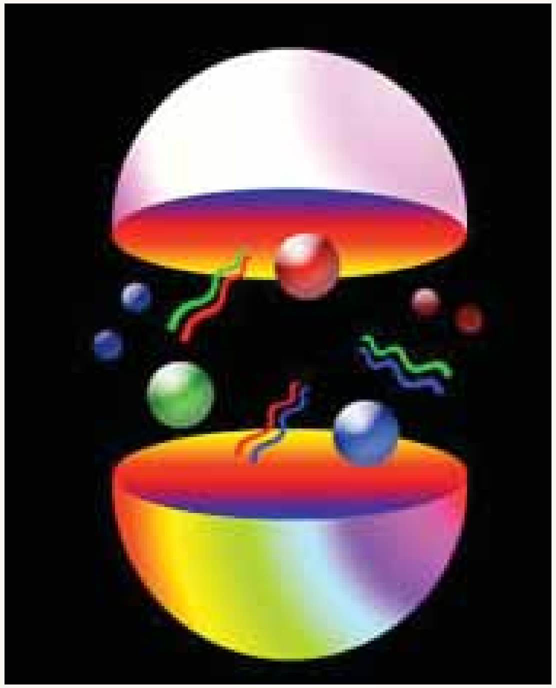
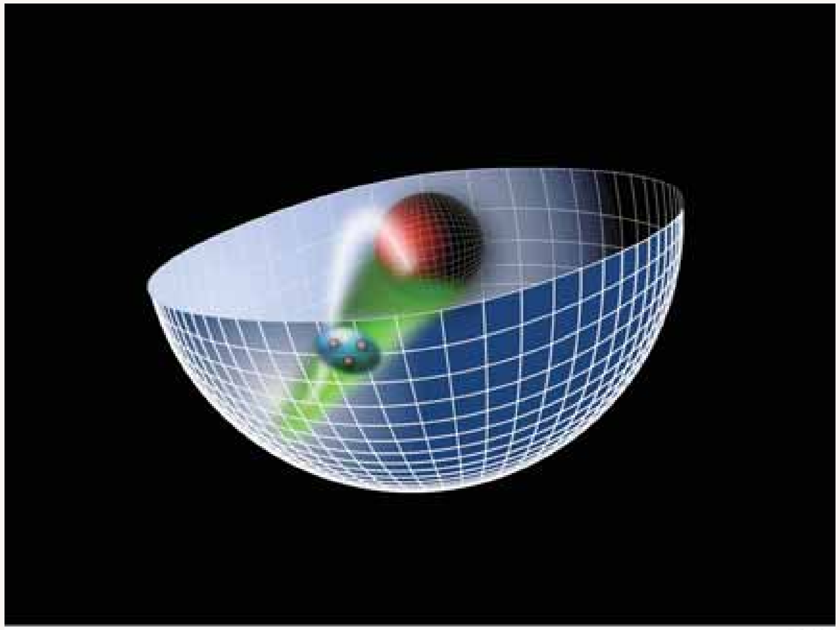
AdS/CFT and QCD



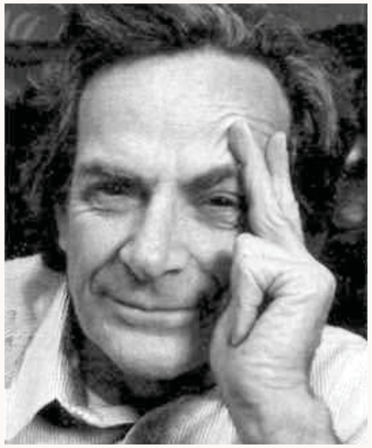


Stan Brodsky SLAC/IPPP

Fritzsch Symposium LMU June 6, 2008

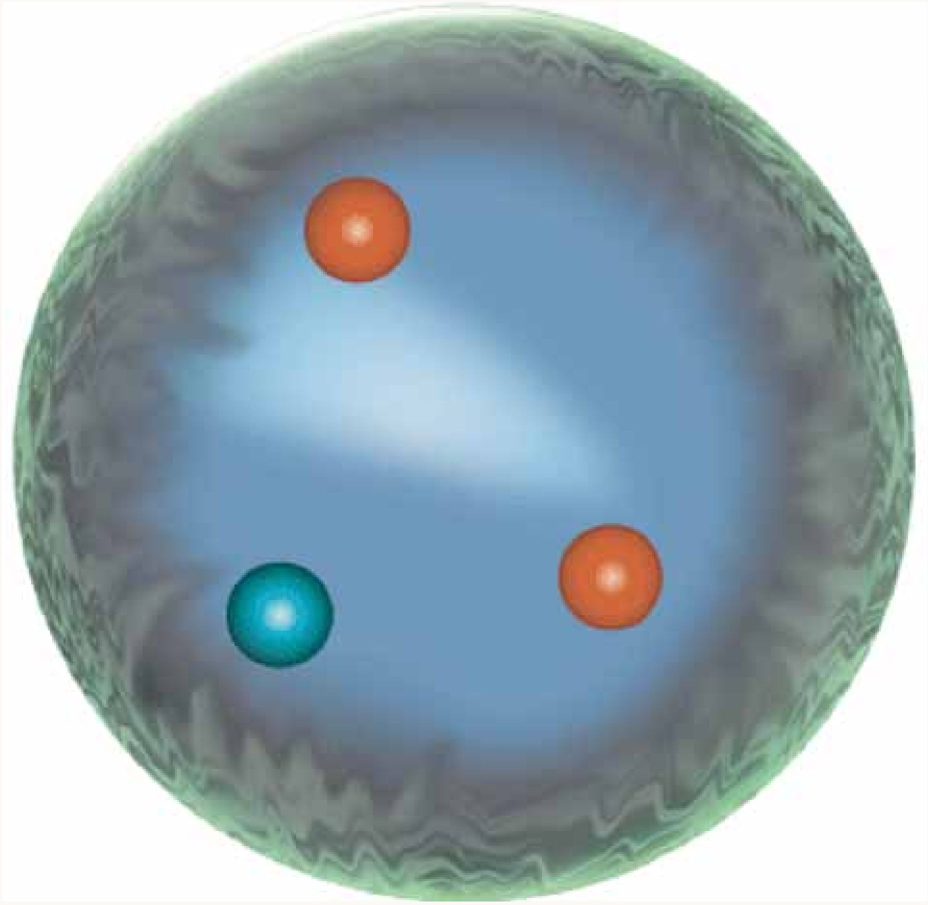
Quarks in the Proton

Bjorken: Scaling



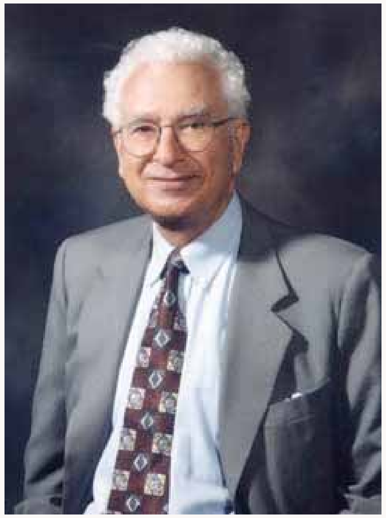
Feynman: Parton model

$p = (u\,u\,d)$



$1\,fm$

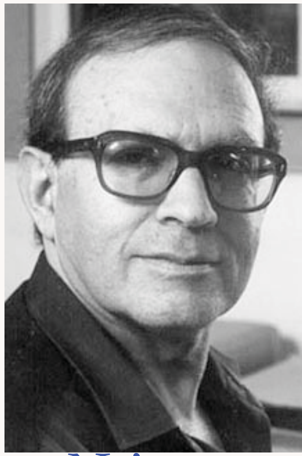
$10^{-15}m = 10^{-13}cm$



Gell Mann: **Eightfold Way**

"Three quarks for Muster Mark!"

Zweig: "Aces, Deuces, Treys"

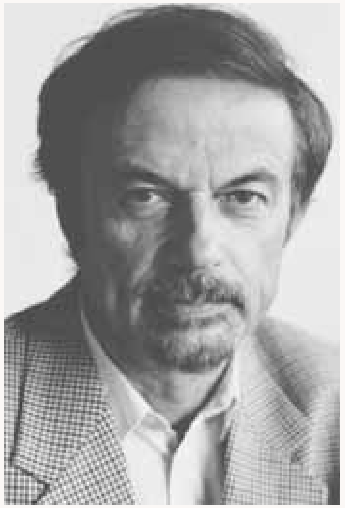


Ne'eman

Fritzsch Symposium
June 6, 2008

AdS/QCD

Stan Brodsky
SLAC & IPPP



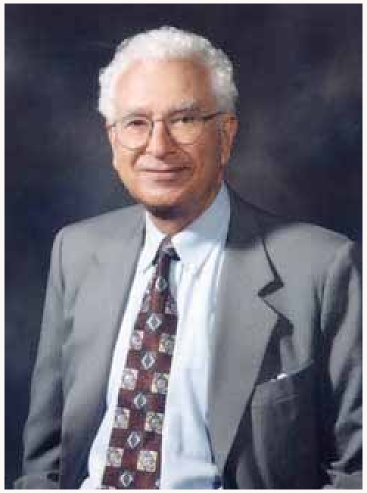
Current Algebra: Quarks and What Else?

Harald Fritzsch*†

and

Murray Gell–Mann**†

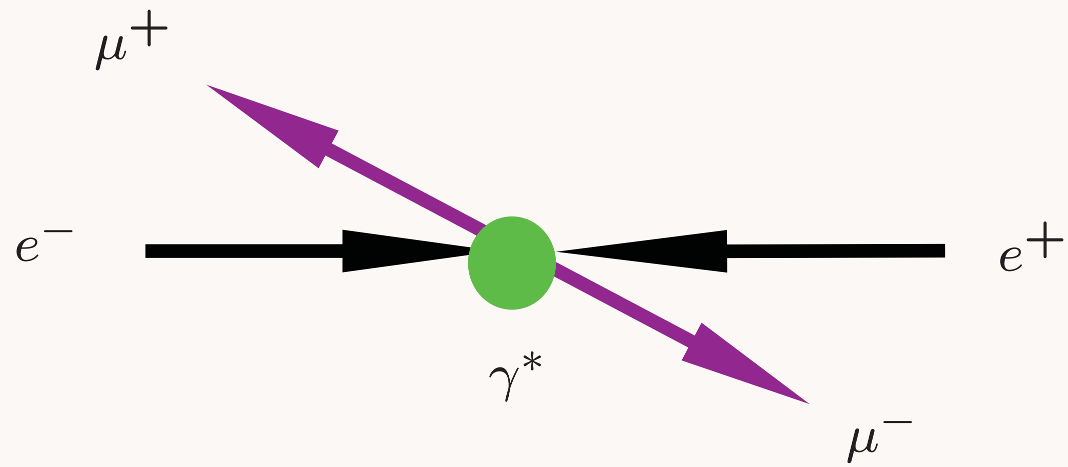
CERN, Geneva, Switzerland



Proceedings of the XVI International Conference on High Energy Physics, Chicago, 1972. Volume 2, p. 135 (J. D. Jackson, A. Roberts, eds.)

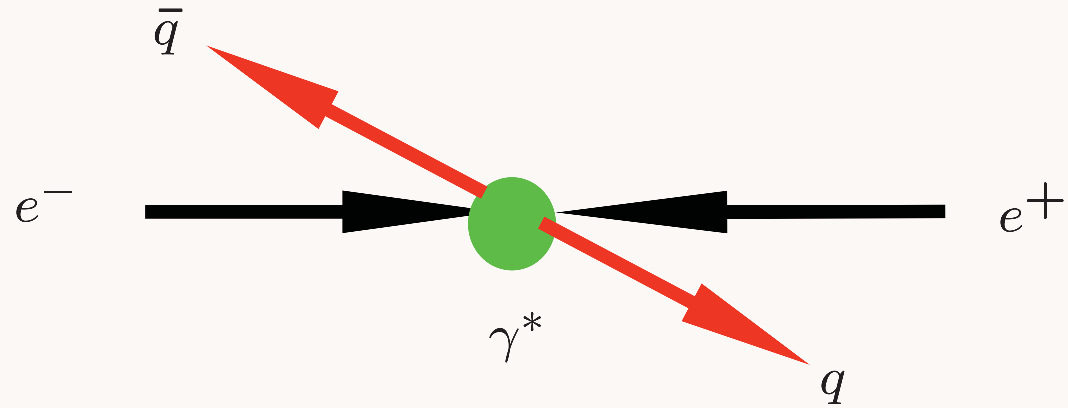
Fritzsch and Gell-Mann introduce 'Color'

Electron-Positron Annihilation



$$e^+e^- \to \gamma^* \to \mu^+\mu^-$$

Electron-Positron Annihilation

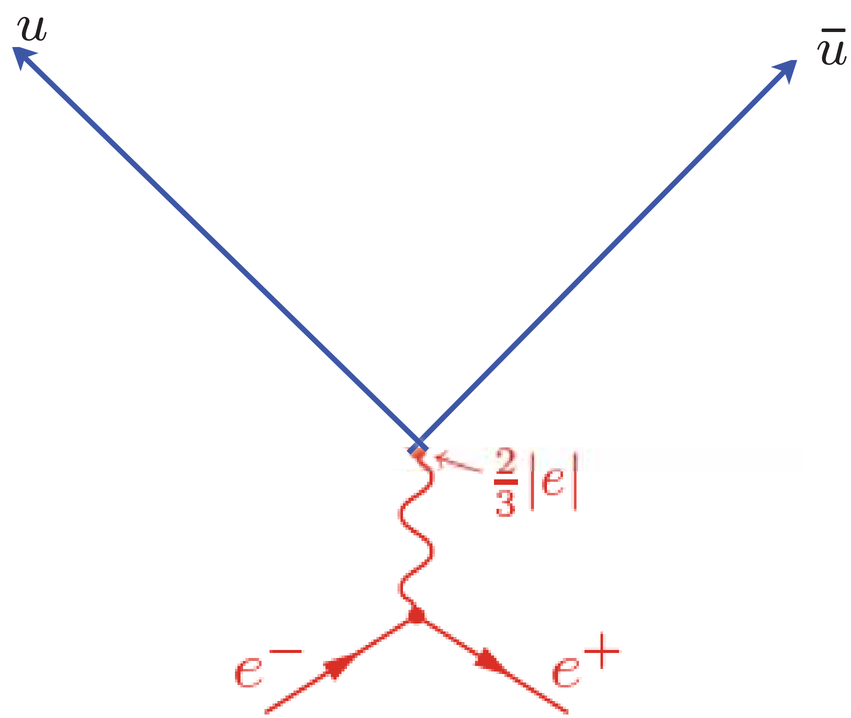


$$e^+e^- \to \gamma^* \to q\bar{q}$$

Rate proportional to quark charge squared and number of colors

$$R_{e^+e^-}(E_{cm}) = N_{colors} \times \sum_q e_q^2$$

How to Count Quarks



For $10\ \text{GeV} < E_{\text{cm}} < 40\ \text{GeV}$,

$$\frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-} = \underset{\text{colors}}{\underset{\uparrow}{3}} \times \left[\underset{d}{\underset{\uparrow}{\left(\frac{1}{3}\right)^2}} + \underset{u}{\underset{\uparrow}{\left(\frac{2}{3}\right)^2}} + \underset{s}{\underset{\uparrow}{\left(\frac{1}{3}\right)^2}} + \underset{c}{\underset{\uparrow}{\left(\frac{2}{3}\right)^2}} + \underset{b}{\underset{\uparrow}{\left(\frac{1}{3}\right)^2}} \right]$$

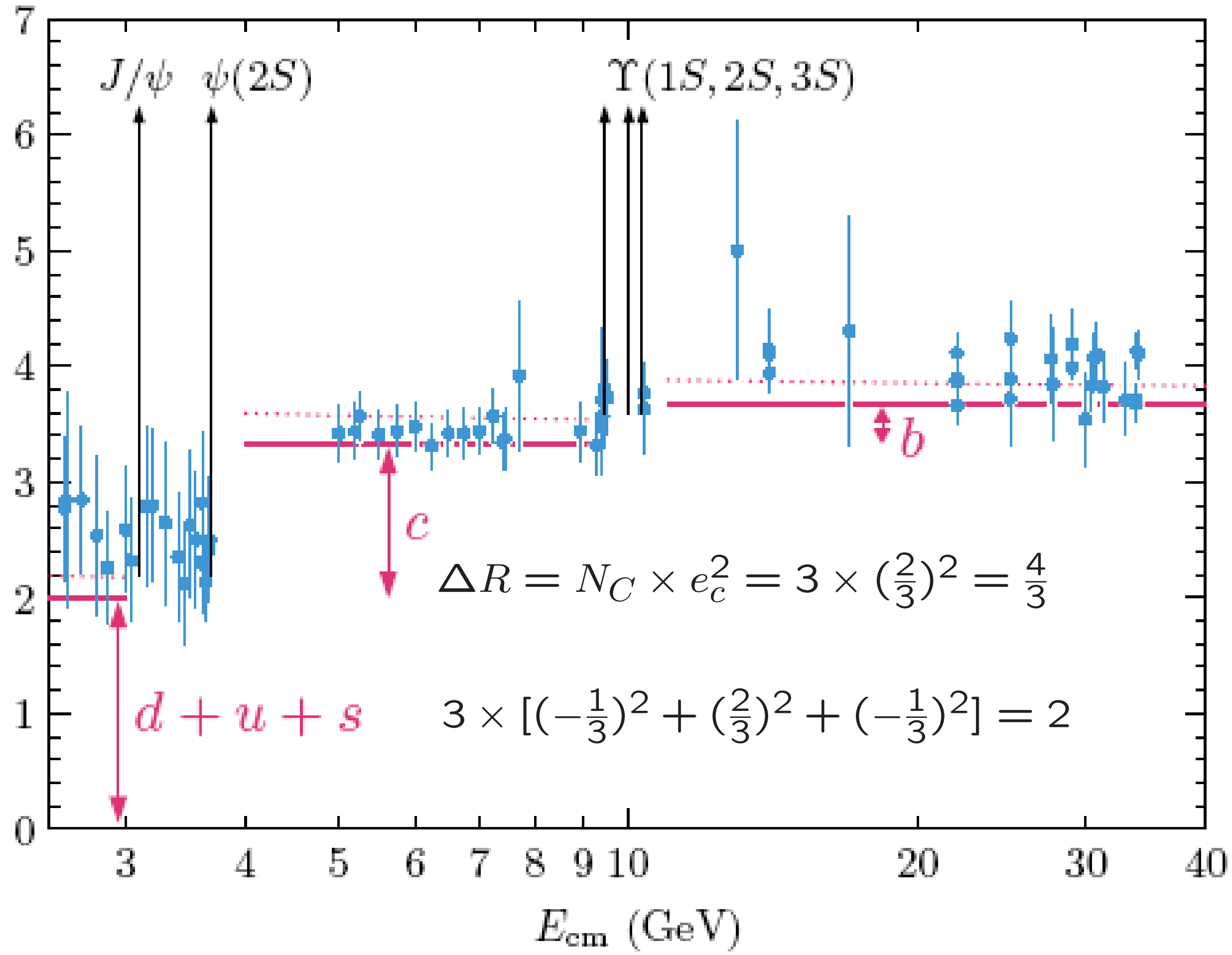
SPEAR Electron-Positron Collider

$J/\psi = (c\bar{c})_{1S}$

How to Count Quarks

$\Upsilon = (b\bar{b})_{1S}$

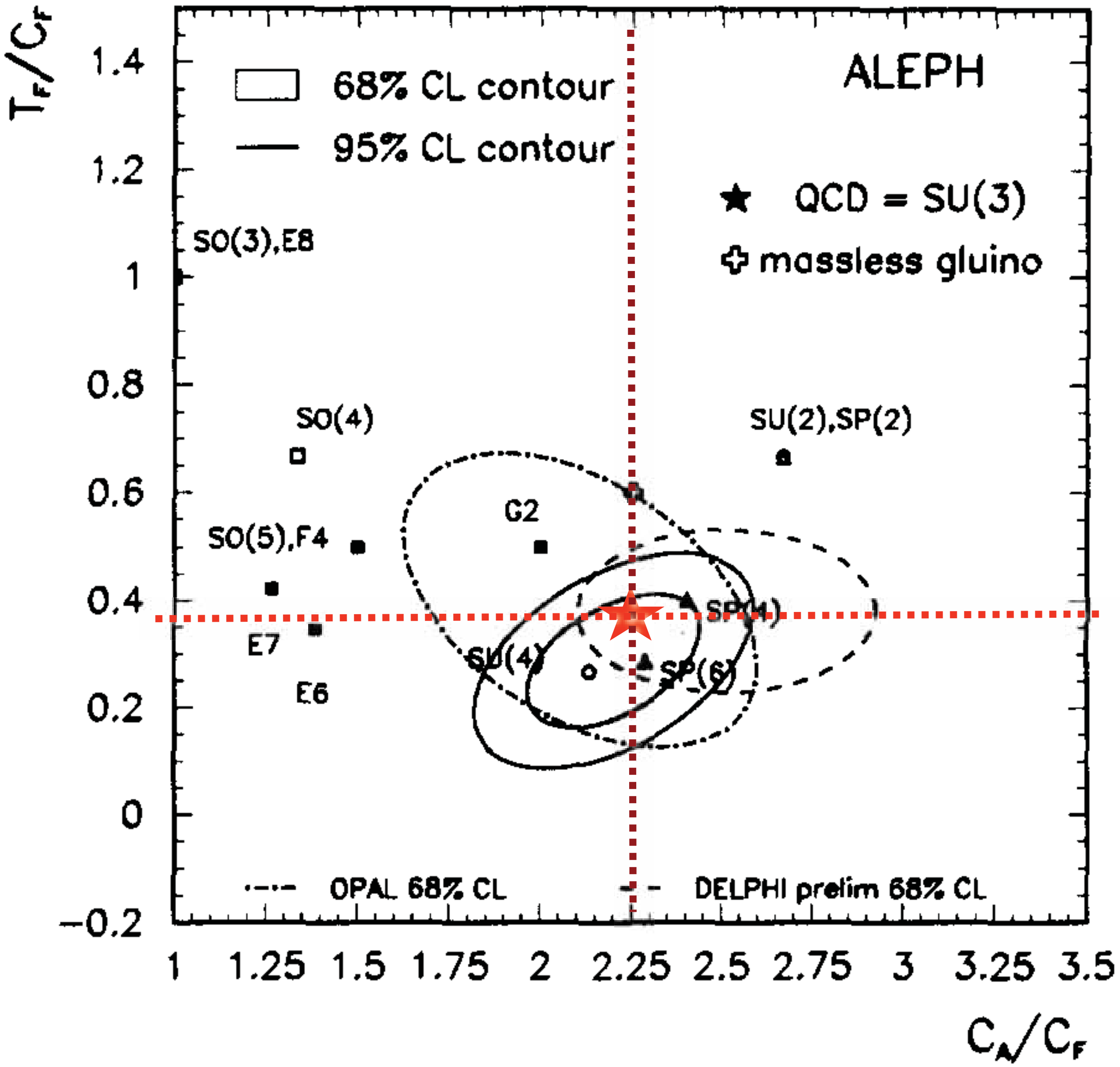
$R = \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$



$3 \times (-\frac{1}{3})^2 = \frac{1}{3}$

$N_C = 3$

$$R_{e^+e^-}(E_{cm}) = N_{colors} \times \sum_q e_q^2$$



Ratio of Hadron Multiplicities from Quark and Gluon Jets determine color group!

$$\frac{n_g^H}{n_q^H} = \frac{C_A}{C_F} = \frac{N_C}{(N_C^2-1)/2N_C} = \frac{9}{4}$$

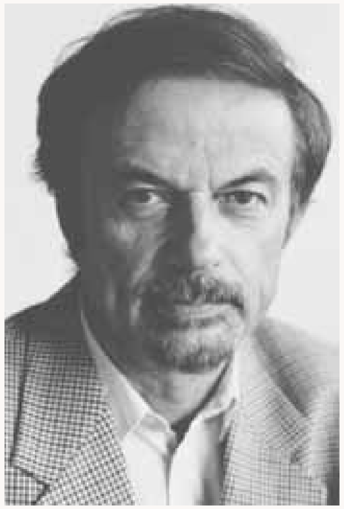
$$\frac{T_F}{C_F} = \frac{1/2}{(N_C^2-1)/2N_C} = \frac{3}{8}$$

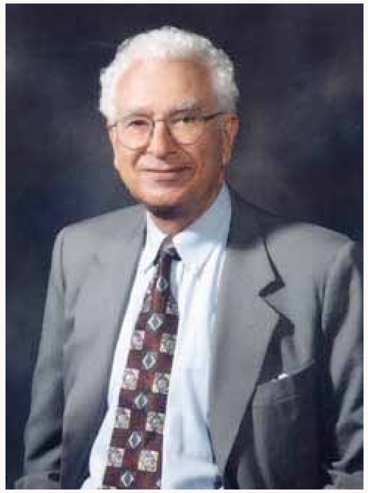
$$SU(N_C)$$
$$N_C = 3$$

★ *QCD*

A Measurement of the QCD color factors and a limit on the light gluino.
By ALEPH Collaboration (R. Barate *et al.*). Published in **Z.Phys.C76:1-14,1997**.

Hadron Multiplicity in Color Gauge Theory Models.
Stanley J. Brodsky (SLAC) , J.F. Gunion (UC, Davis) . SLAC-PUB-1749, UCD-76-5, May 1976. 13pp.
Published in **Phys.Rev.Lett.37:402-405,1976**.





Volume 47B, number 4 PHYSICS LETTERS 26 November 1973

ADVANTAGES OF THE COLOR OCTET GLUON PICTURE ☆

H. FRITZSCH*, M. GELL-MANN and H. LEUTWYLER**

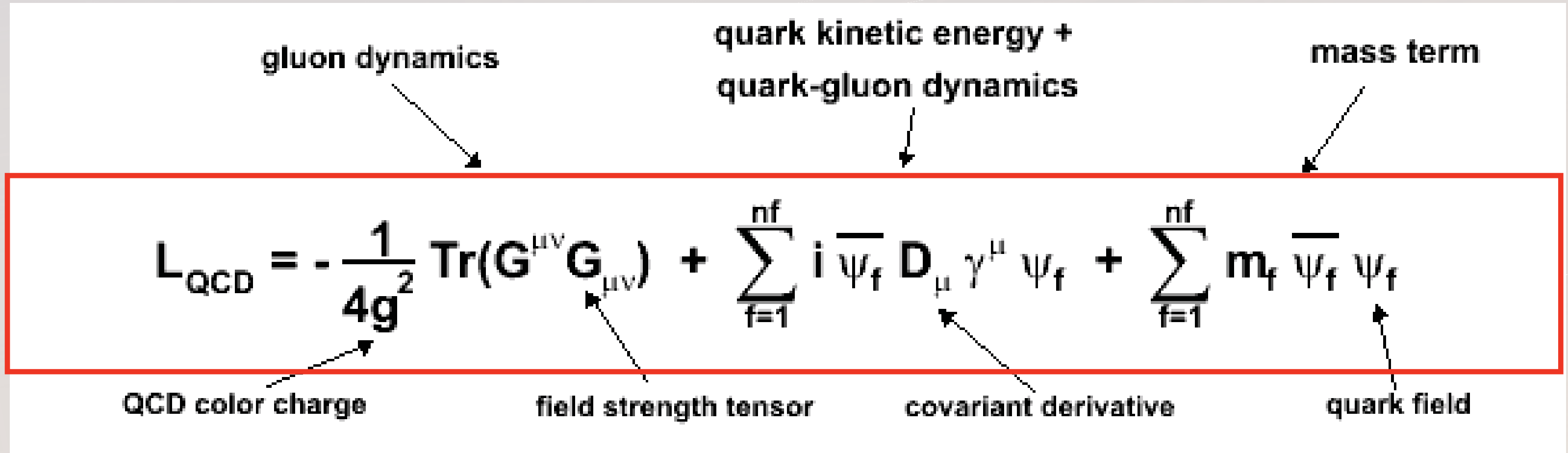
California Institute of Technology, Pasadena, Calif. 91109, USA

Received 1 October 1973

It is pointed out that there are several advantages in abstracting properties of hadrons and their currents from a Yang–Mills gauge model based on colored quarks and color octet gluons.

Fritzsch, Gell-Mann, and Leutwyler introduce ‘‘Quantum Chromodynamics’ (QCD) as the Gauge Theory of the Strong Interactions

QCD Lagrangian



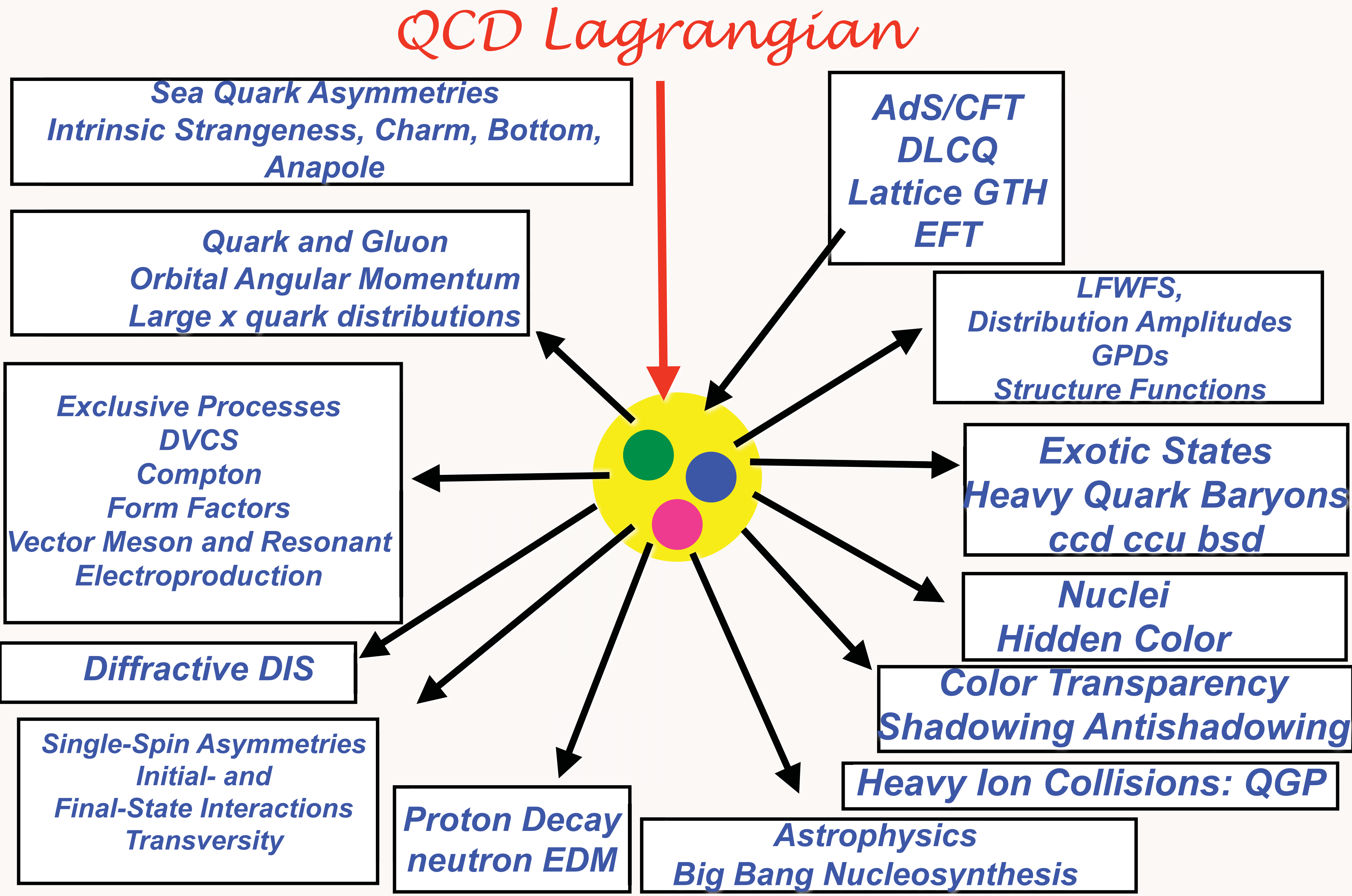
$$L_{QCD} = -\frac{1}{4g^2} Tr(G^{\mu\nu} G_{\mu\nu}) + \sum_{f=1}^{nf} i \overline{\psi_f} D_\mu \gamma^\mu \psi_f + \sum_{f=1}^{nf} m_f \overline{\psi_f} \psi_f$$

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

Dimensionless Coupling
Renormalizable
Asymptotic Freedom
Color Confinement

The World of Quarks and Gluons:

- Quarks and Gluons: Fundamental constituents of hadrons and nuclei
- Remarkable and novel properties of *Quantum Chromodynamics (QCD)*
- New Insights from higher space-time dimensions: Light-Front Holography: AdS/CFT



QCD Lagrangian
Sea Quark Asymmetries
Intrinsic Strangeness, Charm, Bottom,
Anapole
AdS/CFT
DLCQ
Lattice GTH
EFT
Quark and Gluon
Orbital Angular Momentum
Large x quark distributions
LFWFS,
Distribution Amplitudes
GPDs
Structure Functions
Exclusive Processes
DVCS
Compton
Form Factors
Vector Meson and Resonant
Electroproduction
Exotic States
Heavy Quark Baryons
ccd ccu bsd
Nuclei
Hidden Color
Diffractive DIS
Color Transparency
Shadowing Antishadowing
Single-Spin Asymmetries
Initial- and
Final-State Interactions
Transversity
Heavy Ion Collisions: QGP
Proton Decay
neutron EDM
Astrophysics
Big Bang Nucleosynthesis

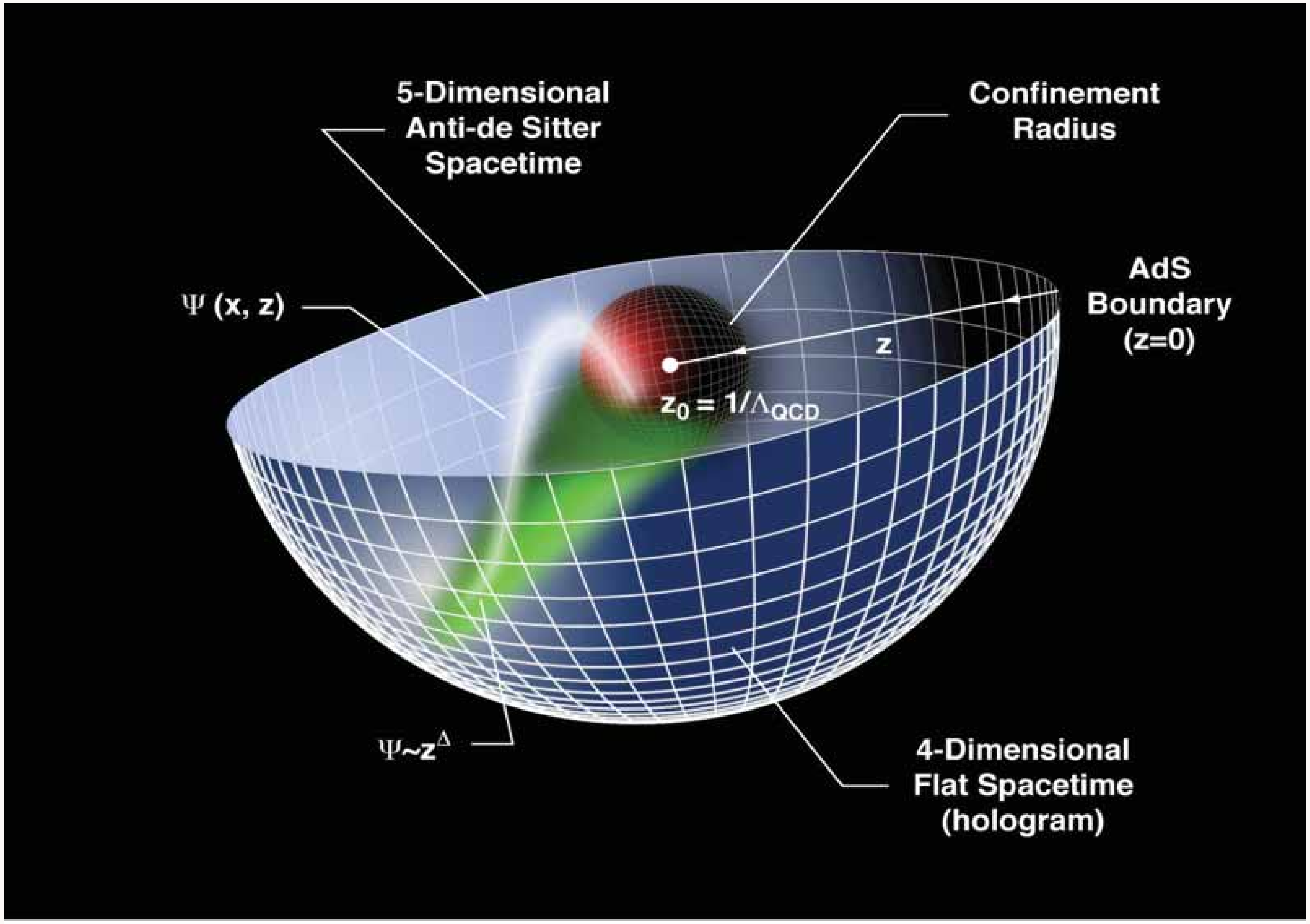
- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

- 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, QGP, CGL, ...

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

—Mark Twain

Applications of AdS/CFT to QCD



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

in collaboration with Guy de Teramond

Goal:

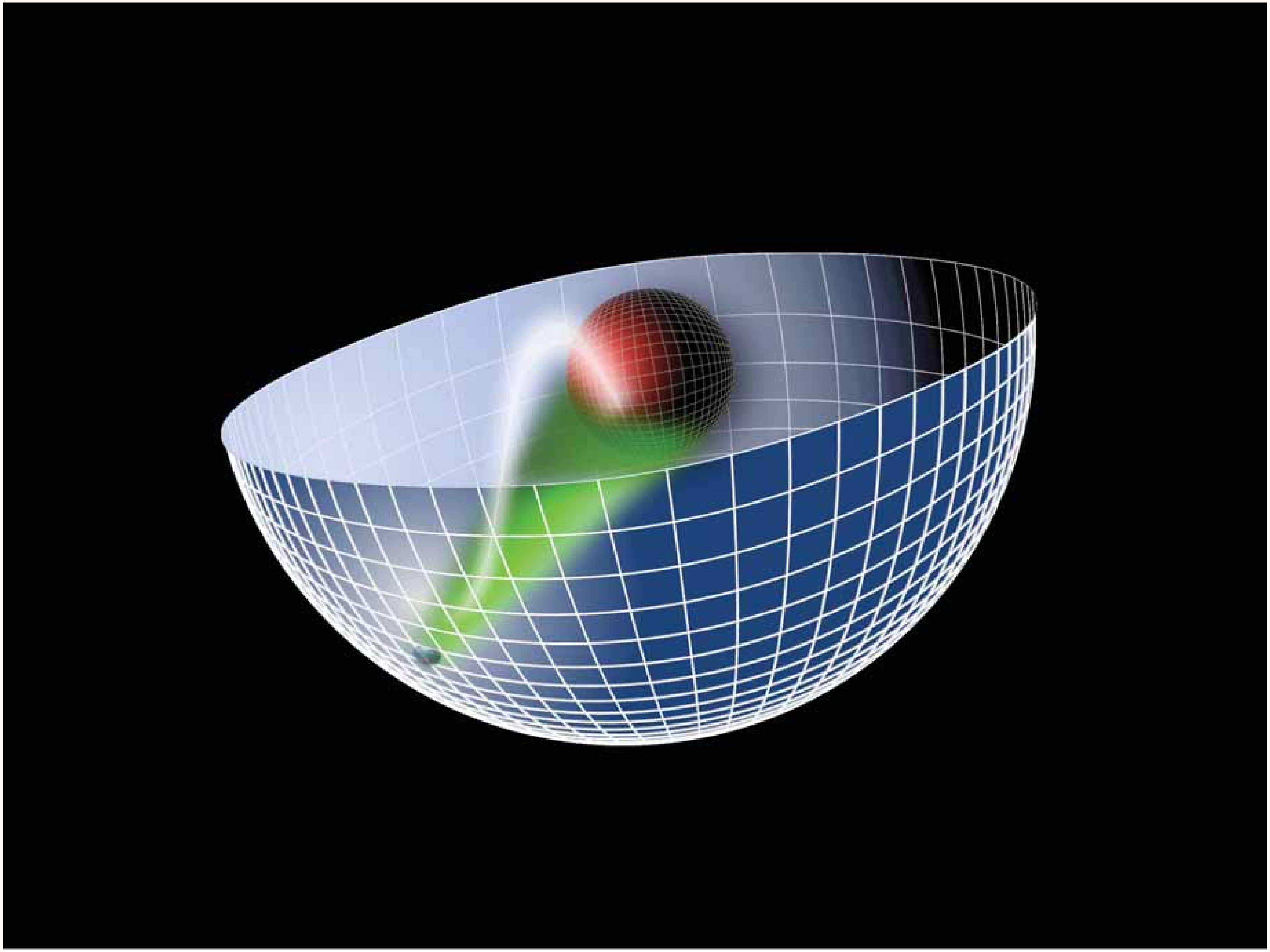
- **Use AdS/CFT to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances**

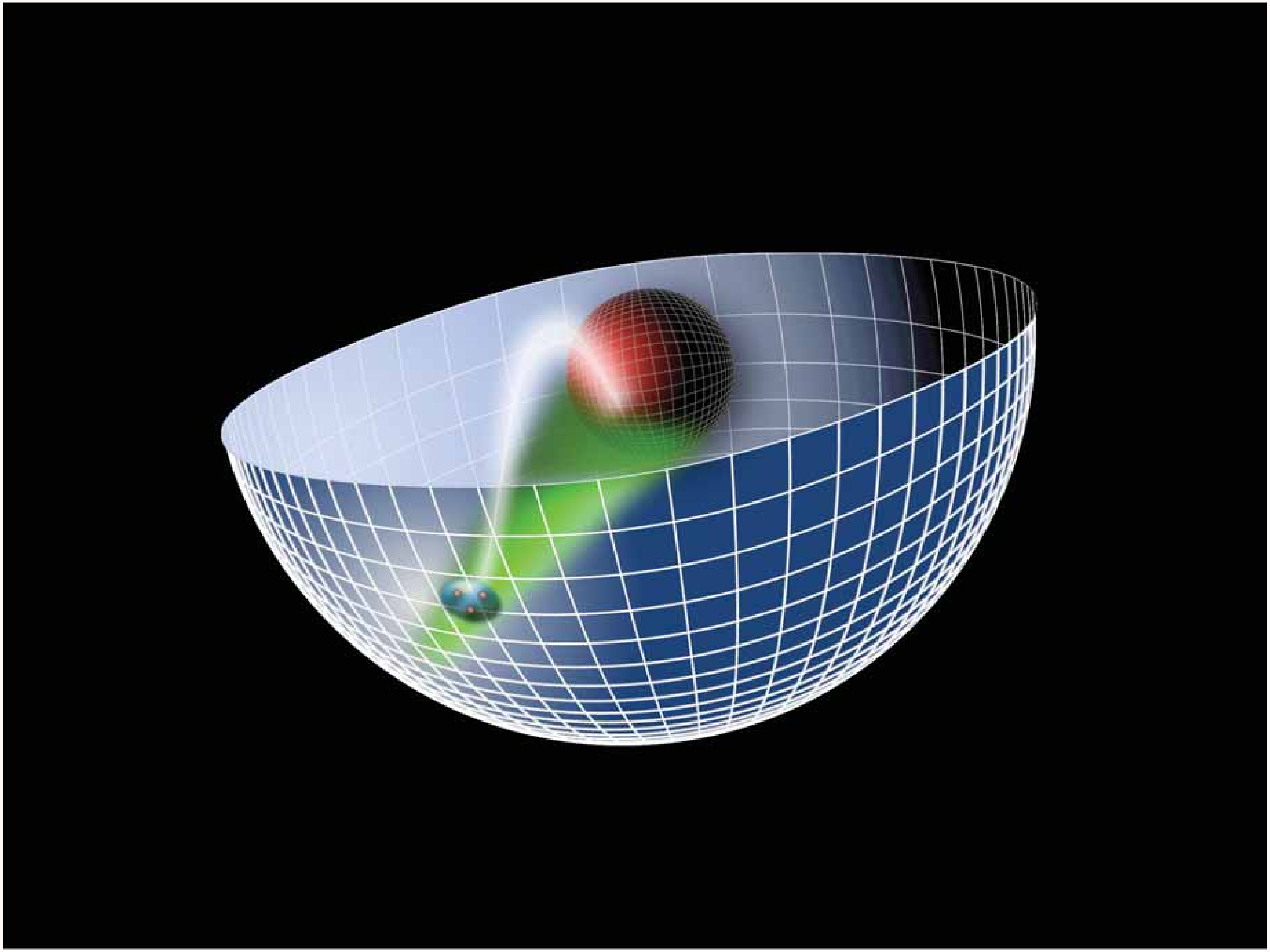
- **Analogous to the Schrodinger Theory for Atomic Physics**

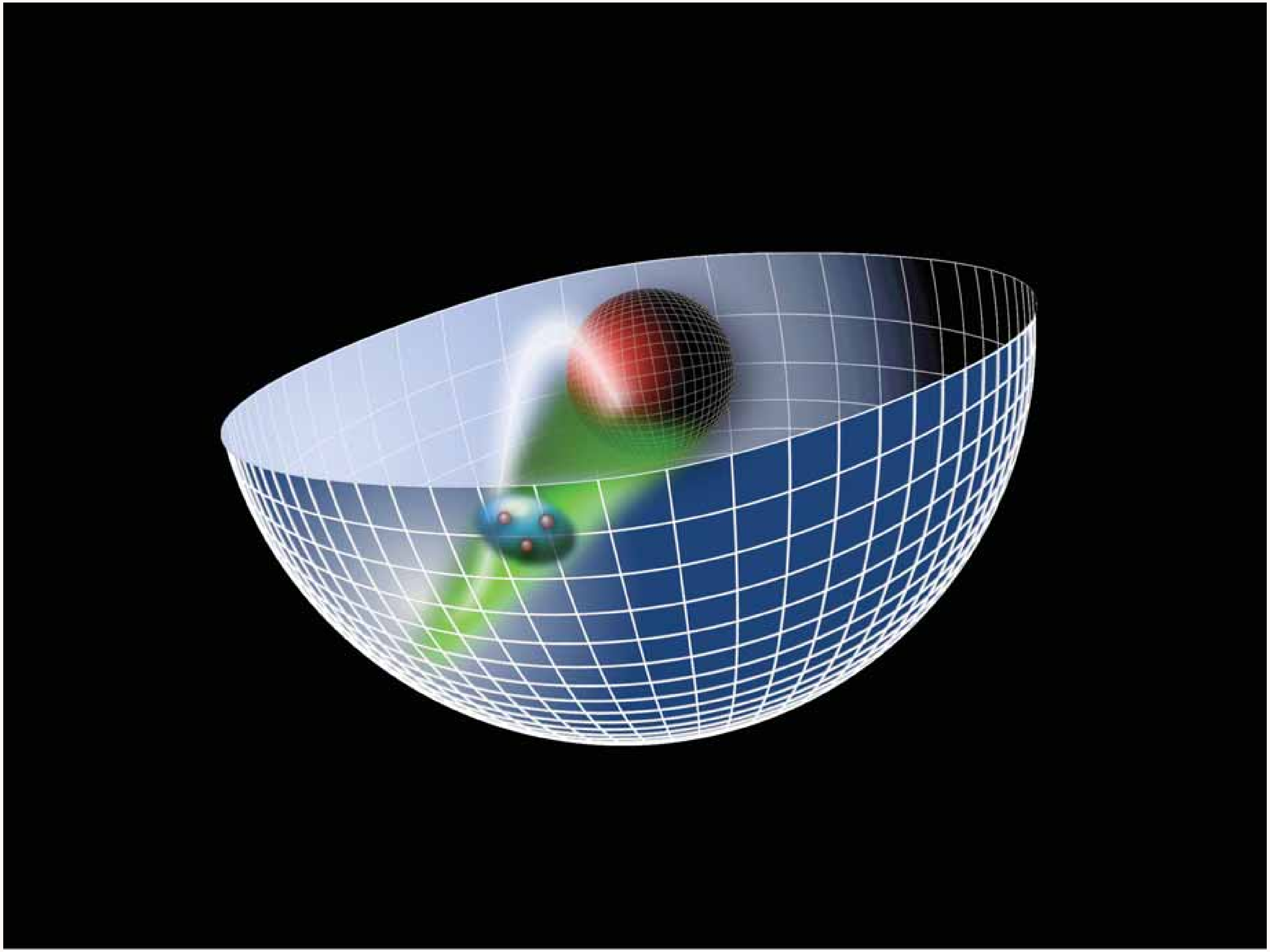
- *AdS/QCD Light-Front Holography*

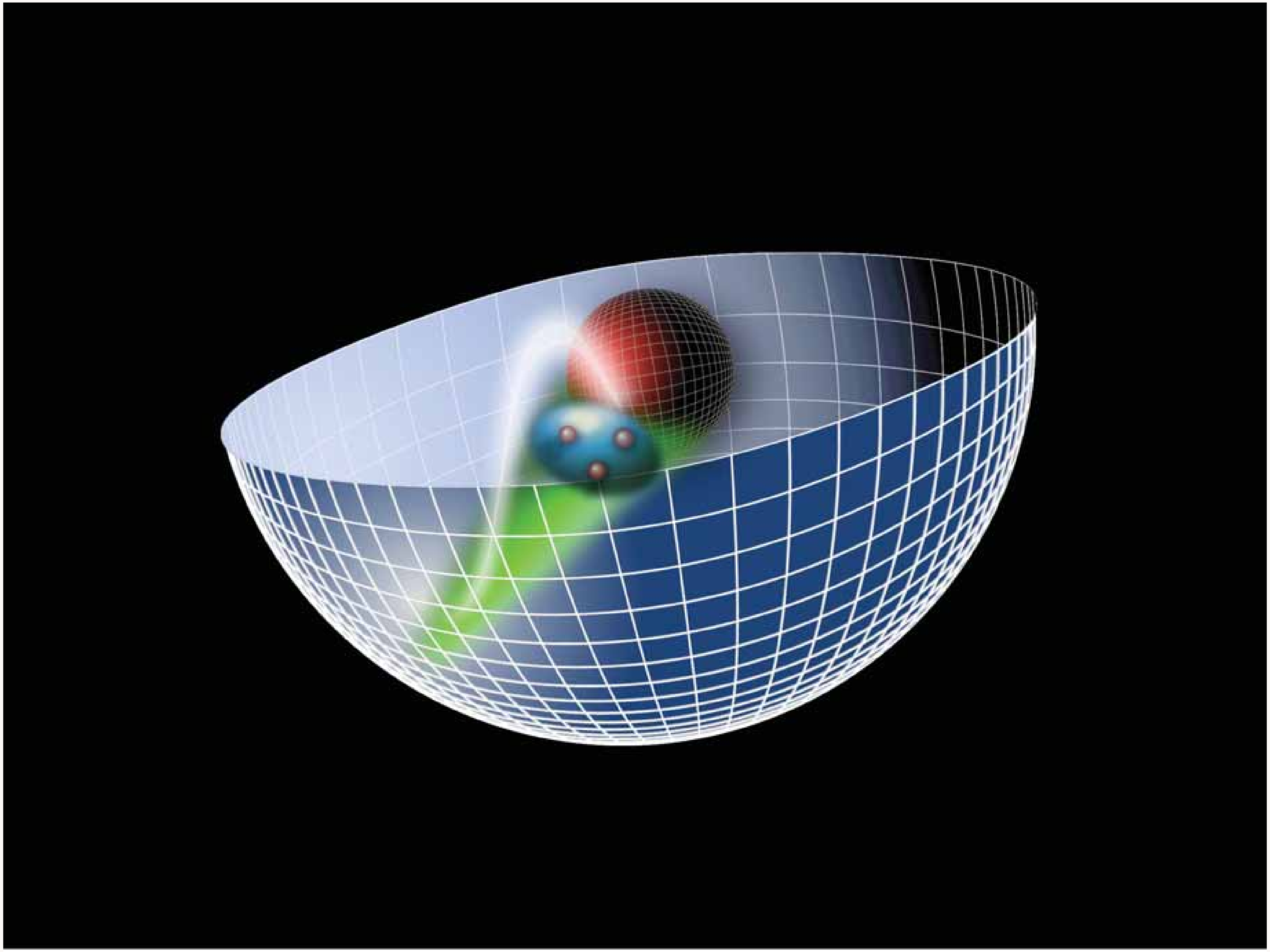
- *Hadronic Spectra and Light-Front Wavefunctions*

- *Hadronization at the Amplitude Level*









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.

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

Maldacena:

Map AdS_5 X 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

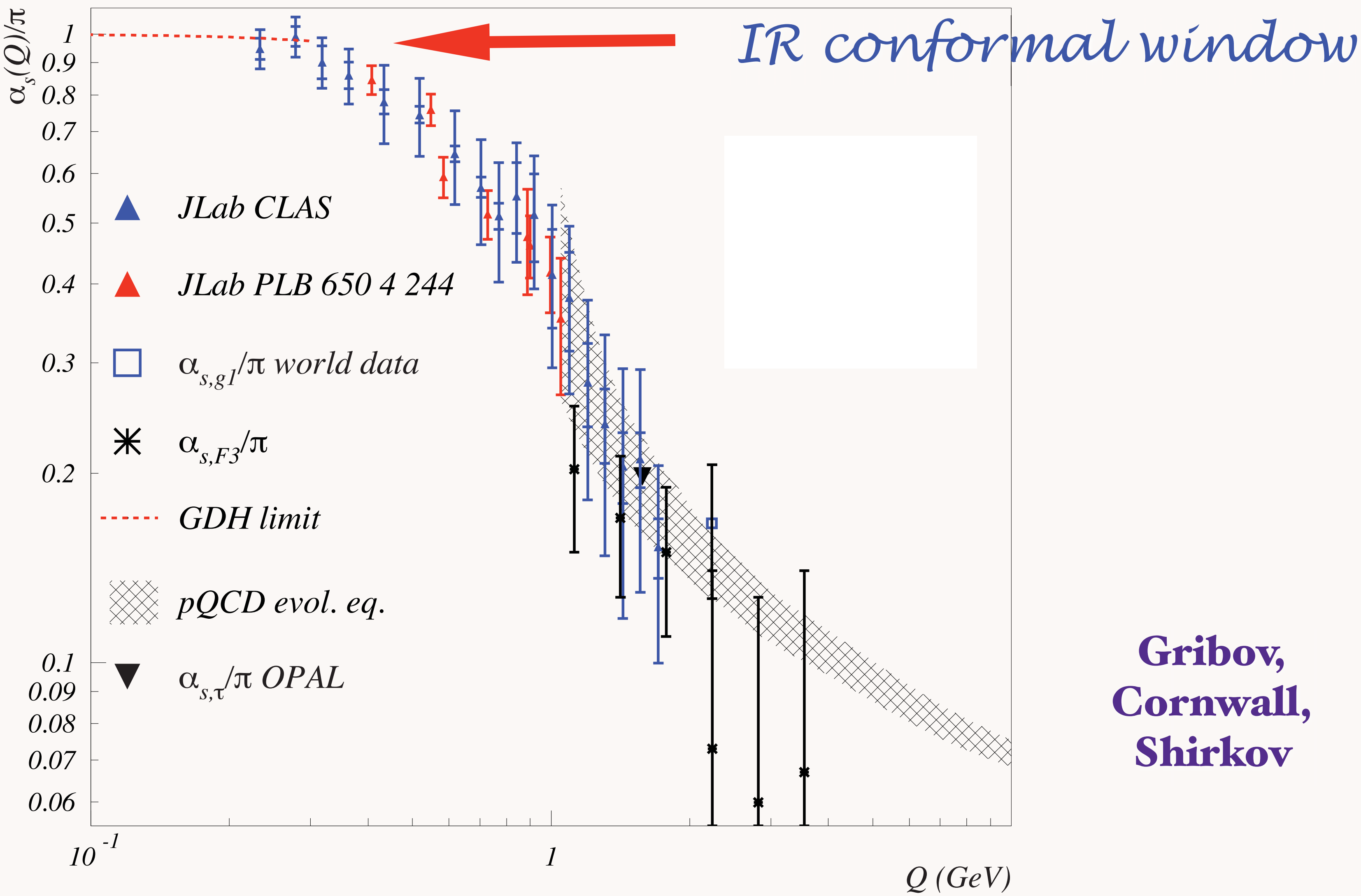
- **Conformal window in theIR:**

$$\alpha_s(Q^2) \simeq \text{const at small } Q^2$$

- **Use mathematical mapping of the conformal group SO(4,2) to AdS5 space**

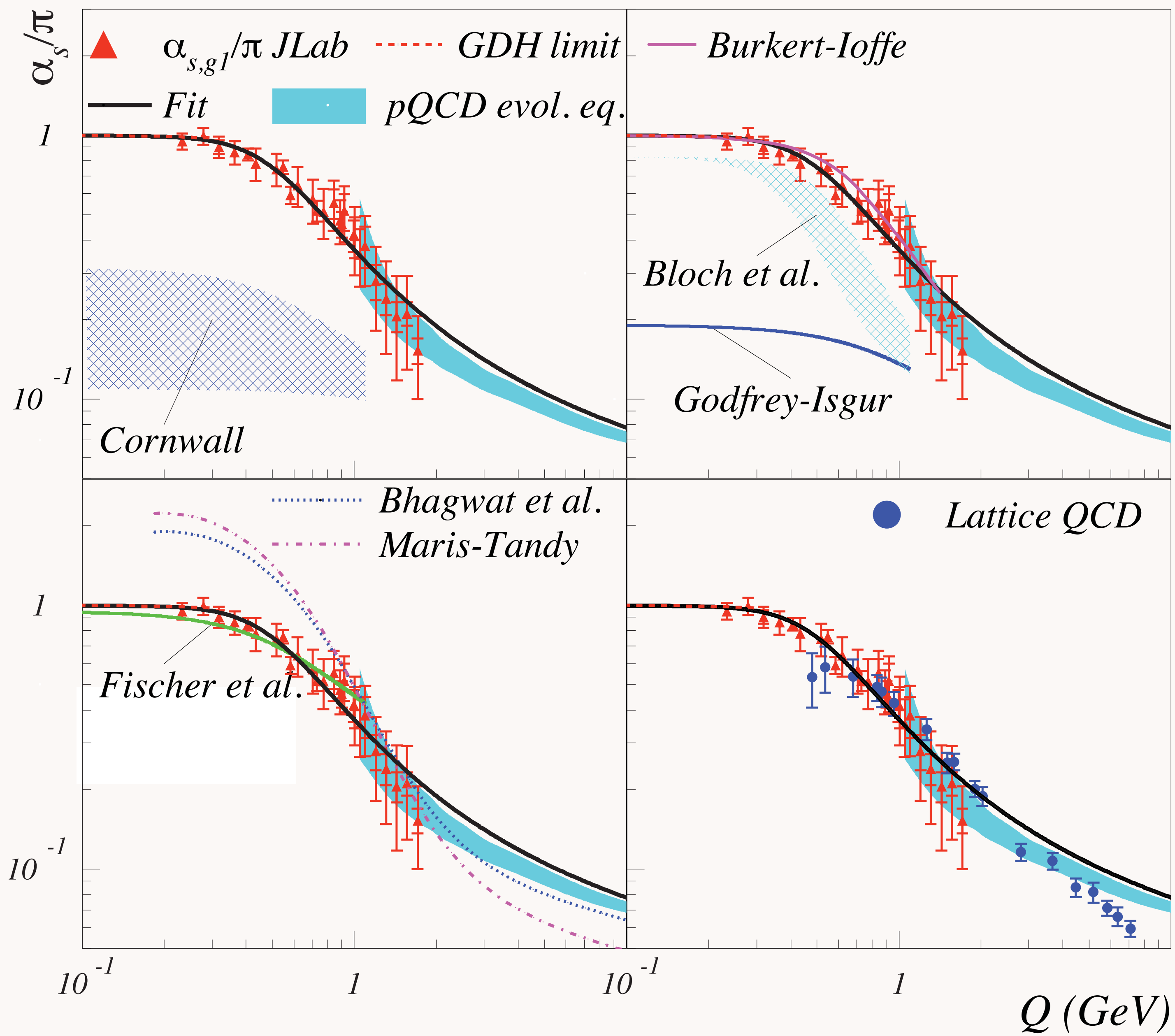
Deur, Korsch, et al: Effective Charge from Bjorken Sum Rule

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



Gribov, Cornwall, Shirkov

Deur, Korsch, et al.



IR Conformal Window for QCD?

- *Dyson-Schwinger Analysis:* **QCD Coupling has IR Fixed Point**

- *Evidence from Lattice Gauge Theory*

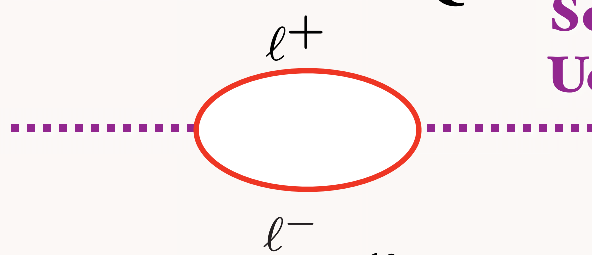
- Define coupling from observable: **indications of IR fixed point for QCD effective charges**

Shrock, de Teramond, sjb

- **Confined gluons and quarks have maximum wavelength**

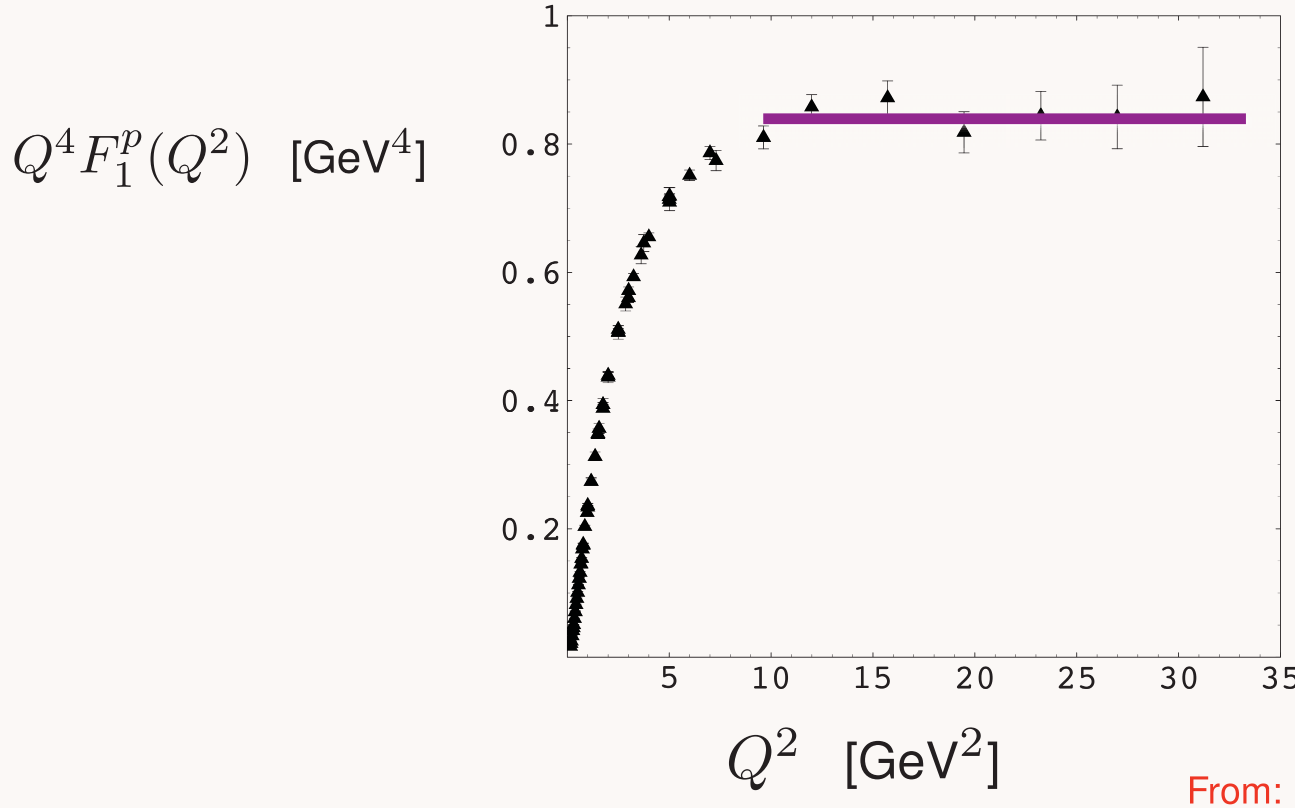
- **Decoupling of QCD vacuum polarization at small Q^2**

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



Serber-Uehling

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



$$F_1(Q^2) \sim \left[1/Q^2\right]^{n-1}, \quad n = 3$$

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

- Phenomenological success of dimensional scaling laws for exclusive processes

$$d\sigma/dt \sim 1/s^{n-2}, \quad n = n_A + n_B + n_C + n_D,$$

implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies
Farrar and sjb (1973); Matveev *et al.* (1973).

- Derivation of counting rules for gauge theories with mass gap dual to string theories in warped space (hard behavior instead of soft behavior characteristic of strings) Polchinski and Strassler (2001).

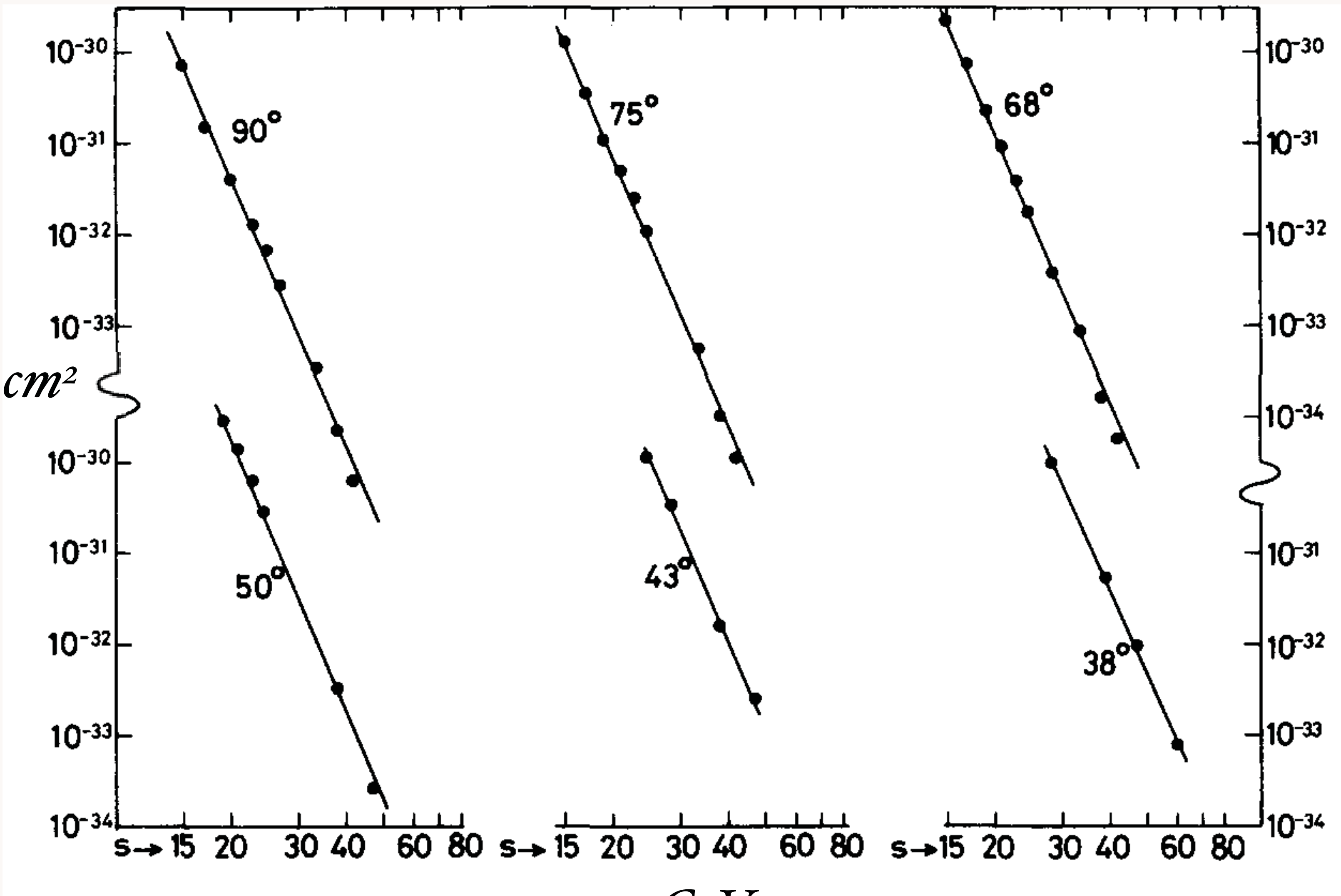
Brodsky and Farrar, Phys. Rev. Lett. 31 (1973) 1153
Matveev et al., Lett. Nuovo Cimento, 7 (1973) 719

Quark Counting Rules for Exclusive Processes

- Power-law fall-off of the scattering rate reflects degree of compositeness
- The more composite -- the faster the fall-off
- Power-law counts the number of quarks and gluon constituents
- Form factors: probability amplitude to stay intact
- $F_H(Q) \propto \frac{1}{(Q^2)^{n-1}}$ n = # elementary constituents

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

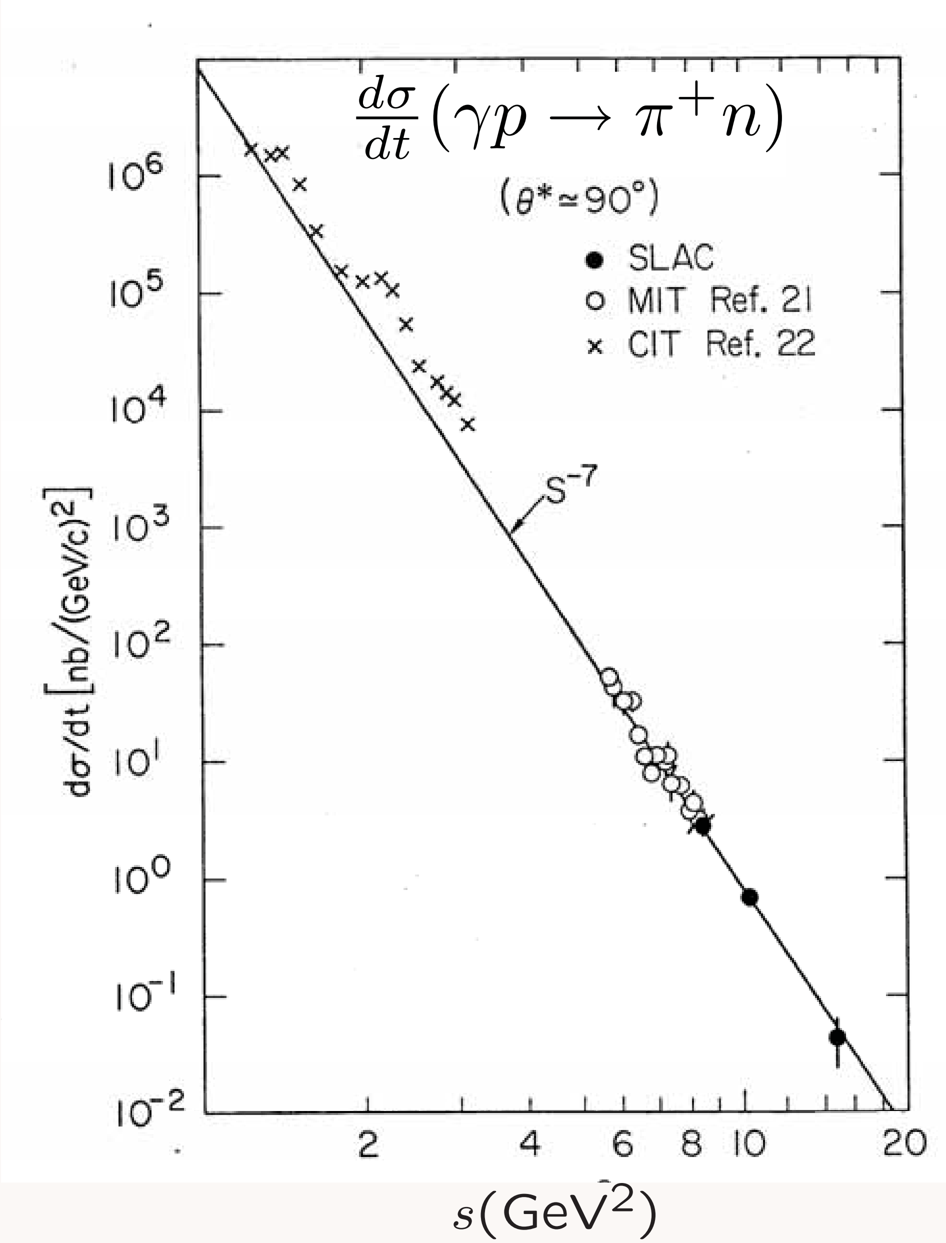


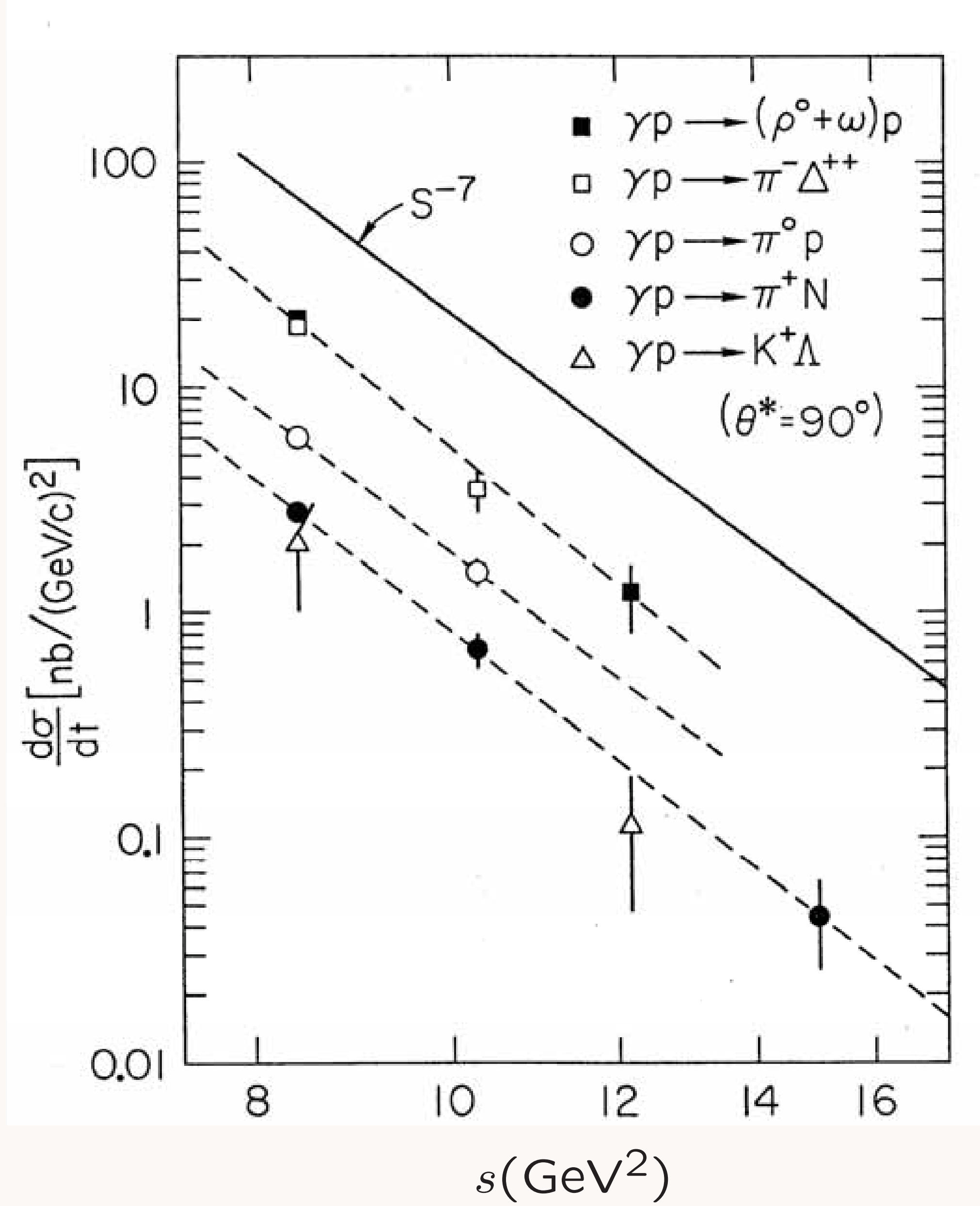
Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

Angular distribution -- quark interchange





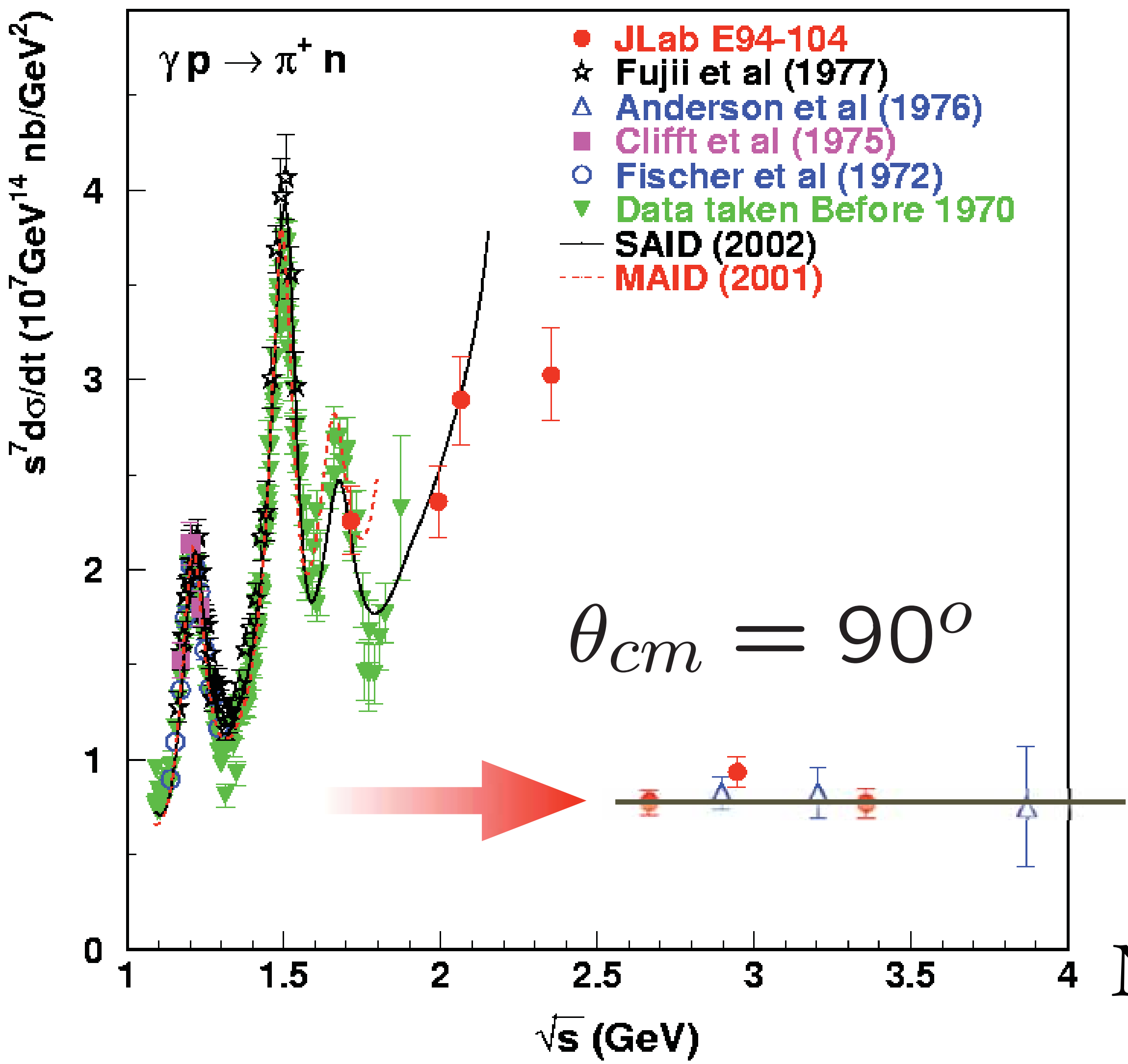
Conformal Invariance:

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

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:

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

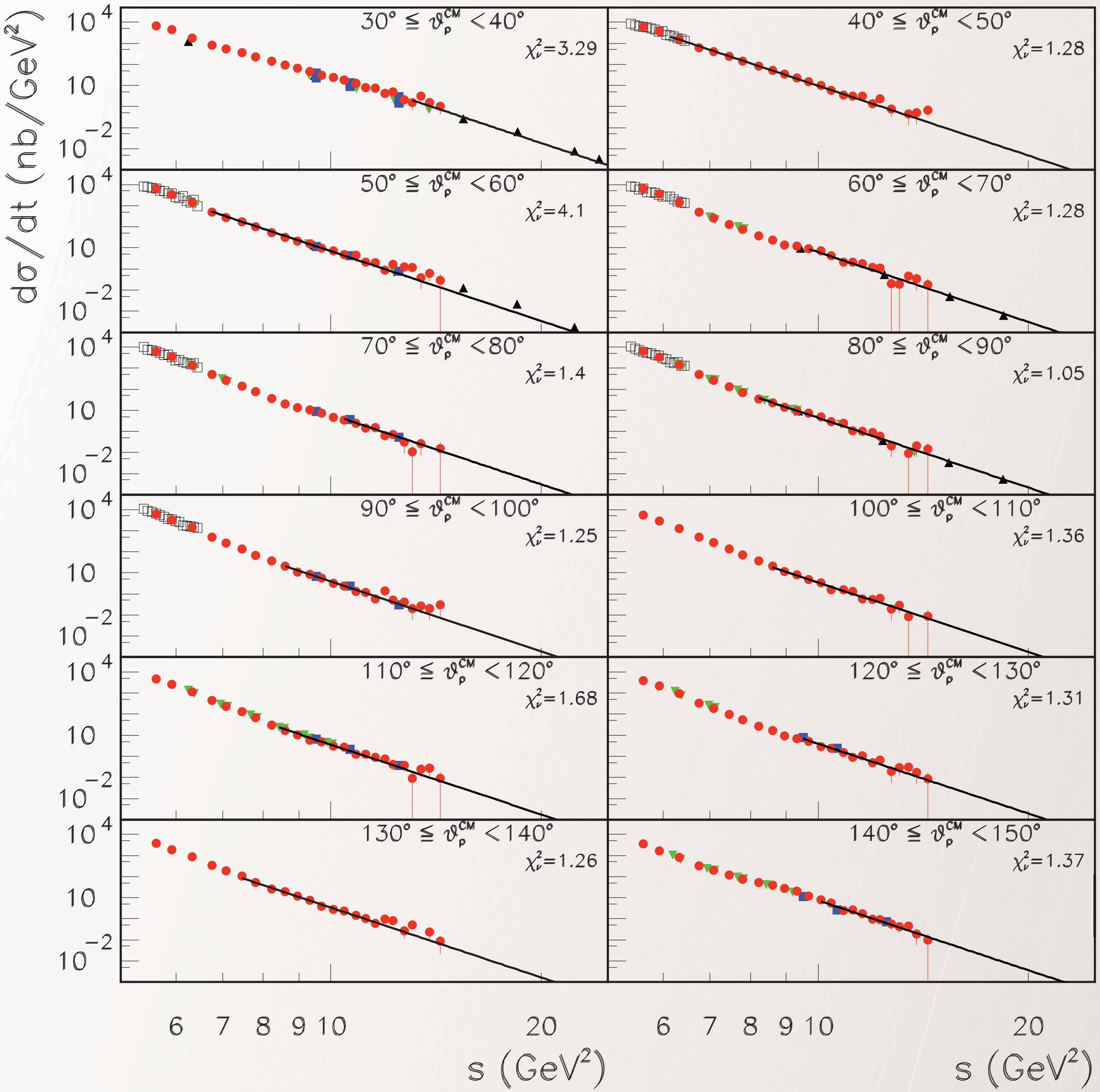
$$s^7\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = F(\theta_{CM})$$

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

No sign of running coupling

Conformal invariance

Deuteron Photodisintegration



J-Lab

PQCD and AdS/CFT:

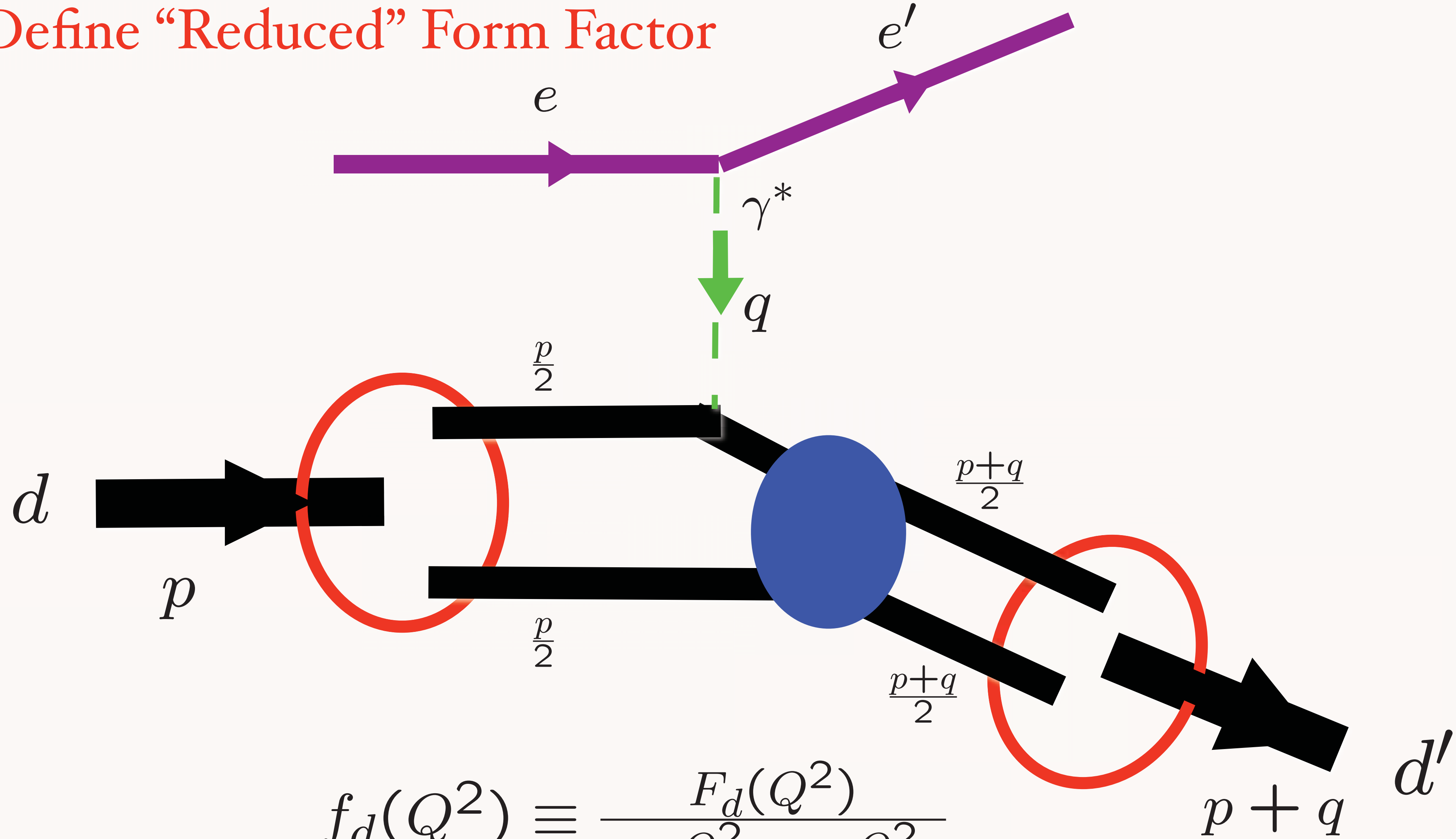
$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B\to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

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

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

Reflects conformal invariance

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

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

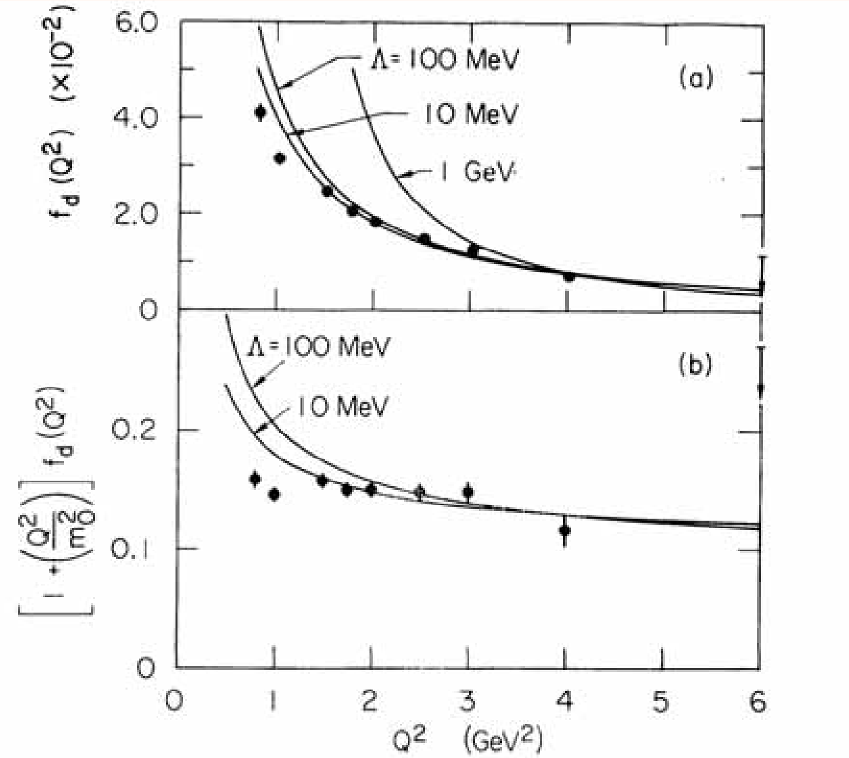
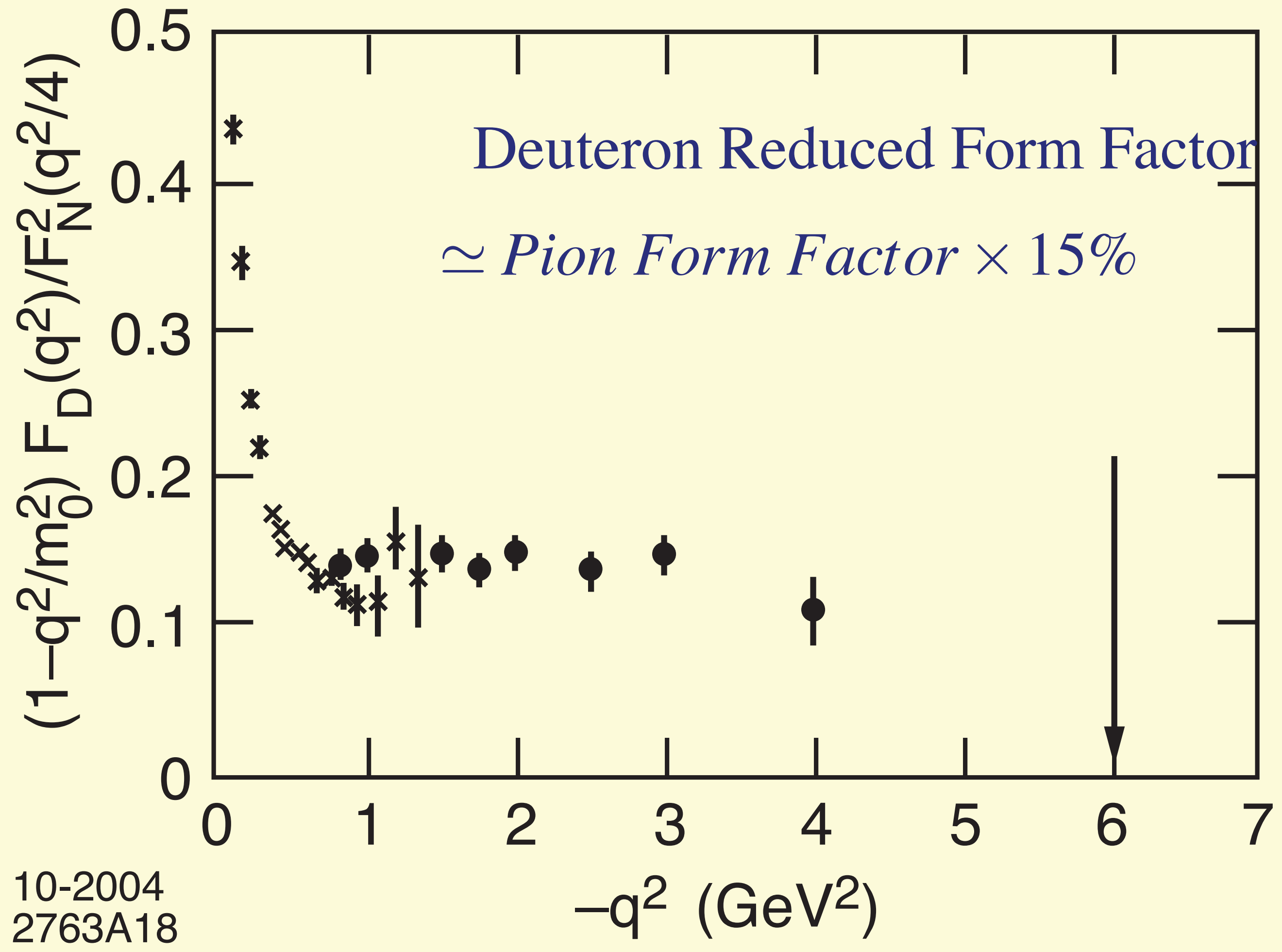


FIG. 2. (a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$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



- 15% Hidden Color in the Deuteron

Hidden Color in QCD

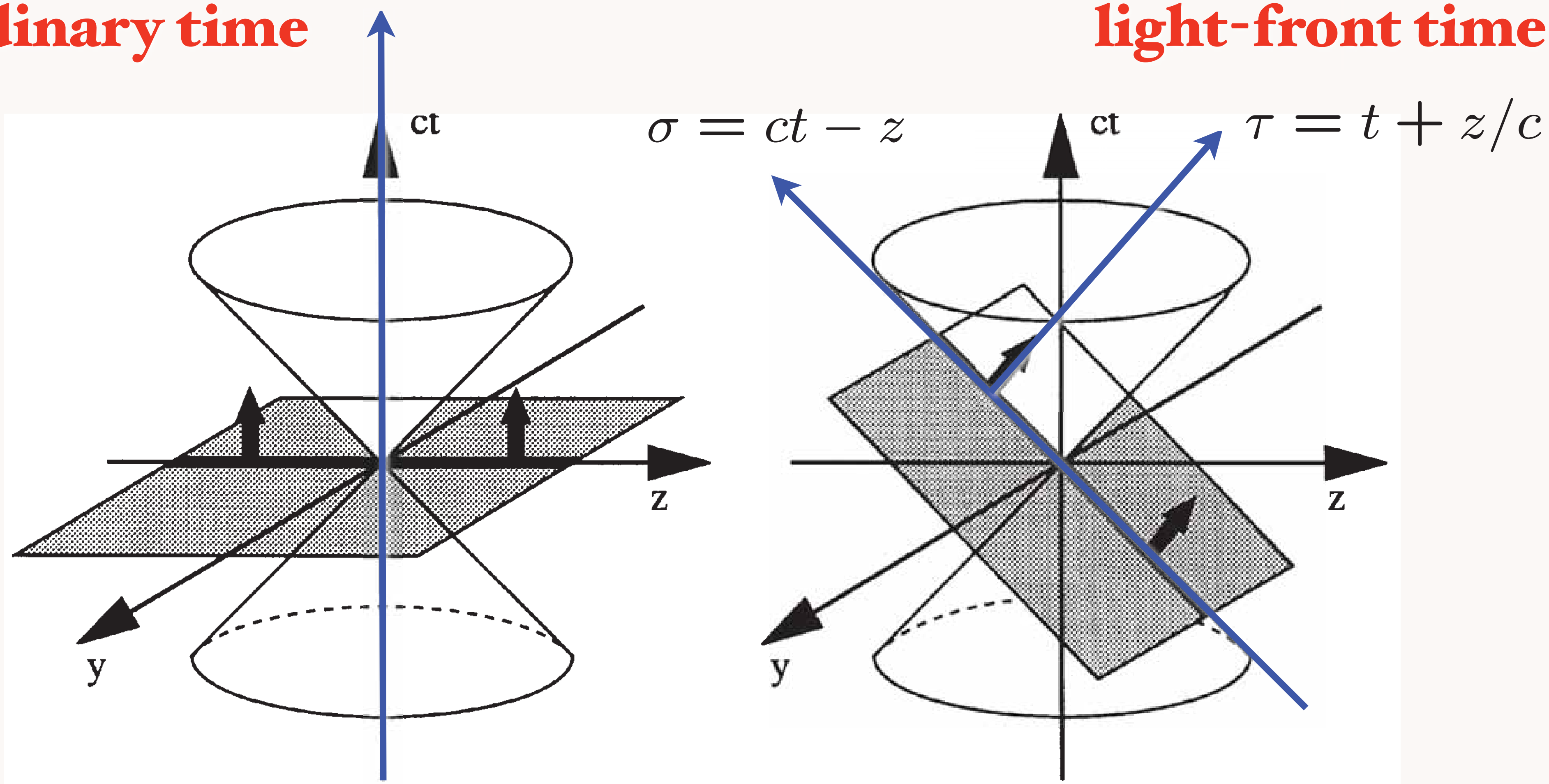
Lepage, Ji, sjb

- Deuteron six quark wavefunction:
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Dirac's Amazing Idea: The Front Form

Evolve in ordinary time

Evolve in light-front time!



Instant Form **Front Form**

Each element of
flash photograph
illuminated
at same LF time

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

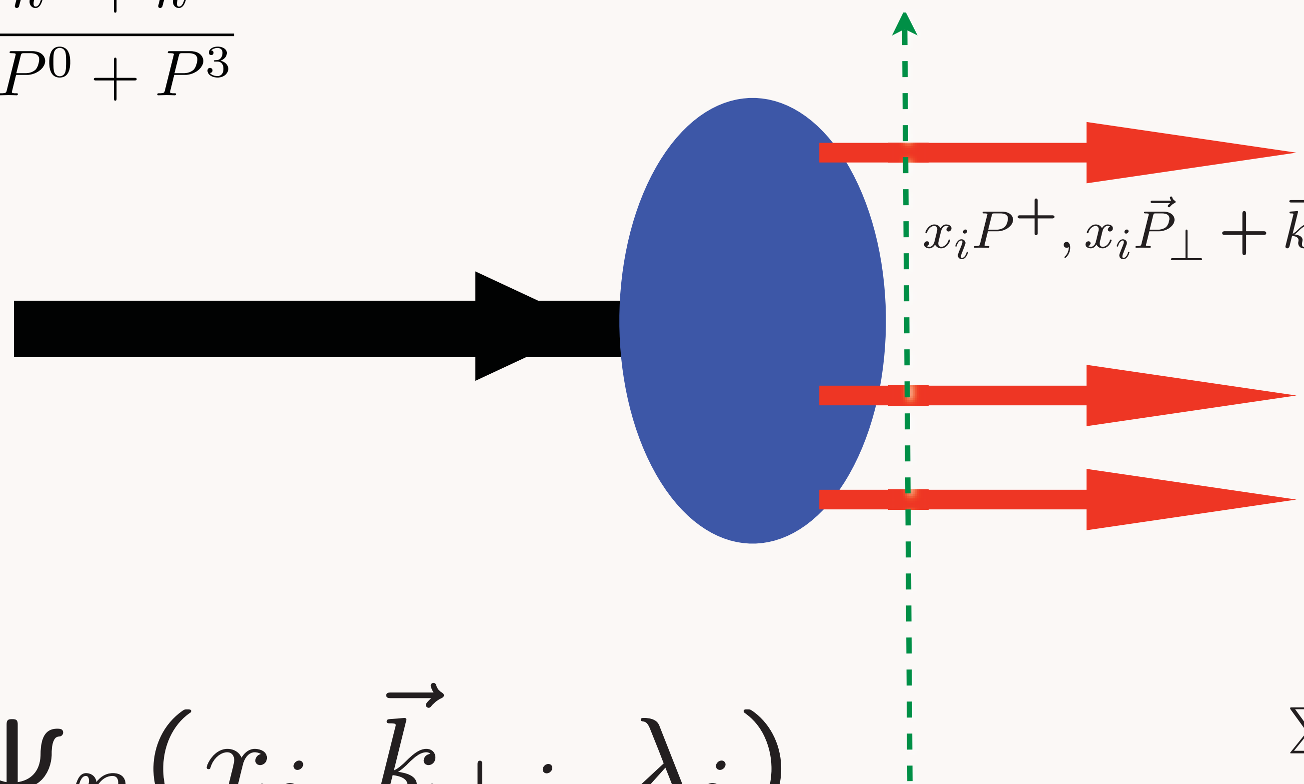
H E L E N   B R A D L E Y   -   P H O T O G R A P H Y

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Fixed $\tau = t + z/c$

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$

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



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

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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Angular Momentum on the Light-Front

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

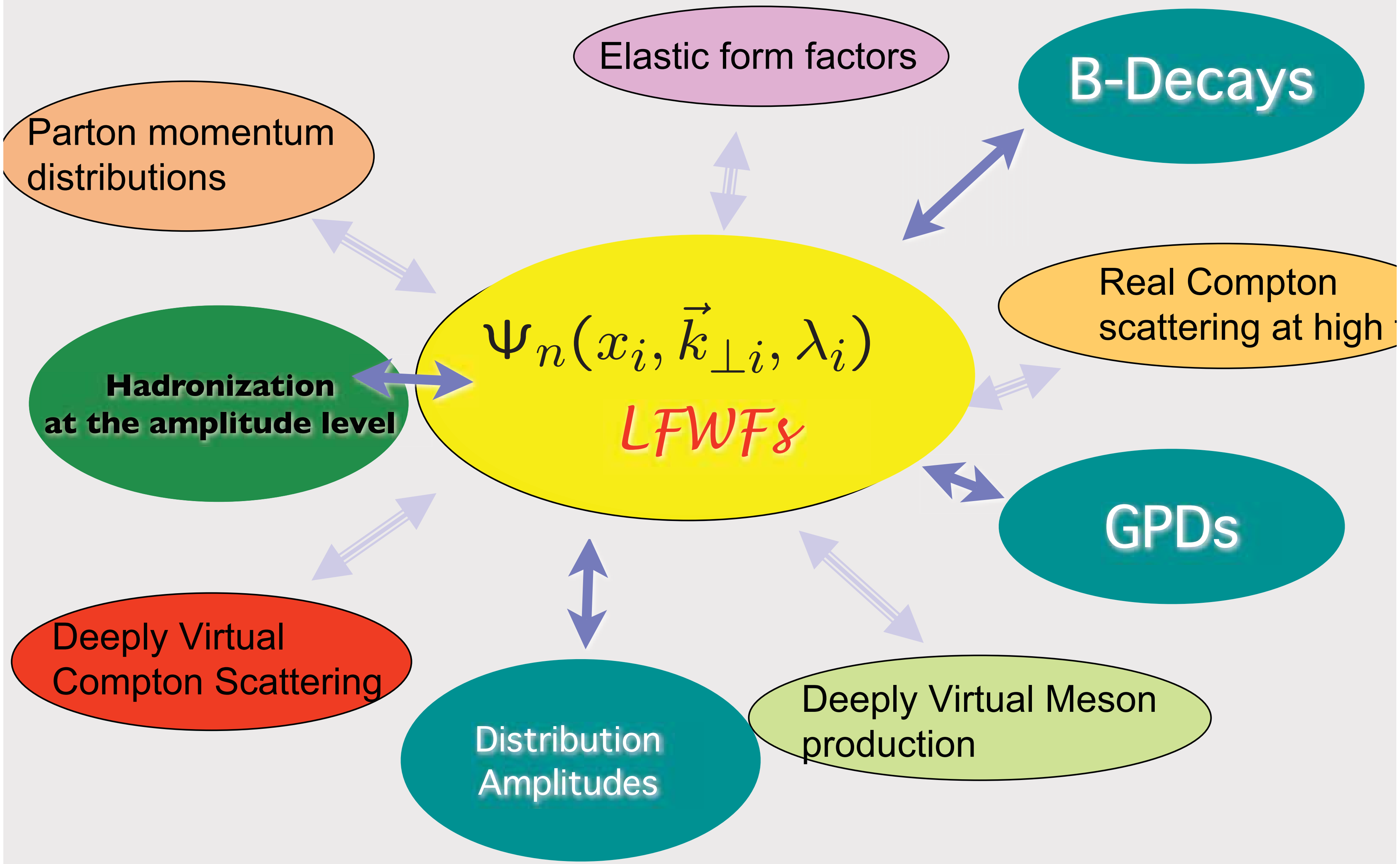
Conserved
LF Fock state by Fock State

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

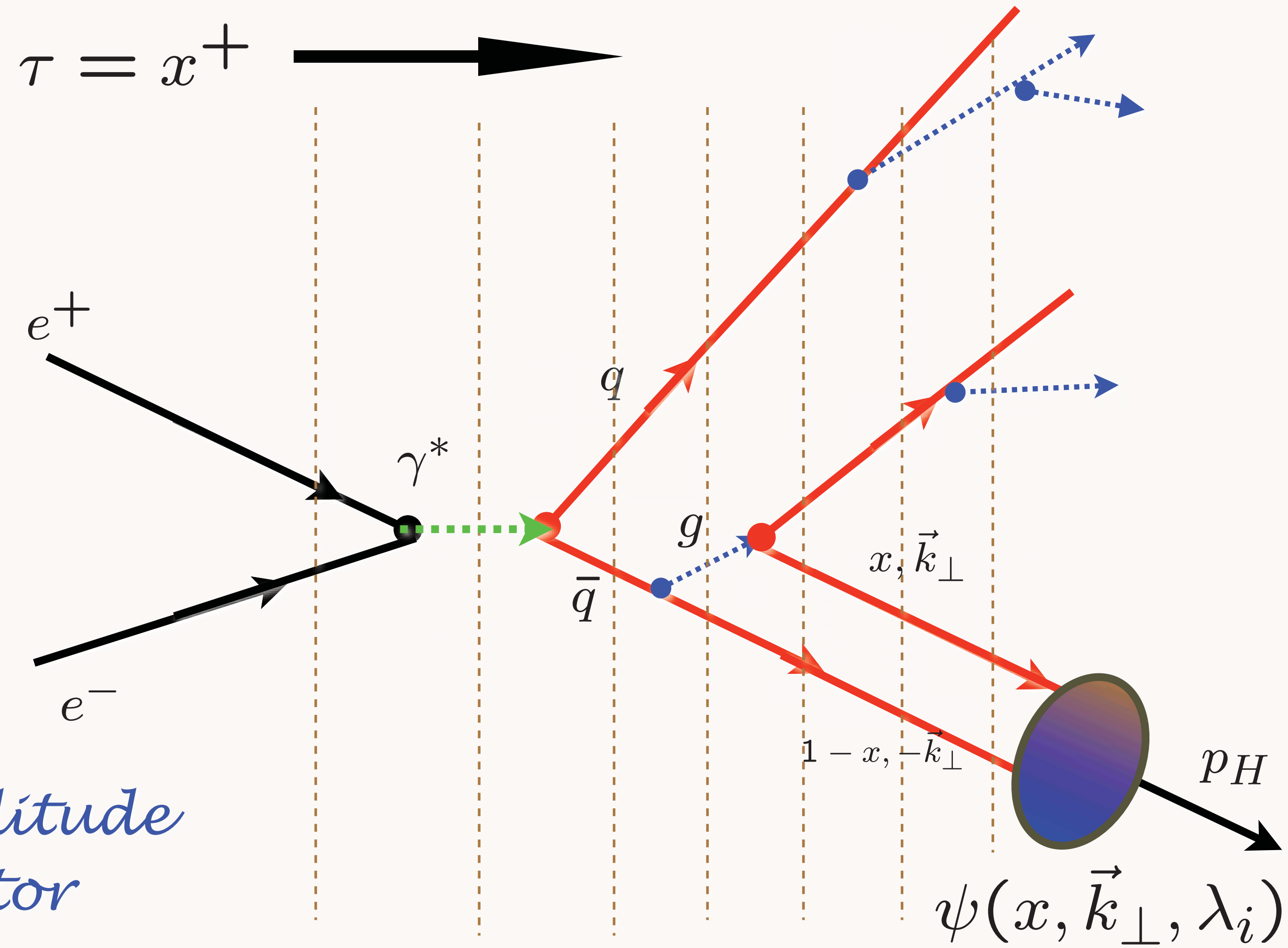
n-1 orbital angular momenta

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

A Unified Description of Hadron Structure



Hadronization at the Amplitude Level



Event amplitude generator

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

Hadron Dynamics at the Amplitude Level

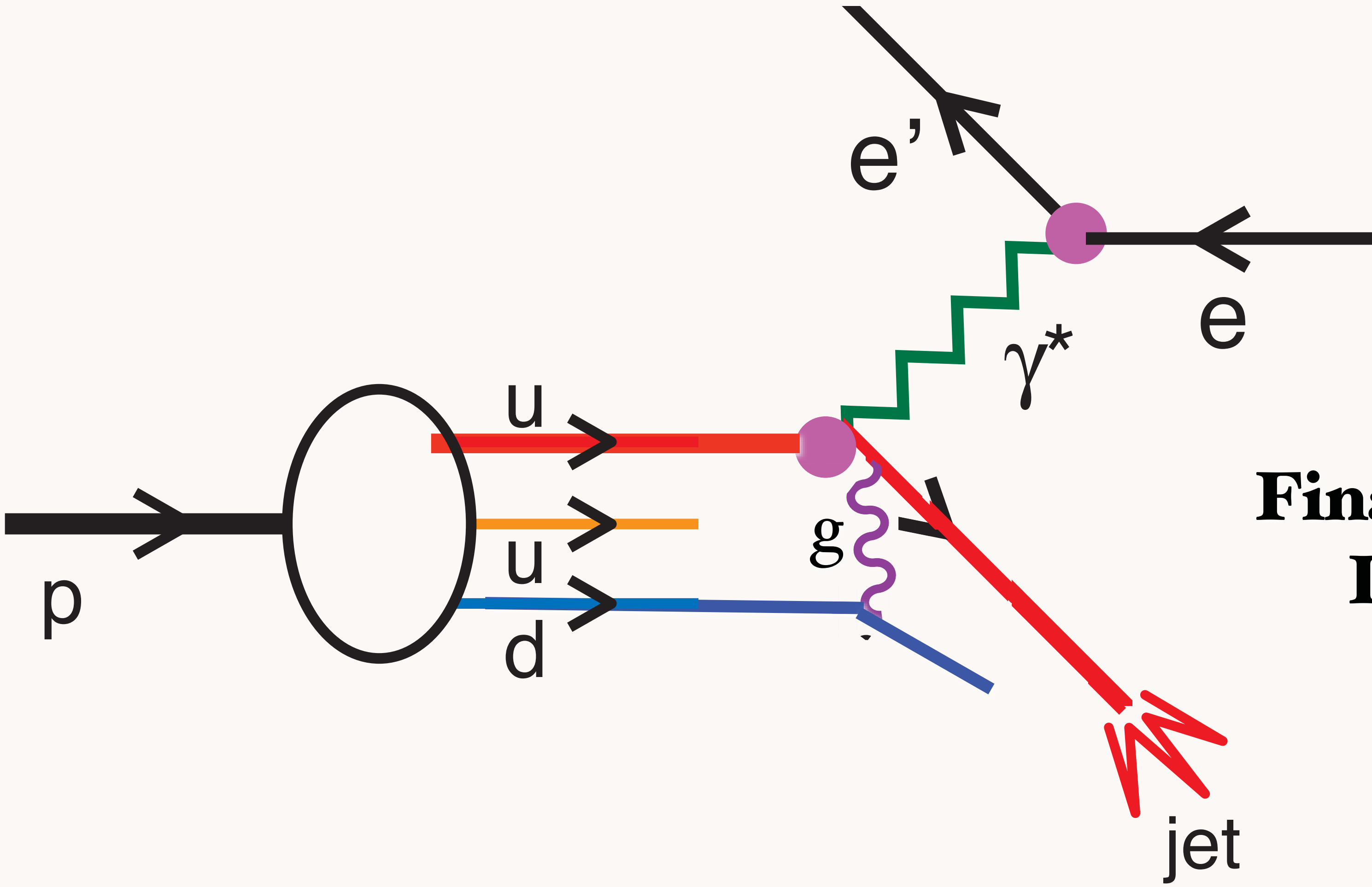
- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes, distribution amplitudes, direct subprocesses, hadronization.

- Relation of spin, momentum, and other distributions to physics of the hadron itself.

- Connections between observables, orbital angular momentum

- Role of FSI and ISIs: Diffractive DIS, Sivers effect

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:

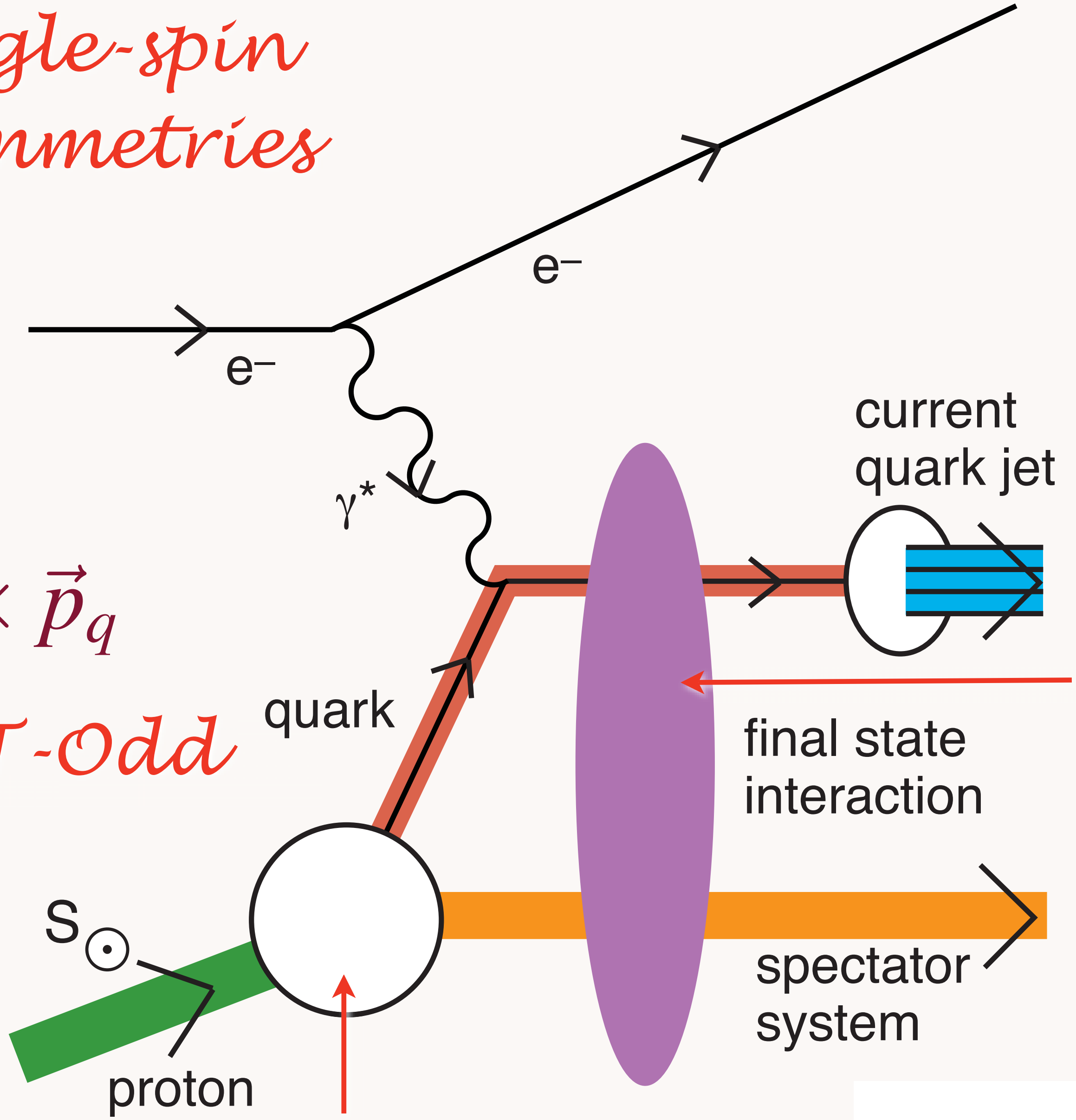
Final-state interactions of struck quark can be neglected

Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

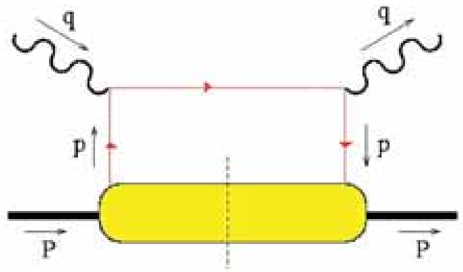


$$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

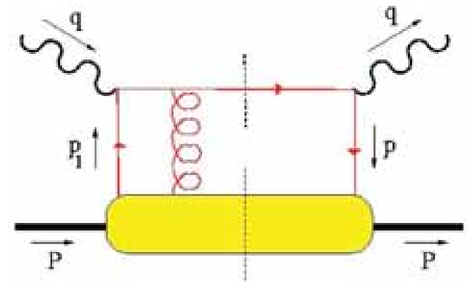
Pseudo-T-Odd

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

Light-Front Wavefunction S and P- Waves



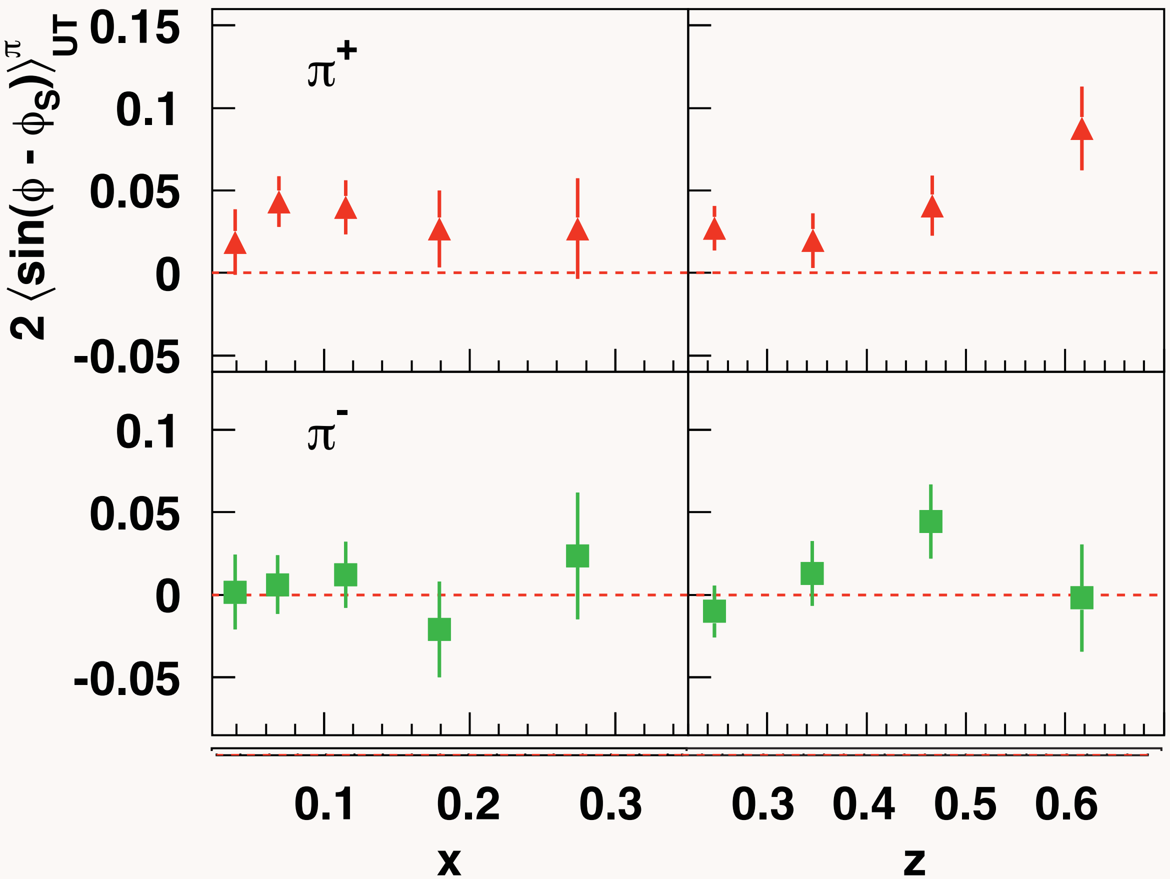
can interfere with



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^-...

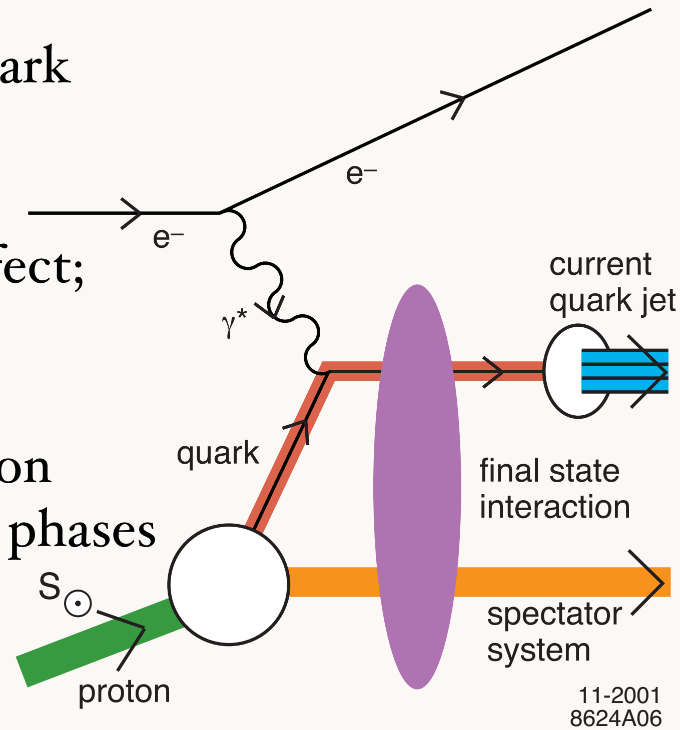
Gamberg: Hermes data compatible with BHS model

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

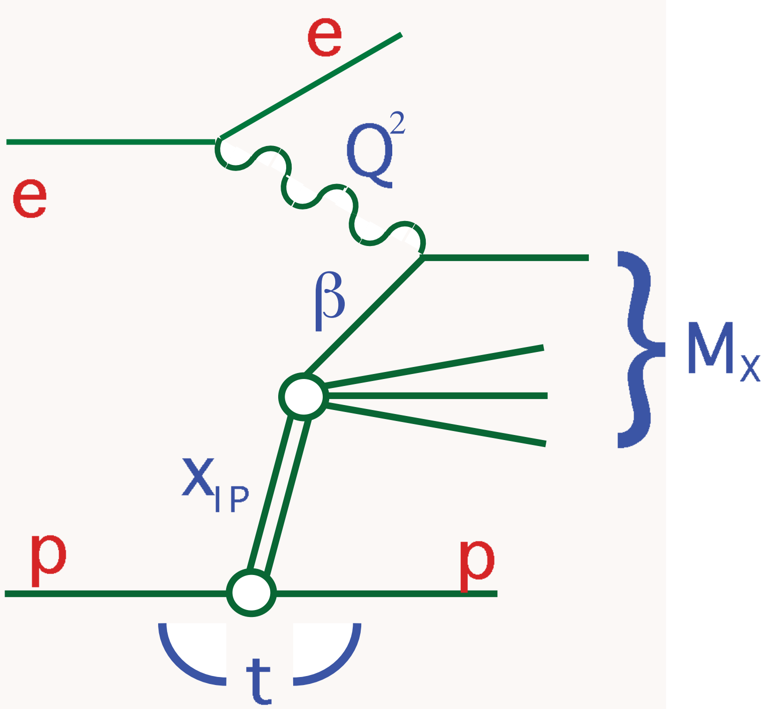
Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

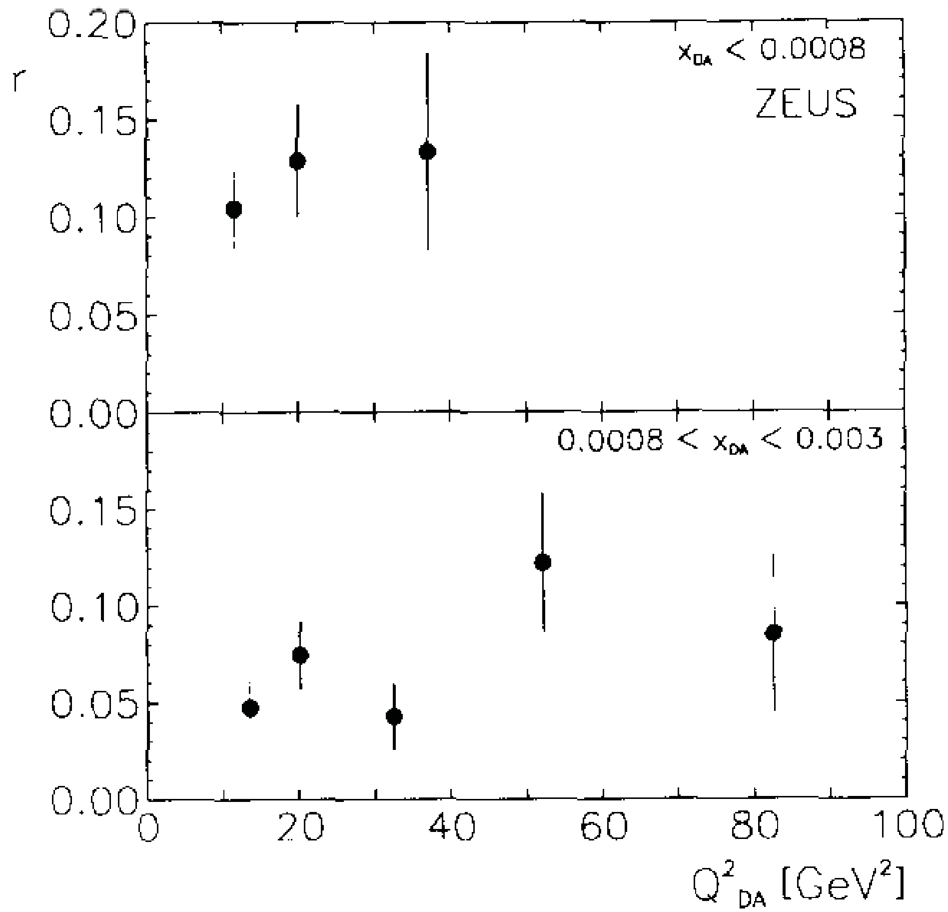
$$\mathbf{i}\,\vec{S}\cdot\vec{p}_{jet}\times\vec{q}$$

- 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!



Remarkable observation at HERA





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

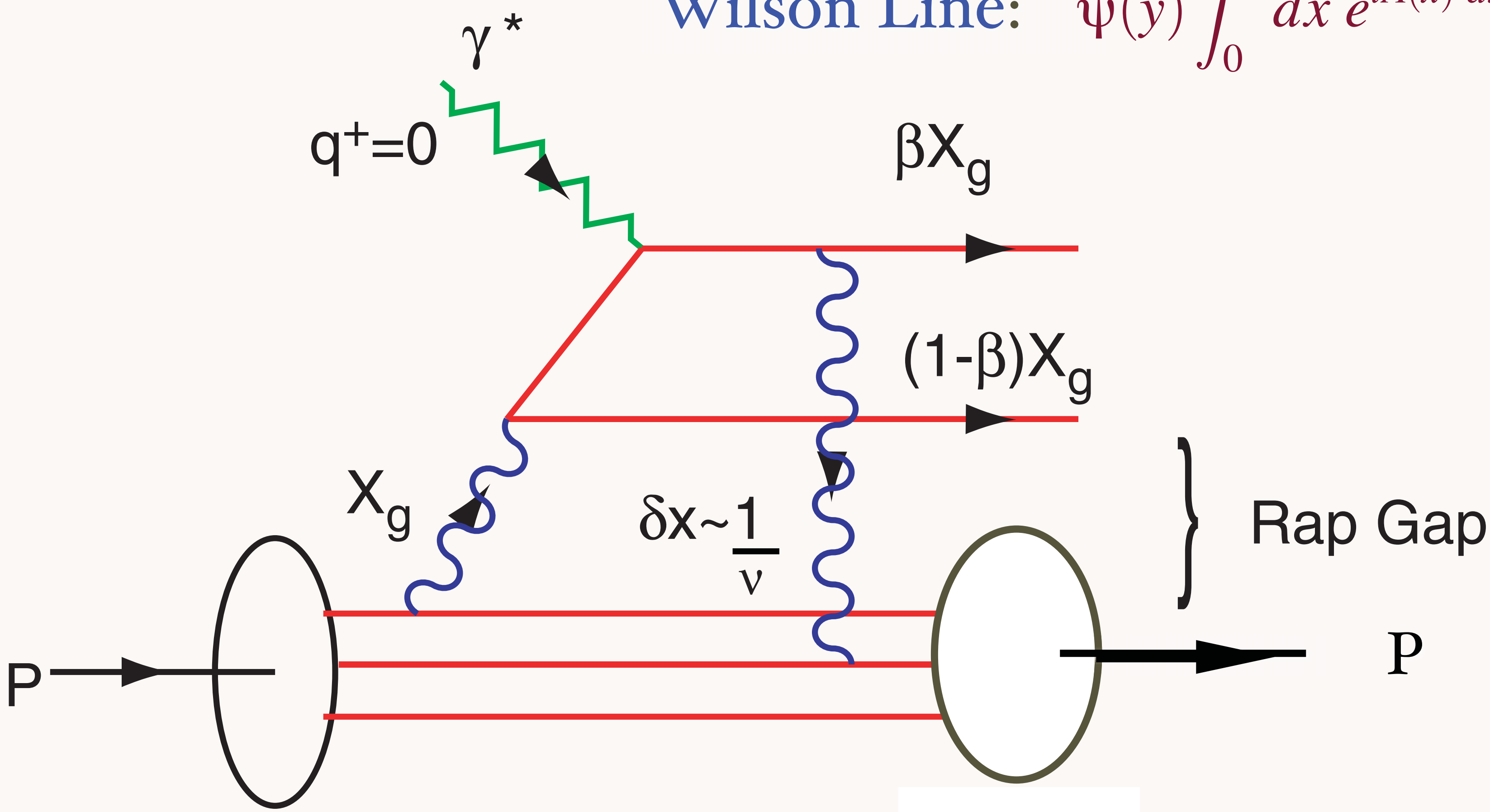
10% to 15% of DIS events are diffractive !

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

Hoyer, Marchal, Peigne, Sannino, sjb

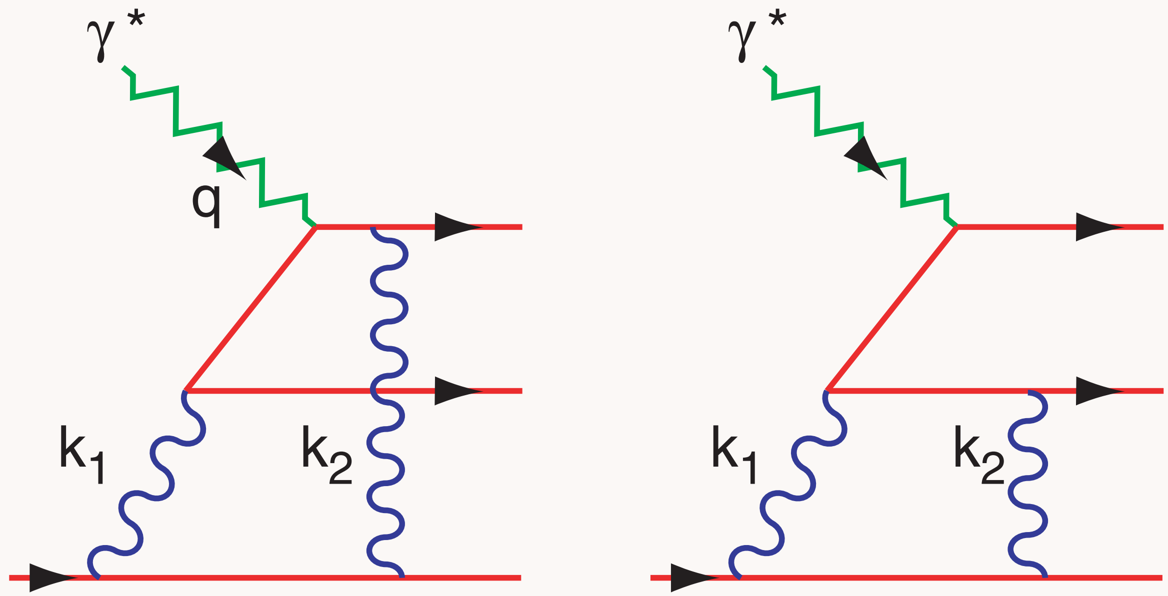
QCD Mechanism for Rapidity Gaps

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



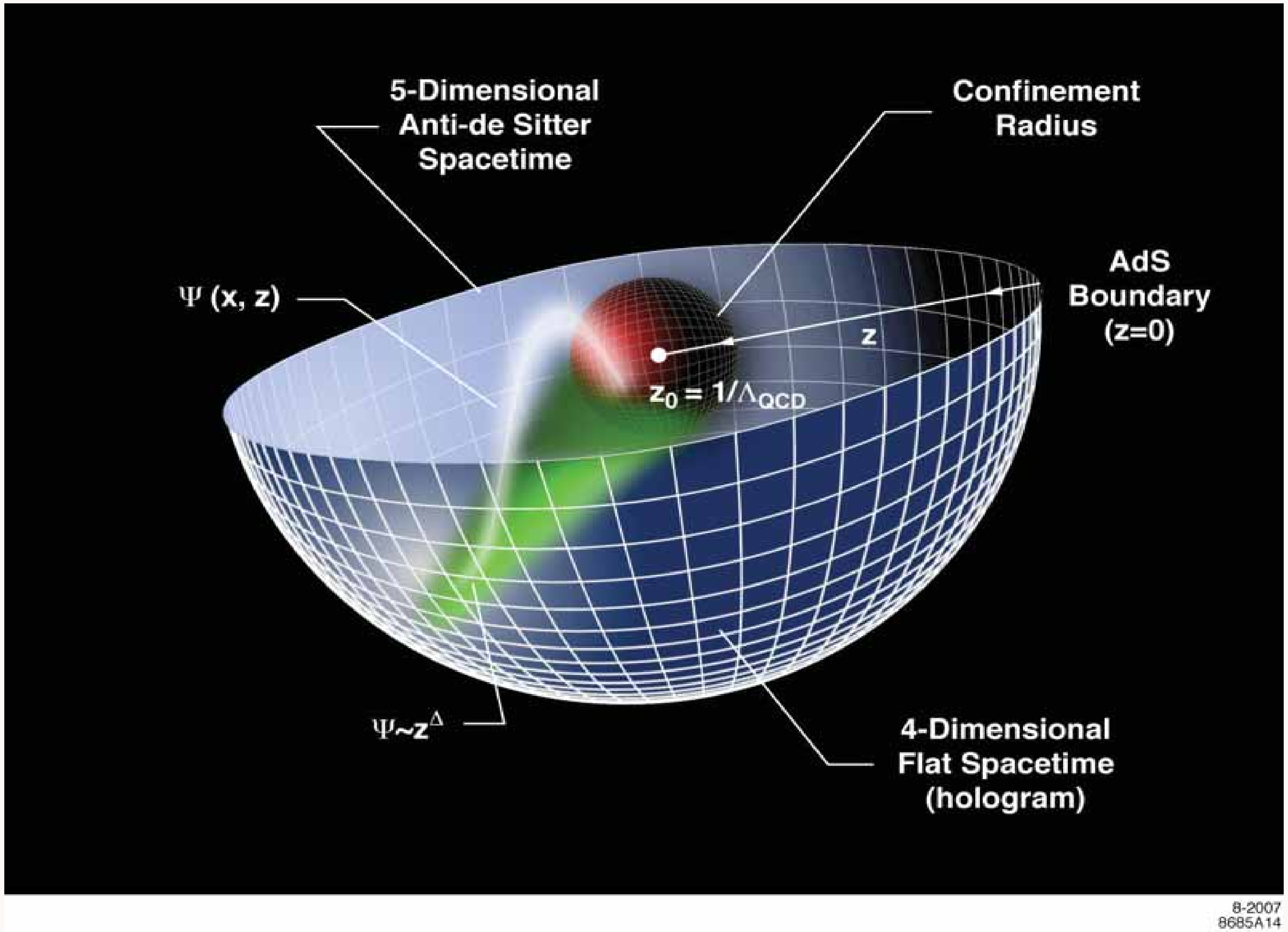
Reproduces lab-frame color dipole approach

Final State Interactions in QCD



Feynman Gauge　　　　Light-Cone Gauge

Result is Gauge Independent

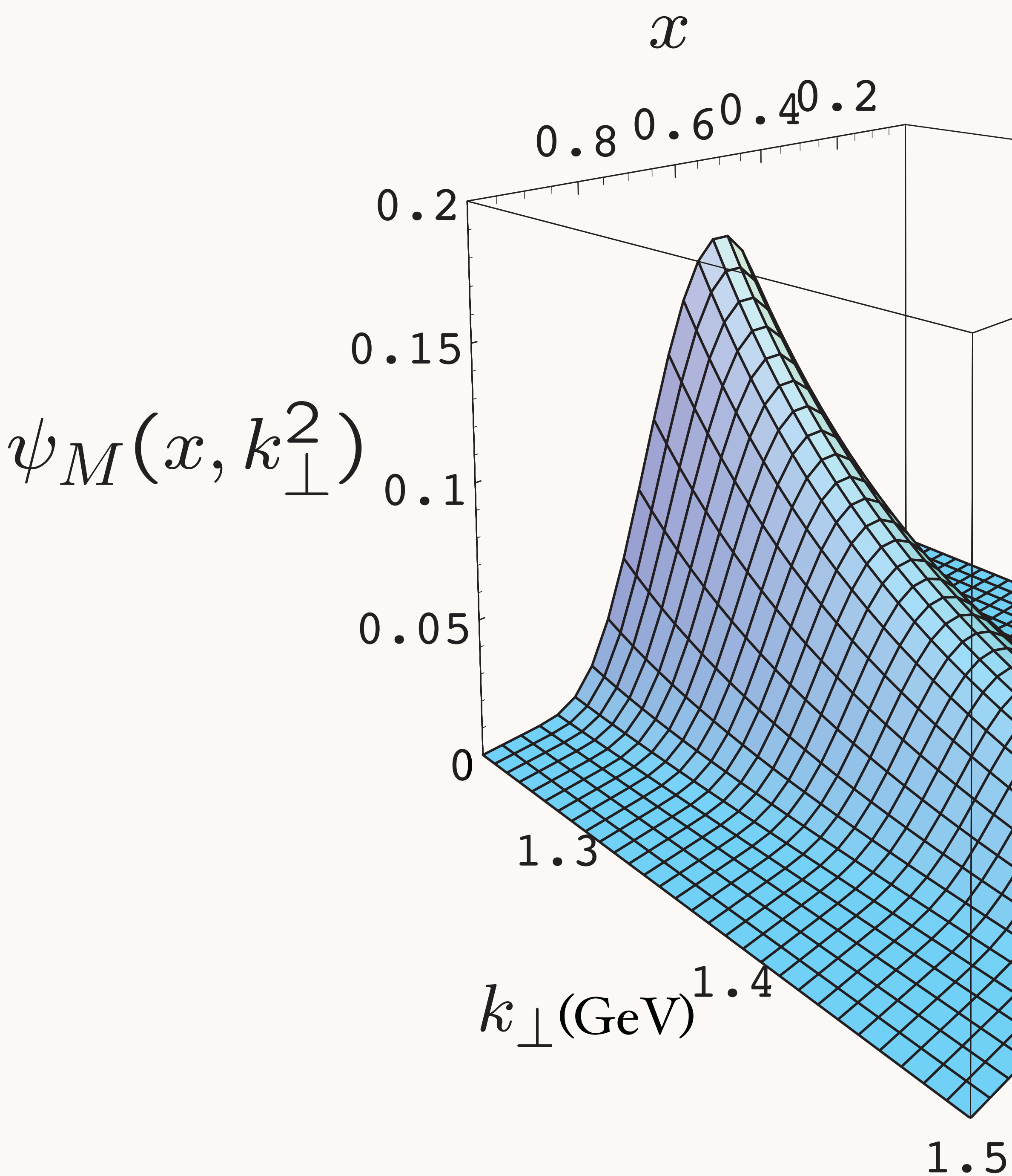


- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\rm QCD}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model) Polchinski and Strassler (2001).

- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model) Karch, Katz, Son and Stephanov (2006).

We will consider both holographic models

Prediction from AdS/CFT: Meson LFWF



"Soft Wall" model

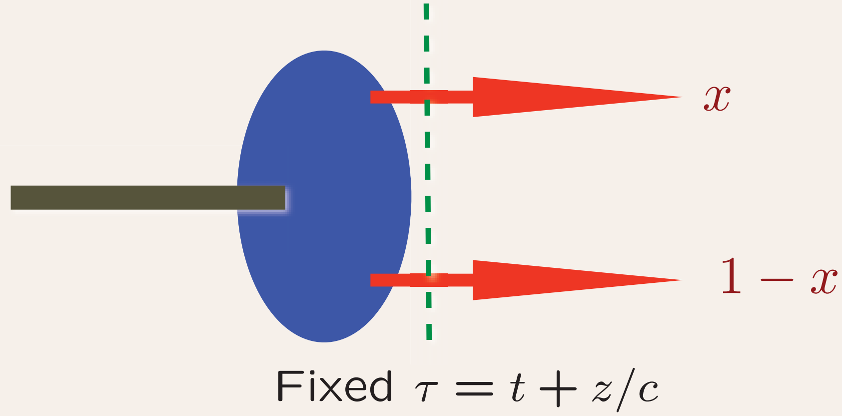
de Teramond, sjb

Hadron Distribution Amplitudes

Lepage, sjb

$$\phi_H(x_i, Q)$$

$$\sum_i x_i = 1$$



$k_\perp^2 < Q^2$

- Fundamental gauge invariant non-perturbative input to hard exclusive processes, heavy hadron decays. Defined for Mesons, Baryons

- Evolution Equations from PQCD, OPE, Conformal Invariance

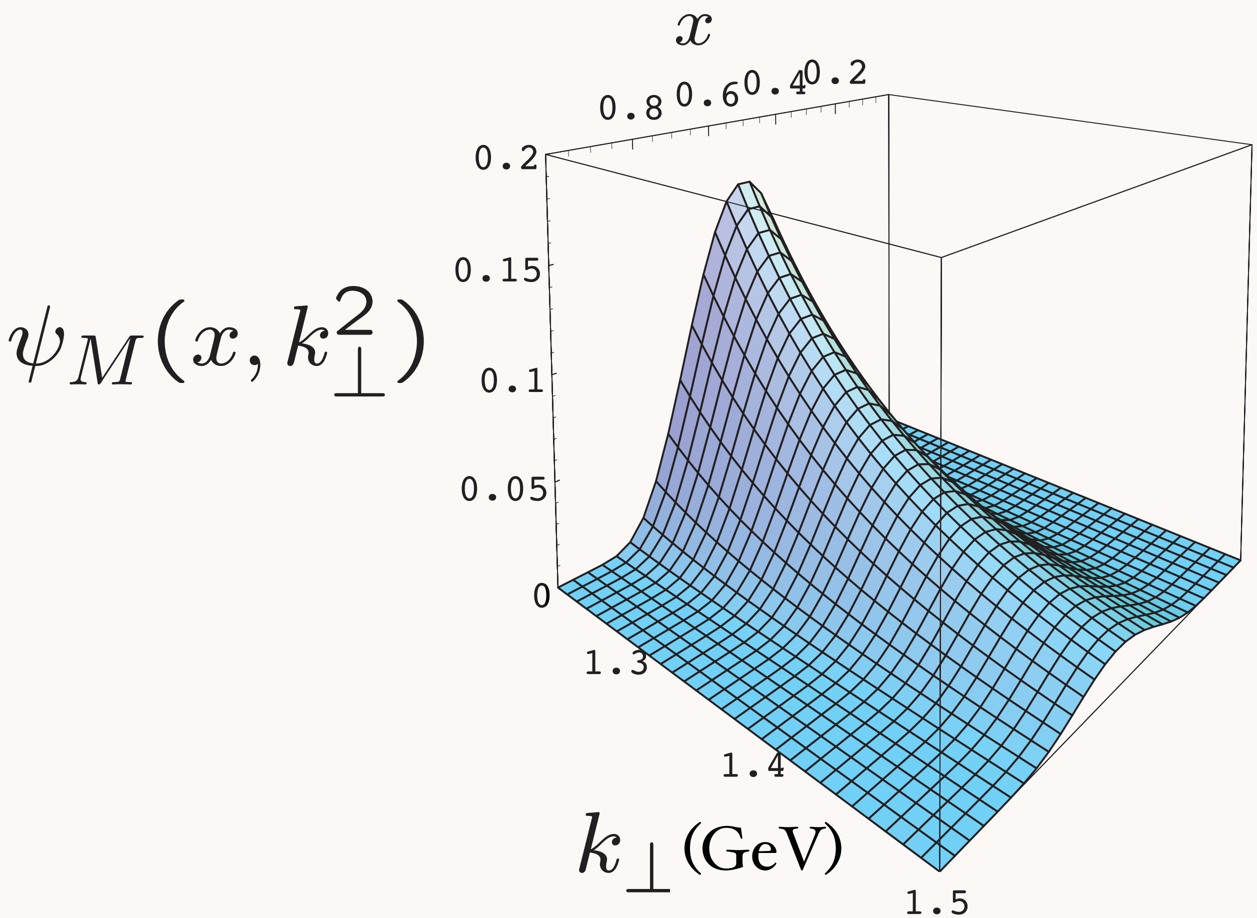
Lepage, sjb
Frishman, Lepage, Sachrajda, sjb
Peskin Braun
Efremov, Radyushkin Chernyak etal

- Compute from valence light-front wavefunction in light-cone gauge

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

Prediction from AdS/CFT: Meson LFWF

de Teramond, sjb



"Soft Wall" model

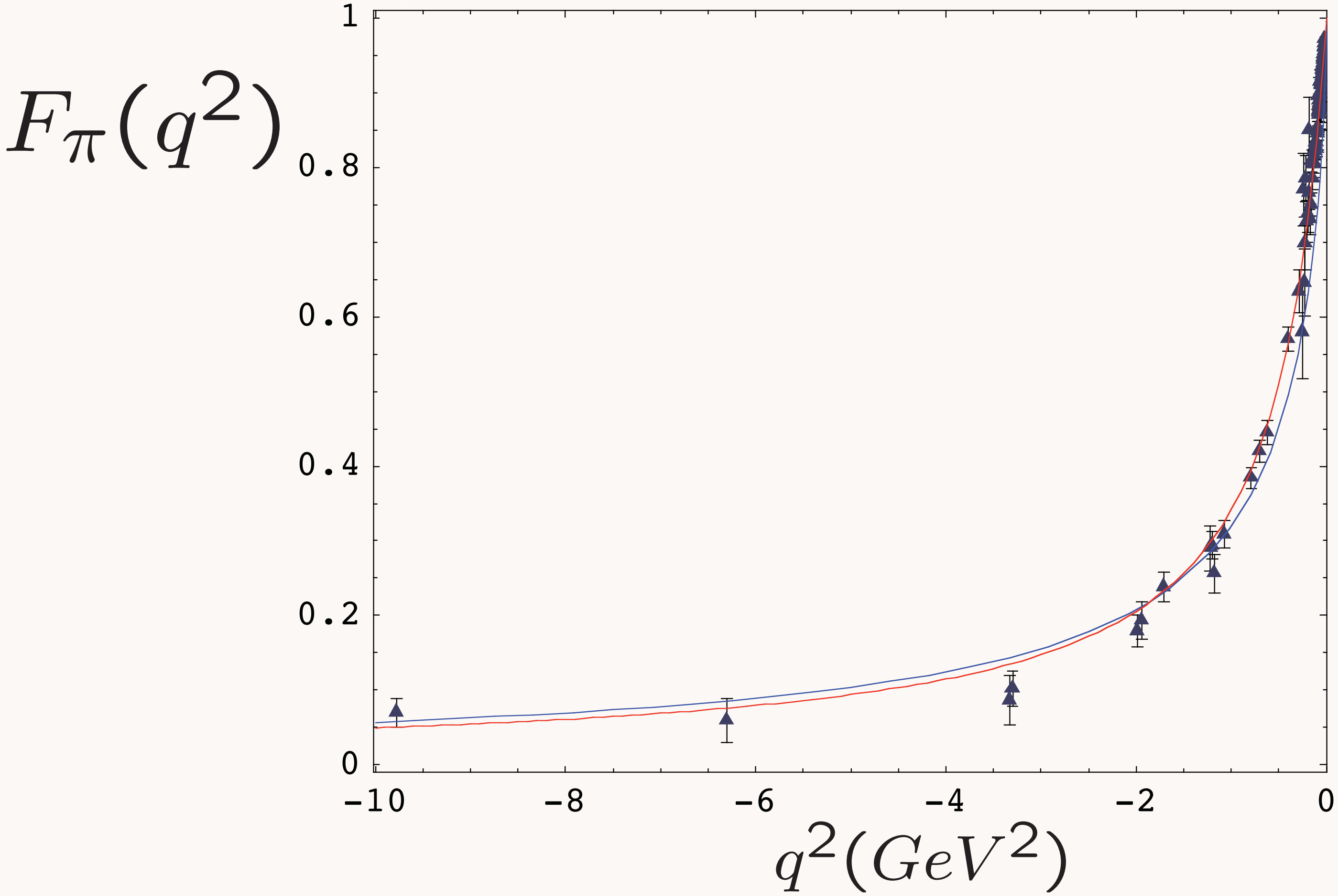
$\kappa = 0.375$ GeV

massless quarks

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

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

Spacelike pion form factor from AdS/CFT



Data Compilation
Baldini, Kloe and Volmer

Soft Wall: Harmonic Oscillator Confinement

Hard Wall: Truncated Space Confinement

One parameter - set by pion decay constant

de Teramond, sjb

See also: Radyushkin