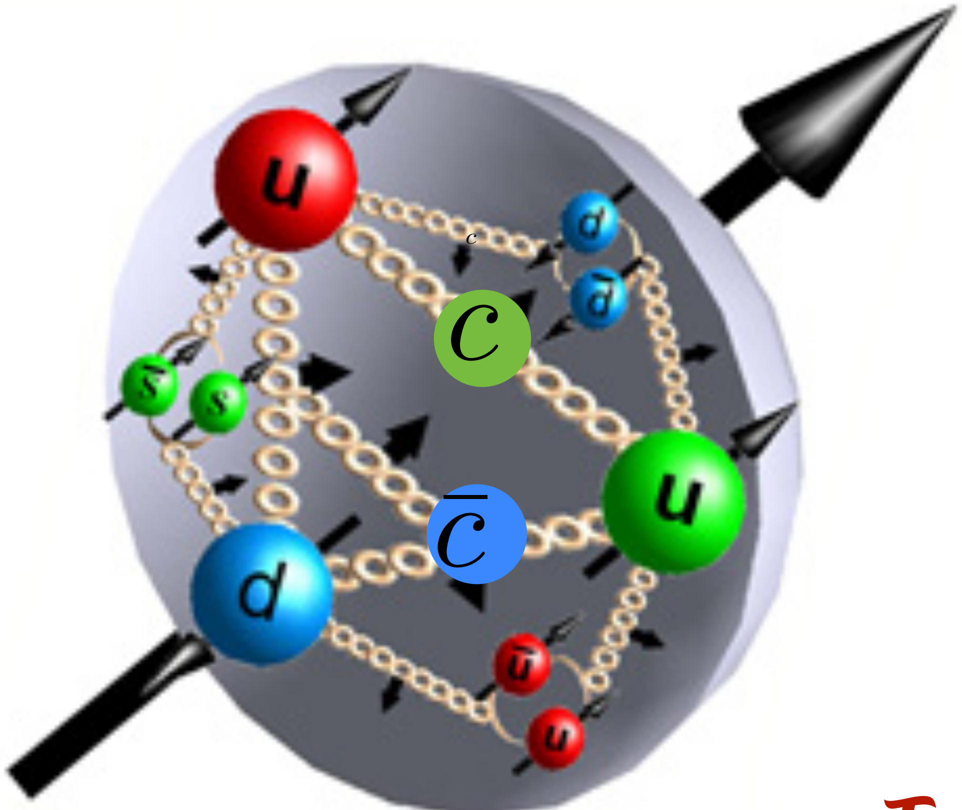
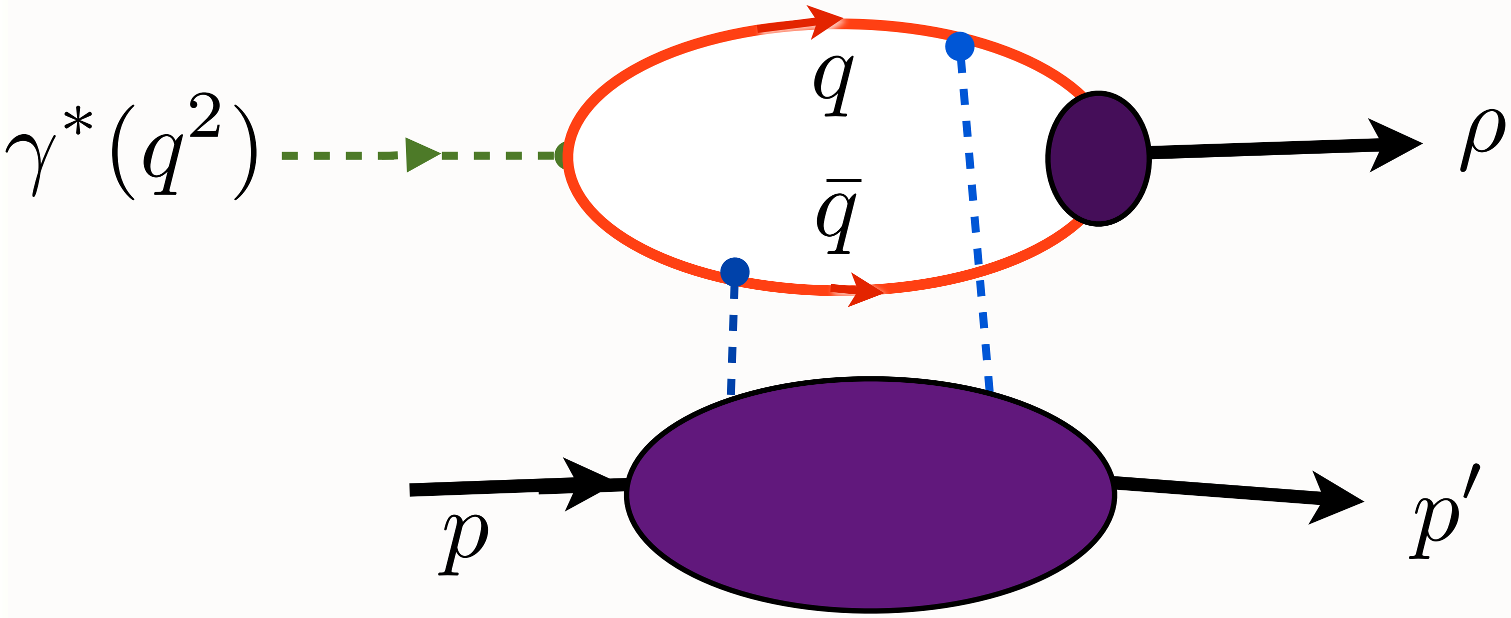
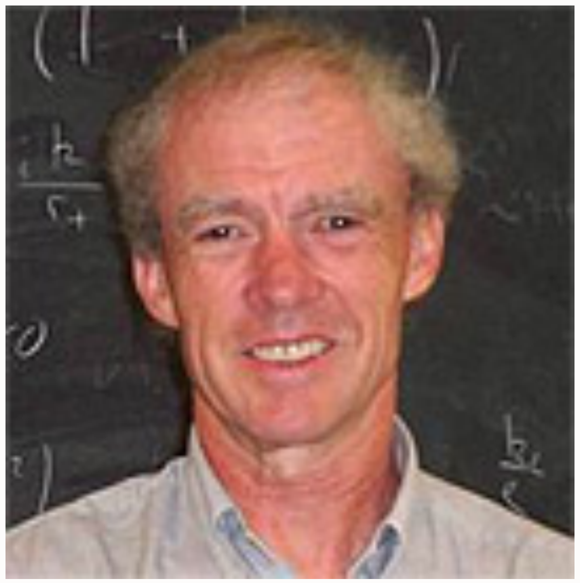
Exclusive Processes and New Perspectives for QCD





Jack Gunion Fest

March 28-29, 2014
University of California, Davis



Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

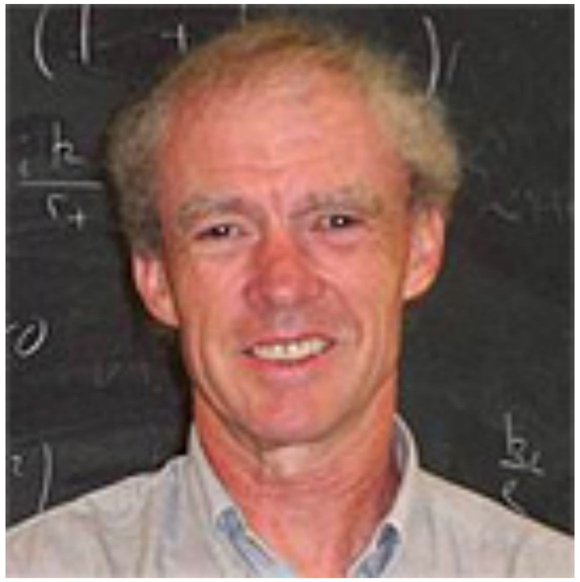
31 Joint Papers!!

Composite Theory of Large Angle Scattering and New Tests of Parton Concepts
J.F. Gunion, Stanley J. Brodsky, Richard Blankenbecler (SLAC). Apr 1972. 19 pp.
Published in **Phys.Lett. B39 (1972) 649**
SLAC-PUB-1037

Composite Theory of Inclusive Scattering at Large Transverse Momenta
J.F. Gunion, Stanley J. Brodsky, Richard Blankenbecler (SLAC). Jun 1972. 21 pp.
Published in **Phys.Rev. D6 (1972) 2652**
SLAC-PUB-1053

Large Angle Scattering and the Interchange Force
J.F. Gunion, Stanley J. Brodsky, Richard Blankenbecler (SLAC). Feb 1973. 76 pp.
Published in **Phys.Rev. D8 (1973) 287**
SLAC-PUB-1183
DOI: 10.1103/PhysRevD.8.287

The Connection Between Regge Behavior And Fixed Angle Scattering
Richard Blankenbecler, Stanley J. Brodsky (SLAC), J.F. Gunion (MIT, LNS), R. Savit (SLAC).
Aug 1973. 56 pp.
Published in **Phys.Rev. D8 (1973) 4117**
SLAC-PUB-1294



SLAC 1972, 1973

$$\frac{d\sigma}{dt}(AB \to CD)$$

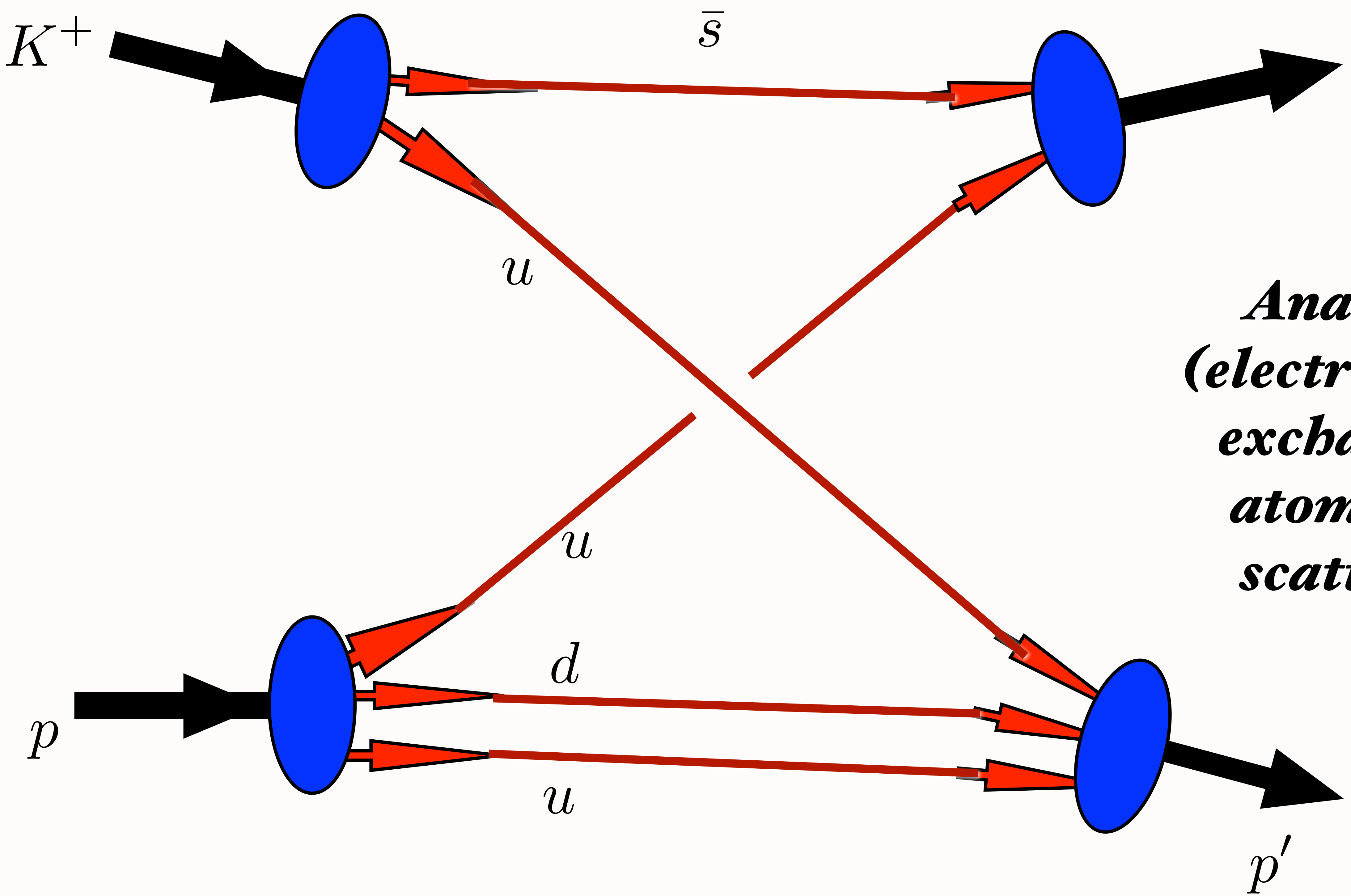
at high transverse momentum

$$\pi p \to \pi p$$

$$pp \to pp$$

$$\gamma p \to K\Lambda$$

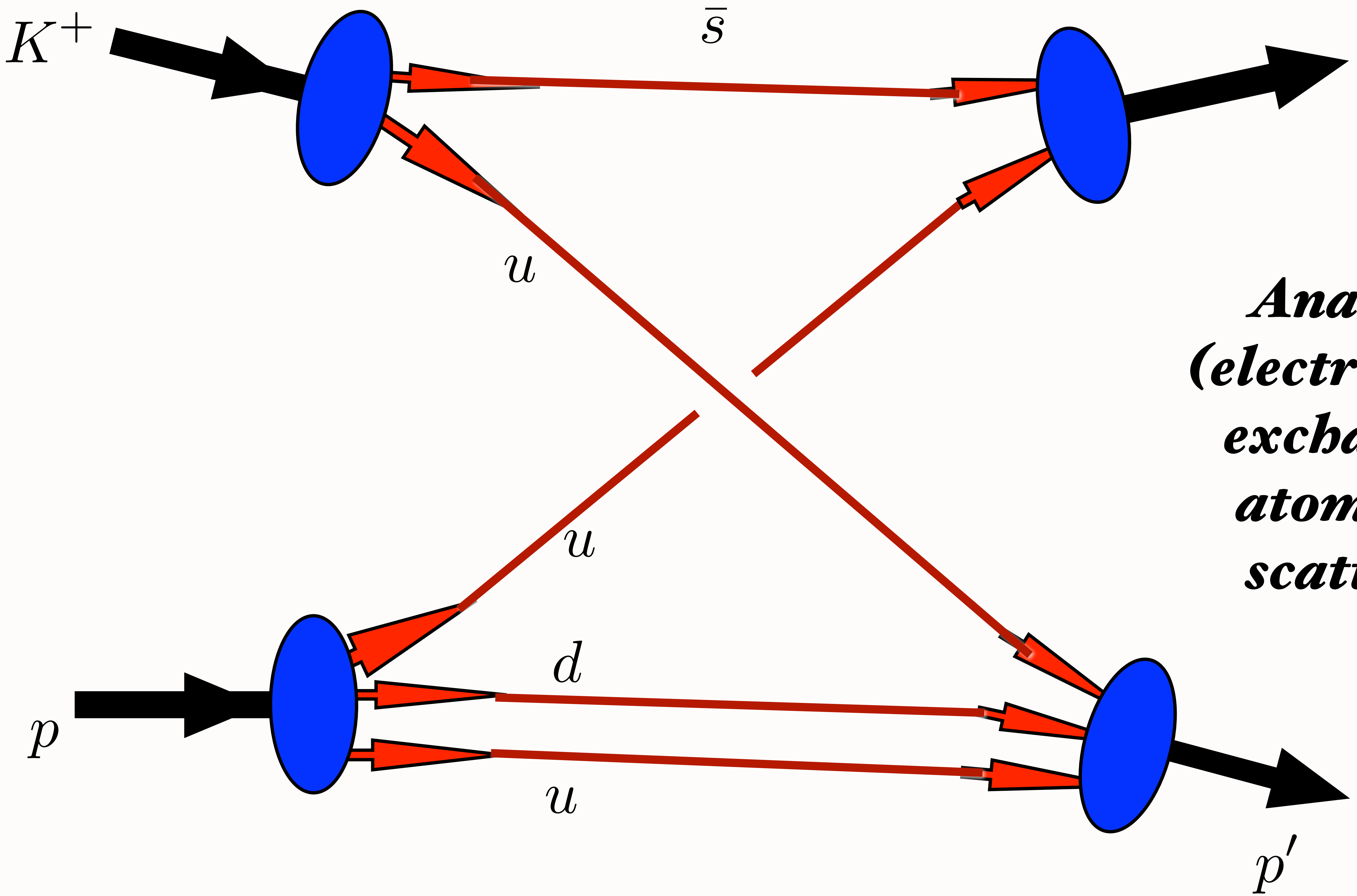
- *Pioneering papers on Hard Exclusive Processes*
- *Fixed-Angle Scaling, Angular Dependence*
- *Dominance of Quark Interchange*
- *Reggeons recede to negative integers!* $\alpha_R(t) \to -1$ at large negative t



Analog of (electron) spin exchange in atom atom scattering

Constituent Interchange Model (CIM)

Blankenbecler, Gunion, sjb (1972)

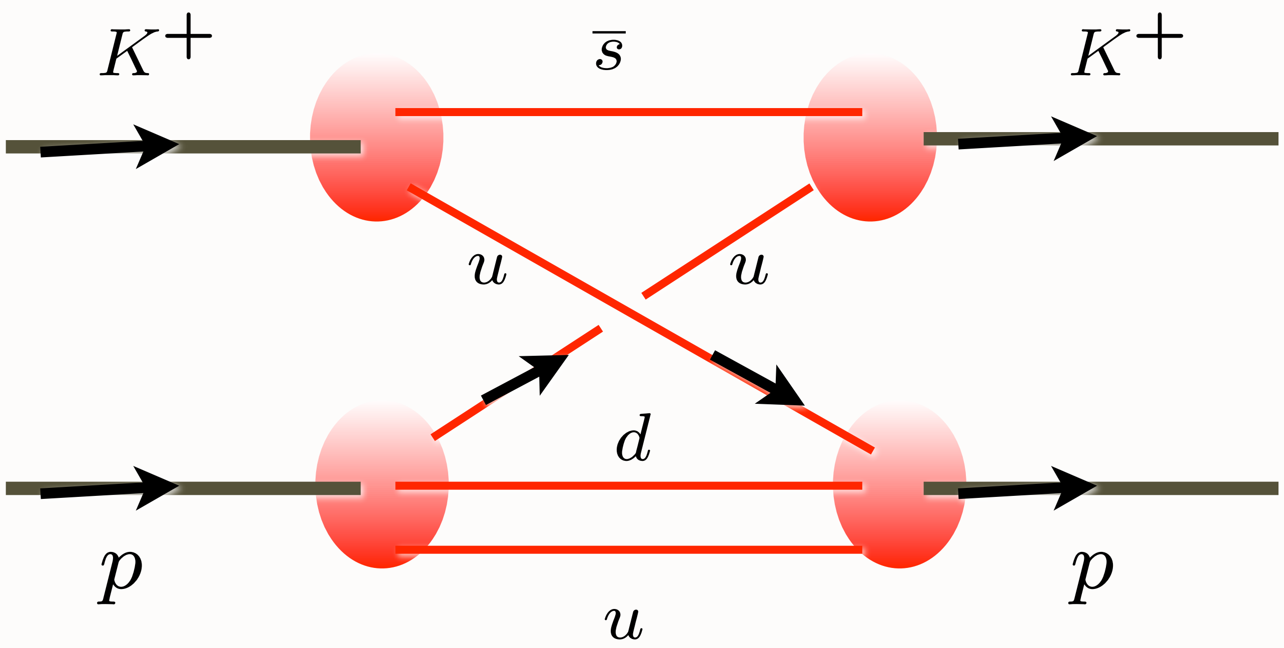


Analog of (electron) spin exchange in atom atom scattering

Constituent Interchange Model (CIM)

Blankenbecler, Gunion, sjb (1972)

CIM: Blankenbecler, Gunion, sjb



$$\frac{d\sigma}{dt} = \frac{|M(s,t)|^2}{s^2}$$

$$M(t,u)_{\text{interchange}} \propto \frac{1}{ut^2}$$

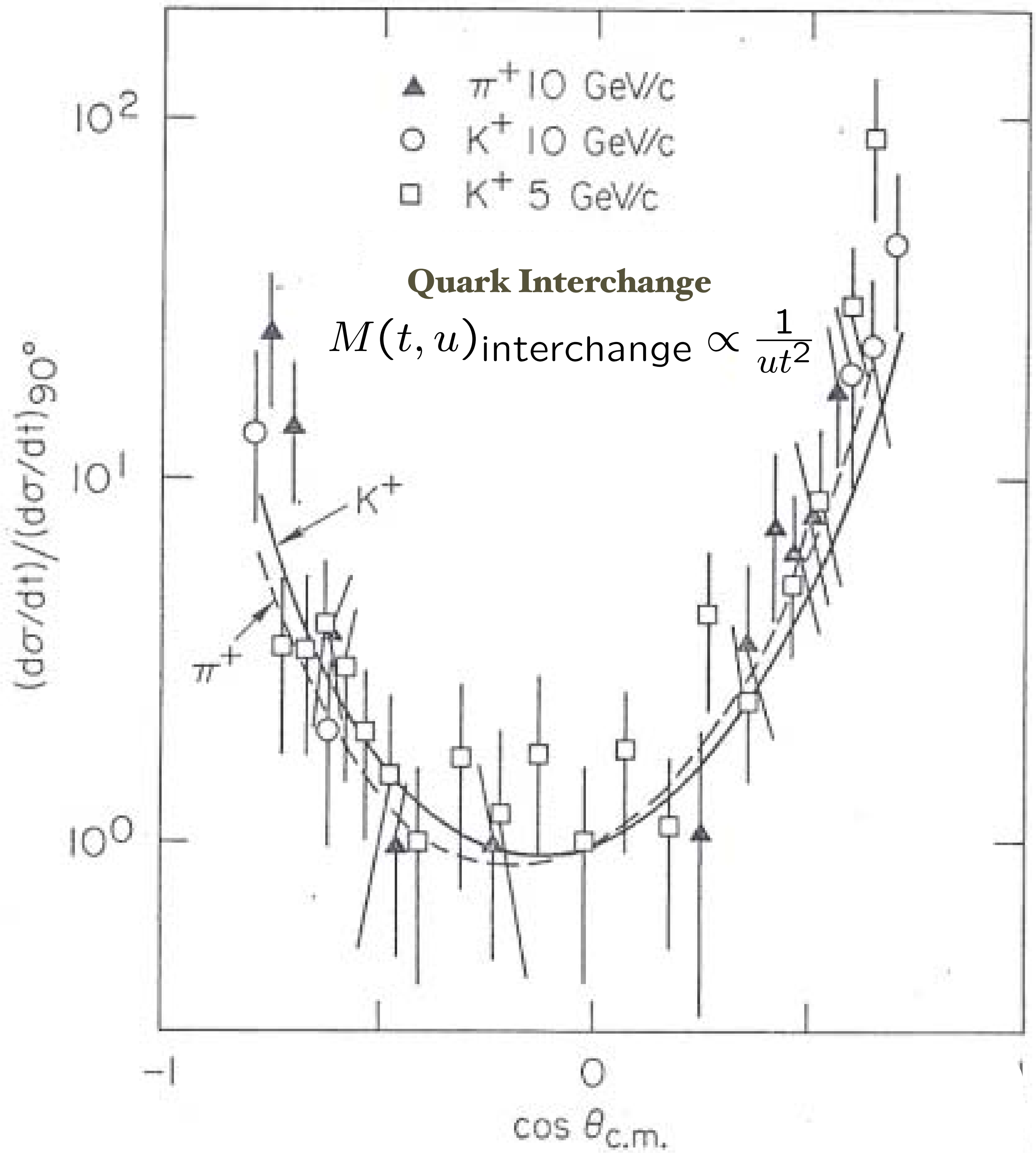
$$M(s,t)_{A+B\to C+D}$$

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

$$\Delta = s - \sum_i \frac{k^2_{\perp i} + m_i^2}{x_i}$$

Agrees with electron exchange in atom-atom scattering in nonrelativistic limit

$$K^+ p \rightarrow K^+ p$$



AdS/CFT explains why quark interchange is dominant interaction at high momentum transfer in exclusive reactions

$$M(t,u)_{\text{interchange}} \propto \frac{1}{ut^2}$$

$$\frac{d\sigma}{dt}(K^+ p \rightarrow K^+ p) \propto \frac{1}{s^2 u^2 t^4}$$

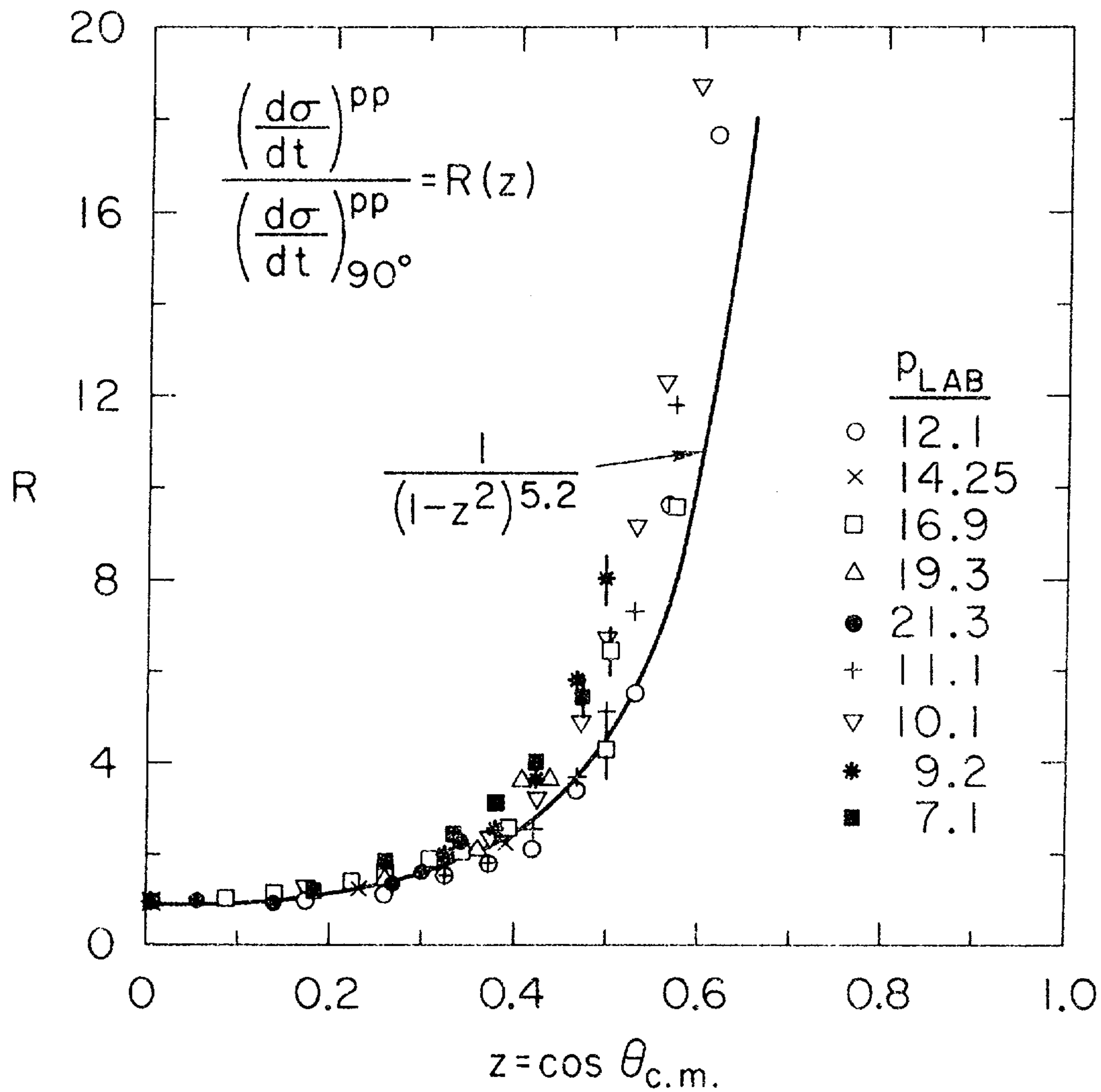
Non-linear Regge behavior:

$$\alpha_R(t) \rightarrow -1$$

$$\frac{d\sigma}{dt}(MB \rightarrow MB) = \frac{F(\theta_{cm})}{s^8} \text{ at fixed } \theta_{cm}$$

Test of BBG Quark Interchange Mechanism

Test of BBG Quark Interchange Mechanism in $pp \to pp$

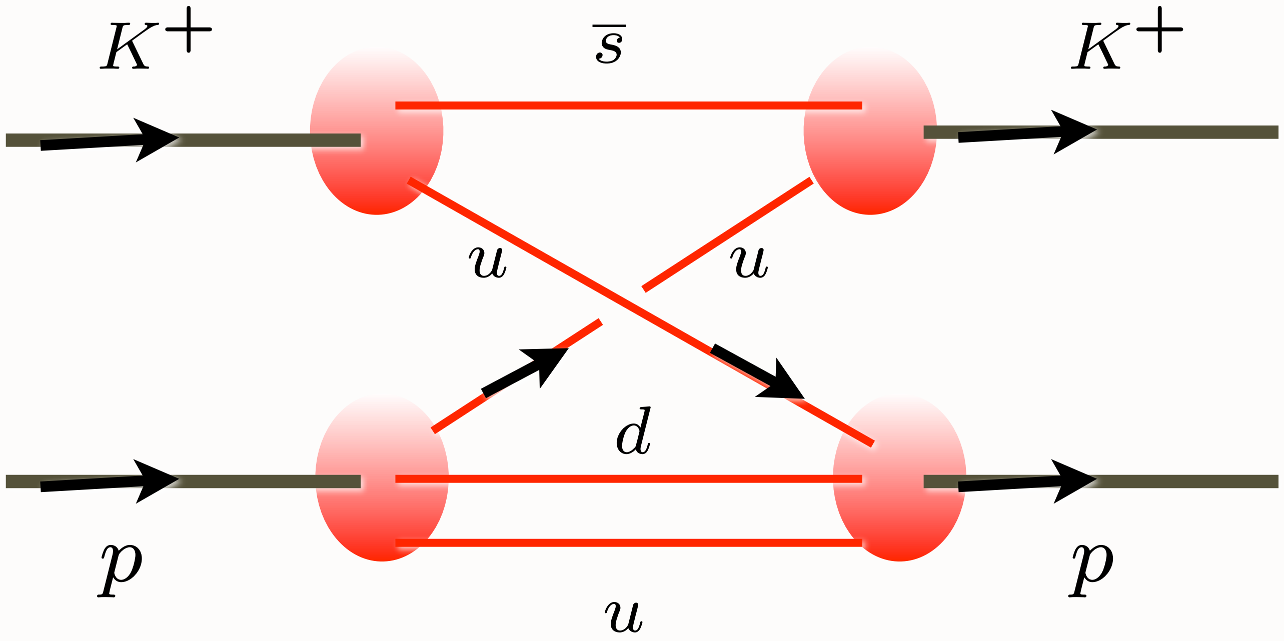


$$\frac{d\sigma}{dt}(pp \to pp) \propto \frac{1}{s^2 u^4 t^4}$$

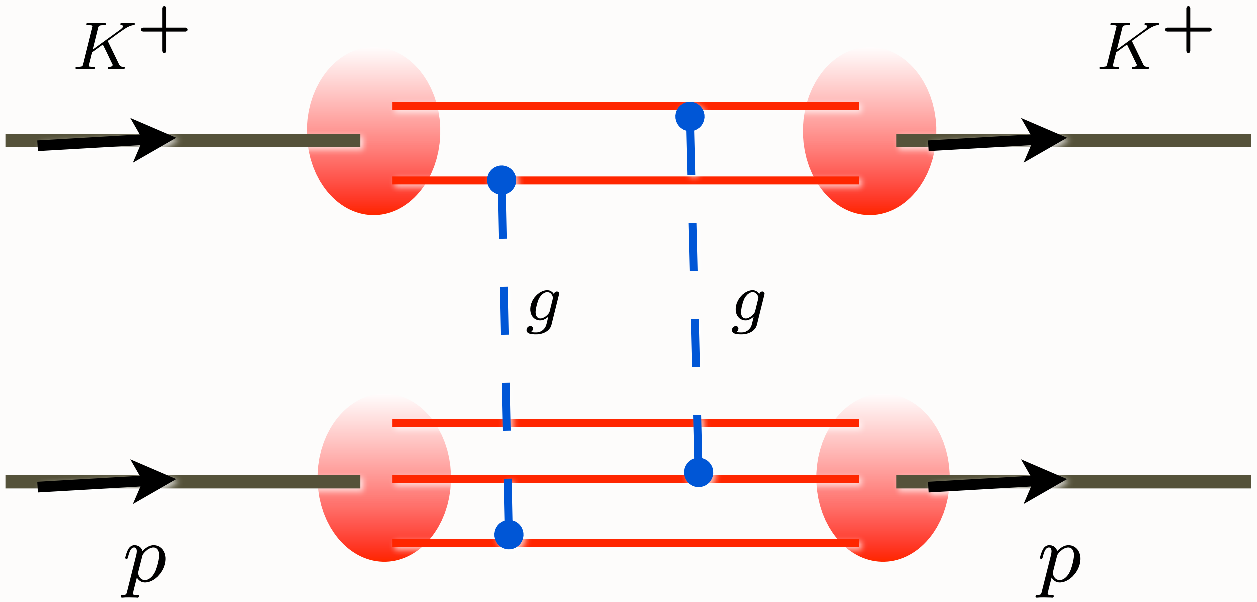
$$\frac{d\sigma}{dt}(pp \to pp) = \frac{F(\theta_{cm})}{s^{10}} \text{ at fixed } \theta_{cm}$$

$$\alpha_R(t) \to -2$$

CIM: Blankenbecler, Gunion, sjb



Quark Interchange
(Spin exchange in atom-atom scattering)



Gluon Exchange
(Van der Waal -- Landshoff)

$$\frac{d\sigma}{dt} = \frac{|M(s,t)|^2}{s^2}$$

$$M(t,u)_{\text{interchange}} \propto \frac{1}{ut^2}$$

$$M(s,t)_{\text{gluonexchange}} \propto sF(t)$$

Comparison of Exclusive Reactions at Large t

B. R. Baller,[a] G. C. Blazey,[b] H. Courant, K. J. Heller, S. Heppelmann,[c] M. L. Marshak, E. A. Peterson, M. A. Shupe, and D. S. Wahl[d]
University of Minnesota, Minneapolis, Minnesota 55455

D. S. Barton, G. Bunce, A. S. Carroll, and Y. I. Makdisi
Brookhaven National Laboratory, Upton, New York 11973

and

S. Gushue[e] and J. J. Russell
Southeastern Massachusetts University, North Dartmouth, Massachusetts 02747
(Received 28 October 1987; revised manuscript received 3 February 1988)

Cross sections or upper limits are reported for twelve meson-baryon and two baryon-baryon reactions for an incident momentum of 9.9 GeV/c, near 90° c.m.: $\pi^{\pm}p \rightarrow p\pi^{\pm}, p\rho^{\pm}, \pi^{+}\Delta^{\pm}, K^{+}\Sigma^{\pm}, (\Lambda^0/\Sigma^0)K^0$; $K^{\pm}p \rightarrow pK^{\pm}$; $p^{\pm}p \rightarrow pp^{\pm}$. By studying the flavor dependence of the different reactions, we have been able to isolate the quark-interchange mechanism as dominant over gluon exchange and quark-antiquark annihilation.

$\pi^{\pm}p \rightarrow p\pi^{\pm}$,

$K^{\pm}p \rightarrow pK^{\pm}$,

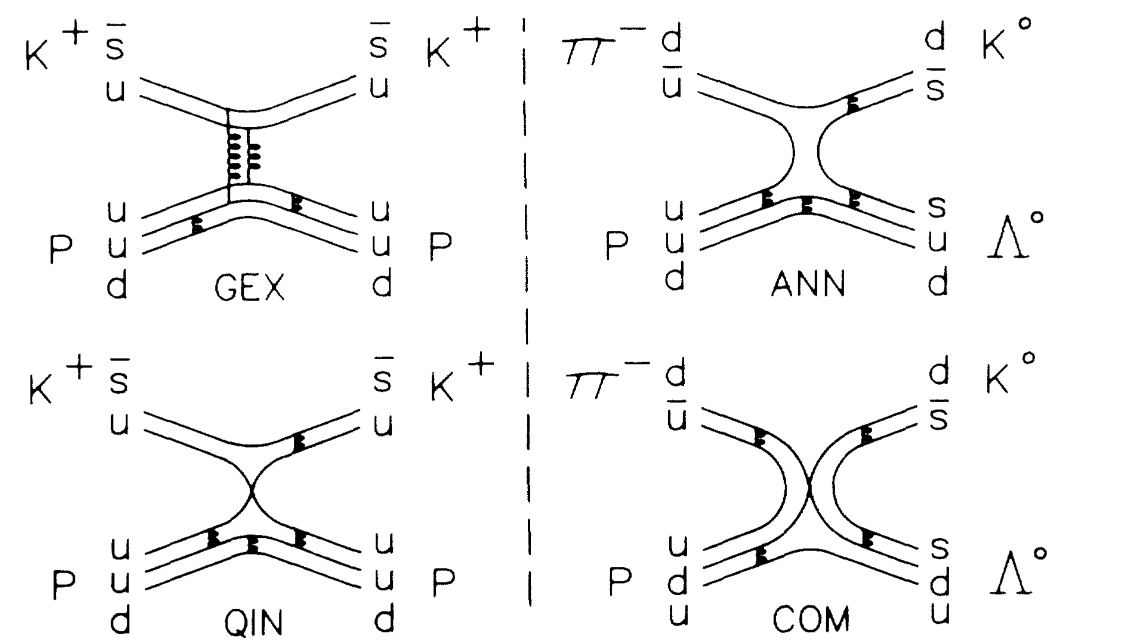
$\pi^{\pm}p \rightarrow p\rho^{\pm}$,

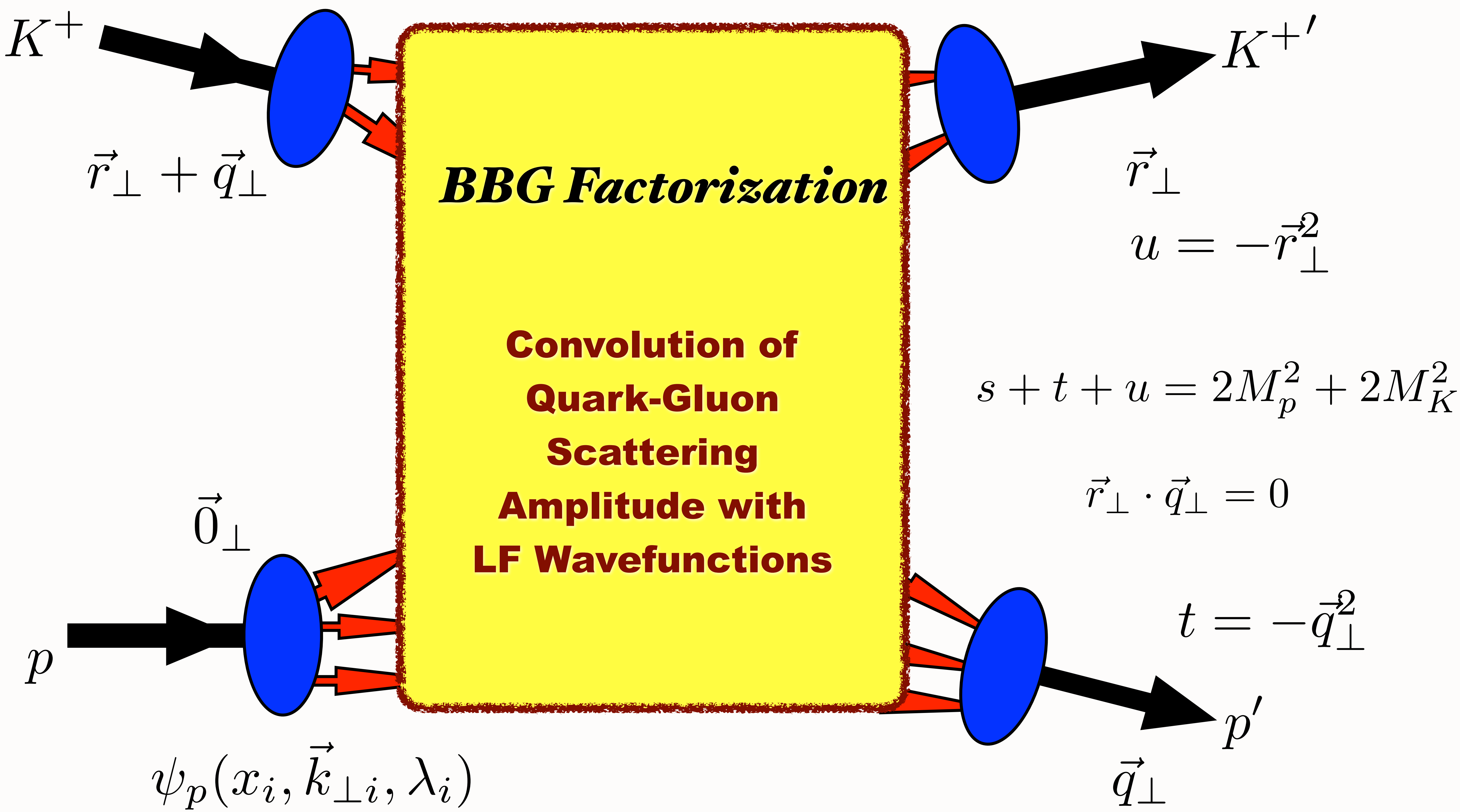
$\pi^{\pm}p \rightarrow \pi^{+}\Delta^{\pm}$,

$\pi^{\pm}p \rightarrow K^{+}\Sigma^{\pm}$,

$\pi^{-}p \rightarrow \Lambda^0K^0, \Sigma^0K^0$,

$p^{\pm}p \rightarrow pp^{\pm}$.

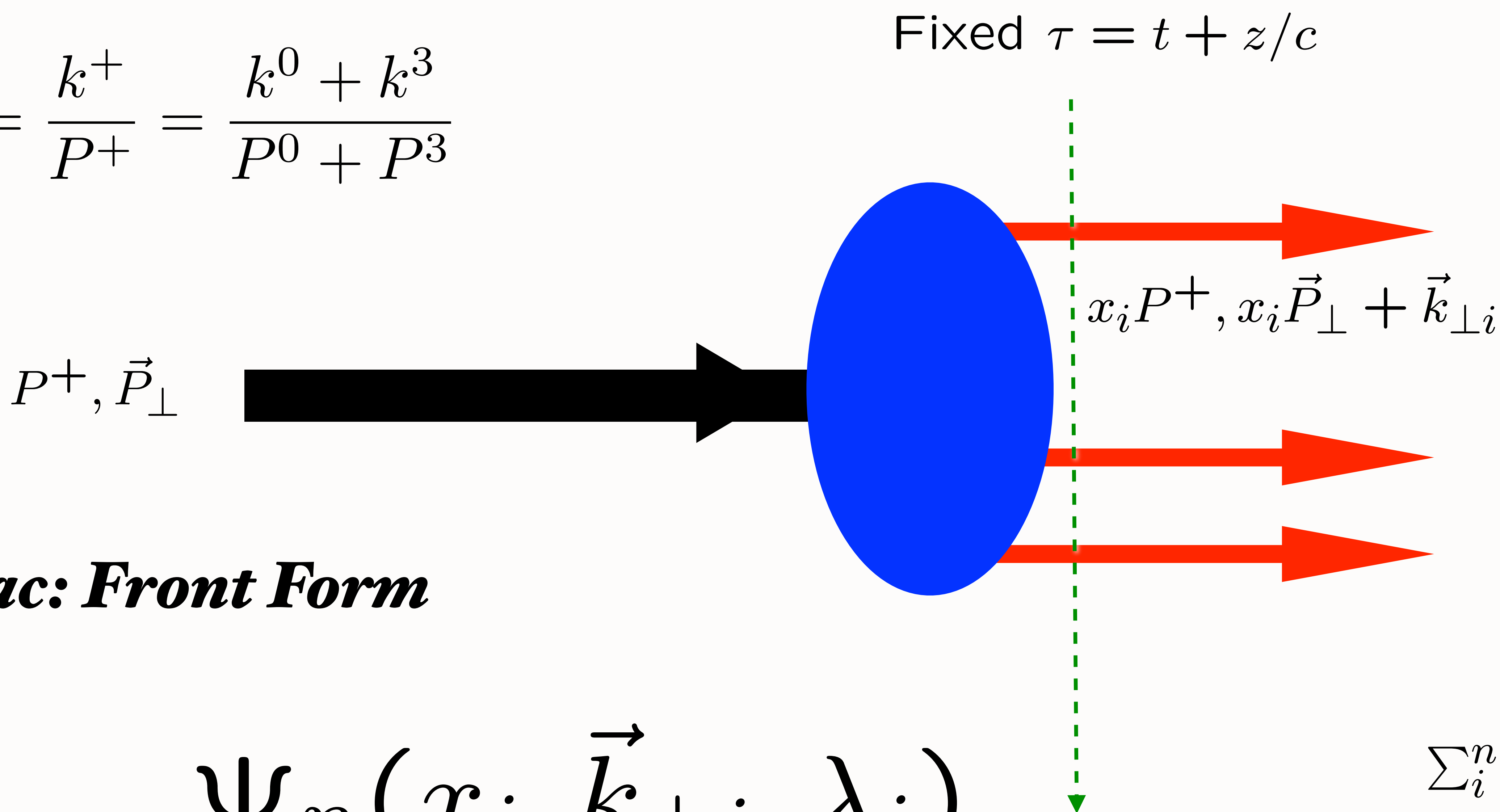




BBG: Light-Front Wavefunctions
(frame-independent)

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

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



Dirac: Front Form

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

$\sum_i^n x_i = 1$

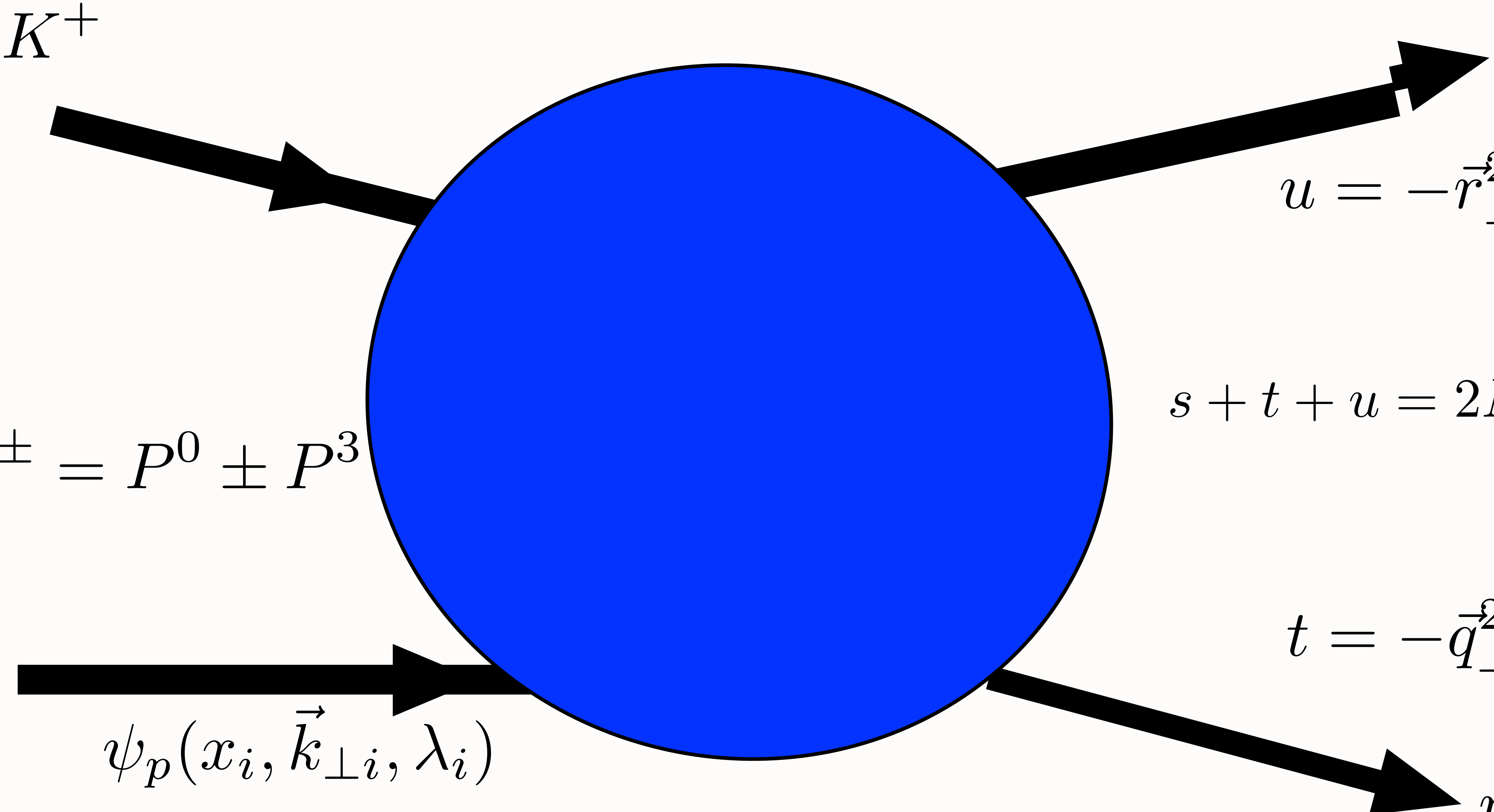
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Invariant under boosts! Independent of P^μ

Causal, Frame-independent, Simple Vacuum,
Current Matrix Elements are overlap of LFWFS

$$K^\mu = \left(P^+, \frac{M_K^2 + r_\perp^2 + q_\perp^2}{P^+}, \vec{q}_\perp + \vec{r}_\perp\right)$$

$$K^{\mu\prime} = \left(P^+, \frac{M_K^2 + r_\perp^2}{P^+}, \vec{r}_\perp\right)$$



$$u = -\vec{r}_\perp^{\,2}$$

$$s + t + u = 2M_p^2 + 2M_K^2$$

$$P^\pm = P^0 \pm P^3$$

$$t = -\vec{q}_\perp^{\,2}$$

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

$$P^\mu = (P^+, P^-, \vec{P}_\perp) = \left(P^+, \frac{M_p^2}{P^+}, \vec{0}_\perp\right)$$

$$P^{\mu\prime} = \left(P^+, \frac{M_p^2 + q_\perp^2}{P^+}, \vec{q}_\perp\right)$$

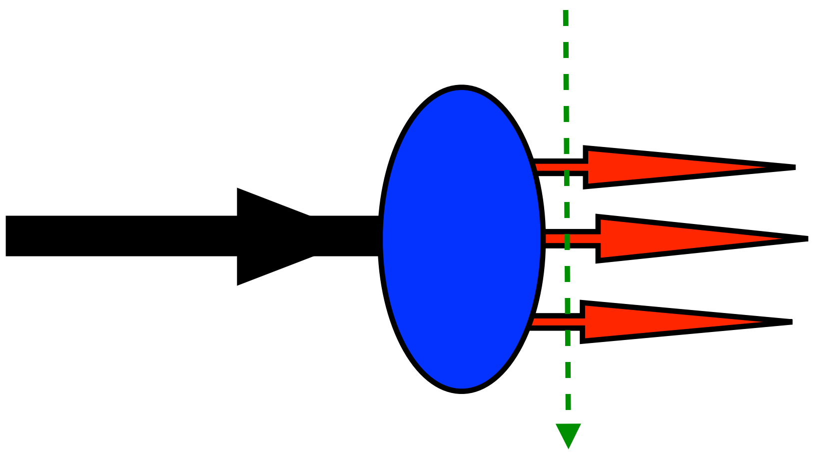
BBG: Remarkable LF Frame

Bj: "Fool's ISR Frame"

Ideal for
QCD factorization proofs
Single A+=0 Gauge

Light-Front Wavefunctions

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



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

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

Invariant under boosts. Independent of P^μ

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

Direct connection to QCD Lagrangian

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

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

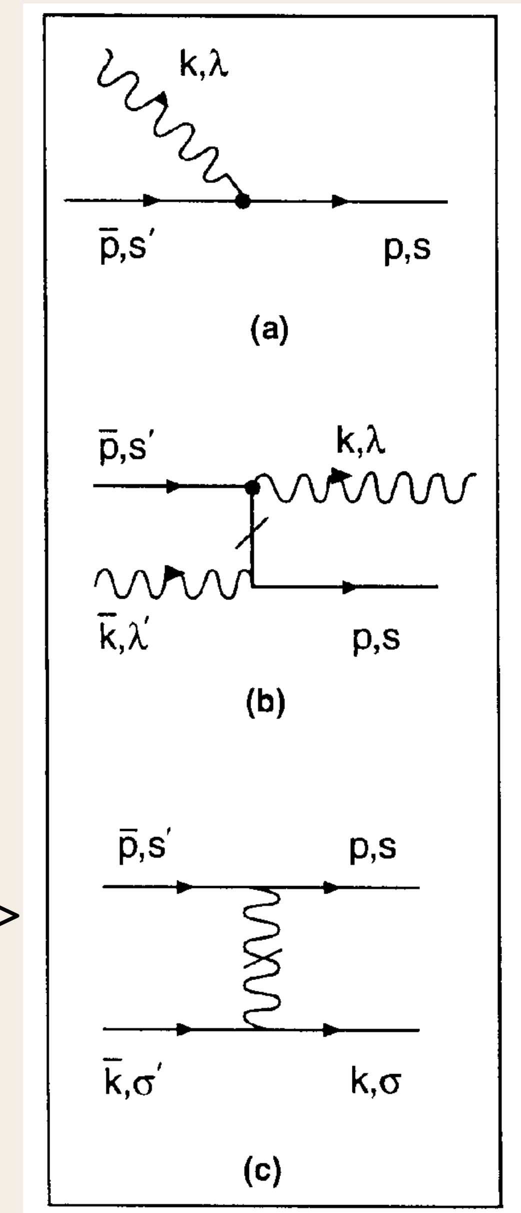
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$

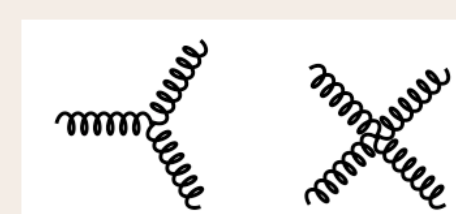
H^{int}_{LF}: Matrix in Fock Space

$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$

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



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions



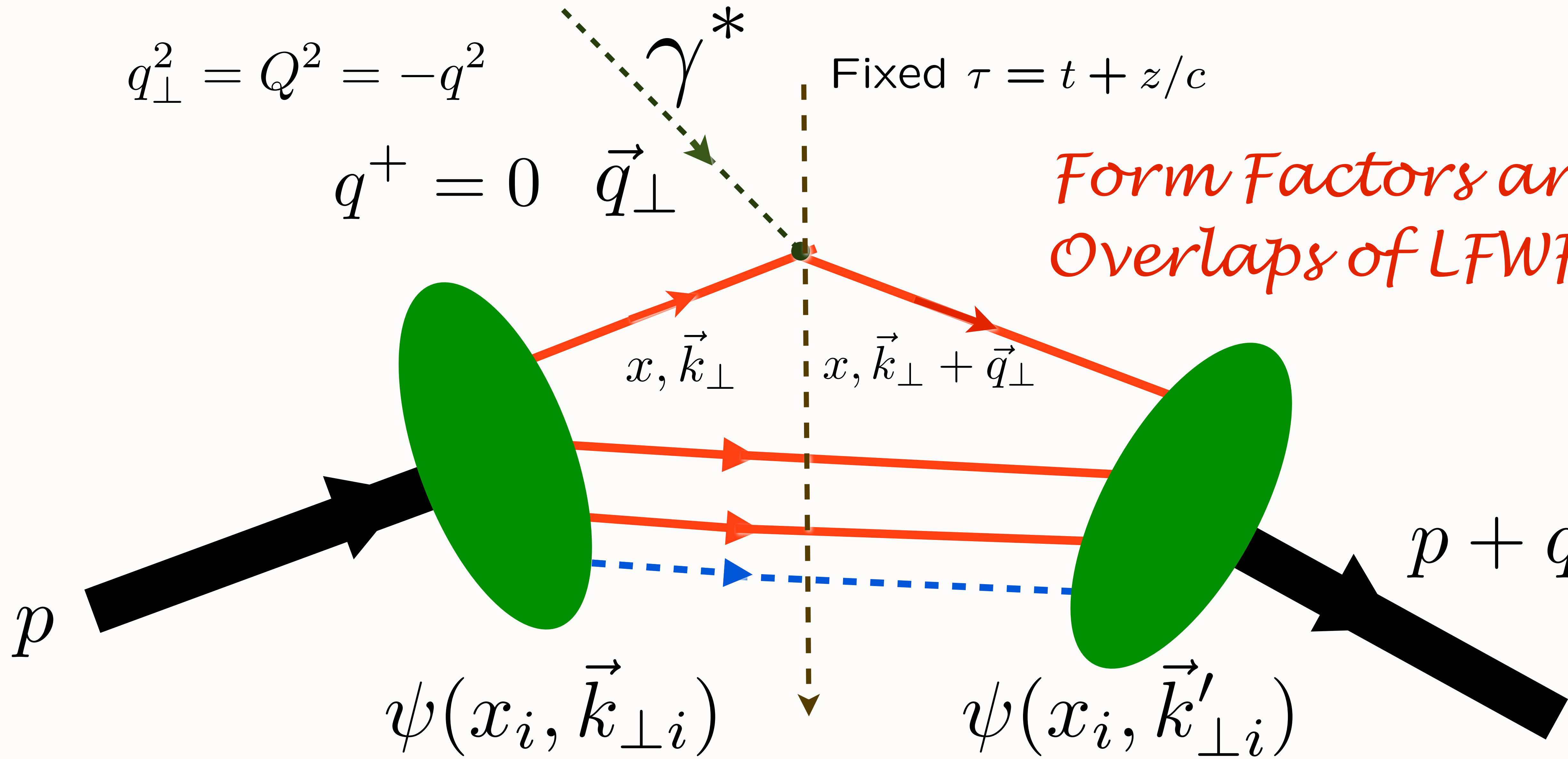
LFWFs: Off-shell in P- and invariant mass

H^{int}_{LF}

DLCQ, BLFQ

$$< p+q|j^+(0)|p >= 2p^+F(q^2)$$

Interaction picture



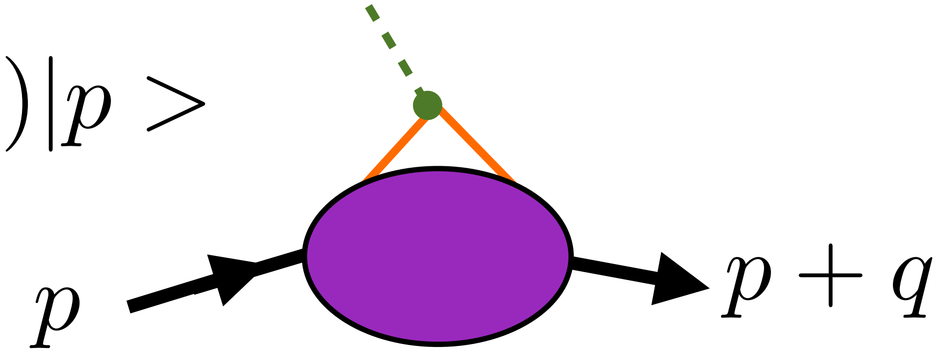
struck $\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

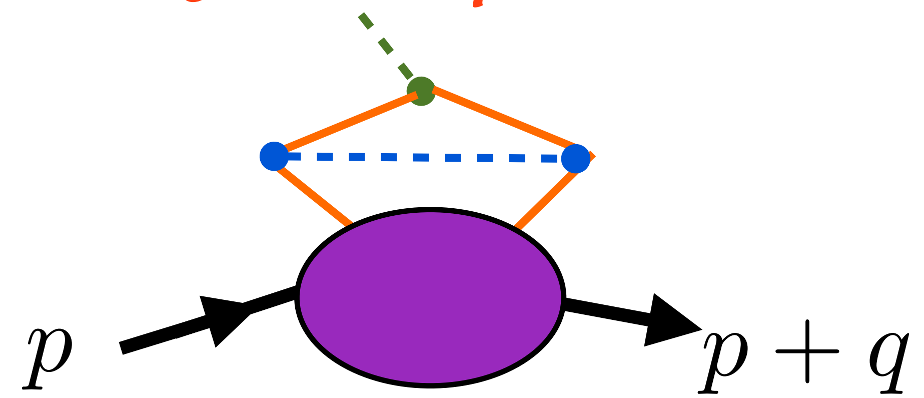
spectators $\vec{k}'_{\perp i} = \vec{k}_{\perp i} - x_i\vec{q}_\perp$

Drell &Yan, West
Drell, sjb
Exact LF formula!

Calculation of proton form factor in Instant Form

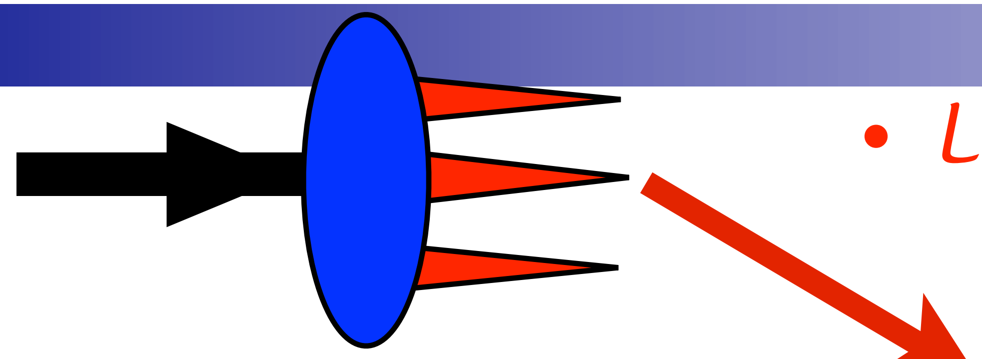
$$< p+q|J^{\mu}(0)|p >$$



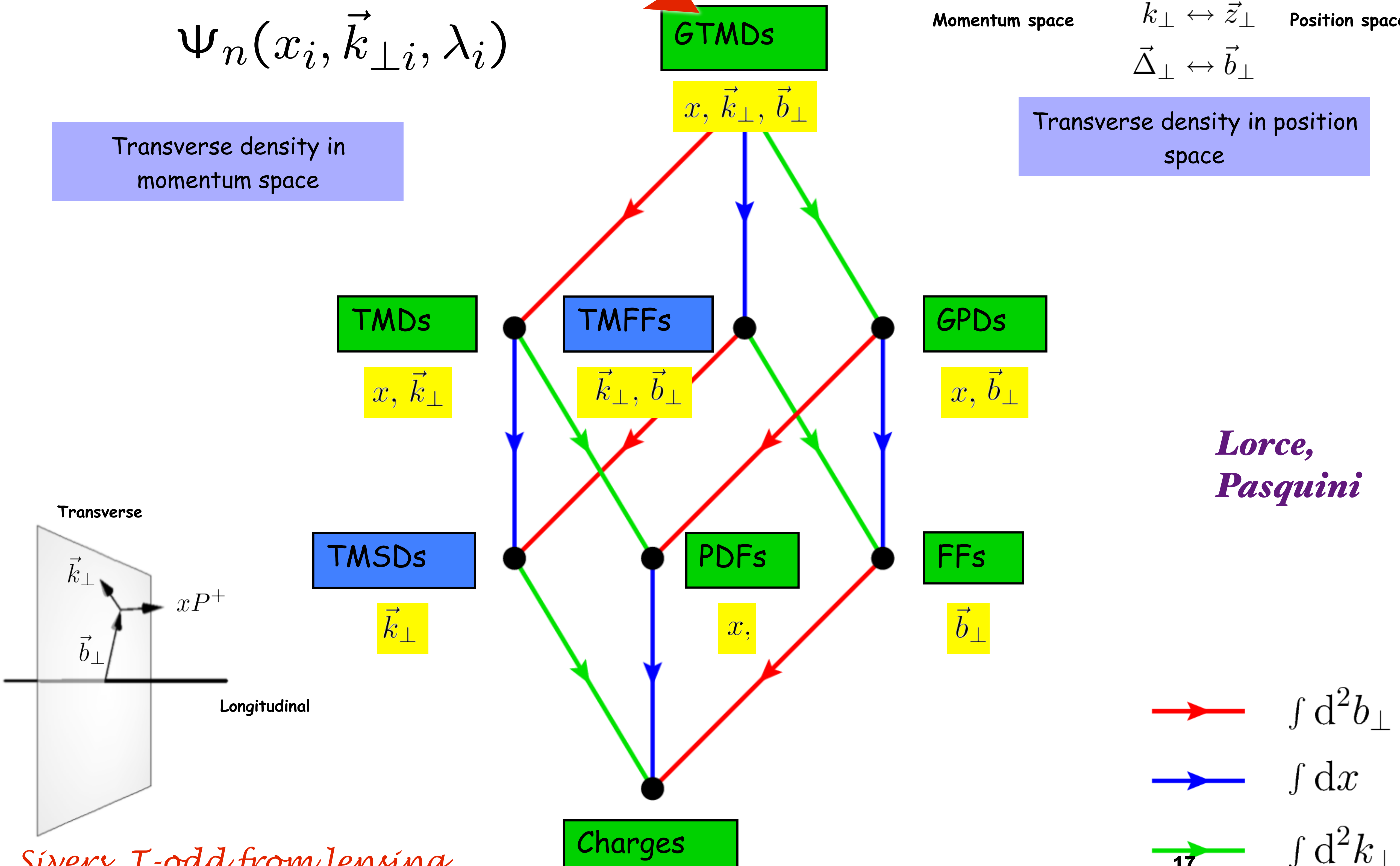


- **Need to boost proton wavefunction from p to p+q: Extremely complicated dynamical problem; particle number changes**
- **Need to couple to all currents arising from vacuum!! Remains even after normal-ordering**
- **Each time-ordered contribution is frame-dependent**

- *Light Front Wavefunctions:*

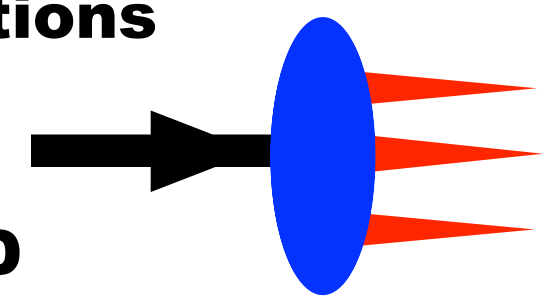


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Lorce, Pasquini

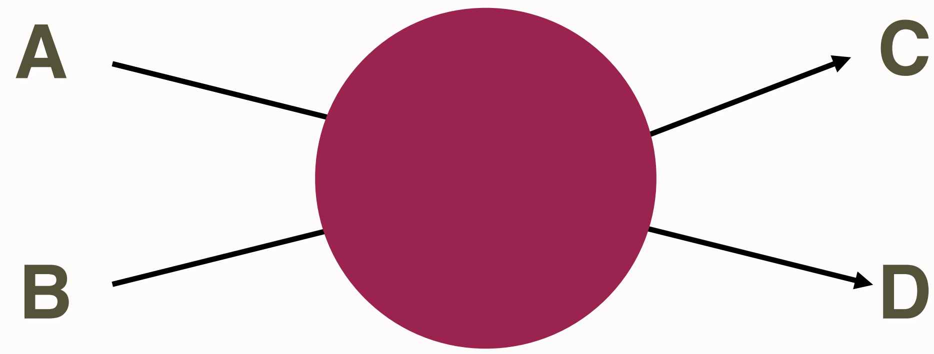
Sivers, T-odd from lensing



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

- **LF wavefunctions play the role of Schrödinger wavefunctions in Atomic Physics**
- **LFWFs=Hadron Eigensolutions: Direct Connection to QCD Lagrangian**
- **Relativistic, frame-independent: no boosts, no disc contraction, Melosh built into LF spinors**
- **Hadronic observables computed from LFWFs: Form factors, Structure Functions, Distribution Amplitudes, GPDs, TMDs, Weak Decays, ... modulo `lensing' from ISIs, FSIs**
- **Cannot compute current matrix elements using instant form from eigensolutions alone -- need to include vacuum currents!**
- **Hadron Physics without LFWFs is like Biology without DNA!**

Counting Rules:
Inspired by BBG



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

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

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

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

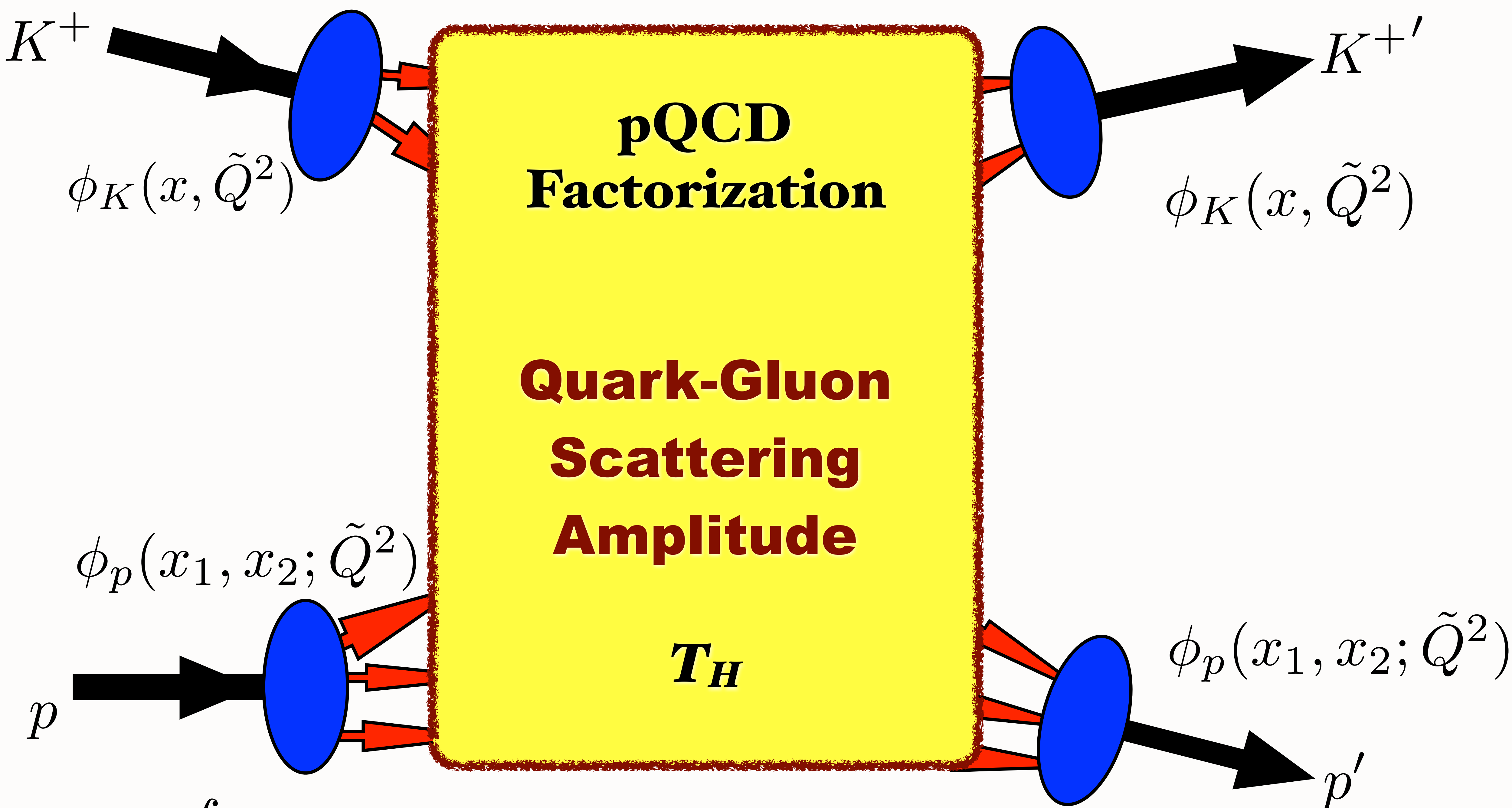
Farrar & sjb;
Matveev, Muradyan, Tavkhelidze

pQCD predicts the leading-twist scaling behavior of fixed-CM angle exclusive amplitudes

$$s, -t >> m^2_\ell$$

Non-Perturbative Proof from AdS/CFT: **Polchinski and Strassler**

Lepage, sjb; Efremov and Radyushkin



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

Distribution Amplitudes
(gauge and frame-independent)

PQCD and Exclusive Processes

Lepage; SJB
Efremov, Radyuskin

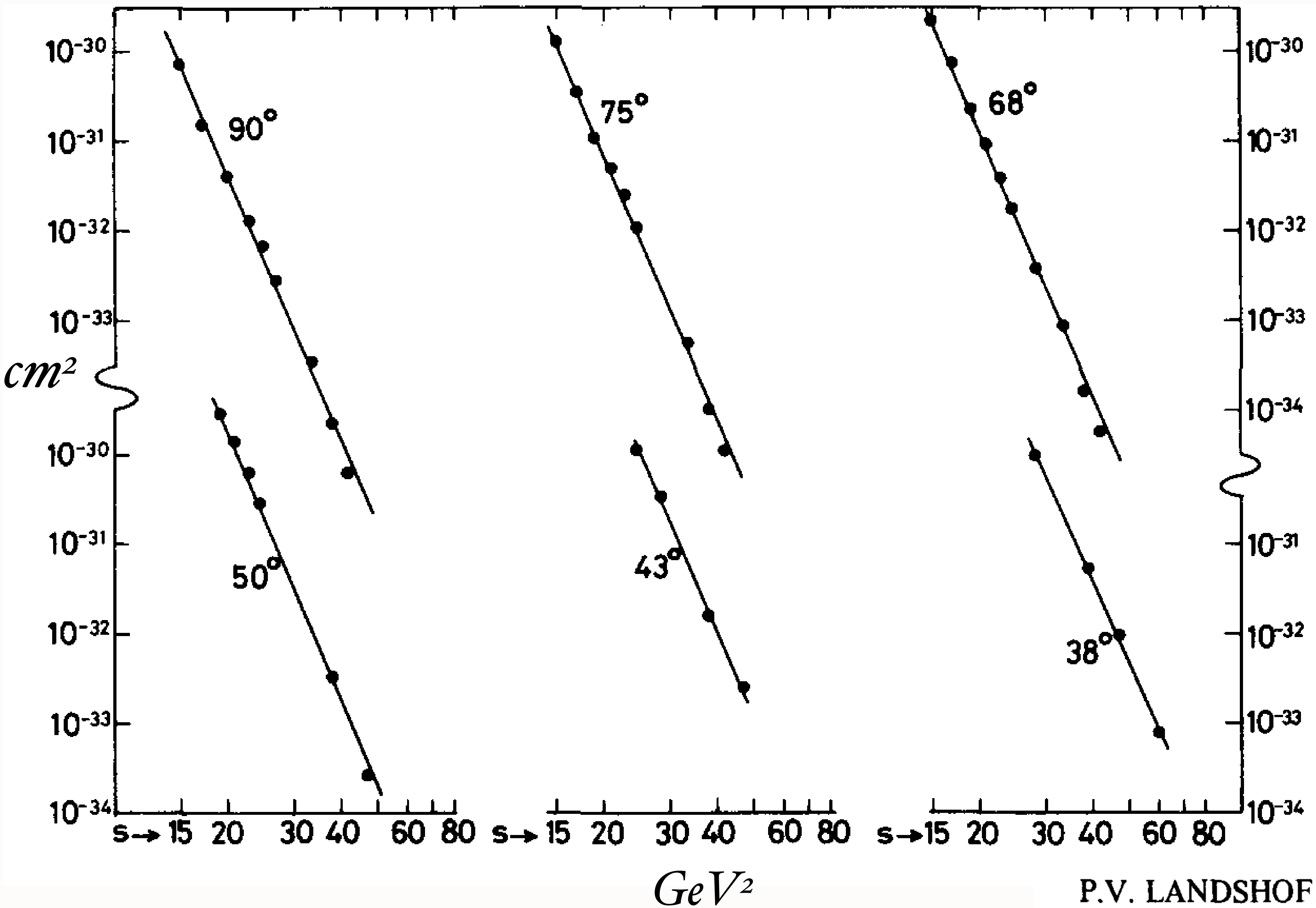
$$M = \int \prod dx_i dy_i \phi_F(x, \tilde{Q}) \times T_H(x_i, y_i, \tilde{Q}) \phi_I(y_i, Q)$$

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

Farrar; SJB
Matveev, Muradyan, Tavkhalidz

Inspired by BBG Factorization

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

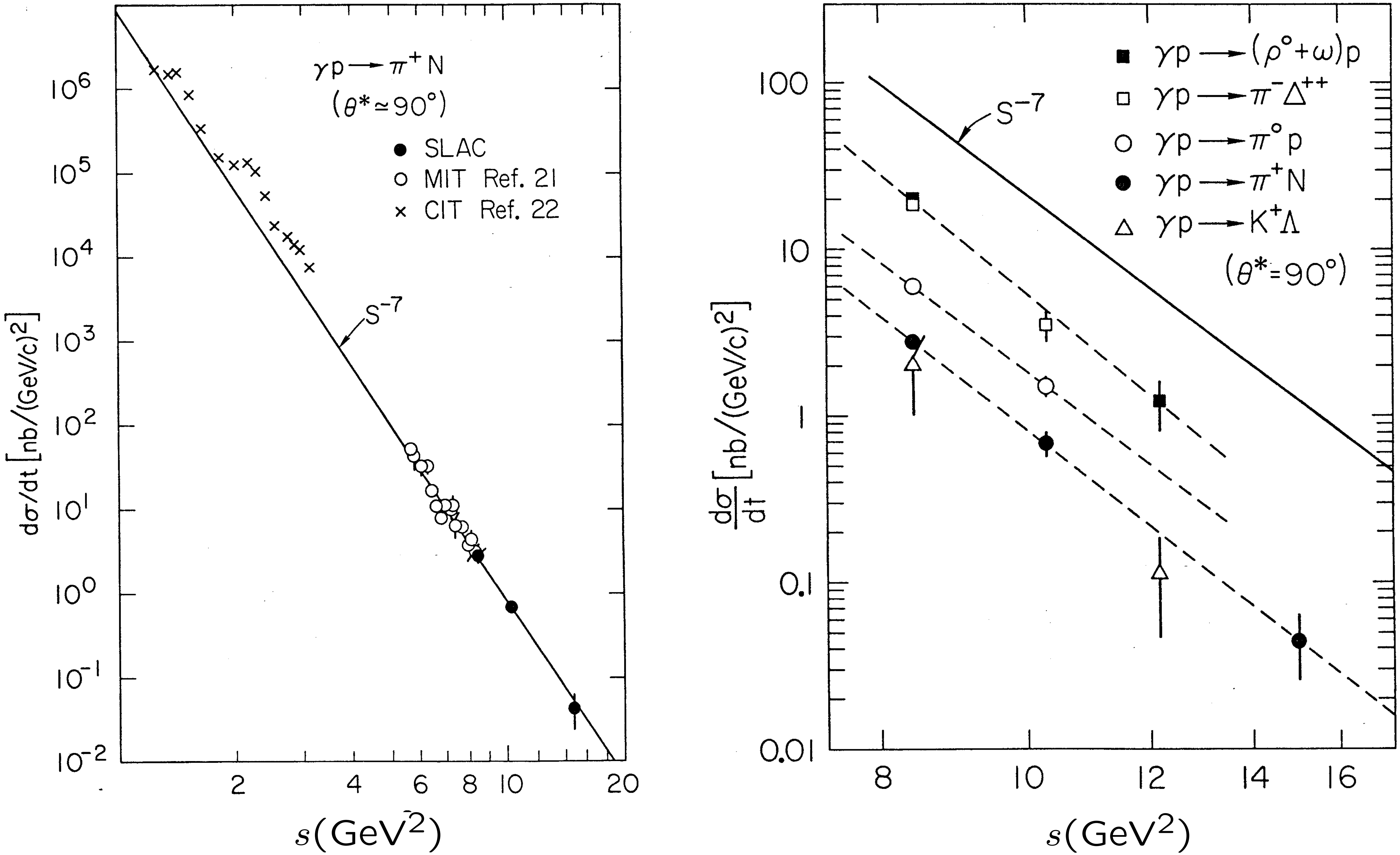


P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

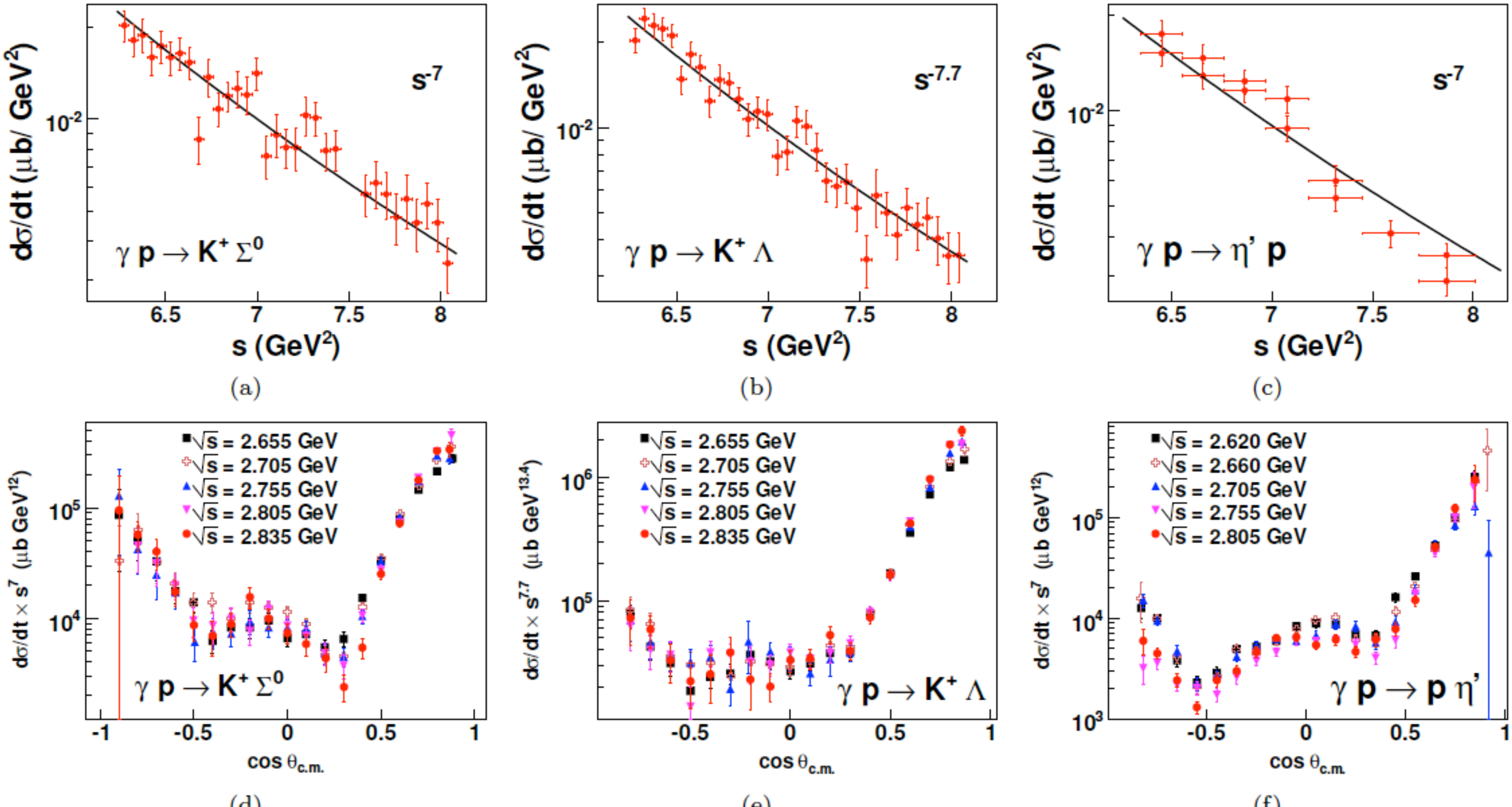


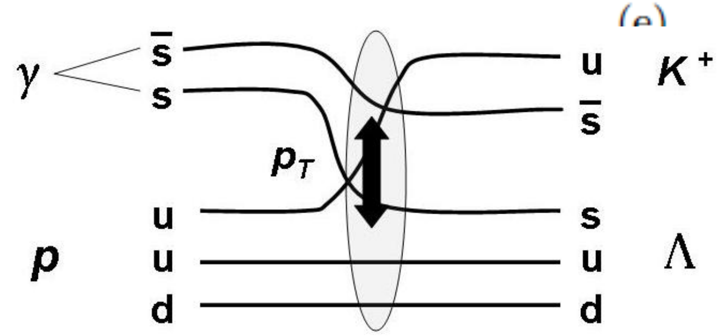
Counting Rules: $n = 9 - 2 = 7$ $$\frac{d\sigma}{dt}(\gamma p \rightarrow MB) = \frac{F(\theta_{cm})}{s^7}$$

Conformal intreractions; AdS/QCD

Scaling behavior in exclusive meson photoproduction from Jefferson Lab at large momentum transfers

$-0.95 \leq \cos\theta_{\mathrm{c.m.}} \leq 0.95.$





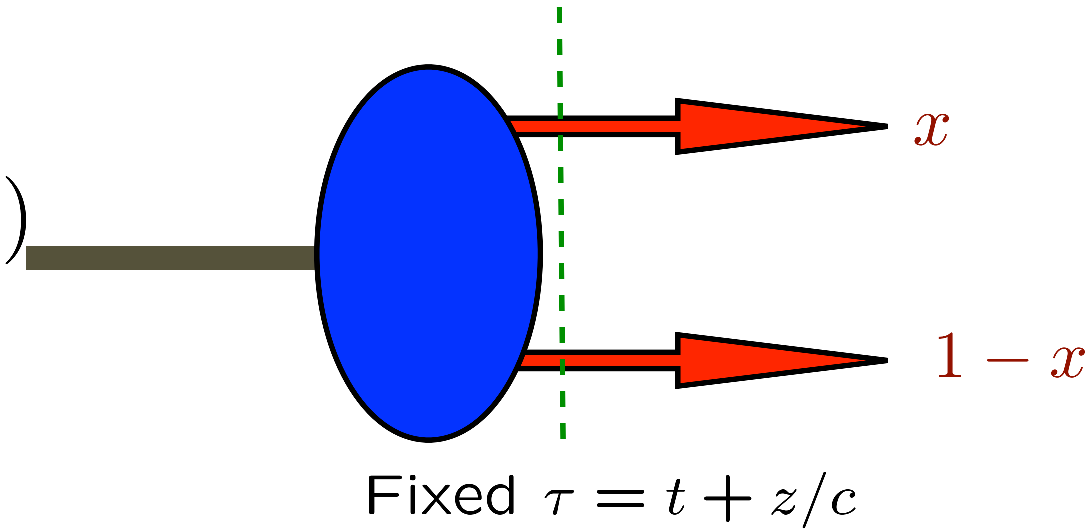
Biplab Dey

Hard Exclusive Processes

- **PQCD Factorization**
- **Convolution of Hadron Distribution Amplitudes with Hard QCD**
- **Leading Twist: Counting Rules**
- **Hadron Helicity Conservation**
- **Color Transparency**
- **BBG Quark Interchange**
- **Absence of Landshoff Amplitudes**
- **Puzzle: Huge Krisch R_{NN}**

Hadron Distribution Amplitudes

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



$k_\perp^2 < Q^2$

$$\sum_i x_i = 1$$

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

Lepage, sjb

Efremov, Radyushkin

- **ERBL Evolution Equations from PQCD, OPE,**
- **Conformal Invariance**

Sachrajda, Frishman Lepage, Braun, Gardi

- **Compute from valence light-front wavefunction in light-cone gauge**
- **Anomalous Dimensions, OPE**

ERBL Evolution of Meson Distribution Amplitude

$$x_1 x_2 Q^2 \frac{\partial}{\partial Q^2} \tilde{\phi}(x_i, Q) = C_F \frac{\alpha_s(Q^2)}{4\pi} \left\{ \int_0^1 [dy] V(x_i, y_i) \tilde{\phi}(y_i, Q) - x_1 x_2 \tilde{\phi}(x_i, Q) \right\}$$

where $\tilde{\phi} = x_1 x_2 \phi$

$$V(x_i, y_i) = 2\left[x_1 y_2 \theta(y_1 - x_1) \left(\delta_{h_1 \bar{h}_2} + \frac{\Delta}{y_1 - x_1} \right) + (1 \leftrightarrow 2) \right] = V(y_i, x_i),$$

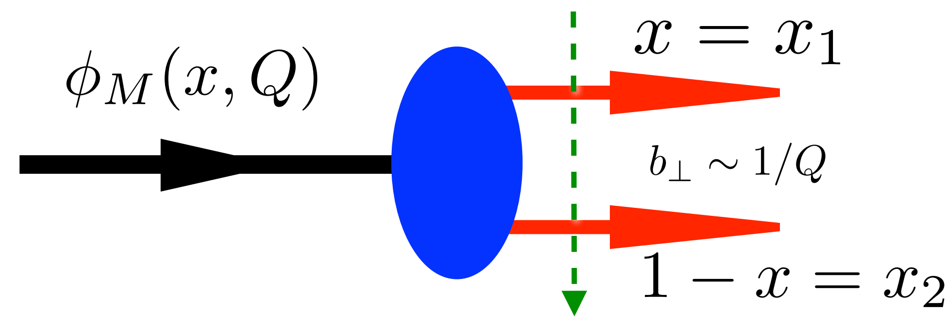
and $\Delta \tilde{\phi}(y_i, Q) \equiv \tilde{\phi}(y_i, Q) - \tilde{\phi}(x_i, Q)$.

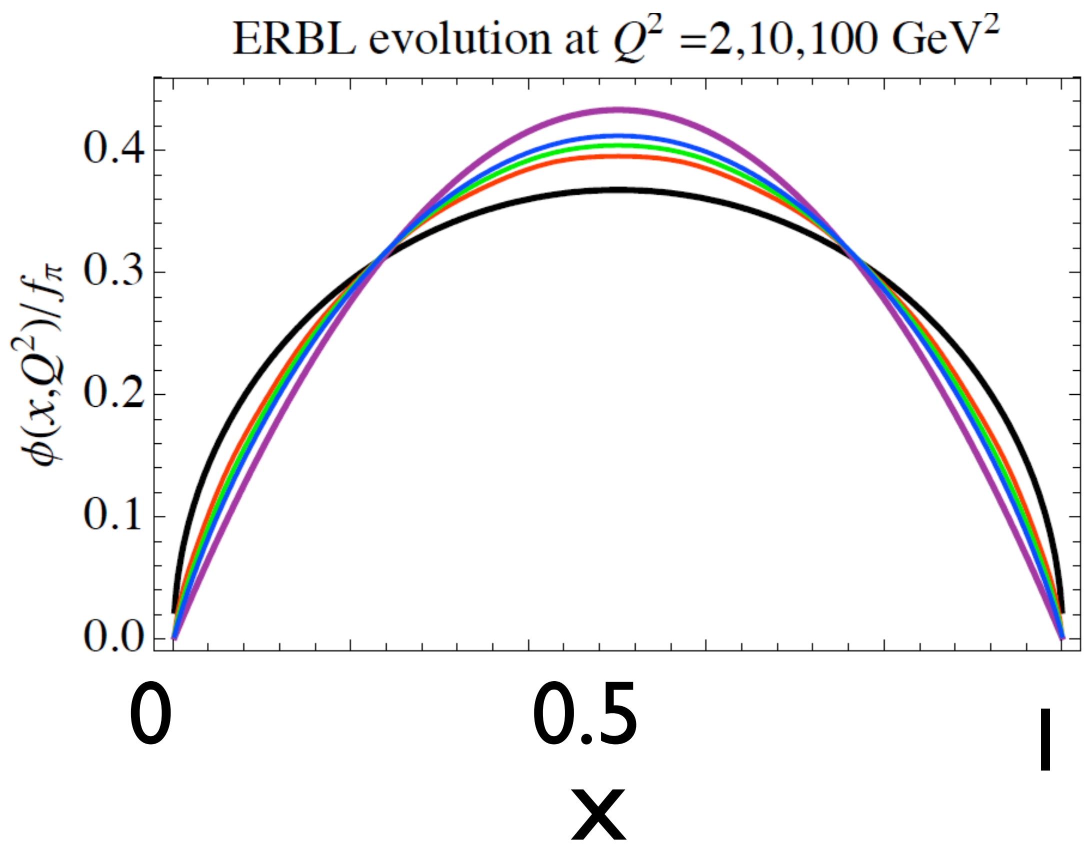
$$\phi(x_i, Q) = x_1 x_2 \sum_{n=0}^{\infty} a_n C_n^{3/2}(x_1 - x_2) \left(\ln \frac{Q^2}{\Lambda^2} \right)^{-\gamma_n}$$

where

$$\gamma_n = \frac{C_F}{\beta} \left(1 + 4 \sum_2^{n+1} \frac{1}{k} - \frac{2\delta_{h_1 \bar{h}_2}}{(n+1)(n+2)} \right) \geq 0 .$$

Fixed $\tau = t + z/c$



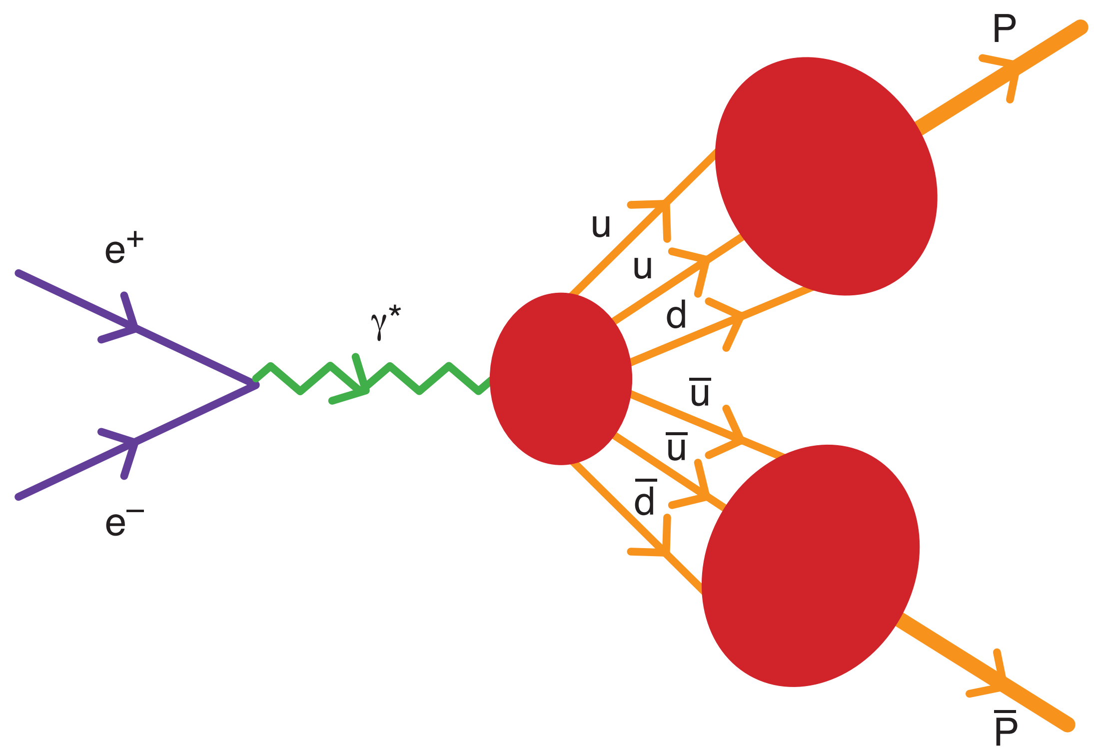


Evolves from $\sqrt{x(1-x)}$ to $x(1-x)$

$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

AdS/QCD

Timelike proton form factor in PQCD

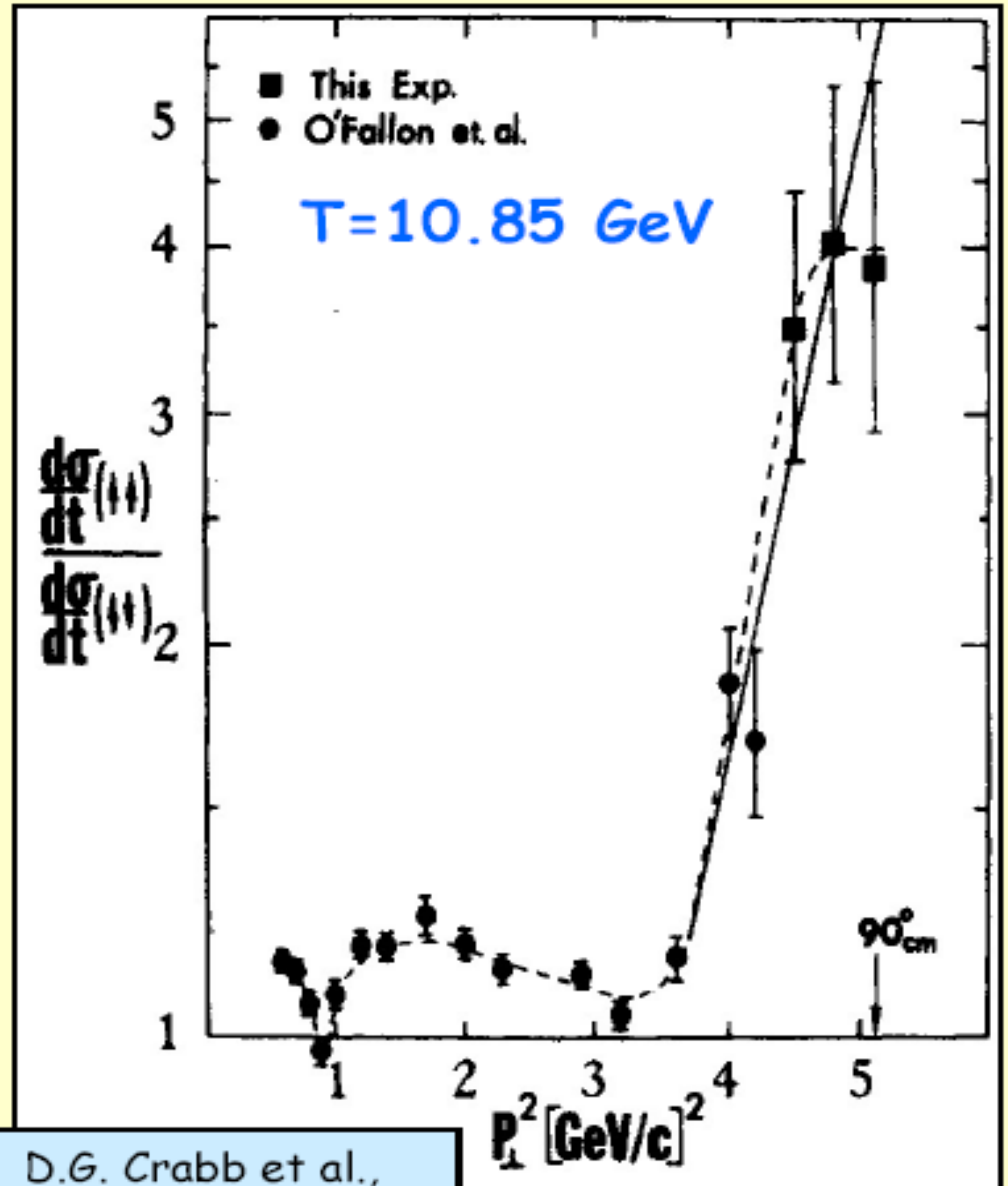


$$G_M(Q^2) \quad \rightarrow \quad \frac{\alpha_s^2(Q^2)}{Q^4} \sum_{n,m} b_{nm} \left(\log \frac{Q^2}{\Lambda^2} \right)^{\gamma_n^B + \gamma_n^B}$$

$$\times \quad \left[1 + \mathcal{O}\left(\alpha_s(Q^2), \frac{m^2}{Q^2} \right) \right]$$

Lepage and Sjb

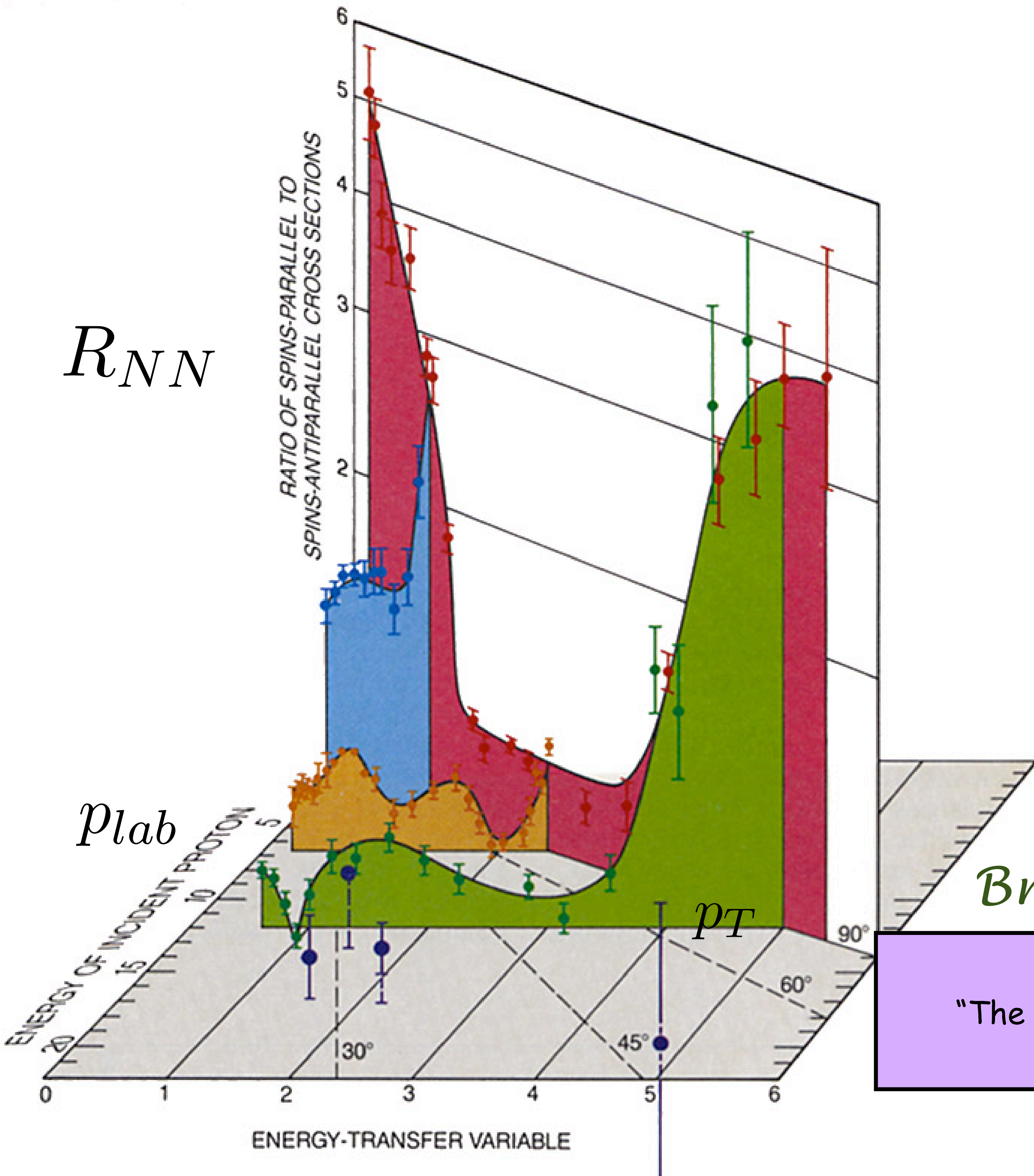
Unexpected spin effects in pp elastic scattering

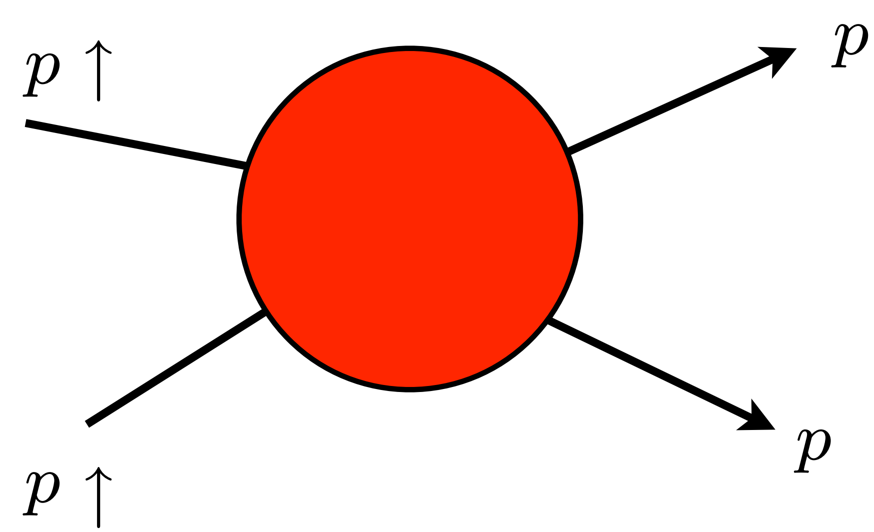


D.G. Crabb et al., PRL 41, 1257 (1978)

Spin Correlations in Elastic $p - p$ Scattering

R_{NN}





polarization normal to scattering plane

Ratio reaches 4:1 !

Heppelmann et al.

Breakdown of Color Transparency

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

de Teramond & sjb: B=2 Resonance near Charm Threshold

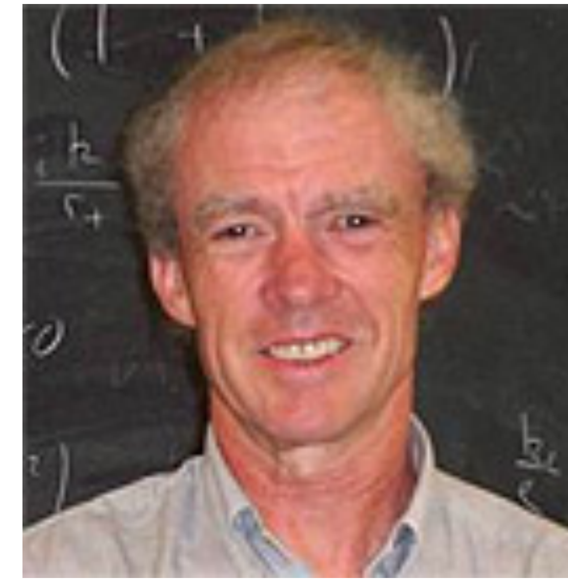
$$|uuduudc\bar{c}>$$

Compton Scattering And Fixed Poles In Parton Field Theoretic Models

Stanley J. Brodsky, Francis E. Close, J.F. Gunion (SLAC). Oct 1971. 14 pp.
Published in **Phys.Rev. D5 (1972) 1384**
SLAC-PUB-0973

Phenomenology of Photon Processes, Vector Dominance and Crucial Tests for Parton Models

Stanley J. Brodsky, Francis E. Close, J.F. Gunion (SLAC). Jan 1972. 44 pp.
Published in **Phys.Rev. D6 (1972) 177**
SLAC-PUB-1012
DOI: 10.1103/PhysRevD.6.177



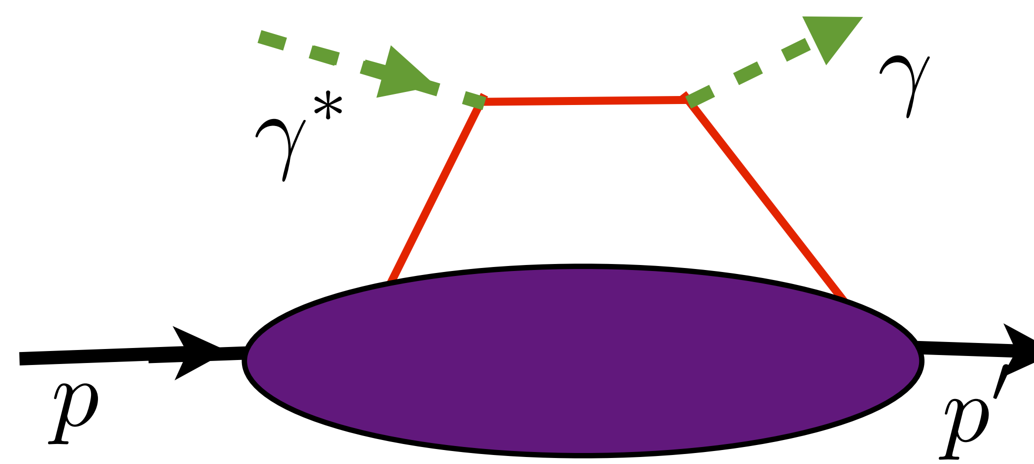
A Gauge - Invariant Scaling Model Of Current Interactions With Regge Behavior And Finite Fixed Pole Sum Rules

Stanley J. Brodsky, Francis E. Close, J.F. Gunion (SLAC). May 1973. 71 pp.
Published in **Phys.Rev. D8 (1973) 3678**
SLAC-PUB-1243
DOI: 10.1103/PhysRevD.8.3678

SLAC 1972, 1973

- *Pioneering papers on DVCS*
- *Interference with Bethe-Heitler*
- *J=0 Fixed Pole in Real Part*
- *Gauge Invariance, Leading Twist, Regge behavior*

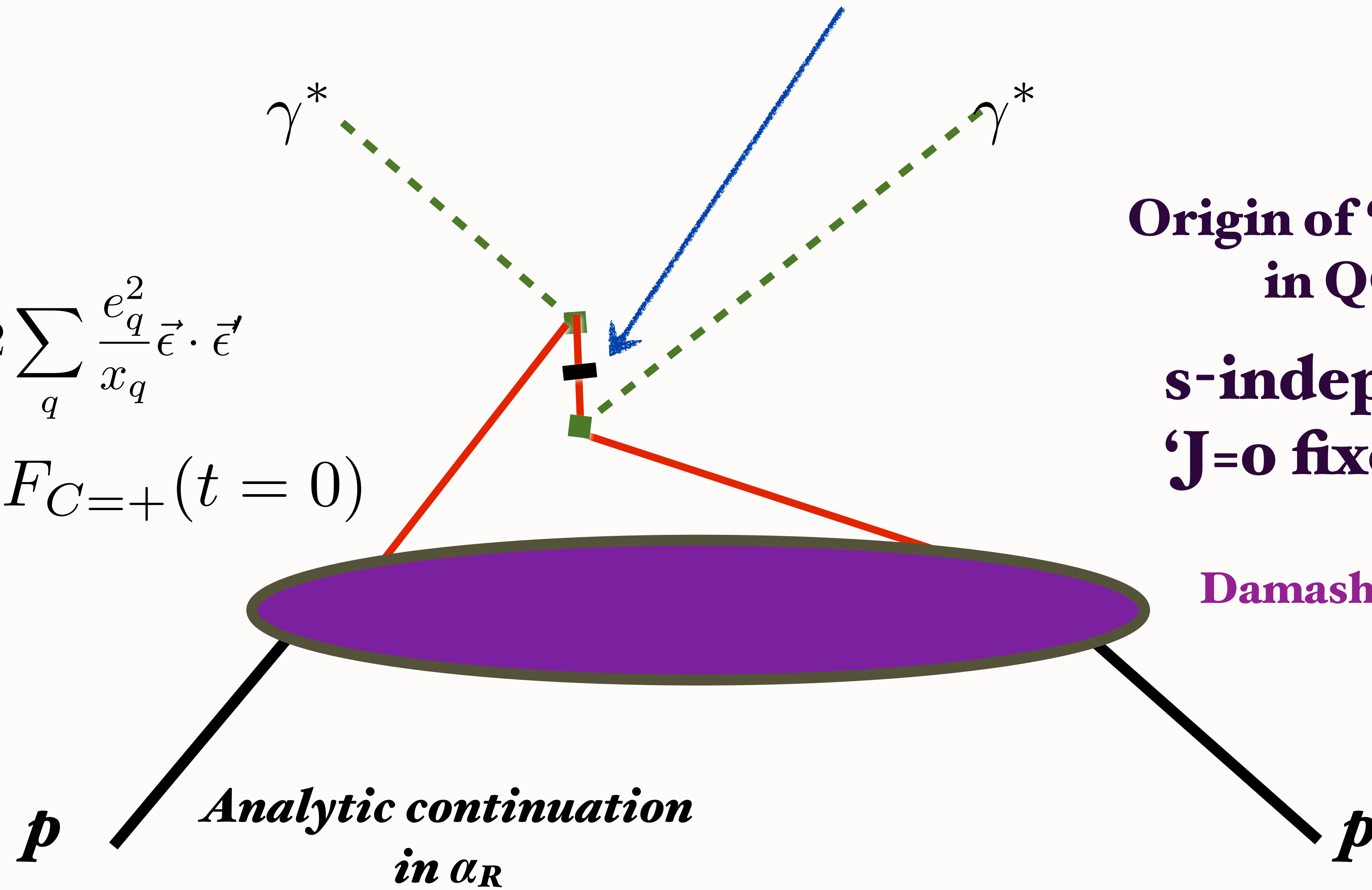
$$\gamma^* p \to \gamma p'$$



Leading-Twist Contribution to Real Part of DVCS

Close, Gunion, sjb
Szczepaniak, Llanes Estrada, sjb

LF Instantaneous interaction



$$T = -2 \sum_q \frac{e_q^2}{x_q} \vec{\epsilon} \cdot \vec{\epsilon}'$$

$$T \propto s^0 F_{C=+}(t=0)$$

Origin of 'D-Term' in QCD

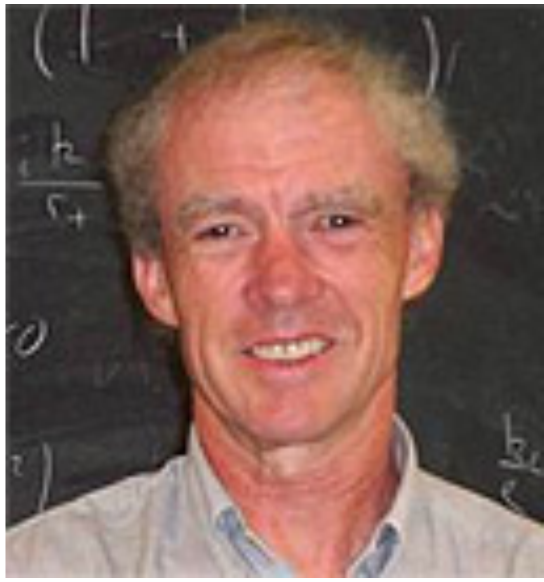
s-independent 'J=0 fixed pole'

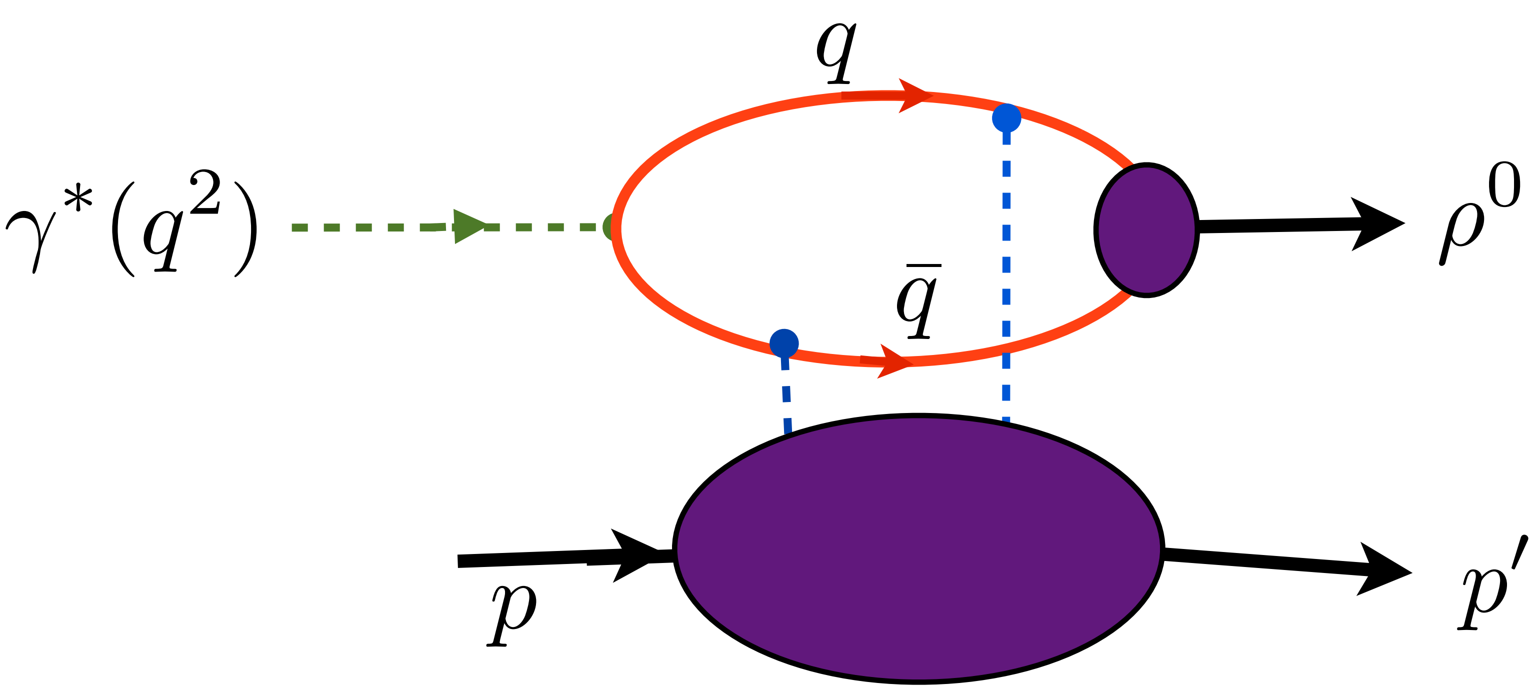
Damashek, Gilman

Diffractive leptoproduction of vector mesons in QCD

Stanley J. Brodsky (SLAC) , L. Frankfurt (Tel Aviv U.) , J.F. Gunion (UC, Davis) , Alfred H. Mueller (Columbia U.) , M. Strikman (Penn State U.)
Jan 1994 - 34 pages

Phys.Rev. D50 (1994) 3134-3144
DOI: 10.1103/PhysRevD.50.3134
SLAC-PUB-6412, CU-TP-617, UCD-93-36
e-Print: hep-ph/9402283 | PDF





- *Factorization Principle*
- *LF Wave Function, Distribution Amplitude*
- *s, 1/Q^6 dependence,* σ_L/σ_T

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

J. R. Forshaw*

Consortium for Fundamental Physics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom

R. Sandapen†

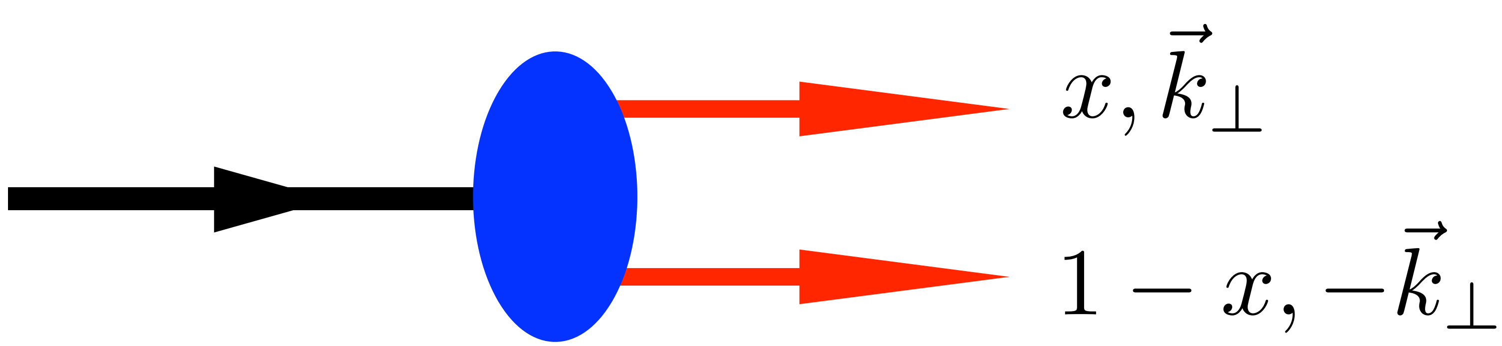
Département de Physique et d'Astronomie, Université de Moncton, Moncton, New Brunswick E1A3E9, Canada

(Received 5 April 2012; published 20 August 2012)

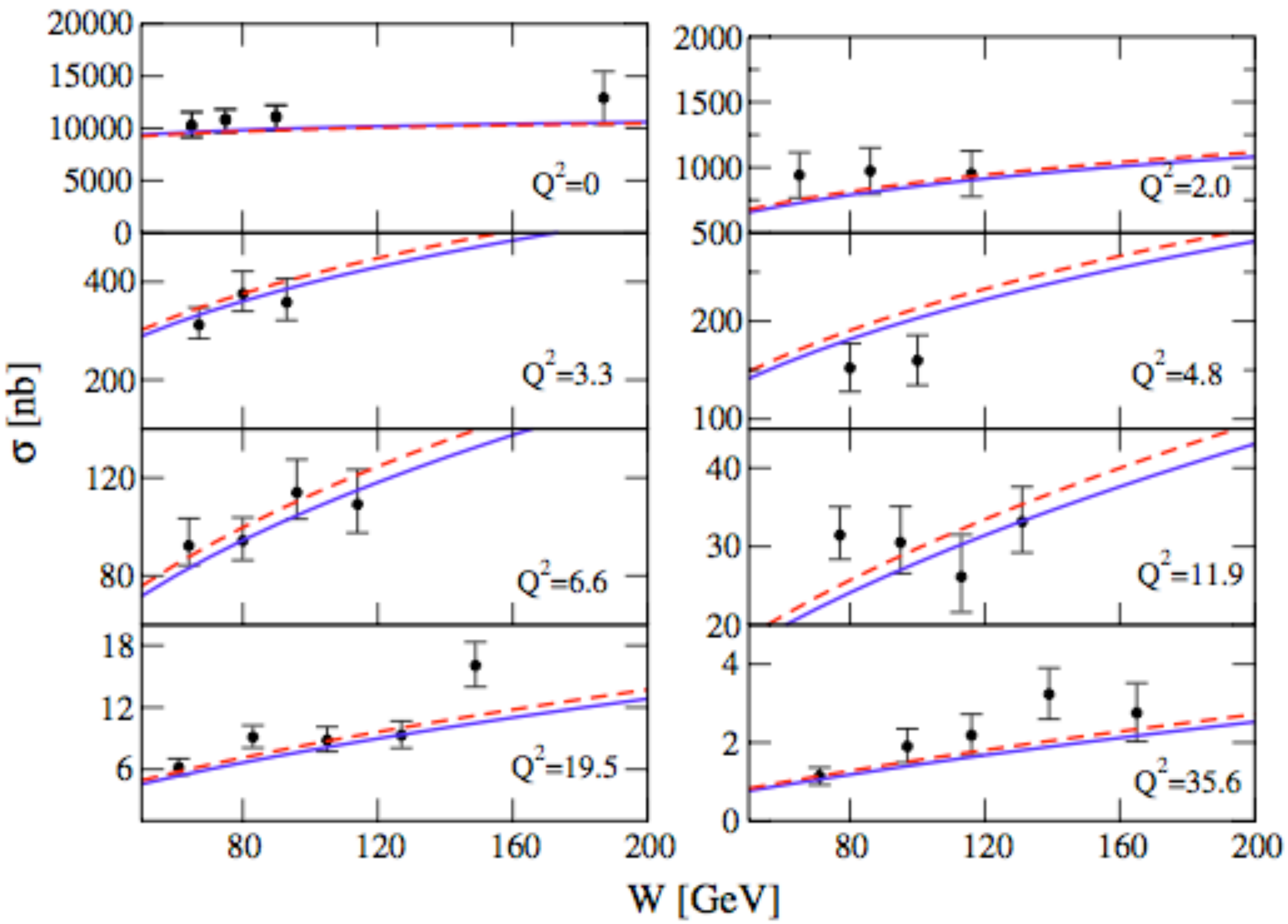
We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive ρ-meson electroproduction that are in agreement with data collected at the Hadron Electron Ring Accelerator electron–proton collider.

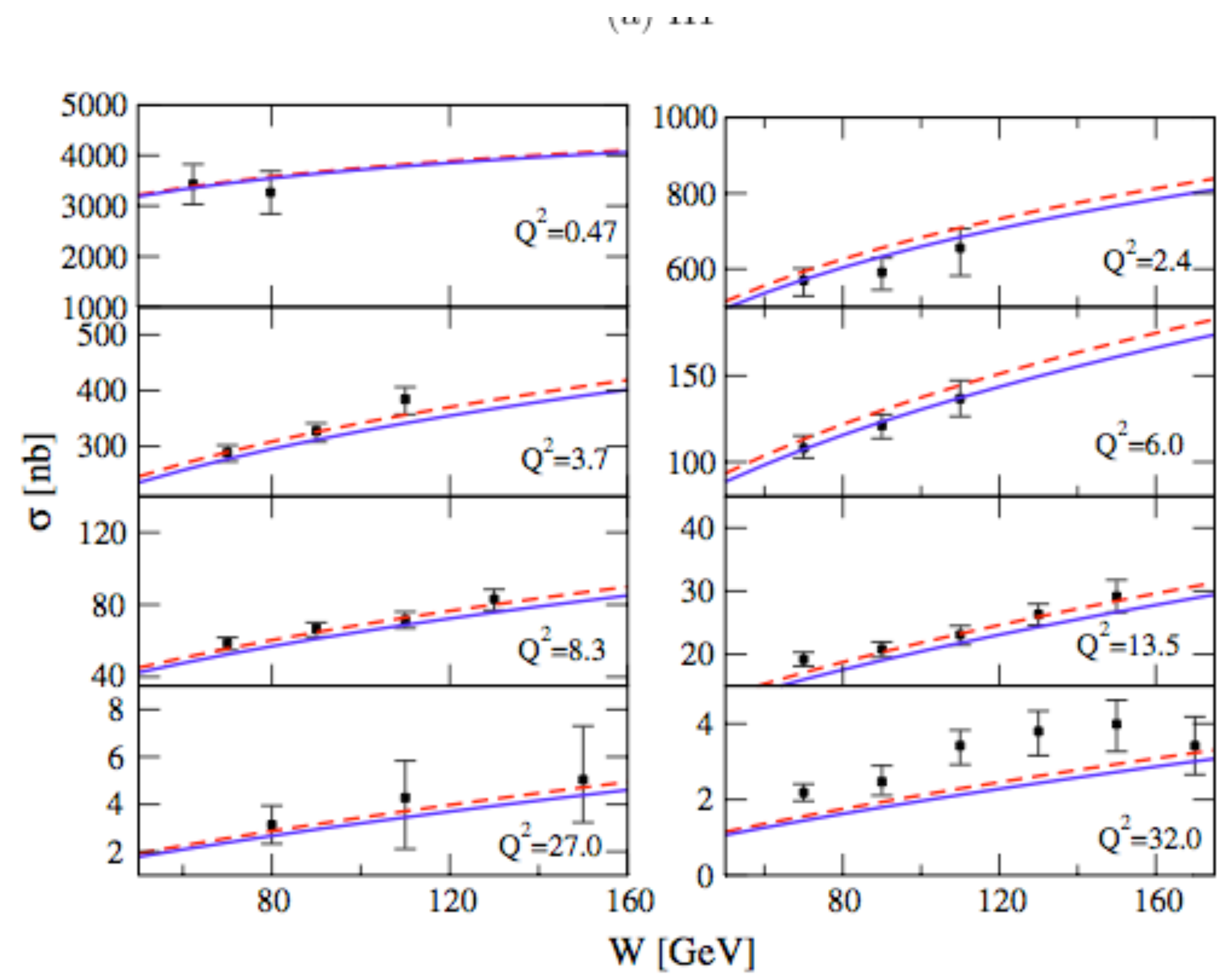
$$\psi_M(x,k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

Fixed $\tau = t + z/c$



AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

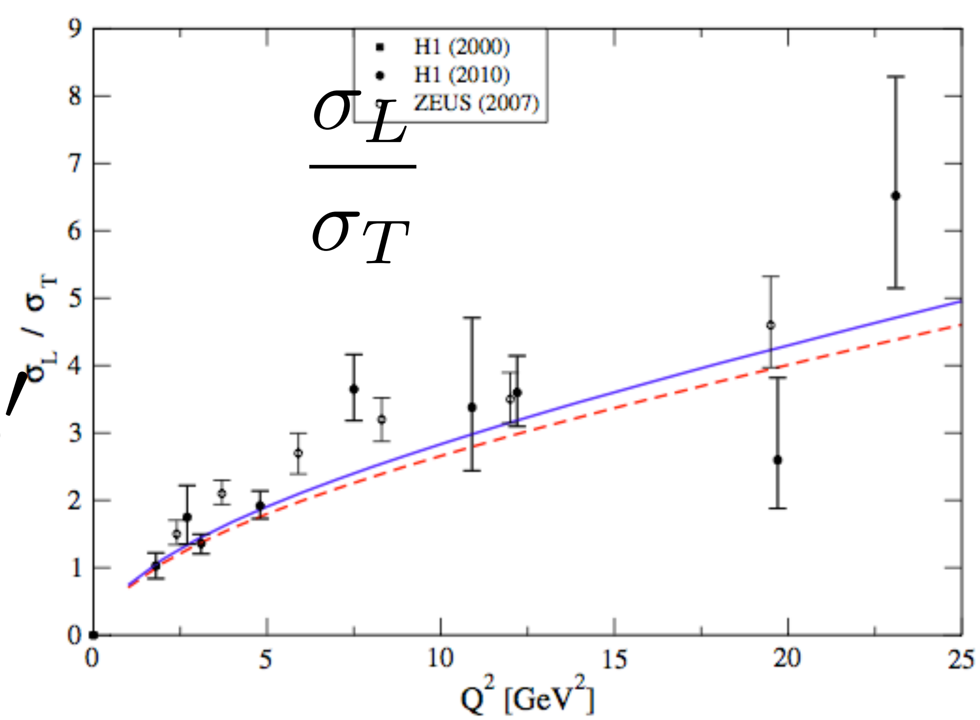




(b) ZEUS

J. R. Forshaw, R. Sandapen

$$\gamma^* p \to \rho^0 p'$$



Prediction from Light-Front Holography

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

Atomic Physics from First Principles

$\mathcal{L}_{QED} \rightarrow$ H_{QED}

QED atoms: positronium and muonium

$$(H_0 + H_{int}) \; |\Psi> = E \; |\Psi>$$

Coupled Fock states

Eliminate higher Fock states and retarded interactions

$$[-\frac{\Delta^2}{2m_{\rm red}} + V_{\rm eff}(\vec{S}, \vec{r})] \; \psi(\vec{r}) = E \; \psi(\vec{r})$$

Effective two-particle equation

Includes Lamb Shift, quantum corrections

$$[-\frac{1}{2m_{\rm red}} \frac{d^2}{dr^2} + \frac{1}{2m_{\rm red}} \frac{\ell(\ell+1)}{r^2} + V_{\rm eff}(r, S, \ell)] \; \psi(r) = E \; \psi(r)$$

Spherical Basis r, θ, ϕ

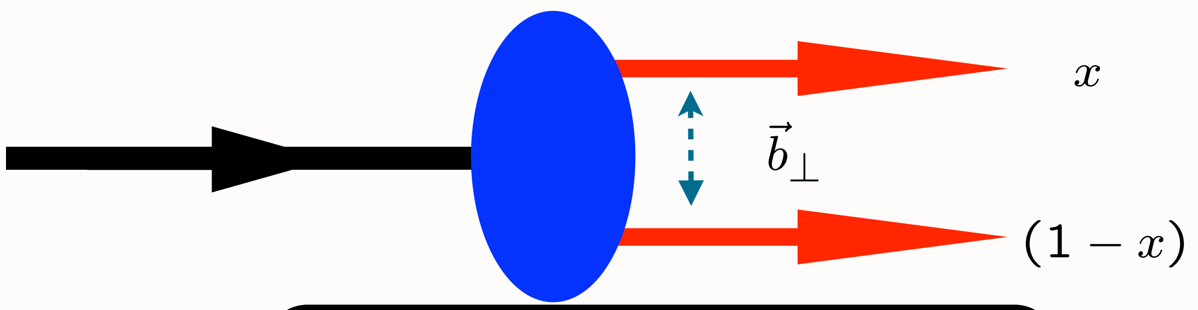
$$V_{eff} \rightarrow V_C(r) = -\frac{\alpha}{r}$$

Coulomb potential

Semiclassical first approximation to QED --> **Bohr Spectrum**

Light-Front QCD

Fixed $\tau = t + z/c$



$$\zeta^2 = x(1-x)b_\perp^2$$

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

$$(H^0_{LF} + H^I_{LF})|\Psi> = M^2|\Psi>$$

Coupled Fock states

Eliminate higher Fock states and retarded interactions

$$[\frac{\vec{k}_\perp^2 + m^2}{x(1-x)} + V_{\text{eff}}^{LF}]\ \psi_{LF}(x, \vec{k}_\perp) = M^2\ \psi_{LF}(x, \vec{k}_\perp)$$

Effective two-particle equation

$$[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{4\zeta^2} + U(\zeta, S, L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

Azimuthal Basis

ζ, ϕ

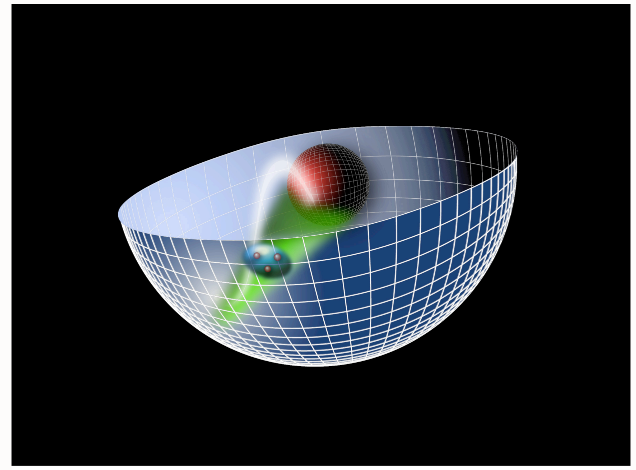
AdS/QCD:

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Confining AdS/QCD potential!

Sums an infinite # diagrams

Semiclassical first approximation to QCD *de Tèramond, Dosch, sjb*



AdS/QCD
Soft-Wall Model

Light-Front Holography

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

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Conformal Symmetry
of the action

Confinement scale:

$$\kappa \simeq 0.6 \ GeV$$

$$1/\kappa \simeq 1/3 \ fm$$

- **de Alfaro, Fubini, Furlan:** ***Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!***

Meson Spectrum in Soft Wall Model

Pion: Negative term for J=0 cancels positive terms from LFKE and potential

- Effective potential: $U(\zeta^2) = \kappa^4 \zeta^2 + 2\kappa^2 (J-1)$
- LF WE

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2 + 2\kappa^2(J-1)\right)\phi_J(\zeta) = M^2 \phi_J(\zeta)$$

- Normalized eigenfunctions $\langle\phi|\phi\rangle = \int d\zeta \, \phi^2(z)^2 = 1$

$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L} e^{-\kappa^2\zeta^2/2} L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)$$

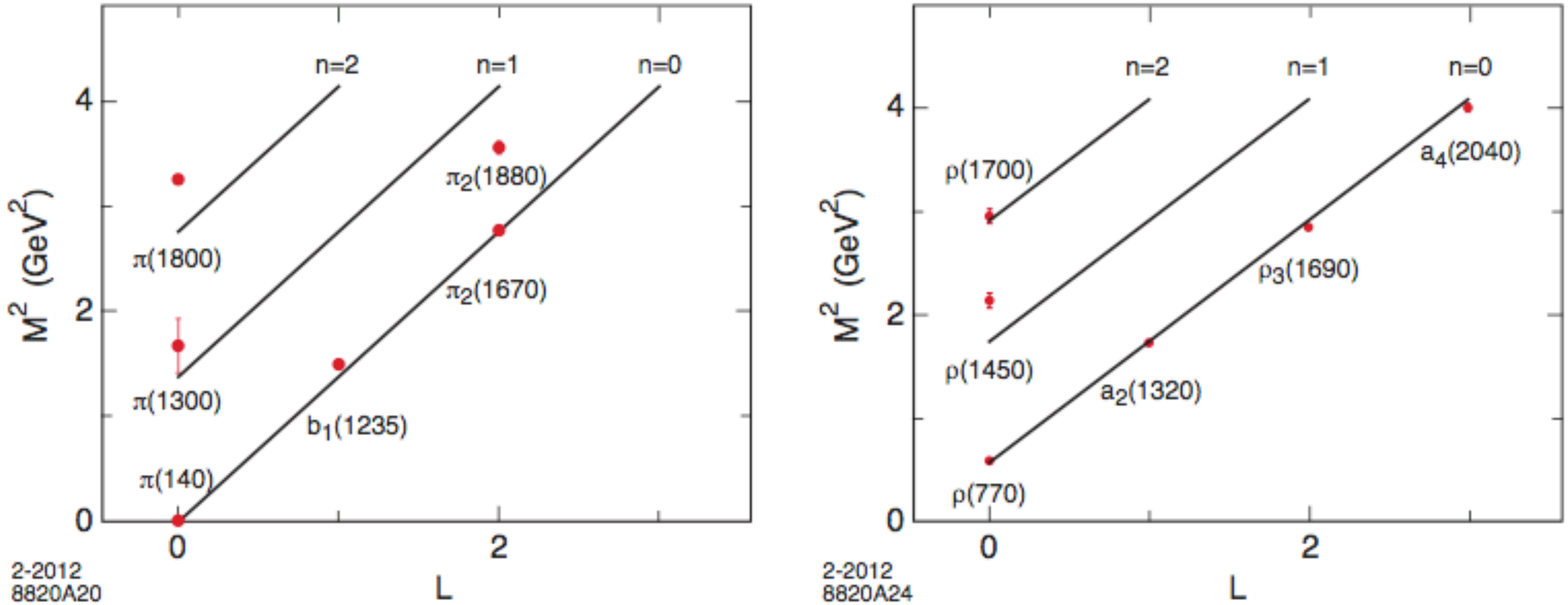
G. de Teramond, H. G. Dosch, sjb

- $J = L + S, I = 1$ meson families $\mathcal{M}^2_{n,L,S} = 4\kappa^2\,(n + L + S/2)$

$4\kappa^2$ for $\Delta n = 1$
$4\kappa^2$ for $\Delta L = 1$
$2\kappa^2$ for $\Delta S = 1$

$m_q = 0$

Massless pion in Chiral Limit! ***Same slope in n and L!***



I=1 orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ-meson families ($\kappa = 0.54$ GeV)

- Triplet splitting for the $I = 1$, $L = 1$, $J = 0, 1, 2$, vector meson a-states

$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

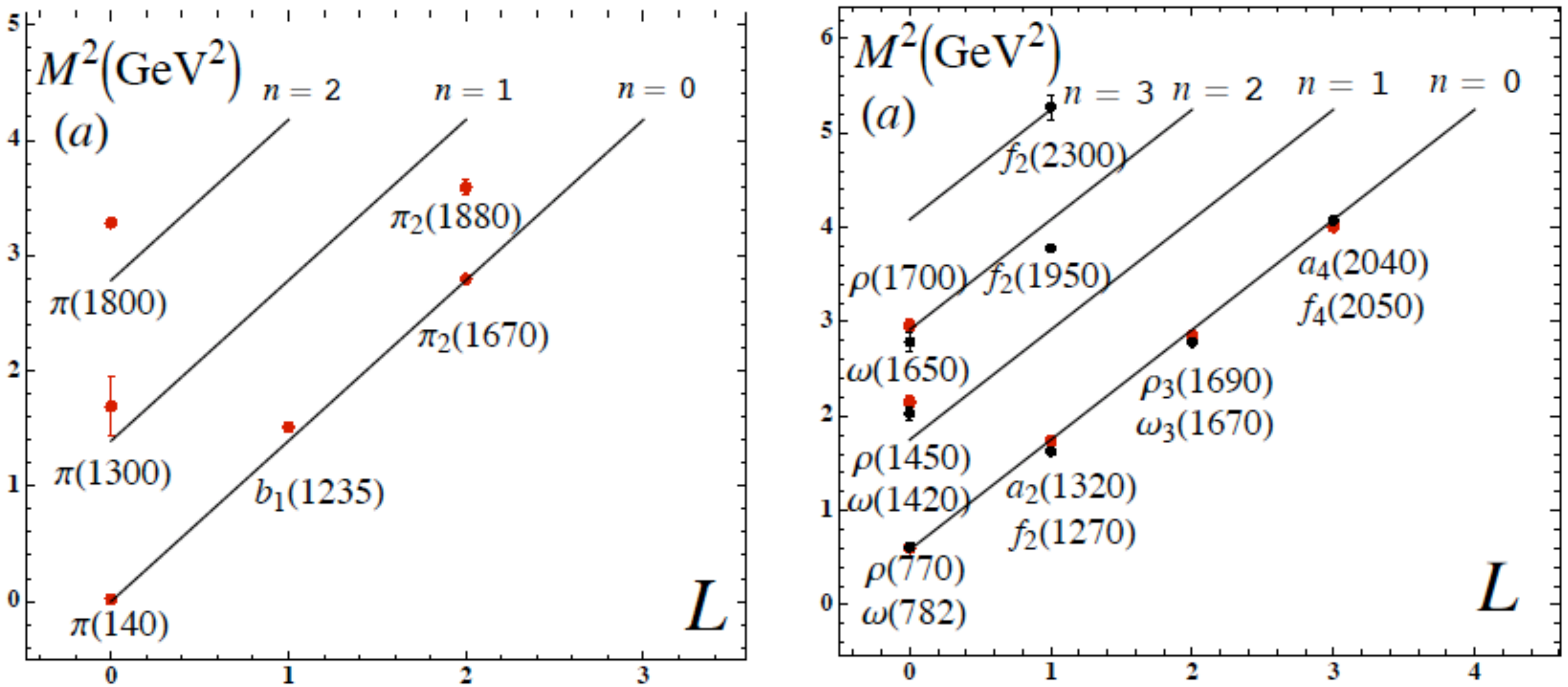
Mass ratio of the ρ and the a_1 mesons: coincides with Weinberg sum rules

G. de Teramond, H. G. Dosch, sjb

Prediction from AdS/QCD: Meson Spectrum

de Tèramond, Dosch, sjb

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

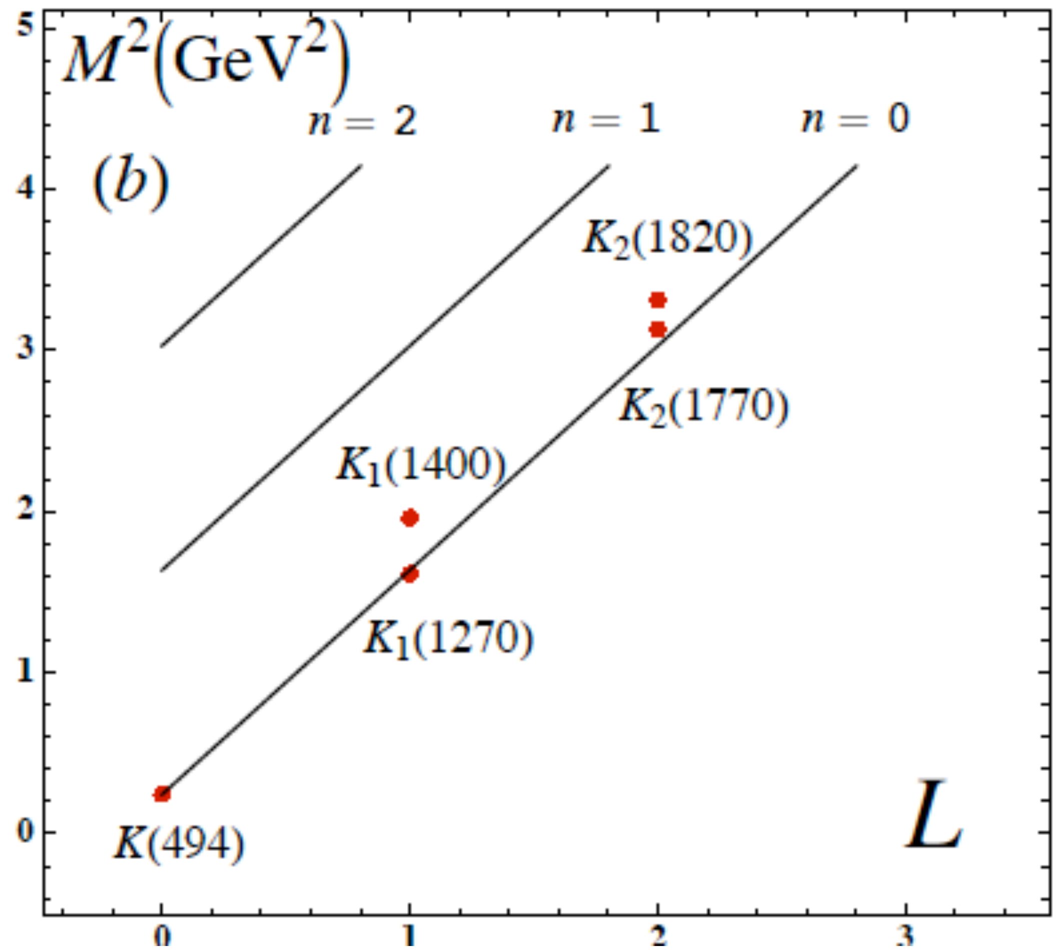


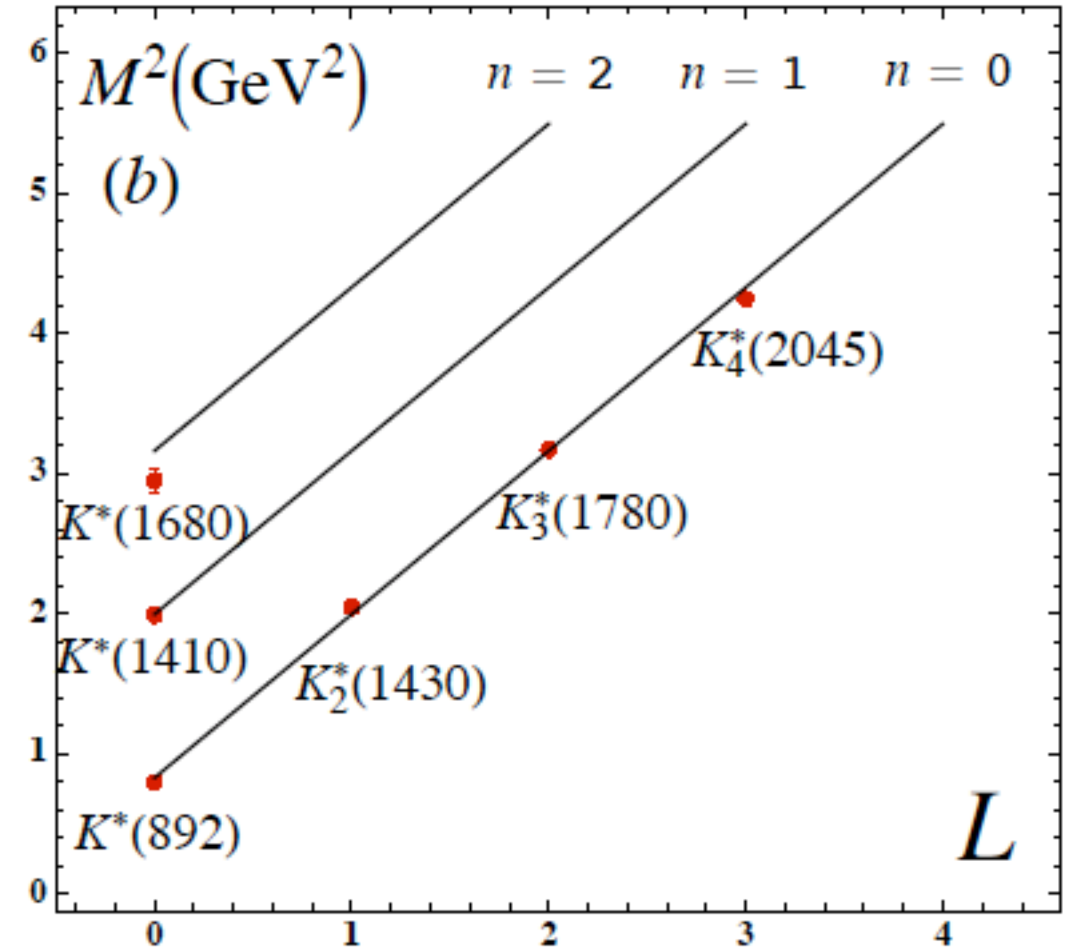
$\kappa = 0.59\ MeV$ $\kappa = 0.54\ MeV$

Kaon Spectrum

de Tèramond, Dosch, sjb

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





$$\delta M^2 = \sum_i < \frac{m_i^2}{x_i} >$$

Weisberger

$$m_q = 46 \ MeV, \ m_s = 357 \ MeV$$

Orbital and Radial Excitations

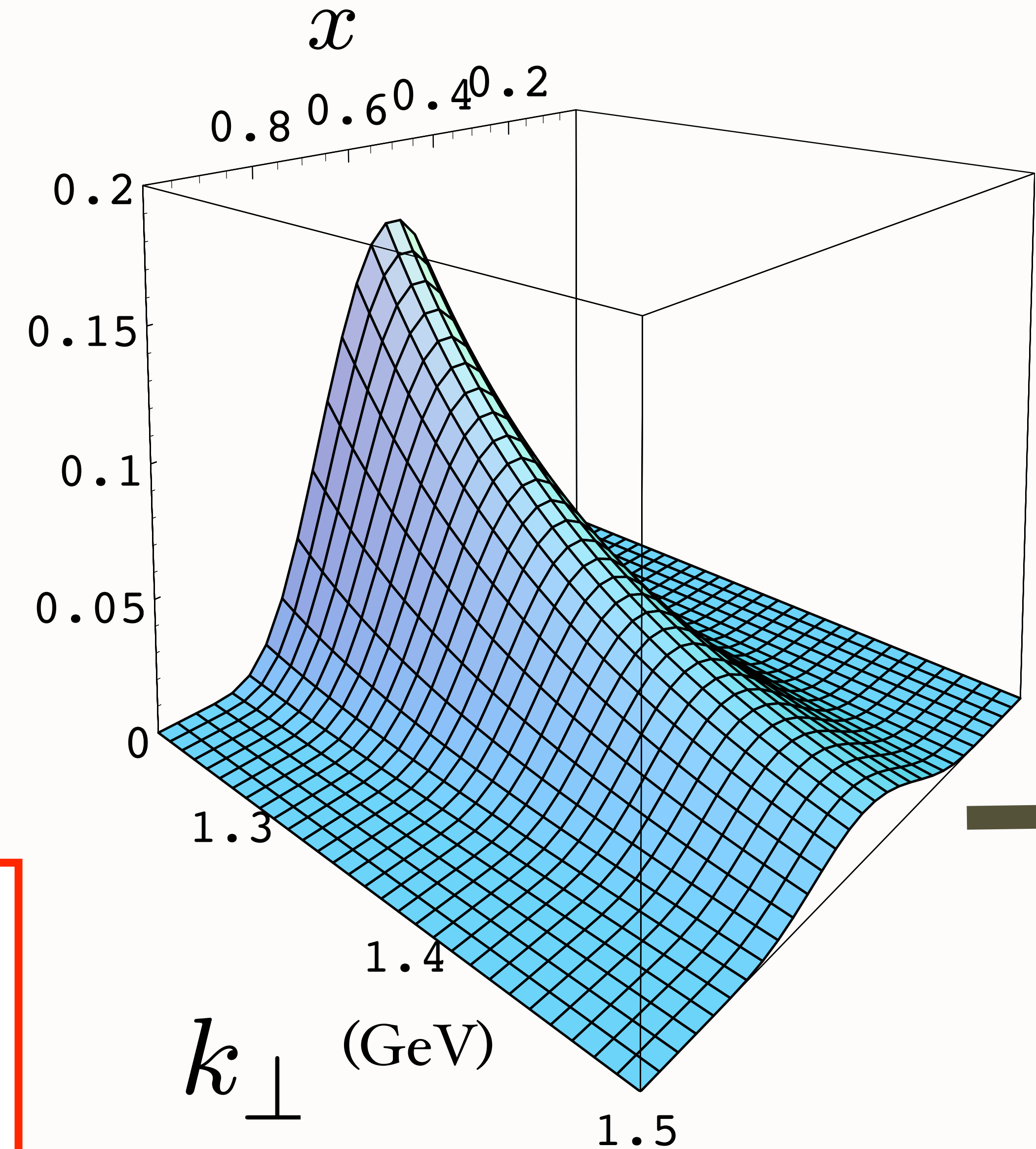
Remarkable Features of Light-Front Schrödinger Equation

- ***Relativistic, frame-independent***
- ***QCD scale appears - unique LF potential***
- ***Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter***
- ***Zero-mass pion for zero mass quarks!***
- ***Regge slope same for n and L -- not usual HO***
- ***Splitting in L persists to high mass -- contradicts conventional wisdom based on breakdown of chiral symmetry***
- ***Phenomenology: LFWFs, Form factors, electroproduction***
- ***Extension to heavy quarks***

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

Stan Brodsky
SLAC
NATIONAL ACCELERATOR LABORATORY

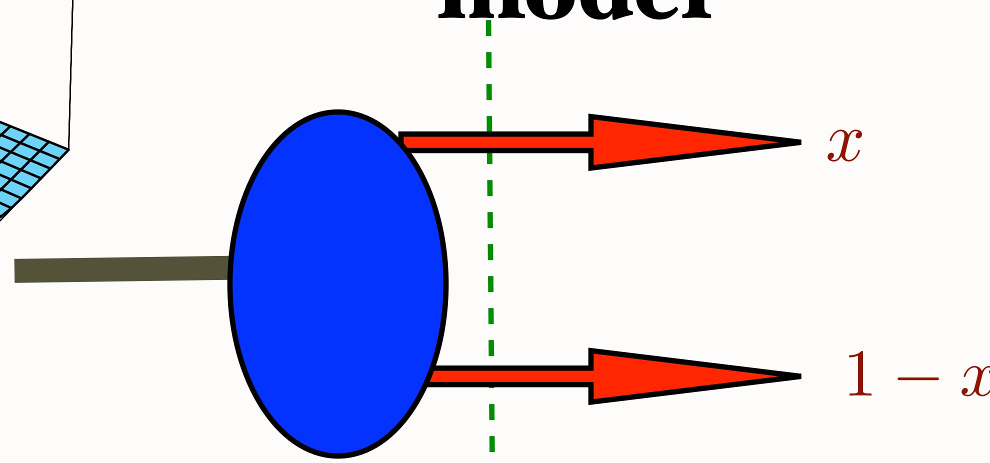
Prediction from AdS/QCD: Meson LFWF



$\psi_M(x, k_\perp^2)$

de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$k_\perp^2, x$

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

$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

$$f_\pi = \sqrt{P_{q\bar{q}}}\frac{\sqrt{3}}{8}\kappa = 92.4 \text{ MeV}$$

Provides Connection of Confinement to Hadron Structure

- LF eigenvalue equation $P_\mu P^\mu|\phi\rangle = M^2|\phi\rangle$ is a LF wave equation for ϕ

$$\Big(\underbrace{-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2}}_{kinetic\ energy\ of\ partons} + \underbrace{U(\zeta)}_{confinement}\Big)\phi(\zeta) = M^2\phi(\zeta)$$

- Critical value $L=0$ corresponds to lowest possible stable solution, the ground state of the LF Hamiltonian

- Relativistic and frame-independent LF Schrödinger equation: U is instantaneous in LF time

- A linear potential V_{eff} in the *instant form* implies a quadratic potential U_{eff} in the *front form* at large $q\bar{q}$ separation (thus linear Regge trajectories for small quark masses!)

$$U_{eff} = V_{eff}^2 + 2\sqrt{p^2+m_q^2}\,V_{eff} + 2\,V_{eff}\sqrt{p^2+m_{\bar{q}}^2}$$

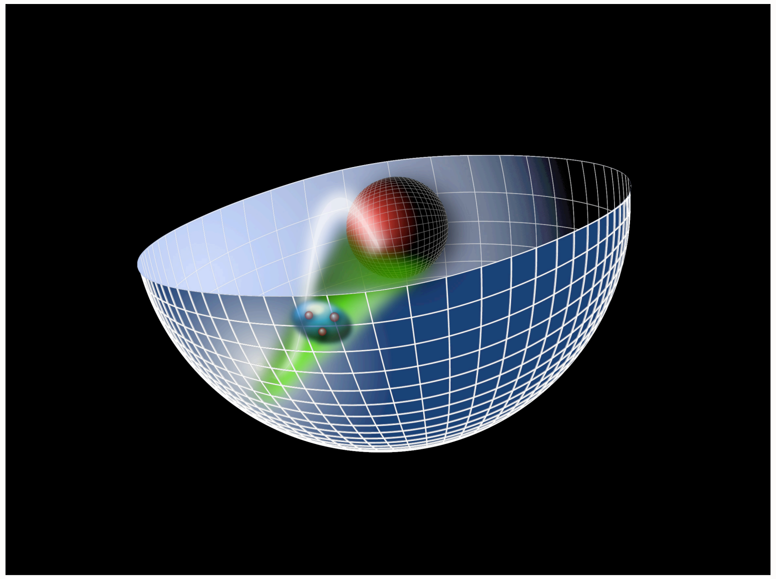
- Result follows from comparison of invariant mass in the *instant form* in the CMS, $\mathbf{P}=0$, with invariant mass in *front form* in the constituent rest frame (CRF): $\mathbf{p}_q + \mathbf{p}_{\bar{q}} = 0$

Trawinski, de Teramond, Dosch, Glazek, sjb

Light-Front Schrödinger Equation

- **As Simple as Schrödinger Theory in Atomic Physics**
- **Relativistic, Frame-Independent, Color-Confining**
- **Confinement in QCD -- What sets the QCD mass scale?**
- **QCD Coupling at all scales**
- **Hadron Spectroscopy**
- **Light-Front Wavefunctions**
- **Form Factors, Structure Functions,Hadronic Observables**
- **Constituent Counting Rules**
- **Hadronization at the Amplitude Level**
- **Insights into QCD Condensates**
- **Chiral Symmetry**

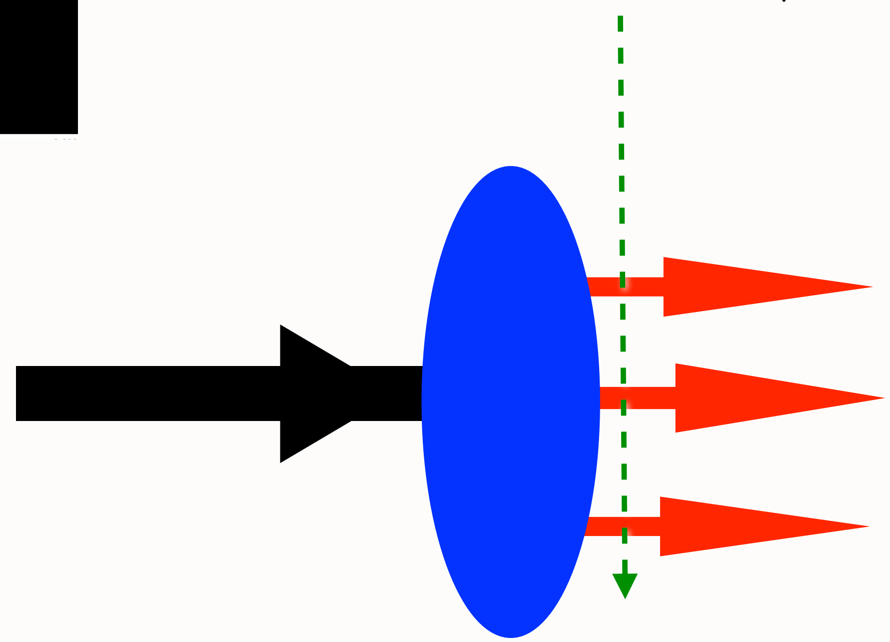
$\phi(z)$



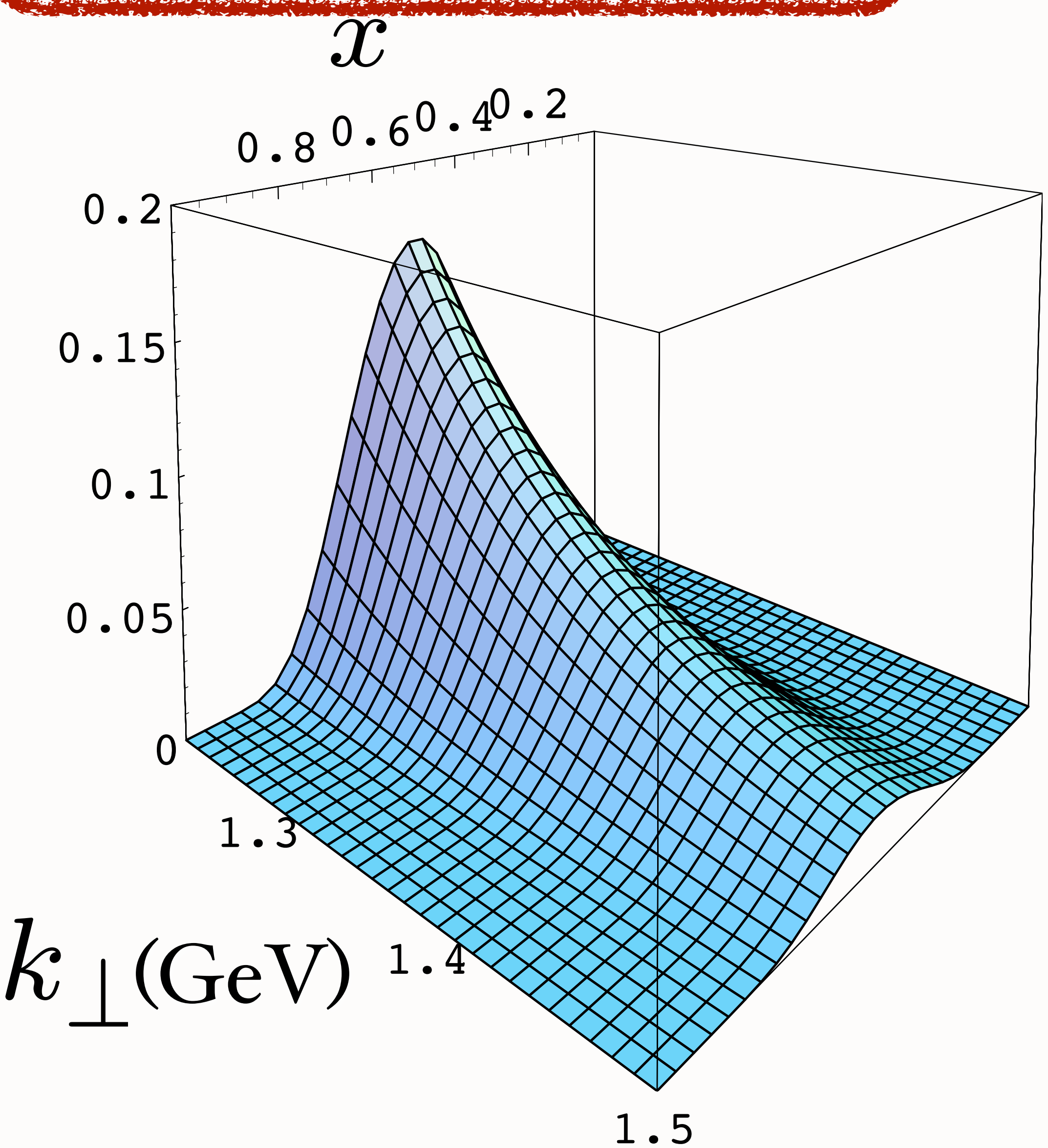
AdS5: Conformal Template for QCD

- *Light-Front Holography*

Duality of AdS$_5$ with LF Hamiltonian Theory

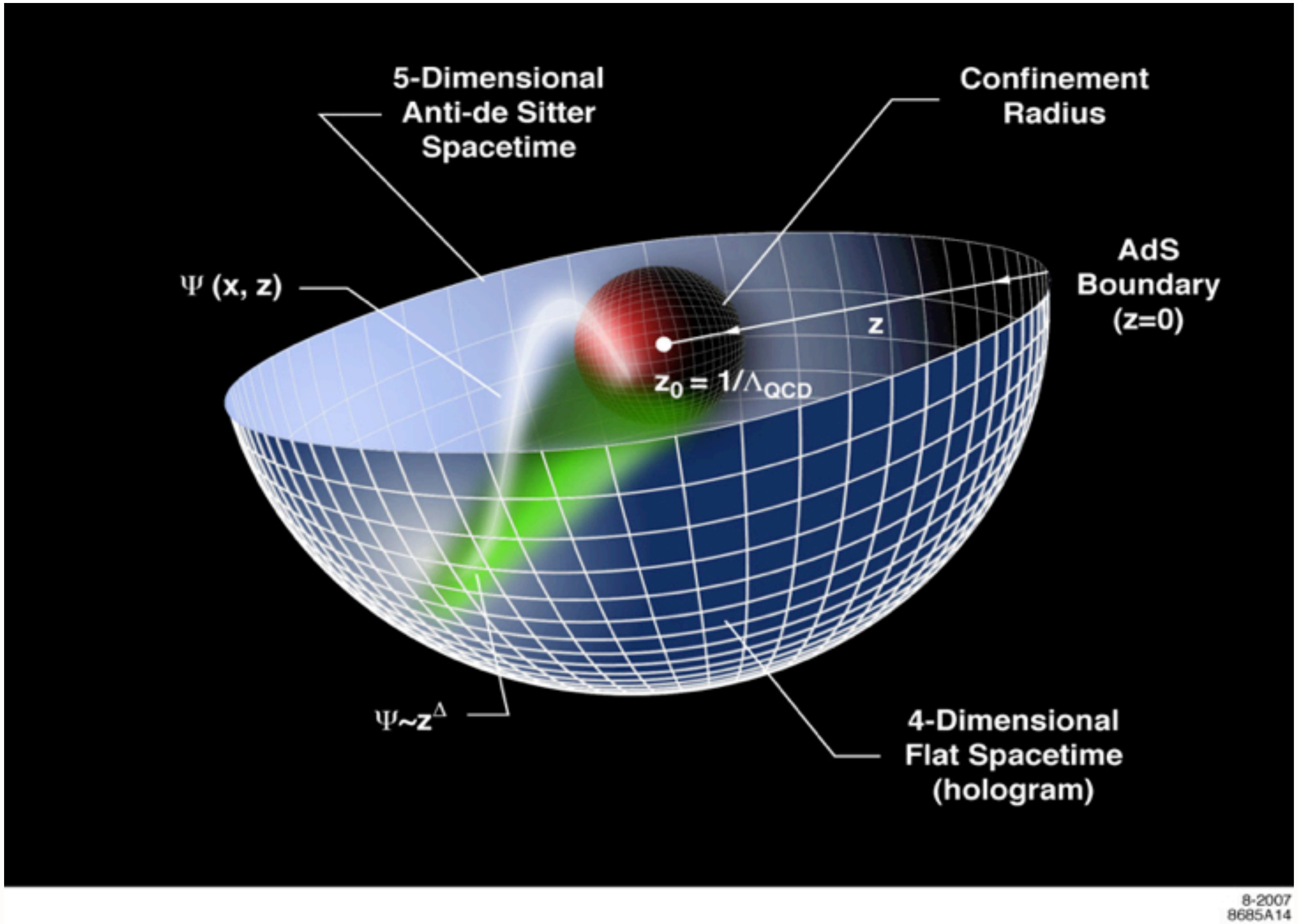


$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



- *Light Front Wavefunctions:*

Light-Front Schrödinger Equation
Spectroscopy and Dynamics



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

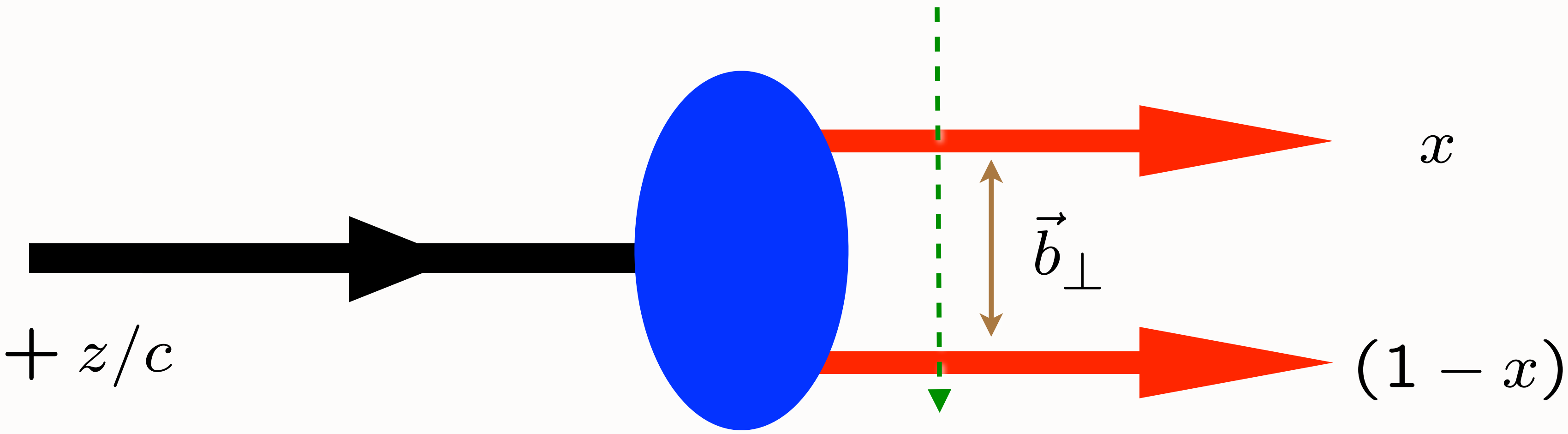
- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\rm QCD}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model) Polchinski and Strassler (2001).
- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model) Karch, Katz, Son and Stephanov (2006).

de Teramond, sjb

LF(3+1) ⟷ AdS_5

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

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



Fixed $\tau = t + z/c$

$$\psi(x, \zeta) = \sqrt{x(1-x)}\,\zeta^{-1/2}\phi(\zeta)$$

$$(\mu R)^2 = L^2 - (J-2)^2$$

Light-Front Holography: *Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements and identical equations of motion*

Light-Front Holography

- **AdS_5/CFT_4 Duality between AdS5 and Conformal Gauge Theory in 3+1 at fixed LF time** G. de Téramond, H. G. Dosch, sjb

  Valery E. Lyubovitskij, Tanja Branz, Thomas Gutsche, Ivan Schmidt, Alfredo Vega

- **AdS_4/CFT_3 Construction from Collective Fields"** Robert de Mello Koch, Antal Jevicki, Kewang Jin, João P. Rodrigues

- **"Exact holographic mapping and emergent space-time geometry"** Xiao-Liang Qi

- **Ehrenfest arguments:** Glazek and Trawinski

Dilaton-Modified AdS/QCD

$$ds^2 = e^{\varphi(z)} \frac{R^2}{z^2}(\eta_{\mu\nu} x^\mu x^\nu - dz^2)$$

- **Soft-wall dilaton profile breaks conformal invariance** $e^{\varphi(z)} = e^{+\kappa^2 z^2}$
- **Color Confinement**
- **Introduces confinement scale** κ
- **Uses AdS_5 as template for conformal theory**

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

Positive-sign dilaton

- Dosch, de Teramond, sjb

AdS Soft-Wall Schrodinger Equation for bound state of two scalar constituents:

$$\left[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + U(z)\right]\Phi(z) = \mathcal{M}^2\Phi(z)$$

$$U(z) = \kappa^4 z^2 + 2\kappa^2(L+S-1)$$

Derived from variation of Action for Dilaton-Modified AdS_5

Identical to Light-Front Bound State Equation!

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

Introduce "Dilaton" to simulate confinement analytically

- Nonconformal metric dual to a confining gauge theory

$$ds^2 = \frac{R^2}{z^2} e^{\varphi(z)} \left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right)$$

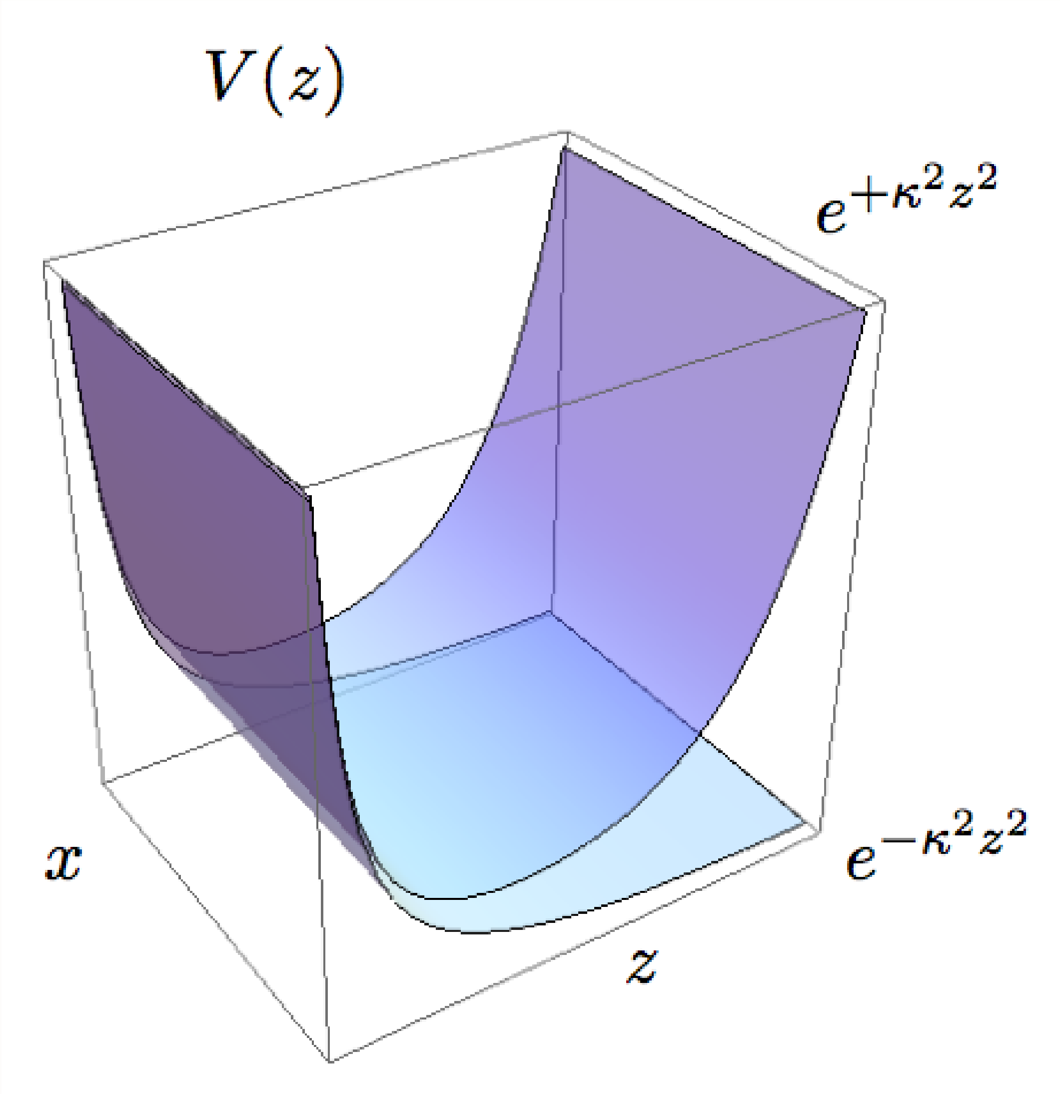
where $\varphi(z) \to 0$ at small z for geometries which are asymptotically AdS_5

- Gravitational potential energy for object of mass m

$$V = mc^2 \sqrt{g_{00}} = mc^2 R \frac{e^{\varphi(z)/2}}{z}$$

- Consider warp factor $\exp(\pm\kappa^2 z^2)$

- Plus solution: $V(z)$ increases exponentially confining any object in modified AdS metrics to distances $\langle z \rangle \sim 1/\kappa$

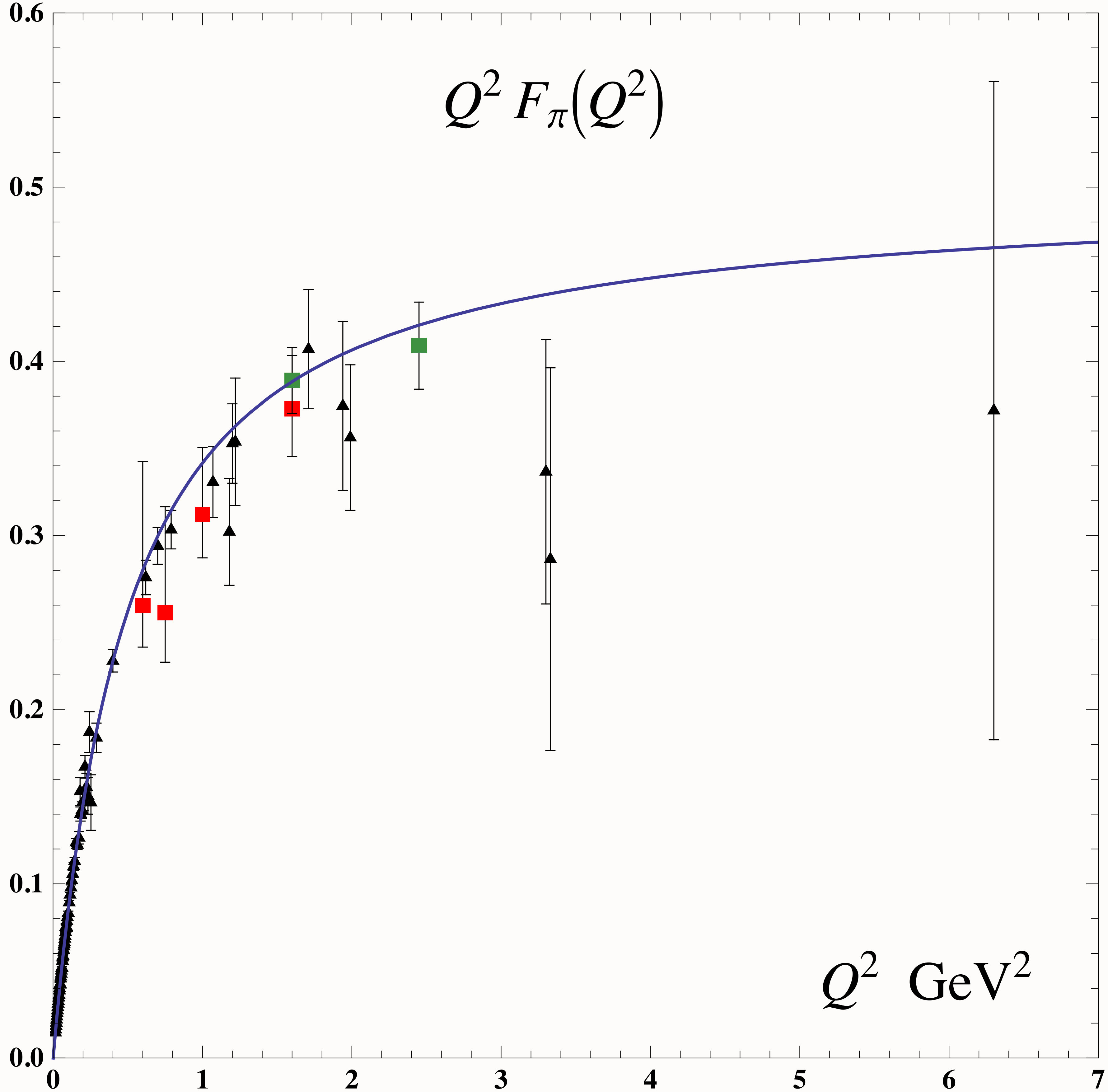


Klebanov and Maldacena

$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

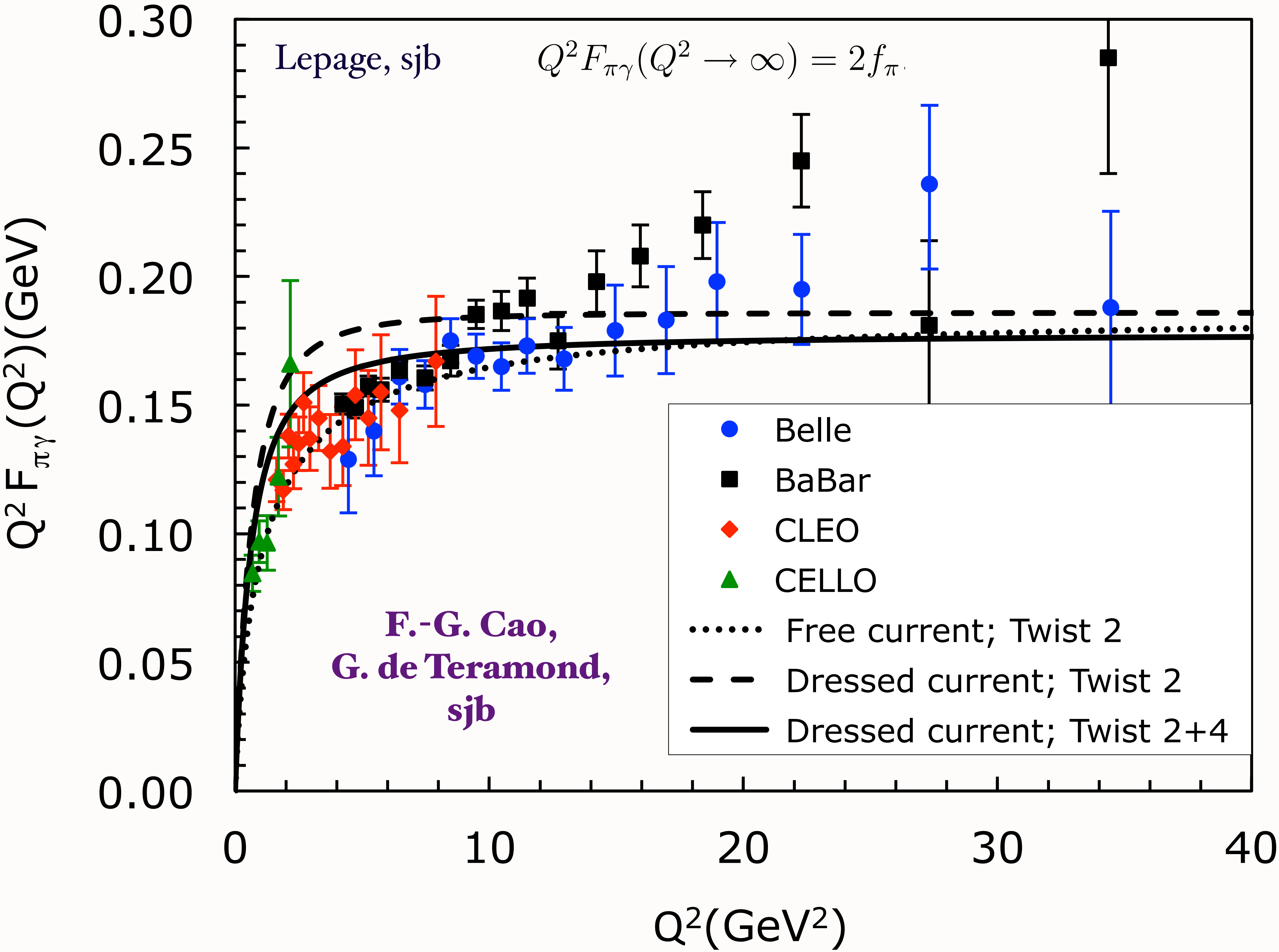
Positive-sign dilaton

- de Teramond, sjb



$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
1
2
3
4
5
6
7

Photon-to-pion transition form factor



Current Matrix Elements in AdS Space (SW)

sjb and GdT
Grigoryan and Radyushkin

- Propagation of external current inside AdS space described by the AdS wave equation

$$\left[z^2\partial_z^2 - z\left(1 + 2\kappa^2 z^2\right)\partial_z - Q^2 z^2\right] J_\kappa(Q,z) = 0.$$

Dressed Current in Soft-Wall Model

- Solution bulk-to-boundary propagator

$$J_\kappa(Q,z) = \Gamma\left(1 + \frac{Q^2}{4\kappa^2}\right) U\left(\frac{Q^2}{4\kappa^2}, 0, \kappa^2 z^2\right),$$

where $U(a,b,c)$ is the confluent hypergeometric function

$$\Gamma(a)U(a,b,z) = \int_0^\infty e^{-zt} t^{a-1}(1+t)^{b-a-1} dt.$$

- Form factor in presence of the dilaton background $\varphi = \kappa^2 z^2$

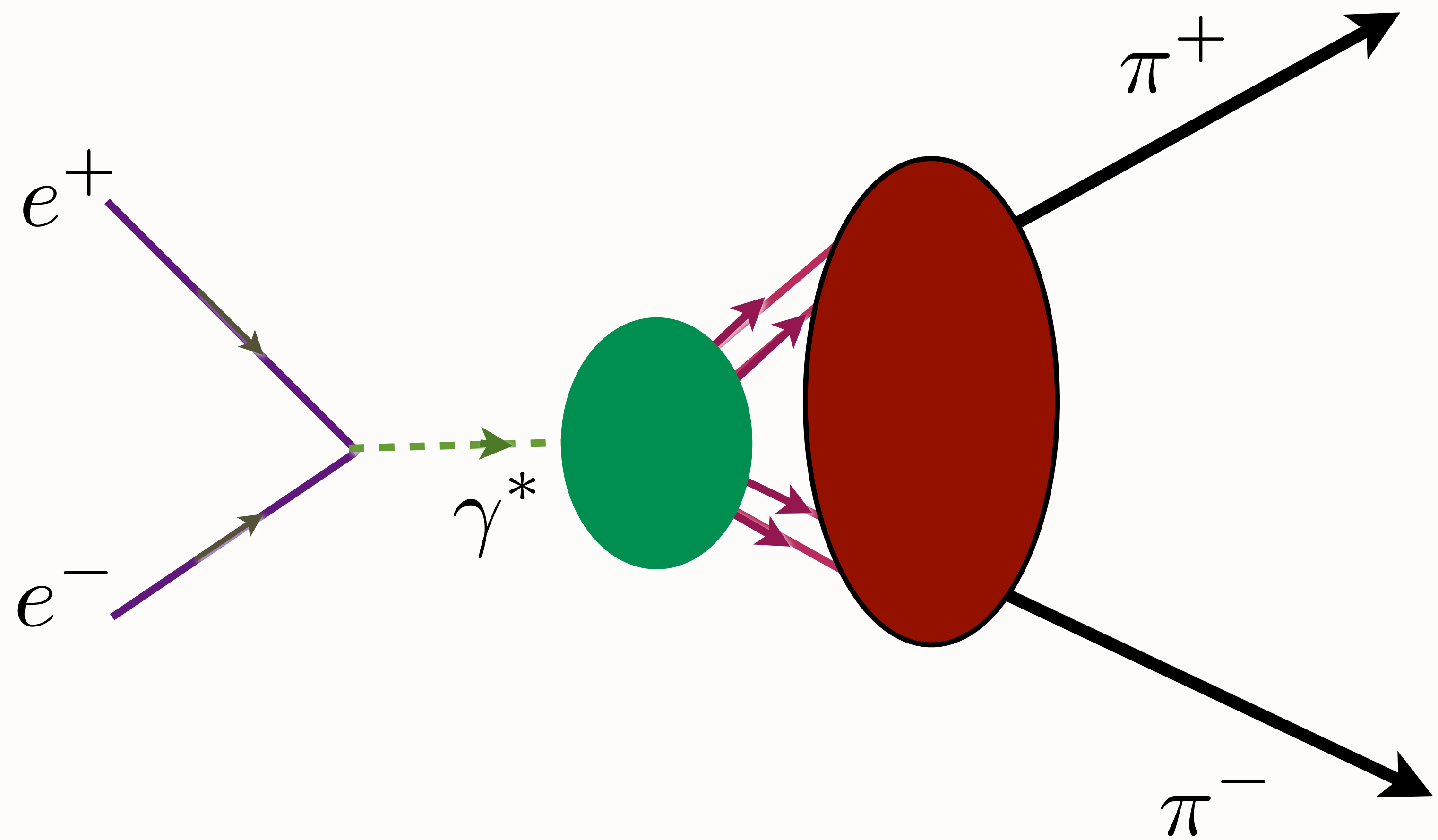
$$F(Q^2) = R^3 \int \frac{dz}{z^3}\, e^{-\kappa^2 z^2} \Phi(z) J_\kappa(Q,z) \Phi(z).$$

- For large $Q^2 \gg 4\kappa^2$

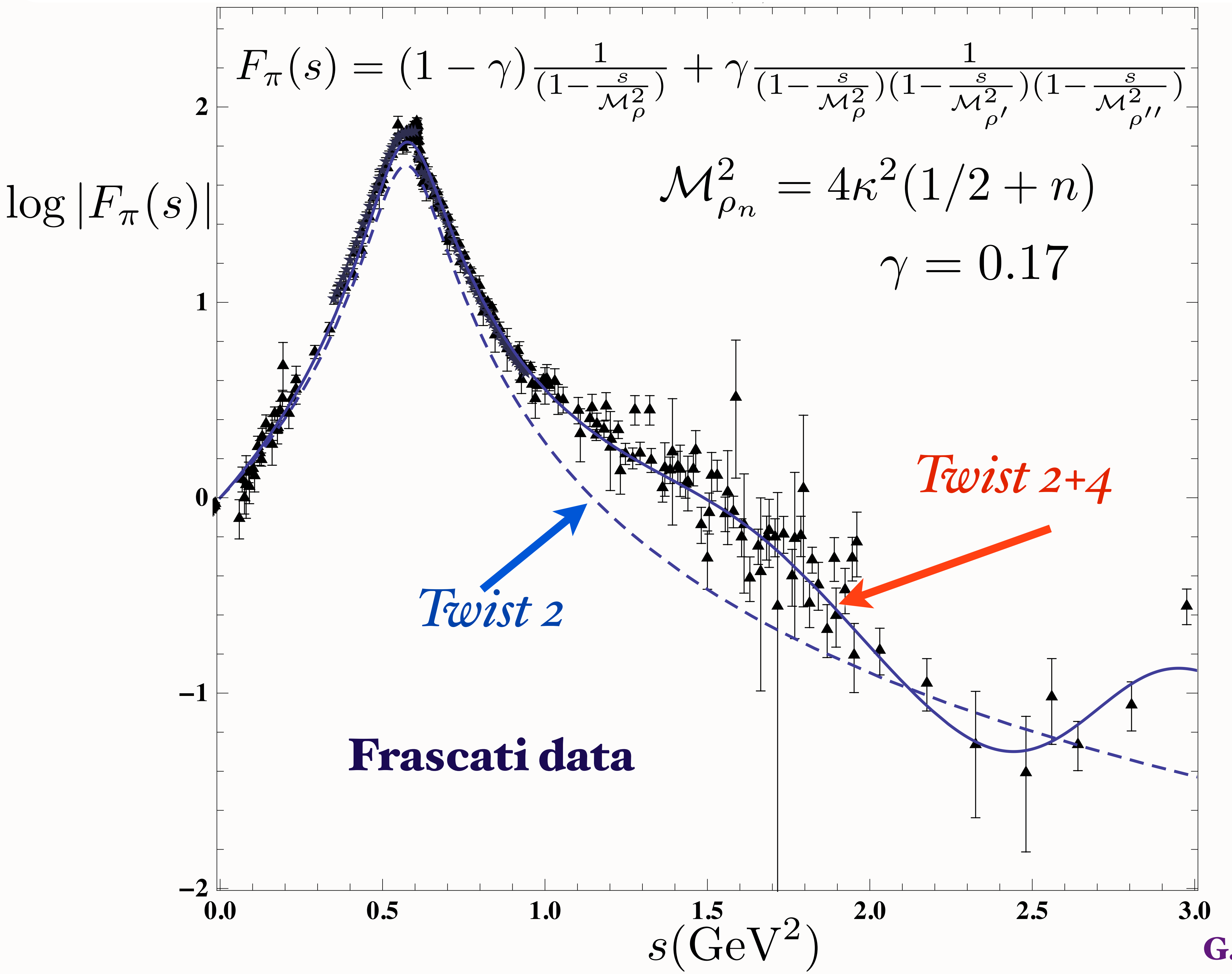
$$J_\kappa(Q,z) \to zQK_1(zQ) = J(Q,z),$$

the external current decouples from the dilaton field.

Dressed soft-wall current brings in higher Fock states and more vector meson poles



Timelike Pion Form Factor from AdS/QCD and Light-Front Holography



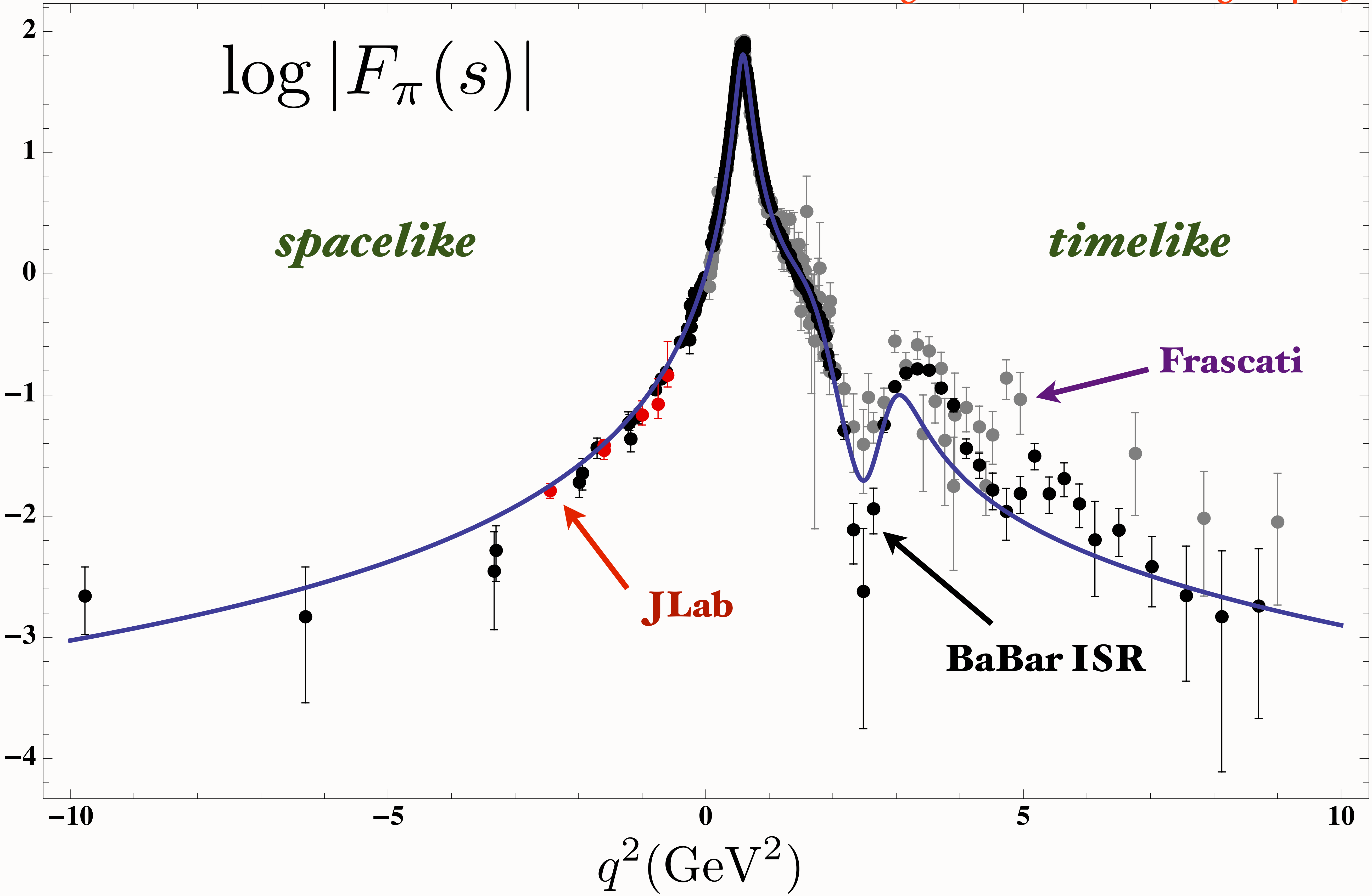
Prescription for Timelike poles :

$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

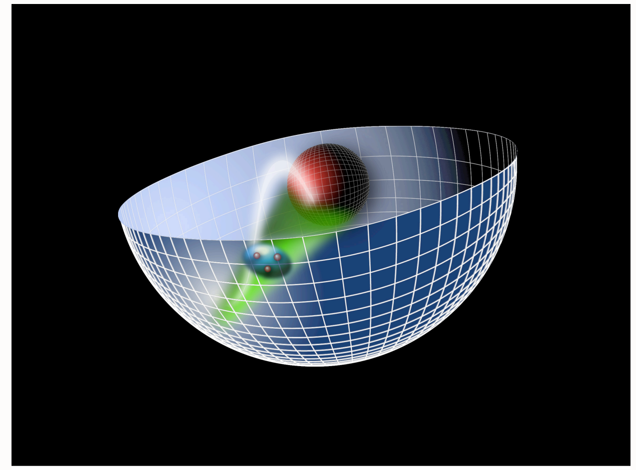
14% four-quark probability

G. de Teramond & sjb

Pion Form Factor from AdS/QCD and Light-Front Holography



de Tèramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

Light-Front Holography

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

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Conformal Symmetry
of the action

Confinement scale:

$$\kappa \simeq 0.6\ GeV$$

$$1/\kappa \simeq 1/3\ fm$$

- **de Alfaro, Fubini, Furlan:** ***Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!***

Uniqueness

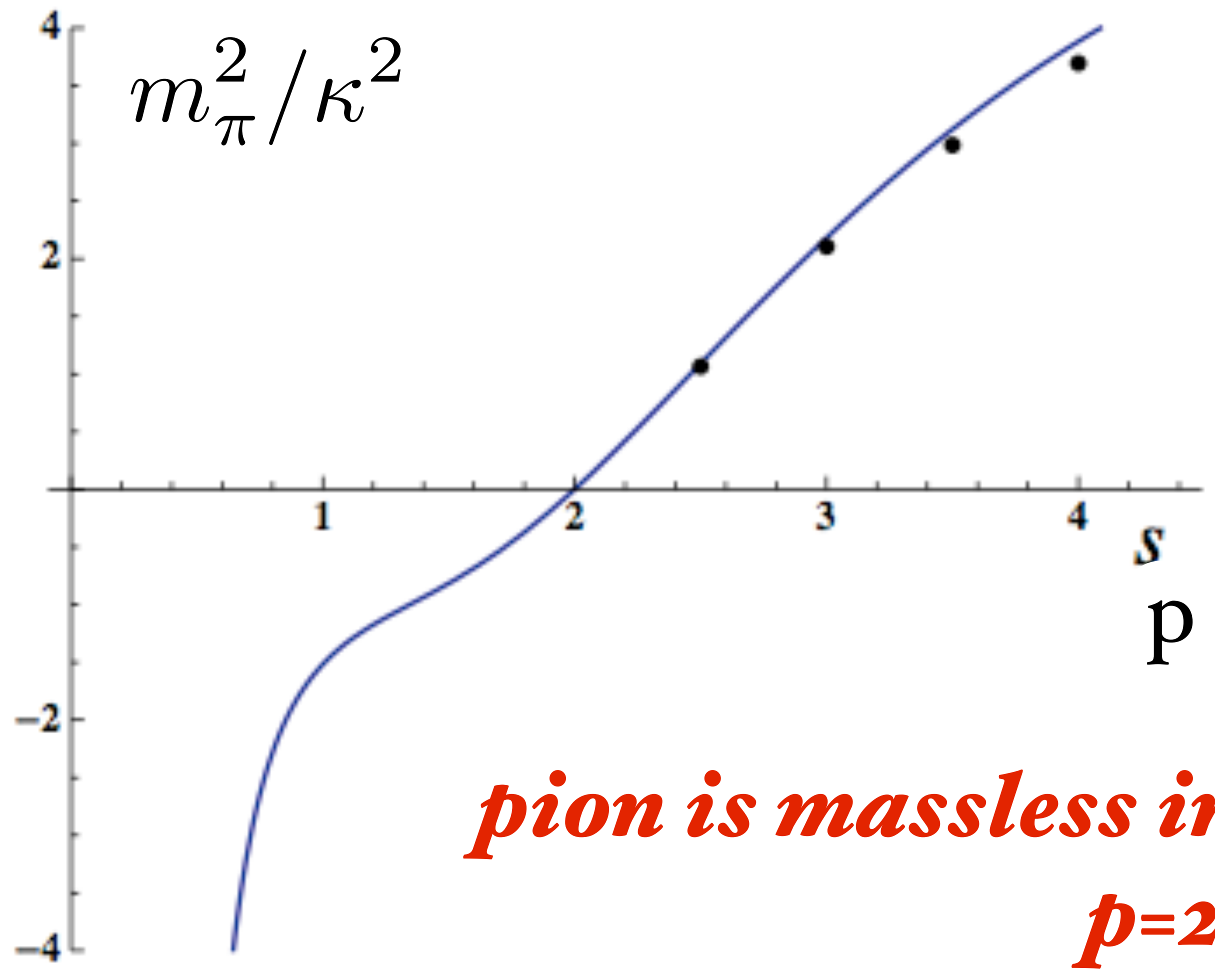
de Teramond, Dosch, sjb

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1) \qquad e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

- **ζ^2 confinement potential and dilaton profile unique!**
- **Linear Regge trajectories in n and L: same slope!**
- **Massless pion in chiral limit!   No vacuum condensate!**
- **Conformally invariant action for massless quarks retained despite mass scale**
- **Same principle, equation of motion as de Alfaro, Furlan, Fubini, Conformal Invariance in Quantum Mechanics Nuovo Cim. A34 (1976) 569**

Uniqueness of Dilaton

$$\varphi_p(z) = \kappa^p z^p$$



pion is massless in chiral limit iff p=2!

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

- **Dosch, de Teramond, sjb**

QCD Lagrangian

Fundamental Theory of Hadron and Nuclear Physics

gluon dynamics

quark kinetic energy + quark-gluon dynamics

quark mass term

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \quad G^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu - g[A^\mu, A^\nu]$$

Classically Conformal if m_q=0

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

Scale-Invariant Coupling
Renormalizable
Asymptotic Freedom
Color Confinement

QCD Mass Scale from Confinement not Explicit

IL NUOVO CIMENTO VOL. 34 A, N. 4 21 Agosto 1976

Conformal Invariance in Quantum Mechanics.

V. DE ALFARO

Istituto di Fisica Teorica dell'Università - Torino
Istituto Nazionale di Fisica Nucleare - Sezione di Torino

S. FUBINI and G. FURLAN (*)

CERN - Geneva

(ricevuto il 3 Maggio 1976)

Summary. — The properties of a field theory in one over-all time dimension, invariant under the full conformal group, are studied in detail. A compact operator, which is not the Hamiltonian, is diagonalized and used to solve the problem of motion, providing a discrete spectrum and normalizable eigenstates. The role of the physical parameters present in the model is discussed, mainly in connection with a semi-classical approximation.

- **de Alfaro, Fubini, Furlan**

$$G|\psi(\tau)>= i\frac{\partial}{\partial\tau}|\psi(\tau)>$$

$$G = uH + vD + wK$$

New term

$$G = H_\tau = \frac{1}{2}\left(-\frac{d^2}{dx^2} + \frac{g}{x^2} + \frac{4uw - v^2}{4}x^2\right)$$

Retains conformal invariance of action despite mass scale!

$$4uw - v^2 = \kappa^4 = [M]^4$$

Identical to LF Hamiltonian with unique potential and dilaton!

- **Dosch, de Teramond, sjb**

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1 - 4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L + S - 1)$$

What determines the QCD mass scale Λ_{QCD}?

- Mass scale does not appear in the QCD Lagrangian (massless quarks)
- Dimensional Transmutation? Requires external constraint such as $\alpha_s(M_Z)$
- dAFF: Confinement Scale κ appears spontaneously via the Hamiltonian: $G = uH + vD + wK$ $\quad 4uw - v^2 = \kappa^4 = [M]^4$
- The confinement scale regulates infrared divergences, connects Λ_{QCD} to the confinement scale κ
- Only dimensionless mass ratios (and M times R) predicted
- Mass and time units [GeV] and [sec] from physics external to QCD
- New feature: bounded frame-independent relative time between constituents

dAFF: New Time Variable

$$\tau = \frac{2}{\sqrt{4uw - v^2}} \arctan\left(\frac{2tw + v}{\sqrt{4uw - v^2}}\right),$$

- **Identify with difference of LF time $\Delta x^+/P^+$ between constituents**
- **Finite range**
- **Measure in Double Parton Processes**

J.F. Gunion and Z. Kunszt

Interpretation of Mass Scale κ

- Does not affect conformal symmetry of QCD action
- Self-consistent regularization of IR divergences
- Determines all mass and length scales for zero quark mass
- Compute scheme-dependent $\Lambda_{\overline{MS}}$ determined in terms of κ
- Value of κ itself not determined -- place holder
- Need external constraint such as f_π

Diffractive Excitation in QCD

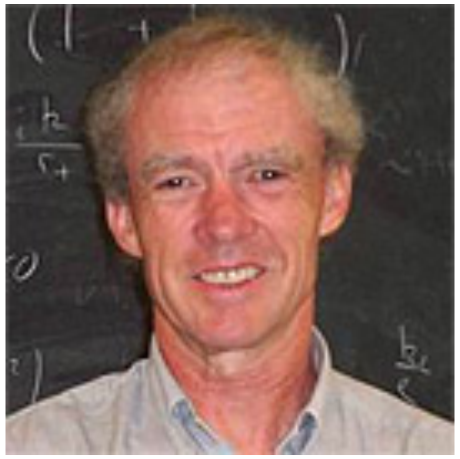
G. Bertsch (Santa Barbara, KITP), Stanley J. Brodsky (SLAC & Santa Barbara, KITP), A.S. Goldhaber, J.F. Gunion (Santa Barbara, KITP).

May 1981. 13 pp.

Published in **Phys.Rev.Lett. 47 (1981) 297**

SLAC-PUB-2748, NSF-ITP-81-34

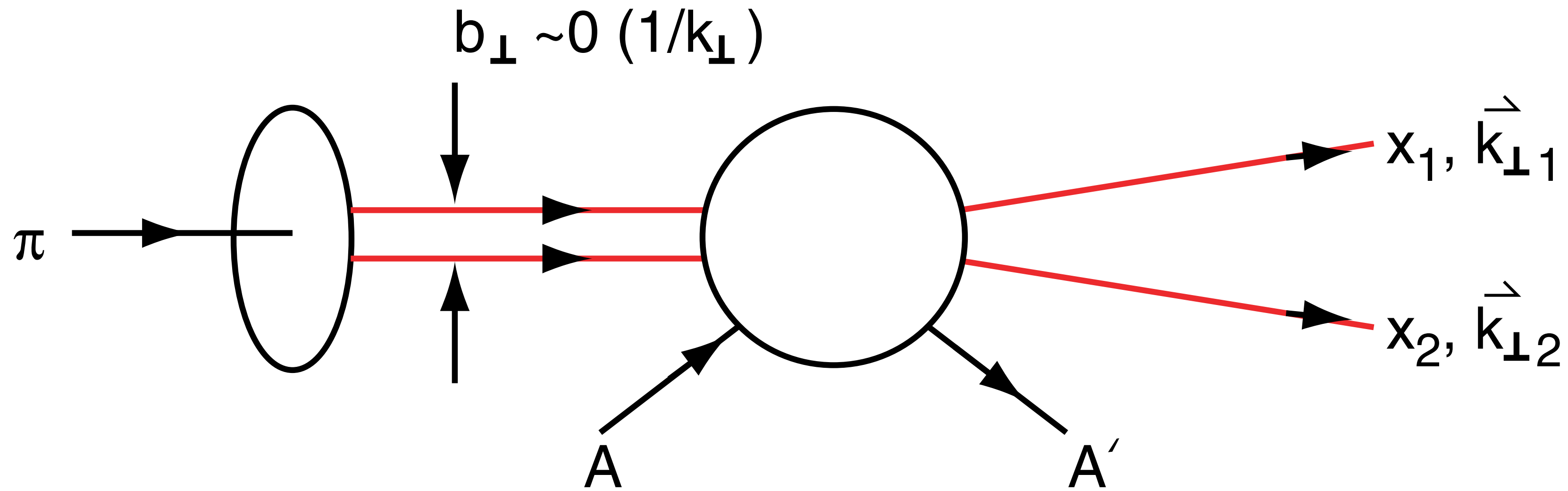
DOI: 10.1103/PhysRevLett.47.297



- *Pioneering paper on Diffractive QCD*
- *Color Transparency and Opacity*
- *Diffractive DiJet Production*
- *Measure LFWF*

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



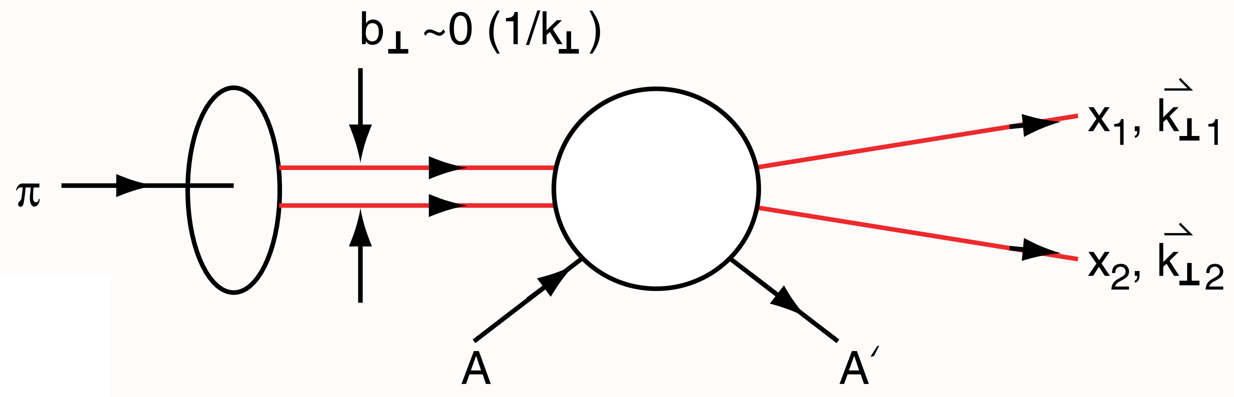
$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

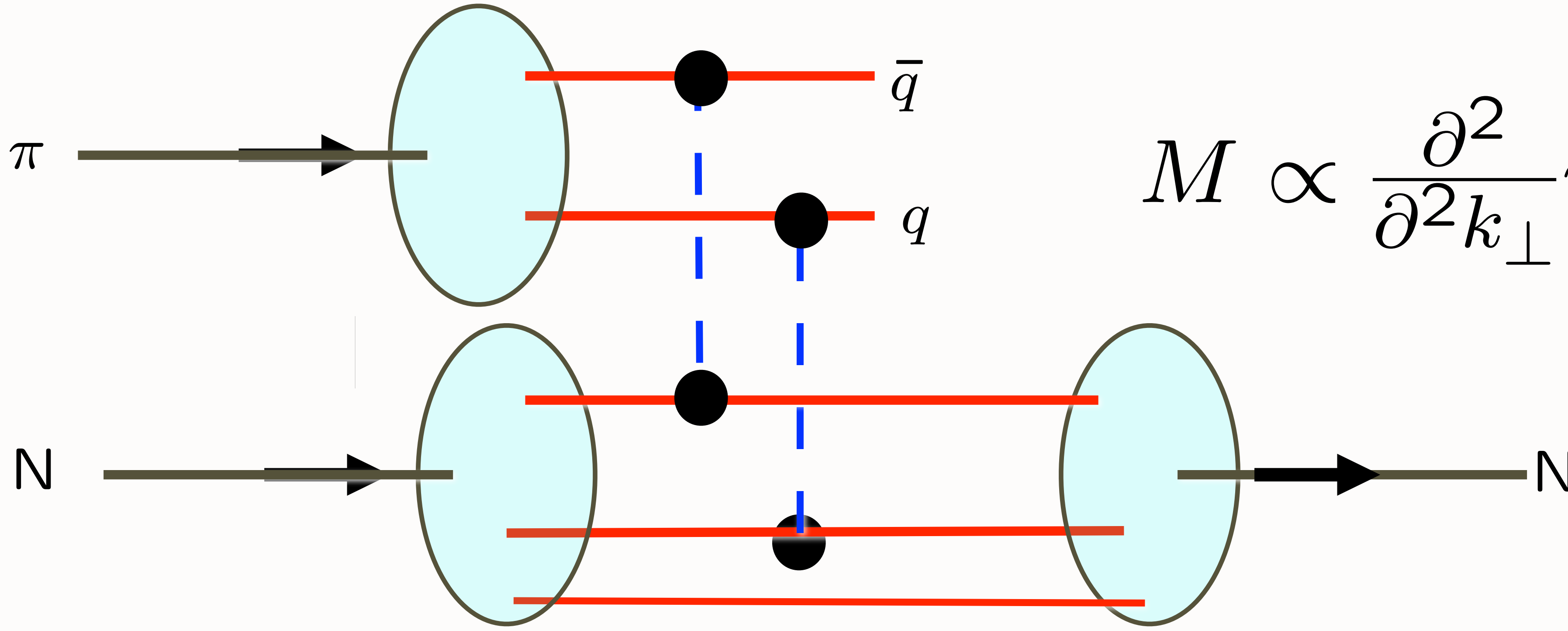
Minimal momentum transfer to nucleus

Nucleus left Intact!

E791 FNAL Diffractive DiJet



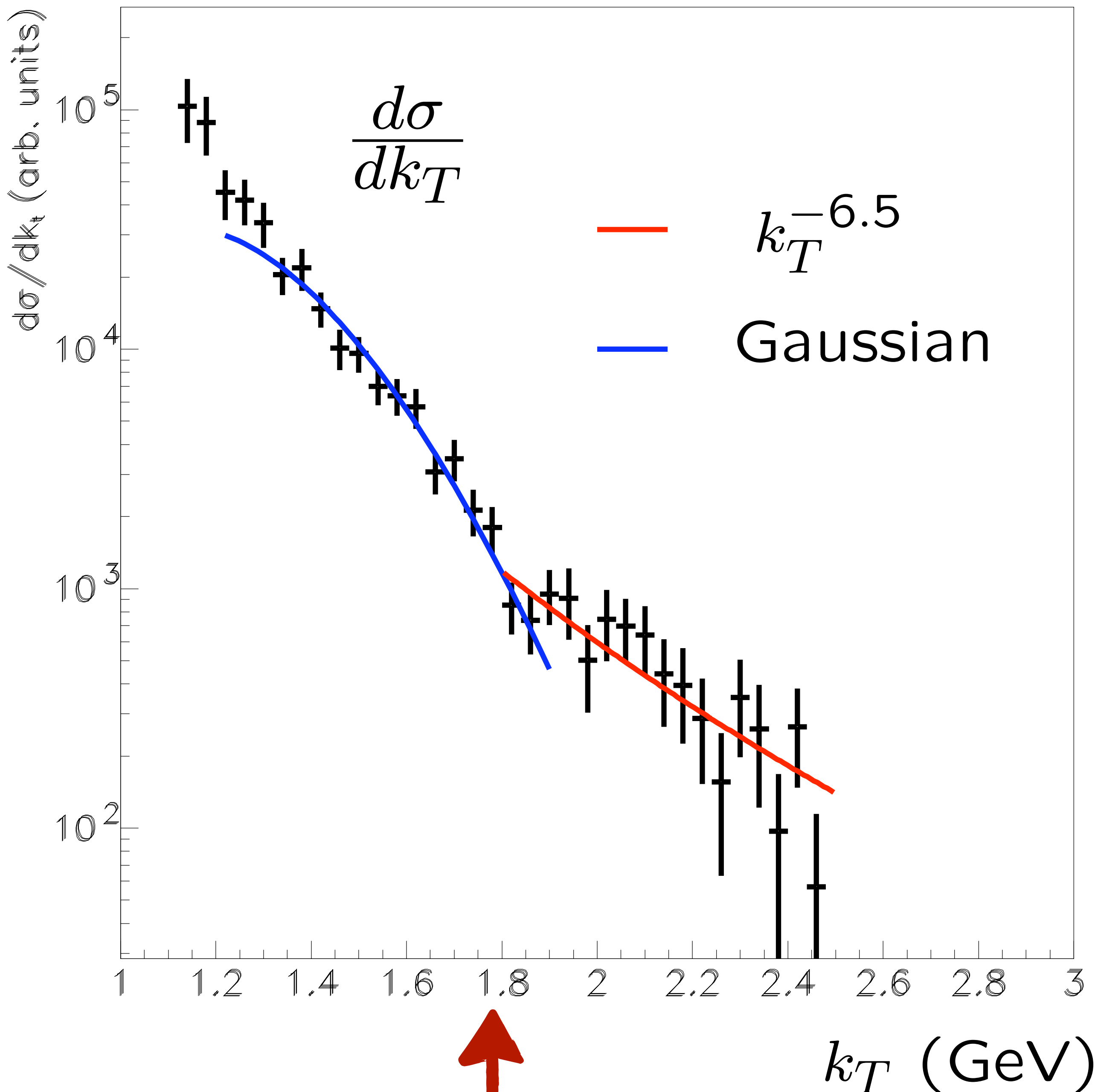
Two-gluon exchange measures the second derivative of the pion light-front wavefunction



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

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

E791 Diffractive Di-Jet transverse momentum distribution



Crossing point

Two Components: confinement plus gluon exchange

Gaussian behavior predicted by AdS/QCD

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

$$\frac{d\sigma}{dk_T} \propto e^{-\frac{k_T^2}{\kappa^2}} \quad (x \sim \frac{1}{2})$$

High transverse power-law fall-off consistent with PQCD, ERBL Evolution $k_T^{-6.5}$

relative jet transverse momentum

$$k_T = 2k_\perp$$

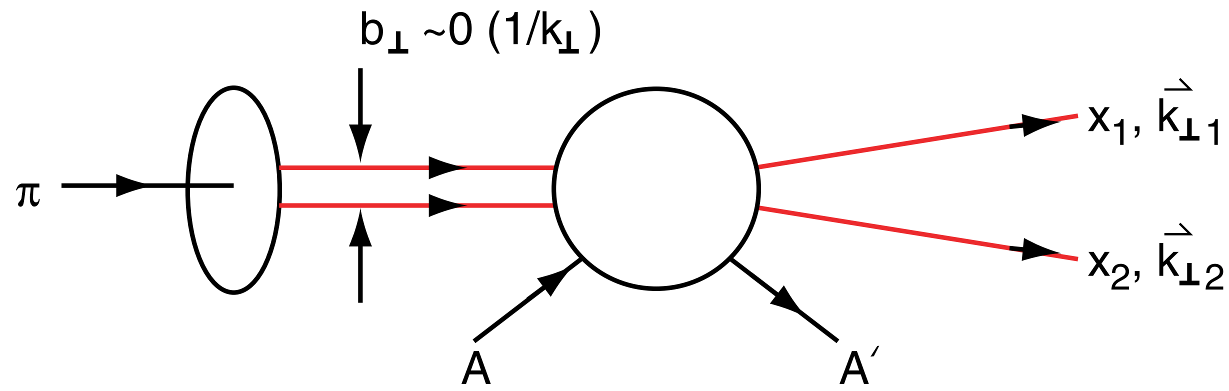
Color Transparency

A. H. Mueller, sjb

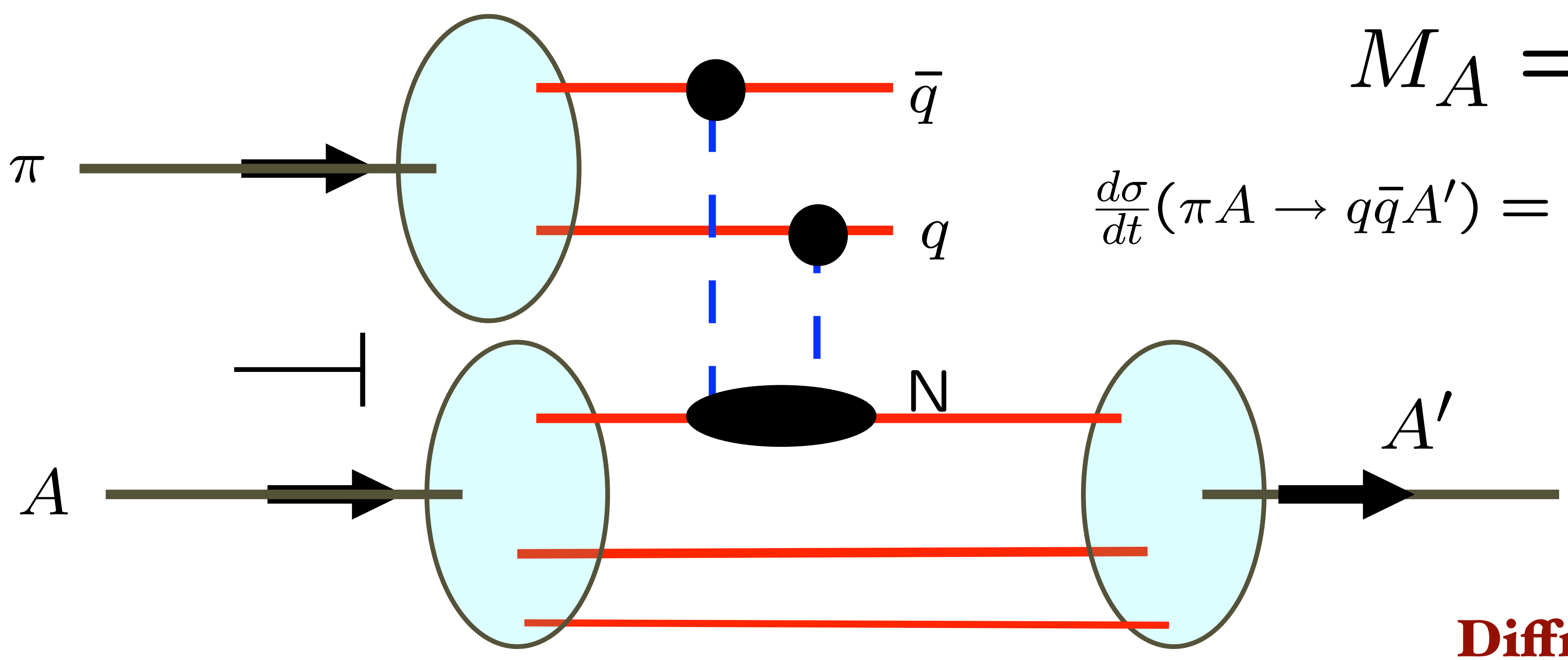
Bertsch, Gunion, Goldhaber, sjb

- **Fundamental test of gauge theory in hadron physics**
- **Small color dipole moments interact weakly in nuclei**
- **Complete coherence at high energies**
- **Clear Demonstration of CT from Diffractive Di-Jets**

Key Ingredients in the E791 Experiment



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



$$M_A = A\ M_N$$

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

Target left intact

Diffraction, Rapidity gap

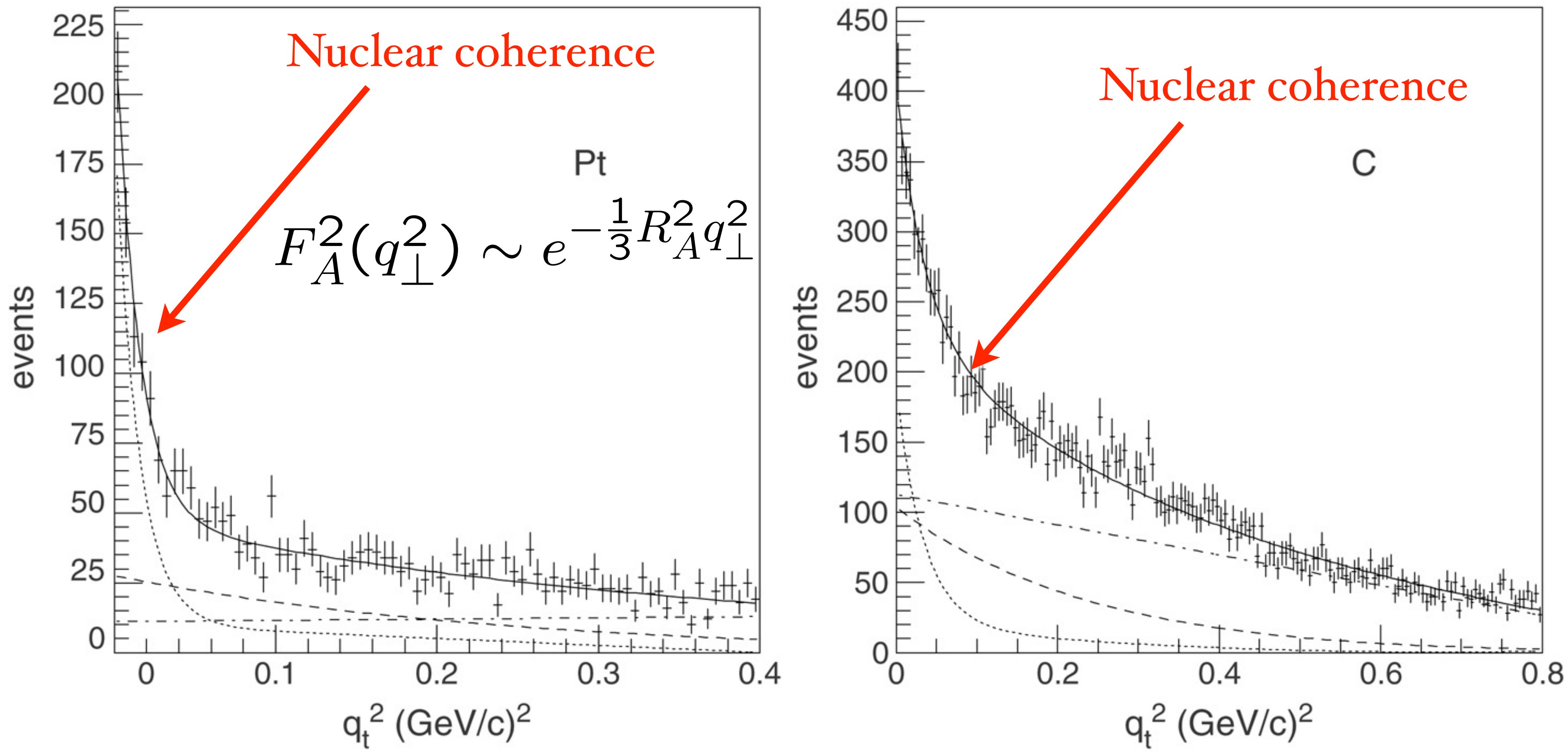
Gunion, Frankfurt, Mueller, Strikman, sjb
Frankfurt, Miller, Strikman

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

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

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

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



Mueller, sjb;
Bertsch, Gunion, Goldhaber, sjb;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

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

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

Ashery E791

α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

Factor of 7

Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

- Consider five-dim gauge fields propagating in AdS_5 space in dilaton background $\varphi(z) = \kappa^2 z^2$

$$S = -\frac{1}{4} \int d^4x \, dz \, \sqrt{g} \, e^{\varphi(z)} \, \frac{1}{g_5^2} \, G^2$$

- Flow equation

$$\frac{1}{g_5^2(z)} = e^{\varphi(z)} \frac{1}{g_5^2(0)} \quad \text{or} \quad g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0)$$

where the coupling $g_5(z)$ incorporates the non-conformal dynamics of confinement

- YM coupling $\alpha_s(\zeta) = g_{YM}^2(\zeta)/4\pi$ is the five dim coupling up to a factor: $g_5(z) \to g_{YM}(\zeta)$

- Coupling measured at momentum scale Q

$$\alpha_s^{AdS}(Q) \sim \int_0^\infty \zeta d\zeta \, J_0(\zeta Q) \, \alpha_s^{AdS}(\zeta)$$

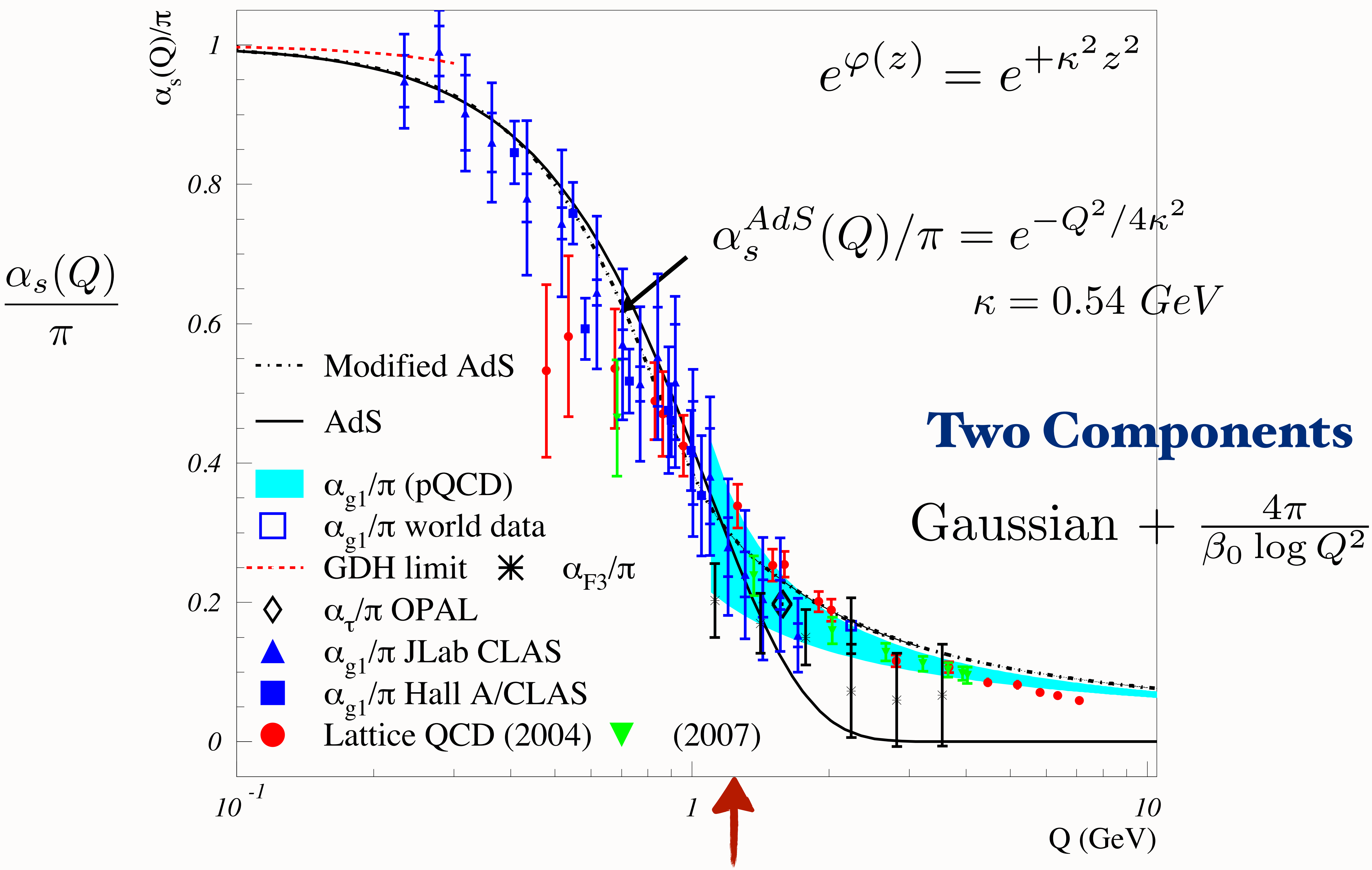
- Solution

$$\alpha_s^{AdS}(Q^2) = \alpha_s^{AdS}(0) \, e^{-Q^2/4\kappa^2}.$$

where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

Running Coupling from Light-Front Holography and AdS/QCD

Analytic QCD Coupling, defined at all scales, IR Fixed Point



Crossing point

Deur, de Teramond, sjb

Two-Components in QCD

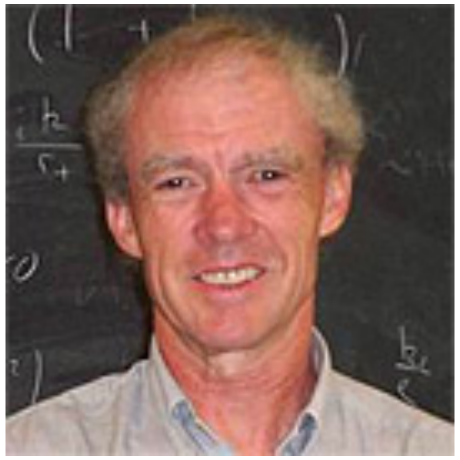
- Scale-Invariant Contribution from Gluonic Interactions
- Non-Perturbative Color-Confining Interaction from AdS/QCD and dAFF $U(z) = \kappa^4 z^2 + 2\kappa^2(L + S - 1)$
- Crossover at $\tilde{Q} \sim 2\kappa \sim 1.2 \ GeV$
- Phenomenology: Cross-over seen in Cornell potential, diffractive dijets, and running coupling
- Sets starting point for ERBL evolution of distribution amplitude and DGLAP evolution of structure functions

AdS/QCD and Light-Front Holography

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

- **Zero mass pion for m_q =0 (n=J=L=0)**
- **Regge trajectories: equal slope in n and L**
- **Form Factors at high Q^2: Dimensional counting** $[Q^2]^{n-1} F(Q^2) \to \text{const}$
- **Space-like and Time-like Meson and Baryon Form Factors**
- **Running Coupling for NPQCD** $\alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$
- **Meson Distribution Amplitude** $\phi_\pi(x) \propto f_\pi \sqrt{x(1-x)}$

Hadron Multiplicity in Color Gauge Theory Models
Stanley J. Brodsky (SLAC), J.F. Gunion (UC, Davis). May 1976. 13 pp.
Published in **Phys.Rev.Lett. 37 (1976) 402-405**
SLAC-PUB-1749, UCD-76-5
DOI: 10.1103/PhysRevLett.37.402



- *Pioneering paper on color effects in Jet Production*

- *Key Prediction verified at* in $e^+e^- \to q\bar{q}g$

$$\frac{dn}{dy}|_g = \frac{9}{4}\frac{dn}{dy}|_q$$

On The multiplicity difference between quark and gluon jets
J.William Gary (UC, Riverside). Sep 1993. 16 pp.
Published in **Phys.Rev. D49 (1994) 4503-4509**

Dirac Equation for Nucleons in Soft-Wall AdS/QCD

- We write the Dirac equation

$$(\alpha\Pi(\zeta) - \mathcal{M})\,\psi(\zeta) = 0,$$

in terms of the matrix-valued operator Π

$$\Pi_\nu(\zeta) = -i\left(\frac{d}{d\zeta} - \frac{\nu + \frac{1}{2}}{\zeta}\gamma_5 - \kappa^2\zeta\gamma_5\right),$$

and its adjoint $\Pi^\dagger$, with commutation relations

$$\left[\Pi_\nu(\zeta), \Pi_\nu^\dagger(\zeta)\right] = \left(\frac{2\nu+1}{\zeta^2} - 2\kappa^2\right)\gamma_5.$$

- Solutions to the Dirac equation

$$\psi_+(\zeta) \sim z^{\frac{1}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^\nu(\kappa^2\zeta^2),$$
$$\psi_-(\zeta) \sim z^{\frac{3}{2}+\nu} e^{-\kappa^2\zeta^2/2} L_n^{\nu+1}(\kappa^2\zeta^2).$$

$$\nu = L + 1$$

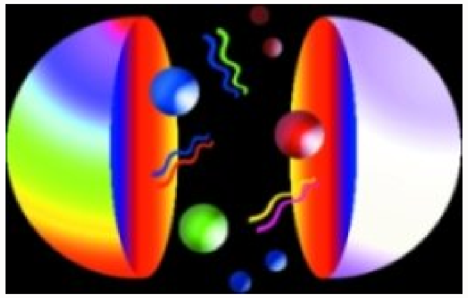
- Eigenvalues

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

Fermionic Modes and Baryon Spectrum

[Hard wall model: GdT and S. J. Brodsky, PRL **94**, 201601 (2005)]

[Soft wall model: GdT and S. J. Brodsky, (2005), arXiv:1001.5193]



From Nick Evans

- Nucleon LF modes

$$\psi_+(\zeta)_{n,L} = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{3/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+1}\left(\kappa^2\zeta^2\right)$$

$$\psi_-(\zeta)_{n,L} = \kappa^{3+L}\frac{1}{\sqrt{n+L+2}}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{5/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+2}\left(\kappa^2\zeta^2\right)$$

- Normalization

$$\int d\zeta\, \psi_+^2(\zeta) = \int d\zeta\, \psi_-^2(\zeta) = 1$$

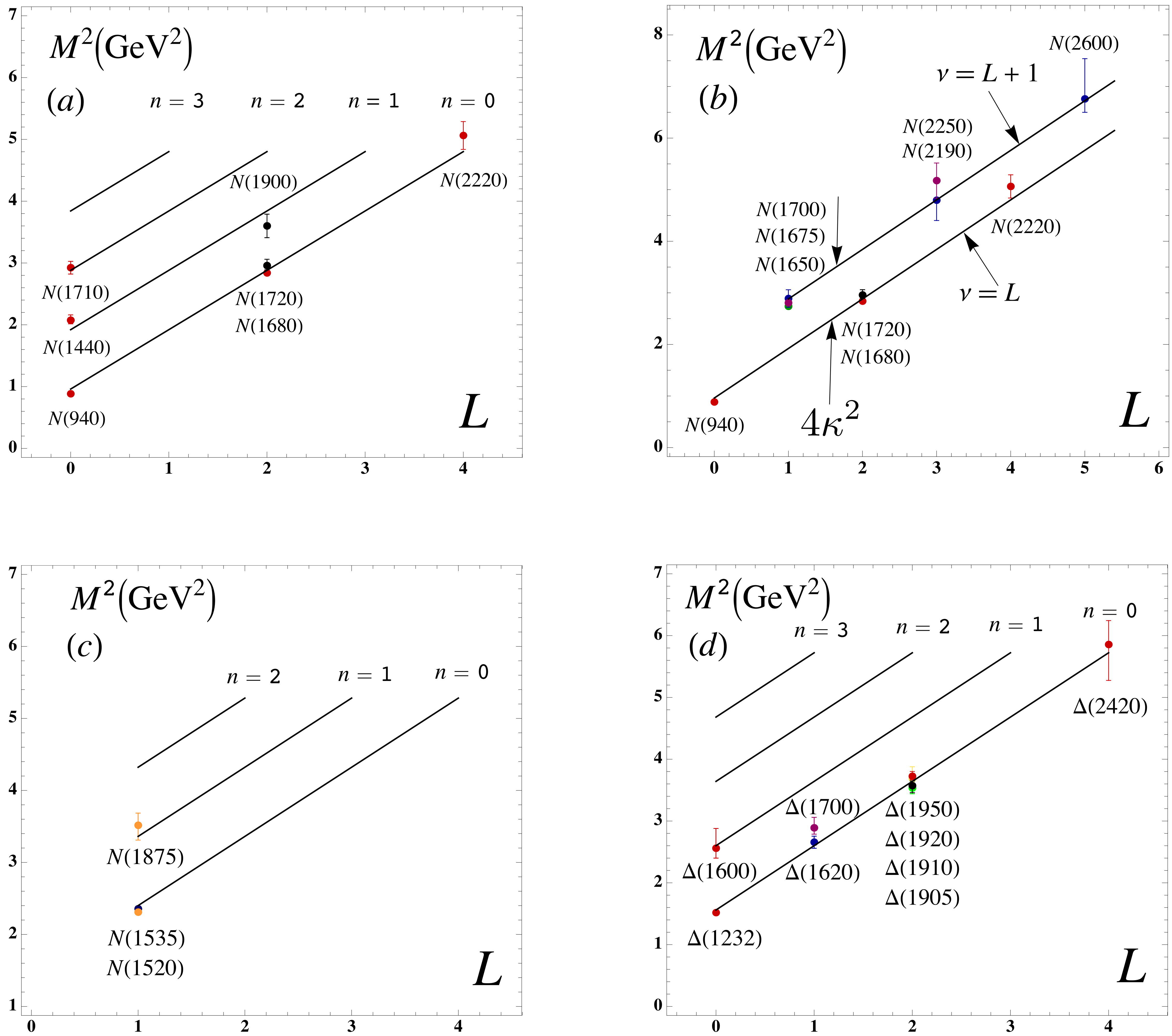
Chiral Symmetry of Eigenstate!

- Eigenvalues

$$\mathcal{M}^2_{n,L,S=1/2} = 4\kappa^2\left(n+L+1\right)$$

- "Chiral partners"

$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$



$M^2(\mathrm{GeV}^2)$
(a)
n = 3
n = 2
n = 1
n = 0
N(1900)
N(2220)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
L
$M^2(\mathrm{GeV}^2)$
(b)
ν = L + 1
N(2600)
N(2250)
N(2190)
N(1700)
N(1675)
N(1650)
N(2220)
ν = L
N(1720)
N(1680)
N(940)
$4\kappa^2$
L
$M^2(\mathrm{GeV}^2)$
(c)
n = 2
n = 1
n = 0
N(1875)
N(1535)
N(1520)
L
$M^2(\mathrm{GeV}^2)$
(d)
n = 3
n = 2
n = 1
n = 0
Δ(2420)
Δ(1700)
Δ(1950)
Δ(1920)
Δ(1910)
Δ(1905)
Δ(1600)
Δ(1620)
Δ(1232)
L

Chiral Features of Soft-Wall AdS/QCD Model

- **Boost Invariant**
- **Trivial LF vacuum! No condensate, but consistent with GMOR**
- **Massless Pion**
- **Hadron Eigenstates (even the pion) have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S_q^z >= 0$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

No mass -degenerate parity partners!

Space-Like Dirac Proton Form Factor

- Consider the spin non-flip form factors

$$F_+(Q^2) = g_+ \int d\zeta \, J(Q,\zeta) |\psi_+(\zeta)|^2,$$
$$F_-(Q^2) = g_- \int d\zeta \, J(Q,\zeta) |\psi_-(\zeta)|^2,$$

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 $\psi_+(\zeta)$ and $\psi_-(\zeta)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

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

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

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

- Compute Dirac proton form factor using SU(6) flavor symmetry

$$F_1^p(Q^2) = R^4 \int \frac{dz}{z^4} V(Q,z) \Psi_+^2(z)$$

- Nucleon AdS wave function

$$\Psi_+(z) = \frac{\kappa^{2+L}}{R^2} \sqrt{\frac{2n!}{(n+L)!}} z^{7/2+L} L_n^{L+1}\left(\kappa^2 z^2\right) e^{-\kappa^2 z^2/2}$$

- Normalization $\quad (F_1{}^p(0) = 1, \quad V(Q=0,z) = 1)$

$$R^4 \int \frac{dz}{z^4} \Psi_+^2(z) = 1$$

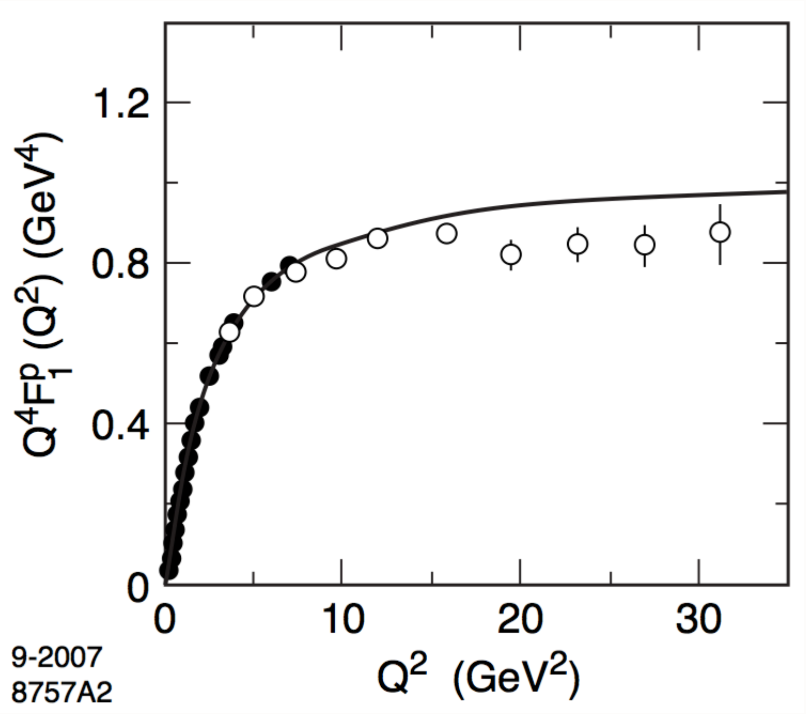
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

$$V(Q,z) = \kappa^2 z^2 \int_0^1 \frac{dx}{(1-x)^2} \, x^{\frac{Q^2}{4\kappa^2}} e^{-\kappa^2 z^2 x/(1-x)}$$

- Find

$$F_1^p(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)}$$

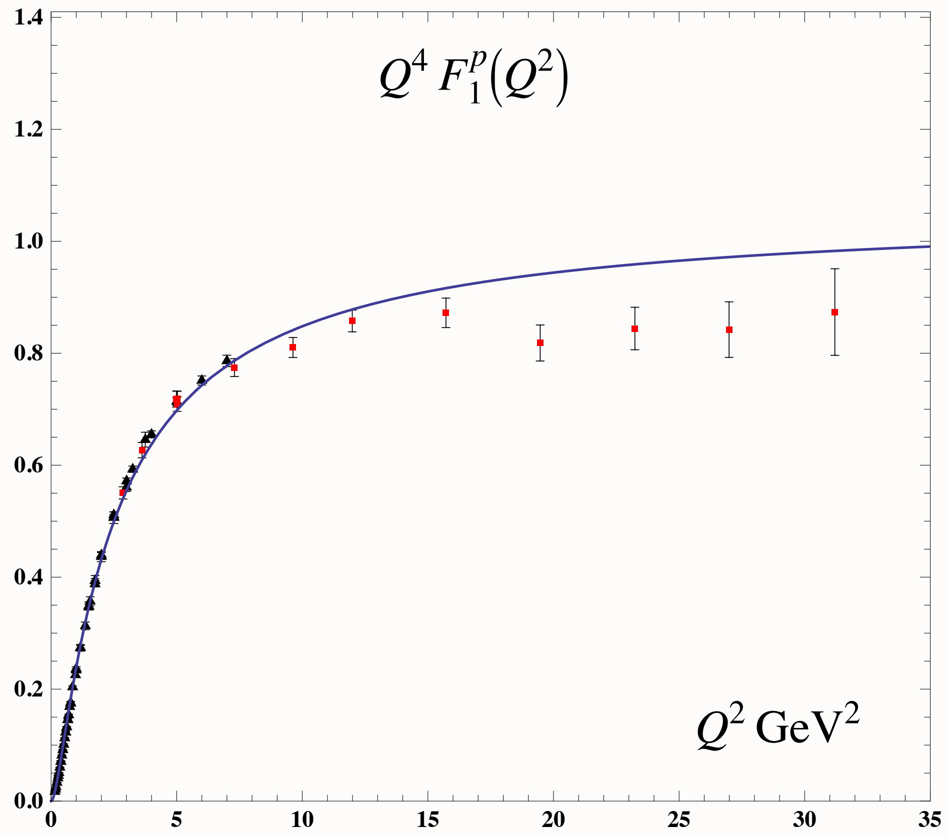
with $\mathcal{M}_{\rho_n}^2 \to 4\kappa^2(n+1/2)$

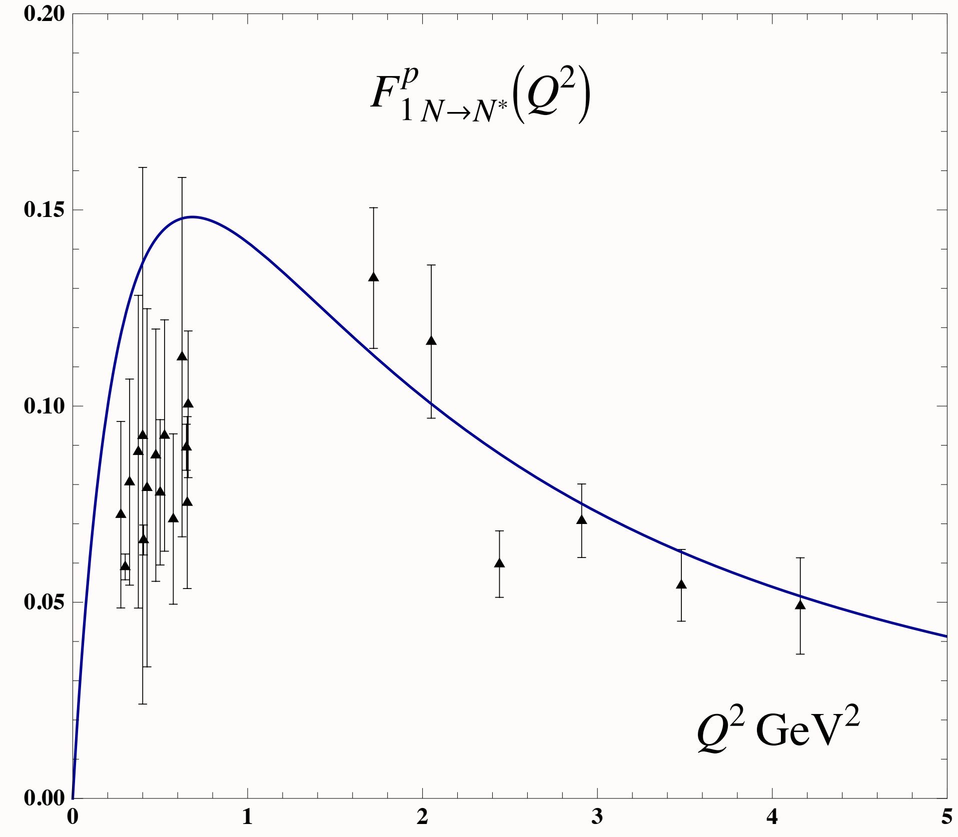


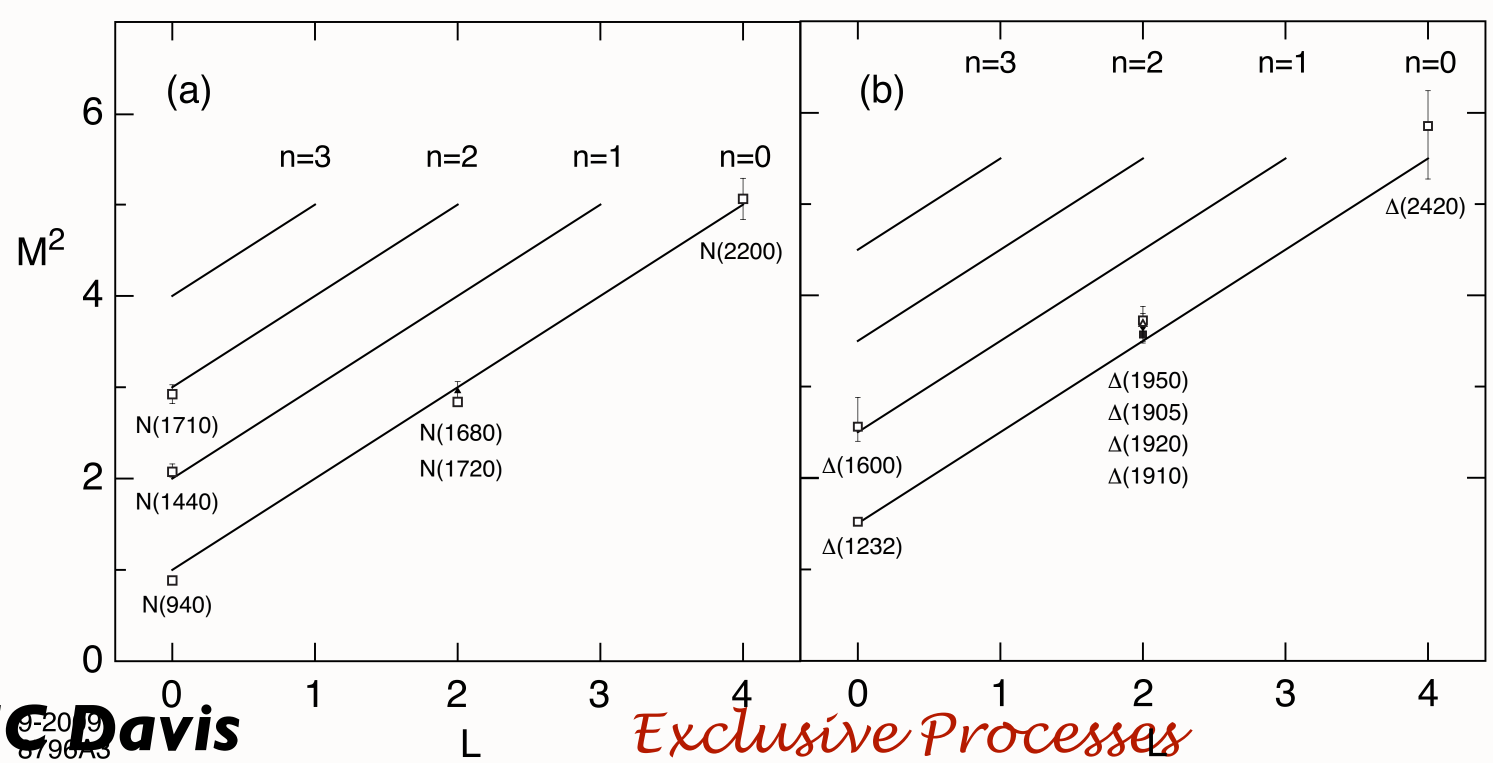
Predict hadron spectroscopy and dynamics

Excited Baryons in Holographic QCD

G. de Teramond & sjb







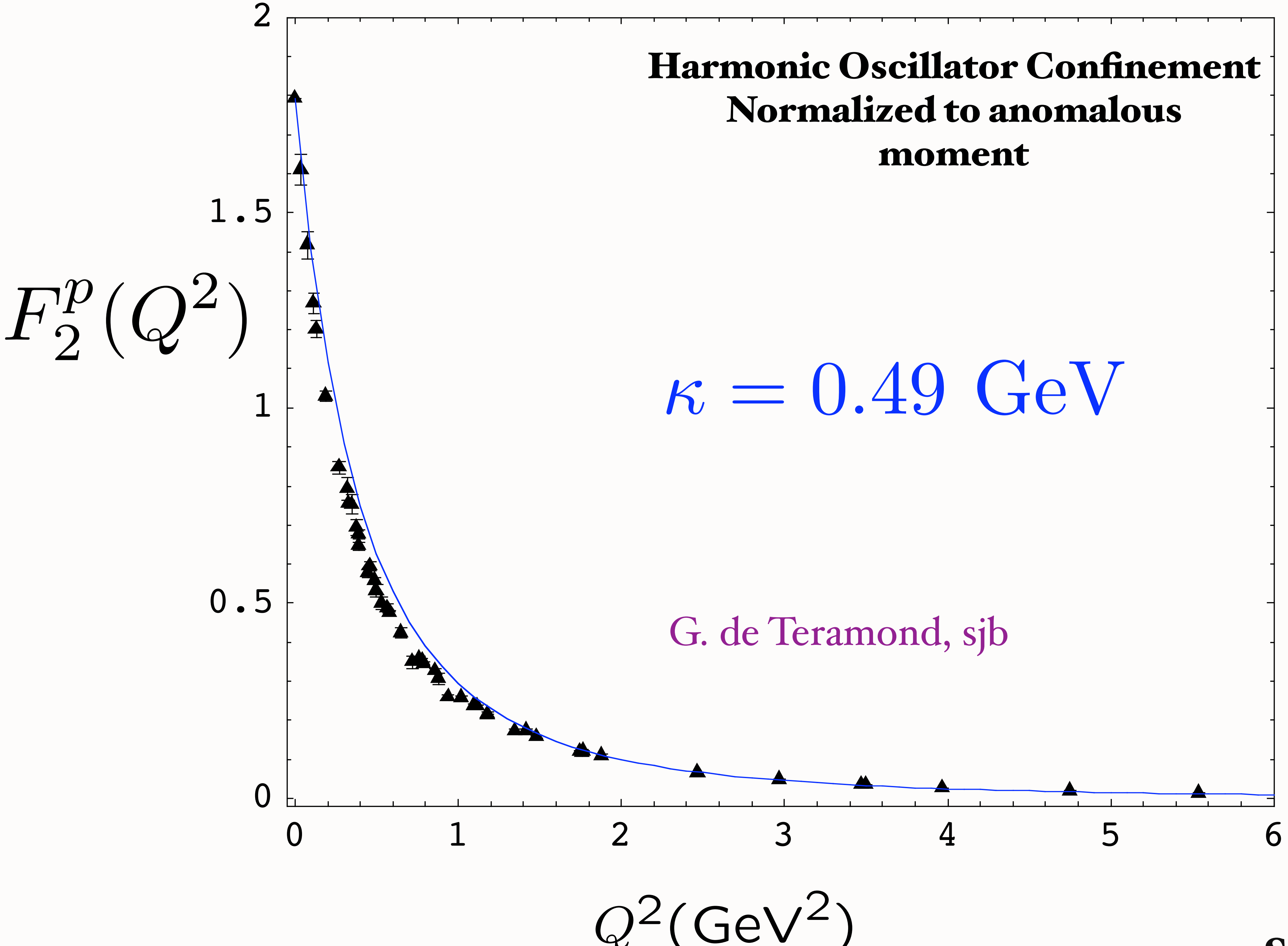
Gunion Fest, UC Davis
March 28-29, 2014

Exclusive Processes
and New Perspectives for QCD

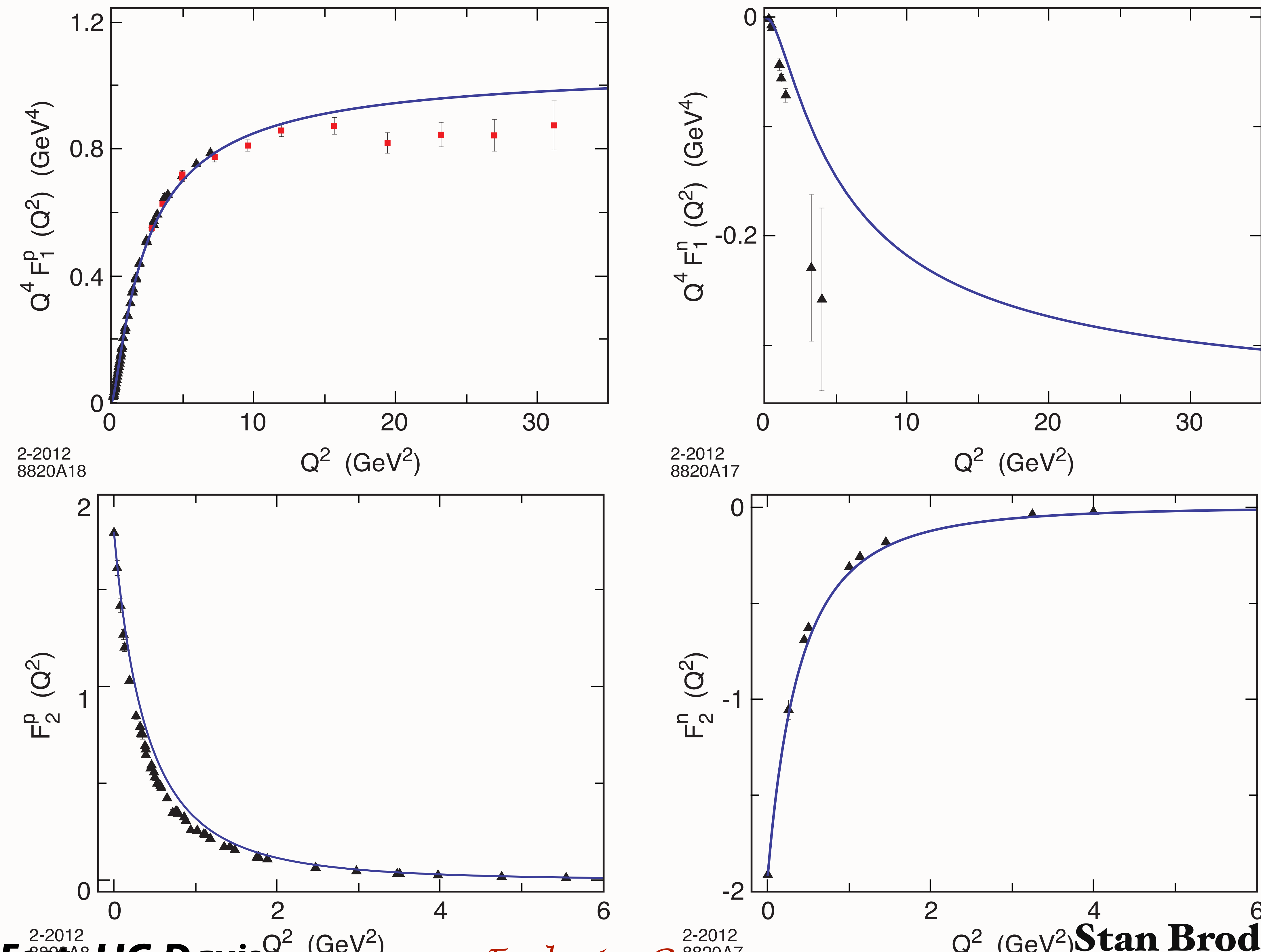
Stan Brodsky
SLAC
NATIONAL ACCELERATOR LABORATORY

Spacelike Pauli Form Factor

From overlap of $L = 1$ and $L = 0$ LFWFs



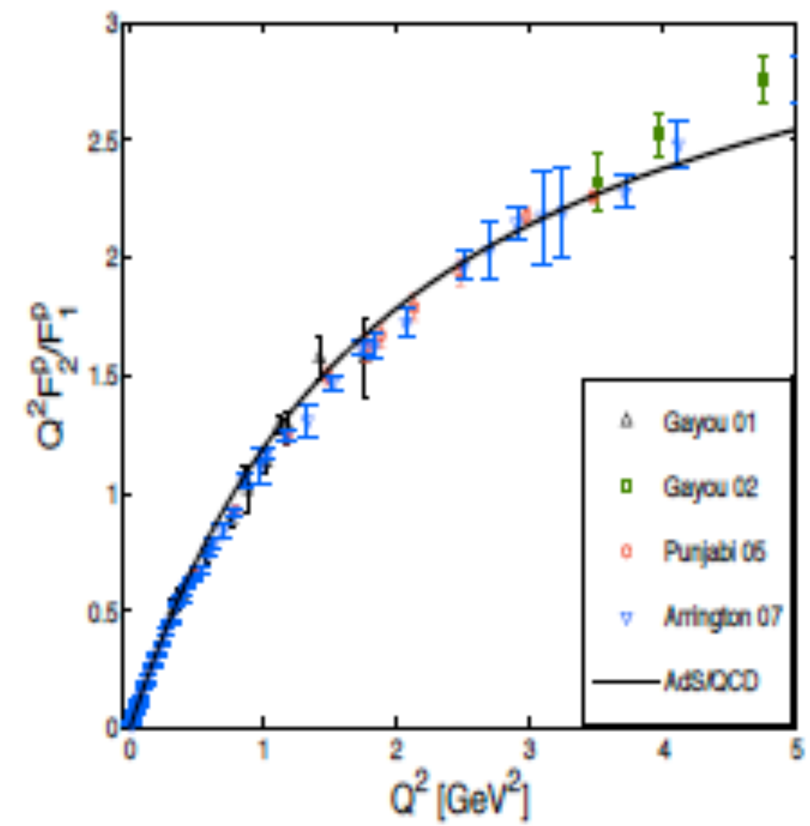
Using $SU(6)$ flavor symmetry and normalization to static quantities

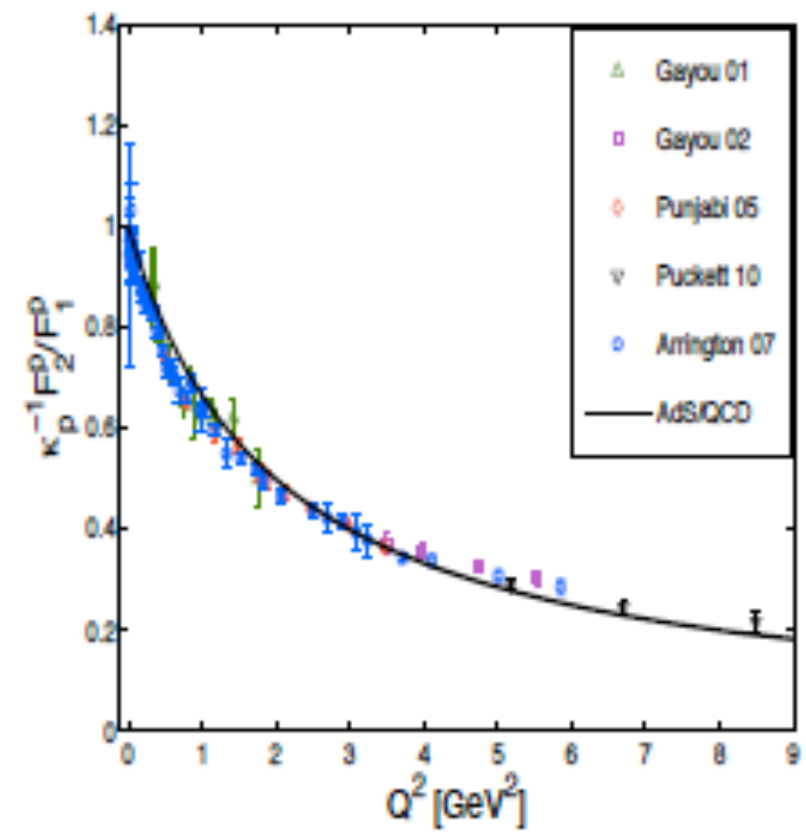


Nucleon and flavor form factors in a light front quark model in AdS/QCD

Dipankar Chakrabarti, Chandan Mondal

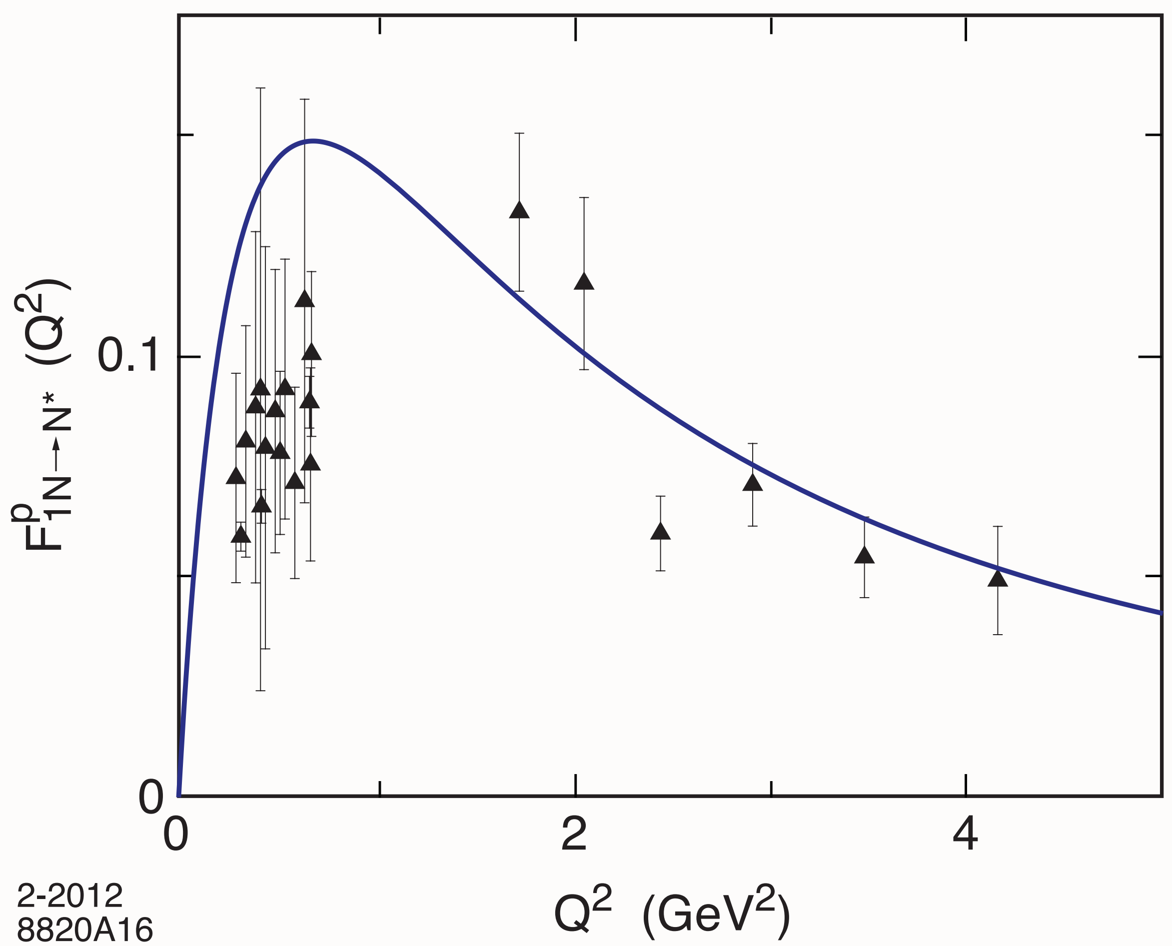
[1]Department of Physics, Indian Institute of Technology Kanpur, Kanpur-208016, India.





Nucleon Transition Form Factors

$$F^{p}_{1\,N\to N^*}(Q^2) = \frac{\sqrt{2}}{3}\frac{\frac{Q^2}{\mathcal{M}_\rho^2}}{\left(1+\frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1+\frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}.$$



Proton transition form factor to the first radial excited state. Data from JLab

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

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

The Light Front Fock State Wavefunctions

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

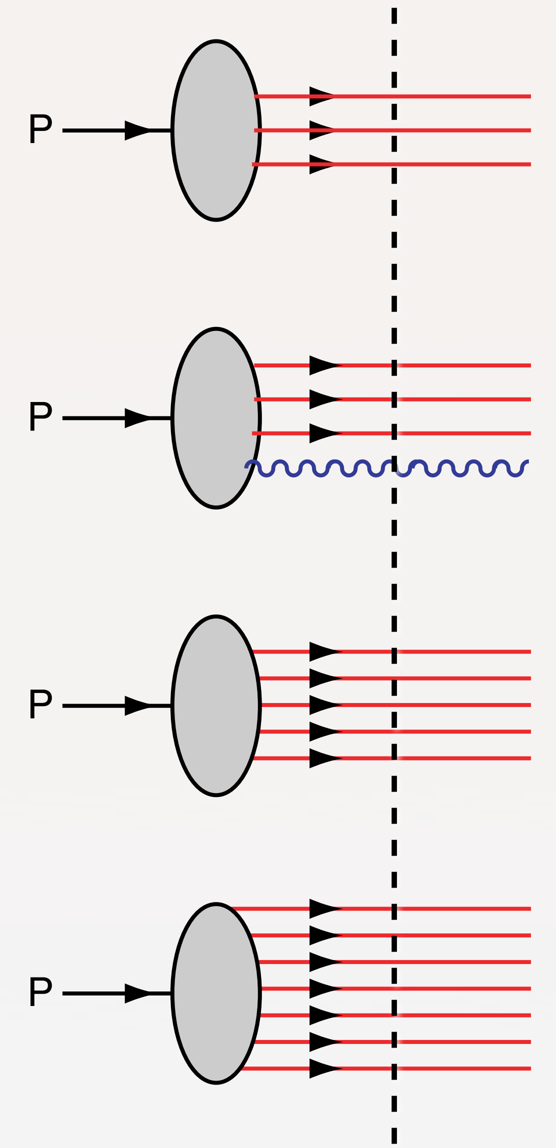
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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
s(x), c(x), b(x) at high x !

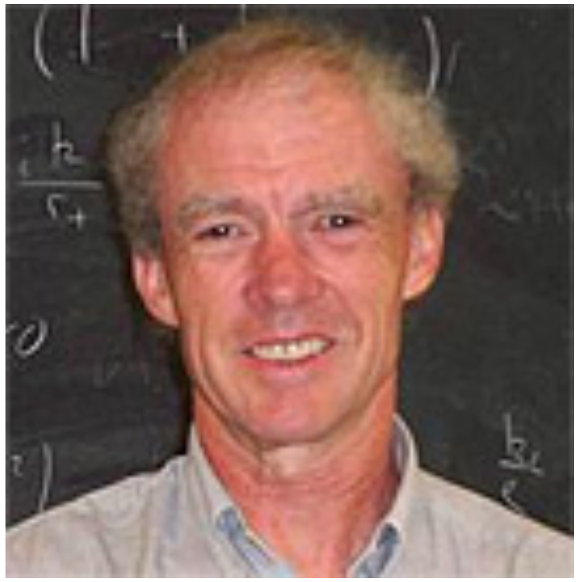
$\bar{s}(x) \neq s(x)$
$\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states BFKL Pomeron

Hidden Color

Intrinsic Chevrolets!

Intrinsic Chevrolets At The SSC
Stanley J. Brodsky (SLAC), John C. Collins (IIT, Chicago & Argonne), Stephen D. Ellis (Washington U., Seattle), John F. Gunion (UC, Davis), Alfred H. Mueller (Columbia U.). Aug 1984. 10 pp.
DOE/ER/40048-21 P4, C84/06/23
C84-06-23 (Snowmass Summer Study 1984:0227)



Heavy Particle Production At The SSC
Stanley J. Brodsky (SLAC), Howard E. Haber (UC, Santa Cruz & SLAC), J.F. Gunion (UC, Davis).
Mar 1984. 11 pp.
SLAC-PUB-3300, C84/02/13
Invited paper given at Conference: C84-02-13 (SSC/DPF Workshop 1984:100)

A Higher Twist Correction To Heavy Quark Production
Stanley J. Brodsky (SLAC), John F. Gunion (UC, Davis), Davison E. Soper (Oregon U.). Jun 1987. 7 pp.
OITS-359, C87/03/08
Invited talk given at Conference: C87-03-08 (Moriond 1987: Hadrons:85)

The Physics of Heavy Quark Production in Quantum Chromodynamics
Stanley J. Brodsky (SLAC), J.F. Gunion (UC, Davis), Davison E. Soper (Oregon U.). May 1987. 61 pp.
Published in **Phys.Rev. D36 (1987) 2710**
SLAC-PUB-4193, UCD-87-7
DOI: 10.1103/PhysRevD.36.2710

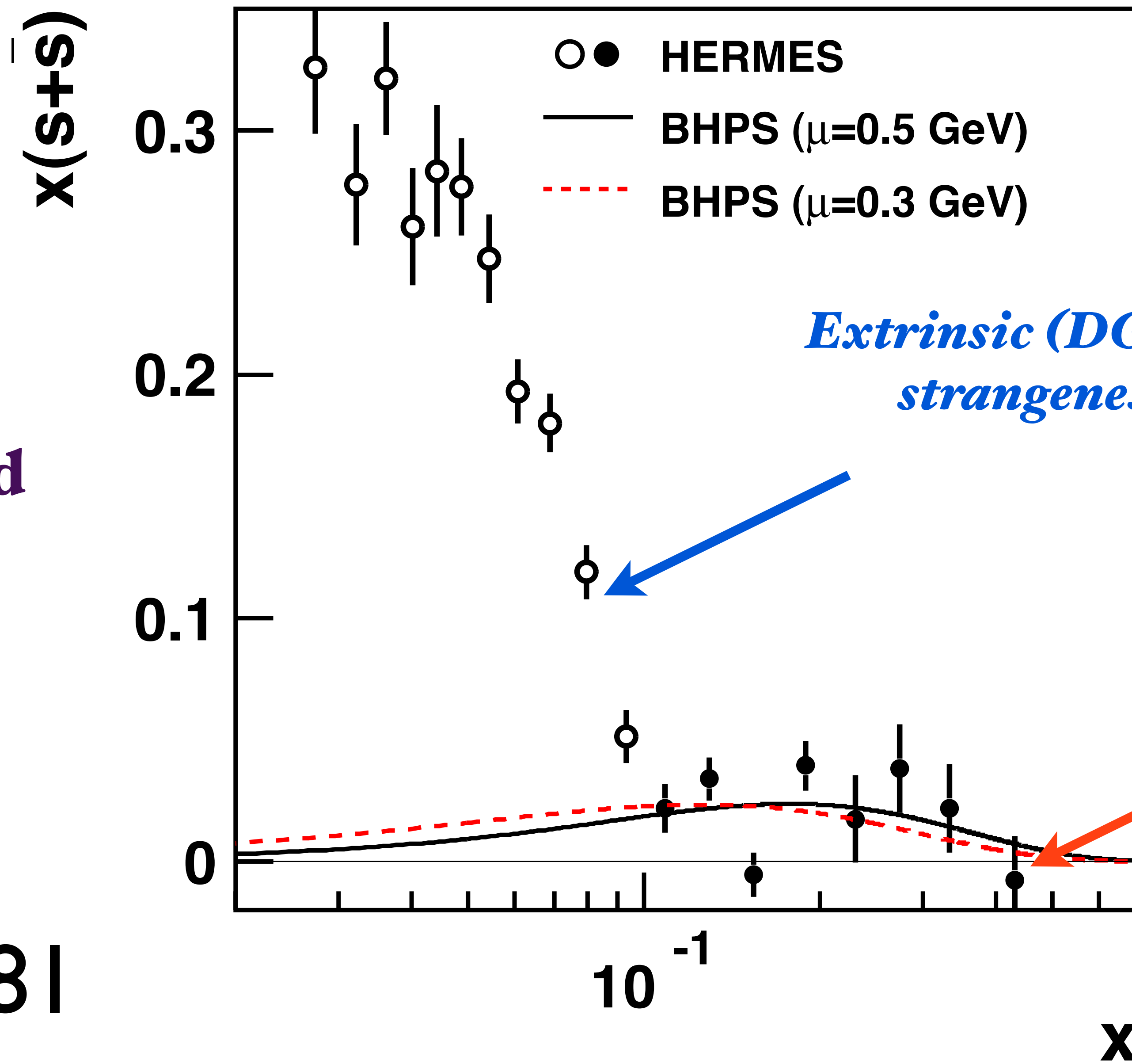
Heavy Quark Production Processes In QCD
Stanley J. Brodsky (SLAC), J.F. Gunion (UC, Davis). Dec 1984. 18 pp.
Published in **eConf C840723 (1984) 025**
SLAC-PUB-3527, C84-07-23, SSI-1984-025
Invited talk given at Conference: C84-07-23 (SLAC Summer Inst.1984:603) Proceedings

- *Pioneering Papers on Intrinsic Heavy Quark Fock States of Hadrons*

- *Rigorous scaling law from OPE:* $\frac{1}{M_Q^2}$

Novel SUSY and Higgs Production Mechanisms

HERMES: Two components to s(x,Q²)!



Extrinsic (DGLAP) strangeness!

BHPS: Hoyer, Sakai, Peterson, sjb

Collins, Ellis, Gunion Mueller, sjb Polyakov, et al.

Intrinsic strangeness!

W. C. Chang and J.-C. Peng

arXiv:1105.2381

Consistent with intrinsic charm data

QCD: $\frac{1}{M_Q^2}$ scaling

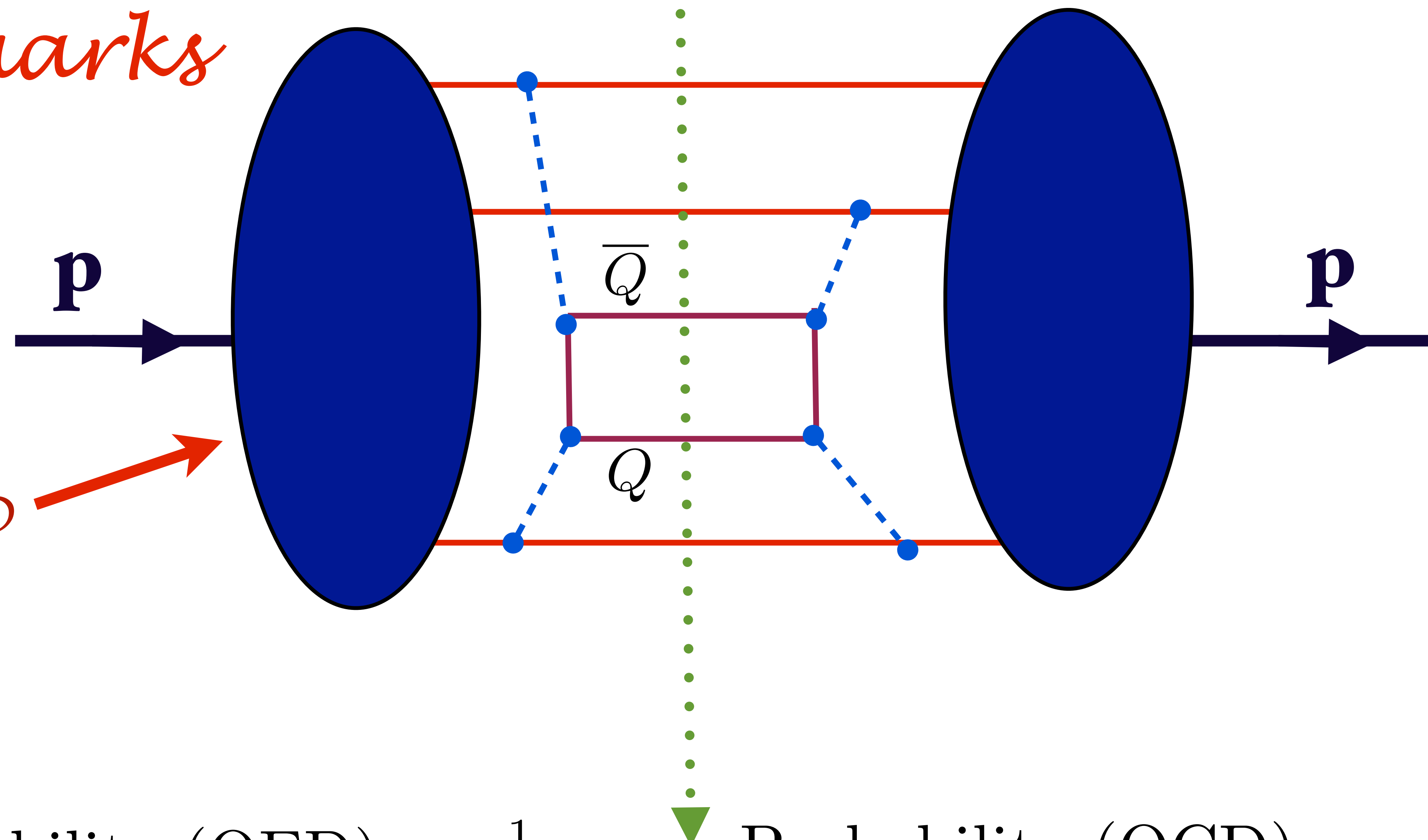
Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

$$s(x,Q^2) = s(x,Q^2)_{\text{extrinsic}} + s(x,Q^2)_{\text{intrinsic}}$$

Proton Self Energy Intrinsic Heavy Quarks

Fixed LF time

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



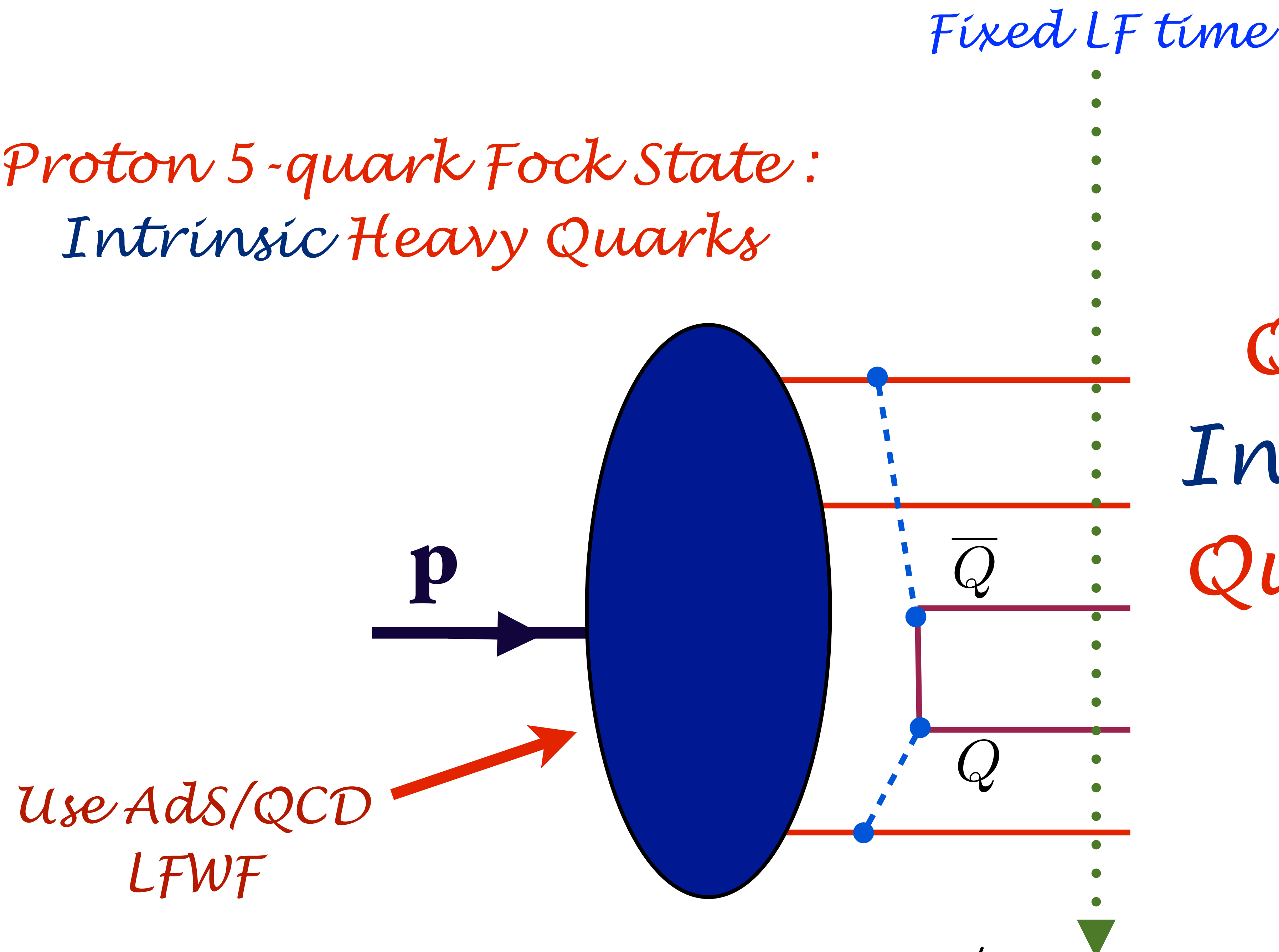
Use AdS/QCD LFWF

Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

Minimal off-shellness

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$ $\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
Polyakov, et al.

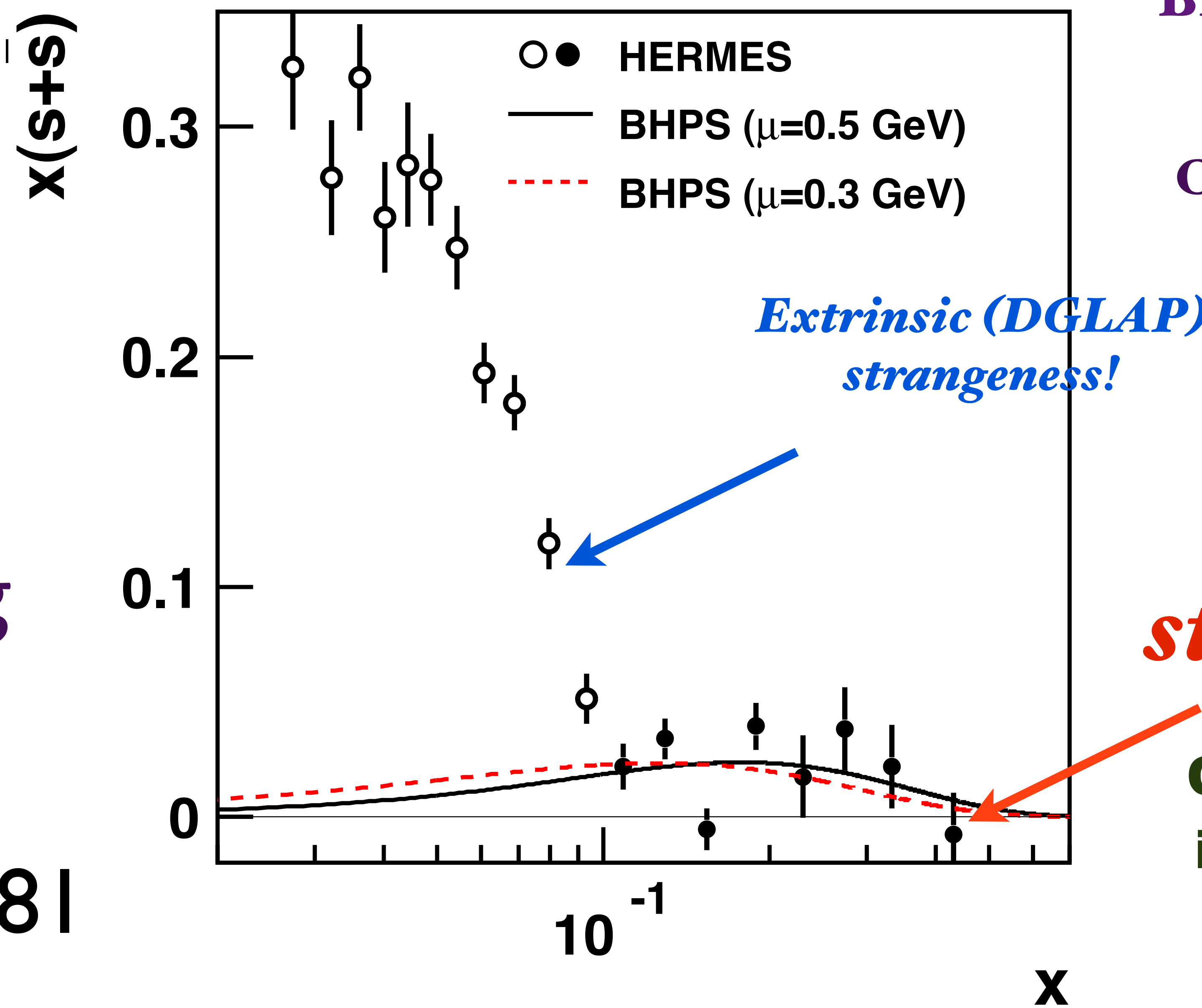
HERMES: Two components to s(x,Q²)!

BHPS: Hoyer, Sakai, Peterson, sjb

Collins, Ellis, Gunion Mueller, sjb Polyakov, et al.

W. C. Chang and J.-C. Peng

arXiv:1105.2381



Comparison of the HERMES $x(s(x)+\bar{s}(x))$ data with the calculations based on the BHPS model. The solid and dashed curves are obtained by evolving the BHPS result to $Q^2 = 2.5$ GeV^2 using $\mu = 0.5$ GeV and $\mu = 0.3$ GeV, respectively. The normalizations of the calculations are adjusted to fit the data at $x > 0.1$ with statistical errors only, denoted by solid circles.

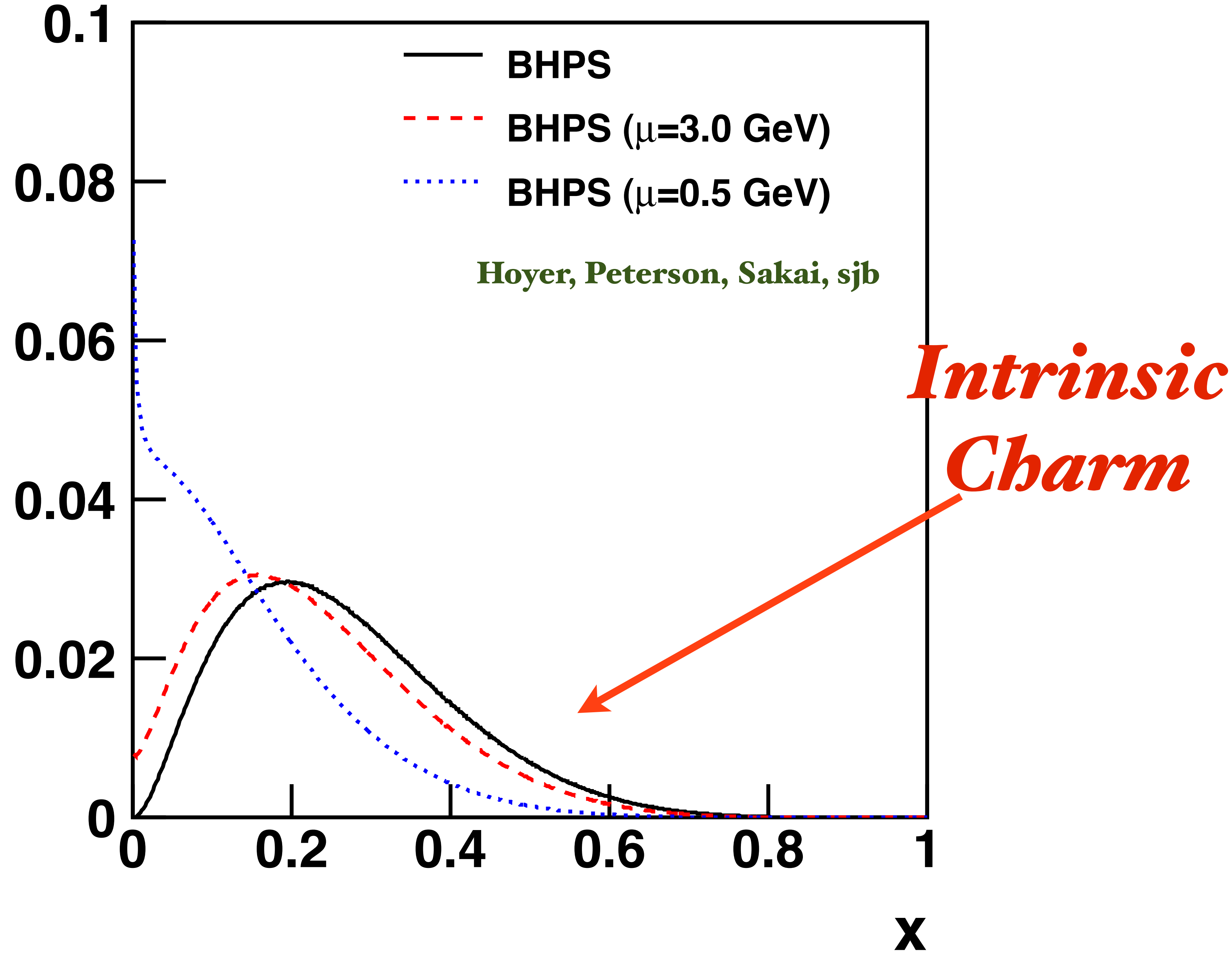
Intrinsic strangeness!

Consistent with intrinsic charm data

QCD: $\frac{1}{M_Q^2}$ scaling

$$s(x,Q^2) = s(x,Q^2)_{\rm extrinsic} + s(x,Q^2)_{\rm intrinsic}$$

QCD: $(1/m_Q^2)$ scaling: predict IC !



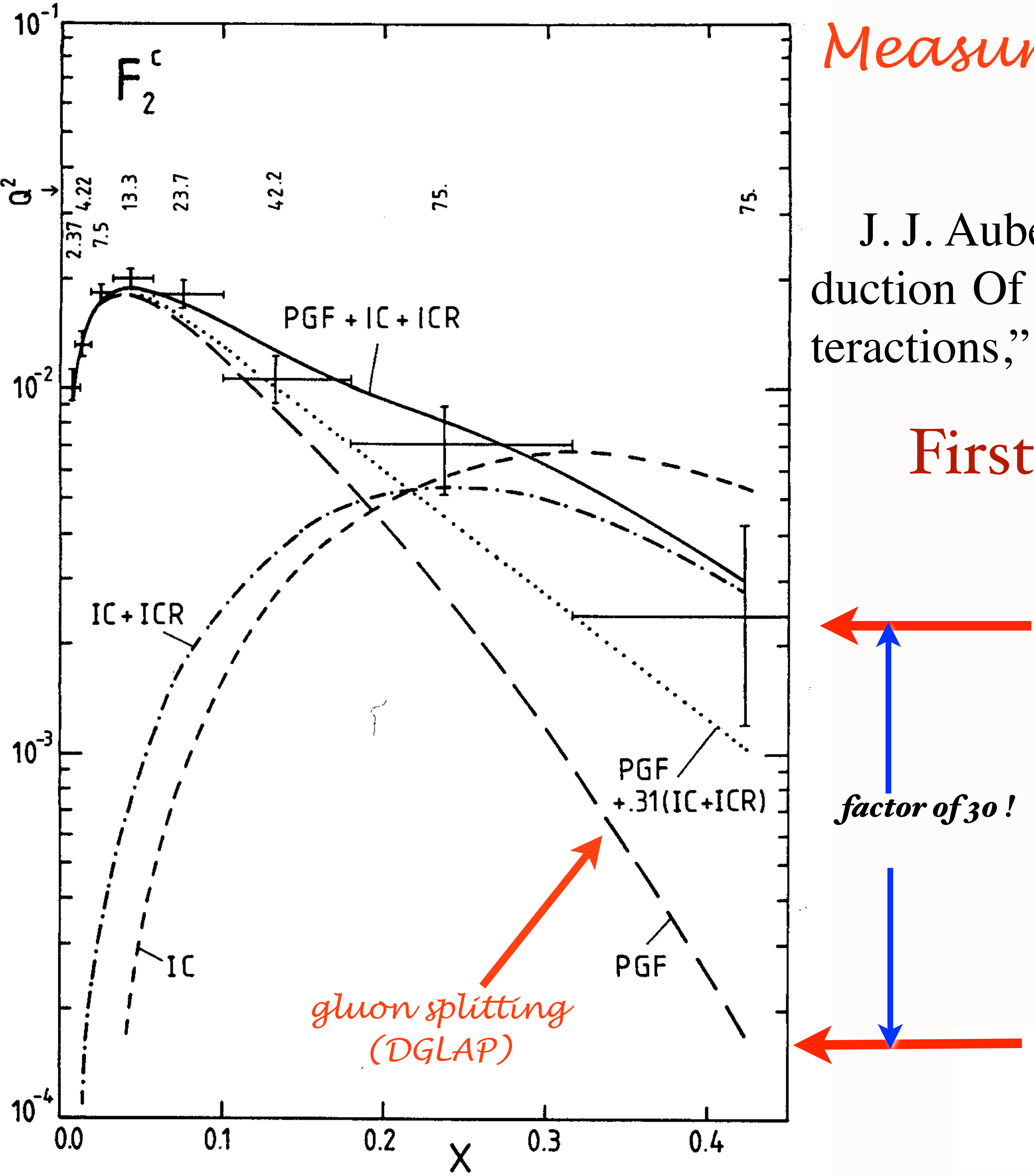
W. C. Chang and J.-C. Peng

arXiv: 1105.2381

Calculations of the $\bar{c}(x)$ distributions based on the BHPS model. The solid curve corresponds to the calculation using Eq. 1 and the dashed and dotted curves are obtained by evolving the BHPS result to $Q^2 = 75$ GeV^2 using $\mu = 3.0$ GeV, and $\mu = 0.5$ GeV, respectively. The normalization is set at $\mathcal{P}_5^{c\bar{c}} = 0.01$.

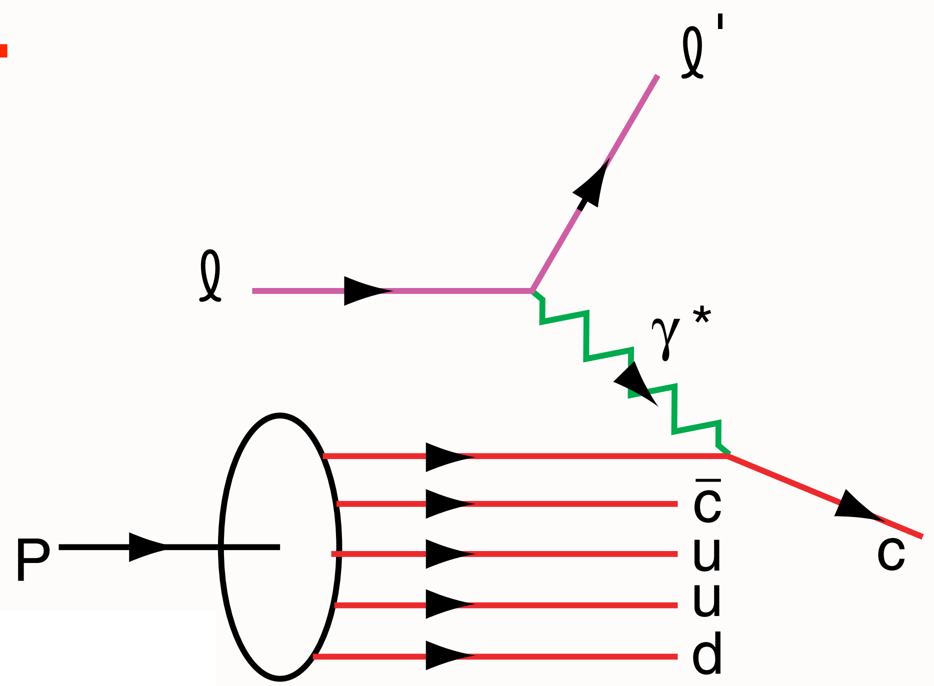
Consistent with EMC

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

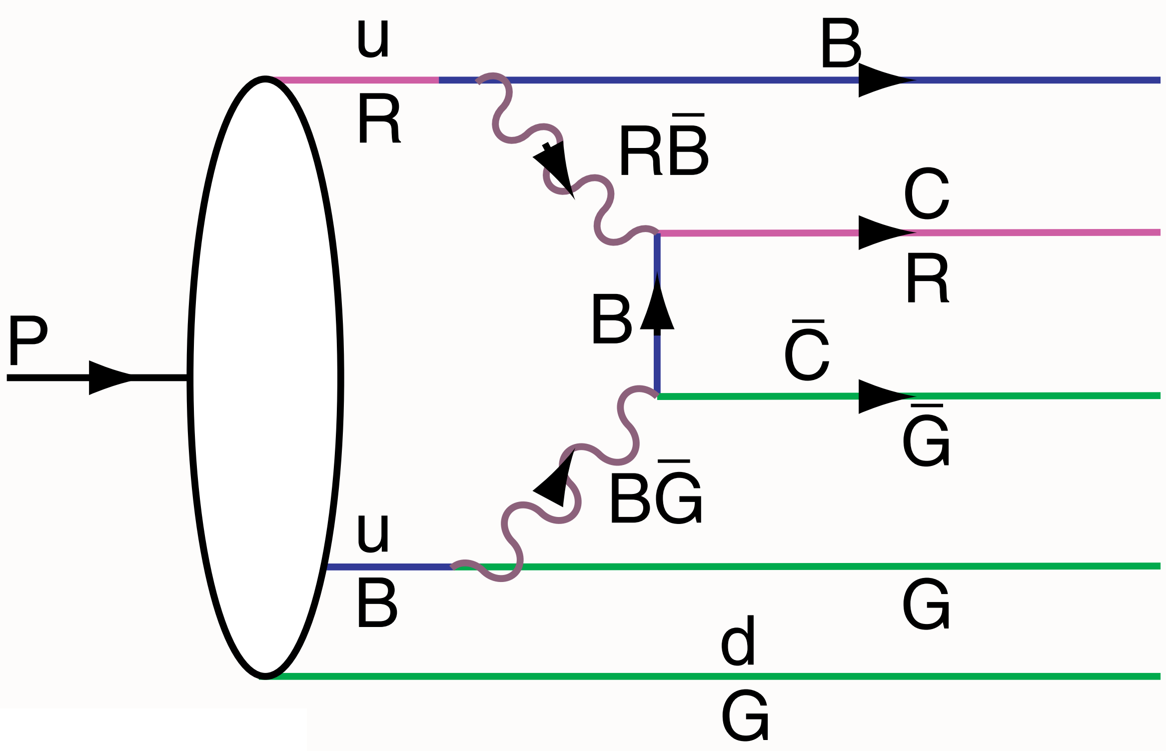


DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

$$c(x, Q^2) = c(x, Q^2)_{\text{extrinsic}} + c(x, Q^2)_{\text{intrinsic}}$$

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

Collins, Ellis, Gunion, Mueller, sjb; 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

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

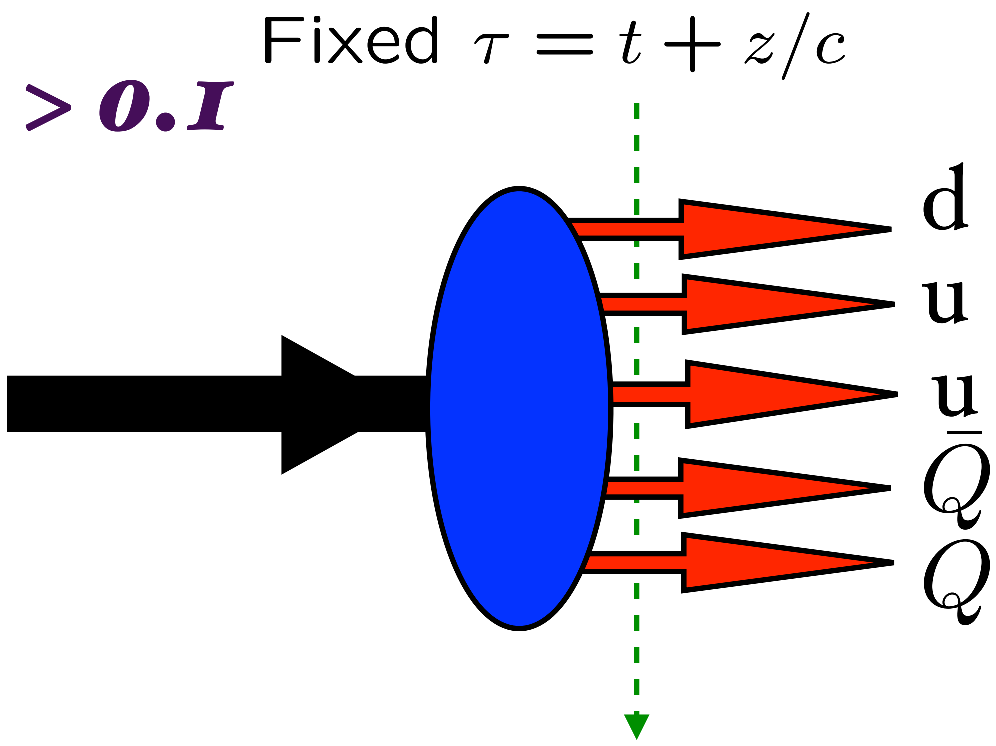
High x charm!

Charm at Threshold

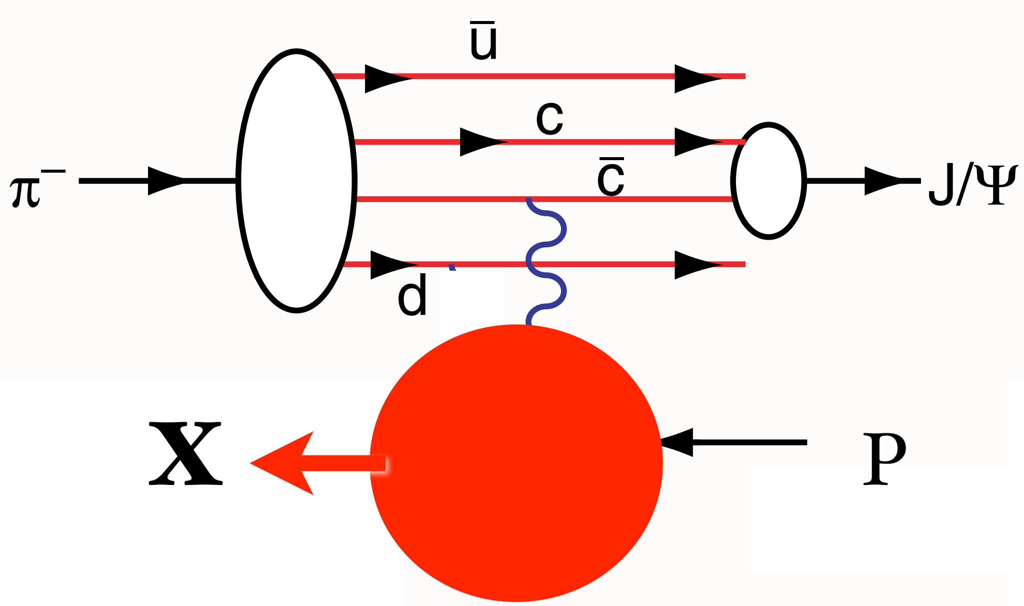
Action Principle: Minimum KE, maximal potential

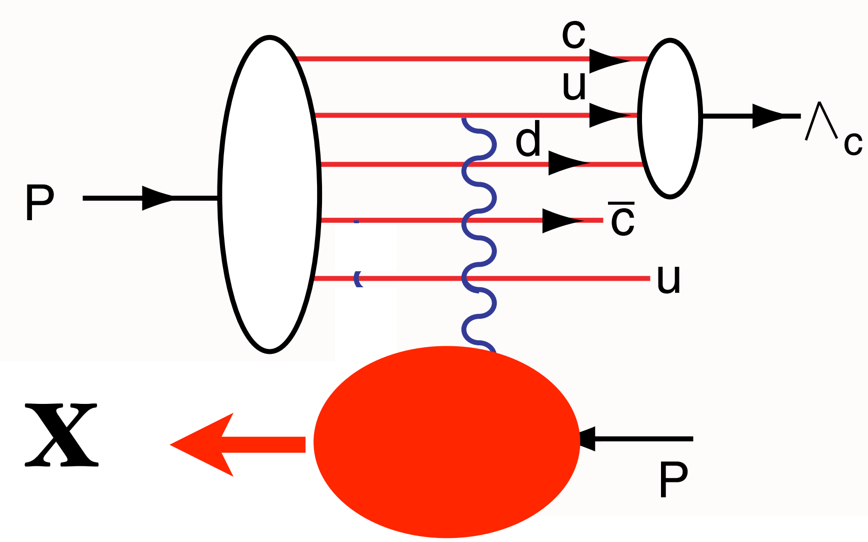
Properties of Non-Perturbative Five-Quark Fock-State

- ***Dominant configuration: same rapidity***
- ***Heavy quarks have most momentum***
- ***Correlated with proton quantum numbers***
- ***Duality with meson-baryon channels***
- ***strangeness asymmetry at x > 0.1***
- ***Maximally energy efficient***



Leading Hadron Production from Intrinsic Charm





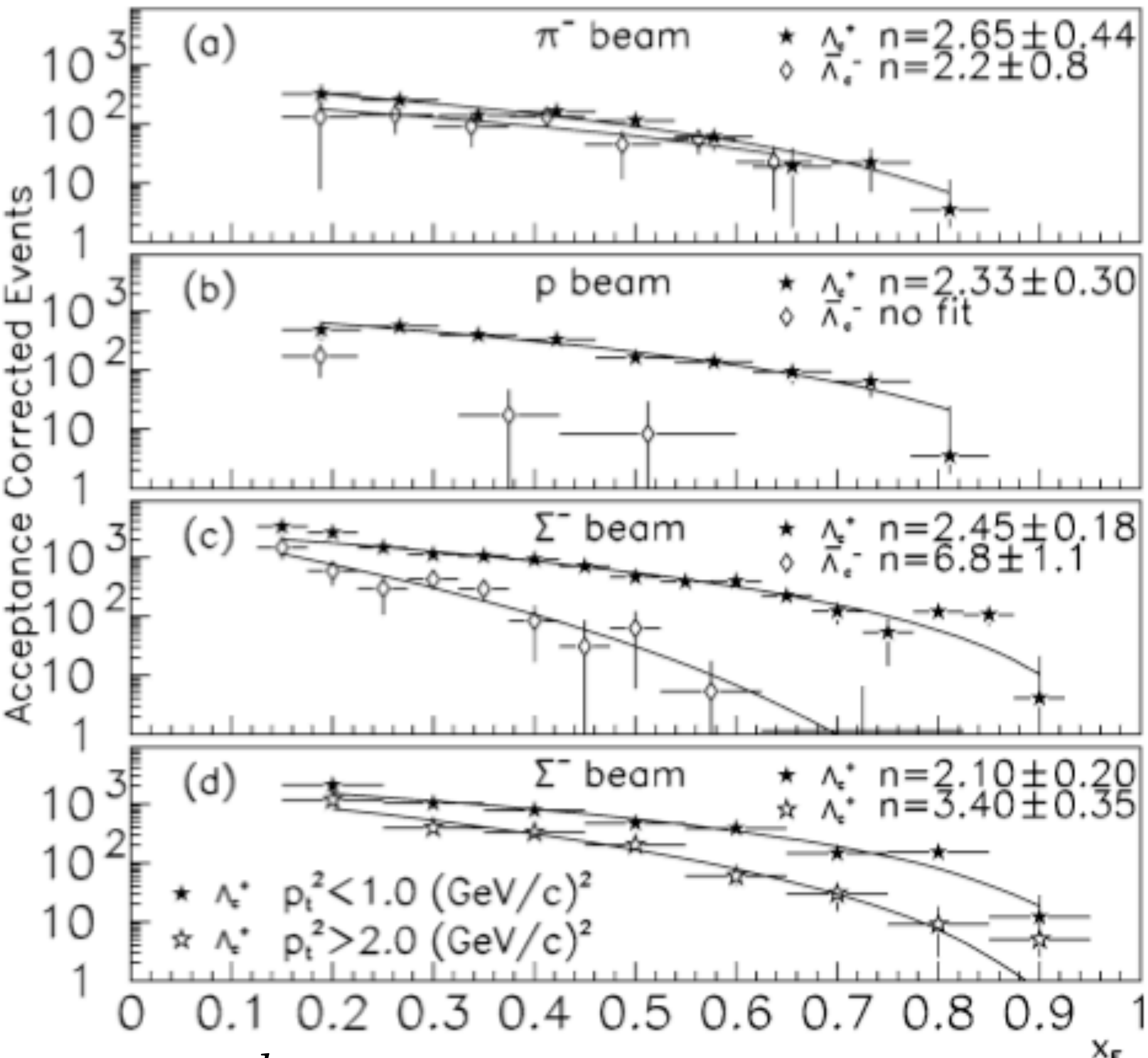
Spectator counting rules

Blankenbecler, sjb

$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

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

SELEX Collaboration / Physics Letters B 528 (2002) 49–57



$$\frac{d\sigma}{dx_F}(pA \to \Lambda_c X) \sim (1 - x_F)^p$$

Large x_F production close to the maximum allowed by phase space!

Spectator counting rules

leaves 2 spectator quarks

$\Lambda_c(cud)$

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

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

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

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

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

Explain Tevatron anomalies: $p\bar{p} \to \gamma c X, Z c X$

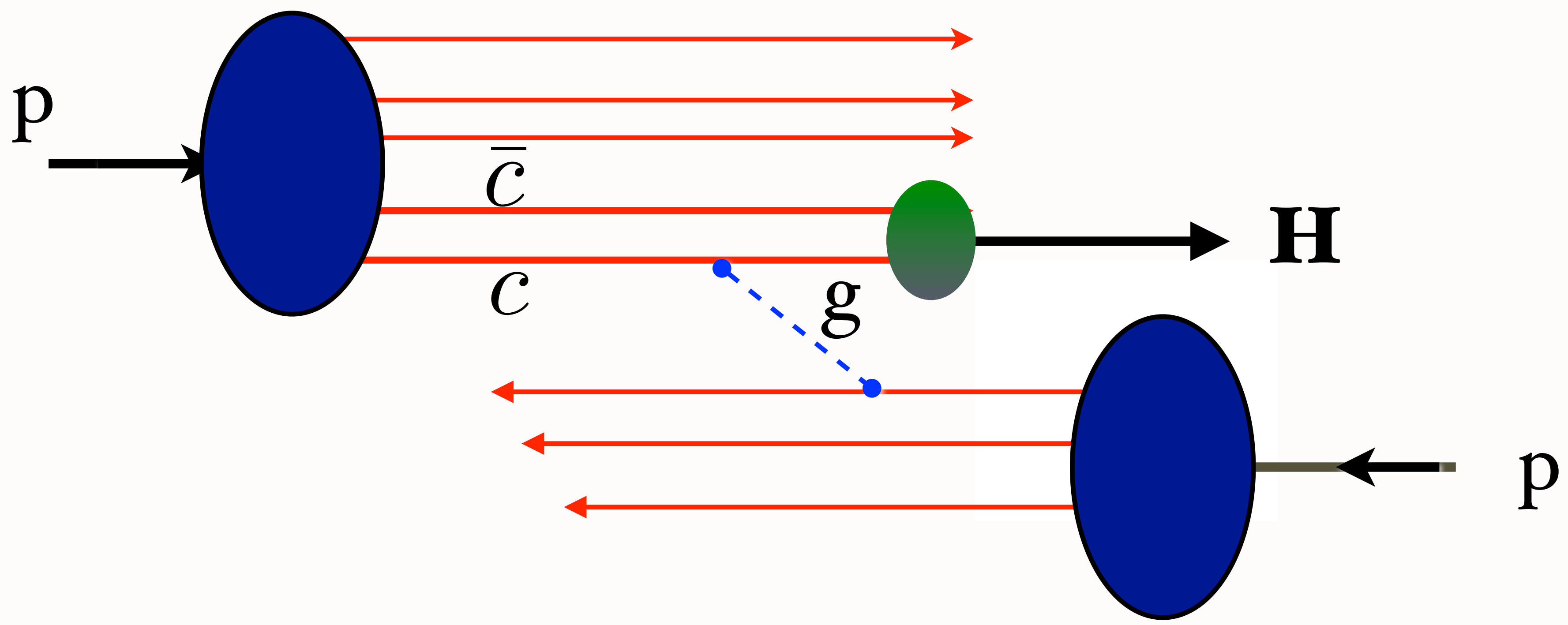
Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

Goldhaber, Kopeliovich, Schmidt, Soffer sjb

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \to H\,X$$

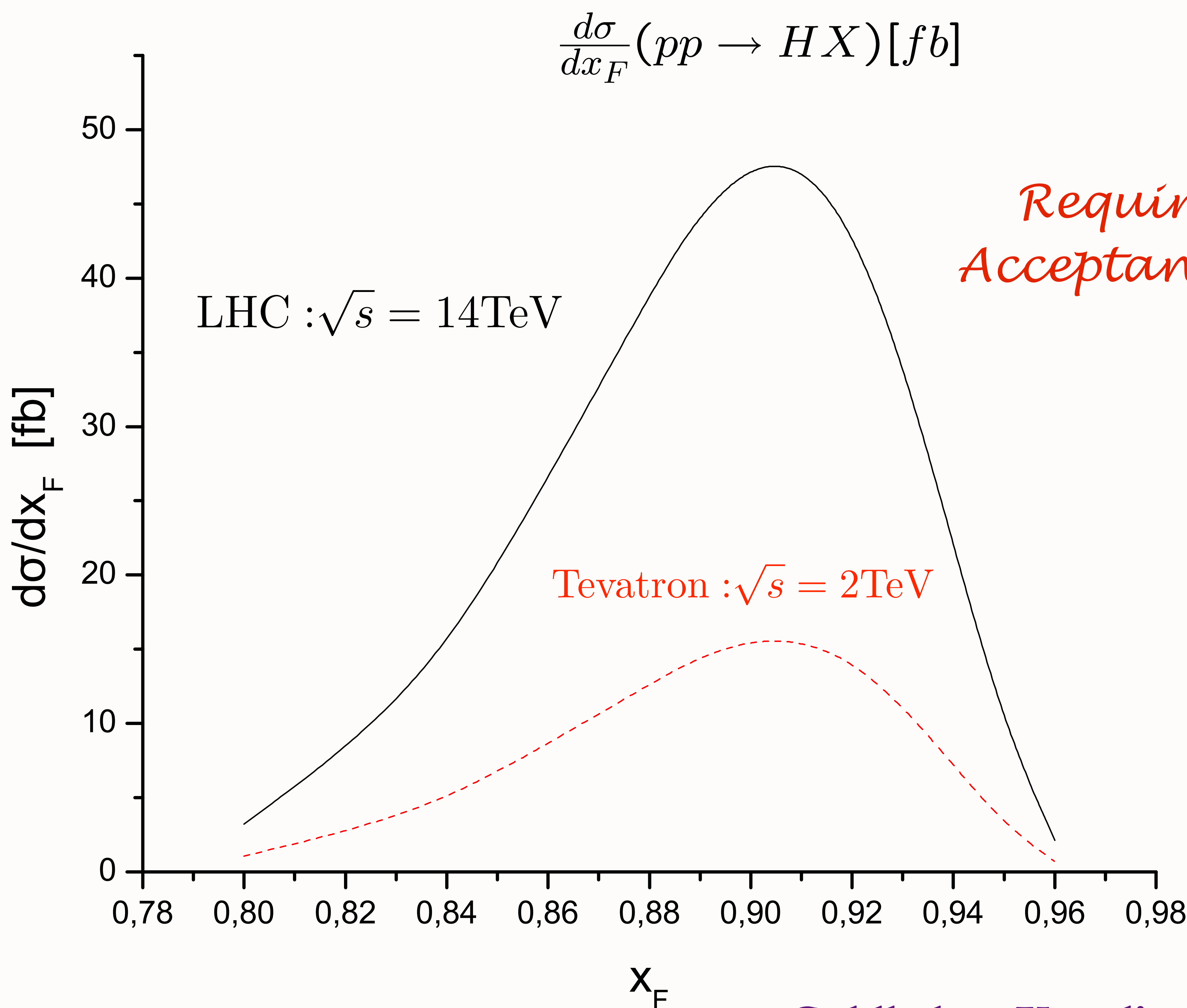
Also: intrinsic strangeness, bottom, top

Higgs can have > 80% of Proton Momentum!

New production mechanism for Higgs

AFTER: Higgs production at threshold!

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



Requires Forward Acceptance at the LHC

Goldhaber, Kopeliovich, Schmidt, sjb

Gunion, Soper, sjb

Charm at Threshold

- *Intrinsic charm Fock state puts 80% of the proton momentum into the electroproduction process*
- *1/velocity enhancement from FSI*
- *CLEO data for quarkonium production at threshold*
- *Krisch effect shows B=2 resonance*
- *all particles produced at small relative rapidity--resonance production*
- *Many exotic hidden and open charm resonances will be produced at JLab (12 GeV)*

Do heavy quarks exist in the proton at high x?

Conventional wisdom:

Heavy quarks generated only at low x
via DGLAP evolution
from gluon splitting

$$s(x, \mu_F^2) = c(x, \mu_F^2) = b(x, \mu_F^2) \equiv 0$$

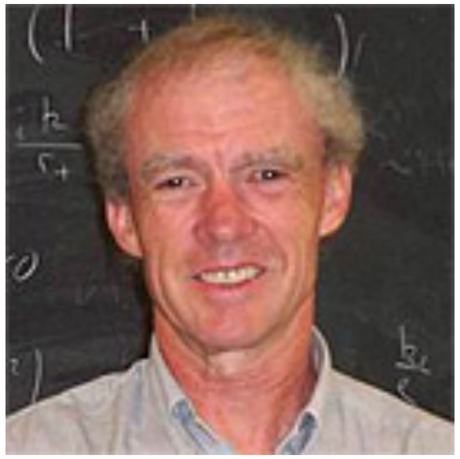
$$\text{at starting scale } Q_0^2 = \mu_F^2$$

Conventional wisdom is wrong even in QED!

Analysis of Particle Production at Large Transverse Momentum
Richard Blankenbecler, Stanley J. Brodsky (SLAC), J.F. Gunion (Pittsburgh U.). May 1975. 56 pp.
Published in **Phys.Rev. D12 (1975) 3469-3487**
SLAC-PUB-1585

DOI: 10.1103/PhysRevD.12.3469

Physical Effects of Hadronic Bremsstrahlung. Reactions at Large and Small Momentum Transfers
Richard Blankenbecler, Stanley J. Brodsky (SLAC), J.F. Gunion (MIT, LNS), R. Savit (SLAC). Jan 1974. 40 pp.
Published in **Phys.Rev. D10 (1974) 2153**
SLAC-PUB-1378



- *Theory of Direct Subprocesses*
- *Exclusive-Inclusive Connection with CIM*
- *Fixed-x_T Scaling, Spectator Counting Rules*
- *Regge Behavior at large t*

Bjorken, Kogut, Soper; Blankenbecler, Gunion, sjb; Blankenbecler, Schmidt

Crucial Test of Leading -Twist QCD: Scaling at fixed x_T

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{cm})}{p_T^{n_{\mathrm{eff}}}}$$

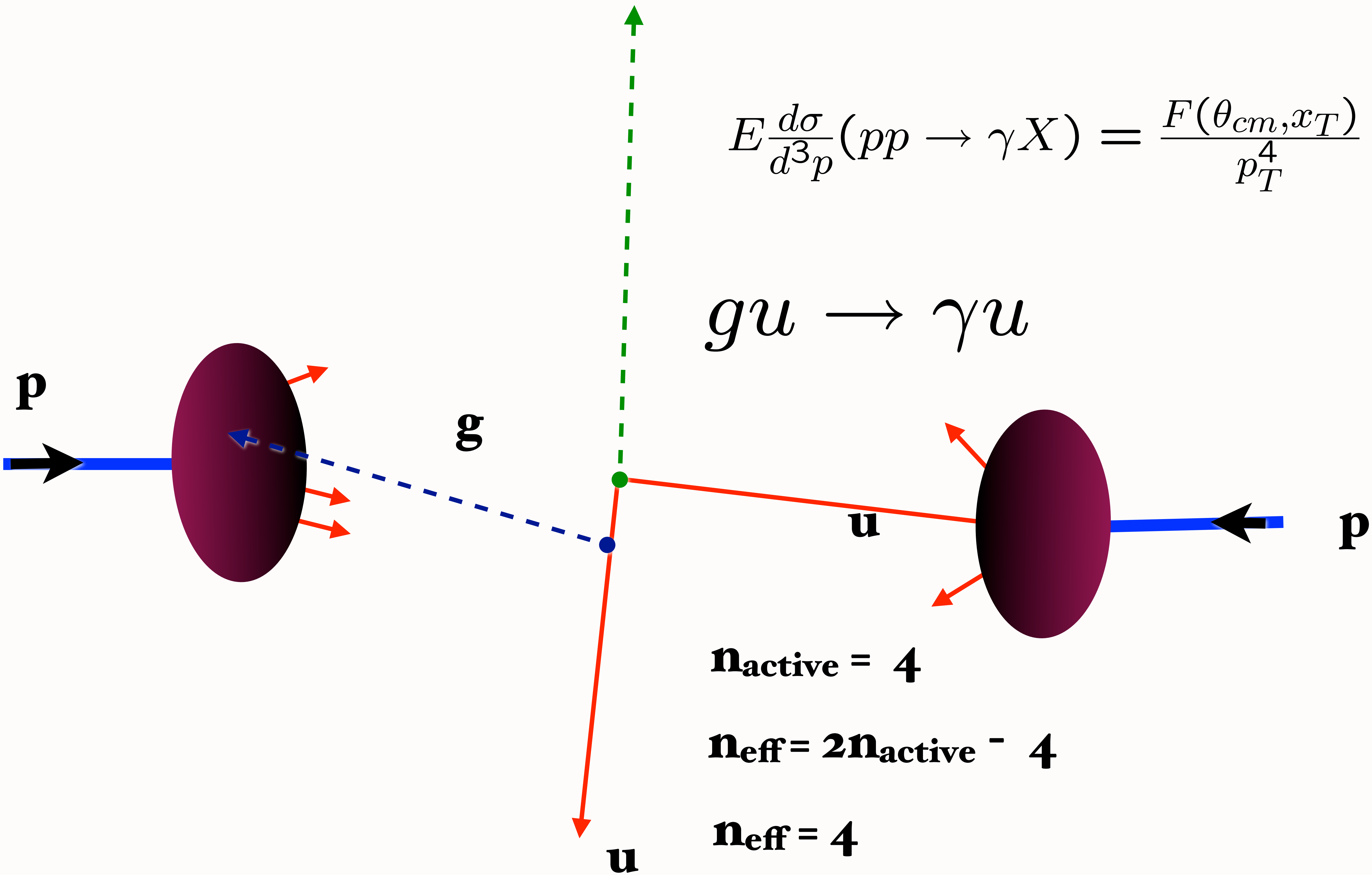
$$x_T = \frac{2p_T}{\sqrt{s}}$$

Parton model: $n_{\mathrm{eff}} = 4$

As fundamental as Bjorken scaling in DIS

scaling law: $n_{\mathrm{eff}} = 2\, n_{\mathrm{active}} - 4$

$$pp \to \gamma X$$



$$E\frac{d\sigma}{d^3p}(pp \to \gamma X) = \frac{F(\theta_{cm}, x_T)}{p_T^4}$$

$$gu \to \gamma u$$

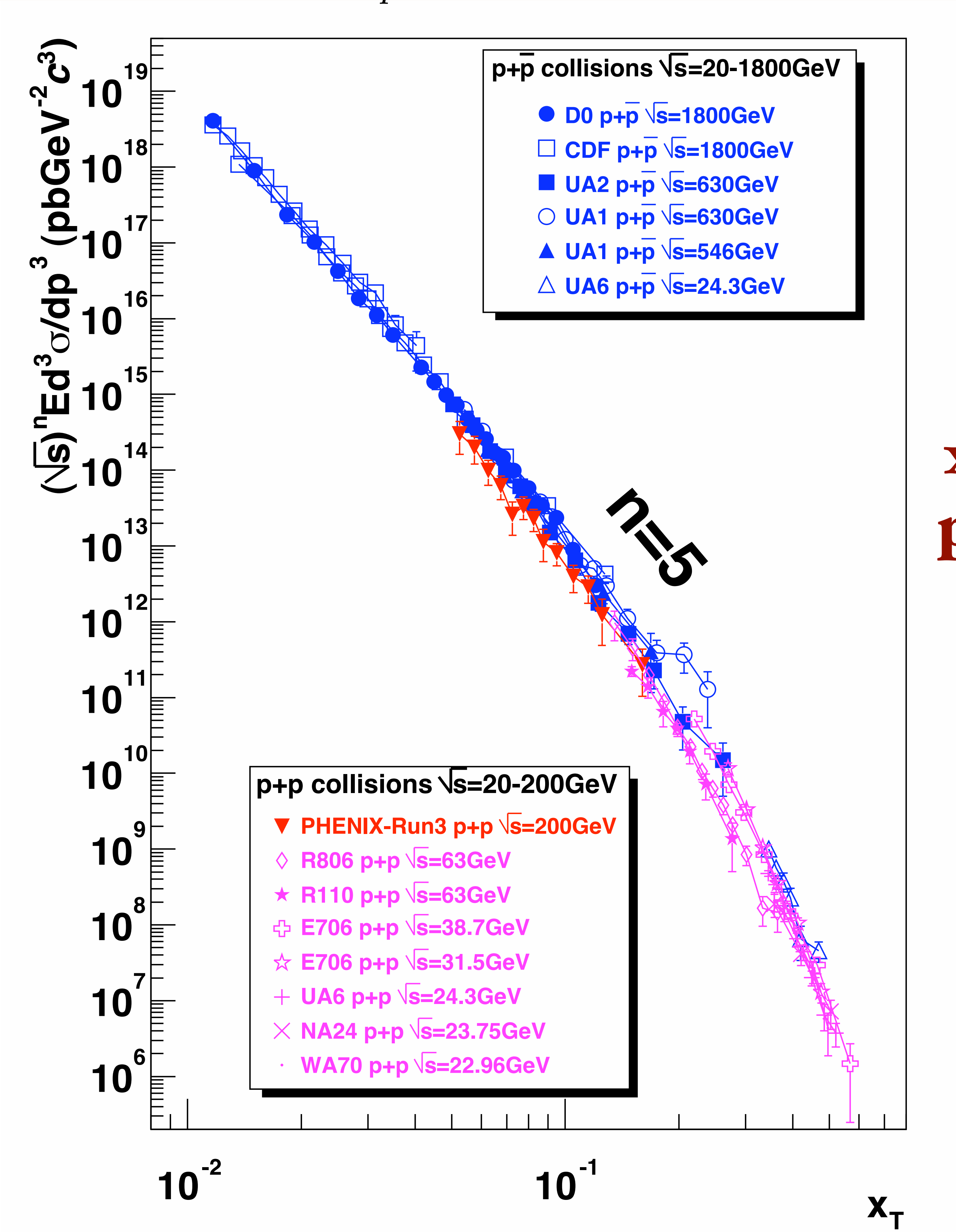
$n_{active} = 4$

$n_{eff} = 2n_{active} - 4$

$n_{eff} = 4$

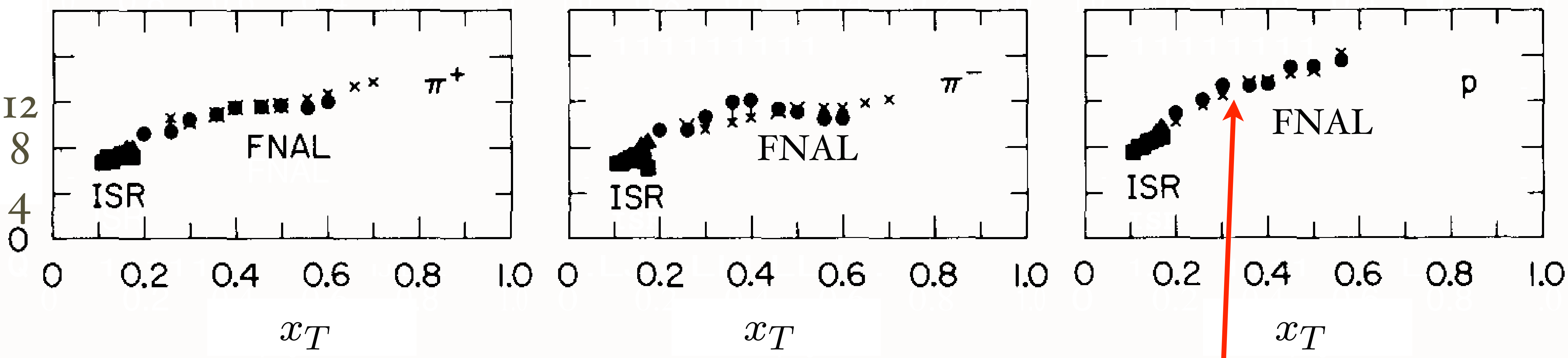
$\sqrt{s}^n E \frac{d\sigma}{d^3p}(pp \to \gamma X)$ at fixed x_T

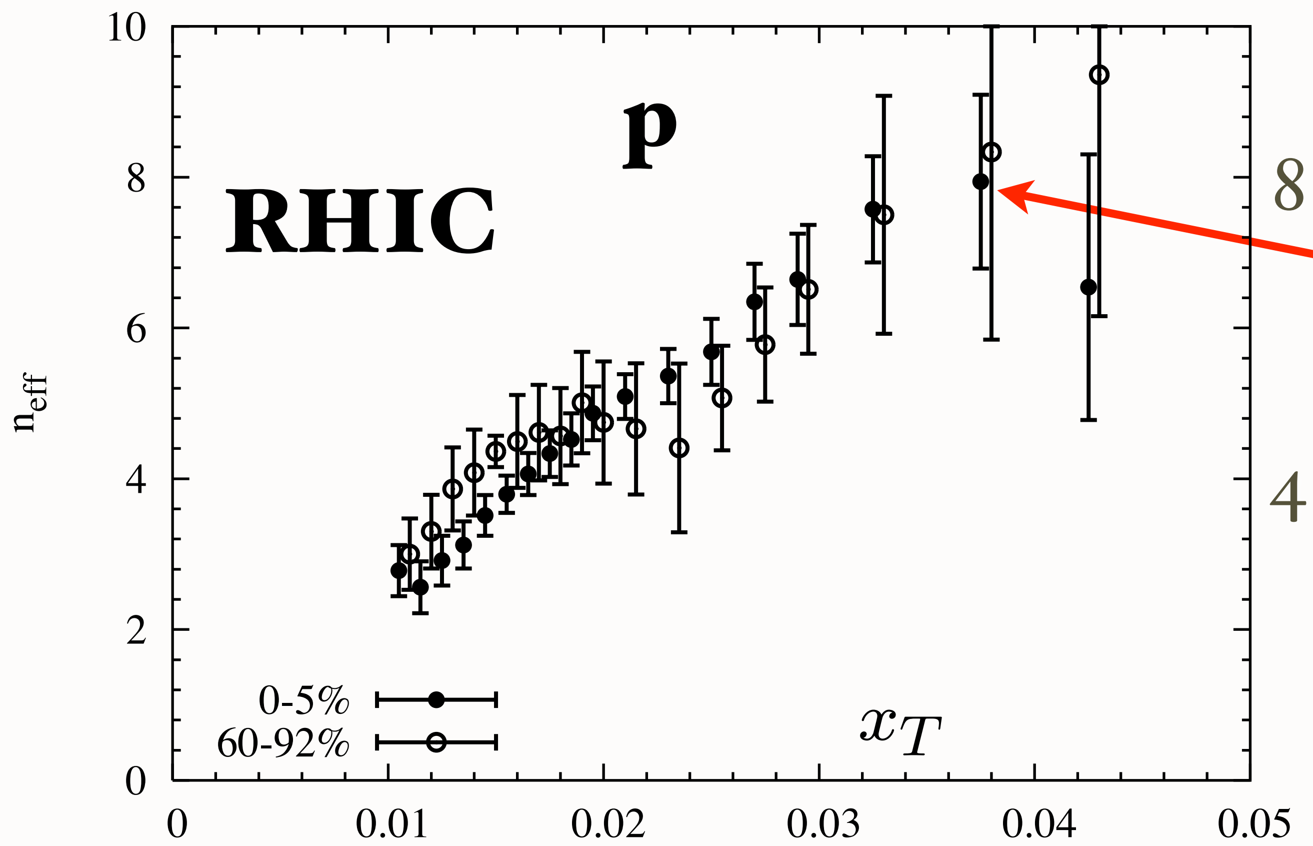
Tannenbaum



x_T-scaling of direct photon production: consistent with PQCD

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T,\theta_{CM})}{p_T^{n_{eff}}}$$



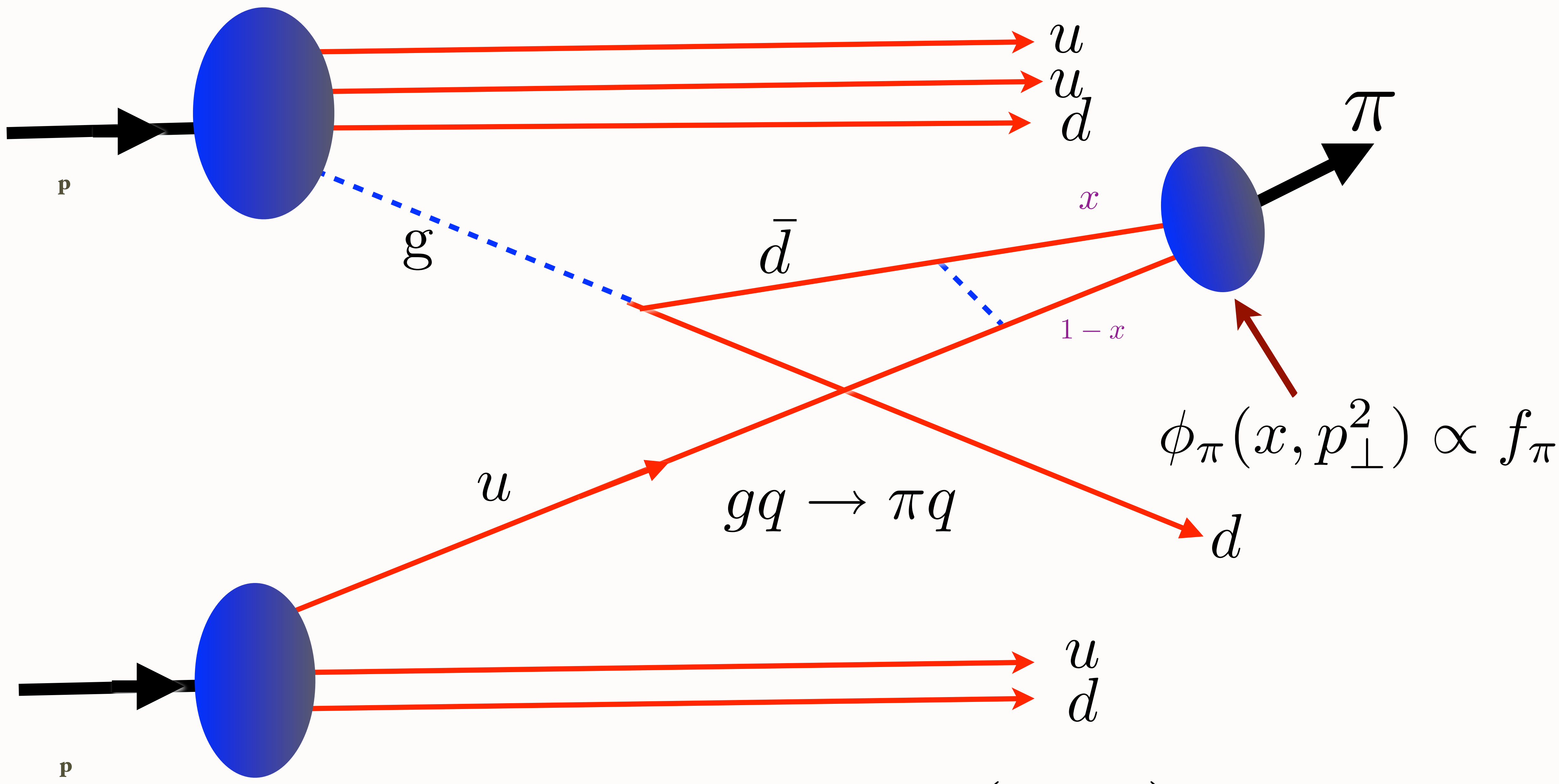


$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{12}}$$

$$E\frac{d\sigma}{d^3p}(pp \to pX) = \frac{F(x_T,\theta_{CM})}{p_T^{8}}$$

Trend consistent with RHIC at small x_T

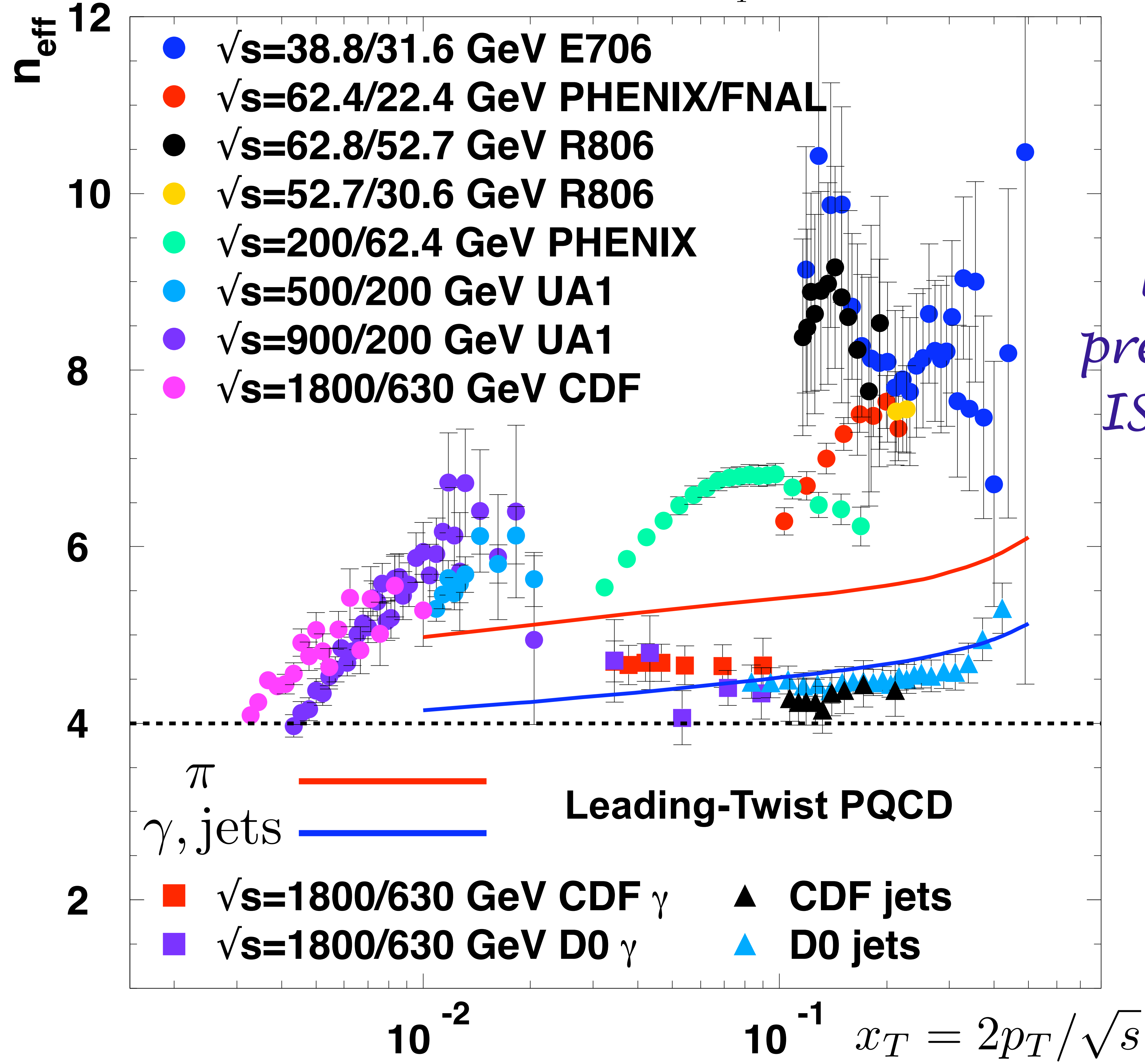
Direct Higher-Twist Contribution to Hadron Production



$$\frac{d\sigma}{d^3p/E} = \alpha_s^3 f_\pi^2 \frac{F(x_\perp, y)}{p_\perp^6}$$

No Fragmentation Function

$$E\frac{d\sigma}{d^3p}(pp \to HX) = \frac{F(x_T, \theta_{CM} = \pi/2)}{p_T^{n_{\rm eff}}}$$

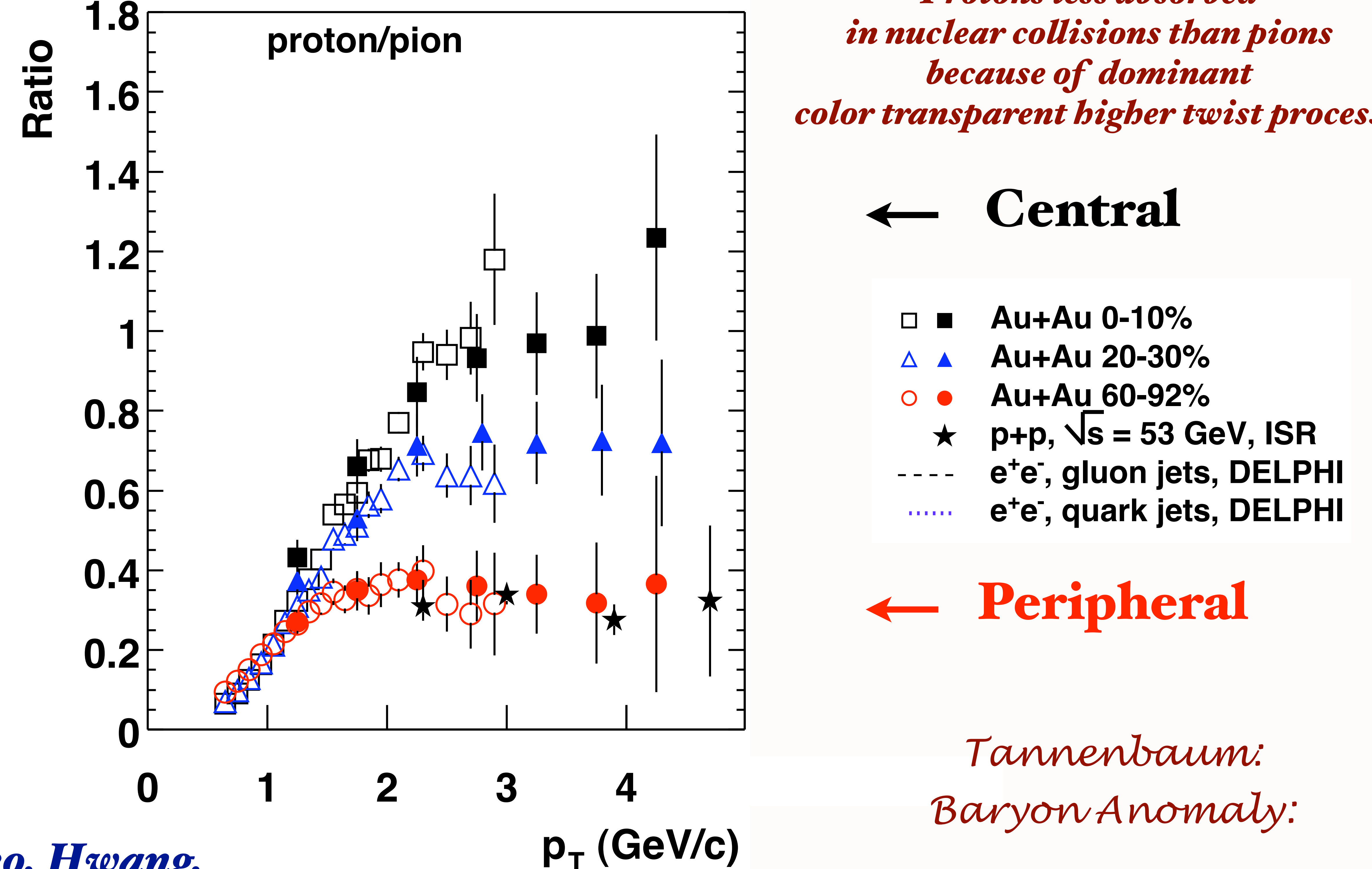


Leading-twist prediction fails at ISR, FNAL, RHIC, CDF!

Arleo, Hwang, Sickles, sjb

S. S. Adler *et al*. PHENIX Collaboration *Phys. Rev. Lett.* **91**, 172301 (2003).

Particle ratio changes with centrality!



Protons less absorbed in nuclear collisions than pions because of dominant color transparent higher twist process

Central

Peripheral

Tannenbaum:

Baryon Anomaly:

Arleo, Hwang, Sickles, sjb

Scale dependence

Pion scaling exponent extracted vs. $p_\perp$ at fixed $x_\perp$

2-component toy-model

$$\sigma^{\rm model}(pp \to \pi \ \mathrm{X}) \propto \frac{A(x_\perp)}{p_\perp^4} + \frac{B(x_\perp)}{p_\perp^6}$$

Define effective exponent

$$\begin{aligned} n_{\rm eff}(x_\perp, p_\perp, B/A) &\equiv -\frac{\partial \ln \sigma^{\rm model}}{\partial \ln p_\perp} + n^{\rm NLO}(x_\perp, p_\perp) - 4 \\ &= \frac{2B/A}{p_\perp^2 + B/A} + n^{\rm NLO}(x_\perp, p_\perp) \end{aligned}$$

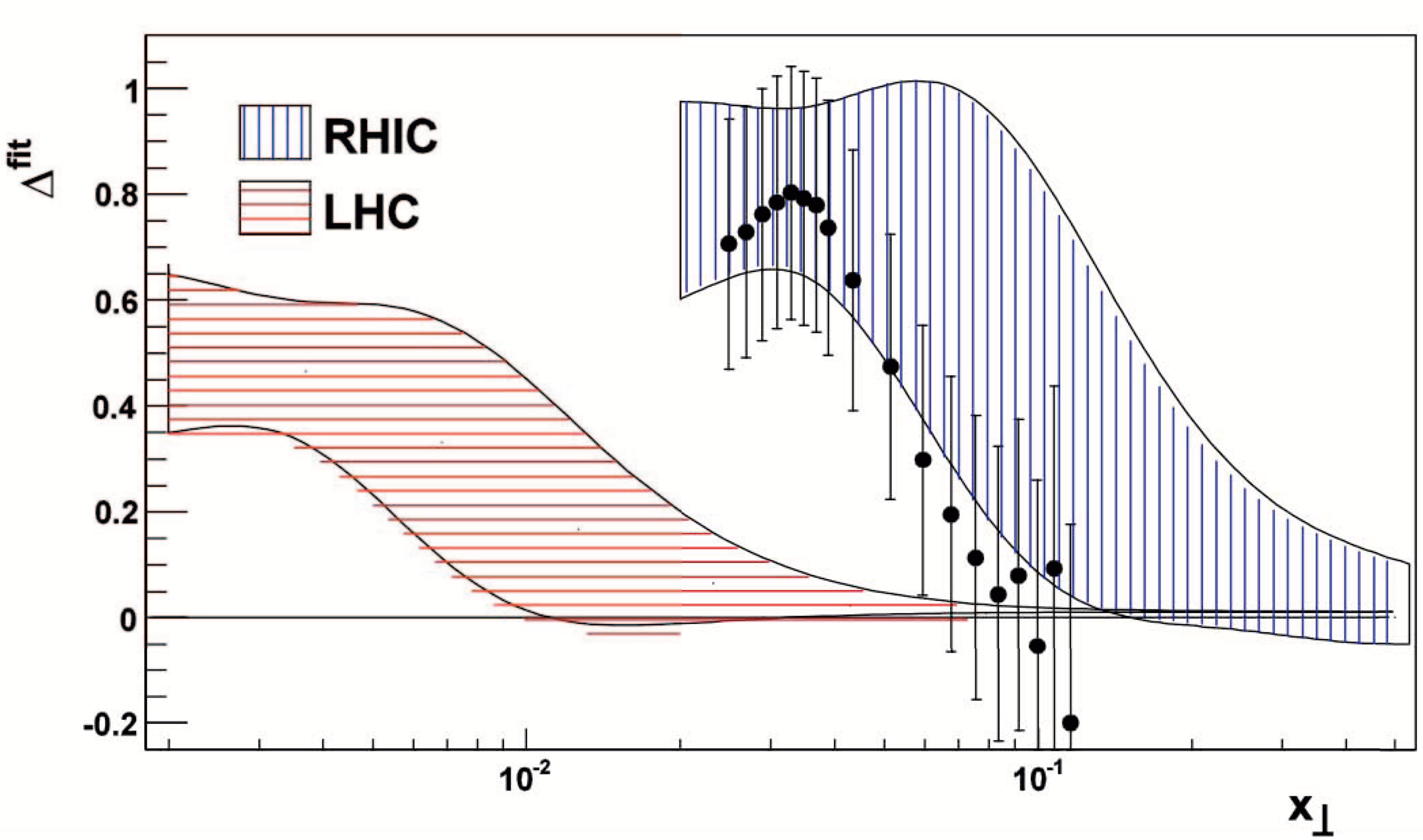
Arleo, Hwang, Sickles, sjb

RHIC/LHC predictions

PHENIX results

Scaling exponents from $\sqrt{s} = 500$ GeV preliminary data

[A. Bezilevsky, APS Meeting]



- Magnitude of Δ and its $x_\perp$-dependence consistent with predictions

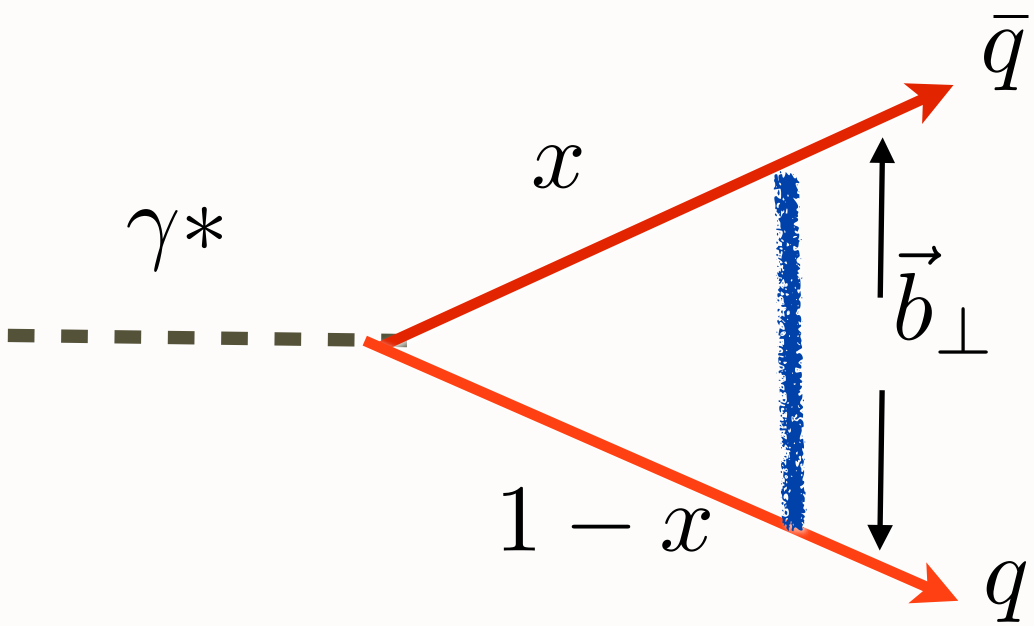
Arleo,Hwang, Sickles, sjb

Two-Dimensional Confinement

Interesting feature

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

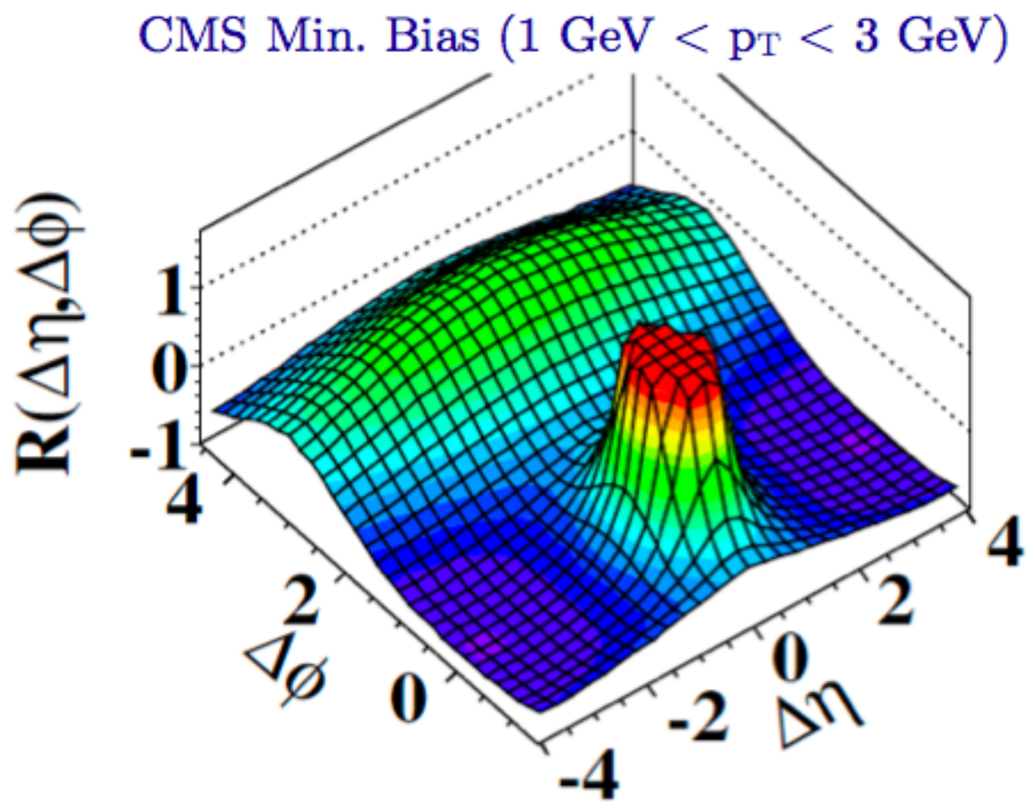
$$\vec{\zeta}_\perp = \vec{b}_\perp \sqrt{x(1-x)}$$



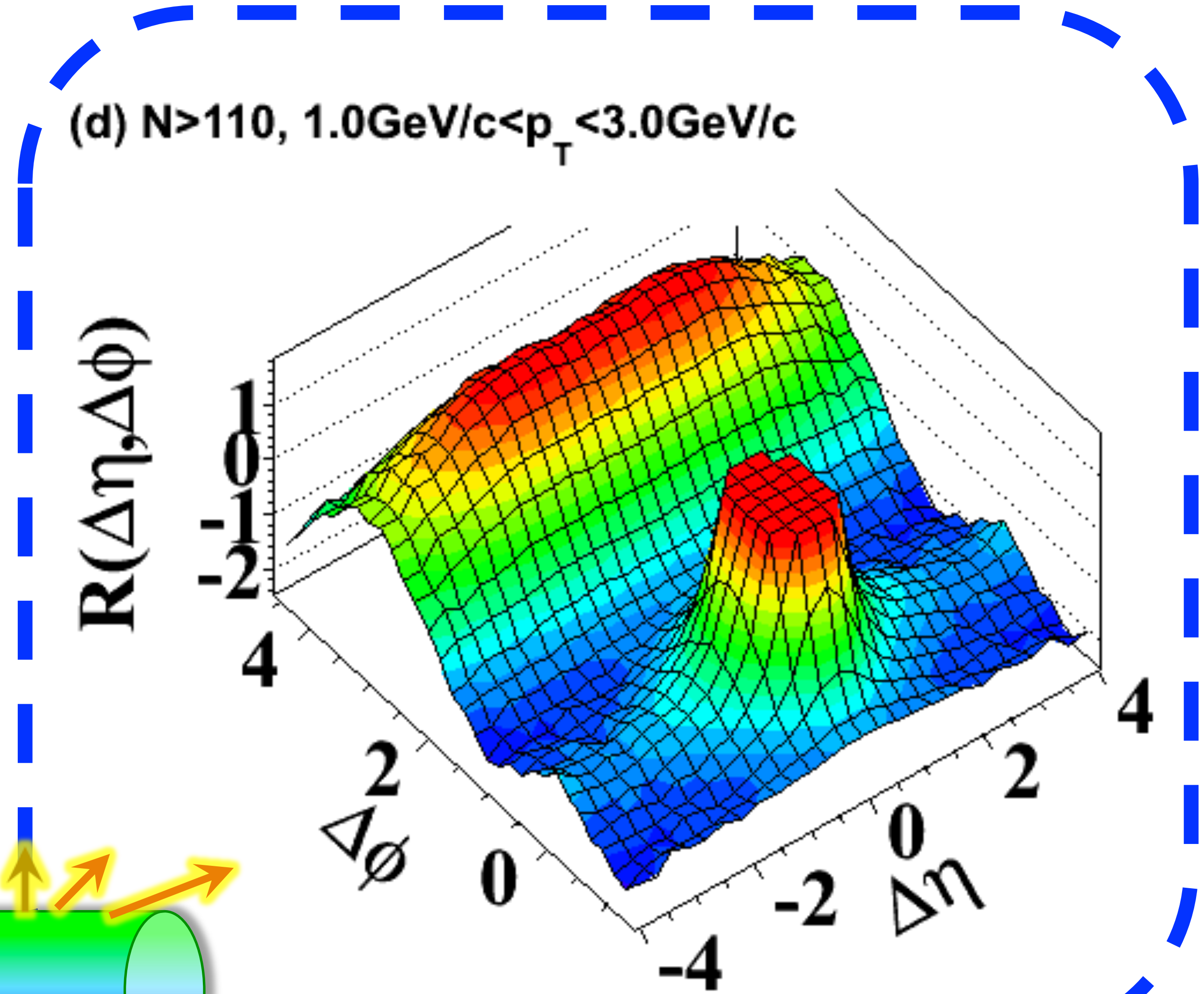
confinement in plane of pair

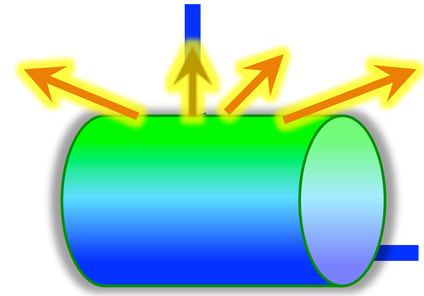
Ridge in high-multiplicity p p collisions

Two-particle correlations: CMS results



"Discovery"



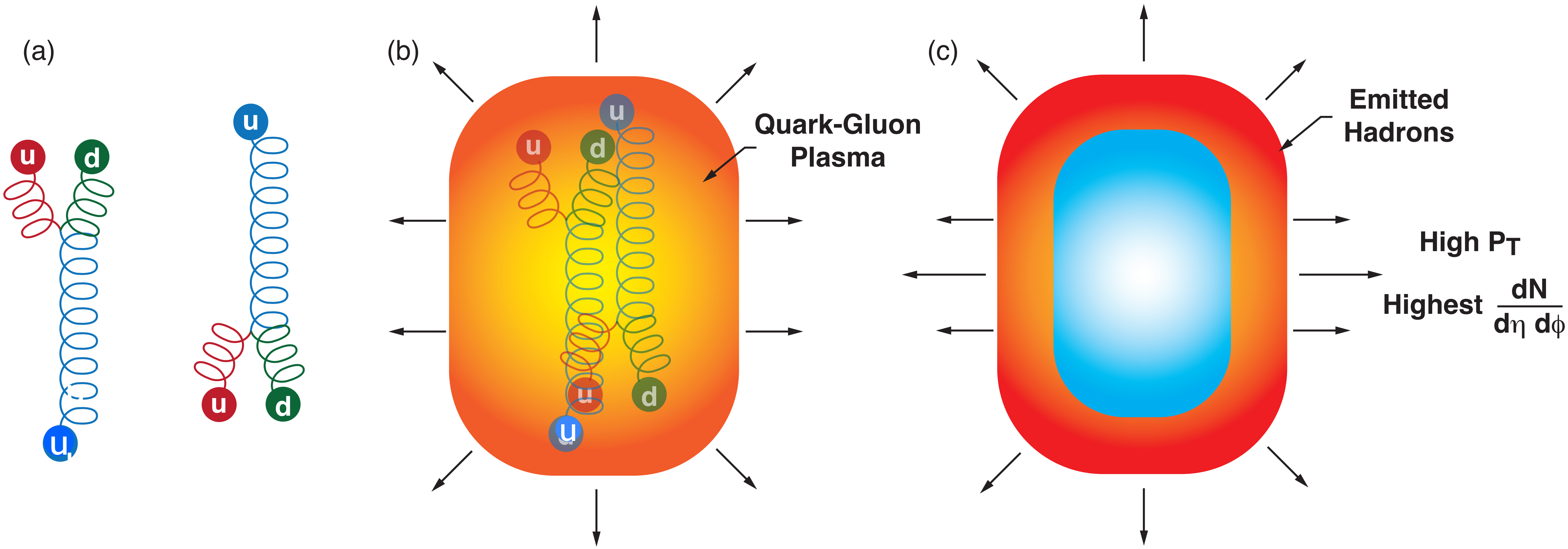


- **Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV**

Raju Venugopalan

Possible origin of same-side CMS ridge in p p Collisions

Bjorken, Goldhaber, sjb



$$\vec{V} = \sum_{i=1}^{N} [\cos 2\phi_i \hat{x} + \sin 2\phi_i \hat{y}]$$

Principle of Maximum Conformality (PMC)

QCD Observables

$$\mathcal{O} = C(\alpha_s(\mu_0^2)) + B(\beta \log \frac{Q^2}{\mu_0^2}) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

Scale-Free Conformal Series

Running Coupling Effects

Higher Twist from Hadron Dynamics

Intrinsic Heavy Quarks

Light by Light Loops

BLM/PMC: Absorb β-terms into running coupling

$$\mathcal{O} = C(\alpha_s(Q^{*2})) + D(\frac{m_q^2}{Q^2}) + E(\frac{\Lambda^2_{QCD}}{Q^2}) + F(\frac{\Lambda^2_{QCD}}{m_Q^2}) + G(\frac{m_q^2}{m_Q^2})$$

Principle of Maximum Conformality (PMC)

- **Sets pQCD renormalization scale correctly at every finite order**
- **Predictions are scheme-independent**
- **Satisfies all principles of the renormalization group**
- **Agrees with Gell Mann-Low procedure for pQED in Abelian limit**
- **Shifts all β terms into α_s, leaving conformal series**
- **Automatic procedure: R_δ scheme**
- **Number of flavors n_f set**
- **Eliminates n! renormalon growth**
- **Choice of initial scale irrelevant**
- **Eliminates unnecessary systematic error -- conventional guess is scheme-dependent, disagrees with QED**
- **Reduces disagreement with pQCD for top/anti-top asymmetry at Tevatron from 3σ to 1σ**

Xing-Gang Wu, Matin Mojaza
Leonardo di Giustino, SJB

Set multiple renormalization scales --
Lensing, DGLAP, ERBL Evolution ...

$Choose\ renormalization\ scheme;\ e.g.\ \alpha_s^R(\mu_R^{\rm init})$

↓

$Choose\ \mu_R^{init};\ arbitrary\ initial\ renormalization\ scale$

↓

$Identify\ \{\beta_i^R\}-terms\ using\ n_f-terms$

$through\ the\ PMC-BLM\ correspondence\ principle$

↓

$Shift\ scale\ of\ \alpha_s\ to\ \mu_R^{\rm PMC}\ to\ eliminate\ \{\beta_i^R\}-terms$

↓

$Conformal\ Series$

$Result\ is\ independent\ of\ \mu_R^{\rm init}\ and\ scheme\ at\ fixed\ order$

Principle of Maximum Conformality

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

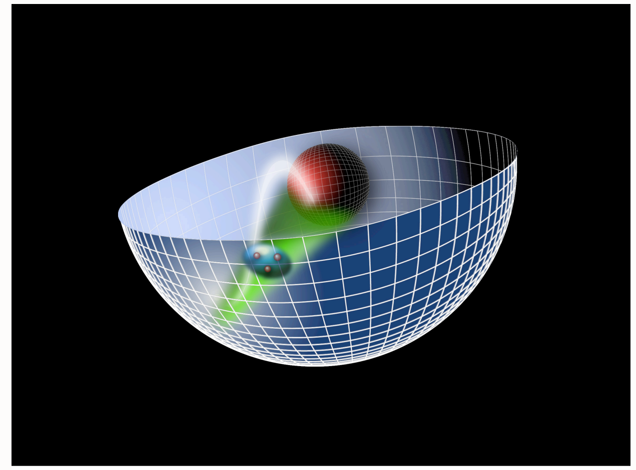
QED Scale Setting at $N_C=0$

Eliminates unnecessary systematic uncertainty

δ -Scheme automatically identifies β -terms!

Xing-Gang Wu, Matin Mojaza
Leonardo di Giustino, SJB

de Tèramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

Light-Front Holography

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

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

Unique Confinement Potential!

Conformal Symmetry
of the action

Confinement scale:

$$\kappa \simeq 0.6\ GeV$$

$$1/\kappa \simeq 1/3\ fm$$

- **de Alfaro, Fubini, Furlan:**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

An analytic first approximation to QCD

AdS/QCD + Light-Front Holography

- **As Simple as Schrödinger Theory in Atomic Physics**
- **LF radial variable ζ conjugate to invariant mass squared**
- **Relativistic, Frame-Independent, Color-Confining**
- **Unique confining potential!**
- **QCD Coupling at all scales: Essential for Gauge Link phenomena**
- **Hadron Spectroscopy and Dynamics from one parameter**
- **Wave Functions, Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates: Zero cosmological constant!**
- **Systematically improvable with DLCQ-BLFQ Methods**

Advantages of the Front Form

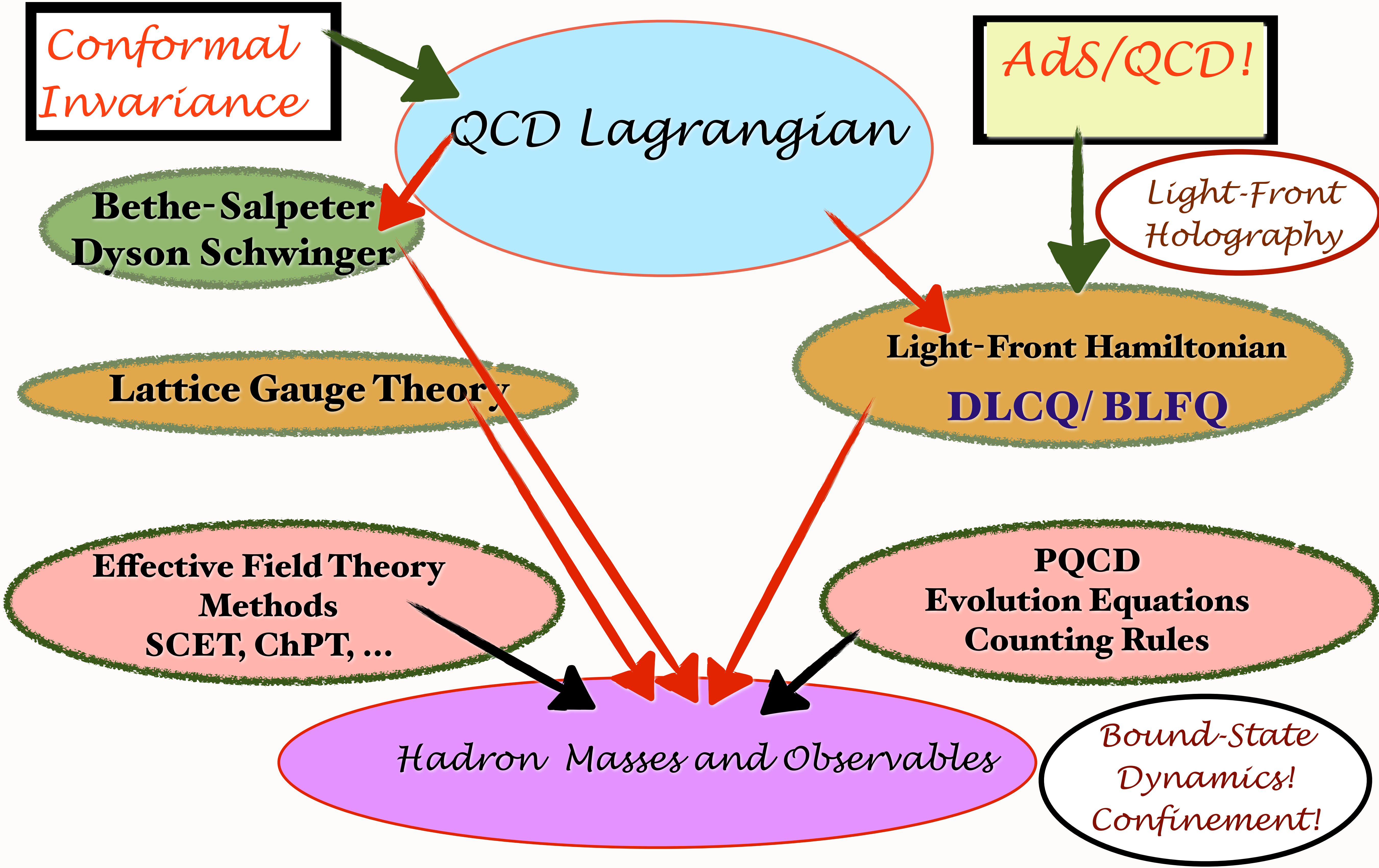
- **Light-Front Time-Ordered Perturbation Theory: Elegant, Physical**
- **Frame-Independent**
- **Few LF Time-Ordered Diagrams (not n!) -- all k^+ must be positive**
- **J^z conserved at each vertex**
- **Cluster Decomposition -- only proof for relativistic theory**
- **Automatically normal-ordered; LF Vacuum trivial up to zero modes**
- **Renormalization: Alternate Denominator Subtractions: Tested to three loops in QED**
- **Reproduces Parke-Taylor Rules and Amplitudes (Stasto-Cruz)**
- **Hadronization at the Amplitude Level with Confinement**

Light-Front vacuum can simulate empty universe

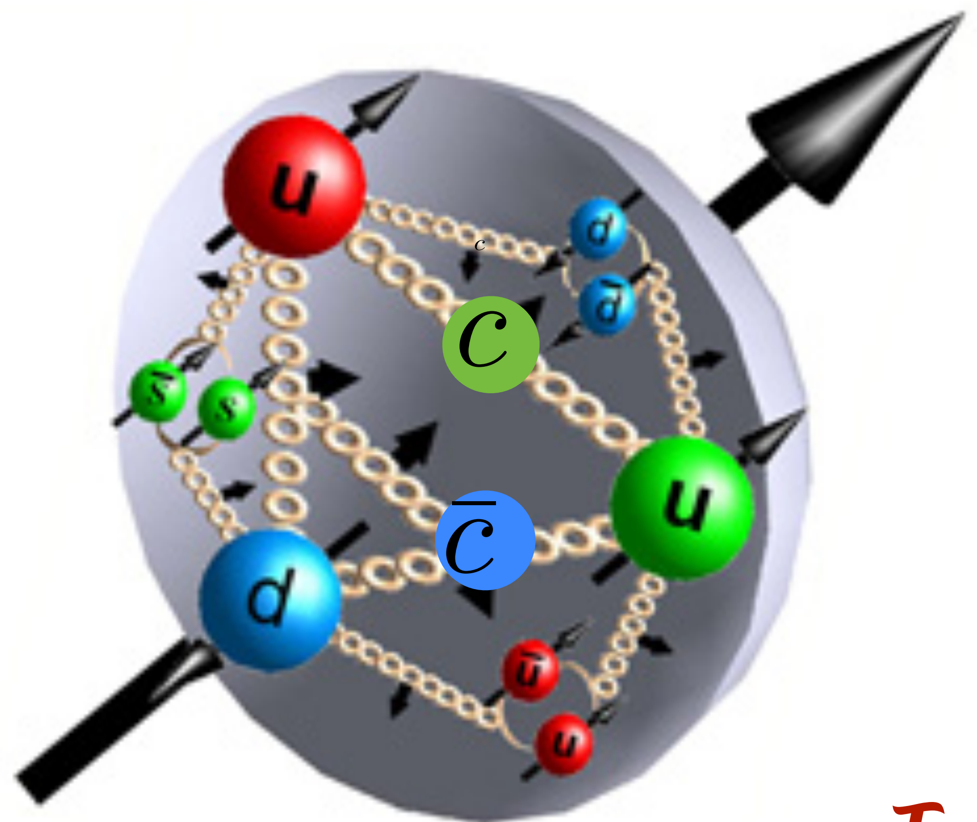
Shrock, Tandy, Roberts, sjb

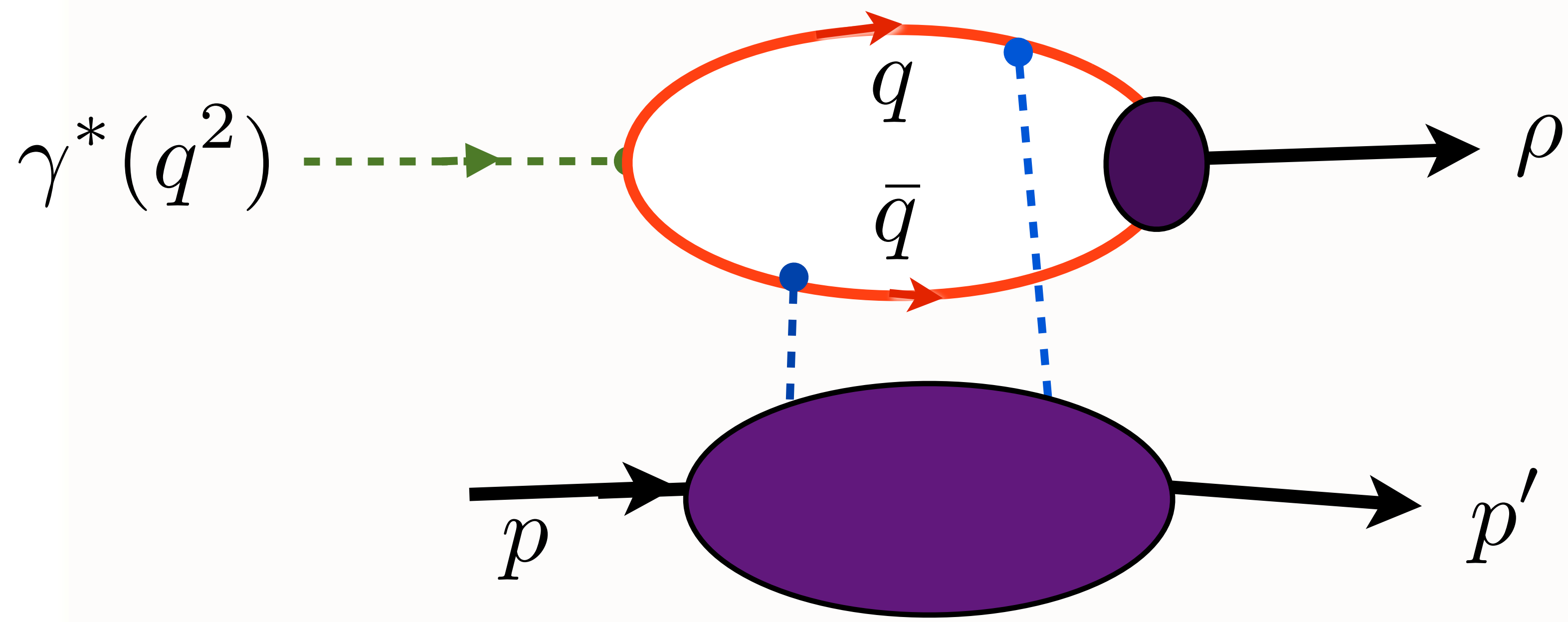
- **Independent of observer frame**
- **Causal**
- **Lowest invariant mass state M= 0.**
- **Trivial up to $k^+=0$ zero modes-- already normal-ordering**
- **Higgs theory consistent with trivial LF vacuum (Srivastava, sjb)**
- **QCD and AdS/QCD: "In-hadron"condensates (Maris, Tandy Roberts) -- GMOR satisfied.**
- **QED vacuum; no loops**
- **Zero cosmological constant from QED, QCD**

Predict Hadron Properties from First Principles!



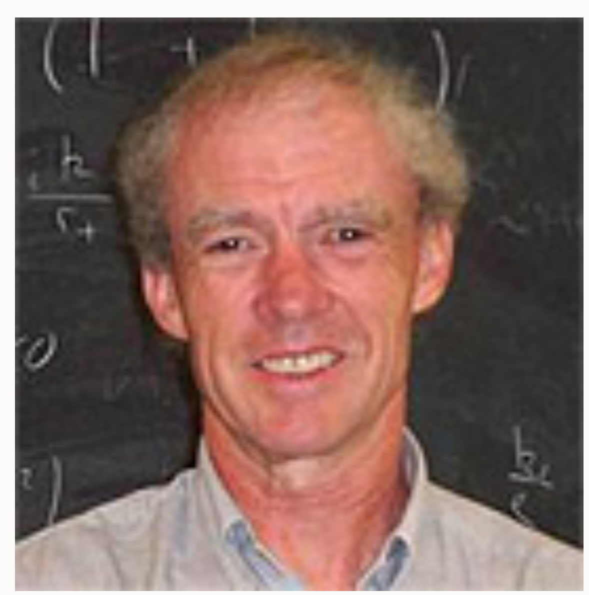
Exclusive Processes and New Perspectives for QCD





Jack Gunion Fest

March 28-29, 2014
University of California, Davis



Happy Birthday #70!!

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY