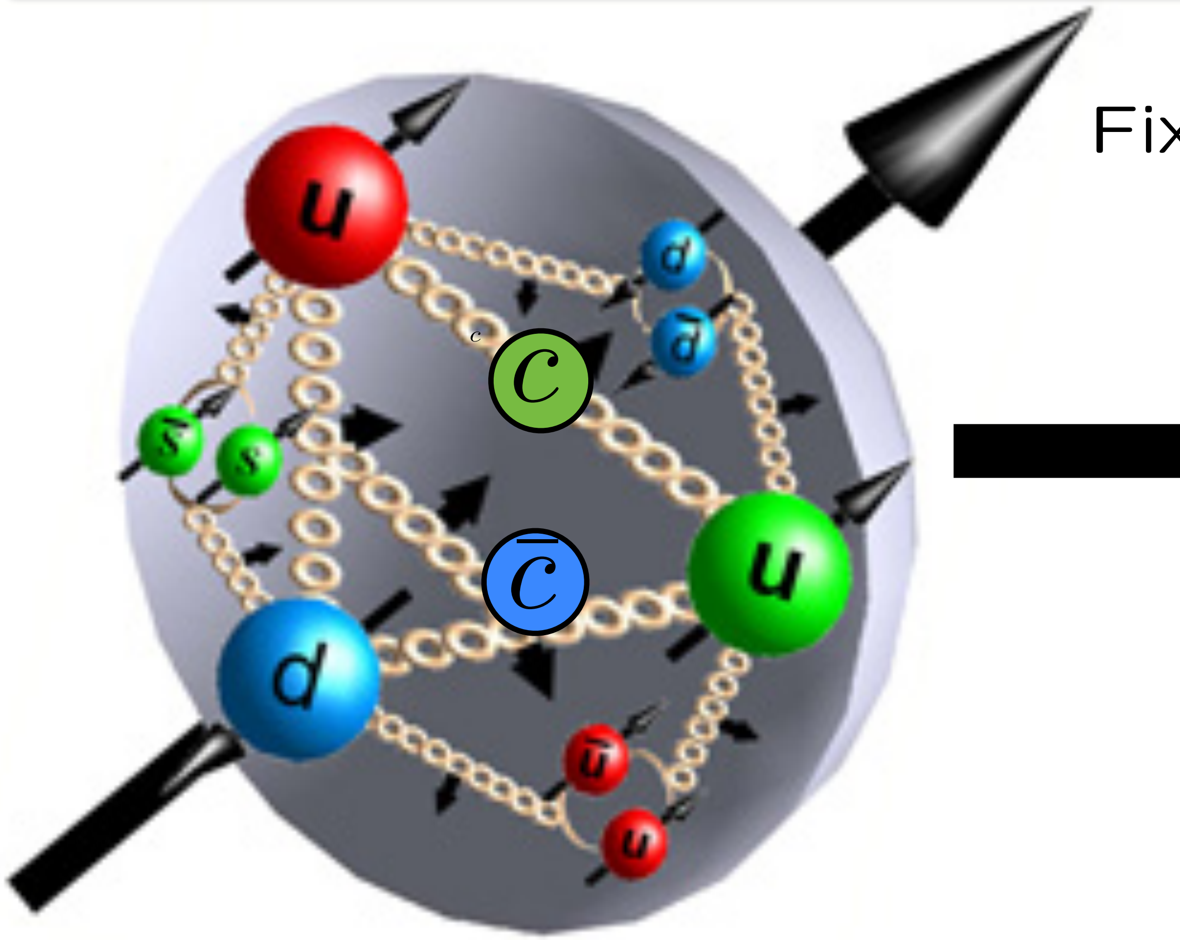
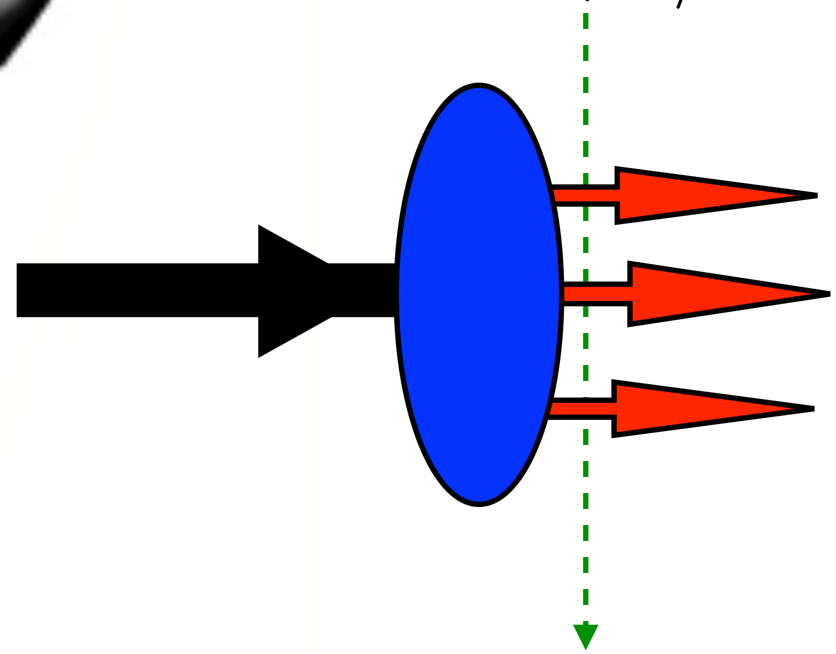
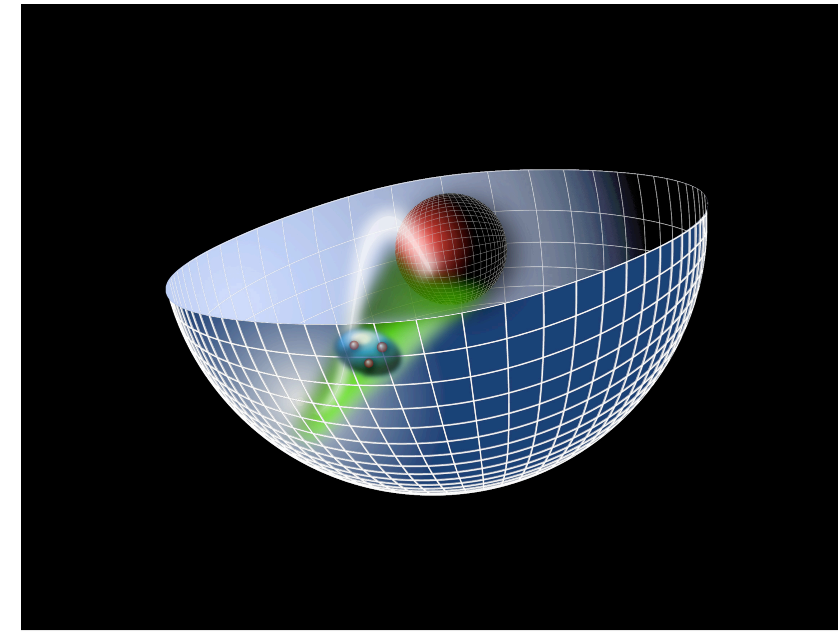
Physics on the Light Front: A Novel Approach to Quark Confinement and QCD Phenomena







Colloquium
March 22, 2018

Instituto de Física Teórica
UAM-CSIC

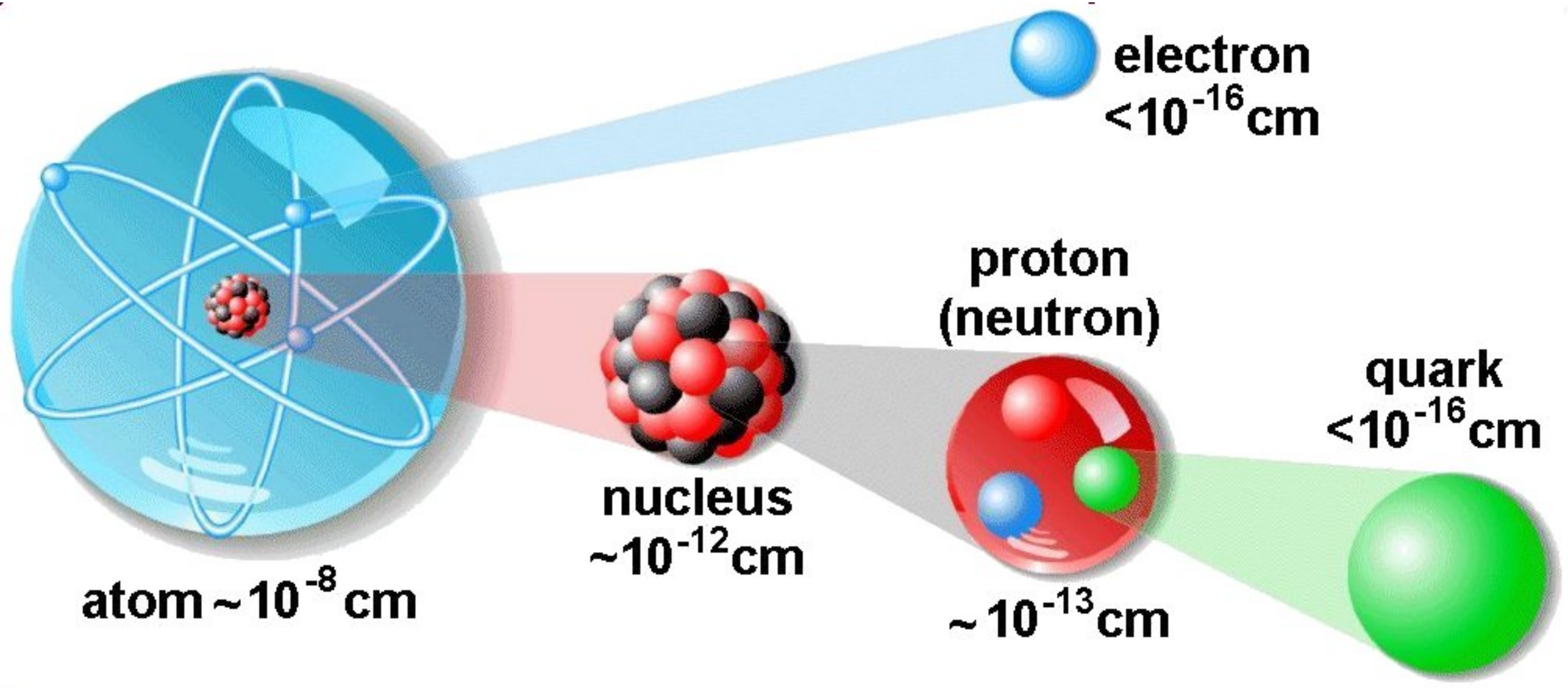
Stan Brodsky

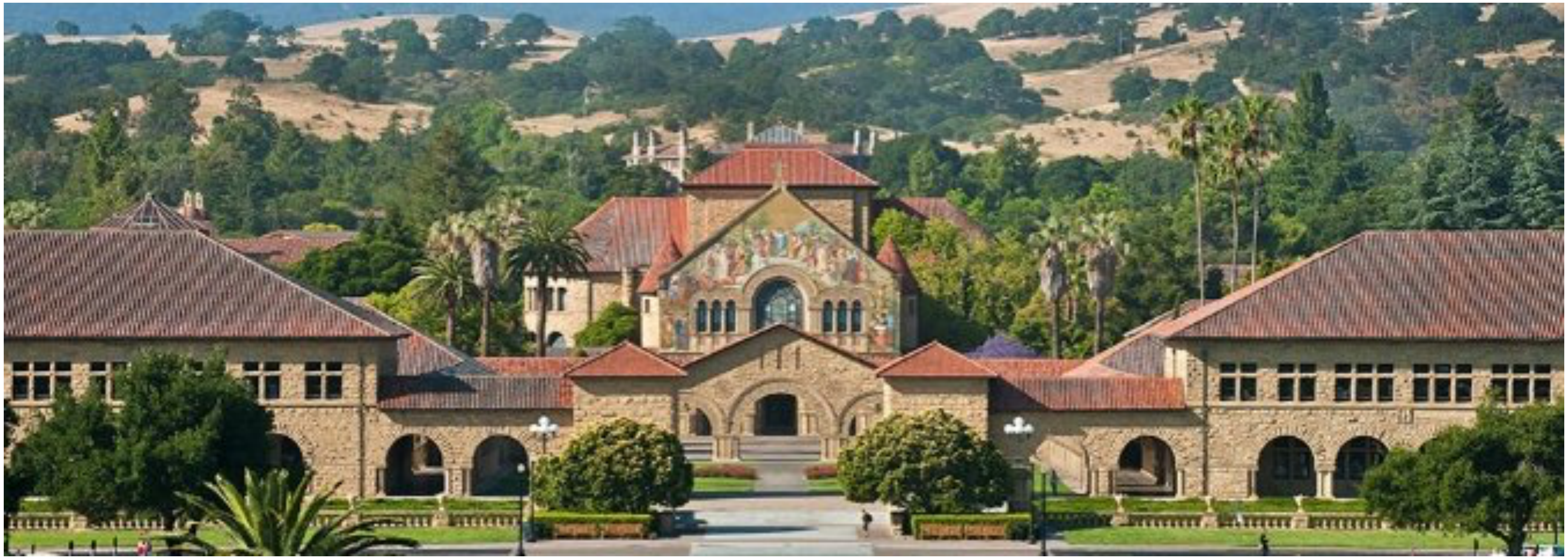
SLAC NATIONAL ACCELERATOR LABORATORY

with Guy de Tèramond, Hans Günter Dosch, Cedric Lorcè, and Alexandre Deur

Goal of Science:

To understand the laws of physics and the fundamental composition of matter at the shortest possible distances.





SLAC
NATIONAL ACCELERATOR LABORATORY

STANFORD
UNIVERSITY

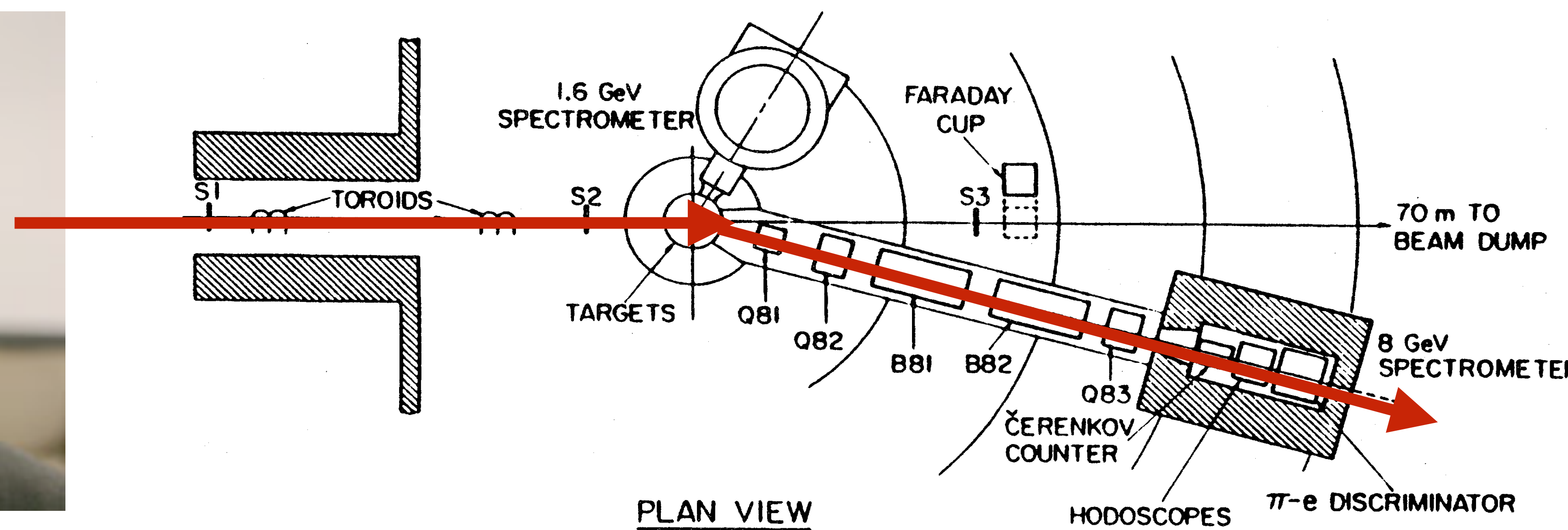
Discovery of the Quark Structure of Matter

SLAC
NATIONAL ACCELERATOR LABORATORY

1967

SLAC Two-Mile Linear Accelerator

Pief

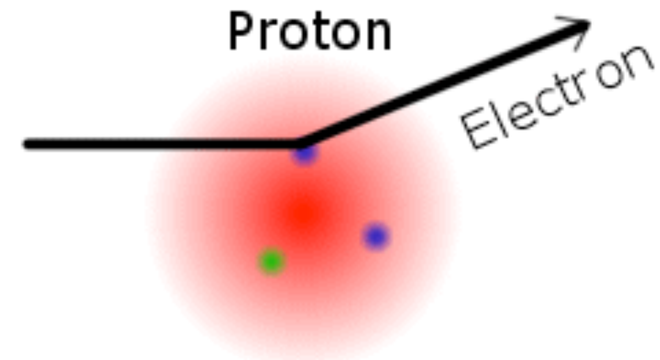


1967 SLAC Experiment:

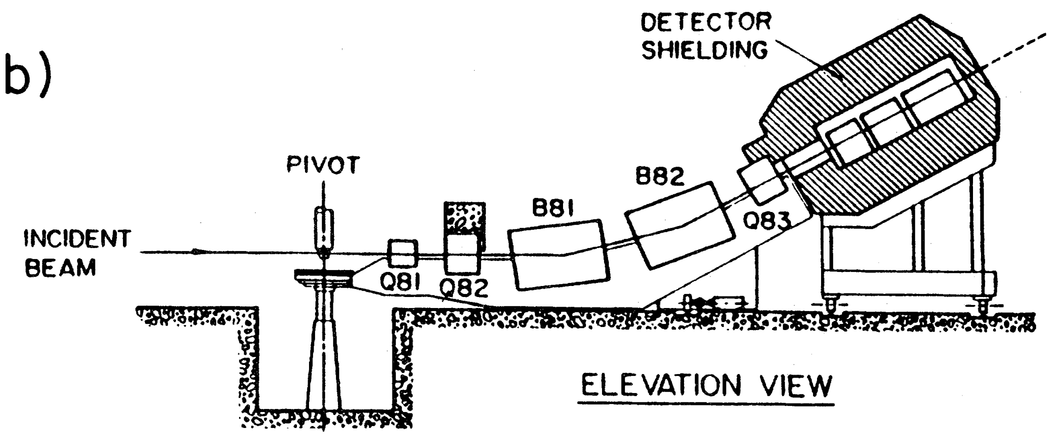
Scatter 20 GeV/c Electrons on protons in a Hydrogen Target

Discovery of the Quark Structure of Matter

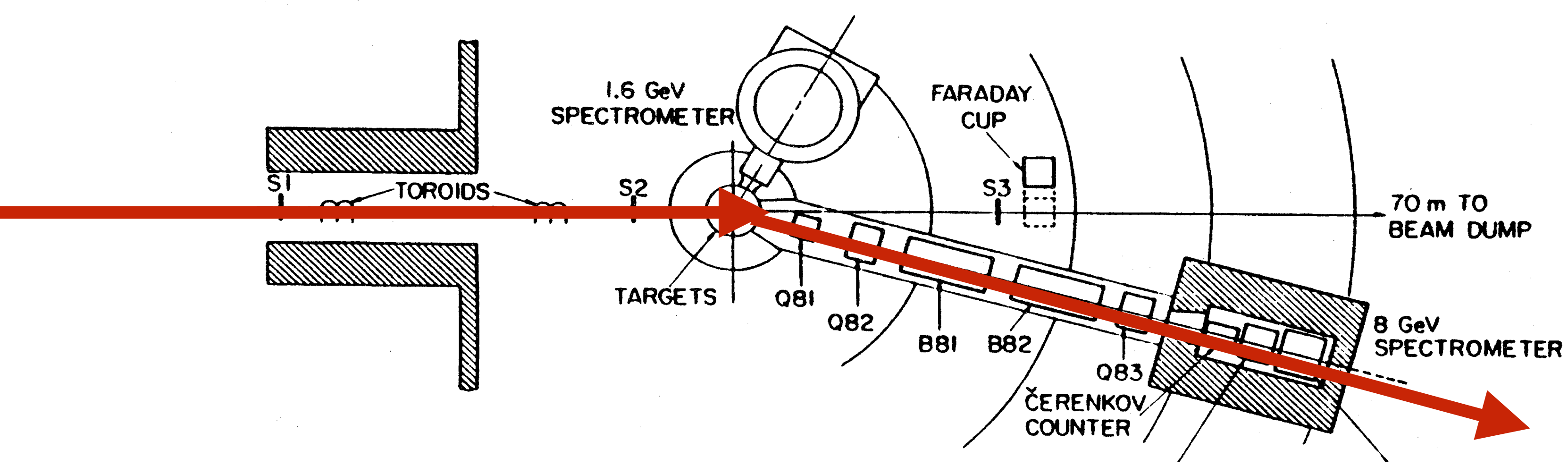
$$ep \longrightarrow e'X$$

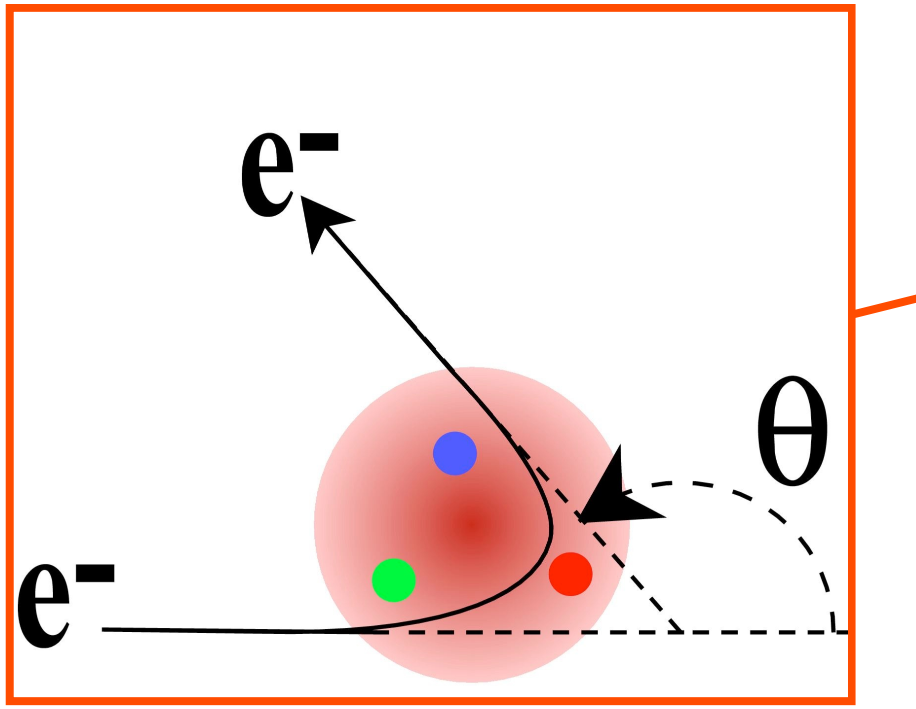


(b)



Discovery of quarks!



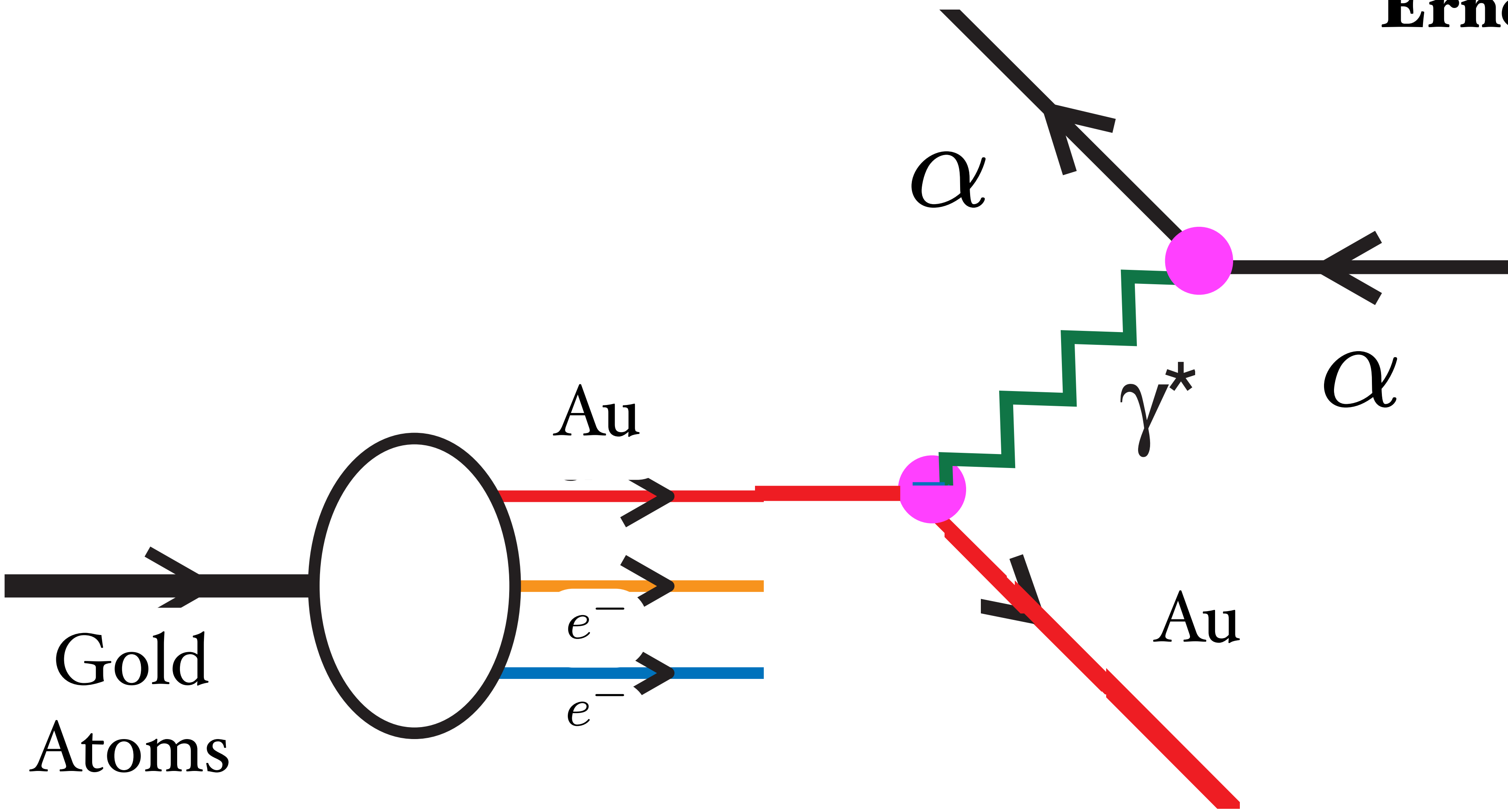


Deep inelastic scattering: Experiments on the proton and the observation of scaling*

Friedman, Kendall, Taylor: 1990 Nobel Prize

First Evidence for Nuclear, Composite Structure of Atoms

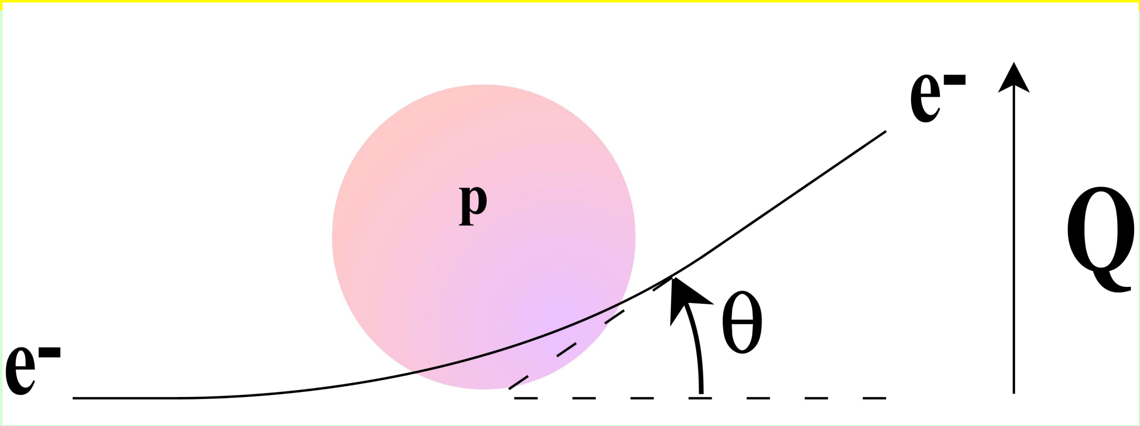
Ernest Rutherford
1911



Scattering at Large Angles!
"Point-like" Nucleus

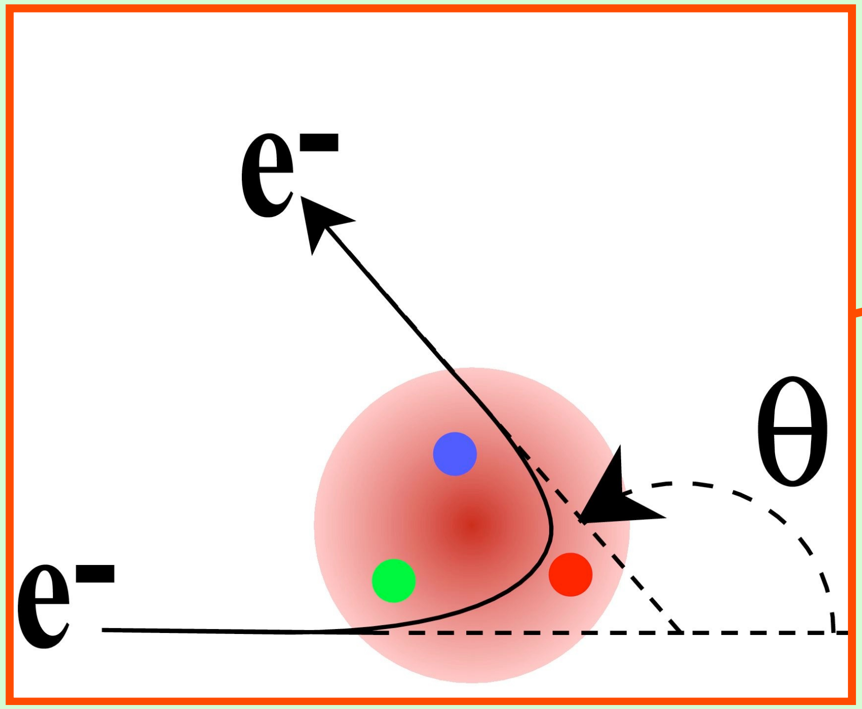
Rutherford Scattering

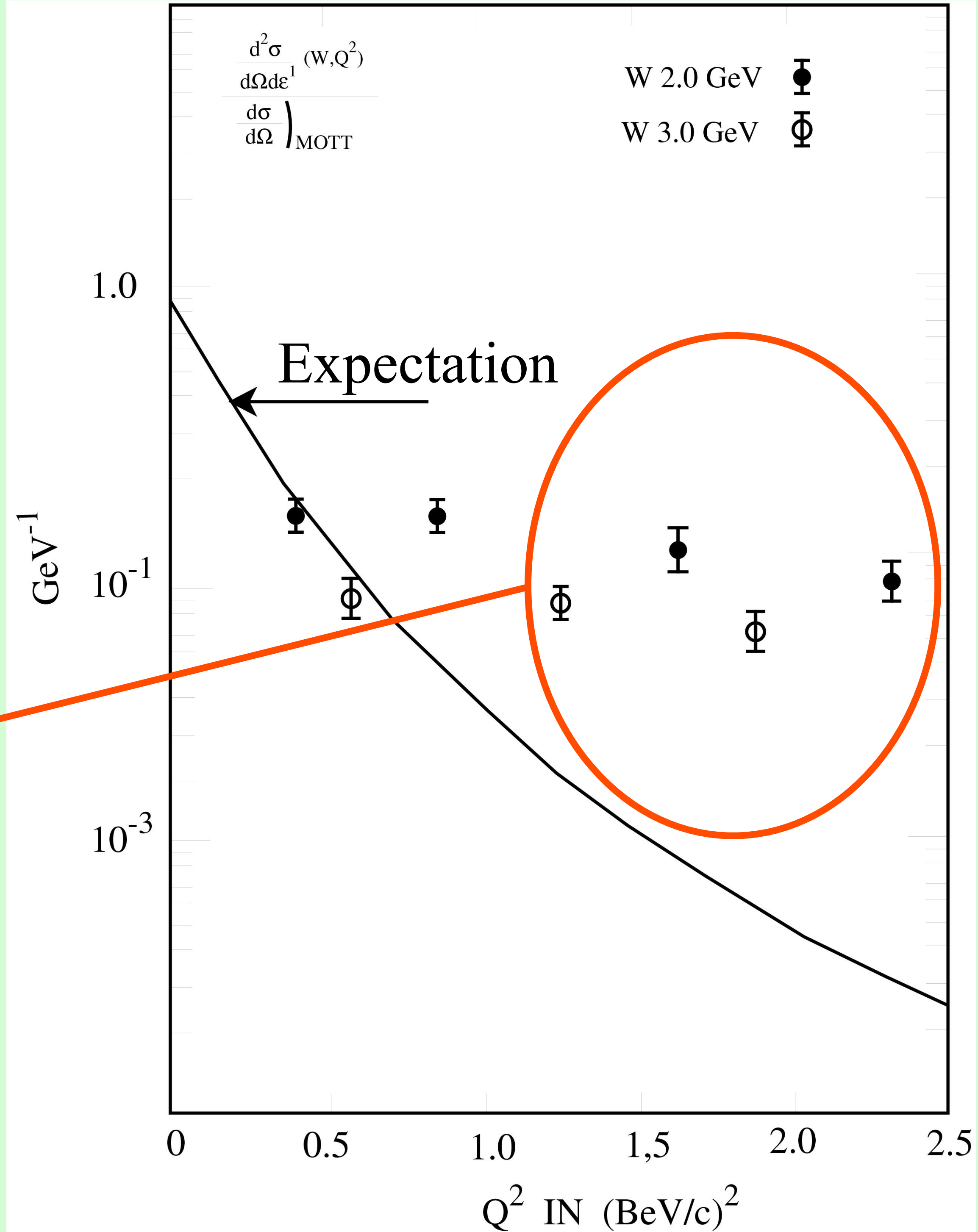
Deep inelastic electron-proton scattering



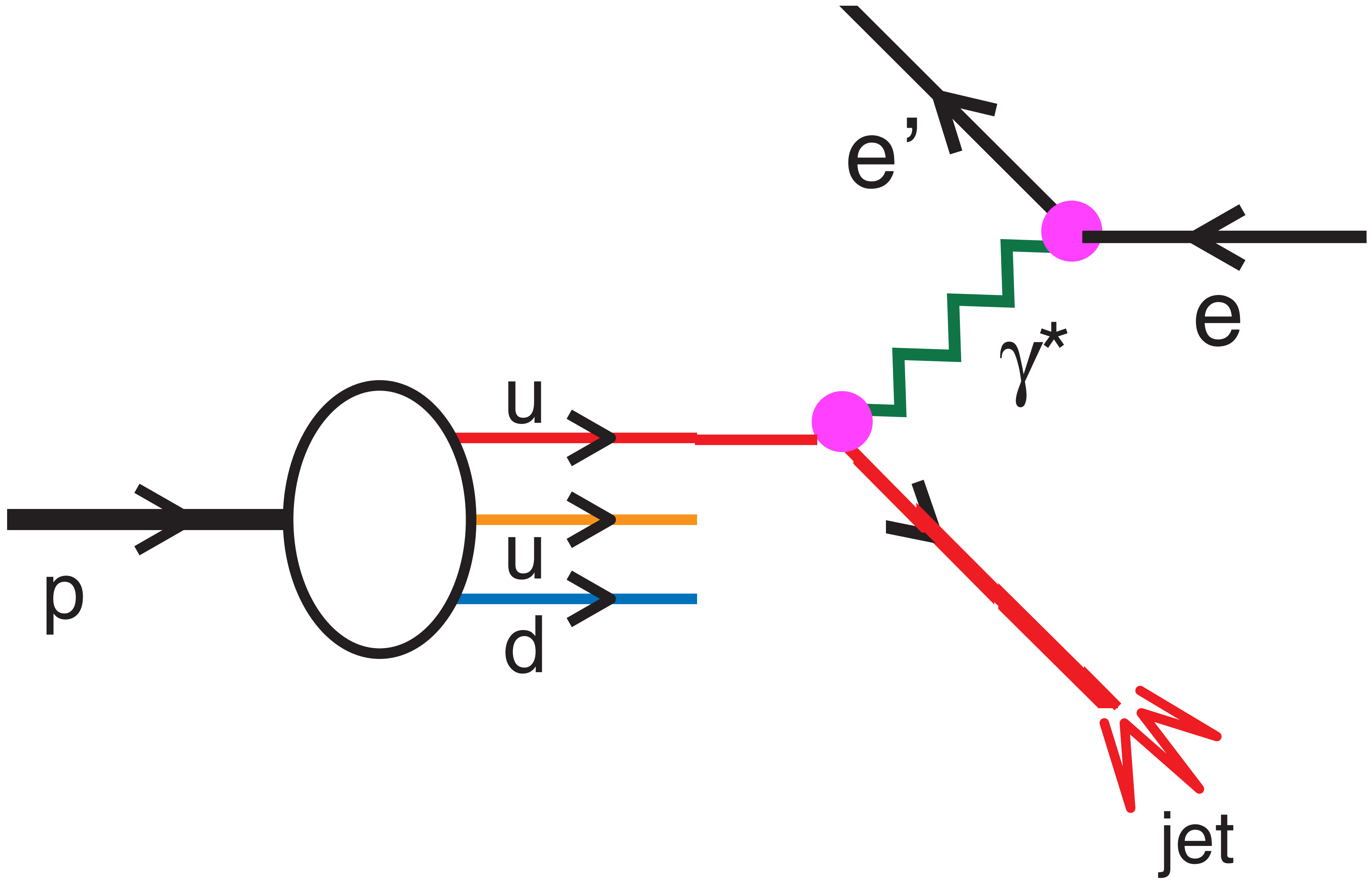
- Rutherford scattering using *very* high-energy electrons striking protons

Discovery of quarks!





SLAC 1967: First Evidence for Quark Structure of Matter

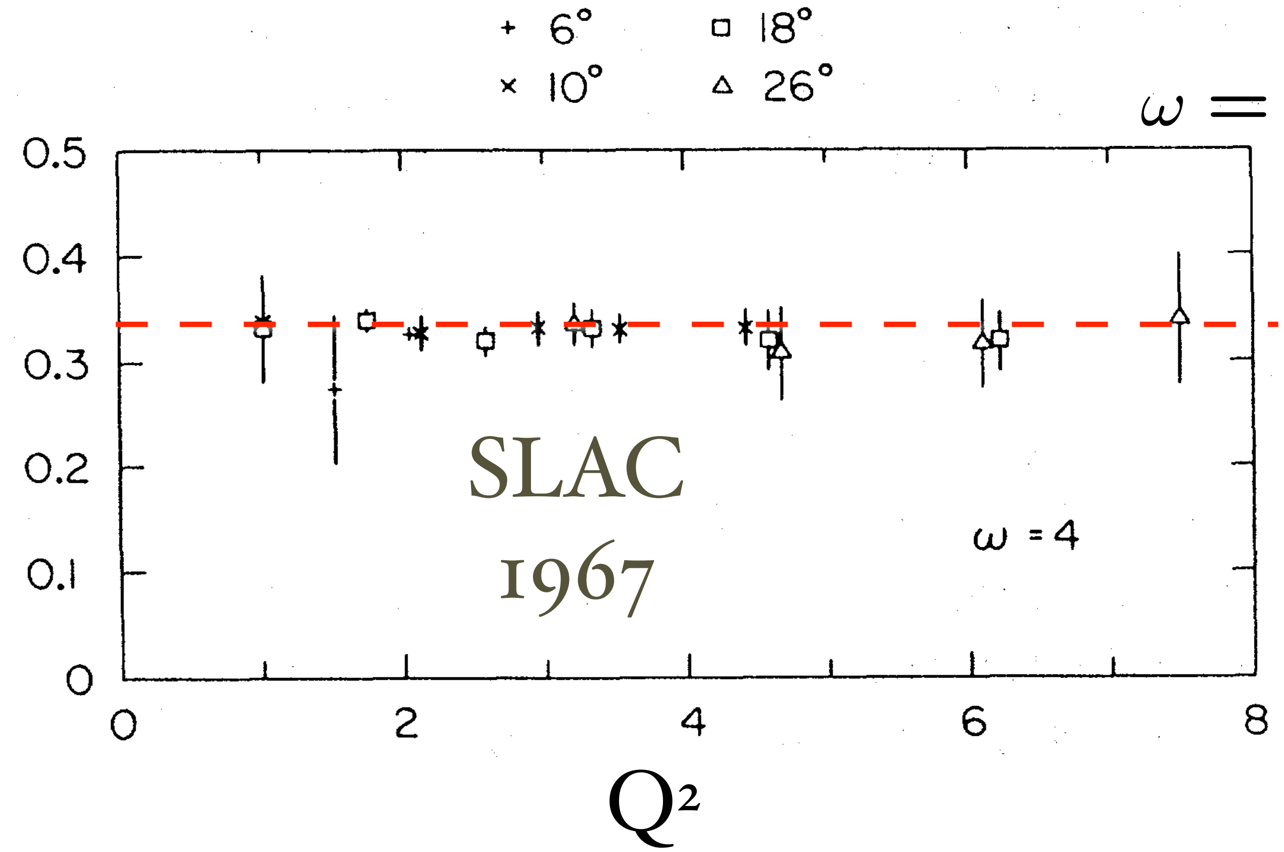


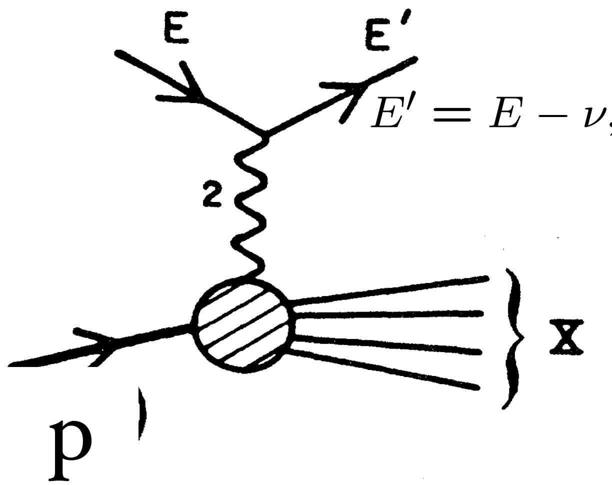
Deep Inelastic Electron-Proton Scattering

$$ep \longrightarrow e'X$$

$$\omega = \frac{2M_p\nu}{Q^2}$$

$$F_2(x = 1/4, Q^2)$$





$E' = E - \nu, \vec{q}$

$$Q^2 = \vec{q}^2 - \nu^2$$

No intrinsic length scale !

Measure rate as a function of energy loss ν and momentum transfer Q

Scaling at fixed $x_{Bjorken} = \frac{Q^2}{2M_p\nu} = \frac{1}{\omega}$

$\omega = 4 \longrightarrow x_{bj} = 0.25$ (quark momentum fraction)

Discovery of Bjorken Scaling:
Electron scatters on point-like quarks!

$Q^4 \times \frac{d\sigma}{dQ^2} = F(x_{Bj})$ independent of Q²

Scale-free

Quarks + Scaling



Friedman Kendall Taylor

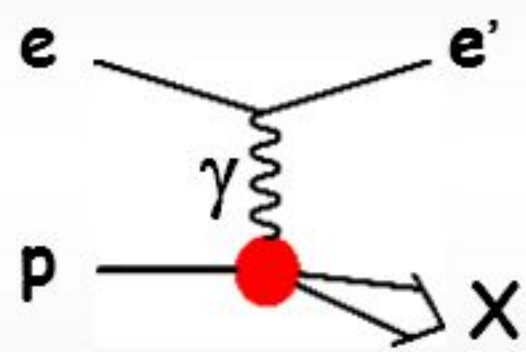
Nobel Prize

1990

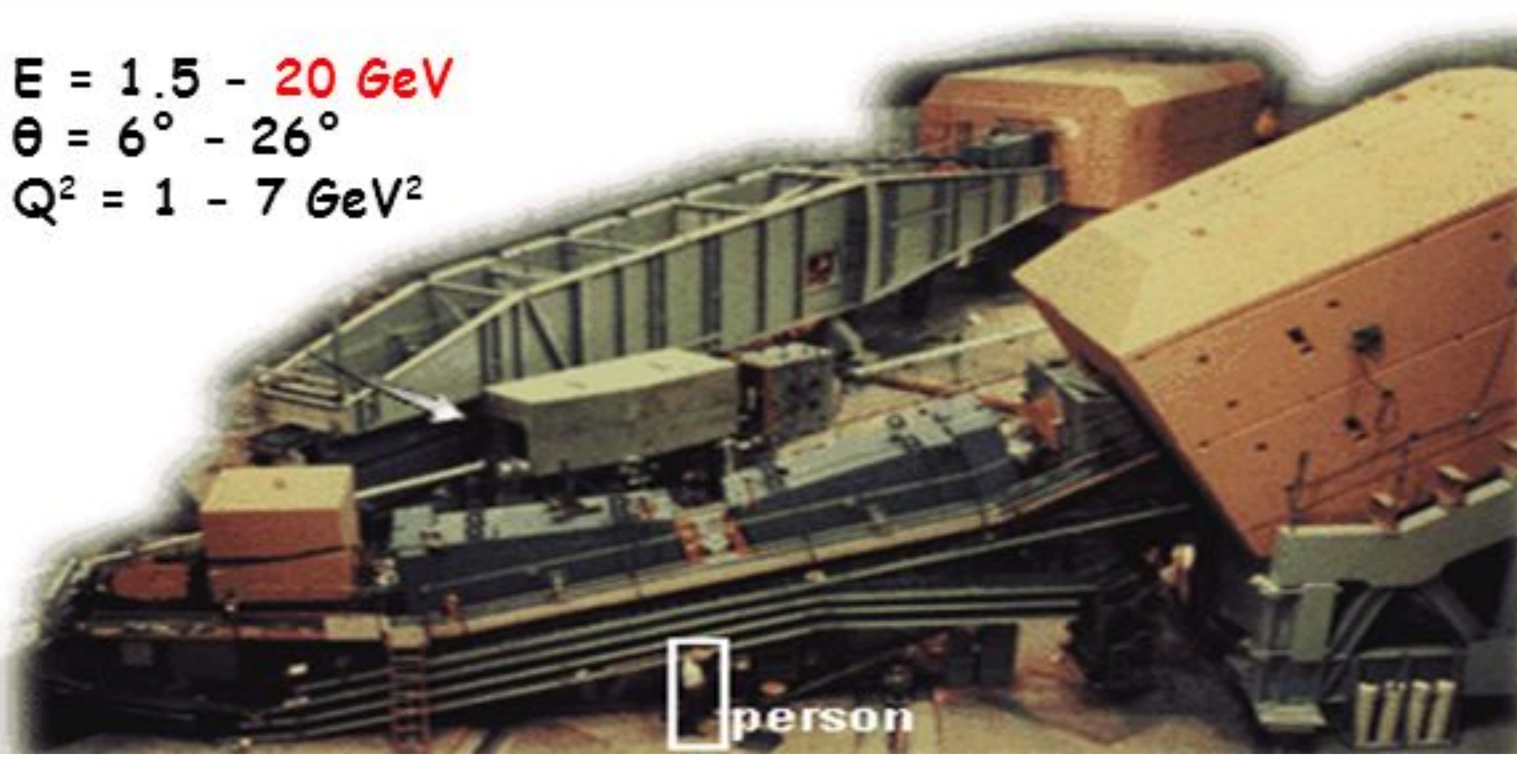
Stanford Linear Accelerator

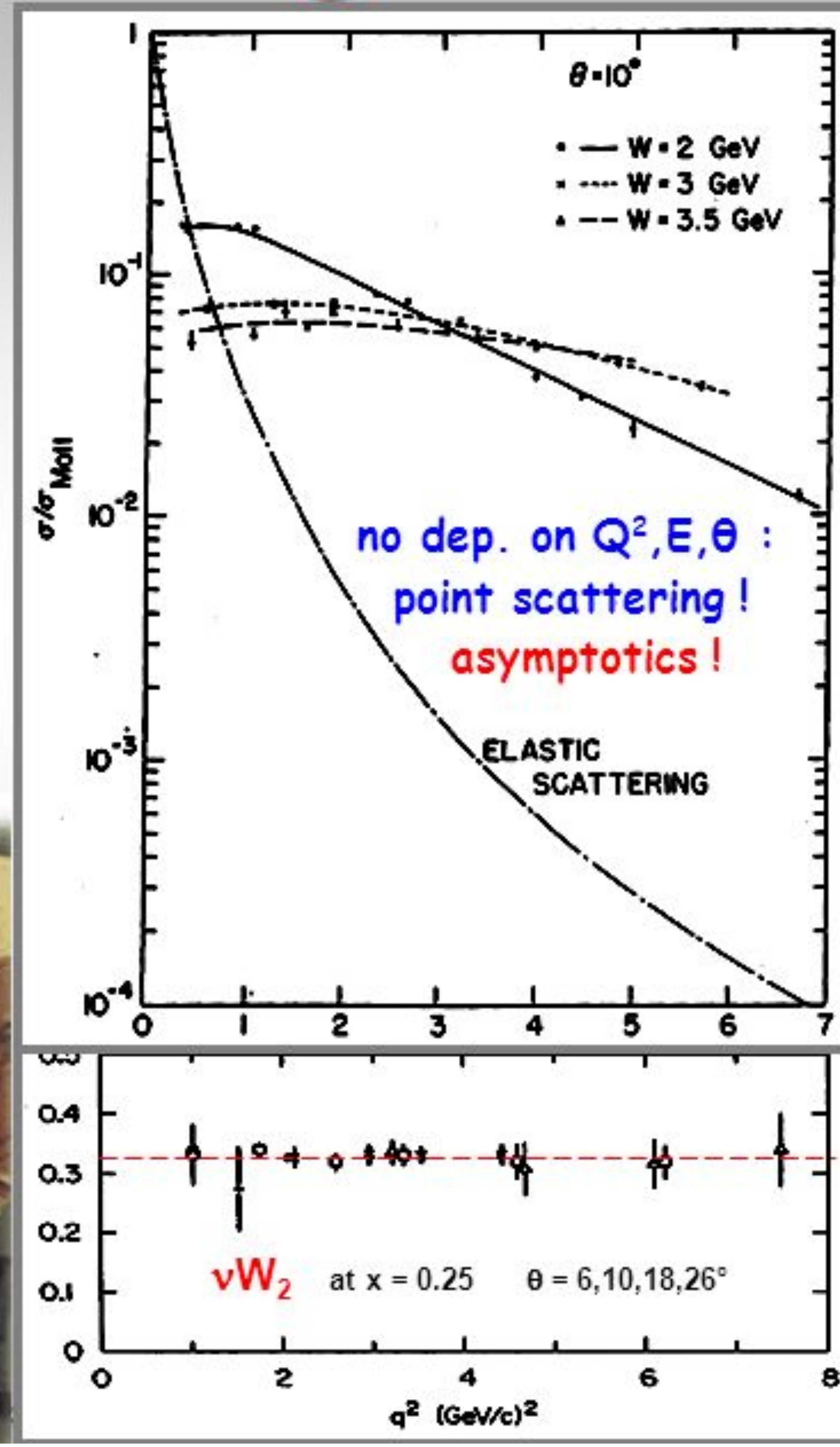
1967-1971

Electron-Proton Deep Inelastic Scattering

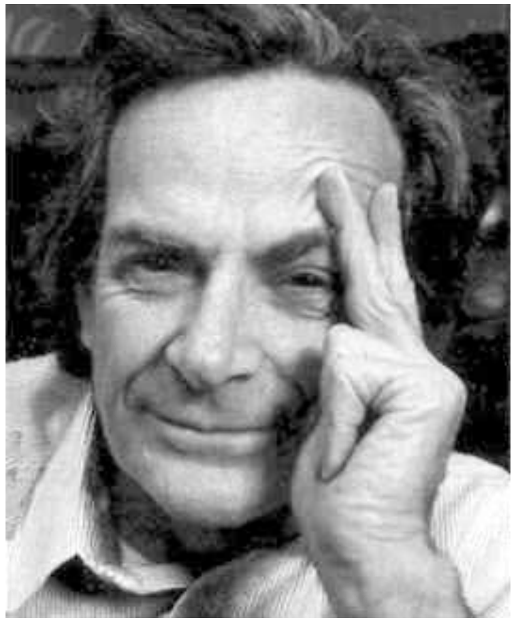


E = 1.5 - 20 GeV
θ = 6° - 26°
Q^2 = 1 - 7 GeV^2





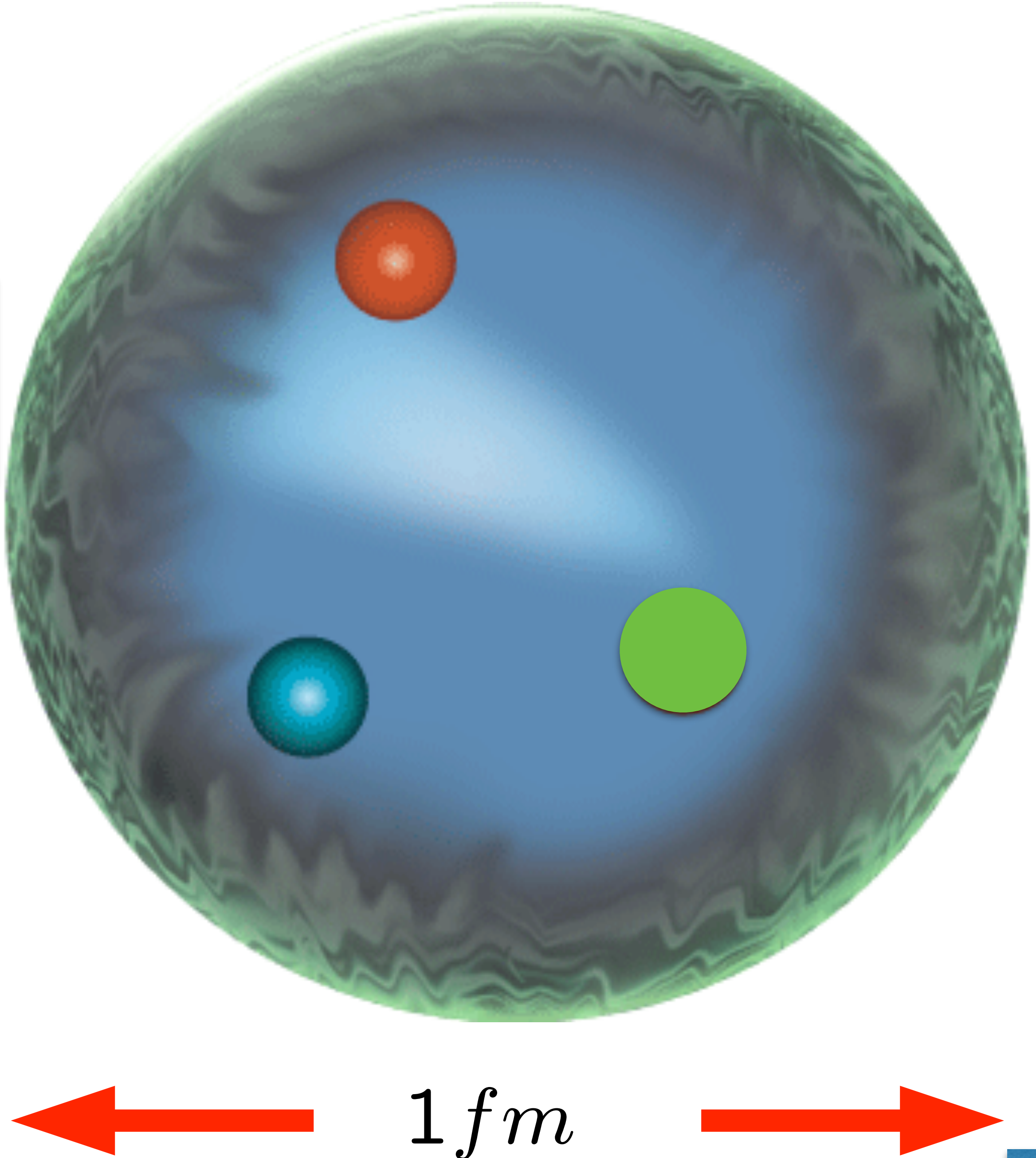
Quarks in the Proton



Feynman: "Parton" model

Bjorken: Scaling

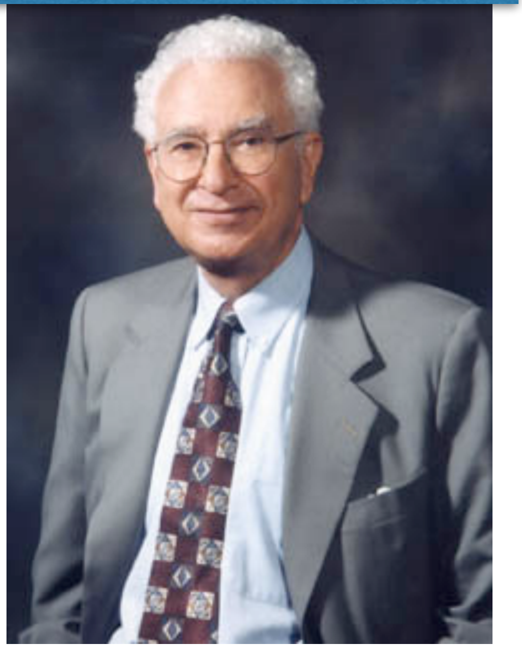
$$p = (u\,u\,d)$$



$$1\,fm$$

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

Zweig: "Aces, Deuces, Treys"



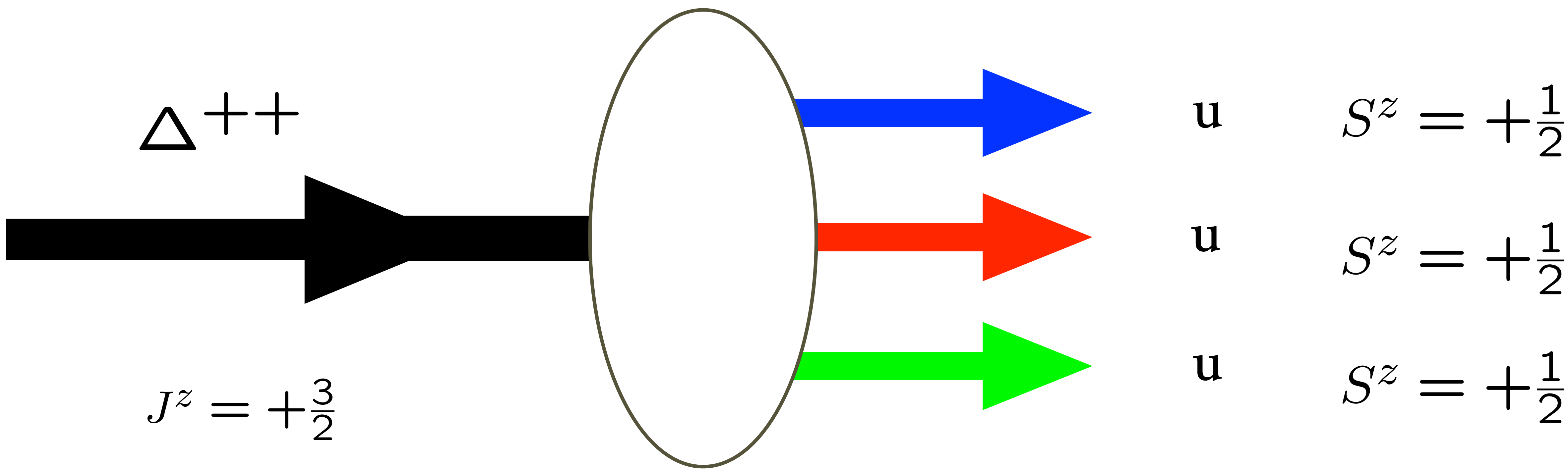
Gell Mann: "Three Quarks for Mr. Mark"

Why are there three colors of quarks?

Greenberg

Pauli Exclusion Principle!

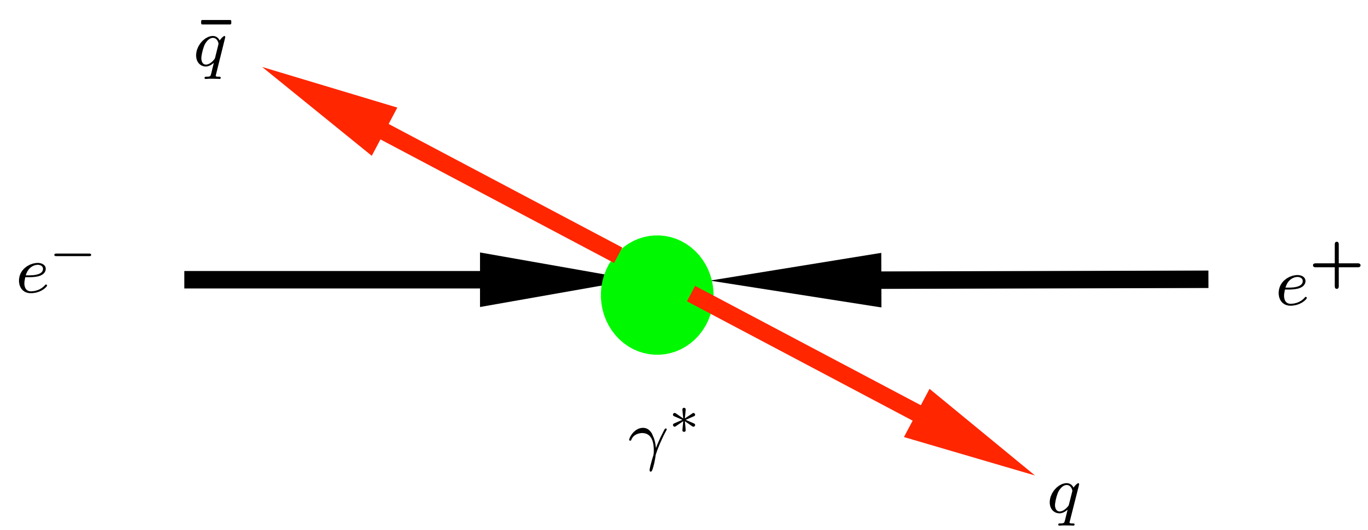
spin-half quarks cannot be in same quantum state !



Three Colors (Parastatistics) Solves Paradox

3 Colors Combine : WHITE $\quad SU(N_C), N_C = 3$

Electron-Positron Annihilation

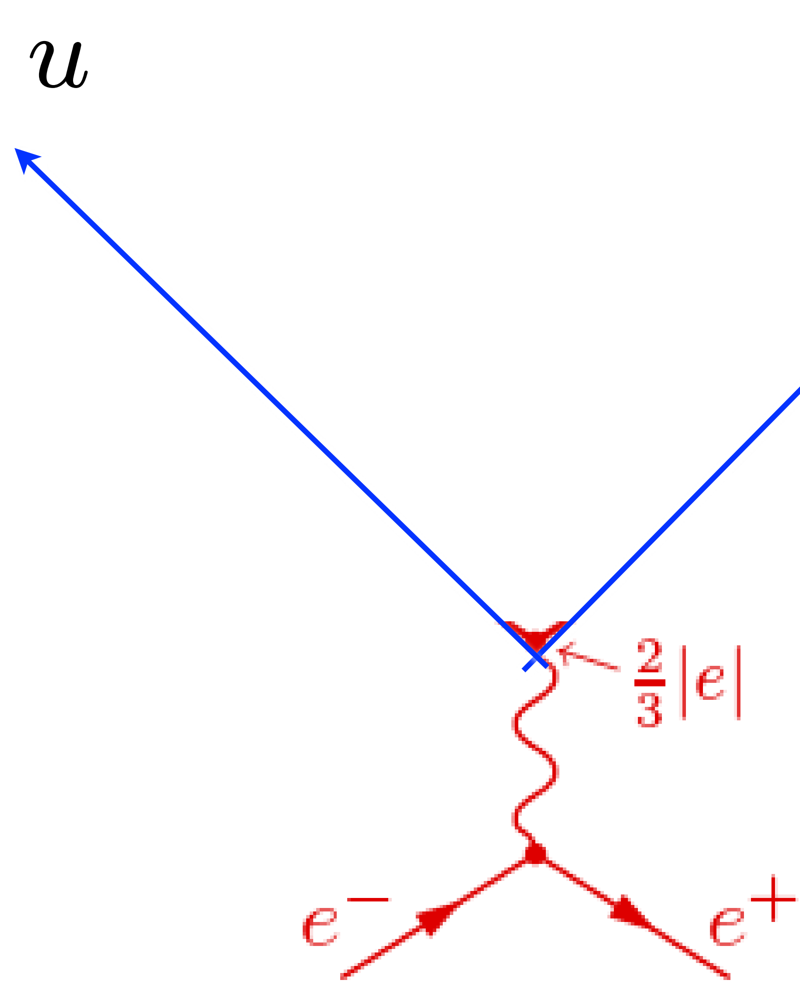


$$e^+e^- \to \gamma^* \to q\bar{q}$$

Ratio of quark-pair production to muon pair production proportional to quark charge squared times the number of colors

$$R_{e^+e^-}(s) = \frac{\sigma(e^+e^- \to \ q\bar{q})}{\sigma(e^+e^- \to \ \mu^+\bar{\mu}^-)} = N_C \times \sum_q e_q^2$$

How to Count Quarks



Color-triplet quark representation

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

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

SPEAR Electron-Positron Collider SLAC 1972

Burt Richter

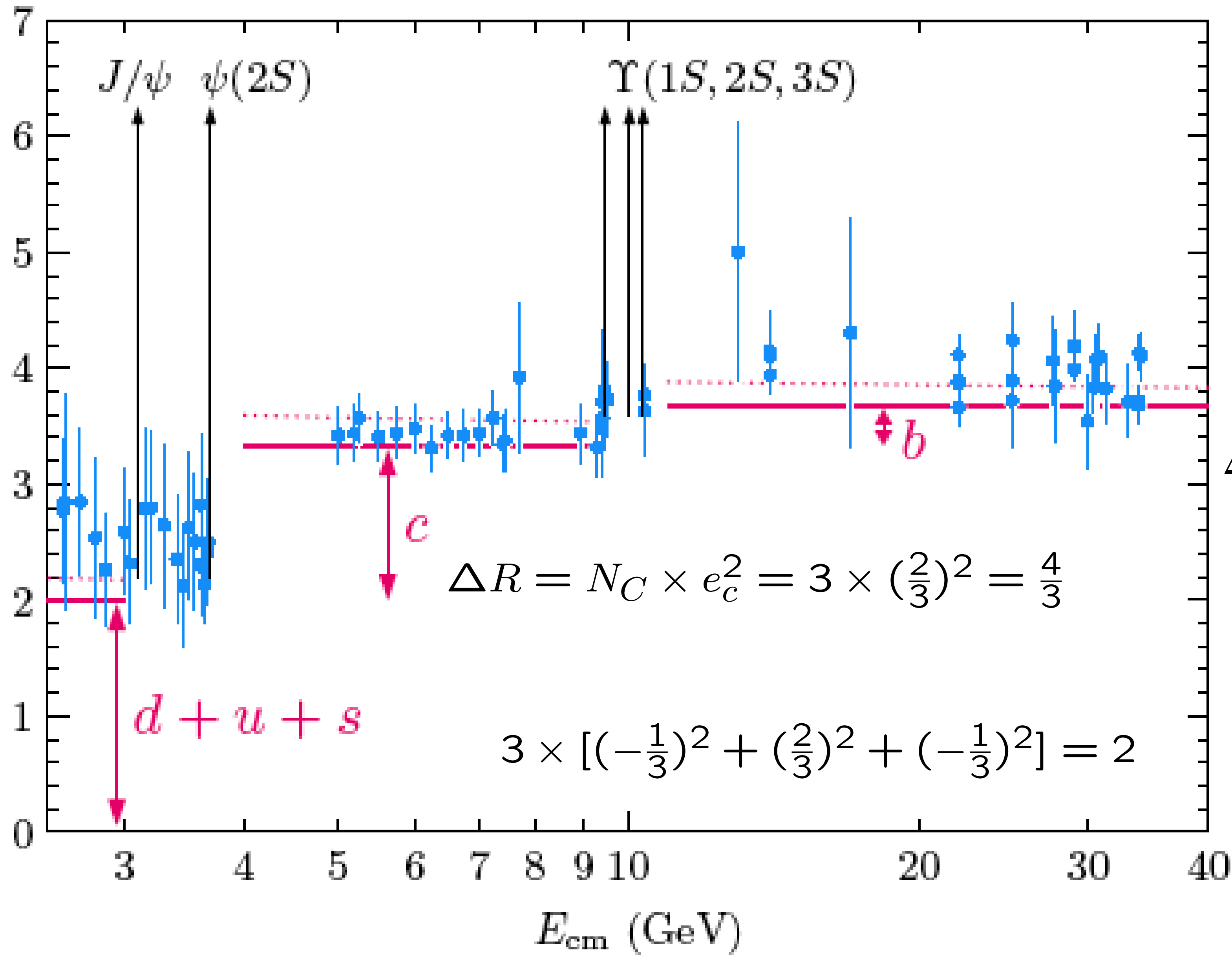
Martin Perl

How to Count Quarks

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

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

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



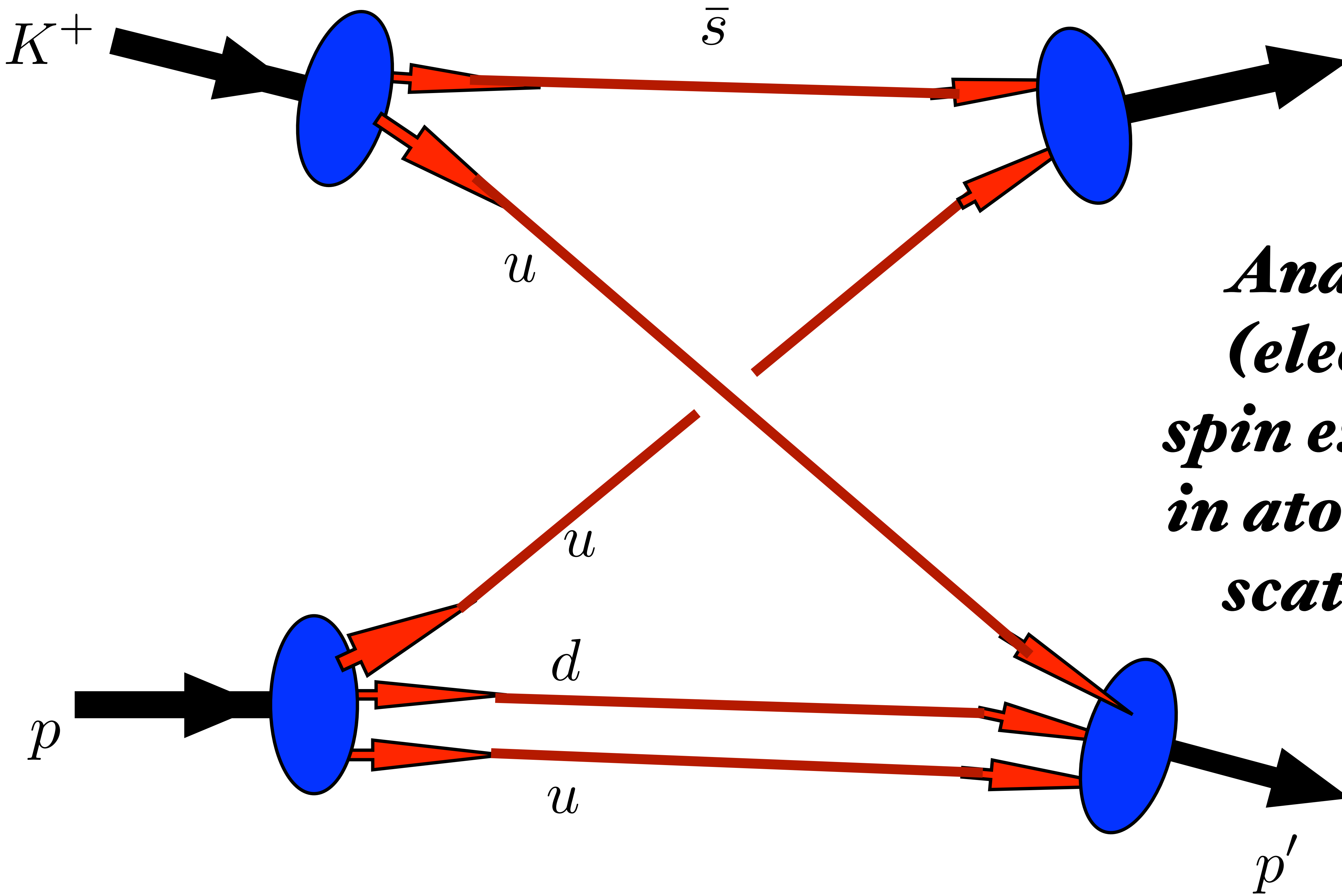
$\Delta R_b = N_C \times e_b^2 = 3 \times (-\frac{1}{3})^2 = \frac{1}{3}$

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

$$\boxed{N_C = 3}$$

$$R(s) \to 3 \sum_q^{n_f} Q_q^2 \, ,$$

$$K^+ p \to K^+ p$$

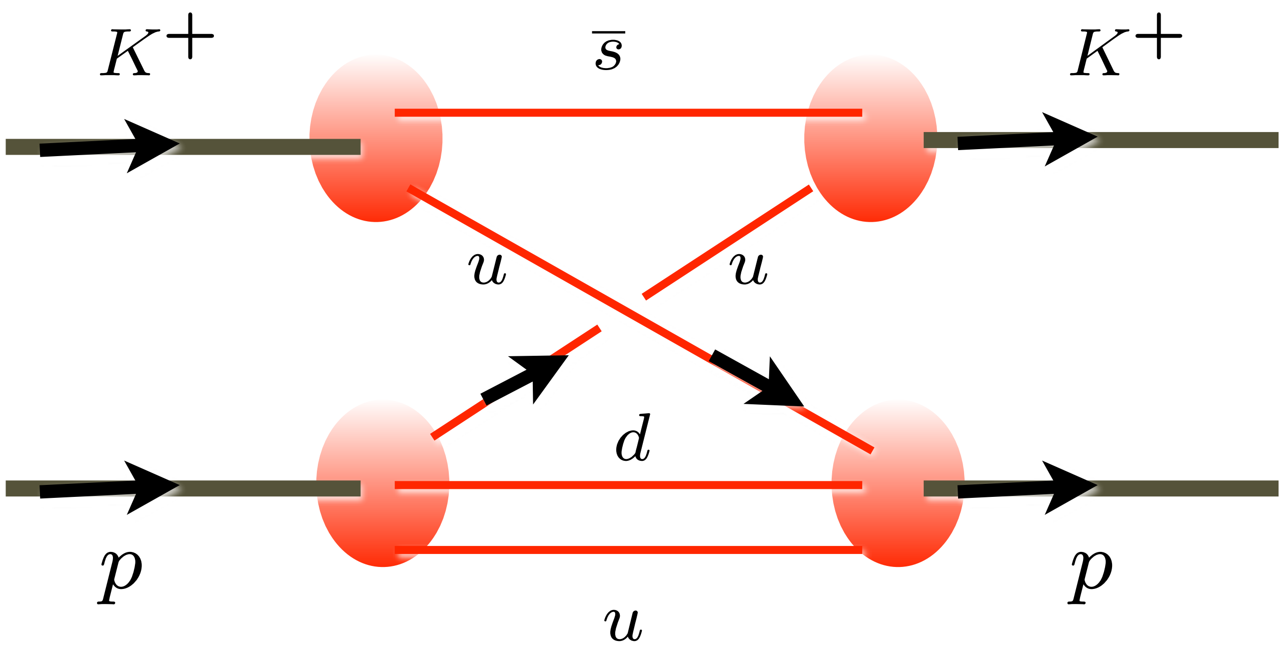


Analog of (electron) spin exchange in atom-atom scattering

Constituent Interchange

Blankenbecler, Gunion, sjb

Blankenbecler, Gunion, sjb



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

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

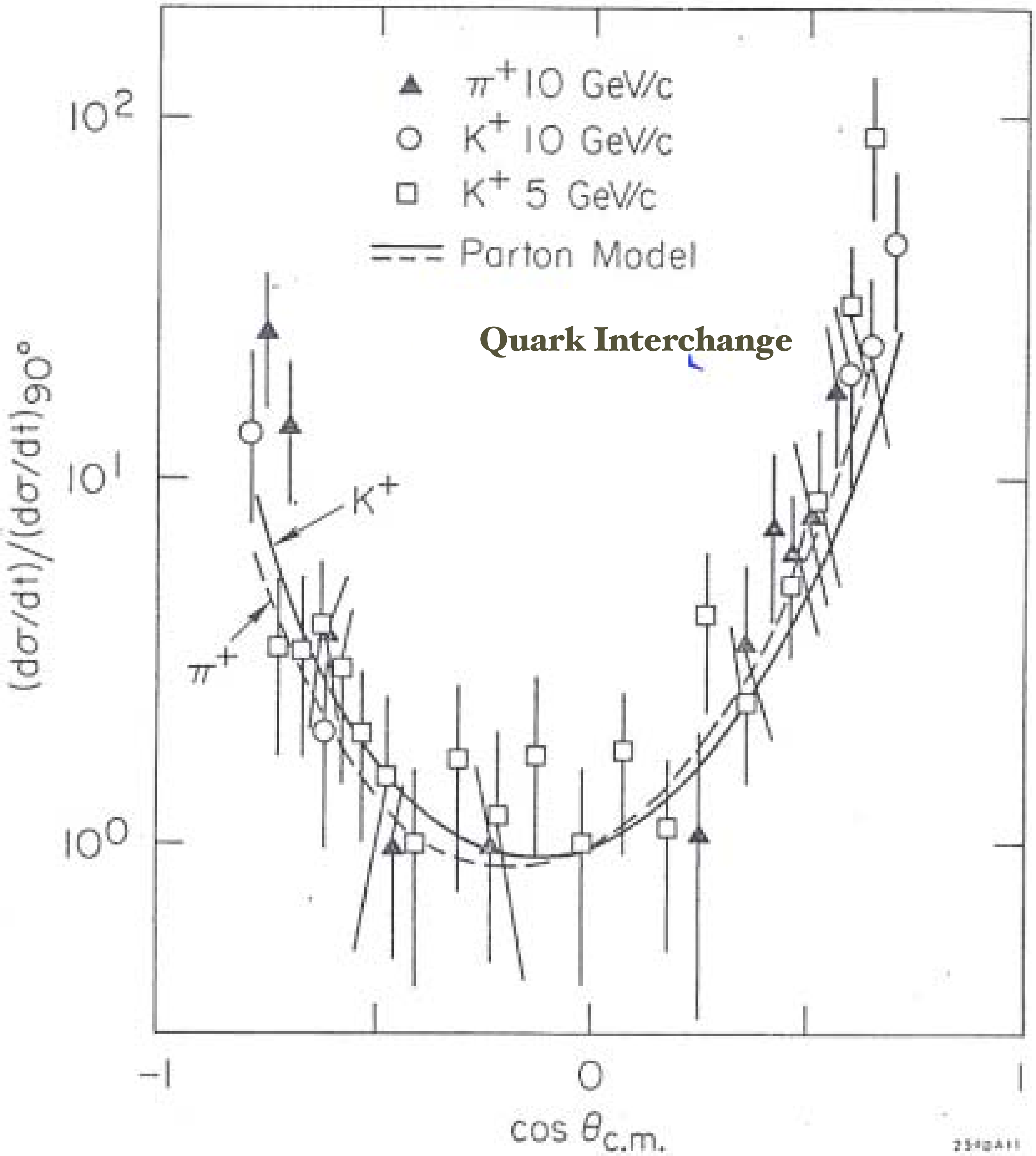
$$M(s,t)_{A+B\to C+D}$$

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

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

Product of four light-front wavefunctions

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



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

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

$$\frac{d\sigma}{dt}(K^+p \to K^+p) = \frac{F(t/s)}{s^8}$$

Non-linear Regge behavior:

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

$$\frac{d\sigma}{dt} = \frac{f(t/s)}{s^{N-2}}$$

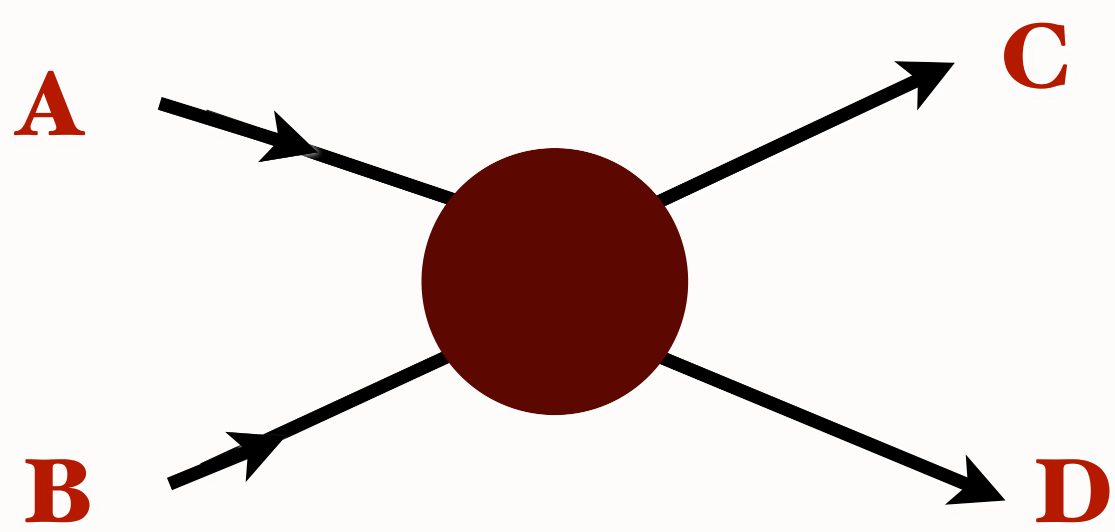
N-2 =# fundamental constituents -2 = 2+3+2 +3- 2=8

"Counting Rules" *Farrar and sjb; Muradyan, Matveev, Tavkelidze*

"Counting Rule" *Farrar and sjb; Muradyan, Matveev, Tavkelidze*

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

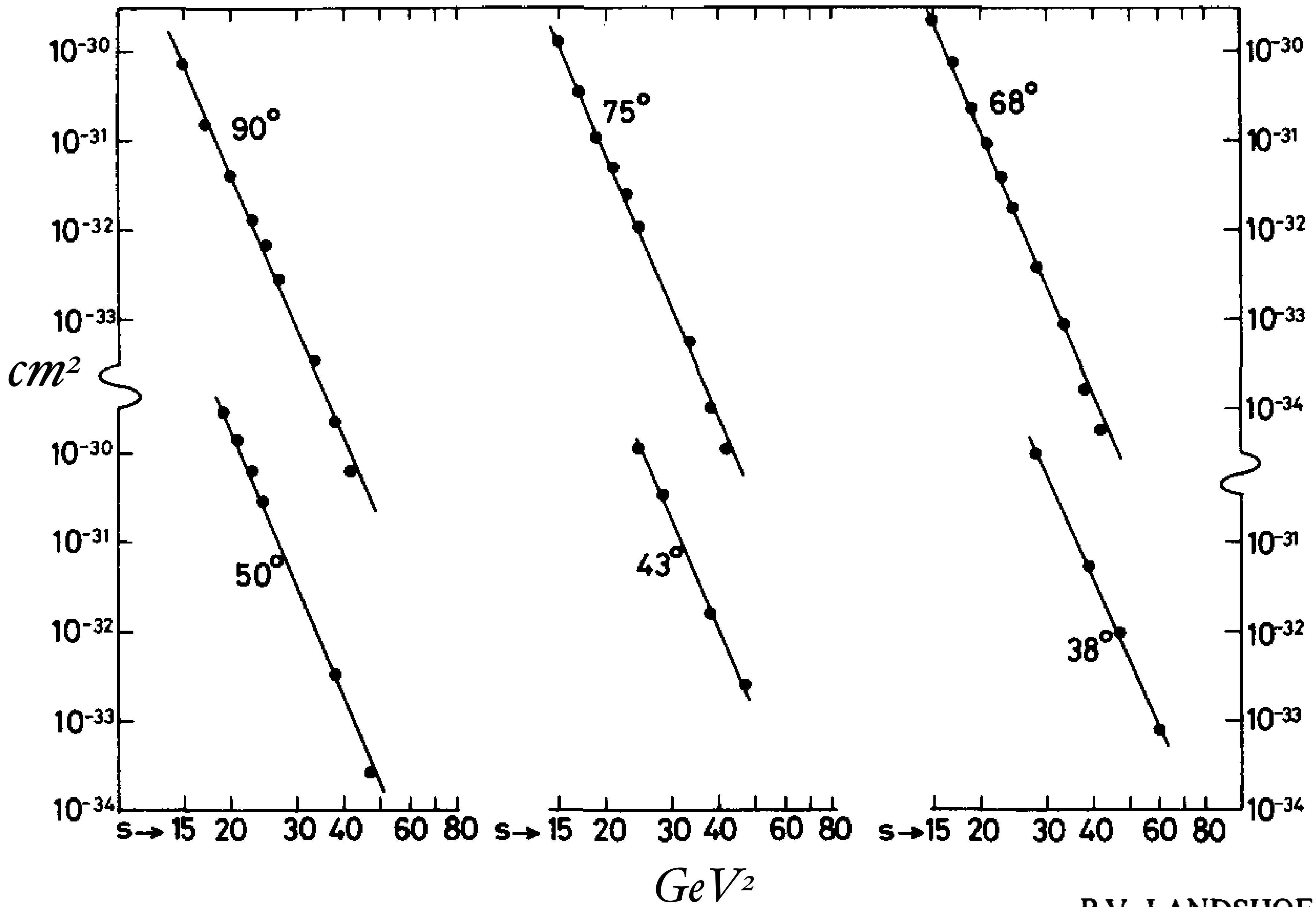
$$n_{tot}=n_A+n_B+n_C+n_D$$



e.g. $n_{tot}-2=n_A+n_B+n_C+n_D-2=10$ for $pp\to pp$

Predict: $$\frac{d\sigma}{dt}(p+p\to p+p)=\frac{F(\theta_{CM})}{s^{10}}$$

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

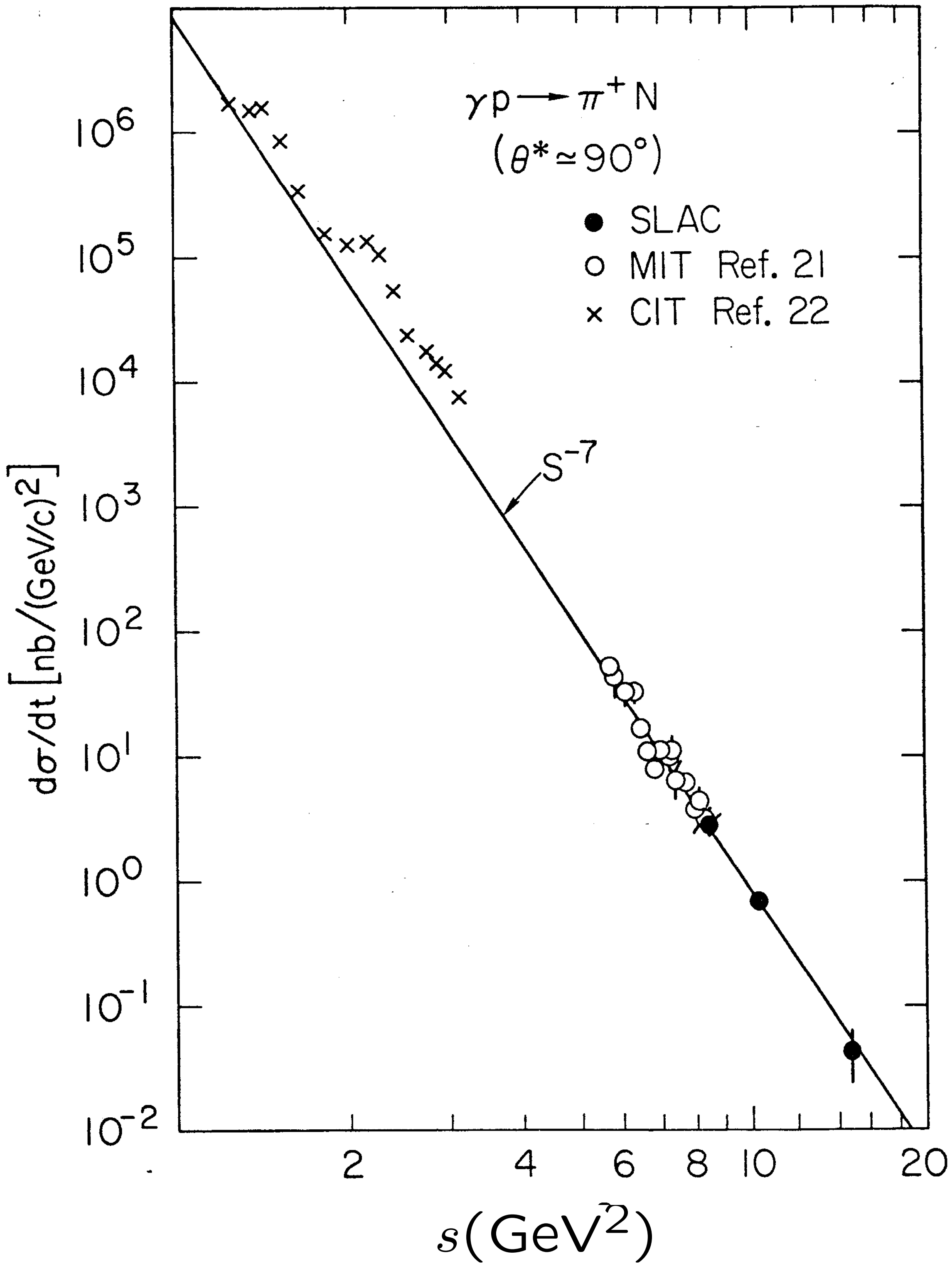


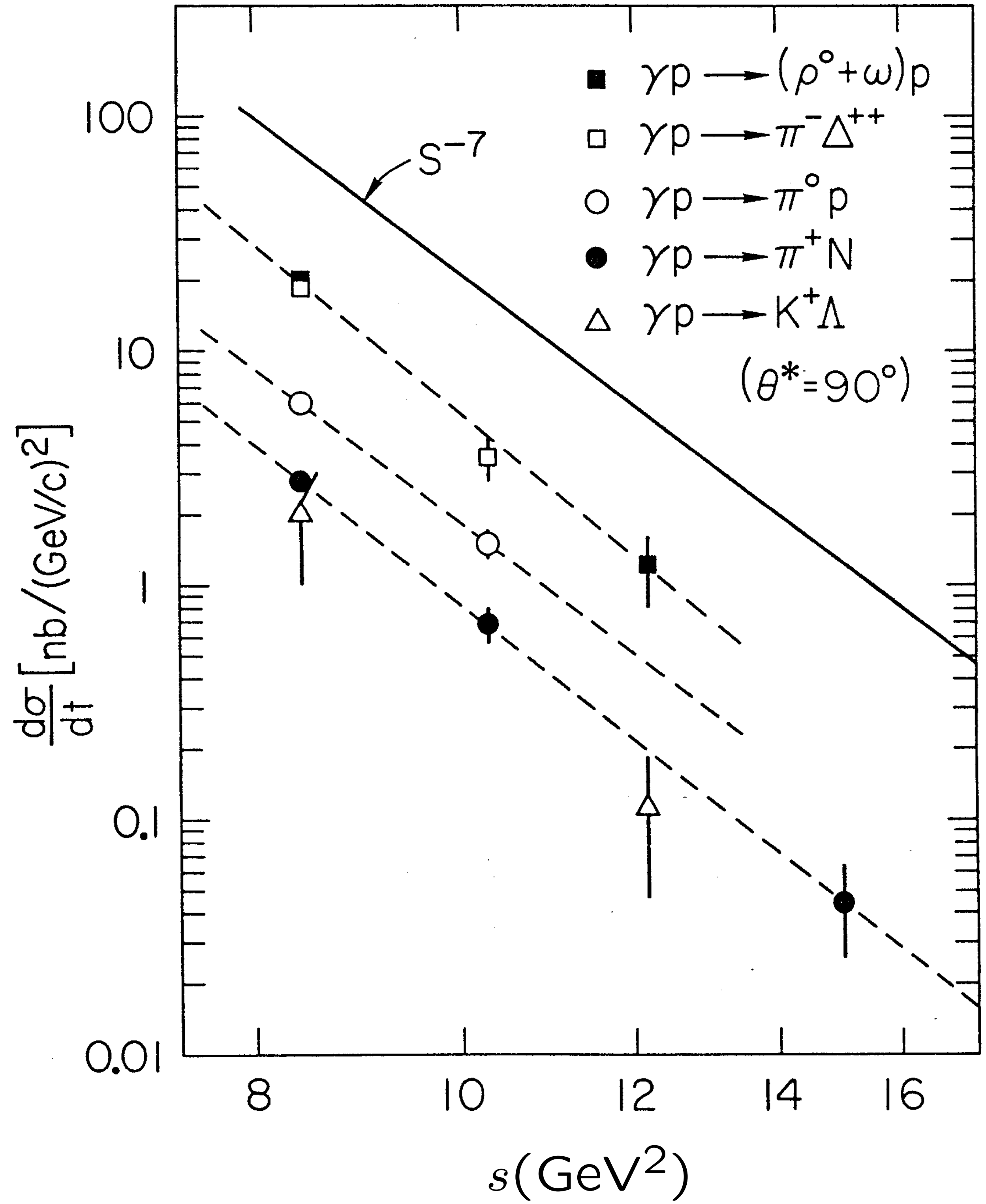
Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal, scale-free interactions

P.V. LANDSHOFF and J.C. POLKINGHORNE

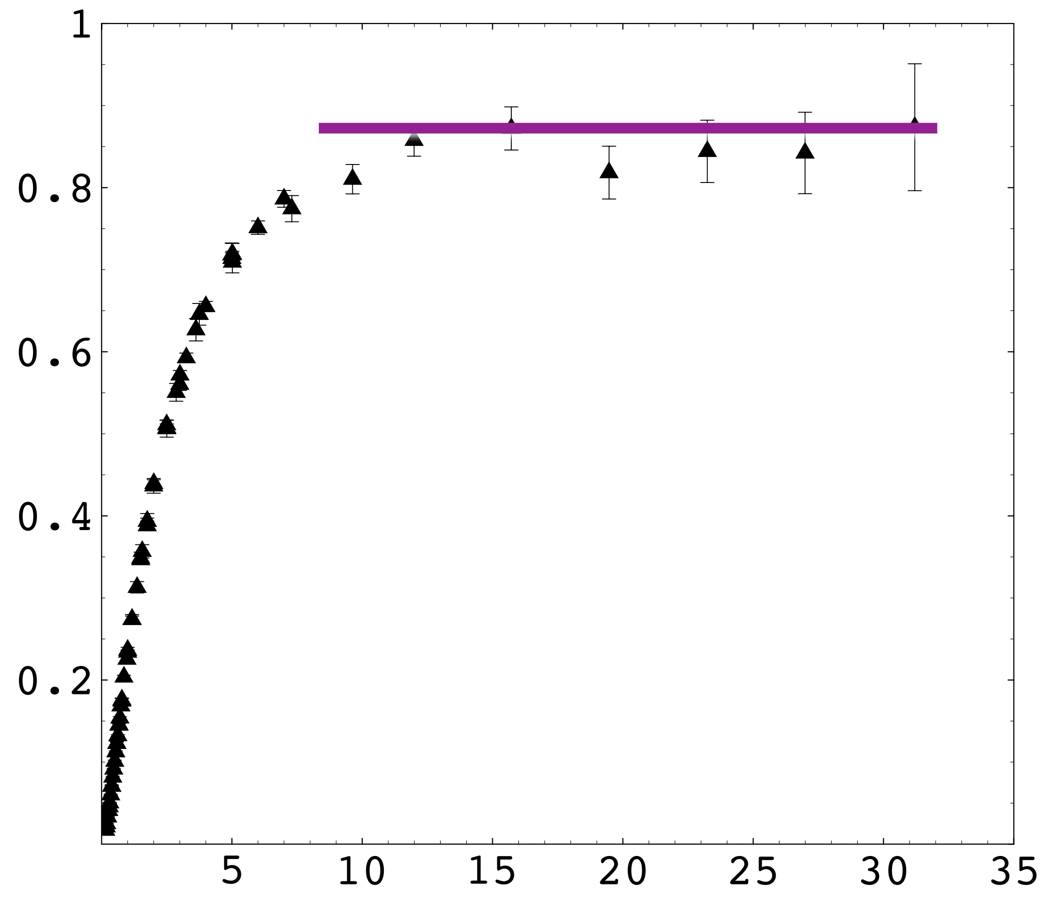




Counting Rules: N=9

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

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



Q^2 [GeV^2]

$$\frac{d\sigma}{dQ^2}(\ell H \to \ell' H') \propto \alpha^2 \frac{F_H^2(Q^2)}{Q^4}$$

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

measured in electron-proton elastic scattering

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).

Reflect underlying conformal, scale-free interactions

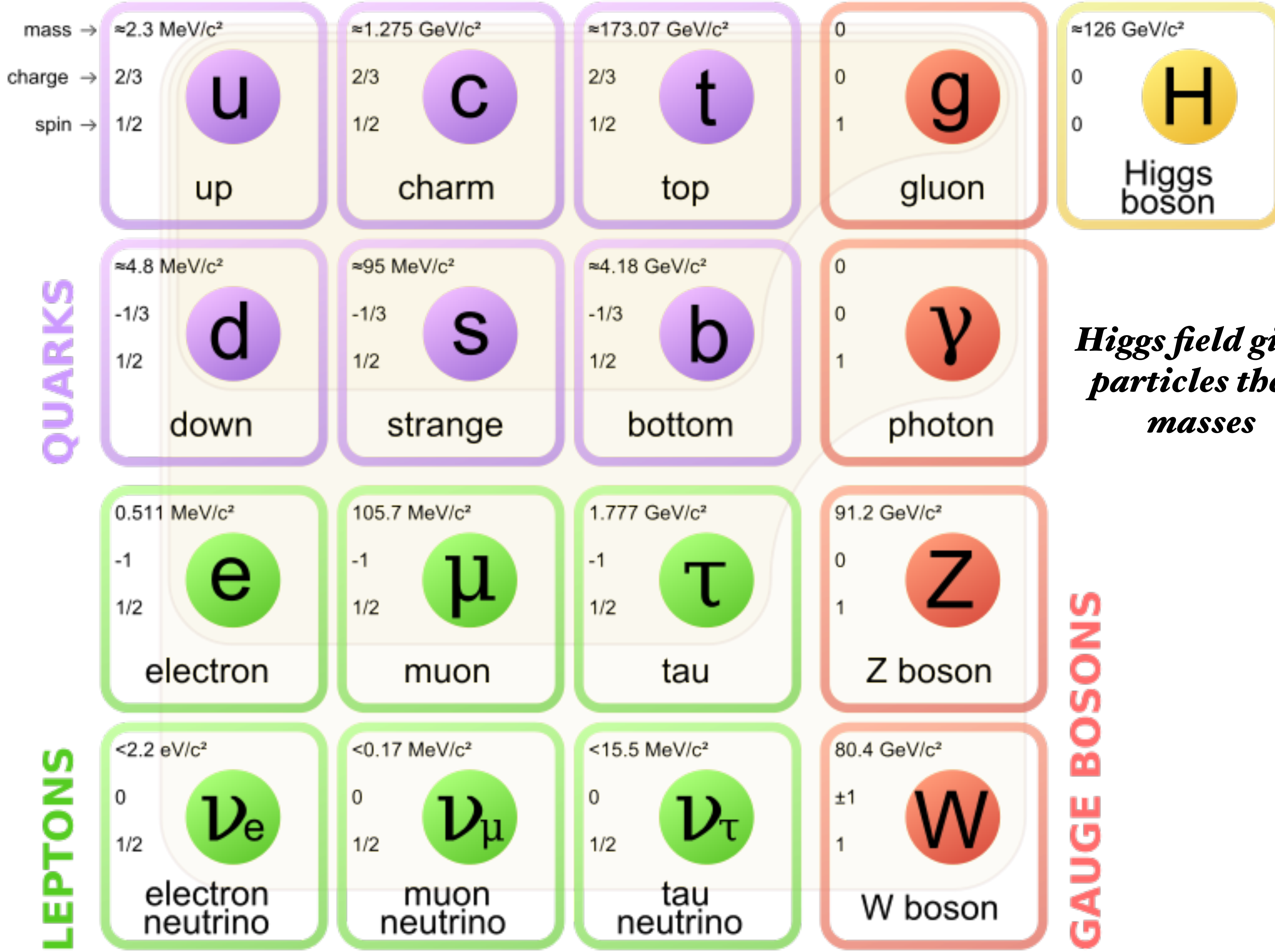
Evidence for Quarks

- Scale-Invariant Electron-Proton Inelastic Scattering: $ep \to e'X$
- Electron scatters on pointlike constituents with fractional charge; final-state jets
- Electron-Positron Annihilation: $e^+e^- \to X$
  Production of pointlike pairs with fractional charges
- 3 colors; quark, antiquark, gluon jets
- Exclusive hard scattering reactions: $pp \to pp, \ \gamma p \to \pi^+ n, \ ep \to ep$
- Probability that hadron stays intact counts number of its pointlike constituents: *Quark Counting Rules*

Quark interchange describes angular distributions

Farrar and sjb; Matveev et al; Lepage, sjb; Blankenbecler, Gunion, sjb

Fundamental Constituents underlying atoms, nuclei, and hadrons



Higgs field gives particles their masses

QCD Lagrangian

Quantum Chromodynamics

gluon dynamics

quark kinetic energy +
quark-gluon dynamics

mass term

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

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

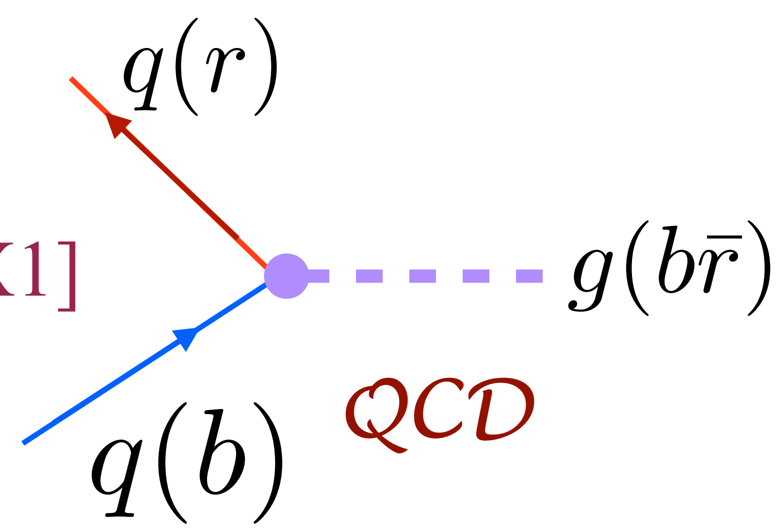
Yang Mills Gauge Principle:
Color Rotation and Phase
Invariance at Every Point of
Space and Time

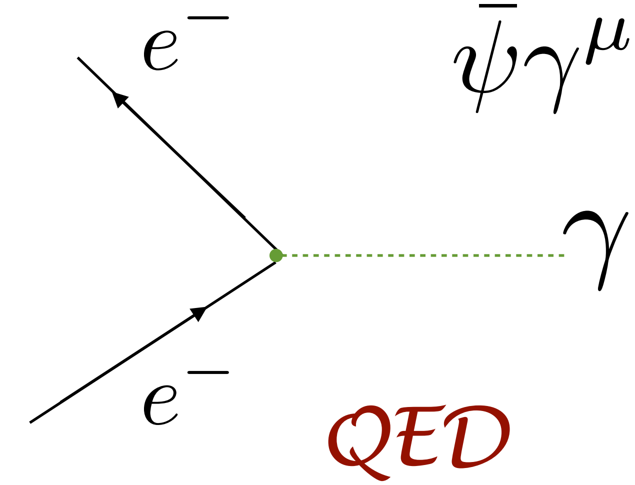
Scale-Invariant Coupling
Renormalizable
Nearly-Conformal
Asymptotic Freedom
Color Confinement

Fundamental Couplings of QCD and QED

$$\bar{\psi}\gamma^{\mu}A^{\mu}\bar{\psi}$$

[1X3] [3X3] [3X1]



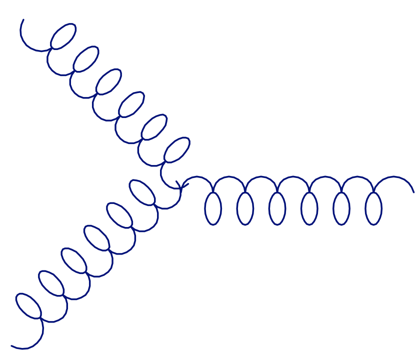


$$\bar{\psi}\gamma^{\mu}A^{\mu}\bar{\psi}$$

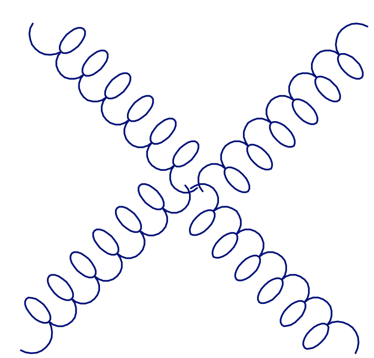
$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_{\mu}\gamma^{\mu}\Psi_f + \sum_{f=1}^{n_f} m_f\bar{\Psi}_f\Psi_f$$

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

Gluon vertices



QCD



$$G^{\mu\nu}G_{\mu\nu}$$

gluon self couplings

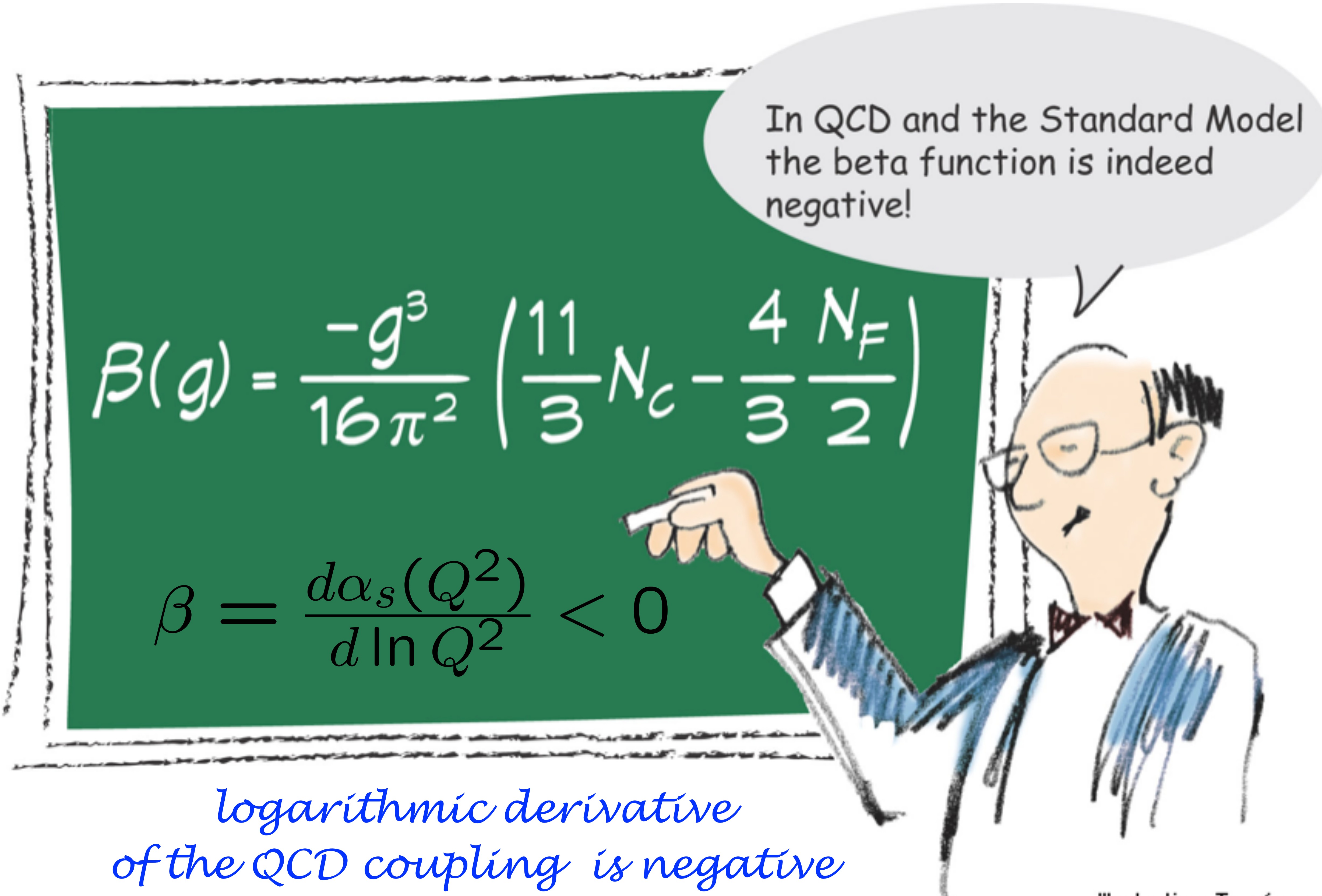
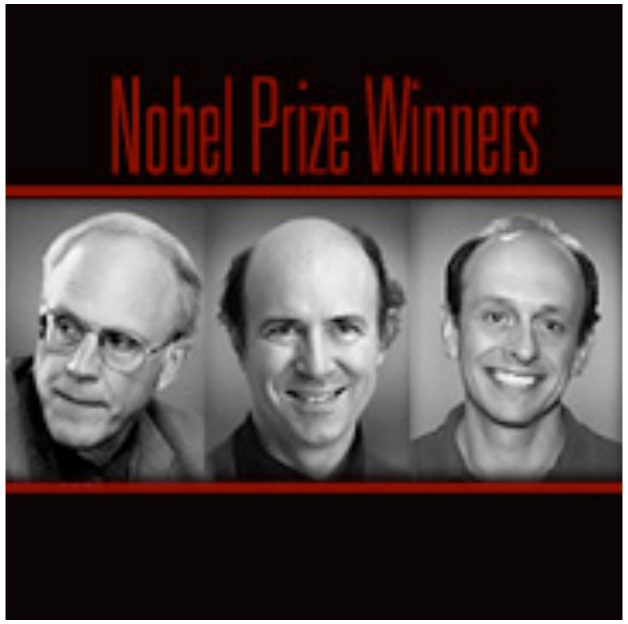


Illustration: Typoform

logarithmic derivative
of the QCD coupling is negative
Coupling becomes weaker at short
distances = high momentum transfer

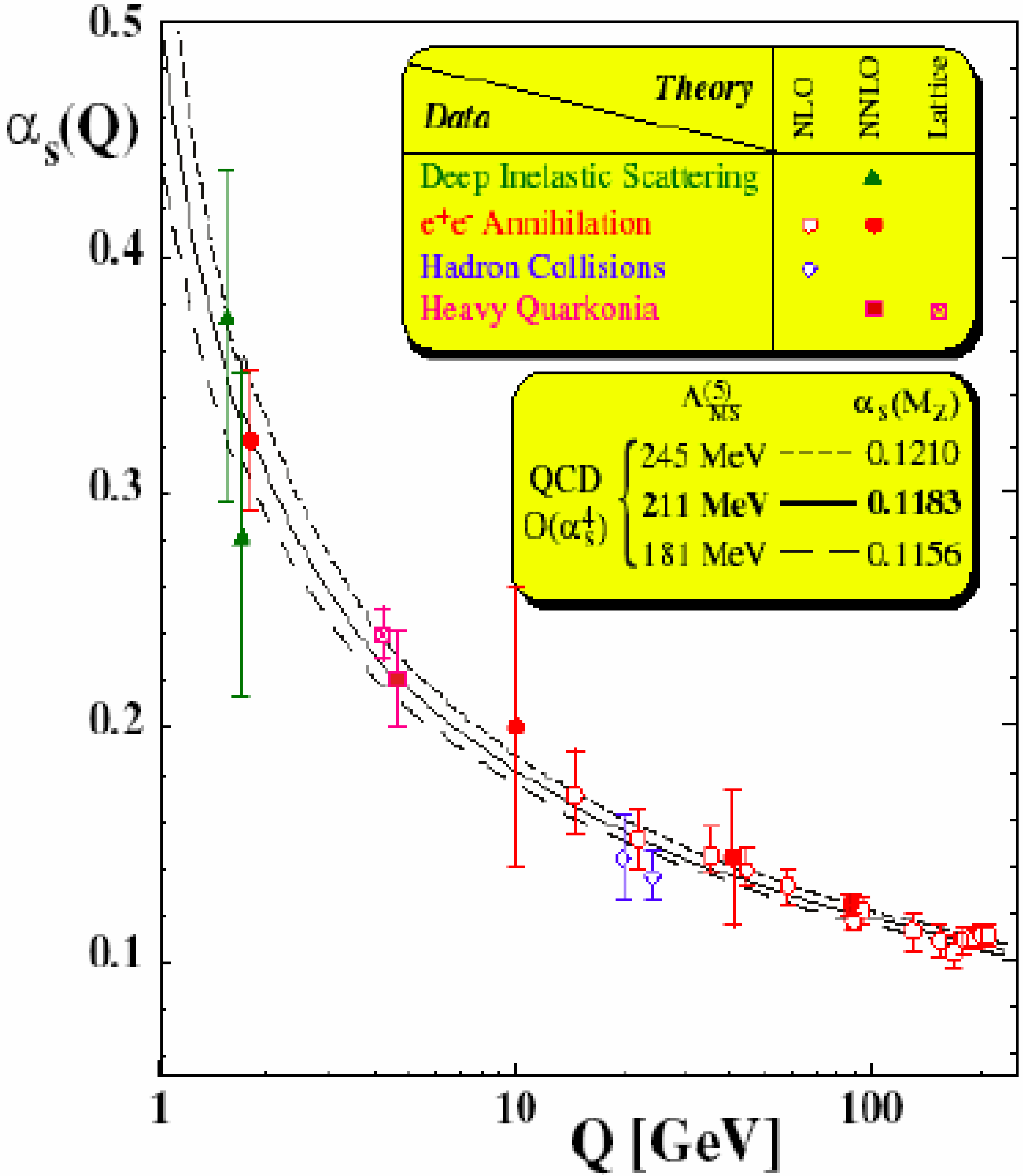
Verification of Asymptotic Freedom

$$\alpha_s(Q) \propto \frac{1}{\ln Q}$$



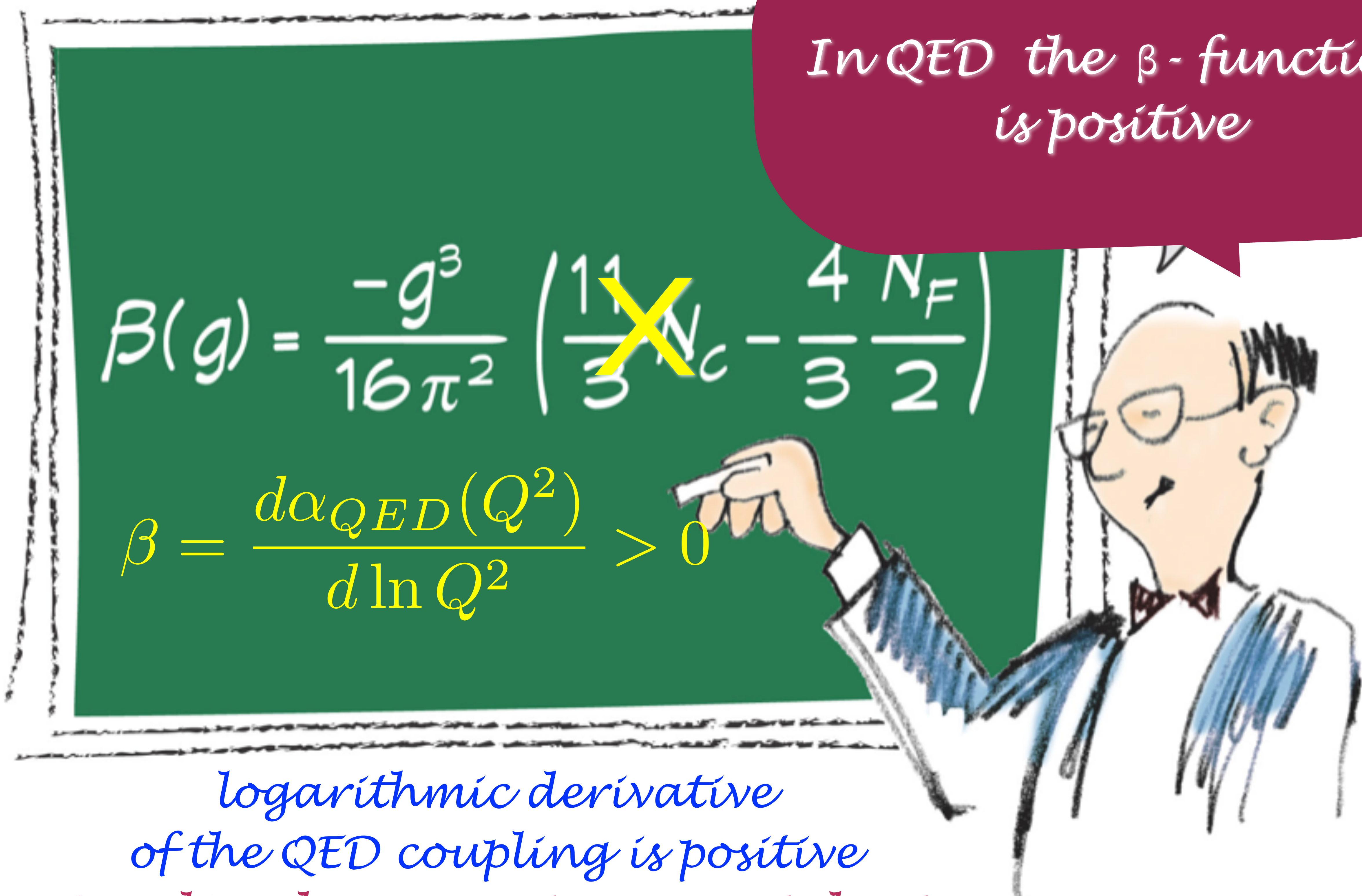
$$\frac{\sigma(e^+e^- \to \text{three jets})}{\sigma(e^+e^- \to \text{two jets})}$$

proportional to $\alpha_s(Q)$



Ratio of rate for $e^+e^- \to q\bar{q}g$ to $e^+e^- \to q\bar{q}$ at $Q = E_{CM} = E_{e^-} + E_{e^+}$

In QED the β - function is positive



$$\beta = \frac{d\alpha_{QED}(Q^2)}{d\ln Q^2} > 0$$

logarithmic derivative
of the QED coupling is positive
Coupling becomes stronger at short distances = high momentum transfer

Landau Pole!

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

Huet, sjb

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

$$\boxed{\text{QCD} \to \text{Abelian Gauge Theory}}$$

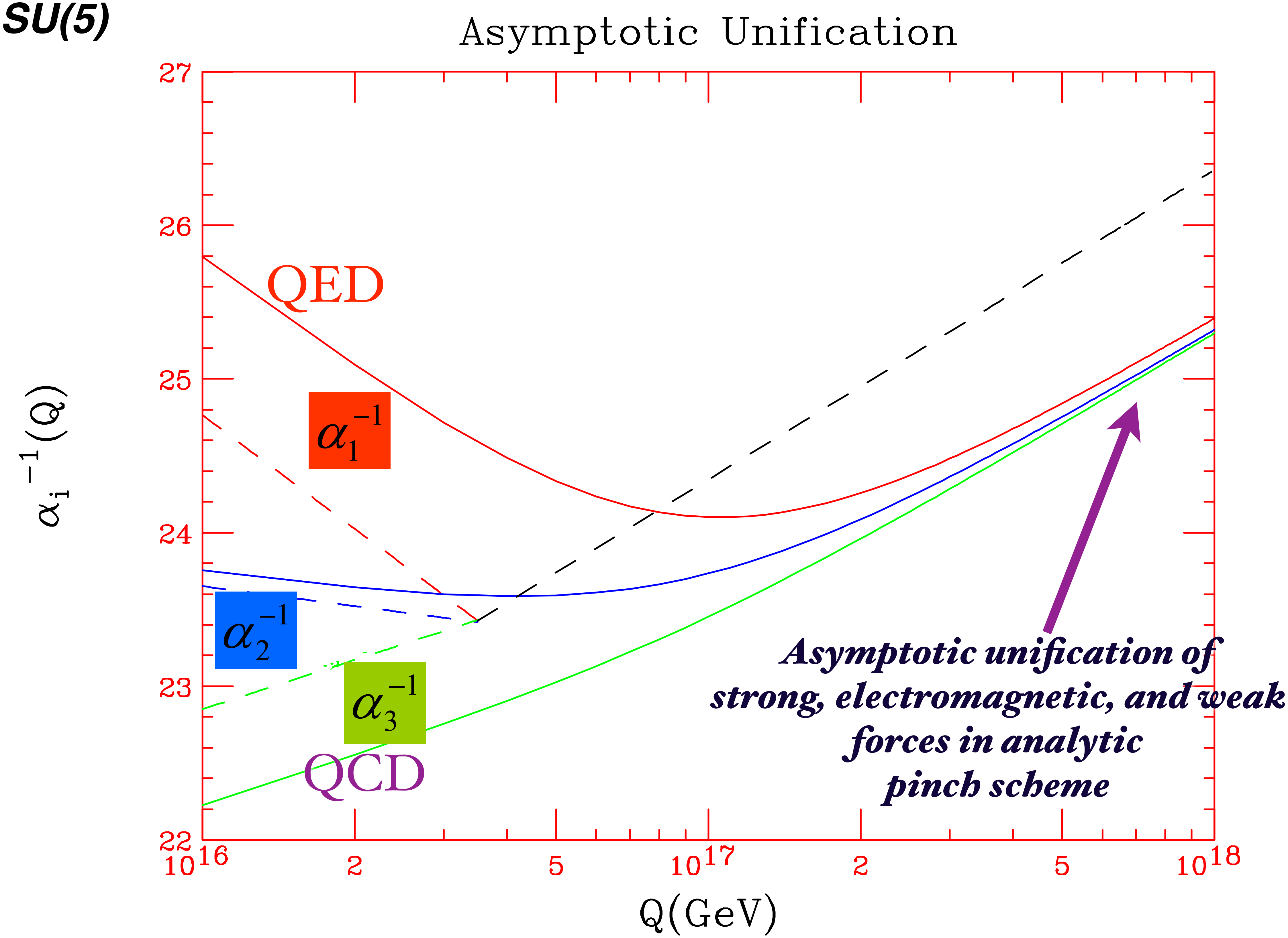
Analytic Feature of SU(Nc) Gauge Theory

All analyses for Quantum Chromodynamics must be applicable to Quantum Electrodynamics

Must Use Same Scale Setting Procedure! BLM/PMC

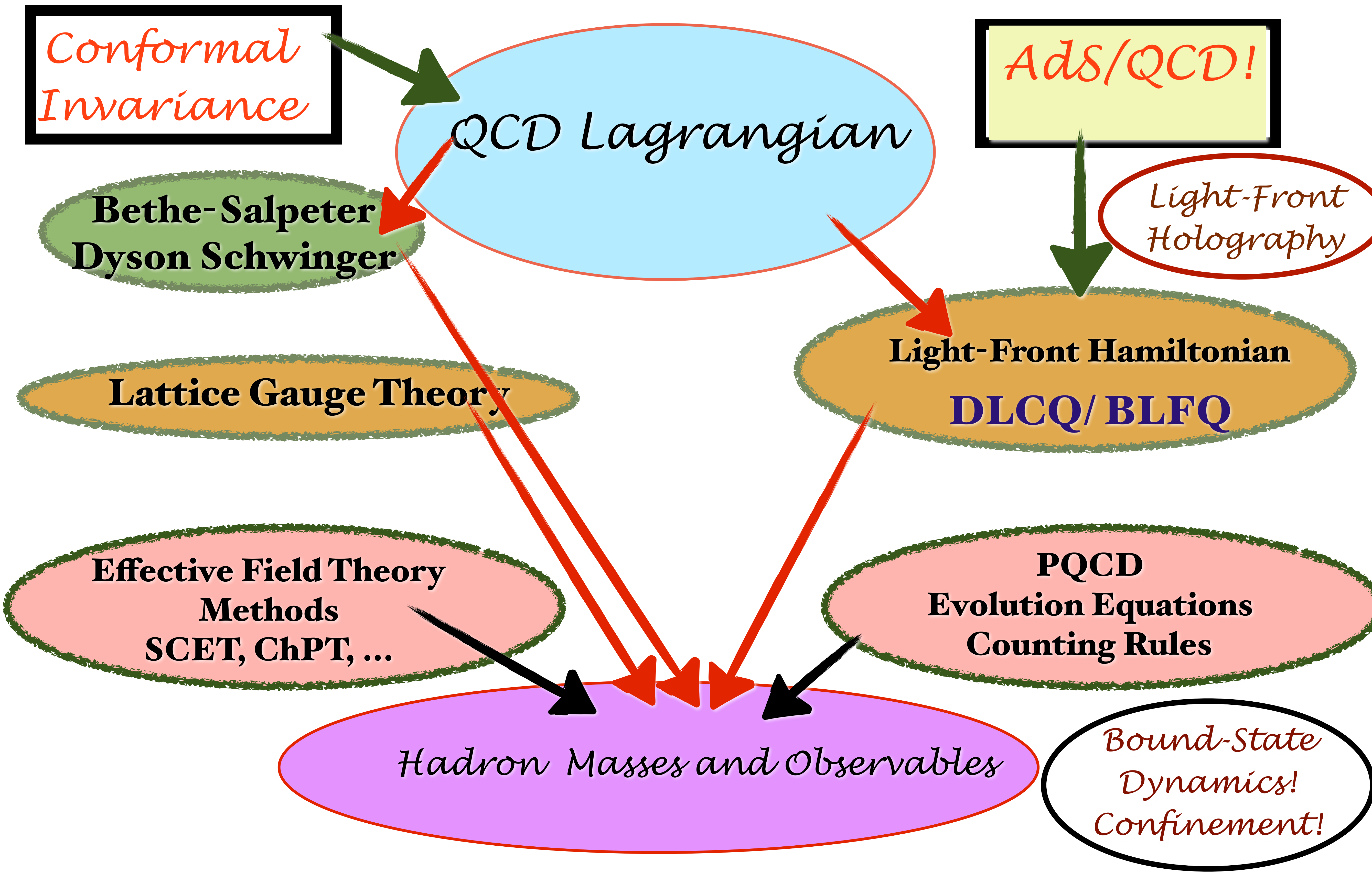
Supersymmetric SU(5)

Binger, sjb

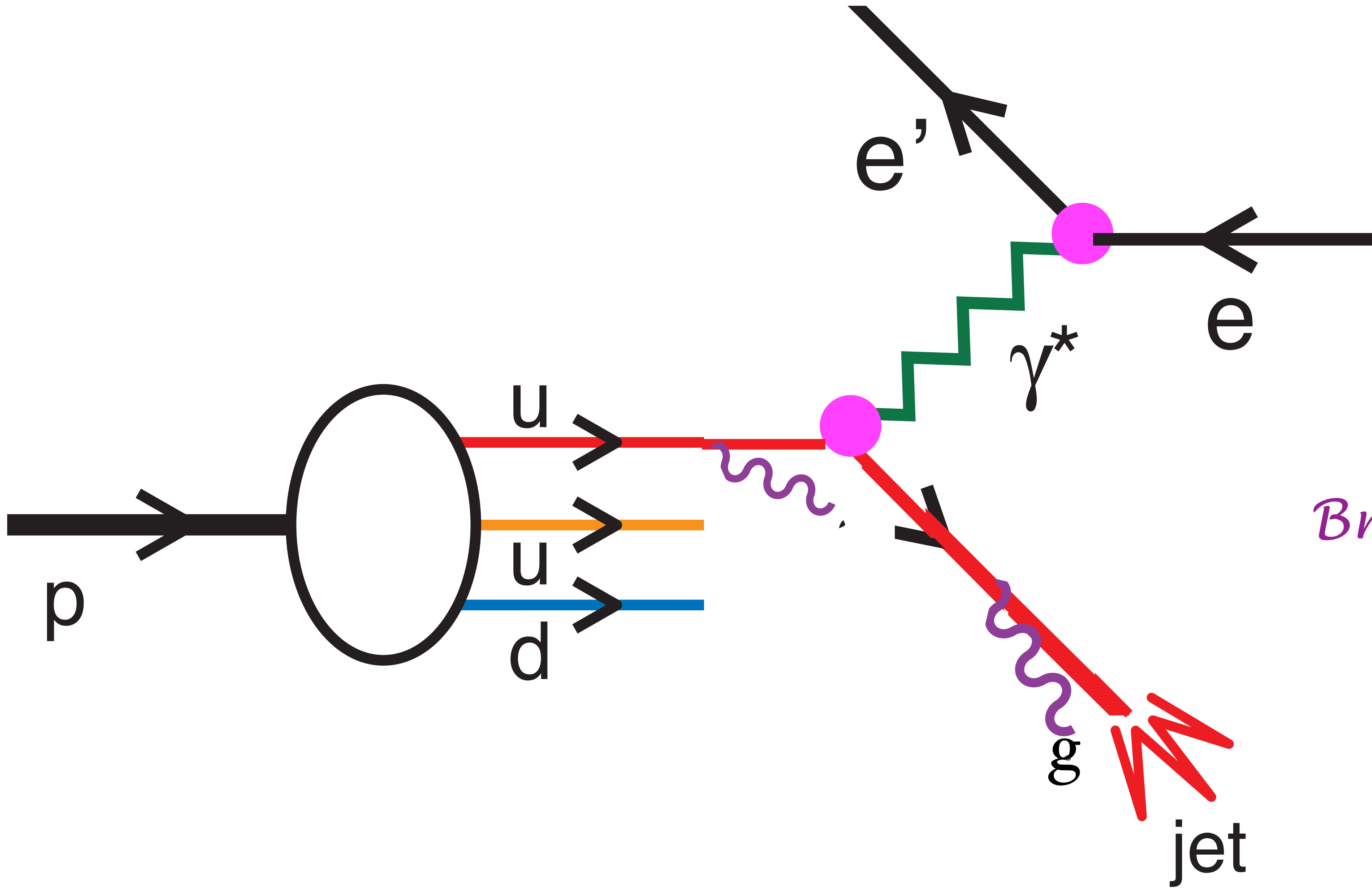


Must Use Same Scale-Setting Procedure! BLM/PMC

Predict Hadron Properties from First Principles!



Deep Inelastic Electron-Proton Scattering



Gluonic Bremsstrahlung

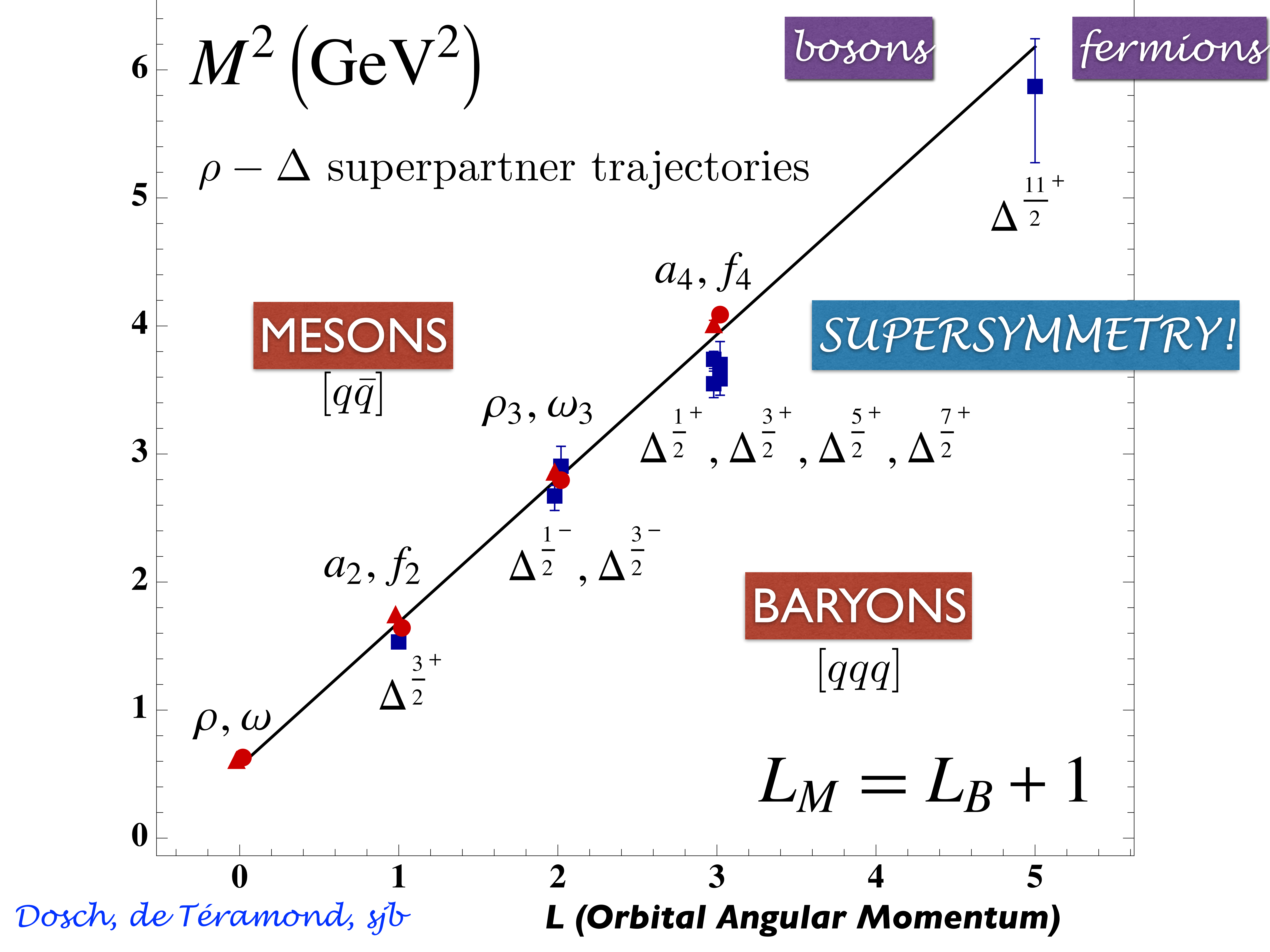
DGLAP Evolution

First Evidence for Quark Structure of Matter

But why do hadrons - not quarks - appear in the final state ?
Why and how are quarks and gluons confined within hadrons?

Fundamental Question: Quark Confinement!!

- ***What is the mechanism that confines quarks and gluons?***
- ***What sets the mass of the proton when m_q=0 ?***
- ***QCD: No knowledge of MeV units:***
  Only ratios of masses can be predicted!
- ***Novel proposal by de Alfaro, Fubini, and Furlan (DAFF):***
  Mass scale κ can appear in Hamiltonian leaving the action conformal!
- ***Unique Color-Confinement Potential***



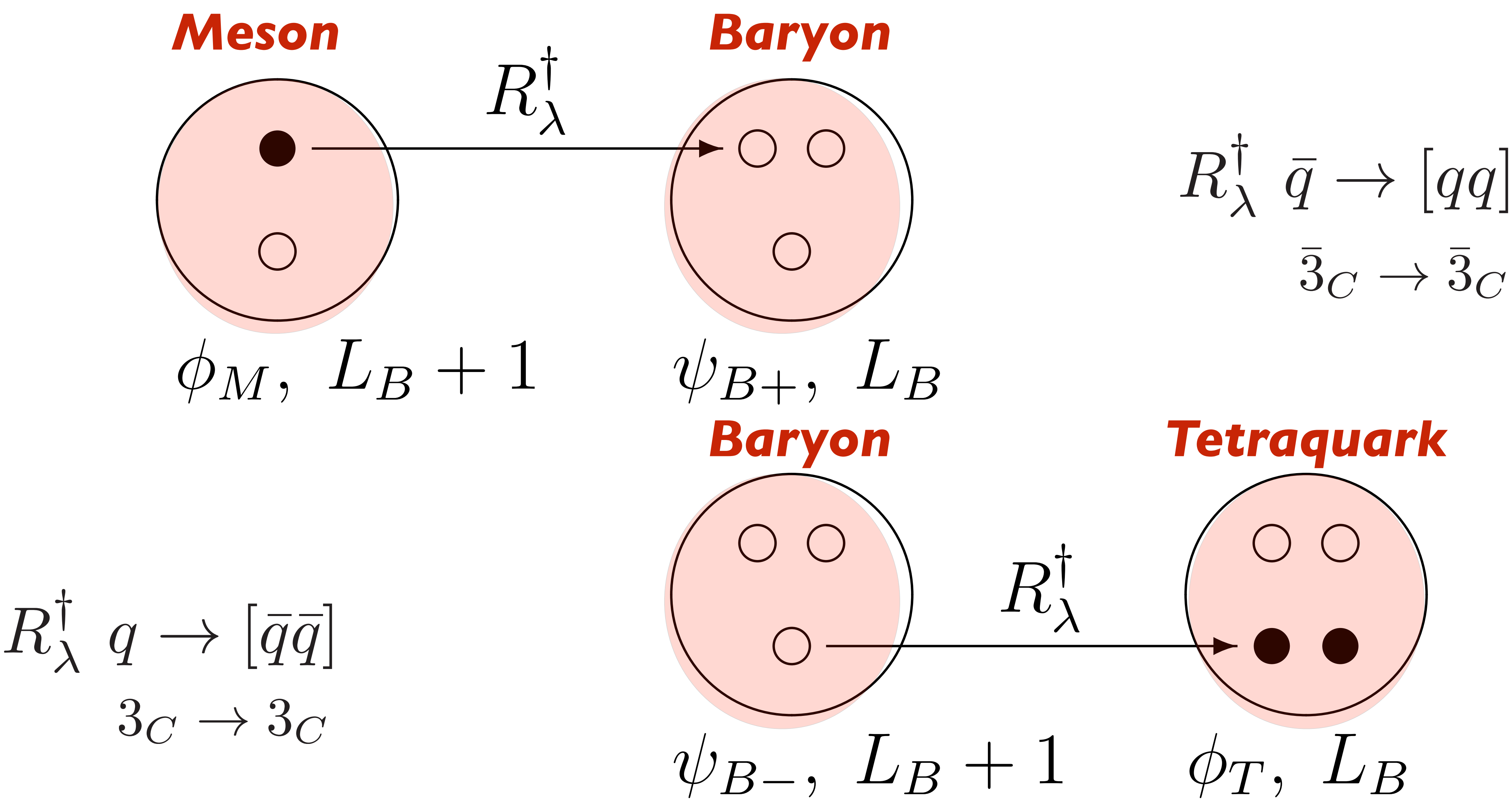
$M^2\,(\mathrm{GeV}^2)$
bosons
fermions
$\rho - \Delta$ superpartner trajectories
$\Delta_{\frac{11}{2}^+}$
a_4, f_4
MESONS
$[q\bar{q}]$
SUPERSYMMETRY!
ρ_3, ω_3
$\Delta_{\frac{1}{2}^+}, \Delta_{\frac{3}{2}^+}, \Delta_{\frac{5}{2}^+}, \Delta_{\frac{7}{2}^+}$
$\Delta_{\frac{1}{2}^-}, \Delta_{\frac{3}{2}^-}$
a_2, f_2
BARYONS
$[qqq]$
$\Delta_{\frac{3}{2}^+}$
ρ, ω
$L_M = L_B + 1$
0
1
2
3
4
5
6
L (Orbital Angular Momentum)
Dosch, de Téramond, sjb

Guy de Tèramond, Hans Günter Dosch, sjb

Superconformal Algebra

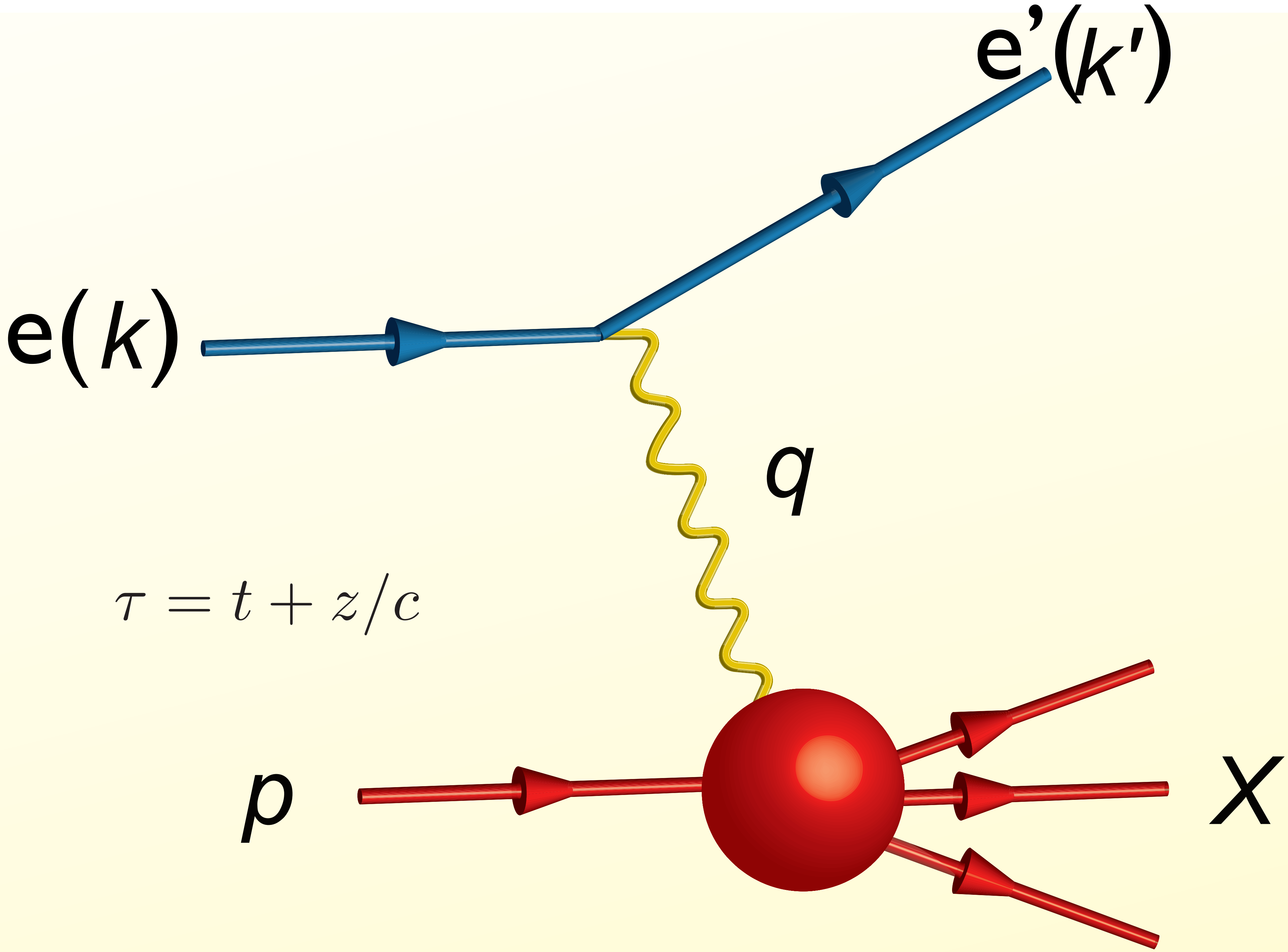
2X2 Hadronic Multiplets: 4-Plet

Bosons, Fermions with Equal Mass!



Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

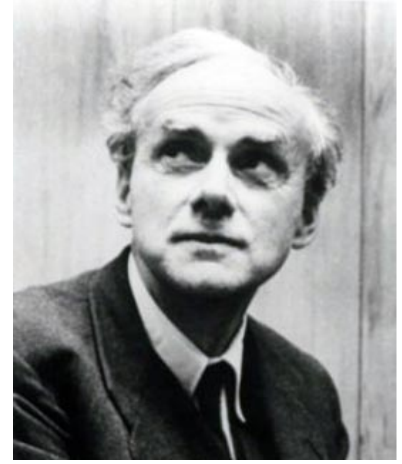
Causality: Information and correlations constrained by speed of light



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

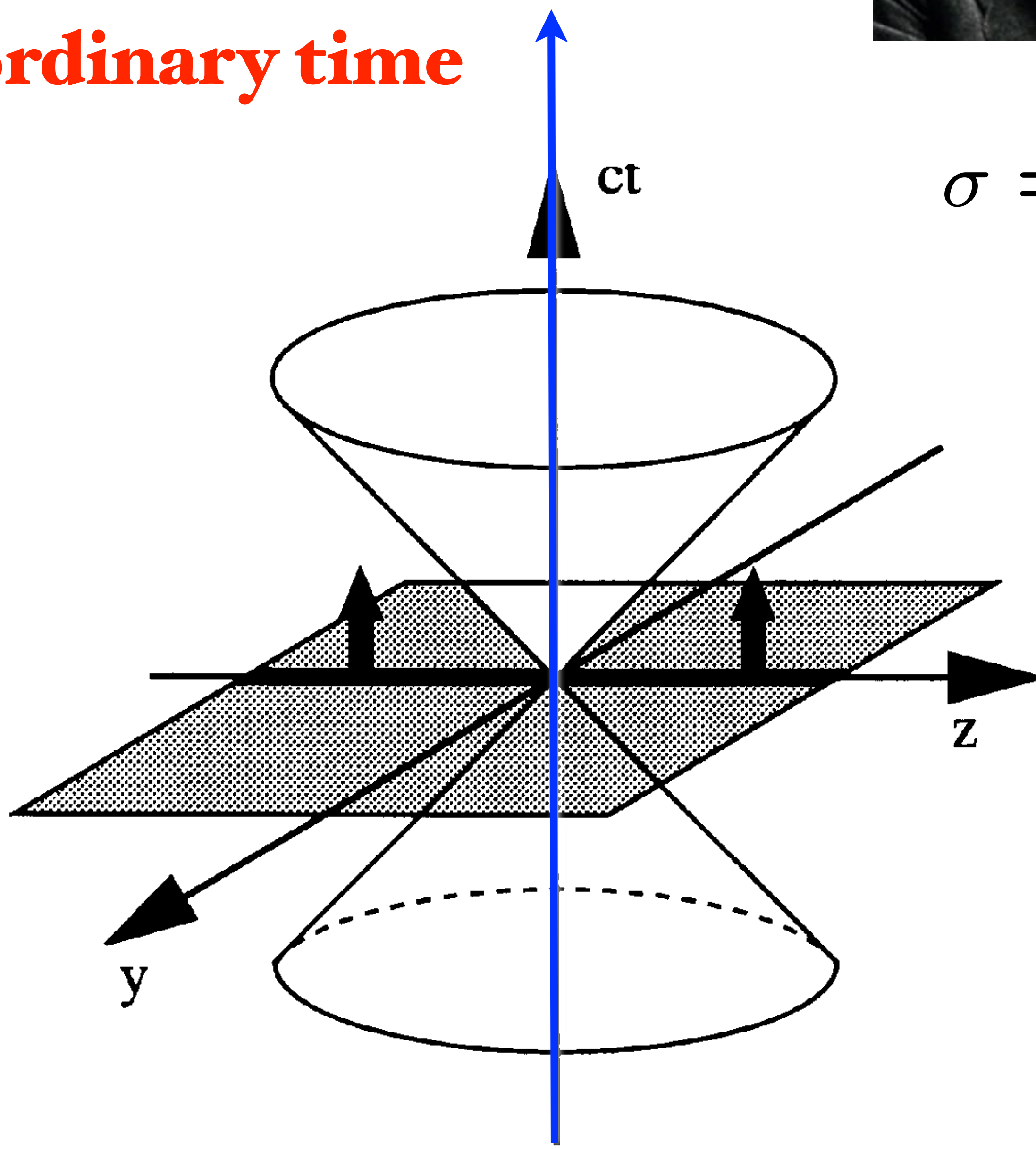
The scattered electron measures the proton's structure at the speed of light — like a flash photograph

Dirac's Amazing Idea: The "Front Form"



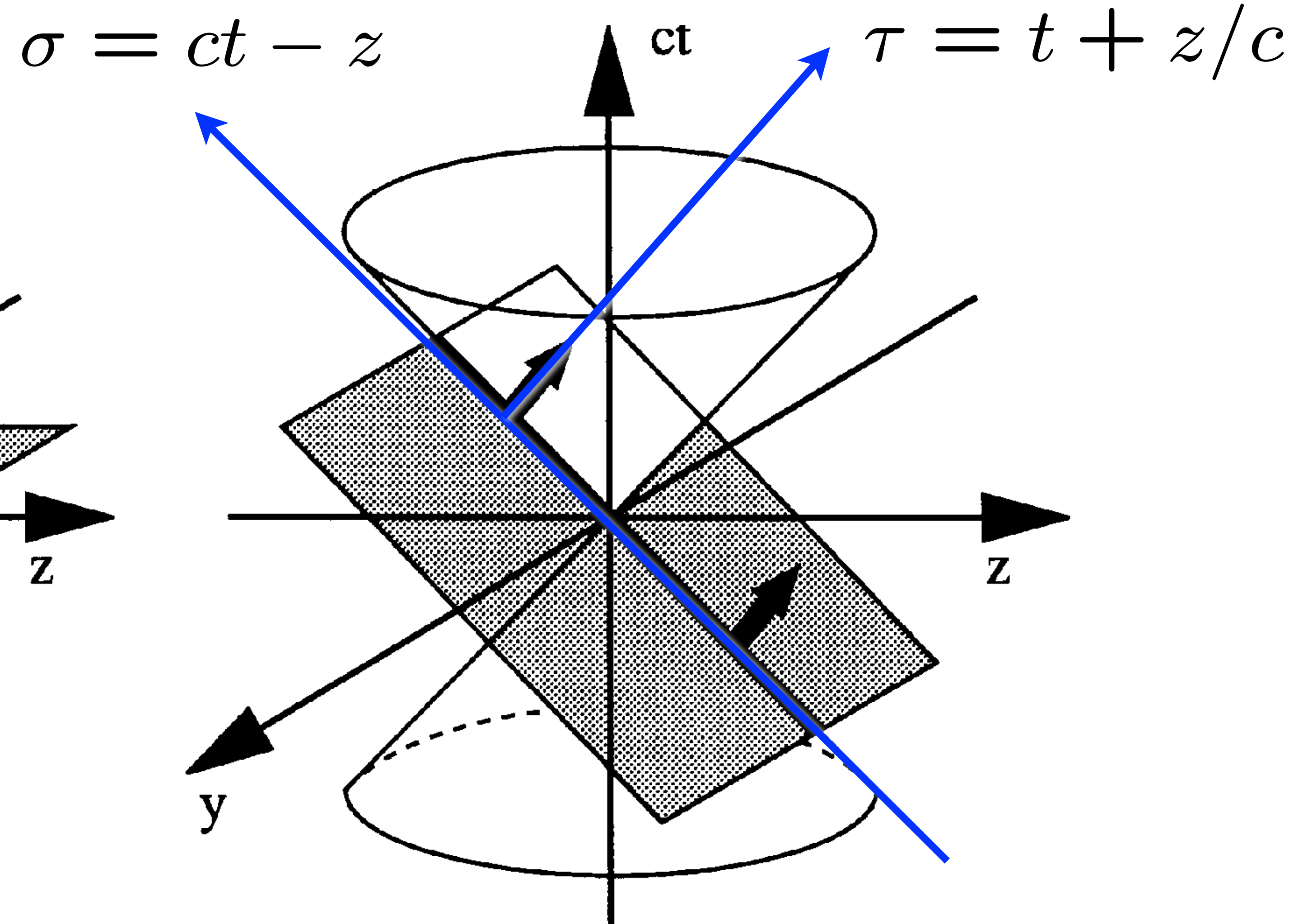
P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

Evolve in ordinary time



Instant Form

Evolve in light-front time!



Front Form

- **No dependence on observer's frame**
- **Boosts are kinematical**

Light-Front Time

Each element of
flash photograph
illuminated
at same LF time

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

Causal, frame-independent

$$P^{\pm} = P^0 \pm P^z$$

Evolve in LF time

$$P^- = i\frac{d}{d\tau}$$

Eigenstate -- independent of τ

$$\text{Eigenvalue } P^- = \frac{\mathcal{M}^2 + \vec{P}^2_\perp}{P^+}$$

$$H_{LF} = P^+ P^- - \vec{P}^2_\perp$$

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

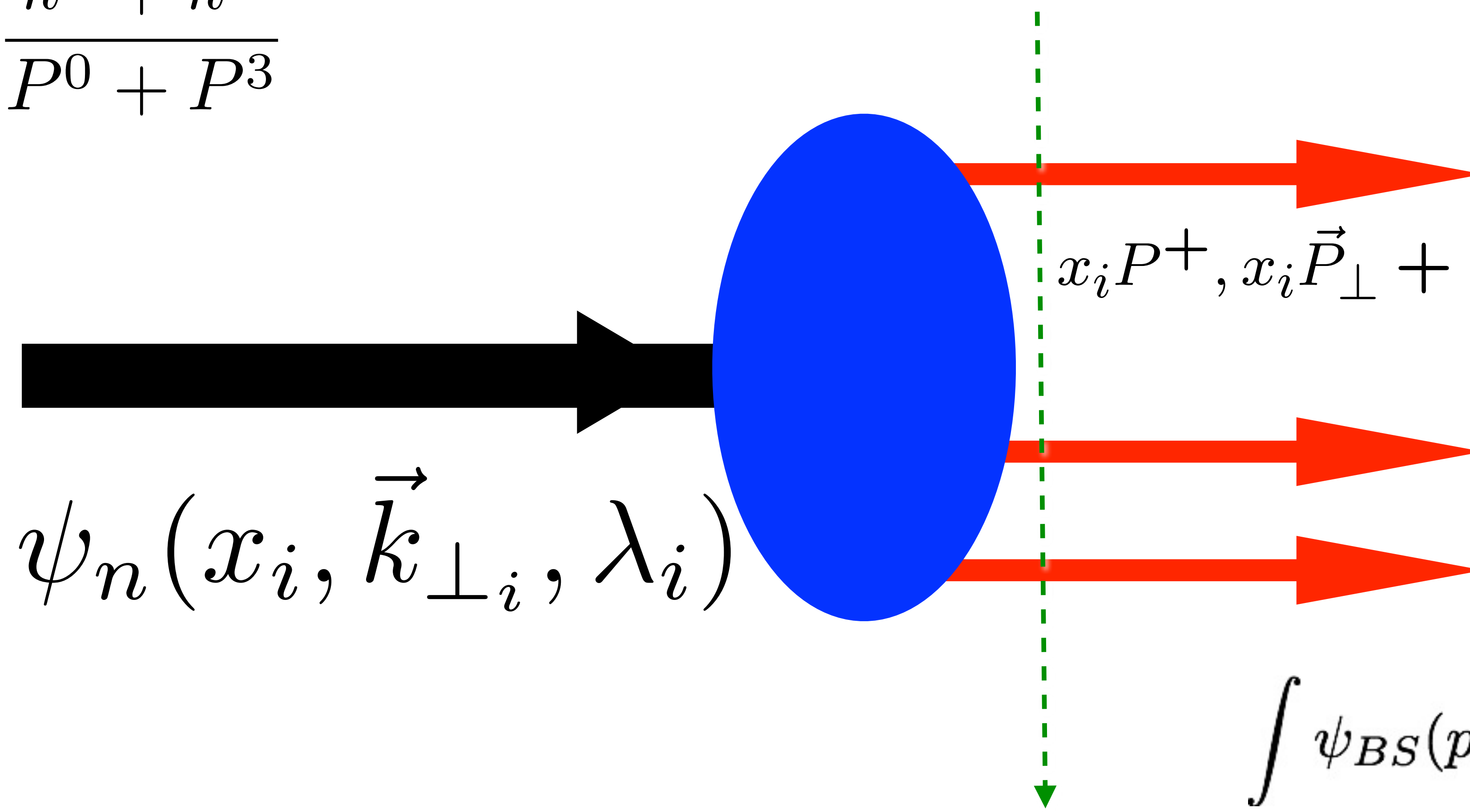
HELEN BRADLEY - PHOTOGRAPHY

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

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

Fixed $\tau = t + z/c$

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



$\sum_i^n x_i = 1$

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

$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

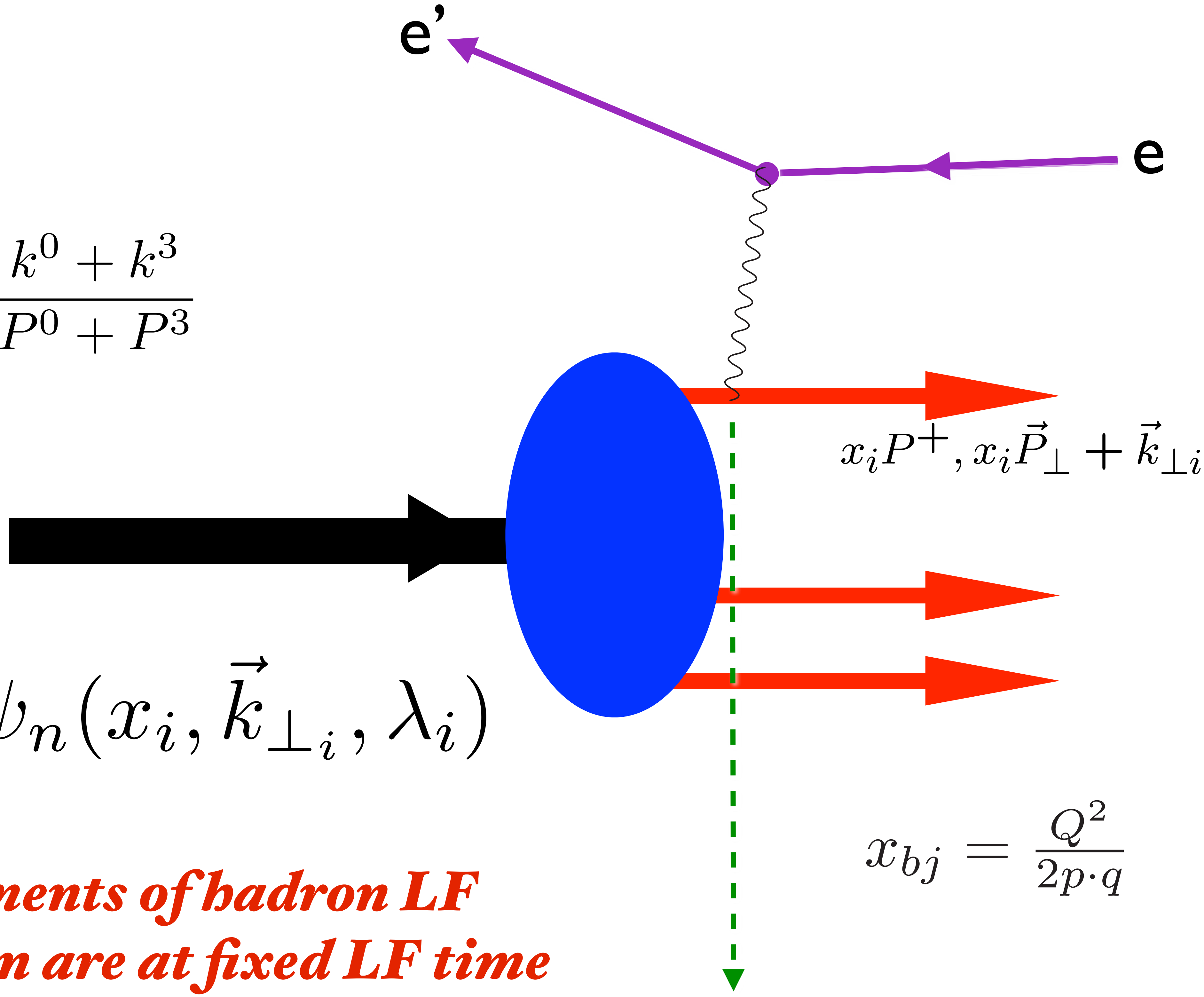
$$\int \psi_{BS}(p,k)dk^- \rightarrow \psi_{LF}$$

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

Invariant under boosts! Independent of P^μ

Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS

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



$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

$$x_{bj} = \frac{Q^2}{2p \cdot q}$$

Measurements of hadron LF wavefunction are at fixed LF time

Fixed $\tau = t + z/c$

Like a flash photograph!

$$\boxed{x_{bj} = x = \frac{k^+}{P^+}}$$

Frame Independent : Poincarè Invariance

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

Front Form

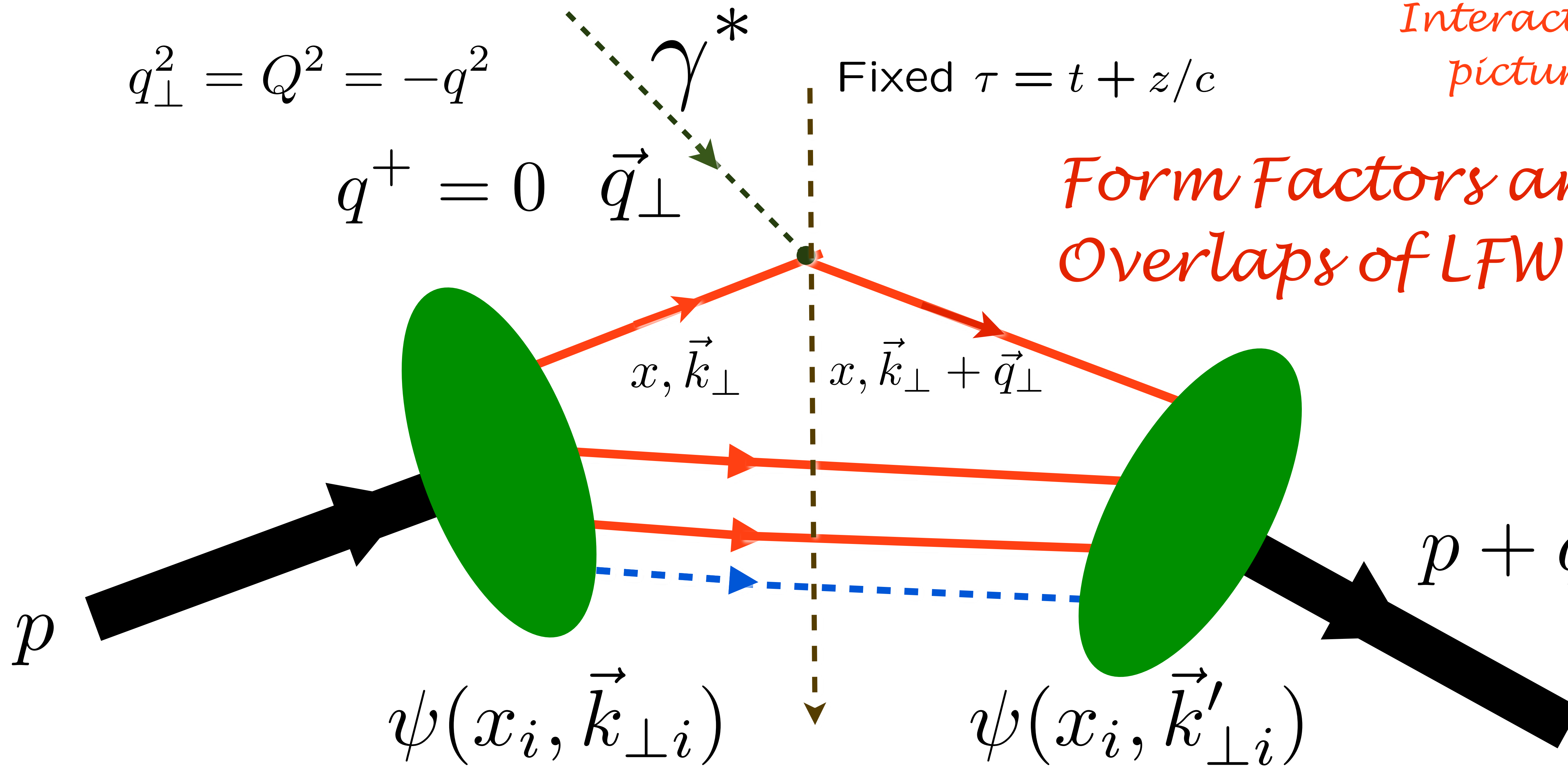
Interaction picture

$$q_\perp^2 = Q^2 = -q^2$$

Fixed $\tau = t + z/c$

$$q^+ = 0 \quad \vec{q}_\perp$$

Form Factors are Overlaps of LFWFs



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

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

Drell &Yan, West
Exact LF formula!

Drell, sjb

Exact LF Formula for Pauli Form Factor

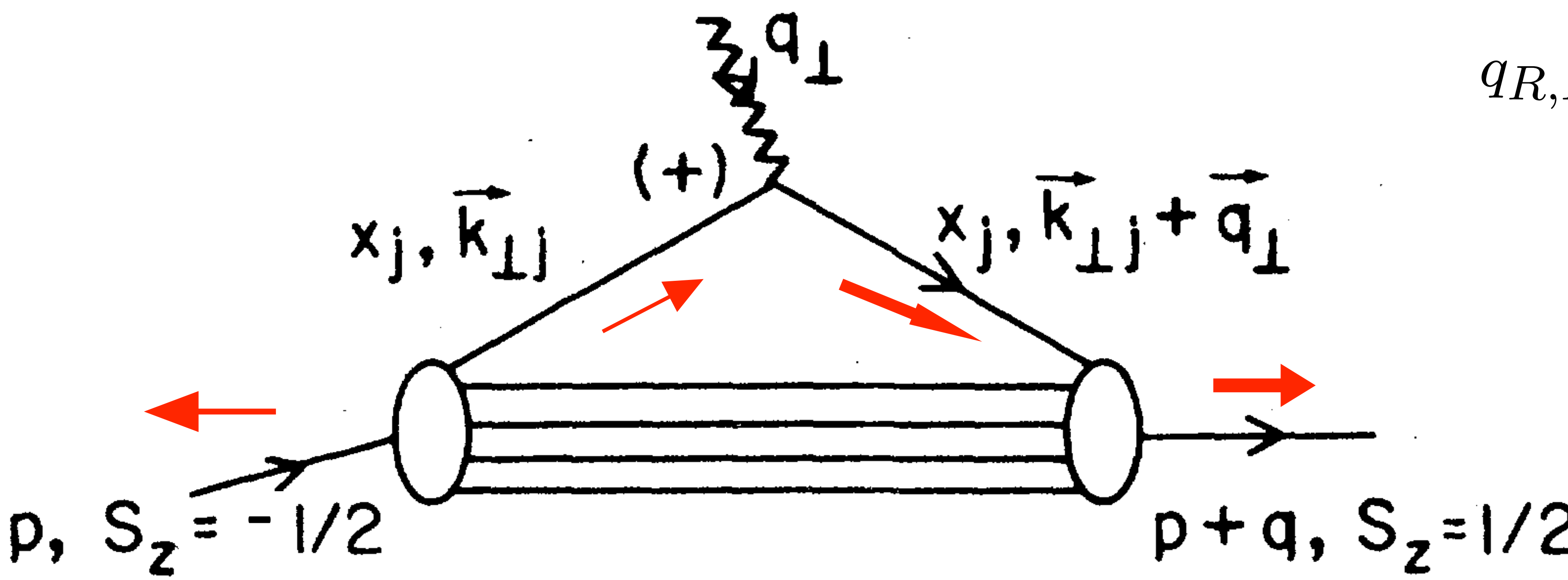
Drell, sjb

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

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

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

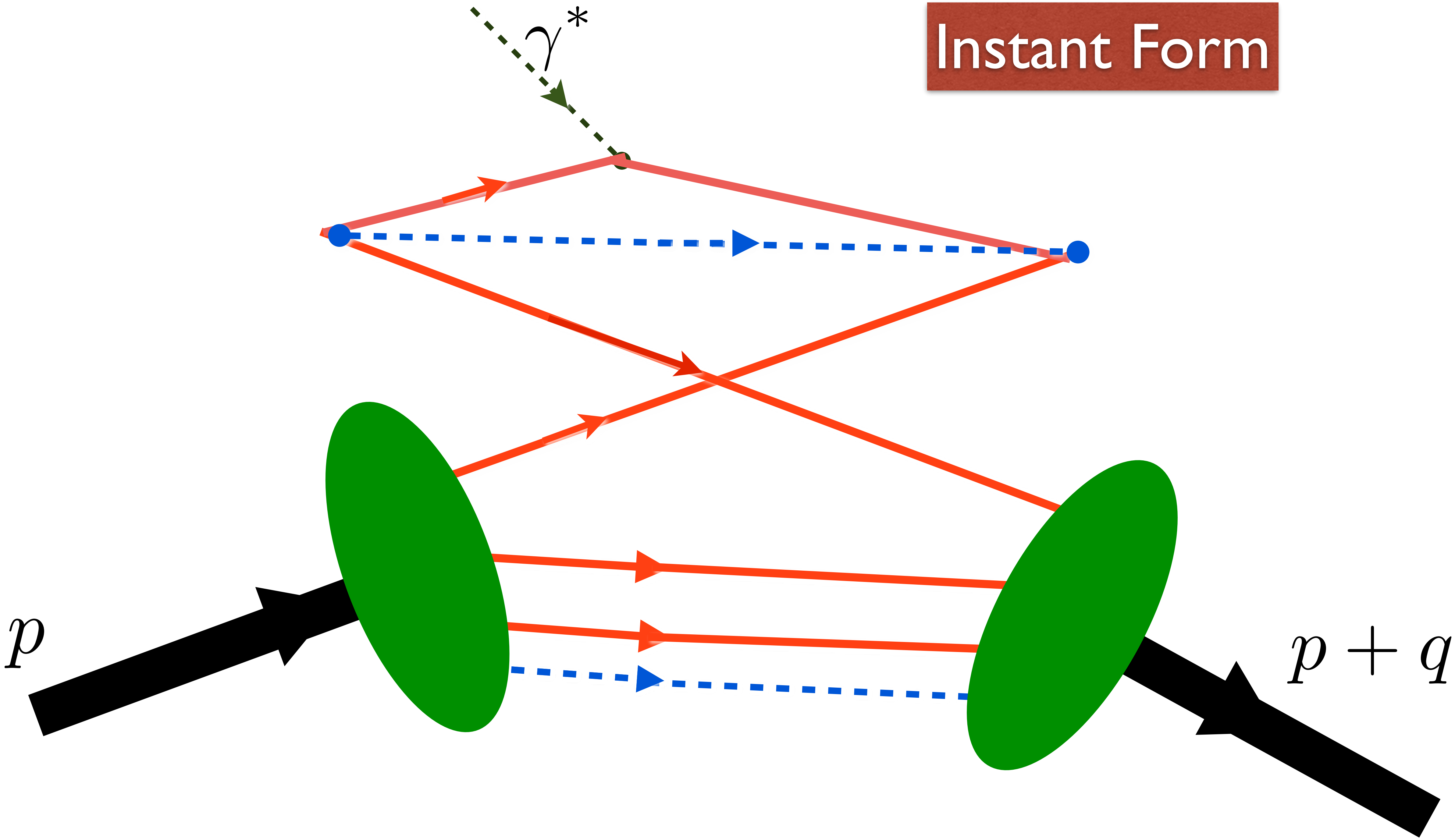
$$q_{R,L} = q^x \pm i q^y$$



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

Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

Instant Form



Must include vacuum-induced currents to compute form factors and other current matrix elements!

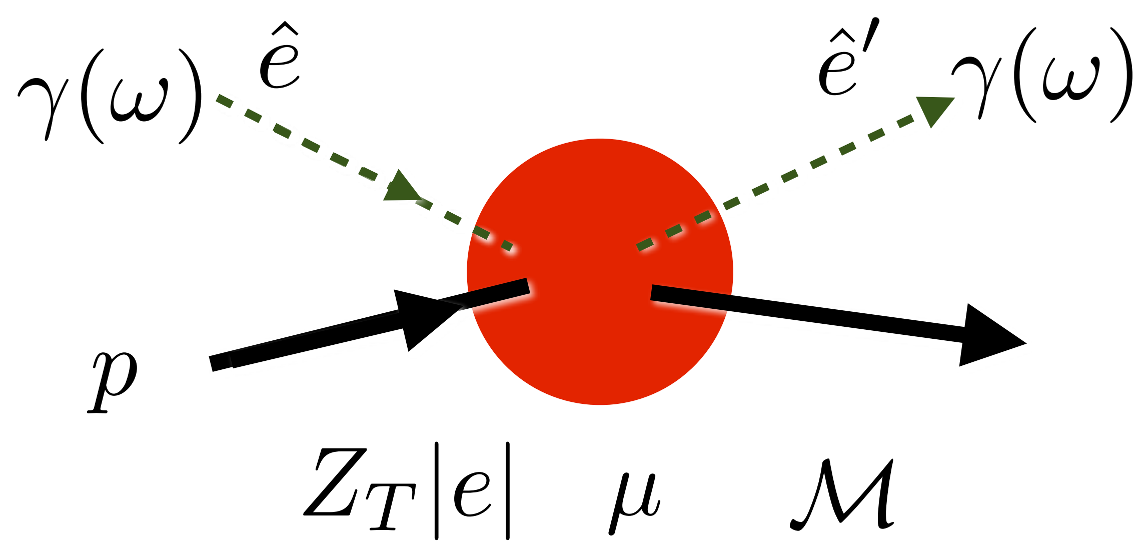
Boosts are dynamical in instant form

Low Energy Forward Compton Scattering

Low energy theorem: Spin-1/2 Target

$$S_{fi} = -2\pi i\delta(E_f - E_i)\ M_{fi}$$

$$M_{fi} = \frac{1}{2\omega}(2\pi)^3\,\delta^3(P_f - P_i)\left[\frac{{Z_T}^2e^2}{\mathcal{M}}\,\hat{\mathbf{e}}'\cdot\hat{\mathbf{e}}\delta_{fi} + 2i\omega\left(\mu - \frac{Z_T e}{2\mathcal{M}}\right)^2 \boldsymbol{\sigma}_{fi}\cdot\hat{\mathbf{e}}'\times\hat{\mathbf{e}} + O(\omega^2)\right]$$



Amplitude determined by static properties of target

$k\cdot p = \omega\mathcal{M}$ Photon lab energy $\omega \to 0, \theta \to 0$

Erroneous claim (Barton & Dombey): LET Wrong!

Single particle wave-packet

Primack, sjb

$$\phi(x) = \int \frac{d^3p}{(2\pi)^{3/2}} \sqrt{\frac{m}{p^0}}\, u(p)\, \phi(p)\, e^{-ip.x}$$

$$u(p) = \sqrt{\frac{p^0+m}{2m}} \begin{pmatrix} 1 \\ \dfrac{\sigma \cdot \mathbf{p}}{p^0+m} \end{pmatrix} \chi.$$

Instant Form Wavefunction of moving bound state:

Not product of independent boosts!

$$\varphi_{E\mathbf{P}}(\mathbf{x}_a \quad \mathbf{x}_b\,,\, X^0)_{SM}$$

$$= \frac{E+\mathscr{M}}{2\mathscr{M}} \int \frac{d^3p}{(2\pi)^{3/2}} \left(\frac{p_a{}^0+m_a}{2p_a{}^0}\,\frac{p_b{}^0+m_b}{2p_b{}^0}\right)^{1/2}$$

$$\times \begin{pmatrix} 1 + \dfrac{\sigma_a \cdot \mathbf{P}}{\mathscr{M}+E}\,\dfrac{\sigma_a \cdot \mathbf{p}}{2m_a+k_a} \\ \sigma_a \cdot \left(\dfrac{\mathbf{P}}{\mathscr{M}+E} + \dfrac{\mathbf{p}}{2m_a+k_a}\right) \end{pmatrix} \otimes \begin{pmatrix} 1 - \dfrac{\sigma_b \cdot \mathbf{P}}{\mathscr{M}+E}\,\dfrac{\sigma_b \cdot \mathbf{p}}{2m_b+k_b} \\ \sigma_b \cdot \left(\dfrac{\mathbf{P}}{\mathscr{M}+E} - \dfrac{\mathbf{p}}{2m_b+k_b}\right) \end{pmatrix}$$

$$\times\ \phi_{\mathscr{M}}(\mathbf{p})\, \chi_{SM} \exp[i\mathbf{p}\cdot\tilde{\mathbf{x}} + i\mathbf{P}\cdot\mathbf{X}] \exp[-iEX^0].$$

$$\tilde{\mathbf{x}} = \mathbf{x} + (\gamma-1)\,\hat{\mathbf{V}}\hat{\mathbf{V}}\cdot\mathbf{x}\ ;\quad p^0_{a,b} = \sqrt{\mathbf{p}^2+m^2_{a,b}}\,,\quad k_{a,b} \equiv -\tau_{b,a}(U+W).$$

Correct Boosted Wavefunction needed for LET, DGH!

Gravitational Form Factors

$$\langle P'|T^{\mu\nu}(0)|P\rangle \;=\; \overline{u}(P')\Big[\,A(q^2)\gamma^{(\mu}\overline{P}^{\nu)} + B(q^2)\frac{i}{2M}\overline{P}^{(\mu}\sigma^{\nu)\alpha}q_\alpha$$
$$+C(q^2)\frac{1}{M}(q^\mu q^\nu - g^{\mu\nu}q^2)\Big]\,u(P)\;,$$

where $q^\mu = (P'-P)^\mu$, $\overline{P}^\mu = \frac{1}{2}(P'+P)^\mu$, $a^{(\mu}b^{\nu)} = \frac{1}{2}(a^\mu b^\nu + a^\nu b^\mu)$

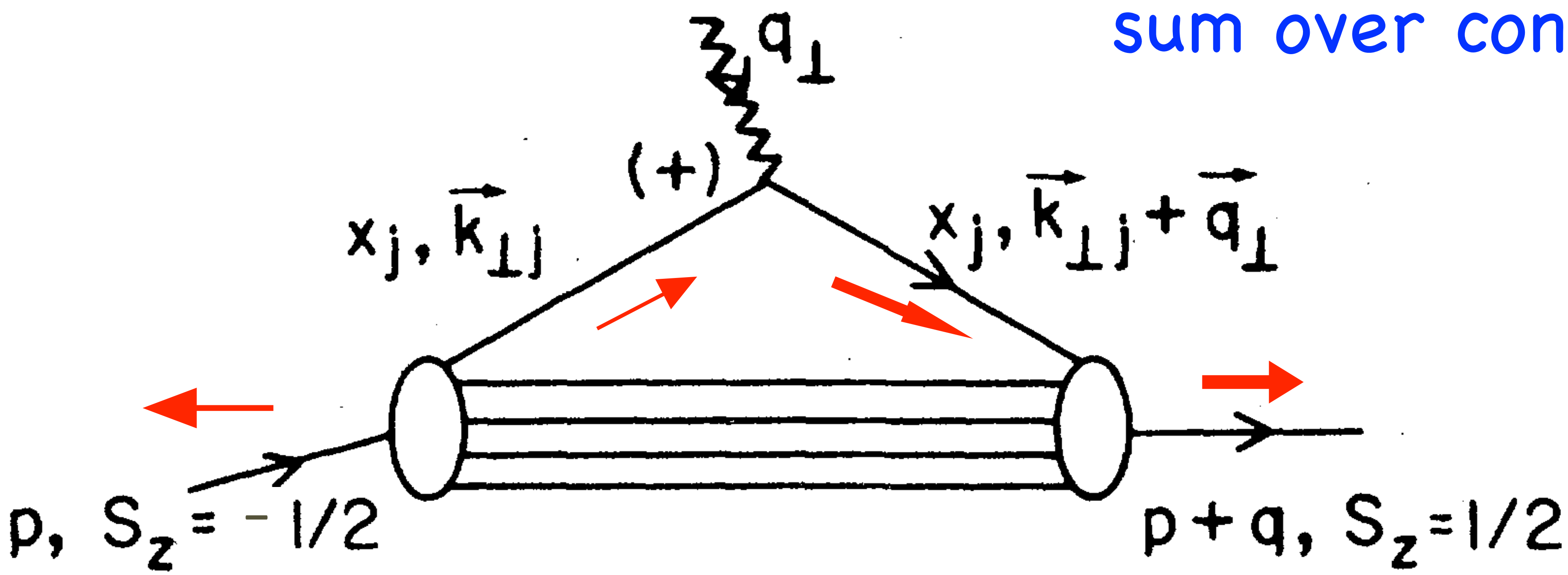
$$\left\langle P+q,\uparrow\left|\frac{T^{++}(0)}{2(P^+)^2}\right|P,\uparrow\right\rangle = A(q^2)\;,$$

$$\left\langle P+q,\uparrow\left|\frac{T^{++}(0)}{2(P^+)^2}\right|P,\downarrow\right\rangle = -(q^1-\mathrm{i}q^2)\frac{B(q^2)}{2M}\;.$$

Vanishing Anomalous gravitomagnetic moment B(0)

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

graviton



sum over constituents

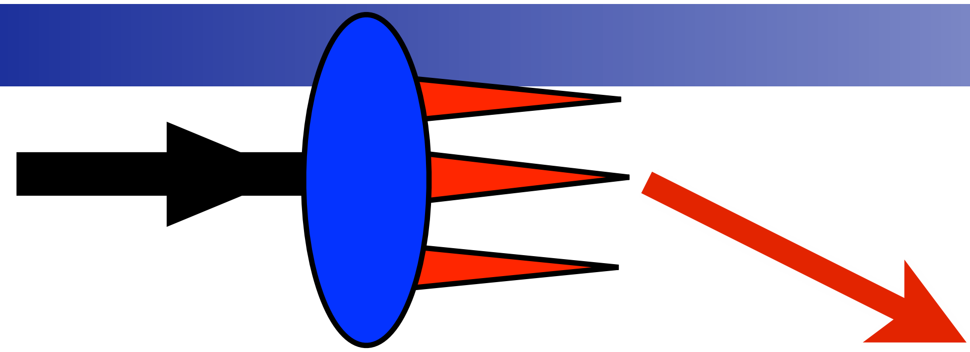
Hwang, Schmidt, Ma, sjb; Holstein et al

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

Each Fock State

Light-Front vs. Instant Form

- **Light-Front Wavefunctions are frame-independent**
- **Boosting an instant-form wavefunctions is a dynamical problem -- extremely complicated even in QED**
- **Vacuum state is lowest energy eigenstate of Hamiltonian**
- **Light-Front Vacuum same as vacuum of the free Hamiltonian**
- **Zero anomalous gravitomagnetic moment**
- **Instant-Form Vacuum infinitely complex even in QED**
- **n! time-ordered diagrams in Instant Form**
- **Causal commutators using LF time; simple cluster decomposition**



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

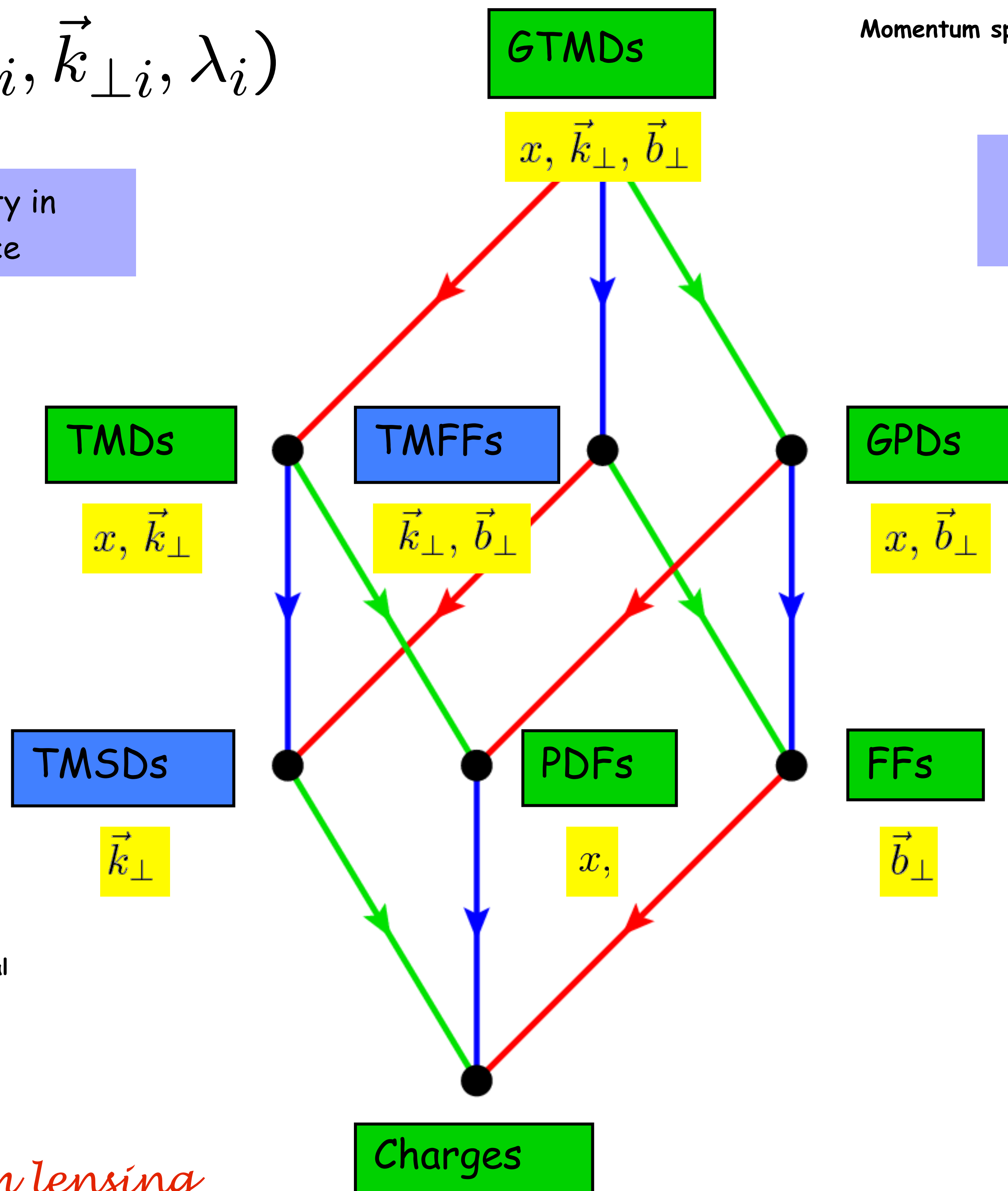
Light-Front Wavefunctions underly hadronic observables

Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ Position space

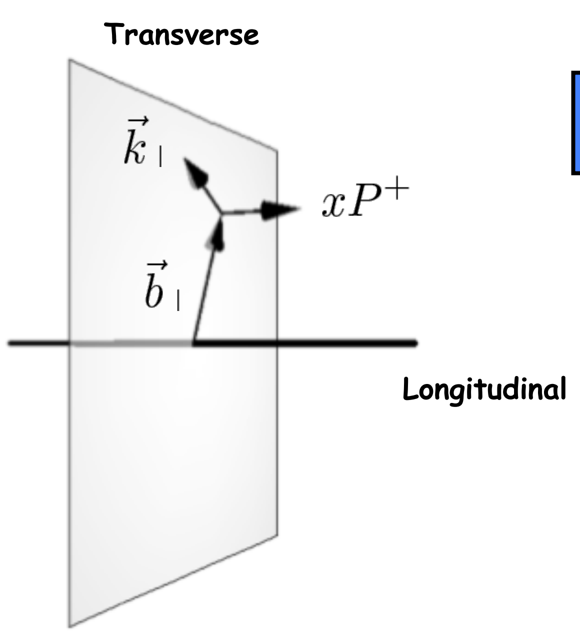
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in momentum space

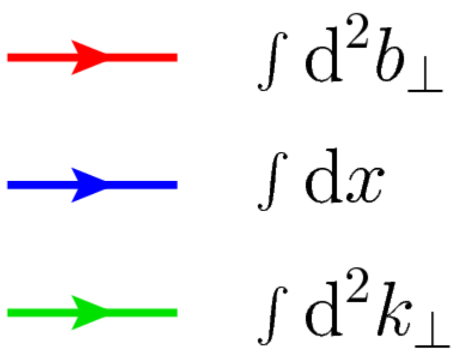
Transverse density in position space



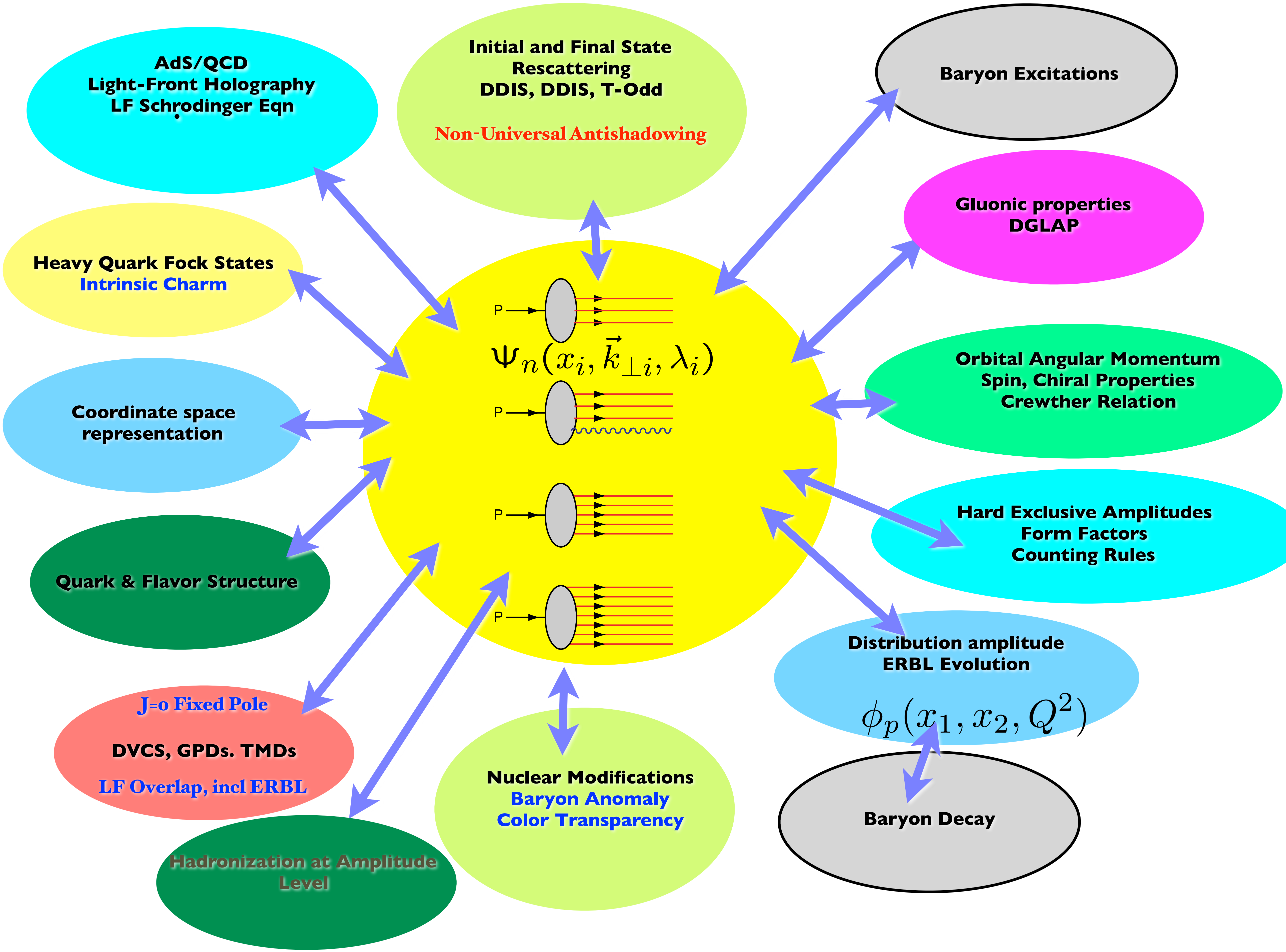
Lorcè, Pasquini



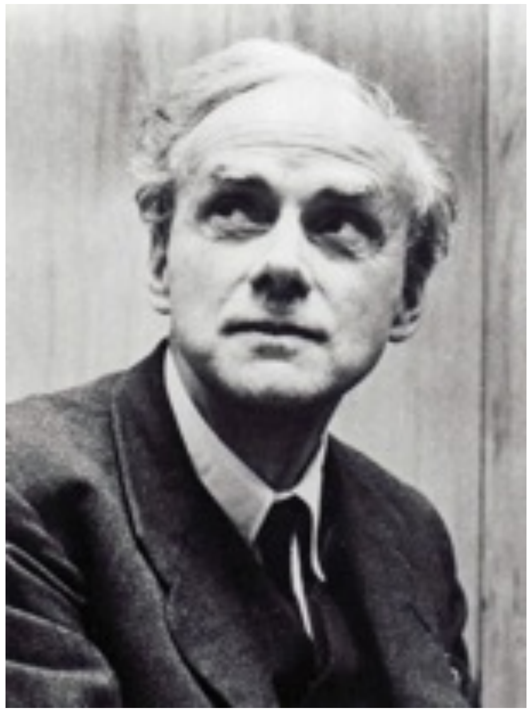
Sivers, T-odd from lensing

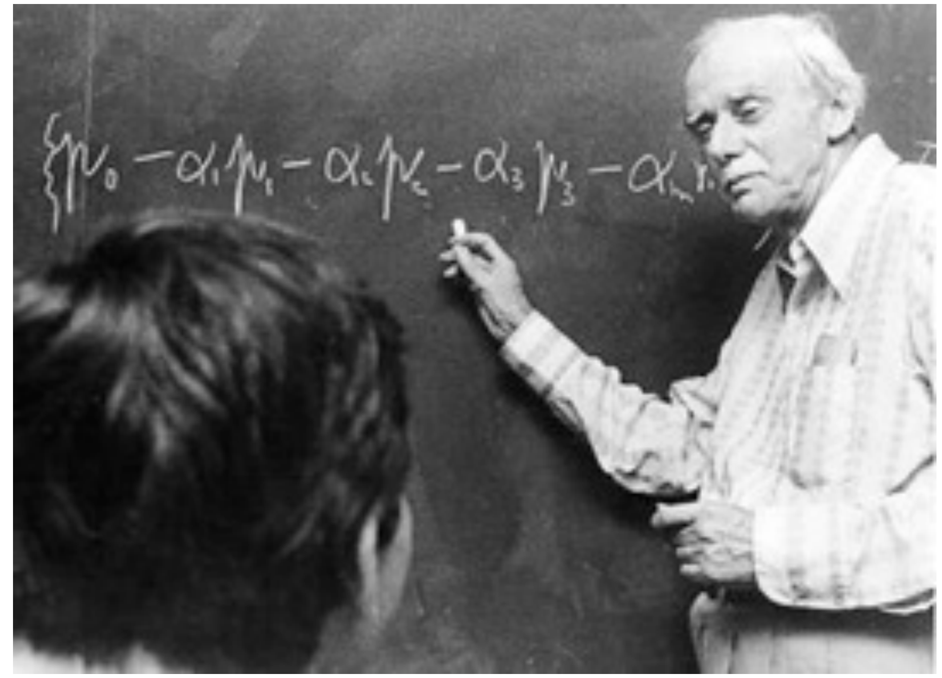


QCD and the LF Hadron Wavefunctions



P.A.M. Dirac (1977)





"Working with a front is a process that is unfamiliar to physicists.

But still I feel that the mathematical simplification that it introduces is all-important.

I consider the method to be promising and have recently been making an extensive study of it.

It offers new opportunities, while the familiar instant form seems to be played out " - P.A.M. Dirac (1977)

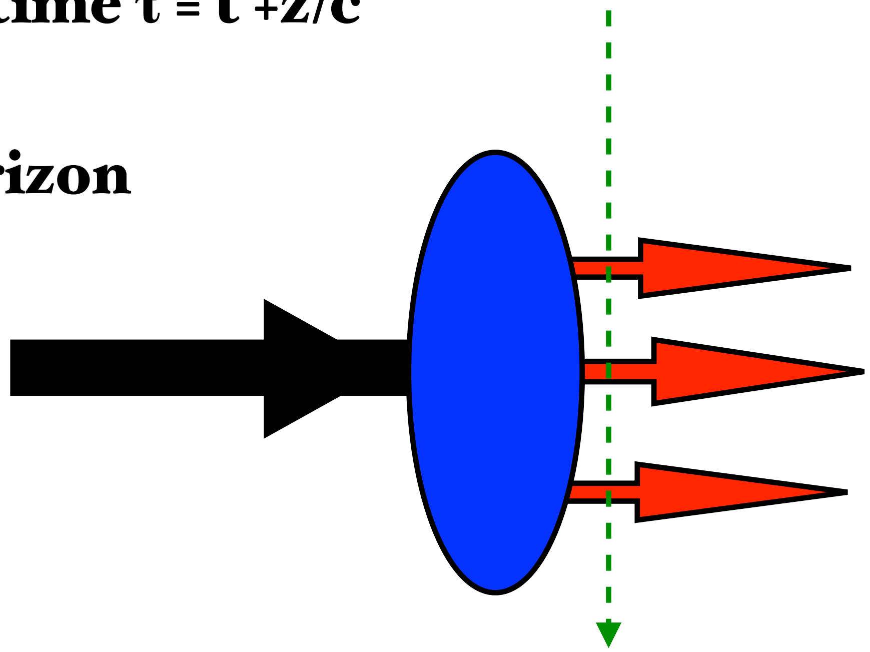
Advantages of the Dirac's Front Form for Hadron Physics

- Measurements are made at fixed τ
- Causality is automatic
- Structure Functions are squares of LFWFs
- Form Factors are overlap of LFWFs
- LFWFs are frame-independent -- no boosts!
- No dependence on observer's frame
- LF Holography: Dual to AdS space
- LF Vacuum trivial up to zero modes
- Profound implications for Cosmological Constant

R. Shrock, sjb

Unique Features of Light-Front Quantization

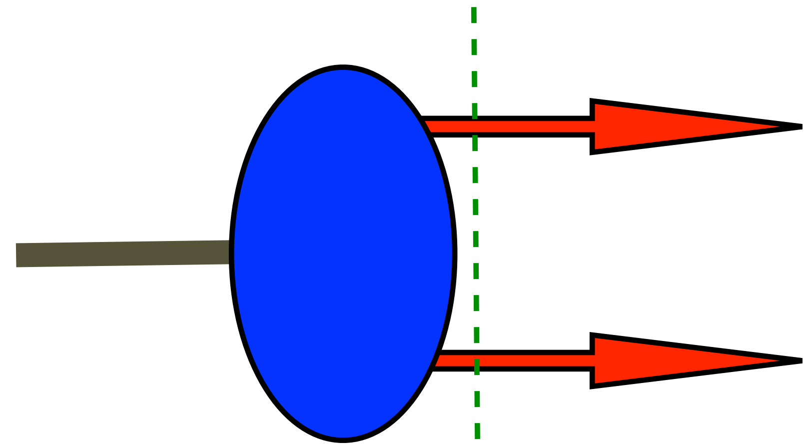
- **Boosts are Kinematical**
- **LF wavefunctions independent of bound-state four-momentum P^μ**
- **Current Matrix Elements and Form Factors are overlaps of LFWFs**
- **Measurements made at fixed light-front time $\tau = t + z/c$**
- **States defined at fixed τ within causal horizon**
- **Normal-ordering built in**
- **Jz conservation, $J^z = S^z + L^z$**
- **Cluster Decomposition**
- **LF Vacuum Trivial up to Zero-Modes (Higgs)**
- **Zero Cosmological Constant (No Vacuum Loops)**



$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

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

- Evolution Equations from PQCD, OPE

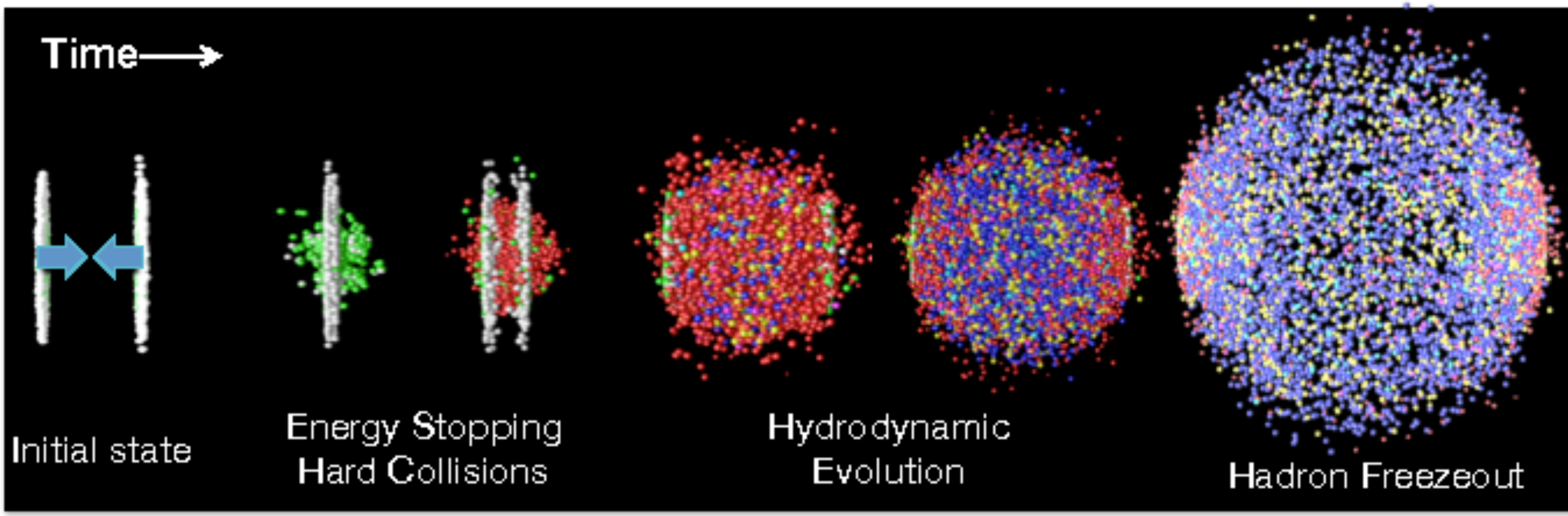
Efremov, Radyushkin

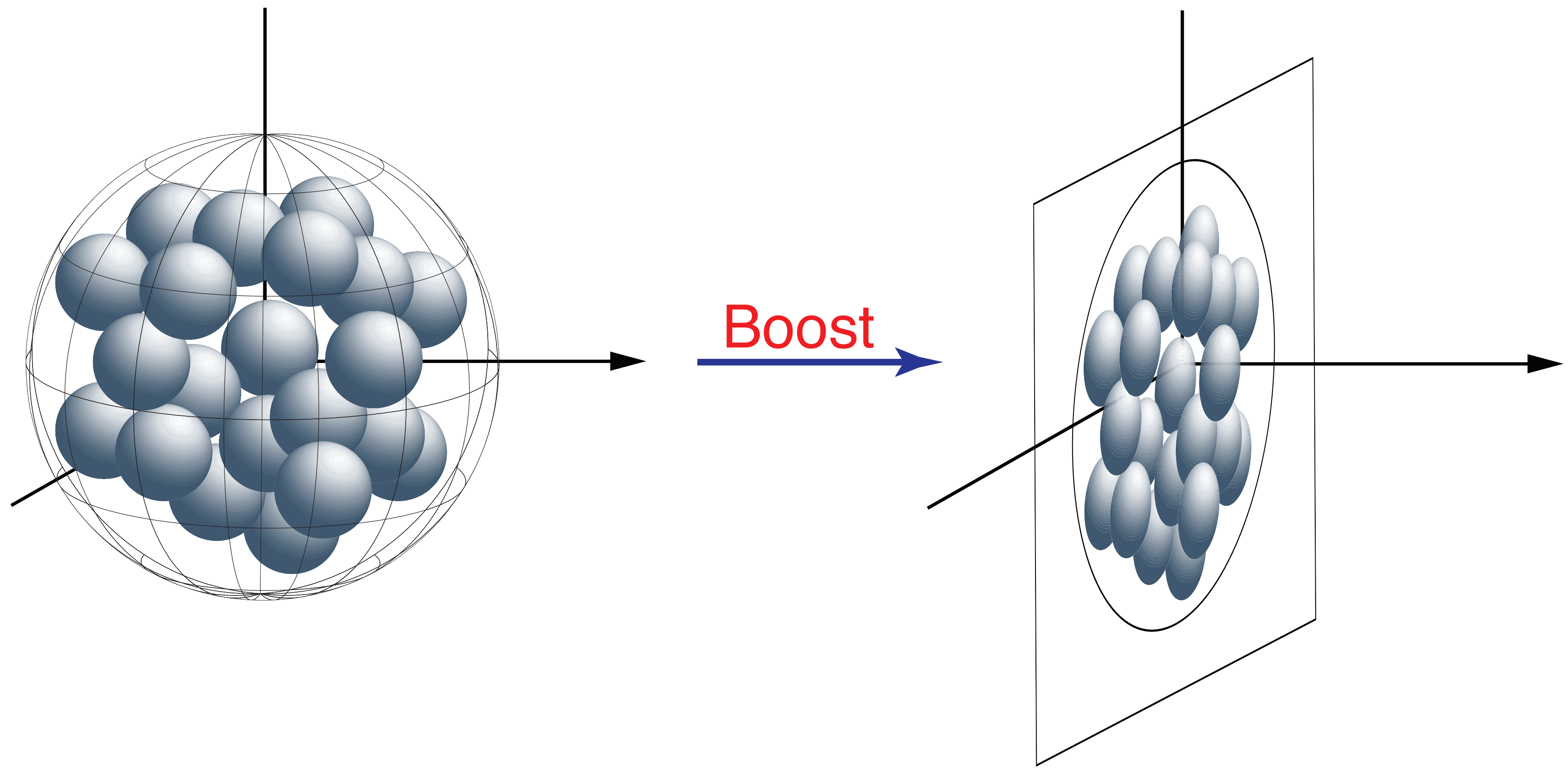
- Conformal Expansions

Sachrajda, Frishman
Lepage, sjb

- Compute from valence light-front wavefunction

Representation of Ion-Ion Collisions at RHIC, LHC





A large nucleus before and after an ultra-relativistic boost.

Is this really true? Will an electron-proton collider see different results than a fixed target experiment such as SLAC because the nucleus is squashed to a pancake?

No length contraction — no pancakes!

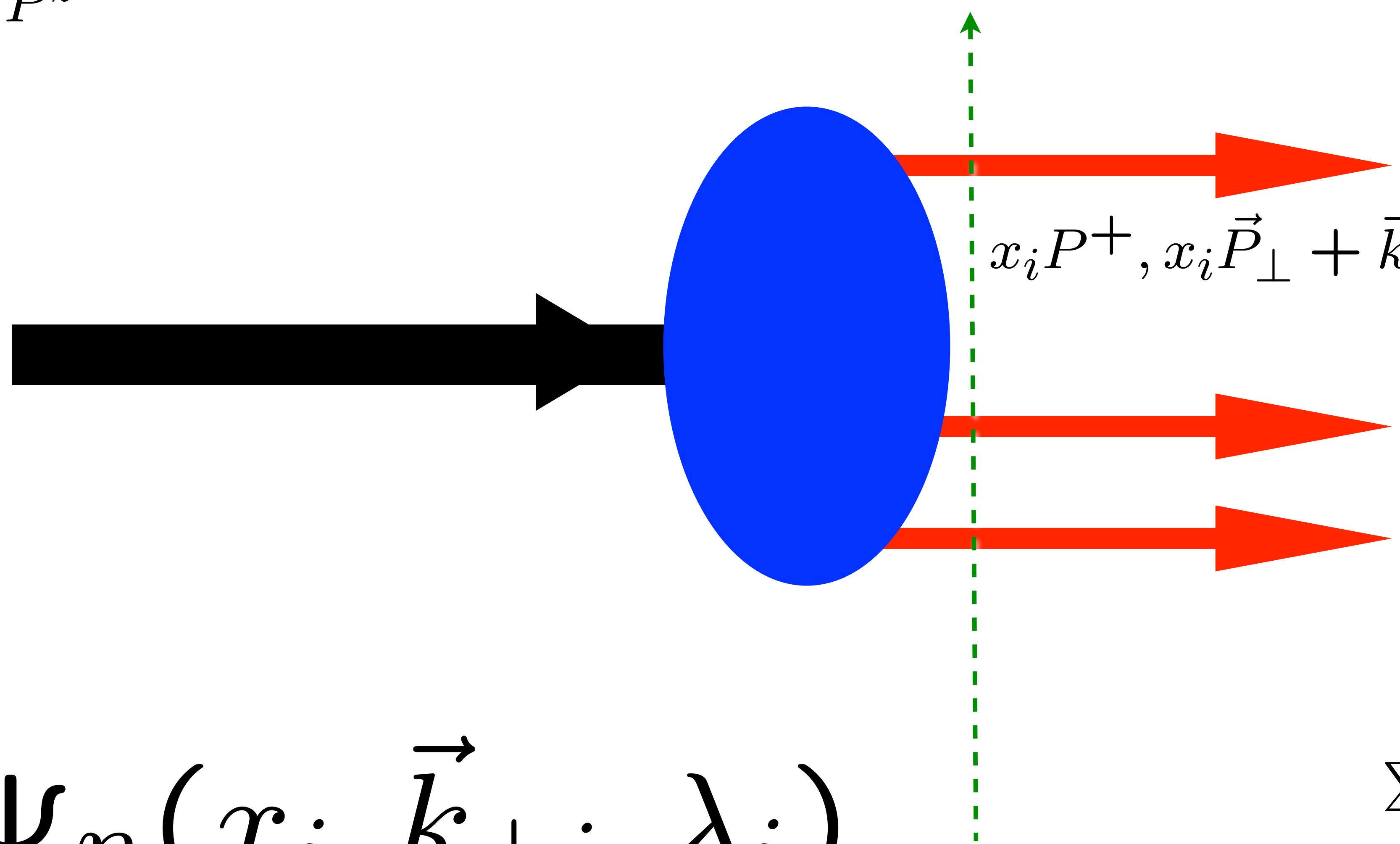
Penrose
Terrell
Weiskopf

We do not observe the nucleus at one time t!

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

Fixed $\tau = t + z/c$

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



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

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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Angular Momentum on the Light-Front

LC gauge A⁺=0

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

Conserved
LF Fock state by Fock State

Gluon orbital angular momentum defined in physical lc gauge

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

n-1 orbital angular momenta

Orbital Angular Momentum is a property of LFWFS

Nonzero Anomalous Moment -->
Nonzero quark orbital angular momentum!

Light-Front Perturbation Theory for *p*QCD

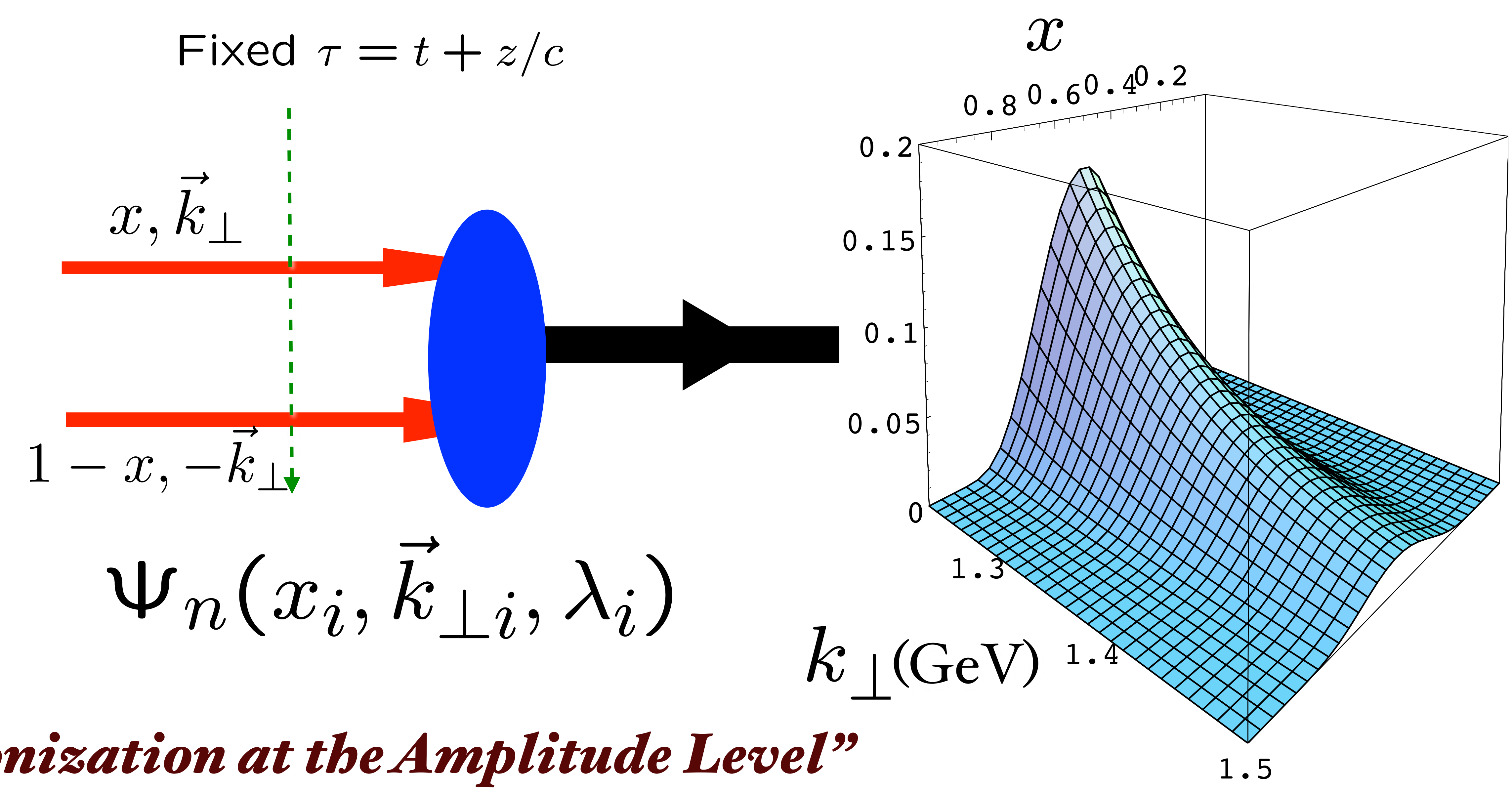
$$T = H_I + H_I \frac{1}{\mathcal{M}^2_{initial} - \mathcal{M}^2_{intermediate} + i\epsilon} H_I + \cdots$$

- *"History": Compute any subgraph only once since the LFPth numerator does not depend on the process — only the denominator changes!*
- *Wick Theorem applies, but few amplitudes since all $k^+ > 0$.*
- *J_z Conservation at every vertex* $\boxed{\left| \sum_{initial} S^z - \sum_{final} S_z \right| \leq n}$ *at order g^n*

  K. Chiu, sjb
- *Unitarity is explicit*
- *Loop Integrals are 3-dimensional* $\int_0^1 dx \int d^2 k_\perp$
- *hadronization: coalesce comoving quarks and gluons to hadrons using light-front wavefunctions* $\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

- *Light Front Wavefunctions:* $\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

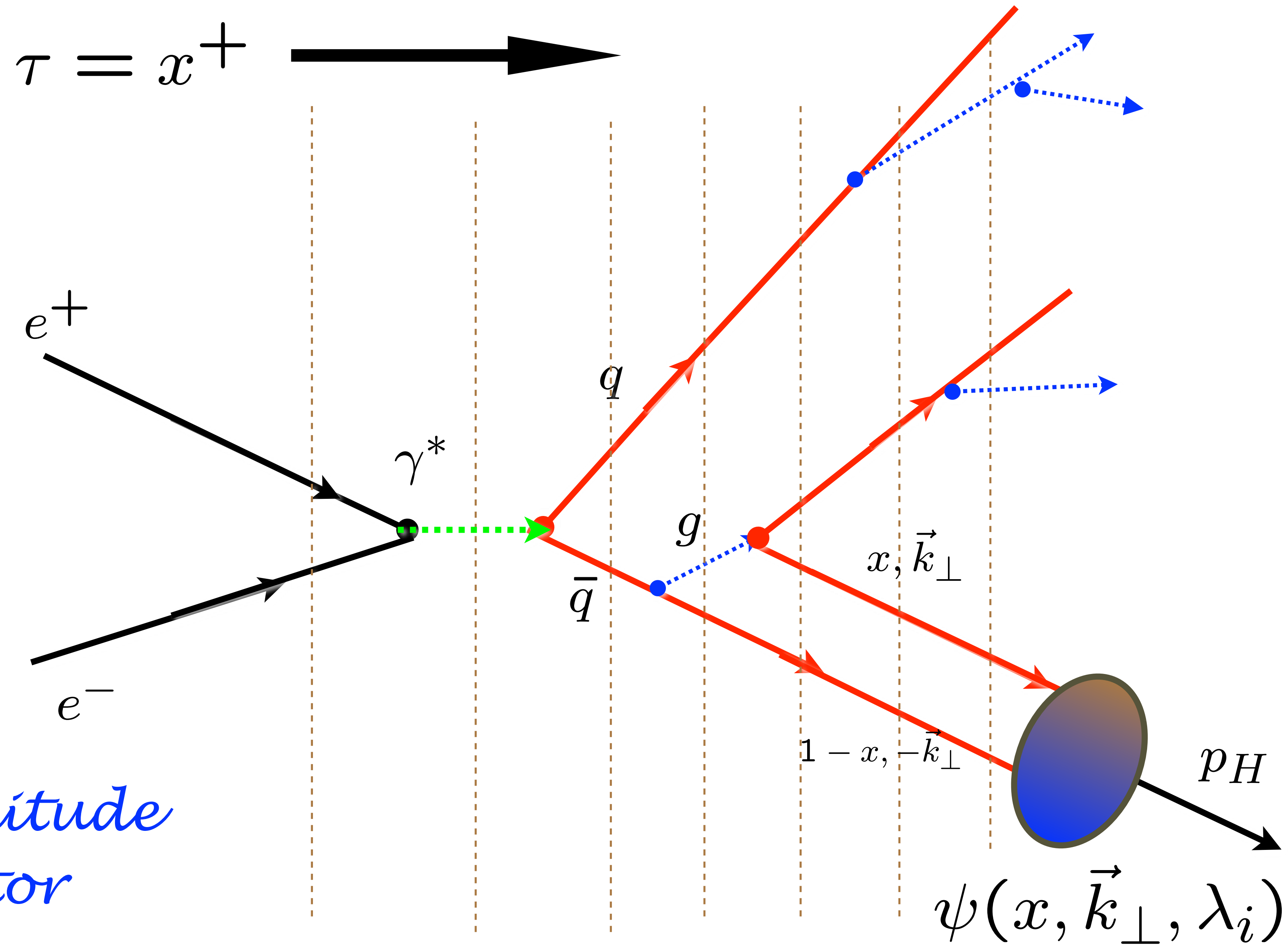
off-shell in P^- and invariant mass $\mathcal{M}^2_{q\bar{q}}$



"Hadronization at the Amplitude Level"

Boost-invariant LFWF connects confined quarks and gluons to hadrons

Hadronization at the Amplitude Level

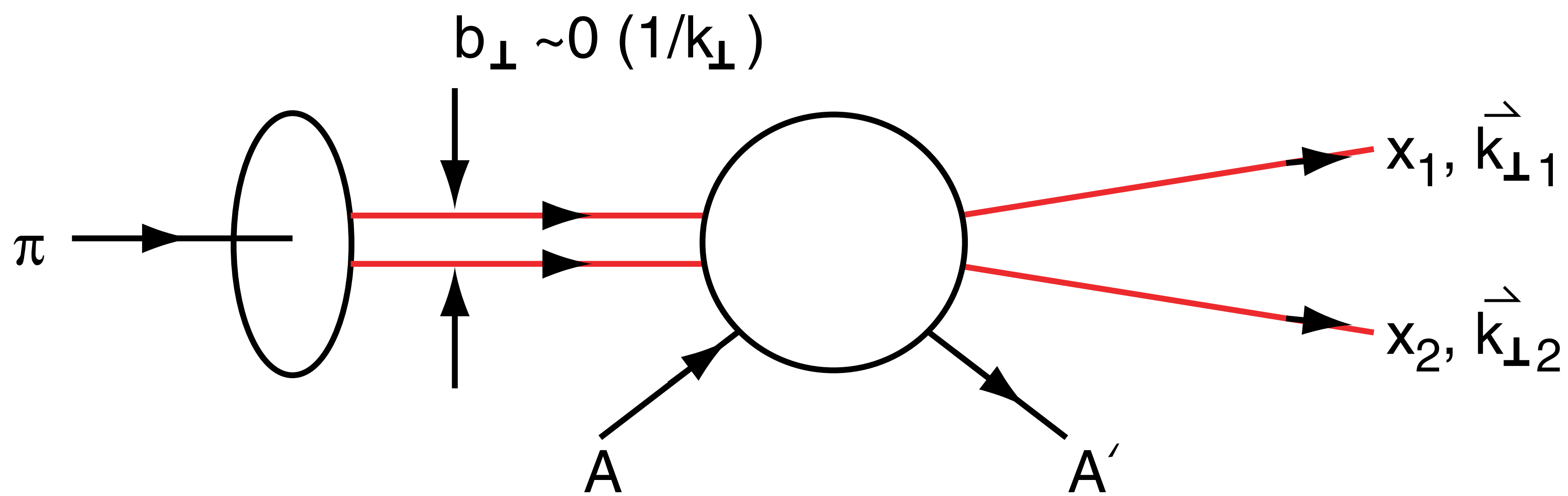


Event amplitude generator

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

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



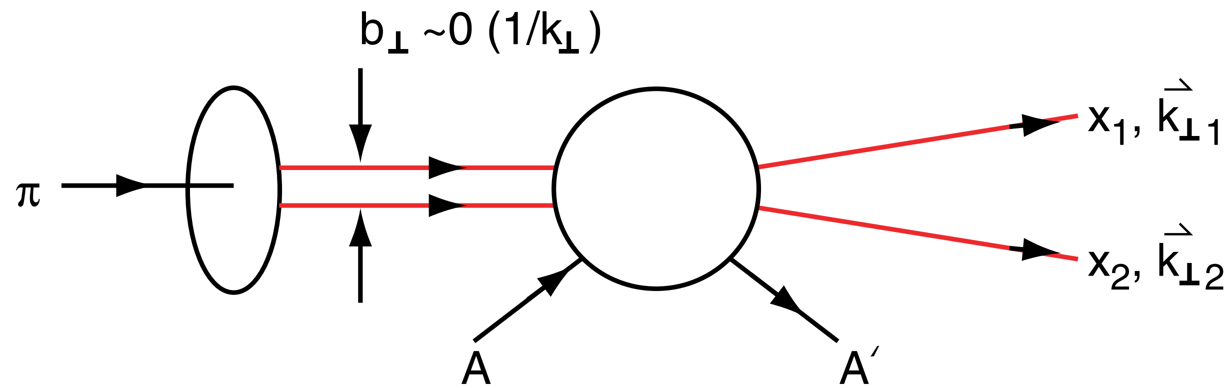
$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

Minimal momentum transfer to nucleus

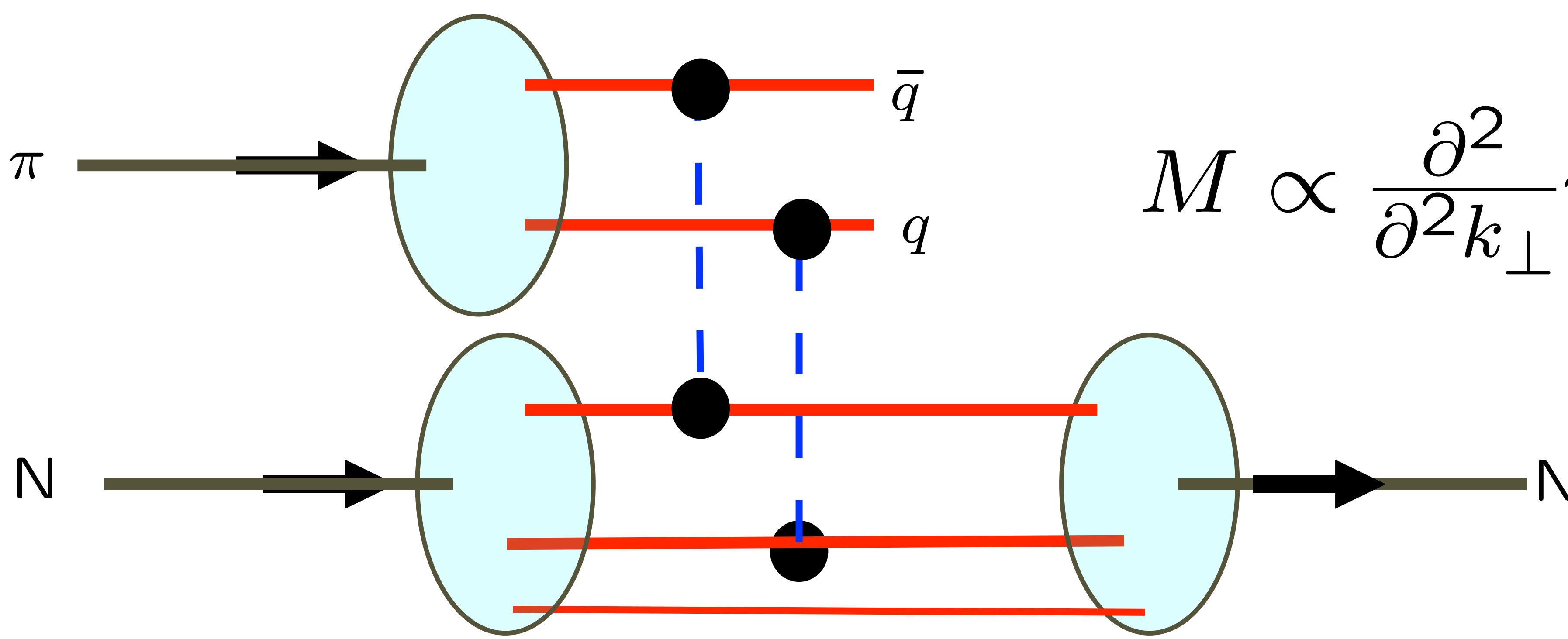
Nucleus left Intact!

E791 FNAL Diffractive DiJet



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

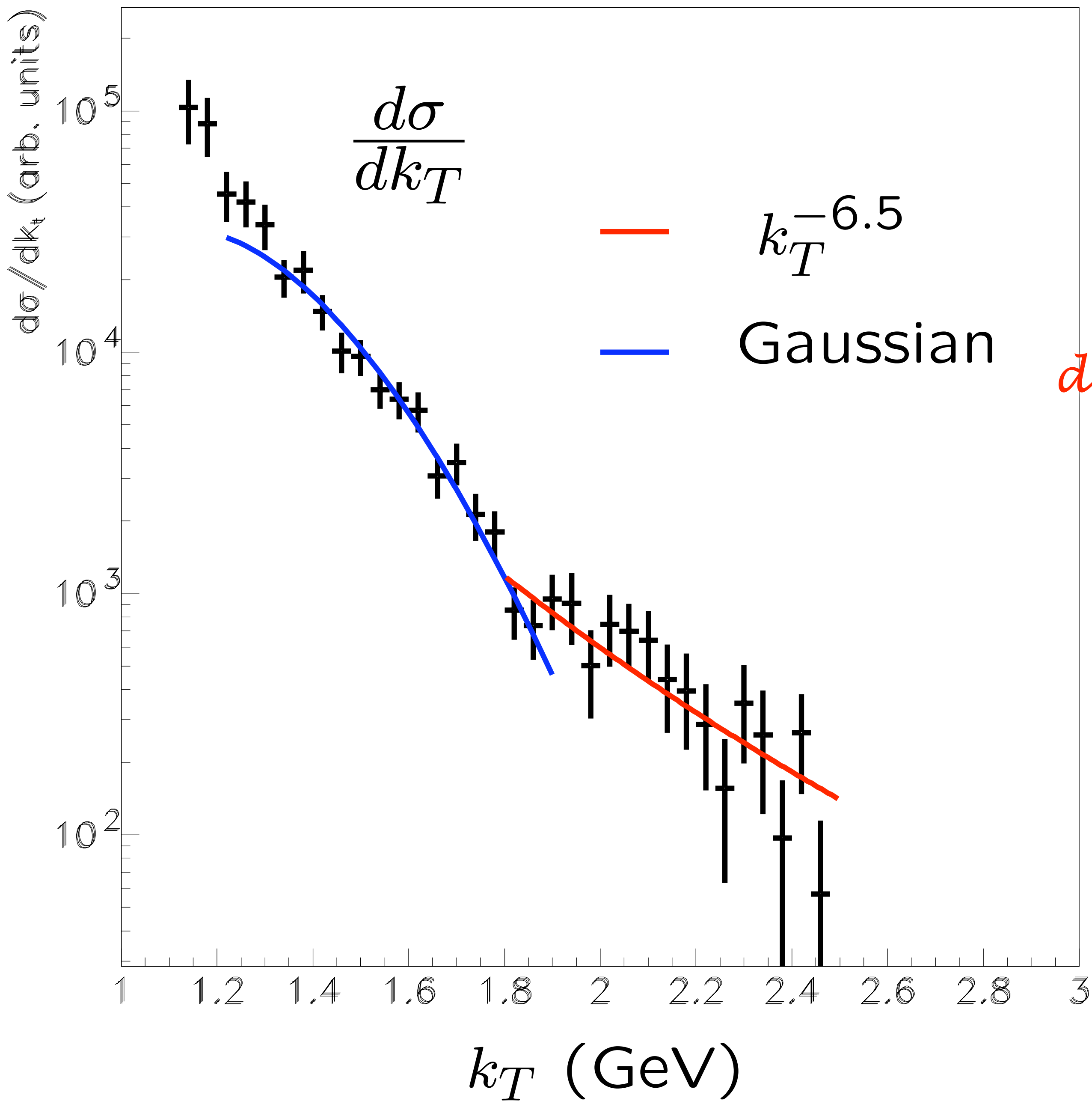
Two-gluon exchange measures the second derivative of the pion light-front wavefunction



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

Fermilab E791 Experiment, Ashery et al.

Diffractive Di-Jet transverse momentum distribution

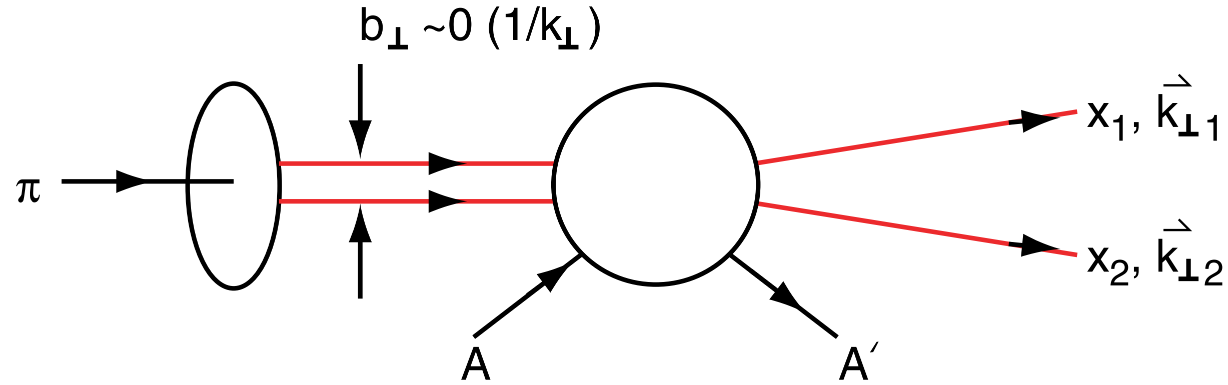


Two Components

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

Gaussian component similar to AdS/CFT HO LFWF

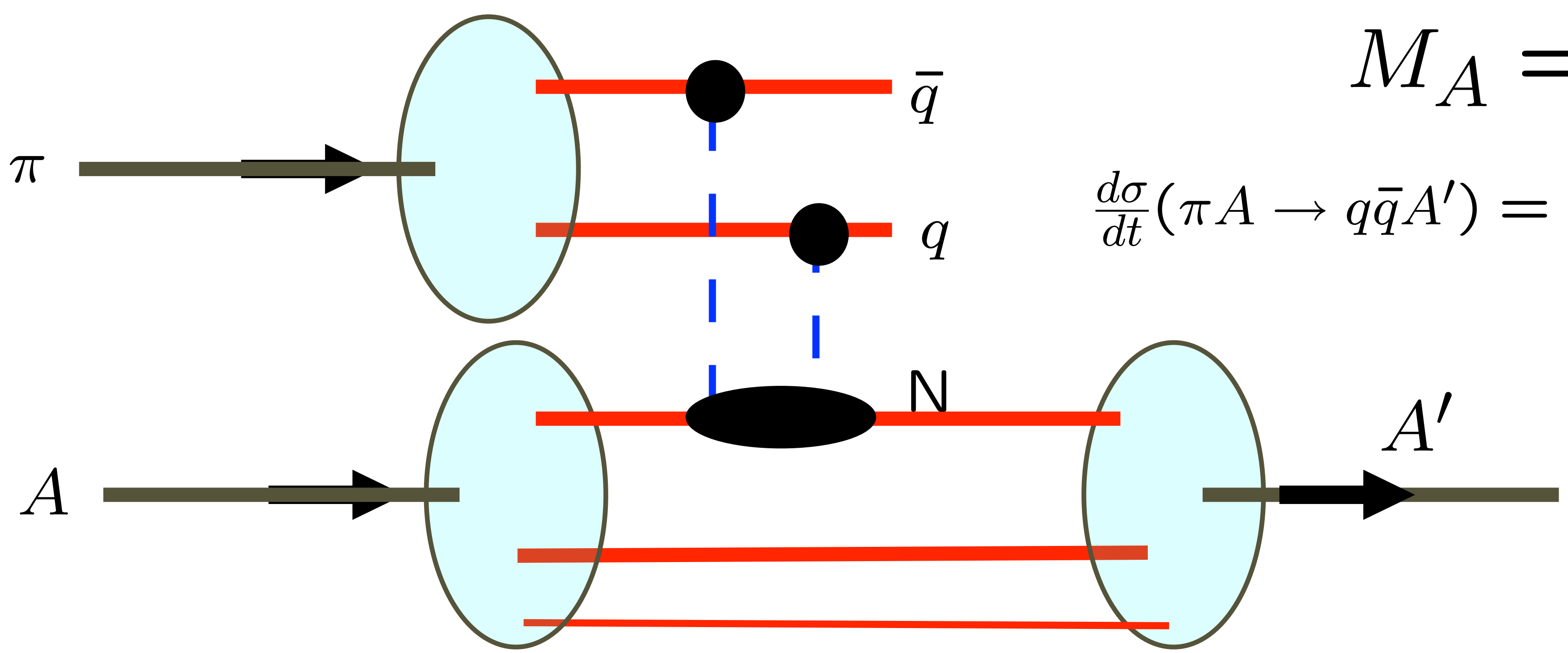
Fermilab E791 Experiment, Ashery et al.



large $k_\perp$, small $b_\perp$

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

QCD COLOR Transparency



$$M_A = A\ M_N$$

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

Target left intact

Diffraction, Rapidity gap

Frankfurt Miller Strikman

Mueller, sjb; Bertsch et al;
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

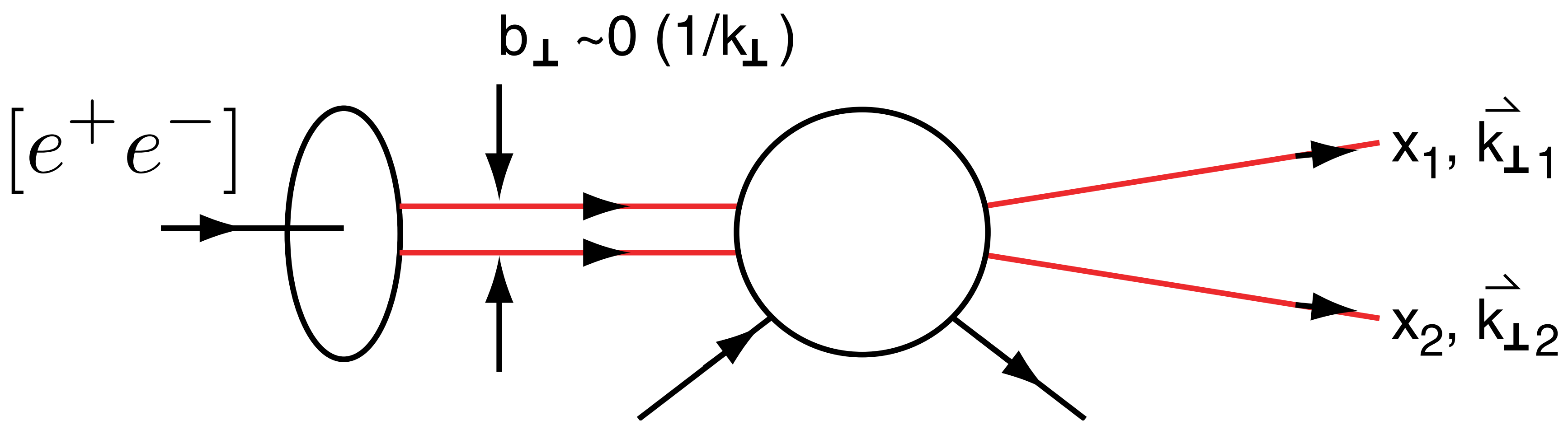
Ashery E791

α (Incoh.) $= 0.70 \pm 0.1$

Conventional Glauber Theory Ruled Out !

Factor of 7

Diffractive Dissociation of Atoms



$$M \propto \frac{\partial}{\partial \vec{k}_\perp} \psi_{e^+e^-}(x, \vec{k}_\perp)$$

Measure Light-Front Wavefunction of Positronium and Other Atoms

Minimal momentum transfer to Target

Target left Intact!

Single-spin asymmetries

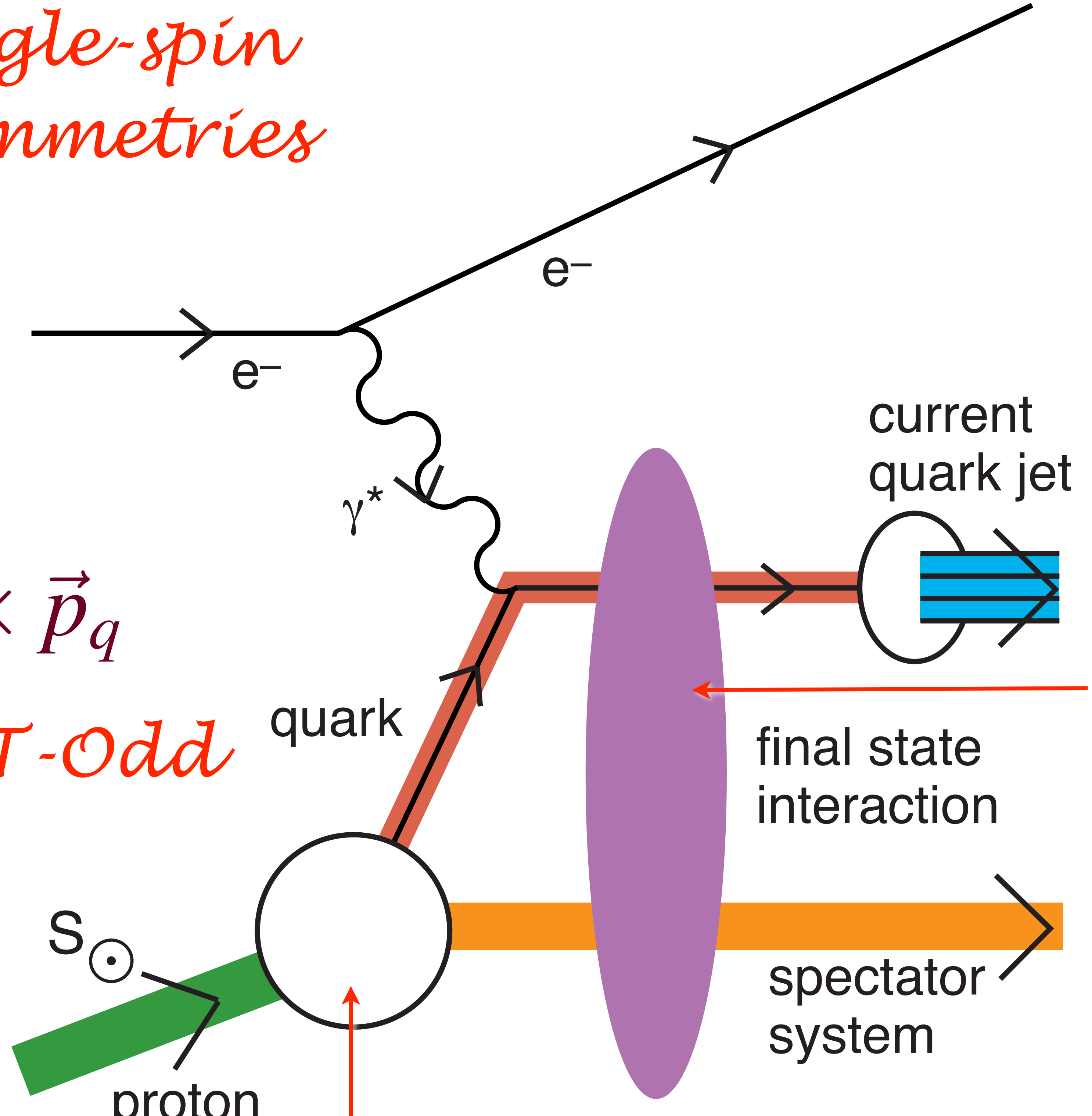
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

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

Pseudo- T-Odd

"Lensing" involves soft scales



Collins, Burkardt, Ji, Yuan. Pasquini, ...

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

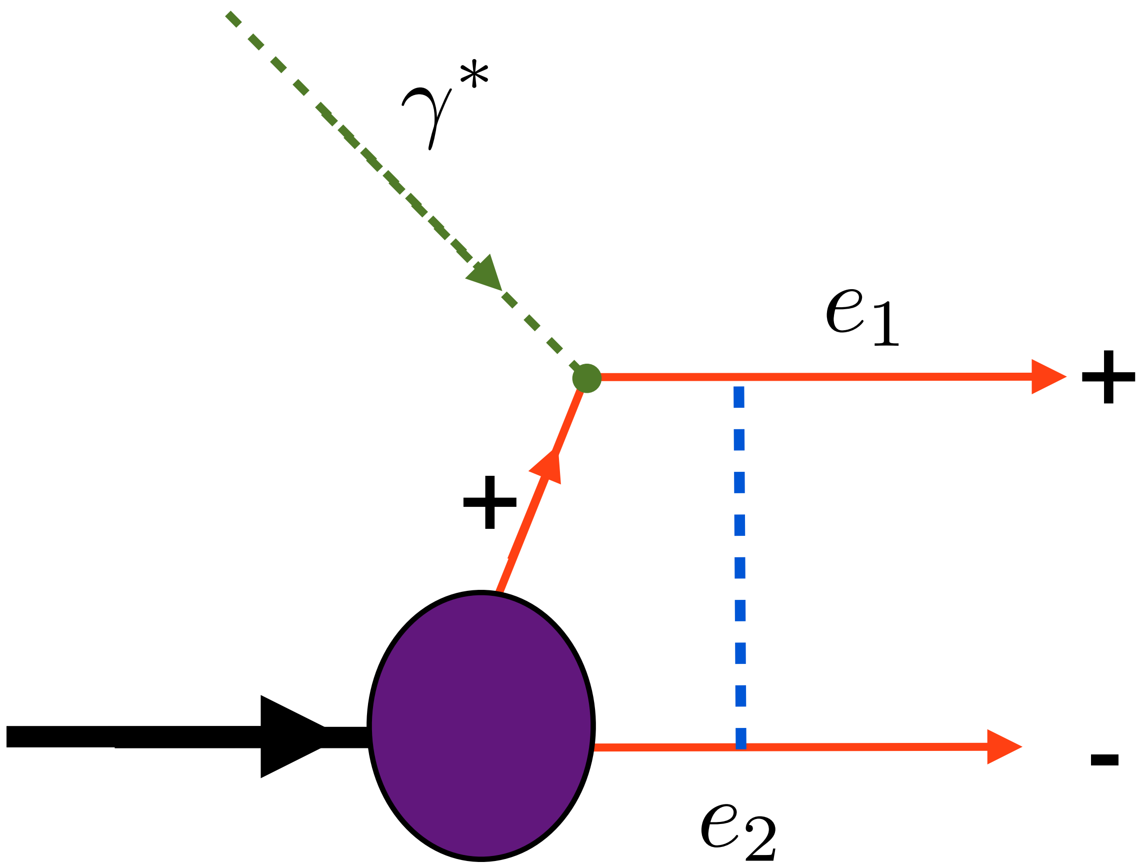
"Lensing Effect"

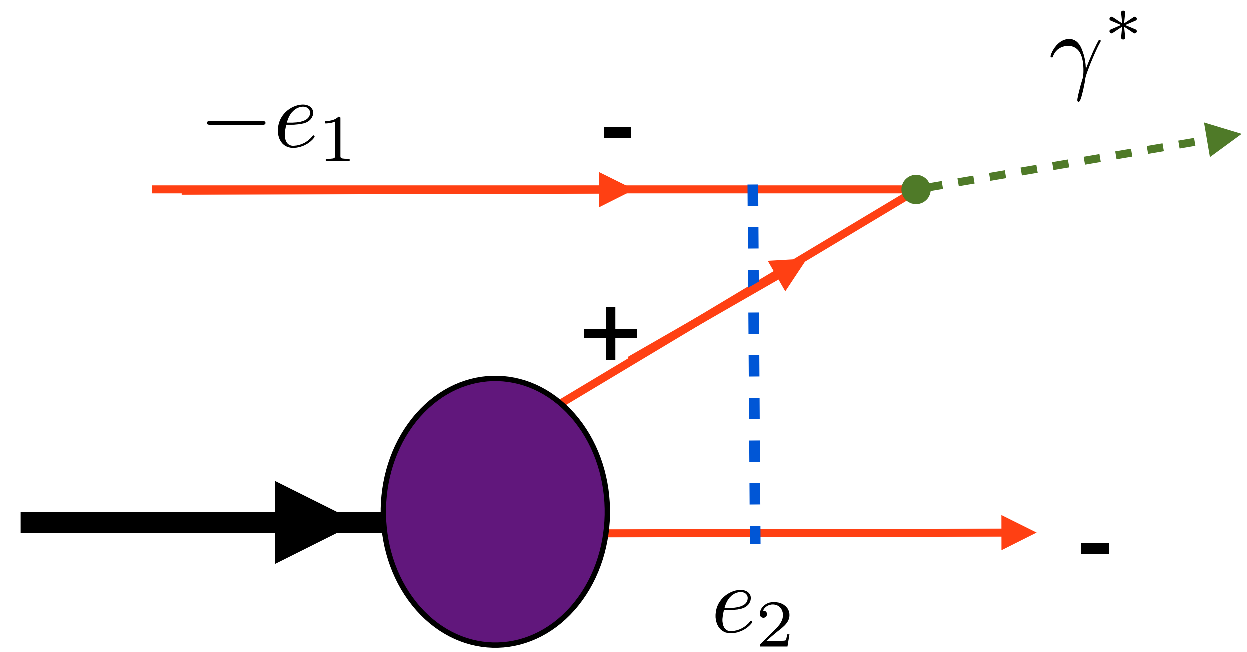
Light-Front Wavefunction S and P- Waves!

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!

Violates Conventional Wisdom!





DIS

Attractive, opposite-sign rescattering potential

DY

Repulsive, same-sign scattering potential

Dae Sung Hwang, Yuri V. Kovchegov, Ivan Schmidt, Matthew D. Sievert, sjb

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

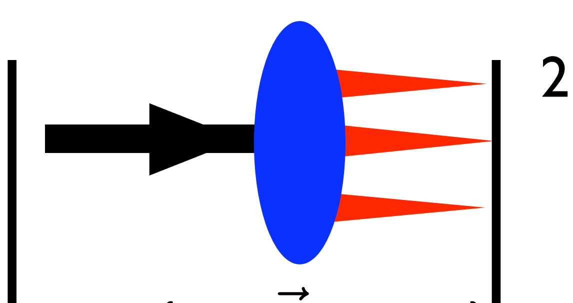
Hwang, Schmidt, sjb,

Mulders, Boer

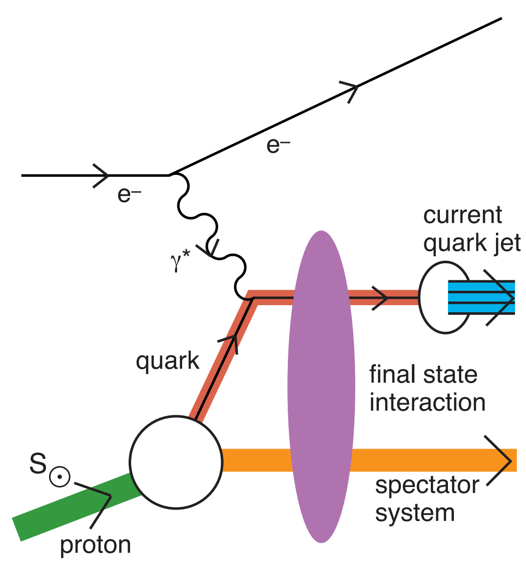
Qiu, Sterman

Collins, Qiu

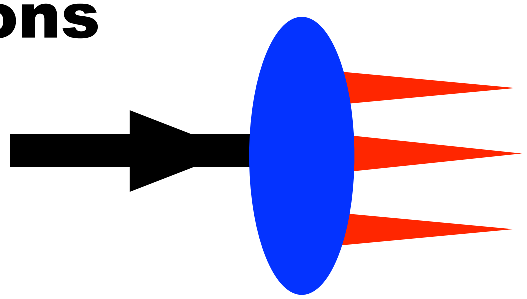
Pasquini, Xiao, Yuan, sjb



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



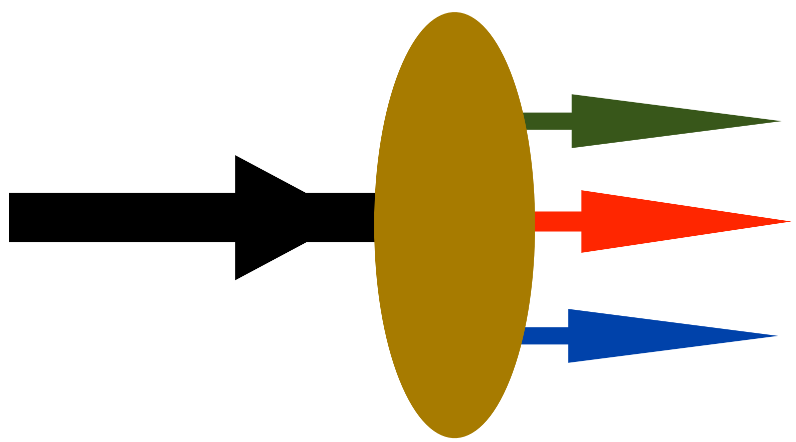
- **LF wavefunctions play the role of Schrödinger wavefunctions in Atomic Physics**



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

- **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!**

- *Hadron Physics without LFWFs is like Biology without DNA!*



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

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

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

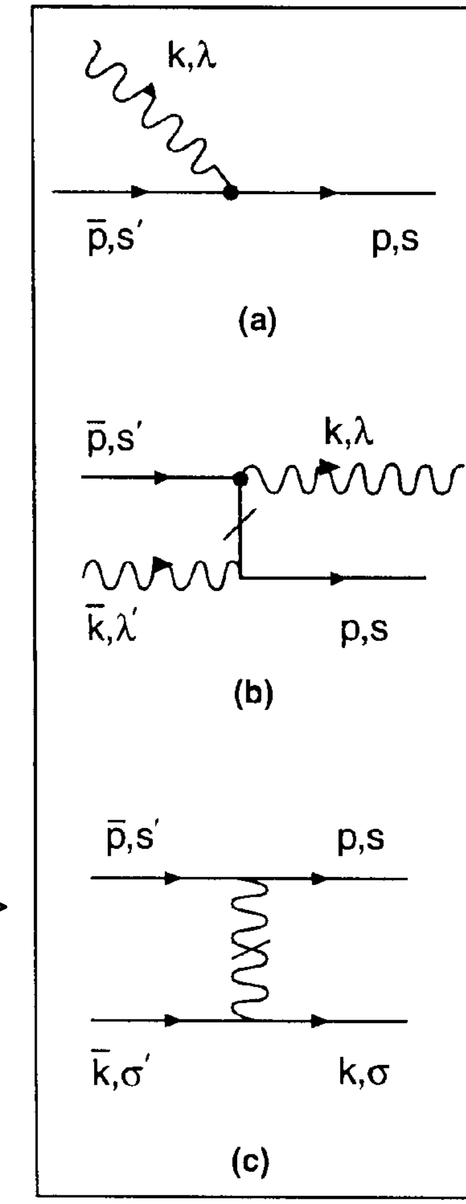
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

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

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

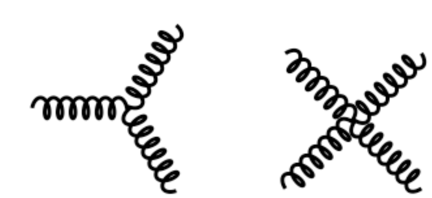
$$H^{QCD}_{LF} |\Psi_h> = \mathcal{M}^2_h |\Psi_h>$$

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



Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions

LFWFs: Off-shell in P- and invariant mass



H^{int}_{LF}

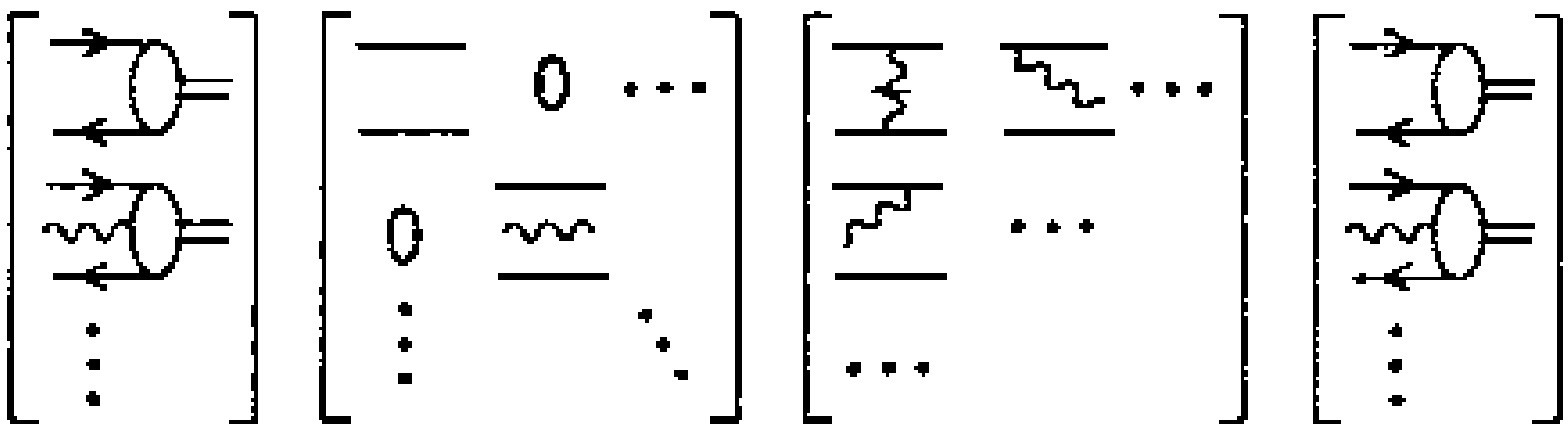
LIGHT-FRONT MATRIX EQUATION

G.P. Lepage, sjb

Rigorous Method for Solving Non-Perturbative QCD!

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

$A^+ = 0$



Minkowski space; frame-independent; no fermion doubling; no ghosts

Causal, Frame-Independent

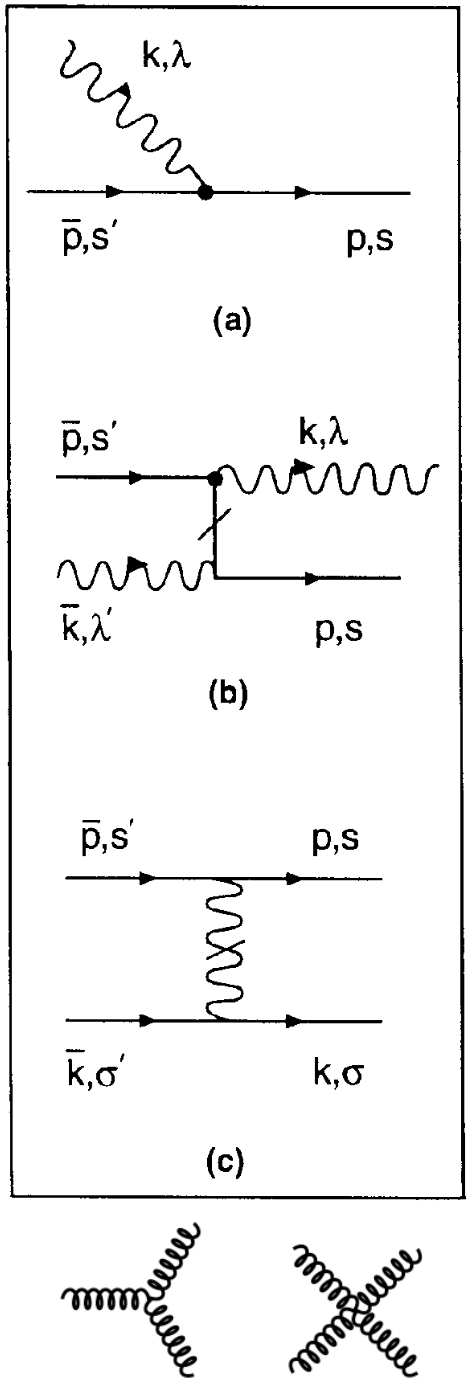
Light-Front QCD

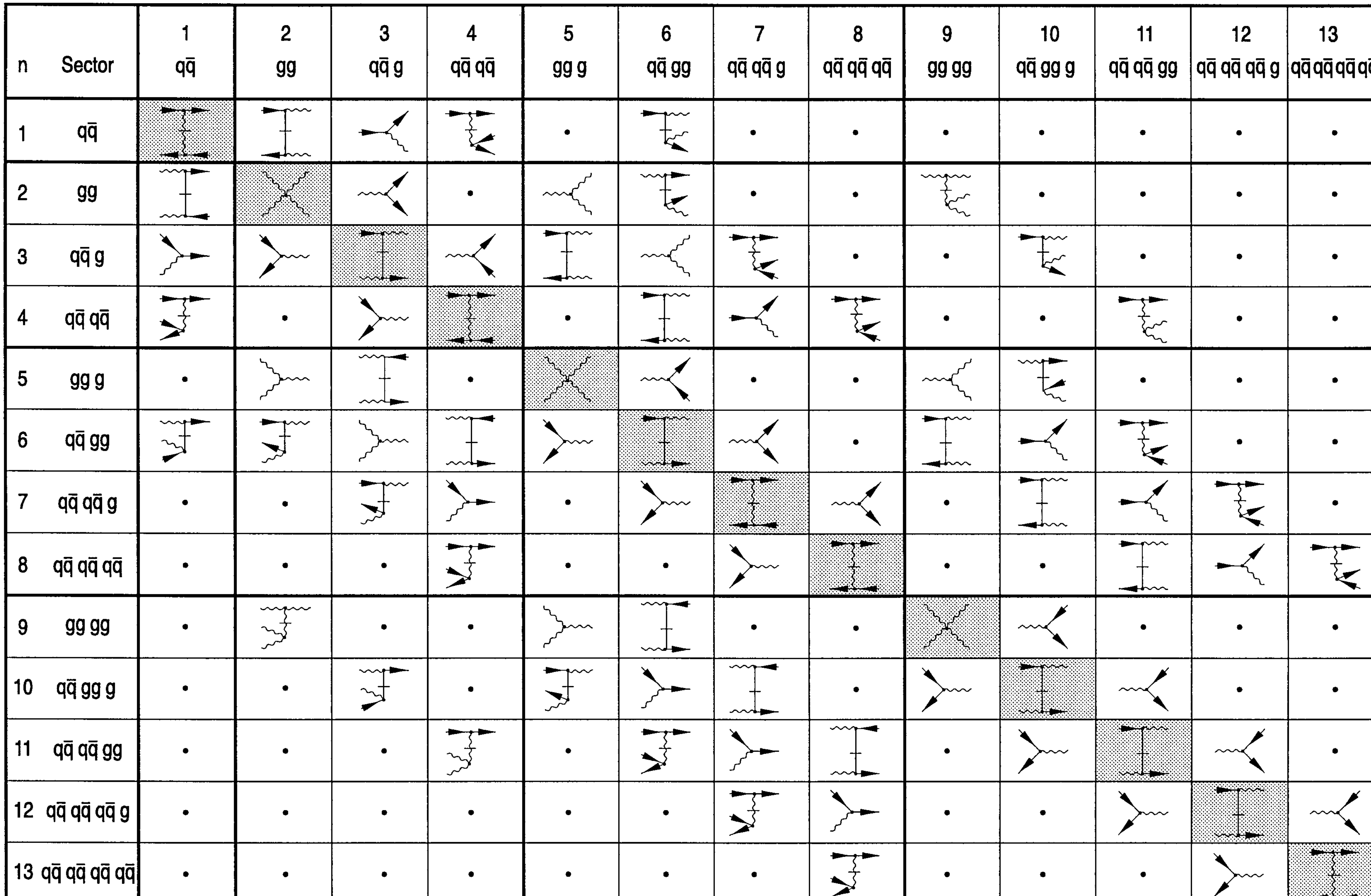
Heisenberg Equation

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

DLCQ: Solve QCD(1+1) for any quark mass and flavors

Hornbostel, Pauli, sjb

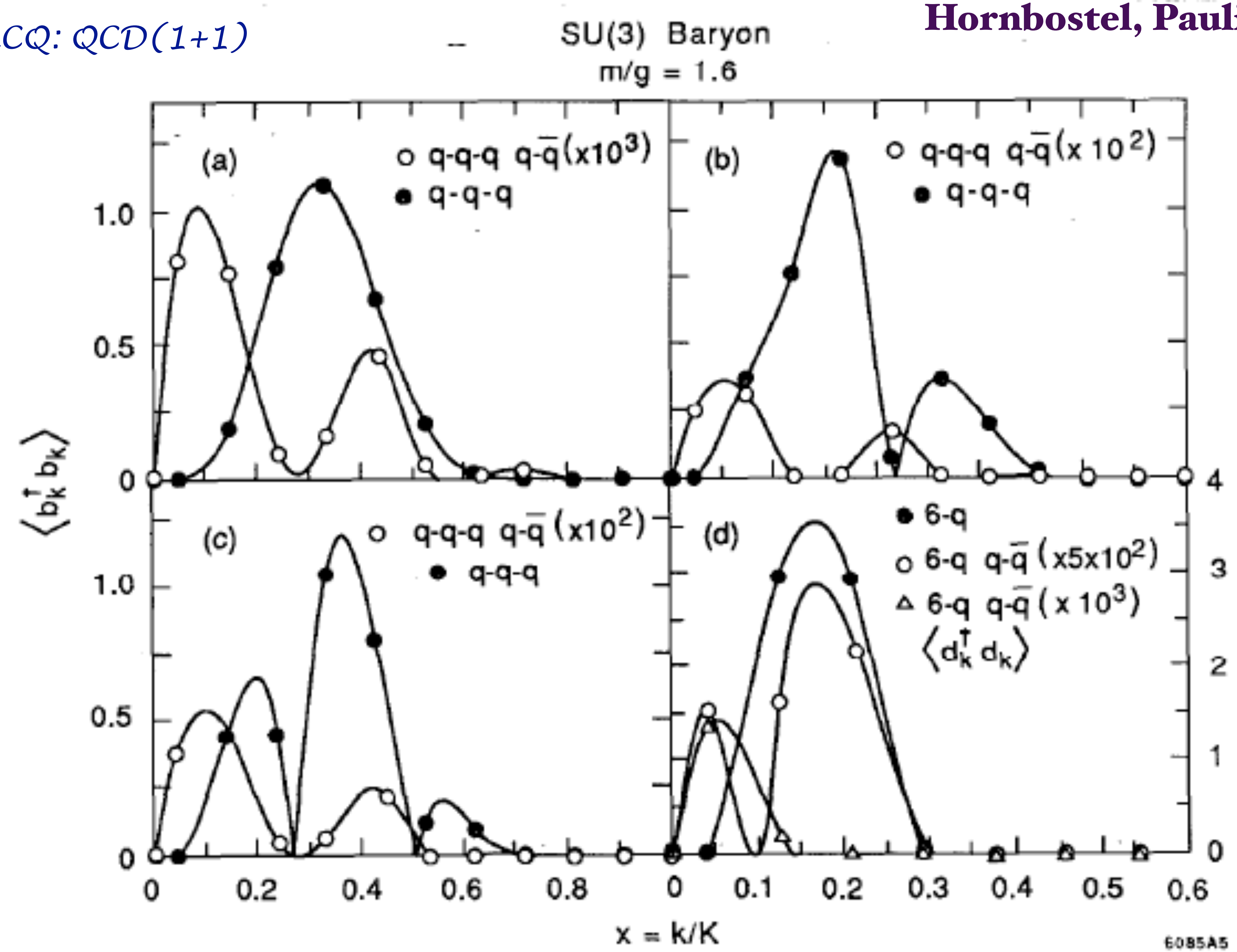




Minkowski space; frame-independent; no fermion doubling; no ghosts
trivial vacuum

DLCQ: QCD(1+1)

Hornbostel, Pauli, sjb



a-c) First three states in $N = 3$ baryon spectrum, 2K=21. d) First $B = 2$ state.

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

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

The Light Front Fock State Wavefunctions

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

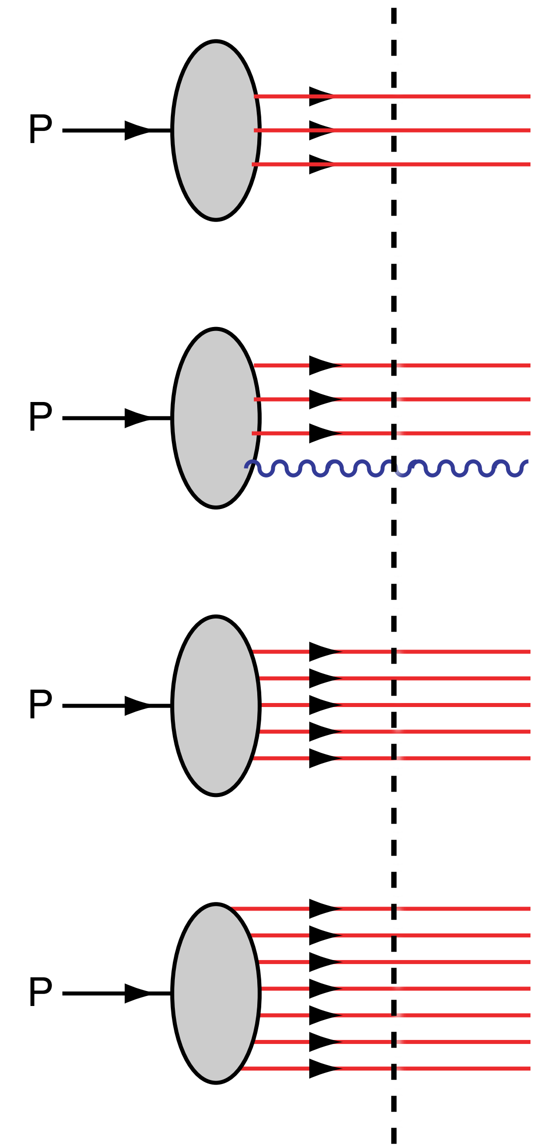
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fractions

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

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 !

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

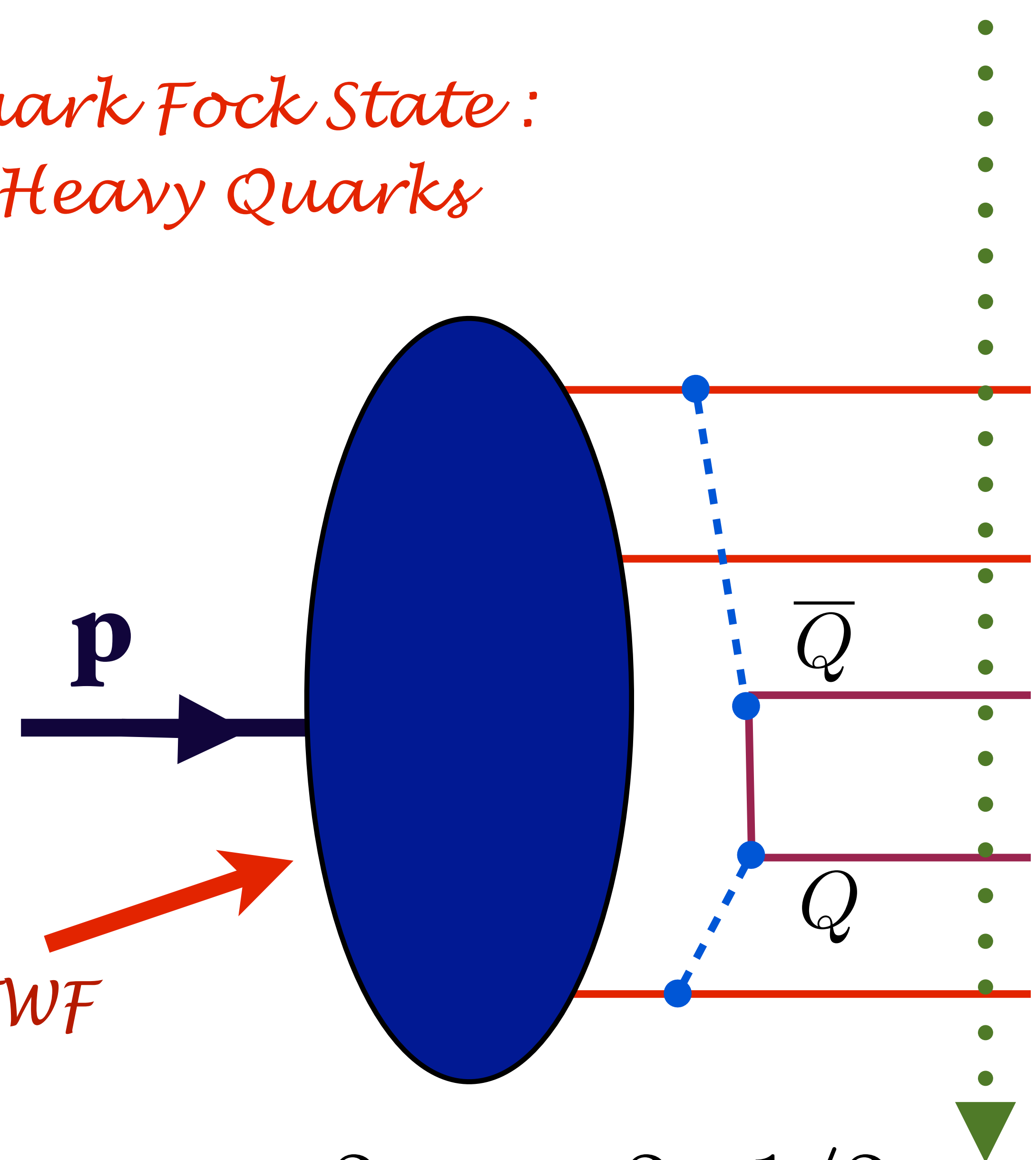
$\bar{u}(x) \neq \bar{d}(x)$

Hidden Color

Novel Effects Derived from Light-Front Wavefunctions

- Color Transparency
- Intrinsic heavy quarks at high x
- Asymmetries $s(x) \neq \bar{s}(x), \; \bar{u}(x) \neq \bar{d}(x)$
- Spin correlations, counting rules at x to 1
- Diffractive deep inelastic scattering $ep \to epX$
- Nuclear Effects: Hidden Color

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



Use AdS/QCD LFWF

QCD predicts Intrinsic Heavy Quarks at high x

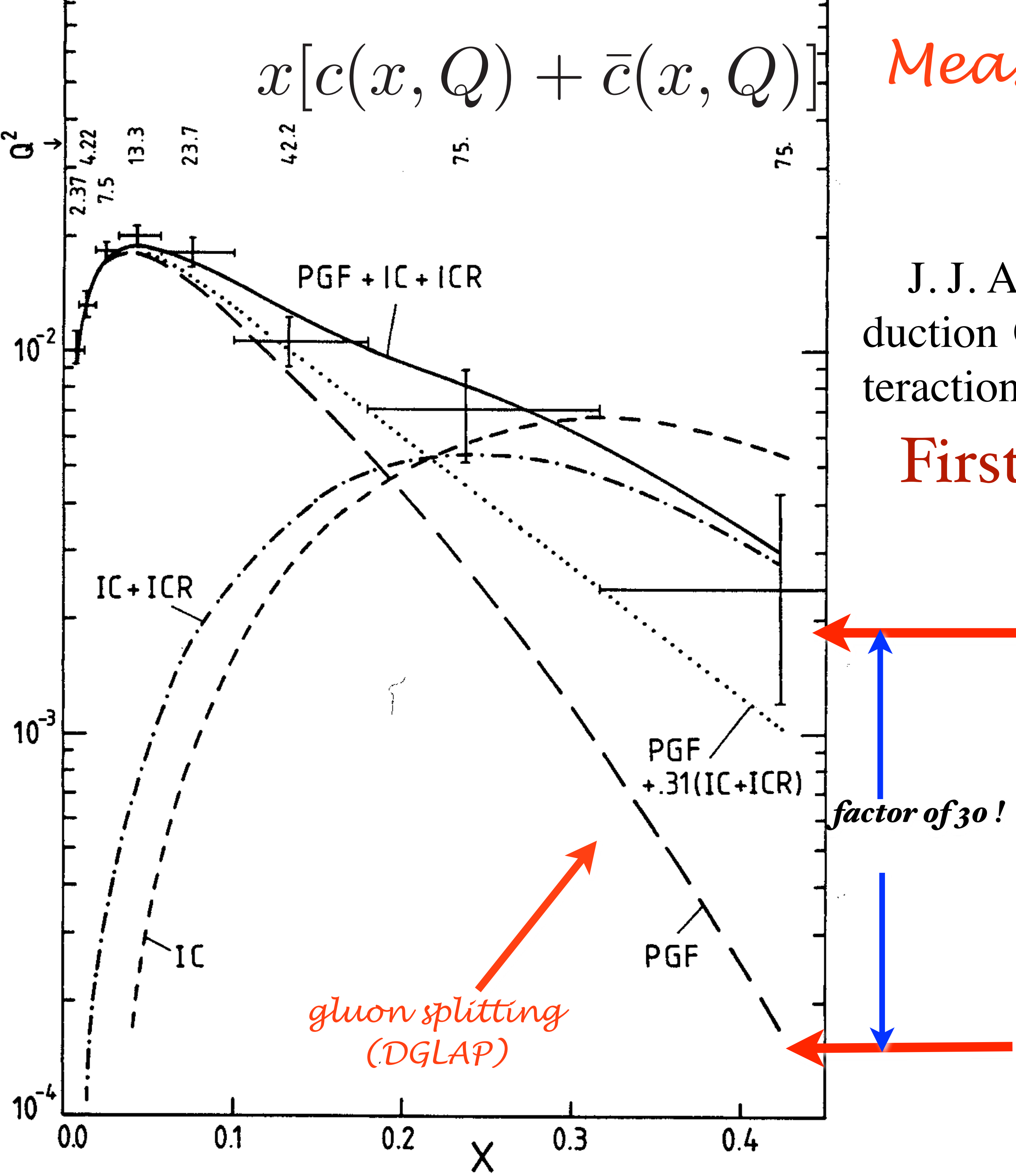
Minimal off-shellness

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

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

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

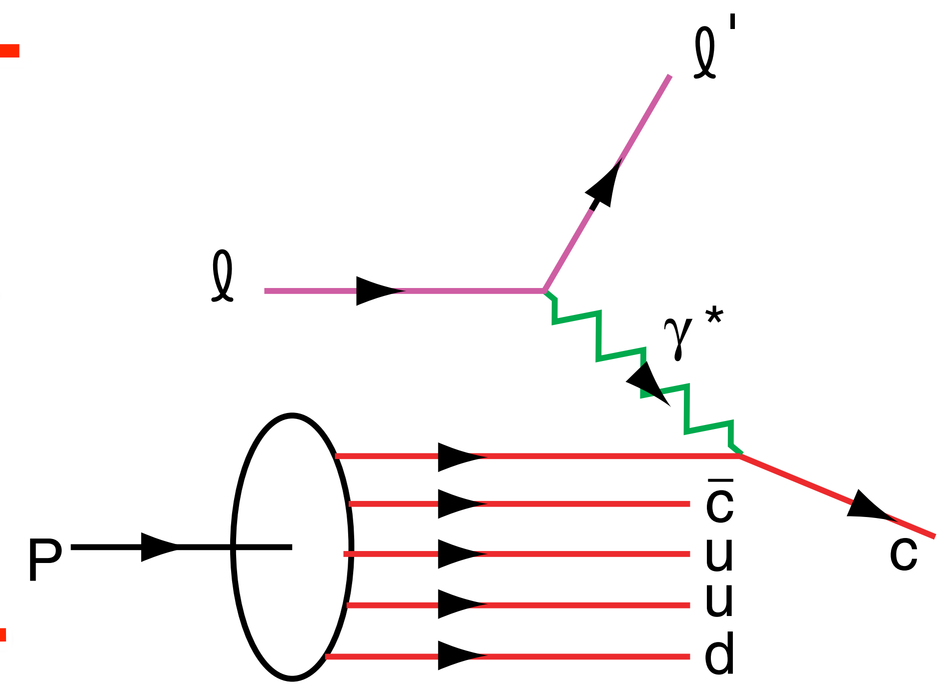
Measurement of Charm Structure Function!



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

Hoyer, Peterson, Sakai, sjb



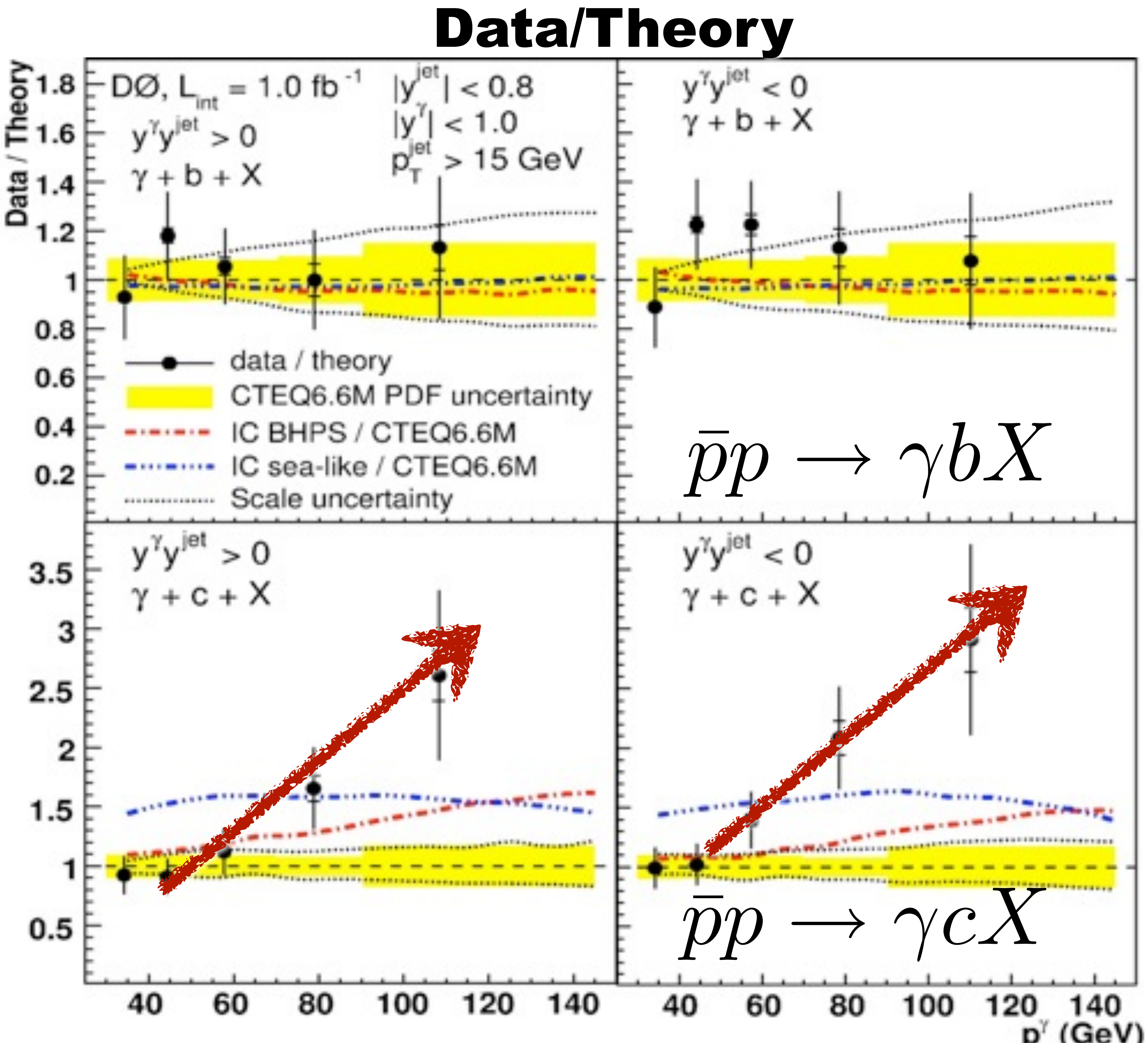
DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

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

PRL **102,** 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV



$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

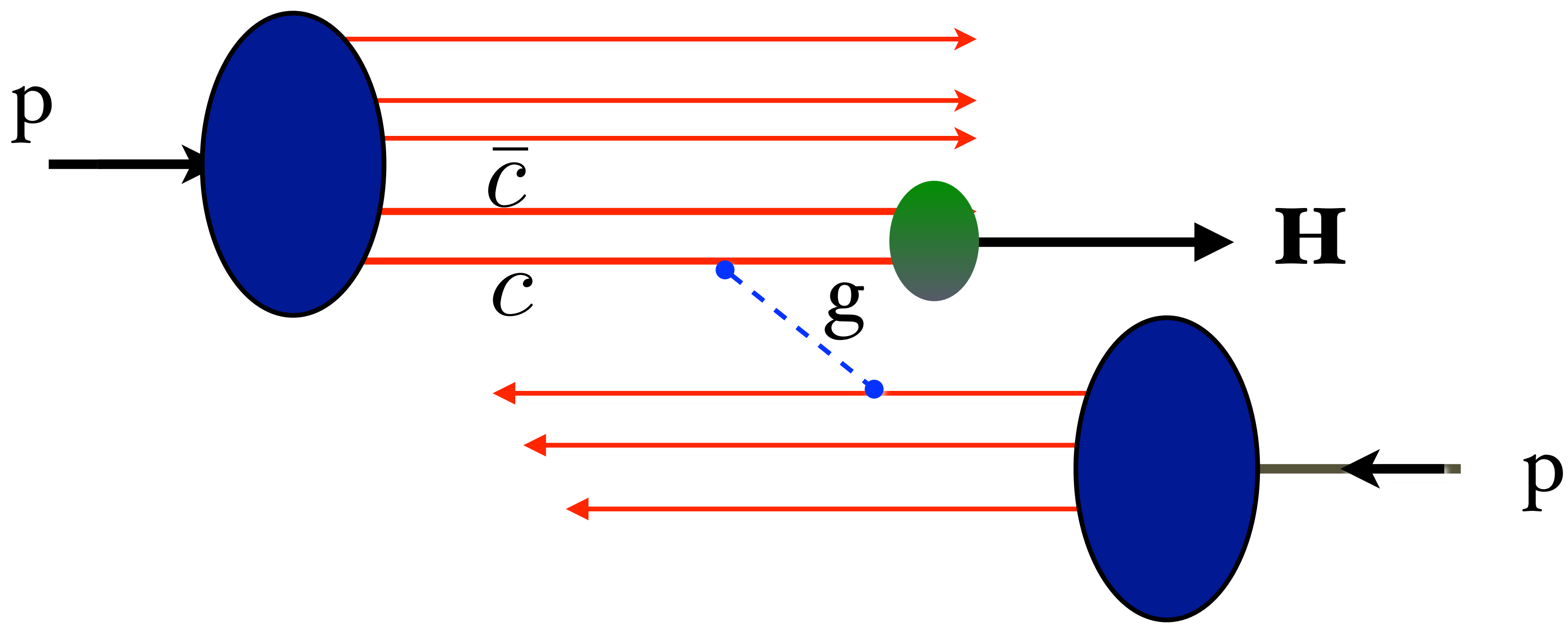
Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1

Consistent with EMC measurement of charm structure function at high x

Goldhaber, Kopeliovich, Schmidt, Soffer sjb

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



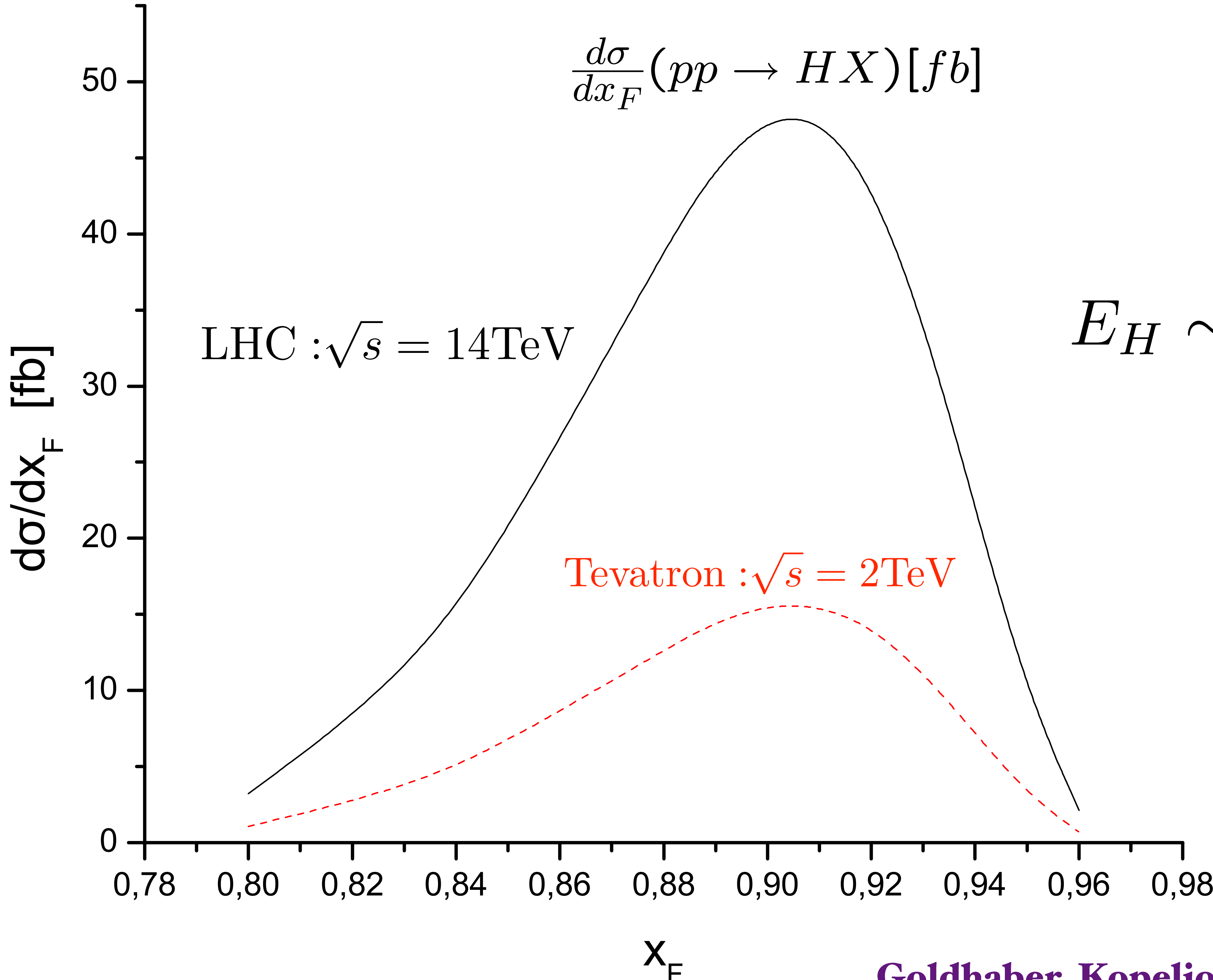
$$pp \to H X$$

Also: intrinsic strangeness, bottom, top

Higgs can have > 80% of Proton Momentum!

New production mechanism for Higgs

Intrinsic Heavy Quark Contribution to Inclusive Higgs Production



$$E_H \sim 0.9 E_p$$

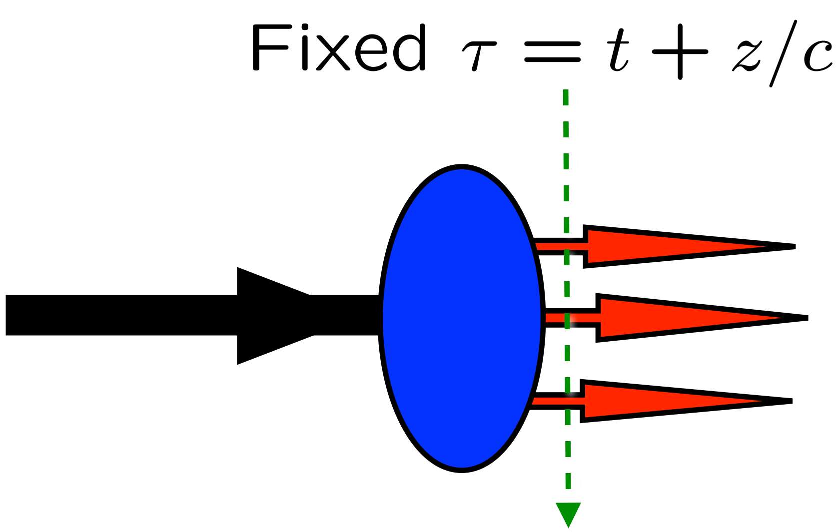
Goldhaber, Kopeliovich, Schmidt, sjb

Measure $H \rightarrow ZZ^* \rightarrow \mu^+\mu^-\mu^+\mu^-$.

Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

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



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

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

Invariant under boosts. Independent of P^μ

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

Direct connection to QCD Lagrangian

Off-shell in invariant mass

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

QCD Lagrangian

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

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

Classical Chiral Lagrangian is Conformally Invariant

Where does the QCD Mass Scale come from?

QCD does not know what MeV units mean!
Only Ratios of Masses Determined

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

Unique confinement potential!

Need a First Approximation to QCD

Comparable in simplicity to Schrödinger Theory in Atomic Physics

Relativistic, Frame-Independent, Color-Confining

Origin of hadronic mass scale if $m_q=0$?

Origin of Quark and Gluon Confinement?

$$H_{QED}$$

QED atoms: positronium and muonium

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

Coupled Fock states

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

Effective two-particle equation

Includes Lamb Shift, quantum corrections

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

Spherical Basis r, θ, ϕ

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

Coulomb potential

Bohr Spectrum

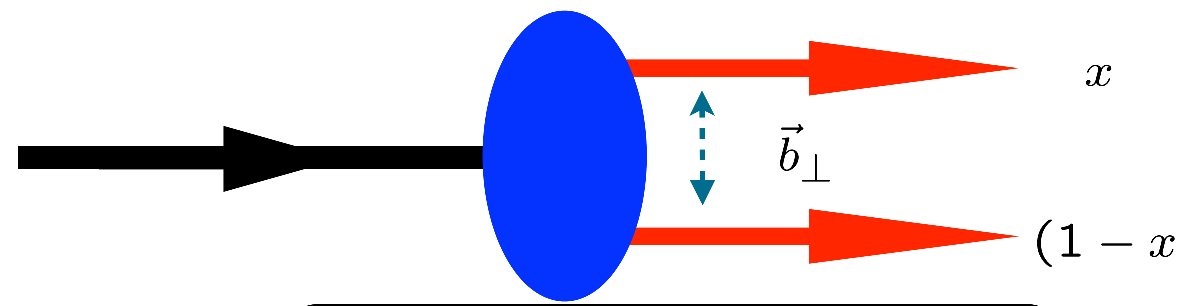
Semiclassical first approximation to QED

Schrödinger Eq.

Light-Front QCD

Fixed $\tau = t + z/c$

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



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

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

Coupled Fock states

Eliminate higher Fock states and retarded interactions

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

Effective two-particle equation

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

Azimuthal Basis

$$\zeta, \phi$$

$$m_q = 0$$

AdS/QCD:

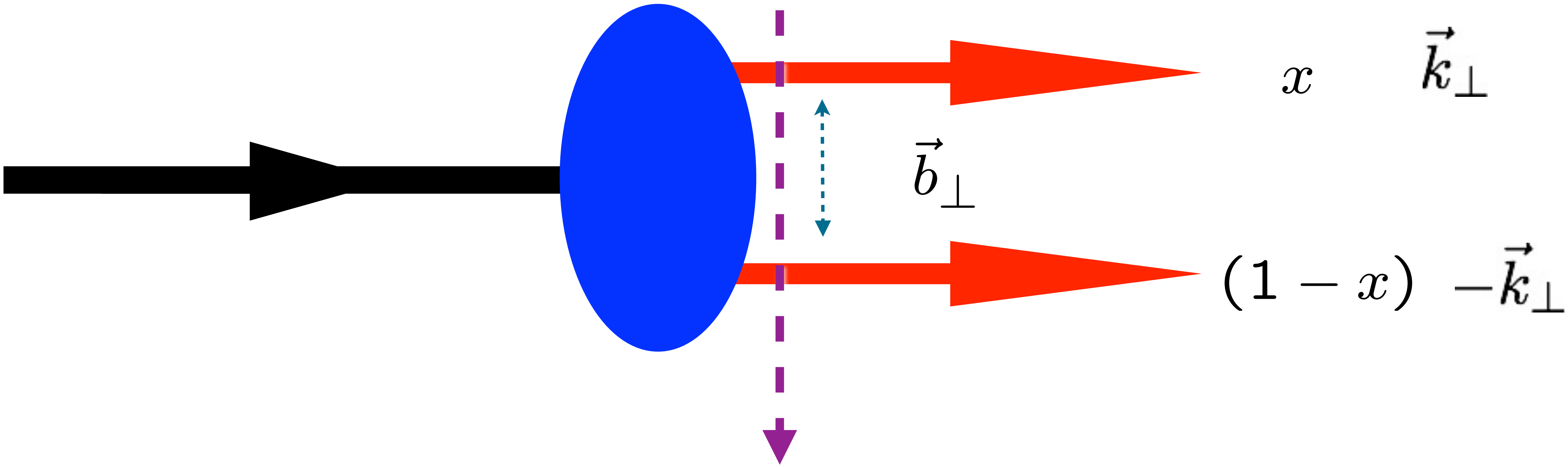
$$\boxed{U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L + S - 1)}$$

Confining AdS/QCD potential!

Sums an infinite # diagrams

Semiclassical first approximation to QCD

Fixed $\tau = t + z/c$



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

Invariant transverse separation

ζ^2 conjugate to $\frac{k_\perp^2}{x(1-x)} = (p_q + p_{\bar{q}})^2 = \mathcal{M}^2_{q+\bar{q}}$

Radial variable of the light front

Derivation of the Light-Front Radial Schrodinger Equation directly from LF QCD

$$\mathcal{M}^2 = \int_0^1 dx \int \frac{d^2\vec{k}_\perp}{16\pi^3} \frac{\vec{k}_\perp^2}{x(1-x)} \left|\psi(x,\vec{k}_\perp)\right|^2 + \text{interactions}$$

$$= \int_0^1 \frac{dx}{x(1-x)} \int d^2\vec{b}_\perp \, \psi^*(x,\vec{b}_\perp) \left(-\vec{\nabla}^2_{\vec{b}_{\perp\ell}}\right) \psi(x,\vec{b}_\perp) + \text{interactions.}$$

Change variables

$$(\vec{\zeta},\varphi), \; \vec{\zeta} = \sqrt{x(1-x)}\vec{b}_\perp : \quad \nabla^2 = \frac{1}{\zeta}\frac{d}{d\zeta}\left(\zeta\frac{d}{d\zeta}\right) + \frac{1}{\zeta^2}\frac{\partial^2}{\partial\varphi^2}$$

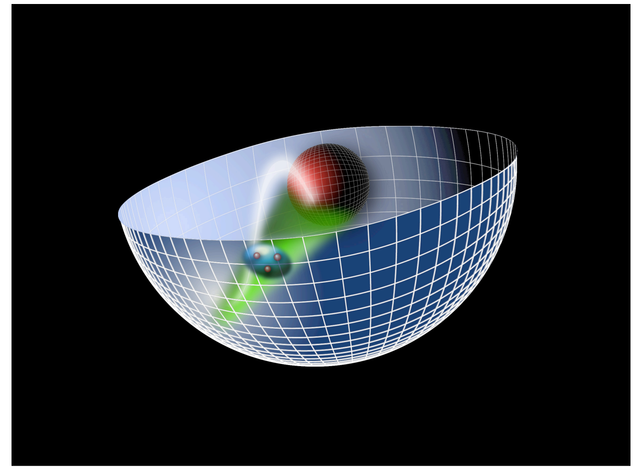
$$\mathcal{M}^2 = \int d\zeta \, \phi^*(\zeta)\sqrt{\zeta}\left(-\frac{d^2}{d\zeta^2} - \frac{1}{\zeta}\frac{d}{d\zeta} + \frac{L^2}{\zeta^2}\right)\frac{\phi(\zeta)}{\sqrt{\zeta}} + \int d\zeta \, \phi^*(\zeta) U(\zeta) \phi(\zeta)$$

$$= \int d\zeta \, \phi^*(\zeta)\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right)\phi(\zeta)$$

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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



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

Light-Front Holography

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

Light-Front Schrödinger Equation

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

Unique
Confinement Potential!

Preserves Conformal Symmetry
of the action

$$\kappa \simeq 0.5\ GeV$$

Confinement scale:

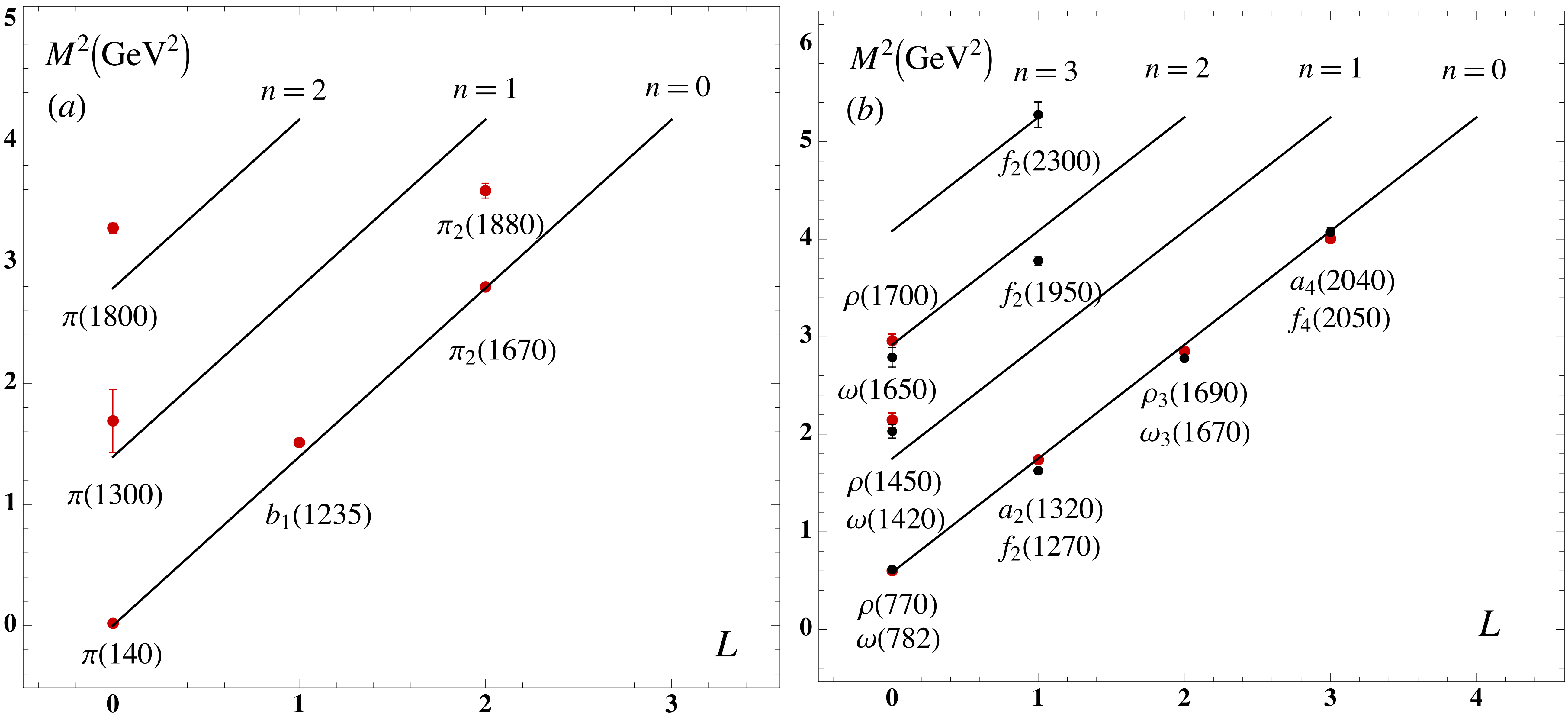
$$1/\kappa \simeq 1/3\ fm$$

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

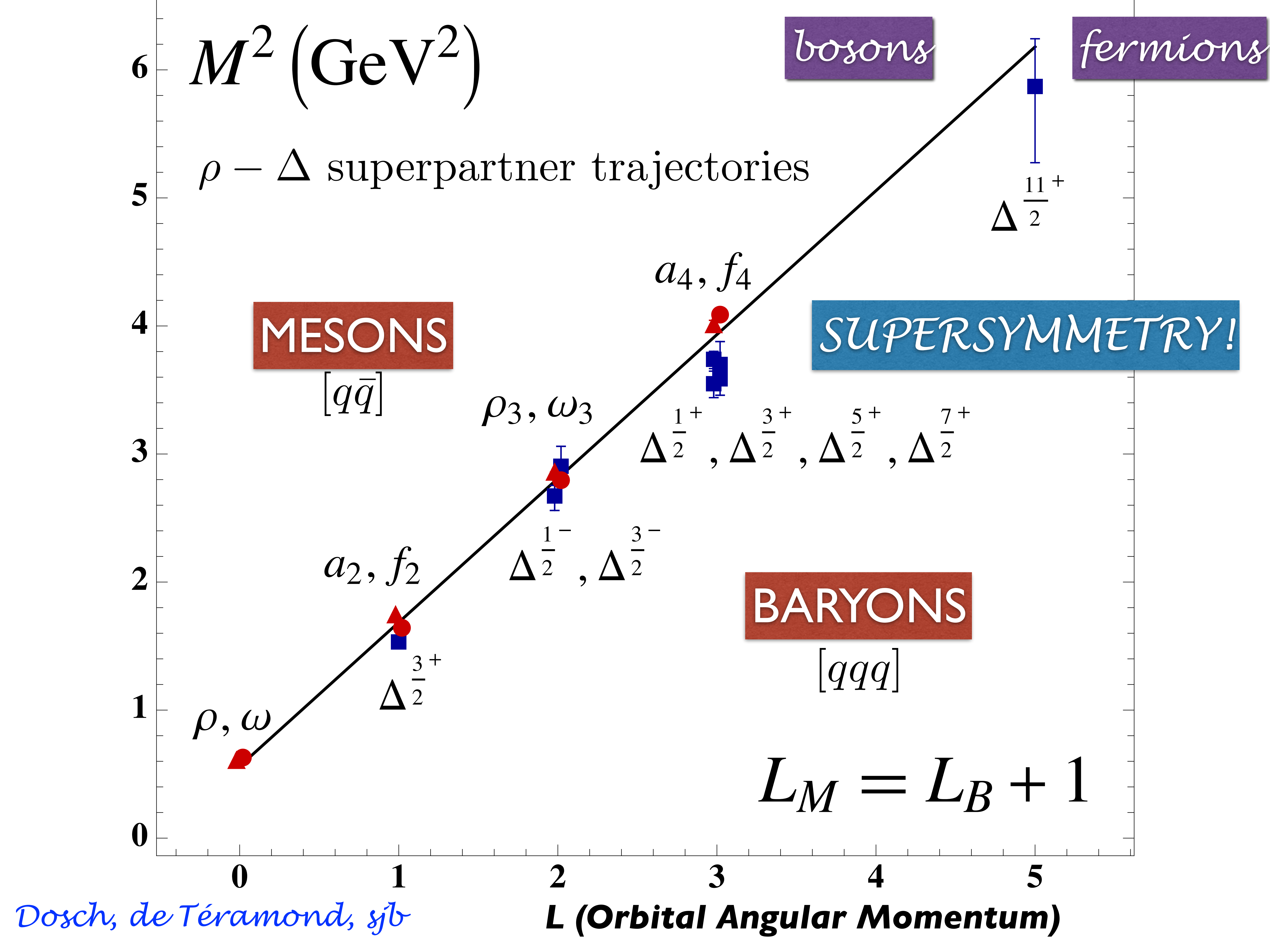
Scale can appear in Hamiltonian and EQM
without affecting conformal invariance of action!

$$m_u = m_d = 0$$

de Tèramond, Dosch, sjb



$$\boxed{M^2(n, L, S) = 4\kappa^2(n + L + S/2)}$$

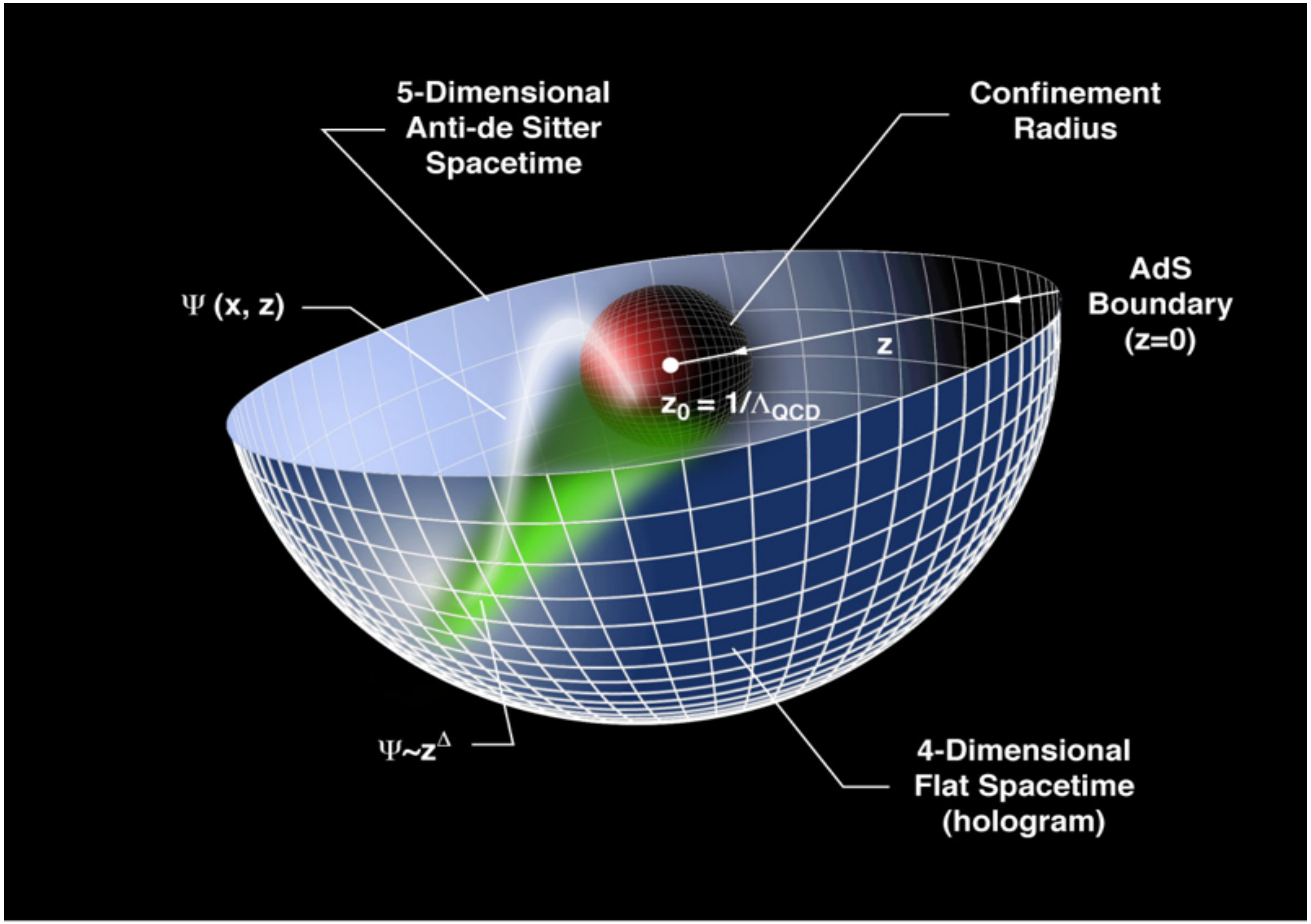

$M^2\,(\mathrm{GeV}^2)$
$\rho - \Delta$ superpartner trajectories
bosons
fermions
$\Delta_{\frac{11}{2}^+}$
a_4, f_4
MESONS
$[q\bar{q}]$
SUPERSYMMETRY!
ρ_3, ω_3
$\Delta_{\frac{1}{2}^+}, \Delta_{\frac{3}{2}^+}, \Delta_{\frac{5}{2}^+}, \Delta_{\frac{7}{2}^+}$
$\Delta_{\frac{1}{2}^-}, \Delta_{\frac{3}{2}^-}$
a_2, f_2
BARYONS
$[qqq]$
$\Delta_{\frac{3}{2}^+}$
ρ, ω
$L_M = L_B + 1$
0
1
2
3
4
5
6
L (Orbital Angular Momentum)
Dosch, de Téramond, sjb

Goal:

- **Use AdS/QCD to provide an approximate, covariant, and analytic model of hadron structure with confinement at large distances, conformal behavior at short distances**
- **Analogous to Schrödinger Theory for Atomic Physics**
- *AdS/QCD Light-Front Holography*
- *Hadronic Spectra and Light-Front Wavefunctions*

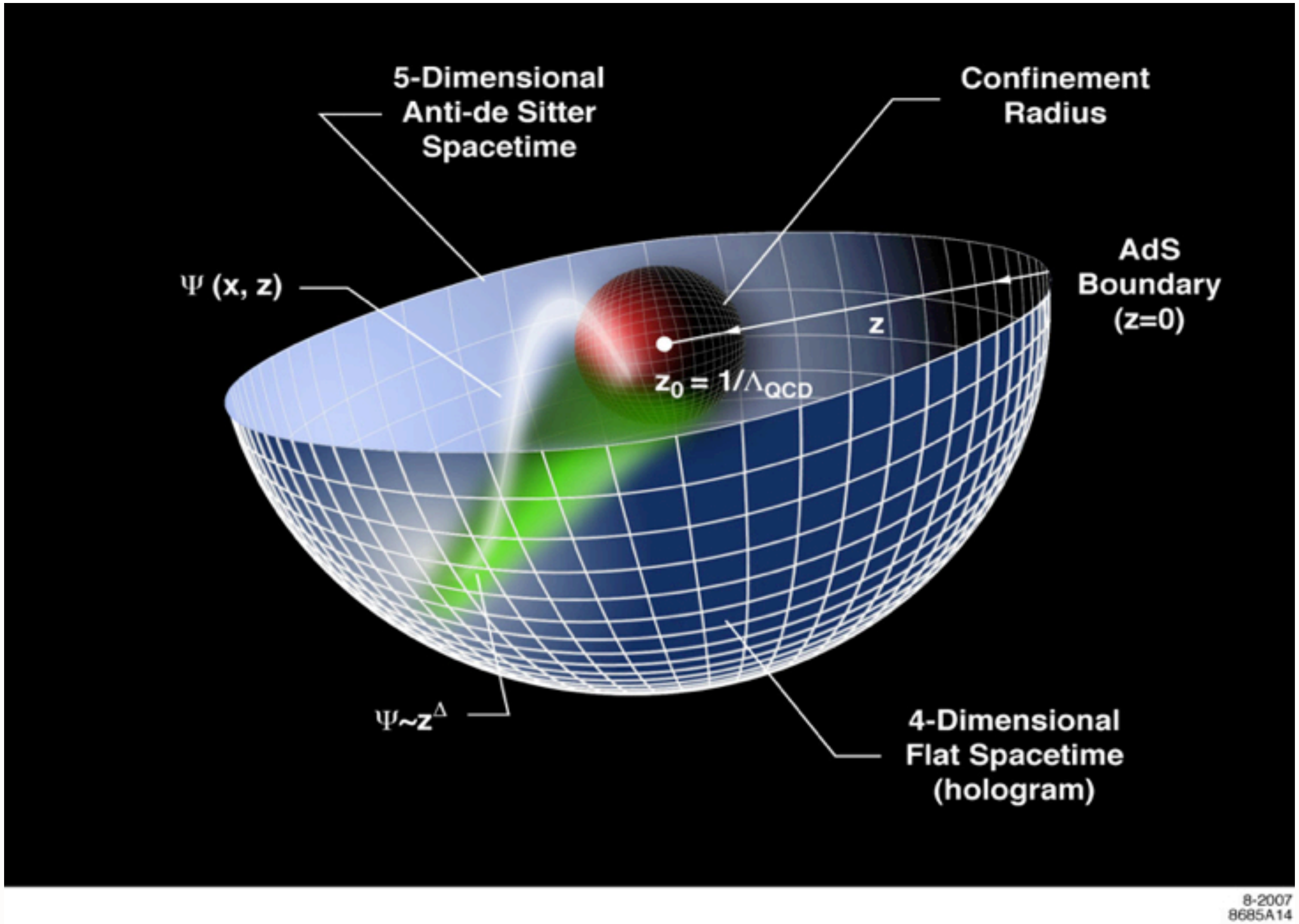
Light-Front Schrödinger Equation

Applications of AdS/CFT to QCD



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

in collaboration with Guy de Tèramond



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).

AdS/CFT

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

invariant measure

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

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

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

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

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

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

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

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**

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

Positive-sign dilaton

- Dosch, de Teramond, sjb

AdS Soft-Wall Schrödinger 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!

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

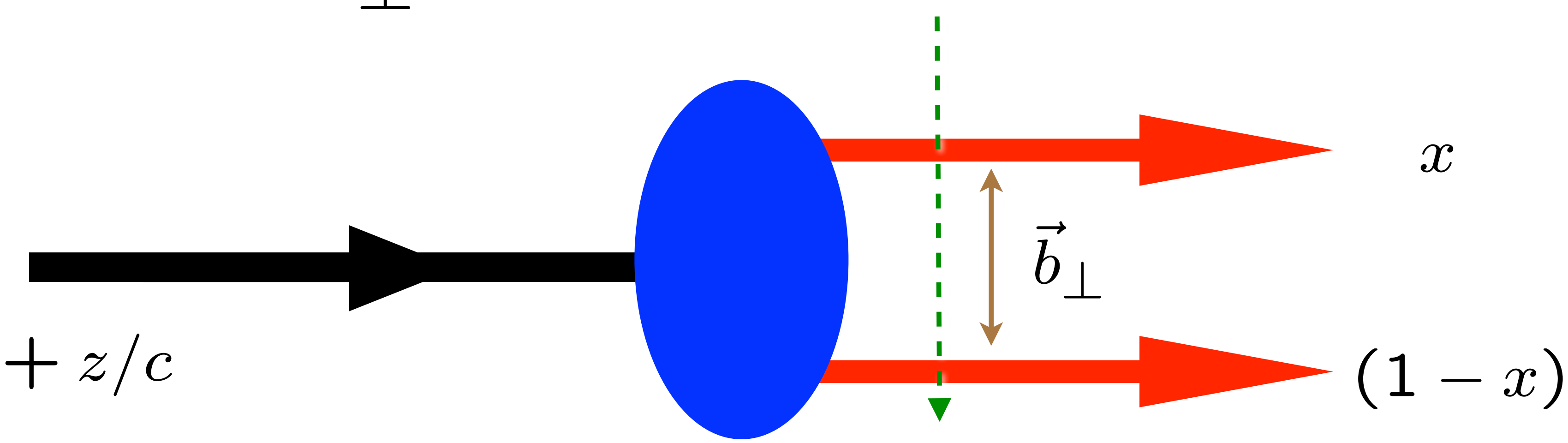
de Teramond, sjb

LF(3+1) ⟷ AdS_5

Light-Front Holographic Dictionary

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

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



Fixed $\tau = t + z/c$

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

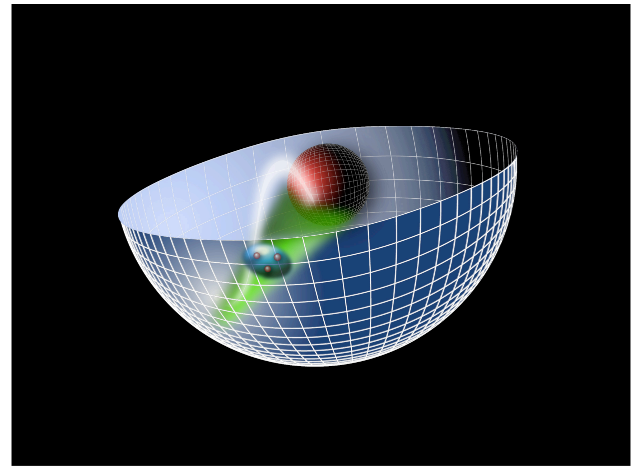
$$(\mu R)^2 = L^2 - (J-2)^2$$

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*

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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



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

Light-Front Holography

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

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: $\kappa \simeq 0.5\ GeV$

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

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

Meson Spectrum in Soft Wall Model

$$\boxed{m_\pi = 0 \text{ if } m_q = 0}$$

Massless pion!

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

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

Positive LFKE **Positive LFPE** **Negative for J=0**

$$\boxed{M_\pi^2 = 0 \;!}$$

- Eigenvalues

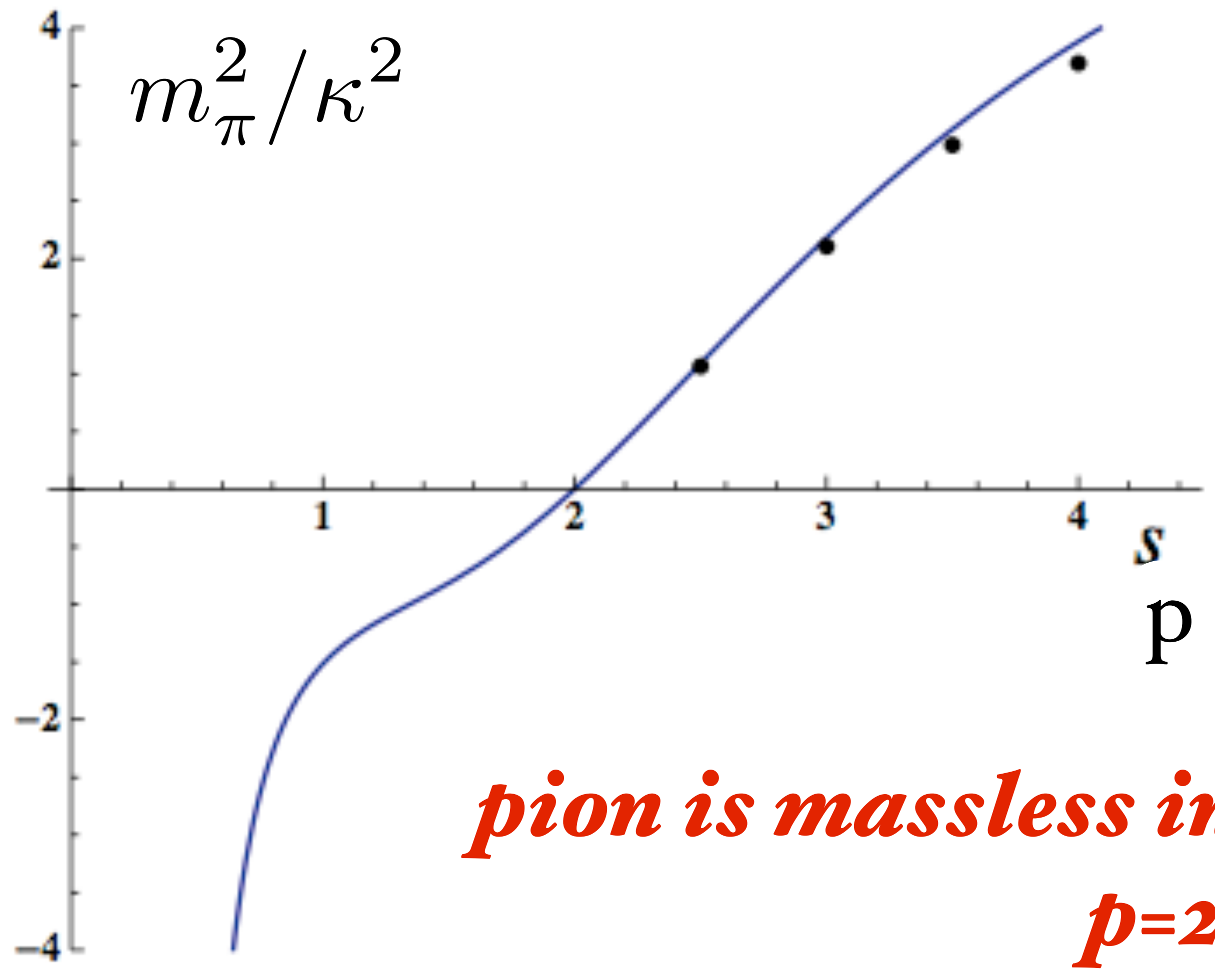
$$\boxed{\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)}$$

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

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

Uniqueness of Dilaton

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



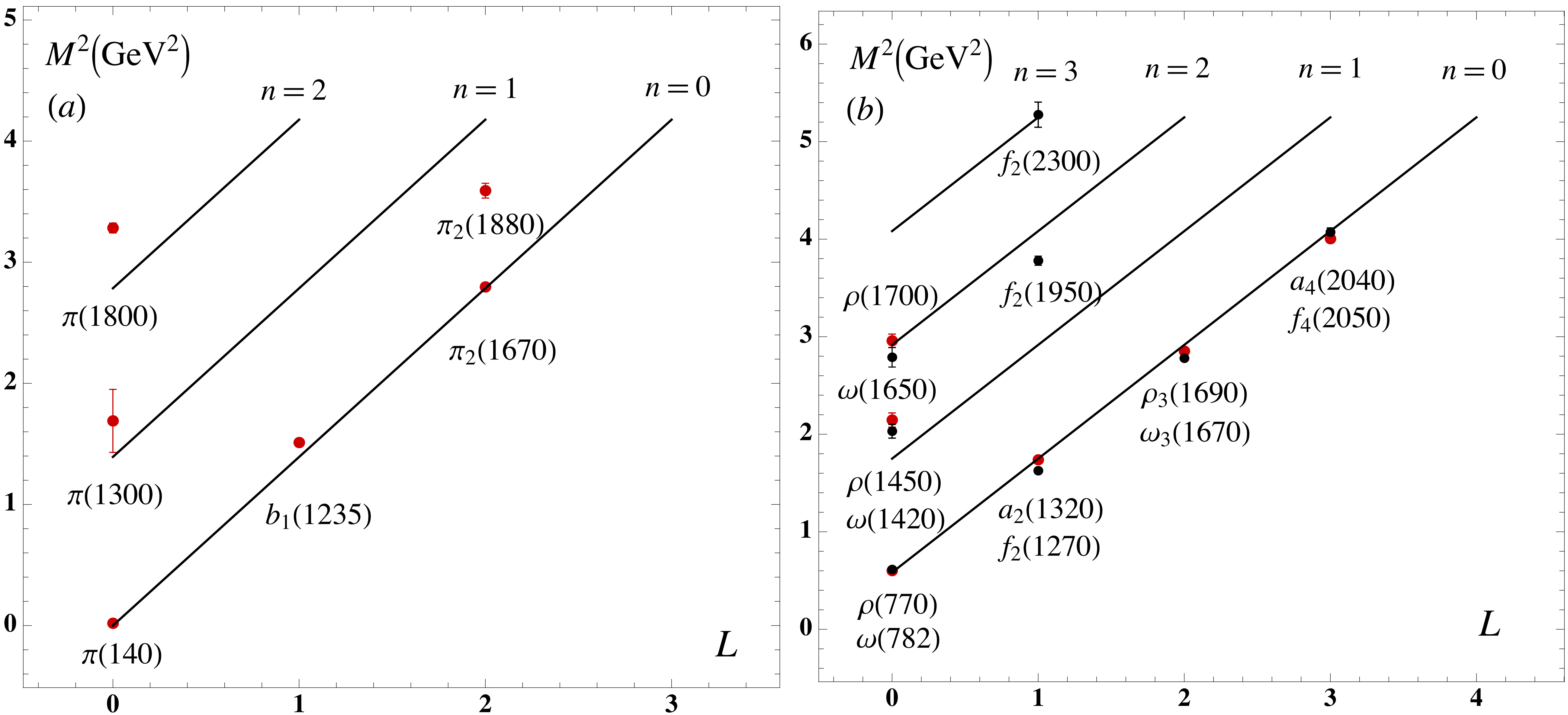
pion is massless in chiral limit iff p=2!

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

- **Dosch, de Tèramond, sjb**

$$m_u = m_d = 0$$

de Tèramond, Dosch, sjb

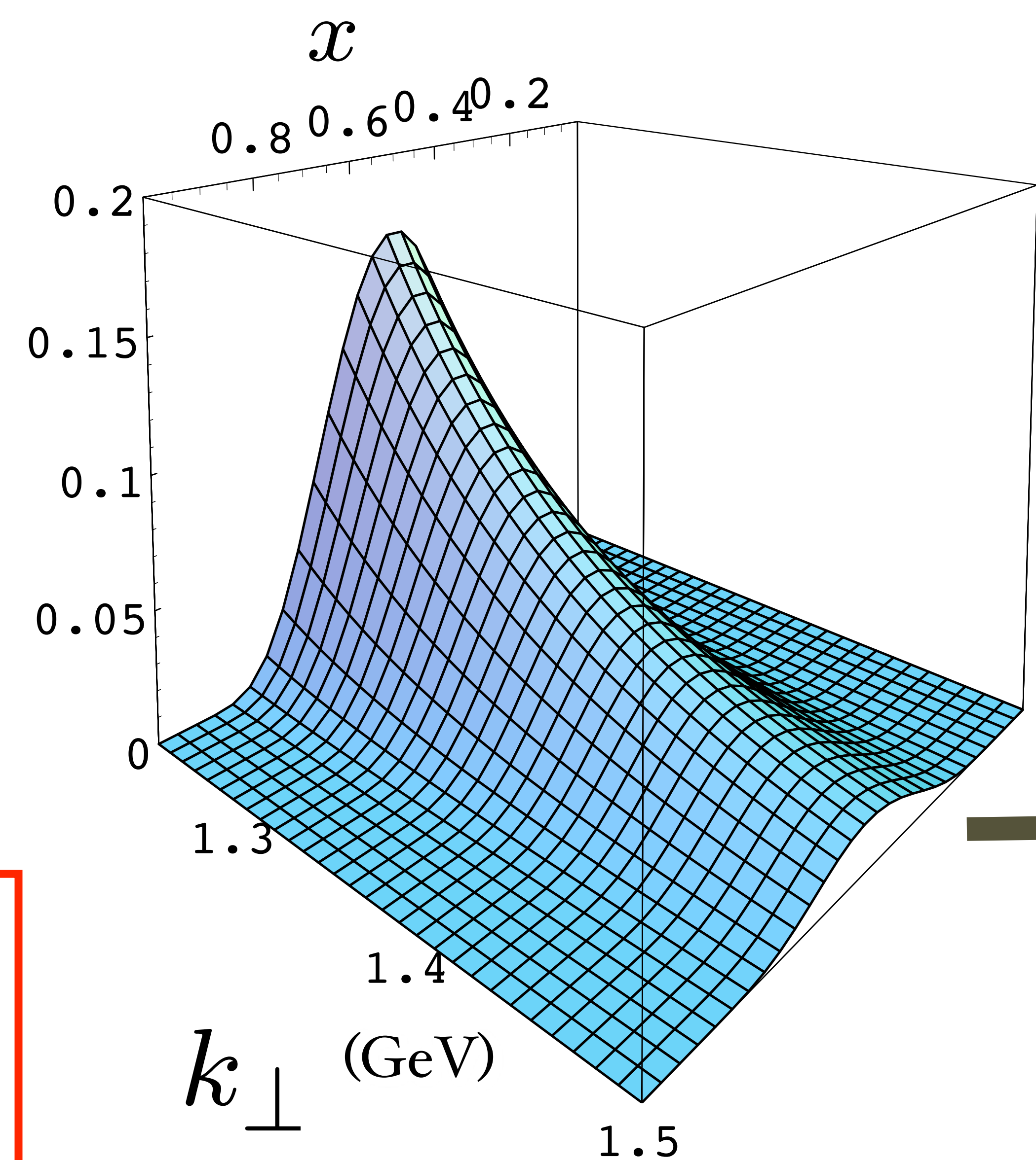


$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

Prediction from AdS/QCD: Meson LFWF

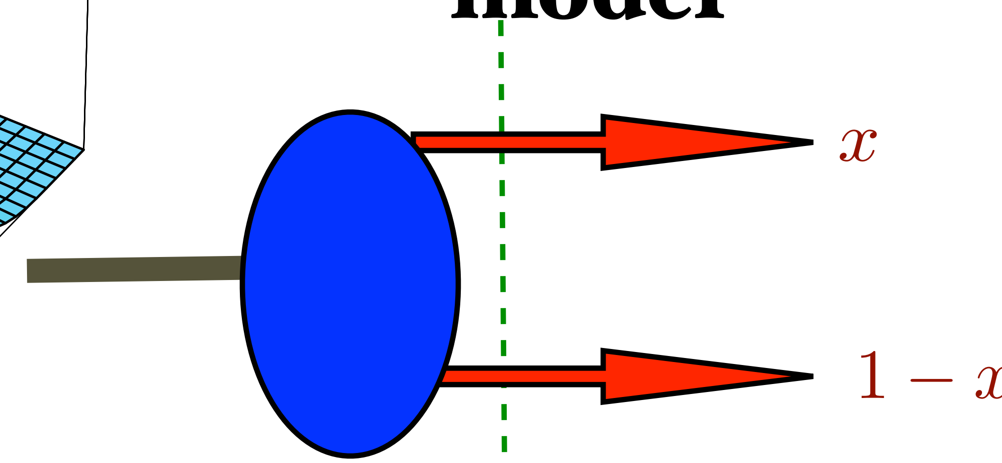
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

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



de Teramond, Cao, sjb

"Soft Wall" model



massless quarks

Note coupling

$$k_\perp^2, x$$

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

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

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

Same as DSE!

Provides Connection of Confinement to Hadron Structure

PRL **109,** 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

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)

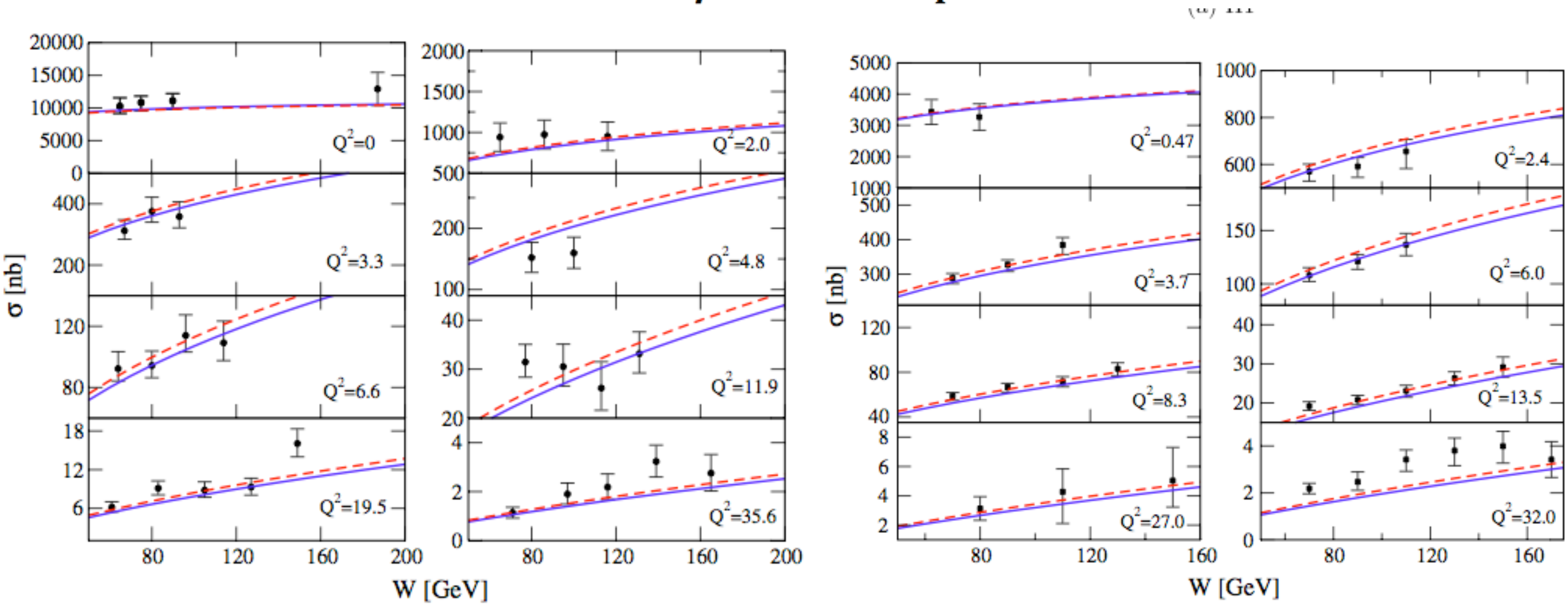
We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive ρ-meson electroproduction that are in agreement with data collected at the Hadron Electron Ring Accelerator electron–proton collider.

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

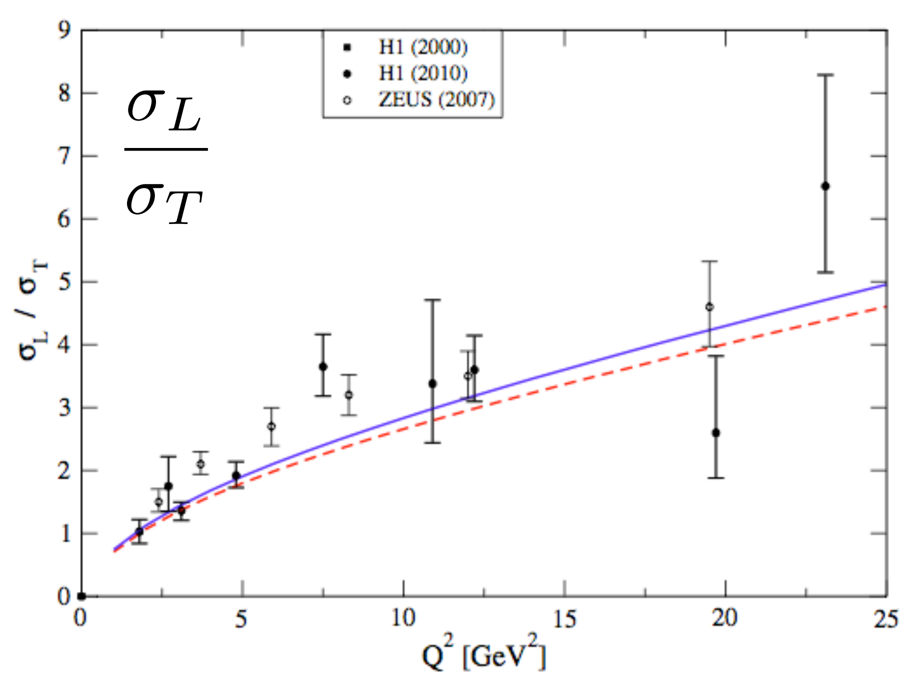
$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

PRL **109,** 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

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



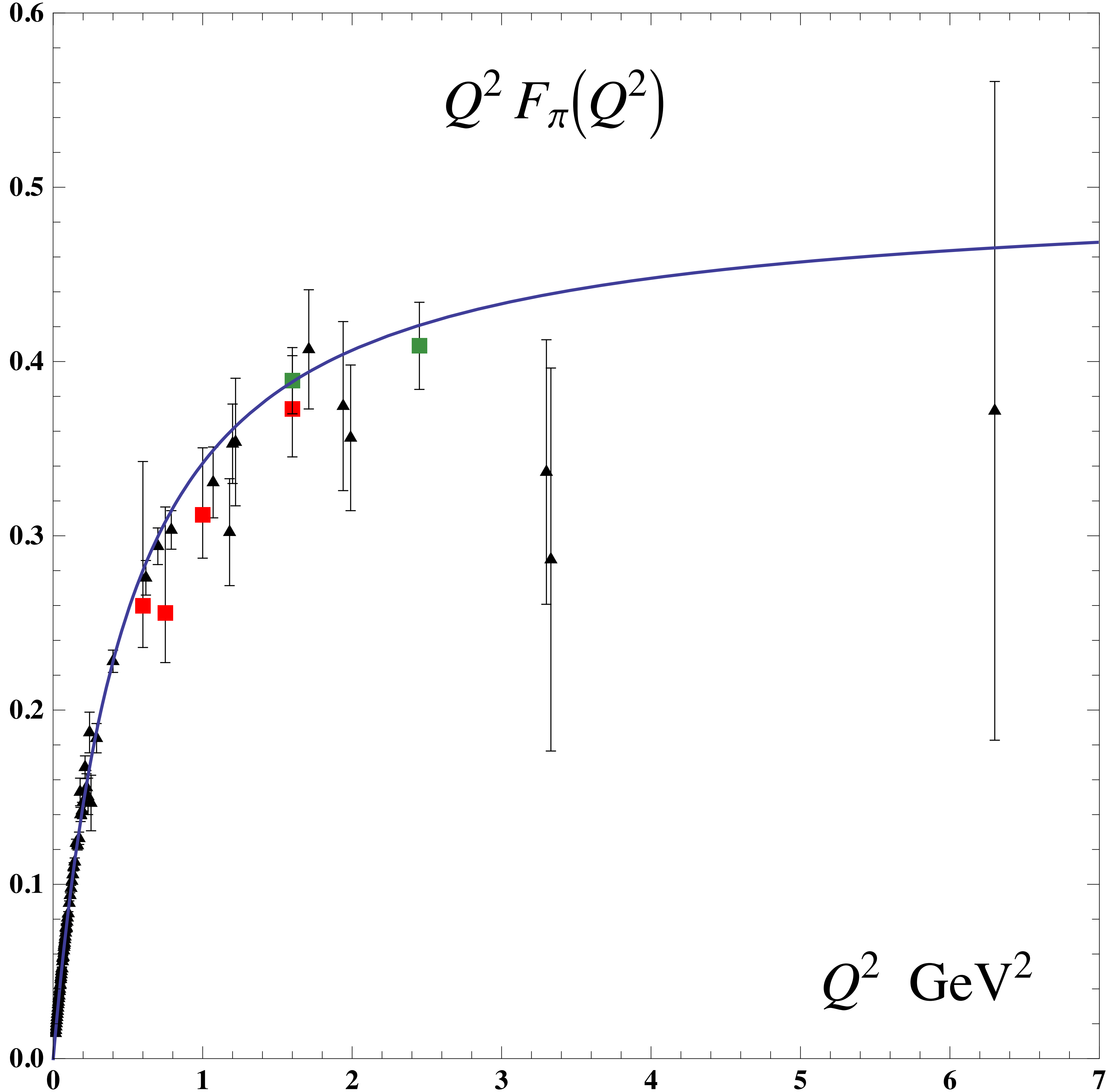
(a) H1 (b) ZEUS



J. R. Forshaw, R. Sandapen

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

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

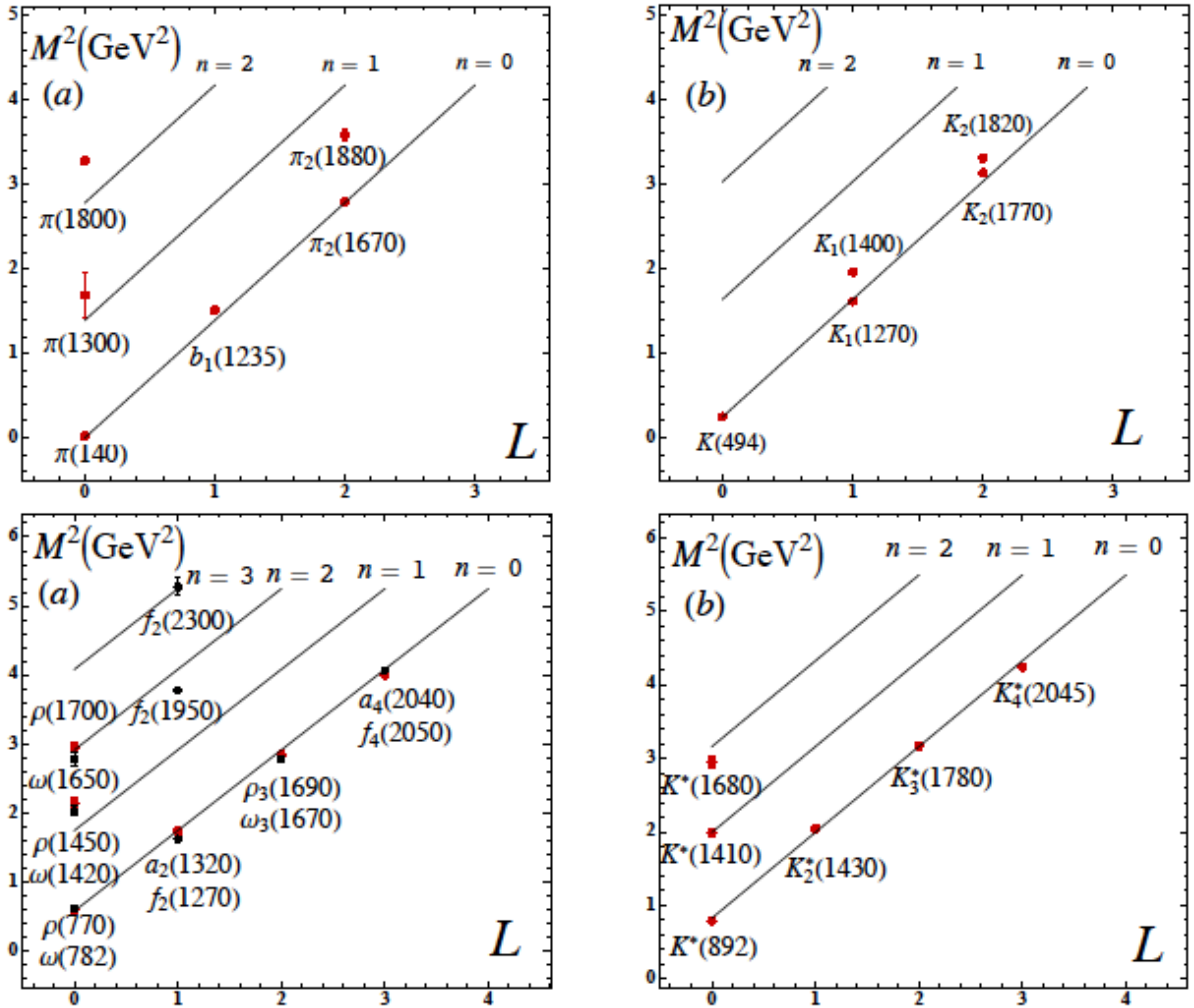


$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
1
2
3
4
5
6
7

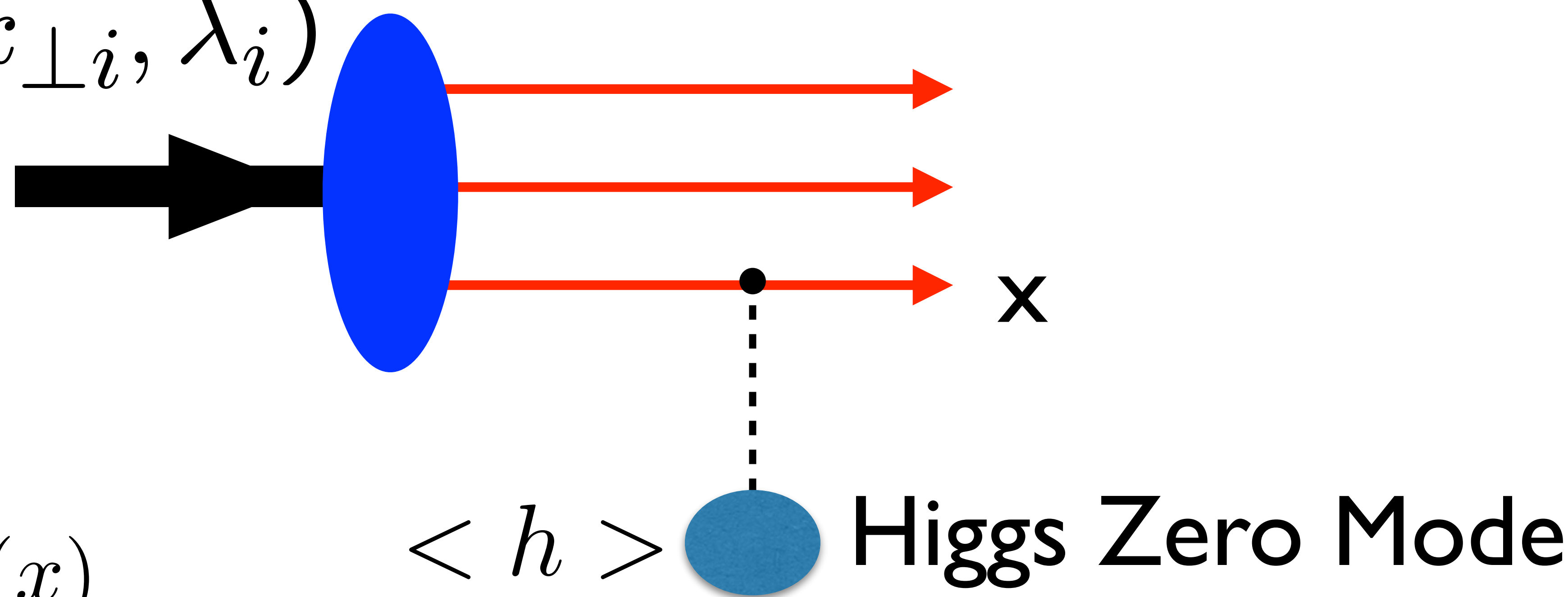
De Tèramond, Dosch, sjb

$$m_u = m_d = 46 \text{ MeV}, \quad m_s = 357 \text{ MeV}$$

$$M^2 = M_0^2 + \left\langle X \left| \frac{m_q^2}{x} \right| X \right\rangle + \left\langle X \left| \frac{m_{\bar q}^2}{1-x} \right| X \right\rangle$$



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



$$g_q \bar{\psi}_q(x) \psi_q(x) h(x)$$

Yukawa Higgs coupling of confined quark to Higgs zero mode gives

$$\bar{u}u \;\, g_q < h >= \frac{m_q}{x_q} m_q = \frac{m_q^2}{x_q}$$

$$H_{LF} = \sum_q \frac{k_{\perp q}^2 + m_q^2}{x_q}$$

- **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**

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

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

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**

Connection to the Linear Instant-Form Potential

Linear instant nonrelativistic form $V(r) = Cr$ for heavy quarks

$\Updownarrow$

Harmonic Oscillator $U(\zeta) = \kappa^4 \zeta^2$ LF Potential for relativistic light quarks

A.P. Trawinski, S.D. Glazek, H. D. Dosch, G. de Teramond, sjb

Haag, Lopuszanski, Sohnius (1974)

Superconformal Quantum Mechanics

$$\{\psi, \psi^+\} = 1 \qquad B = \frac{1}{2}[\psi^+, \psi] = \frac{1}{2}\sigma_3$$

$$\psi = \frac{1}{2}(\sigma_1 - i\sigma_2), \quad \psi^+ = \frac{1}{2}(\sigma_1 + i\sigma_2)$$

$$Q = \psi^+[-\partial_x + \frac{f}{x}], \quad Q^+ = \psi[\partial_x + \frac{f}{x}], \qquad S = \psi^+ x, \quad S^+ = \psi x$$

$$\{Q, Q^+\} = 2H, \quad \{S, S^+\} = 2K$$

$$\{Q, S^+\} = f - B + 2iD, \quad \{Q^+, S\} = f - B - 2iD$$

generates conformal algebra

[H,D]= i H, [H, K] =2 i D, [K, D] = - i K

Superconformal Quantum Mechanics

Baryon Equation $Q \simeq \sqrt{H}, \quad S \simeq \sqrt{K}$

$\boxed{\text{Consider } R_w = Q + wS;}$ w: dimensions of mass squared

$$G = \{R_w, R_w^+\} = 2H + 2w^2K + 2wfI - 2wB \qquad 2B = \sigma_3$$

Retains Conformal Invariance of Action

Fubini and Rabinovici

New Extended Hamiltonian G is diagonal:

$$G_{11} = \left(-\partial_x^2 + w^2x^2 + 2wf - w + \frac{4(f+\frac{1}{2})^2 - 1}{4x^2}\right)$$

$$G_{22} = \left(-\partial_x^2 + w^2x^2 + 2wf + w + \frac{4(f-\frac{1}{2})^2 - 1}{4x^2}\right)$$

$$\boxed{\text{Identify } f - \tfrac{1}{2} = L_B \;, \quad w = \kappa^2}$$

Eigenvalue of G: $M^2(n, L) = 4\kappa^2(n + L_B + 1)$

LF Holography

Baryon Equation

Superconformal Quantum Mechanics

$$\Big(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(L_B+1) + \frac{4L_B^2-1}{4\zeta^2}\Big)\psi_J^+ = M^2\psi_J^+$$

$$\Big(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2 L_B + \frac{4(L_B+1)^2-1}{4\zeta^2}\Big)\psi_J^- = M^2\psi_J^-$$

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

S=1/2, P=+

both chiralities

Meson Equation

$$\Big(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(J-1) + \frac{4L_M^2-1}{4\zeta^2}\Big)\phi_J = M^2\phi_J$$

$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

Same κ!

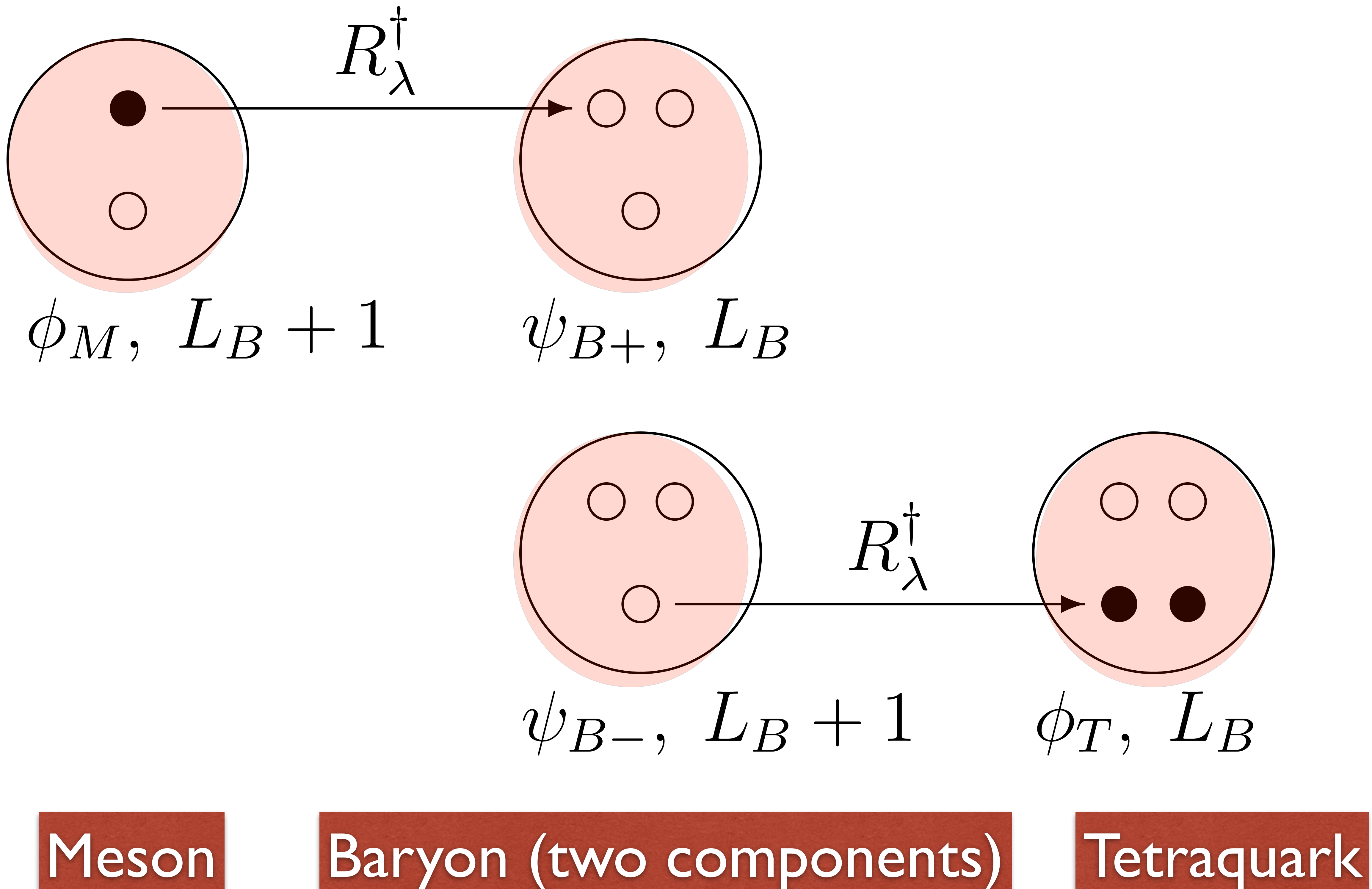
S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

Meson-Baryon Degeneracy for $L_M = L_B + 1$

de Tèramond, Dosch, Lorce, sjb

Superconformal Algebra

2X2 Hadronic Multiplets



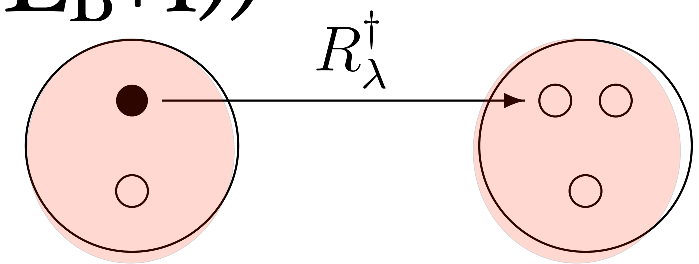
de Tèramond, Dosch, Lorce, sjb

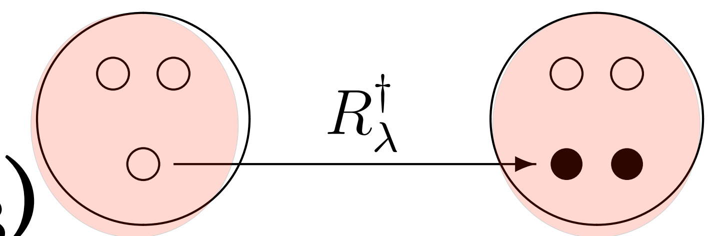
Superconformal Algebra

2X2 Hadronic Multiplets

$$\begin{pmatrix} \phi_M(L_M = L_B + 1) & \psi_{B-}(L_B + 1) \\ \psi_{B+}(L_B) & \phi_T(L_T = L_B) \end{pmatrix}$$

- quark-antiquark meson ($L_M = L_B+1$))
- quark-diquark baryon (L_B)
- quark-diquark baryon (L_B+1)
- diquark-antidiquark tetraquark ($L_T = L_B$)
- Universal Regge slopes $\lambda = \kappa^2$





$$M_H^2/\lambda = \overbrace{\underbrace{(2n + L_H + 1)}_{kinetic} + \underbrace{(2n + L_H + 1)}_{potential}}^{\text{contribution from 2-dim light-front harmonic oscillator}} + \overbrace{2(L_H + s) + 2\chi}^{\text{contribution from AdS and superconformal algebra}} + < \sum_i \frac{m_i^2}{x_i} >$$

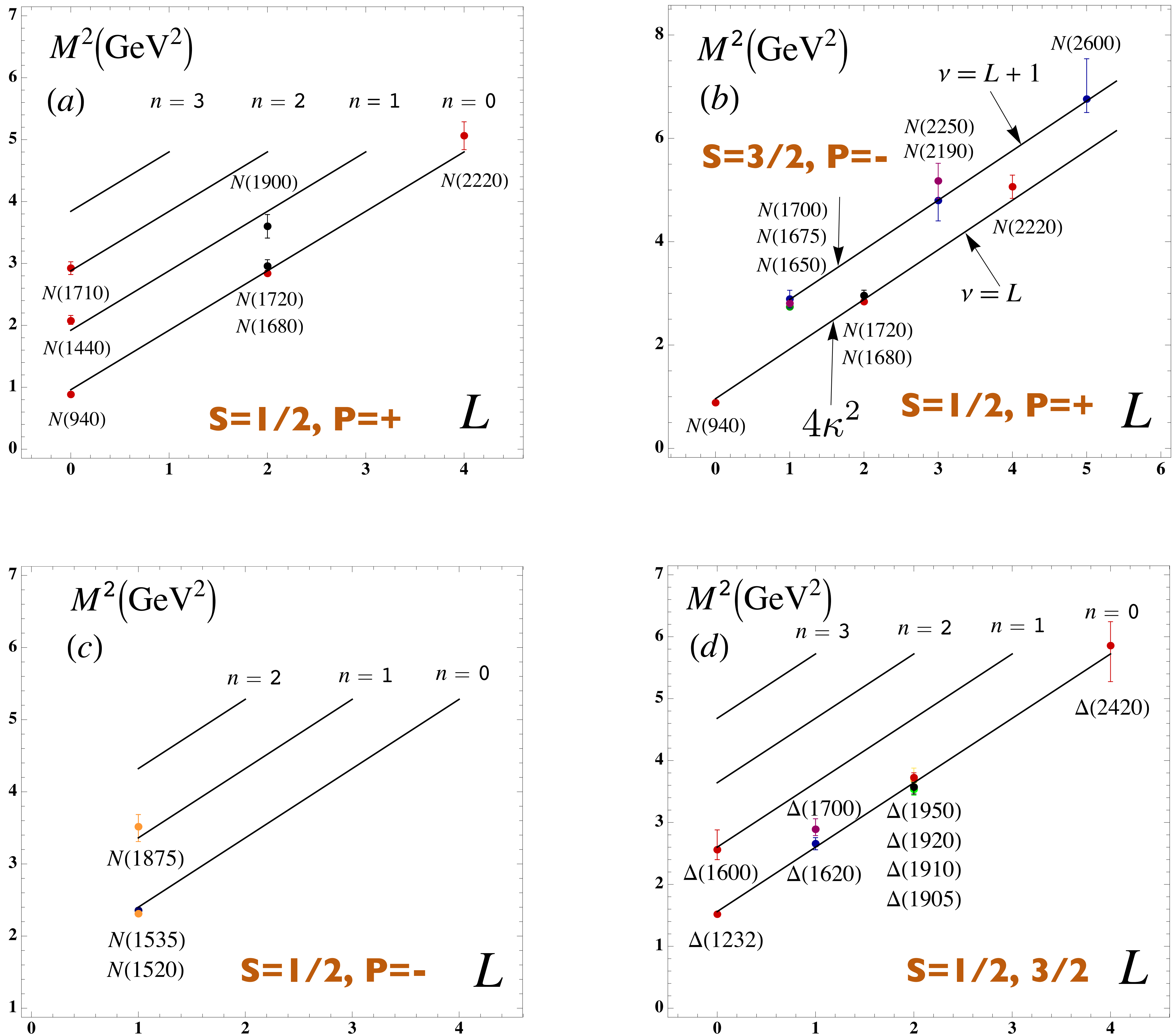
$\chi(mesons) = -1$ $\qquad$ $\chi(baryons, tetraquarks) = +1$

Meson			Baryon			Tetraquark		
q-cont	$J^{P(C)}$	Name	q-cont	J^P	Name	q-cont	$J^{P(C)}$	Name
$\bar{q}q$	0^{-+}	$\pi(140)$	—	—	—	—	—	—
$\bar{q}q$	1^{+-}	$b_1(1235)$	$[ud]q$	$(1/2)^+$	$N(940)$	$[ud][\bar{u}\bar{d}]$	0^{++}	$f_0(980)$
$\bar{q}q$	2^{-+}	$\pi_2(1670)$	$[ud]q$	$(1/2)^-$	$N_{\frac{1}{2}^-}(1535)$	$[ud][\bar{u}\bar{d}]$	1^{-+}	$\pi_1(1400)$
				$(3/2)^-$	$N_{\frac{3}{2}^-}(1520)$			$\pi_1(1600)$
$\bar{q}q$	1^{--}	$\rho(770),\ \omega(780)$	—	—	—	—	—	—
$\bar{q}q$	2^{++}	$a_2(1320),\ f_2(1270)$	$[qq]q$	$(3/2)^+$	$\Delta(1232)$	$[qq][\bar{u}\bar{d}]$	1^{++}	$a_1(1260)$
$\bar{q}q$	3^{--}	$\rho_3(1690),\ \omega_3(1670)$	$[qq]q$	$(1/2)^-$	$\Delta_{\frac{1}{2}^-}(1620)$	$[qq][\bar{u}\bar{d}]$	2^{--}	$\rho_2(\sim 1700)?$
				$(3/2)^-$	$\Delta_{\frac{3}{2}^-}(1700)$			
$\bar{q}q$	4^{++}	$a_4(2040),\ f_4(2050)$	$[qq]q$	$(7/2)^+$	$\Delta_{\frac{7}{2}^+}(1950)$	$[qq][\bar{u}\bar{d}]$	3^{++}	$a_3(\sim 2070)?$
$\bar{q}s$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar{q}s$	$1^{+(-)}$	$\bar{K}_1(1270)$	$[ud]s$	$(1/2)^+$	$\Lambda(1115)$	$[ud][\bar{s}\bar{q}]$	$0^{+(+)}$	$K_0^*(1430)$
$\bar{q}s$	$2^{-(+)}$	$K_2(1770)$	$[ud]s$	$(1/2)^-$	$\Lambda(1405)$	$[ud][\bar{s}\bar{q}]$	$1^{-(+)}$	$K_1^*(\sim 1700)?$
				$(3/2)^-$	$\Lambda(1520)$			
$\bar{s}q$	$0^{-(+)}$	$K(495)$	—	—	—	—	—	—
$\bar{s}q$	$1^{+(-)}$	$K_1(1270)$	$[sq]q$	$(1/2)^+$	$\Sigma(1190)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$a_0(980)$
								$f_0(980)$
$\bar{s}q$	$1^{-(-)}$	$K^*(890)$	—	—	—	—	—	—
$\bar{s}q$	$2^{+(+)}$	$K_2^*(1430)$	$[sq]q$	$(3/2)^+$	$\Sigma(1385)$	$[sq][\bar{q}\bar{q}]$	$1^{+(+)}$	$K_1(1400)$
$\bar{s}q$	$3^{-(-)}$	$K_3^*(1780)$	$[sq]q$	$(3/2)^-$	$\Sigma(1670)$	$[sq][\bar{q}\bar{q}]$	$2^{-(-)}$	$K_2(\sim 1700)?$
$\bar{s}q$	$4^{+(+)}$	$K_4^*(2045)$	$[sq]q$	$(7/2)^+$	$\Sigma(2030)$	$[sq][\bar{q}\bar{q}]$	$3^{+(+)}$	$K_3(\sim 2070)?$
$\bar{s}s$	0^{-+}	$\eta(550)$	—	—	—	—	—	—
$\bar{s}s$	1^{+-}	$h_1(1170)$	$[sq]s$	$(1/2)^+$	$\Xi(1320)$	$[sq][\bar{s}\bar{q}]$	0^{++}	$f_0(1370)$
								$a_0(1450)$
$\bar{s}s$	2^{-+}	$\eta_2(1645)$	$[sq]s$	$(?)^?$	$\Xi(1690)$	$[sq][\bar{s}\bar{q}]$	1^{-+}	$\Phi'(1750)?$
$\bar{s}s$	1^{--}	$\Phi(1020)$	—	—	—	—	—	—
$\bar{s}s$	2^{++}	$f_2'(1525)$	$[sq]s$	$(3/2)^+$	$\Xi^*(1530)$	$[sq][\bar{s}\bar{q}]$	1^{++}	$f_1(1420)$
$\bar{s}s$	3^{--}	$\Phi_3(1850)$	$[sq]s$	$(3/2)^-$	$\Xi(1820)$	$[sq][\bar{s}\bar{q}]$	2^{--}	$\Phi_2(\sim 1800)?$
$\bar{s}s$	2^{++}	$f_2(1950)$	$[ss]s$	$(3/2)^+$	$\Omega(1672)$	$[ss][\bar{s}\bar{q}]$	$1^{+(+)}$	$K_1(\sim 1700)?$

Meson Baryon Tetraquark

New Organization of the Hadron Spectrum

M. Nielsen and SJB

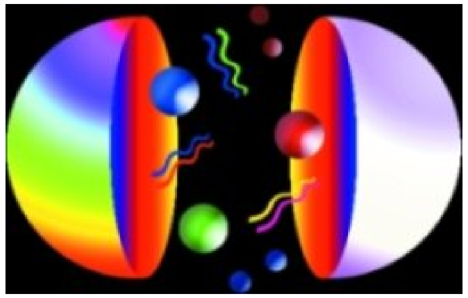


$M^2(\mathrm{GeV}^2)$
(a)
$n = 3$
$n = 2$
$n = 1$
$n = 0$
N(2220)
N(1900)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(b)
N(2600)
$\nu = L + 1$
N(2250)
N(2190)
S=3/2, P=-
N(1700)
N(1675)
N(1650)
N(2220)
$\nu = L$
N(1720)
N(1680)
N(940)
$4\kappa^2$
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(c)
$n = 2$
$n = 1$
$n = 0$
N(1875)
N(1535)
N(1520)
S=1/2, P=-
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)
S=1/2, 3/2
L

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

$$\boxed{\int d\zeta\,\psi_+^2(\zeta) = \int d\zeta\,\psi_-^2(\zeta) = 1/2}$$

Chiral Symmetry of Eigenstate!

- Eigenvalues

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

- "Chiral partners"

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

Nucleon: Equal Probability for L=0,1

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** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$\boxed{J^z = +1/2 :< L^z >= 1/2, < S^z_q >= 0}$$

- **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

$$\begin{aligned} F_+(Q^2) &= g_+ \int d\zeta\, J(Q,\zeta) |\psi_+(\zeta)|^2, \\ F_-(Q^2) &= g_- \int d\zeta\, J(Q,\zeta) |\psi_-(\zeta)|^2, \end{aligned}$$

  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

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

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

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

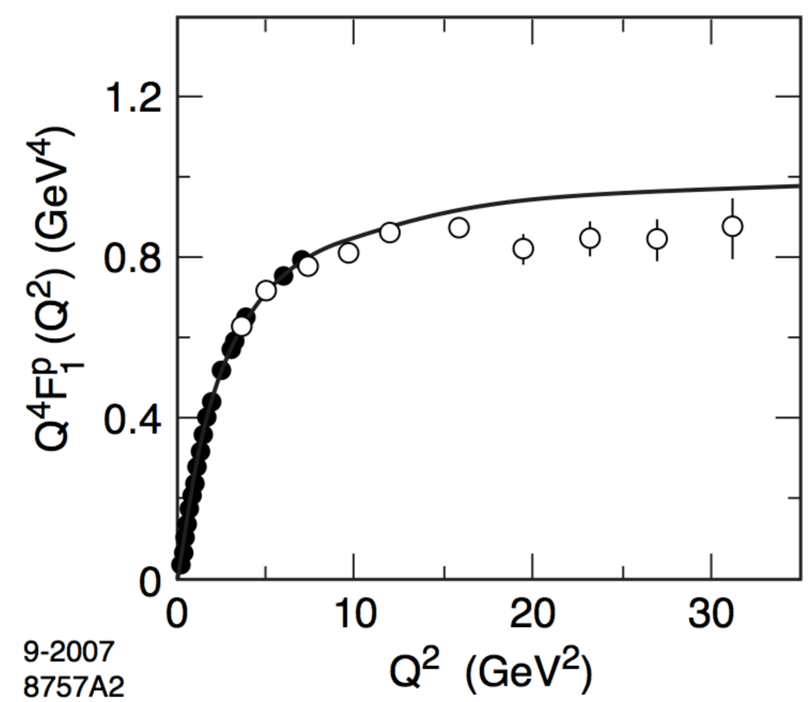
- Bulk-to-boundary propagator [Grigoryan and Radyushkin (2007)]

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

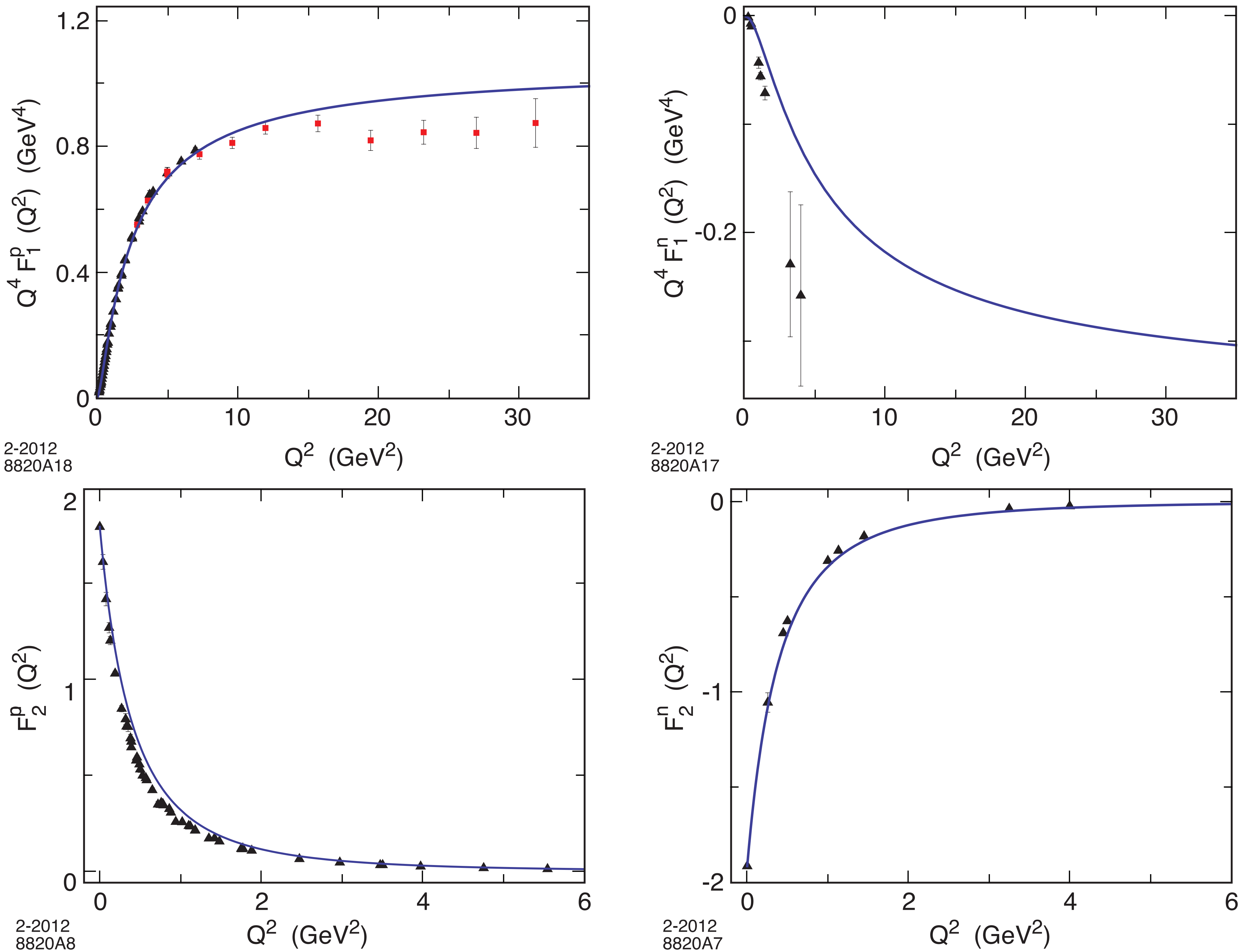
- Find

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

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

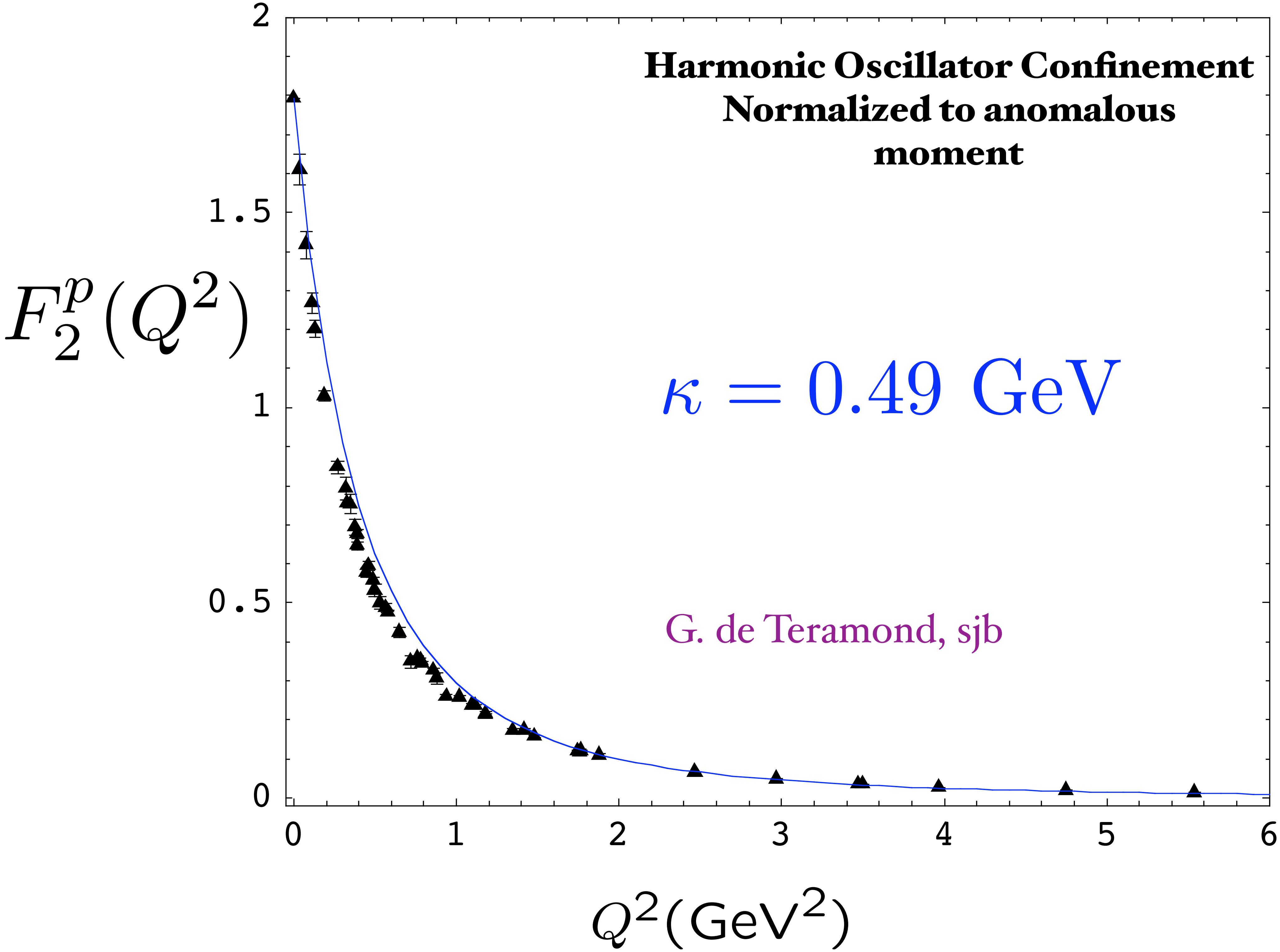


Using $SU(6)$ flavor symmetry and normalization to static quantities

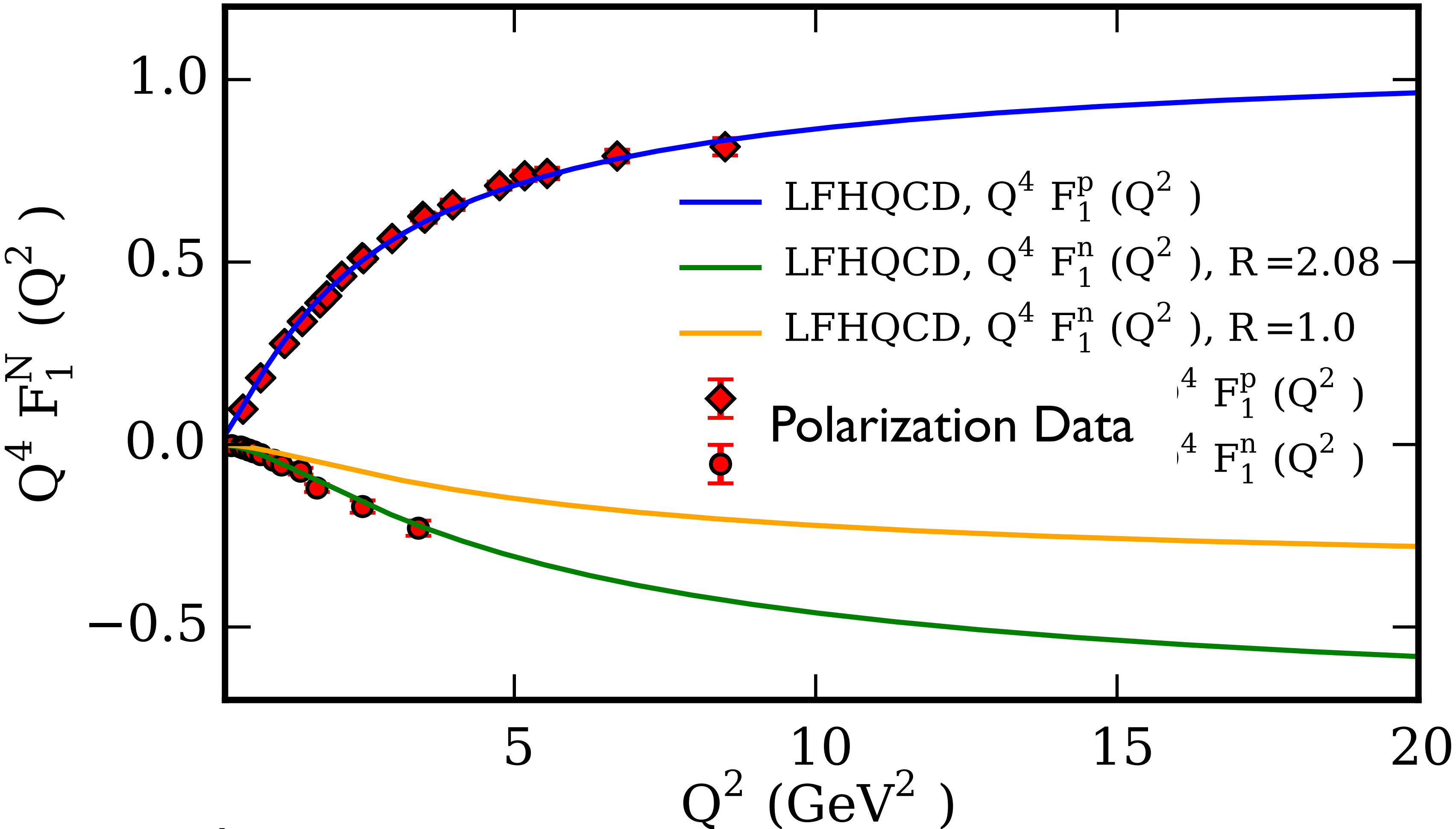


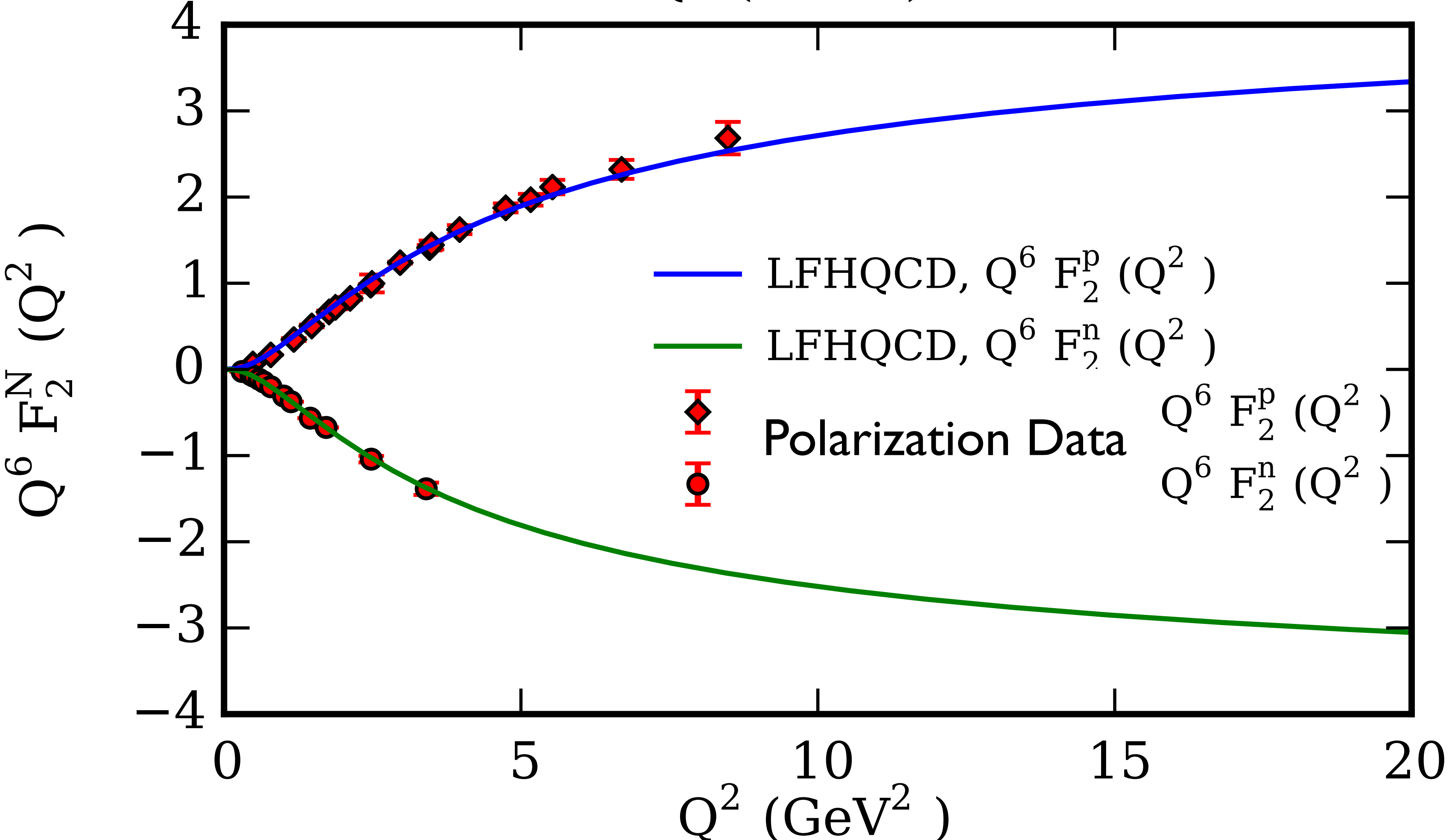
Spacelike Pauli Form Factor

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



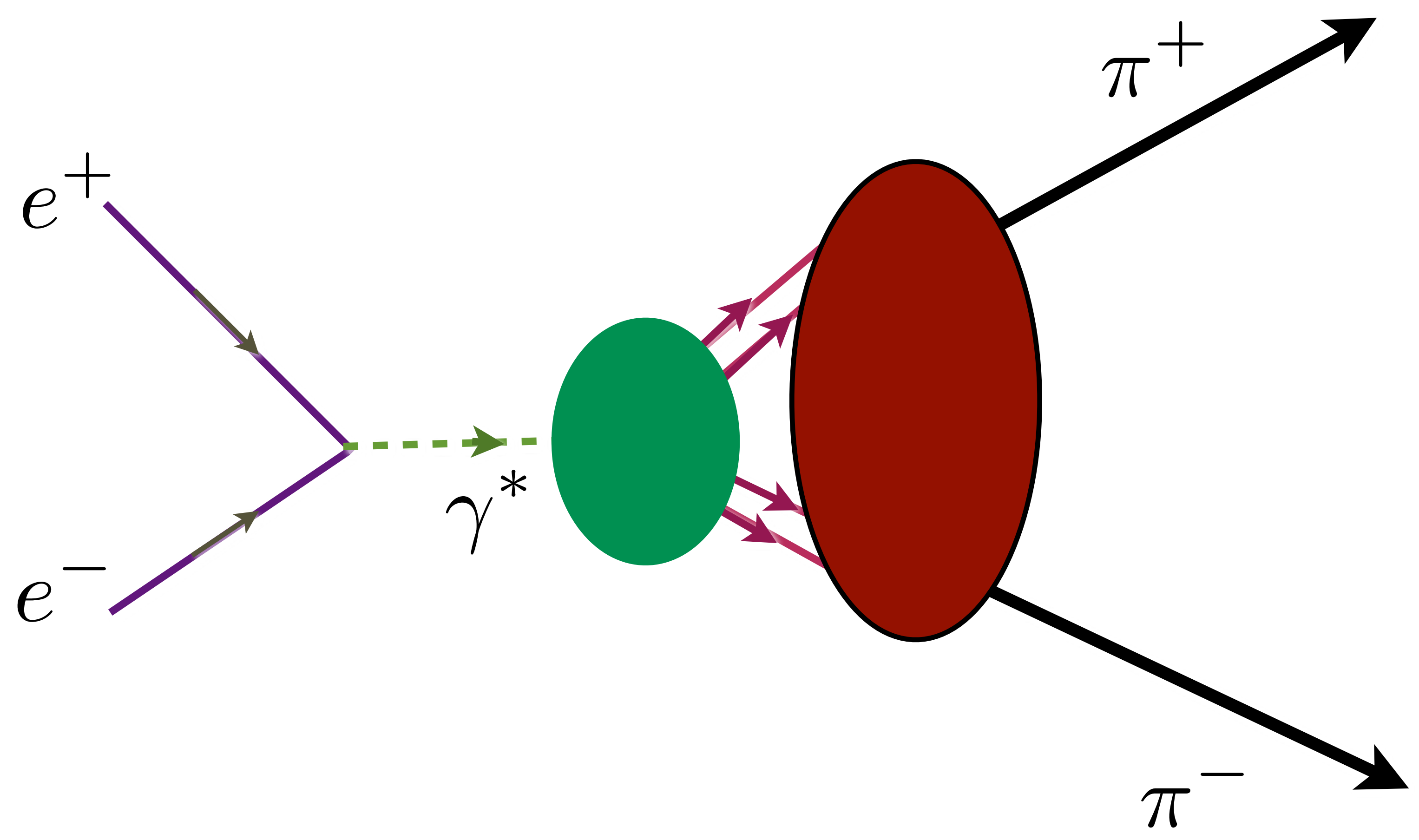
Sufian, de Teramond, Deur, Dosch, sjb



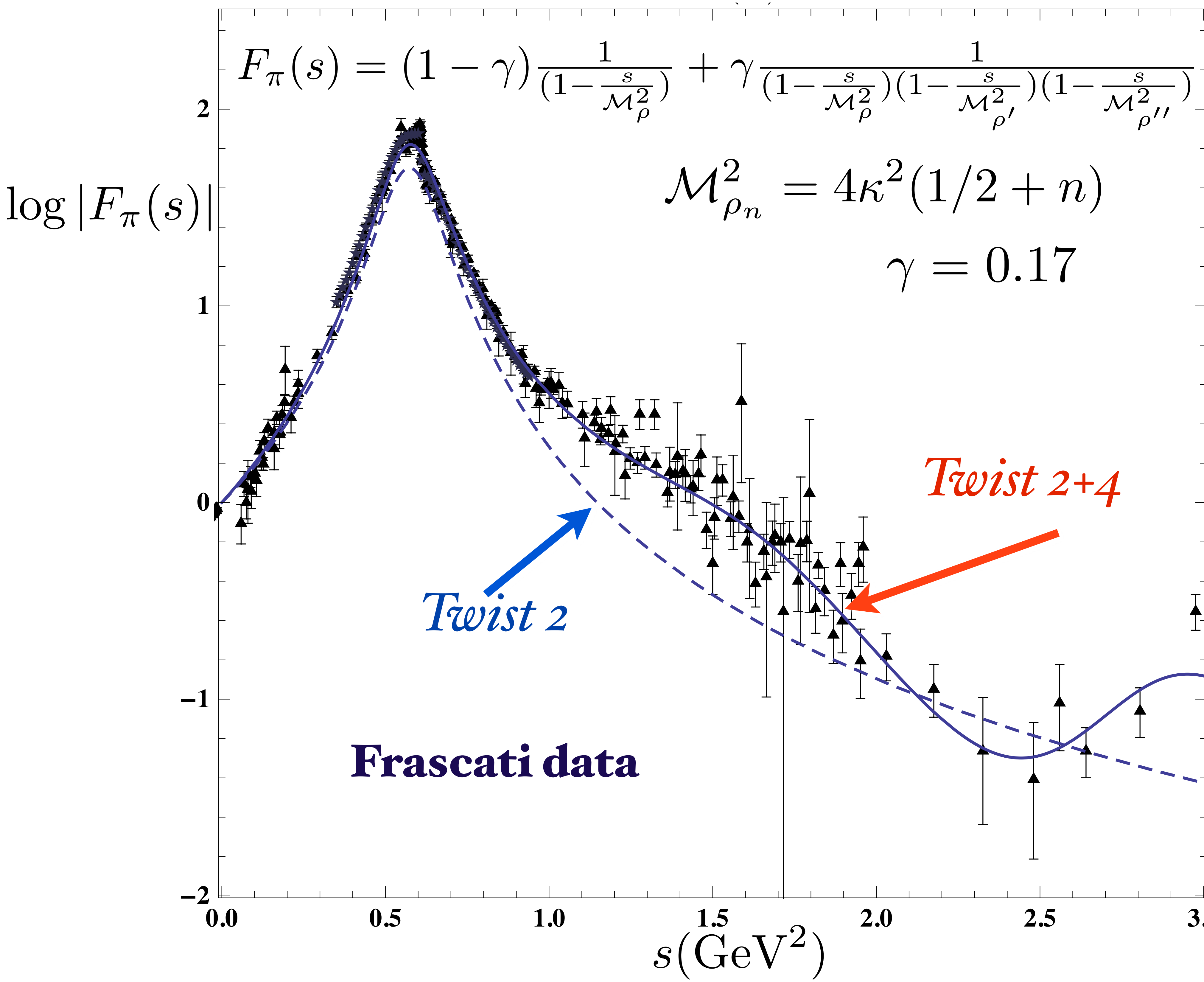


Include 5-quark Fock states

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

LF Holography

Baryon Equation

Superconformal Quantum Mechanics

$$\Big(-\partial_\zeta^2+\kappa^4\zeta^2+2\kappa^2(L_B+1)+\frac{4L_B^2-1}{4\zeta^2}\Big)\psi_J^+=M^2\psi_J^+$$

$$\Big(-\partial_\zeta^2+\kappa^4\zeta^2+2\kappa^2L_B+\frac{4(L_B+1)^2-1}{4\zeta^2}\Big)\psi_J^-=M^2\psi_J^-$$

$$M^2(n,L_B)=4\kappa^2(n+L_B+1)$$

S=1/2, P=+

both chiralities

Meson Equation

$$\Big(-\partial_\zeta^2+\kappa^4\zeta^2+2\kappa^2(J-1)+\frac{4L_M^2-1}{4\zeta^2}\Big)\phi_J=M^2\phi_J$$

$$M^2(n,L_M)=4\kappa^2(n+L_M)$$

Same κ!

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

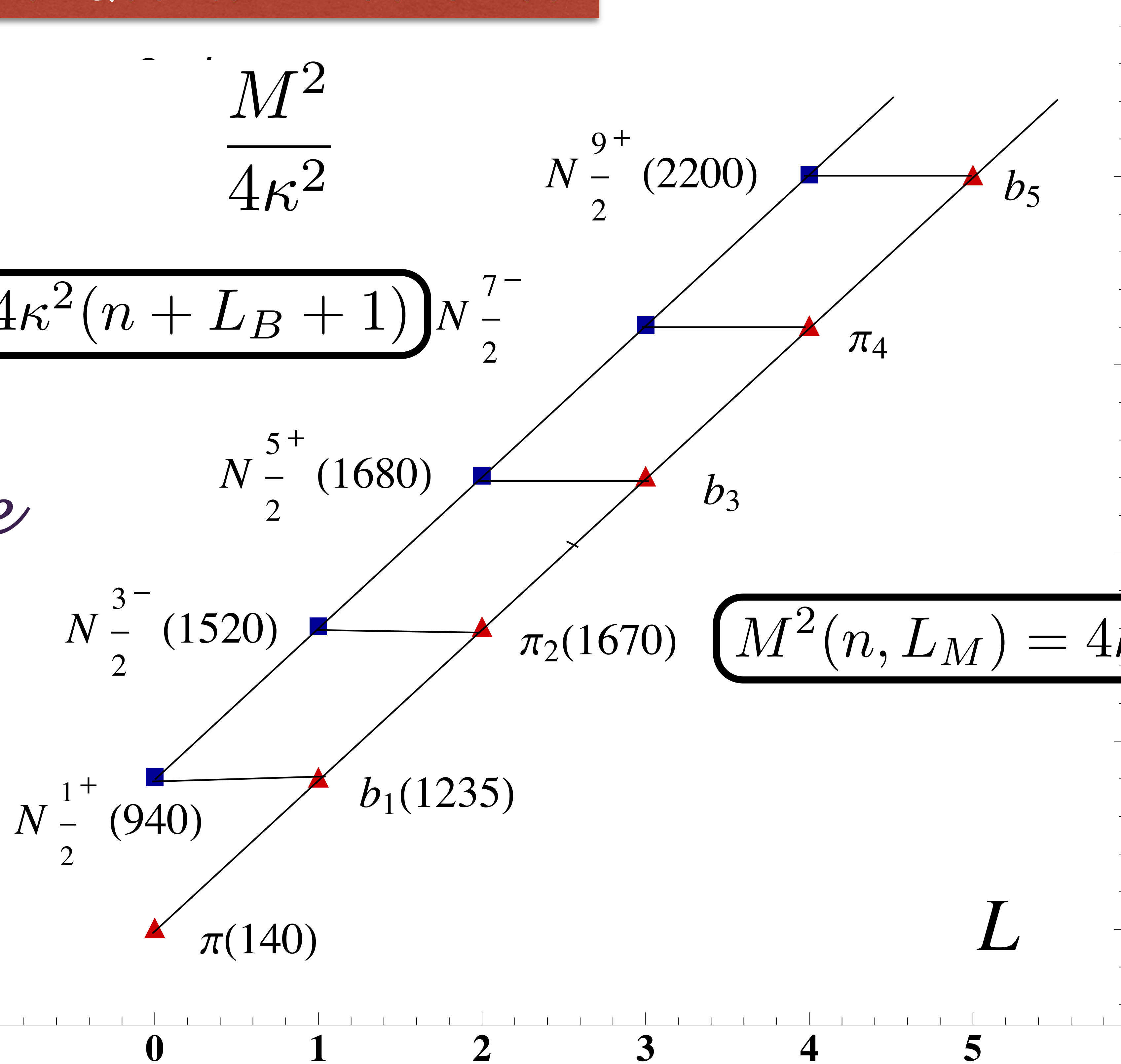
Meson-Baryon Degeneracy for $L_M=L_B+1$

Superconformal Quantum Mechanics

de Tèramond, Dosch, sjb

$$\boxed{M^2(n, L_B) = 4\kappa^2(n + L_B + 1)}$$

Same slope



$$\boxed{M^2(n, L_M) = 4\kappa^2(n + L_M)}$$

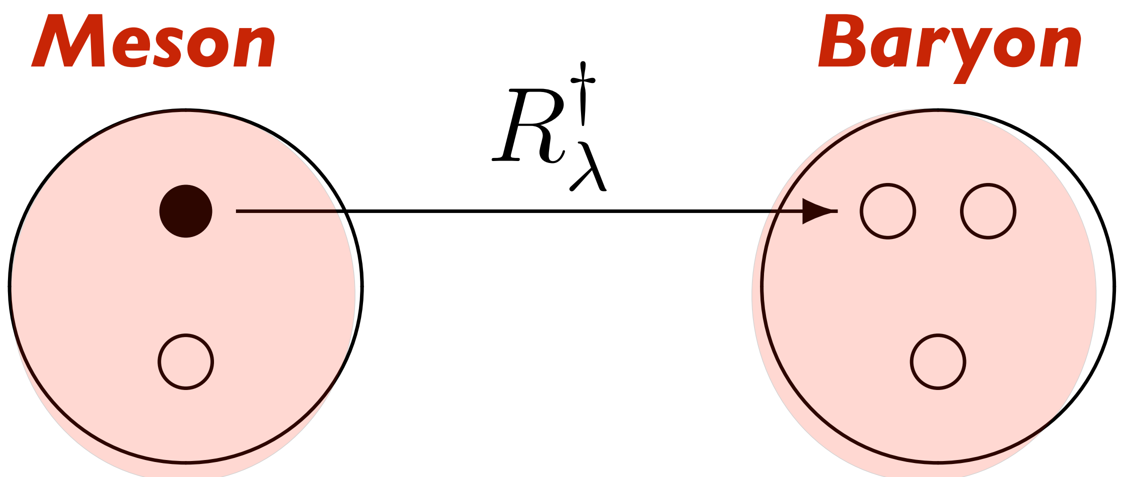
$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

Superconformal Algebra

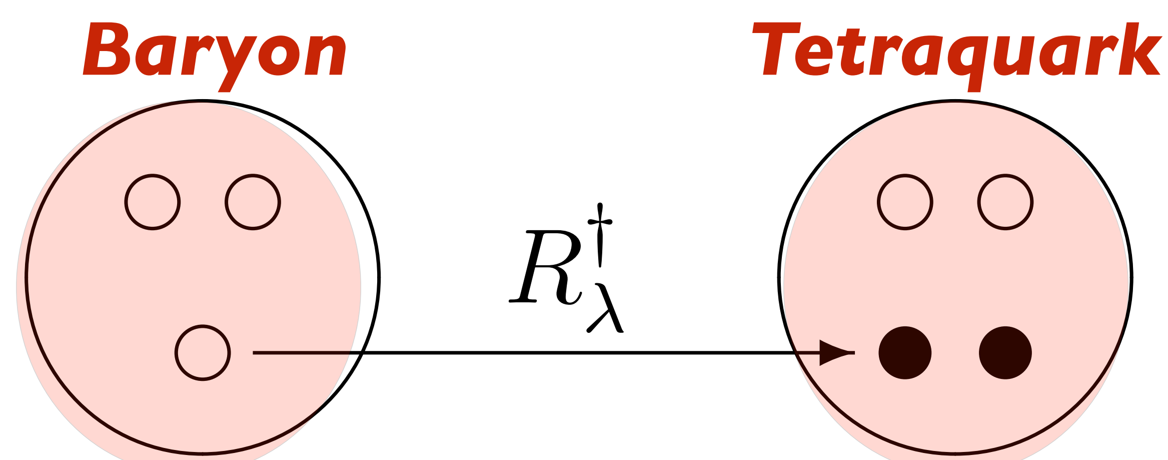
2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



$\phi_M, \; L_B + 1$ $\qquad$ $\psi_{B+}, \; L_B$

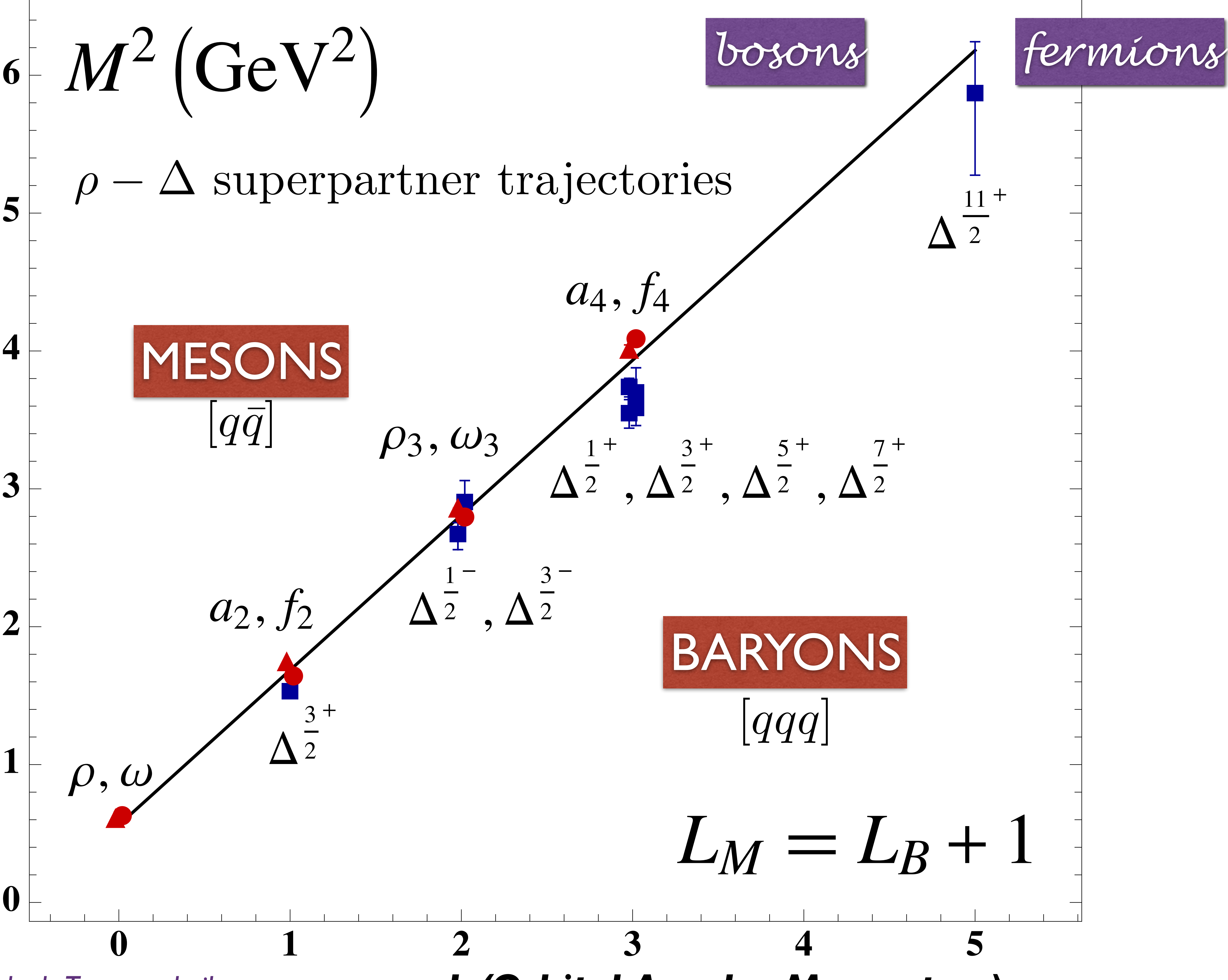
$$R^\dagger_\lambda \; \bar{q} \to [qq]$$
$$\bar{3}_C \to \bar{3}_C$$



$\psi_{B-}, \; L_B + 1$ $\qquad$ $\phi_T, \; L_B$

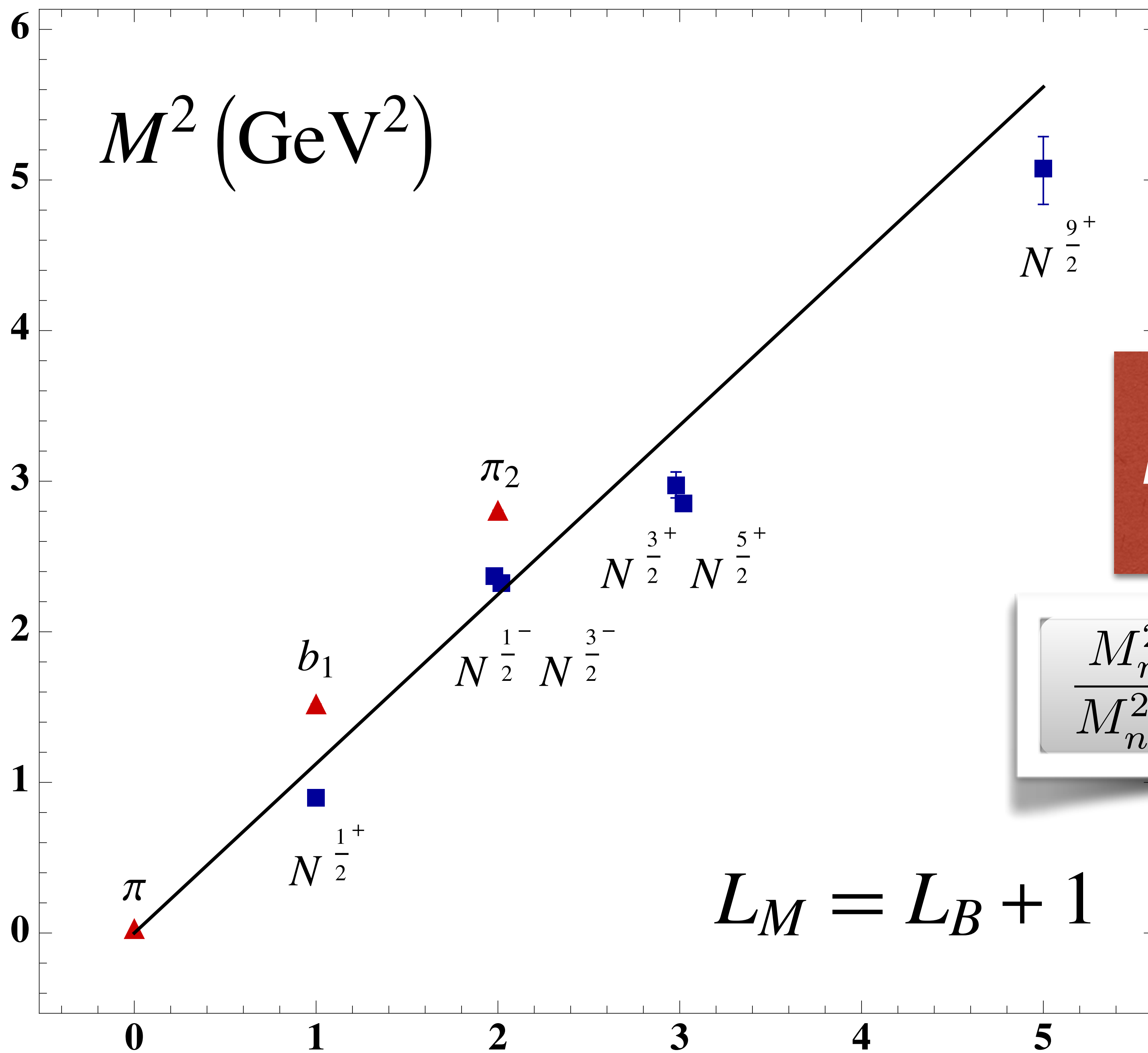
$$R^\dagger_\lambda \; q \to [\bar{q}\bar{q}]$$
$$3_C \to 3_C$$

Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1



$M^2\,(\mathrm{GeV}^2)$
bosons
fermions
$\rho - \Delta$ superpartner trajectories
MESONS
$[q\bar{q}]$
BARYONS
$[qqq]$
ρ, ω
a_2, f_2
ρ_3, ω_3
a_4, f_4
$\Delta^{\frac{3}{2}^+}$
$\Delta^{\frac{1}{2}^-}, \Delta^{\frac{3}{2}^-}$
$\Delta^{\frac{1}{2}^+}, \Delta^{\frac{3}{2}^+}, \Delta^{\frac{5}{2}^+}, \Delta^{\frac{7}{2}^+}$
$\Delta^{\frac{11}{2}^+}$
$L_M = L_B + 1$
L (Orbital Angular Momentum)
Dosch, de Teramond, sjb

Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!

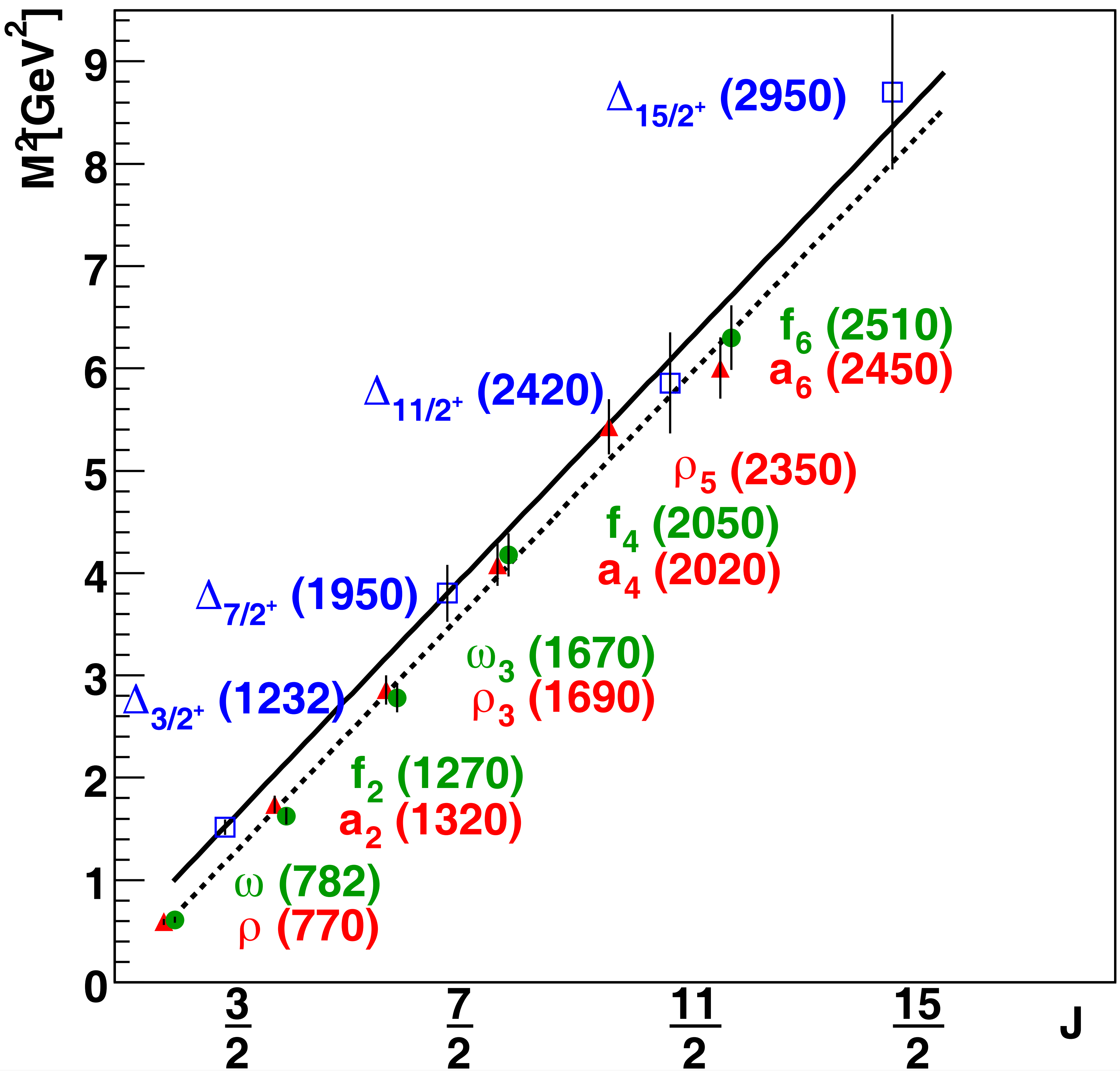


Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

S=0, I=1 Meson is superpartner of S=1/2, I=1 Baryon

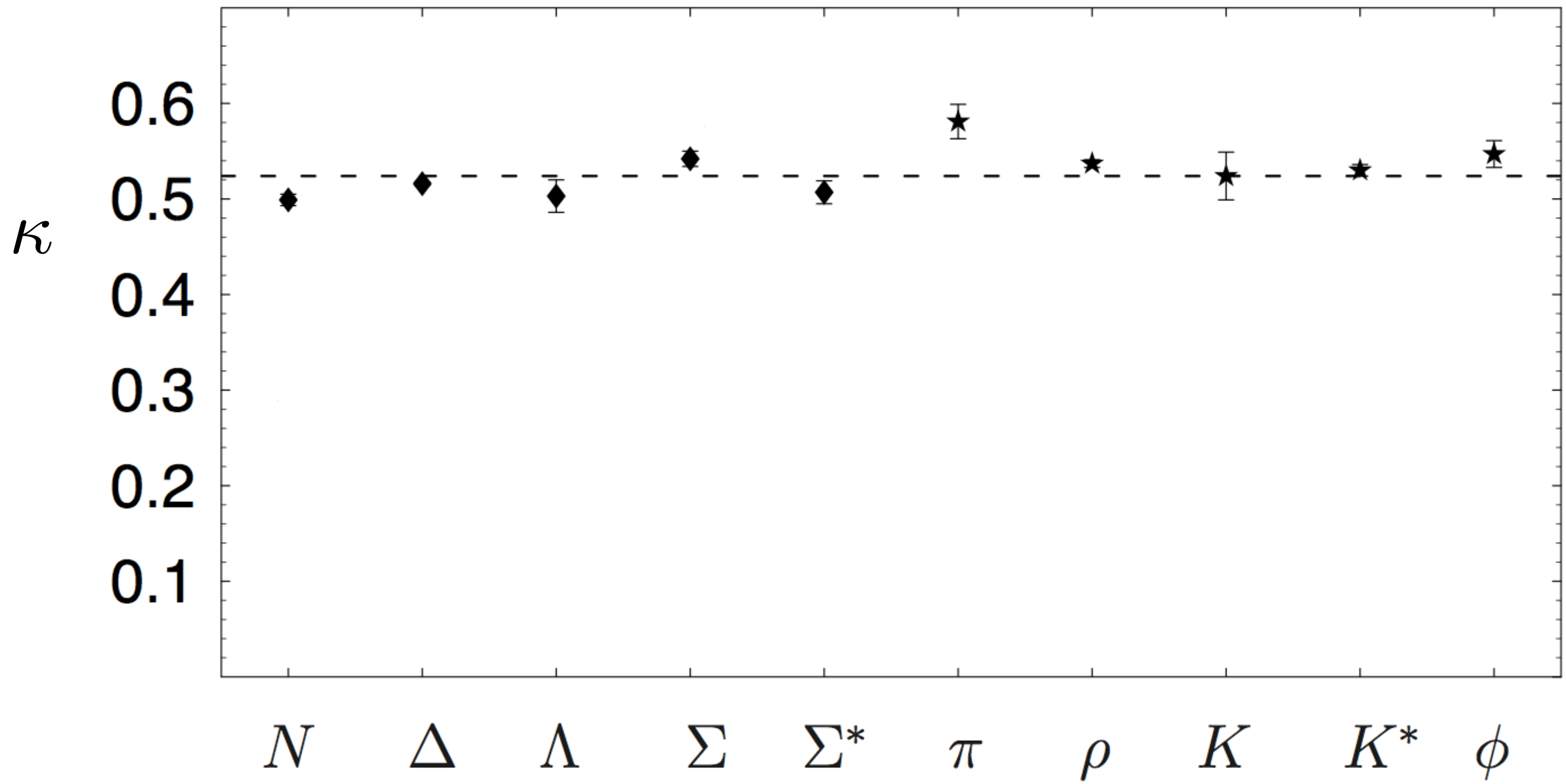
E. Klempt and B. Ch. Metsch



The leading Regge trajectory: Δ resonances with maximal J in a given mass range.
Also shown is the Regge trajectory for mesons with J = L+S.

Dosch, de Tèramond, Lorcè, sjb

$$m_u = m_d = 46 \text{ MeV}, \; m_s = 357 \text{ MeV}$$



Fit to the slope of Regge trajectories, including radial excitations

Same Regge Slope for Meson, Baryons: Supersymmetric feature of hadron physics

Features of Supersymmetric Equations

- $J = L + S$ baryon simultaneously satisfies both equations of G with L , L+1 for same mass eigenvalue

- $J^z = L^z + 1/2 = (L^z + 1) - 1/2$ $\quad S^z = \pm 1/2$

- Baryon spin carried by quark orbital angular momentum: $\langle J^z \rangle = L^z + 1/2$

- Mass-degenerate meson "superpartner" with $L_M = L_B + 1$. *"Shifted meson-baryon Duality"*

Meson and baryon have same κ !

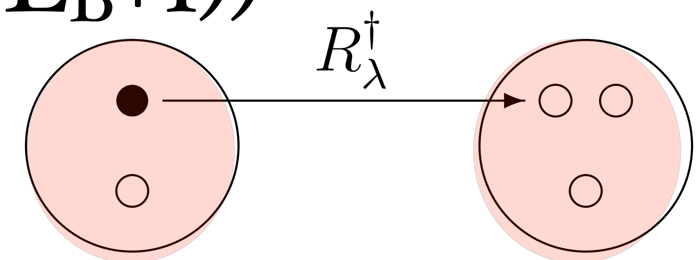
de Tèramond, Dosch, Lorce, sjb

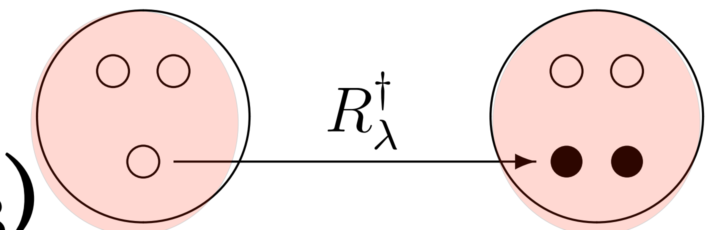
Superconformal Algebra

2X2 Hadronic Multiplets

$$\begin{pmatrix} \phi_M(L_M = L_B + 1) & \psi_{B-}(L_B + 1) \\ \psi_{B+}(L_B) & \phi_T(L_T = L_B) \end{pmatrix}$$

- quark-antiquark meson ($L_M = L_B+1$))
- quark-diquark baryon (L_B)
- quark-diquark baryon (L_B+1)
- diquark-antidiquark tetraquark ($L_T = L_B$)
- Universal Regge slopes $\lambda = \kappa^2$





$$M_H^2/\lambda = \overbrace{\underbrace{(2n + L_H + 1)}_{kinetic} + \underbrace{(2n + L_H + 1)}_{potential}}^{\textit{contribution from 2-dim light-front harmonic oscillator}} + \overbrace{2(L_H + s) + 2\chi}^{\textit{contribution from AdS and superconformal algebra}} + < \sum_i \frac{m_i^2}{x_i} >$$

$\chi(mesons) = -1$ $\quad$ $\chi(baryons, tetraquarks) = +1$

de Tèramond, Dosch, Lorce, sjb

New World of Tetraquarks

$$3_C \times 3_C = \bar{3}_C + 6_C$$

Bound!

- Diquark: Color-Confined Constituents: Color $\bar{3}_C$
- Diquark-Antidiquark bound states $\bar{3}_C \times 3_C = 1_C$

$$\sigma(TN) \simeq 2\sigma(pN) - \sigma(\pi N)$$

$$2\left[\sigma([\{qq\}N) + \sigma(qN)\right] - [\sigma(qN) + \sigma(\bar{q}N)] = [\sigma(\{qq\}N) + \sigma(\{qq\}N)]$$

Candidates $f_0(980) I = 0, J^P = 0^+$, partner of proton

$a_1(1260) I = 0, J^P = 1^+$, partner of $\Delta(1233)$

Underlying Principles

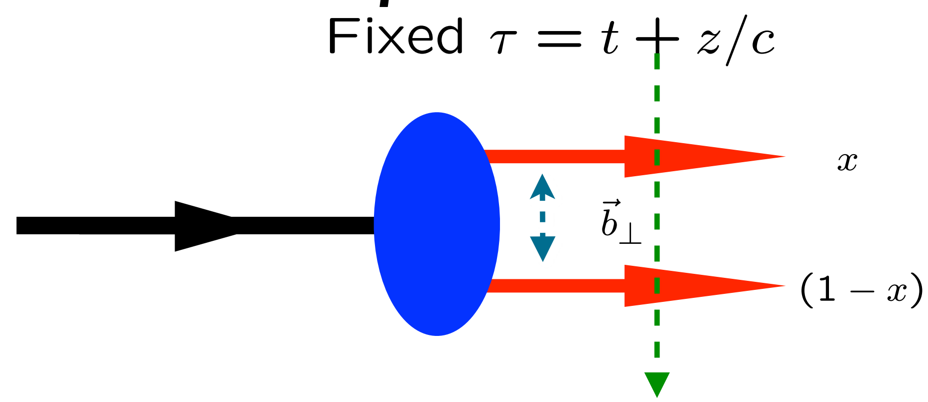
- ***Poincarè Invariance: Independent of the observer's Lorentz frame***

- ***Quantization at Fixed Light-Front Time τ***

- ***Causality: Information within causal horizon***

- ***Light-Front Holography: AdS$_5$ = LF (3+1)***

$$z \leftrightarrow \zeta \text{ where } \zeta^2 = b_\perp^2 x(1-x)$$



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

- ***Single fundamental hadronic mass scale κ: but retains the Conformal Invariance of the Action (dAFF)!***

- ***Unique color-confining LF Potential!*** $U(\zeta^2) = \kappa^4 \zeta^2$

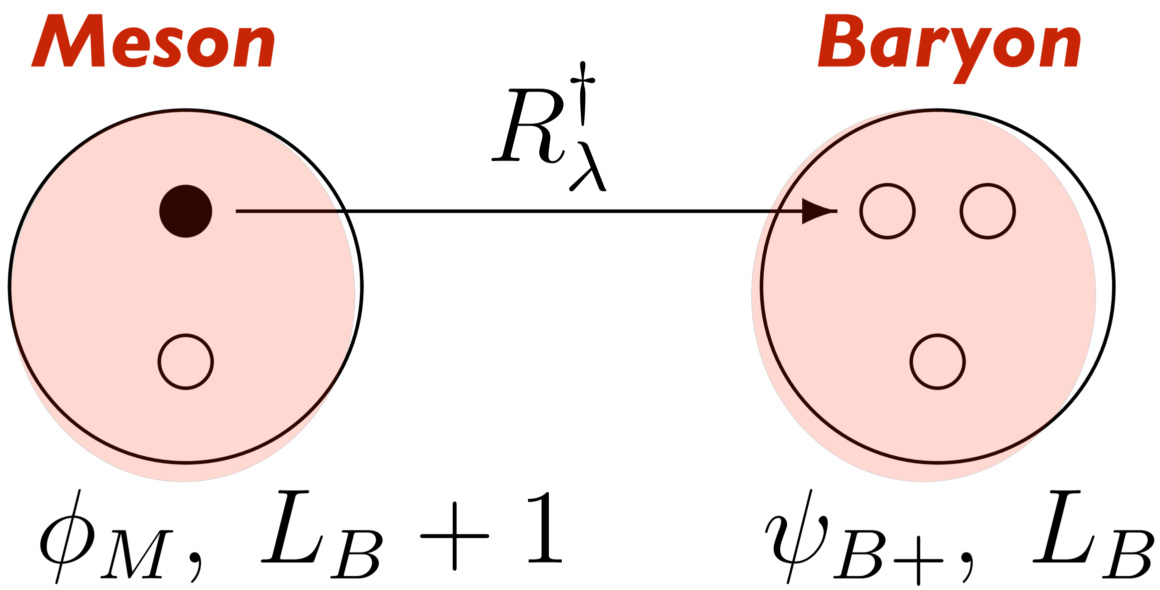
- ***Superconformal Algebra: Mass Degenerate 4-Plet:***

$$\boxed{\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]}$$

Superconformal Algebra

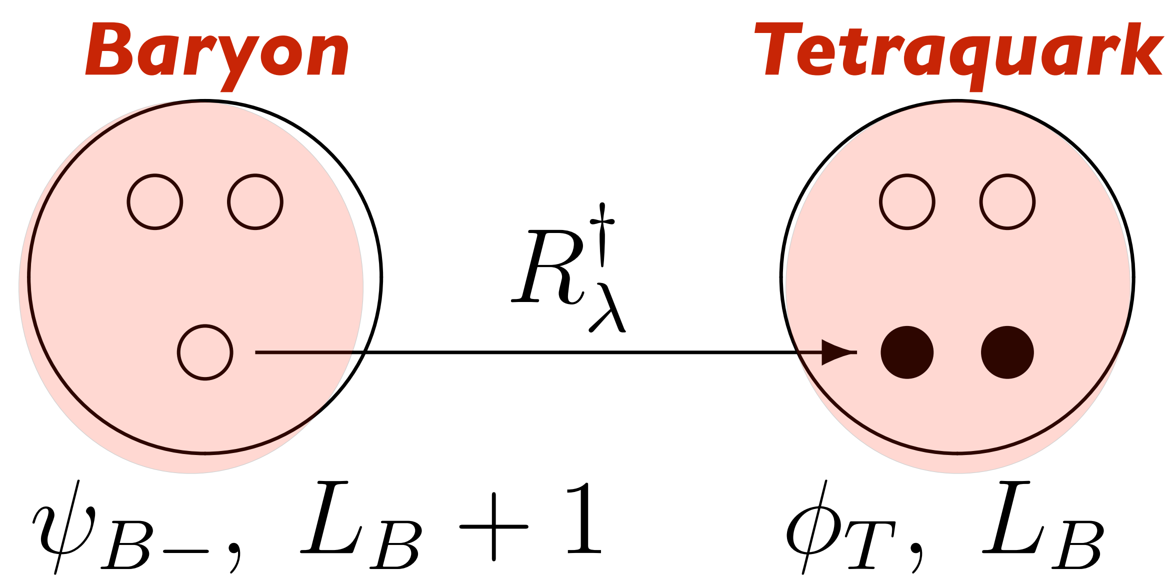
2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



$$R^\dagger_\lambda \ \bar{q} \to [qq]$$

$$\bar{3}_C \to \bar{3}_C$$



$$R^\dagger_\lambda \ q \to [\bar{q}\bar{q}]$$

$$3_C \to 3_C$$

Proton: |u[ud]> Quark + Scalar Diquark
Equal Weight: L=0, L=1

Some Features of AdS/QCD

- ***Regge spectroscopy—same slope in n,L for mesons, baryons***
- ***Chiral features for m_q=0: m_π=0, chiral-invariant proton***
- ***Hadronic LFWFs***
- ***Counting Rules***
- ***Connection between hadron masses and*** $\Lambda_{\overline{MS}}$

Superconformal AdS Light-Front Holographic QCD (LFHQCD)

Meson-Baryon Mass Degeneracy for $L_M=L_B+1$

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

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

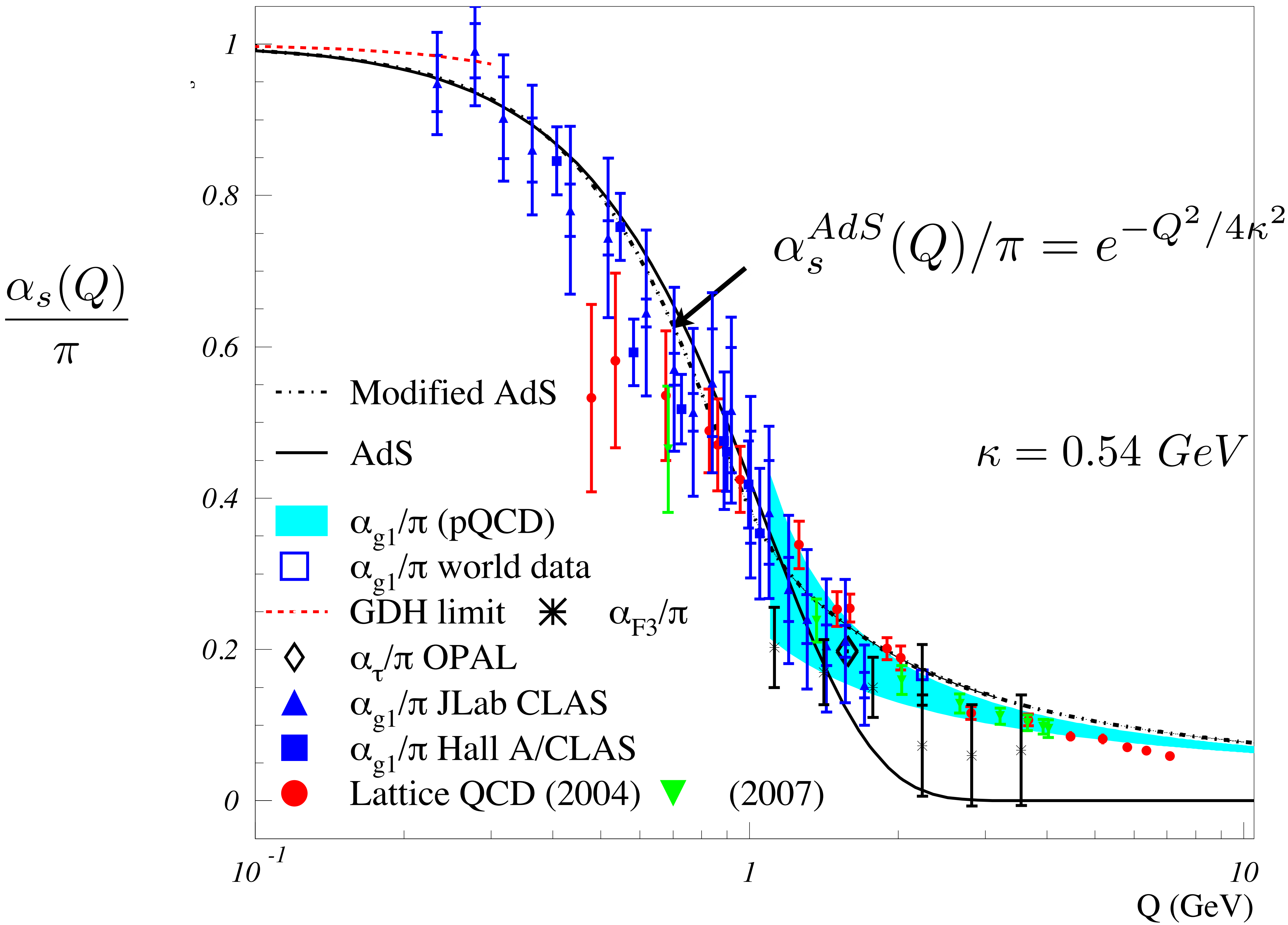
where the coupling α_s^{AdS} incorporates the non-conformal dynamics of confinement

Bjorken sum rule defines effective charge $\alpha_{g1}(Q^2)$

$$\int_0^1 dx[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)] \equiv \frac{g_a}{6}[1 - \frac{\alpha_{g1}(Q^2)}{\pi}]$$

- ***Can be used as standard QCD coupling***
- ***Well measured***
- ***Asymptotic freedom at large Q^2***
- ***Computable at large Q^2 in any pQCD scheme***
- ***Universal β_0, β_1***

Analytic, defined at all scales, IR Fixed Point



AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

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

Deur, de Teramond, sjb

Deur, de Tèramond, sjb

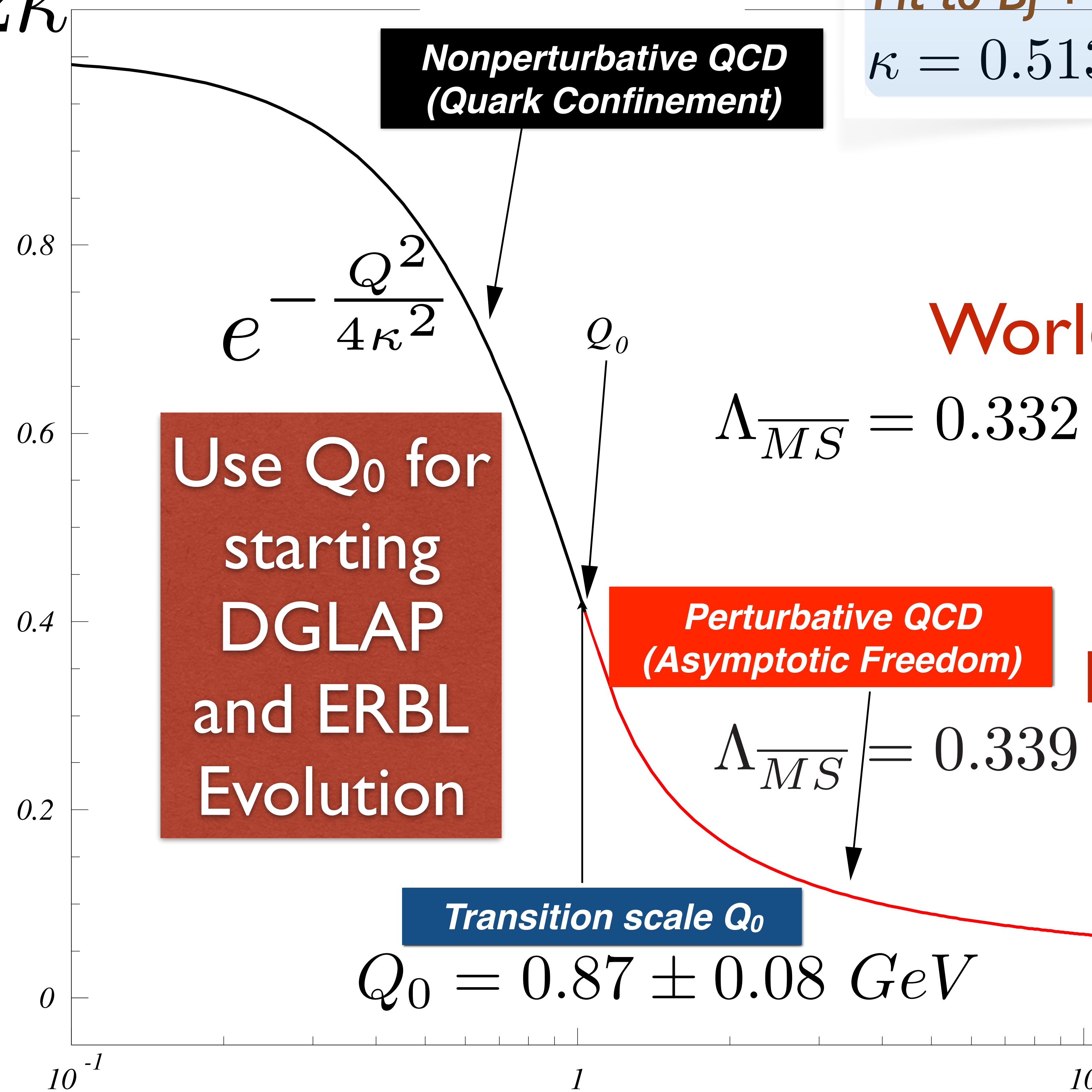
$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

All-Scale QCD Coupling

Fit to Bj + DHG Sum Rules:

$$\kappa = 0.513 \pm 0.007\ GeV$$



World Data:

$$\Lambda_{\overline{MS}} = 0.332 \pm 0.019\ GeV$$

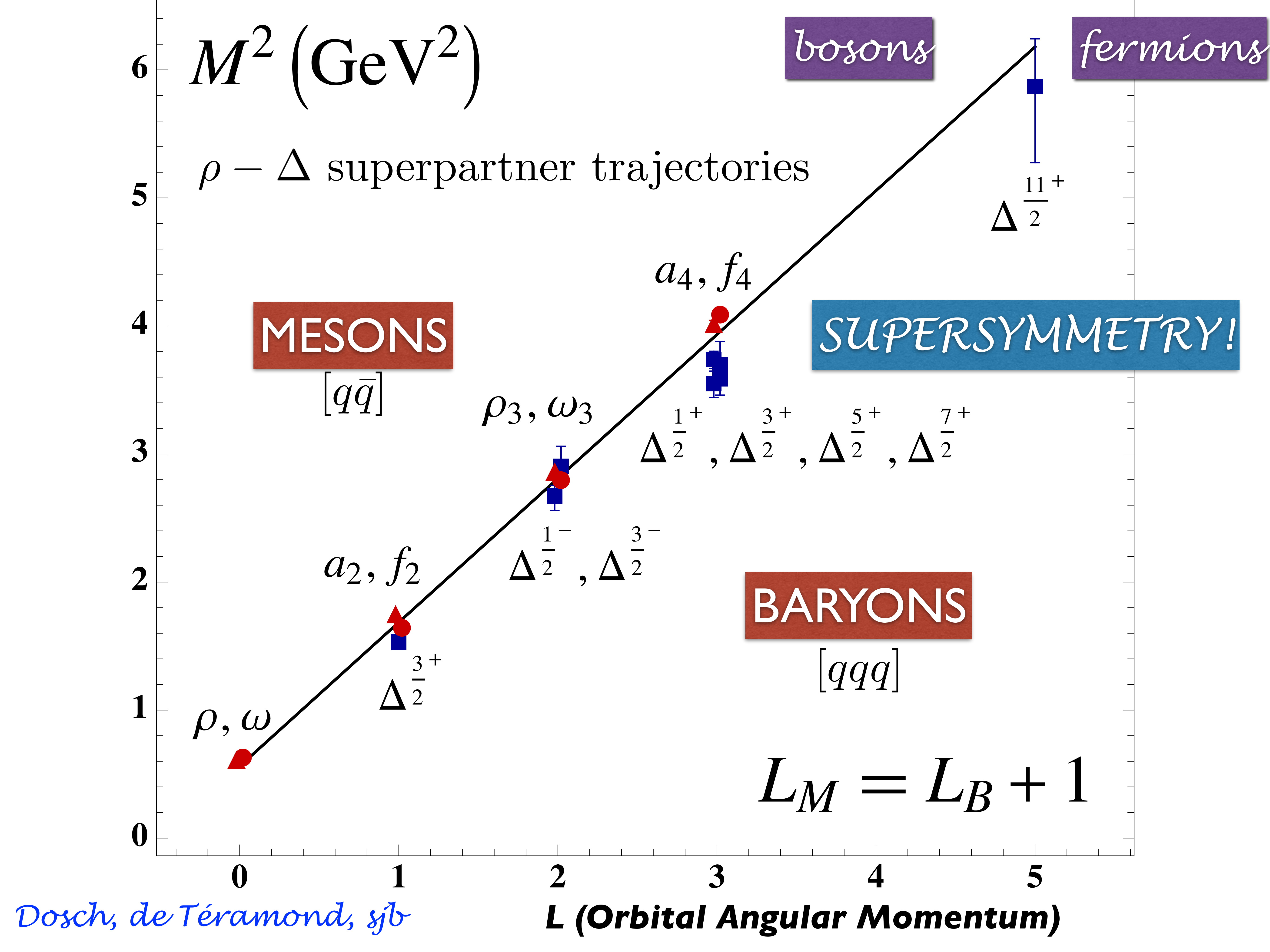
Prediction

$$\Lambda_{\overline{MS}} = 0.339 \pm 0.017\ GeV$$

$$Q_0 = 0.87 \pm 0.08\ GeV$$

$\lambda \equiv \kappa^2$

$\overline{MS}$ scheme



$M^2\,(\mathrm{GeV}^2)$
$\rho - \Delta$ superpartner trajectories
bosons
fermions
MESONS
$[q\bar{q}]$
SUPERSYMMETRY!
BARYONS
$[qqq]$
ρ, ω
a_2, f_2
ρ_3, ω_3
a_4, f_4
$\Delta_{\frac{3}{2}^+}$
$\Delta_{\frac{1}{2}^-}, \Delta_{\frac{3}{2}^-}$
$\Delta_{\frac{1}{2}^+}, \Delta_{\frac{3}{2}^+}, \Delta_{\frac{5}{2}^+}, \Delta_{\frac{7}{2}^+}$
$\Delta_{\frac{11}{2}^+}$
$L_M = L_B + 1$
0
1
2
3
4
5
6
L (Orbital Angular Momentum)
Dosch, de Téramond, sjb

Fundamental Hadronic Features of Hadrons

- Partition of the Proton's Mass: Potential vs. Kinetic Contributions

Virial Theorem

$$\Delta\mathcal{M}^2_{LFKE} = \kappa^2(1+2n+L)$$
$$\Delta\mathcal{M}^2_{LFPE} = \kappa^2(1+2n+L)$$

- Color Confinement $U(\zeta^2) = \kappa^4\zeta^2$
- Role of Quark Orbital Angular Momentum in the Proton

Equal L=0,1

- Quark-Diquark Structure
- Quark Mass Contribution $\Delta M^2 = < \frac{m_q^2}{x} >$

from the Yukawa coupling to the Higgs zero mode

- Baryonic Regge Trajectory $M^2_p(n, L_B) = 4\kappa^2(n + L_B + 1)$
- Mesonic Supersymmetric Partners $L_M = L_B + 1$
- Proton Light-Front Wavefunctions and Dynamical Observables

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

- Form Factors, Distribution Amplitudes, Structure Functions
- Non-Perturbative - Perturbative OCD Transition $Q_0 = 0.87 \pm 0.08\ GeV\ \overline{MS}\ scheme$
- Dimensional Transmutation:

$$m_p \simeq 3.21\ \Lambda_{\overline{MS}}$$
$$m_\rho \simeq 2.2\ \Lambda_{\overline{MS}}$$

de Tèramond, Dosch, sjb

Tony Zee

"Quantum Field Theory in a Nutshell"

Dreams of Exact Solvability

"In other words, if you manage to calculate m_P it better come out proportional to Λ_{QCD} since Λ_{QCD} is the only quantity with dimension of mass around.

Light-Front Holography:

Similarly for m_ρ.

$$m_p \simeq 3.21\ \Lambda_{\overline{MS}}$$

$$m_\rho \simeq 2.2\ \Lambda_{\overline{MS}}$$

Put in precise terms, if you publish a paper with a formula giving m_ρ/m_P in terms of pure numbers such as 2 and π, the field theory community will hail you as a conquering hero who has solved QCD exactly."

$$(m_q = 0)$$

$$m_\pi = 0$$

$$\frac{m_\rho}{m_P} = \frac{1}{\sqrt{2}}$$

$$\frac{\Lambda_{\overline{MS}}}{m_\rho} = 0.455 \pm 0.031$$

Features of AdS/QCD

de Tèramond, Dosch, Deur, sjb

- **Color confining potential $\kappa^4\zeta^2$ and universal mass scale from dilaton**

$$e^{\phi(z)} = e^{\kappa^2 z^2} \qquad \alpha_s(Q^2) \propto \exp -Q^2/4\kappa^2$$

- **Dimensional transmutation** $\Lambda_{\overline{MS}} \leftrightarrow \kappa \leftrightarrow m_H$

- **Chiral Action remains conformally invariant despite mass scale** *DAFF*

- **Light-Front Holography: Duality of AdS and frame-independent LF QCD**

- **Reproduces observed Regge spectroscopy — same slope in n, L, and J for mesons and baryons**

- **Massless pion for massless quark**

- **Supersymmetric meson-baryon dynamics and spectroscopy: $L_M = L_B + 1$**

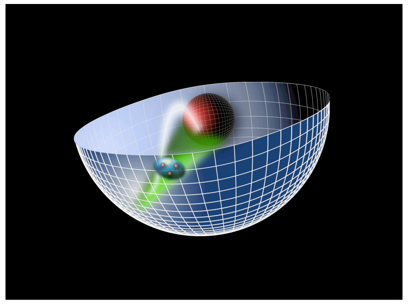
- **Dynamics: LFWFs, Form Factors, GPDs**

Superconformal Quantum Mechanics
Fubini and Rabinovici

Underlying Principles

- *Poincarè Invariance: Independent of the observer's Lorentz frame: Quantization at Fixed Light-Front Time τ*
- *Causality: Information within causal horizon: Light-Front*
- *Light-Front Holography: AdS_5 = LF (3+1)*

$$z \leftrightarrow \zeta \text{ where } \zeta^2 = b_\perp^2 x(1-x)$$



- *Introduce mass scale κ while retaining the Conformal Invariance of the Action (dAFF)*
- *Unique Dilaton in AdS_5:* $e^{+\kappa^2 z^2}$
- *Unique color-confining LF Potential* $U(\zeta^2) = \kappa^4 \zeta^2$
- *Superconformal Algebra: Mass Degenerate 4-Plet:*

$$\boxed{\text{Meson } q\bar{q} \leftrightarrow \text{Baryon } q[qq] \leftrightarrow \text{Tetraquark } [qq][\bar{q}\bar{q}]}$$

de Tèramond, Dosch, Lorce, sjb

Future Directions for AdS/QCD

- **Hadronization at the Amplitude Level**
- **Diffractive dissociation of pion and proton to jets**
- **Factorization Scale for ERBL, DGLAP evolution: Q_0**
- **Calculate Sivers Effect including FSI and ISI**
- **Compute Tetraquark Spectroscopy: Sequential Clusters**
- **Update SU(6) spin-flavor symmetry**
- **Heavy Quark States: Supersymmetry, not conformal**
- **Compute higher Fock states; e.g. Intrinsic Heavy Quarks**
- **Nuclear States — Hidden Color**
- **Basis LF Quantization** *Vary, sjb*

"One of the gravest puzzles of theoretical physics"

DARK ENERGY AND
THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE

Department of Physics, University of California, Santa Barbara, CA 93106, USA
Kavil Institute for Theoretical Physics, University of California,
Santa Barbara, CA 93106, USA
zee@kitp.ucsb.edu

$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

$$\Omega_\Lambda = 0.76(expt)$$

$$(\Omega_\Lambda)_{EW} \sim 10^{56}$$

Extraordinary conflict between the conventional definition of the vacuum in quantum field theory and cosmology

Elements of the solution:
(A) Light-Front Quantization: causal, frame-independent vacuum
(B) New understanding of QCD "Condensates"
(C) Higgs Light-Front Zero Mode

Standard Model on the Light-Front

- **Same phenomenological predictions**
- **Higgs field has three components**
- **Real part creates Higgs particle**
- **Imaginary part (Goldstone) become longitudinal components of W, Z**
- ***Higgs VEV of instant form becomes $k^+=0$ LF zero mode!***
- **Analogous to a background static classical Zeeman or Stark Fields**
- **Zero contribution to $T^\mu{}_\mu$; zero coupling to gravity**

We view the universe as light reaches us along the light-front at fixed

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

Front Form Vacuum Describes the Empty, Causal Universe

Two Definitions of Vacuum State

Instant Form: Lowest Energy Eigenstate of Instant-Form Hamiltonian

$$H|\psi_0 >= E_0|\psi_0 >, E_0 = min\{E_i\}$$

Eigenstate defined at one time t over all space; Acausal! Frame-Dependent

Front Form: Lowest Invariant Mass Eigenstate of Light-Front Hamiltonian

$$H_{LF}|\psi_0 >_{LF}= M_0^2|\psi_0 >_{LF}, M_0^2 = 0.$$

Frame-independent eigenstate at fixed LF time $\tau = t+z/c$ within causal horizon

Frame-independent description of the causal physical universe!

Light-Front vacuum can simulate empty universe

Shrock, Tandy, Roberts, sjb

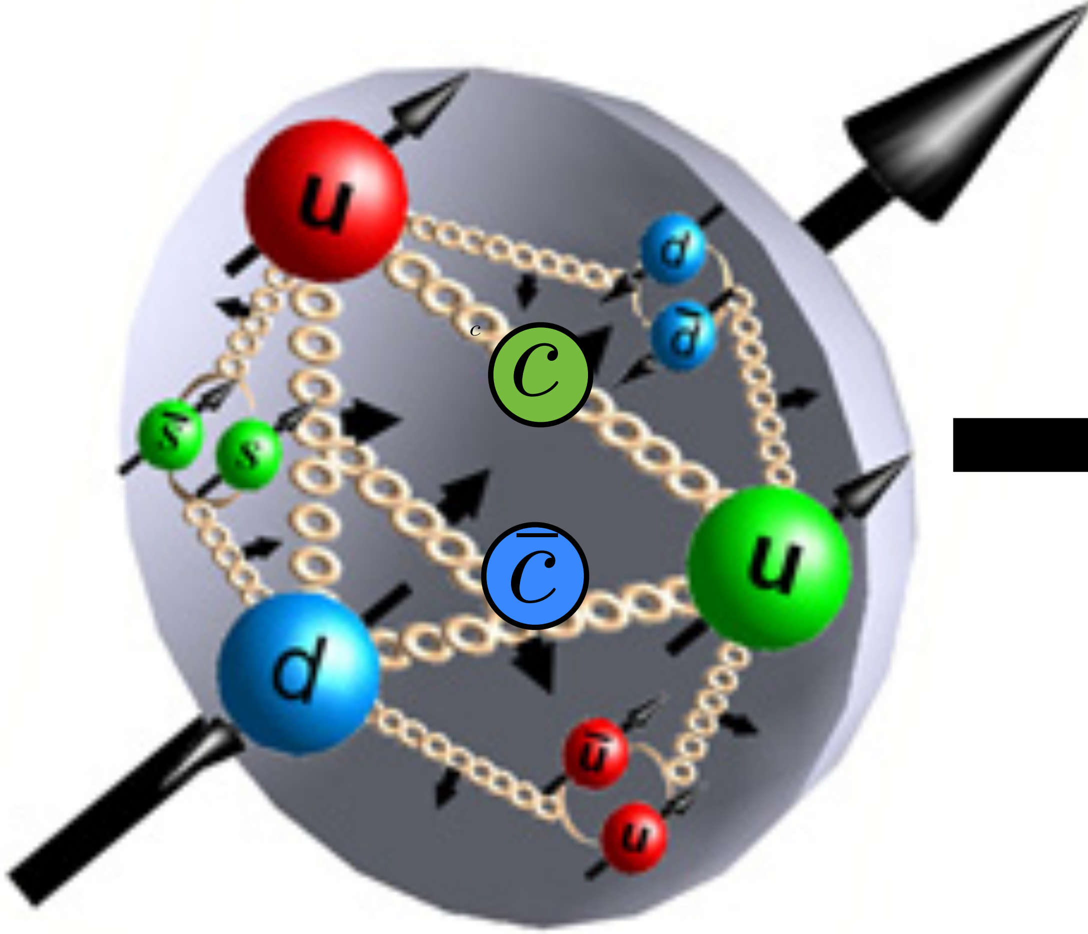
- **Independent of observer frame**
- **Causal**
- **Lowest invariant mass state M= 0.**
- **Trivial up to $k^+=0$ zero modes-- already normal-ordering**
- **Higgs theory consistent with trivial LF vacuum (Srivastava, sjb)**

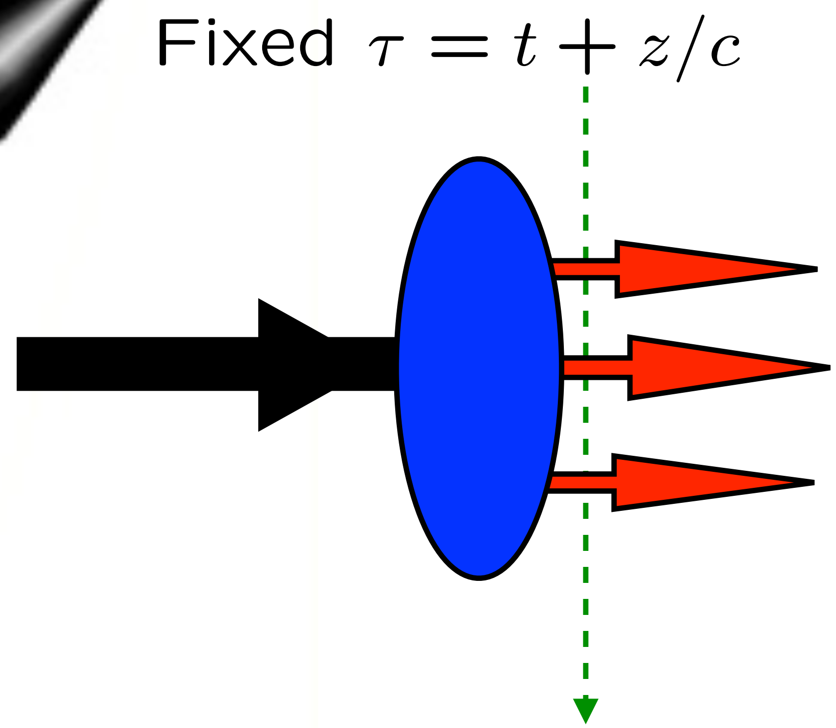
  Higgs VEV —> Higgs Zero Mode
- **QCD and AdS/QCD: "In-hadron" SVV condensates (Maris, Tandy, Roberts; Casher Susskind)**
- **GMOR satisfied.**
- **QED vacuum; no loops**
- **Zero cosmological constant from QED, QCD, EW!**

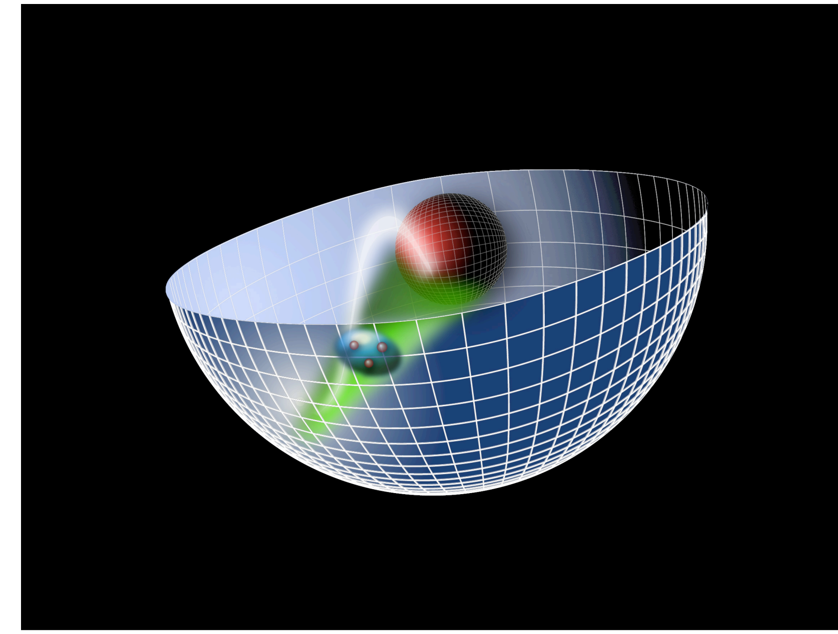
Challenge Conventional Wisdom

- **Nuclear Structure Functions obey QCD sum rules**
- **ISI and FSI are higher twist effects and universal**
- **High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!**
- **Heavy quarks in hadrons only arise from gluon splitting: ``*Intrinsic Charm, Bottom*"**
- **Renormalization scale cannot be fixed : BLM/PMC**
- **QCD gives 10^{42} to the cosmological constant**
- **Colliding Pancakes at RHIC**
- **Nuclei are Composites of Nucleons: "*Hidden Color*"**
- **Hadron Interactions are Static: ``*Color Transparency*"**

Physics on the Light Front: A Novel Approach to Quark Confinement and QCD Phenomena







Colloquium
March 22, 2018

Instituto de Física Teórica
UAM-CSIC

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

with Guy de Tèramond, Hans Günter Dosch, Cedric Lorcè, and Alexandre Deur