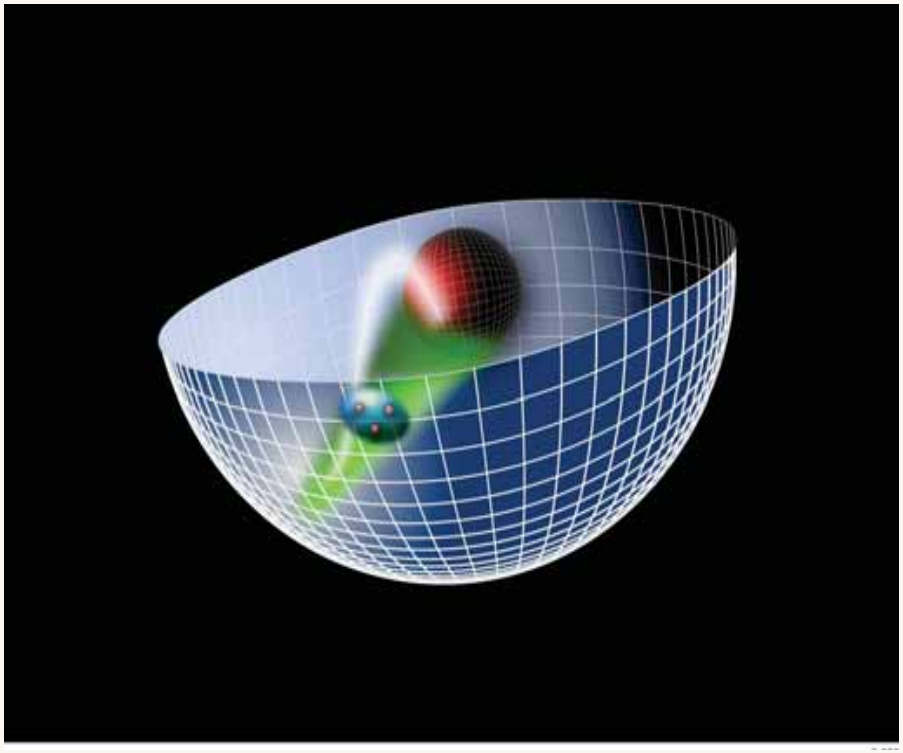
Light-Front Holography:
AdS/QCD and Novel Effects in QCD

Geiger and Rutherford



Stan Brodsky, SLAC/IPPP

University of Manchester, August 5, 2008

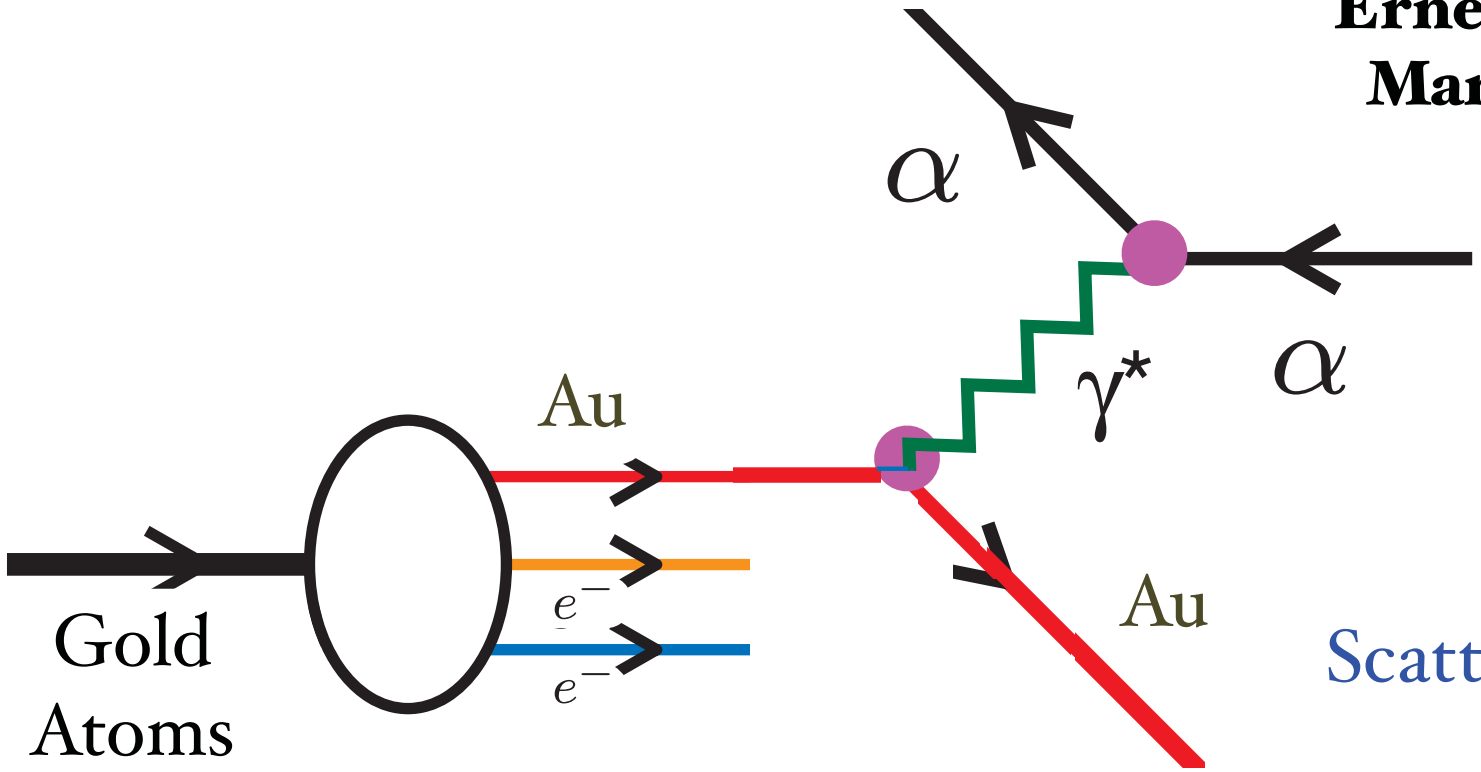
Physics at Manchester University

J J Thomson. Study and research 1871-76 (entered at age 14). Left and discovered the electron, awarded Nobel prize.
J H Poynting. Student 1867-72 (one of the very first students in the new Physical Laboratories) Lecturer 1876-79. Left to become Professor at Mason College (which became Birmingham University).
C T R Wilson. Student 1884-87. Went to Cambridge, invented the expansion cloud chamber and was awarded Nobel prize.
E Rutherford. 1907-1919. Nobel prize 1908.
J Chadwick. Researcher 1910-11, got MSc. Left for Cambridge, discovered neutron and awarded Nobel prize.
H Geiger. Researcher 1910-14. Did the original "Rutherford scattering" experiment with Marsden. Devised ionisation counter.
N Bohr. Research Staff 1913-14. Worked on structure of atom. Awarded Nobel prize.
W L Bragg. Director 1919-1937. Nobel prize for X-ray crystallography, shared with Dad, 1915.
N Mott. Lecturer 1929-30. Left for Cambridge and then Professor at new University in Bristol. Awarded Nobel prize in 1977.
H Bethe. Research staff 1932. Left for Cornell. Awarded Nobel prize.

Douglas Hartree. 1929-1946. Built and operated a differential analyser to evaluate the wave functions of multi-electron atoms.
P M Blackett 1937-53. Director. Awarded Nobel prize for developing cloud chamber and confirming positron.
G D Rochester Discovered strange particles in 1947 with C C Butler.
C C Butler co-discovered strange particles in 1947. Went on to be head of dept at Imperial College and then VC at Loughborough.
A Wolfendale. PhD 1954 in cosmic rays. Former Astronomer Royal.

First Evidence for Nuclear Structure of Atoms

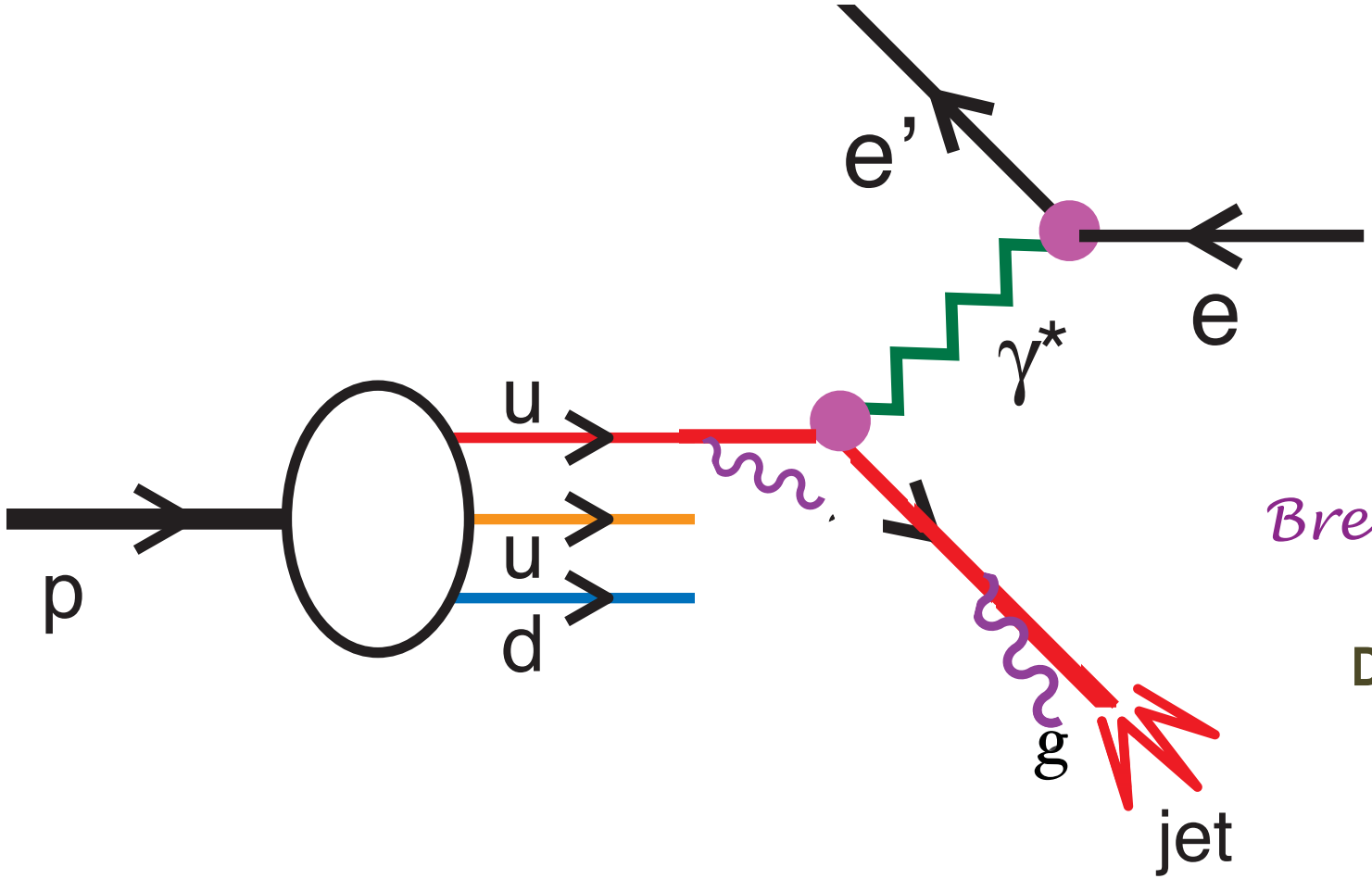
Ernest Rutherford
Manchester 1911



Scattering at Large Angles
"Point-like" Nucleus

Rutherford Scattering

First Evidence for Quark Structure of Matter

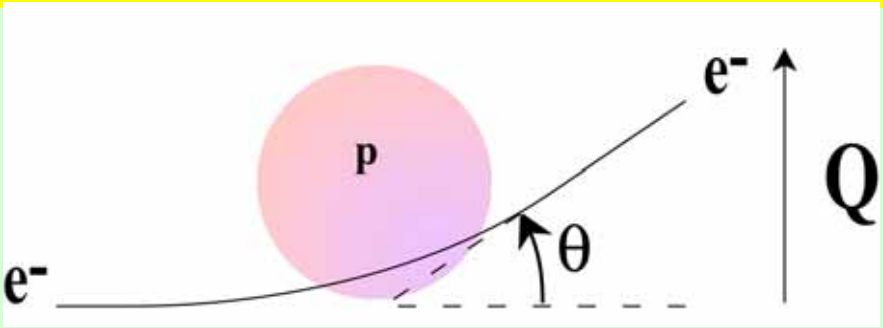


Gluonic Bremmstrahlung

DGLAP Evolution

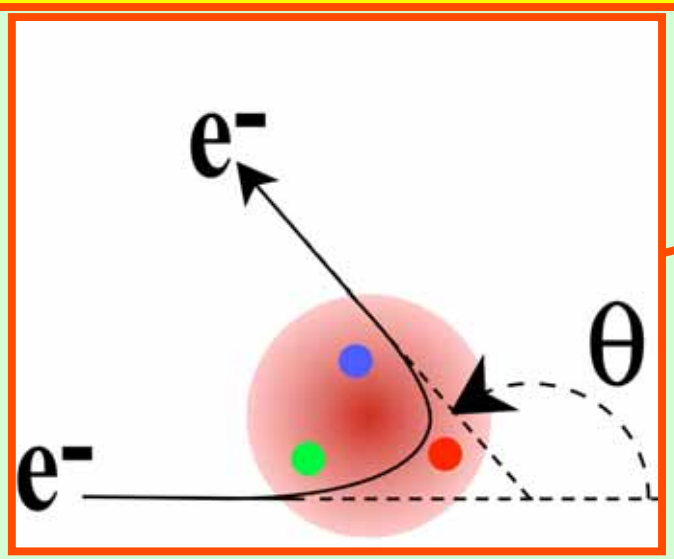
Deep Inelastic Electron-Proton Scattering

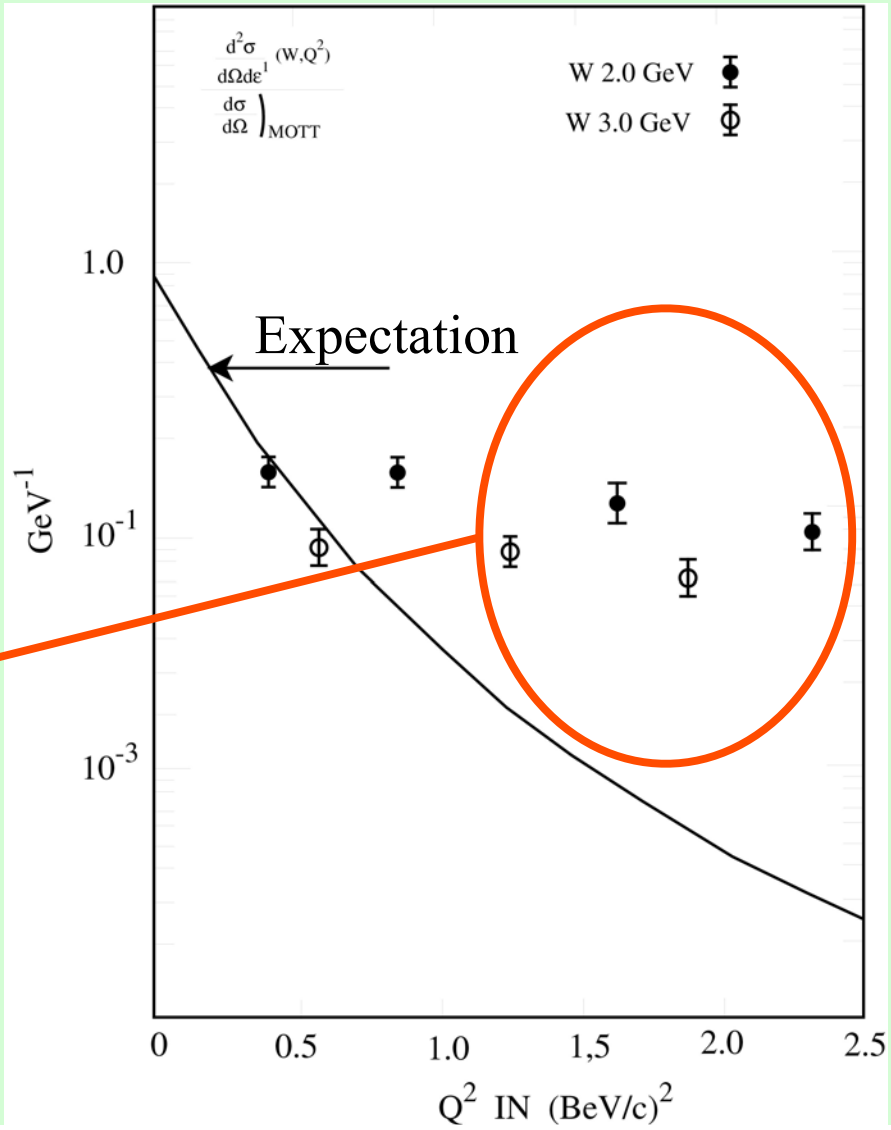
Deep inelastic electron-proton scattering



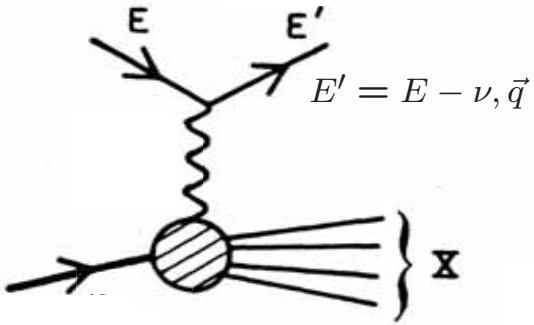
- **Rutherford scattering using *very* high-energy electrons striking protons**

Discovery of quarks!

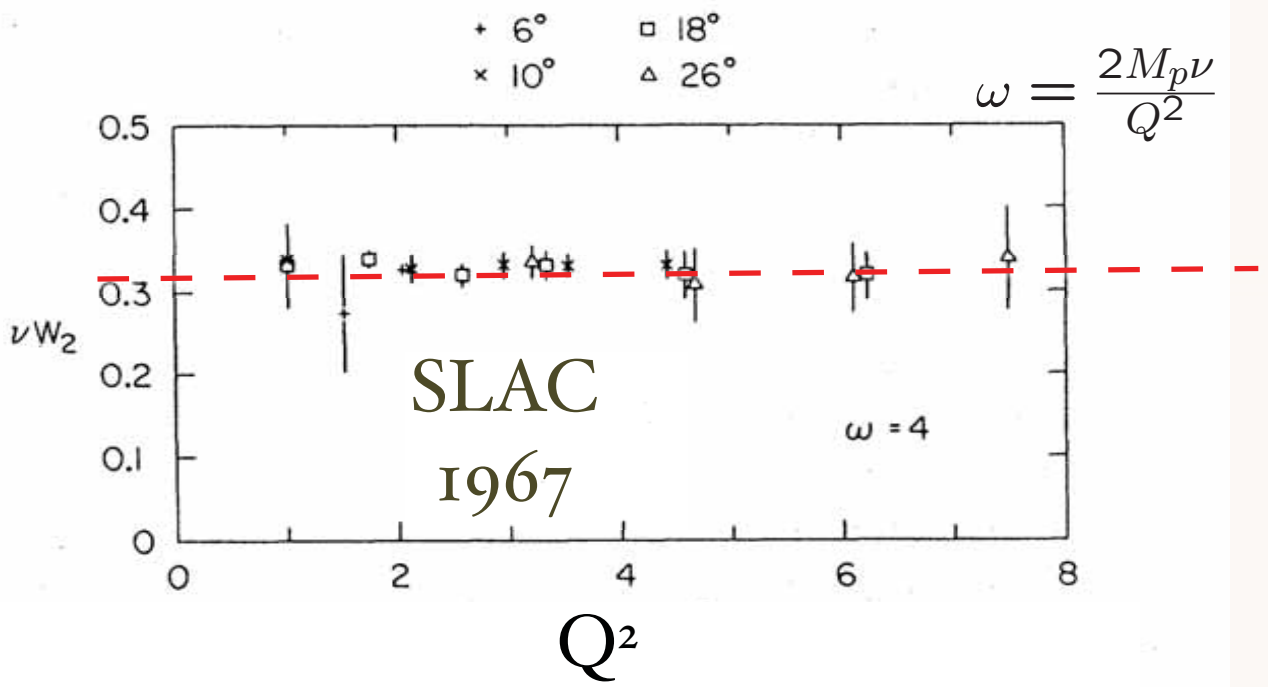




$$ep \to e'X$$



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



No intrinsic length scale !

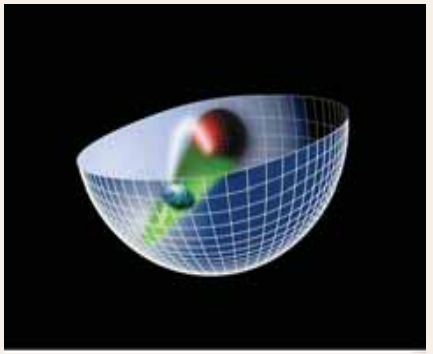
Measure rate as a function of energy loss ν and momentum transfer Q

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

Discovery of Bjorken Scaling

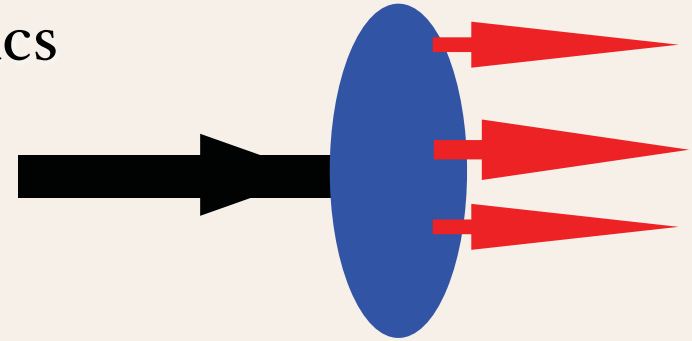
Electron scatters on point-like quarks!

- Quarks and Gluons:
  Fundamental constituents of hadrons and nuclei
- *Quantum Chromodynamics (QCD)*
- New Insights from higher space-time dimensions: *AdS/QCD*



- *Light-Front Holography*
- *Hadronization at the Amplitude Level*
- *Light Front Wavefunctions:* analogous to the Schrodinger wavefunctions of atomic physics

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



QCD Lagrangian

$$\mathcal{L}_{QCD} = \bar{\psi}_i(i\gamma_\mu D^\mu_{ij} - m\delta_{ij})\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$= \bar{\psi}_i(i\gamma_\mu\partial_\mu - m)\psi_i - gA^a_\mu\bar{\psi}_i\gamma^\mu T^a_{ij}\psi_j - \tfrac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$

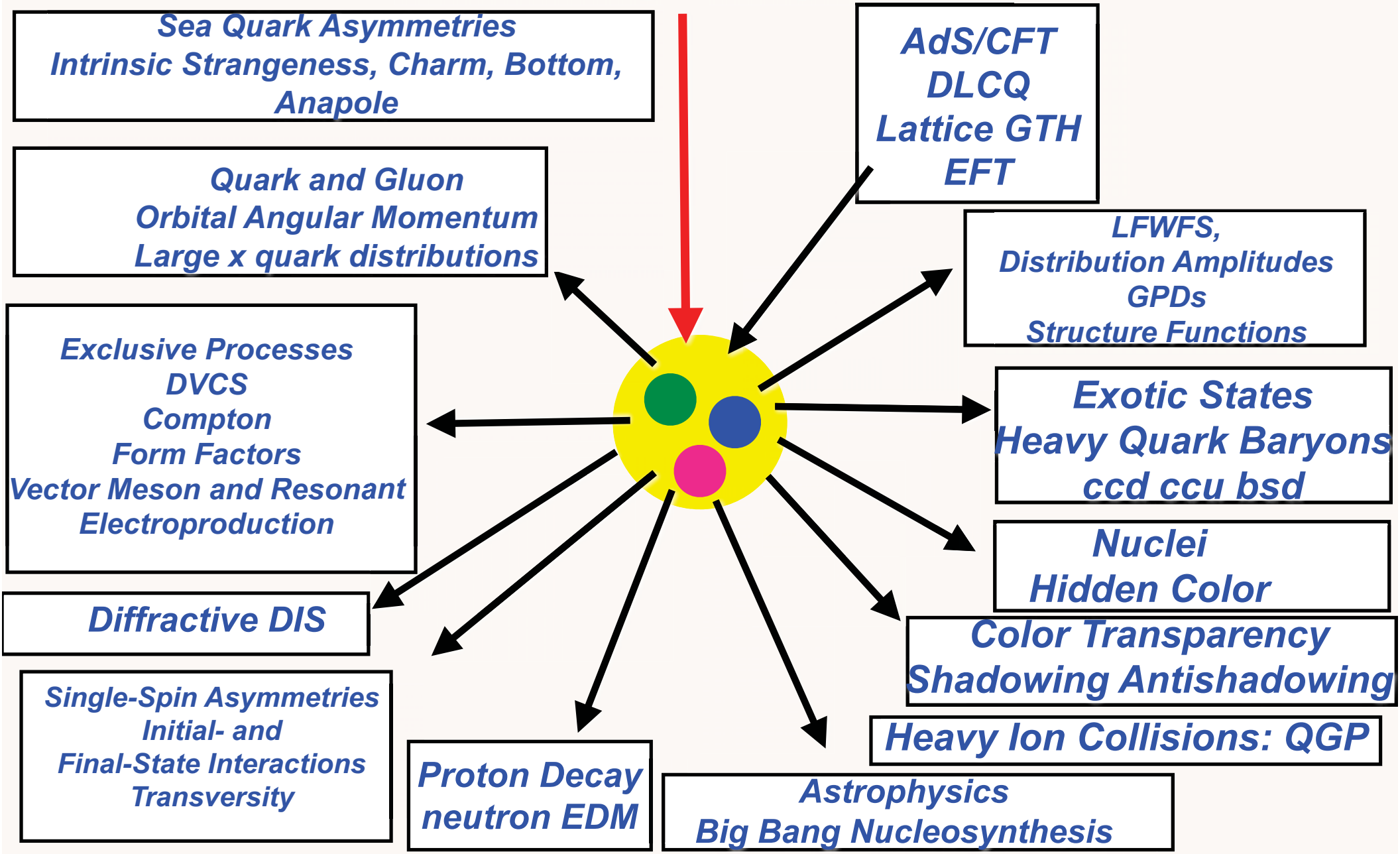
Yang-Mills Gauge Principle: Invariance under Color Rotation and Phase Change at Every Point of Space and Time

Dimensionless Coupling
Renormalizable
Asymptotic Freedom
Color Confinement

Huet & sjb

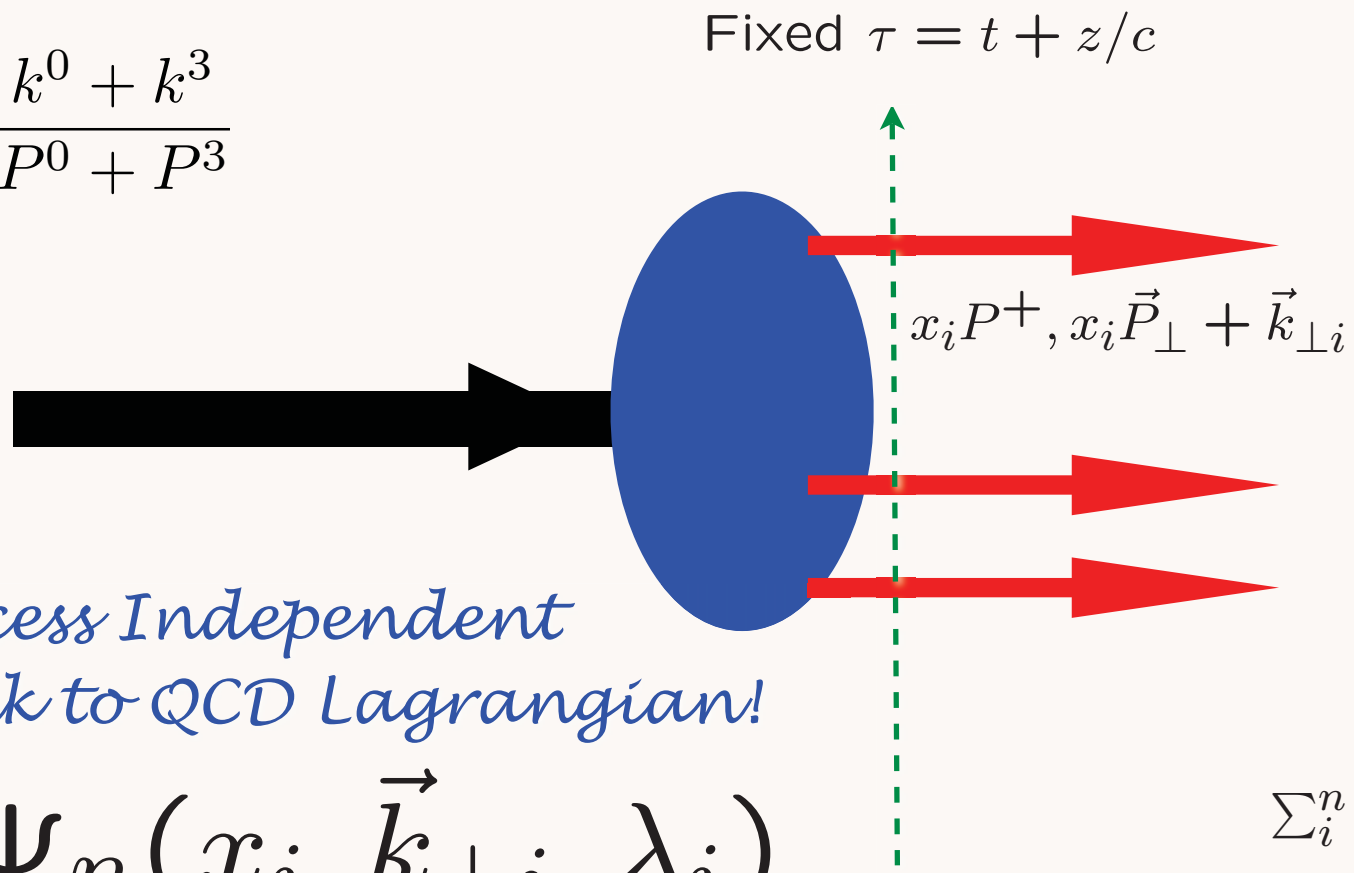
QCD $\rightarrow$ QED if $N_C \rightarrow 0$ at fixed $\alpha = C_F\alpha_s$. $C_F = \frac{N_C^2-1}{2N_C}$

QCD Lagrangian



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

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



Process Independent

Direct Link to QCD Lagrangian!

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

$$\sum_i^n x_i = 1$$

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

Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions

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

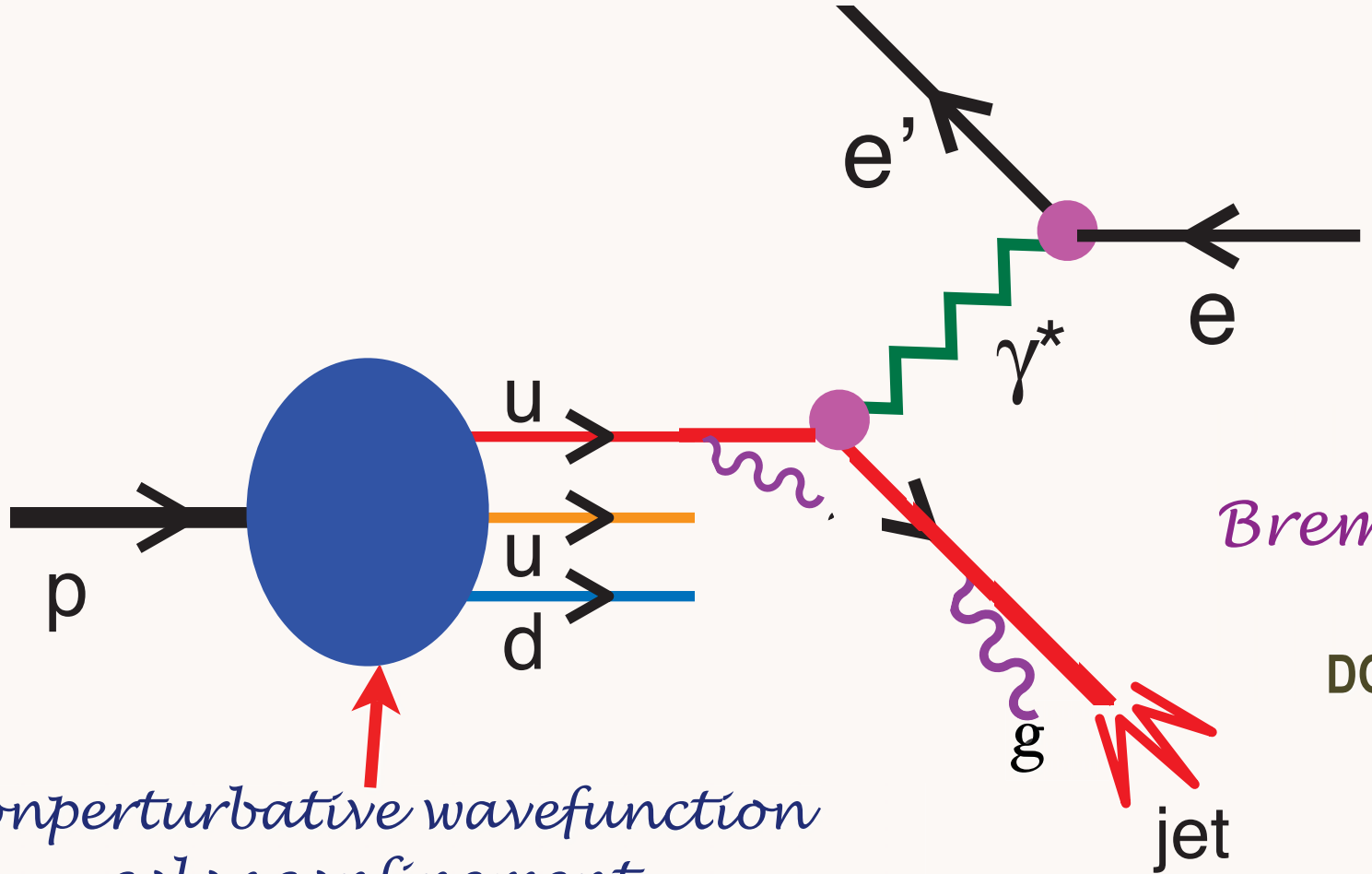
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \qquad x_i = \frac{k_i^+}{P+}$$

Invariant under boosts. Independent of P^μ

$$H_{LF}^{QCD}|\psi> = M^2|\psi>$$

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

Deep Inelastic Electron-Proton Scattering



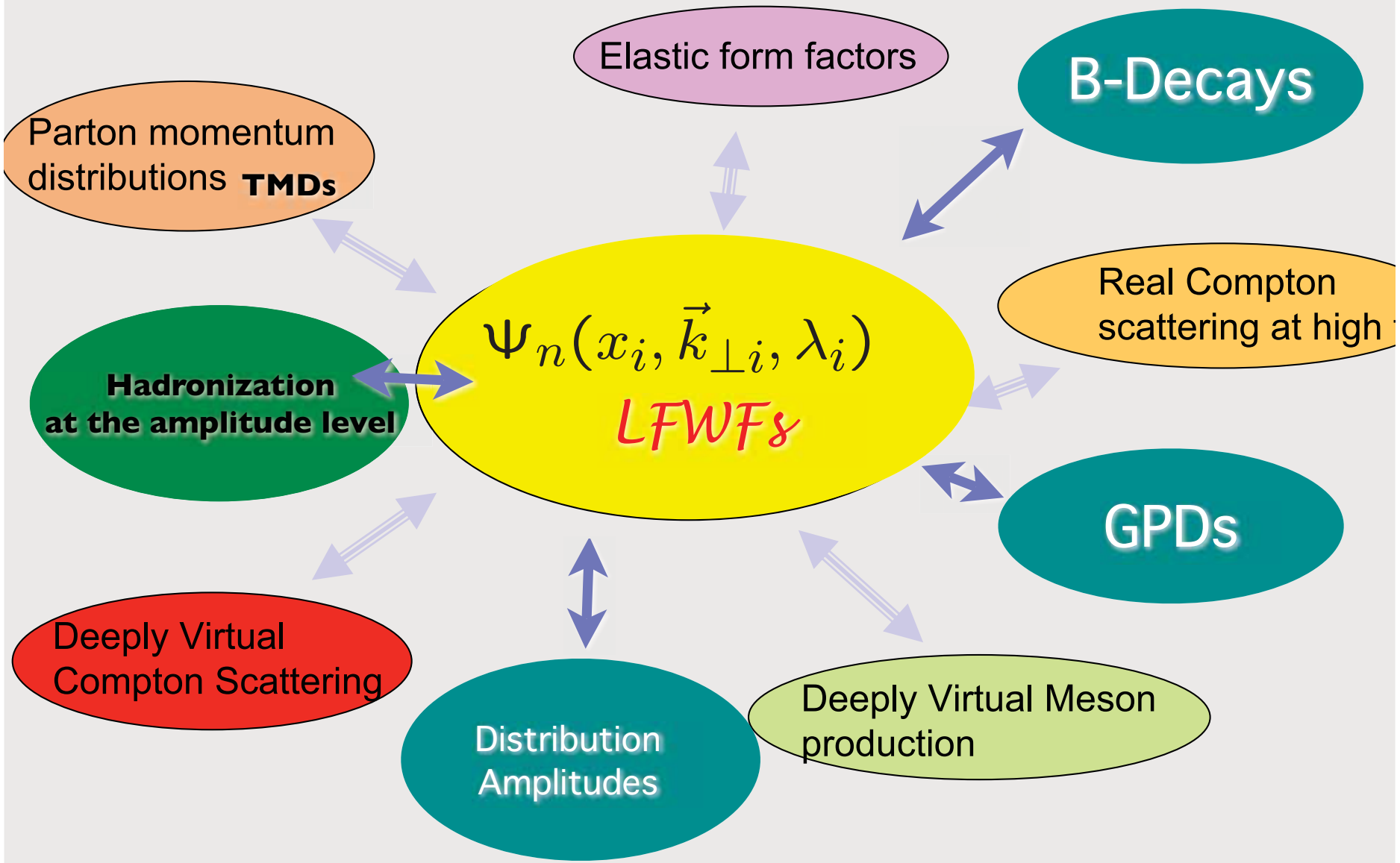
Gluonic Bremmstrahlung

DGLAP Evolution

Nonperturbative wavefunction
color confinement
spin, momenta, orbital angular momentum ....

Light-Front Quantization: Rigorous realization of IMF

A Unified Description of Hadron Structure



Each element of flash photograph illuminated at same LF time

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

Boundary conditions set at fixed

$$\tau = \tau_0$$

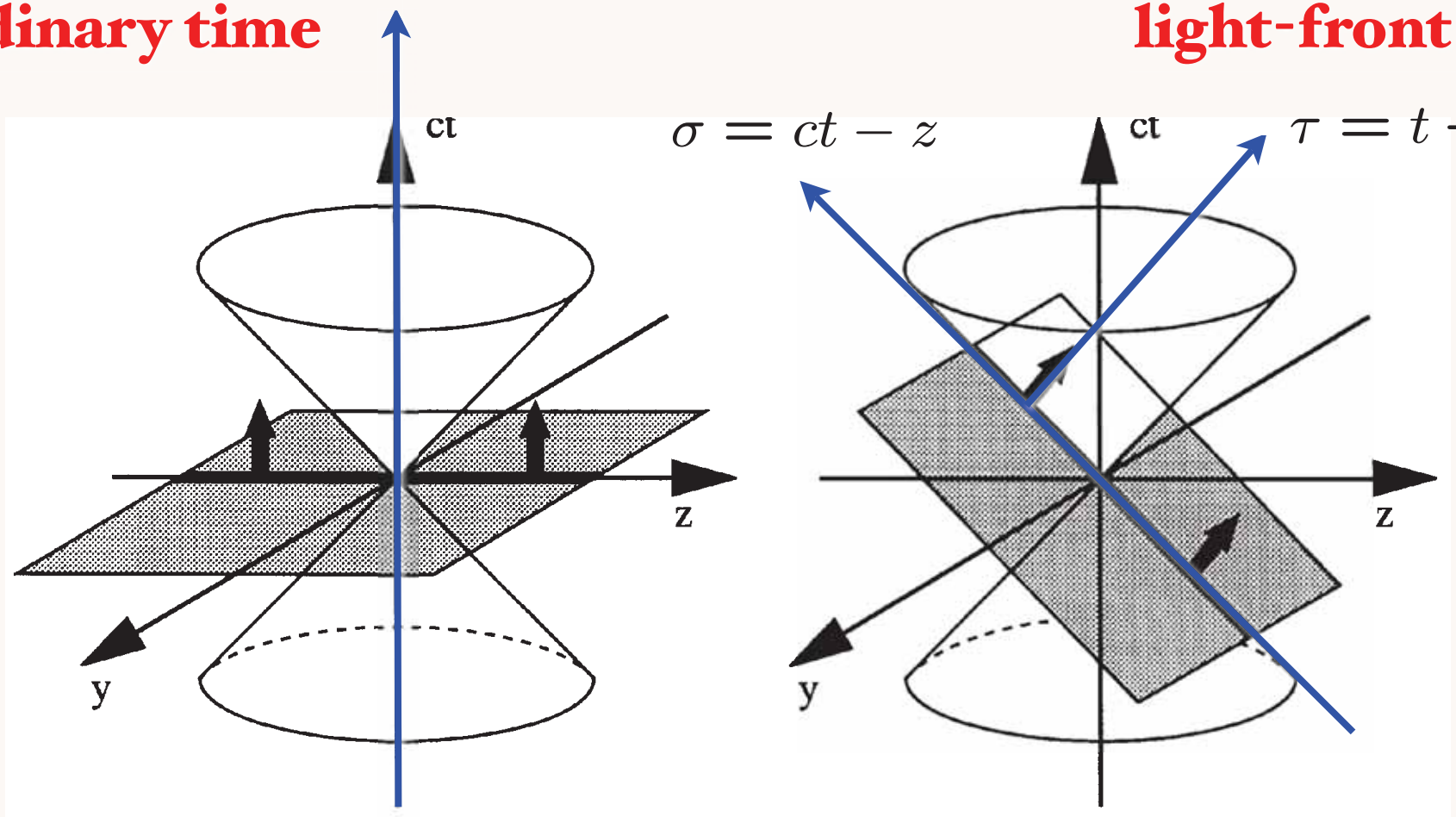
HELEN BRADLEY - PHOTOGRAPHY

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

Dirac's Amazing Idea: The Front Form

Evolve in ordinary time

Evolve in light-front time!



Instant Form **Front Form**

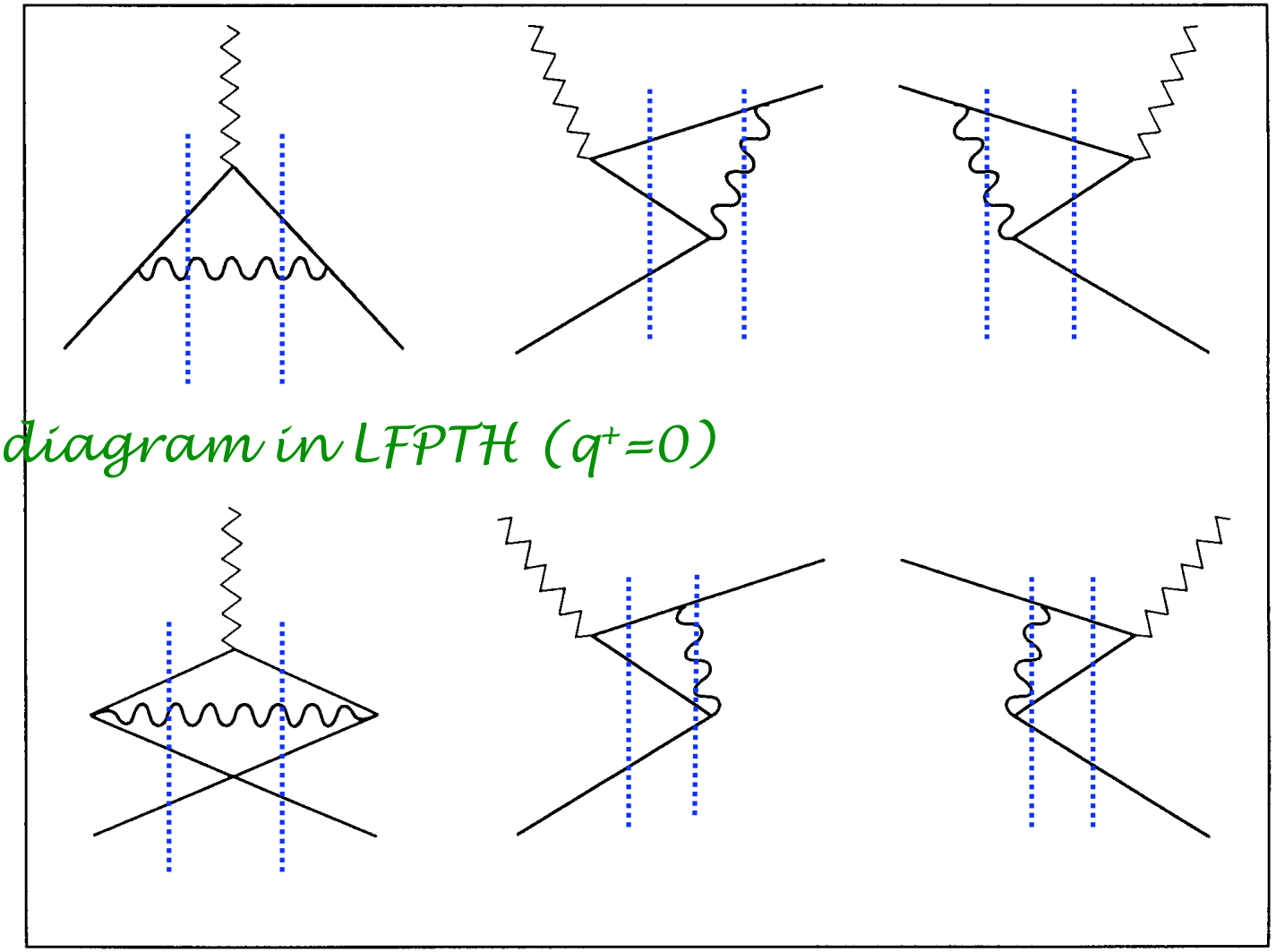
'Tis a mistake / Time flies not
It only hovers on the wing
Once born the moment dies not
'tis an immortal thing

...A moment standing still for ever.

James Montgomery 1833

Sed fugit, interea, fugit irreparabile tempus.
VIRG. *Georg.* iii. 284.

Calculation of lepton g-2 in TOPTH (Instant form)



Only diagram in LFPTH ($q^+=0$)

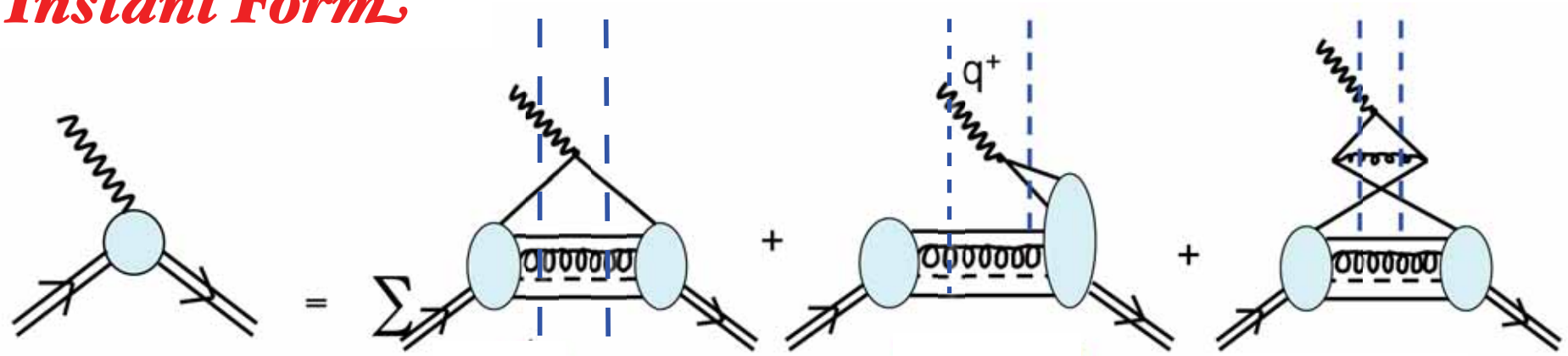
n! diagrams at order e^n

energy denominators:
frame dependent and non-analytic

$$\sqrt{(\vec{p}+\vec{q}-\vec{k})^2+m^2}$$

Calculation of Form Factors in Equal-Time Theory

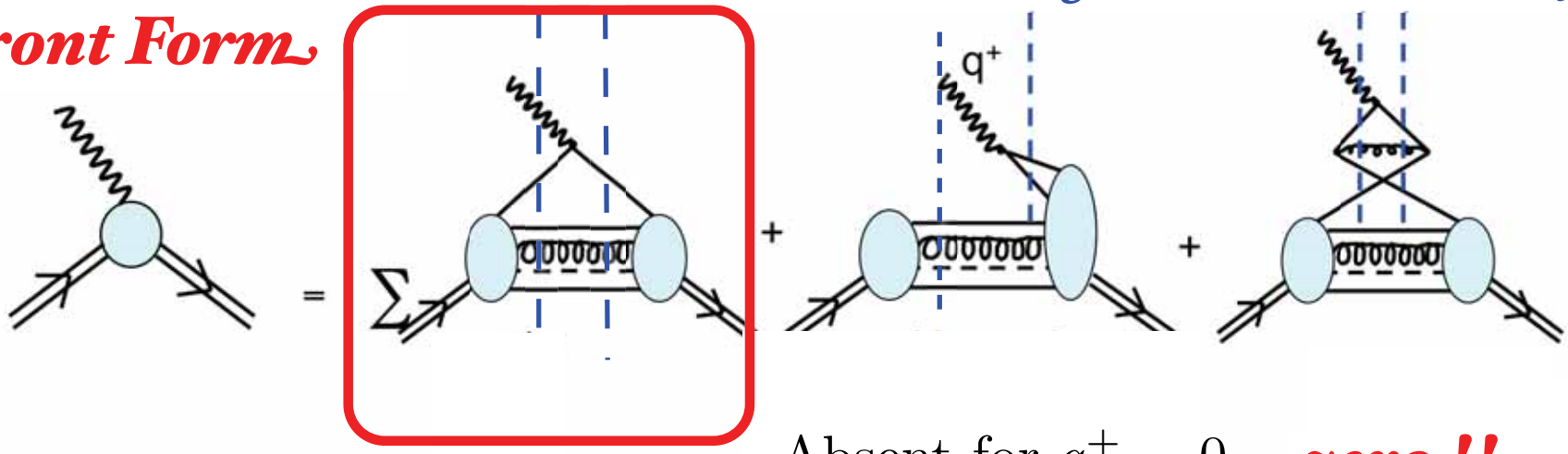
Instant Form



Need vacuum-induced currents

Calculation of Form Factors in Light-Front Theory

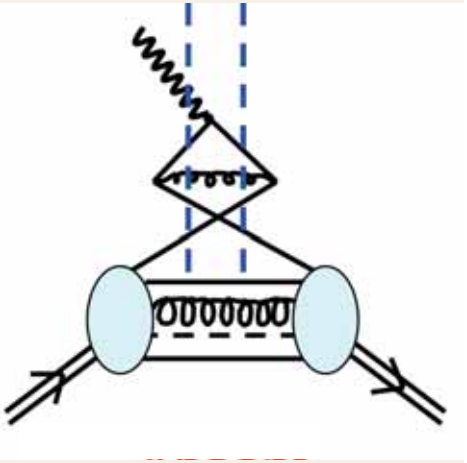
Front Form



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

Calculation of Hadron Form Factors Instant Form

- Current matrix elements of hadron include interactions with vacuum-induced currents arising from infinitely-complex vacuum
- Pair creation from vacuum occurs at any time before probe acts -- acausal
- Knowledge of hadron wavefunction insufficient to compute current matrix elements
- Requires dynamical boost of hadron wavefunction -- unknown except at weak binding
- Complex vacuum even for QED
- None of these complications occur for quantization at fixed LF time (front form)



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

Drell, sjb

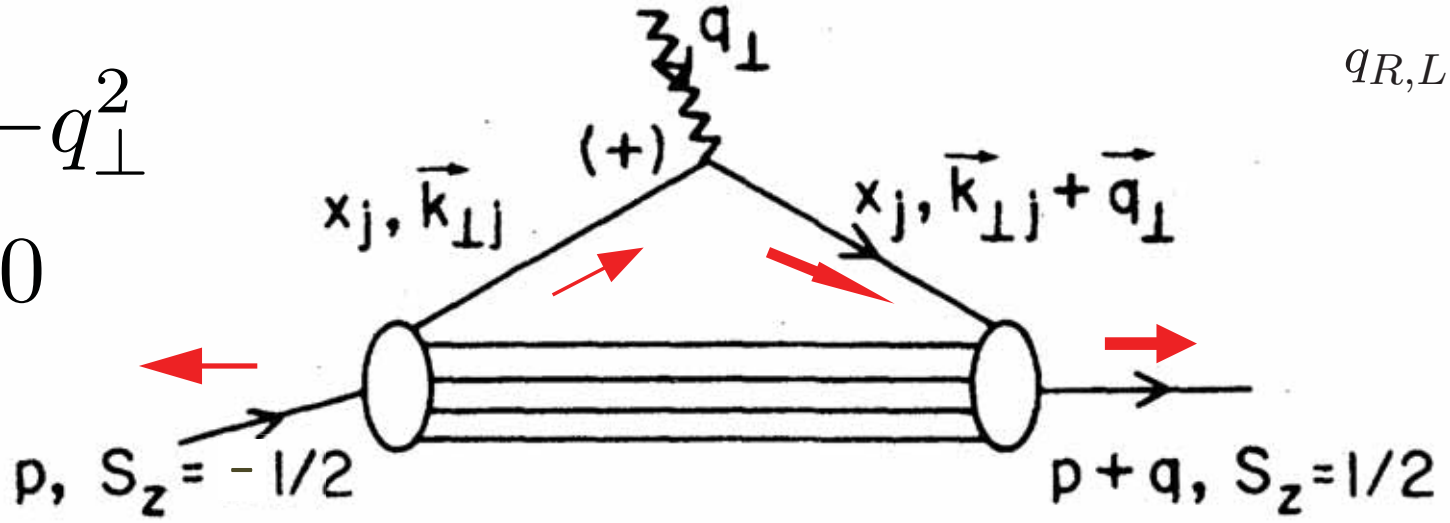
$$\Big[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \Big]$$

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

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

$$q^+ = 0$$

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



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

Checked to $\mathcal{O}\alpha^3$ *in QED* Pinsky, Suaya, sjb

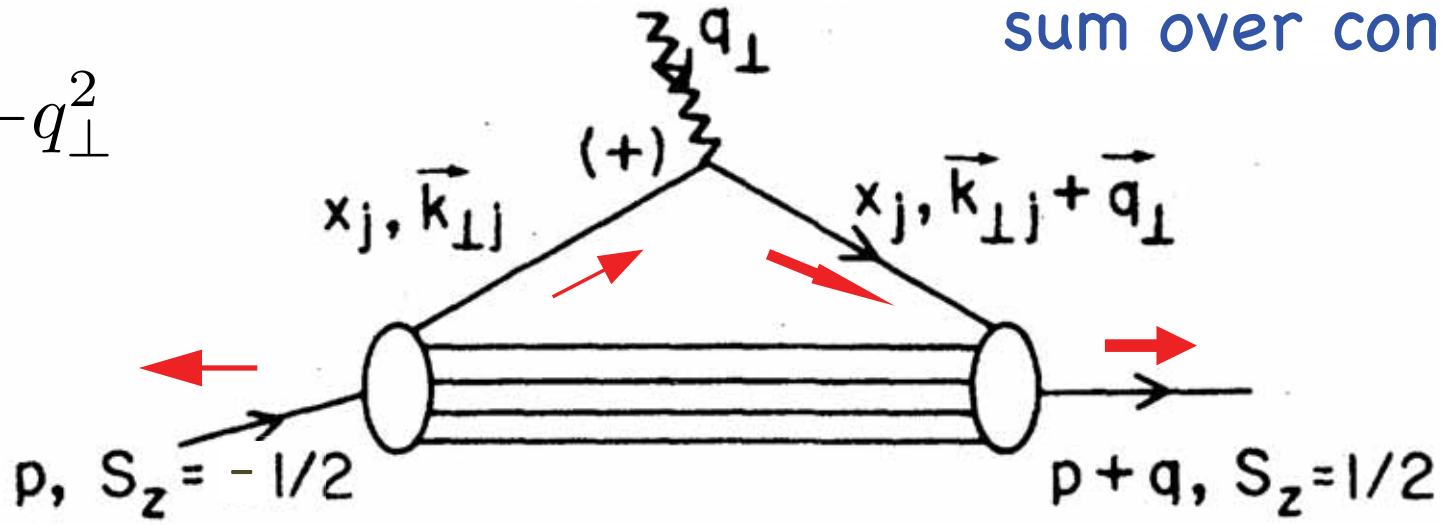
Anomalous gravitomagnetic moment B(0)

Okun, Kobzarev, Teryaev: B(0) Must vanish because of Equivalence Theorem

graviton

sum over constituents

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



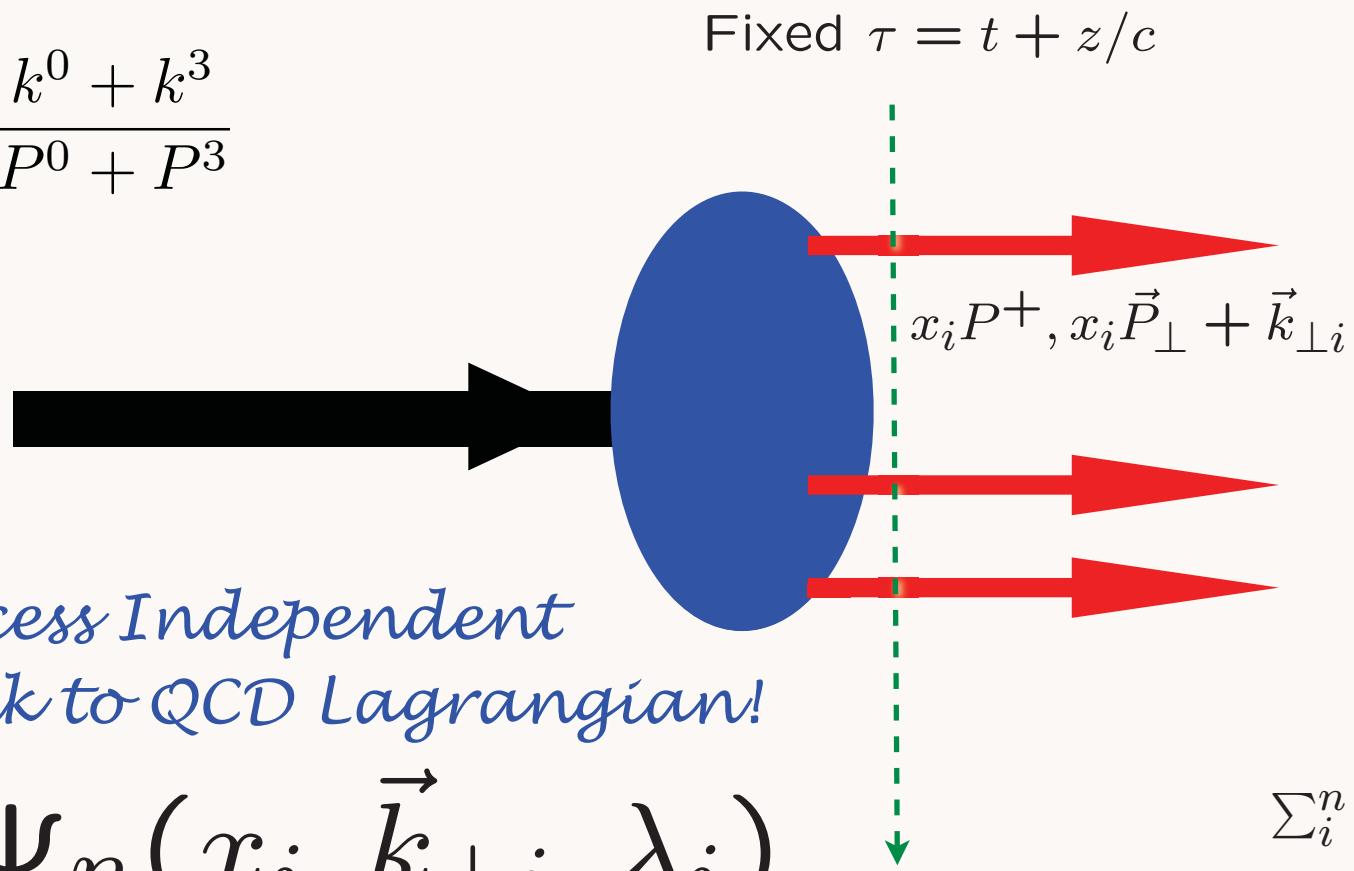
Hwang, Ma, Schmidt, sjb; Holstein et al

B(0) = 0

Each Fock State

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

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



Process Independent

Direct Link to QCD Lagrangian!

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

$$\sum_i^n x_i = 1$$

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

Invariant under boosts! Independent of P^μ

Angular Momentum on the Light-Front

A^+=0 gauge: No unphysical degrees of freedom

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

Conserved
LF Fock state by Fock State

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

n-1 orbital angular momenta

Nonzero Anomalous Moment requires Nonzero orbital angular momentum

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

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

The Light Front Fock State Wavefunctions

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

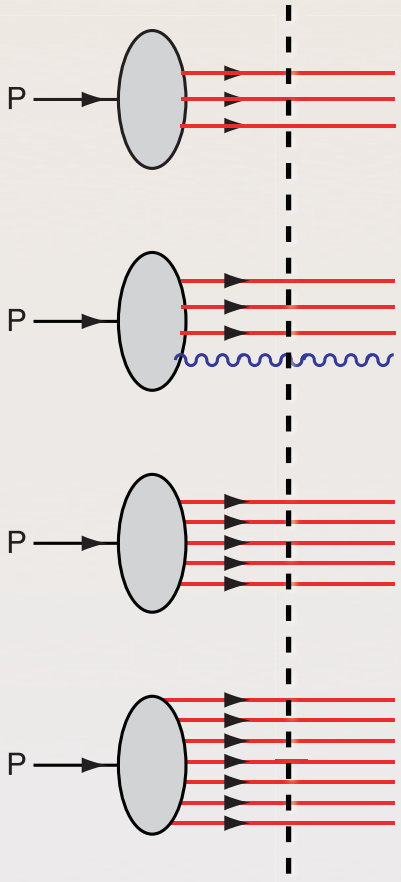
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

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

are boost invariant.

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



Fixed LF time

Intrinsic heavy quarks, $\bar{s}(x) \neq s(x)$

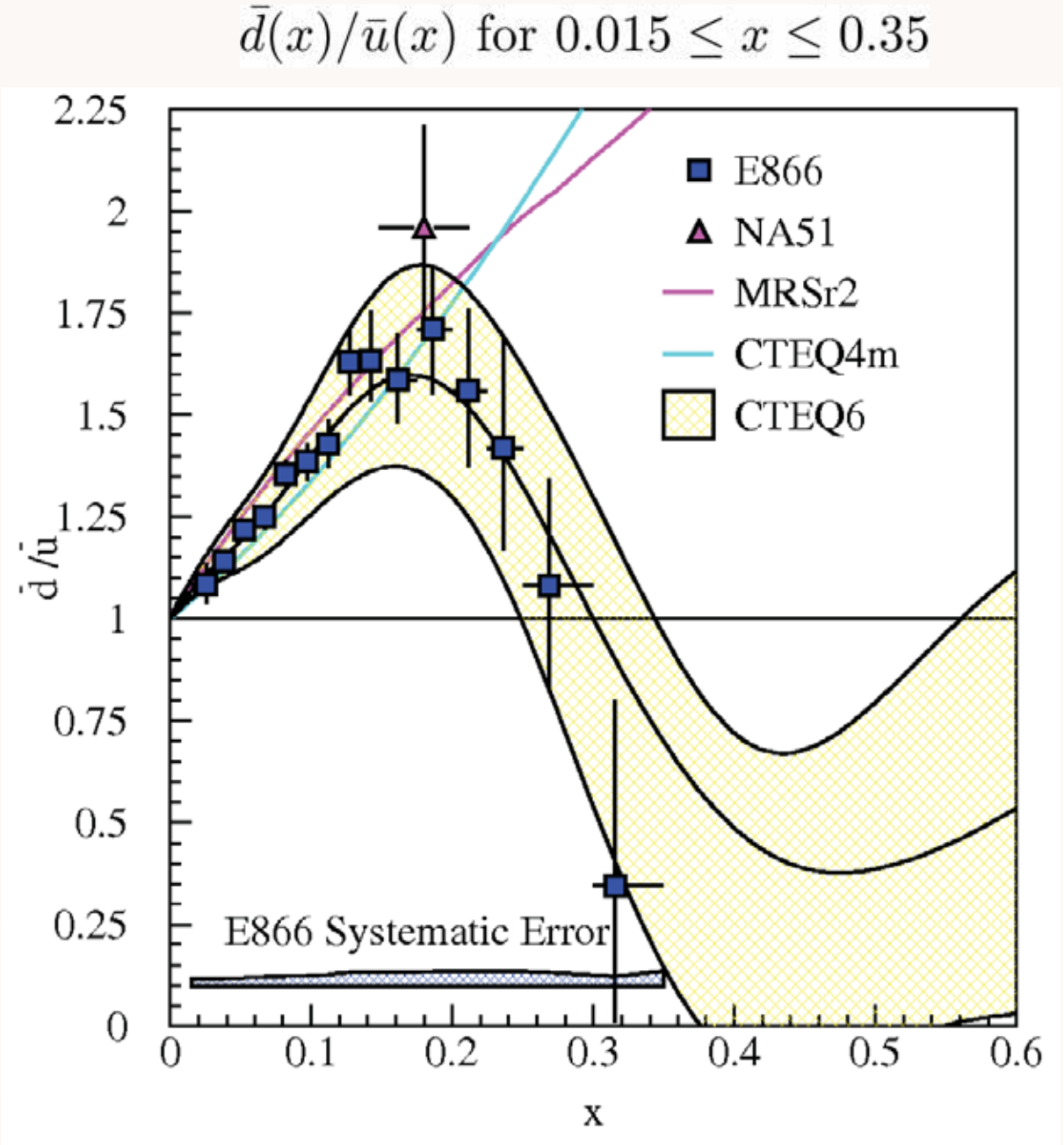
$\bar{u}(x) \neq \bar{d}(x)$

- E866/NuSea (Drell-Yan)

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

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

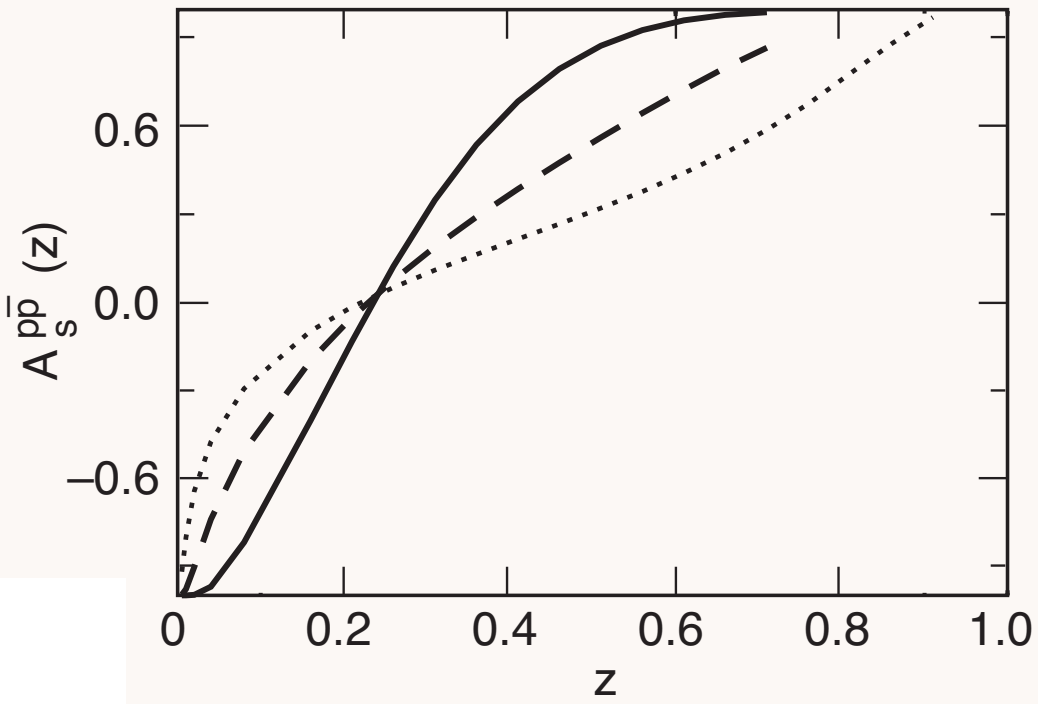
Intrinsic glue, sea, heavy quarks



Compare protons versus anti-proton in $\bar{s}$ current quark fragmentation

$$D_{s\to p}(z) \neq D_{s\to \bar{p}}(z)$$

Tag s quark via high x_F Λ production in proton fragmentation region.



B.Q. Ma and sjb

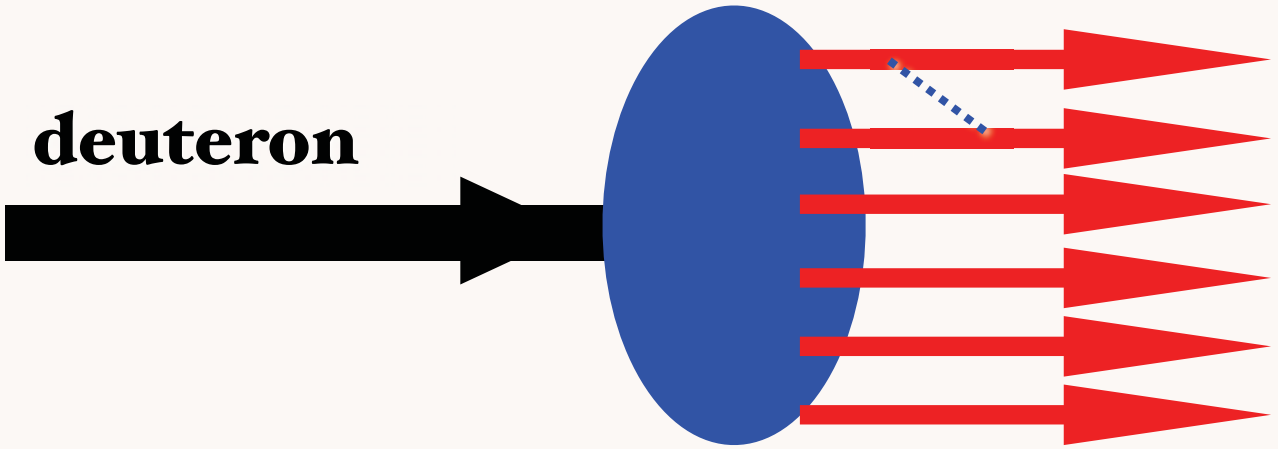
$$A_s^{p\bar{p}}(z) = \frac{D_{s\to p}(z) - D_{s\to \bar{p}}(z)}{D_{s\to p}(z) + D_{s\to \bar{p}}(z)}$$

Consequence of $s_p(x) \neq \bar{s}_p(x)$ $\qquad |uuds\bar{s}> \simeq |K^+\Lambda>$

Hidden Color of Deuteron

Evolution of 5 color-singlet Fock states

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



$$\Phi_n(x_i, Q) = \int^{k_{\perp i}^2 < Q^2} \Pi' d^2k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

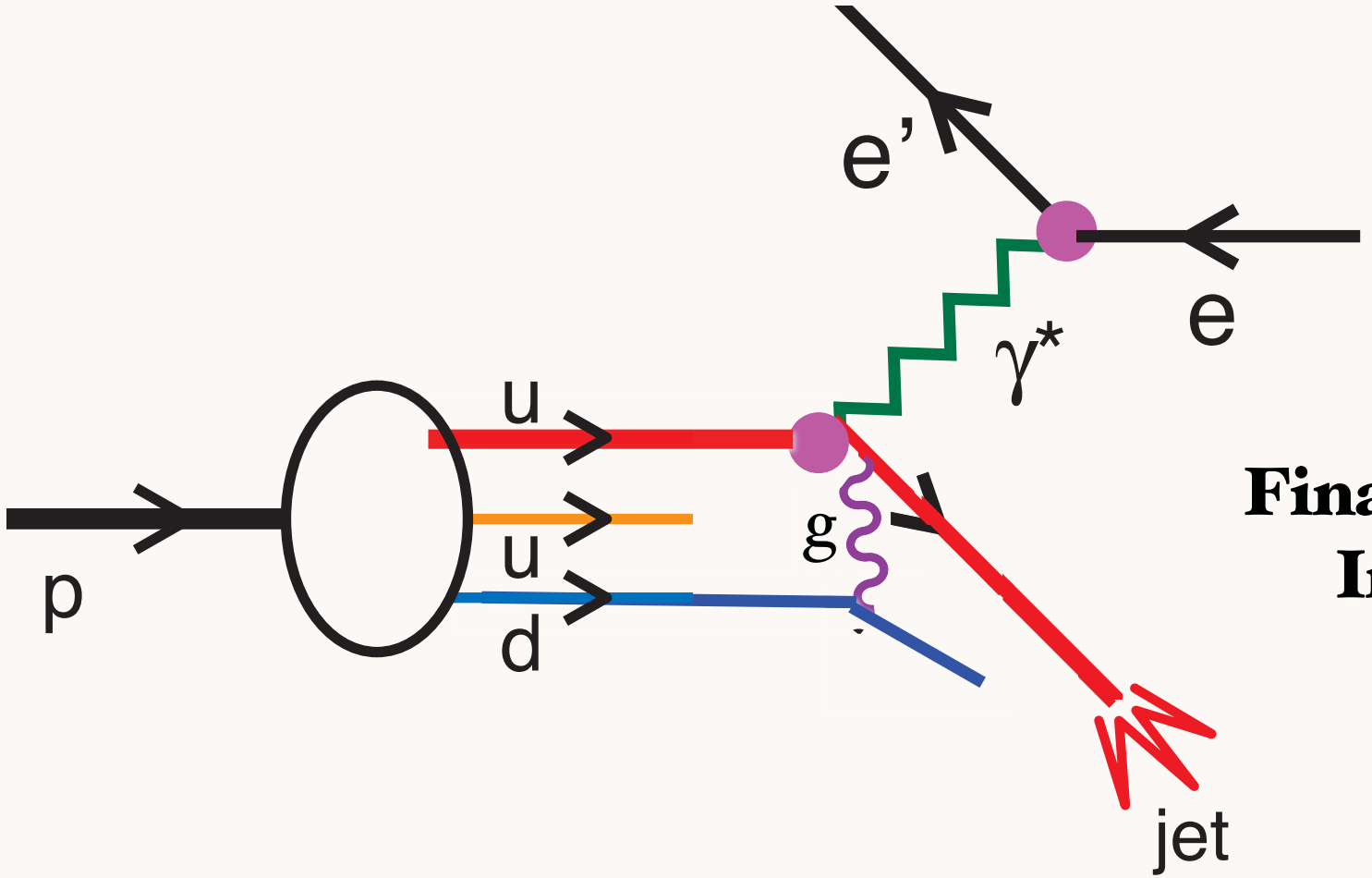
Ji, Lepage, sjb

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Light-Front QCD Phenomenology

- Hidden color, Intrinsic glue, sea, Color Transparency
- Physics of spin, orbital angular momentum
- Near Conformal Behavior of LFWFs at Short Distances; PQCD constraints
- Vanishing anomalous gravitomagnetic moment
- Relation between edm and anomalous magnetic moment
- Cluster Decomposition Theorem for relativistic systems
- OPE: DGLAP, ERBL evolution; invariant mass scheme

Deep Inelastic Electron-Proton Scattering



Final-State QCD Interaction

Conventional wisdom:
Final-state interactions of struck quark can be neglected

Single-spin asymmetries

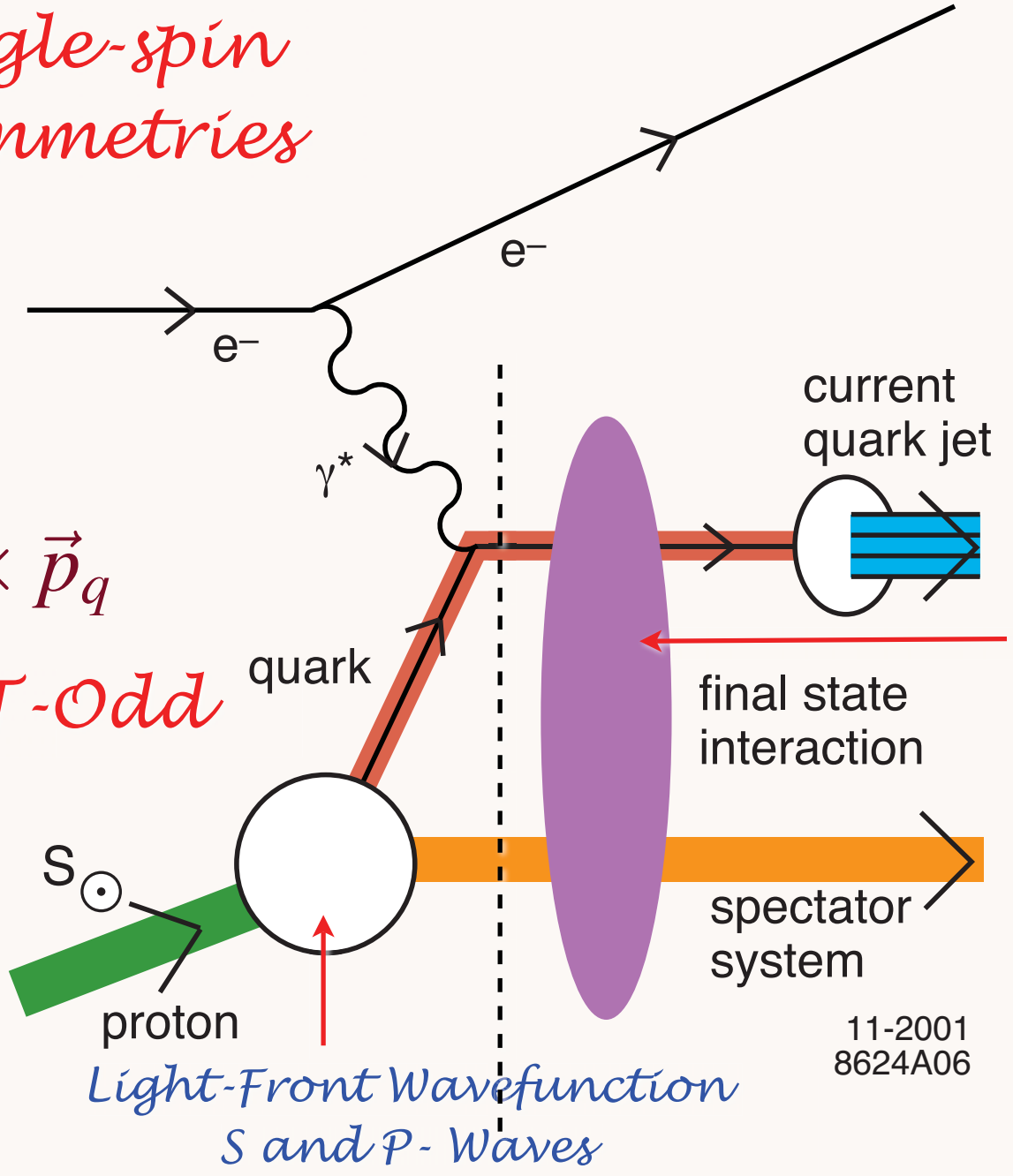
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

Pseudo-T-Odd



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

Light-Front Wavefunction S and P- Waves

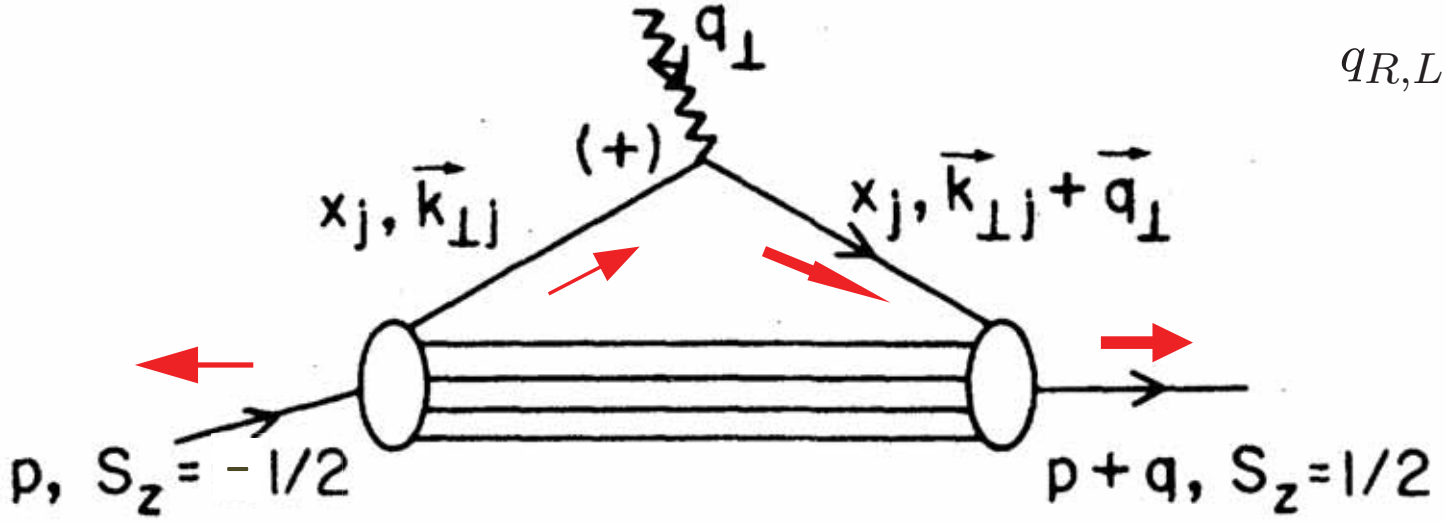
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \, \times$$

Drell, sjb

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

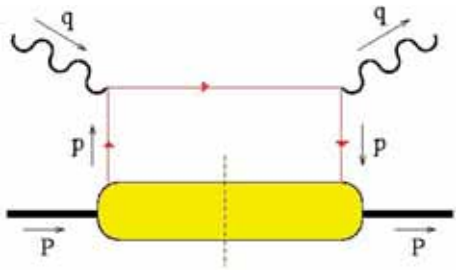
$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

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

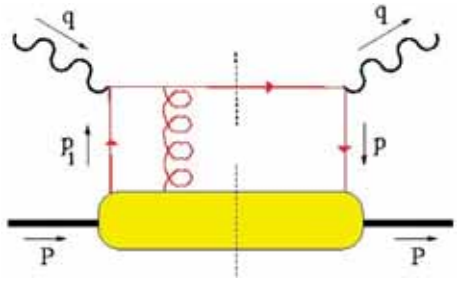


Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

Same matrix elements appear in Sivers effect



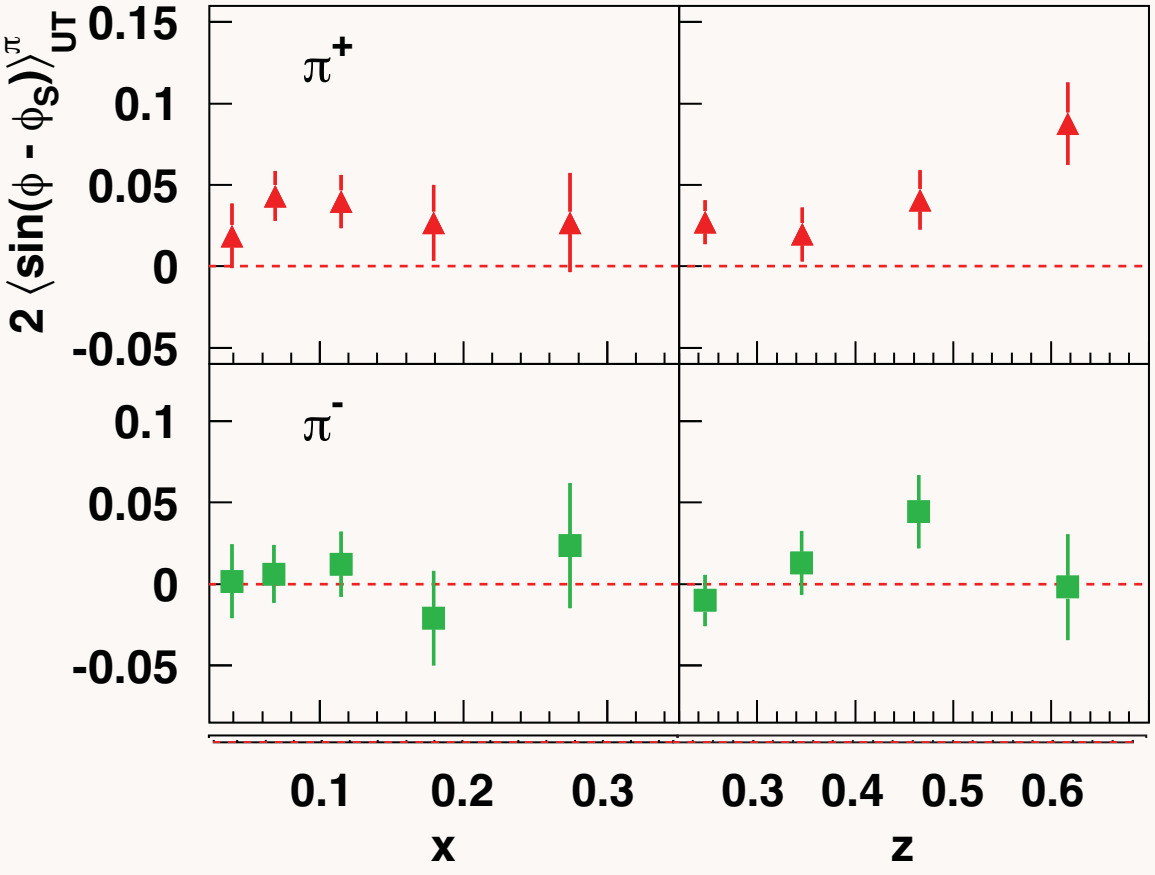
can interfere with



and produce a T-odd effect! (also need $L_z \neq 0$)

HERMES coll., A. Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002.

Sivers asymmetry from HERMES



- First evidence for non-zero Sivers function!
- ⇒ presence of non-zero **quark orbital angular momentum**!
- Positive for π^+...
  Consistent with zero for π^-...

Gamberg: Hermes data compatible with BHS model

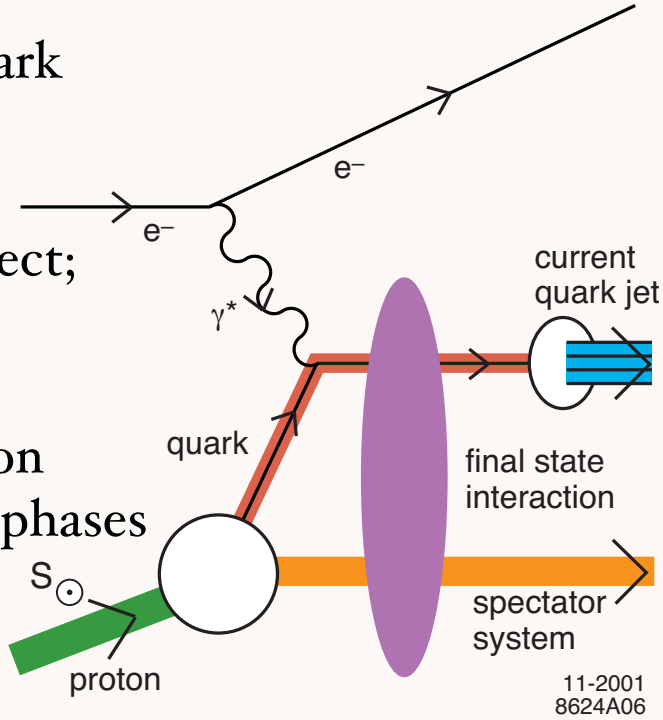
Schmidt, Lu: Hermes charge pattern follow quark contributions to anomalous moment

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

- Leading-Twist Bjorken Scaling!

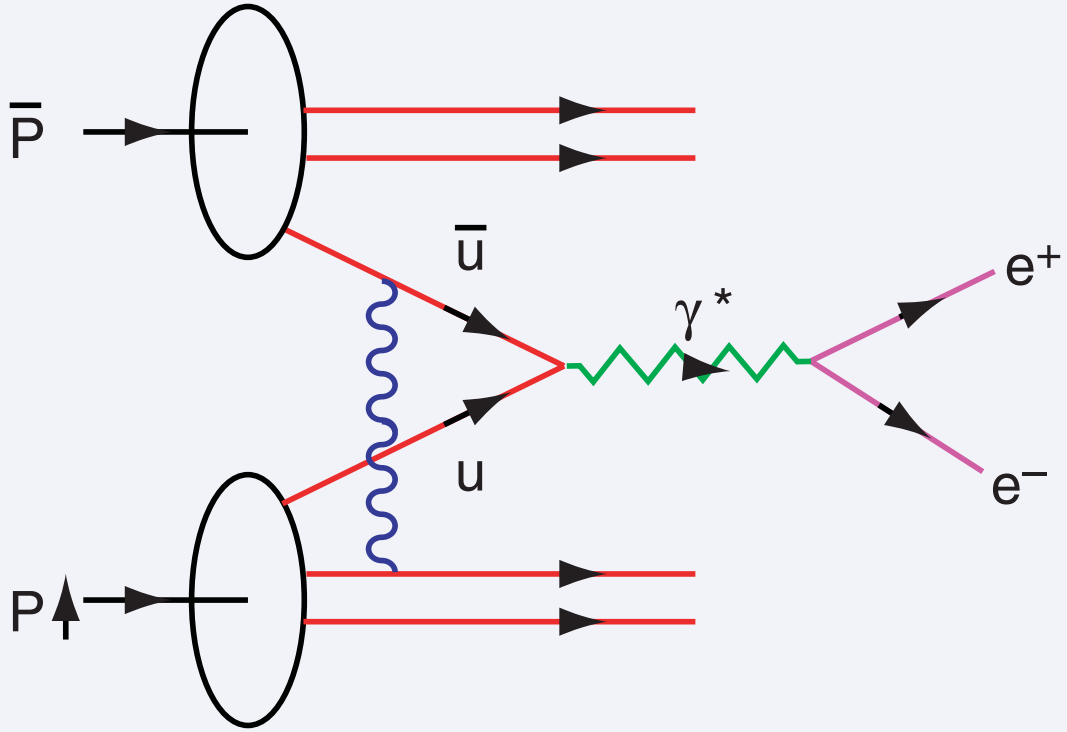
$$\mathbf{i}\,\vec{S}\cdot\vec{p}_{jet}\times\vec{q}$$

- Requires nonzero orbital angular momentum of quark
- Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves; Wilson line effect; gauge independent
- Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases
- QCD phase at soft scale: IR Fixed Point?



- New window to QCD coupling and running gluon mass in the IR
- QED S and P Coulomb phases infinite -- difference of phases finite

Predict Opposite Sign SSA in DY !



Collins; Hwang, Schmidt. sjb

Single Spin Asymmetry In the Drell Yan Process

$\vec{S}_p \cdot \vec{\overline{p}} \times \vec{q}_{\gamma^*}$

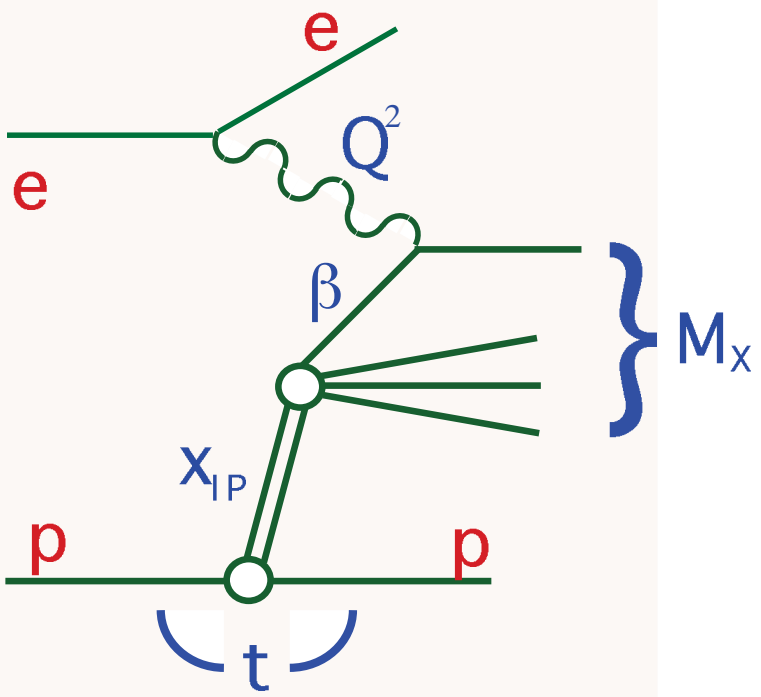
Quarks Interact in the Initial State

Interference of Coulomb Phases for *S* and *P* states

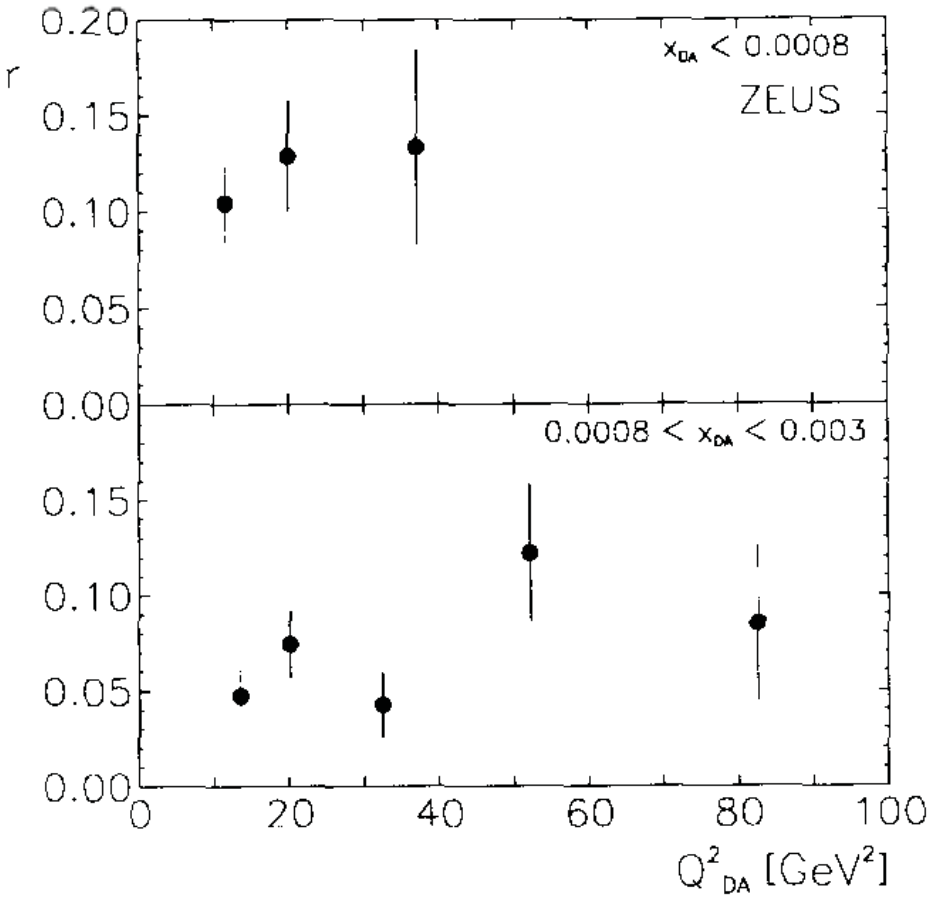
Produce Single Spin Asymmetry [Siver's Effect]Proportional to the Proton Anomalous Moment and α_s.

Opposite Sign to DIS! No Factorization

Remarkable observation at HERA



10% to 15% of DIS events are diffractive !



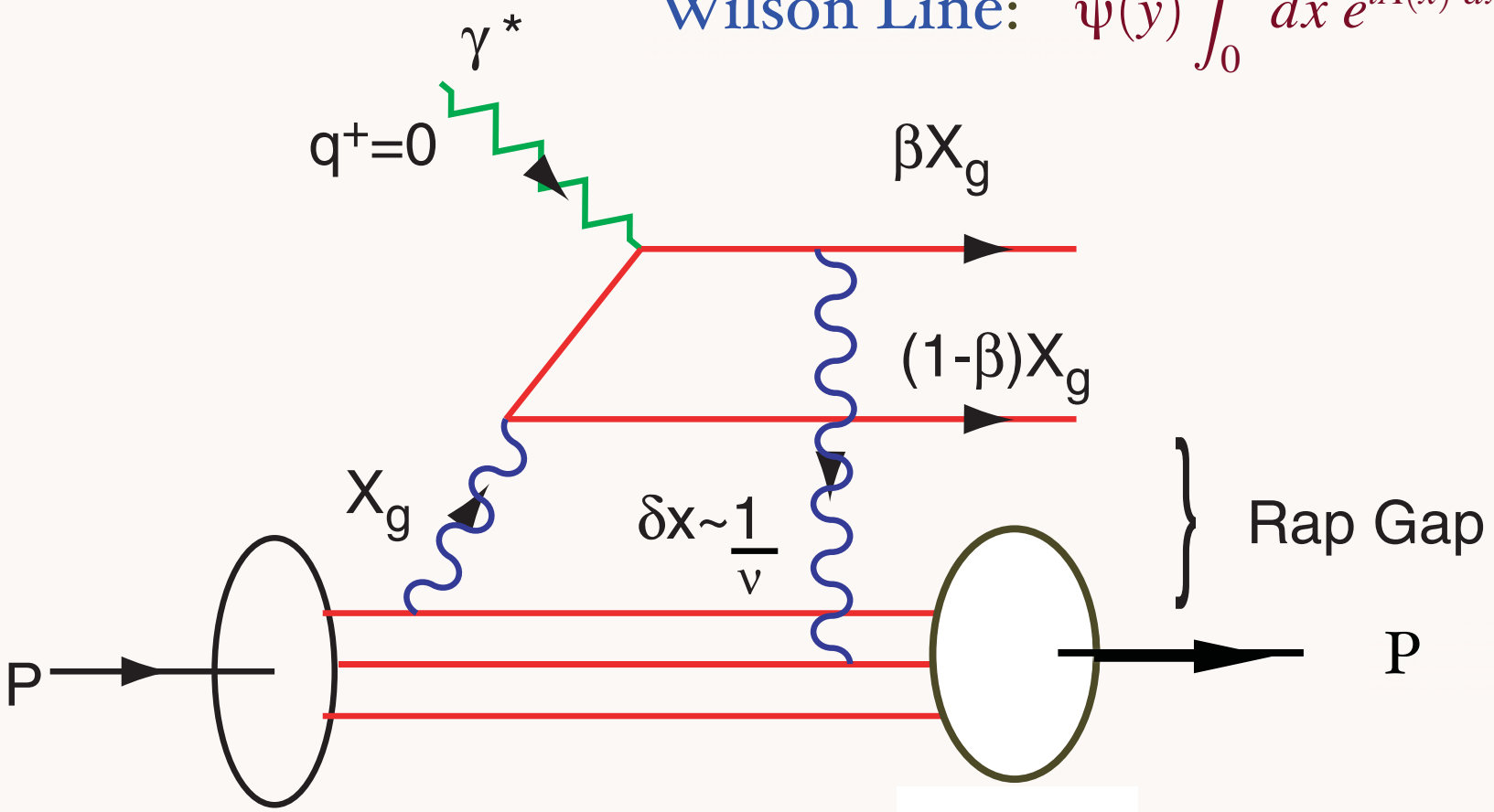
Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

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

Hoyer, Marchal, Peigne, Sannino, sjb

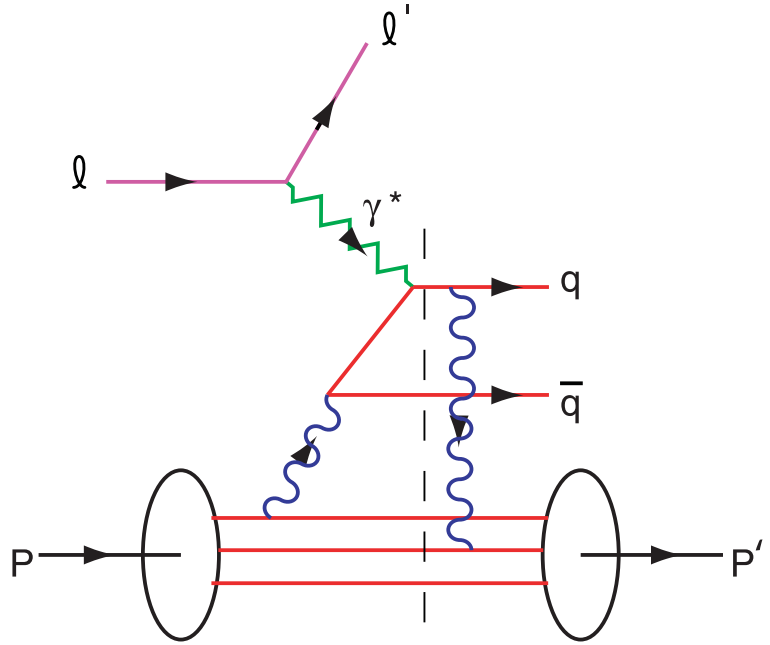
QCD Mechanism for Rapidity Gaps

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



Origin of Diffractive DIS

Reproduces lab-frame color dipole approach



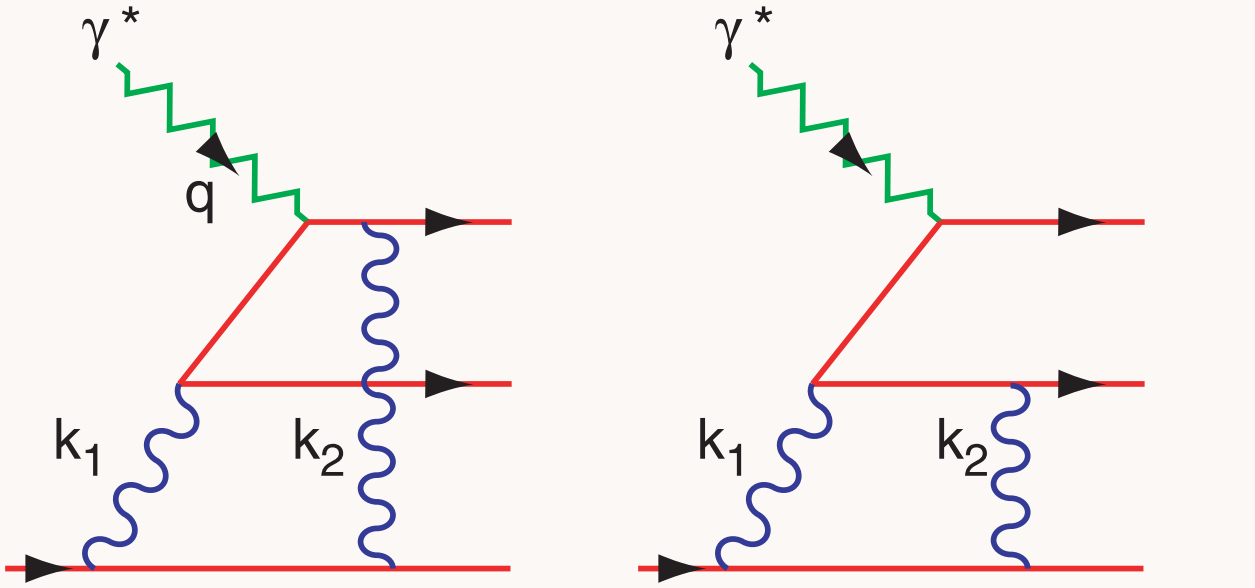
Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

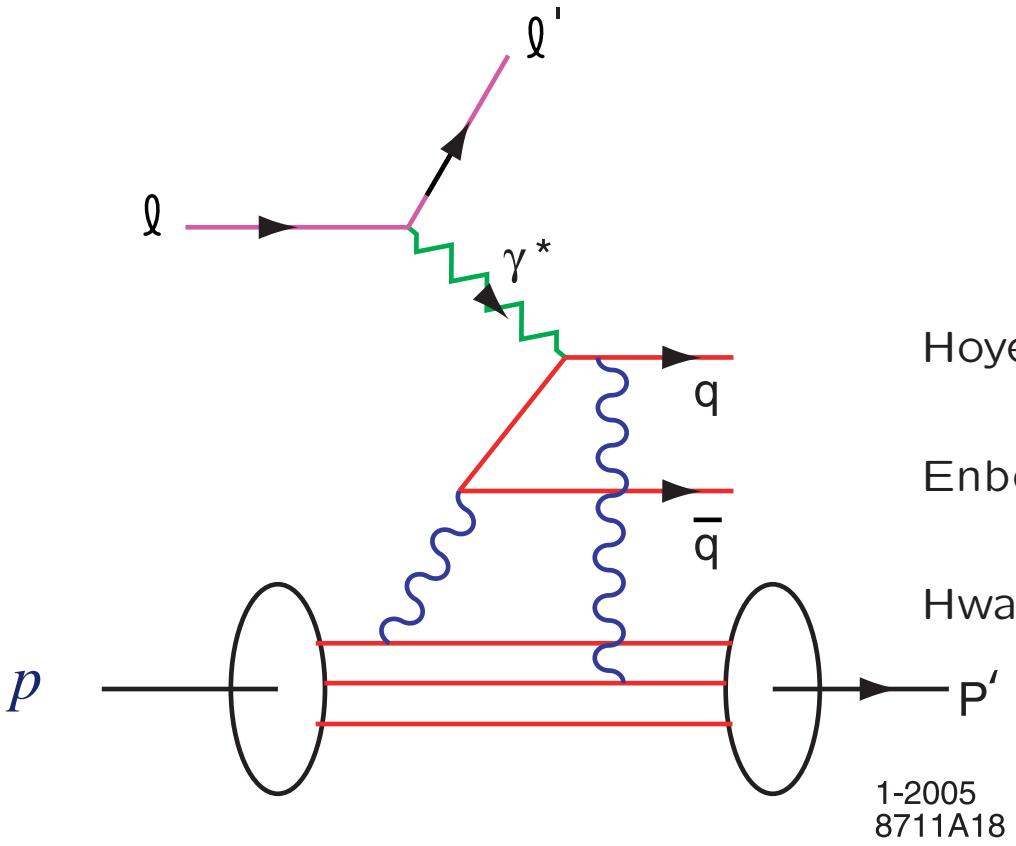
Final State Interactions in QCD



Feynman Gauge Light-Cone Gauge

Result is Gauge Independent

Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Physics of Rescattering

- Diffractive DIS: New Insights into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions!
- T-odd single-spin asymmetries,
- Nuclear Shadowing, Non-Universal Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon