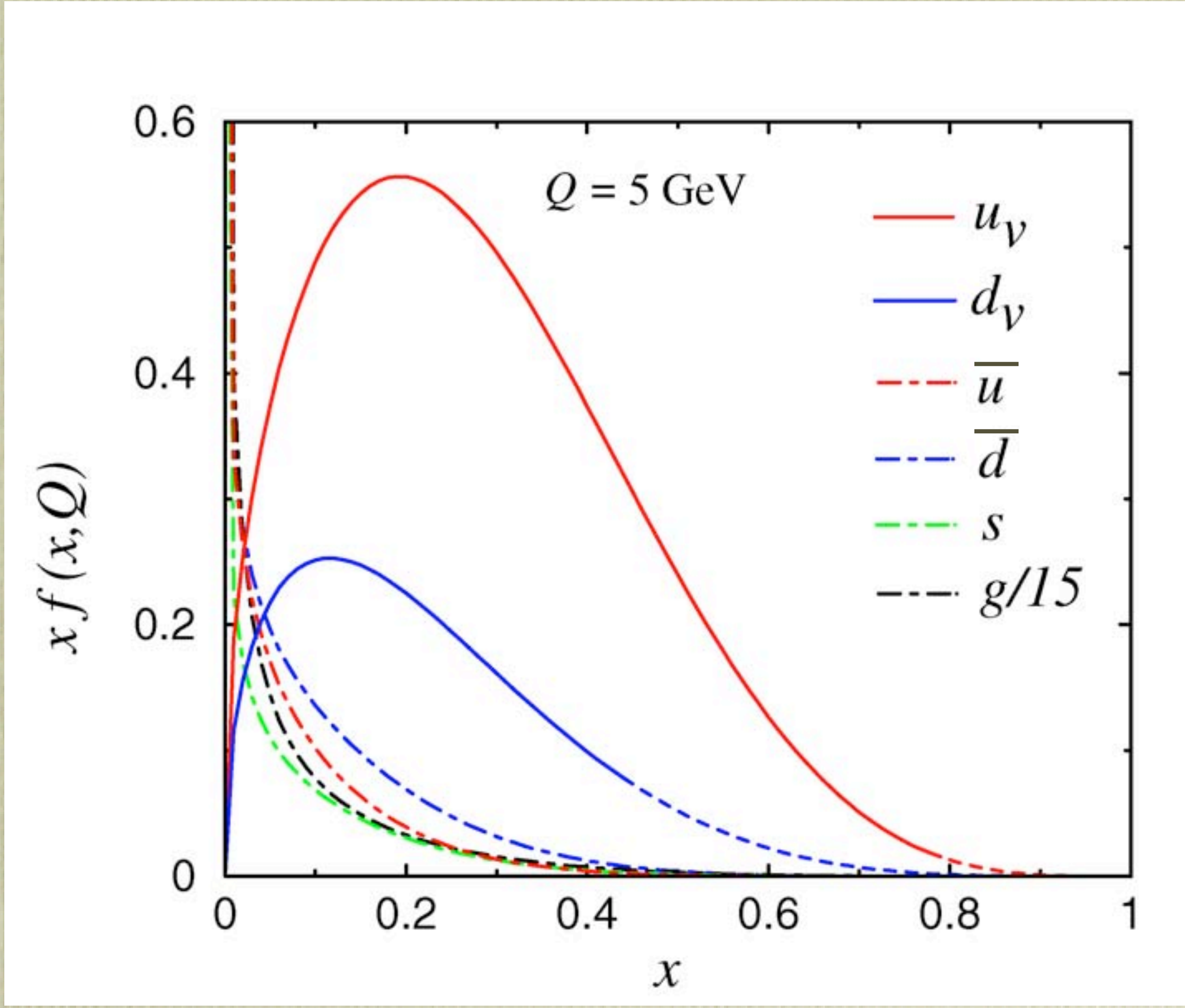
New Perspectives for Deep Inelastic Scattering and QCD

- What is the quark and gluon composition of the proton?
- What new experiments and facilities do we need to measure fundamental features of QCD?

DIS Summary

Thanks on behalf of Theorists

- Thanks to the experimentalists and accelerator physicists who have built the accelerators, storage rings, and experimental facilities; carried out remarkable DIS experiments, and for producing the new measurements.
- The central challenge: to test QCD and explain these fundamental phenomena from first principles.
- This is a central goal of both hadron and nuclear physics.



DIS Summary

Major Issues for DIS in QCD

- Understand hadron structure at the amplitude level-- Exclusive Processes
- Momentum, spin, flavor dependence of hadron distribution
- Angular momentum
- Role of heavy flavors, sea quarks, asymmetries
- Higher Twist Correlations
- Diffractive/ high energy small x nonlinear effects
- Nuclear Phenomena, hadronization

Hard Diffraction from Rescattering

- Diffractive DIS: New Insight into Final State Interactions in QCD
- Origin of Hard Pomeron
- Structure Functions not Probability Distributions
- T-odd Single-Spin Asymmetries
- Diffractive dijets/ trijets
- Color Transparency, Color Opaqueness

New QCD Insights

- Role of Rescattering in Diffractive DIS, SSAs
- Connection of DDIS to Shadowing and Antishadowing
- Non-universality of Antishadowing
- IR Freezing of αs
- Saturation
- AdS/CFT

Hadrons Fluctuate in Particle Number

- Proton Fock States

  $|uud>, |uudg>, |uuds\bar{s}>, |uudc\bar{c}>, |uudb\bar{b}> \cdots$

- Strange and Anti-Strange Quarks not Symmetric

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

- "Intrinsic Charm": High momentum heavy quarks

- "Hidden Color": Deuteron not always p + n

- Orbital Angular Momentum Fluctuations - Anomalous Magnetic Moment

Farrar, Jackson
Gunion
Lepage, SJB
Burkardt, Schmidt, SJB
Ji, Ma, Yuan

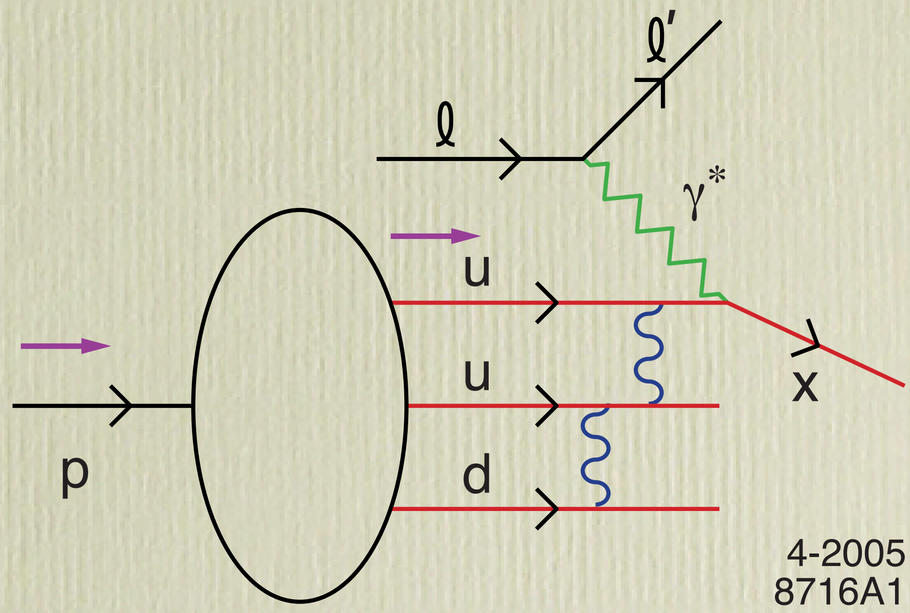
- Measure behavior of proton LFWF at large x_{bj}

- Strong function of quark spin projection relative to proton spin projection

PQCD:

$q(x) \sim (1-x)^3 \qquad S_q^z = S_p^z$

$q(x) \sim (1-x)^5 \qquad S_q^z = -S_p^z$



Traditional PQCD Method
Iterate QCD Kernel

Why is large x Important?

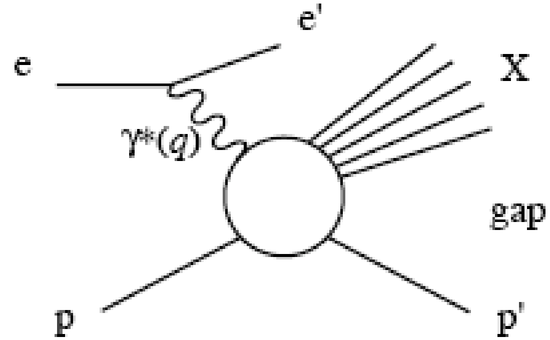
- Sensitive to details of hadronic structure
  valence, sea quark, and gluon distributions

- Detailed predictions from PQCD and AdS/CFT

- Helicity Retention & Spectator Counting Rules

- DGLAP must be modified:
  quenched at $x \to 1$

DDIS

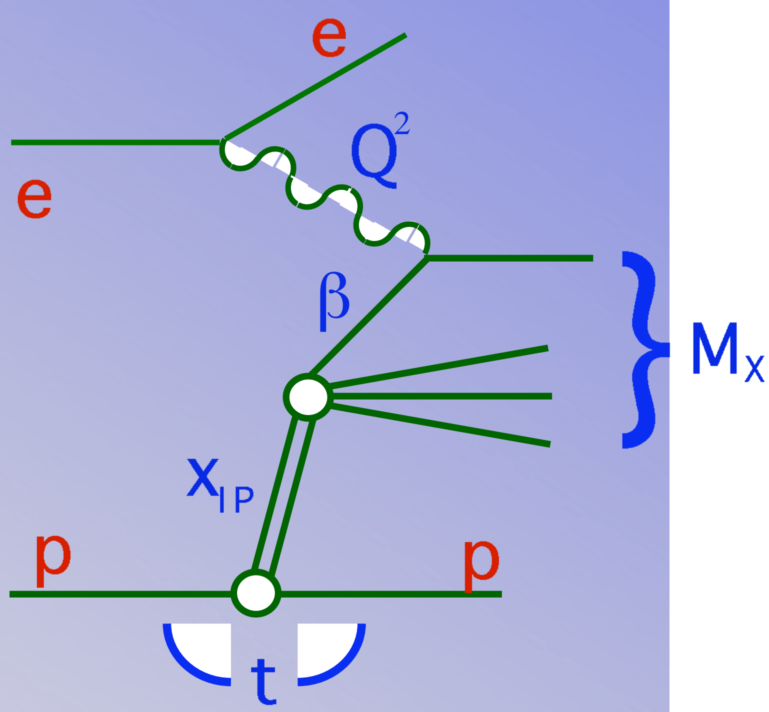


- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

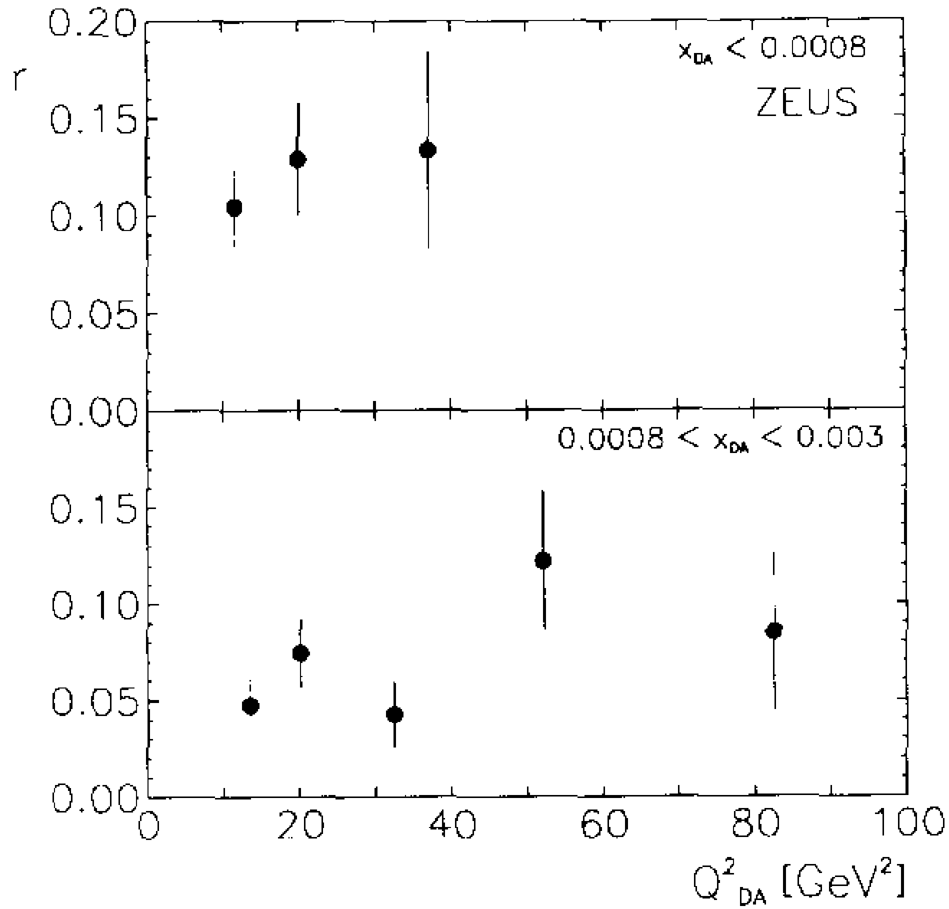
Enberg

Diffractive Deep Inelastic Lepton-Proton Scattering

- New result from HERA: Essentially all of the rapidity gap events leave just an isolated proton



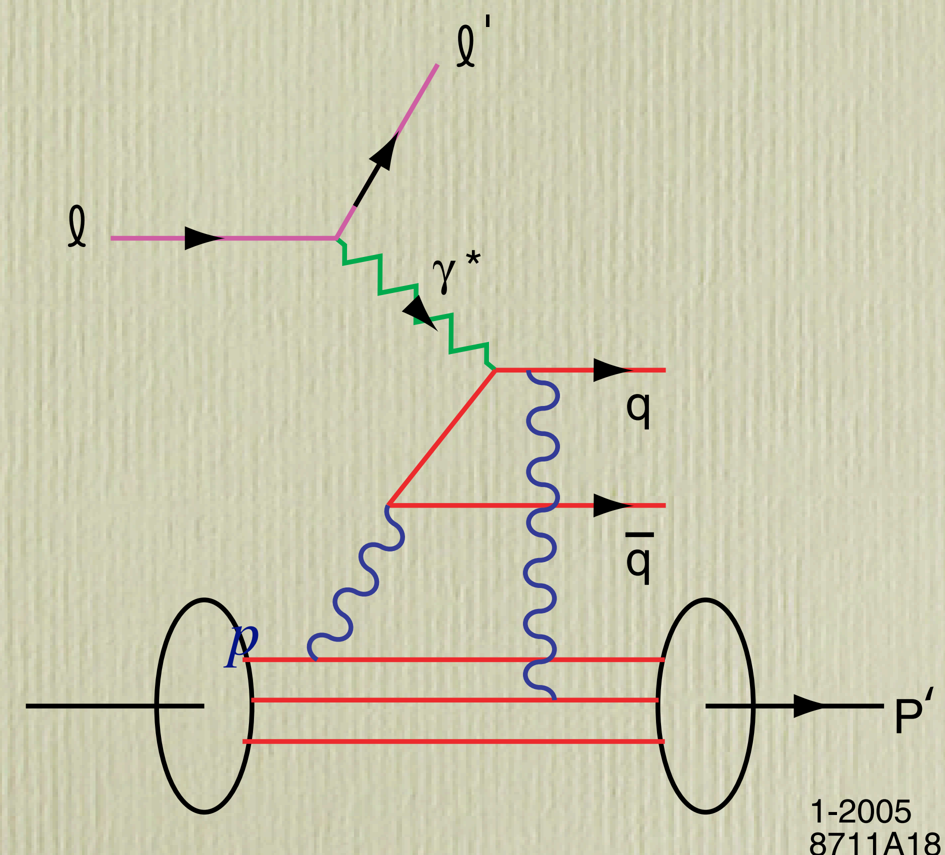
10% of DIS events are diffractive !



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).

Final State Interaction Produces Diffractive DIS

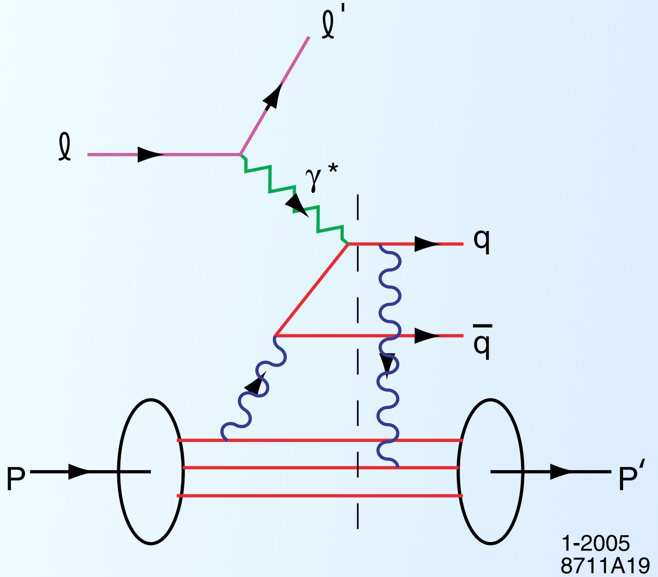


Quark Rescattering

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

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB



Integration over on-shell domain produces phase i
Need Imaginary Phase to Generate
Pomeron

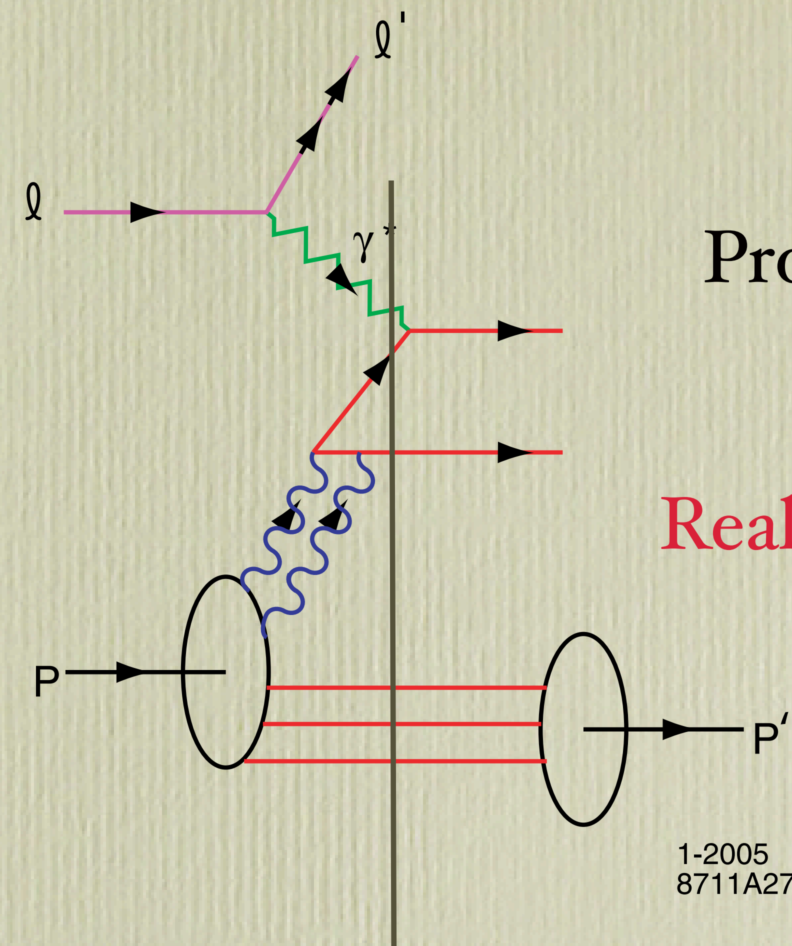
Need Imaginary Phase to Generate
T-Odd Single-Spin Asymmetry

Physics of FSI not in Wavefunction of Target

Problem: Wrong Phase

Real; should be imaginary

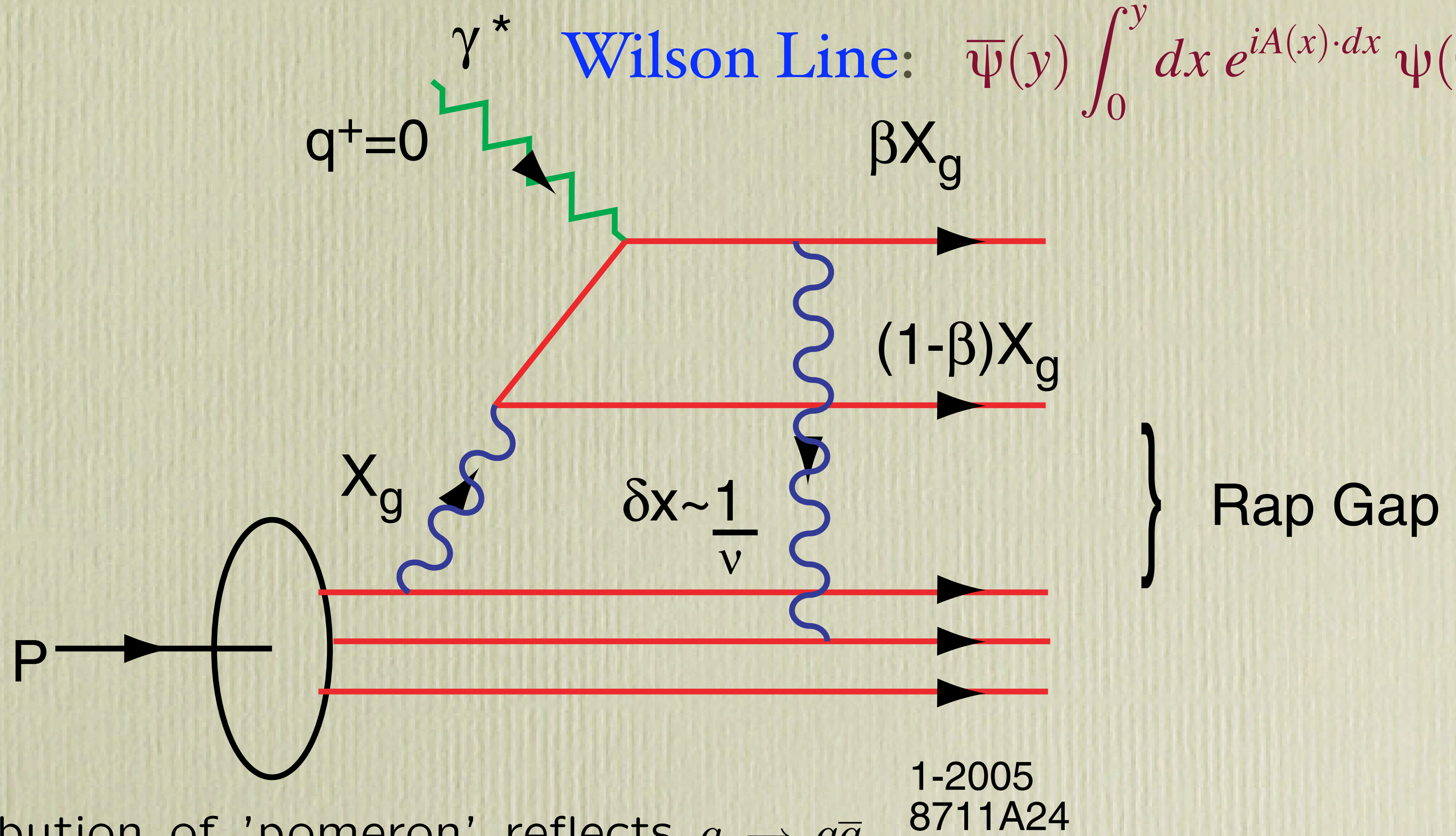
Pomeron is not a constituent of proton



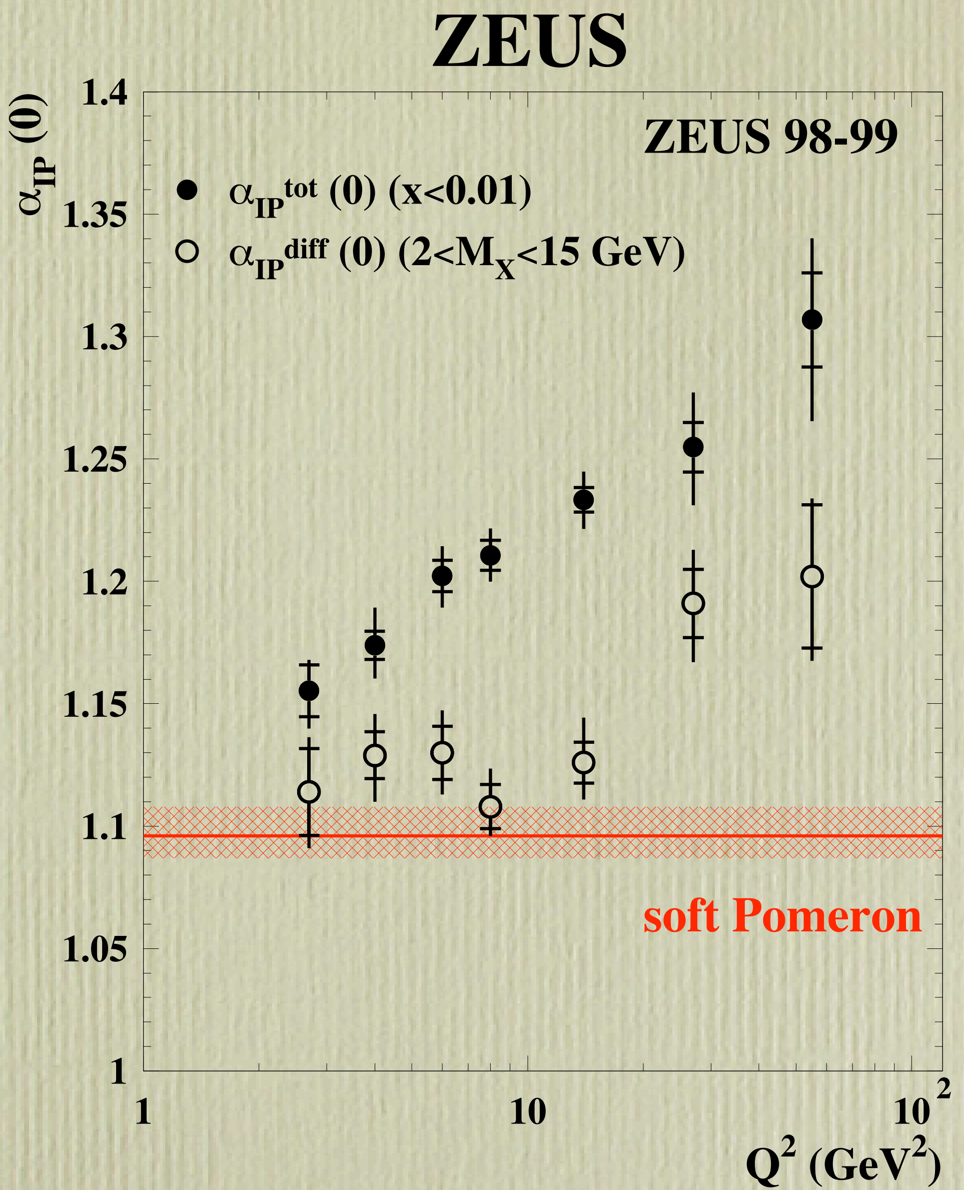
Need Final State Interactions !

QCD Mechanism for Rapidity Gaps

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



β distribution of 'pomeron' reflects $g \to q\overline{q}$ splitting function



$$\sigma_{tot} \propto s^{\alpha_{tot}-1}$$

$$\sigma_{diff} \propto s^{2\alpha_{diff}-2}$$

No factorization of hard pomeron

S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002) [arXiv:hep-ph/0104291].
S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, arXiv:hep-ph/0409119.

DESY 05-011 hep-ex/0501060 January 2005
Study of deep inelastic inclusive and diffractive scattering with the ZEUS forward plug calorimeter
ZEUS Collaboration

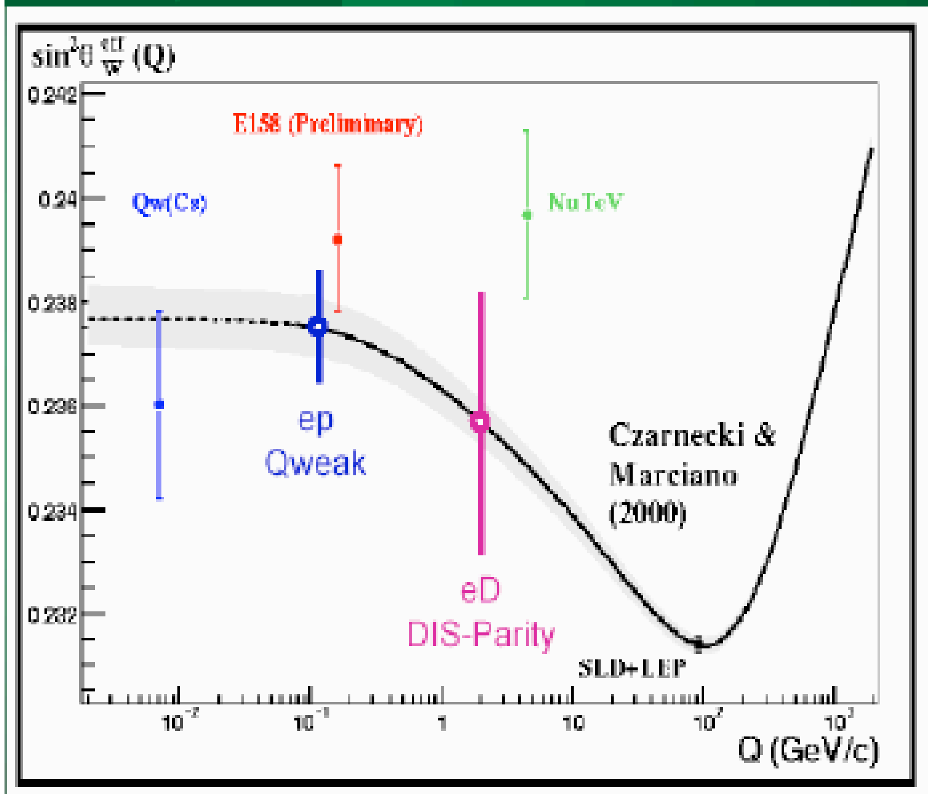
Hard Diffraction in pp collisions

- Probability of one gap 1%, two gaps 0.1%
- DIS: One gap: 10%
- Thus Hard Pomeron does not factorize
- Ratio of two gap to one gap in hadron physics similar to DDIS/DIS.

Goulianis

problem waiting for solution/explanation

→ NuTeV anomaly



From talk by Y. Kolomensky
At SLAC summer institute, August 2004

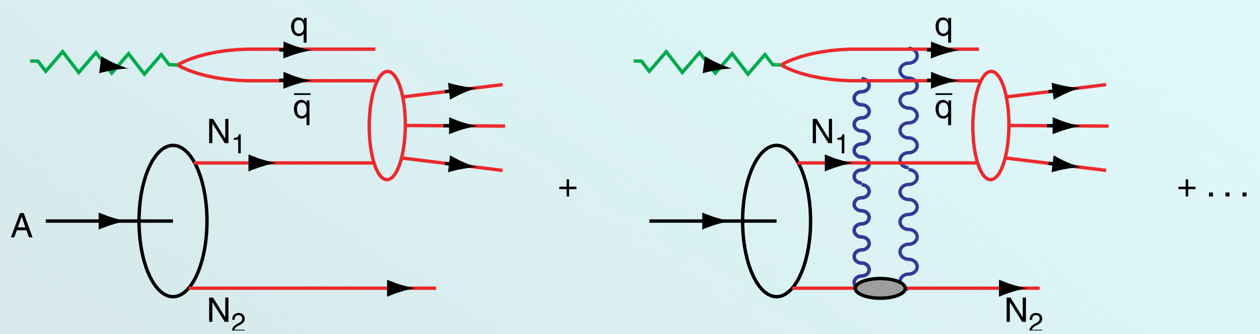
$\sin^2\theta_W$ determined from the ratio:

$$R = \frac{\sigma^{\nu}_{NC} - \sigma^{\bar{\nu}}_{NC}}{\sigma^{\nu}_{CC} - \sigma^{\bar{\nu}}_{CC}}$$

Assumptions:

- Isospin symmetry ie. $u_p(x)=d_n(x)$ (u in proton as d in neutron)
- Sea momentum symmetry: $s=\bar{s}$ and $c=\bar{c}$
- Nuclear effects common in W and Z exchange

Origin of Nuclear Shadowing in Glauber - Gribov Theory

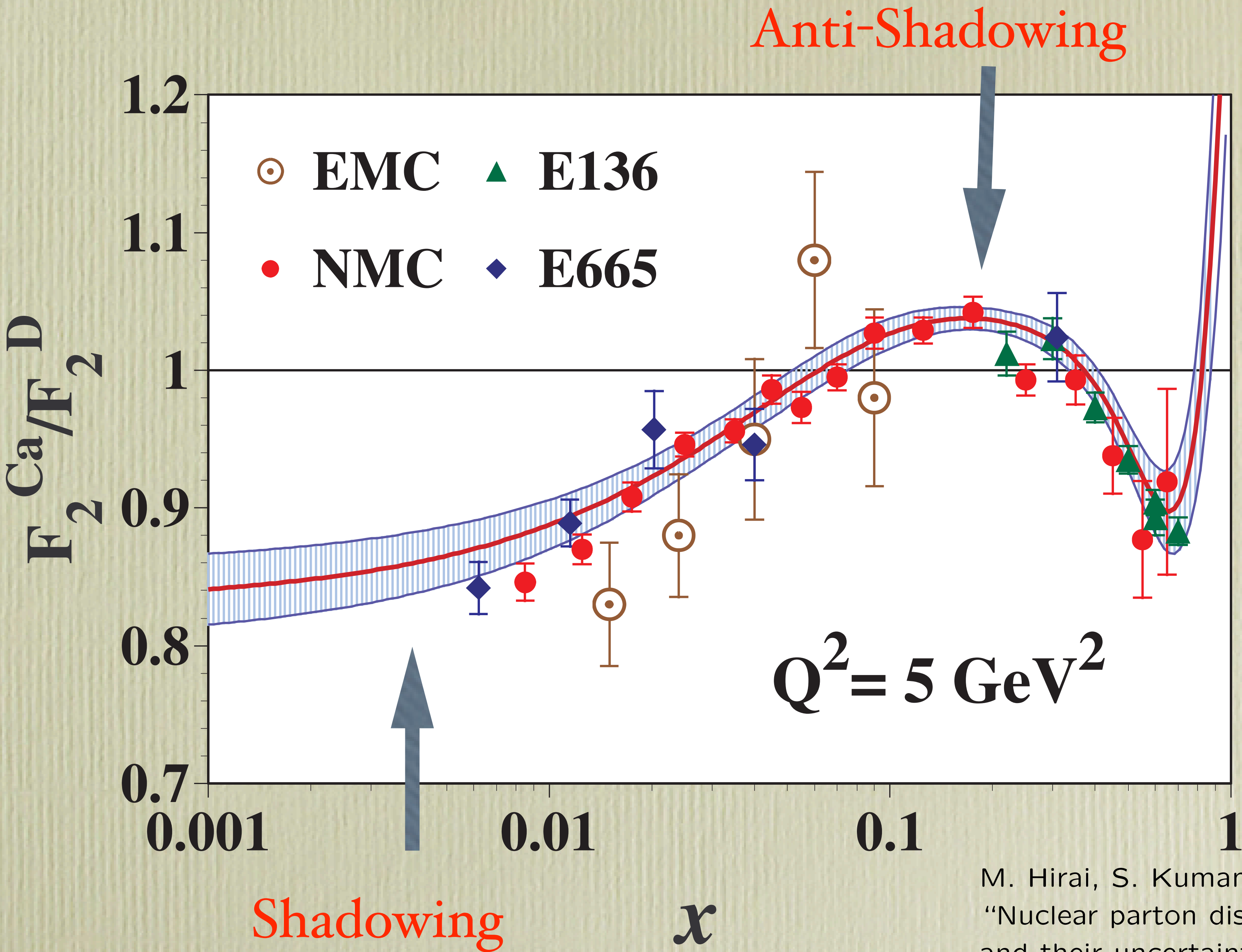


Interference of one-step and two-step processes

Interaction on upstream nucleon diffractive

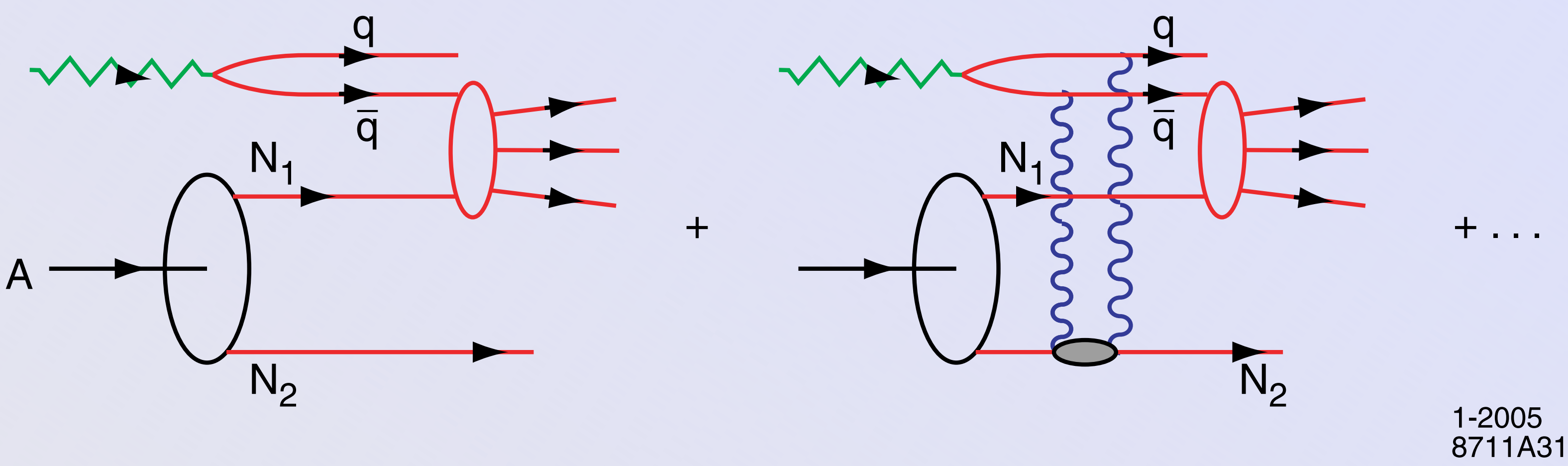
Phase i X i = - 1 produces destructive interference

No Flux reaches down stream nucleon



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].

Nuclear Shadowing in QCD



Nuclear Shadowing not included in nuclear LFWF !

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing: Destructive Interference
of Two-Step and One-Step Processes
Pomeron Exchange

- Antishadowing: Constructive Interference
of Two-Step and One-Step Processes!
Reggeon and Odderon Exchange

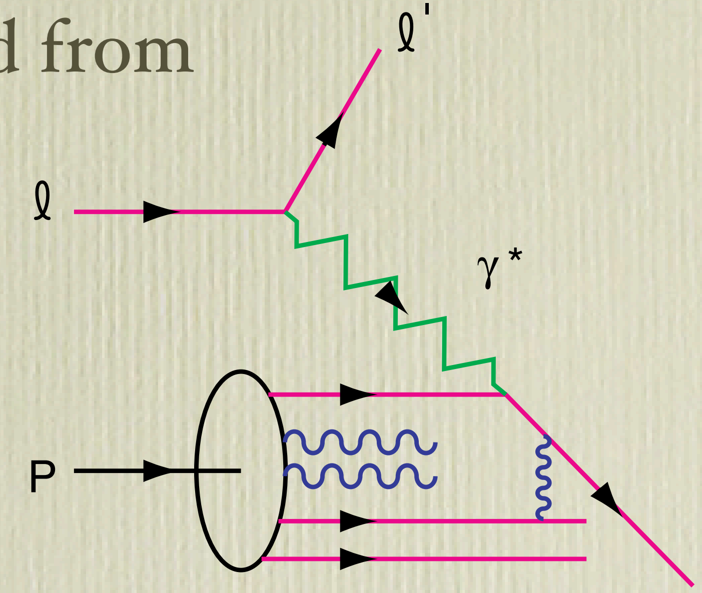
- Antishadowing is Not Universal!
Electromagnetic and weak currents:
different nuclear effects !
Potentially significant for NuTeV Anomaly}

Estimate 20% effect on extraction of $\sin^2\theta_W$ for NuTeV

Need new experimental studies of antishadowing in

- Parity-violating DIS
- Spin Dependent DIS
- Charged and Neutral Current DIS

- Quarks Reinteract in Final State
- Analogous to Coulomb phases, but not unitary
- Observable effects: DDIS, SSI, shadowing, antishadowing
- Structure functions cannot be computed from LFWFs computed in isolation
- Wilson line not 1 even in lcg



Hard Diffraction

Final State Interactions Produce T-Odd (Sivers Effect)

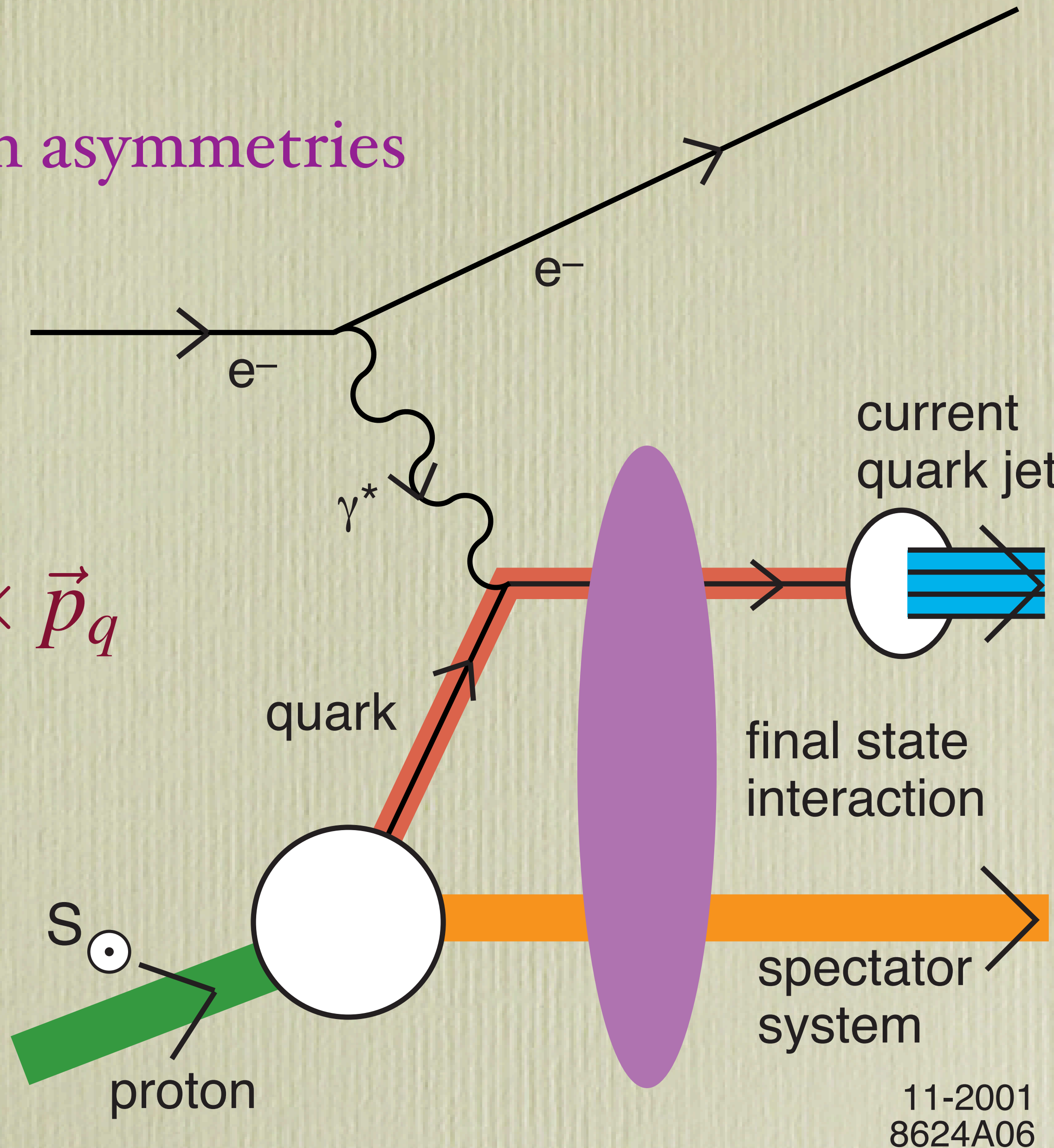
- Bjorken Scaling!
- Arises from Interference of Final State Coulomb Phase in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment

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

Single-spin asymmetries

Sivers Effect

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



Hadron Dynamics at the Amplitude Level

- DIS studies have primarily focussed on probability distributions: integrated and unintegrated
- We need to determine hadron wavefunctions!
- Test QCD at the amplitude level!
- Phases, multi-parton correlations, spin, angular momentum

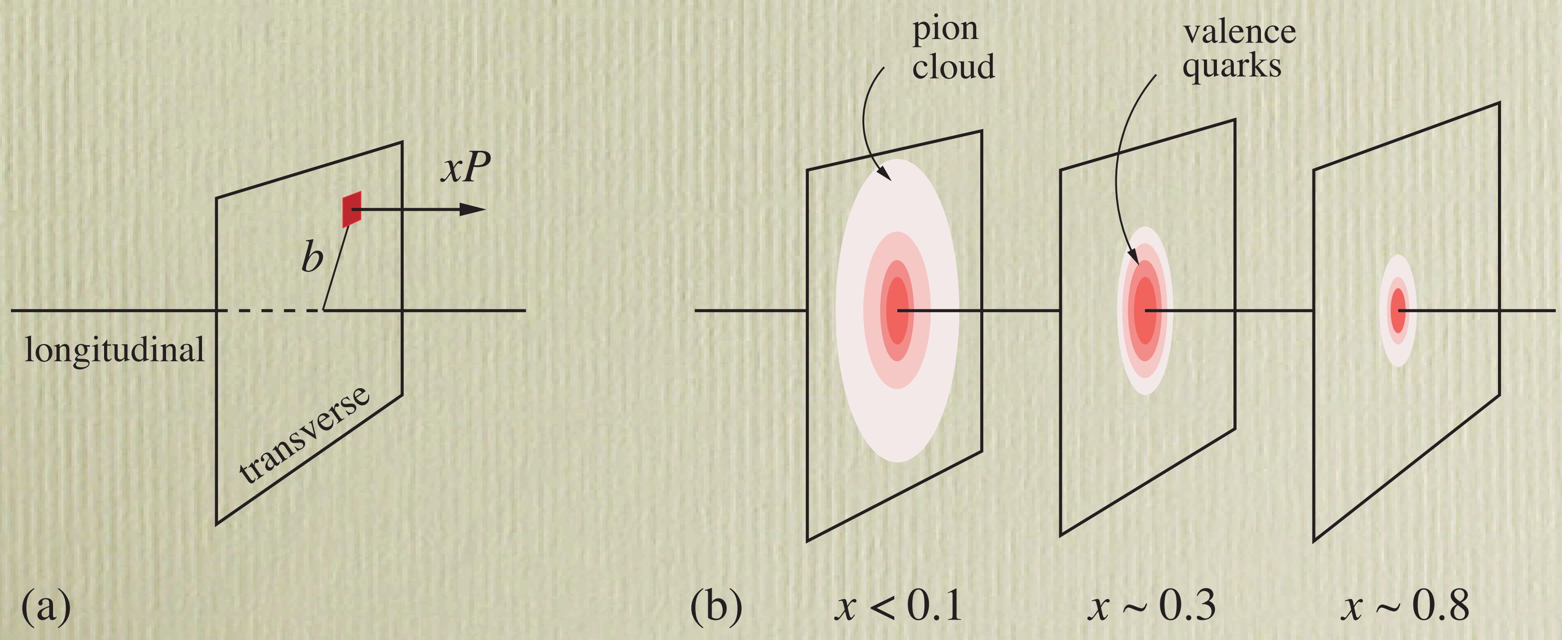
$$\gamma^* p \to \gamma p', \gamma^* p \to \pi^+ n',$$

Deeply Virtual Compton Scattering

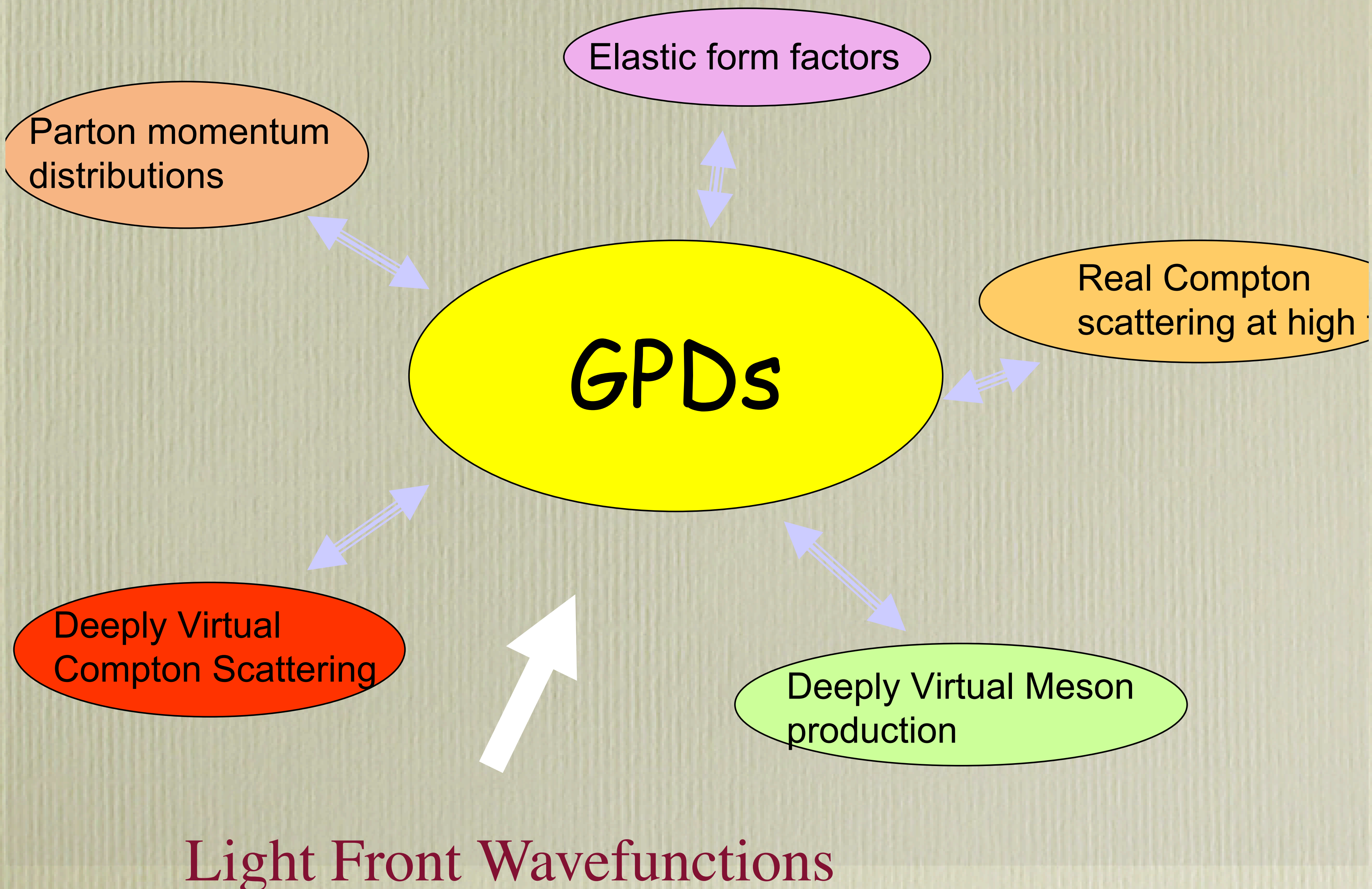
- Remarkable sensitivity to spin, flavor, dynamics
- Real and Imaginary parts from Bethe-Heitler Int.
- Sum Rules connecting to Form Form factors, Lz
- J=0 fixed pole: test QCD contact interaction
- Evolution Equations; Regge effects, PQCD constraints
- Light-front wavefunctions

DVCS ==> Generalized Parton Distributions

- Unintegrated distributions
- 3-dimensional picture of Hadron Structure
- Direct Connection to LFWFs



A Unified Description of Hadron Structure



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

$$H_{LC}^{QCD} = P_\mu P^\mu = \quad P^- P^+ - \vec{P}_\perp^2$$

The hadron state $|\Psi_h\rangle$ is expanded in a Fock-state complete basis of non-interacting n-particle states $|n\rangle$ with an infinite number of components

$$\left|\Psi_h(P^+, \vec{P}_\perp)\right\rangle =$$

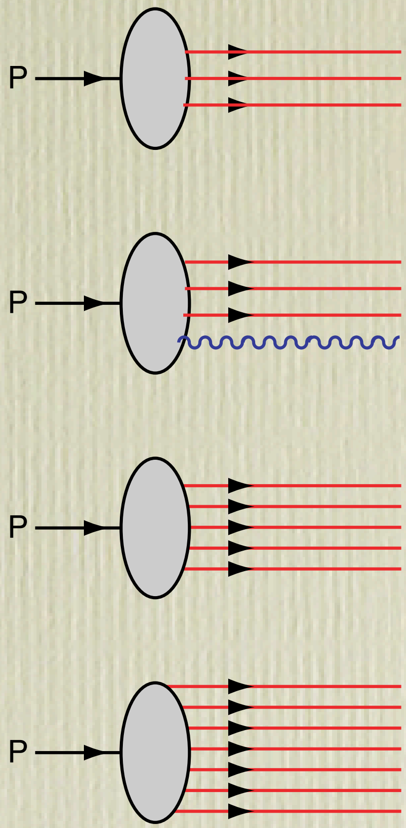
$$\sum_{n,\lambda_i} \int \; [dx_i \; d^2\vec{k}_{\perp i}] \psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i)$$

$$\times \; |n : x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i\rangle$$

$$\sum_n \int [dx_i \; d^2\vec{k}_{\perp i}] \; |\psi_{n/h}(x_i, \vec{k}_{\perp i}, \lambda_i)|^2 = 1$$

The Light-Front Fock Expansion

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



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

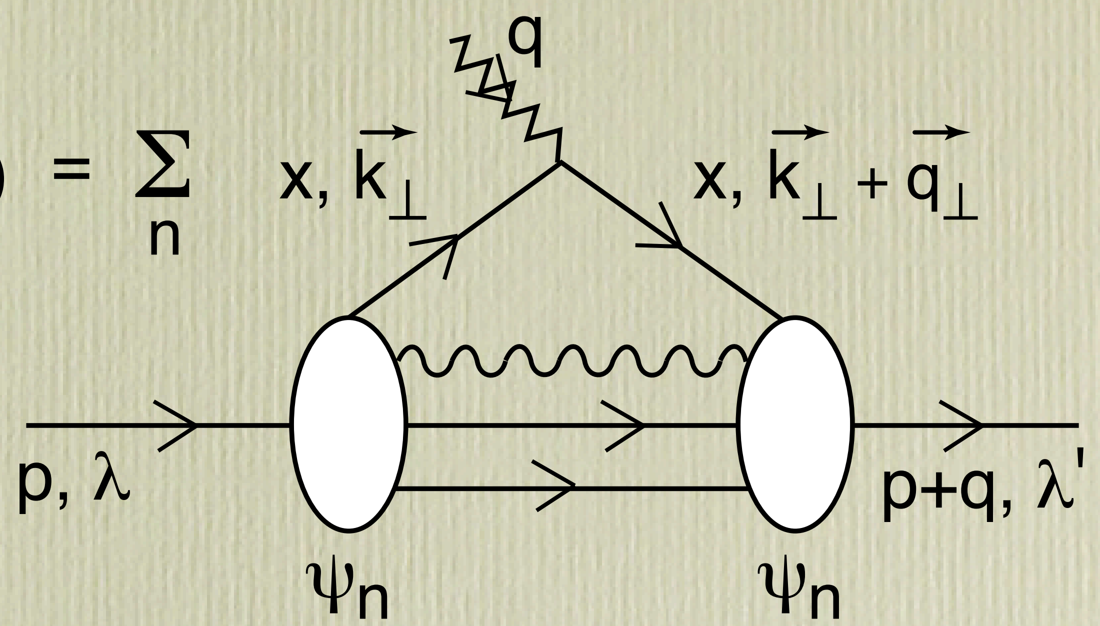
$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

are boost invariant.

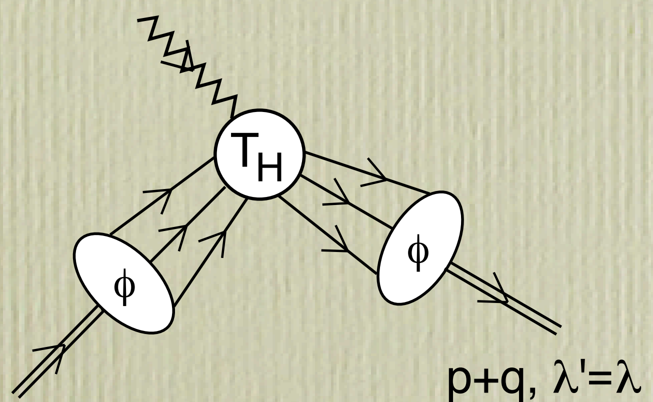
$$\sum_i^n k_i^+ = P^+, \ \sum_i^n x_i = 1, \ \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$

Form Factors $\ell p \to \ell' p'$ $\langle p' \lambda' | J^+ (0) | p\lambda \rangle$

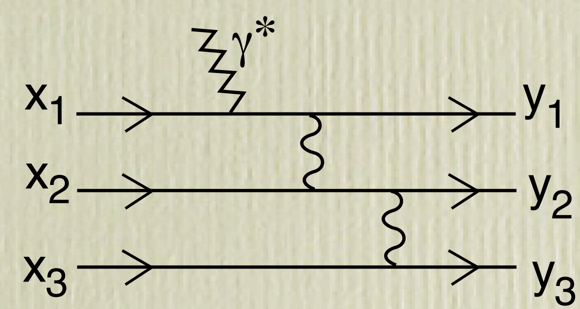
$F_{\lambda\lambda'}(Q^2) = \sum_n$



⇨ Large Q^2



$T_H = \sum$

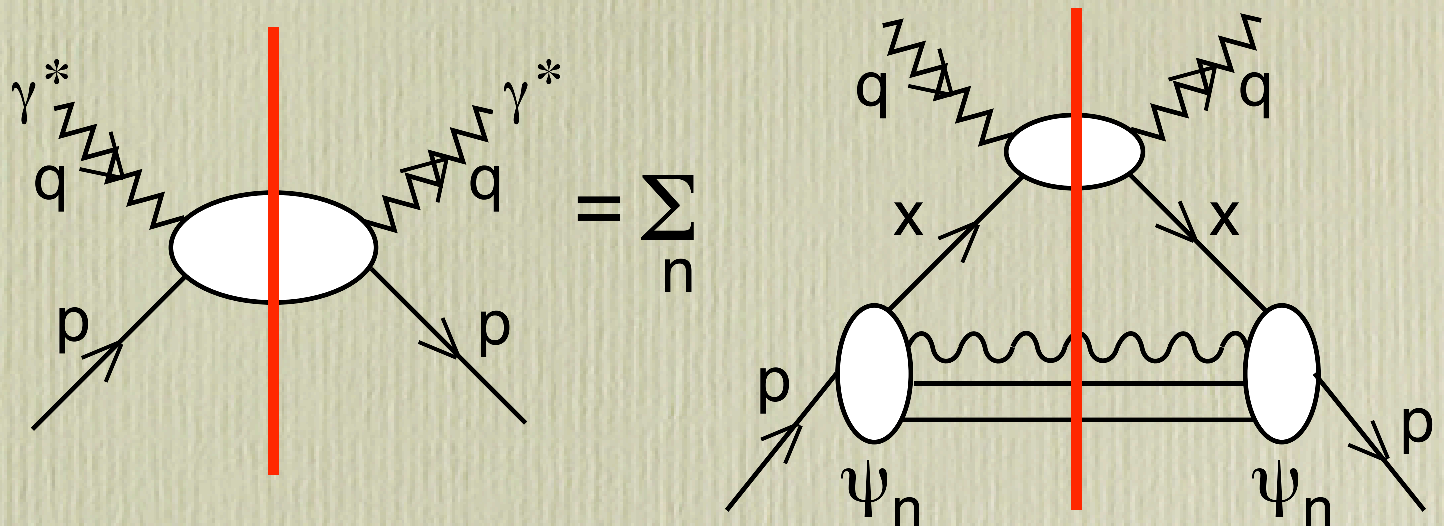


$+ \ \ldots$

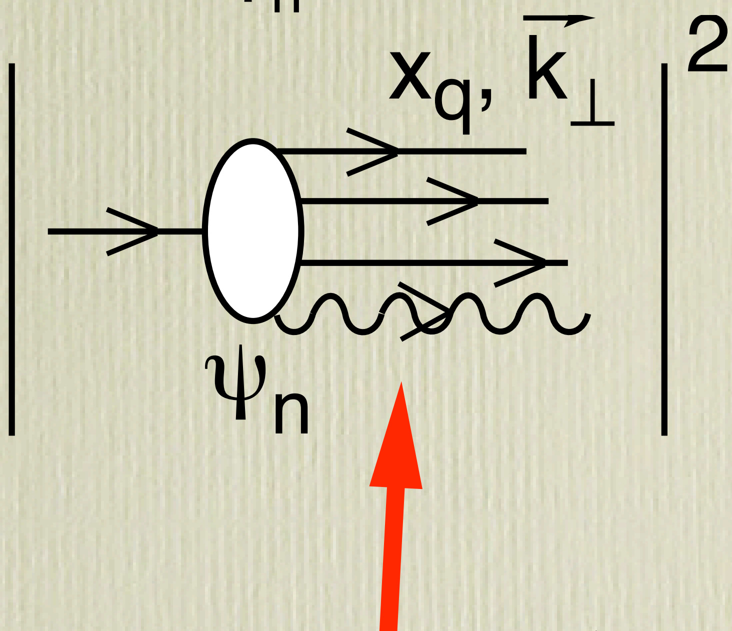
$= \frac{\alpha_s^2}{Q^4} \ f(x_i, y_i,)$

Scaling from PQCD or AdS/CFT

Deep Inelastic Lepton Proton Scattering



Imaginary Part of
Forward Virtual Compton Amplitude

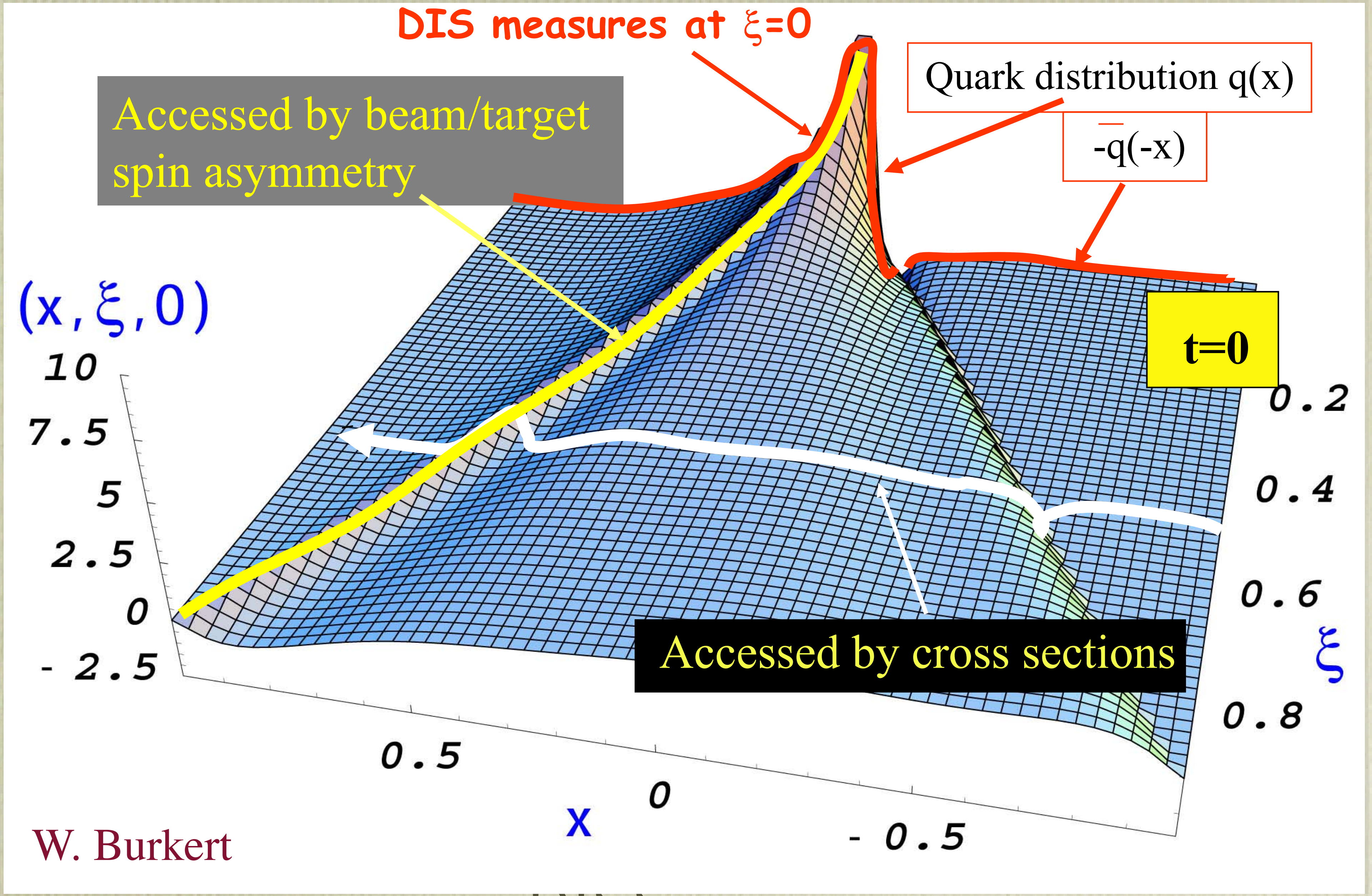


$q(x,Q^2) = \sum_n \int^{k_\perp^2 \leq Q^2 \perp} d^2k_\perp \, |\Psi_n(x,k_\perp)|^2$

$x = x_q$

Light-Front Wave Functions $\psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

Access GPDs through x-section & asymmetries

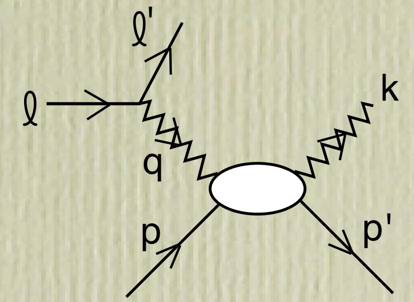


Generalized Parton Distributions

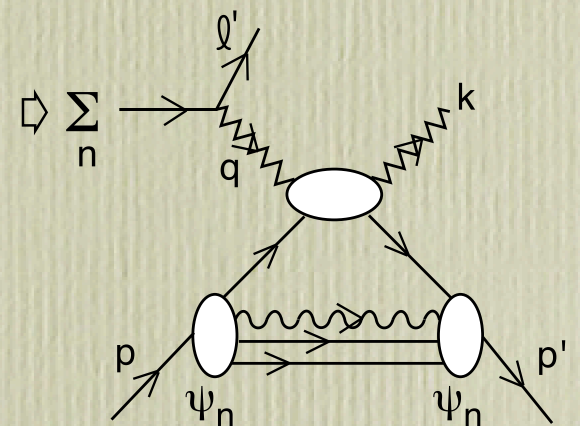
$\langle p' \lambda' | J^{\mu}(z) J^{\nu}(0) | p \lambda \rangle$

Large $-q^2 = Q^2$

$\gamma^* p \rightarrow \gamma p'$



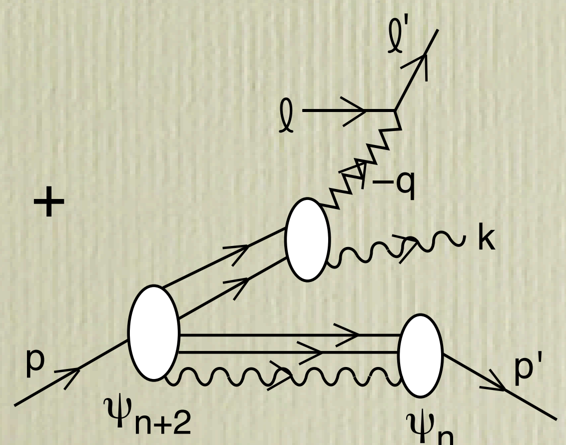
$n = n'$



Deeply Virtual Compton Scattering

$n = n' - 2$

+



Required for Lorentz Invariance

ERBL Evolution

QCD at The Amplitude Level

- LFWFs boost invariant
- Direct connection to form factors, structure functions, distribution amplitudes, GPDs
- Higher Twist Correlation
- Orbital Angular Momentum
- Sum Rules
- Validated in QED, Bethe-Salpeter
- DLCQ

QCD Coupling

- What is the behavior of $\alpha s(Q)$ at low momentum?
- QED, EW -- define coupling from observable, predict other observables
- How can DIS give information on αs?

- Define effective charge (Grunberg)

$$\int_0^1 dx[g_{1n}(x,Q^2) - g_{1p}(x,Q^2)] \equiv \frac{g_A}{6}(1 - \frac{\alpha_{g_1}(Q^2)}{\pi})$$

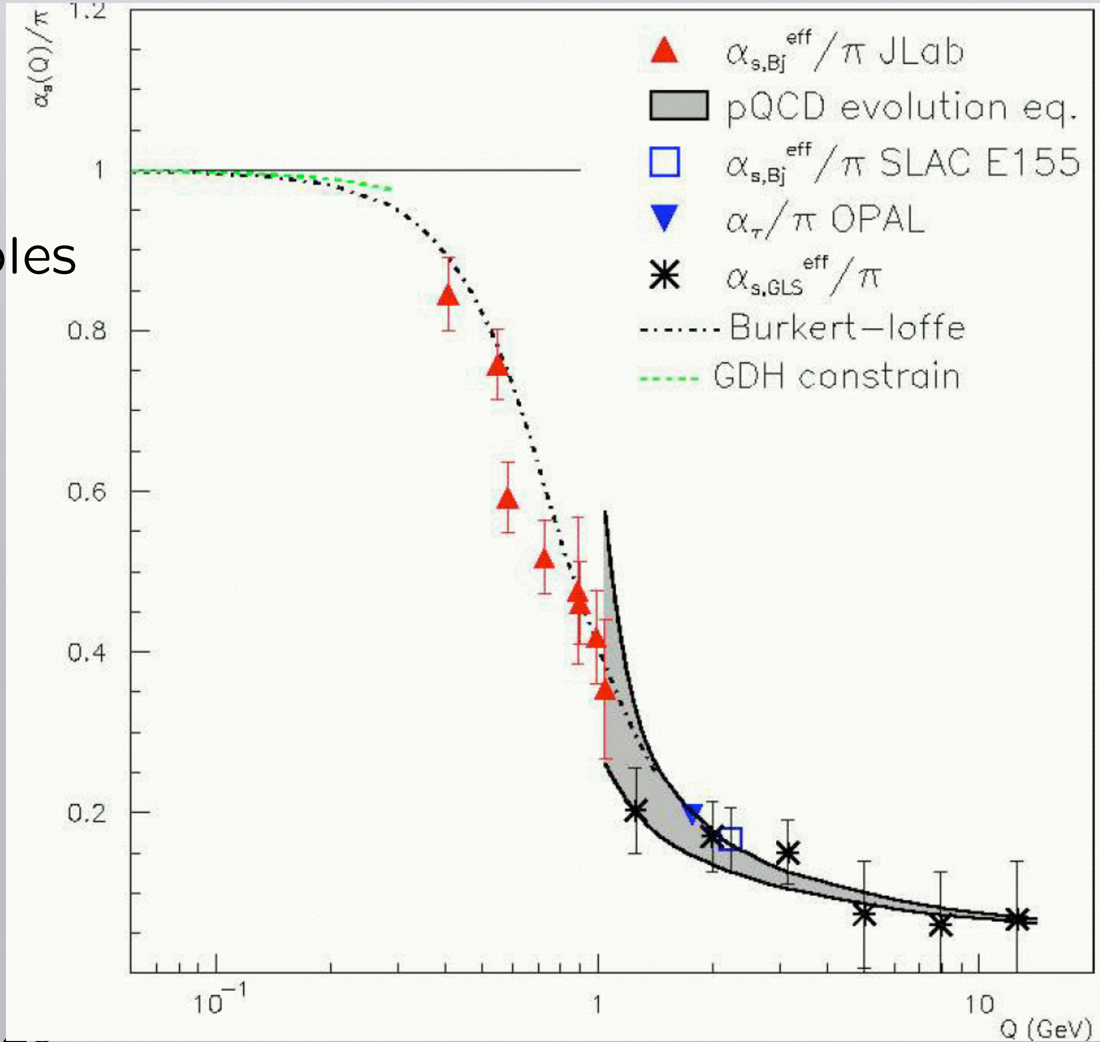
- $\frac{d}{dQ^2}\alpha_{g_1}(Q^2) = \beta(Q^2)$:
standard QCD evolution

- β_0, β_1 universal

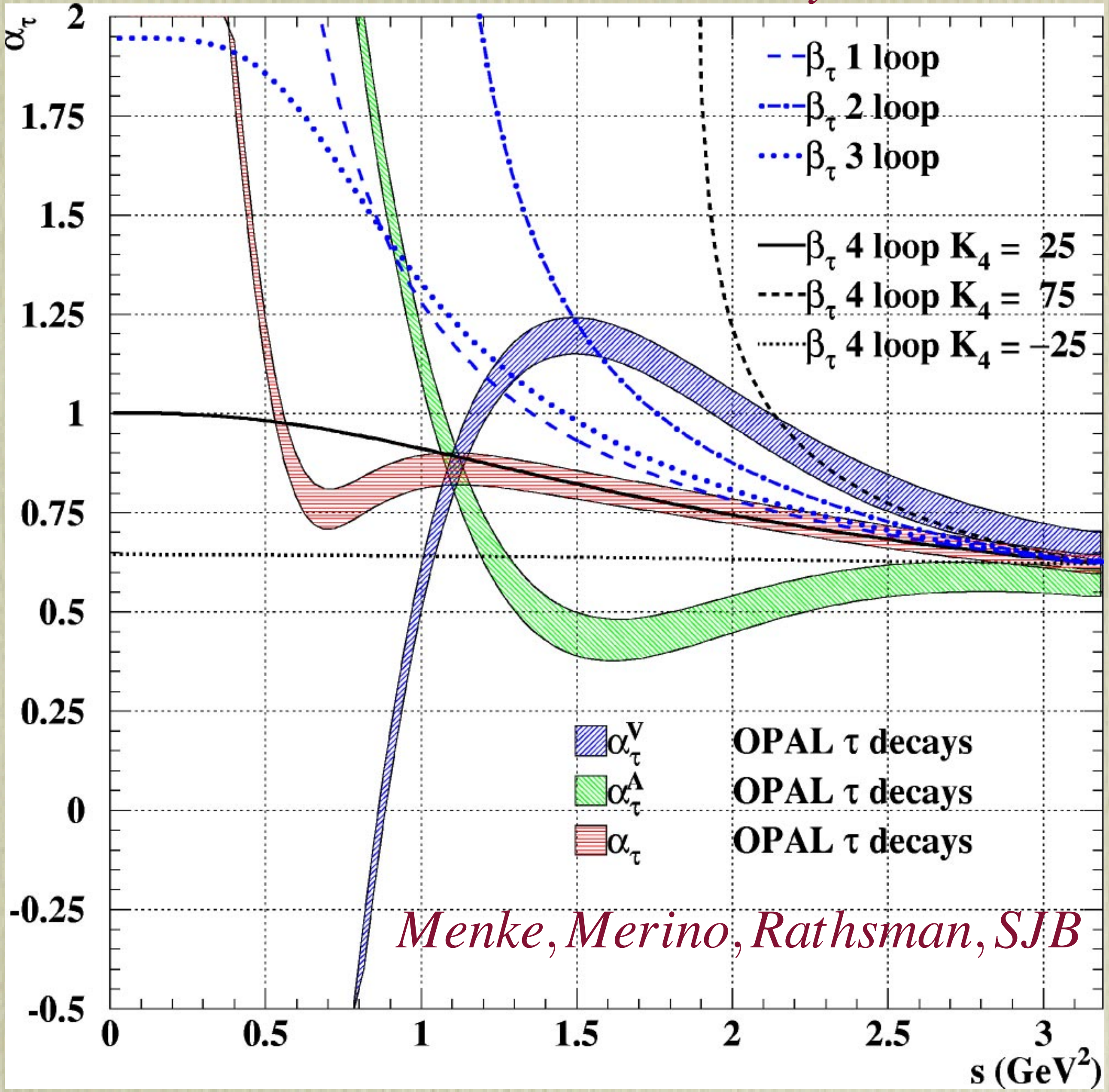
- Connect $\alpha_{g_1}(Q^2)$ to other observables
via Commensurate Scale Relations

- Eliminate $\alpha_{\overline{MS}}$

A. Deur, et al
Preliminary



QCD Effective Coupling from *hadronic τ decay*



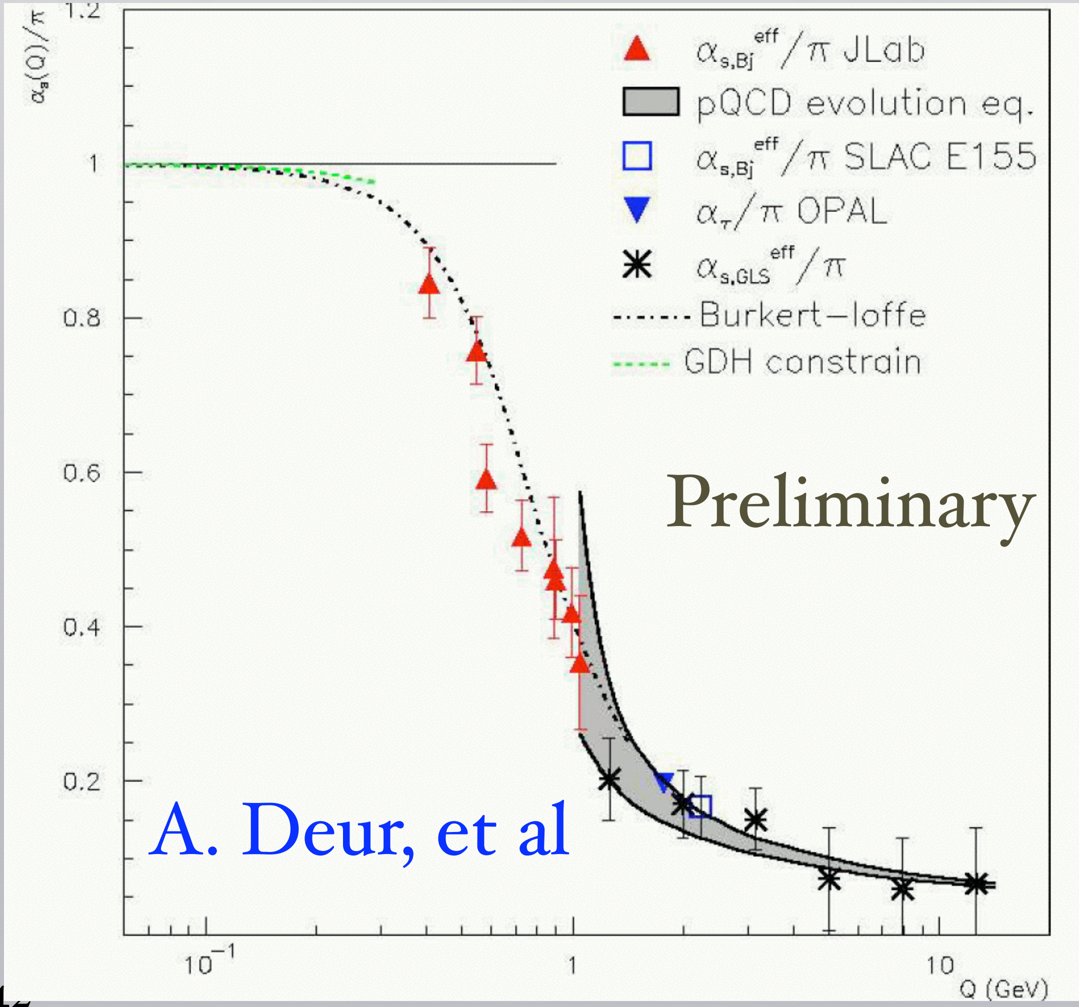
- Generalized Crewther Relation

$$[1 - \frac{\alpha_{g_1}(Q^2)}{\pi}] \times [1 + \frac{\alpha_R(s^*)}{\pi}] = 1$$

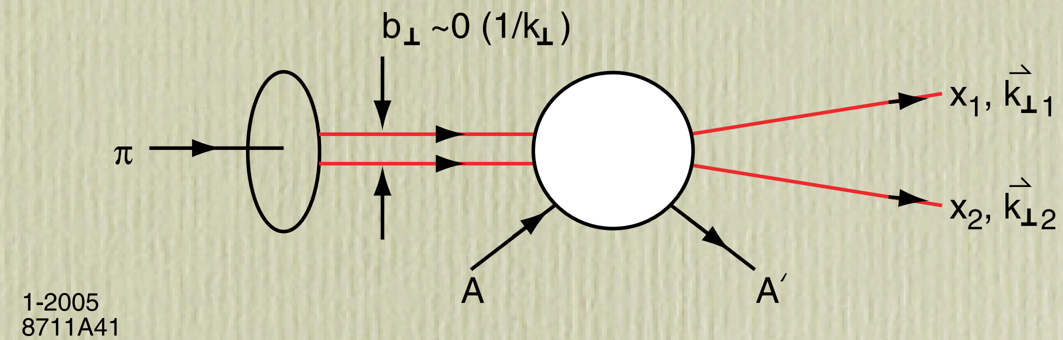
at $s^* = CQ^2$.

- Exact at leading twist.
- No scale ambiguity!
- Extraordinary Test of QCD
- $\frac{\alpha_{g_1}(Q^2)}{\pi}$:
Analytic at quark thresholds.

G.Gabadadze, H.J.Lu, A.Kataev, J.Rathsman, SJB



Diffractive Dissociation of Pion



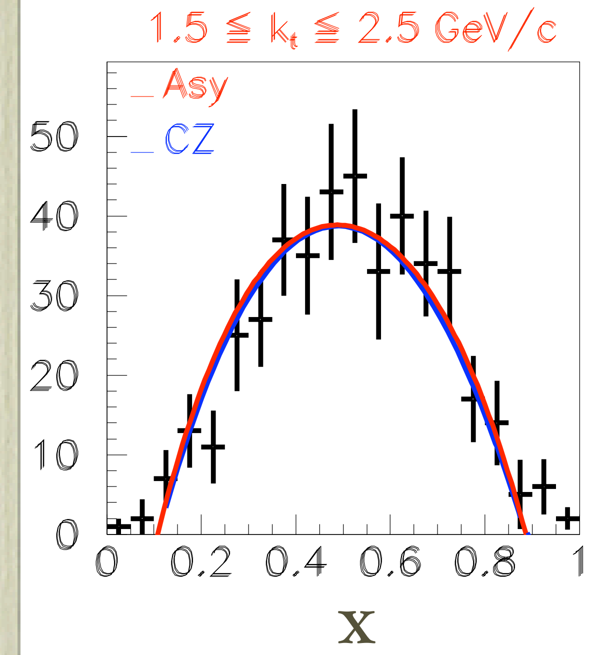
Measure Light-Front Wavefunction of Pion
Two-gluon Exchange
Minimal momentum transfer to nucleus
Nucleus left Intact

Diffractive Dissociation of a Pion into Dijets

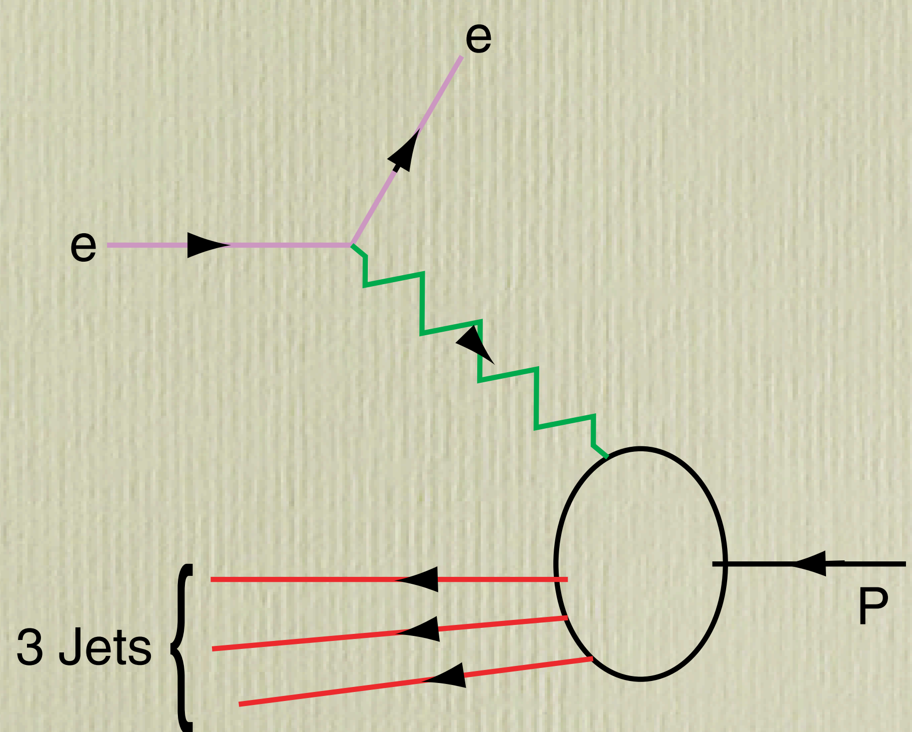
$$\pi A \rightarrow Jet\,Jet\,A'$$

- E789 Fermilab Experiment
  Ashery et al
- 500 GeV pions collide on nuclei keeping it intact
- Measure momentum of two jets
- Study momentum distributions of pion LF wavefunction

$$\psi^{\pi}_{q\bar{q}}(x, \vec{k}_{\perp})$$



Coulomb Dissociate Proton to Three Jets at HERA !



Measure $\Psi_{qqq}(x_i, \vec{k}_{\perp i})$ valence wavefunction of proton

- Use high energy Coulomb dissociation:

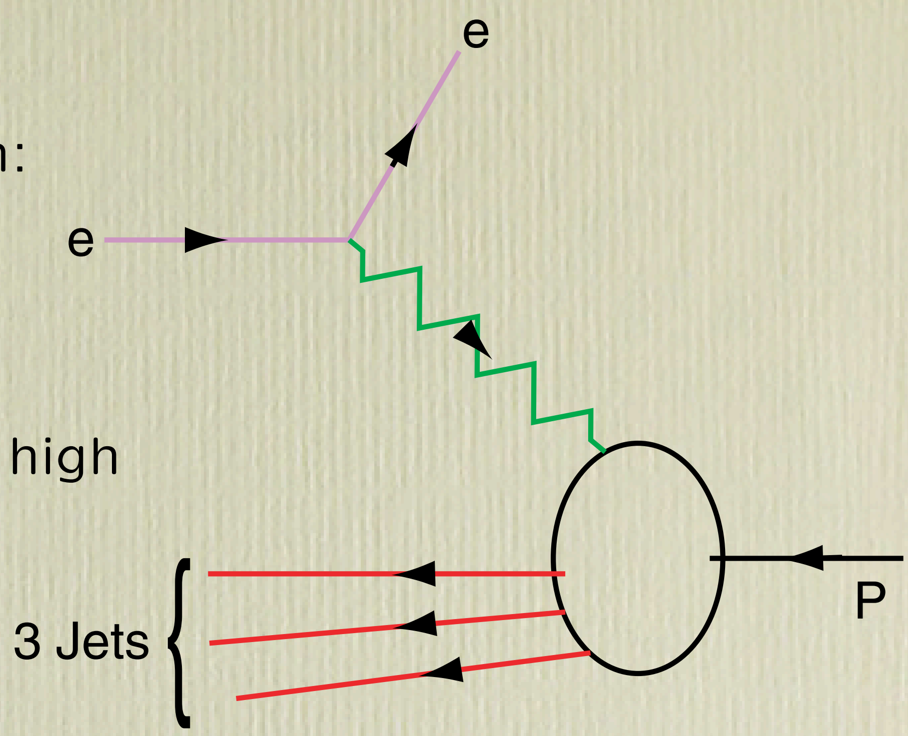
$p + e \to JetJetJet + e'$

to resolve hadron wavefunction

- Measure x_i and $\vec{k}_{\perp i}$ of three jets with high p_T

- Coulomb dissociation measures:

$\sum e_q \frac{\partial}{\partial \vec{k}_{\perp q}} \psi_{q\bar{q}}(x_i, \vec{k}_{\perp_i}, \lambda_i)$



$\sum k_{\perp i} = 0$, $\sum x_i = 1.$

- Use $\gamma^* \to V$ as diffractive target of variable size

$$p + \gamma^* \to JetJetJet + \rho$$

- Pomeron exchange measures double derivative (resolves color dipole).

- Need new HERA3 detector capable of resolving three jets (Jade algorithm) with flavor tagging at forward rapidities

AdS/CFT and QCD

- Non-Perturbative Derivation of Dimensional Counting Rules (Strassler and Polchinski)
- Light-Front Wavefunctions: Confinement at Long Distances and Conformal Behavior at short distances (de Teramond and Sjb)
- Power-law fall-off at large transverse momentum, x --> 1
- Hadron Spectra, Regge Trajectories

Compute LFWFs from First Principles

- Very difficult using Euclidean lattice
- Discretized light-cone quantization: Diagonalize light-cone Hamiltonian
- Bethe-Salpeter Dyson-Schwinger Eqns
- Transverse lattice
- AdS/CFT guidance

AdS/CFT

- Use mapping of SO(4,2) to AdS5
- Scale Transformation represented by wavefunction in 5th dimension
- Holographic model: Confinement at large distances and conformal symmetry at short distances
- Match solutions a large r to conformal dimension of hadron wavefunction at short distances
- Truncated space simulates "bag" boundary conditions

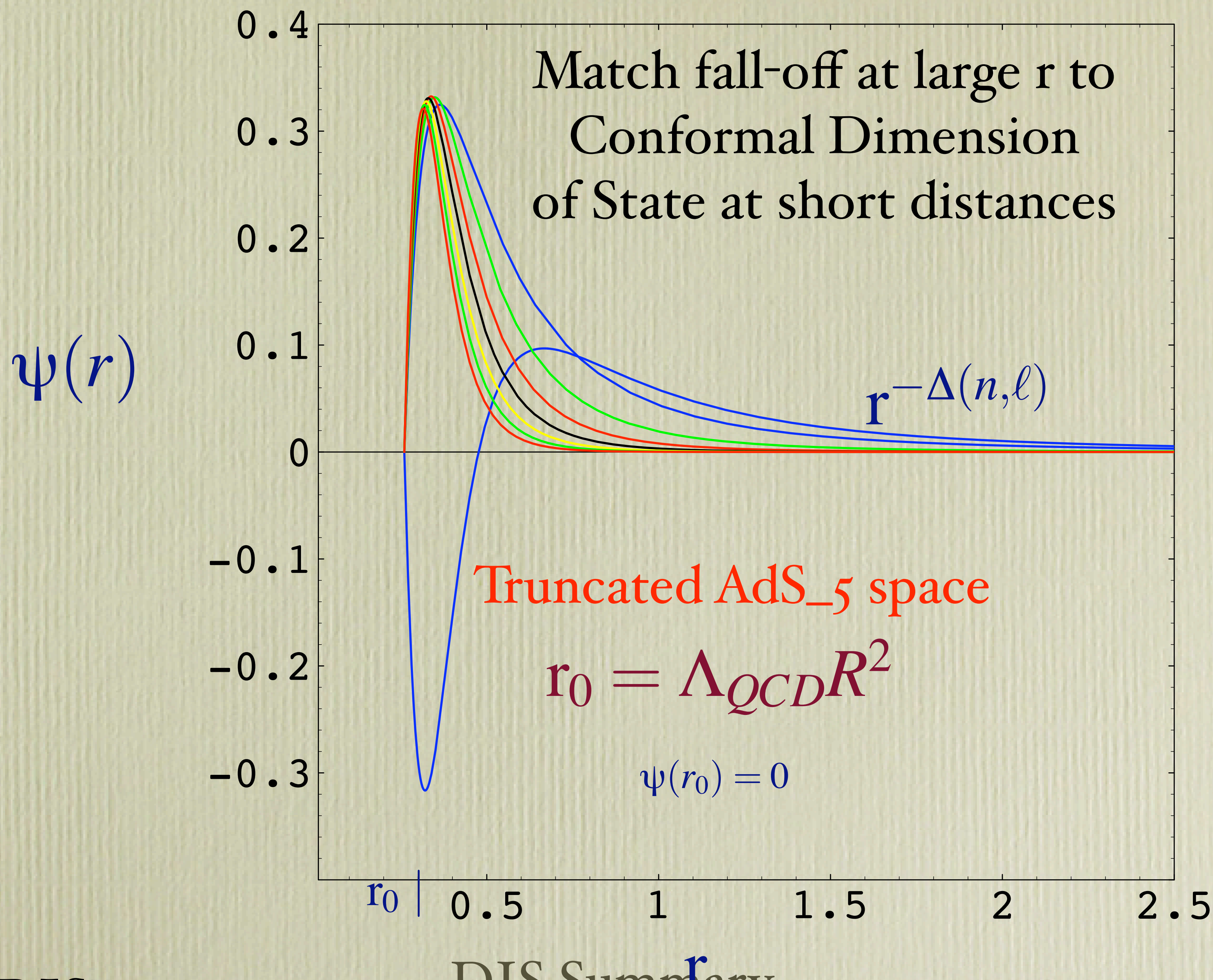
AdS/CFT

- Light-Front Wavefunctions can be determined by matching functional dependence in fifth dimension to scaling in impact space.

$$\left[z^2\ \partial_z^2 - (d-1)z\ \partial_z + z^2\ \mathcal{M}^2 - (\mu R)^2\right] f(z) = 0,$$

- Relative orbital angular momentum

- High transverse momentum behavior matches PQCD LFWF: Belitsky, Ji, Yuan



Match fall-off at large r to
Conformal Dimension
of State at short distances
$\psi(r)$
$\mathrm{r}^{-\Delta(n,\ell)}$
Truncated AdS_5 space
$\mathrm{r}_0 = \Lambda_{QCD} R^2$
$\psi(r_0) = 0$
r_0
r
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.5
1
1.5
2
2.5

AdS/CFT Baryon Spectroscopy

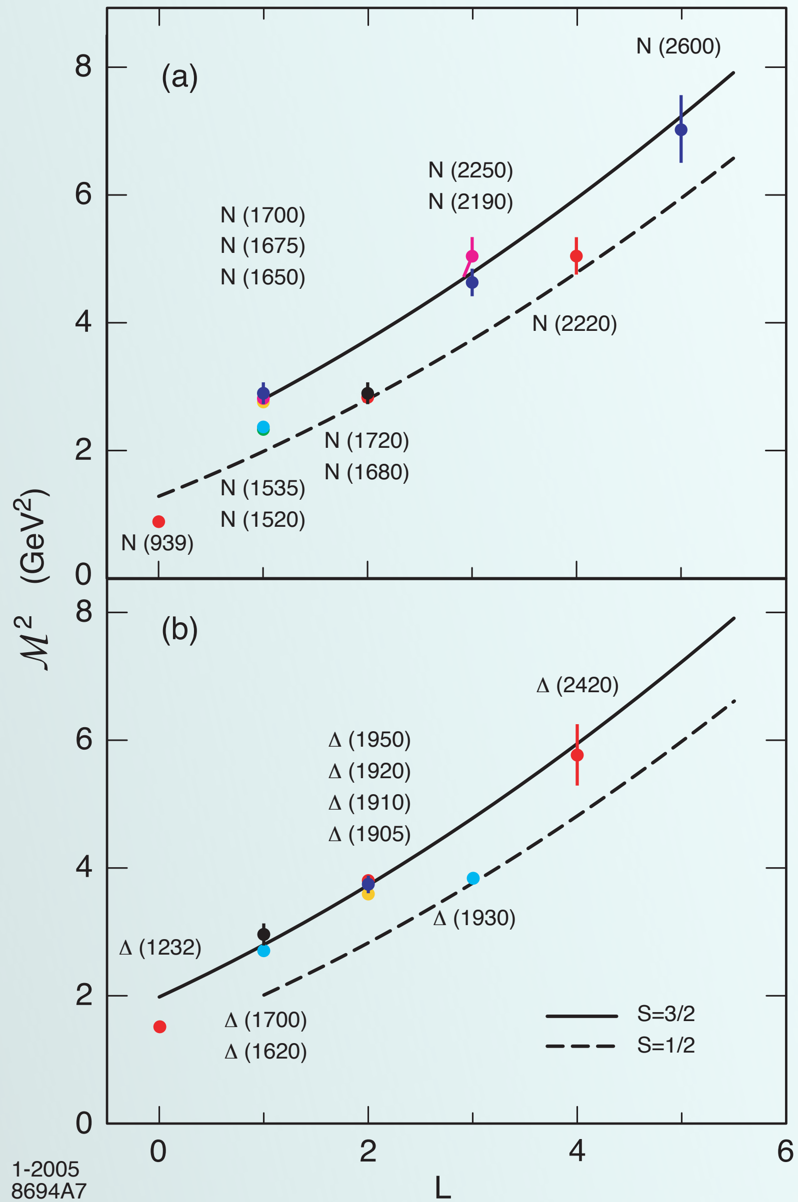


FIG. 2: Predictions for the light baryon orbital spectrum for $\Lambda_{QCD} = 0.22$ GeV. The lower curves corresponds to baryon states dual to spin-$\frac{1}{2}$ modes in the bulk and the upper to states dual to spin-$\frac{3}{2}$ modes.

One Parameter

$\Lambda_{QCD} = 0.22$ GeV

G. F. de Teramond and S. J. Brodsky, arXiv:hep-th/0501022.

AdS/CFT Meson Spectroscopy

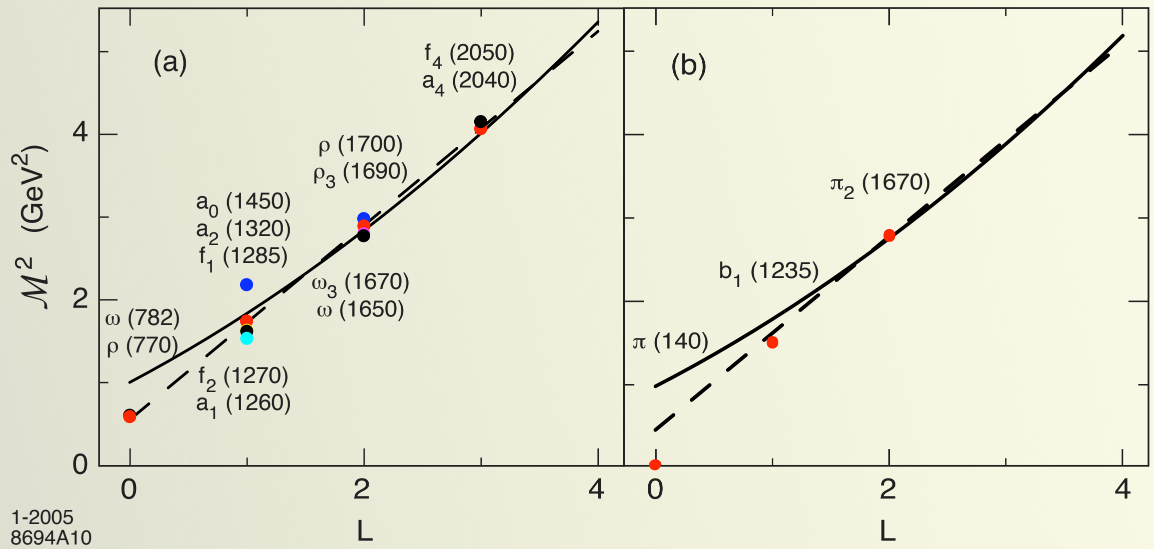
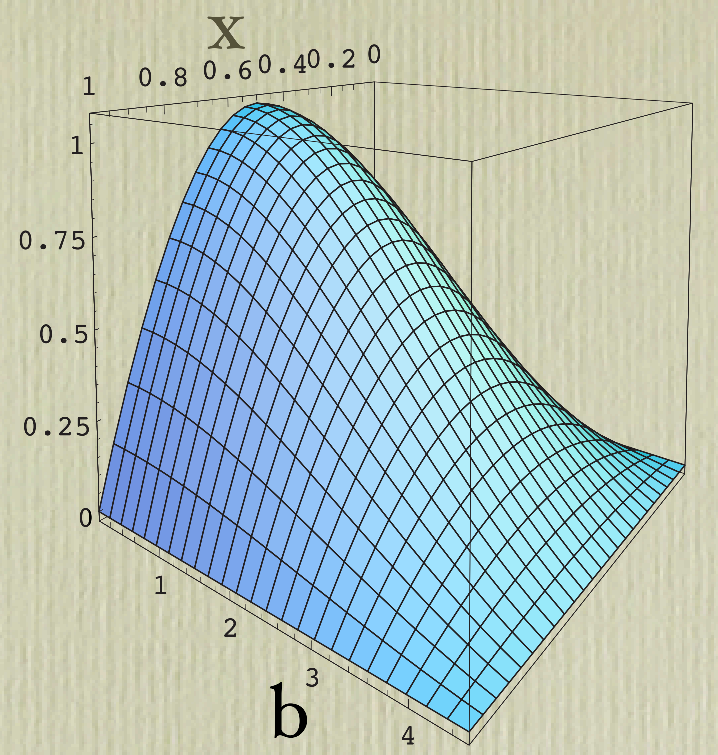


FIG. 1: Light meson orbital states for $\Lambda_{QCD} = 0.263$ GeV. Results for the vector mesons are shown in (a) and for the pseudoscalar mesons in (b). The dashed line has slope 1.16 GeV^2 and is drawn for comparison.

G. F. de Teramond and S. J. Brodsky, "The hadronic spectrum of a holographic dual of QCD," arXiv:hep-th/0501022.

Holographic LFWF



AdS/CFT

Figure 1: Ground state light-front wavefunction in impact space $\psi(x,b)$ for a two-parton state in a holographic QCD model for $n=2, \ell=0, k=1$.

$$\psi_{n,\ell,k}(x,r) = B_{n,\ell,k}\ x(1-x)\frac{J_{n+\ell-1}\left(r\beta_{n-1,k}\Lambda_{QCD}\right)}{r},$$

b = r

GdT & Sjb (preliminary)

Why is large x Important?

- Sensitive to details of hadronic structure valence, sea quark, and gluon distributions

- Detailed predictions from PQCD and AdS/CFT

- Helicity Retention & Spectator Counting Rules

- DGLAP must be modified: **quenched** at $x \to 1$

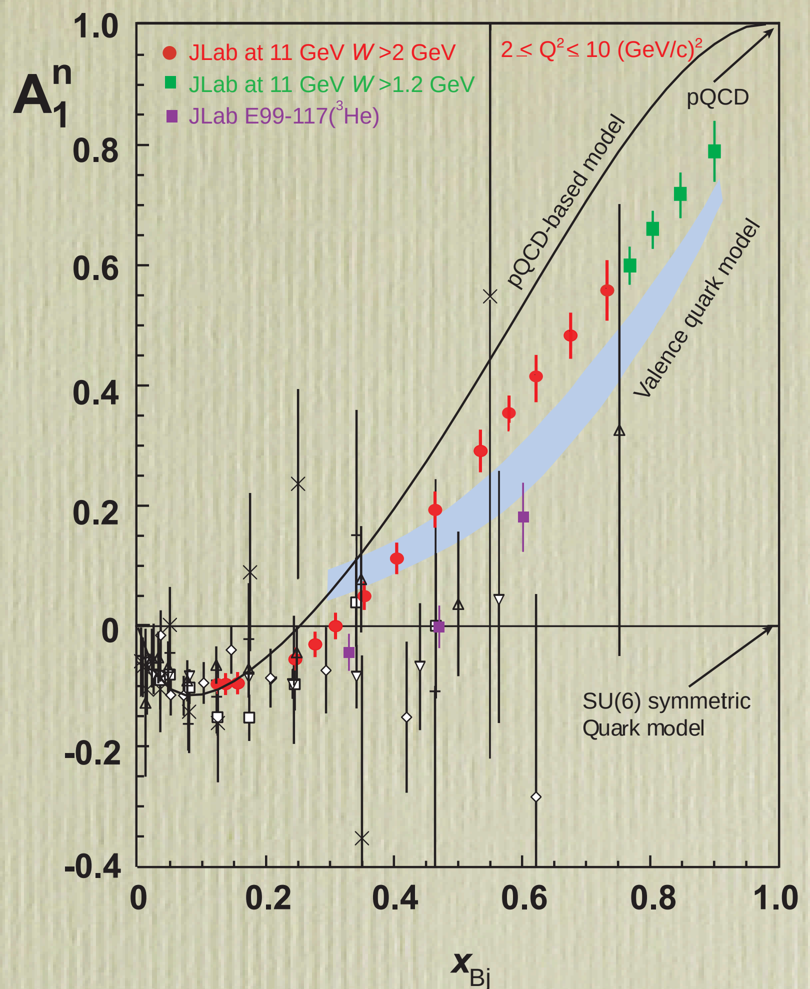


Figure 12: Projected measurement of the neutron polarization asymmetry, A_1^n, with the 12 GeV Upgrade. The shaded band represents the range of predictions of valence quark models; the solid line is the prediction of a pQCD–based quark model.

Why is PQCD Relevant?

$x_{bj} \to 1$ Is A Far Off-Shell Domain of The Hadron Light-Front Wavefunction $\psi_n(x_i, k_{\perp i}, \lambda_i)$

$\sum_{i=1}^{n} x_i = 1$

Thus $x_{bj} \to 1$ implies $x_i \to 0$ for all spectators

$x \equiv \frac{k^+}{P^+} \equiv \frac{k^0+k^z}{P^0+P^z}$

Thus $x_{bj} \to 1$ requires $k^z \to -\infty$
since $k_\perp^2 + m^2 \neq 0$.

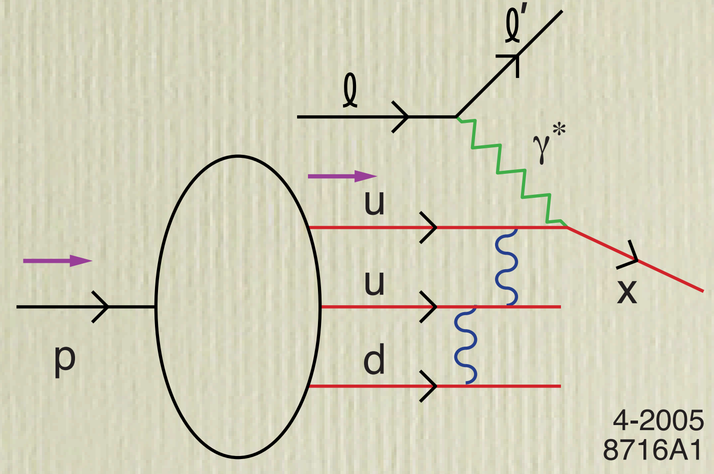
Why is PQCD Relevant?

The spectator system has a timelike mass $(P-k)^2 = M^2_{spect} > 0$

The struck quark is far off-shell:

$$k_F^2 - m^2 = x[M_p^2 - \mathcal{M}^2] \simeq -\frac{k_\perp^2 + M^2_{spect}}{1-x}$$

Thus $k_F^2 \to -\infty$ for $x_{bj} \to 1$.



Lepage, SJB

Why is large x Important?

- Higher-twist subprocess enhanced: $\frac{1}{(1-x)^p}$

- Exclusive-Inclusive Duality

- Intrinsic heavy quarks **at large** x

- Utilize maximal energy of beam:
  e.g., forward Higgs production

Two approaches to evaluating LFWFs at Short Distances

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

$k_\perp^2 >> \Lambda_{QCD}^2$ and/or $x_i \to 1$

- Use PQCD (minimally connected tree graphs)

- AdS/CFT (duality between string theory and conformal field theory)

In practice: QCD: Approximately Conformal

$$\left|\Psi_h(P^+,\vec{P}_\perp)\right\rangle = \sum_{n,\lambda_i}\int [dx_i\ d^2\vec{k}_{\perp i}]\ \psi_{n/h}(x_i,\vec{k}_{\perp i},\lambda_i)\ |n : x_iP^+, x_i\vec{P}_\perp+\vec{k}_{\perp i},\lambda_i\rangle$$

Conformal Behavior:

$$\psi_{n/h}(\vec{k}_\perp) \to (k_\perp)^\ell \left[\frac{1}{\vec{k}_\perp^2}\right]^{n+\delta_n+\ell-1} .$$

Model Form from PQCD or AdS/CFT :

$$\psi_{n/h}(x_i,\vec{k}_{\perp i},\lambda_i,l_{zi}) \sim \frac{(g_s\ N_C)^{\frac{1}{2}(n-1)}}{\sqrt{N}_C}\prod_{i=1}^{n-1}(k_{i\perp}^{\pm})^{|l_{zi}|}\left[\frac{\Lambda_o}{\mathcal{M}^2-\sum_i\frac{\vec{k}_{\perp i}^2+m_i^2}{x_i}+\Lambda_o^2}\right]^{n+|l_z|-1}$$

Near-Conformal Behavior of LFWFs Lead to PQCD Scaling Laws

- Bjorken Scaling of DIS
- Counting Rules of Structure Functions at large x
- Dimensional Counting Rules for Exclusive Processes and Form Factors
- Conformal Relations between Observables
- No Renormalization Scale Ambiguity

Counting Rules:

$$q(x) \sim (1-x)^{2n_{spect}-1} \text{ for } x \to 1$$

$$F(Q^2) \sim (\frac{1}{Q^2})^{(n-1)}$$

$$\frac{d\sigma}{dt}(AB \to CD) \sim \frac{F(t/s)}{s^{(n_{participants}-2)}}$$

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

$$\frac{d\sigma}{d^3p/E}(AB \to CX) \sim F(\hat{t}/\hat{s}) \times \frac{(1-x_R)^{(2n_{spectators}-1)}}{(p_T^2)^{(n_{participants}-2)}}$$

PQCD:

Valence quark distributions in the proton

$n_{spectator} = 2$

$q^+(x) \sim (1-x)^3 \qquad S^z_q = S^z_p$

$q^-(x) \sim (1-x)^5 \qquad S^z_q = -S^z_p$

Sea quark distributions $n_{spectator} = 4$

$q^+(x) \sim (1-x)^7 \qquad S^z_q = S^z_p$

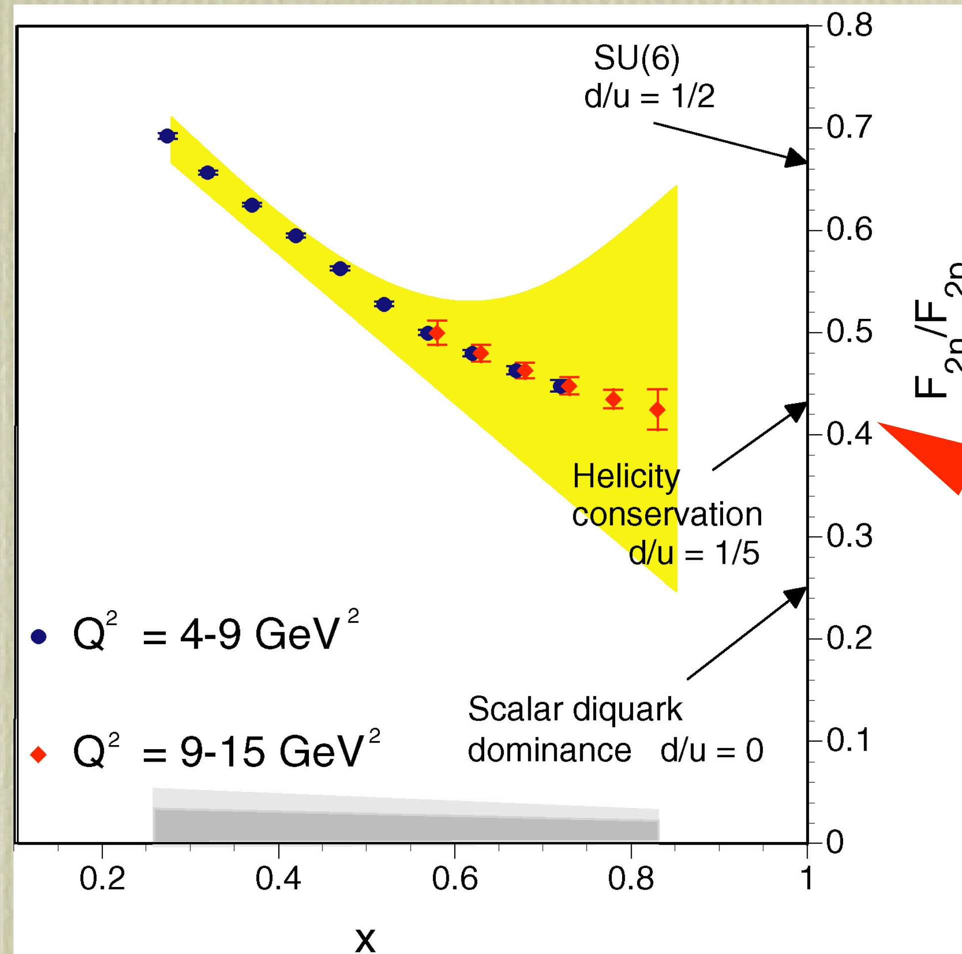
$q^-(x) \sim (1-x)^9 \qquad S^z_q = -S^z_p$

$SU(6)$ Flavor-Spin Symmetry:

$u^+ : u^- : d^+ : d^-$

5/3 : 1/3 : 1/3 : 2/3 for proton

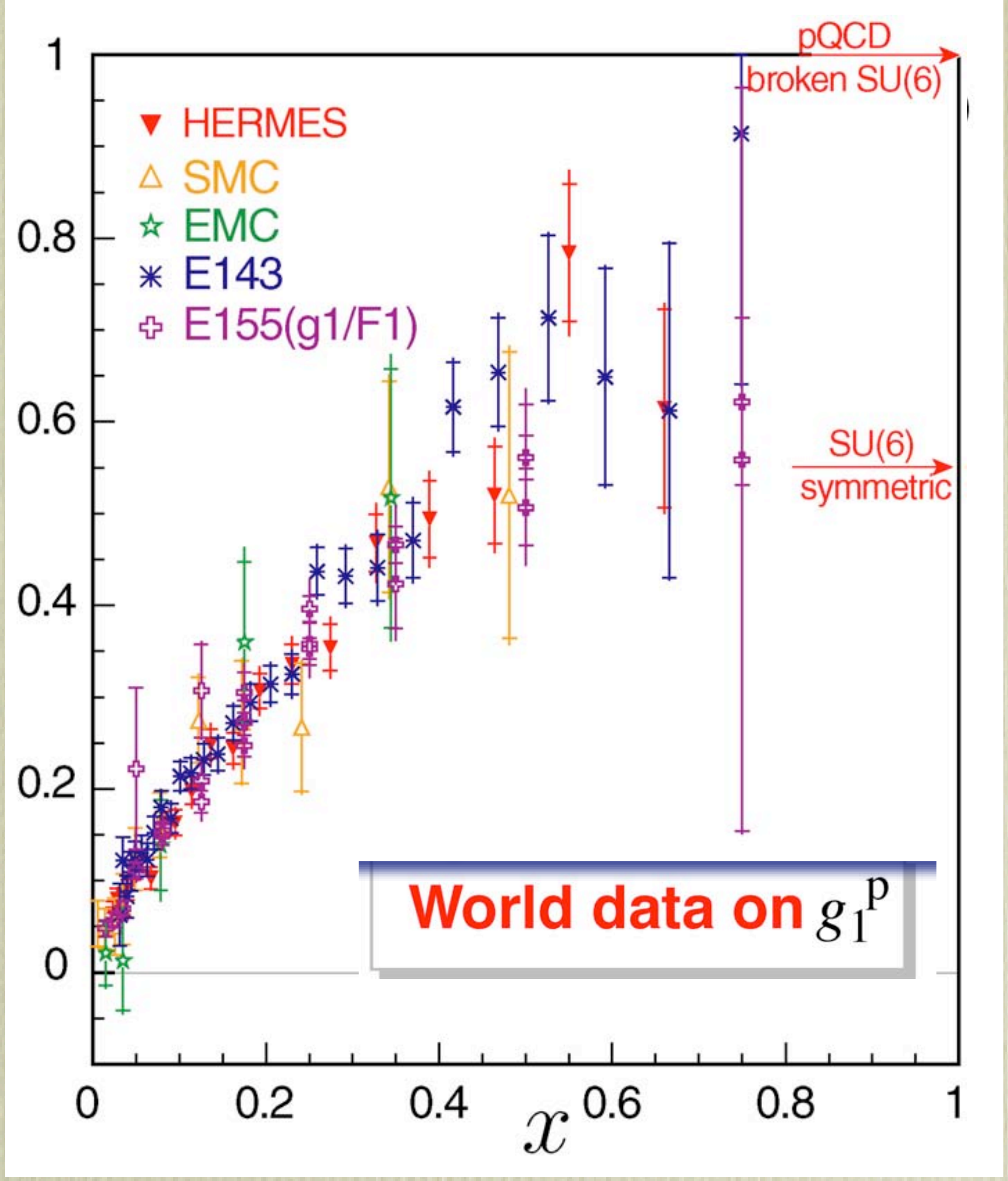
Thus
$d(x)/u(x) \to d^+(x)/u^+(x) \to 1/5$
at $x \to 1$ in proton



PQCD

$$\frac{F_{2n}(x)}{F_{2p}(x)} \to \frac{\sum_{q/p} e_q^2 q_p^+(x)}{\sum_{q/p} e_q^2 q_n^+(x)} = \frac{5\frac{1}{9}+\frac{4}{9}}{5\frac{4}{9}+\frac{1}{9}} = \frac{3}{7}$$ = 0.4286 ...

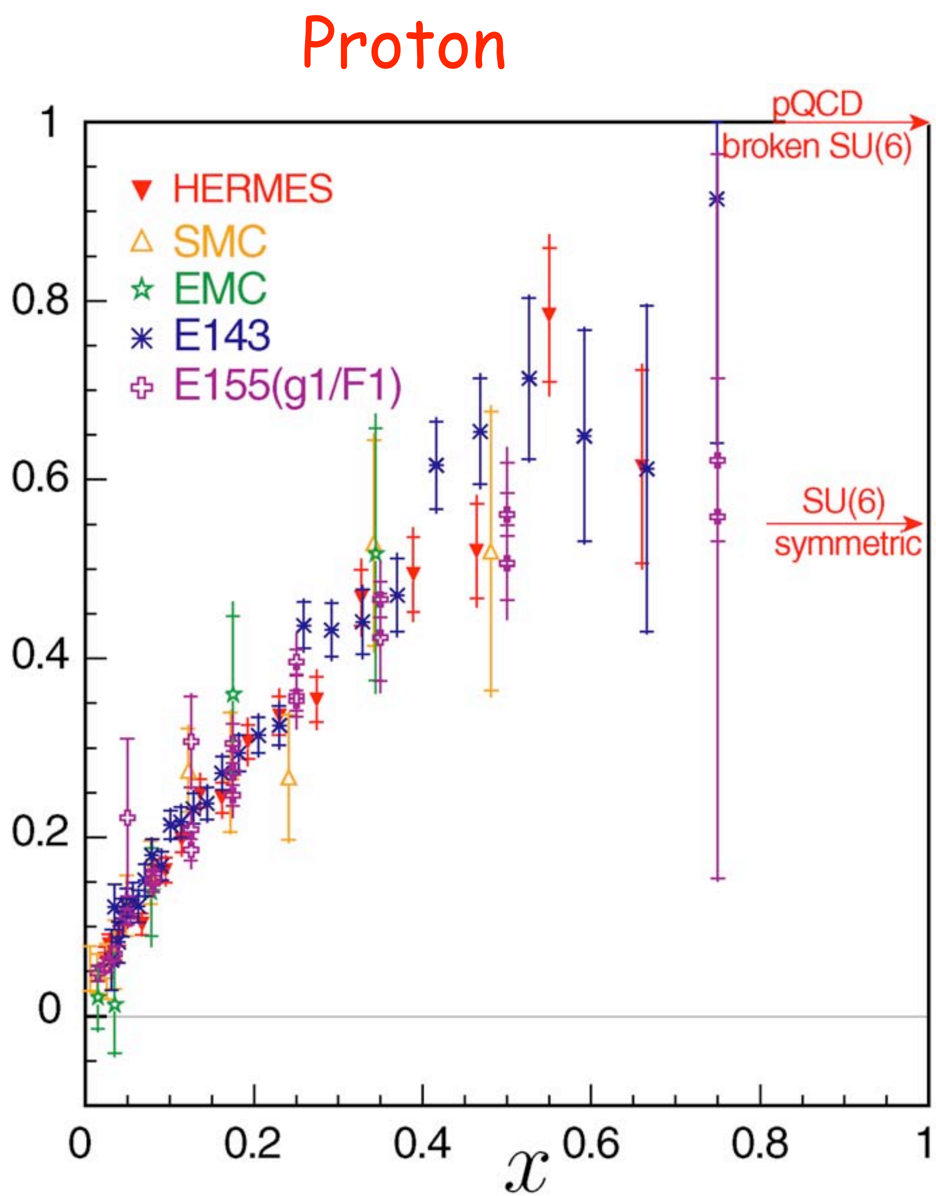
at $x \to 1$

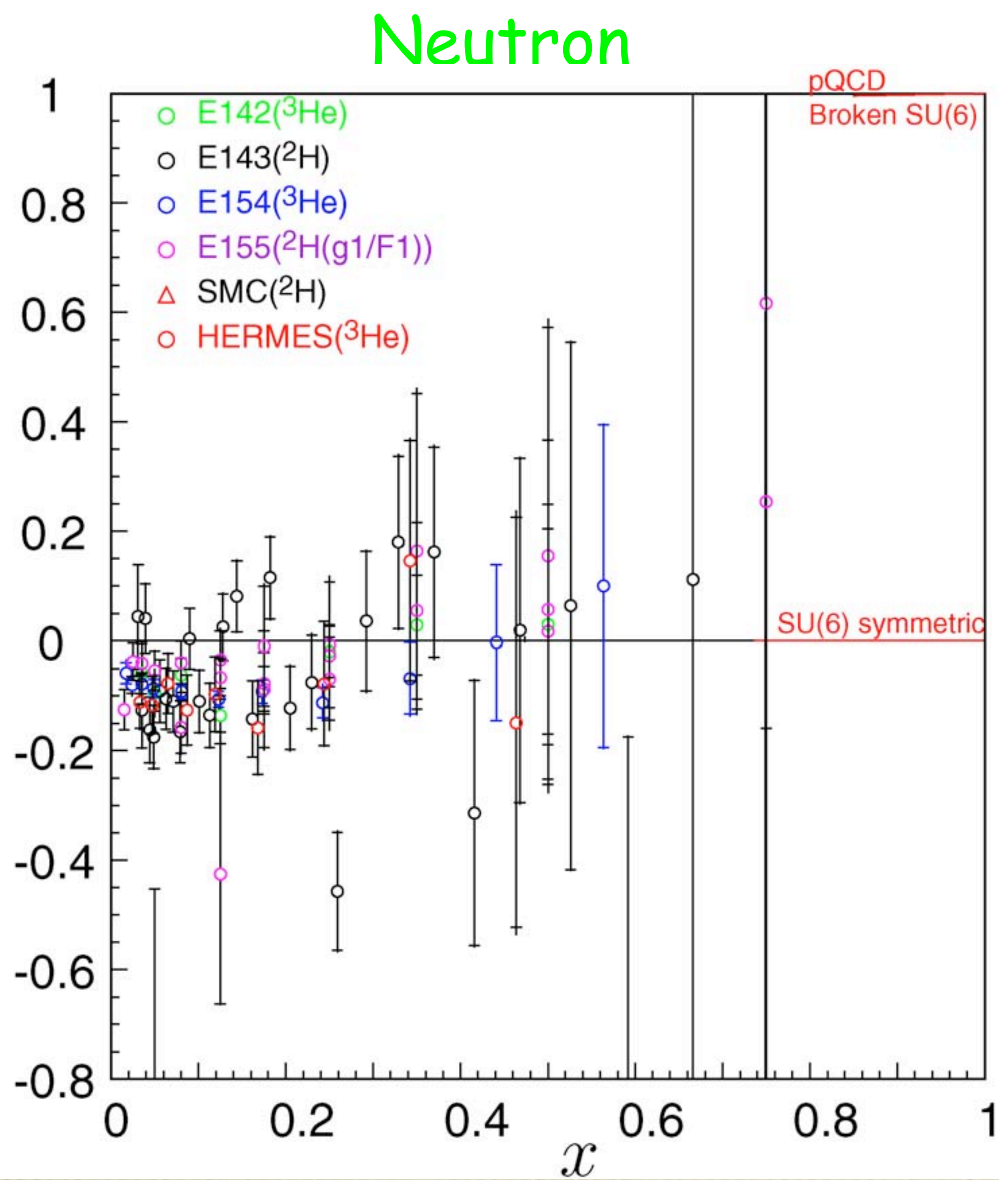


DIS Summary

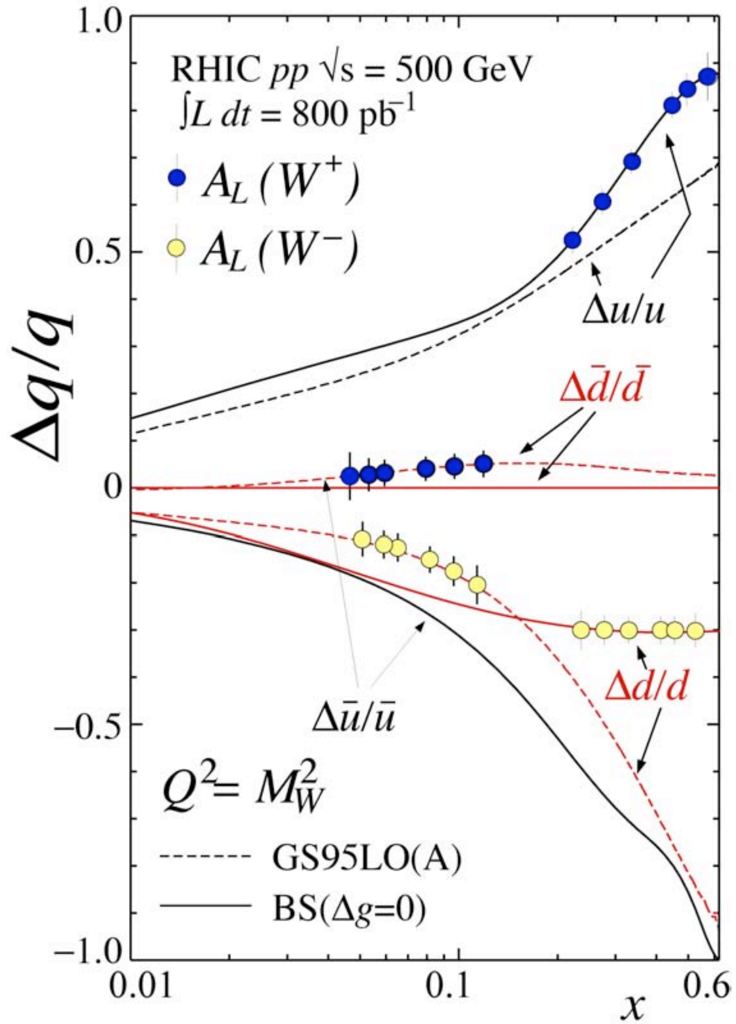
Stan Brodsky, SLAC

World data for A_1

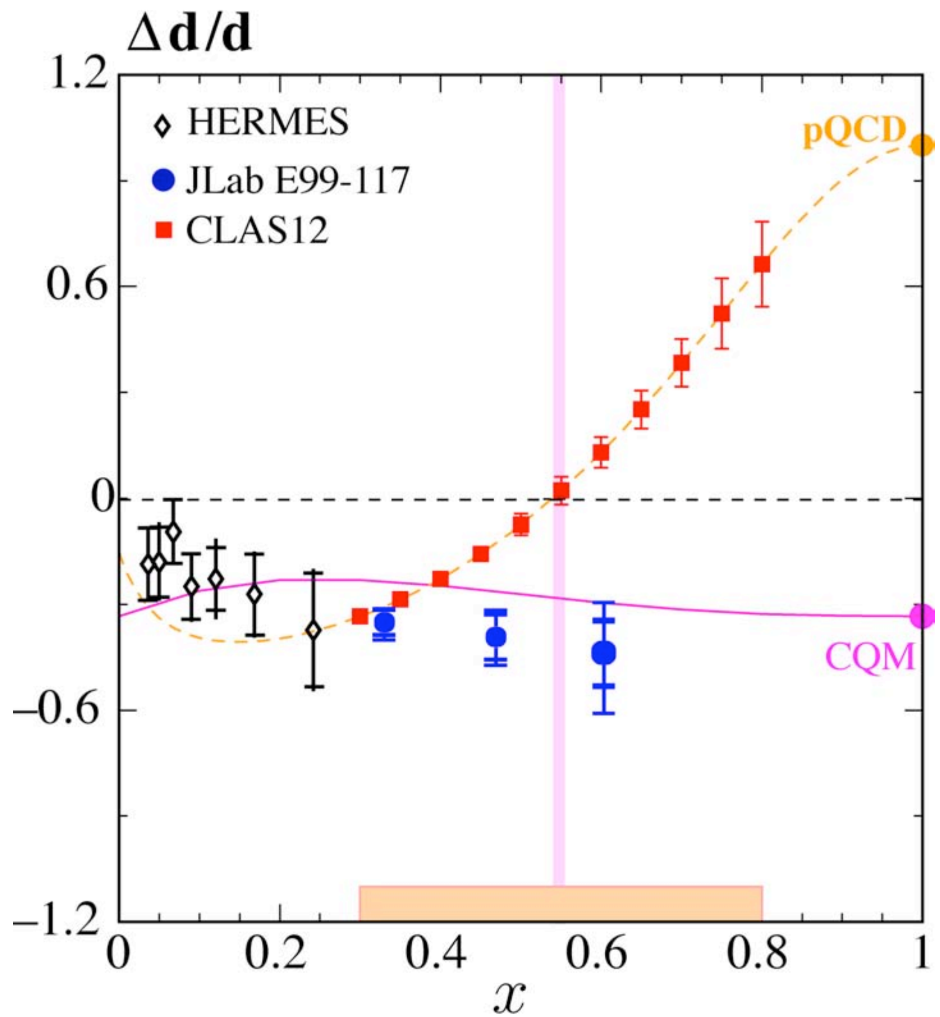




At RHIC with W production

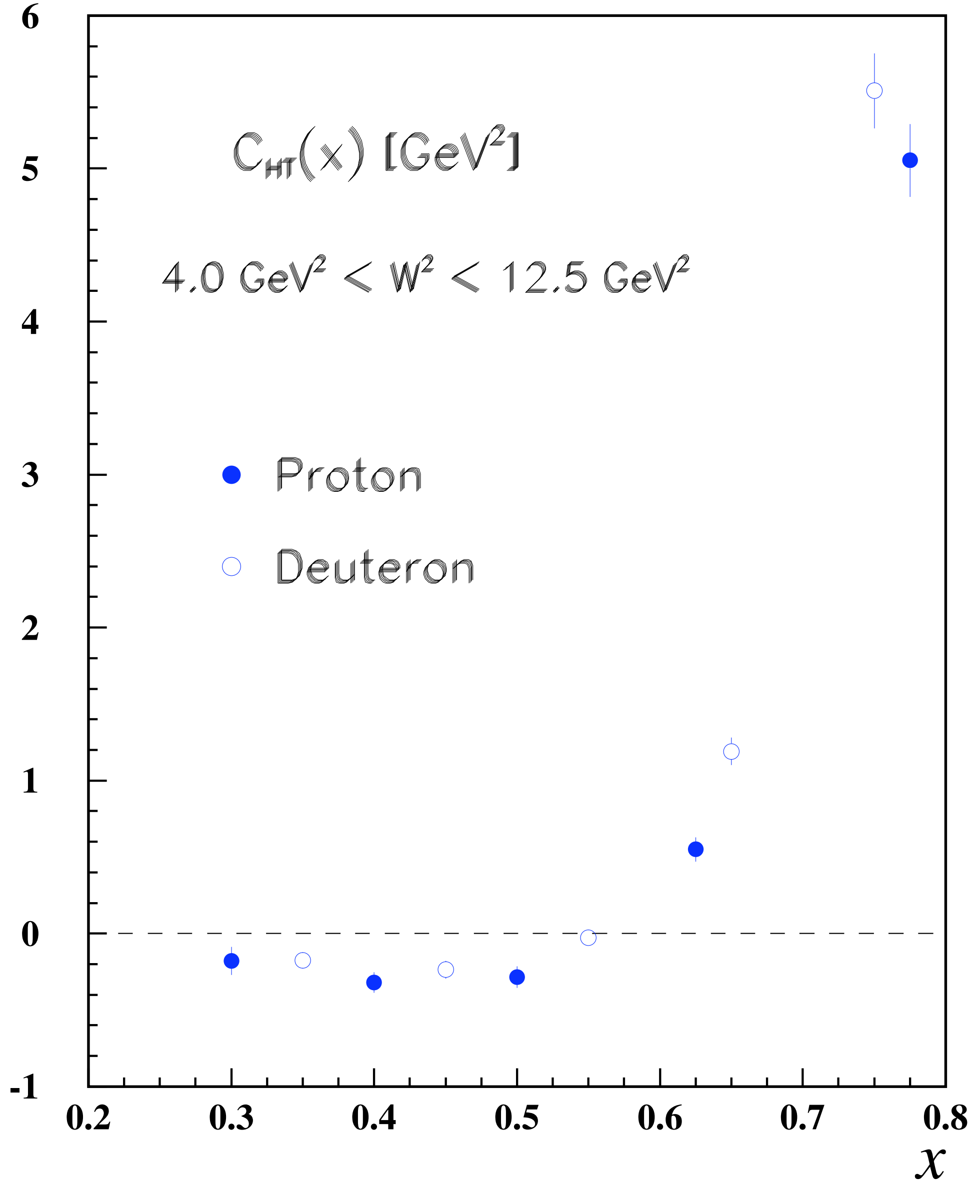


At JLab 12 GeV with SIDIS



Meziani

Higher Twist Effect

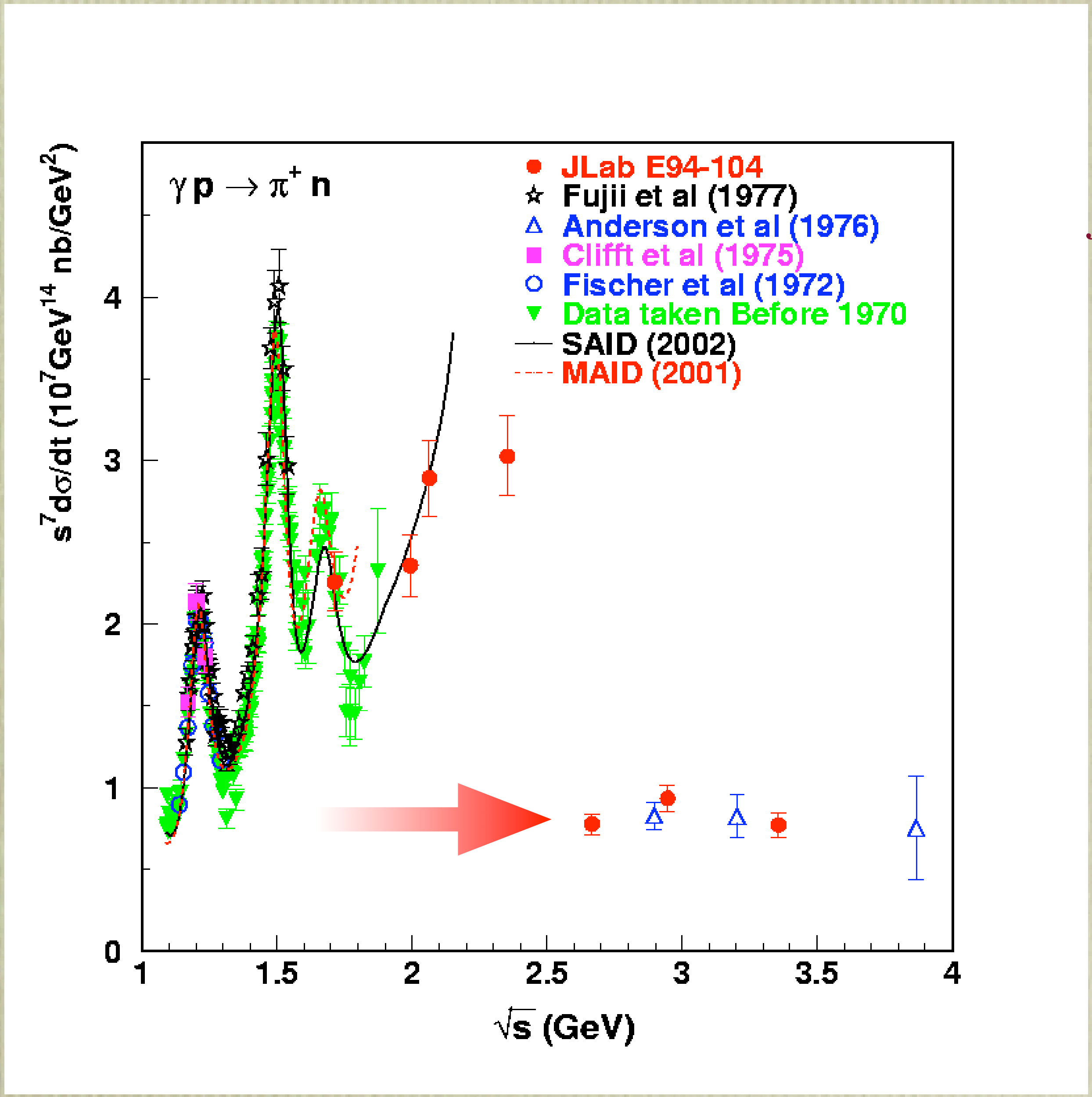


from (u u) $\gamma^* \to (uu)$

$$\frac{F_\pi^2(Q^2)}{(1-x)^2} \simeq \frac{C}{Q^4(1-x)^2}$$

DIS Summary

Test of PQCD Scaling



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

PQCD and AdS/CFT:

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

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

Possible substructure at strangeness and charm thresholds

Novel Nuclear Effects

- Hidden Color
- Shadowing/ Antishadowing; Non-universality
- EMC Effect
- x > 1
- Exclusive Nuclear Processes
- Color Transparency of Quasielastic processes

- New Topics at JLAB 12 GeV:

- Hidden Color at large t: γd to $\Delta^{++} \Delta^{-}$

- Color Transparency Tests

- Charm at Threshold

- s(x) vs. Anti-s(x) Distributions LF Quantization

- J=0 Fixed Pole

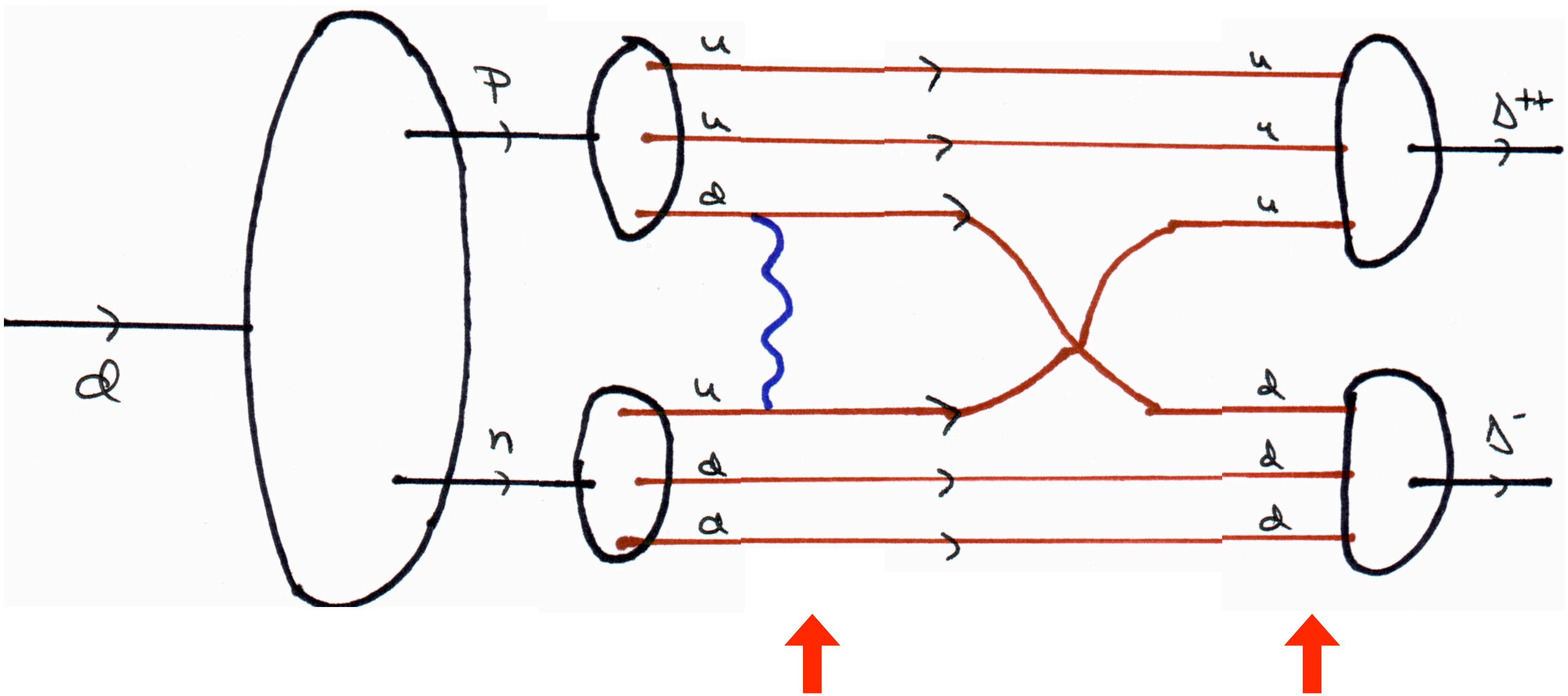
- Charged cubed

Lepage, Ji, sjb

Hidden Color in QCD

- Deuteron six quark wavefunction:
- 5 color-singlet combinations of 6 color-triplets -- one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

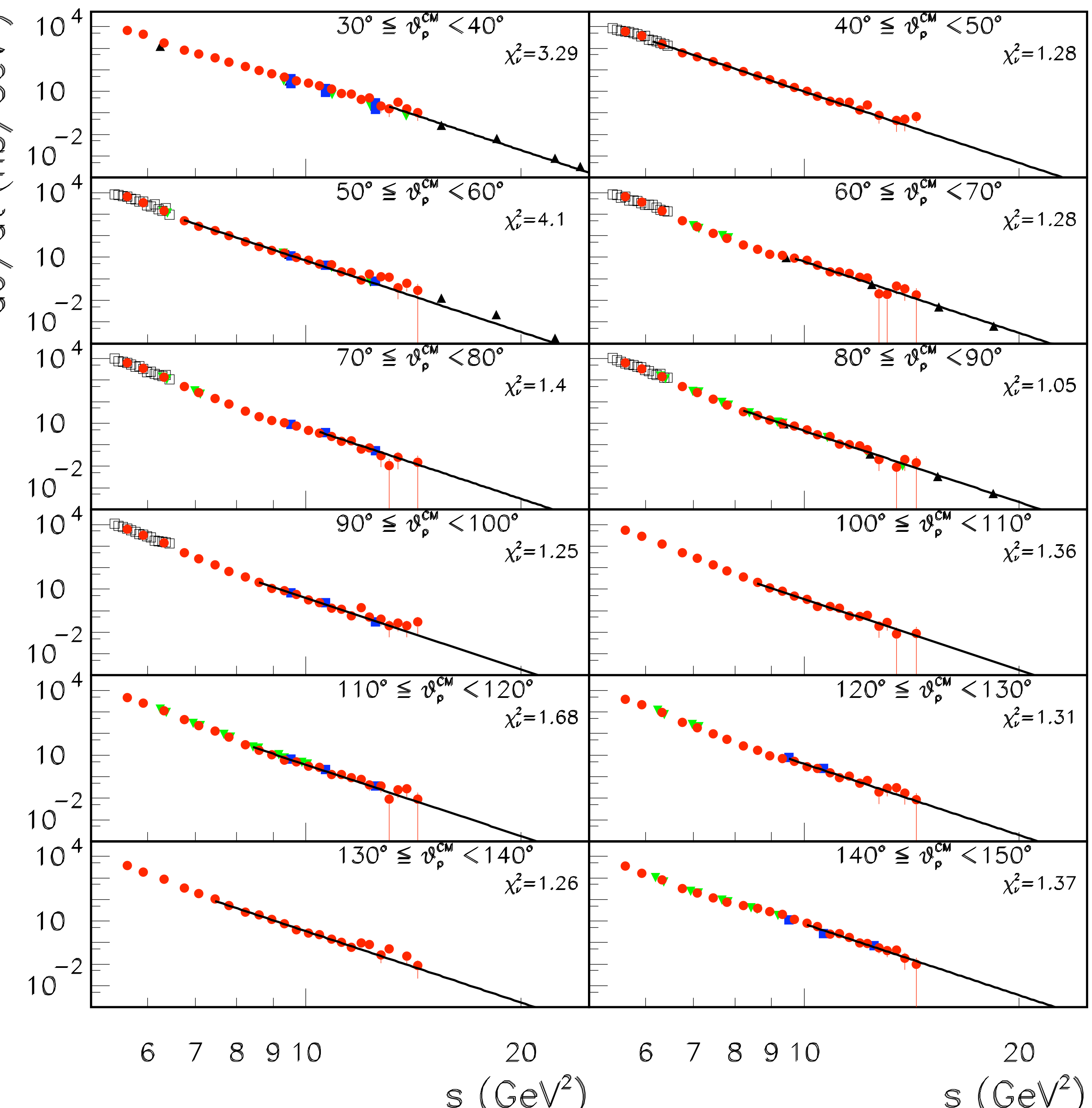
Structure of Deuteron in QCD



Hidden Color Fock State

Delta-Delta Fock State

Deuteron Photodisintegration & Dimensional Counting Rules



PQCD and AdS/CFT:

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

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

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

Duality

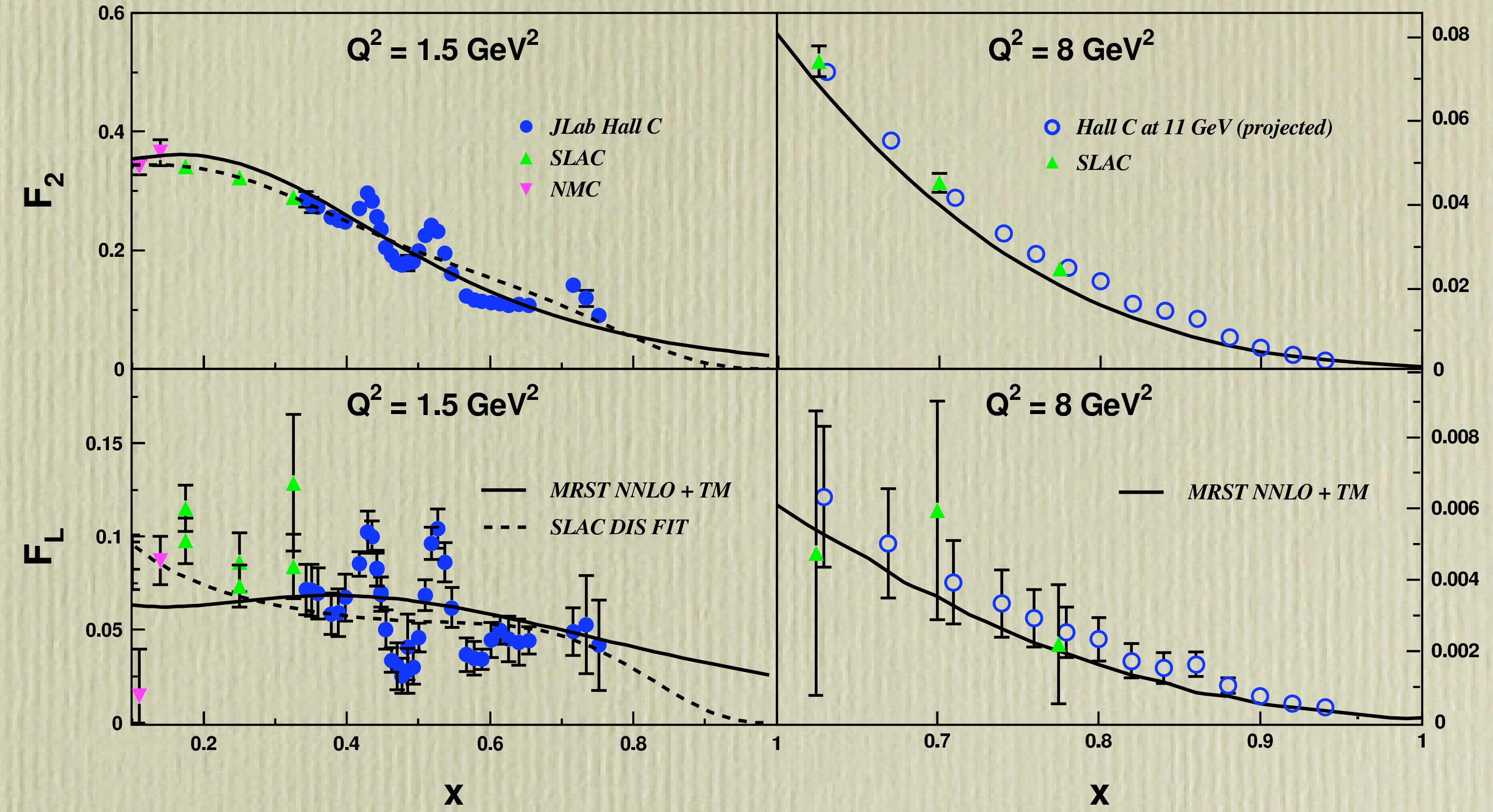


Figure 16: The potential of the 12 GeV Upgrade for exploring quark–hadron duality in the nucleon structure functions F_2 (upper row) and F_L (lower row). The left panels show the Hall C data taken at 6 GeV, the right panels the projected high–x and high–Q^2 data at 12 GeV.

Crucial Prediction of PQCD

$(1\text{-}x)^3$ vs. $(1\text{-}x)^5$

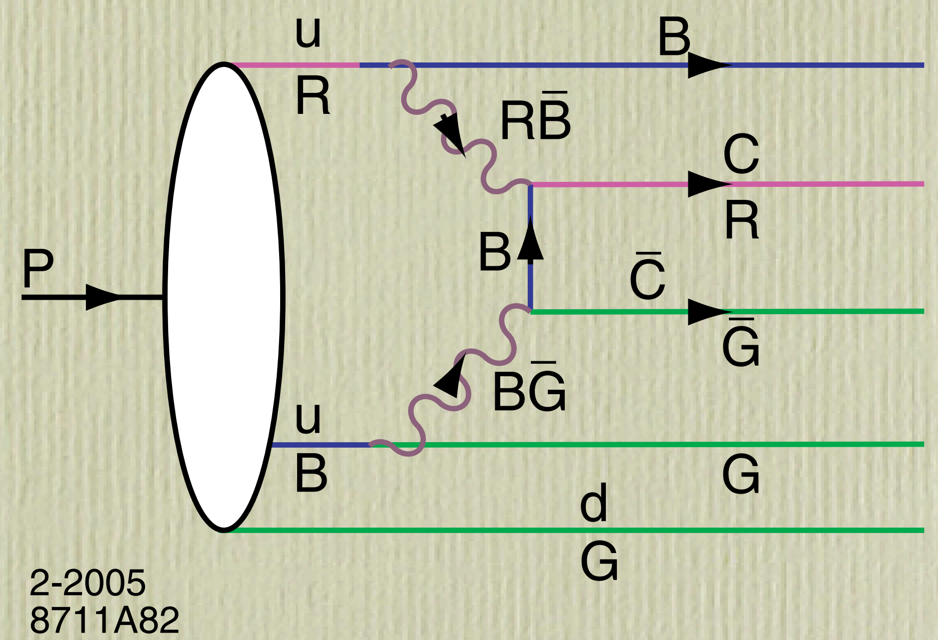
- Higher-twist subprocess enhanced: $\frac{1}{(1-x)^p}$

- Exclusive-Inclusive Duality

- Intrinsic heavy quarks **at large** x

- Utilize maximal energy of beam:
  e.g., forward Higgs production

Intrinsic Charm in Proton



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

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

$c\bar{c}$ in Color Octet

High x charm

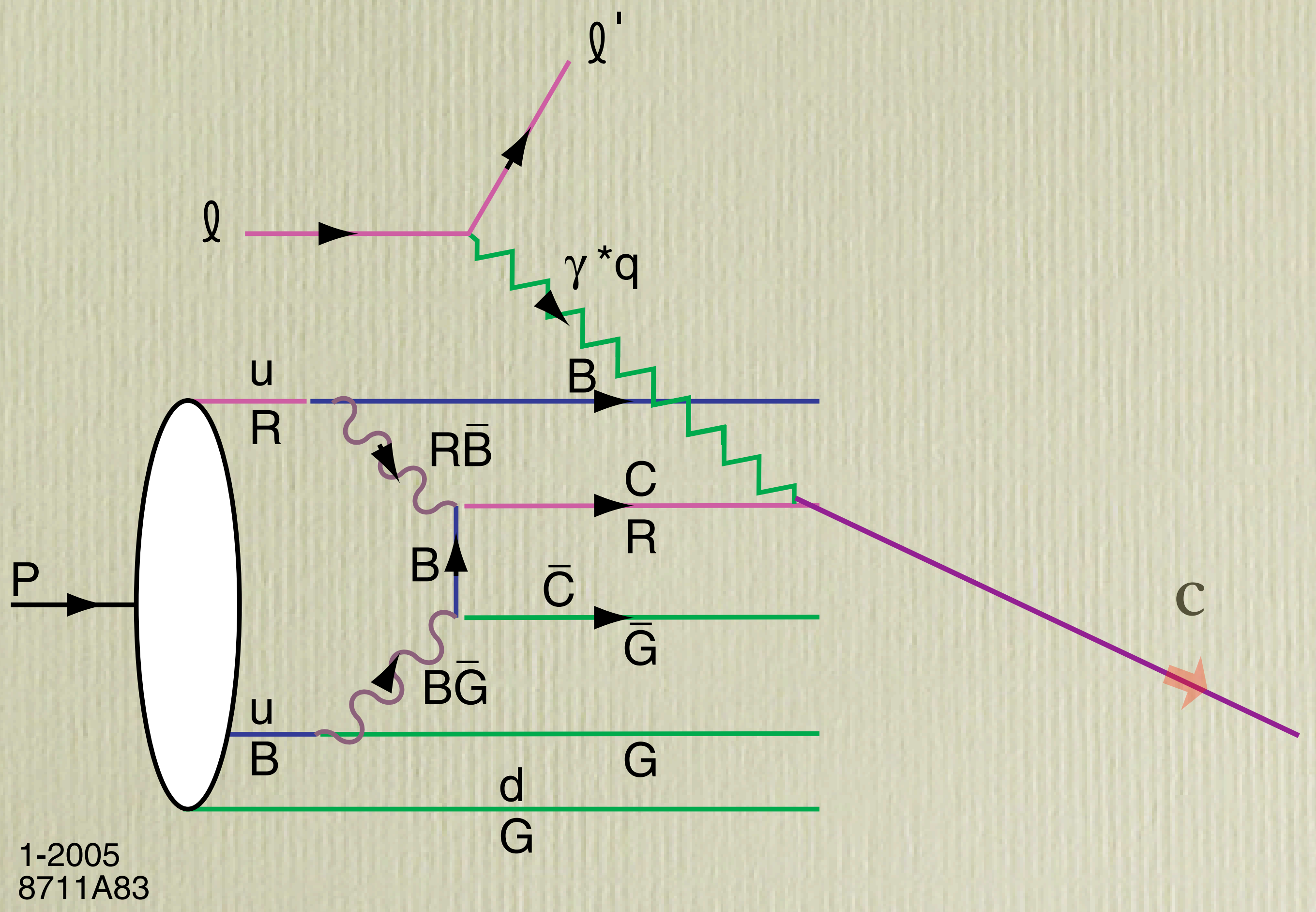
Distribution peaks at equal rapidity (velocity)

Therefore heavy particles carry the largest momentum fractions

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

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

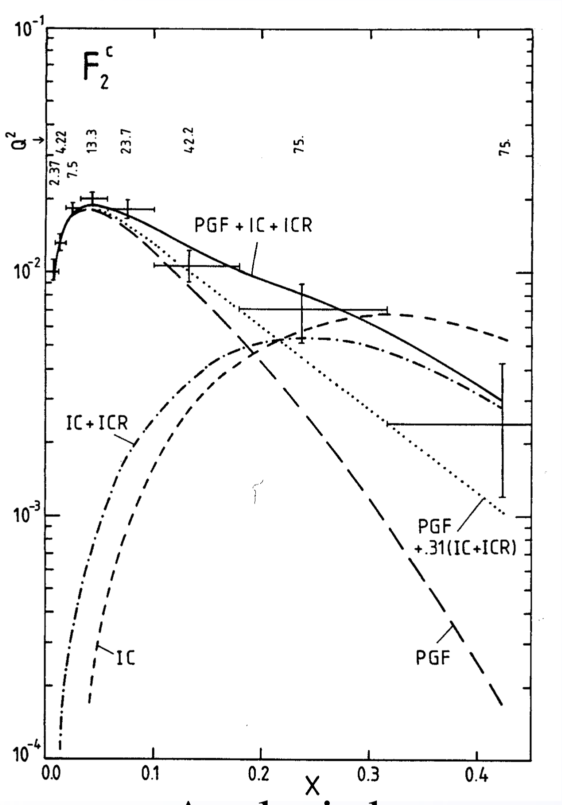
Measure c(x) in Deep Inelastic Lepton-Proton Scattering

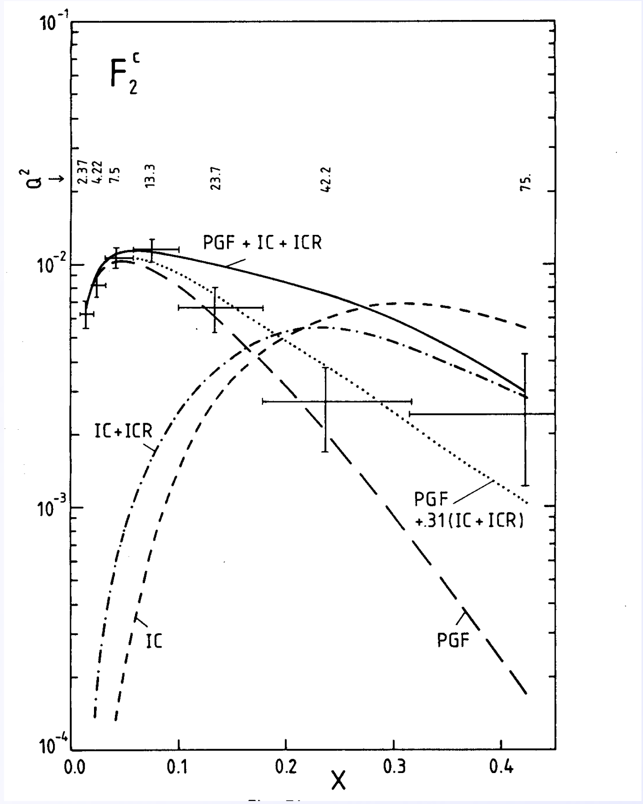


EMC Measurements of the Charm Structure Function

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

1% IC

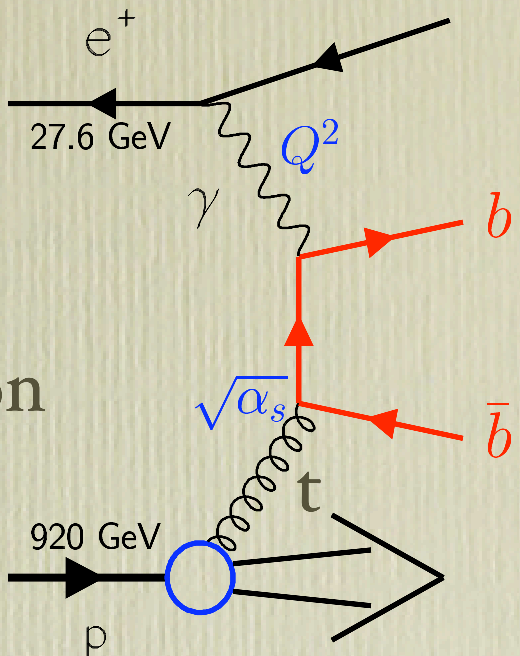




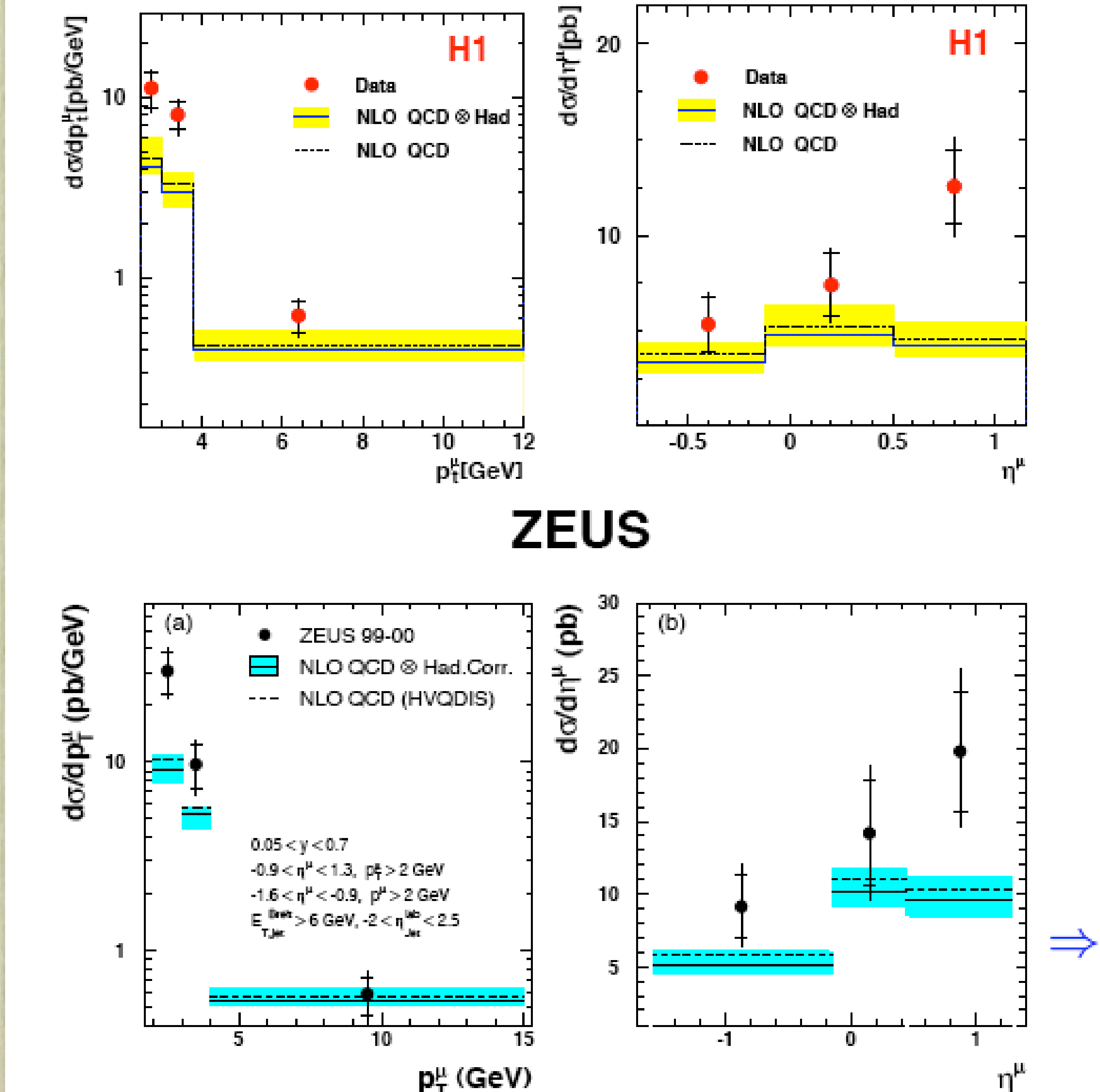
Analysis by
E. Hoffmann and R. Moore, Z. Phys. C 20, 71 (1983).

Photon Gluon Fusion Factor 30 too small

$\gamma^* p \to b\, X$



- New data on inclusive b electroproduction
- H1 and DO
- Anomalously large signals forward rapidity, low transverse momentum
- scale problem? QED: $\gamma^* g \to b\bar{b} : \alpha(t = p_g^2)$
- IB?


H1
Data
NLO QCD ⊗ Had
NLO QCD
dσ/dp$_t^\mu$[pb/GeV]
p$_t^\mu$[GeV]
dσ/dη$^\mu$[pb]
η$^\mu$
ZEUS
(a)
ZEUS 99-00
NLO QCD ⊗ Had.Corr.
NLO QCD (HVQDIS)
0.05 < y < 0.7
-0.9 < η$^\mu$ < 1.3, p$_T^\mu$ > 2 GeV
-1.6 < η$^\mu$ < -0.9, p$^\mu$ > 2 GeV
E$_{T,Jet}^{Breit}$ > 6 GeV, -2 < η$_{Jet}^{lab}$ < 2.5
dσ/dp$_T^\mu$ (pb/GeV)
p$_T^\mu$ (GeV)
(b)
dσ/dη$^\mu$ (pb)
η$^\mu$

⇒

Behnke

- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \to J/\psi X$ (Mueller, Gunion, Tang, SJB)

- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab) (Kopeliovitch, Schmidt, Soffer, SJB)

- IC Explains $J/\psi \to \rho\pi$ puzzle (Karliner, SJB)

- IC leads to new effects in B decay (Gardner, SJB)

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

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

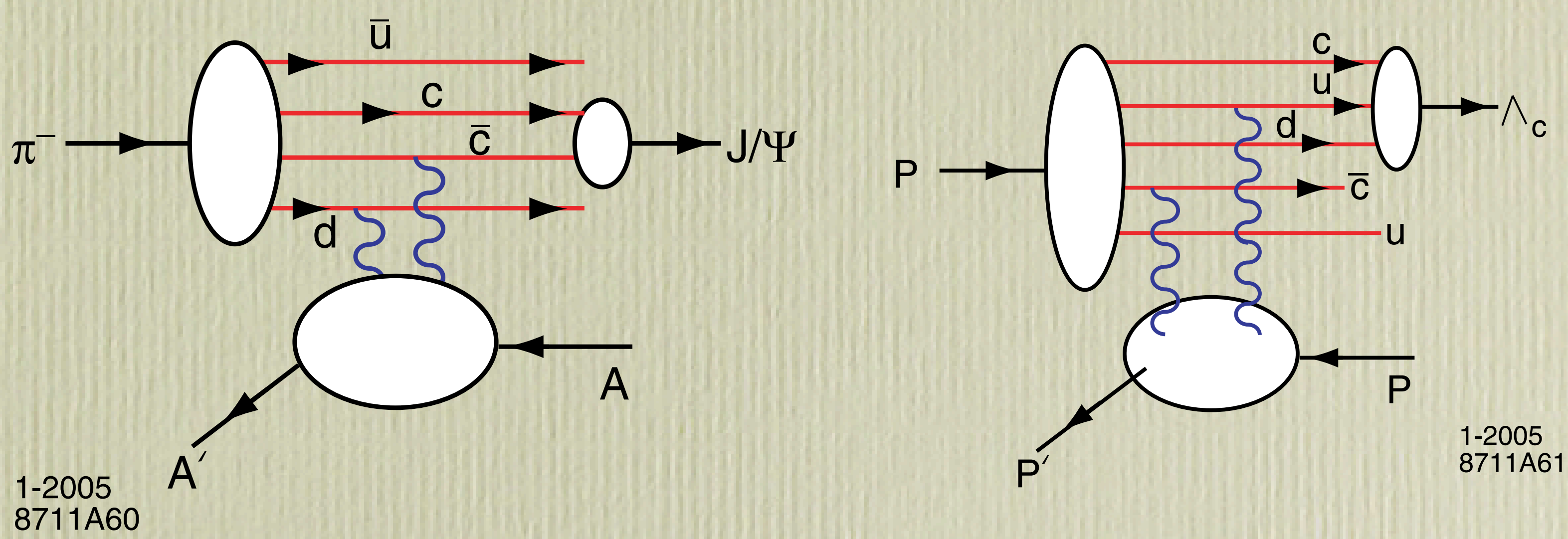
- High x_F $pp \to J/\psi J/\psi X$

- 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)

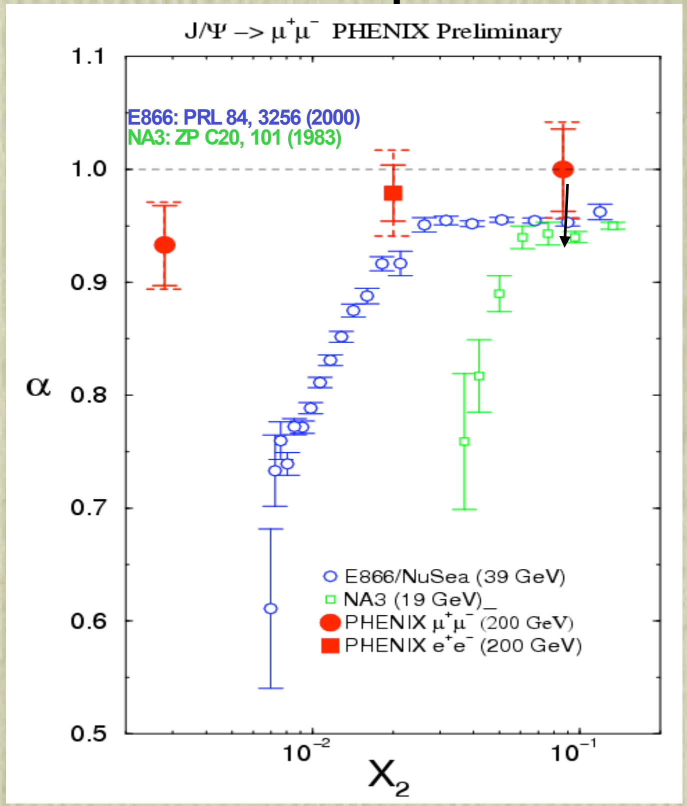
Diffractive Dissociation of Intrinsic Charm

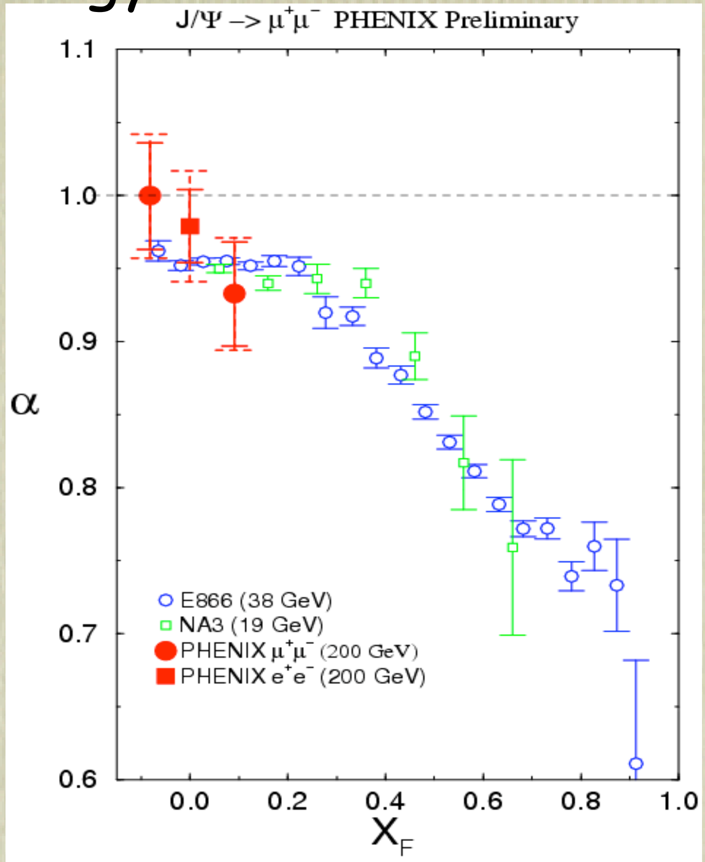


Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

PHENIX compared to lower energy measurements





Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

Data favors (weak) shadowing + (weak) absorption (a > 0.92)

With limited statistics difficult to disentangle nuclear effects

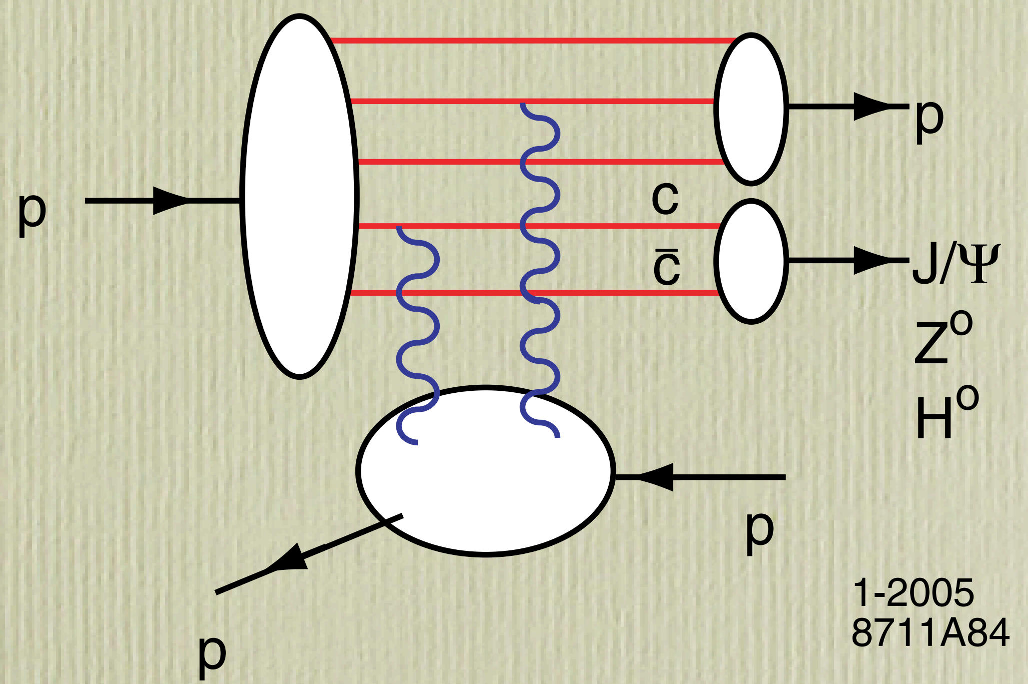
Will need another dAu run! (more pp data also)

Not universal versus X_2 : shadowing is not the main story.

BUT does scale with x_F ! - why?

(Initial-state gluon energy loss -which goes as x_1~x_F - expected to be weak at RHIC energy)

Intrinsic Charm Mechanism for Double Diffraction



$$\mathrm{p\,p} \to J/\psi\; p\; p$$

$$x_{J/\psi} = x_c + x_{\bar{c}}$$

High x_F !

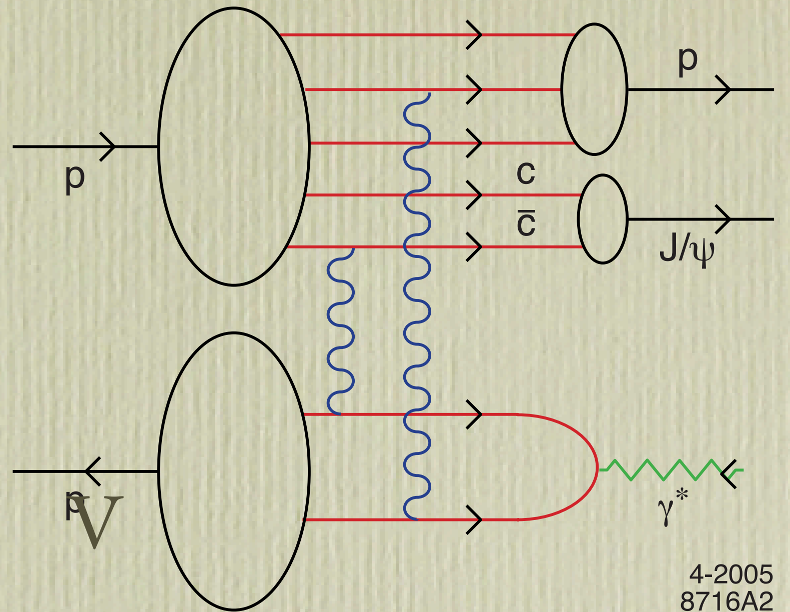
Intrinsic $c\bar{c}$ pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

Collision produces color-singlet J/ψ through color exchange

Schmidt, Soffer, sjb

RHIC Experiment

New Test of Intrinsic Charm



V

Doubly Diffractive DIS Reactions

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

$$\gamma^* p \to \rho + D + \Lambda_c$$

Charm produced at high x_F and small p_T in proton fragmentation region

DIS Summary

Enlarge Role CTEQ,MRST, ...

Extend structure function analysis
to full information on
quark, gluon structure of hadrons

- generalized (unintegrated) parton distributions
- hadron distribution amplitudes $\phi_H(x, Q^2)$
- light-front wavefunctions

- Include large x charm, bottom contributions

- No scale Q_0 where g, sea quarks are zero

- DGLAP modified at $x \sim 1$

- PQCD constraints at $x \to 1$: just as valid as DGLAP

Renormalization Scale Fixing

- Renormalization Scale Fixing:

Not true that any μ_R allowed:

flavor thresholds

Not true that HO estimated by varying μ_R

- $\mu_R = Q/2, 2Q$

arbitrary convention

scheme dependent

Scale-setting in QCD

- BLM procedure: renormalization scale set by absorbing β terms: used in QED, EW, lattice QCD
- Physical scales; multiples scales okay
- Satisfies transitivity property of renormalization group
- Remaining theory identical to conformal theory
- eliminates renormalon n! growth of perturbative expansion
- stabilizes BFKL pomeron; relevant to b electroproduction anomalies?

Future Directions in DIS

- $\gamma d \to \Delta^{++}\Delta^{-}$
  signature for hidden color

- Charm and bottom structure functions at large x: Test intrinsic charm/bottom
  $\frac{b(x,Q^2)}{c(x,Q^2)} \simeq \frac{m_c^2}{m_b^2} \simeq \frac{1}{10}$

- Test universality of nuclear effects
  Antishadowing depends on current, polarization

Demise of HERA, Hermes

- Critical experimental facilities for DIS
- Premature Cancellation reminiscent of ISR
- Polarization and nuclear beams at HERA left undone
- We should be talking about:
- New experiments, DVCS, Diffractive, Heavy Quarks, Trijets, Forward Detectors, HERA3
- New Forward Detectors

Jlab 12 GeV Upgrade

- Comprehensive QCD DIS program with intense, continuous, polarized beams & targets + extensive facilities
- Ideal energy domain for study of valence regime
- Parity violation, nuclear targets, exclusive channels, spin asymmetries, correlations
- DVCS, meson electroproduction, charm at threshold , color transparency, hadronization, hidden color, exotics, higher twist, ...
- Complimentary to GSI antiproton program

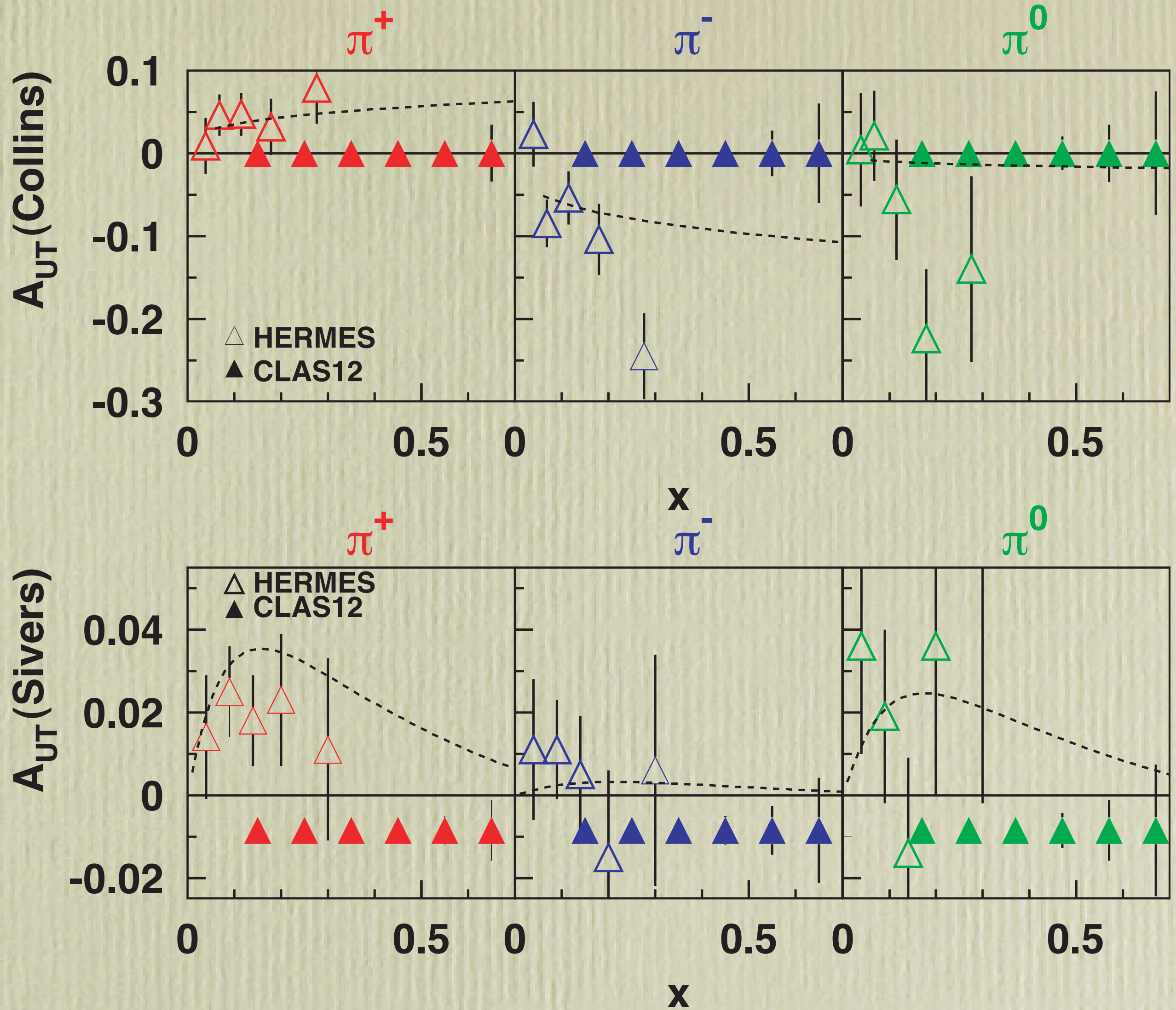


Figure 15: Projected measurements of the Collins and Sivers transverse single–spin asymmetries in semi-inclusive pion production at 12 GeV. The HERMES data are shown for comparison. The curves represent the phenomenological parameterizations of Ref. [Ef04].

High Energy Frontier

- Remarkable nonlinear effects which can be studied with perturbative QCD methods
- small x, large s, dense gluonic field produced in DIS
- BFKL, BK, color saturation, color glass condensate, collective effects
- Hard Pomeron+ Odderon: particle/antiparticle asymmetries
- Some correspondence to nuclear shadowing

High Energy Options

- e-RHIC: Polarized electron and proton/nucleus collide
- proton/nuclear ring at Jlab: ELIC
- LHC plus electron ring : High energy frontier
- Forward detectors essential for physics of the proton