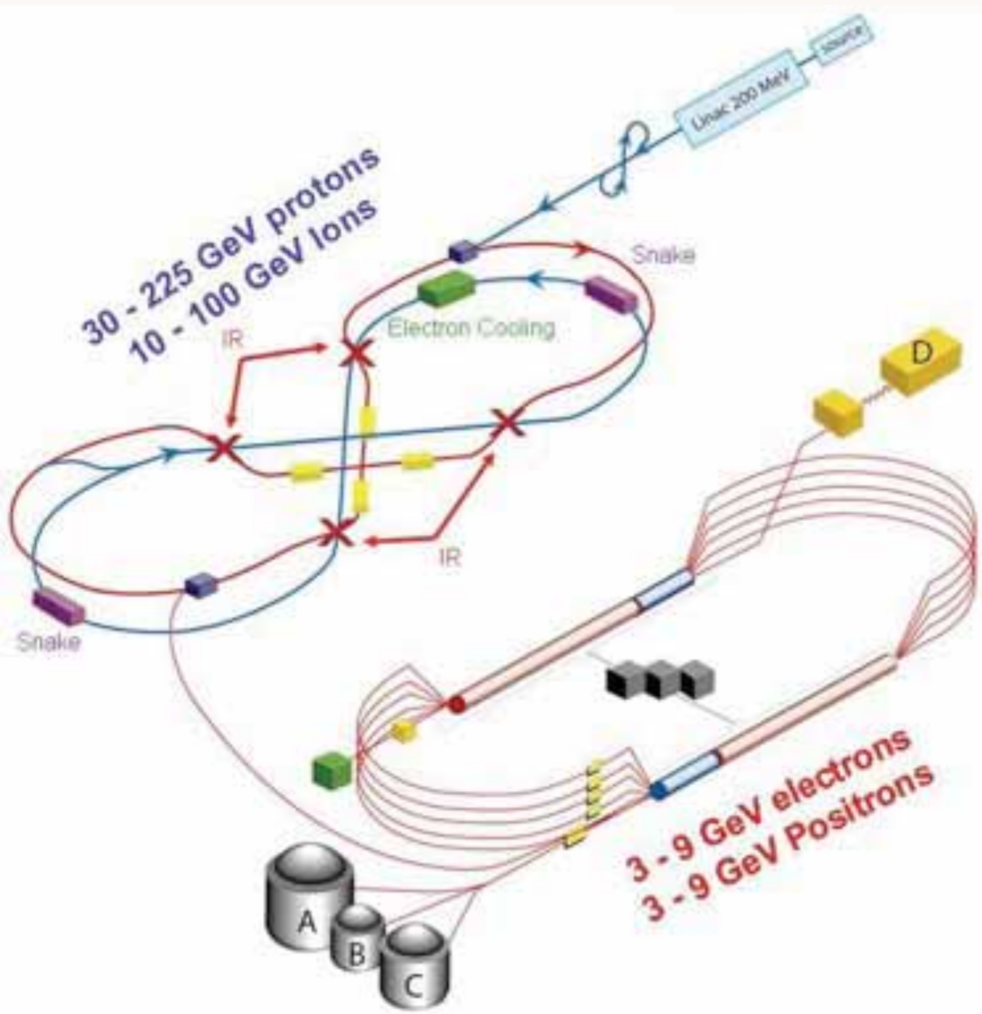
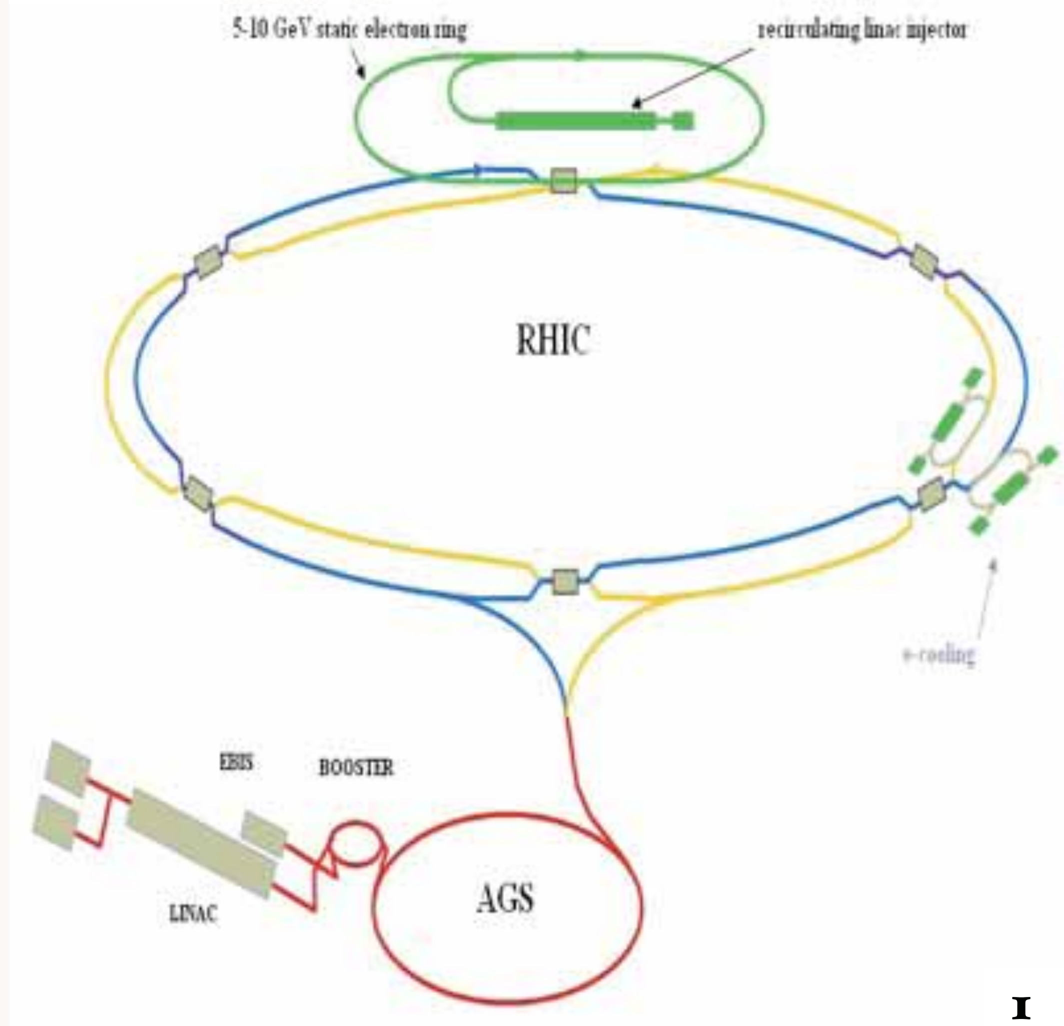
Novel Exclusive QCD Phenomena at an Electron-Ion Collider

Stan Brodsky, SLAC

Rutgers, March 14, 2010

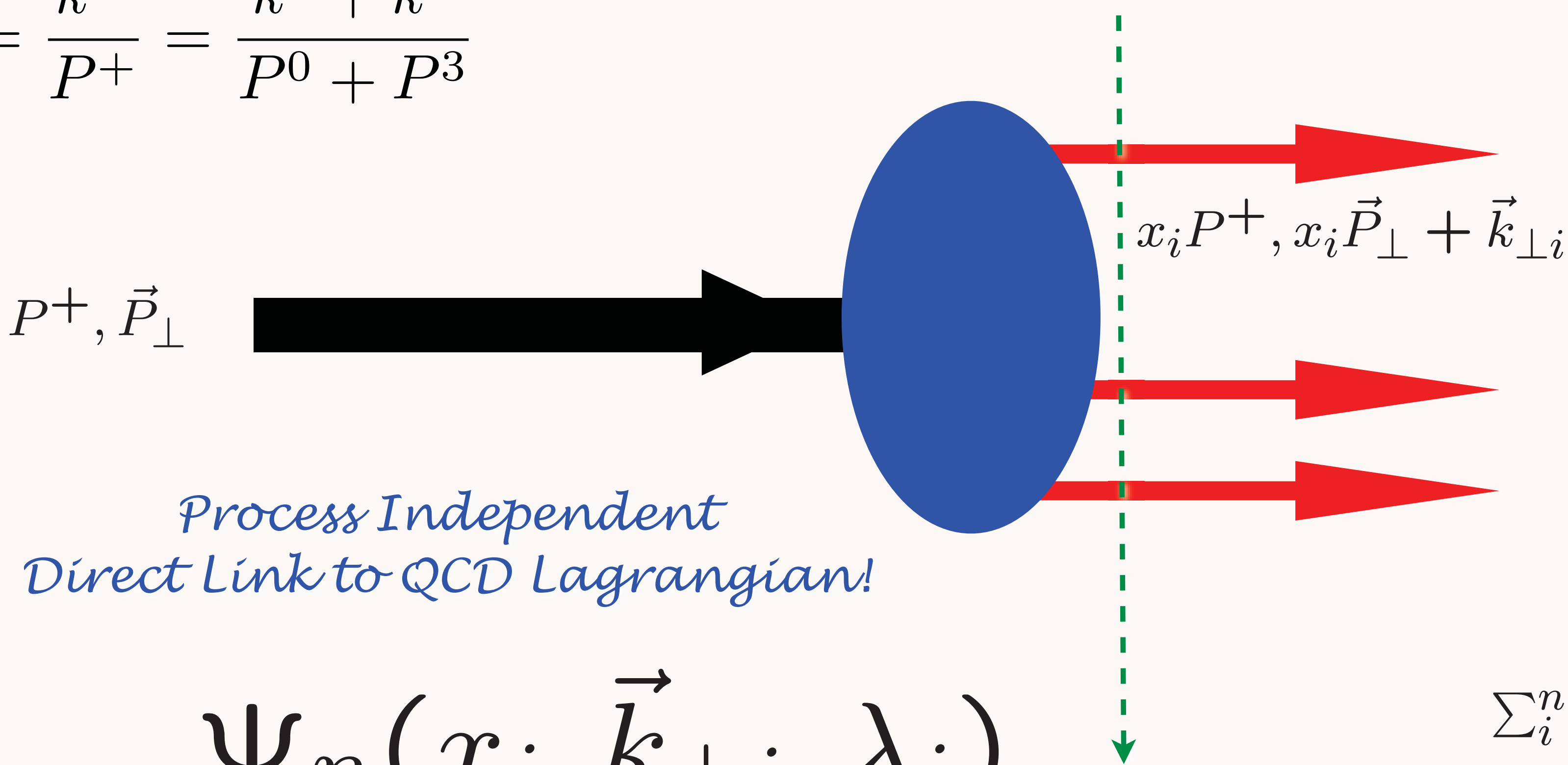




Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

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

Fixed $\tau = t + z/c$



Process Independent
Direct Link to QCD Lagrangian!

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

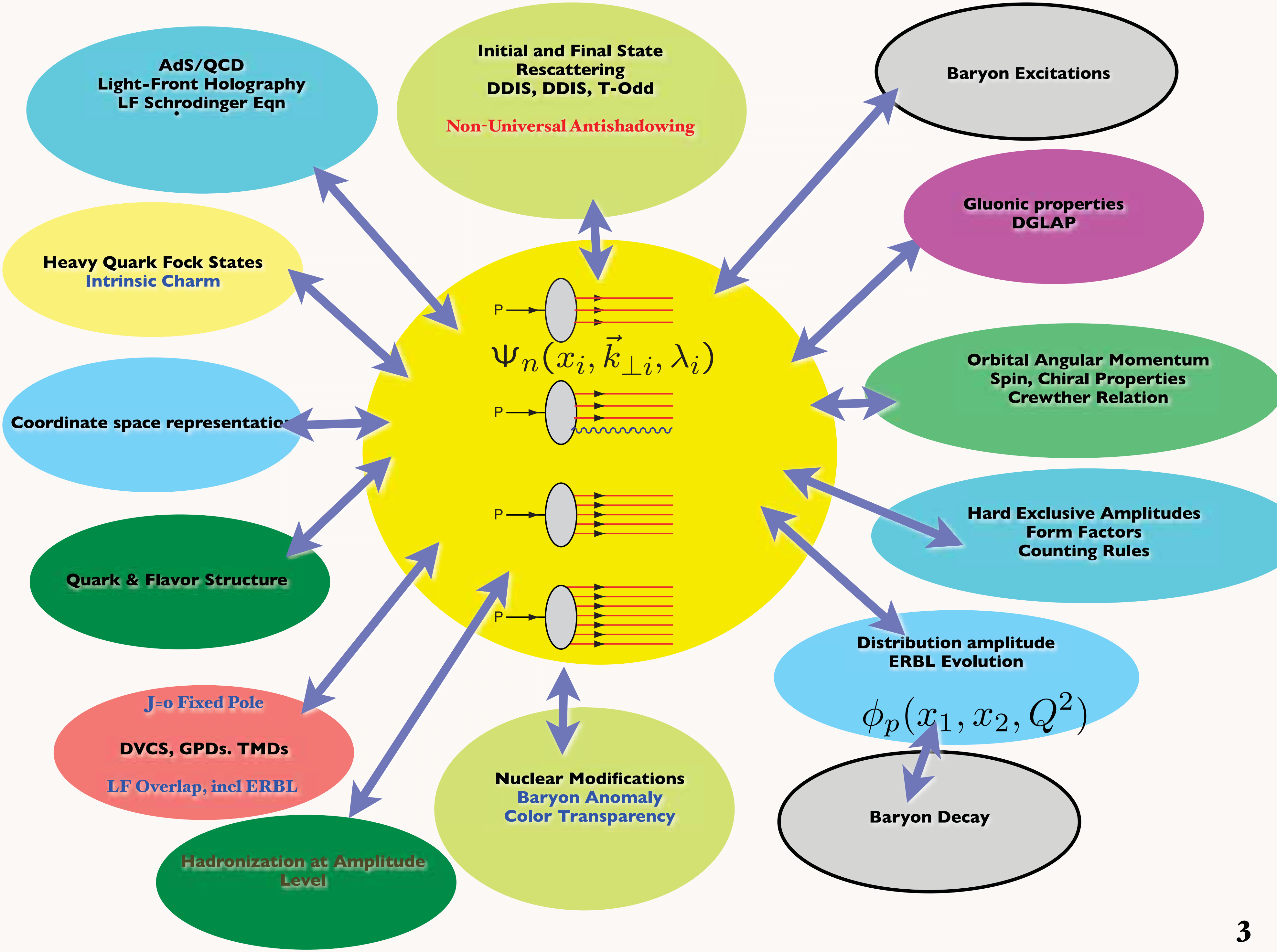
$\sum_i^n x_i = 1$

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

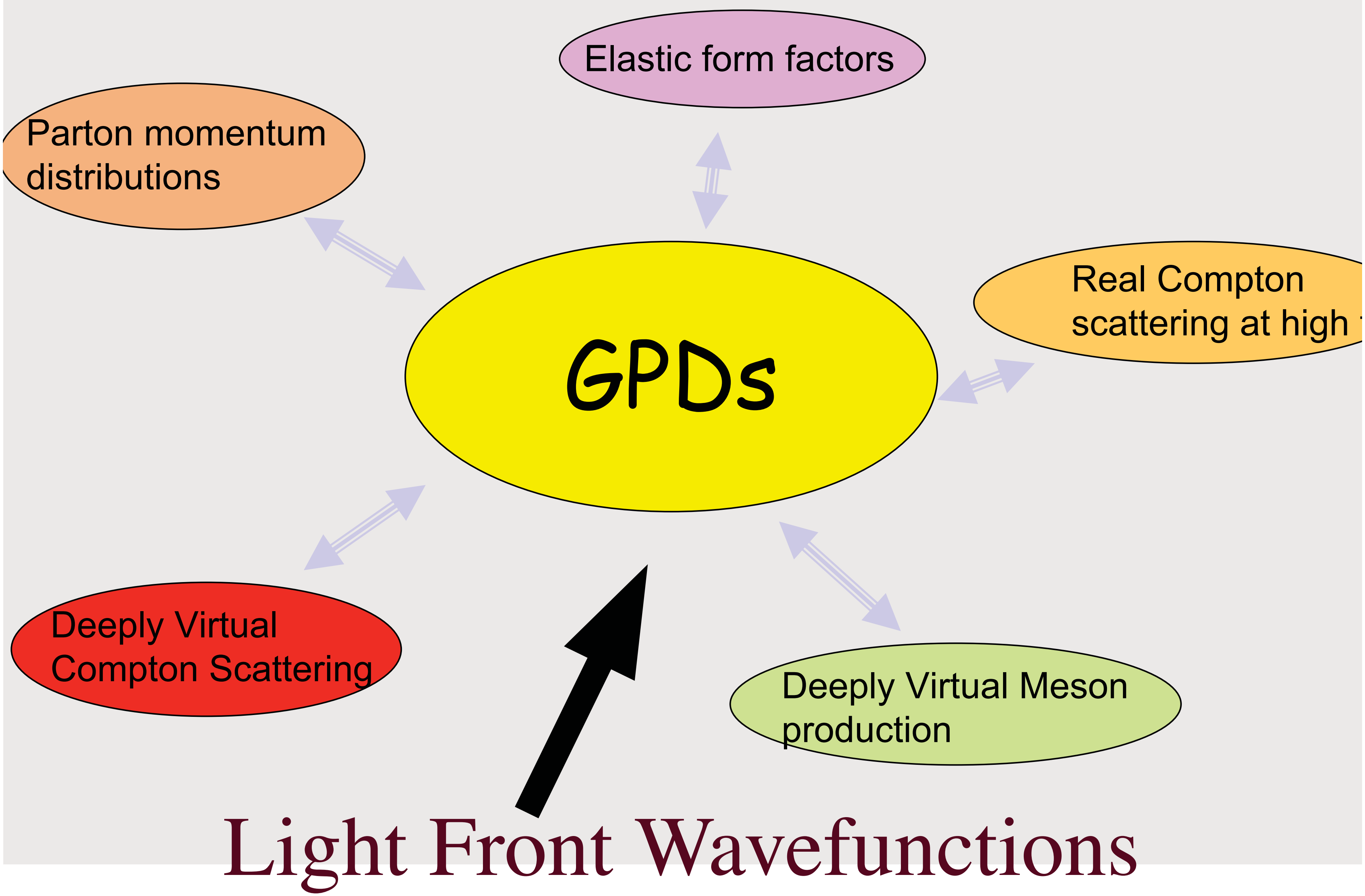
Invariant under boosts! Independent of P^μ

Orbital Angular Momentum is a property of the LFWFS

QCD and the LF Hadron Wavefunctions



A Unified Description of Hadron Structure



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

Gluon orbital angular momentum defined in physical lc gauge

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

n-1 orbital angular momenta

Orbital Angular Momentum is a property of the LFWFS

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

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

The Light Front Fock State Wavefunctions

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

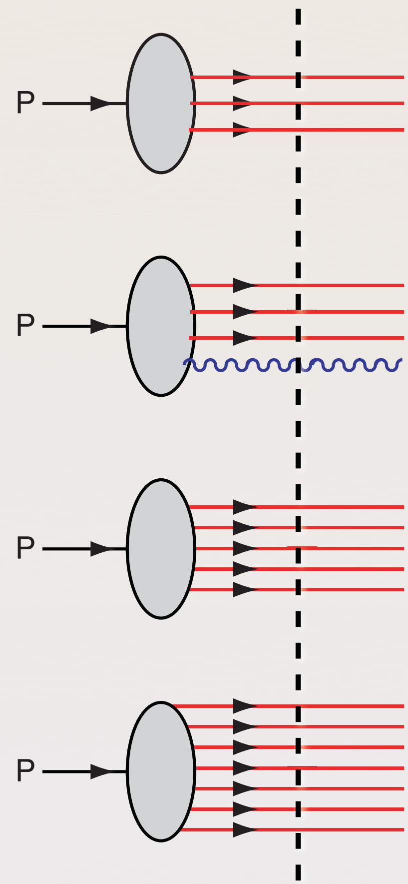
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

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.

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



Intrinsic heavy quarks $\bar{u}(x) \neq \bar{d}(x)$

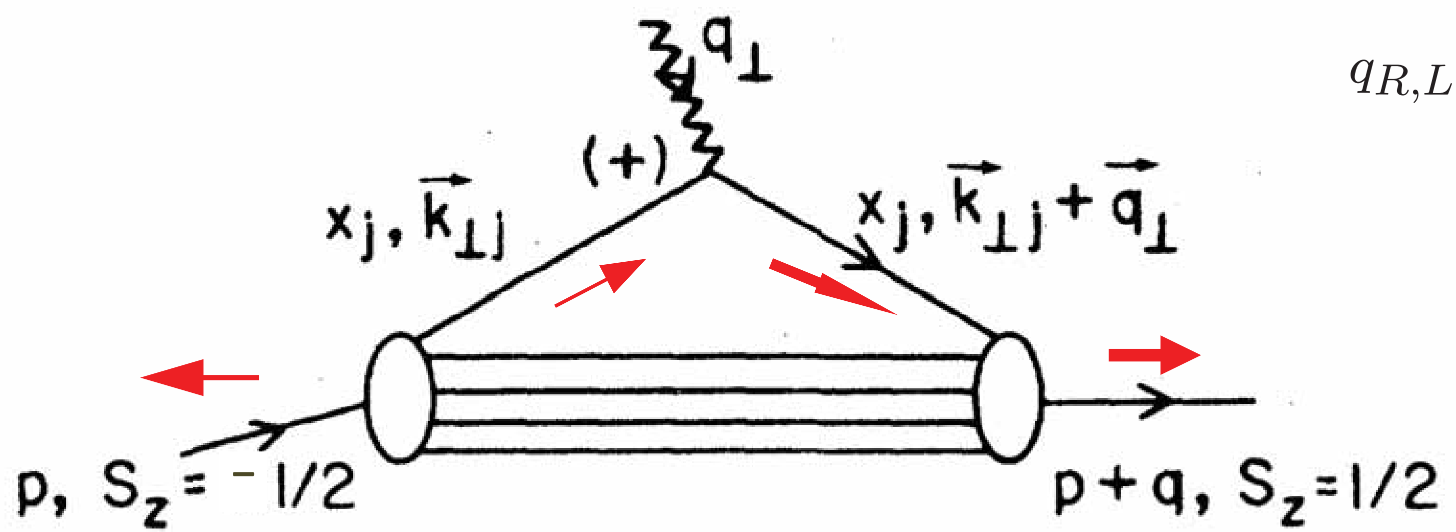
Mueller: BFKL DYNAMICS $\bar{s}(x) \neq s(x)$

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

Drell, sjb

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

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



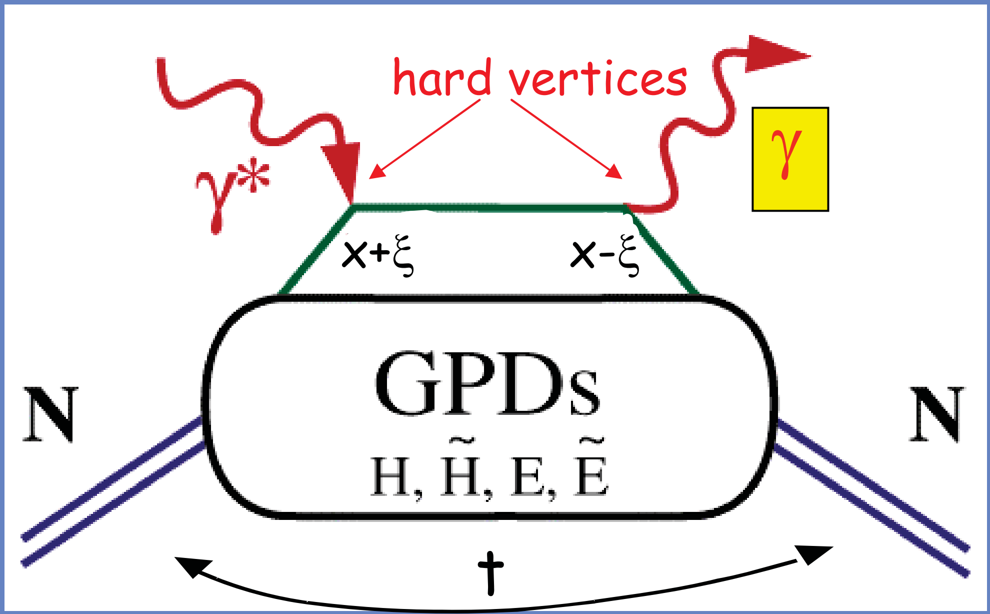
$$q_{R,L} = q^x \pm i q^y$$

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

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

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

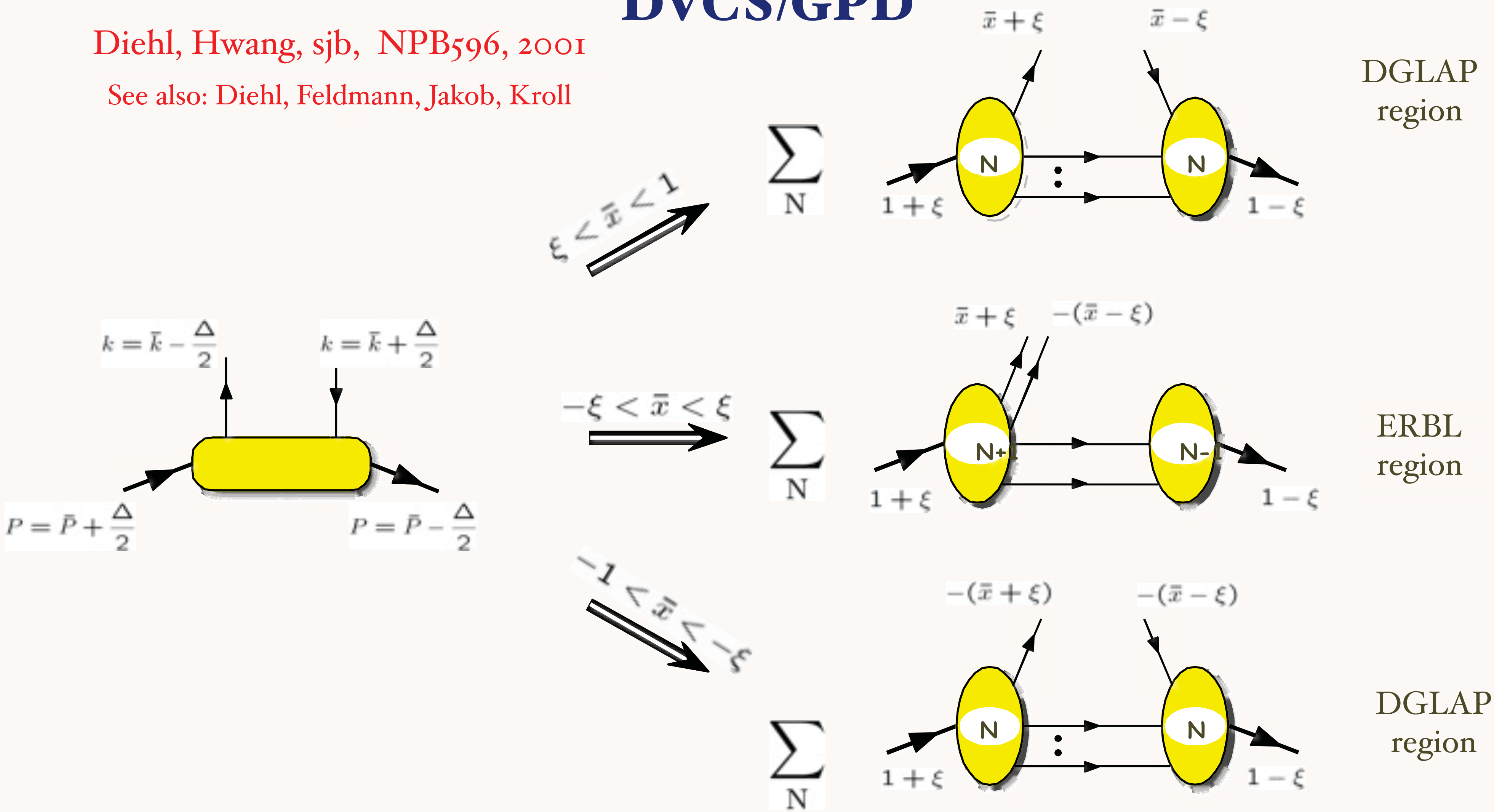
$H(x,\xi,t), E(x,\xi,t), \ldots$ "Generalized Parton Distributions"

Light-Front Wave Function Overlap Representation

DVCS/GPD

Diehl, Hwang, sjb, NPB596, 2001

See also: Diehl, Feldmann, Jakob, Kroll



Example of LFWF representation of GPDs (n+1 => n-1)

Diehl, Hwang, sjb

$$\frac{1}{\sqrt{1-\zeta}}\frac{\Delta^1 - i\Delta^2}{2M} E_{(n+1\to n-1)}(x,\zeta,t)$$

$$= \left(\sqrt{1-\zeta}\right)^{3-n} \sum_{n,\lambda_i} \int \prod_{i=1}^{n+1} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{16\pi^3}\, 16\pi^3 \delta\left(1-\sum_{j=1}^{n+1} x_j\right) \delta^{(2)}\left(\sum_{j=1}^{n+1} \vec{k}_{\perp j}\right)$$

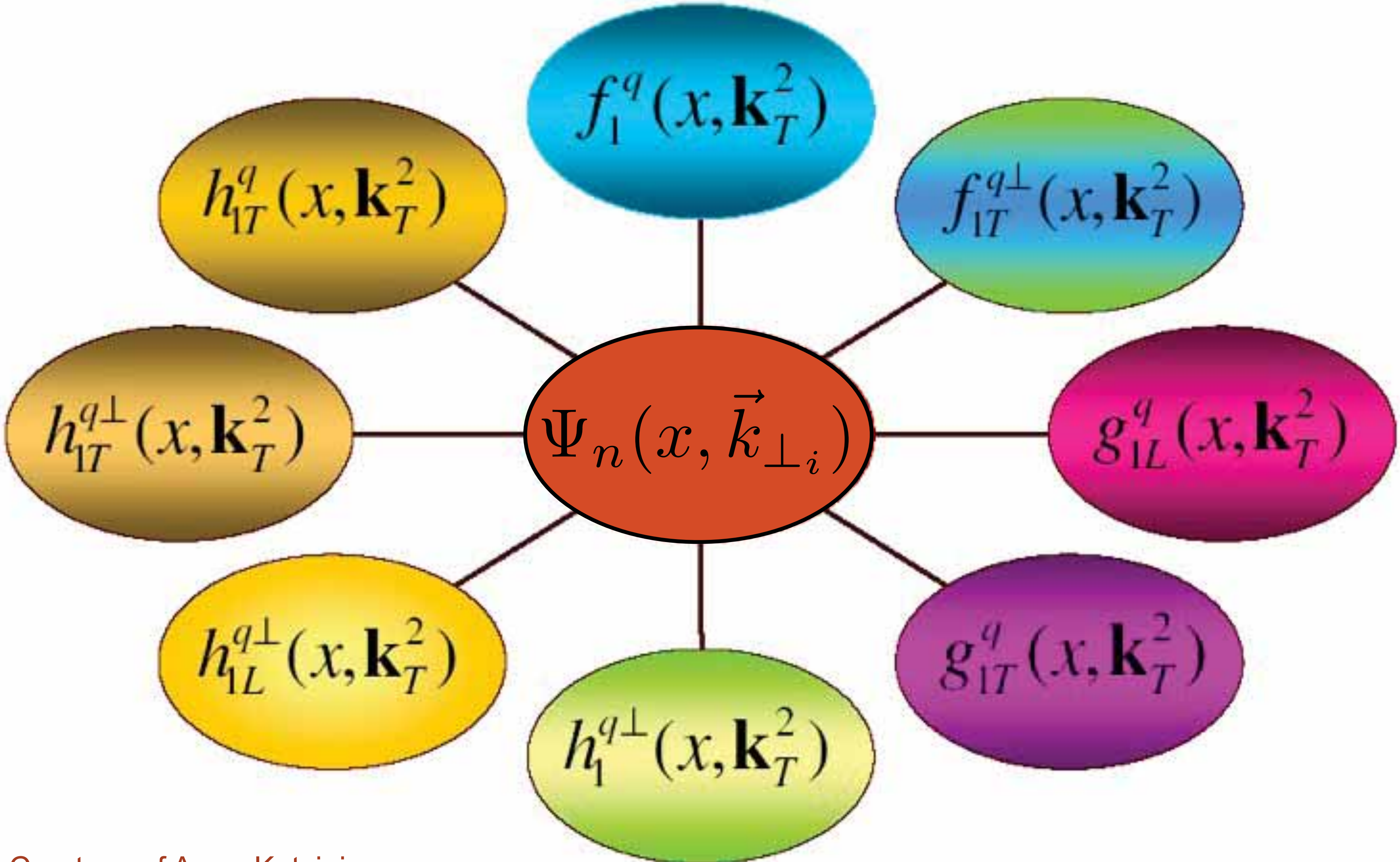
$$\times 16\pi^3 \delta(x_{n+1}+x_1-\zeta)\delta^{(2)}(\vec{k}_{\perp n+1}+\vec{k}_{\perp 1}-\vec{\Delta}_\perp)$$

$$\times \delta(x-x_1)\psi^{\uparrow *}_{(n-1)}(x'_i,\vec{k}'_{\perp i},\lambda_i)\psi^{\downarrow}_{(n+1)}(x_i,\vec{k}_{\perp i},\lambda_i)\delta_{\lambda_1-\lambda_{n+1}},$$

where $i = 2, \ldots, n$ label the $n-1$ spectator partons which appear in the final-state hadron wavefunction with

$$x'_i = \frac{x_i}{1-\zeta}, \qquad \vec{k}'_{\perp i} = \vec{k}_{\perp i} + \frac{x_i}{1-\zeta}\vec{\Delta}_\perp.$$

8 leading-twist spin-$k_\perp$ dependent distribution functions



Courtesy of Aram Kotzinian

Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

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

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

Form factors (sum rules)

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

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

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

Verified using LFWFs

Diehl, Hwang, sjb

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

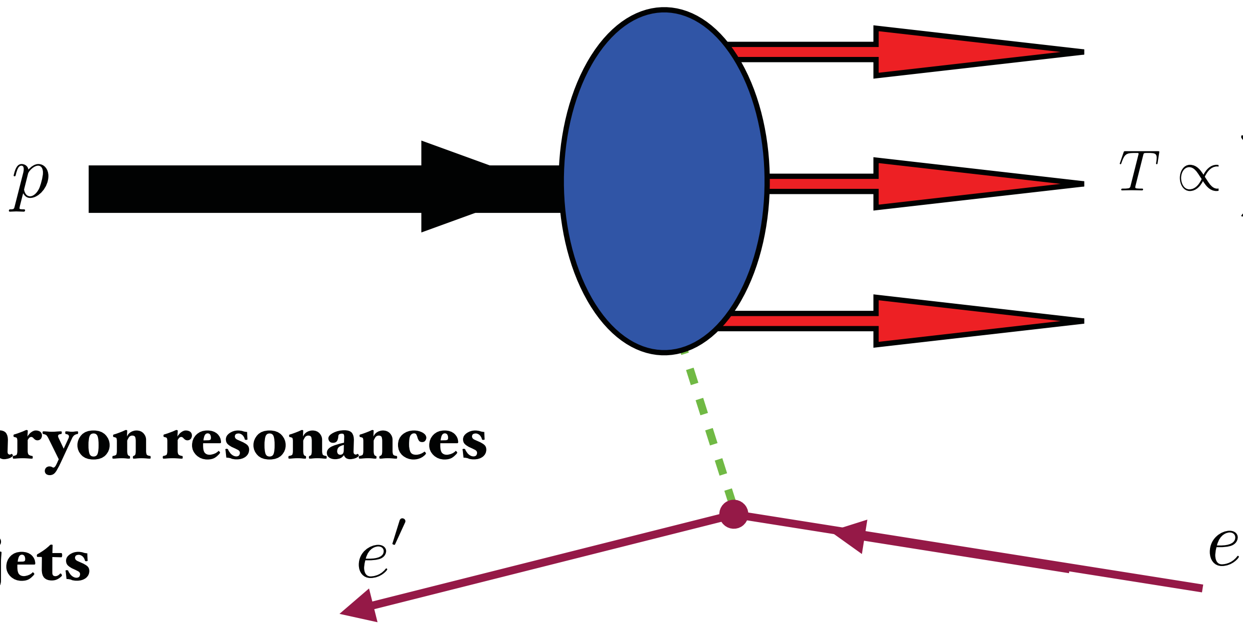
Quark angular momentum (Ji's sum rule)

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

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

Interpret Electroproduction as Coulombic Excitation

Many possible B= 1 final states can reveal electric-dipole structure of proton LFWF



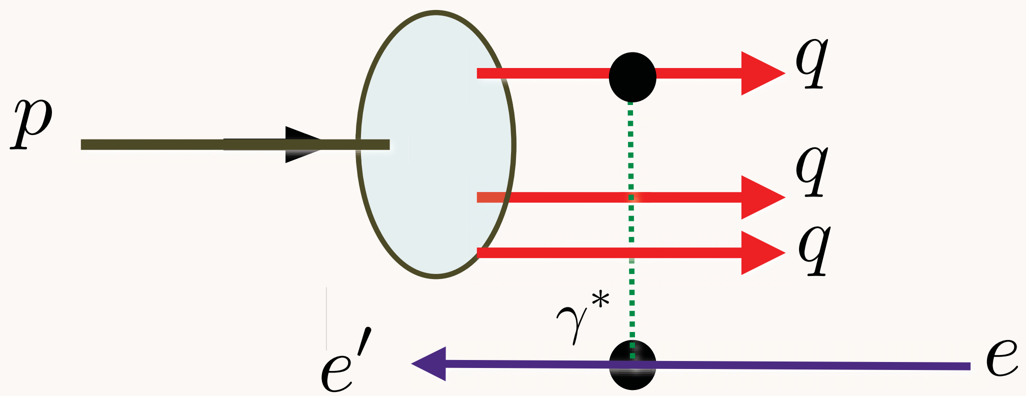
$$T \propto \sum_j e_j \frac{d}{d\vec{k}_{\perp j}} \psi_n(x_i, \vec{k}_{\perp i}, \lambda$$

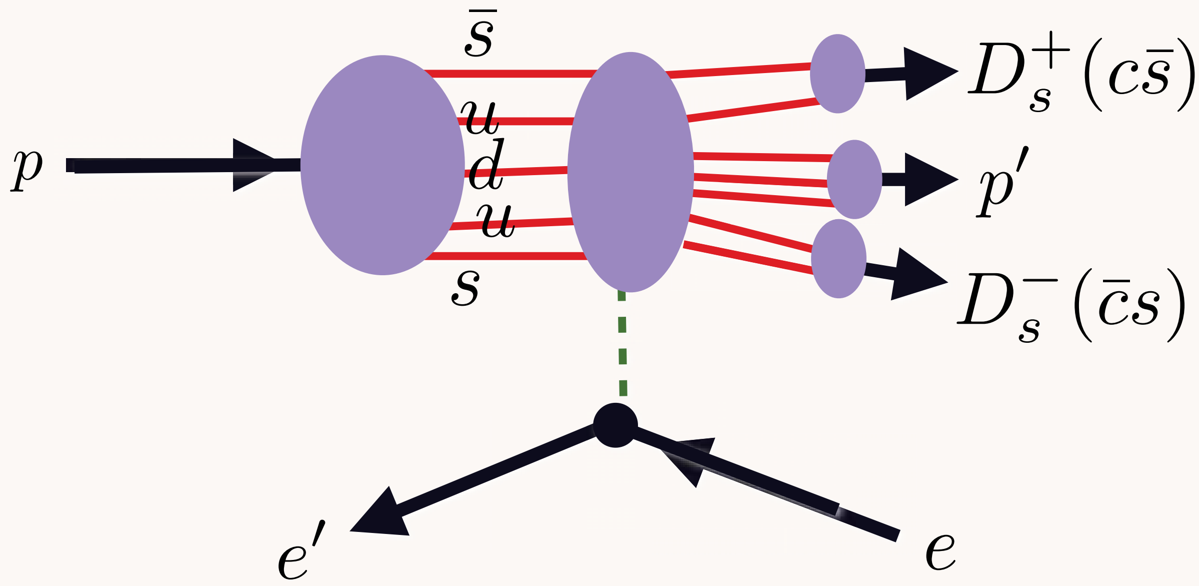
- **baryon resonances**
- **3 jets**
- **exclusive meson-baryon; baryon-meson-meson**
- **exclusive charm and bottom pairs; charmed and bottom baryons; heavy quarkonium from heavy quark intrinsic sea**
- **"hidden-color states from deuteron such as Δ Δ**

Coulomb Dissociation of the Proton to Jets

$$p\ e \to jet\ jet\ jet\ e'$$

Coulomb exchange measures the first derivative of the proton light-front wavefunction



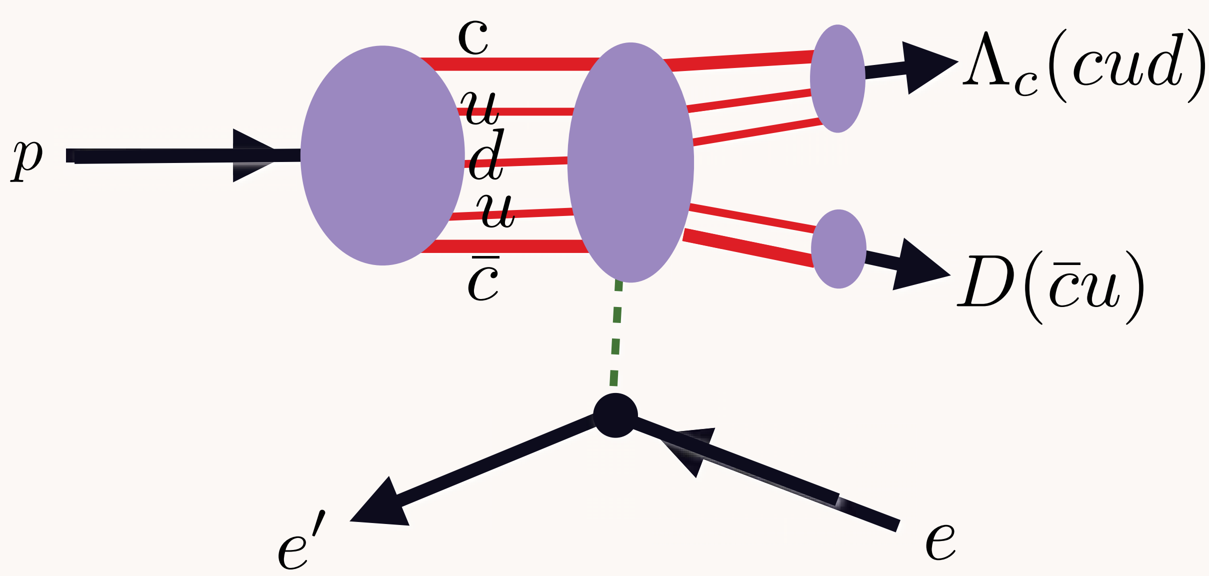


Look for $D_s^-(\bar{c}s)$ vs. $D_s^+(c\bar{s})$ asymmetry

Reflects s vs. $\bar{s}$ asymmetry in proton $|uuds\bar{s}>$ Fock LF state.

Asymmetry natural from $|K^+\Lambda>$ excitation **Ma, sjb**

Assumes symmetric charm and anti-charm distributions



Dissociate proton to high x_F heavy-quark pair

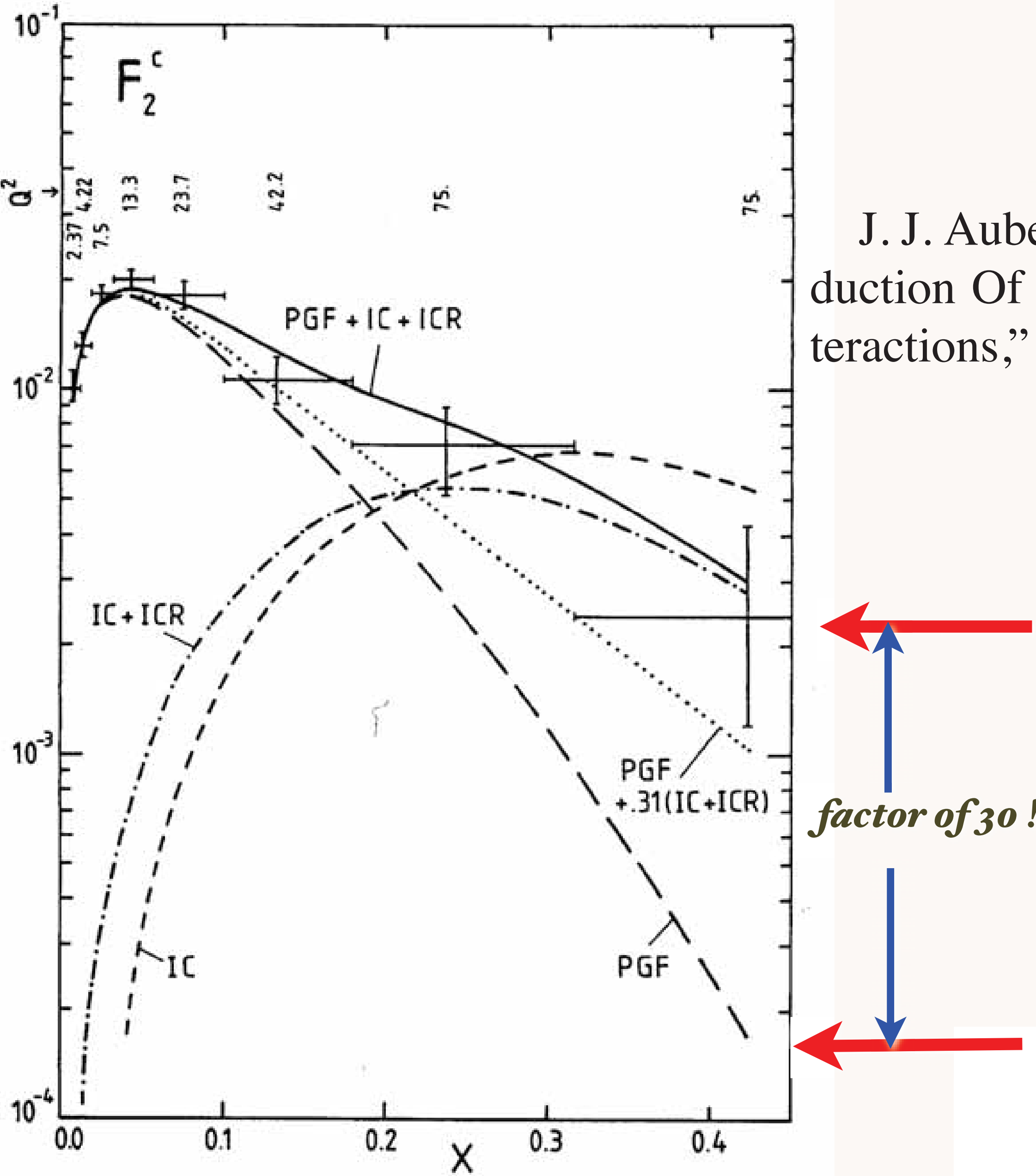
$$\gamma^* p \rightarrow \Lambda_c(cdd) + D(\bar{c}u), \gamma^* p \rightarrow \Lambda_b(bud) B^+(\bar{b}u)$$

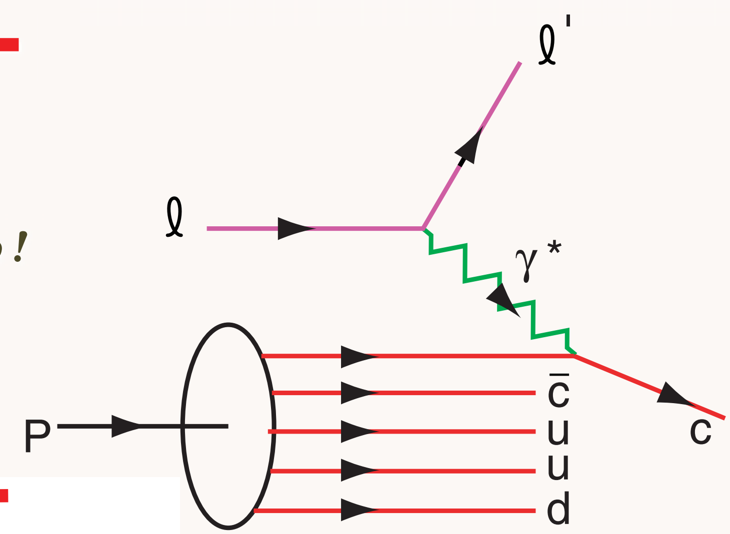
Test intrinsic charm, bottom

Measurement of Charm Structure Function

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

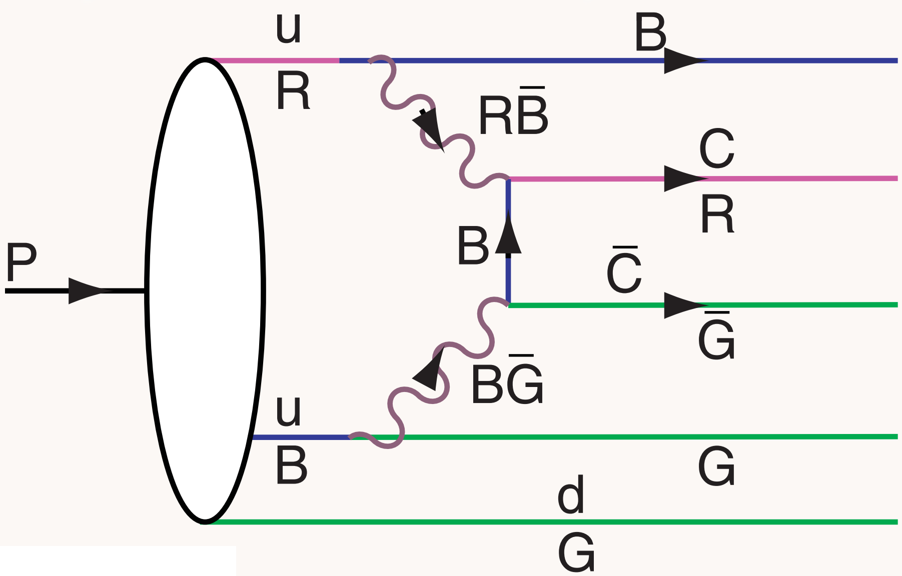
First Evidence for Intrinsic Charm





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

Hoyer, Peterson, Sakai, sjb



$|uudc\bar{c}>$ Fluctuation in Proton

QCD: Probability $\frac{\sim\Lambda^2_{QCD}}{M^2_Q}$

$|e^+e^-\ell^+\ell^->$ Fluctuation in Positronium

QED: Probability $\frac{\sim(m_e\alpha)^4}{M^4_\ell}$

OPE derivation - M.Polyakov et al.

$< p|\frac{G^3_{\mu\nu}}{m^2_Q}|p >$ vs. $< p|\frac{F^4_{\mu\nu}}{m^4_\ell}|p >$

$c\bar{c}$ in Color Octet

Distribution peaks at equal rapidity (velocity)
Therefore heavy particles carry the largest momentum fractions

$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm!

Charm at Threshold

- EMC data: $c(x, Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

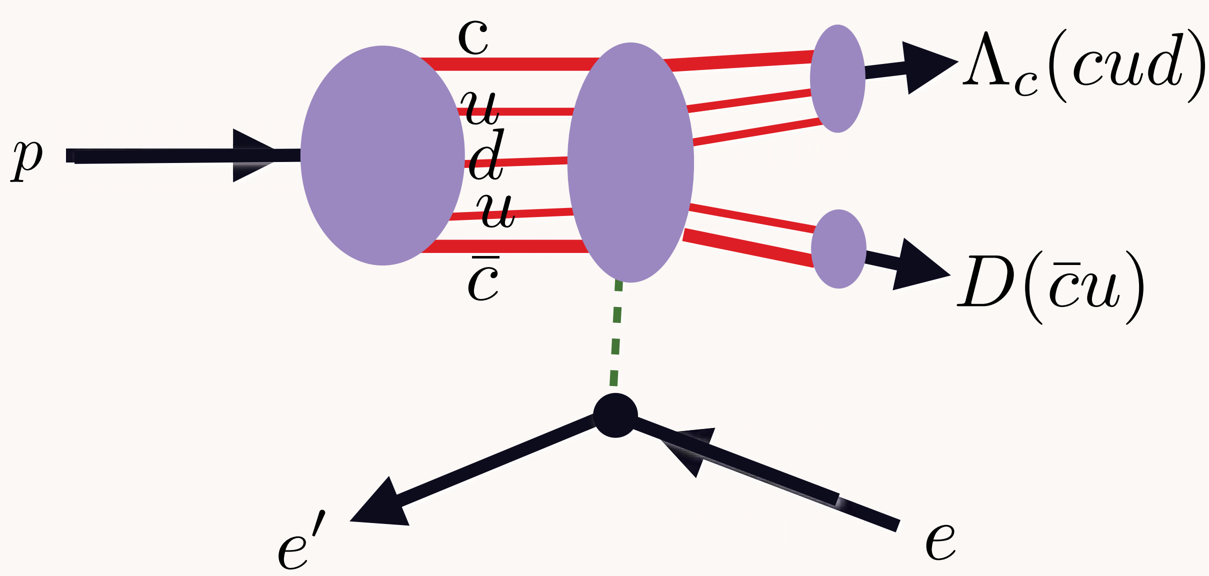
- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

- High x_F $pp \to \Xi(ccd)X$ (SELEX)

IC Structure Function: Critical Measurement for EIC



Dissociate proton to high x_F heavy-quark pair

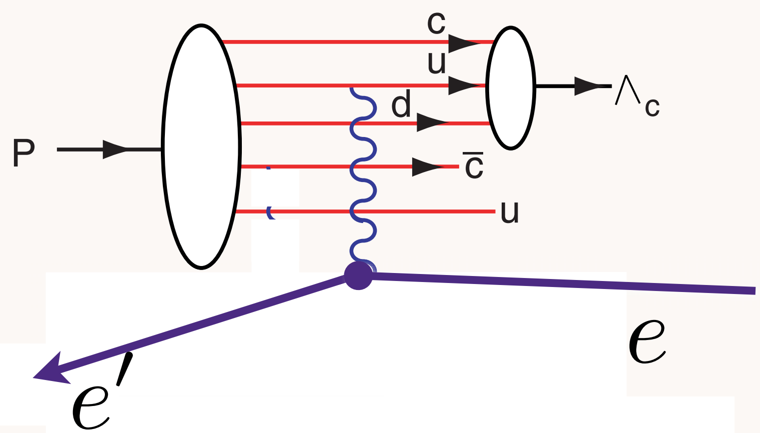
$$\gamma^* p \to \Lambda_c(cdd) + D(\bar{c}u), \gamma^* p \to \Lambda_b(bud) B^+(\bar{b}u)$$

Test intrinsic charm, bottom

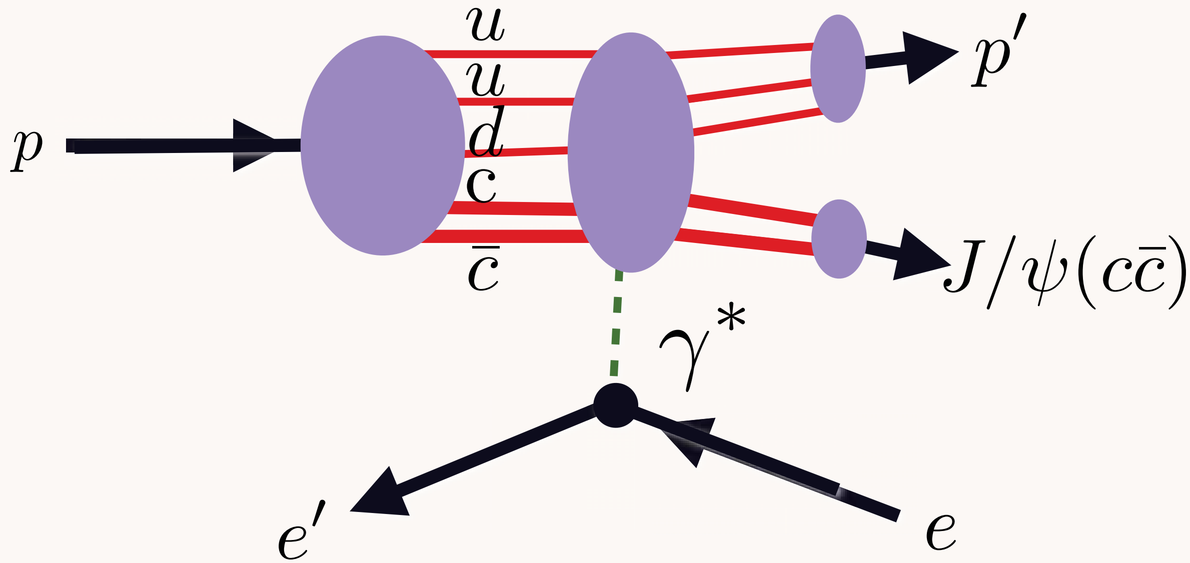
Leading charm production in proton fragmentation region at the EIC

Intrinsic charm and bottom quarks have same rapidity as valence quarks

Produce $\Xi(ccd), B(\bar{b}u), \Lambda(cbu), \Xi(bbu)$



Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

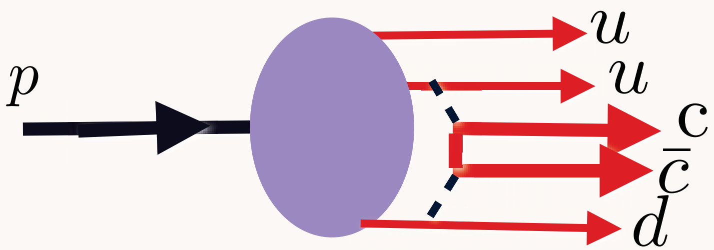


Lansberg, sjb

Dissociate proton to high x_F Quarkonium:

$$\gamma^* p \to J/\psi + p'$$

$$\gamma^* p \to \Upsilon + p'$$



But disfavored since

$$|p> \simeq |(uud)_{8_C}(c\bar{c})_{8C}>$$

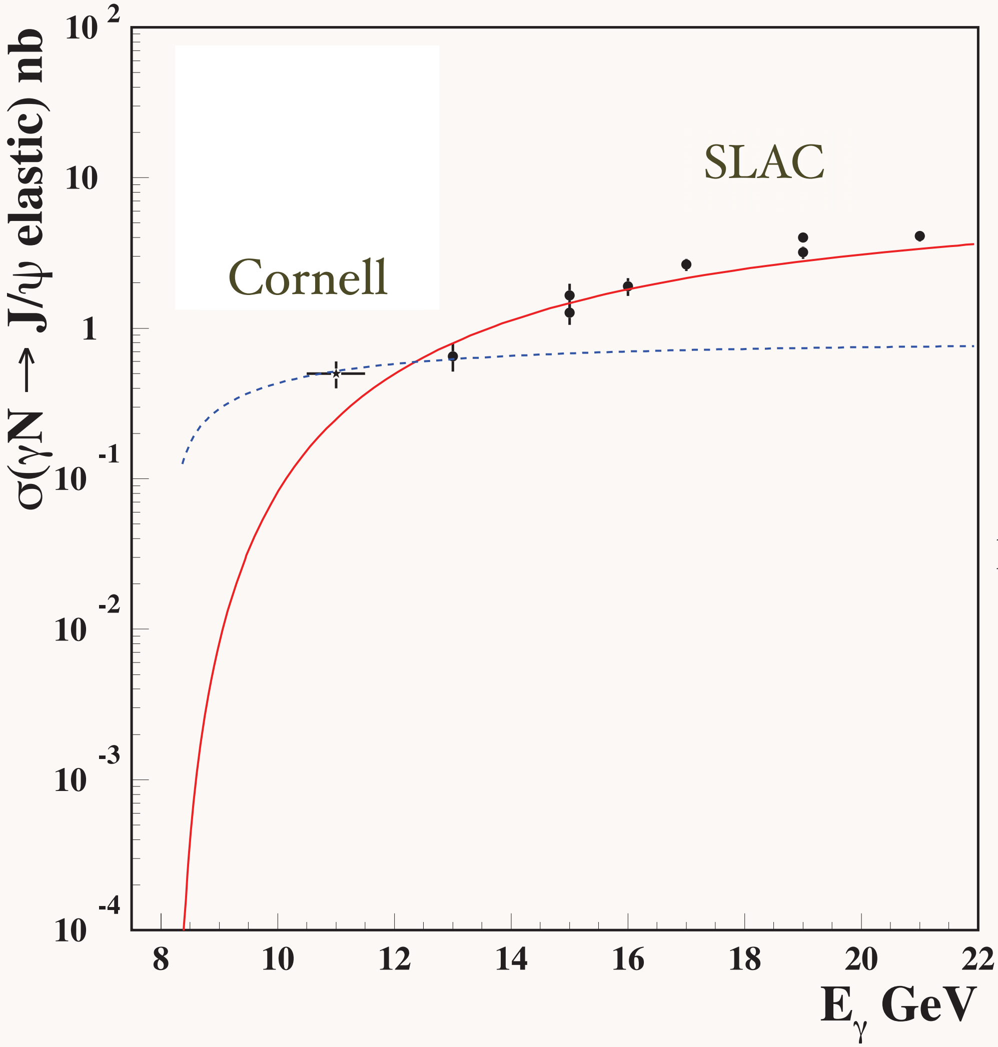
Collins, Ellis, Haber, Mueller, sjb

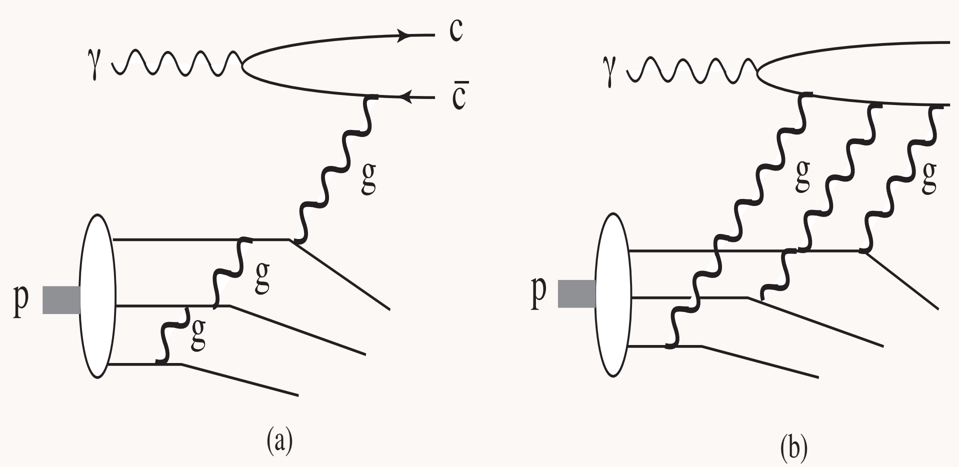
M. Polyakov et al.

Test intrinsic charm, bottom

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb





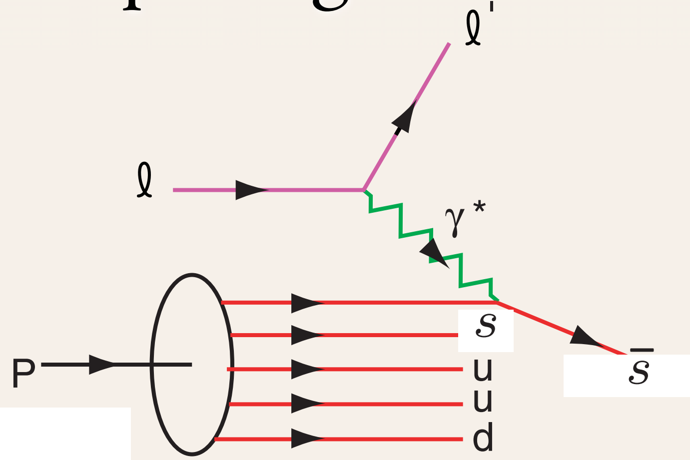
Leading twist contribution

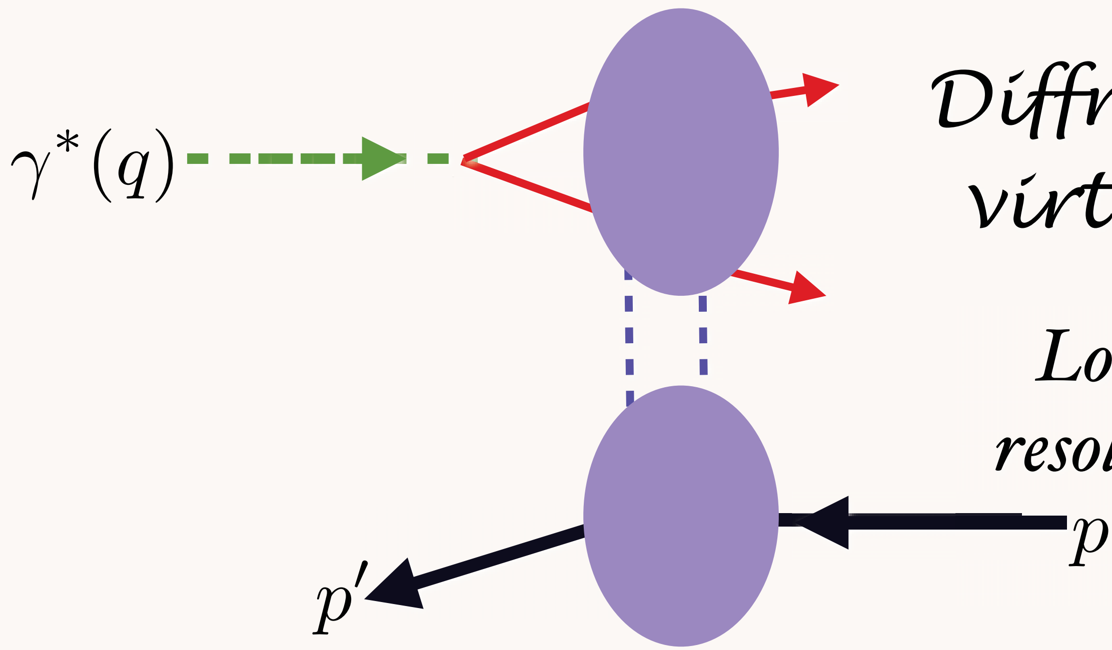
Dominant near threshold

Measure strangeness distribution from DIS at EIC

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

- Non-symmetric strange and antistrange sea
- Non-perturbative input; e.g $|uuds\bar{s}> \simeq |\Lambda(uds)K^+(\bar{s}u)>$
- Crucial for interpreting NuTeV anomaly





Diffractively dissociate virtual photonic state

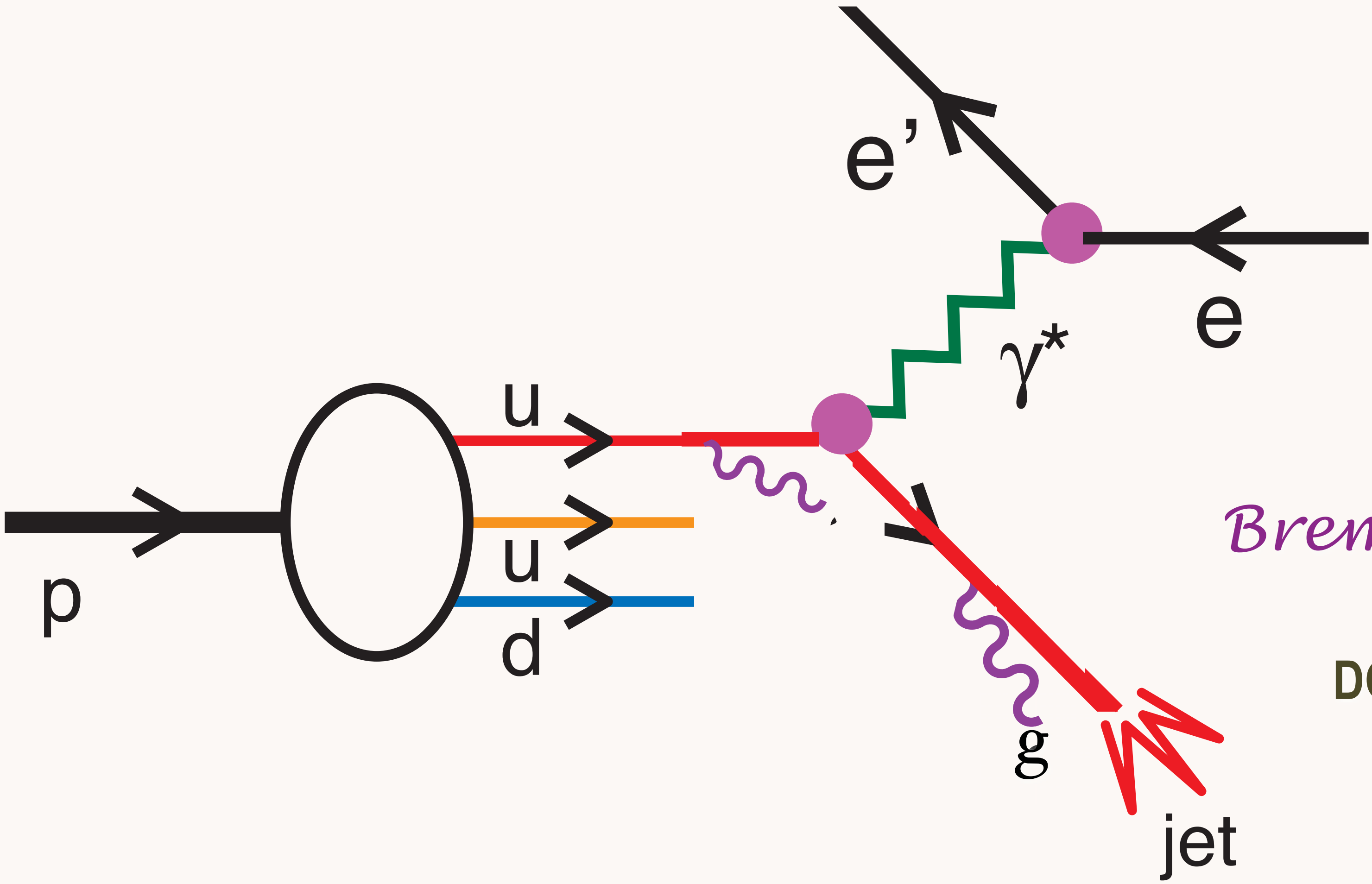
Low-Nussinov Pomeron resolves second derivative of LFWF

$$T \propto \frac{d^2}{d^2\vec{k}_{\perp j}} \psi_n(x_i, k_{\perp i}, \lambda_i)$$

Final states: vector mesons, heavy 1-- quarkonia, two jets, baryon pairs, meson pairs ...

Study hadronization at the amplitude level

Deep Inelastic Electron-Proton Scattering



Gluonic Bremmstrahlung

DGLAP Evolution

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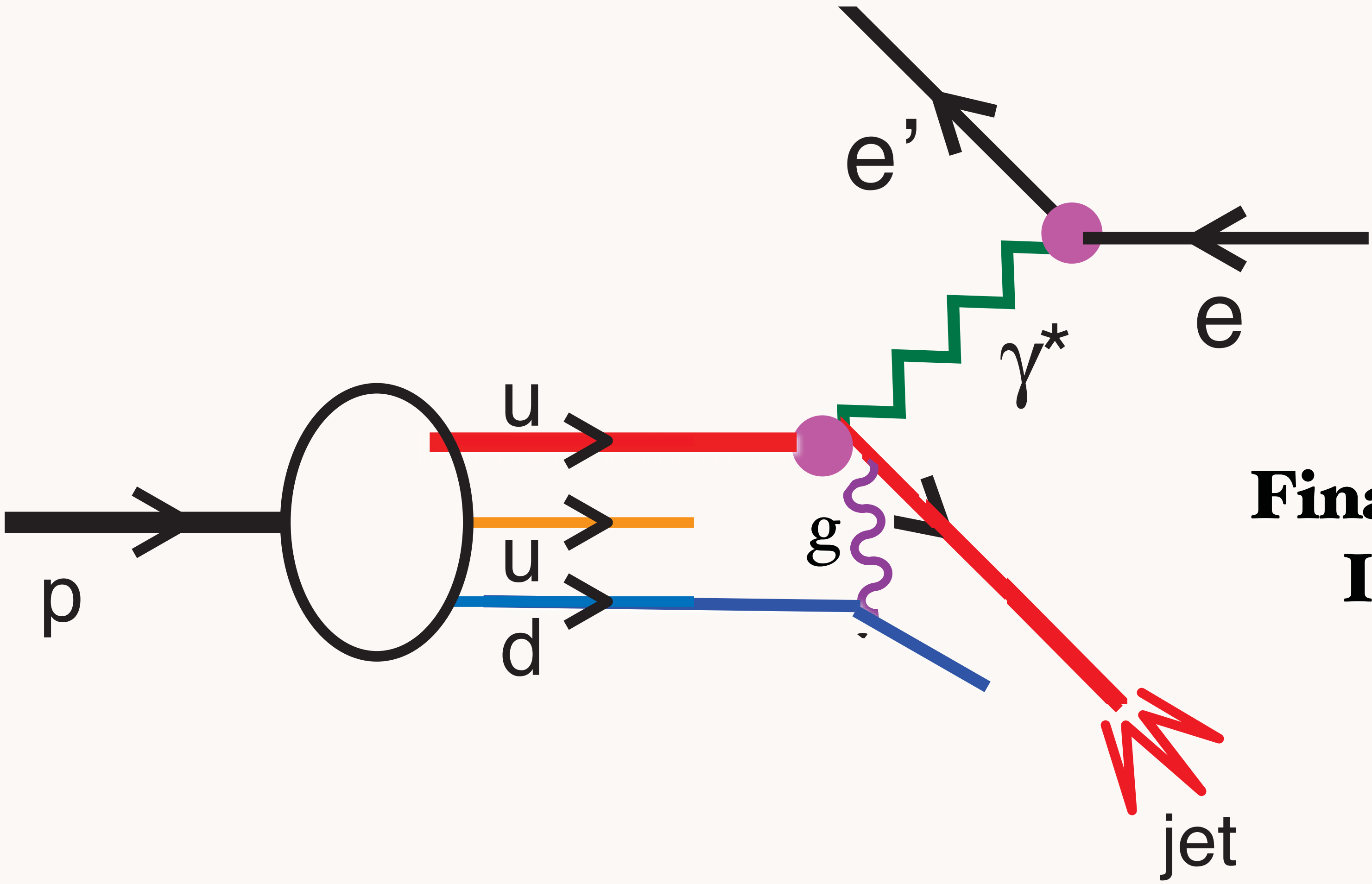
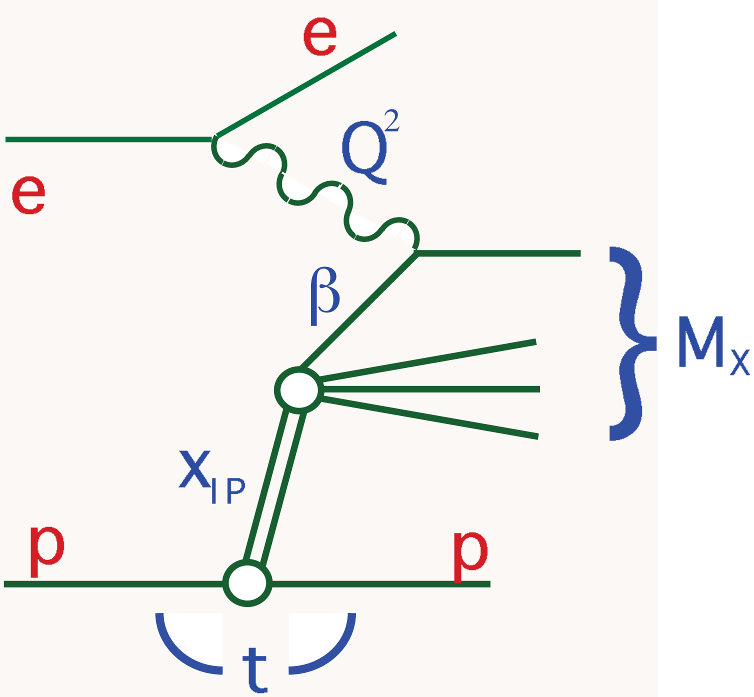
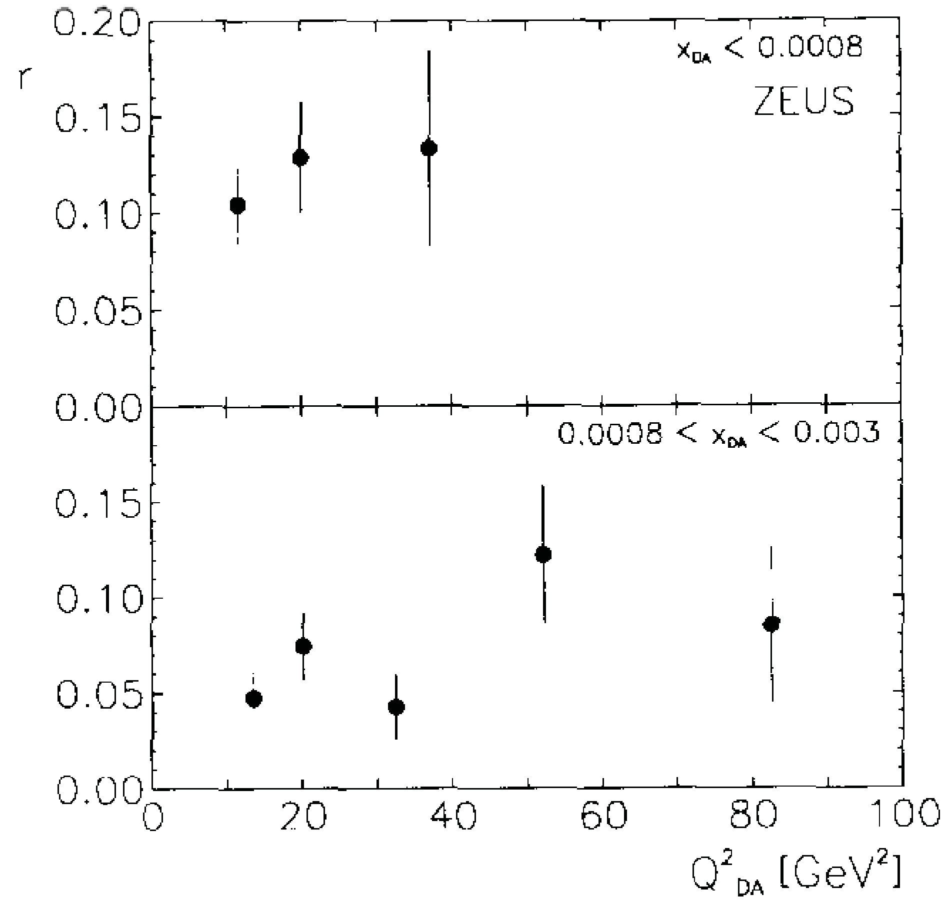


Final-State QCD Interaction

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

Remarkable observation at HERA





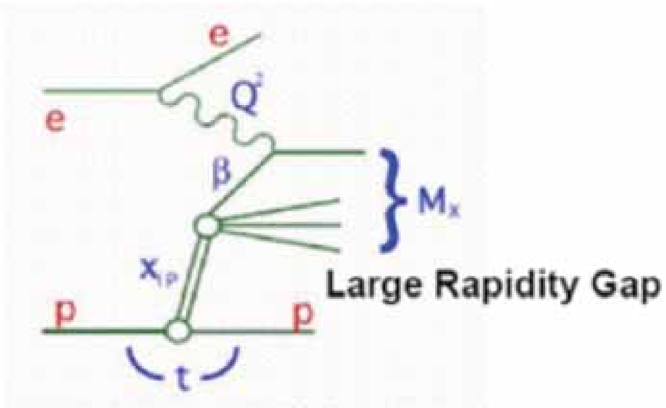
Fraction r of events with a large rapidity gap, $\eta_{max} < 1.5$, as a function of Q^2_{DA} for two ranges of x_{DA}. No acceptance corrections have been applied.

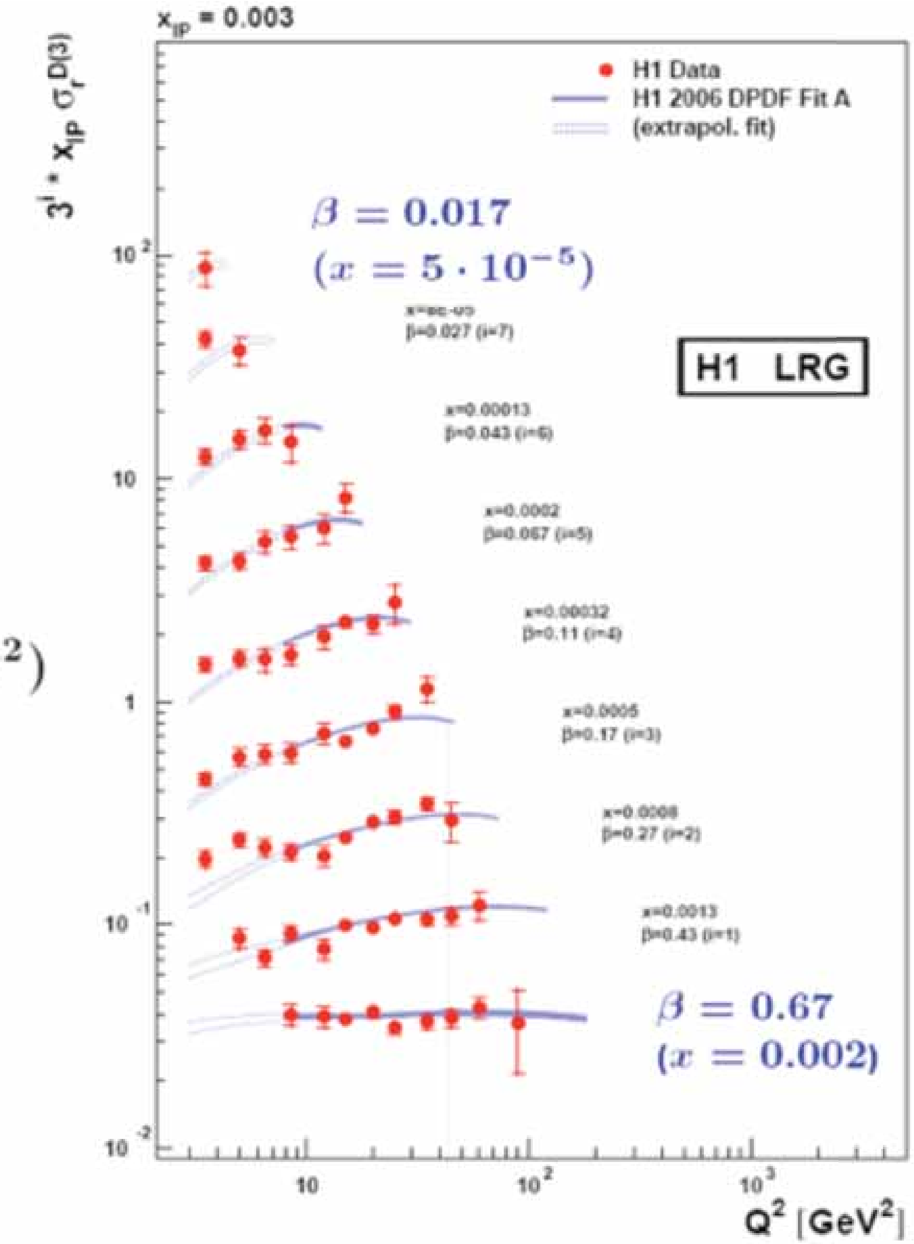
10% to 15% of DIS events are diffractive !

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

de Roeck

Diffractive Structure Function F_2^D





Diffractive inclusive cross section

$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

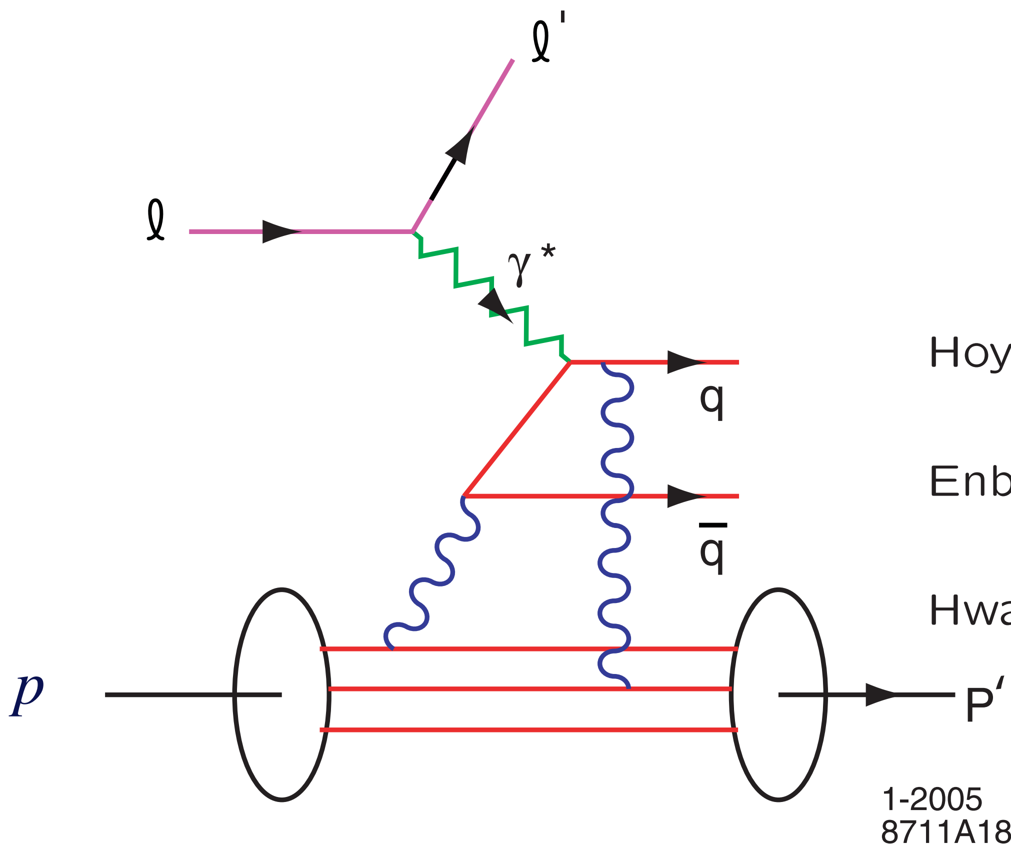
$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\,\mathrm{GeV}^2$

Precise measurements *sys 5%, stat 5–20 %*

Final-State Interaction Produces Diffractive DIS



Quark Rescattering

Hoyer, Marchal, Peigne, Sannino, SJB (BHM

Enberg, Hoyer, Ingelman, SJB

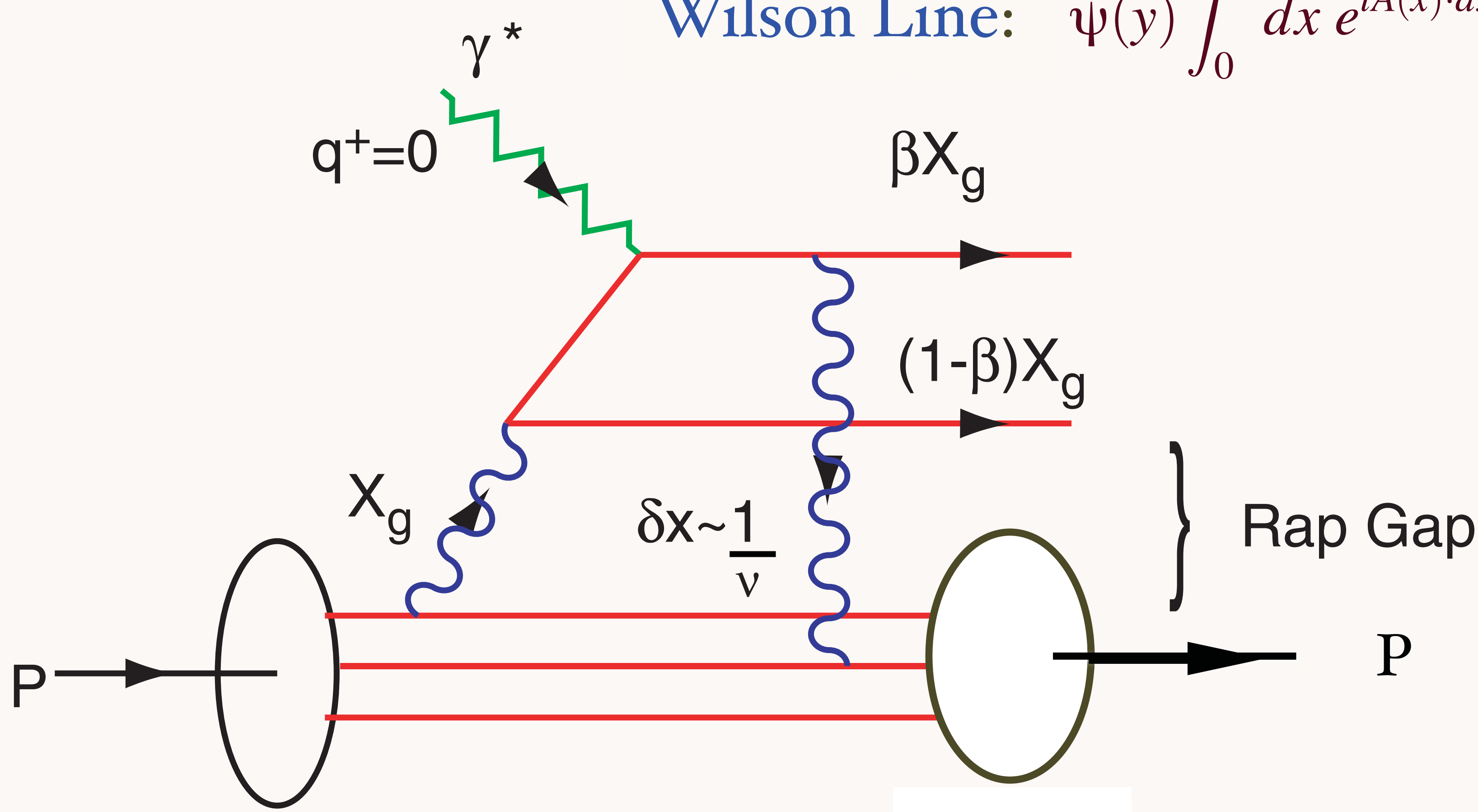
Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

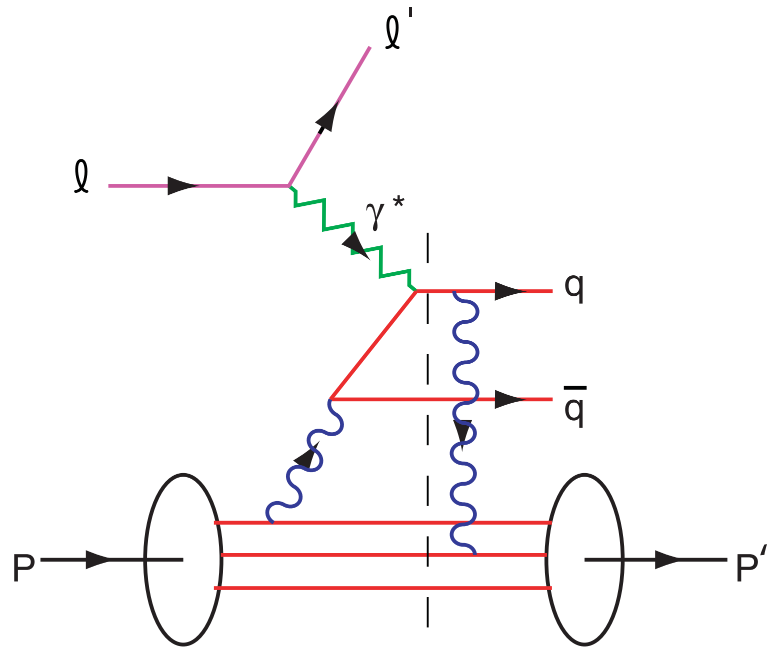
Hoyer, Marchal, Peigne, Sannino, sjb

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

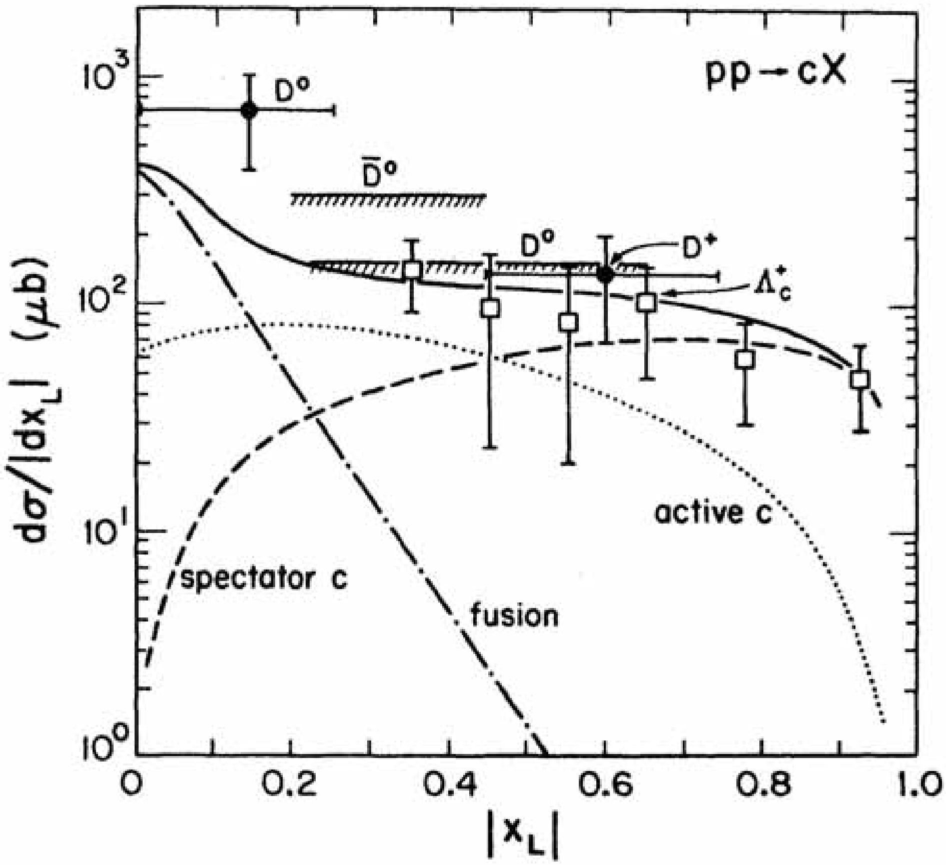


Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate Pomeron

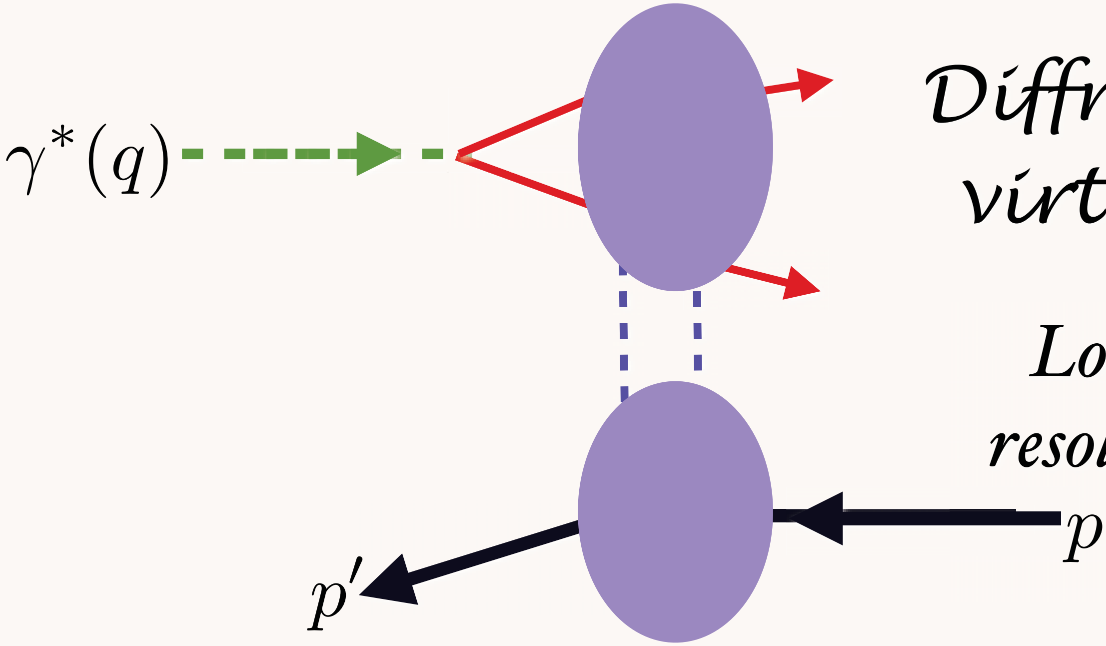
Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target



Model similar to Intrinsic Charm

V. D. Barger, F. Halzen and W. Y. Keung, "The Central And Diffractive Components Of Charm Production," Phys. Rev. D 25, 112 (1982).



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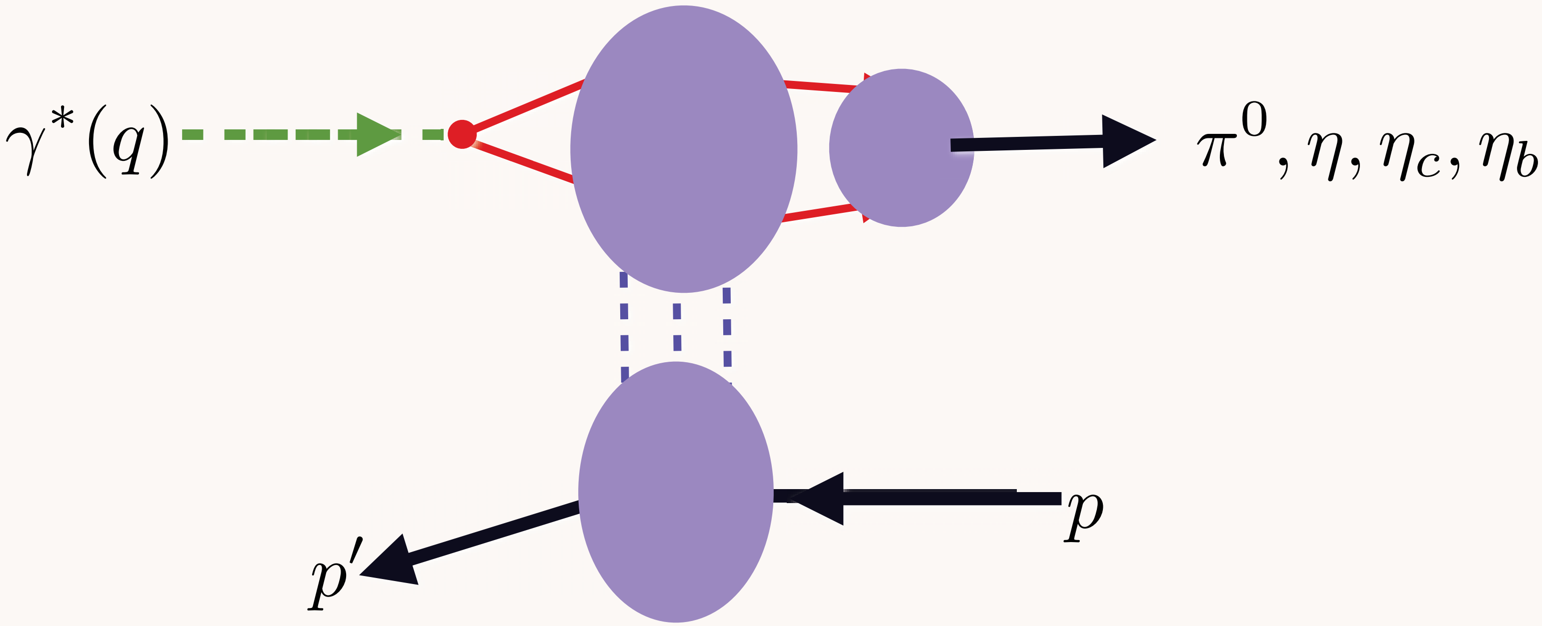
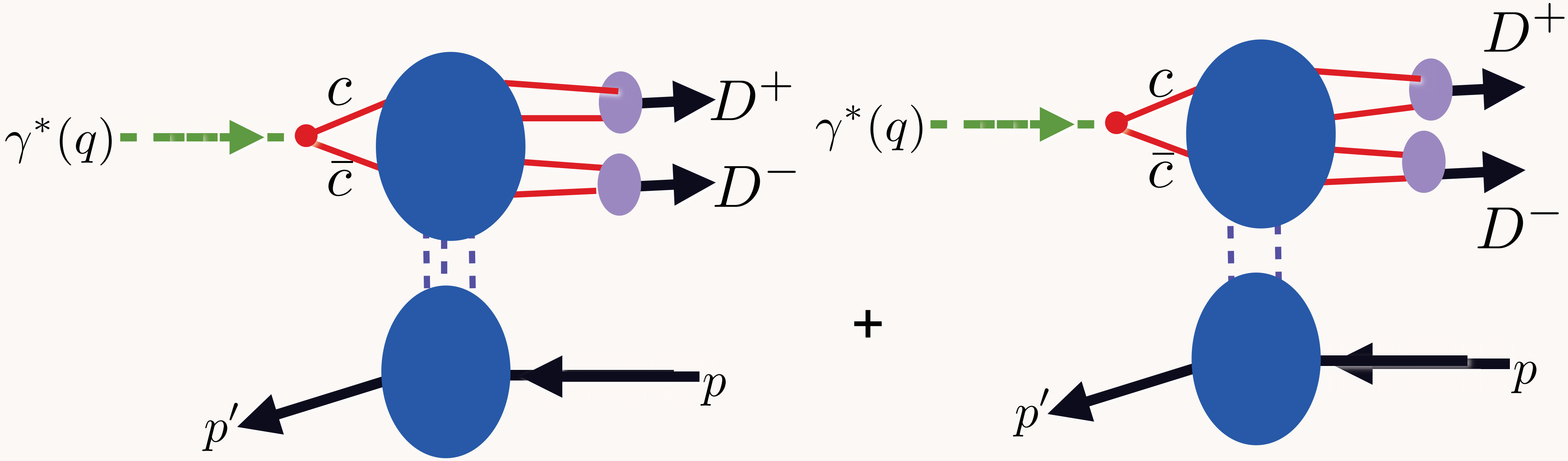


Odderon has never been observed!



Odderon-Pomeron Interference leads to D^+ D^- and B^+ B^- charge and angular asymmetry

Merino, Rathsman, sjb

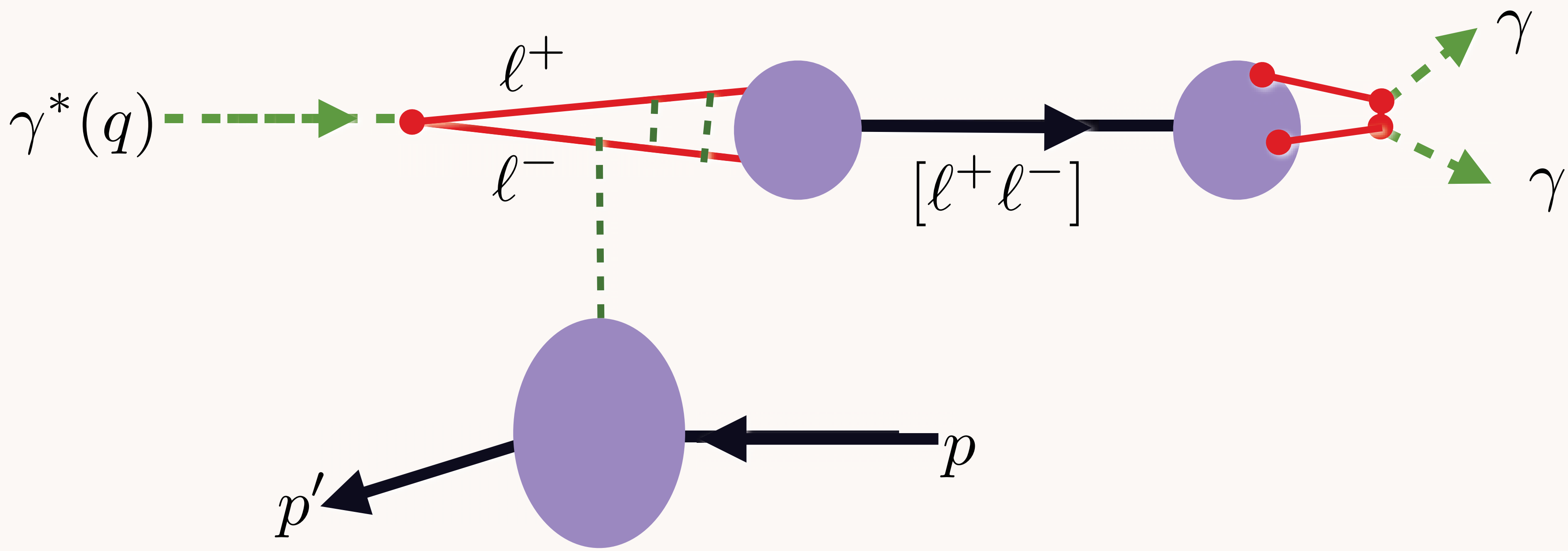
Odderon at amplitude level

Strong enhancement at heavy-quark pair threshold from QCD Sakharov-Schwinger-Sommerfeld effect

$$\frac{\pi \alpha_s(\beta^2 s)}{\beta}$$

Hoang, Kuhn, sjb

$$\gamma^* p \to [\ell^+ \ell^-] + p$$



Lebed, sjb

Produce relativistic "true muonium" and "true tauonium" jut below threshold

$$|\pi : \underline{P}\rangle = \sum_{n,\lambda_i} \int \overline{\prod_i} \frac{dx_i d^2\vec{k}_{\perp i}}{\sqrt{x_i} 16\pi^3} \left| n : x_i P^+, x_i \overrightarrow{P}_\perp + \vec{k}_{\perp i}, \lambda_i \right\rangle \psi_{n/\pi}(x_i, \vec{k}_{\perp i}, \lambda_i)$$

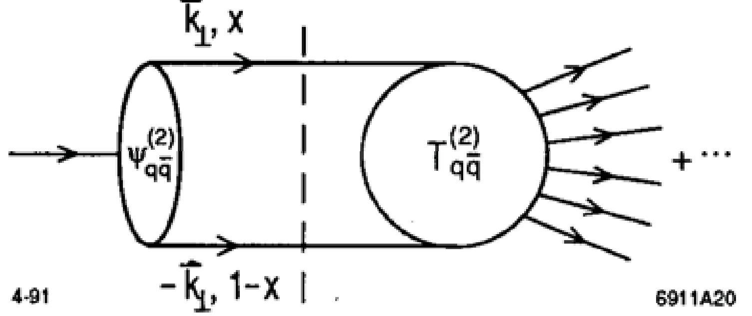
$$\sum_{n,\lambda_i} \int \overline{\prod_i} \frac{dx_i d^2\vec{k}_{\perp i}}{16\pi^3} |\psi_{n/\pi}(x_i, \vec{k}_{\perp i}, \lambda_i)|^2 = 1$$

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

$$\sum_{\lambda_i} \int \overline{\prod_i} \frac{dx_i d^2\vec{k}_{\perp i}}{\sqrt{x_i} 16\pi^3} \psi_n^{(\Lambda)}(x_i, \vec{k}_{\perp i}, \lambda_i)\ T_n^{(\Lambda)}(x_i P^+, x_i \overrightarrow{P}_\perp + \vec{k}_{\perp i}, \lambda_i)$$

$k_\perp^2 < \Lambda^2$ $\qquad$ $k_\perp^2 > \Lambda^2$

Renormalization Group Invariance:
The factorization scale Λ is arbitrary



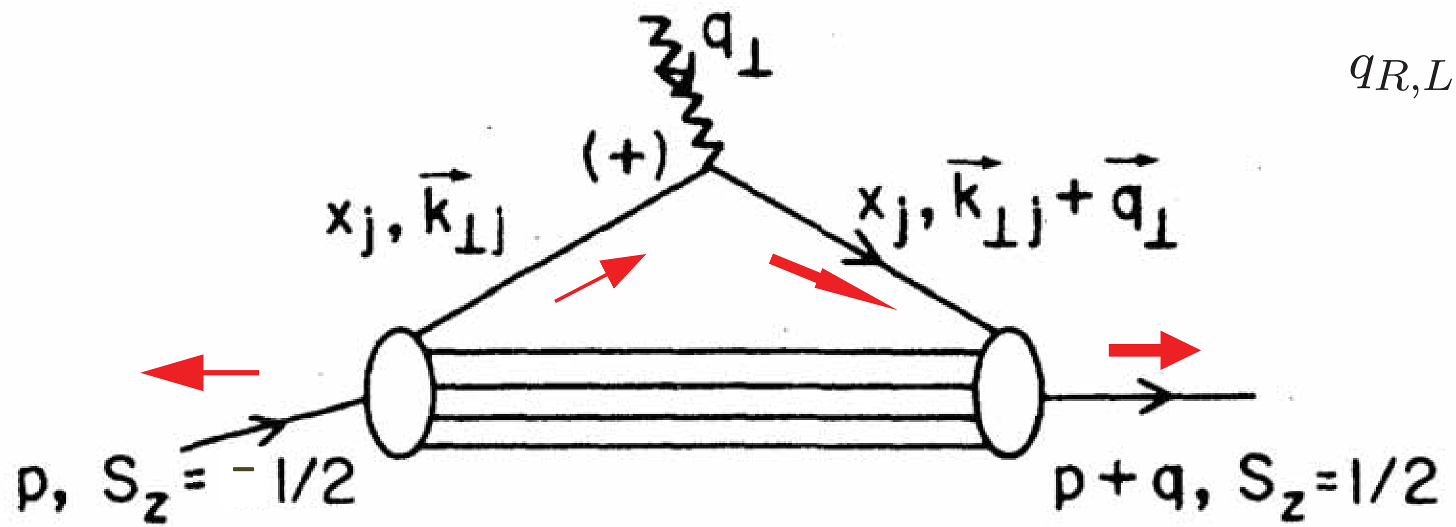
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

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

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

Drell, sjb

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



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

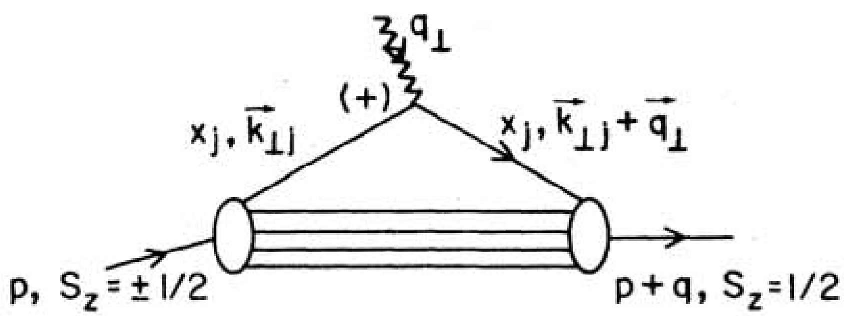
Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

$$\sum_{\lambda_i} \int \overline{\prod_i} \frac{dx_i d^2\vec{k}_{\perp i}}{\sqrt{x_i} 16\pi^3} \psi_n^{(\Lambda)}(x_i, \vec{k}_{\perp i}, \lambda_i)\; T_n^{(\Lambda)}(x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i)$$

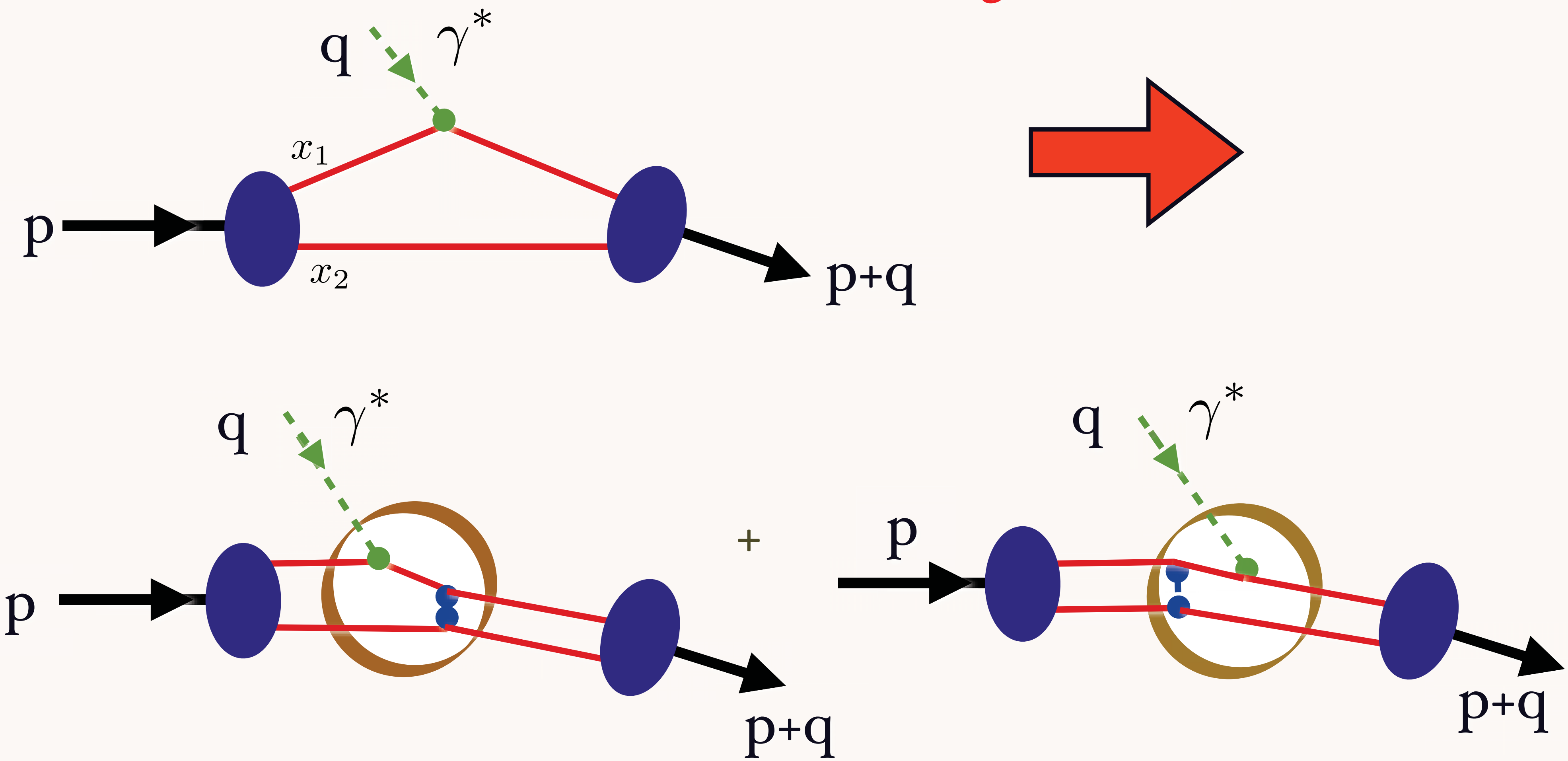
$$F(\vec{q}_\perp^{\,2}) = \sum_{n,\lambda_i} \sum_a e_a \int \overline{\prod_i} \frac{dx_i\, d^2\vec{k}_{\perp i}}{16\pi^3} \psi_n^{(\Lambda)*}(x_i, \vec{l}_{\perp i}, \lambda_i)\, \psi_n^{(\Lambda)}(x_i, \vec{k}_{\perp i}, \lambda_i).$$

Here e_a is the charge of the struck quark, $\Lambda^2 \gg \vec{q}_\perp^{\,2}$, and

$$\vec{l}_{\perp i} \equiv \begin{cases} \vec{k}_{\perp i} - x_i \vec{q}_\perp + \vec{q}_\perp & \text{for the struck quark} \\ \vec{k}_{\perp i} - x_i \vec{q}_\perp & \text{for all other partons.} \end{cases}$$



QCD analysis of Pion Form Factor at High Q^2



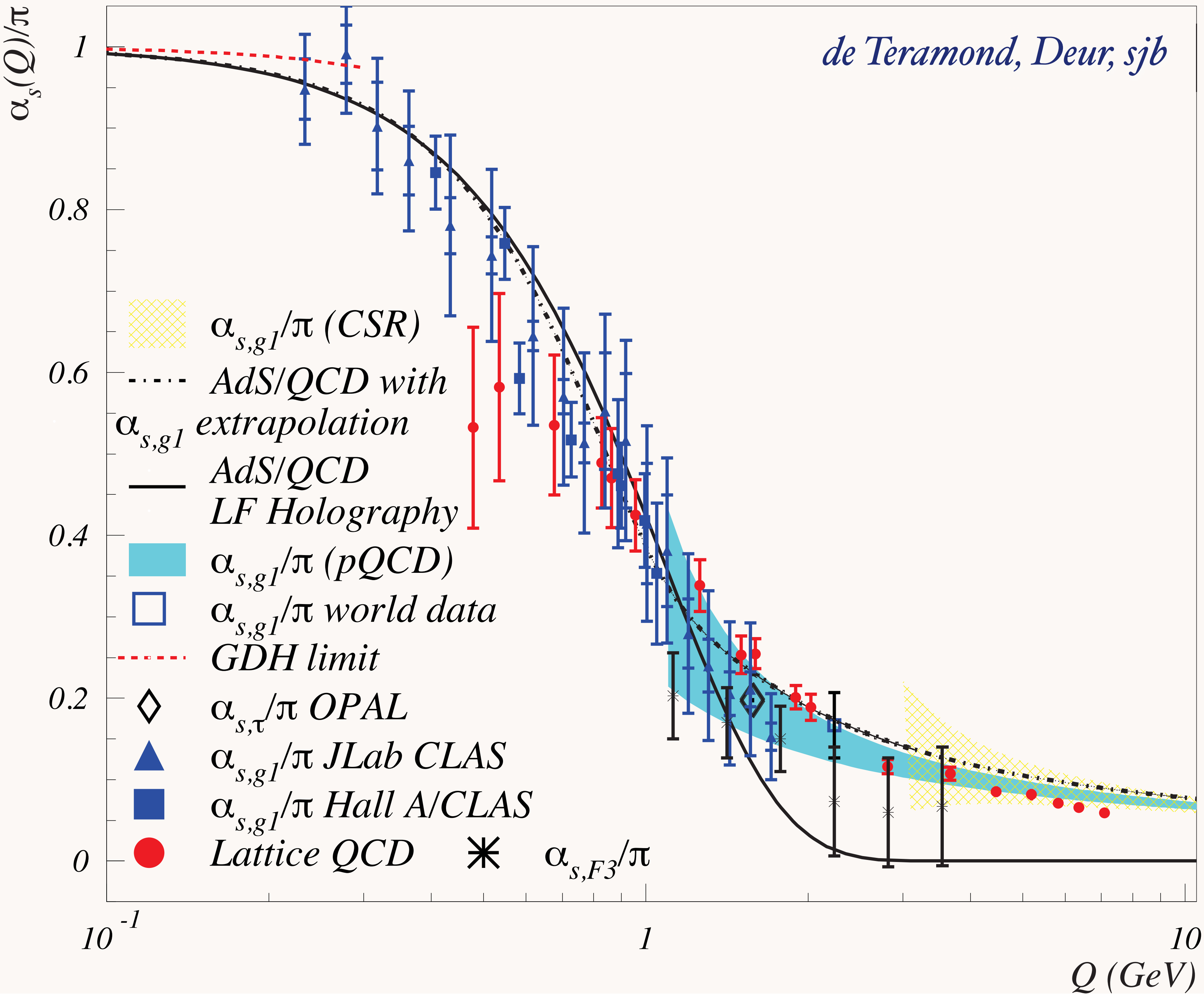
Iterate kernel of LFWF to expose hard-scattering amplitude T_H

$$T_H(q\bar{q} + \gamma^* \to q\bar{q}) = 16\pi C_F \frac{\alpha_s(Q^{*2})}{x_2 y_2 Q^2}$$

$$C_F = \frac{N_C^2 - 1}{2N_C} = \frac{4}{3}$$

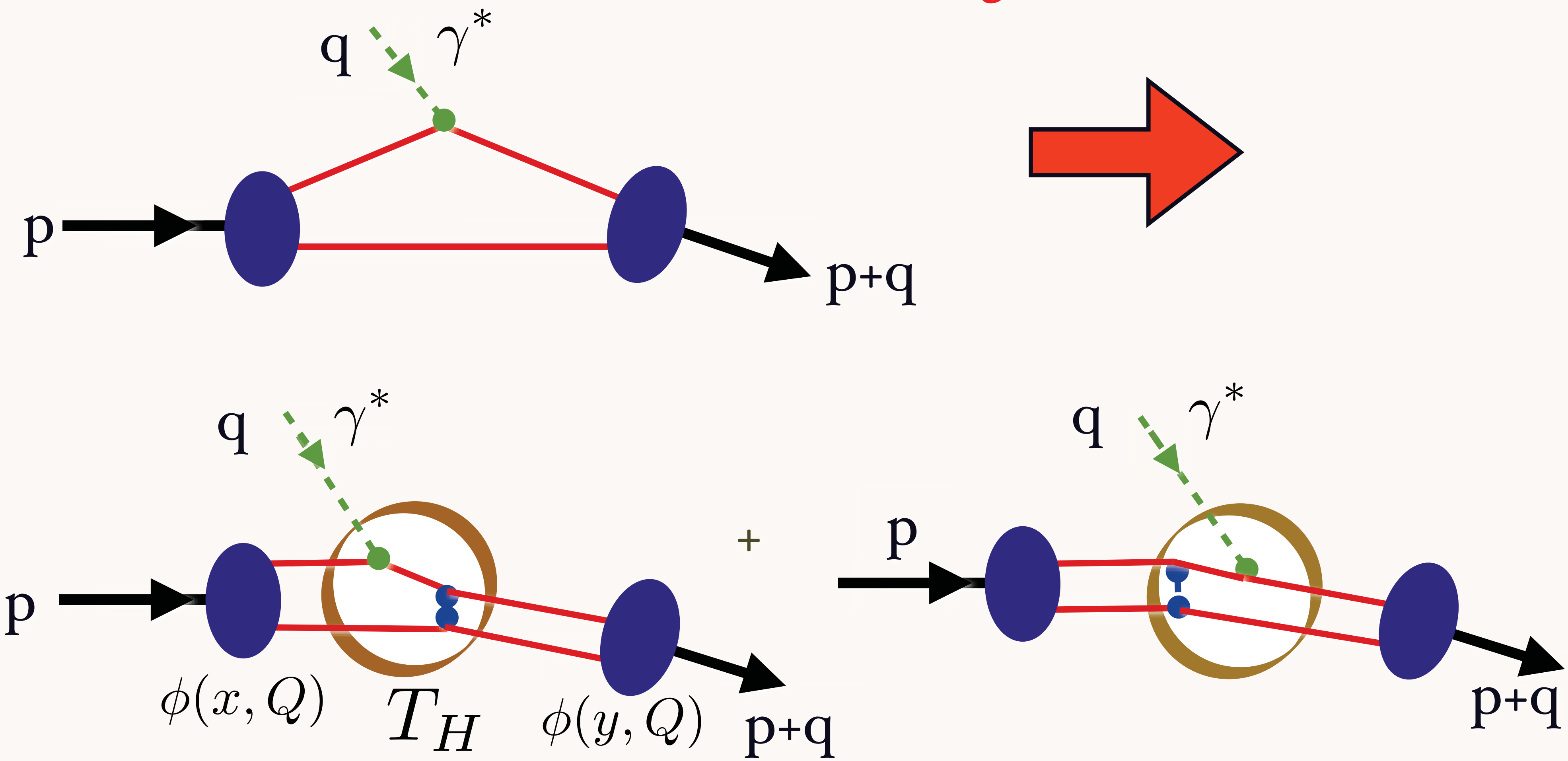
$$Q^{*2} = e^{-5/3} x_2 y_2 Q^2 \text{ in } \overline{MS} \text{ scheme}$$

No renormalization scale ambiguity!



de Teramond, Deur, sjb
$\alpha_s(Q)/\pi$
1
0.8
0.6
0.4
0.2
0
10^{-1}
1
10
Q (GeV)
$\alpha_{s,g1}/\pi$ (CSR)
AdS/QCD with $\alpha_{s,g1}$ extrapolation
AdS/QCD LF Holography
$\alpha_{s,g1}/\pi$ (pQCD)
$\alpha_{s,g1}/\pi$ world data
GDH limit
$\alpha_{s,\tau}/\pi$ OPAL
$\alpha_{s,g1}/\pi$ JLab CLAS
$\alpha_{s,g1}/\pi$ Hall A/CLAS
Lattice QCD
$\alpha_{s,F3}/\pi$

QCD analysis of Pion Form Factor at High Q^2

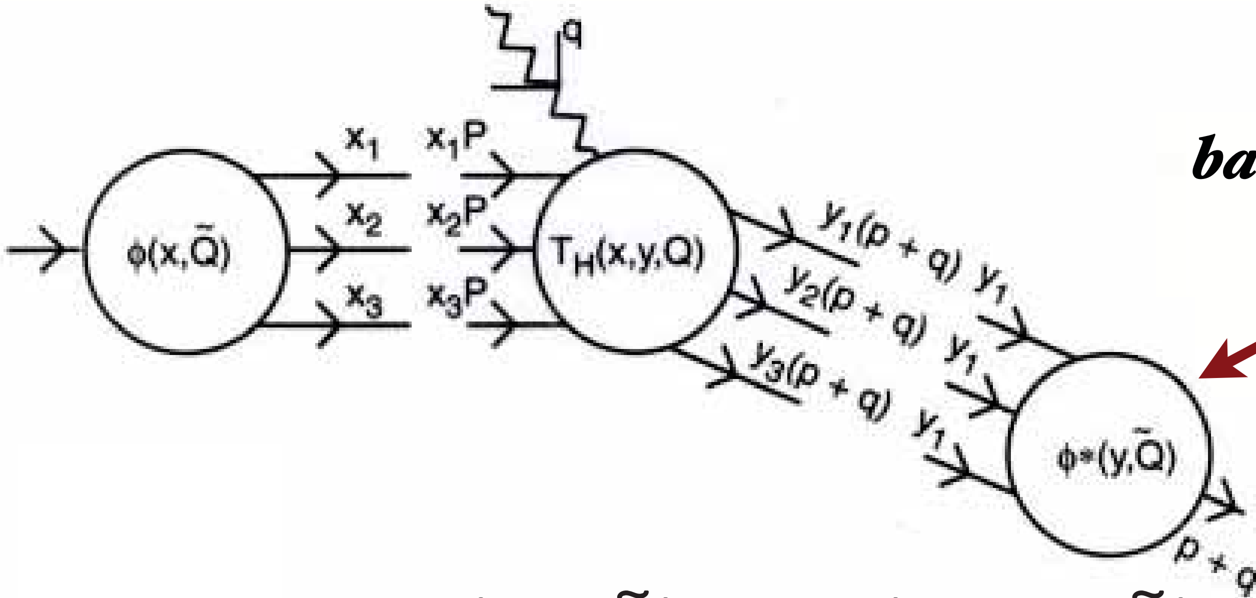


Iterate kernel of LFWF to expose hard-scattering amplitude T_H

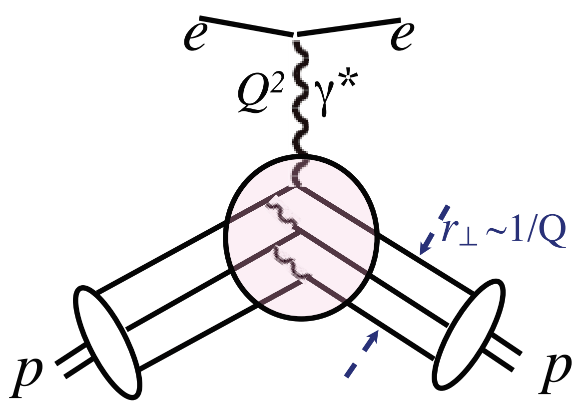
$$F_M(Q^2) = \int_0^1 dx \int_0^1 dy\ \phi(x,Q) T_H(x,y,Q) \phi(y,Q) \rightarrow 16\pi f_M^2 \frac{\alpha_s(Q^2)}{Q^2}$$

Leading-Twist PQCD Factorization for form factors, exclusive amplitudes

Lepage, sjb



$$M = \int \Pi dx_i dy_i \phi_F(x_i, \tilde{Q}) \times T_H(x_i, y_i, \tilde{Q}) \times \phi_I(y_i, \tilde{Q})$$



If $\alpha_s(\tilde{Q}^2) \simeq$ constant

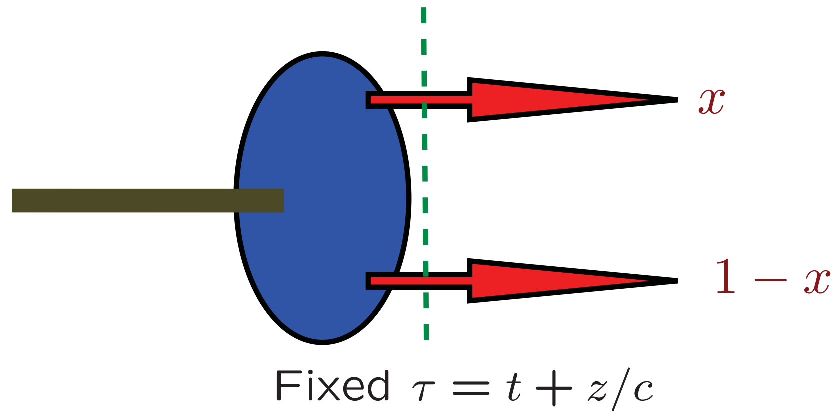
$Q^4 F_1(Q^2) \simeq$ constant

Hadron Distribution Amplitudes

Lepage, sjb

$$\phi_H(x_i, Q)$$

$$\sum_i x_i = 1$$



$$k_\perp^2 < Q^2$$

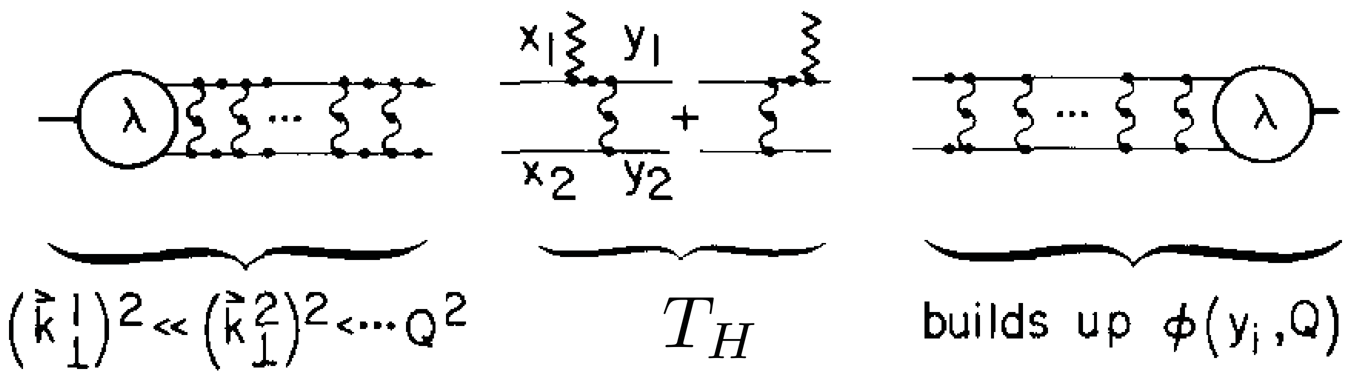
- Fundamental gauge invariant non-perturbative input to hard exclusive processes, heavy hadron decays. Defined for Mesons, Baryons

Lepage, sjb
Frishman, Lepage, Sachrajda, sjb
Peskin Braun
Efremov, Radyushkin Chernyak etal

- Evolution Equations from PQCD, OPE, Conformal Invariance

- Compute from valence light-front wavefunction in light-cone gauge

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



$$F_M(Q^2) = \int_0^1 dx_1\, dx_2\, \delta\left(1 - \sum_j x_j\right) \int_0^1 dy_1\, dy_2\, \delta\left(1 - \sum_j y_j\right) \phi^\dagger(y_i, Q)\, T_H(y_i, x_i, Q)\, \phi(x_i, Q)\,,$$

where

$$T_H = 16\pi C_F (\alpha_s(Q^2)/Q^2)(1/x_2 y_2) \quad (C_F = \tfrac{4}{3})\,,$$

$$\alpha_s(Q^2) = 4\pi/\beta \log(Q^2/\Lambda^2) \quad (\beta = 11 - \tfrac{2}{3} n_{\text{flavors}})\,,$$

Renormalization Group Invariance
The factorization scale $\Lambda \sim Q$ is arbitrary

$$\phi(x_i, Q) = (\log(Q^2/\Lambda^2))^{-C_F/\beta} \int_0^{Q^2} \frac{dk_\perp^2}{16\pi^2}\, \psi(x_i, k_\perp) \equiv x_1 x_2\, \tilde{\phi}(x_i, Q)\,,$$

Distribution Amplitude

G. P. Lepage, sjb

Here Q is used as the factorization scale

$$\phi(x,Q) = \int d^2k_\perp \theta(k_\perp^2 < Q^2)\psi(x,\vec{k}_\perp)$$

$$\text{Define } \xi = \frac{\beta_0}{4\pi}\int_0^{Q^2} \frac{dk_\perp^2}{k_\perp^2}\alpha_s(k_\perp^2) \simeq \log\log\frac{Q^2}{\Lambda^2_{\rm QCD}}$$

$$x_1x_2\{(\partial/\partial\xi)\tilde{\phi}(x_i,Q) + (C_{\rm F}/\beta)\tilde{\phi}(x_i,Q)\} = \int_0^1 {\rm d}y_1\,{\rm d}y_2\,\delta\left(1-\sum_j y_j\right)V(x_i,y_i)\tilde{\phi}(y_i,Q)$$

where

$$V(x_i,y_i) = 2(C_{\rm F}/\beta)\{y_1x_2\theta(y_2-x_2)(\delta_{h_1\bar{h}_2} + \Delta/(y_2-x_2)) + (1\leftrightarrow 2)\} = V(y_i,x_i)$$

$$(\Delta\tilde{\phi} \equiv \tilde{\phi}(y_i,Q) - \tilde{\phi}(x_i,Q))\,,$$

ERBL Evolution

Efremov, Radyushkin
G. P. Lepage, sjb

The evolution equation has a general solution

$$\phi(x_i, Q) = x_1 x_2 \sum_{n=0}^{\infty} a_n C_n^{3/2}(x_1 - x_2) \exp(-\gamma_n \xi) ,$$

where the Gegenbauer polynomials $C_n^{3/2}$ are eigenfunctions of $V(x_i, y_i)$. The corresponding eigenvalues are

$$\gamma_n = (C_F/\beta) \left\{ 1 + 4 \sum_{2}^{n+1} \frac{1}{k} - 2\delta_{h_1 \bar{h}_2} / (n+1)(n+2) \right\} \geqslant 0 .$$

The coefficients a_n can be determined from the soft wavefunction:

$$a_n (\log(\lambda^2/\Lambda^2))^{-\gamma_n} = \frac{2(2n+3)}{(2+n)(1+n)} \int_{-1}^{1} d(x_1 - x_2) C_n^{3/2}(x_1 - x_2) \phi(x_i, \lambda^2) .$$

where $\delta_{h_1 \bar{h}_2} = 1$ for antiparallel $q\bar{q}$ spins

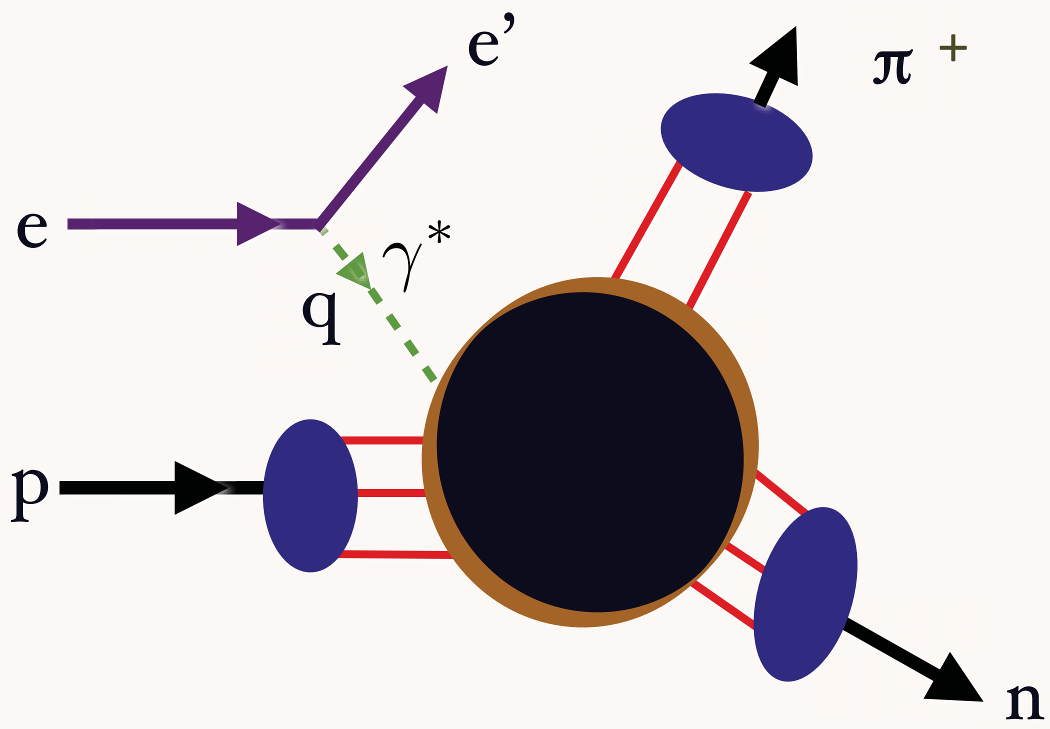
$$\begin{aligned} \phi(x_i, Q) &\to a_0 x_1 x_2, && h_1 + h_2 = 0, \\ &\to a_0 x_1 x_2 (\log(Q^2/\Lambda^2))^{-C_F/\beta}, && |h_1 + h_2| = 1, \end{aligned}$$

$Q^2 \to \infty$

$$F_\pi(Q^2) \to 16\pi\, \alpha_s(Q^2) f_\pi^2 / Q^2, \quad \text{as } Q^2 \to \infty .$$

Exclusive Electroproduction

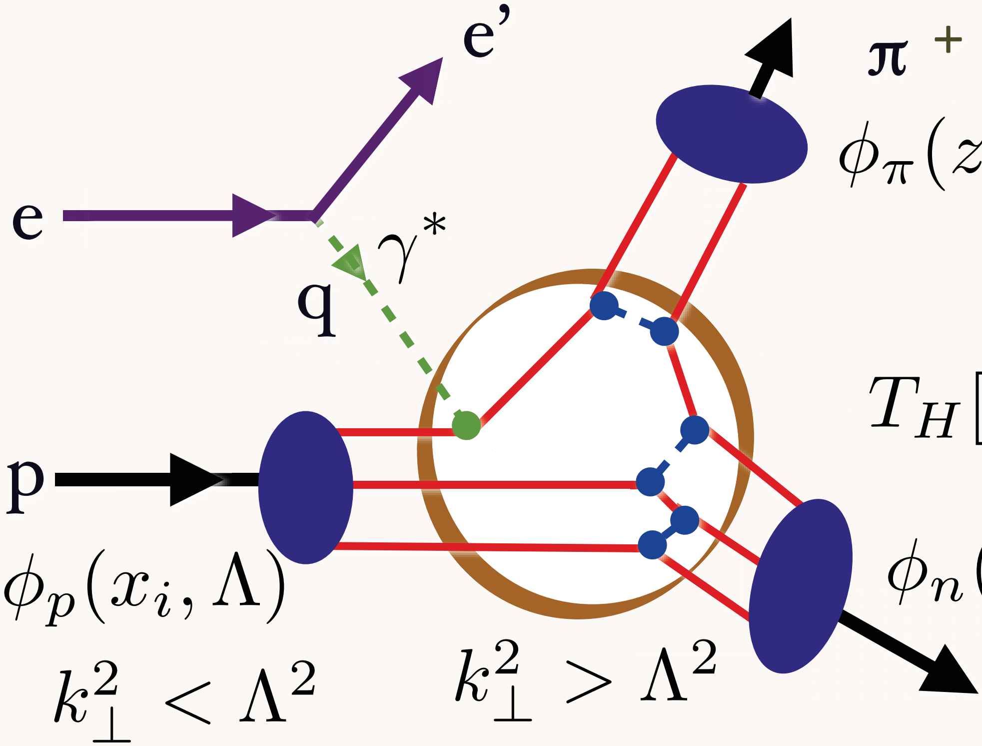
$$ep \to e'\pi^+ n$$



Iterate kernel of LFWF to expose hard-scattering ampltude

QCD Factorization
Exclusive Electroproduction

$$ep \rightarrow e'\pi^+ n$$



$\phi_\pi(z_i, \Lambda)$

γ^*

$T_H[\gamma^* + (uud) \rightarrow (u\bar{d})(ddu)]$

$\phi_p(x_i, \Lambda)$

$\phi_n(y_i, \Lambda)$

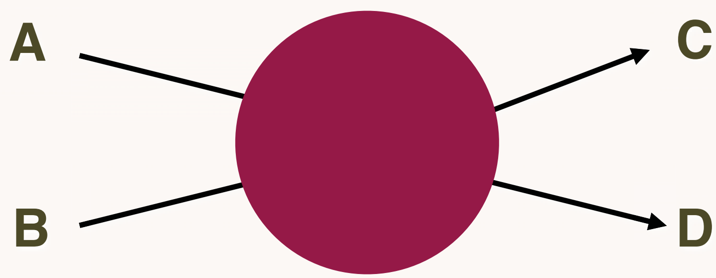
$k_\perp^2 < \Lambda^2$ $\quad$ $k_\perp^2 > \Lambda^2$

$$T = \int_0^1 dx \int_0^1 dy \int_0^1 dx\ \phi_p(x, \Lambda) T_H(x, y, z; Q^2, s, t; \Lambda) \phi_n(y, \Lambda) \phi_\pi^+(z, \Lambda)$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^7} \text{ at fixed } Q^2/s, t/s$$

Universal distribution amplitudes. Renormalization Group Invariance:
The factorization scale Λ is arbitrary. The renormalization scale is unambiguous

Proof from AdS/QCD: Polchinski and Strassler



$$\frac{d\sigma}{dt}(s,t) = \frac{F(\theta_{\rm cm})}{s^{[n_{\rm tot}-2]}} \qquad s = E^2_{\rm cm}$$

$$F_H(Q^2) \sim [\frac{1}{Q^2}]^{n_H - 1}$$

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

Fixed t/s or $\cos\theta_{cm}$

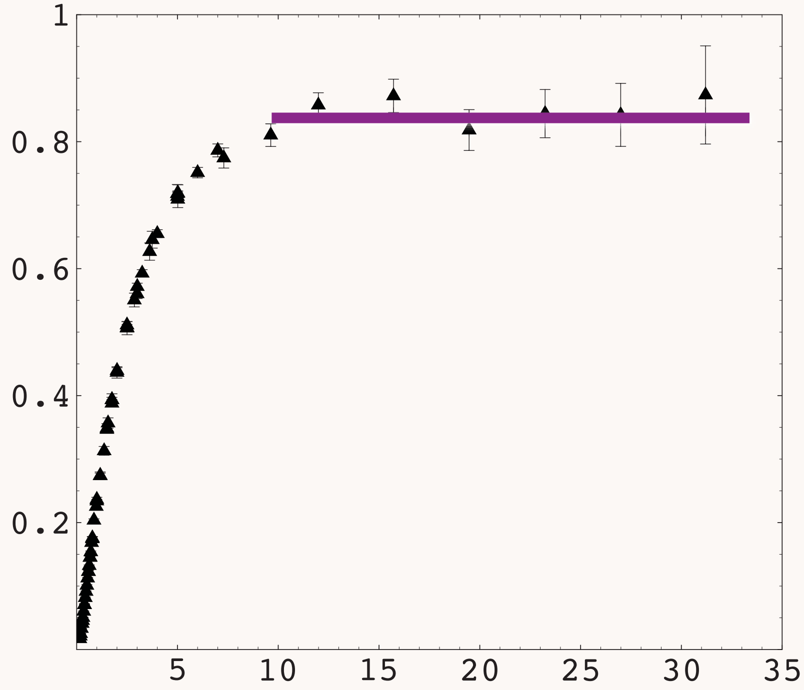
Farrar & sjb;
Matveev, Muradyan, Tavkhelidze

QCD predicts leading-twist scaling behavior of fixed-CM angle exclusive amplitudes

$$s, -t >> m^2_\ell$$

Extension to soft pions: Strikman, Pobylitsa, Polyakov $D : N + \pi$

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



Q^2 [GeV^2]

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

From: M. Diehl *et al.* Eur. Phys. J. C **39**, 1 (2005).

- Phenomenological success of dimensional scaling laws for exclusive processes

$$d\sigma/dt \sim 1/s^{n-2}, \quad n = n_A + n_B + n_C + n_D,$$

implies QCD is a strongly coupled conformal theory at moderate but not asymptotic energies

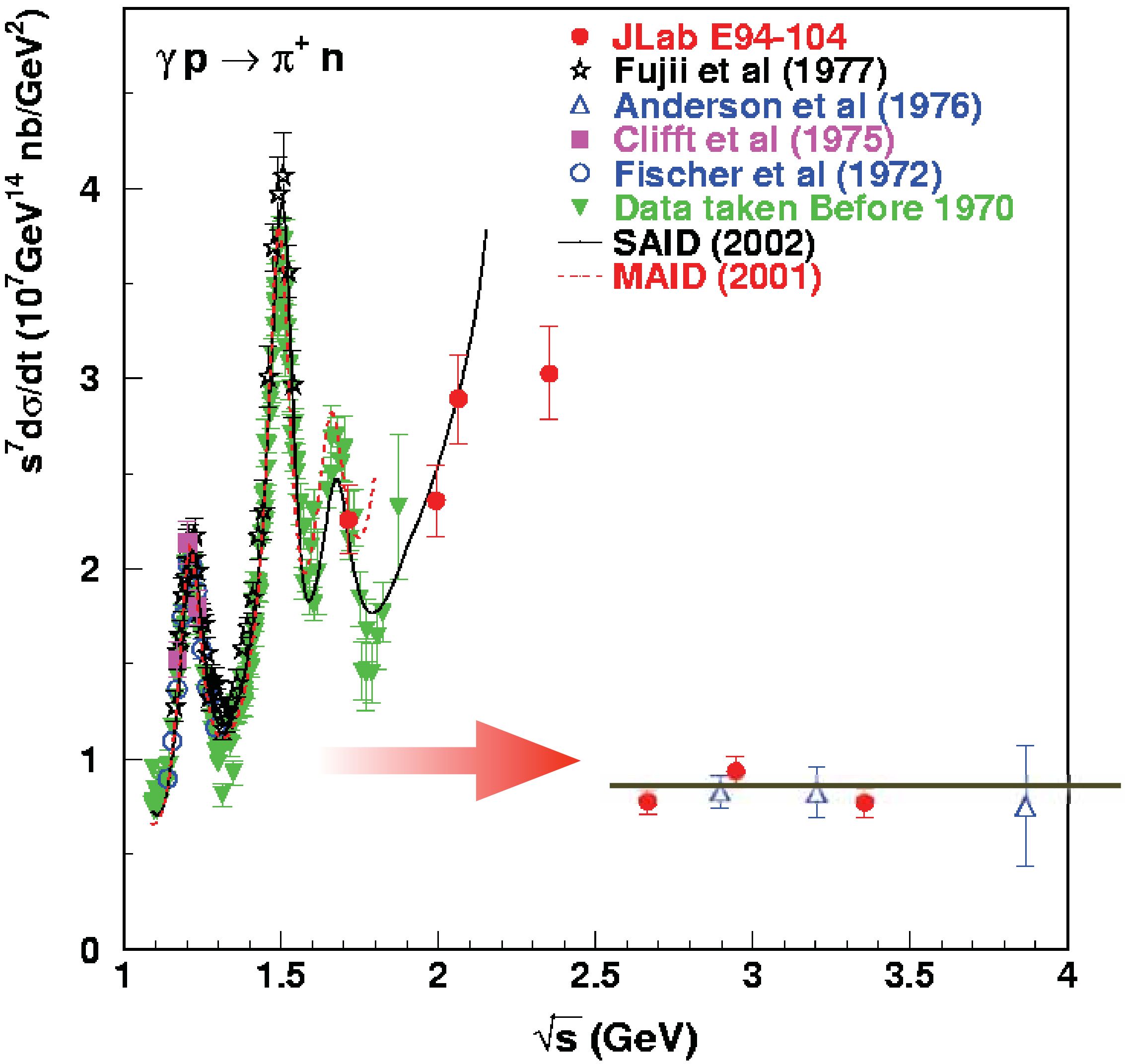
Farrar and sjb (1973); Matveev *et al.* (1973).

- Derivation of counting rules for gauge theories with mass gap dual to string theories in warped space (hard behavior instead of soft behavior characteristic of strings) Polchinski and Strassler (2001).

Test of Scaling Laws

Constituent counting rules

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

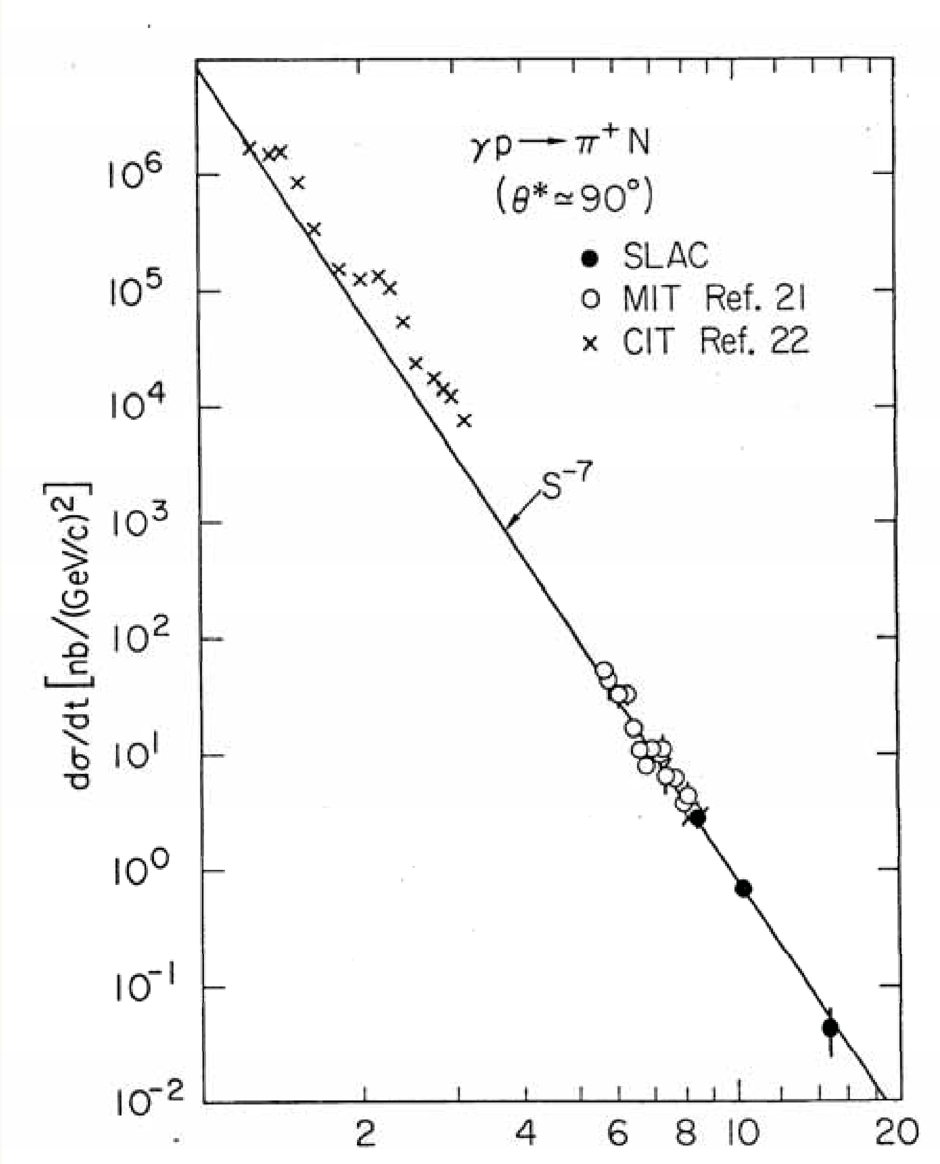


$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B \to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

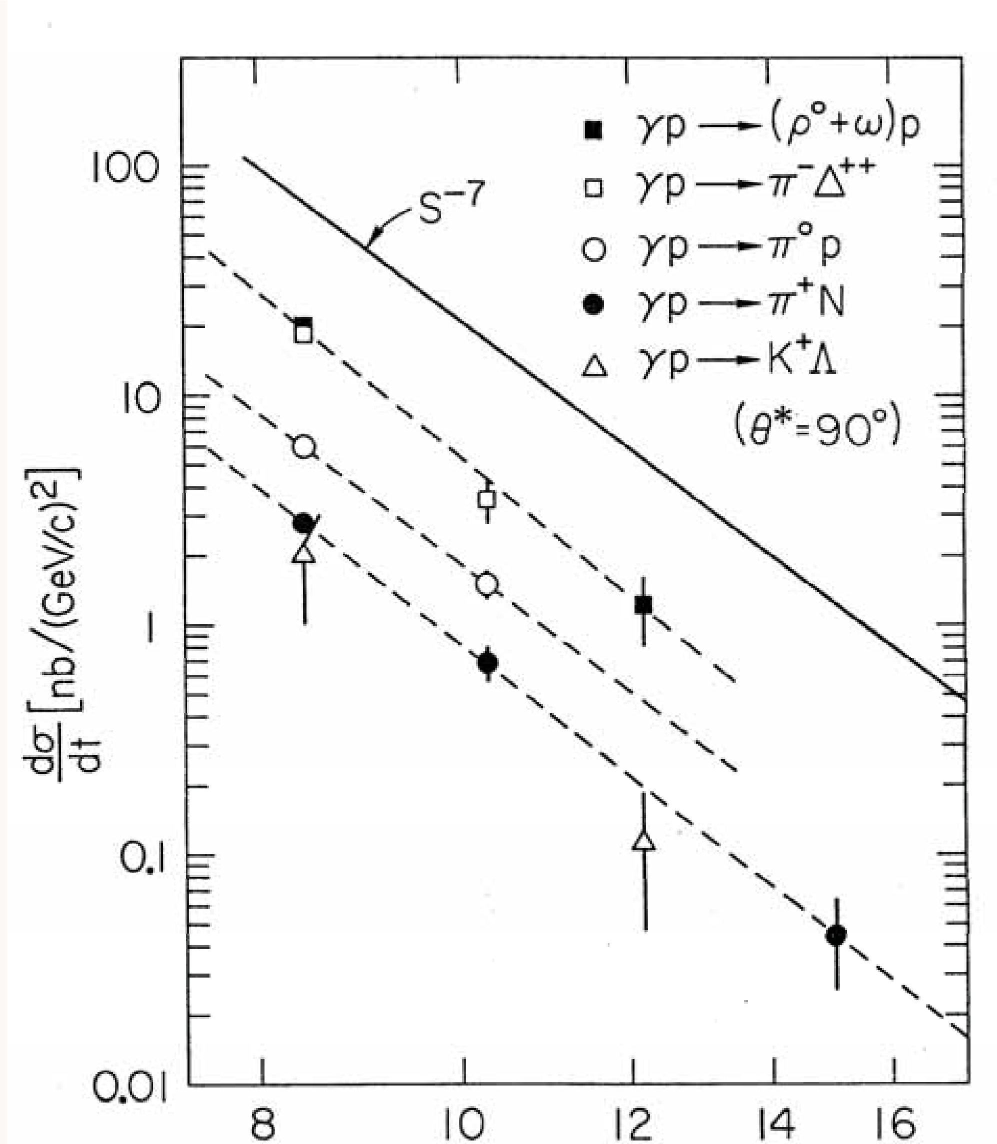
$$s^7\frac{d\sigma}{dt}(\gamma p \to \pi^+ n) = F(\theta_{CM})$$
$$n_{tot} = 1+3+2+3 = 9$$

$s^7 d\sigma/dt(\gamma p \to \pi^+ n) \sim const$
fixed θ_{CM} scaling

Conformal invariance at high momentum transfers!



$s(\mathrm{GeV}^2)$



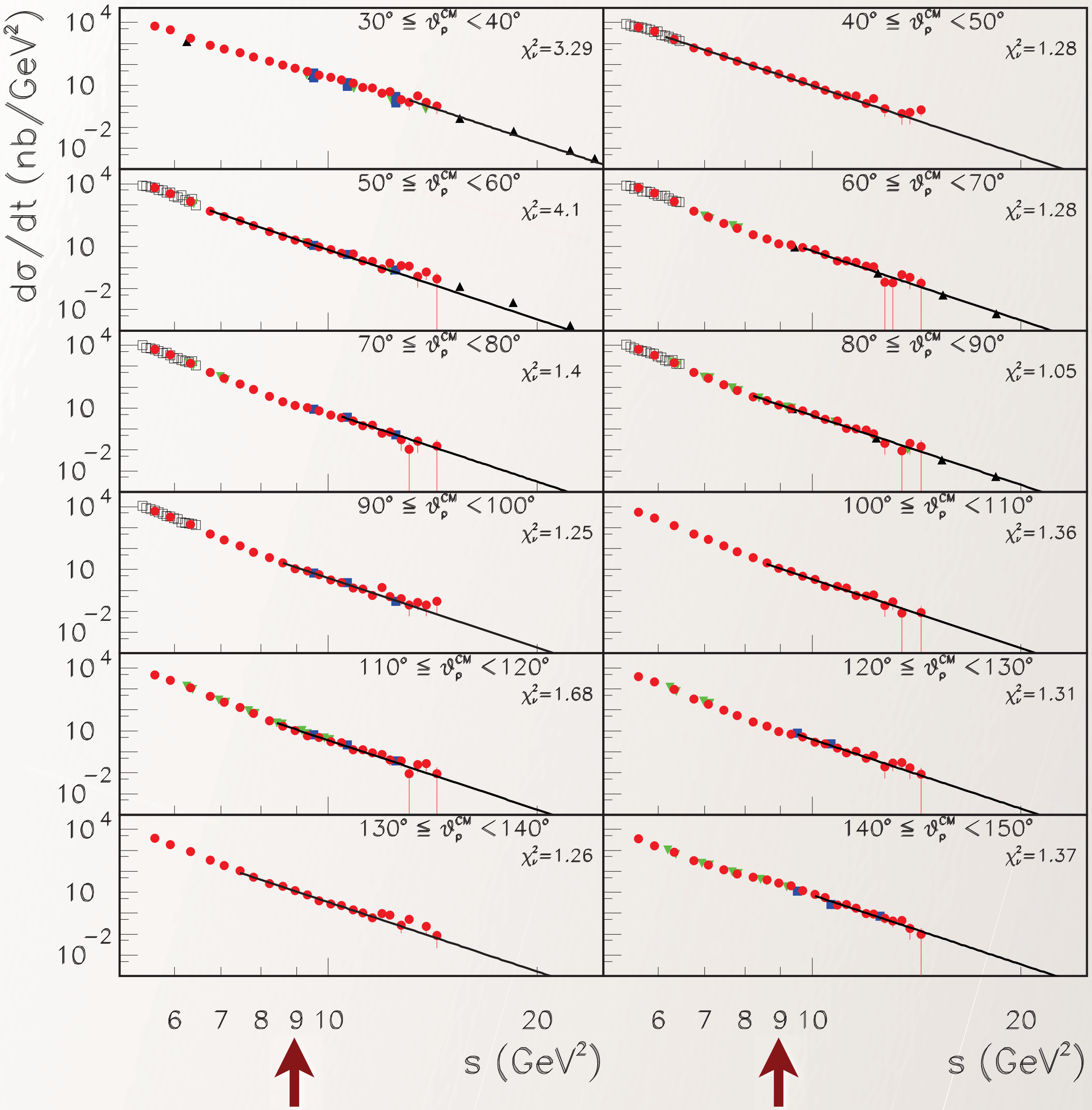
$s(\mathrm{GeV}^2)$

Counting Rules: n=9

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

Deuteron Photodisintegration and Dimensional Counting

P.Rossi et al, P.R.L. 94, 012301 (2005)



PQCD and AdS/CFT:

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

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

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

$$\gamma d \to (uuddd us\bar{s}) \to np$$

at $s \simeq 9$ GeV^2

$$\gamma d \to (uuddd uc\bar{c}) \to np$$

at $s \simeq 25$ GeV^2

$\gamma d \rightarrow np$

$\gamma d \rightarrow (uudddus\bar{s}) \rightarrow np$ at $s = 9$ GeV^2

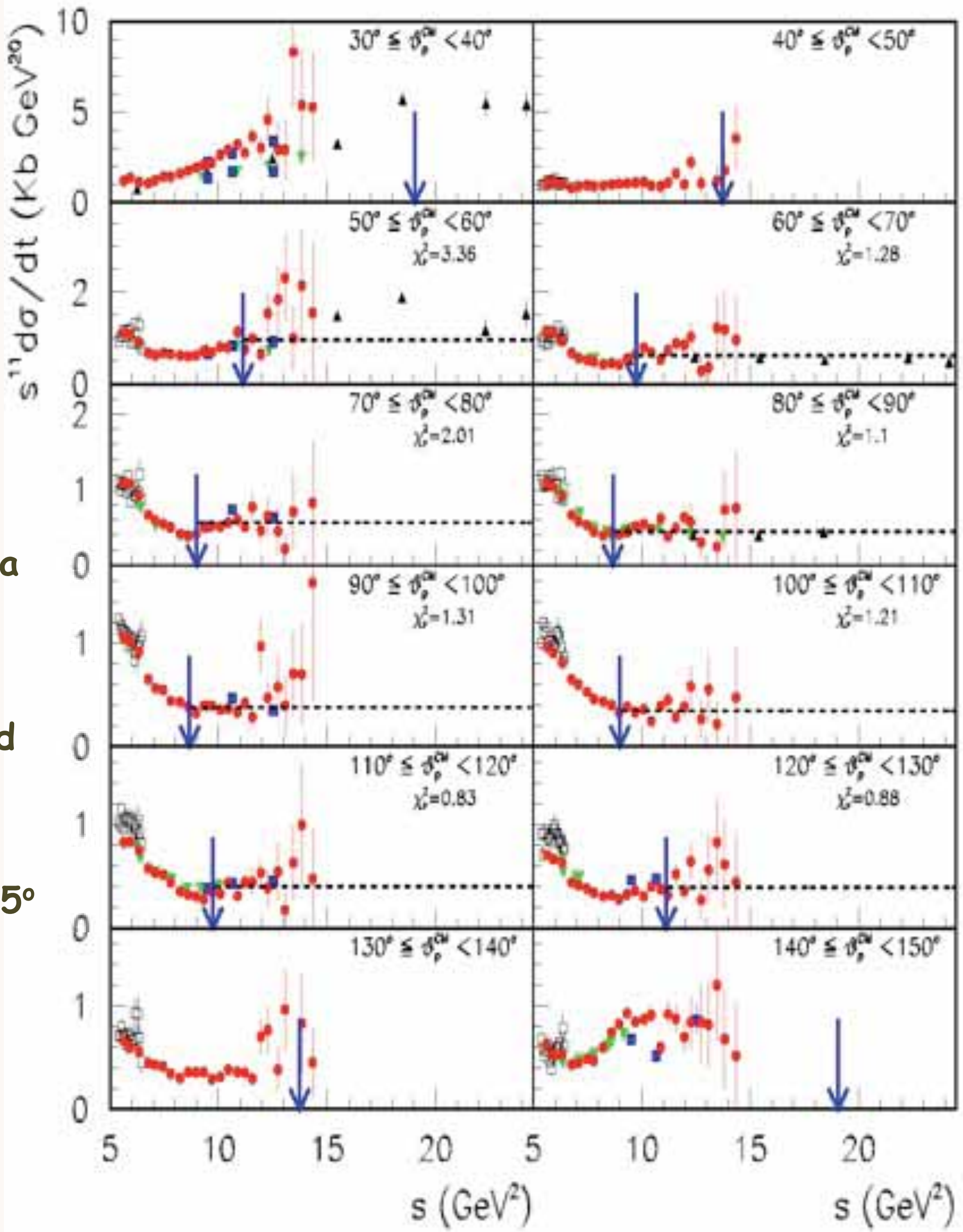
Fit of dσ/dt data for the central angles and $P_T \geq 1.1$ GeV/c with $A\ s^{-11}$

For all but two of the fits $\chi^2 \leq 1.34$

- Better χ^2 at 55° and 75° if different data sets are renormalized to each other
- No data at $P_T \geq 1.1$ GeV/c at forward and backward angles
- Clear s^{-11} behaviour for last 3 points at 35°

Data consistent with CCR

P.Rossi et al, P.R.L. 94, 012301 (2005)



- Remarkable Test of Quark Counting Rules
- Deuteron Photo-Disintegration $\gamma d \to np$

$$\frac{d\sigma}{dt} = \frac{F(t/s)}{s^{n_{tot}-2}}$$

- $$n_{tot} = 1 + 6 + 3 + 3 = 13$$

Scaling characteristic of
scale-invariant theory at short distances

Conformal symmetry

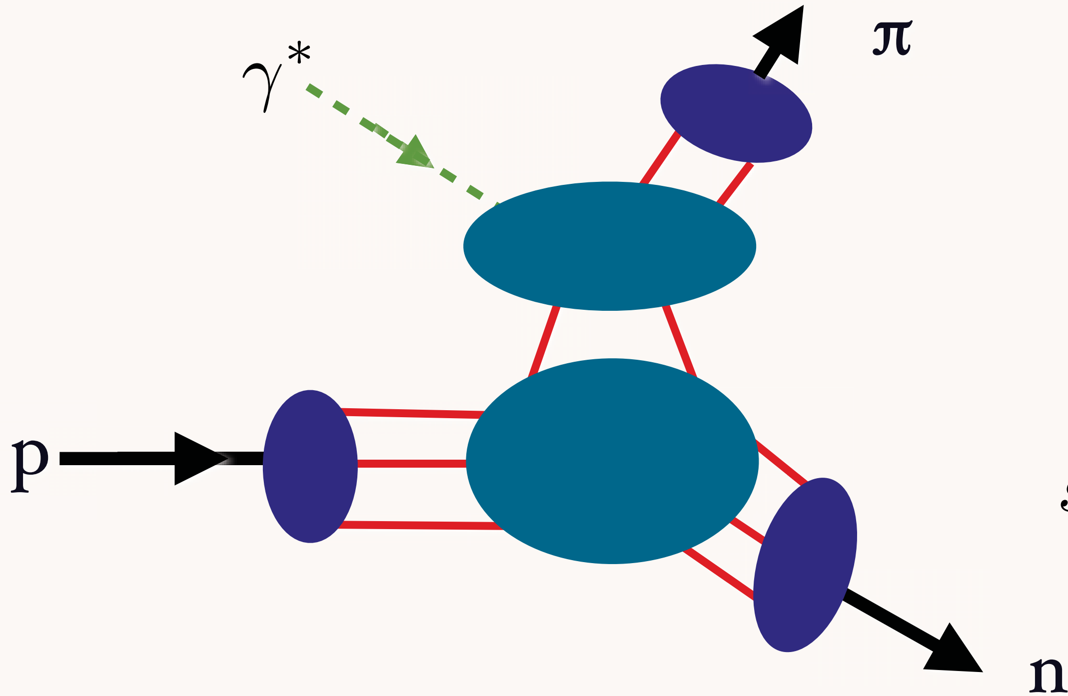
Hidden color: $$\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$$

at high p_T

Ratio predicted to approach 2:5

Exclusive Electroproduction

$$ep \to e'\pi^+ n$$



Hard Reggeon Domain

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t) \beta_R(t)$$

$$\alpha_R(t) \to -1$$ *Reflects elementary exchange of quarks in t-channel*

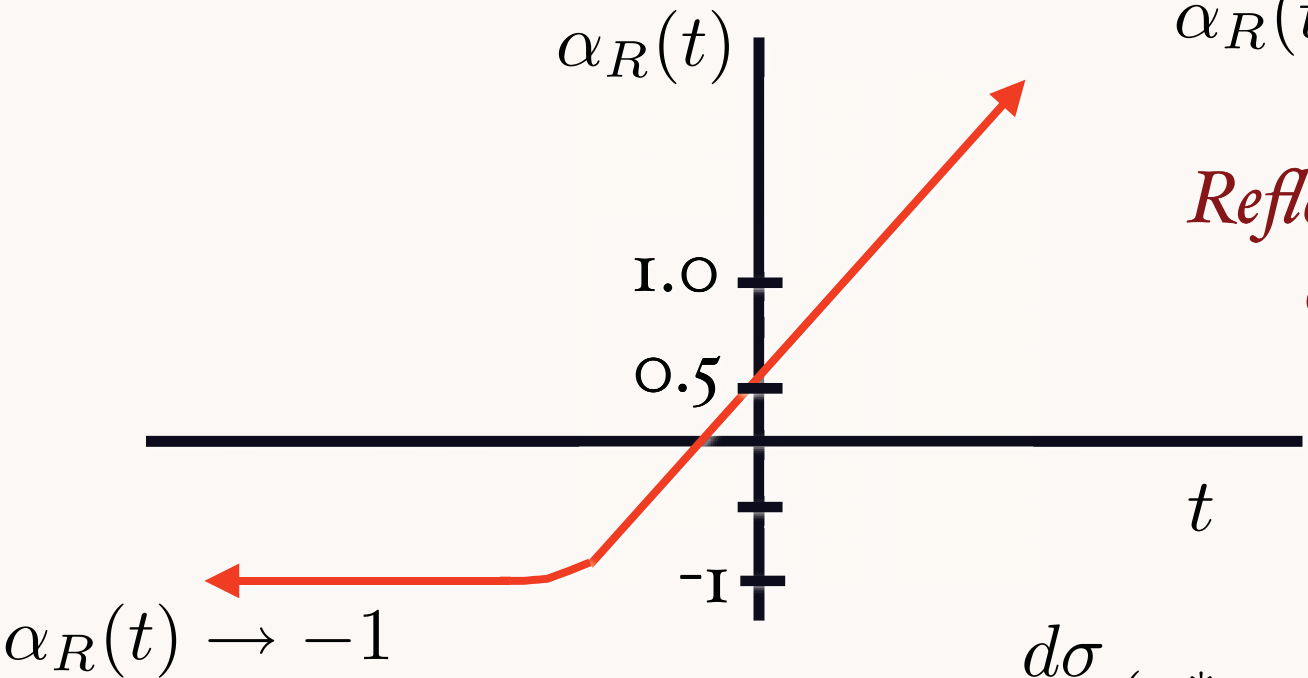
$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^7} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Gunion, Blankenbecler, Savit, sjb

Regge domain

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t) \beta_R(t) \qquad s >> -t, Q^2$$



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

Reflects elementary exchange of quarks in t-channel

$$\beta_R(t) \sim \frac{1}{t^2}$$

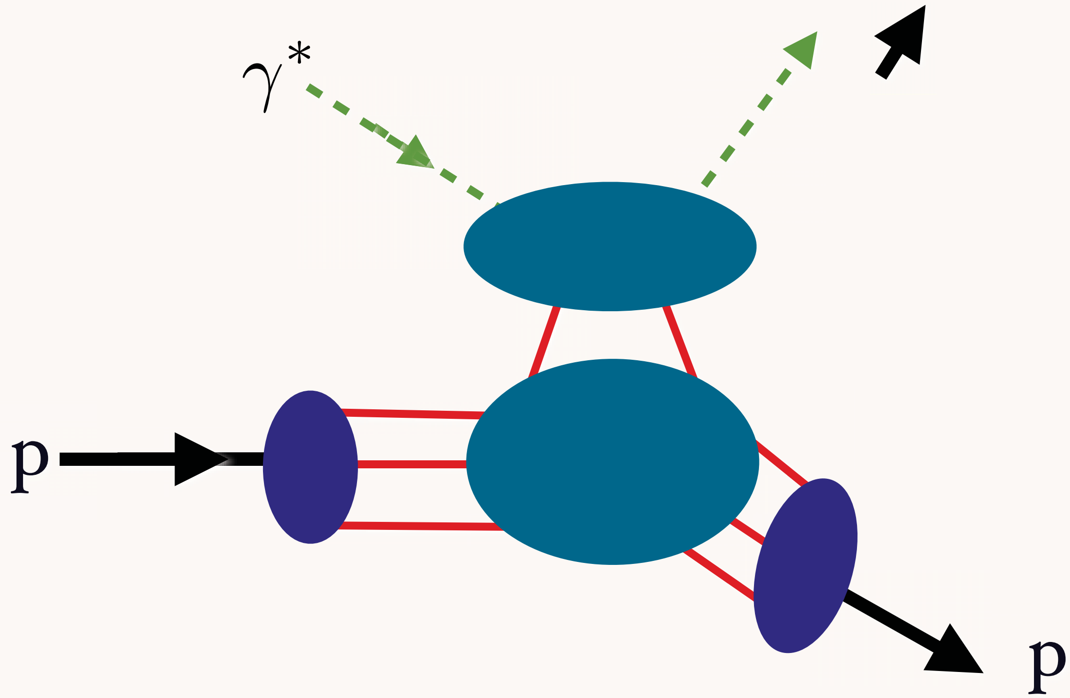
$$\frac{d\sigma}{dt}(\gamma^* p \to \pi^+ n) \to \frac{1}{s^3} \beta_R^2(t)$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^3} \frac{1}{t^4} \sim \frac{1}{s^7} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Fundamental test of QCD

Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p$$



Hard Reggeon Domain

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s^{\alpha}_R(t) \beta_R(t)$$

$$\alpha_R(t) \to 0$$

Reflects elementary coupling of two photons to quarks

$$\beta_R(t) \sim \frac{1}{t^2}$$

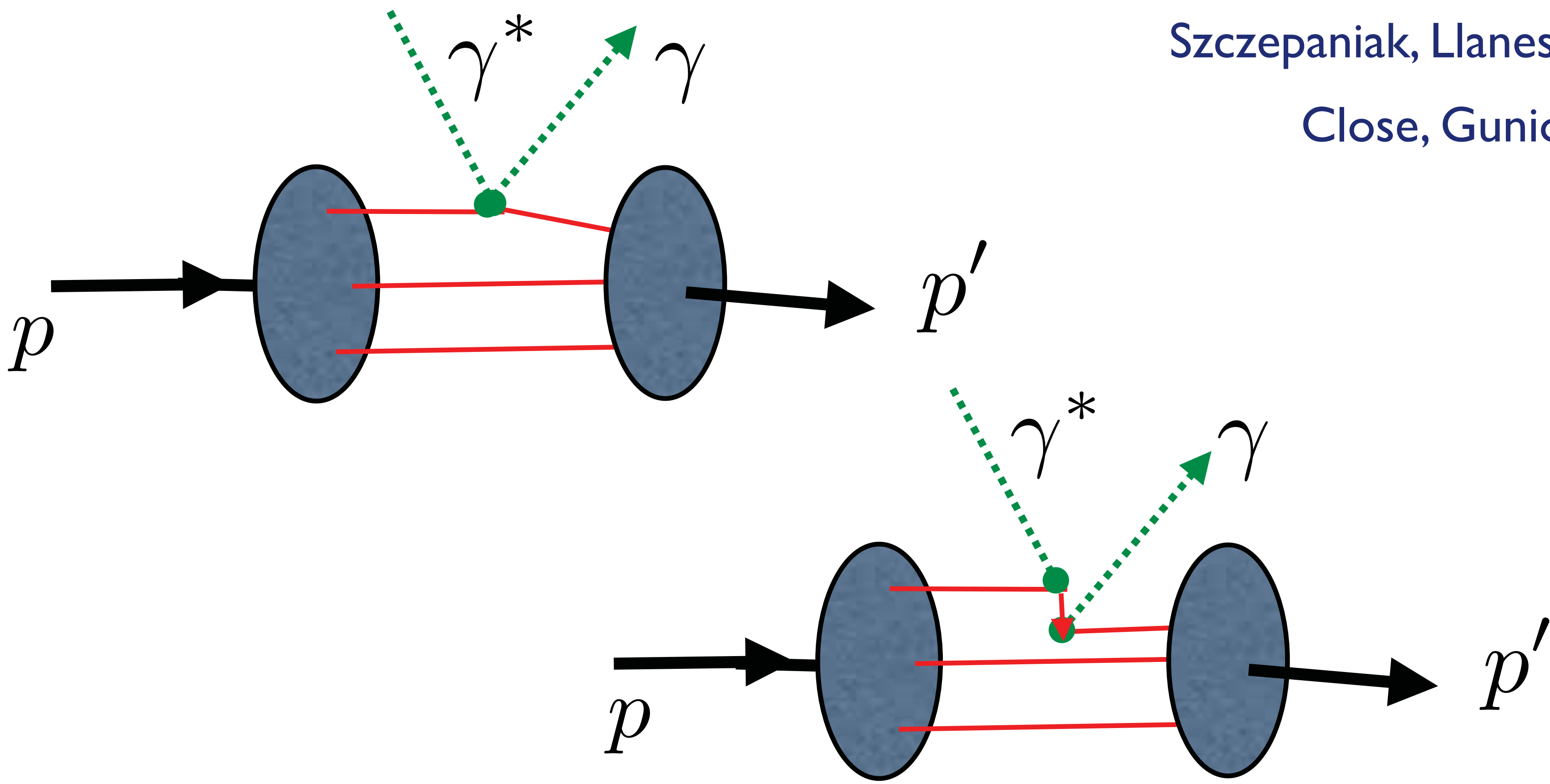
$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\frac{1}{t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

J=0 Fixed Pole Contribution to DVCS

- J=0 fixed pole -- direct test of QCD locality -- from seagull or instantaneous contribution to Feynman propagator

Szczepaniak, Llanes-Estrada, sjb

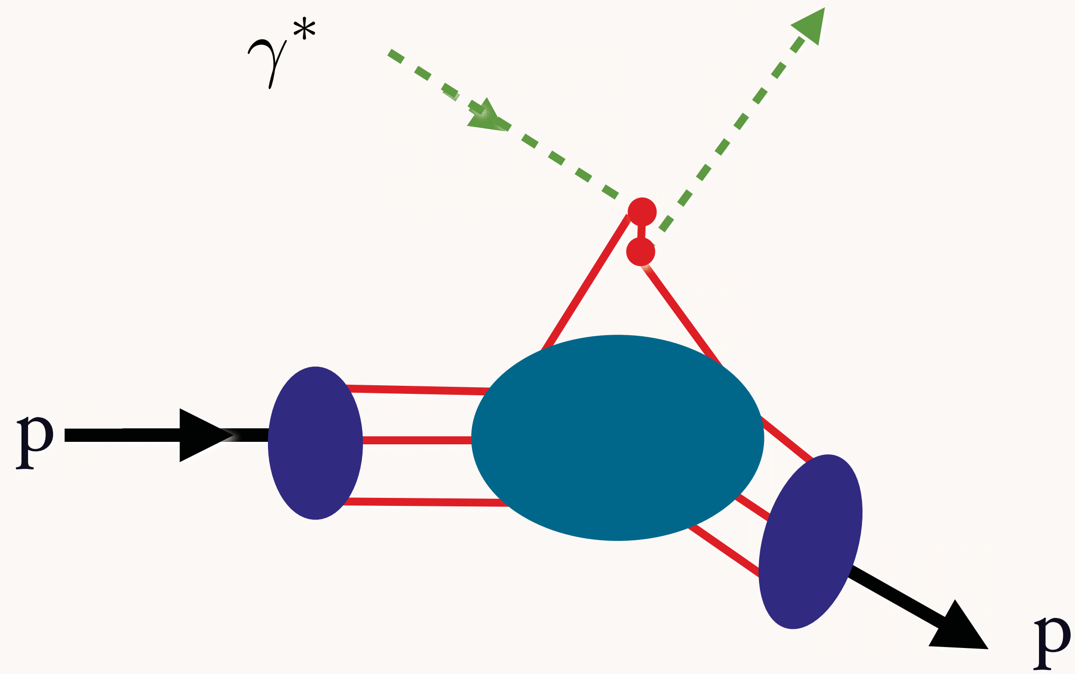
Close, Gunion, sjb



Real amplitude, independent of Q^2 at fixed t

Deeply Virtual Compton Scattering

$$\gamma^* p \to \gamma p$$



Seagull interaction (instantaneous quark exchange or Z-graph)

$$s >> -t, Q^2 >> \Lambda^2_{QCD}$$

Hard Reggeon Domain

$$T(\gamma^*(q)p \to \gamma(k) + p) \sim \epsilon \cdot \epsilon' \sum_R s^{\alpha}_R(t)\beta_R(t)$$

$$\alpha_R(t) \to 0$$

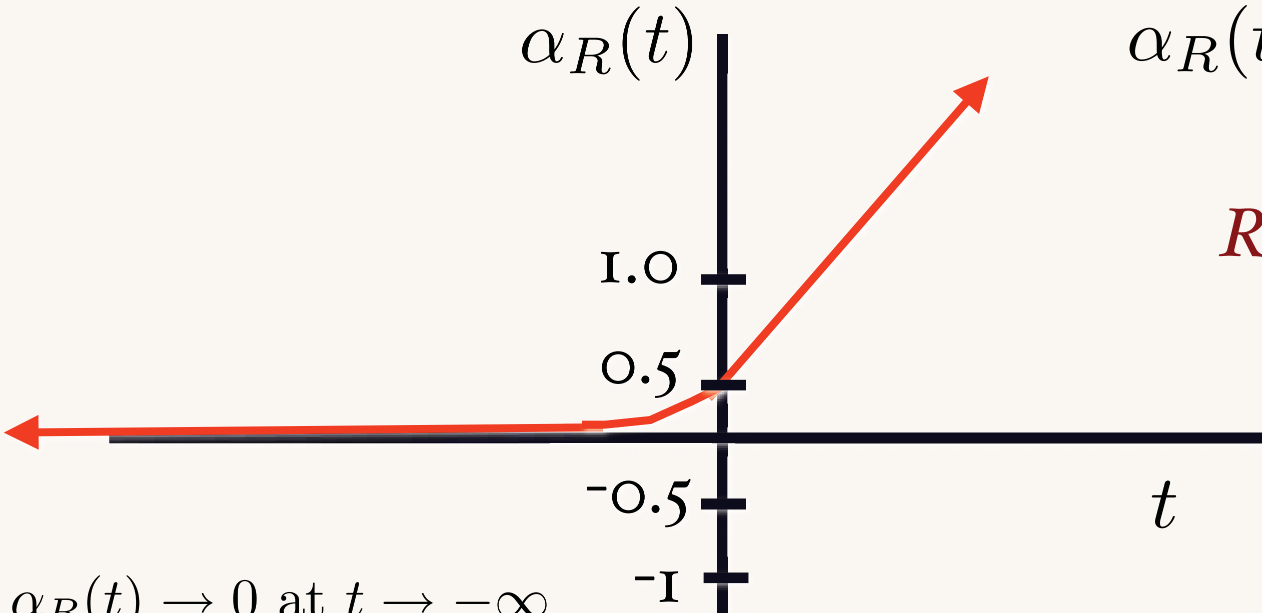
Reflects elementary coupling of two photons to quarks

$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt} \sim \frac{1}{s^2}\frac{1}{t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{Q^2}{s}, \frac{t}{s}$$

Regge domain

$$T(\gamma^* p \to \pi^+ n) \sim \epsilon \cdot p_i \sum_R s_R^{\alpha}(t)\beta_R(t) \qquad s >> -t, Q^2$$



$\alpha_R(t) \to 0$ at $t \to -\infty$

$\alpha_R(t) \to 0$ at $t \to -\infty$

J=0 fixed pole

Reflects elementary coupling of two photons to quarks

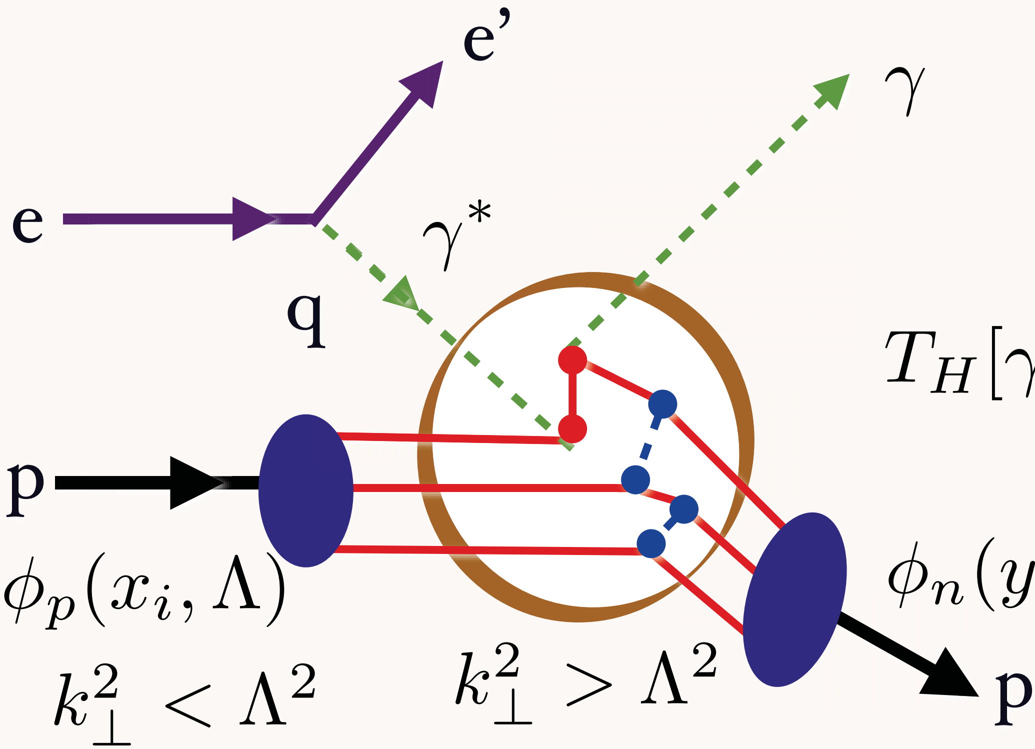
$$\beta_R(t) \sim \frac{1}{t^2}$$

$$\frac{d\sigma}{dt}(\gamma^* p \to \gamma p) \to \frac{1}{s^2}\beta_R^2(t) \sim \frac{1}{s^2 t^4} \sim \frac{1}{s^6} \text{ at fixed } \frac{t}{s}, \frac{Q^2}{s}$$

Fundamental test of QCD

QCD Factorization
DVCS in hard-scattering domain

$$ep \to e'\gamma p$$



$$T_H[\gamma^* + (uud) \to \gamma + (uud)]$$

$$\phi_n(y_i, \Lambda)$$

$$T = \int_0^1 dx \int_0^1 dy \int_0^1 dx\ \phi_p(x,\Lambda) T_H(x,y,z;Q^2,s,t;\Lambda)\phi_n(y,\Lambda)\phi_\pi^+(z,\Lambda)$$

Universal distribution amplitudes. Renormalization Group Invariance:
The factorization scale Λ is arbitrary. The renormalization scale is unambiguous

Novel Feature of DVCS

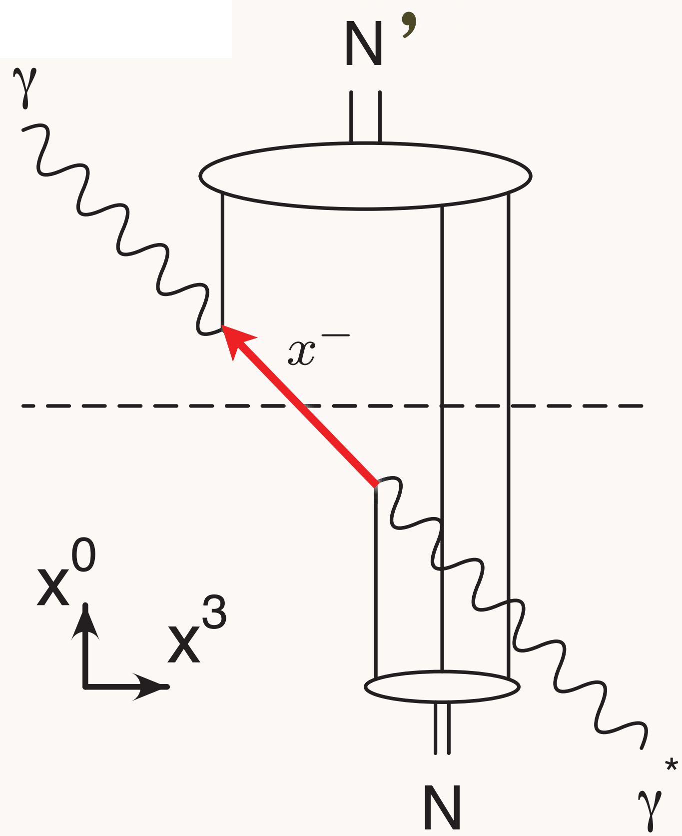
- J=0 fixed pole -- direct test of QCD locality -- from seagull or instantaneous contribution to Feynman propagator
- Amplitude independent of Q2 at fixed t
- <1/x> Moment
- Dominance of Handbag diagram?
- Breakdown at large t ; effects of FSI in DIS, diffractive intermediate states
- Timelike studies at BaBar/Belle and GSI FAIR
- BH/Compton interference from charge asymmetry

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

Space-time picture of DVCS

P. Hoyer

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



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

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

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

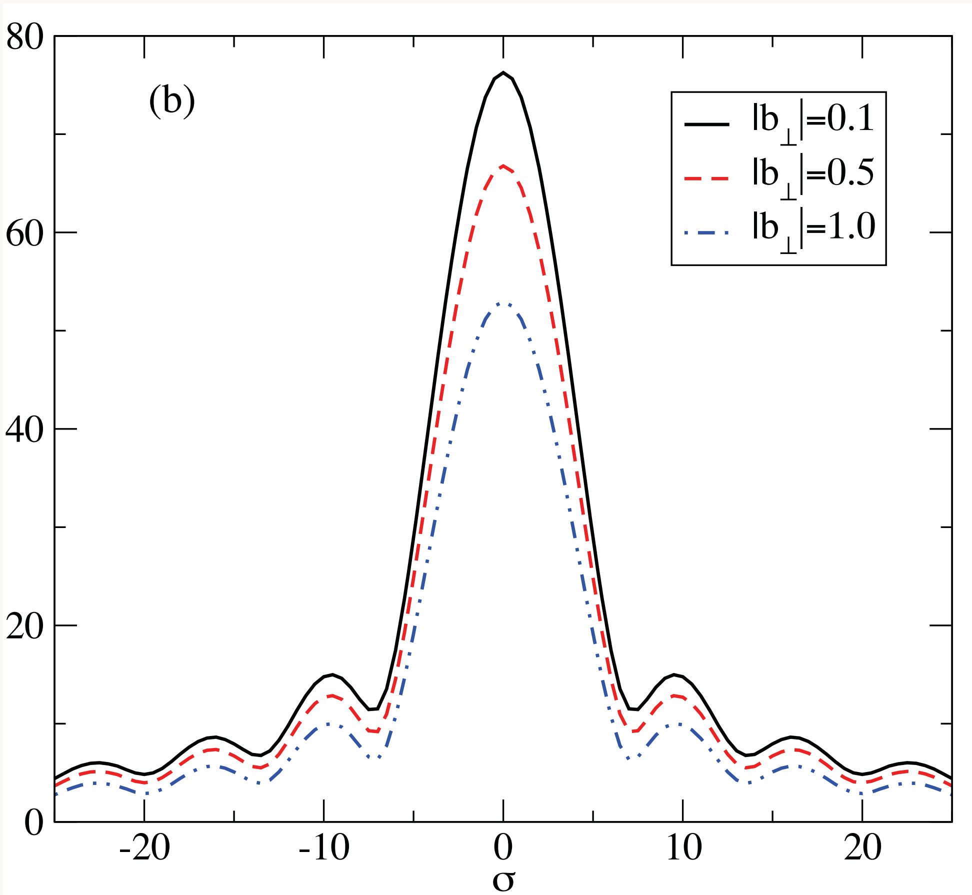
S. J. Brodsky[a], D. Chakrabarti[b], A. Harindranath[c], A. Mukherjee[d], J. P. Vary[e,a,f]

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

Hadron Optics

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

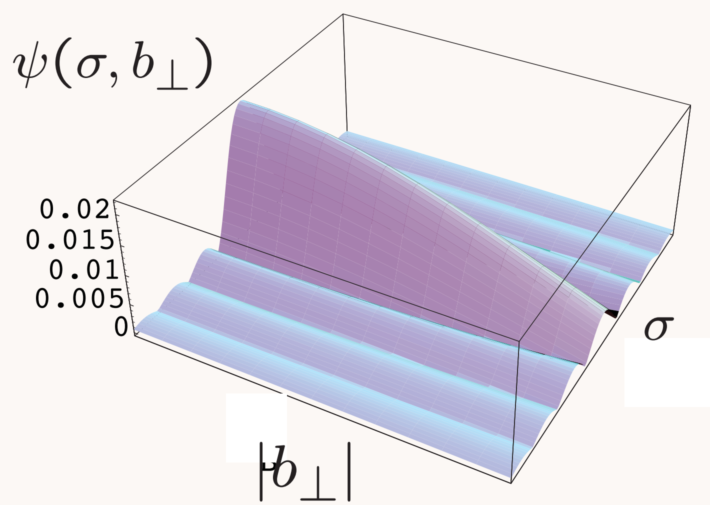
$$\sigma = \frac{1}{2} x^- P^+ \quad \xi = \frac{Q^2}{2p.q}$$



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

DVCS Amplitude using holographic QCD meson LFWF

$$\Lambda_{QCD} = 0.32$$



Spatial Structure of DVCS

The Fourier transform of the DVCS amplitude with respect to the momentum transfer and the skewness parameter can provide a three-dimensional spatial picture of the proton at fixed light-front time. Measurements of the DVCS cross sections with specific proton and photon polarizations can thus provide comprehensive probes of the spin as well as spatial structure of the proton at the most fundamental level of QCD.

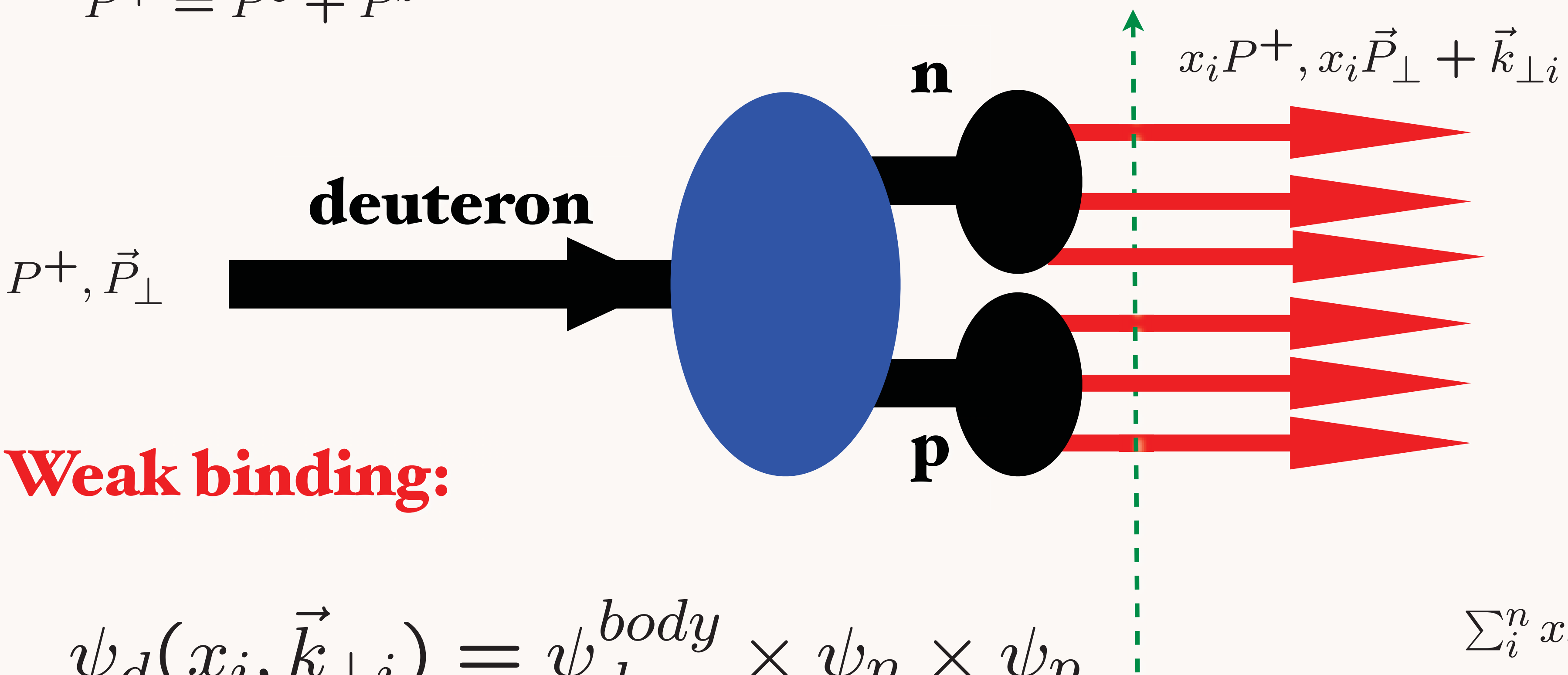
Properties of Hard Exclusive Reactions

- Dimensional Counting Rules at fixed CM angle
- Hadron Helicity Conservation
- Color Transparency
- Hidden color
- s >> -t >> Λ_{QCD}: Reggeons have negative-integer intercepts at large -t
- J=0 Fixed pole in DVCS
- Quark interchange
- Renormalization group invariance
- No renormalization scale ambiguity
- Exclusive inclusive connection with spectator counting rules
- Diffractive reactions from pomeron, Reggeon, odderon

Deuteron Light-Front Wavefunction

Fixed $\tau = t + z/c$

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



Weak binding:

$$\psi_d(x_i, \vec{k}_{\perp i}) = \psi_d^{body} \times \psi_n \times \psi_p$$

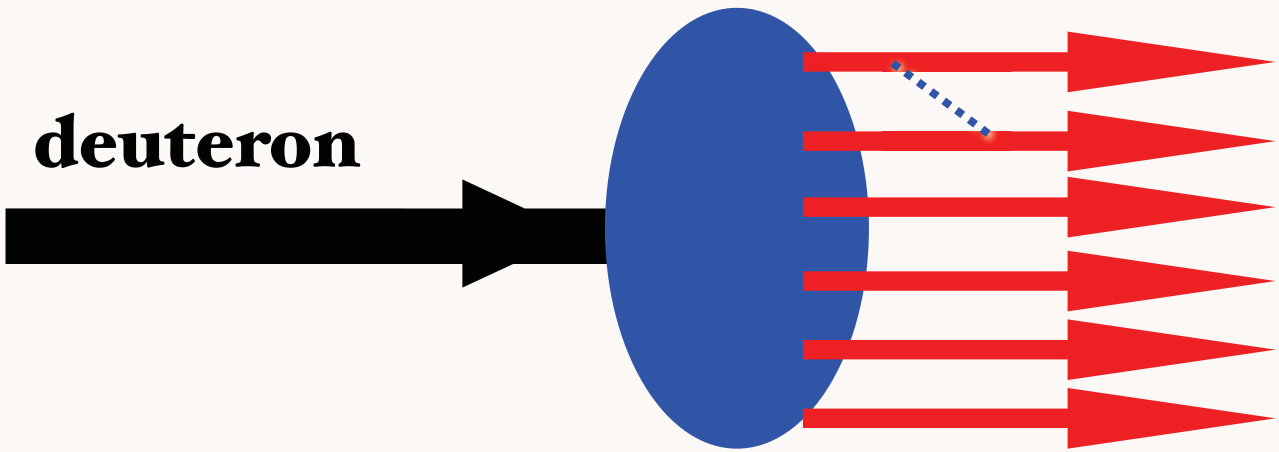
$\sum_i^n x_i = 1$

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

Two color-singlet combinations of three 3_C

Evolution of 5 color-singlet Fock states

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



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

$\sum_i^n x_i = 1$

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

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Hidden Color of Deuteron

Deuteron six-quark state has five color - singlet configurations, only one of which is n-p.

Asymptotic Solution has Expansion

$$\psi_{[6]\{33\}} = \left(\frac{1}{9}\right)^{1/2} \psi_{NN} + \left(\frac{4}{45}\right)^{1/2} \psi_{\Delta\Delta} + \left(\frac{4}{5}\right)^{1/2} \psi_{CC}$$

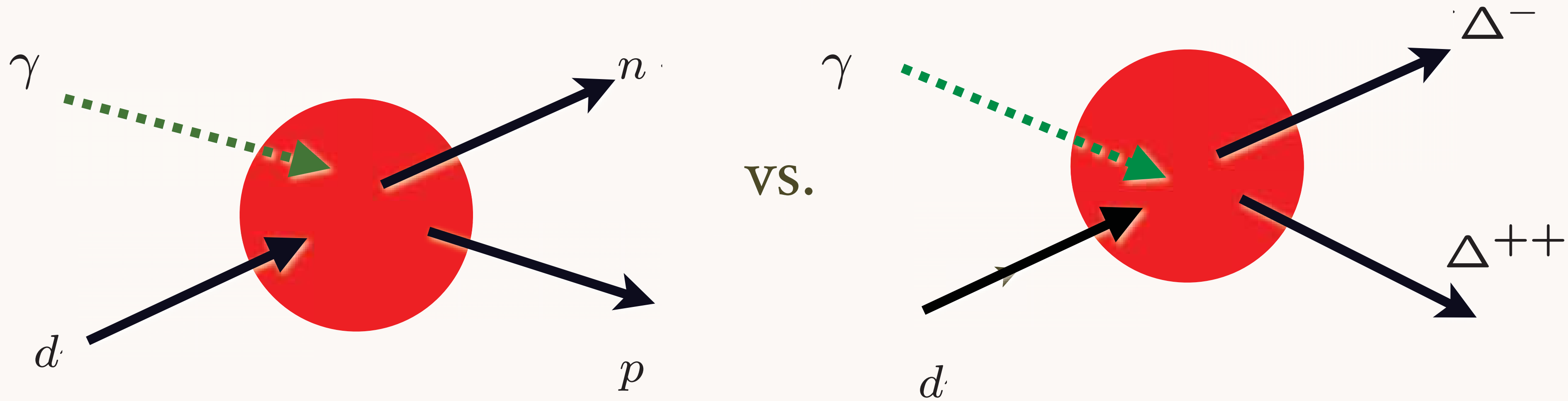
Look for strong transition to Delta-Delta

Test of Hidden Color in Deuteron Photodisintegration

$$R = \frac{\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{--})}{\frac{d\sigma}{dt}(\gamma d \to pn)}$$

Ratio predicted to approach 2:5

Ratio should grow with transverse momentum as the hidden color component of the deuteron grows in strength.



Possible contribution from pion charge exchange at small t.

Single-spin asymmetries

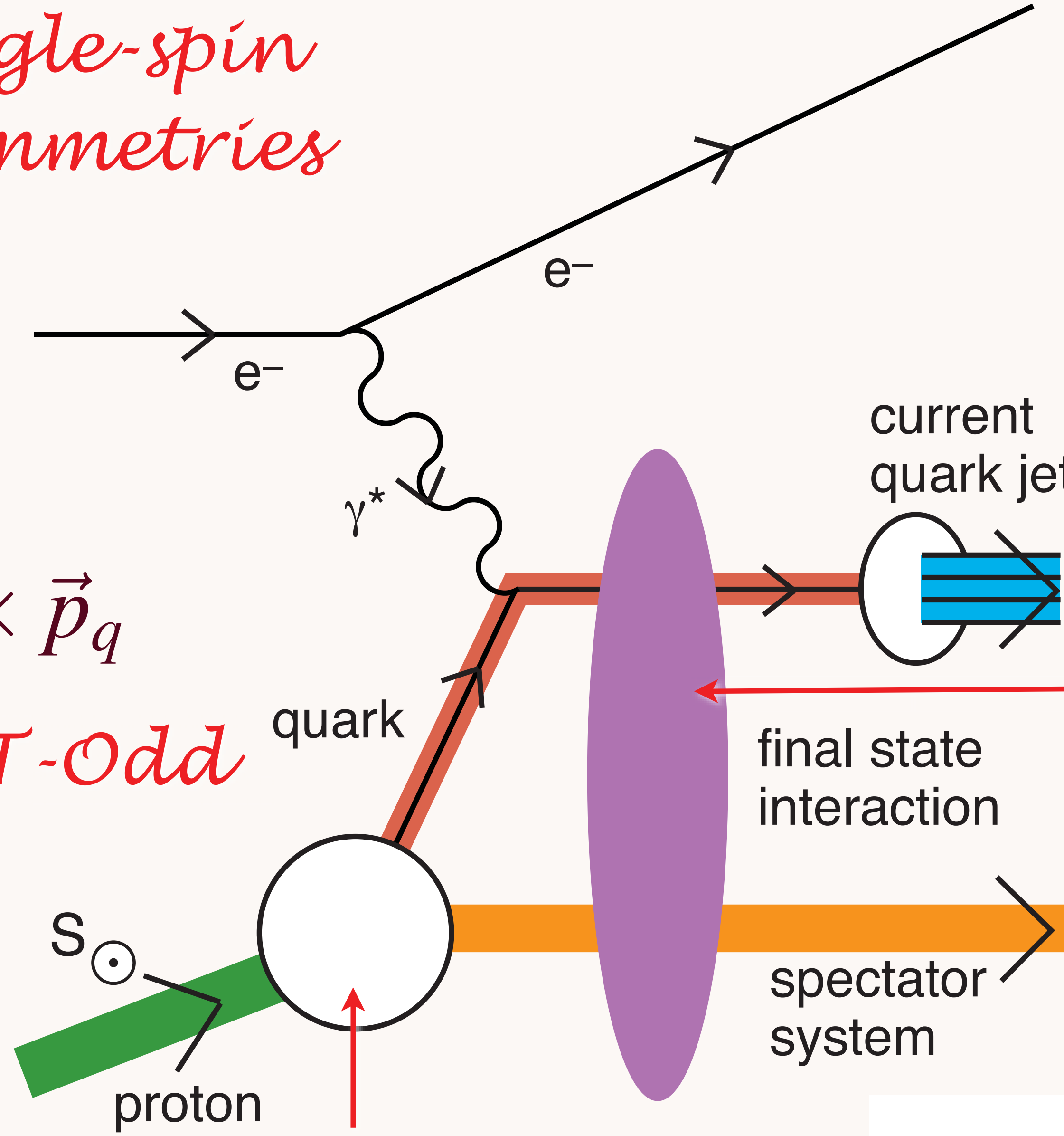
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

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

Pseudo-T-Odd



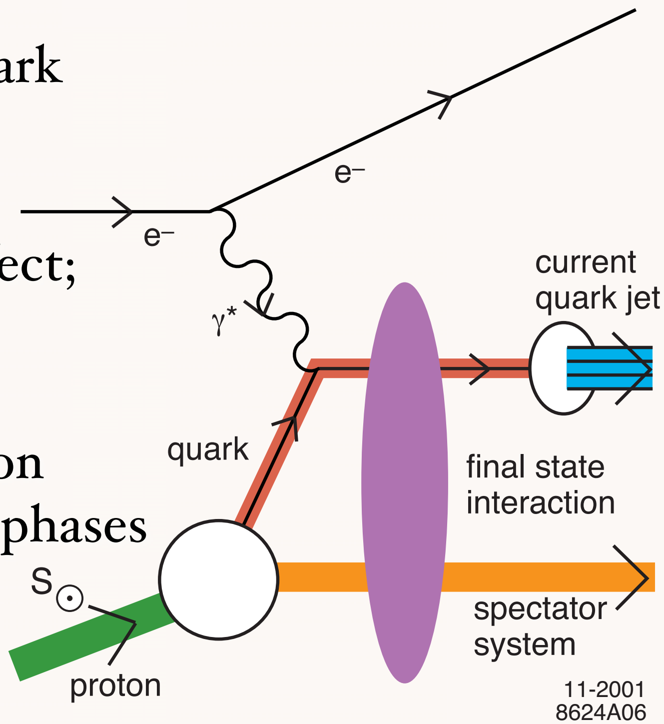
QCD S- and P- Coulomb Phases --Wilson Line

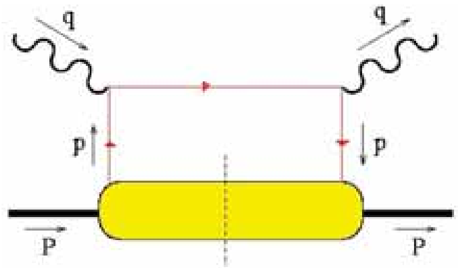
Light-Front Wavefunction S and P-Waves

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

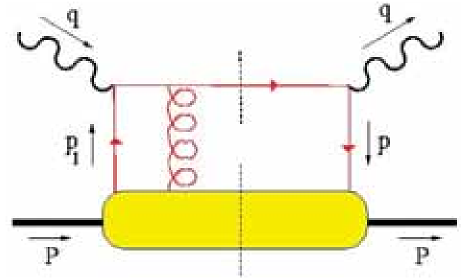
$$\mathbf{i}\, \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

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





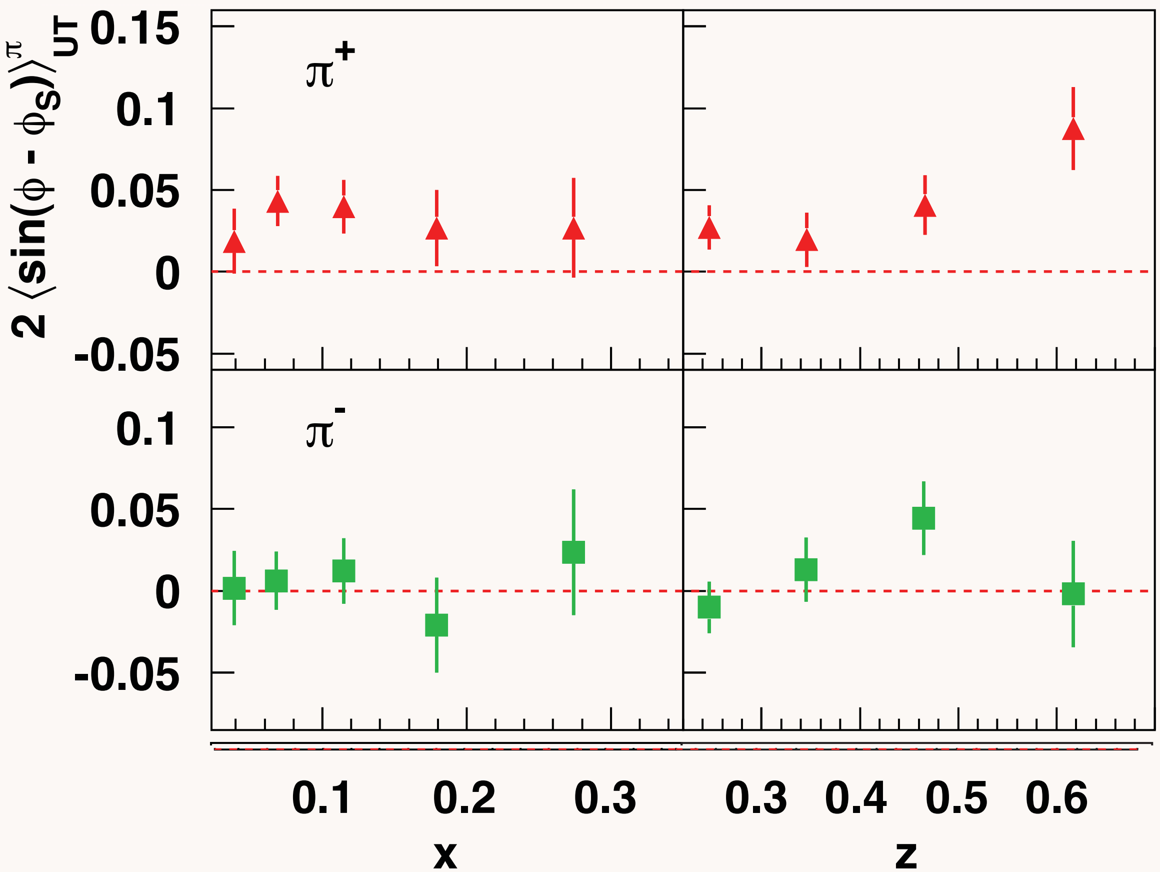
can interfere with



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

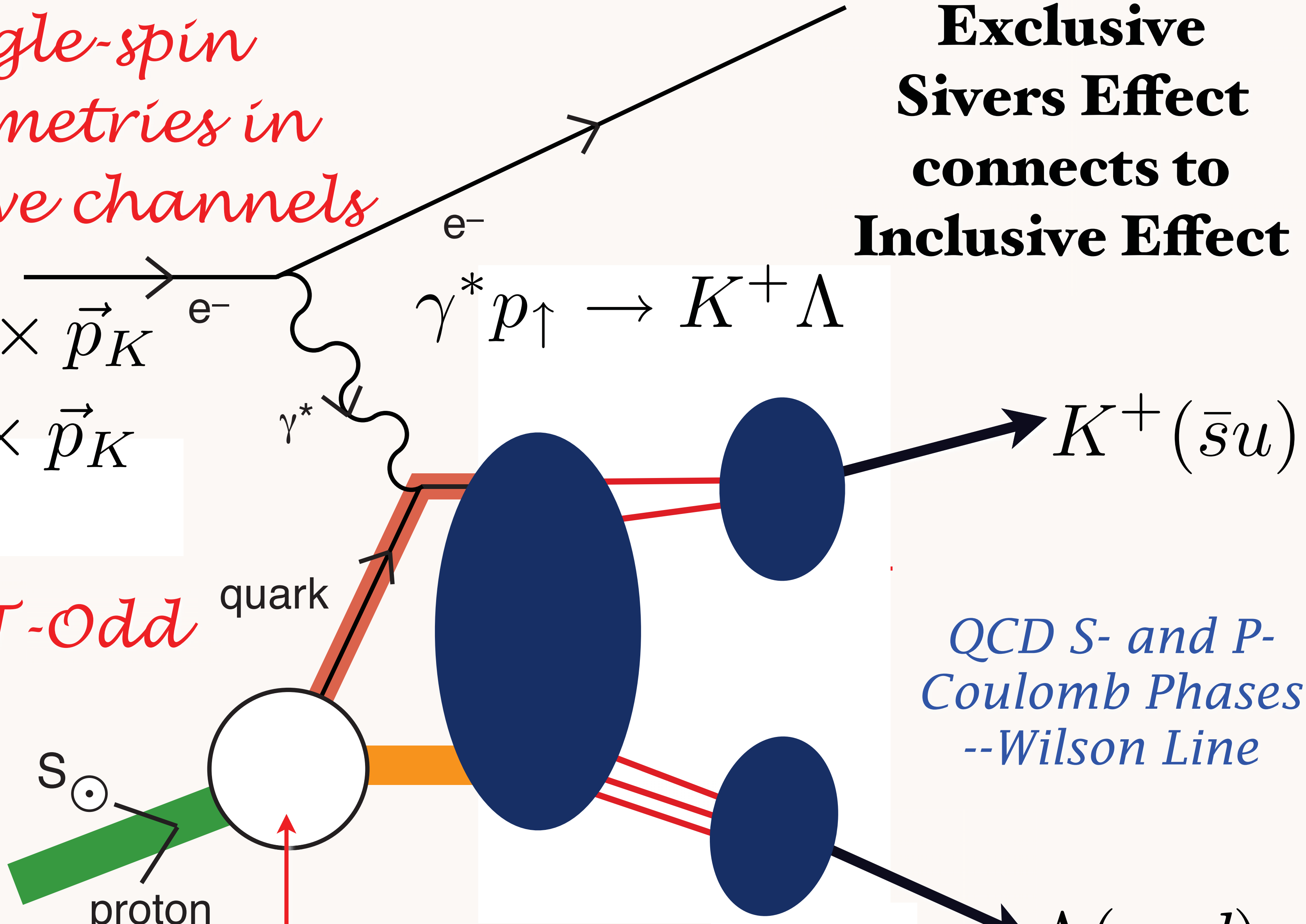
Single-spin asymmetries in exclusive channels

Exclusive Sivers Effect connects to Inclusive Effect

$$i\vec{S}_\Lambda \cdot \vec{q} \times \vec{p}_K$$

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

Pseudo-T-Odd



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

Light-Front Wavefunction S and P- Waves

Perturbative QCD Analysis of Structure Functions at x ~ 1

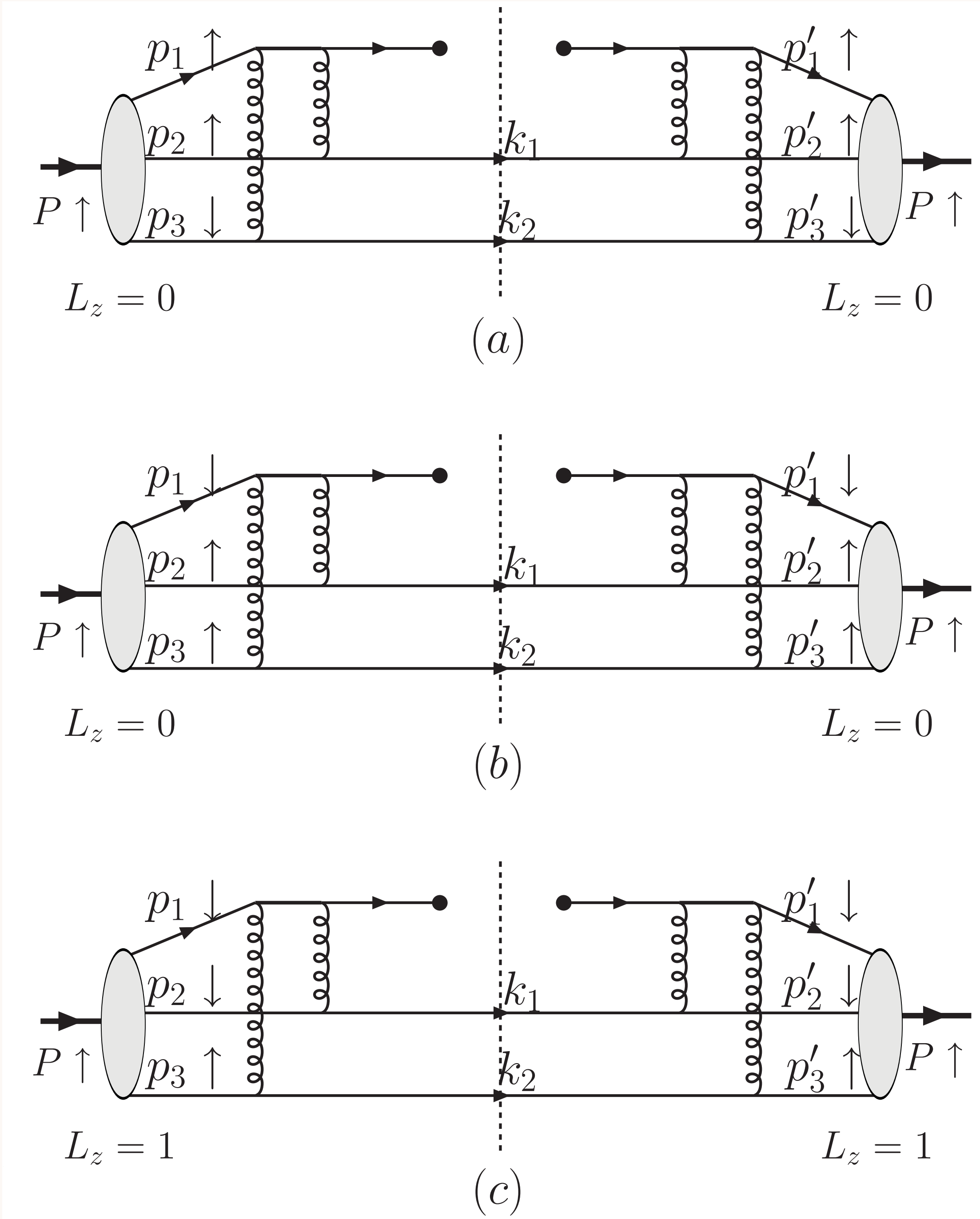
- Struck quark far off-shell at large x $k_F^2 \simeq -\frac{k_\perp^2}{1-x}$
- Lowest-order connected PQCD diagrams dominate
- Spectator counting rules $(1-x)^{2n_s - 1 + 2\Delta S_z}$
- Helicity retention at large x
- Exclusive-Inclusive Connection

$$q^{+}(x) \propto (1-x)^3$$

$$q^{-}(x) \propto (1-x)^5 \log^2(1-x)$$

From nonzero orbital angular momentum

Avakian, sjb, Deur, Yuan



Features of Hard Exclusive Processes in PQCD

Lepage, sjb; Duncan, Mueller

- Factorization of perturbative hard scattering subprocess amplitude and nonperturbative distribution amplitudes $M = \int T_H \times \Pi \phi_i$
- Dimensional counting rules reflect conformal invariance: $M \sim \frac{f(\theta_{CM})}{Q^{N_{tot}-4}}$
- Hadron helicity conservation: $\sum_{initial} \lambda_i^H = \sum_{final} \lambda_j^H$
- Color transparency Mueller, sjb;
- Hidden color Ji, Lepage, sjb;
- Evolution of Distribution Amplitudes

Lepage, sjb; Efremov, Radyushkin

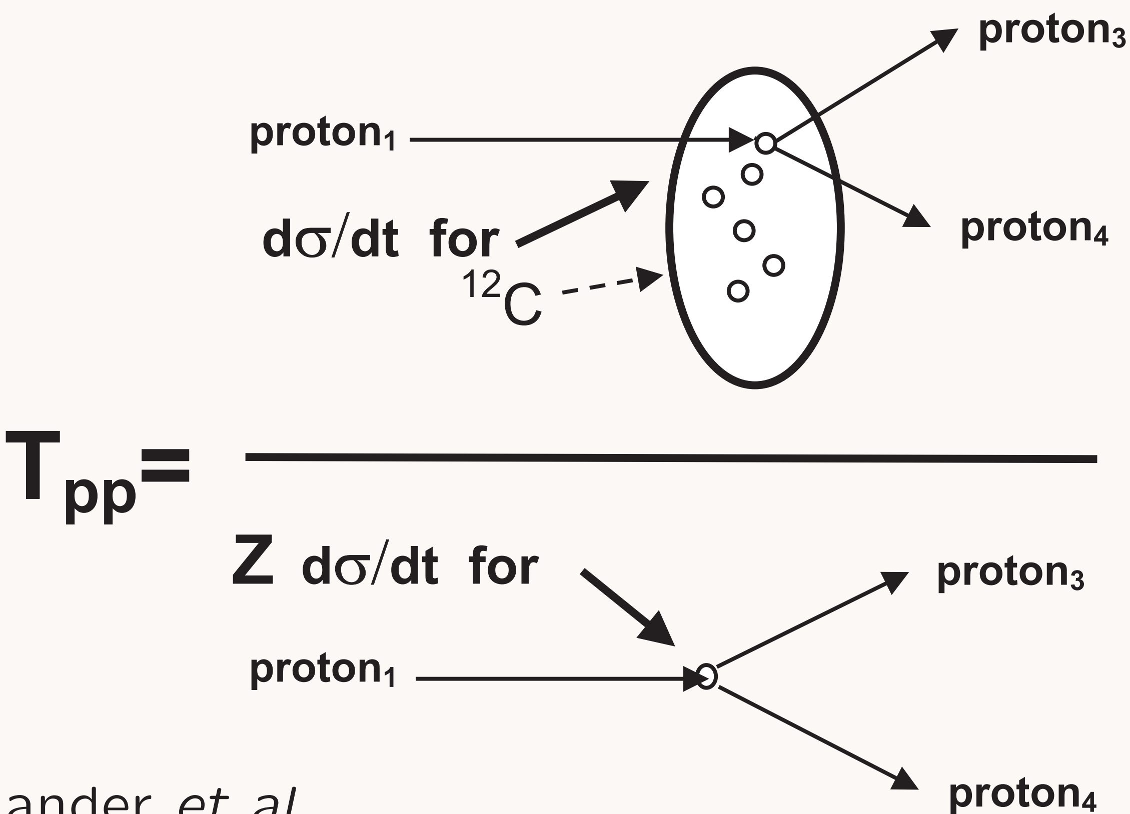
Color Transparency

Bertsch, Gunion, Goldhaber, sjb

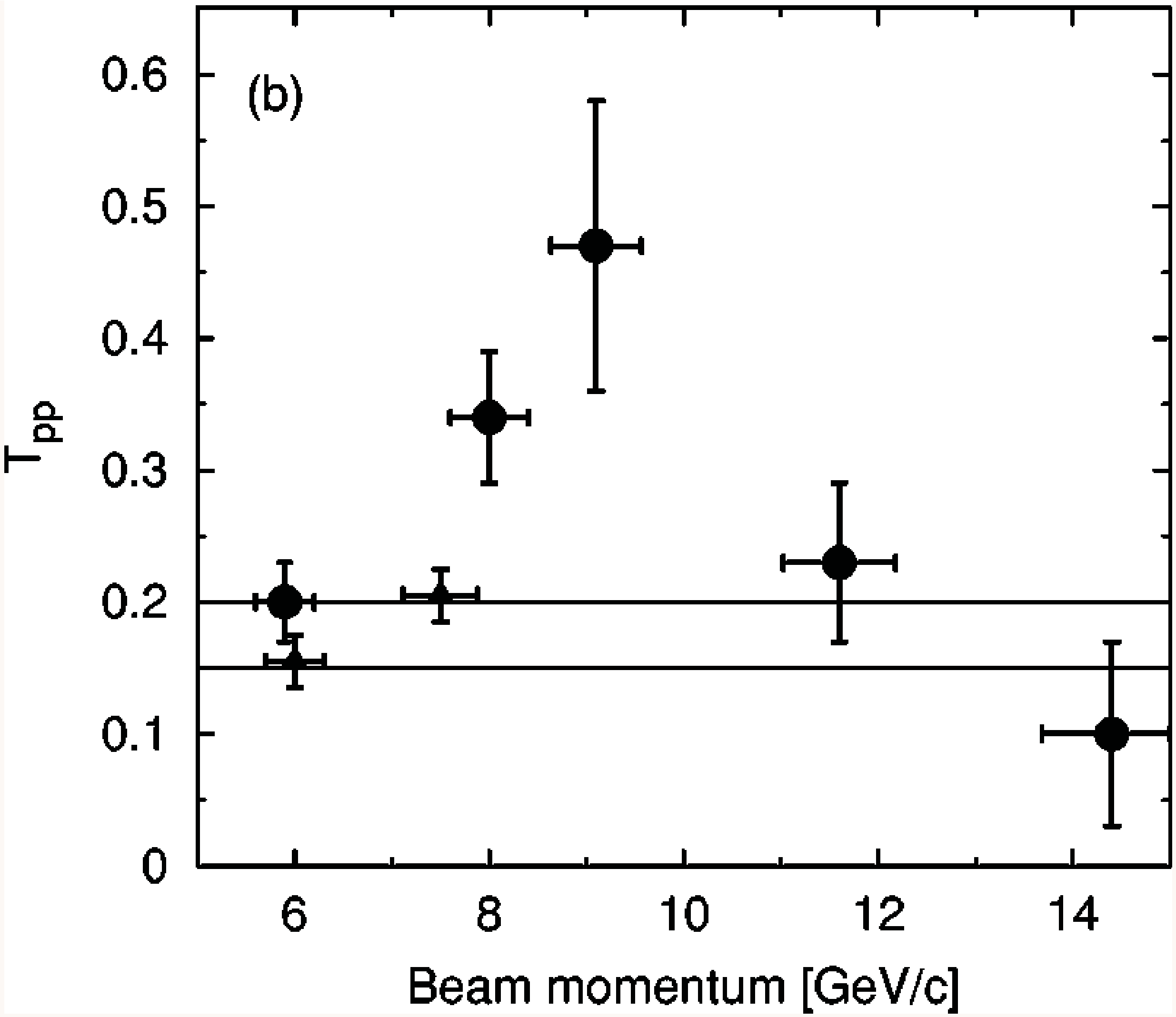
A. H. Mueller, sjb

- Fundamental test of gauge theory in hadron physics
- Small color dipole moments interact weakly in nuclei
- Complete coherence at high energies
- Clear Demonstration of CT from Diffractive Di-Jets

Color Transparency Ratio



J. L. S. Aclander *et al.*,
"Nuclear transparency in $\theta_{CM} = 90^0$ quasielastic $A(p, 2p)$ reactions,"
Phys. Rev. C **70**, 015208 (2004), [arXiv:nucl-ex/0405025].

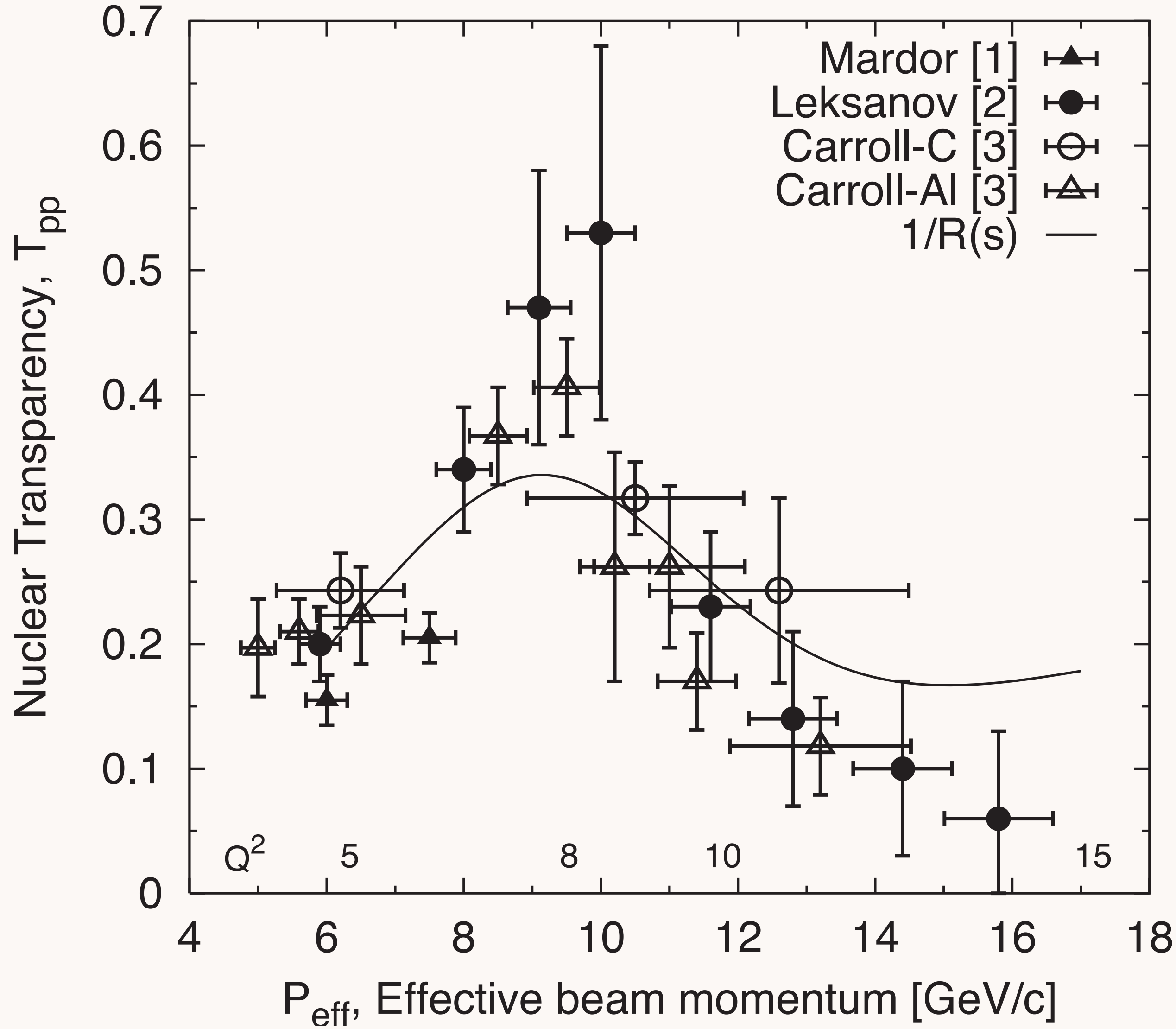


PHYSICAL REVIEW C **70**, 015208 (2004)

Nuclear transparency in $90^{\circ}_{\text{c.m.}}$ quasielastic $A(p,2p)$ reactions

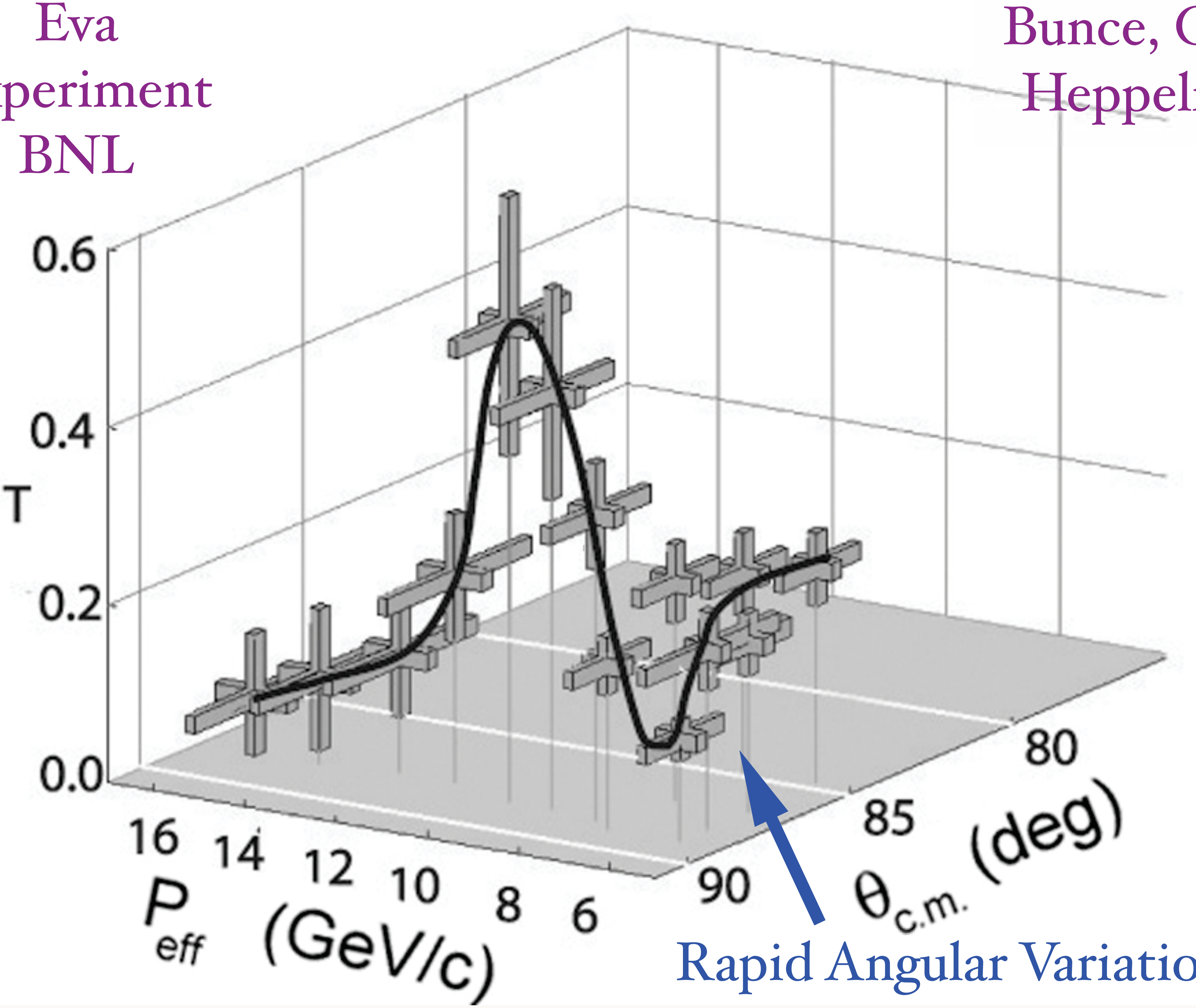
J. Aclander,[7] J. Alster,[7] G. Asryan,[1,*] Y. Averiche,[5] D. S. Barton,[1] V. Baturin,[2,†] N. Buktoyarova,[1,†] G. Bunce,[1]
A. S. Carroll,[1,‡] N. Christensen,[3,§] H. Courant,[3] S. Durrant,[2] G. Fang,[3] K. Gabriel,[2] S. Gushue,[1] K. J. Heller,[3] S. Heppelmann,[2]
I. Kosonovsky,[7] A. Leksanov,[2] Y. I. Makdisi,[1] A. Malki,[7] I. Mardor,[7] Y. Mardor,[7] M. L. Marshak,[3] D. Martel,[4]
E. Minina,[2] E. Minor,[2] I. Navon,[7] H. Nicholson,[8] A. Ogawa,[2] Y. Panebratsev,[5] E. Piasetzky,[7] T. Roser,[1] J. J. Russell,[4]
A. Schetkovsky,[2,†] S. Shimanskiy,[5] M. A. Shupe,[3,∥] S. Sutton,[8] M. Tanaka,[1,¶] A. Tang,[6] I. Tsetkov,[5] J. Watson,[6] C. White,[3]
J-Y. Wu,[2] and D. Zhalov[2]

Color Transparency fails when A_{nn} is large



Eva Experiment BNL

Bunce, Carroll, Heppelman...



Rapid Angular Variation!

Features of Light-Front Formalism

- *Hidden Color* Nuclear Wavefunction
- *Color Transparency, Opaqueness*
- *Intrinsic glue, sea quarks, intrinsic charm*
- Simple proof of Factorization theorems for hard processes (Lepage, sjb)
- *Direct mapping to AdS/CFT* (de Teramond, sjb)
- New Effective LF Equations (de Teramond, sjb)
- Light-Front Amplitude Generator

Light-Front Wavefunctions

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

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

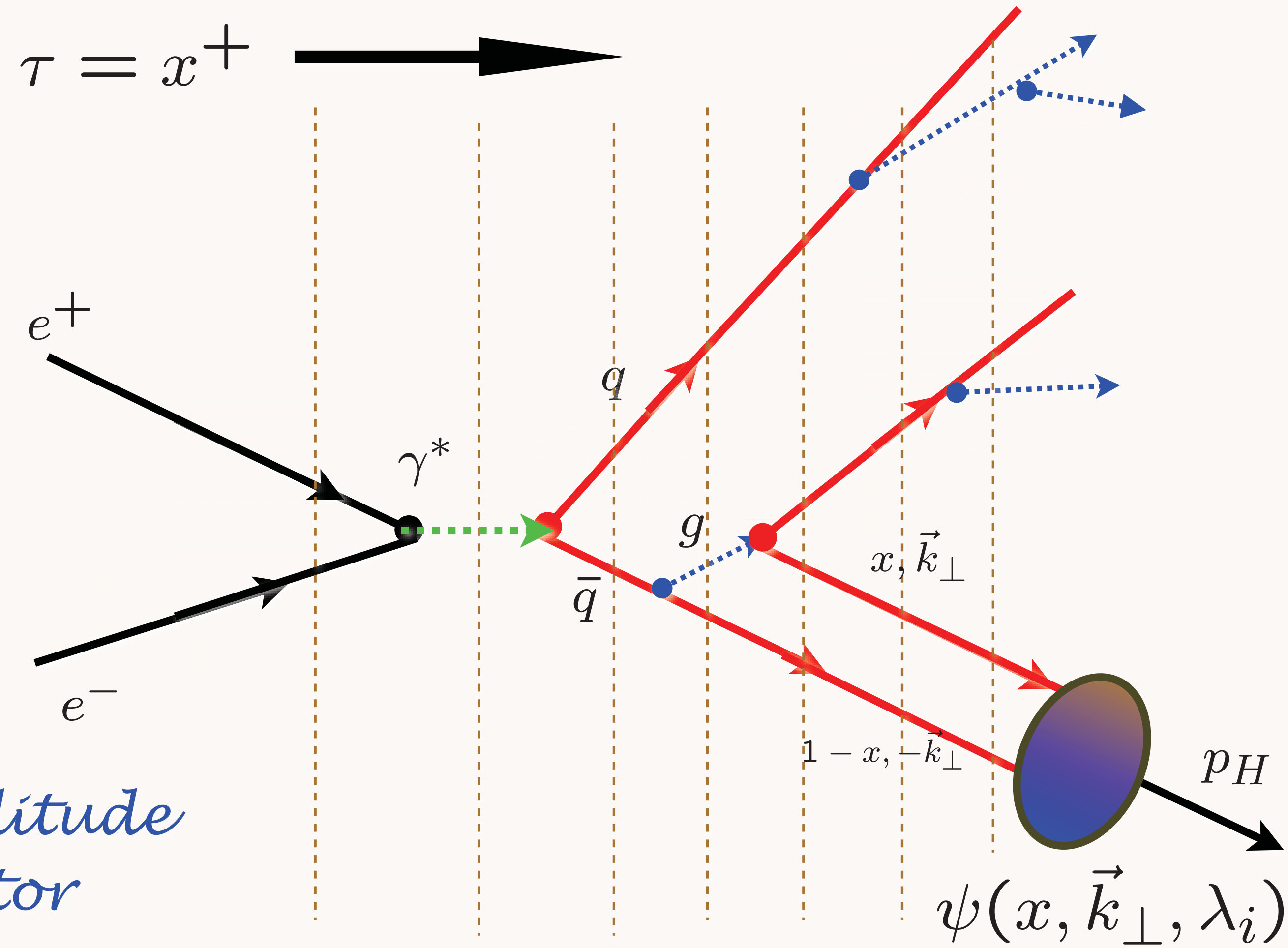
$$x_i = \frac{k_i^+}{P^+}$$

Invariant under boosts. Independent of P^μ

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

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

Hadronization at the Amplitude Level



Relativistic Anti-hydrogen production

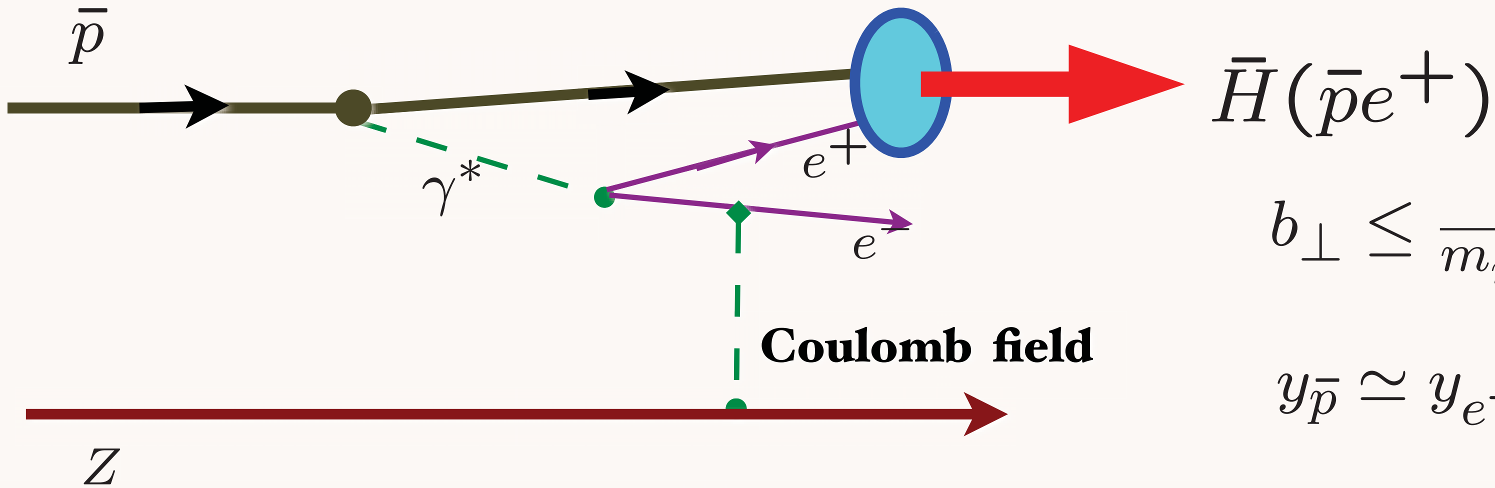
Event amplitude generator

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

Formation of Relativistic Anti-Hydrogen

Measured at CERN-LEAR and FermiLab

Munger, Schmidt, sjb



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

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

Coalescence of off-shell co-moving positron and antiproton

Wavefunction maximal at small impact separation and equal rapidity

"Hadronization" at the Amplitude Level

Novel EIC Topics

- DVCS, DVMS, Hard Exclusive Processes at the Amplitude Level
- Diffractive DIS
- Hidden Color in Deuteron
- $x > 1$ in Nuclei
- Shadowing, antishadowing, EMC
- Jet Energy Loss
- Proton, Nucleus Fragmentation

Novel EIC Topics

- Color Transparency in Hard Exclusive Processes
- Intrinsic Charm, Bottom and high x
- Heavy Hadron Studies; Nuclear Dependence
- Structure functions at high x; Quenching of DGLAP
- Pion, Kaon Structure Function
- Coulomb Dissociation of Proton to Jets

Novel EIC Topics

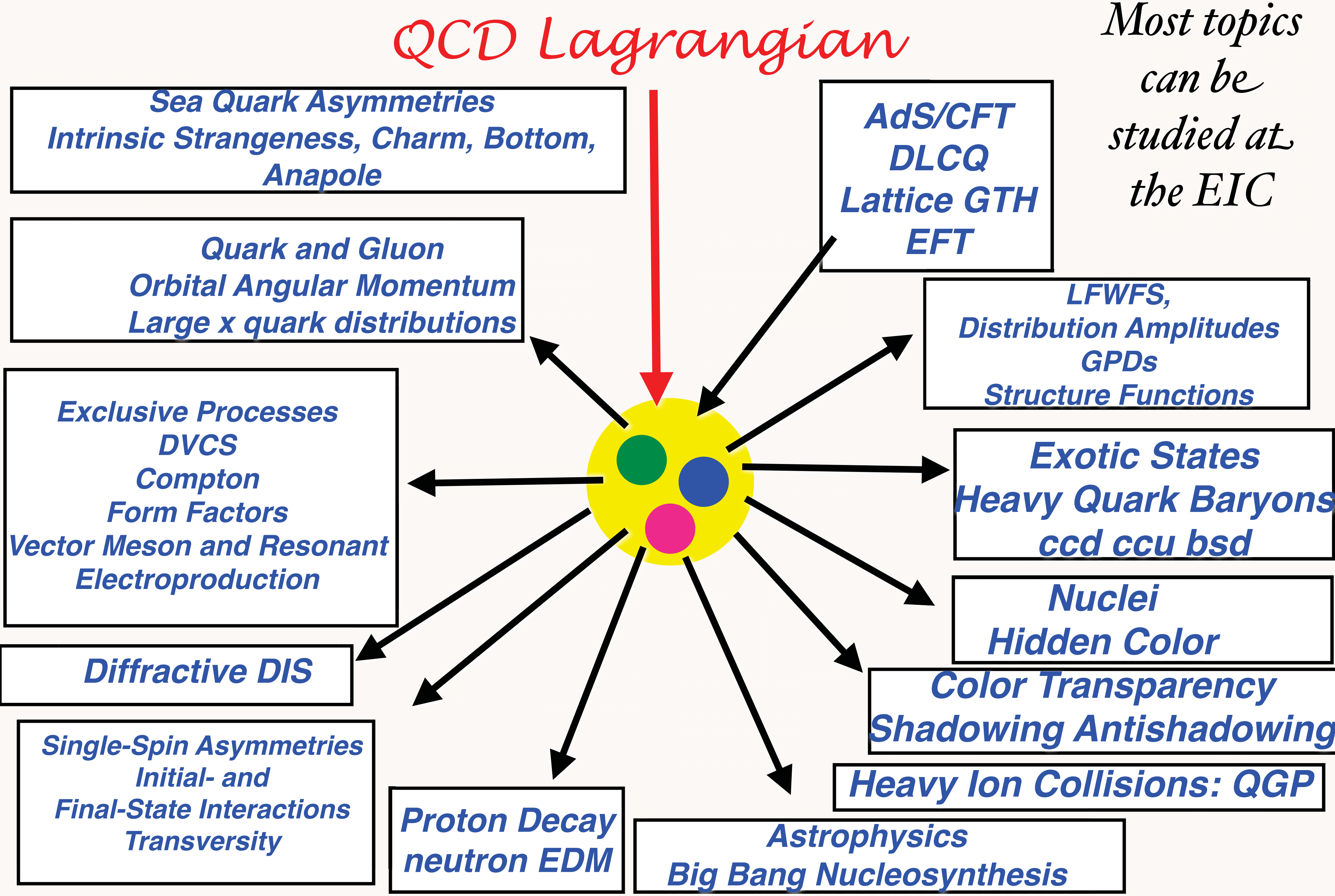
- Hard Photon Inclusive production
- Bjorken Sum Rule, Generalized Crewther Relation
- Exclusive-Inclusive Connection
- Higher Twist
- Single Spin Asymmetries; Jet correlations
- Neutral and Charge Current Studies; NuTeV anomaly

- Although we know the QCD Lagrangian, we have only begun to understand its remarkable properties and features.

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

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

—Mark Twain


QCD Lagrangian
Most topics can be studied at the EIC
Sea Quark Asymmetries
Intrinsic Strangeness, Charm, Bottom, Anapole
AdS/CFT
DLCQ
Lattice GTH
EFT
Quark and Gluon
Orbital Angular Momentum
Large x quark distributions
LFWFS,
Distribution Amplitudes
GPDs
Structure Functions
Exclusive Processes
DVCS
Compton
Form Factors
Vector Meson and Resonant Electroproduction
Exotic States
Heavy Quark Baryons
ccd ccu bsd
Nuclei
Hidden Color
Diffractive DIS
Color Transparency
Shadowing Antishadowing
Single-Spin Asymmetries
Initial- and
Final-State Interactions
Transversity
Heavy Ion Collisions: QGP
Proton Decay
neutron EDM
Astrophysics
Big Bang Nucleosynthesis