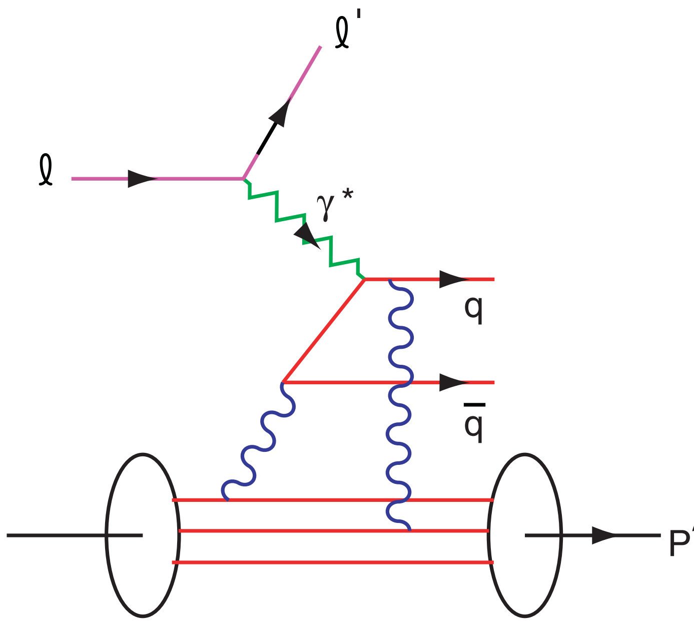
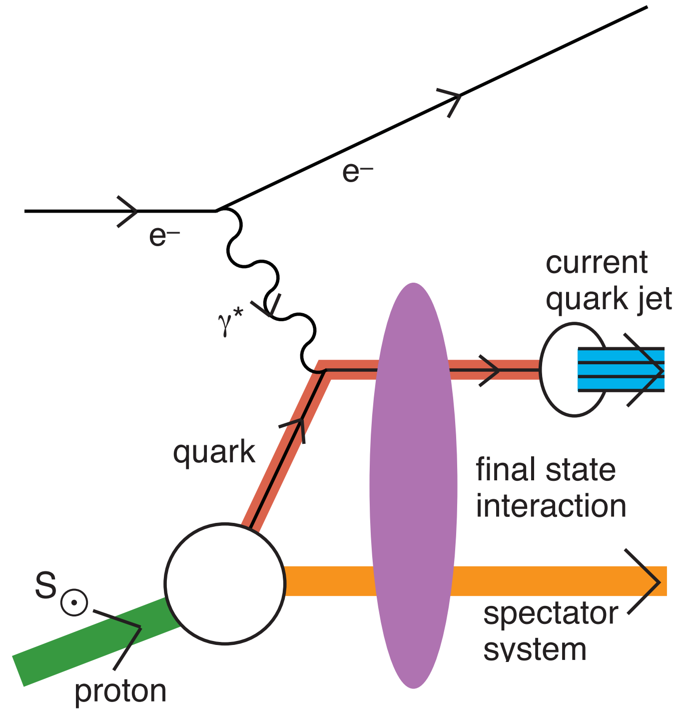
Novel QCD Phenomenology

Stan Brodsky, SLAC/IPPP

Queen guitarist Brian May has handed in his astronomy PhD thesis - 36 years after abandoning it to join the band.



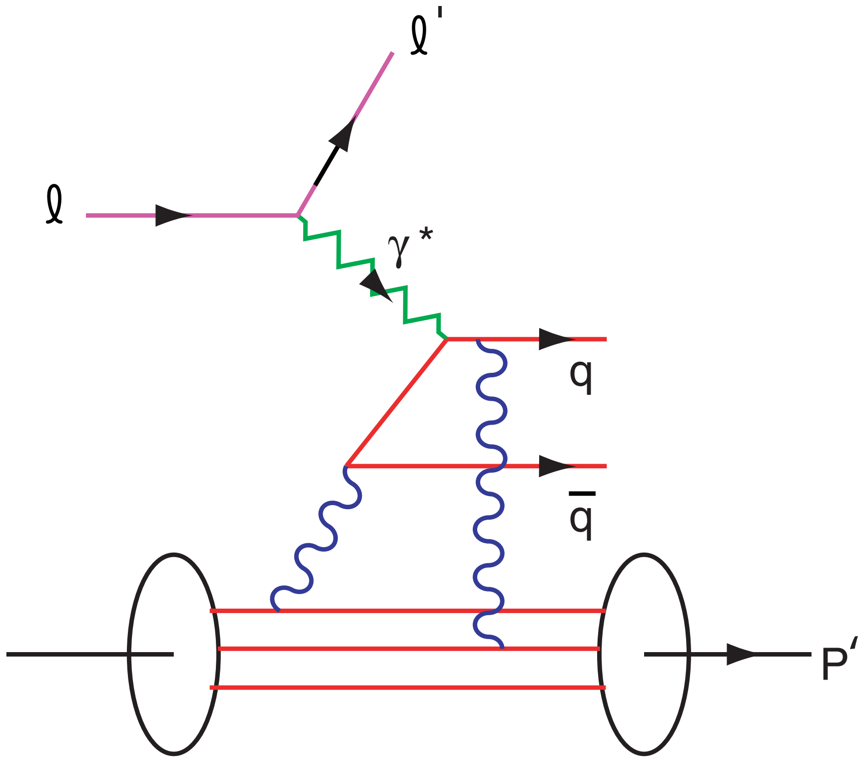


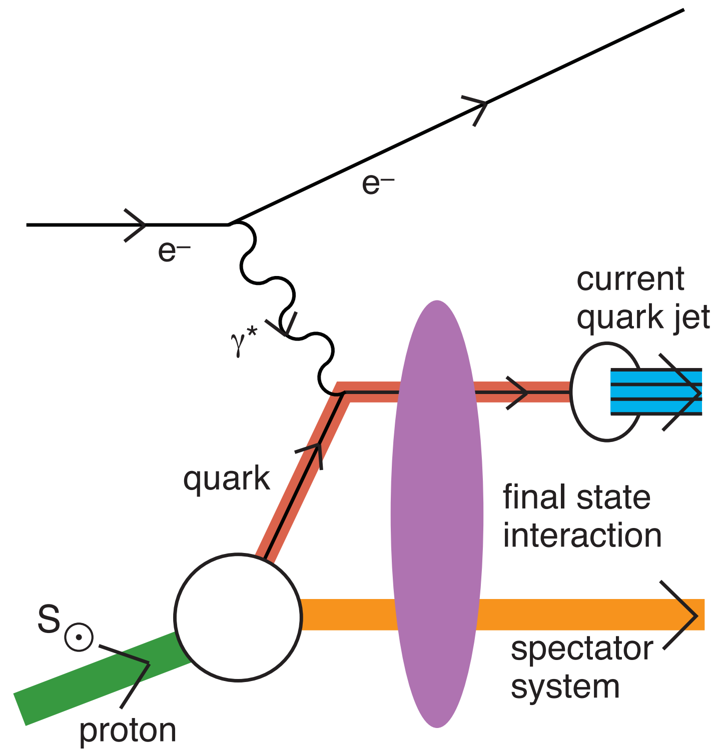
Imperial College, London

16 Sep 2008

Novel QCD Phenomenology

Stan Brodsky, SLAC/IPPP





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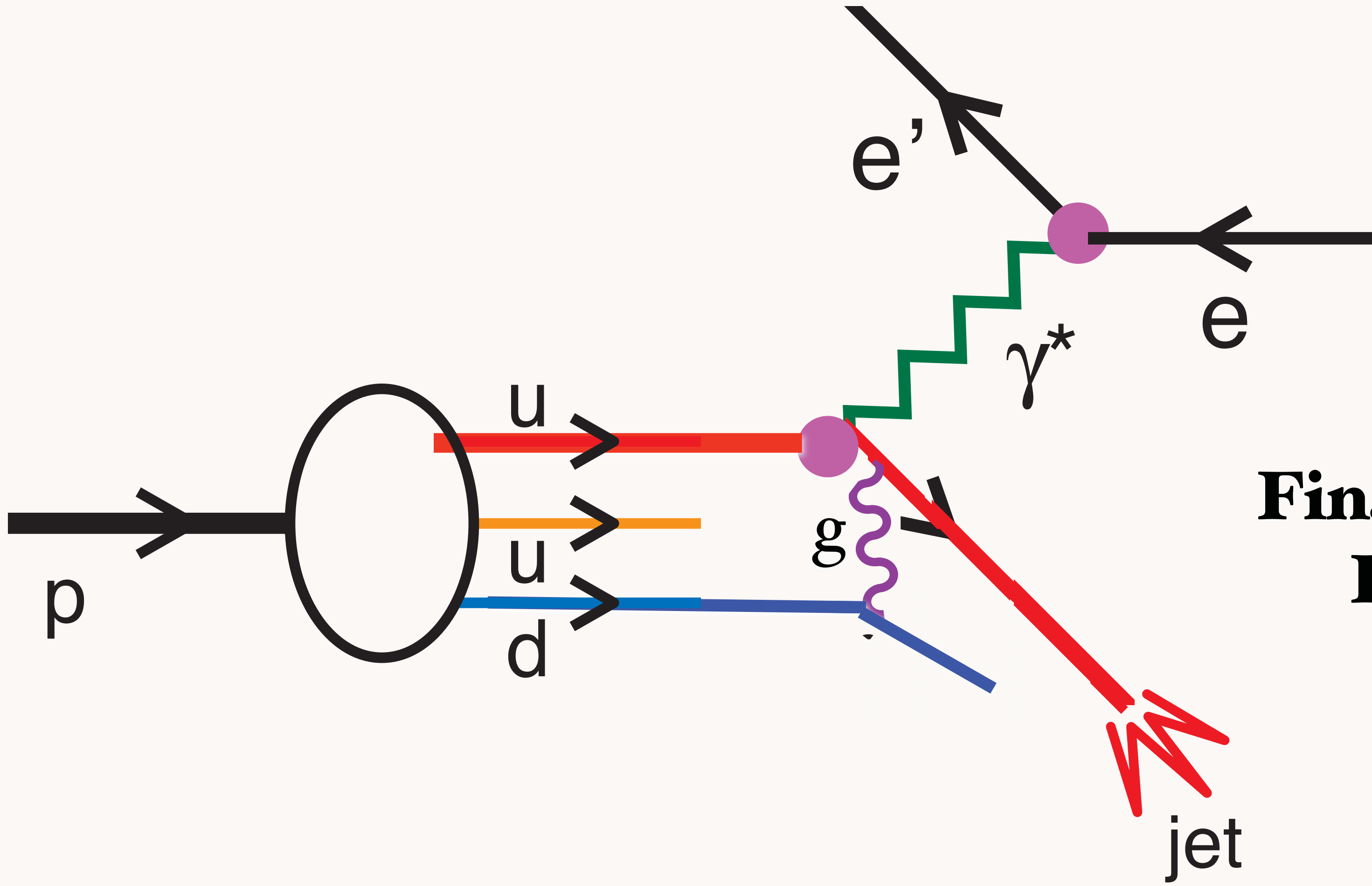
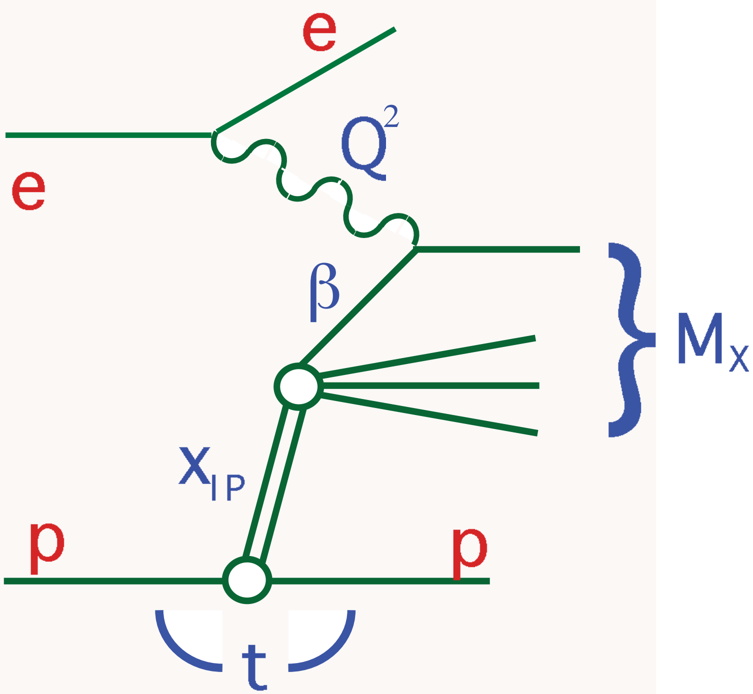
Deep Inelastic Electron-Proton Scattering

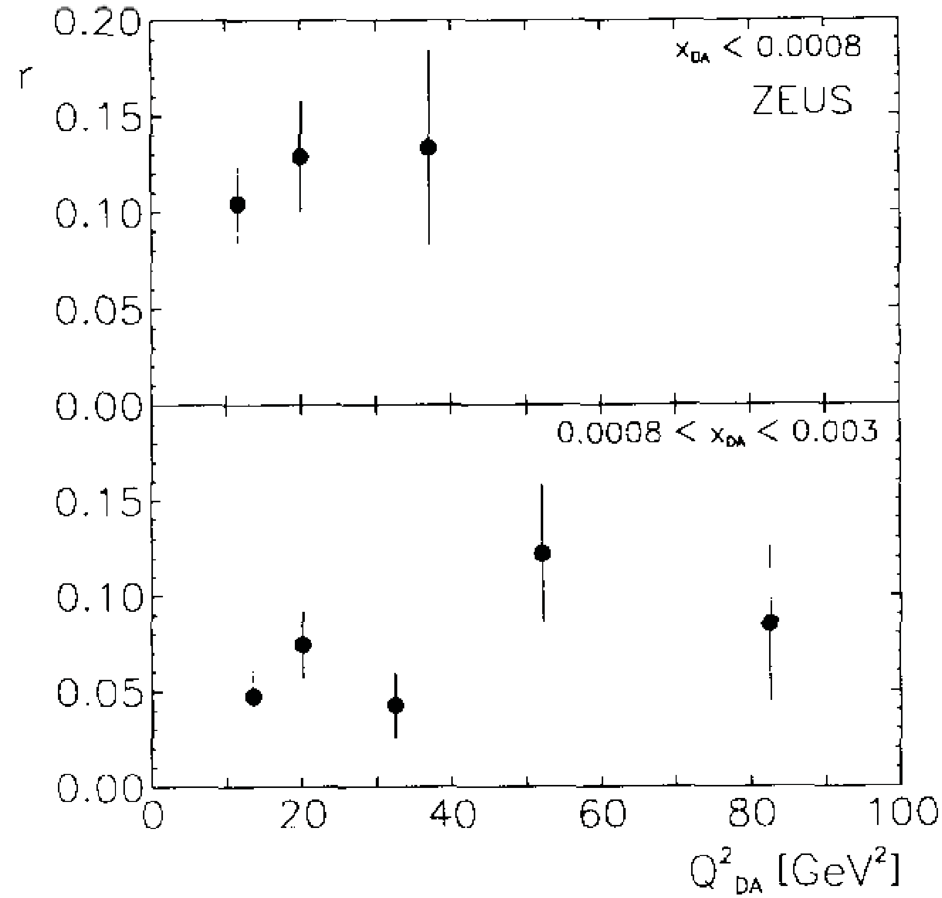


Final-State QCD Interaction

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

Remarkable observation at HERA





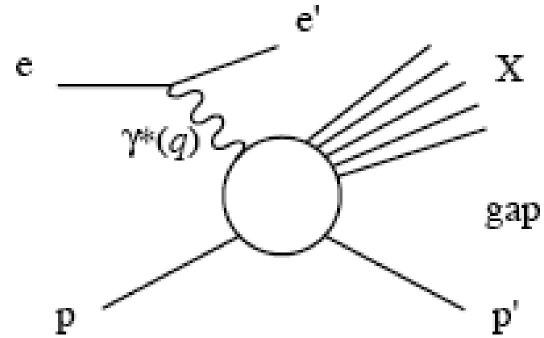
Fraction r of events with a large rapidity gap, $\eta_{\max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

10% to 15% of DIS events are diffractive !

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

DDIS

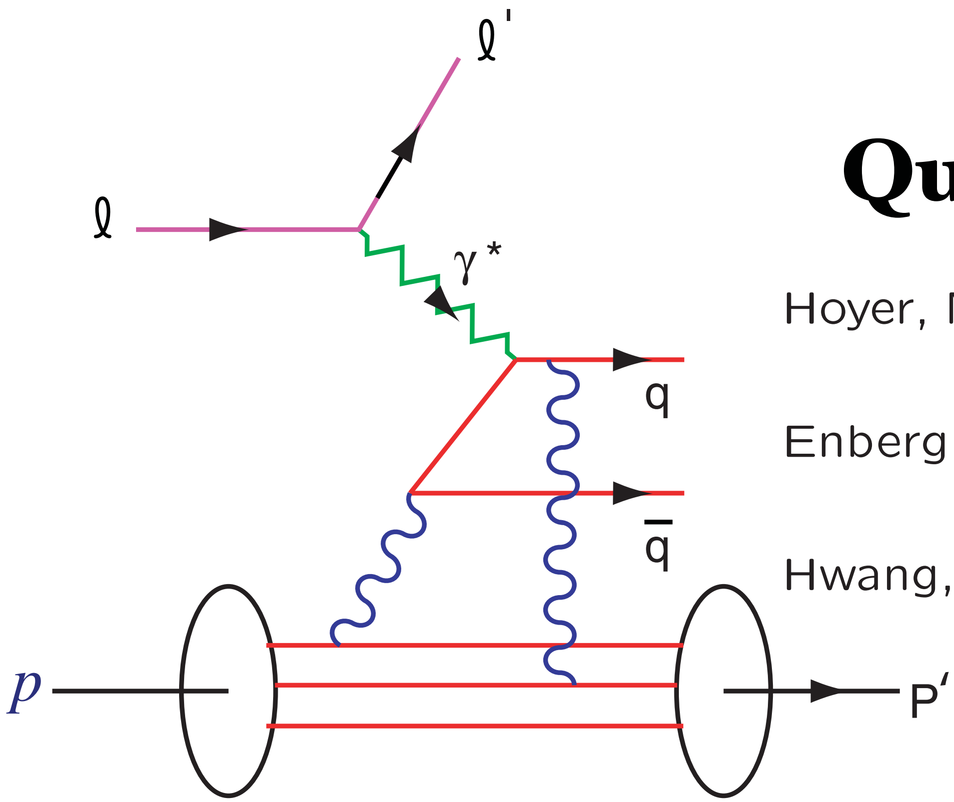
Diffractive Deep Inelastic Lepton-Proton Scattering



- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron

Profound effect: target stays intact despite production of a massive system X

Final-State QCD Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

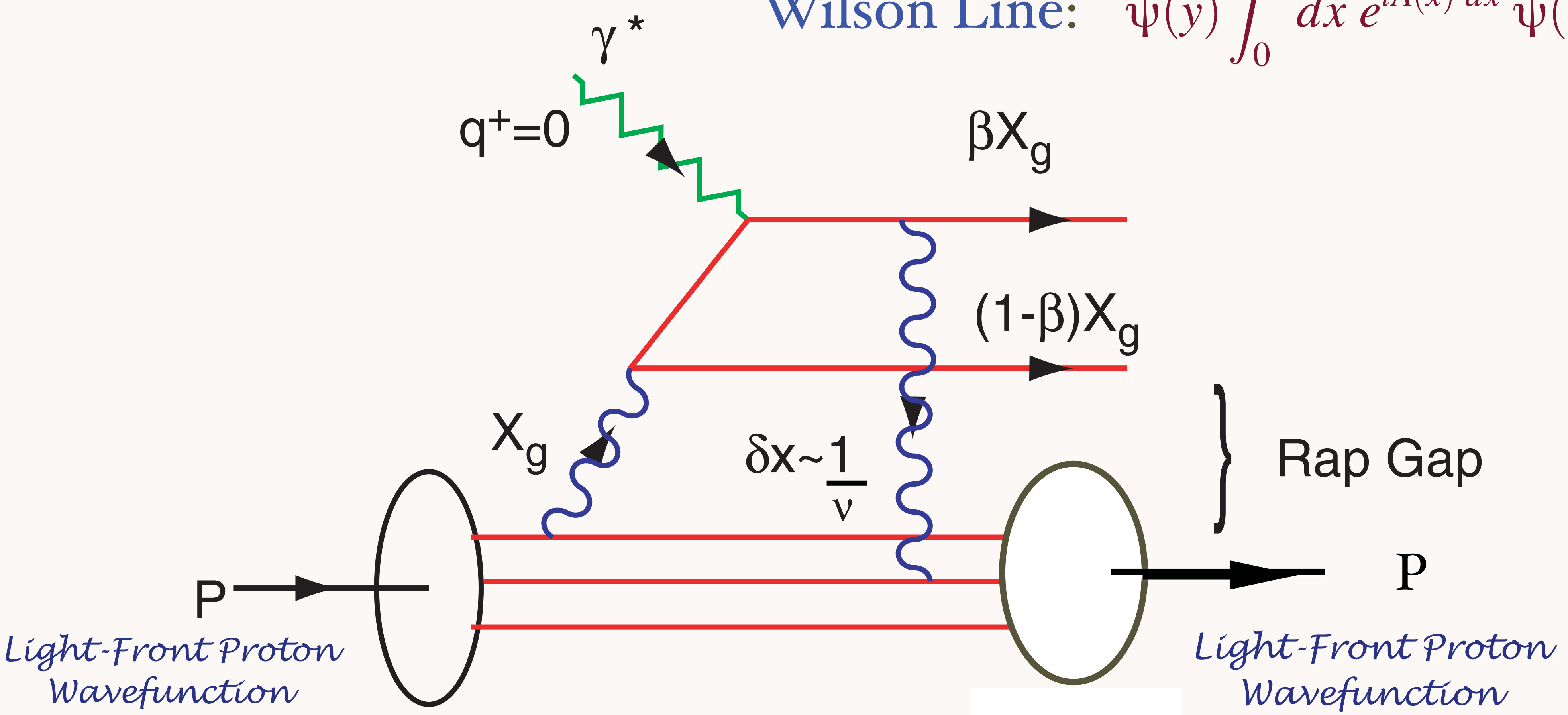
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Hoyer, Marchal, Peigne, Sannino, sjb

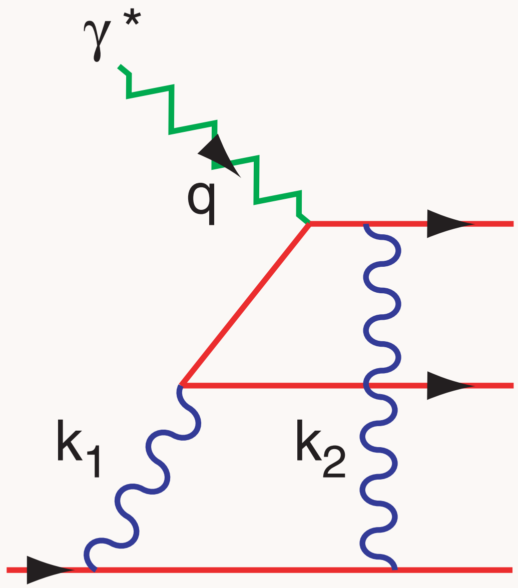
QCD Mechanism for Rapidity Gaps

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

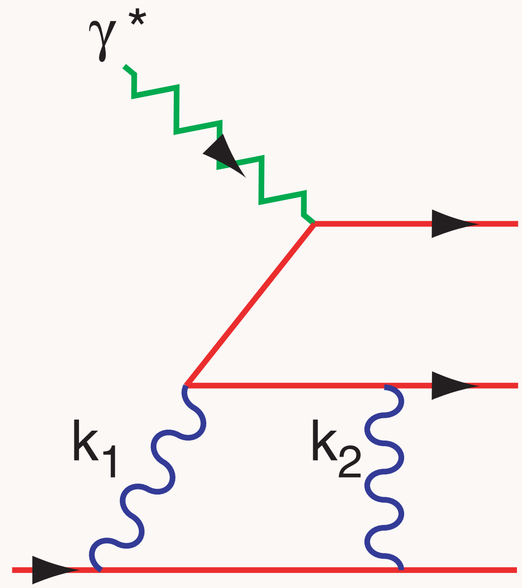


Reproduces lab-frame color dipole approach

Final State Interactions in QCD

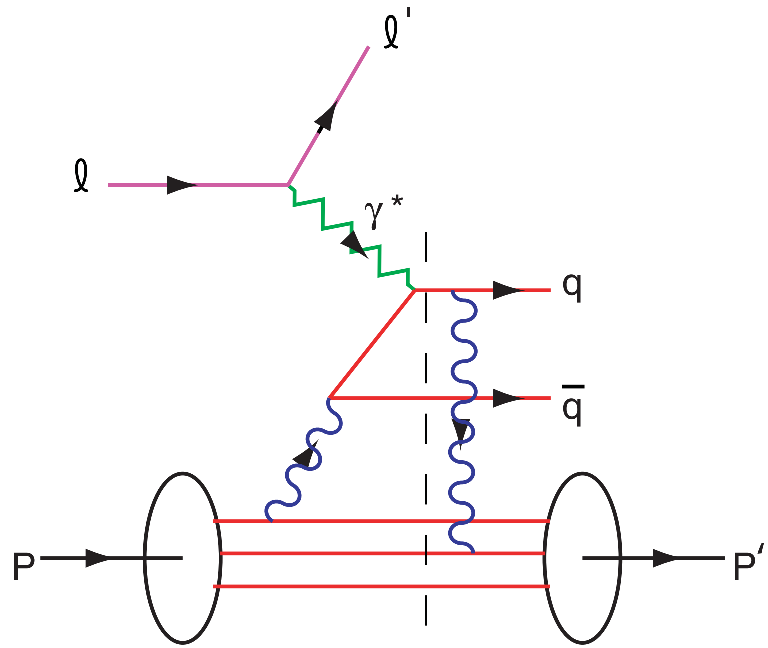


Feynman Gauge



Light-Cone Gauge

Result is Gauge Independent

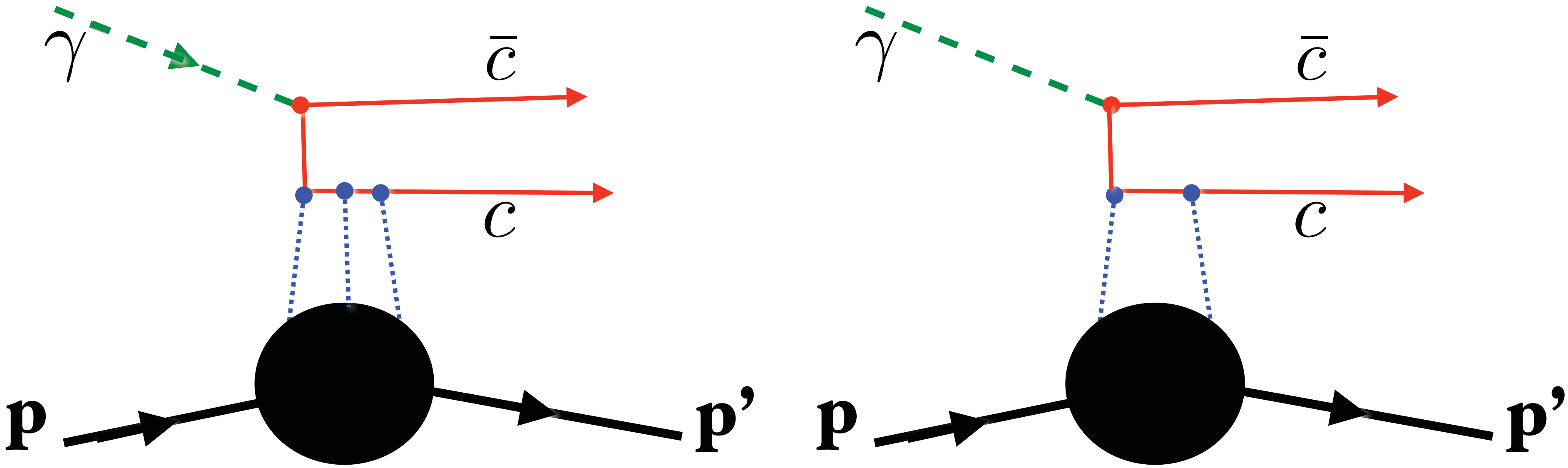


Integration over on-shell domain produces phase i

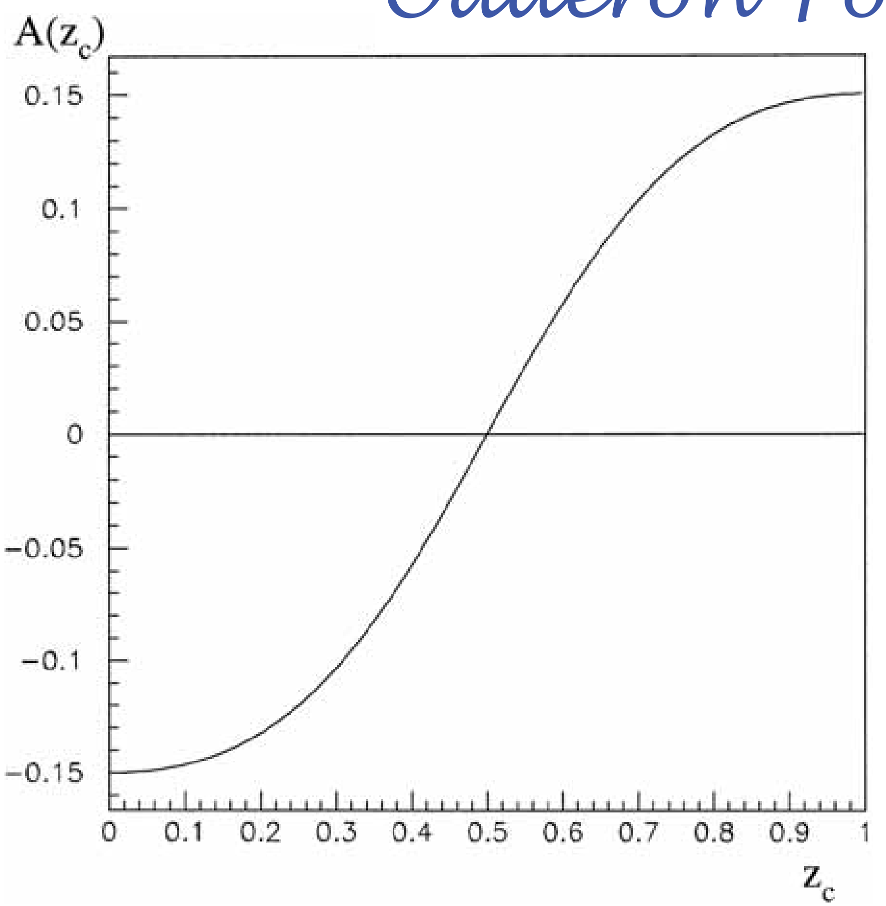
Need Imaginary Phase to Generate Pomeron

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

Physics of FSI not in Wavefunction of Target



Odderon-Pomeron Interference!



$$\frac{d\sigma}{dz_c}(\gamma p \to c\bar{c}p')$$

$$\mathscr{A}\left(t \simeq 0, M_X^2, z_c\right) \simeq 0.45 \left(\frac{s_{\gamma p}}{M_X^2}\right)^{-0.25} \frac{2\,z_c - 1}{z_c^2 + (1 - z_c)^2}$$

Measure charm momentum asymmetry in photon fragmentation region

Only one charm quark needs to be measured

Merino, Rathsman, sjb

Single-spin asymmetries

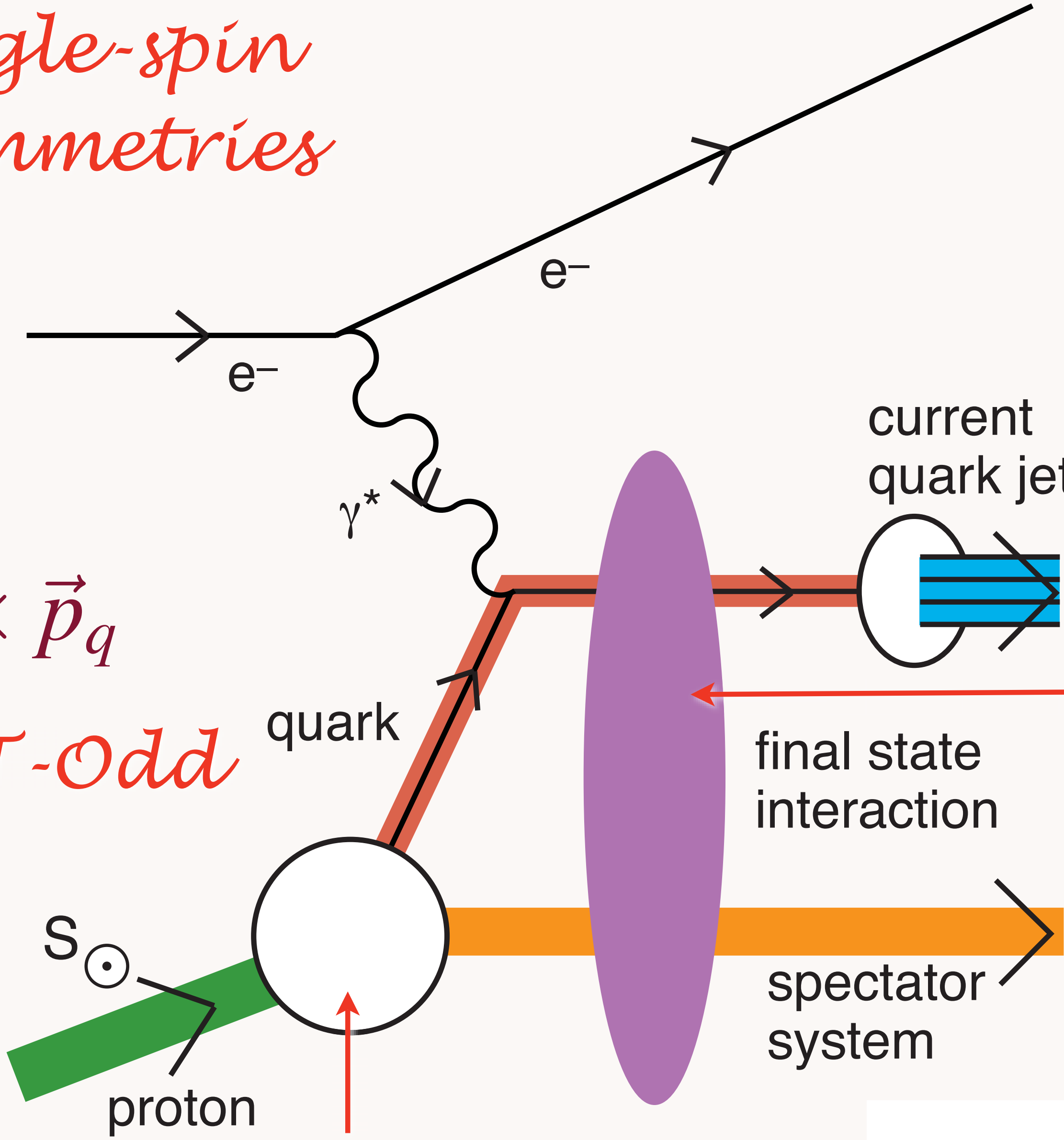
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

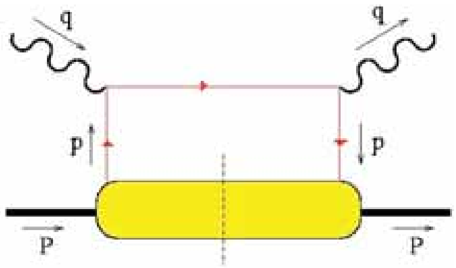
$i \, \vec{S}_p \cdot \vec{q} \times \vec{p}_q$

Pseudo-T-Odd

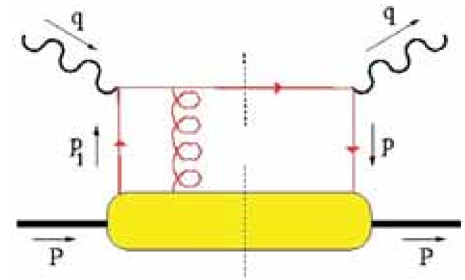


QCD S- and P- Coulomb Phases --Wilson Line

Light-Front Wavefunction S and P- Waves



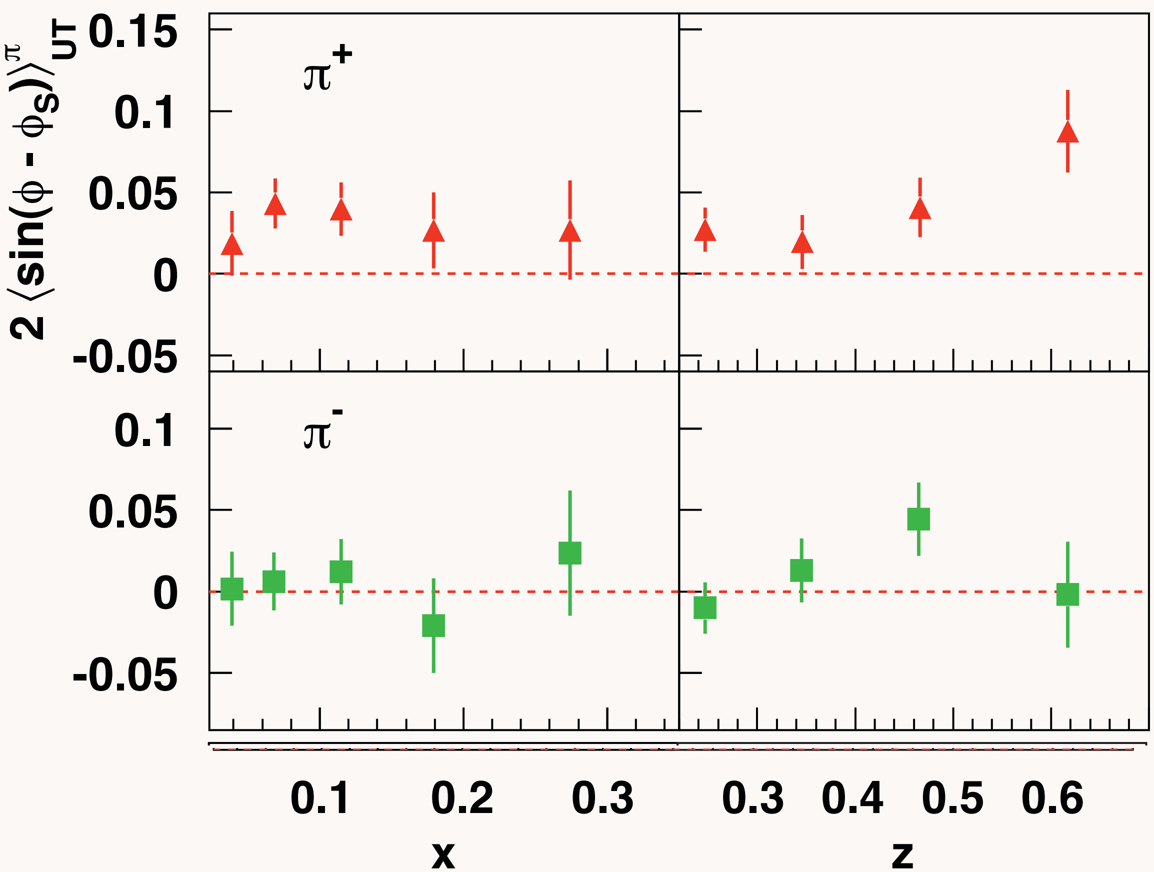
can interfere with



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

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

Sivers asymmetry from HERMES



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

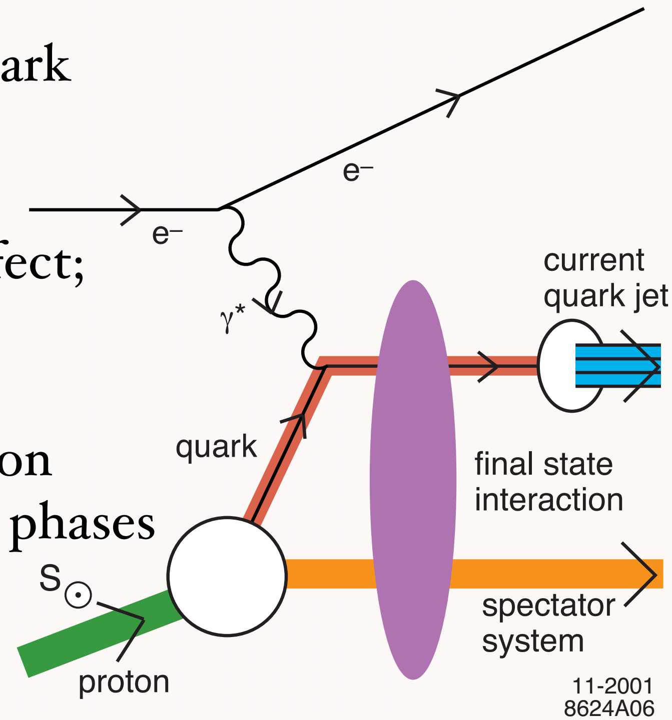
Gamberg: Hermes data compatible with BHS model

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

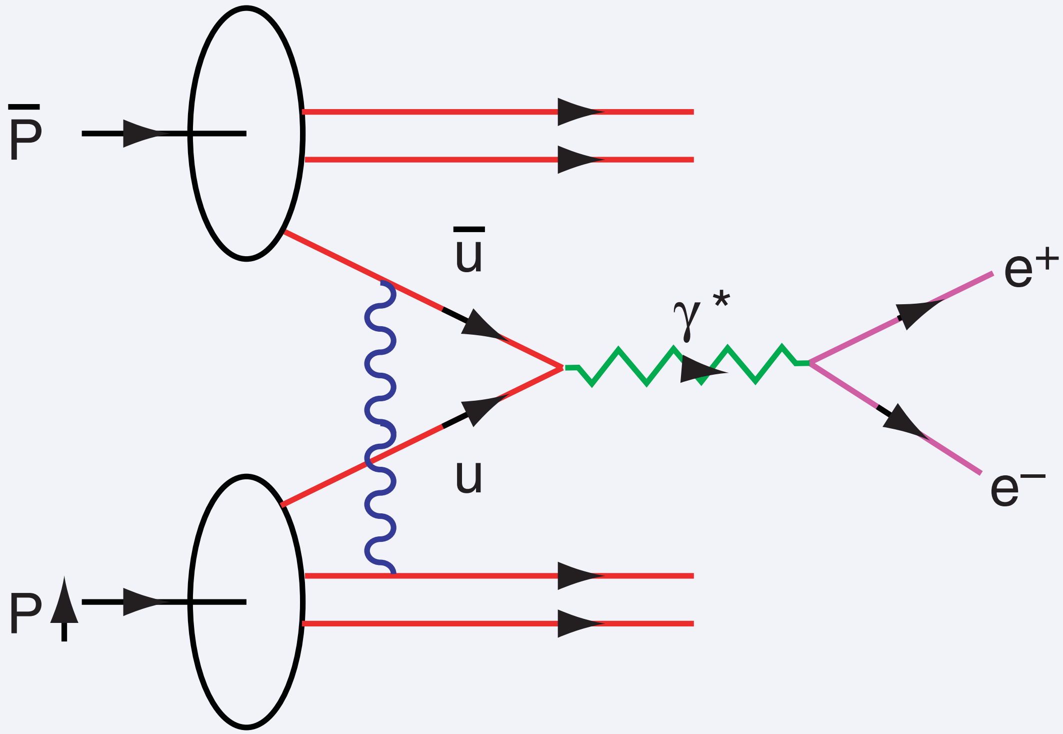
Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

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

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



Predict Opposite Sign SSA in DY !



Collins;
Hwang, Schmidt.
sjb

Single Spin Asymmetry In the Drell Yan Process

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

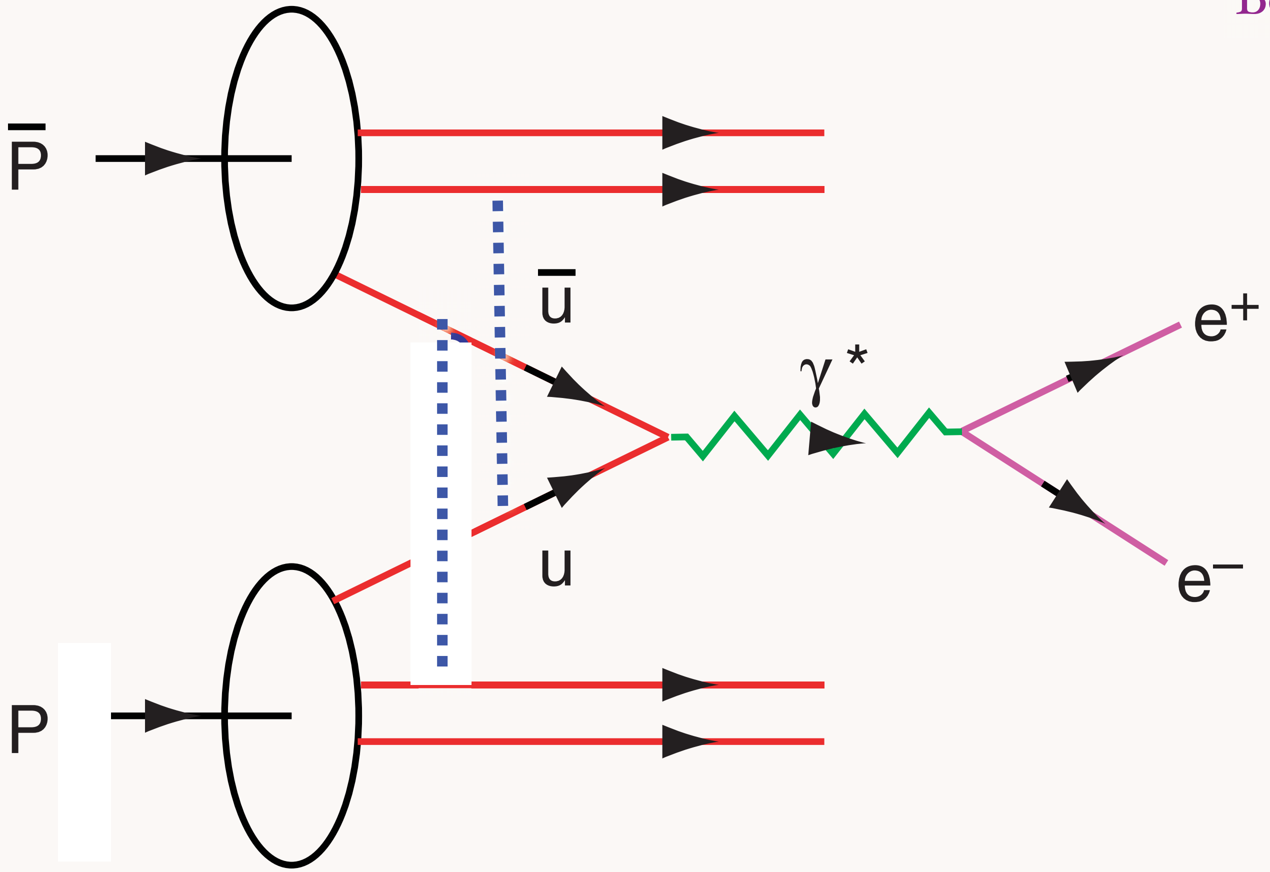
Quarks Interact in the Initial State

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

Boer, Hwang, sjb

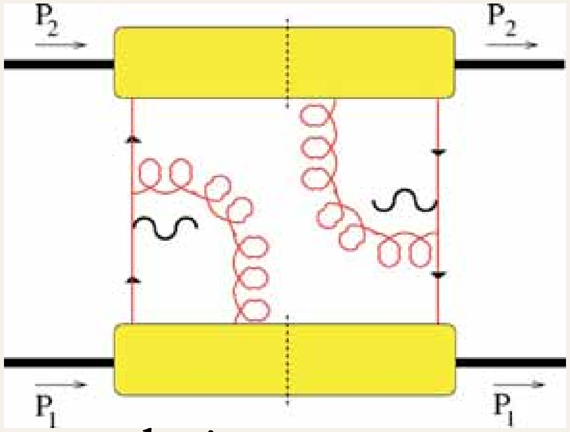


DY $\cos 2\phi$ **correlation at leading twist from double ISI**

Anomalous effect from Double ISI in Massive Lepton Production

Boer, Hwang, sjb

$\cos 2\phi$ correlation



- Leading Twist, valence quark dominated
- Violates Lam-Tung Relation!
- Not obtained from standard PQCD subprocess analysis
- Normalized to the square of the single spin asymmetry in semi-inclusive DIS
- No polarization required
- Challenge to standard picture of PQCD Factorization

Double Initial-State Interactions generate anomalous $\cos 2\phi$

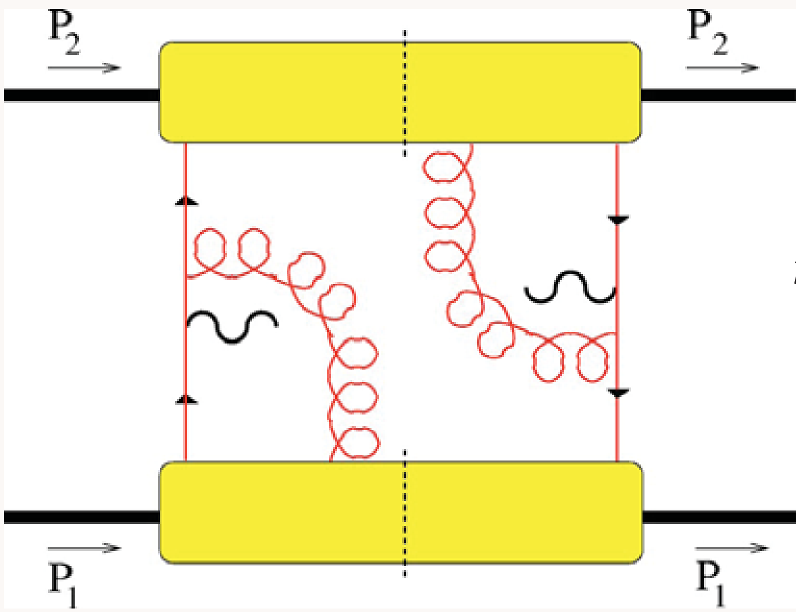
Boer, Hwang, sjb

Drell-Yan planar correlations

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi\right)$$

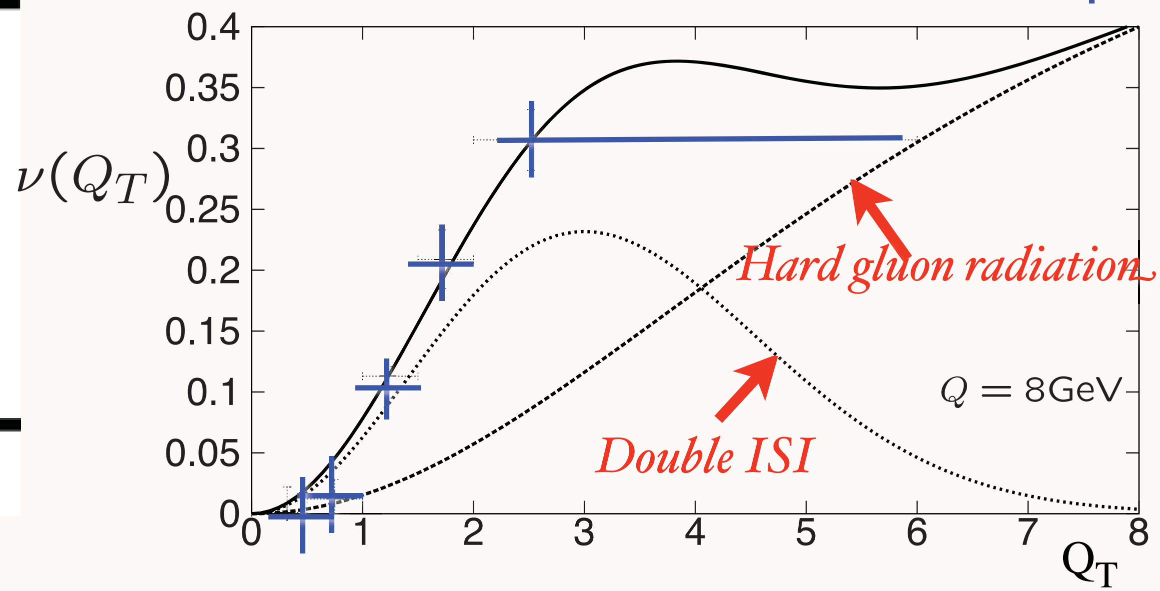
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \propto h_1^{\perp}(\pi)\, h_1^{\perp}(N)$$

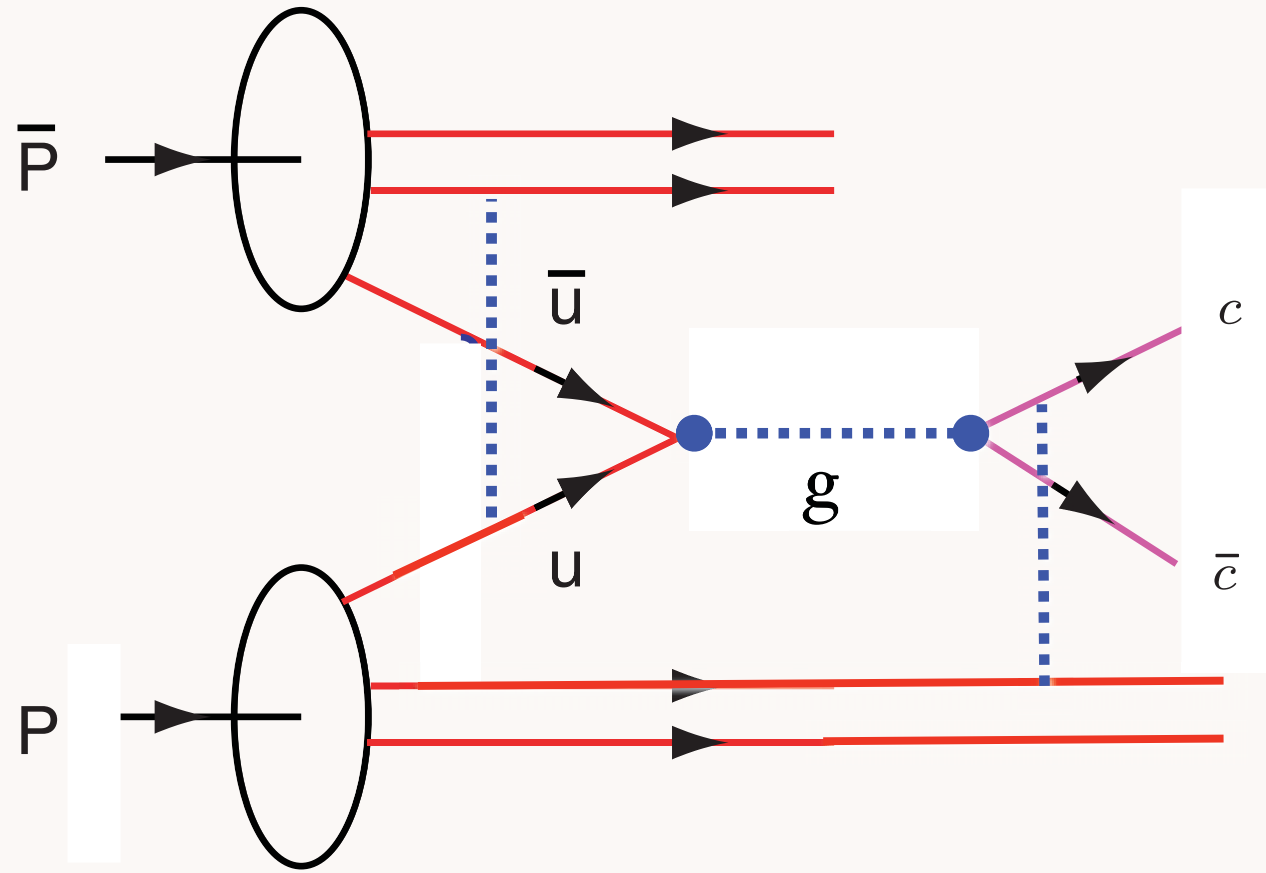


Violates Lam-Tung relation!

$\pi N \to \mu^+\mu^- X$ NA10



Model: Boer,

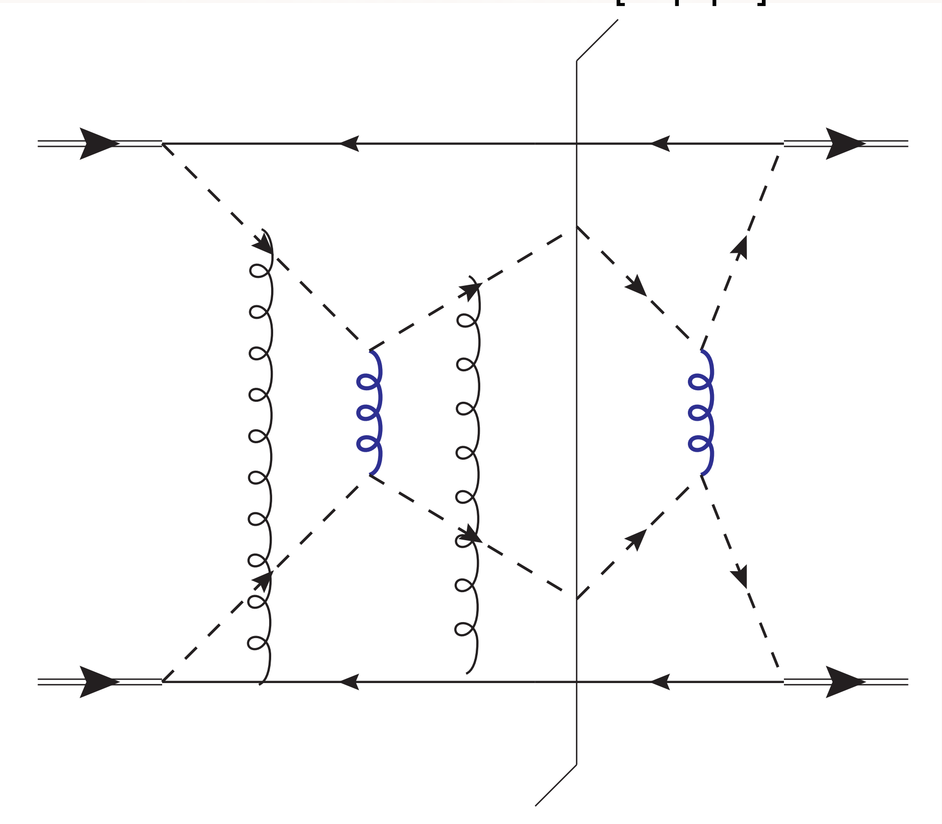


Problem for factorization when both ISI and FSI occur

Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

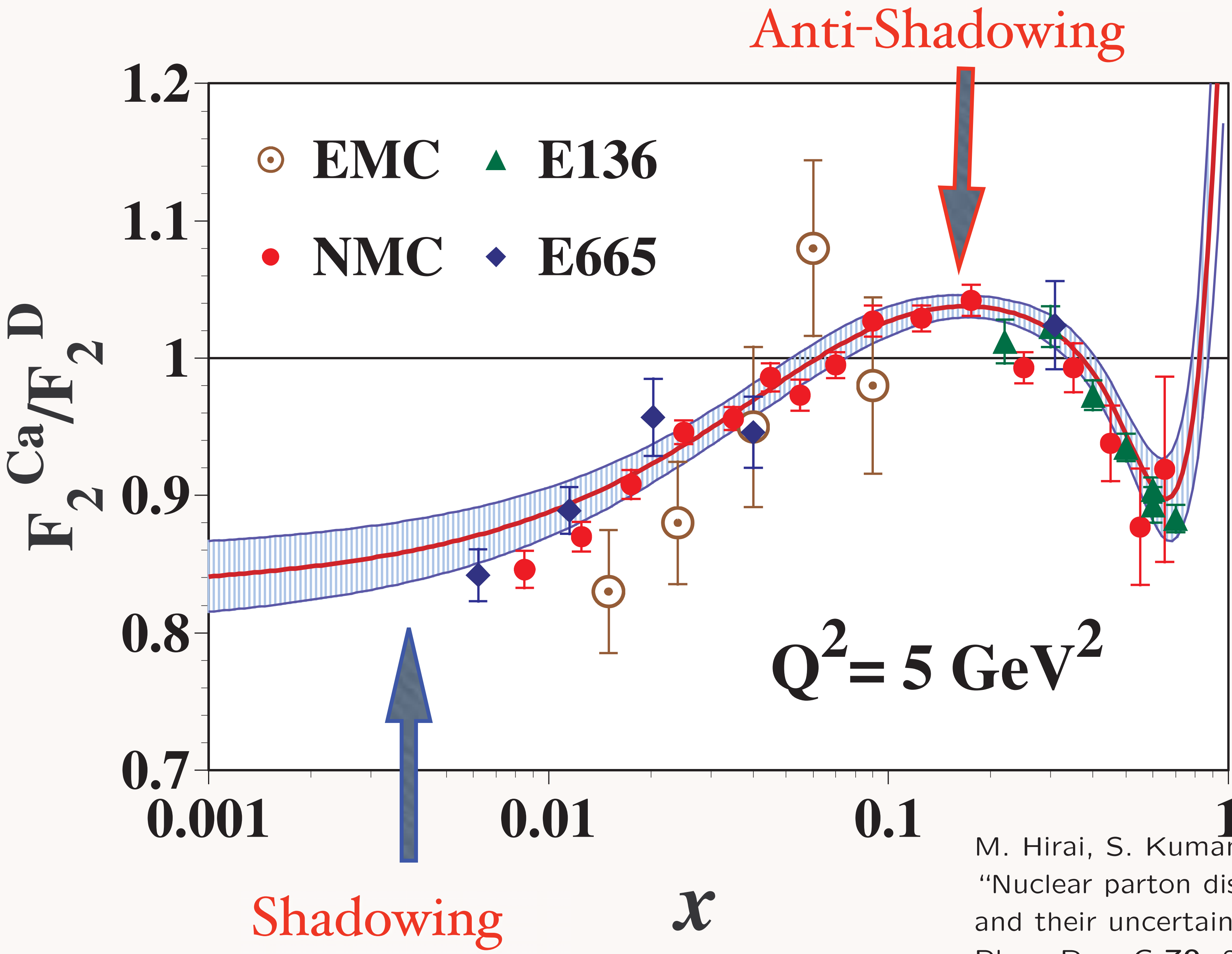
e-Print: **arXiv:0705.2141** [hep-ph]



The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

Novel Aspects of QCD in ep scattering

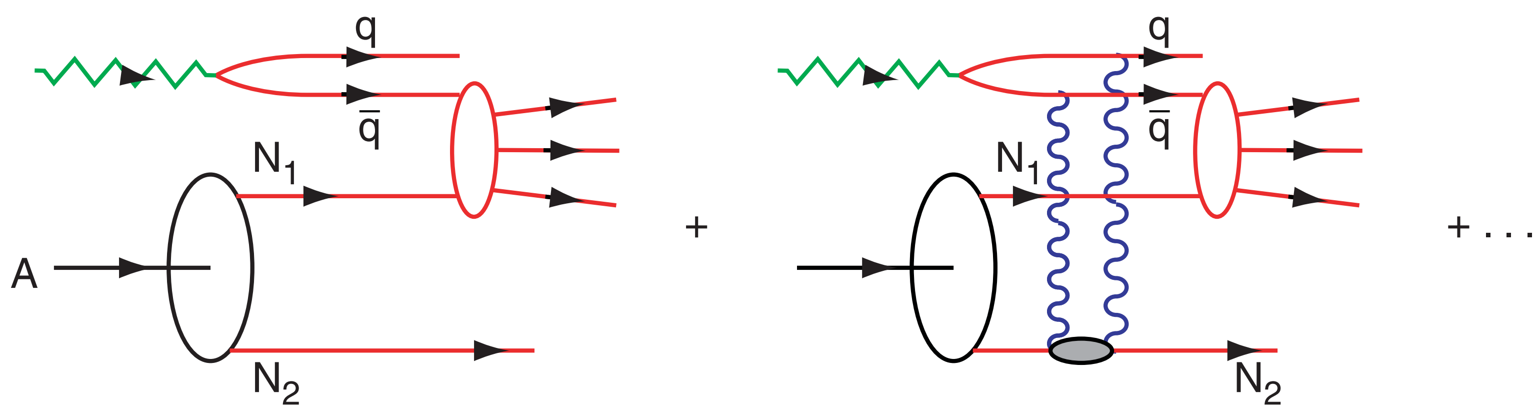
- Initial and final-state interactions are not power suppressed DIS; Wilson line correction to handbag diagram in DVCS
- Leading-twist Bjorken-scaling single-spin asymmetry:
- Leading-twist Bjorken-scaling Diffractive DIS
- Diffractive Electroproduction; Color Transparency
- DIS at high energy reflects interactions of color-dipole of virtual photon with proton and nucleus: shadowing, saturation:
- Breakdown of parton model concepts: Structure functions are not probability distributions
- Nuclear LFWFS are universal, but the measured nuclear parton distributions are not universal -- antishadowing is flavor-dependent



M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093].

Stodolsky
Pumplin, sjb
Gribov

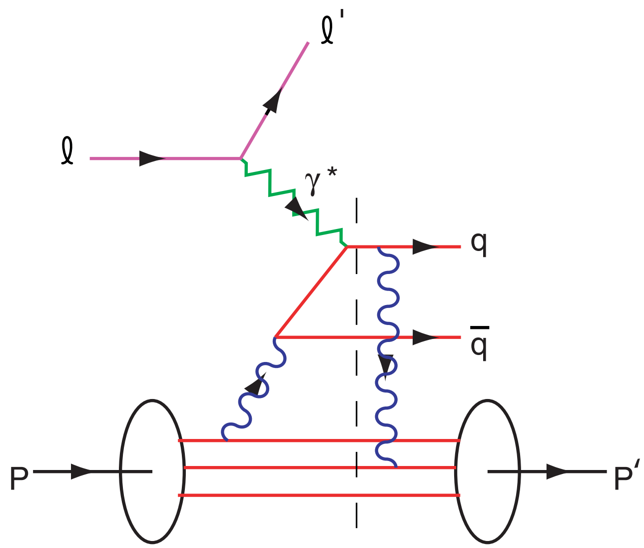
Nuclear Shadowing in QCD



Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus



Shadowing depends on leading-twist DDIS

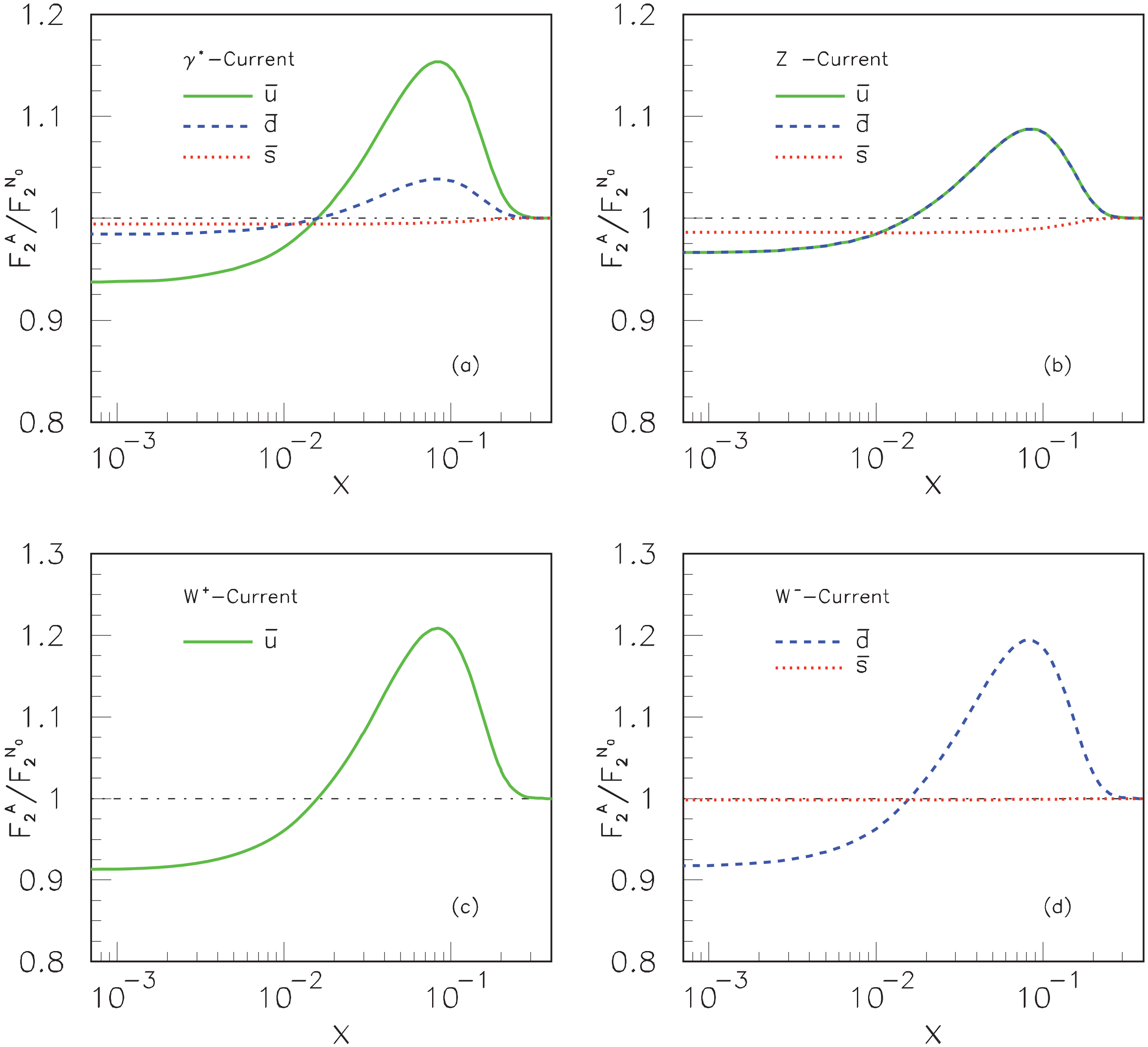
Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

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

Physics of FSI not in Wavefunction of Target

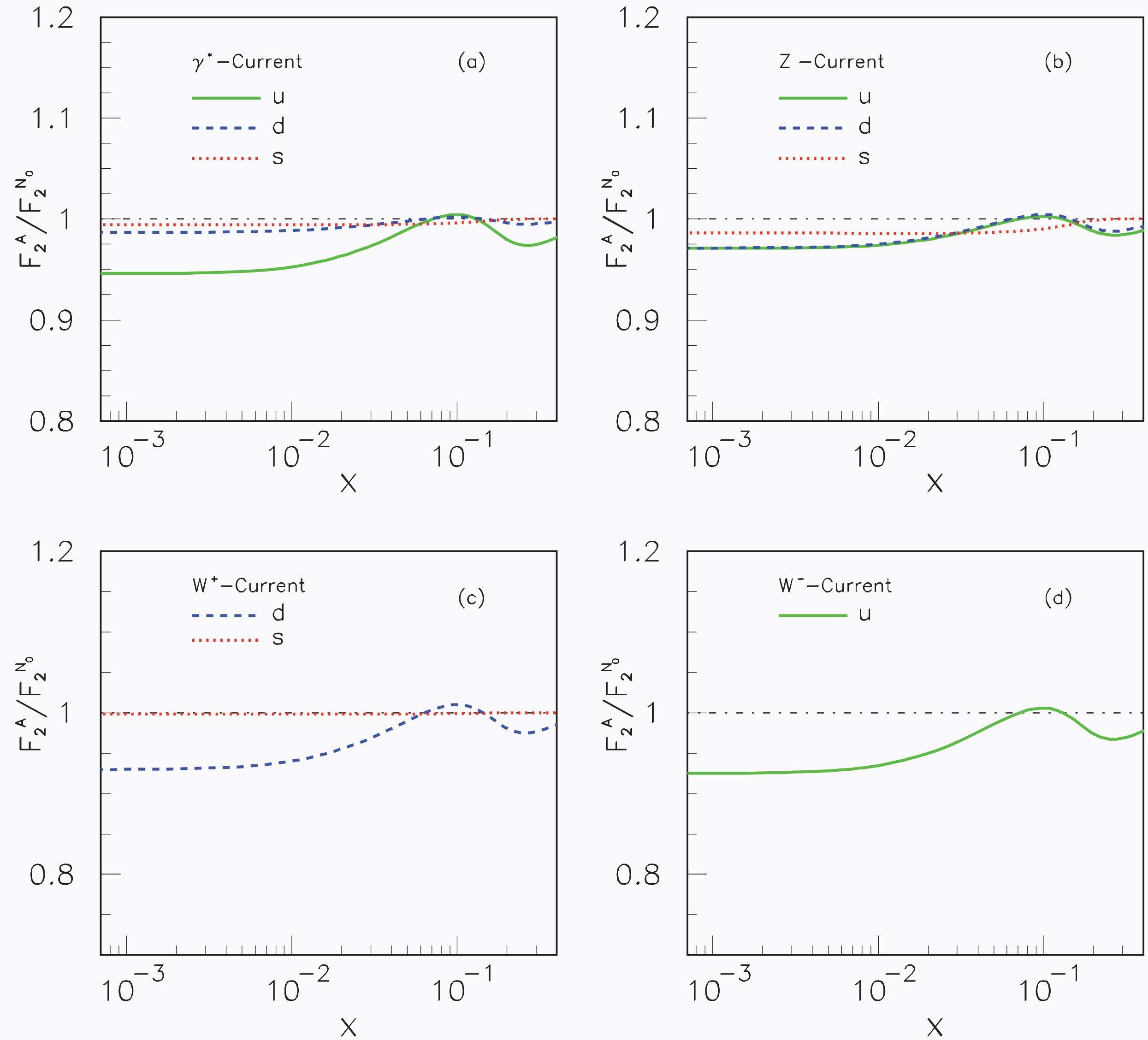
Antishadowing (Reggeon exchange) is not universal!



Schmidt, Yang; sjb

Nuclear Antishadowing not universal !

Shadowing and Antishadowing of DIS Structure Functions



S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Modifies NuTeV extraction of $\sin^2\theta_W$

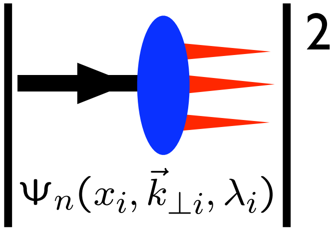
Test in flavor-tagged lepton-nucleus collisions

Physics of Rescattering

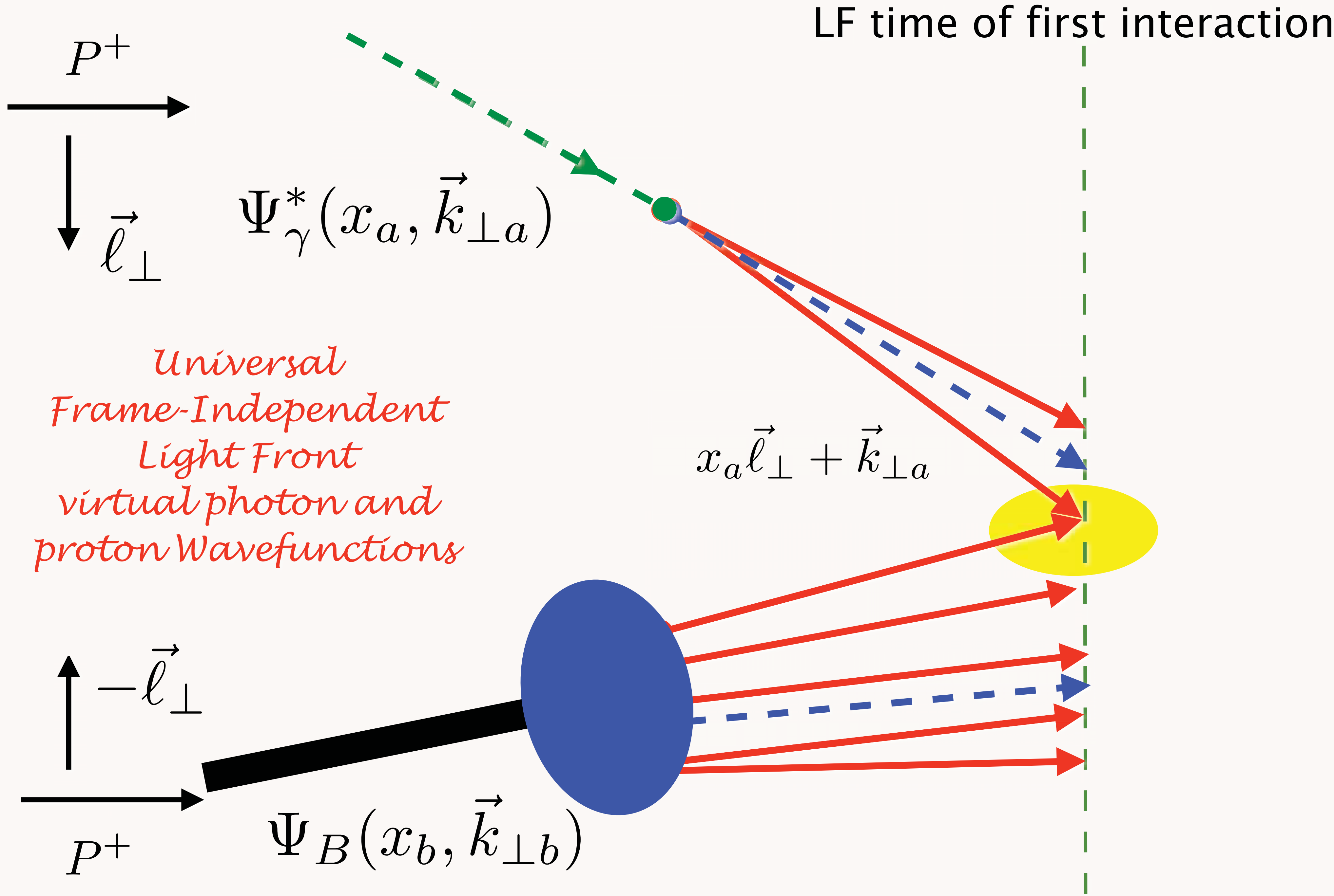
- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing- Not in Target WF
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY angular distribution at leading twist from double ISI-- not given by PQCD factorization -- breakdown of factorization!
- Wilson Line Effects not 1 even in LCG
- Must correct hard subprocesses for initial and final-state soft gluon attachments
- Corrections to Handbag Approximation in DVCS

Hoyer, Marchal, Peigne, Sannino, sjb

Static vs. Dynamic Structure Functions



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	Not Proven
• DGLAP Evolution; mod. at large x	DGLAP Evolution
• No Diffractive DIS	Hard Pomeron and Odderon: DDIS

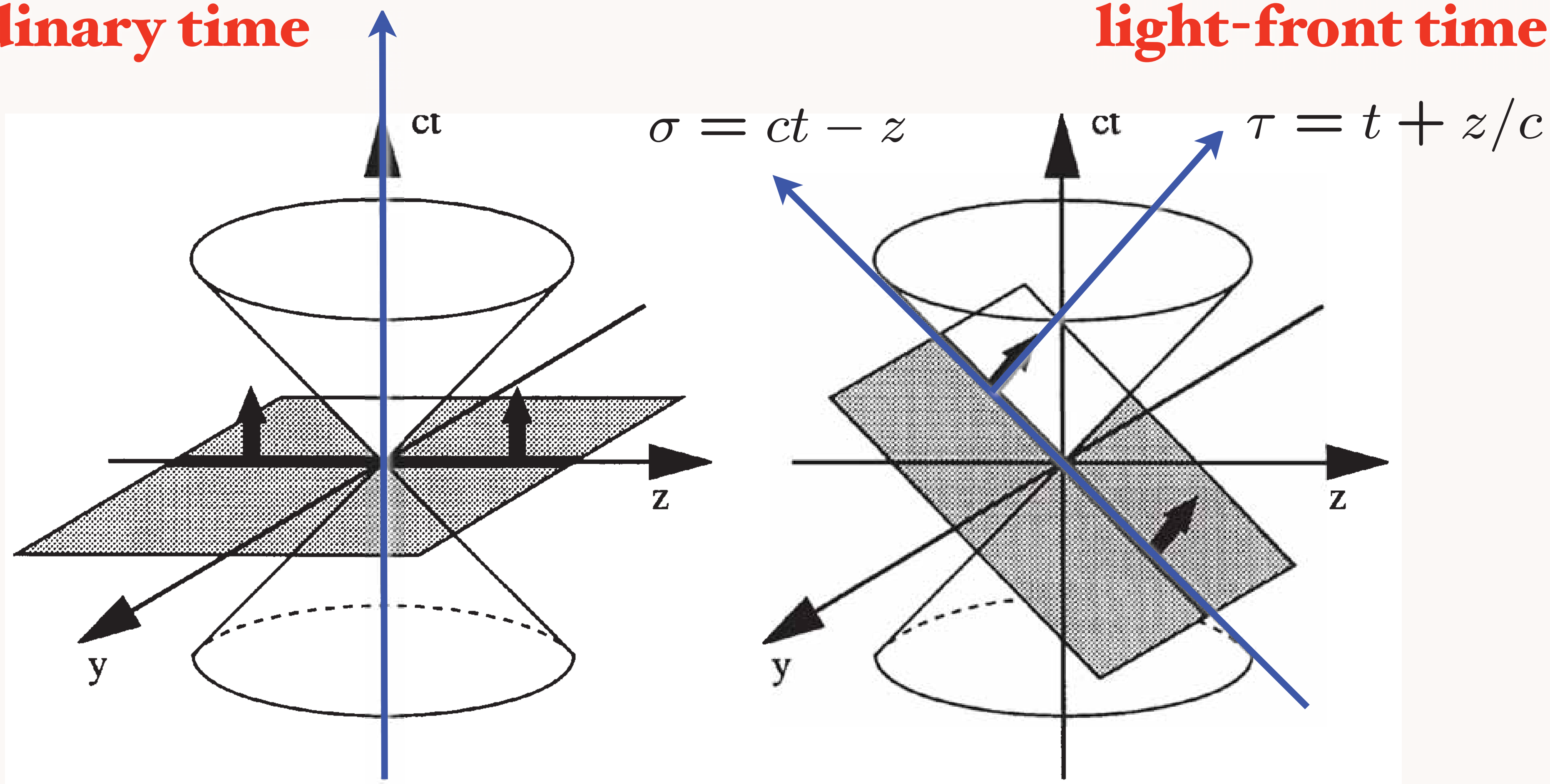

LF time of first interaction
P^+
$\vec{\ell}_\perp$
$\Psi^*_\gamma(x_a, \vec{k}_{\perp a})$
Universal
Frame-Independent
Light Front
virtual photon and
proton Wavefunctions
$x_a\vec{\ell}_\perp + \vec{k}_{\perp a}$
$-\vec{\ell}_\perp$
P^+
$\Psi_B(x_b, \vec{k}_{\perp b})$

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

Each element of flash photograph illuminated at same LF time

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

Evolve in LF time

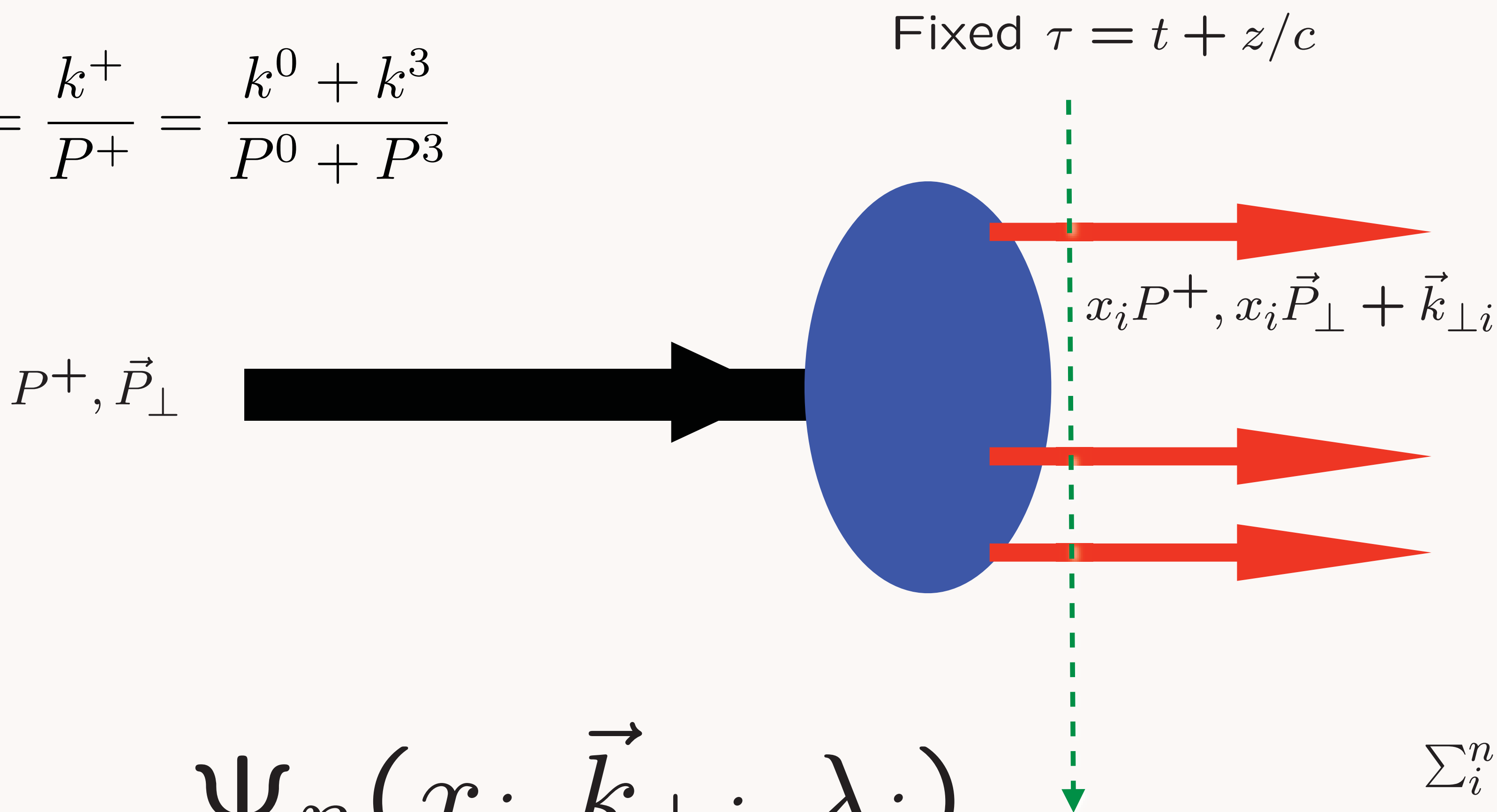
$$P^{-} = i\frac{d}{d\tau}$$

Eigenstate -- independent of τ

HELEN BRADLEY - PHOTOGRAPHY

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

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



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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

Light-Front Wavefunctions

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

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

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

Invariant under boosts. Independent of P^μ

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

Direct connection to QCD Lagrangian

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

Light-Front QCD

Heisenberg Matrix Formulation

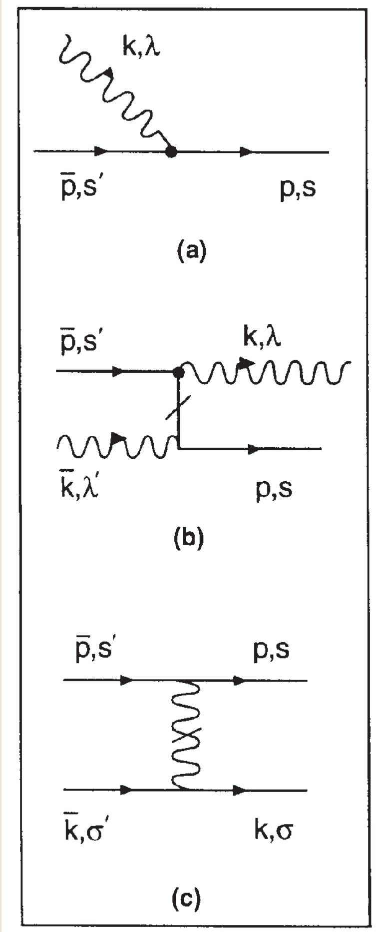
Physical gauge: $A^+ = 0$

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

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

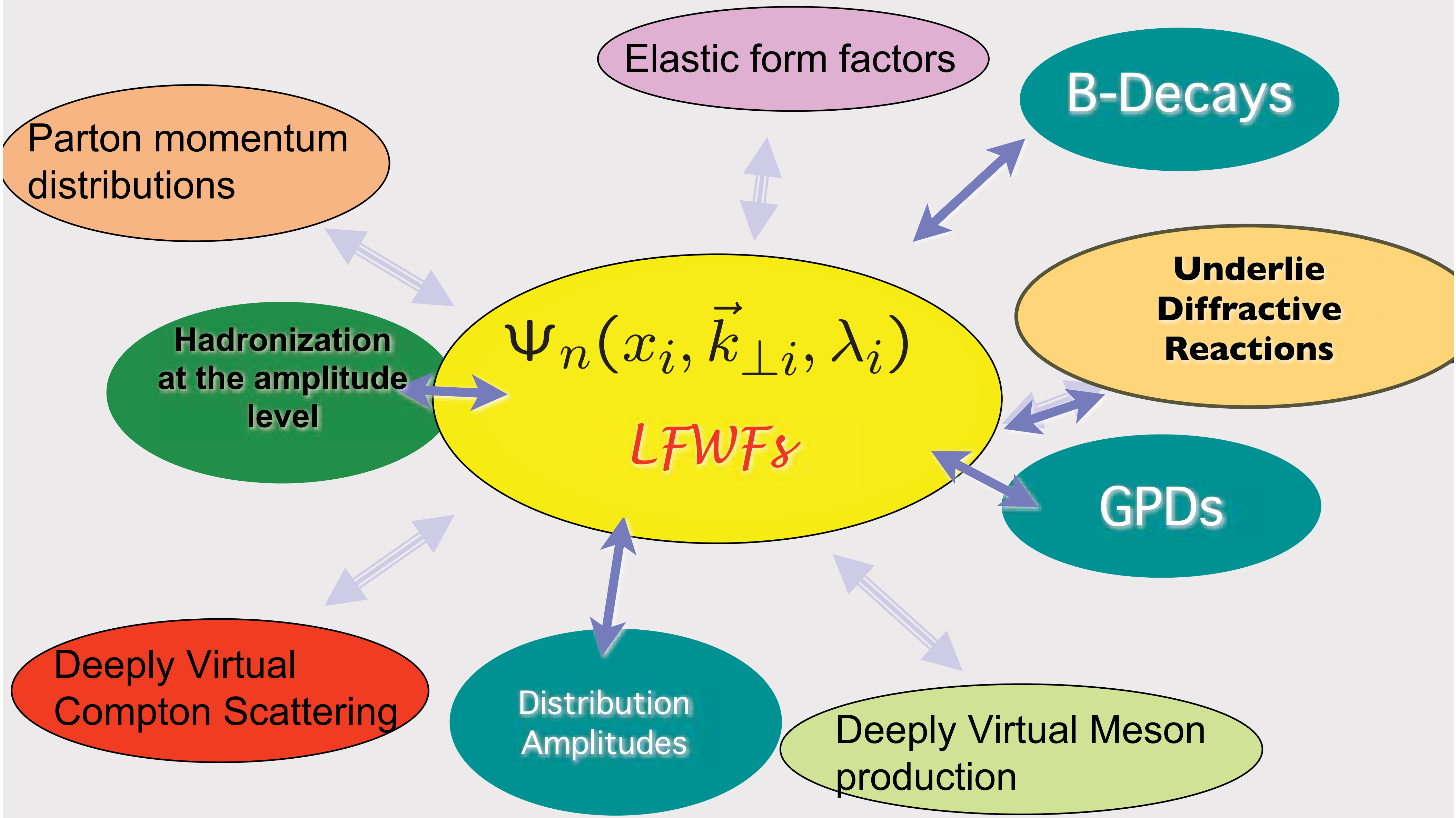
H_{LF}^{int}: Matrix in Fock Space

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



Eigenvalues and Eigensolutions give Hadron Spectrum and Light-Front wavefunctions

A Unified Description of Hadron Structure



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

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

The Light Front Fock State Wavefunctions

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

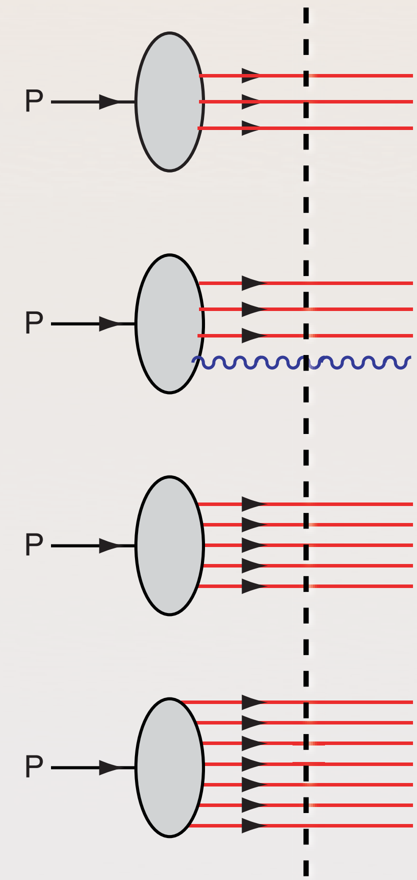
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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

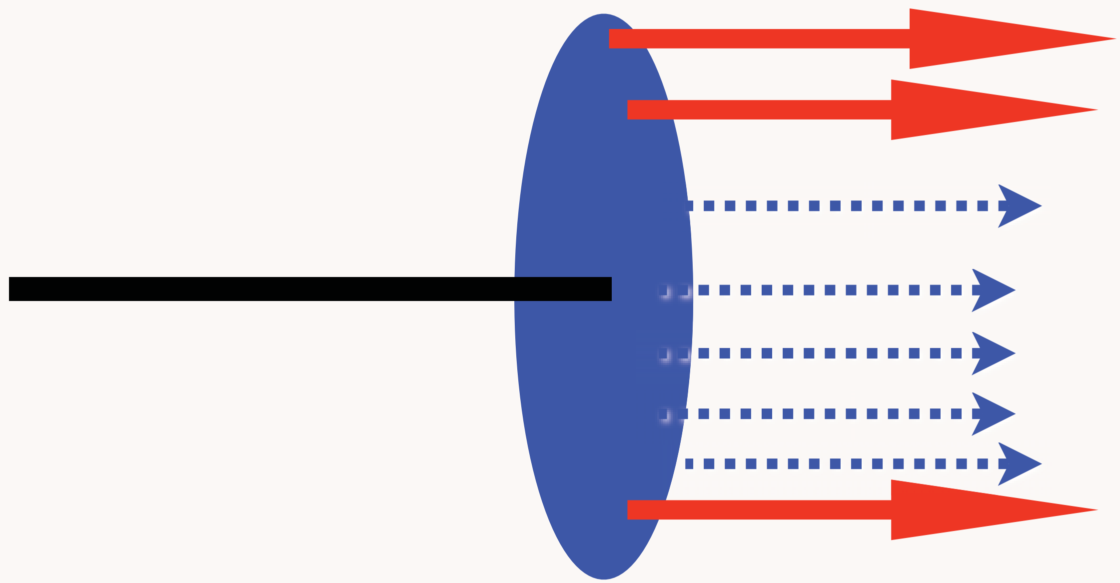
Intrinsic heavy quarks, $\bar{s}(x) \neq s(x)$

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

Soft gluons in the infinite momentum wave function and the BFKL **pomeron.**
Alfred H. Mueller (SLAC & Columbia U.) . SLAC-PUB-10047, CU-TP-609, Aug 1993. 12pp.
Published in **Nucl.Phys.B415:373-385,1994**.

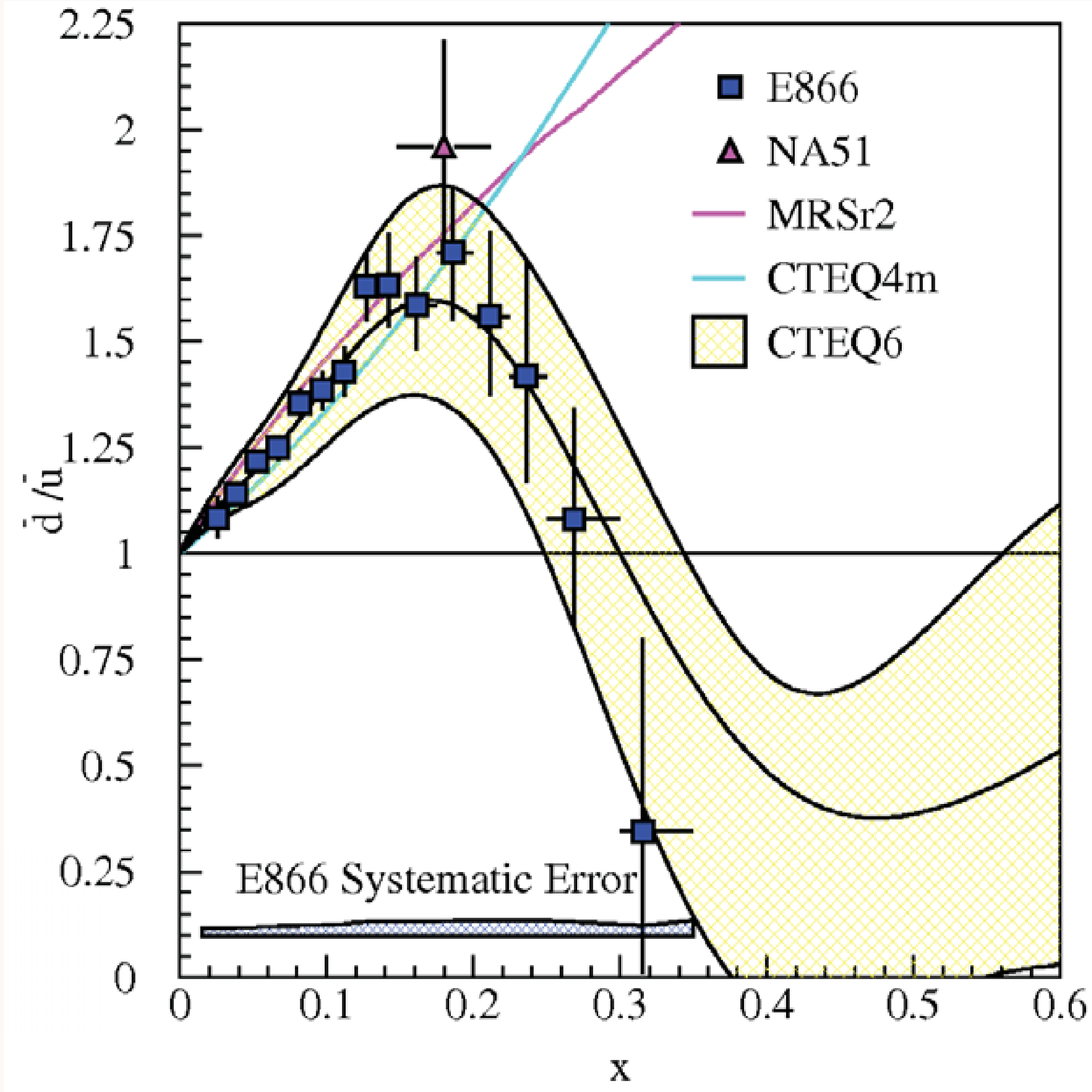
Light cone wave functions at small x.
F. Antonuccio (Heidelberg, Max Planck Inst. & Heidelberg U.) , S.J. Brodsky (SLAC) , S. Dalley (CERN) .
Phys.Lett.B412:104-110,1997.
e-Print: **hep-ph/9705413**

Mueller: BFKL derived from multi-gluon Fock State



Antonuccio, Dalley, sjb: Ladder Relations

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



- E866/NuSea (Drell-Yan)

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

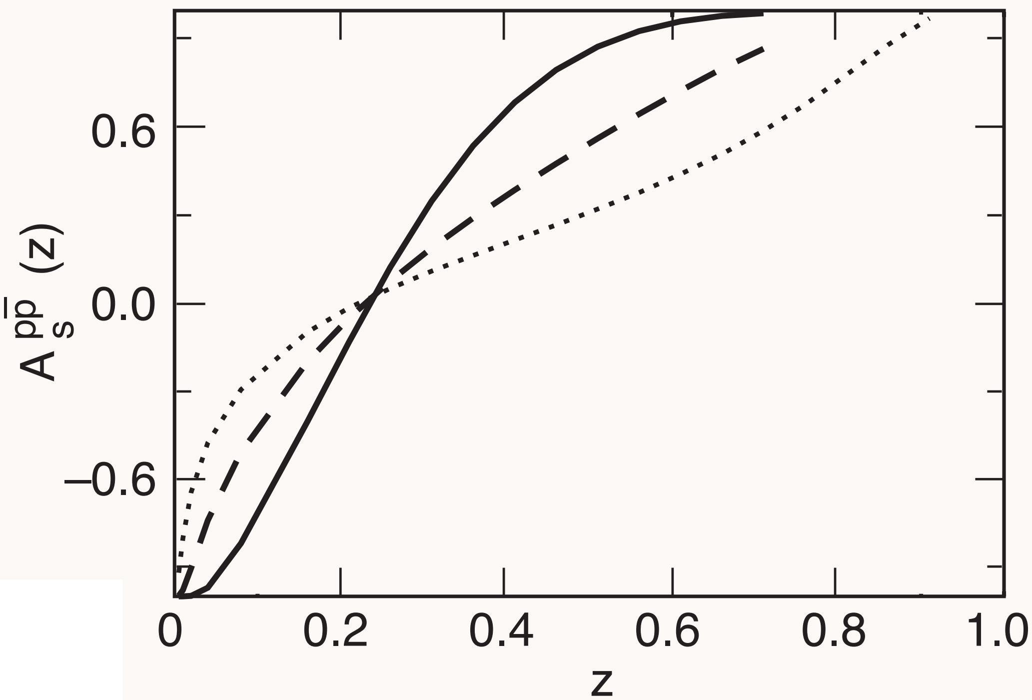
$$s(x) \neq \bar{s}(x)$$

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

Angular Momentum on the Light-Front

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

Conserved
LF Fock state by Fock State

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

n-1 orbital angular momenta

Nonzero Anomalous Moment -->Nonzero orbital angular momentum

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

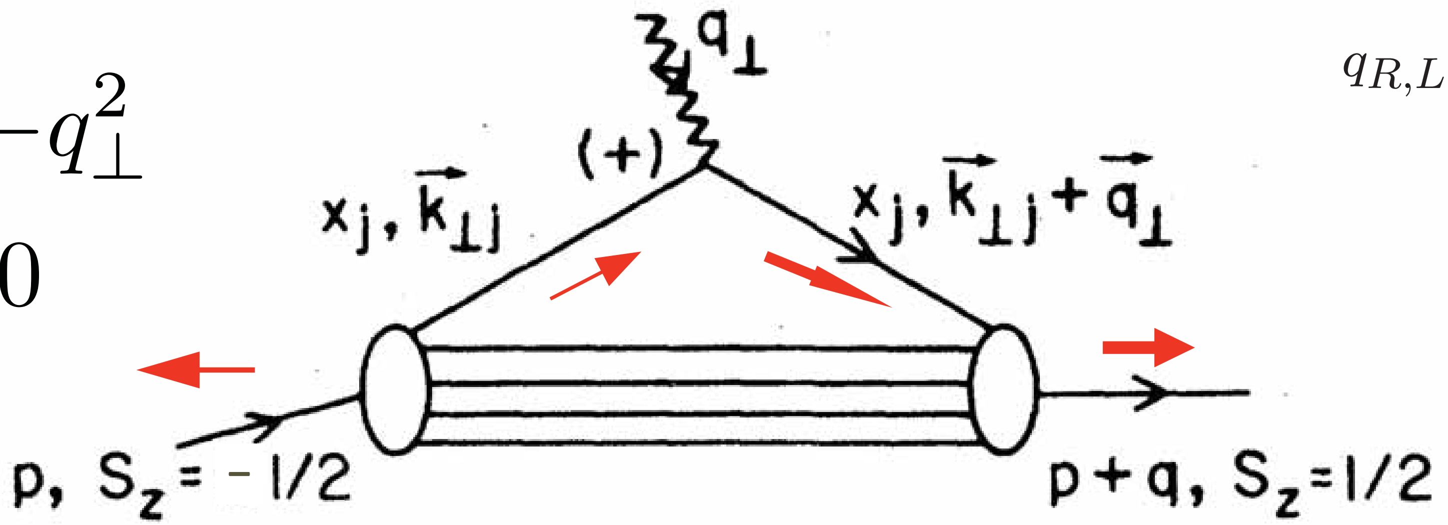
Drell, sjb

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

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

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

$$q^+ = 0$$



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

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

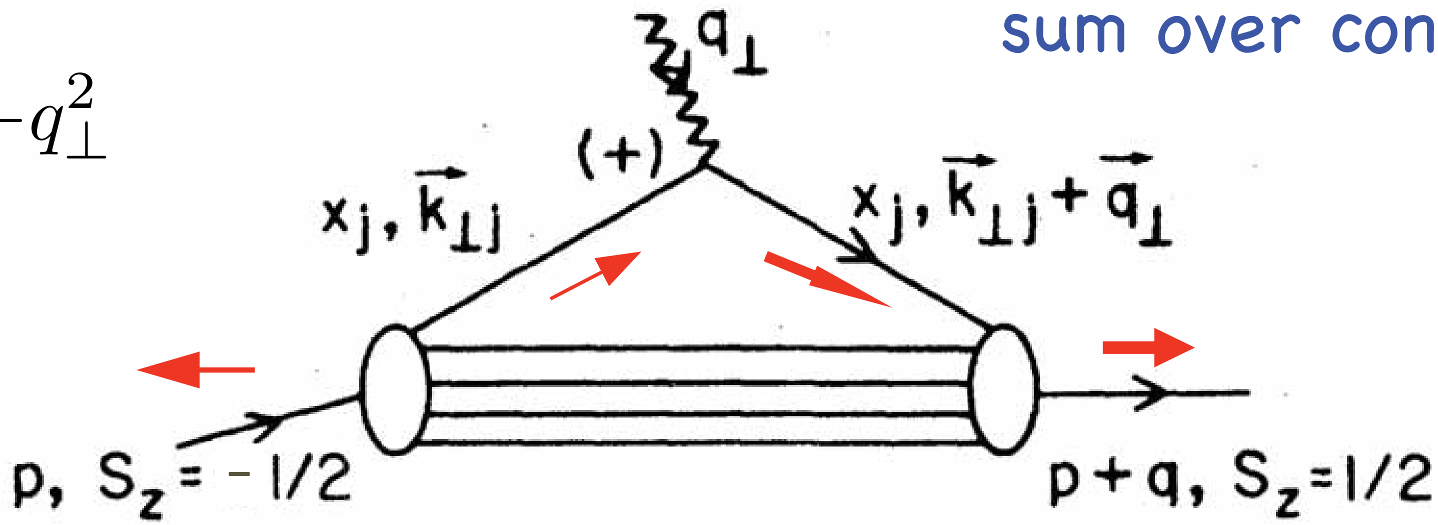
Anomalous gravitomagnetic moment B(0)

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

graviton

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

sum over constituents



Hwang, Schmidt, sjb;
Holstein et al

B(0) = 0

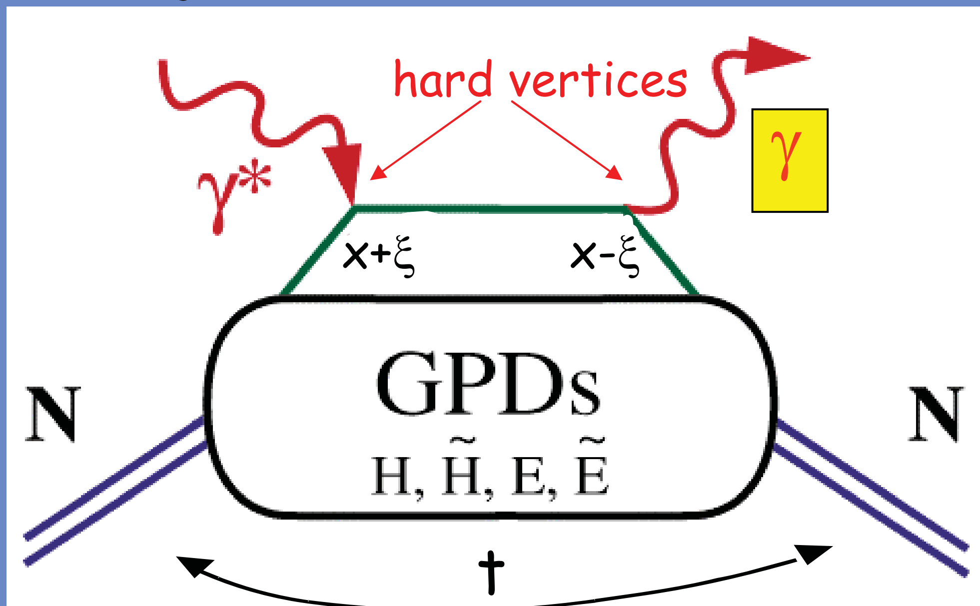
Each Fock State

Some Applications of Light-Front Wavefunctions

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

GPDs & Deeply Virtual Exclusive Processes
- New Insight into Nucleon Structure

Deeply Virtual Compton Scattering (DVCS)



x – quark momentum fraction

ξ– longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

$H(x,\xi,t), E(x,\xi,t), \ldots$ "Generalized Parton Distributions"

Quark angular momentum (Ji sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx\left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

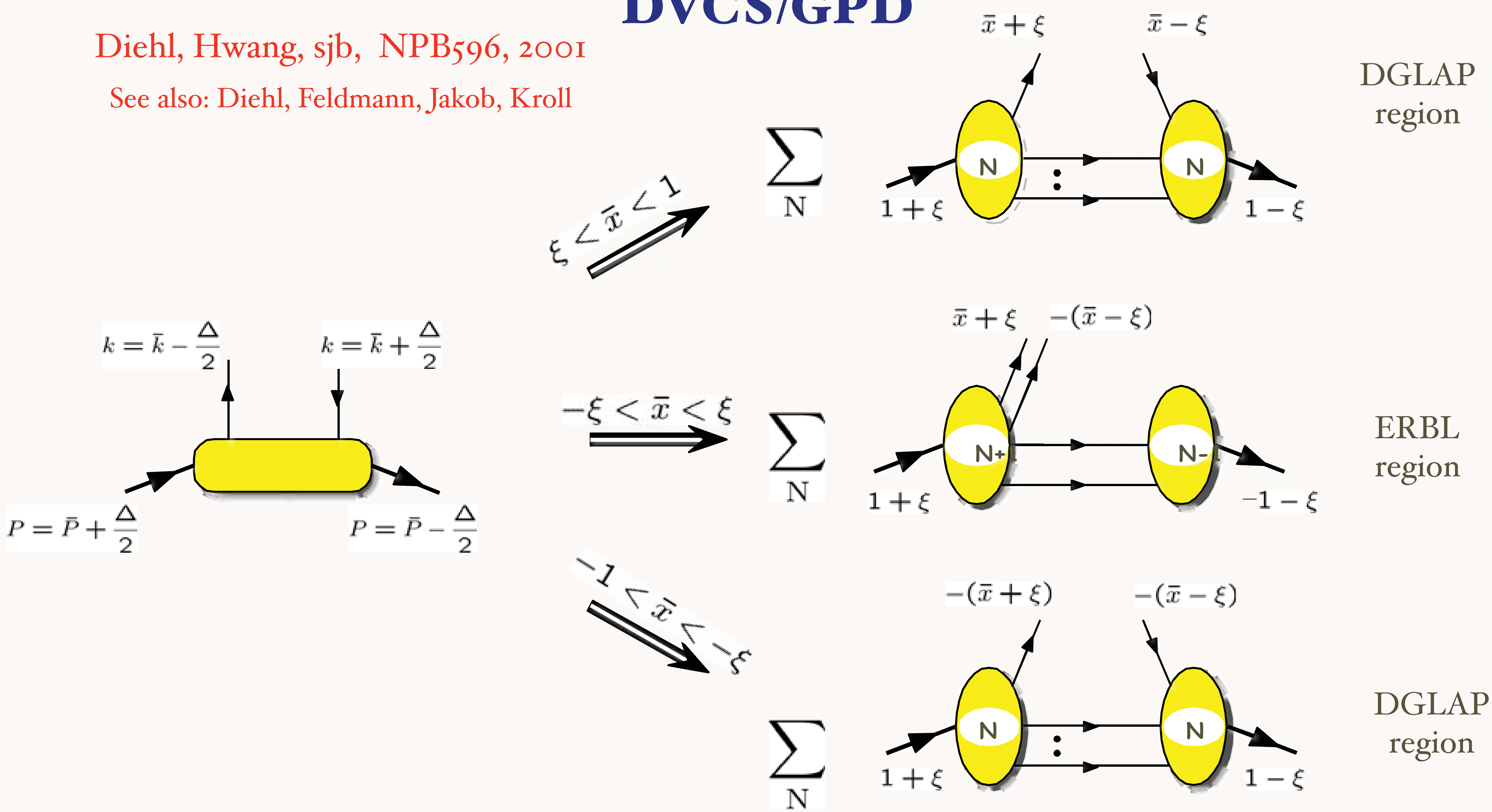
X. Ji, Phy.Rev.Lett.78,610(1997)

Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



N=3 VALENCE QUARK ⇒ Light-cone Constituent quark model

N=5 VALENCE QUARK + QUARK SEA ⇒ Meson-Cloud model

Link to DIS and Elastic Form Factors

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) \right] = F_1(t) \quad \text{Dirac f.f.}$$

$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t) \right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x), \quad -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \quad \Delta\bar{q}(-x)$$

Verified using LFWFs

Diehl, Hwang, sjb

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

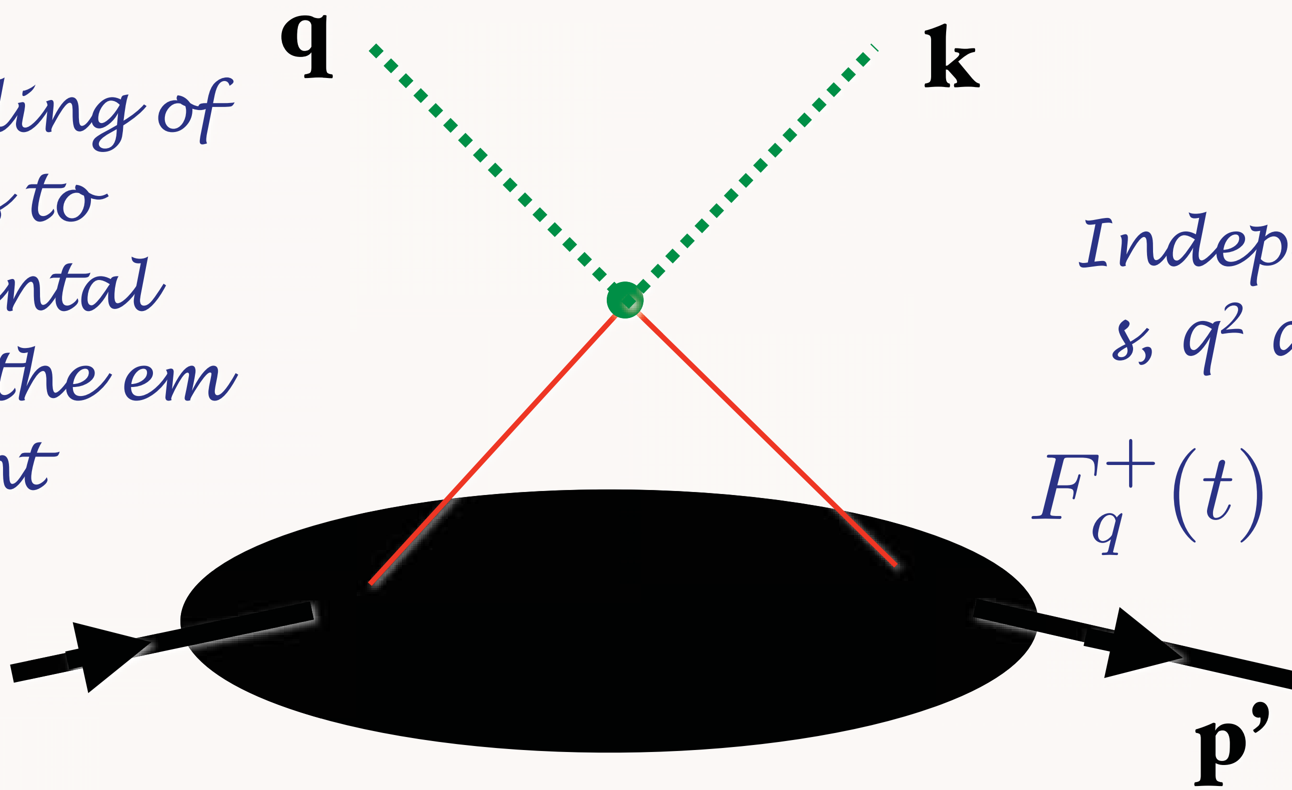
Quark angular momentum (Ji's sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

'Seagull' contribution to real and virtual Compton scattering

Local coupling of photons to fundamental carriers of the em current



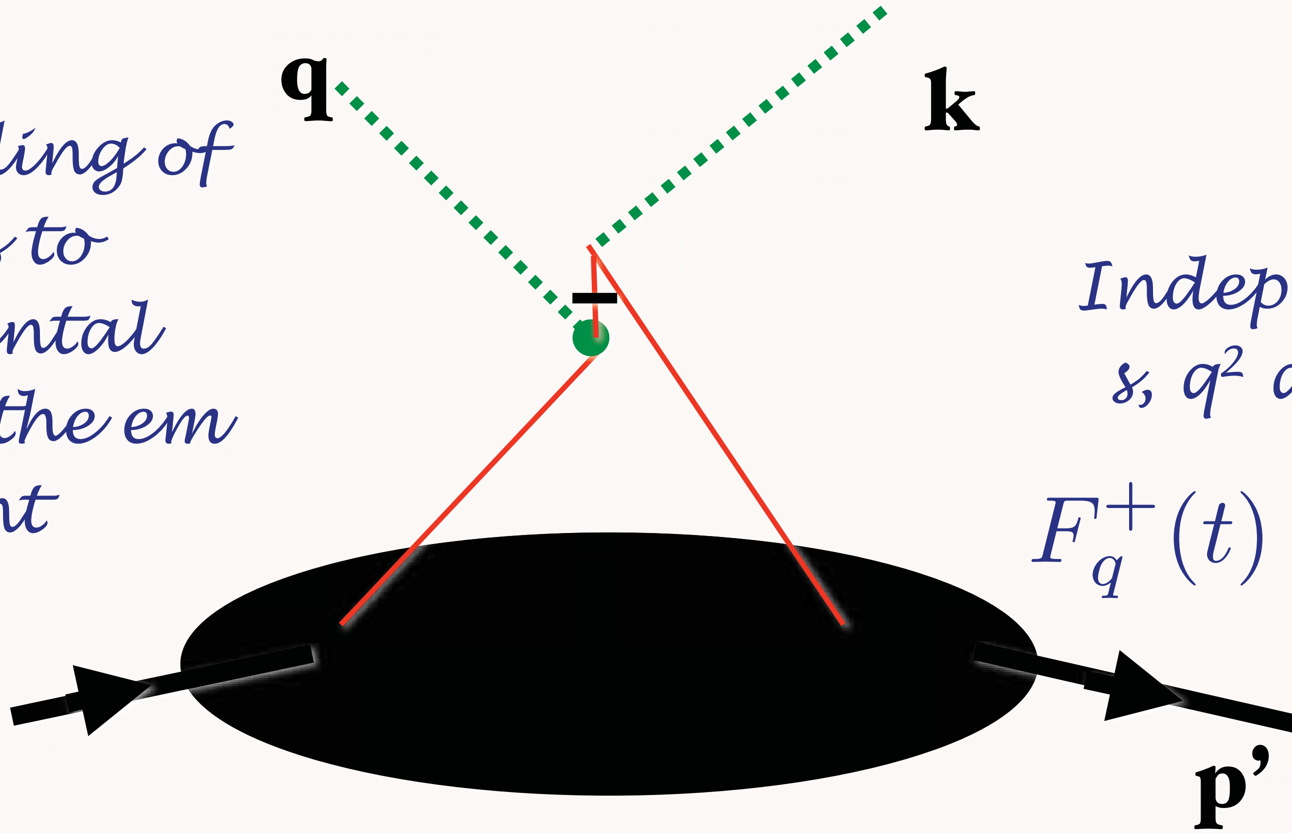
Independent of s, q^2 at fixed t

$$F_q^+(t) = < \frac{1}{x} >$$

$$M = -2 \sum_{q/p} e_q^2 F_q^+(t) \vec{\epsilon} \cdot \vec{\epsilon}'$$

Instantaneous fermion exchange contribution to real and virtual Compton scattering

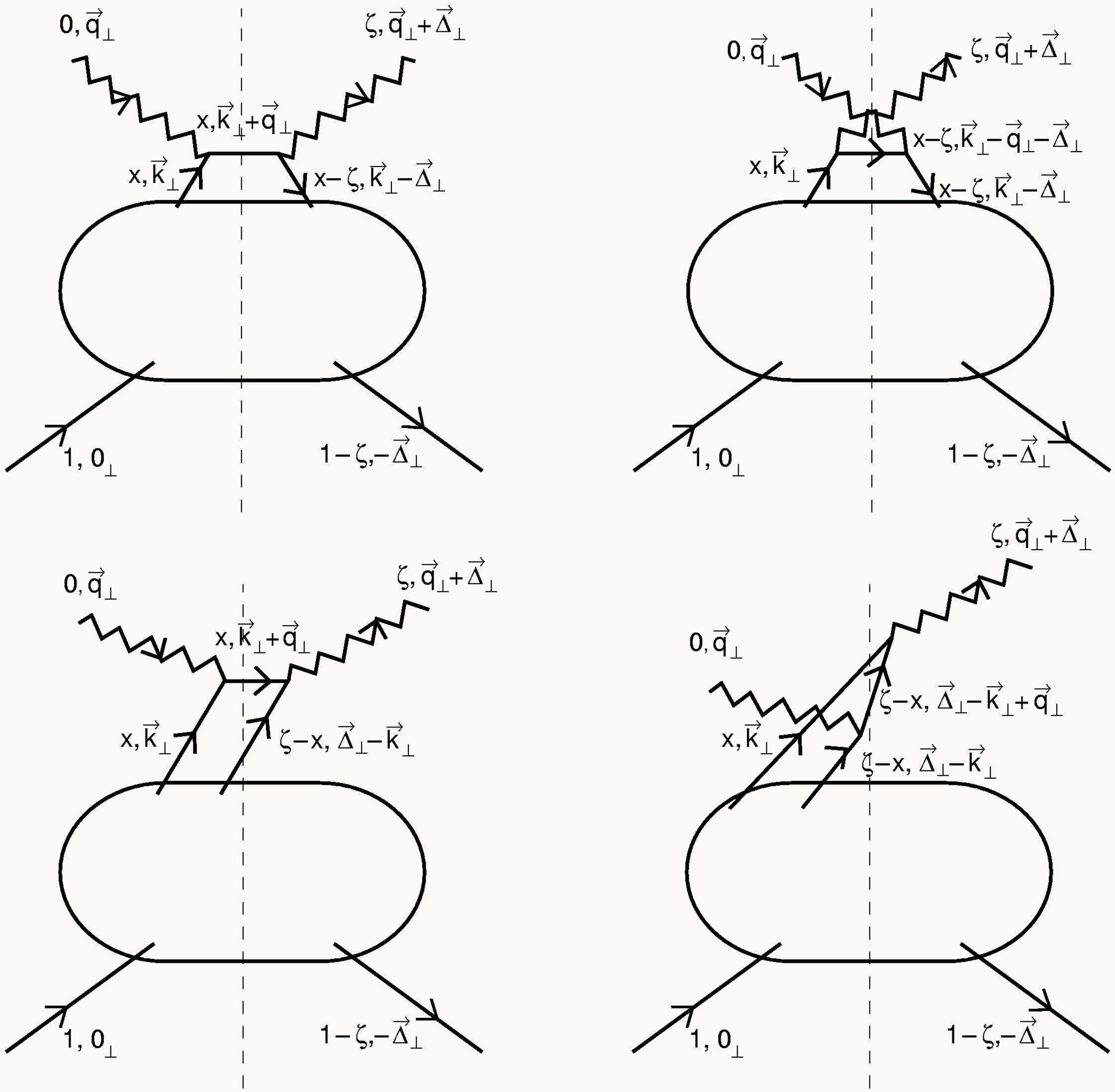
Local coupling of photons to fundamental carriers of the em current



Independent of s, q² at fixed t

$$F_q^+(t) = < \frac{1}{x} >$$

$$M = -2 \sum_{q/p} e_q^2 F_q^+(t) \vec{\epsilon} \cdot \vec{\epsilon}'$$



$$A_{J=0} \sim e_q^2 s^0 F(t)$$

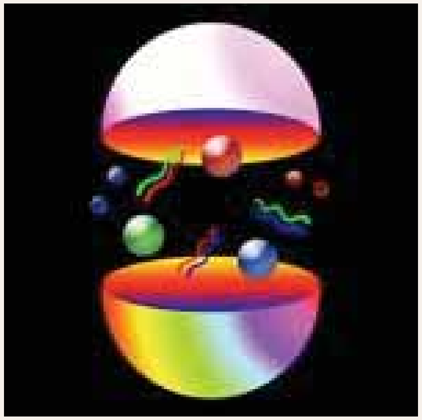
Local J=0 fixed pole contribution

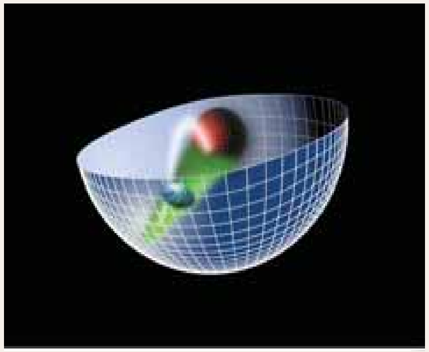
Close, Gunion, sjb; Szczepaniak, Llanes-Estrada, sjb

Light-cone wavefunction representation of deeply virtual Compton scattering ☆

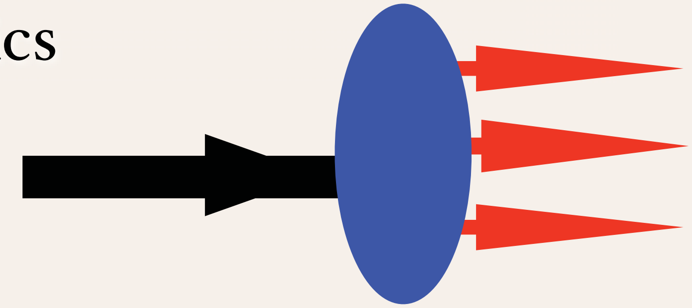
Stanley J. Brodsky [a], Markus Diehl [a,1], Dae Sung Hwang [b]

- 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

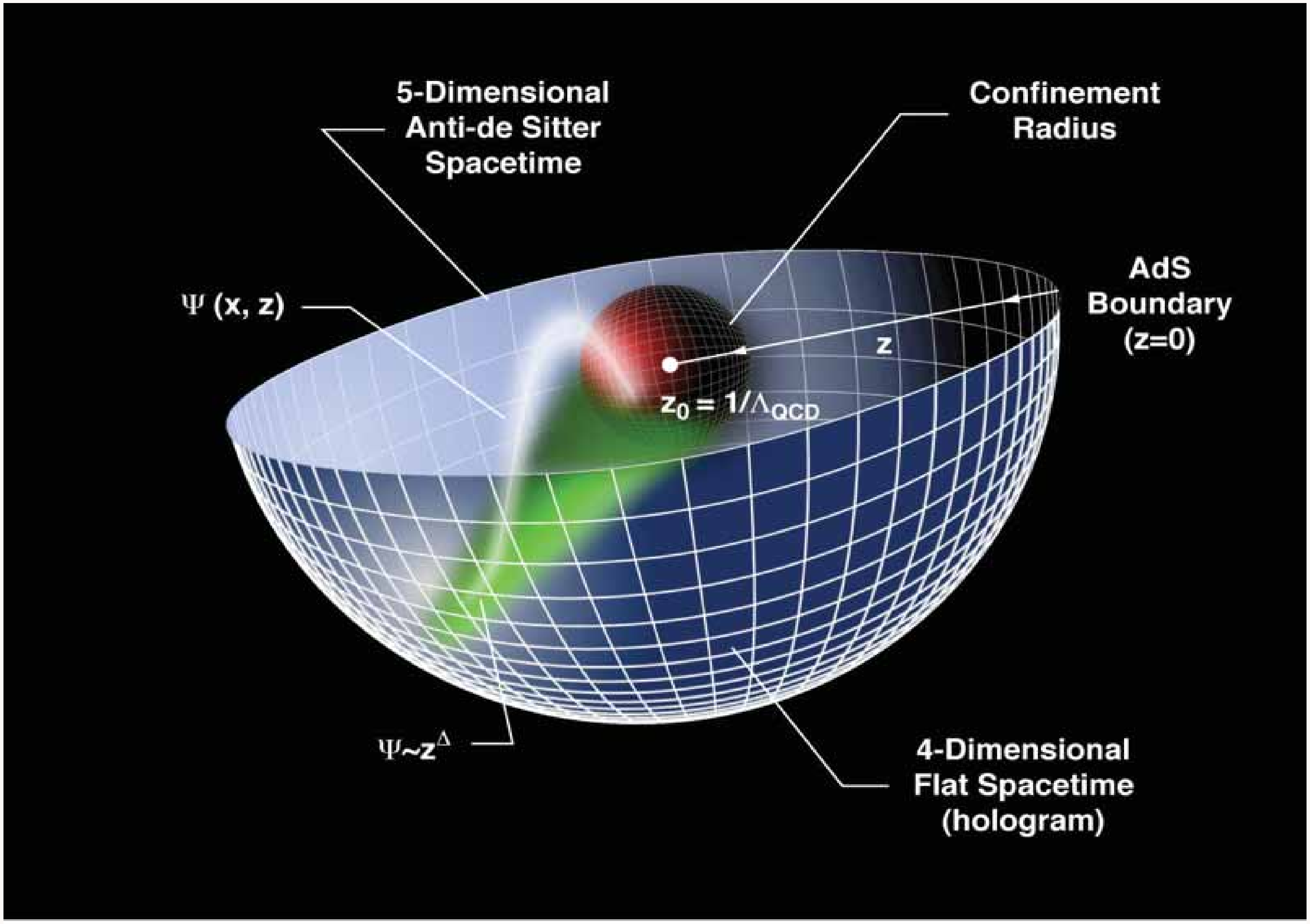




$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



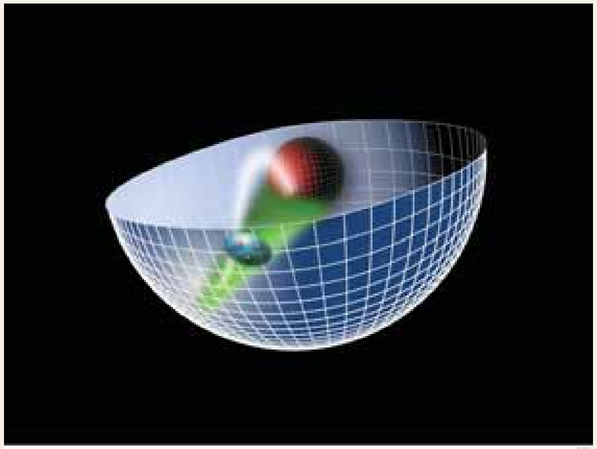
Applications of AdS/CFT to QCD



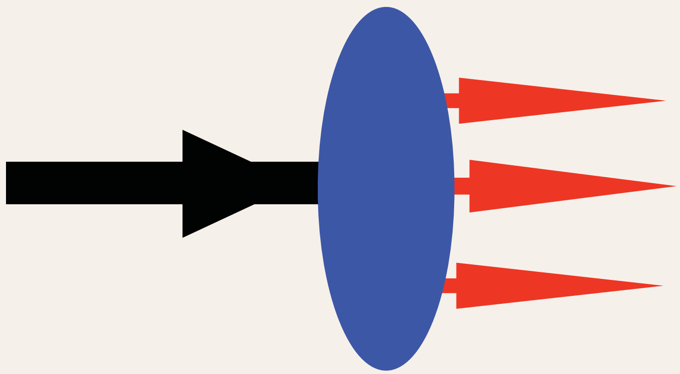
Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond

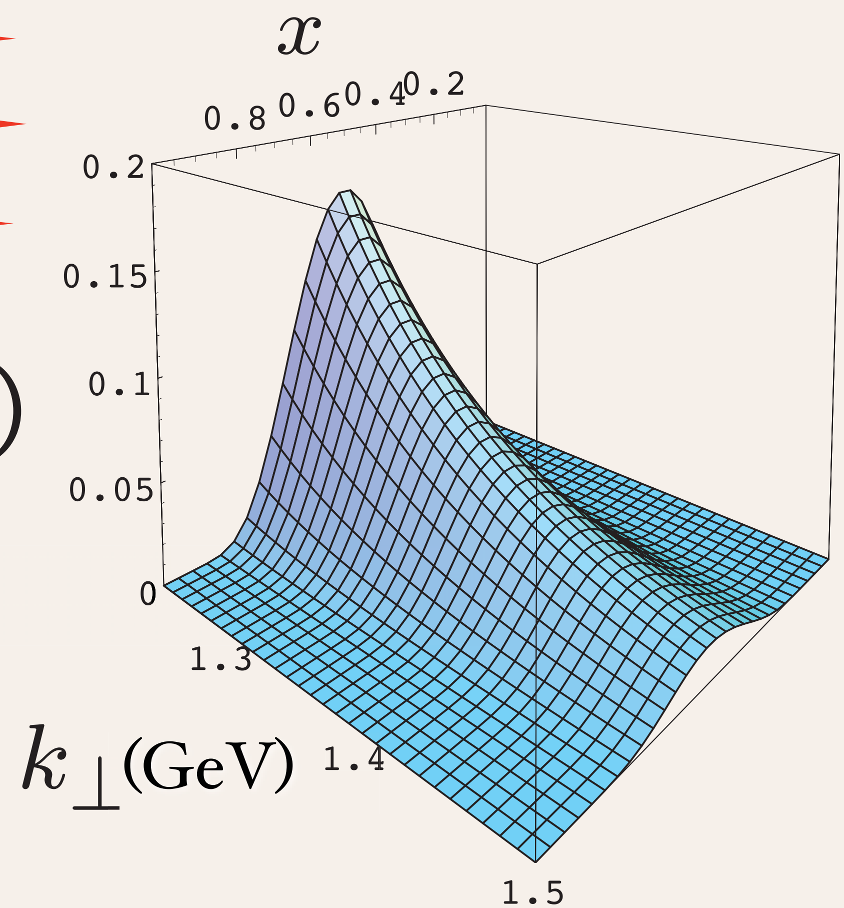
$$\phi(z)$$



- *Light-Front Holography*



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



- *Light Front Wavefunctions:*

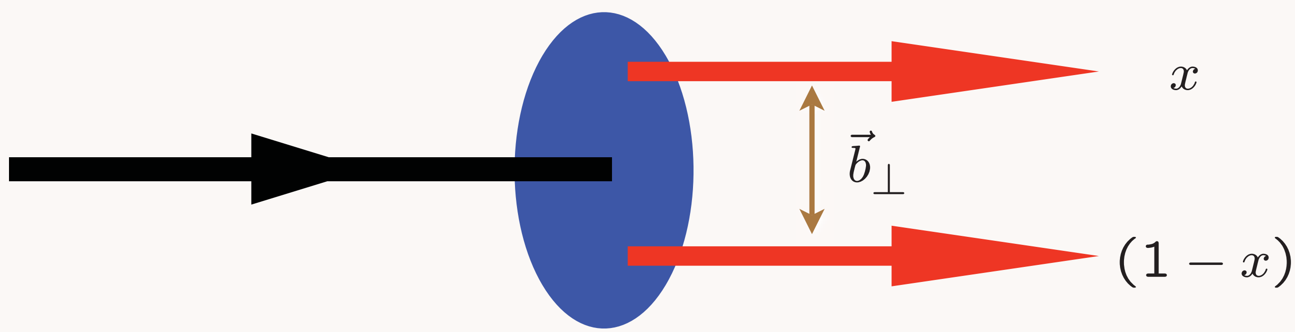
  Schrödinger Wavefunctions of Hadron Physics

LF(3+1) $\qquad\qquad$ AdS_5

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

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

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



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

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

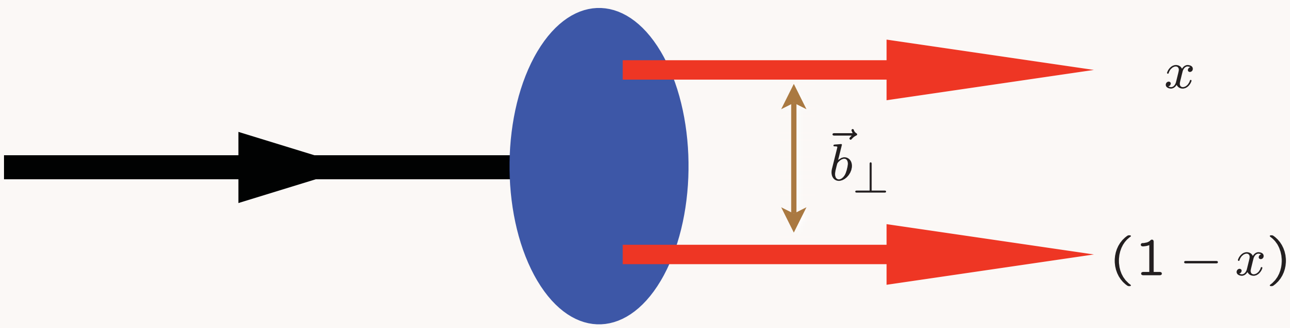
Light-Front Holography: Map AdS/CFT to 3+1 LF Theory

Relativistic LF radial equation

Frame Independent

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

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



$$U(\zeta) = \kappa^4\zeta^2$$

soft wall confining potential:

G. de Teramond, sjb

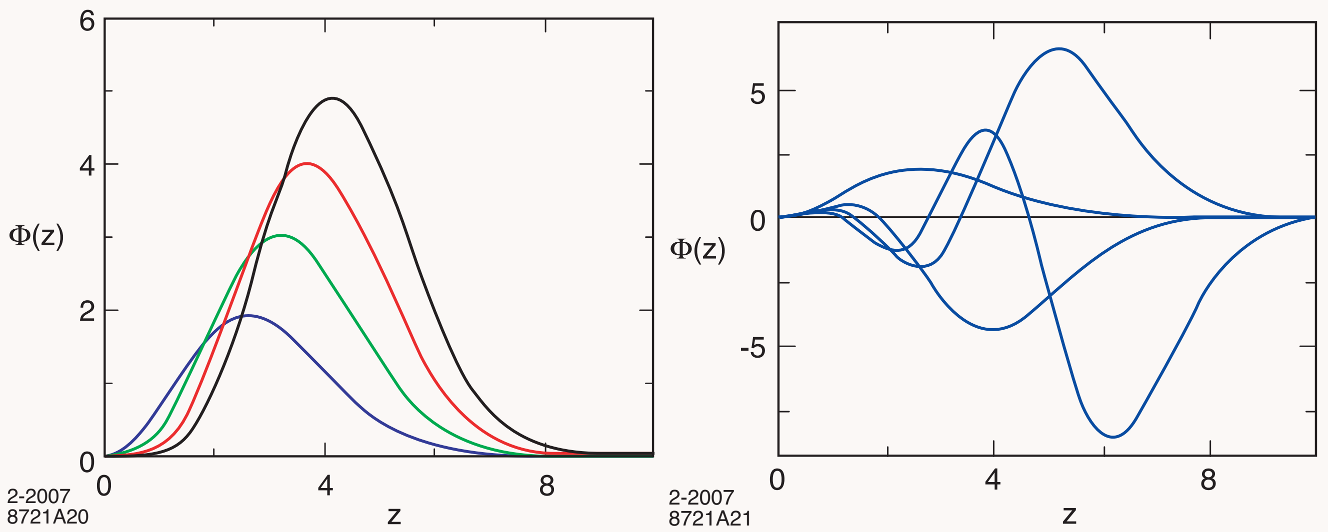
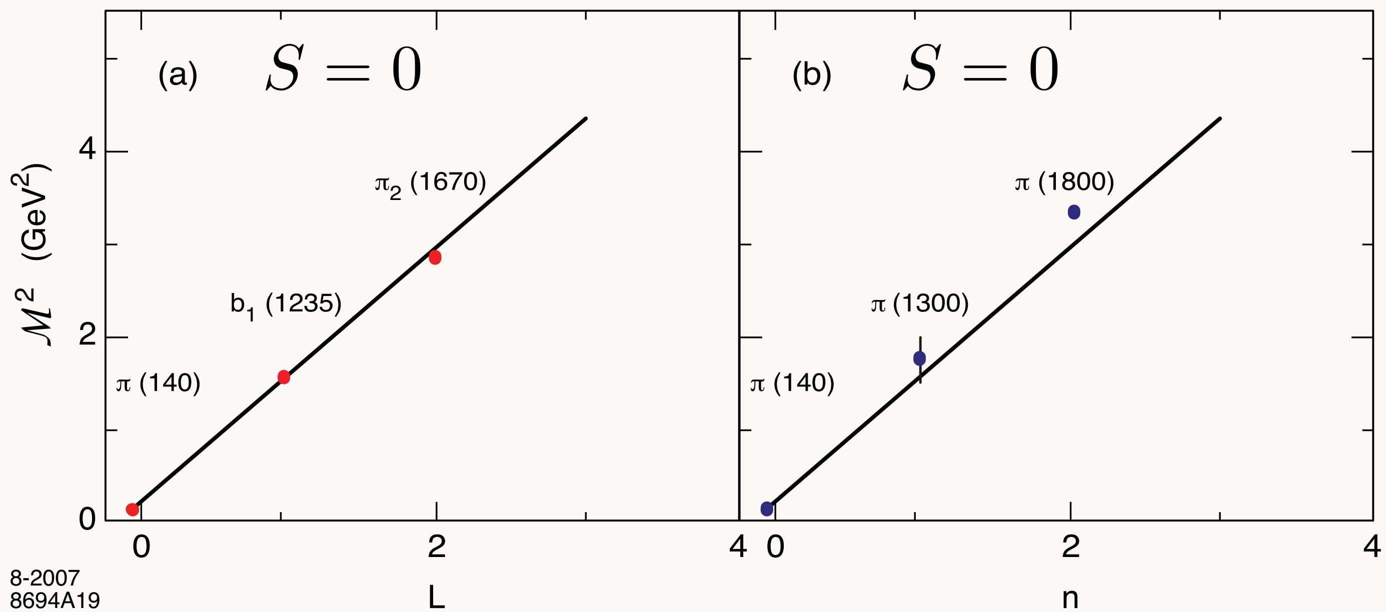


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

Soft Wall Model



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

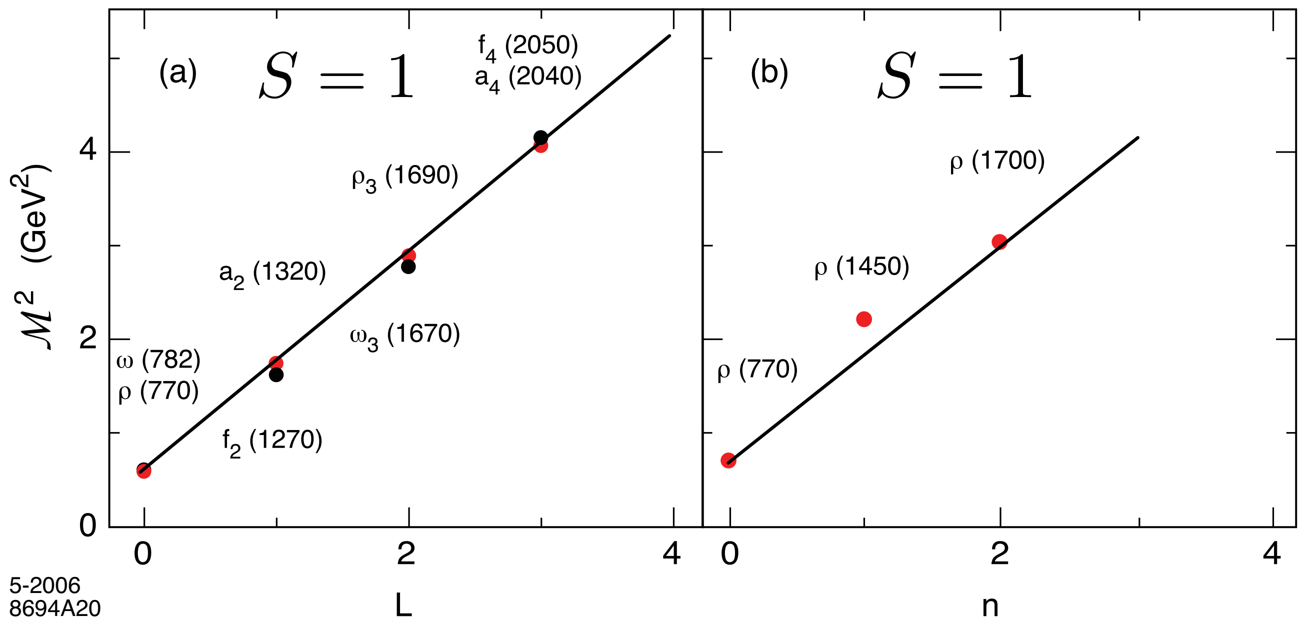
Soft-wall model

- Effective LF Schrödinger wave equation

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

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

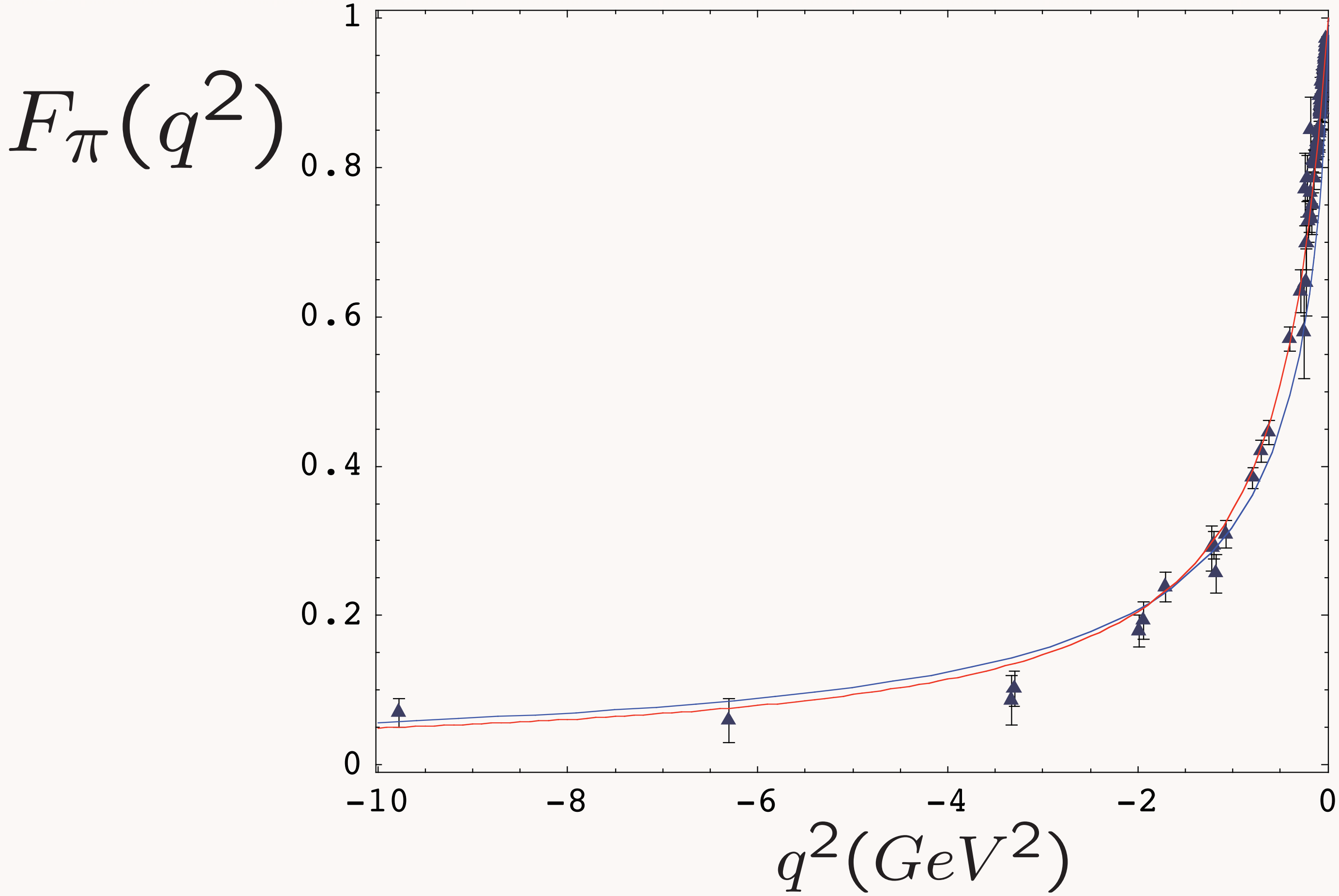
- Compare with Nambu string result (rotating flux tube): $M_n^2(L) = 2\pi\sigma\,(n+L+1/2)$.



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

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

Spacelike pion form factor from AdS/CFT



Data Compilation
Baldini, Kloe and Volmer

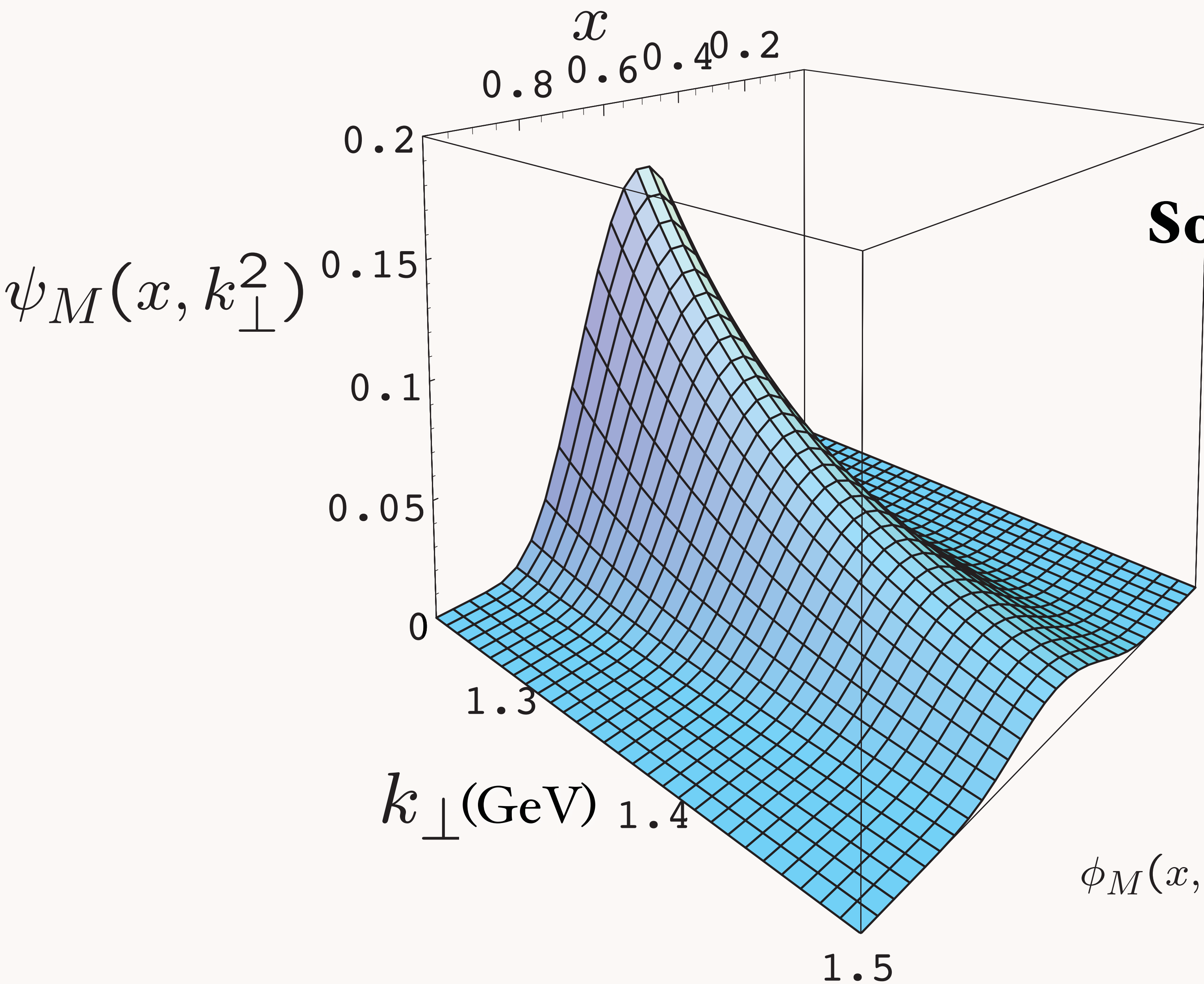
Soft Wall: Harmonic Oscillator Confinement

Hard Wall: Truncated Space Confinement

One parameter - set by pion decay constant

de Teramond, sjb
See also: Radyushkin

Prediction from AdS/CFT: Meson LFWF



Soft Wall Model

de Teramond, sjb

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

Increases PQCD prediction for $F_\pi(Q^2)$ by 16/9

Second Moment of Pion Distribution Amplitude

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

$$\xi = 1 - 2x$$

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

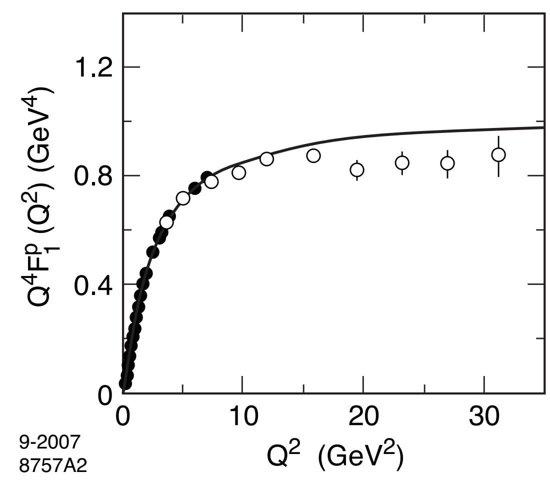
$$< \xi^2 >_\pi = 1/4 = 0.25 \qquad \phi_{AdS/QCD} \propto \sqrt{x(1-x)}$$

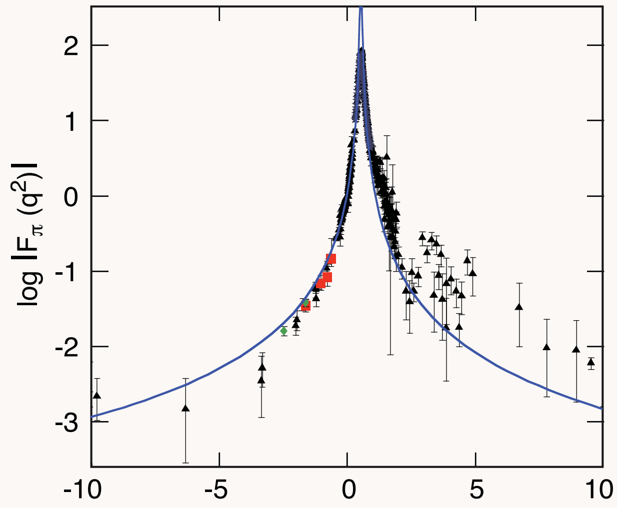
Lattice (I) $< \xi^2 >_\pi = 0.28 \pm 0.03$ Donnellan et al.

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

Other Applications of Light-Front Holography

- Light baryon spectrum
- Light meson spectrum
- Nucleon form-factors: space-like region
- Pion form-factors: space and time-like regions
- Gravitational form factors of composite hadronss
- n-parton holographic mapping
- Heavy flavor mesons





hep-th/0501022

hep-ph/0602252

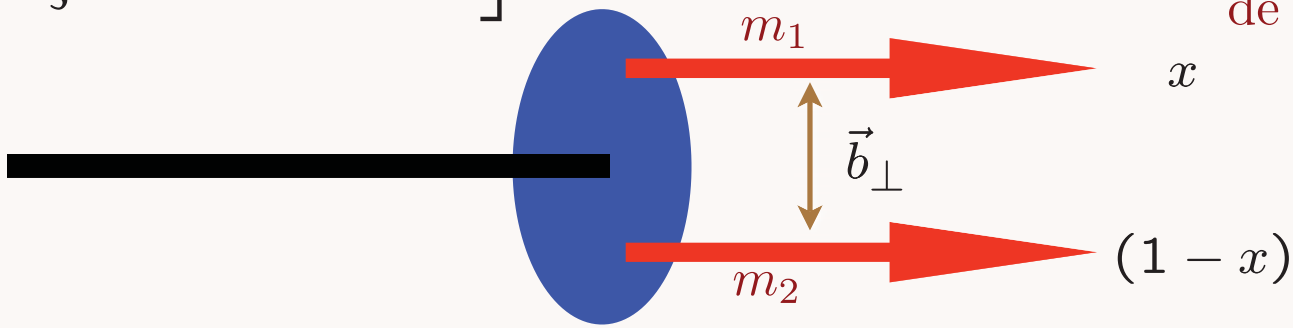
arXiv:0707.3859

arXiv:0802.0514

arXiv:0804.0452

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

de Teramond, sjb



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

Holographic Variable

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

LF Kinetic Energy in momentum space

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

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

Result: Soft-Wall LFWF for massive constituents

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

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

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

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

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

J/ψ

LFWF peaks at

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

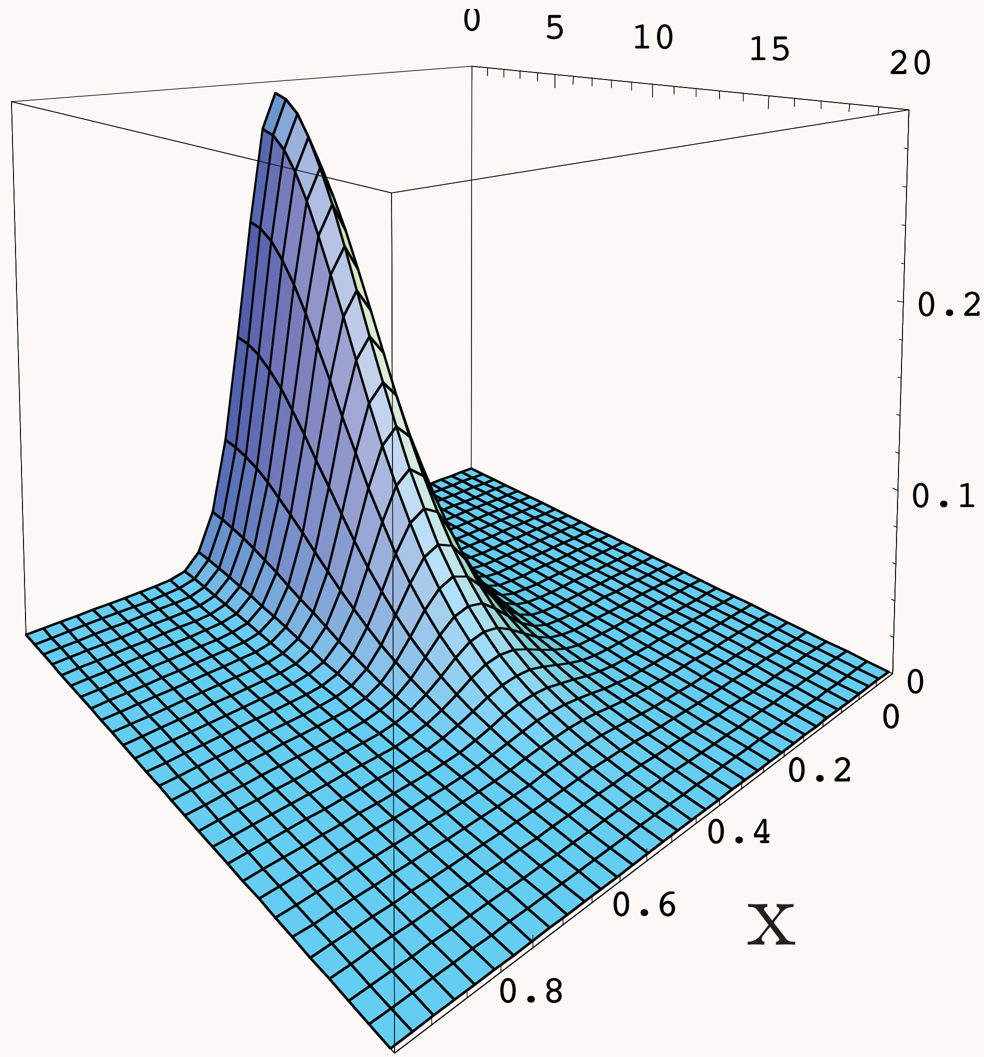
where

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

minimum of LF energy denominator

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

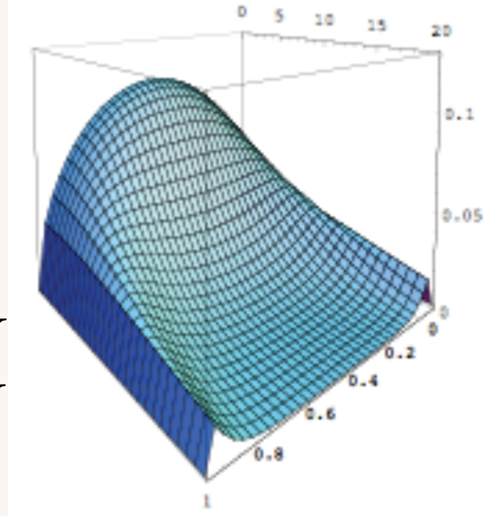
$$\psi_{J/\psi}(x, b)$$

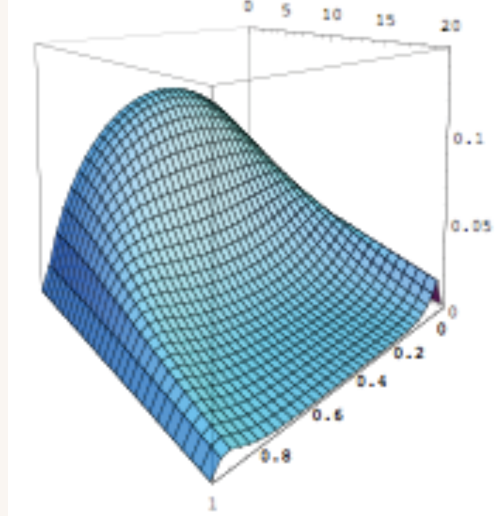


$$m_a = m_b = 1.25 \text{ GeV}$$

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

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



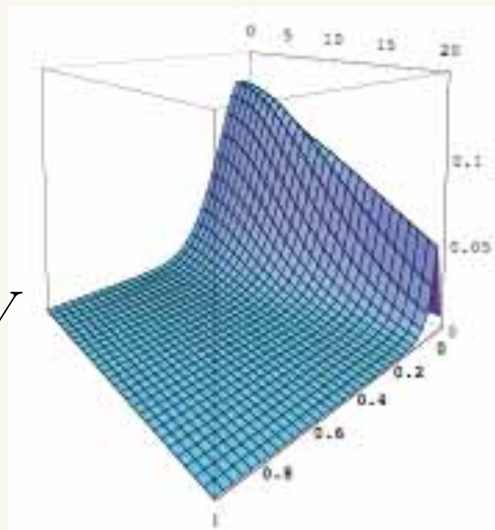


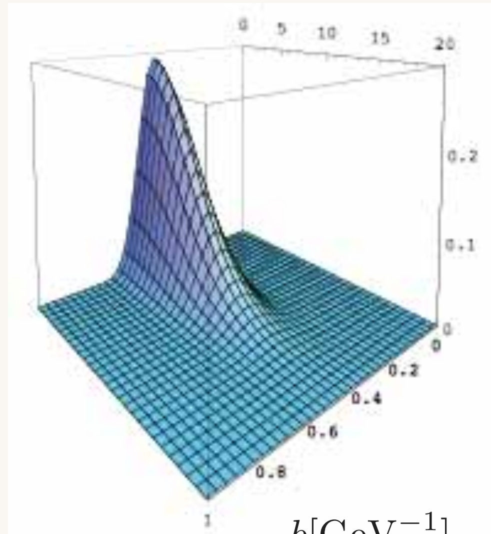
$|K^+ >= |u\bar{s}>$

$m_s = 95\ MeV$

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

$m_c = 1.25\ GeV$

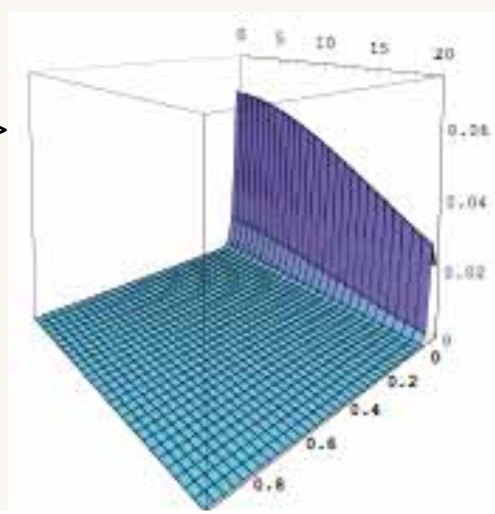


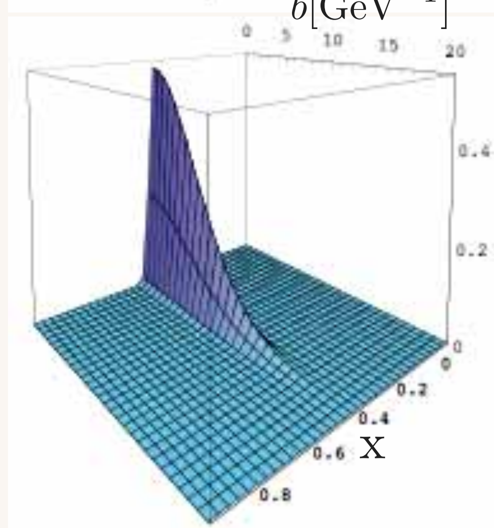


$|\eta_c >= |c\bar{c}>$

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

$m_b = 4.2\ GeV$





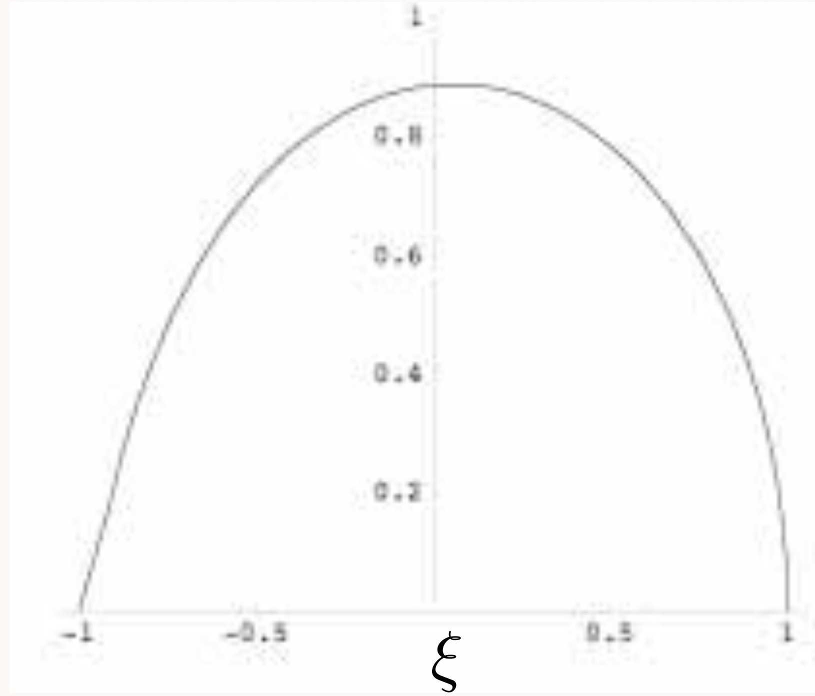
$|\eta_b >= |b\bar{b}>$

$\kappa = 375\ MeV$

First Moment of Kaon Distribution Amplitude

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

$$\xi = 1 - 2x$$



$$< \xi >_K = 0.04 \pm 0.02 \qquad \kappa = 375 \ MeV$$

Range from $m_s = 65 \pm 25$ MeV (PDG)

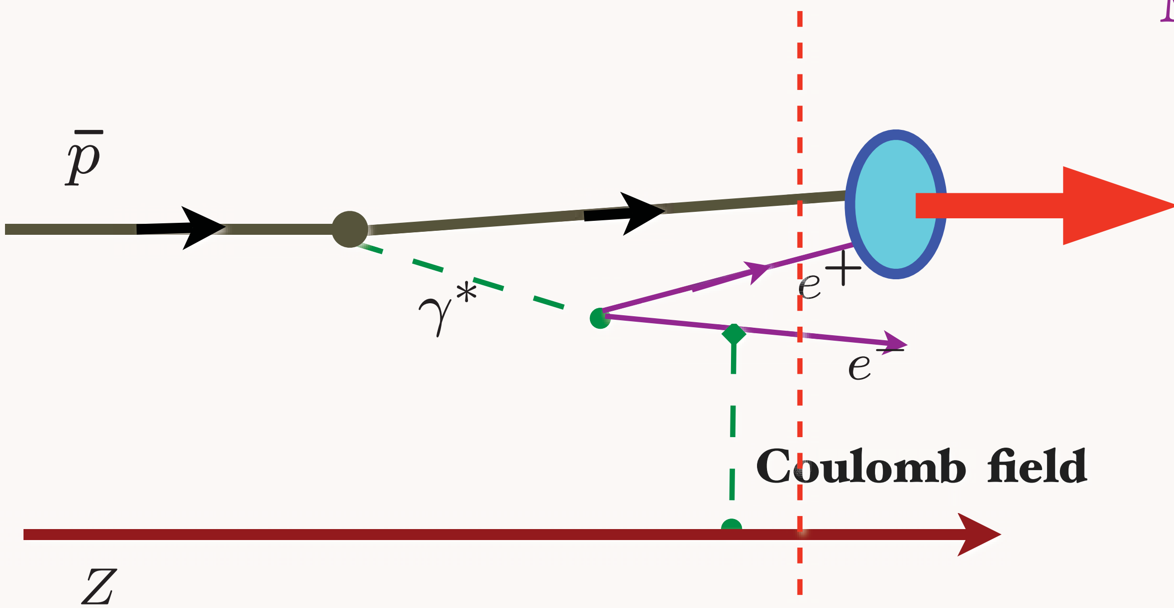
$$< \xi >_K = 0.029 \ \pm 0.002$$ Donnellan et al.

$$< \xi >_K = 0.0272 \pm 0.0005$$ Braun et al.

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



$\bar{H}(\bar{p}e^+)$

$$b_\perp \leq \frac{1}{m_{red}\alpha}$$

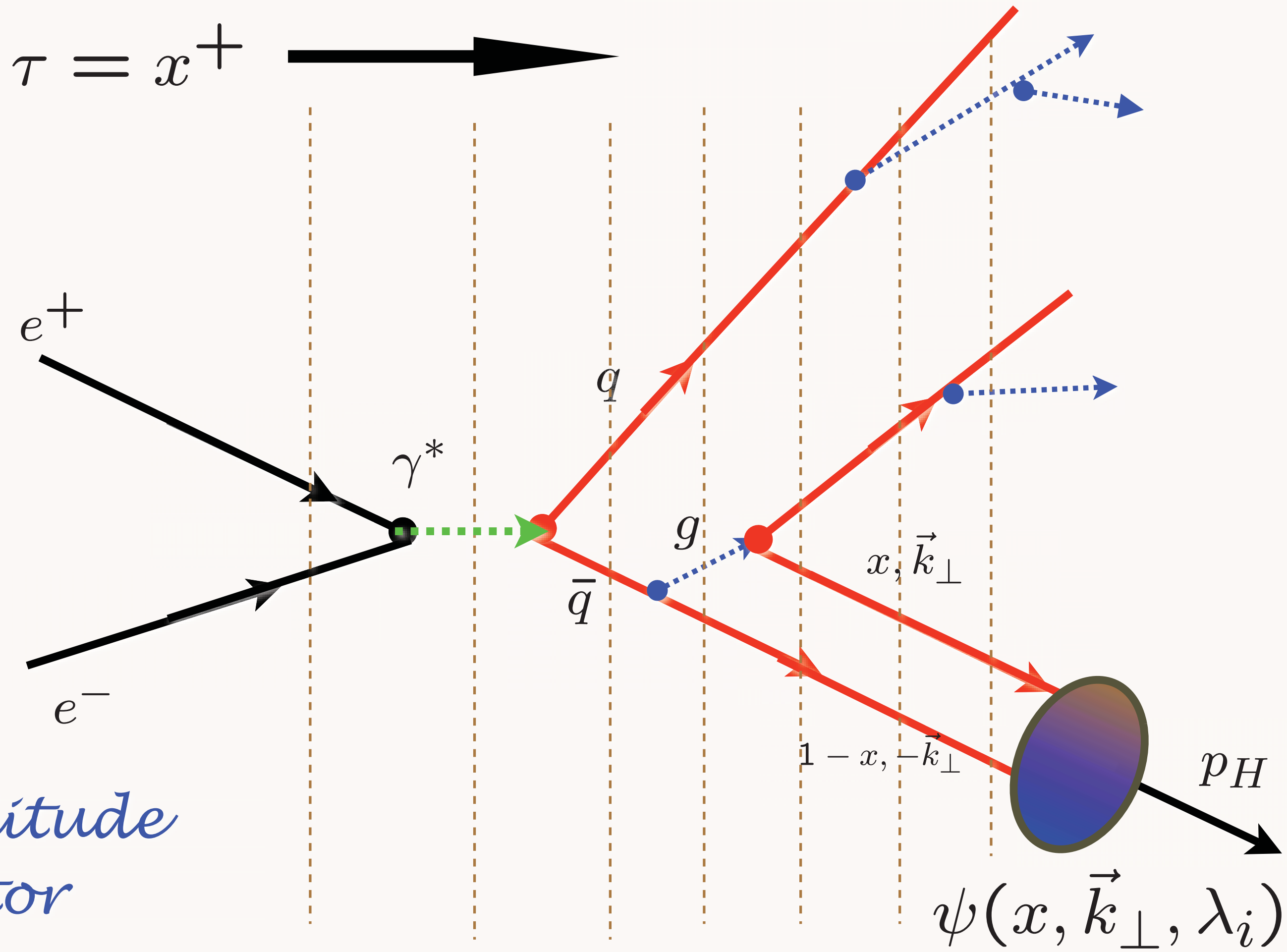
$$y_{\bar{p}} \simeq y_{e^+}$$

Coalescence of off-shell *co-moving positron and antiproton*

Wavefunction maximal at small impact separation and equal rapidity

"Hadronization" at the Amplitude Level

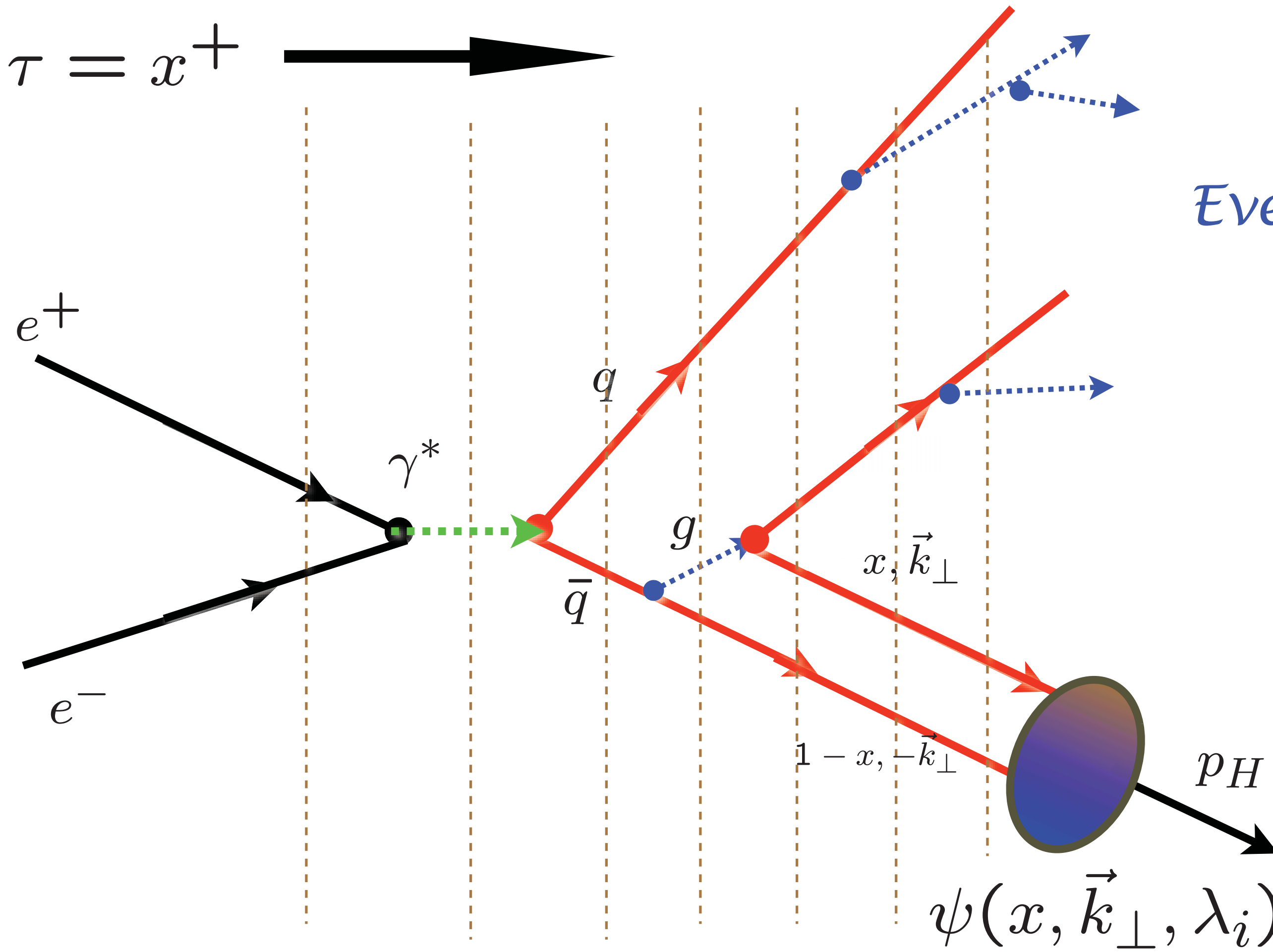
Hadronization at the Amplitude Level



Event amplitude generator

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

Hadronization at the Amplitude Level



Event amplitude generator

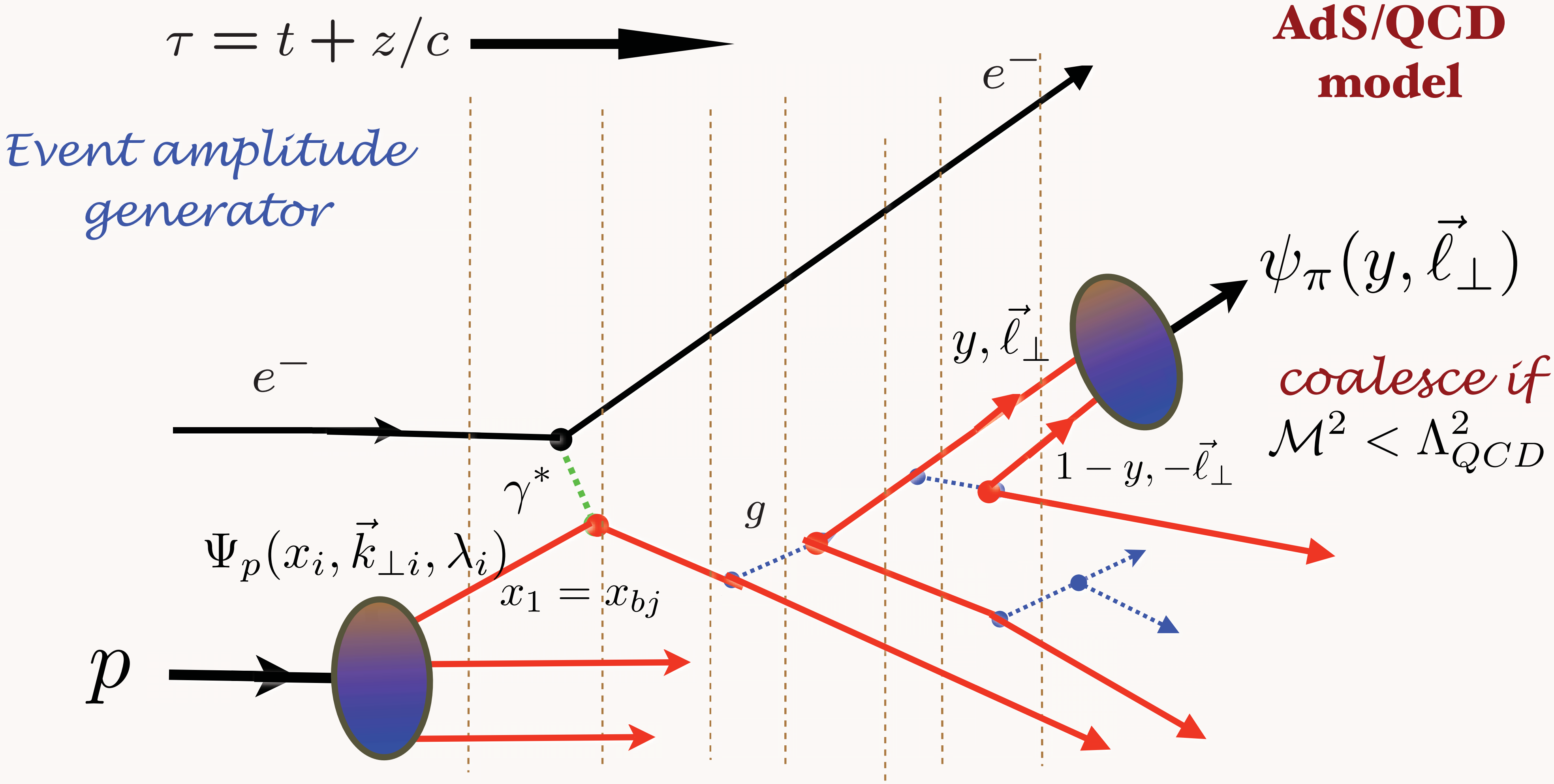
Capture if $\zeta^2 = x(1-x)b_\perp^2 > \frac{1}{\Lambda_{QCD}^2}$

AdS/QCD Hard Wall Confinement:

i.e.,

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

Jet Hadronization at the Amplitude Level



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

Three Pictures of High Energy Lepton-Proton Collisions

Infinite momentum frame **Parton Model**

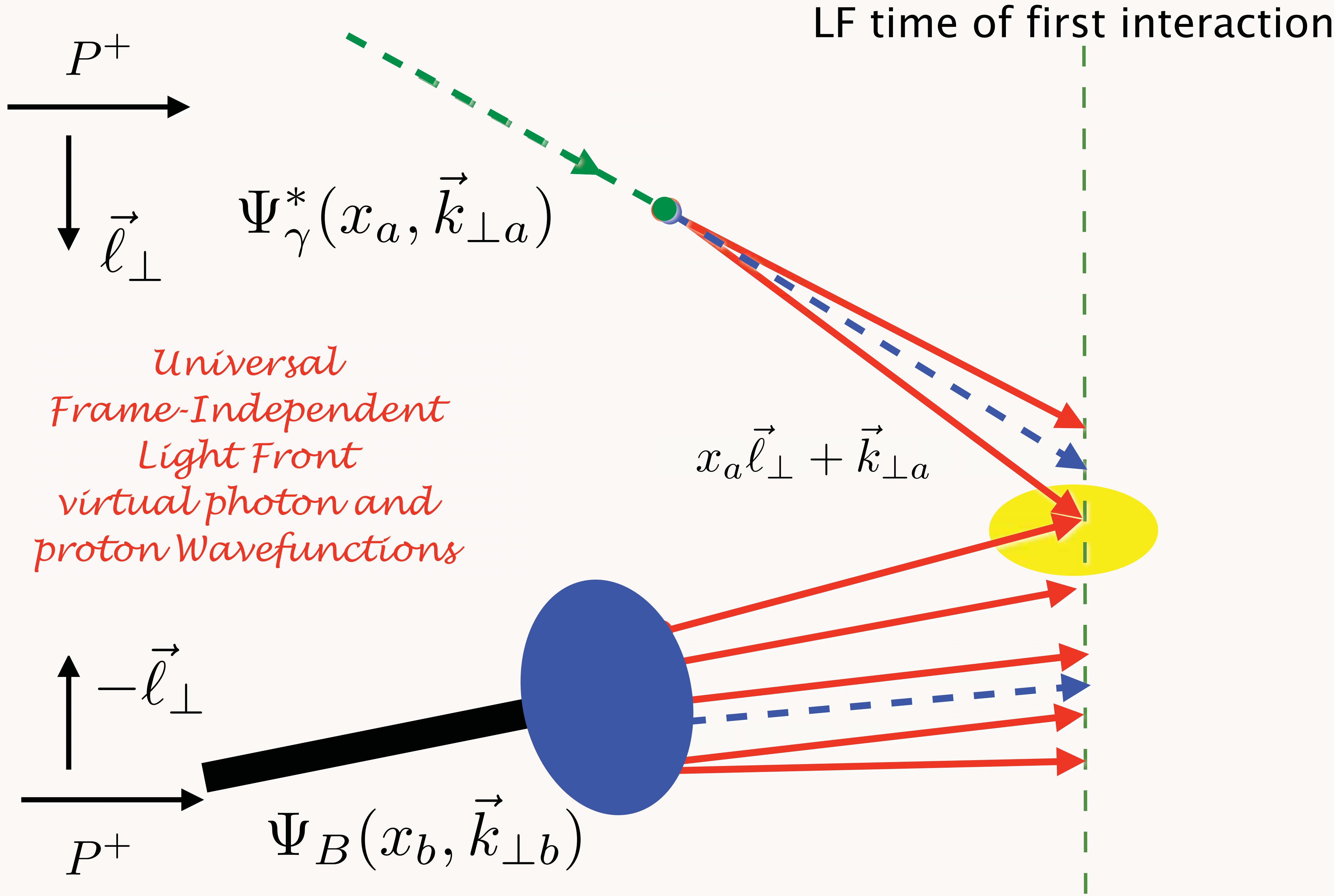
Simple Virtual Photon Probes Complex Evolved Proton

Proton Rest Frame **Color-Dipole Model**

Color Dipole of Virtual Photon Scatters on a Static Proton

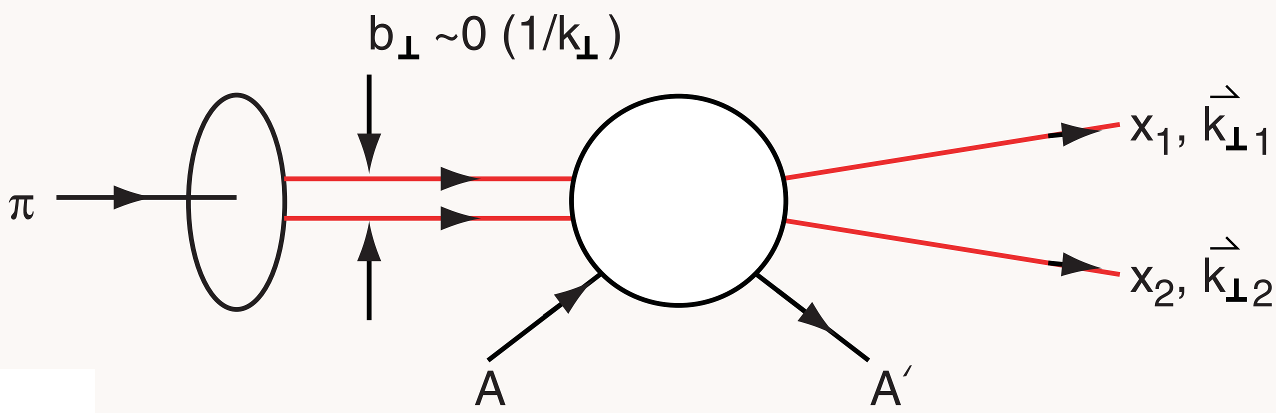
Frame-Independent **Light-Front HamiltonianTheory**

Collision of Light-Front Wavefunctions of Virtual Photon and Proton


LF time of first interaction
P^+
$\vec{\ell}_\perp$
$\Psi^*_\gamma(x_a, \vec{k}_{\perp a})$
Universal
Frame-Independent
Light Front
virtual photon and
proton Wavefunctions
$x_a\vec{\ell}_\perp + \vec{k}_{\perp a}$
$-\vec{\ell}_\perp$
P^+
$\Psi_B(x_b, \vec{k}_{\perp b})$

Diffractive Dissociation of Pion into Quark Jets

E791 Ashery et al.



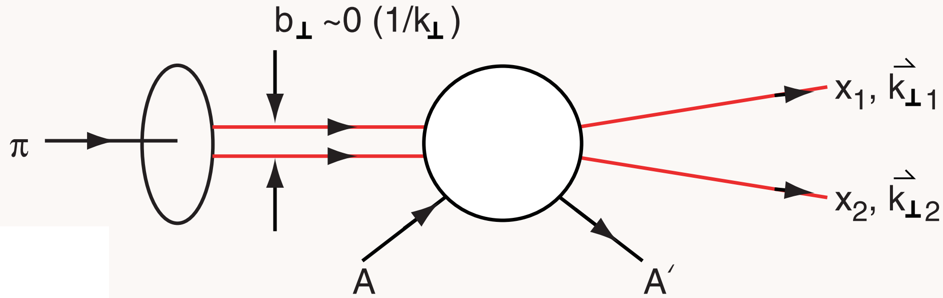
$$M \propto \frac{\partial^2}{\partial^2 k_\perp} \psi_\pi(x, k_\perp)$$

Measure Light-Front Wavefunction of Pion

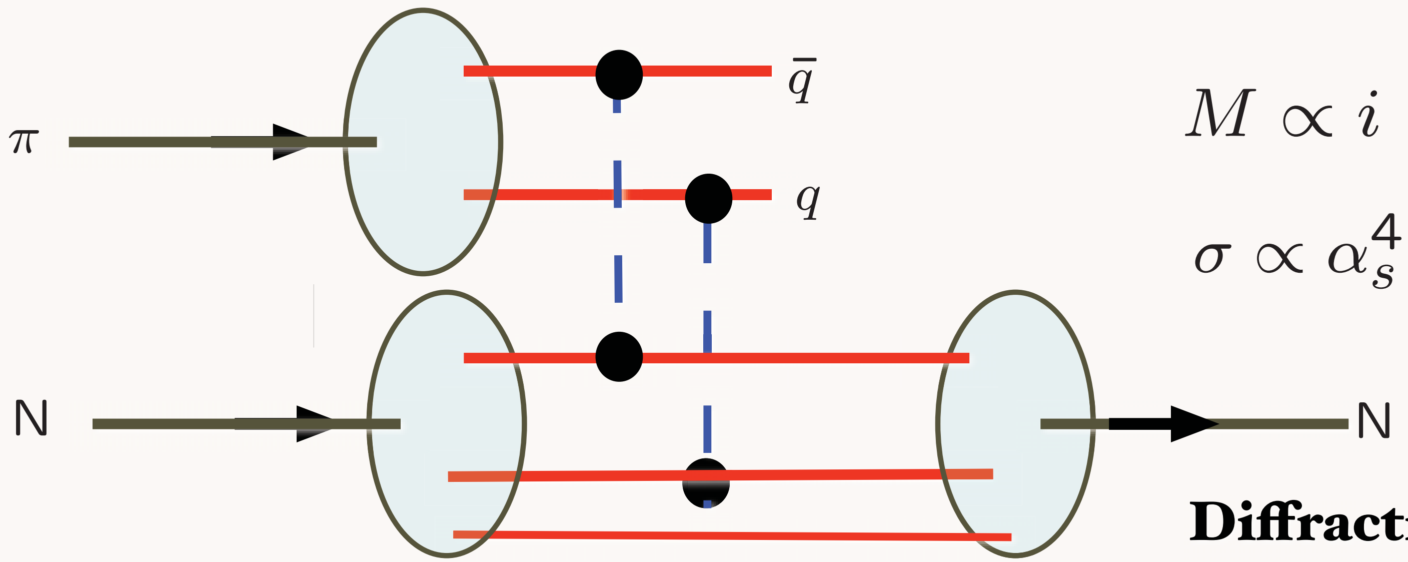
Minimal momentum transfer to nucleus

Nucleus left Intact!

Key Ingredients in Ashery Experiment



Two-gluon exchange gives imaginary amplitude proportional to energy, constant diffractive cross sections



$$M \propto i\ s\ \alpha_s^2\ b_\perp^\pi\ b_\perp^N$$

$$\sigma \propto \alpha_s^4\ (b_\perp^\pi)^2\ (b_\perp^N)^2$$

Target left intact

Diffraction, Rapidity gap