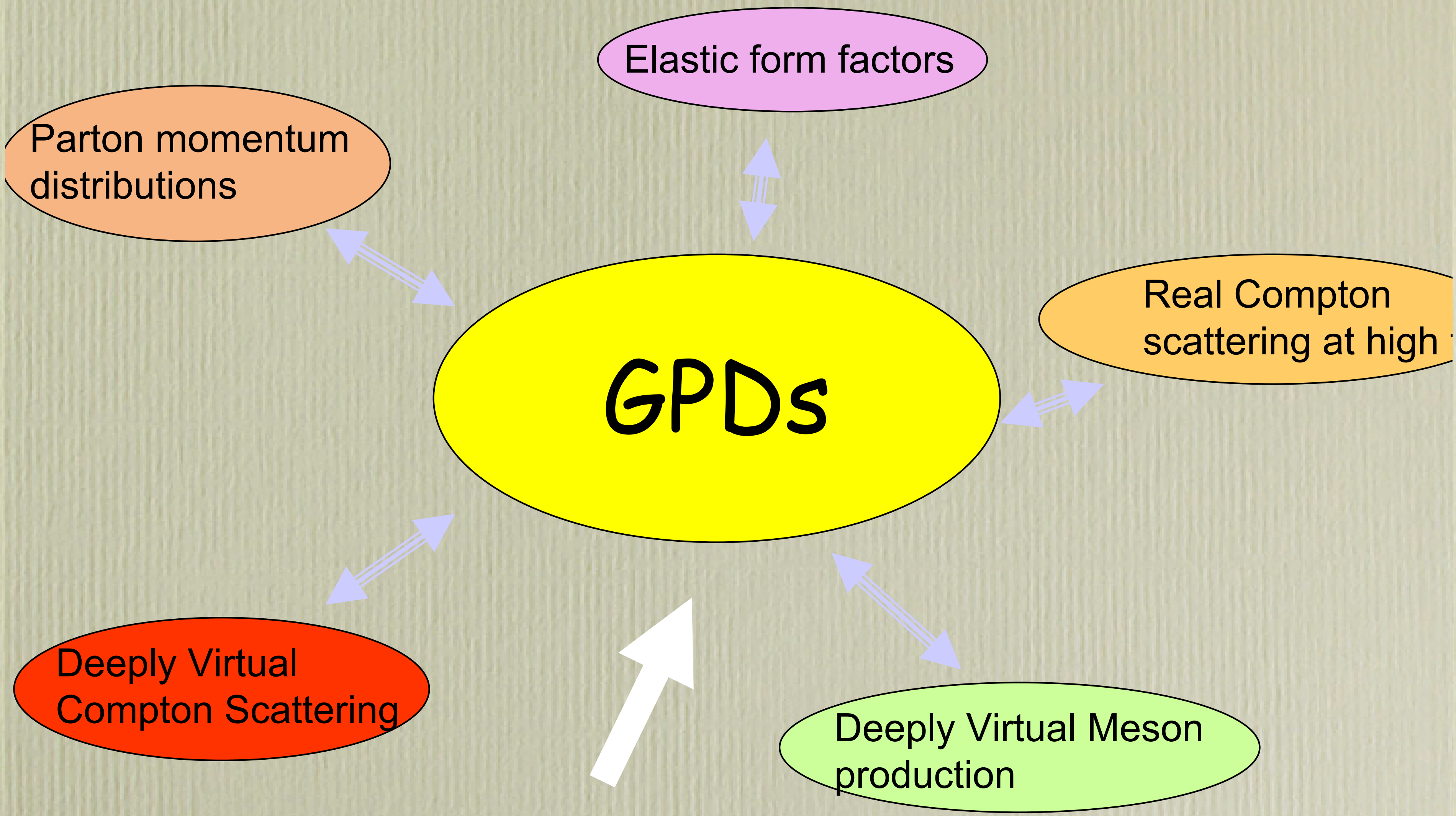
New Perspectives on QCD from AdS/CFT

- Progress in hadron physics: Must confront the structure of hadrons at the amplitude level!
- Proton is lightest eigenstate of the QCD Hamiltonian with B=1, Q=1.
- AdS/CFT provides a remarkably simple picture of the quark structure of the proton
- AdS/CFT: Anti-deSitter Space/ Conformal Field Theory

New Perspectives on QCD from AdS/CFT

- LFWFs: Fundamental description of hadrons at amplitude level
- Near Conformal QCD
- Holographic Model: Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra
- Quark-interchange and scattering amplitudes

A Unified Description of Hadron Structure



Light Front Wavefunctions

New Perspectives AdS/CFT

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

Light-Front Wavefunctions

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

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

$$\mathrm{H}_{LF}^{QCD}|\psi> = M^2|\psi>$$

Invariant under boosts! Independent of P^μ

New Perspectives AdS/CFT

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

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

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

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

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

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

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

Solving the LF Heisenberg Equation

- Discretized Light-Cone Quantization
- Transverse Lattice
- Bethe-Salpeter/Dyson Schwinger at fixed LF time
- Use AdS/CFT solutions as starting point!
- Many model field theories solved
- Structure of Solutions known

Light Front Fock State Methods

In QCD the Hilbert space is constructed in terms of a complete Fock basis of non interacting constituents at fixed light-front time, where the amplitudes are n-parton light-front wave functions $\psi_{n/h}$ corresponding to the expansion of color singlet hadron states

$\tau = t + z/c$

$$|\Psi_h\rangle = \sum_n \psi_{n/h}|n\rangle$$

The light-front Fock-state wavefunction provides a frame-independent representation of relativistic composite systems in QCD at the amplitude level, in terms of quark and gluon degrees of freedom which carry the symmetries within the hadrons.

The Light-Front Fock Expansion

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

The Light Front Fock State Wavefunctions

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

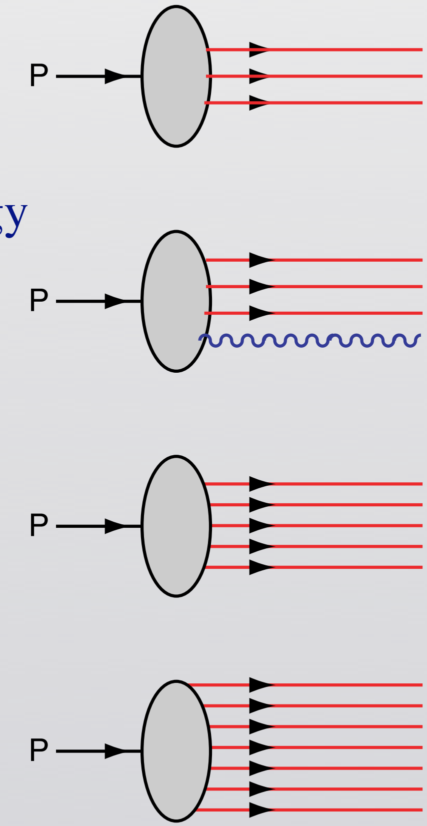
are boost invariant; they are independent of the hadron's energy and momentum P^μ!

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.

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



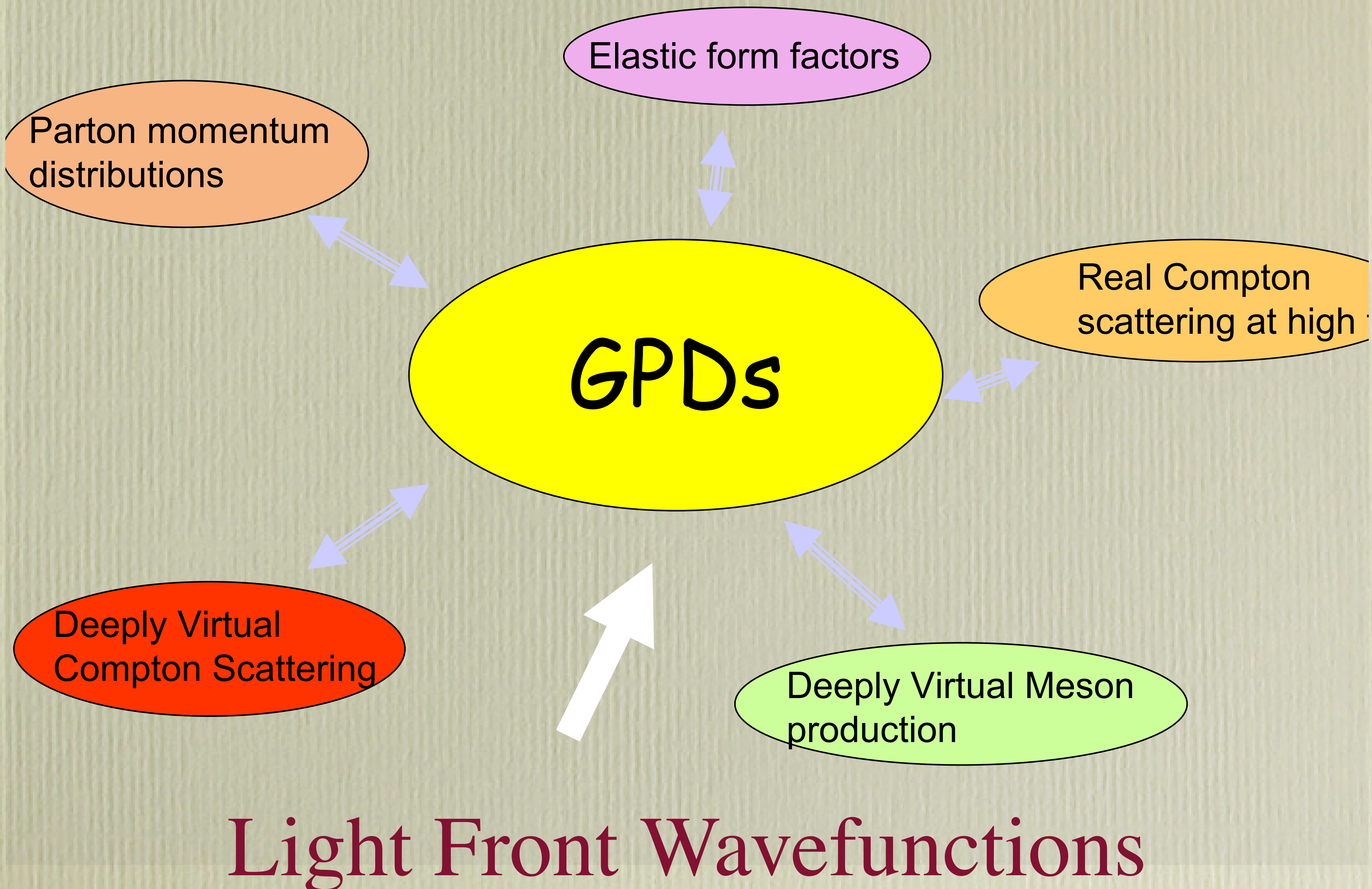
Quantum Mechanics + Relativity

- Fluctuations in momentum, position, particle number -- particle # cannot be determine
- QCD: Hadrons Fluctuate in Size -- >
  - "Color Transparency"
- Hadrons can pass through a Nucleus without Interactions
- Fluctuations in Flavor, Color, and Spin

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

A Unified Description of Hadron Structure



New Perspectives AdS/CFT

Structure functions: compute from square of LFWFs

Form Factors: Overlap of initial and final LFWFS

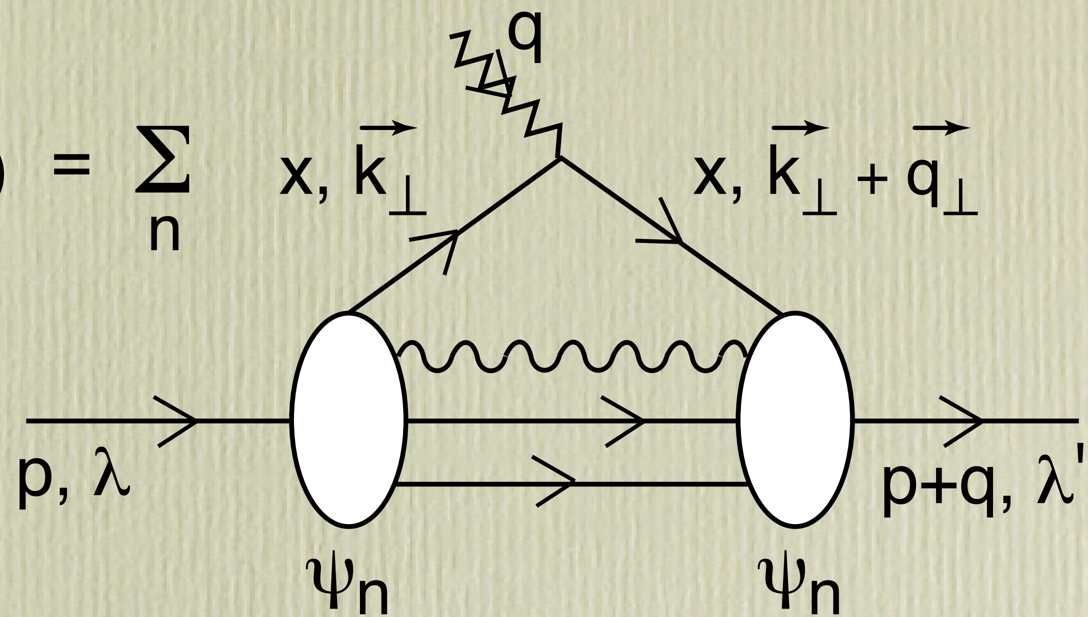
Generalized Parton Distributions: Overlap of initial and final LFWFs, $\delta n = 0, 2$.

Fixed Angle Scattering Reactions $A + B \to C + D$: Overlap of four LFWFS

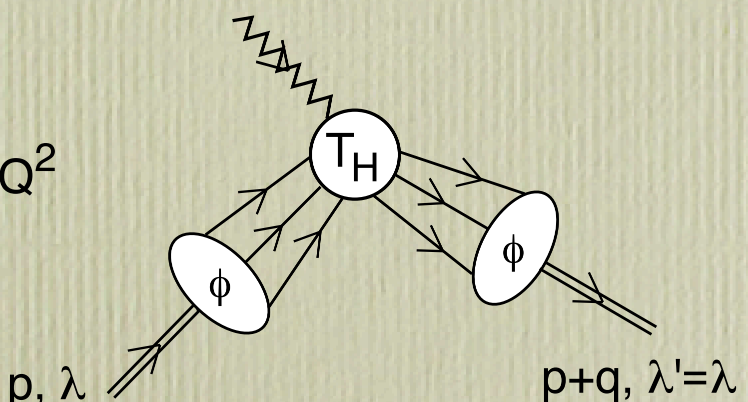
Sivers Function, anomalous moments, EDM

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

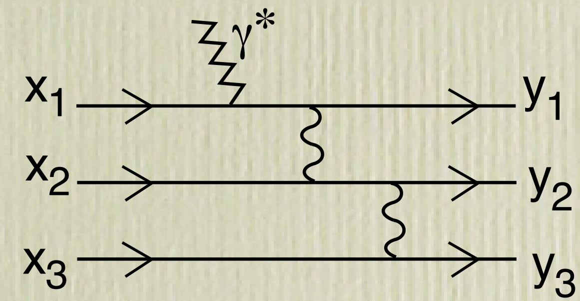
$F_{\lambda\lambda'}(Q^2) = \sum_n$



$\Rightarrow$ Large Q^2



$T_H = \sum$



$+ \;\ldots$

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

Scaling from PQCD or AdS/CFT

Exact Representation of Form Factors using LFWFs

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

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

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

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

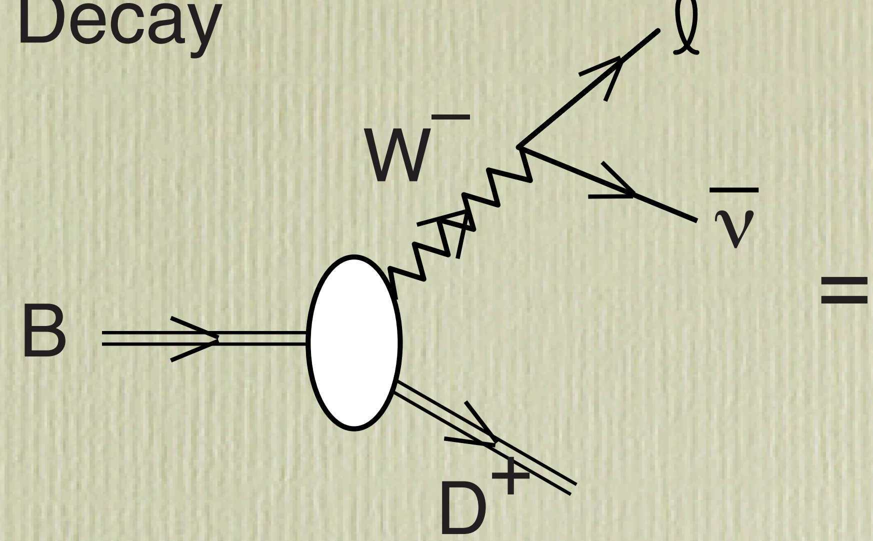
for each spectator. The momentum transfer is $q^2 = -\vec{q}_\perp^{\,2} = -2P \cdot q = -Q^2$. The measure of the phase-space integration is

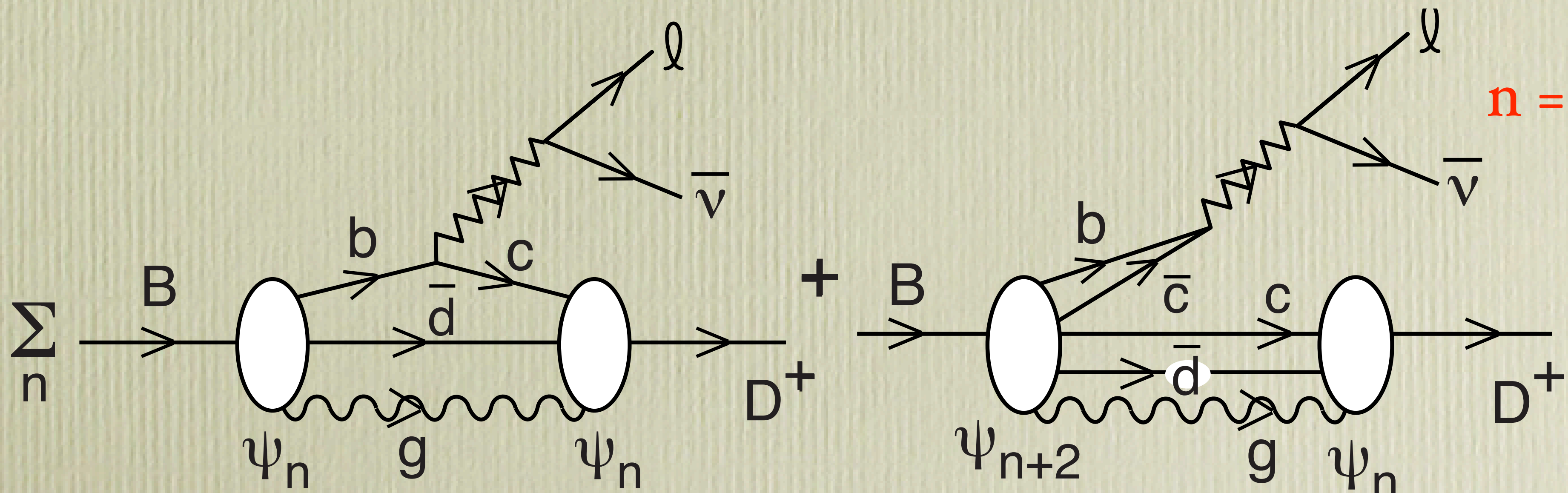
$$\left[dx_i\right] = \prod_{i=1}^{n} \frac{dx_i}{\sqrt{x_i}}\, \delta\left(1 - \sum_{j=1}^{n} x_j\right), \tag{4}$$

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

Weak Exclusive Decay

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

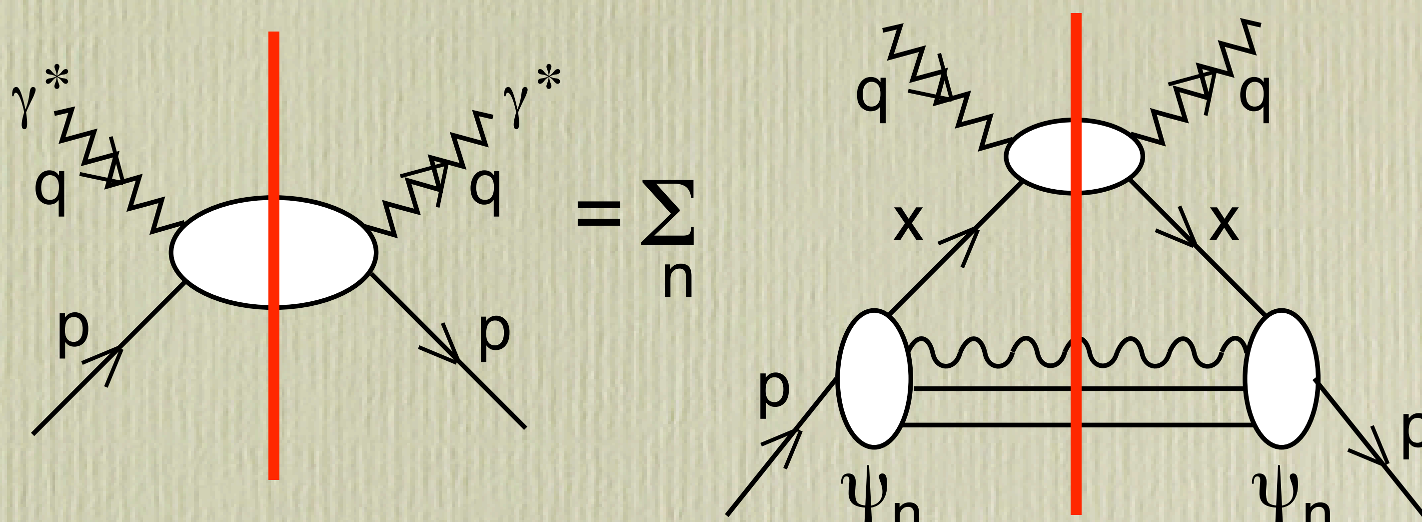


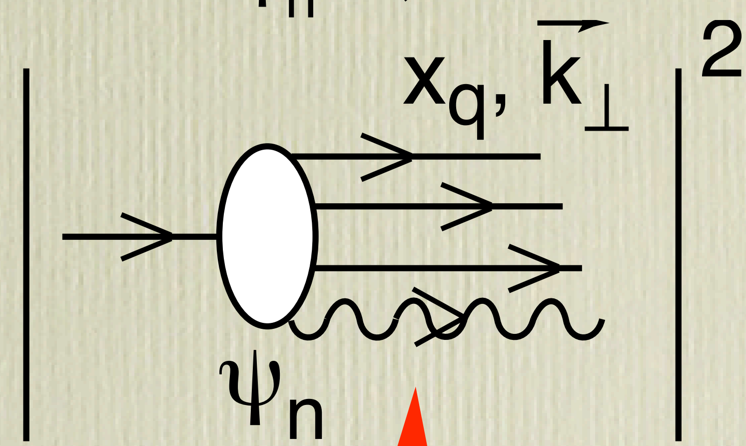


n = n' + 2

Annihilation amplitude needed for Lorentz Invariance

Deep Inelastic Lepton Proton Scattering





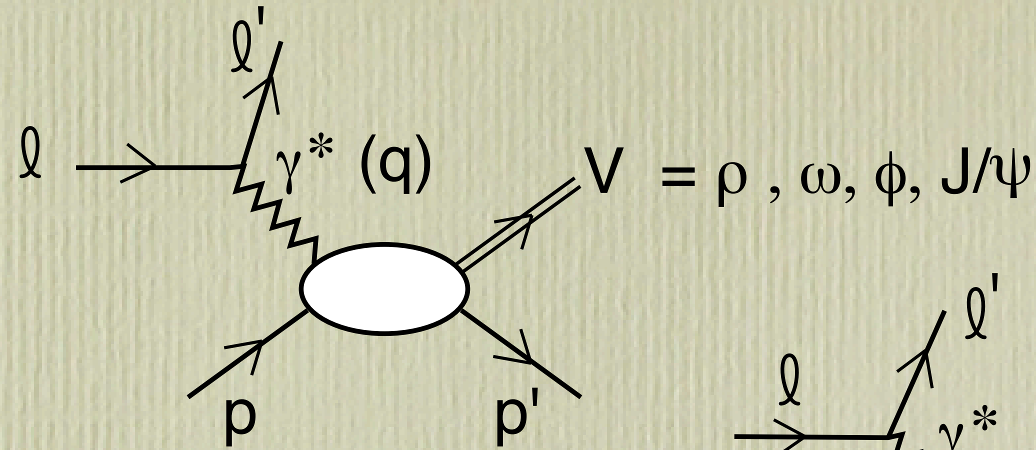
Imaginary Part of
Forward Virtual Compton Amplitude

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

$$x = x_q$$

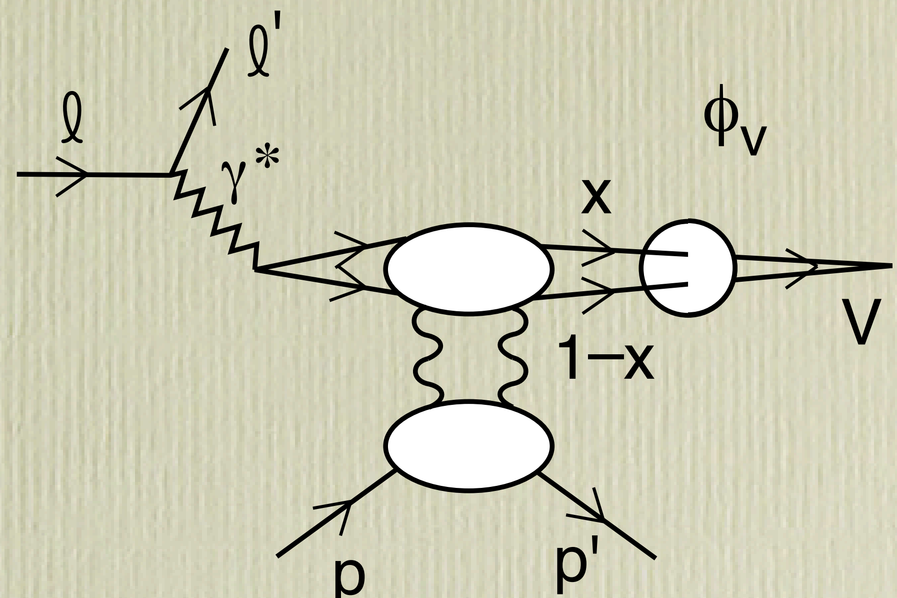
Light-Front Wave Functions $\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

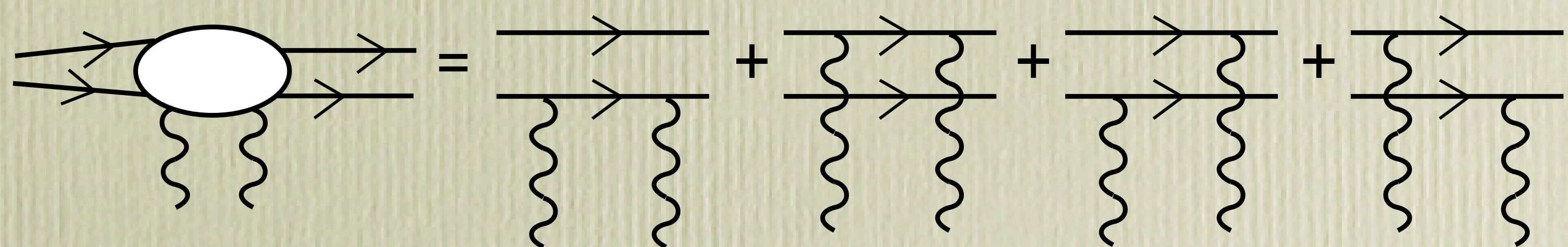
Vector Meson Leptoproduction



Large $-q^2 = Q^2$

⇨

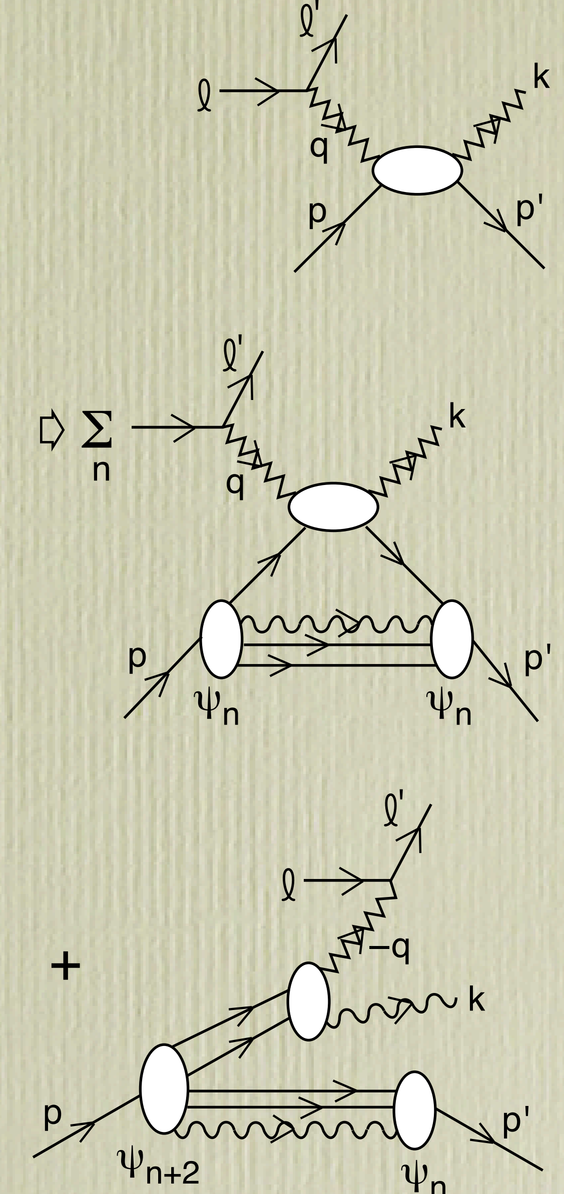




$$\phi(x,Q) = \int d^2k_\perp \Psi_{q\bar{q}}(x,\vec{k}_\perp)$$

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

Large $-q^2 = Q^2$



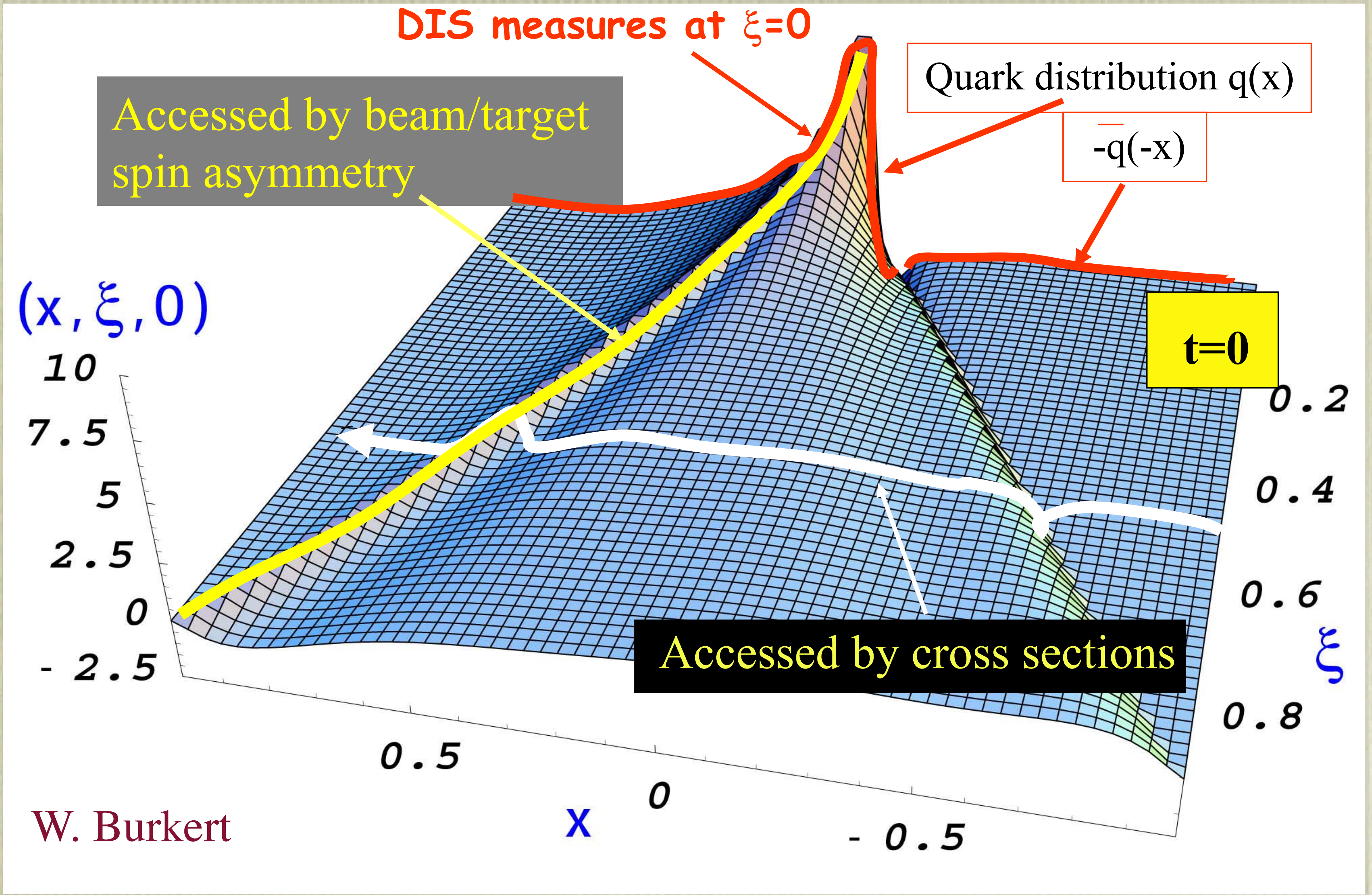
$$\gamma^* p \to \gamma p'$$

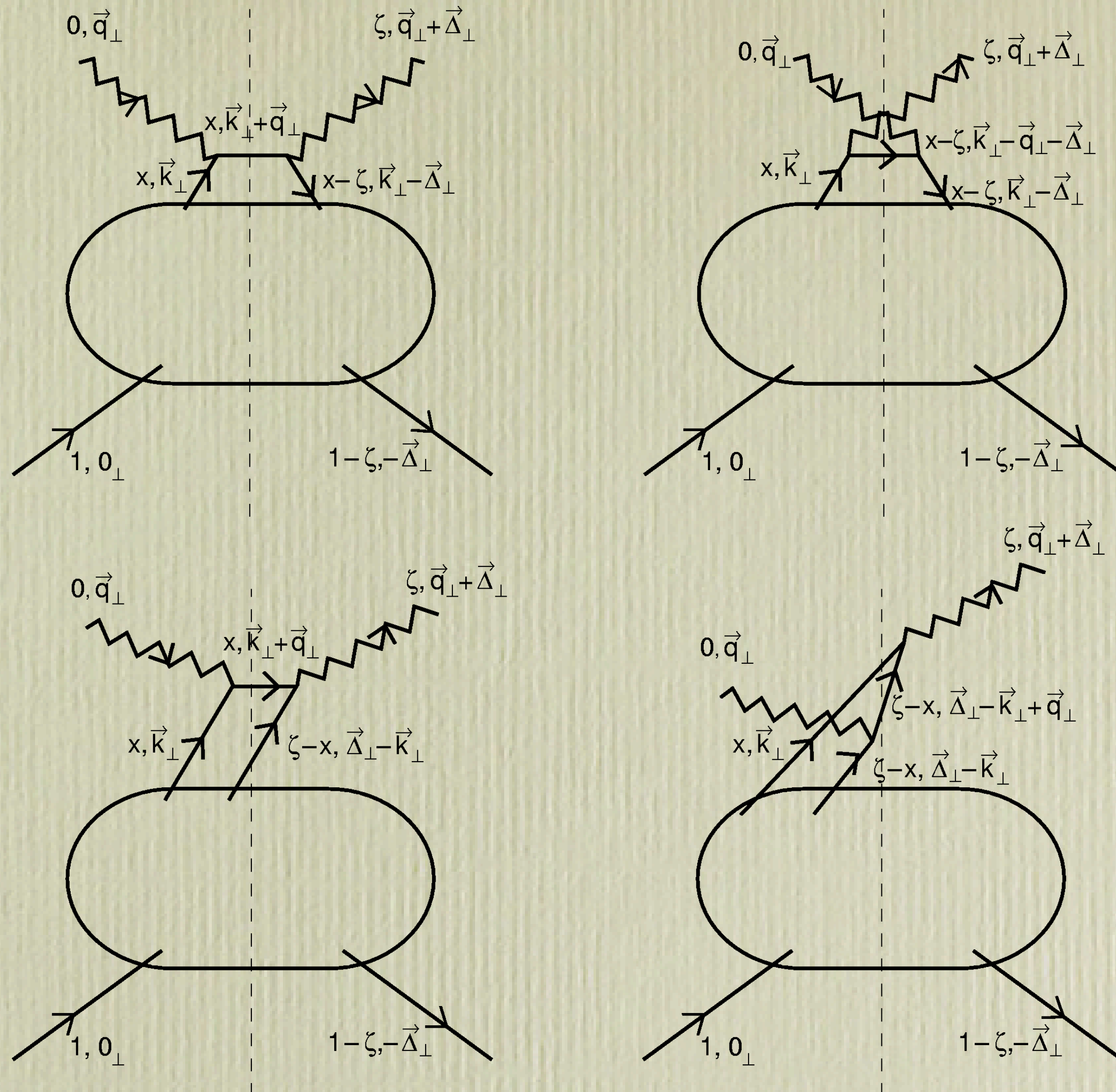
Given LFWFs, compute all GPDs !

Deeply Virtual Compton Scattering

$n = n' + 2$

Access GPDs through x-section & asymmetries





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)

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

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

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

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)

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

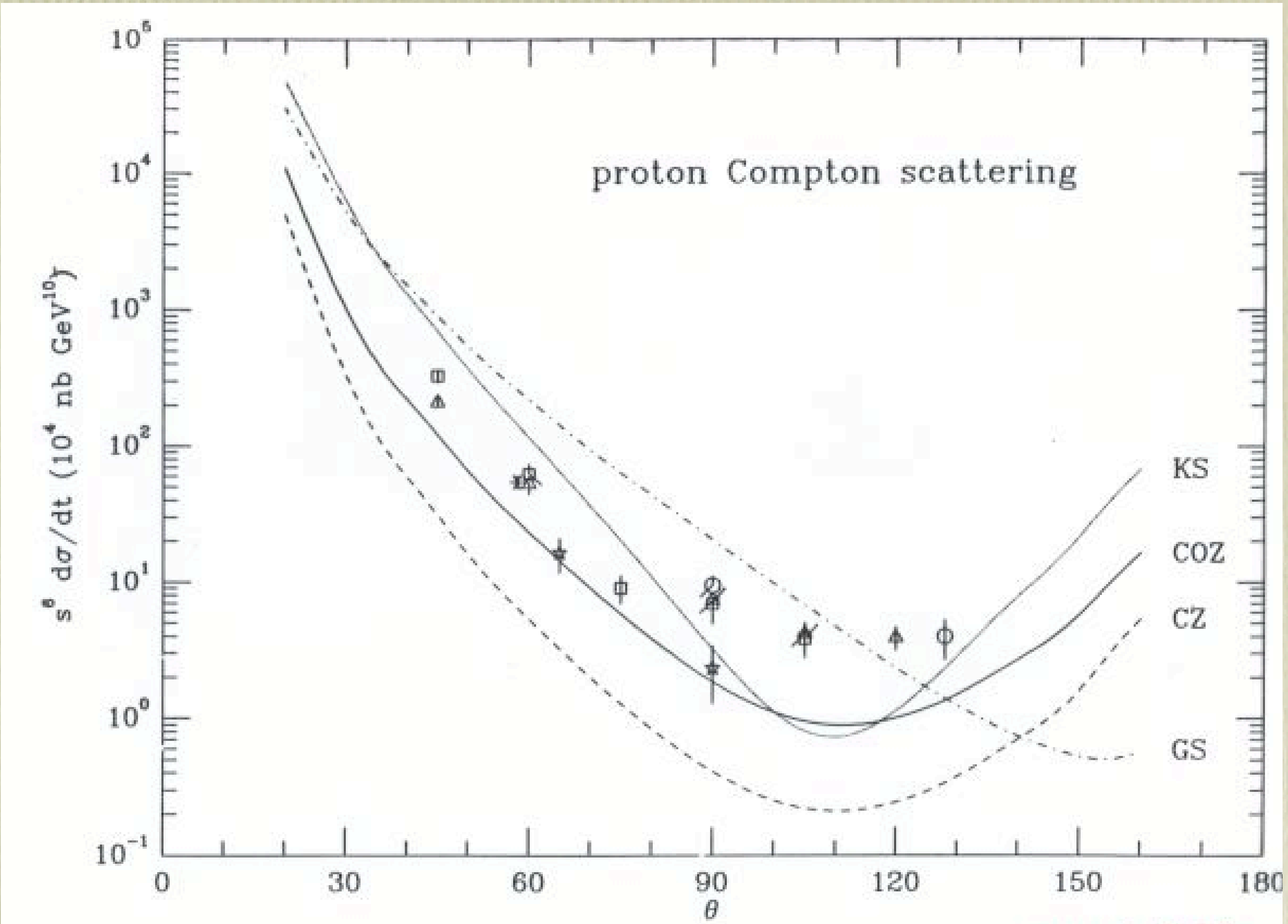
$$= \left(\sqrt{1-\zeta}\right)^{3-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n+1} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3} 16\pi^3 \delta\left(1 - \sum_{j=1}^{n+1} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n+1} \vec{k}_{\perp j}\right)$$
$$\times 16\pi^3 \delta(x_{n+1} + x_1 - \zeta)\delta^{(2)}(\vec{k}_{\perp n+1} + \vec{k}_{\perp 1} - \vec{\Delta}_\perp)$$
$$\times \delta(x - x_1)\psi^{\uparrow *}_{(n-1)}(x'_i, \vec{k}'_{\perp i}, \lambda_i)\psi^{\downarrow}_{(n+1)}(x_i, \vec{k}_{\perp i}, \lambda_i)\delta_{\lambda_1 - \lambda_{n+1}},$$

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

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

- LFWFs boost invariant
- Direct connection to form factors, structure functions, distribution amplitudes, GPDs
- Higher Twist Correlation
- Orbital Angular Momentum
- Sum Rules
- Validated in QED, Bethe-Salpeter
- DLCQ

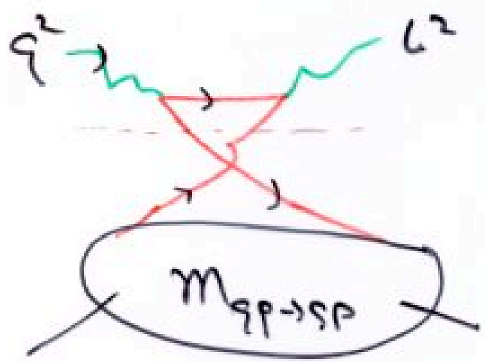
Large-Angle Compton Scattering



Given $\mathcal{M}_{qp\to qp}(\hat{s}, t)$

predict $T_{\mu\nu}(q^2, p\cdot q, t)$

gauge-invariant
crossing symmetric



+ crossed graph

“J=0 Fixed Pole”

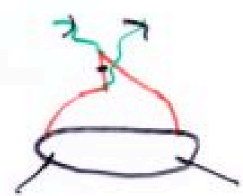
Measure Real part from interference with B.H.

Im $T_{\mu\nu}(q^2, p\cdot q, t=0) = W_{\mu\nu}(q^2, p\cdot q)$

Bj-scaling structure functions

Extra J=0 pieces from "fixed pole"

instantaneous quark exchange



Two-photon contact Interaction -- Unique to gauge theory

Close, Gunion, SJB

Test J=0 Fixed Pole: $s^2\, d\sigma/dt(\gamma p \to \gamma p) \simeq F^2_0(t)$

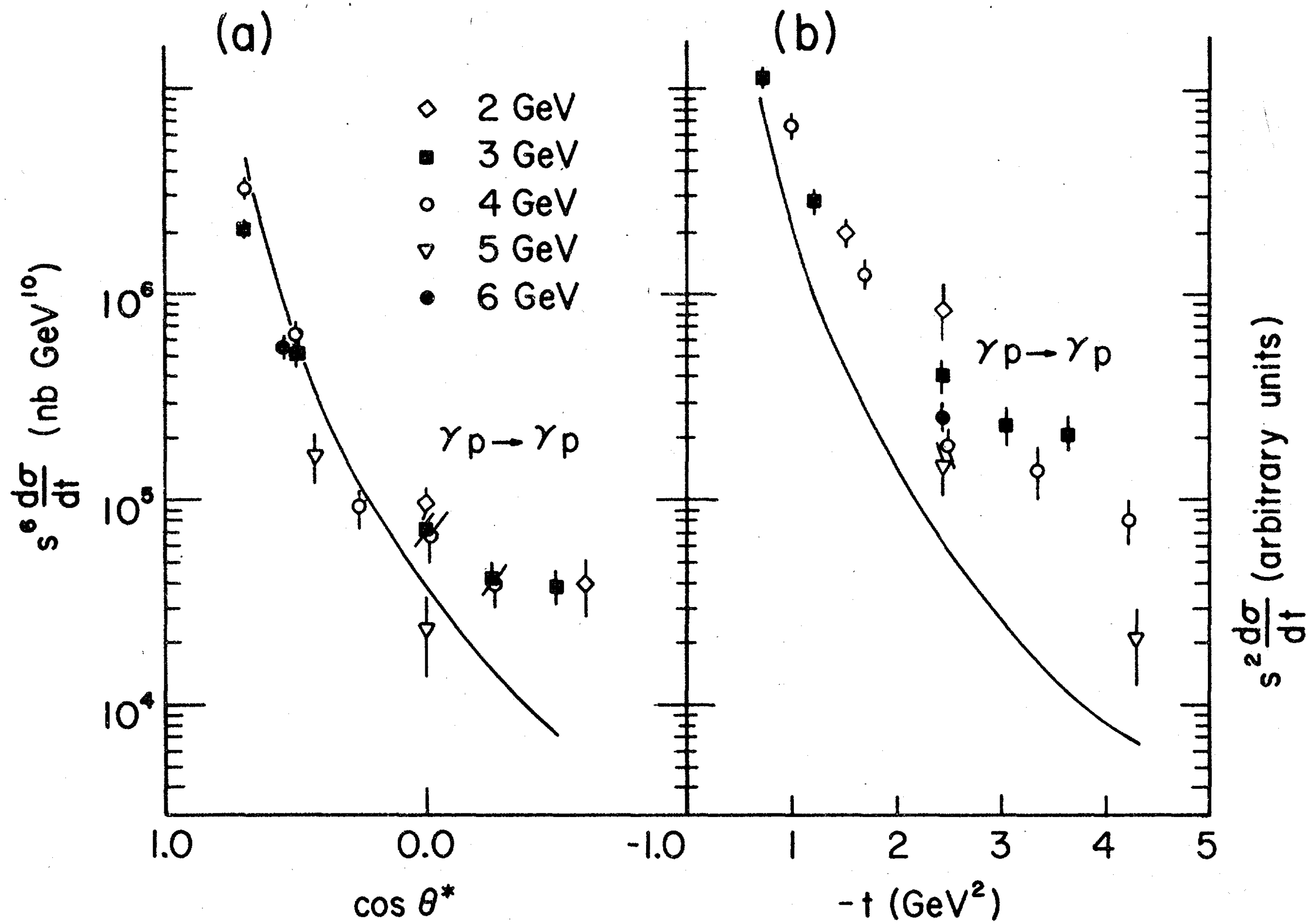


FIG. 5. (a) A test of the dimensional-counting prediction for Compton scattering. The solid line is the prediction of Scott (Ref. 6) at asymptotic s and t. (b) A test for existence of $J=0$ fixed pole in the Compton amplitude (see text). The solid line exhibits t^{-4} dependence.

Cornell Measurements of Compton Scattering

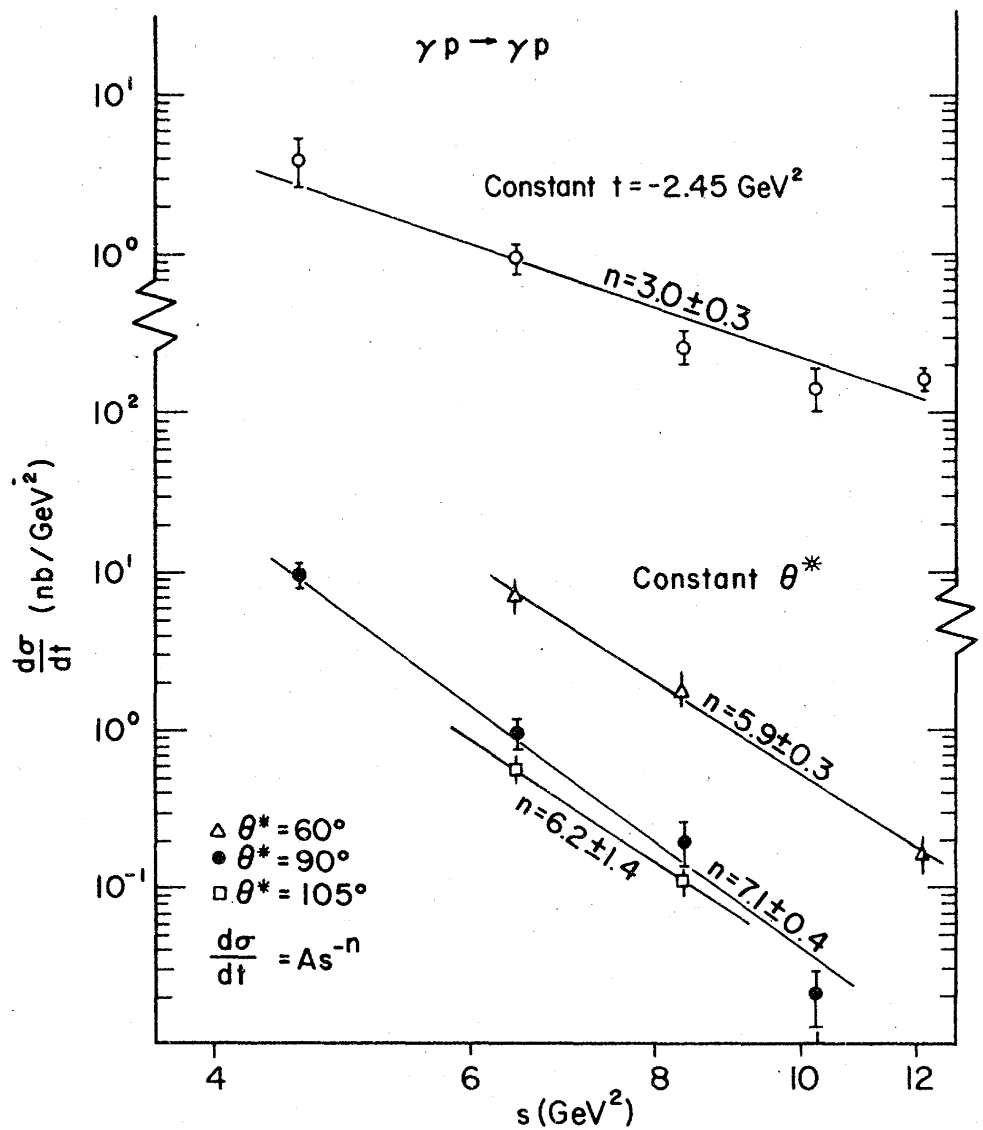
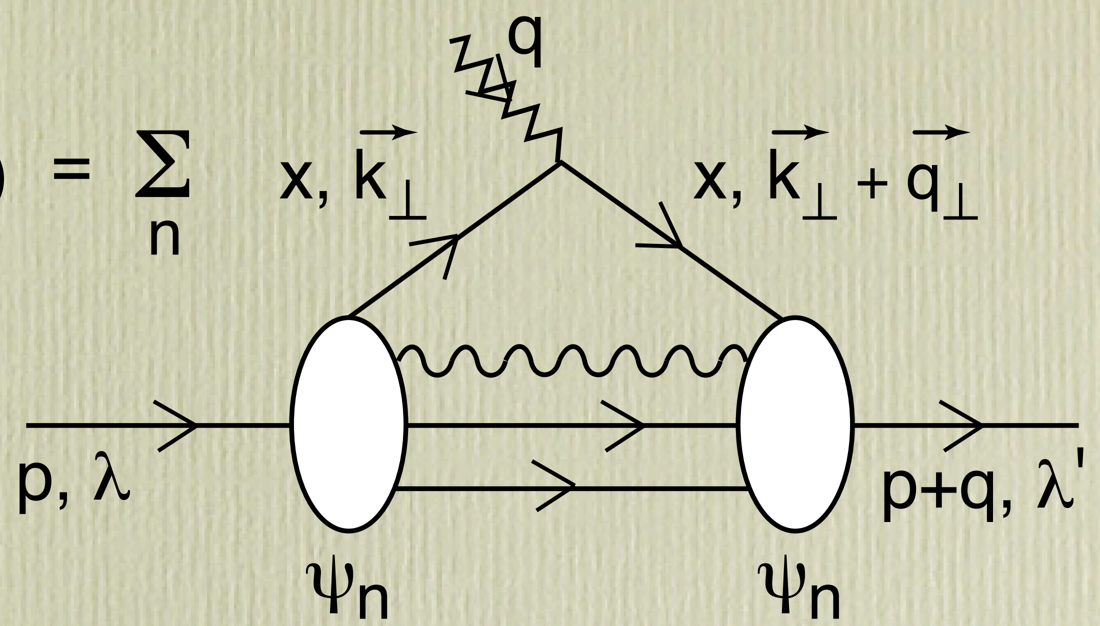


FIG. 6. Compton-scattering cross sections at constant t and at constant θ^*. The straight lines are fits to the data. The fits shown here have no energy cuts.

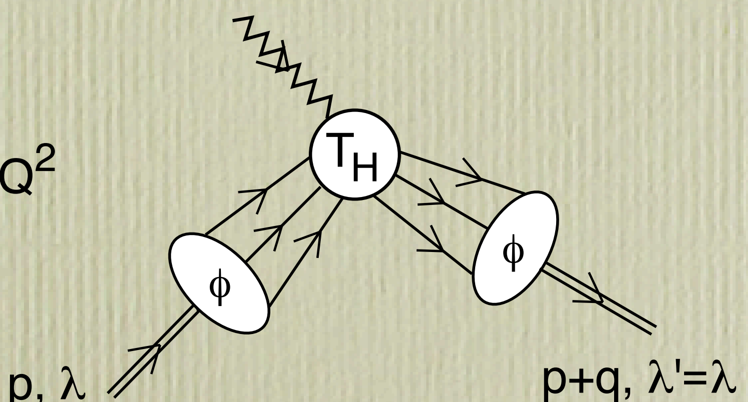
J=0: Predict n=2

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

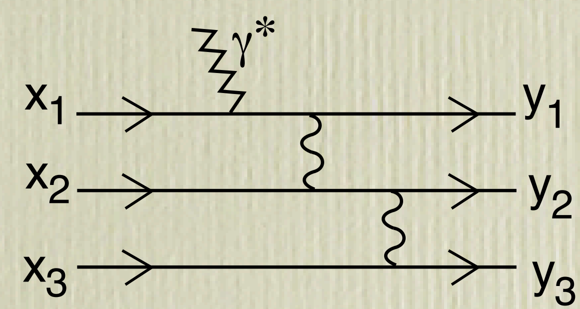
$$F_{\lambda\lambda'}(Q^2) = \sum_n$$



⇨ Large Q^2



$T_H = \sum$



$+ \ \ldots$

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

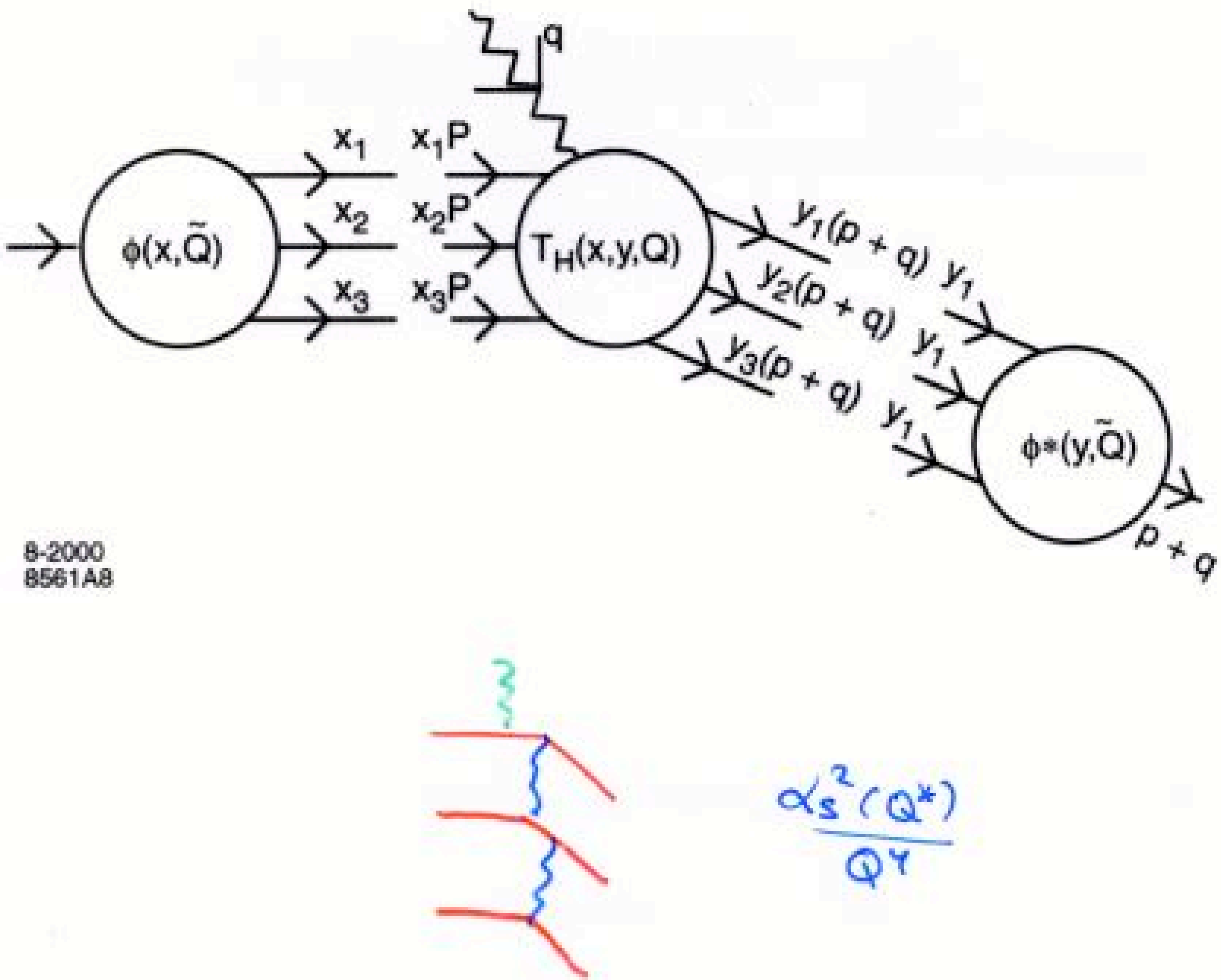
Scaling from PQCD or AdS/CFT

Hadron Distribution Amplitudes

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

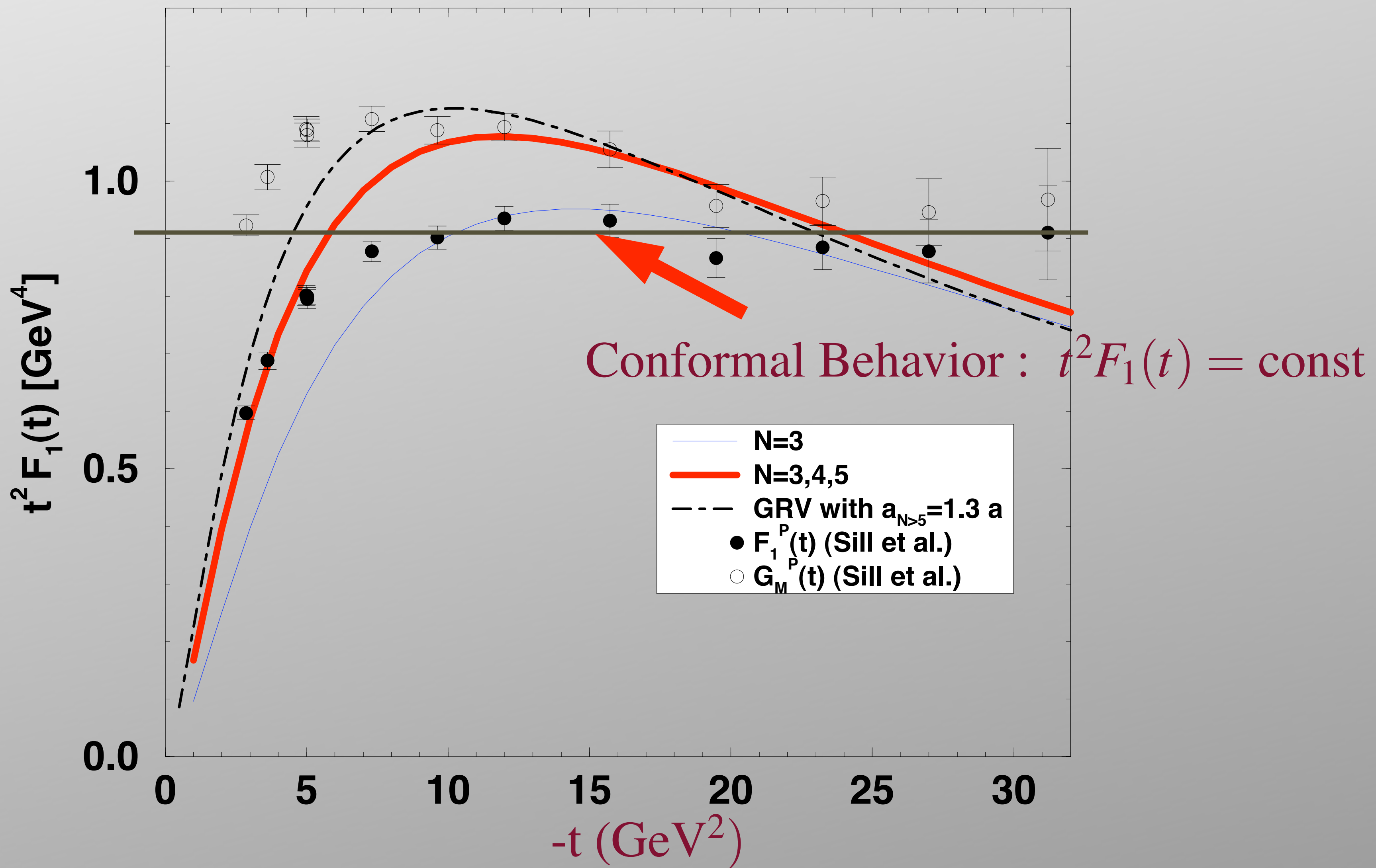
- Fundamental measure of valence wavefunction
- Gauge Independent (includes Wilson line)
- Evolution Equations, OPE
- Conformal Expansion
- Hadronic Input in Factorization Theorems

Lepage; SJB
Efremov, Radyuskin



q
x_1
x_1P
x_2
x_2P
x_3
x_3P
$\phi(x,\tilde{Q})$
$T_H(x,y,Q)$
$y_1(p+q)$ y_1
$y_2(p+q)$ y_1
$y_3(p+q)$ y_1
$\phi^*(y,\tilde{Q})$
$p+q$
8-2000
8561A8
$\frac{\alpha_s^2(Q^*)}{Q^4}$

Proton Form Factor



P. Kroll

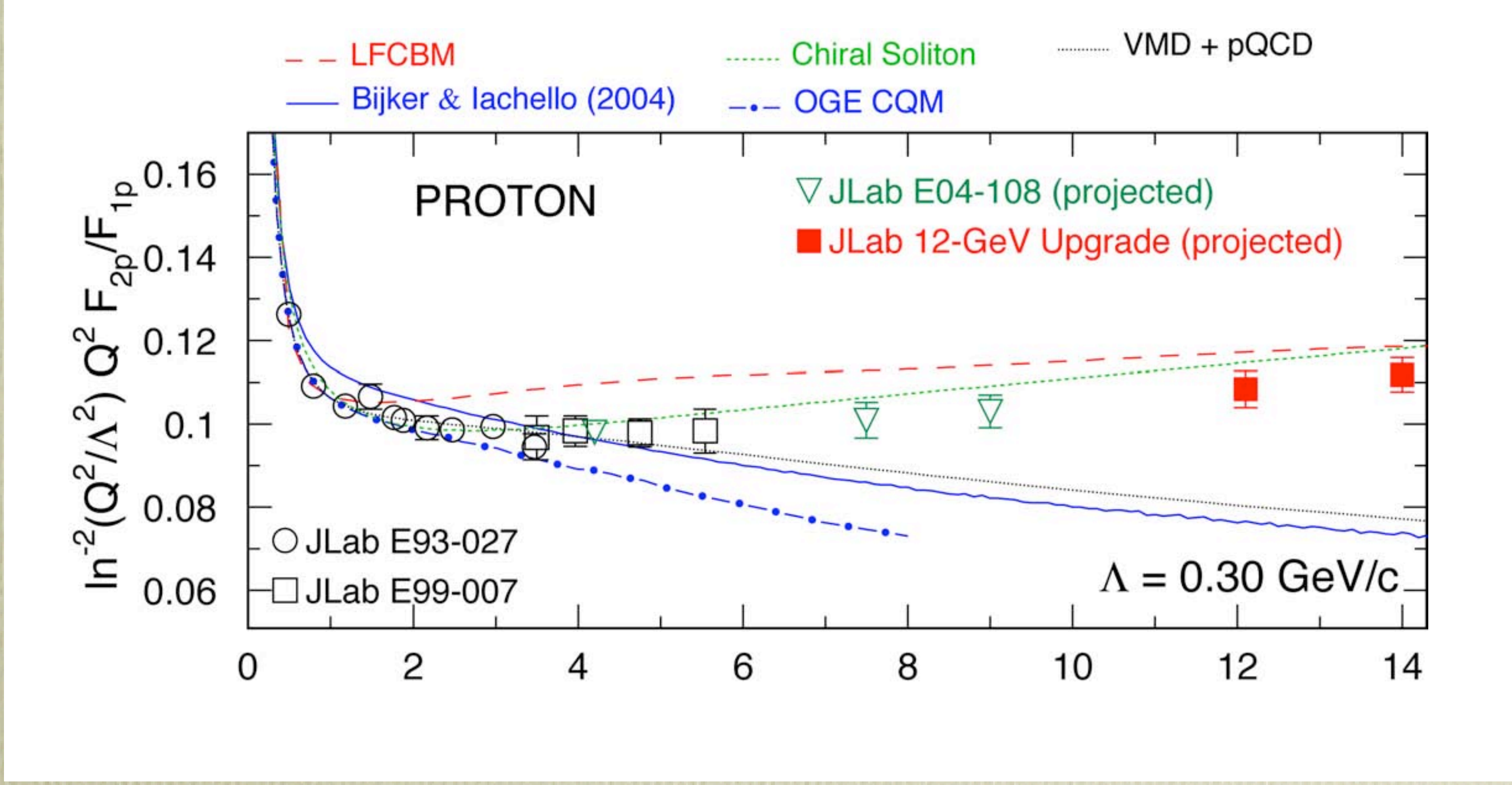
New Perspectives AdS/CFT

PQCD prediction:

Ji, Ma, Yuan

$$\frac{F_2(Q^2)}{F_1(Q^2)} \longrightarrow \frac{\Lambda^2_{QCD} \ln^2 Q^2}{Q^2}$$

Contribution from nonzero orbital angular momentum $L_z = \pm 1$



Counting Rules:

BF, MMT

$$q(x) \sim (1-x)^{2n_{spect}-1} \text{ for } x \to 1$$

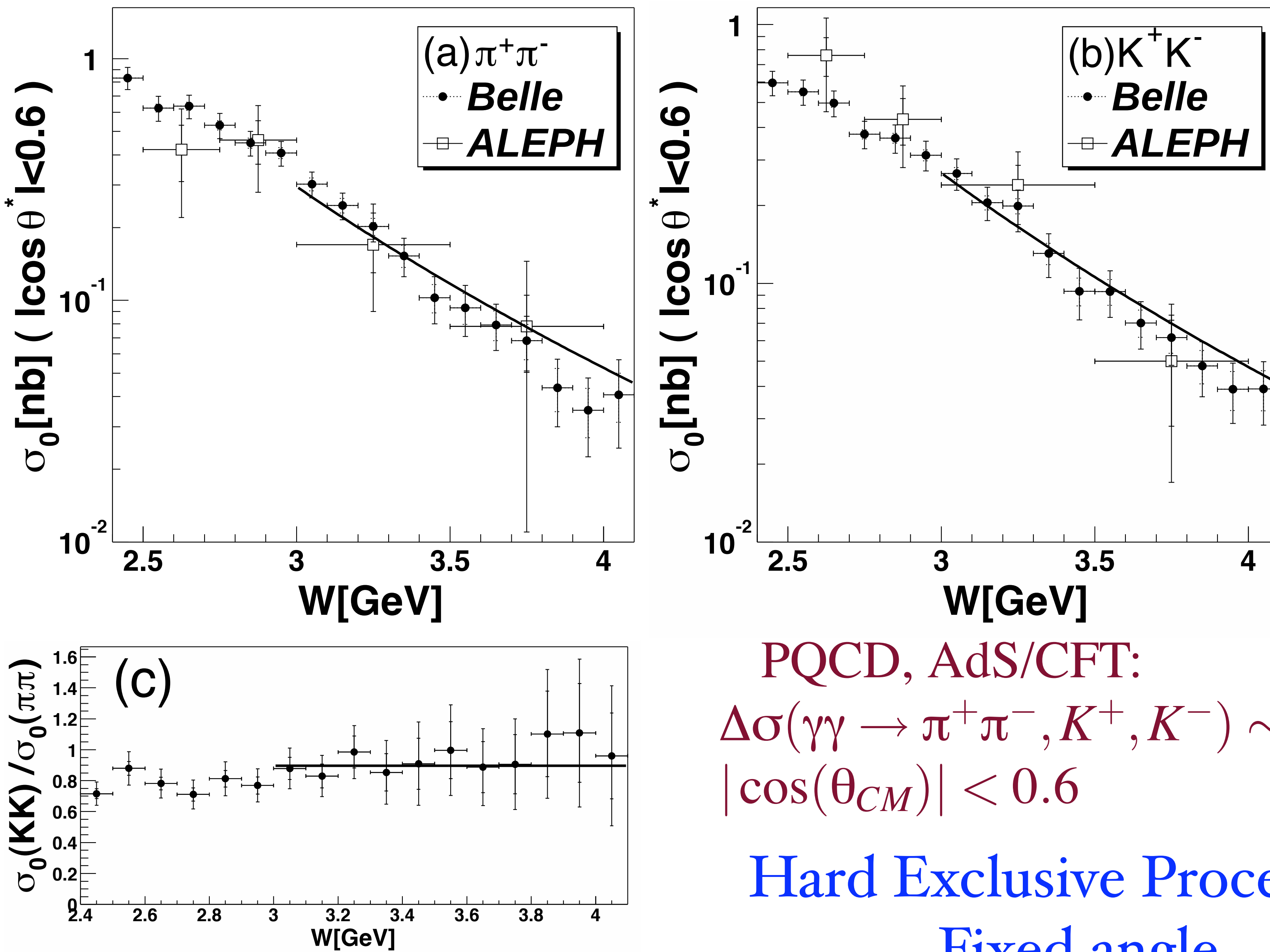
$$F(Q^2) \sim (\frac{1}{Q^2})^{(n-1)}$$

$$\frac{d\sigma}{dt}(AB \to CD) \sim \frac{F(t/s)}{s^{(n_{participants}-2)}}$$

$$n_{participants} = n_A + n_B + n_C + n_D$$

$$\frac{d\sigma}{d^3p/E}(AB \to CX) \sim F(\hat{t}/\hat{s}) \times \frac{(1-x_R)^{(2n_{spectators}-1)}}{(p_T^2)^{(n_{participants}-2)}}$$

Rules follow if theory is conformal at short distances



PQCD, AdS/CFT:

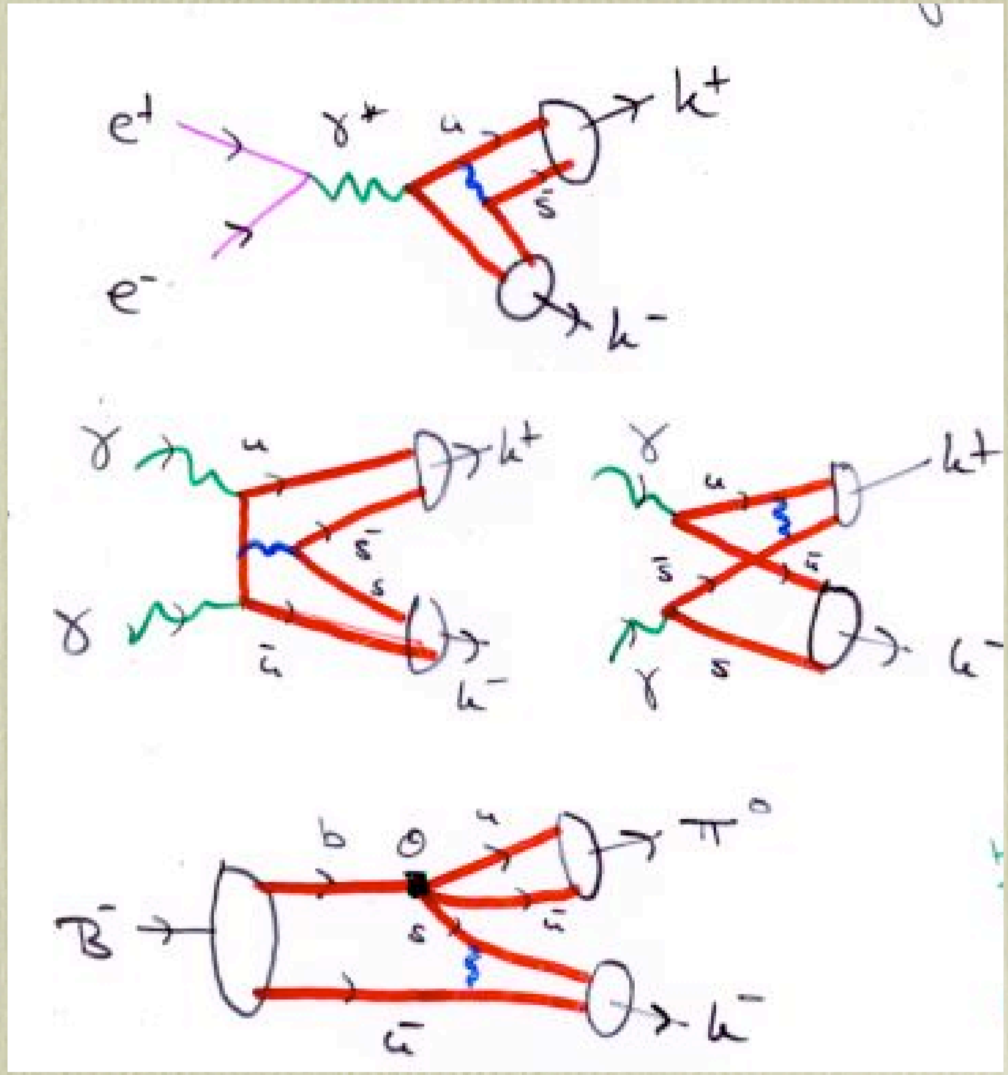
$\Delta\sigma(\gamma\gamma \to \pi^+\pi^-, K^+, K^-) \sim 1/W^6$

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

Hard Exclusive Processes: Fixed angle

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.

Common Ingredients:
Universal LFWFS, Distribution Amplitudes



$$F_M(s)=\frac{16\pi\alpha_s}{3s}\int_0^1 dx\,dy\frac{\phi_M^*(x,\tilde{Q}_x)\phi_M^*(y,\tilde{Q}_y)}{x(1-x)y(1-y)}$$

when $\phi_M(x,Q)=\phi_M(1-x,Q)$ is assumed.[7] Thus much of the dependence on $\phi(x,Q)$ can be removed from $\mathscr{M}_{\lambda\lambda'}$ by expressing it in terms of the meson form factor—i.e.,

$$\left.\begin{array}{l}\mathscr{M}_{++}\\ \mathscr{M}_{--}\end{array}\right\}=16\pi\alpha F_M(s)\left[\frac{\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\text{c.m.}}}\right],$$

$$\left.\begin{array}{l}\mathscr{M}_{+-}\\ \mathscr{M}_{-+}\end{array}\right\}=16\pi\alpha F_M(s)\left[\frac{\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\text{c.m.}}}+2\langle e_1e_2\rangle g[\theta_{\text{c.m.}};\phi_M]\right],$$

up to corrections of order α_s and m^2/s. Now the only dependence on ϕ_M, and indeed the only unknown quantity, is in the θ-dependent factor

$$g[\theta_{\text{c.m.}};\phi_M]=\frac{\displaystyle\int_0^1 dx\,dy\frac{\phi_M^*(x,\tilde{Q})\phi_M^*(y,\tilde{Q})}{x(1-x)y(1-y)}\,\frac{a[y(1-y)+x(1-x)]}{a^2-b^2\cos^2\theta_{\text{c.m.}}}}{\displaystyle\int_0^1 dx\,dy\frac{\phi_M^*(x,\tilde{Q})\phi_M^*(y,\tilde{Q})}{x(1-x)y(1-y)}}.$$

The spin-averaged cross section follows immediately from these expressions

$$\frac{d\sigma}{dt}=\frac{2}{s}\frac{d\sigma}{d\cos\theta_{\text{c.m.}}}=\frac{1}{16\pi s^2}\frac{1}{4}\sum_{\lambda\lambda'}|\mathscr{M}_{\lambda\lambda'}|^2$$

$$=16\pi\alpha^2\left|\frac{F_M(s)}{s}\right|^2\left\{\frac{\langle(e_1-e_2)^2\rangle^2}{(1-\cos^2\theta_{\text{c.m.}})^2}+\frac{2\langle e_1e_2\rangle\langle(e_1-e_2)^2\rangle}{1-\cos^2\theta_{\text{c.m.}}}g[\theta_{\text{c.m.}};\phi_M]\right.$$

$$\left.+\,2\langle e_1e_2\rangle^2g^2[\theta_{\text{c.m.}};\phi_M]\right\}.$$

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

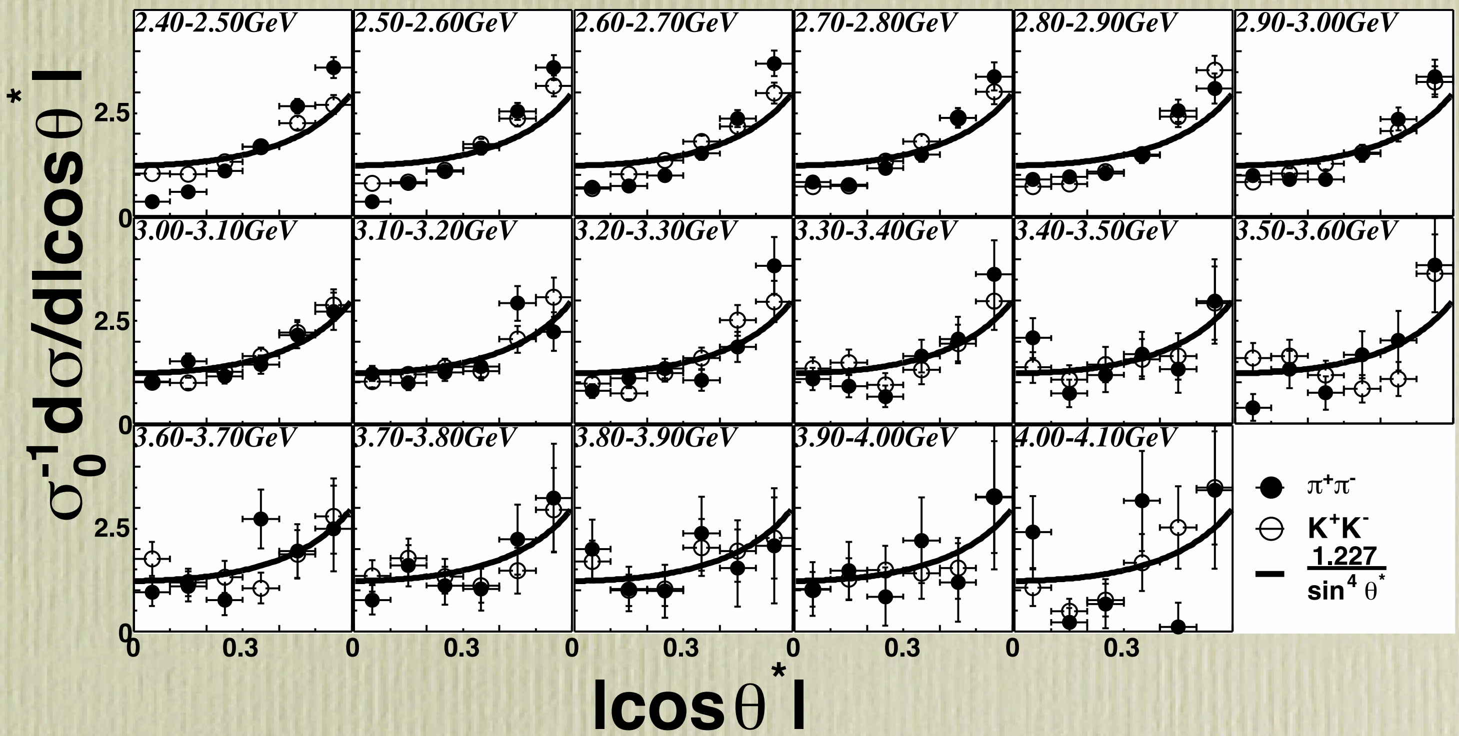


Fig. 4. Angular dependence of the cross section, $\sigma_0^{-1}d\sigma/d|\cos\theta^*|$, for the $\pi^+\pi^-$(closed circles) and K^+K^-(open circles) processes. The curves are $1.227 \times \sin^{-4}\theta^*$. The errors are statistical only.

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

Critical Test of PQCD vs. "Handbag"

sjb, gpl

$$\frac{\Delta\sigma(\gamma\gamma \to \pi^0\pi^0)}{\Delta\sigma(\gamma\gamma \to \pi^+\pi^-)}$$

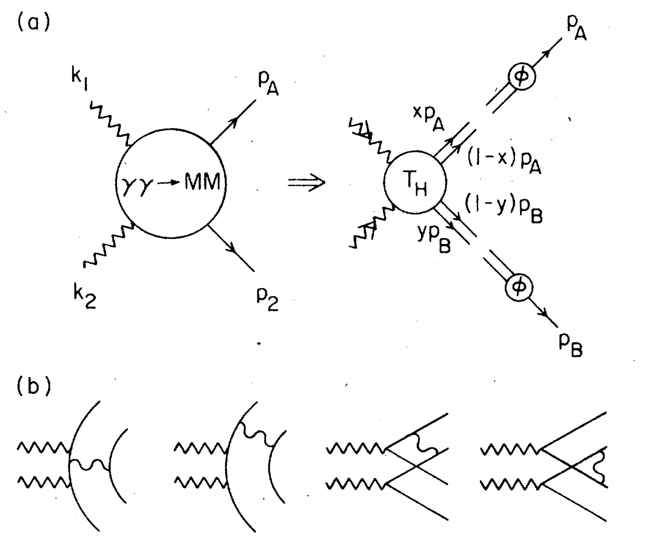


FIG. 1. (a) Factorized structure of the $\gamma\gamma \to M\overline{M}$ amplitude in QCD at large momentum transfer. The T_H amplitude is computed with quarks collinear with the outgoing mesons. (b) Diagram contributing to T_H ($\gamma\gamma \to M\overline{M}$) to lowest order in α_s.

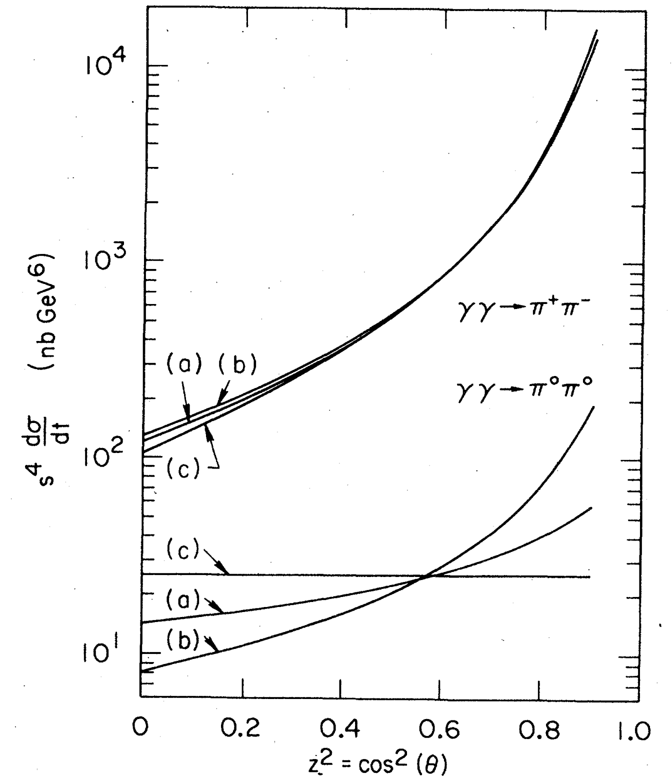


FIG. 3. QCD predictions for $\gamma\gamma \to \pi\pi$ to leading order in QCD. The results assume the pion-form-factor parametrization $F_\pi(s) \sim 0.4\ \mathrm{GeV}^2/s$. Curves (a), (b), and (c) correspond to the distribution amplitudes $\phi_M = x(1-x)$, $[x(1-x)]^{1/4}$, and $\delta(x-\frac{1}{2})$, respectively. Predictions for other helicity-zero mesons are obtained by multiplying with the scale constants given in Table I.

Handbag model (Diehl, Kroll et al) neglects $e_1 \times e_2$ cross terms

$\gamma\gamma \to \pi^+\pi^-$

$\gamma\gamma \to \pi^0\pi^0$

Critical discriminant: Handbag vs.PQCD

$\gamma\gamma \to K^+K^-$

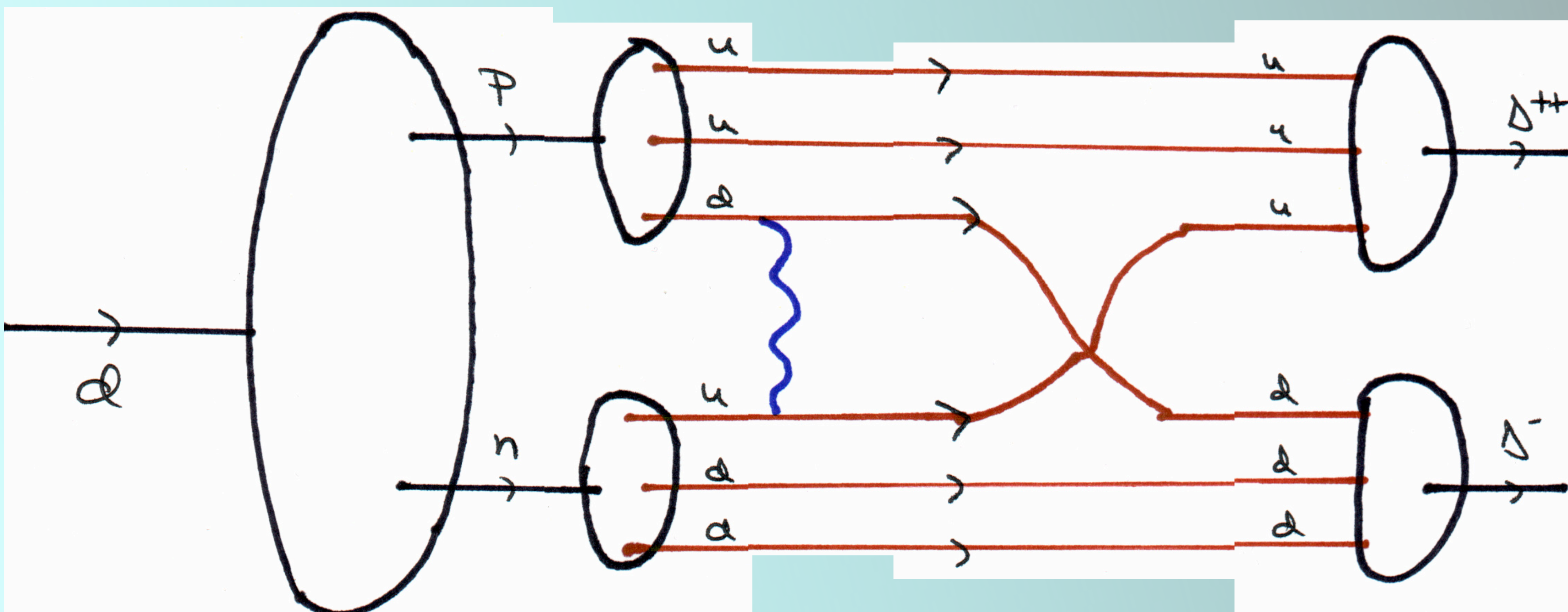
$\gamma\gamma \to p\bar{p}$

$\gamma^*\gamma \to H\overline{H}$ Timelike DVCS!

Hidden Color in QCD

- 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

Structure of Deuteron in QCD



Hidden Color Fock State

Delta-Delta Fock State

Evolution Equation for Deuteron

- Distribution Amplitude 5 x 1 Column Matrix
- n p at large distances
- Equal weights at short distances
- Hidden Color: First principle prediction of QCD

G.P. Lepage, C. R. Ji, SJB

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

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

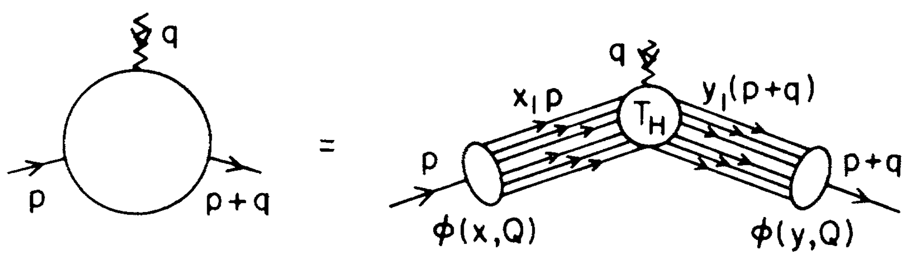


FIG. 1. The general structure of the deuteron form factor at large Q^2.

ref: Lepage, Ji, sjb

QCD Prediction for Deuteron Form Factor

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

Chertok, Lepage, Ji, sjb

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

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

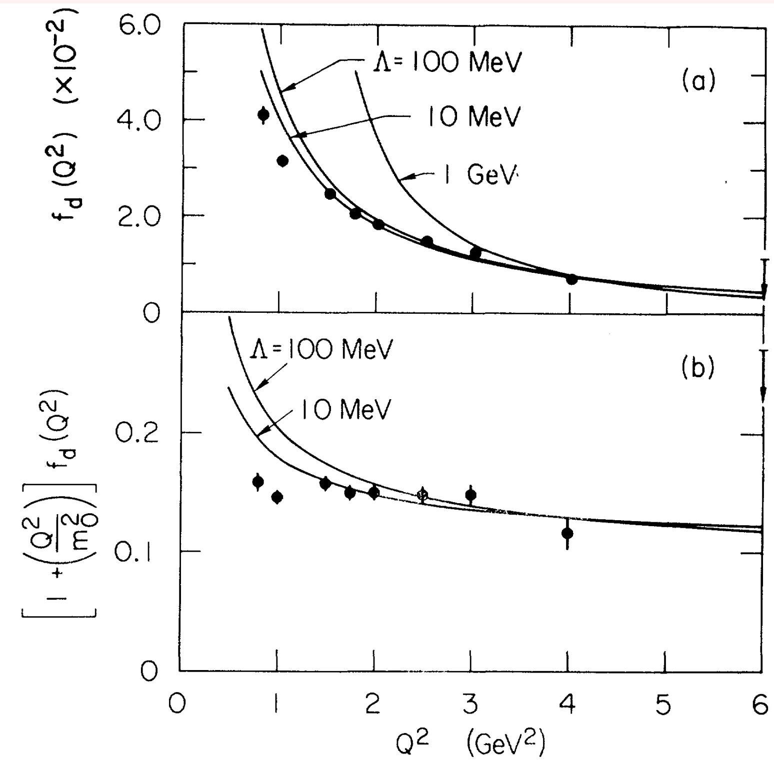
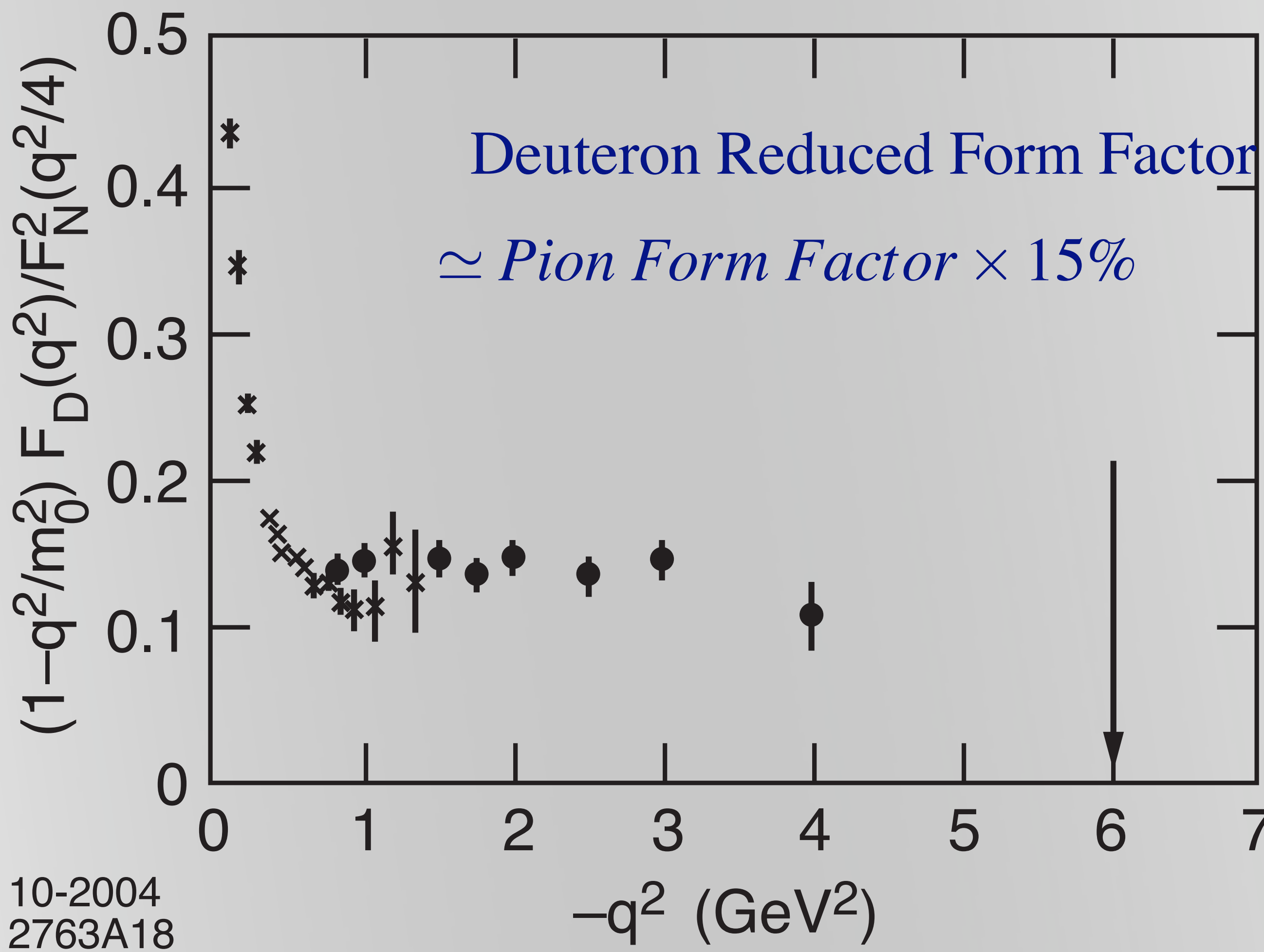


FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$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



Resembles pion form factor times 15%

15% Hidden Color in the Deuteron

Hidden Color of Deuteron

Deuteron six-quark state has five color - singlet configurations, only one of which is n-p.

Asymptotic Solution has Expansion

$$\psi_{[6]\{33\}} = \left(\frac{1}{9}\right)^{1/2} \psi_{NN} + \left(\frac{4}{45}\right)^{1/2} \psi_{\Delta\Delta} + \left(\frac{4}{5}\right)^{1/2} \psi_{CC}$$

Look for strong transition to Delta-Delta

Counting Rules:

BF, MMT

$q(x) \sim (1-x)^{2n_{spect}-1}$ for $x \to 1$

$F(Q^2) \sim (\frac{1}{Q^2})^{(n-1)}$

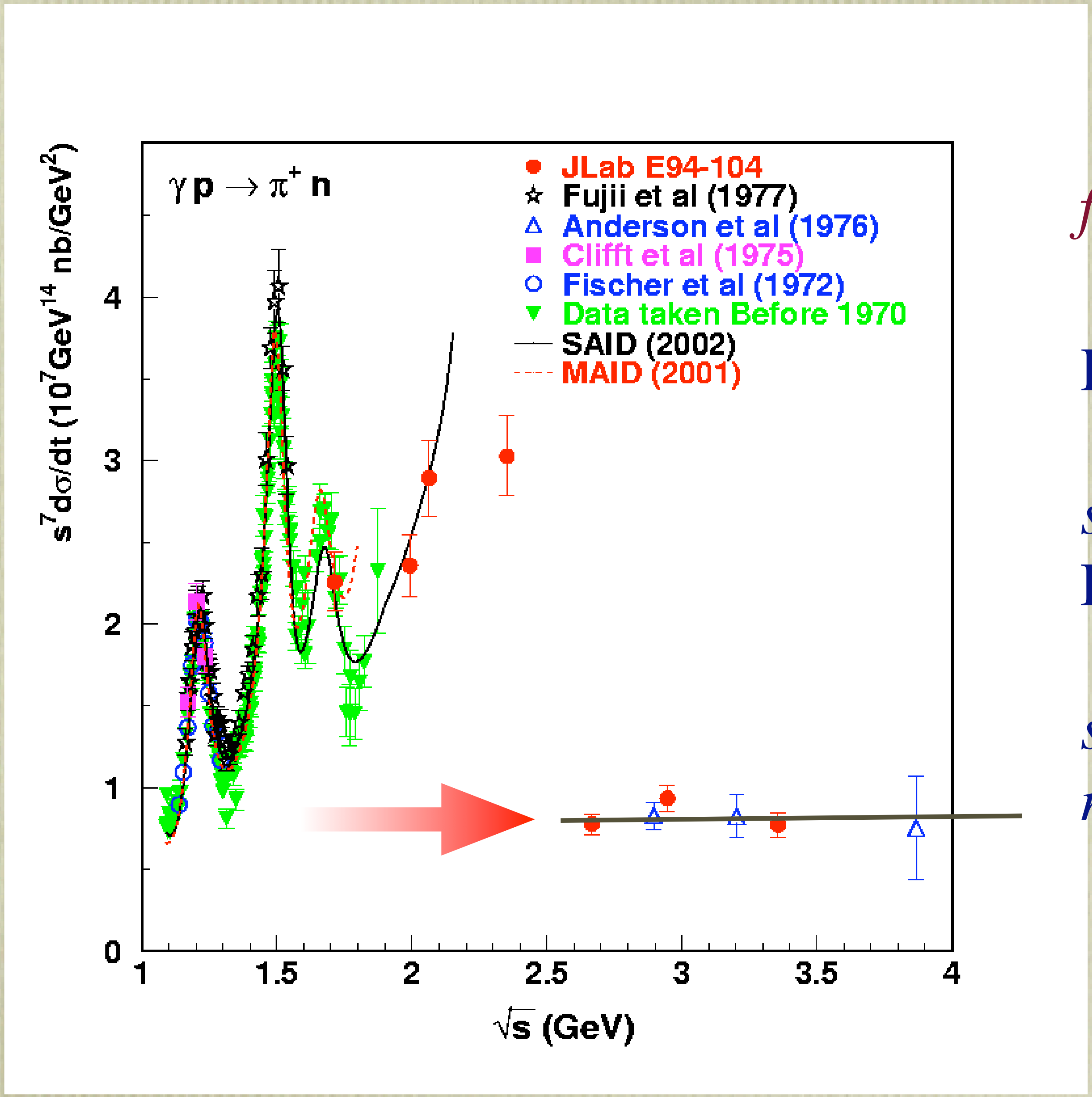
$\frac{d\sigma}{dt}(AB \to CD) \sim \frac{F(t/s)}{s^{(n_{participants}-2)}}$

$n_{participants} = n_A + n_B + n_C + n_D$

$\frac{d\sigma}{d^3p/E}(AB \to CX) \sim F(\hat{t}/\hat{s}) \times \frac{(1-x_R)^{(2n_{spectators}-1)}}{(p_T^2)^{(n_{participants}-2)}}$

Rules follow if theory is conformal at short distances

Test of PQCD Scaling



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

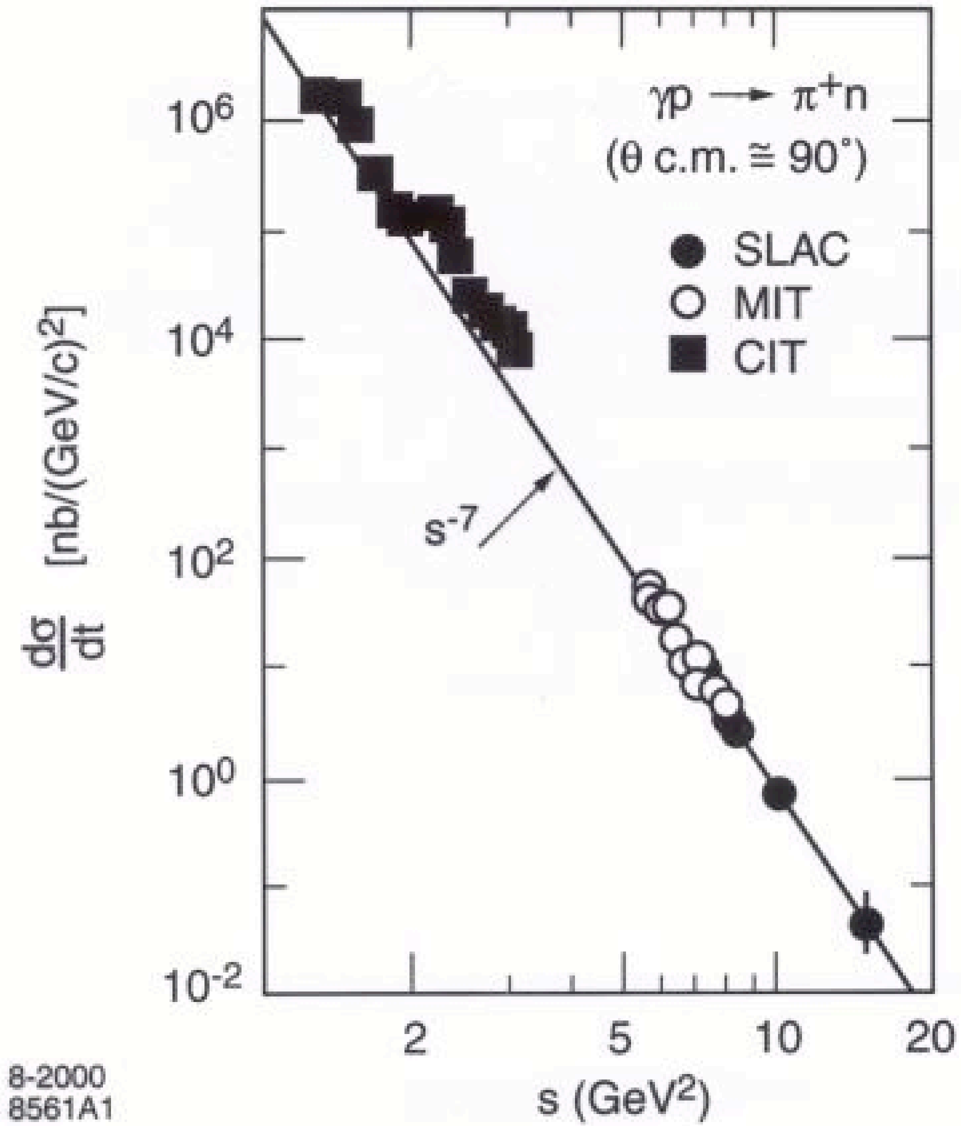
fixed θ_{CM} scaling

PQCD and AdS/CFT:

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

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

Possible substructure at strangeness and charm thresholds



γp → π⁺n
(θ c.m. ≅ 90°)
SLAC
MIT
CIT
s-7
10^6
10^4
10^2
10^0
10^-2
dσ/dt [nb/(GeV/c)^2]
2
5
10
20
s (GeV^2)
8-2000
8561A1

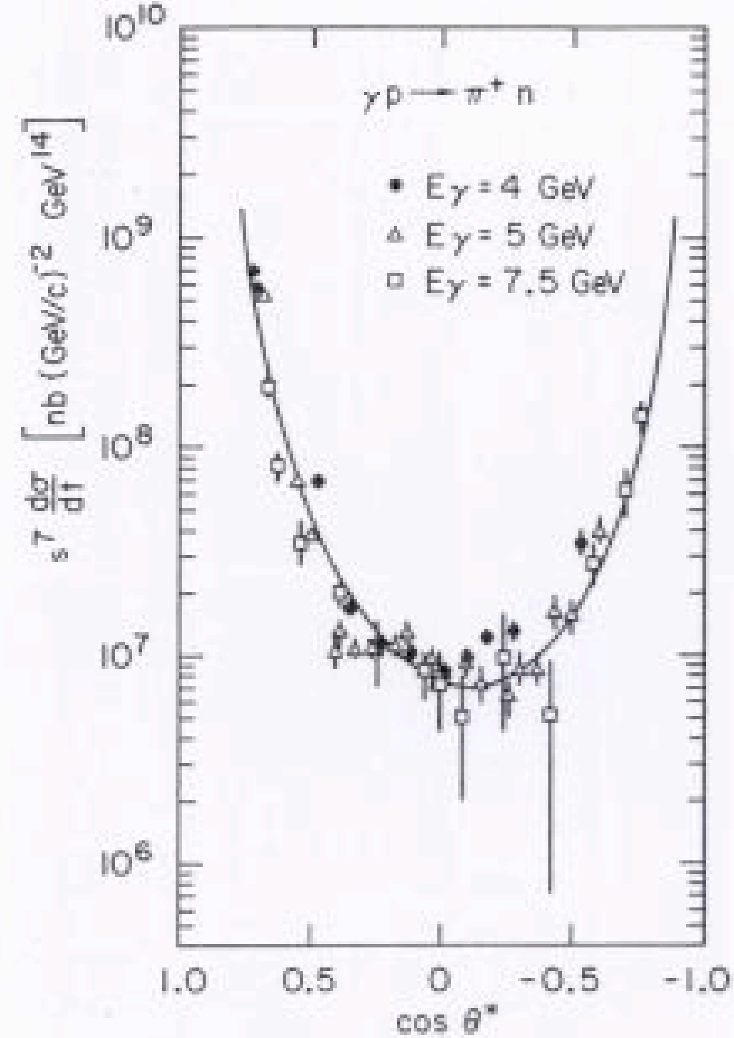
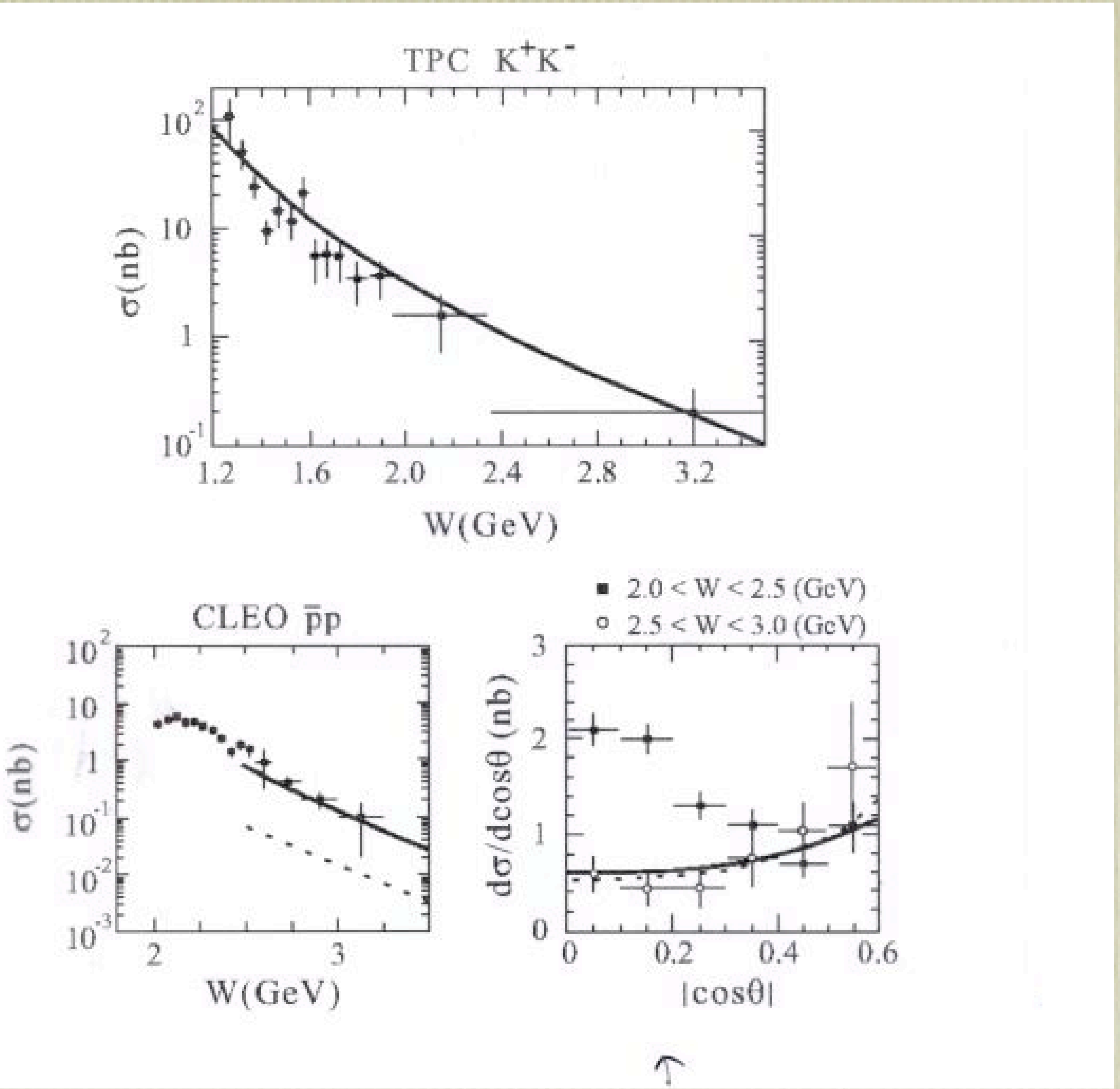


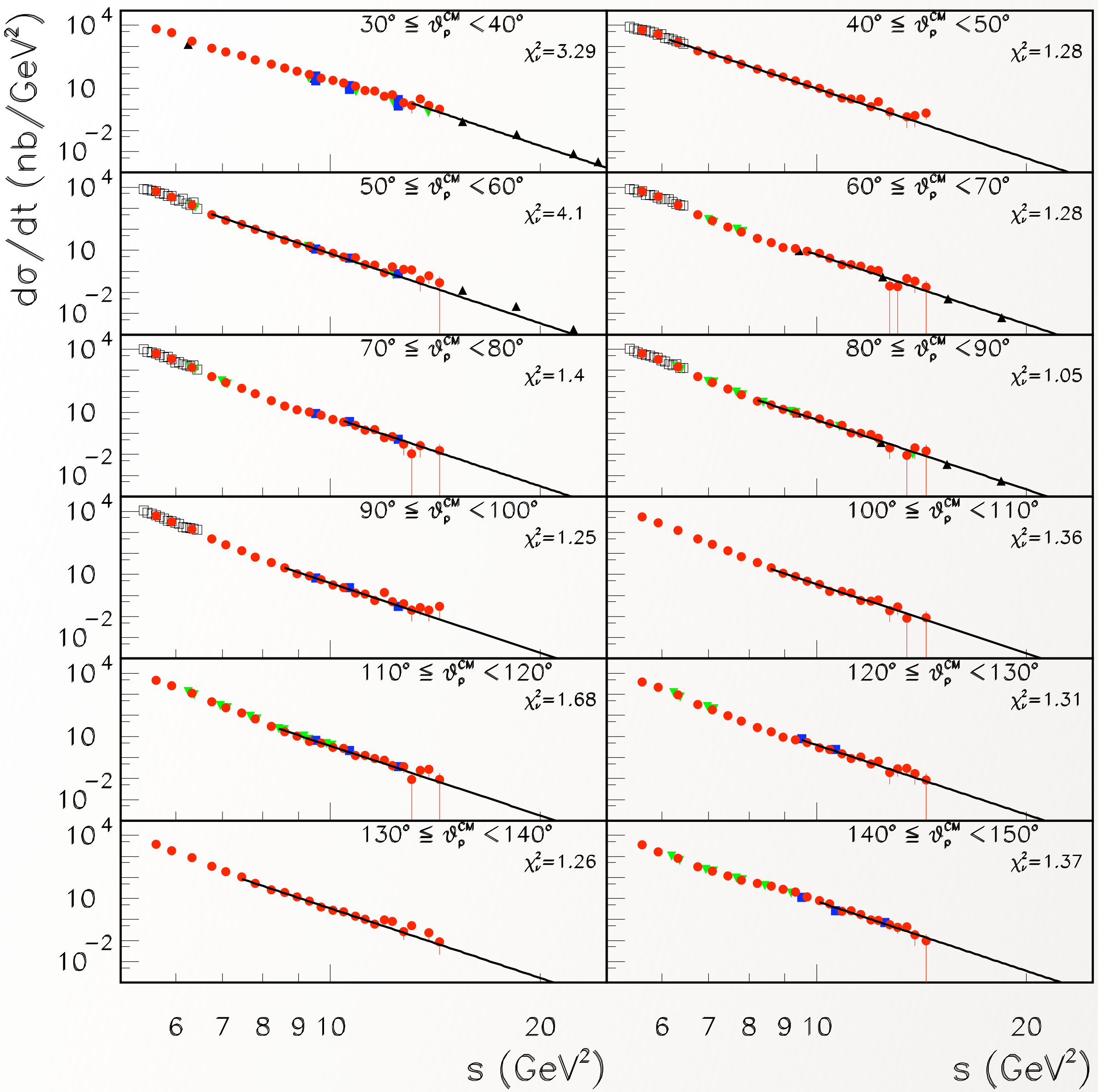
FIG. 6. $s^7 d\sigma/dt$ versus $\cos\theta^*$ for the reaction $\gamma p \to \pi^+ n$. The solid line shows the empirical function $(1-z)^{-5}(1+z)^{-4}$ where ($z = \cos\theta^*$), which is an empirical fit to the angular distribution.



Two Regimes

New Perspectives AdS/CFT

Deuteron Photodisintegration & Dimensional Counting Rules



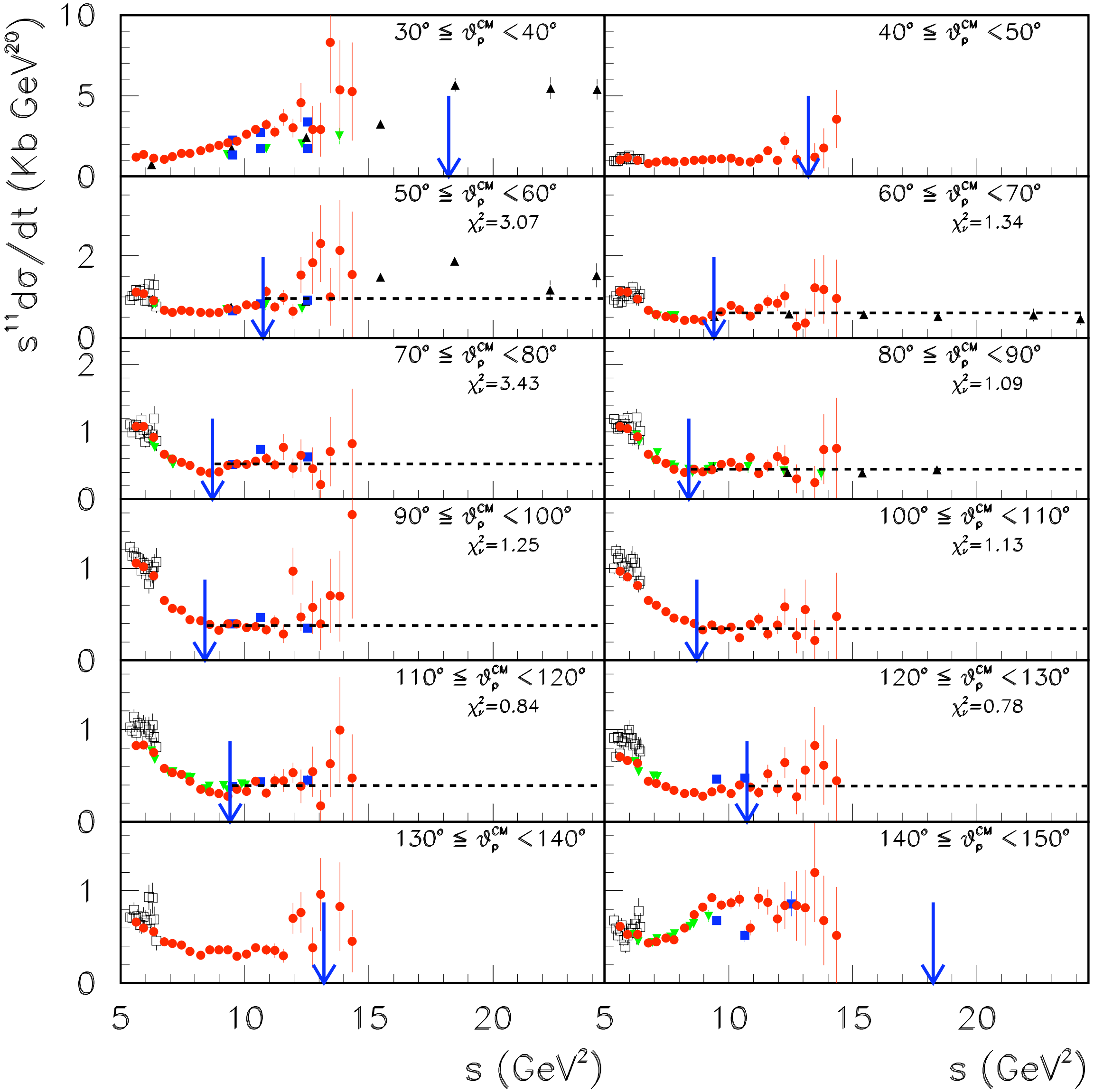
PQCD and AdS/CFT:

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

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

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

Deuteron-Photodisintegration



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

- 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

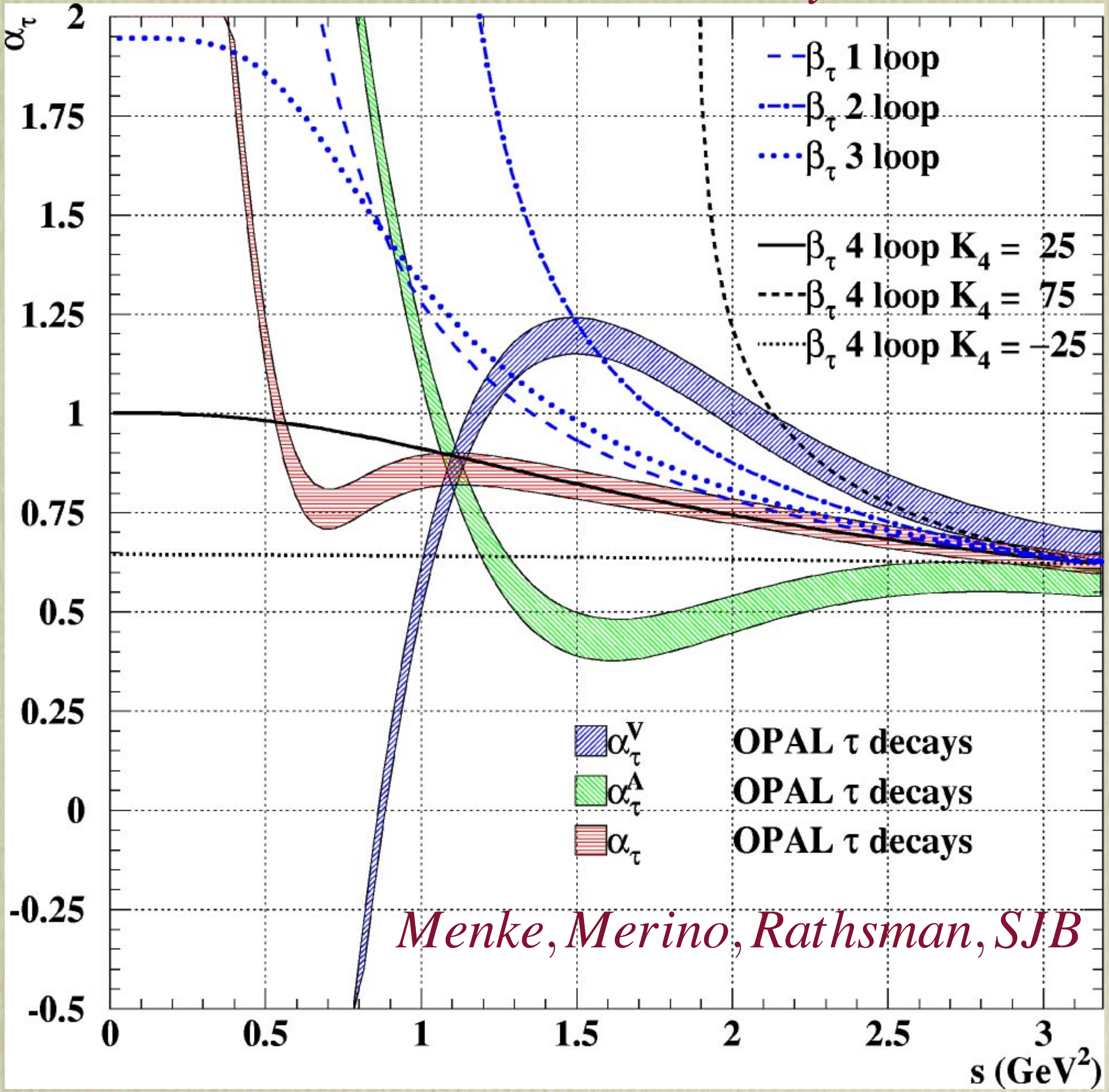
Why do dimensional counting rules work so well?

- PQCD predicts powers of α_s, logs, pinch contributions
- QCD coupling evaluated in IR regime!
- Conformal behavior at short distances, confinement at large distances: AdS/CFT

QCD Coupling

- What is the behavior of $\alpha_s(Q)$ at low momentum?
- QED, EW -- define coupling from observable, predict other observables
- How can DIS give information on α_s?

QCD Effective Coupling from *hadronic τ decay*



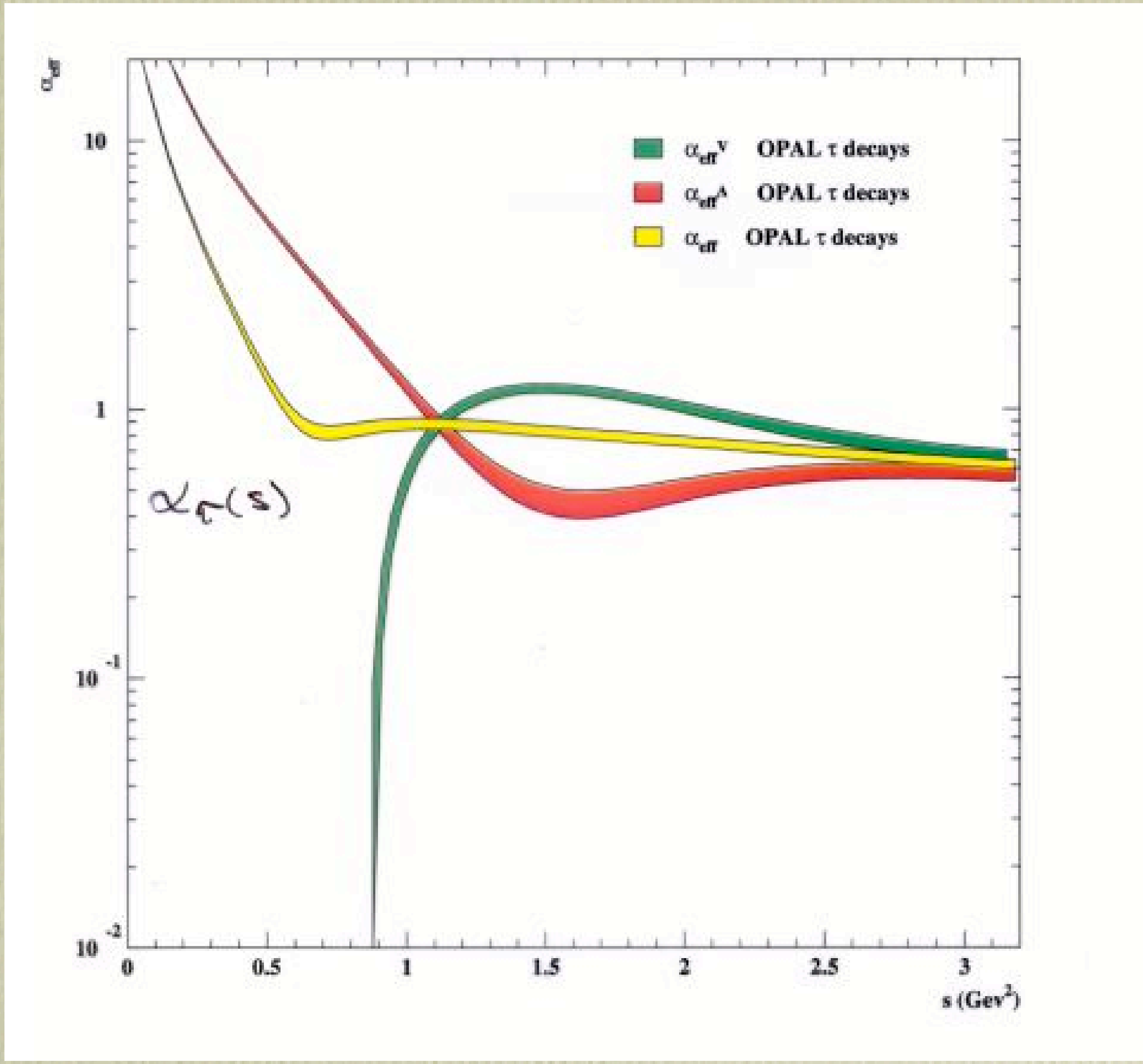
New Perspectives AdS/CFT

Define QCD Coupling from Observable

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

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

Relate observable to observable at commensurate scales



Menke, Merino, Rathsman, SJB

- Define effective charge (Grunberg)

$$\int_0^1 dx[g_{1n}(x,Q^2)-g_{1p}(x,Q^2)] \equiv \frac{g_A}{6}(1-\frac{\alpha_{g_1}(Q^2)}{\pi})$$

- $\frac{d}{dQ^2}\alpha_{g_1}(Q^2) = \beta(Q^2)$:
standard QCD evolution

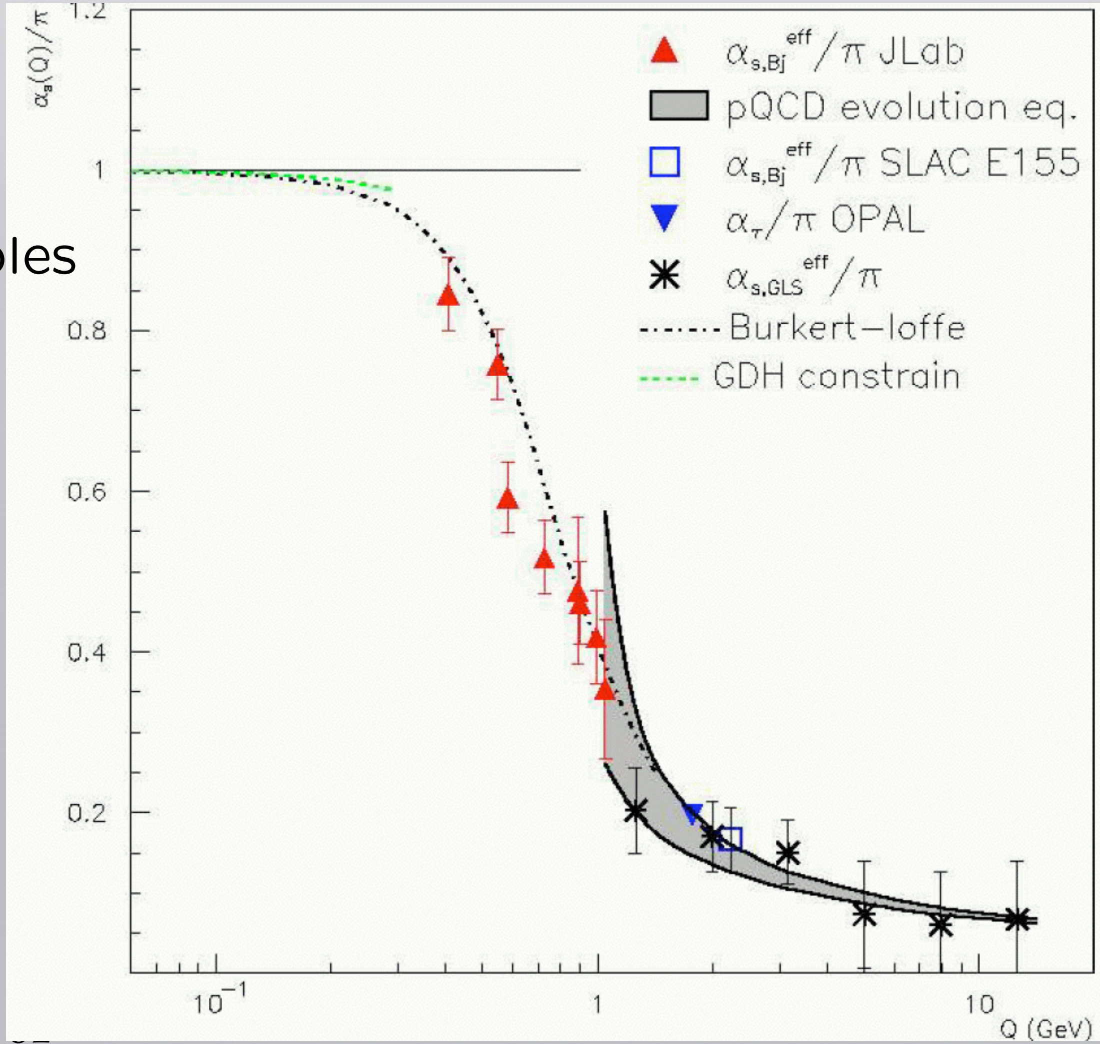
- β_0, β_1 universal

- Connect $\alpha_{g_1}(Q^2)$ to other observables via Commensurate Scale Relations

- Eliminate $\alpha_{\overline{MS}}$

A. Deur, et al

Preliminary



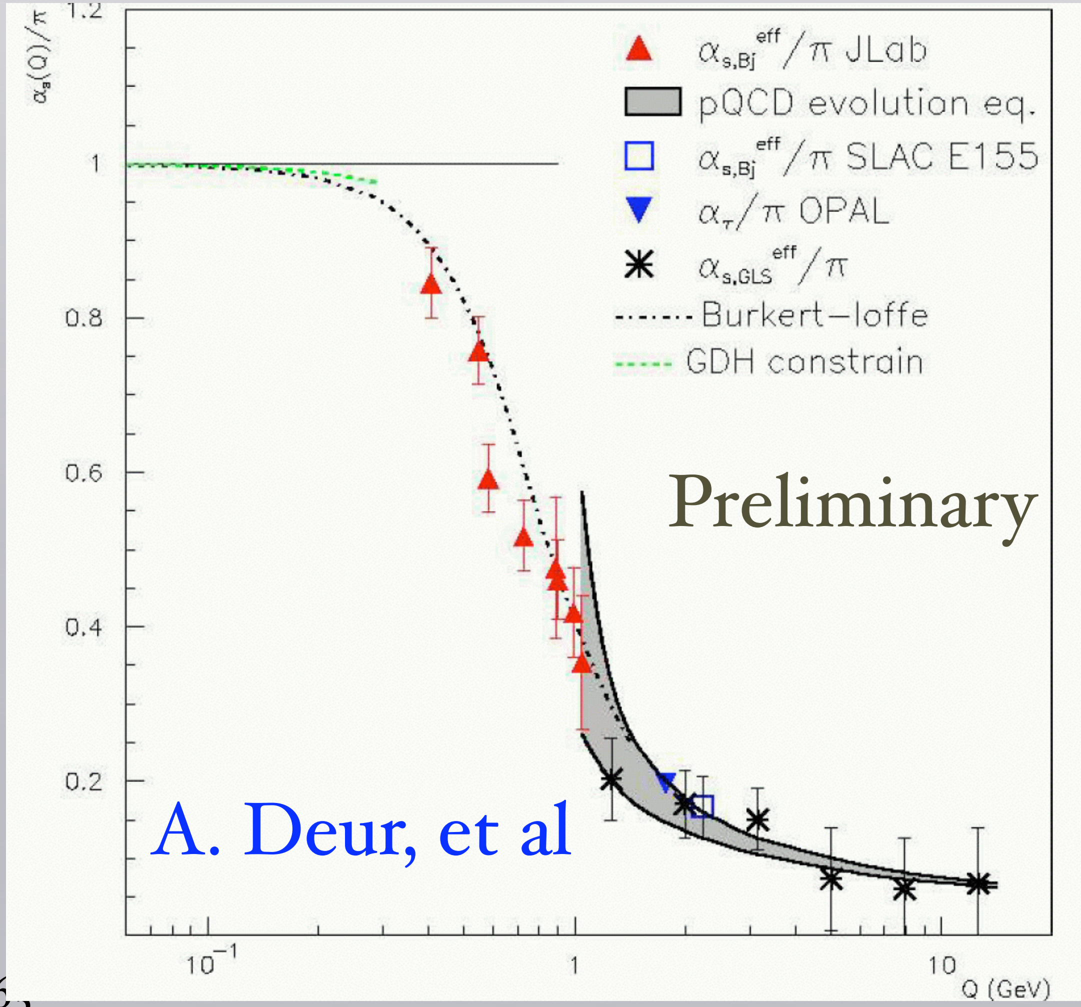
- Generalized Crewther Relation

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

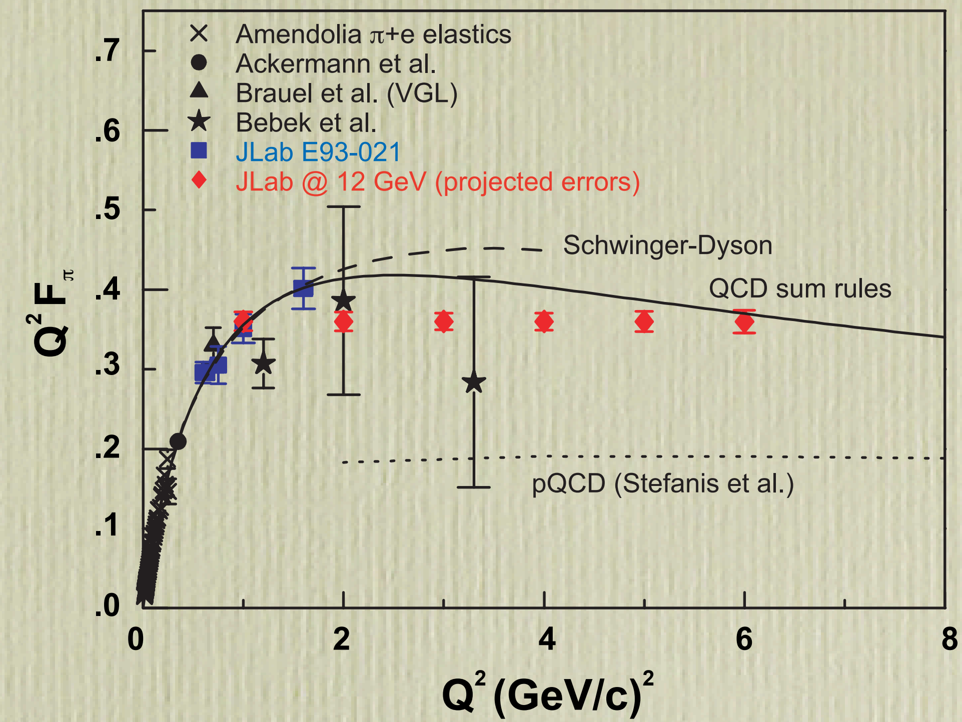
at $s^* = CQ^2$.

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

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



Spacelike Pion Form Factor



lowest order PQCD

Resummation?

Figure 11: Projected measurements of the pion electromagnetic form factor, $F_\pi(Q^2)$, made possible by the proposed 12 GeV Upgrade. Also shown are various model predictions for its behavior in the region $Q^2 \sim$ few GeV^2. Perturbative QCD predicts $F_\pi \sim 1/Q^2$ for $Q^2 \to \infty$.

PQCD LO Normalization depends on

value of $\alpha_s(Q^2)$ at small $Q^{*2} = (1/20)\ Q^2$!

New Perspectives AdS/CFT

In practice: QCD: Approximately conformal

Phenomenological and theoretical evidence:

$\alpha_s(Q^2)$: IR Fixed Point – nearly constant in infrared

Alkhofer, et al.

Typical BLM scale (Pion Form Factor)

$\overline{Q}^2 = e^{-5/3} < (1-x)(1-y) > Q^2 \sim \frac{Q^2}{20}$

Running coupling typically evaluated at modest scales.

$$F_\pi = 16\pi \frac{f_\pi^2 \ \alpha_s(\overline{Q}^2)}{Q^2}$$

C. Ji, Robertson, Pang, SJB

Conformal Symmetry $\mathcal{L}_{classical}$ renormalizable theory

* Poincaré plus

* dilation $[x^\mu \to \lambda x^\mu]$

* conformal transformation $\left[\text{inversion}\left(x^\mu \to -\frac{x^\mu}{x^2}\right)\right.$

$\left.\otimes \text{ translation } \otimes \text{ inversion}\right]$

broken by

masses

quantum loops : running coupling, ...

For $\beta = \frac{d\alpha_s(Q^2)}{d \ln Q^2} = 0$ (e.g. fixed point theory)

* PQCD $\Rightarrow$ conformal theory

all orders proof : G. Parisi , PL 39B, 643 (1972)

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

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
- Apply AdS/CFT

Near-Conformal Behavior of LFWFs Lead to PQCD Scaling Laws

- Bjorken Scaling of DIS
- Counting Rules of Structure Functions at large x
- Dimensional Counting Rules for Exclusive Processes and Form Factors
- Conformal Relations between Observables
- No Renormalization Scale Ambiguity

Why is large x Important?

- Sensitive to details of hadronic structure valence, sea quark, and gluon distributions

- Detailed predictions from PQCD and AdS/CFT

- Helicity Retention & Spectator Counting Rules

- DGLAP must be modified: **quenched** at $x \to 1$

- Measure behavior of proton LFWF at large x_{bj}

- Strong function of quark spin projection relative to proton spin projection

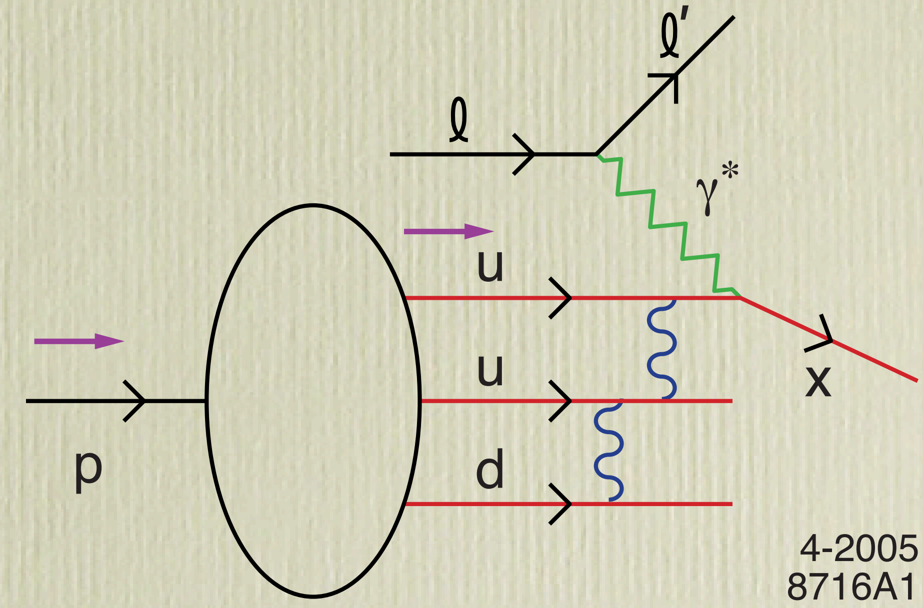
Farrar, Jackson
Gunion
Lepage, SJB
Burkardt, Schmidt, SJB
Ji, Ma, Yuan

PQCD:

$q(x) \sim (1-x)^3 \qquad S^z_q = S^z_p$

$q(x) \sim (1-x)^5 \qquad S^z_q = -S^z_p$

Traditional PQCD Method
Iterate QCD Kernel



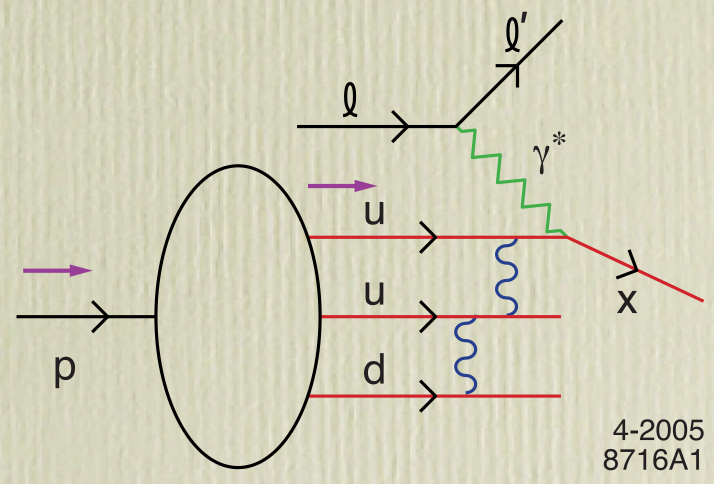
Why is PQCD Relevant?

The spectator system has a timelike mass $(P-k)^2 = M^2_{spect} > 0$

The struck quark is far off-shell:

$$k_F^2 - m^2 = x[M_p^2 - \mathcal{M}^2] \simeq -\frac{k_\perp^2 + M^2_{spect}}{1-x}$$

Thus $k_F^2 \rightarrow -\infty$ for $x_{bj} \rightarrow 1$.



Lepage, SJB

PQCD Analysis at LO

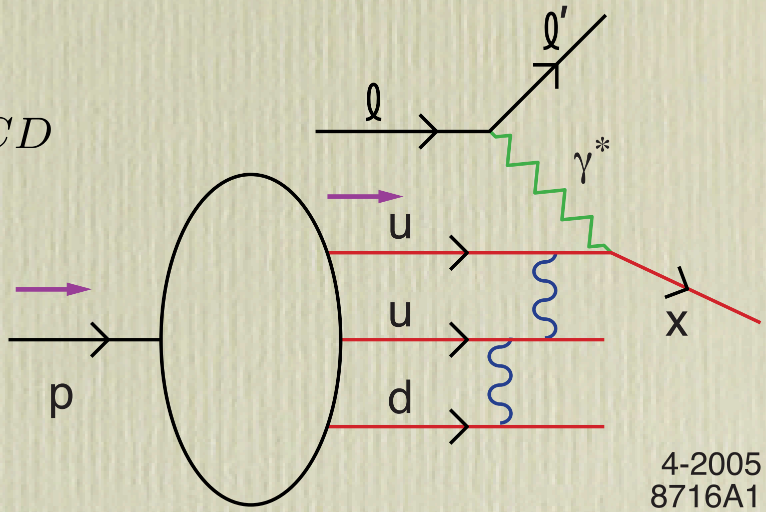
- Four hard propagators, two compensated by numerator factors

- PQCD interactions valid at $|k^2| > \Lambda^2_{QCD}$
Same regime as DGLAP

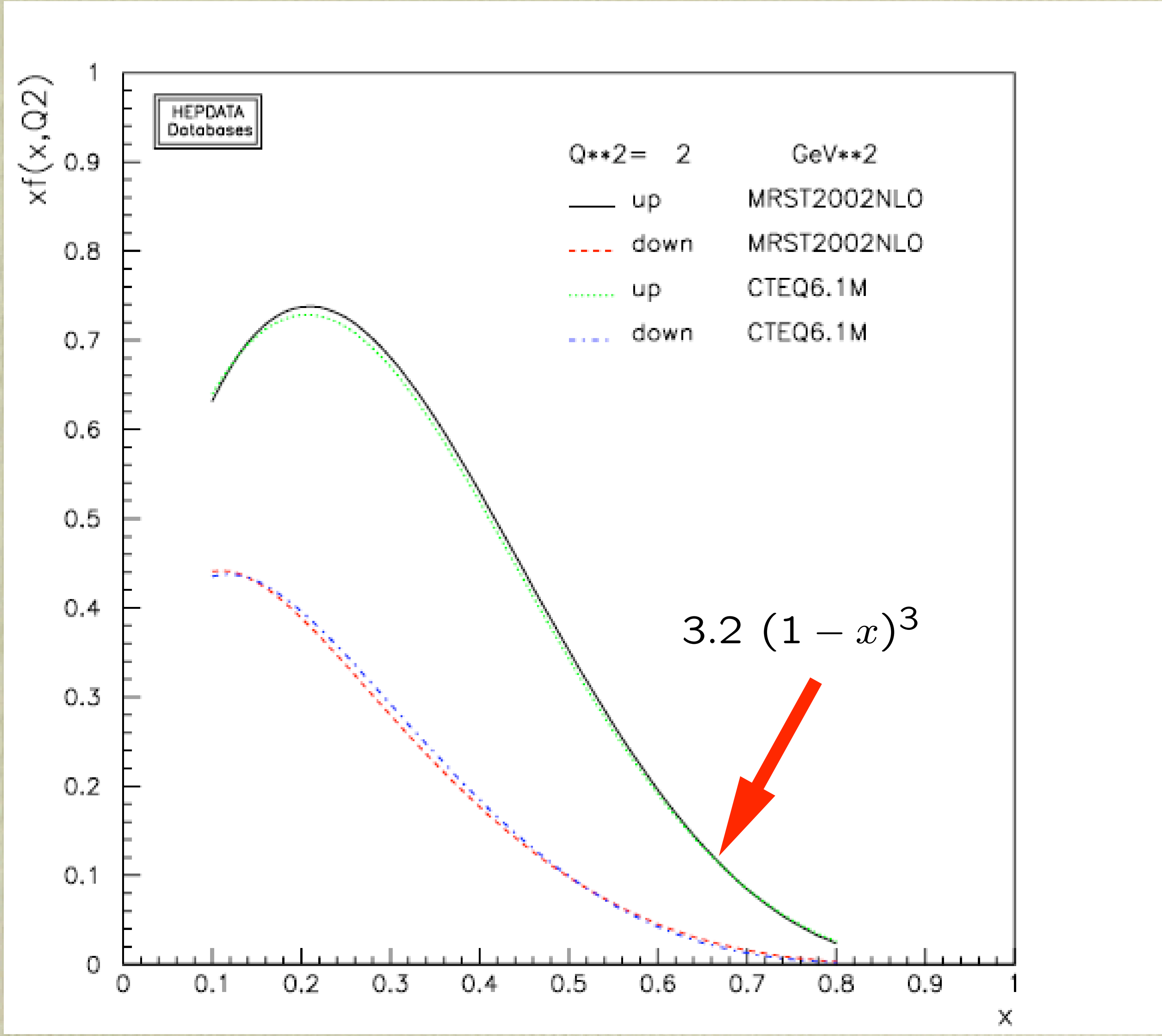
- Cannot postpone PQCD validity

- Duality with Exclusive Channels
at fixed $W^2 = \frac{(1-x)Q^2}{x}$ for $\sigma_T(x, Q^2), \sigma_L(x, Q^2)$

- Suppression at $x \to 1$ if $L_z \neq 0$.

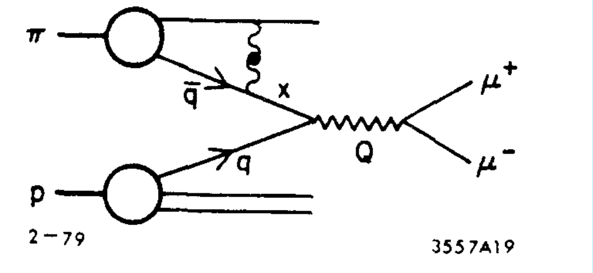


Lepage, SJB


HEPDATA
Databases
Q**2= 2 GeV**2
up MRST2002NLO
down MRST2002NLO
up CTEQ6.1M
down CTEQ6.1M
xf(x,Q2)
x
$3.2\ (1-x)^3$

Higher Twist Essential at x → 1

Valence quark distributions in the pion



$q^{\pm}(x) \sim (1-x)^2$

Higher twist term:

$\frac{C}{Q^2}$ (longitudinal polarization)

Dominates Drell-Yan reactions at large x_F

$\frac{d\sigma}{dx_F d\cos\theta}(\pi p \to \ell^+\ell^- X)$

$\propto (1-x_F)^2(1+\cos^2\theta) + \frac{C}{Q^2}(\sin^2\theta)$

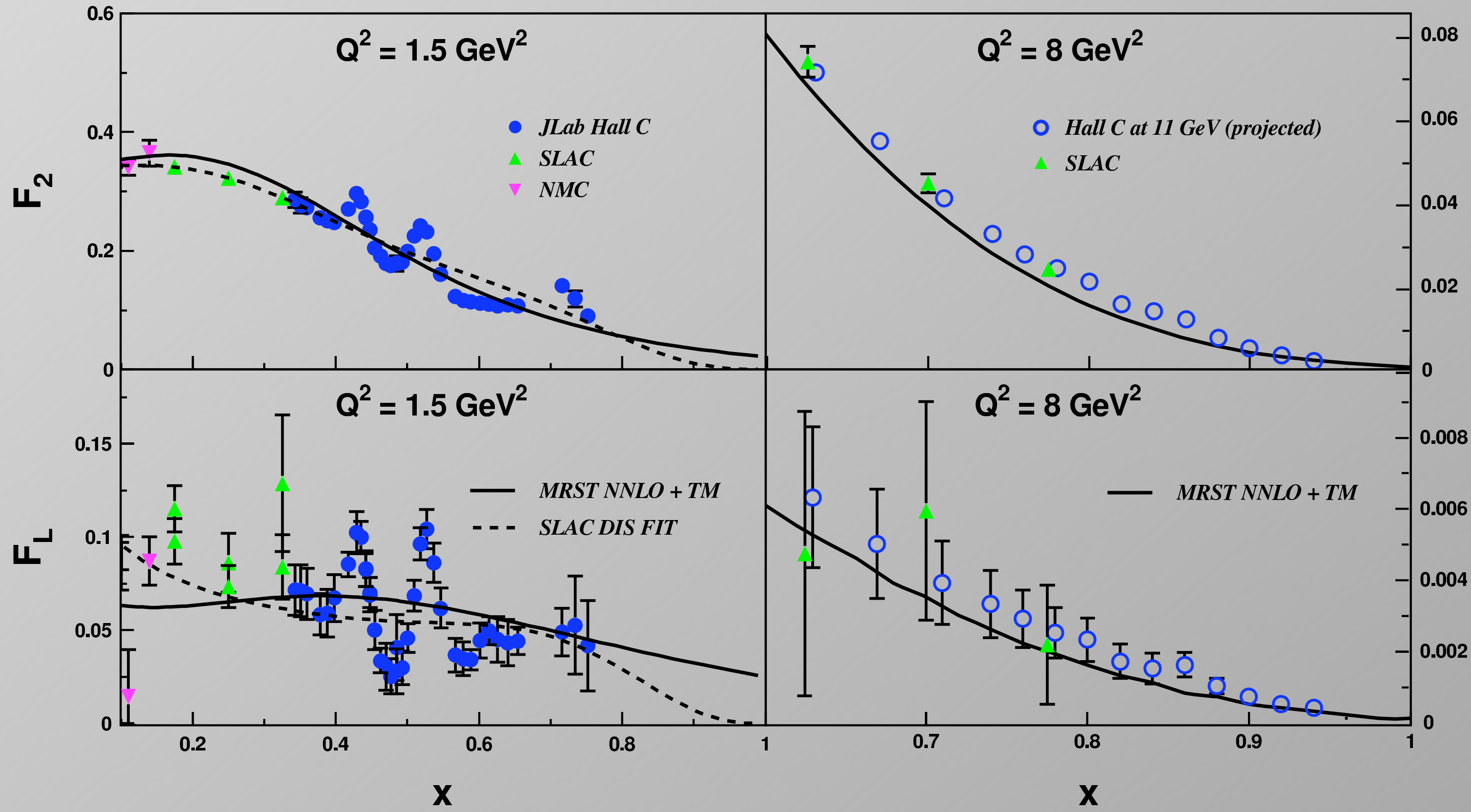


Figure 16: The potential of the 12 GeV Upgrade for exploring quark–hadron duality in the nucleon structure functions F_2 (upper row) and F_L (lower row). The left panels show the Hall C data taken at 6 GeV, the right panels the projected high–x and high–Q^2 data at 12 GeV.

$(1-x)^3$ at large x

dual to

$t^2 F_1(t) = const$ at large t

Duality at fixed W

Why is PQCD Relevant?

$x_{bj} \to 1$ Is A Far Off-Shell Domain of The Hadron Light-Front Wavefunction $\psi_n(x_i, k_{\perp i}, \lambda_i)$

$\sum_{i=1}^{n} x_i = 1$

Thus $x_{bj} \to 1$ implies $x_i \to 0$ for all spectators

$x \equiv \frac{k^+}{P^+} \equiv \frac{k^0 + k^z}{P^0 + P^z}$

Thus $x_{bj} \to 1$ requires $k^z \to -\infty$
since $k_\perp^2 + m^2 \neq 0$.

PQCD:

Valence quark distributions in the proton
$n_{spectator} = 2$

$q^+(x) \sim (1-x)^3 \qquad S^z_q = S^z_p$

$q^-(x) \sim (1-x)^5 \qquad S^z_q = -S^z_p$

Sea quark distributions $n_{spectator} = 4$

$q^+(x) \sim (1-x)^7 \qquad S^z_q = S^z_p$

$q^-(x) \sim (1-x)^9 \qquad S^z_q = -S^z_p$

$SU(6)$ Flavor-Spin Symmetry:

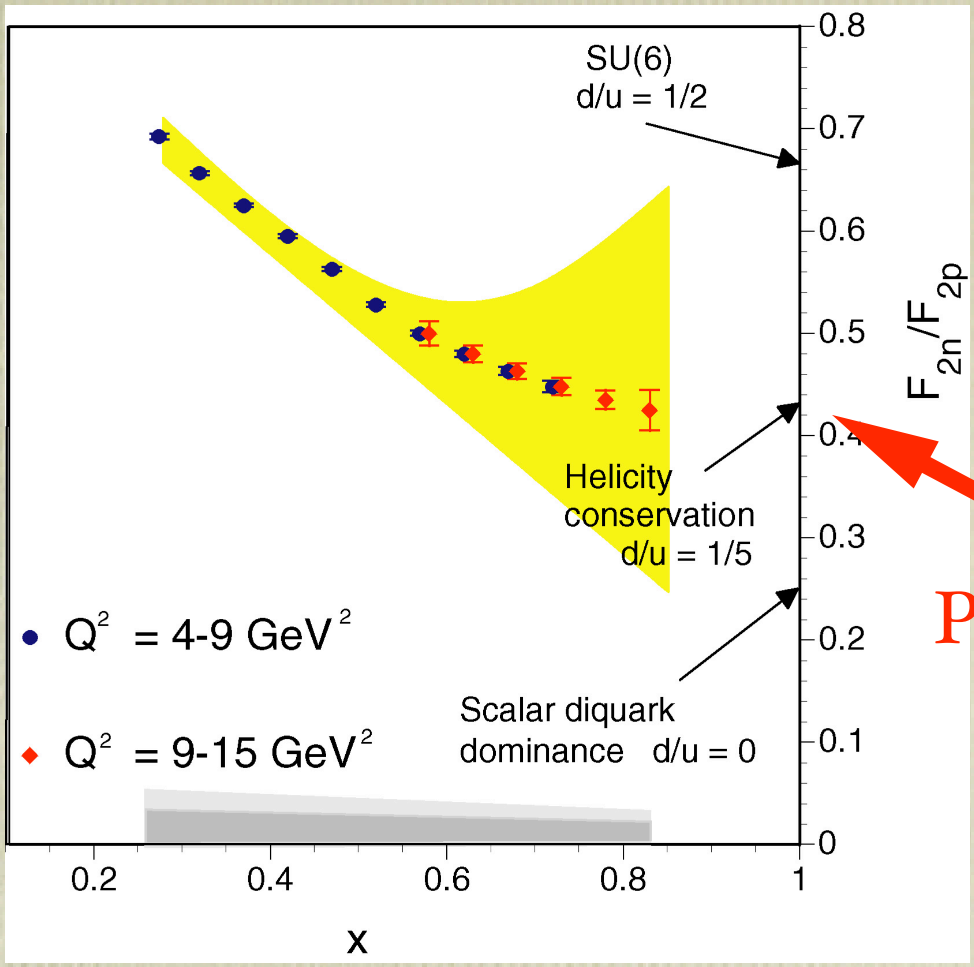
$u^+ : u^- : d^+ : d^-$

5/3 : 1/3 : 1/3 : 2/3 for proton

Thus

$d(x)/u(x) \to d^+(x)/u^+(x) \to 1/5$

at $x \to 1$ in proton



PQCD

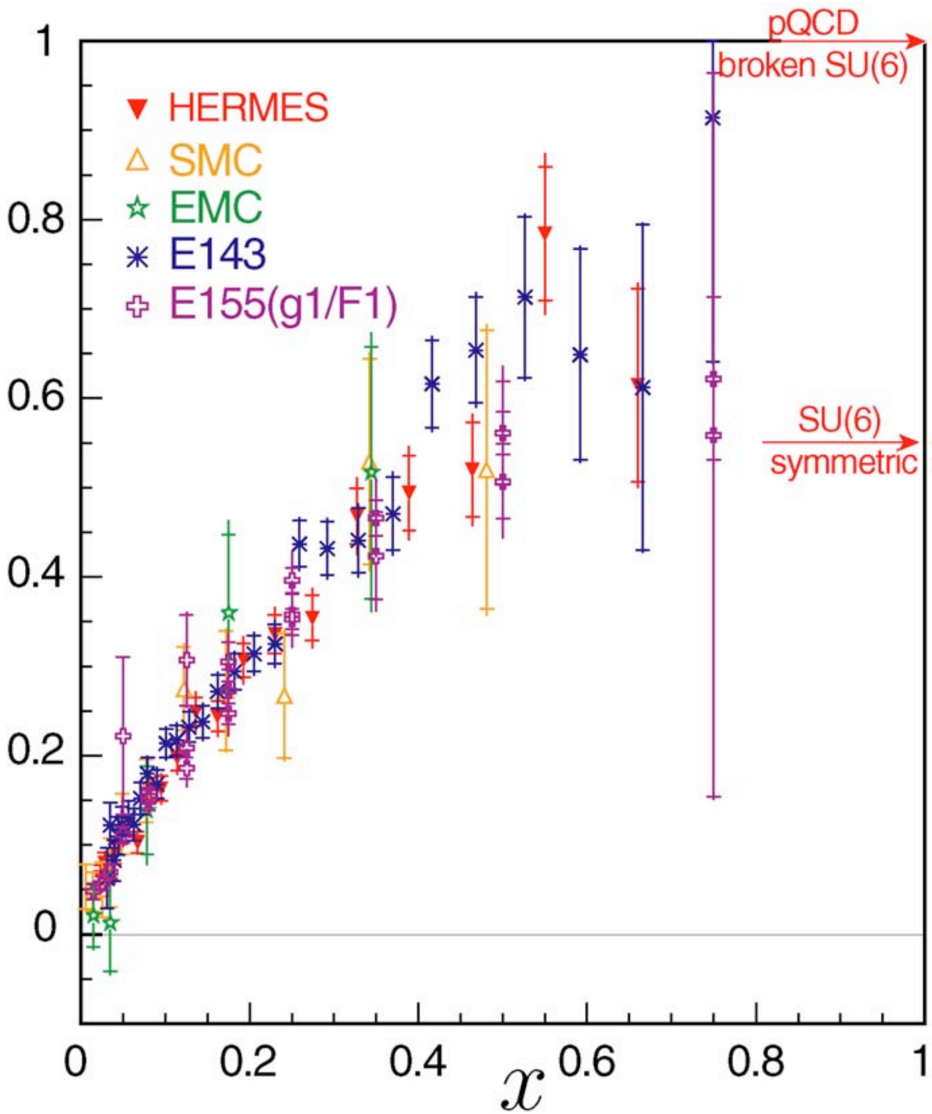
$$\frac{F_{2n}(x)}{F_{2p}(x)} \to \frac{\sum_{q/p} e_q^2 q_p^+(x)}{\sum_{q/p} e_q^2 q_n^+(x)} = \frac{5\frac{1}{9}+\frac{4}{9}}{5\frac{4}{9}+\frac{1}{9}} = \frac{3}{7} = 0.4286 \ldots$$

at $x \to 1$

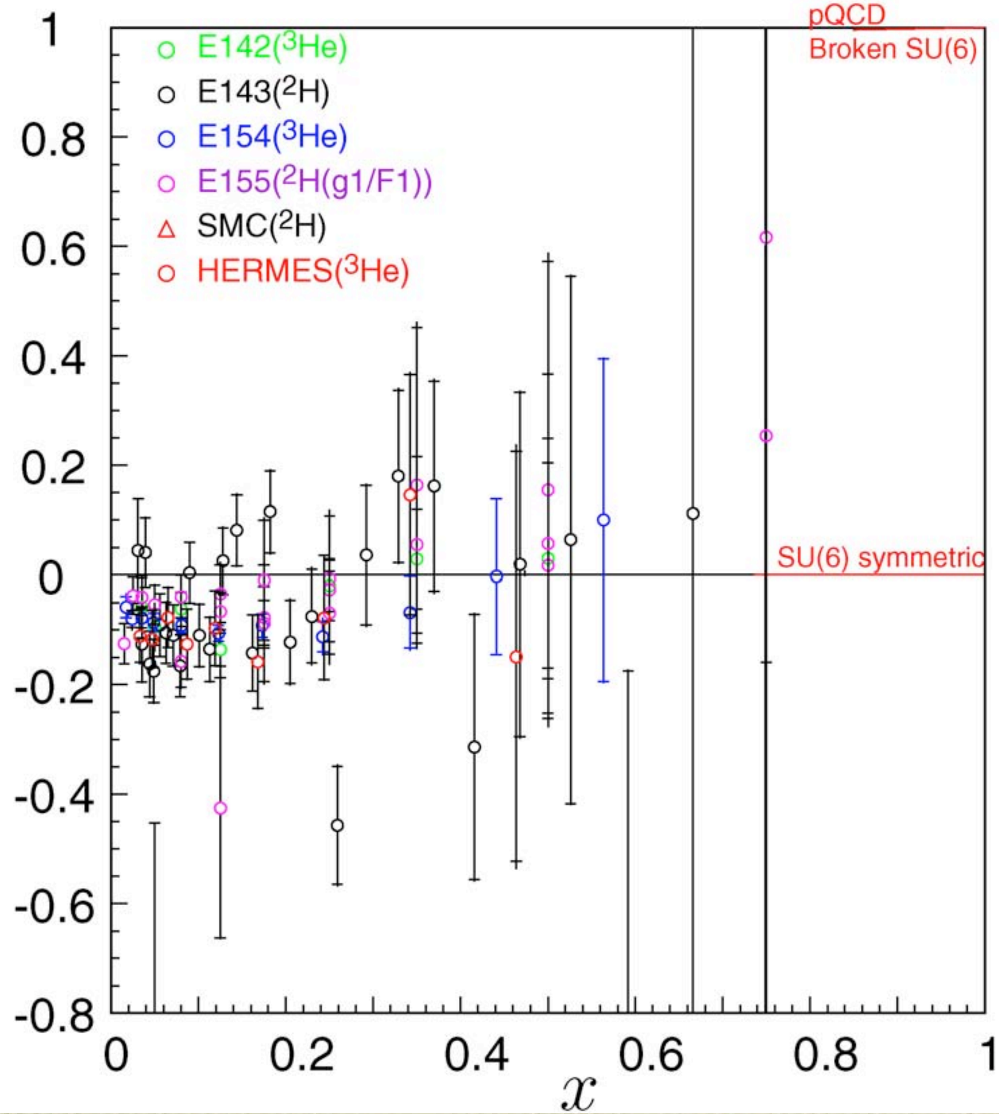
Farrar Jackson

World data for A_1

Proton



Neutron



Conflict between DGLAP and Exclusive/Inclusive Duality

DGLAP:

$$F_2(x,Q^2) \sim (1-x)^{V+\tilde{\xi}(Q^2,k^2)}\, P(\tilde{\xi})$$

where V is the PQCD Counting Rule prediction

$$\tilde{\xi}(Q^2,k^2) = \frac{C_F}{\pi}\int_{k^2}^{Q^2} \frac{d\ell^2}{\ell^2}\,\alpha_s(\ell^2) \sim O(\log\log Q^2)$$

If one uses this form at fixed $W^2 = \frac{(1-x)Q^2}{x}$, one obtains transition form factors

$$F^2(Q^2) \sim \left(\frac{\mathcal{M}^2}{Q^2}\right)^{V+1+\tilde{\xi}(Q^2,k^2)} P(\tilde{\xi})$$

which falls faster than any power!

Application of DGLAP is incorrect.

Struck quark is off-shell at fixed W^2

$$-k^2 \sim \frac{k_\perp^2 + \tilde{m}^2}{1-x}$$

where $\tilde{m}$ is the mass of the spectator system.

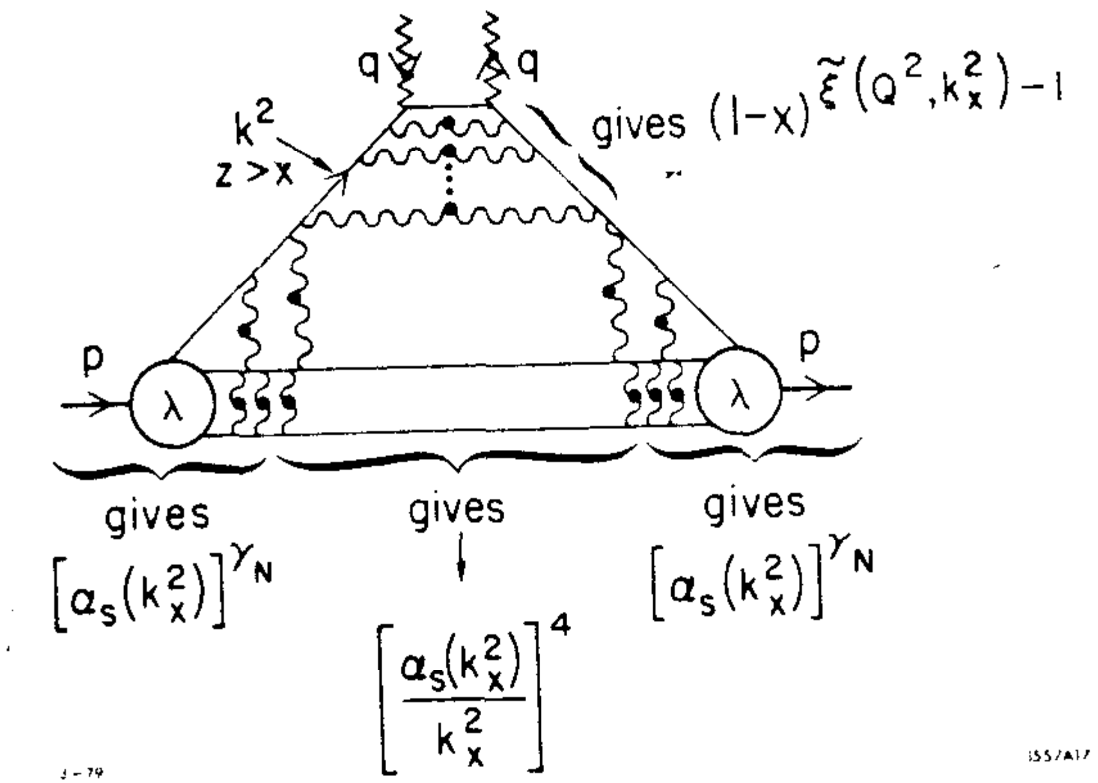
$$\tilde{\xi} = \frac{4C_F}{11-2/3\, n_f} \log \frac{\alpha_s(k^2)}{\alpha_s(Q^2)}$$

$$\Rightarrow \frac{C_F}{\pi} \alpha_s(Q^2) \log\left(\frac{\mathcal{M}^2}{\vec{k}_\perp^2 + \tilde{m}^2}\right) \text{ at fixed } \mathcal{M}^2,\ Q^2 \to \infty.$$

i.e.: $\tilde{\xi}$ actually vanishes as $1/\log Q^2$ in the fixed $\mathcal{M}^2$ domain.

$$F_2(x,Q^2) \sim (1-x)^{V + \tilde{\xi}(Q^2,k^2)} P(\tilde{\xi})$$

Exclusive-Inclusive Duality Valid



$$F_{2N}(x,Q^2) \sim C(\tilde\xi)(1-x)^{3+\tilde\xi(Q^2,k_x^2)}\,\alpha_s^4(k_x^2) \cdot \left[\sum_j a_j (\log k_x^2/\Lambda^2)^{-\gamma_j^{(N)}}\right]^2$$

Why is large x Important?

- Higher-twist subprocess enhanced: $\frac{1}{(1-x)^p}$
- Exclusive-Inclusive Duality
- Intrinsic heavy quarks **at large** $\mathbf{x}$
- Utilize maximal energy of beam:
  e.g., forward Higgs production

AdS/CFT ⇒

Near - Conformal QCD

* All orders, strong coupling derivation of

  dimensional counting rules

  counting rules for LFWFs

* $\sum_n (C_n \alpha_s^n)^{*} \Rightarrow \sqrt{\alpha_s}$

* $\alpha_\tau, \alpha_R \Rightarrow$ I.R. Fixed point

* $\alpha_\tau \cong 0.9$

$$\Rightarrow \alpha_{excl}(q^2) = \frac{1}{4\pi} \frac{Q^2 F_\pi(Q^2)}{|Q^2 F_{\pi\gamma}(Q^2)|^2} \cong 0.8$$

* Template for QCD

* Commensurate Scale Relations

* Systematically correct for $\beta \neq 0$, $m_q \neq 0$

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

- Light Front Wavefunctions:

$$\left|\Psi_h(P^+, \vec{P}_\perp)\right\rangle = \sum_{n,\lambda_i} \int \; [dx_i \; d^2\vec{k}_{\perp i}] \; \psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i) \; |n : x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i\rangle$$

Conformal Behavior:

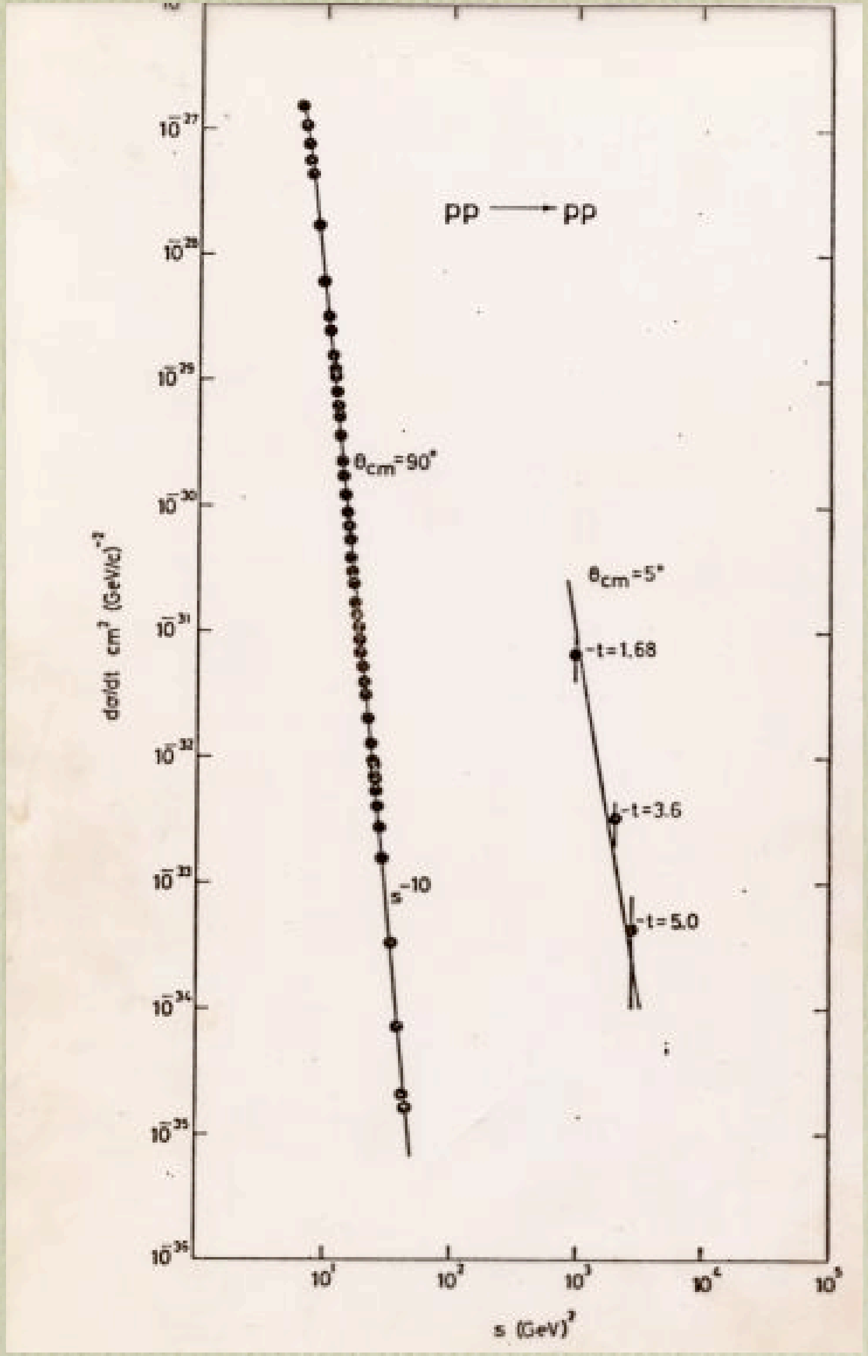
$$\psi_{n/h}(\vec{k}_\perp) \to (k_\perp)^\ell \left[\frac{1}{\vec{k}_\perp^2}\right]^{n+\delta_n+\ell-1} .$$

Model Form from PQCD or AdS/CFT :

$$\psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i, l_{zi}) \sim \frac{(g_s \; N_C)^{\frac{1}{2}(n-1)}}{\sqrt{\mathcal{N}_C}} \prod_{i=1}^{n-1} (k_{i\perp}^{\pm})^{|l_{zi}|} \left[\frac{\Lambda_o}{\mathcal{M}^2 - \sum_i \frac{\vec{k}_{\perp i}^2 + m_i^2}{x_i} + \Lambda_o^2}\right]^{n+|l_z|-1}$$

Key Quantity of Nuclear and Hadron Physics

Proton-Proton
Scattering



PP → PP
$\theta_{cm}=90°$
s^{-10}
$\theta_{cm}=5°$
-t=1.68
-t=3.6
-t=5.0
dσ/dt cm² (GeV/c)⁻²
s (GeV)²

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

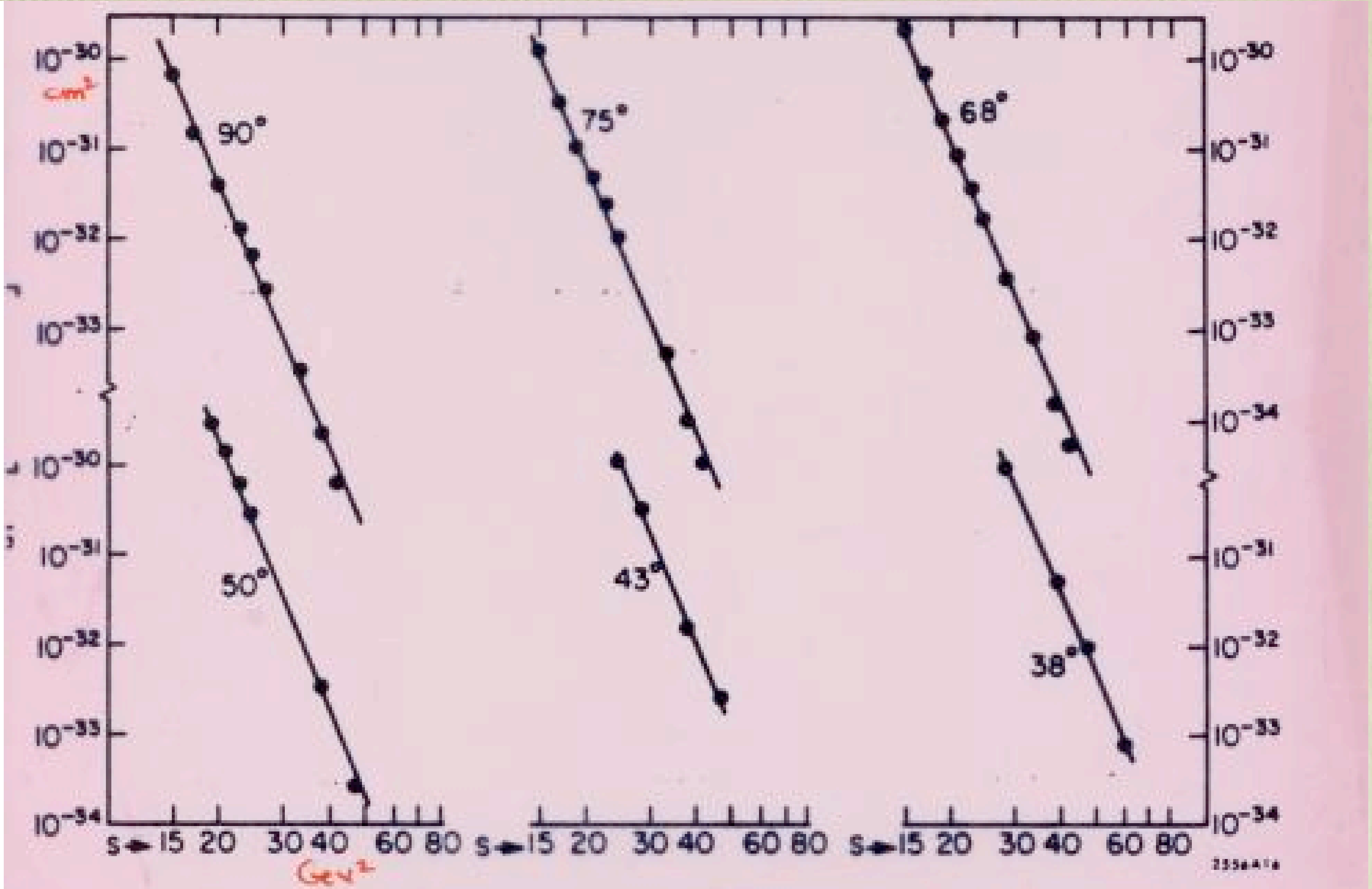


Figure 22. Test of fixed θ_{CM} scaling for elastic pp scattering. The data compilation is Landshoff and Polkinghorne.

Compute LFWFs from First Principles

- Very difficult using Euclidean lattice
- Discretized light-cone quantization: Diagonalize light-cone Hamiltonian
- Bethe-Salpeter Dyson-Schwinger Eqns
- Transverse lattice
- AdS/CFT guidance

AdS/CFT Correspondence

Anti de Sitter — conformal field theory

Maldacena (1998)

Remarkable duality between

Supergravity string theory in 10 dimensions

and

Supersymmetric Yang-Mills field theory

in 3+1 Minkowski space-time

$$\boxed{AdS_5 \otimes S^5 \Leftrightarrow SO(4,2) \otimes (\mathcal{N}=4)}$$

5 dim. Sphere

symmetries of conformal transformations + Poincare Invariance of Minkowski space

$\mathcal{N}=4$ SUSY

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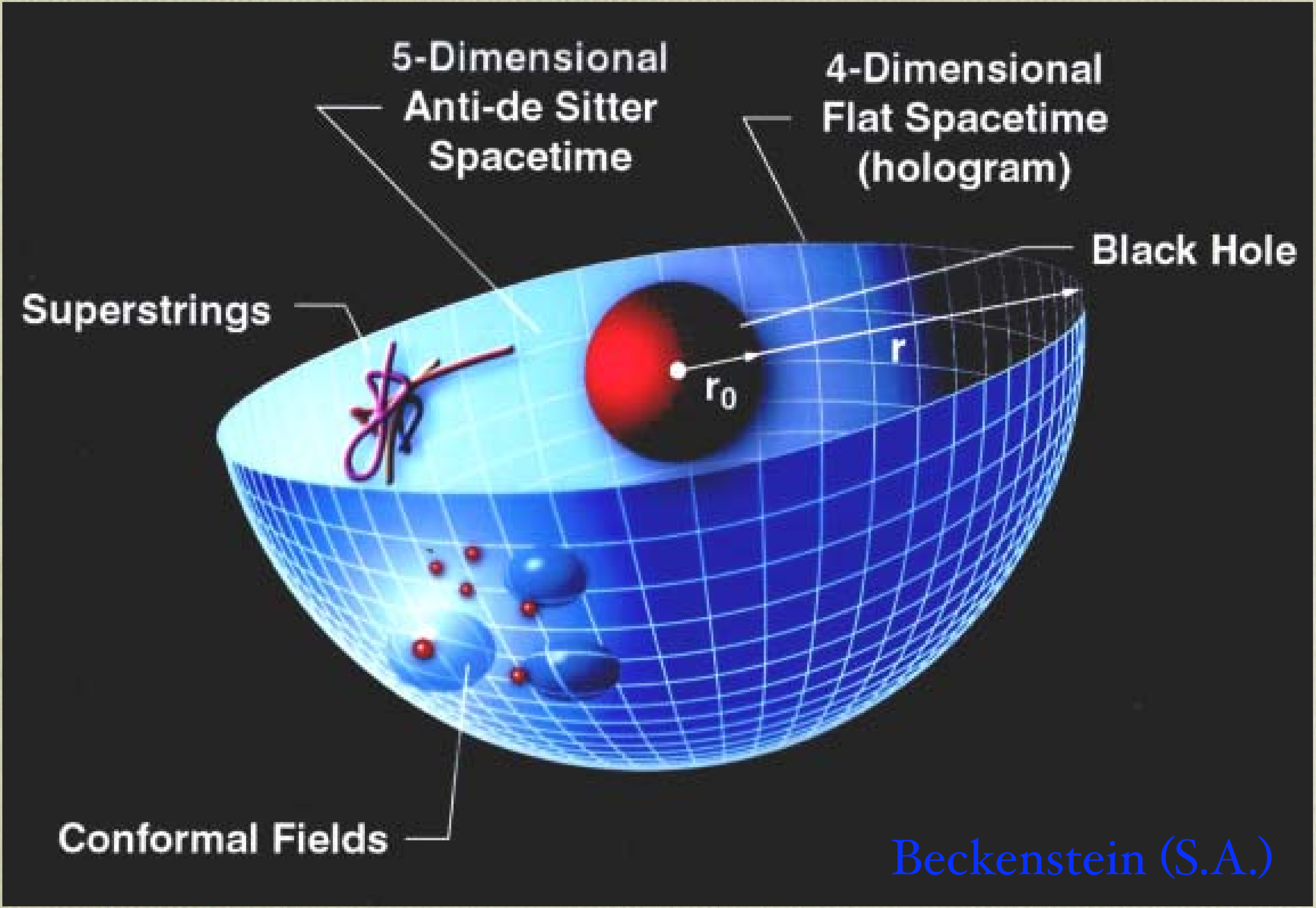
  hep-th/0207071

* S. J. Rey + J. T. Lee
  hep-th/9803001

* S. J. Brodsky + G. F. de Teramond
  hep-th/0310227

* O. Aharony, S. S. Gubser, J. M. Maldacena, H. Ooguri
  + Y. Oz hep-th/9905111



Beckenstein (S.A.)

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 --> 1
- Hadron Spectra, Regge Trajectories

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 $\begin{cases} \text{Minkowski space} & R^{(3,1)} \\ AdS_5 & \end{cases}$

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

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

AdS/CFT

- Use mapping of SO(4,2) to AdS5

- Scale Transformations represented by wavefunction Ψ(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

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

AdS/CFT

- Light-Front Wavefunctions can be determined by matching functional dependence in fifth dimension to scaling in impact space.
- $$\left[z^2\, \partial_z^2 - (d-1) z\, \partial_z + z^2\, \mathcal{M}^2 - (\mu R)^2\right] f(z) = 0,$$
- Relative orbital angular momentum
- High transverse momentum behavior matches PQCD LFWF: Belitsky, Ji, Yuan

Example of conformal string theory calculation

$AdS_5 \otimes S^5$: $\quad z = R^2/r$

$$ds^2 = \frac{r^2}{R^2}(dt^2 - d\vec{x}^2) - \frac{R^2}{r^2} dr^2 - R^2 \, d\Omega_5^2(y)$$

$$= \frac{R^2}{z^2}(dx_\mu^2 - dz^2) - R^2 d\Omega_5^2$$

10-dimensional string amplitude $\Phi(x, z, y)$

Laplace Eqn $S=0$

$$\frac{1}{\sqrt{g}} \frac{\partial}{\partial x^A}\left(\sqrt{g}\, g^{AB} \frac{\partial}{\partial x^B} \Phi\right) = 0$$

$$\sqrt{g} = (R^2/z)^{d+1} \sqrt{\Omega(y)}$$

$d=4$

$$\Phi(x, z, y) = \sum_\ell \Phi_\ell(x, z)\, \phi_\ell(y)$$

Spherical harmonics

hadronic plane wave in 3+1

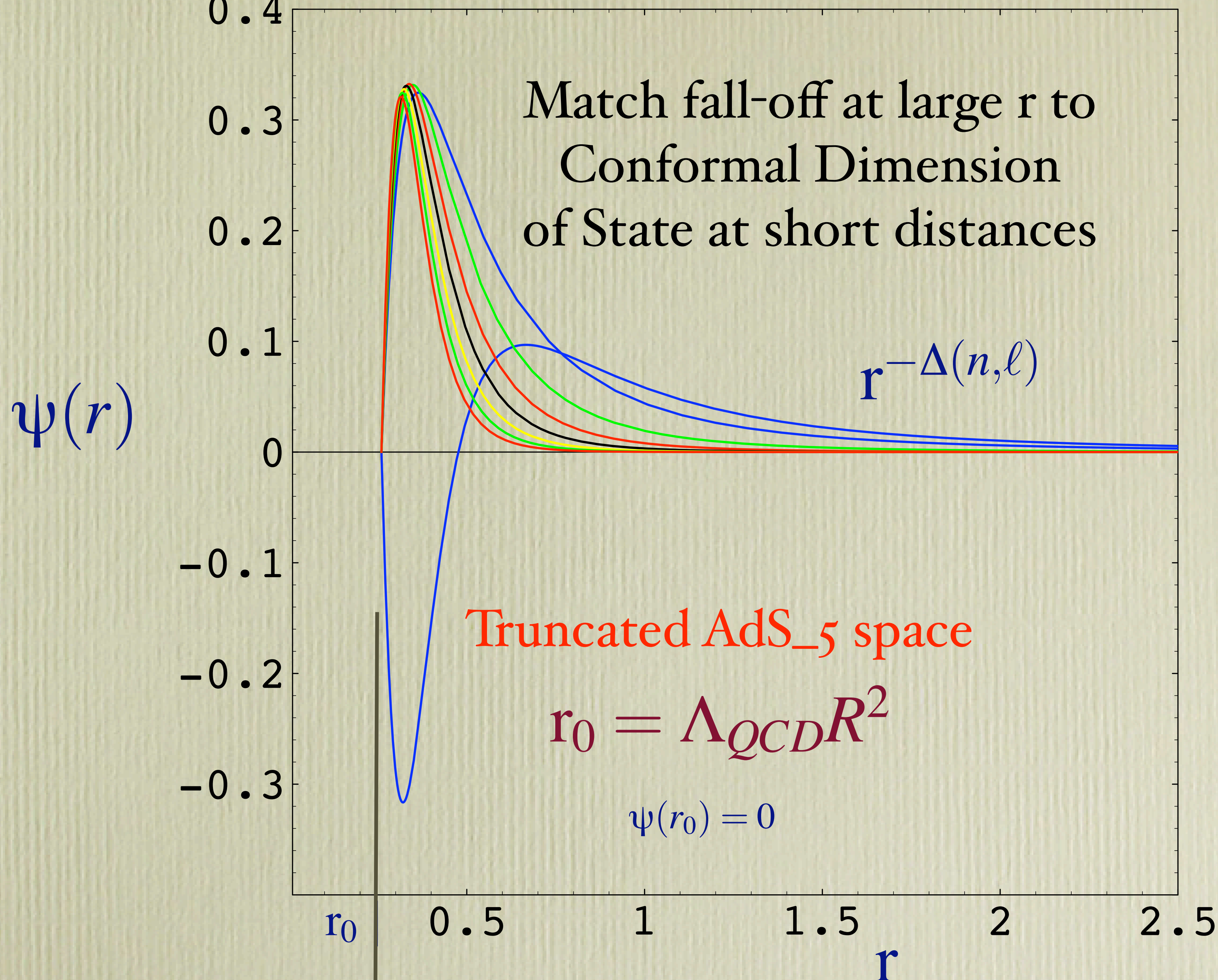
$$\Phi_\ell(x, z) = e^{-iP\cdot x} f(z)$$

"dilaton" amplitude

$$* \quad \left[z^2 \frac{d^2}{dz^2} - (d-1)\, z \frac{\partial}{\partial z} - (\lambda R)^2 + z^2 M^2\right] F(z) = 0$$

$$* \quad (\lambda R)^2 = \ell(\ell + d)$$

New Perspectives AdS/CFT


Match fall-off at large r to
Conformal Dimension
of State at short distances
$r^{-\Delta(n,\ell)}$
$\psi(r)$
Truncated AdS_5 space
$r_0 = \Lambda_{QCD} R^2$
$\psi(r_0) = 0$
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
r_0
0.5
1
1.5
2
2.5
r

Solution: Cylindrical Bessel Functions

$$\Psi(x,r) = C_1 e^{-iP.x} r^{-d/2} \begin{cases} J_\alpha\left(\frac{mR^2}{r}\right) \\ N_\alpha\left(\frac{mR^2}{r}\right) \end{cases}$$ ok

where

$$\alpha^2 = \left(\frac{d}{2}\right)^2 + (\lambda R)^2$$ $d=4$

$$(\lambda R)^2 = \ell(\ell+d)$$ eigenvalues on S^{d+1}

At large r:

$$\psi(r) \sim r^{-\Delta}$$

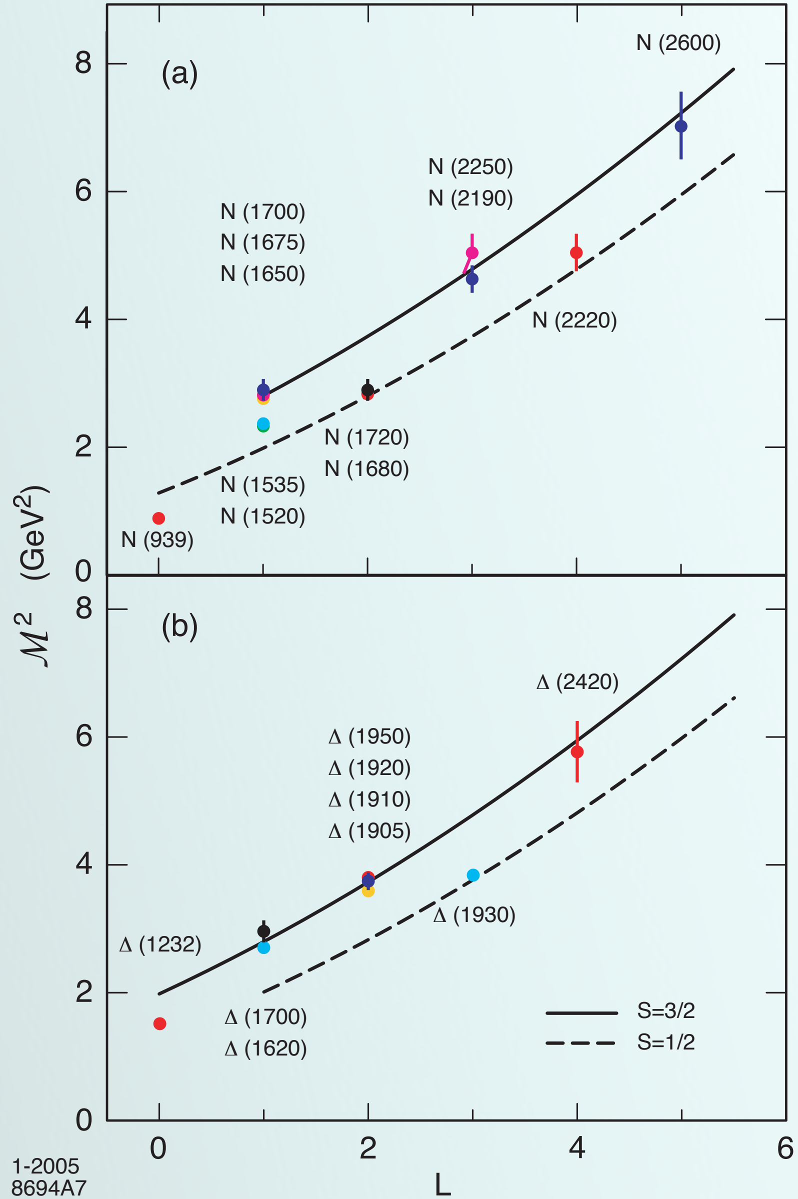
$$\Delta = \frac{1}{2}\left(d + \sqrt{d^2 + 4\lambda^2 R^2}\right)$$

$$= d + \ell$$

Thus for hard scattering $r \sim Q R^2$

$$\psi(Q) \sim Q^{-\Delta}$$

AdS/CFT Baryon Spectroscopy



One Parameter

$\Lambda_{QCD} = 0.22$ GeV

FIG. 2: Predictions for the light baryon orbital spectrum for $\Lambda_{QCD} = 0.22$ GeV. The lower curves corresponds to baryon states dual to spin-$\frac{1}{2}$ modes in the bulk and the upper to states dual to spin-$\frac{3}{2}$ modes.

G. F. de Teramond and S. J. Brodsky, arXiv:hep-th/0501022.

AdS/CFT Meson Spectroscopy

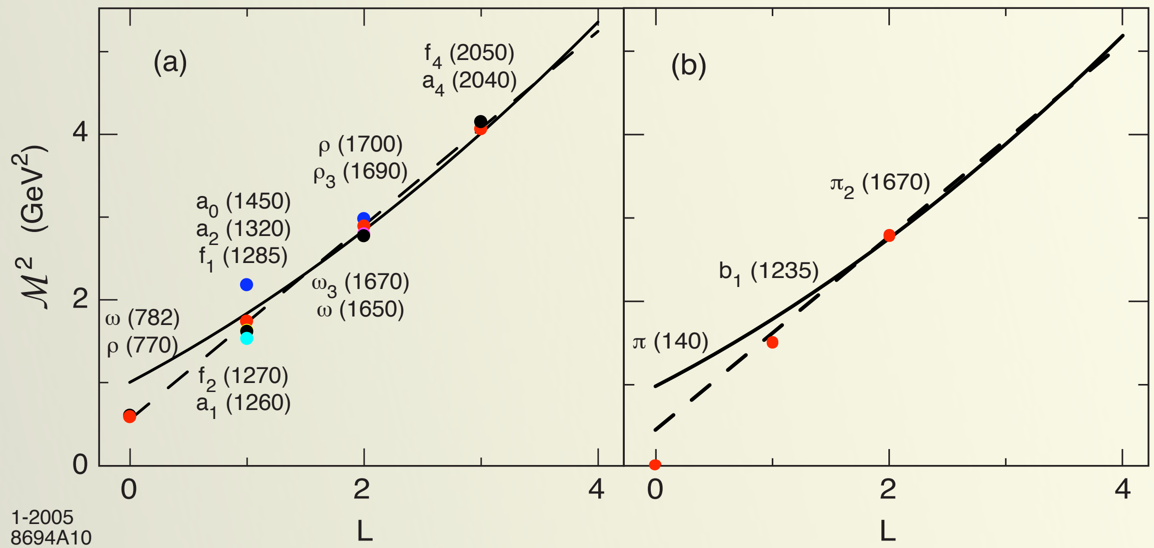


FIG. 1: Light meson orbital states for $\Lambda_{QCD} = 0.263$ GeV. Results for the vector mesons are shown in (a) and for the pseudoscalar mesons in (b). The dashed line has slope 1.16 GeV^2 and is drawn for comparison.

G. F. de Teramond and S. J. Brodsky, "The hadronic spectrum of a holographic dual of QCD," arXiv:hep-th/0501022.

Features of HolographicModel

- Ratio of proton to Delta trajectories= ratio of zeroes of Bessel functions.
- Only 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

AdS/CFT

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

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

- Relative orbital angular momentum

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

Can we relate hadron wavefunctions in 3+1 to the $AdS_5 \otimes S^5$ solutions ?

Use light-front Fock expansion at fixed $\tau = t + z/c$ $\qquad H_{LF} |\Psi_h\rangle = m_h^2 |\Psi_h\rangle$

$x_i = k_i^+/P^+$

n-1 integrations

$$|\Psi_h(P^+, \vec{P}_\perp)\rangle = \sum_{n,\lambda_i} \int [dx_i\, d^2k_{\perp i}]\, \psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i)\, |n: x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i\rangle$$

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

Introduce UV regulatn: $\quad k_{\perp i}^2 < \Lambda^2 = Q^2$

$$|\Psi_h(Q)\rangle \quad , \quad |\Psi_{n/h}(Q)\rangle$$

$$\Psi_{n/h}(Q) \sim \int^Q [d^2k_\perp]^{n-1} [a^\dagger(k_\perp)]^n \psi_n(\vec{k}_\perp)$$

$$\psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i, l_{zi}) \sim \frac{(g_s \ N_C)^{\frac{1}{2}(n-1)}}{\sqrt{\mathcal{N}_C}}$$

$$\times \prod_{i=1}^{n-1} (k_{i\perp}^{\pm})^{|l_{zi}|} \left[\frac{\Lambda_{QCD}}{\mathcal{M}^2 - \sum_i \frac{\vec{k}_{\perp i}^2 + m_i^2}{x_i} + \Lambda_{QCD}^2} \right]^{n+|l_z|-1}$$

de Teramond, SJB

The form is compatible with the scaling properties predicted by the AdS/CFT correspondence including orbital angular momentum.

Impact Space Representation of LFWFs

We define the total position coordinate of a hadron or its transverse center of momentum $\vec{R}_\perp$ in terms of the energy momentum tensor $T^{\mu\nu}$

$$\vec{R}_\perp = \frac{1}{P^+} \int dx^- \int d^2\vec{r}_\perp T^{++} \vec{r}_\perp. \tag{6}$$

In terms of partonic variables:

$$x_i \vec{r}_{\perp i} = \vec{R}_\perp + \vec{b}_{\perp i}, \tag{7}$$

where the variables $\vec{r}_{\perp i}$ are the physical coordinates and $\vec{b}_\perp$ are the frame-independent internal coordinates. Thus, $\vec{R}_\perp = \sum_i x_i \vec{r}_{\perp i}$ and $\sum_i \vec{b}_{\perp i} = 0$.

Normalizable string modes representing mesons states in AdS follow from the solution of [8]

$$\left[z^2\, \partial_z^2 - (d-1)z\, \partial_z + z^2\, \mathcal{M}^2 + (\mu R)^2 + d - 1\right] f(z) = 0, \tag{32}$$

where $\Phi(x,z) = e^{-iP\cdot x} f(z)$, with $P_\mu P^\mu = \mathcal{M}^2$. We impose truncated space boundary conditions $\Phi(x, z_o) = 0$. The normalizable modes are

$$\Phi_{\alpha,k}(x,z) = C_{\alpha,k}\; e^{-iP\cdot x} z^2 J_\alpha\left(z\beta_{\alpha,k}\Lambda_{QCD}\right), \tag{33}$$

with $\alpha = 1 + L$ $(d = 4)$, $\mathcal{M} = \beta\Lambda_{QCD}$. Thus

$$\frac{J_\alpha^2\left(b\mathcal{M}\right)}{b^2} = B\int_0^1 \frac{dx}{\sqrt{x(1-x)}}\; |\psi(x,b)|^2, \tag{34}$$

with B a constant. If we impose the condition:

$$\psi\left(x, |\vec{b}_\perp| = b_o\right) = 0, \tag{35}$$

then

$$\psi(x,b) = \gamma(x)\chi(b), \tag{36}$$

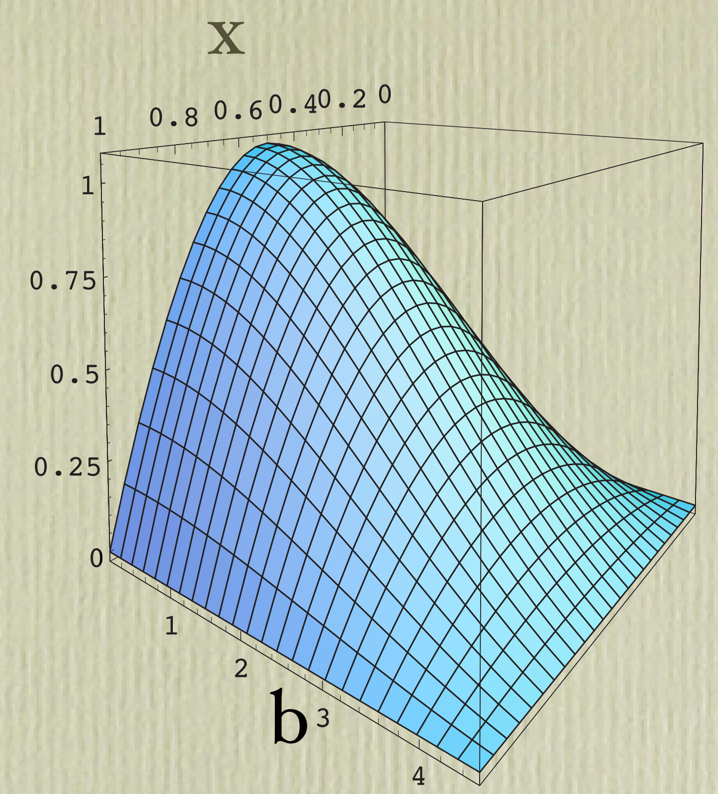
To first approximation we determine $\gamma(x)$ from the $x \to 0$ and $x \to 1$ limits, thus $\gamma(x) = x(1-x)$. We obtain for $\psi(x,b)$

$$\psi(x,b) = Cx(1-x)\frac{J_\alpha\left(b\mathcal{M}\right)}{b}, \tag{37}$$

The two-parton state including orbital angular momentum ℓ and radial modes is:

$$\psi_{n,\ell,k}(x,b) = B_{n,\ell,k}\; x(1-x)\frac{J_{n+\ell-1}\left(b\beta_{n-1,k}\Lambda_{QCD}\right)}{b}, \tag{38}$$

Holographic LFWF



AdS/CFT

b ⬅ z

Figure 1: Ground state light-front wavefunction in impact space $\psi(x, b)$ for a two-parton state in a holographic QCD model for $n = 2, \ell = 0, k = 1$.

GdT & Sjb (preliminary)

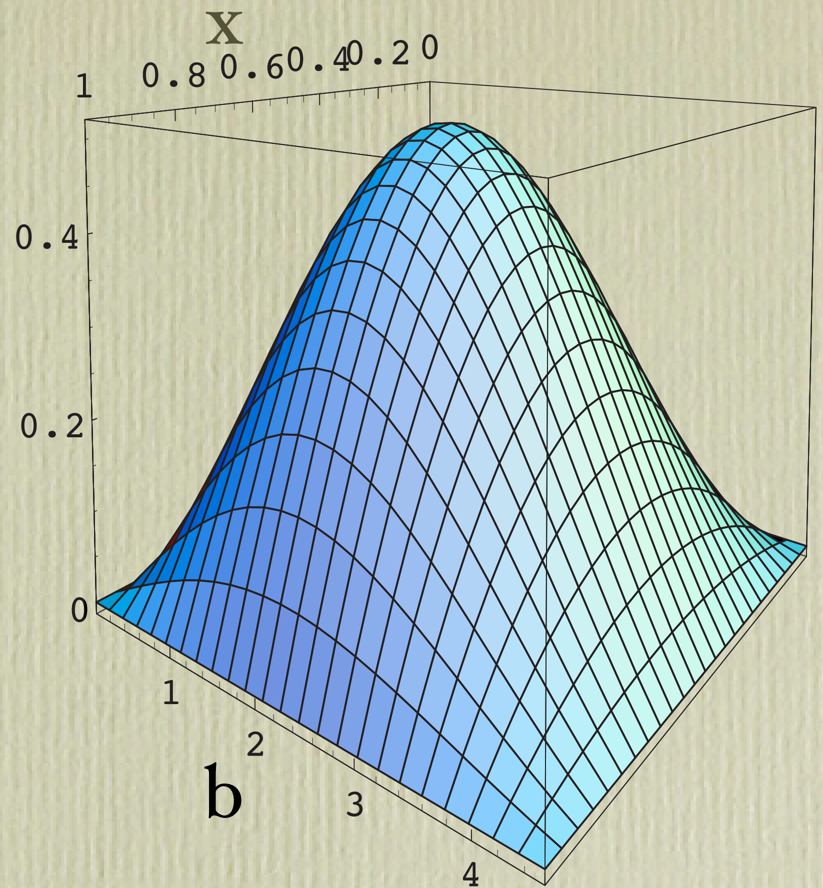


Figure 2: First orbital exited state light-front wavefunction in impact space $\psi(x, b)$ for a two-parton state in a holographic QCD model for $n = 2, \ell = 1, k = 1$.

$\psi(x,b)$ $(n=2,\ell=0,k=2)$

GdT & Sjb
(preliminary)

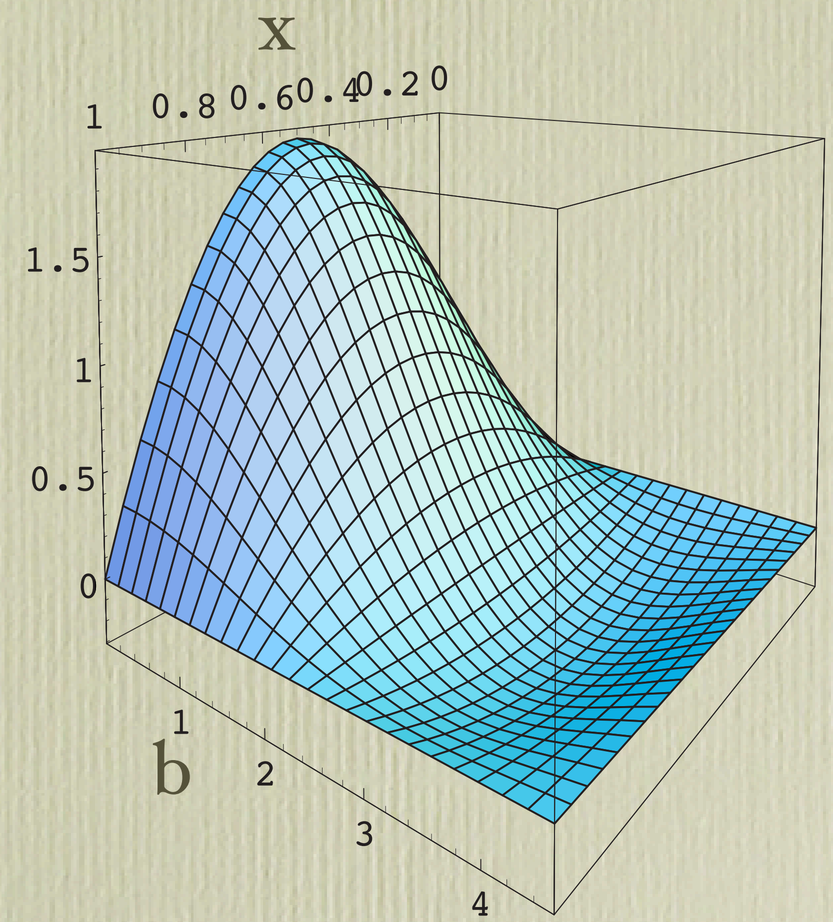


Figure 3: First radial exited state light-front wavefunction in impact space $\psi(x,b)$ for a two-parton state in a holographic QCD model for $n=2,\ell=0,k=2$.

Two approaches to evaluating LFWFs at Short Distances

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

$k_\perp^2 >> \Lambda_{QCD}^2$ and/or $x_i \to 1$

- Use PQCD (minimally connected tree graphs)
- AdS/CFT (duality between string theory and conformal field theory)

In practice: QCD: Approximately Conformal

Use PQCD to analyze LFWF at high x or large $k_\perp^2$:

Central Behavior:

$$\psi_n(x_i, k_{\perp i}, \lambda_i) \sim [\frac{\Lambda_{QCD}}{\mathcal{M}_n^2}]^{(n-1)}$$

$$\mathcal{M}_n^2 \equiv \sum_{i=1}^n (\frac{k_\perp^2 + m^2}{x})_i$$

Modified by Orbital angular momentum factors $\vec{k}_\perp^{L_z}$

Truncated Space Model

In AdS space the form factor is the overlap integral of the normalizable string modes dual to the incoming and outgoing hadron Φ_I and Φ_F and the non-normalizable mode J, dual to the external source:

$$\begin{aligned} F(Q^2)_{I \to F} &= R^{3+2\sigma} \int_0^\infty \frac{dz}{z^{3+2\sigma}} \, e^{(3+2\sigma)A(z)} \Phi_F(z) \; J(Q,z) \; \Phi_I(z) \\ &\simeq R^{3+2\sigma} \int_0^{z_o} \frac{dz}{z^{3+2\sigma}} \, \Phi_F(z) \; J(Q,z) \; \Phi_I(z), \end{aligned} \tag{18}$$

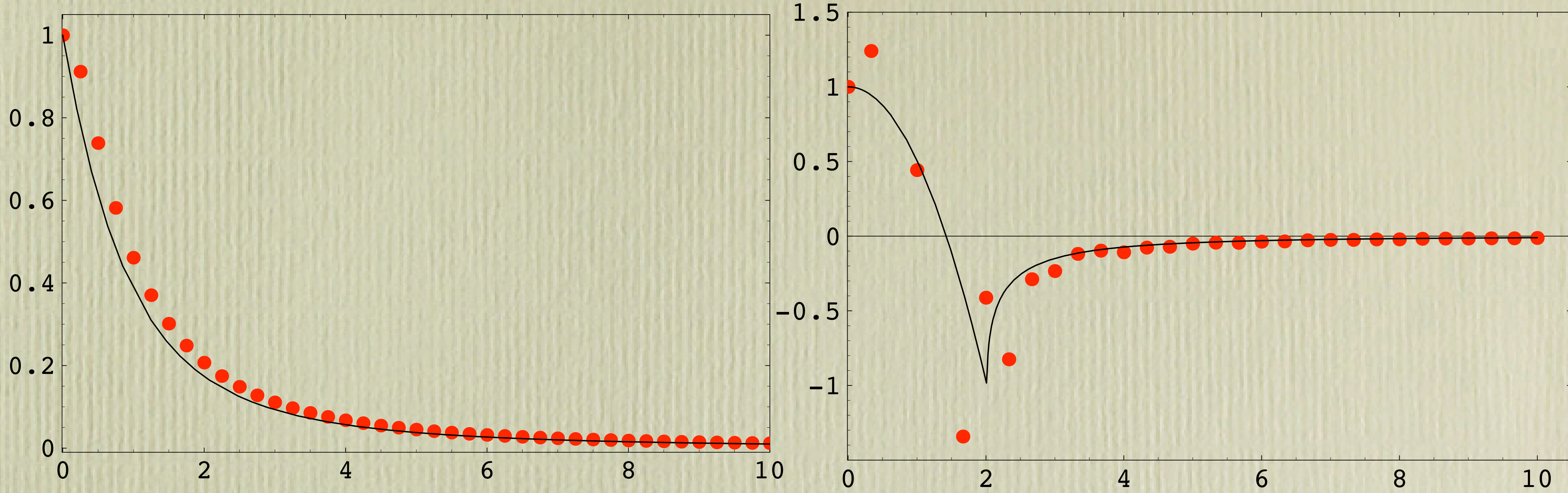
where σ represents the hadron spin. The non-normalizable mode J has the limiting value 1 at zero momentum transfer to recover hadron normalization, $F(0) = 1$, and has as boundary limit the external current. Thus

$$\lim_{Q \to 0} J(Q,z) = \lim_{z \to 0} J(Q,z) = 1. \tag{19}$$

Consider a specific AdS mode corresponding to an n partonic state $\Phi^{(n)}$ which behaves as $\Phi^{(n)} \sim z^{\Delta_n}$ in the boundary limit $z \to 0$. From (18):

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau - 1}, \tag{20}$$

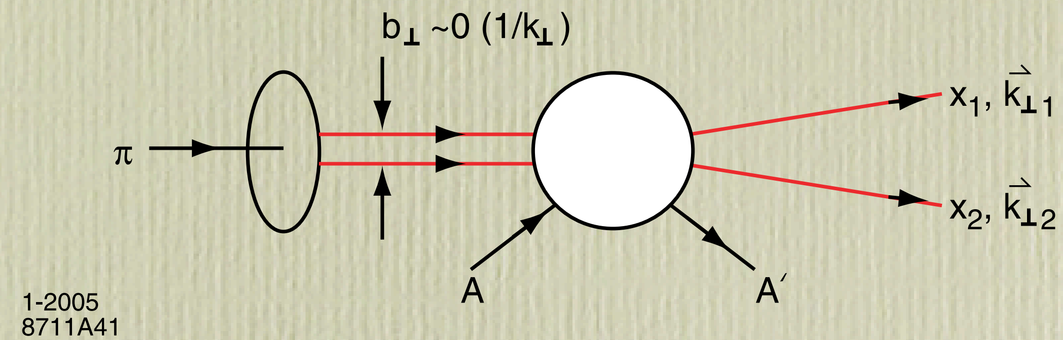
where $\tau = \Delta_n - \sigma_n = n$, $\sigma_n = \sum_{i=1}^n \sigma_i$.



Spacelike and timelike pion form factor from holographic model

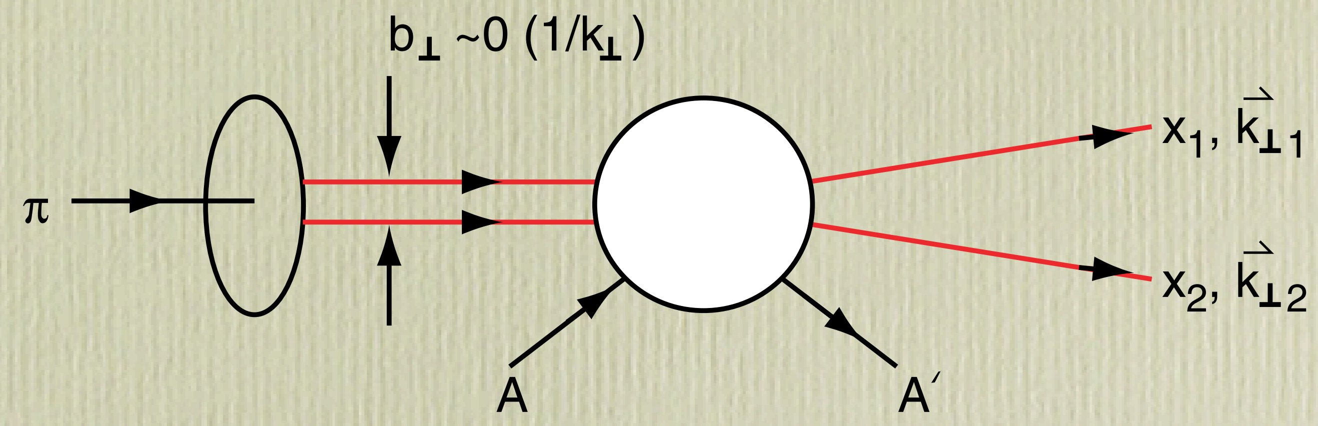
gdt&sjb preliminary

Diffractive Dissociation of Pion

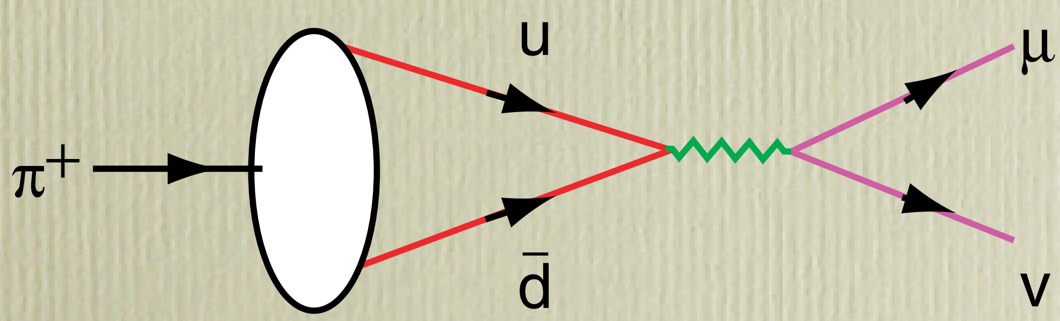


- Measure Light-Front Wavefunction of Pion
- Two-gluon Exchange
- Minimal momentum transfer to nucleus
- Nucleus left Intact

Fluctuation of a Pion to a Compact Color Dipole State



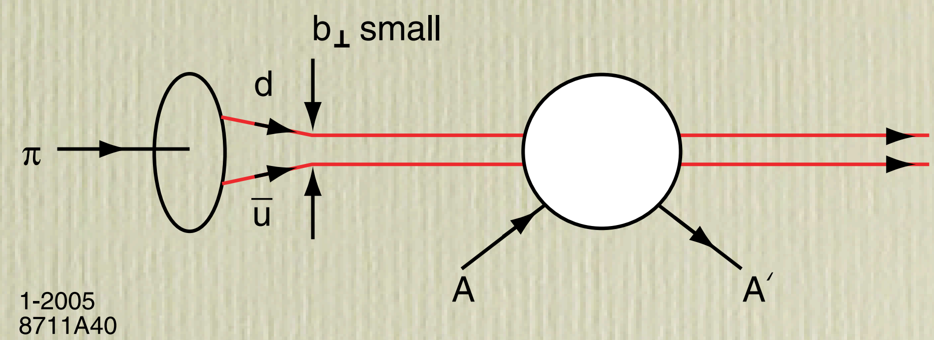
Color-Transparent Fock State For High Transverse Momentum Di-Jets



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



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

Diffractive Dijet Cross Section Color Transparent!

Color Transparency

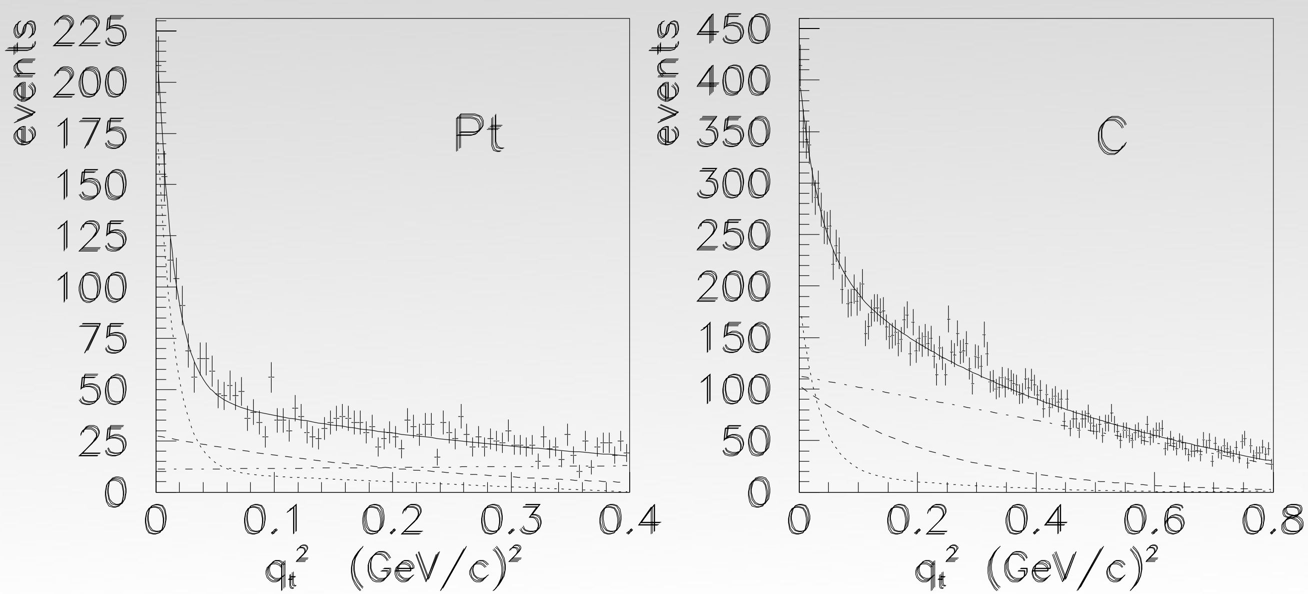
- **Fully coherent interactions between pion and nucleons.**
- **Emerging Di-Jets do not interact with nucleus.**

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

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

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

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



Verification of QCD Color Transparency

FermiLab E791
Ashery et al

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

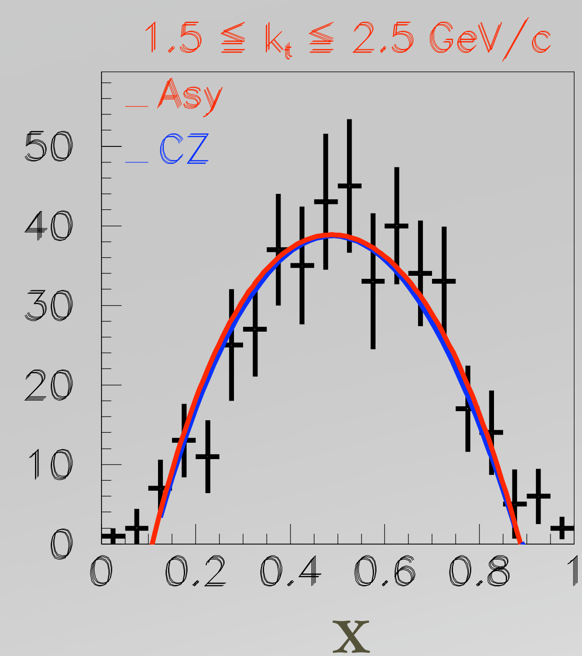
Conventional Glauber Theory Ruled Out !

Diffractive Dissociation of a Pion into Dijets

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

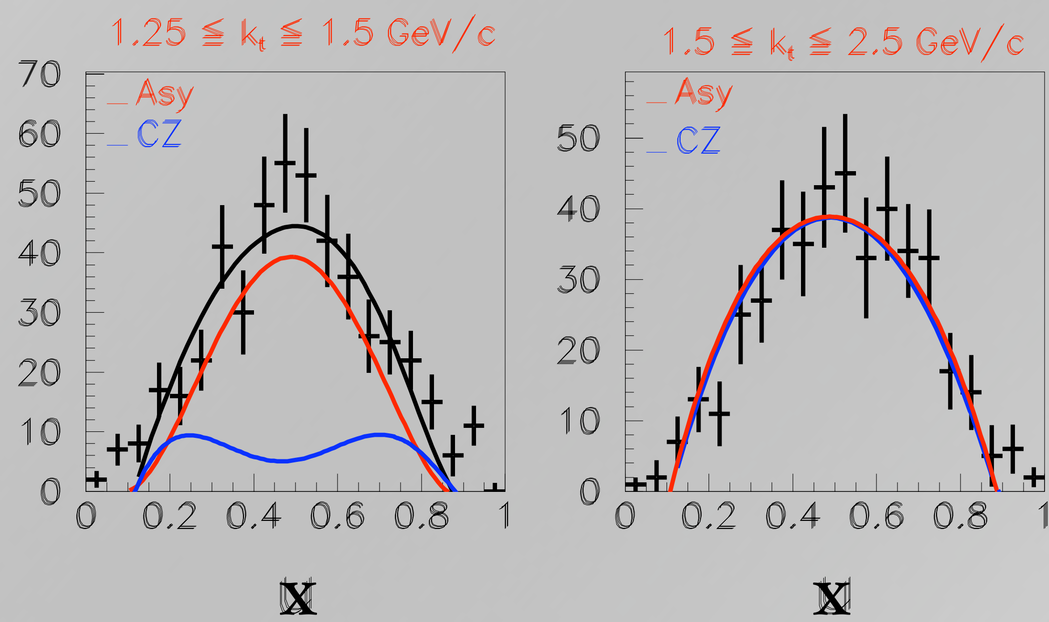
- E789 Fermilab Experiment Ashery et al
- 500 GeV pions collide on nuclei keeping it intact
- Measure momentum of two jets
- Study momentum distributions of pion LF wavefunction

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



THE $q\bar{q}$ MOMENTUM WAVE FUNCTION MEASURED BY DI-JETS

Fermilab E791 Collaboration, PRL 86, 4768 (2001)



$1.5\text{GeV}/c \leq k_t \leq 2.5\text{GeV}/c;\ Q^2 \sim 16\ (\text{GeV}/c)^2:$ $\phi^2 > 0.9\phi^2_{\text{Asy}}$

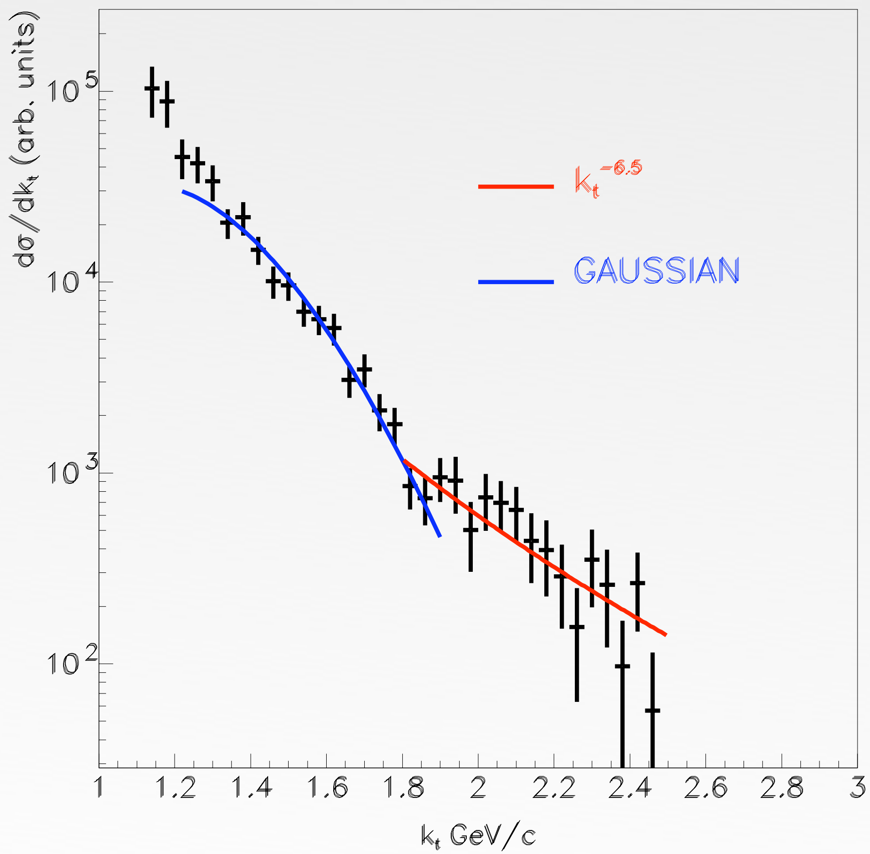
$1.25\text{GeV}/c \leq k_t \leq 1.5\text{GeV}/c;\ Q^2 \sim 8\ (\text{GeV}/c)^2:$

Possible change of x shape at small k_t

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 k_T dependence consistent with PQCD/AdS/CFT

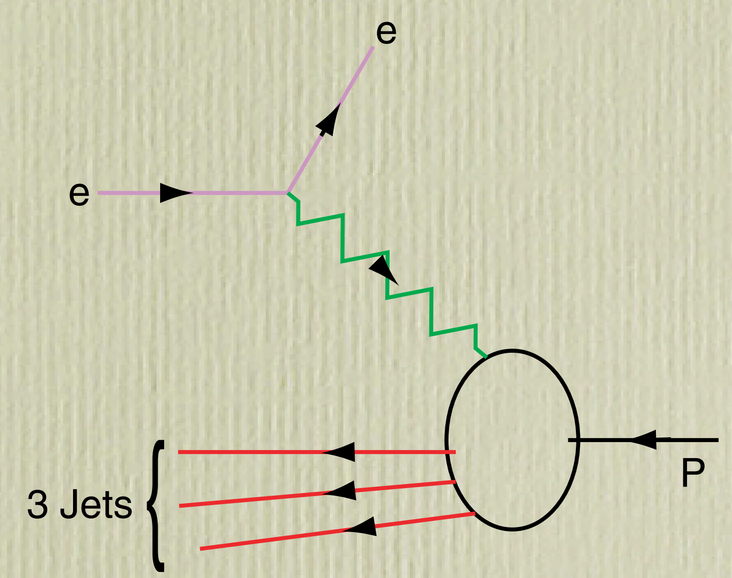
Diffractive Dissociation of Pion into Di-Jets

- 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



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

- Light Front Wavefunctions:

$$\left|\Psi_h(P^+, \vec{P}_\perp)\right\rangle = \sum_{n,\lambda_i} \int \left[dx_i\, d^2\vec{k}_{\perp i}\right] \psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i) \left|n : x_i P^+, x_i\vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i\right\rangle$$

Conformal Behavior:

$$\psi_{n/h}(\vec{k}_\perp) \to (k_\perp)^\ell \left[\frac{1}{\vec{k}_\perp^2}\right]^{n+\delta_n+\ell-1} .$$

Model Form from PQCD or AdS/CFT :

$$\psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i, l_{zi}) \sim \frac{(g_s\ N_C)^{\frac{1}{2}(n-1)}}{\sqrt{N_C}} \prod_{i=1}^{n-1} (k_{i\perp}^{\pm})^{|l_{zi}|} \left[\frac{\Lambda_o}{\mathcal{M}^2 - \sum_i \frac{\vec{k}_{\perp i}^2 + m_i^2}{x_i} + \Lambda_o^2}\right]^{n+|l_z|-1}$$

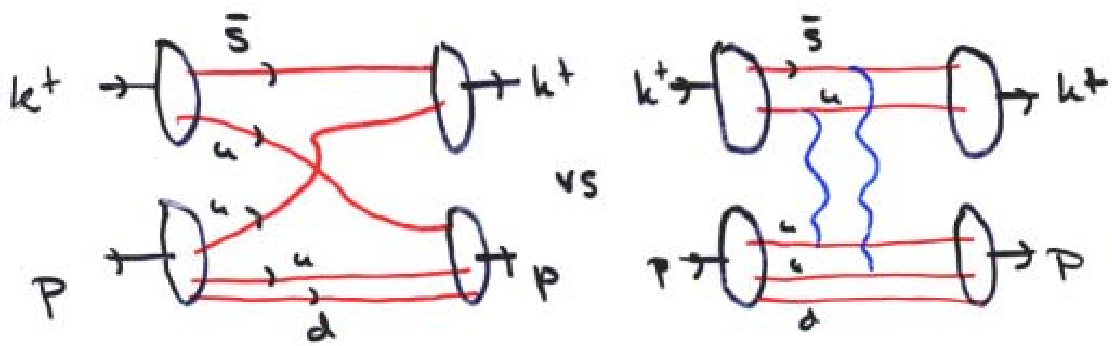
Near-Conformal Behavior of LFWFs Lead to PQCD Scaling Laws

- Bjorken Scaling of DIS
- Counting Rules of Structure Functions at large x
- Dimensional Counting Rules for Exclusive Processes and Form Factors
- Conformal Relations between Observables
- No Renormalization Scale Ambiguity

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



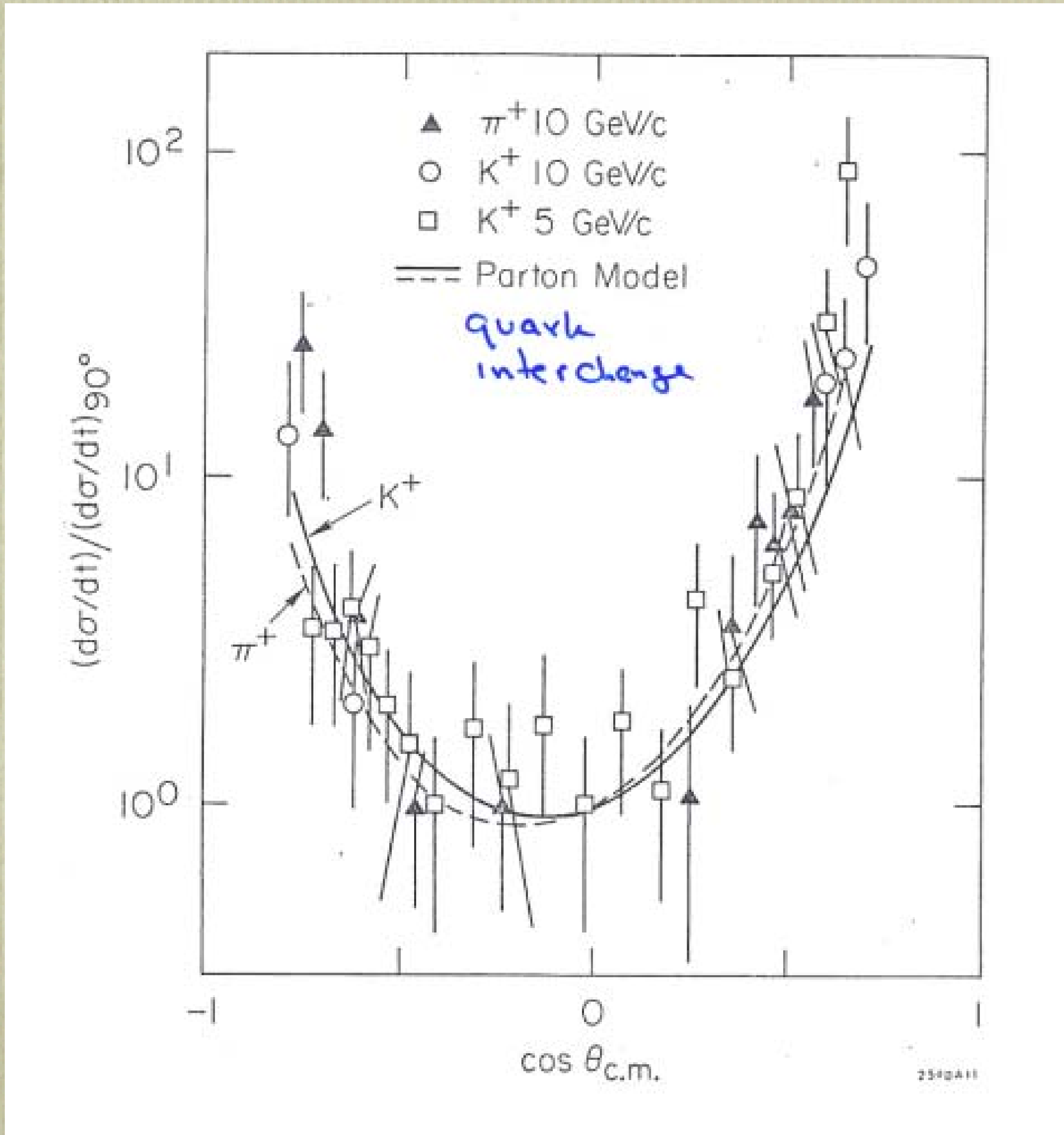
Quark Interchange $\qquad$ gluon exchange

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

Large N_C: Quark Interchange Dominant

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

't Hooft limit, AdS/CFT



New Perspectives AdS/CFT

Stan Brodsky, SLAC

$$M_{FI} = \langle \psi_F | E - K | \psi_I \rangle$$

$$\equiv \langle \psi_F | \Delta | \psi_I \rangle \qquad ($$

$$= \frac{1}{2(2\pi)^3} \int d^2k \int_0^1 \frac{dx}{x^2(1-x)^2} \, \Delta \psi_C(\vec{k}_\perp - x\vec{r}_\perp, x) \psi_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x) \psi_A(\vec{k}_\perp - x\vec{r}_\perp + (1-x)\vec{q}_\perp, x) \psi_B(\vec{k}_\perp, x),$$

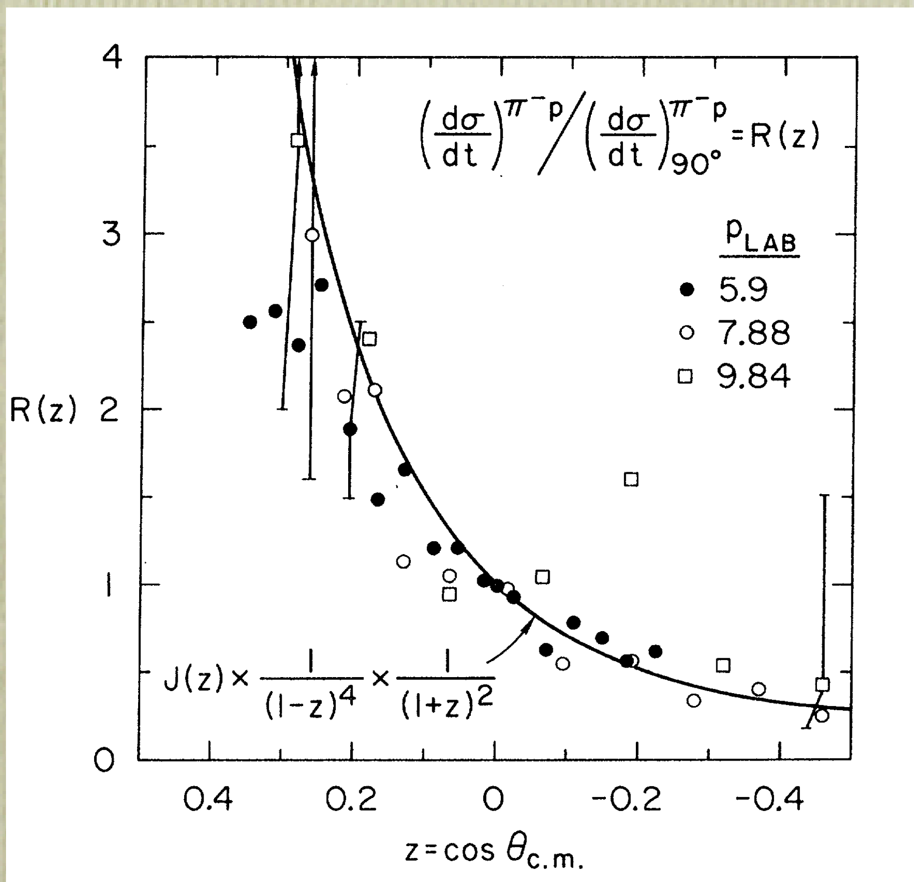
$$($$

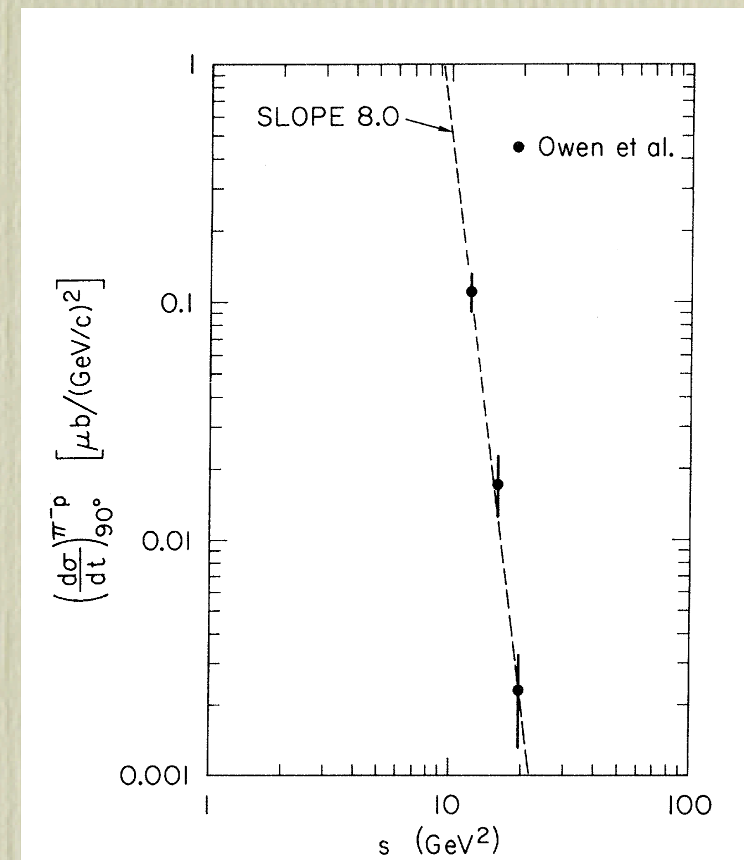
where

$$\Delta = s - M_A{}^2 - M_B{}^2 - K_a - K_b - K_c - K_d$$

$$= M_A{}^2 + M_B{}^2 - S_A(\vec{k}_\perp + (1-x)\vec{q}_\perp - x\vec{r}_\perp, x) - S_B(\vec{k}_\perp, x)$$

$$= M_C{}^2 + M_D{}^2 - S_C(\vec{k}_\perp - x\vec{r}_\perp, x) - S_D(\vec{k}_\perp + (1-x)\vec{q}_\perp, x) \; . \qquad ($$





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.

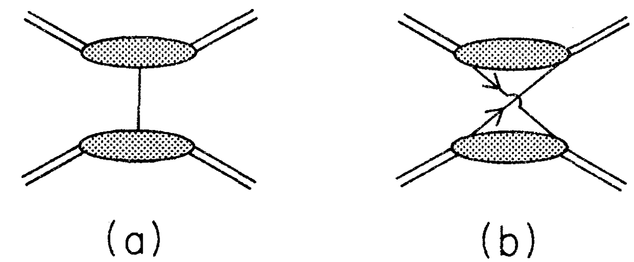
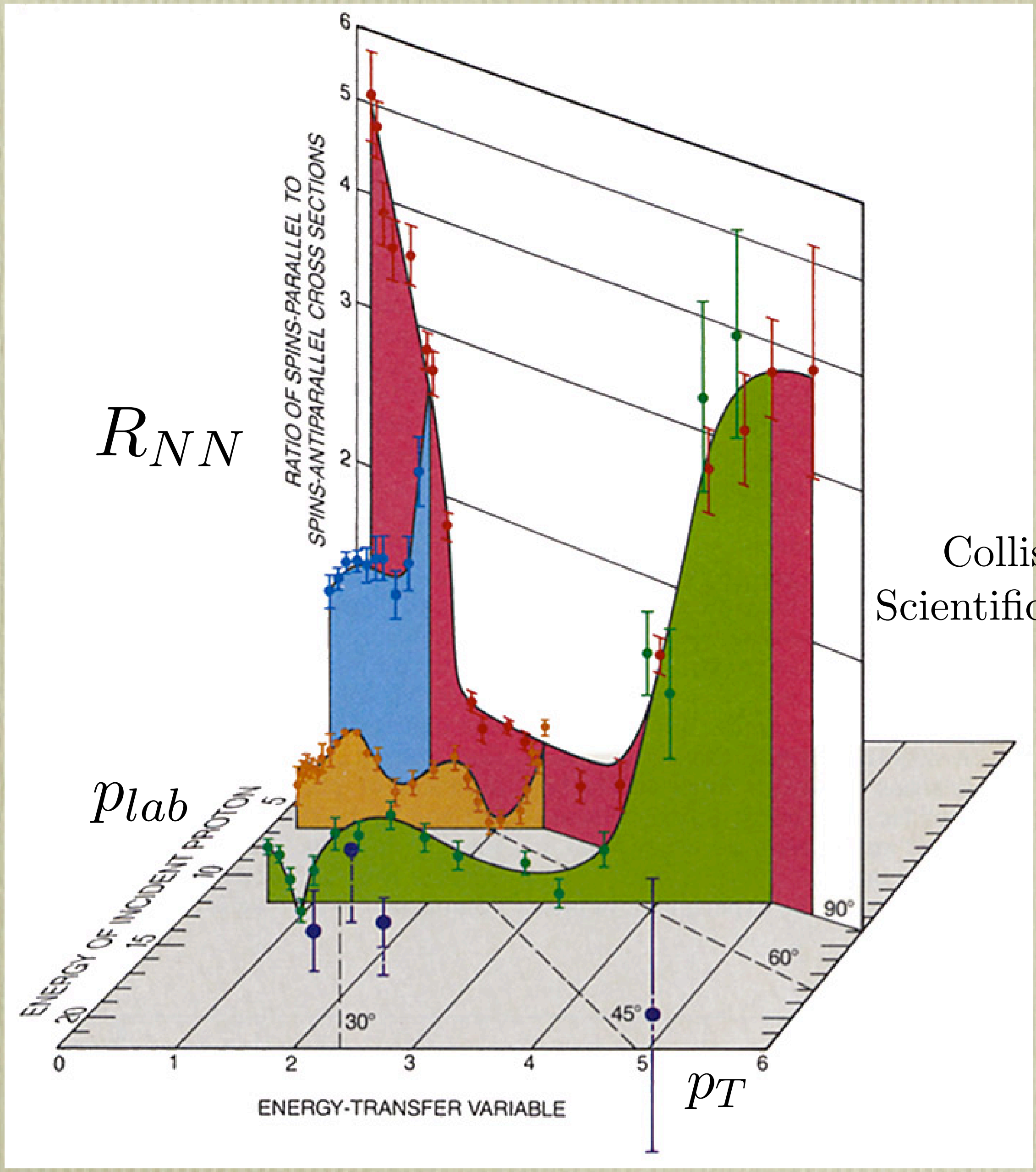


FIG. 1. The two basic types of interactions between hadrons: (a) gluon interchange and (b) constituent interchange.

The remarkable anomalies of proton-proton scattering

- Double spin correlations
- Single spin correlations
- Color transparency

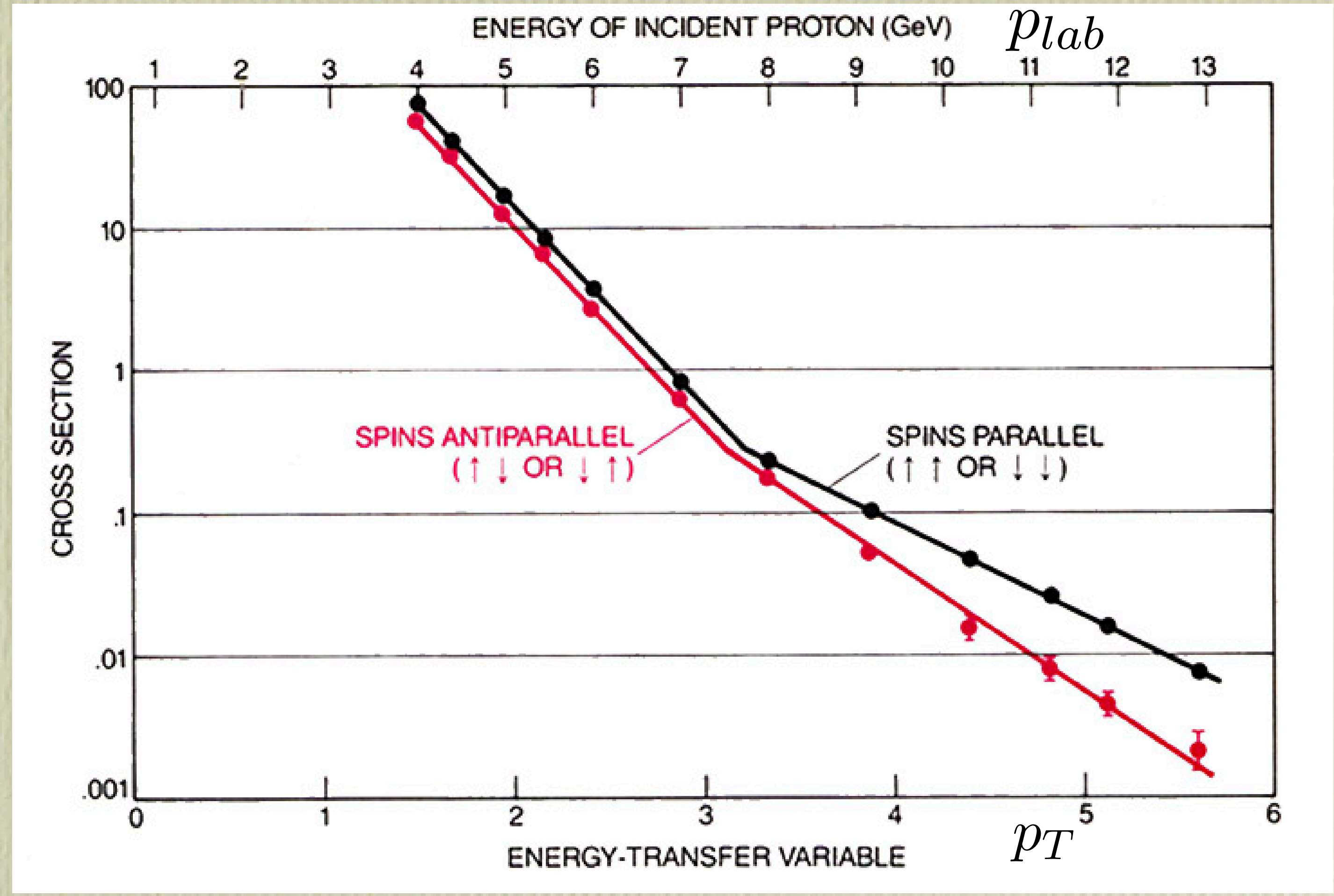
Spin Correlations in Elastic $p-p$ Scattering



Ratio reaches 4:1 !

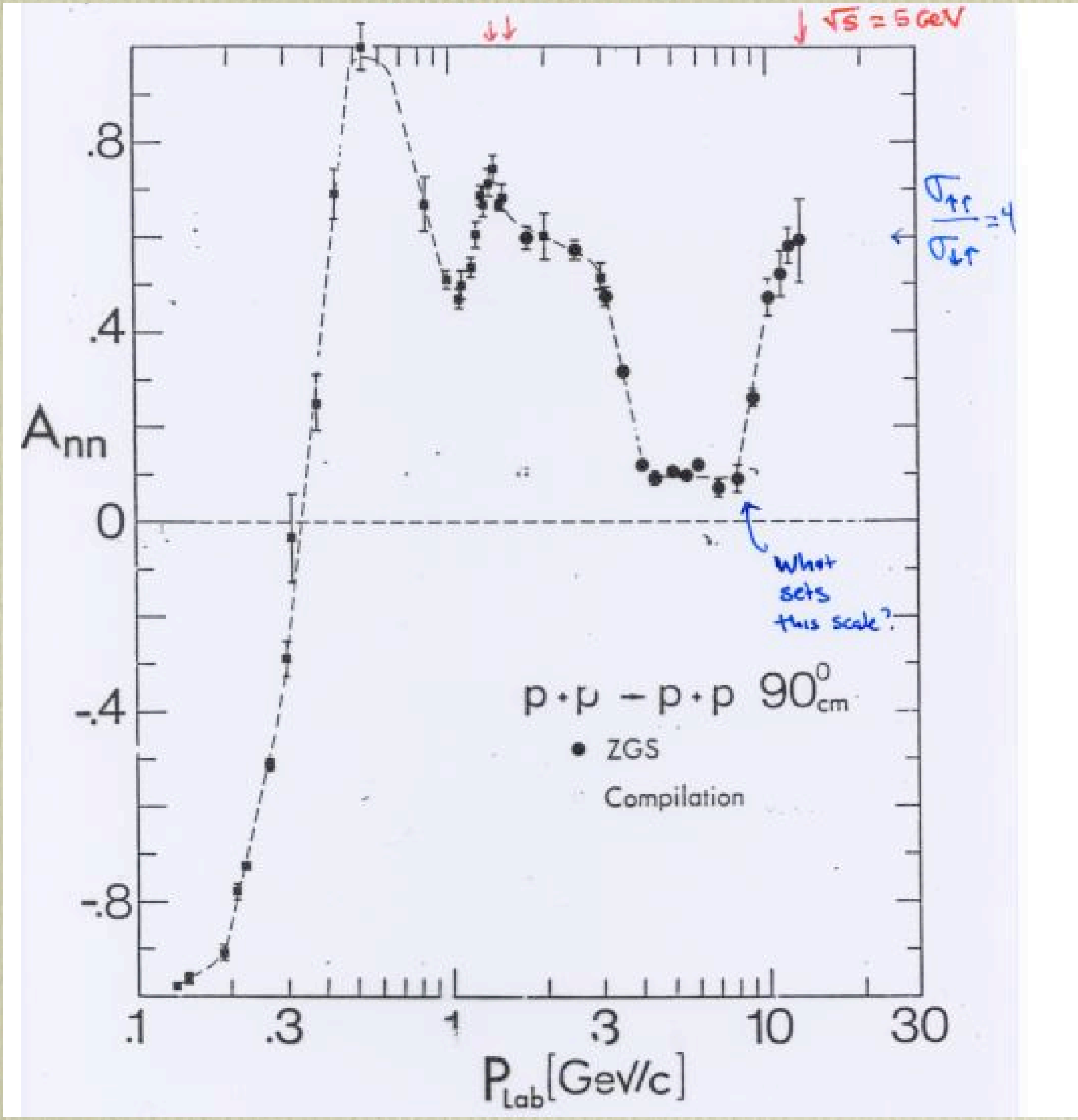
Collisions Between Spinning Protons (A. D. Krisch)
Scientific American, 255, 42-50 (August, 1987).

$$\frac{d\sigma_{\uparrow\uparrow}}{dt}(pp \to pp) \text{ at } \theta_{CM} = \pi/2$$

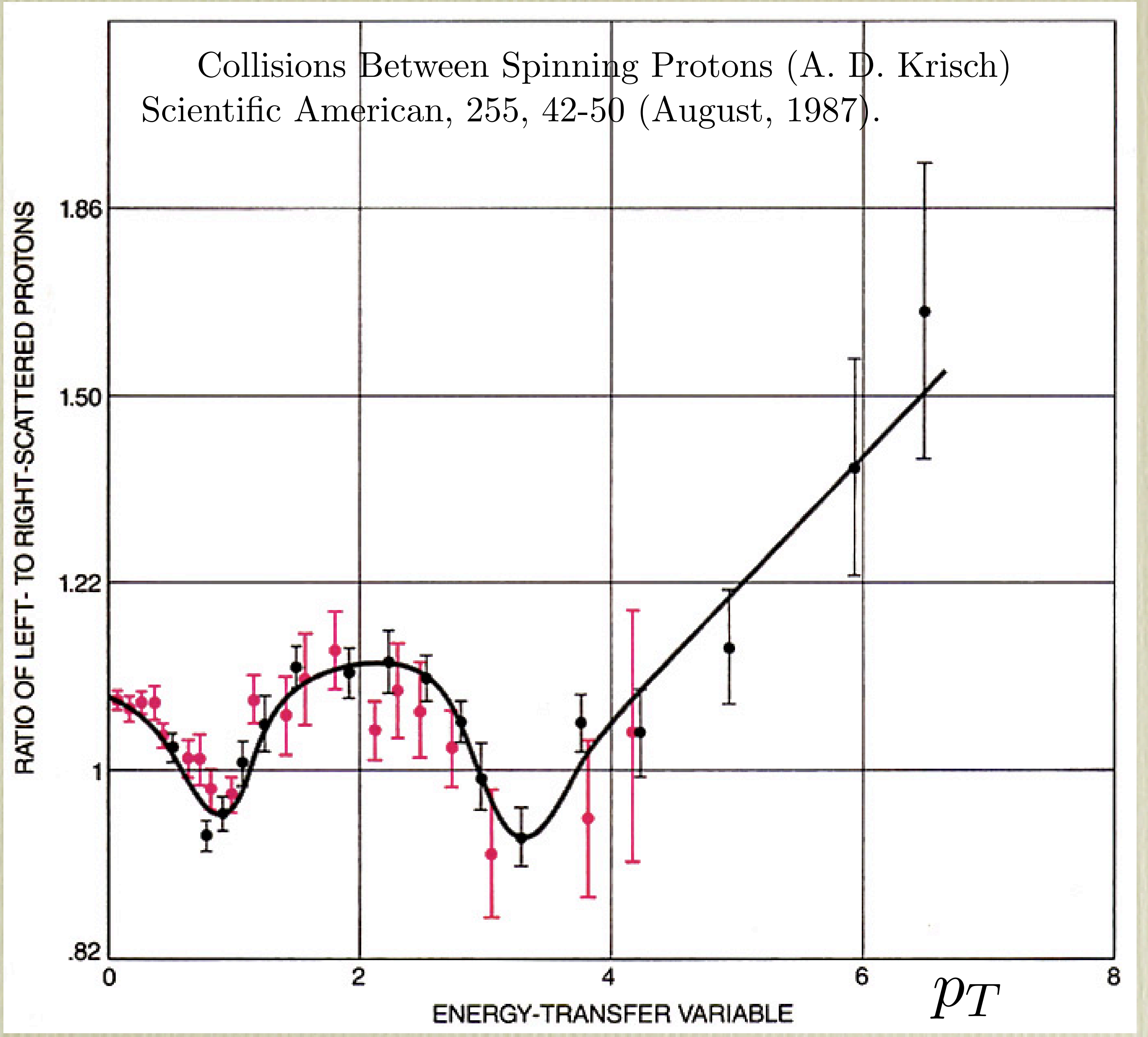


Collisions Between Spinning Protons (A. D. Krisch)
Scientific American, 255, 42-50 (August, 1987).

p Δ Strangeness Charm



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

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

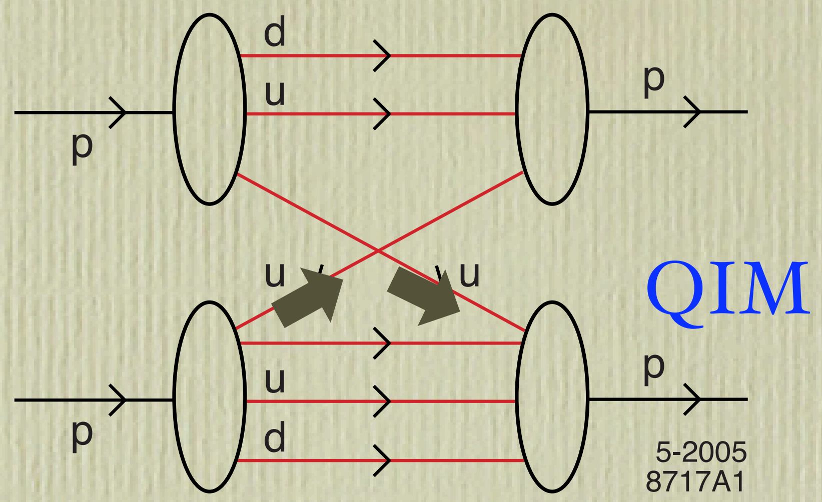
Interference of QIM and
Landshoff "Pinch" (triple scattering)
contributions

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



$$\frac{d\sigma}{dt}(pp \to pp) = C\,\frac{F_p^{\,2}(t)F_p^{\,2}(u)}{s^2}$$

$$\frac{d\sigma}{dt} = \frac{1}{s^{10}} f(\theta_{\rm c.m.})\,, \quad f(\theta_{\rm c.m.}) \sim \left(\frac{1}{1-\cos^2\theta}\right)^4 .$$

The biggest failure of the interchange mechanism is in the spin correlation. For all angles we predict from Table I

$$A_{nn} = \frac{1}{3}\,\frac{1-(\frac{3}{31})^2\chi^2}{1+\frac{1}{3}(\frac{3}{31})^2\chi^2}\,, \tag{3.11}$$

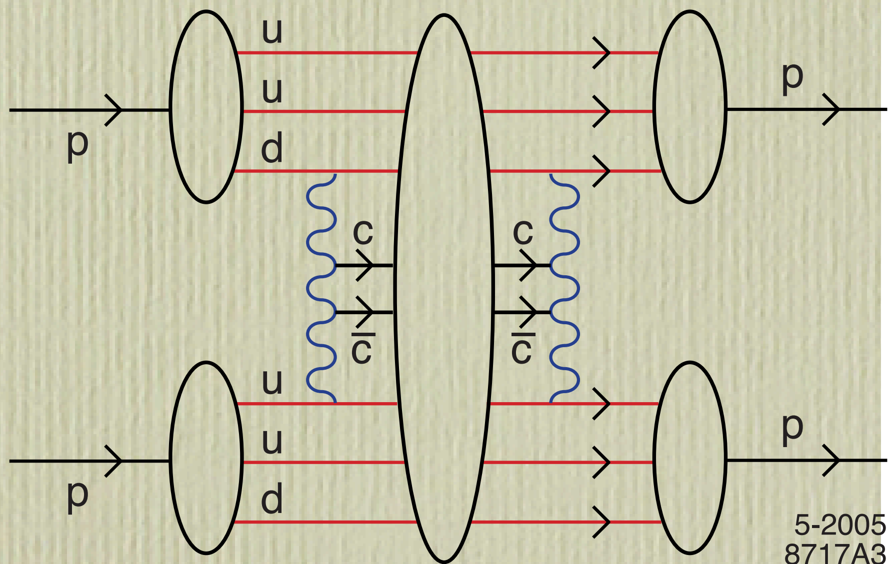
where

$$\chi = \frac{f(\theta)-f(\pi-\theta)}{f(\theta)+f(\pi-\theta)} .$$

Thus A_{nn} is predicted to be within 2% of $\frac{1}{3}$ even when $\chi = 1$ [$\chi = 0$ for the form in Eq. (3.6)]. The data clearly indicate that A_{nn} is not a constant near $\frac{1}{3}$.

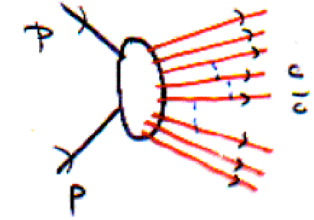
Our expectation, then, is that there is an additional amplitude which strongly interferes with the quark-interchange contributions at Argonne energies; most plausibly, the quark-interchange contribution is dominant at asymptotic t and u, and the interfering amplitude is most important at low t and u. As we shall discuss below, the behavior of A_{ll} and A_{ss} in the interference region can play an important role in sorting out the possible subasymptotic contributions.

These results for the quark-interchange model have also been obtained by Farrar, Gottlieb, Sivers, and Thomas,[12] who also consider the possibility that nonperturbative effects (quark-quark scattering via instantons) can explain the data.



Spin, Coherence at heavy quark threshold

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



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

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

8 quarks in S-wave odd parity!

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

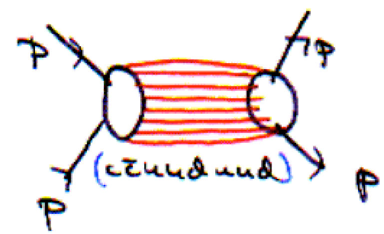
$B = 2$

resonance near threshold ?

SAB + determined

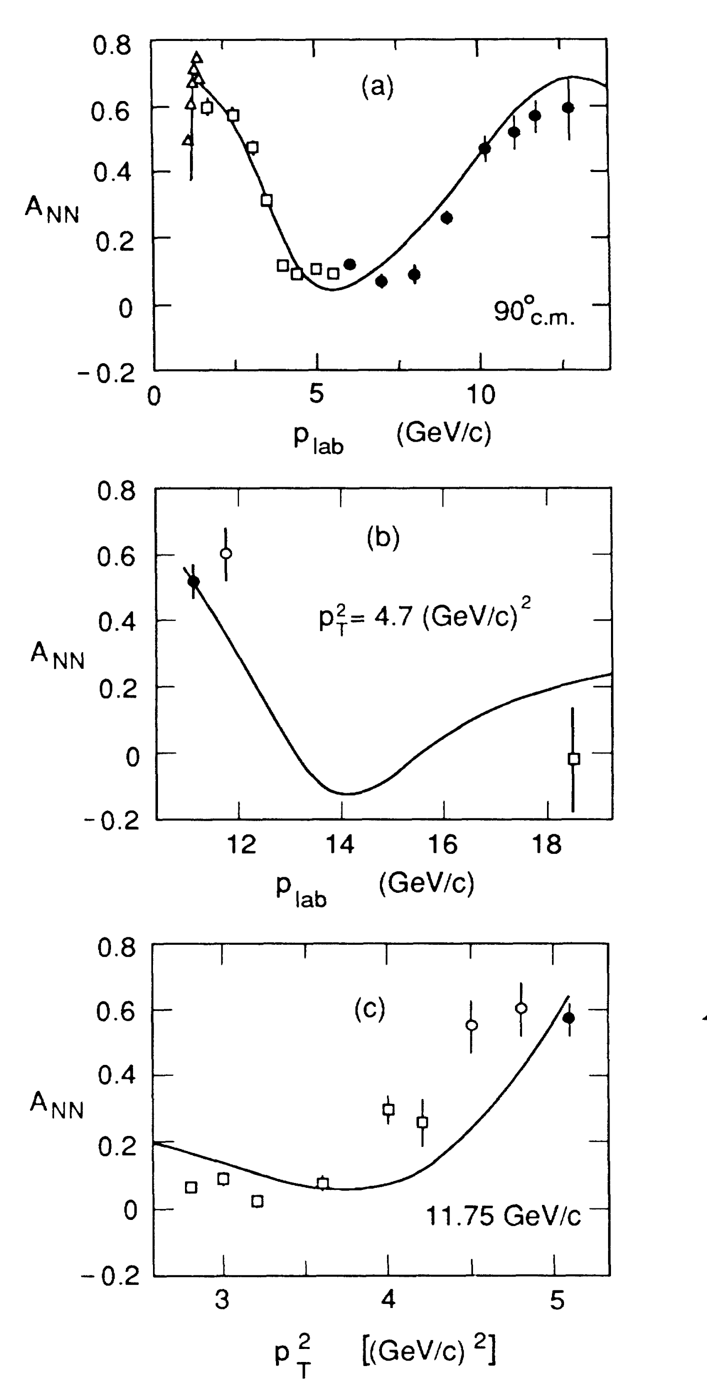
$\frac{d\sigma}{dt}(pp \to pp)$

$\sqrt{s} \sim 5$ GeV



$A_{NN} = 1$ for $J=L=S=1$ $p\uparrow p\uparrow$ 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).

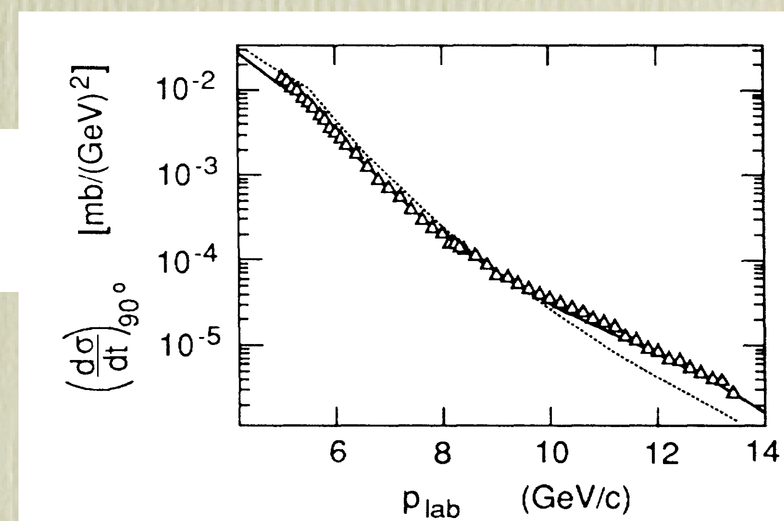
Quark Interchange + 8-Quark Resonance

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

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

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

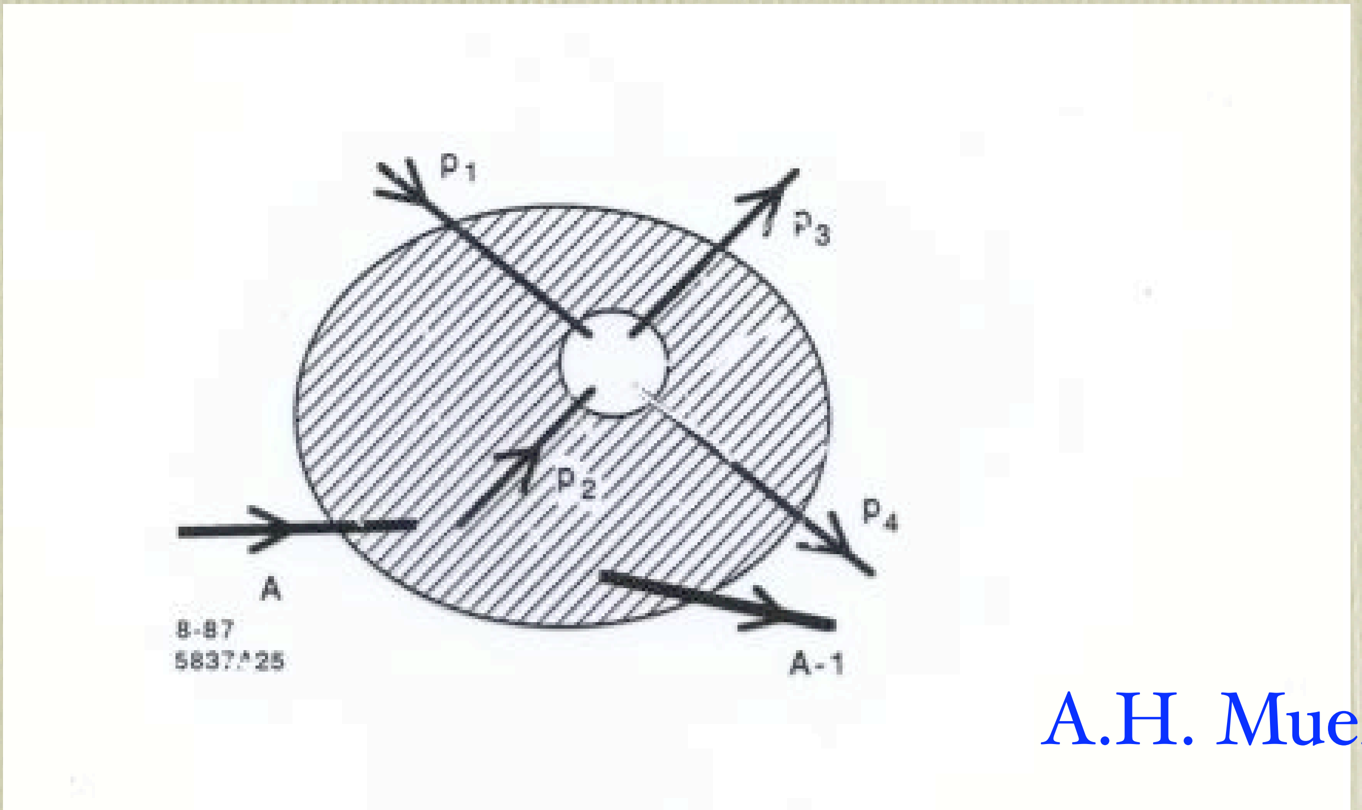
$$A_{NN} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)}$$



New Perspectives AdS/CFT

Test Color Transparency

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



A.H. Mueller, SJB

A. Mueller
SJB

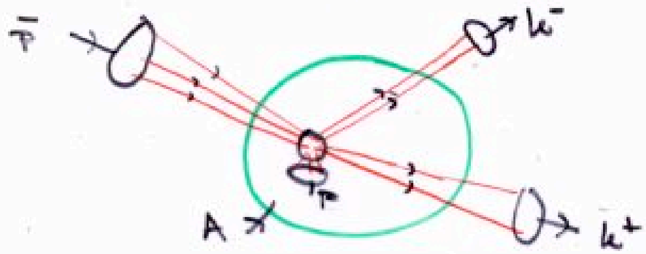
Color Transparency

in quasi-elastic $\bar{p}$ reactions

$$\phi(x,Q) \to \psi(x, b_\perp \sim O(\tfrac{1}{Q}))$$

small color dipole fluctuation

T_H ~ pointlike at large s,t.



$$\frac{d\sigma}{dt}(\bar{p} A \to k^+ k^- (A-1))$$

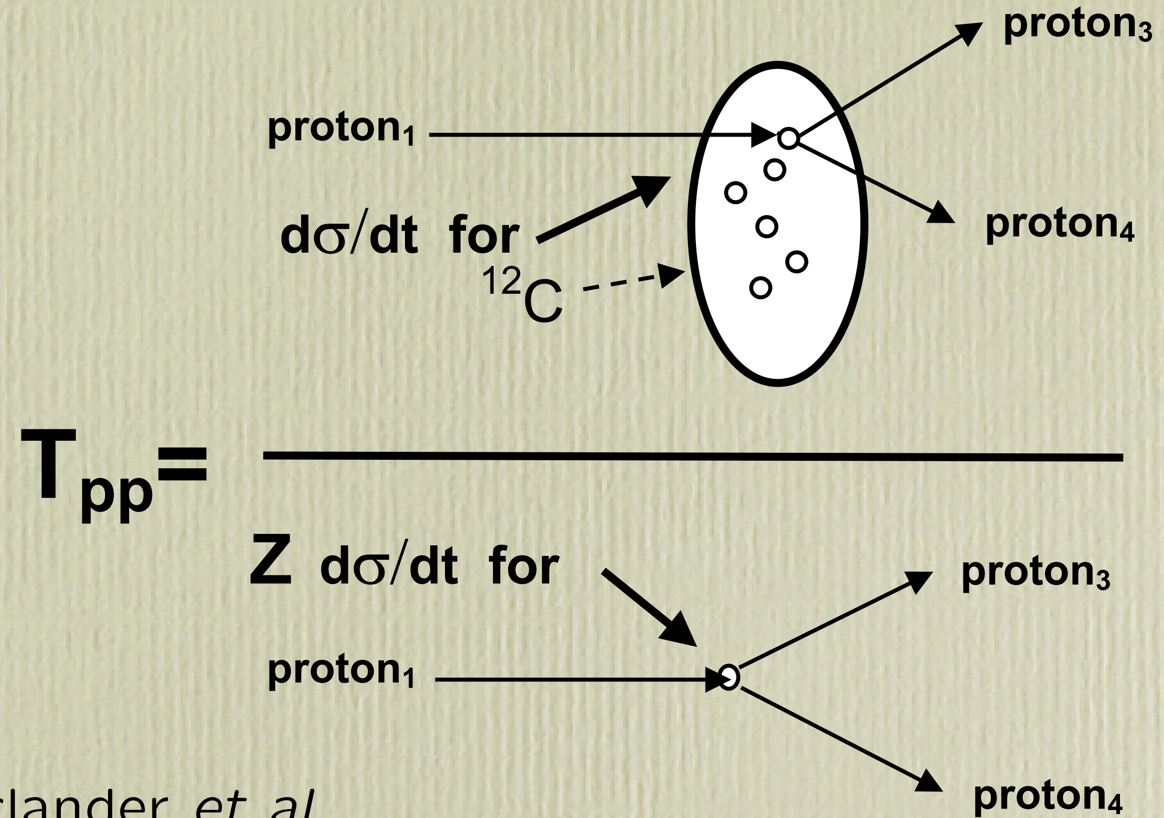
$$\simeq Z \frac{d\sigma}{dt}(\bar{p} p \to k^+ k^-)$$

Compare Glauber : $Z^{1/3}$!

Note: requires $\bar{p}, k^-, k^+$ to stay small over nuclear volume

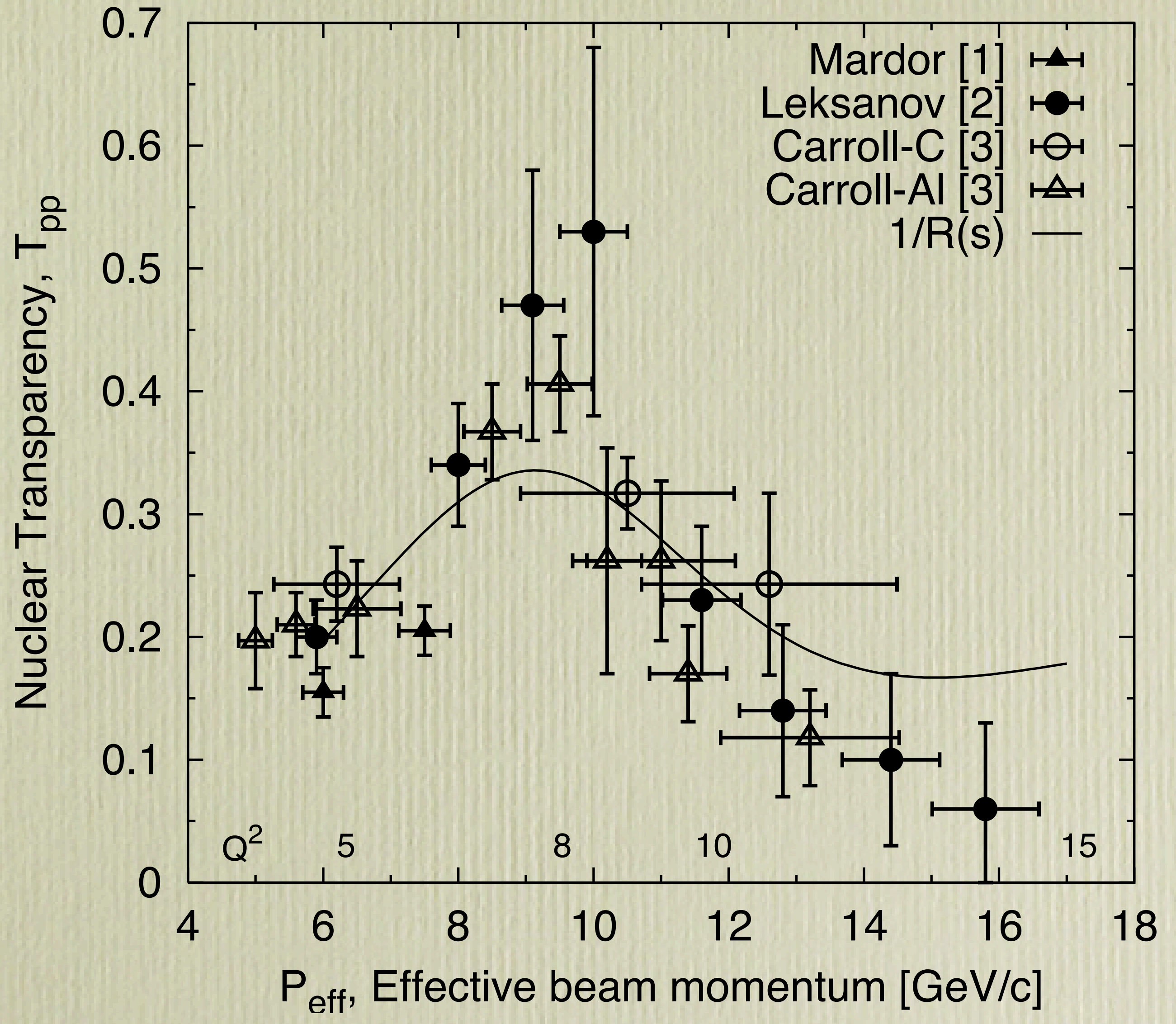
Formation time const.

Color Transparency Ratio

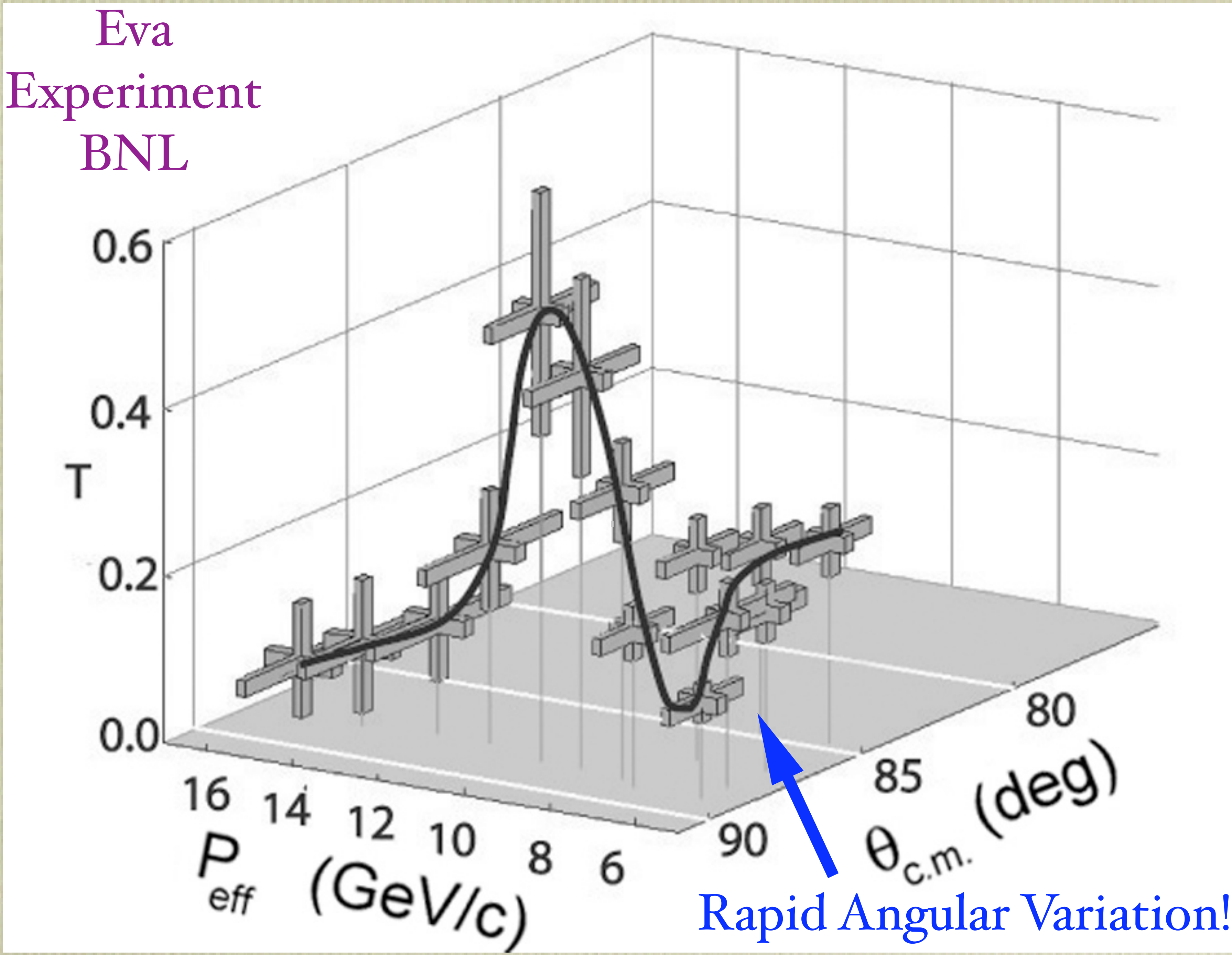


J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p, 2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

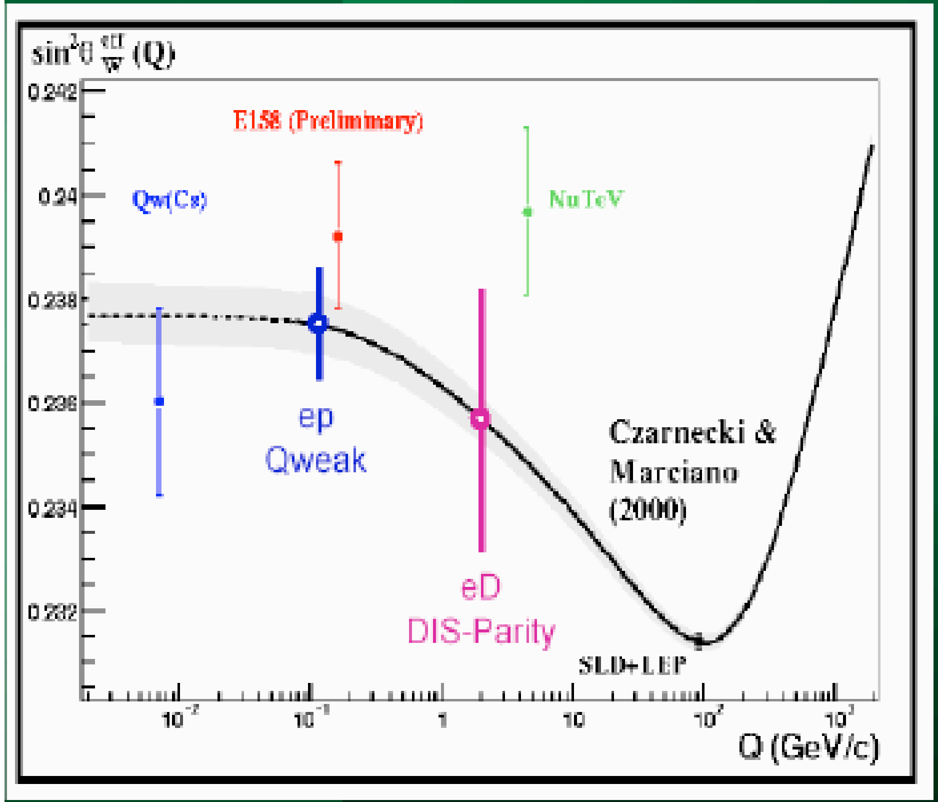
Color Transparency fails when Ann is large



New Perspectives AdS/CFT


Eva
Experiment
BNL
0.6
0.4
T
0.2
0.0
16
14
12
10
8
6
P_{eff} (GeV/c)
90
85
80
$\theta_{c.m.}$ (deg)
Rapid Angular Variation!

problem waiting for solution/explanation
→ NuTeV anomaly



From talk by Y. Kolomensky
At SLAC summer institute, August 2004

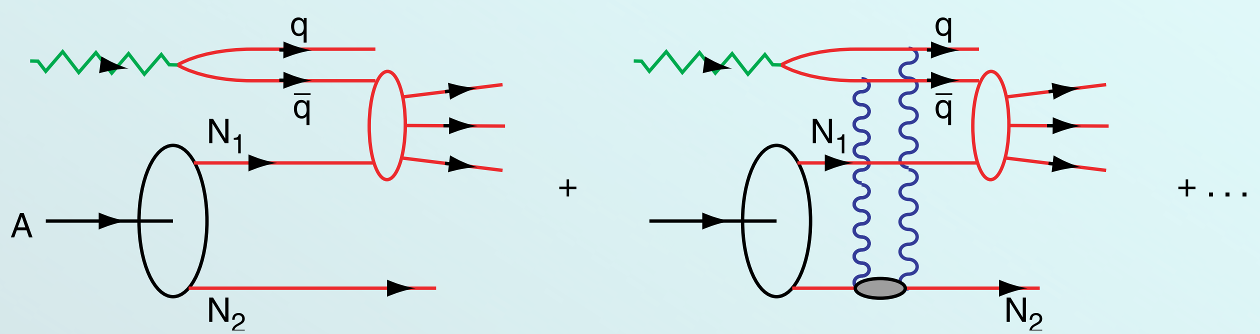
$\sin^2\theta_W$ determined from the ratio:

$$R = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}}$$

Assumptions:

- Isospin symmetry ie. $u_p(x)=d_n(x)$ (u in proton as d in neutron)
- Sea momentum symmetry: $s=\bar{s}$ and $c=\bar{c}$
- Nuclear effects common in W and Z exchange

Origin of Nuclear Shadowing in Glauber - Gribov Theory



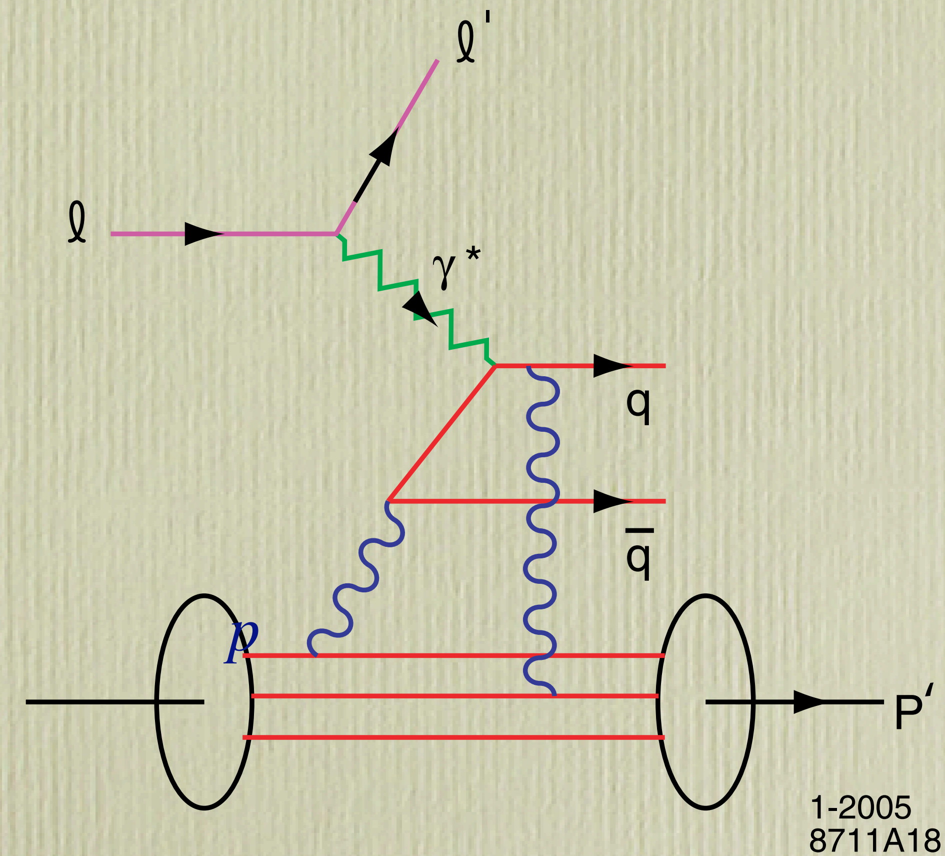
Interference of one-step and two-step processes

Interaction on upstream nucleon diffractive

Phase i X i = - 1 produces destructive interference

No Flux reaches down stream nucleon

Final State Interaction Produces Diffractive DIS



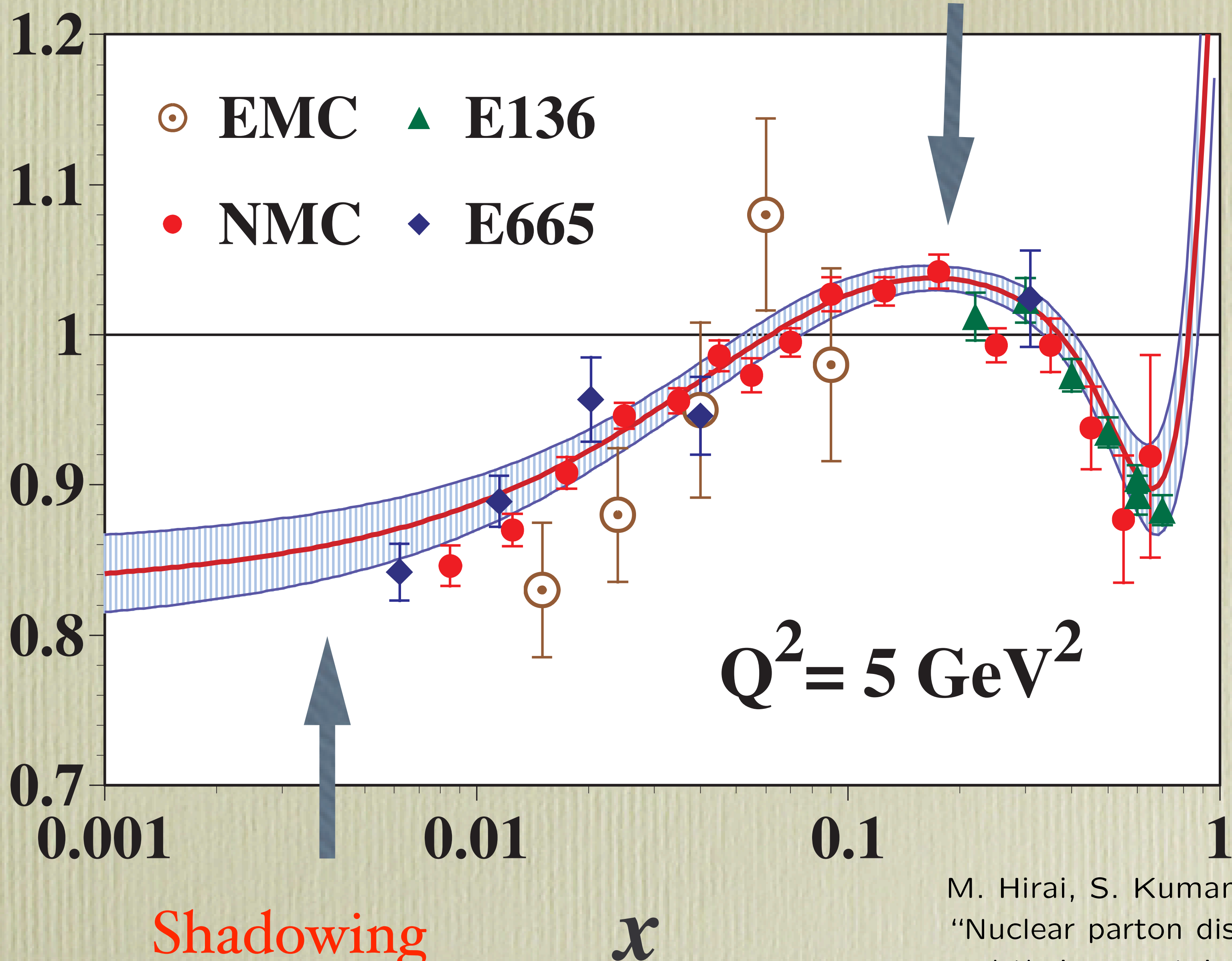
Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

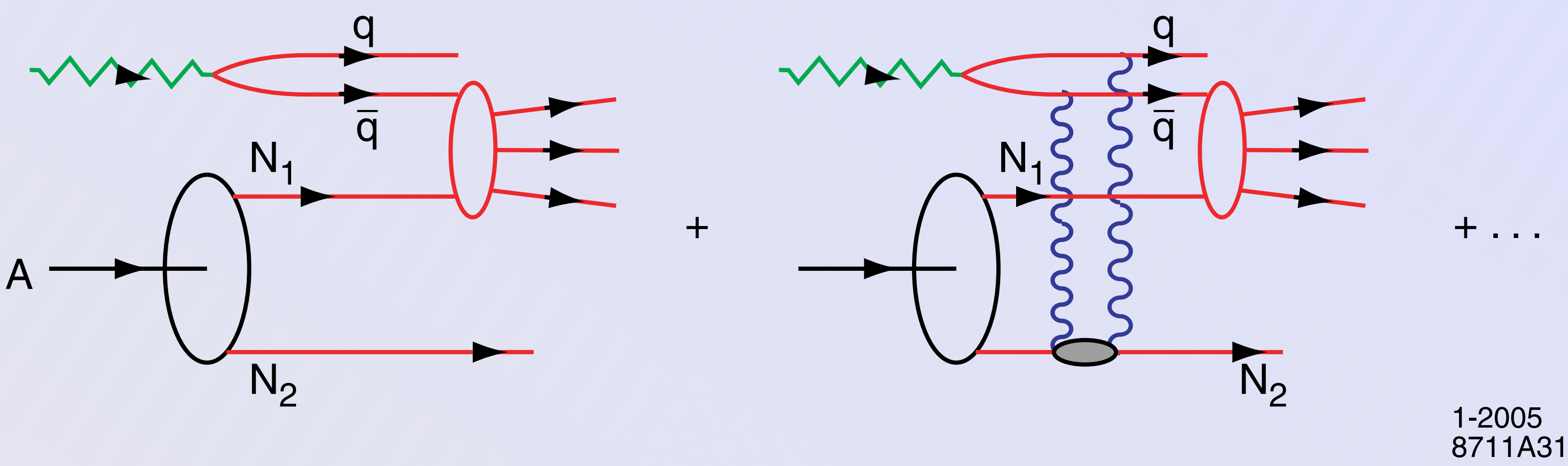
Anti-Shadowing



Shadowing

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 !

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}

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

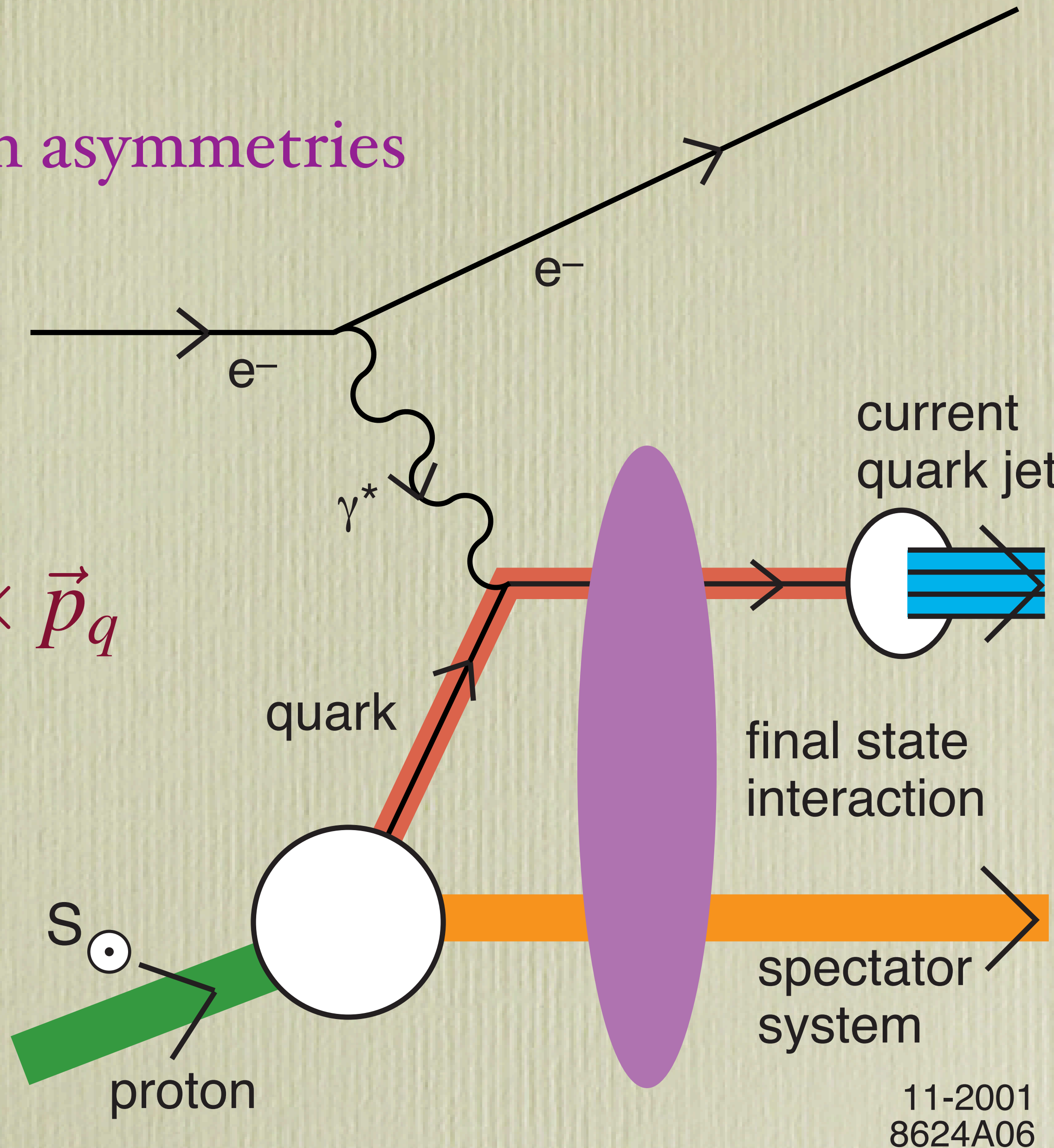
Need new experimental studies of antishadowing in

- Parity-violating DIS
- Spin Dependent DIS
- Charged and Neutral Current DIS

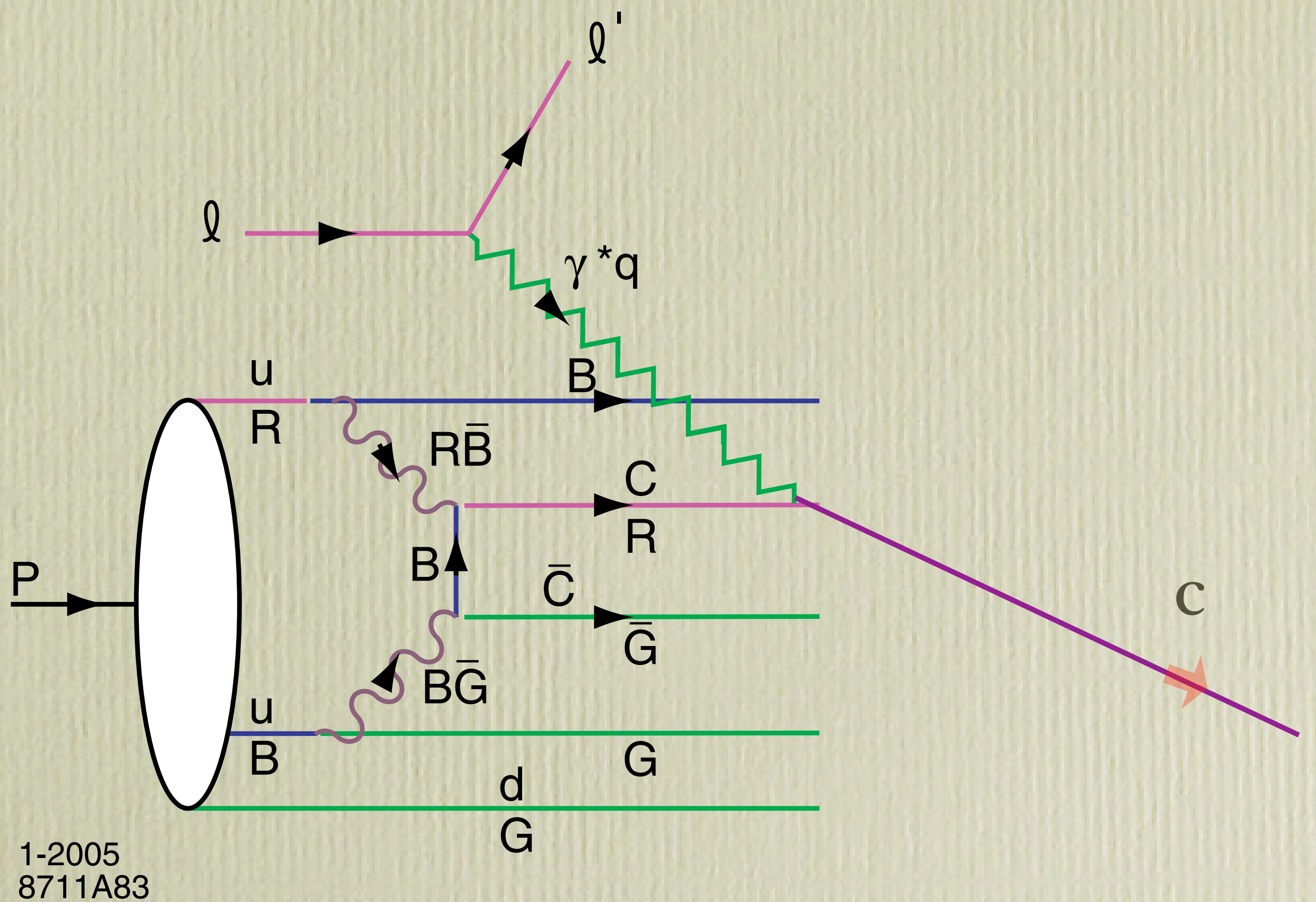
Single-spin asymmetries

Sivers Effect

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

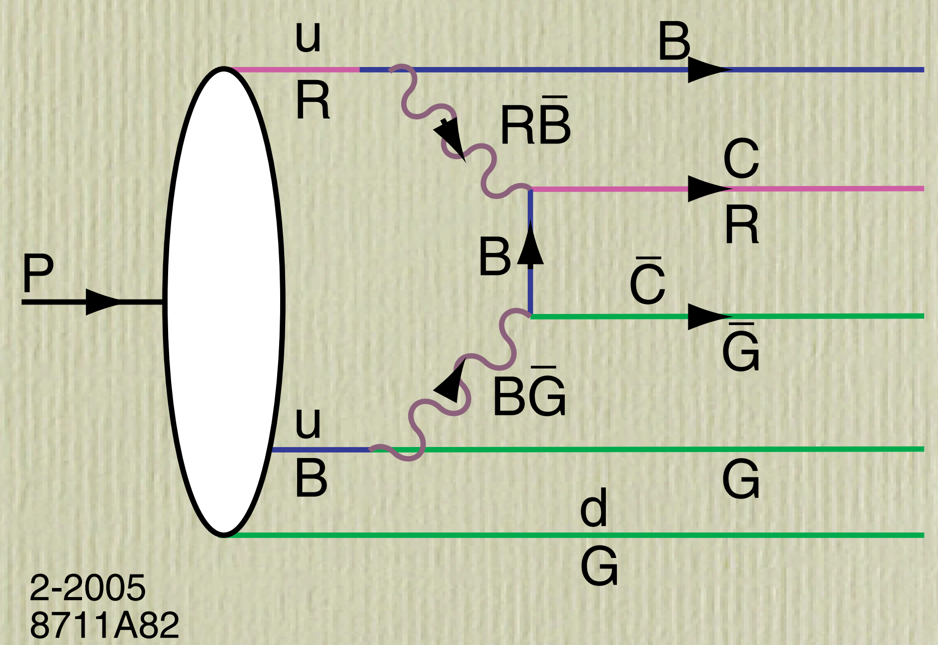


Measure c(x) in Deep Inelastic Lepton-Proton Scattering



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 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 $pp \to \Lambda_b X$

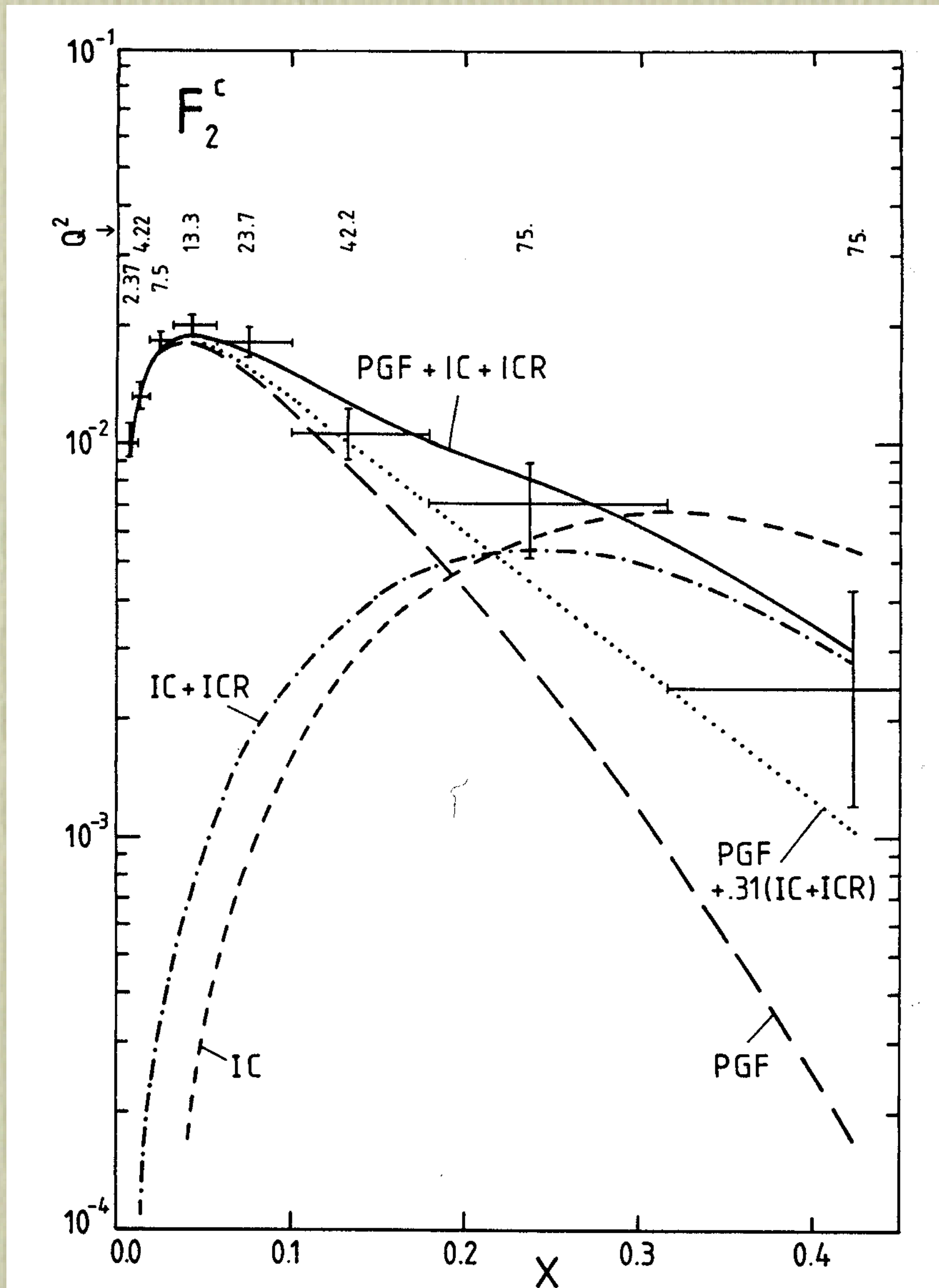
- High x_F $pp \to \Xi(ccd) X$ (SELEX)

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

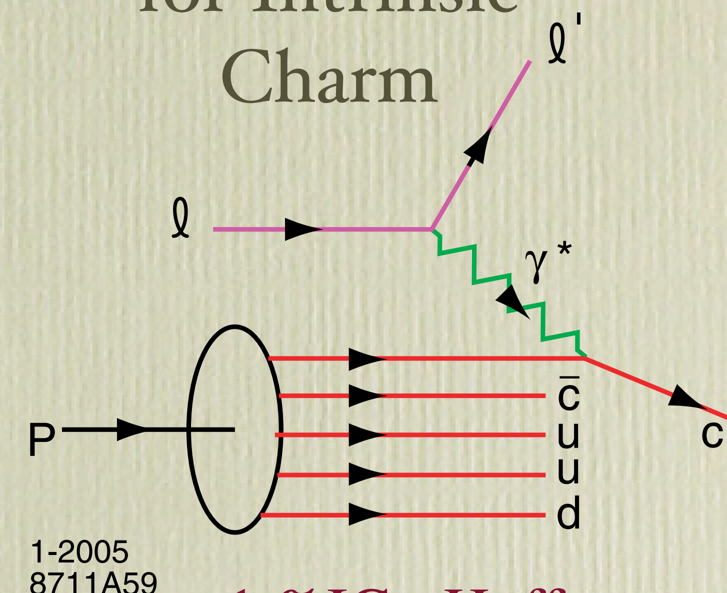
- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in B decay (Gardner, SJB)



Measurement of Charm Structure Function

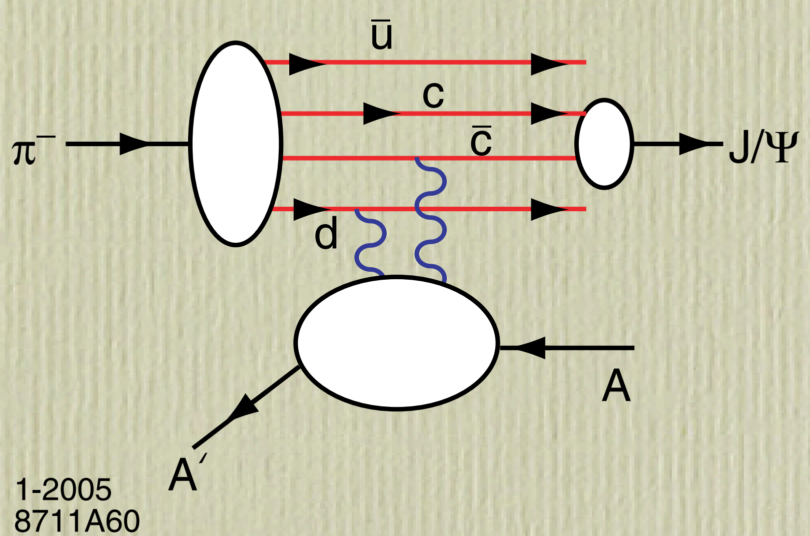
Evidence for Intrinsic Charm

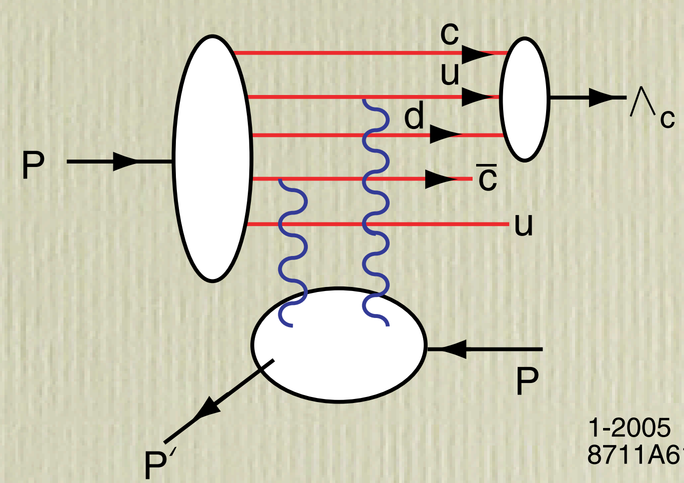


1 %IC - Hoffmann, Moore

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

Diffractive Dissociation of Intrinsic Charm

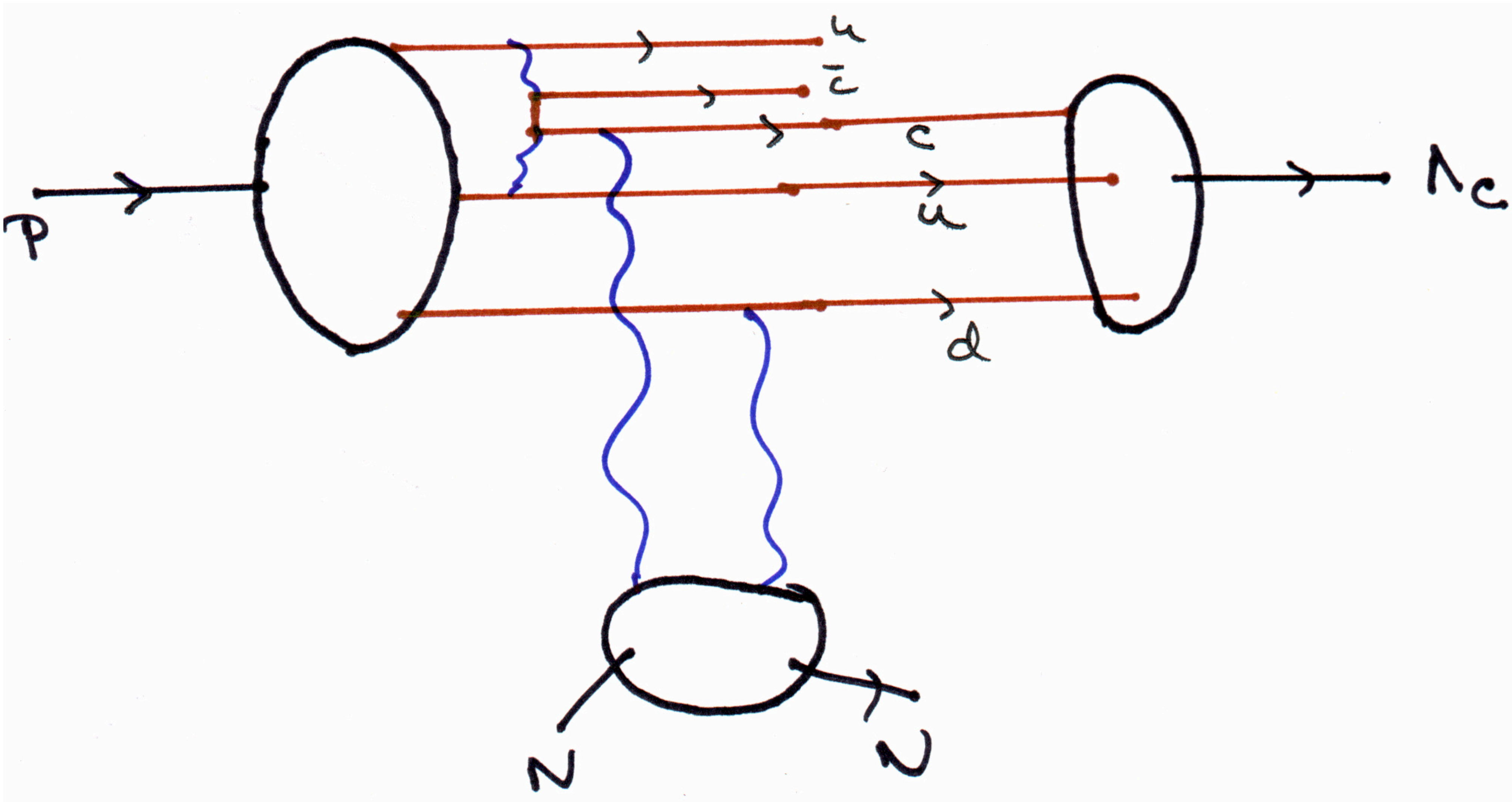




Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

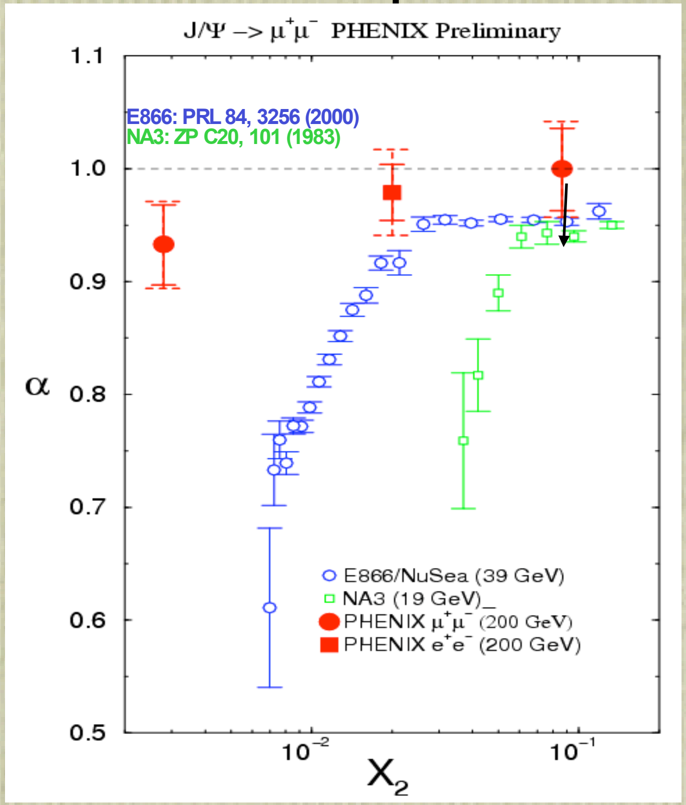
$p\ p \to p\Lambda_c X$

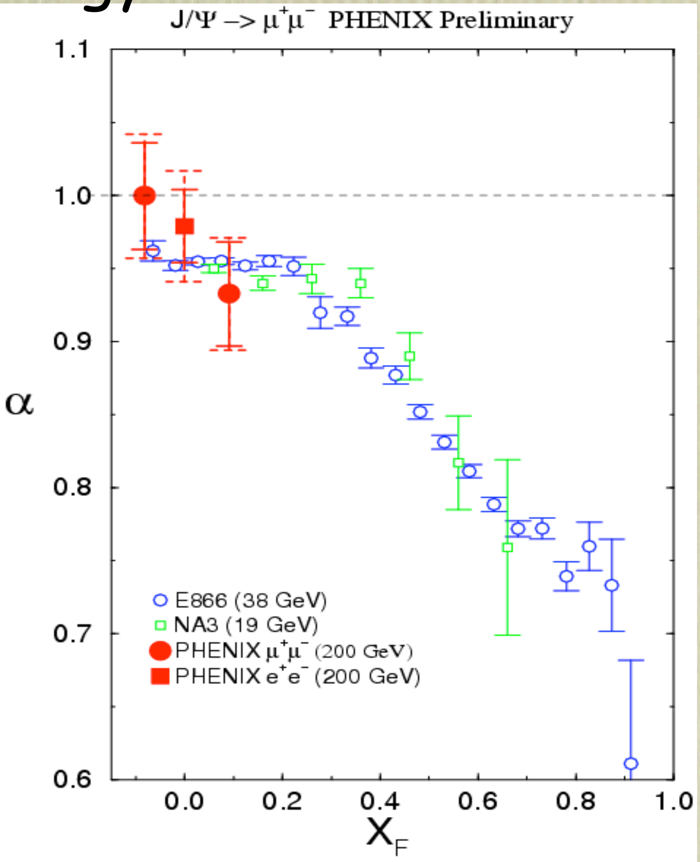
Diffractive Dissociation of Intrinsic Charm



J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

PHENIX compared to lower energy measurements





Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

Data favors (weak) shadowing + (weak) absorption (a > 0.92)

With limited statistics difficult to disentangle nuclear effects

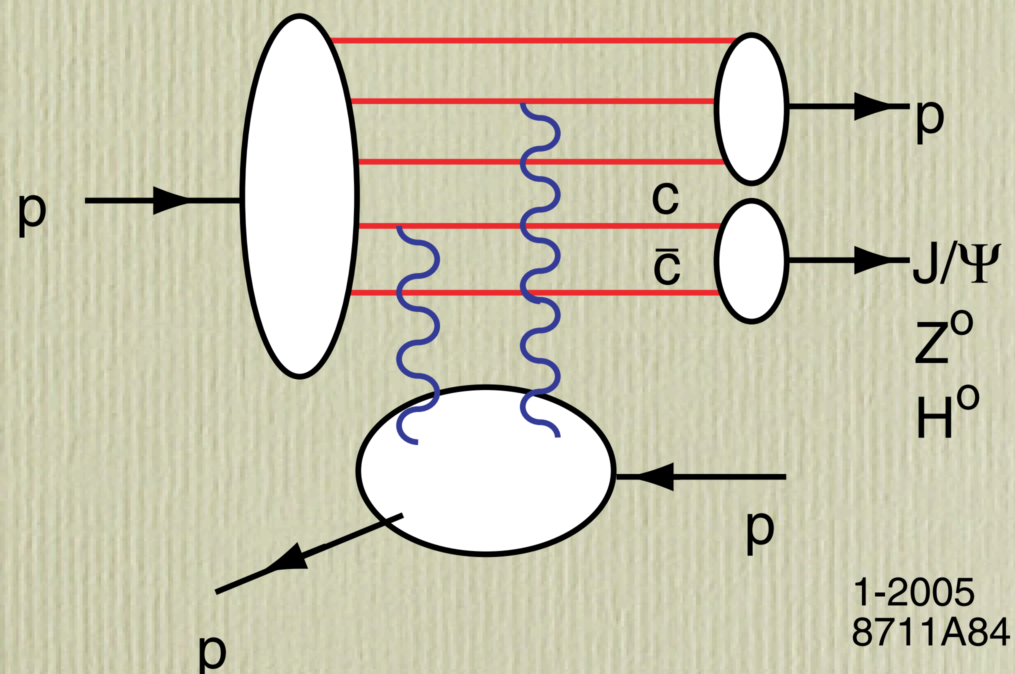
Will need another dAu run! (more pp data also)

Not universal versus X_2 : shadowing is not the main story.

BUT does scale with x_F ! - why?

(Initial-state gluon energy loss -which goes as x_1~x_F - expected to be weak at RHIC energy)

Intrinsic Charm Mechanism for Double Diffraction



$$\mathrm{p\ p} \to J/\psi\ p\ p$$

$$x_{J/\psi} = x_c + x_{\bar{c}}$$

High x_F !

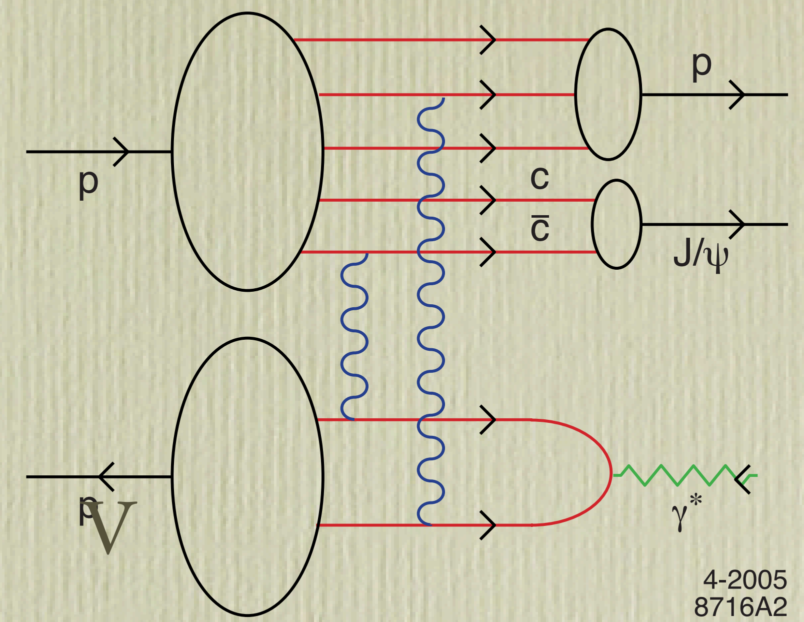
Intrinsic $c\bar{c}$ pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

Collision produces color-singlet J/ψ through color exchange

Schmidt, Soffer, sjb

RHIC Experiment

New Test of Intrinsic Charm



Doubly Diffractive DIS Reactions

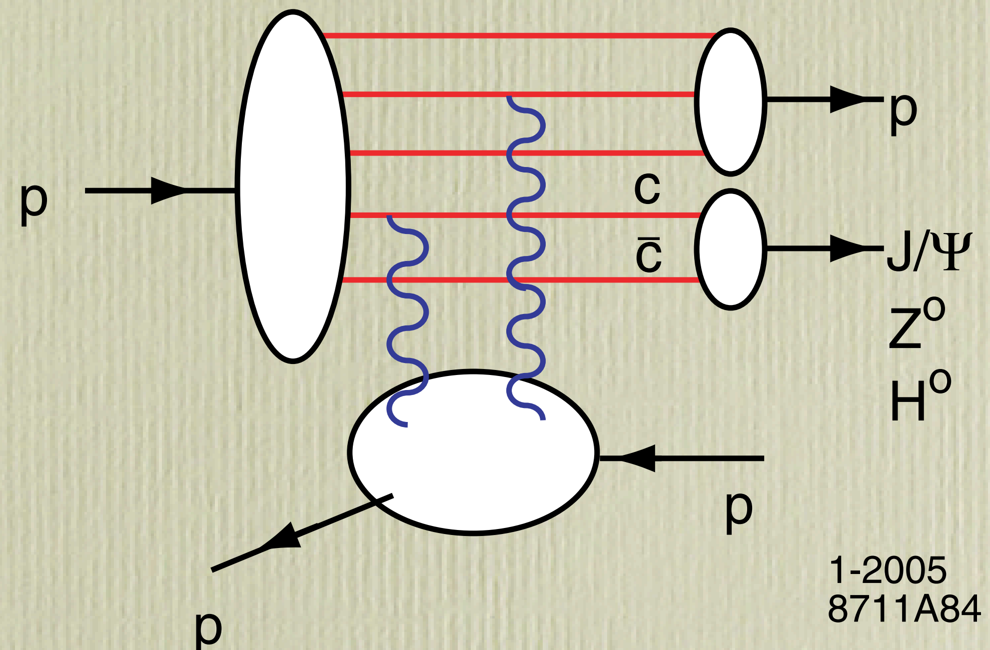
$$\gamma^* p \to \rho + J/\psi + p$$

$$\gamma^* p \to \rho + D + \Lambda_c$$

Charm produced at high x_F and small p_T
in proton fragmentation region

New Mechanism for Forward Higgs production

Doubly Diffractive



Kopeliovitch, Schmidt, Soffer,
SJB

Nuclear Chromodynamics

The Emergence of Nuclei from QCD. Studies of scattering between two nucleons at low energy demonstrate that their interactions can be described in part in terms of the exchange of mesons. This insight is the basis for many successful models of nuclear structure. However, the fundamental constituents of nuclei are quarks and gluons, whose interactions are described by QCD. Both nucleons and mesons are composites of quarks, that can not exist in isolation due to confinement. This leads to some of the most fundamental questions in modern nuclear physics:

- How do the nucleon-based models of nuclear physics with interacting nucleons and mesons arise as an approximation to the quark-gluon picture of QCD?
- In probing ever-shorter distances within the nucleus, what is the role of the fundamental constituents of QCD — quarks and gluons — in the description of nuclei?
- Does the nuclear environment modify the quark-gluon structure of nucleons and mesons?

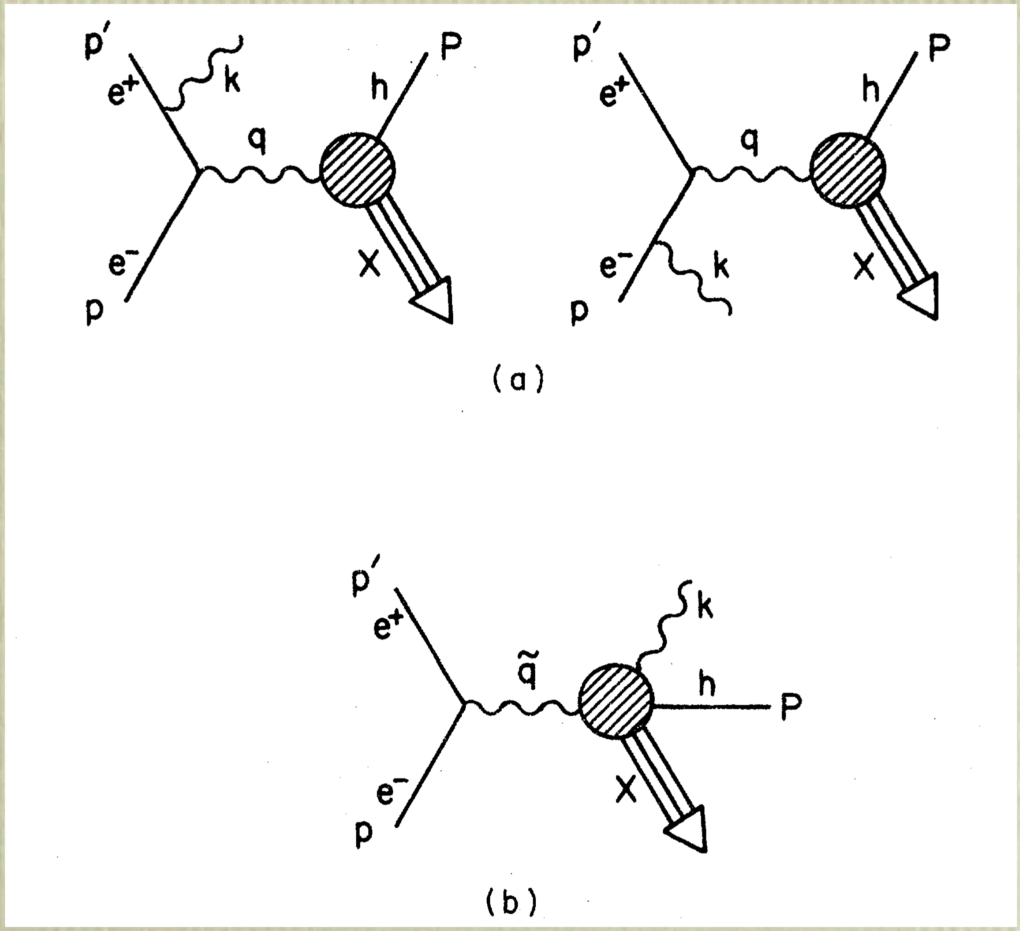
Rigorous Prediction of QCD:

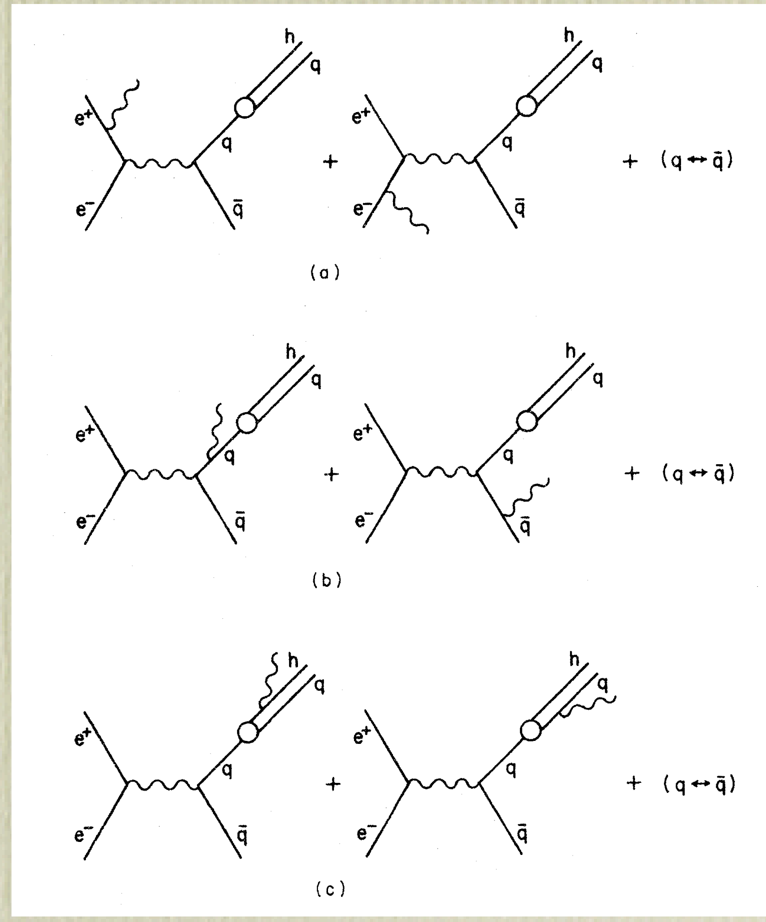
Hidden Color!

EMC and Anti-Shadowing

New Perspectives AdS/CFT

S. J. Brodsky, C. E. Carlson and R. Suaya,
"Charge Asymmetry In $e^+e^- \to \gamma+$ Hadrons:
New Tests Of The Quark - Parton Model And Fractional Charge,"
Phys. Rev. D **14**, 2264 (1976).





S. J. Brodsky, C. E. Carlson and R. Suaya,
"Charge Asymmetry In $e^+e^- \to \gamma +$ Hadrons:
New Tests Of The Quark - Parton Model And Fractional Charge,"
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$$R_h^{(3)}(x) \equiv \frac{\Delta_h}{k_0 d\sigma/d^3k\, d\Omega_\mu + k_0 d\sigma/d^3k\, d\Omega_{\bar{\mu}}} = \sum_q \frac{e_q^{\,3}}{e^3}[D_q^h(x) - D_{\bar{q}}^h(x)].$$

$$\Delta_h \equiv \frac{d\sigma(e^+e^- \to \gamma h X)}{(d^3k/k_0)d\Omega_h dx} - \frac{d\sigma(e^+e^- \to \gamma \bar{h} X)}{(d^3k/k_0)d\Omega_{\bar{h}} dx}$$

Charged-Cubed Sum Rule!

Quantum-number sum rules. We can define the effective multiplicity of hadron h from fragmentation of quark q as

$$n_q^h = \int_0^1 dx\, D_q^h(x). \qquad (10)$$

Then

$$\int_0^1 R_h^{(2)}(x)\, dx = \sum_q \frac{e_q^{\,2}}{e^2}(n_q^h + n_{\bar{q}}^h) = (n_h + n_{\bar{h}}) \sum_q \frac{e_q^{\,2}}{e^2}, \qquad (11)$$

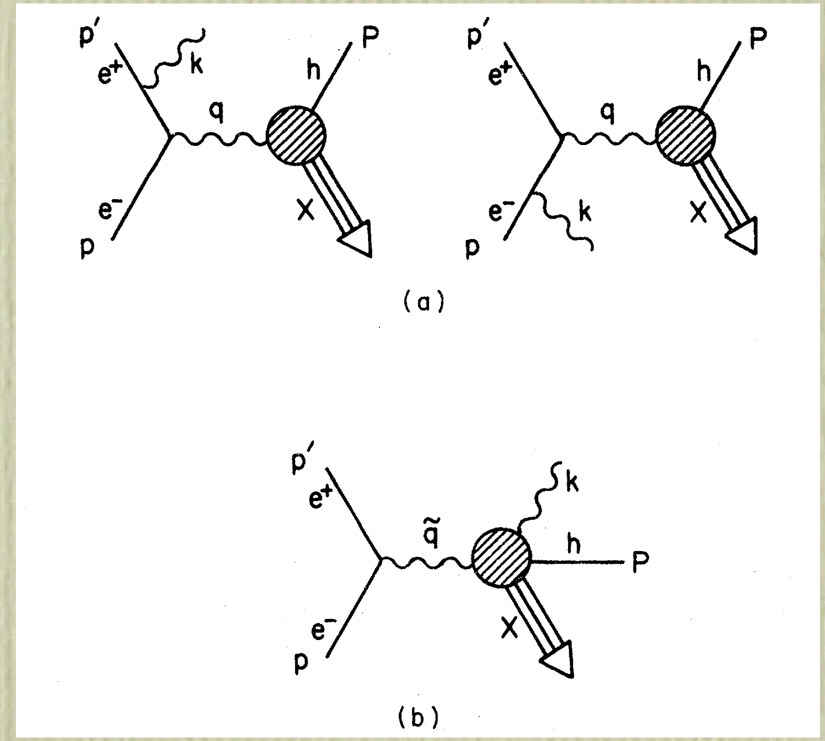
$$n_h + n_{\bar{h}} = \frac{1}{\sigma}\int_0^1 dx \frac{d\sigma}{dx}(e^+e^- \to hX)$$

is the hadron multiplicity in e^+e^- annihilation. The integral of the hadron asymmetry is

$$\int_0^1 dx\, R_h^{(3)}(x) = \sum_q \frac{e_q^{\,3}}{e^3}(n_q^h - n_q^{\bar{h}}). \qquad (12)$$

Note that Eq. (12) is convergent because of the absence of the Pomeron contribution.

New Application: Timelike DVCS



Apply BCS to Exclusive Processes

Timelike $e^+e^- \to \pi^+\pi^-\gamma$

Measure "timelike annihilation" DVCS
$\gamma^* \to \pi^+\pi^-\gamma$

Interferes with Bremsstrahlung from the annihilating leptons.

Electron-Positron asymmetry measures interference of pion form factor and DVCS amplitude.

Afanasev, SJB, CEC?

Re $M^\dagger(\gamma^* \to \pi^+\pi^-) \times M(\gamma^* \to \pi^+\pi^-\gamma)$

Extend to all hadron pairs.

Single spin asymmetries give conjugate phase.

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

Solving the LF Heisenberg Equation

- Discretized Light-Cone Quantization
- Transverse Lattice
- Bethe-Salpeter/Dyson Schwinger at fixed LF time
- Use AdS/CFT solutions as starting point!
- Many model field theories solved
- Structure of Solutions known

Quantum Chromodynamics

- A Scientific Revolution for Nuclear and Hadron Physics
- Novel features of Nuclear Chromodynamics: Hidden Color, Color Transparency
- Conformal Aspects of QCD
- The N-N Interaction in QCD
- Origin of Shadowing & Anti-Shadowing

New Perspectives AdS/CFT