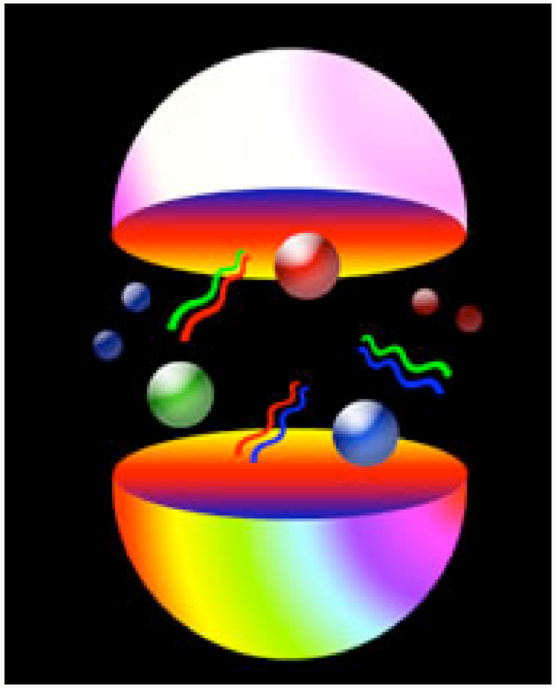
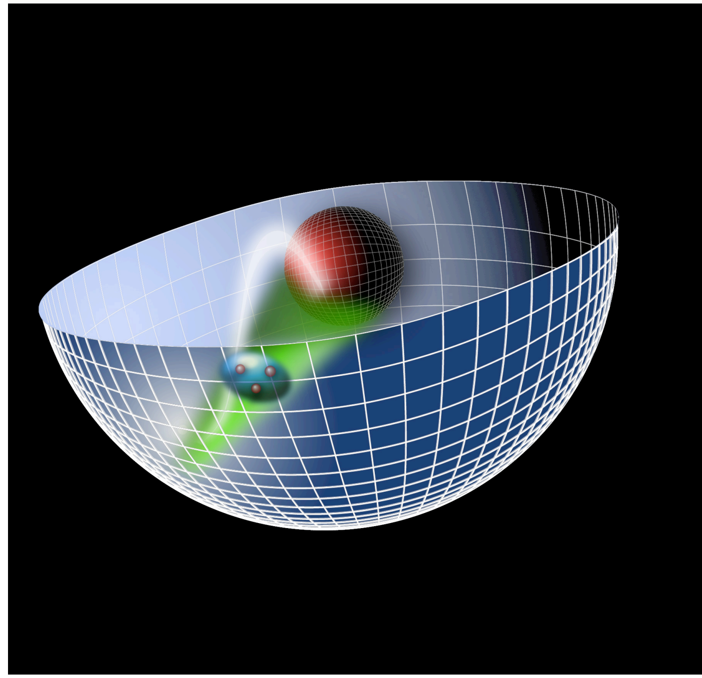
AdS/CFT and Hadronic Physics on the Light Front



Lev Davidovich Landau

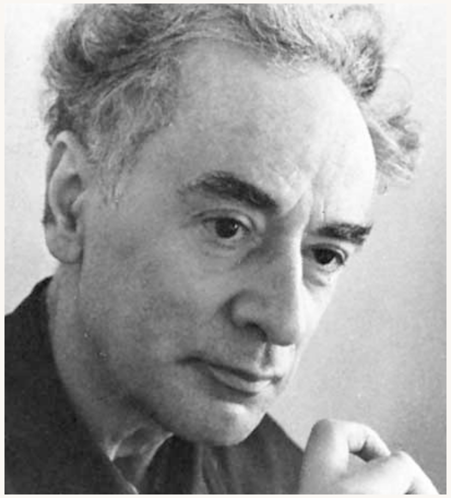


Stan Brodsky   SLAC/IPPP

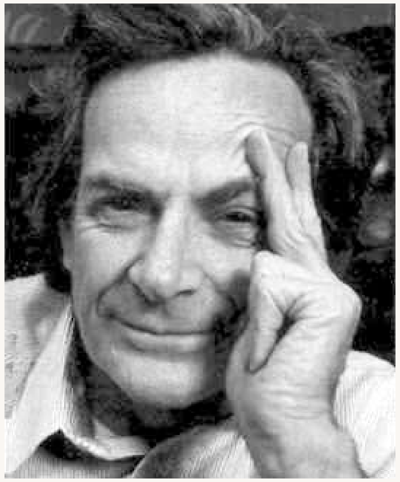
Landau Memorial Meeting   Moscow   June 20, 2008

Landau's Impact

- **International Influence throughout Atomic, Nuclear, Electroweak, High Energy Physics**
- **Fundamentals of Quantum Field Theory**
- **CP Invariance, Neutrino Physics**
- **Renormalization theory, Landau Singularity**
- **Remarkable Students, Legacy of Russian Schools**

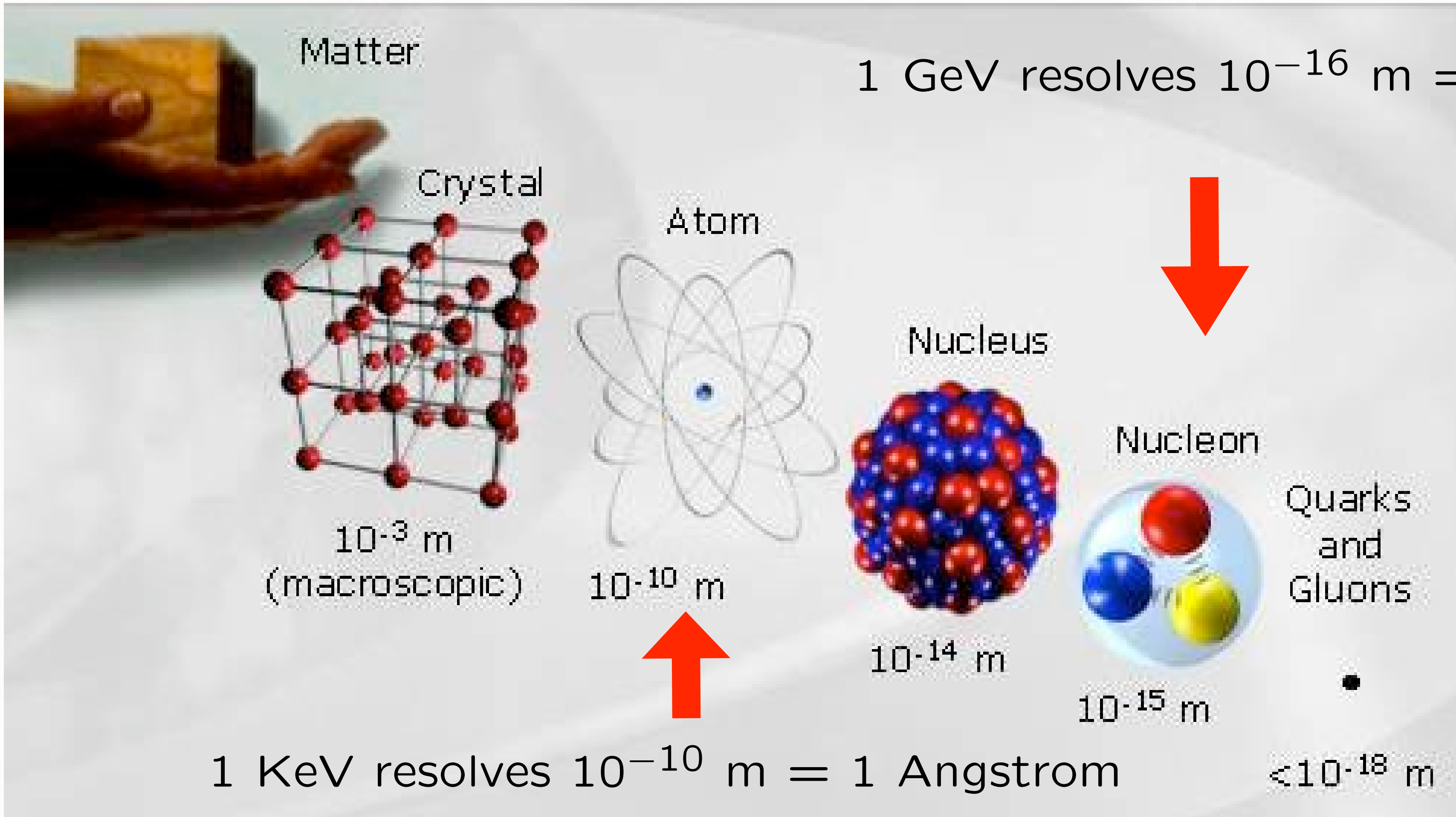


Physical Intuition!



Searching for the Ultimate Constituents

$1\ \text{GeV resolves } 10^{-16}\ \text{m} = 0.1\ \text{fm}$



$1\ \text{KeV resolves } 10^{-10}\ \text{m} = 1\ \text{Angstrom}$

Electrons, Quarks, and Gluons may be truly pointlike!

$1\ \text{TeV resolves } 10^{-19}\ \text{m} = 0.0001\ \text{fm}$

THE PERIODIC TABLE

Particles like the electron (fermions, spin 1/2)

Leptons		Quarks (each in 3 "colors")	
e 0.511 MeV	ν_e < 0.000003	d 7	u 3
μ 106	ν_μ < 0.2	s 120	c 1200
τ 1777	ν_τ < 20	b 4300	t 175,000
-1	0	$-1/3$	$2/3$ ← charge

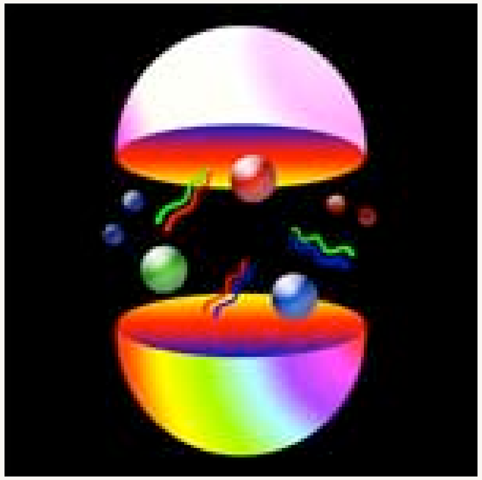
Particles like the photon (bosons, spin 1)

γ 0	photon	"electromagnetism"
g 0	gluon (8 "colors")	"strong interaction"
$W^\pm$ 80,420	Z^0 91,188	"weak interaction"

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: Holography: AdS/CFT

QCD Lagrangian

gluon dynamics

quark kinetic energy + quark-gluon dynamics

mass term

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

QCD color charge

field strength tensor

covariant derivative

quark field

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

Dimensionless Coupling

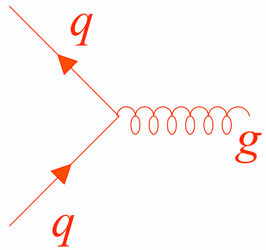
Renormalizable

Asymptotic Freedom

Color Confinement

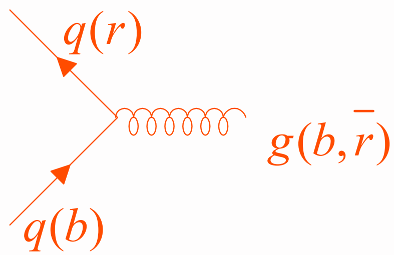
Fundamental Couplings

Only quarks and gluons involve basic vertices: Quark-gluon vertex

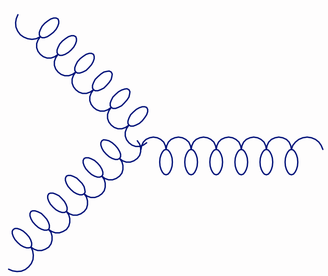


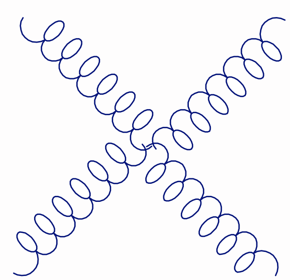
Similar to QED

More exactly



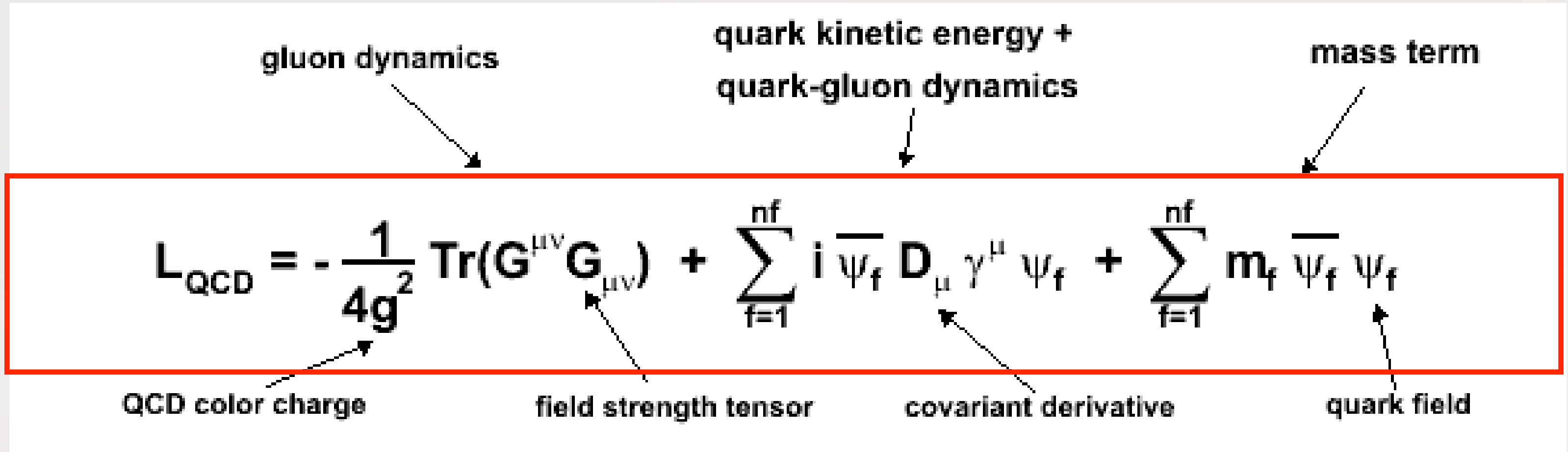
Gluon vertices





colored particles couple to gluons

QCD Lagrangian



$[C_F = \frac{N_C^2-1}{2N_C}]$

$\lim N_C \to 0$ at fixed $\alpha = C_F \alpha_s, n_\ell = n_F / C_F$

Analytic limit of QCD: Abelian Gauge Theory

QCD ➡ QED Huet, sjb

QED: Underlies Atomic Physics, Molecular Physics, Chemistry, Electromagnetic Interactions ...

QCD: Underlies Hadron Physics, Nuclear Physics,

Theoretical Tools:

- Feynman diagrams and perturbation theory, evolution equations
- Bethe Salpeter and Dyson-Schwinger Equations
- Lattice Gauge Theory
- Discretized Light-Front Quantization
- AdS/CFT !

Given the elementary gauge theory interactions, all fundamental processes described in principle!

Example from QED:

Electron gyromagnetic moment - ratio of spin precession frequency to Larmor frequency in a magnetic field

$\frac{1}{2}g_e = 1.001\ 159\ 652\ 201(30)$ QED prediction (Kinoshita, et al.)

$\frac{1}{2}g_e = 1.001\ 159\ 652\ 193(10)$ Measurement (Dehmelt, et al.)

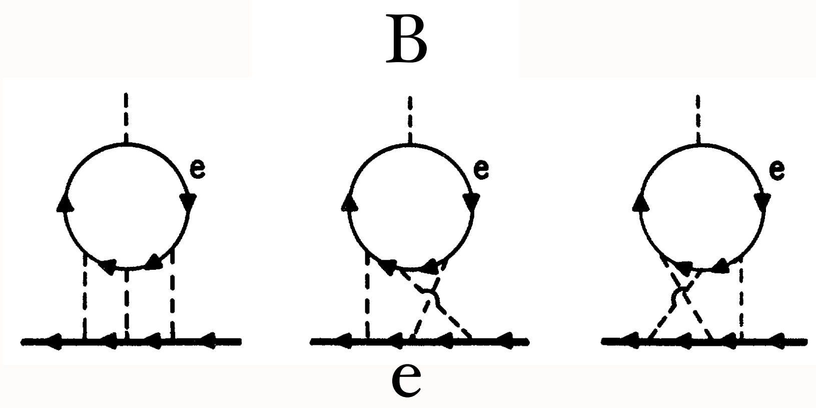
$$\frac{1}{2}g_e = 1.001\ 159\ 652\ 180\ 85\ [0.76\ ppt]$$

Dirac: $g_e \equiv 2$ Measurement (Gabrielse, et al.)

QED provides an asymptotic series relating g and α,

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$
$$+ a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}},$$

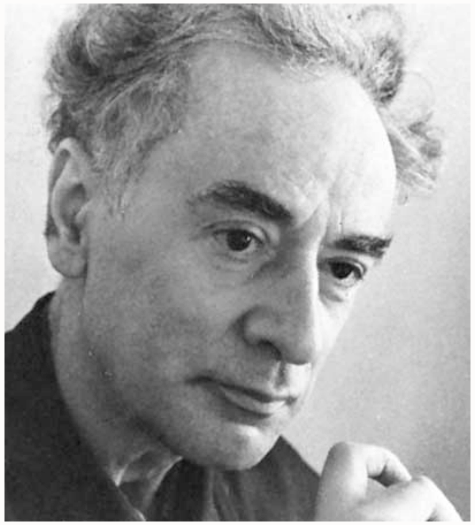
Light-by-Light Scattering Contribution to C_6

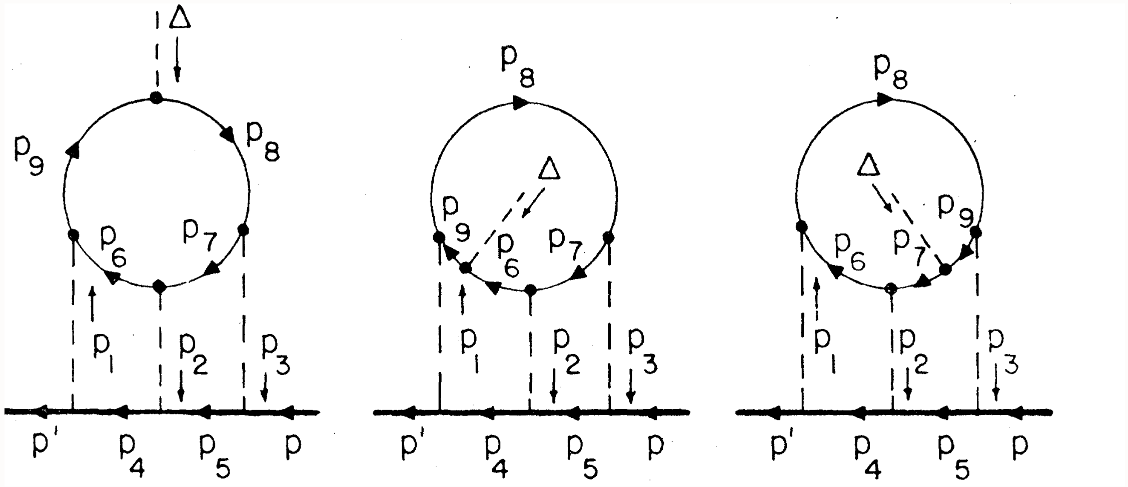


$$\alpha^{-1} = 137.035\,999\,710\,(90)\,(33)\,[0.66 \text{ ppb}][0.24 \text{ ppb}],$$
$$= 137.035\,999\,710\,(96)\,[0.70 \text{ ppb}].$$

G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, and B. Odom, Phys. Rev. Lett. **97**, 030802 (2006).

In 1959 Landau and Bjorken developed, independently and simultaneously, the analogy of Feynman graphs to electrical circuit theory and the use of Kirchhoff's laws to analyze their singularity structure





Light-by-light contribution to the muon and electron anomalous magnetic moments

Aldins, Dufner, Kinoshita, sjb

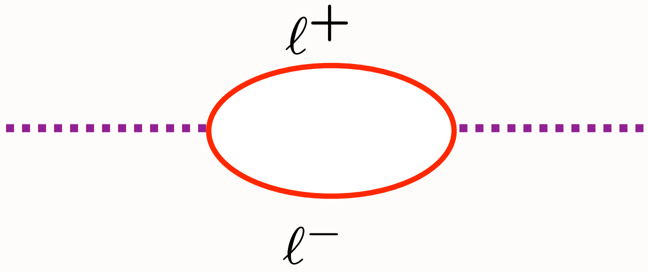
Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell Mann-Low Effective Charge

QED One-Loop Vacuum Polarization



$t = -Q^2 < 0$

(t spacelike)

$$\Pi(Q^2) = \frac{\alpha(0)}{3\pi}\left[\frac{5}{3} - \frac{4m^2}{Q^2} - \left(1 - \frac{2m^2}{Q^2}\right)\sqrt{1 + \frac{4m^2}{Q^2}}\log\frac{1+\sqrt{1+\frac{4m^2}{Q^2}}}{\left|1-\sqrt{1+\frac{4m^2}{Q^2}}\right|}\right]$$

Analytically continue to timelike t: Complex

$$\Pi(Q^2) = \frac{\alpha(0)}{15\pi}\frac{Q^2}{m^2} \qquad Q^2 << 4M^2$$ **Serber-Uehling**

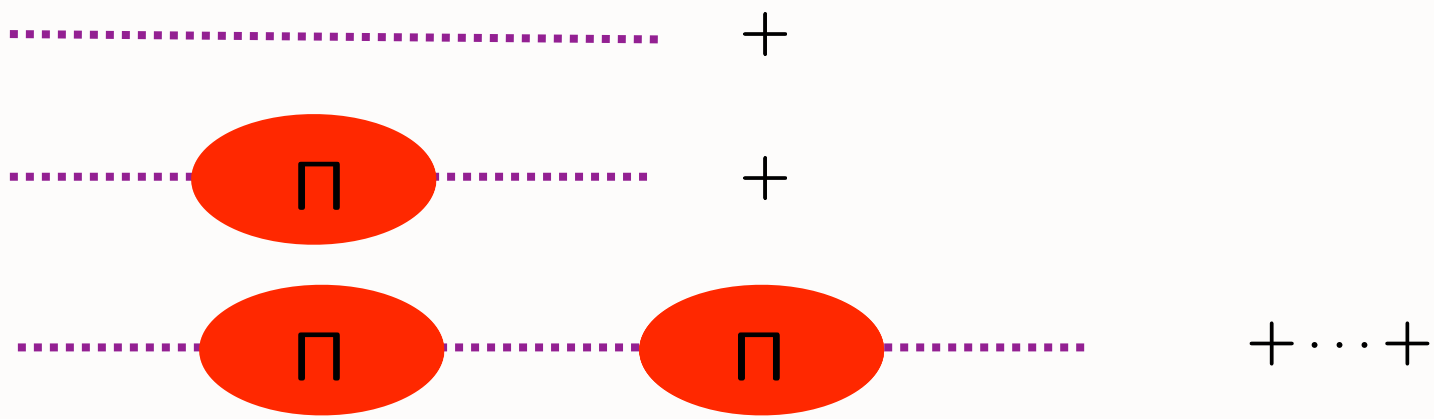
$$\Pi(Q^2) = \frac{\alpha(0)}{3\pi}\frac{\log Q^2}{m^2} \qquad Q^2 >> 4M^2$$ **Landau Pole**

$$\beta = \frac{d(\frac{\alpha}{4\pi})}{d\log Q^2} = \frac{4}{3}\left(\frac{\alpha}{4\pi}\right)^2 n_\ell > 0$$

QED Effective Charge

$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

All-orders lepton loop corrections to dressed photon propagator



$$\alpha(t) = \frac{\alpha(t_0)}{1-\Pi(t,t_0)} \qquad \Pi(t,t_0) = \frac{\Pi(t)-\Pi(t_0)}{1-\Pi(t_0)}$$

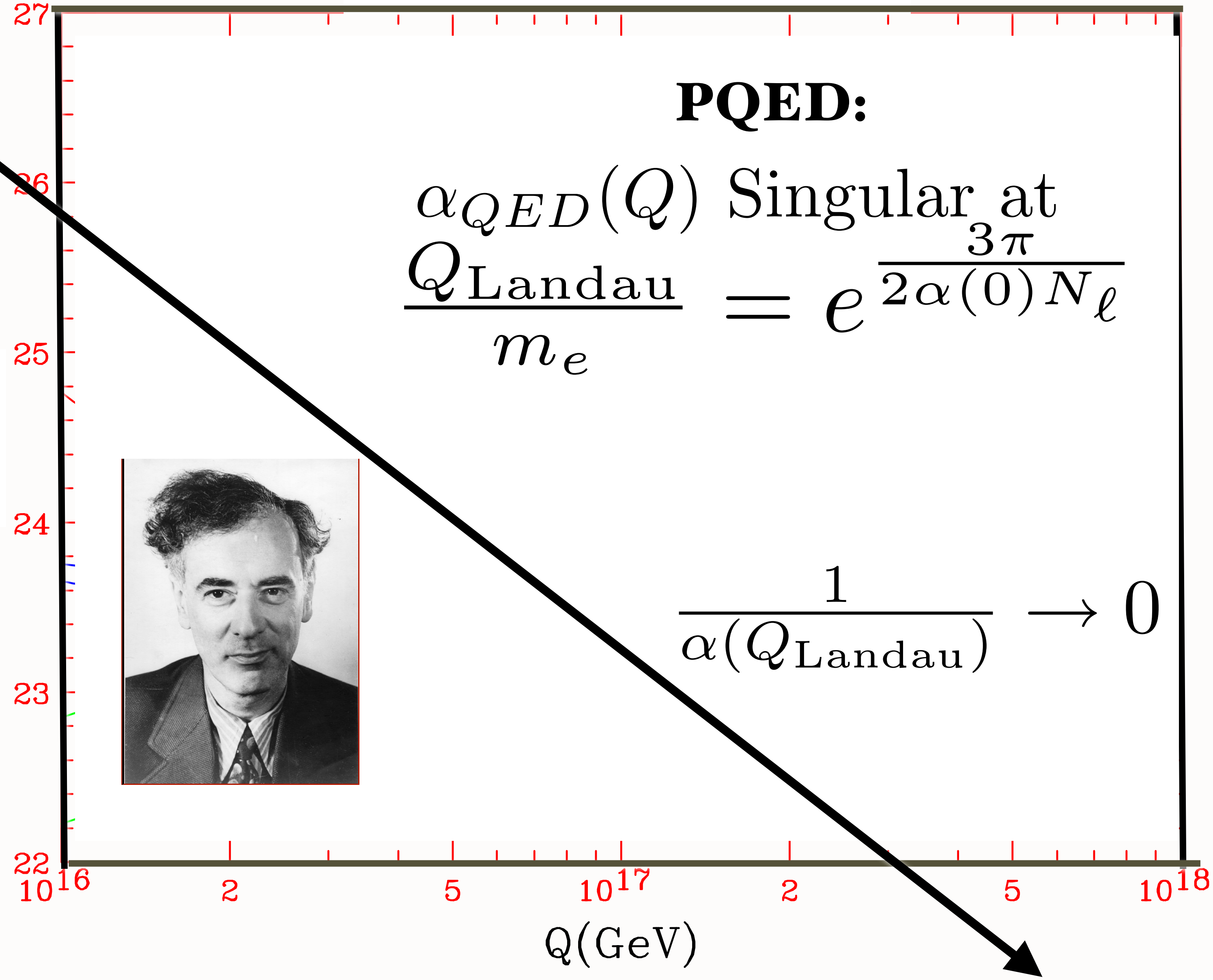
Initial scale t_0 is arbitrary -- Variation gives RGE Equations

Physical renormalization scale t never arbitrary

$$\frac{1}{\alpha(0)} = 137.035999084(51)[0.37\text{ppb}]$$

Landau Pole

$$\frac{1}{\alpha_{\rm QED}(Q)}$$



PQED:

$\alpha_{QED}(Q)$ Singular at

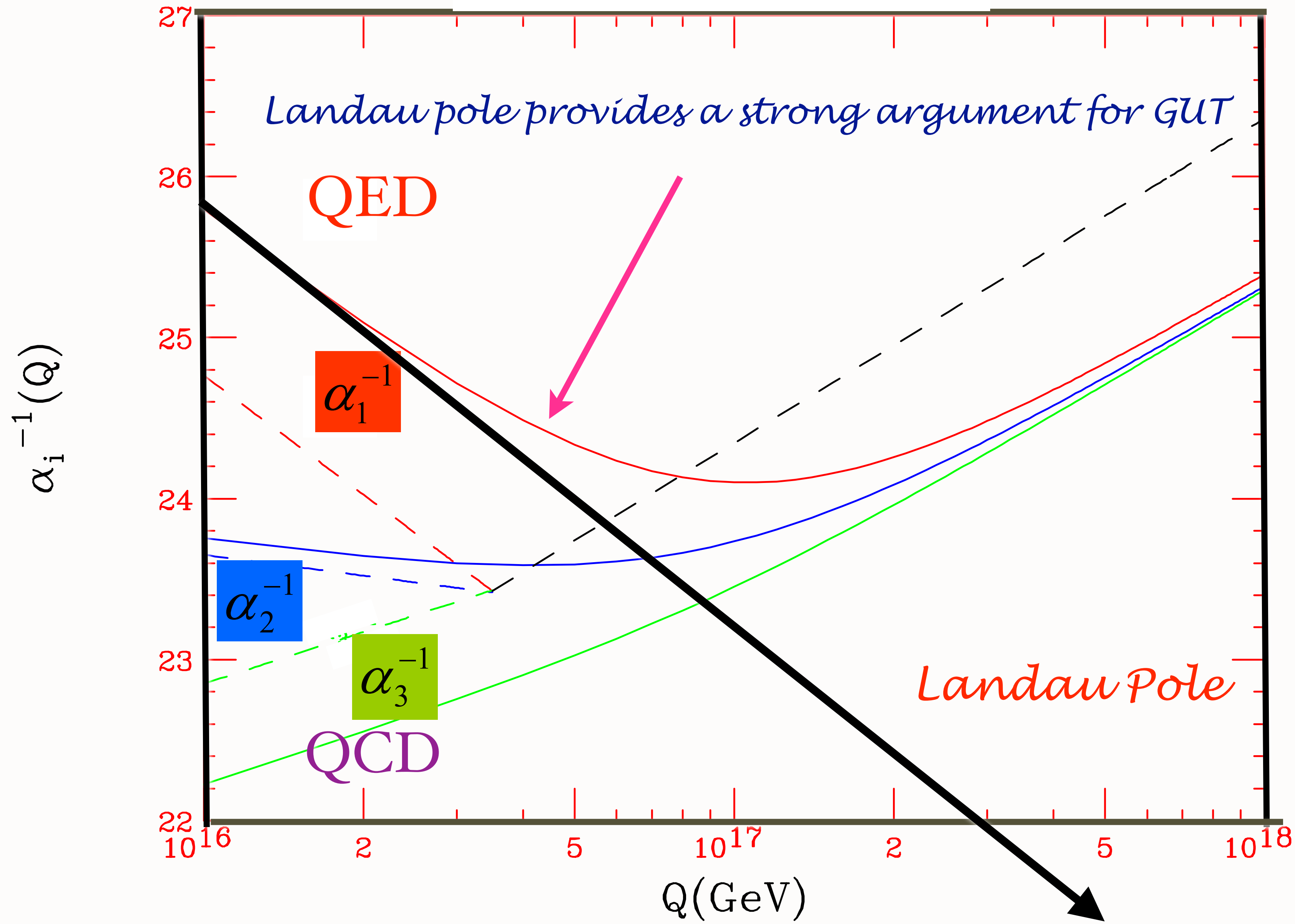
$$\frac{Q_{\rm Landau}}{m_e} = e^{\frac{3\pi}{2\alpha(0)N_\ell}}$$

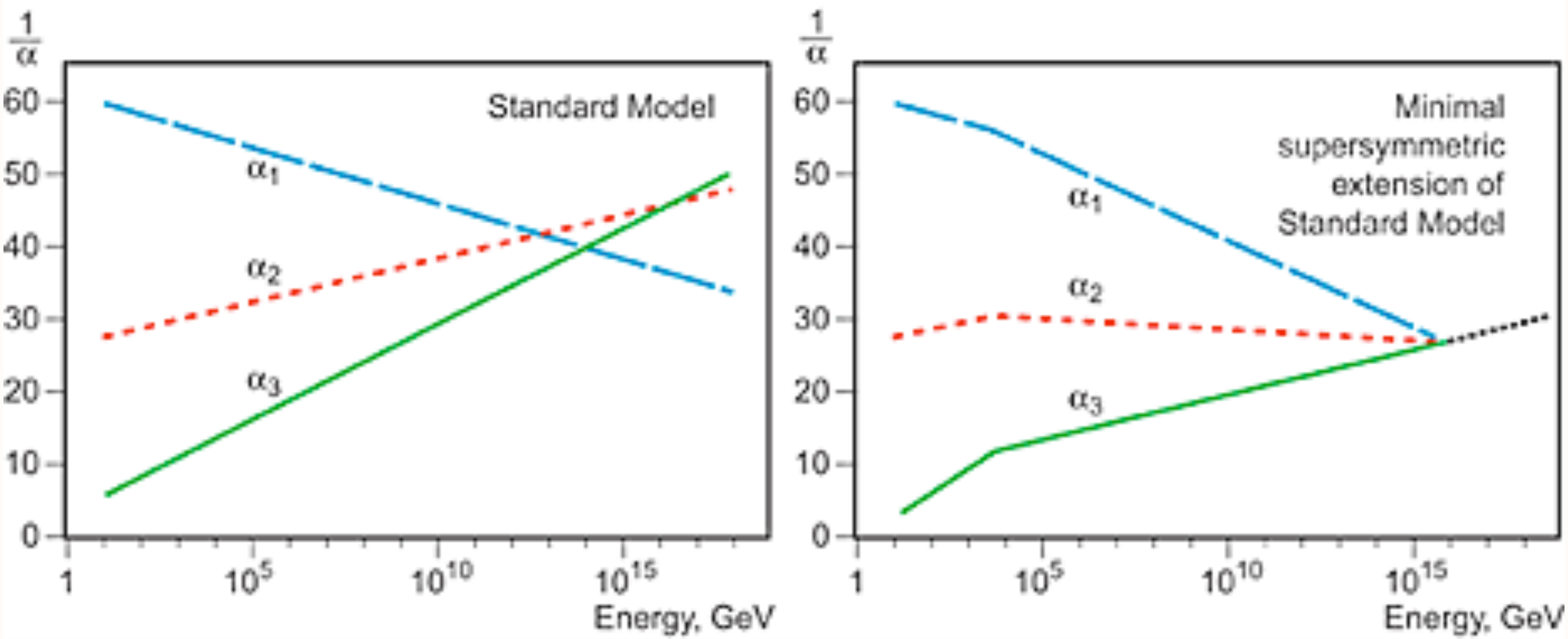
$$\frac{1}{\alpha(Q_{\rm Landau})} \to 0$$

Supersymmetric SU(5)

Coupling Unification

M. Binger, sjb

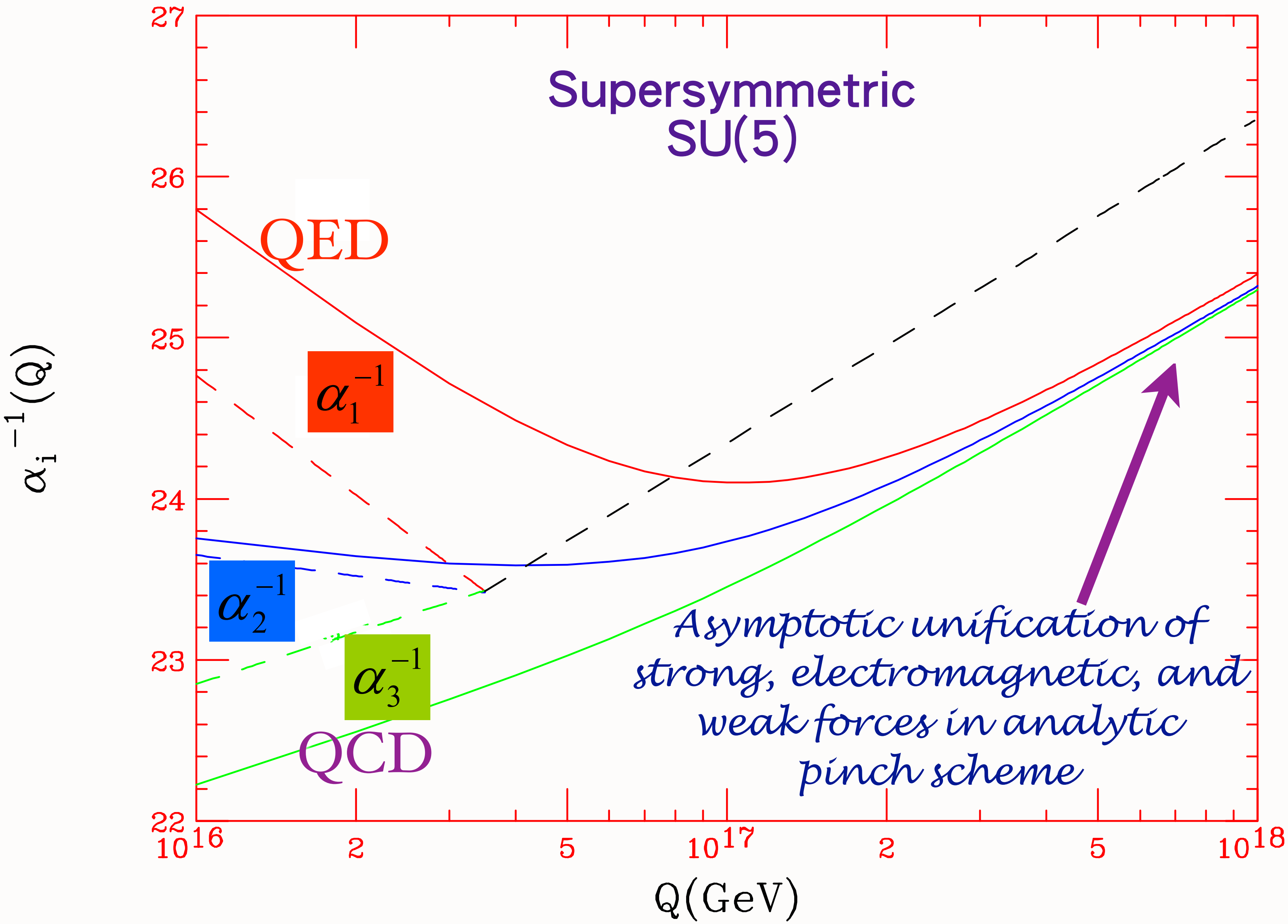




Coupling Unification in Nonanalytic $\overline{ms}$ Scheme

Analytic Coupling Unification

Binger, sjb



Lesson from QED:

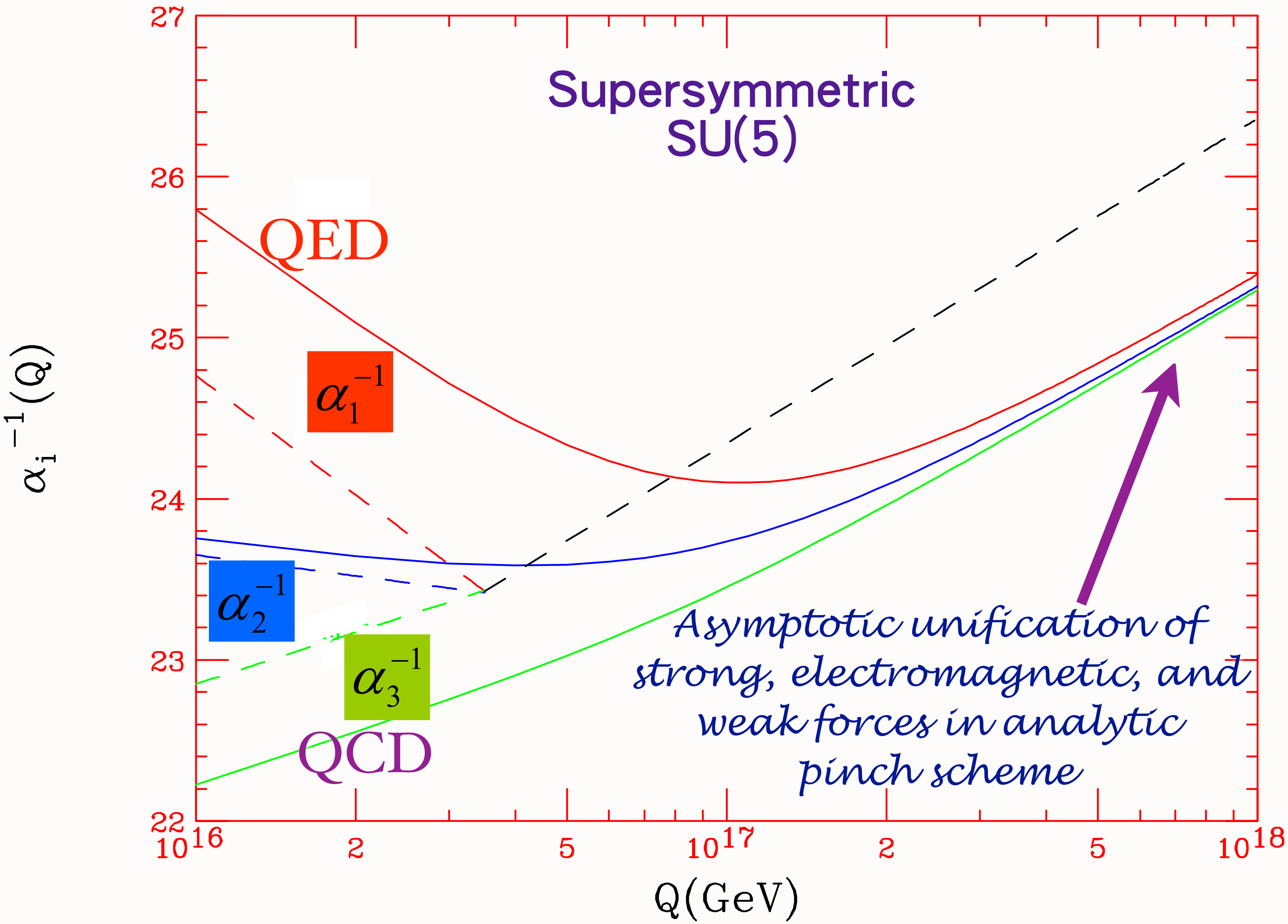
Use Physical Scheme to Characterize QCD Coupling

- Use Physical Observable to define QCD coupling
- No Renormalization Scale Ambiguity
- Analytic: Smooth behavior as one crosses new quark threshold
- New perspective on grand unification

Binger, Sjb

Analytic Coupling Unification

Binger, sjb



Lesson from QED:
Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[1 + \frac{\alpha_R(Q)}{\pi}\right].$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2)\right] \equiv \frac{1}{3}\left|\frac{g_A}{g_V}\right|\left[1 - \frac{\alpha_{g_1}(Q)}{\pi}\right]$$

$$\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2\right.$$
$$+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f$$
$$\left.+ \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} + \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right]$$
$$+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2\right.$$
$$\left.+ \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648}f^2\right\}.$$

Eliminate MSbar,
Find Amazing Simplification

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q^{\,2} \left[1 + \frac{\alpha_R(Q)}{\pi} \right] .$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left(\frac{\alpha_R(Q^{**})}{\pi} \right)^2 + \left(\frac{\alpha_R(Q^{***})}{\pi} \right)^3$$

Geometric Series in Conformal QCD

Generalized Crewther Relation

Lu, Kataev, Gabadadze, Sjb

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

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

$$\sqrt{s^*}\simeq 0.52Q$$

Conformal relation true to all orders in perturbation theory

No radiative corrections to axial anomaly

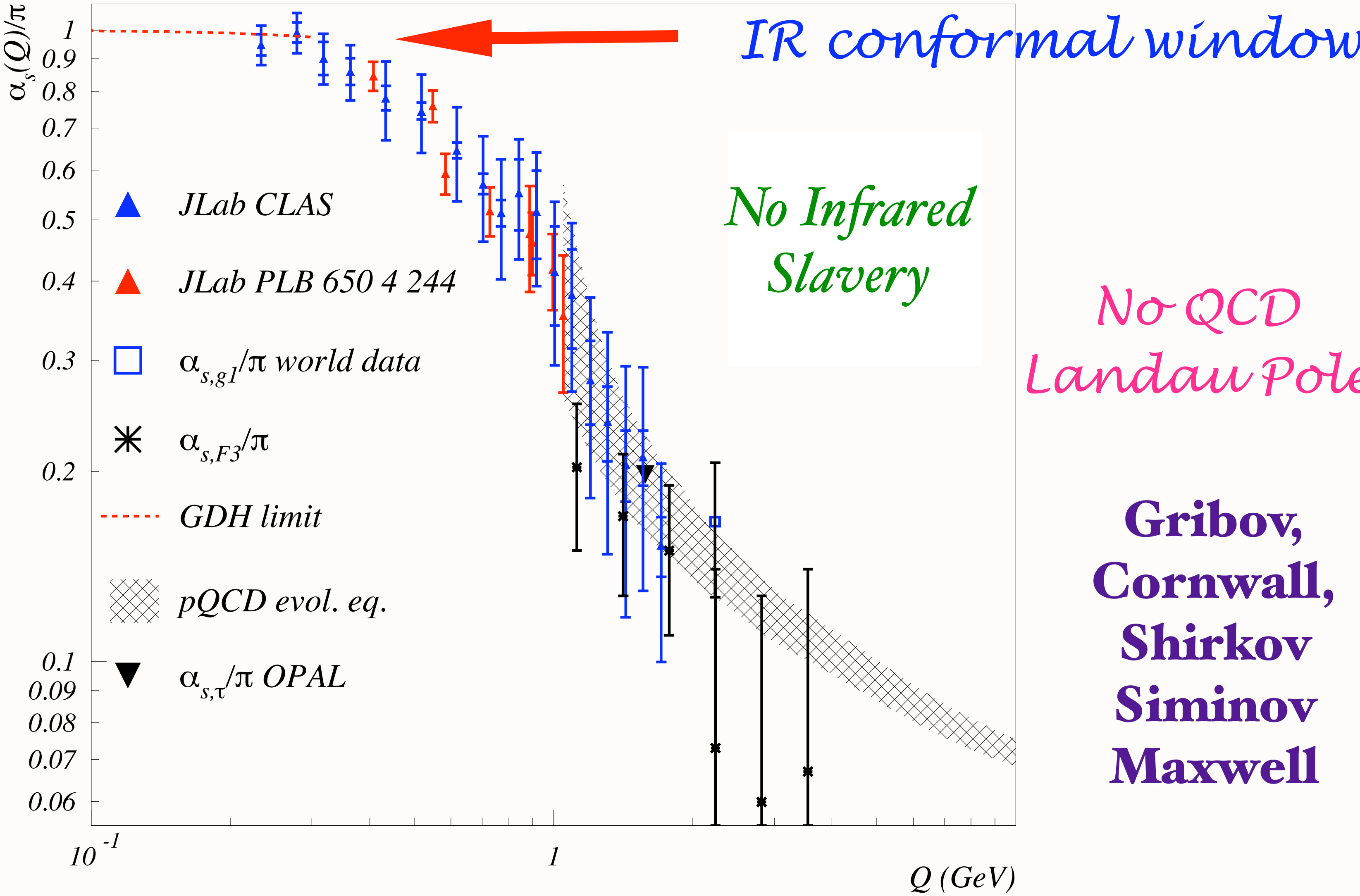
Nonconformal terms set relative scales (BLM)

Analytic matching at quark thresholds

No renormalization scale ambiguity!

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

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



No QCD Landau Pole

Gribov, Cornwall, Shirkov Siminov Maxwell

Lesson from QED:

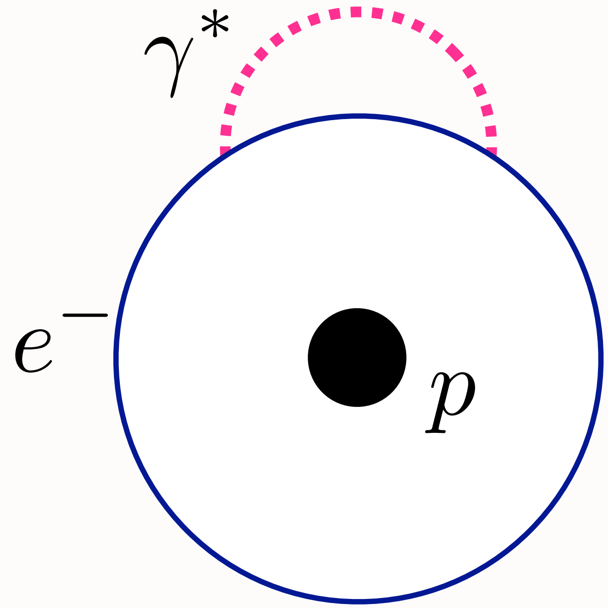
Lamb Shift in Hydrogen

$$\Delta E \sim \alpha (Z\alpha)^4 \ln (Z\alpha)^2 m_e$$

Bethe Log

$$\lambda < \frac{1}{Z\alpha m_e}$$

$$k > Z\alpha m_e$$



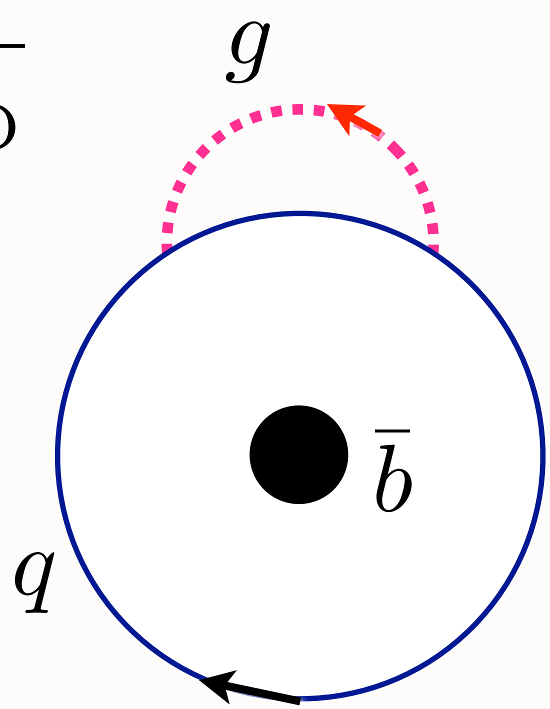
Maximum wavelength of bound electron

Infrared divergence of free electron propagator removed because of atomic binding

Lesson from QED and Lamb Shift:

maximum wavelength of bound quarks and gluons

$$k > \frac{1}{\Lambda_{QCD}} \qquad \lambda < \Lambda_{QCD}$$



B-Meson

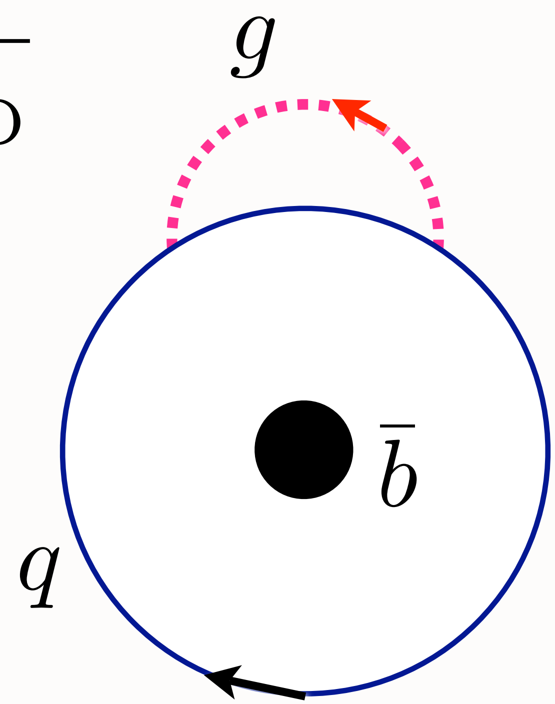
Shrock, sjb

gluon and quark propagators cutoff in IR because of color confinement

Lesson from QED and Lamb Shift:

maximum wavelength of bound quarks and gluons

$$k > \frac{1}{\Lambda_{QCD}} \qquad \lambda < \Lambda_{QCD}$$



B-Meson

Shrock, sjb

Use Dyson-Schwinger Equation for bound-state quark propagator: find confined condensate

$$< \bar{b}|\bar{q}q|\bar{b} > \text{ not } < 0|\bar{q}q|0 >$$

Lesson from QED and Lamb Shift:

Consequences of Maximum Quark and Gluon Wavelength

- Infrared integrations regulated by confinement
- Infrared fixed point of QCD coupling

$$\alpha_s(Q^2) \text{ finite}, \beta \rightarrow 0 \text{ at small } Q^2$$

- Bound state quark and gluon Dyson-Schwinger Equation
- Quark and Gluon Condensates exist within hadrons

Shrock, sjb

Determinations of the vacuum Gluon Condensate

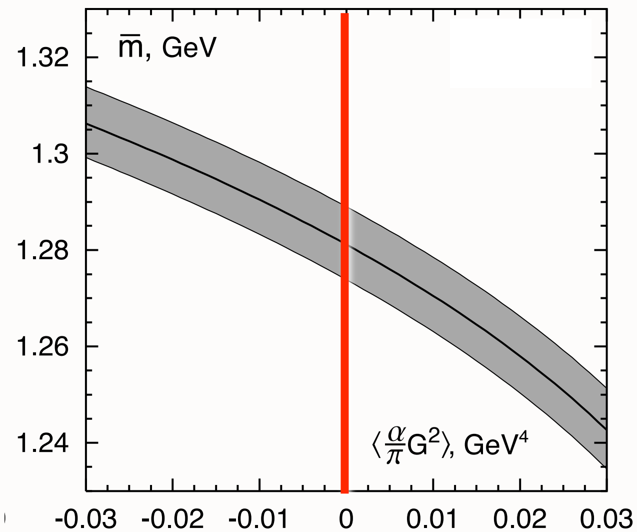
$$< 0|\frac{\alpha_s}{\pi} G^2|0 > [\mathrm{GeV}^4]$$

-0.005 ± 0.003 from τ decay. Davier et al.

$+0.006 \pm 0.012$ from τ decay. Geshkenbein, Ioffe, Zyablyuk

$+0.009 \pm 0.007$ from charmonium sum rules

Ioffe, Zyablyuk



Consistent with zero vacuum condensate

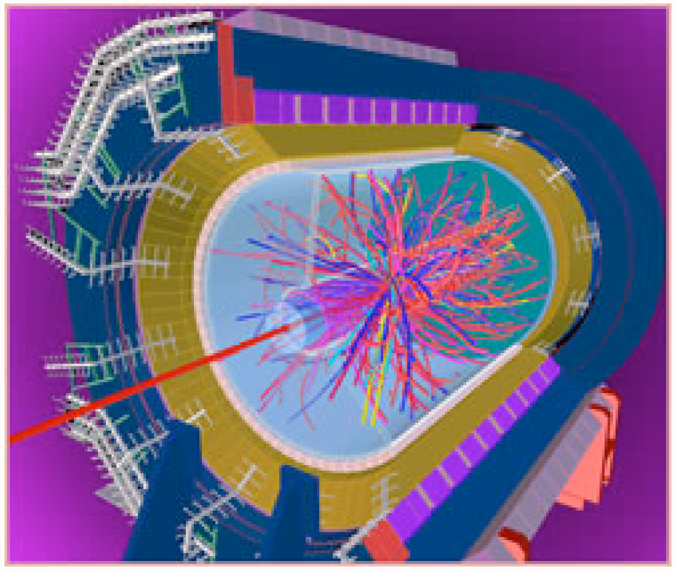
Quark and Gluon condensates reside within hadrons, not vacuum

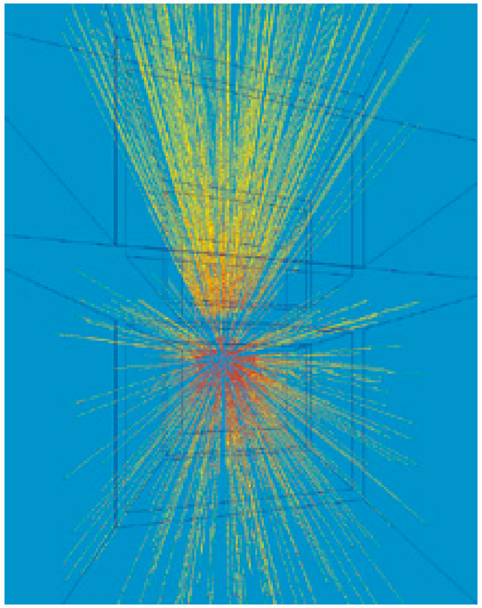
- Bound-State Dyson-Schwinger Equations
- Domain becomes infinite at zero pion mass
- Finite volume phase transition
- Analogous to finite-size superconductor!
- Phase change observed at RHIC within a single-nucleus-nucleus collisions-- quark gluon plasma!
- Implications for cosmological constant -- reduction by 55 orders of magnitude!

"Confined QCD Condensates" Shrock, sjb

Collide Gold Nuclei Together

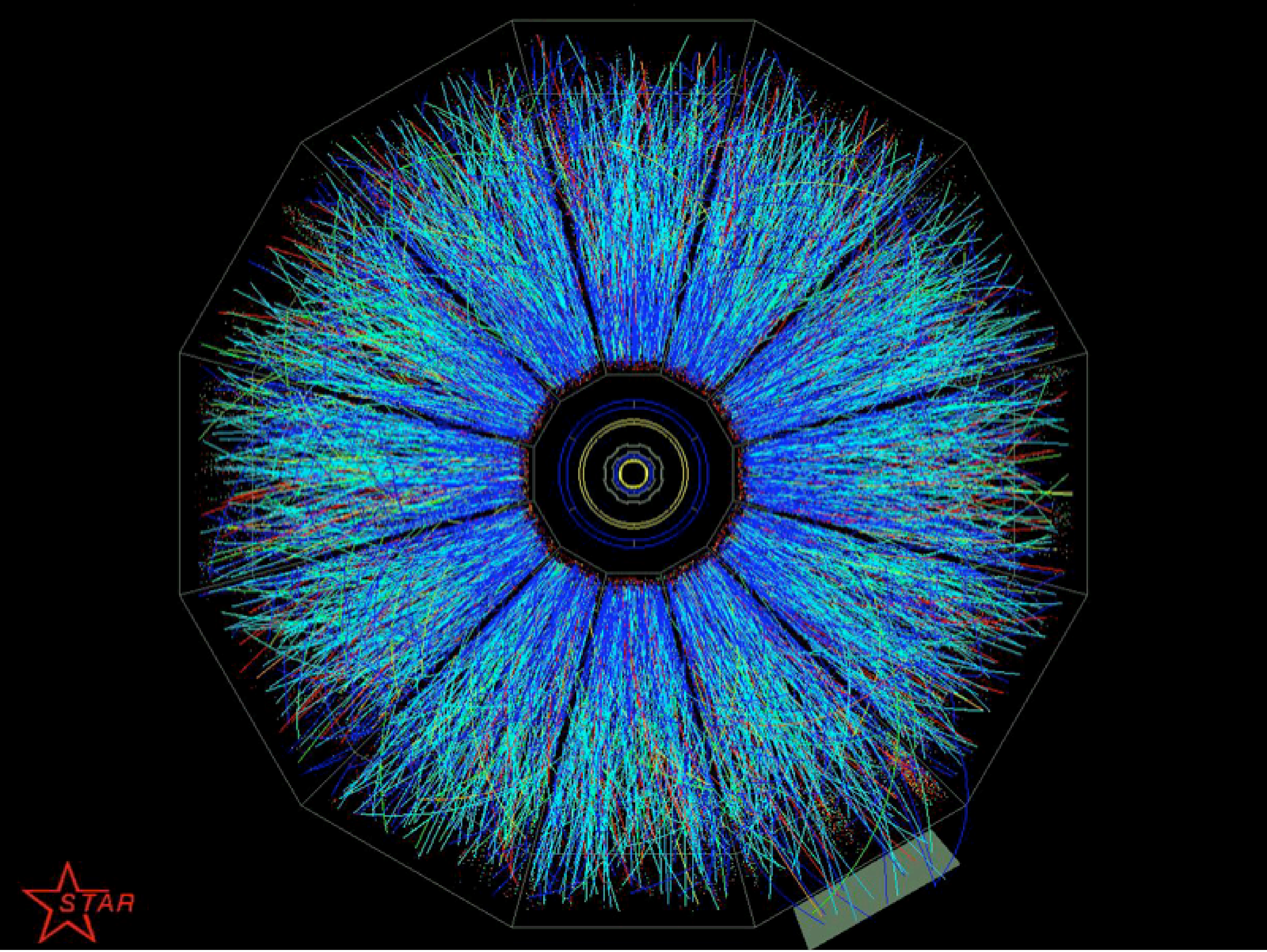
STAR Time-Projection Chamber at RHIC



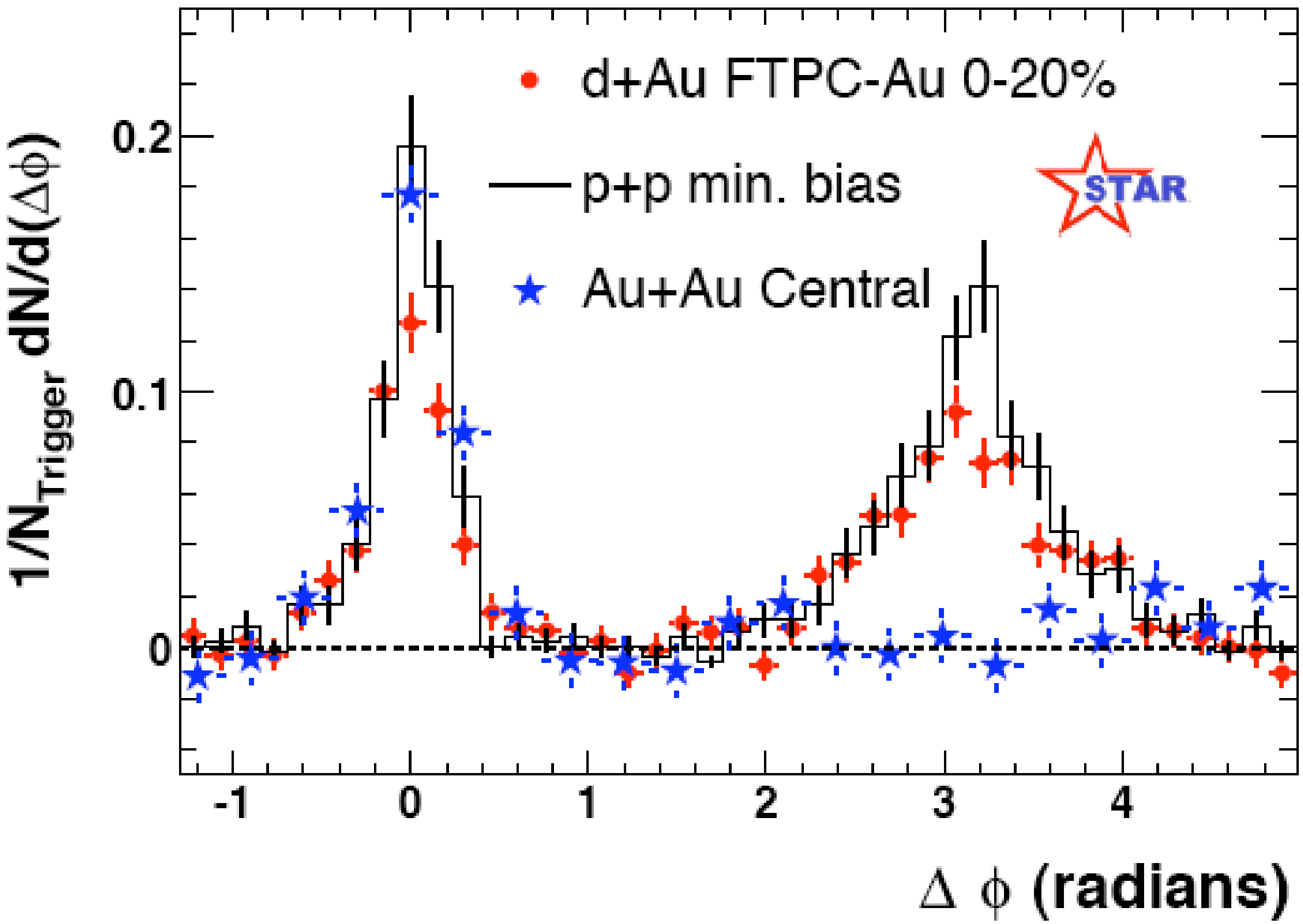


Produce thousands of particles in each collision

Evidence of Quark-Gluon Plasma


STAR

Away-side particles quenched in Au-Au Collisions

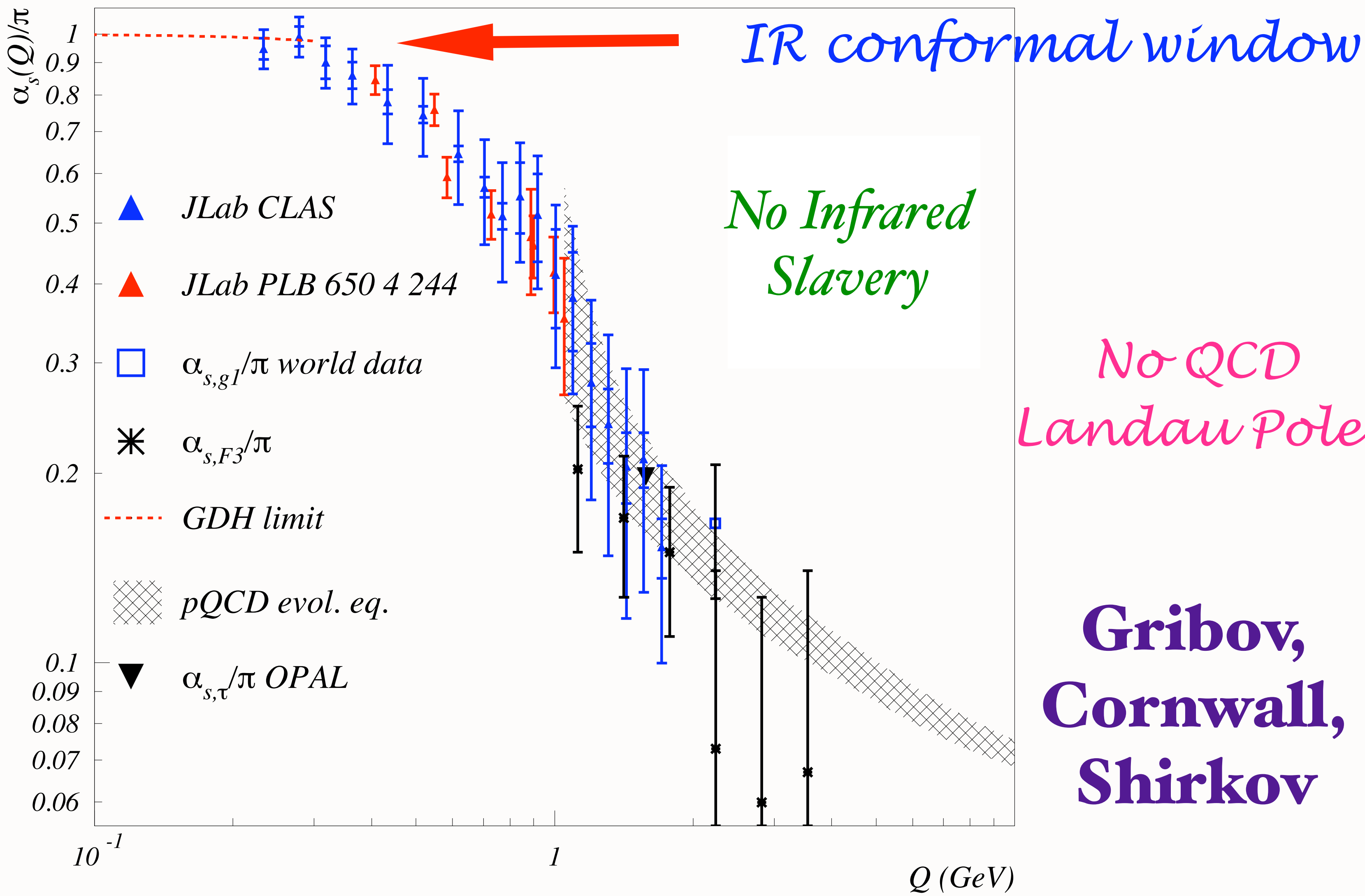


Gluon density 50 times more dense than cold nuclear matter !

Phase change within a single nucleus-nucleus collision

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

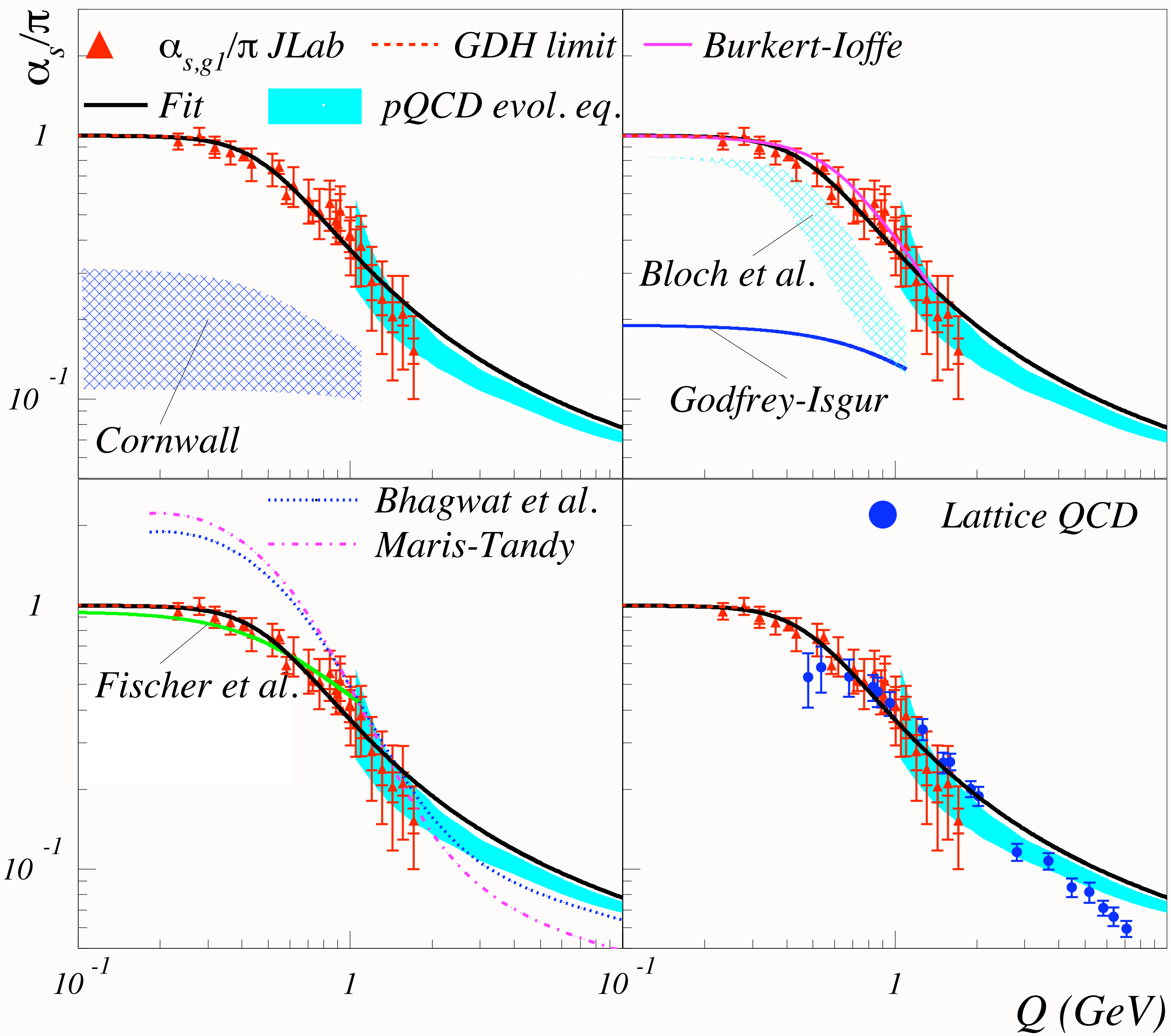
$$\Gamma_{bj}^{p-n}(Q^2) \equiv \frac{g_A}{6}[1 - \frac{\alpha_s^{g_1}(Q^2)}{\pi}]$$



No QCD Landau Pole!

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*

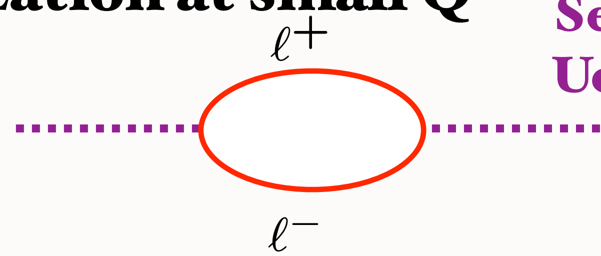
- Define coupling from observable: **indications of IR fixed point for QCD effective charges**

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

Shrock, de Teramond, sjb

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

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



Serber-Uehling

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

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.

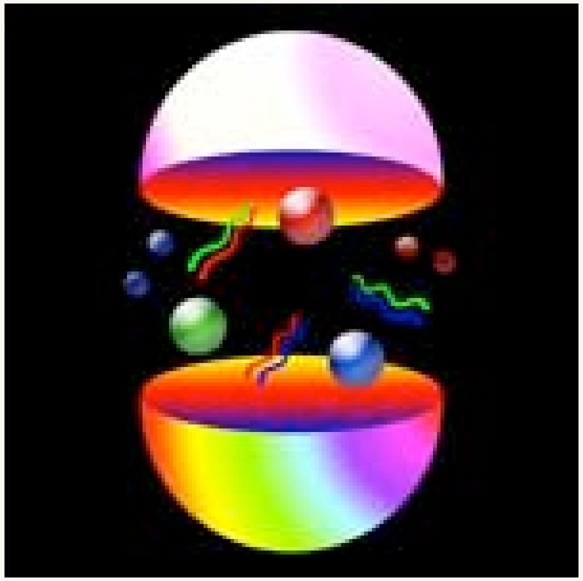
- Novel QCD Phenomena: hidden color, color transparency, strangeness asymmetry, intrinsic charm, anomalous heavy quark phenomena, anomalous spin effects, single-spin asymmetries, odderon, diffractive deep inelastic scattering, dangling gluons, shadowing, antishadowing, QGP, CGL, ...

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

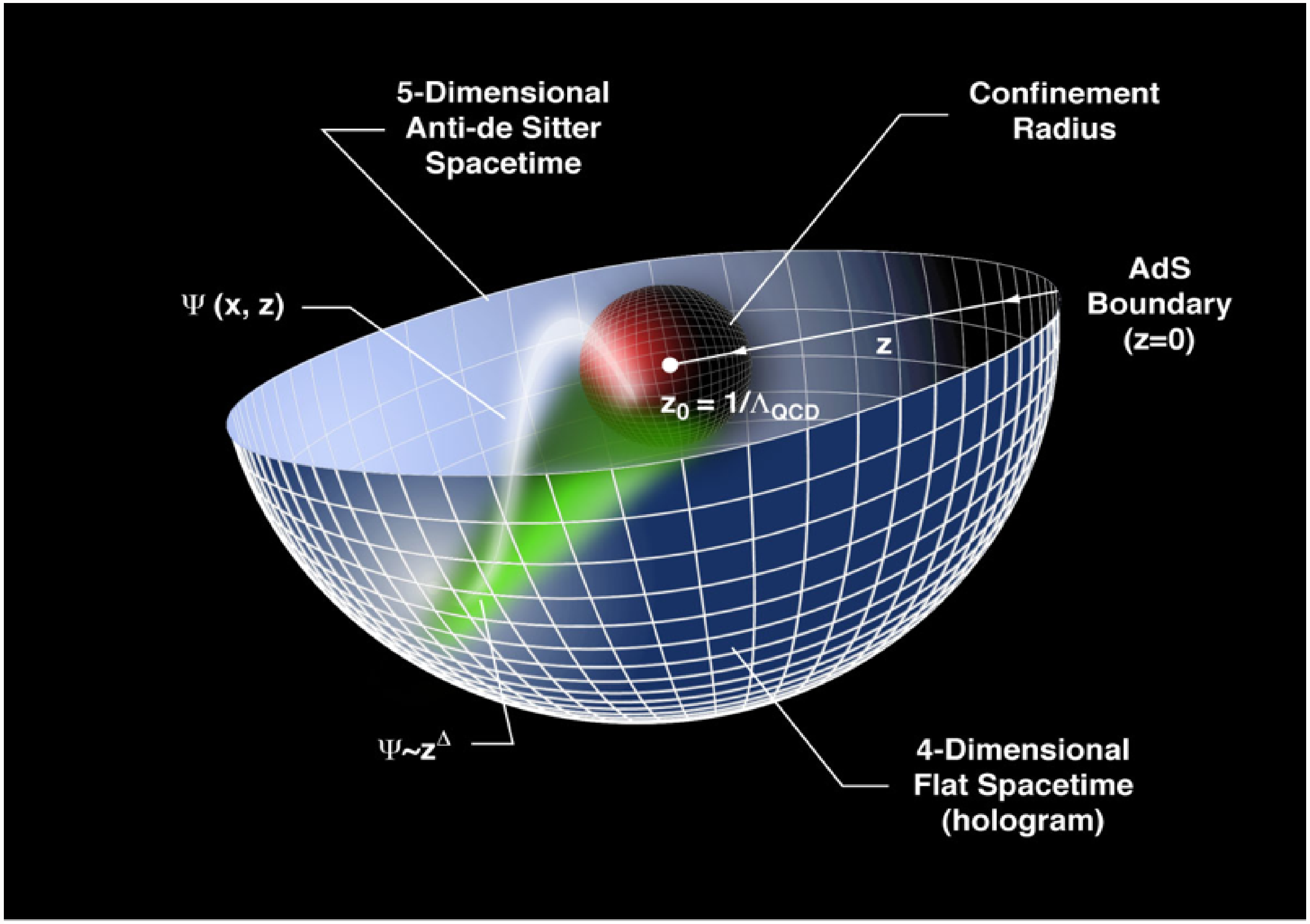
—Mark Twain

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



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:

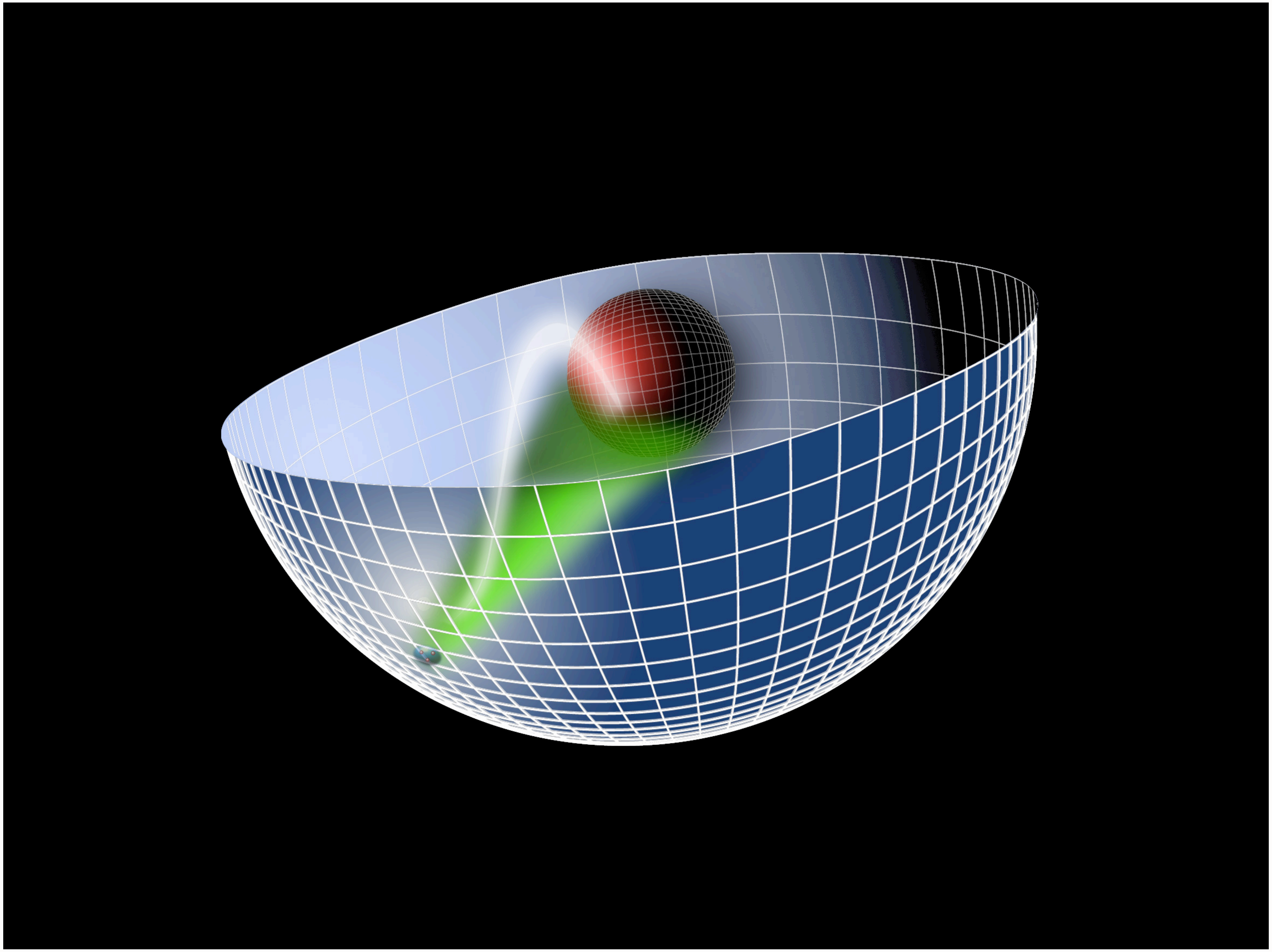
- **Use AdS/CFT to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances**

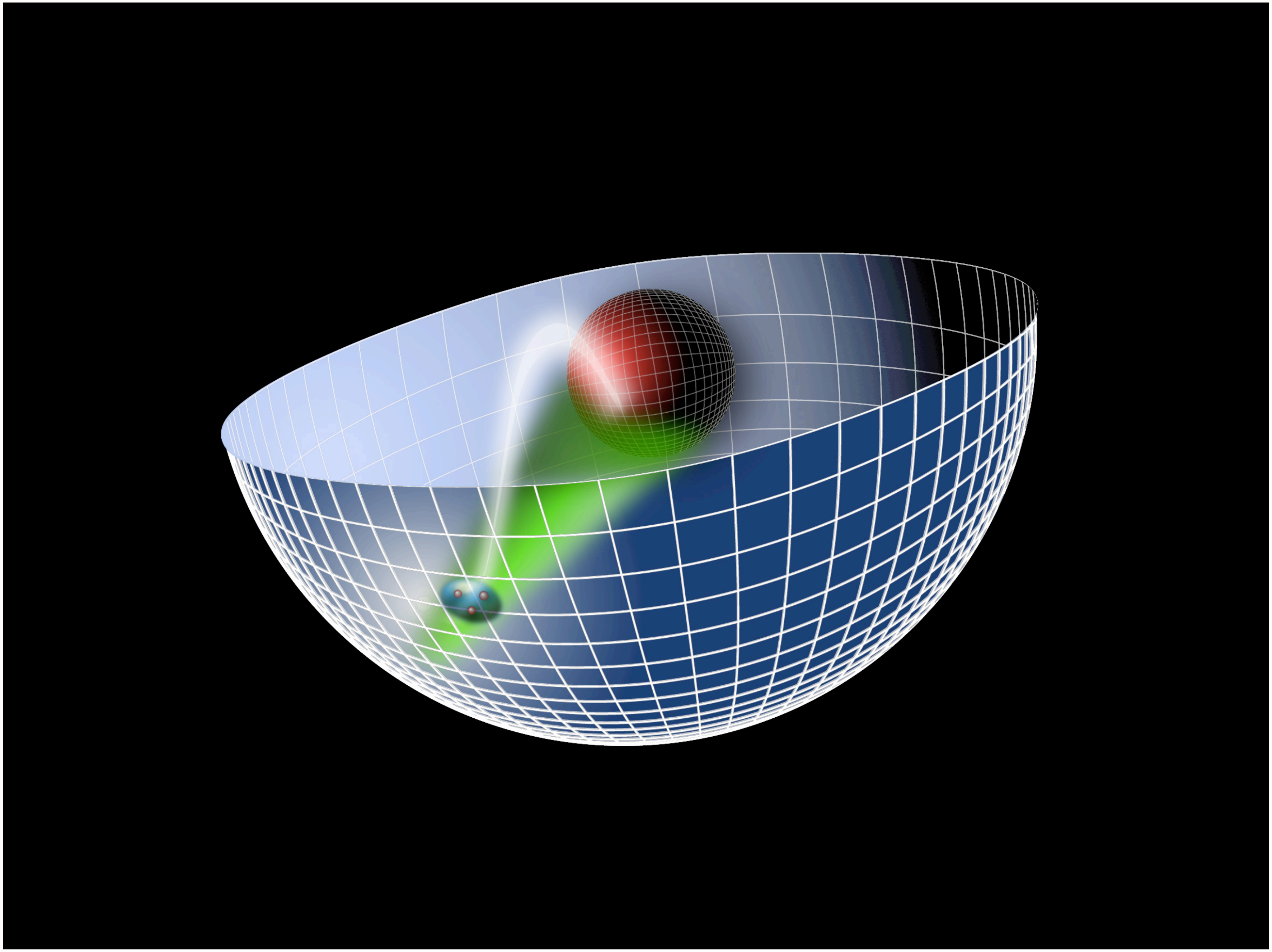
- **Analogous to the Schrodinger Theory for Atomic Physics**

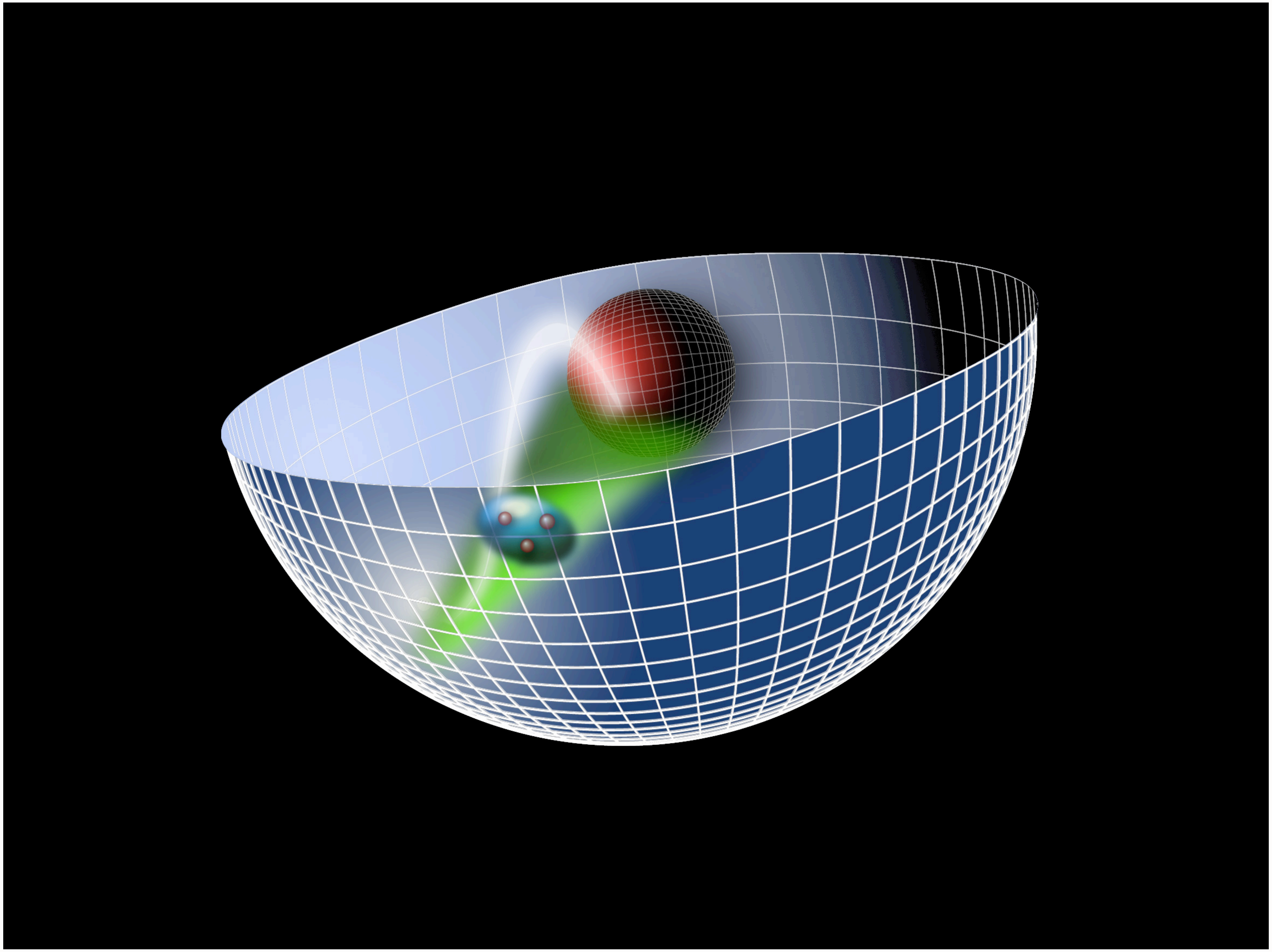
- *AdS/QCD Light-Front Holography*

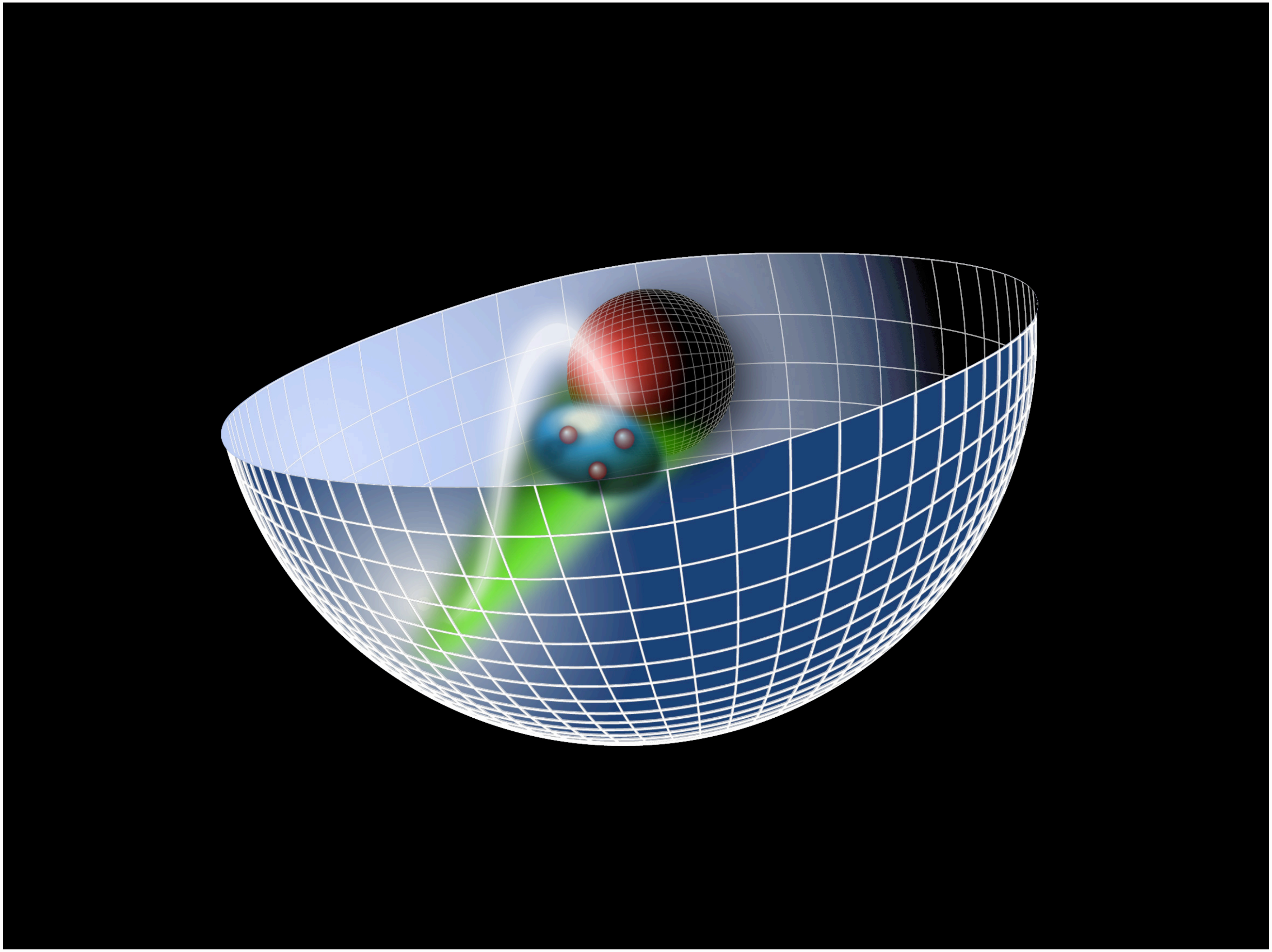
- *Hadronic Spectra and Light-Front Wavefunctions*

- *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

$x^\mu \rightarrow \lambda x^\mu, \; z \rightarrow \lambda z$, 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.

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

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

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

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

Maldacena:

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

- **QCD is not conformal**; however, it has manifestations of a scale-invariant theory: Bjorken scaling, dimensional counting for hard exclusive processes

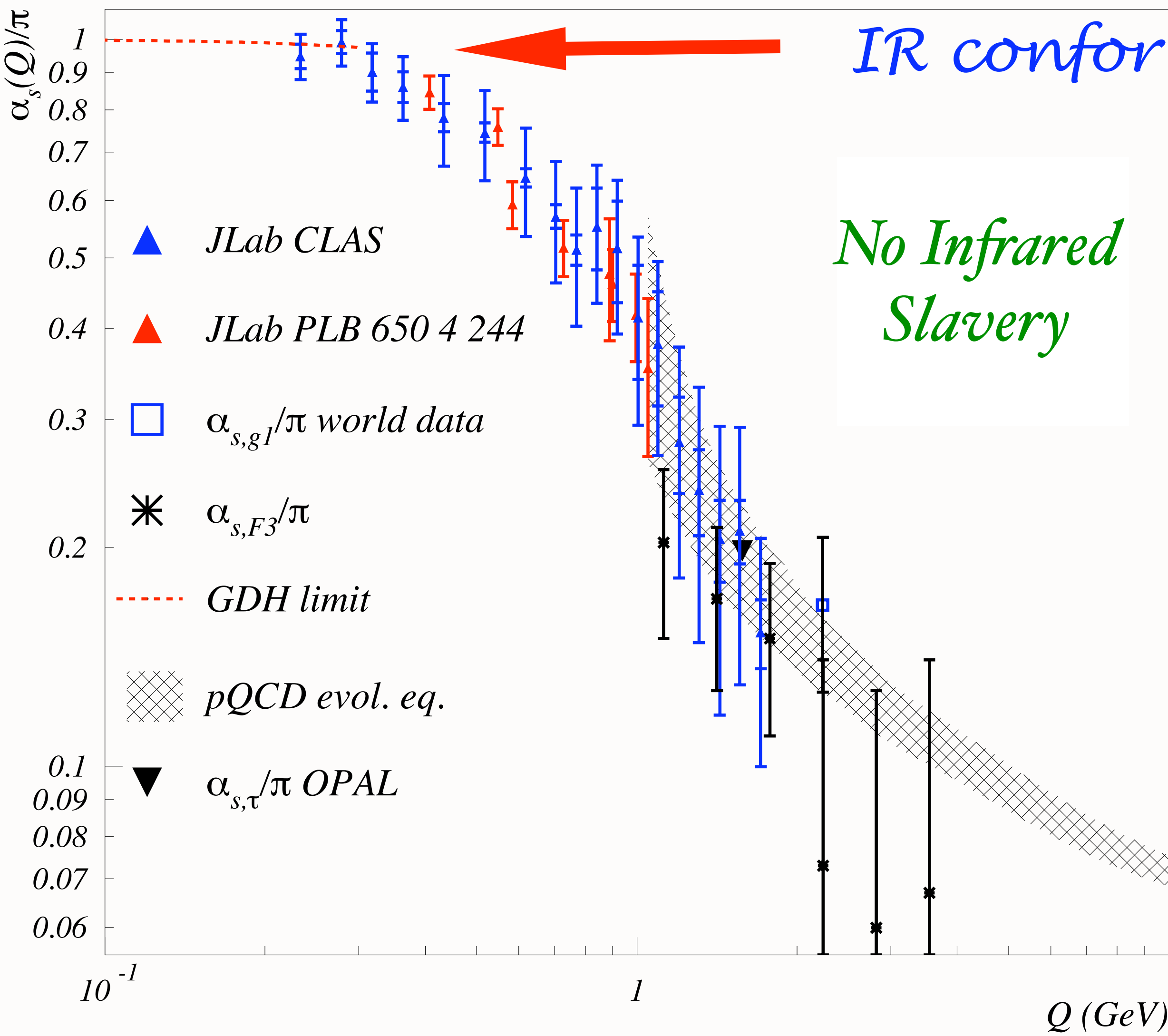
- **Conformal window in theIR:**

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

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

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

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



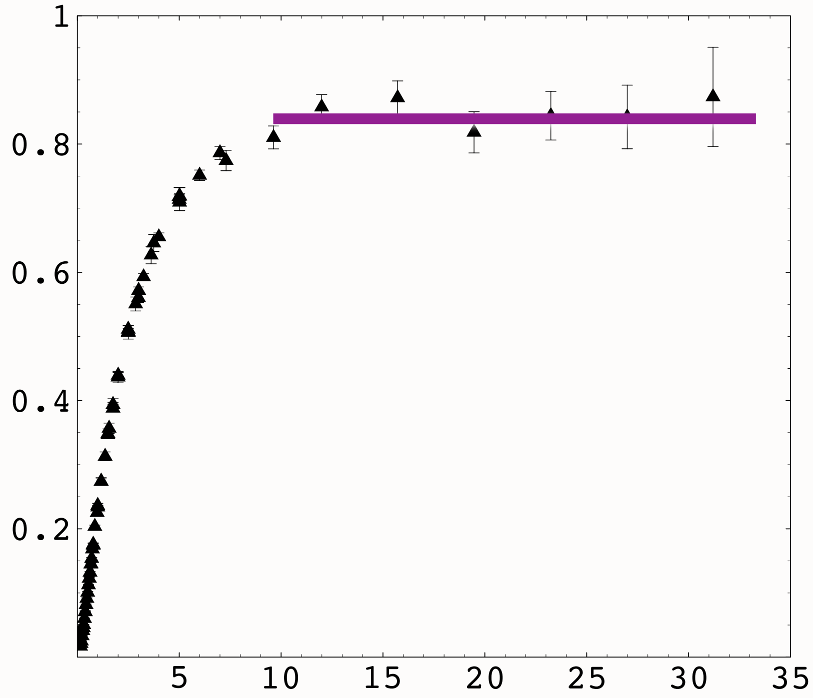
IR conformal window

No Infrared Slavery

No QCD Landau Pole!

Gribov, Cornwall, Shirkov

$Q^4 F_1^p(Q^2)$ [GeV^4]



Q^2 [GeV^2]

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

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).

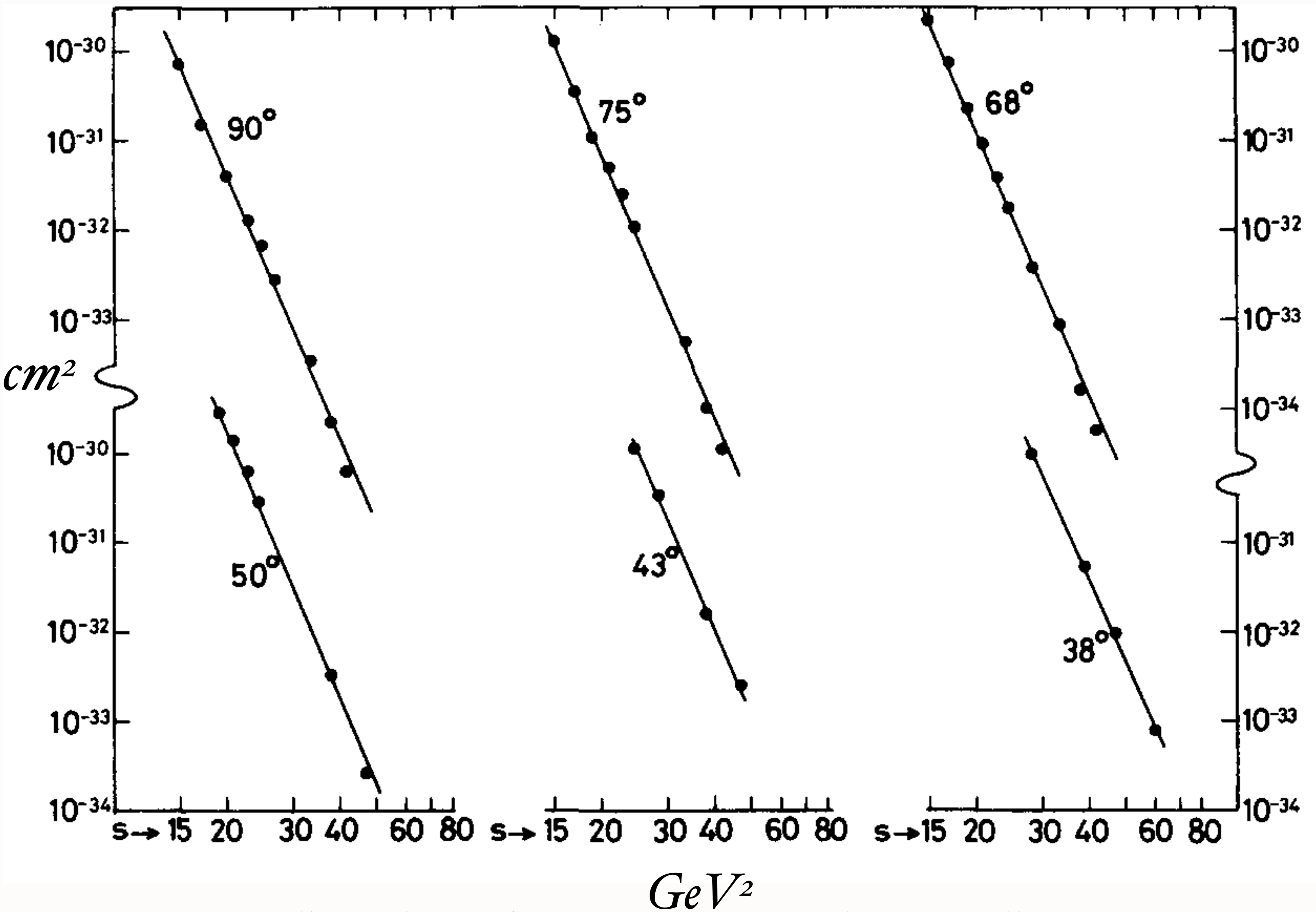
Brodsky and Farrar, Phys. Rev. Lett. 31 (1973) 1153
Matveev et al., Lett. Nuovo Cimento, 7 (1973) 719

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

P.V. LANDSHOFF and J.C. POLKINGHORNE

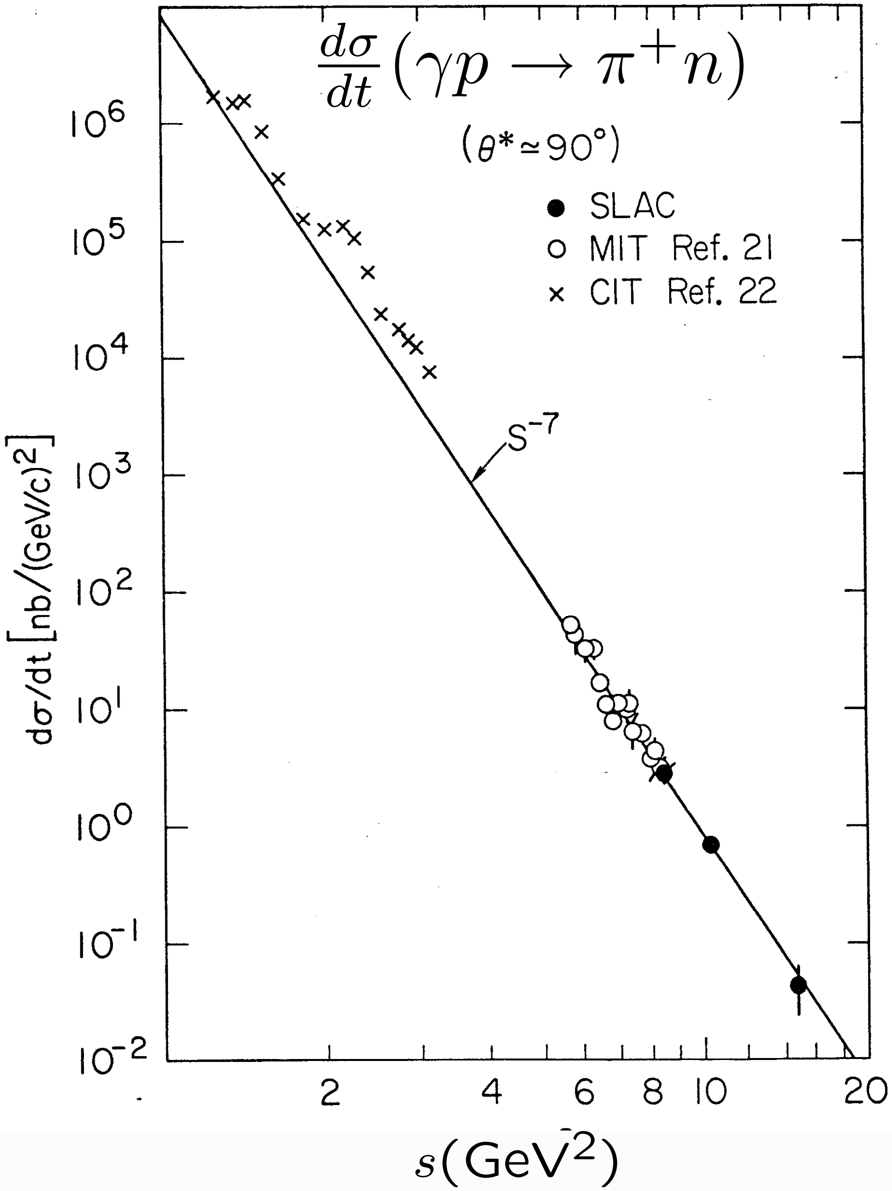


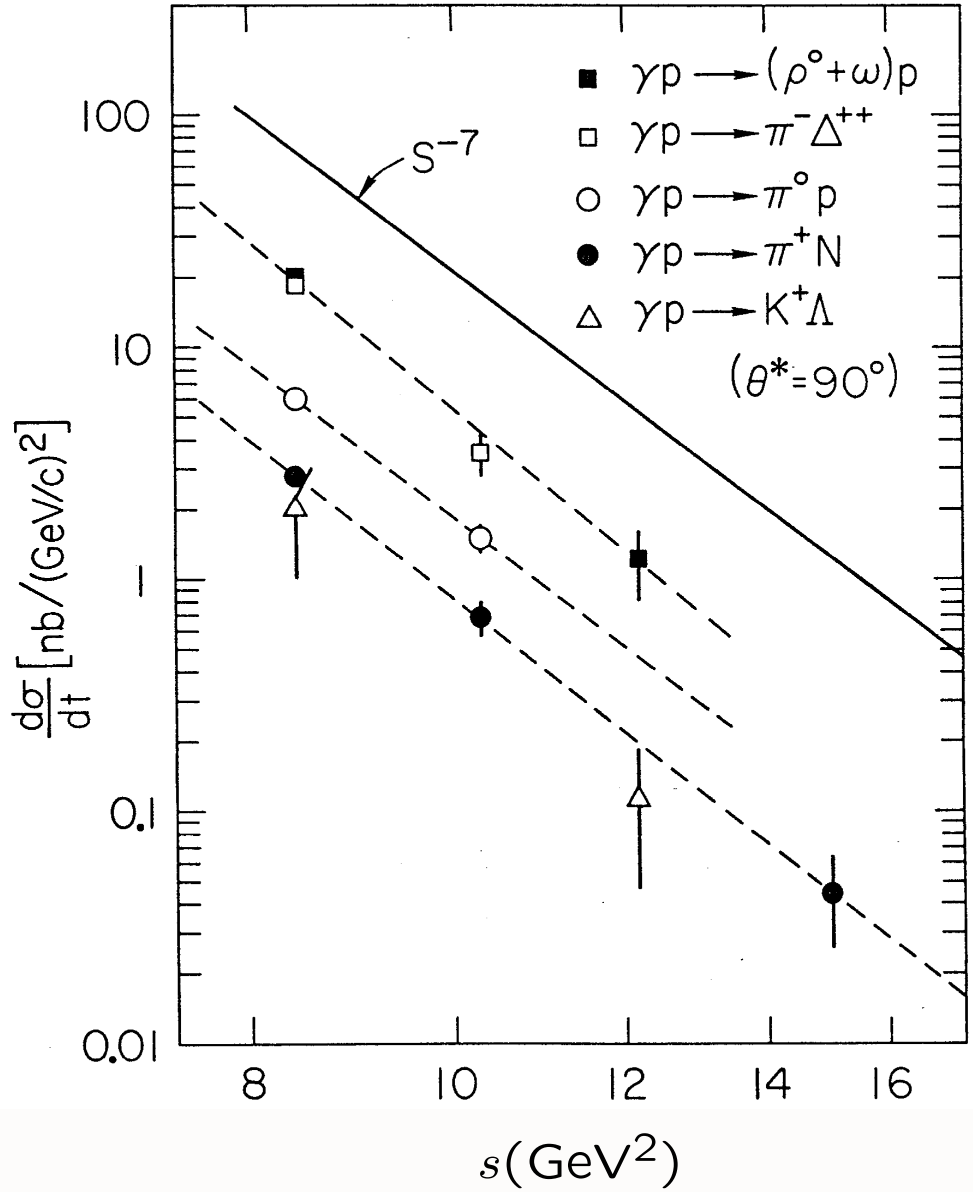
Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal scale-free interactions

Angular distribution -- quark interchange





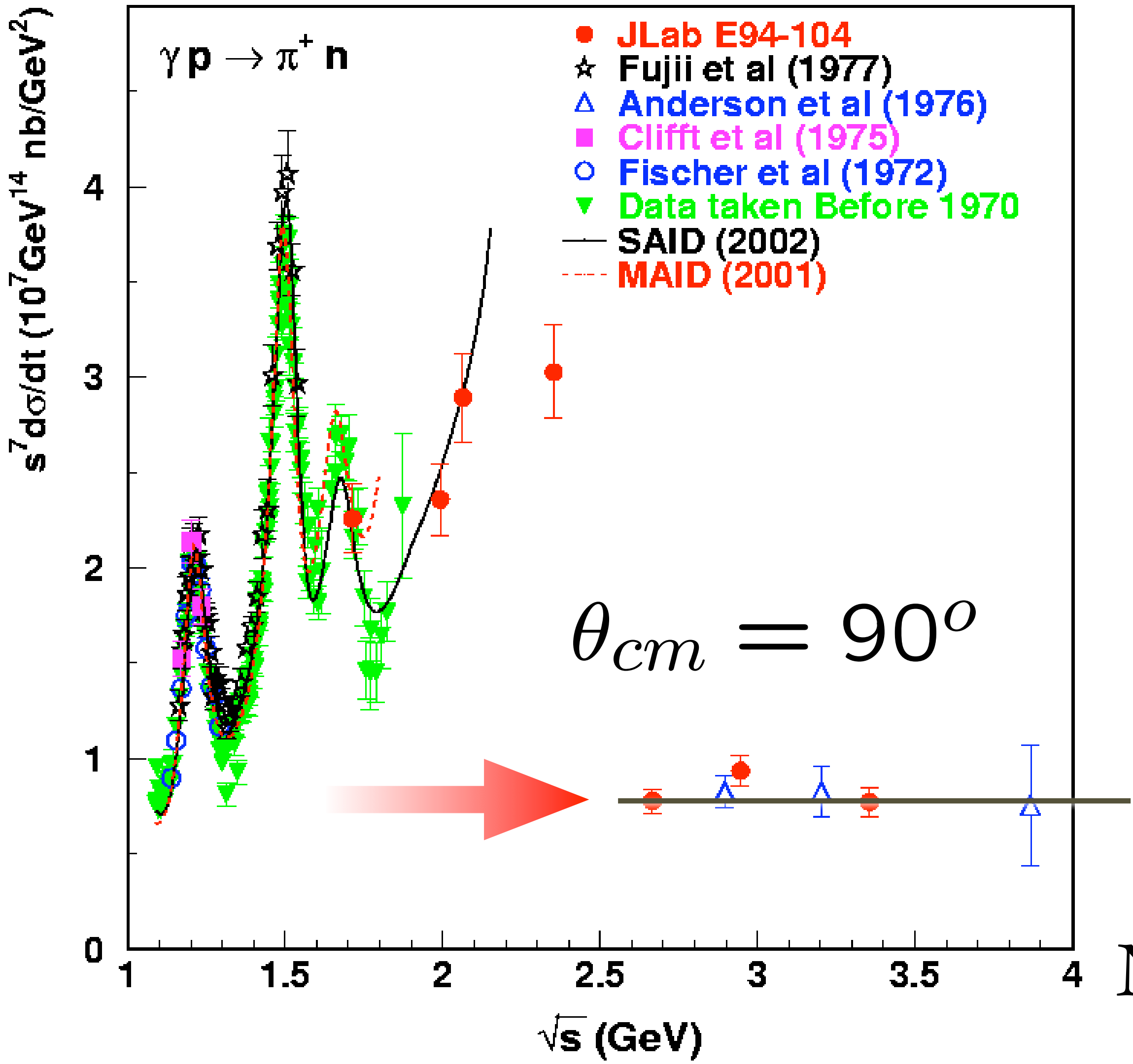
Conformal Invariance:

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

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:

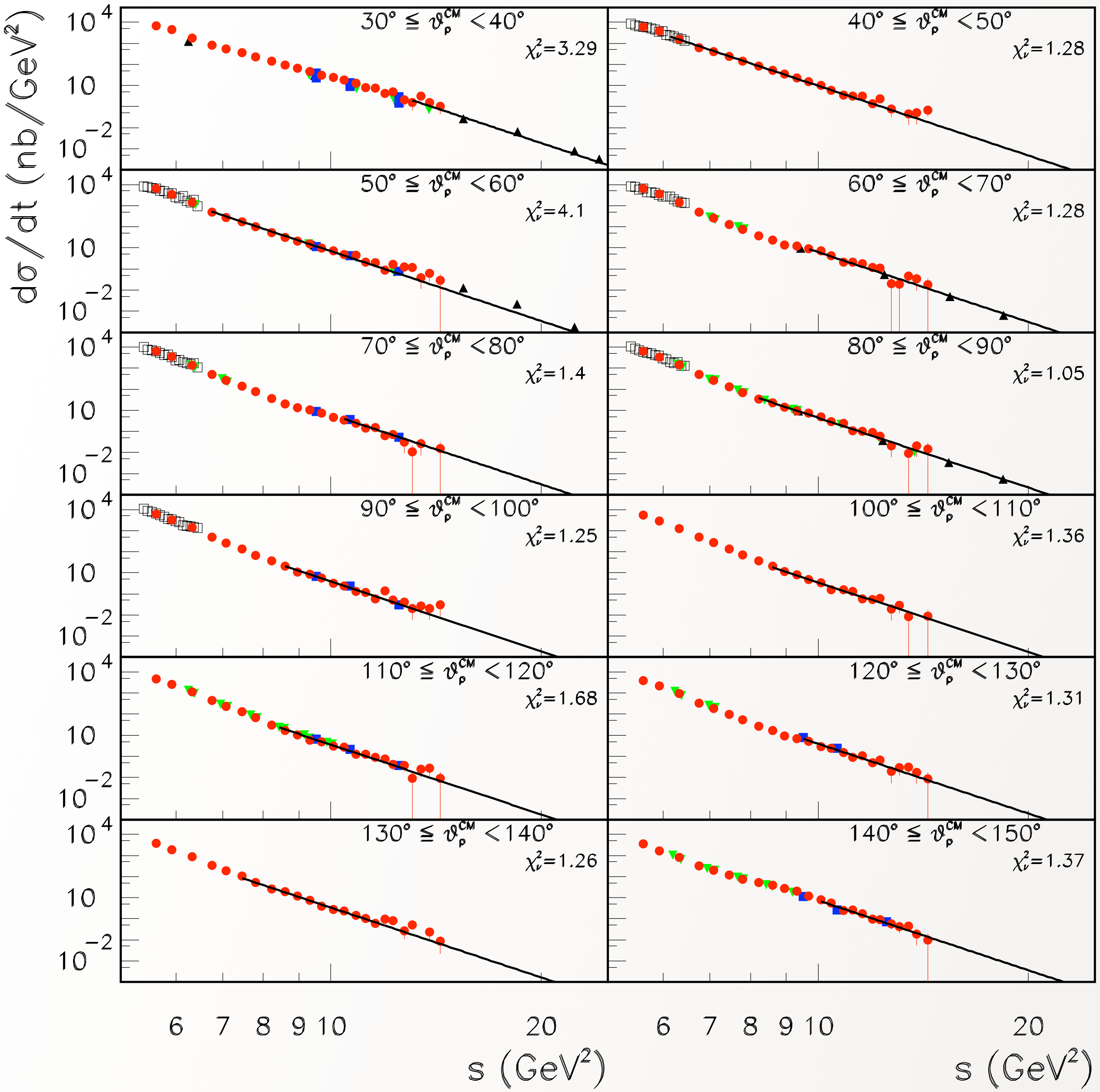
$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B \to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

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

No sign of running coupling

Conformal invariance

Deuteron Photodisintegration



J-Lab

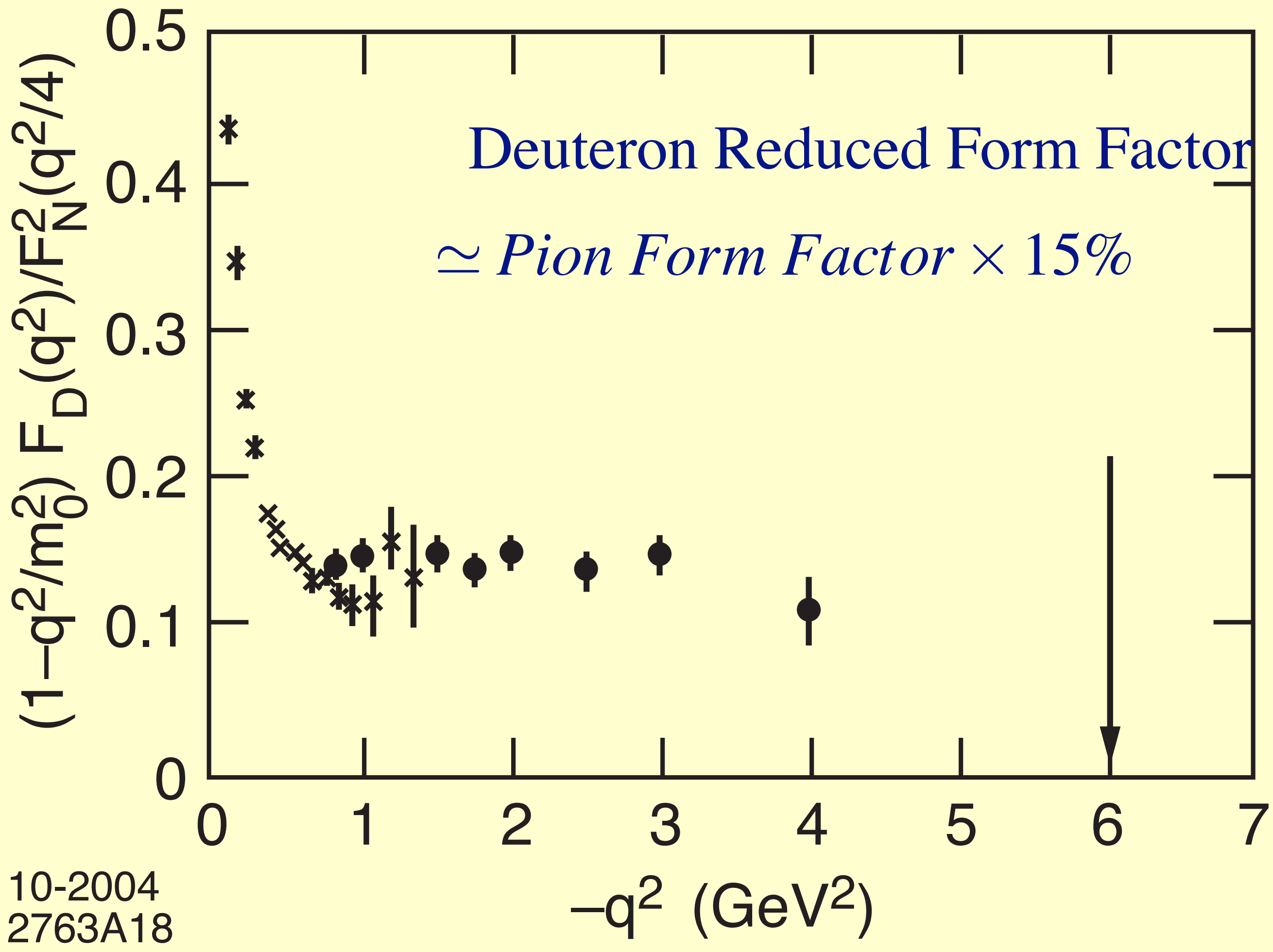
PQCD and AdS/CFT:

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

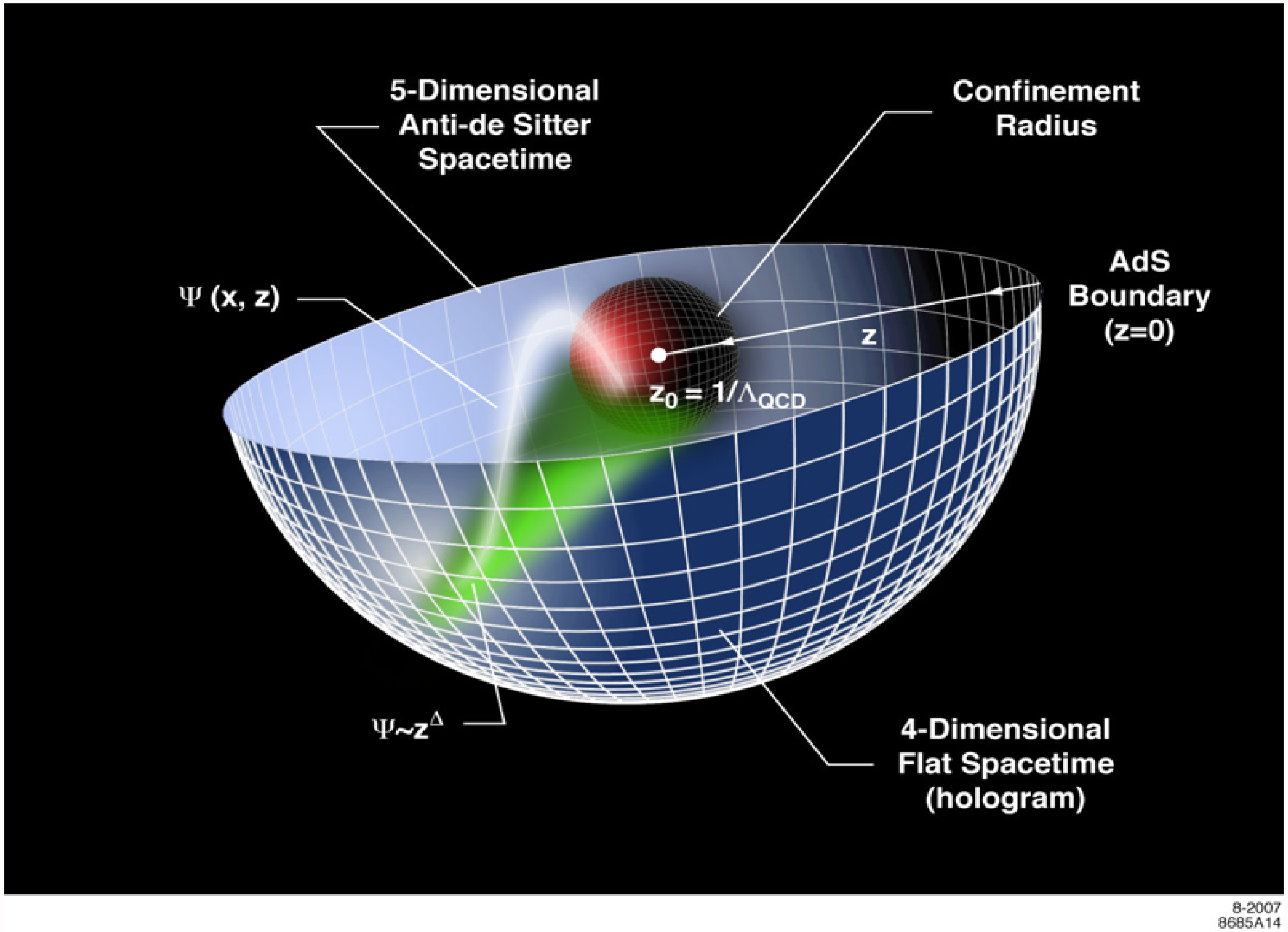
$$s^{11}\frac{d\sigma}{dt}(\gamma d\to np) = F(\theta_{CM})$$

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

Reflects conformal invariance



- 15% Hidden Color in the Deuteron



- 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

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

- Goal: Use AdS/CFT to provide an approximate model of hadron structure with confinement at large distances, conformal behavior at short distances

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

- Karch, Katz, Son, Stephanov: Linear Confinement

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

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

AdS/CFT

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

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

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

AdS Schrodinger Equation for bound state of two scalar constituents:

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

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

Interpret L as orbital angular momentum

Derived from variation of Action in AdS_5

Hard wall model: truncated space

$$\phi(z = z_0 = \frac{1}{\Lambda_c}) = 0.$$

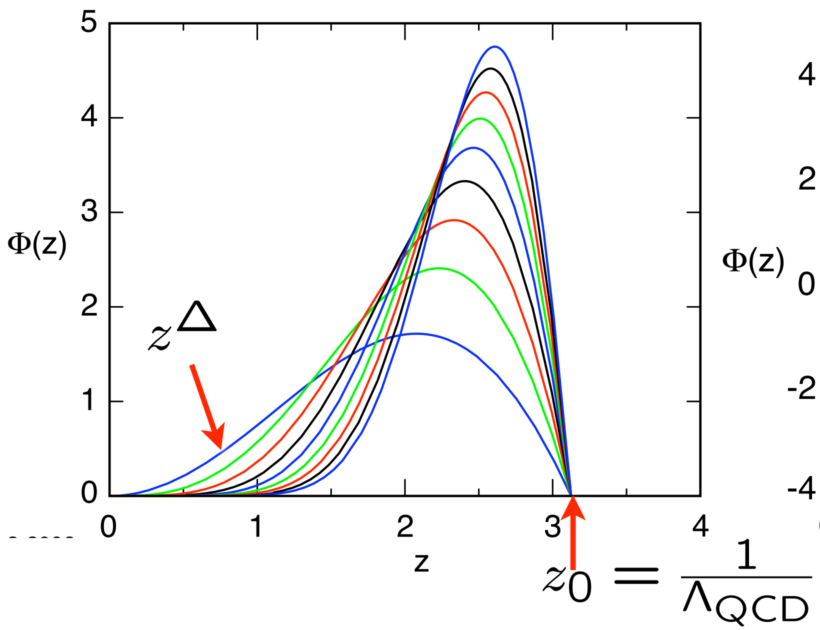
Match fall-off at small z to conformal twist-dimension at short distances

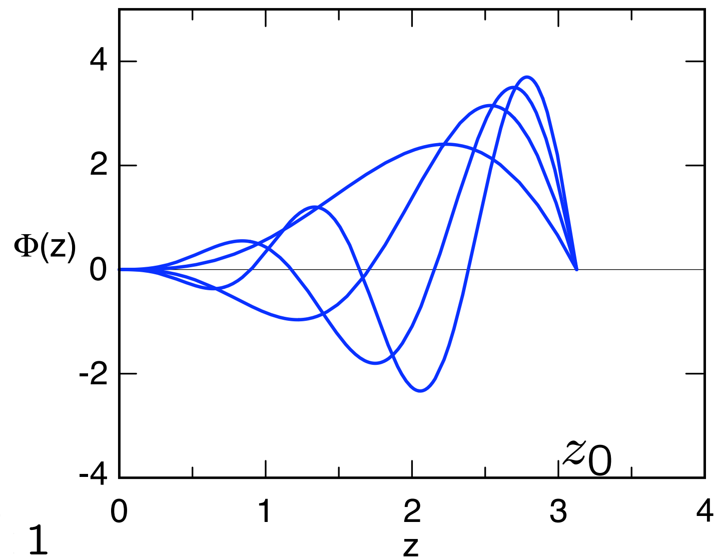
twist

- Pseudoscalar mesons: $\mathcal{O}_{2+L} = \overline{\psi}\gamma_5 D_{\{\ell_1} \dots D_{\ell_m\}}\psi$ ($\Phi_\mu = 0$ gauge). $\Delta = 2 + L$

- 4-d mass spectrum from boundary conditions on the normalizable string modes at $z = z_0$, $\Phi(x, z_o) = 0$, given by the zeros of Bessel functions $\beta_{\alpha,k}$: $\mathcal{M}_{\alpha,k} = \beta_{\alpha,k}\Lambda_{QCD}$

- Normalizable AdS modes $\Phi(z)$





$S = 0$ Meson orbital and radial AdS modes for $\Lambda_{QCD} = 0.32$ GeV.

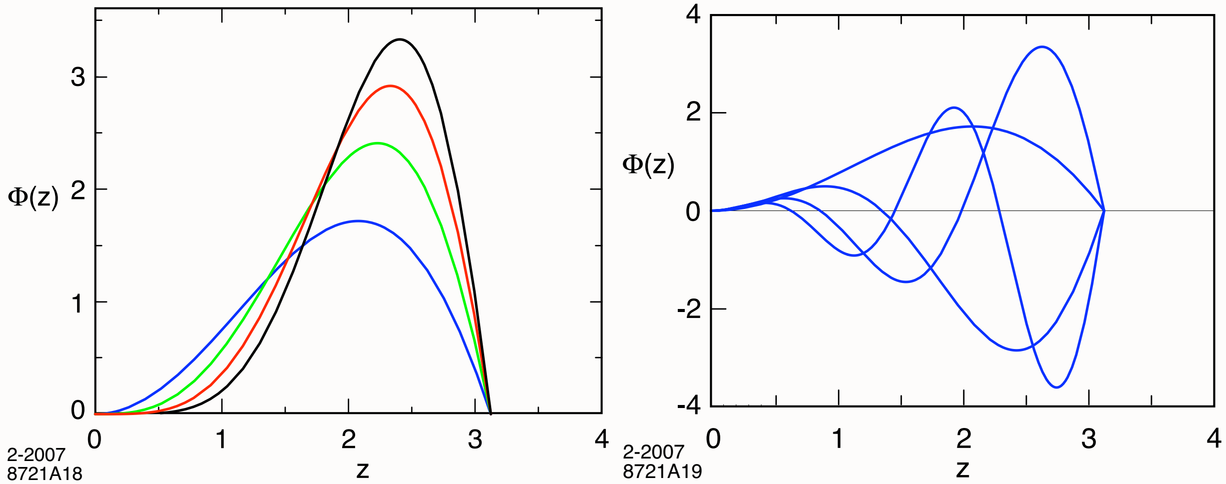


Fig: Orbital and radial AdS modes in the hard wall model for $\Lambda_{\rm QCD}$ = 0.32 GeV .

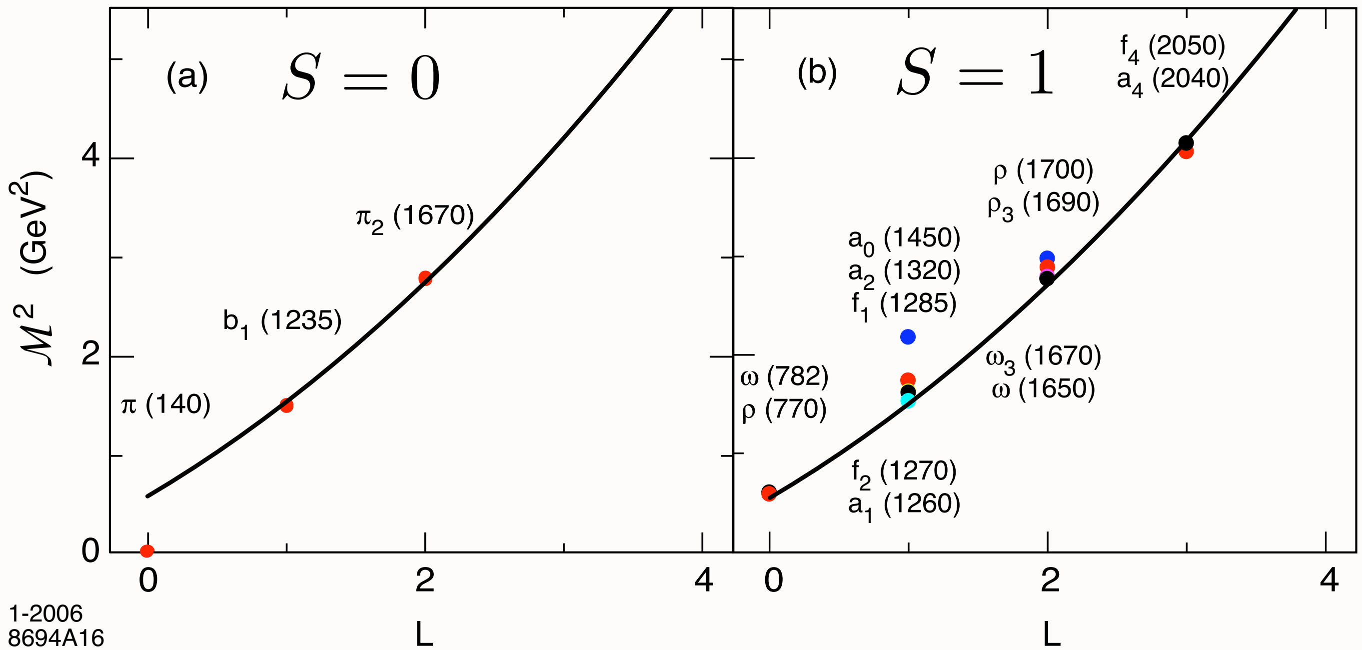


Fig: Light meson and vector meson orbital spectrum $\Lambda_{QCD} = 0.32$ GeV

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

AdS Schrodinger Equation for bound state of two scalar constituents:

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

Hard wall model: truncated space

$$V(z) = -\frac{1-4L^2}{4z^2} \qquad \phi(z = z_0 = 1/\Lambda_0) = 0$$

Soft wall model: Harmonic oscillator confinement

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

Derived from variation of Action in AdS_5

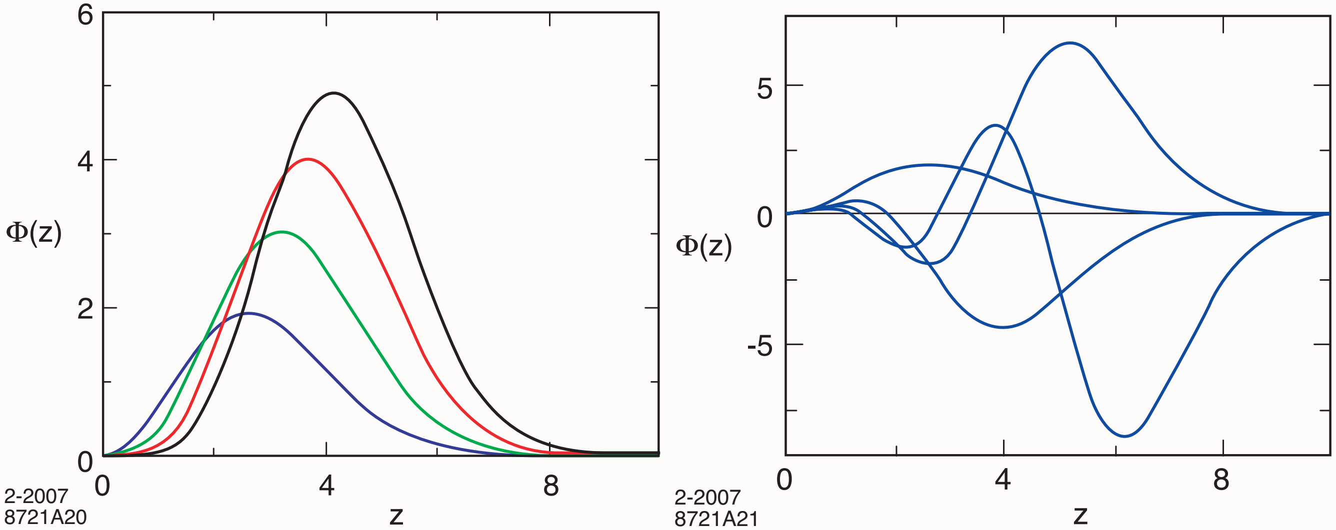
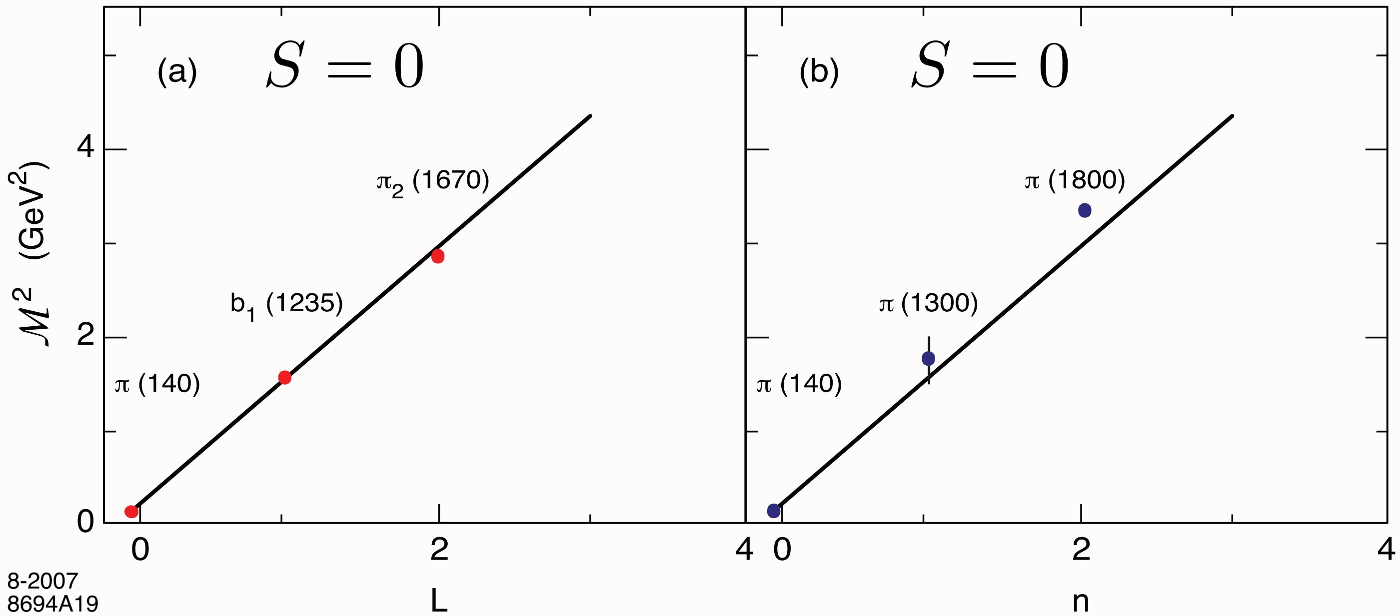


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .



Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

Soft-wall model

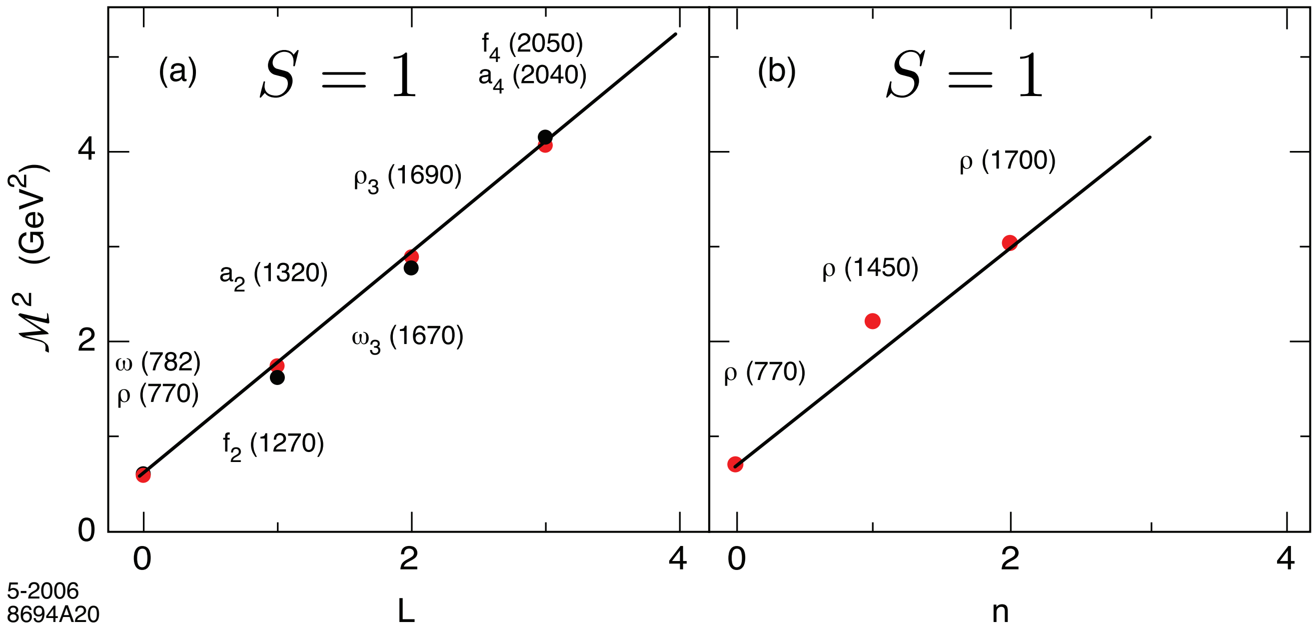
- Effective LF Schrödinger wave equation

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

with eigenvalues $\mathcal{M}^2 = 2\kappa^2(2n + 2L + S)$.

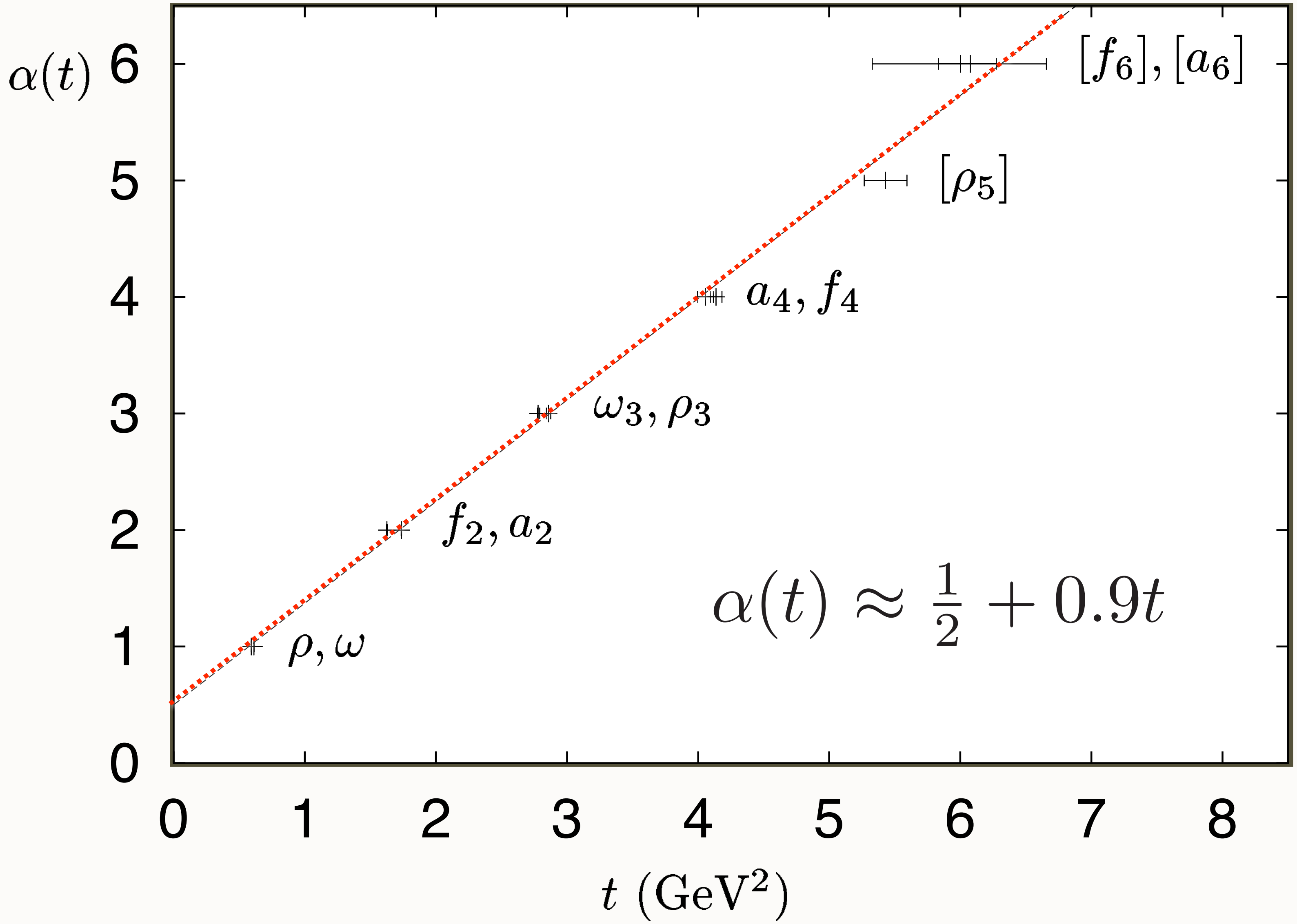
Same slope in n and L

- Compare with Nambu string result (rotating flux tube): $M_n^2(L) = 2\pi\sigma\,(n + L + 1/2)$.



Vector mesons orbital (a) and radial (b) spectrum for $\kappa = 0.54$ GeV.

- Glueballs in the bottom-up approach: (HW) Boschi-Filho, Braga and Carrion (2005); (SW) Colangelo, De Facio, Jugeau and Nicotri(2007).



AdS/QCD Soft Wall Model -- Reproduces Linear Regge Trajectories

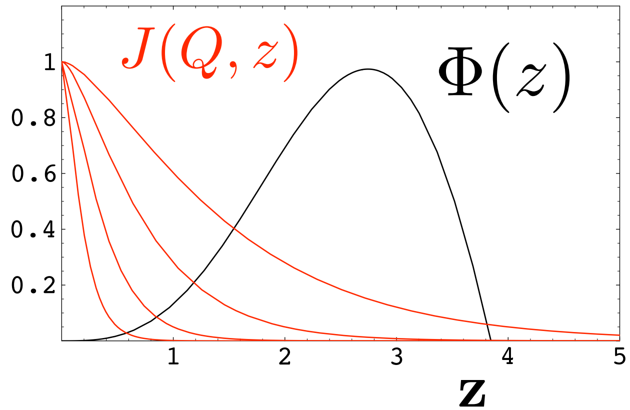
Hadron Form Factors from AdS/CFT

Propagation of external perturbation suppressed inside AdS.

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

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

High Q²
from
small z ~ 1/Q



Polchinski, Strassler
de Teramond, sjb
Andreev

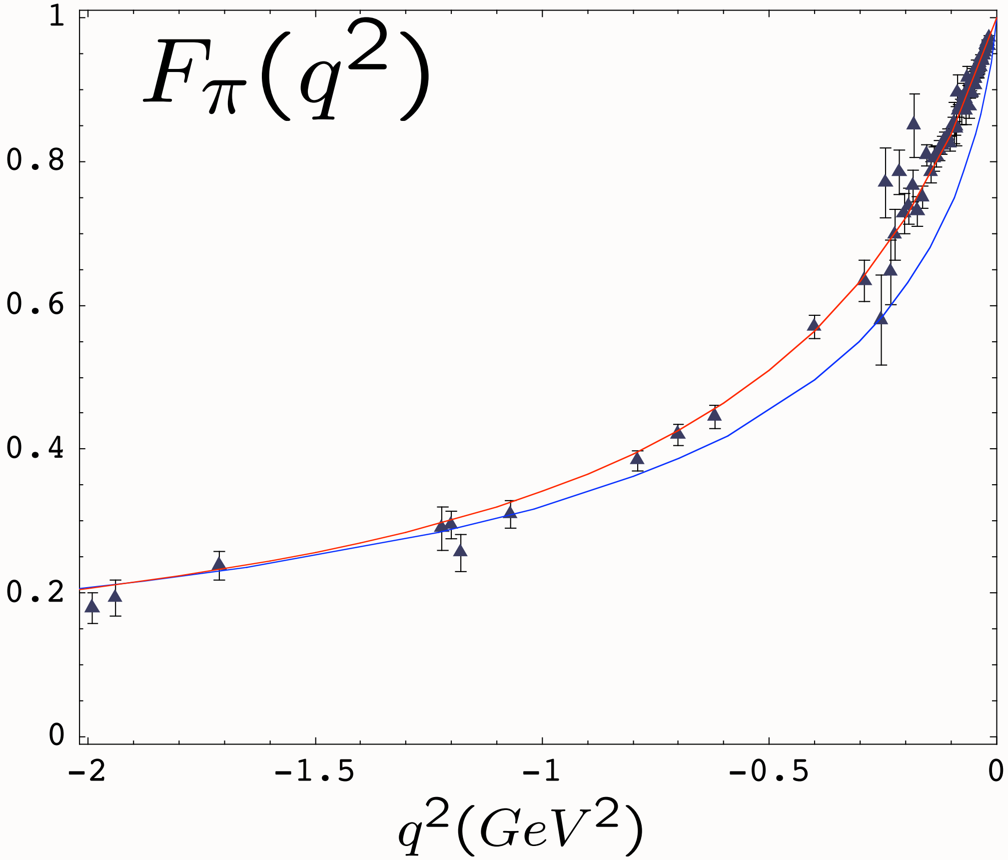
Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, Φ
scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

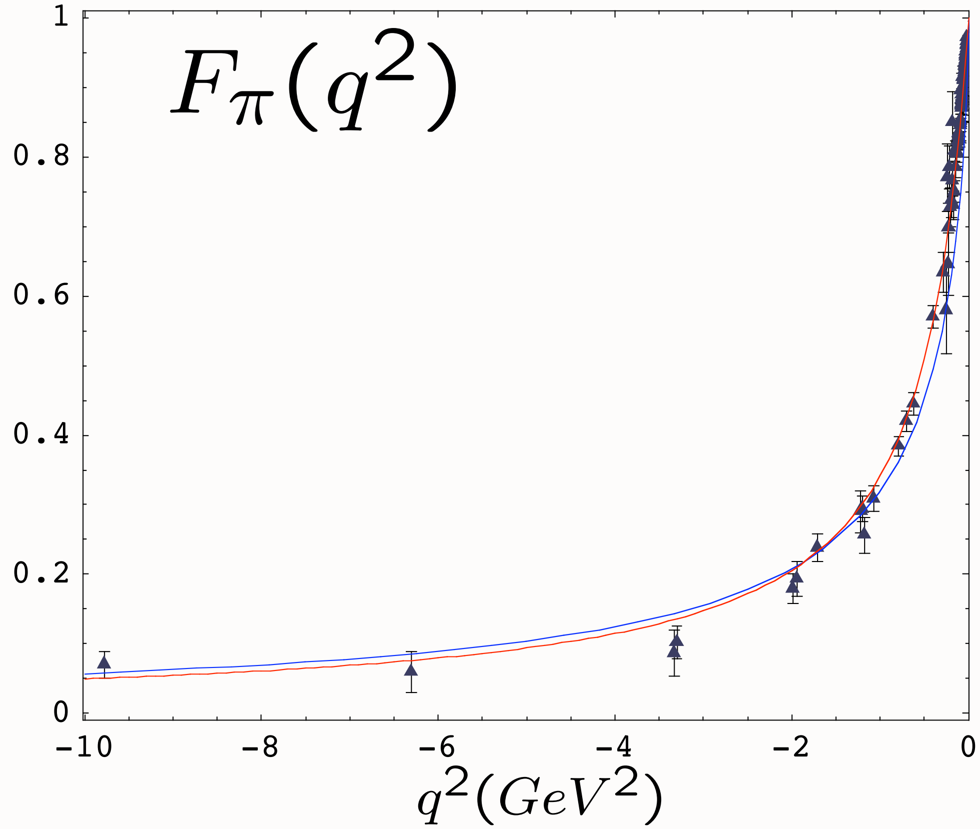
$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1},$$

Dimensional Quark Counting Rule
General result from AdS/CFT

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

Spacelike pion form factor from AdS/CFT





Data Compilation from Baldini, Kloe and Volmer

SW: Harmonic Oscillator Confinement

HW: Truncated Space Confinement

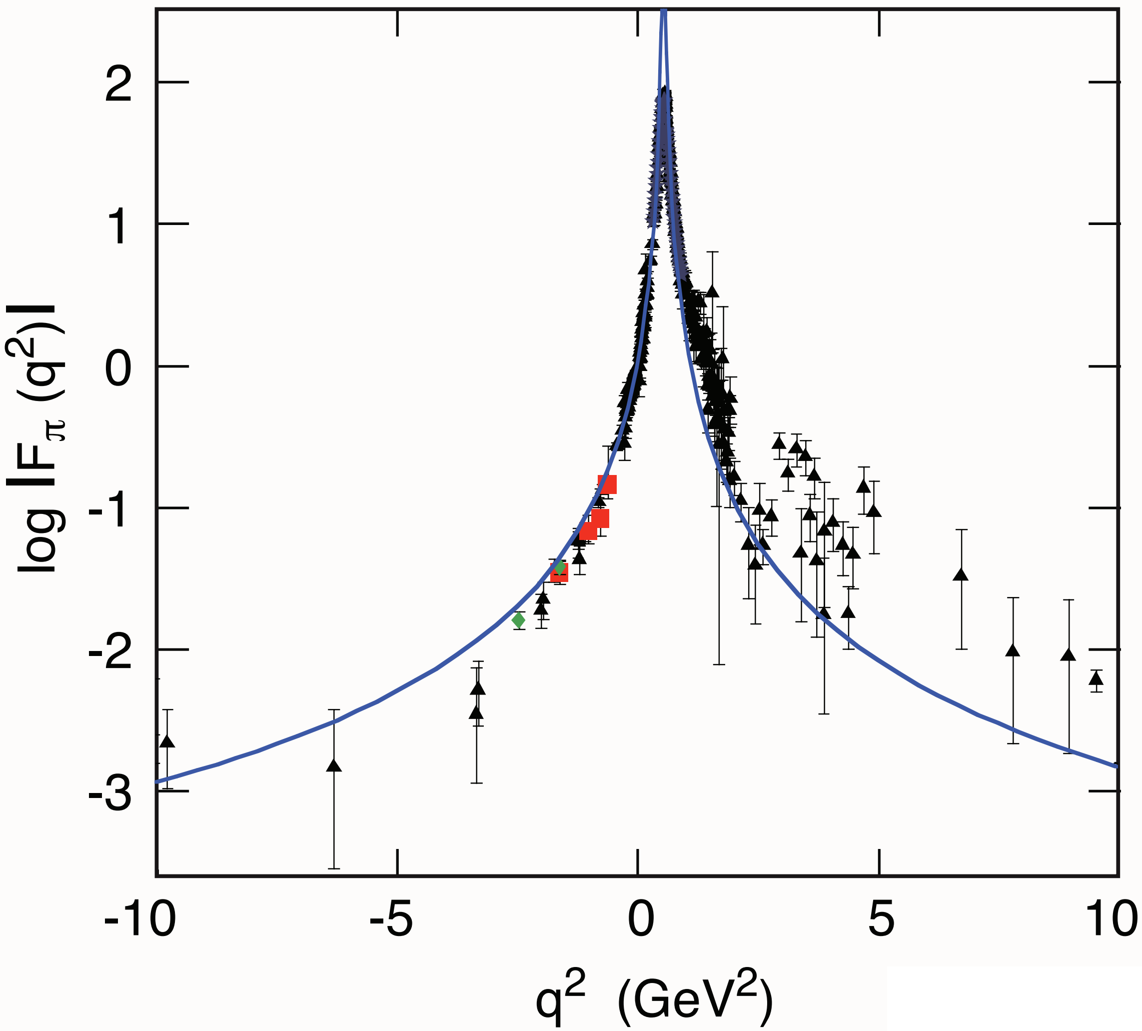
One parameter - set by pion decay constant

de Teramond, sjb

- Analytical continuation to time-like region $q^2 \to -q^2$

$$M_\rho = 2\kappa = 750 \text{ MeV}$$

- Strongly coupled semiclassical gauge/gravity limit hadrons have zero widths (stable).



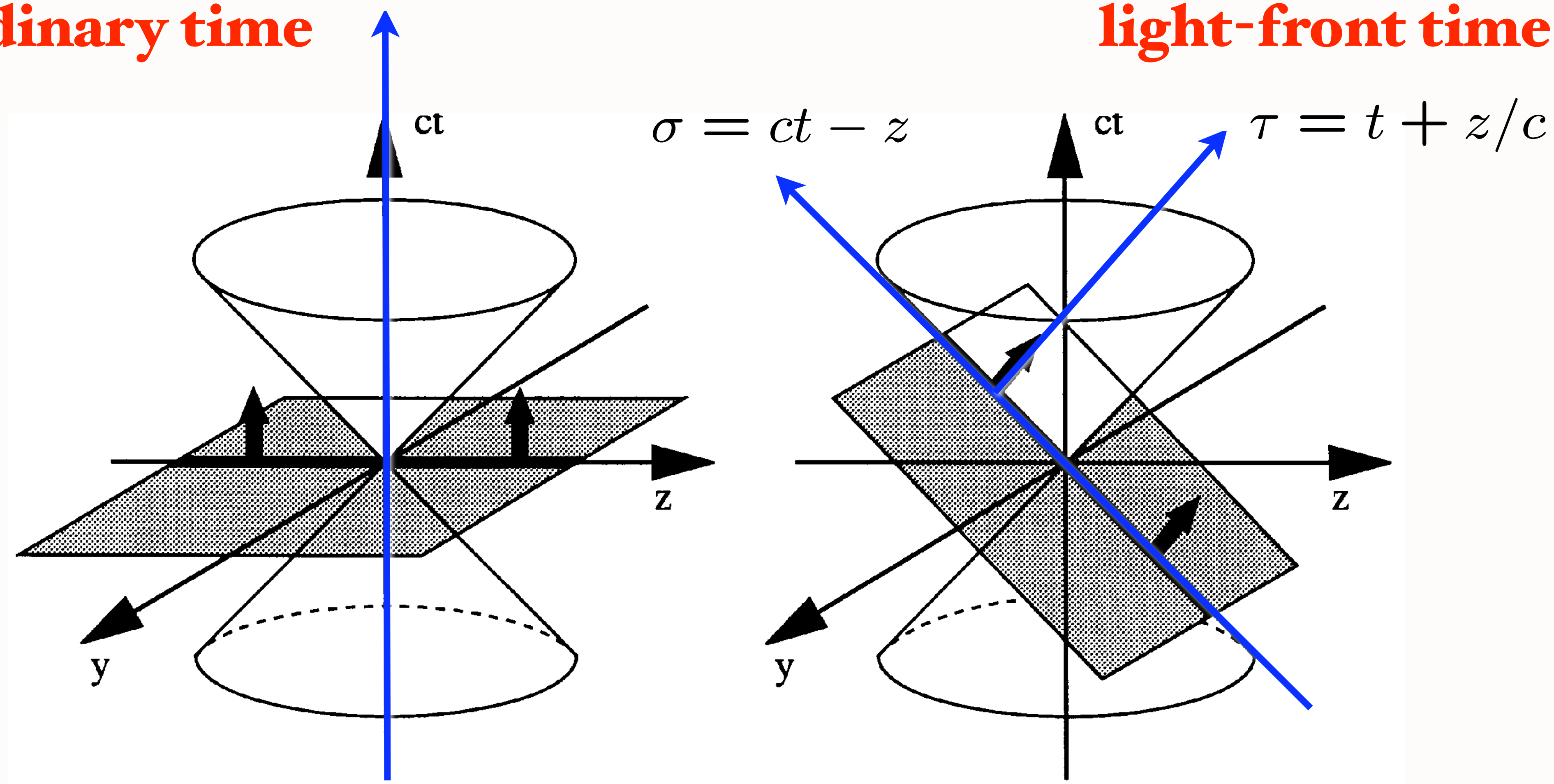
Space and time-like pion form factor for $\kappa = 0.375$ GeV in the SW model.

- Vector Mesons: Hong, Yoon and Strassler (2004); Grigoryan and Radyushkin (2007).

Dirac's Amazing Idea: The Front Form

Evolve in ordinary time

Evolve in light-front time!



Instant Form **Front Form**

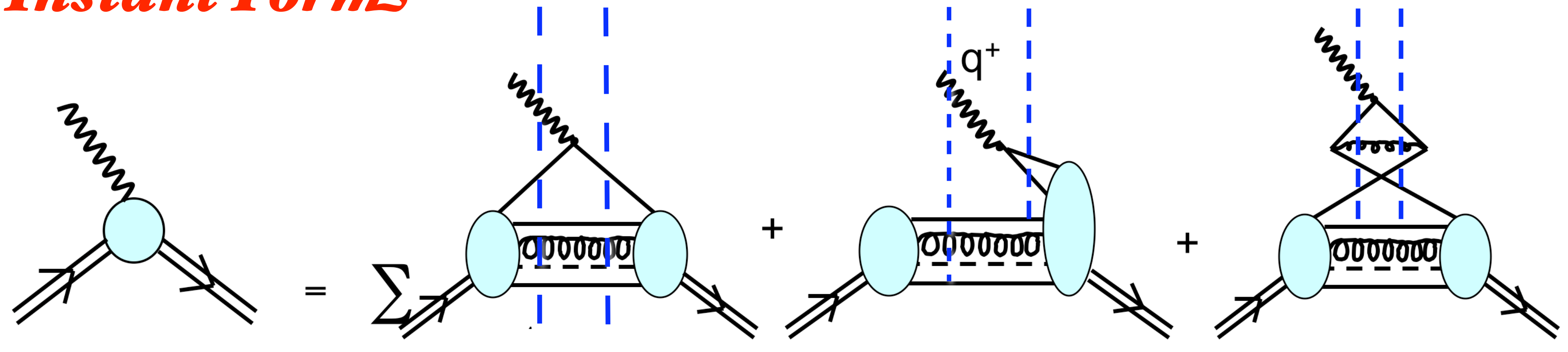
Each element of
flash photograph
illuminated
at same LF time

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

HELEN BRADLEY - PHOTOGRAPHY

Calculation of Form Factors in Equal-Time Theory

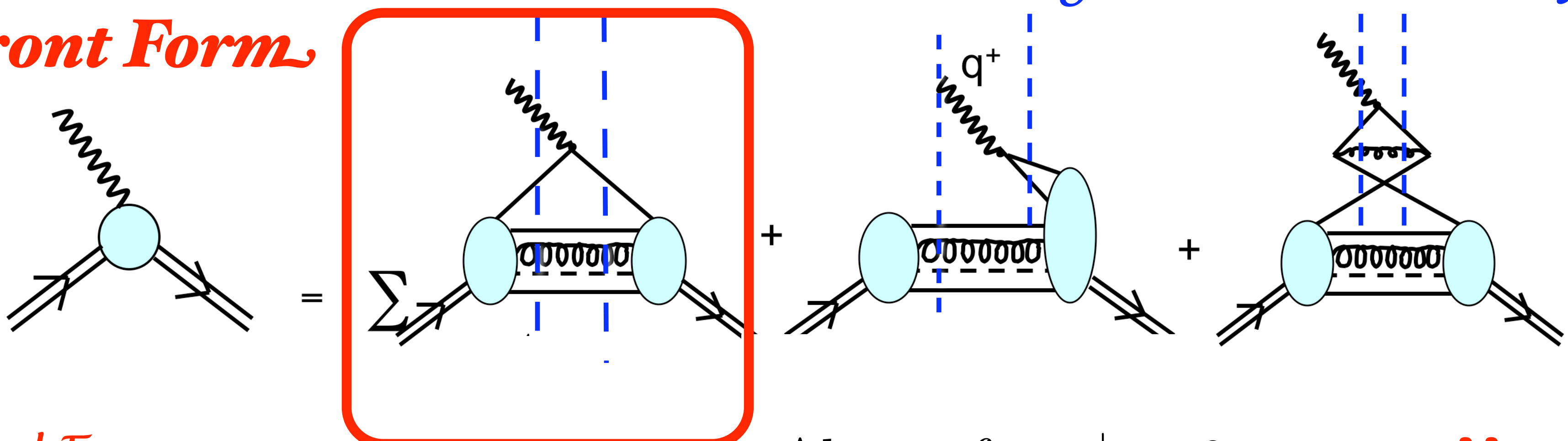
Instant Form



Need vacuum-induced currents

Calculation of Form Factors in Light-Front Theory

Front Form

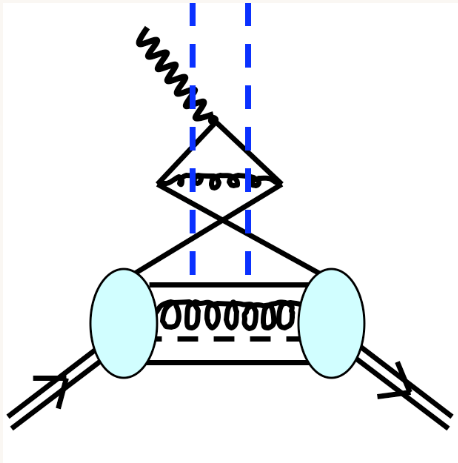


Simple LF vacuum

Absent for $q^+ = 0$ **zero !!**

Calculation of Hadron Form Factors in Instant Form

- Current matrix elements of hadron include interactions with vacuum-induced currents arising from infinitely-complex vacuum



- Pair creation from vacuum occurs at any time before probe acts -- acausal

- Knowledge of hadron wavefunction insufficient to compute current matrix elements

- Requires dynamical boost of hadron wavefunction -- unknown except at weak binding

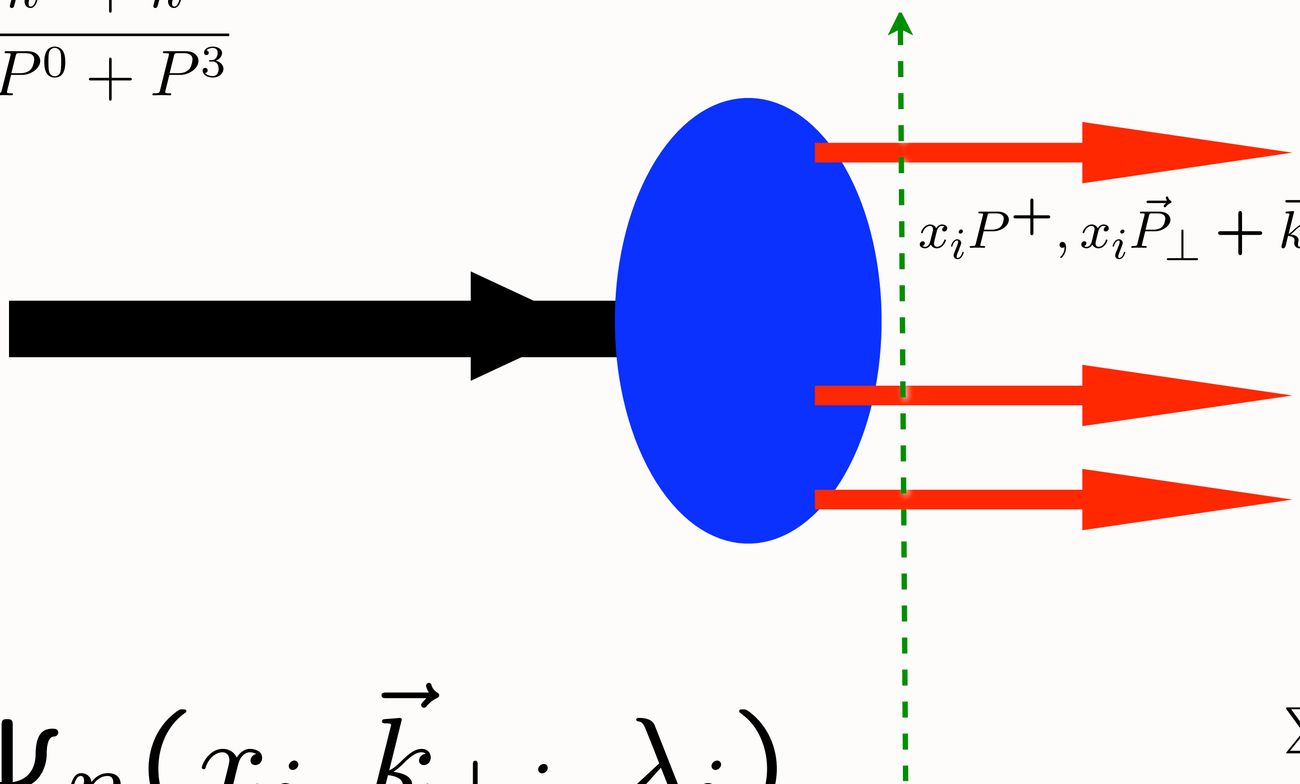
- Complex vacuum even for QED

- None of these complications occur for quantization at fixed LF time (front form)

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

Fixed $\tau = t + z/c$

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



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Angular Momentum on the Light-Front

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

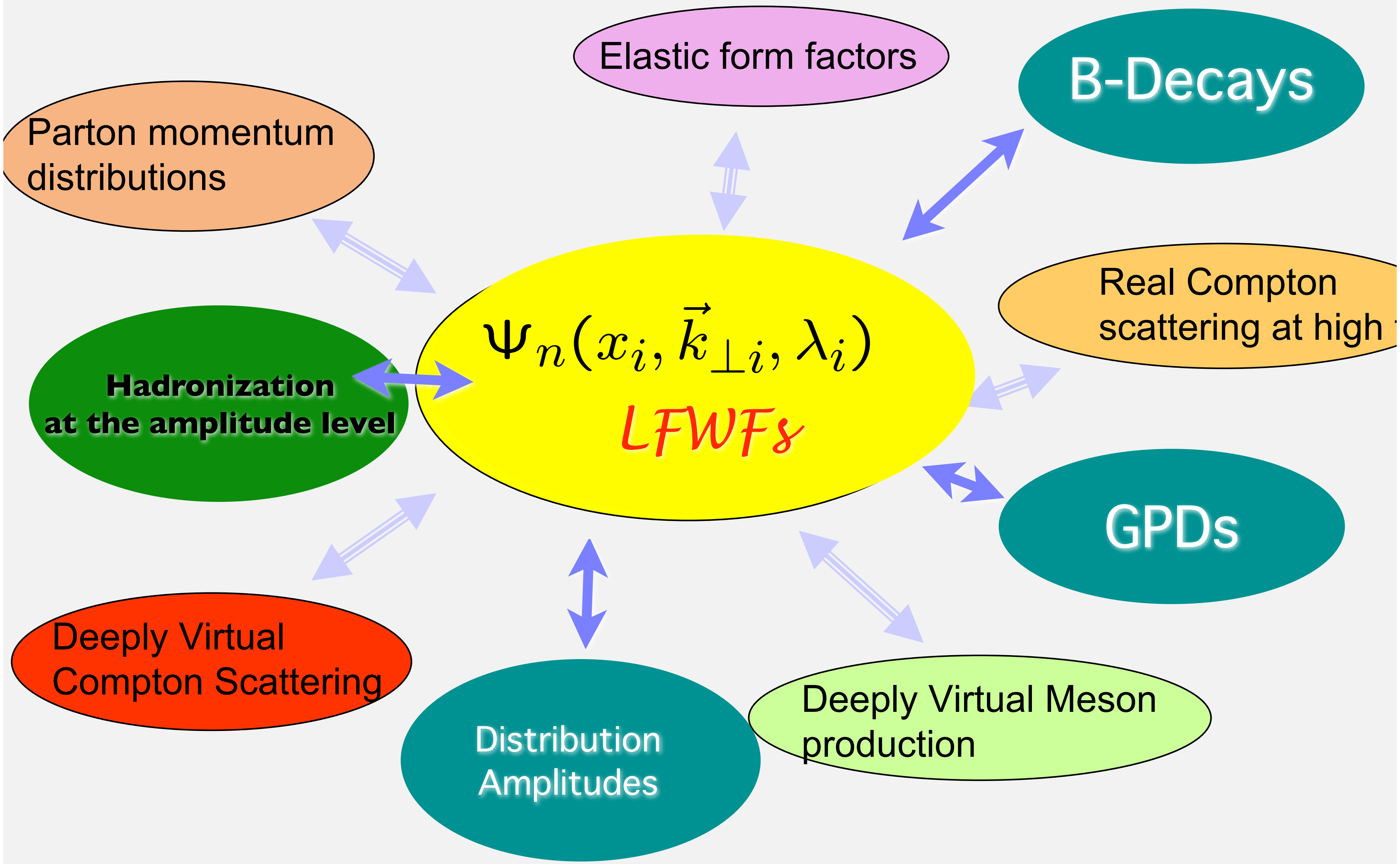
Conserved
LF Fock state by Fock State

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

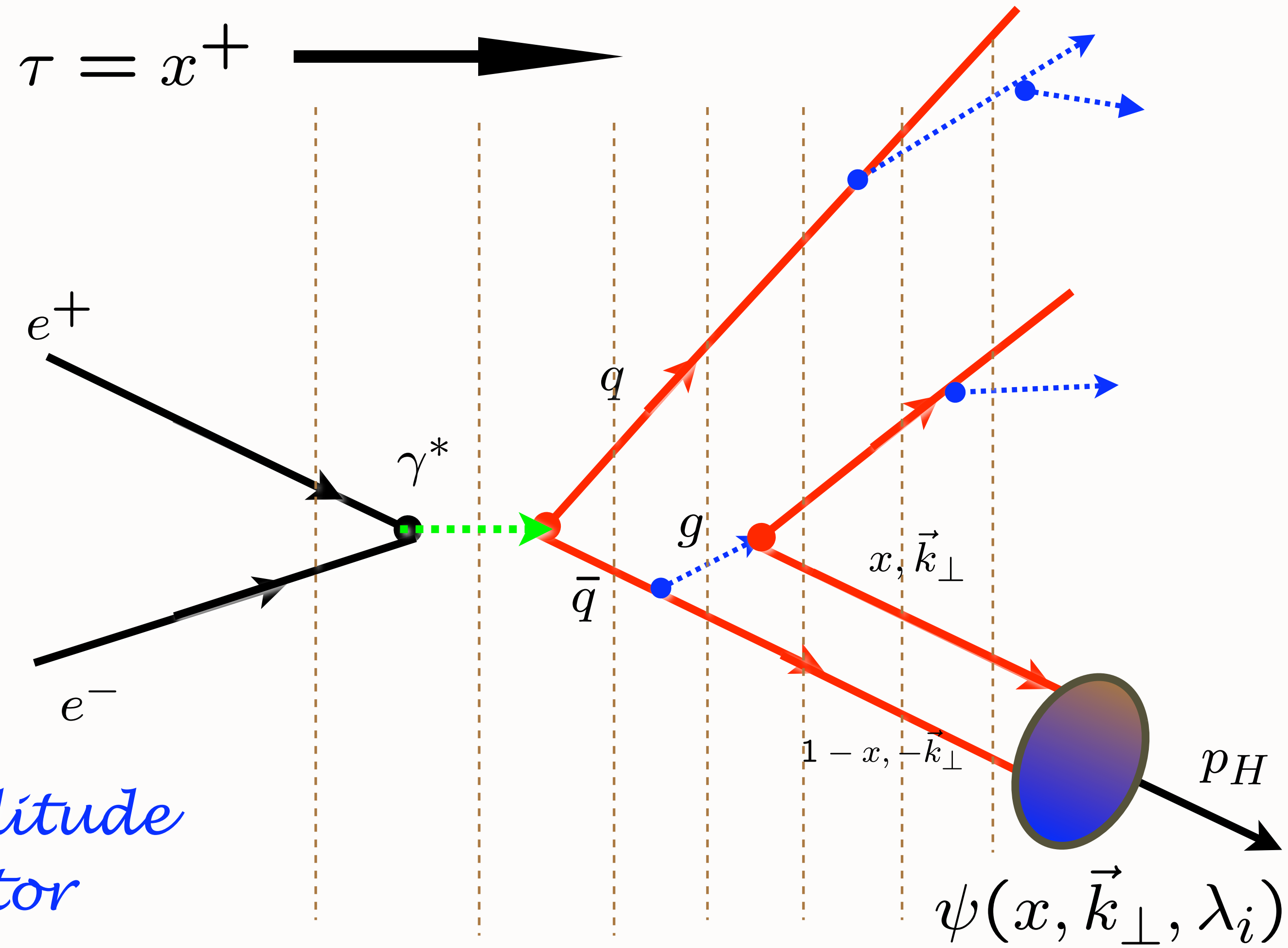
n-1 orbital angular momenta

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

Light-Front Representation of Two-Body Meson Form Factor

- Drell-Yan-West form factor

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

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

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

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

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

Soper

Holographic Mapping of AdS Modes to QCD LFWFs

- Integrate Soper formula over angles:

$$F(q^2) = 2\pi \int_0^1 dx \, \frac{(1-x)}{x} \int \zeta d\zeta J_0\left(\zeta q \sqrt{\frac{1-x}{x}}\right) \tilde{\rho}(x,\zeta),$$

with $\widetilde{\rho}(x,\zeta)$ QCD effective transverse charge density.

- Transversality variable

$$\zeta = \sqrt{\frac{x}{1-x}} \left| \sum_{j=1}^{n-1} x_j \mathbf{b}_{\perp j} \right|.$$

- Compare AdS and QCD expressions of FFs for arbitrary Q using identity:

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

the solution for $J(Q,\zeta) = \zeta Q K_1(\zeta Q)$!

- Electromagnetic form-factor in AdS space:

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

where $J(Q^2,z) = zQK_1(zQ)$.

- Use integral representation for $J(Q^2,z)$

$$J(Q^2,z) = \int_0^1 dx\, J_0\left(\zeta Q\sqrt{\frac{1-x}{x}}\right)$$

- Write the AdS electromagnetic form-factor as

$$F_{\pi^+}(Q^2) = R^3 \int_0^1 dx \int \frac{dz}{z^3}\, J_0\left(zQ\sqrt{\frac{1-x}{x}}\right) |\Phi_{\pi^+}(z)|^2$$

- Compare with electromagnetic form-factor in light-front QCD for arbitrary Q

$$\boxed{\left|\tilde\psi_{q\overline{q}/\pi}(x,\zeta)\right|^2 = \frac{R^3}{2\pi}\, x(1-x)\frac{|\Phi_\pi(\zeta)|^2}{\zeta^4}}$$

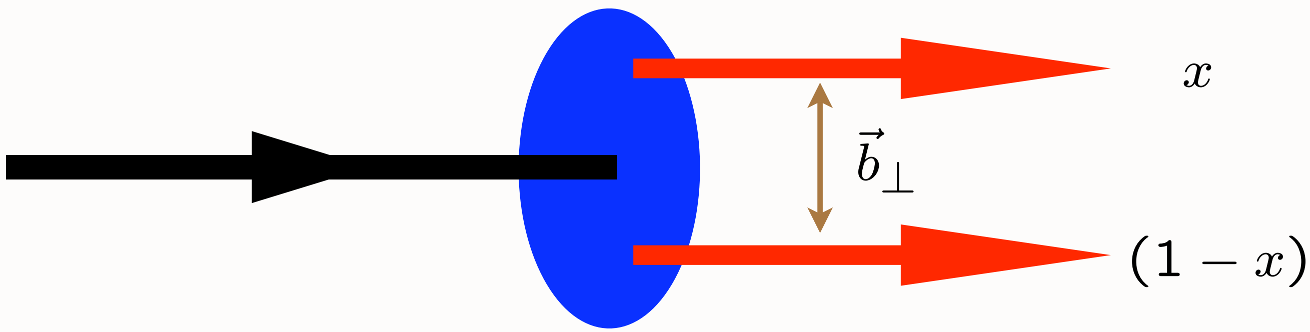
with $\zeta = z,\ 0 \leq \zeta \leq \Lambda_{\rm QCD}$

LF(3+1) $\quad\longleftrightarrow\quad$ AdS$_5$

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

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

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



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

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

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

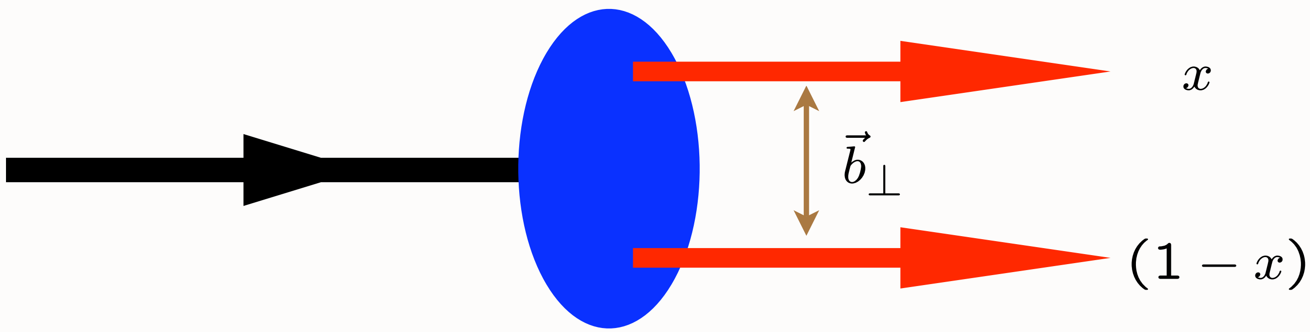
Relativistic LF radial equation

Frame Independent

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

G. de Teramond, sjb

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



Effective conformal potential:

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

$$+\kappa^4\zeta^2$$

confining potential:

Gravitational Form Factor in AdS space

- Hadronic gravitational form-factor in AdS space

$$A_\pi(Q^2) = R^3 \int \frac{dz}{z^3} H(Q^2, z) \left|\Phi_\pi(z)\right|^2,$$

Abidin & Carlson

where $H(Q^2, z) = \frac{1}{2} Q^2 z^2 K_2(zQ)$

- Use integral representation for $H(Q^2, z)$

$$H(Q^2, z) = 2 \int_0^1 x\, dx\, J_0\left(zQ\sqrt{\frac{1-x}{x}}\right)$$

- Write the AdS gravitational form-factor as

$$A_\pi(Q^2) = 2R^3 \int_0^1 x\, dx \int \frac{dz}{z^3} J_0\left(zQ\sqrt{\frac{1-x}{x}}\right) \left|\Phi_\pi(z)\right|^2$$

- Compare with gravitational form-factor in light-front QCD for arbitrary Q

$$\left|\tilde{\psi}_{q\bar{q}/\pi}(x, \zeta)\right|^2 = \frac{R^3}{2\pi} x(1-x) \frac{\left|\Phi_\pi(\zeta)\right|^2}{\zeta^4},$$

Identical to LF Holography obtained from electromagnetic current

Light-Front AdS_5 Duality

At fixed x^+
$$ds^2 = -\frac{R^2}{z^2}(dx_\perp^2 + dz^2)$$

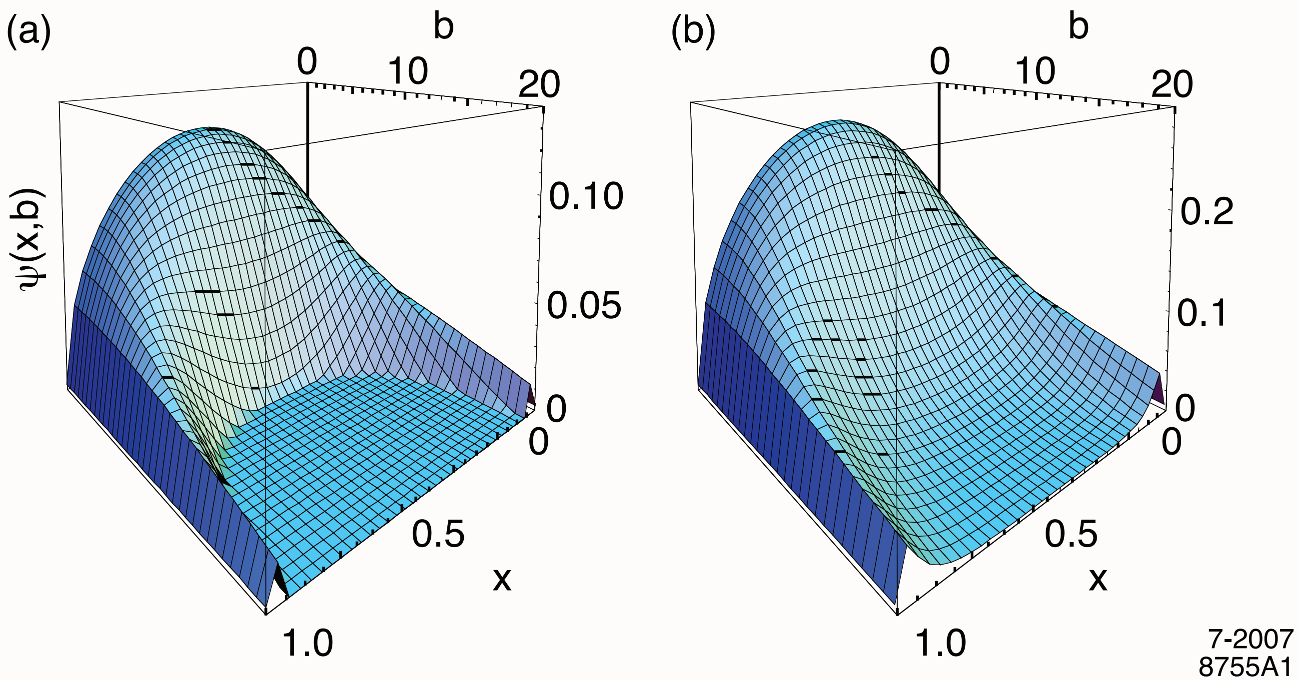
Invariant under $dx_\perp^2 \to \lambda^2 dx_\perp^2$
$$z \to \lambda z$$

Example: Pion LFWF

- Two parton LFWF bound state:

$$\widetilde{\psi}^{HW}_{\overline{q}q/\pi}(x,\mathbf{b}_\perp) = \frac{\Lambda_{\rm QCD}\sqrt{x(1-x)}}{\sqrt{\pi}J_{1+L}(\beta_{L,k})} J_L\left(\sqrt{x(1-x)}\,|\mathbf{b}_\perp|\beta_{L,k}\Lambda_{\rm QCD}\right)\theta\left(\mathbf{b}_\perp^2 \le \frac{\Lambda^{-2}_{\rm QCD}}{x(1-x)}\right),$$

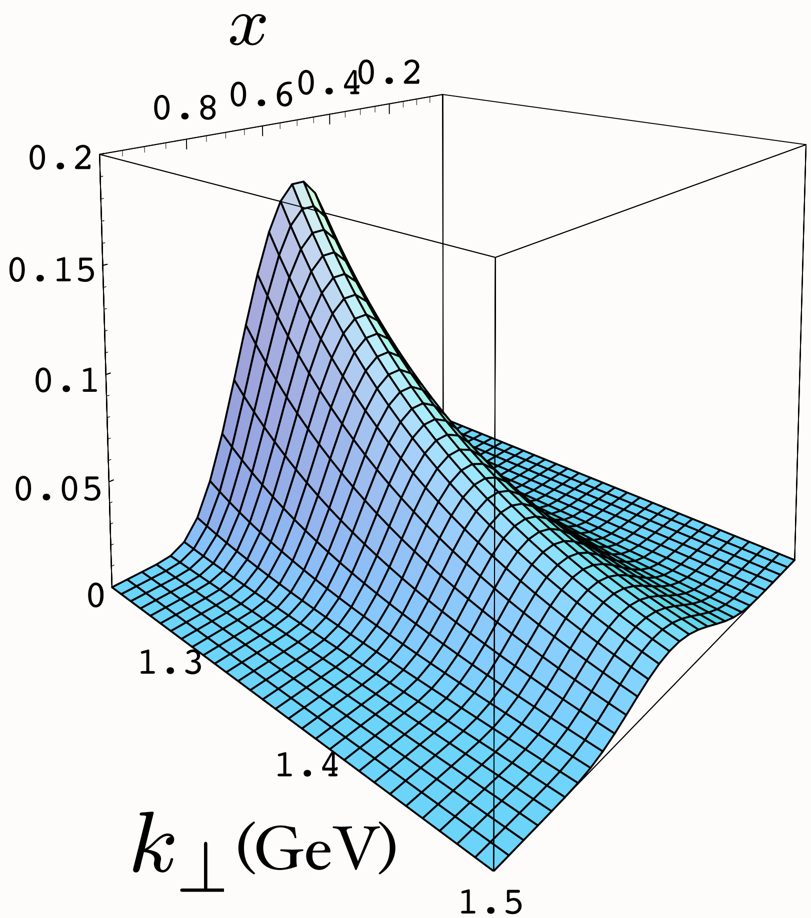
$$\widetilde{\psi}^{SW}_{\overline{q}q/\pi}(x,\mathbf{b}_\perp) = \kappa^{L+1}\sqrt{\frac{2n!}{(n+L)!}}\,[x(1-x)]^{\frac{1}{2}+L}|\mathbf{b}_\perp|^L e^{-\frac{1}{2}\kappa^2 x(1-x)\mathbf{b}_\perp^2} L_n^L\left(\kappa^2 x(1-x)\mathbf{b}_\perp^2\right).$$



Ground state pion LFWF in impact space. (a) HW model $\Lambda_{\rm QCD} = 0.32$ GeV, (b) SW model $\kappa = 0.375$ GeV.

Prediction from AdS/CFT: Meson LFWF

de Teramond, sjb



"Soft Wall" model

$\kappa = 0.375$ GeV

massless quarks

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}} \qquad \phi_M(x, Q_0) \propto \sqrt{x(1-x)}$$

Second Moment of Pion Distribution Amplitude

$$< \xi^2 >= \int_{-1}^{1} d\xi \; \xi^2 \phi(\xi)$$

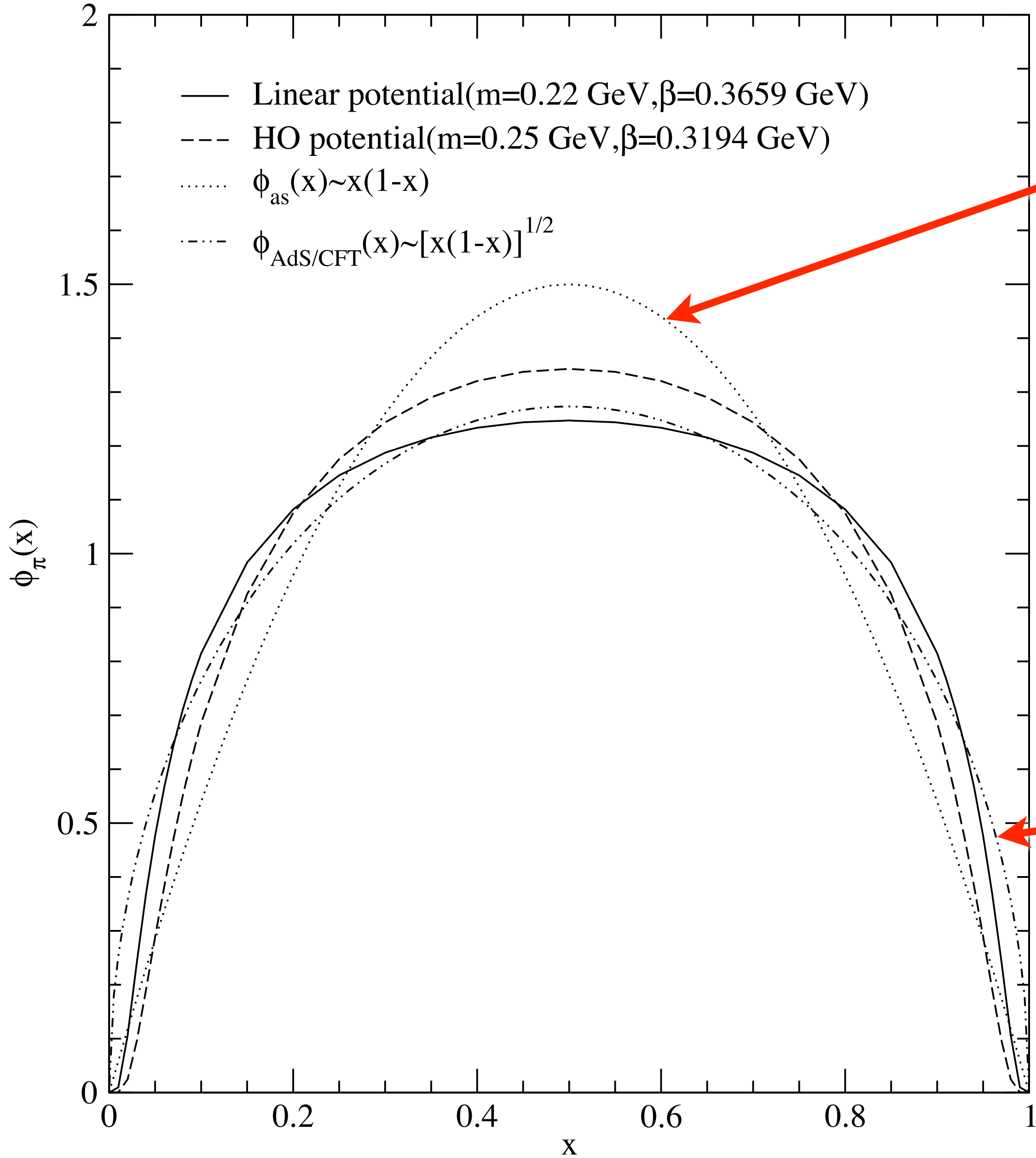
$$\xi = 1 - 2x$$

$$< \xi^2 >_\pi = 1/5 = 0.20 \qquad \phi_{asympt} \propto x(1-x)$$

$$< \xi^2 >_\pi = 1/4 = 0.25 \qquad \phi_{AdS/QCD} \propto \sqrt{x(1-x)}$$

Lattice (I) $< \xi^2 >_\pi = 0.28 \pm 0.03$ — Donnellan et al.

Lattice (II) $< \xi^2 >_\pi = 0.269 \pm 0.039$ — Braun et al.



$$\phi_{asympt} \sim x(1-x)$$

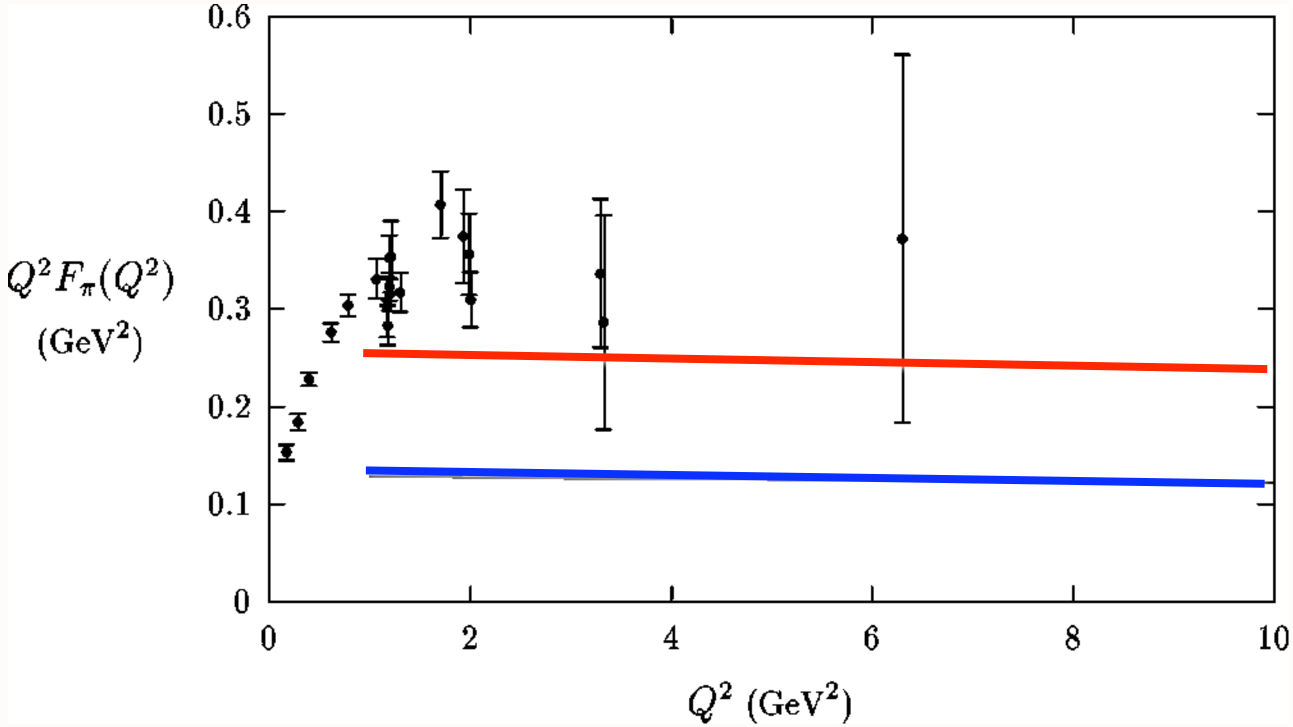
AdS/CFT:

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

Lepage, sjb

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

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



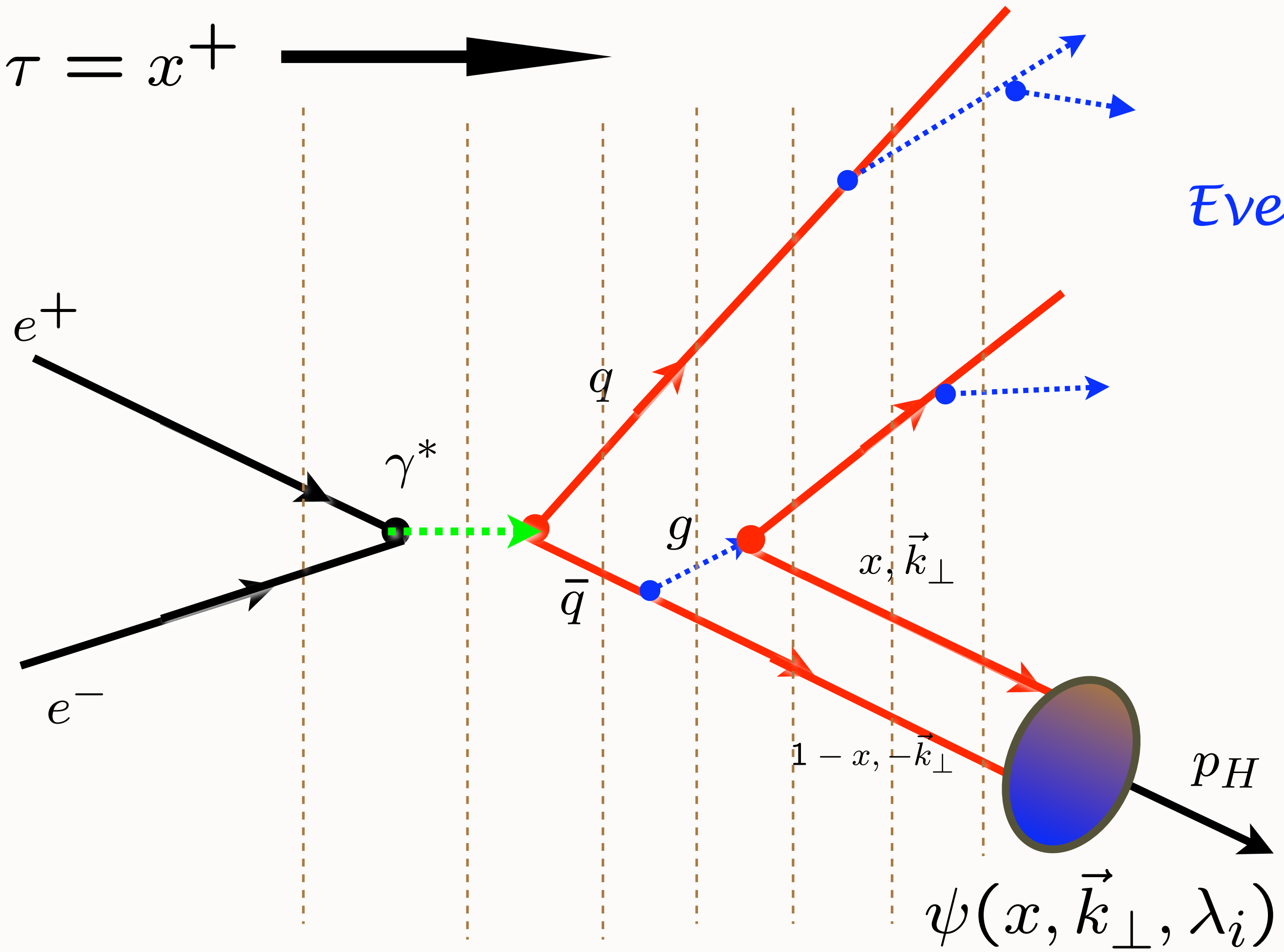
$\phi(x, Q_0) \propto \sqrt{x(1-x)}$

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

Normalized to f_π

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

Hadronization at the Amplitude Level



Event amplitude generator

AdS/QCD Hard Wall

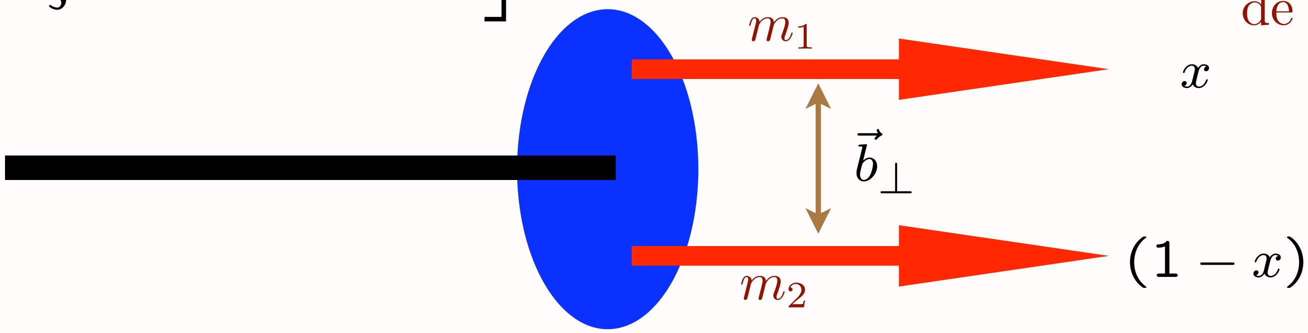
Capture if $\zeta^2 = x(1-x)b_\perp^2 > \frac{1}{\Lambda^2_{QCD}}$

i.e.,

$\mathcal{M}^2 = \frac{k_\perp^2}{x(1-x)} < \Lambda^2_{QCD}$

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

de Teramond, sjb



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

Holographic Variable

$$-\frac{d}{d\zeta^2} \equiv \frac{k_\perp^2}{x(1-x)}$$

LF Kinetic Energy in momentum space

Assume LFWF is a dynamical function of the quark-antiquark invariant mass squared

$$-\frac{d}{d\zeta^2} \to -\frac{d}{d\zeta^2} + \frac{m_1^2}{x} + \frac{m_2^2}{1-x} \equiv \frac{k_\perp^2 + m_1^2}{x} + \frac{k_\perp^2 + m_2^2}{1-x}$$

Result: Soft-Wall LFWF for massive constituents

$$\psi(x, \mathbf{k}_\perp) = \frac{4\pi c}{\kappa\sqrt{x(1-x)}} e^{-\frac{1}{2\kappa^2}\left(\frac{\mathbf{k}_\perp^2}{x(1-x)} + \frac{m_1^2}{x} + \frac{m_2^2}{1-x}\right)}$$

LF WF in impact space: soft-wall model with massive quarks

$$\psi(x, \mathbf{b}_\perp) = \frac{c\,\kappa}{\sqrt{\pi}} \sqrt{x(1-x)}\, e^{-\frac{1}{2}\kappa^2 x(1-x)\mathbf{b}_\perp^2 - \frac{1}{2\kappa^2}\left[\frac{m_1^2}{x} + \frac{m_2^2}{1-x}\right]}$$

$$z \to \zeta \to \chi$$

$$\chi^2 = b^2 x(1-x) + \frac{1}{\kappa^4}\left[\frac{m_1^2}{x} + \frac{m_2^2}{1-x}\right]$$

J/ψ

LFWF peaks at

$$x_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

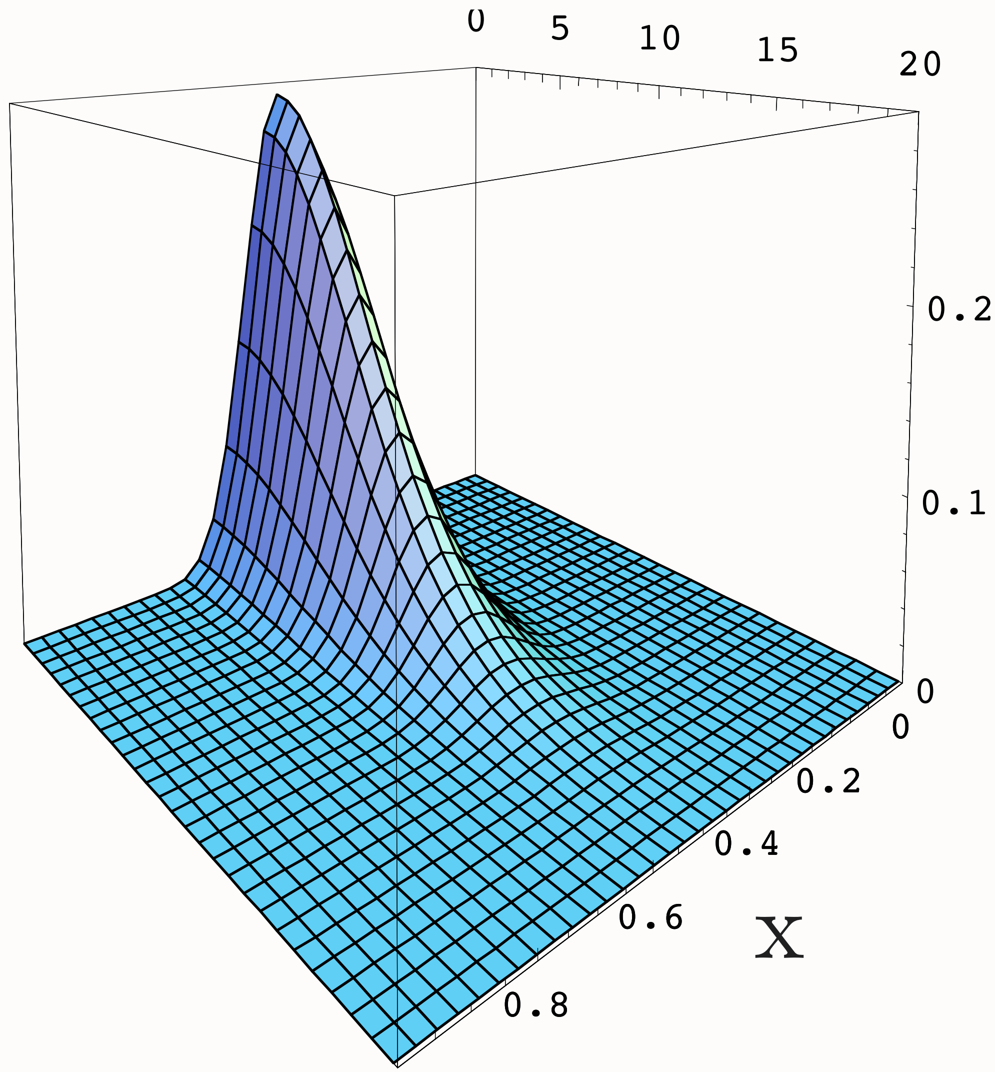
where

$$m_{\perp i} = \sqrt{m^2 + k_\perp^2}$$

minimum of LF energy denominator

$$\kappa = 0.375 \text{ GeV}$$

$$\psi_{J/\psi}(x, b)$$



$$m_a = m_b = 1.25 \text{ GeV}$$

$|\pi^+ >= |u\bar{d}>$

$m_u = 2\ MeV$
$m_d = 5\ MeV$

$|K^+ >= |u\bar{s}>$

$m_s = 95\ MeV$

$|D^+ >= |c\bar{d}>$

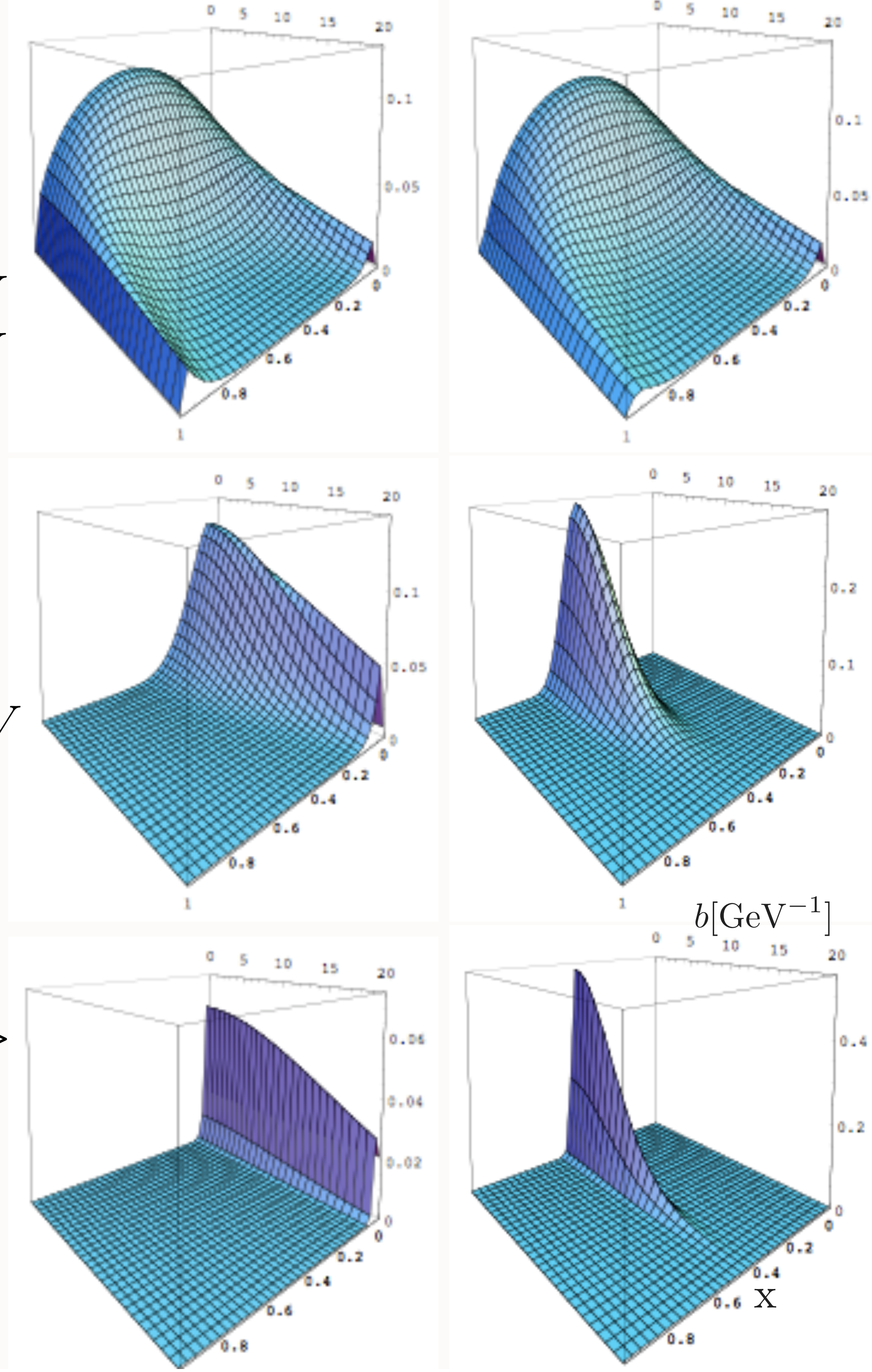
$m_c = 1.25\ GeV$

$|\eta_c >= |c\bar{c}>$

$|B^+ >= |u\bar{b}>$

$m_b = 4.2\ GeV$

$|\eta_b >= |b\bar{b}>$

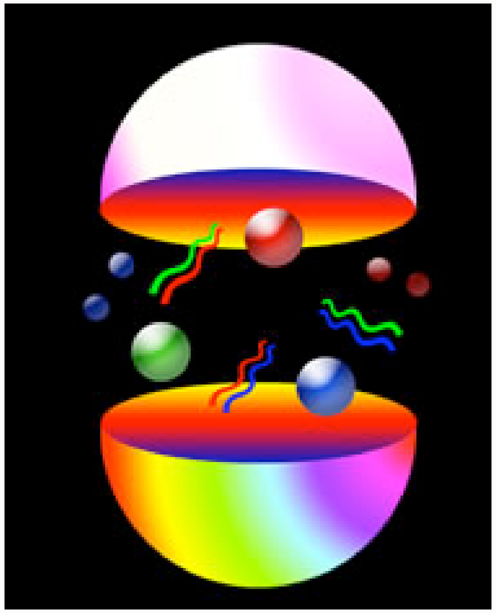


$\kappa = 375\ MeV$

- Baryons Spectrum in "bottom-up" holographic QCD

GdT and Brodsky: hep-th/0409074, hep-th/0501022.

Baryons in Ads/CFT



- Action for massive fermionic modes on AdS_{d+1}:

$$S[\overline{\Psi}, \Psi] = \int d^{d+1}x \sqrt{g}\, \overline{\Psi}(x,z) \left(i\Gamma^\ell D_\ell - \mu \right) \Psi(x,z).$$

- Equation of motion: $\left(i\Gamma^\ell D_\ell - \mu \right) \Psi(x,z) = 0$

$$\left[i \left(z\eta^{\ell m}\Gamma_\ell \partial_m + \frac{d}{2}\Gamma_z \right) + \mu R \right] \Psi(x^\ell) = 0.$$

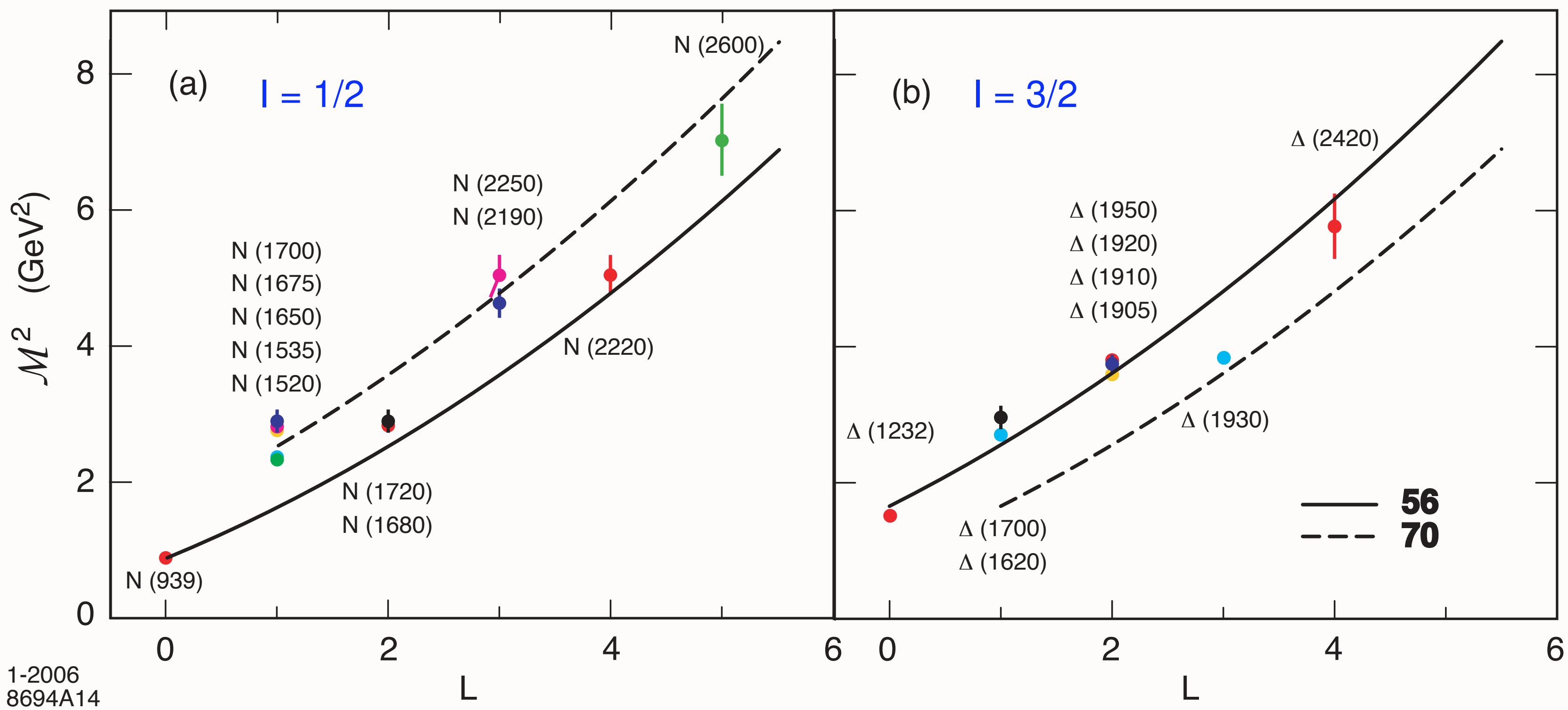


Fig: Light baryon orbital spectrum for Λ_{QCD} = 0.25 GeV in the HW model. The $\mathbf{56}$ trajectory corresponds to L even $P = +$ states, and the $\mathbf{70}$ to L odd $P = -$ states.

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

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 $-1/2$.

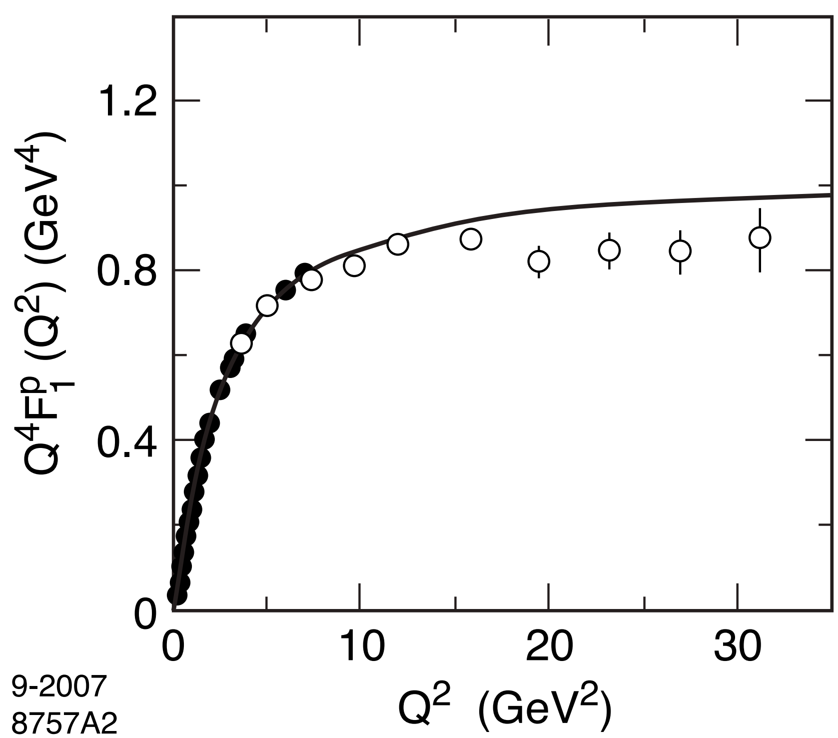
- For $SU(6)$ spin-flavor symmetry

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

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

- Scaling behavior for large Q^2: $Q^4 F_1^p(Q^2) \to \text{constant}$

Proton $\tau = 3$



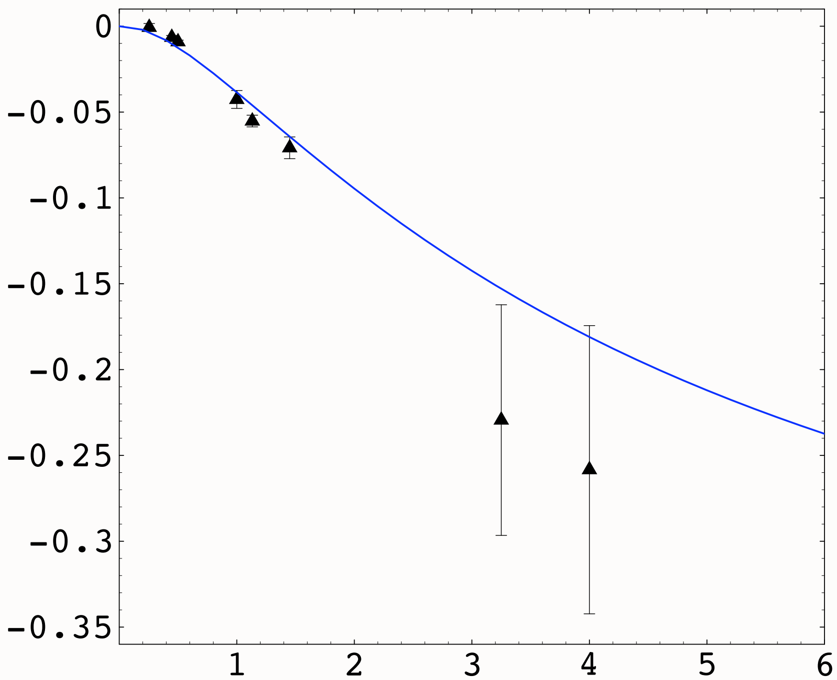
SW model predictions for $\kappa = 0.424$ GeV. Data analysis from: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

Dirac Neutron Form Factor

(Valence Approximation)

Truncated Space Confinement

$Q^4 F_1^n(Q^2)$ [GeV^4]



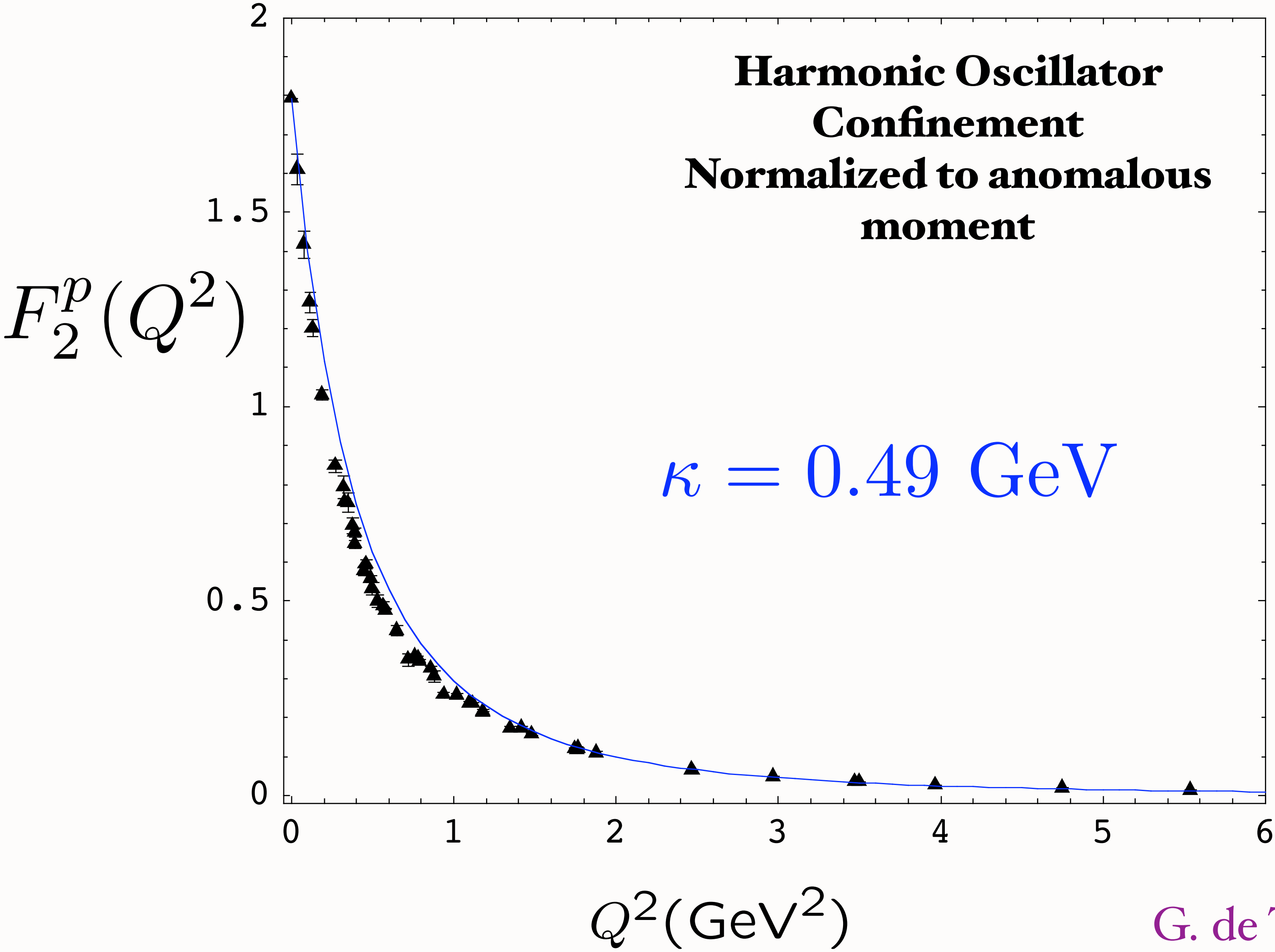
Q^2 [GeV^2]

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

Spacelike Pauli Form Factor

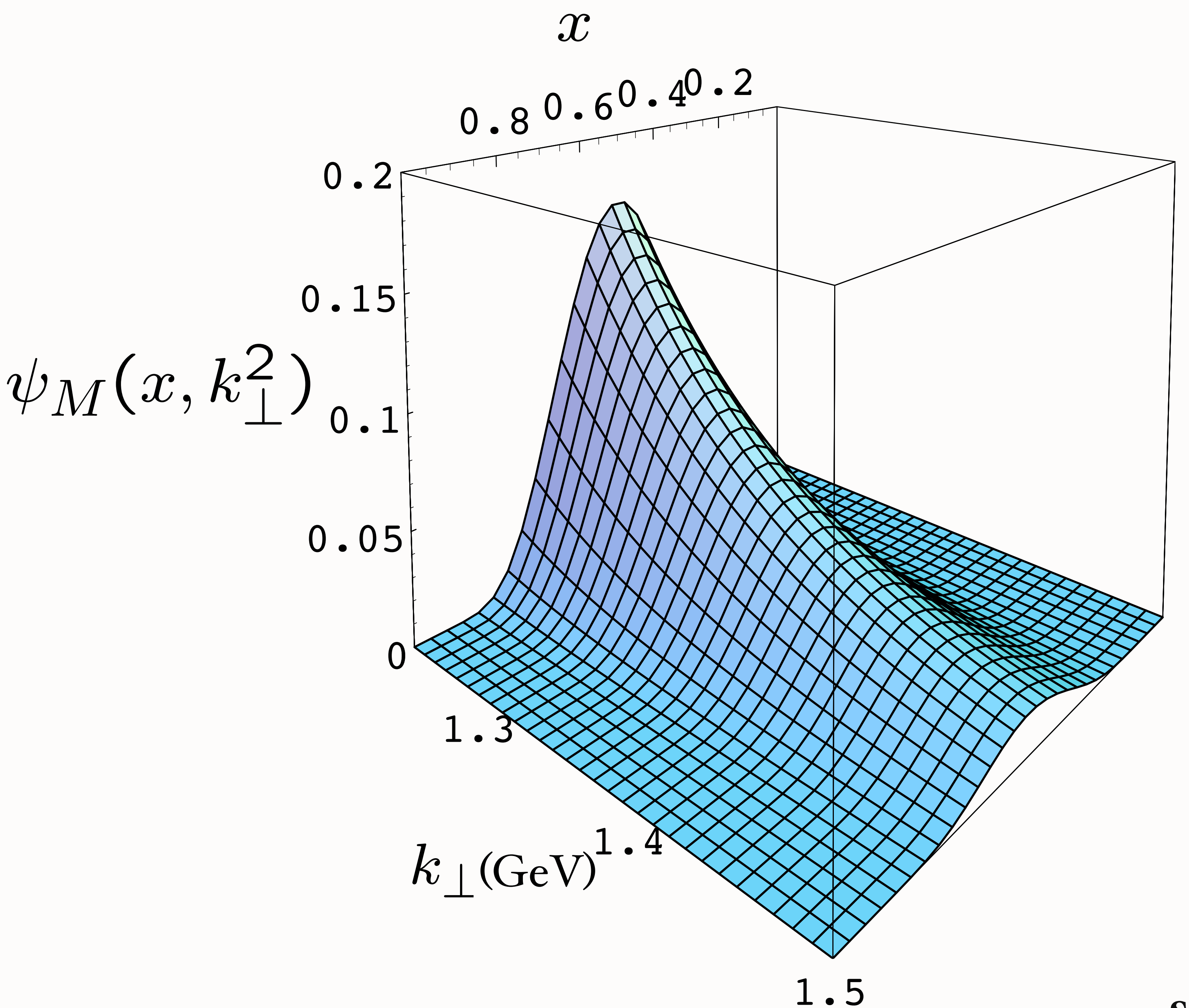
Preliminary

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



G. de Teramond, sjb

Prediction from AdS/CFT: Meson LFWF



"Soft Wall" model

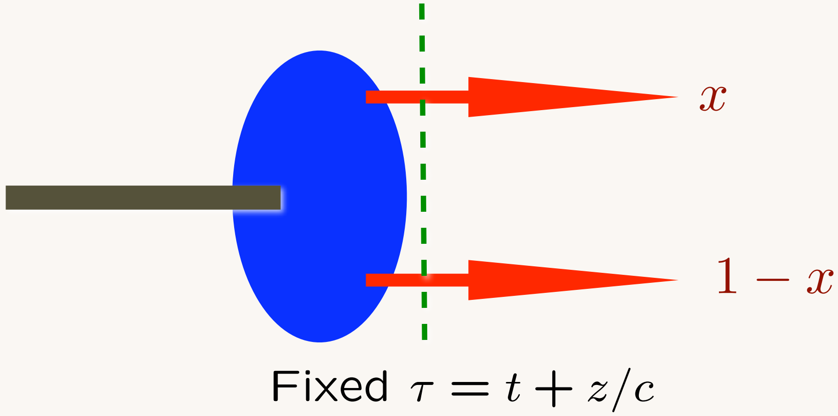
de Teramond, sjb

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

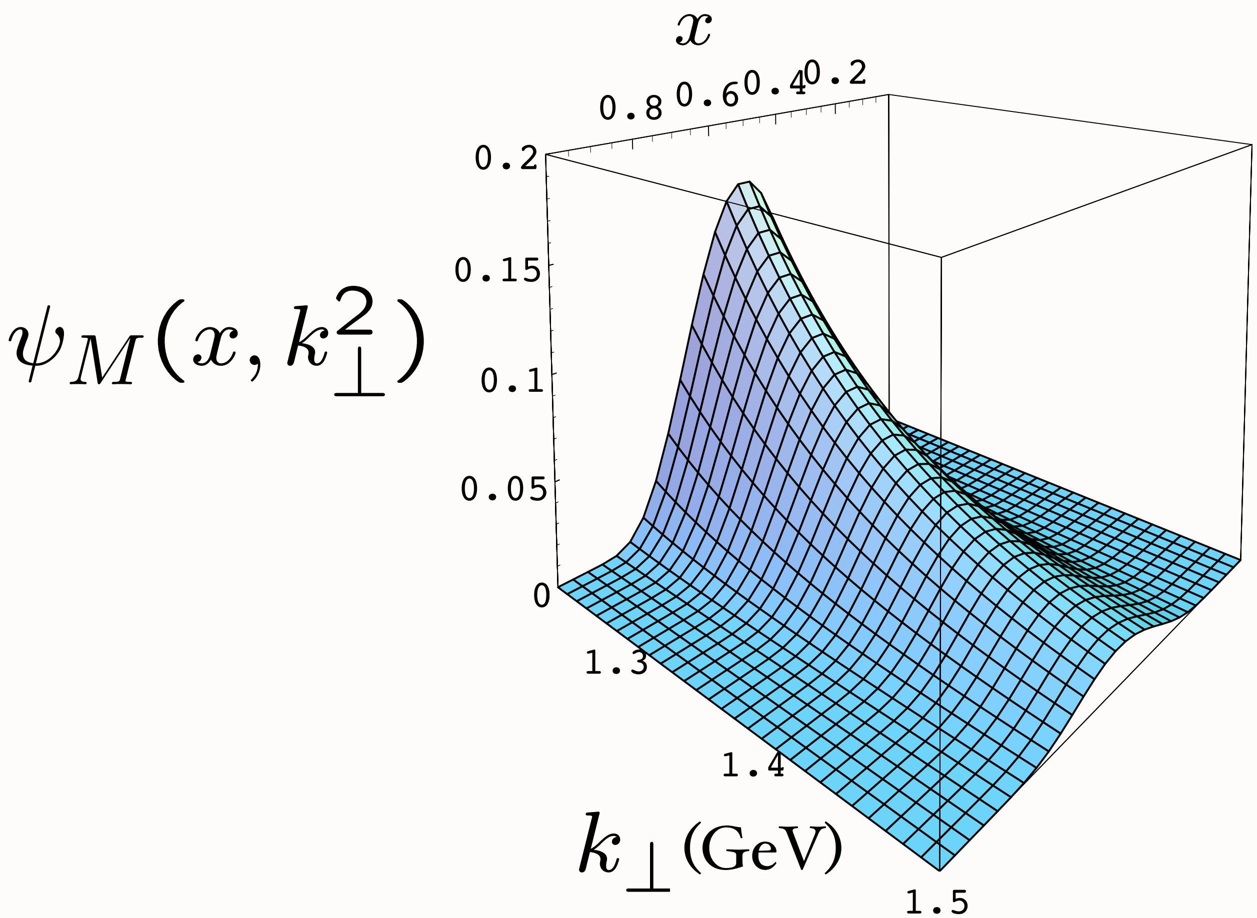
- Evolution Equations from PQCD, OPE, Conformal Invariance

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

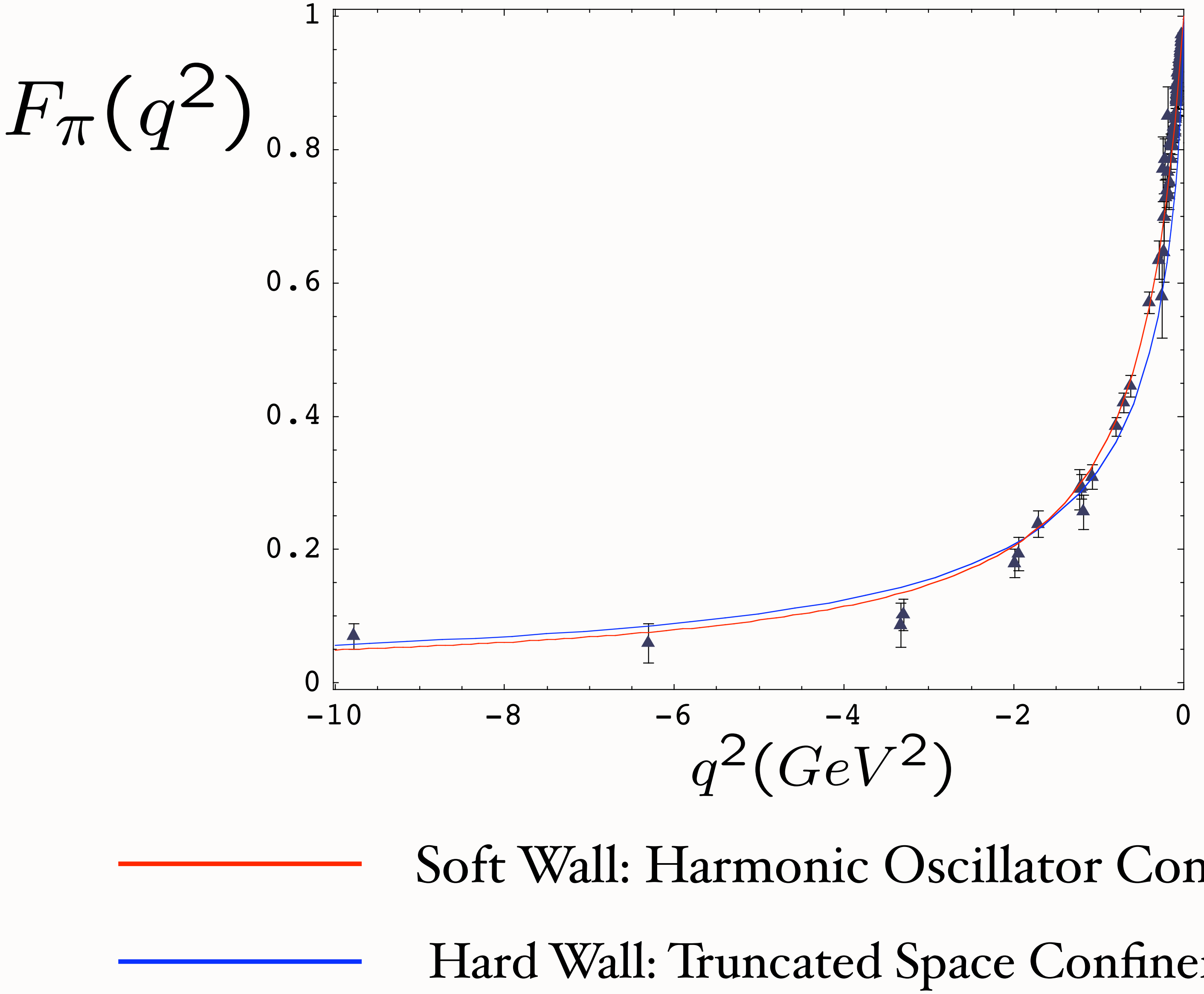
$\kappa = 0.375$ GeV

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

One parameter - set by pion decay constant

de Teramond, sjb
See also: Radyushkin

Light-Front Wavefunctions

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

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

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

Invariant under boosts. Independent of P^μ

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

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

How can we systematically improve AdS/QCD?

AdS/QCD: Semiclassical model

No Particle Creation

Valence Fock State only

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

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

The Light Front Fock State Wavefunctions

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

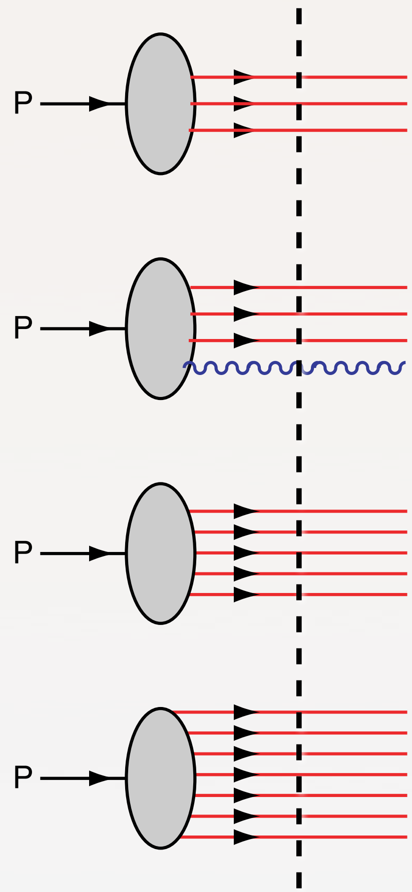
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

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

are boost invariant.

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



Fixed LF time

Intrinsic heavy quarks

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

Mueller: BFKL DYNAMICS

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

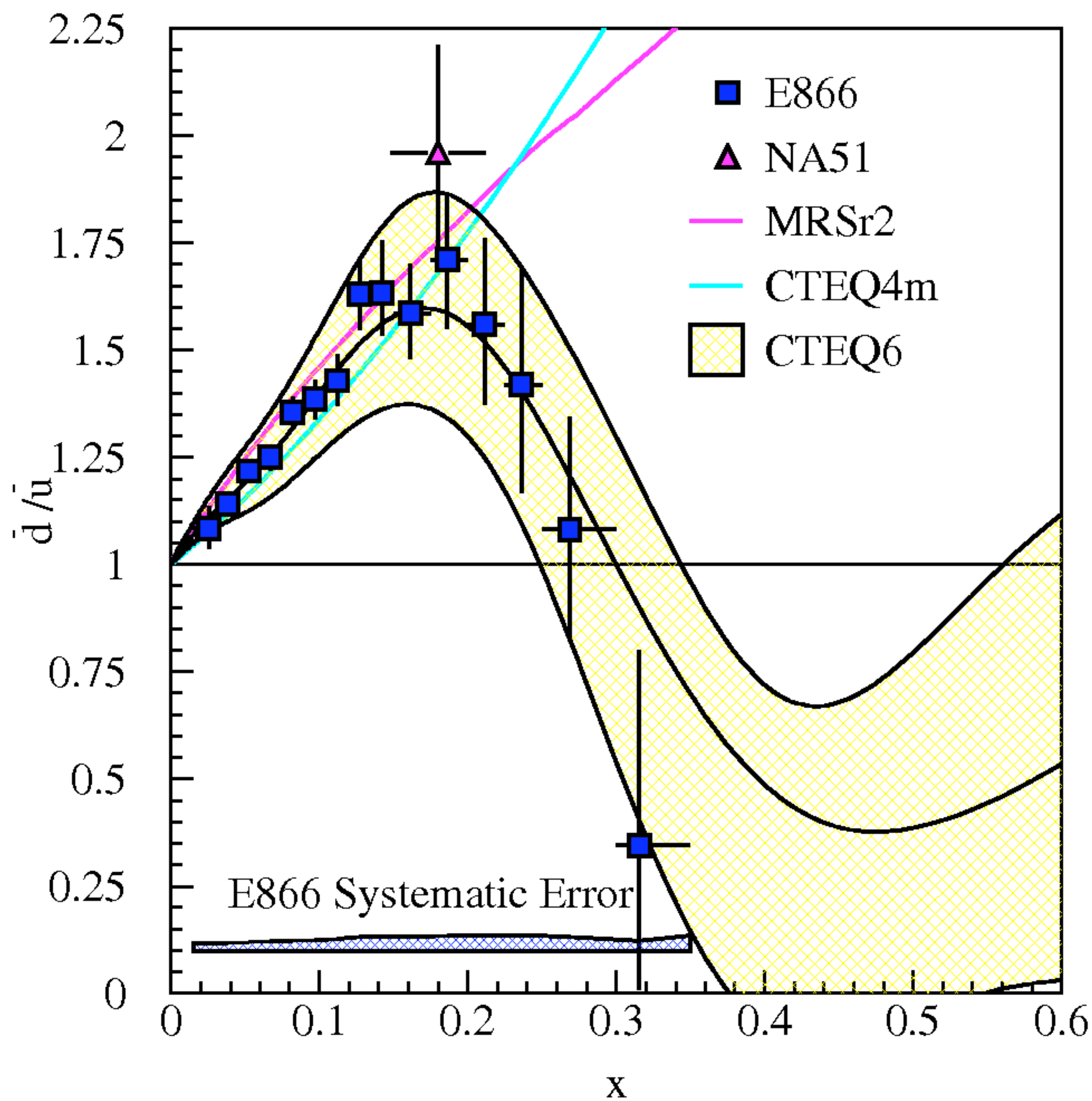
Light Antiquark Flavor Asymmetry

- Naïve Assumption from gluon splitting:

$$\bar{d}(x) = \bar{u}(x)$$

- E866/NuSea (Drell-Yan)

$\bar{d}(x)/\bar{u}(x)$ for $0.015 \leq x \leq 0.35$

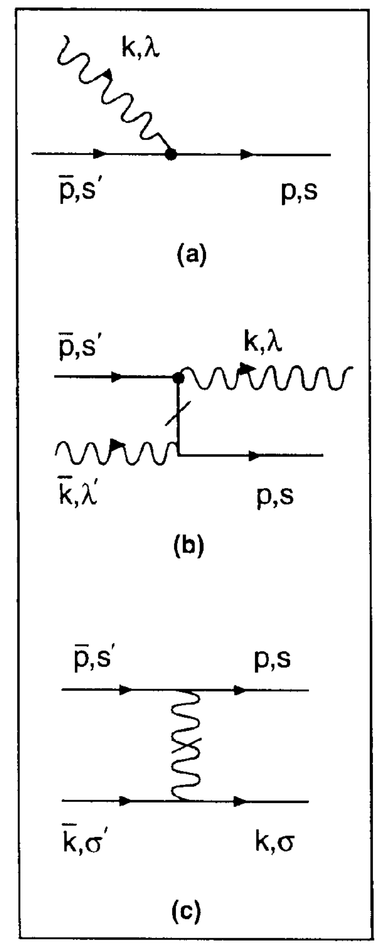


Light-Front QCD

Heisenberg Matrix Formulation

$$L^{QCD} \to H_{LF}^{QCD}$$

Physical gauge: $A^+ = 0$



$$H_{LF}^{QCD} = \sum_i [\frac{m^2 + k_\perp^2}{x}]_i + H_{LF}^{int}$$

H_{LF}^{int}: Matrix in Fock Space

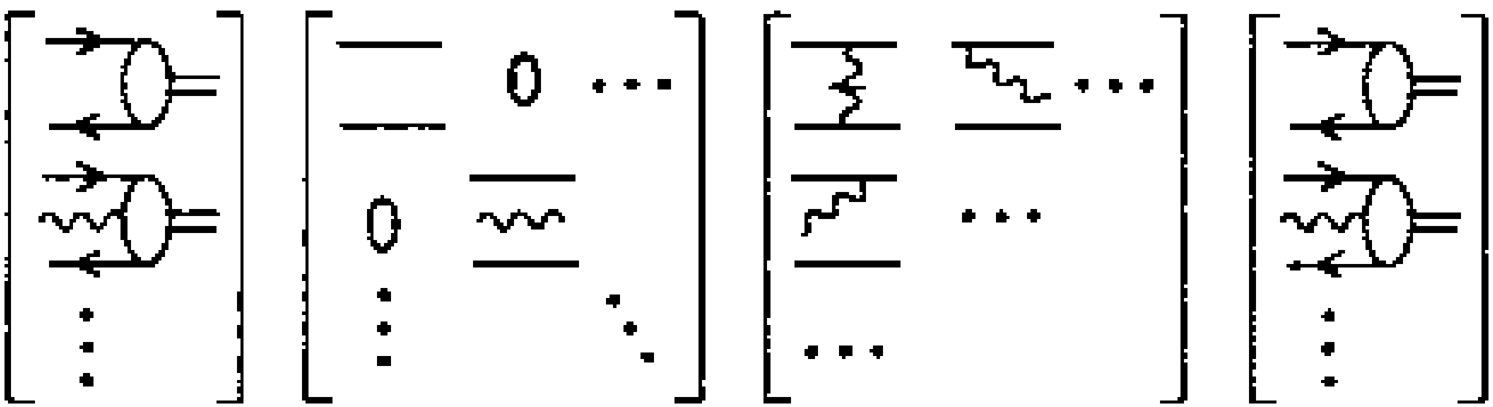
$$H_{LF}^{QCD} |\Psi_h> = \mathcal{M}_h^2 |\Psi_h>$$

Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

DLCQ: Periodic BC in x^-. Discrete k^+; frame-independent truncation

LIGHT-FRONT SCHRODINGER EQUATION

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^2 + m_i^2}{x_i}\right) \begin{bmatrix} \psi_{q\bar q/\pi} \\ \psi_{q\bar q g/\pi} \\ \vdots \end{bmatrix} = \begin{bmatrix} \langle q\bar q|\, V\, |q\bar q\rangle & \langle q\bar q|\, V\, |q\bar q g\rangle & \cdots \\ \langle q\bar q g|\, V\, |q\bar q\rangle & \langle q\bar q g|\, V\, |q\bar q g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \psi_{q\bar q/\pi} \\ \psi_{q\bar q g/\pi} \\ \vdots \end{bmatrix}$$



$A^+ = 0$

G.P. Lepage, sjb

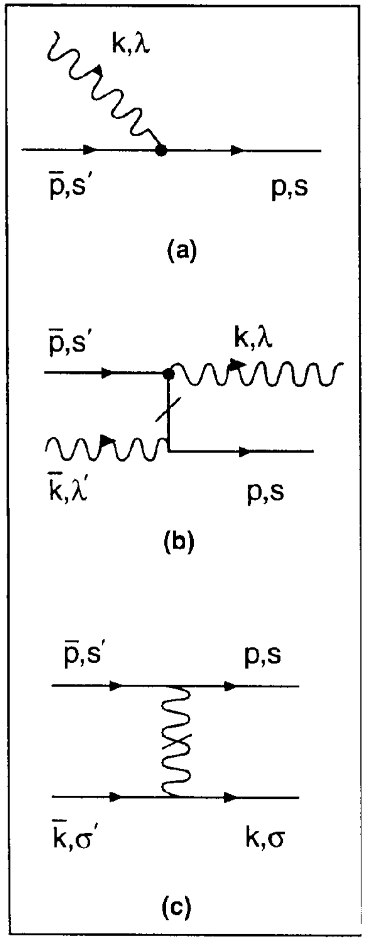
Light-Front QCD

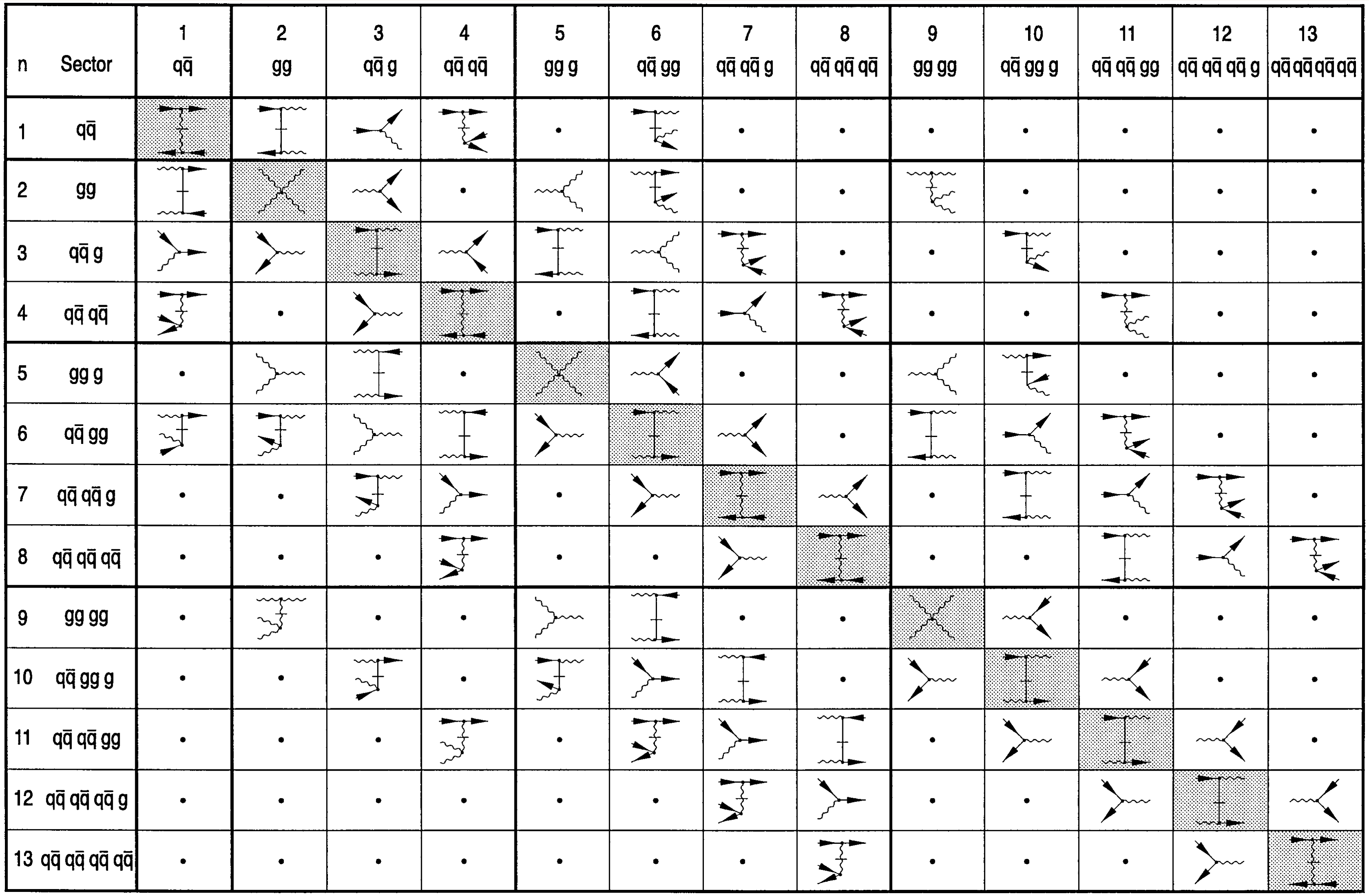
Heisenberg Matrix Formulation

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

DLCQ

Discretized Light-Cone Quantization





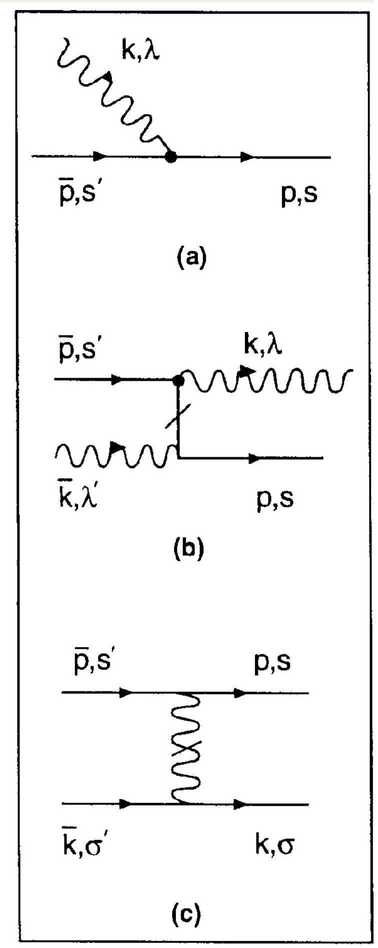
Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

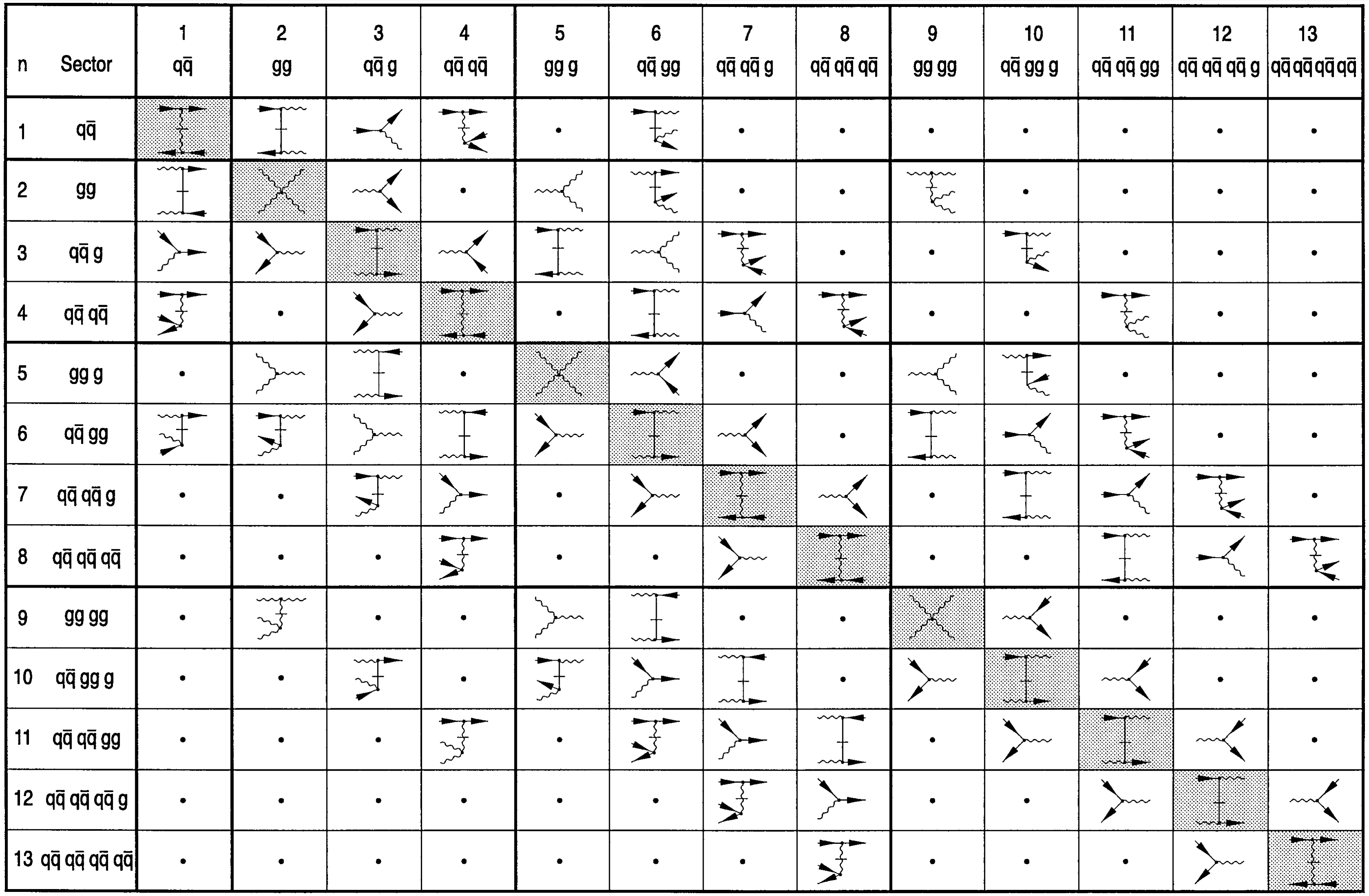
H.C. Pauli & sjb

DLCQ: Frame-independent, No fermion doubling; Minkowski Space

Light-Front QCD Heisenberg Equation

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





Use AdS/QCD basis functions

Use AdS/CFT orthonormal LFWFs as a basis for diagonalizing the QCD LF Hamiltonian

- Good initial approximant: generates all Fock states
- Better than plane wave basis

Pauli, Hornbostel, Hiller, McCartor, sjb

- DLCQ discretization -- highly successful 1+1
- Use independent HO LFWFs, remove CM motion

Vary, Harinandrath, Maris, sjb

- Similar to Shell Model calculations

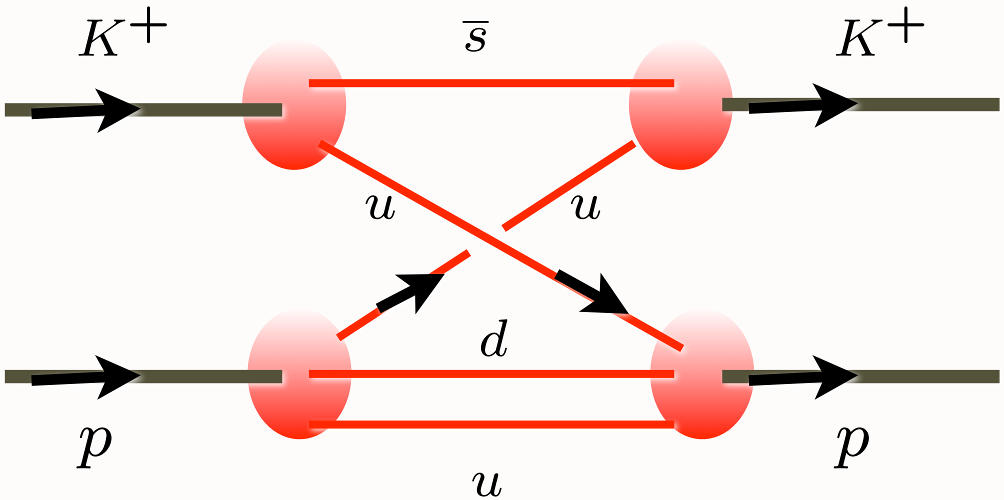
Holographic Connection between LF and AdS/CFT

- Predictions for hadronic spectra, light-front wavefunctions, interactions
- Deduce meson and baryon wavefunctions, distribution amplitude, structure function from holographic constraint
- Identification of Orbital Angular Momentum Casimir for SO(2): LF Rotations
- Extension to massive quarks

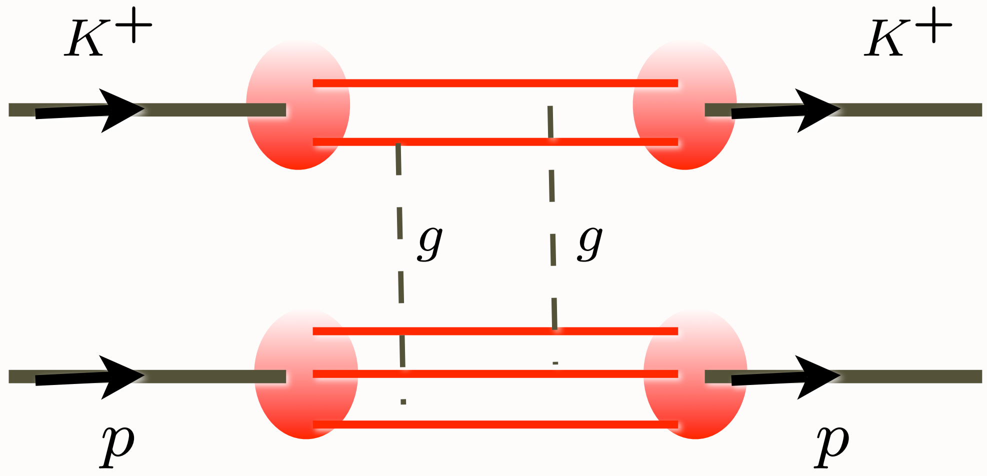
New Perspectives for QCD from AdS/CFT

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

CIM: Blankenbecler, Gunion, sjb



Quark Interchange
(Spin exchange in atom-atom scattering)



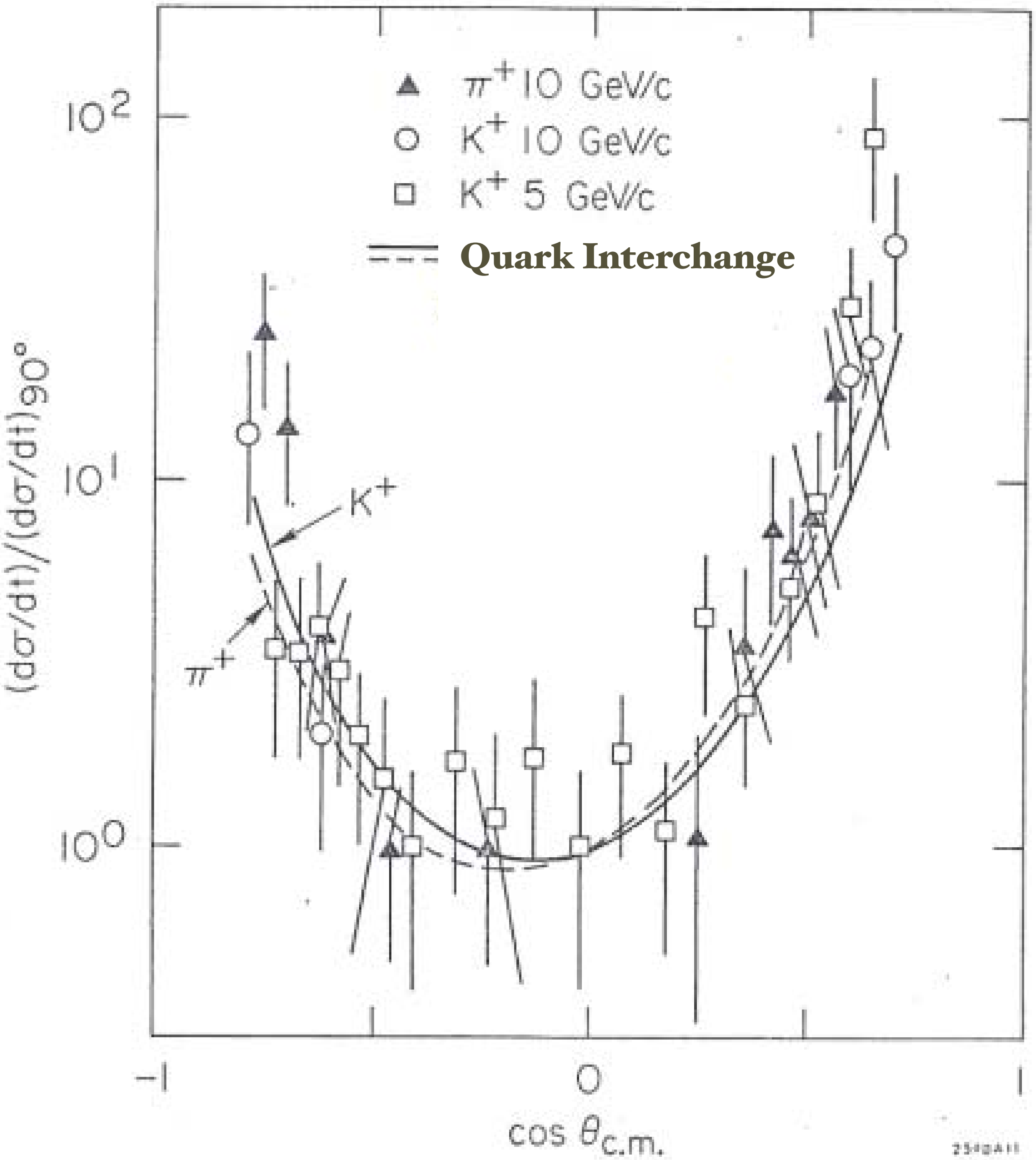
Gluon Exchange
(Van der Waal -- Landshoff)

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

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

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

MIT Bag Model (de Tar), large N_C, ('t Hooft), AdS/CFT all predict dominance of quark interchange:



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

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

Non-linear Regge behavior:

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

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.

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

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

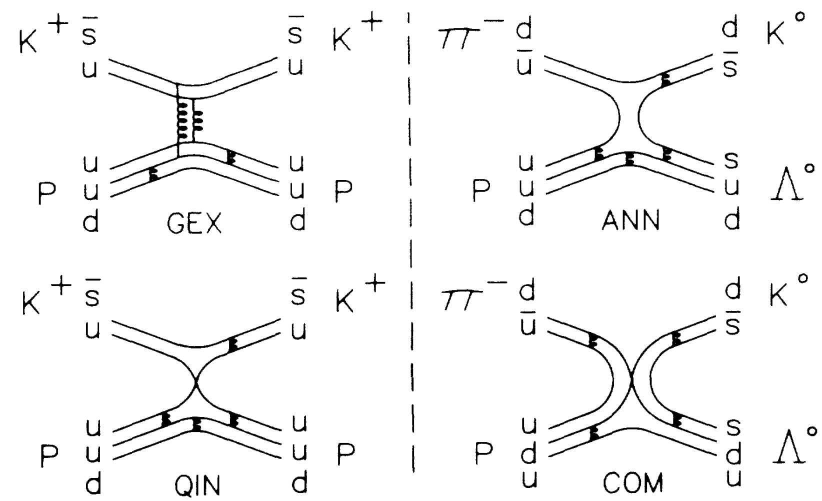
$\pi^{\pm}p \rightarrow p\rho^{\pm}$,

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

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

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

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



New Perspectives on QCD Phenomena from AdS/CFT

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

Hadron Dynamics at the Amplitude Level

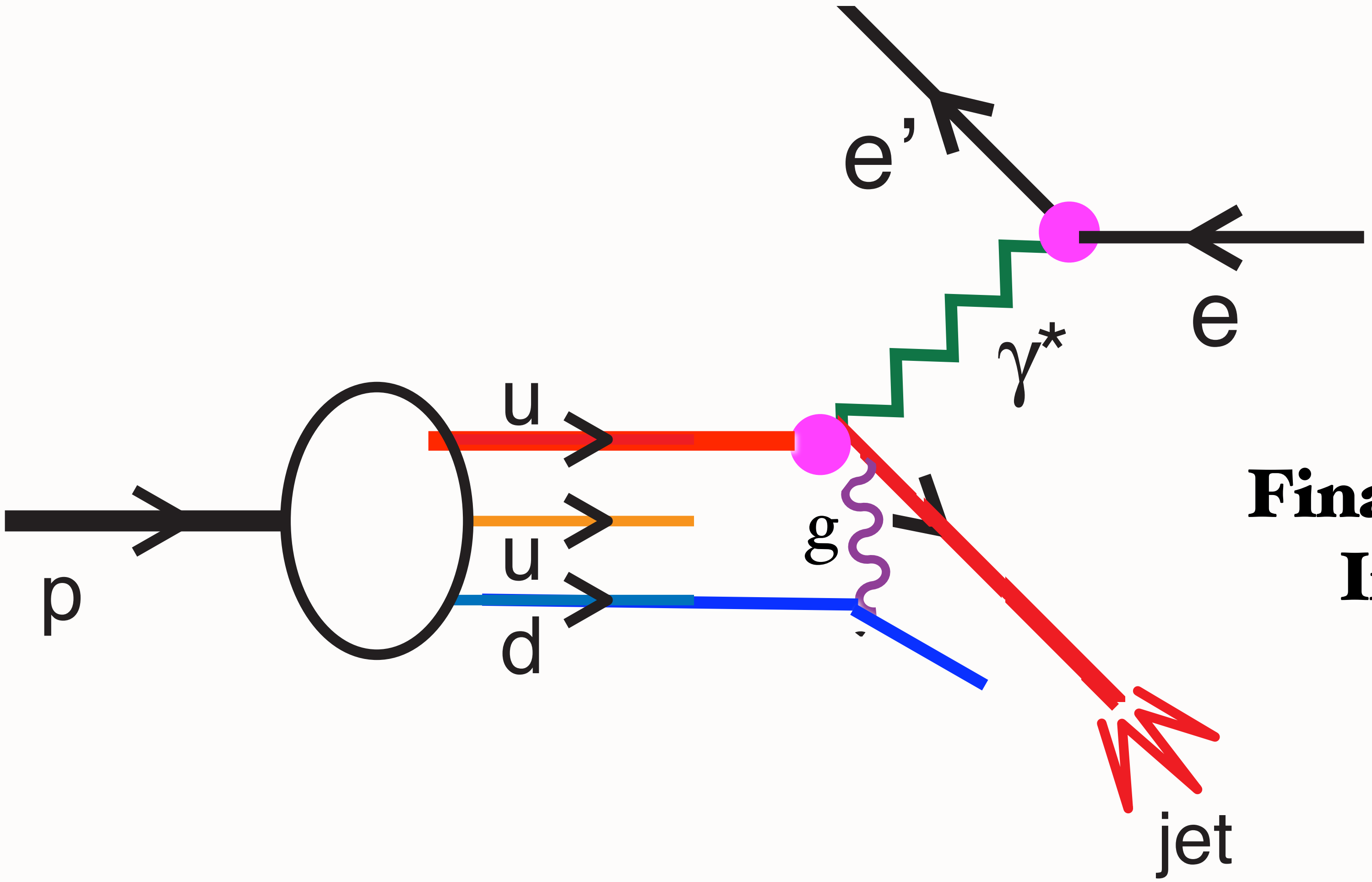
- LFWFS are the universal hadronic amplitudes which underlie structure functions, GPDs, exclusive processes, distribution amplitudes, direct subprocesses, hadronization.

- 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:

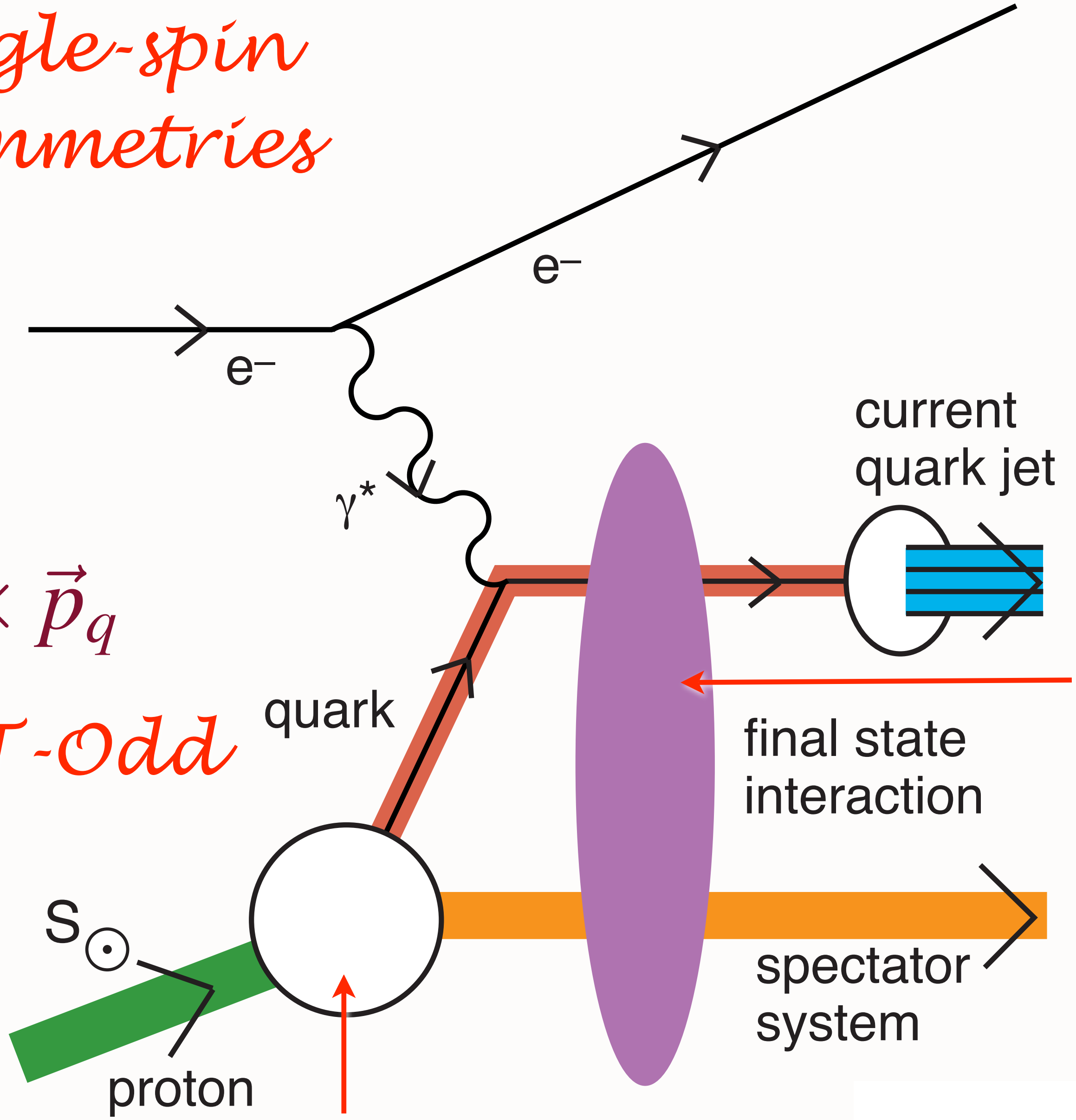
Final-state interactions of struck quark can be neglected

Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

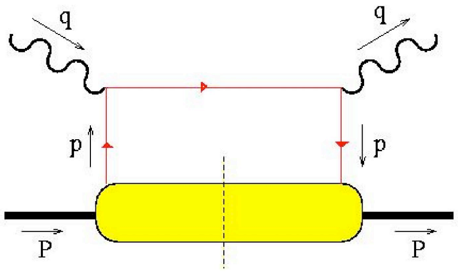


$i\ \vec{S}_p \cdot \vec{q} \times \vec{p}_q$

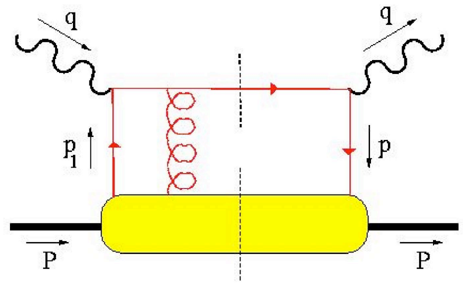
Pseudo-T-Odd

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

Light-Front Wavefunction S and P- Waves



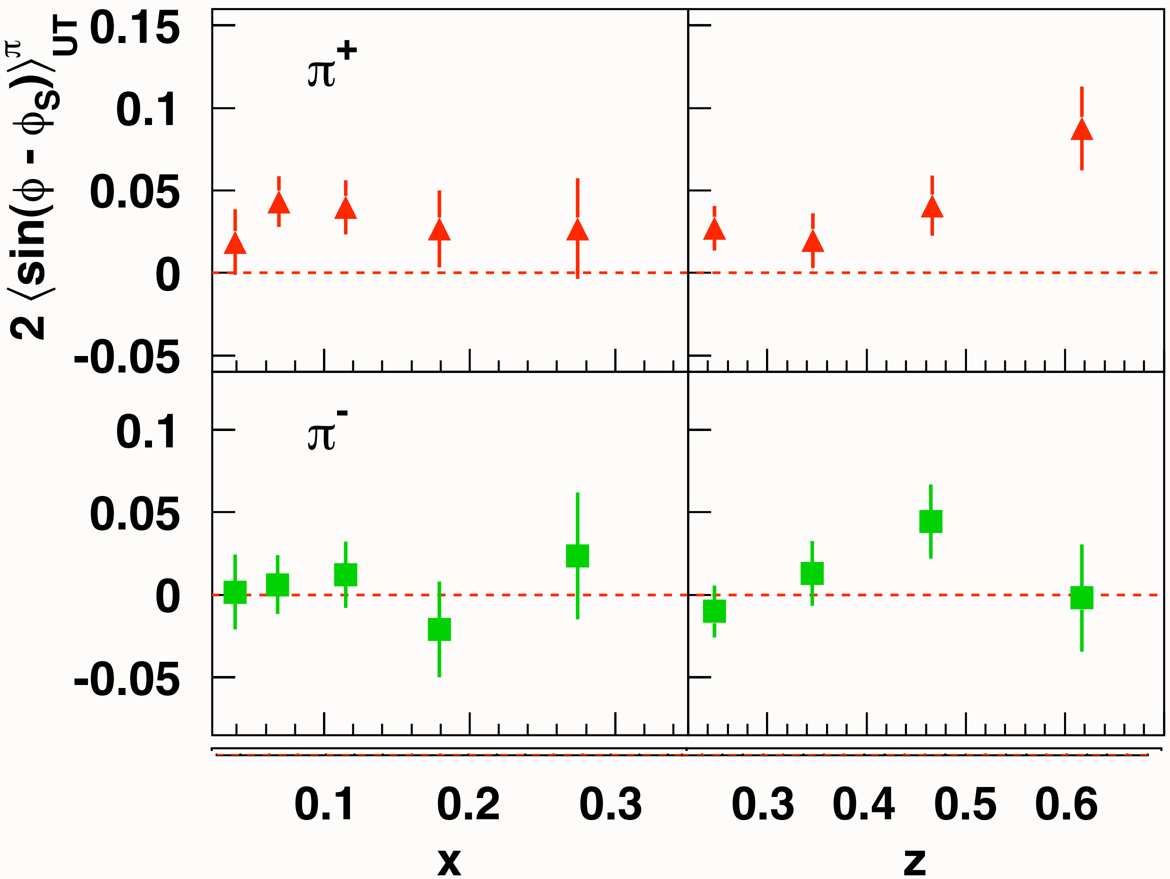
can interfere with



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!
- $\Rightarrow$ presence of non-zero **quark orbital angular momentum**!
- Positive for π^+...
  Consistent with zero for π^-...

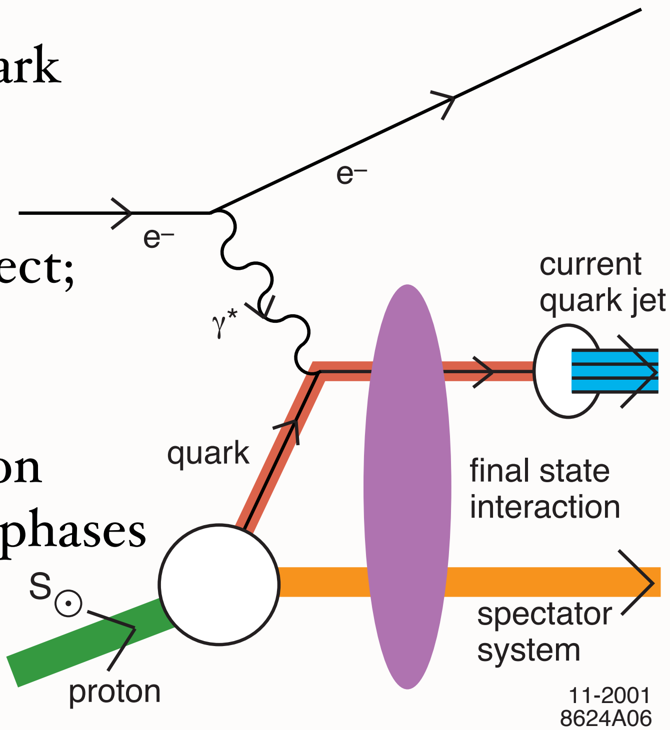
Gamberg: Hermes data compatible with BHS model

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

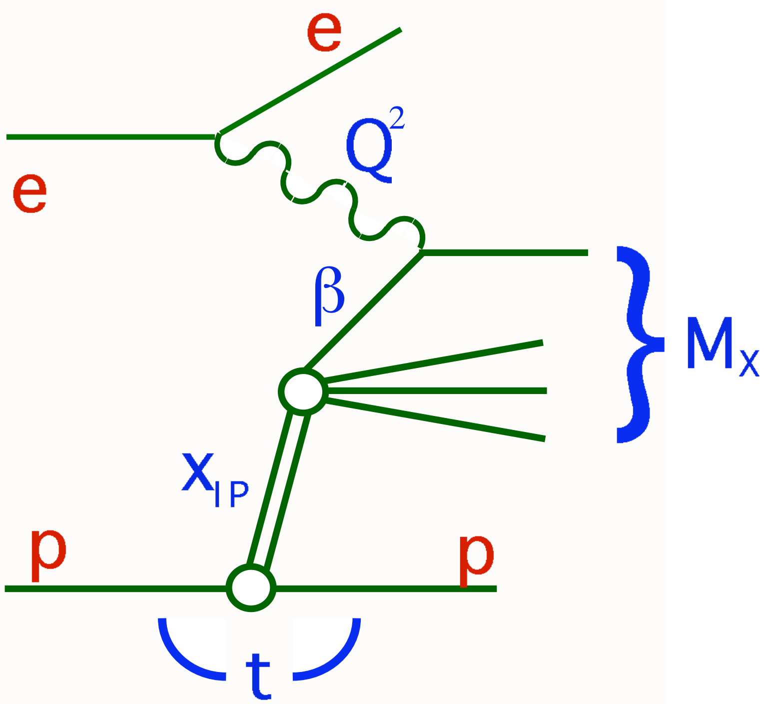
Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

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

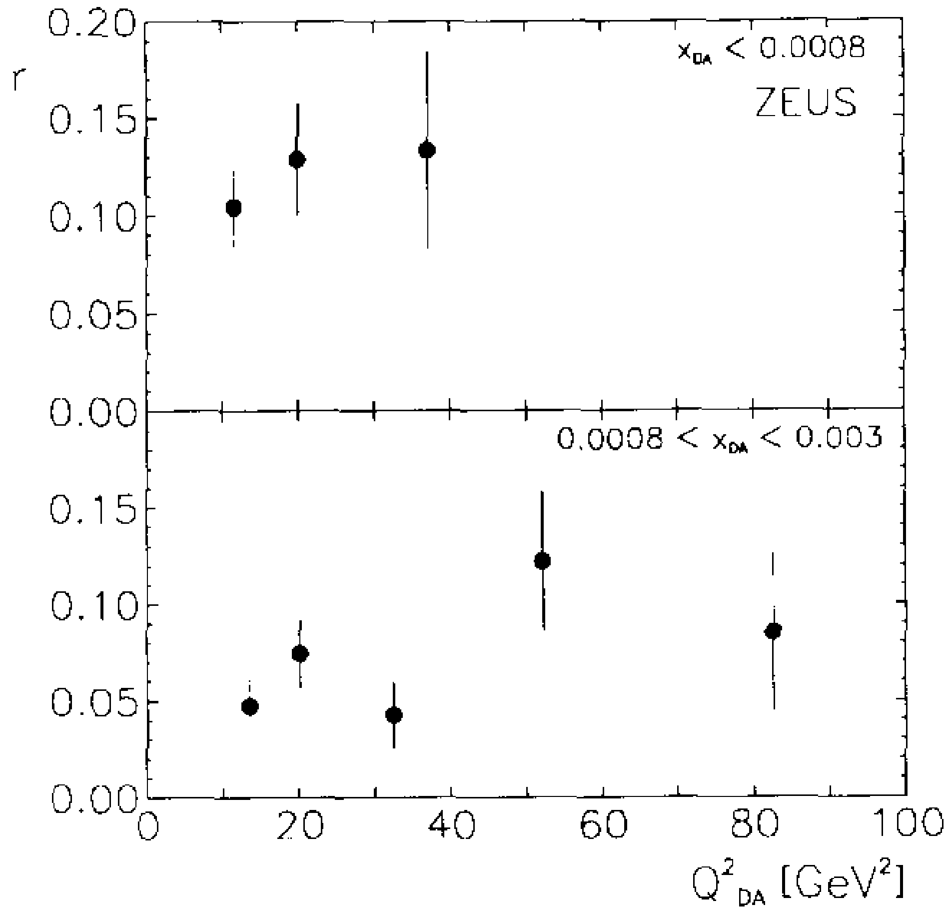
- Leading-Twist Bjorken Scaling!
- Requires nonzero orbital angular momentum of quark
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state 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



10% to 15% of DIS events are diffractive !



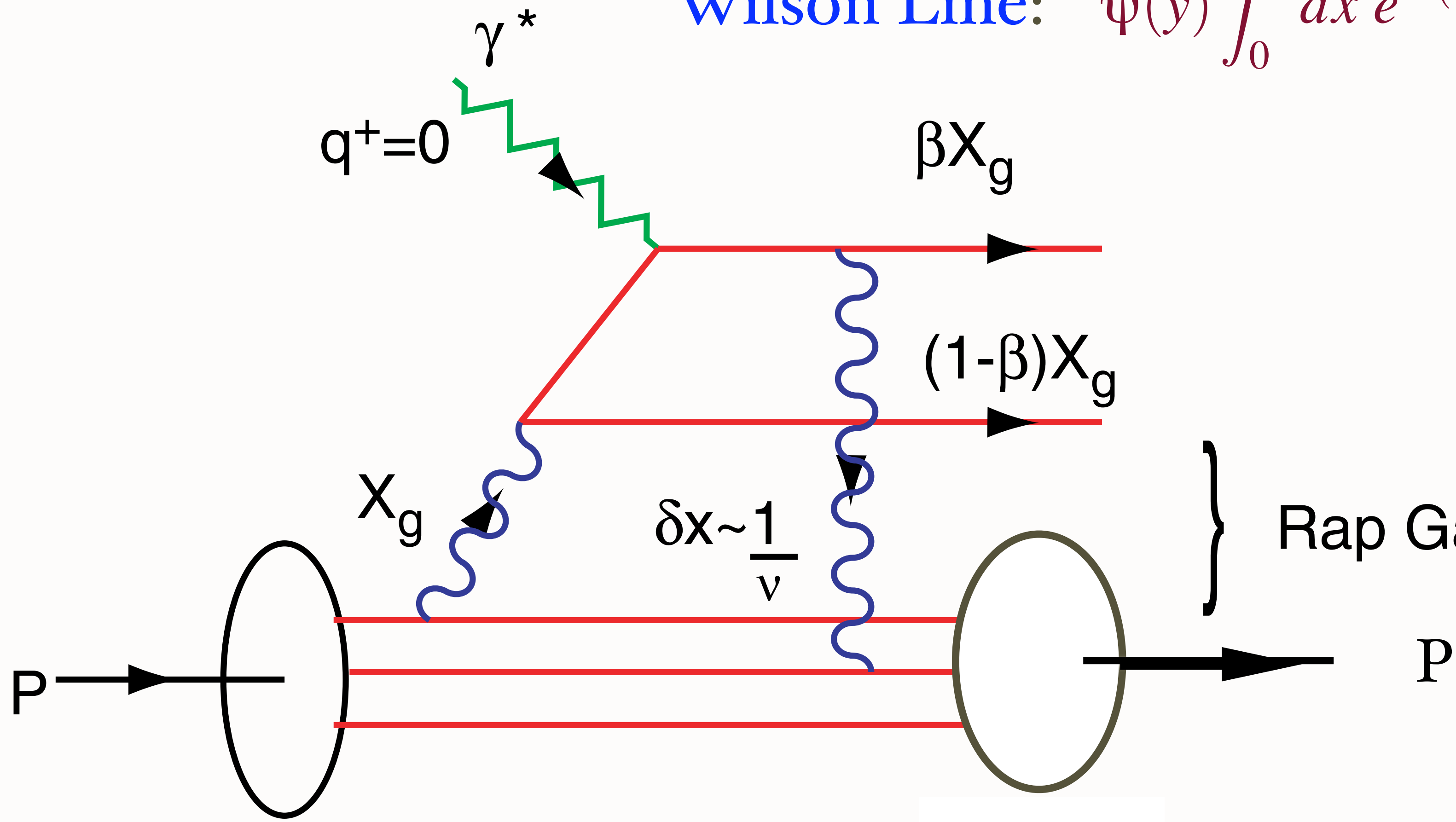
Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

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

Hoyer, Marchal, Peigne, Sannino, sjb

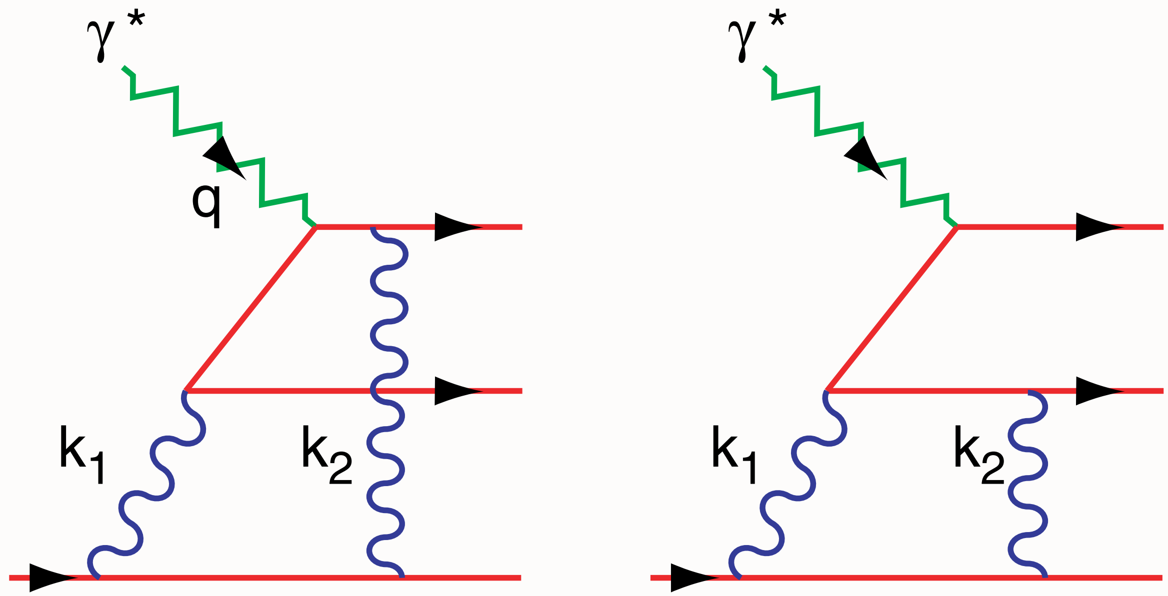
QCD Mechanism for Rapidity Gaps

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

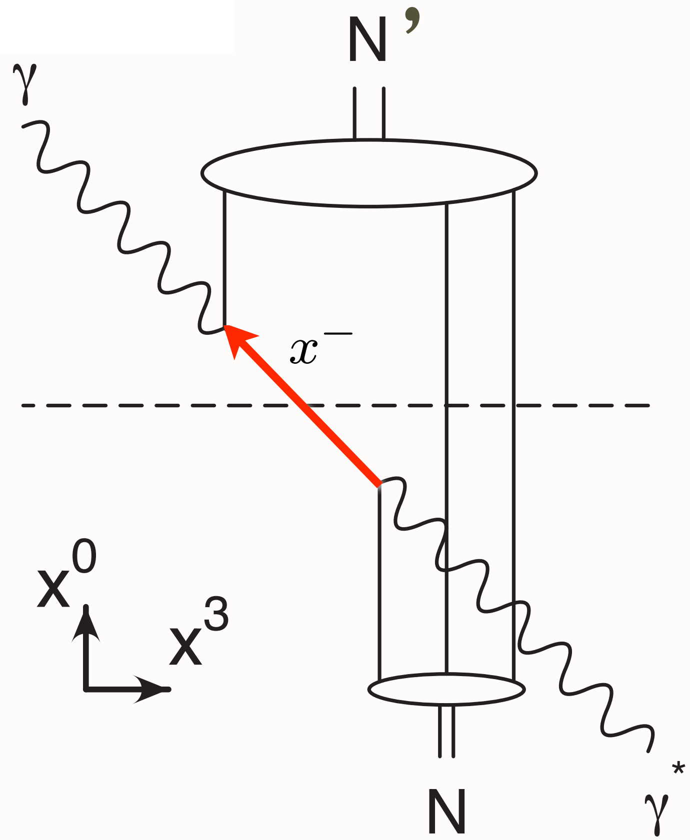
Result is Gauge Independent

Some Applications of Light-Front Wavefunctions

- Exact formulae for form factors, quark and gluon distributions; vanishing anomalous gravitational moment; edm connection to anm
- Deeply Virtual Compton Scattering, generalized parton distributions, angular momentum sum rules
- Exclusive weak decay amplitudes
- Single spin asymmetries: Role of ISI and FSI
- Factorization theorems, DGLAP, BFKL, ERBL Evolution
- Quark interchange amplitude
- Relation of spin, momentum, and other distributions to physics of the hadron itself.

Space-time picture of DVCS

P. Hoyer



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

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

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

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

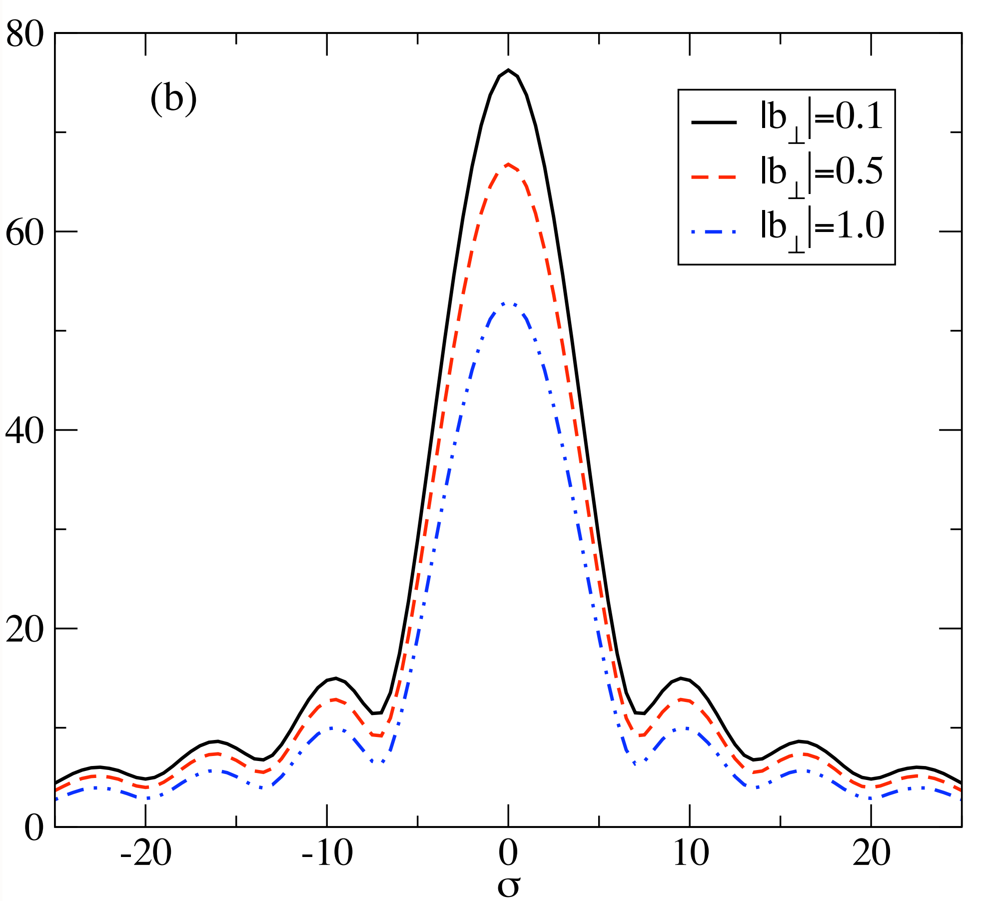
S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

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

Hadron Optics

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

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

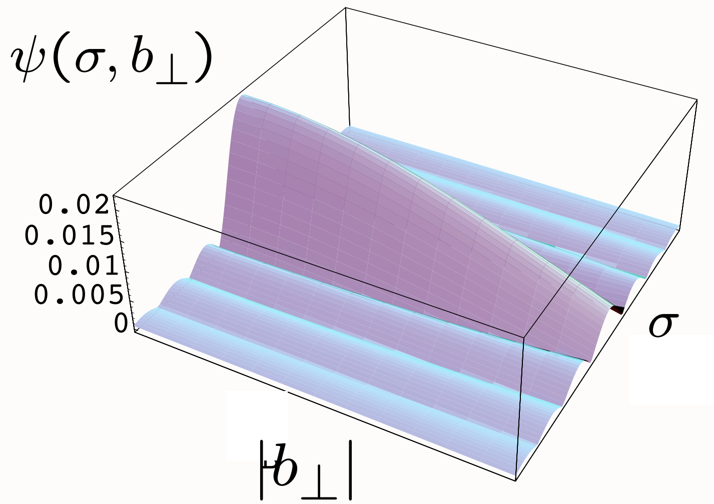


The Fourier Spectrum of the DVCS amplitude in σ space for different fixed values of $|b_\perp|$.

GeV units

DVCS Amplitude using holographic QCD meson LFWF

$$\Lambda_{QCD} = 0.32$$



String Theory

↓

AdS/CFT

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

↓

Goal: First Approximant to QCD

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

AdS/QCD

Conformal behavior at short distances
+ Confinement at large distance

↓

Semi-Classical QCD / Wave Equations

↓

Holography

Boost Invariant 3+1 Light-Front Wave Equations

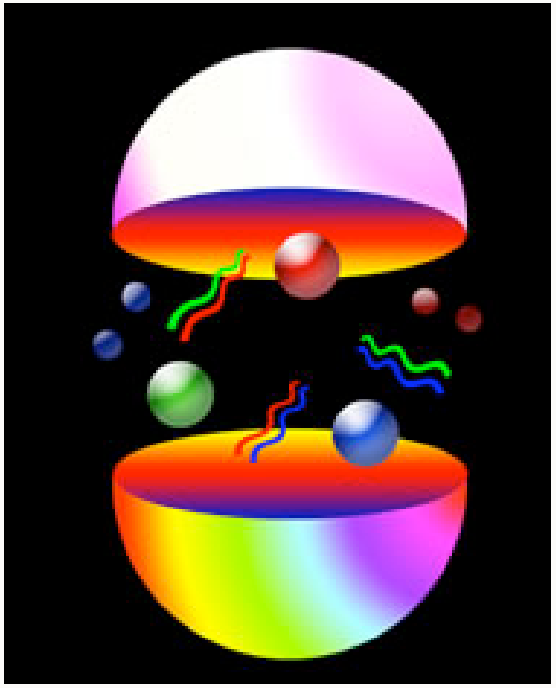
↓

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

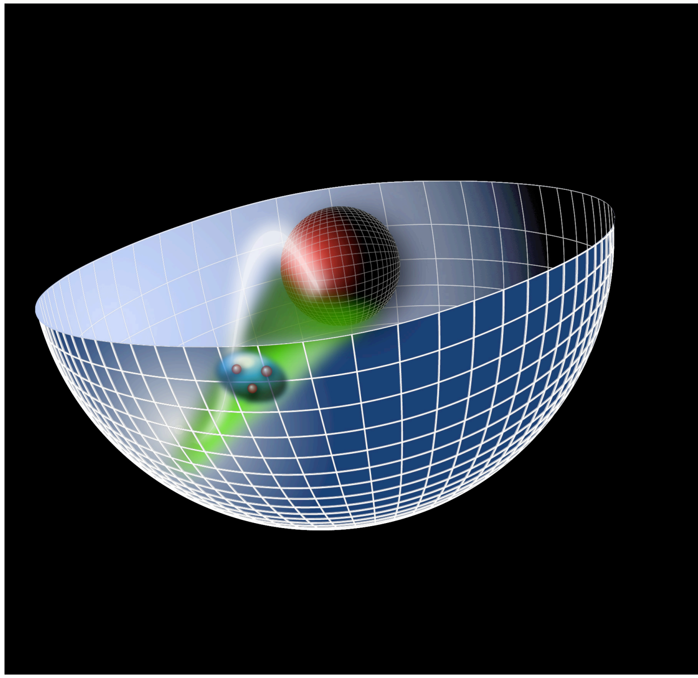
Integrable!

Hadron Spectra, Wavefunctions, Dynamics

AdS/CFT and Hadronic Physics on the Light Front



Lev Davidovich Landau



Stan Brodsky SLAC/IPPP

Landau Memorial Meeting Moscow June 20, 2008

Light-Front Holography and AdS/QCD Correspondence.
Stanley J. Brodsky, Guy F. de Teramond . SLAC-PUB-13220, Apr 2008. 14pp.
e-Print: **arXiv:0804.3562** [hep-ph]

Light-Front Dynamics and AdS/QCD Correspondence: Gravitational Form Factors of Composite Hadrons.
Stanley J. Brodsky (SLAC) , Guy F. de Teramond (Ecole Polytechnique, CPHT & Costa Rica U.) . SLAC-PUB-13192, Apr 2008. 12pp. e-Print: **arXiv:0804.0452** [hep-ph]

AdS/CFT and Light-Front QCD.
Stanley J. Brodsky, Guy F. de Teramond . SLAC-PUB-13107, Feb 2008. 38pp.
Invited talk at International School of Subnuclear Physics: 45th Course: Searching for the "Totally Unexpected" in the LHC Era, Erice, Sicily, Italy, 29 Aug - 7 Sep 2007.
e-Print: **arXiv:0802.0514** [hep-ph]

AdS/CFT and Exclusive Processes in QCD.
Stanley J. Brodsky, Guy F. de Teramond . SLAC-PUB-12804, Sep 2007. 29pp. Temporary entry
e-Print: **arXiv:0709.2072** [hep-ph]

Light-Front Dynamics and AdS/QCD Correspondence: The Pion Form Factor in the Space- and Time-Like Regions.
Stanley J. Brodsky (SLAC) , Guy F. de Teramond (Costa Rica U. & SLAC) . SLAC-PUB-12554, SLAC-PUB-12544, Jul 2007. 20pp.
Published in **Phys.Rev.D77:056007,2008**.
e-Print: **arXiv:0707.3859** [hep-ph]