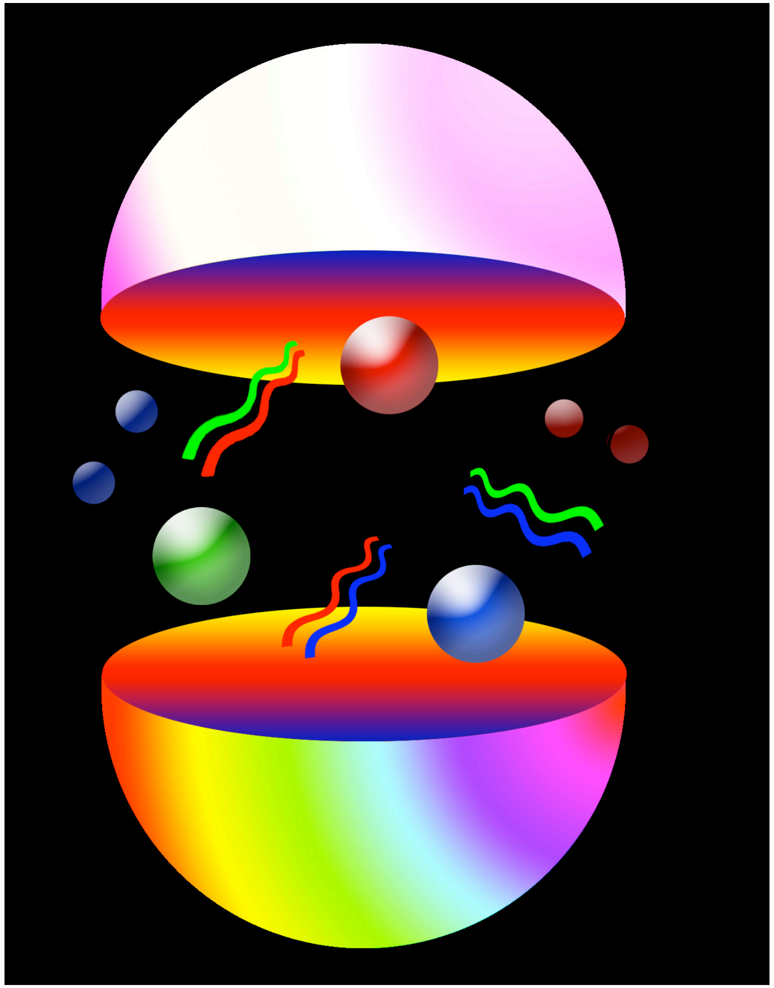
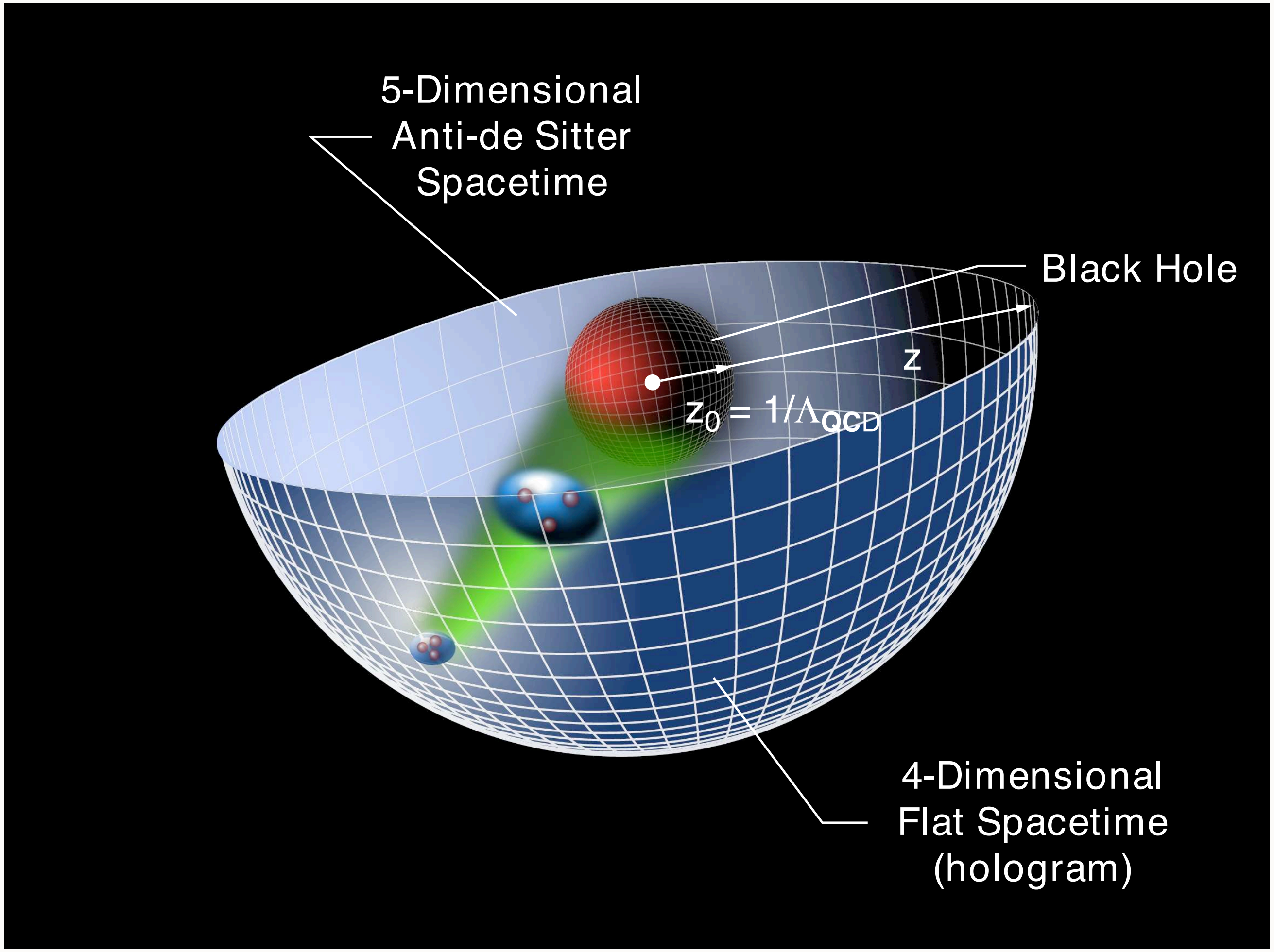
New Insights from AdS/CFT and JLAB Tests of QCD

Stan Brodsky, SLAC





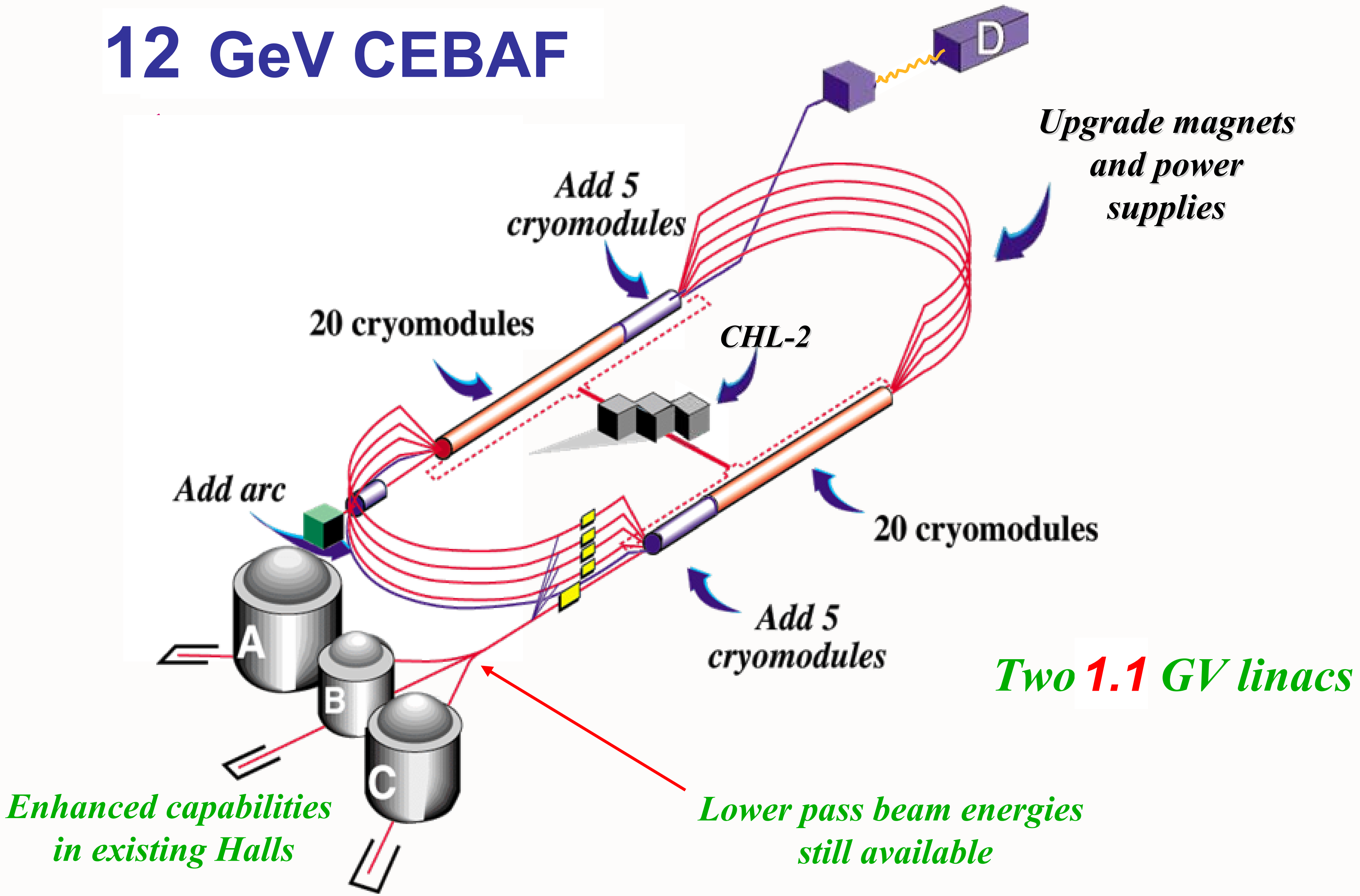
- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, dangling gluons, shadowing, antishadowing ...

Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities.

—Mark Twain

12 GeV CEBAF



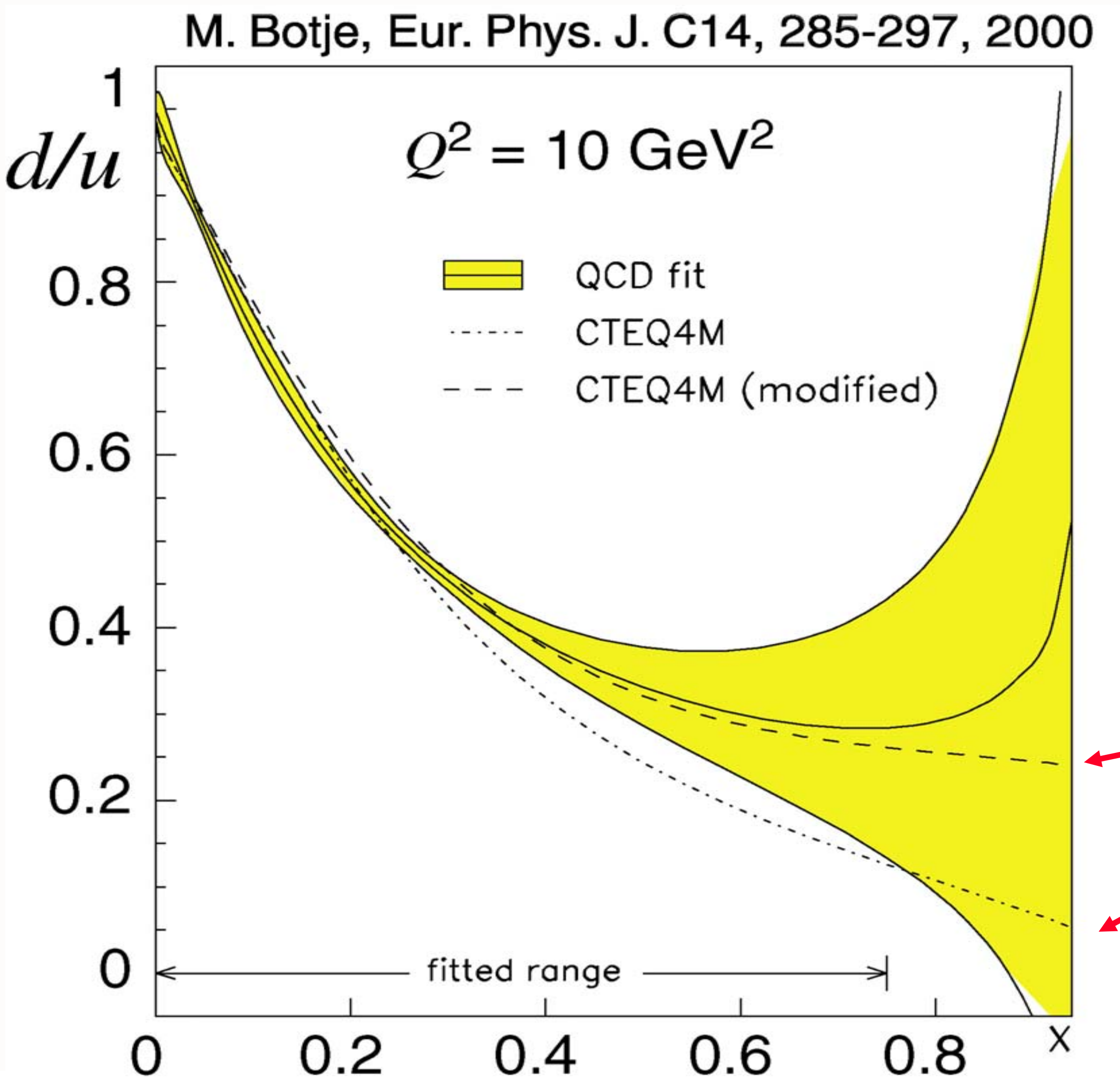
Two **1.1** *GV linacs*

Key Novel Physics Issues for JLab 12

- Hidden Color of Nuclear Wavefunctions
- Dynamics of Charm at Threshold
- Dynamics at x near 1: helicity retention
- QCD at the Amplitude Level - Light-Front Wavefunctions -- Connection to AdS/QCD
- Mapping out the spin and flavor structure of hadrons
- Initial- and Final- State Interactions
- Color transparency --Recent JLab success

A.W. Thomas:

After 35 years: Miserable Lack of Knowledge of Valence d-Quarks



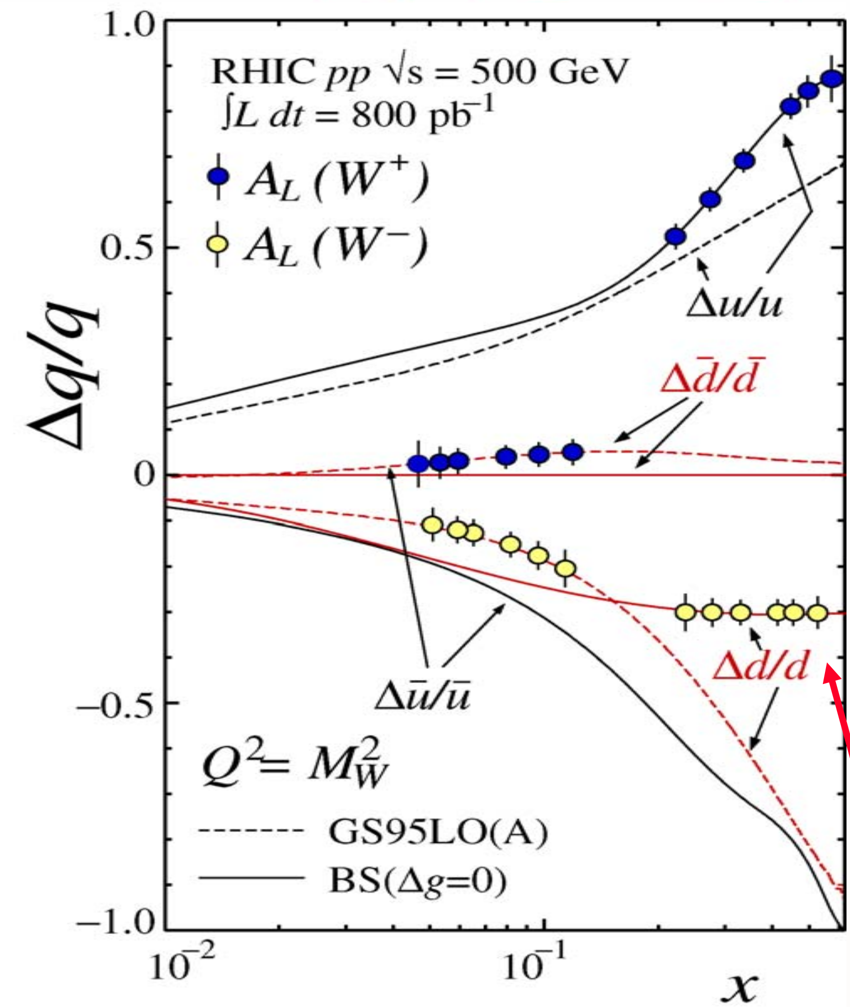
Charm distribution is much more uncertain

pQCD

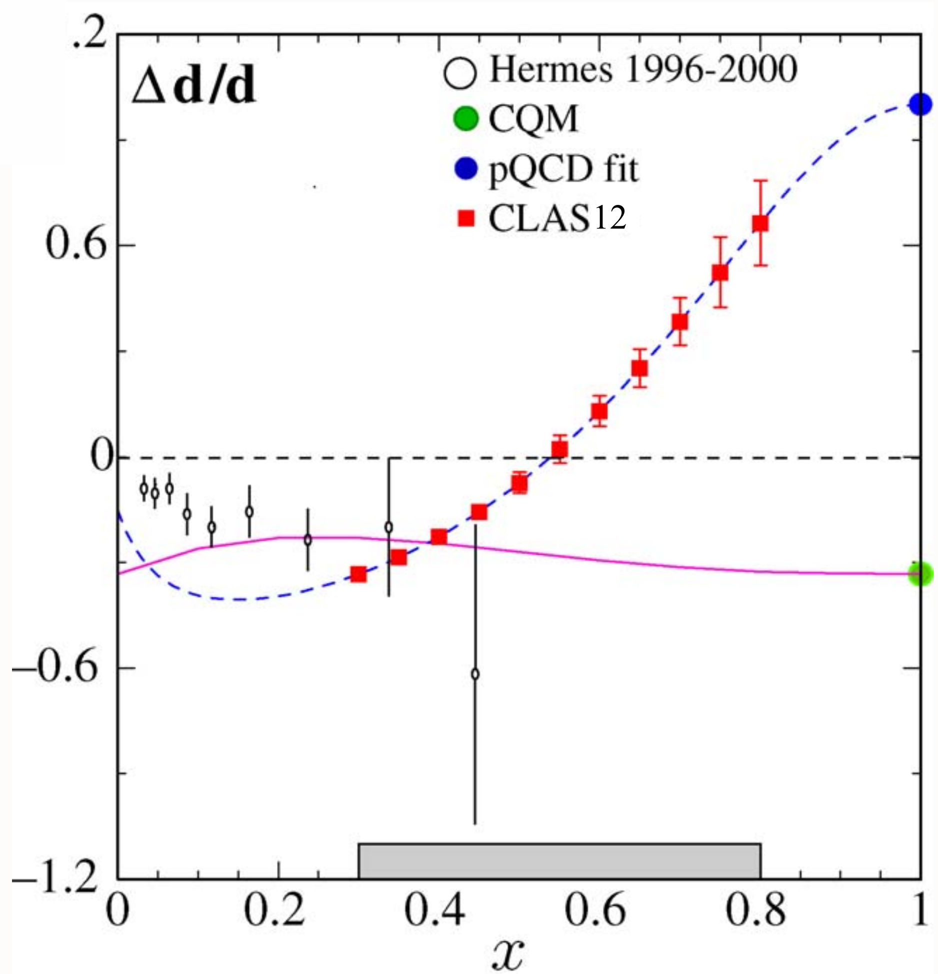
di-quark correlations

At RHIC with W production

$$A_L^{W^+} \approx \frac{\Delta u(x_1)\,\bar{d}(x_2) - \Delta\bar{d}(x_1)\,u(x_2)}{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)}$$



At JLab with 12 GeV upgrade



Stops below x=0.5 AND needs valence d(x)

Perturbative QCD Analysis of Structure Functions at x ~ 1

- Struck quark far-off shell $k_F^2 \propto \frac{-k_\perp^2}{1-x}$
- Lowest order connected diagrams dominate
- Helicity retention at large x
- DGLAP evolution quenched
- Exclusive-Inclusive Connection

$$\xi(Q^2, Q_0^2) = \frac{1}{4\pi} \int_{Q_0^2}^{Q^2} d\ell^2 \; \frac{\alpha_s(\ell^2)}{\ell^2}$$

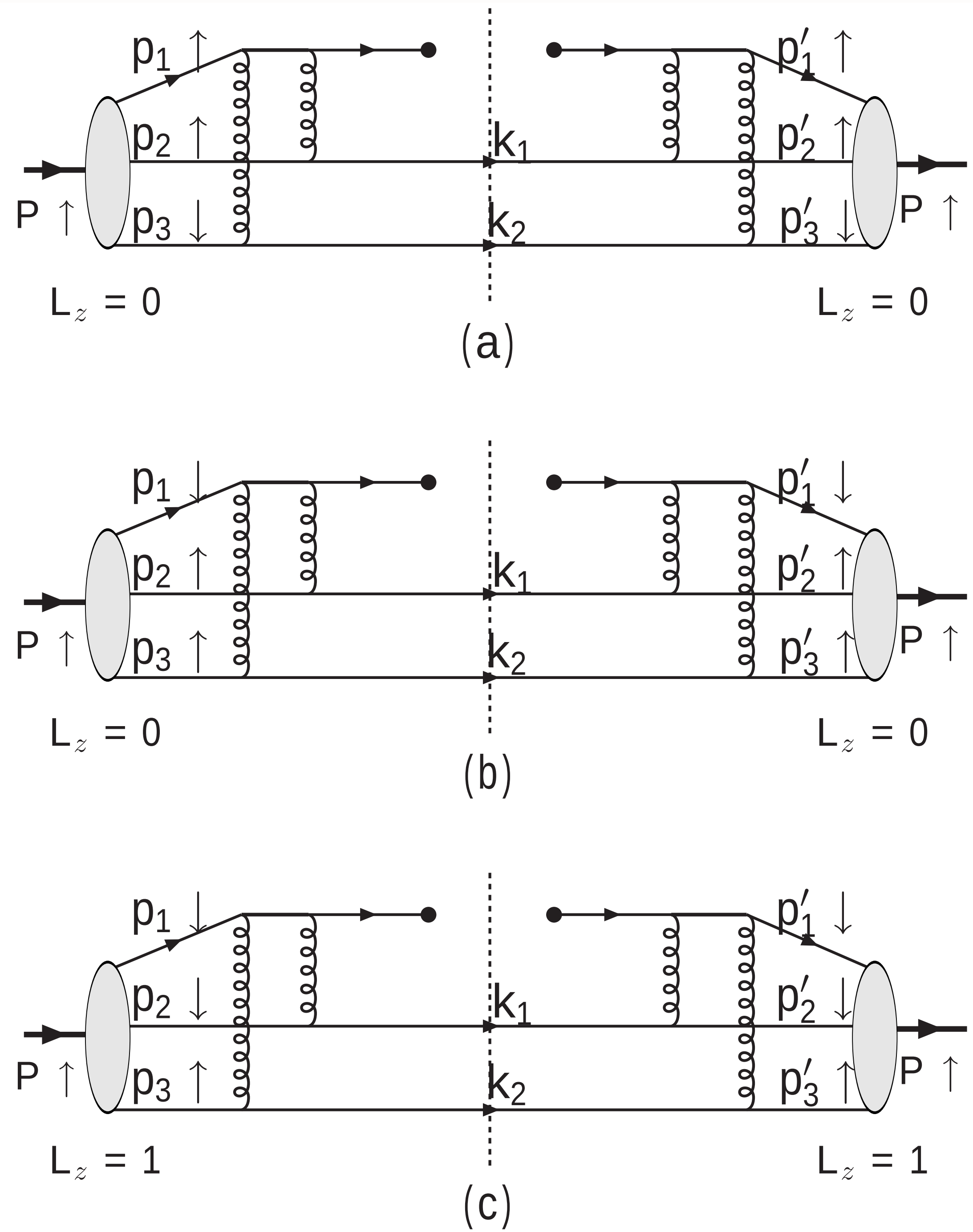
$$\xi(Q^2, Q_0^2) = \frac{1}{4\pi} \int_{Q_0^2}^{Q^2} d\ell^2 \; \frac{\alpha_s(\ell^2)}{\ell^2 + \frac{k_\perp^2}{1-x}}$$

$$q^+(x) \propto (1-x)^3$$

$$q^-(x) \propto (1-x)^5 \log^2(1-x)$$

From nonzero orbital angular momentum

Avakian, sjb, Deur, Yuan



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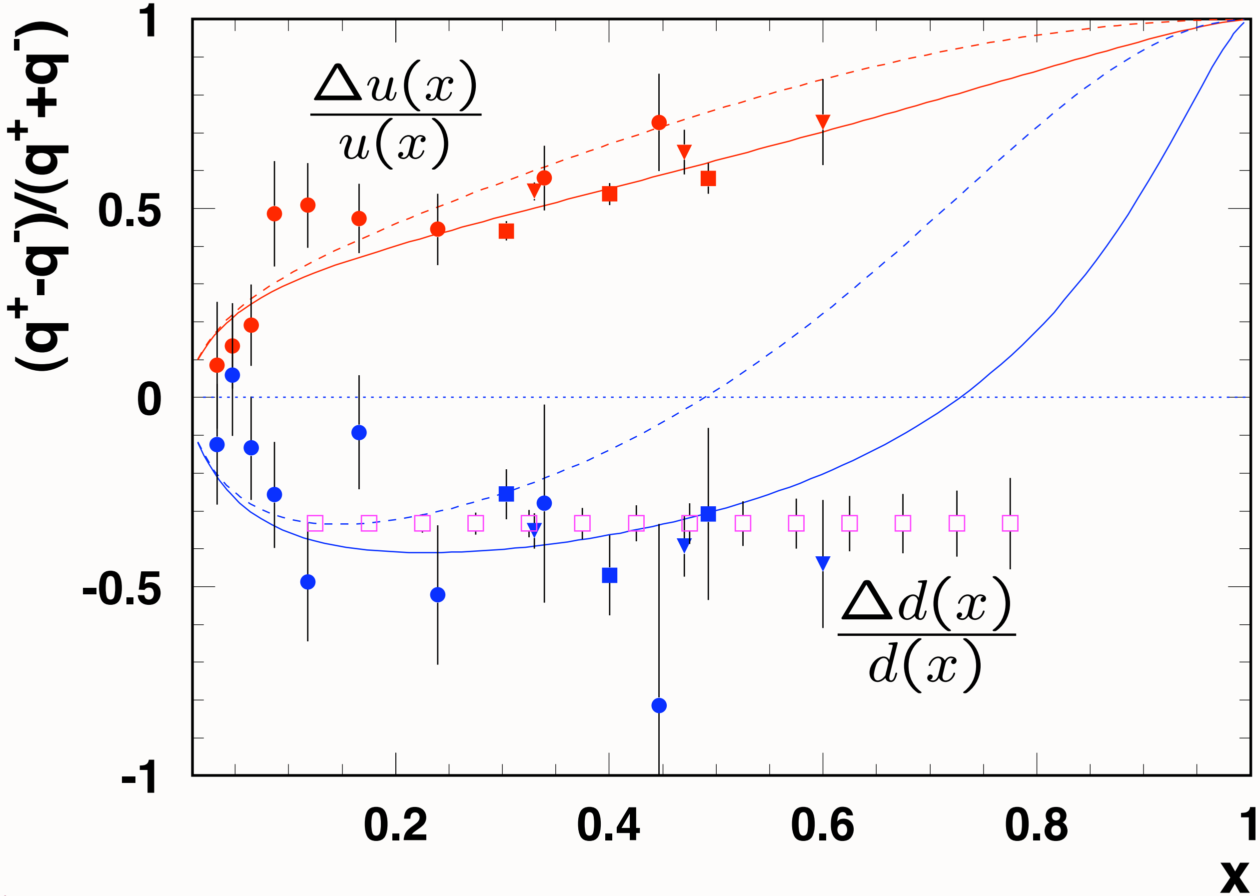


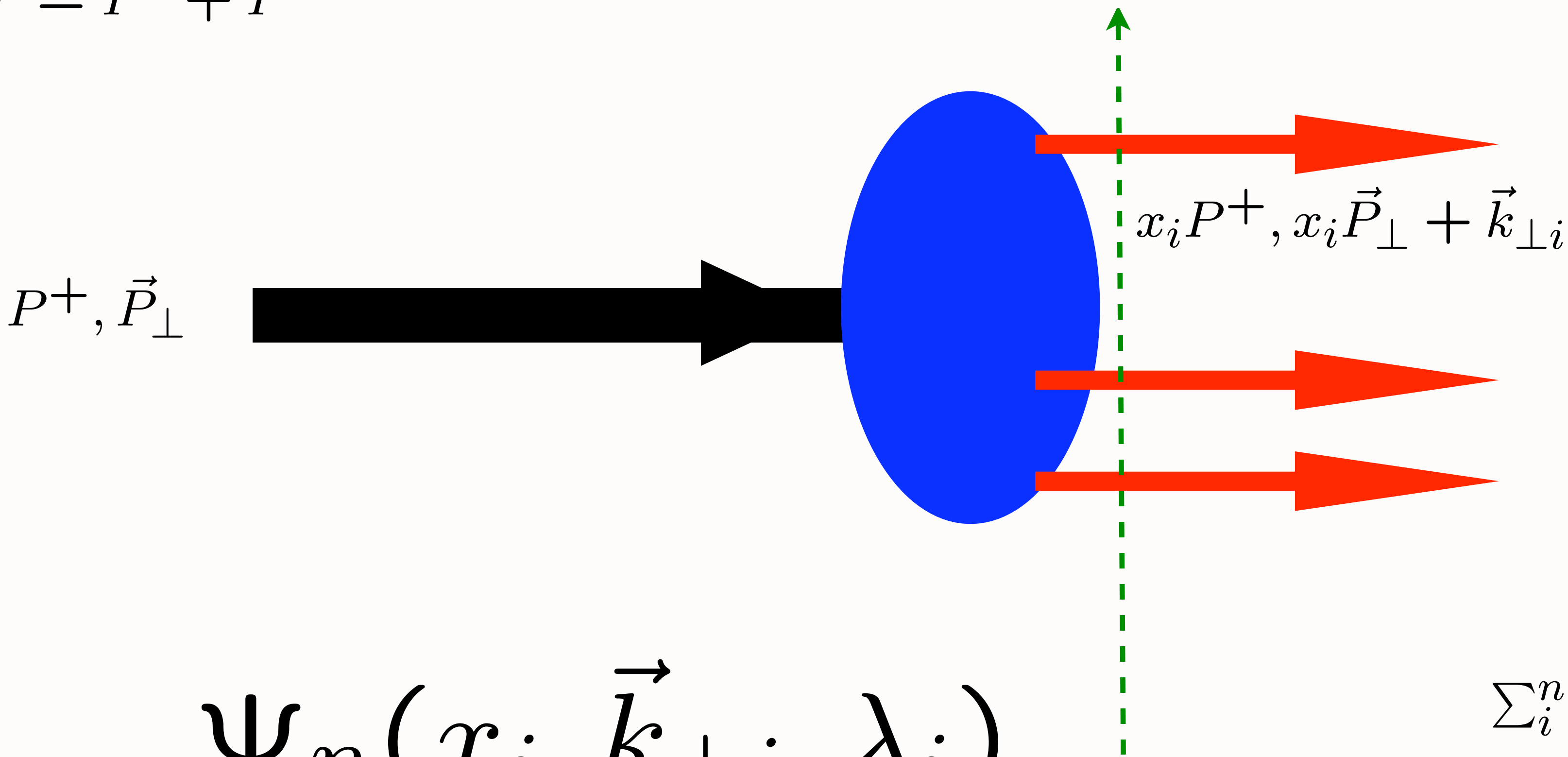
Avakian, sjb, Deur, Yuan

Similar to Ji, Balitsky, Yuan's PQCD analysis of $F_2(Q^2)/F_1(Q^2)$

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

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



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

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

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

The Light Front Fock State Wavefunctions

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

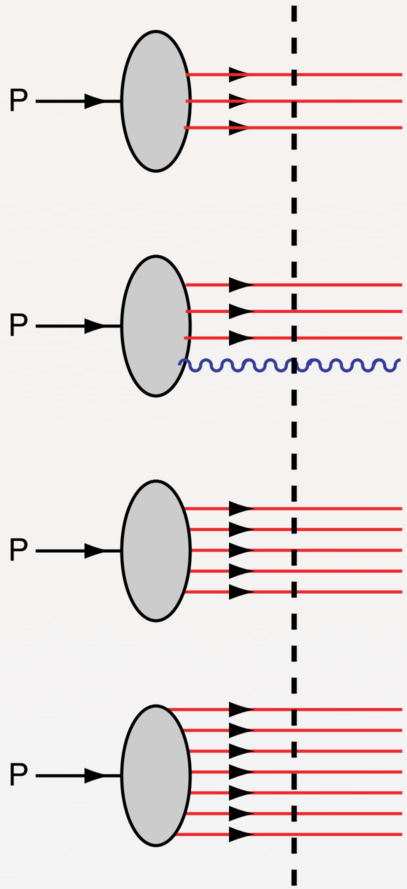
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

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

are boost invariant.

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



Fixed LF time

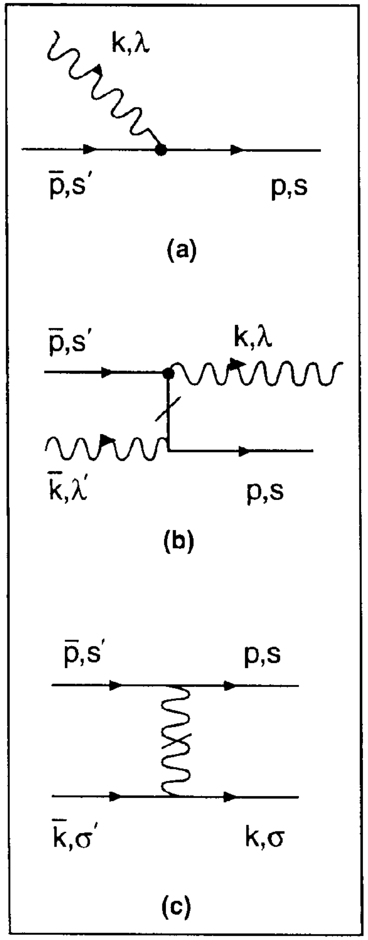
Intrinsic heavy quarks,

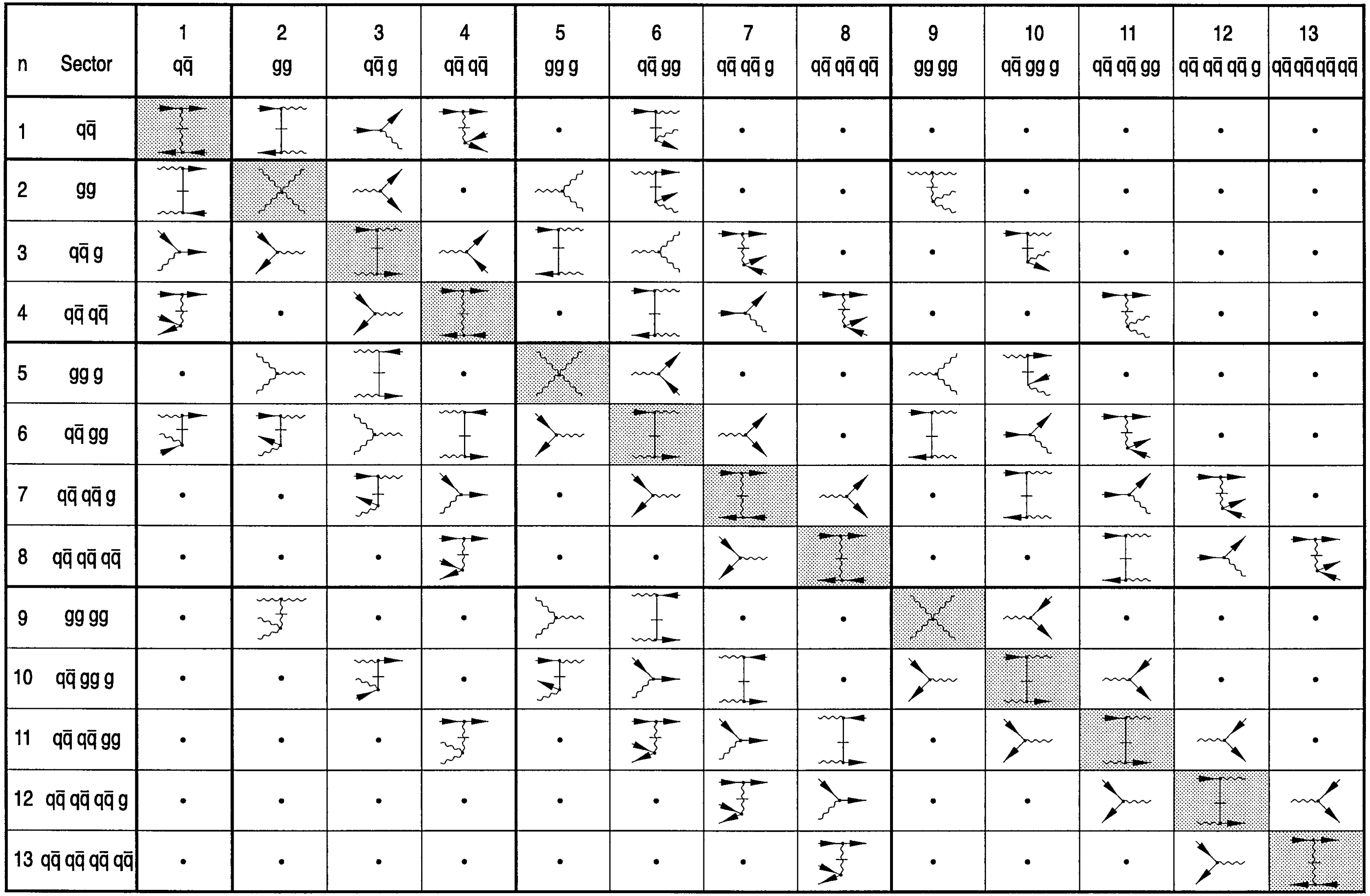
$$\bar{s}(x) \neq s(x)$$
$$\bar{u}(x) \neq \bar{d}(x)$$

Light-Front QCD Heisenberg Equation

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

DLCQ





Pauli, Pinsky, sjb

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

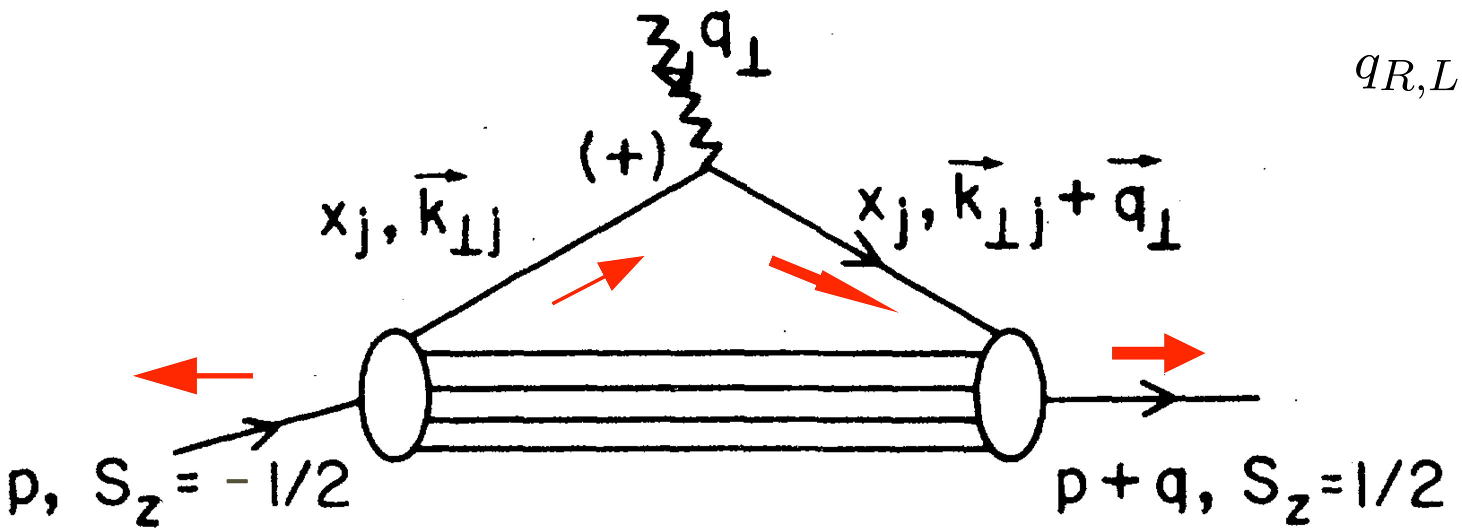
Nonzero Anomalous Moment -->Nonzero orbital angular momentum

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

Drell, sjb

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

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



$q_{R,L} = q^x \pm i q^y$

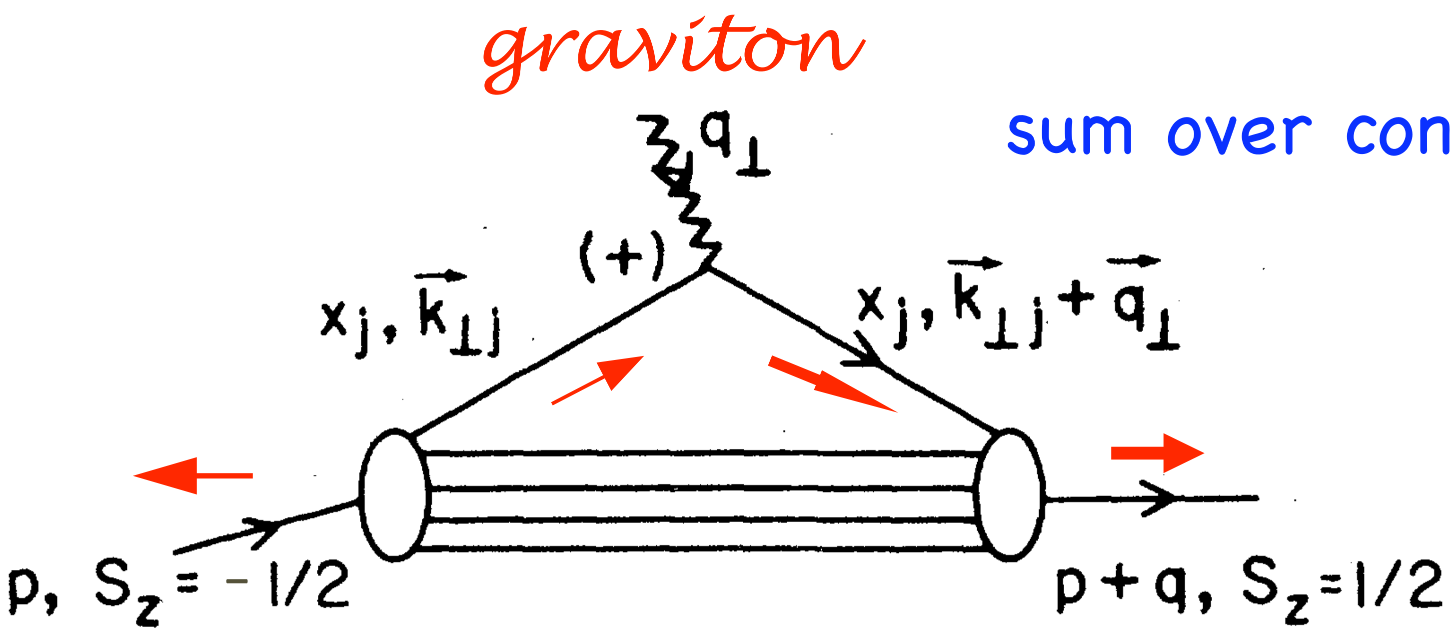
$\boxed{\text{Must have } \Delta\ell_z = \pm 1 \text{ to have nonzero } F_2(q^2)}$

Same matrix elements appear in Sivers effect

-- connection to quark anomalous moments

Anomalous gravitomagnetic moment B(0)

Okun et al: *B(0) Must vanish because of Equivalence Theorem*



sum over constituents

Hwang, Schmidt, sjb; Holstein et al

$\boxed{B(0) = 0}$

Each Fock State

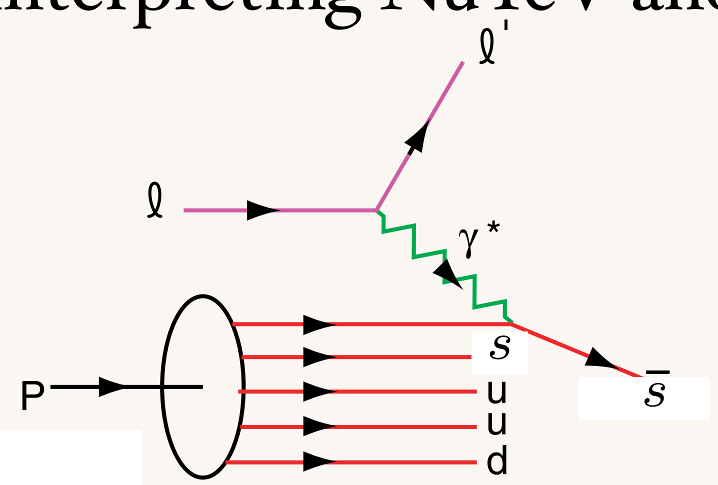
Remarkable Features of Hadron Structure

- Valence quarks carry less than half of the proton's spin and momentum
- Non-zero quark orbital angular momentum
- Asymmetric sea: $\bar{u}(x) \neq \bar{d}(x)$ relation to meson cloud
- Non-symmetric strange and antistrange sea $\bar{s}(x) \neq s(x)$
- Intrinsic charm and bottom at high x
- Hidden-Color Fock states of the Deuteron

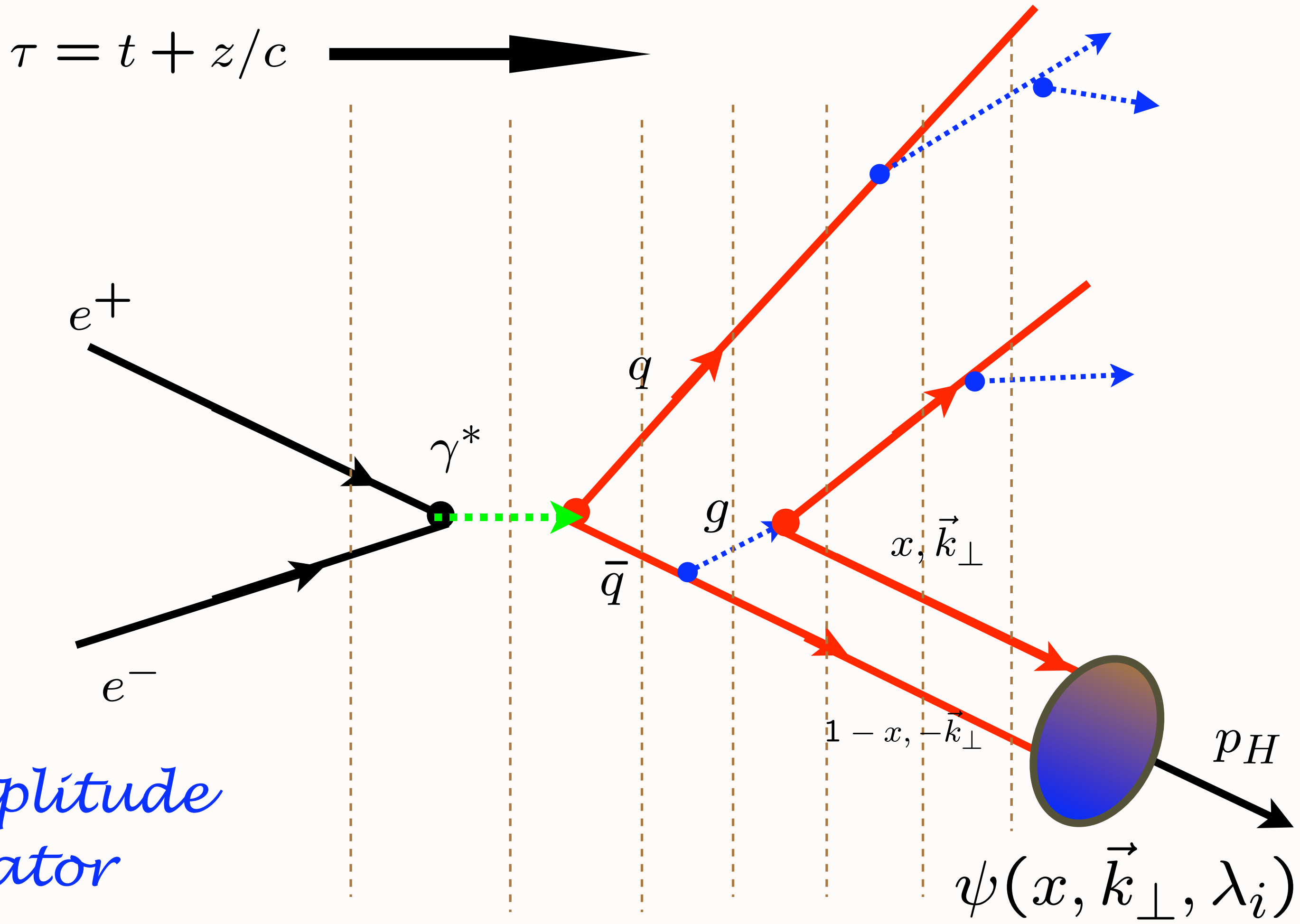
Measure strangeness distribution from DIS at JLab12

$$\bar{s}(x) \neq s(x) \qquad ep \to e' K X$$

- Non-symmetric strange and antistrange sea
- Non-perturbative input; e.g $|uuds\bar{s}> \simeq |\Lambda(uds) K^+(\bar{s}u)>$
- Crucial for interpreting NuTeV anomaly



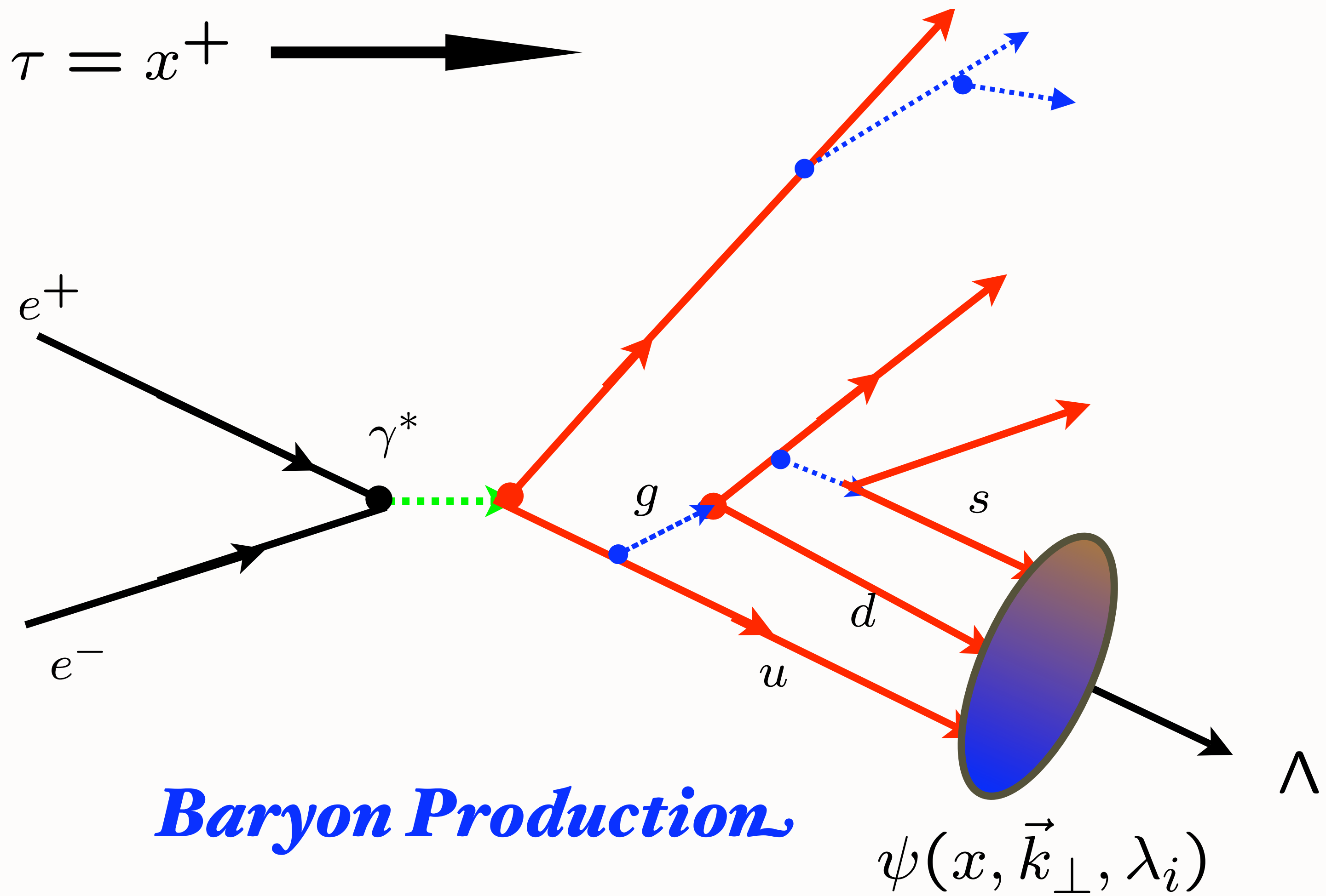
Hadronization at the Amplitude Level



Event amplitude generator

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via Light-Front Wavefunctions

Hadronization at the Amplitude Level



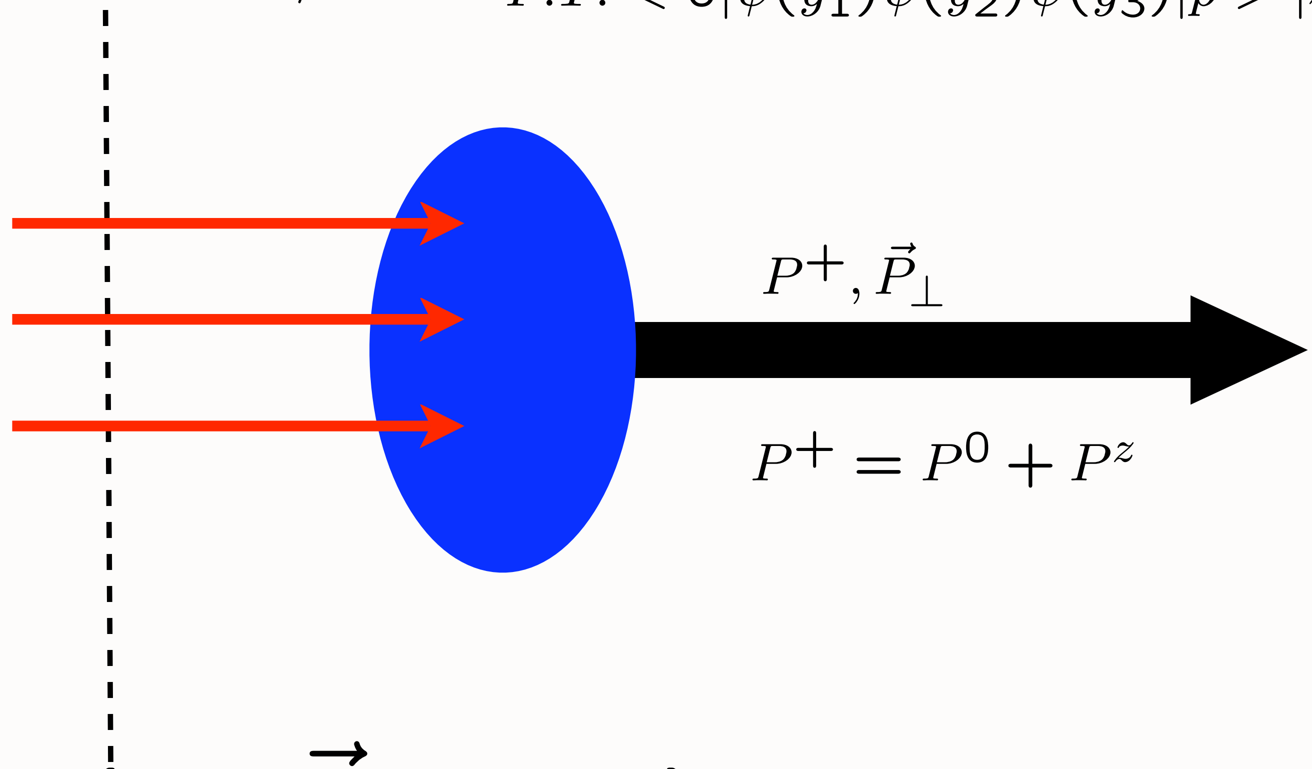
Baryon Production

Construct helicity amplitude using Light-Front Perturbation theory; coalesce quarks via LFWFs

Light-Front Wavefunctions

Fixed $\tau = t + z/c$

$F.T. < 0|\psi(y_1)\psi(y_2)\psi(y_3)|p > |_{\tau_i=0}$



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

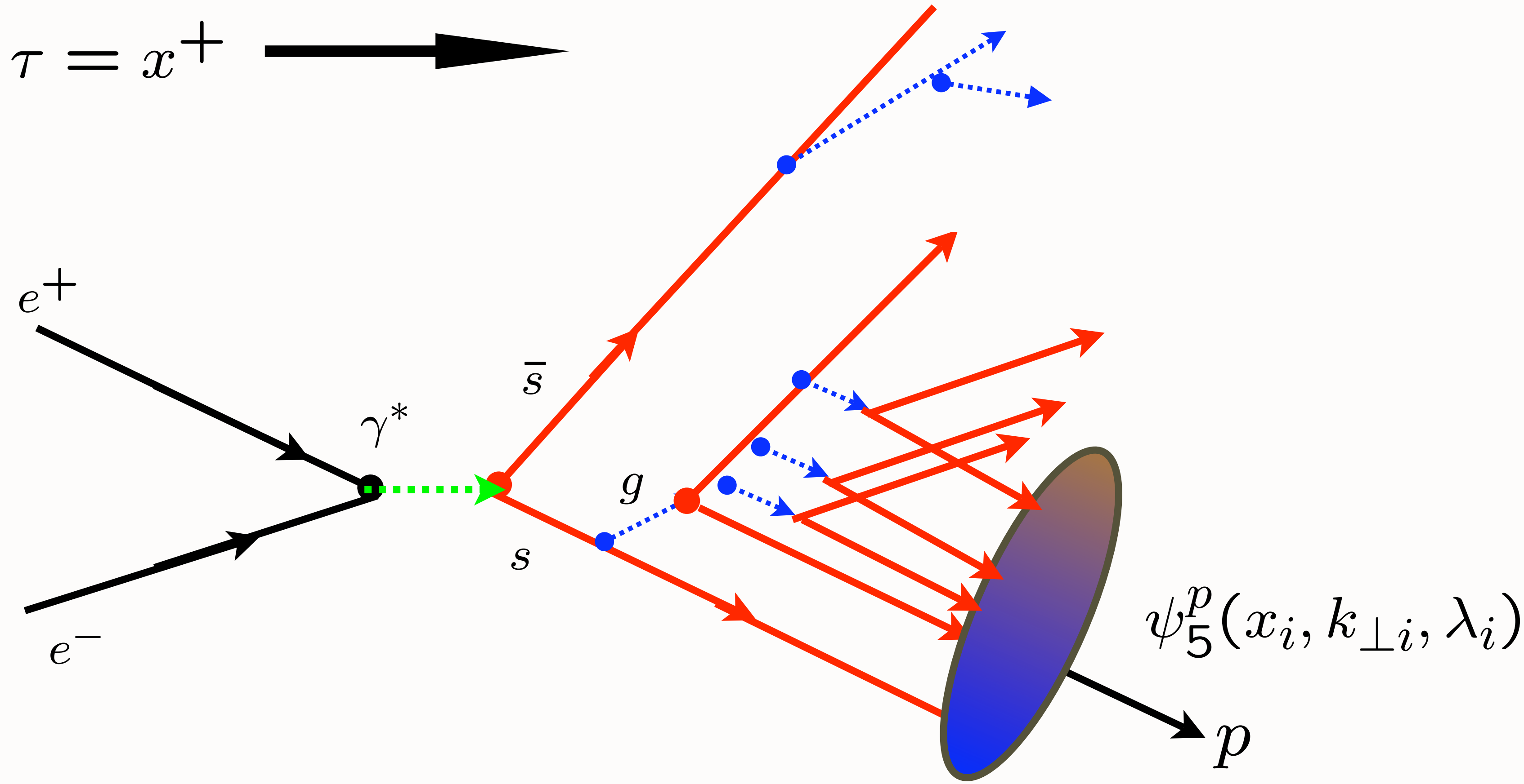
$\sum_i^n x_i = 1$

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

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

Invariant under boosts! Independent of P^μ

Hadronization at the Amplitude Level

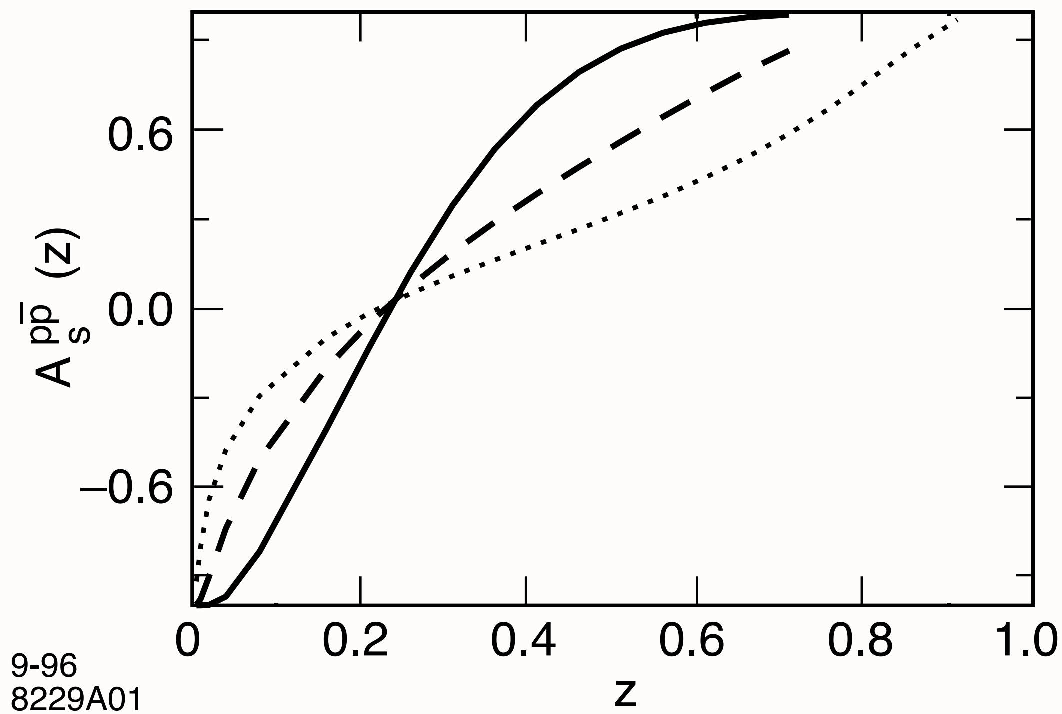


Higher Fock State Coalescence $|uuds\bar{s}>$

Asymmetric Hadronization ! $D_{s \to p}(z) \neq D_{s \to \bar{p}}(z)$

B-Q Ma, sjb

$$D_{s\to p}(z) \neq D_{s\to \bar{p}}(z)$$

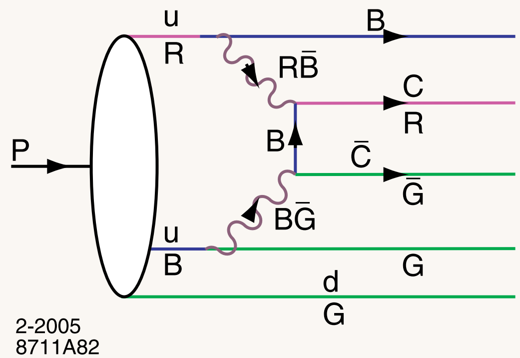


$$A_s^{p\bar{p}}(z) = \frac{D_{s\to p}(z) - D_{s\to \bar{p}}(z)}{D_{s\to p}(z) + D_{s\to \bar{p}}(z)}$$

Consequence of $s_p(x) \neq \bar{s}_p(x)$ $\quad |uuds\bar{s} > \simeq |K^+\Lambda >$

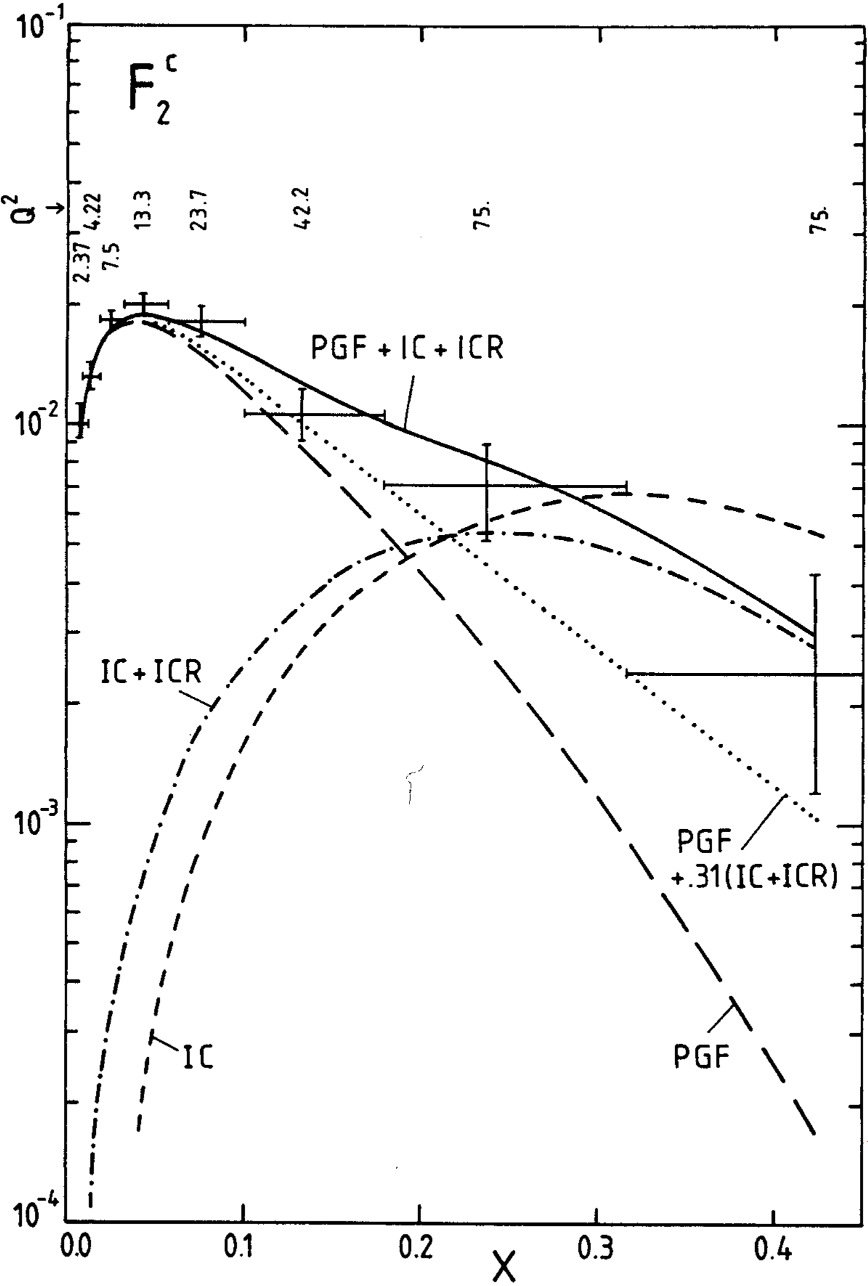
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



- Rigorous prediction of QCD, OPE
- Color-Octet Colo-Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests

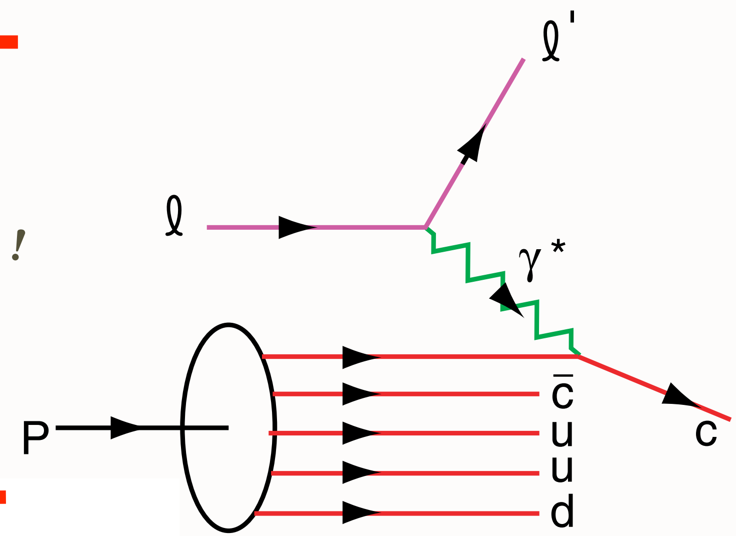
Measurement of Charm Structure Function



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

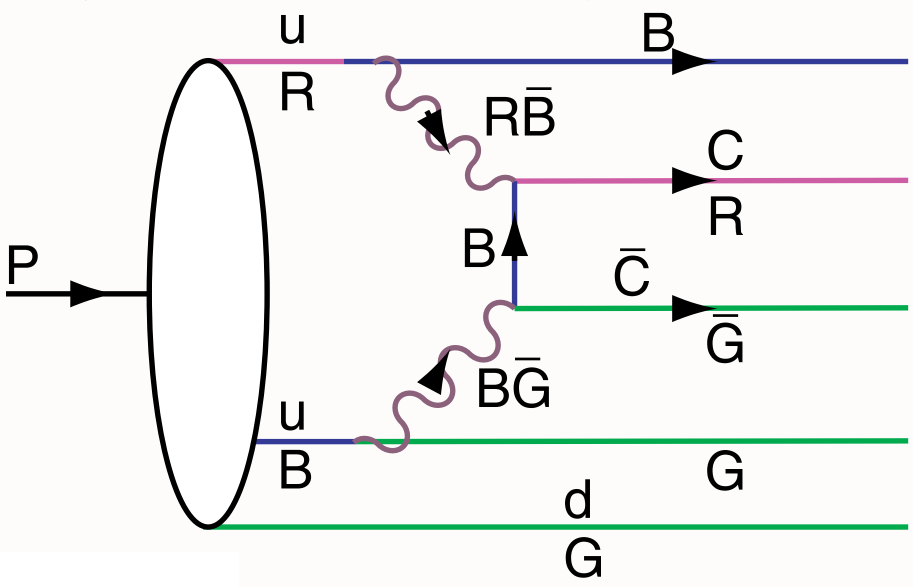
First Evidence for Intrinsic Charm

factor of 30 !



DGLAP / Photon-Gluon Fusion: factor of 30 too small

Hoyer, Peterson, Sakai, sjb



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

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

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

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

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

$c\bar{c}$ in Color Octet

Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm! *Charm at Threshold*

- New QCD physics in proton-proton elastic scattering at the charm threshold
- Anomalously large charm photoproduction at threshold?
- Octoquark resonances?
- Color Transparency disappears at charm threshold
- Huge transversity correlation at charm threshold

"Exclusive Transversity"

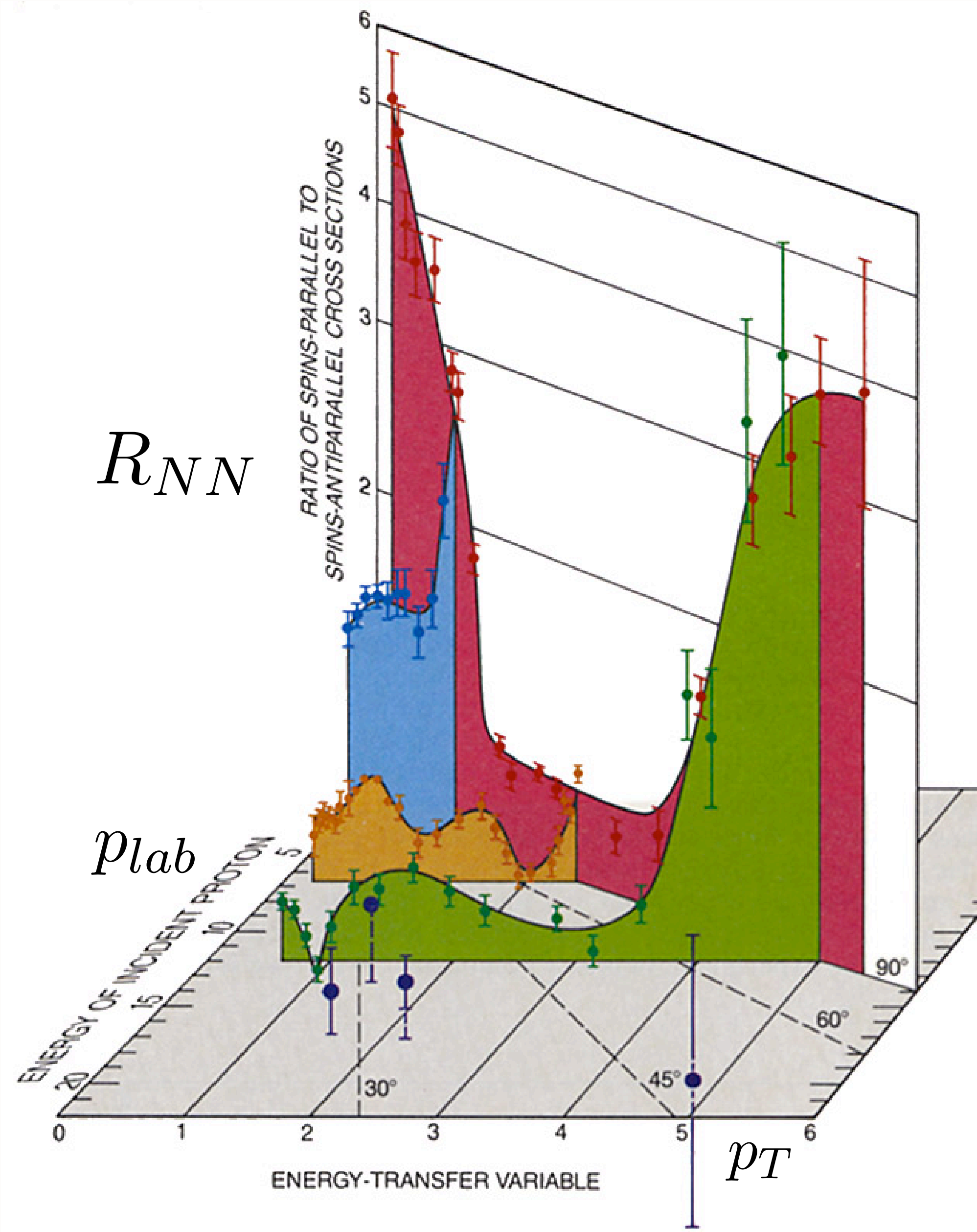
A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

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

Hard scattering takes place only with spins ↑↑

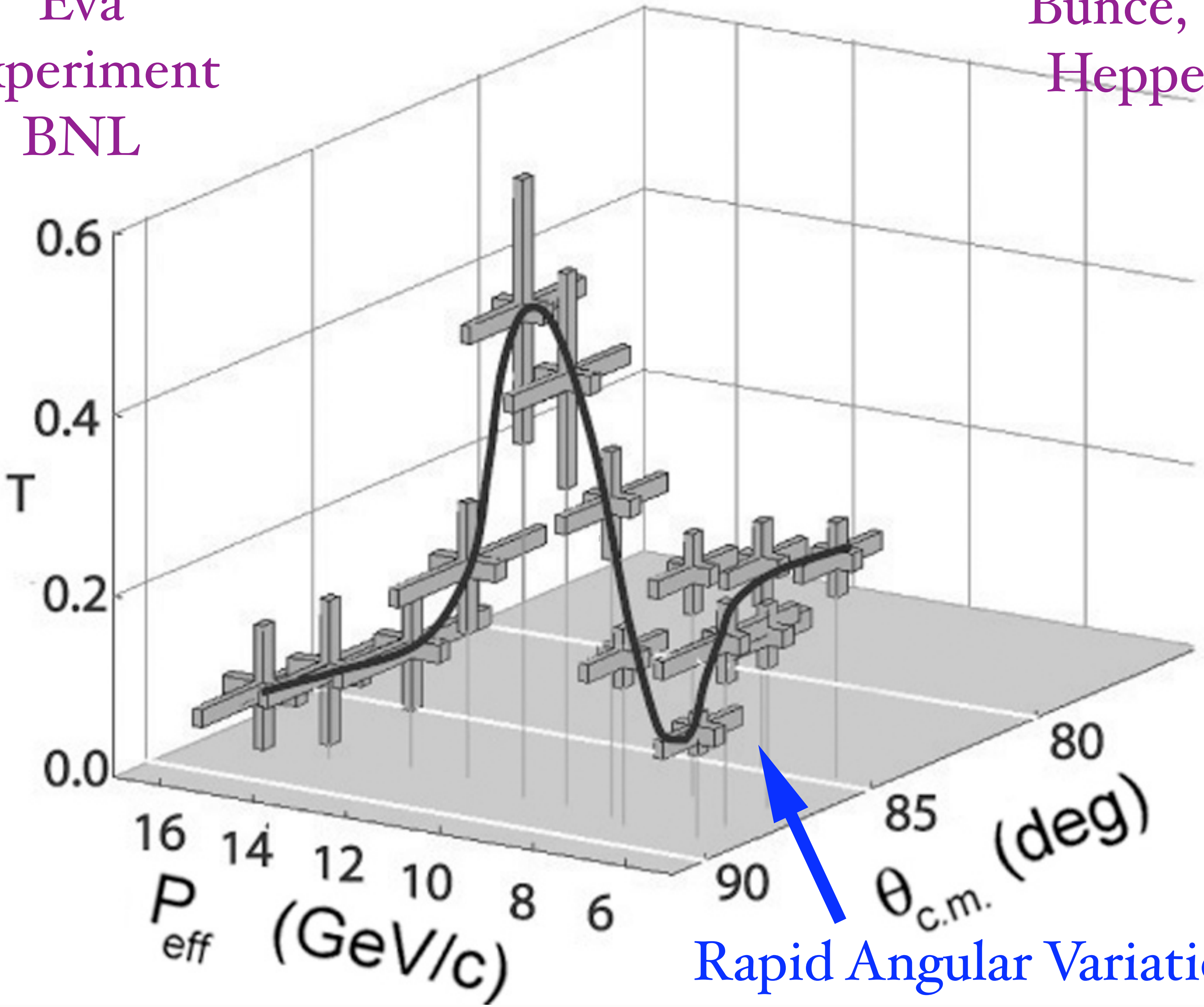
Coincidence?: Quenching of Color Transparency

Coincidence?: Charm and Strangeness Thresholds

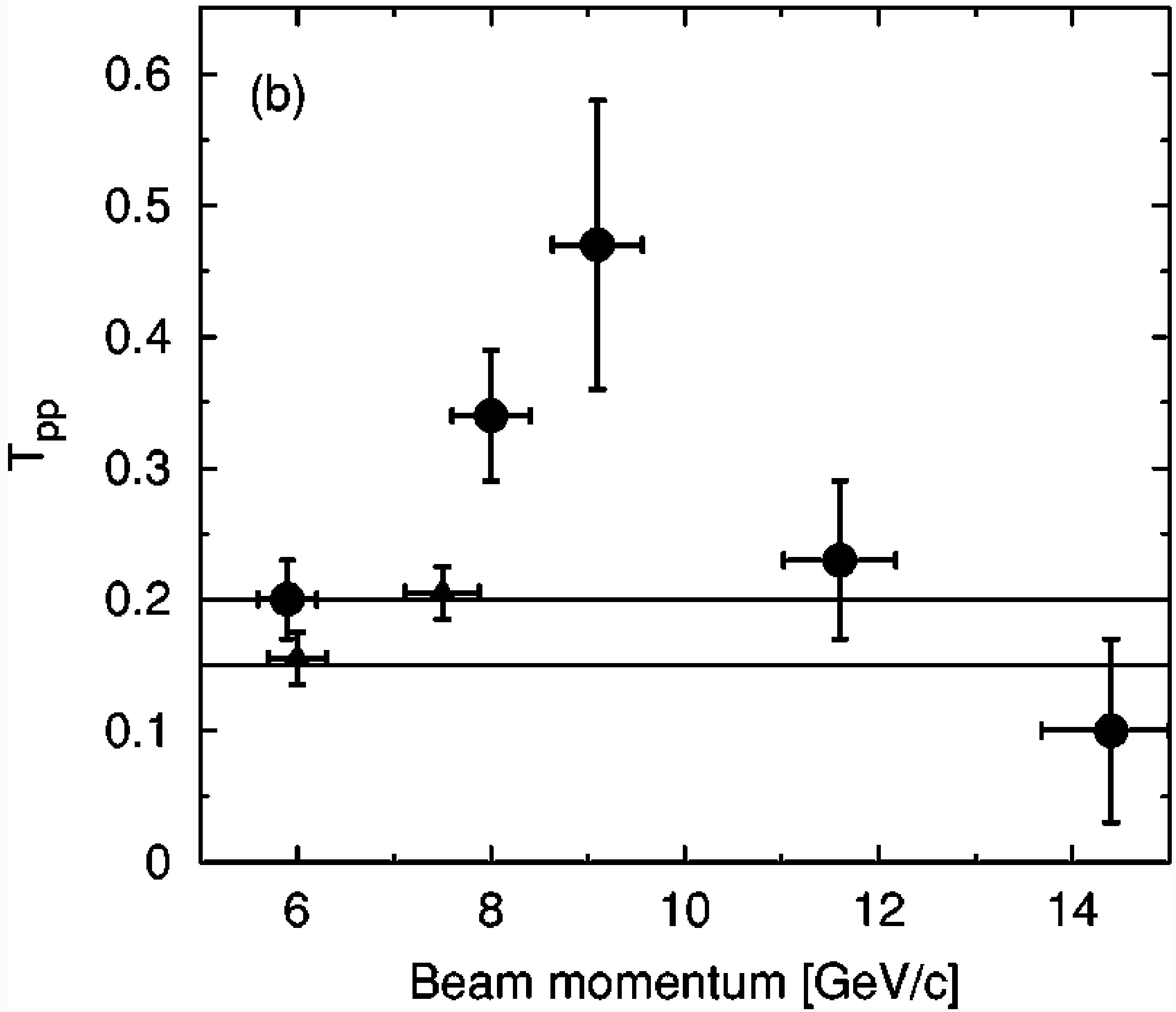


Eva Experiment BNL

Bunce, Carroll, Heppelman...



Rapid Angular Variation!



PHYSICAL REVIEW C **70**, 015208 (2004)

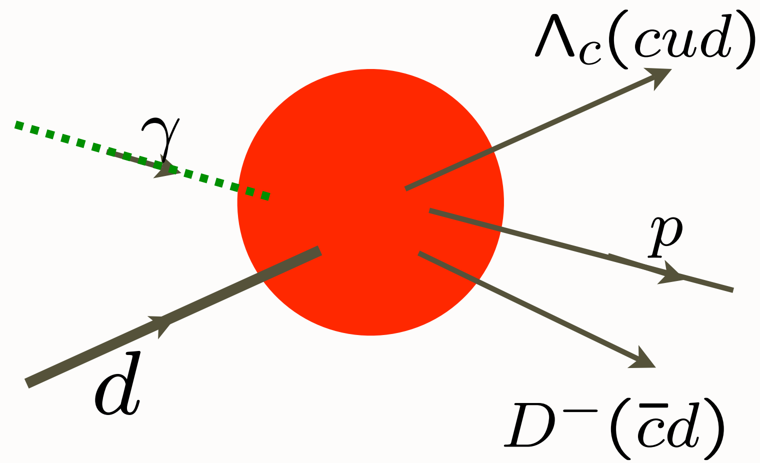
Nuclear transparency in $90^{\circ}_{\mathrm{c.m.}}$ quasielastic $A(p,2p)$ reactions

J. Aclander,[7] J. Alster,[7] G. Asryan,[1,*] Y. Averiche,[5] D. S. Barton,[1] V. Baturin,[2,†] N. Buktoyarova,[1,†] G. Bunce,[1] A. S. Carroll,[1,‡] N. Christensen,[3,§] H. Courant,[3] S. Durrant,[2] G. Fang,[3] K. Gabriel,[2] S. Gushue,[1] K. J. Heller,[3] S. Heppelmann,[2] I. Kosonovsky,[7] A. Leksanov,[2] Y. I. Makdisi,[1] A. Malki,[7] I. Mardor,[7] Y. Mardor,[7] M. L. Marshak,[3] D. Martel,[4] E. Minina,[2] E. Minor,[2] I. Navon,[7] H. Nicholson,[8] A. Ogawa,[2] Y. Panebratsev,[5] E. Piasetzky,[7] T. Roser,[1] J. J. Russell,[4] A. Schetkovsky,[2,†] S. Shimanskiy,[5] M. A. Shupe,[3,||] S. Sutton,[8] M. Tanaka,[1,¶] A. Tang,[6] I. Tsetkov,[5] J. Watson,[6] C. White,[3] J-Y. Wu,[2] and D. Zhalov[2]

Key Experiment at JLab

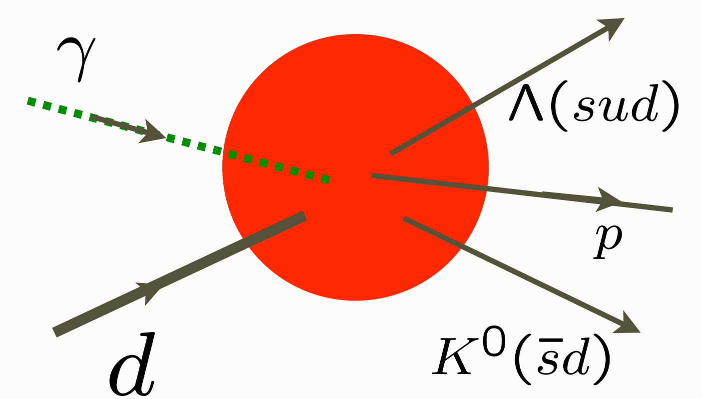
Open Charm Photoproduction

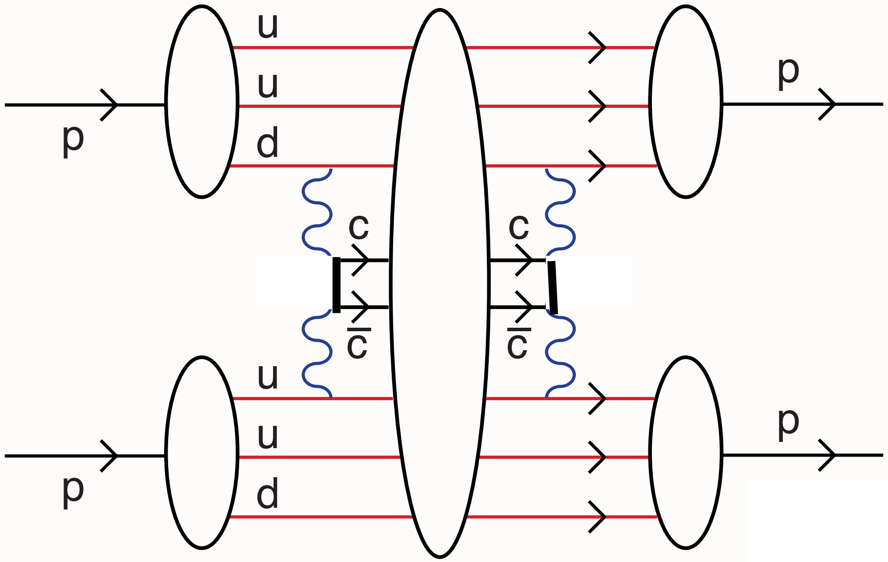
$$\gamma d \to p \Lambda_c D^-$$



Resonances or Threshold Enhancement needed to explain Krisch Effect

$$\gamma d \to p \Lambda K^0$$





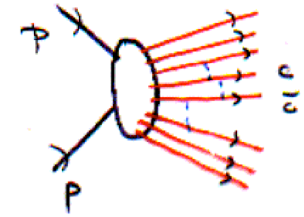
QCD Schwinger-Sommerfeld Enhancement at Heavy Quark Threshold

Hebecker, Kuhn, sjb

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).

Spin, Coherence at heavy quark thresholds

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



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

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

8 quarks in S-wave odd parity!

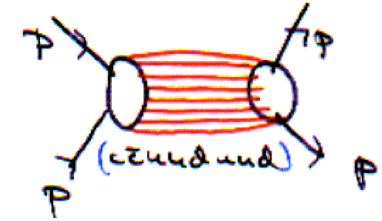
$\therefore$ $J = L = S = 1$ for pp

$B = 2$

resonance near threshold?

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

$\sqrt{s} \sim 5$ GeV



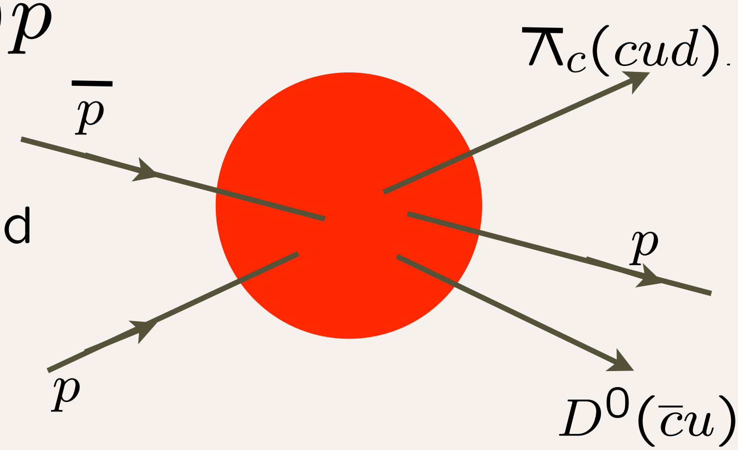
$A_{NN} = 1$ for $J=L=S=1$ $p\!\uparrow p\!\uparrow$ only

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

Key QCD Experiment at GSI

Open Charm

$$\bar{p}p \to \bar{\Lambda}_c(\overline{cud})D^0(\bar{c}u)p$$



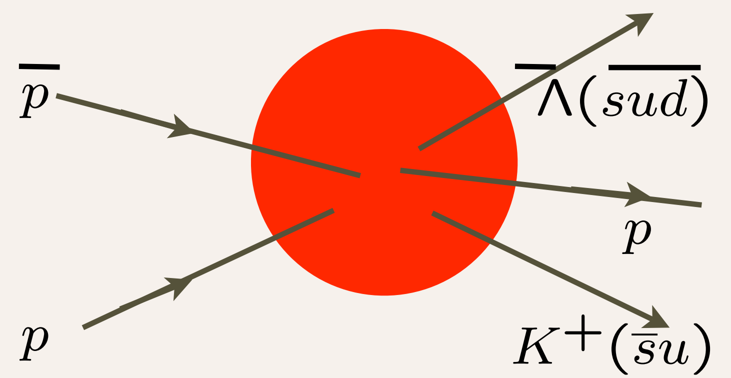
Total open charm cross section at threshold

$$\sigma(pp \to cX) \simeq 1 \mu b$$

needed to explain Krisch A_{NN}

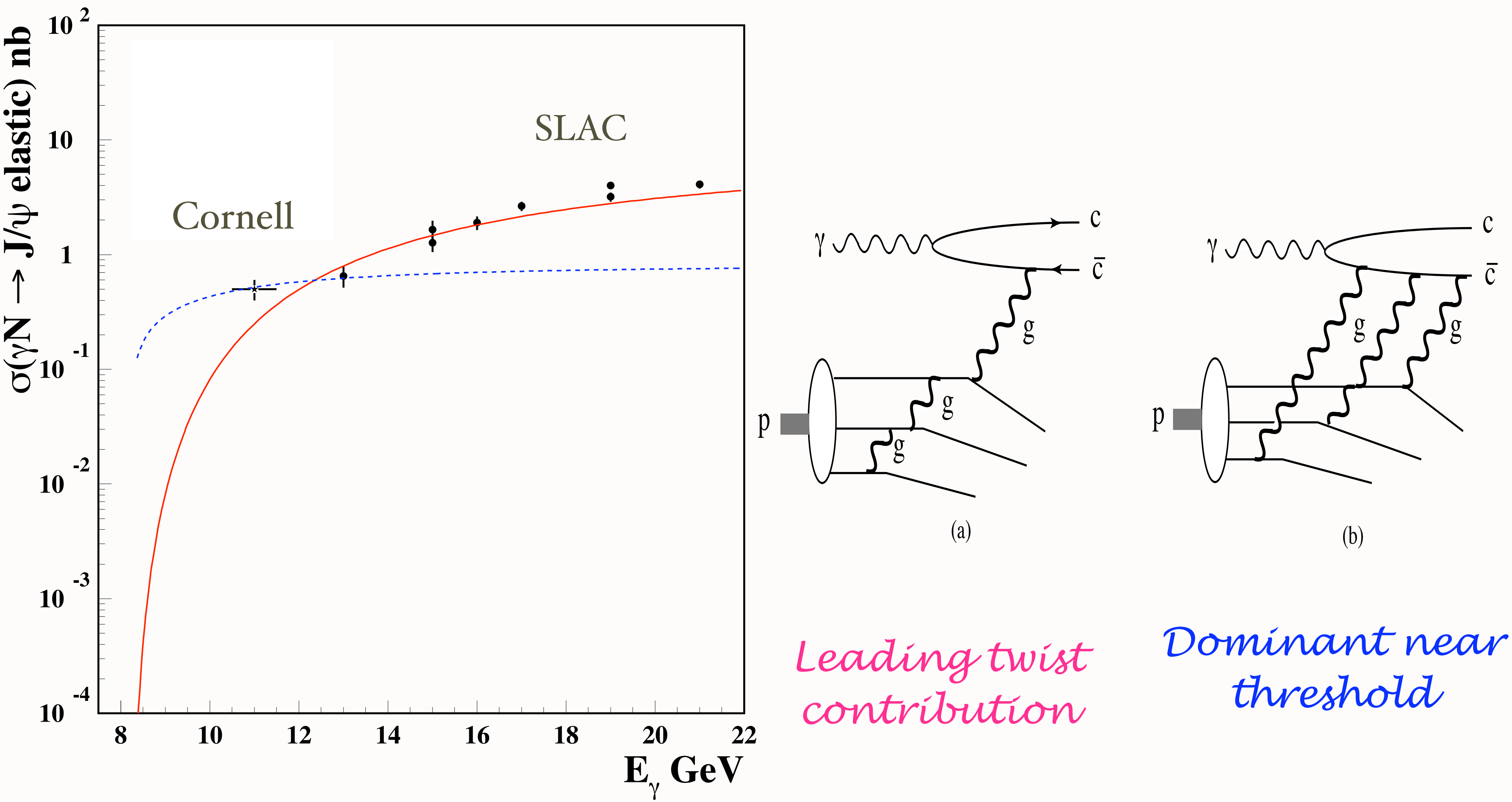
Compare with strangeness channels

$$pp \to \Lambda(sud)K^+(\bar{s}u)p$$

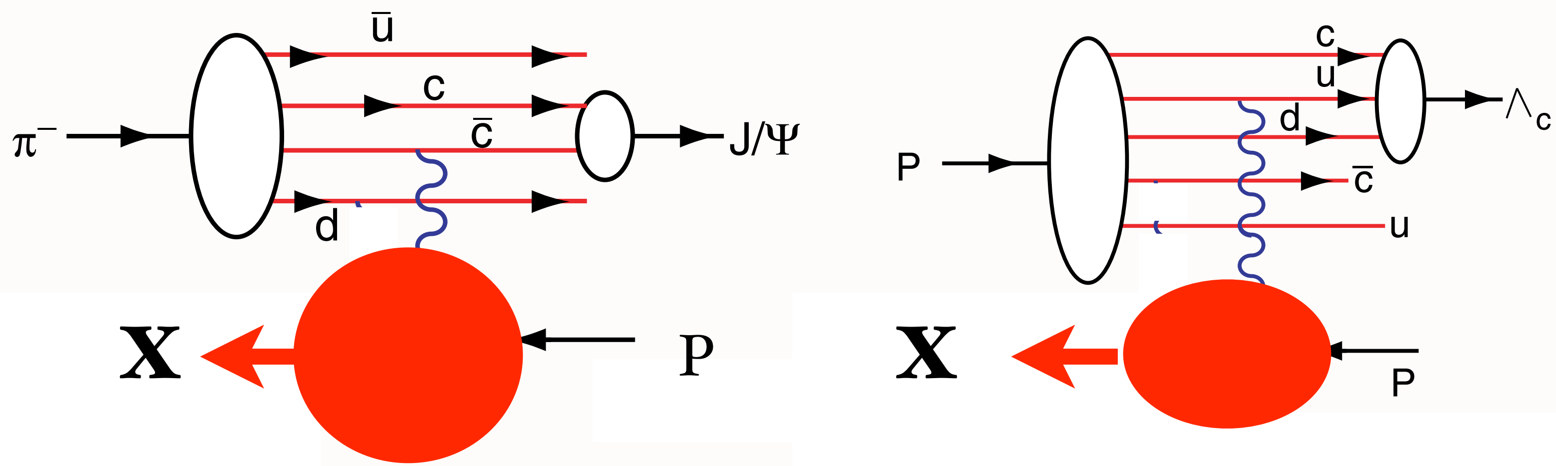


$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb

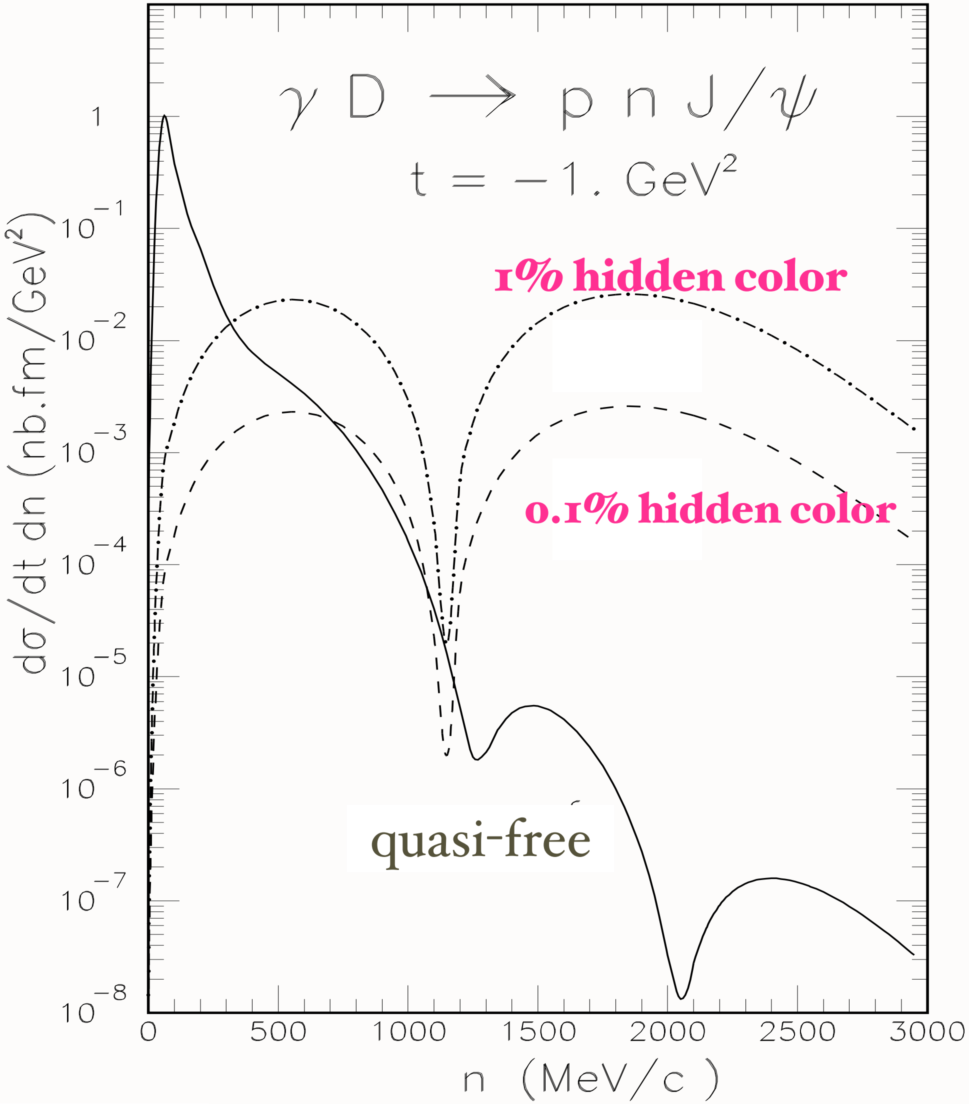


Leading Hadron Production from Intrinsic Charm

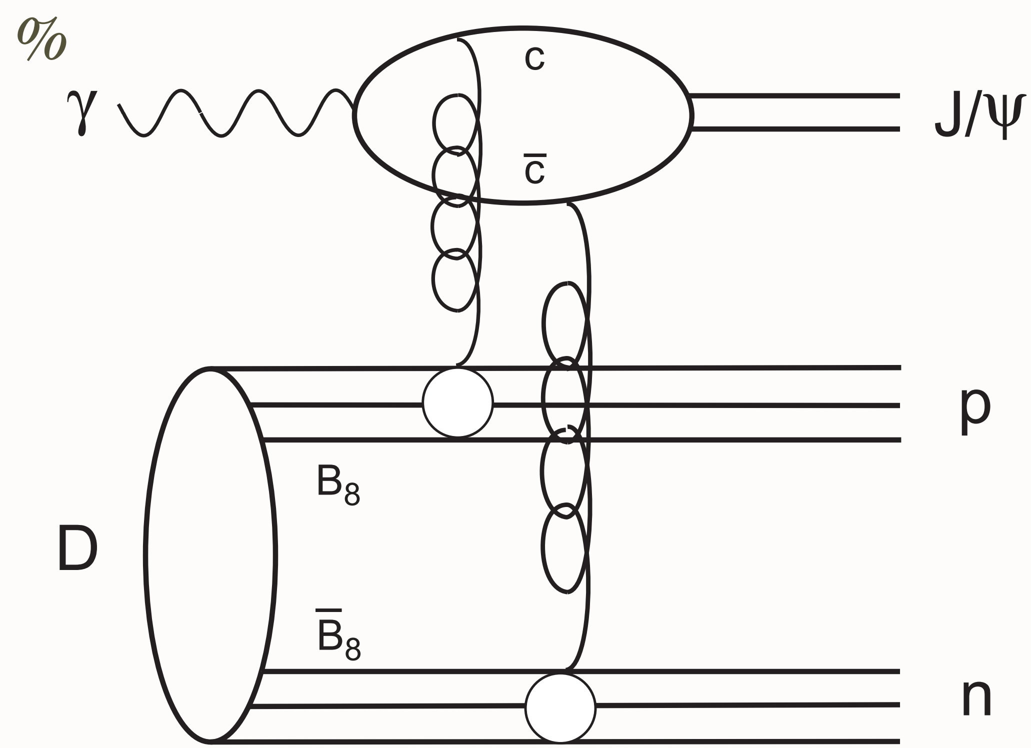


Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

Chudakov, Hoyer, Laget, sjb



The variation of the cross-section of the reaction $\gamma D \to pnJ/\psi$ against the neutron momentum $|\vec{n}|$, at fixed t. Solid line: quasi-free contribution. Dashed line: contribution of a hidden-color component when its probability is 0.1%. Dash-dotted curve: the same for a probability of 1%.



$\gamma D \to n\ p\ J/\psi$

Hidden color contribution

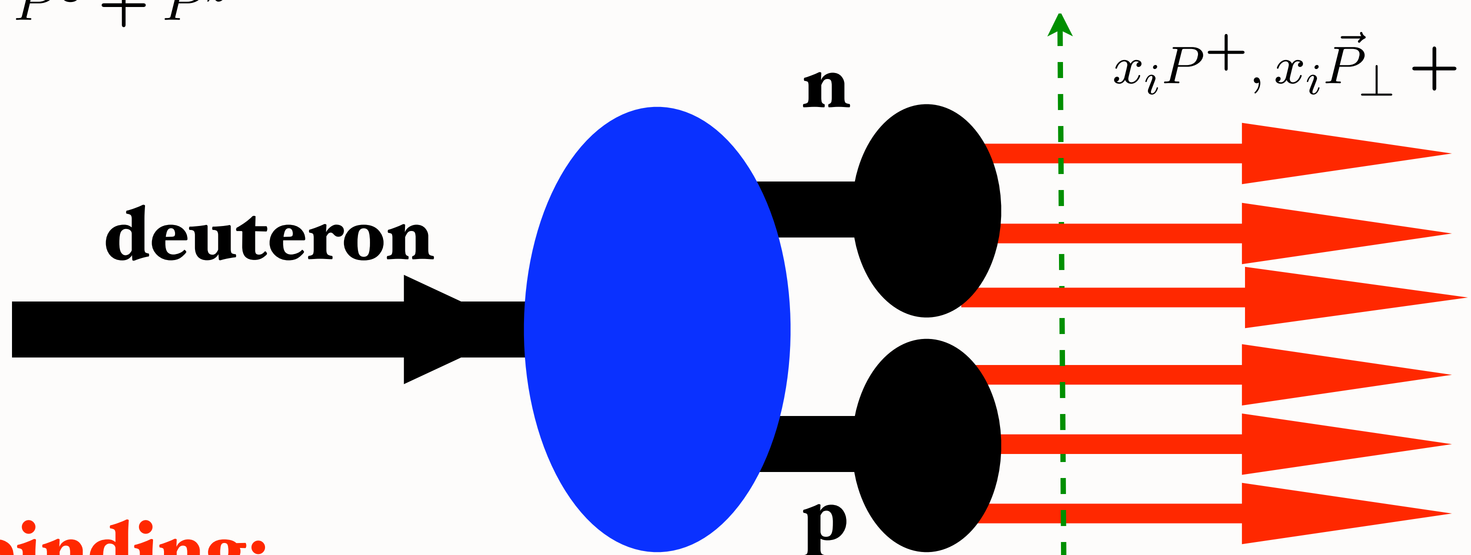
Deuteron Light-Front Wavefunction

Fixed $\tau = t + z/c$

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

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

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



Weak binding:

$$\psi_d(x_i, \vec{k}_{\perp i}) = \psi_d^{body} \times \psi_n \times \psi_p$$

$\sum_i^n x_i = 1$

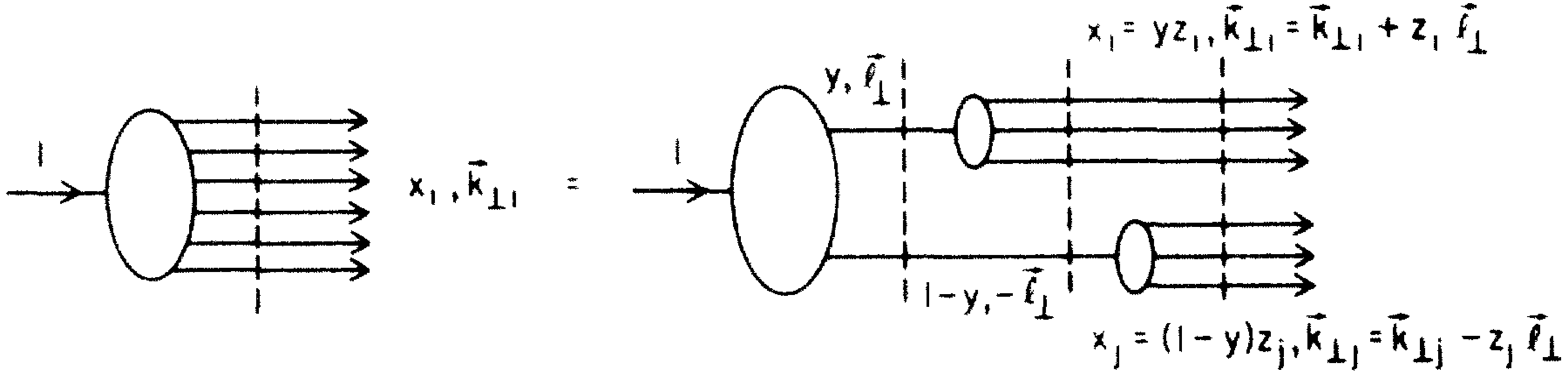
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Two color-singlet combinations of three 3_C

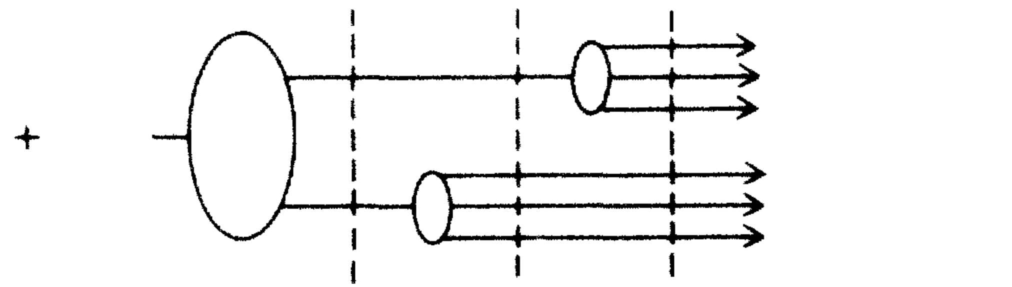
Ji, sjb

Properties of Deuteron Light-Front Wavefunction

- Cluster Decomposition Theorem for relativistic systems
- Factorization of LFWF in weak binding limit
- Reduced Nuclear Form Factor
- No Wigner Boosts - Melosh factors built in
- Low energy theorems
- $\psi_d(x_i, \vec{k}_{\perp i}) = \psi_d^{body} \times \psi_n \times \psi_p$



Weak binding: Cluster decomposition on the LF



$$z_i = \frac{x_i}{y}, \quad \mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - z_i \boldsymbol{l}_\perp \quad (i = 1,2,3),$$

$$z_j = \frac{x_j}{1-y}, \quad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} - z_j \boldsymbol{l}_\perp \quad (j = 4,5,6),$$

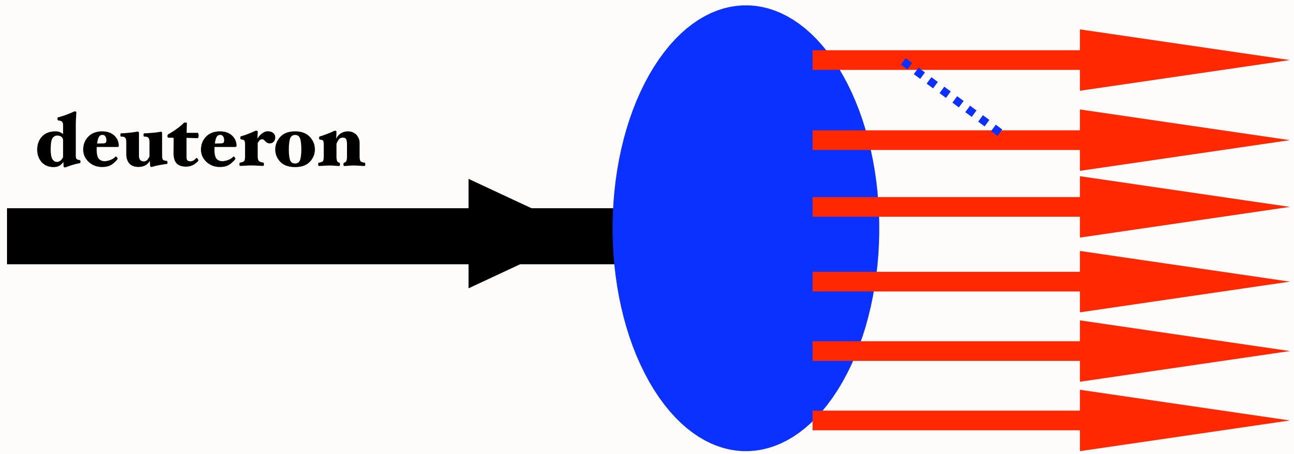
$$y = \sum_{i=1}^{3} x_i$$

$$\vec{\ell}_\perp = \sum_{i=1}^{3} \vec{k}_{\perp i}$$

$$\Psi_d(x_i, \mathbf{k}_{\perp i}) = \psi_d^{\text{body}}(y, \boldsymbol{l}_\perp)\, \psi_N(z_i, \mathbf{k}'_{\perp i})\, \psi_N(z_j, \mathbf{k}'_{\perp j}) \; .$$

Evolution of 5 color-singlet Fock states

$$\Psi^{\mathbf{d}}_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



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

$\sum_i^n x_i = 1$

$$\Phi_n(x_i, Q) = \int^{k^2_{\perp i} < Q^2} \Pi' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Quantum Chromodynamic Predictions for the Deuteron Form Factor

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

where the hard-scattering amplitude

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

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

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

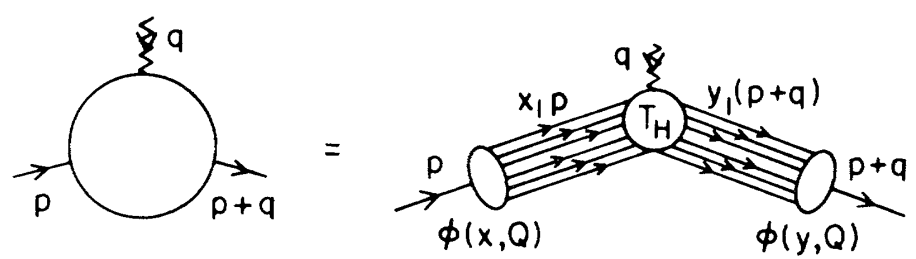
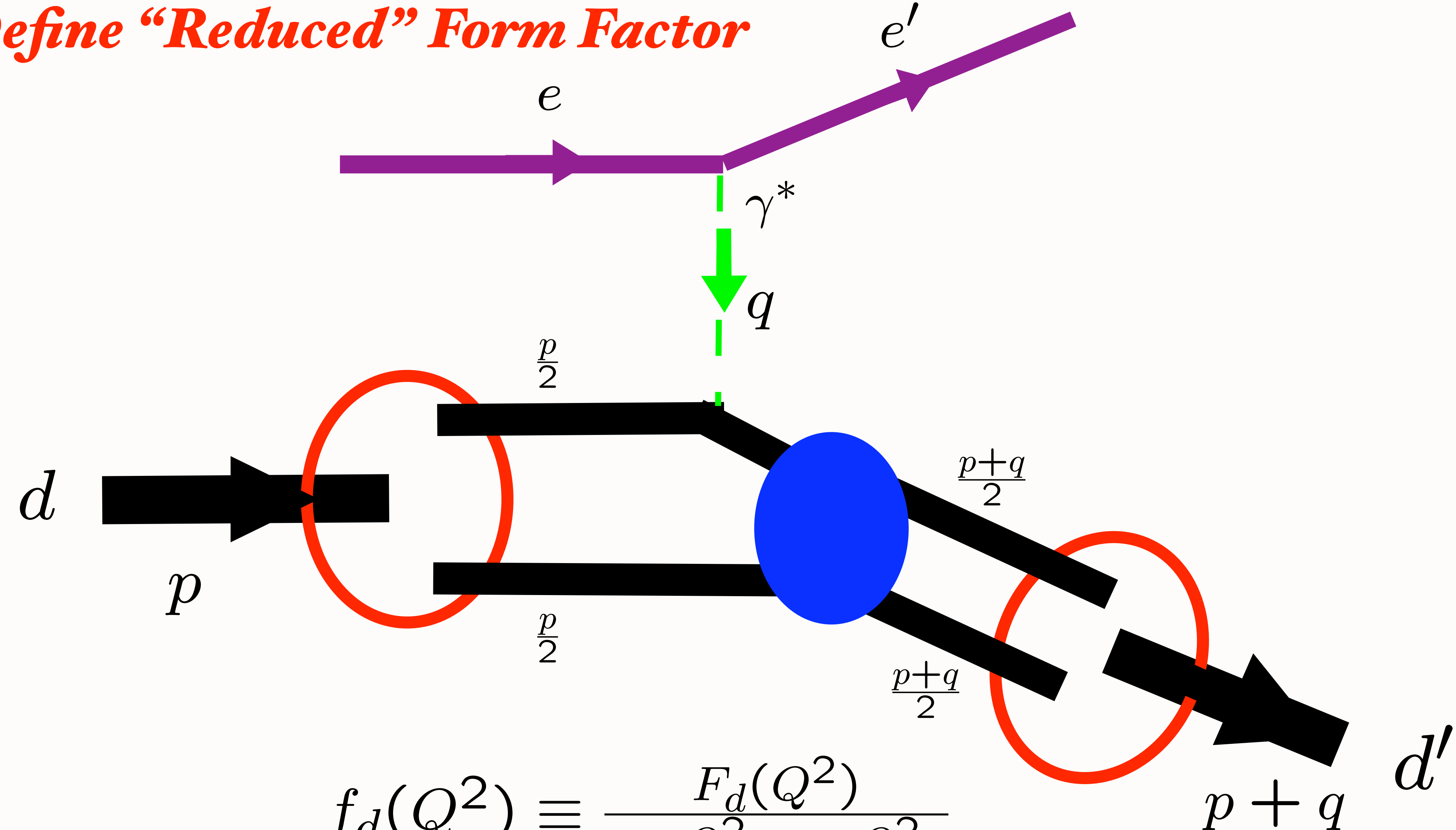


FIG. 1. The general structure of the deuteron form factor at large Q^2.

Ji, Lepage, sjb

Define "Reduced" Form Factor



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

Elastic electron-deuteron scattering

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

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

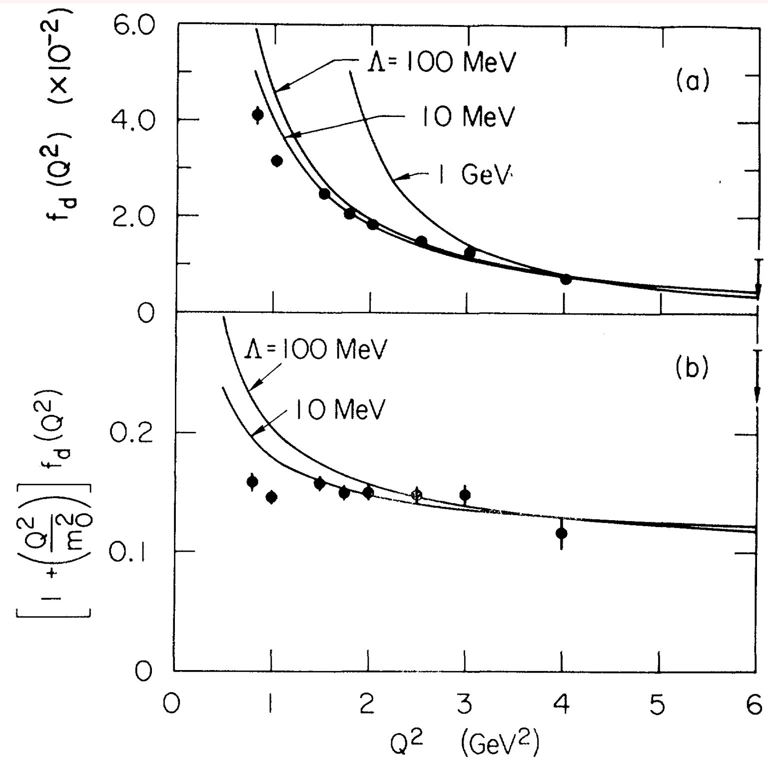
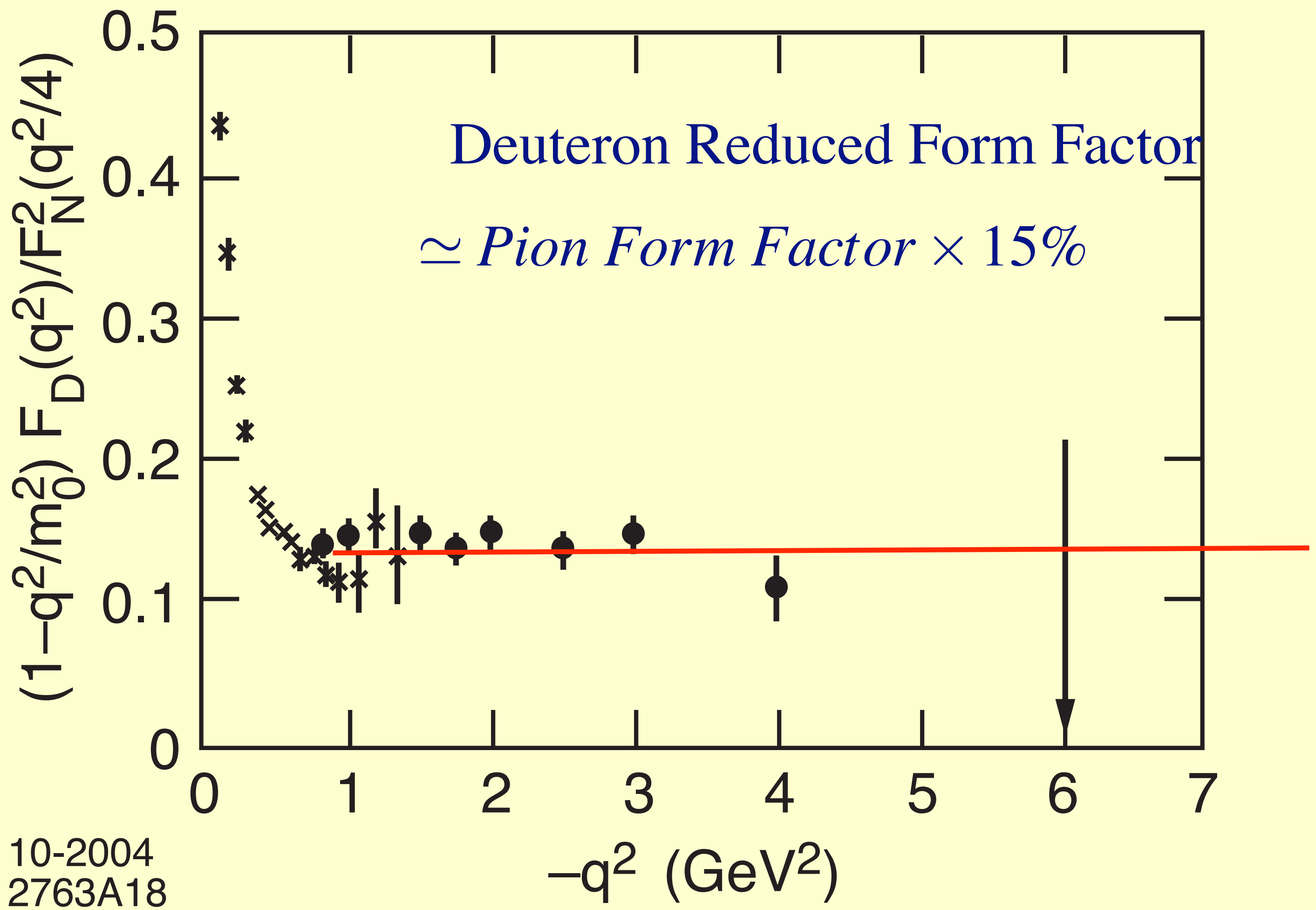


FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$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



- Large Magnitude: Evidence for Hidden Color in the Deuteron

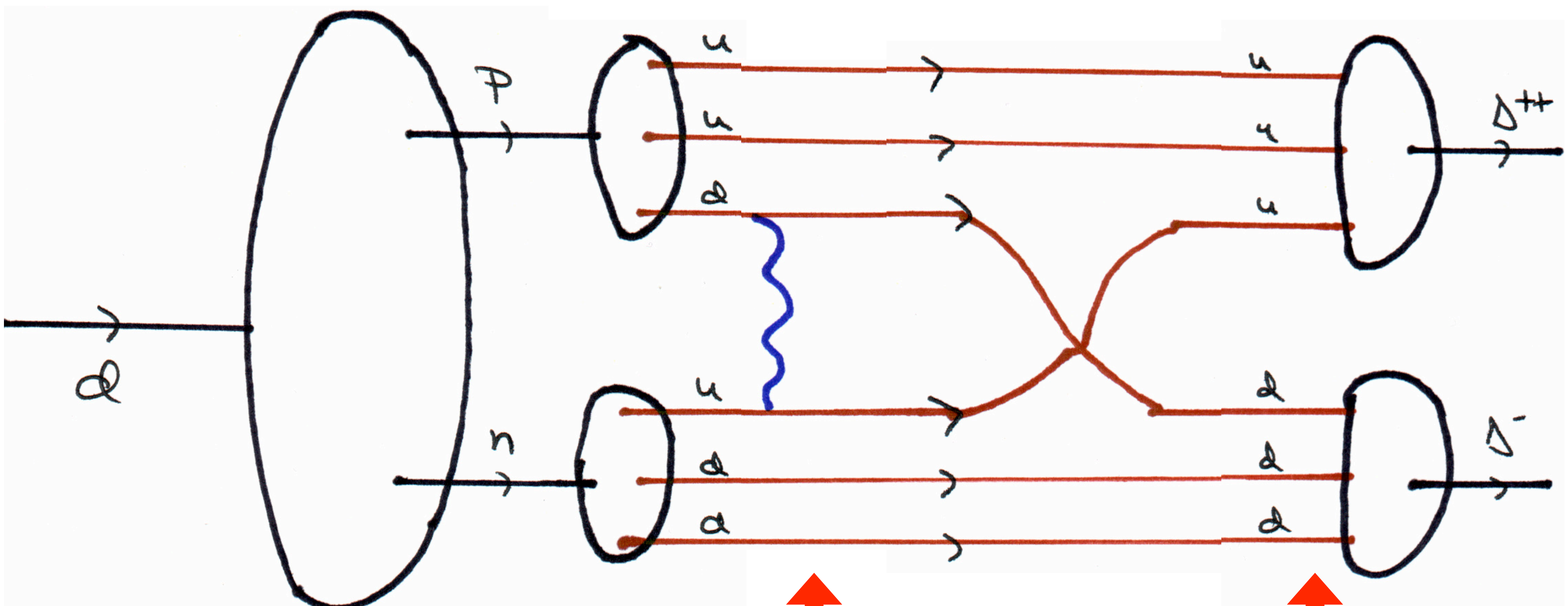
Hidden Color in QCD

Lepage, Ji, sjb

- **Deuteron six-quark wavefunction**
- **5 color-singlet combinations of 6 color-triplets -- only 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**

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

Structure of Deuteron in QCD



Hidden Color Fock State

Delta-Delta Fock State

Lepage, 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.

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

$\gamma d \to np$

$\gamma d \to (uuddd us\bar{s}) \to np$ at $s = 9$ GeV^2

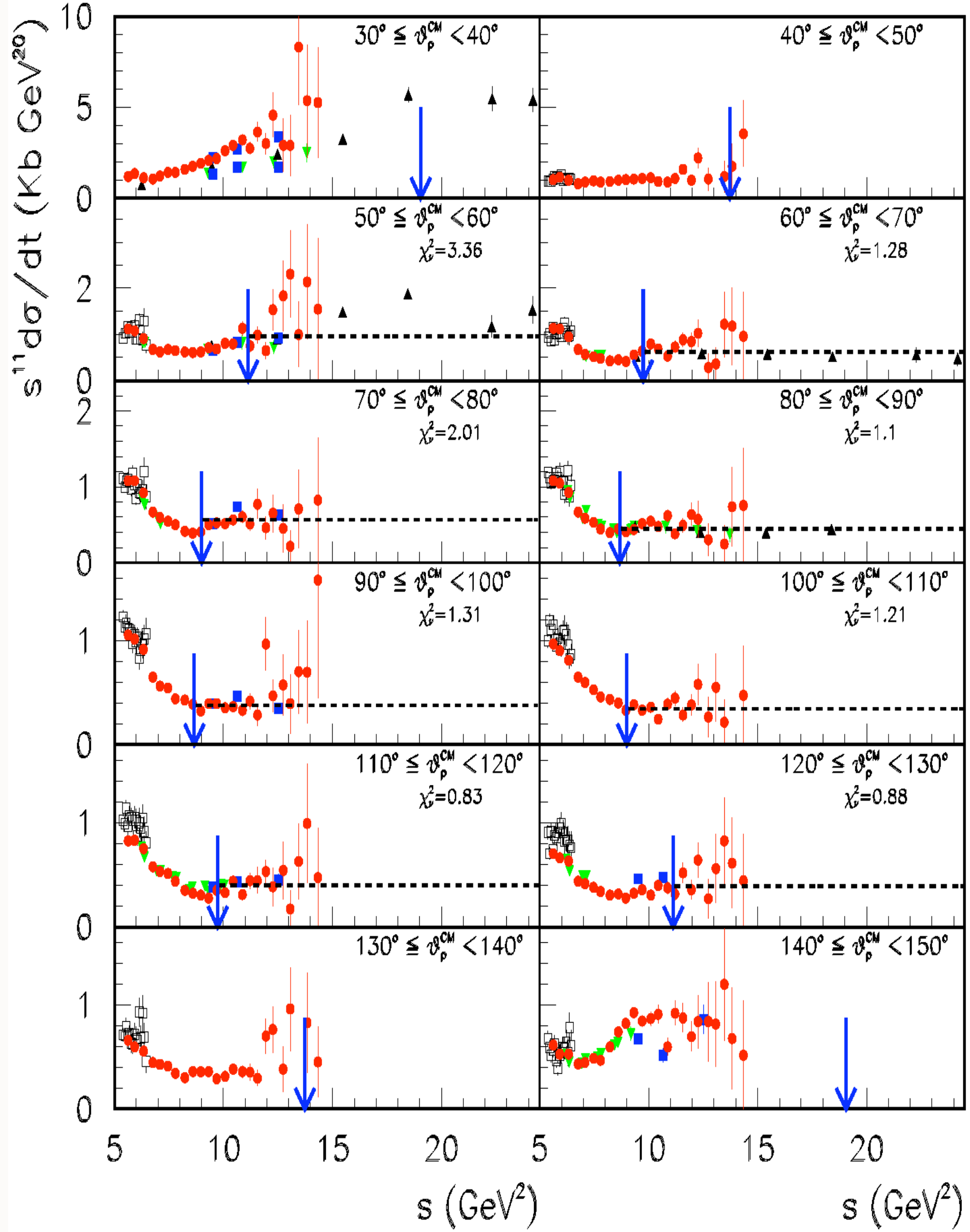
Fit of dσ/dt data for the central angles and $P_T \geq 1.1$ GeV/c with $A\ s^{-11}$

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 γd → 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

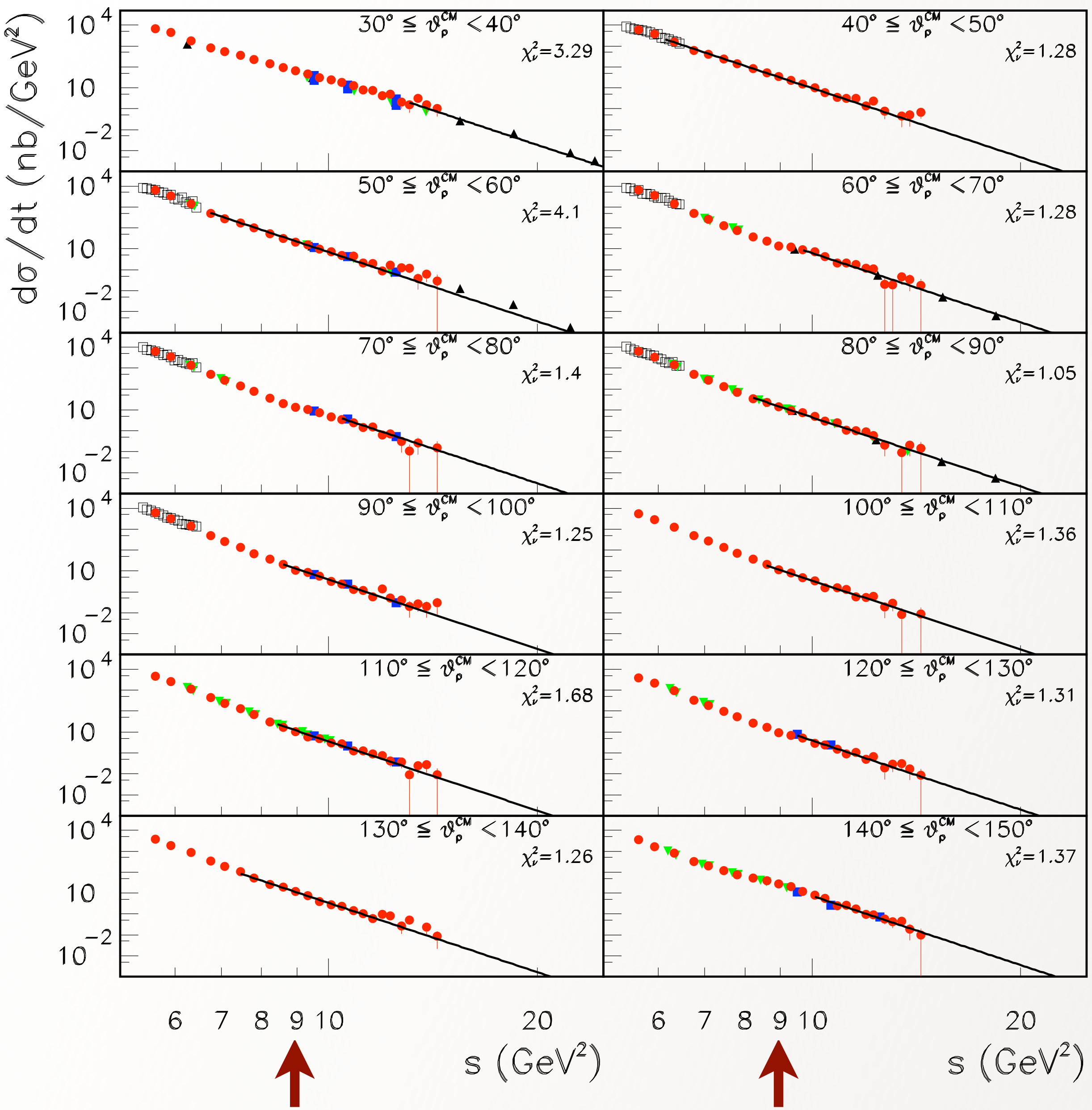
Hidden color: $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$

at high p_T

Ratio predicted to approach 2:5

Deuteron Photodisintegration and Dimensional Counting

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



PQCD and AdS/CFT:

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

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

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

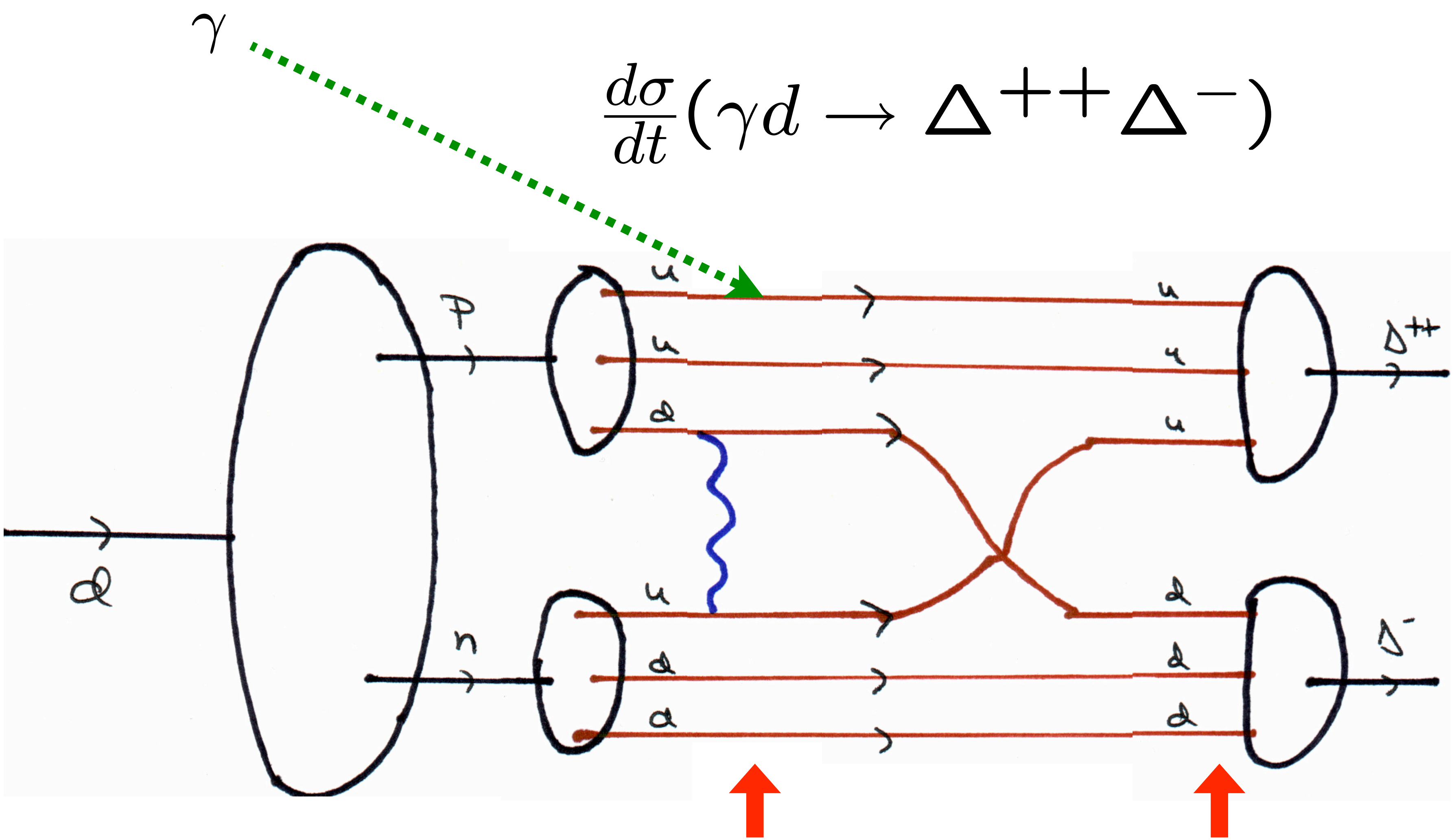
$$\gamma d \to (uuddduss\bar{s}) \to np$$

at $s \simeq 9$ GeV^2

$$\gamma d \to (uuddduc\bar{c}) \to np$$

at $s \simeq 25$ GeV^2

Test of Hidden Color in Deuteron Photodisintegration



Hidden Color Fock State

Delta-Delta Fock State

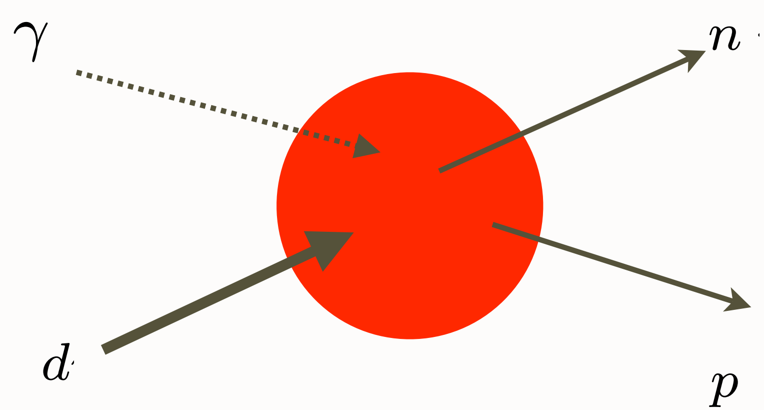
Test of Hidden Color in Deuteron Photodisintegration

$$R = \frac{\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{--})}{\frac{d\sigma}{dt}(\gamma d \to pn)}$$

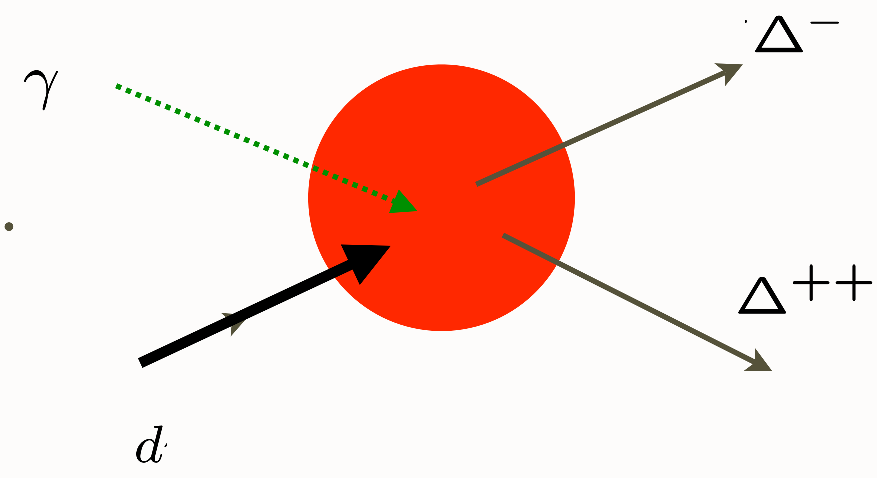
Ratio predicted to approach 2:5

Possible contribution from pion charge exchange at small t.

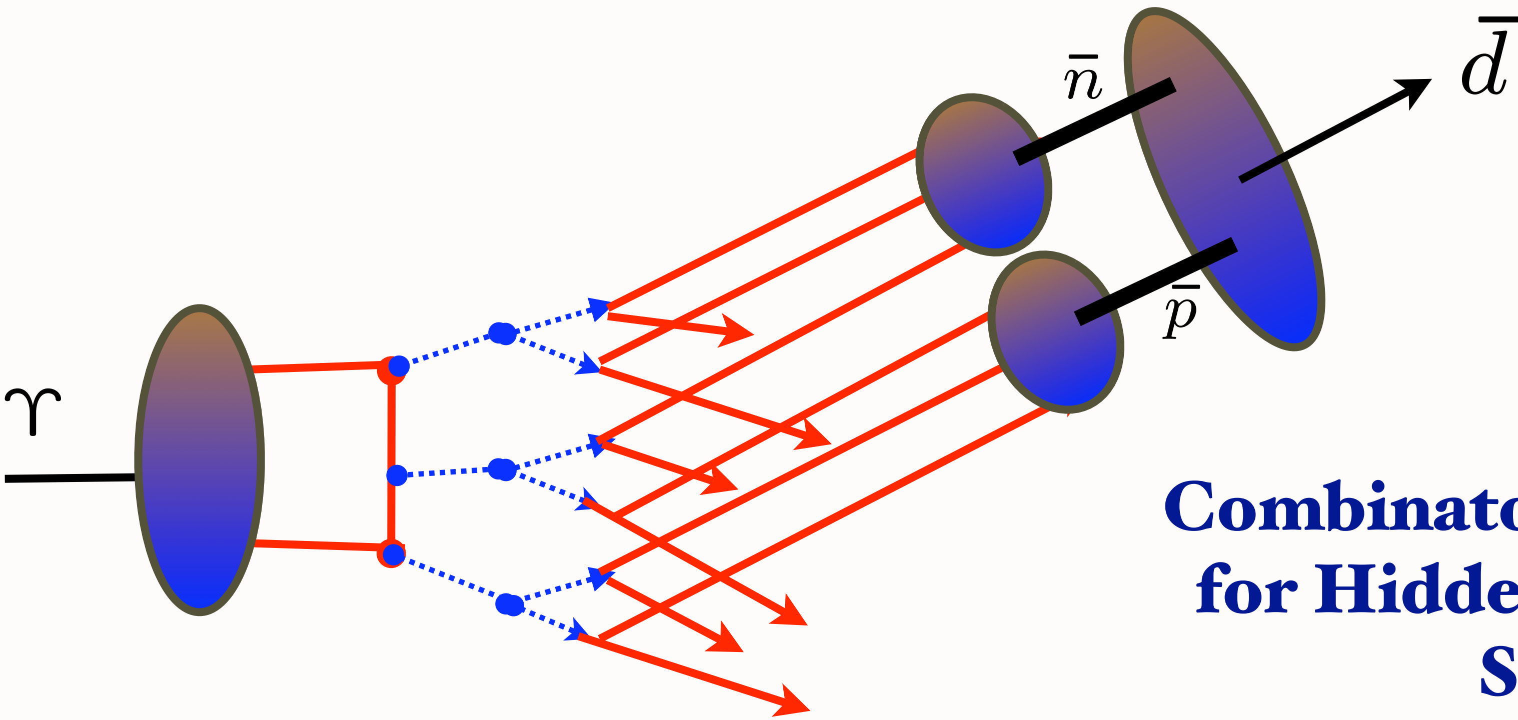
Ratio should grow with transverse momentum as the hidden color component of the deuteron grows in strength.



vs.



Anti-Deuteron Production at the Amplitude Level



Combinatoric Advantage for Hidden-Color Fock States

$$\Upsilon \to ggg \to q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q} \to \bar{d}\ X$$

Compare Anti-Deuteron production with double anti-baryon production

$$\Upsilon \to ggg \to q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q}\ q\bar{q} \to \bar{p}\ \bar{n}\ X$$

Key Test of Hidden Color

- CLEO measurement: Upsilon decay to anti-deuteron

$$\Upsilon \to ggg \to \bar{d} X$$

- Is ratio of deuteron production to production of anti-nucleon pairs determined by standard Nuclear Physics?

$$R = \frac{\Gamma(\Upsilon \to \bar{d} X)}{\Gamma(\Upsilon \to \bar{p}\bar{n} X)}$$

Standard contribution: Need to integrate double differential distribution

$$\int d^2k_\perp \int_0^1 dx) |\psi^d_{\bar{n}\bar{p}}(x, k_\perp)|^2 \times \frac{d\sigma}{d^3p_{\bar{n}} d^3p_{\bar{p}}}(\Upsilon \to \bar{n}\bar{p} X)$$

Single-spin asymmetries

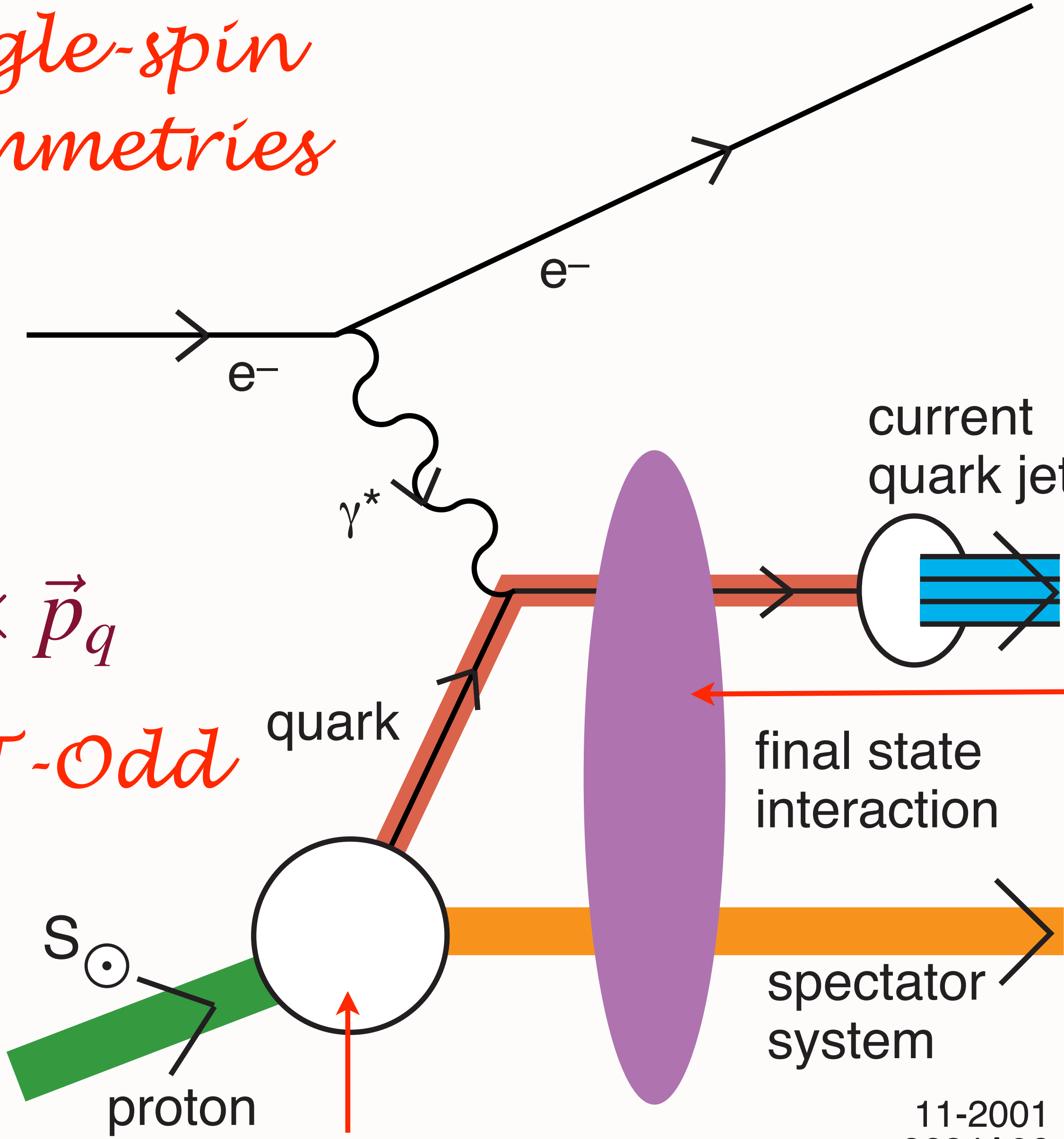
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

Pseudo-T-Odd



QCD S- and P-Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves

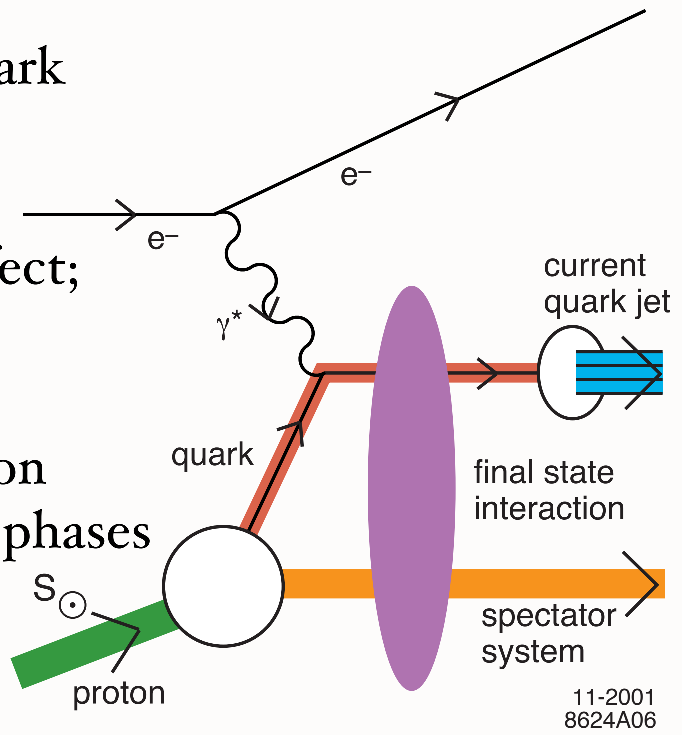
Physics of Rescattering

- Diffractive DIS: New Insights 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

Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

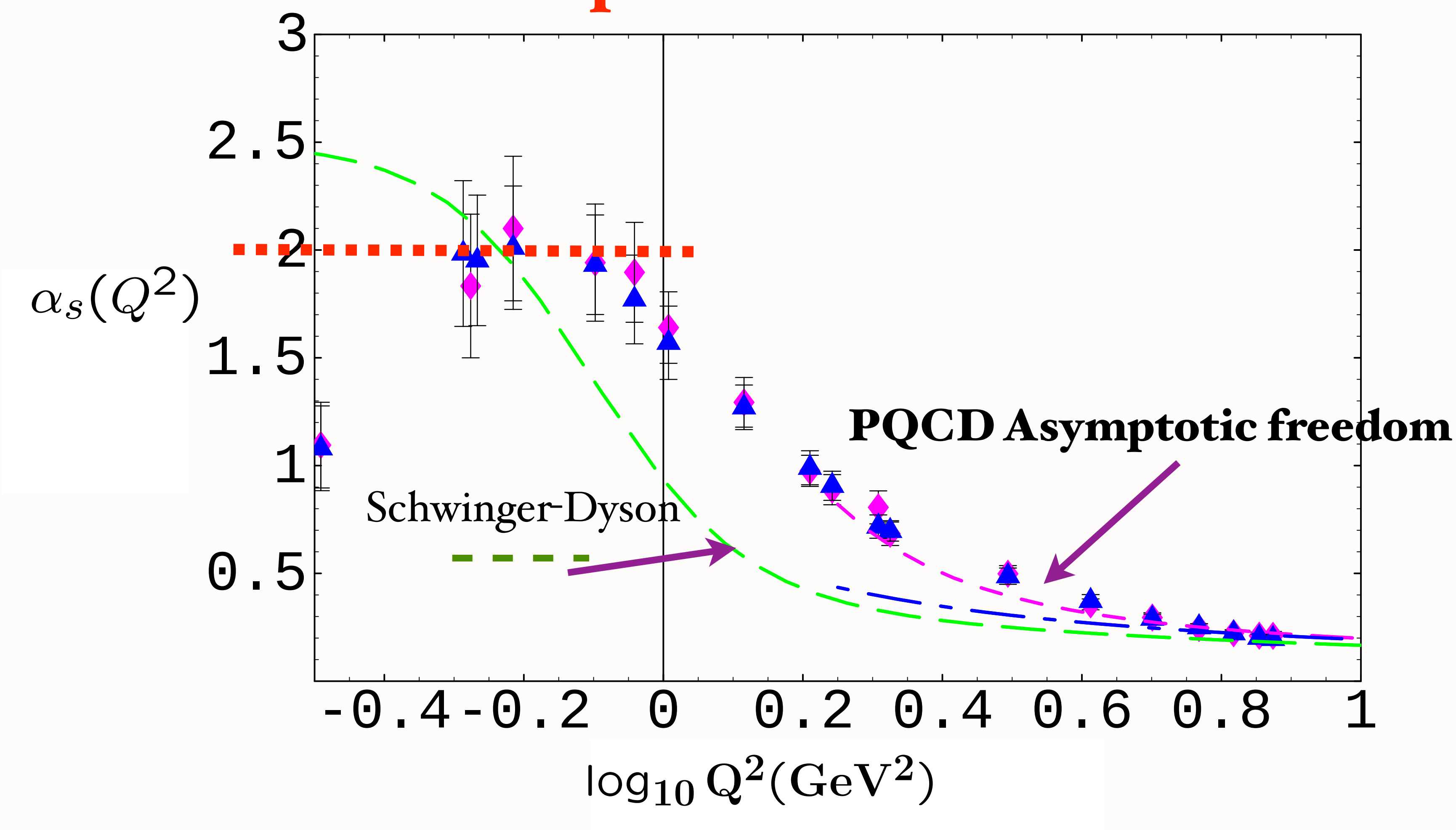
$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$

- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD phase at soft scale
- New window to QCD coupling and running gluon mass in the IR
- QED S and P Coulomb phases infinite -- difference of phases finite



Conformal window
Infrared fixed-point

$$\beta(Q^2) = \frac{d\alpha_s(Q^2)}{d\log Q^2} \to 0$$

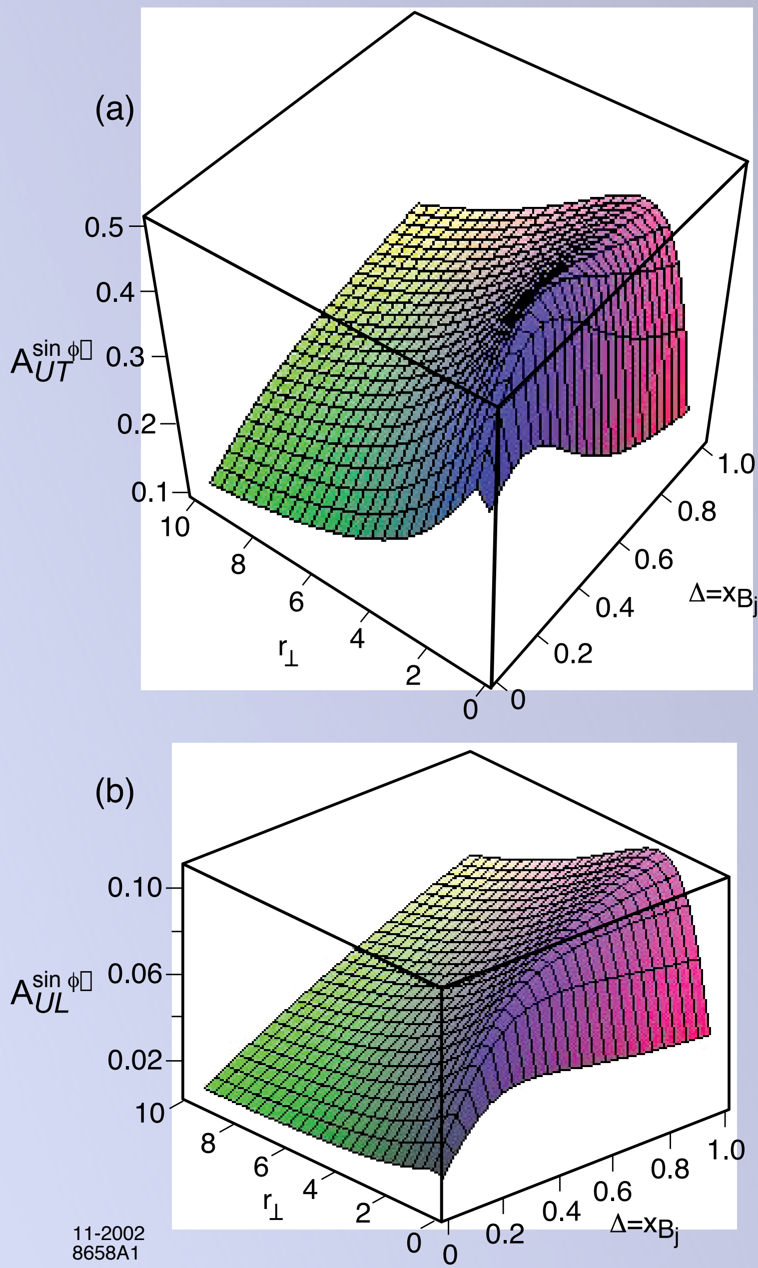


Shirkov
Gribov
Dokshitser
Siminov
Maxwell
Cornwall

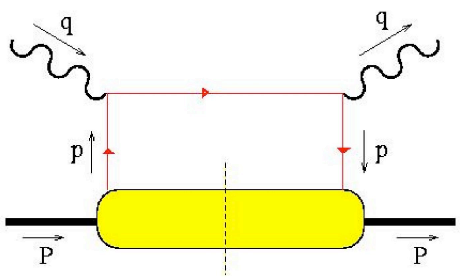
lattice: Furui, Nakajima (MILC)

DSE: Alkofer, Fischer, von Smekal et al.

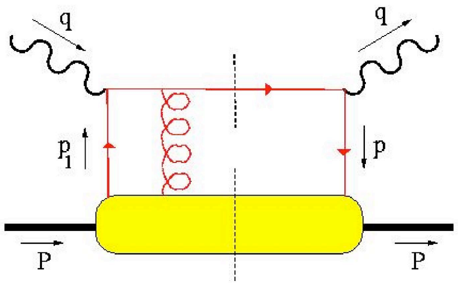
Prediction for Single-Spin Asymmetry



Hwang, Schmidt, sjb



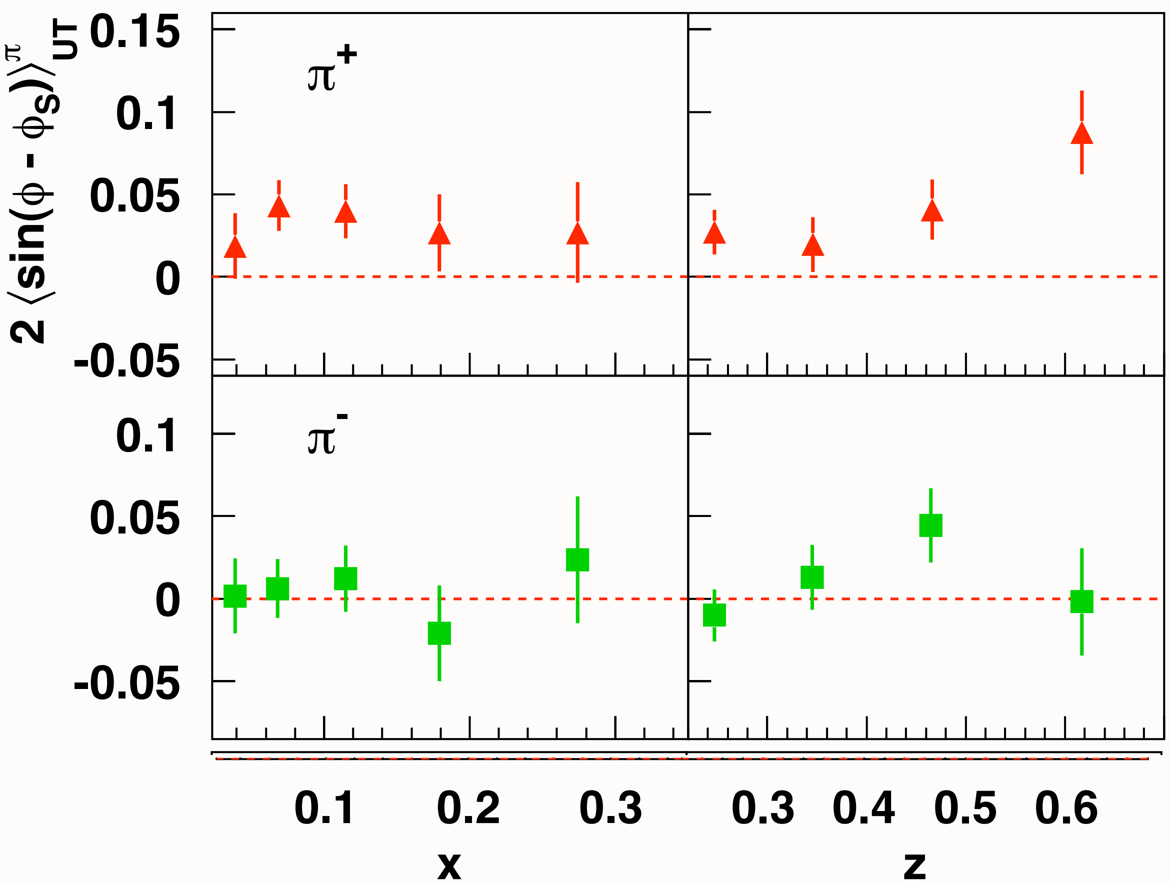
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

Sivers asymmetry from HERMES



- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for **π⁺**... Consistent with zero for **π⁻**...

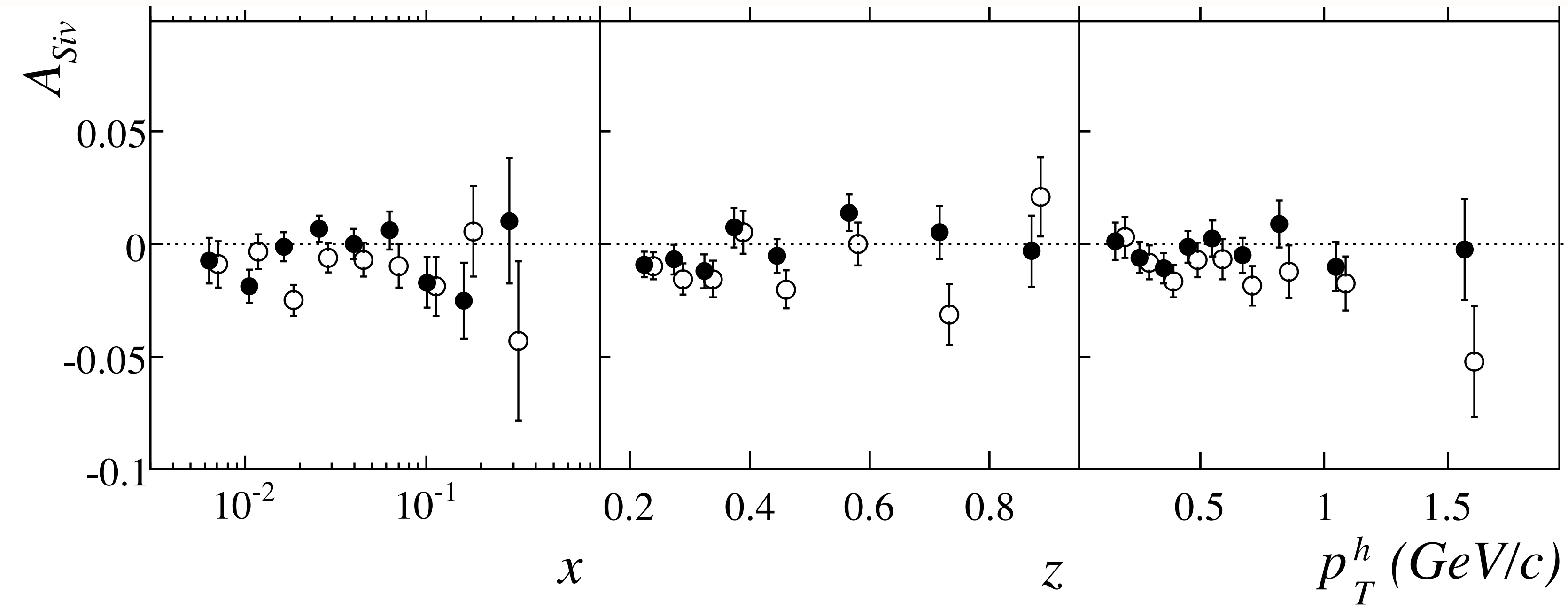
Gamberg: Hermes data compatible with BHS model

Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

A new measurement of the Collins and Sivers asymmetries on a transversely polarised deuteron target

The COMPASS Collaboration

hep-ex/0610068



Sivers SSA cancels on an isospin zero target --
gluon contribution to the Sivers asymmetry small
small gluon contribution to orbital angular momentum of nucleon

Gardner, sjb

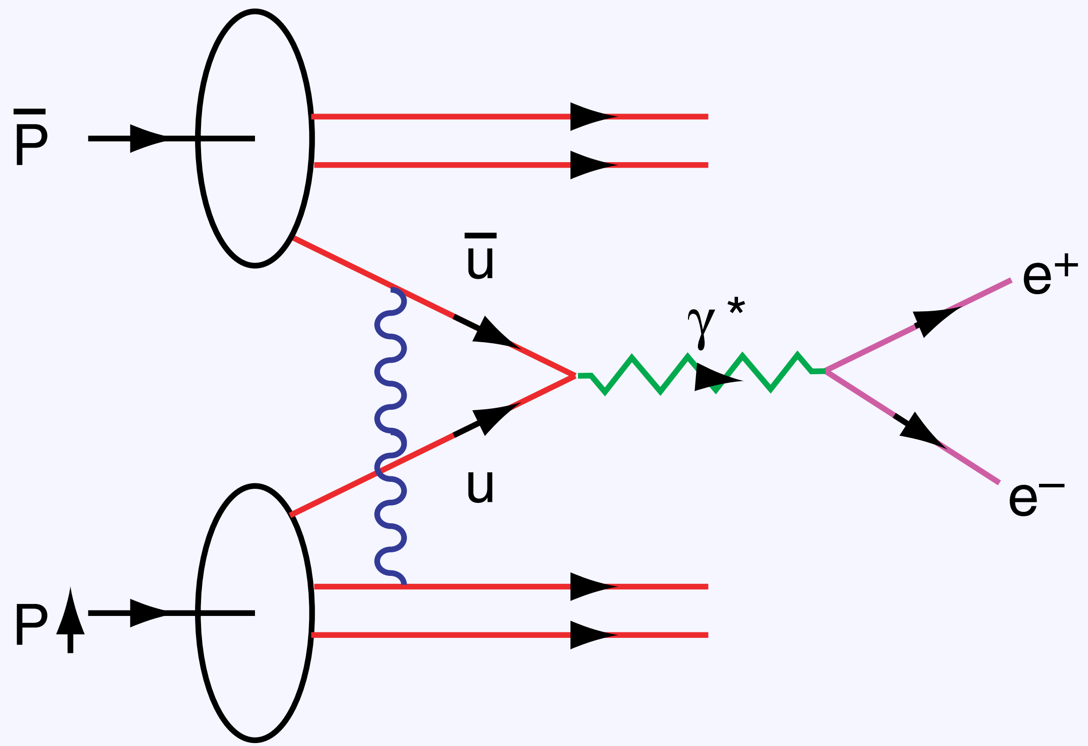
Recent COMPASS data on deuteron: small Sivers effect

- The anomalous magnetic moment, the Sivers function, and the generalized parton distribution E can all be connected to matrix elements involving the orbital angular momentum of the nucleon's constituents.
- The SSA can be generated by either a quark or gluon mechanism, and the isospin structure of the two mechanisms is distinct. The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentum carried by gluons in the nucleon, is small.
- Studies of the SSA in ϕ or K^+K^- production, via $\gamma^* g \to s\bar{s} \to \phi + X$ or $\gamma^* g \to s\bar{s} \to K^+K^- + X$ should provide additional constraints on the gluon mechanism.

Gardner, sjb

Predict Opposite Sign SSA in DY !

Collins;
Hwang, Schmidt.
sjb



Single Spin Asymmetry In the Drell Yan Process

$\vec{S}_p \cdot \vec{\bar{p}} \times \vec{q}_{\gamma^*}$

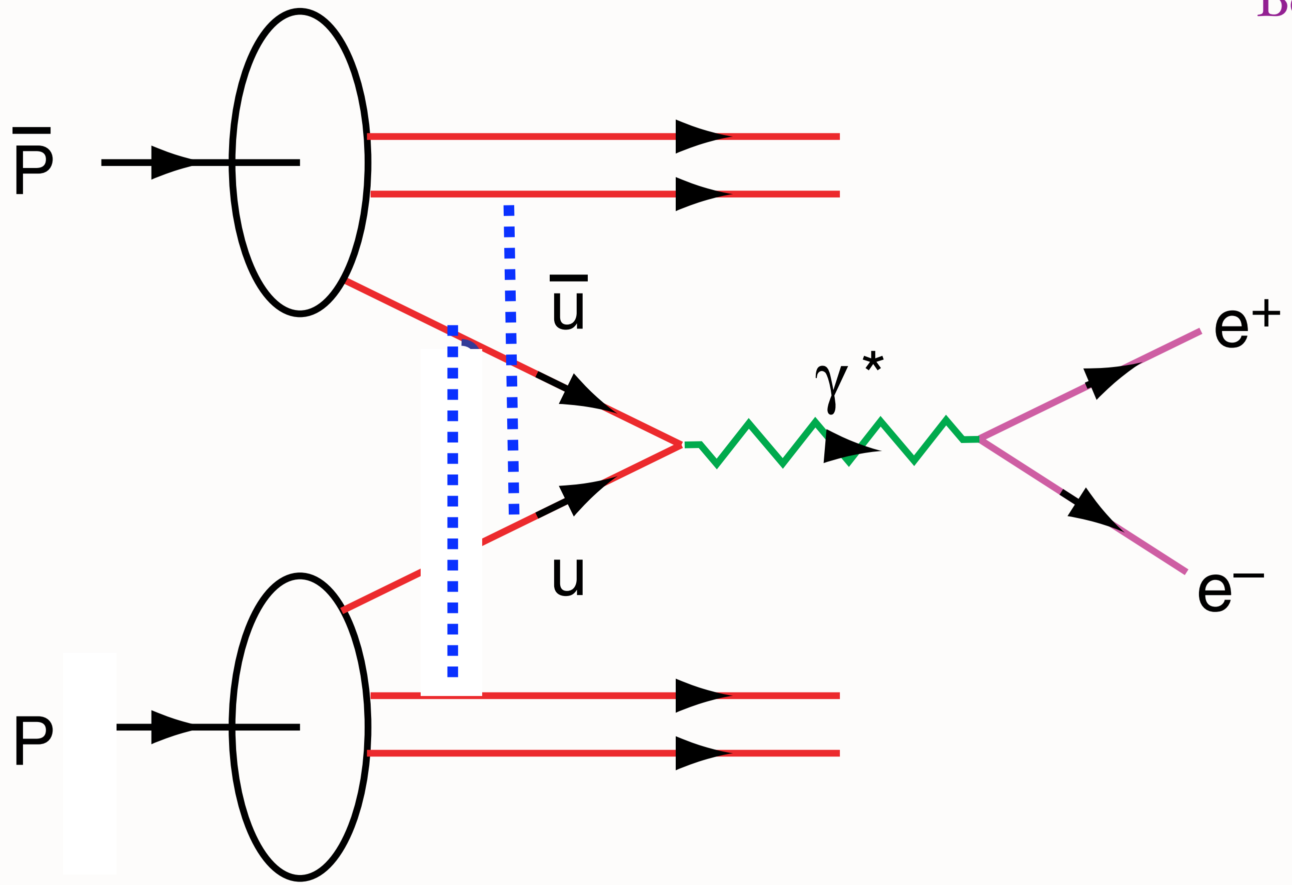
Quarks Interact in the Initial State

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.

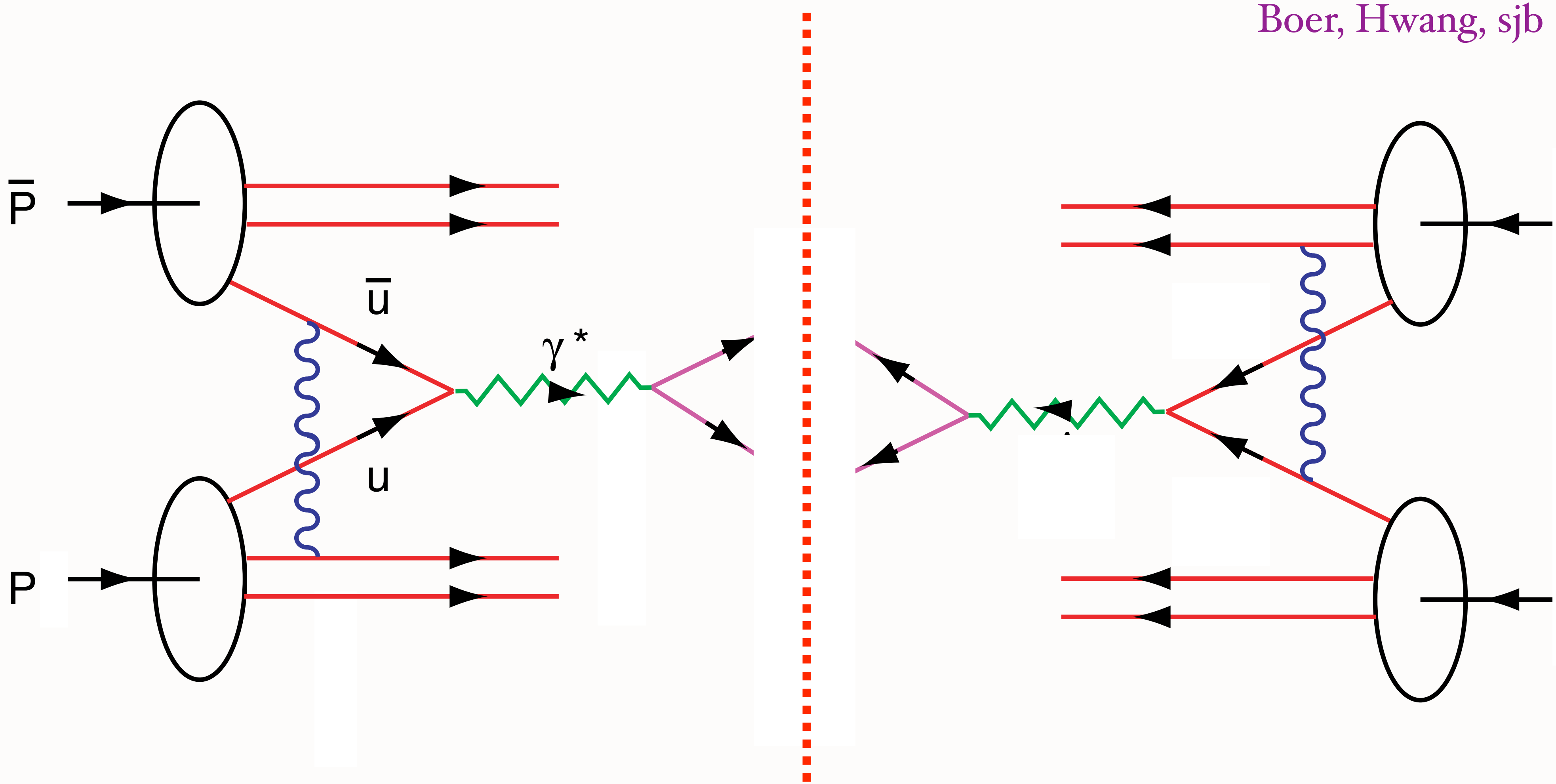
Opposite Sign to DIS! No Factorization

Boer, Hwang, sjb



DY $\cos 2\phi$ correlation at leading twist from double ISI

Boer, Hwang, sjb

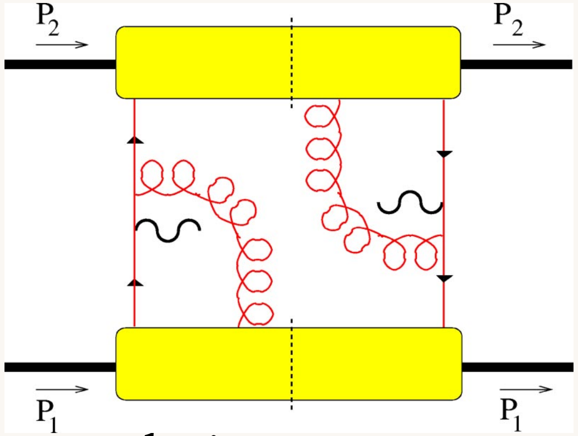


DY $\cos 2\phi$ **correlation at leading twist from double ISI**

Anomalous effect from Double ISI in Massive Lepton Production

Boer, Hwang, sjb

$\cos 2\phi$ correlation



- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization

Double Initial-State Interactions generate anomalous $\cos 2\phi$

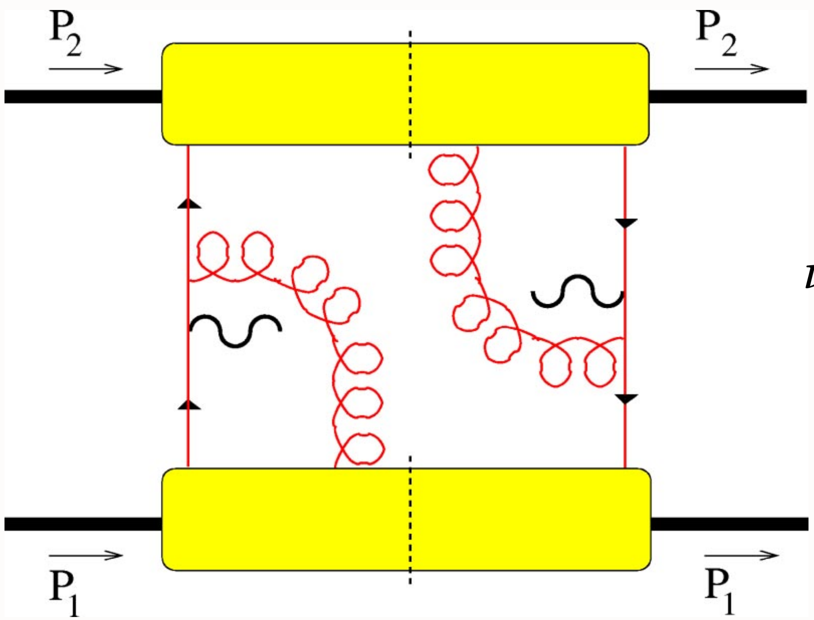
Boer, Hwang, sjb

Drell-Yan planar correlations

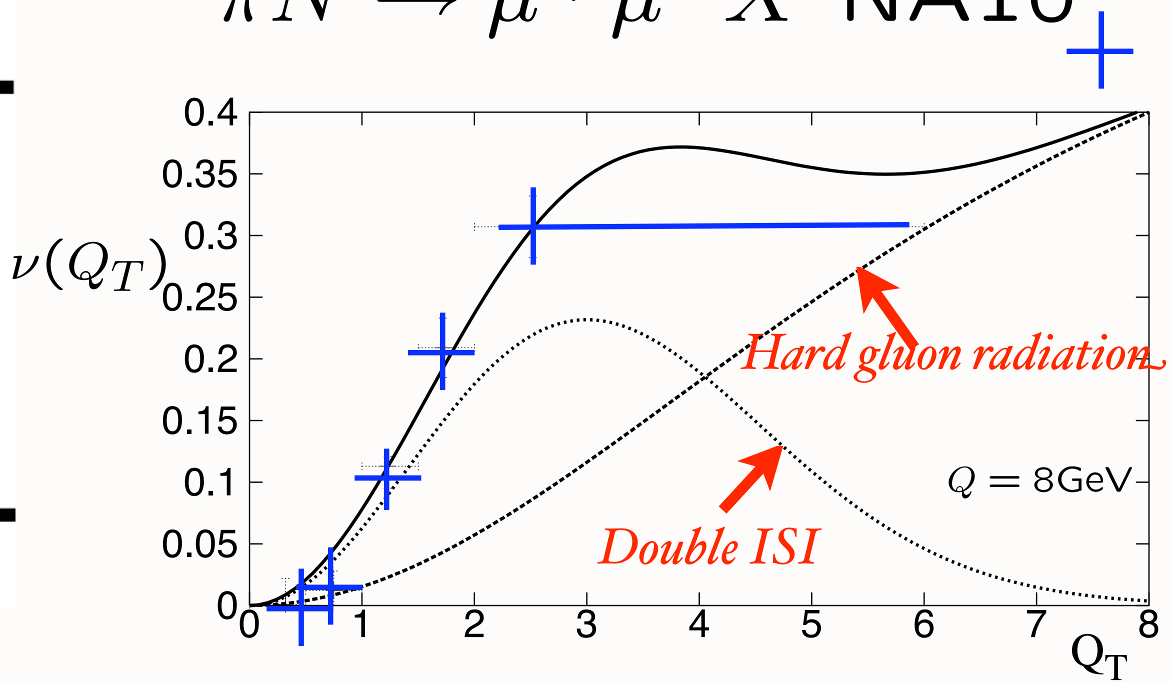
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^{\perp}(\pi)\, h_1^{\perp}(N)$$

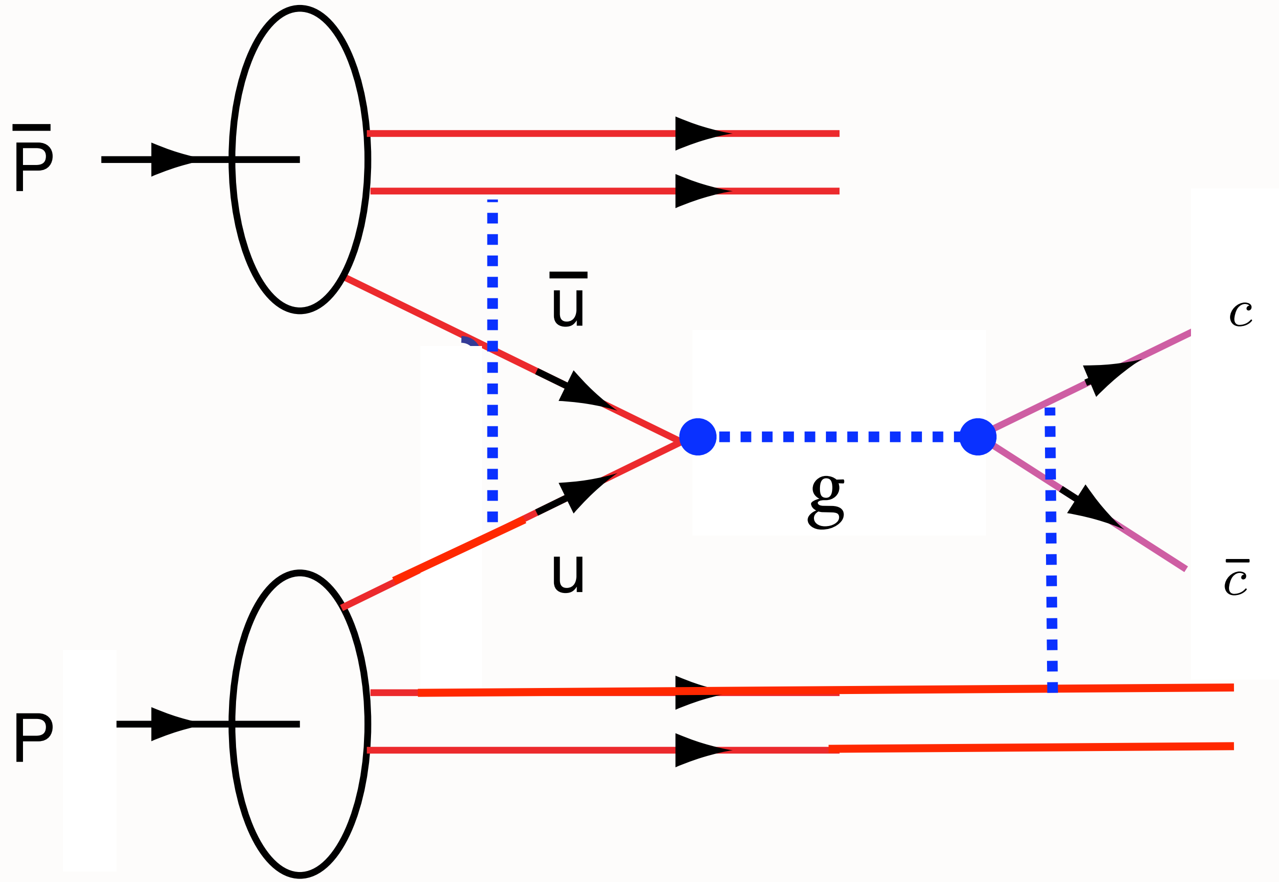


$\pi N \to \mu^+\mu^- X$ NA10



Violates Lam-Tung relation!

Model: Boer,

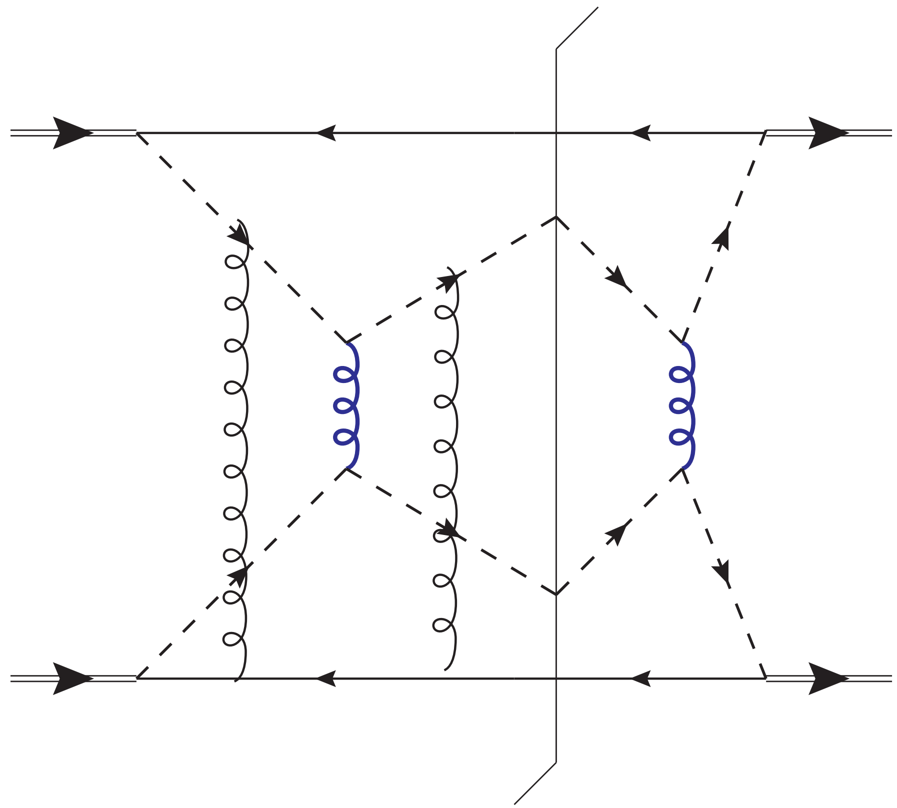


Problem for factorization when both ISI and FSI occur

Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

e-Print: **arXiv:0705.2141** [hep-ph]



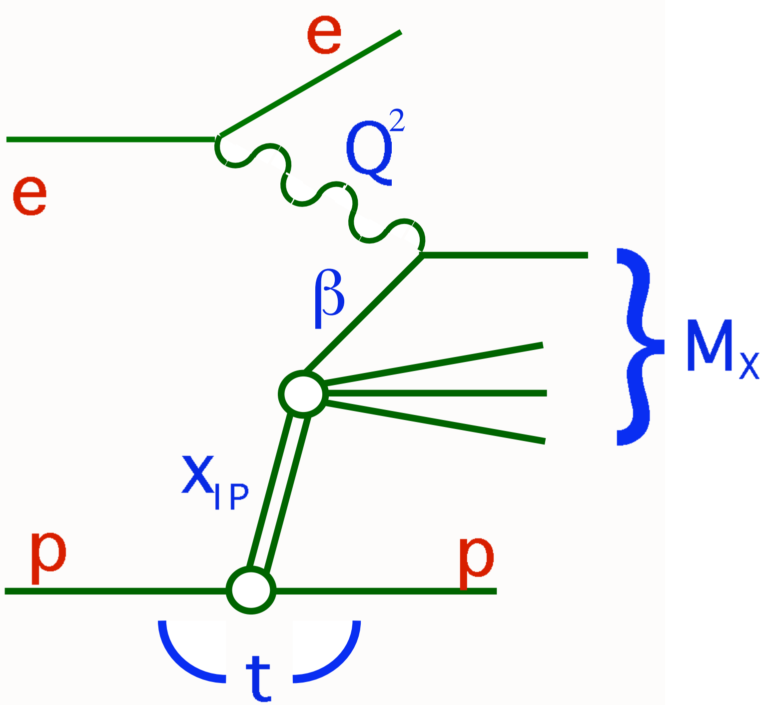
The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

“Dangling Gluons”

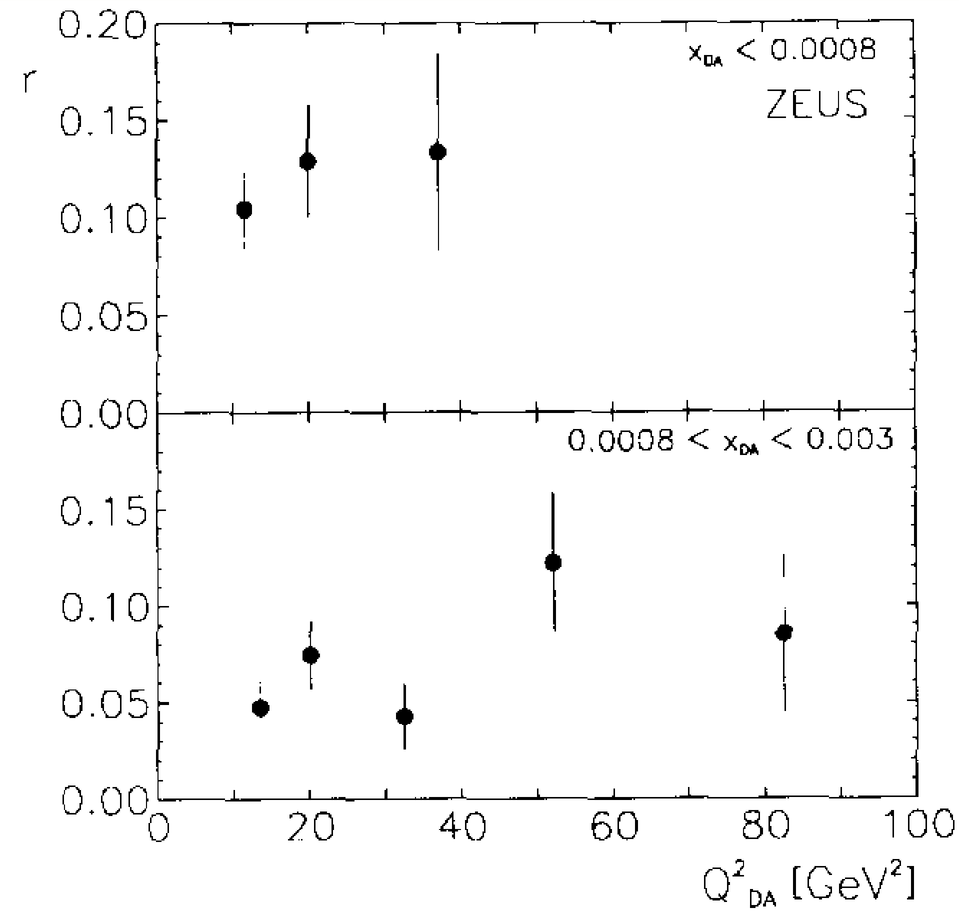
- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing- Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY $\cos 2\phi$ distribution at leading twist from double ISI-- not given by PQCD factorization -- breakdown of factorization!
- Wilson Line Effects not 1 even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments
- Corrections to Handbag Approximation in DVCS!

Hoyer, Marchal, Peigne, Sannino, sjb

Remarkable observation at HERA



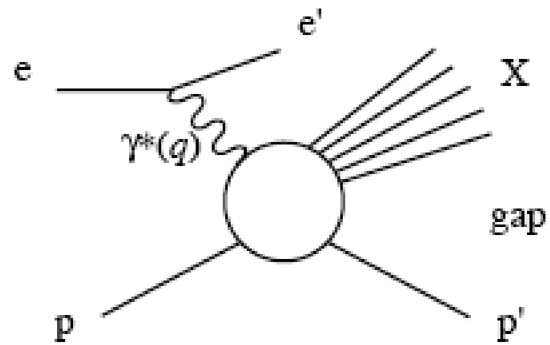
10% to 15% of DIS events are diffractive !



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

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

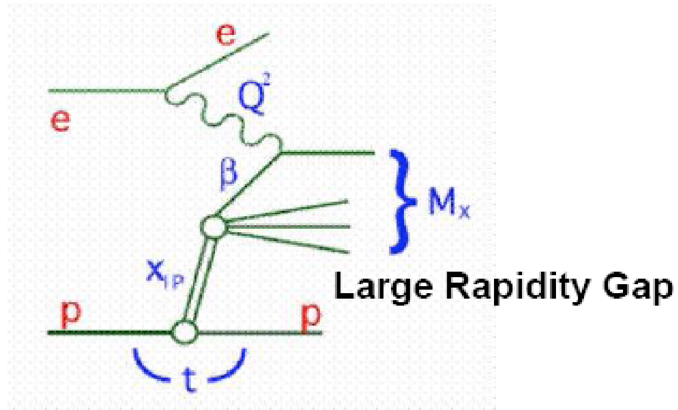
DDIS



- 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??

Diffractive Deep Inelastic Lepton-Proton Scattering

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

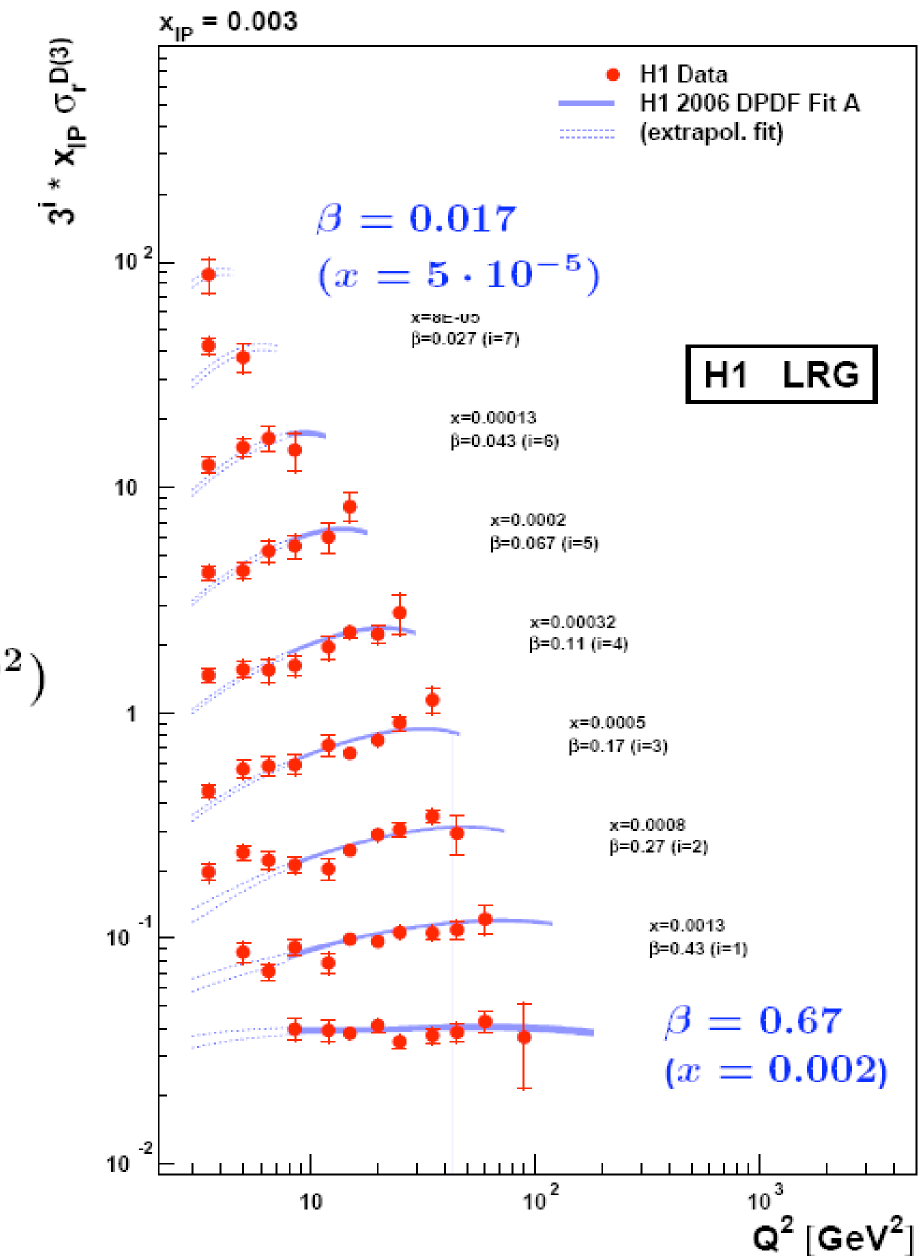
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

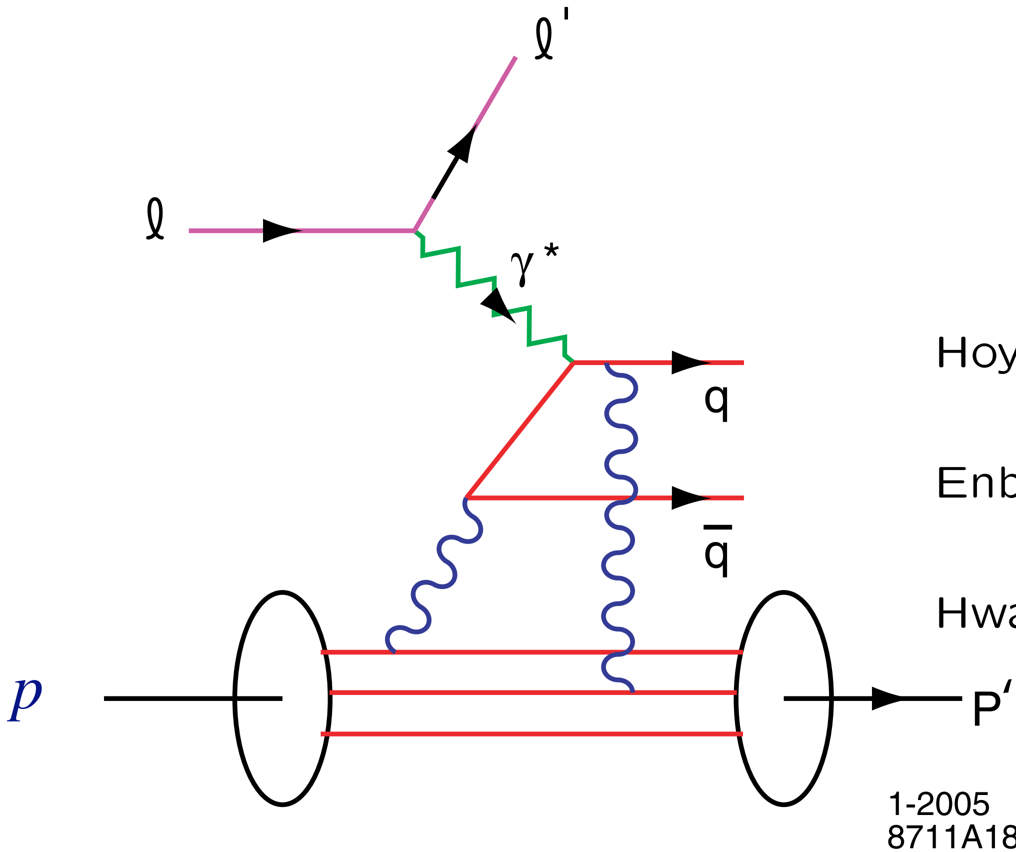
extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

Precise measurements *sys 5%, stat 5–20 %*



Final-State Interaction Produces Diffractive DIS



Quark Rescattering

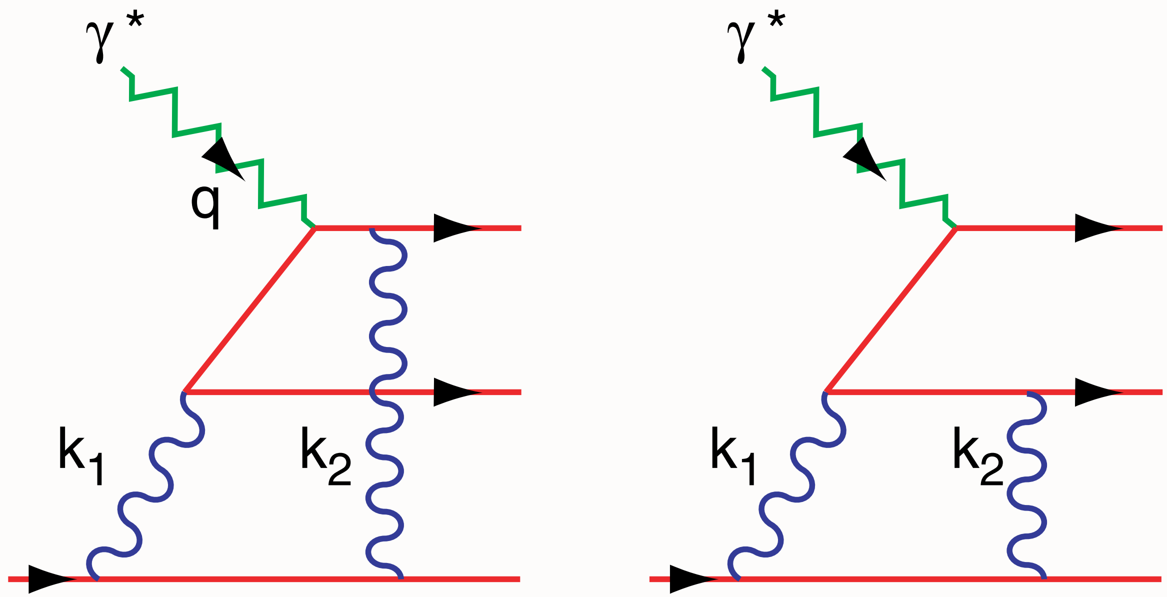
Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Final State Interactions in QCD



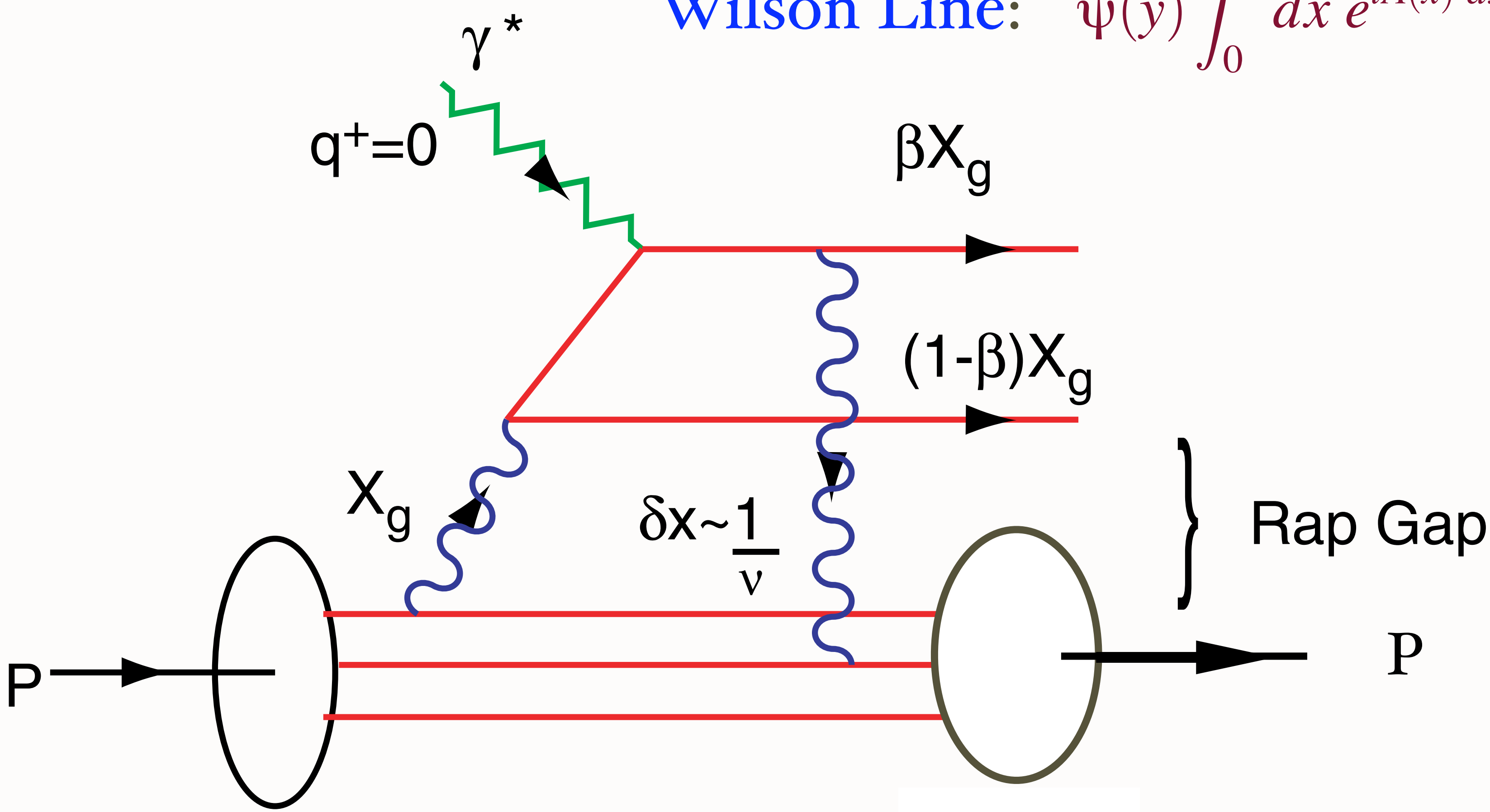
Feynman Gauge   Light-Cone Gauge

Result is Gauge Independent

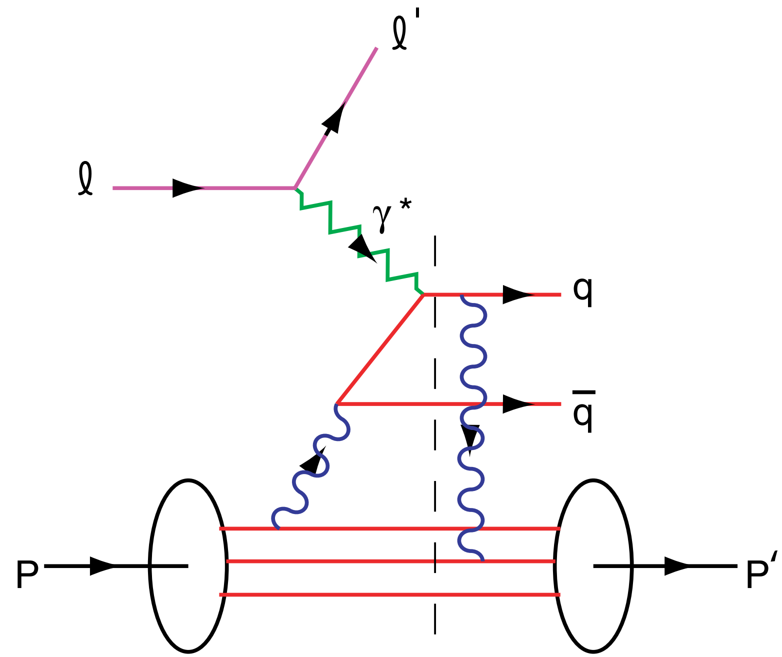
Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

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



Reproduces lab-frame color dipole approach

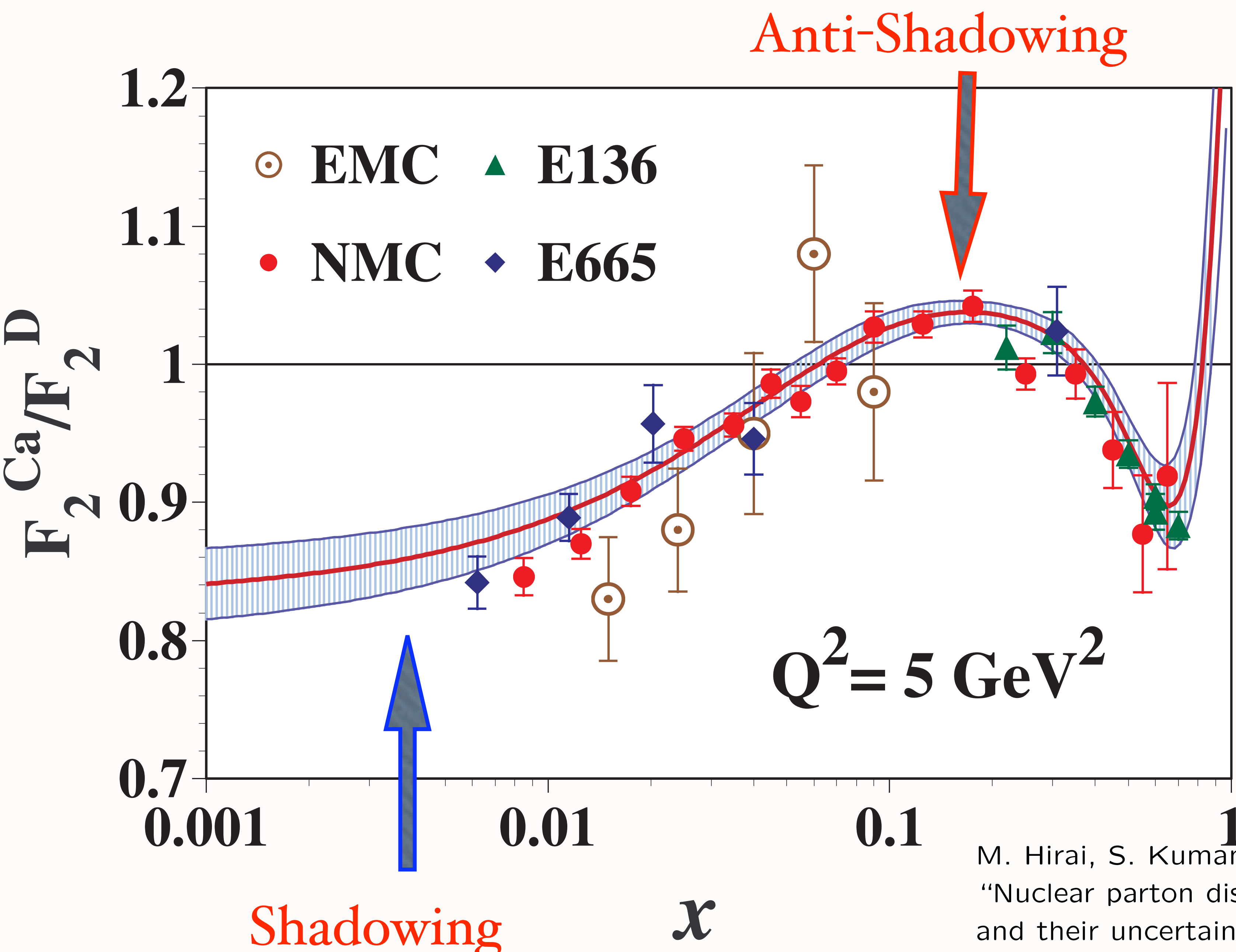


Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

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

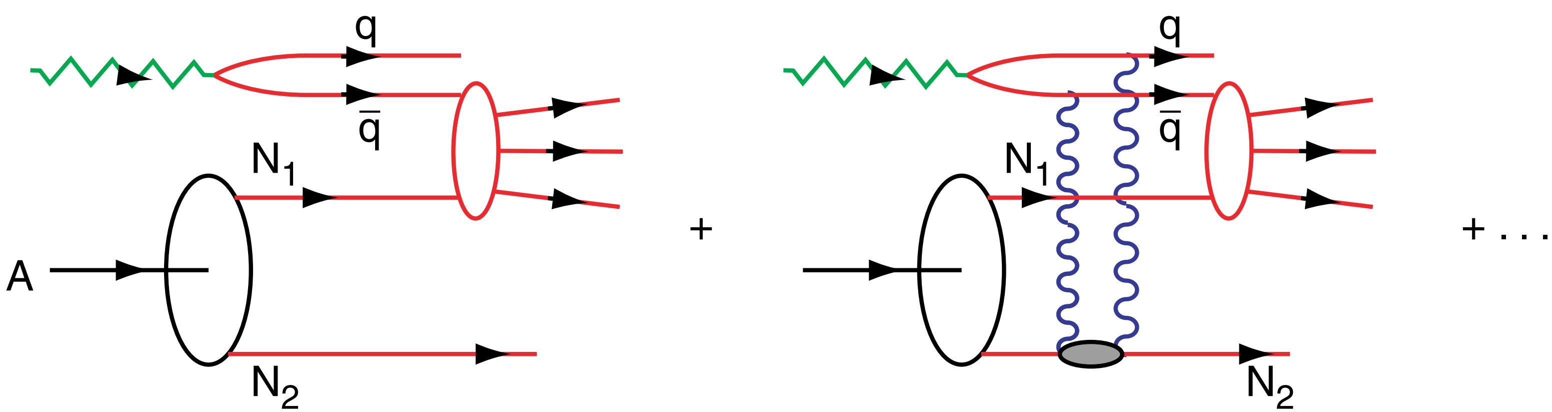
Physics of FSI not in Wavefunction of Target



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].

Stodolsky
Pumplin, sjb
Gribov

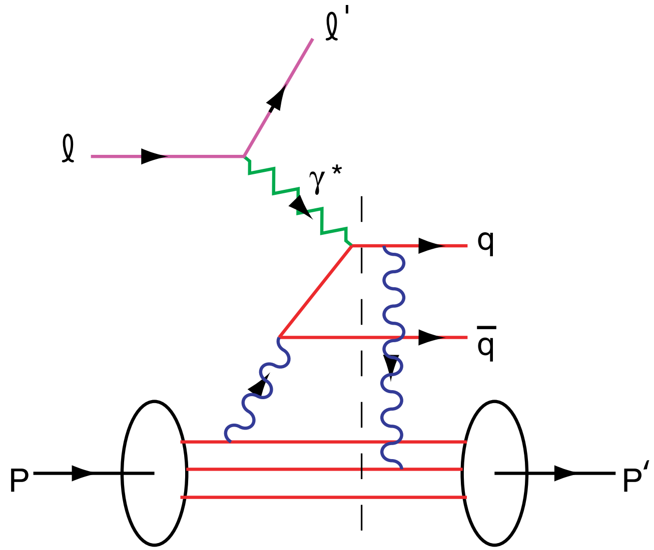
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



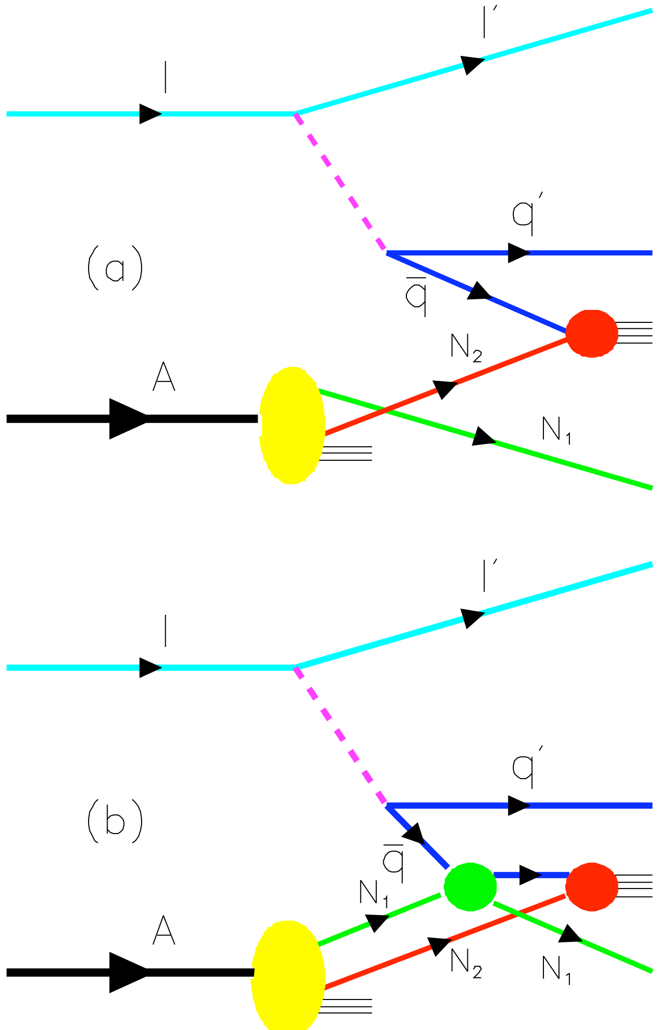
Shadowing depends on understanding leading-twist-diffraction in DIS

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



The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.

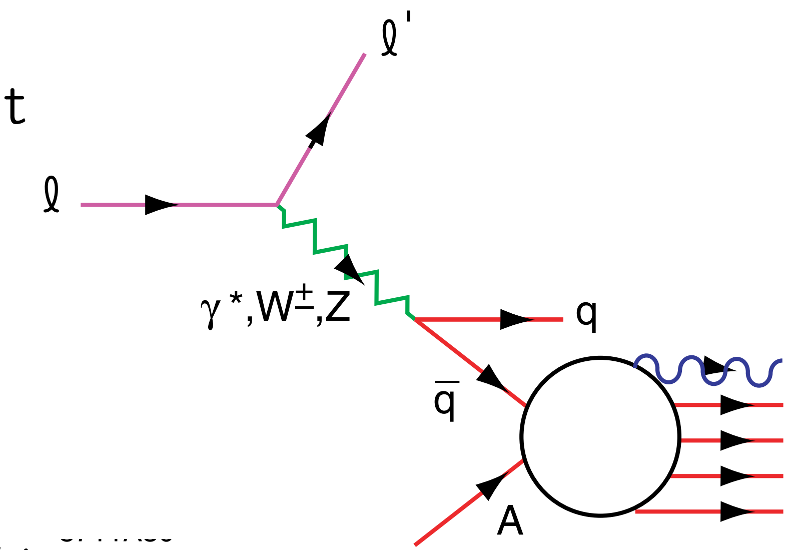
If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Observed HERA DDIS produces nuclear shadowing

Origin of Regge Behavior of Deep Inelastic Structure Functions

Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$



Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

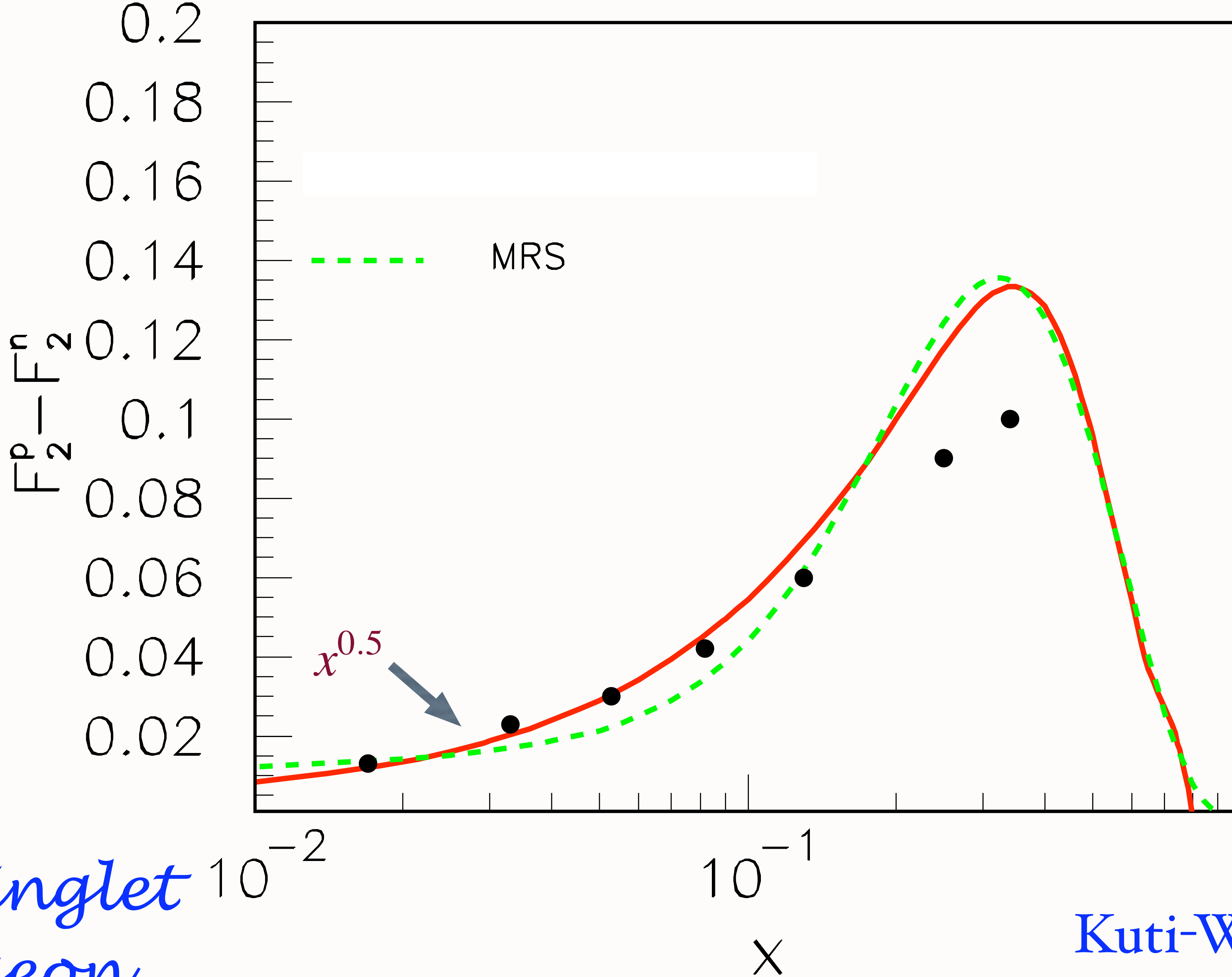
Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small x_{bj}.

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

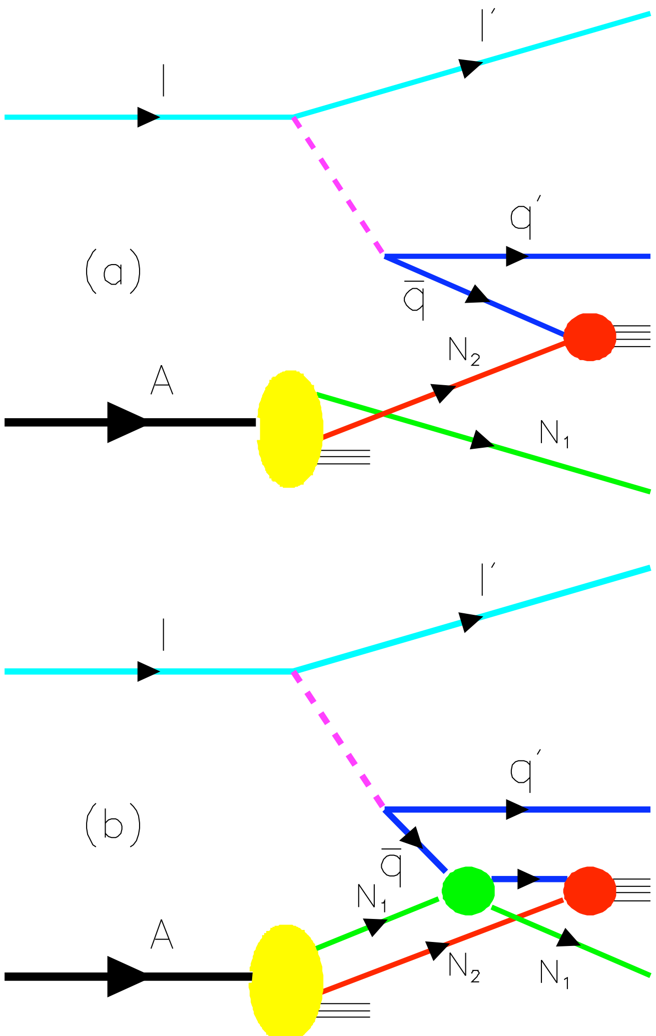
Schmidt, Yang, Lu, sjb

Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior



The one-step and two-step processes in DIS on a nucleus.

If the scattering on nucleon N_1 is via $C = -$ Reggeon or Odderon exchange, the one-step and two-step amplitudes are **constructive in phase, enhancing** the $\bar{q}$ flux reaching N_2

$\rightarrow$ Antishadowing of the DIS nuclear structure functions

H. J. Lu, sjb
Schmidt, Yang, sjb

Reggeon Exchange

Phase of two-step amplitude relative to one step:

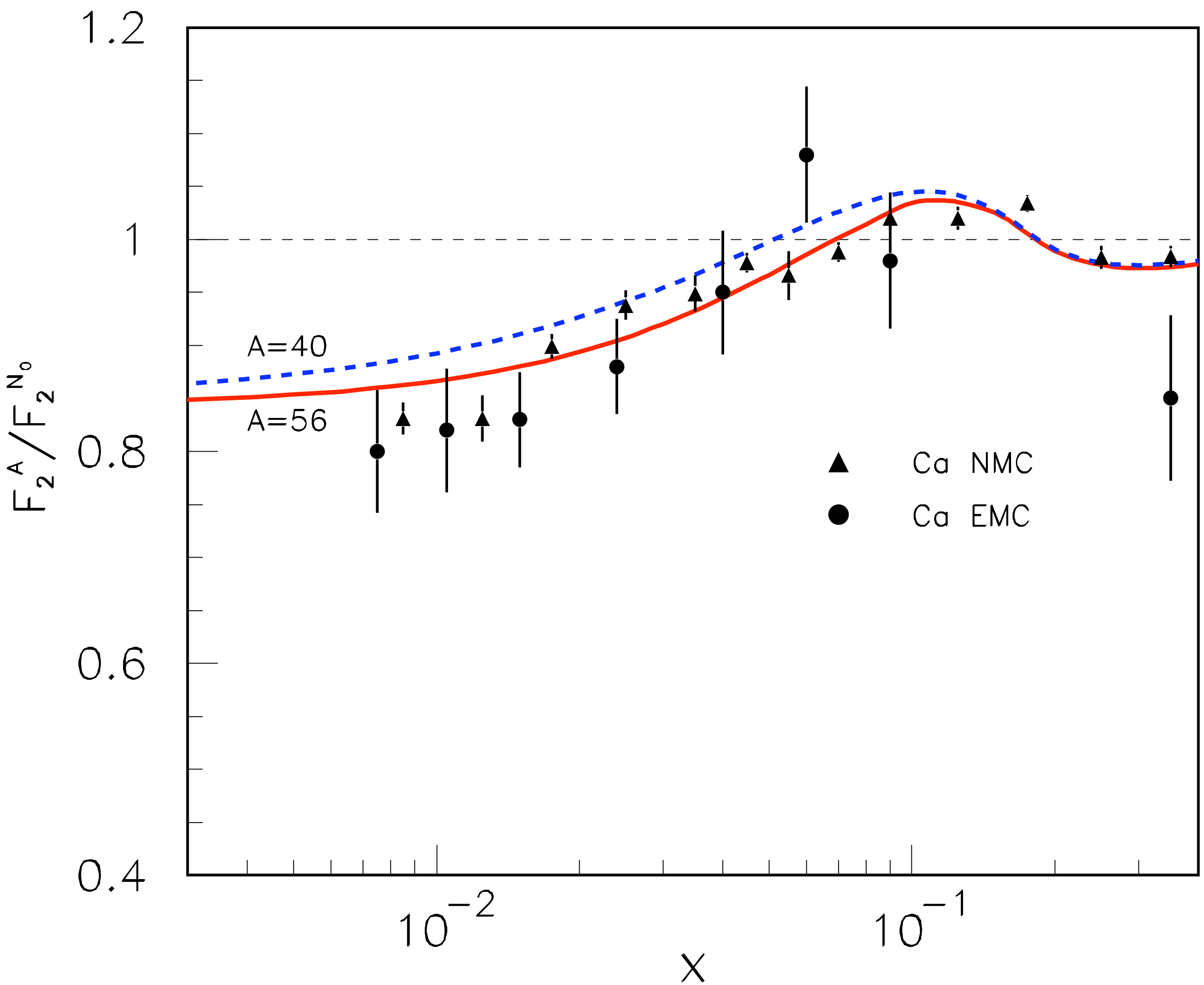
$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

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



Predicted nuclear shadowing and and antishadowing at $Q^2 = 1\ \mathrm{GeV}^2$

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].

Shadowing and Antishadowing in Lepton-Nucleus Scattering

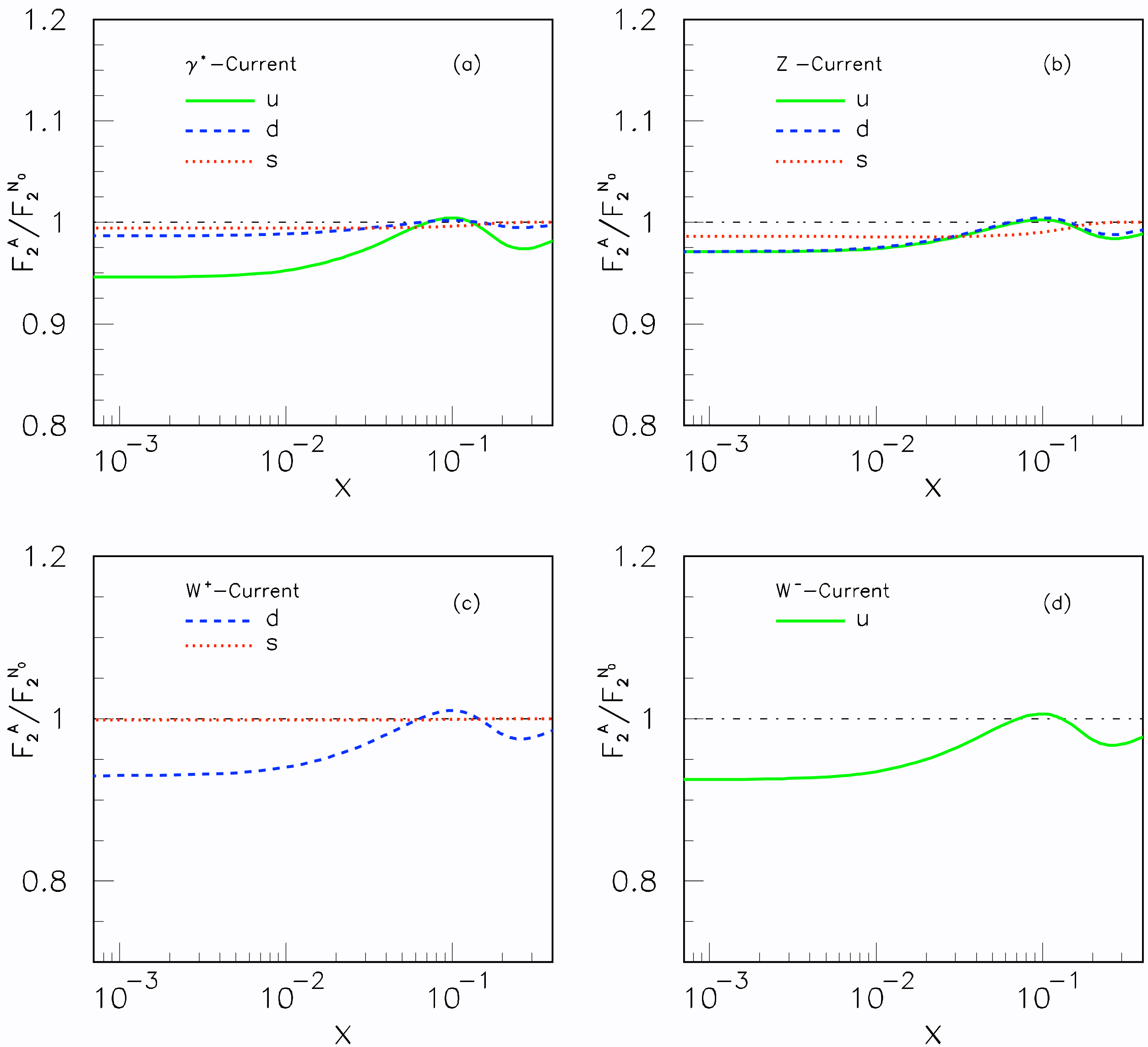
- Shadowing: Destructive Interference
of Two-Step and One-Step Processes
Pomeron Exchange

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

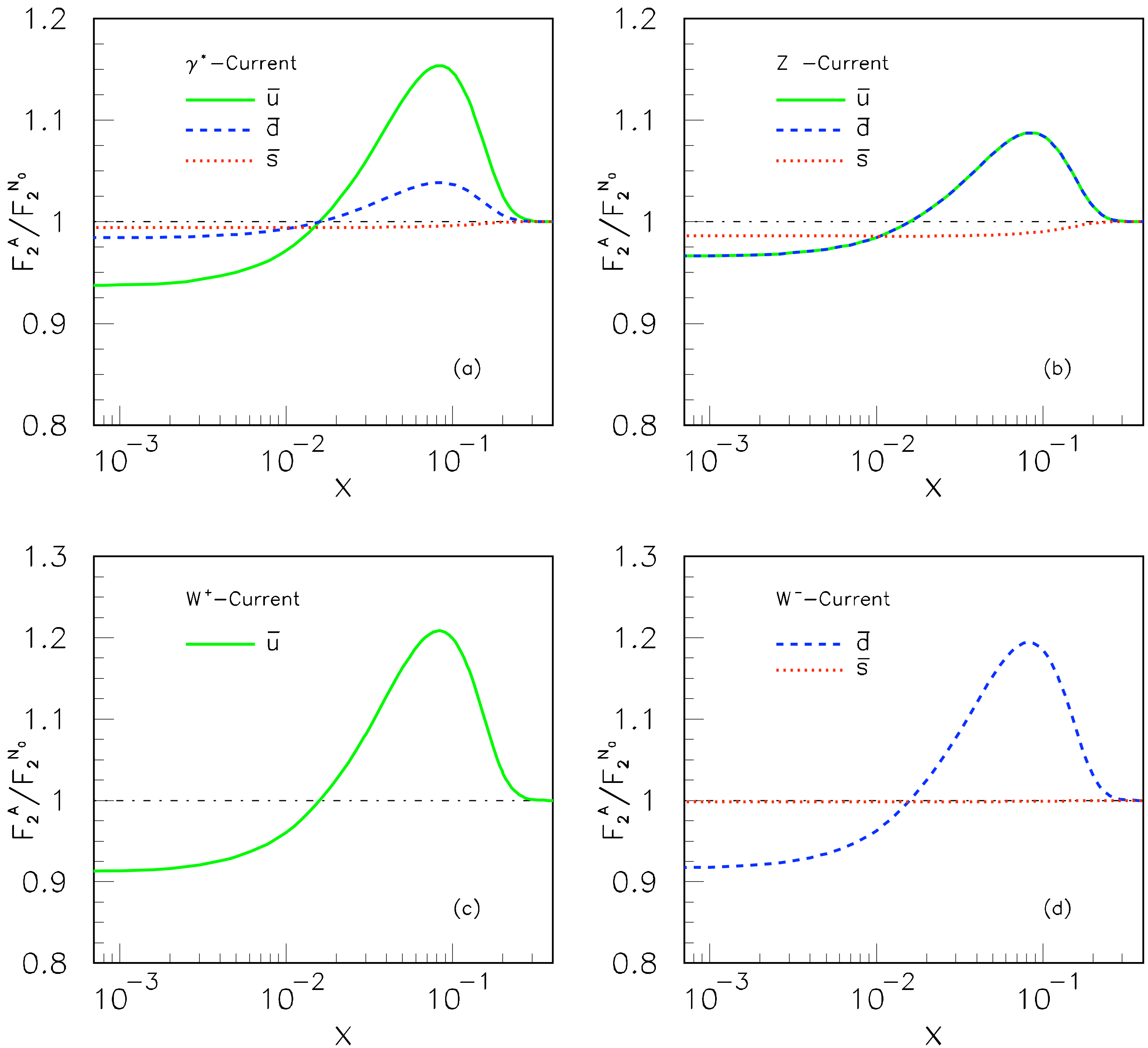
- Antishadowing is Not Universal!
Electromagnetic and weak currents:
different nuclear effects !
Potentially significant for NuTeV Anomaly}

Jian-Jun Yang
Ivan Schmidt
Hung Jung Lu
sjb

Shadowing and Antishadowing of DIS Structure Functions



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].



Nuclear Effect not Universal !

Light-Front Wavefunctions

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

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

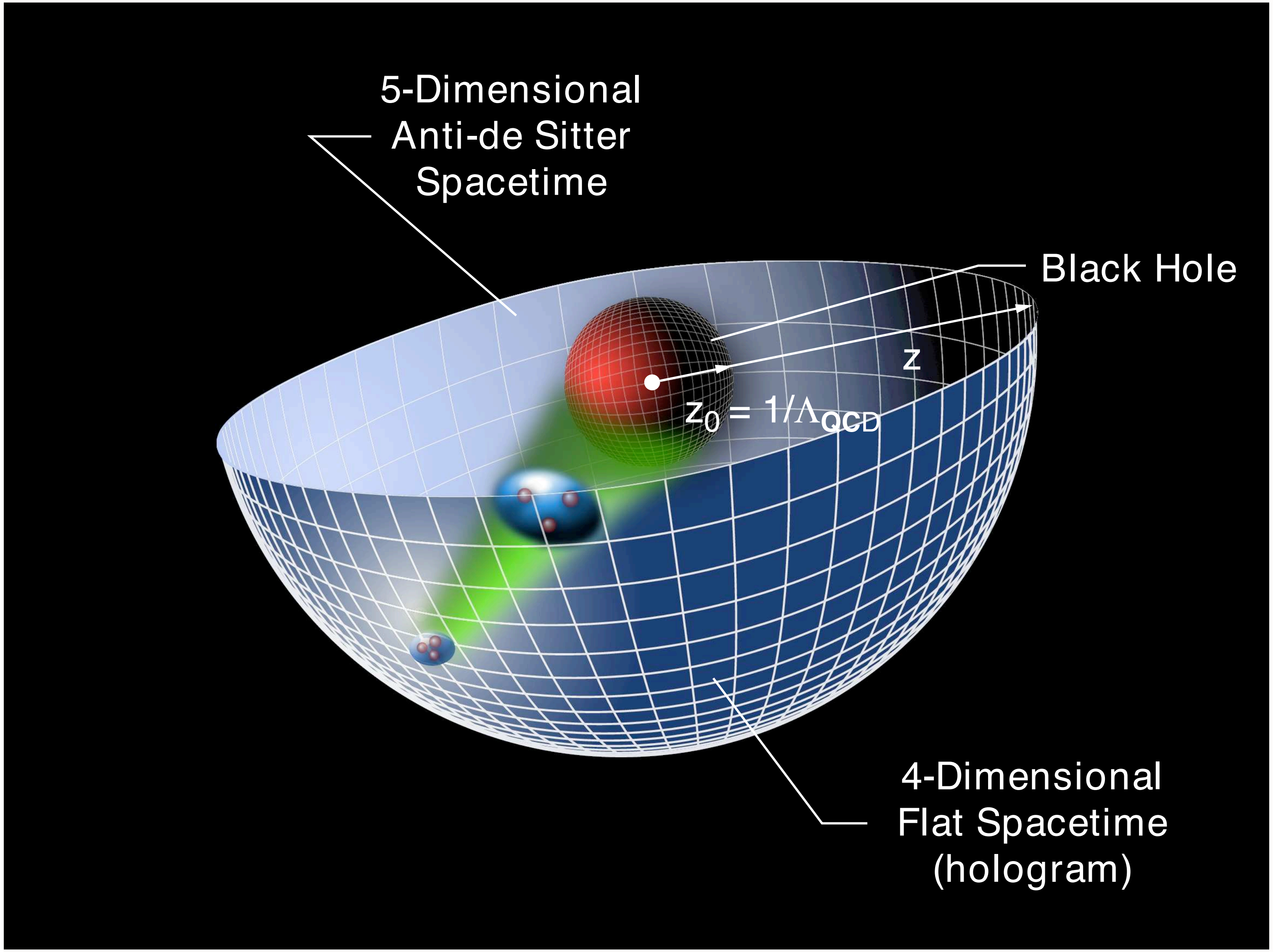
$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

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

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

Applications of AdS/CFT to QCD

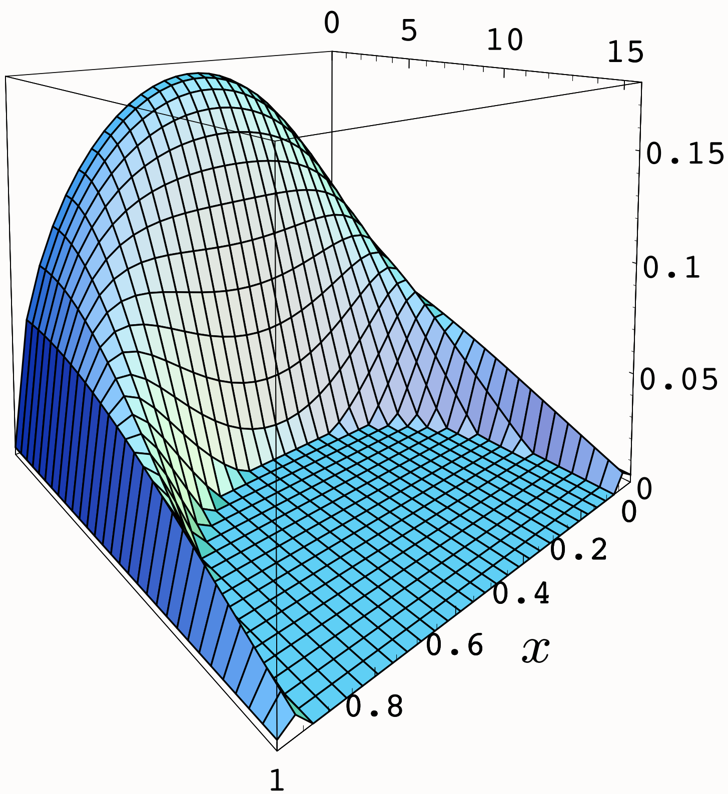


Changes in physical length scale mapped to evolution in the 5th dimension z

New work: Grigoryan, Radysuhkin

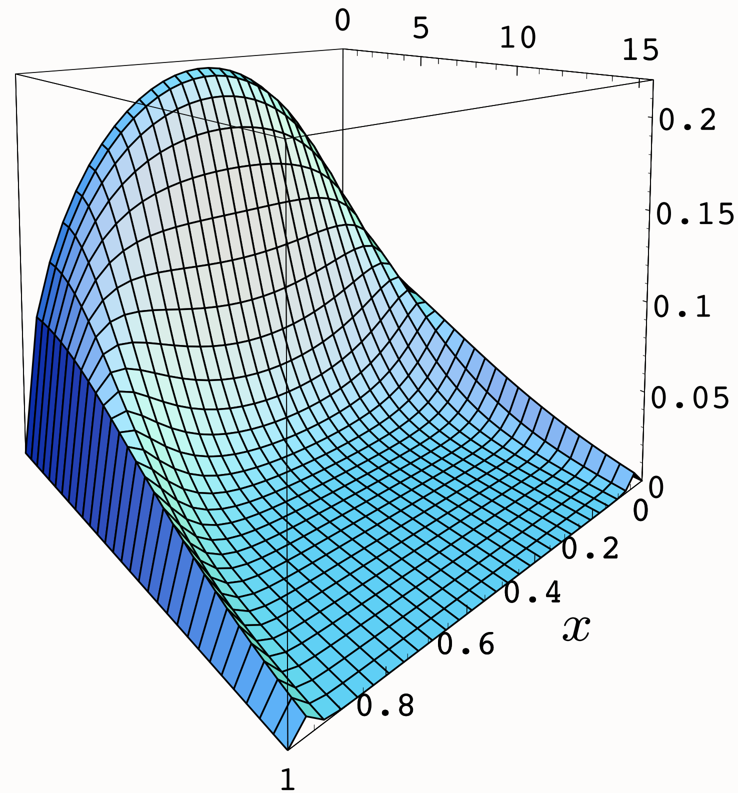
in collaboration with Guy de Teramond

AdS/CFT Predictions for Meson LFWF $\psi(x, b_\perp)$



$\Lambda_{QCD} = 0.32$ GeV

Truncated Space



$\kappa = 0.76$ GeV

Harmonic Oscillator

Goal:

- **Use AdS/CFT to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances**

- **Analogous to the Schrodinger Equation for Atomic Physics**

- *AdS/QCD Holographic Model*

AdS/CFT: Anti-de Sitter Space / Conformal Field Theory

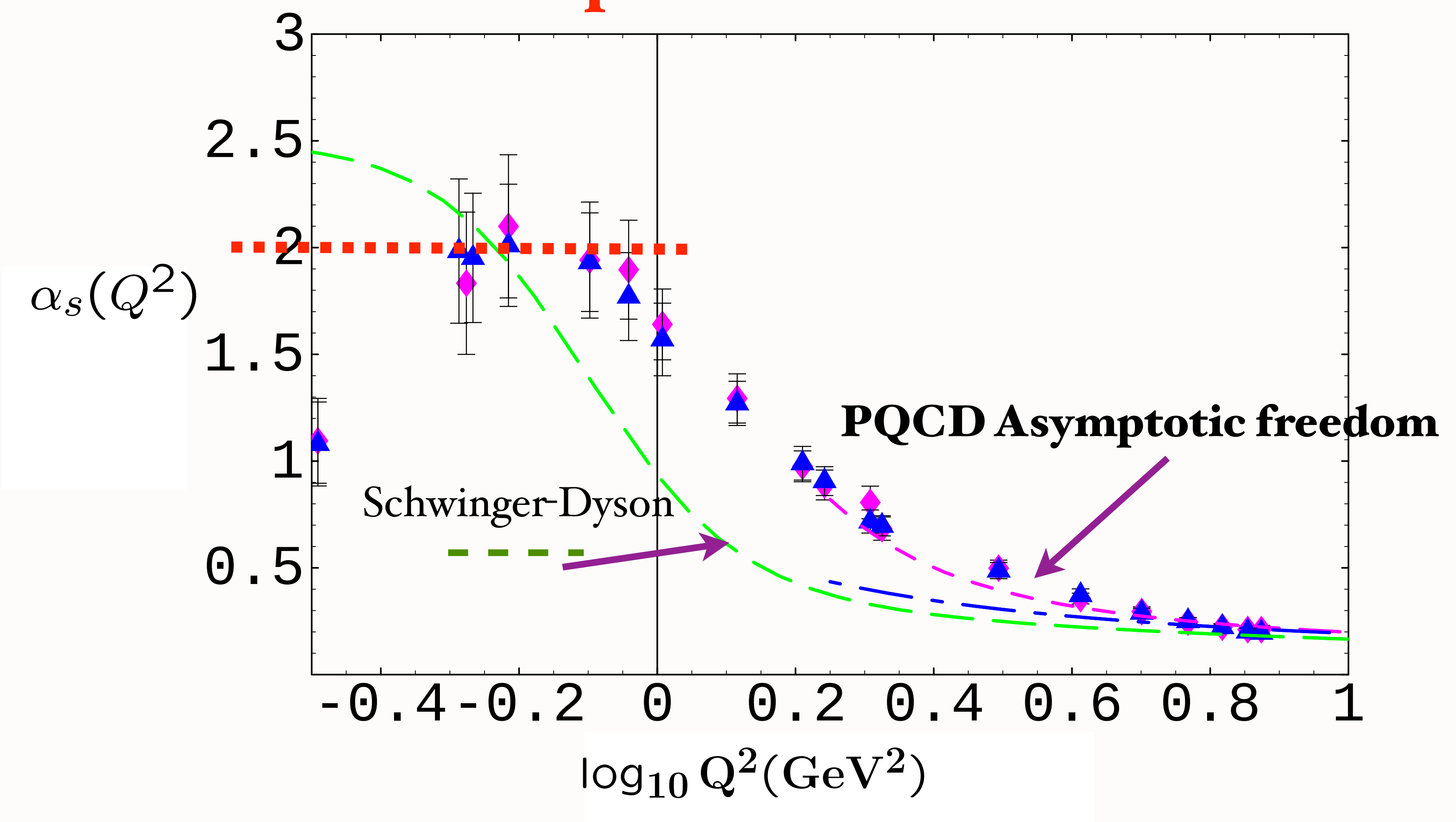
Maldacena:

Map $AdS_5 \times S_5$ to conformal N=4 SUSY

- **QCD is not conformal**; however, it has manifestations of a scale-invariant theory: Bjorken scaling, dimensional counting for hard exclusive processes
- **Conformal window:** $\alpha_s(Q^2) \simeq \text{const at small } Q^2$
- **Use mathematical mapping of the conformal group SO(4,2) to AdS5 space**

Conformal window
Infrared fixed-point

$$\beta(Q^2) = \frac{d\alpha_s(Q^2)}{d\log Q^2} \to 0$$



Shirkov
Gribov
Dokshitser
Siminov
Maxwell
Cornwall

lattice: Furui, Nakajima (MILC)

DSE: Alkofer, Fischer, von Smekal et al.

IR Fixed-Point for QCD?

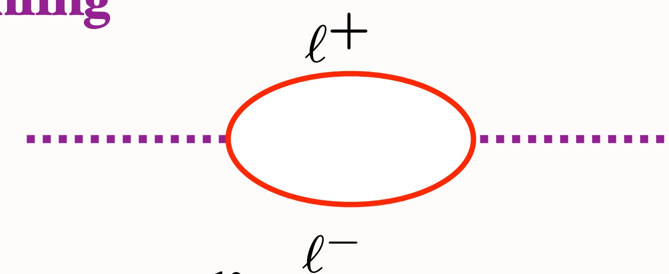
- *Dyson-Schwinger Analysis:* **QCD Coupling has IR Fixed Point**
  Alkofer, Fischer, von Smekal et al.

- *Evidence from Lattice Gauge Theory* Furui, Nakajima

- Define coupling from observable: **indications of IR fixed point for QCD effective charges**

- Confined or massive gluons: **Decoupling of QCD vacuum polarization at small Q^2** **Serber-Uehling**

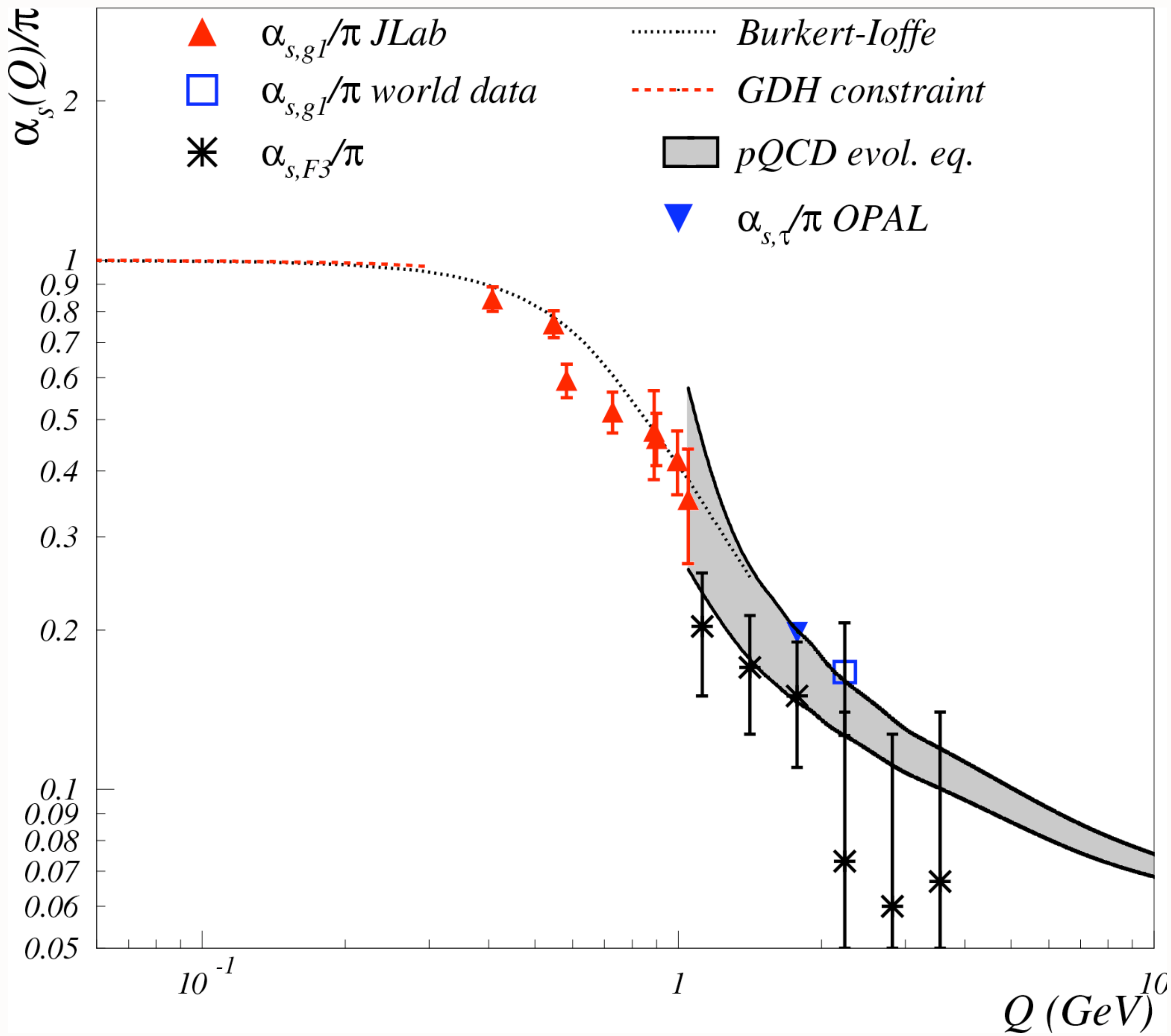
$$\Pi(Q^2) \to \frac{\alpha}{15\pi}\frac{Q^2}{m^2} \qquad Q^2 << 4m^2$$



- **Justifies application of AdS/CFT in strong-coupling conformal window**

Deur, Korsch, et al: Effective Charge from Bjorken Sum Rule

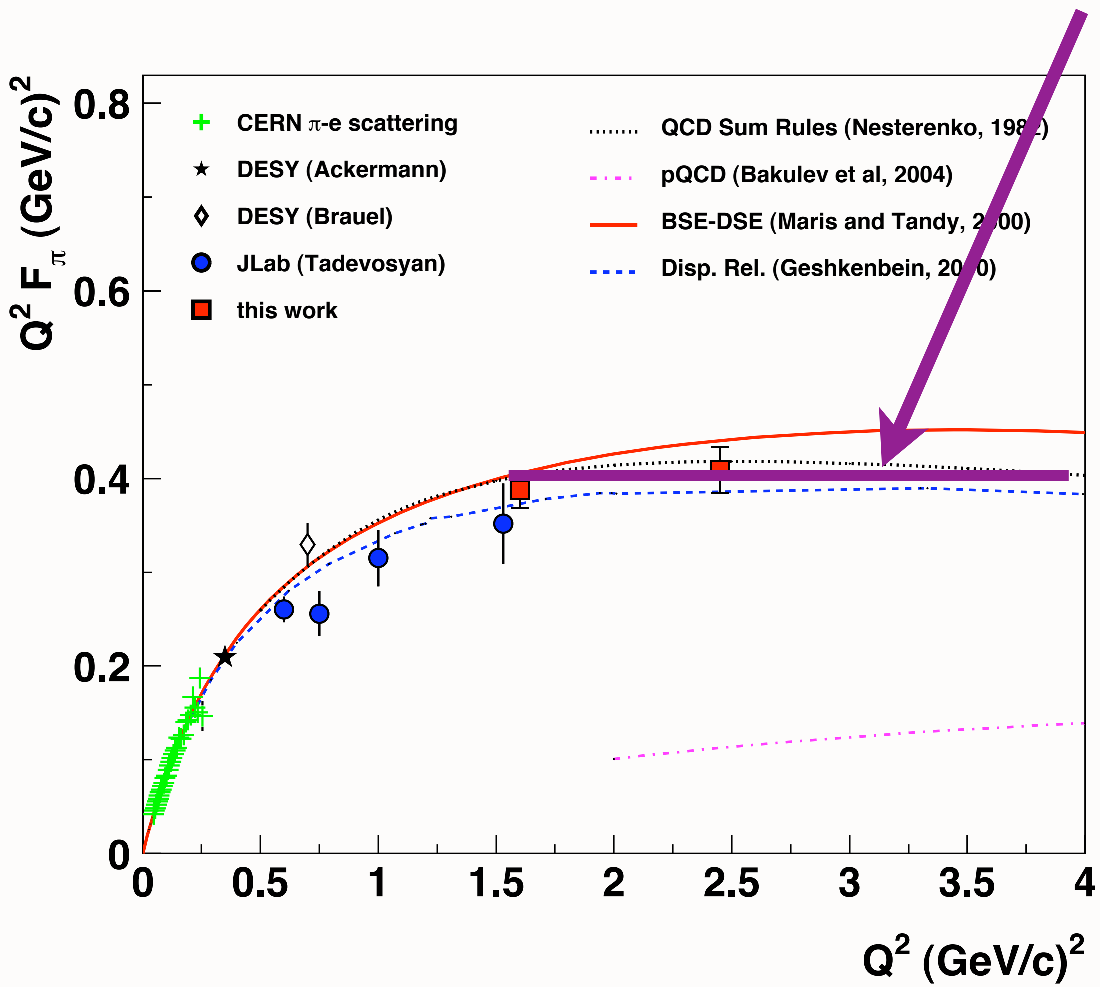
$$\Gamma_{bj}^{p-n}(Q^2) \equiv \frac{g_A}{6}\left[1 - \frac{\alpha_s^{g_1}(Q^2)}{\pi}\right]$$

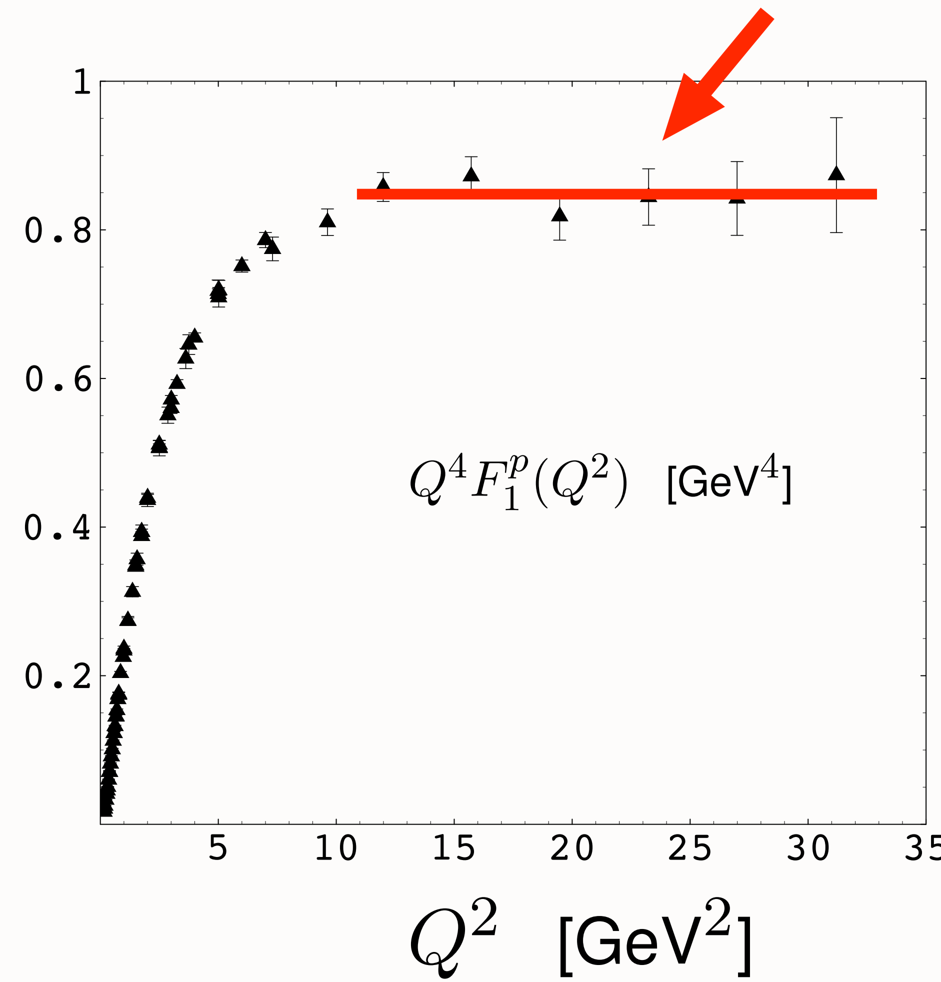


It would be good to measure this at small Q <1 GeV

Conformal behavior: $Q^2 F_\pi(Q^2) \to$ const

$Q^4 F_1(Q^2) \to$ const





Determination of the Charged Pion Form Factor at Q2=1.60 and 2.45 (GeV/c)2.
By Fpi2 Collaboration (T. Horn *et al.*). Jul 2006. 4pp.
e-Print Archive: **nucl-ex/0607005**

G. Huber

Generalized parton distributions from nucleon form-factor data.
M. Diehl (**DESY**) , **Th. Feldmann** (**CERN**) ,
R. Jakob, **P. Kroll** (**Wuppertal U.**) .
DESY-04-146, CERN-PH-04-154, WUB-04-08, Aug 2004. 68pp.
Published in Eur.Phys.J.C39:1-39,2005
e-Print Archive: **hep-ph/0408173**

Conformal Theories are invariant under the Poincare and conformal transformations with

$$\mathbf{M}^{\mu\nu}, \mathbf{P}^{\mu}, \mathbf{D}, \mathbf{K}^{\mu},$$

the generators of SO(4,2)

SO(4,2) has a mathematical representation on AdS5

Scale Transformations

- Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2),$$

invariant measure

$x^\mu \to \lambda x^\mu, \; z \to \lambda z$, maps scale transformations into the holographic coordinate z.

- AdS mode in z is the extension of the hadron wf into the fifth dimension.

- Different values of z correspond to different scales at which the hadron is examined.

$$x^2 \to \lambda^2 x^2, \quad z \to \lambda z.$$

$x^2 = x_\mu x^\mu$: invariant separation between quarks

- The AdS boundary at $z \to 0$ correspond to the $Q \to \infty$, UV zero separation limit.

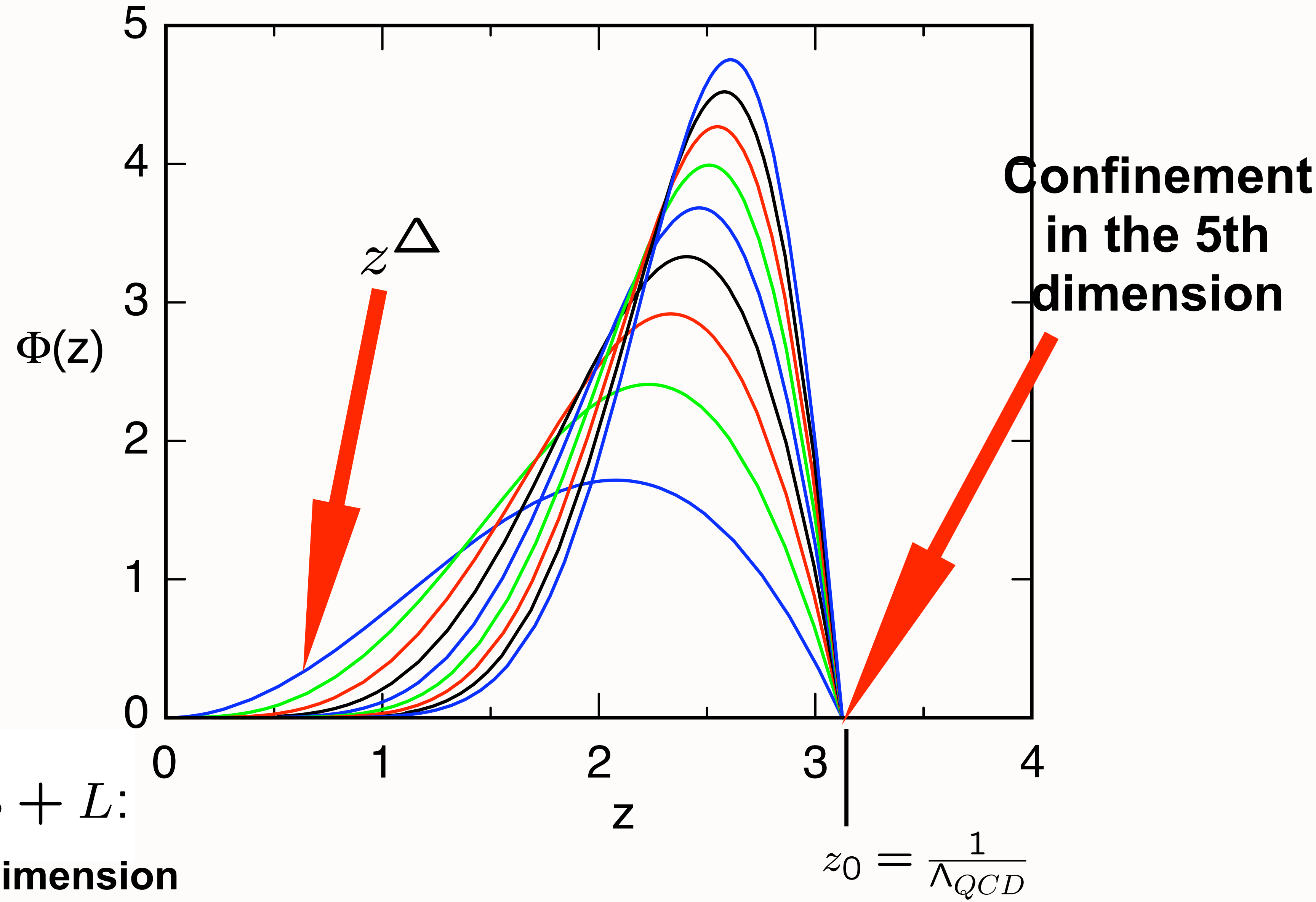
Guy de Teramond
SJB

AdS/CFT

- Use mapping of conformal group SO(4,2) to AdS5
- Scale Transformations represented by wavefunction $\psi(z)$ in 5th dimension $x_\mu^2 \to \lambda^2 x_\mu^2$ $z \to \lambda z$
- Holographic model: Confinement at large distances and conformal symmetry in interior $0 < z < z_0$
- Match solutions at small z to conformal dimension of hadron wavefunction at short distances $\psi(z) \sim z^\Delta$ at $z \to 0$
- Truncated space simulates "bag" boundary conditions

$$\psi(z_0) = 0 \qquad z_0 = \frac{1}{\Lambda_{QCD}}$$

Identify hadron by its interpolating operator at z --> 0



$\Delta = 3 + L$:

Twist dimension of baryon

de Teramond, sjb

- 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 an approximate model of hadron structure with confinement at large distances, conformal behavior at short distances

- de Teramond, sjb: AdS/QCD Holographic Model: Initial "semi-classical" approximation to QCD. Predict light-quark hadron spectroscopy, form factors.

- Karch, Katz, Son, Stephanov: Linear Confinement

- Mapping of AdS amplitudes to 3+ 1 Light-Front equations, wavefunctions

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

$$\Phi(z) = z^{3/2}\phi(z)$$

AdS Schrodinger Equation for bound state of two scalar constituents

$$[-\frac{d^2}{dz^2} + V(z)]\phi(z) = M^2\phi(z)$$

Truncated space

$$V(z) = -\frac{1-4L^2}{4z^2} \qquad \phi(z = z_0 = \frac{1}{\Lambda_c}) = 0.$$

Alternative: Harmonic oscillator confinement

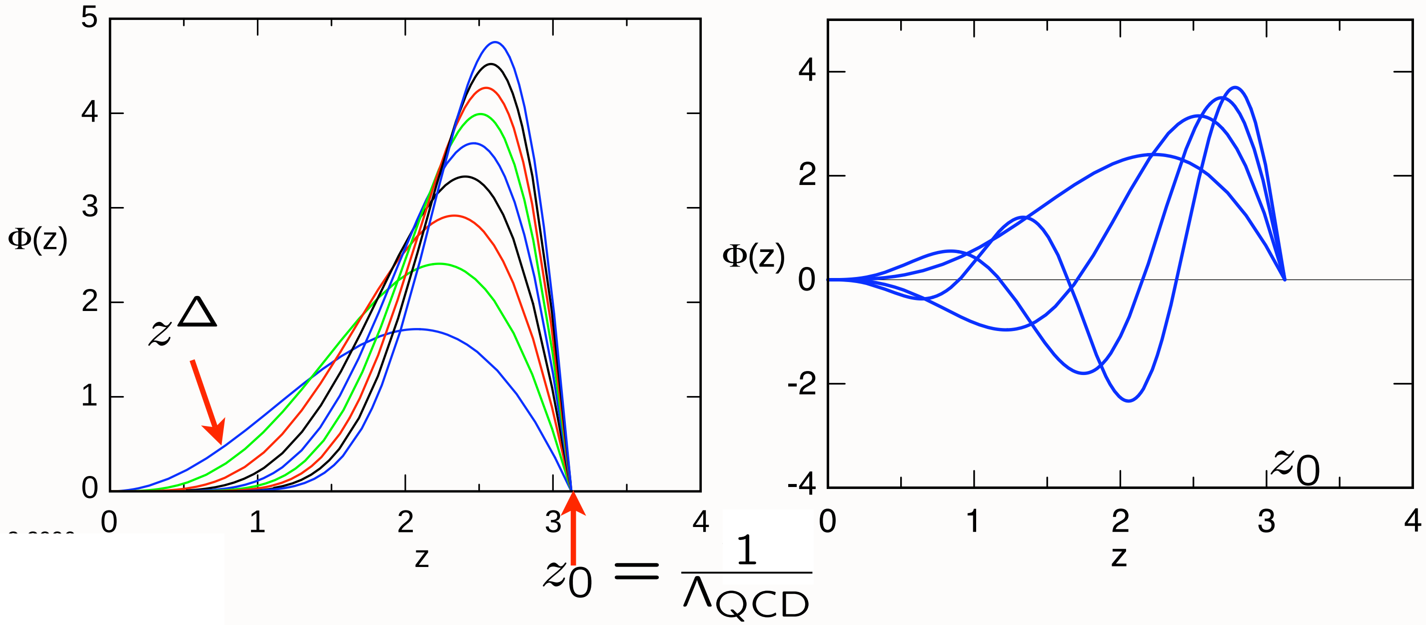
$$V(z) = -\frac{1-4L^2}{4z^2} + \kappa^4 z^2$$

Karch, et al.

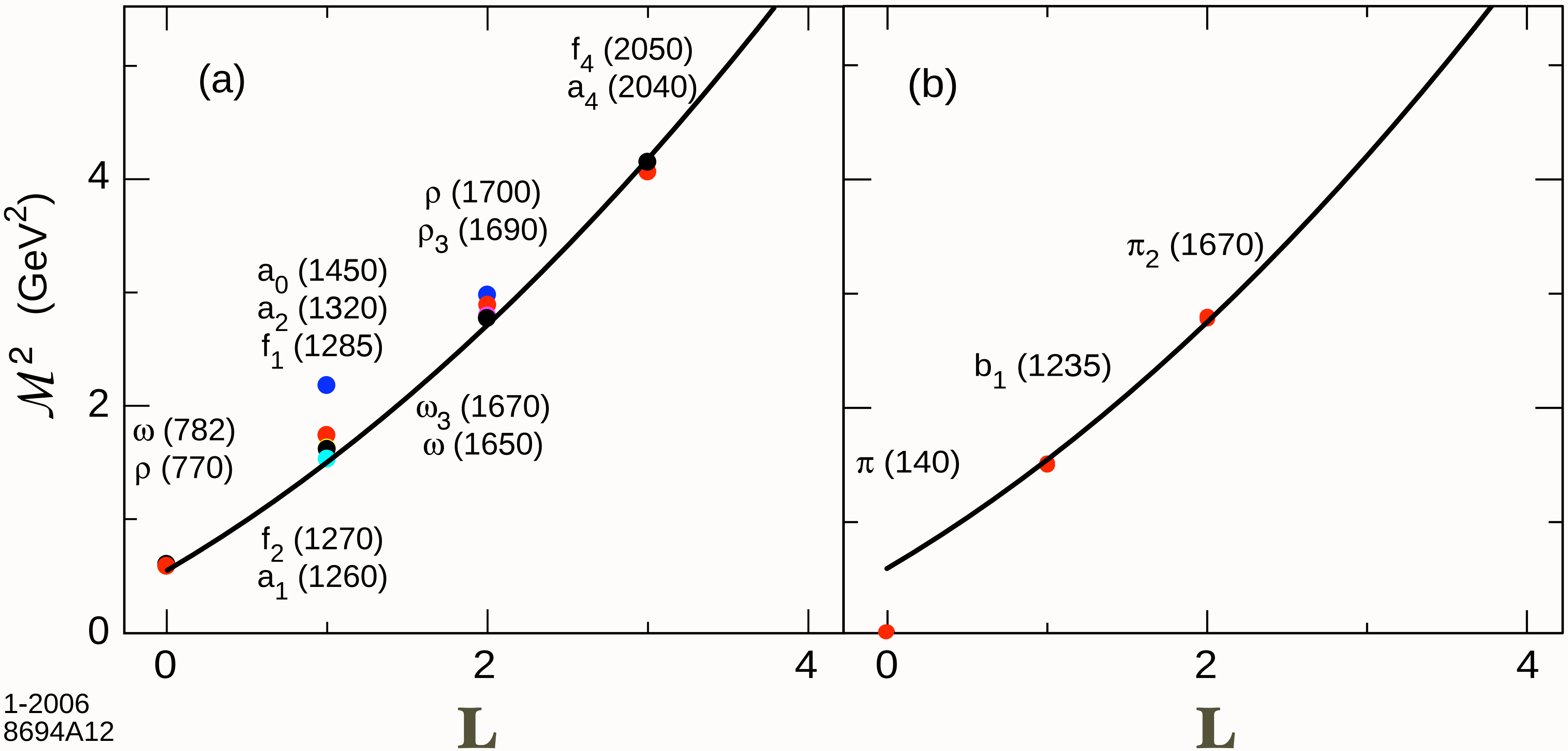
Derived from variation of Action in AdS_5

Match fall-off at small z to conformal twist dimension at short distances

- Pseudoscalar mesons: $\mathcal{O}_{3+L} = \overline{\psi}\gamma_5 D_{\{\ell_1} \dots D_{\ell_m\}}\psi$ ($\Phi_\mu = 0$ gauge).
- 4-d mass spectrum from boundary conditions on the normalizable string modes at $z = z_0$, $\Phi(x, z_o) = 0$, given by the zeros of Bessel functions $\beta_{\alpha,k}$: $\mathcal{M}_{\alpha,k} = \beta_{\alpha,k}\Lambda_{QCD}$
- Normalizable AdS modes $\Phi(z)$



Meson orbital and radial AdS modes for $\Lambda_{QCD} = 0.32$ GeV.



Light meson orbital spectrum $\Lambda_{QCD} = 0.32 \text{ GeV}$

Guy de Teramond
SJB

Baryon Spectrum

- Baryon: twist-three, dimension $\frac{9}{2} + L$

$$\mathcal{O}_{\frac{9}{2}+L} = \psi D_{\{\ell_1} \dots D_{\ell_q} \psi D_{\ell_{q+1}} \dots D_{\ell_m\}} \psi, \qquad L = \sum_{i=1}^{m} \ell_i .$$

Wave Equation: $\boxed{\left[z^2\, \partial_z^2 - 3z\, \partial_z + z^2 \mathcal{M}^2 - \mathcal{L}_\pm^2 + 4\right] f_\pm(z) = 0}$

with $\mathcal{L}_+ = L + 1$, $\mathcal{L}_- = L + 2$, and solution

$$\Psi(x, z) = C e^{-iP \cdot x} z^2 \Big[J_{1+L}(z\mathcal{M})\, u_+(P) + J_{2+L}(z\mathcal{M})\, u_-(P) \Big].$$

- 4-d mass spectrum $\Psi(x, z_o)^\pm = 0 \quad \Longrightarrow \quad$ parallel Regge trajectories for baryons !

$$\mathcal{M}^+_{\alpha,k} = \beta_{\alpha,k} \Lambda_{QCD}, \qquad \mathcal{M}^-_{\alpha,k} = \beta_{\alpha+1,k} \Lambda_{QCD}.$$

- Ratio of eigenvalues determined by the ratio of zeros of Bessel functions !

Prediction from AdS/QCD

Only one parameter!

Entire light quark baryon spectrum

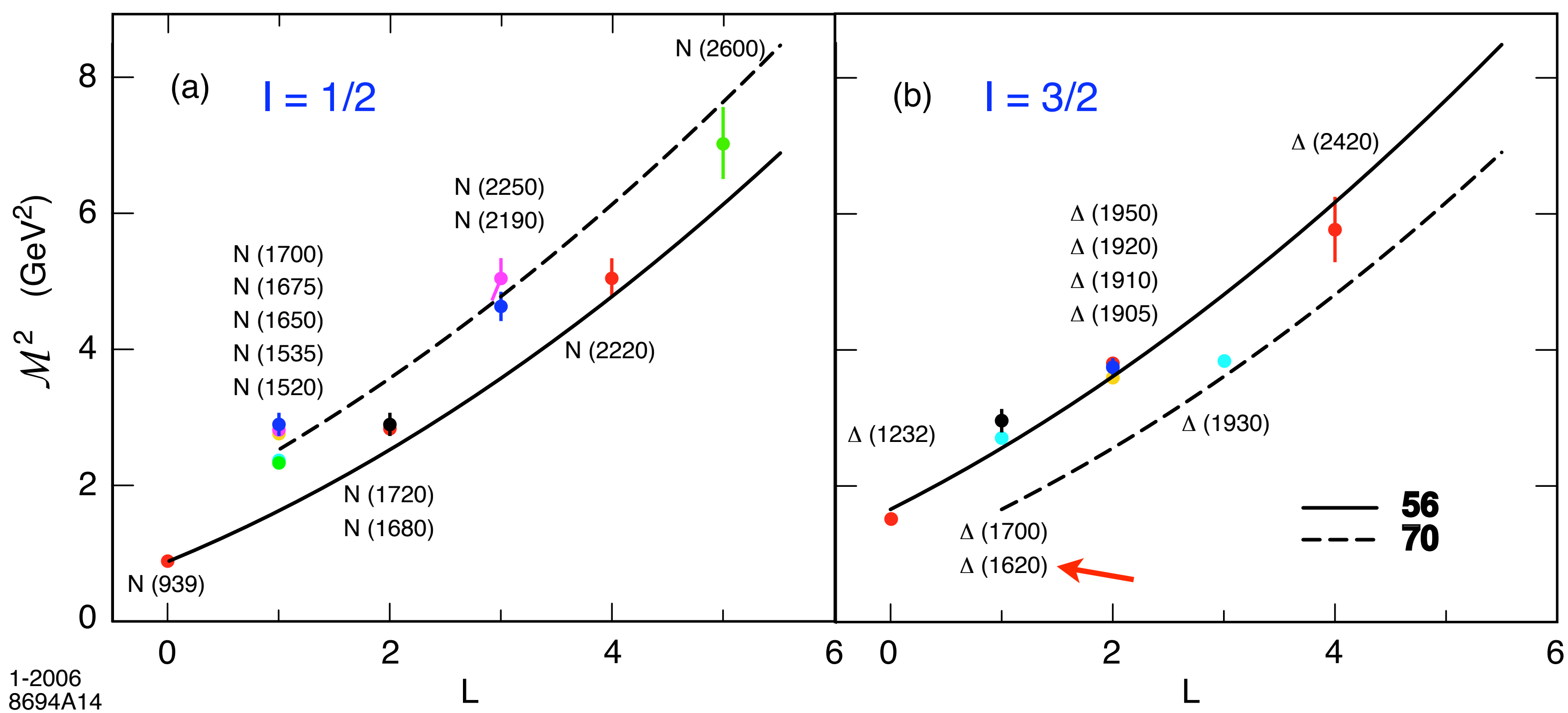


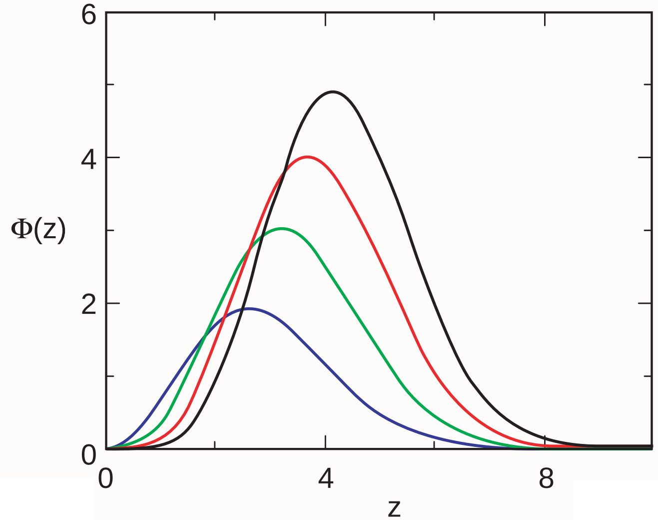
Fig: Predictions for the light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV. The $\mathbf{56}$ trajectory corresponds to L even $P = +$ states, and the $\mathbf{70}$ to L odd $P = -$ states.

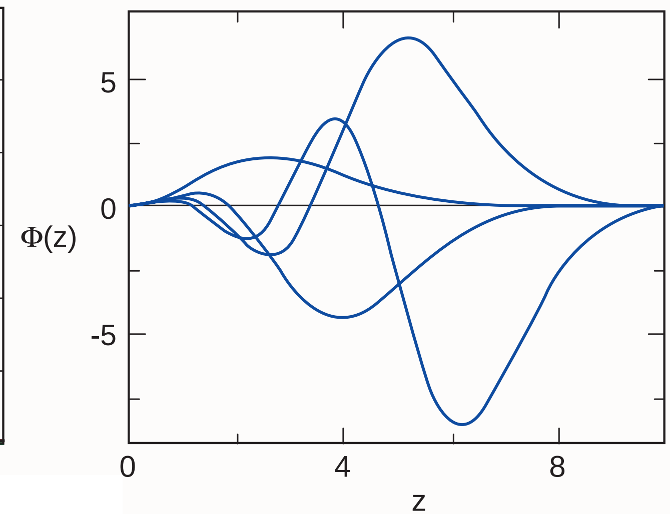
Guy de Teramond
SJB

- $SU(6)$ 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	$N\frac{7}{2}^{-}$ $N\frac{9}{2}^{-}$ $N\frac{11}{2}^{-}(2600)$ $N\frac{13}{2}^{-}$

AdS/QCD



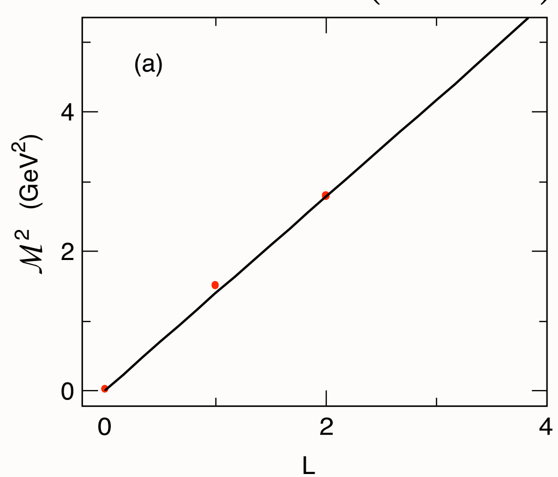


Guy de Teramond
SJB

Pion orbital and radial modes in a soft wall model.

$$\mathcal{M}^2 = 4\kappa^2(n+L)$$

Harmonic Oscillator "Soft Wall" Model



Zero pion mass

Pion Regge Trajectory $\kappa = 0.59$ GeV

Non-Conformal Extension of Algebraic Integrability

- Consider the generator (short-distance Coulombic and long-distance linear potential)

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu+\frac{1}{2}}{\zeta} - \kappa^2\zeta\right),$$

and its adjoint $\Pi_\nu^\dagger$ with commutation relations

$$\left[\Pi_\nu(\zeta), \Pi_\nu^\dagger(\zeta)\right] = \frac{2\nu+1}{\zeta^2} - 2\kappa^2.$$

- Light-cone hamiltonian Hamiltonian $H_{LC} = \Pi_\nu^\dagger \Pi_\nu + C$ is positive definite $\langle\phi|H_{LC}|\phi \geq 0$ for $\nu^2 \geq 0$, and $C \geq -4\kappa^2$.
- Orbital and radial excited states are constructed from the ladder operators from $\nu = 0$ state

$$\phi_L(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{1/2+L}e^{-\kappa^2\zeta^2/2}L_n^L\left(\kappa^2\zeta^2\right).$$

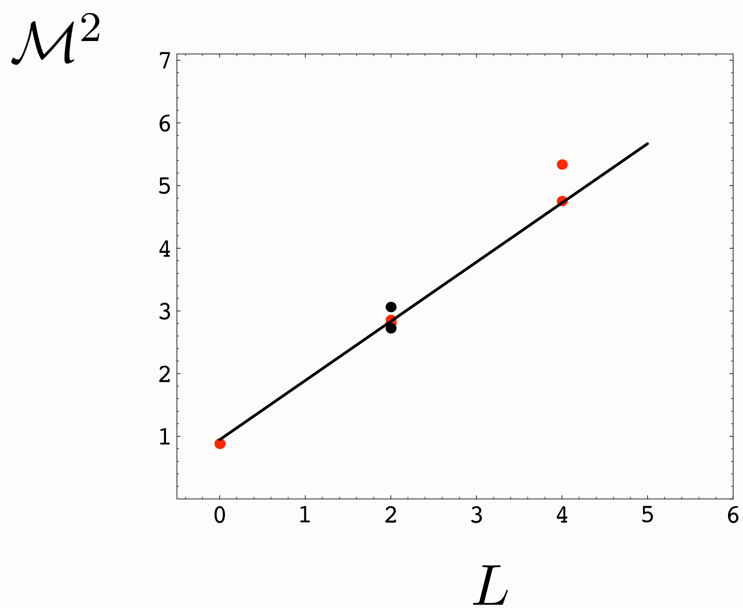
- Identify the zero mode ($C = -4\kappa^2$) with the pion $\boxed{\mathcal{M}^2 = 4\kappa^2(n+L).}$
- Similar model with background dilaton: Karch, Katz, Son and Stephanov (2006).

- Baryon: twist-dimension $3+L \quad (\nu = L+1)$

$$\mathcal{O}_{3+L} = \psi D_{\{\ell_1} \dots D_{\ell_q} \psi D_{\ell_{q+1}} \dots D_{\ell_m\}} \psi, \qquad L = \sum_{i=1}^{m} \ell_i.$$

- Define the zero point energy (identical as in the meson case) $\mathcal{M}^2 \to \mathcal{M}^2 - 4\kappa^2$:

$$\mathcal{M}^2 = 4\kappa^2(n+L+1).$$



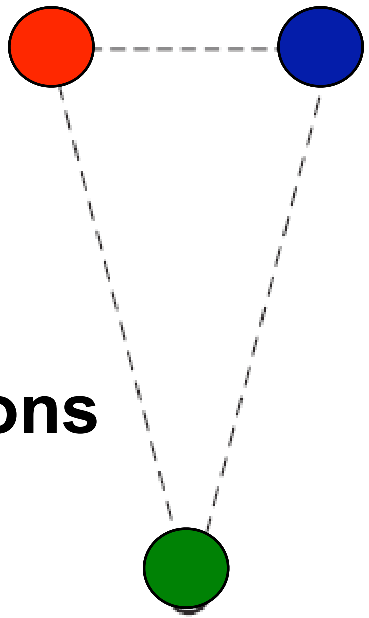
Proton Regge Trajectory $\kappa = 0.49$GeV

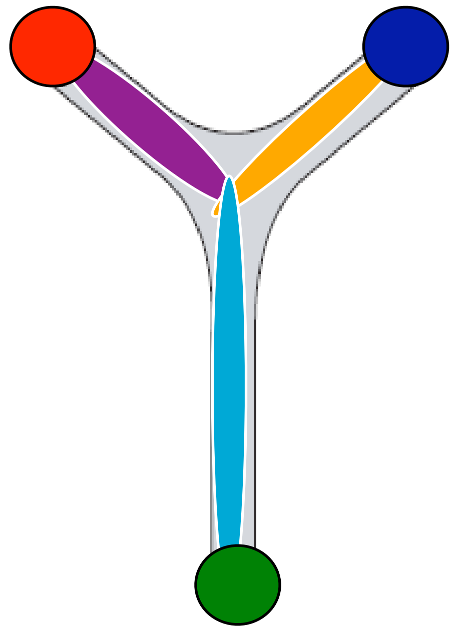
Quark or string model ?

E. Klempt

What are the forces between quarks in baryons ?

Confinement potential
Coulomb
Instanton induced interactions
Goldstone exchange





String model favored: $M^2 = C\ (n + L)$
Agrees with Soft Wall AdS/QCD

String-like flux tube of gluon field

Parity doublets

E. Klempt

2430(40)	$11/2^+$	$9/2^+$	$7/2^+$	$5/2^+$	$9/2^-$	$7/2^-$	$5/2^-$	$3/2^-$
	2400(125)	2400(125)	2350(100)		2300(100)		2400(125)	

2210(60)	$7/2^-$	$5/2^-$	$3/2^-$	$1/2^-$	$7/2^+$	$5/2^+$	$3/2^+$	$1/2^+$
	2200(80)			2150(100)		2220(125)		

1932(33)	$7/2^+$	$5/2^+$	$3/2^+$	$1/2^+$	$5/2^-$	$3/2^-$	$1/2^-$
	1959(15)	1910(30)	1920(80)	1910(40)	1940(30)	1940(100)	1890(50)

1624(4)	$3/2^-$	$1/2^-$	$3/2^+$
	1700(30)	1620(20)	1600(50)

1232	$3/2^+$
	1232

*

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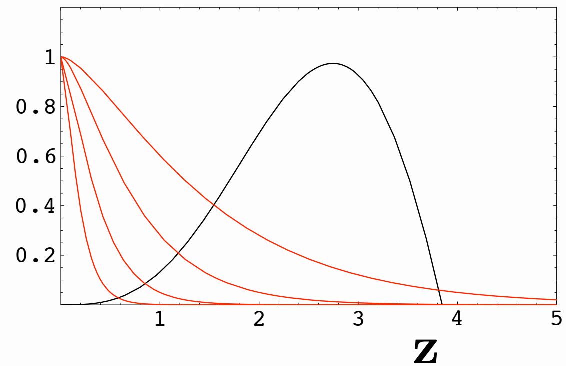
Hadron Form Factors from AdS/CFT

- Propagation of external perturbation suppressed inside AdS. $J(Q,z) = zQK_1(zQ)$
- At large Q^2 the important integration region is $z \sim 1/Q$.

$$F(Q^2)_{I\to F} = \int \frac{dz}{z^3}\Phi_F(z)J(Q,z)\Phi_I(z)$$

$\mathbf{J}(\mathbf{Q},\mathbf{z}), \ \mathbf{\Phi}(\mathbf{z})$

High Q^2
from
small z $\sim 1/Q$



Polchinski, Strassler
de Teramond, sjb

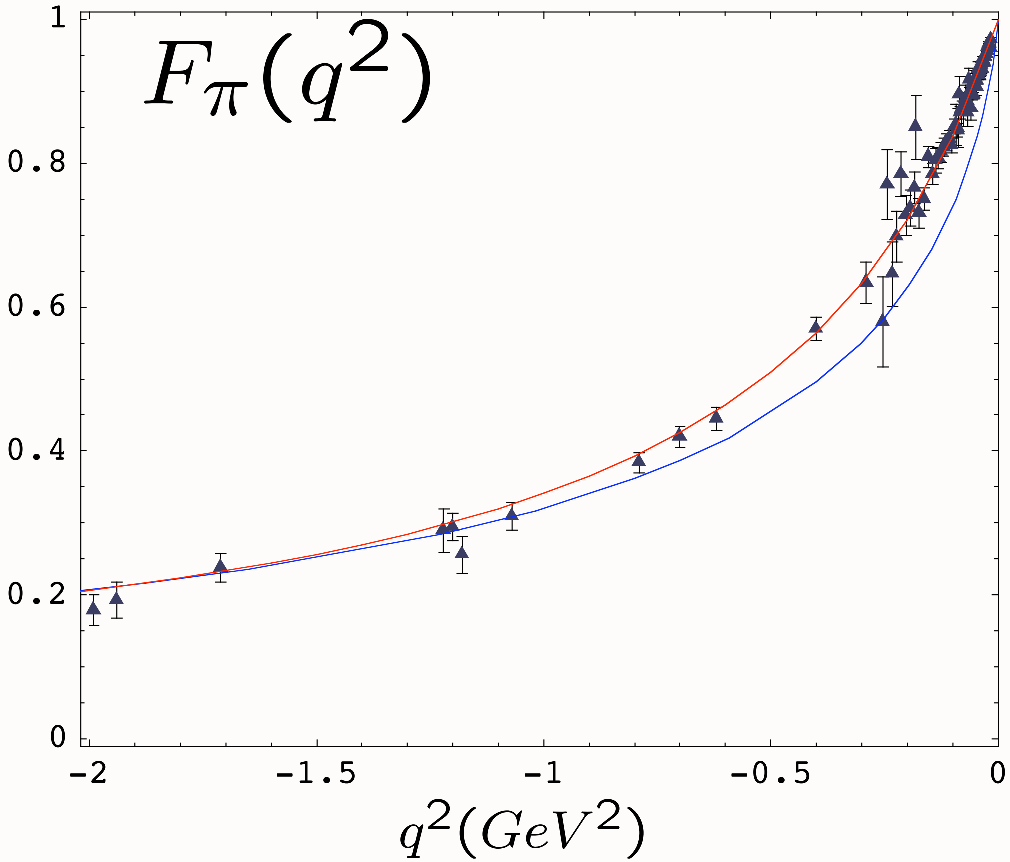
- Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, $\Phi^{(n)}$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

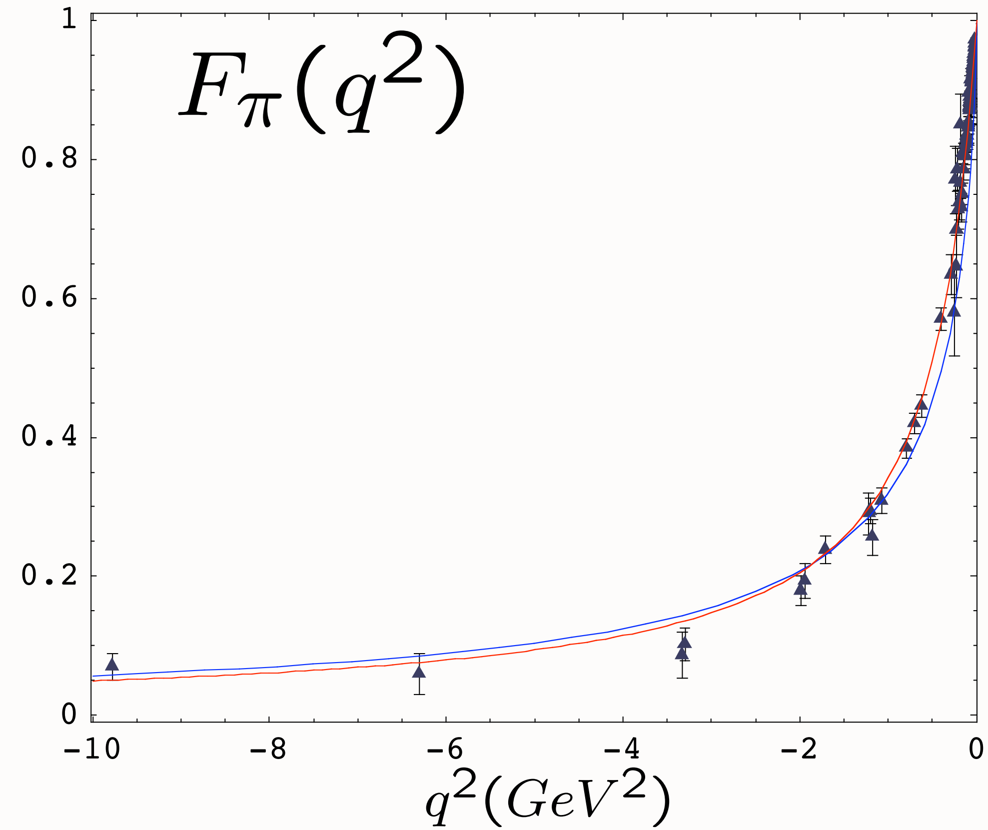
$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1},$$

Dimensional Quark Counting Rules:
General result from
AdS/CFT

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^n \sigma_i$. The twist is equal to the number of partons, $\tau = n$.

Spacelike pion form factor from AdS/CFT





Data Compilation from Baldini, Kloe and Volmer

Harmonic Oscillator Confinement

Truncated Space Confinement

One parameter - set by pion decay constant

de Teramond, sjb
See also: Radyushkin

$$F(Q^2) = R^3 \int_0^\infty \frac{dz}{z^3} \Phi_{P'}(z) J(Q,z) \Phi_P(z).$$

$$\Phi(z) = \frac{\sqrt{2}\kappa}{R^{3/2}} z^2 e^{-\kappa^2 z^2/2}.$$

$$J(Q,z) = zQK_1(zQ).$$

$$F(Q^2) = 1 + \frac{Q^2}{4\kappa^2} \exp\left(\frac{Q^2}{4\kappa^2}\right) Ei\left(-\frac{Q^2}{4\kappa^2}\right)$$

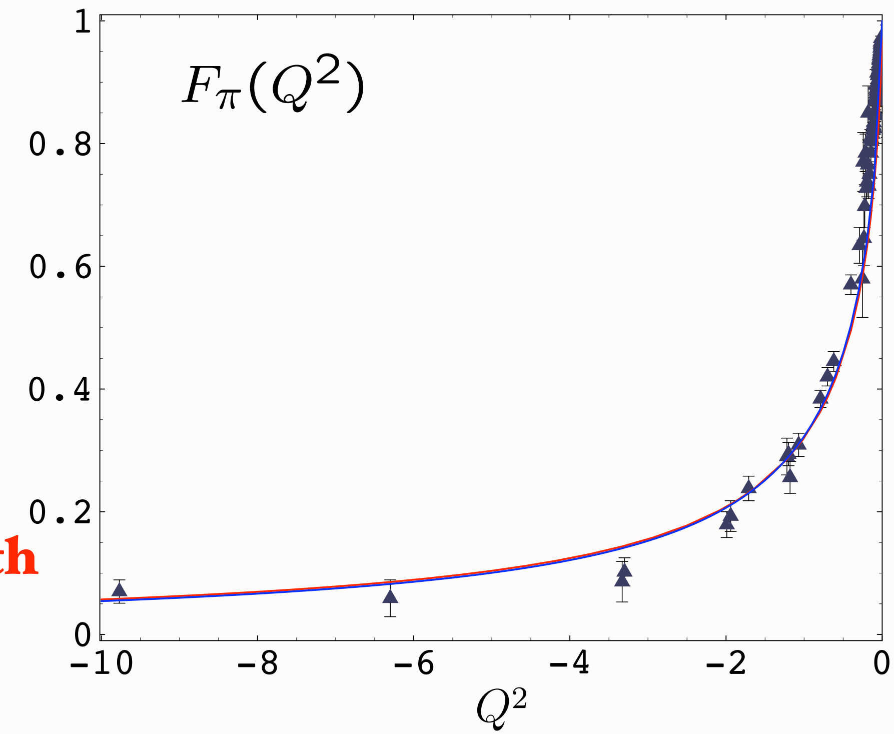
$$Ei(-x) = \int_\infty^x e^{-t}\frac{dt}{t}.$$

Space-like Pion Form Factor

$\kappa = 0.4$ GeV

$\Lambda_{QCD} = 0.2$ GeV.

Identical Results for both confinement models



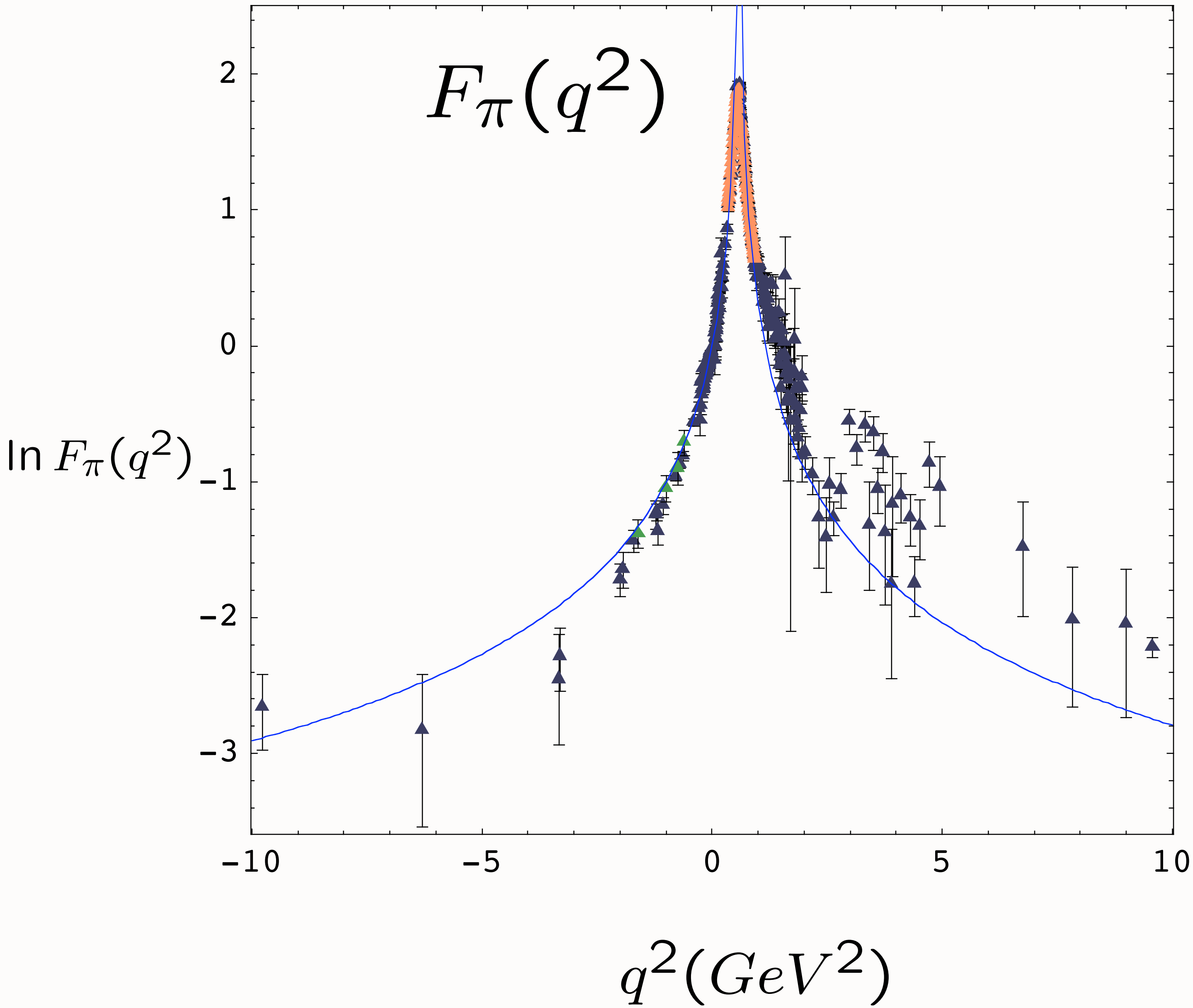
$$F(Q^2) \to \frac{4\kappa^2}{Q^2}$$

$\kappa = 2\Lambda_{QCD}$

High Q^2 from small z ~ 1/Q

Spacelike and Timelike Pion form factor from AdS/CFT

G. de Teramond, sjb



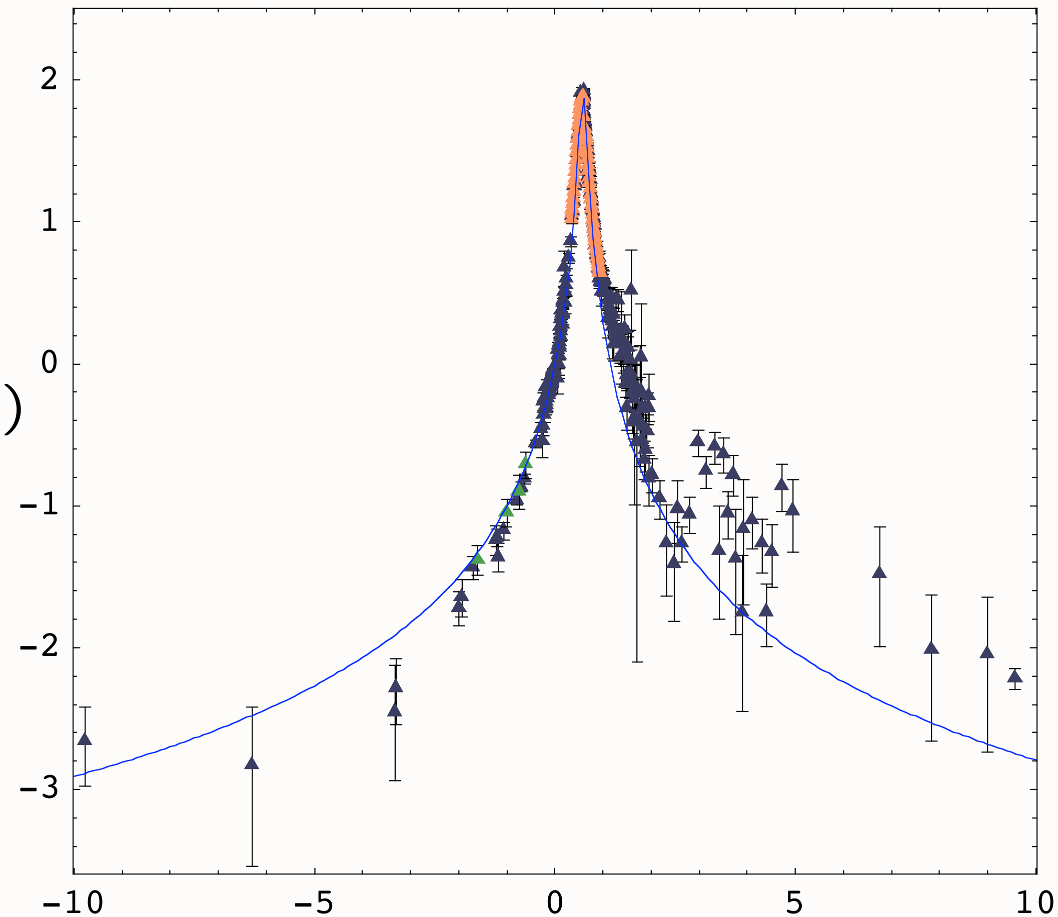
Harmonic Oscillator Confinement scale set by pion decay constant

$\kappa = 0.38$ GeV

Spacelike and Timelike Pion form factor from AdS/CFT

G. de Teramond, sjb

$F_\pi(q^2)$



$q^2 (GeV^2)$

Harmonic Oscillator Confinement

$\kappa = 0.38$ GeV

Analytic continue to timelike momenta and introduce width

$$q^2 \to q^2 + i\epsilon \to q^2 + iM\Gamma$$

Fit to height, predict width

$\Gamma_\rho = 111$ MeV

$\Gamma_\rho^{exp} = 150.3 \pm 1.6$ MeV

Nucleon Form Factors

- Consider the spin non-flip form factors in the infinite wall approximation

$$F_+(Q^2) = g_+ R^3 \int \frac{dz}{z^3} \, J(Q,z) \, |\psi_+(z)|^2,$$
$$F_-(Q^2) = g_- R^3 \int \frac{dz}{z^3} \, J(Q,z) \, |\psi_-(z)|^2,$$

where the effective charges g_+ and g_- are determined from the spin-flavor structure of the theory.

- Choose the struck quark to have $S^z = +1/2$. The two AdS solutions $\psi_+(z)$ and $\psi_-(z)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

- For $SU(6)$ spin-flavor symmetry

$$F_1^p(Q^2) = R^3 \int \frac{dz}{z^3} \, J(Q,z) |\psi_+(z)|^2,$$
$$F_1^n(Q^2) = -\frac{1}{3} R^3 \int \frac{dz}{z^3} \, J(Q,z) \left[|\psi_+(z)|^2 - |\psi_-(z)|^2 \right],$$

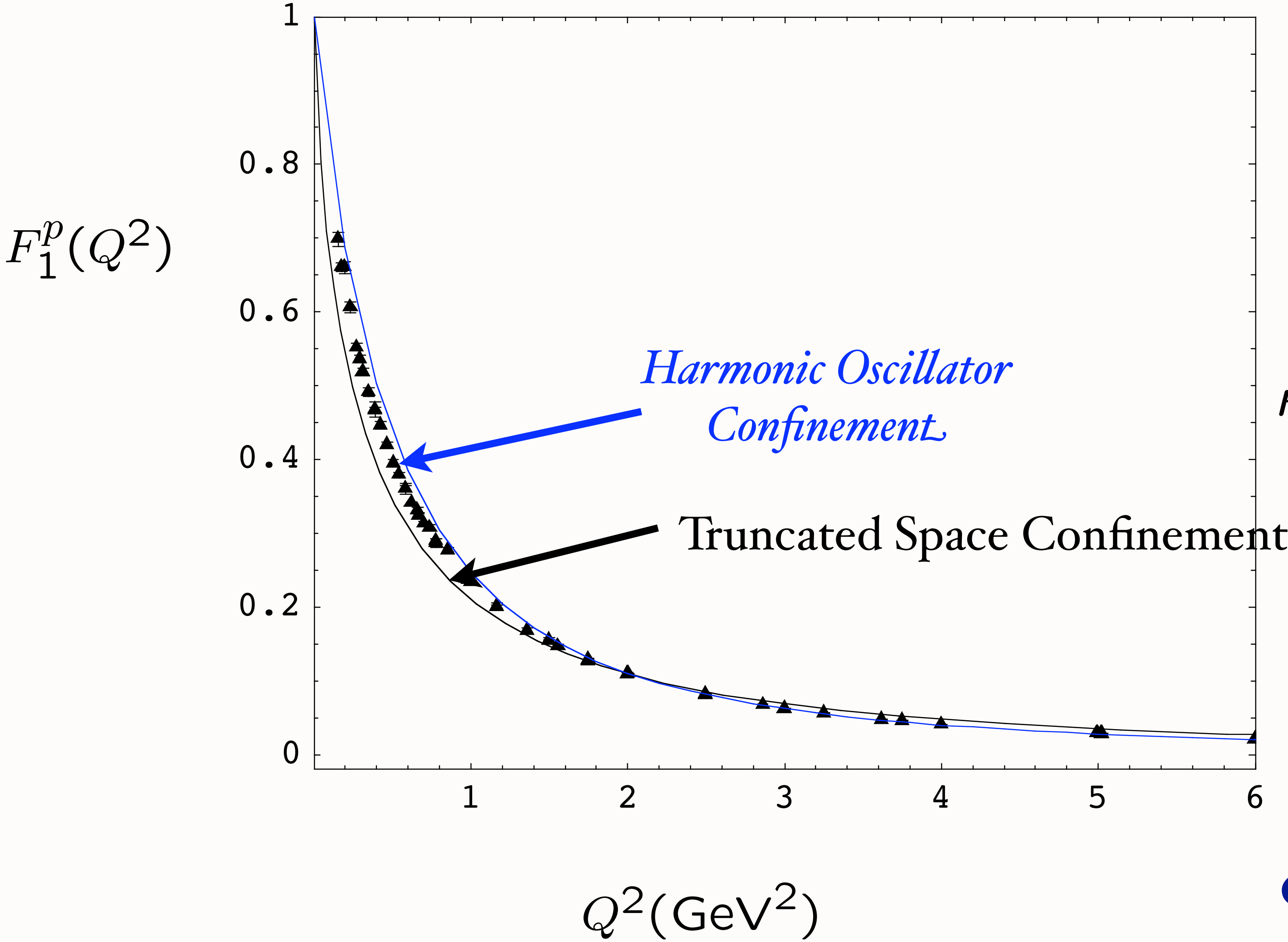
where $F_1^p(0) = 1, \;\; F_1^n(0) = 0$.

- Large Q power scaling: $F_1(Q^2) \to \left[1/Q^2\right]^2$.

G. de Teramond, sjb

G. de Teramond, sjb

Preliminary



$\kappa = 0.424$ GeV

$\Lambda = 0.2$ GeV

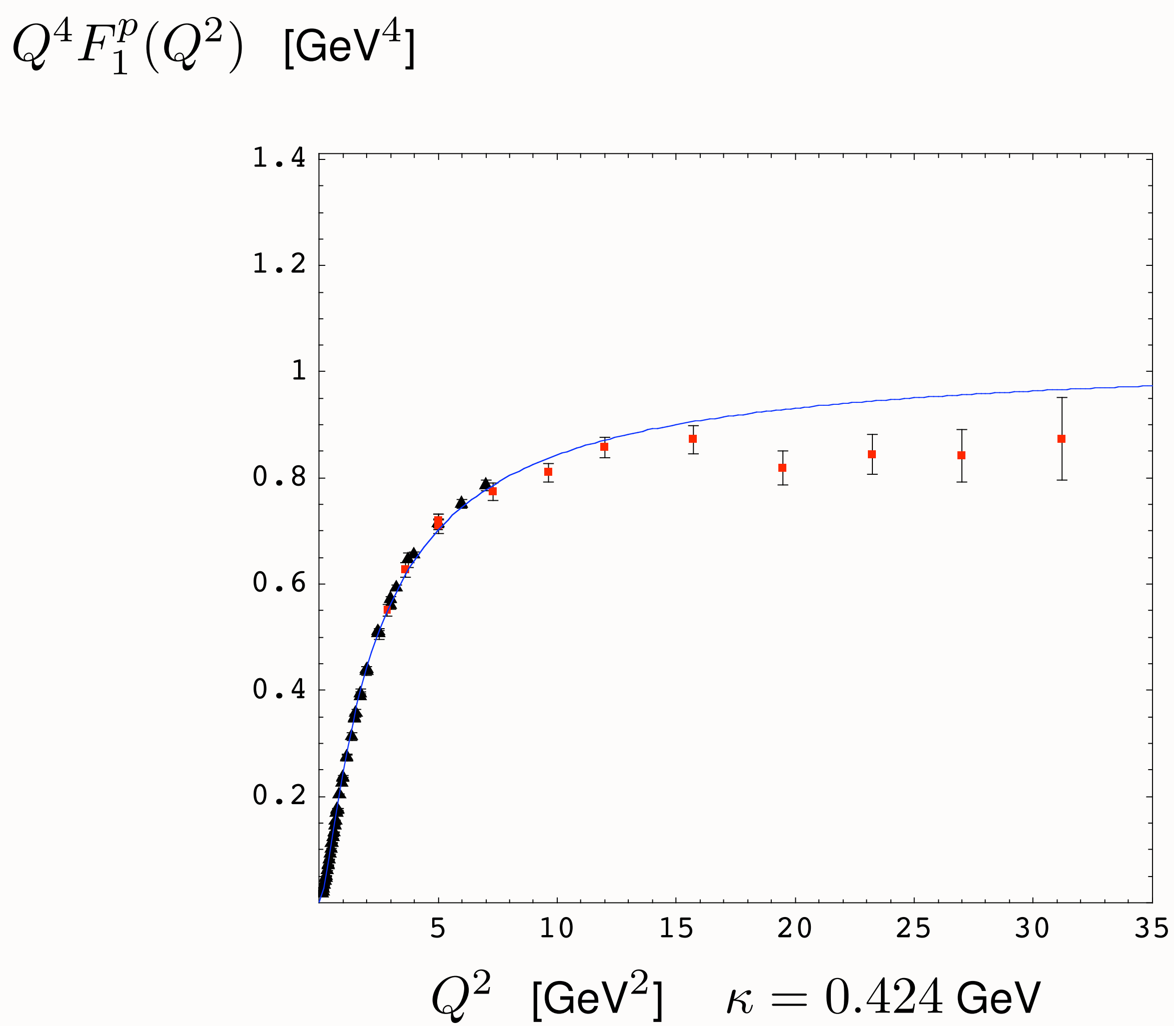
Current modified by metric

$$F_1(Q^2)_{I \to F} = \int \frac{dz}{z^3} \Phi_F^{\uparrow}(z) J(Q,z) \Phi_I^{\uparrow}(z)$$

Space-Like Dirac Proton Form Factor

G. de Teramond, sjb

Preliminary



Data analysis from: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

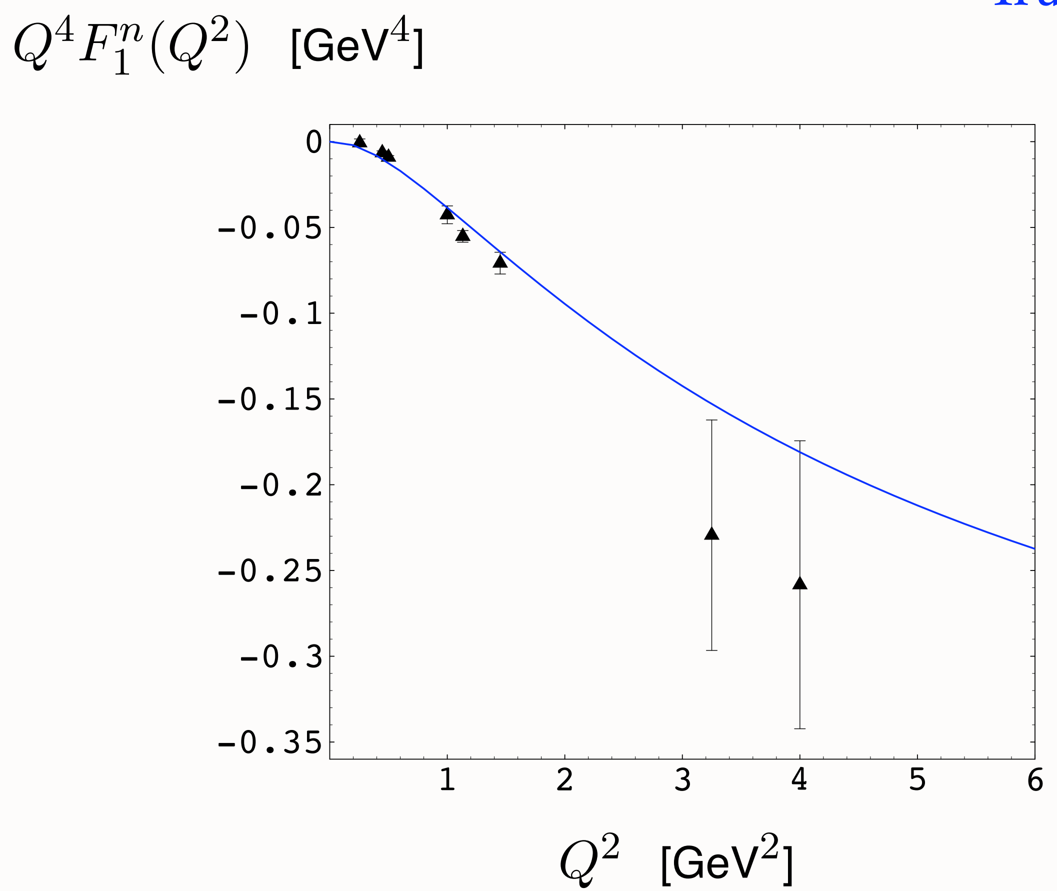
G. de Teramond, sjb

Preliminary

Dirac Neutron Form Factor

(Valence Approximation)

Truncated Space Confinement



Prediction for $Q^4 F_1^n(Q^2)$ for $\Lambda_{\rm QCD} = 0.21$ GeV in the hard wall approximation. Data analysis from Diehl (2005).

Hadronic Form Factor in Space and Time-Like Regions

- The form factor in AdS/QCD is the overlap of the normalizable modes dual to the incoming and outgoing hadron Φ_I and Φ_F and the non-normalizable mode J, dual to the external source (hadron spin σ):

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

- $J(Q,z)$ has the limiting value 1 at zero momentum transfer, $F(0)=1$, and has as boundary limit the external current, $A^\mu = \epsilon^\mu e^{iQ\cdot x} J(Q,z)$. Thus:

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

- Solution to the AdS Wave equation with boundary conditions at $Q=0$ and $z\to 0$:

$$J(Q,z) = zQK_1(zQ).$$

Polchinski and Strassler, hep-th/0209211; Hong, Yong and Strassler, hep-th/0409118.

Light-Front Representation of Two-Body Meson Form Factor

- Drell-Yan-West form factor

$$F(q^2) = \sum_q e_q \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3}\, \psi^*_{P'}(x, \vec{k}_\perp - x\vec{q}_\perp)\, \psi_P(x, \vec{k}_\perp).$$

- Fourrier transform to impact parameter space $\vec{b}_\perp$

$$\psi(x, \vec{k}_\perp) = \sqrt{4\pi} \int d^2\vec{b}_\perp\, e^{i\vec{b}_\perp \cdot \vec{k}_\perp} \widetilde{\psi}(x, \vec{b}_\perp)$$

- Find ($b = |\vec{b}_\perp|$) :

$$\begin{aligned} F(q^2) &= \int_0^1 dx \int d^2\vec{b}_\perp\, e^{ix\vec{b}_\perp \cdot \vec{q}_\perp} \left|\widetilde{\psi}(x, b)\right|^2 \\ &= 2\pi \int_0^1 dx \int_0^\infty b\, db\, J_0\,(bqx)\, \left|\widetilde{\psi}(x, b)\right|^2, \end{aligned}$$

Soper

Identical DYW and AdS5 Formulae: Two-parton case

- Change the integration variable $\zeta = |\vec{b}_\perp|\sqrt{x(1-x)}$

$$F(Q^2) = 2\pi \int_0^1 \frac{dx}{x(1-x)} \int_0^{\zeta_{max}=\Lambda^{-1}_{\rm QCD}} \zeta\, d\zeta\, J_0\left(\frac{\zeta Q x}{\sqrt{x(1-x)}}\right) \left|\widetilde\psi(x,\zeta)\right|^2,$$

- Compare with AdS form factor for arbitrary Q. Find:

Same result for LF and AdS5

$$J(Q,\zeta) = \int_0^1 dx J_0\left(\frac{\zeta Q x}{\sqrt{x(1-x)}}\right) = \zeta Q K_1(\zeta Q),$$

$\zeta \leftrightarrow \mathbf{z}$

the solution for the electromagnetic potential in AdS space, and

$$\boxed{\widetilde\psi(x,\vec{b}_\perp) = \frac{\Lambda_{\rm QCD}}{\sqrt{\pi} J_1(\beta_{0,1})} \sqrt{x(1-x)} J_0\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{0,1}\Lambda_{QCD}\right) \theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda^{-2}_{\rm QCD}}{x(1-x)}\right)}$$

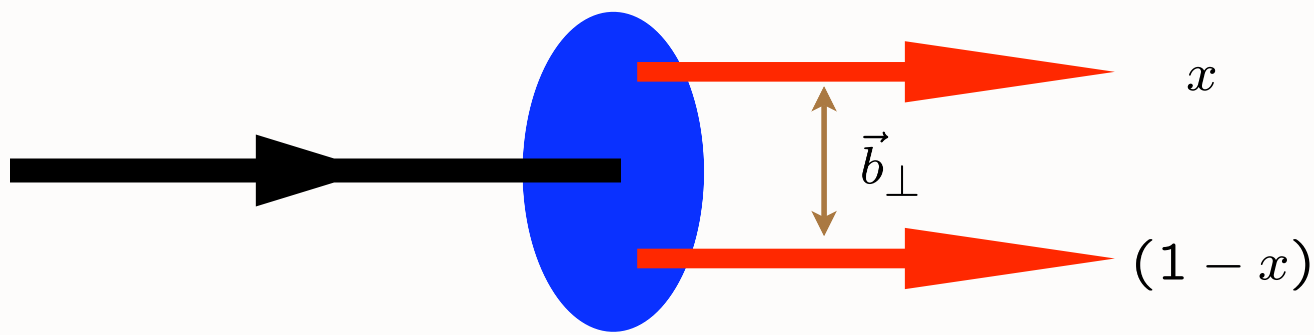
the holographic LFWF for the valence Fock state of the pion $\psi_{\overline{q}q/\pi}$.

- The variable ζ, $0 \le \zeta \le \Lambda^{-1}_{QCD}$, represents the scale of the invariant separation between quarks and is also the holographic coordinate $\zeta = z$!

LF(3+1) $\qquad\qquad$ AdS$_5$

$$\psi(x, \vec{b}_\perp) \quad \longleftrightarrow \quad \phi(z)$$

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^{\,2}} \quad \longleftrightarrow \quad z$$



$$\psi(x, \vec{b}_\perp) = \sqrt{x(1-x)}\;\phi(\zeta)$$

Holography: Unique mapping derived from equality of LF and AdS formula for current matrix elements

Holography: Map AdS/CFT to 3+1 LF Theory

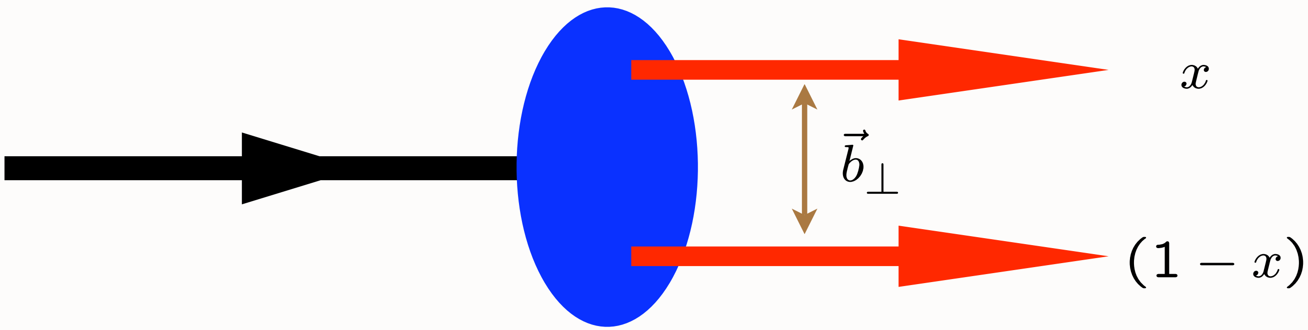
Relativistic LF radial equation

Frame Independent

$$\left[-\frac{d^2}{d\zeta^2} + V(\zeta)\right]\phi(\zeta) = \mathcal{M}^2\phi(\zeta)$$

G. de Teramond, sjb

$$\zeta^2 = x(1-x)\mathbf{b}^2_\perp .$$

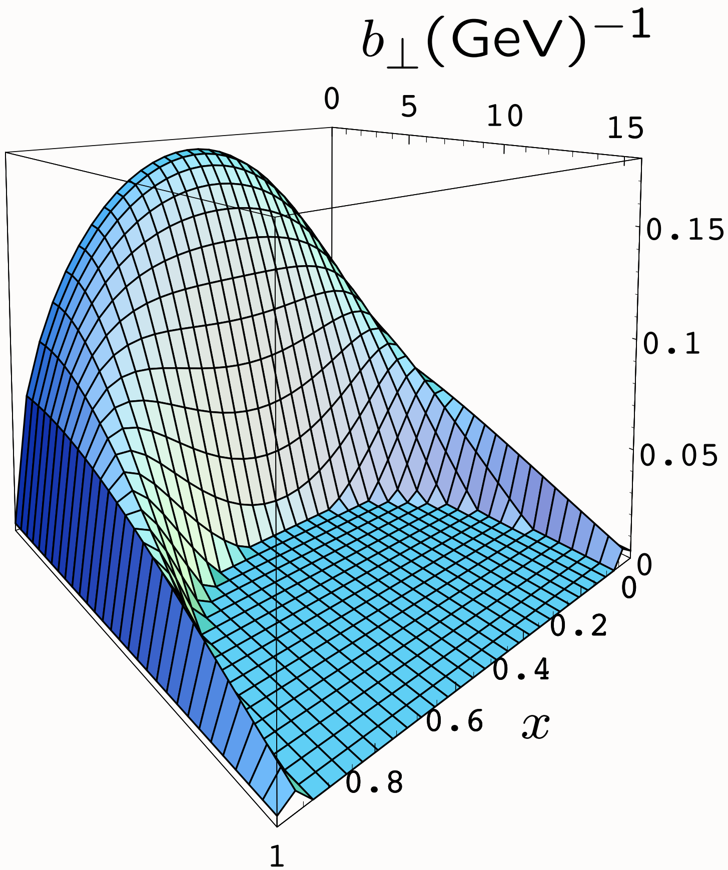


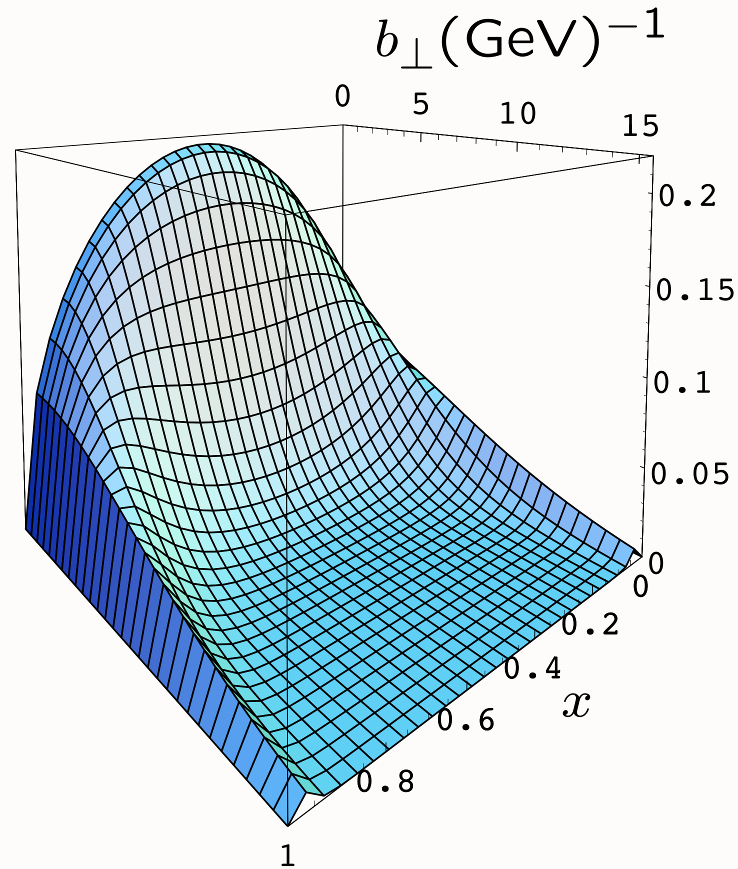
Effective conformal potential:

$$V(\zeta) = -\frac{1-4L^2}{4\zeta^2}.$$

Induced by conformal metric

AdS/CFT Predictions for Meson LFWF $\psi(x, b_\perp)$

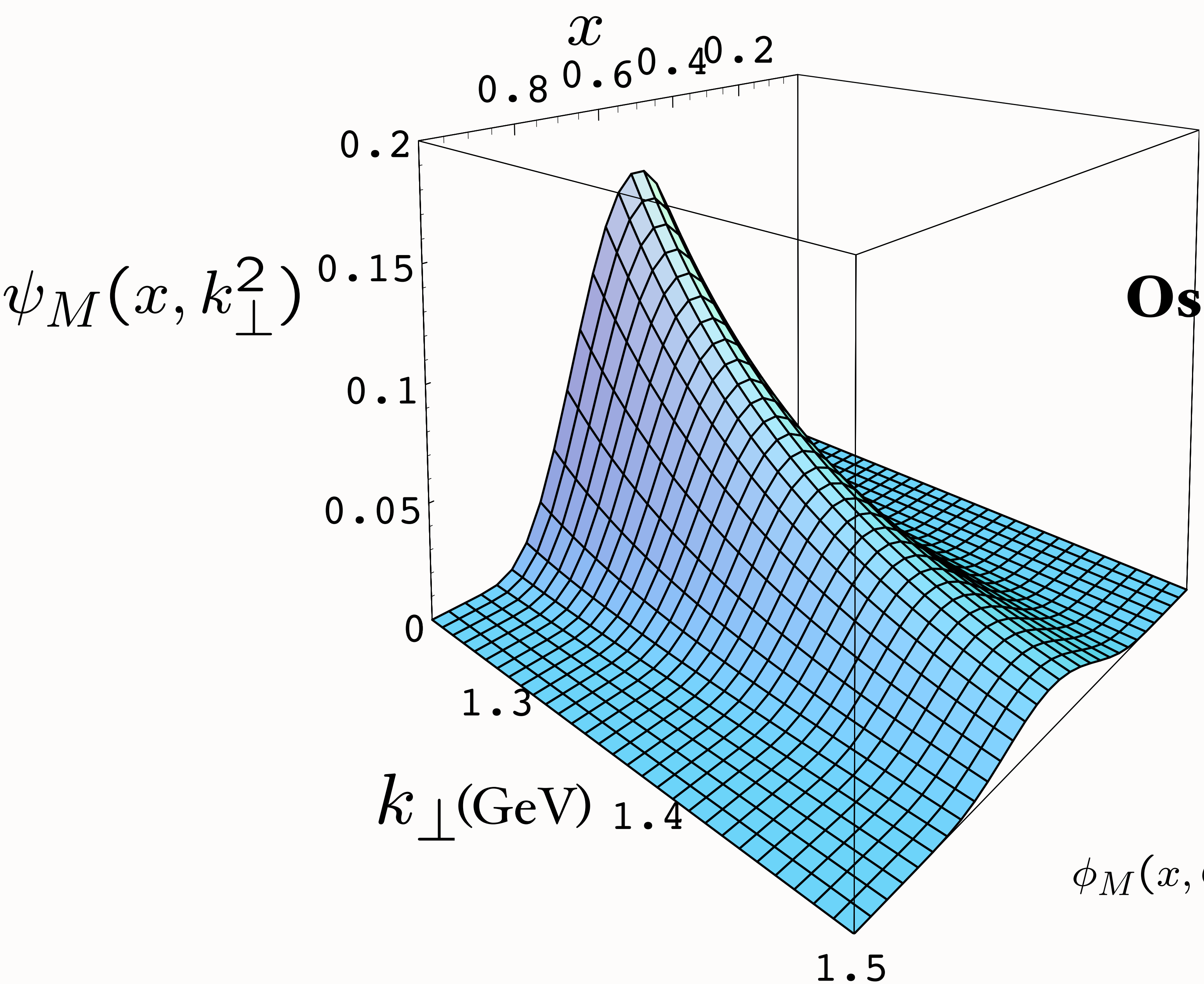




$\Lambda_{QCD} = 0.32 \ \mathrm{GeV}$ $\kappa = 0.76 \ \mathrm{GeV}$

Truncated Space ***Harmonic Oscillator***

Prediction from AdS/CFT: Meson LFWF



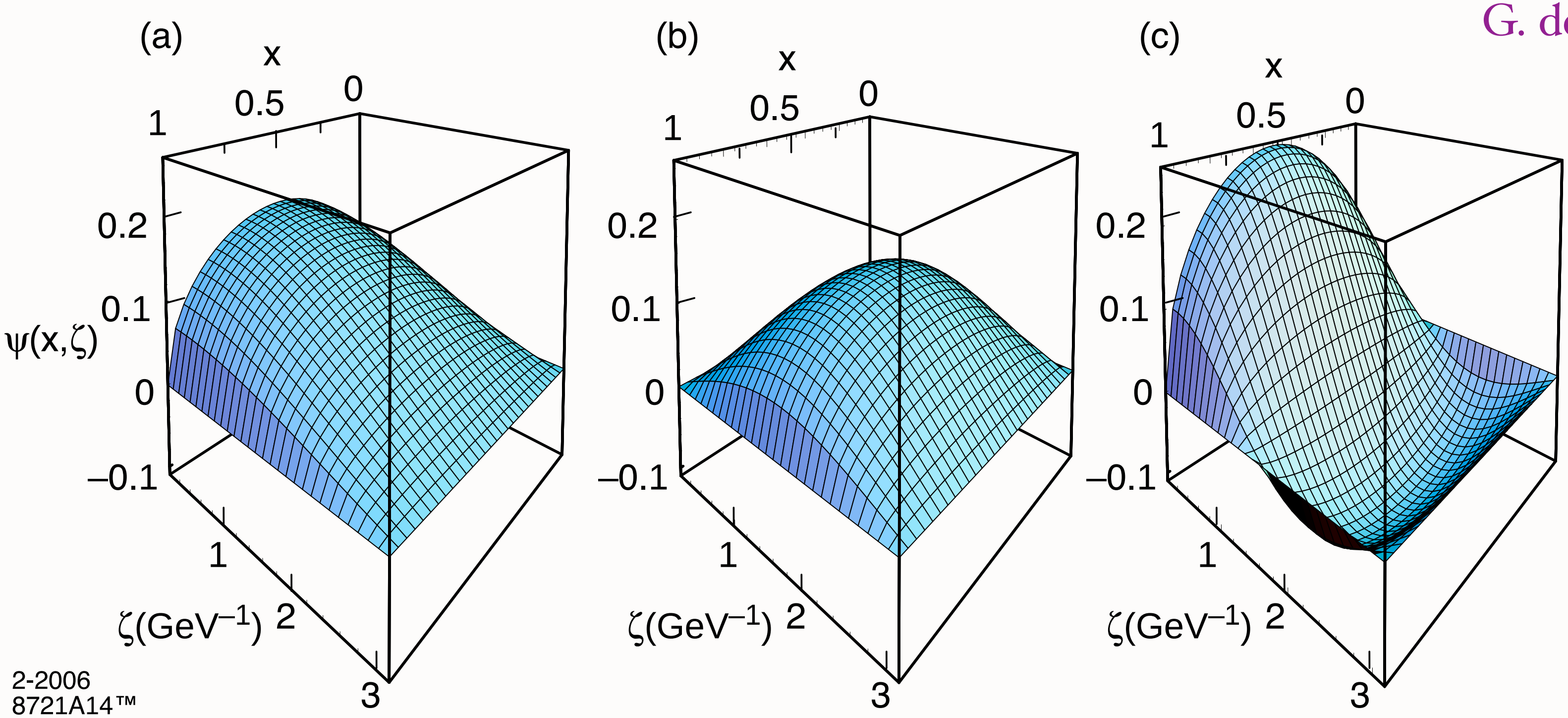
Harmonic Oscillator model

de Teramond, sjb

$$\phi_M(x, Q_0) \propto \sqrt{x(1-x)}$$

AdS/CFT Prediction for Meson LFWF

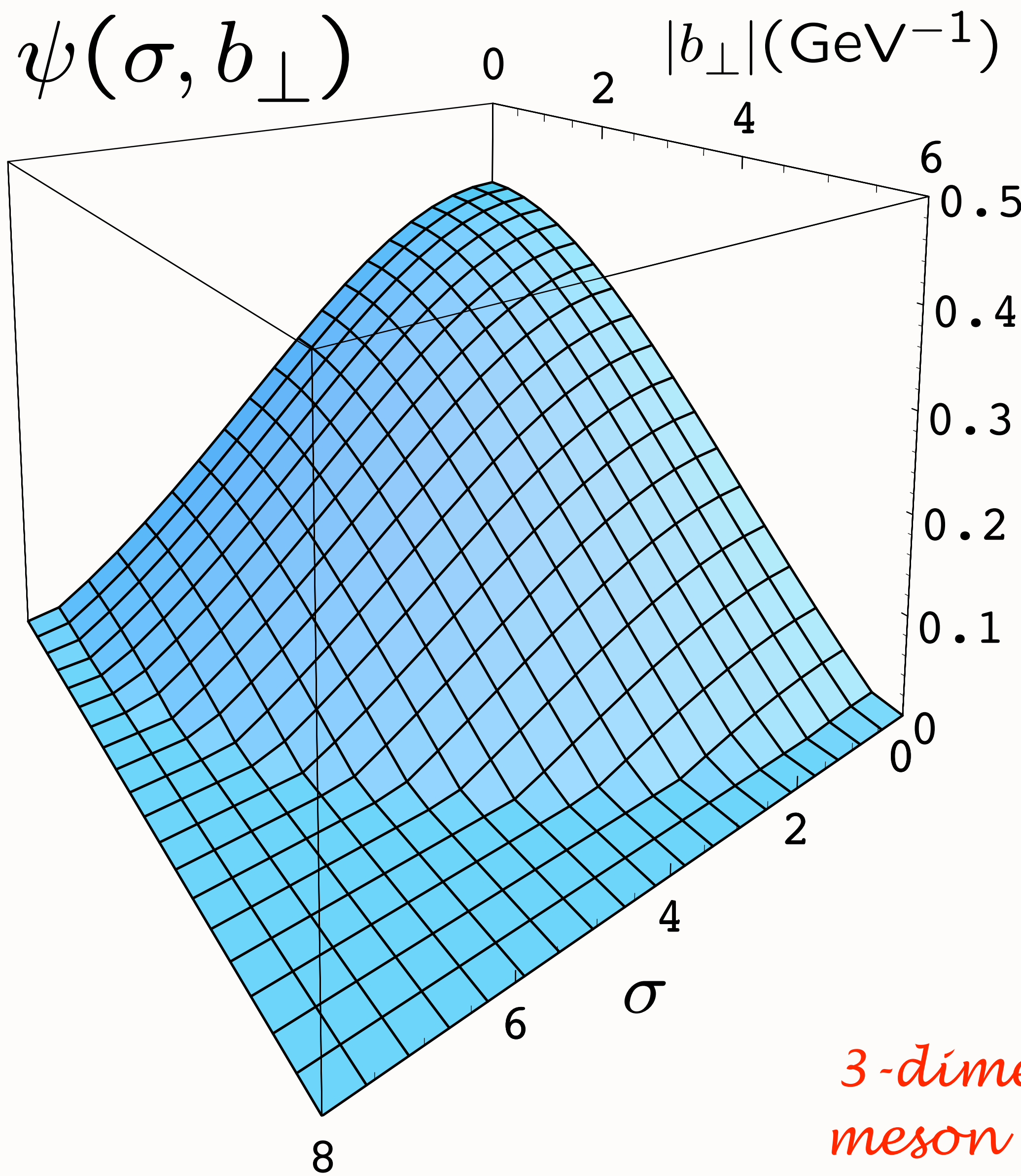
G. de Teramond
SJB

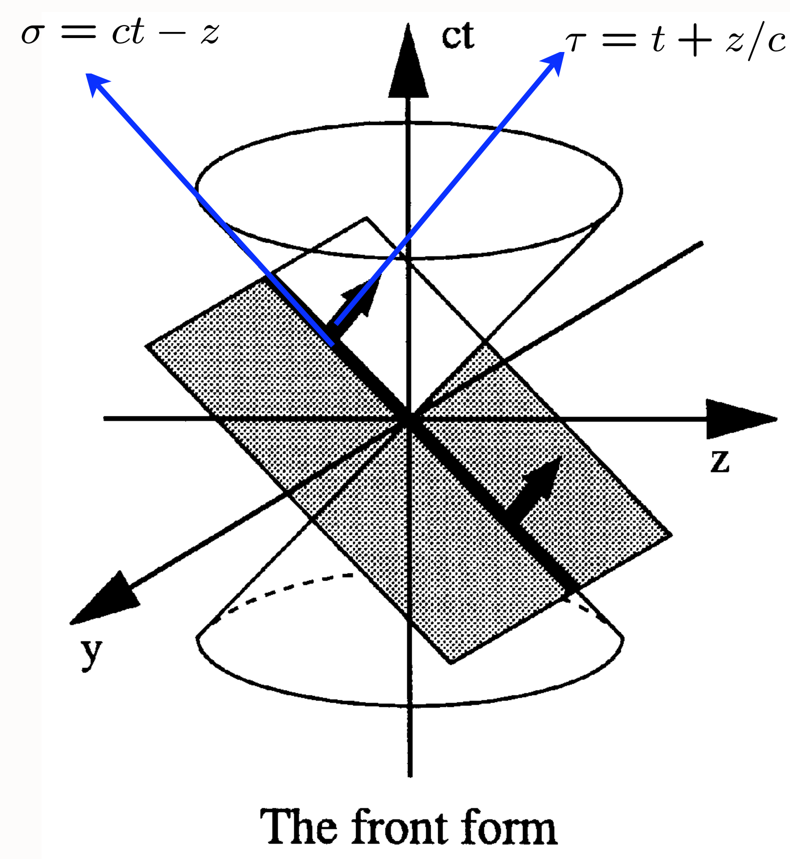


Two-parton holographic LFWF in impact space $\widetilde{\psi}(x, \zeta)$ for $\Lambda_{QCD} = 0.32$ GeV: (a) ground state $L = 0,\ k = 1$; (b) first orbital exited state $L = 1,\ k = 1$; (c) first radial exited state $L = 0,\ k = 2$. The variable ζ is the holographic variable $z = \zeta = |b_\perp|\sqrt{x(1-x)}$.

AdS/CFT Holographic Model

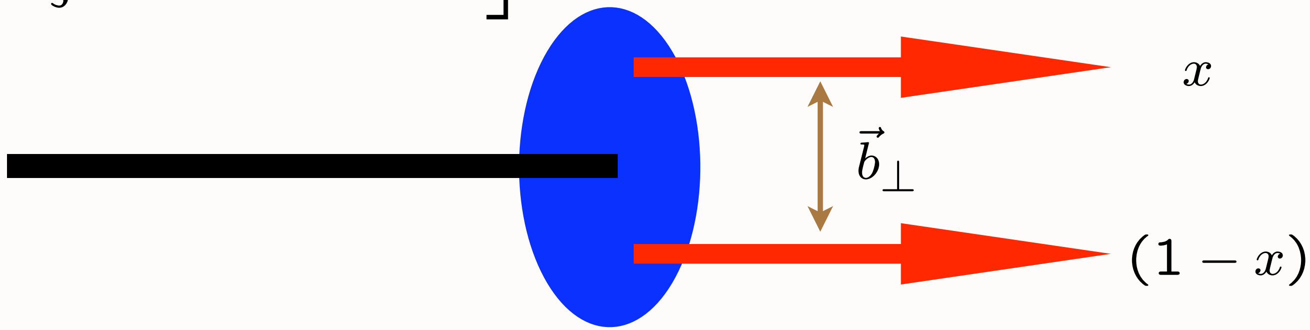
G. de Teramond
SJB





3-dimensional photograph:
meson LFWF at fixed LF Time

$$\left[-\frac{d^2}{d\zeta^2} + V(\zeta)\right]\phi(\zeta) = \mathcal{M}^2\phi(\zeta)$$



$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$$ *Holographic Variable*

$$-\frac{d}{d\zeta^2} \equiv \frac{k_\perp^2}{x(1-x)}$$ *LF Kinetic Energy in momentum space*

Conjecture for mesons with massive quarks

$$-\frac{d}{d\zeta^2} \to -\frac{d}{d\zeta^2} + \frac{m_a^2}{x} + \frac{m_b^2}{1-x} \equiv \frac{k_\perp^2 + m_a^2}{x} + \frac{k_\perp^2 + m_b^2}{1-x}$$

N-parton case

- Define effective single particle transverse density by (Soper, Phys. Rev. D **15**, 1141 (1977))

$$F(q^2) = \int_0^1 dx \int d^2\vec{\eta}_\perp e^{i\vec{\eta}_\perp\cdot\vec{q}_\perp} \tilde{\rho}(x,\vec{\eta}_\perp)$$

- From DYW expression for the FF in transverse position space:

$$\tilde{\rho}(x,\vec{\eta}_\perp) = \sum_n \prod_{j=1}^{n-1} \int dx_j \, d^2\vec{b}_{\perp j} \, \delta(1 - x - \sum_{j=1}^{n-1} x_j) \, \delta^{(2)}(\sum_{j=1}^{n-1} x_j \vec{b}_{\perp j} - \vec{\eta}_\perp) |\psi_n(x_j, \vec{b}_{\perp j})|^2$$

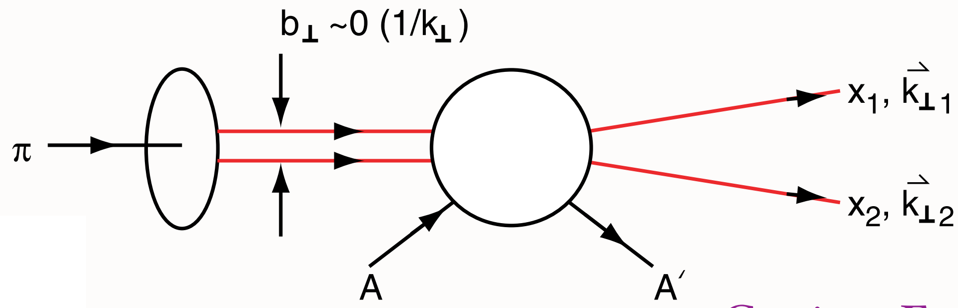
- Compare with the the form factor in AdS space for arbitrary Q:

$$F(Q^2) = R^3 \int_0^\infty \frac{dz}{z^3} e^{3A(z)} \Phi_{P'}(z) \, J(Q,z) \, \Phi_P(z)$$

- Holographic variable z is expressed in terms of the average transverse separation distance of the spectator constituents $\vec{\eta} = \sum_{j=1}^{n-1} x_j \, \vec{b}_{\perp j}$

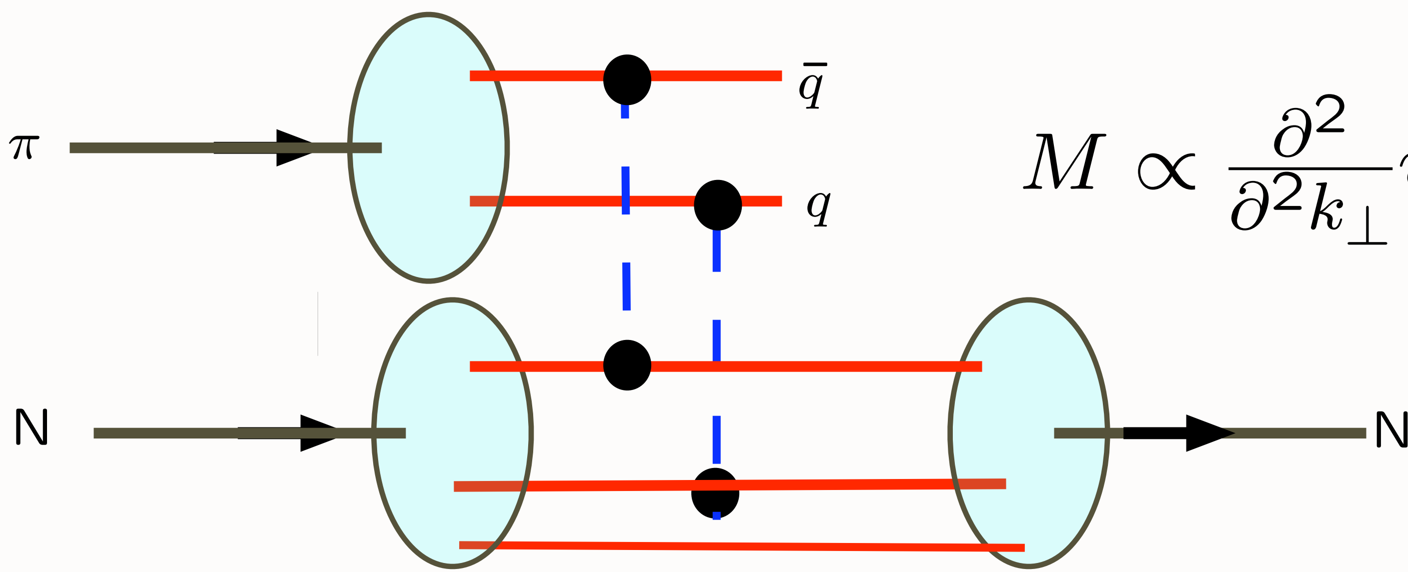
$$\boxed{z = \sqrt{\frac{x}{1-x}} \, \Big| \sum_{j=1}^{n-1} x_j \, \vec{b}_{\perp j} \Big|}$$

E791 FNAL Diffractive DiJet



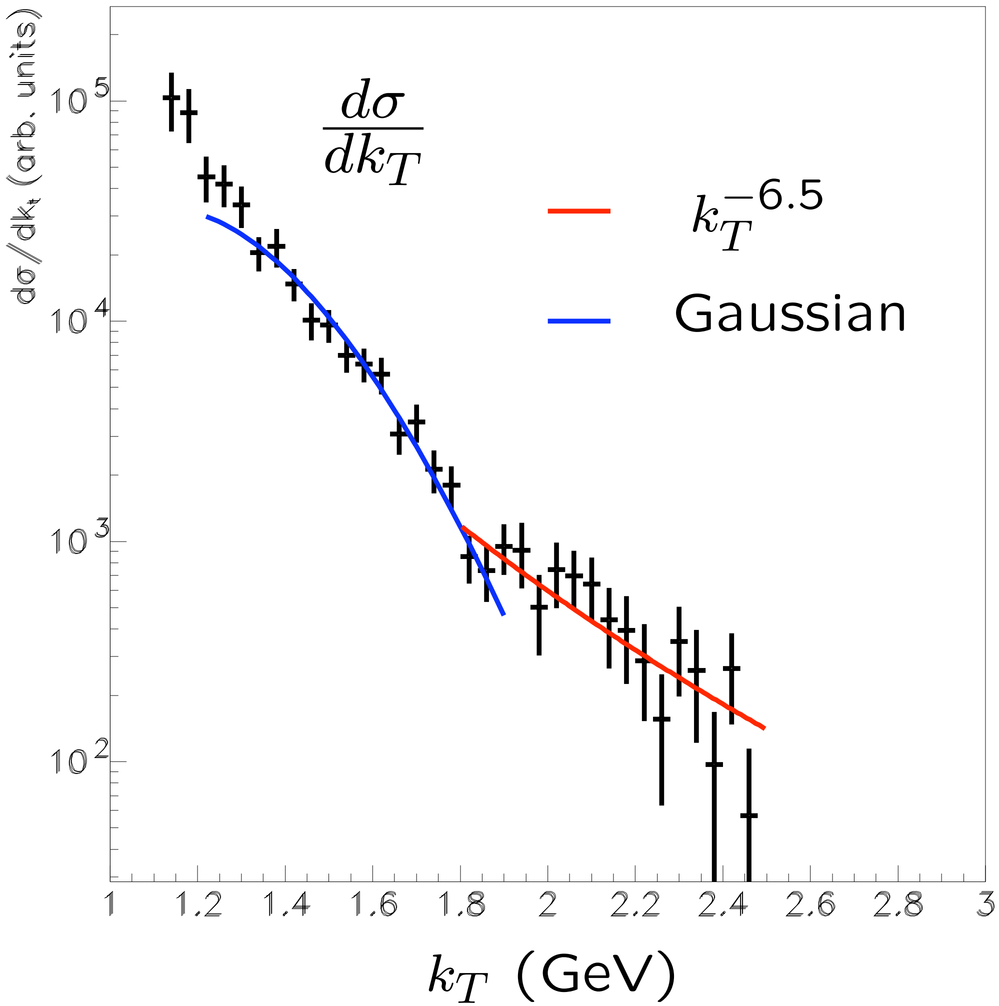
Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

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



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

E791 Diffractive Di-Jet transverse momentum distribution

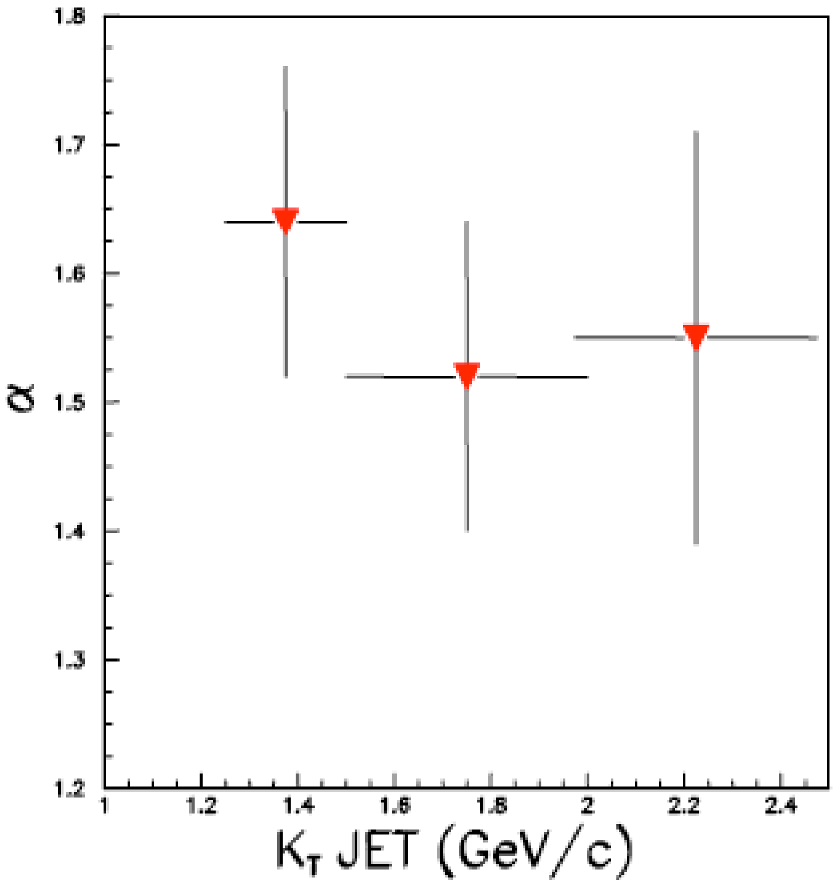


Two Components

High Transverse momentum dependence $k_T^{-6.5}$ *consistent with PQCD, ERBL Evolution*

Gaussian component similar to AdS/CFT HO LFWF

A(π,dijet) data from FNAL



Coherent π^+ diffractive dissociation with 500 GeV/c pions on Pt and C.

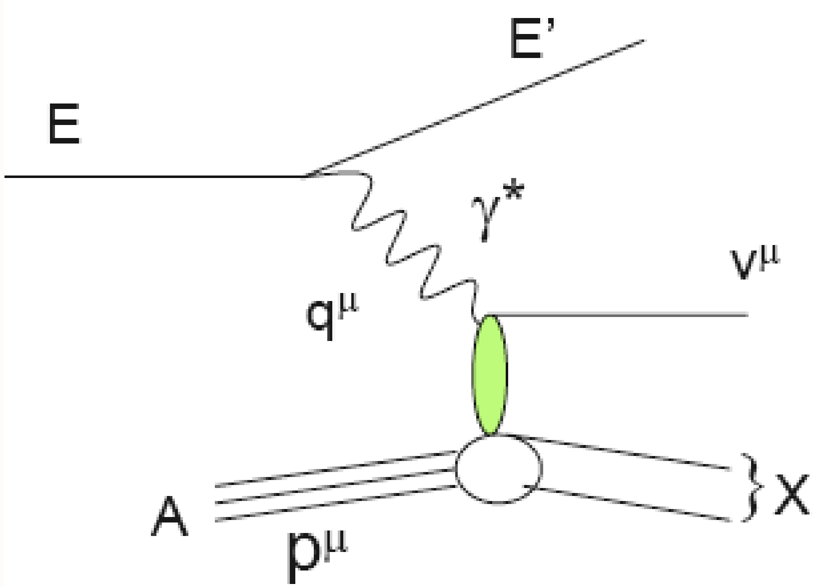
Fit to $\sigma = \sigma_0 A^\alpha$

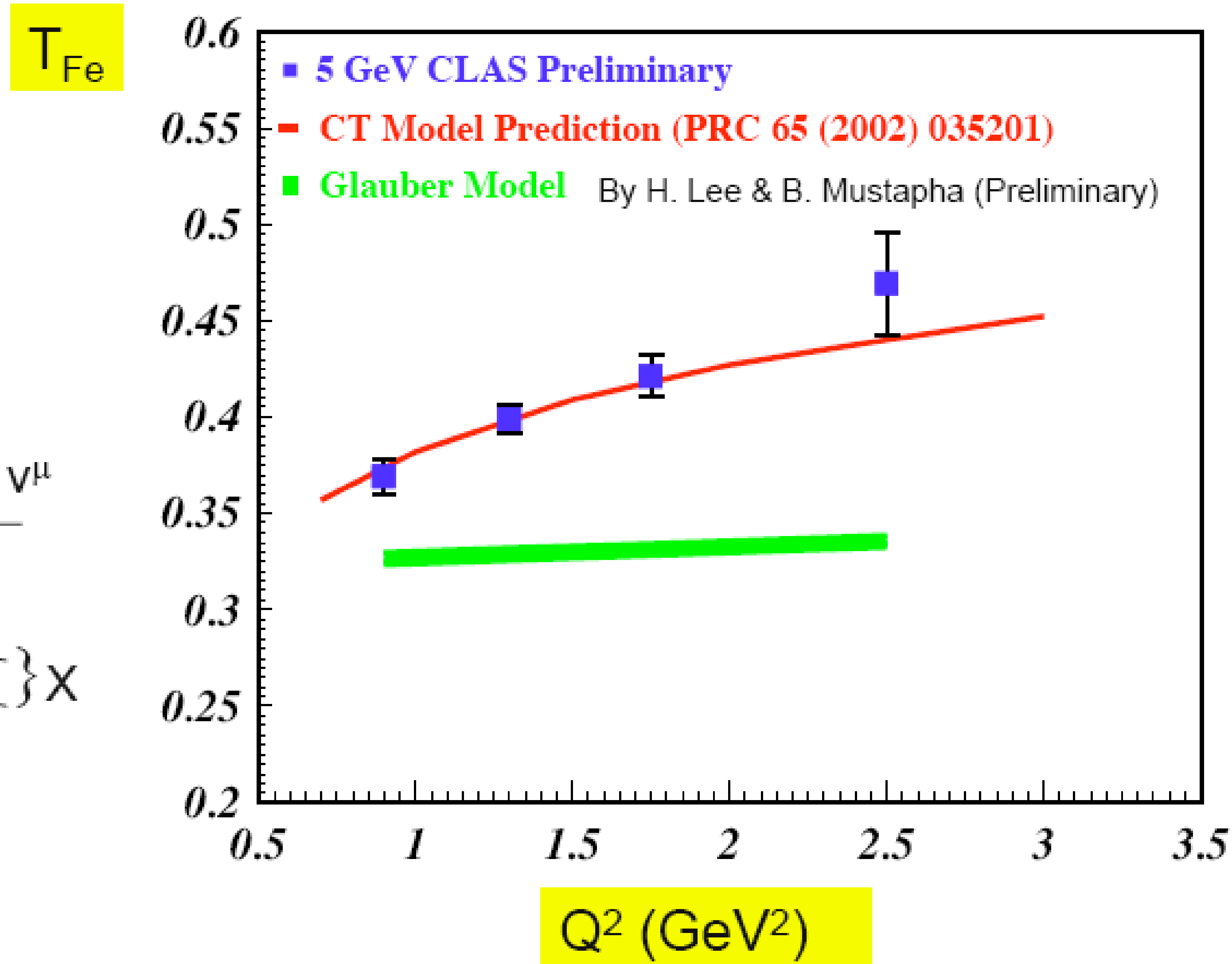
α > 0.76 from pion-nucleus total cross-section.

Aitala et al., PRL 86 4773 (2001)

L. L. Frankfurt, G. A. Miller, and M. Strikman, Found. Of Phys. 30 (2000) 533

Kawtar Hafidi





Theory:

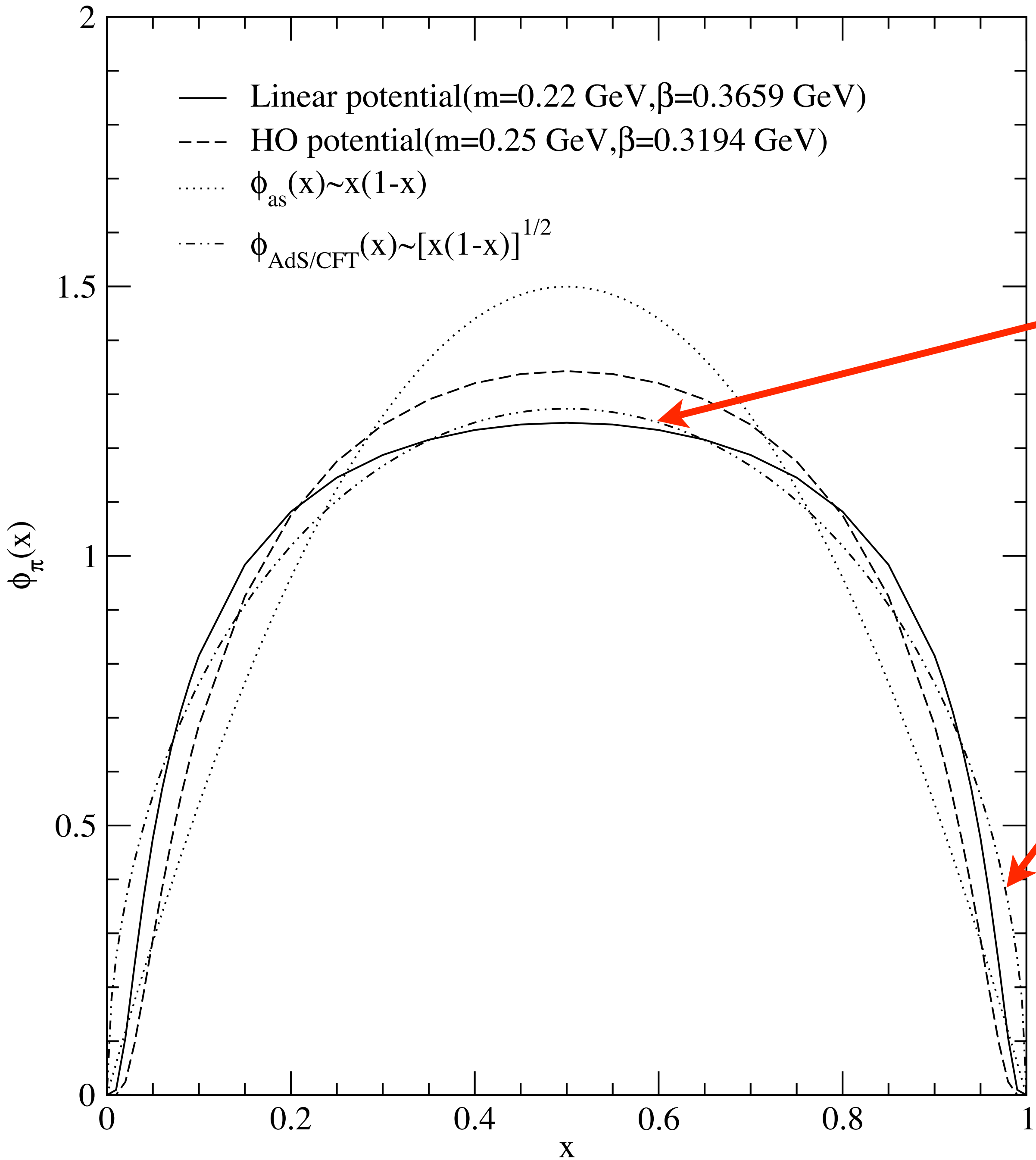
Kopeliovich et al., PRC 65 (2002) 035201

Kawtar Hafidi

Summary and outlook

- The preliminary CLAS results show a clear evidence of CT in ρ^0 electroproduction on nuclei
- CLAS results show a nice agreement with the theoretical model by Kopeliovich et al.
- The 11 GeV measurements will extend both the Q^2 and the ℓ_c range considerably allowing for rich input to the theory for the calculation of the vector meson formation time and its interaction in the nuclear medium

Important tests of CT in meson electroproduction DVMP



AdS/CFT:

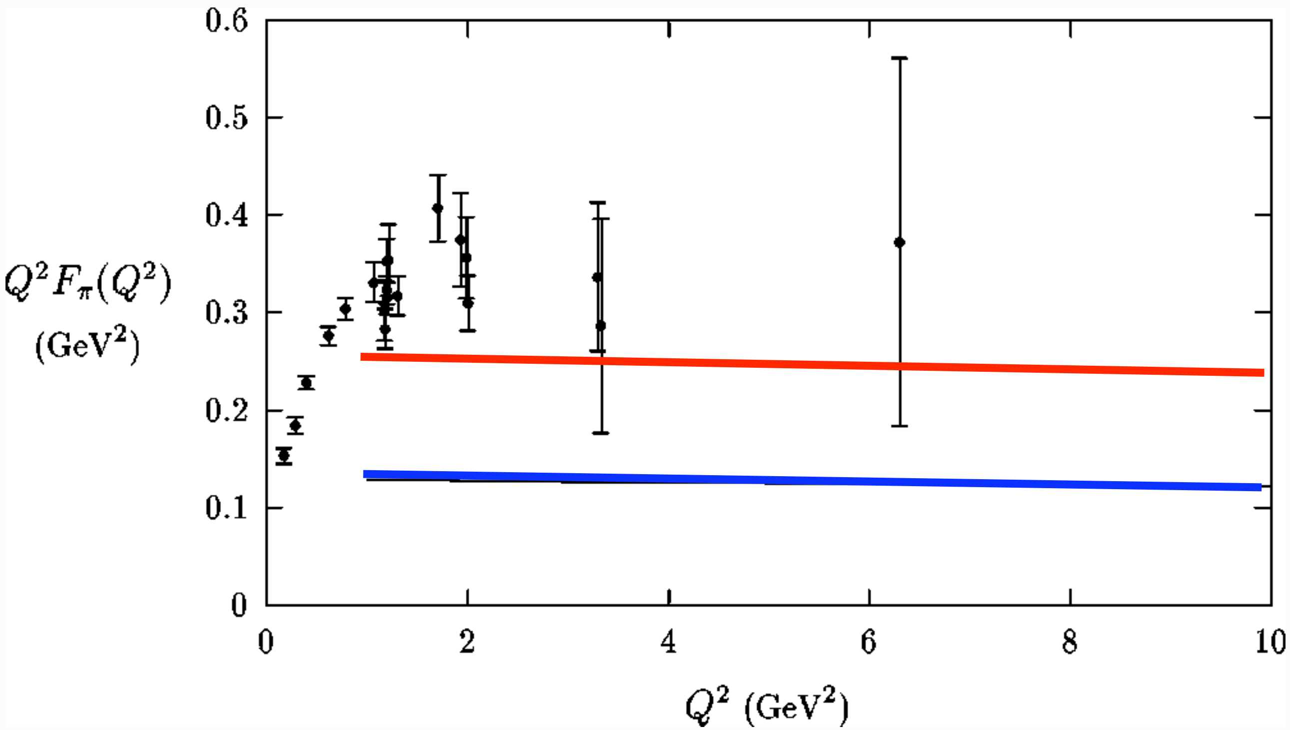
$$\phi(x, Q_0) \propto \sqrt{x(1-x)}$$

Increases PQCD leading twist predictio
$F_\pi(Q^2)$ by factor 16/9

Lepage, sjb

C. Ji, A. Pang, D. Robertson, sjb
Choi, Ji

$$F_\pi(Q^2) = \int_0^1 dx\,\phi_\pi(x) \int_0^1 dy\,\phi_\pi(y) \frac{16\pi C_F \alpha_V(Q_V)}{(1-x)(1-y)Q^2}$$



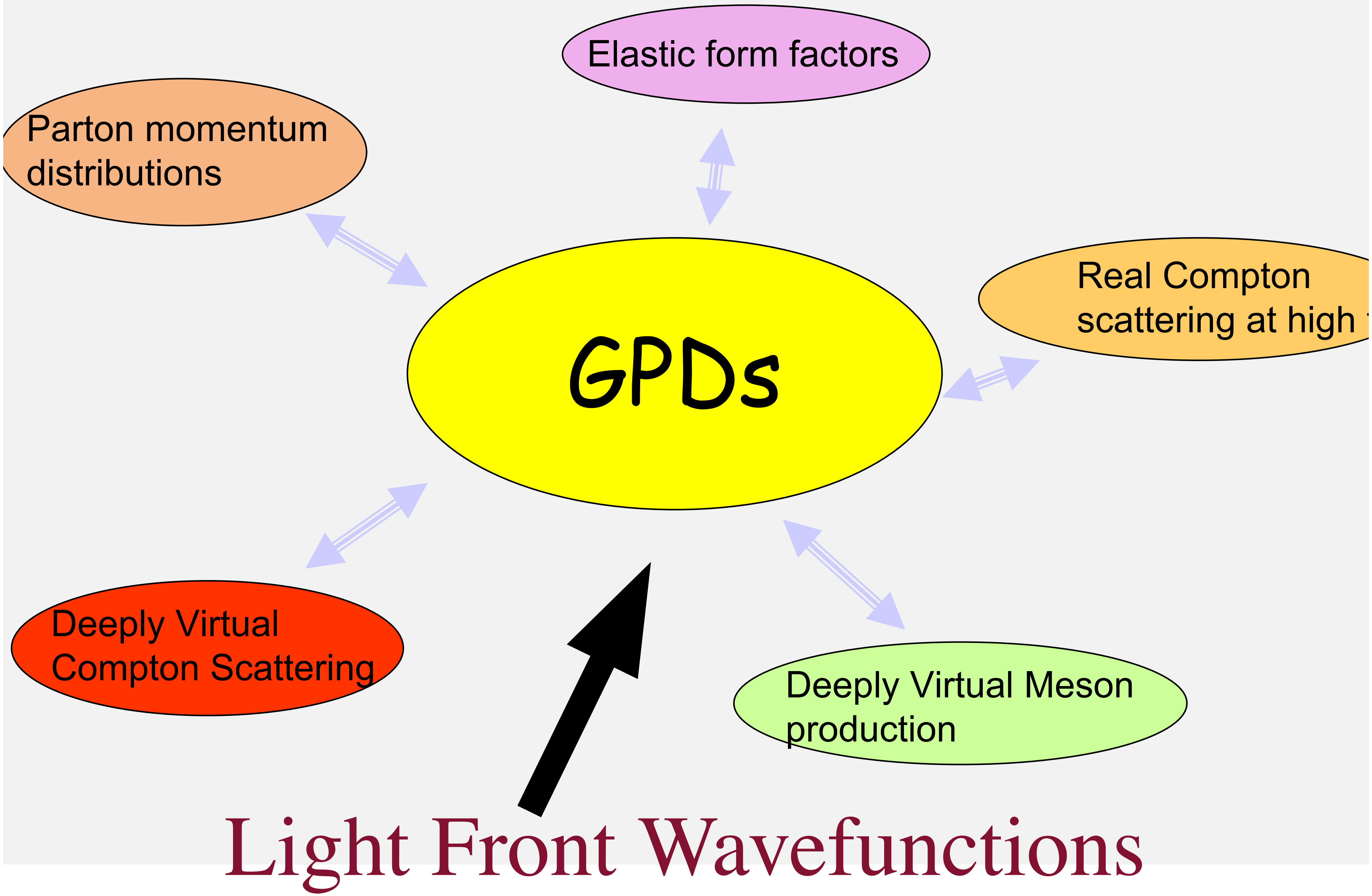
$\phi(x, Q_0) \propto \sqrt{x(1-x)}$

$\phi_{asymptotic} \propto x(1-x)$

Normalized to f_π

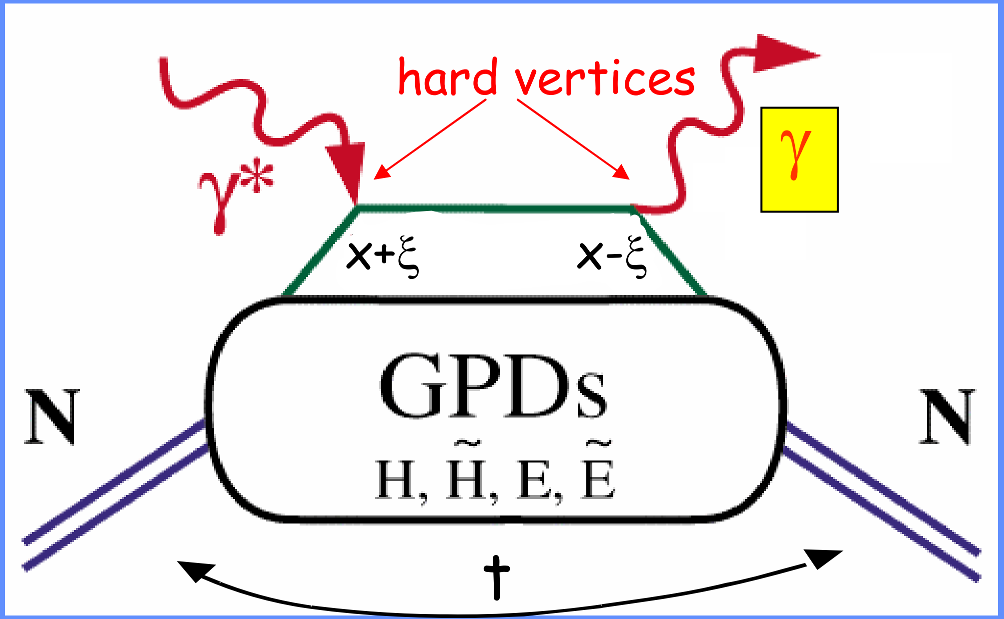
AdS/CFT: Increases PQCD leading twist prediction for $F_\pi(Q^2)$ by factor 16/9

A Unified Description of Hadron Structure



GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

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

H(x,ξ,t), E(x,ξ,t), . . . "Generalized Parton Distributions"

Quark angular momentum (Ji sum rule)

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

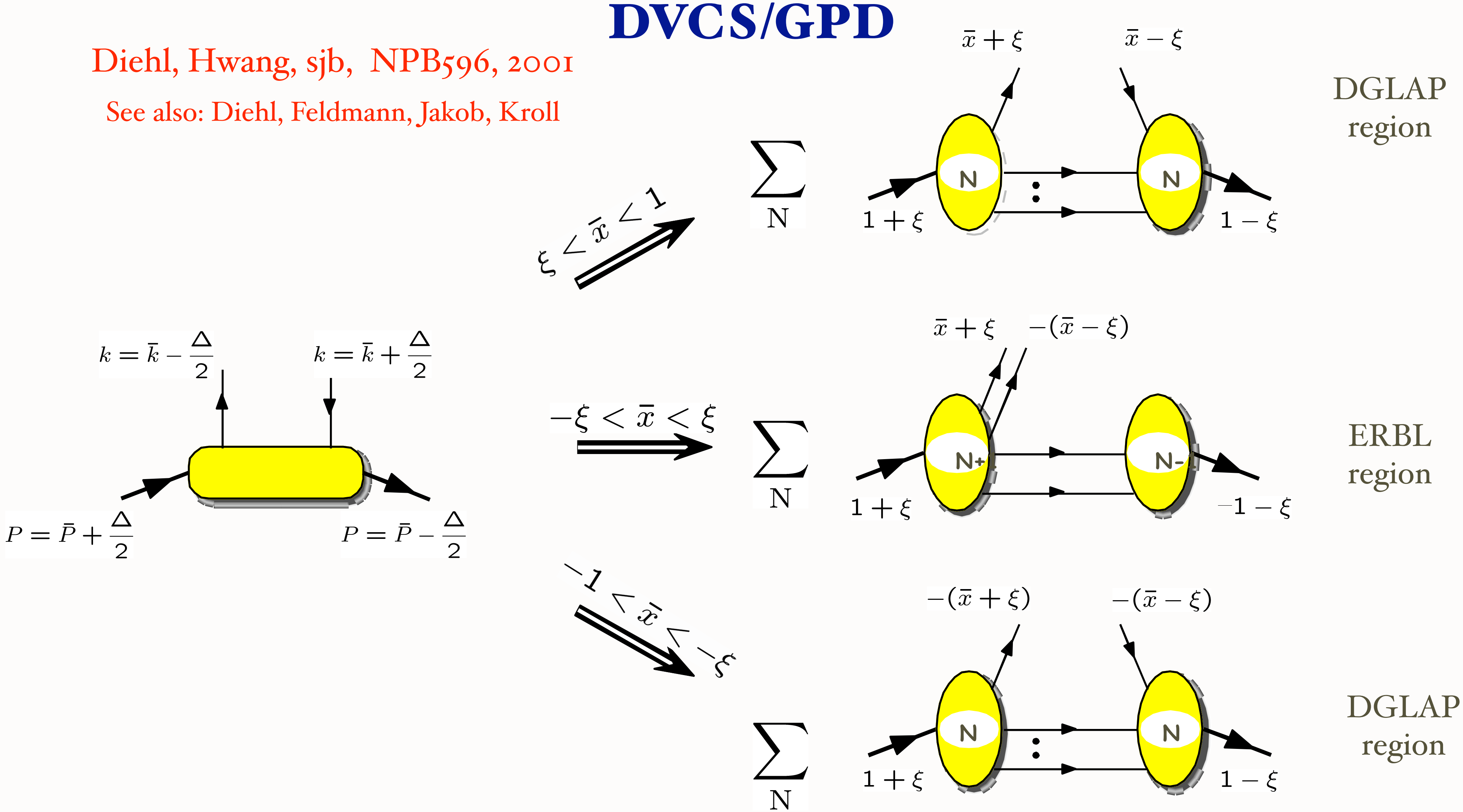
X. Ji, Phy.Rev.Lett.78,610(1997)

Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



N=3 VALENCE QUARK ⇒ Light-cone Constituent quark model

N=5 VALENCE QUARK + QUARK SEA ⇒ Meson-Cloud model

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

$$
\begin{aligned}
&\frac{1}{\sqrt{1-\zeta}} \frac{\Delta^1 - i\Delta^2}{2M} E_{(n+1\to n-1)}(x,\zeta,t) \\
&= \left(\sqrt{1-\zeta}\right)^{3-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n+1} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3} 16\pi^3 \delta\left(1-\sum_{j=1}^{n+1} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n+1} \vec{k}_{\perp j}\right) \\
&\quad \times 16\pi^3 \delta(x_{n+1}+x_1-\zeta)\delta^{(2)}(\vec{k}_{\perp n+1}+\vec{k}_{\perp 1}-\vec{\Delta}_\perp) \\
&\quad \times \delta(x-x_1)\psi^{\uparrow *}_{(n-1)}(x'_i,\vec{k}'_{\perp i},\lambda_i)\psi^{\downarrow}_{(n+1)}(x_i,\vec{k}_{\perp i},\lambda_i)\delta_{\lambda_1-\lambda_{n+1}},
\end{aligned}
$$

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)

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

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

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

Verified using LFWFs

Diehl, Hwang, sjb

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

Quark angular momentum (Ji's sum rule)

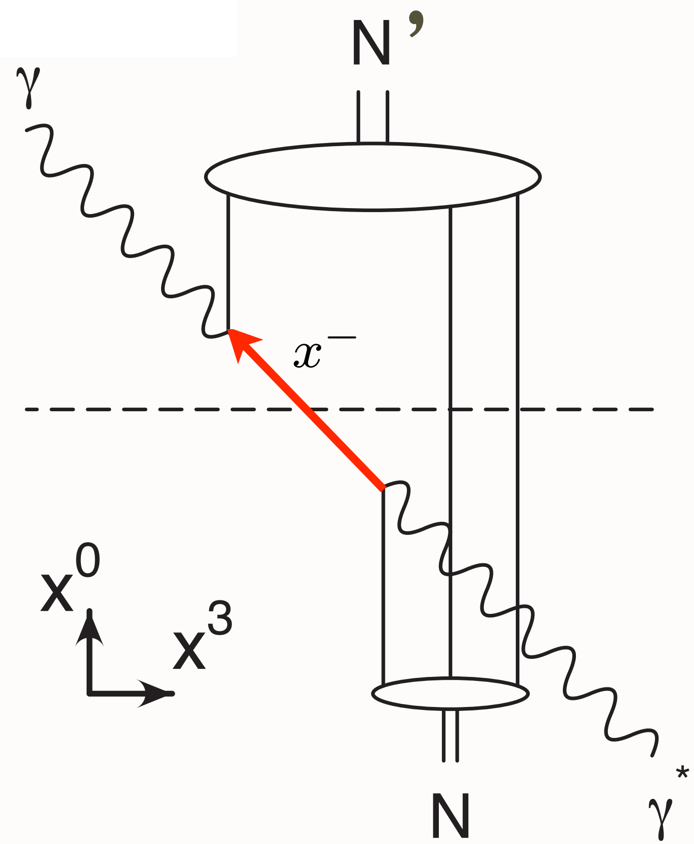
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

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

Space-time picture of DVCS

P. Hoyer

$\sigma = \frac{1}{2} x^- P^+$



$x^+ = \mathbf{x}_\perp = 0)$

The position of the struck quark differs by x^- in the two wave functions

Measure x- distribution from DVCS:
Take Fourier transform of skewness, $\xi = \frac{Q^2}{2p.q}$
the longitudinal momentum transfer

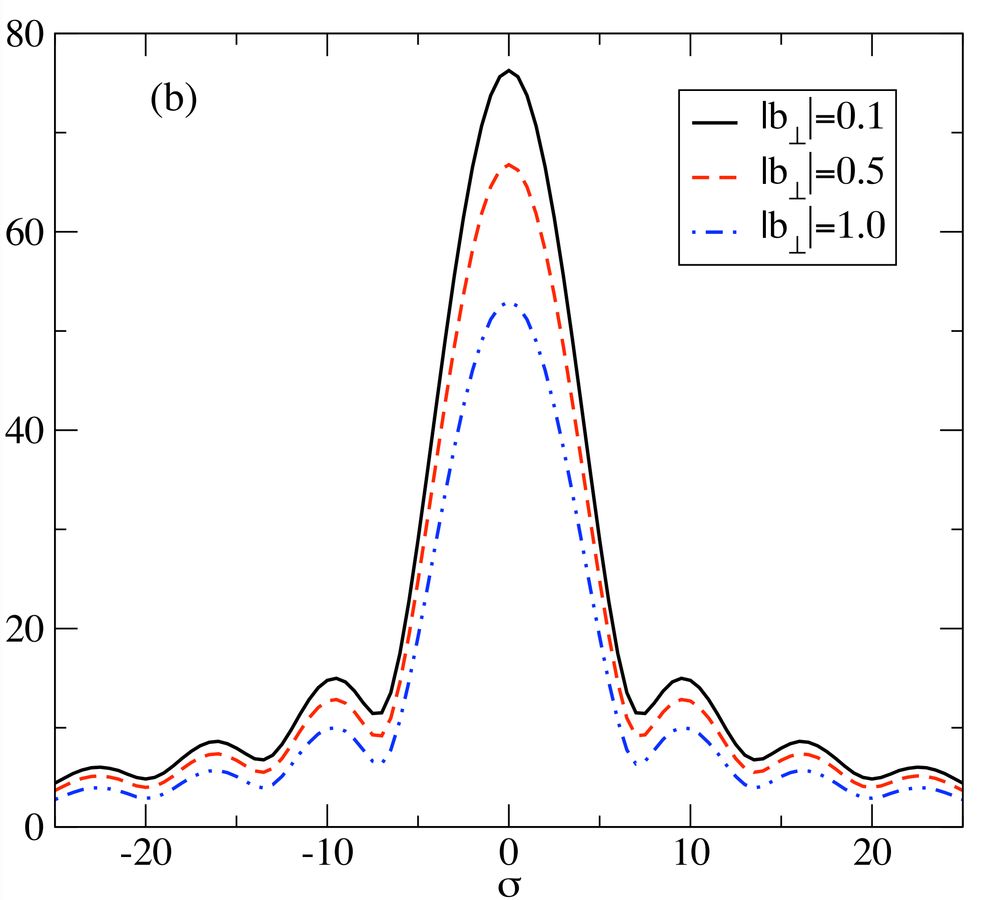
S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

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

Hadron Optics

$$A(\sigma, \vec{b}_\perp) = \frac{1}{2\pi} \int d\xi e^{i\frac{1}{2}\xi\sigma} \tilde{A}(\xi, \vec{b}_\perp)$$

$$\sigma = \frac{1}{2} x^- P^+ \quad \xi = \frac{Q^2}{2p.q}$$

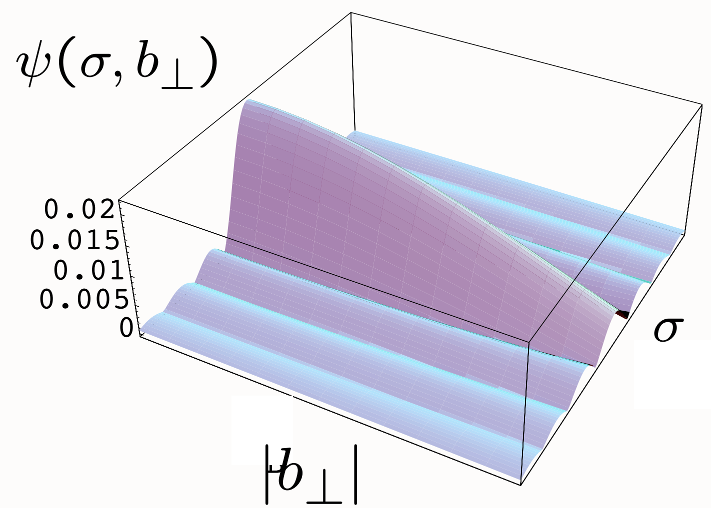


The Fourier Spectrum of the DVCS amplitude in σ space for different fixed values of $|b_\perp|$.

GeV units

DVCS Amplitude using holographic QCD meson LFWF

$$\Lambda_{QCD} = 0.32$$



GPDs & Deeply Virtual Exclusive Processes
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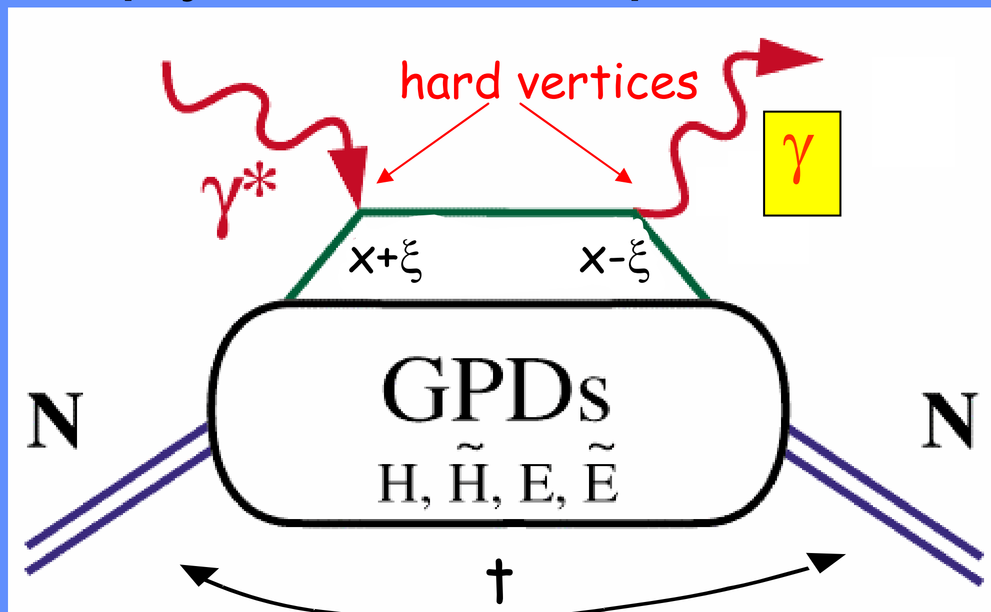
Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

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

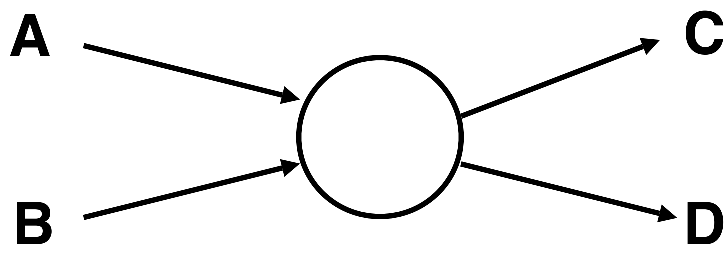
$H(x,\xi,t), E(x,\xi,t), \ldots$ “Generalized Parton Distributions”

Corrections to Handbag aproximation -- not gauge invariant!
Wilson line: SSA and Diffractive in DIS
Cat’s ears
Real Compton: PQCD not handbag

Unconventional Wisdom

- Significant corrections to handbag diagram for Compton scattering and DVCS
- J=0 Fixed Pole
- Regge constraint from DIS for DVCS
- Anti-shadowing is flavor dependent
- Hidden color
- Quenching of DGLAP at large x

Constituent Counting Rules



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

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

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

Fixed t/s or $\cos\theta_{cm}$

Farrar & sjb; Matveev, Muradyan, Tavkhelidze

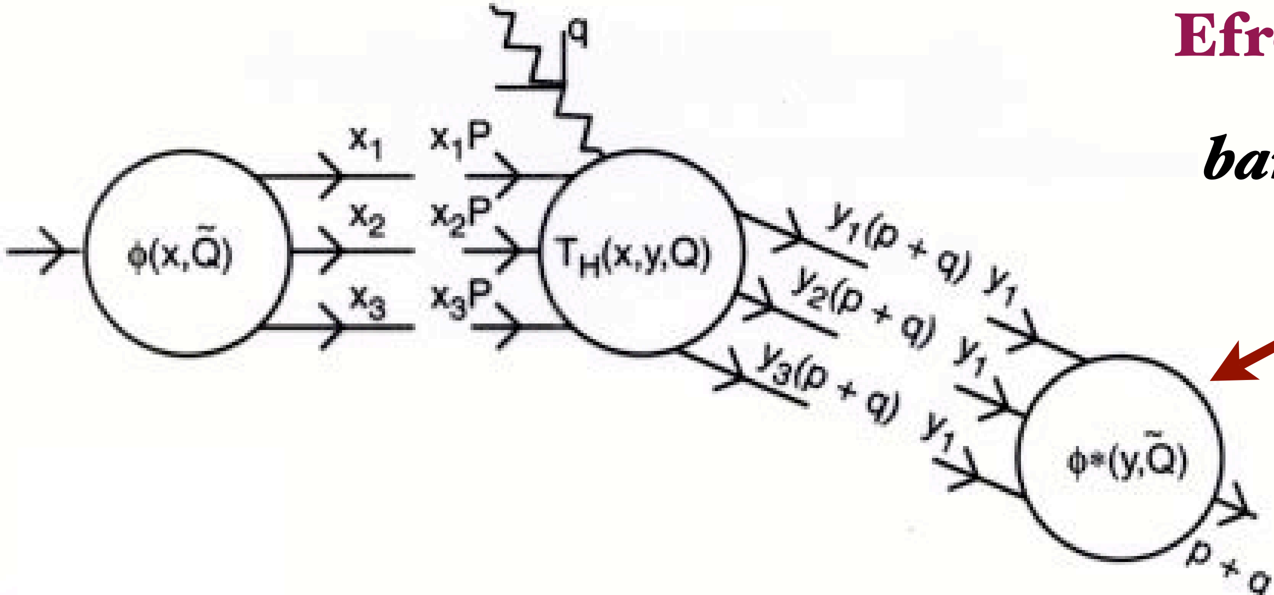
Conformal symmetry and PQCD predict leading-twist scaling behavior of fixed-CM angle exclusive amplitudes

Characteristic scale of QCD: 300 MeV

Many new J-PARC, GSI, J-Lab, Belle, Babar tests

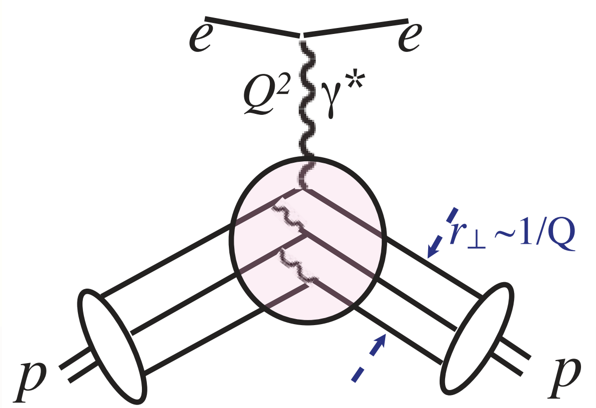
Leading-Twist PQCD Factorization for form factors, exclusive amplitudes

Lepage, sjb
Efremov, Radyushkin



baryon distribution amplitude

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



If $\alpha_s(\tilde{Q}^2) \simeq$ constant

$Q^4 F_1(Q^2) \simeq$ constant

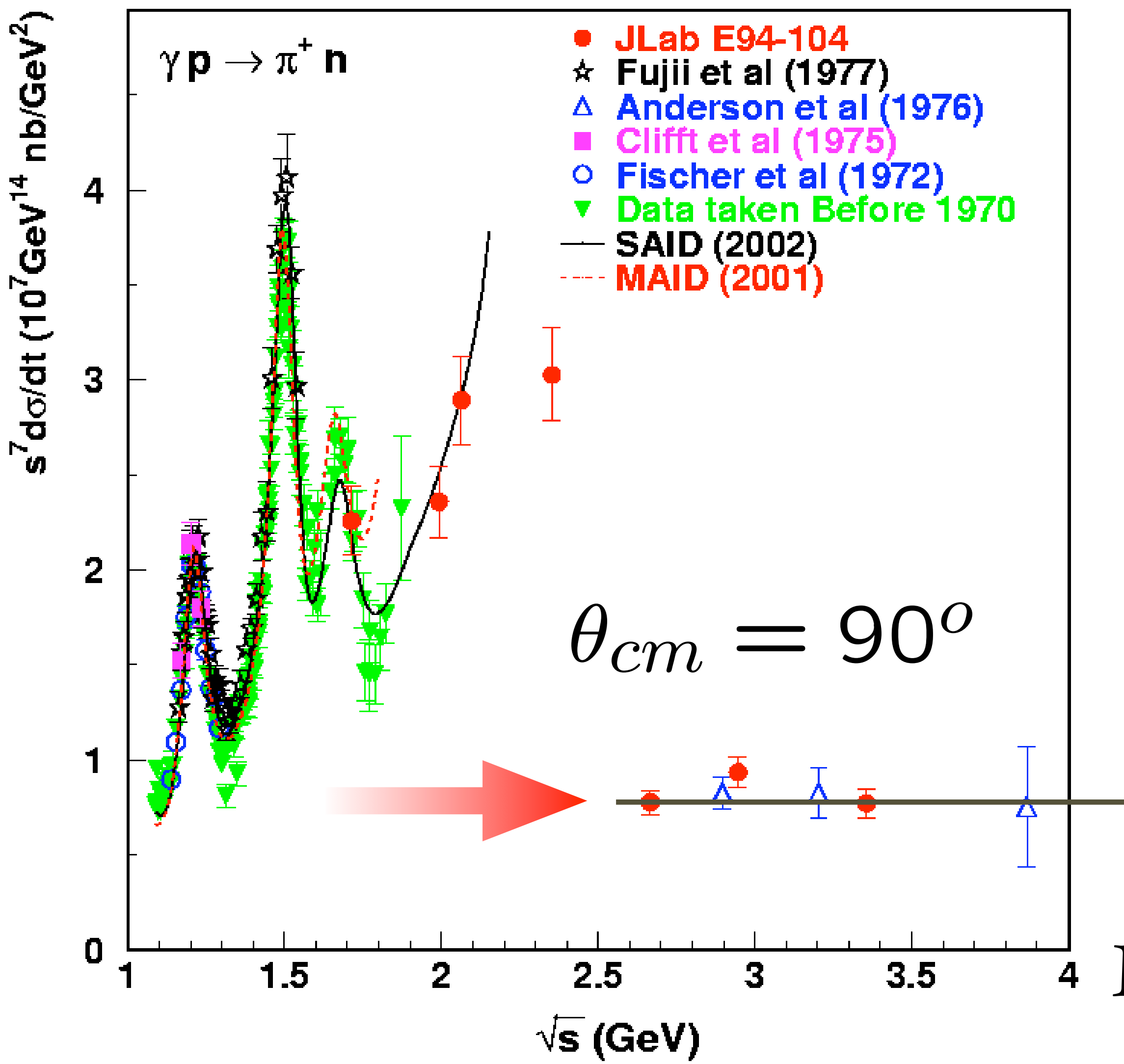
Features of Hard Exclusive Processes in PQCD

- Factorization of perturbative hard scattering subprocess amplitude and nonperturbative distribution amplitudes $M = \int T_H \times \Pi \phi_i$
- Dimensional counting rules reflect conformal invariance: $M \sim \frac{f(\theta_{CM})}{Q^{N_{tot}-4}}$
- Hadron helicity conservation: $\sum_{initial} \lambda_i^H = \sum_{final} \lambda_j^H$
- Color transparency Mueller, sjb;
- Hidden color Ji, Lepage, sjb;
- Evolution of Distribution Amplitudes Lepage, sjb; Efremov, Radyushkin

Test of PQCD Scaling

Constituent counting rules

Farrar, sjb; Muradyan, Matveev, Tavkelidze



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

fixed θ_{CM} scaling

PQCD and AdS/CFT:

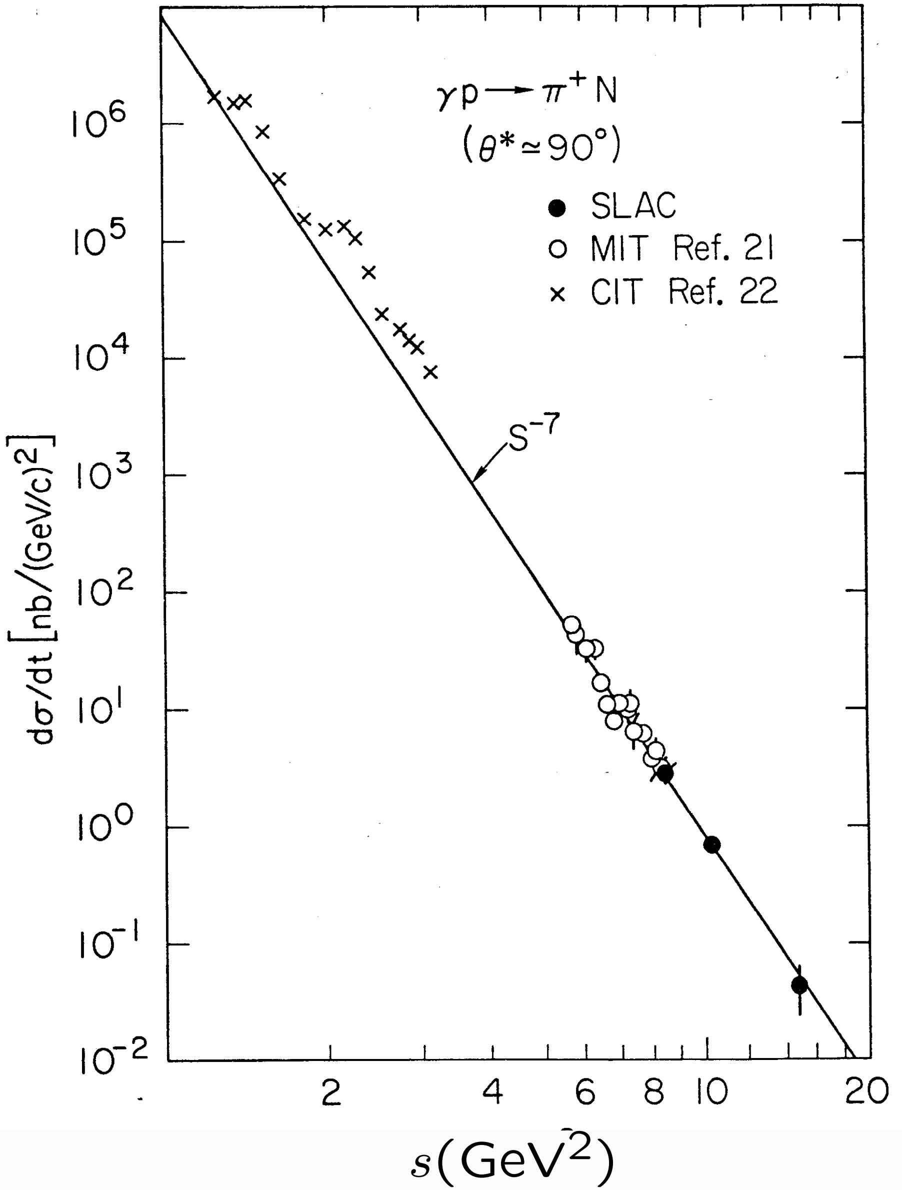
$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B \to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

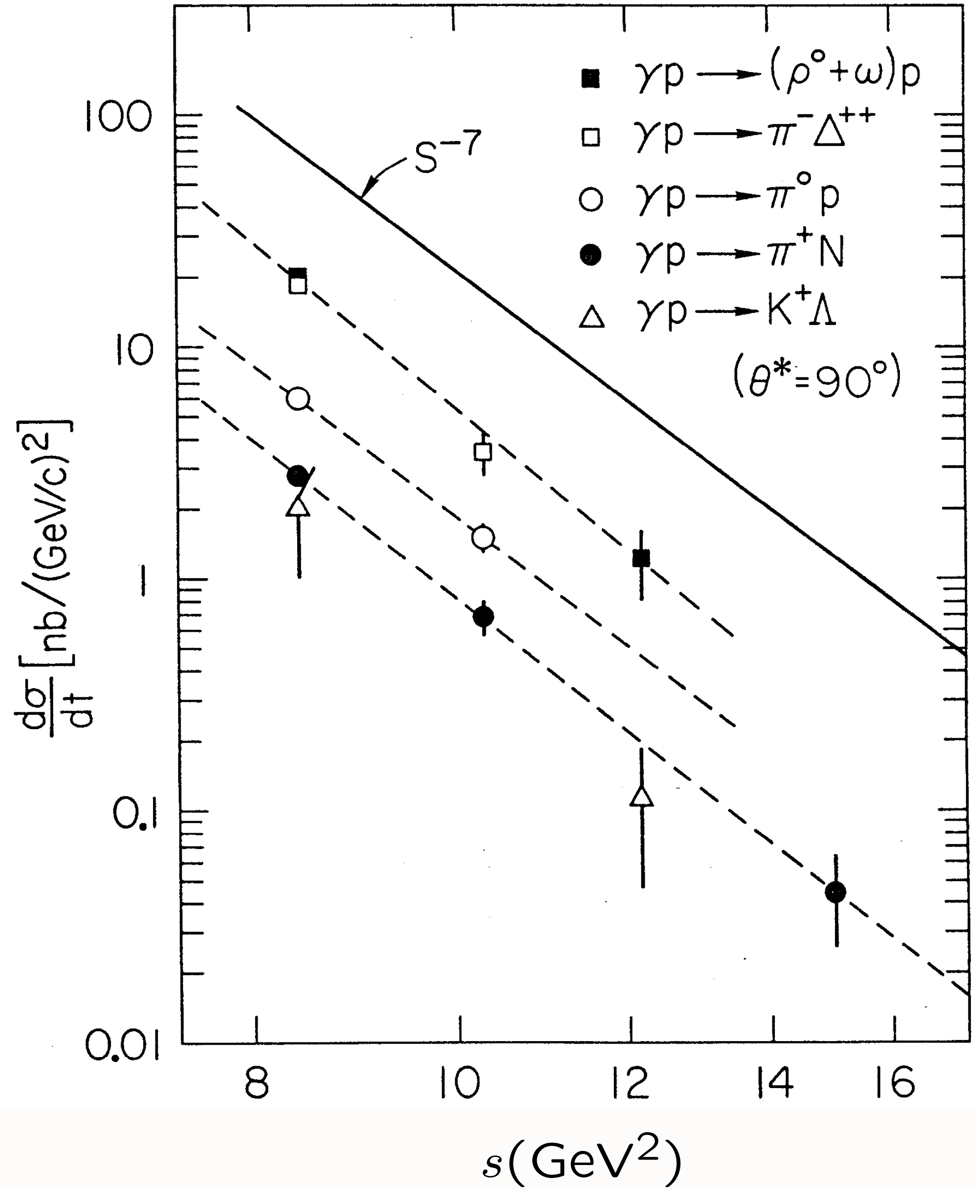
$$s^7\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = F(\theta_{CM})$$

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

No sign of running coupling

Conformal invariance

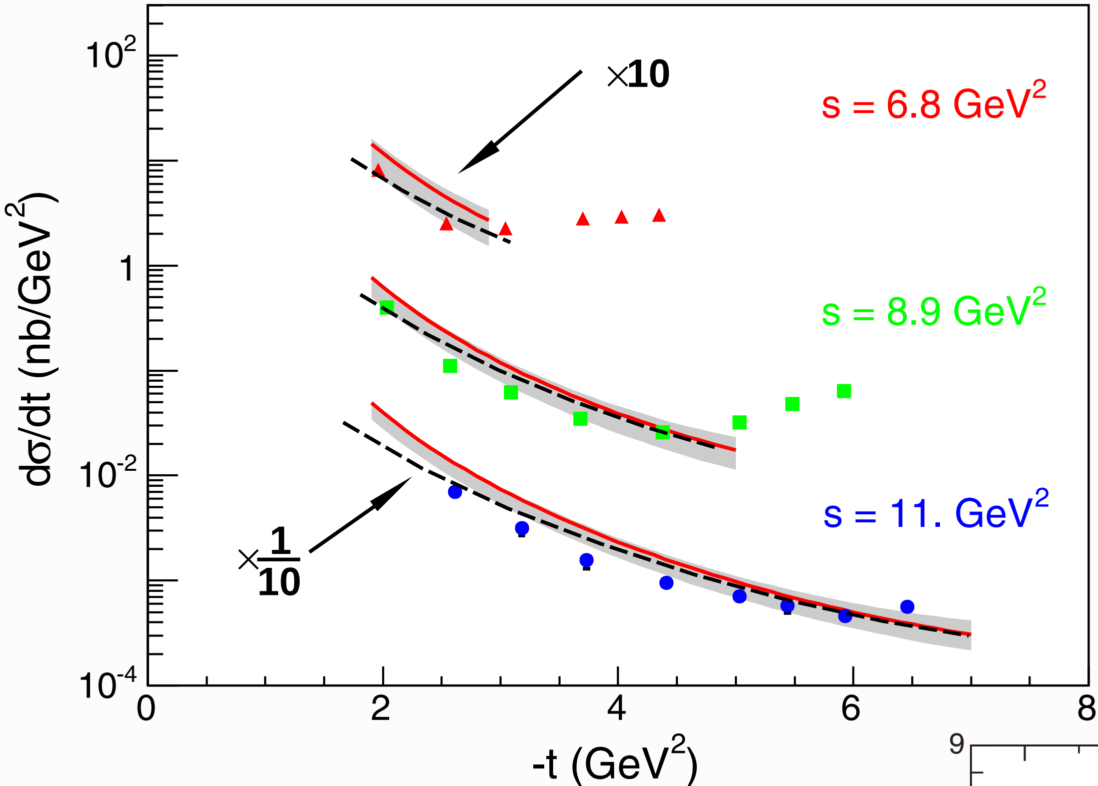




Conformal Invariance:

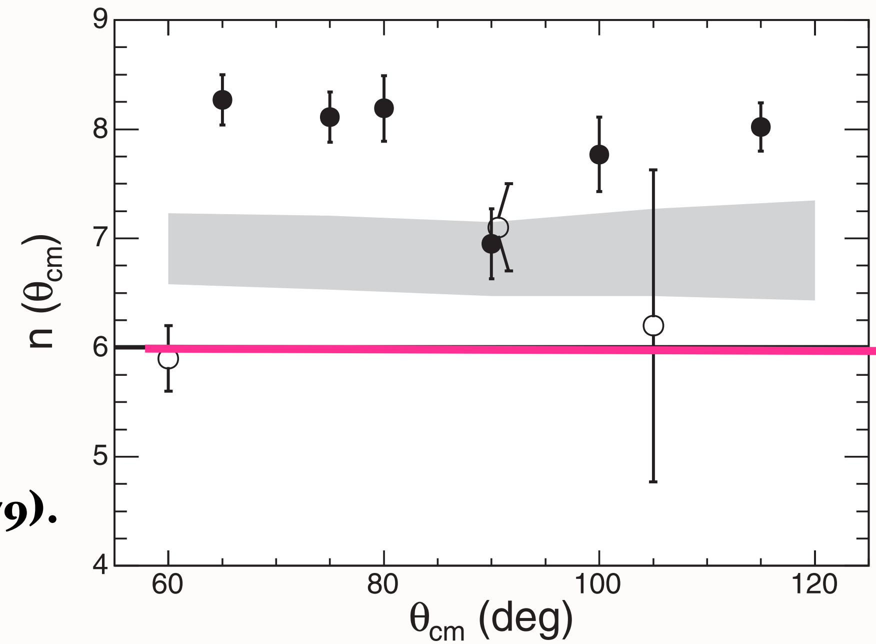
$$\frac{d\sigma}{dt}(\gamma p \to MB) = \frac{F(\theta_{cm})}{s^7}$$

Compton-Scattering Cross Section on the Proton at High Momentum Transfer



Jefferson Lab
Hall A
Collaboration

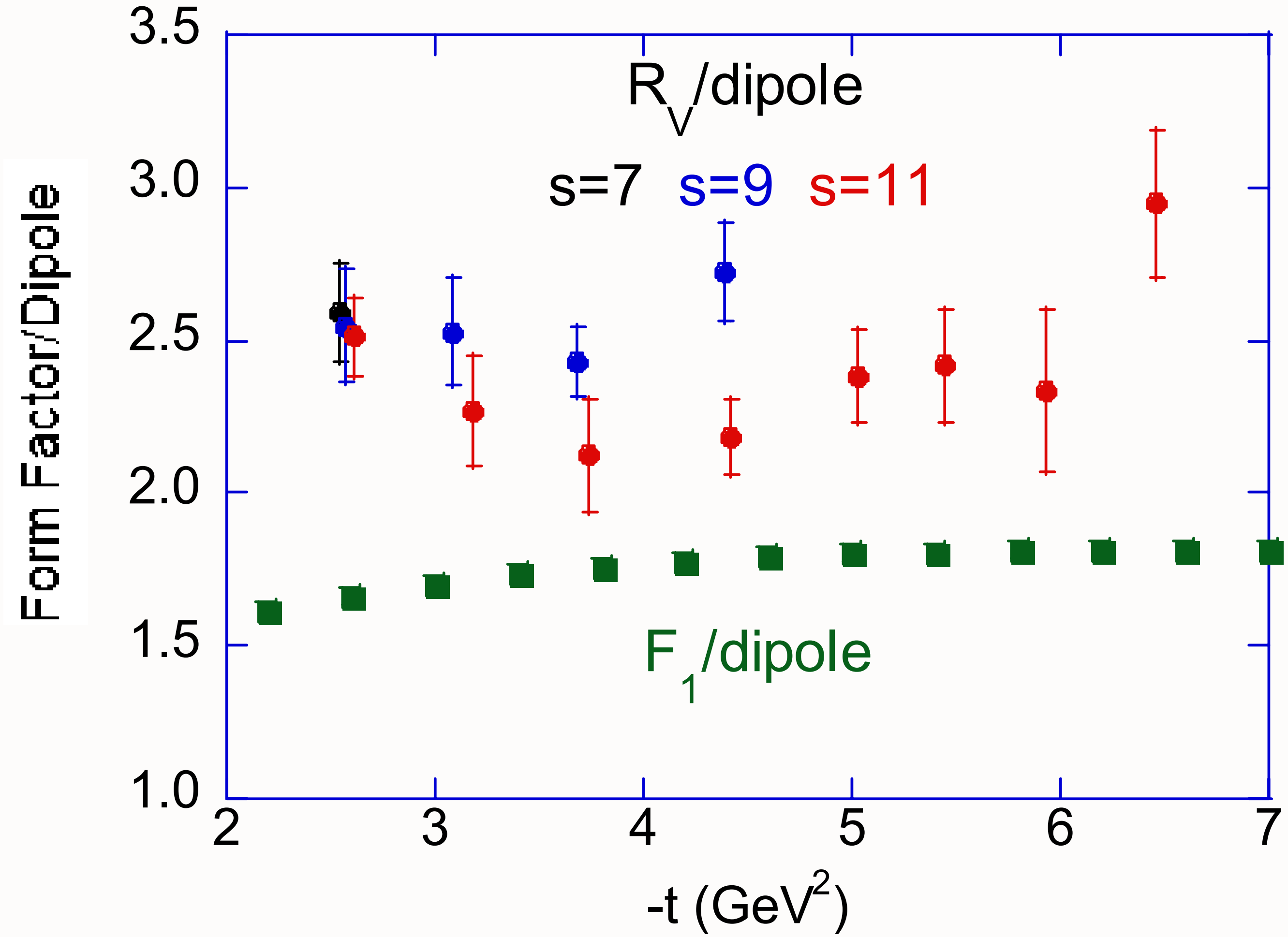
Compton at fixed angles falls faster than photoproduction!



pQCD
n=6

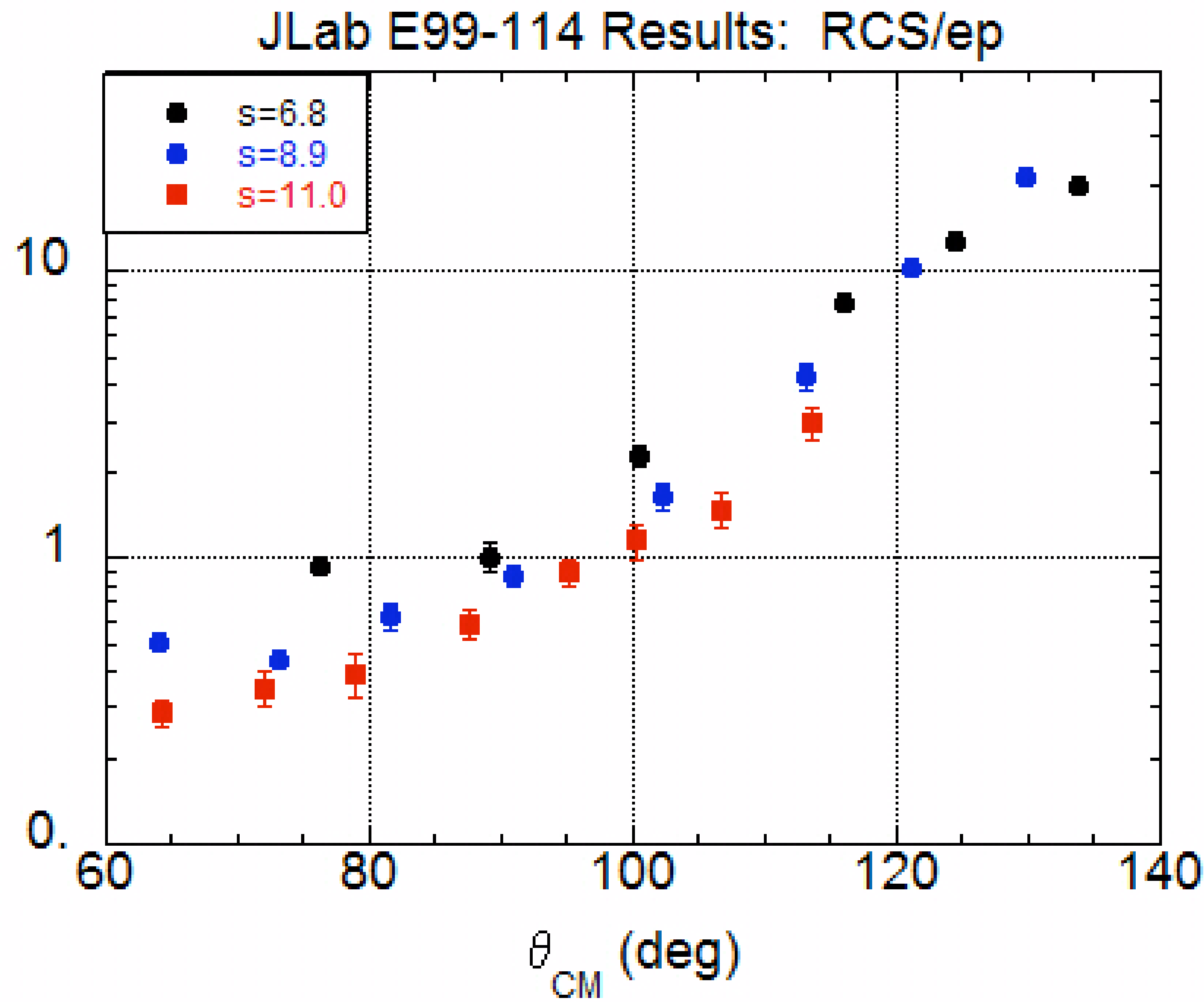
Open points: Cornell measurement
M. A. Shupe et al., Phys. Rev. D 19, 1921 (1979).

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{KN} \left[f_V R_V^2(t) + f_A R_A^2(t) \right]$$



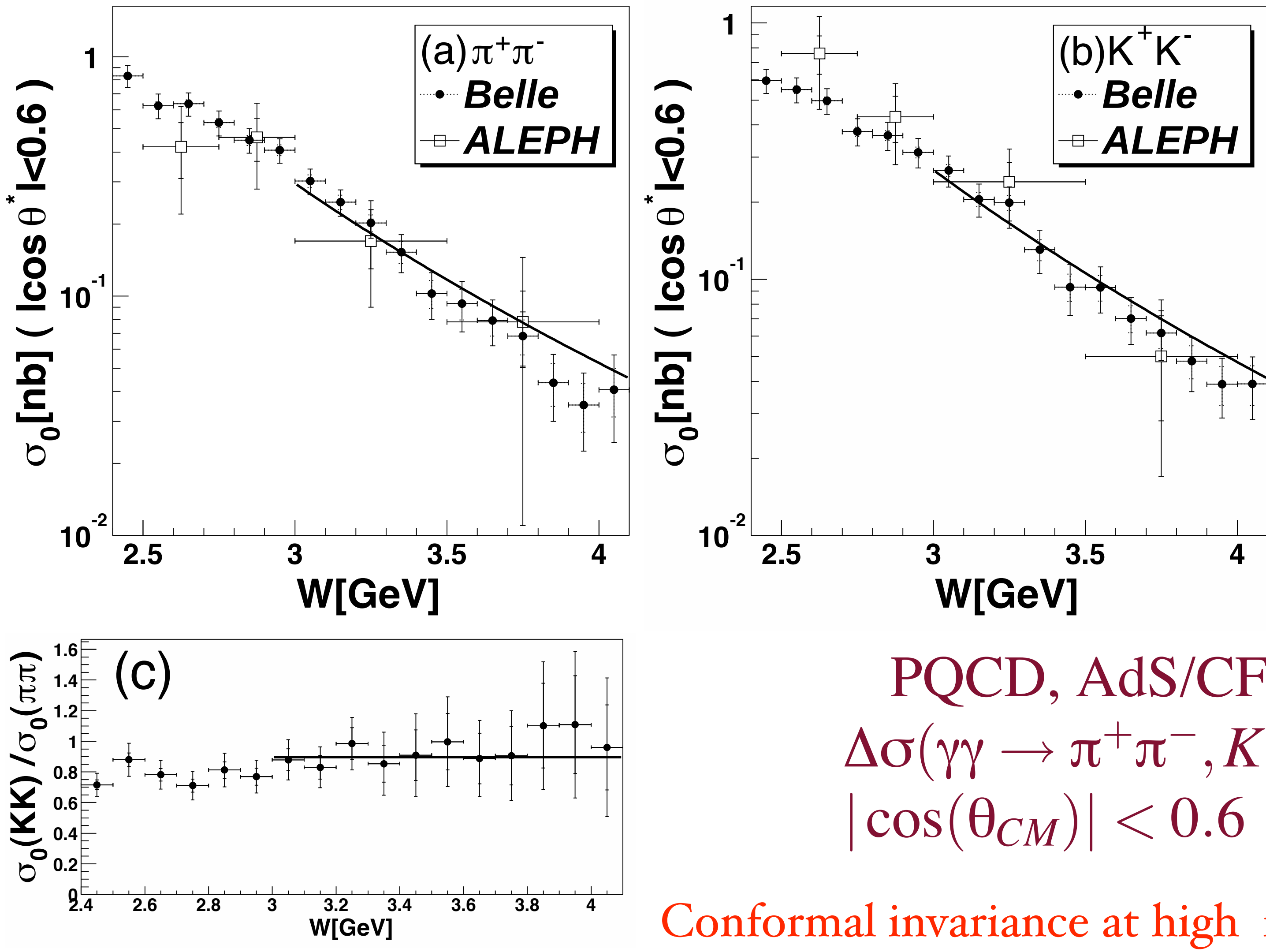
Agrees with PQCD

Ratio of Real Compton-Scattering Cross Section to Electron-Proton Scattering at Fixed CM Angle



Ratio becomes energy-independent at large s

A. Nathan



Two-Photon Reactions

Hard Exclusive Processes: Fixed angle

PQCD, AdS/CFT:

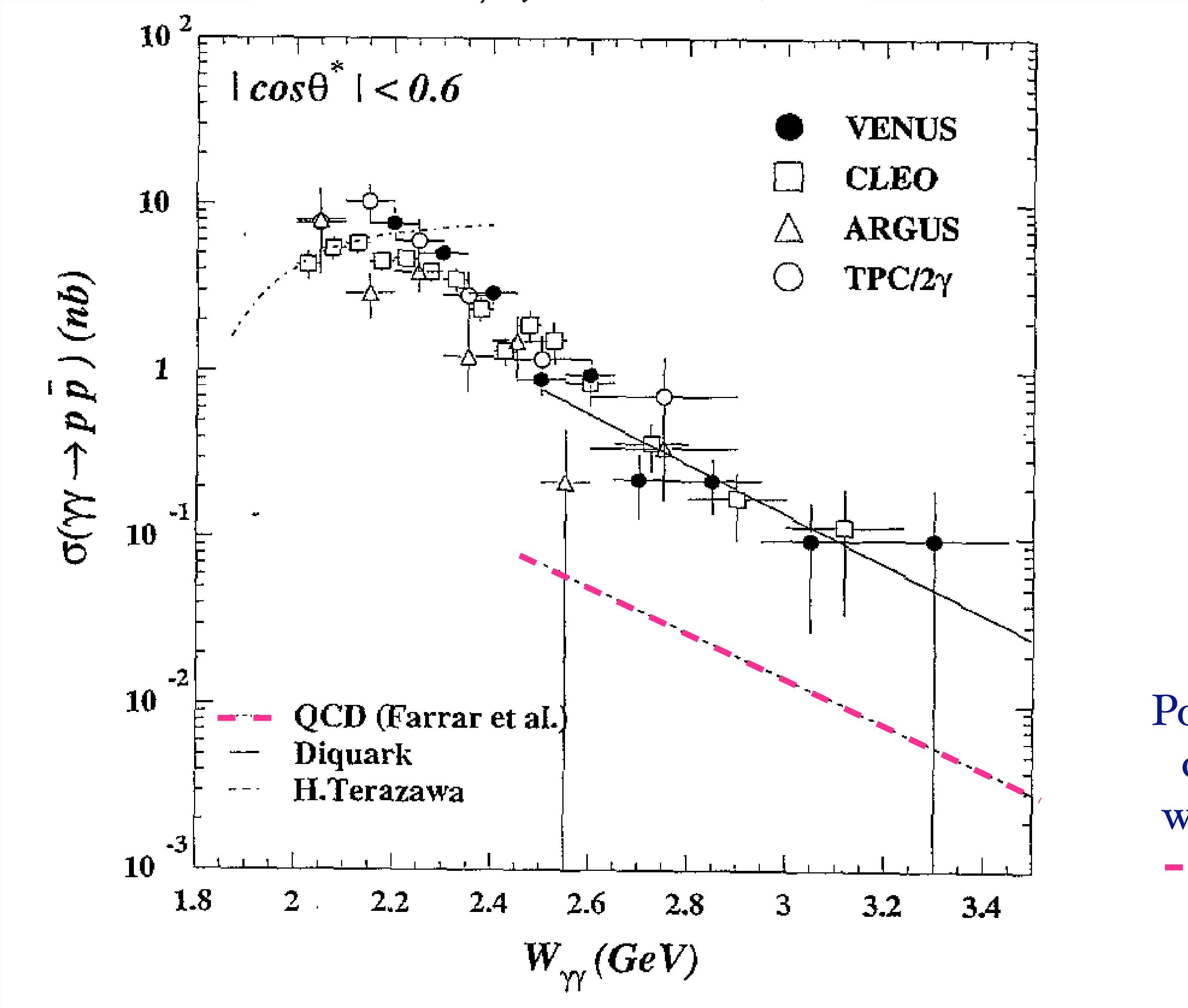
$$\Delta\sigma(\gamma\gamma \to \pi^+\pi^-, K^+, K^-) \sim 1/W^6$$

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

Conformal invariance at high momentum transfers!

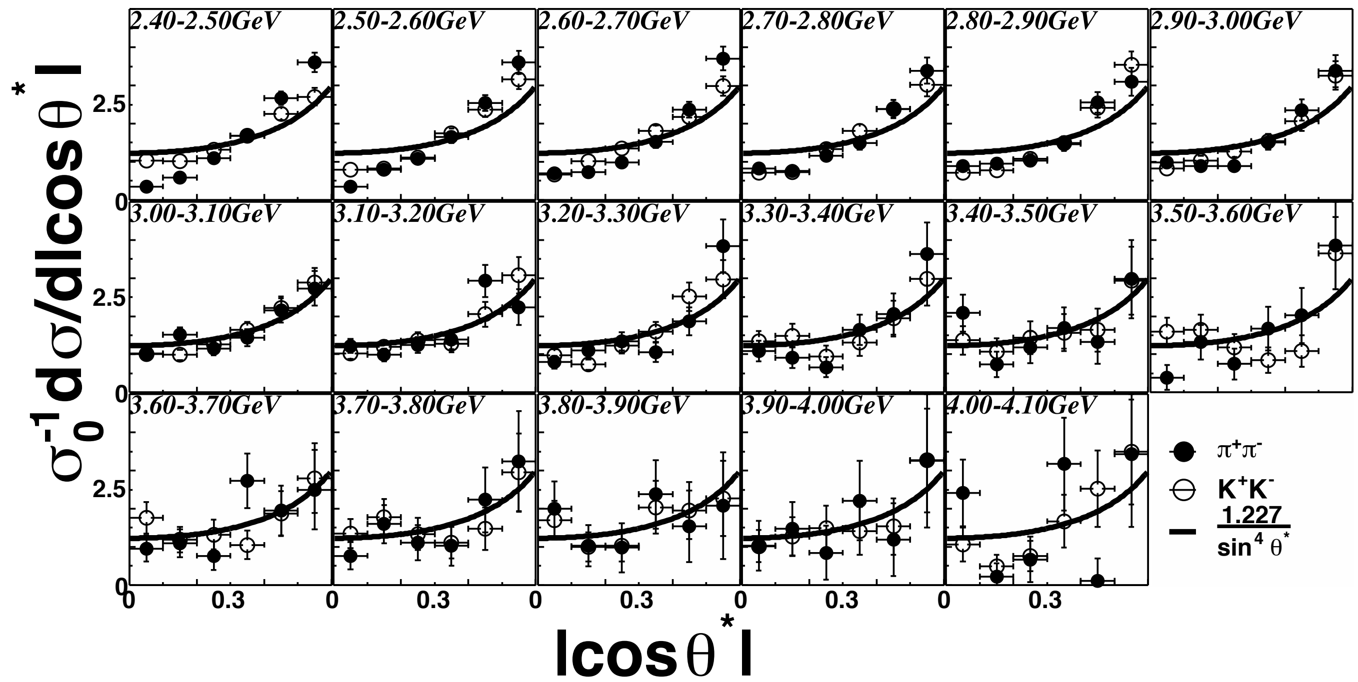
Fig. 5. Cross section for (a) $\gamma\gamma \to \pi^+\pi^-$, (b) $\gamma\gamma \to K^+K^-$ in the c.m. angular region $|\cos\theta^*| < 0.6$ together with a W^{-6} dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data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

VENUS Collaboration / Physics Letters B 407 (1997) 185–192



Power fall-off consistent with PQCD

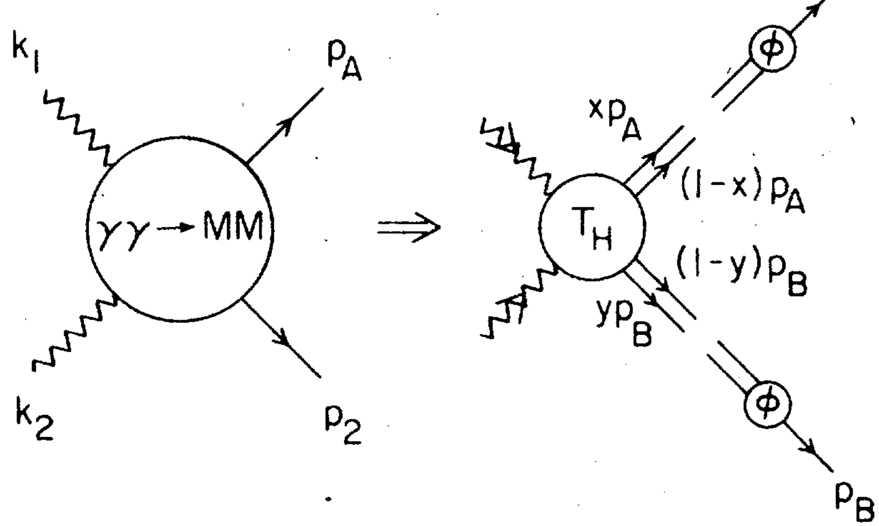
PQCD: $$\frac{d\sigma}{d|\cos\theta^*|}(\gamma\gamma \to M^+M^-) \approx \frac{16\pi\alpha^2}{s}\frac{|F_M(s)|^2}{\sin^4\theta^*},$$

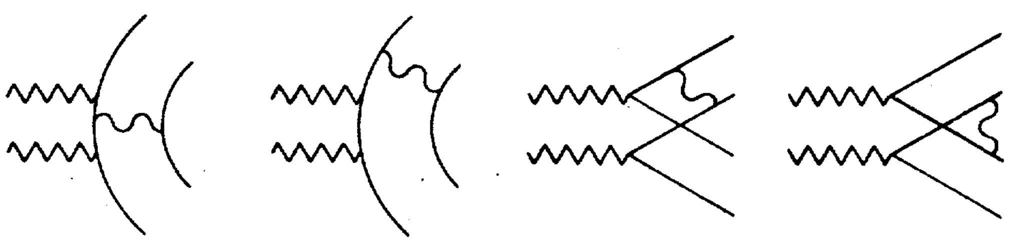


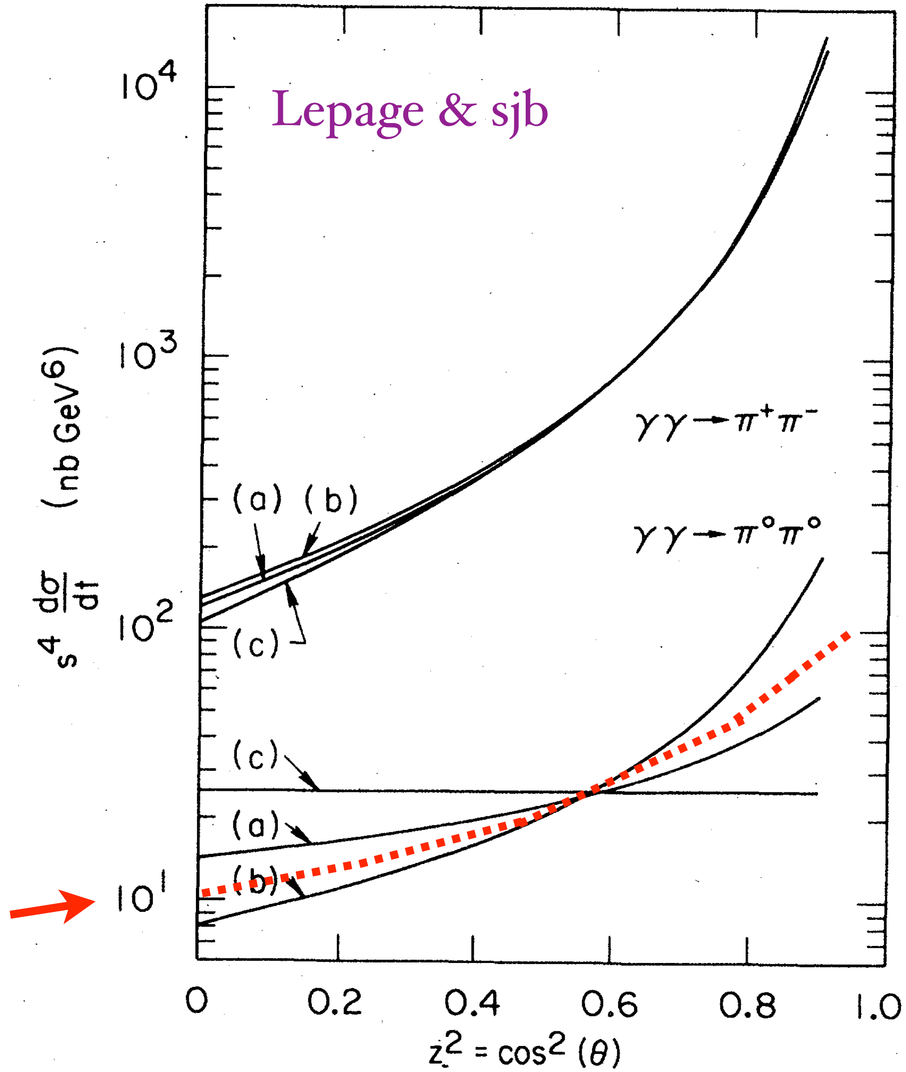
4. Angular dependence of the cross section, $\sigma_0^{-1}d\sigma/d|\cos\theta^*|$, for the $\pi^+\pi^-$(closed circles) and K^+K^-(open circles) processes. The curves are $1.227 \times \sin^{-4}\theta^*$. The errors are statistical only.

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







Neutral pair angular distribution sensitive to AdS/CFT distribution!

$$\phi_\pi^{AdS/QCD}(x) \propto [x(1-x)]^{1/2}$$

(a): $\phi_\pi(x) \propto x(1-x)$

(b): $\phi_\pi(x) \propto [x(1-x)]^{1/4}$

(c): $\phi_\pi(x) \propto \delta(x - 1/2)$

Equal rates for neutral and charged rates in handbag model

Key Experiment at JLab

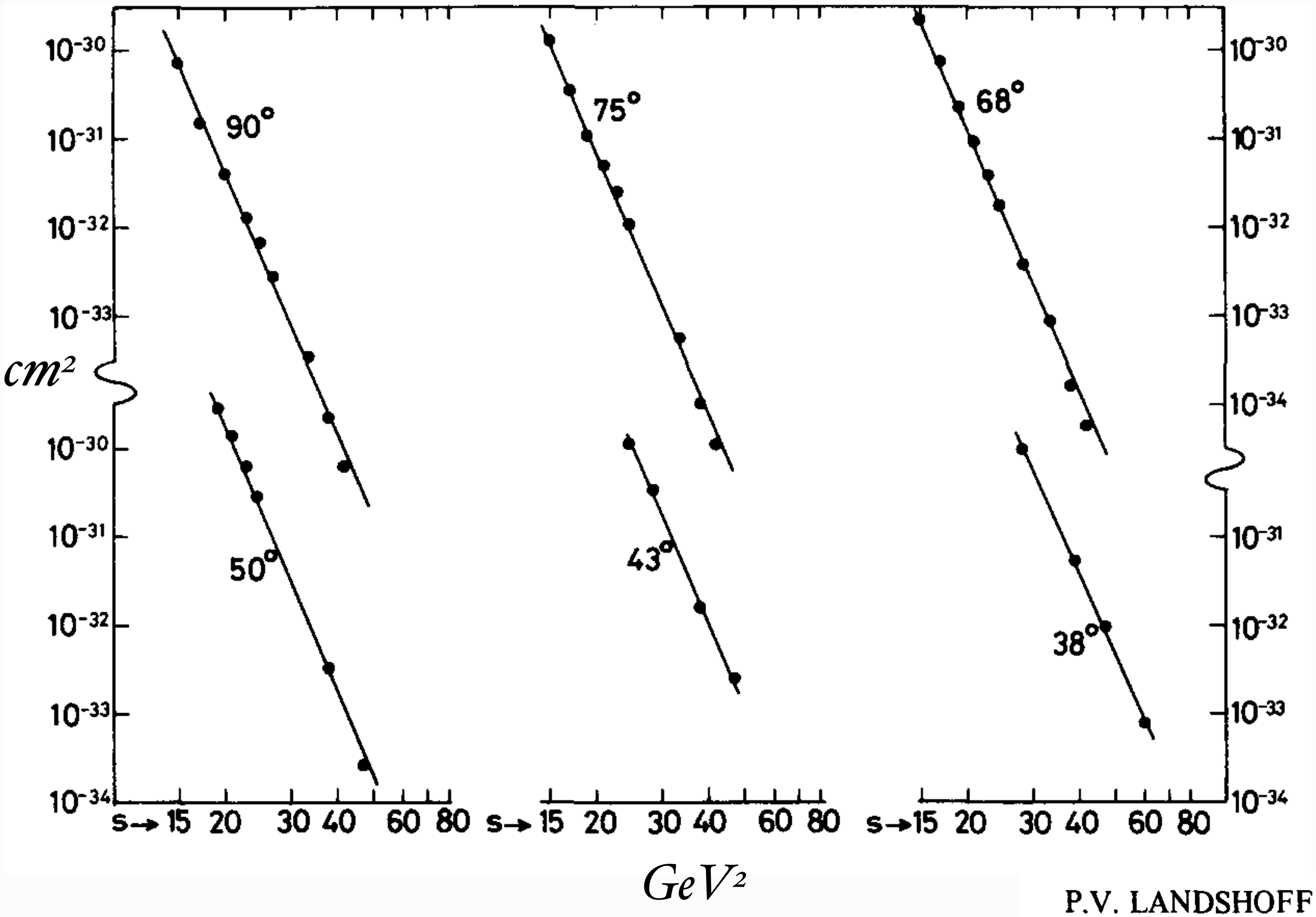
$$R^{Compton}_{n/p} = \frac{\frac{d\sigma}{dt}(\gamma n \to \gamma n)}{\frac{d\sigma}{dt}(\gamma p \to \gamma p)}$$

Measure Compton scattering on neutron

$$R^{Compton}_{n/p} = 2/3$$

Handbag Approximation (not gauge invariant)

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



P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

String Theory

AdS/CFT

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

Goal: First Approximant to QCD

Counting rules for Hard
Exclusive Scattering
Regge Trajectories
QCD at the Amplitude Level

AdS/QCD

Conformal behavior at short
distances
+ Confinement at large
distance

Semi-Classical QCD / Wave Equations

Holography

Boost Invariant 3+1 Light-Front Wave Equations

J =0,1,1/2,3/2 plus L

Integrable!

Hadron Spectra, Wavefunctions, Dynamics

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

New Perspectives for QCD from AdS/CFT

- LFWFs: Fundamental frame-independent description of hadrons at amplitude level
- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra: many applications!
- New basis for diagonalizing Light-Front Hamiltonian
- Physics similar to MIT bag model, but covariant. No problem with support $0 < x < 1$.
- Quark Interchange dominant force at short distances

Features of Light-Front Formalism

- *Hidden Color* Nuclear Wavefunction
- *Color Transparency, Opaqueness*
- *Intrinsic glue, sea quarks, intrinsic charm*
- Simple proof of Factorization theorems for hard processes (Lepage, sjb)
- *Direct mapping to AdS/CFT* (de Teramond, sjb)
- New Effective LF Equations (de Teramond, sjb)
- Light-Front Amplitude Generator