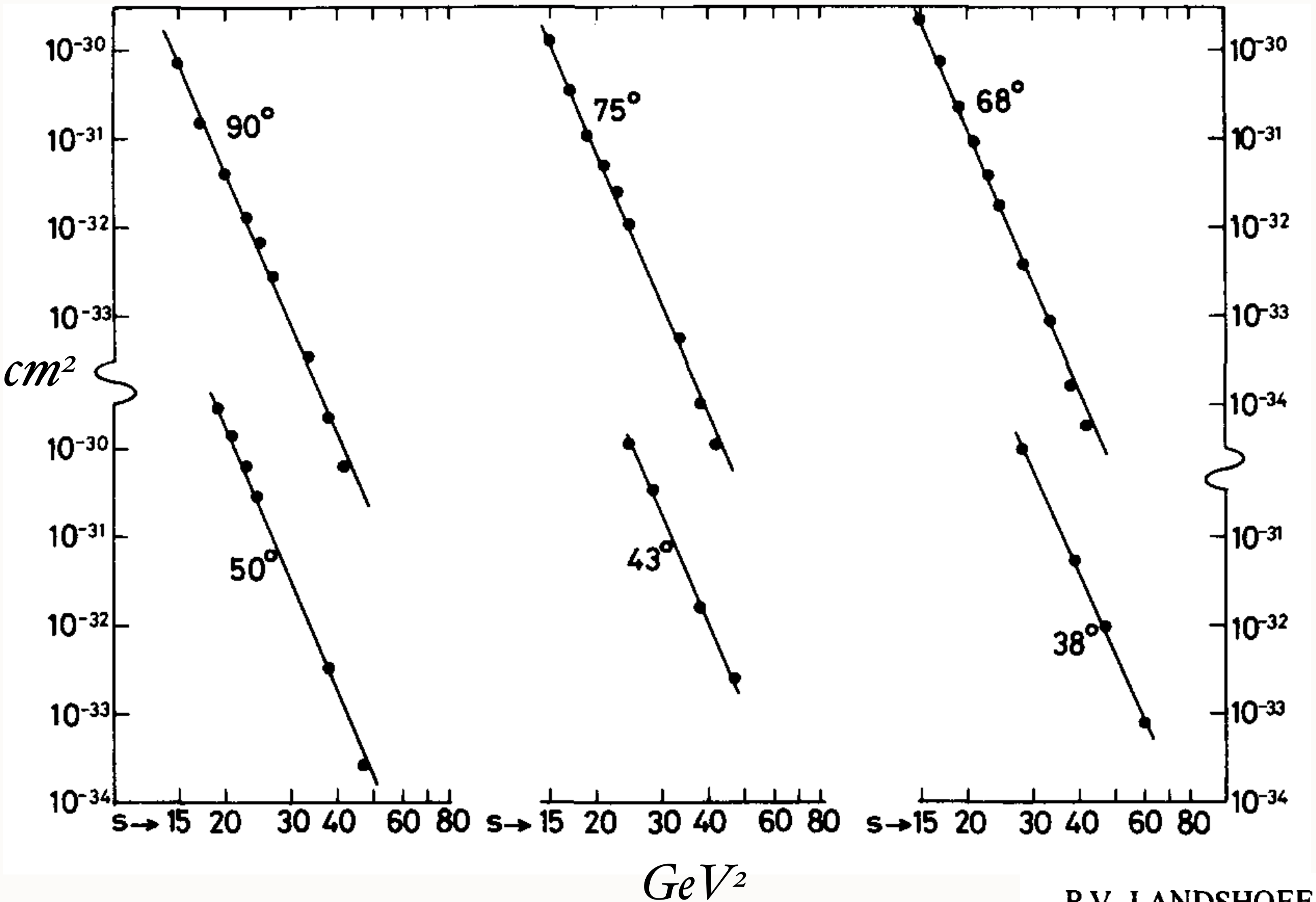
$$\prod_{k=1}^{6} x_k\left[\frac{\partial}{\partial\xi}+\frac{3C_F}{\beta}\right]\tilde{\Phi}(x_i,Q)=-\frac{C_d}{\beta}\int_0^1[dy]\,V(x_i,y_i)\,\tilde{\Phi}(y_i,Q),$$

$$\xi(Q^2)=\frac{\beta}{4\pi}\int_{Q_0^2}^{Q^2}\frac{dk^2}{k^2}\alpha_s(k^2)\sim\ln\left(\frac{\ln(Q^2/\Lambda^2)}{\ln(Q_0^2/\Lambda^2)}\right).$$

$$V(x_i,y_i)=2\prod_{k=1}^{6}x_k\sum_{i\neq j}^{6}\theta(y_i-x_i)\prod_{l\neq i,j}^{6}\delta(x_l-y_l)\frac{y_j}{x_j}\left(\frac{\delta_{h_i\bar{h}_j}}{x_i+x_j}+\frac{\Delta}{y_i-x_i}\right)$$

where $\delta_{h_i\bar{h}_j}=1$ (0) when the helicities of the constituents $\{i,j\}$ are antiparallel (parallel). The infrared singularity at $x_i=y_i$ is cancelled by the factor $\Delta\tilde{\Phi}(y_i,Q)=\tilde{\Phi}(y_i,Q)-\tilde{\Phi}(x_i,Q)$ since the deuteron is a color singlet.

Quark-Counting: $\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{CM})}{s^{10}}$ $n = 4 \times 3 - 2 = 10$



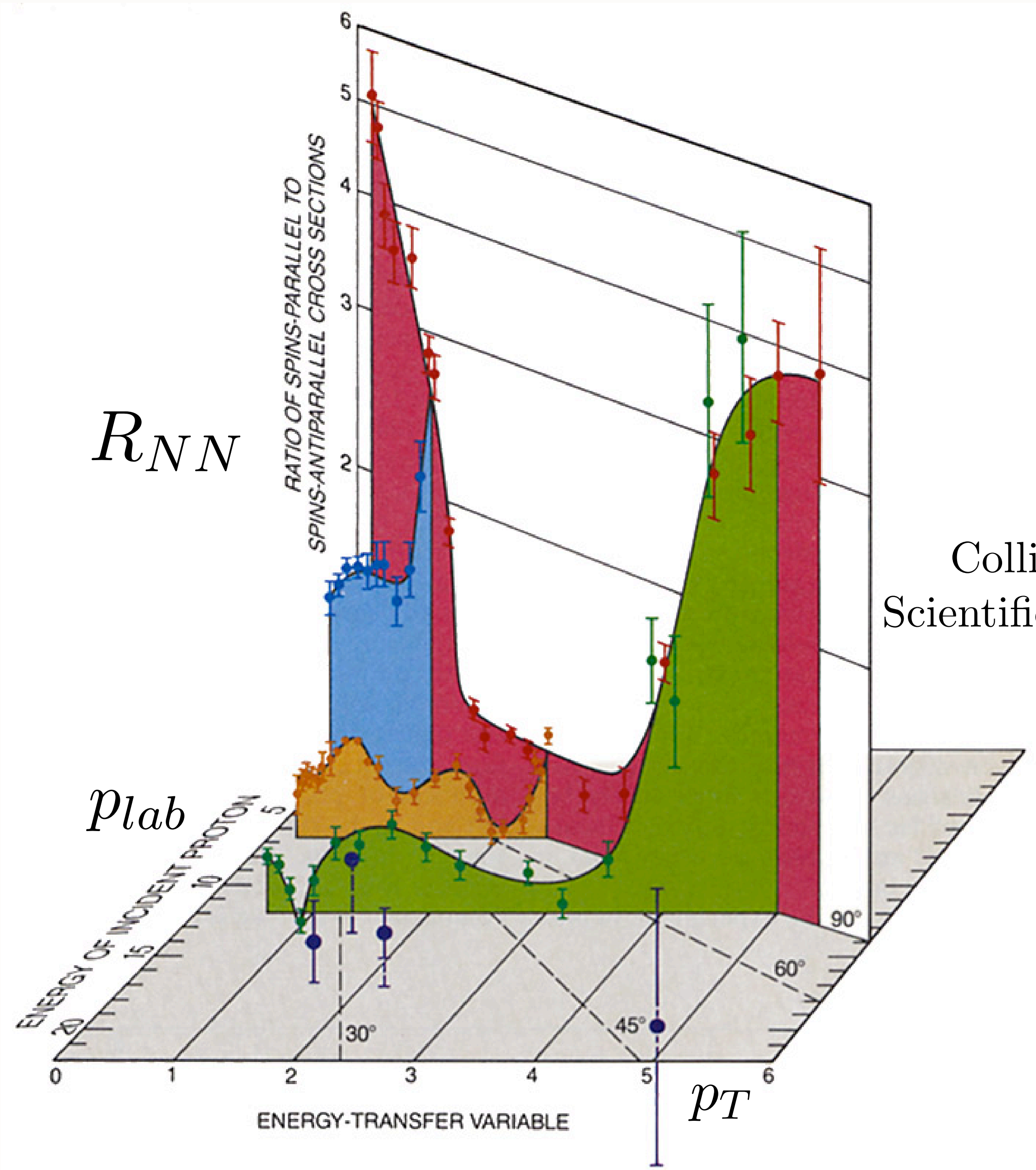
P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

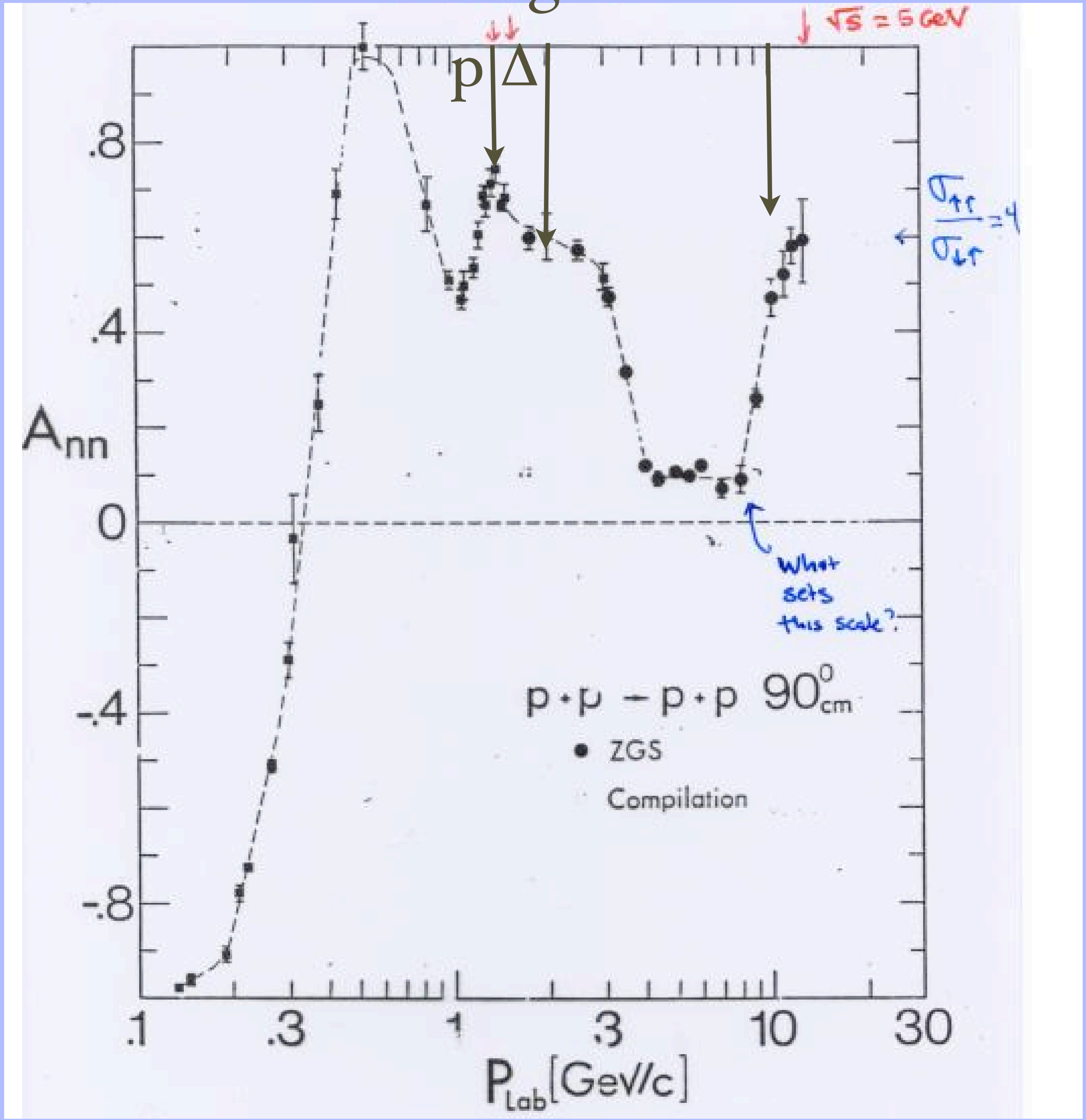
Spin Correlations in Elastic $p - p$ Scattering



Ratio reaches 4:1 !

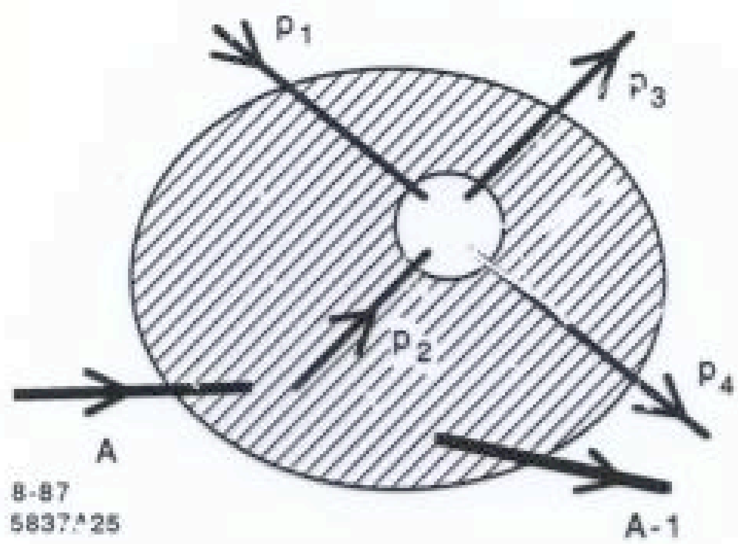
Collisions Between Spinning Protons (A. D. Krisch)
Scientific American, 255, 42-50 (August, 1987).

Strangeness Charm



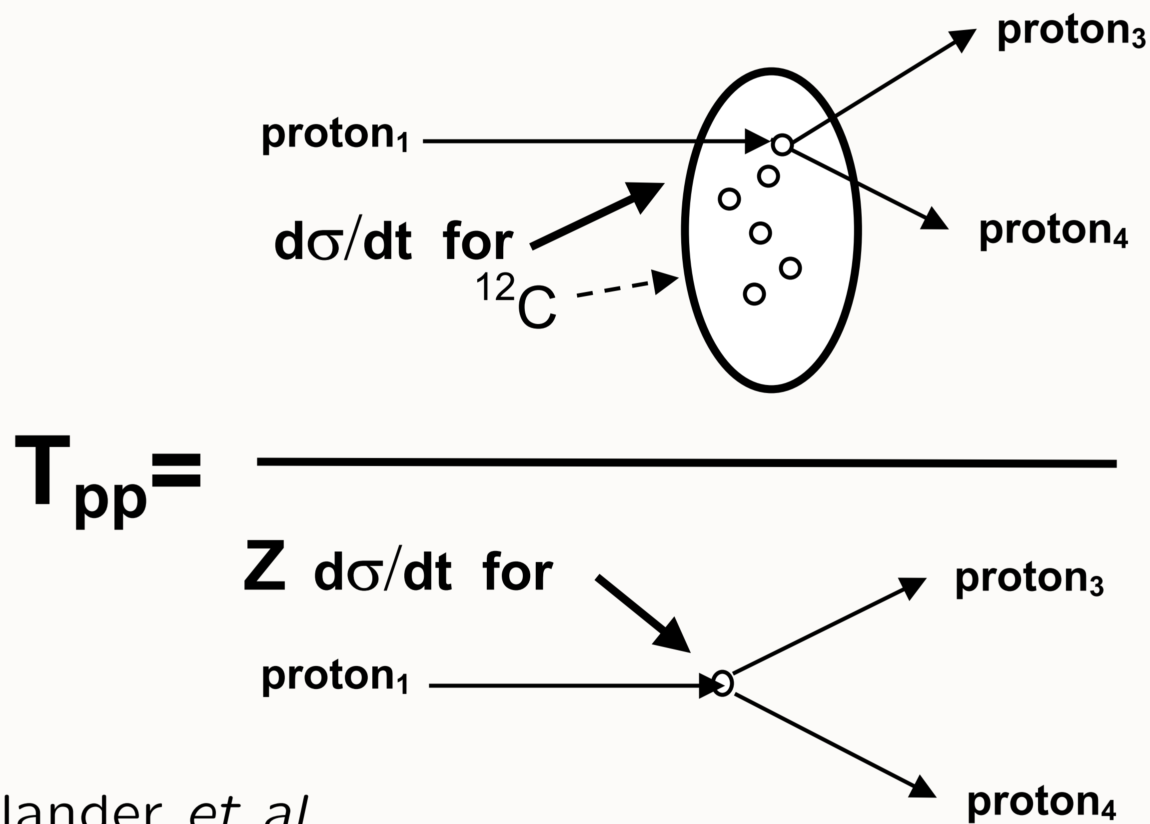
Test Color Transparency

$$\frac{d\sigma}{dt}(pA \to pp(A-1)) \to Z \times \frac{d\sigma}{dt}(pp \to pp)$$



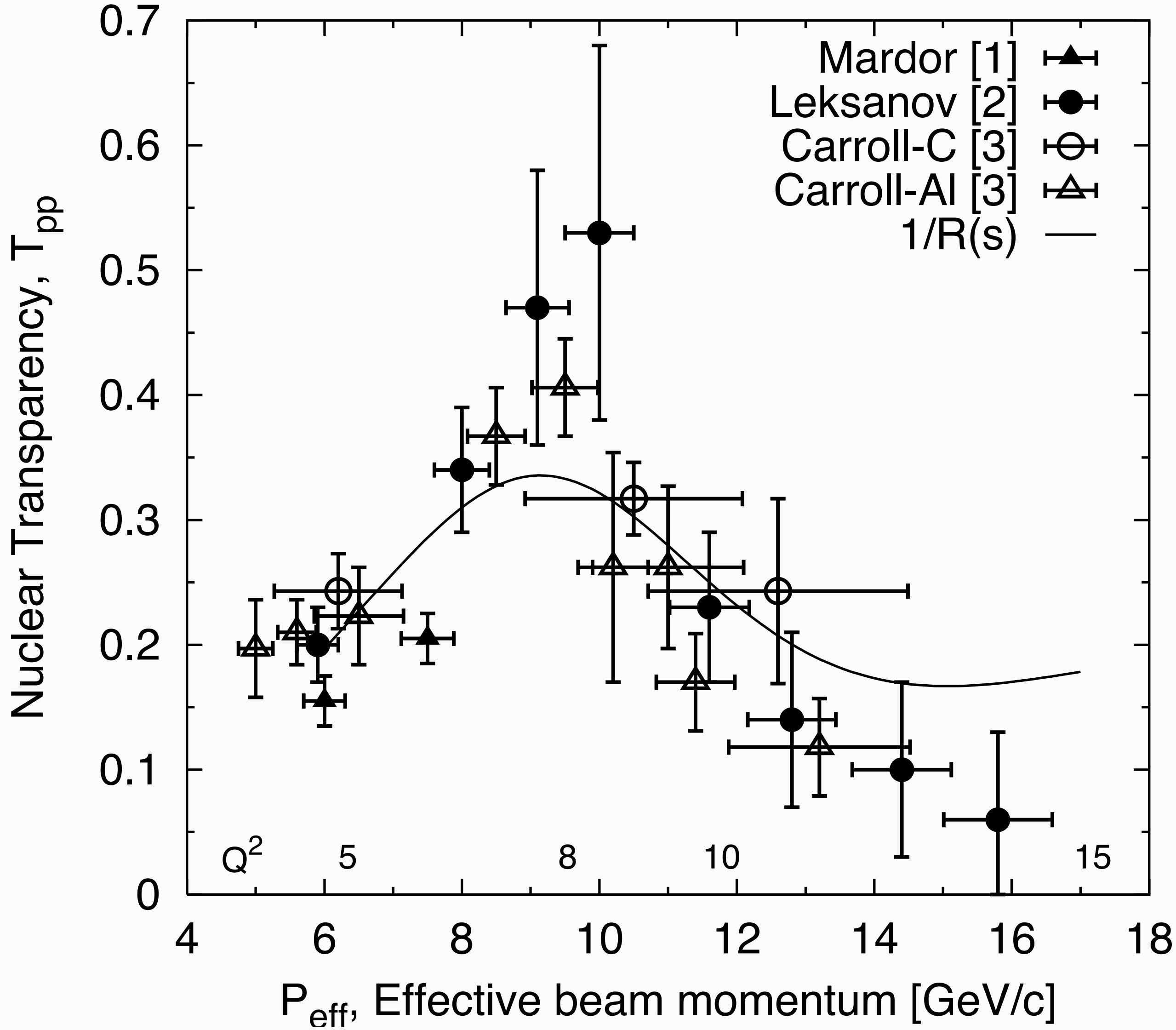
A.H. Mueller, SJB

Color Transparency Ratio



J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p, 2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

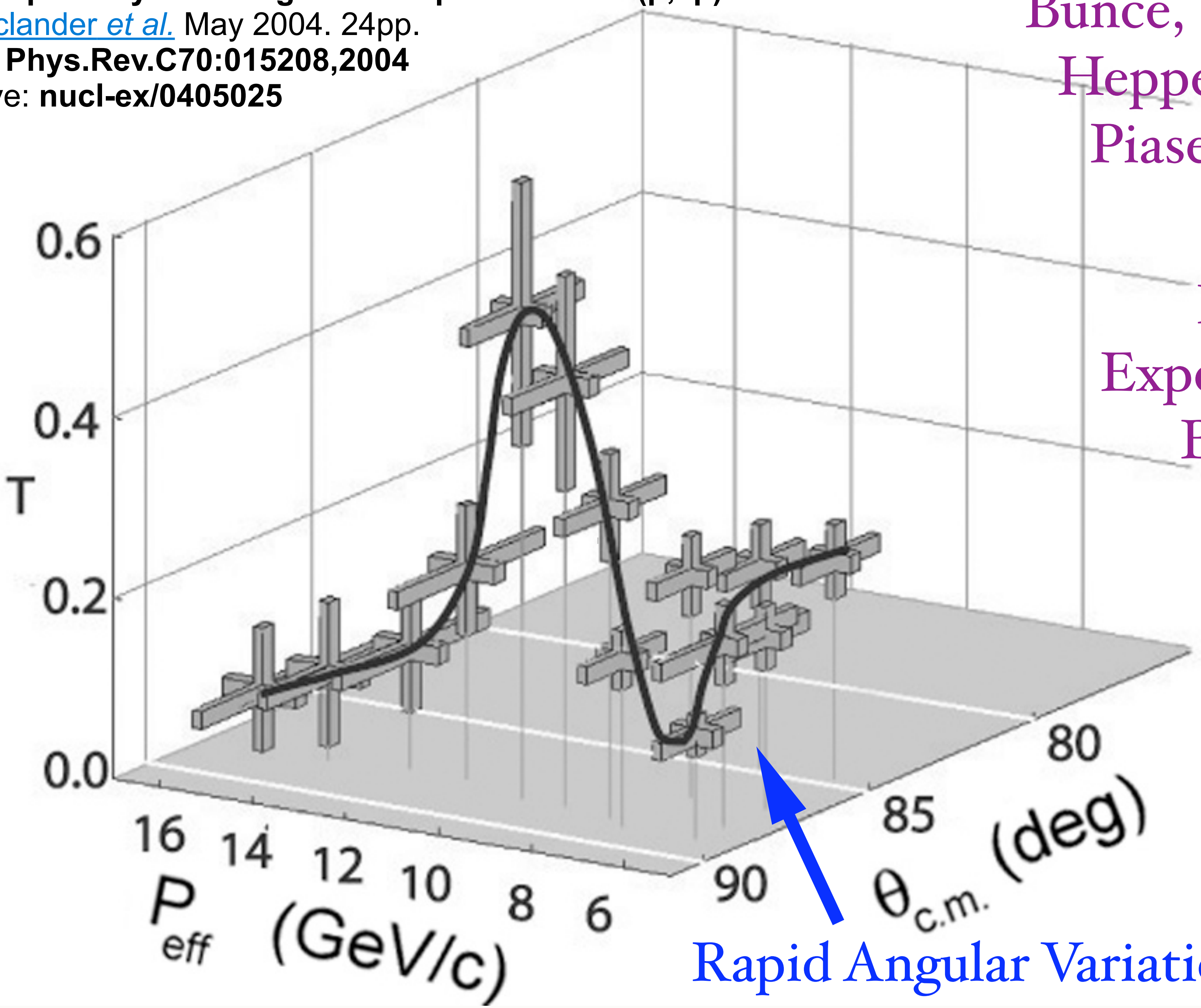
Color Transparency fails when A_{nn} is large



Nuclear transparency in 90 degree c.m. quasielastic A(p,2p) reactions.
Jaime L.S. Aclander *et al.* May 2004. 24pp.
Published in **Phys.Rev.C70:015208,2004**
e-Print Archive: **nucl-ex/0405025**

Bunce, Carroll, Heppelman, Piasetzky

Eva Experiment BNL

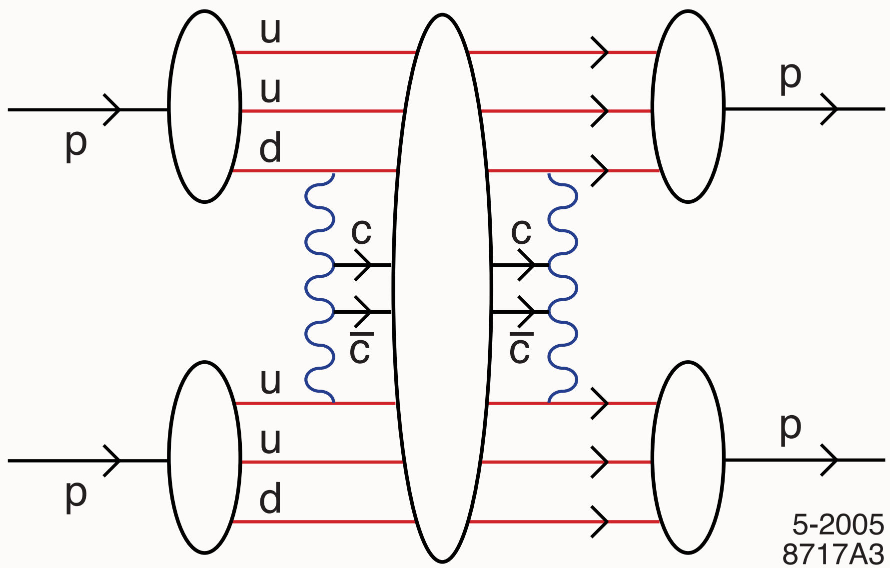


Rapid Angular Variation!

Guy de Teramond & SJB:

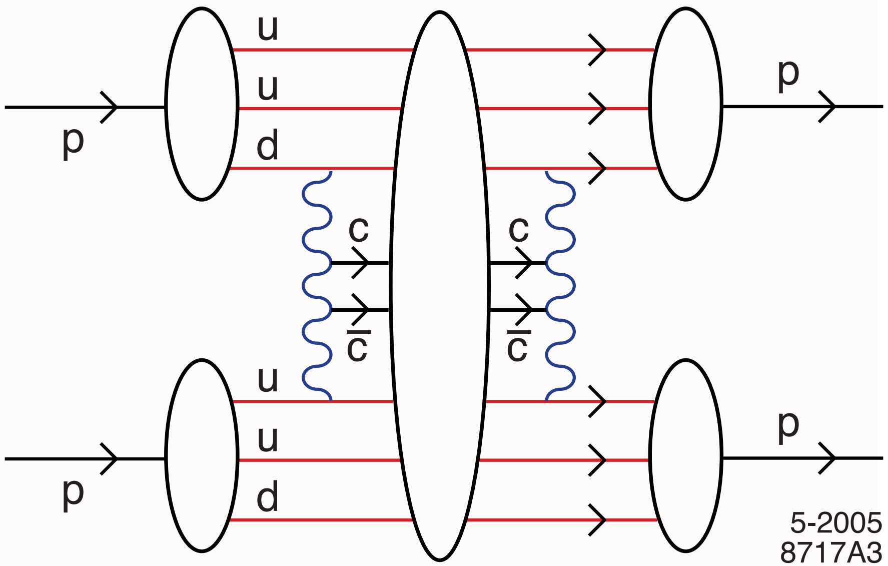
Octoquark Resonance at Charm Threshold ?

J=L=S=1



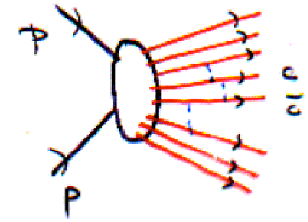
Maximal A_{NN}

Breakdown of Color Transparency



Spin, Coherence at heavy quark thresholds

$p\bar{p} \to Q\bar{Q}\, X$



Strong distortion at threshold $p_{rel} \sim 0$

$\sqrt{s}_{Th} = 3+2 \simeq 5$ GeV $\quad pp \to c\bar{c}\, X$

8 quarks in S-wave odd parity!

$\therefore \; J = L = S = 1$ for pp

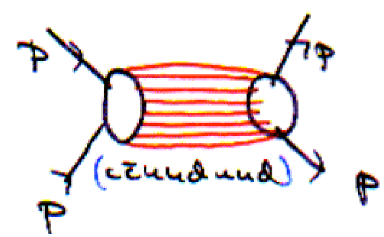
$B = 2$

resonance near threshold?

SJB + determined

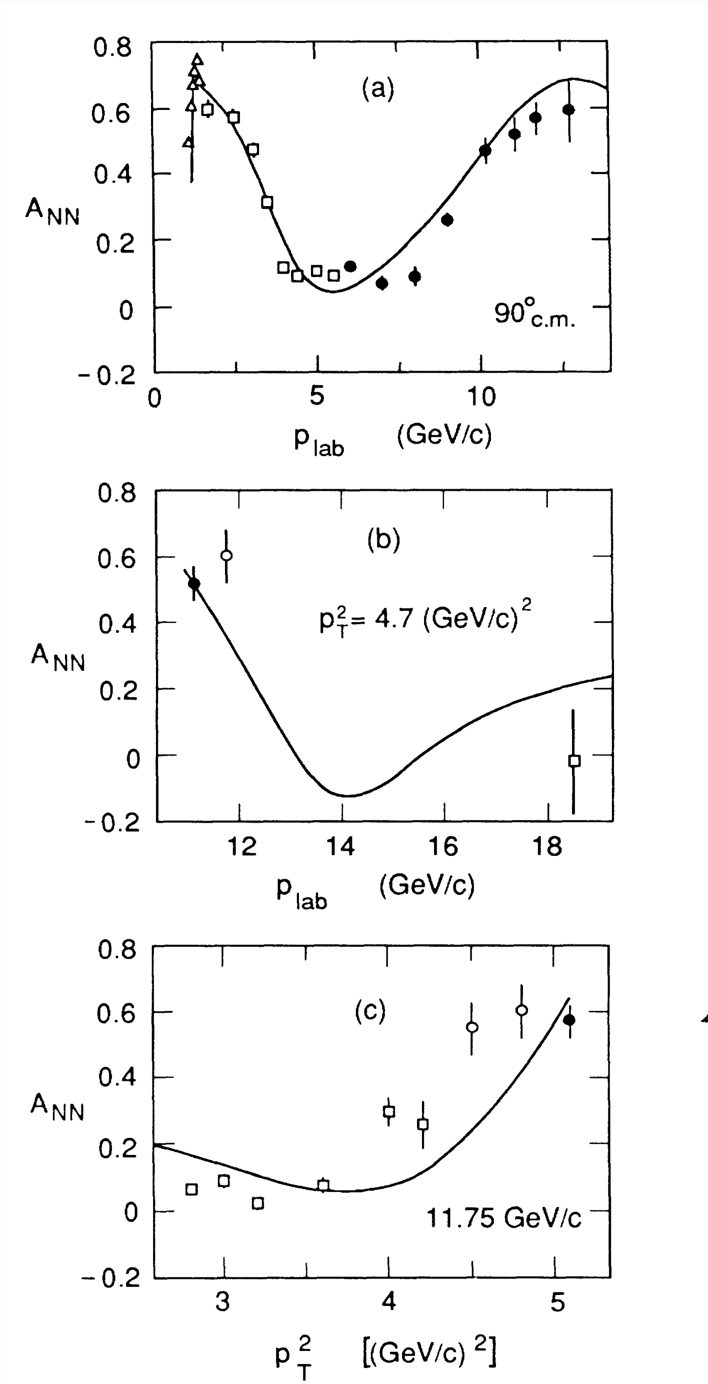
$\frac{d\sigma}{dt}(pp \to pp)$

$\sqrt{s} \sim 5$ GeV



$A_{NN} = 1$ for $J = L = S = 1$ $\quad p\uparrow p\uparrow$ only

expect increase of A_{NN} at $\sqrt{s} = 3, 5, 12$ GeV
$\theta_{cm} = 90°$



S. J. Brodsky and G. F. de Teramond, "Spin Correlations, QCD Color Transparency And Heavy Quark Thresholds In Proton Proton Scattering," Phys. Rev. Lett. **60**, 1924 (1988).

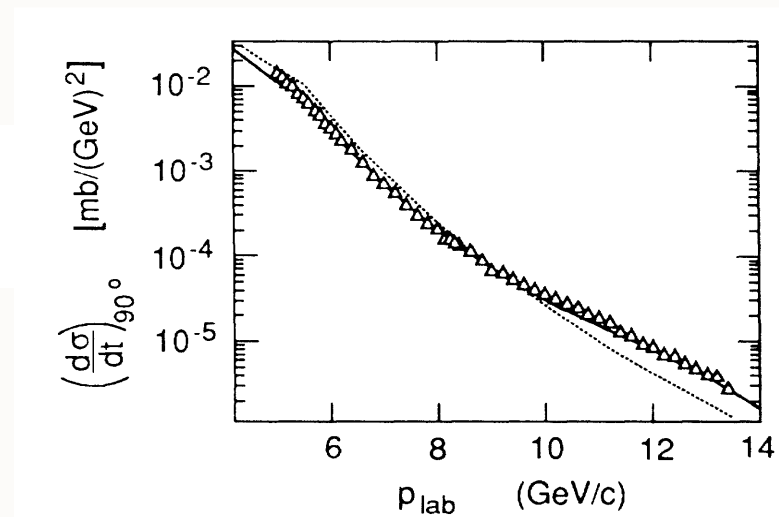
Quark Interchange + 8-Quark Resonance

$|uuduudc\bar{c}>$ Strange and Charm Octoquark!

$M = 3$ GeV, $M = 5$ GeV.

$J = L = S = 1,\ B = 2$

$$A_{NN} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)}$$



- New QCD physics in anti-proton proton elastic scattering at the second charm threshold
- Octoquark resonances?
- Color Transparency
- Exclusive Processes: New physics at GSI