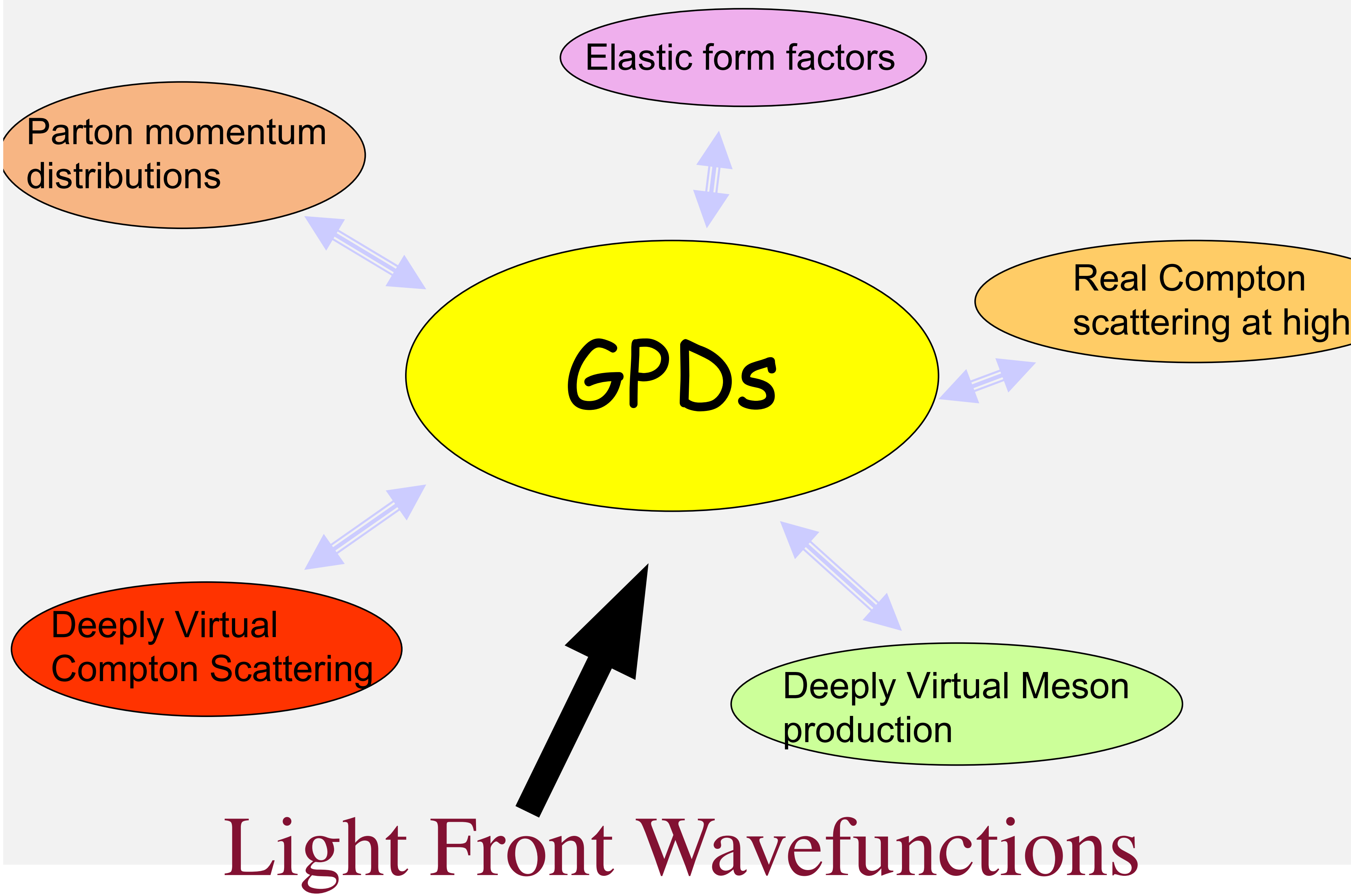
Hadron Dynamics at the Amplitude Level

- DIS studies have primarily focussed on probability distributions: integrated and unintegrated
- We need to determine hadron wavefunctions!
- Test QCD at the amplitude level: Phases, multi-parton correlations, spin, angular momentum
- Wavefunctions: Fundamental QCD Dynamics

A Unified Description of Hadron Structure



Light-Front Wavefunctions

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

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

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

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

Invariant under boosts. Independent of P^μ

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

The Light Front Fock State Wavefunctions

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

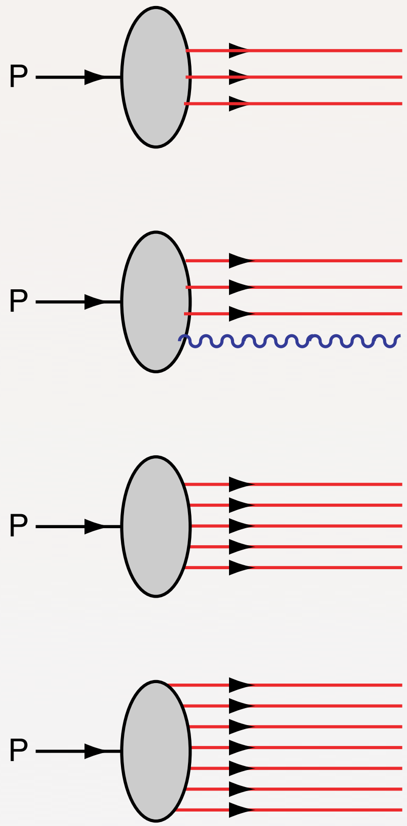
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



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

Compute LFWFS from first principles

$$H_{LC}^{QCD} = P_\mu P^\mu = \quad P^- P^+ - \vec{P}_\perp^2$$

The hadron state $|\Psi_h\rangle$ is expanded in a Fock-state complete basis of non-interacting n-particle states $|n\rangle$ with an infinite number of components

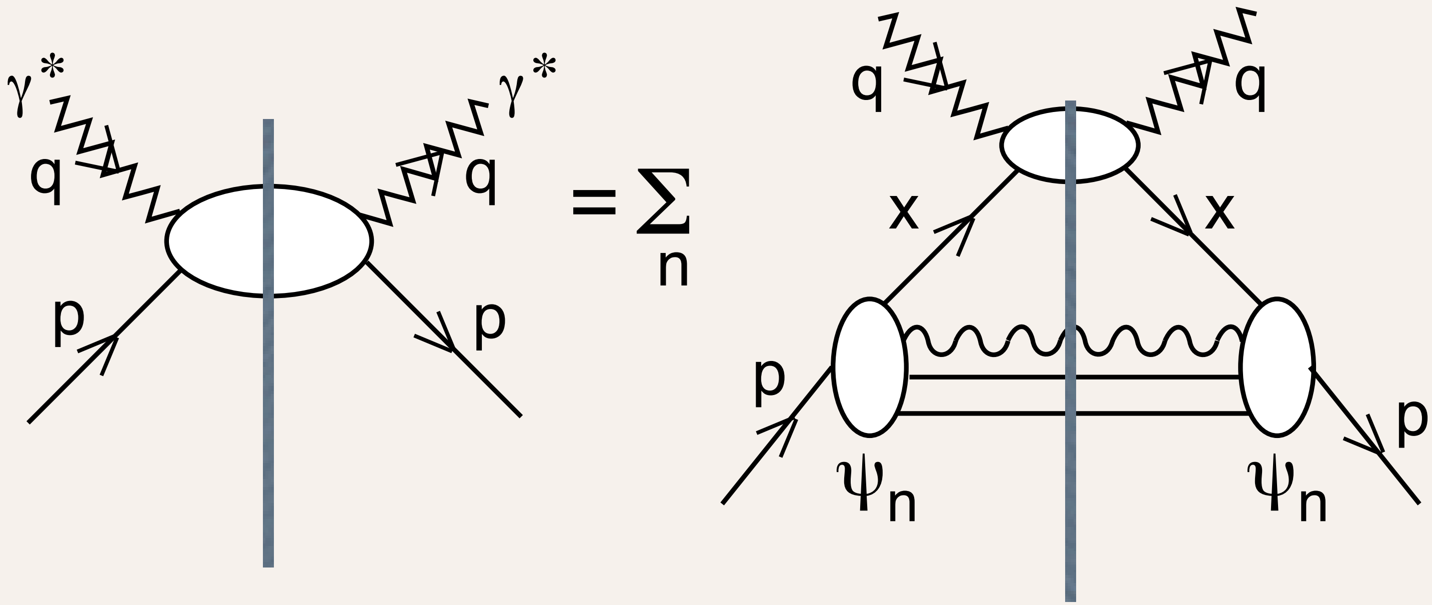
$$\left|\Psi_h(P^+, \vec{P}_\perp)\right\rangle =$$

$$\sum_{n,\lambda_i} \int\ [dx_i\ d^2\vec{k}_{\perp i}]\psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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

$$\sum_n \int [dx_i\ d^2\vec{k}_{\perp i}]\ |\psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i)|^2 = 1$$

Deep Inelastic Lepton Proton Scattering

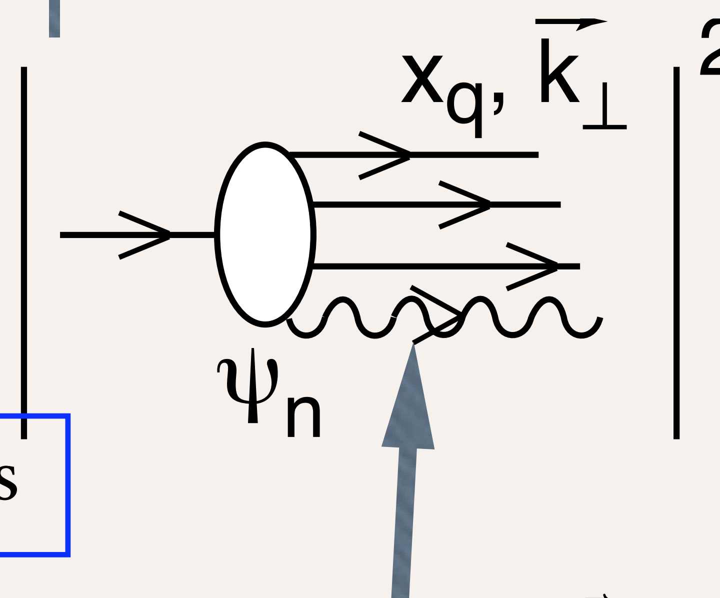


Imaginary Part of
Forward Virtual Compton Amplitude

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

$x = x_q$

All spin, flavor distributions



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

Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes that underlie structure functions, GPDs, exclusive processes.
- Relation of transversity and other distributions to physics of the hadron itself.
- Connections between observables, orbital angular momentum
- Role of FSI and ISIs--Sivers effect

Exact Representation of Form Factors using LFWFs

Hadron form factors can be expressed as a sum of overlap integrals of light-front wave functions:

Drell Yan, West, Drell, SJB

$$F(q^2) = \sum_n \int \left[dx_i\right] \left[d^2\vec{k}_{\perp i}\right] \sum_j e_j \psi^*_n(x_i, \vec{k}'_{\perp i}, \lambda_i) \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i), \tag{1}$$

where the variables of the light-cone Fock components in the final-state are given by

$$\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\ \vec{q}_\perp, \tag{2}$$

for a struck constituent quark and

$$\vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i\ \vec{q}_\perp, \tag{3}$$

for each spectator. The momentum transfer is $q^2 = -\vec{q}_\perp^{\ 2} = -2P \cdot q = -Q^2$. The measure of the phase-space integration is

$$\left[dx_i\right] = \prod_{i=1}^{n} \frac{dx_i}{\sqrt{x_i}}\, \delta\left(1 - \sum_{j=1}^{n} x_j\right), \tag{4}$$

$$\left[d^2\vec{k}_{\perp i}\right] = (16\pi^3) \prod_{i=1}^{n} \frac{d^2\vec{k}_{\perp i}}{16\pi^3} \delta^{(2)}\left(\sum_{\ell=1}^{n} \vec{k}_{\perp \ell}\right). \tag{5}$$

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

Hadron Distribution Amplitudes

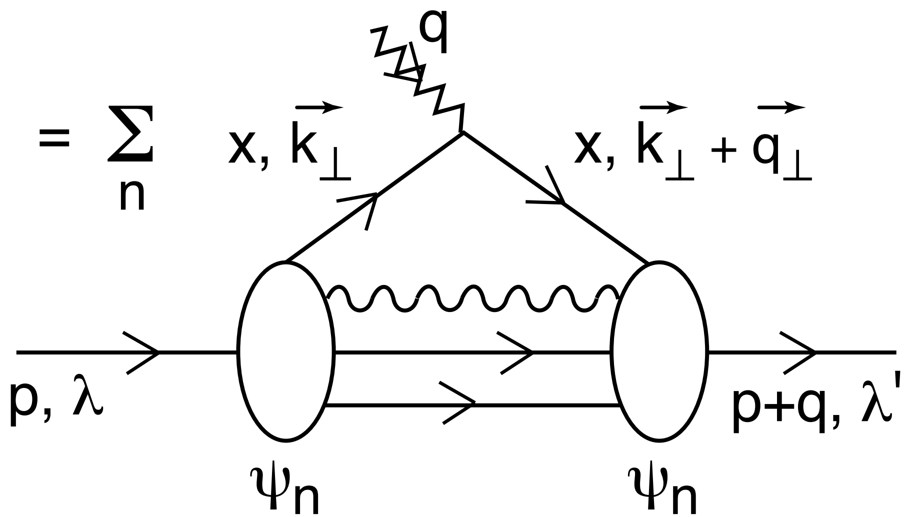
$$\phi(x_i, Q) \equiv \Pi_{i=1}^{n-1} \int^Q d^2\vec{k}_\perp \ \psi_n(x_i, \vec{k}_{\perp i})$$

- Fundamental measure of valence wavefunction
- Gauge Invariant (includes Wilson line)
- Evolution Equations, OPE
- Conformal Expansion
- Hadronic Input in Factorization Theorems

Lepage; SJB
Efremov, Radyuskin

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

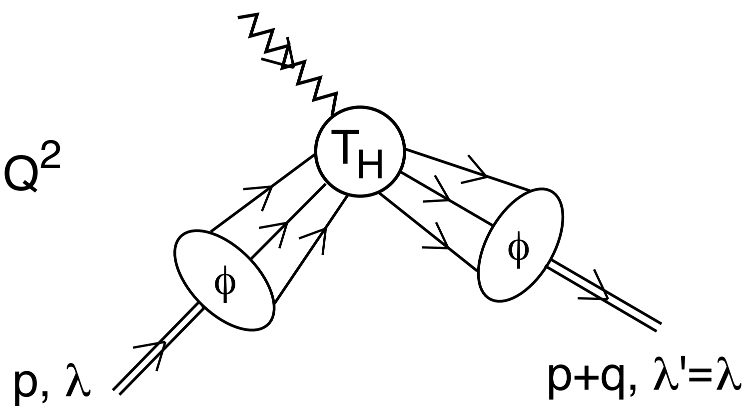
$F_{\lambda\lambda'} (Q^2) = \sum_n$



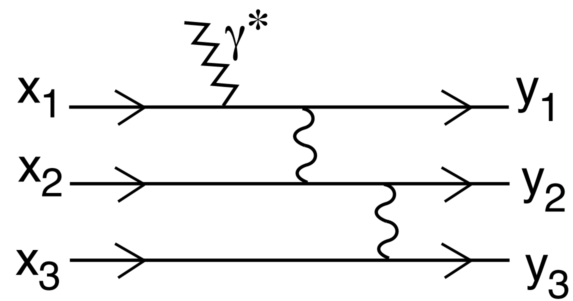
QCD Factorization

Lepage, Sjb
Efremov
Radyushkin

⇨ Large Q^2



$T_H = \sum$

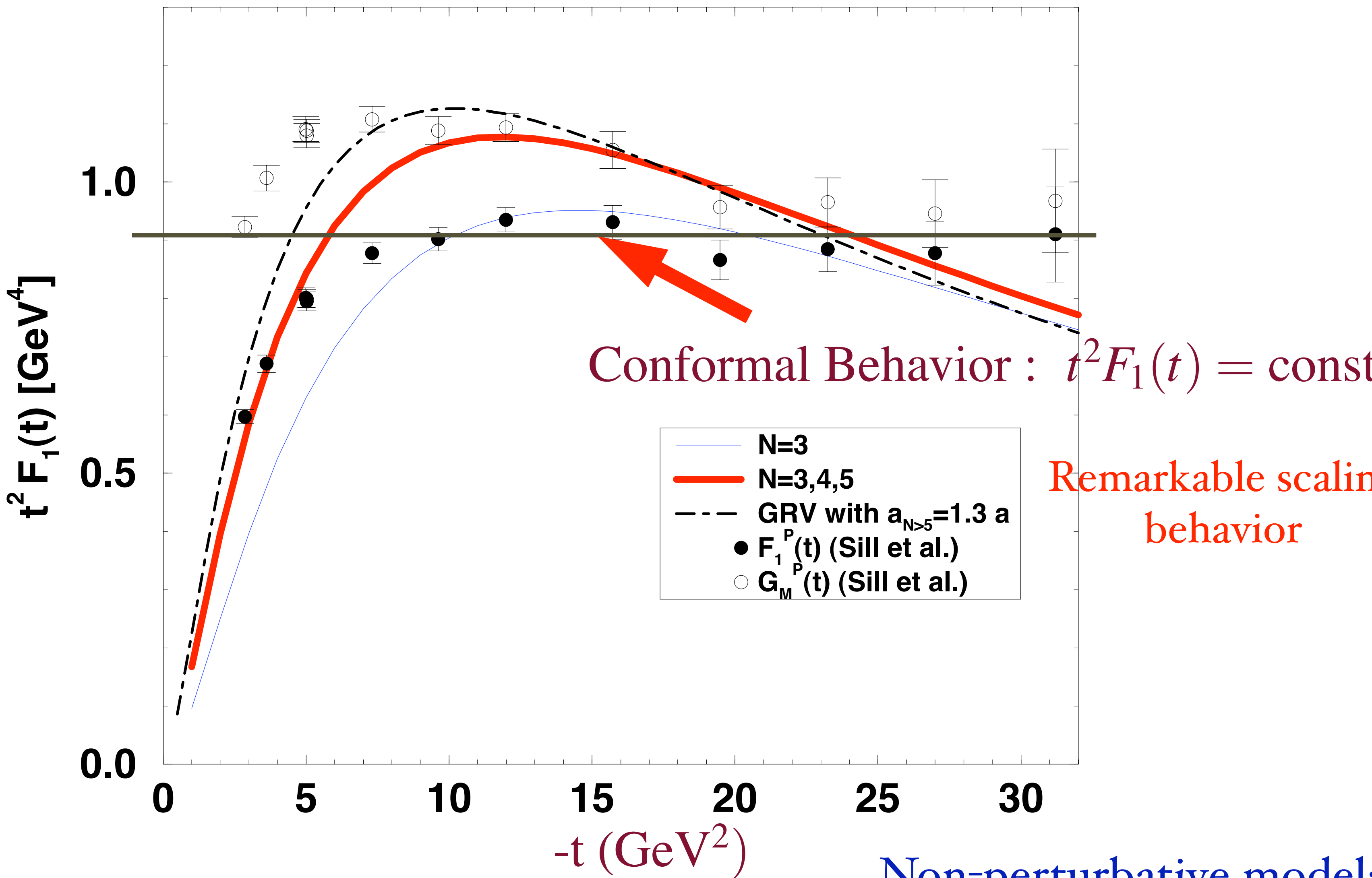


$+ \ \dots$

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

Scaling Laws from PQCD or AdS/CFT

Proton Form Factor



Remarkable scaling behavior

Non-perturbative model: Diehl, Kroll

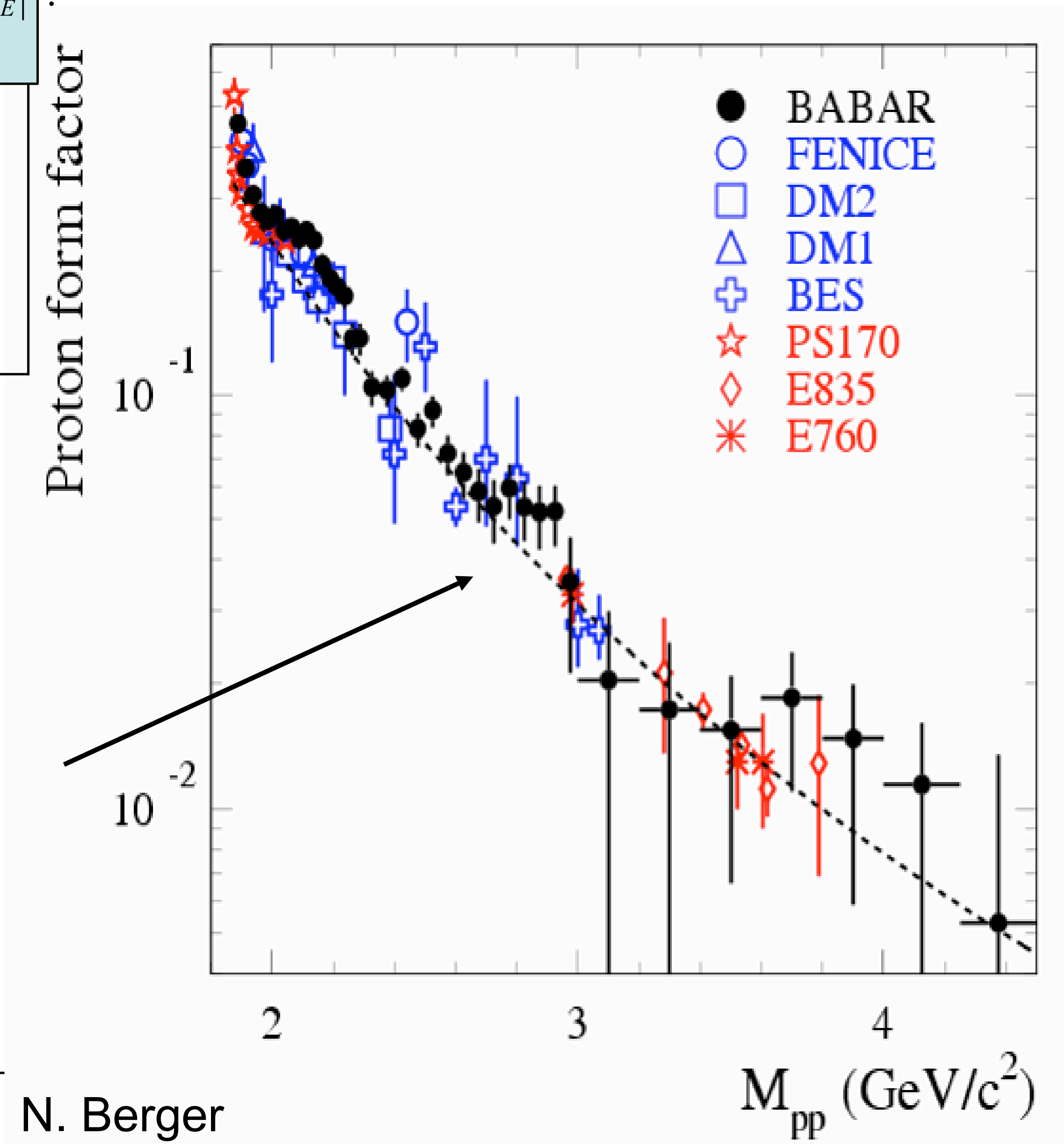
Timelike Proton Form Factor

- Define "Effective" form factor by

$$\sigma = \frac{4\pi\alpha^2\beta C}{3m_{p\bar{p}}^2}|F|^2, \quad |F| = \sqrt{|G_M|^2 + \frac{2m_p^2}{m_{p\bar{p}}^2}|G_E|^2}.$$

- Peak at threshold, sharp dips at 2.25 GeV, 3.0 GeV.
- Good fit to pQCD prediction for high m_{pp}.

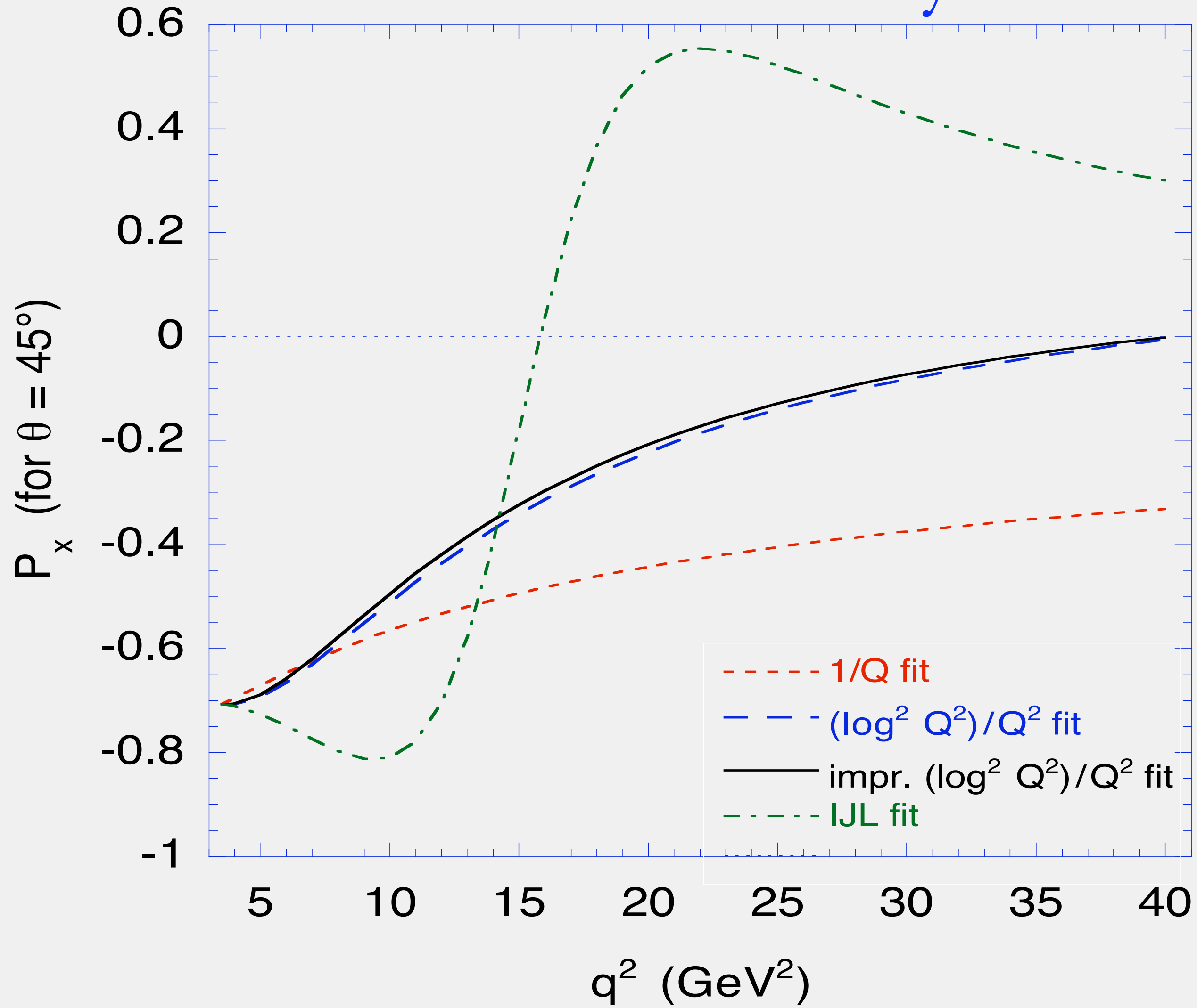
$$F(s) \propto \frac{\log^{-2}\frac{s}{\Lambda^2}}{s^2}$$



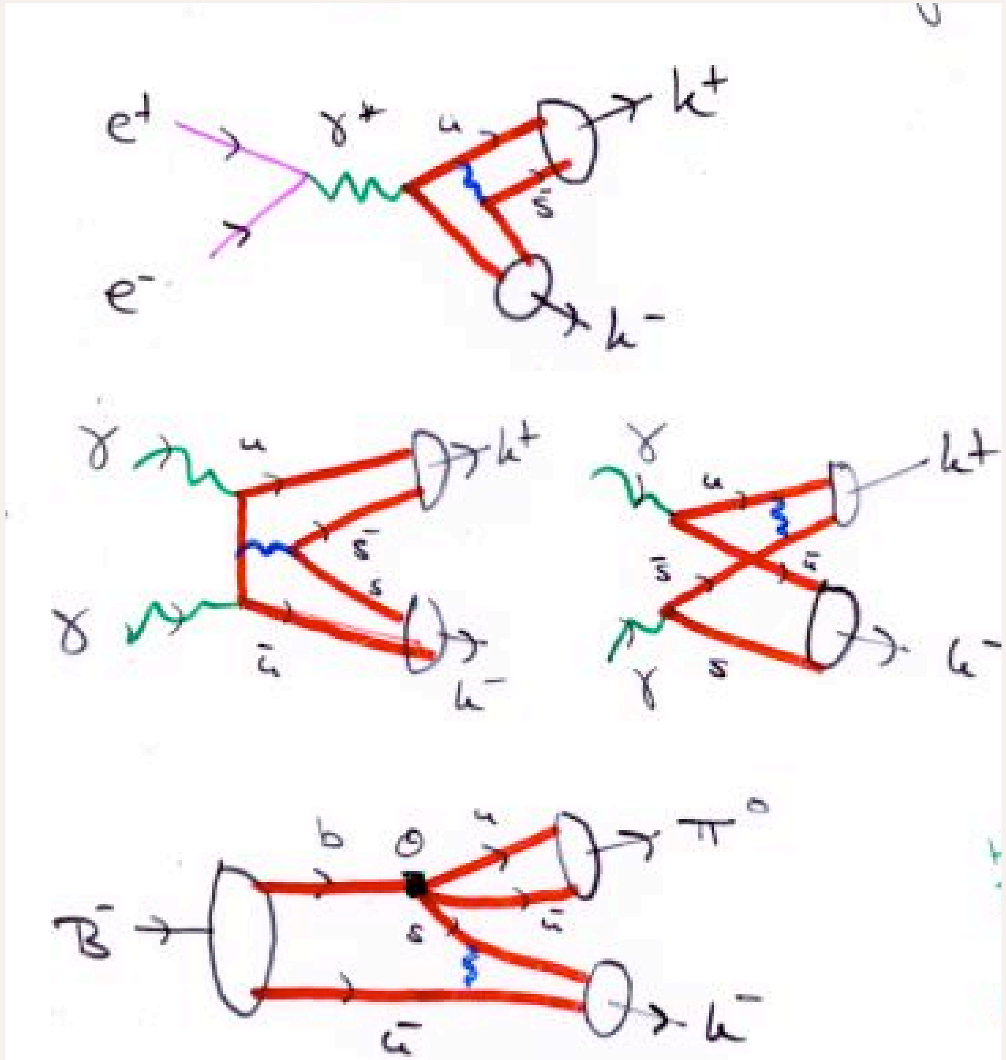
Carlson, Hiller, Hwang, SJB

$$\frac{\mathcal{P}_y}{\mathcal{P}_x} = \frac{\cos\theta}{P_e}\frac{\text{Im } G_M^* G_E}{\text{Re } G_M^* G_E} = \frac{\cos\theta}{P_e}\tan(\delta_E - \delta_M) \; .$$

“Exclusive Transversity”



Common Ingredients:
Universal LFWFS, Distribution Amplitudes



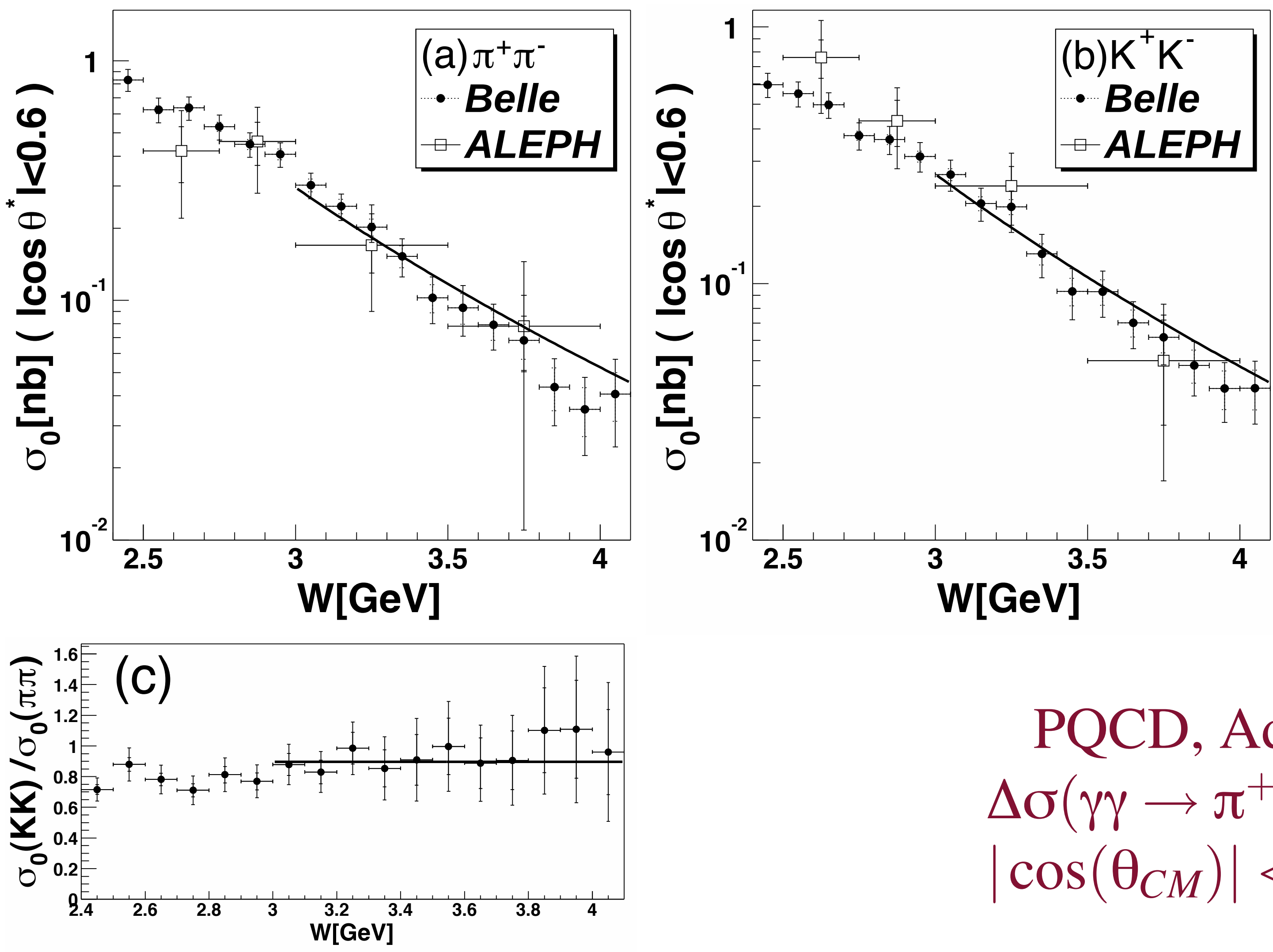


Fig. 5. Cross section for (a) $\gamma\gamma\to\pi^+\pi^-$, (b) $\gamma\gamma\to K^+K^-$ in the c.m. angular region $|\cos\theta^*| < 0.6$ together with a W^{-6} dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data above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

Two Photon Reactions

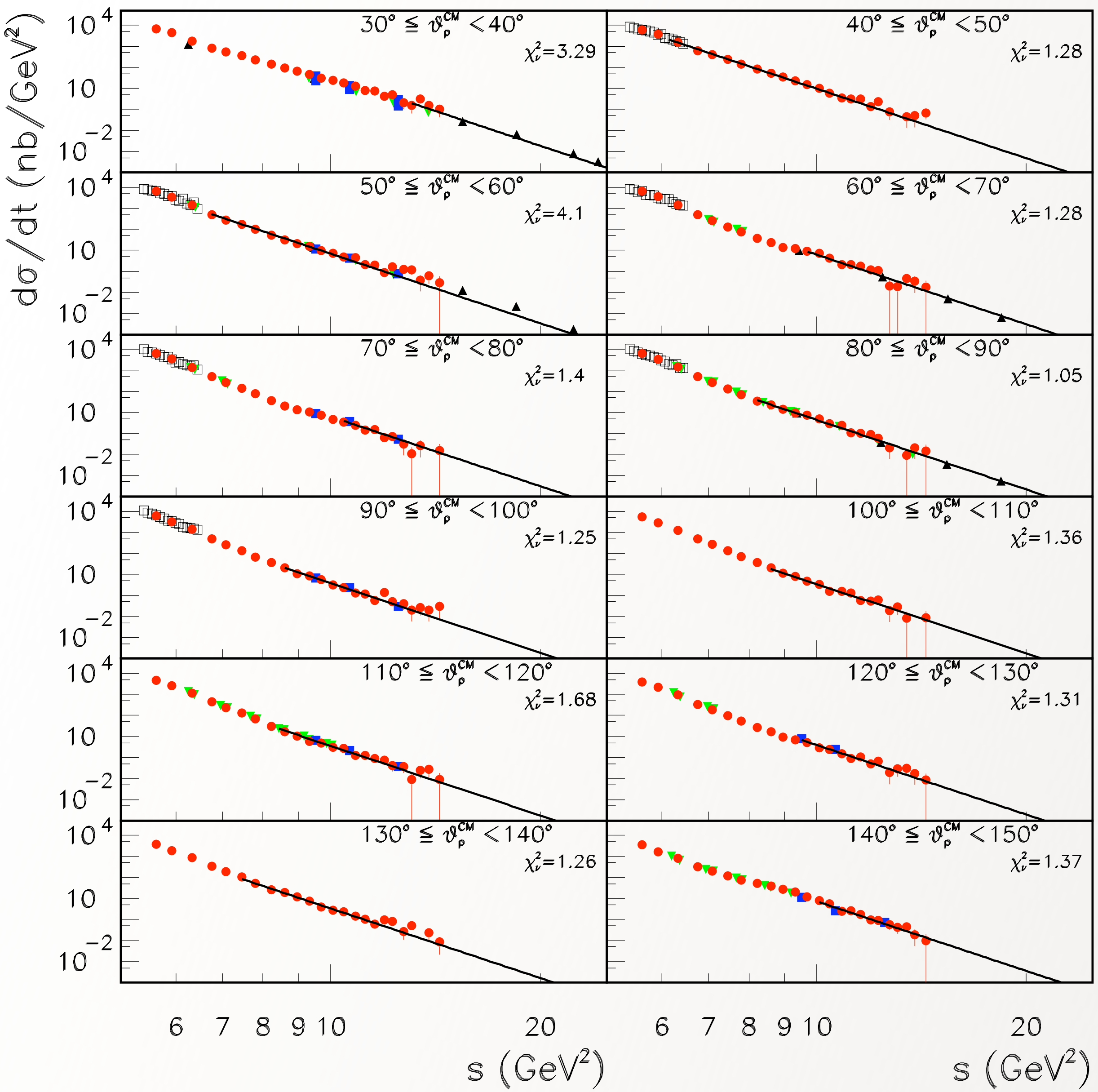
Hard Exclusive Processes: Fixed angle

PQCD, AdS/CFT:

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

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

Deuteron Photodisintegration & Dimensional Counting Rules



PQCD and AdS/CFT:

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

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

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

Check of CCR

Fit of dσ/dt data for the central angles and $P_T \geq 1.1$ GeV/c with

$A\ s^{-11}$

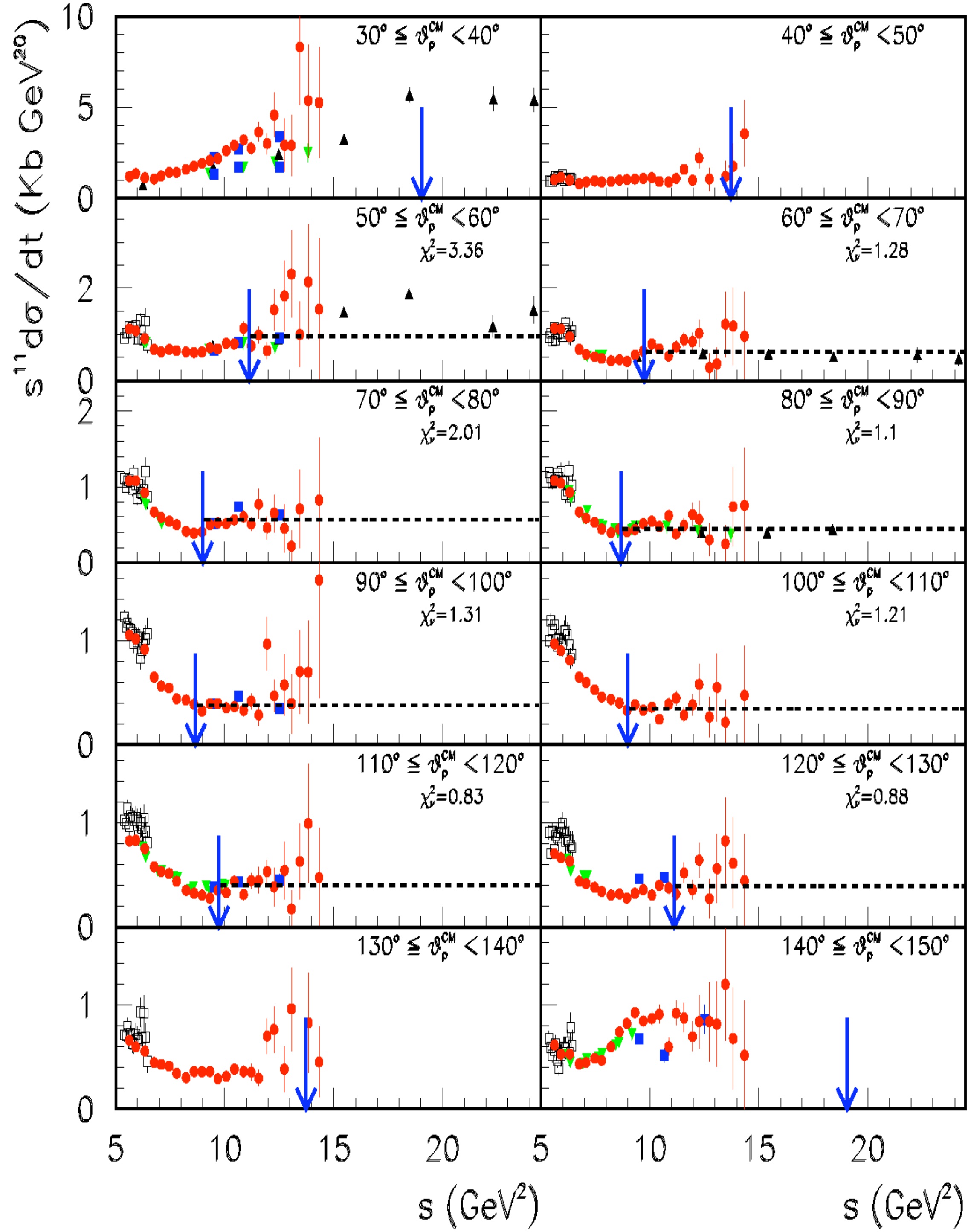
For all but two of the fits

$\chi^2 \leq 1.34$

- 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)



- Remarkable Test of Quark Counting Rules
- Deuteron Photo-Disintegration $\gamma d \to np$
- $$\frac{d\sigma}{dt} = \frac{F(t/s)}{s^{n_{tot}-2}}$$
- $$n_{tot} = 1 + 6 + 3 + 3 = 13$$

Scaling characteristic of
scale-invariant theory at short distances

Conformal symmetry

Hidden color: $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$

at high p_T

Why is Conformal Theory Relevant?

- Dimensional scaling of exclusive processes implies QCD is approximately conformal
- PQCD is conformal when $\beta = 0$
- Evaluate gluon exchange at small effective scales where α_s is approximately constant: IR fixed point
- Apply AdS/CFT

Why do dimensional counting rules work so well?

- PQCD predicts log corrections from powers of α_s, logs, pinch contributions
- QCD coupling evaluated in IR regime.
- IR Fixed point!   DSE: Alkofer, von Smekal et al.
- QED, EW -- define coupling from observable, predict other observable
- Underlying Conformal Symmetry of QCD Lagrangian

Define QCD Coupling from Observable

Grunberg

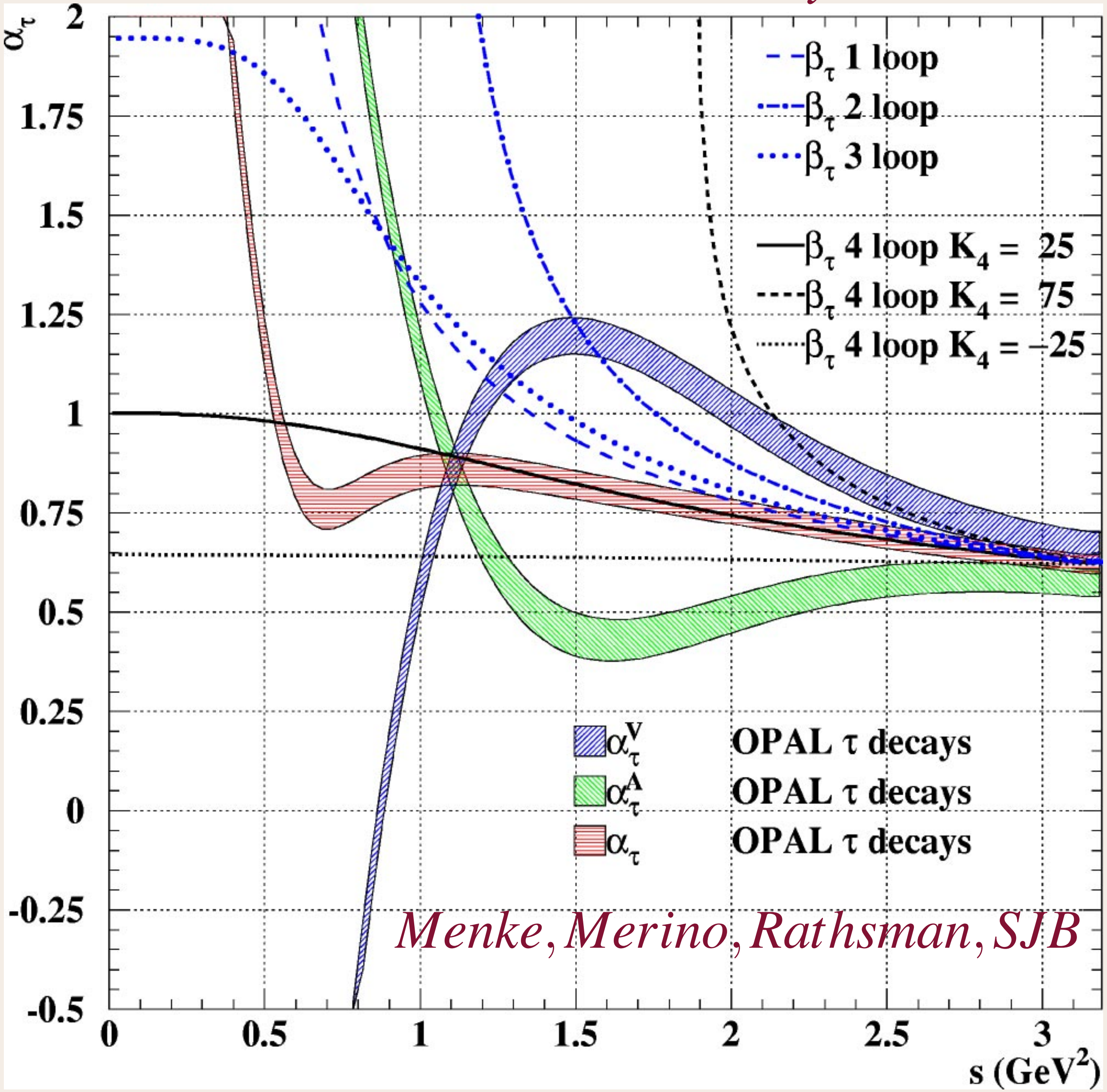
$$R_{e^+e^-\to X}(s) \equiv 3\Sigma_q e_q^2 \; [1 + \frac{\alpha_R(s)}{\pi}]$$

$$\Gamma(\tau \to X e\nu)(m_\tau^2) \equiv \Gamma_0(\tau \to u\bar{d}e\nu) \times [1 + \frac{\alpha_\tau(m_\tau^2)}{\pi}]$$

Relate observable to observable at commensurate scales

H.Lu, sjb

QCD Effective Coupling from *hadronic τ decay*



Menke, Merino, Rathsman, SJB

- Generalized Crewther Relation

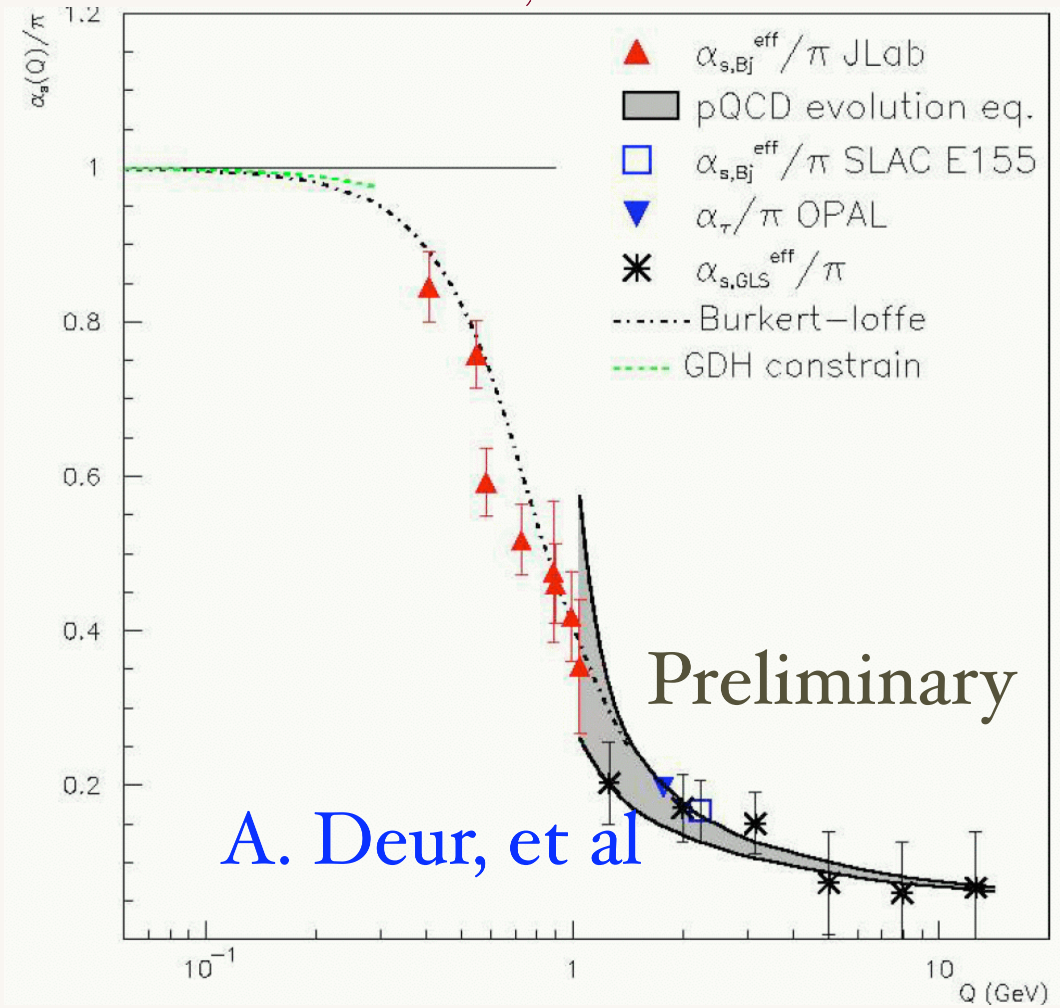
$$[1 - \frac{\alpha_{g_1}(Q^2)}{\pi}] \times [1 + \frac{\alpha_R(s^*)}{\pi}] = 1$$

at $s^* = CQ^2$.

- Exact at leading twist.
- No scale ambiguity!
- Extraordinary Test of QCD
- $\frac{\alpha_{g_1}(Q^2)}{\pi}$:

Analytic at quark thresholds.

G.Gabadadze, H.J.Lu, A.Kataev, J.Rathsman, SJB

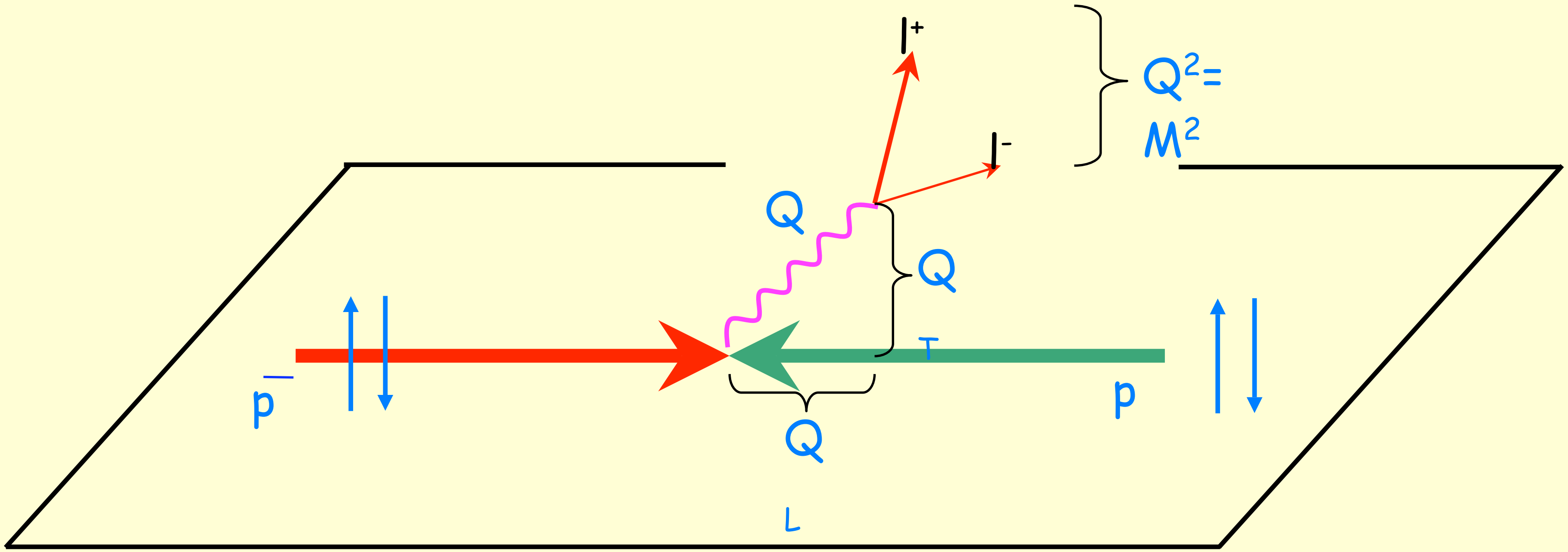


Conformal symmetry: Template for QCD

- Initial approximation to PQCD; correct for non-zero beta function
- Commensurate scale relations: relate observables at corresponding scales
- Infrared fixed-point for α_s
- Effective Charges: analytic at quark mass thresholds
- Eigensolutions of Evolution Equations

Transversity in Drell-Yan Processes

Polarized Antiproton Beam → Polarized Proton Target
(both transversely polarized)



$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)}$$

$q = u, \bar{u}, d, \bar{d}, \ldots$

M invariant Mass of lepton pair

F. Rathsman

pp Elastic Scattering from ZGS/AGS

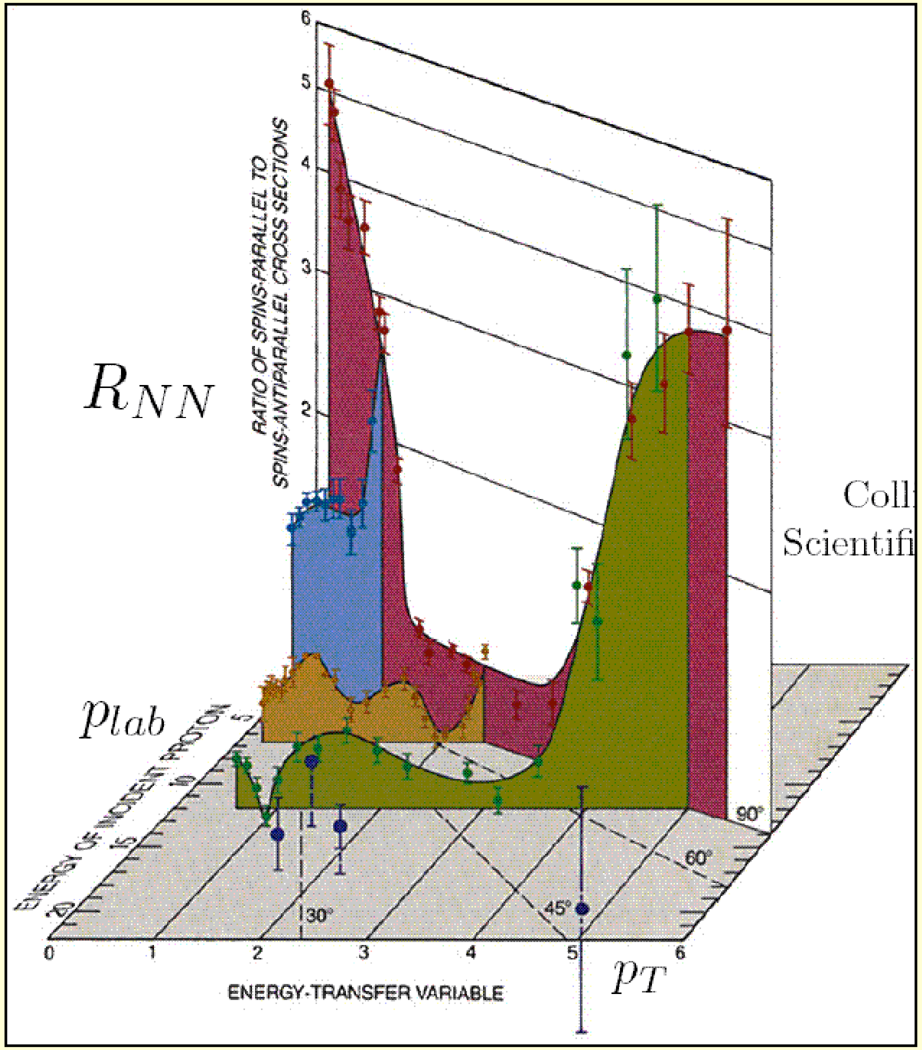
"Exclusive Transversity"

Spin-dependence at large-P_T ($90°_{cm}$):

Hard scattering takes place only with spins ↑↑

Coincidence?: Quenching of Color Transparency

Coincidence?: Charm and Strangeness Thresholds



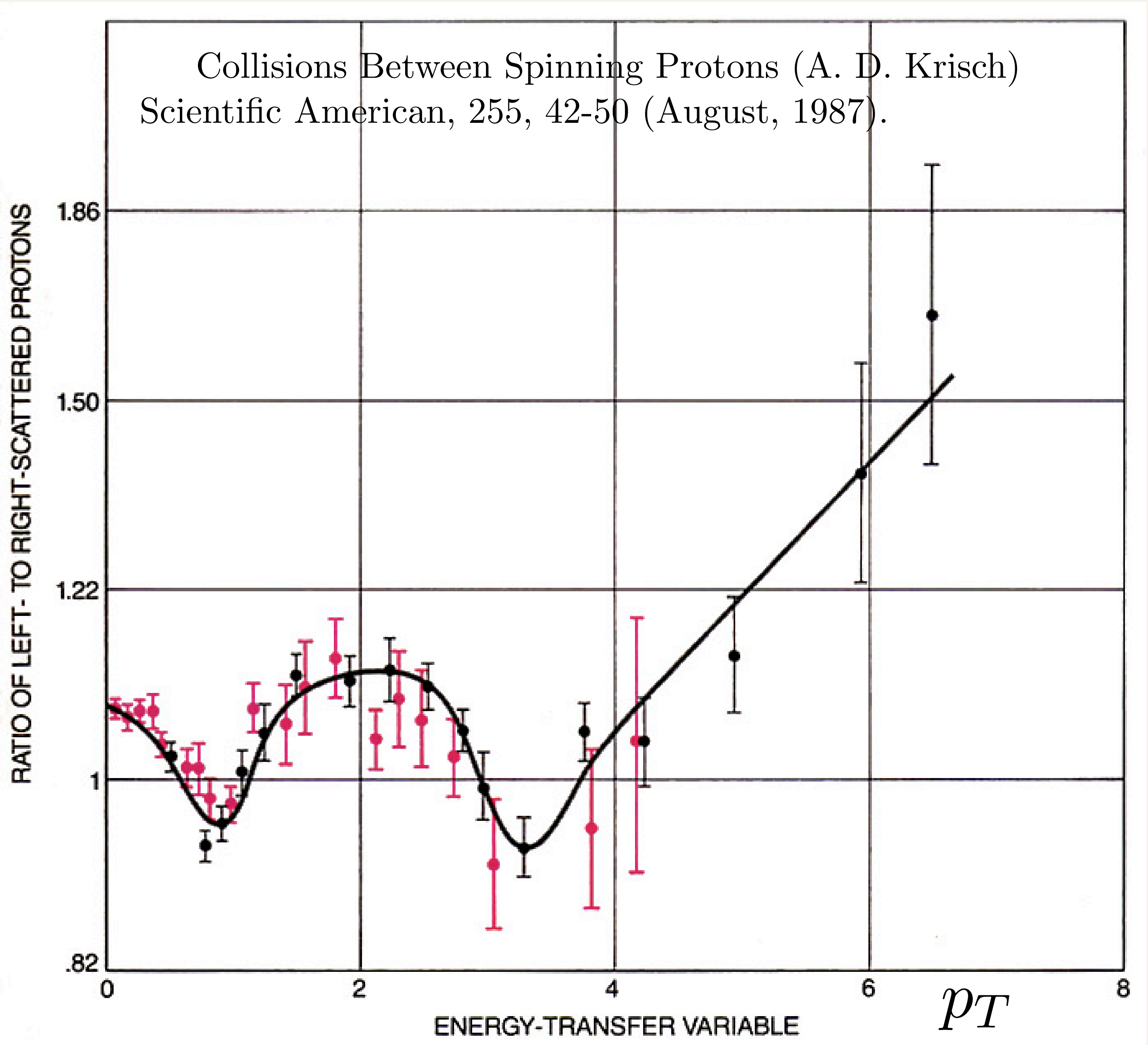
A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

GSI:
Study in antiproton-proton elastic scattering at second charm threshold

The remarkable anomalies of proton-proton scattering

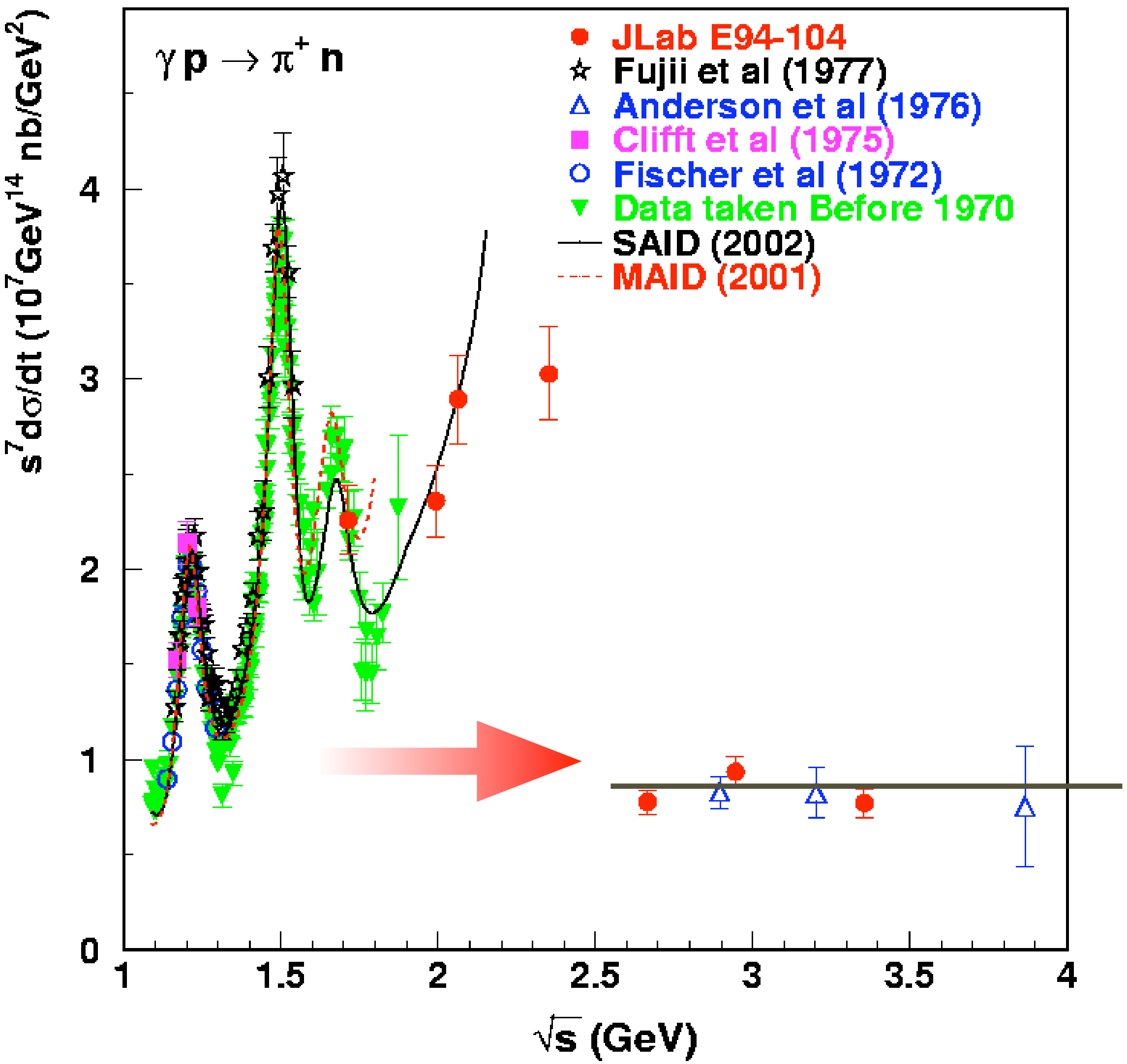
- Double spin correlations
- Single spin correlations
- Color transparency

A_N



Collisions Between Spinning Protons (A. D. Krisch)
Scientific American, 255, 42-50 (August, 1987).
RATIO OF LEFT- TO RIGHT-SCATTERED PROTONS
1.86
1.50
1.22
1
.82
0
2
4
6
8
ENERGY-TRANSFER VARIABLE
p_T

Test of PQCD Scaling



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

fixed θ_{CM} scaling

PQCD and AdS/CFT:

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

$$s^7\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = F(\theta_{CM})$$

$$n_{tot} = 1+3+2+3 = 9$$

Conformal invariance at high momentum transfers!

$$\frac{d\sigma}{dt}(pp \to pp) = \frac{F(t/s)}{s^{9.7 \pm 0.5}}$$

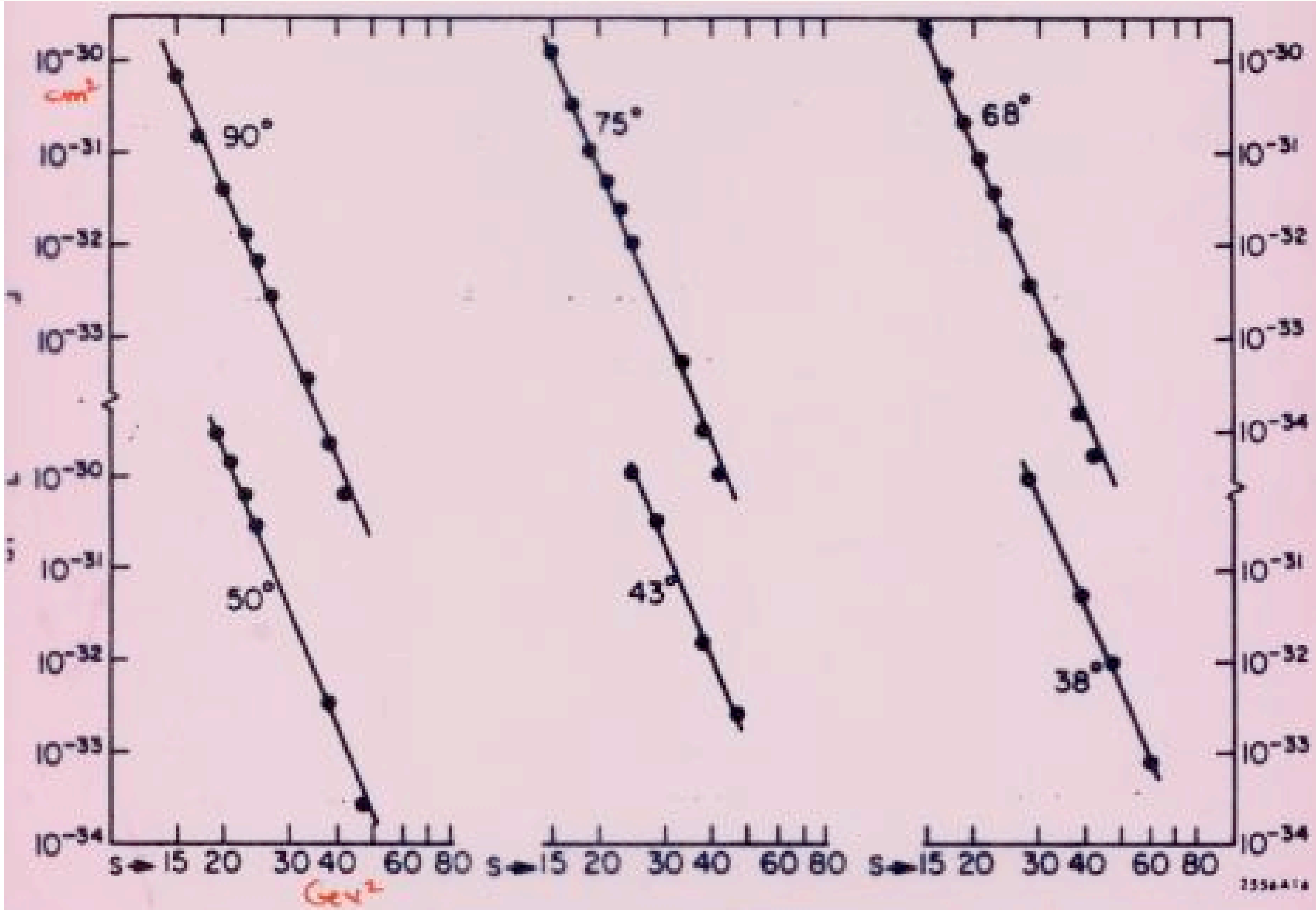
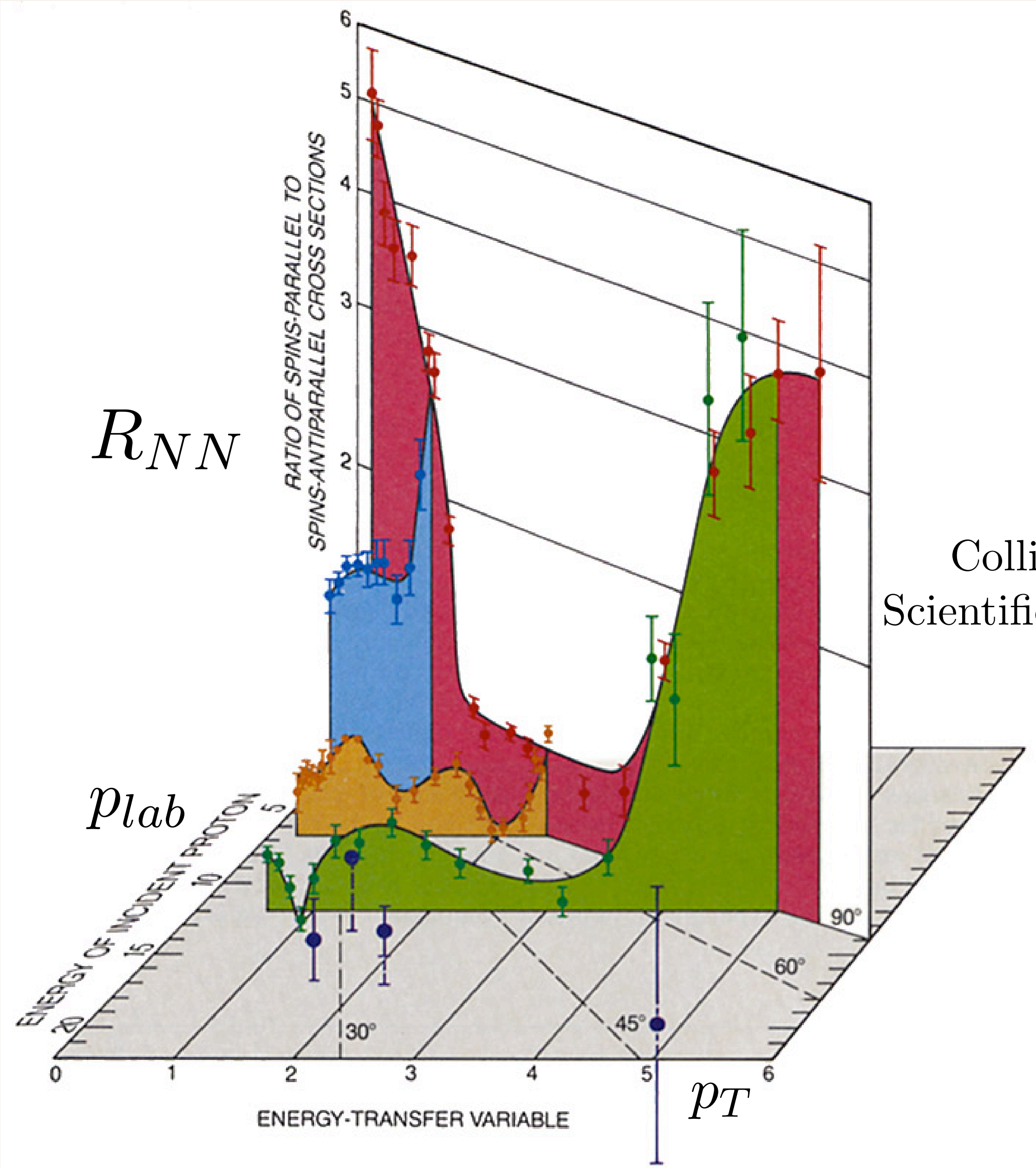


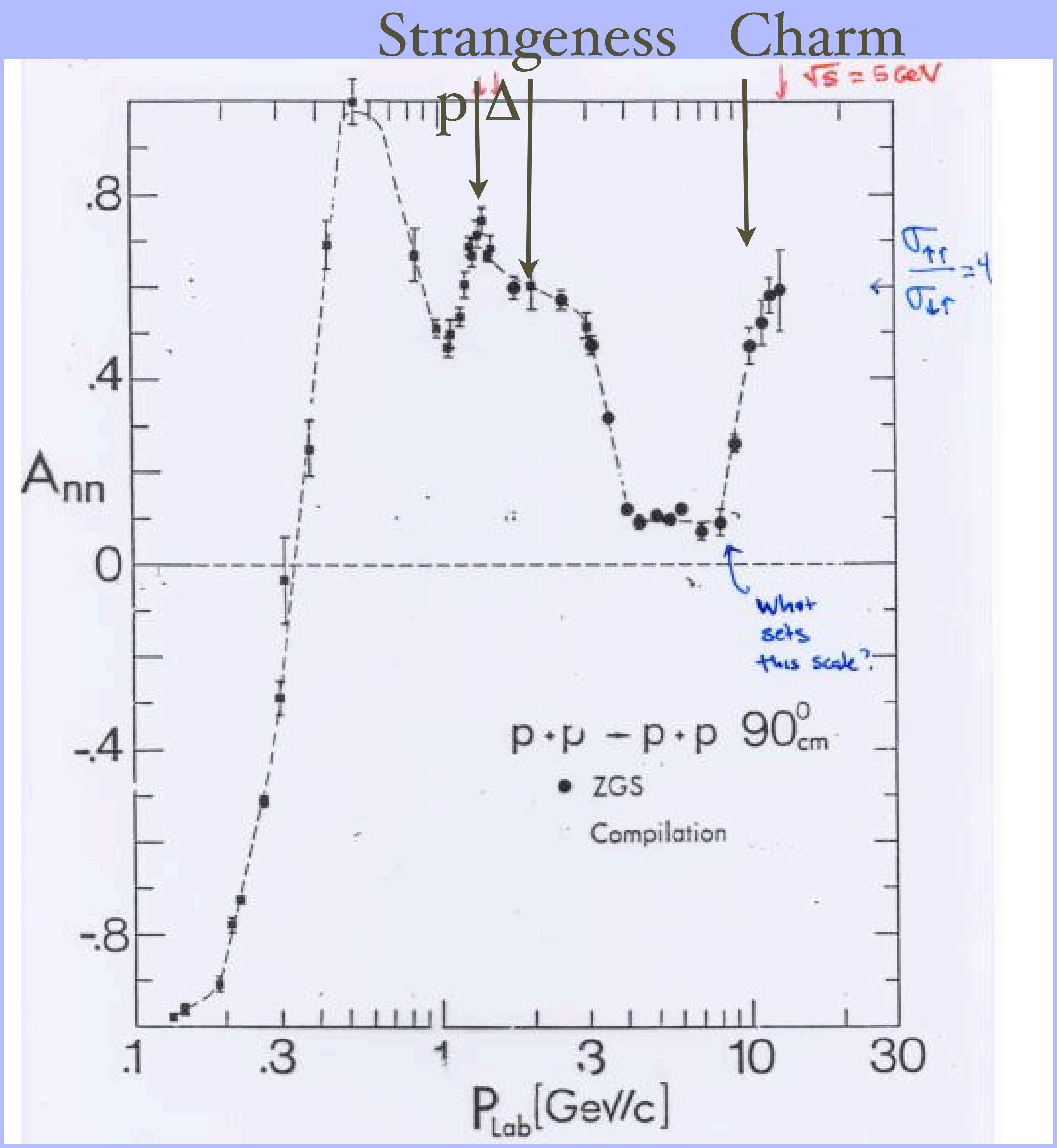
Figure 22. Test of fixed θ_{CM} scaling for elastic pp scattering. The data compilation is Landshoff and Polkinghorne.

Spin Correlations in Elastic $p-p$ Scattering



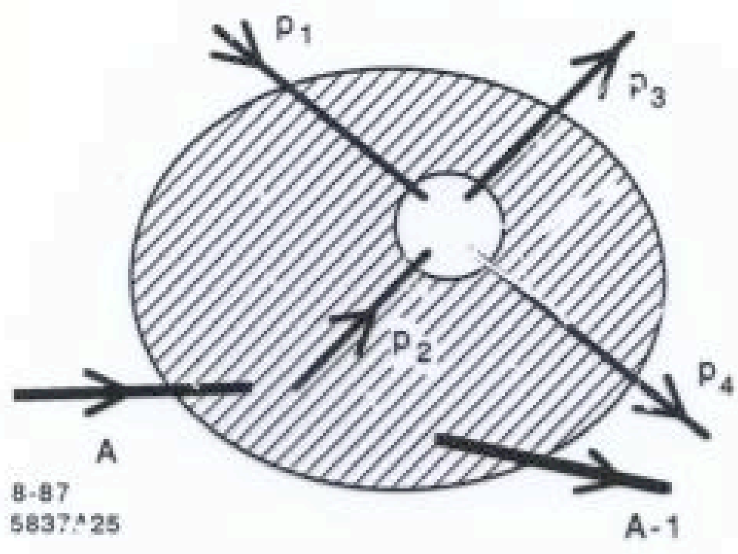
Ratio reaches 4:1 !

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


Strangeness
Charm
p|Δ
$\sqrt{s} = 5$ GeV
.8
.4
0
-.4
-.8
A_{nn}
$\frac{\sigma_{\uparrow\uparrow}}{\sigma_{\downarrow\uparrow}} = 4$
What sets this scale?
p + p → p + p 90^0_{cm}
● ZGS
Compilation
.1
.3
1
3
10
30
P_{Lab} [GeV/c]

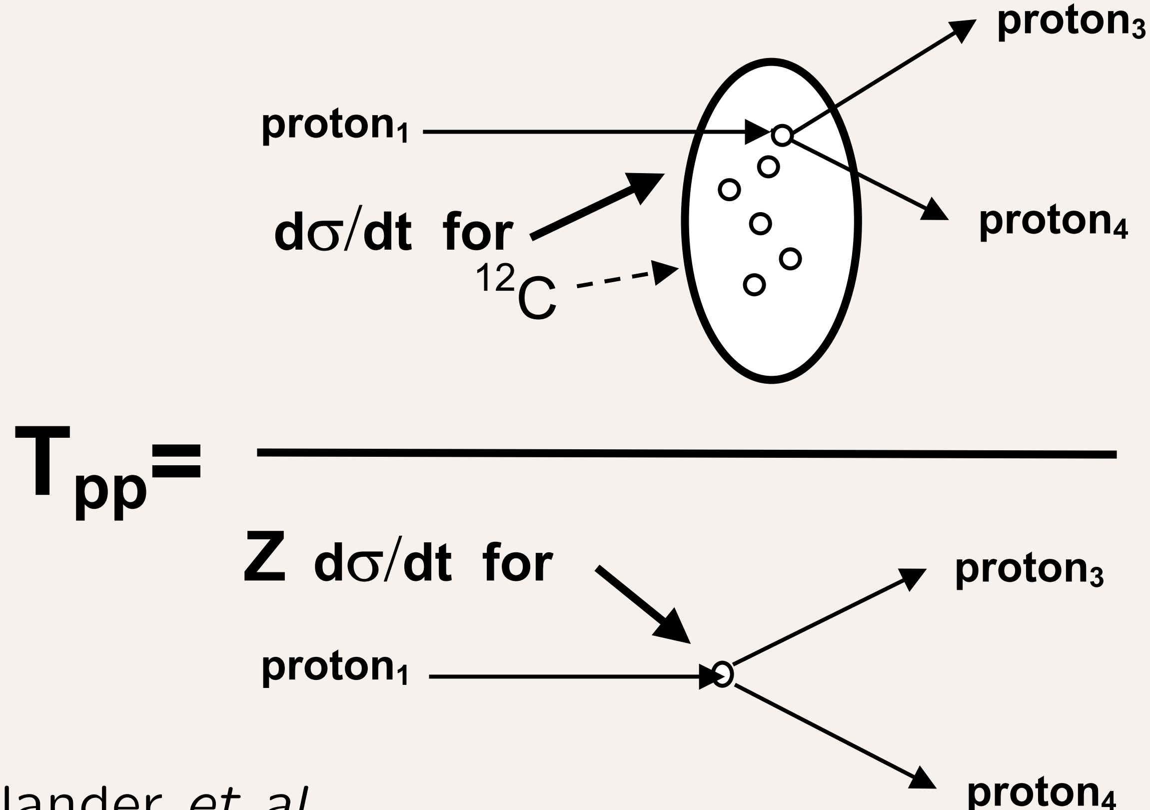
Test Color Transparency

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



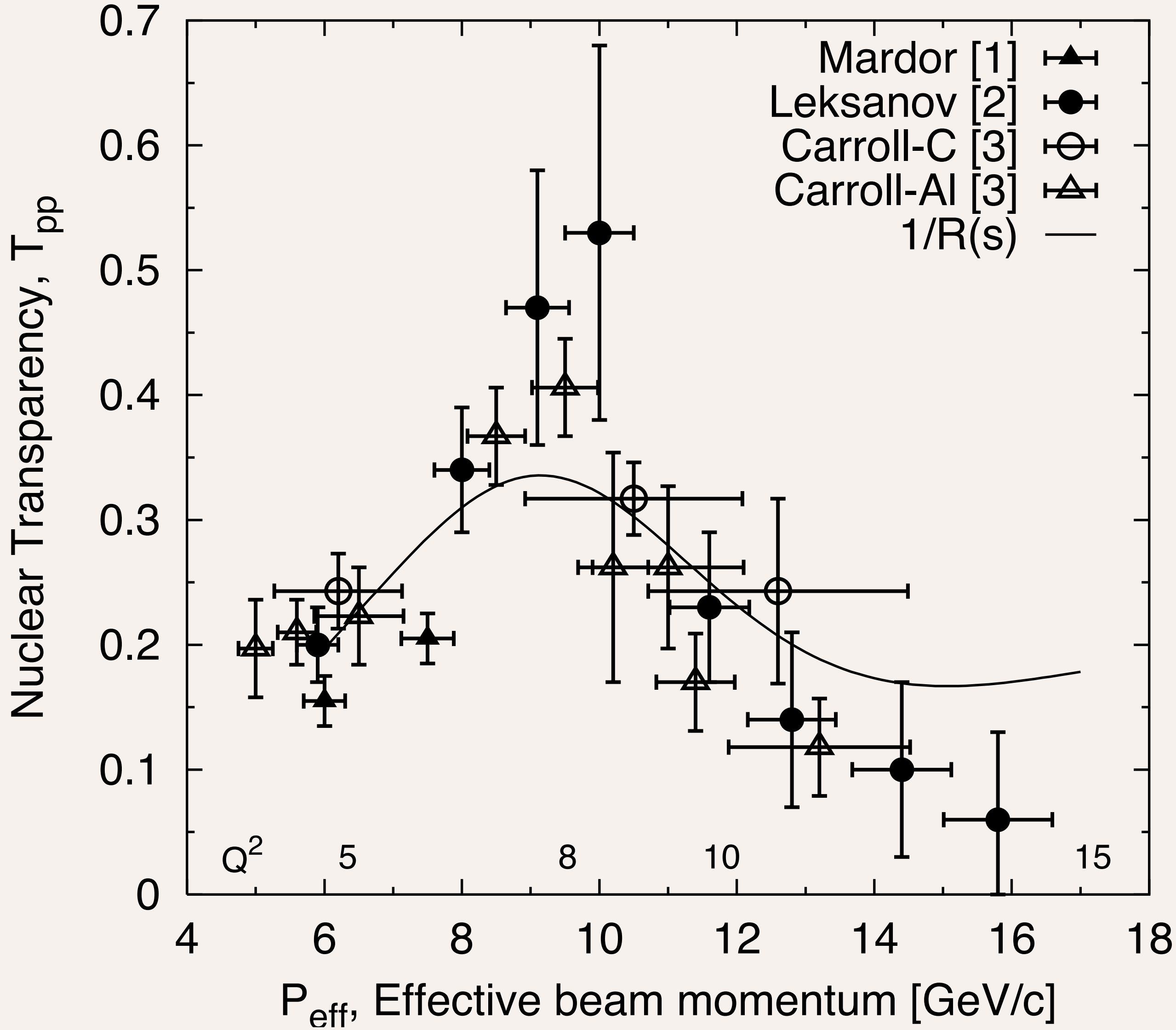
A.H. Mueller, SJB

Color Transparency Ratio



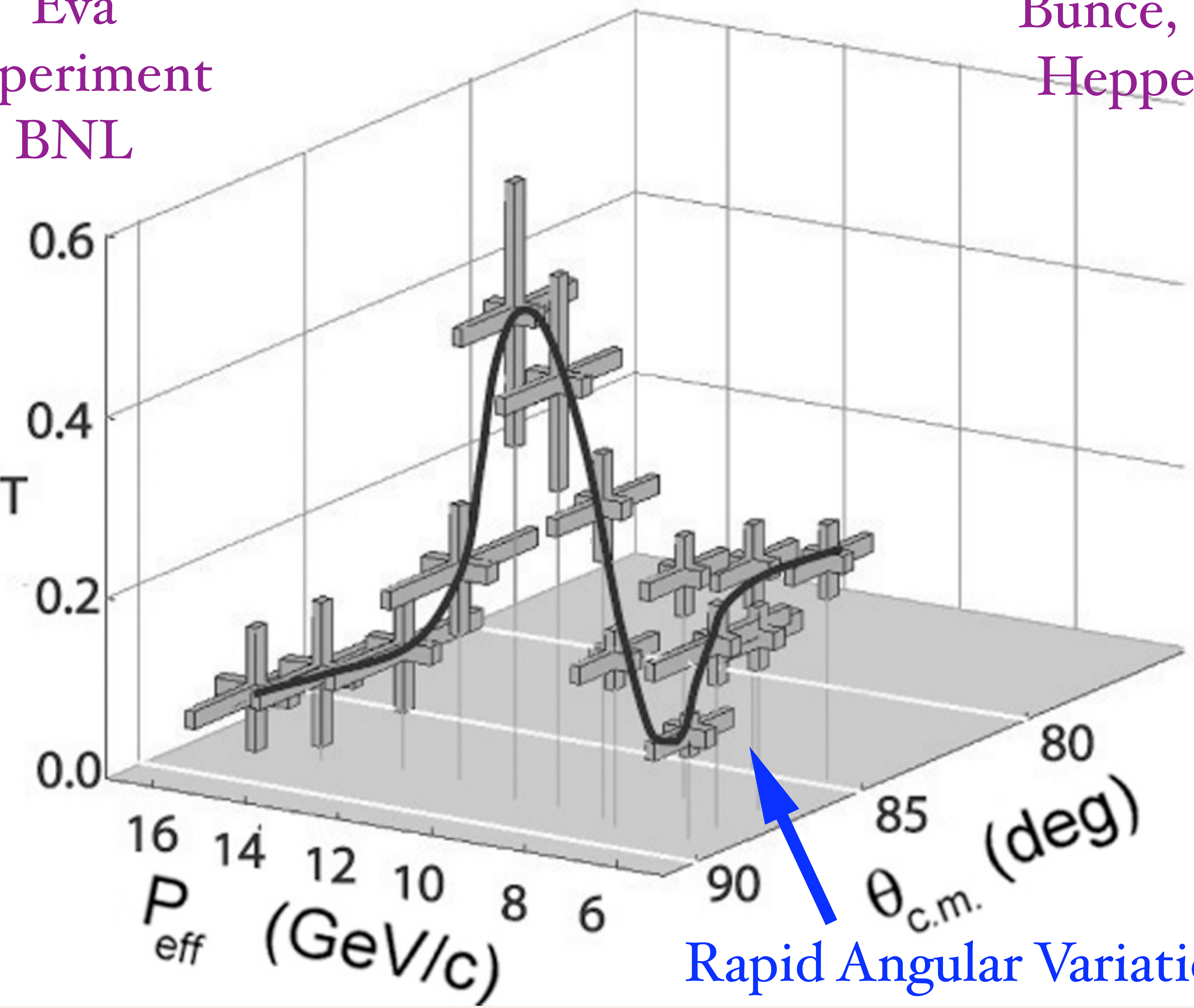
J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p, 2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

Color Transparency fails when A_{nn} is large



Eva
Experiment
BNL

Bunce, Carroll,
Heppelman...



Rapid Angular Variation!

What causes the Krisch Effect?

Largest spin-spin correlation in hadron physics!

An outstanding problem confronting QCD

Carlson, Lipkin, SJB:

Complete analysis of spin correlations

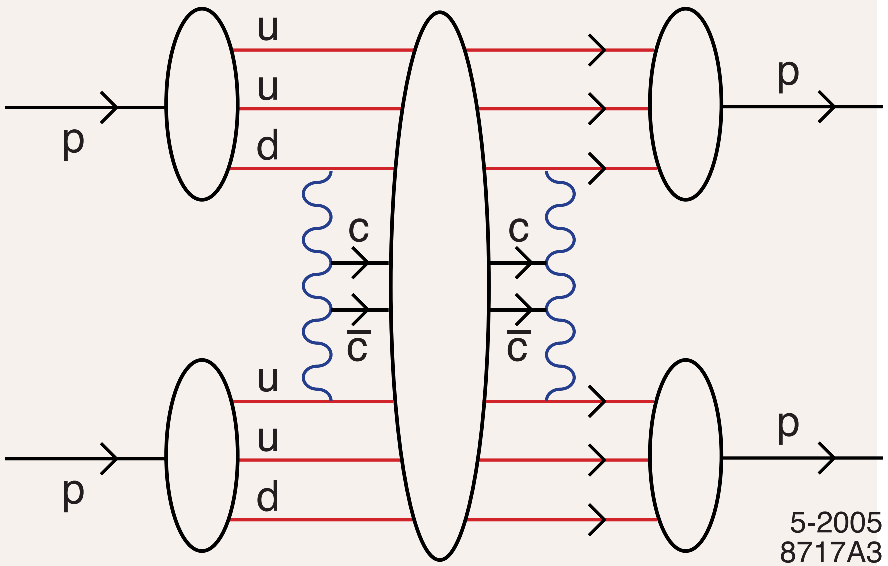
Interference of QIM and Landshoff "Pinch" (triple scattering) contributions

de Teramond, SJB:

Peaks in R_{NN} associated with $p\Delta$, strangeness, charm thresholds

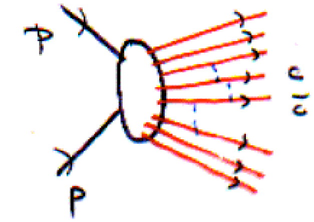
Predict significant strangeness production $\sigma(pp \to sX) \sim 1\ mb$ just above threshold

Predict significant charm production $\sigma(pp \to cX) \sim 1\ \mu b$ just above threshold



Spin, Coherence at heavy quark threshold

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



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

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

8 quarks in S-wave $\quad$ odd parity!

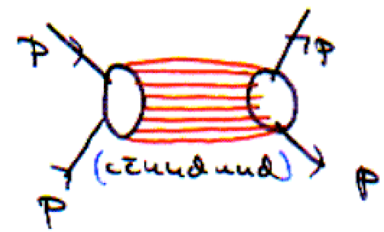
$\therefore\ J = L = S = 1$ for pp

$B = 2$

resonance near threshold ?

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

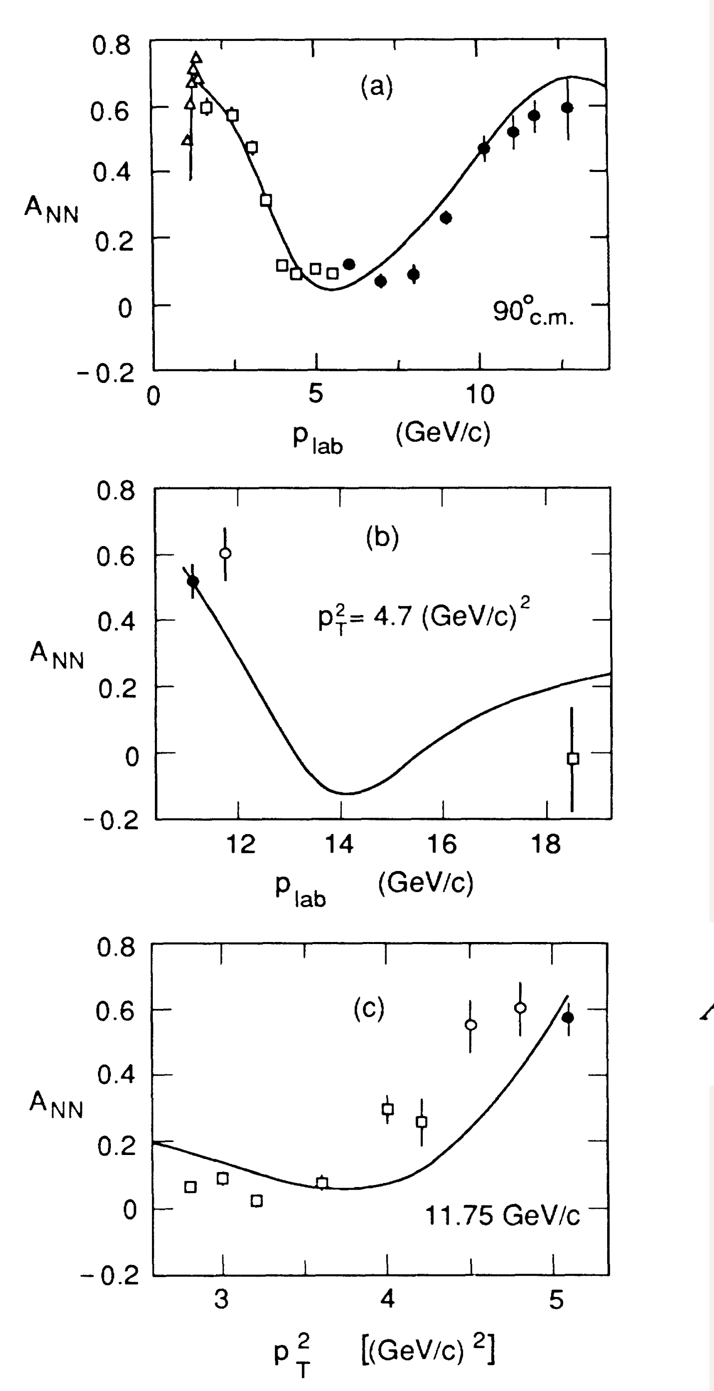
$\sqrt{s} \sim 5$ GeV



$A_{NN} = 1$ 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).

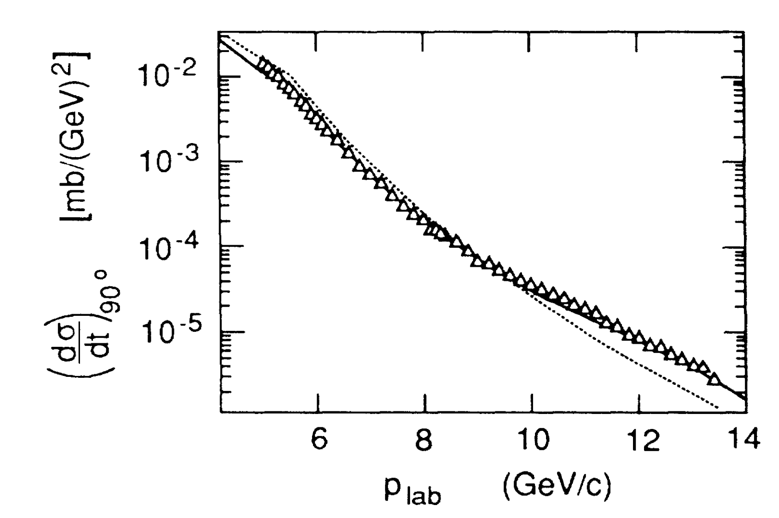
Quark Interchange + 8-Quark Resonance

$|uuduudc\bar{c}>$ 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

Light-Front QCD Phenomenology

- Hidden color, Intrinsic glue, sea, Color Transparency
- Near Conformal Behavior of LFWFs at Short Distances; PQCD constraints
- Vanishing anomalous gravitomagnetic moment
- Relation between edm and anomalous magnetic moment
- Cluster Decomposition Theorem for relativistic systems
- OPE: DGLAP, ERBL evolution; invariant mass scheme

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

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

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

Angular Momentum on the Light-Front

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock state by Fock State

$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

$$
\begin{aligned}
-\frac{B(0)}{2M} &= \lim_{q^1_\perp\to 0}\frac{\partial}{\partial q^1_\perp}\langle P+q,\uparrow|\frac{T^{++}(0)}{2(P^+)^2}|P,\downarrow\rangle\\
&= \lim_{q^1_\perp\to 0}\frac{\partial}{\partial q^1_\perp}\langle\Psi^\uparrow(P^+=1,\vec{P}_\perp=\vec{q}_\perp)|\frac{T^{++}(0)}{2(P^+)^2}|\Psi^\downarrow(P^+=1,\vec{P}_\perp=\vec{0}_\perp)\rangle\\
&= \lim_{q^1_\perp\to 0}\frac{\partial}{\partial q^1_\perp}\sum_a\int\prod_{k=1}^{n-1}\frac{\mathrm{d}^2\vec{k}_{\perp k}\,\mathrm{d}x_k}{16\pi^3}\\
&\quad\times\psi_a^{\uparrow *}(x_1,x_2,\dots,x_{n-1},(1-x_1-x_2-\cdots-x_{n-1}),\\
&\qquad\vec{k}'_{\perp 1},\vec{k}'_{\perp 2},\dots,\vec{k}'_{\perp n-1},(-\vec{k}'_{\perp 1}-\vec{k}'_{\perp 2}-\cdots-\vec{k}'_{\perp n-1}))\\
&\quad\times\left[\sum_{i=1}^{n-1}x_i+(1-x_1-x_2-\cdots-x_{n-1})\right]\\
&\quad\times\psi_a^{\downarrow}(x_1,x_2,\dots,x_{n-1},(1-x_1-x_2-\cdots-x_{n-1}),\\
&\qquad\vec{k}_{\perp 1},\vec{k}_{\perp 2},\dots,\vec{k}_{\perp n-1},(-\vec{k}_{\perp 1}-\vec{k}_{\perp 2}-\cdots-\vec{k}_{\perp n-1})).
\end{aligned}
$$

B(0) = 0

Fock state by Fock state

B(q²) not zero :
QED: 2 photon cut

Vanishing Anomalous Gravitomagnetic Moment

Hwang, Ma, Schmidt, sjb

$$
\begin{aligned}
&=\int\prod_{k=1}^{n-1}\frac{\mathrm{d}^2\vec{k}_{\perp k}\,\mathrm{d}x_k}{16\pi^3}\psi_a^{\uparrow *}(x_1,x_2,\dots,x_{n-1},(1-x_1-x_2-\cdots-x_{n-1}),\\
&\qquad\vec{k}_{\perp 1},\vec{k}_{\perp 2},\dots,\vec{k}_{\perp n-1},(-\vec{k}_{\perp 1}-\vec{k}_{\perp 2}-\cdots-\vec{k}_{\perp n-1}))\\
&\quad\times\left[\sum_{i=1}^{n-1}\left(-1+\sum_{j=1}^{n-1}x_j+(1-x_1-x_2-\cdots-x_{n-1})\right)x_i\frac{\partial}{\partial k^1_{\perp i}}\right]\\
&\quad\times\psi_a^{\downarrow}(x_1,x_2,\dots,x_{n-1},(1-x_1-x_2-\cdots-x_{n-1}),\\
&\qquad\vec{k}_{\perp 1},\vec{k}_{\perp 2},\dots,\vec{k}_{\perp n-1},(-\vec{k}_{\perp 1}-\vec{k}_{\perp 2}-\cdots-\vec{k}_{\perp n-1}))\\
&=0.
\end{aligned}
$$

Equivalence Theorem

Kobsarev, Okun
Taryaev

LFWFs of Electron (n=2)

$J_z = +\frac{1}{2}$

Gives Schwinger Anomalous Moment $\frac{\alpha}{2\pi}$

$$\left\{\begin{array}{ll} \psi^{\uparrow}_{+\frac{1}{2}\,+1}(x,\vec{k}_\perp) = -\sqrt{2}\frac{(-k^1+ik^2)}{x(1-x)}\,\varphi\ , & L_z = -1 \\ \psi^{\uparrow}_{+\frac{1}{2}\,-1}(x,\vec{k}_\perp) = -\sqrt{2}\frac{(+k^1+ik^2)}{1-x}\,\varphi\ , & L_z = 1 \\ \psi^{\uparrow}_{-\frac{1}{2}\,+1}(x,\vec{k}_\perp) = -\sqrt{2}(M-\frac{m}{x})\,\varphi\ , & L_z = 0 \\ \psi^{\uparrow}_{-\frac{1}{2}\,-1}(x,\vec{k}_\perp) = 0\ , & \end{array}\right.$$

where

$$\varphi = \varphi(x,\vec{k}_\perp) = \frac{e/\sqrt{1-x}}{M^2-(\vec{k}_\perp^2+m^2)/x-(\vec{k}_\perp^2+\lambda^2)/(1-x)}\ .$$

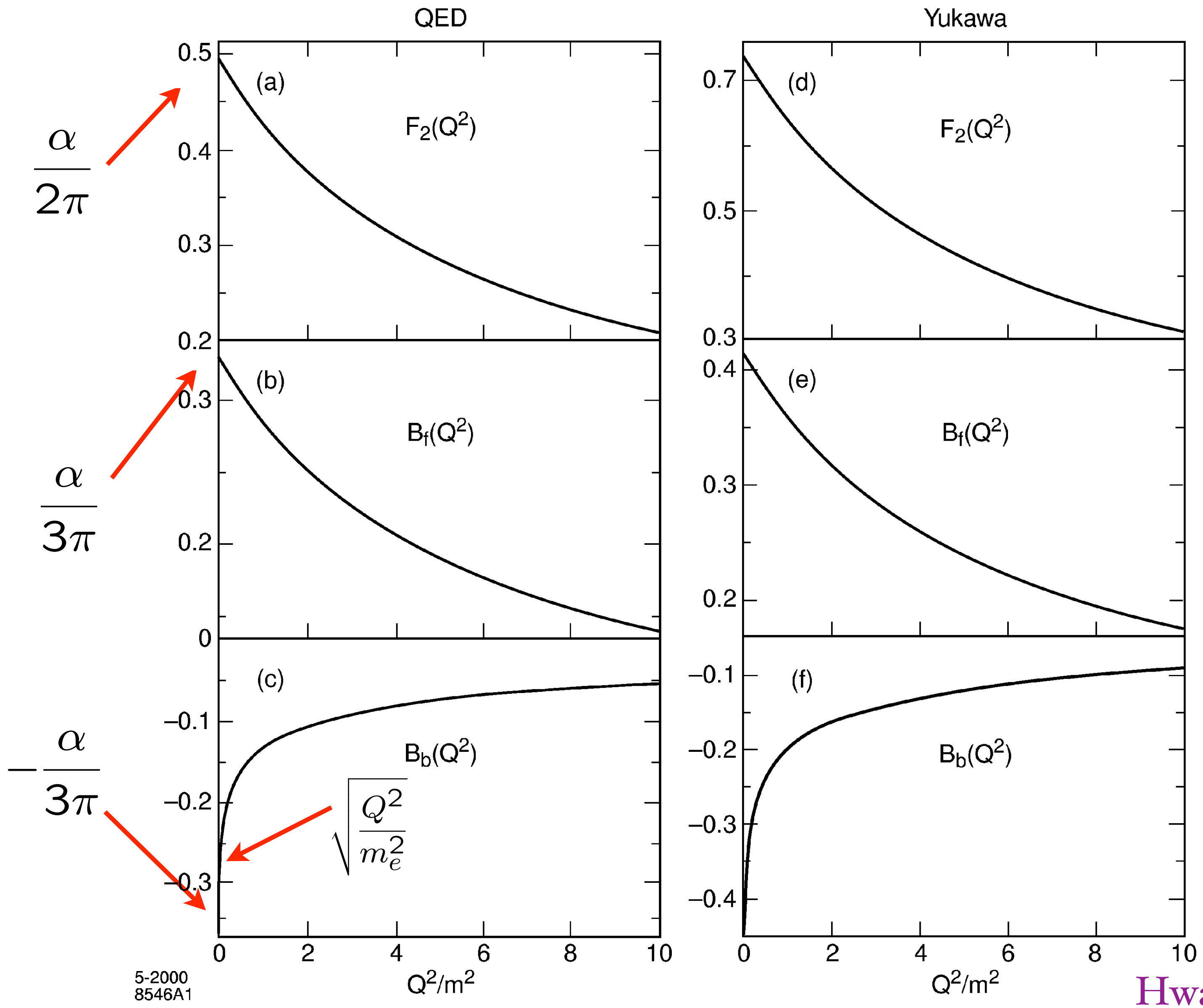
$M \rightarrow m + \lambda$:

Spin-1 mass λ:

Spin-1/2 mass m

$$\left\{\begin{array}{l} \psi^{\downarrow}_{+\frac{1}{2}\,+1}(x,\vec{k}_\perp) = 0\ , \\ \psi^{\downarrow}_{+\frac{1}{2}\,-1}(x,\vec{k}_\perp) = -\sqrt{2}(M-\frac{m}{x})\,\varphi\ , \\ \psi^{\downarrow}_{-\frac{1}{2}\,+1}(x,\vec{k}_\perp) = -\sqrt{2}\frac{(-k^1+ik^2)}{1-x}\,\varphi\ , \\ \psi^{\downarrow}_{-\frac{1}{2}\,-1}(x,\vec{k}_\perp) = -\sqrt{2}\frac{(+k^1+ik^2)}{x(1-x)}\,\varphi\ . \end{array}\right.$$

Drell, sjb
Hwang, Schmidt, sjb



Hwang, Ma, Schmidt, sjb

Helicity-flip electromagnetic and gravitational form factors for spacelike $q^2 = -Q^2 < 0$ from the quantum fluctuations of a fermion at one-loop order in units of α/π for QED and $g^2/4\pi^2$ for the Yukawa theory. The fermion constituent mass is taken as $m_f = M$. The boson constituent is massless.

electron LFWFs provide quark + spin-one diquark model of nucleon

$$q(x,\Lambda^2)_{\text{spin}-1\ \text{diquark}}$$

$$= \int \frac{d^2\vec{k}_\perp dx}{16\pi^3}\theta(\Lambda^2 - \mathcal{M}^2)\ 2\left[\frac{\vec{k}_\perp^2}{x^2(1-x)^2} + \frac{\vec{k}_\perp^2}{(1-x)^2} + (M - \frac{m}{x})^2\right]|\varphi|^2$$

$$\Delta q(x,\Lambda^2)_{\text{spin}-1\ \text{diquark}}$$

$$= \int \frac{d^2\vec{k}_\perp dx}{16\pi^3}\theta(\Lambda^2 - \mathcal{M}^2)\ 2\left[\frac{\vec{k}_\perp^2}{x^2(1-x)^2} + \frac{\vec{k}_\perp^2}{(1-x)^2} - (M - \frac{m}{x})^2\right]|\varphi|^2$$

$$\delta q(x,\Lambda^2)_{\text{spin}-1\ \text{diquark}}$$

$$= \int \frac{d^2\vec{k}_\perp dx}{16\pi^3}\theta(\Lambda^2 - \mathcal{M}^2)\ 4\left[\frac{\vec{k}_\perp^2}{x(1-x)^2}\right]|\varphi|^2 \ .$$

Electron Transversity

Soffer bounds automatically satisfied in LF formalism

$$\varphi = \varphi(x,\vec{k}_\perp) = \frac{e/\sqrt{1-x}}{M^2 - (\vec{k}_\perp^2 + m^2)/x - (\vec{k}_\perp^2 + \lambda^2)/(1-x)}$$

Gardner, Hwang, sjb, in progress

Light-Cone Wavefunction Representations of Anomalous Magnetic Moment and Electric Dipole Moment

In the case of a spin-$\frac{1}{2}$ composite system, the Dirac and Pauli form factors $F_1(q^2)$ and $F_2(q^2)$, electric dipole moment form factor $F_3(q^2)$ are defined by

$$\langle P'|J^\mu(0)|P\rangle = \overline{U}(P')\left[F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i}{2M}\sigma^{\mu\alpha}q_\alpha + F_3(q^2)\frac{-1}{2M}\sigma^{\mu\alpha}\gamma_5 q_\alpha\right]U(P)\,, \quad (47)$$

Compute matrix elements of good current J+

$$F_1(q^2) = \left\langle P+q,\uparrow\left|\frac{J^+(0)}{2P^+}\right|P,\uparrow\right\rangle = \left\langle P+q,\downarrow\left|\frac{J^+(0)}{2P^+}\right|P,\downarrow\right\rangle\,, \quad (48)$$

$$\frac{F_2(q^2)}{2M} = \frac{1}{2}\left[+\frac{1}{-q^1+\mathrm{i}q^2}\left\langle P+q,\uparrow\left|\frac{J^+(0)}{2P^+}\right|P,\downarrow\right\rangle + \frac{1}{q^1+\mathrm{i}q^2}\left\langle P+q,\downarrow\left|\frac{J^+(0)}{2P^+}\right|P,\uparrow\right\rangle\right], \quad (49)$$

$$\frac{F_3(q^2)}{2M} = \frac{i}{2}\left[+\frac{1}{-q^1+\mathrm{i}q^2}\left\langle P+q,\uparrow\left|\frac{J^+(0)}{2P^+}\right|P,\downarrow\right\rangle - \frac{1}{q^1+\mathrm{i}q^2}\left\langle P+q,\downarrow\left|\frac{J^+(0)}{2P^+}\right|P,\uparrow\right\rangle\right]. \quad (50)$$

Relation between edm and anomalous magnetic moment

$$\frac{F_2(q^2)}{2M} = \sum_a \int \frac{\mathrm{d}^2\vec{k}_\perp \mathrm{d}x}{16\pi^3} \sum_j e_j \, \frac{1}{2} \times$$

$$\left[+ \frac{1}{-q^1 + \mathrm{i}q^2} \psi_a^{\uparrow *}(x_i, \vec{k}'_{\perp i}, \lambda_i) \, \psi_a^{\downarrow}(x_i, \vec{k}_{\perp i}, \lambda_i) + \frac{1}{q^1 + \mathrm{i}q^2} \psi_a^{\downarrow *}(x_i, \vec{k}'_{\perp i}, \lambda_i) \, \psi_a^{\uparrow}(x_i, \vec{k}_{\perp i}, \lambda_i) \right]$$

Drell, sjb,

$$\frac{F_3(q^2)}{2M} = \sum_a \int \frac{\mathrm{d}^2\vec{k}_\perp \mathrm{d}x}{16\pi^3} \sum_j e_j \, \frac{i}{2} \times$$

$$\left[+ \frac{1}{-q^1 + \mathrm{i}q^2} \psi_a^{\uparrow *}(x_i, \vec{k}'_{\perp i}, \lambda_i) \, \psi_a^{\downarrow}(x_i, \vec{k}_{\perp i}, \lambda_i) - \frac{1}{q^1 + \mathrm{i}q^2} \psi_a^{\downarrow *}(x_i, \vec{k}'_{\perp i}, \lambda_i) \, \psi_a^{\uparrow}(x_i, \vec{k}_{\perp i}, \lambda_i) \right],$$

Gardner, Hwang, sjb,

$\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$ **struck quark** $\vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i\vec{q}_\perp$ **spectator**

CP-violating phase

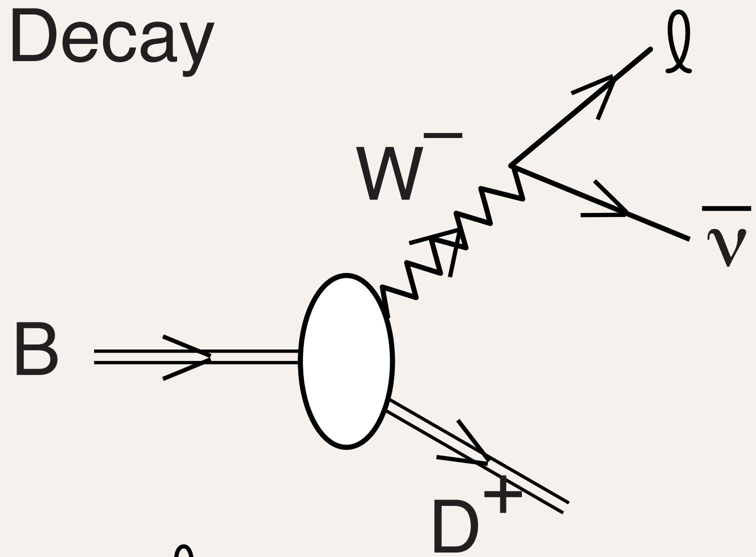
$$F_3(q^2) = F_2(q^2) \times \tan\phi$$

Fock state by Fock state

Gardner, Hwang, sjb,
in progress

Weak Exclusive Decay

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



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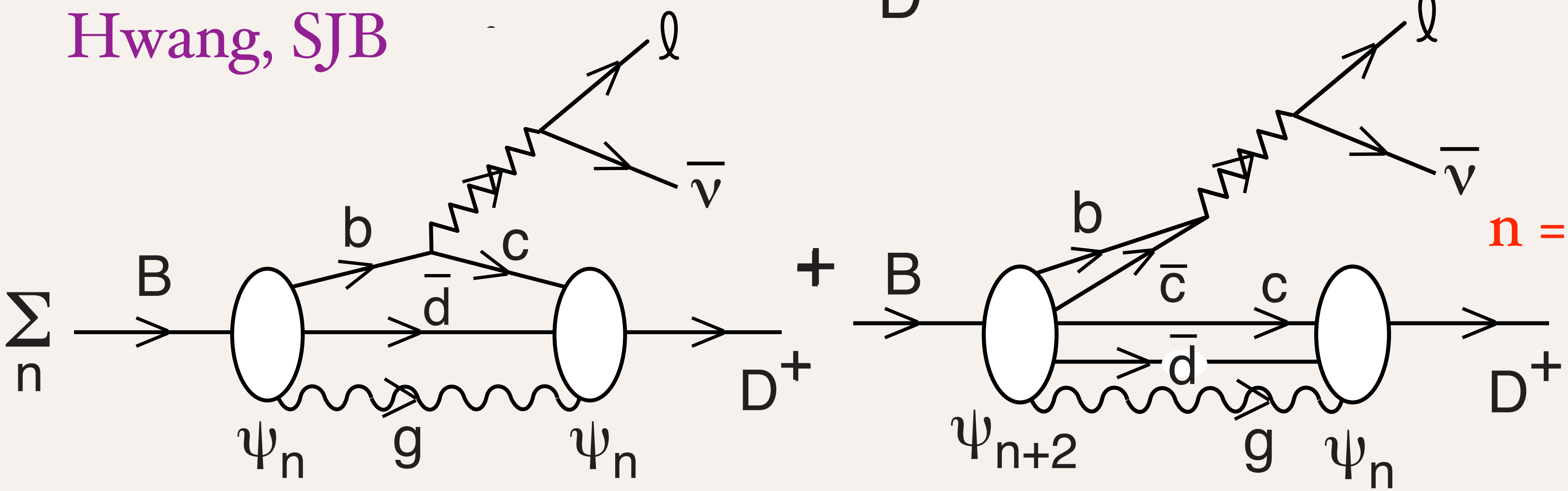
Exact Formula

Hwang, SJB



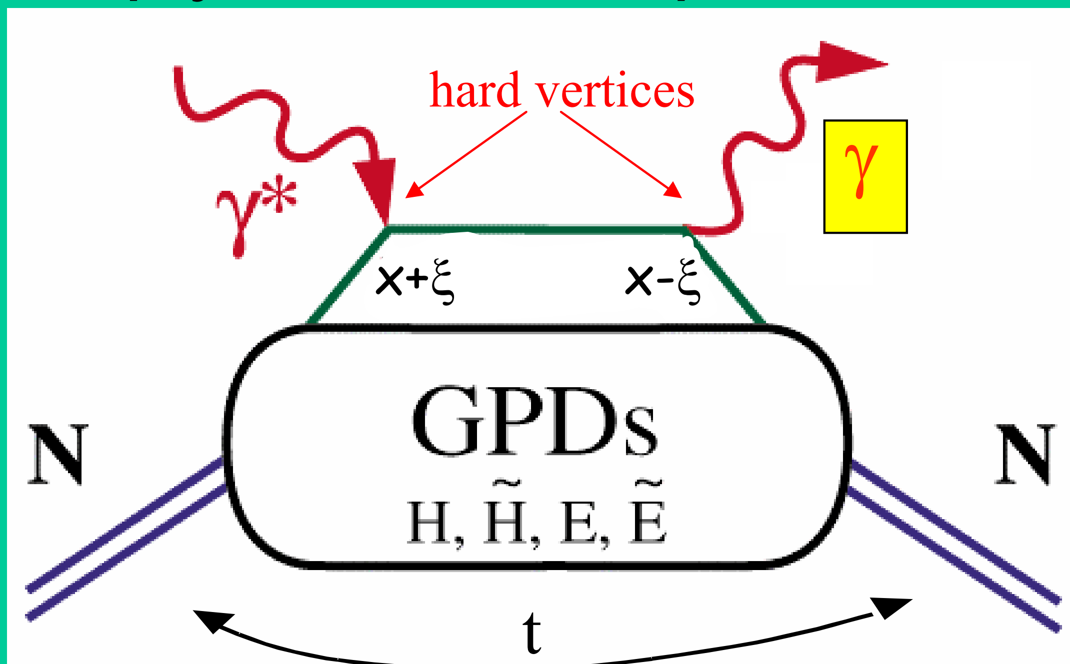
$n = n' + 2$

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

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

$$\xi = \frac{x_B}{2-x_B}$$

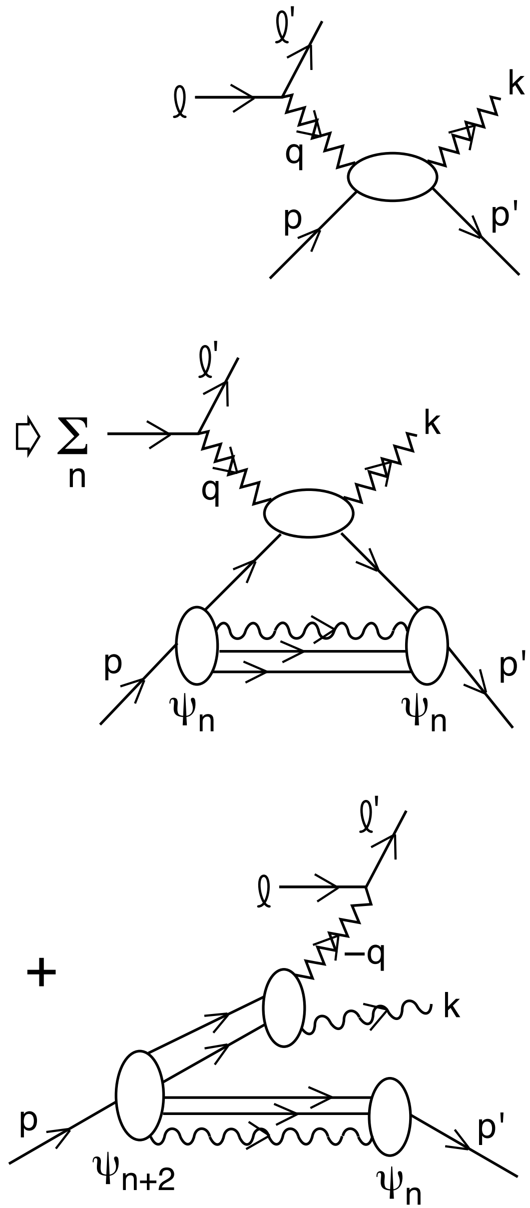
$$\langle p'\,\lambda' |\, J^{\mu}(z)\, J^{\nu}(0)\, | p\,\lambda \rangle$$

Large $-q^2 = Q^2$

$\gamma^* p \to \gamma p'$

Given LFWFs, compute all GPDs !

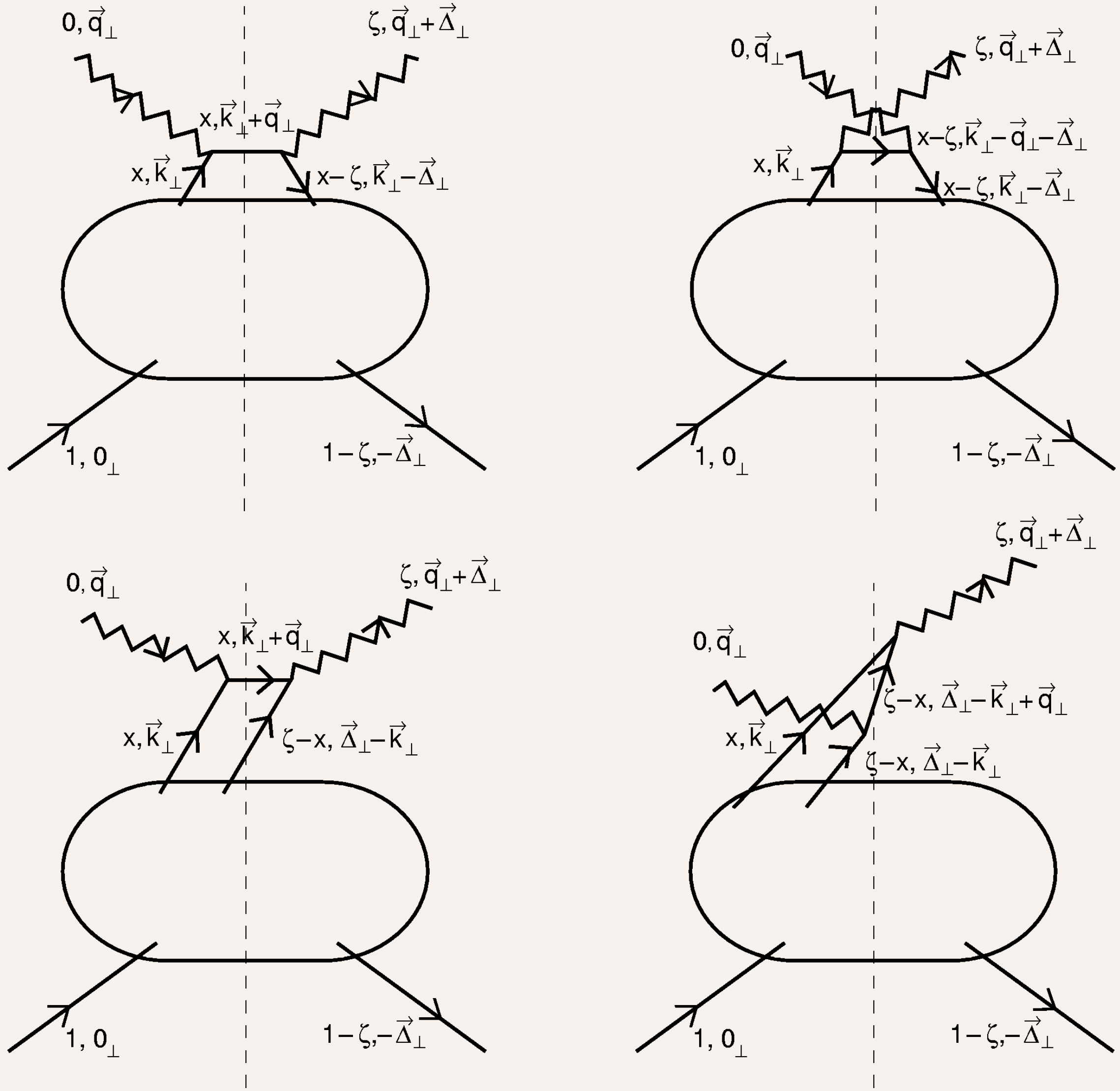
ERBL Evolution



Deeply Virtual Compton Scattering

$n = n' + 2$

Required for Lorentz Invariance



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 $\xi = t = 0$

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

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

Form factors (sum rules)

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

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

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

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

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)

Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p', \gamma^* p \to \pi^+ n',$$

- Remarkable sensitivity to spin, flavor, dynamics
- Measure Real and Imaginary parts from Bethe-Heitler Interference; phase determined by Regge theory (Kuti-Weiskopf)

Close, Gunion, sjb

- J=0 fixed pole: test QCD contact interaction!
- Sum Rules connecting to form factors, Lz
- Evolution Equations (ERBL), PQCD constraints
- Convolutions of Light-front wavefunctions

LFWFS give a fundamental description of hadron observables

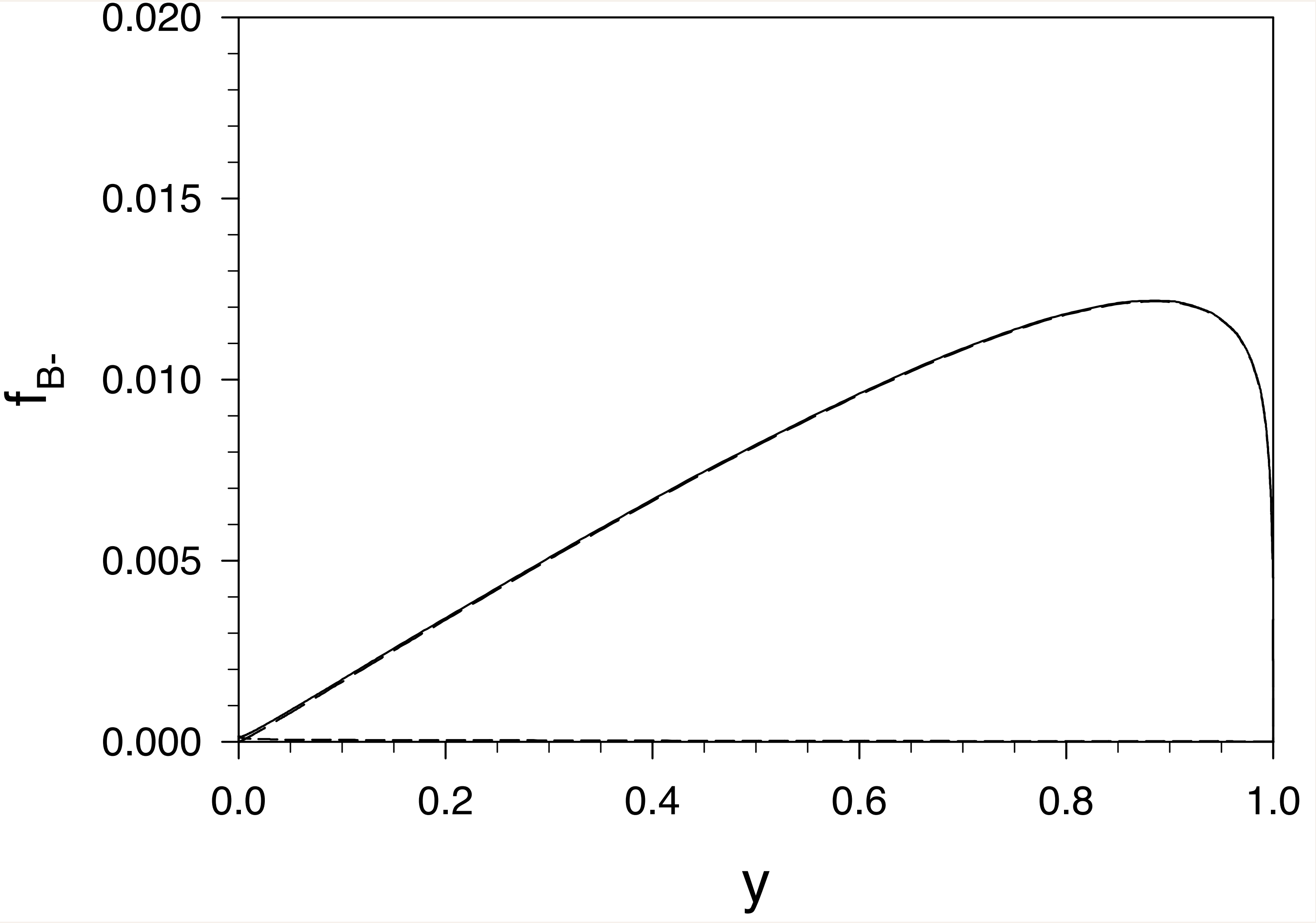
- LFWFS underly structure functions and generalized parton distributions.
- Parton number not conserved: n=n' & n=n'+2 at nonzero skewness
- GPDs are not densities or probability distributions
- Nonperturbative QCD: Lattice, DLCQ, Bethe-Salpeter, AdS/CFT

Solving the LF Heisenberg Eqn.

- 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

Structure function of boson constituent in 3+1 Yukawa theory

Three-particle Fock state truncation



Pauli-Villars Regularization

Hiller, McCartor, sjb

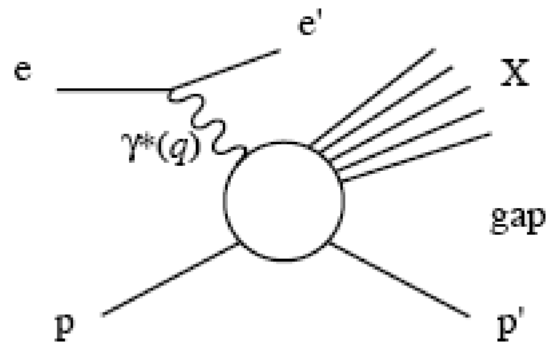
AdS/CFT and QCD

- Non-Perturbative Derivation of Dimensional Counting Rules (Strassler and Polchinski)
- Light-Front Wavefunctions: Confinement at Long Distances and Conformal Behavior at short distances (de Teramond and Sjb)
- Power-law fall-off at large transverse momentum, $x \to 1$
- Hadron Spectra, Regge Trajectories

Hard Diffraction from Rescattering

- Diffractive DIS: New Insight into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions
- T-odd Single-Spin Asymmetries
- Diffractive dijets/ trijets
- Color Transparency, Color Opaqueness

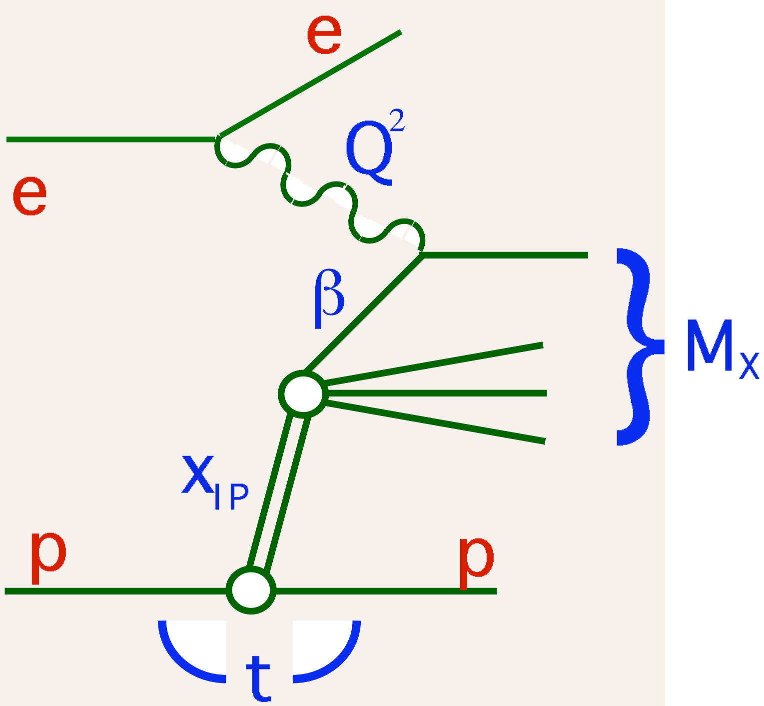
DDIS



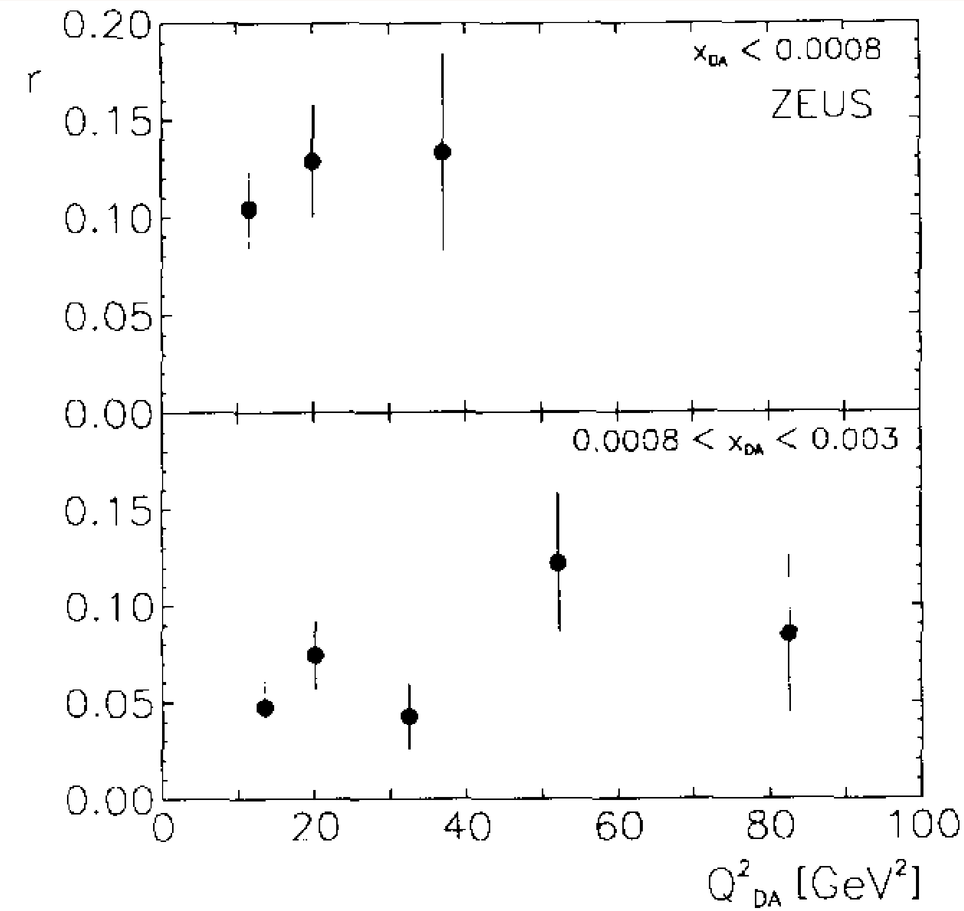
- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

Enberg

Diffractive Deep Inelastic Lepton-Proton Scattering



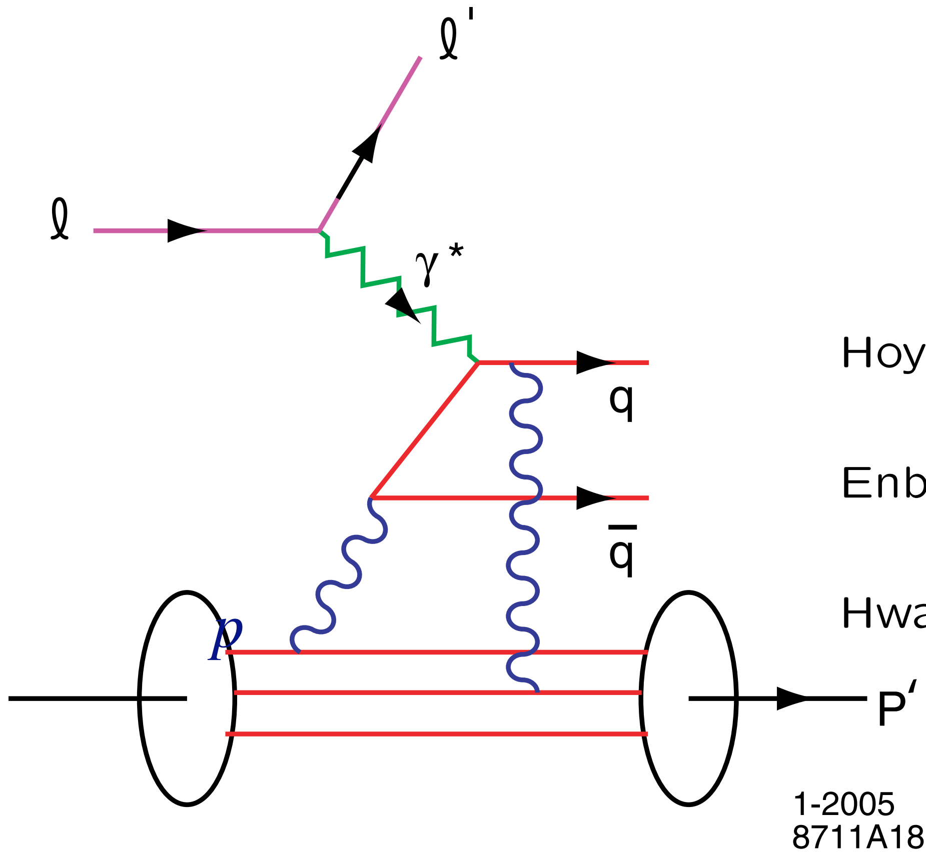
10% of DIS events are diffractive !



Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 315, 481 (1993).

Final State Interaction Produces Diffractive DIS

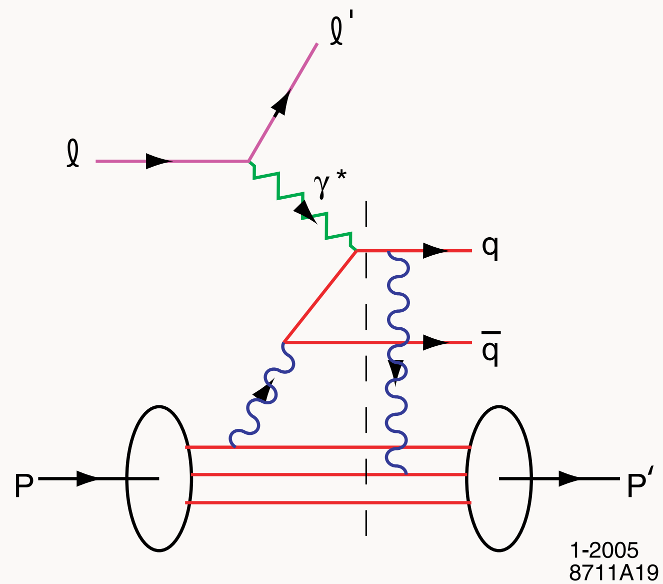


Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate
Pomeron

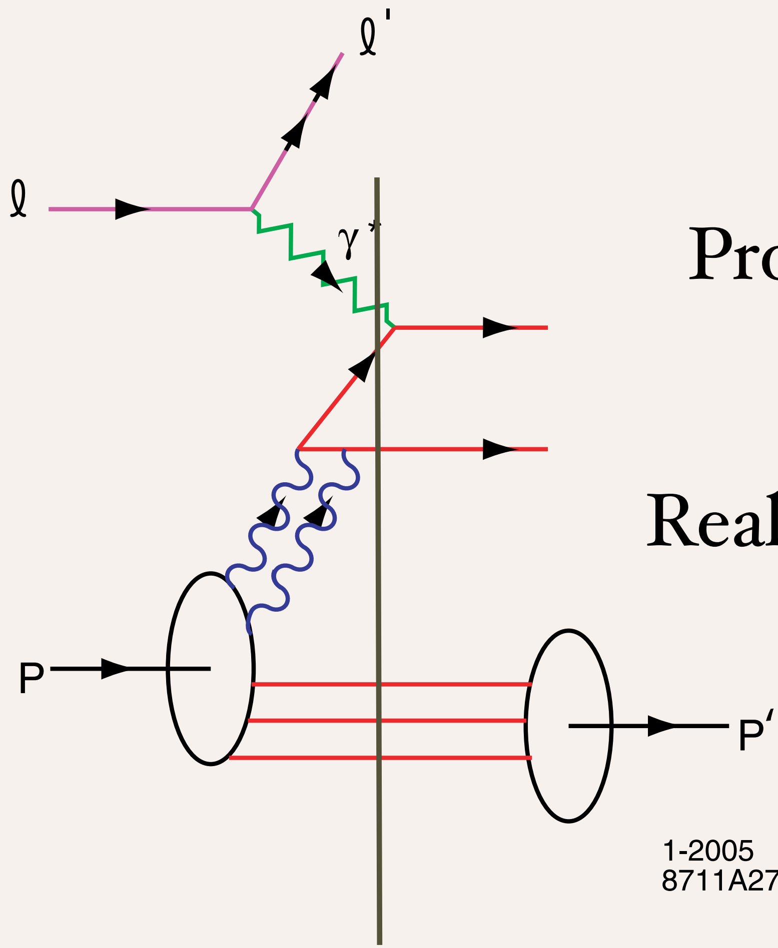
Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

Problem: Wrong Phase

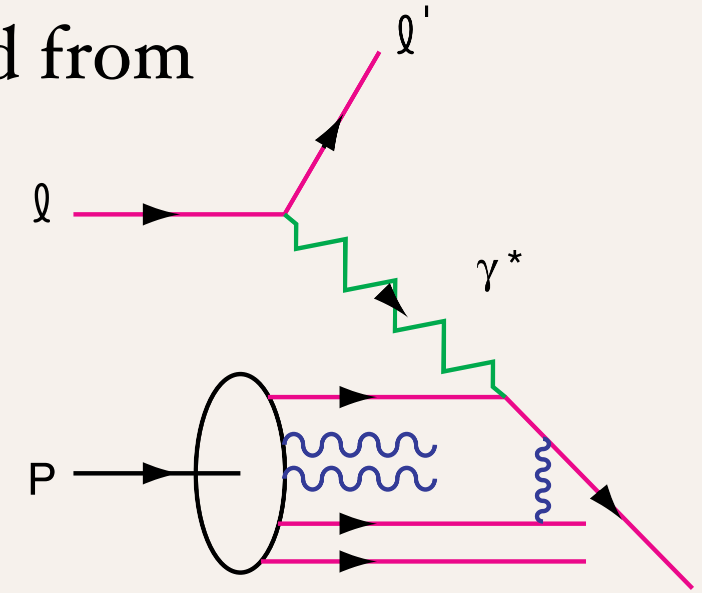
Real; should be imaginary

Pomeron is not a constituent of proton!



Need Final State Interactions !

- Quarks Reinteract in Final State
- Analogous to Coulomb phases, but not unitary
- Observable effects: DDIS, SSI, shadowing, antishadowing
- Structure functions cannot be computed from LFWFs computed in isolation
- Wilson line not 1 even in lcg



QCD factorization

- QCD factorization theorem: Separation of hard and soft
  The quark PDF is given by

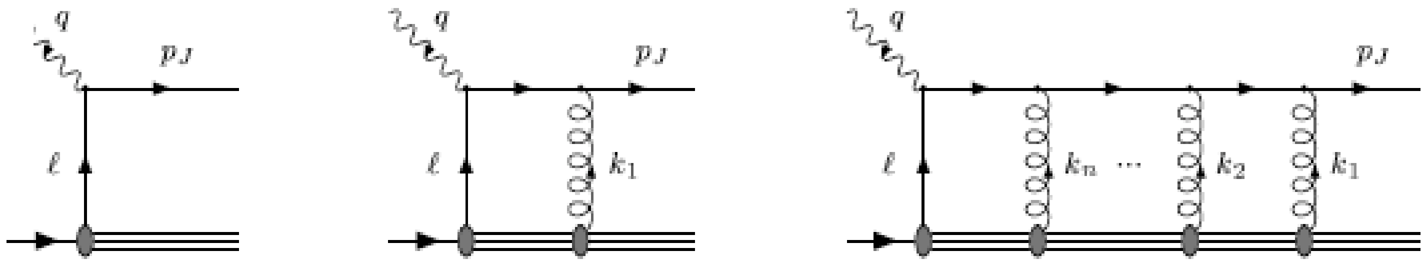
$$f_{q/N} \sim \int dx^- e^{-ix_B p^+ x^-/2} \langle N(p) \,|\, \bar{\psi}(x^-) \gamma^+ W[x^-;0]\, \psi(0) \,|\, N(p) \rangle_{x^+=0}$$

Wilson line: $W[x^-;0] = \mathrm{P}\exp\left[ig \int_0^{x^-} dw^- A_a^+(0, w^-, 0_\perp) t_a\right]$

- DIS: $W[x^-;0] \rightarrow$ *rescattering of struck quark* on target
- $A^+ \rightarrow$ longitudinal *instantaneous* (in x^+) gluon exch.
- No $A^\perp$ within Ioffe coherence length $x^- \sim 1/m_p x_B$

$$\overline{\psi}(y) \int_0^y dx \, e^{iA(x)\cdot dx} \, \psi(0)$$

Wilson line means that DIS looks something like this:



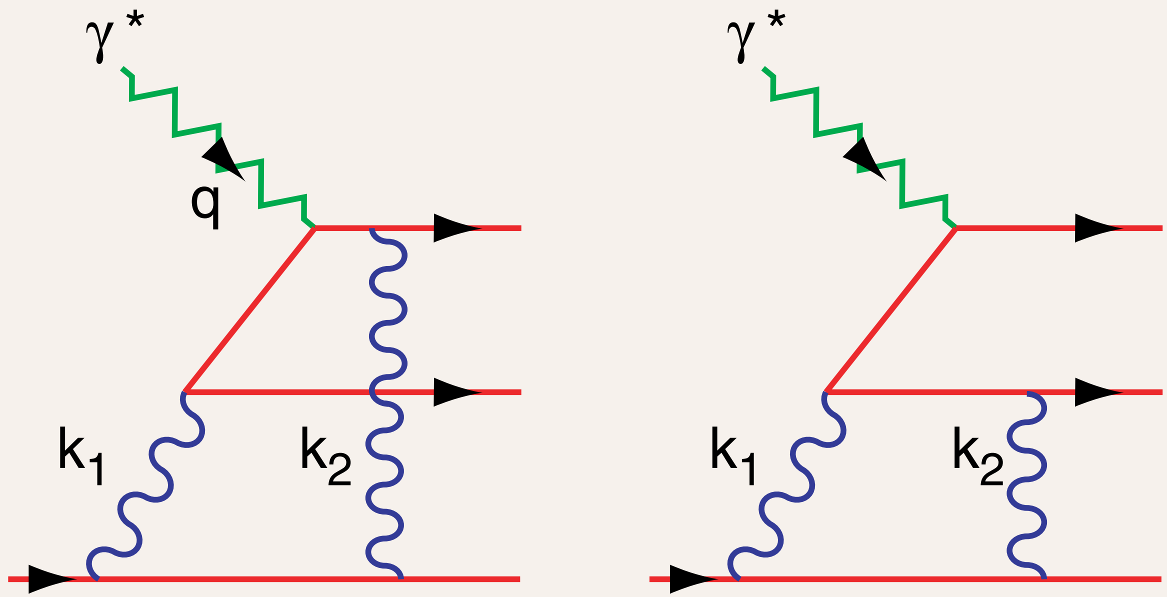
Brodsky, Hoyer, Marchal, Peigné and Sannino (BHMPS) showed that [Phys. Rev. D65 (2002) 114025]

- rescattering can lead to on-shell intermediate states and *imaginary amplitudes* and cannot be ignored in any gauge
- not even in $A^+ = 0$ gauge!

It has also been shown to yield nuclear shadowing and single spin asymmetries.

Enberg

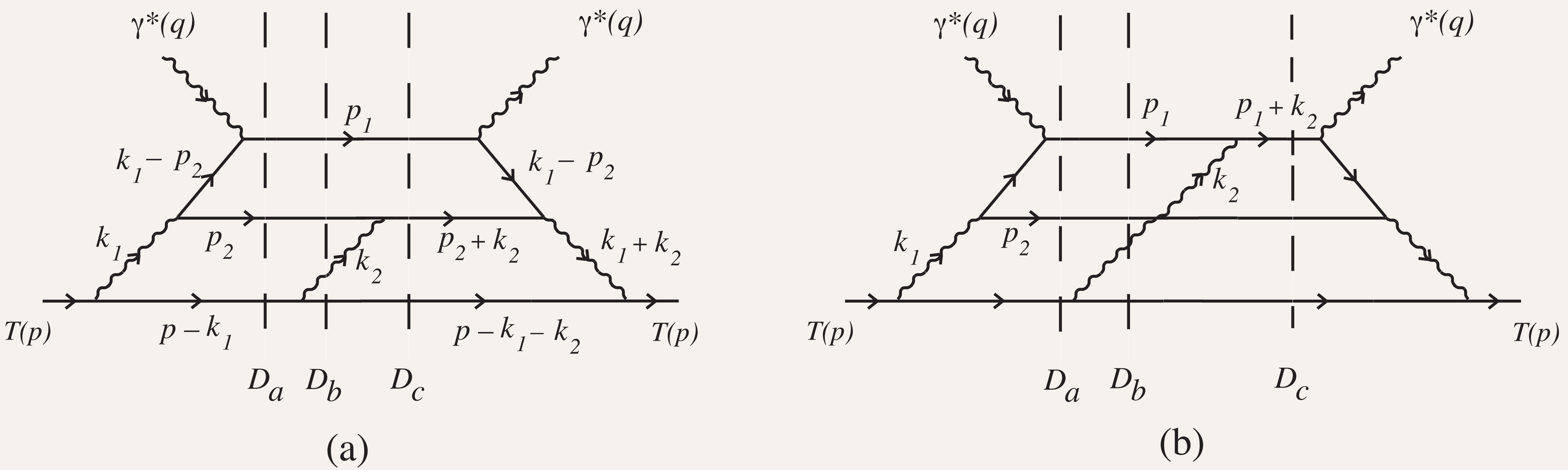
Final State Interactions in QCD



Feynman Gauge Light-Cone Gauge

Result is Gauge Independent

Final State Interactions Non-Zero in QCD

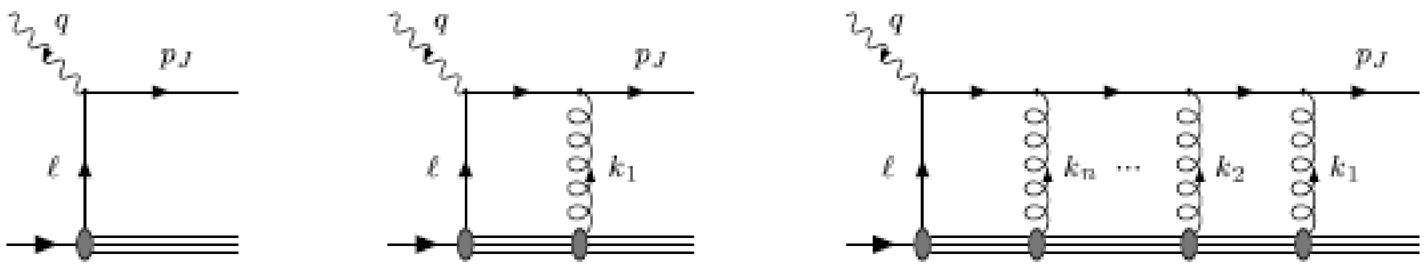


Light-Cone Gauge

Feynman Gauge

BHMPS

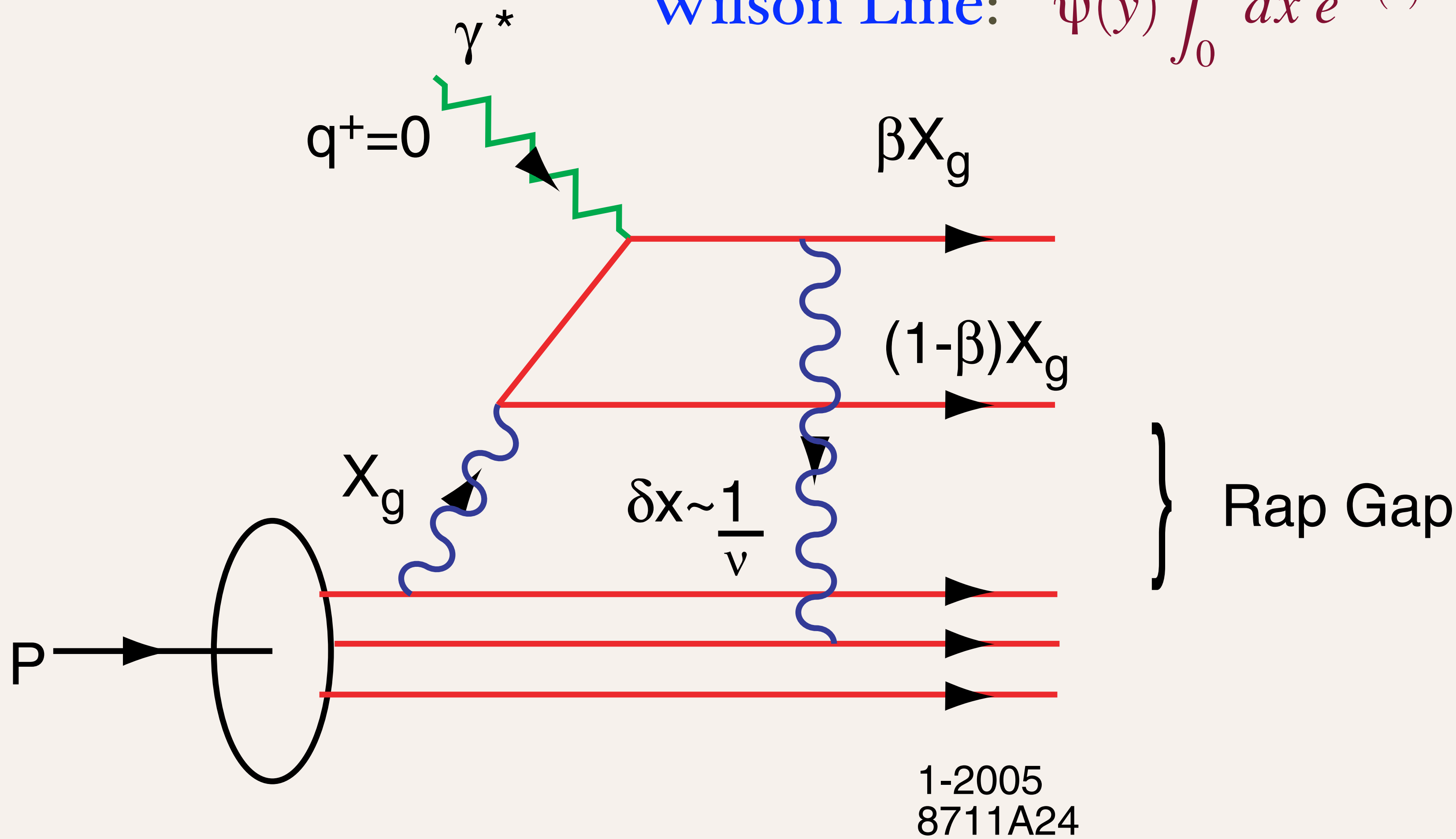
Rescattering and factorization



- Important to realize that the rescattering is compatible with factorization theorems *by construction*
  - the Wilson line is a part of the definition of the PDF, so the rescattering is also a part of the PDF
- When one measures the PDF in experiments, one measures the PDF *including* rescattering
- In a similar way, the diffractive PDFs are included in the inclusive PDFs

QCD Mechanism for Rapidity Gaps

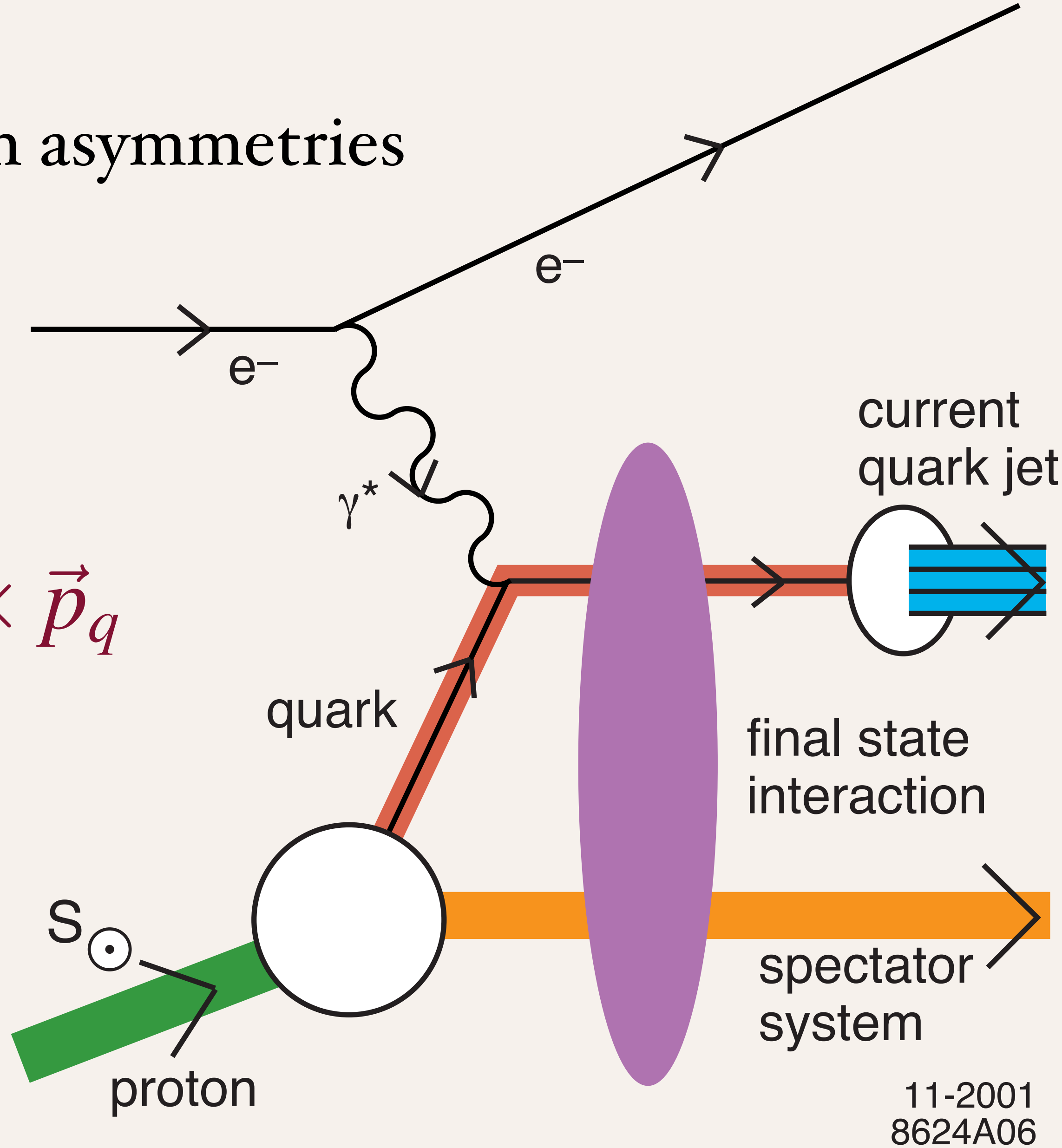
Wilson Line: $\overline{\psi}(y) \int_0^y dx\, e^{iA(x)\cdot dx}\, \psi(0)$



Single-spin asymmetries

Sivers Effect

$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$



Hwang, Schmidt.
sjb

Hard Diffraction from Rescattering

Unification:

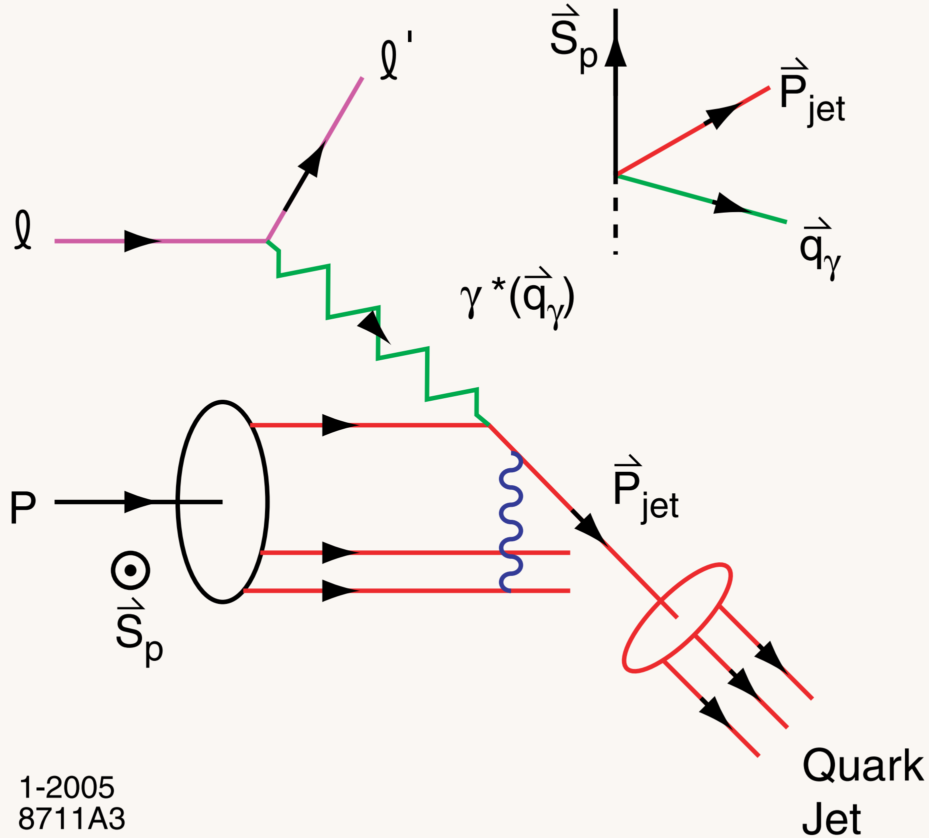
- Diffractive Deep Inelastic Scattering (DDIS)
- Nuclear Shadowing & Antishadowing
- Single Spin Asymmetries (Sivers Effect)
- Fundamental Features of Gauge Theory, Color

Final State Interactions Produce T-Odd (Sivers Effect)

- Bjorken Scaling!
- Arises from Interference of Final State Coulomb Phase in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment
- Sum of Sivers Functions for all quarks and gluons vanishes. (Zero gravitoanomalous magnetic moment

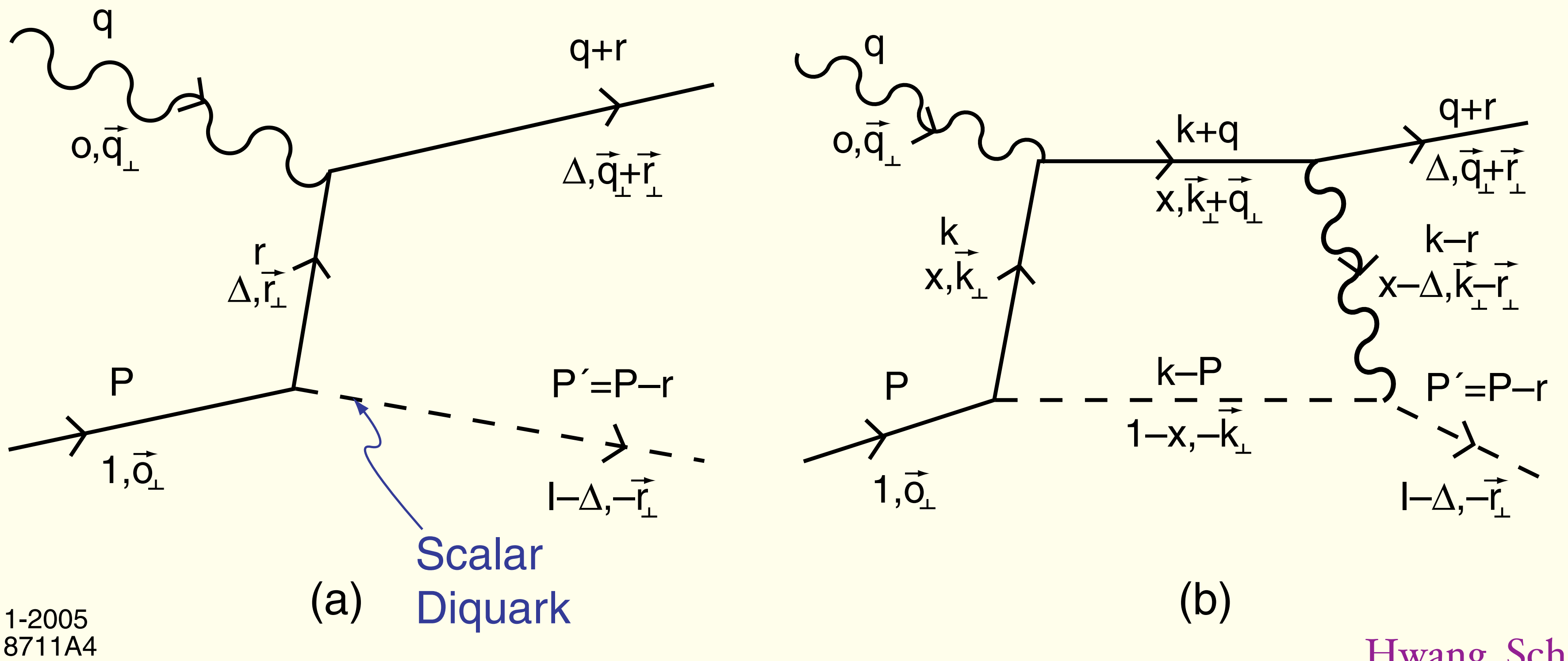
$$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

Hwang, Schmidt. sjb



Quarks Reinteract in the Final State
Interference of Coulomb Phases for *S* and *P* states
Produce Single Spin Asymmetry [Siver's Effect]
$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$
Use thrust or momentum of leading pion
to find jet direction
Measure $\vec{S} \cdot \vec{p}_\pi \times \vec{q}$
Distinguish from Collins Effect [from jet fragmentation]
Proportional to the Proton Anomalous Moment and α_s.

Hwang, Schmidt.
sjb; Burkardt



Hwang, Schmidt.
sjb

Model Calculation producing a target single-spin asymmetry in semi-inclusive leptoproduction

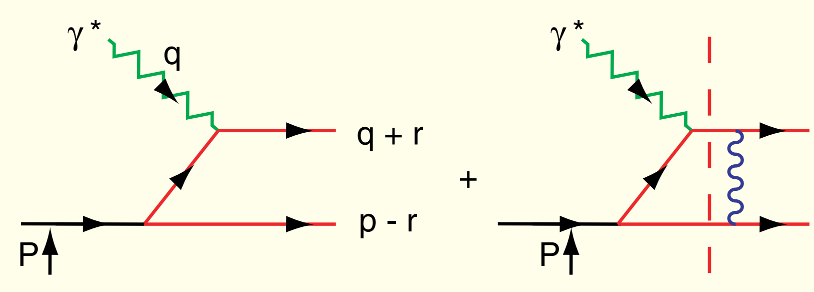
Quarks Reinteract in the Final State

Interference of Coulomb Phases for S and P states

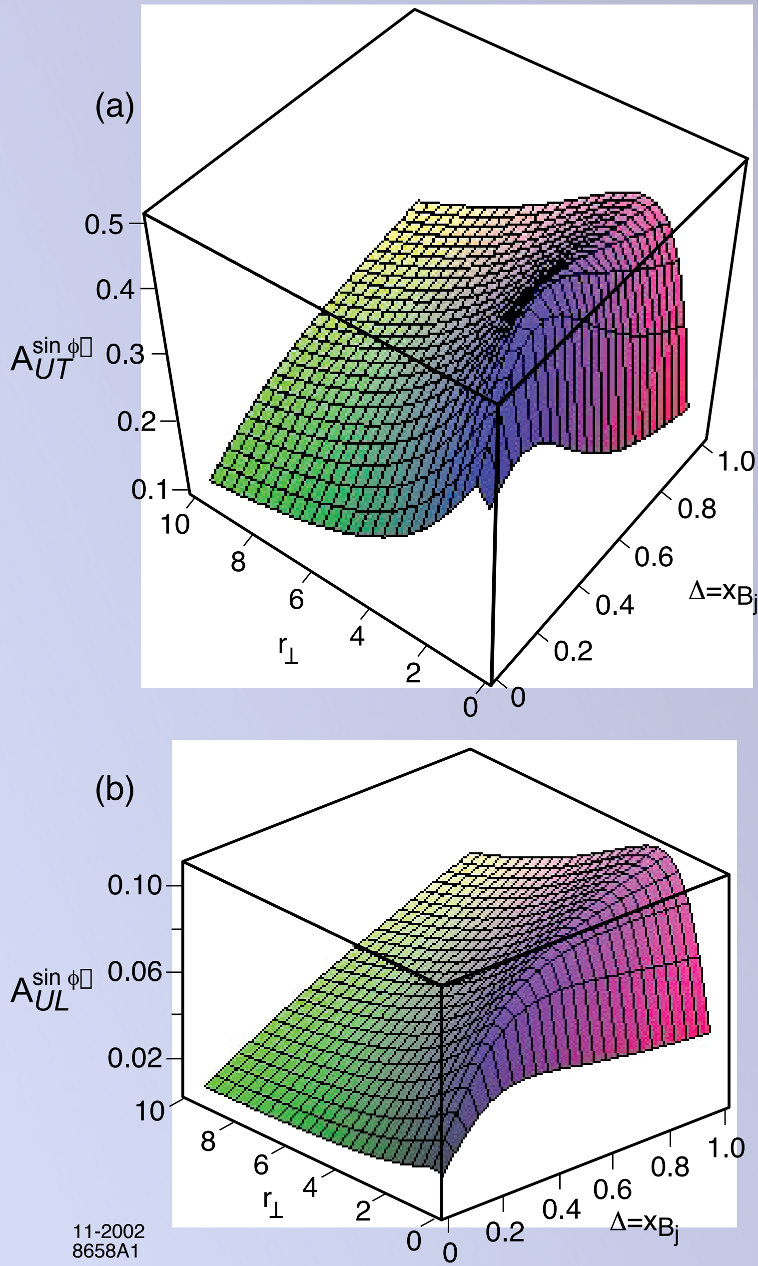
Produce Single Spin Asymmetry [Siver's Effect]

$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$

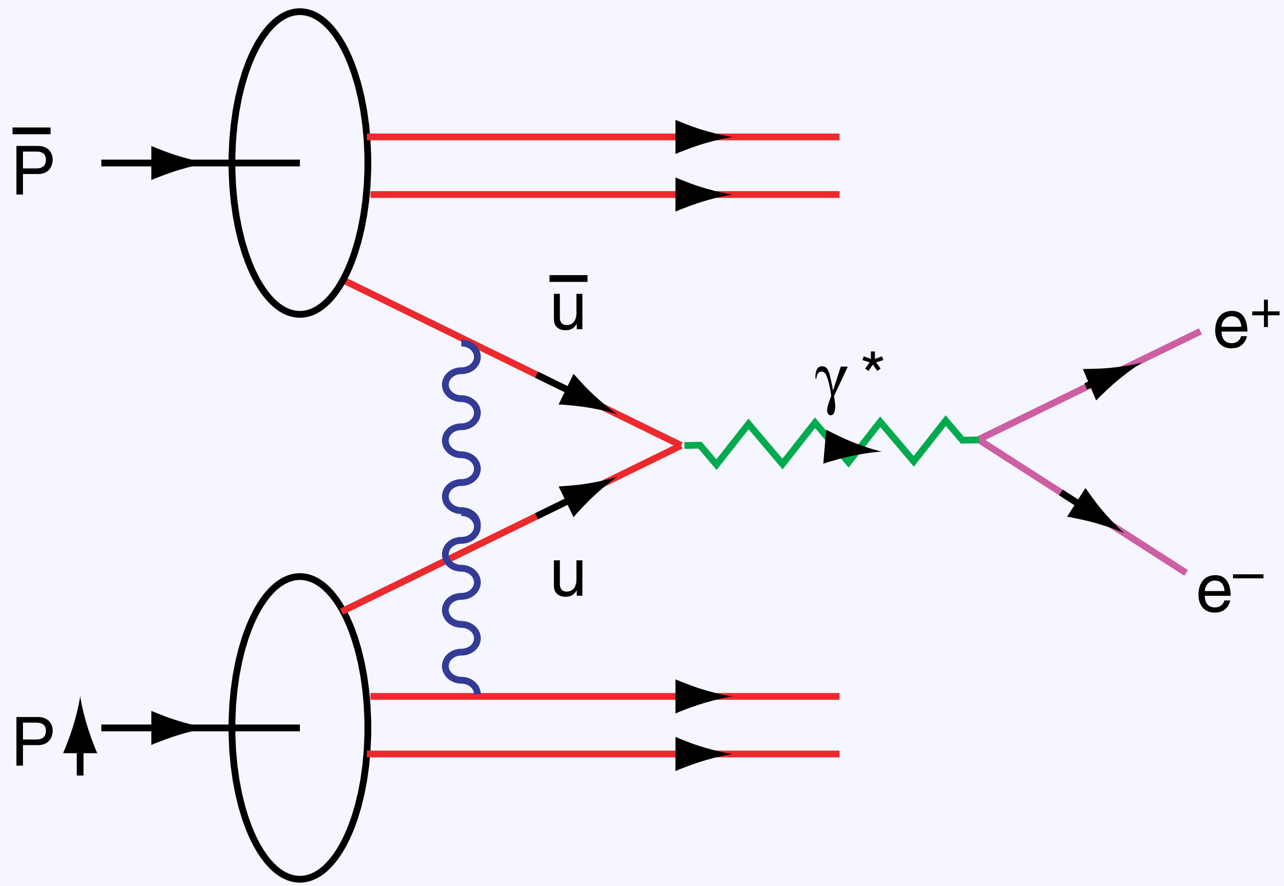
Proportional to the Proton Anomalous Moment and α_s.



Prediction for Single-Spin Asymmetry



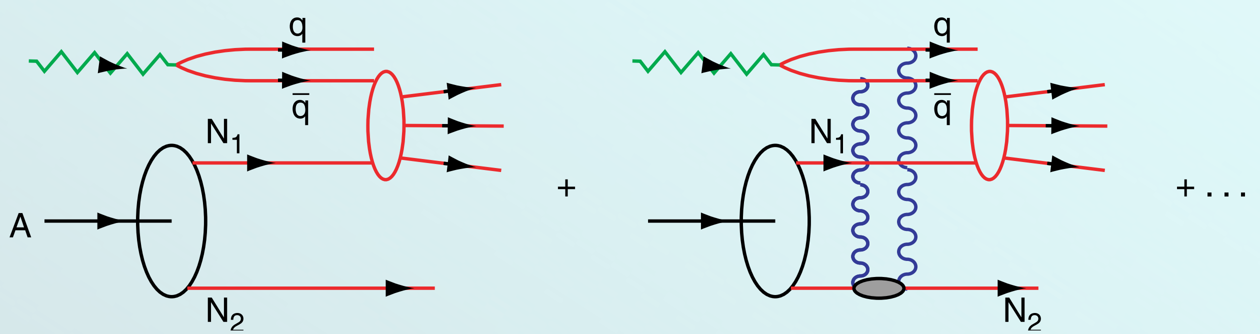
Hwang, Schmidt.
sjb



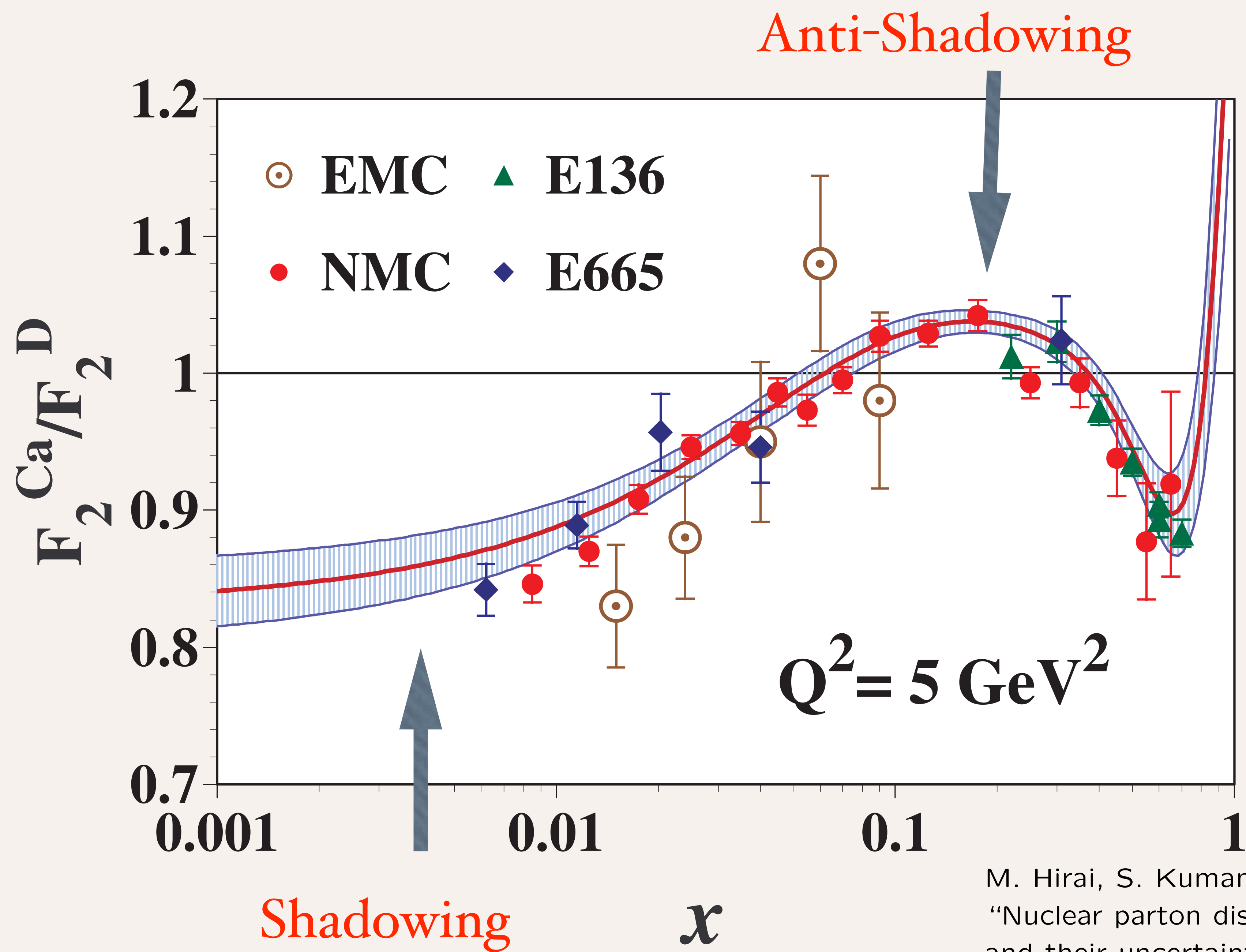
Single Spin Asymmetry In the Drell Yan Process
$\vec{S}_p \cdot \vec{\bar{p}} \times \vec{q}_{\gamma^*}$
Quarks Interact in the Initial State
Interference of Coulomb Phases for S and P states
Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.
Opposite Sign to DIS! No Factorization

Collins;
Hwang, Schmidt.
sjb

Origin of Nuclear Shadowing in Glauber - Gribov Theory

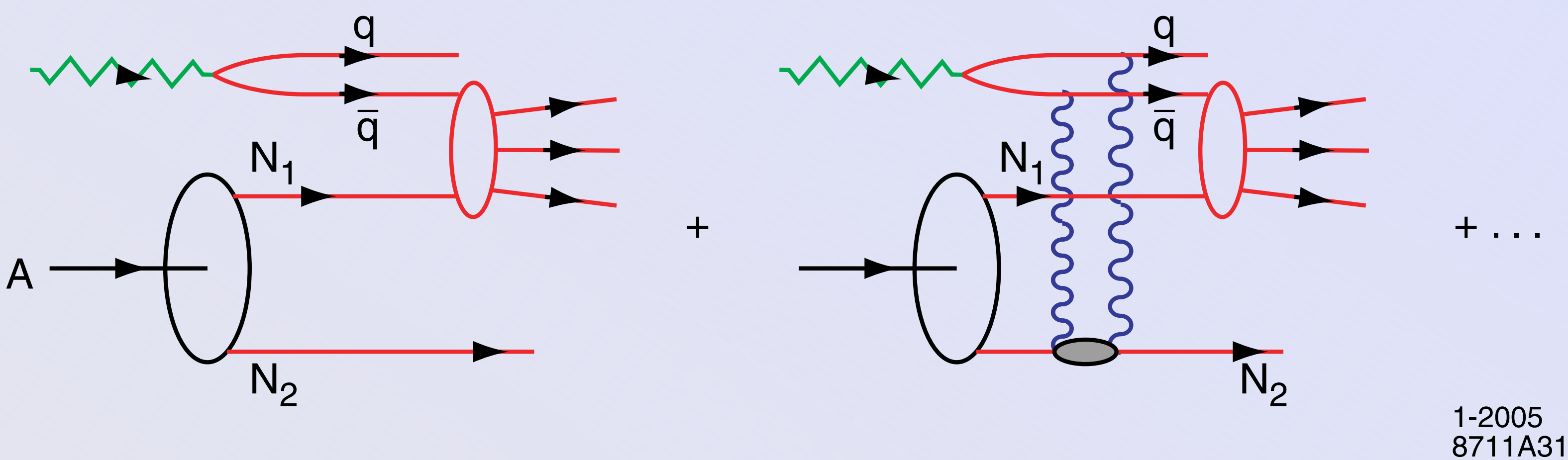


Interference of one-step and two-step processes
Interaction on upstream nucleon diffractive
Phase i X i = - 1 produces destructive interference
No Flux reaches down stream nucleon



M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].

Nuclear Shadowing in QCD



Nuclear Shadowing not included in nuclear LFWF !

Connection to DDIS

Reggeon Exchange

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

Lu, sjb

Constructive Interference

Yang, Schmidt, sjb

Depends on quark flavor!

Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

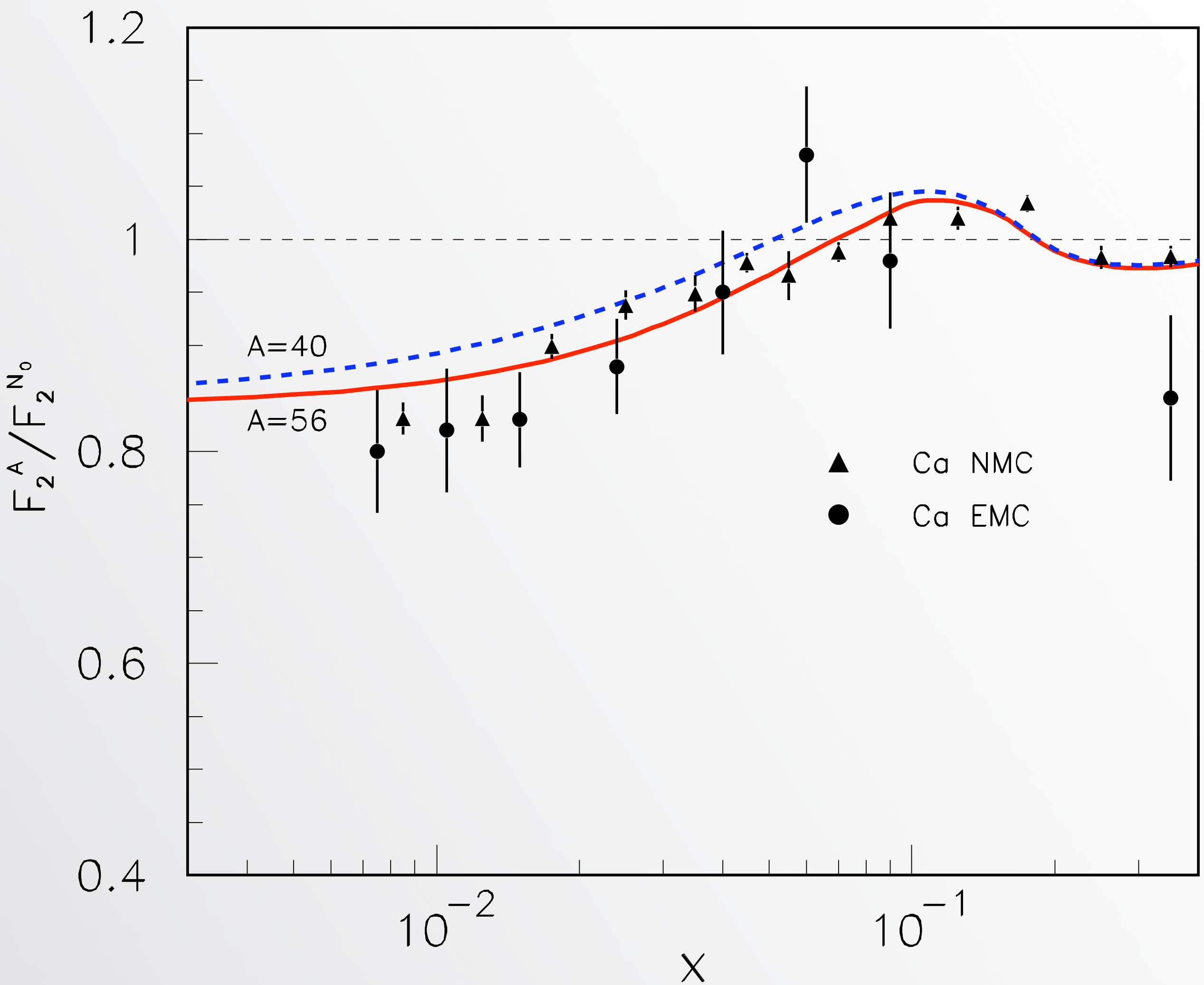
Momentum Sum Rule and antishadowing:
Nikolaev, Zakharov

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference of Two-Step and One-Step Processes *Pomeron Exchange*

- Antishadowing: Constructive Interference of Two-Step and One-Step Processes! *Reggeon and Odderon Exchange*

- Antishadowing is Not Universal! Electromagnetic and weak currents: different nuclear effects ! Potentially significant for NuTeV Anomaly}



The nuclear shadowing and antishadowing effects at $\langle Q^2 \rangle = 1\ \text{GeV}^2$

S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Estimate 20% effect on extraction of $\sin^2\theta_W$ for NuTeV

Need new experimental studies of antishadowing in

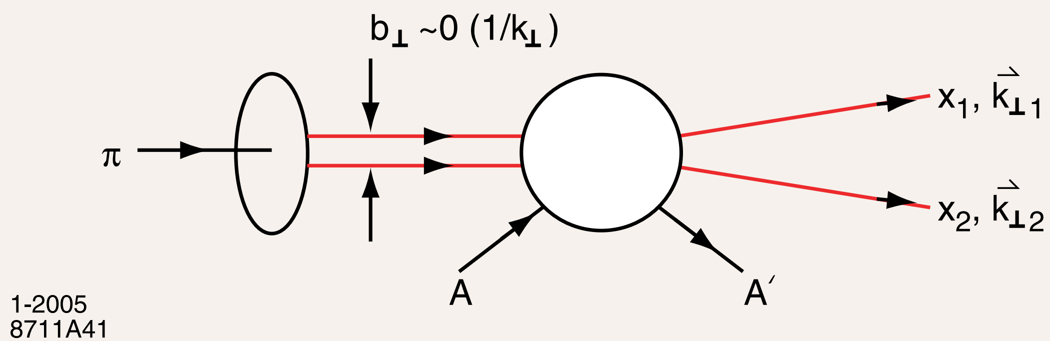
- Parity-violating DIS

Yang, Schmidt, sjb

- Spin Dependent DIS
- Charged and Neutral Current DIS

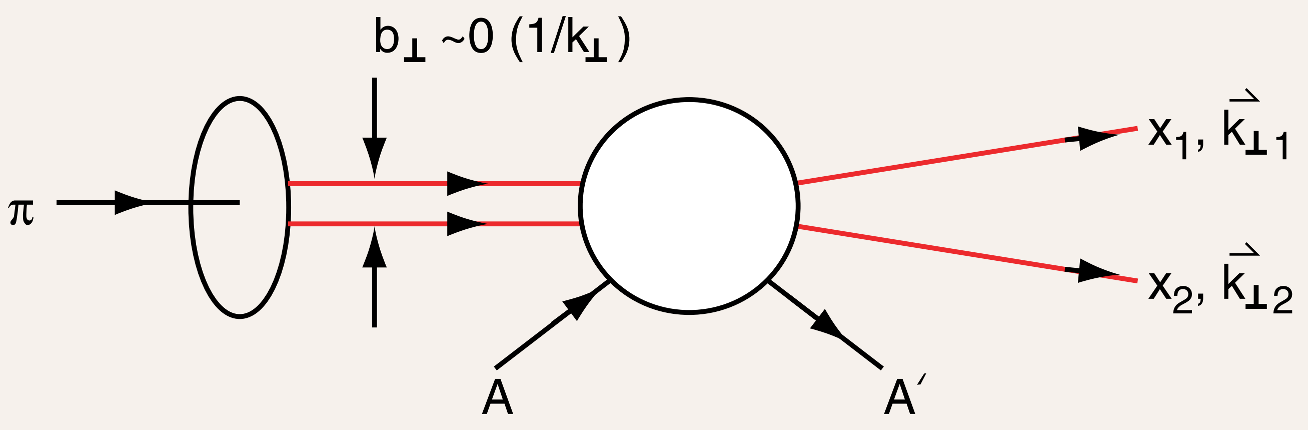
Diffractive Dissociation of Pion

E791 Ashery et al.

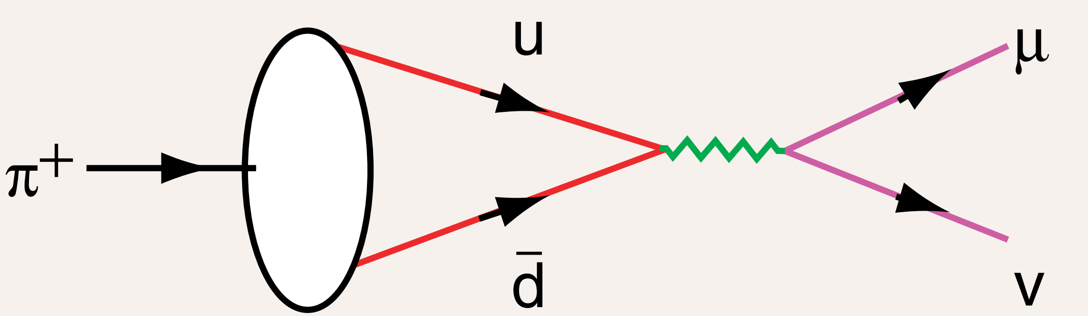


Measure Light-Front Wavefunction of Pion
Two-gluon Exchange
Minimal momentum transfer to nucleus
Nucleus left Intact

Fluctuation of a Pion to a Compact Color Dipole State



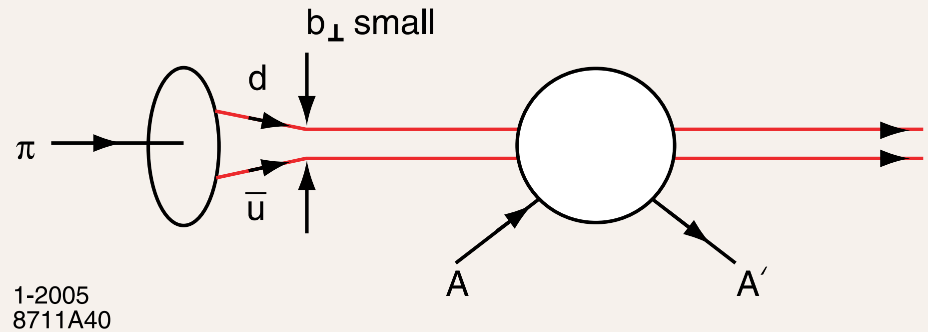
Color-Transparent Fock State For High Transverse Momentum Di-Jets



Same Fock State Determines Weak Decay

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

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

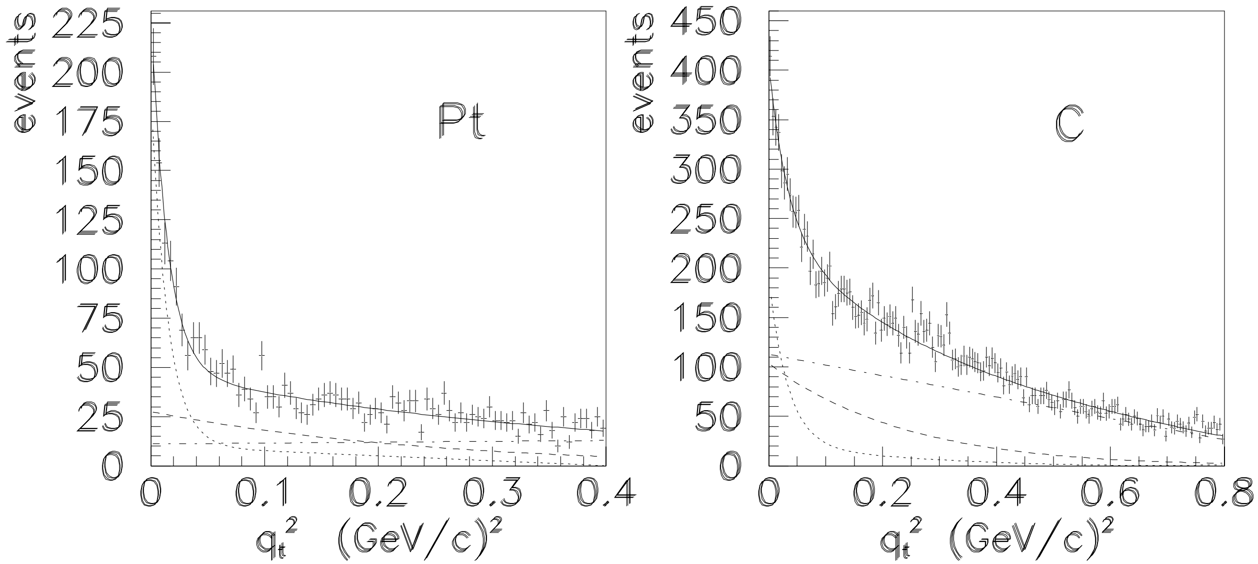
- **Fully coherent interactions between pion and nucleons.**
- **Emerging Di-Jets do not interact with nucleus.**

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

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

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

E791 Collaboration, E. Aitala *et al.*, Phys. Rev. Lett. 86, 4773 (2001)



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 !

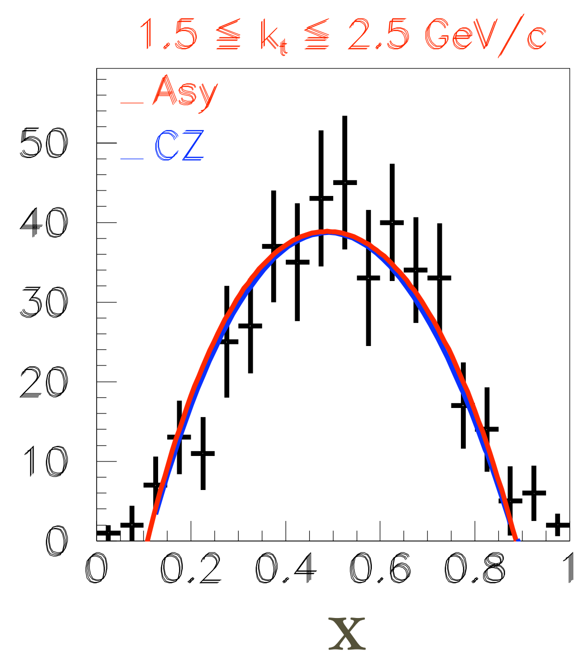
FermiLab E791
Ashery et al

Diffractive Dissociation of a Pion into Dijets

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

- E789 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

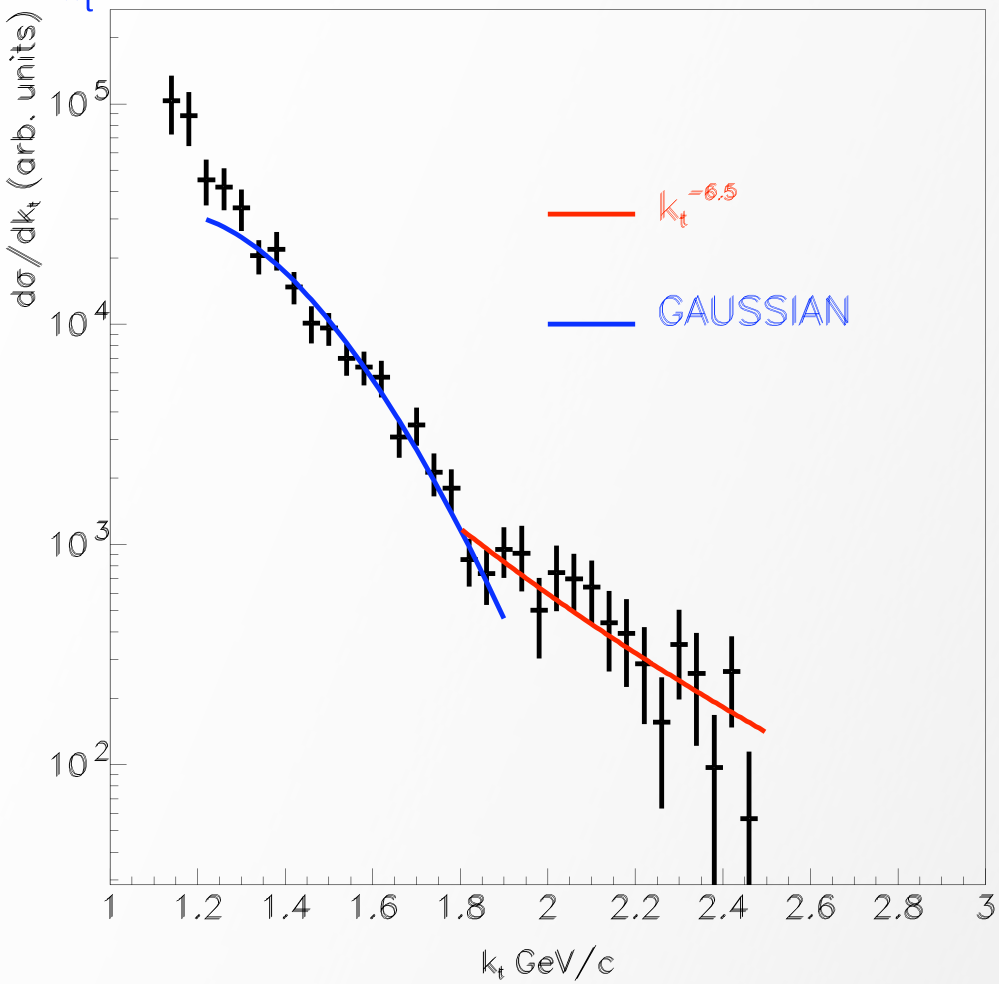
$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_\perp)$$



THE k_t DEPENDENCE OF DI-JETS YIELD

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

With $\psi \sim \frac{\phi}{k_t^2}$, weak $\phi(k_t^2)$ and $\alpha_s(k_t^2)$ dependences and $G(x,k_t^2) \sim k_t^{1/2}$: $\frac{d\sigma}{dk_t} \sim k_t^{-6}$



High Transverse momentum dependence consistent with PQCD/ AdS/CFT

Diffractive Dissociation of Pion into Di-Jets

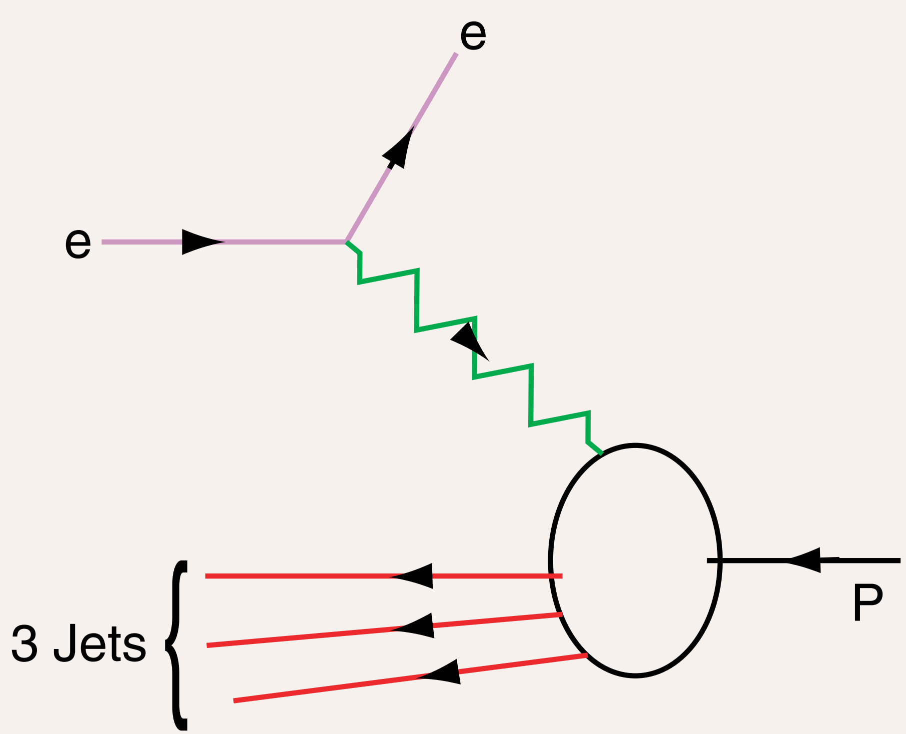
- Verify Color Transparency
- Pion Interacts coherently on each nucleon of nucleus!
- Pion Distribution similar to Asymptotic Form

  Also: AdS/CFT
- Scaling in transverse momentum consistent with PQCD

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

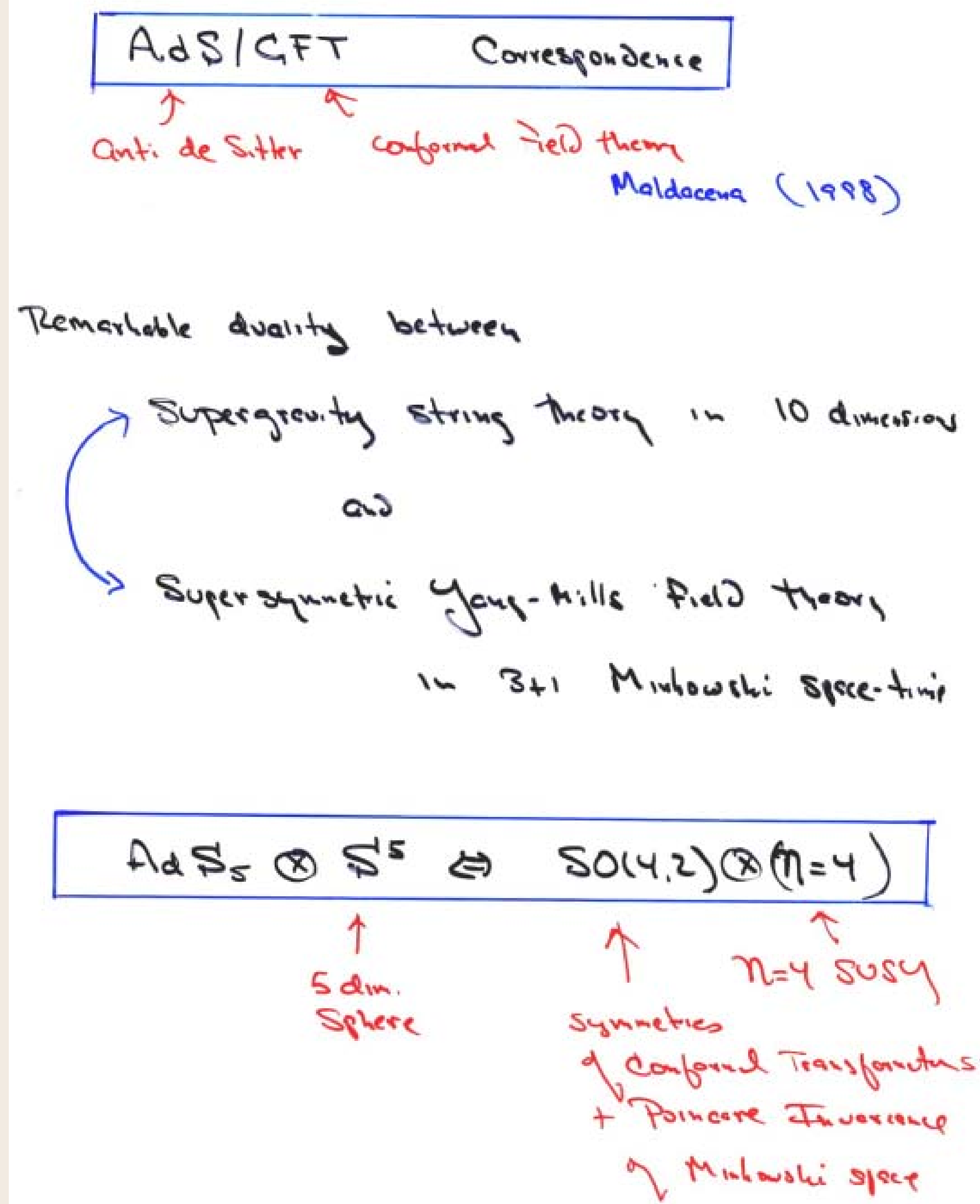
$$\psi(x, k_\perp) \propto x(1-x)$$

Coulomb Dissociate Proton to Three Jets at HERA



Frankfurt
Strikman
Miller

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



Duality between strongly coupled conformal theory and weakly coupled type IIB string theory

Theories with Conformal Symmetry

invariant under Poincare transformations $M^{\mu\nu}, P^{\nu}$
+ Conformal transformations D, K^{ν}

generators form group

$$\boxed{SO(4,2)} \qquad (d=4)$$

SO(4,2) has representations on both

and { Minkowski space $R^{(3,1)}$
AdS$_5$ }

Minkowski metric

$$ds^2 = dt^2 - d\vec{x}^2$$

AdS$_5$ metric

fifth dim. ↙

$$ds^2 = \frac{r^2}{R^2}\left(dt^2 - d\vec{x}^2\right) - \frac{R^2}{r^2}dr^2$$

Dilatations

$$x^\mu \to \lambda x^\mu \quad ; \quad (x^\mu, r) \to \left(\lambda x^\mu, \frac{r}{\lambda}\right)$$

Strongly Coupled Conformal QCD and Holography

- Conformal Theories are invariant under the Poincaré and conformal transformations with $M^{\mu\nu}$, P^μ, D, K^μ, the generators of $SO(4,2)$.

- QCD appears as a nearly-conformal theory in the energy regimes accessible to experiment. Invariance of conformal QCD is broken by quark masses and quantum loops (running coupling). For $\beta = d\alpha_s(Q^2)/dlnQ^2 = 0$ (fixed point theory), PQCD is a conformal theory: Parisi, Phys. Lett. B **39**, 643 (1972).

- Phenomenological success of dimensional scaling laws for exclusive processes $d\sigma/dt \sim 1/s^{n-2}$ (n total number of constituents), implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies (PQCD predicts powers of α_s and logs).

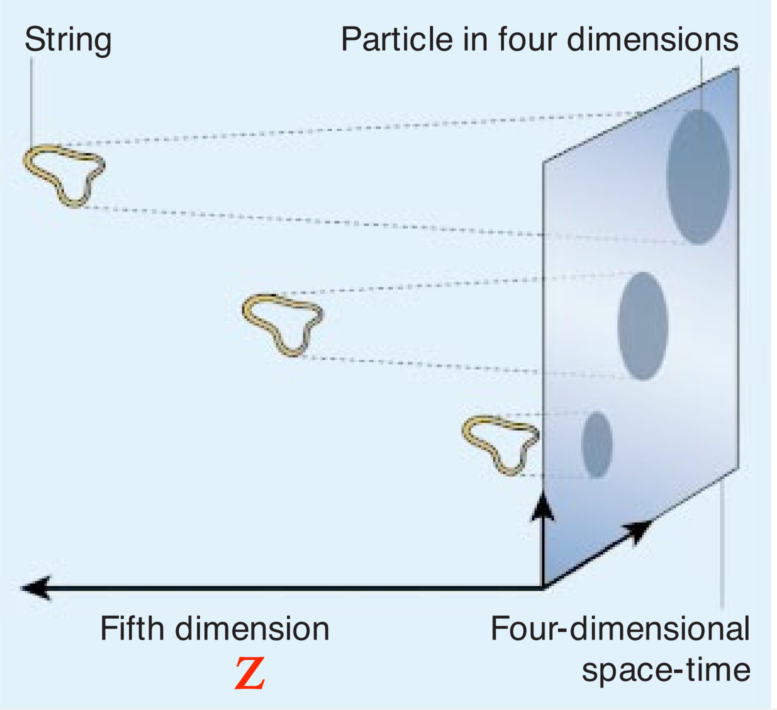
- Theoretical and empirical evidence that $\alpha_s(Q^2)$ has an IR fixed point (constant in the IR): Alkofer, Fischer and Llanes-Estrada, hep-th/0412330; Brodsky, Menke, Merino and Rathsman, hep-ph/0212078; .

AdS5 Metric

Holographic Model

Mapping of Poincare' and Conformal SO(4,2) symmetries of 3+1 space to AdS5 space

J. Maldacena



Strings, particles and extra dimensions. Strings moving in the fifth dimension are represented in the everyday world by their projection onto the four-dimensional boundary of the five-dimensional space-time. The same string located at different positions along the fifth dimension corresponds to particles of different sizes in four dimensions: the further away the string, the larger the particle. The projection of a string that is very close to the boundary of the four-dimensional world can appear to be a point-like particle.

New Perspectives on QCD Phenomena from AdS/CFT

- AdS/CFT: Duality between string theory in Anti-de Sitter Space and Conformal Field Theory
- New Way to Implement Conformal Symmetry
- Holographic Model: Conformal Symmetry at Short Distances, Confinement at large distances
- Remarkable predictions for hadronic spectra, wavefunctions, interactions
- AdS/CFT provides novel insights into the quark structure of hadrons

- Polchinski & Strassler: AdS/CFT builds in conformal symmetry at short distances, counting, rules for form factors and hard exclusive processes; non-perturbative derivation

- Goal: Use AdS/CFT to provide models of hadron structure: confinement at large distances, near conformal behavior at short distances

- Holographic Model: Initial "classical" approximation to QCD: Remarkable agreement with light hadron spectroscopy

- Use AdS/CFT wavefunctions as expansion basis for diagonalizing $H^{LF}{}_{QCD}$; variational methods deTeramond, sjb

AdS/CFT

$z = R^2/r$

- Use mapping of SO(4,2) to AdS_5
- Scale Transformations represented by wavefunction $\Psi(r)$ in 5th dimension

$$x_\mu^2 \to \lambda^2 x_\mu^2 \quad \equiv \quad r \to \frac{r}{\lambda} \quad \equiv \quad z \to \lambda z$$

- Holographic model: Confinement at large distances and conformal symmetry at short distances

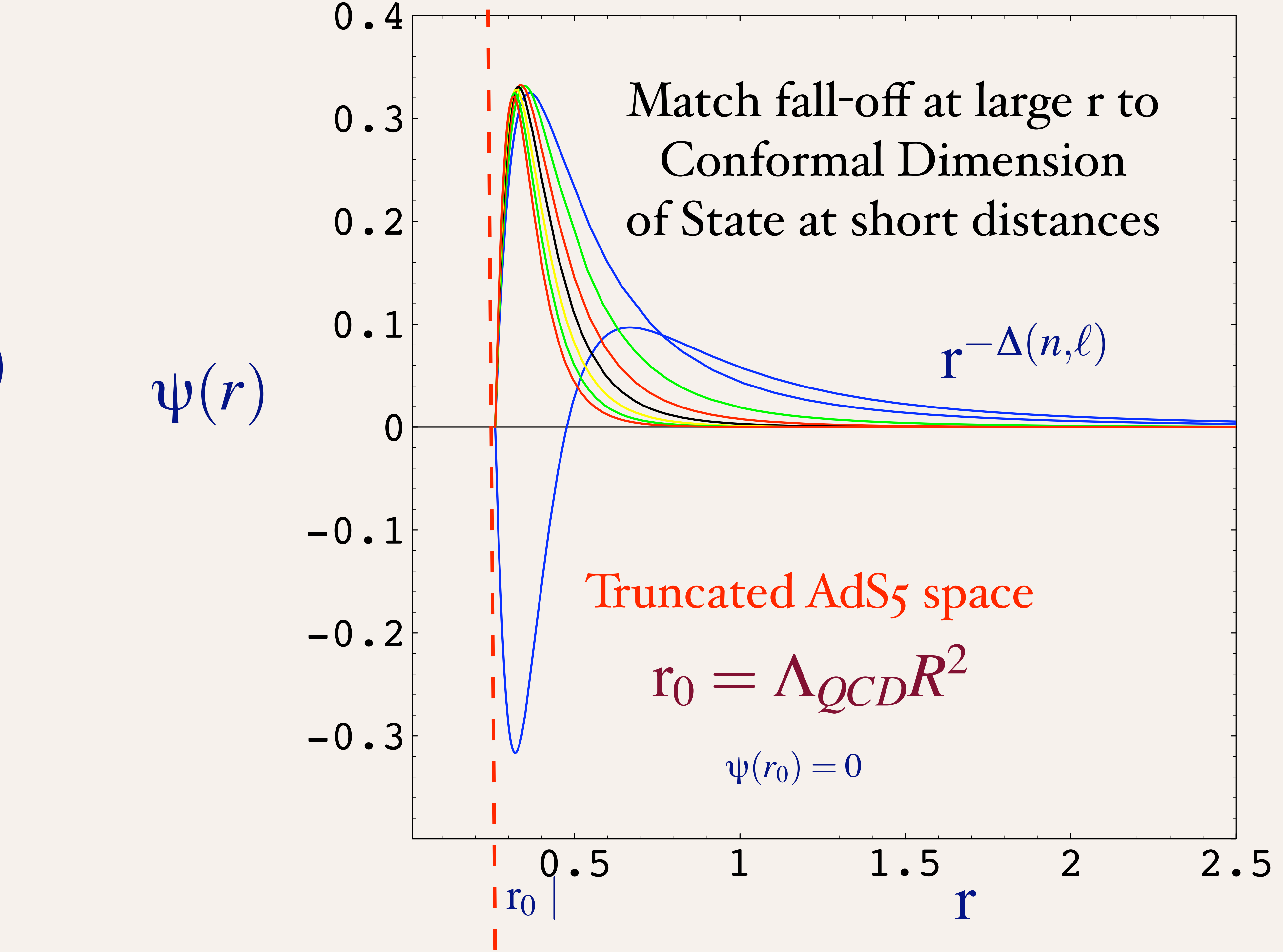
$$0 < z < z_0 = \frac{1}{\Lambda_{QCD}}, \; r > r_0 = \Lambda_{QCD} R^2$$

- Match solutions at large r to conformal dimension of hadron wavefunction at short distances

$$\psi(r) \to r^{-\Delta} \text{ at large } r\text{, small } z$$

- Truncated space simulates "bag" boundary conditions

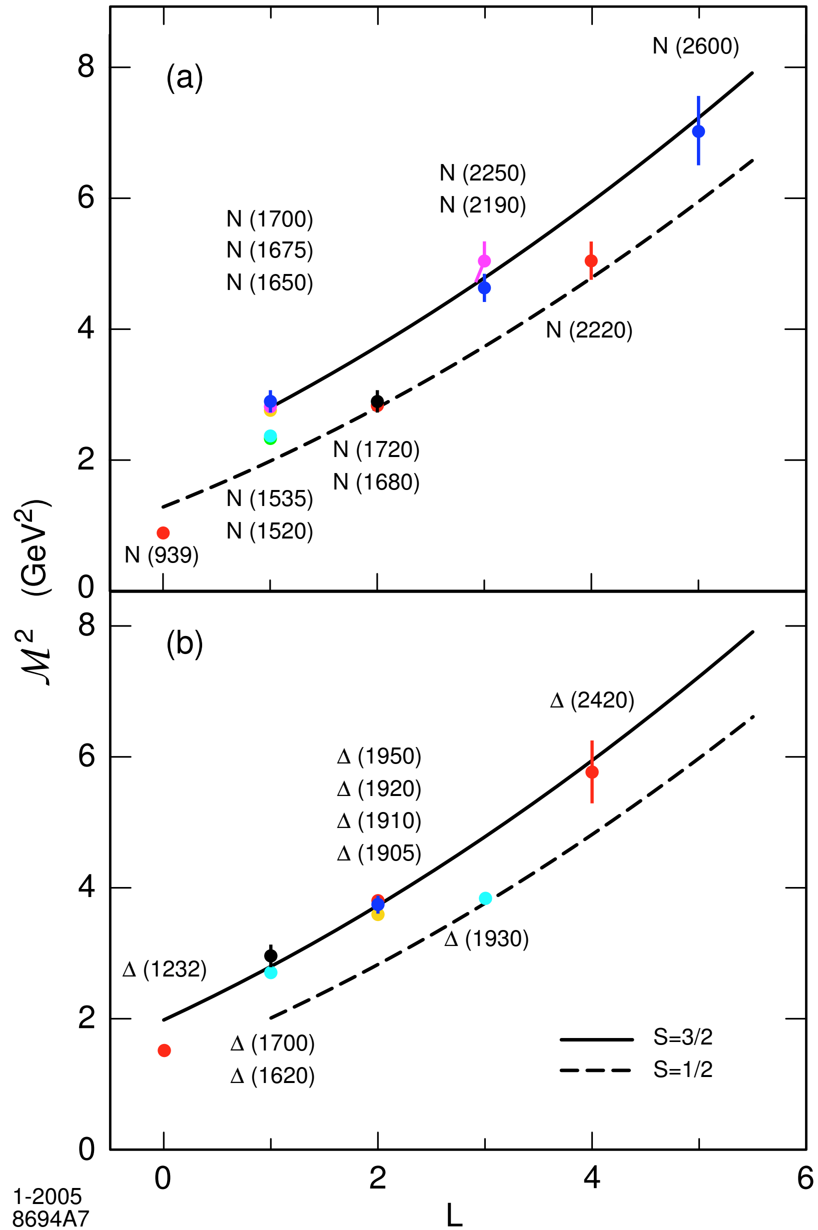
$$\psi(z_0) = \psi(r_0) = 0 \qquad r = \frac{R^2}{z}$$


0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
$\psi(r)$
Match fall-off at large r to
Conformal Dimension
of State at short distances
$r^{-\Delta(n,\ell)}$
Truncated AdS5 space
$r_0 = \Lambda_{QCD} R^2$
$\psi(r_0) = 0$
0.5
1
1.5
2
2.5
r_0
r

Predictions of AdS/CFT

Only one parameter!

Entire light quark baryon spectrum



Guy de Teramond
SJB

Phys.Rev.Lett.94: 201601,2005

hep-th/0501022

Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.22 GeV

- $SU(6)$ multiplet structure for N and Δ orbital states, including internal spin S and L.

$SU(6)$	S	L	Baryon State
56	$\frac{1}{2}$	0	$N\frac{1}{2}^{+}(939)$
	$\frac{3}{2}$	0	$\Delta\frac{3}{2}^{+}(1232)$
70	$\frac{1}{2}$	1	$N\frac{1}{2}^{-}(1535)$ $N\frac{3}{2}^{-}(1520)$
	$\frac{3}{2}$	1	$N\frac{1}{2}^{-}(1650)$ $N\frac{3}{2}^{-}(1700)$ $N\frac{5}{2}^{-}(1675)$
	$\frac{1}{2}$	1	$\Delta\frac{1}{2}^{-}(1620)$ $\Delta\frac{3}{2}^{-}(1700)$
56	$\frac{1}{2}$	2	$N\frac{3}{2}^{+}(1720)$ $N\frac{5}{2}^{+}(1680)$
	$\frac{3}{2}$	2	$\Delta\frac{1}{2}^{+}(1910)$ $\Delta\frac{3}{2}^{+}(1920)$ $\Delta\frac{5}{2}^{+}(1905)$ $\Delta\frac{7}{2}^{+}(1950)$
70	$\frac{1}{2}$	3	$N\frac{5}{2}^{-}$ $N\frac{7}{2}^{-}$
	$\frac{3}{2}$	3	$N\frac{3}{2}^{-}$ $N\frac{5}{2}^{-}$ $N\frac{7}{2}^{-}(2190)$ $N\frac{9}{2}^{-}(2250)$
	$\frac{1}{2}$	3	$\Delta\frac{5}{2}^{-}(1930)$ $\Delta\frac{7}{2}^{-}$
56	$\frac{1}{2}$	4	$N\frac{7}{2}^{+}$ $N\frac{9}{2}^{+}(2220)$
	$\frac{3}{2}$	4	$\Delta\frac{5}{2}^{+}$ $\Delta\frac{7}{2}^{+}$ $\Delta\frac{9}{2}^{+}$ $\Delta\frac{11}{2}^{+}(2420)$
70	$\frac{1}{2}$	5	$N\frac{9}{2}^{-}$ $N\frac{11}{2}^{-}$
	$\frac{3}{2}$	5	$N\frac{7}{2}^{-}$ $N\frac{9}{2}^{-}$ $N\frac{11}{2}^{-}(2600)$ $N\frac{13}{2}^{-}$

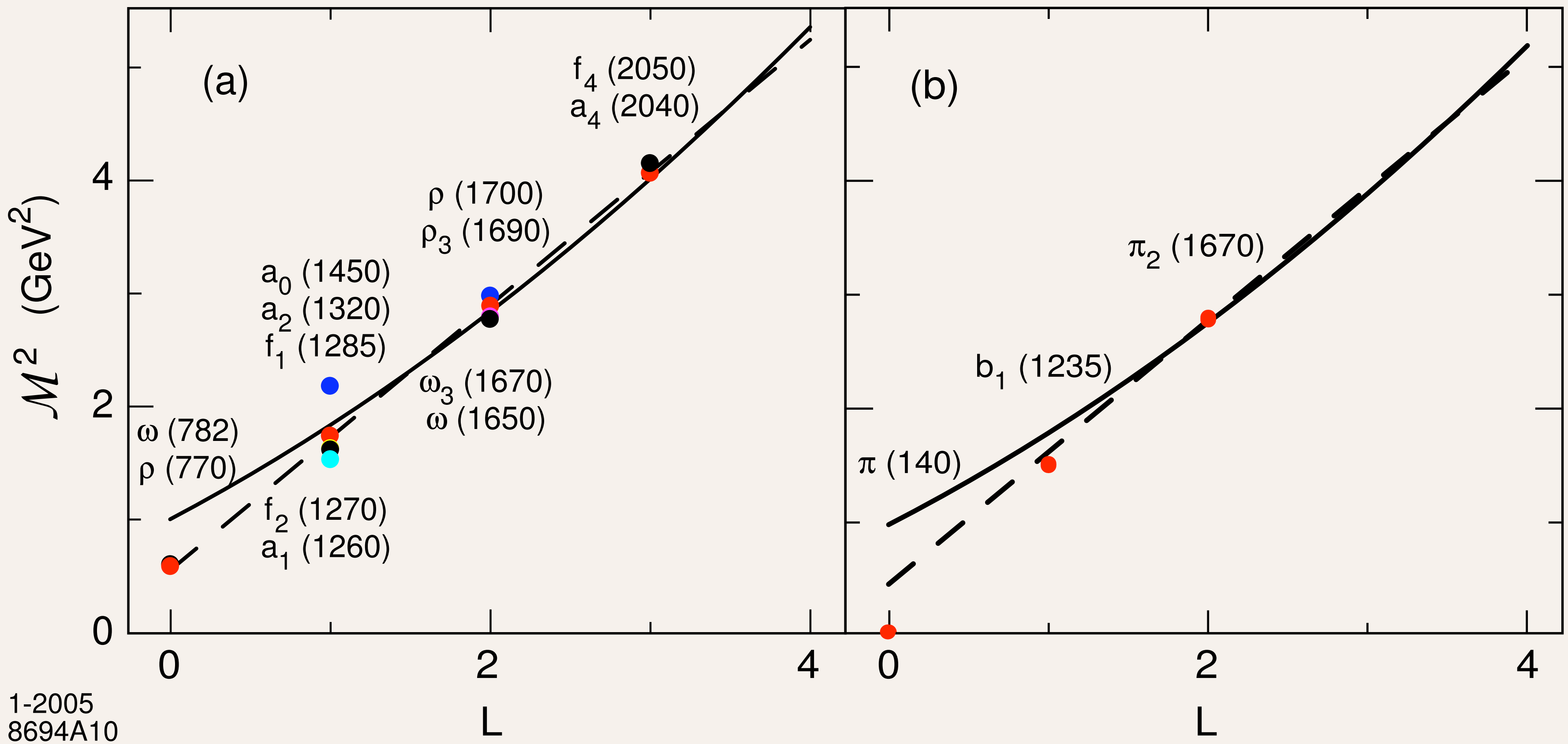


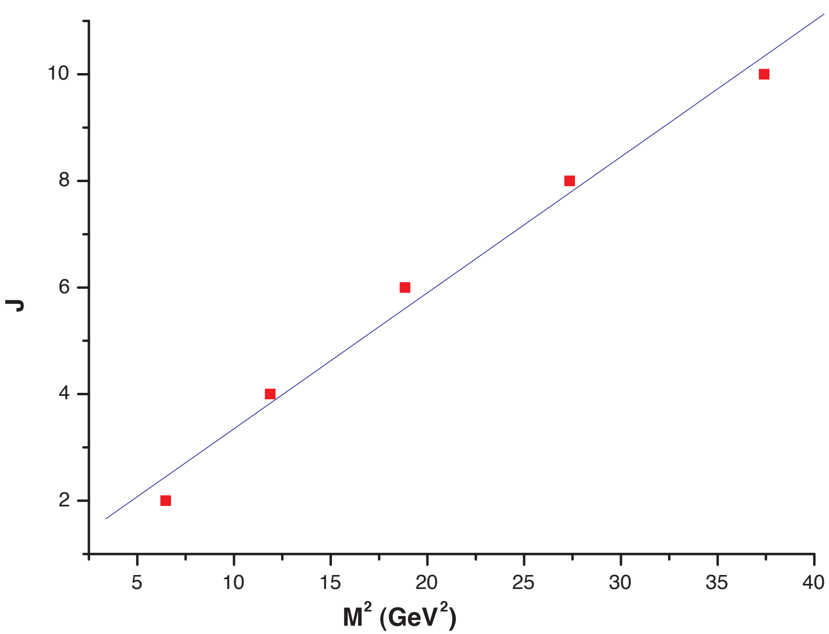
Fig: Light meson orbital spectrum: 4-dim states dual to vector fields in the bulk, $\Lambda_{QCD} = 0.26$ GeV

Guy de Teramond
SJB

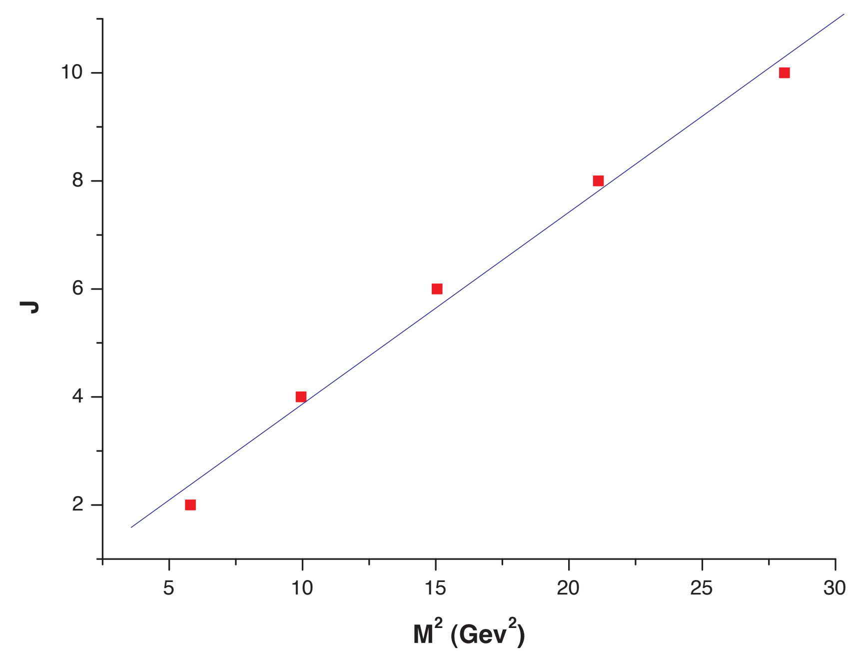
Glueball Regge trajectories from gauge/string duality and the Pomeron

Henrique Boschi-Filho,* Nelson R. F. Braga,† and Hector L. Carrion‡

Instituto de Física, Universidade Federal do Rio de Janeiro,



Neumann Boundary Conditions



Dirichlet Boundary Conditions

Features of HolographicModel

de Teramond sjb

- Ratio of proton to Delta trajectories= ratio of zeroes of Bessel functions.
- One scale Λ_{QCD} determines hadron spectrum (slightly different for mesons and baryons)
- Only quark-antiquark, qqq, and g g hadrons appear at classical level
- Covariant version of bag model: confinement+conformal symmetry

New Perspectives on QCD from AdS/CFT

- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances

- AdS/CFT predicts Light-front wavefunctions: Fundamental description of hadrons at amplitude level

- AdS/CFT: gluonium (gg) , meson ($q\bar{q}$), and baryon (qqq) spectra

- Quark-interchange dominates scattering amplitudes

- No ggg bound states

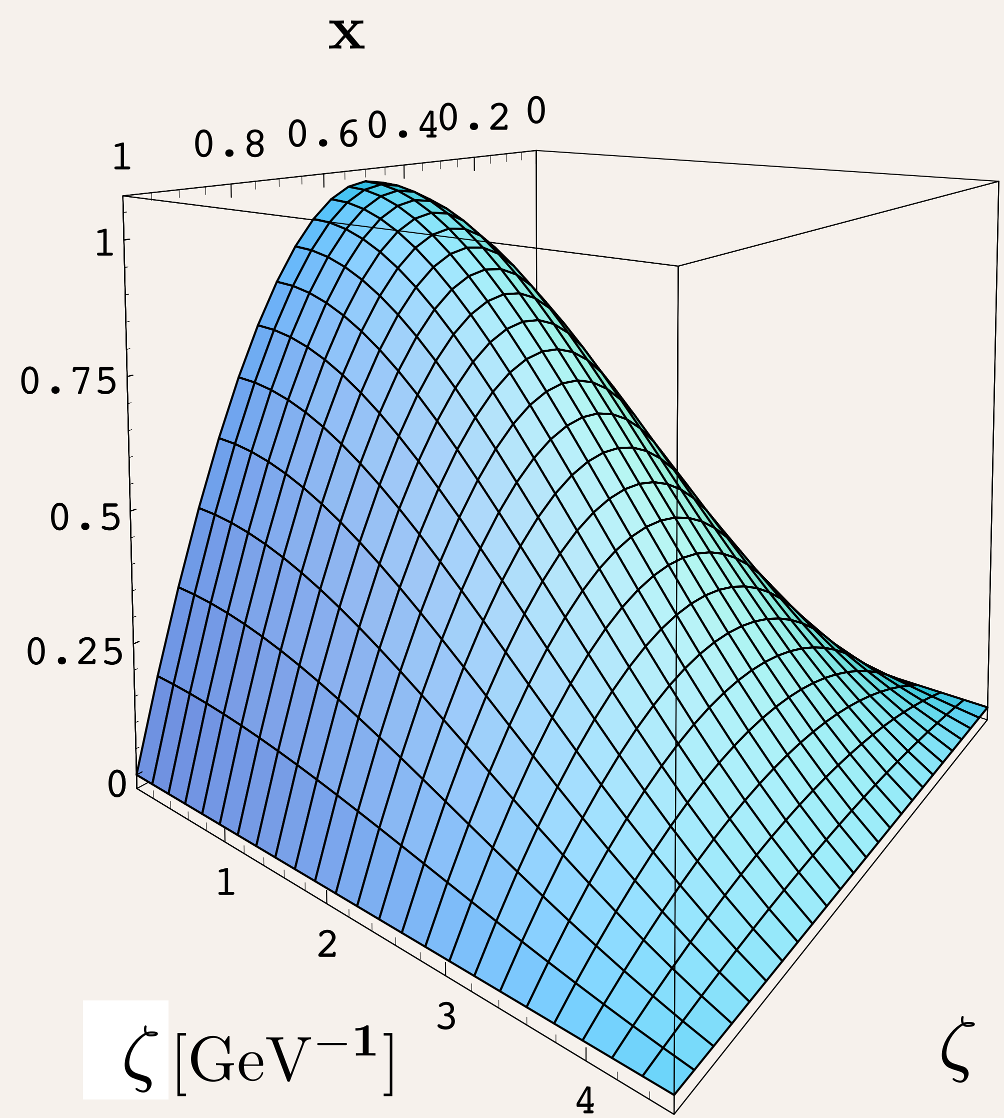
AdS/CFT and Light-Front Wavefunctions

- Light-Front Wavefunctions can be determined by matching functional dependence in fifth dimension to scaling in impact space.

$$\left[z^2\,\partial_z^2 - (d-1)z\,\partial_z + z^2\,\mathcal{M}^2 - (\mu R)^2\right] f(z) = 0,$$

$$z \to \zeta = b\sqrt{x(1-x)}$$

- High transverse momentum behavior matches PQCD LFWF with orbital: Belitsky, Ji, Yuan



AdS/CFT prediction for meson LFWF

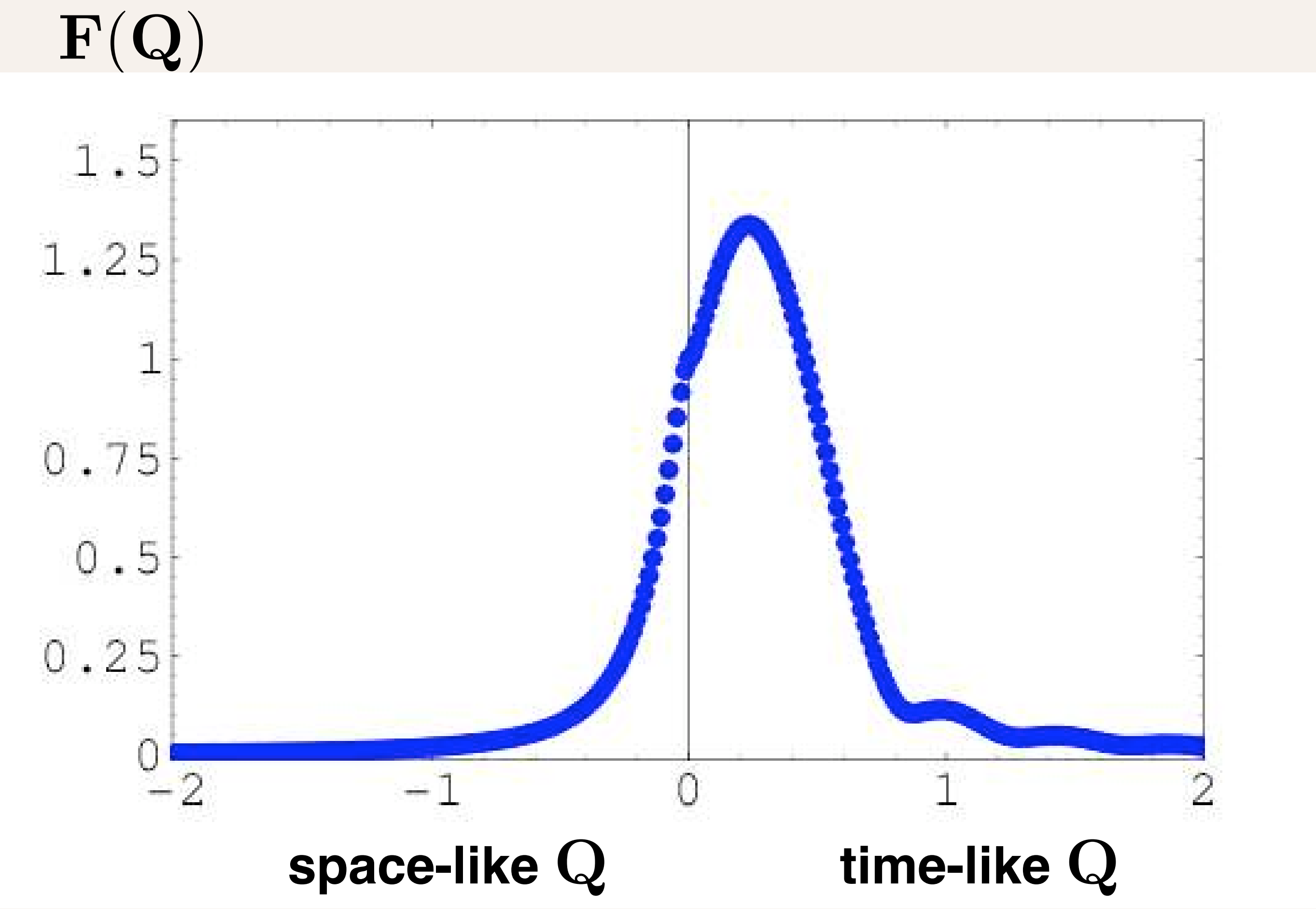
Holographic Model

Guy de Teramond
SJB

$$\zeta = b\sqrt{x(1-x)}$$

Two-parton ground state LFWF in impact space $\psi(x,b)$ for a for $n=2, \ell=0, k=1$.

Prediction for the pion form factor in the holographic model (numerical analysis):



de Teramond, SJB

AdS/CFT prediction for meson LFWF

Guy de Teramond
SJB

$$\psi_L(x, \vec{k}_\perp) = \frac{C}{4\pi} \int_0^{\Lambda_{\rm QCD}^{-1}} d\zeta\, J_0\left(\frac{\zeta |\vec{k}_\perp|}{\sqrt{x(1-x)}}\right) J_{1+L}(\zeta \mathcal{M}) \,.$$

At large $k_\perp$ the LFWF has the scaling behavior

$$\psi(x, \vec{k}_\perp) \to \left[\frac{|\vec{k}_\perp|}{\sqrt{x(1-x)}}\right]^L \left[\frac{x(1-x)}{\vec{k}_\perp^2}\right]^{1+L} ,$$

Holographic Model

Guy de Teramond
SJB

AdS/CFT prediction for meson LFWF

$$\widetilde{\psi}_L(x, \vec{b}_\perp)$$

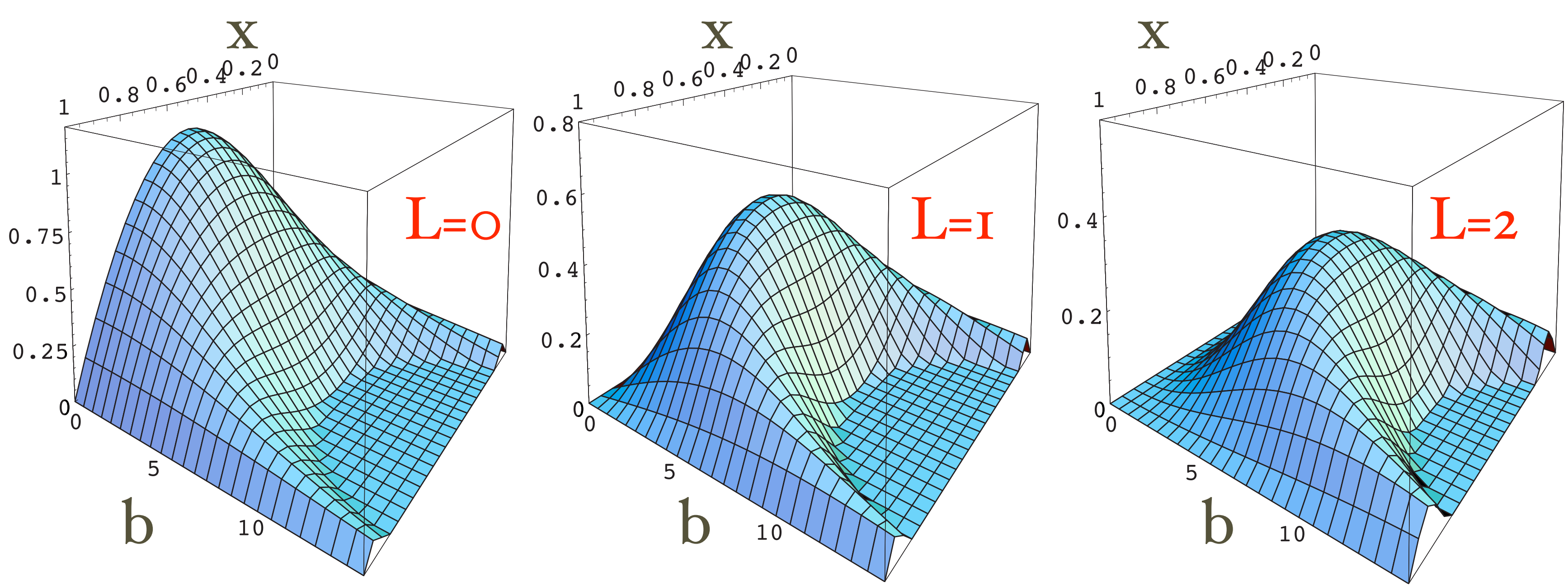


Figure 1: Two-parton bound state light-front wave function $\widetilde{\psi}_L(x, \vec{b}_\perp)$ as function of the constituents longitudinal momentum fraction x and $1 - x$ and the impact space relative coordinate $\vec{b}_\perp$ in a holographic QCD model. The results for the ground state ($L = 0$) are shown in (a). The predictions for first orbital exited states ($L = 1$ and $L = 2$) are shown in (b) and (c) respectively.

AdS/CFT and QCD

Bottom-Up Approach

- Nonperturbative derivation of dimensional counting rules of hard exclusive glueball scattering for gauge theories with mass gap dual to string theories in warped space:

  Polchinski and Strassler, hep-th/0109174.

- Deep inelastic structure functions at small x:

  Polchinski and Strassler, hep-th/0209211.

- Derivation of power falloff of hadronic light-front Fock wave functions, including orbital angular momentum, matching short distance behavior with string modes at AdS boundary:

  Brodsky and de Téramond, hep-th/0310227.

- Low lying hadron spectra, chiral symmetry breaking and hadron couplings in AdS/QCD:

  Boschi-Filho and Braga, hep-th/0209080; hep-th/0212207. de Téramond and Brodsky, hep-th/040907 hep-th/0501022; Erlich, Katz, Son and Stephanov, hep-ph/0501128; Hong, Yong and Strassler, hep-th/0501197; Da Rold and Pomarol, hep-ph/0501218.

New Perspectives on QCD from AdS/CFT

- LFWFs: Fundamental description of hadrons at amplitude level
- QCD is Nearly Conformal
- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra

New Perspectives on QCD from AdS/CFT

- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances

- Physics similar to MIT bag model, but covariant,

- No problem with support $0 < x < 1$.

- Quark-interchange dominant scattering mechanism

Why is quark-interchange dominant over gluon exchange?

Example: $M(K^+p \to K^+p) \propto \frac{1}{ut^2}$

Exchange of common u quark

$M_{QIM} = \int d^2k_\perp dx \ \psi^\dagger_C \psi^\dagger_D \Delta \psi_A \psi_B$

Holographic model (Classical level):

Hadrons enter 5th dimension of AdS_5

Quarks travel freely within cavity as long as separation $z < z_0 = \frac{1}{\Lambda_{QCD}}$

LFWFs obey conformal symmetry producing quark counting rules.

$$M_{FI} = \langle \psi_F | E - K | \psi_I \rangle$$
$$\equiv \langle \psi_F | \Delta | \psi_I \rangle$$
$$= \frac{1}{2(2\pi)^3} \int d^2k \int_0^1 \frac{dx}{x^2(1-x)^2} \Delta \psi_C(\vec{k}_\perp - x\vec{r}_\perp, x) \psi_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x) \psi_A(\vec{k}_\perp - x\vec{r}_\perp + (1-x)\vec{q}_\perp, x) \psi_B(\vec{k}_\perp, x)$$

where

$$\Delta = s - M_A{}^2 - M_B{}^2 - K_a - K_b - K_c - K_d$$
$$= M_A{}^2 + M_B{}^2 - S_A(\vec{k}_\perp + (1-x)\vec{q}_\perp - x\vec{r}_\perp, x) - S_B(\vec{k}_\perp, x)$$
$$= M_C{}^2 + M_D{}^2 - S_C(\vec{k}_\perp - x\vec{r}_\perp, x) - S_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x) \; .$$

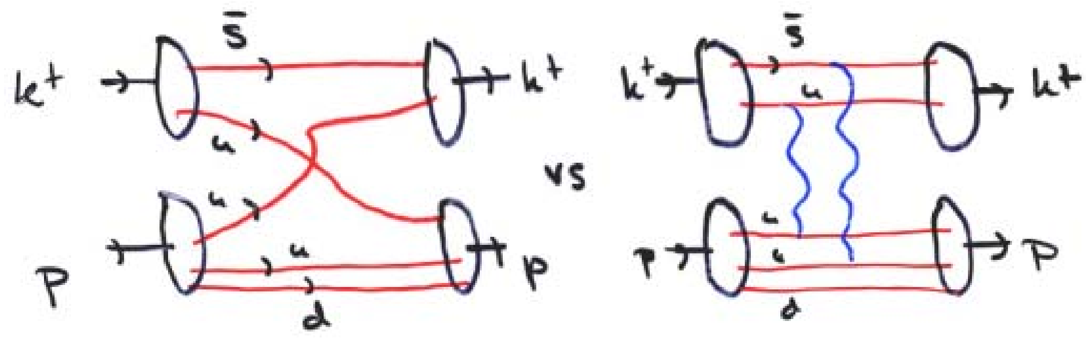
Formula for quark interchange using LFWFs

Blankenbecler, Gunion, sjb; Sivers

Angular Distribution $\quad -t/s = \frac{1}{2}(1-\cos\theta_{cm})$

$$\frac{d\sigma}{dt} = \frac{1}{s^{n_{TOT}-2}} F(t/s)$$

determined by scattering mechanism



Quark Interchange $\quad$ gluon exchange

analogous to spin exchange in atom - atom scattering $\quad$ Van der Waals

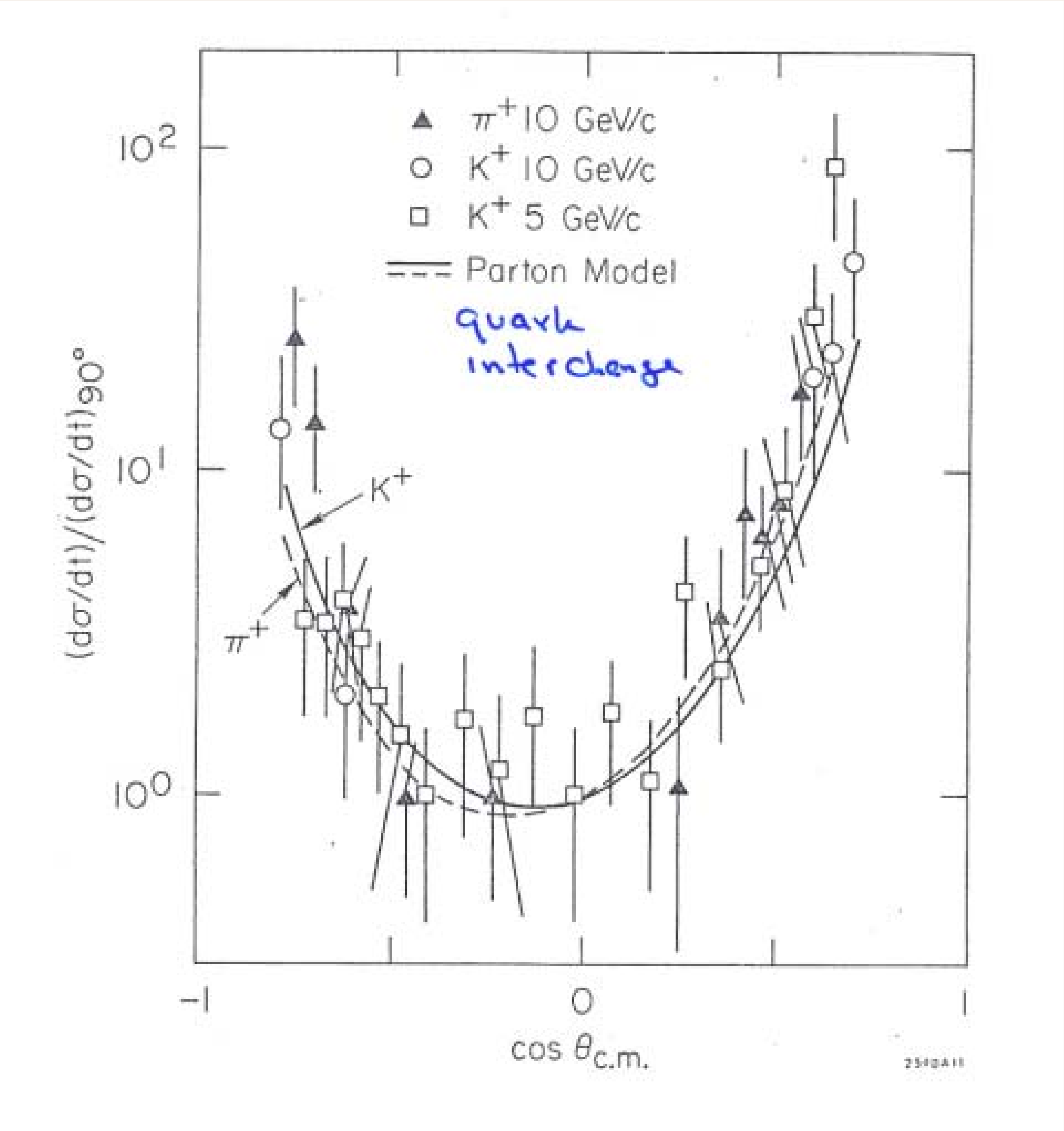
Large N_c : Quark Interchange Dominant

$$\mathcal{M} \sim \frac{1}{u}\frac{1}{t^2}$$

t' Hooft limit , AdS/CFT

Blankenbecler, Gunion, sjb

MIT Bag Model predicts dominance of quark interchange: deTar



π^+ 10 GeV/c
K$^+$ 10 GeV/c
K$^+$ 5 GeV/c
Parton Model
quark interchange
10^2
10^1
10^0
$(d\sigma/dt)/(d\sigma/dt)_{90°}$
K$^+$
π^+
−1
0
1
cos $\theta_{c.m.}$

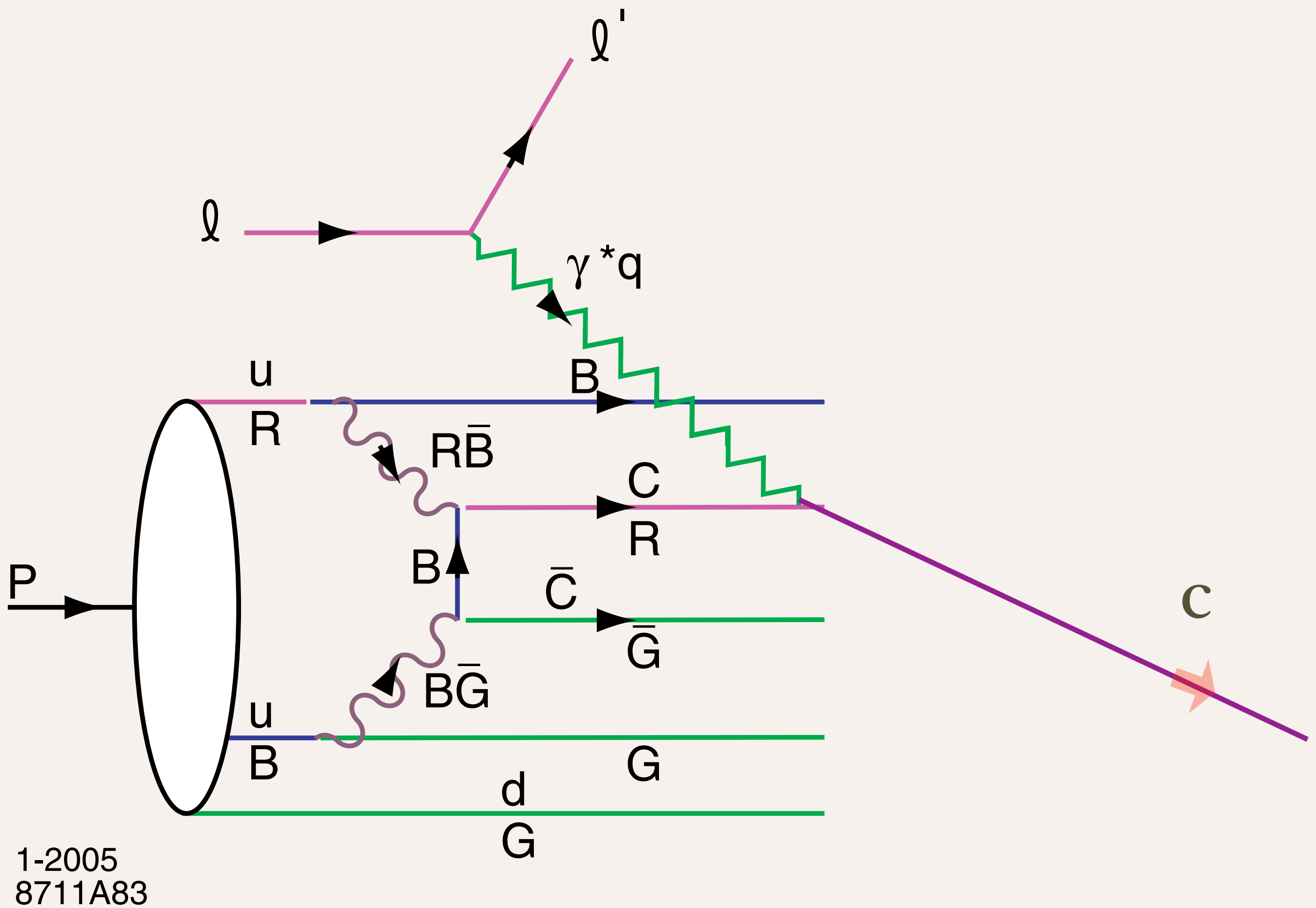
Hadrons Fluctuate in Particle Number

- Proton Fock States

  $|uud>, |uudg>, |uuds\bar{s}>, |uudc\bar{c}>, |uudb\bar{b}> \cdots$
- Strange and Anti-Strange Quarks not Symmetric

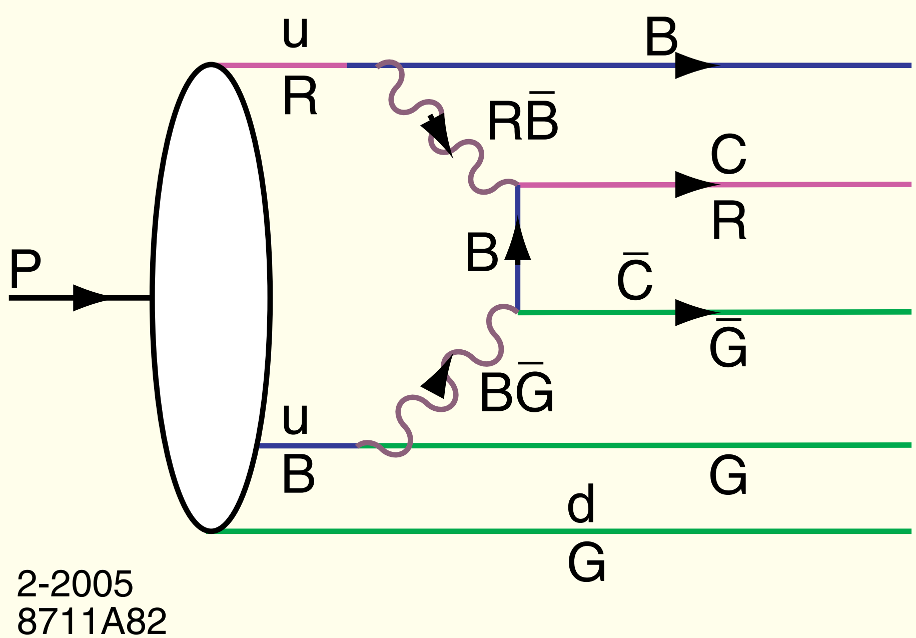
  $s(x) \neq \bar{s}(x)$
- "Intrinsic Charm": High momentum heavy quarks
- "Hidden Color": Deuteron not always p + n
- Orbital Angular Momentum Fluctuations - Anomalous Magnetic Moment

Measure c(x) in Deep Inelastic Lepton-Proton Scattering



Hoyer, Peterson, SJB

Intrinsic Charm in Proton



$|uudc\bar{c}>$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

OPE derivation - M.Polyakov et al.

$c\bar{c}$ in Color Octet

High x charm

Distribution peaks at equal rapidity (velocity)

Therefore heavy particles carry the largest momentum fractions

In contrast:

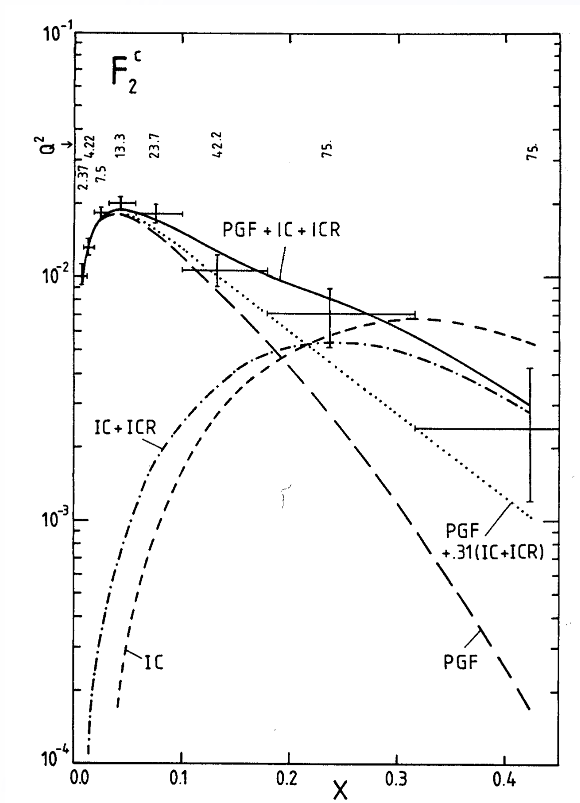
$|e^+e^-\ell^+\ell^->$ Fluctuation in Positronium

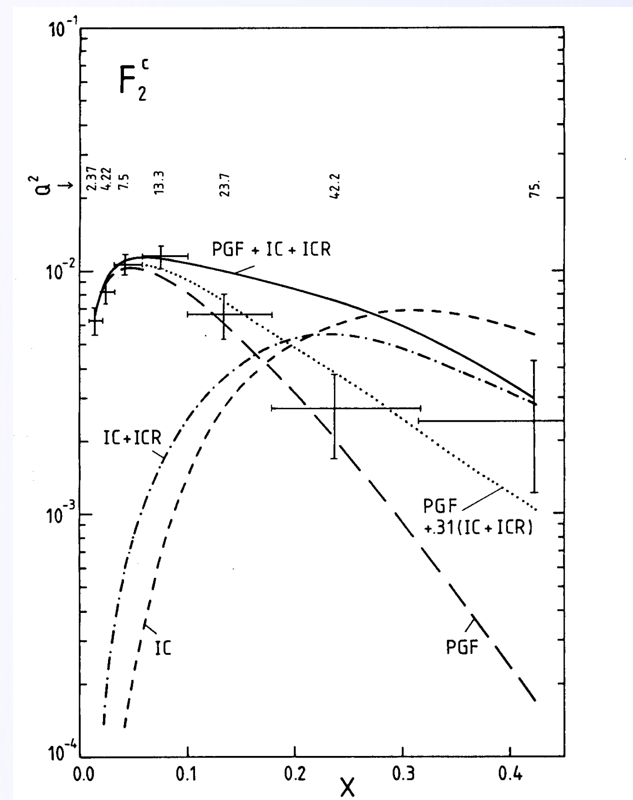
QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

EMC Measurements of the Charm Structure Function

J. J. Aubert et al. [European Muon Collaboration], “Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions,” Nucl. Phys. B 213, 31 (1983).

1% IC





Analysis by
E. Hoffmann and R. Moore, Z. Phys. C 20, 71 (1983).

Photon Gluon Fusion Factor 30 too small

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

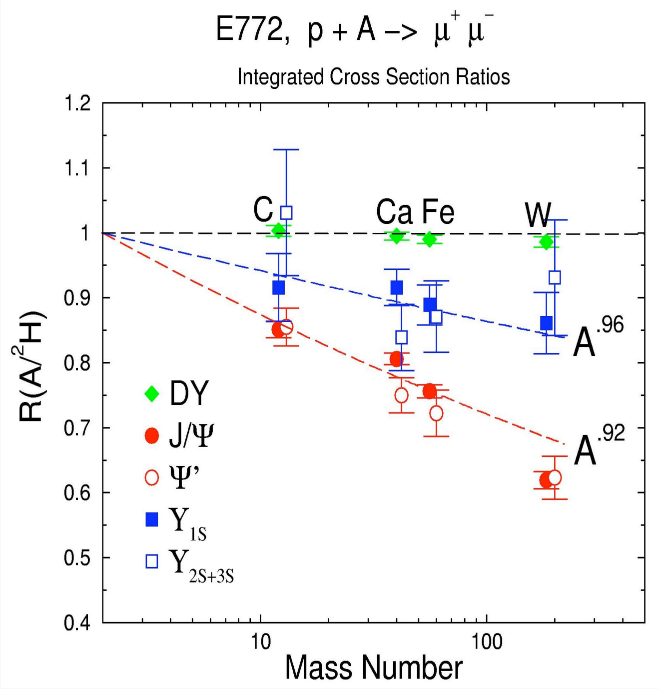
- High x_F $pp \to \Lambda_b X$

- High x_F $pp \to \Xi(ccd) X$ (SELEX)

Nuclear effects in Quarkonium production

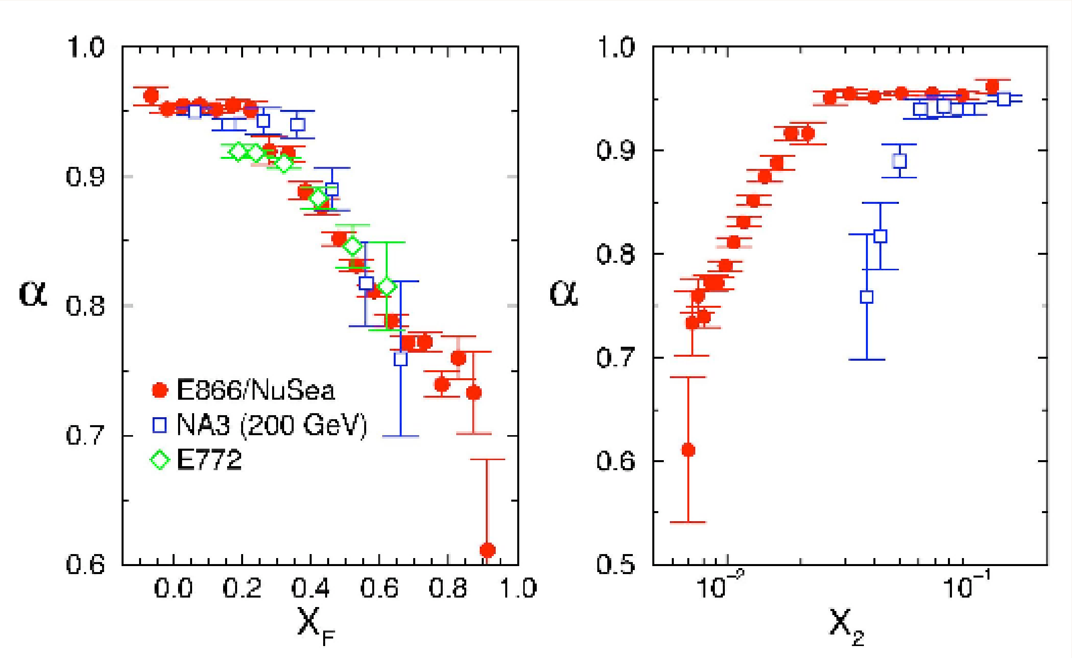
p + A at $s^{1/2}$ = 38.8 GeV

E772 data



$\sigma(p+A) = A^{\alpha}\,\sigma(p+N)$

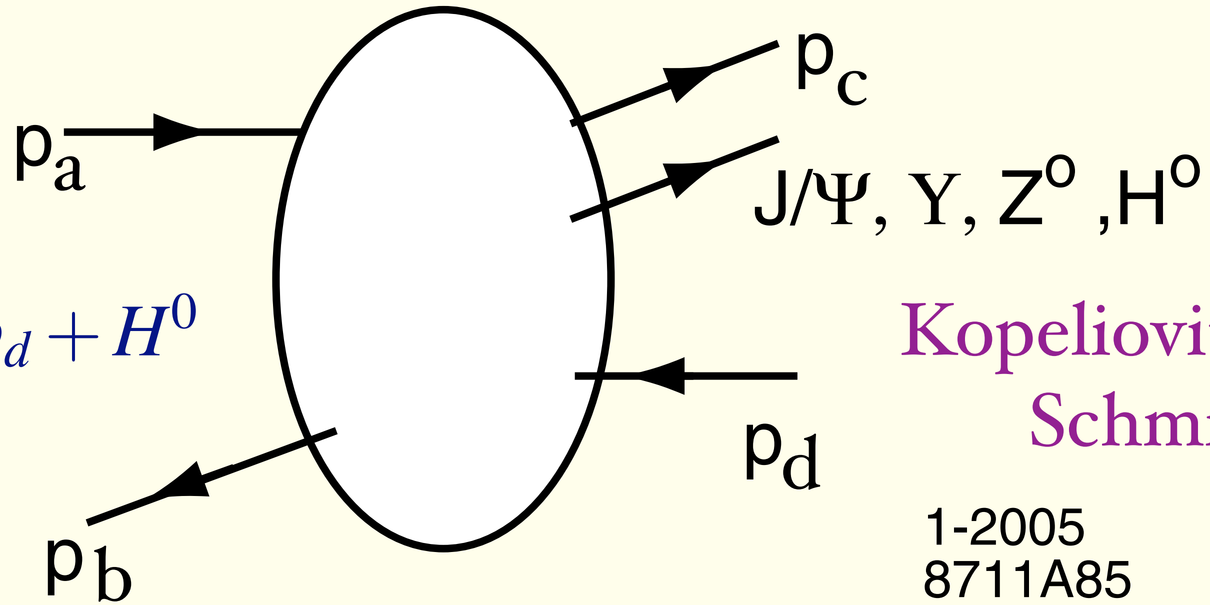
Strong x_F - dependence



Nuclear effects scale with x_F, not x_2 !!!

M.Leitch

Doubly-Diffractive Higgs Production



$p_a + p_b \to p_c + p_d + H^0$

Kopeliovitch, Soffer, Schmidt, sjb

$p_H^\mu = p_a^\mu + p_b^\mu - p_c^\mu - p_d^\mu$

Low transverse momentum protons p_c, p_d

Higgs appears in Missing Mass spectrum dN/dM^2

$M^2 = p_H^2$

Intrinsic Charm: Large range of Higgs momentum $x_F = p_H^z / p_a^z$

Extrapolate from doubly diffractive $J/\psi, \Upsilon, Z^0$ production

Higgs Production at High x_F

$$pp \to H^0 X$$

- Intrinsic Charm and Bottom Couples to Higgs
- Higgs will carry high momentum fraction of projectile momentum
- Small transverse momentum
- Same x_F Distribution as Quarkonium
- Axial Detector?

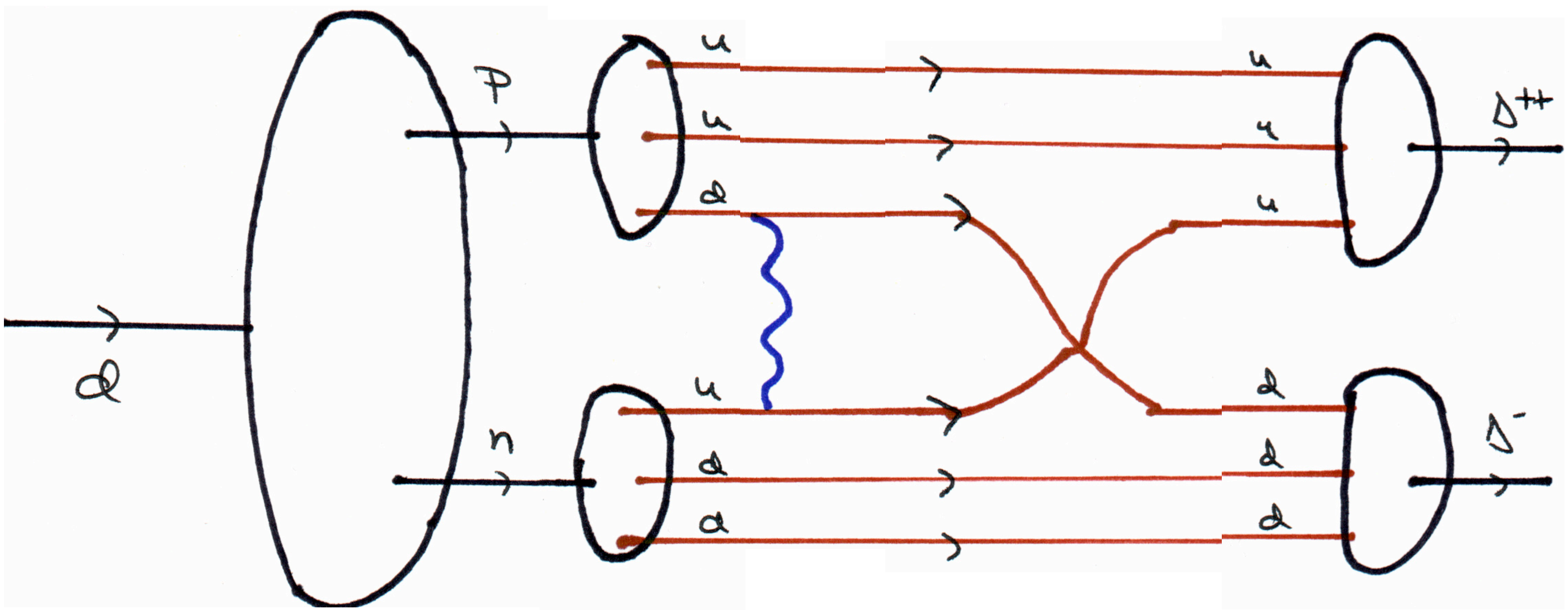
Kopeliovich, Schmidt, Soffer, SJB

Hidden Color in QCD

Lepage, Ji, sjb

- Deuteron six quark wavefunction:
- 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

Structure of Deuteron in QCD



Hidden Color Fock State

Delta-Delta Fock State

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.

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

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

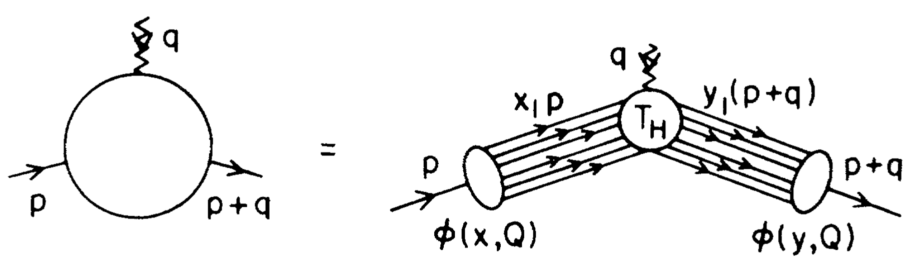


FIG. 1. The general structure of the deuteron form factor at large Q^2.

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

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

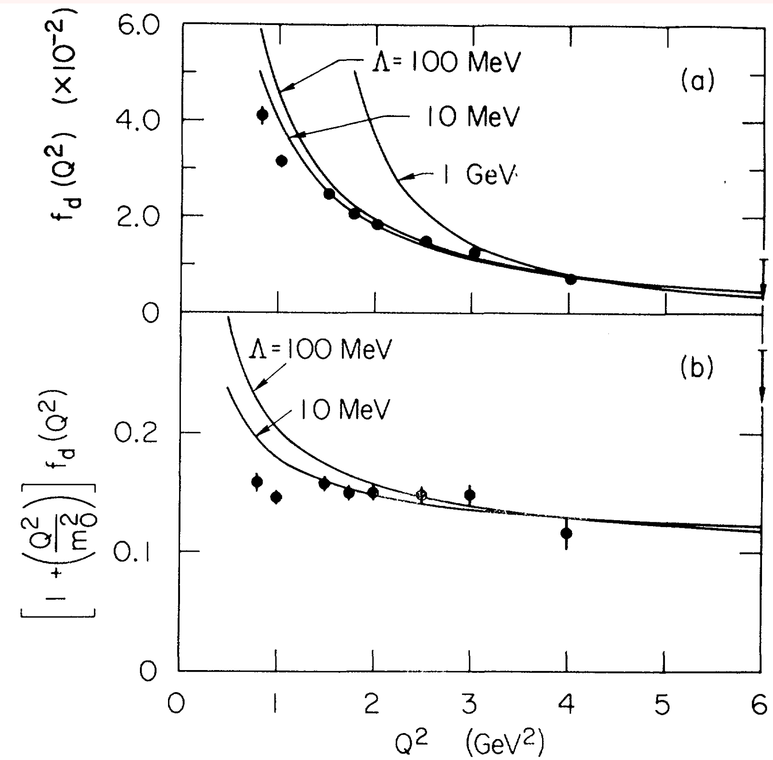
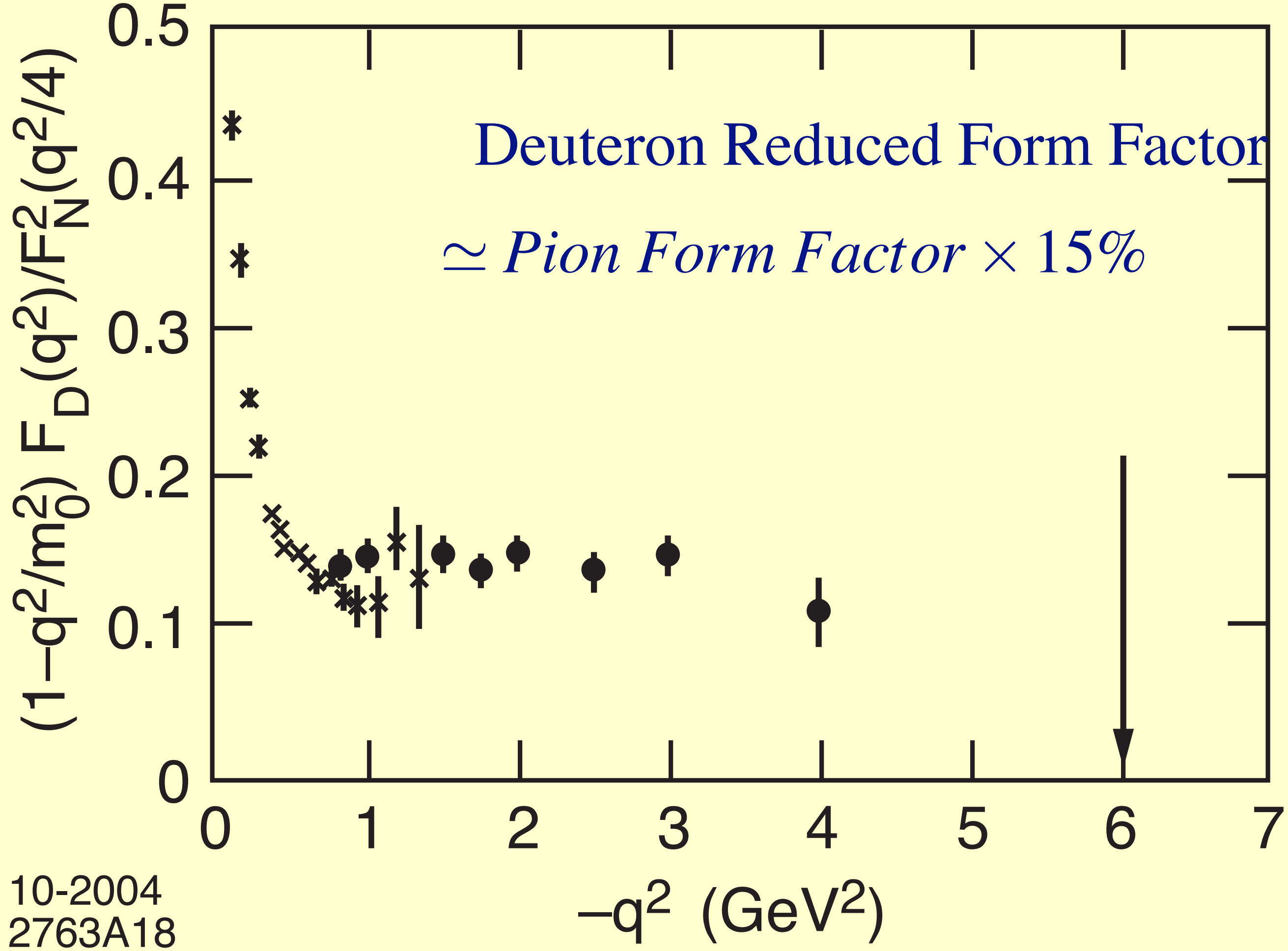


FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$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



- 15% Hidden Color in the Deuteron

Test Hidden Color of Deuteron

- Diffractive, Coulomb Dissociation to $\Delta^{++}\ \Delta^{-}$
- Photodisintegration of Deuteron to $\Delta^{++}\ \Delta^{-}$
- Connection to EMC
- Deuteron not simply n + p

Physics of Rescattering

- Diffractive DIS: New Insight into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions
- T-odd SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon

- Light-Front Fock Expansions
- LFWFs boost invariant
- Direct connection to form factors, structure functions, distribution amplitudes, GPDs
- Higher-Twist Correlations
- Orbital Angular Momentum, physical polarization in $A^+ = 0$ gauge
- Sum Rules
- Validated in QED, Bethe-Salpeter Eqn.

QCD at The Amplitude Level

- Light-Front Fock Expansions
- LFWFs boost invariant
- Direct connection to form factors, structure functions, distribution amplitudes, GPDs
- Higher Twist Correlations
- Orbital Angular Momentum
- Validated in QED, Bethe-Salpeter
- AdS/CFT Holographic Model

New Perspectives on QCD from AdS/CFT

- LFWFs: Fundamental description of hadrons at amplitude level
- QCD is Nearly Conformal
- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra
- Quark-interchange dominates scattering amplitudes

Outlook

- Only one scale Λ_{QCD} determines hadronic spectrum (slightly different for mesons and baryons).
- Ratio of Nucleon to Delta trajectories determined by zeroes of Bessel functions.
- String modes dual to baryons extrapolate to three fermion fields at zero separation in the AdS boundary.
- Only dimension $3, \frac{9}{2}$ and 4 states $\overline{q}q$, qqq, and gg appear in the duality at the classical level!
- Non-zero orbital angular momentum and higher Fock-states require introduction of quantum fluctuations.
- Simple description of space and time-like structure of hadronic form factors.
- Dominance of quark-interchange in hard exclusive processes emerges naturally from the classical duality of the holographic model. Modified by gluonic quantum fluctuations.
- Covariant version of the bag model with confinement and conformal symmetry.