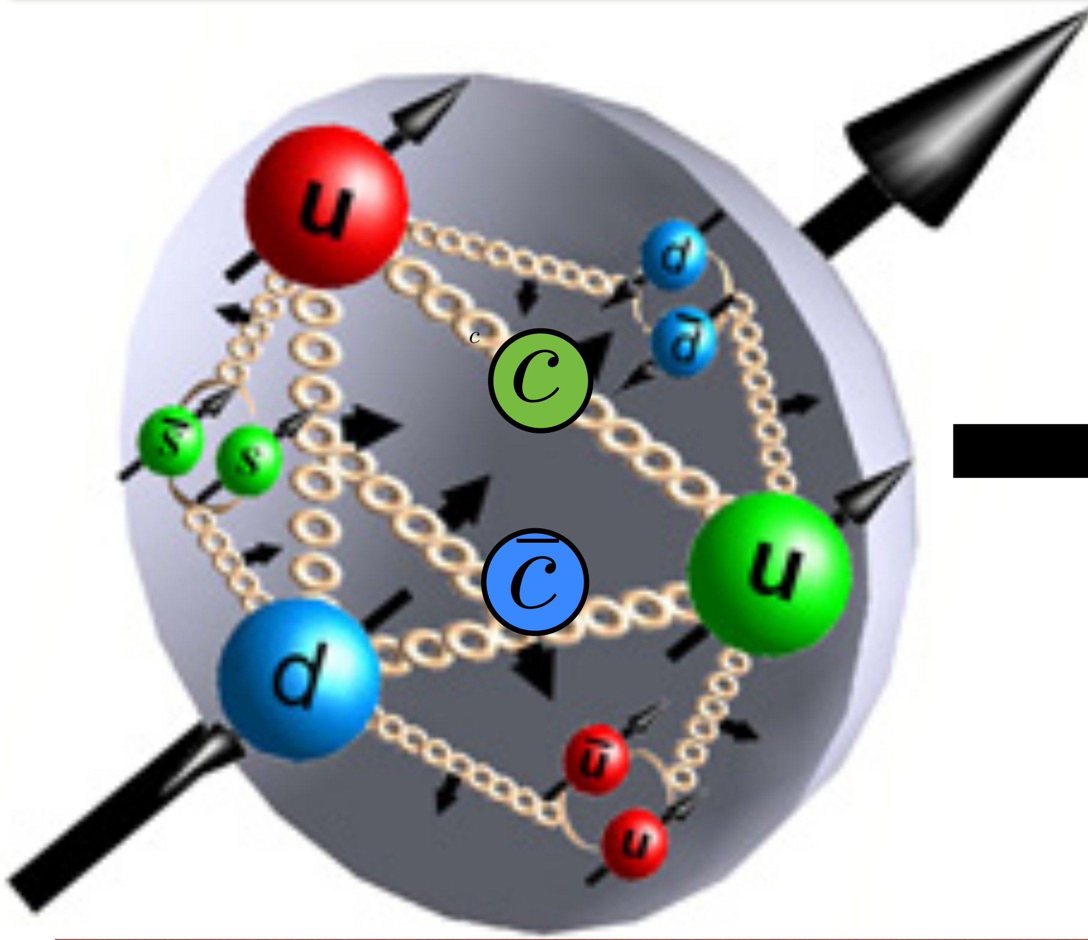
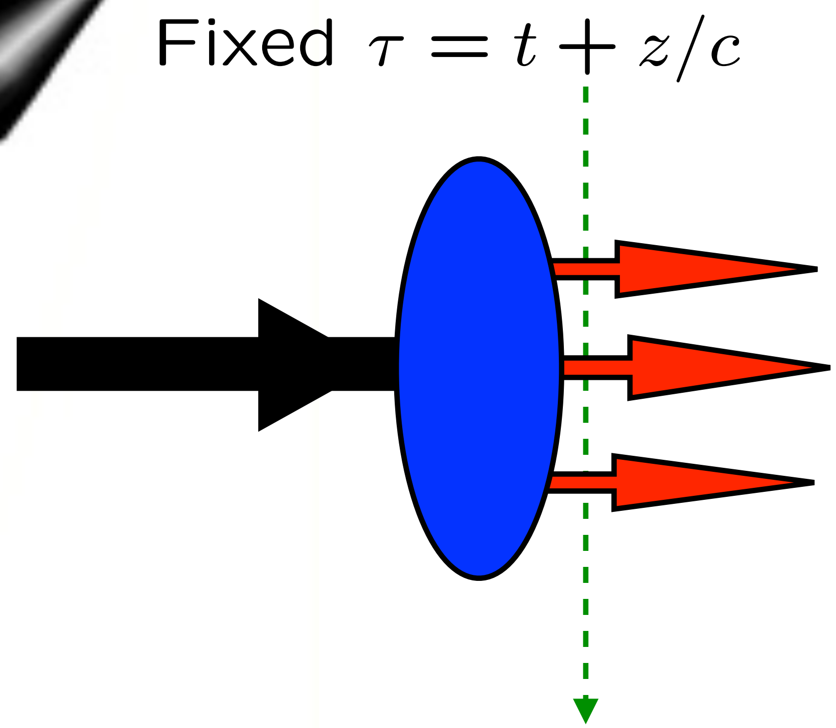
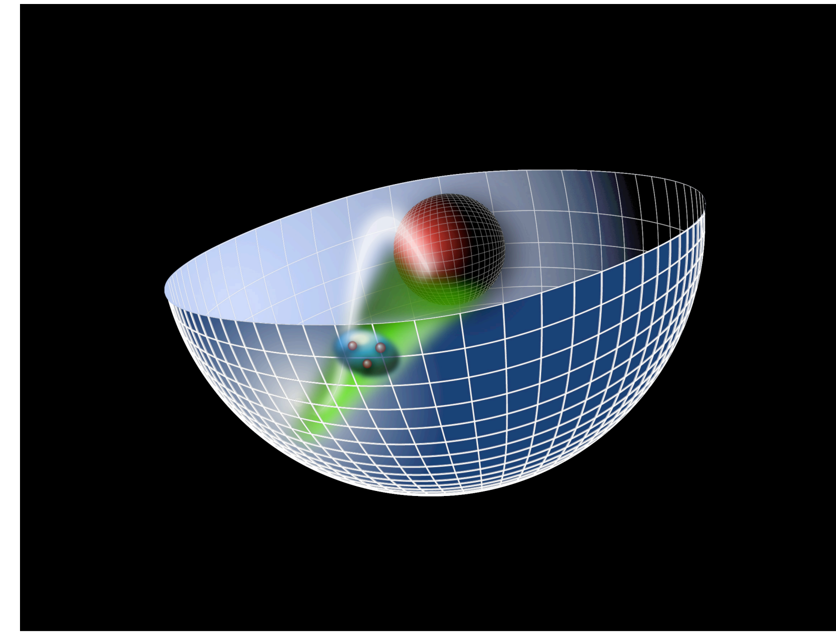
Physics on the Light Front: A Novel Approach to Quark Confinement and QCD Phenomena







The Mexican School of Particles and Fields (MSPF)

The 2018 University of Sonora School of High Energy Physics (USHEP)

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

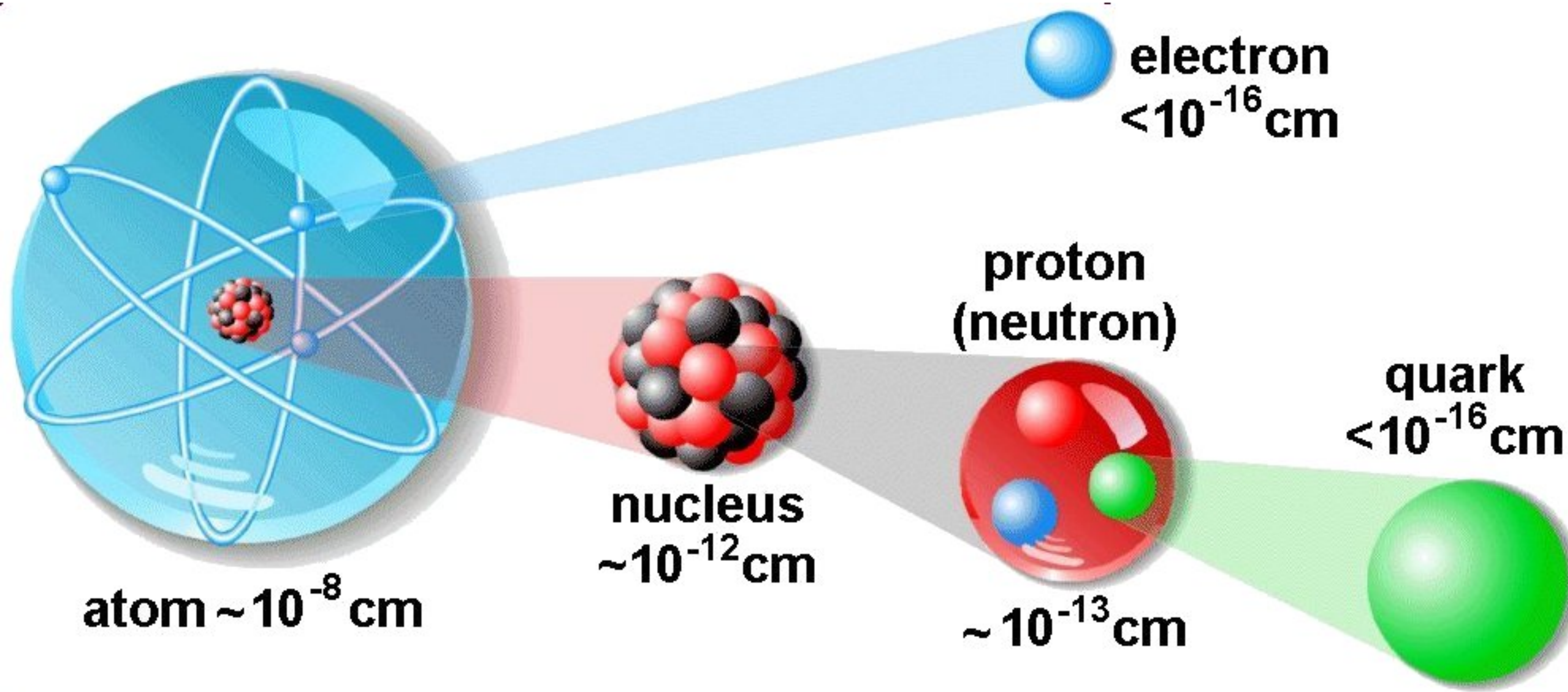
Lecture I

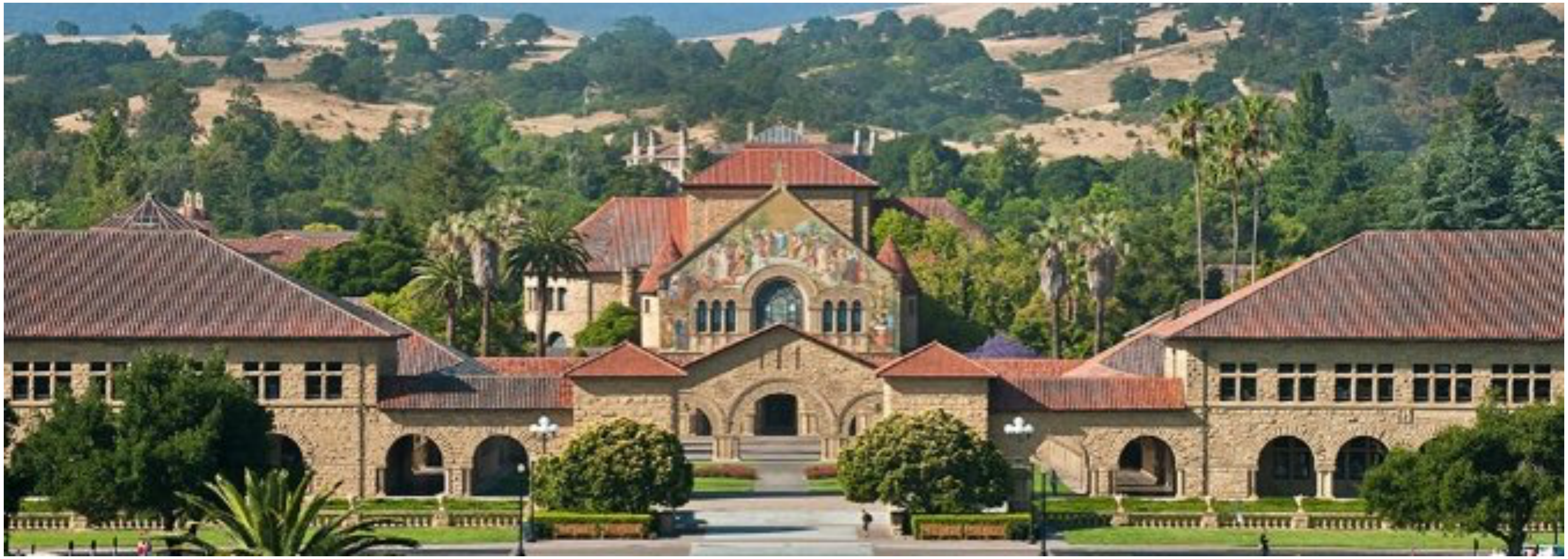
October 22, 2018

with Guy de Tèramond, Hans Günter Dosch, Marina Nielsen, 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.





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Discovery of the Quark Structure of Matter

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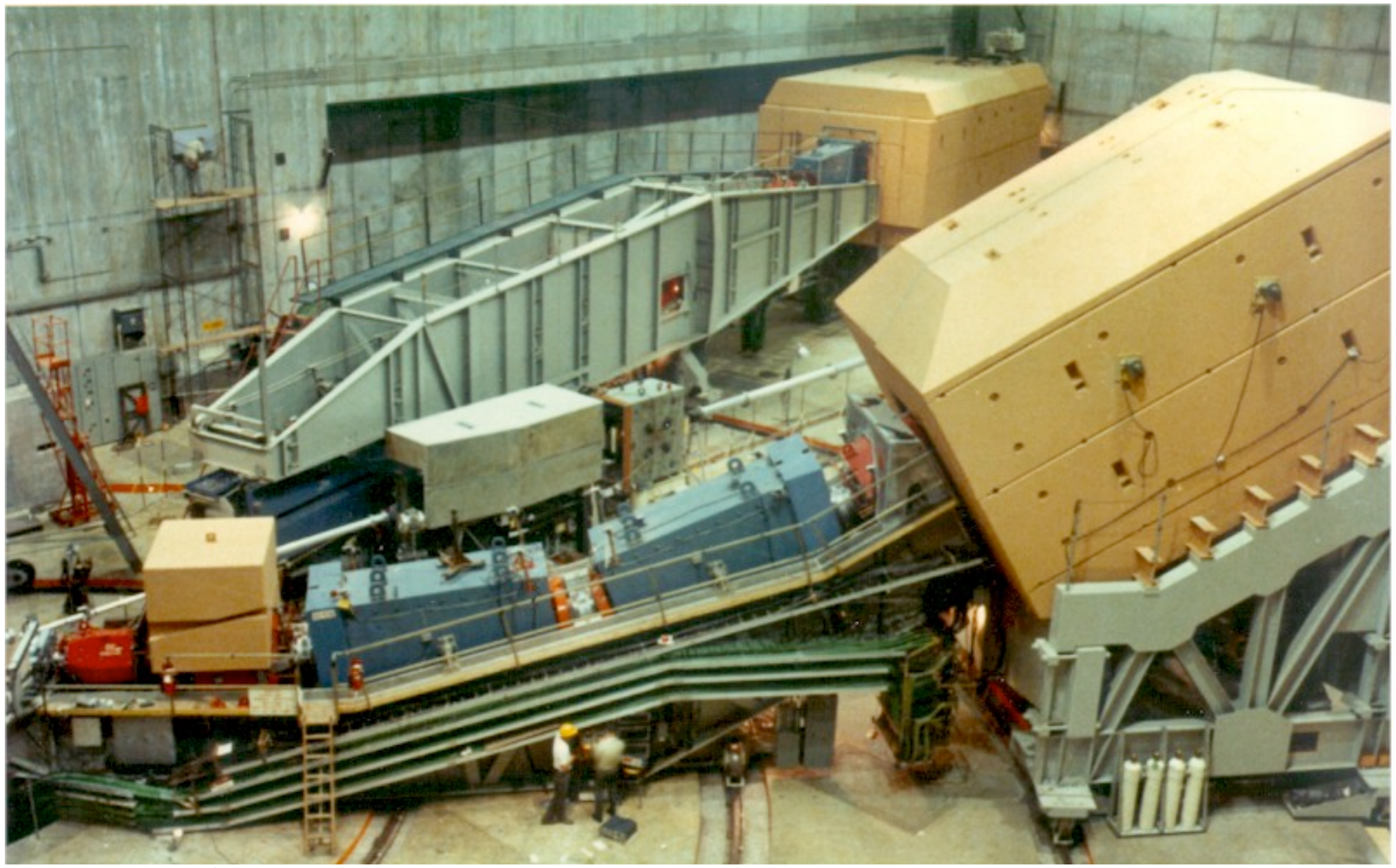
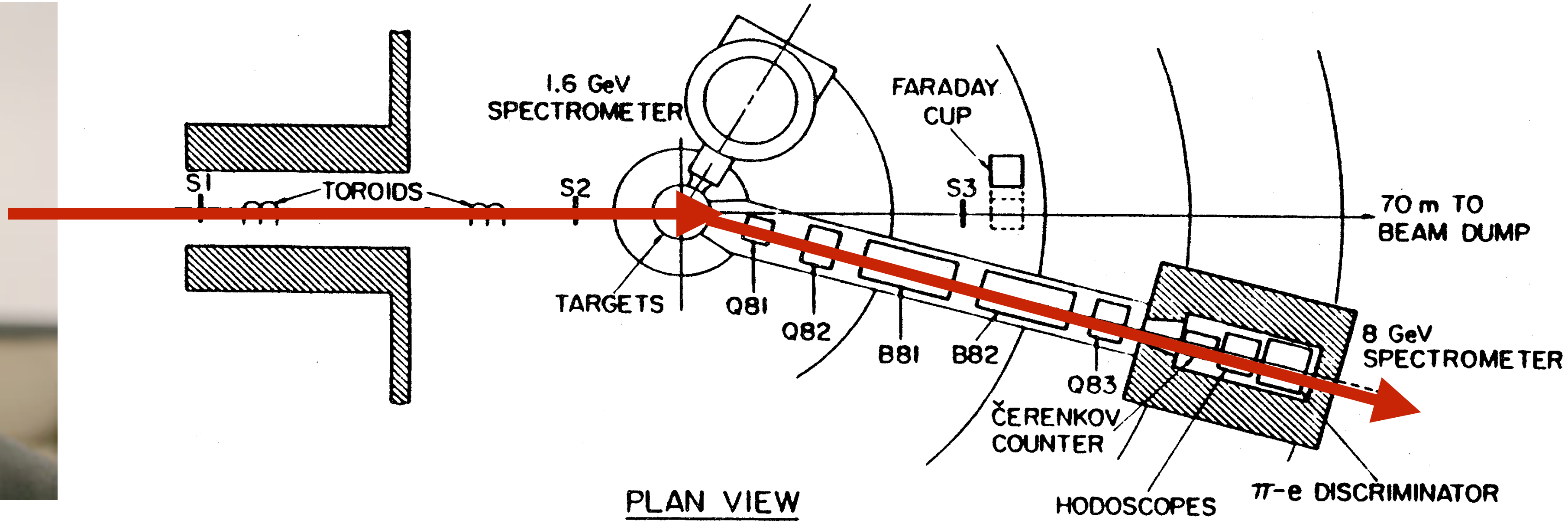
1967

SLAC Two-Mile Linear Accelerator

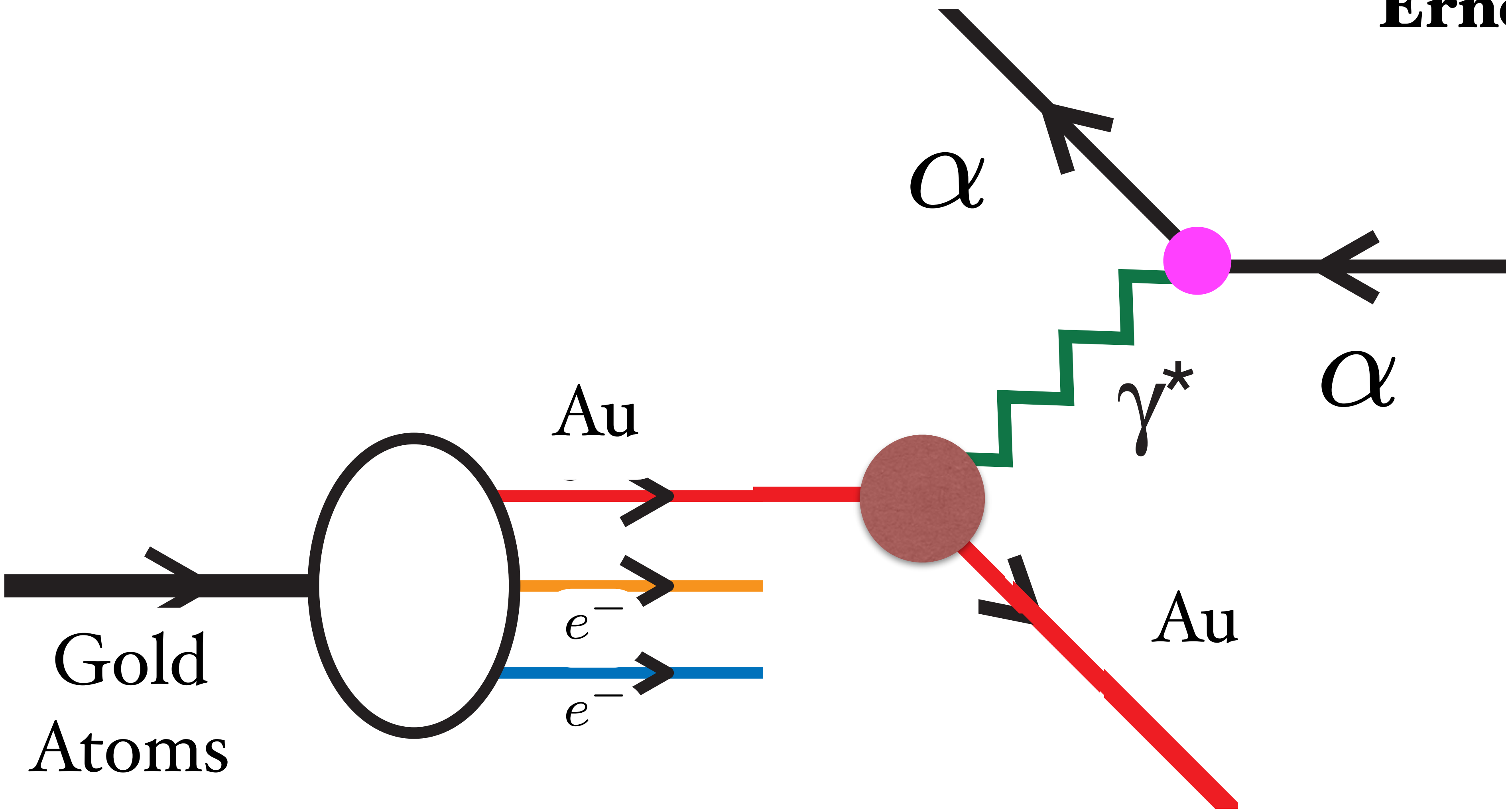


Pief



First Evidence for Nuclear, Composite Structure of Atoms

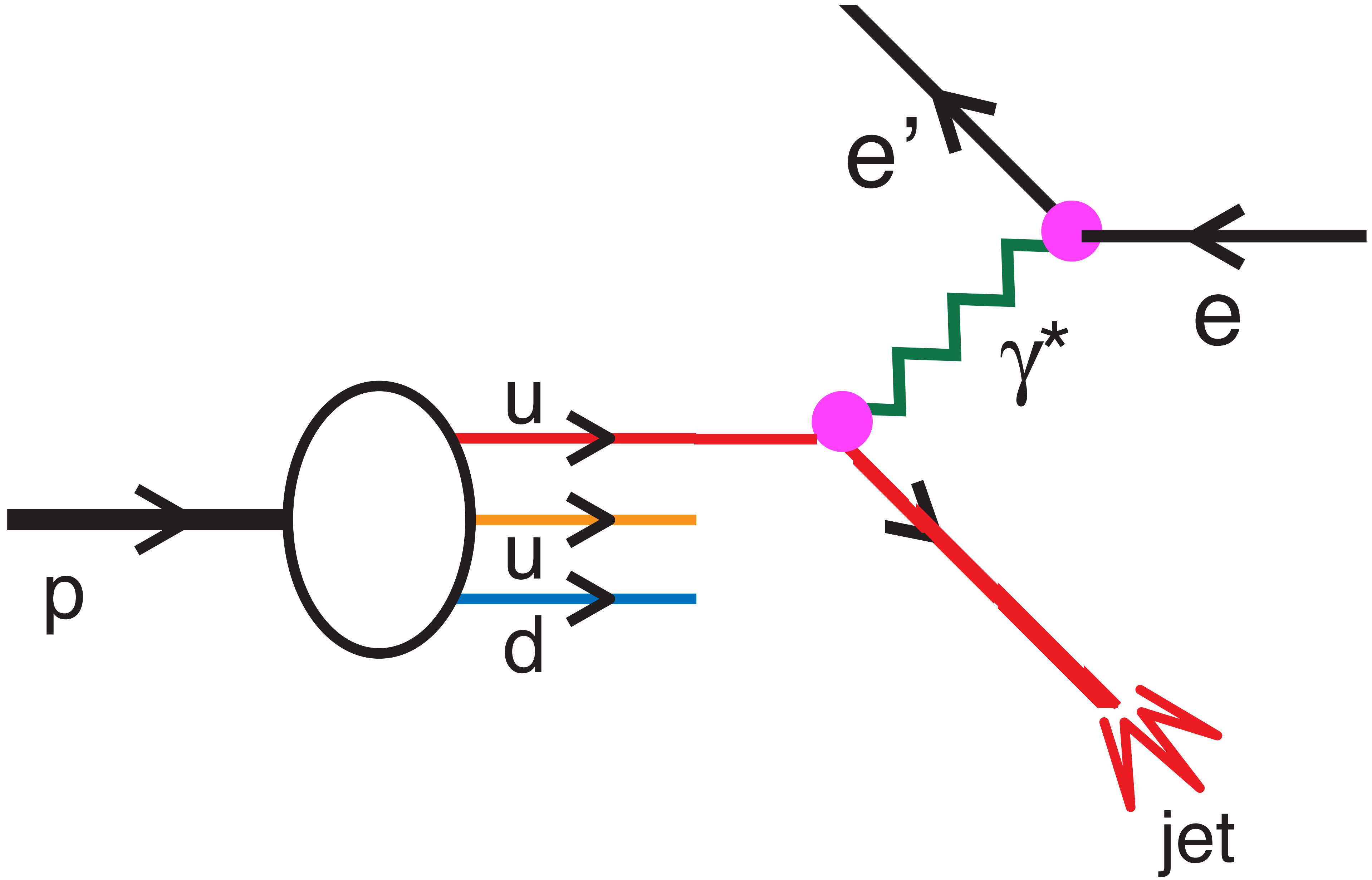
Ernest Rutherford
1911



Scattering at Large Angles!
"Point-like" Nucleus

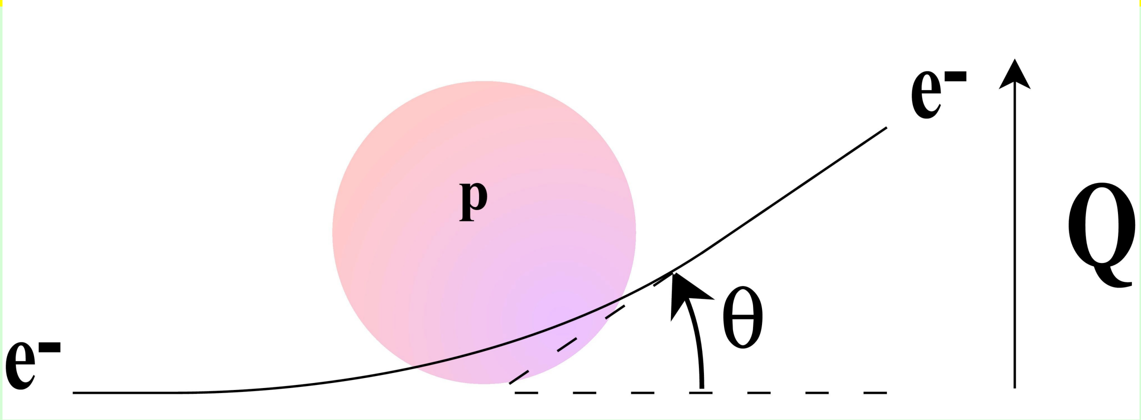
Rutherford Scattering

SLAC 1967: First Evidence for Quark Structure of Matter



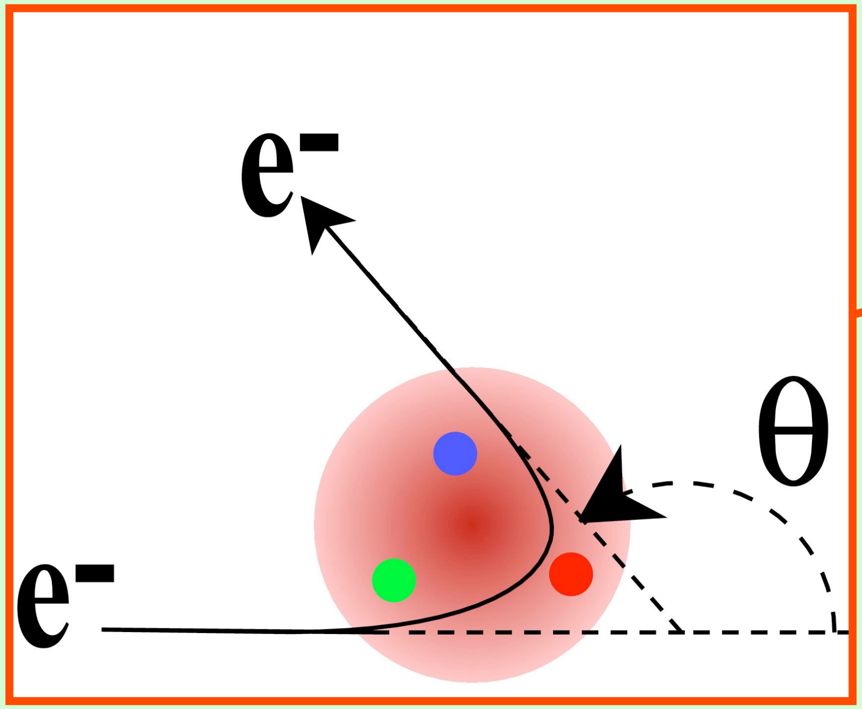
Deep Inelastic Electron-Proton Scattering

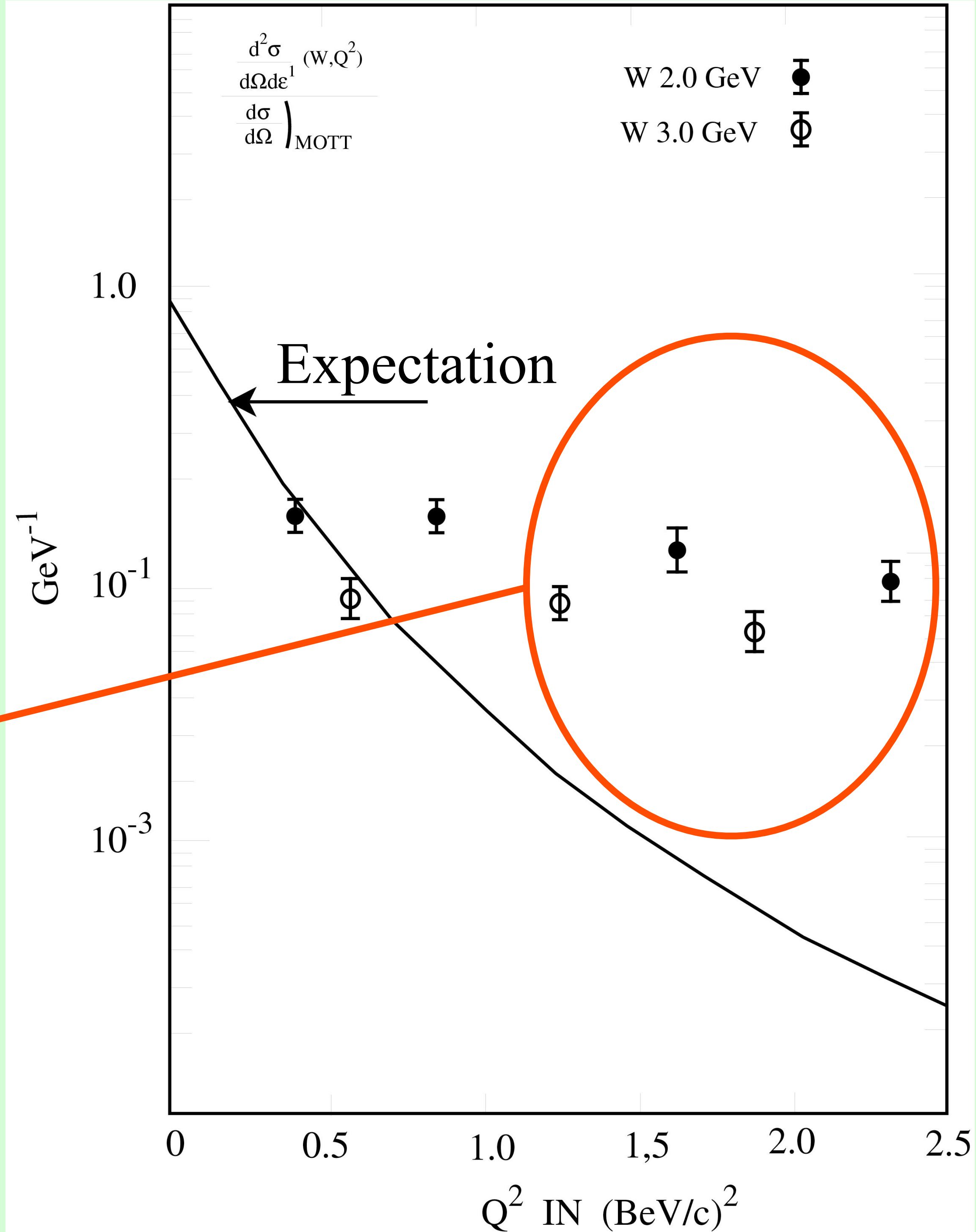
Deep inelastic electron-proton scattering



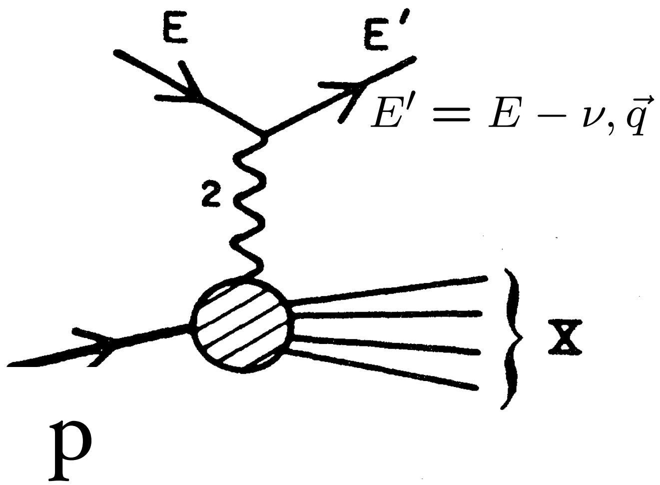
- Rutherford scattering using *very* high-energy electrons striking protons

Discovery of quarks!



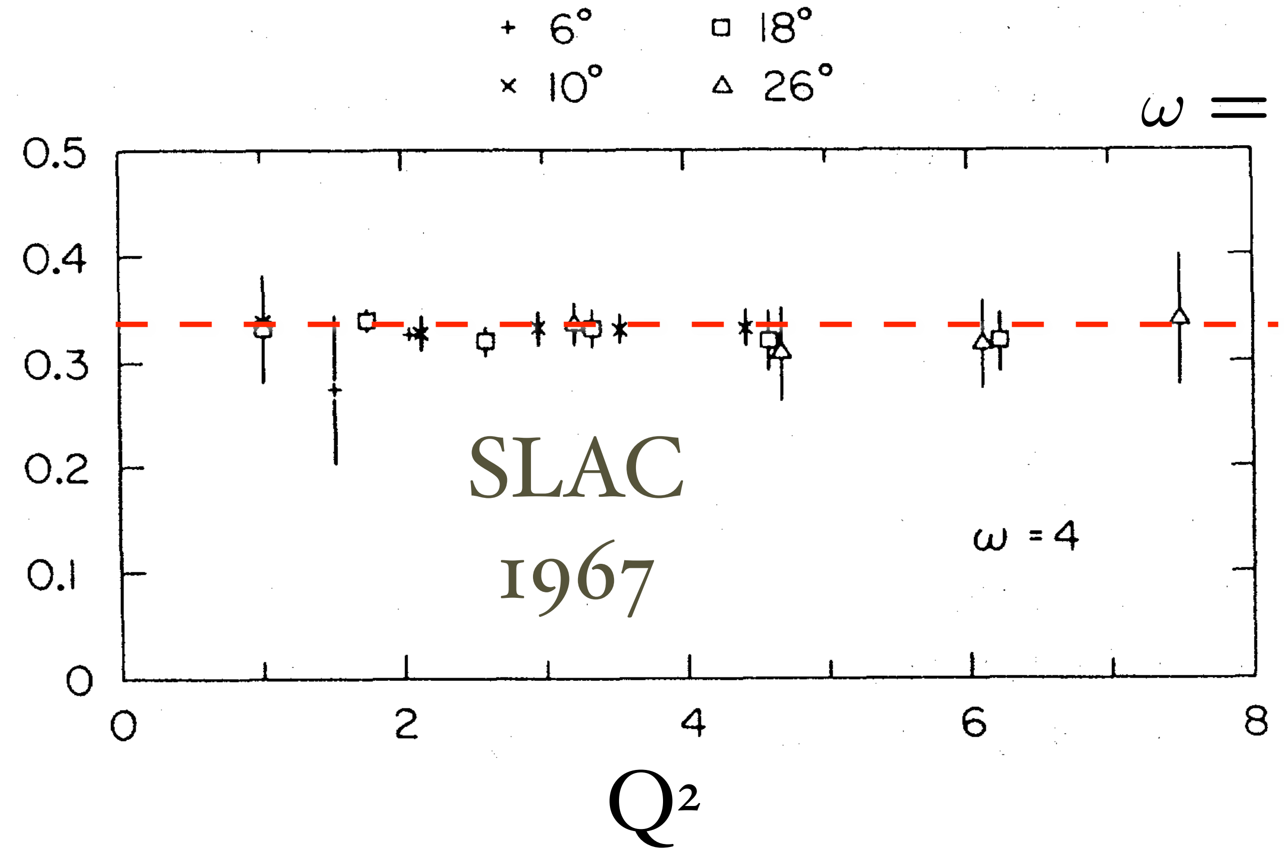


$$ep \longrightarrow e'X$$



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

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



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

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!

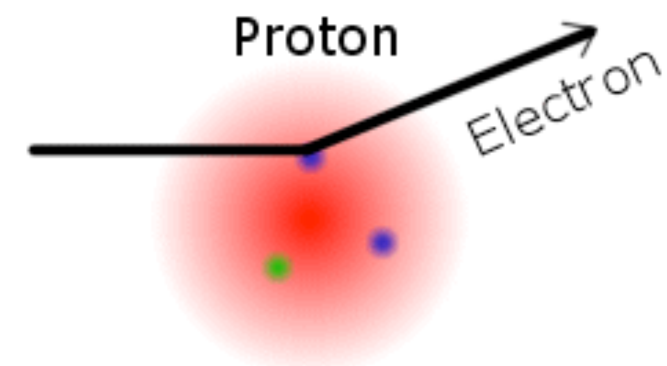
$Q^4 \times \frac{d\sigma}{dQ^2} = F(x_{Bj})$ independent of Q^2 *Scale-free*

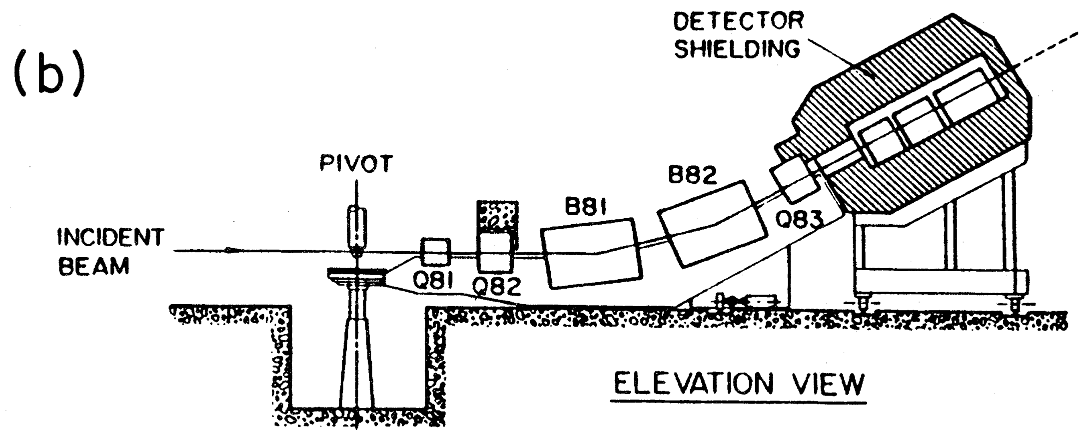
1967 SLAC Experiment:

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

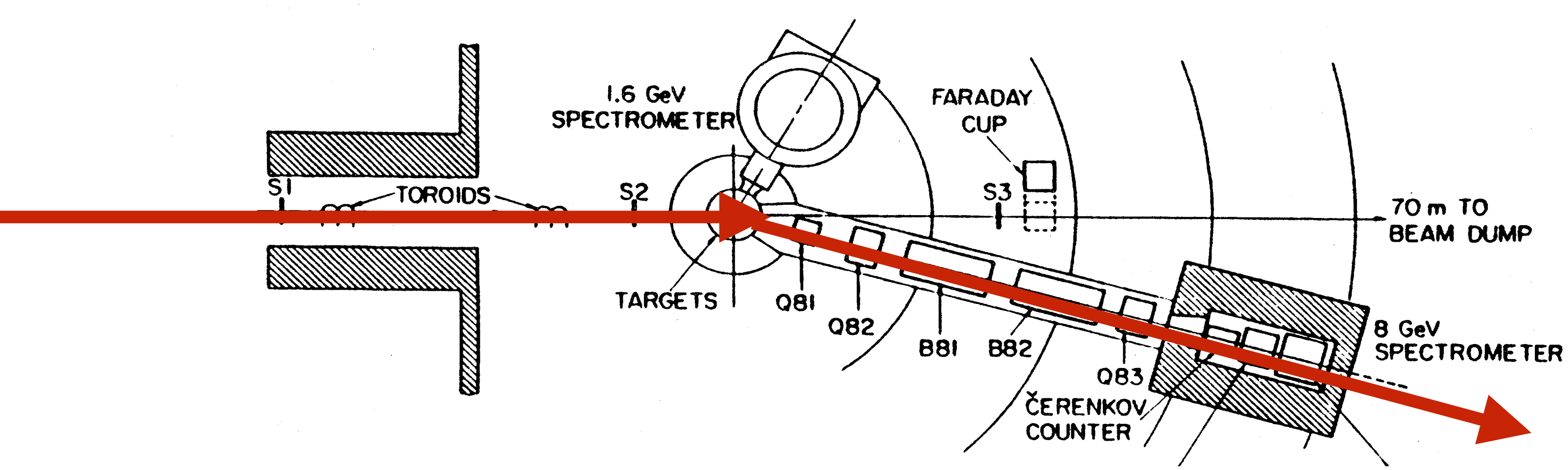
Discovery of the Quark Structure of Matter

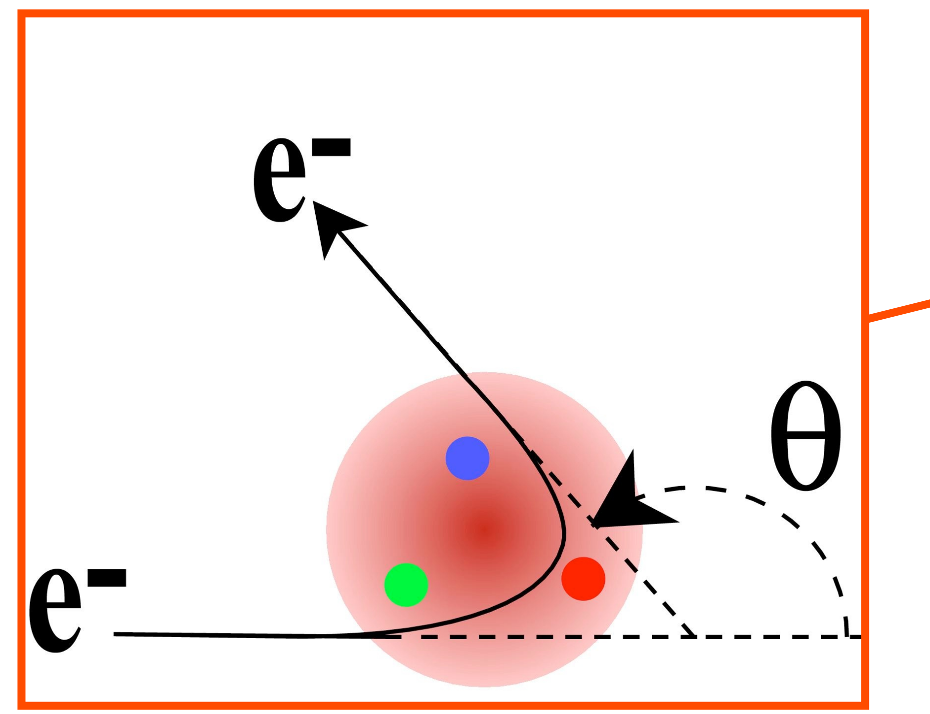
$$ep \longrightarrow e'X$$





Discovery of quarks!





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

Friedman, Kendall, Taylor: 1990 Nobel Prize

Quarks + Scaling

Friedman

Kendall

Taylor

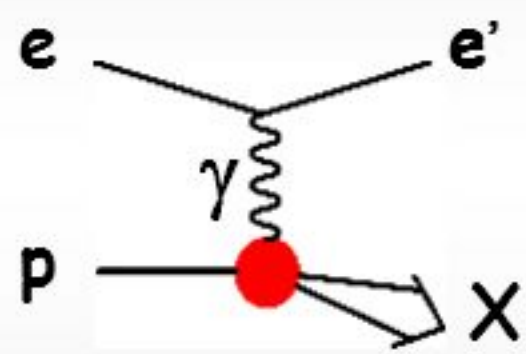
Nobel Prize

1990

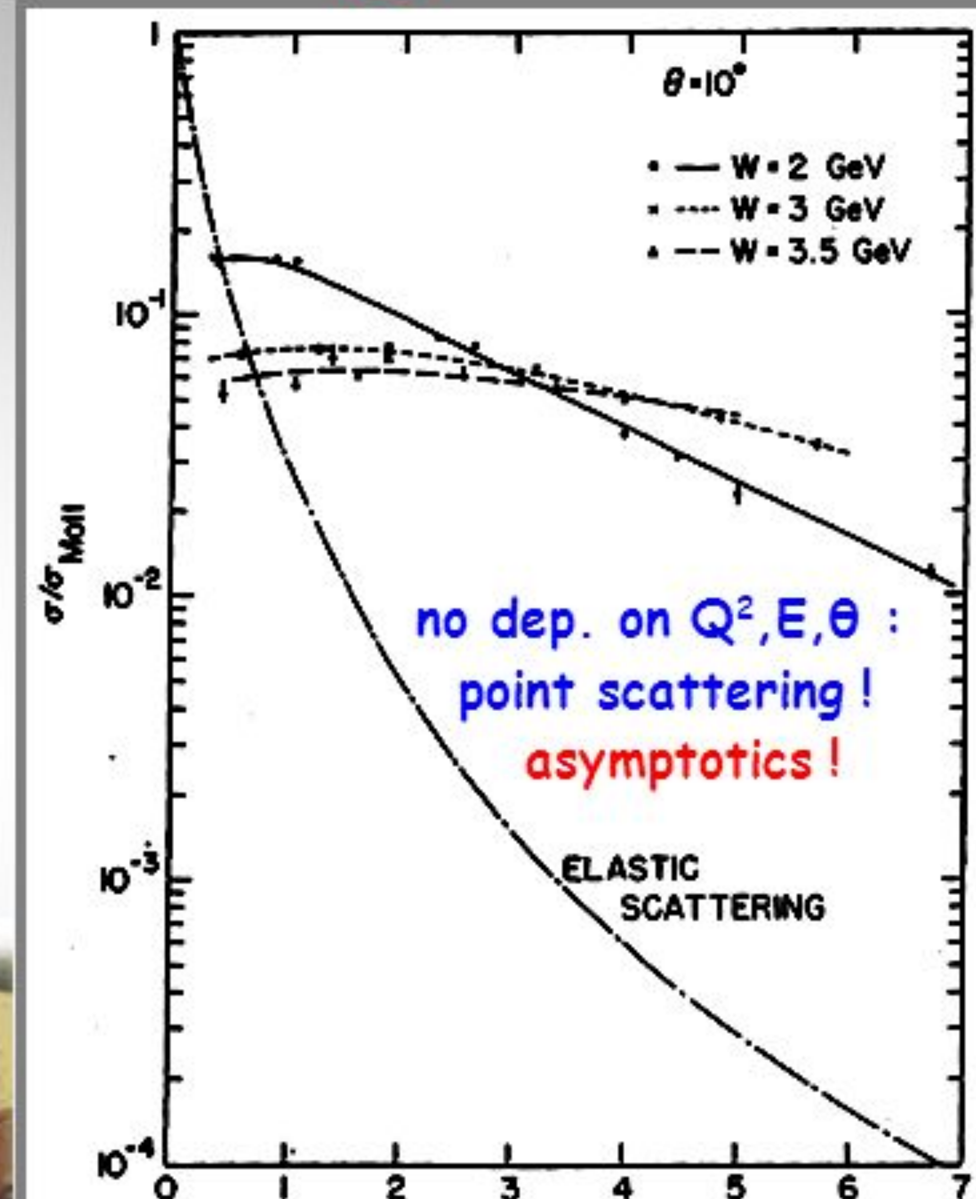
Stanford Linear Accelerator

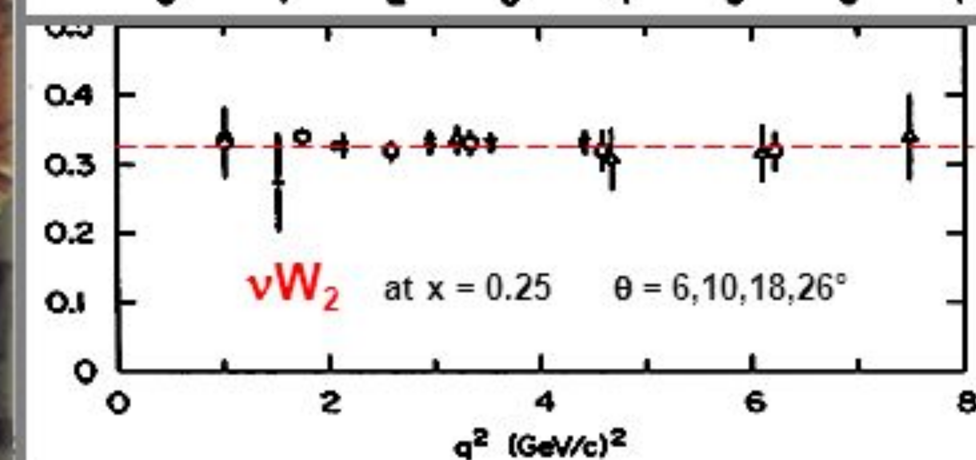
1967-1971

Electron-Proton Deep Inelastic Scattering

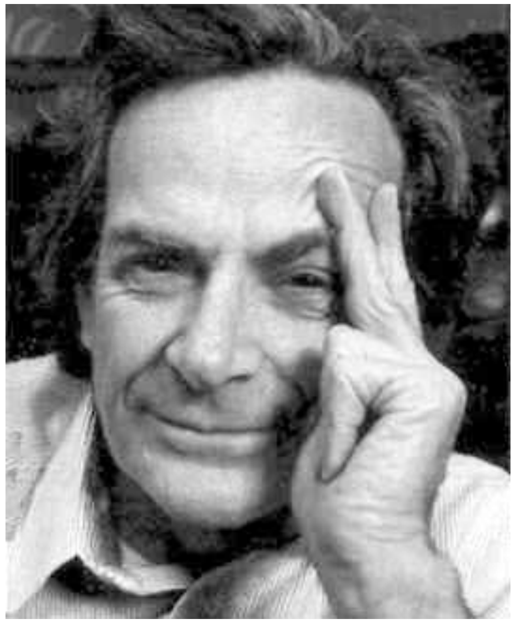


E = 1.5 - 20 GeV
θ = 6° - 26°
Q^2 = 1 - 7 GeV^2





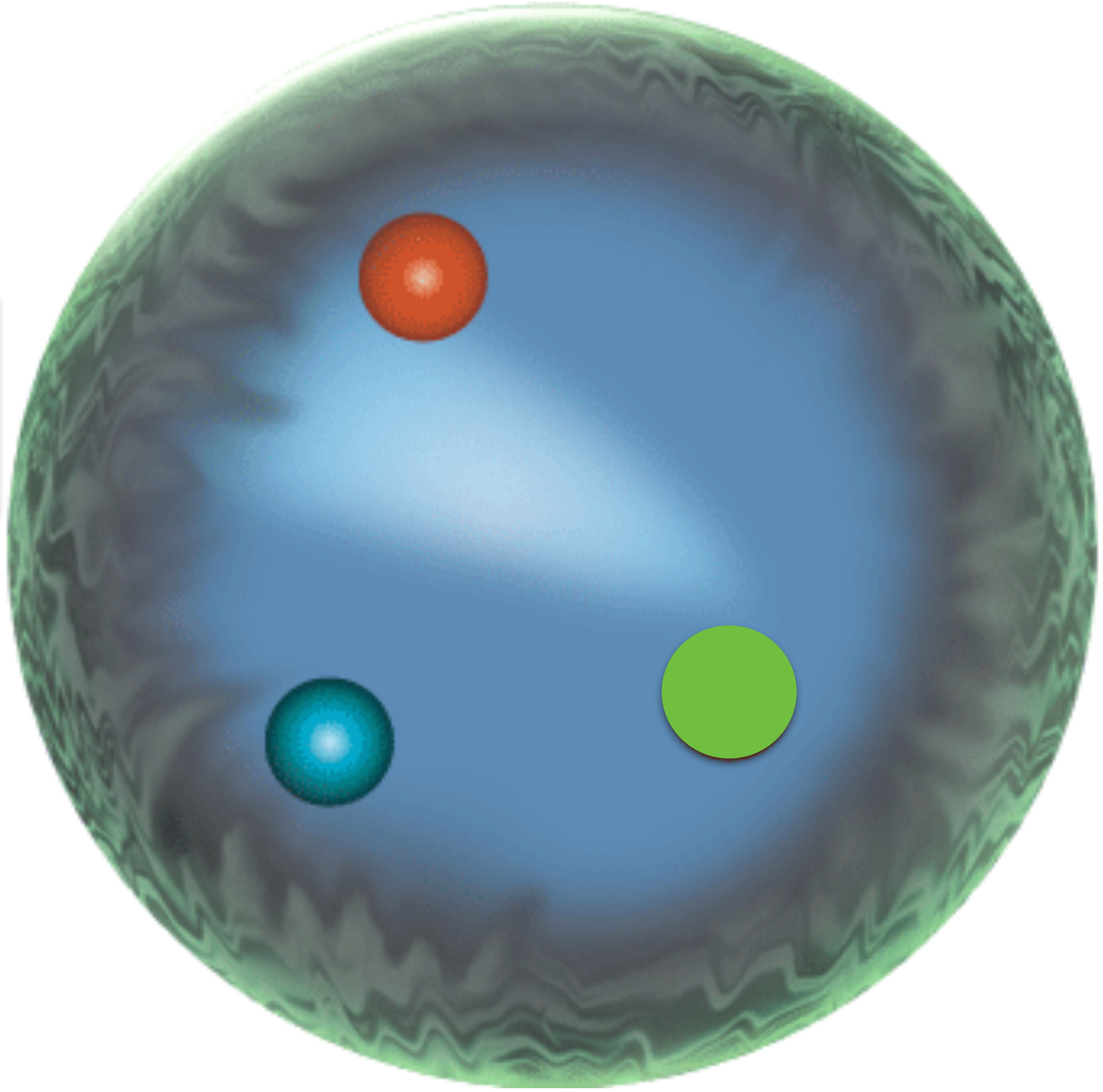
Quarks in the Proton



Feynman: "Parton" model

Bjorken: Scaling

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



$$1\,fm$$

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

Zweig: "Aces, Deuces, Treys"

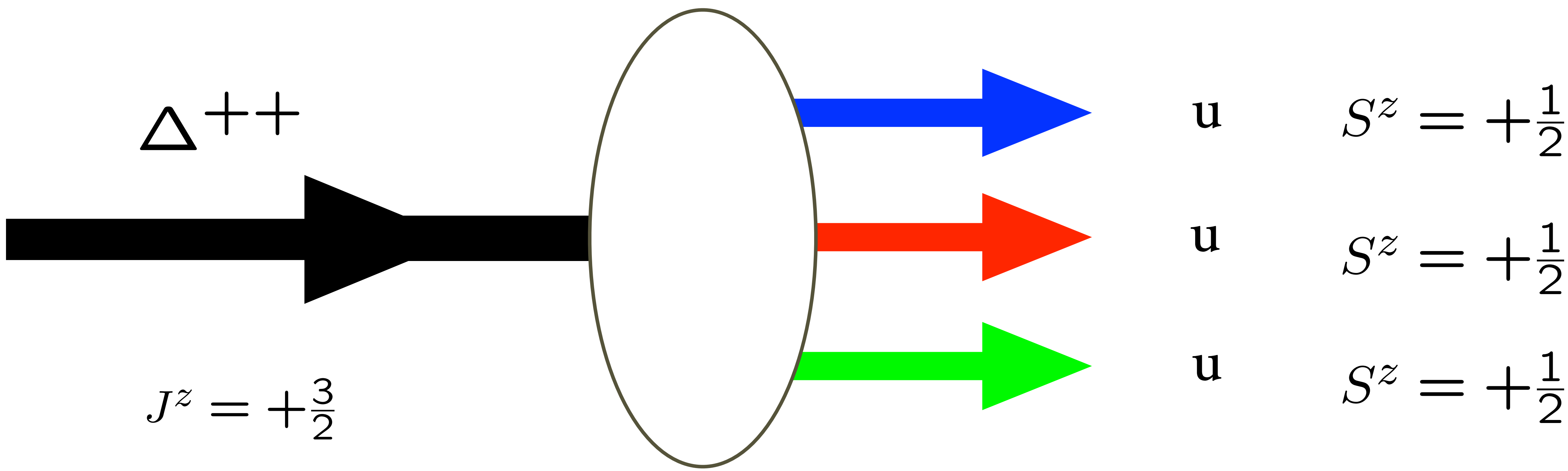
Gell Mann: "Three Quarks for Mr. Mark"

Why are there three colors of quarks?

Greenberg

Pauli Exclusion Principle!

spin-half quarks cannot be in same quantum state !

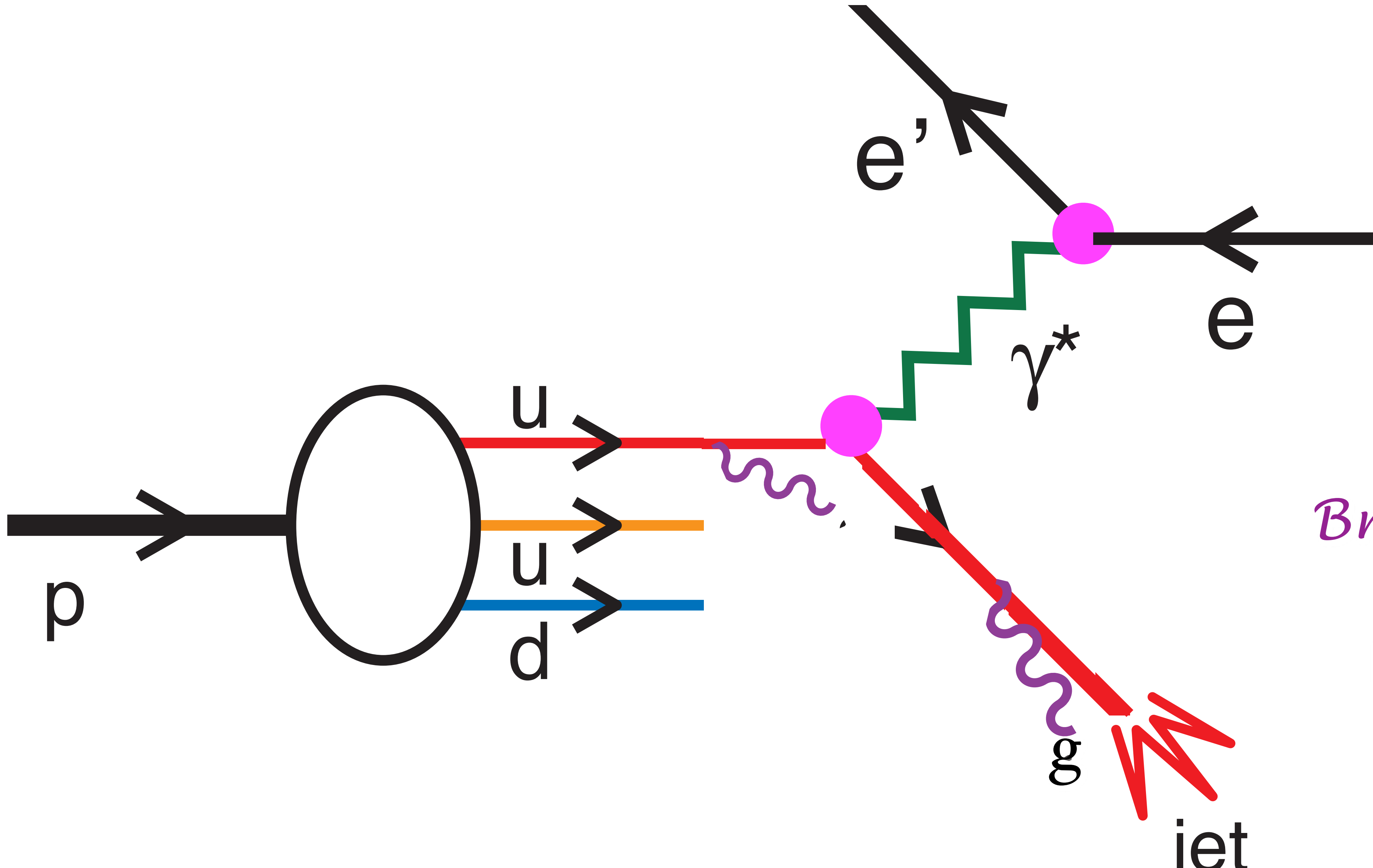


Three Colors (Parastatistics) Solves Paradox

3 Colors Combine : WHITE

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

First Evidence for Quark Structure of Matter



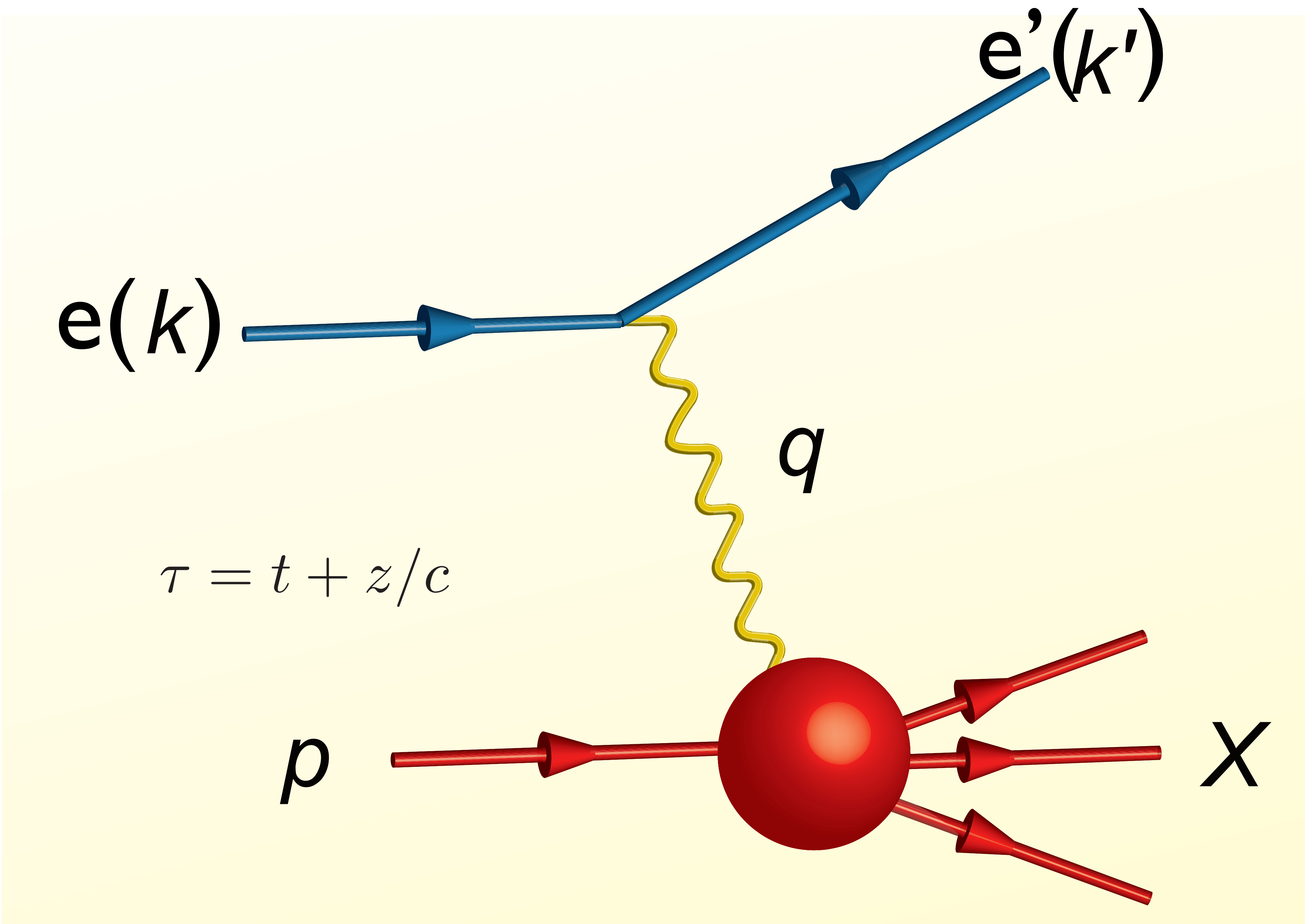
Gluonic Bremsstrahlung

DGLAP Evolution

Deep Inelastic Electron-Proton Scattering

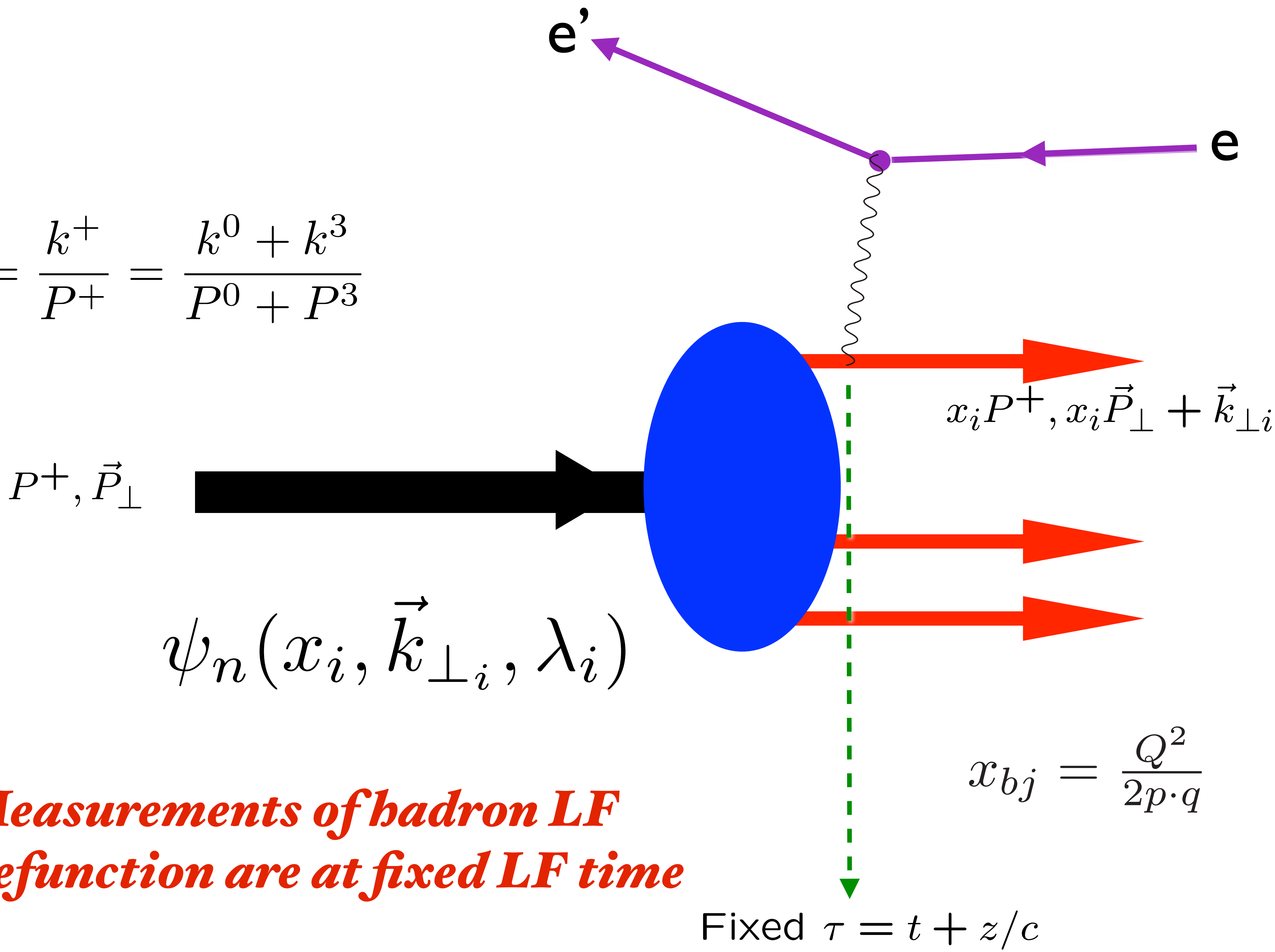
But why don't quark and gluons appear in the final state ?
How are they confined within hadrons?
How is the propagation of quarks and gluons affected by the nuclear environment?

Causality: Information and correlations constrained by speed of light



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

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



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

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

Measurements of hadron LF wavefunction are at fixed LF time

Like a flash photograph!

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

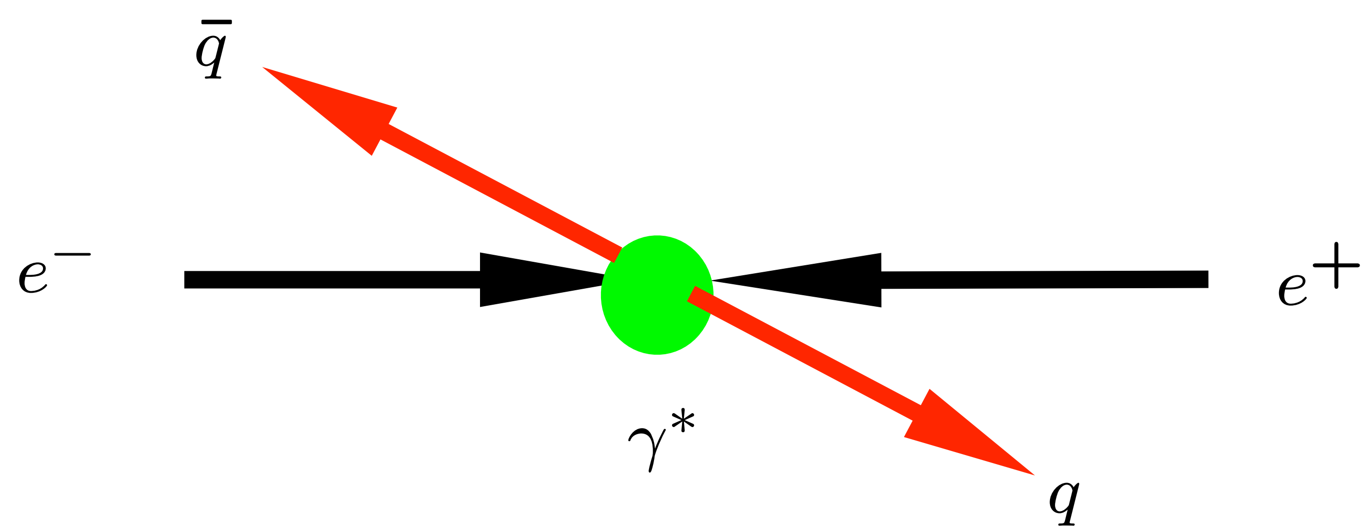
Frame Independent : Poincarè Invariance

SPEAR Electron-Positron Collider SLAC 1972

Burt Richter

Martin Perl

Electron-Positron Annihilation

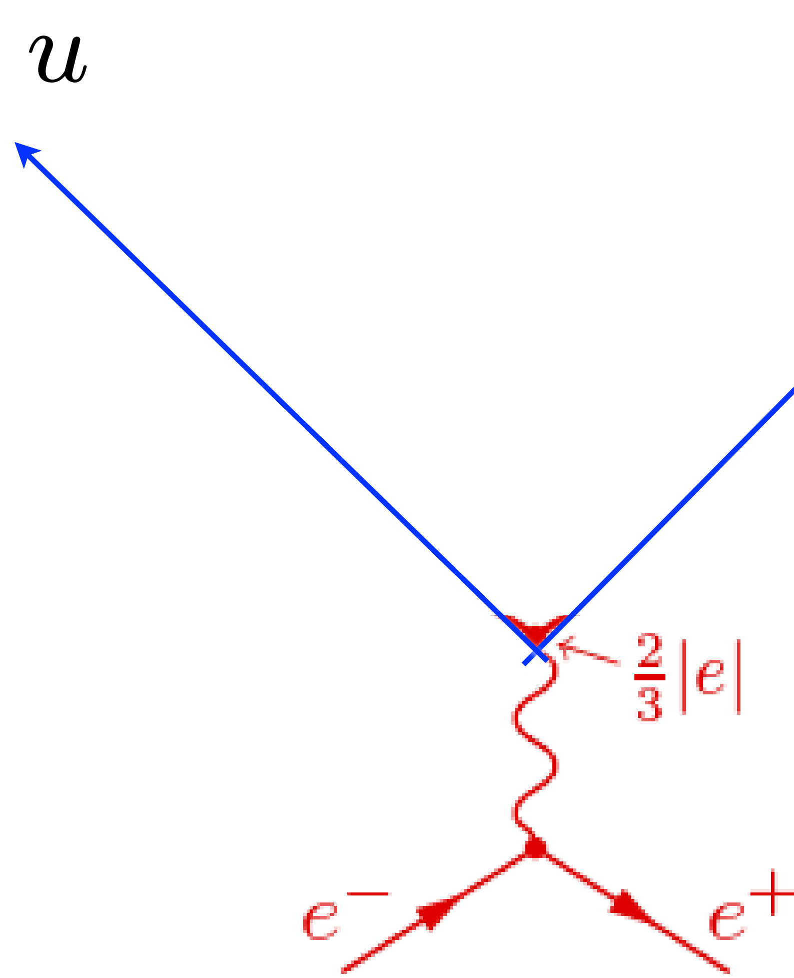


$$e^+e^- \to \gamma^* \to q\bar{q}$$

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

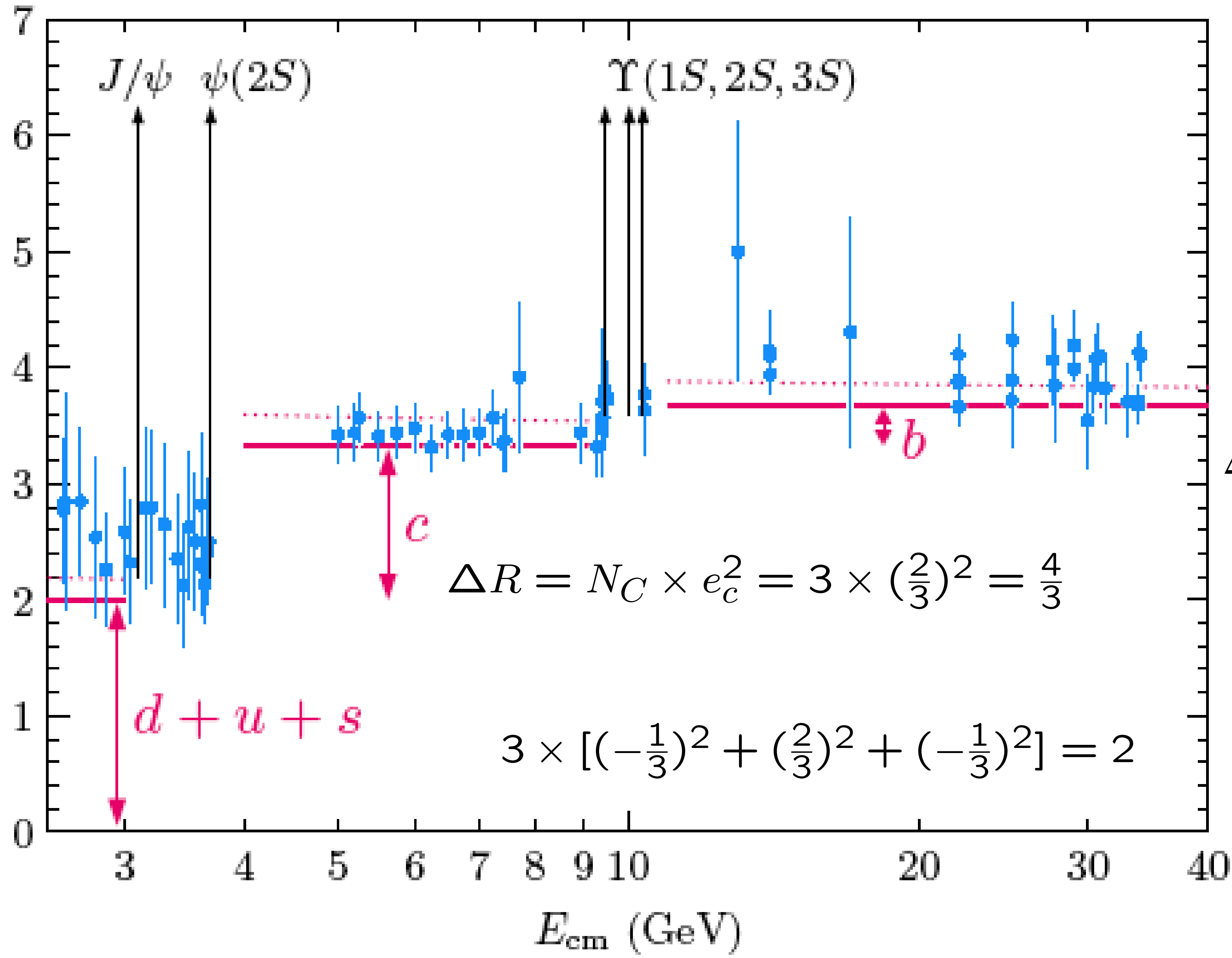
$$\frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-} = \underset{\substack{\uparrow \\ \text{colors}}}{3} \times \left[\underset{\substack{\uparrow \\ d}}{\left(\frac{1}{3}\right)^2} + \underset{\substack{\uparrow \\ u}}{\left(\frac{2}{3}\right)^2} + \underset{\substack{\uparrow \\ s}}{\left(\frac{1}{3}\right)^2}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

How to Count Quarks

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

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

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



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

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

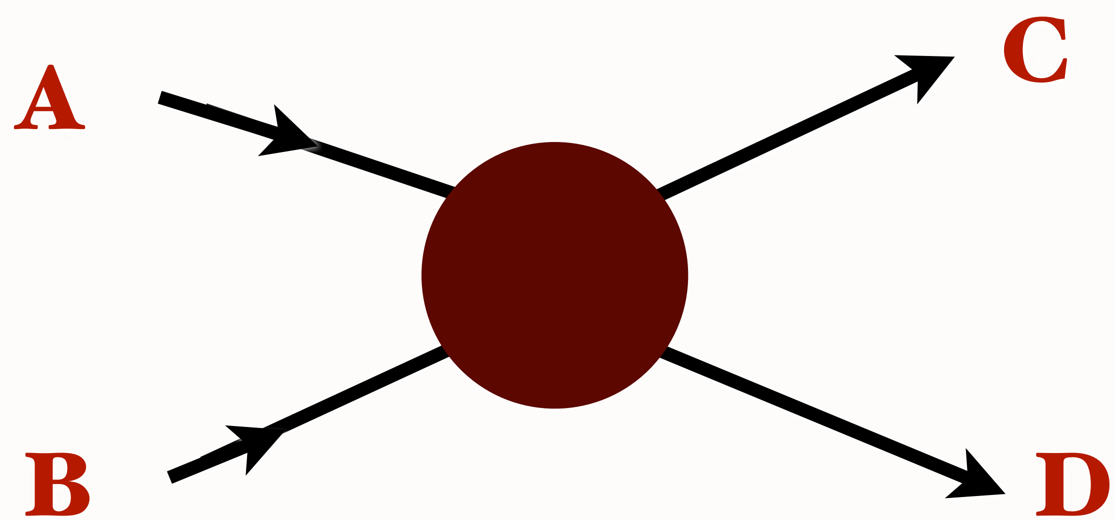
$$\boxed{N_C = 3}$$

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

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

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

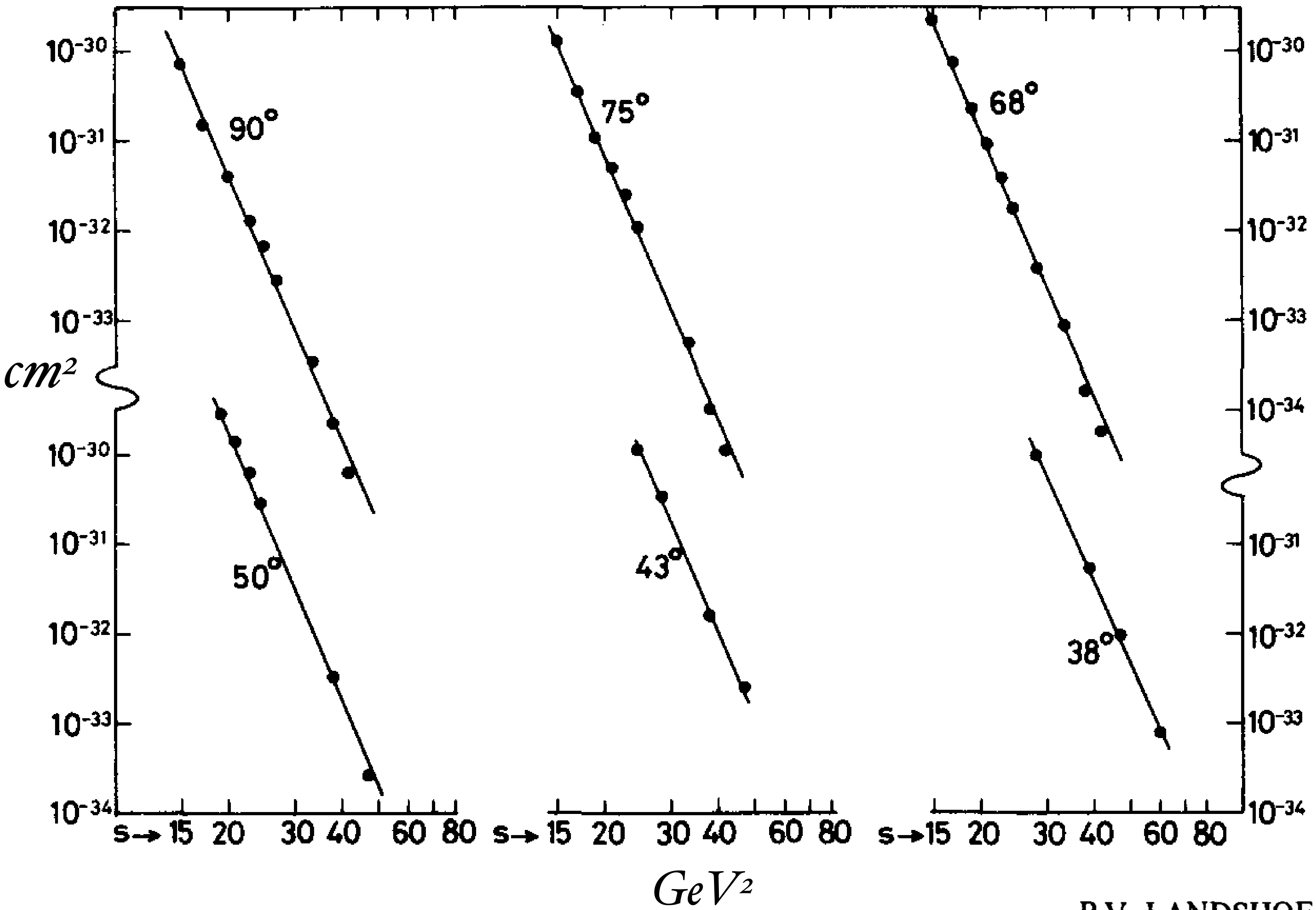
$$n_{tot} = n_A + n_B + n_C + n_D$$



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

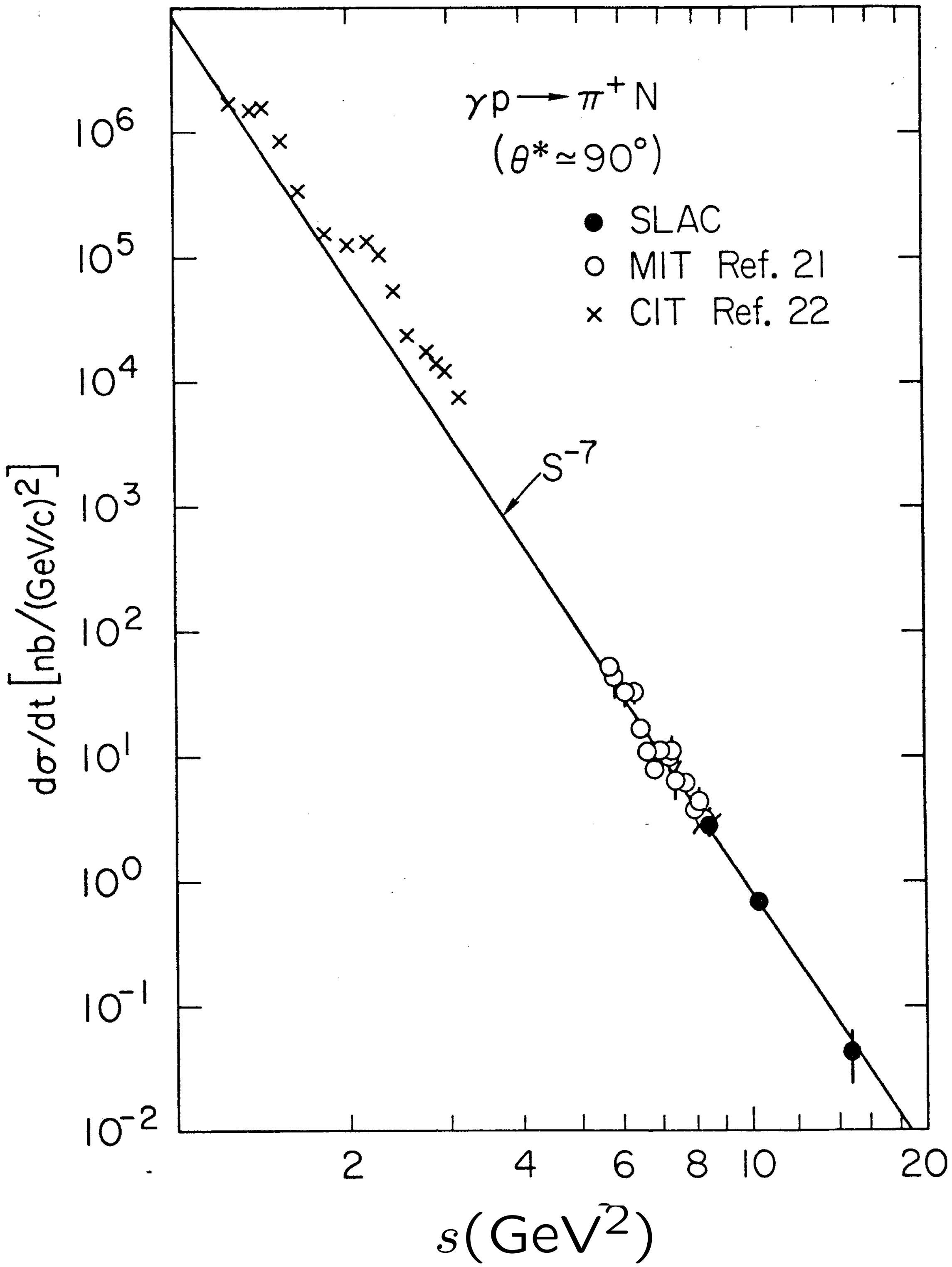


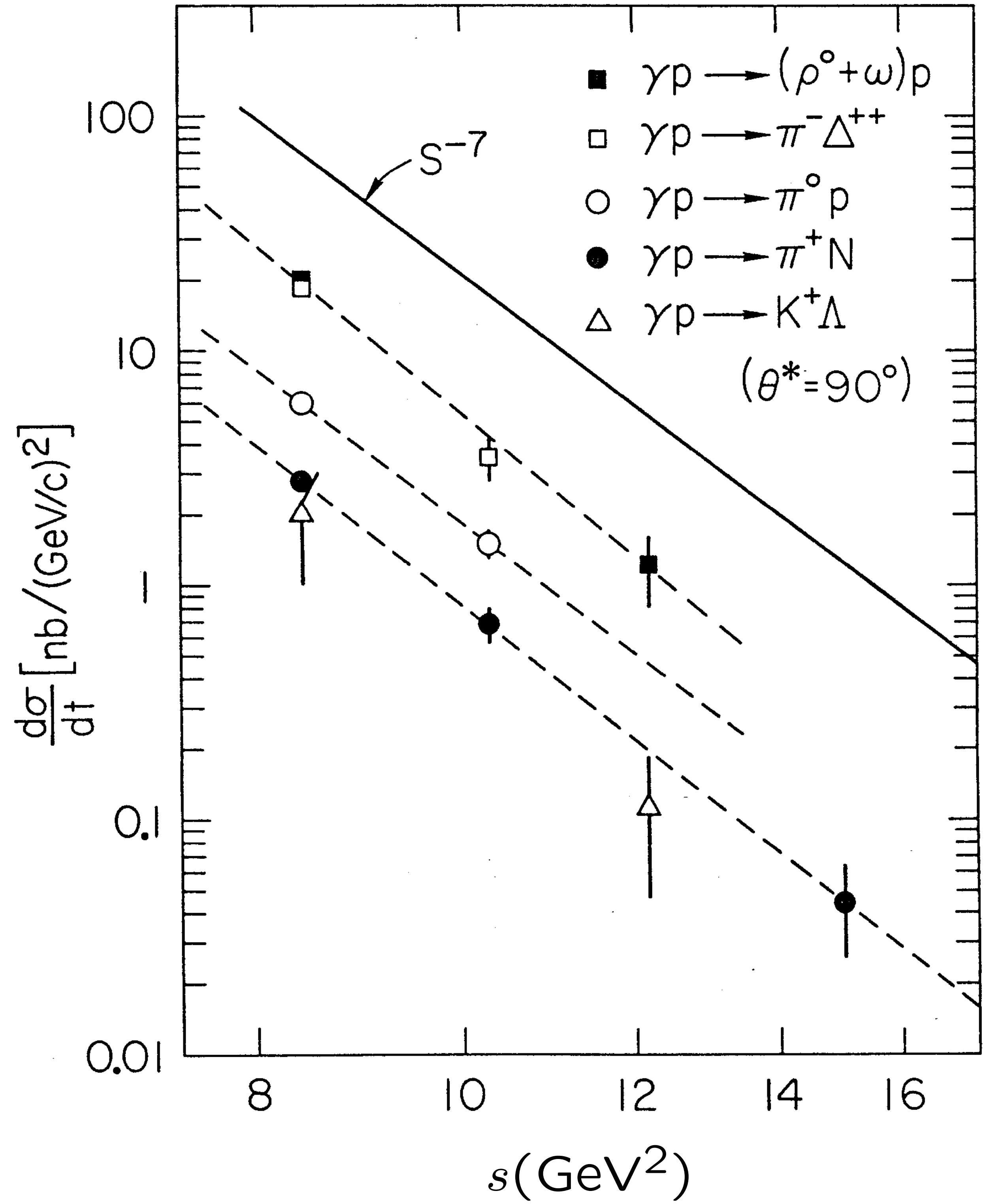
P.V. LANDSHOFF and J.C. POLKINGHORNE

Best Fit

$n = 9.7 \pm 0.5$

Reflects underlying conformal, scale-free interactions

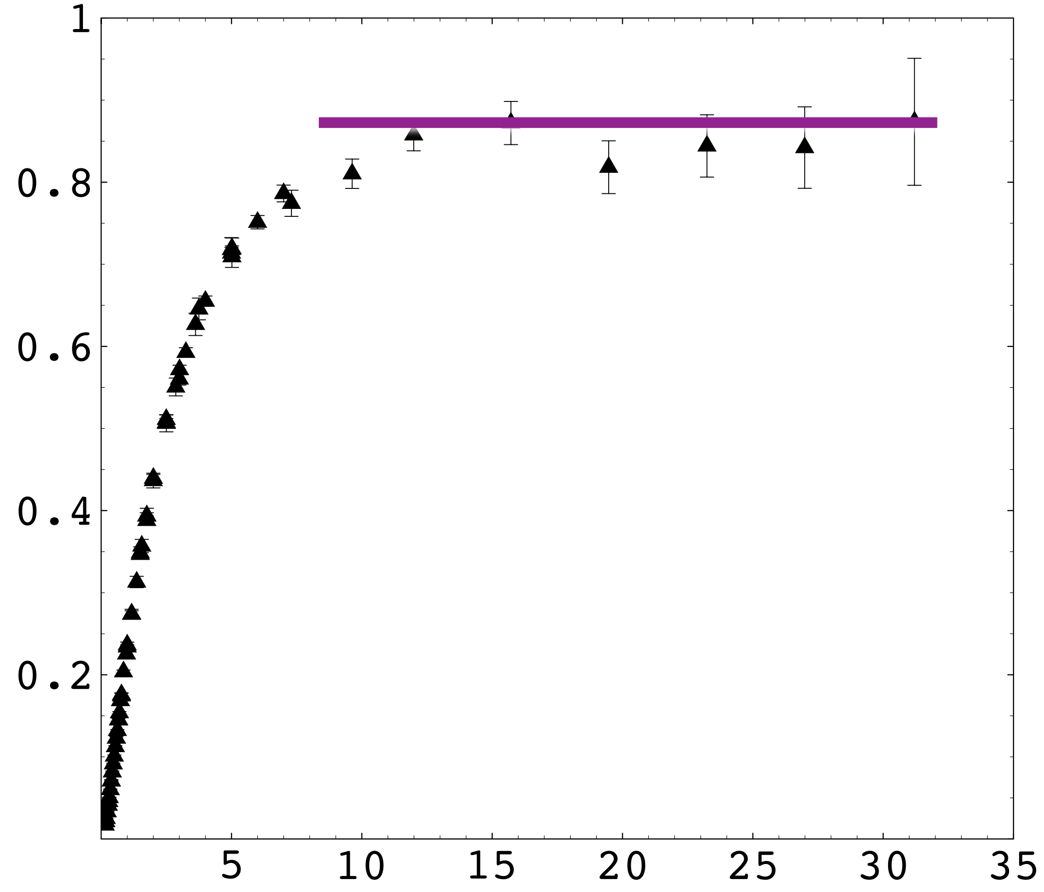




Counting Rules: N=9

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

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

QCD Lagrangian

Quantum Chromodynamics

gluon dynamics

quark kinetic energy + quark-gluon dynamics

mass term

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

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

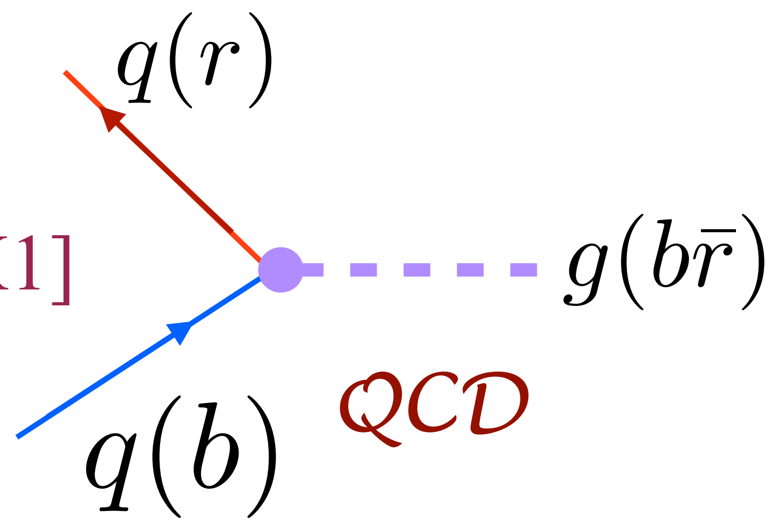
Yang Mills Gauge Principle: Color Rotation and Phase Invariance at Every Point of Space and Time

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

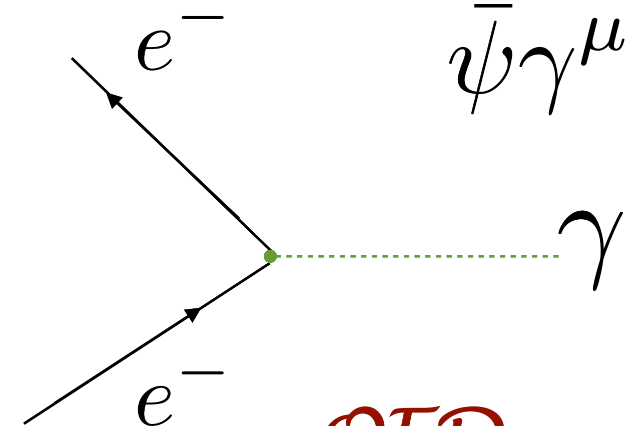
Fundamental Couplings of QCD and QED

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

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



QCD



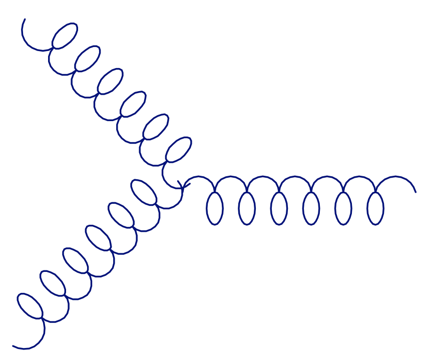
$$\bar{\psi}\gamma^{\mu}A^{\mu}\bar{\psi}$$

QED

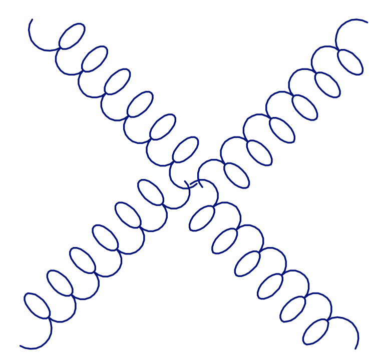
$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_{\mu}\gamma^{\mu}\Psi_f + \sum_{f=1}^{n_f} m_f\bar{\Psi}_f\Psi_f$$

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

Gluon vertices

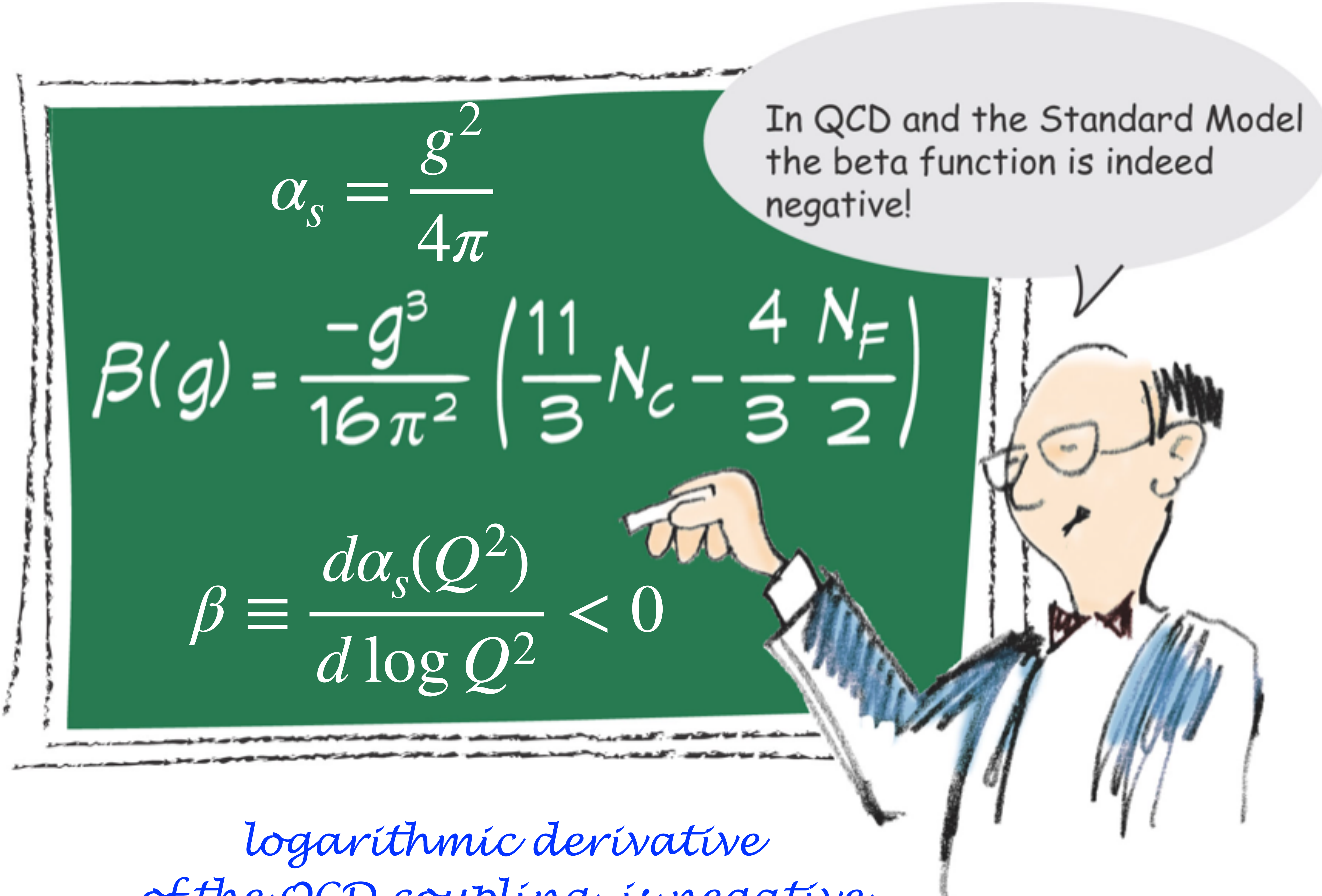


QCD



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

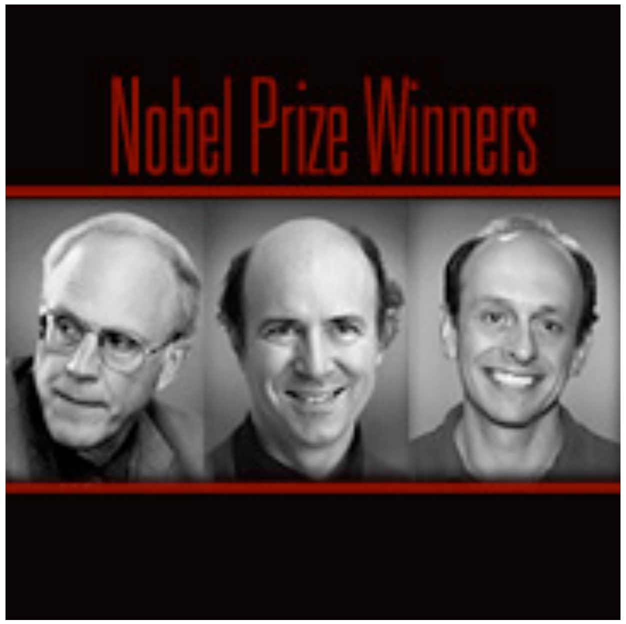
gluon self couplings



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

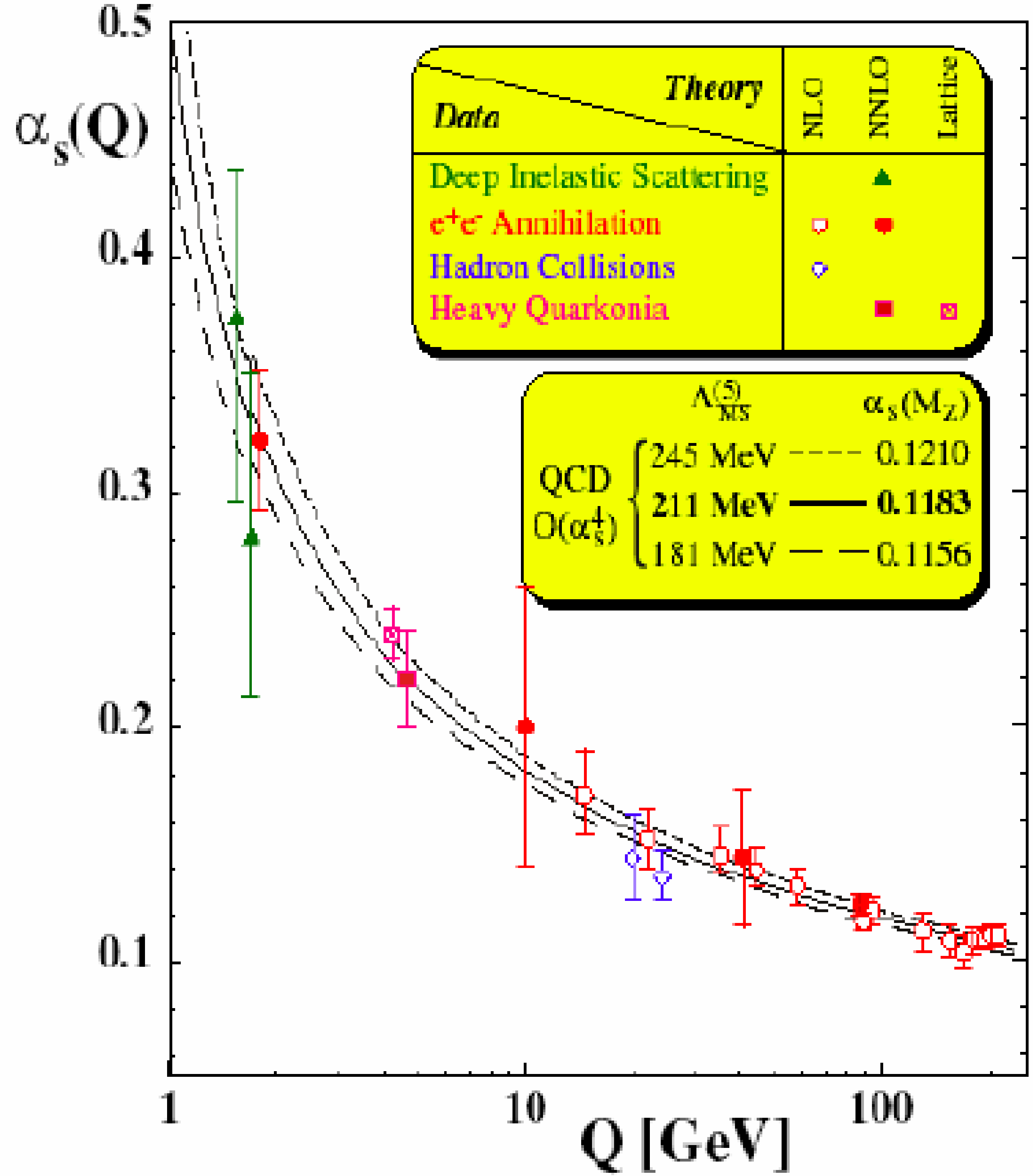
Verification of Asymptotic Freedom

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



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

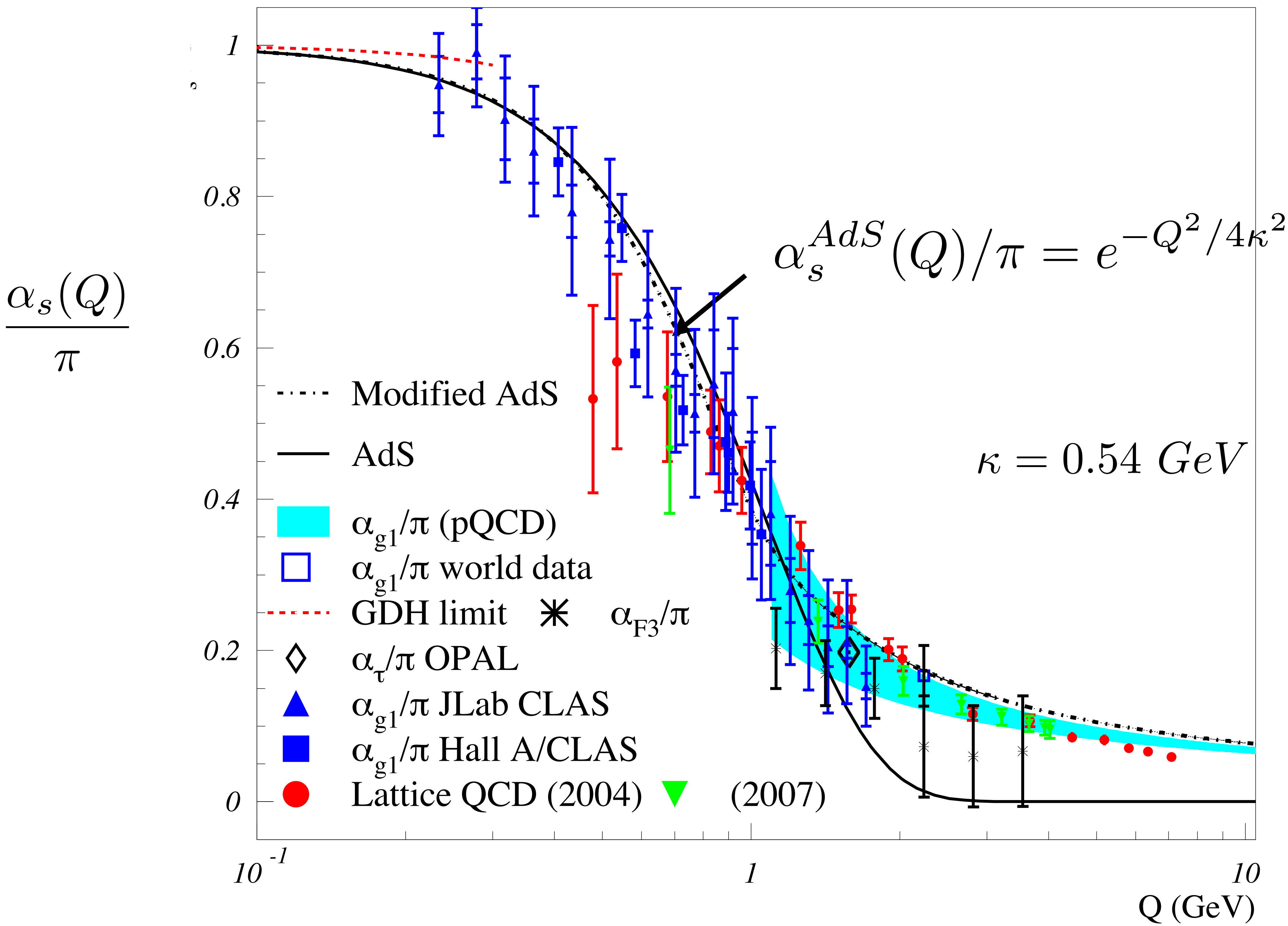
proportional to $\alpha_s(Q)$



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

Running Coupling from Light-Front Holography and AdS/QCD

Analytic, defined at all scales, IR Fixed Point



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

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

Deur, de Téramond, sjb

Deur, de Tèramond, sjb

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

$$m_p = 2\kappa$$

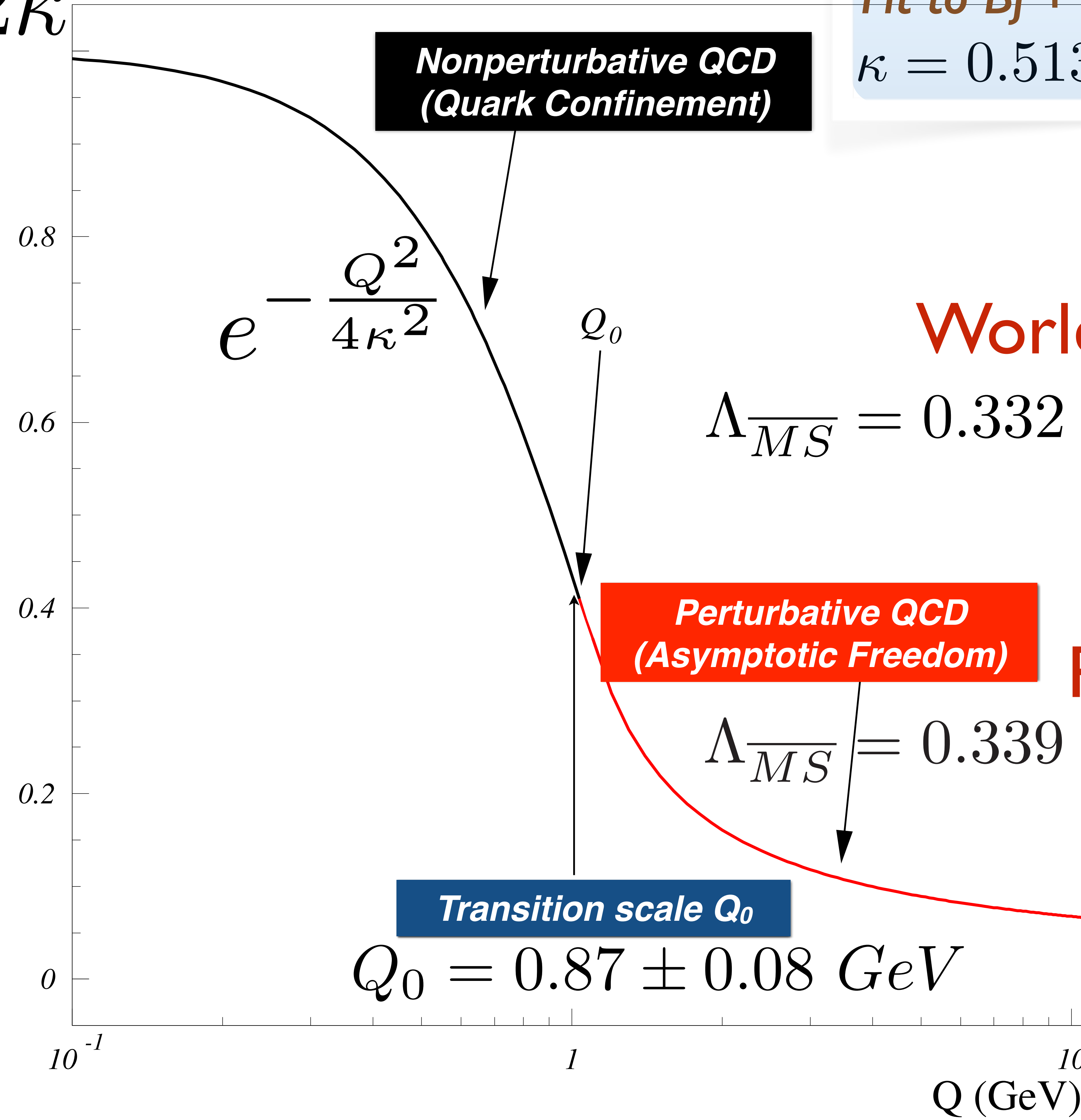
All-Scale QCD Coupling

Fit to Bj + DHG Sum Rules:

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

$$\frac{\alpha^s_{g_1}(Q^2)}{\pi}$$

$$e^{-\frac{Q^2}{4\kappa^2}}$$



World Data:

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

Prediction

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

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

$\overline{MS}$ scheme

Running Coupling from Light-Front Holography and AdS/QCD

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

Huet, sjb

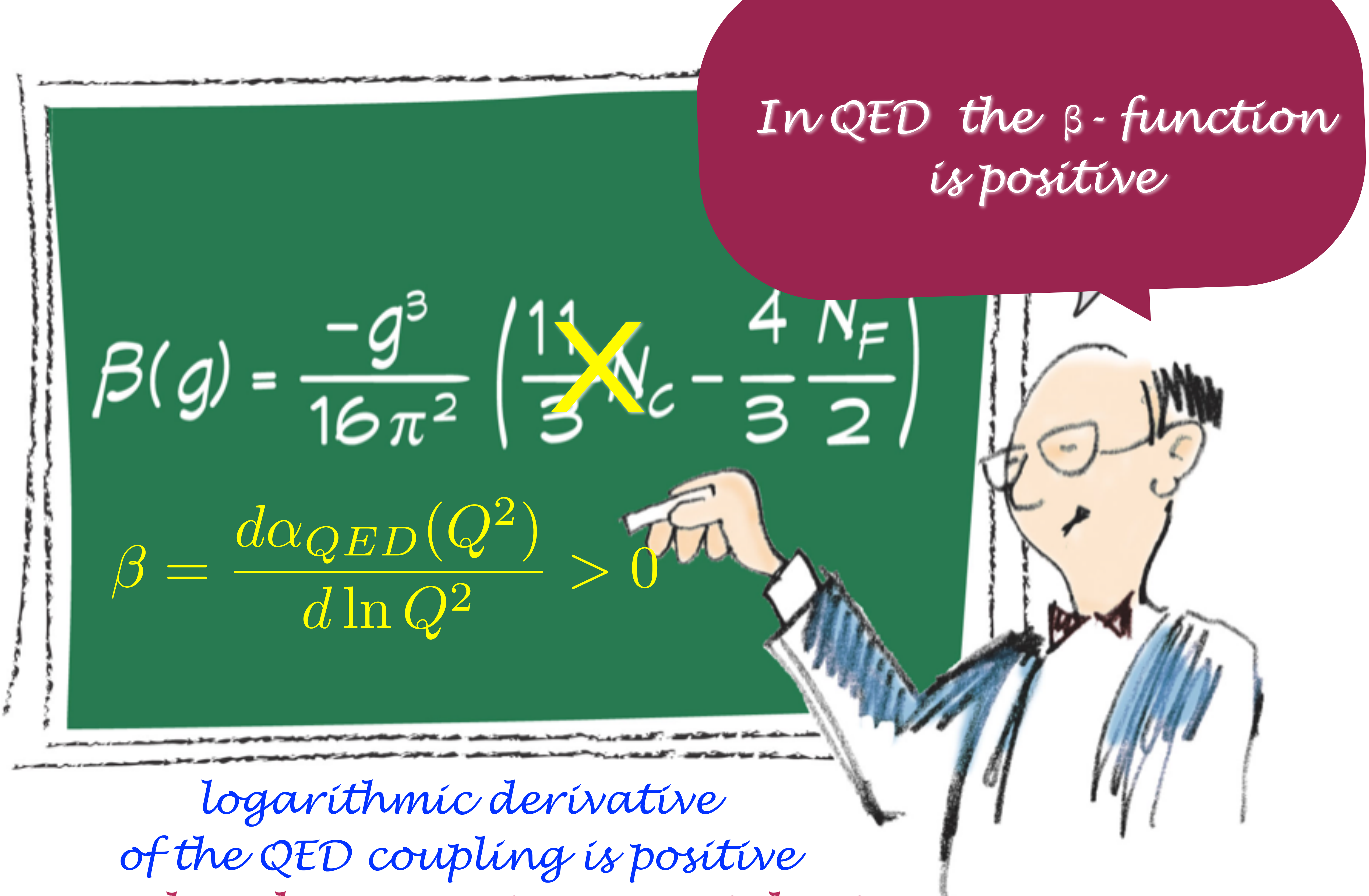
$$\lim N_C \to 0 \text{ at fixed } \alpha = C_F \alpha_s, n_\ell = n_F / C_F$$

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

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

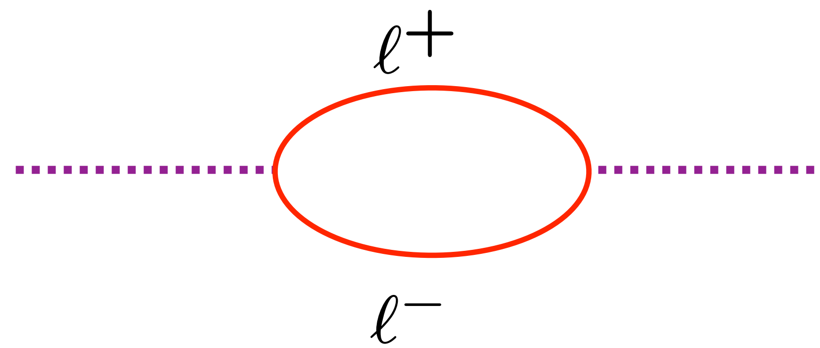


$$\beta = \frac{d\alpha_{QED}(Q^2)}{d\ln Q^2} > 0$$

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

Landau Pole!

QED One-Loop Vacuum Polarization



$t = -Q^2 < 0$

(t spacelike)

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

Analytically continue to timelike t: Complex

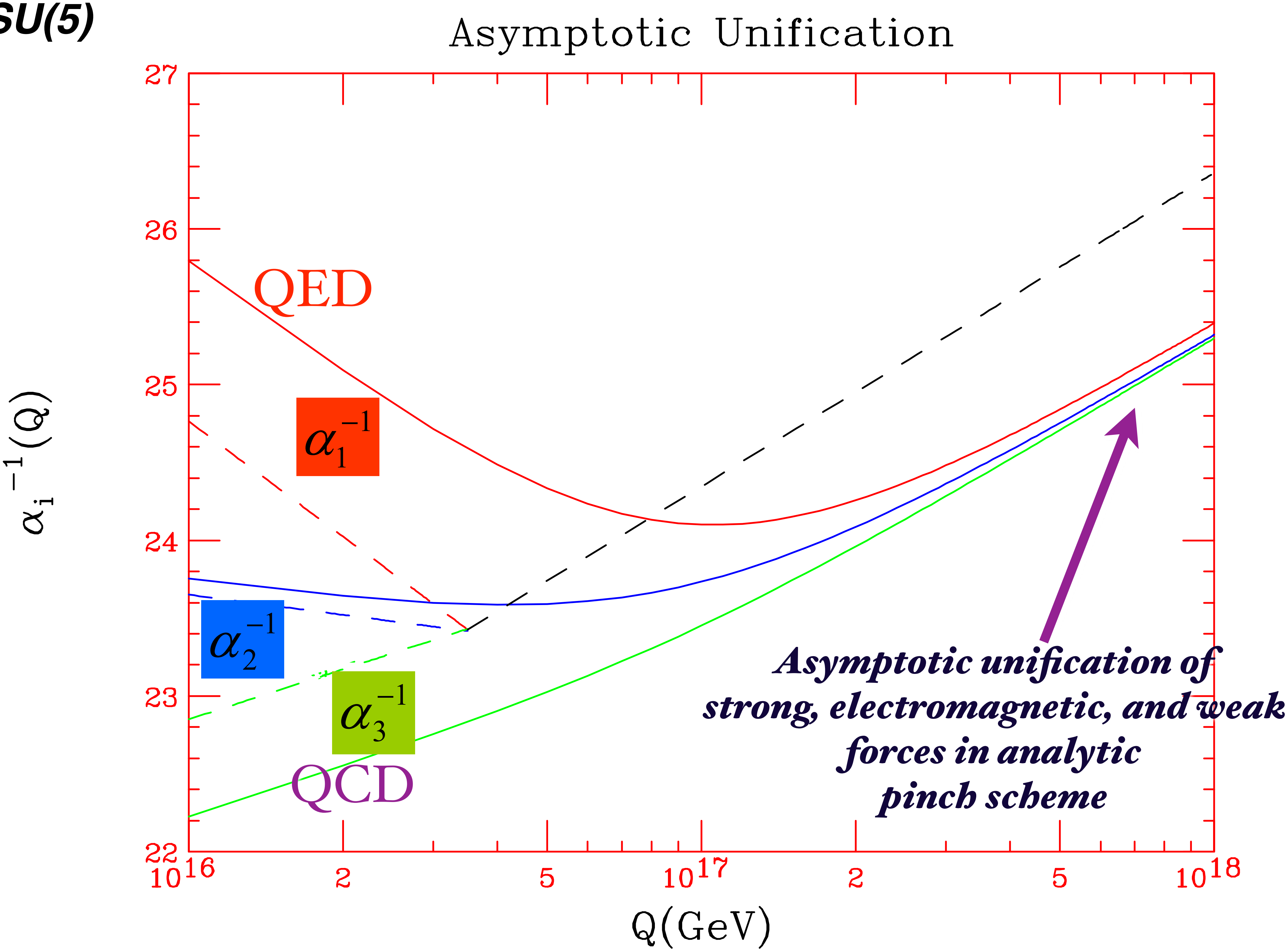
$$\Pi(Q^2) = \frac{\alpha(0)}{15\pi}\frac{Q^2}{m^2}$$ $Q^2 << 4M^2$ **Serber-Uehling**

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

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

Supersymmetric SU(5)

Binger, sjb

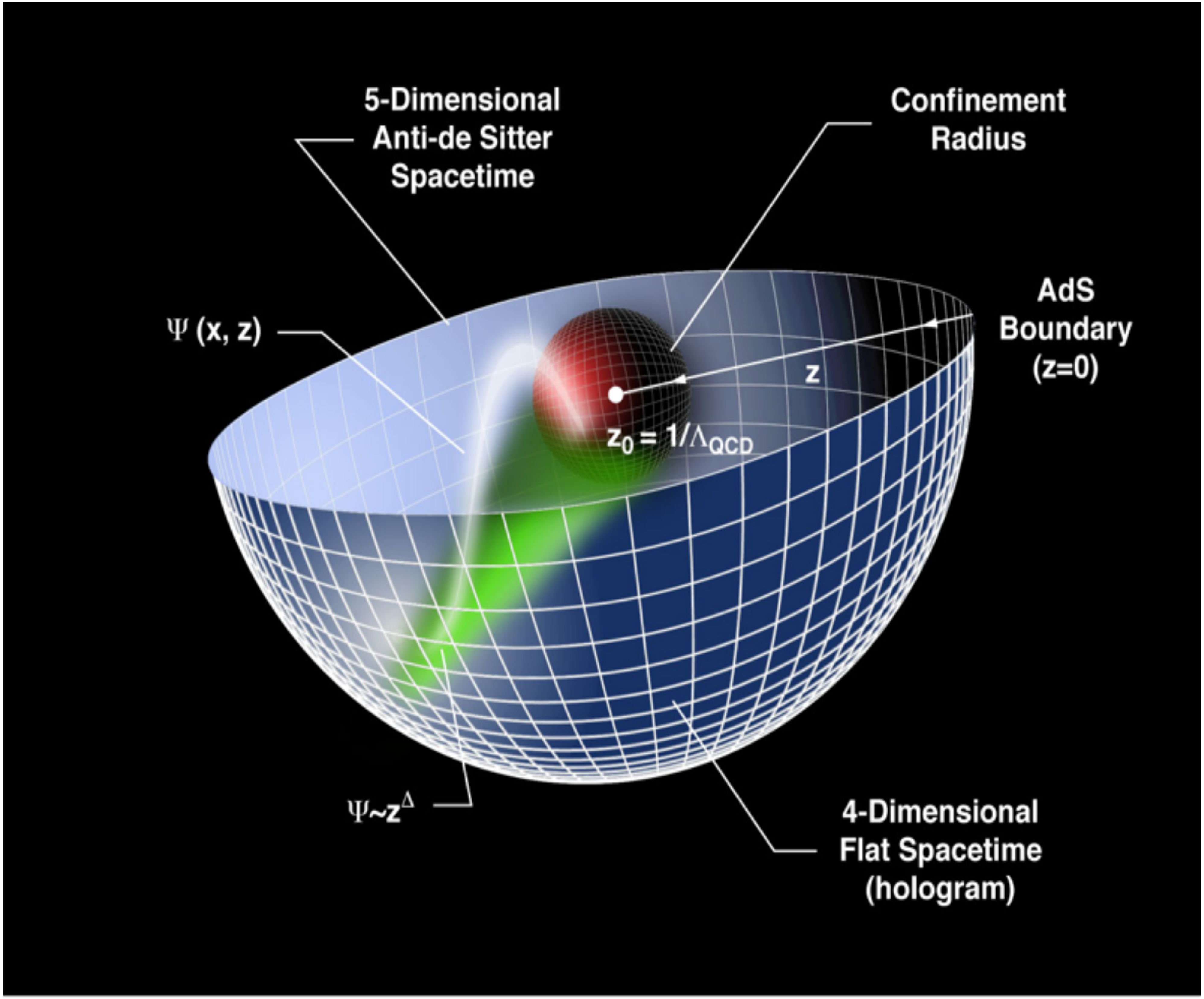


Must Use Same Scale-Setting Procedure! BLM/PMC

Profound Questions for Hadron Physics

- *Origin of the QCD Mass Scale*
- *Color Confinement*
- *Spectroscopy: Tetraquarks, Pentaquarks, Gluonium, Exotic States*
- *Universal Regge Slopes: n, L, both Mesons and Baryons*
- *Massless Pion: Bound State*
- *Dynamics and Spectroscopy*
- *QCD Coupling at all Scales*
- *QCD Vacuum —Do QCD Condensates Exist?*

Applications of AdS/CFT to QCD



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

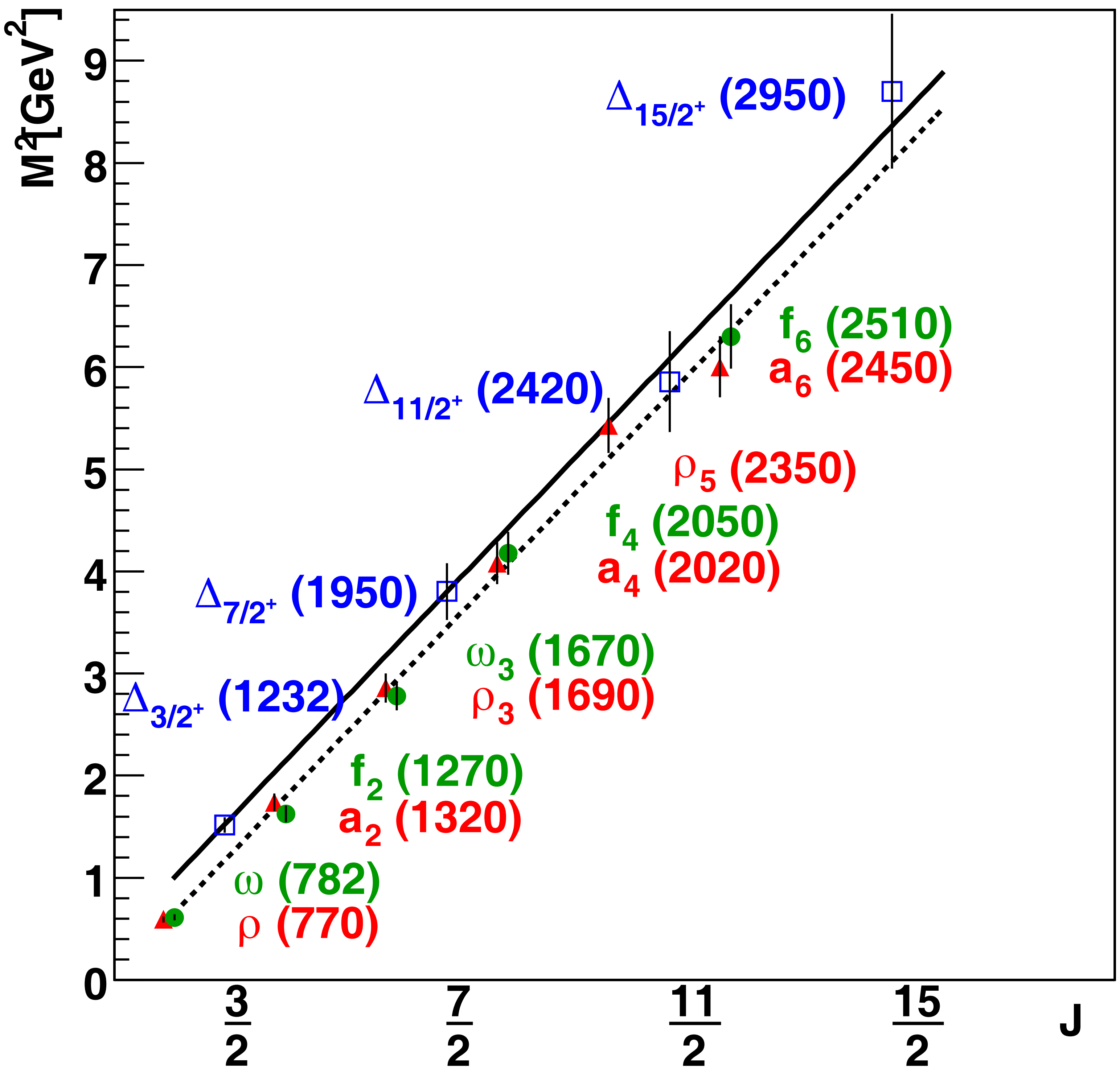
Features of LF Holographic QCD

- Color Confinement, Analytic form of confinement potential
- Massless pion bound state in chiral limit
- QCD coupling at all scales
- Connection of perturbative and nonperturbative mass scales
- Poincare' Invariant
- Hadron Spectroscopy-Regge Trajectories with universal slopes in n, L
- Supersymmetric 4-Plet: Meson-Baryon Tetraquark Symmetry
- Light-Front Wavefunctions
- Form Factors, Structure Functions, Hadronic Observables
- OPE: Constituent Counting Rules
- Hadronization at the Amplitude Level
- Analytic First Approximation to QCD
- Systematically improvable: Basis LF Quantization (BLFQ)

Many phenomenological tests

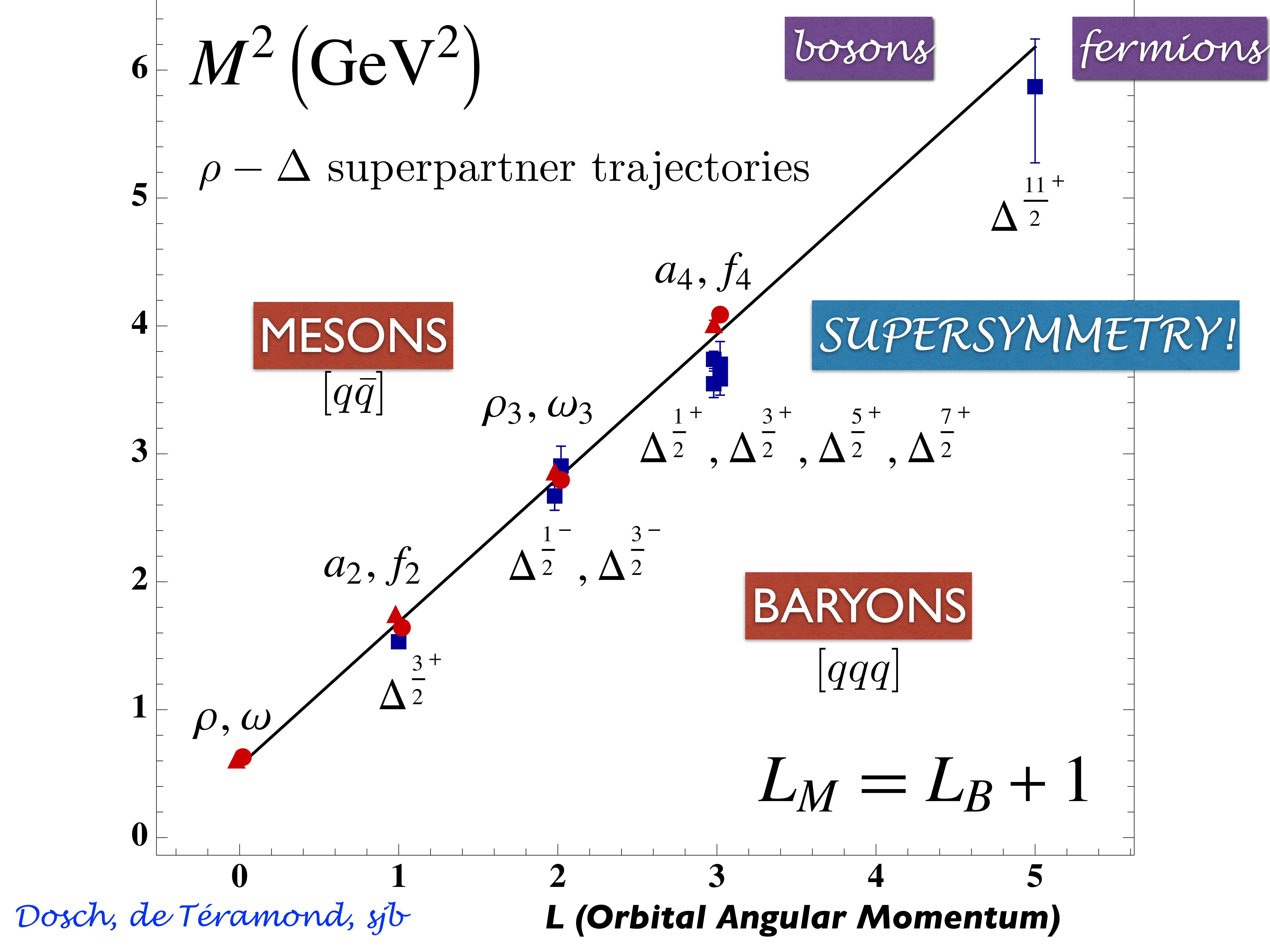
Mesons and Baryons: Same Regge Slope $M^2 \propto J$!

M²[GeV²]



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.

E. Klempt and B. Ch. Metsch 2012



$M^2\,(\mathrm{GeV}^2)$
bosons
fermions
$\rho - \Delta$ superpartner trajectories
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
0 1 2 3 4 5
L (Orbital Angular Momentum)
Dosch, de Téramond, sjb

Quark separation increases with L

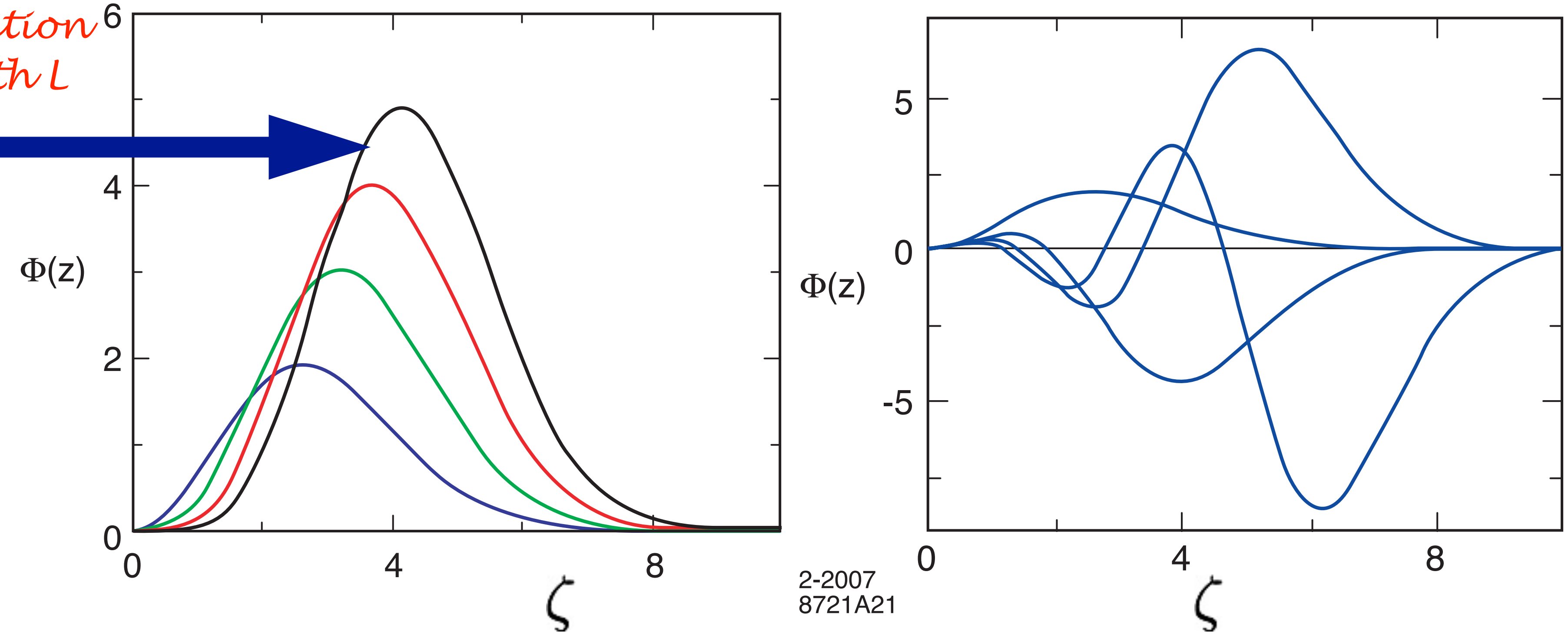
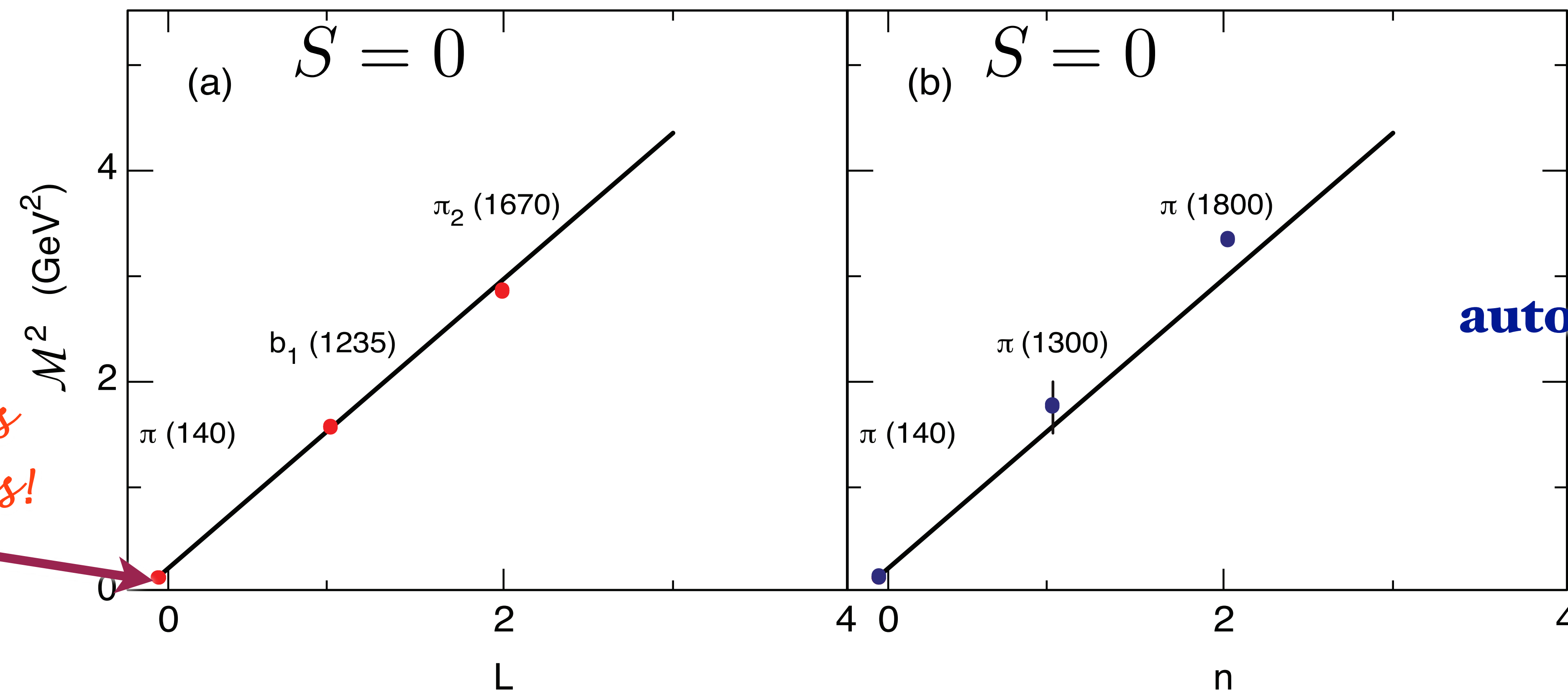


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model

Same slope in n and L!

Pion has zero mass!

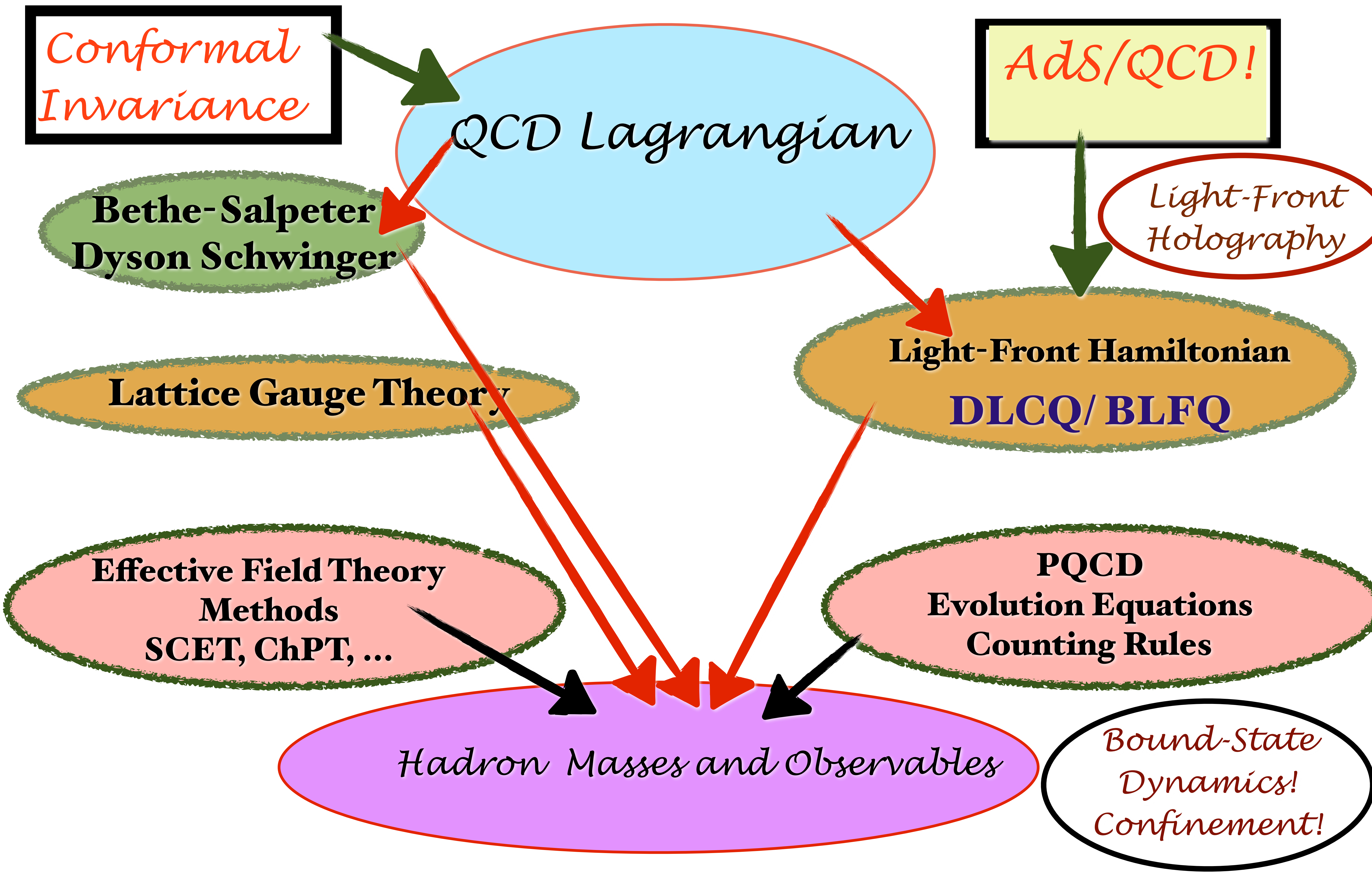


Pion mass automatically zero!

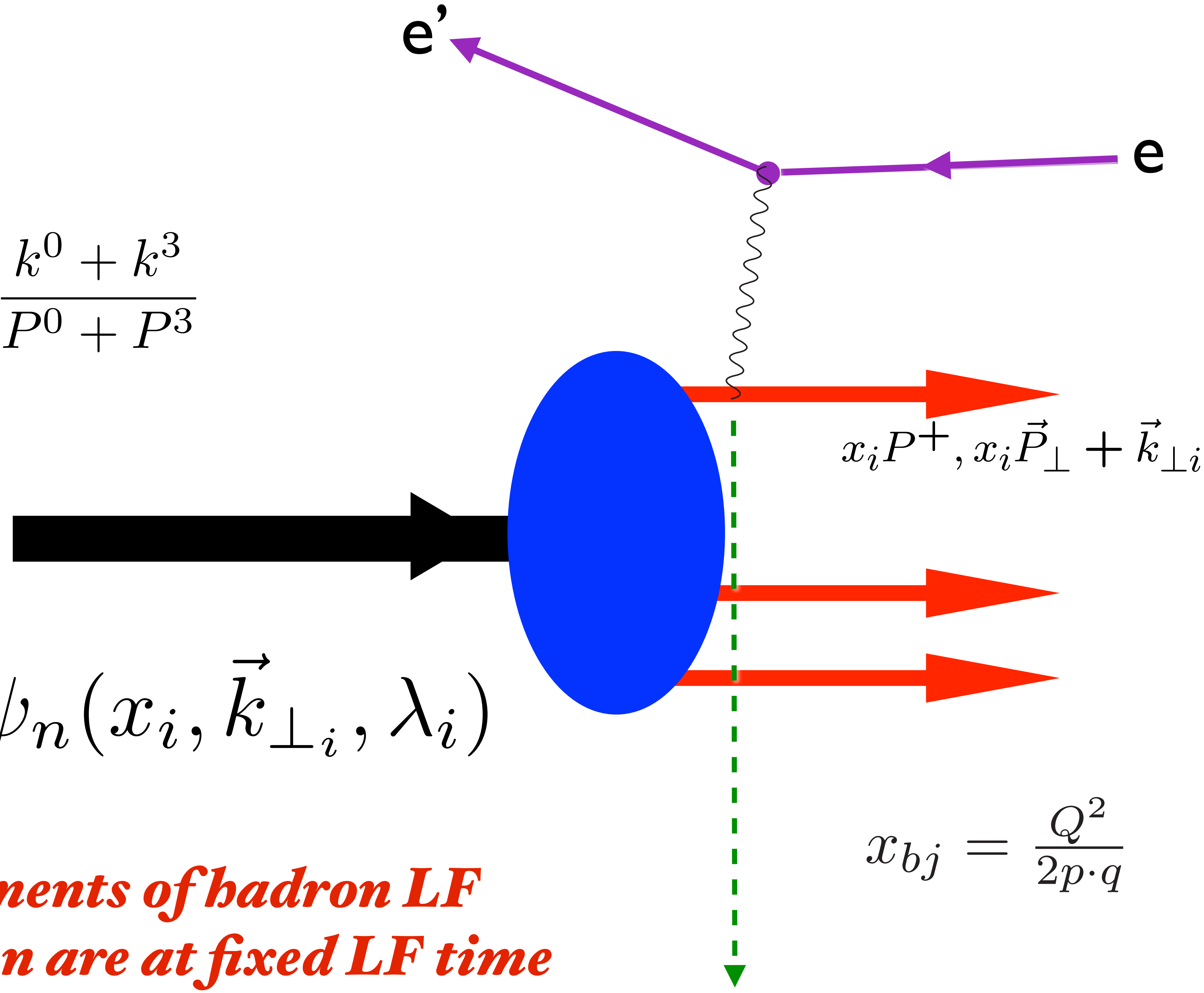
$$m_q = 0$$

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

Predict Hadron Properties from First Principles!



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



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

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

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 Invariant

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

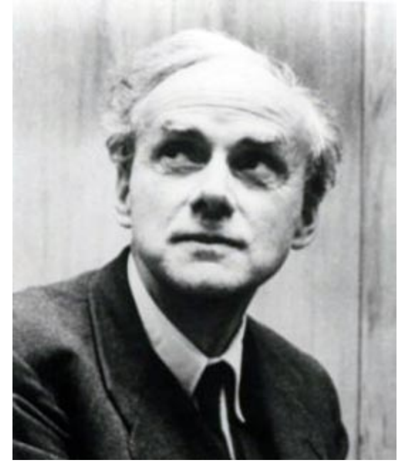
Eigenvalue $P^- = \frac{\mathcal{M}^2 + \vec{P}_\perp^2}{P^+}$

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

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

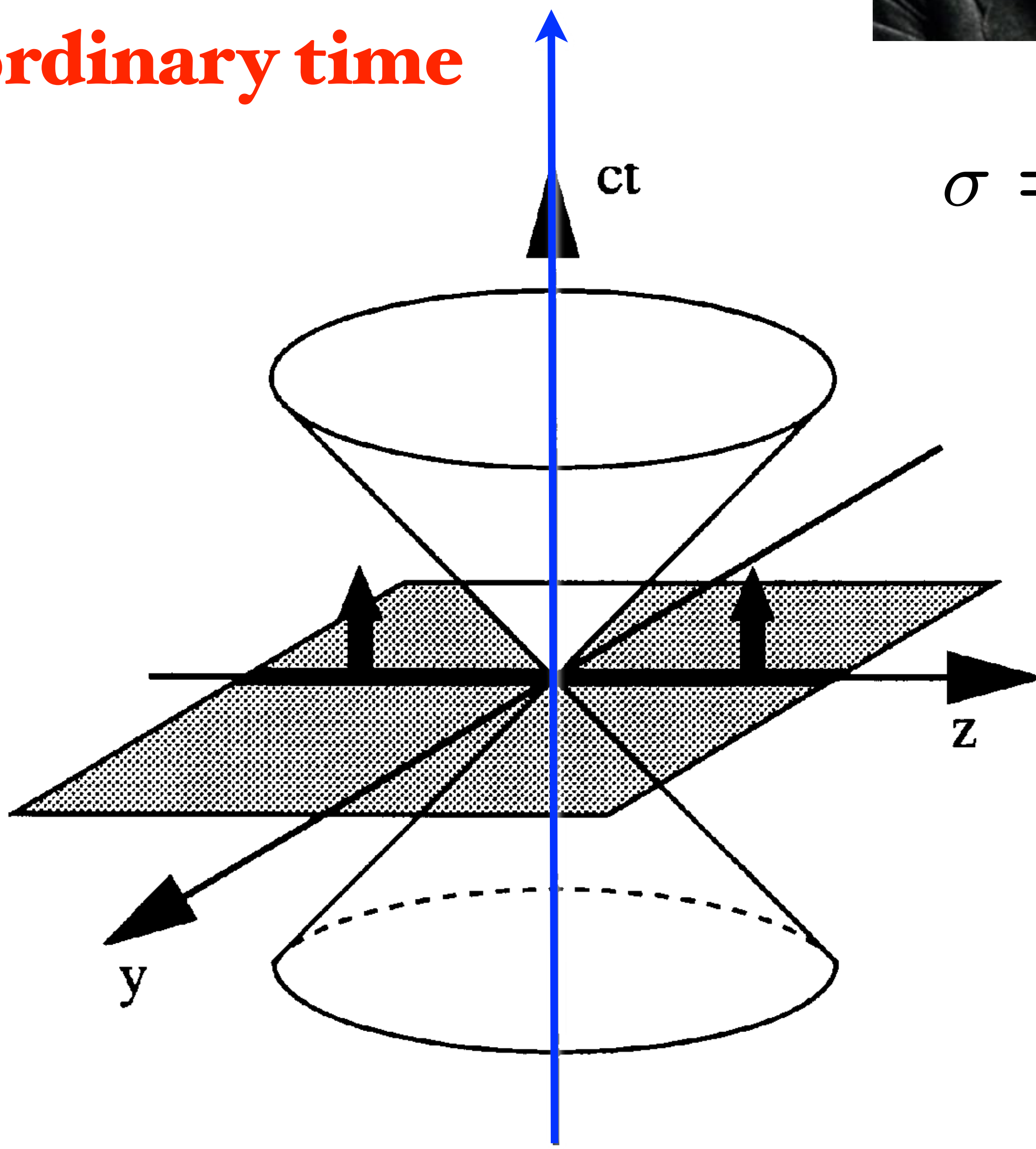
HELEN BRADLEY - PHOTOGRAPHY

Dirac's Amazing Idea: The "Front Form"



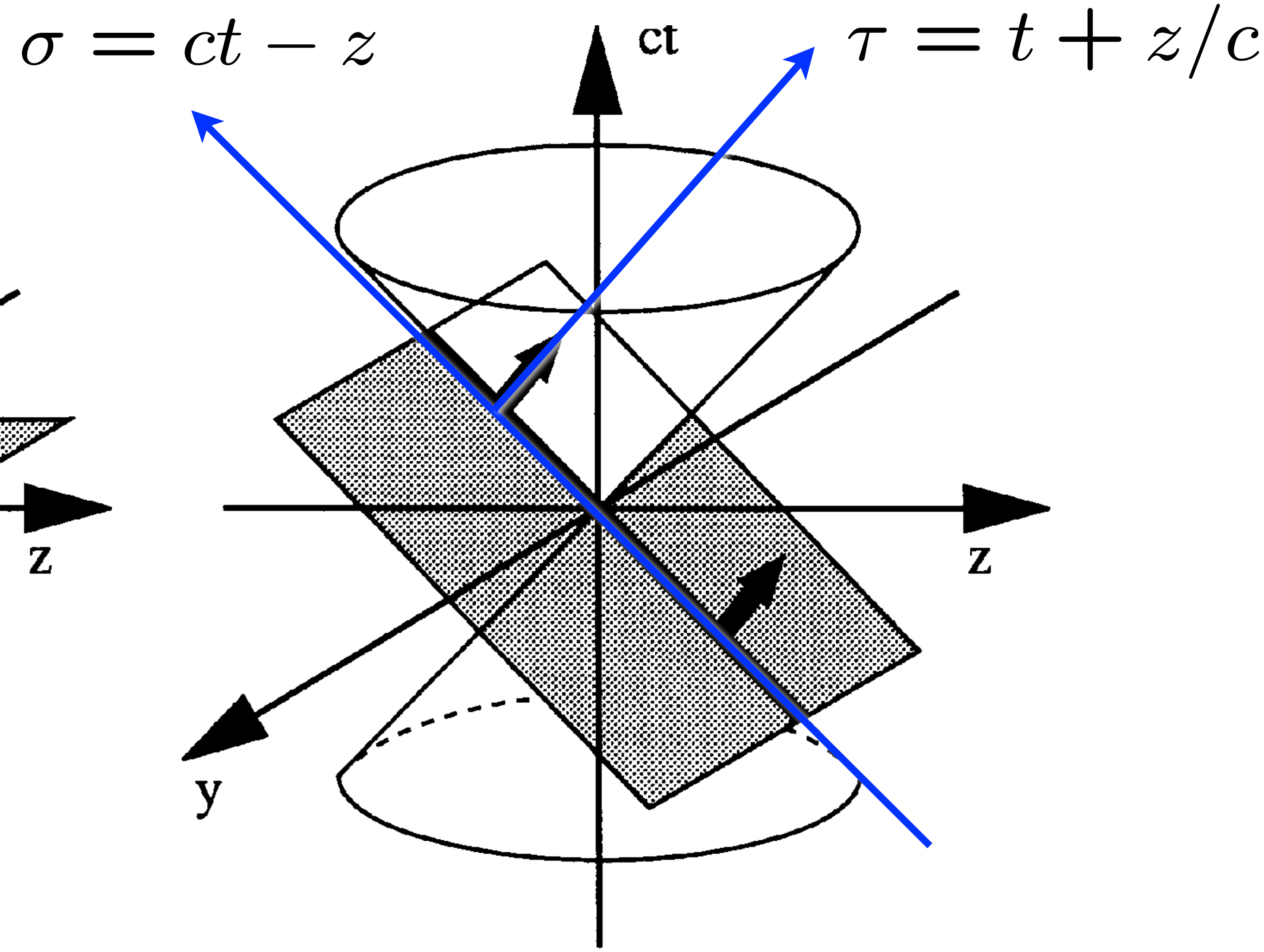
P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

Evolve in ordinary time



Instant Form

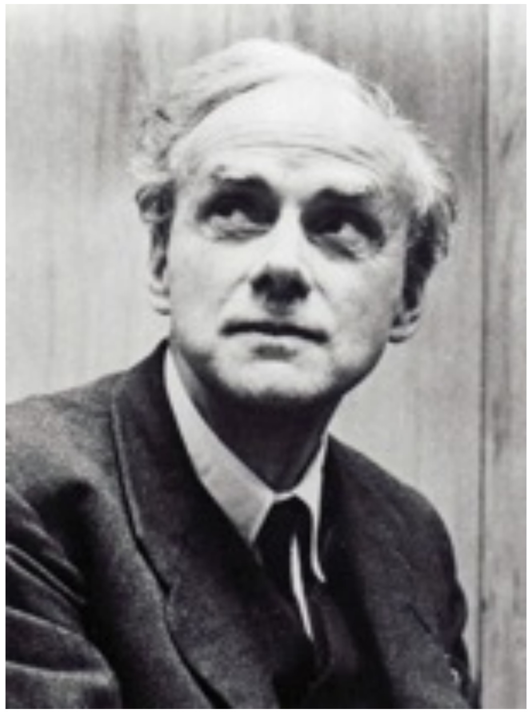
Evolve in light-front time!

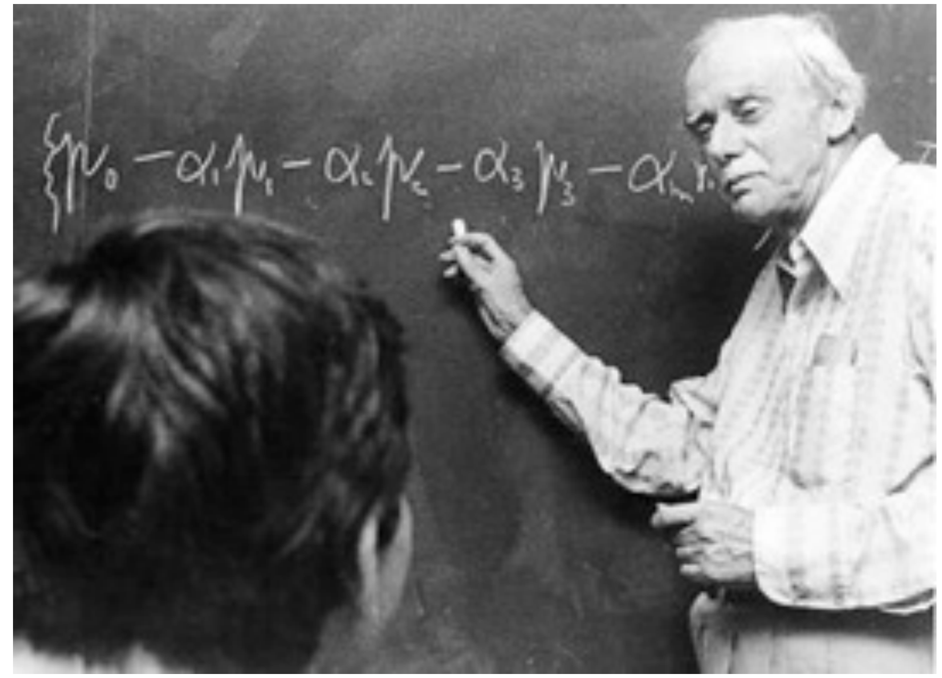


Front Form

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

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.

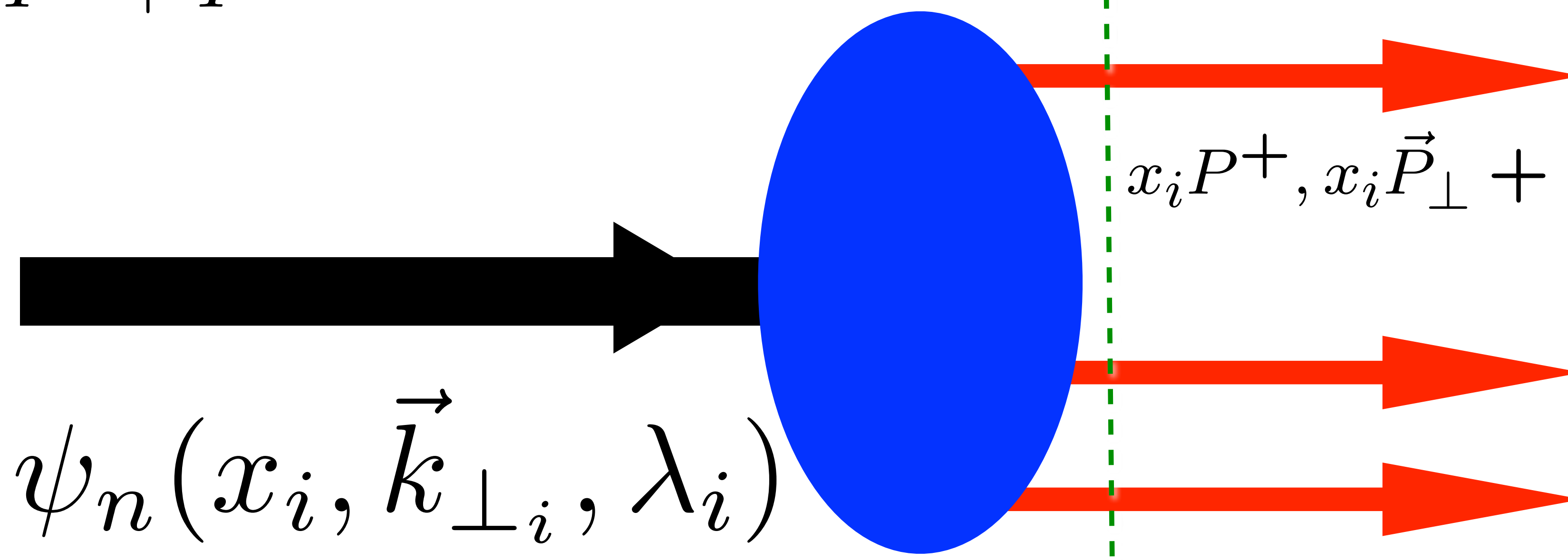
It offers new opportunities, while the familiar instant form seems to be played out " - P.A.M. Dirac (1977)

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

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

Fixed $\tau = t + z/c$

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



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

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

$\sum_i^n x_i = 1$

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

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

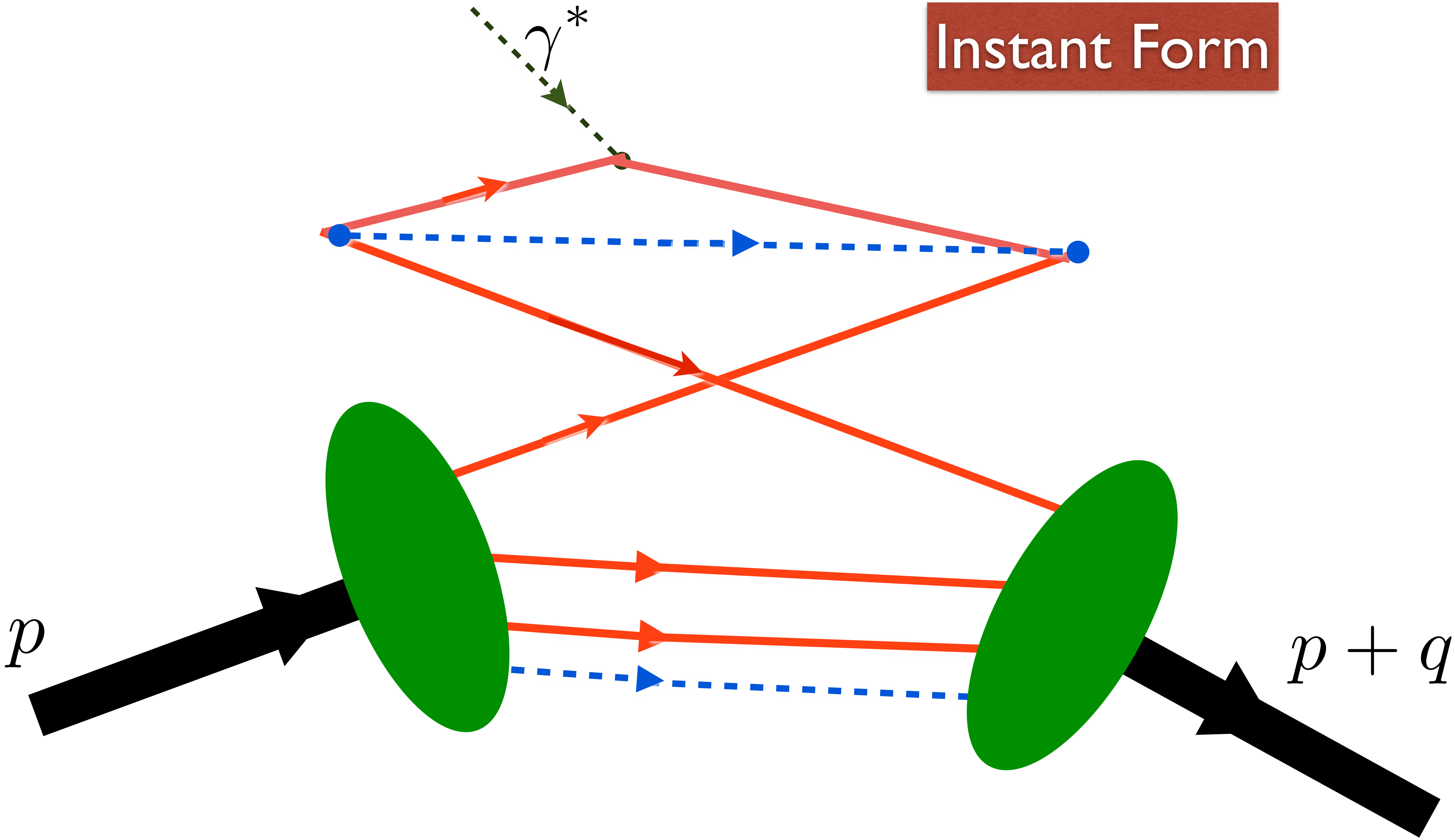
$$\int \psi_{BS}(p,k)dk^- \rightarrow \psi_{LF}$$

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

Invariant under boosts! Independent of P^μ

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

Instant Form

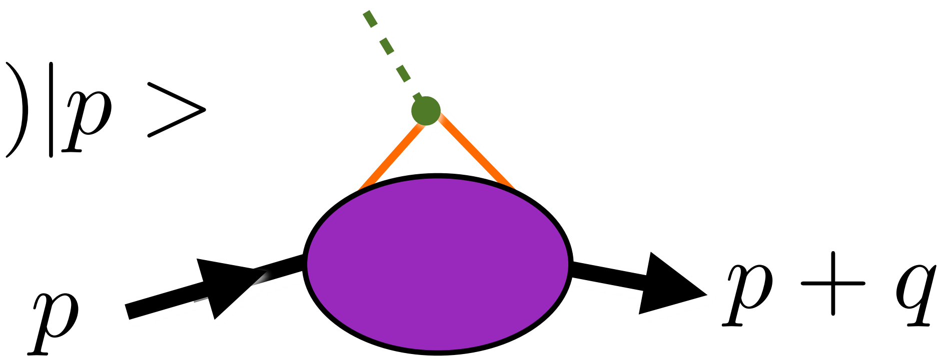


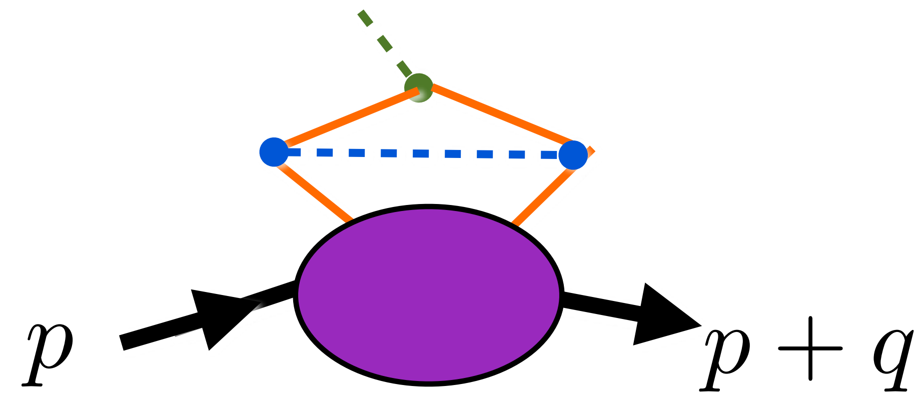
Must include vacuum-induced currents to compute form factors and other current matrix elements!

Boosts are dynamical in instant form

Calculation of proton form factor in Instant Form

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



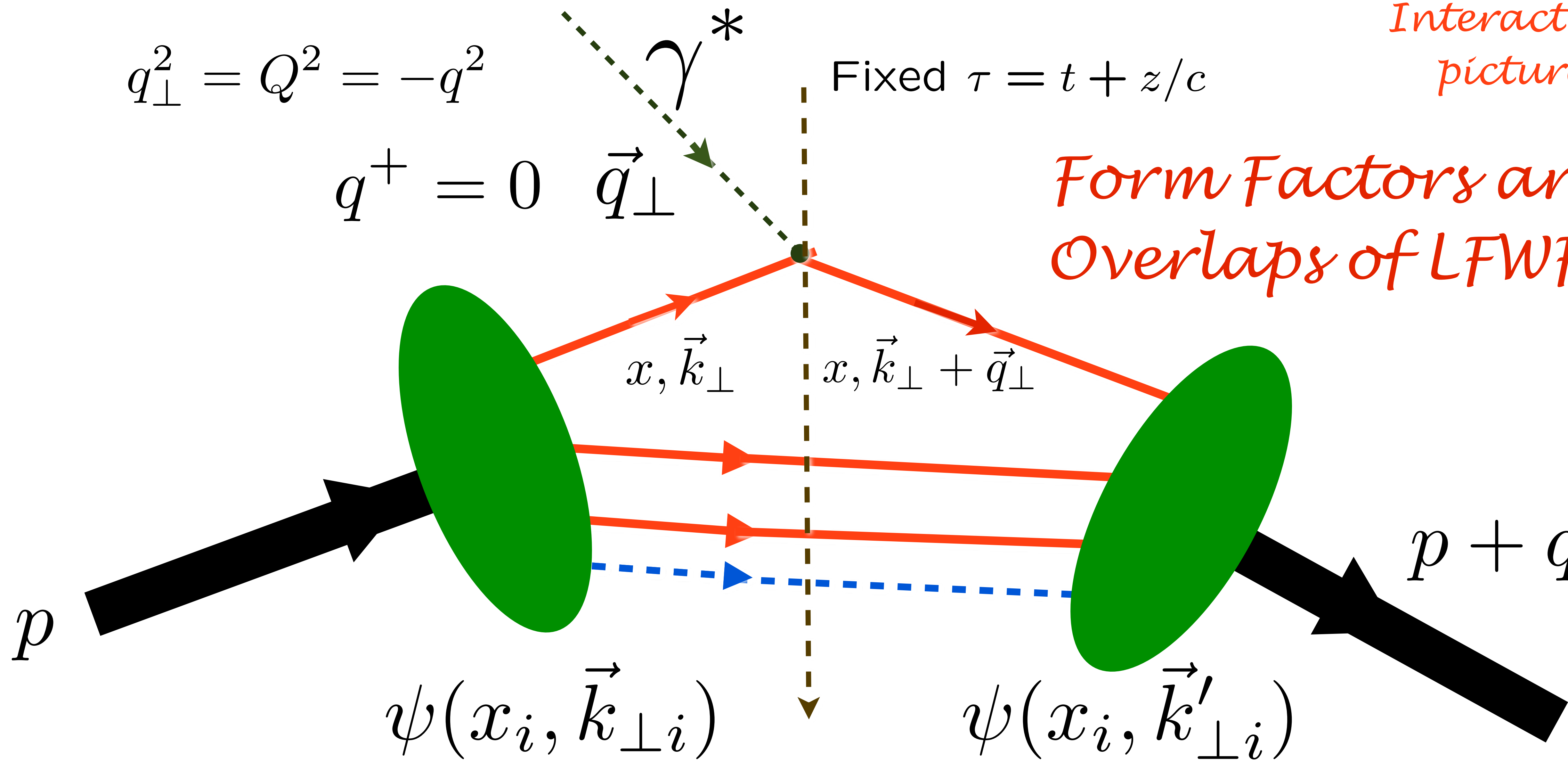


- **Need to boost proton wavefunction: p to p+q. Extremely complicated dynamical problem; particle number changes**
- **Need to couple to all currents arising from vacuum!! Remain even after normal-ordering**
- **Instant-form WFs insufficient to calculate form factors**
- **Each time-ordered contribution is frame-dependent**
- **Divide by disconnected vacuum diagrams**

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

Front Form

Interaction picture



Form Factors are Overlaps of LFWFs

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

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

Drell &Yan, West
Exact LF formula!

Drell, sjb

Exact LF Formula for Pauli Form Factor

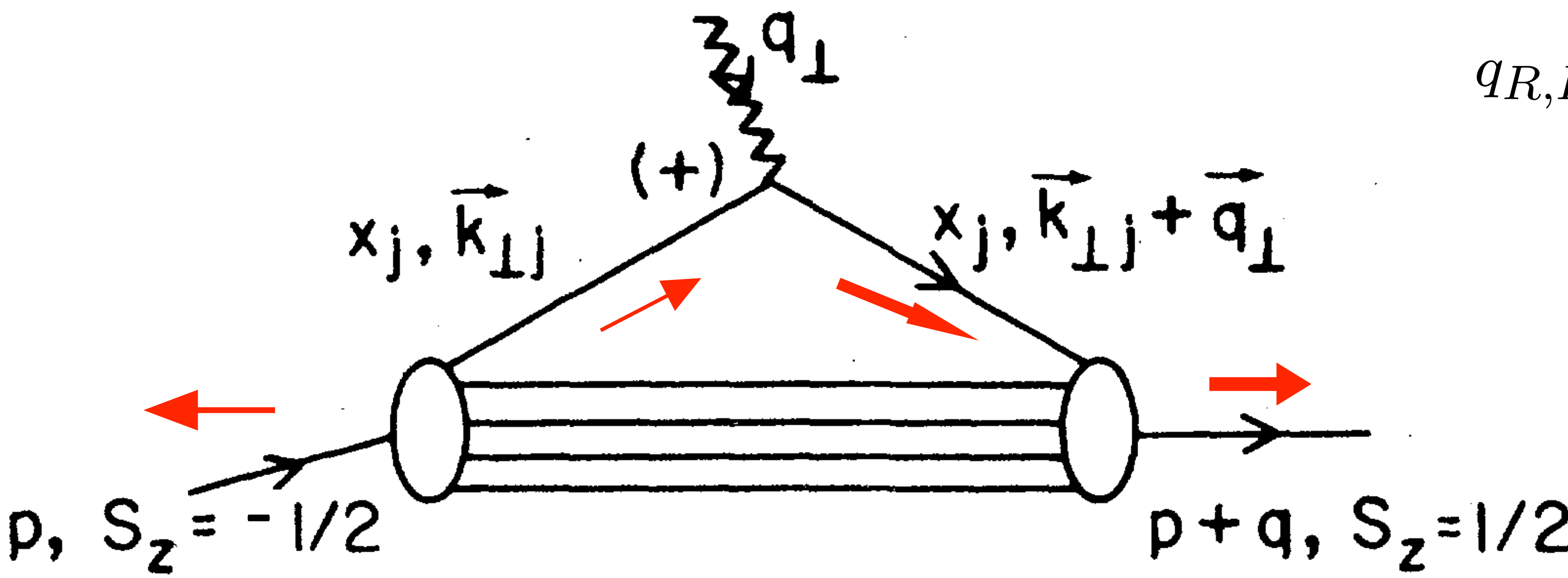
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

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

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

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



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

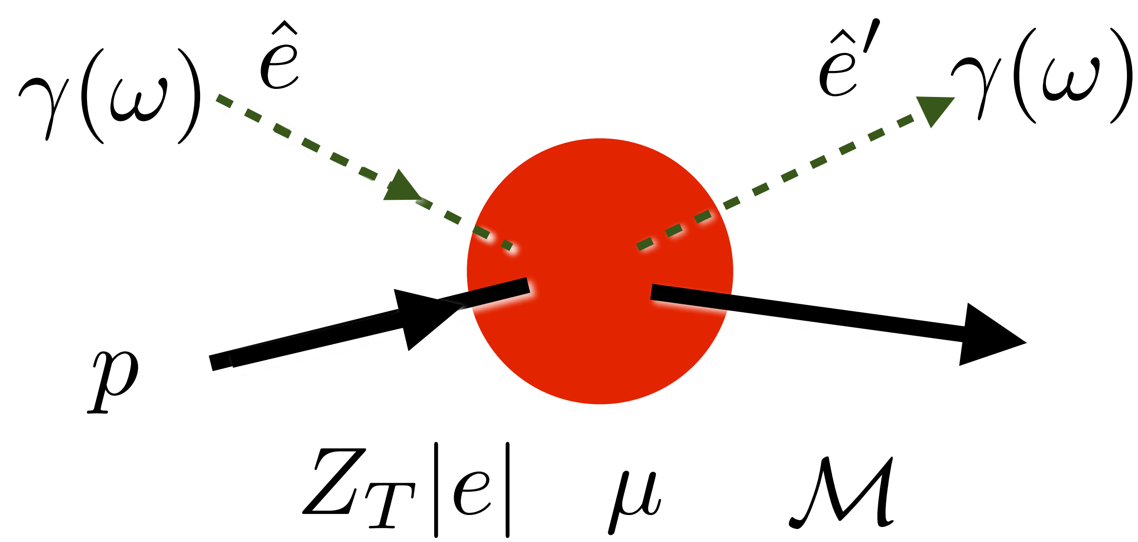
Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

Low Energy Forward Compton Scattering

Low energy theorem: Spin-1/2 Target

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

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



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 and DHG Sum Rule Wrong!

Single particle wave-packet

Primack, sjb

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

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

Instant Form Wavefunction of moving bound state:

Not product of independent boosts!

$$\varphi_{E\mathbf{P}}(\mathbf{x}_a\ \ \mathbf{x}_b\ , X^0)_{SM} = \frac{E+\mathscr{M}}{2\mathscr{M}} \int \frac{d^3p}{(2\pi)^{3/2}} \left(\frac{p_a{}^0+m_a}{2p_a{}^0}\,\frac{p_b{}^0+m_b}{2p_b{}^0}\right)^{1/2}$$

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

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

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

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

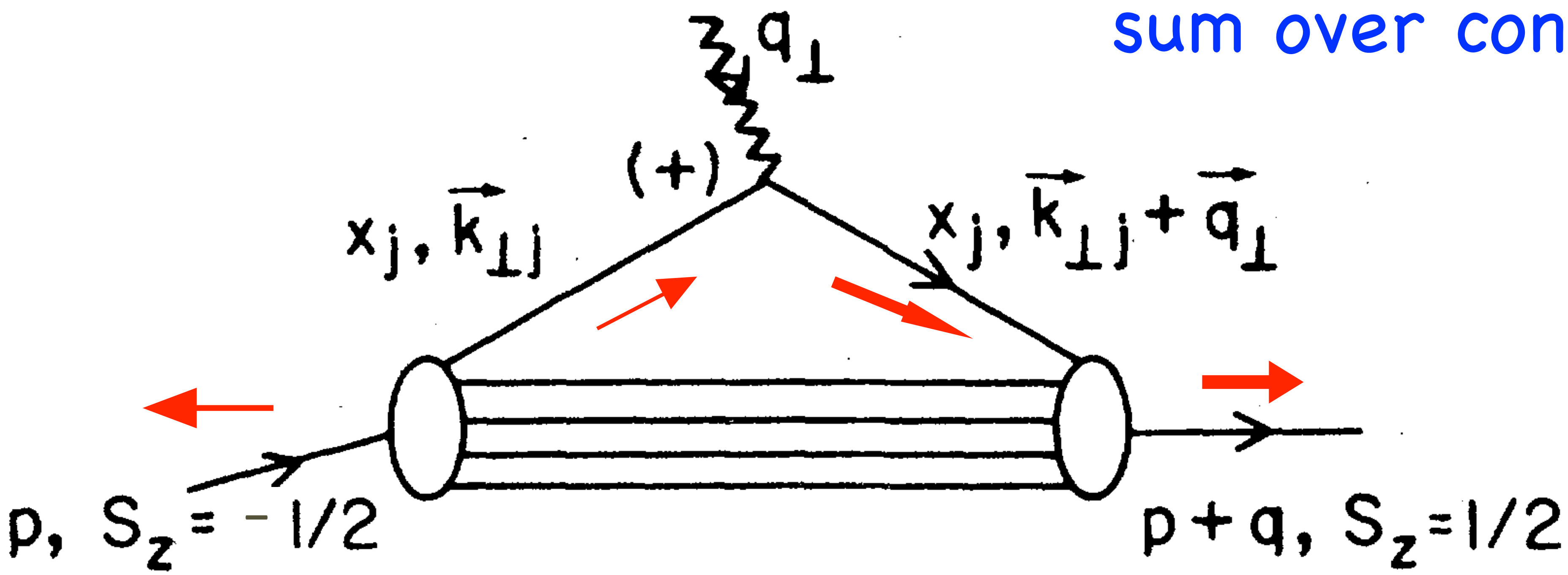
$$\left\langle P+q,\uparrow\left|\frac{T^{++}(0)}{2(P^+)^2}\right|P,\uparrow\right\rangle = A(q^2) \ ,$$

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

Vanishing Anomalous gravitomagnetic moment B(0)

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

graviton



sum over constituents

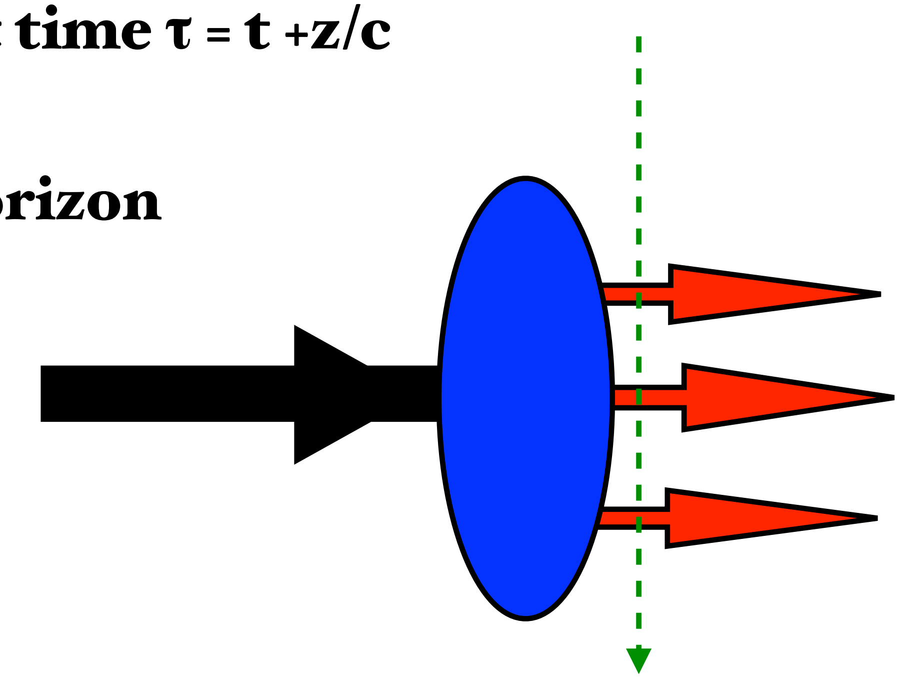
Hwang, Schmidt, Ma, sjb;
Holstein et al

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

Each Fock State

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)**



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

Light-Front vs. Instant Form

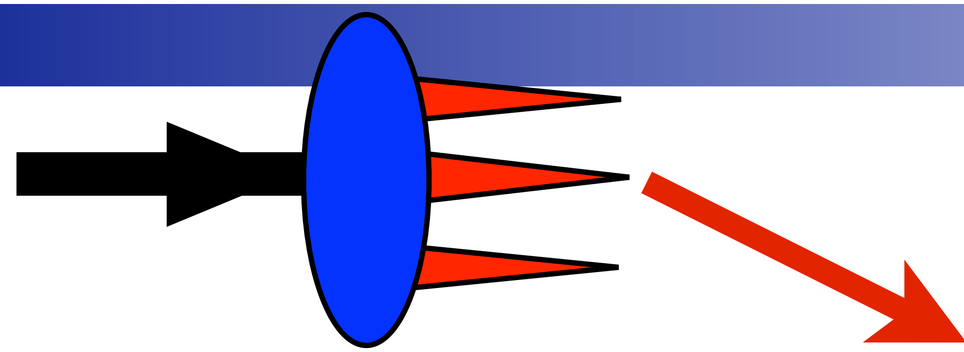
- Light-Front Wavefunctions are frame-independent
- Boosting an instant-form wavefunctions is a dynamical problem -- extremely complicated even in QED
- Vacuum state is lowest mass eigenstate of Hamiltonian
- Light-Front Vacuum same as vacuum of the free Hamiltonian
- Zero anomalous gravitomagnetic moment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

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

Light-Front Wavefunctions underly hadronic observables



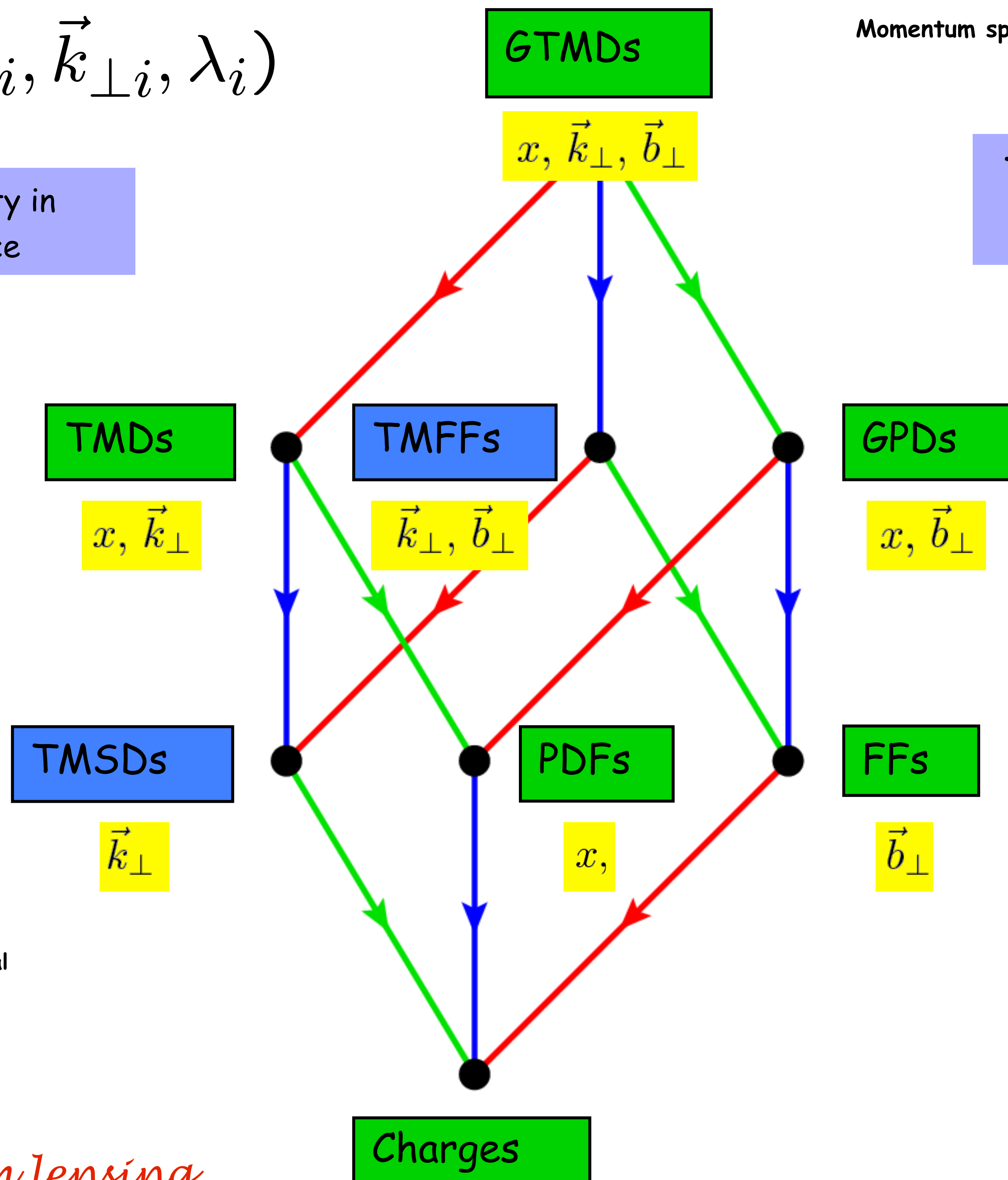
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

Transverse density in momentum space

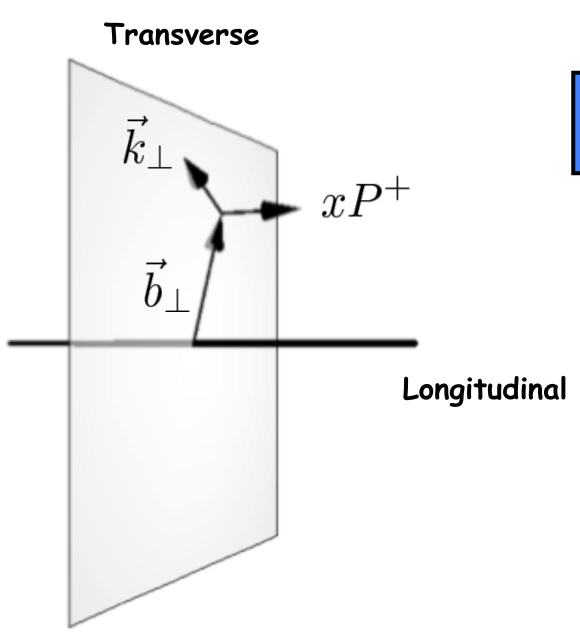
Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ Position space

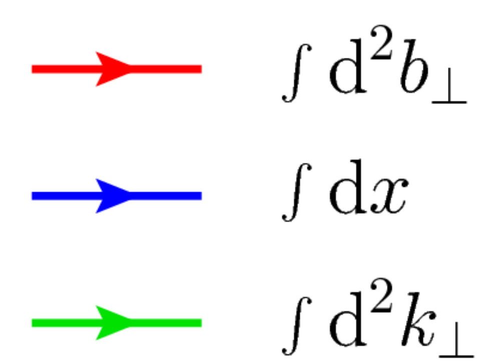
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in position space



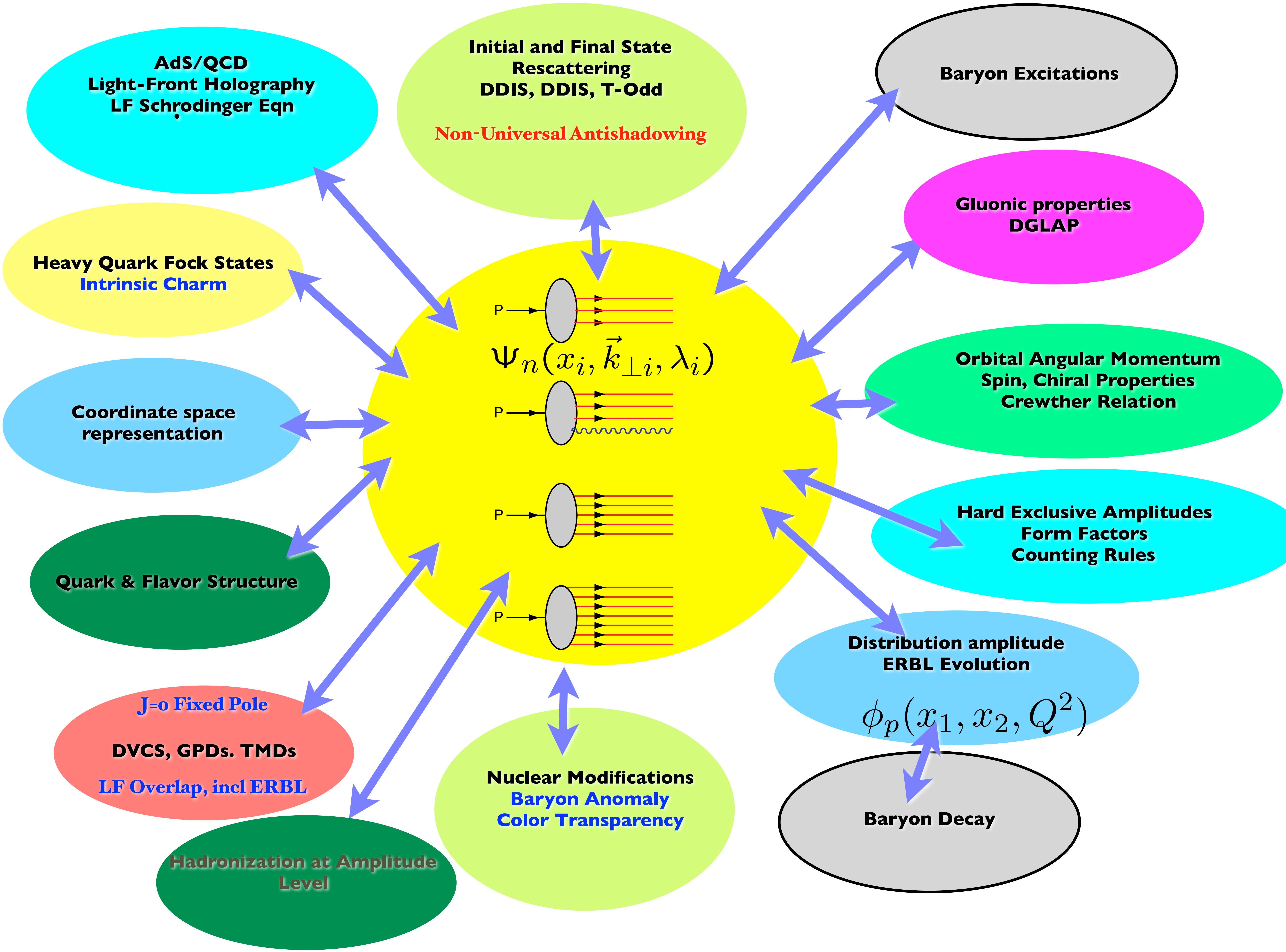
Lorcè, Pasquini





Sivers, T-odd from lensing

QCD and the LF Hadron Wavefunctions



Single-spin asymmetries

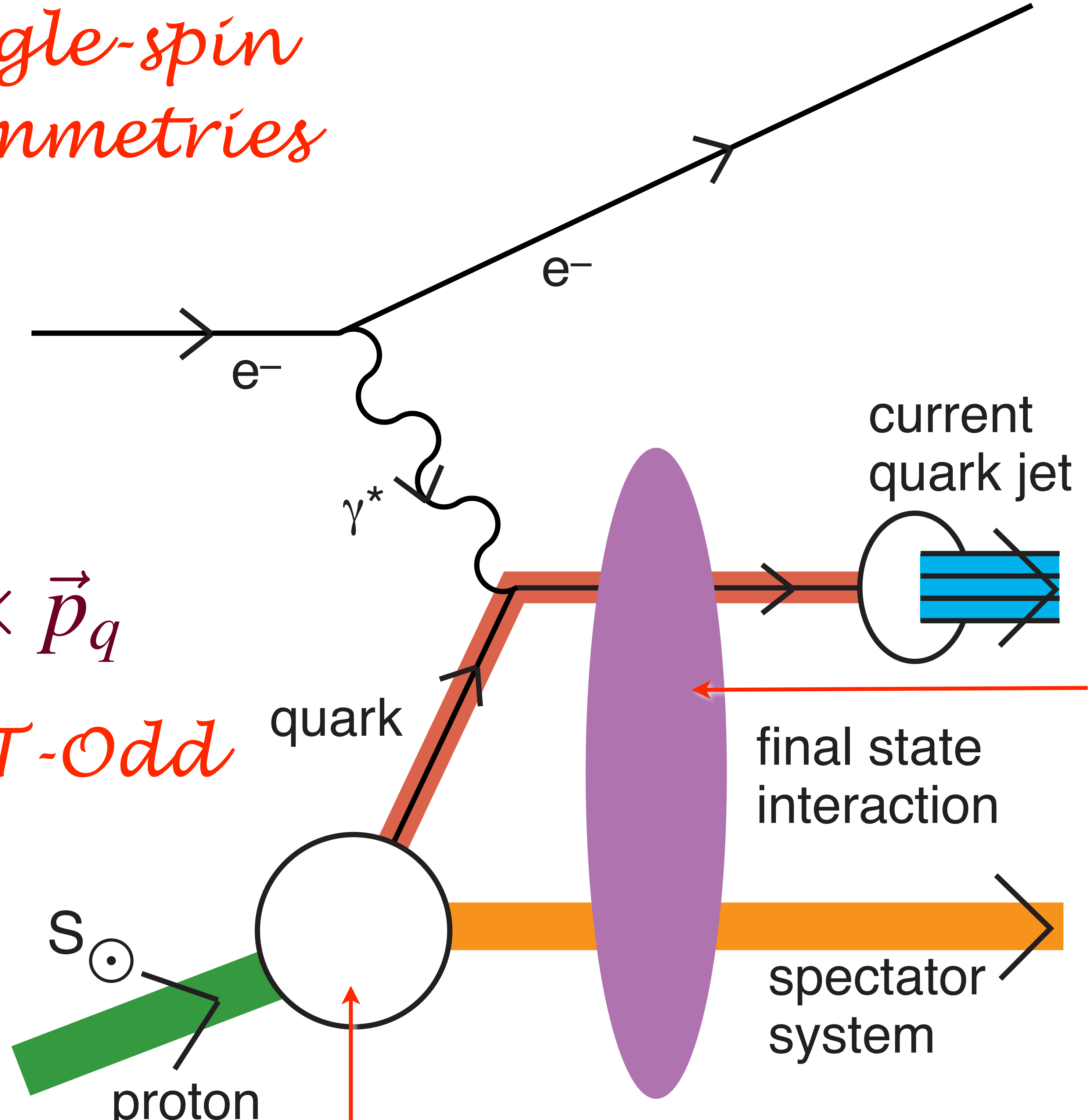
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

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

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

Pseudo- T-Odd



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

“Lensing Effect”

“Lensing” involves soft scales

Light-Front Wavefunction S and P- Waves!

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!

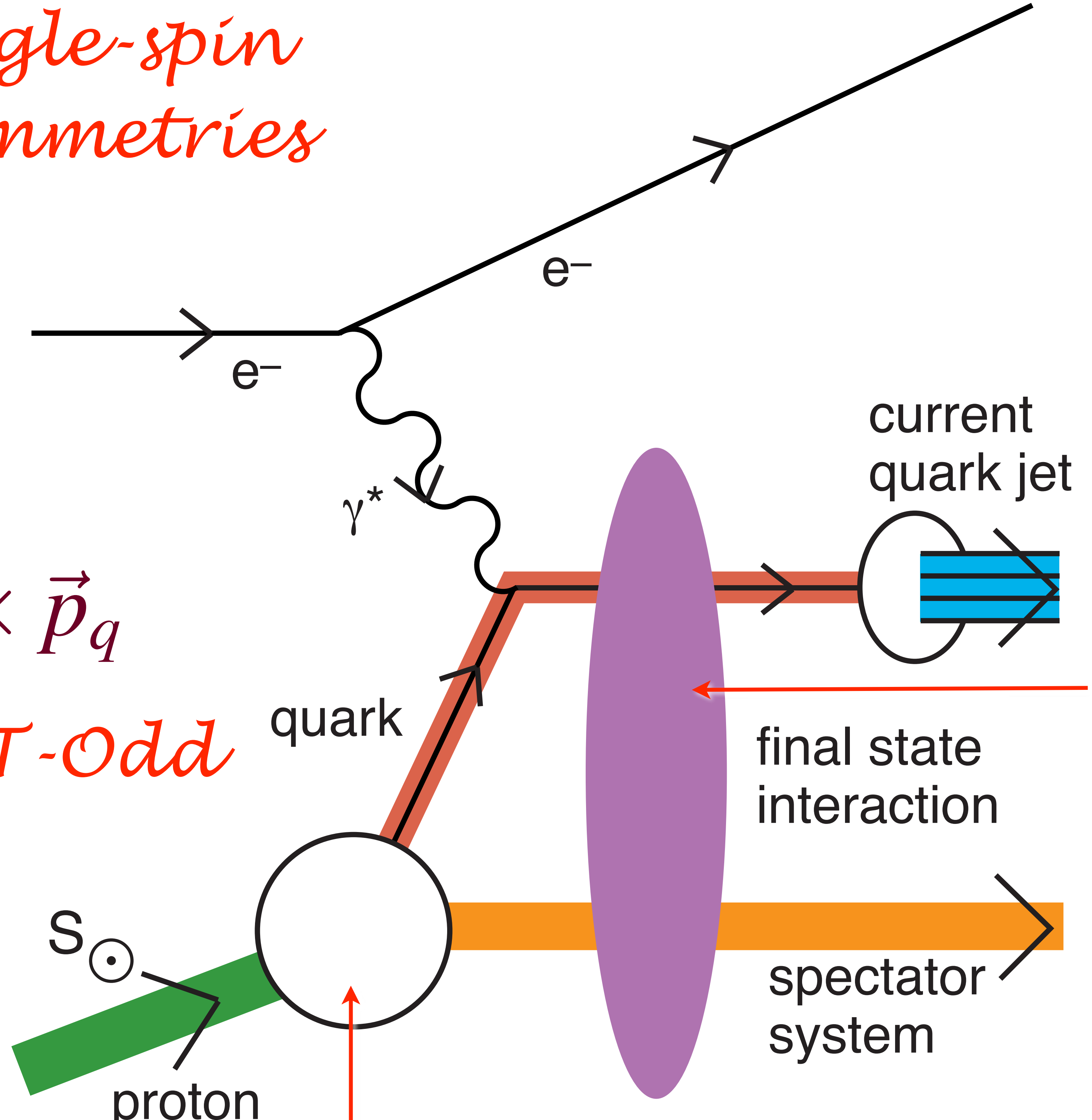
Violates Conventional Wisdom!

Single-spin asymmetries

Leading Twist Sivers Effect

Hwang, Schmidt, sjb

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



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

Pseudo- T-Odd

"Lensing" involves soft scales

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

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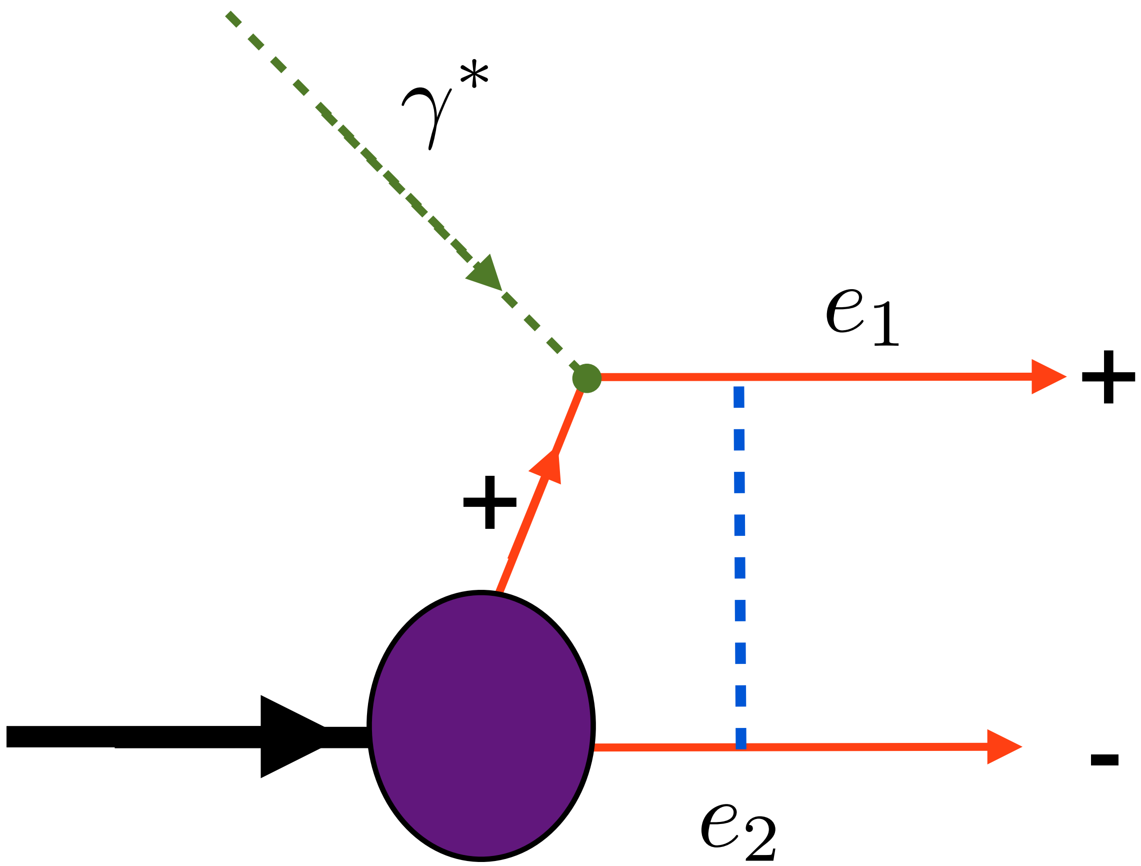
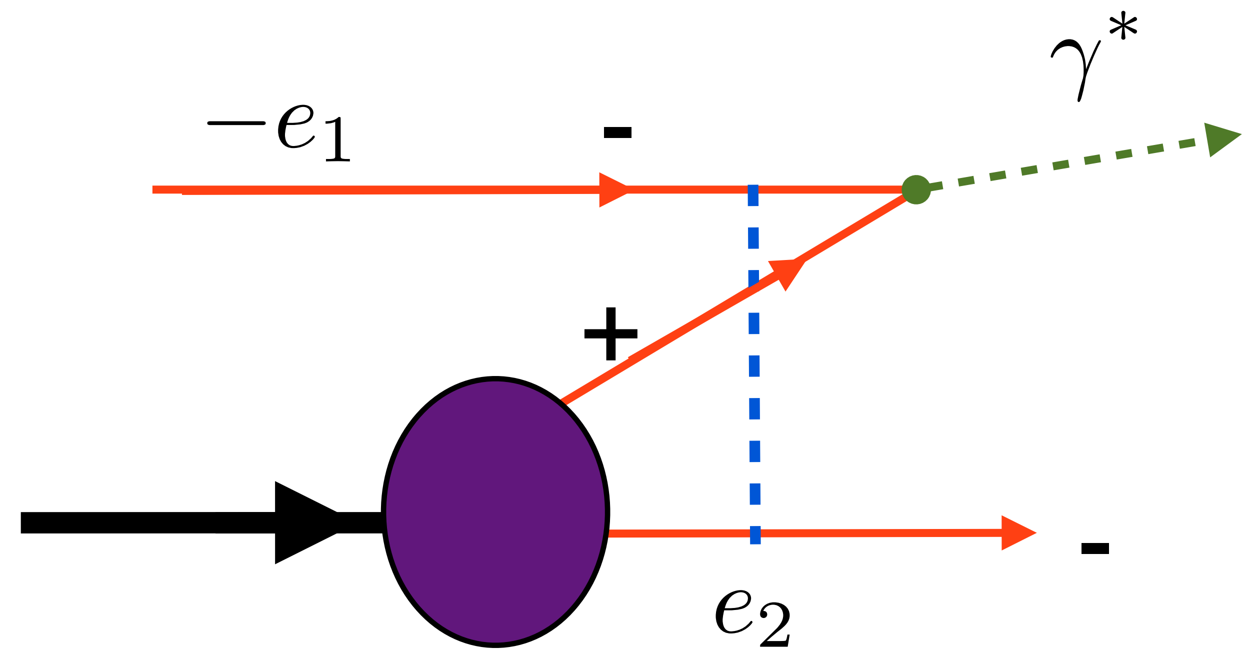


DIS

Attractive, opposite-sign rescattering potential



DY

Repulsive, same-sign scattering potential

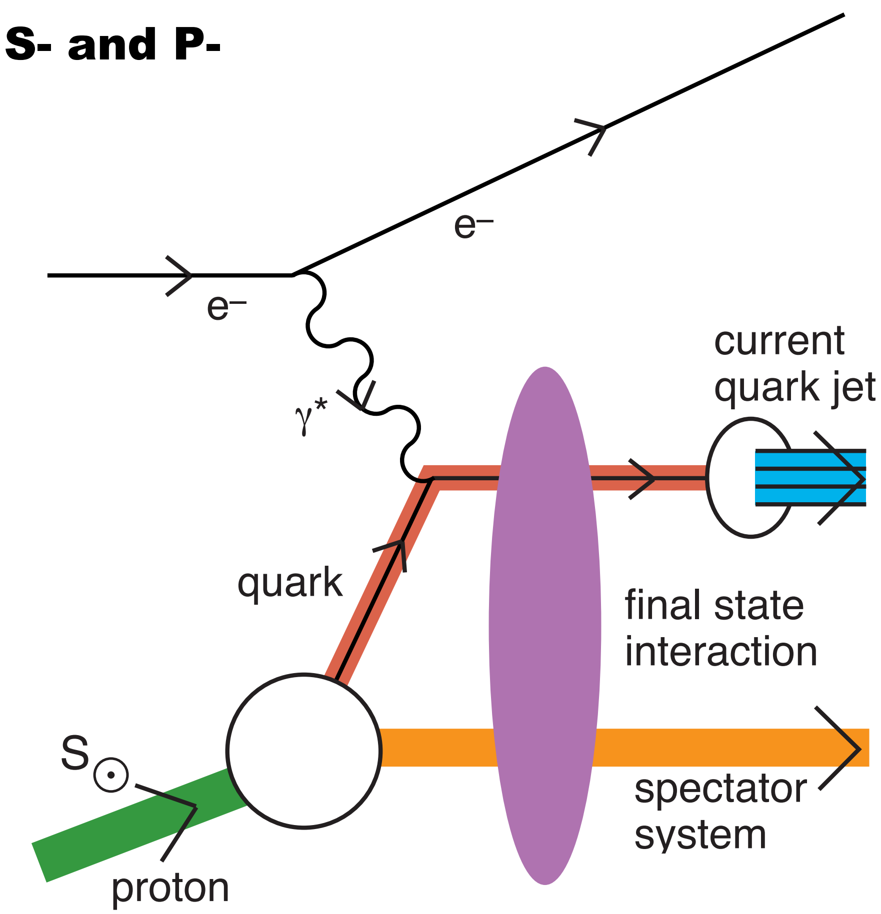
Dae Sung Hwang, Yuri V. Kovchegov, Ivan Schmidt, Matthew D. Sievert, sjb

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

Hwang, Schmidt, sjb
Collins

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

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



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

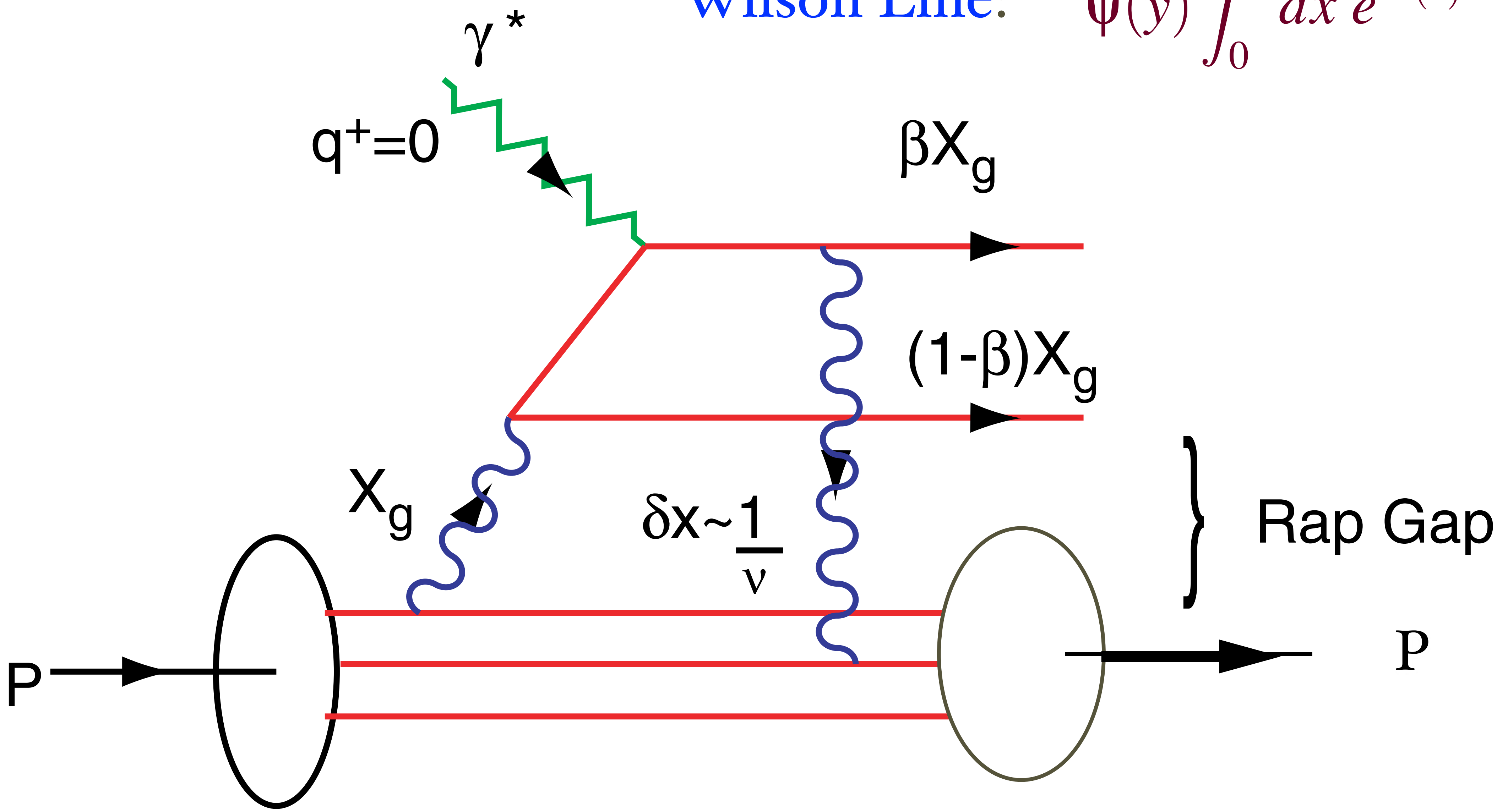
Mulders, Boer **Qiu, Sterman**

Pasquini, Xiao, Yuan, sjb

Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

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



Reproduces lab-frame color dipole approach

DDIS: Input for leading twist nuclear shadowing

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

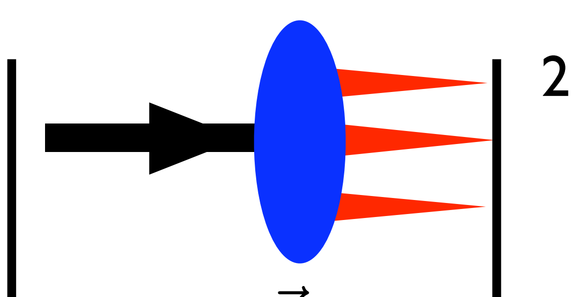
Hwang, Schmidt, sjb,

Mulders, Boer

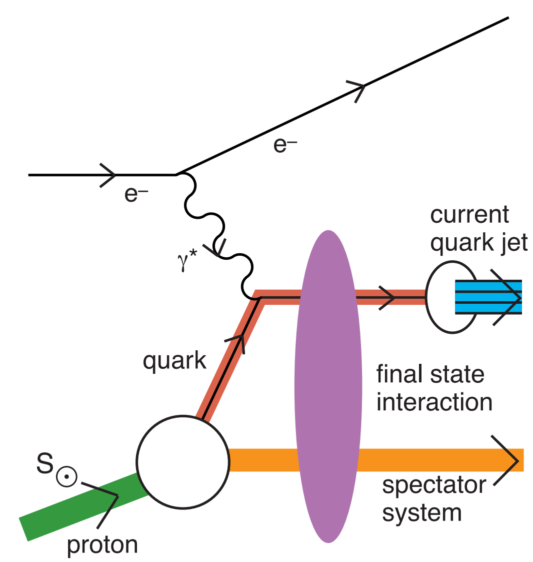
Qiu, Sterman

Collins, Qiu

Pasquini, Xiao, Yuan, sjb



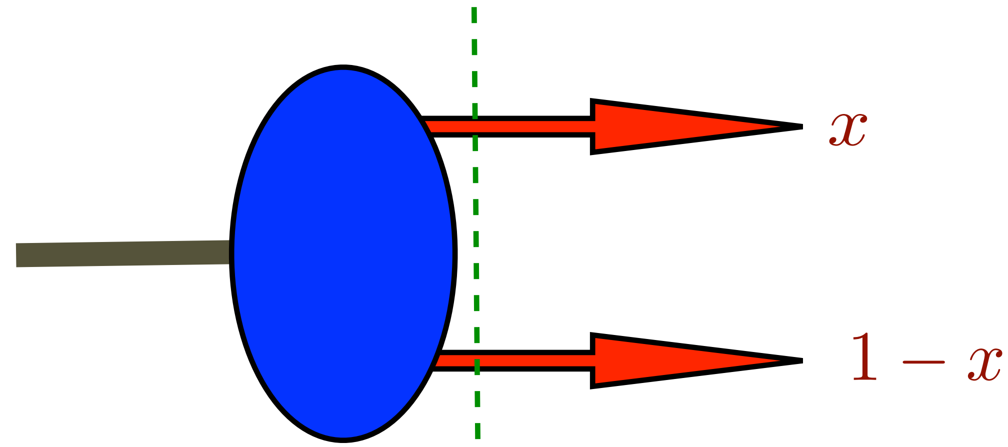
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Hadron Distribution Amplitudes

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

$$\sum_i x_i = 1$$



Fixed $\tau = t + z/c$

$k_\perp^2 < Q^2$

- 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

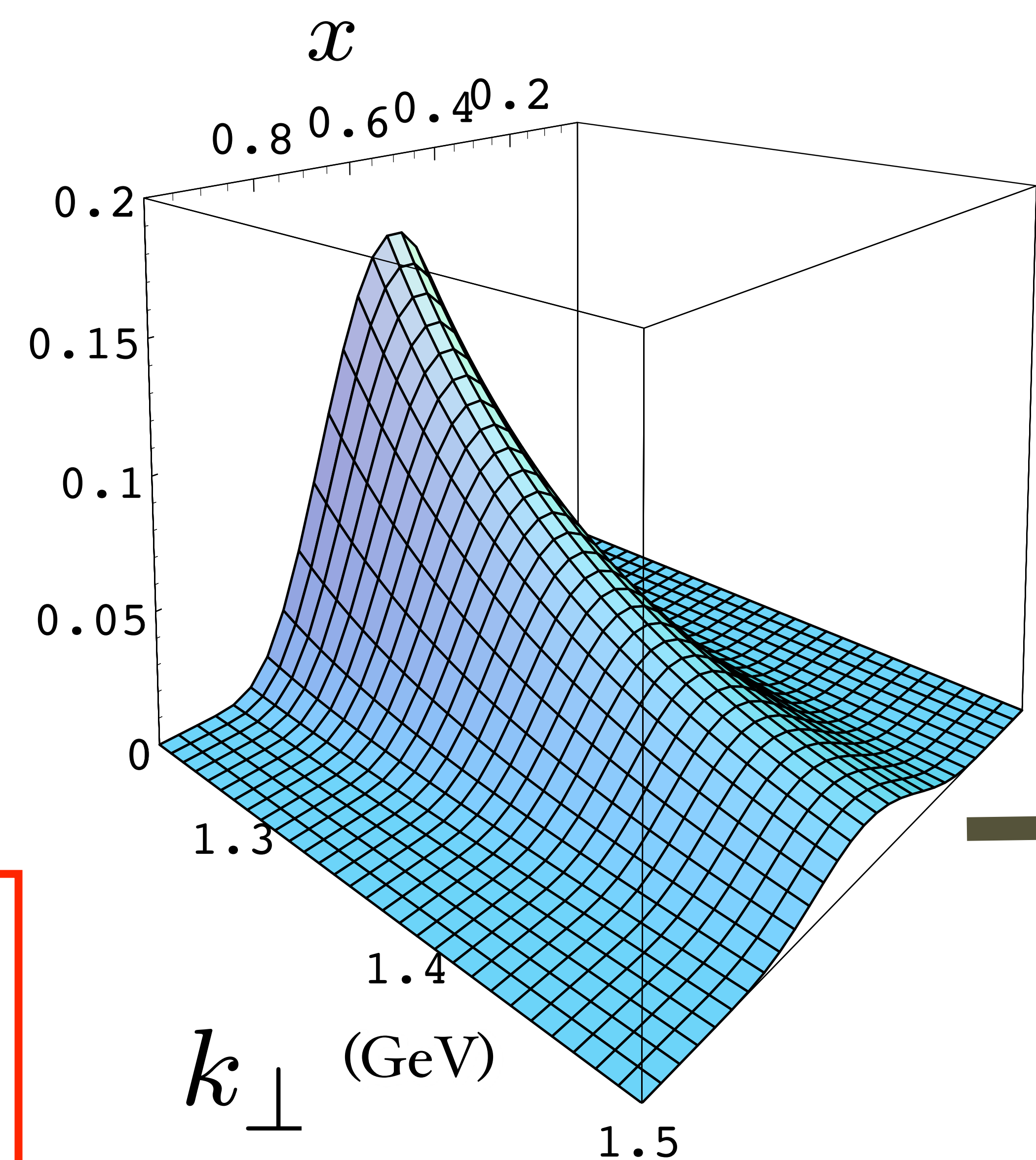
- Compute from valence light-front wavefunction

Prediction from AdS/QCD: Meson LFWF

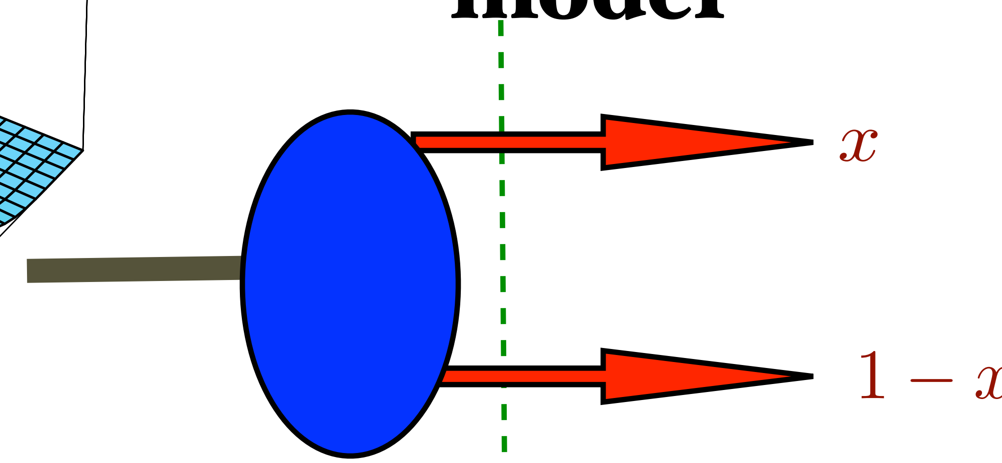
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

de Teramond, Cao, sjb

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



"Soft Wall" model



Note coupling

$$k_\perp^2, x$$

massless quarks

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

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

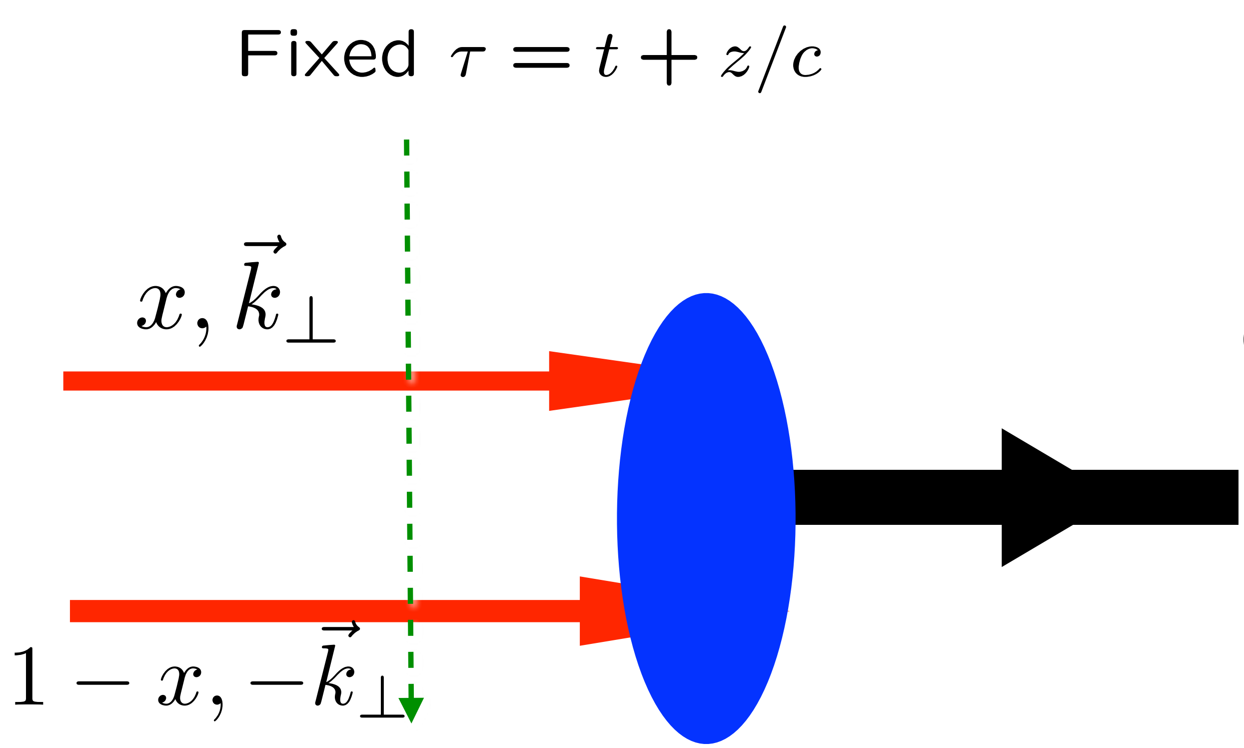
$$f_\pi = \sqrt{P_{q\bar{q}}} \frac{\sqrt{3}}{8} \kappa = 92.4 \text{ MeV}$$

Same as DSE! **C. D. Roberts et al.**

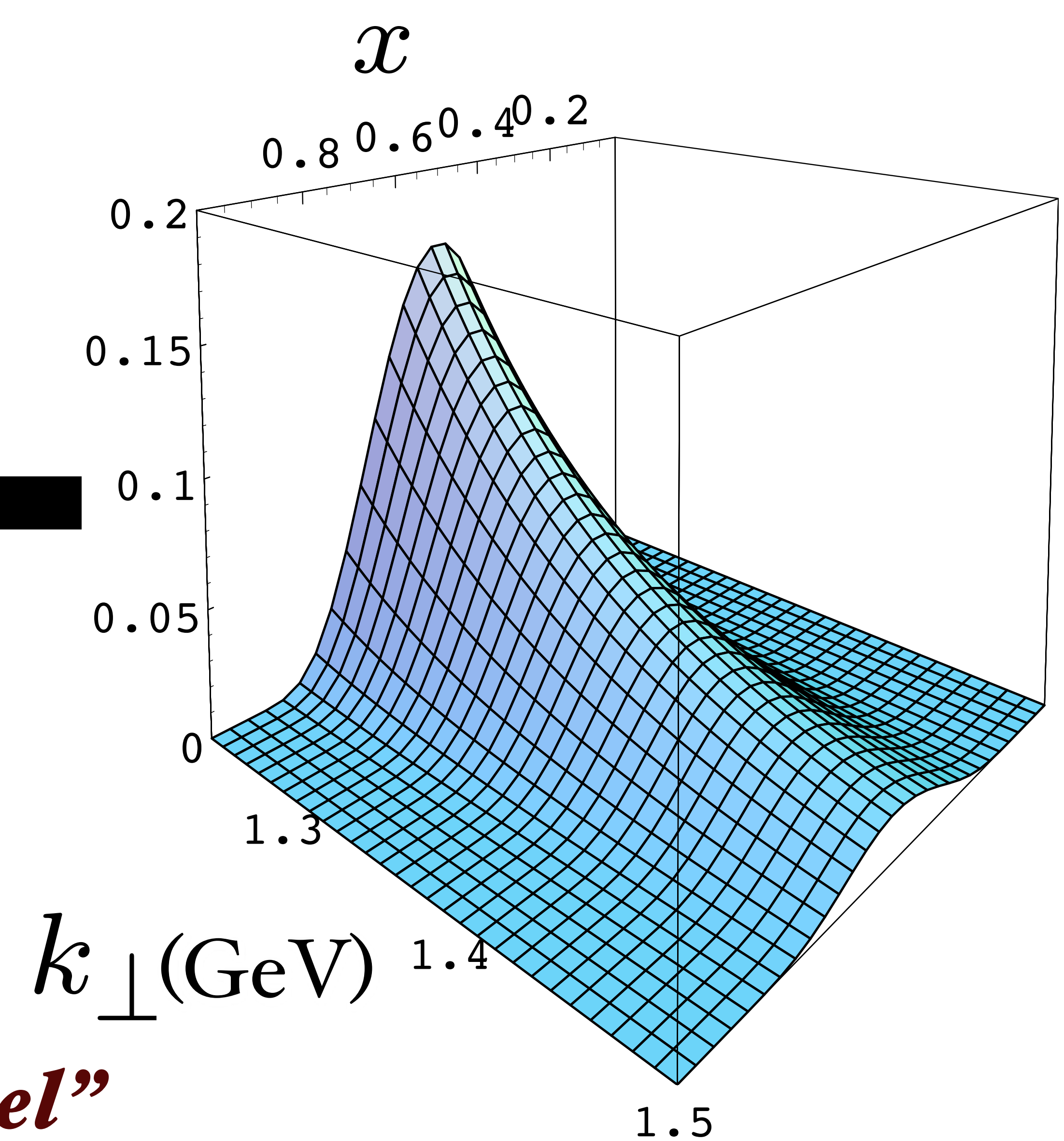
Provides Connection of Confinement to Hadron Structure

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

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



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

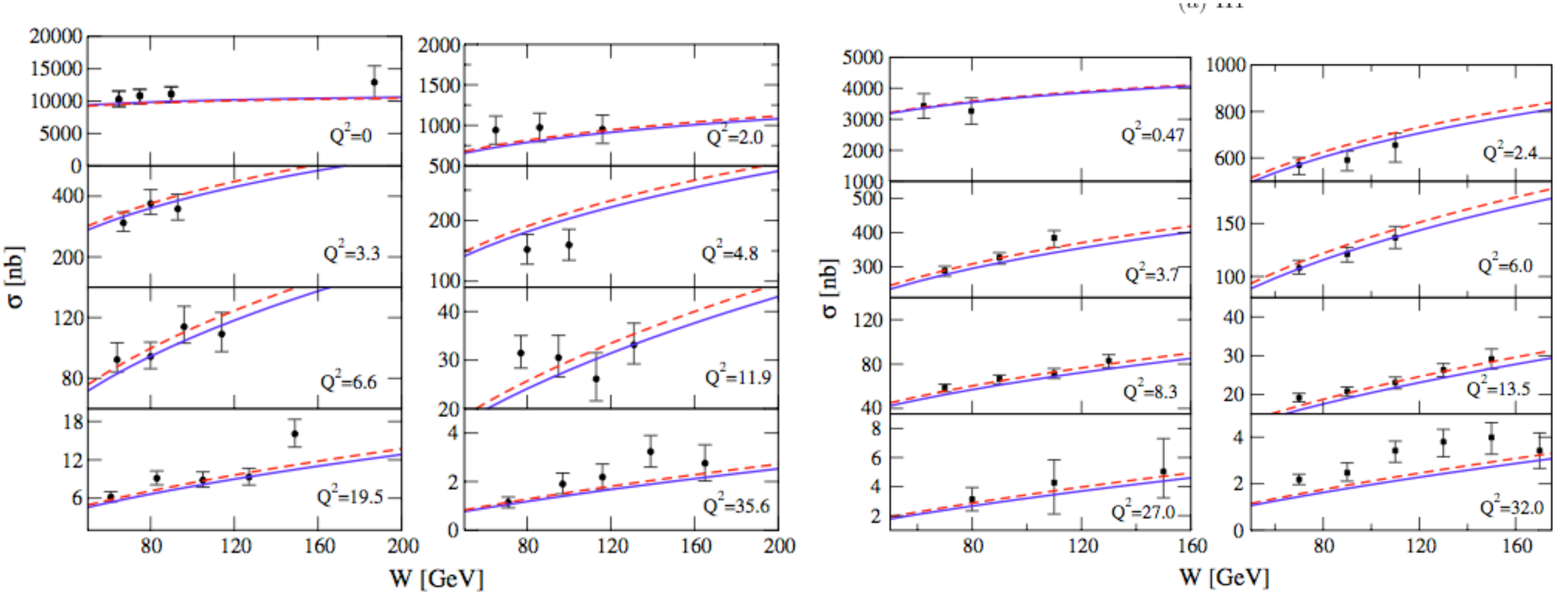


"Hadronization at the Amplitude Level"

Boost-invariant LFWF connects confined quarks and gluons to hadrons

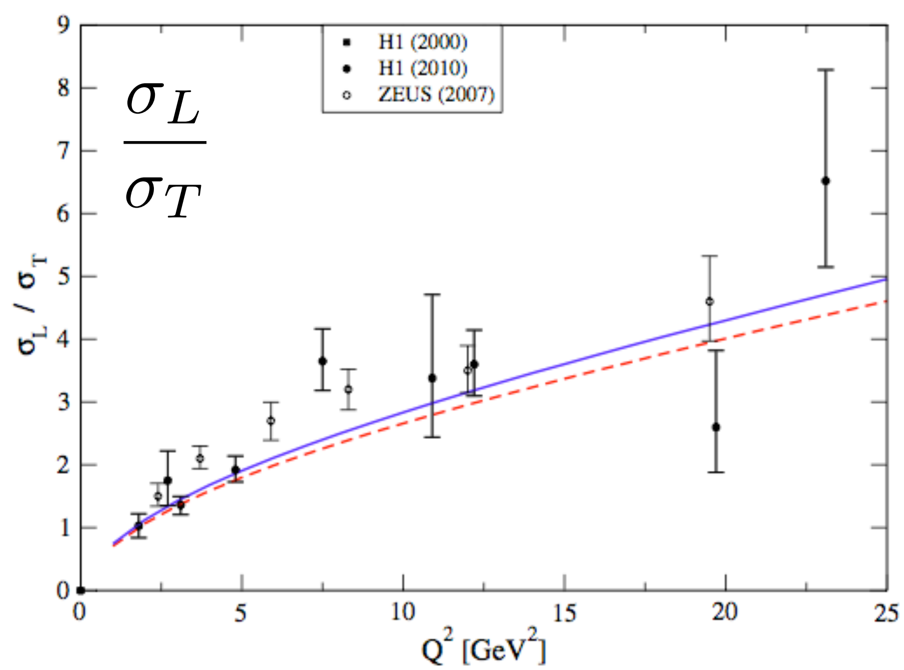
PRL **109,** 081601 (2012) PHYSICAL REVIEW LETTERS week ending 24 AUGUST 2012

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



(a) H1

(b) ZEUS

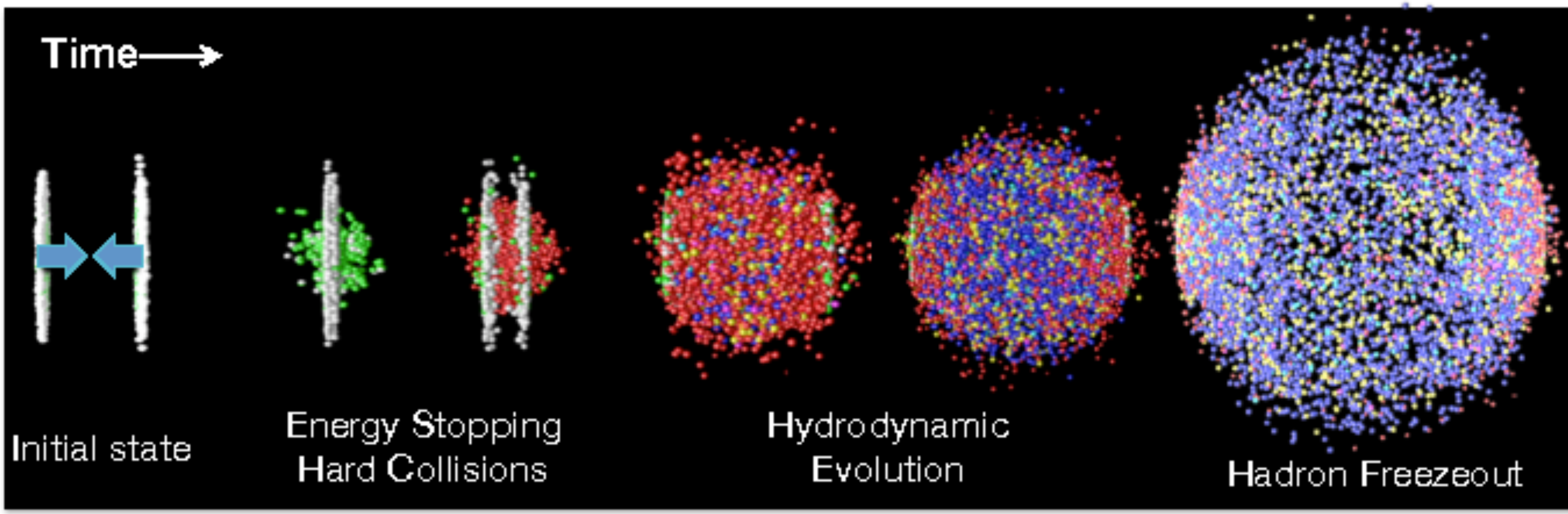


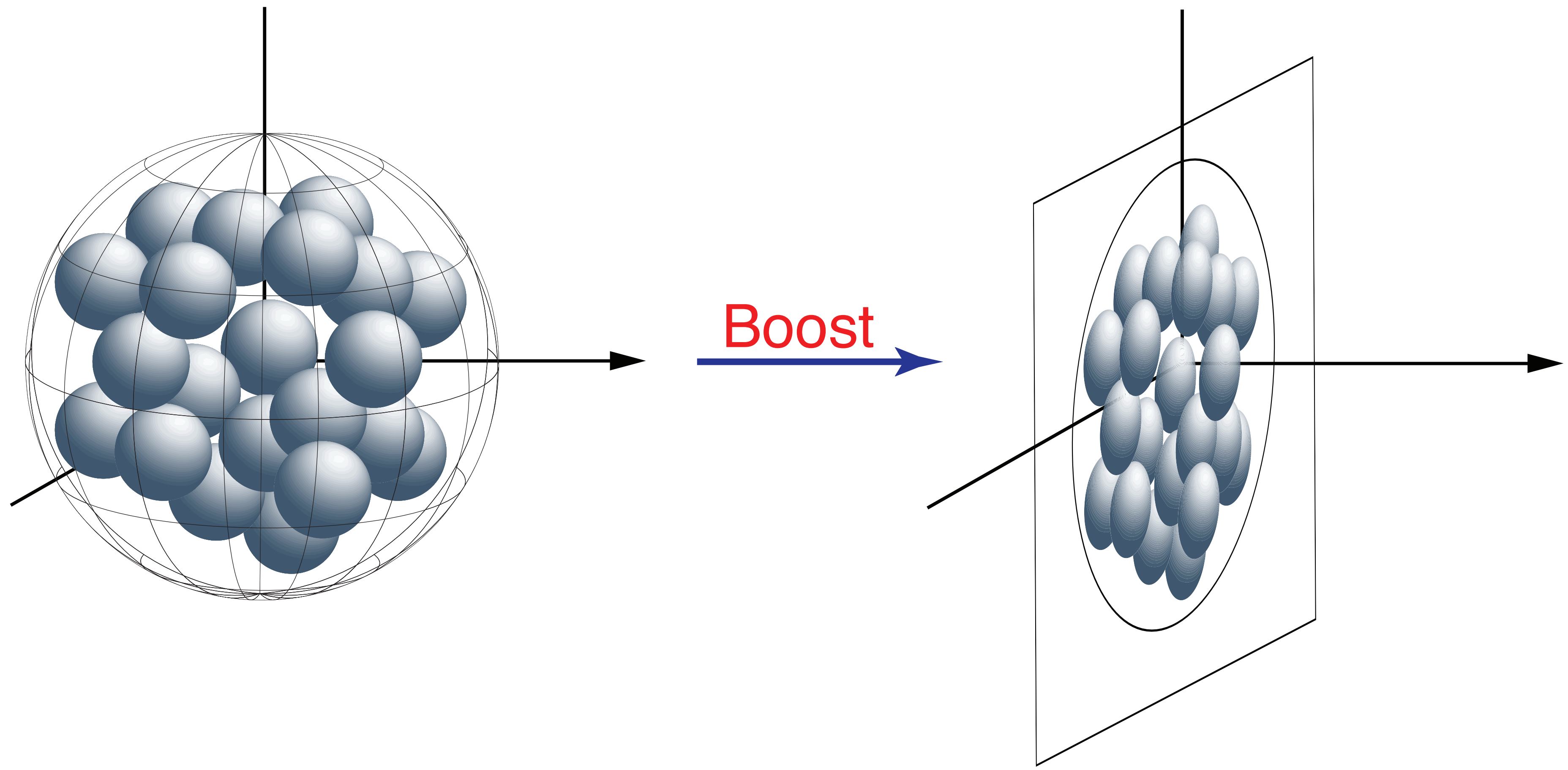
J. R. Forshaw,
R. Sandapen

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

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

Representation of Ion-Ion Collisions at RHIC, LHC





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

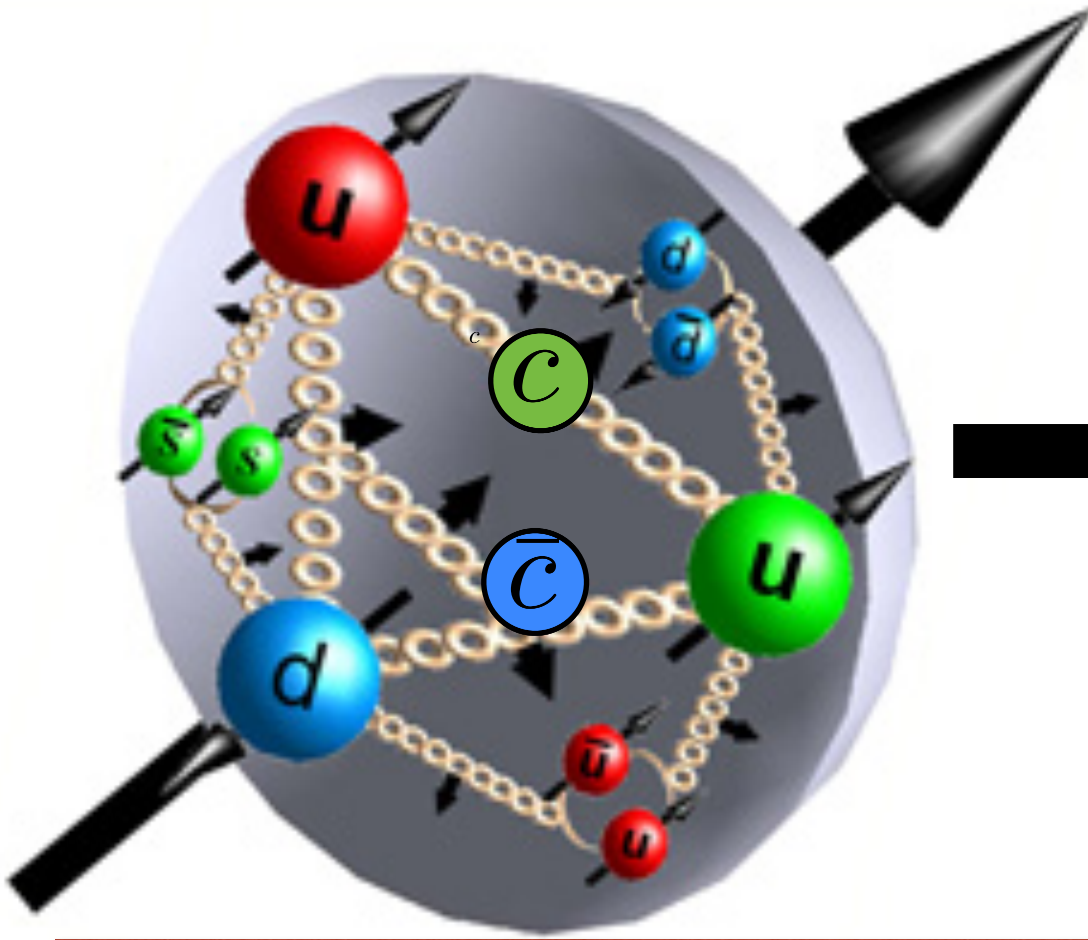
Is this really true? Will an electron-proton collider see different results than a fixed target experiment such as SLAC because the nucleus is squashed to a pancake?

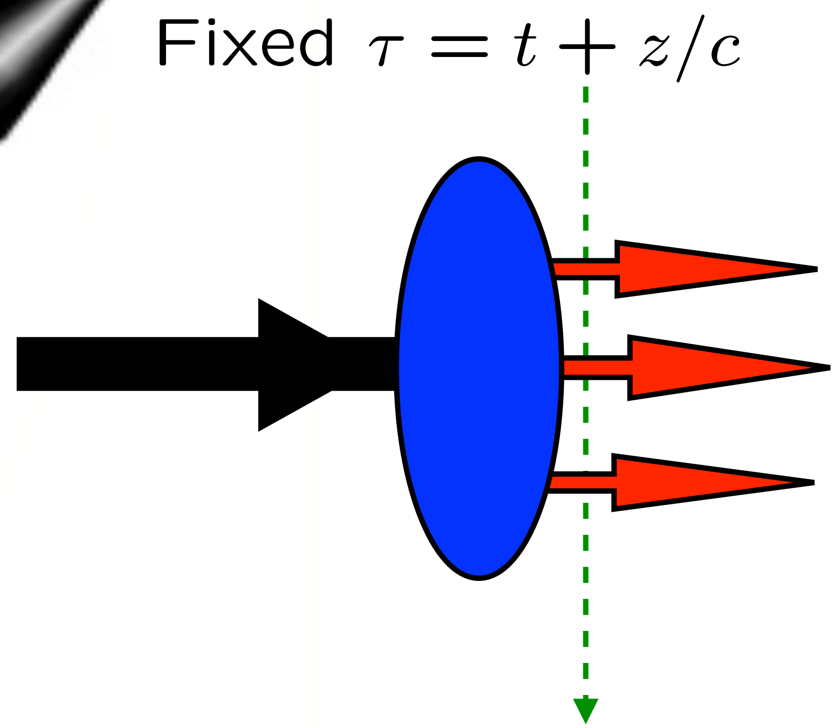
No length contraction — no pancakes!

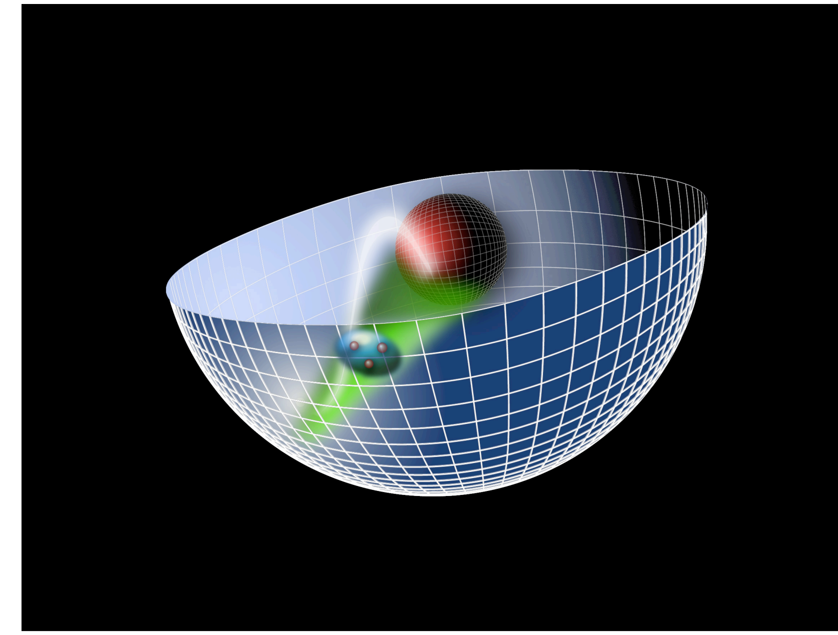
Penrose
Terrell
Weiskopf

We do not observe the nucleus at one time t!

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







The Mexican School of Particles and Fields (MSPF)

The 2018 University of Sonora School of High Energy Physics (USHEP)

Stan Brodsky

Lecture I
October 22, 2018

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