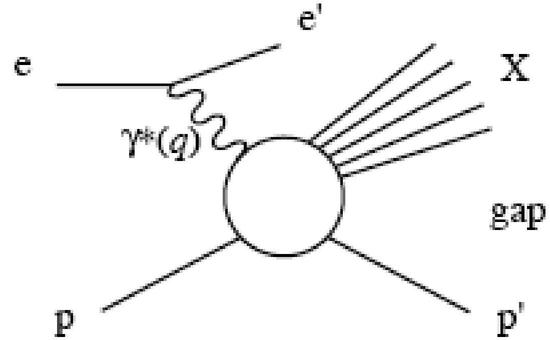
Hard Diffraction from Rescattering

- 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

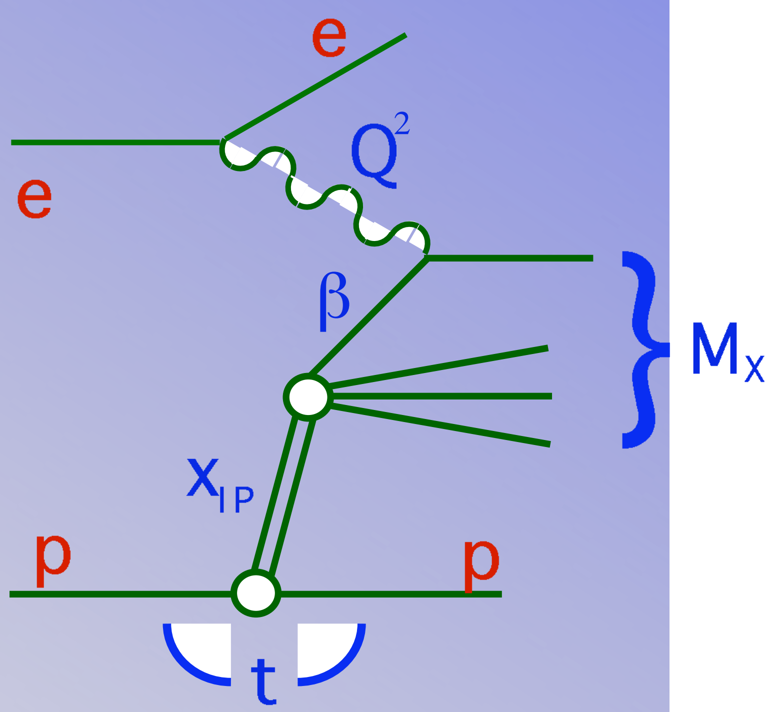
DDIS



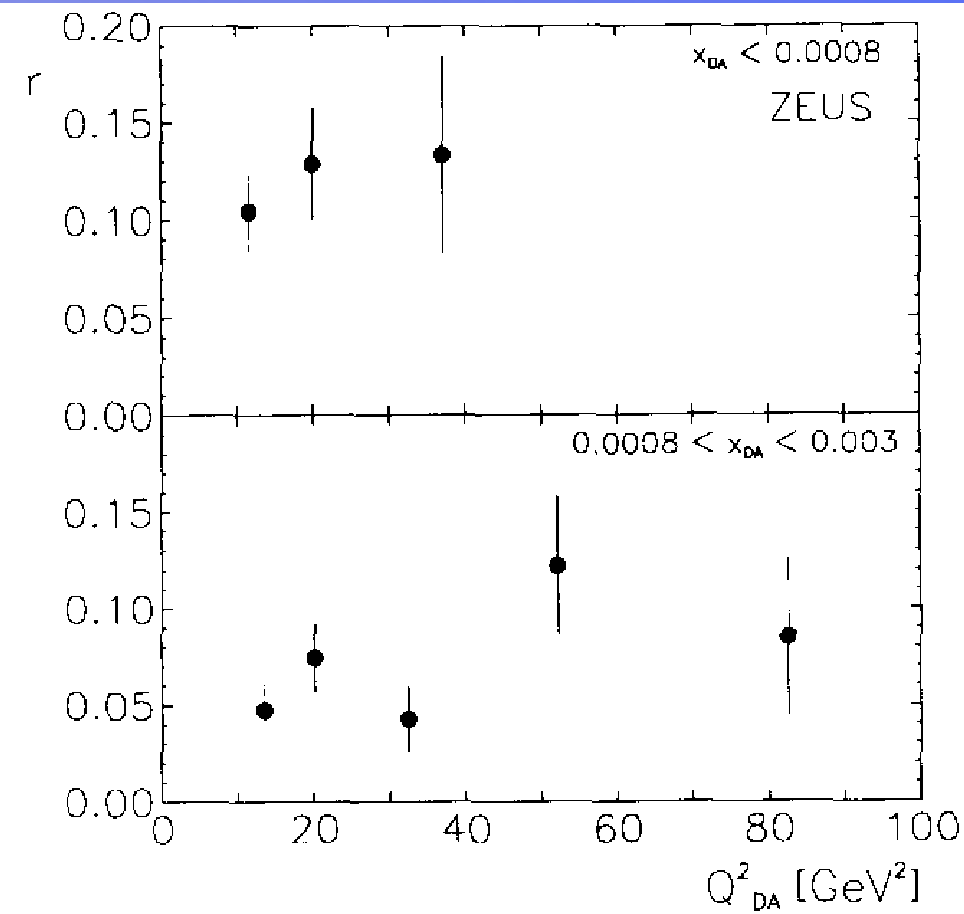
- In a large fraction ($\sim$ 10–15%) of DIS events, the proton escapes intact, keeping a large fraction of its initial momentum
- This leaves a large *rapidity gap* between the proton and the produced particles
- The t-channel exchange must be *color singlet* $\rightarrow$ a pomeron??

Enberg

Diffractive Deep Inelastic Lepton-Proton Scattering



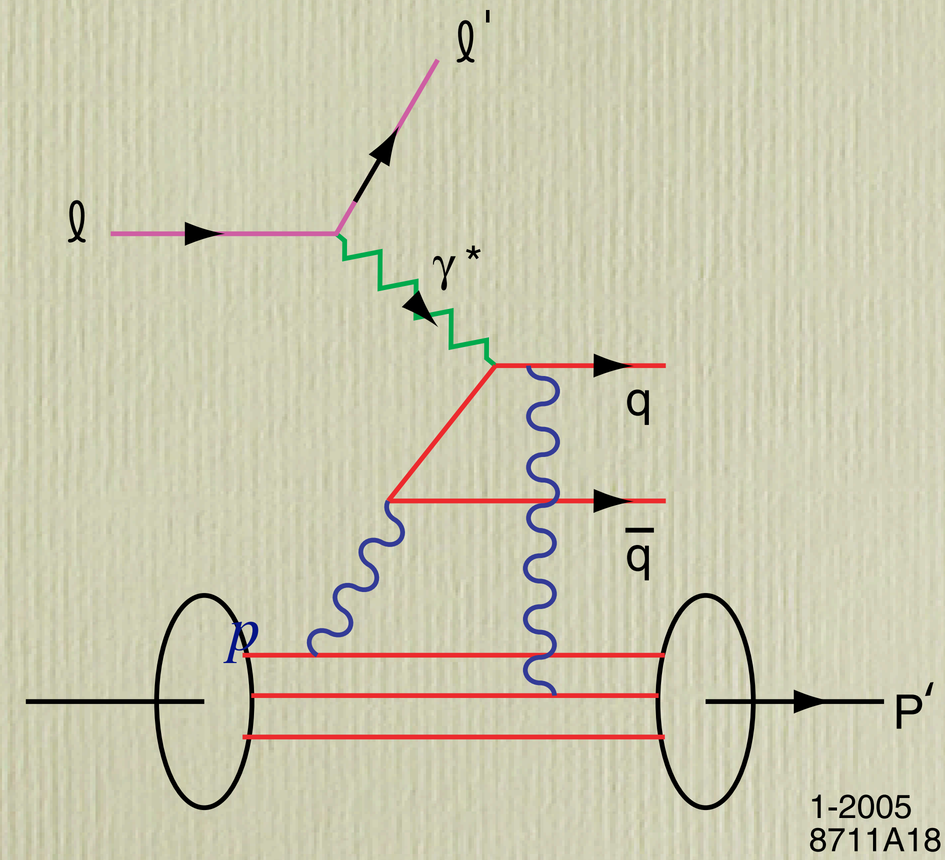
10% of DIS events are diffractive !



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



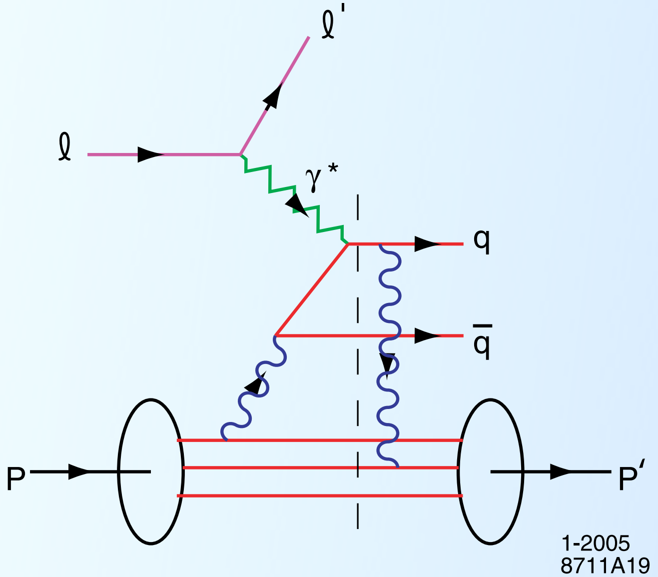
Quark Rescattering

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

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

Hard Diffraction



Integration over on-shell domain produces phase i

Need Imaginary Phase to Generate
Pomeron

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

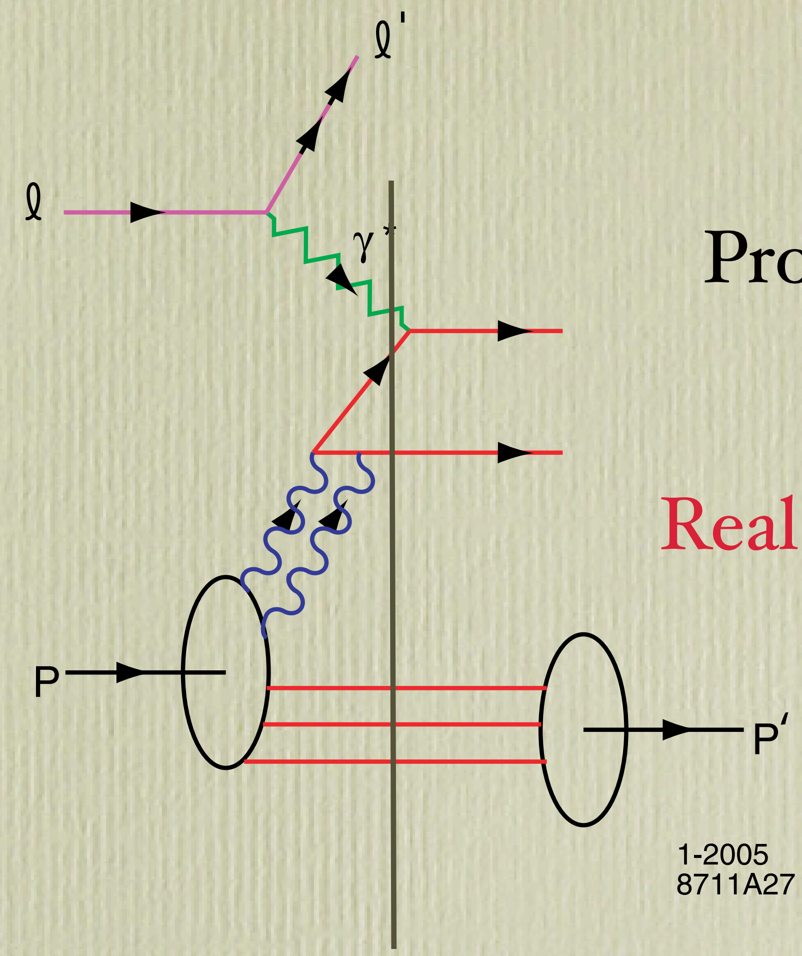
Physics of FSI not in Wavefunction of Target

Hard Diffraction

Problem: Wrong Phase

Real; should be imaginary

Pomeron is not
a constituent
of proton

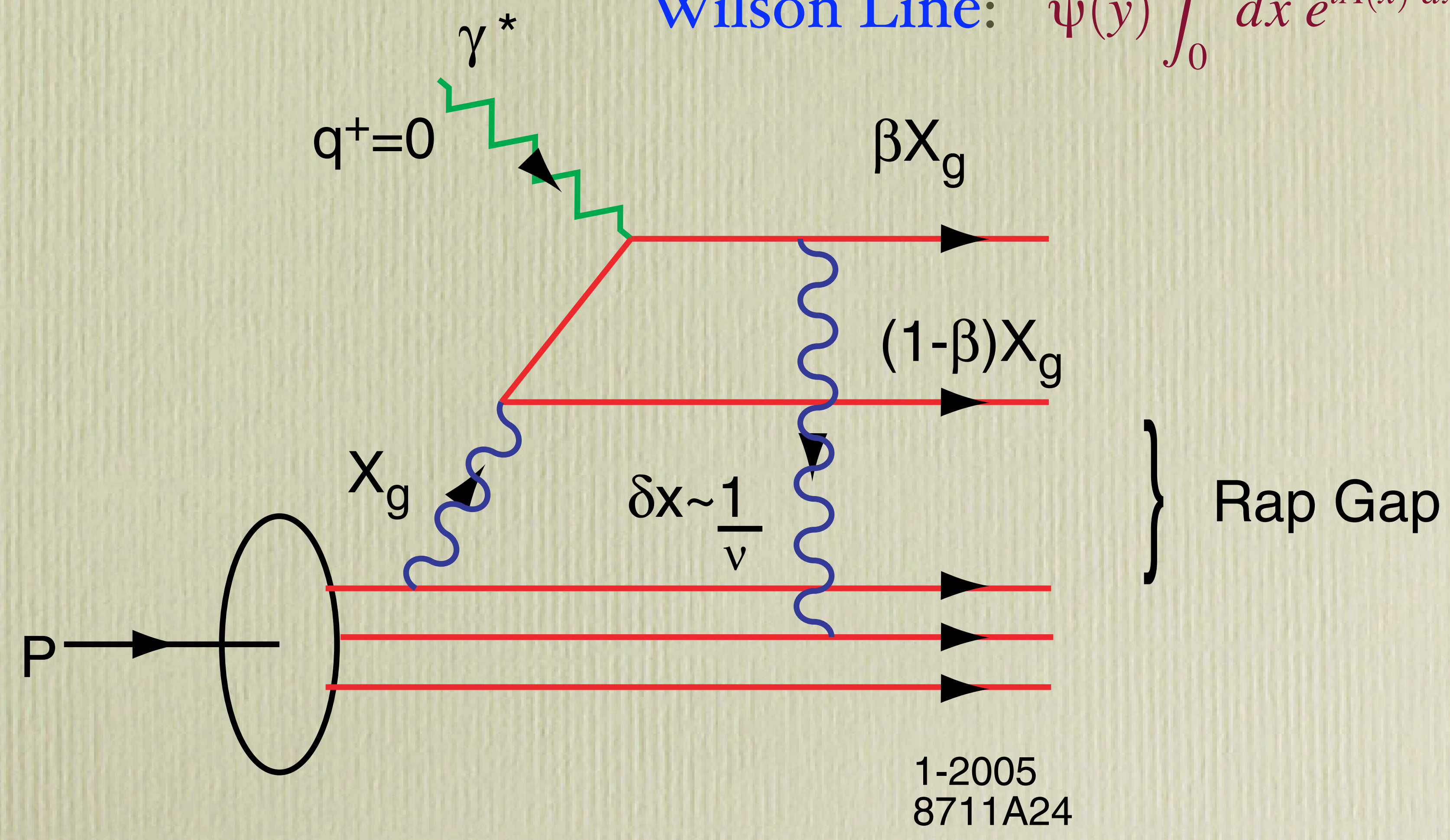


Need Final State Interactions !

Hard Diffraction

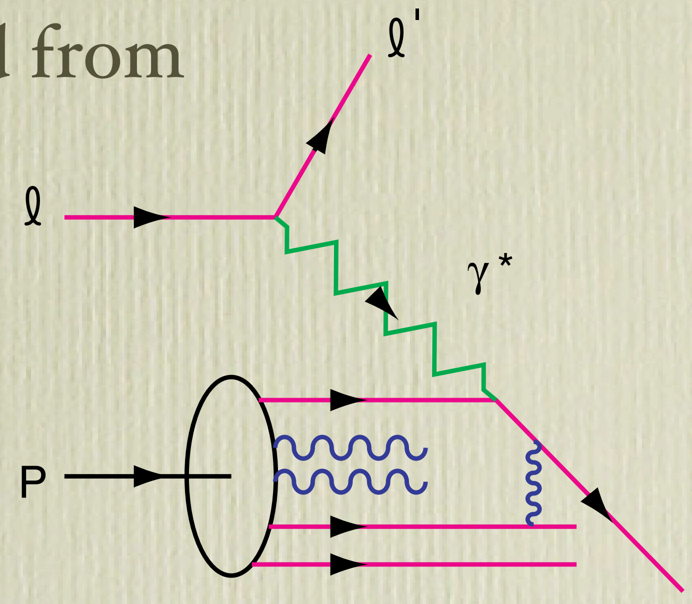
QCD Mechanism for Rapidity Gaps

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



Hard Diffraction

- 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



QCD factorization

- QCD factorization theorem: Separation of hard and soft

  The quark PDF is given by

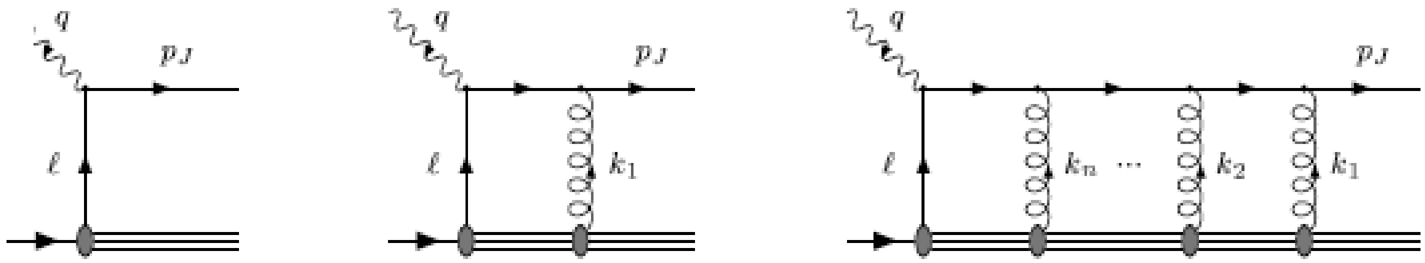
$$f_{q/N} \sim \int dx^- e^{-ix_B p^+ x^-/2} \langle N(p) \,|\, \bar{\psi}(x^-) \gamma^+ W[x^-;0] \, \psi(0) \,|\, N(p) \rangle_{x^+=0}$$

Wilson line: $W[x^-;0] = \mathrm{P}\exp\left[ig \int_0^{x^-} dw^- A_a^+(0, w^-, 0_\perp) t_a \right]$

- DIS: $W[x^-;0] \to$ *rescattering of struck quark* on target
- $A^+ \to$ longitudinal *instantaneous* (in x^+) gluon exch.
- No $A^\perp$ within Ioffe coherence length $x^- \sim 1/m_p x_B$

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

Wilson line means that DIS looks something like this:



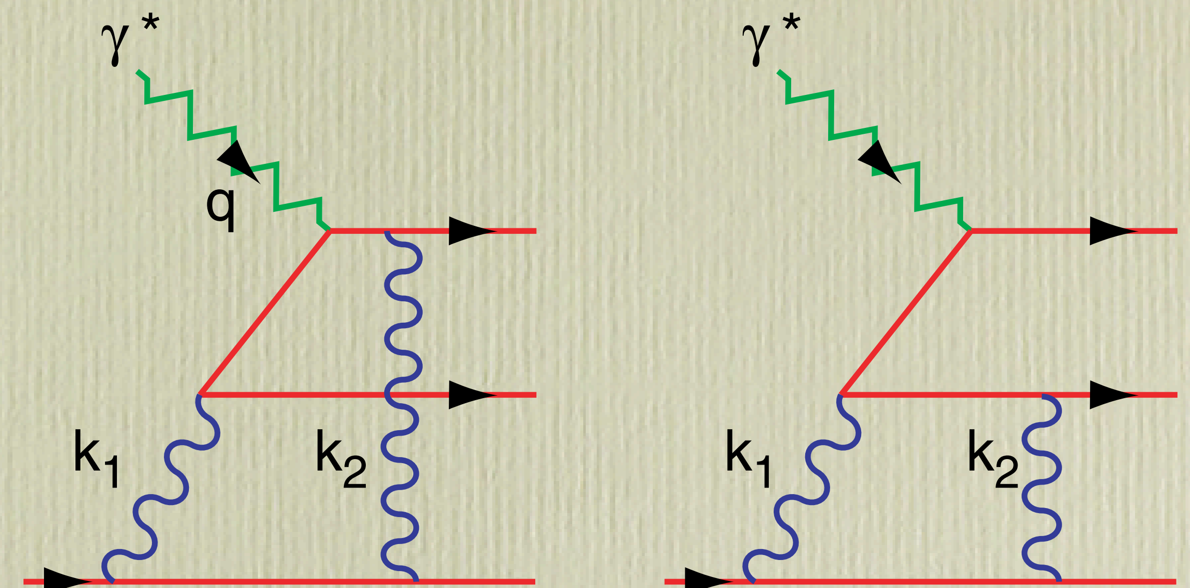
Brodsky, Hoyer, Marchal, Peigné and Sannino (BHMPS) showed that [Phys. Rev. D65 (2002) 114025]

- rescattering can lead to on-shell intermediate states and *imaginary amplitudes* and cannot be ignored in any gauge
- not even in $A^+ = 0$ gauge!

It has also been shown to yield nuclear shadowing and single spin asymmetries.

Enberg

Final State Interactions in QCD



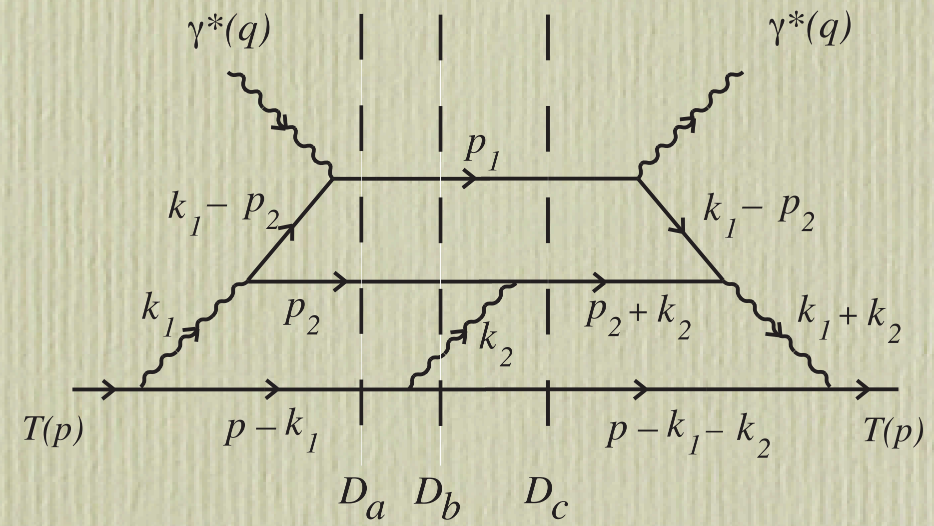
Feynman Gauge

Light-Cone Gauge

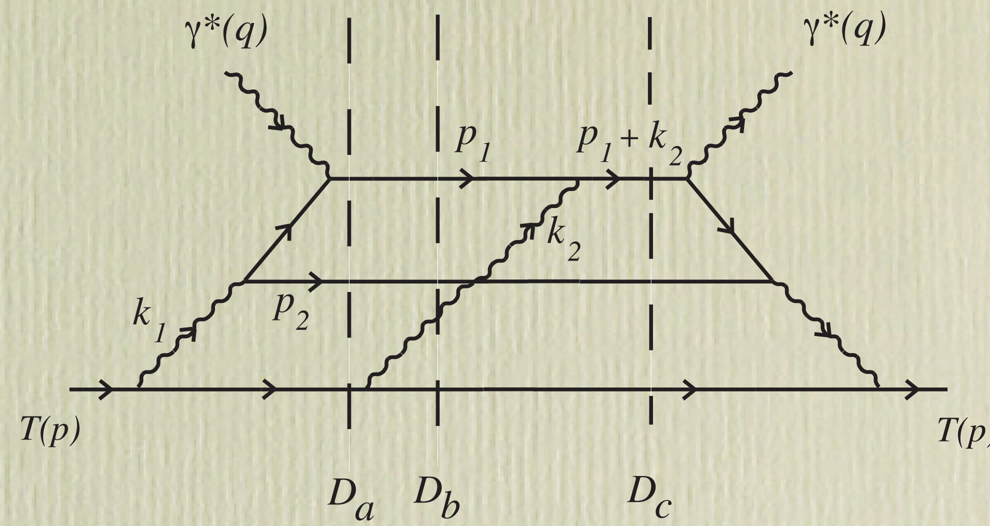
Result is Gauge Independent

Hard Diffraction

Final State Interactions Non-Zero in QCD



(a)



(b)

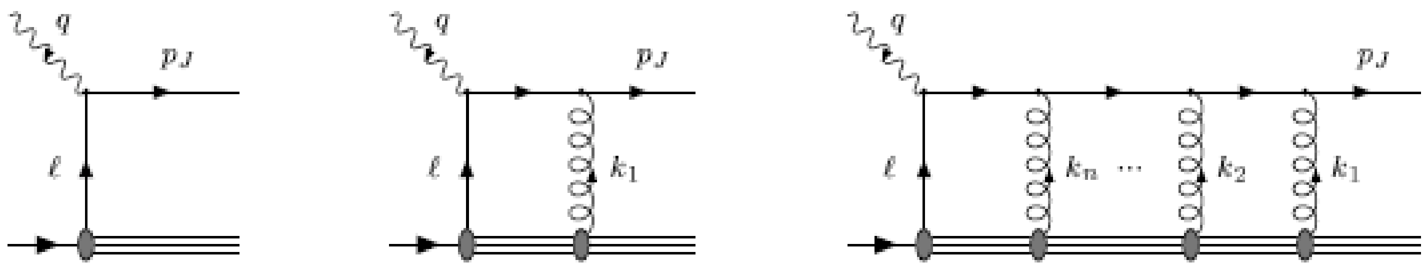
Light-Cone Gauge

Feynman Gauge

BHMPS

Hard Diffraction

Rescattering and factorization



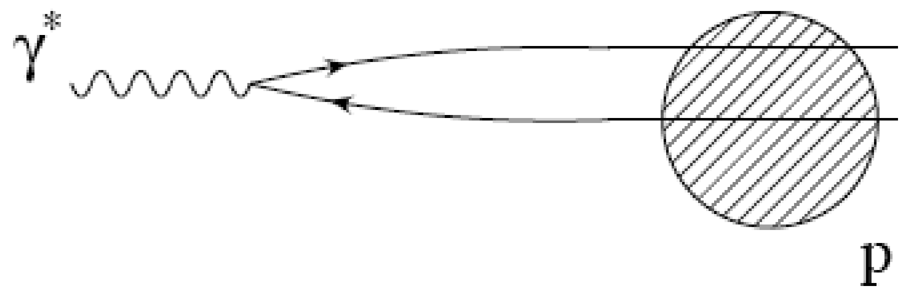
- Important to realize that the rescattering is compatible with factorization theorems *by construction*
  - the Wilson line is a part of the definition of the PDF, so the rescattering is also a part of the PDF
- When one measures the PDF in experiments, one measures the PDF *including* rescattering
- In a similar way, the diffractive PDFs are included in the inclusive PDFs

Dipole models

Many models are based on using the dipole frame

→ Use proton's rest frame, or more generally, a frame where the photon has very large lightcone q^+ momentum

Then the photon fluctuates into a *color dipole* before hitting the proton

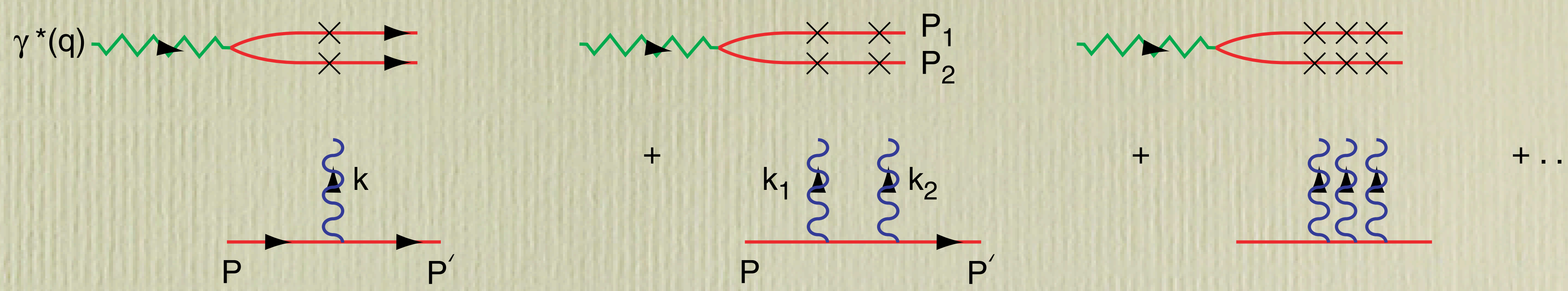


At small x_B the fluctuation is very long-lived and the $q\bar{q}$ pair of the dipole is transversely frozen during the interaction.

Very useful in small-x physics!

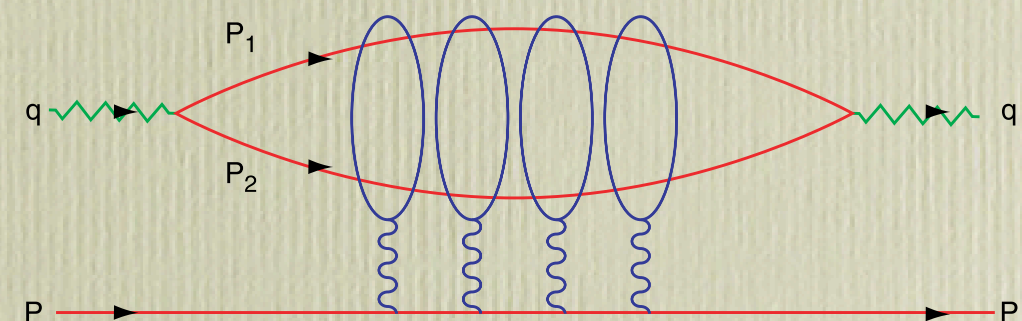
Hebecker Kopeliovitch

Lab Frame Picture



Sum Eikonal Interactions

Similar to Color Dipole Model



Hard Diffraction

$$Q^4 \frac{d\sigma}{dQ^2\, dx_B} = \frac{\alpha_{\rm em}}{16\pi^2} \frac{1-y}{y^2} \frac{1}{2M\nu} \int \frac{dp_2^-}{p_2^-}\, d^2\vec{r}_T\, d^2\vec{R}_T\, |\tilde{M}|^2$$

where

$$|\tilde{M}(p_2^-, \vec{r}_T, \vec{R}_T)| = \left| \frac{\sin\left[g^2\, W(\vec{r}_T, \vec{R}_T)/2\right]}{g^2\, W(\vec{r}_T, \vec{R}_T)/2} \tilde{A}(p_2^-, \vec{r}_T, \vec{R}_T) \right|$$

is the resummed result. The Born amplitude is

$$\tilde{A}(p_2^-, \vec{r}_T, \vec{R}_T) = 2eg^2 MQp_2^-\, V(m_{||} r_T) W(\vec{r}_T, \vec{R}_T)$$

where $m_{||}^2 = p_2^- M x_B + m^2$ and

BHMPS

$$V(m\, r_T) \equiv \int \frac{d^2\vec{p}_T}{(2\pi)^2} \frac{e^{i\vec{r}_T\cdot\vec{p}_T}}{p_T^2 + m^2} = \frac{1}{2\pi} K_0(m\, r_T).$$

The rescattering effect of the dipole of the $q\bar{q}$ is controlled by

$$W(\vec{r}_T, \vec{R}_T) \equiv \int \frac{d^2\vec{k}_T}{(2\pi)^2} \frac{1 - e^{i\vec{r}_T\cdot\vec{k}_T}}{k_T^2} e^{i\vec{R}_T\cdot\vec{k}_T} = \frac{1}{2\pi} \log\left(\frac{|\vec{R}_T + \vec{r}_T|}{R_T}\right).$$

Precursor of Nuclear Shadowing

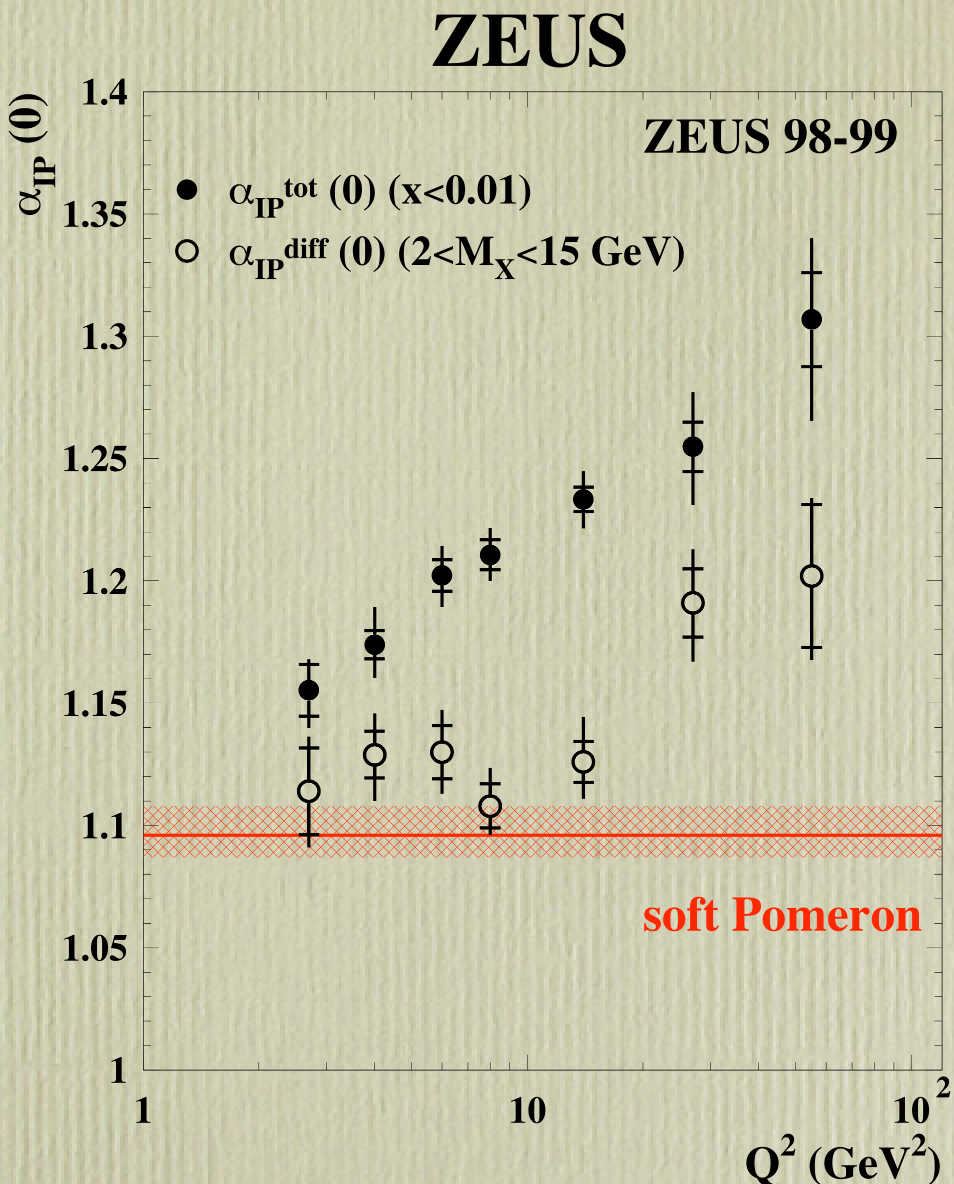
Hard Diffraction

Consequences for DDIS (1)

- Underlying hard scattering sub-process is the same in diffractive and non-diffractive events
- Same Q^2 dependence of diffractive and inclusive PDFs (remember: hard radiation not resolved)
- and same energy (W or x_B) dependence

$\Rightarrow \dfrac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}}$ independent of x_B and Q^2 (as in data)

- Note:
  - In pomeron models the ratio depends on $x_B^{1-\alpha_{I\!P}}$ *which is ruled out*
  - In a two-gluon model with two hard gluons, the diffractive cross section depends on $[f_{g/p}(x_B, Q^2)]^2$



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

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

No factorization of hard pomeron

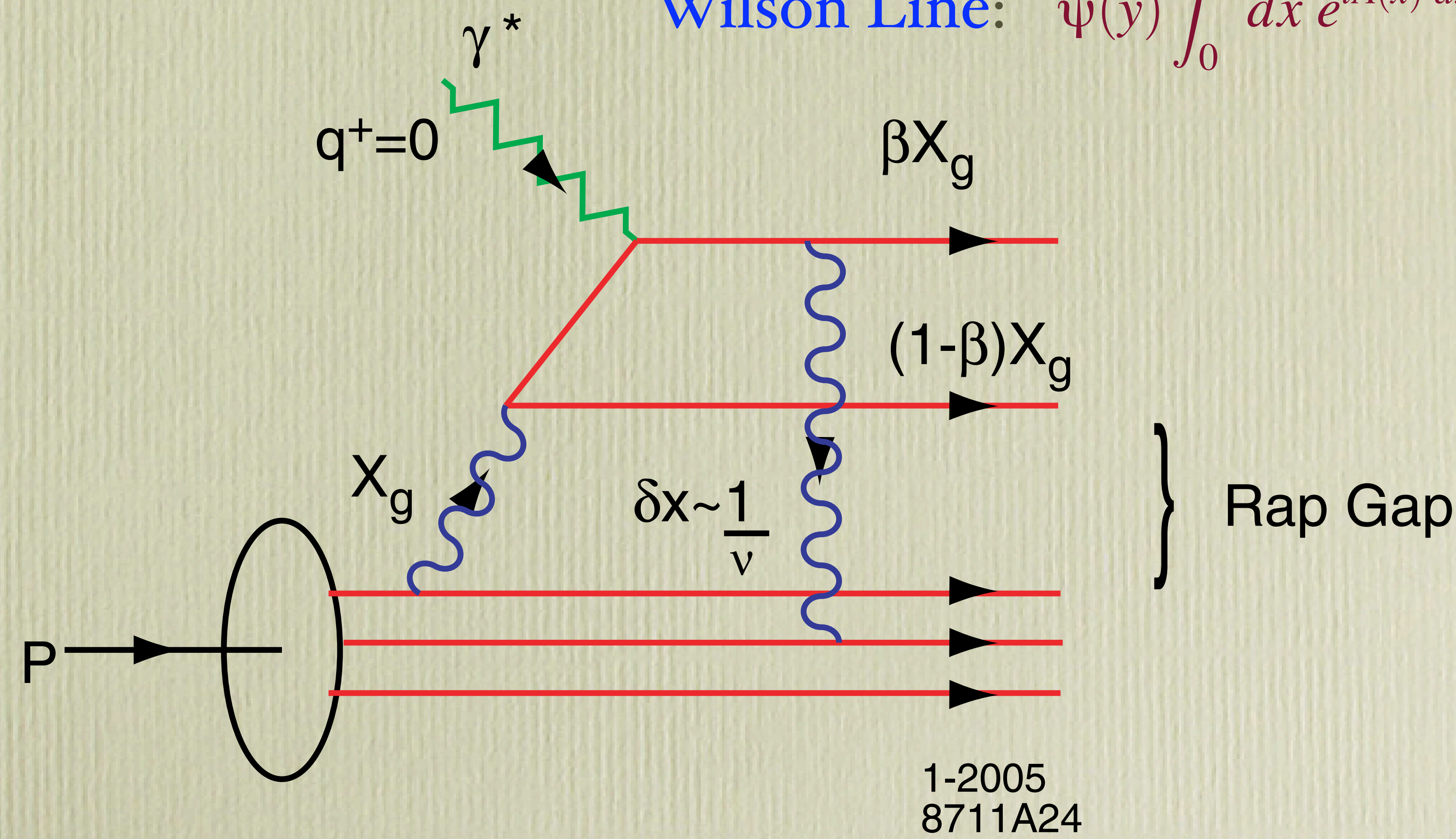
S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D 65, 114025 (2002) [arXiv:hep-ph/0104291].
S. J. Brodsky, R. Enberg, P. Hoyer and G. Ingelman, arXiv:hep-ph/0409119.

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

QCD Mechanism for Rapidity Gaps

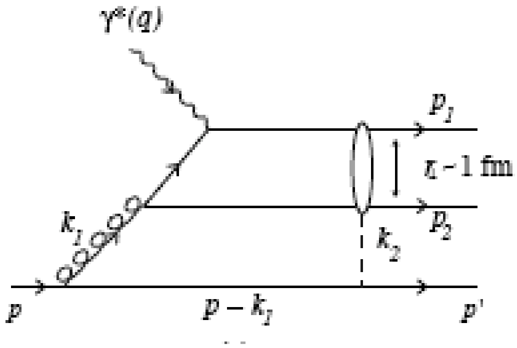
Wilson Line: $\overline{\psi}(y) \int_0^y dx \, e^{iA(x)\cdot dx} \, \psi(0)$



Hard Diffraction

Consequences for DDIS (2)

- Rescattering gluons have small momenta
  $\Rightarrow$ β dependence of diffractive PDFs arises from underlying (non-perturbative) $g \to q\bar{q}$ and $g \to gg$



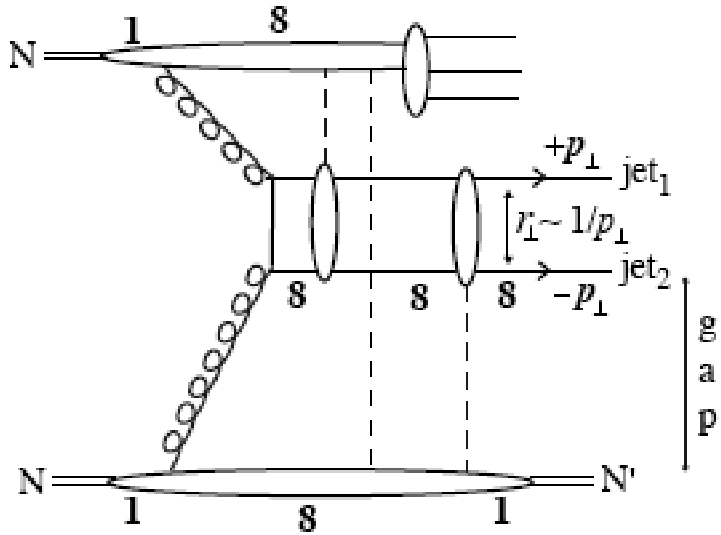
- *Effective* $I\!P$ distribution and quark structure function:

$$f_{I\!P/p}(x_{I\!P}) \propto g(x_{I\!P}, Q_0^2)$$
$$f_{q/I\!P}(\beta, Q_0^2) \propto \beta^2 + (1-\beta)^2$$

- Diffractive amplitudes from rescattering are dominantly *imaginary* — as expected for diffraction (Ingelman–Schlein $I\!P$ model has real amplitudes)

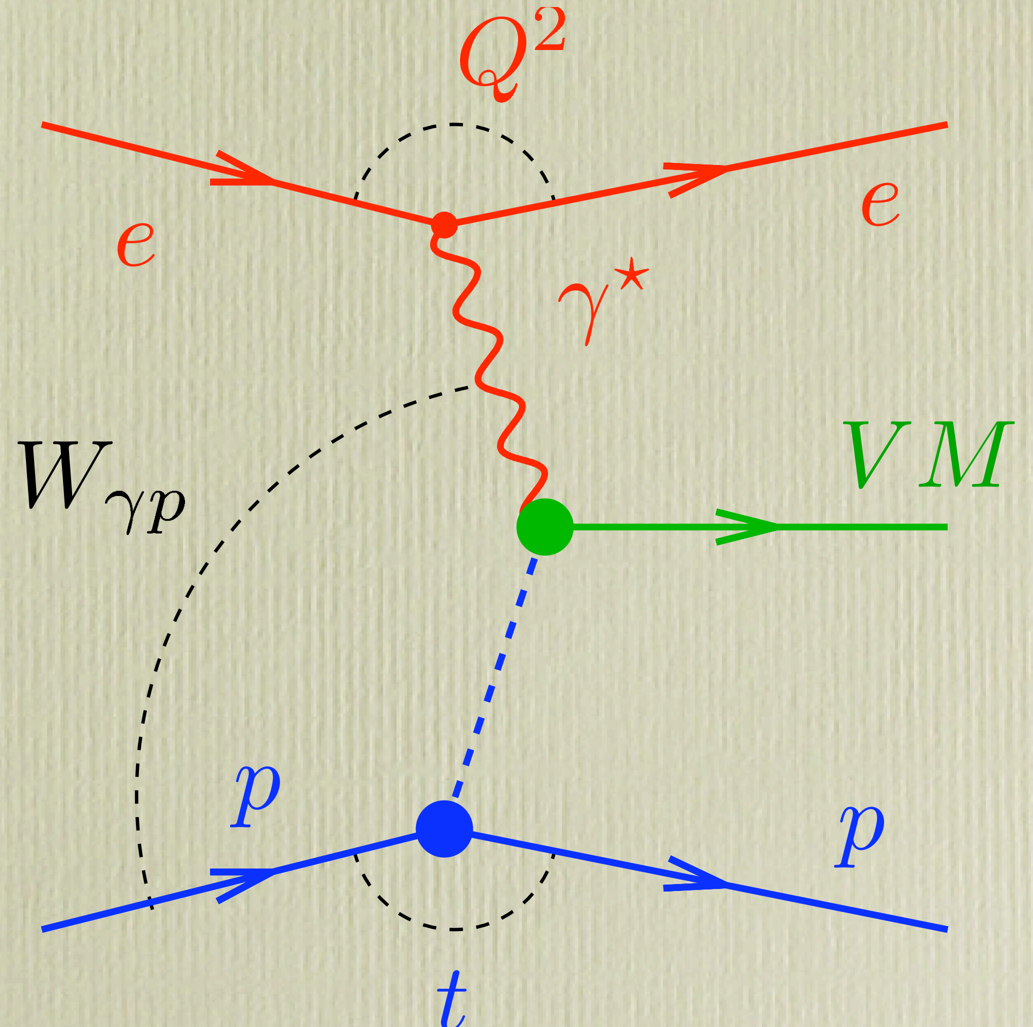
Hadron–hadron collisions

Extend to hard diffraction in hadronic collisions:



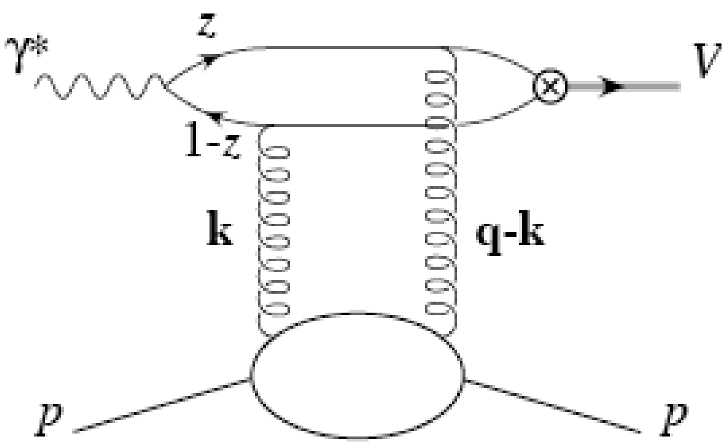
- Diffractive factorization theorem doesn't hold
- Data shows $\sim$ 1% diffraction instead of $\sim$ 10 % in DIS
- Both target and projectile colored $\rightarrow$ different rescattering $\rightarrow$ lower probability for neutralization

Diffractive Vector Meson Electroproduction



Hard Diffraction

Diffractive vector meson production is a similar, but *exclusive*, process



Here the amplitude is dominated by small dipoles and Q^2, M_V, or t can give a perturbative hard scale

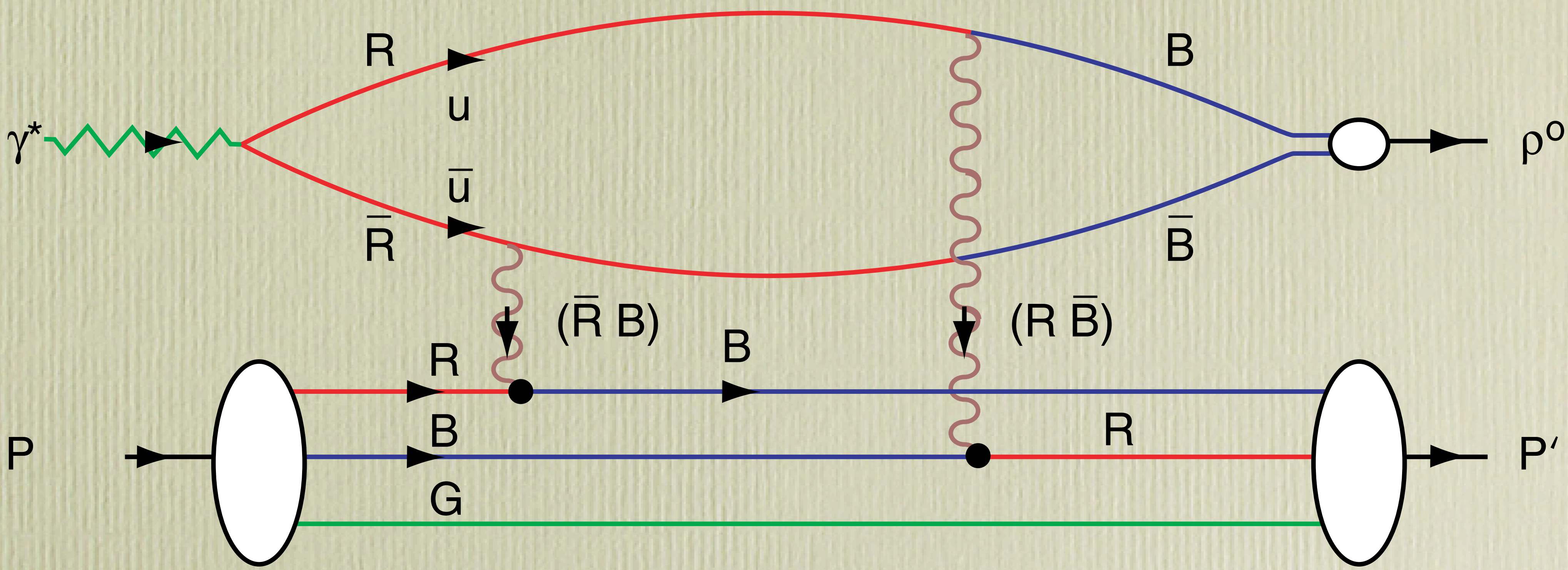
QCD predictions [Gunion, Frankfurt, Strikman, Mueller, SJB) for t, q^2, s and polarization dependence verified.

Color transparency verified – coherent production on every nucleon of nucleus! [Mueller, SJB].

Measures The Distribution Amplitude of the Vector Meson

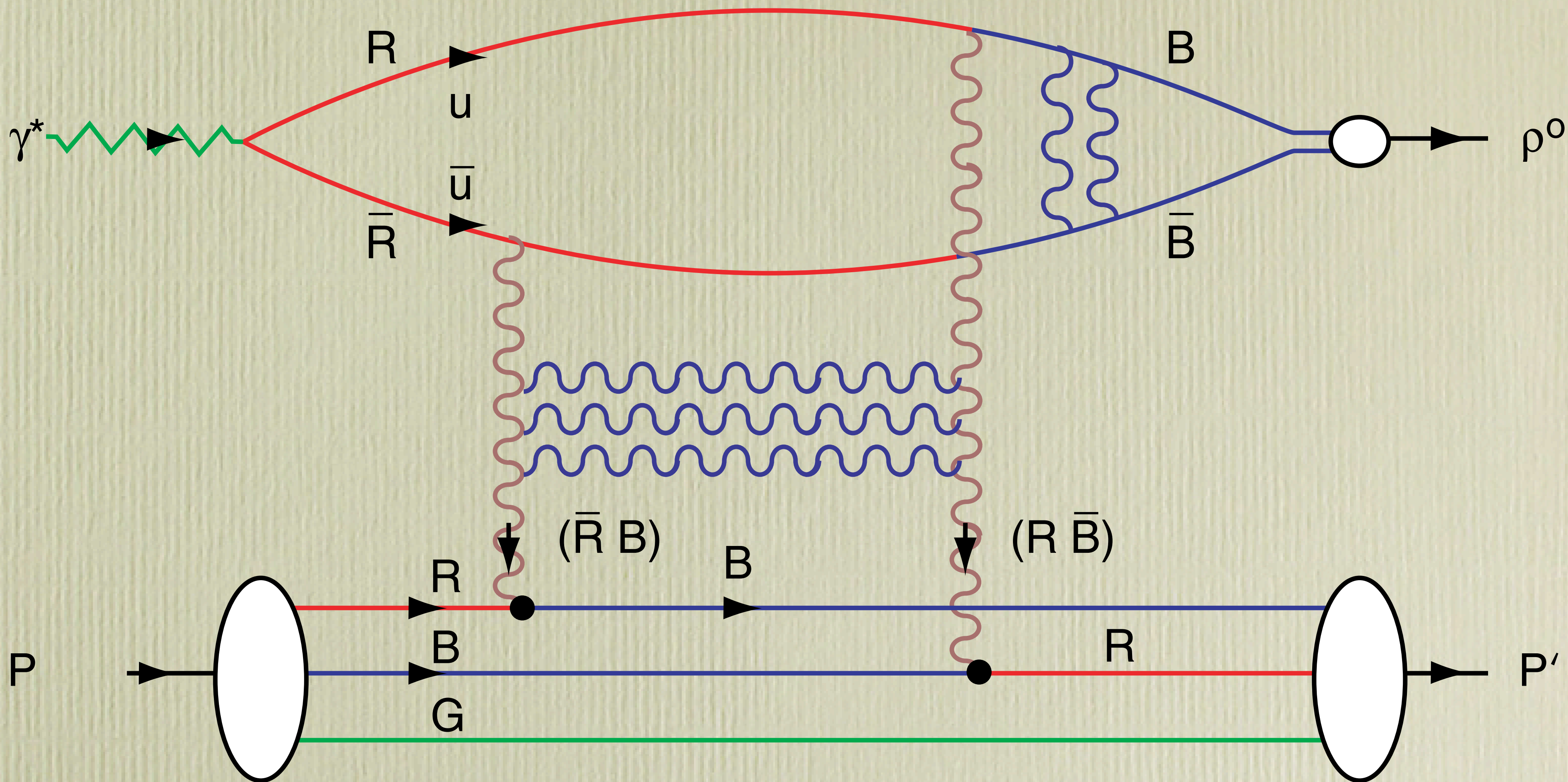
$$\phi(x,Q) = \int^{k_\perp^2 < Q^2} d^2k_\perp \Psi_{q\bar{q}}(x, \vec{k}_\perp, \lambda_i)$$

Diffractive Vector Meson Electroproduction



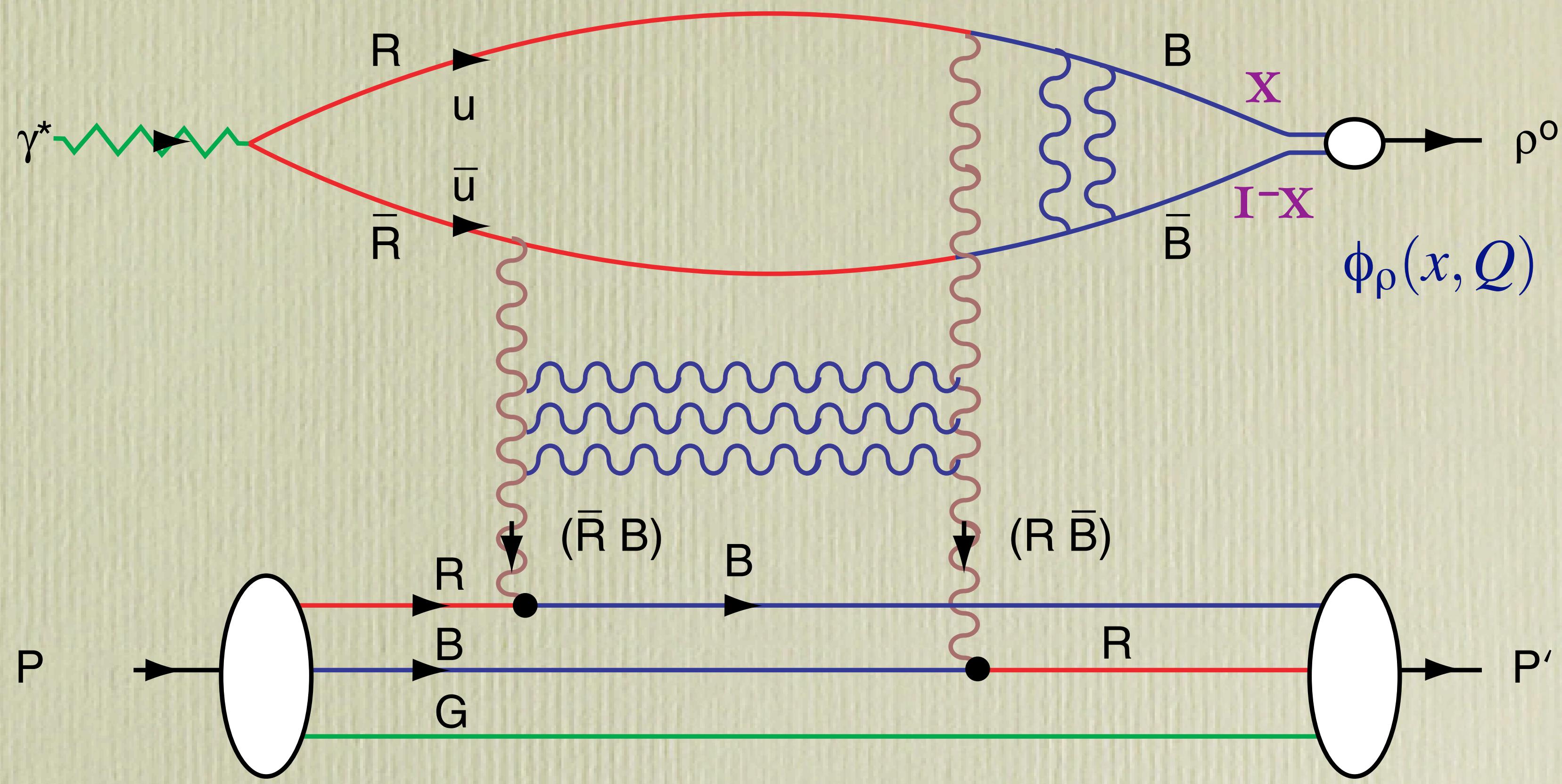
Two gluon exchange

Hard gluons with $k_\perp \sim 1/Q$
couple to small $q\bar{q}$ color singlet:
transverse size: $b_\perp \sim 1/Q$



BFKL Hard Pomeron

$A \sim s^1(1+\alpha_s \log\frac{s}{Q^2}+\alpha_s^2 \log^2\frac{s}{Q^2}+\cdots) \sim s^{\alpha_P(Q^2)}$

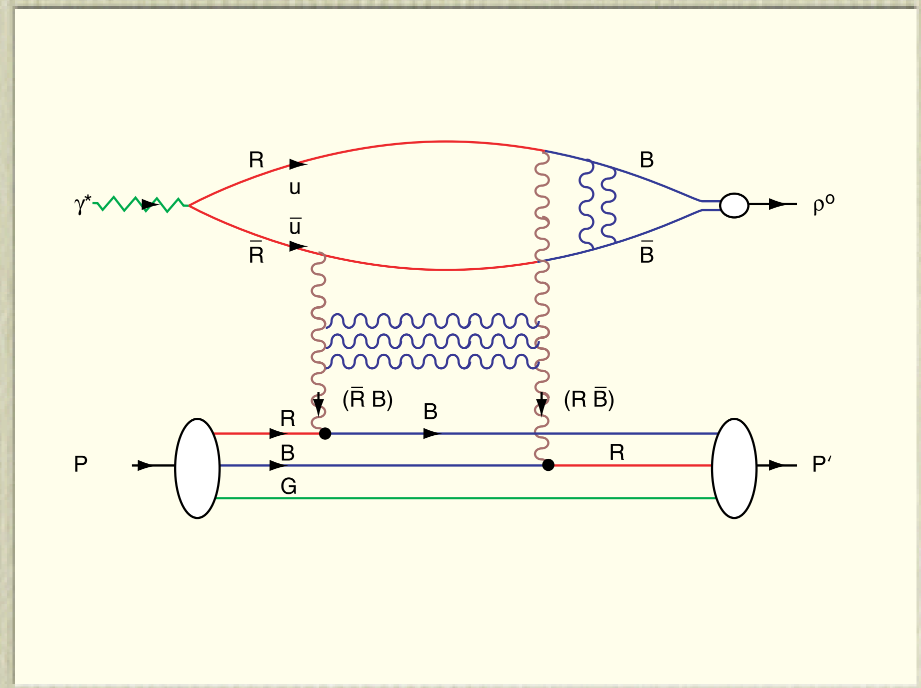


Distribution amplitude of vector meson

$\phi_\rho(x, Q) \sim f_\rho x(1-x)$

ERBL Evolution from PQCD

Successful PQCD predictions for $\frac{d\sigma}{dt}(\gamma^* p \rightarrow \rho^0 p')$: s, Q^2, t dependence σ_L dominance



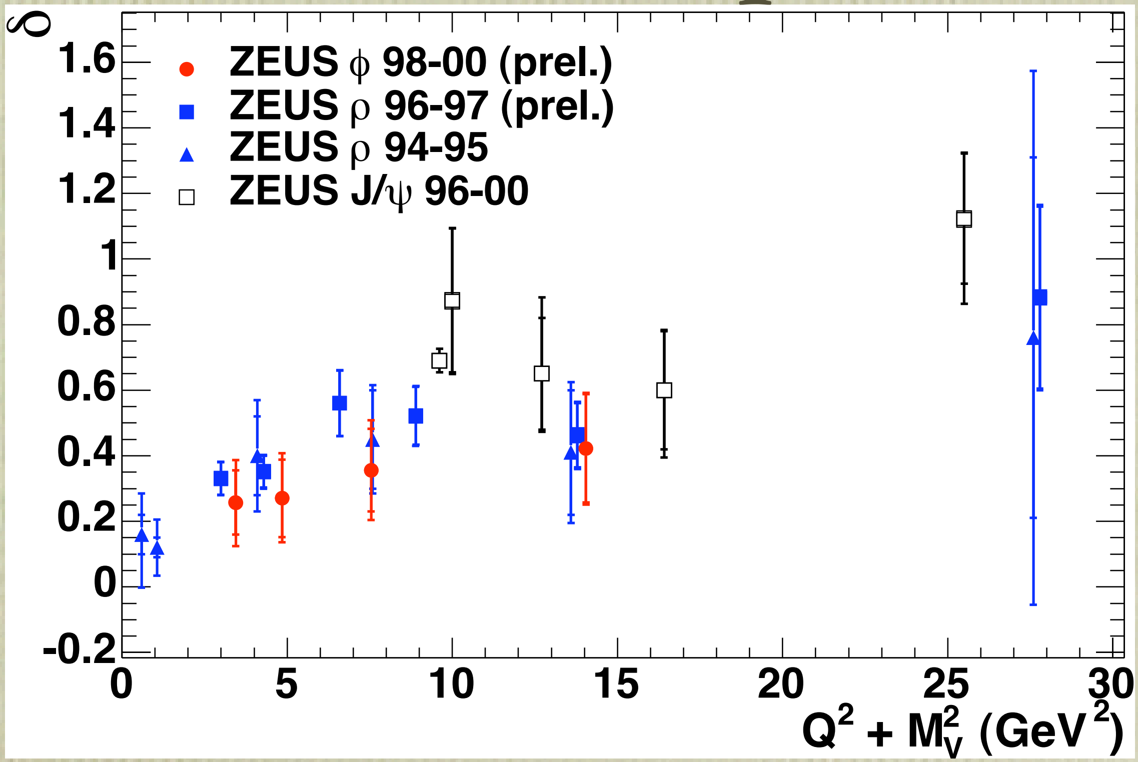
S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller and M. Strikman,

"Diffractive leptoproduction of vector mesons in QCD,"

Phys. Rev. D 50, 3134 (1994)

[arXiv:hep-ph/9402283].

Energy Dependence of Vector Meson Electroproduction



$$\mathrm{W}^{\delta} = s^{\delta/2}$$

W^{δ} dependence vs. $Q^2 + m_V^2$ for elastic vector meson production from ZEUS.

Final State Interactions Produce T-Odd (Sivers Effect)

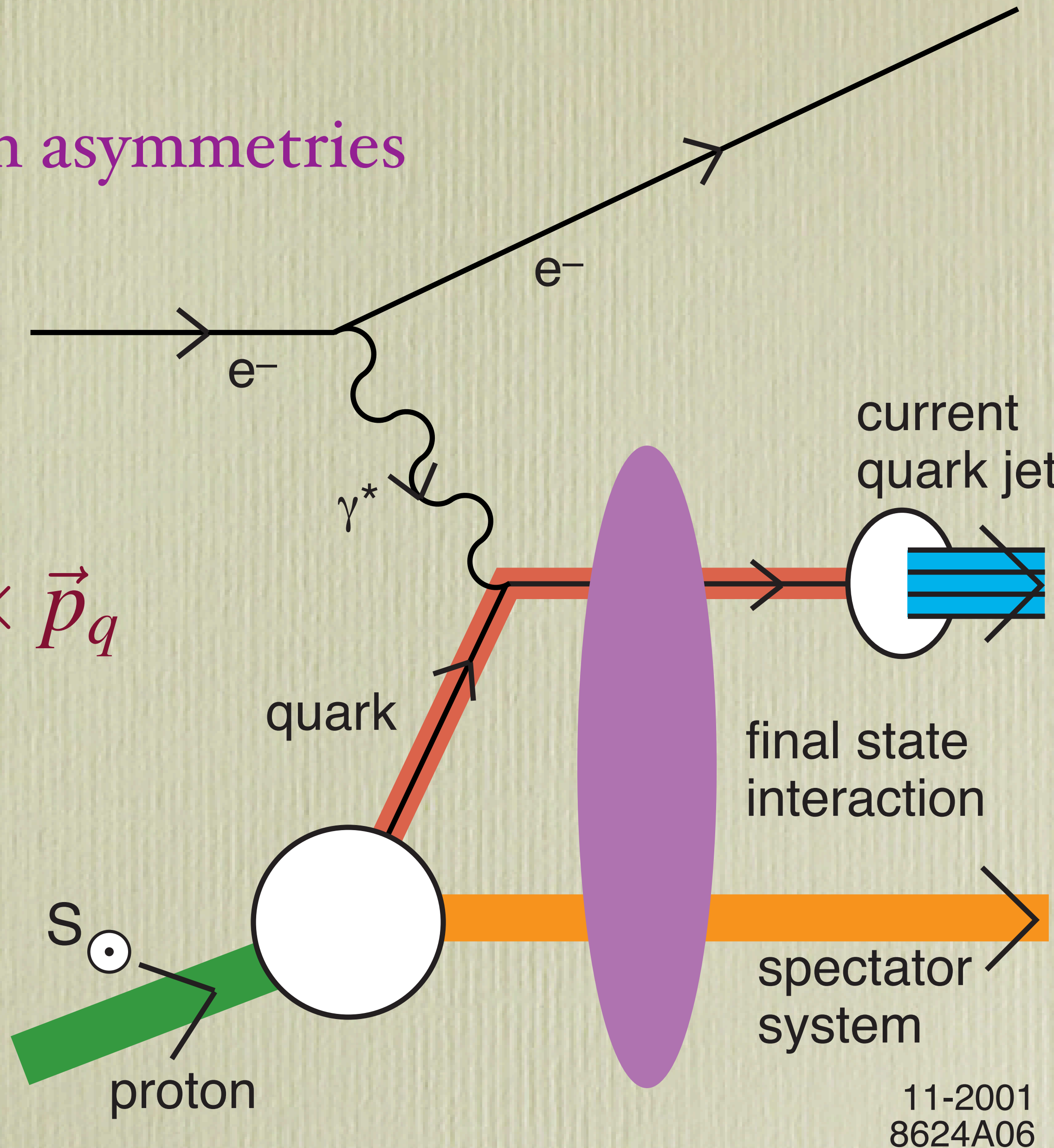
- Bjorken Scaling!
- Arises from Interference of Final State Coulomb Phase in S and P waves
- Relate to the quark contribution to the target proton anomalous magnetic moment

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

Single-spin asymmetries

Sivers Effect

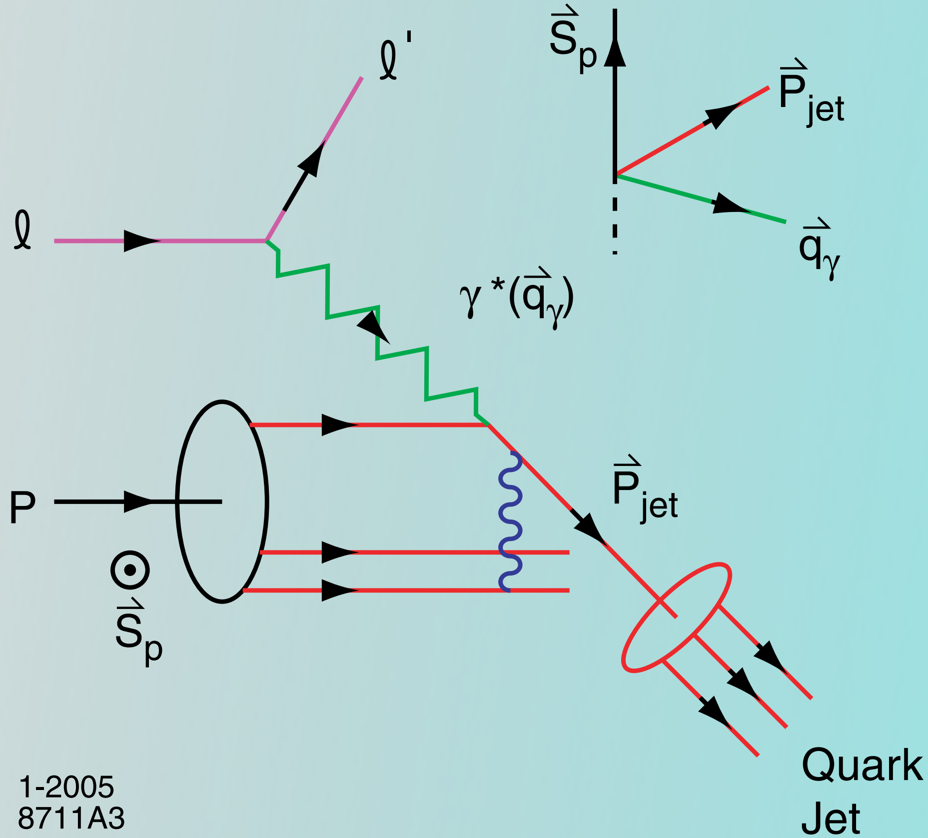
$$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$$



Hard Diffraction

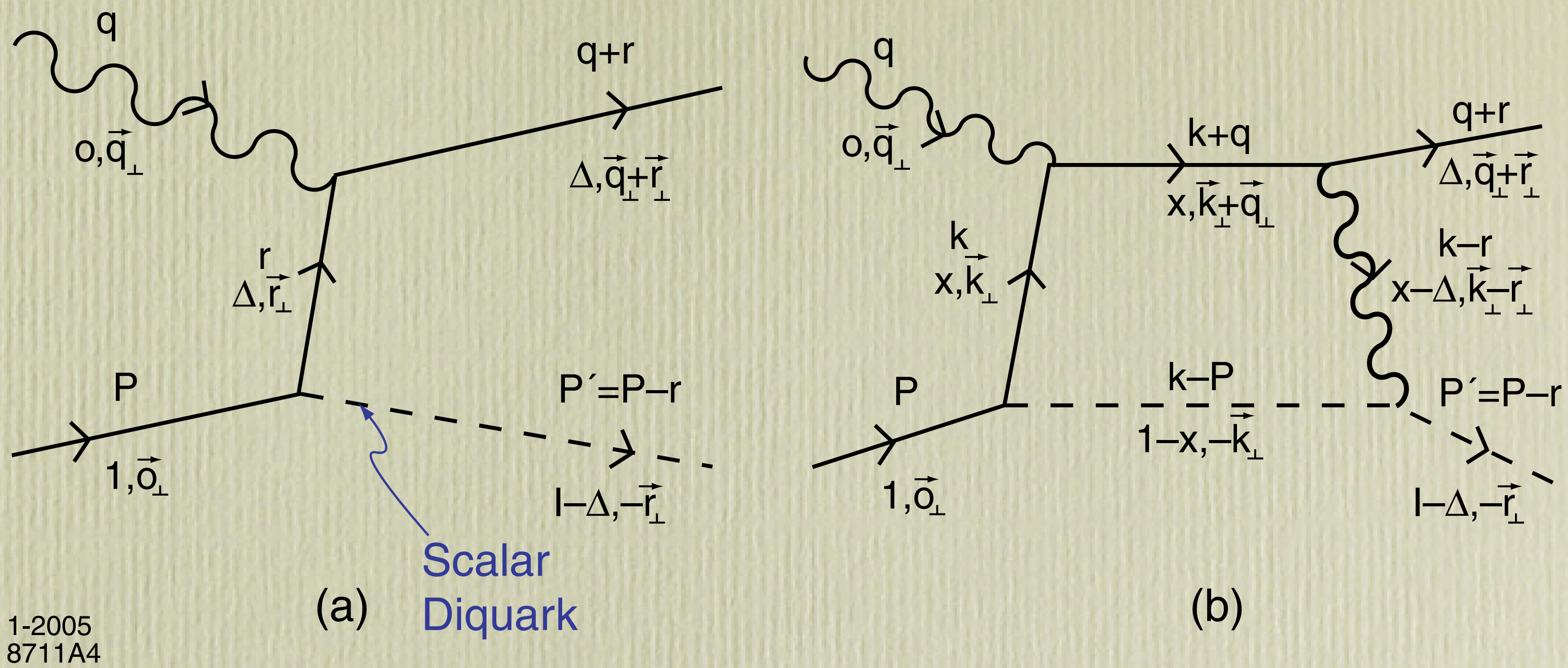
DIS 2005
4-29-05

Stan Brodsky, SLAC



Hwang, Schmidt, SJB

Quarks Reinteract in the Final State
Interference of Coulomb Phases for *S* and *P* states
Produce Single Spin Asymmetry [Siver's Effect]
$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$
Use thrust or momentum of leading pion
to find jet direction
Measure $\vec{S} \cdot \vec{p}_\pi \times \vec{q}$
Distinguish from Collins Effect [from jet fragmentation]
Proportional to the Proton Anomalous Moment and α_s.



Model Calculation producing a target single-spin asymmetry in semi-inclusive leptoproduction

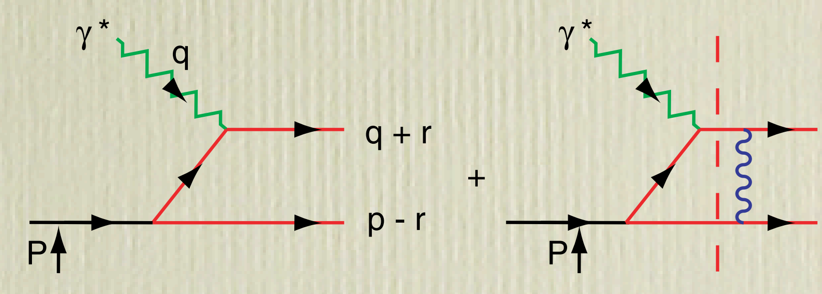
Quarks Reinteract in the Final State

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

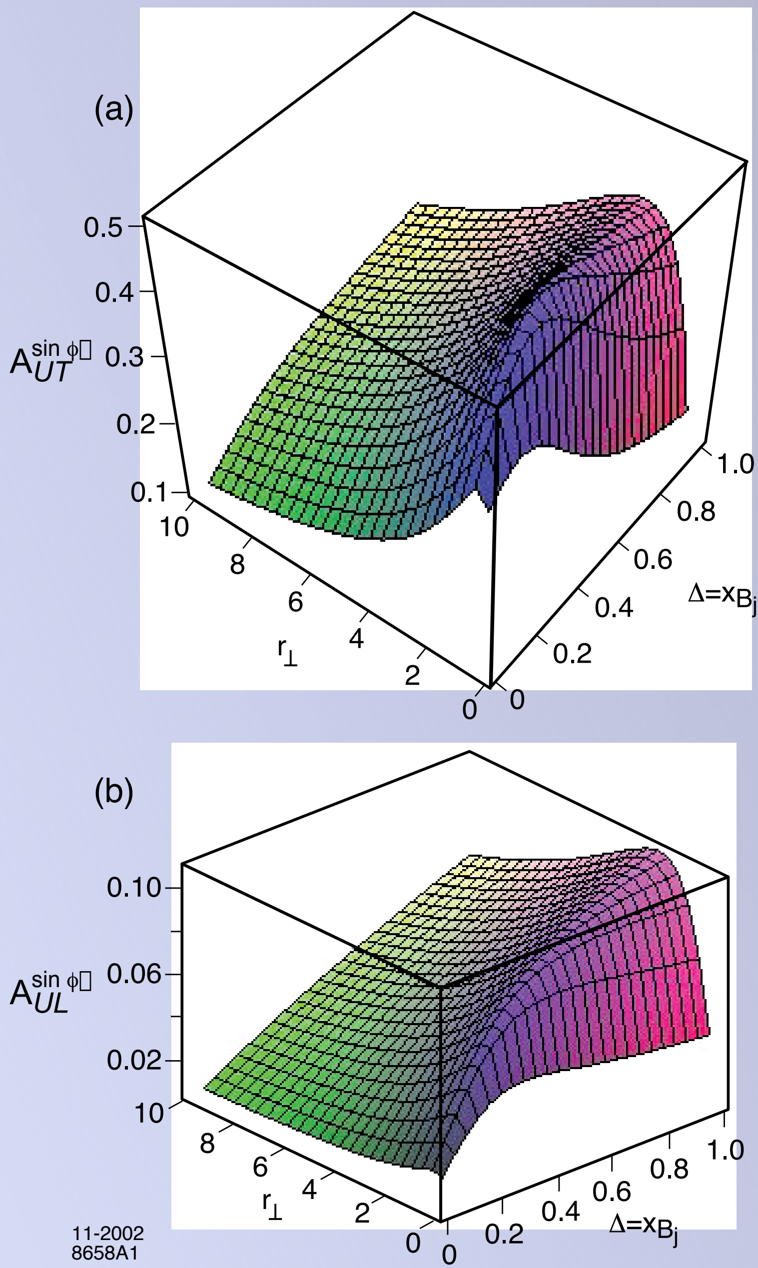
Produce Single Spin Asymmetry [Siver's Effect]

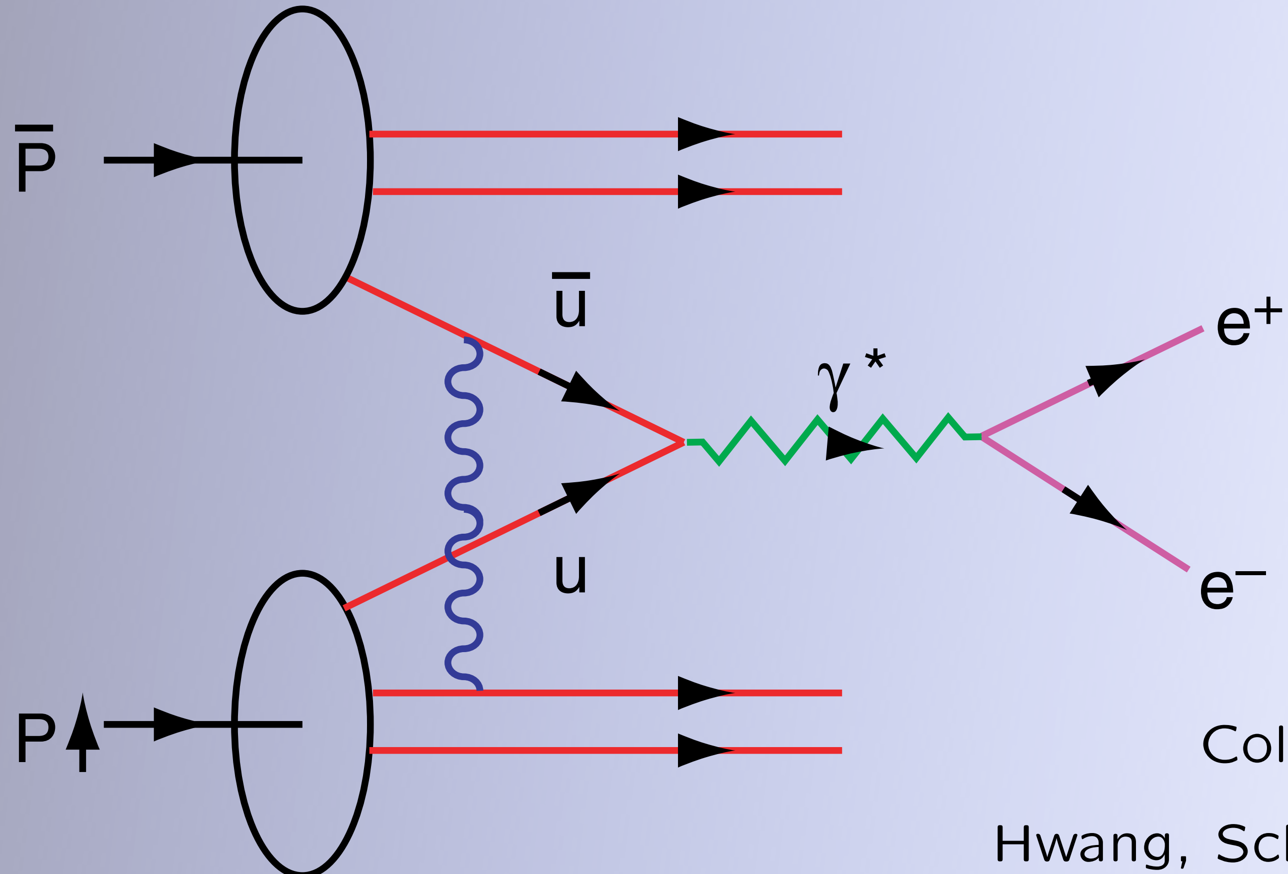
$\vec{S} \cdot \vec{p}_{jet} \times \vec{q}$

Proportional to the Proton Anomalous Moment and α_s.



Prediction for Single-Spin Asymmetry



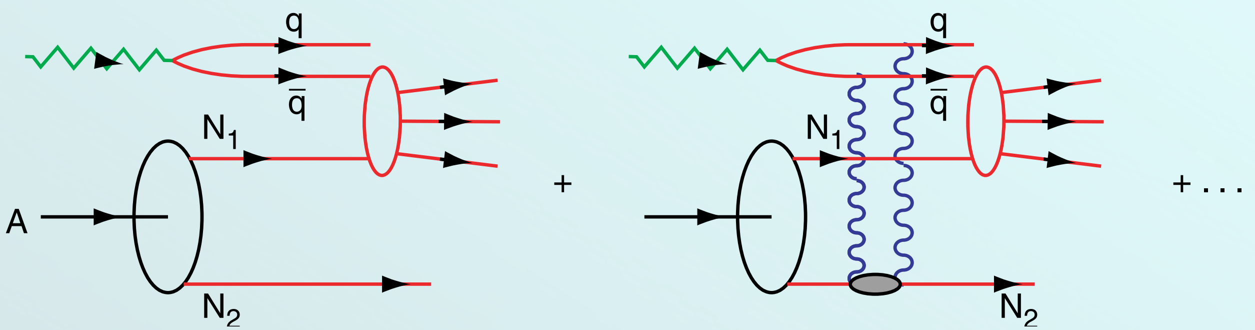


Collins

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

Origin of Nuclear Shadowing in Glauber - Gribov Theory



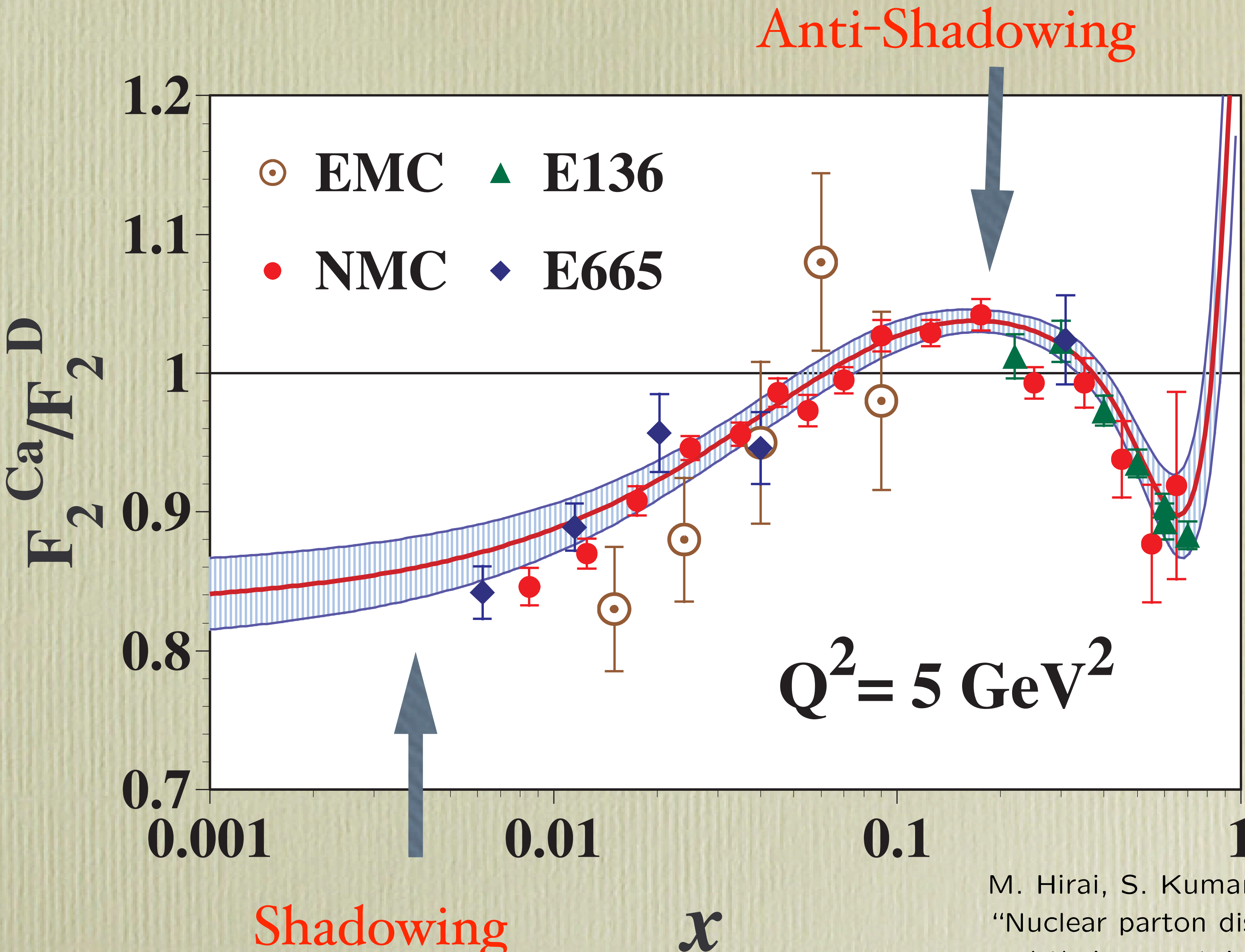
Interference of one-step and two-step processes

Interaction on upstream nucleon diffractive

Phase i X i = - 1 produces destructive interference

No Flux reaches down stream nucleon

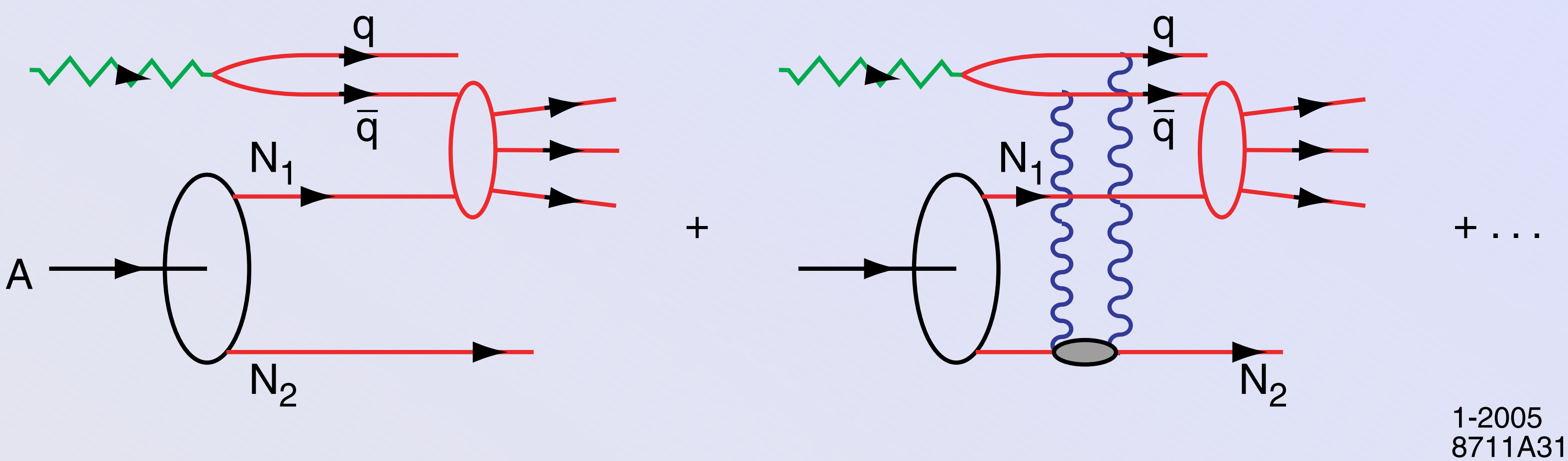
Hard Diffraction



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].

Hard Diffraction

Nuclear Shadowing in QCD



Nuclear Shadowing not included in nuclear LFWF !

Shadowing and Antishadowing in Lepton-Nucleus Scattering

- Shadowing and Antishadowing in DIS arise from interference of multi-nucleon processes in nucleus

Phases!

- Not due to nuclear wavefunction

Wavefunction of stable nucleus is real.
Effect of multi-scattering of $q\bar{q}$ in nucleus.

- Bjorken Scaling :

Interference requires leading-twist diffractive DIS processes

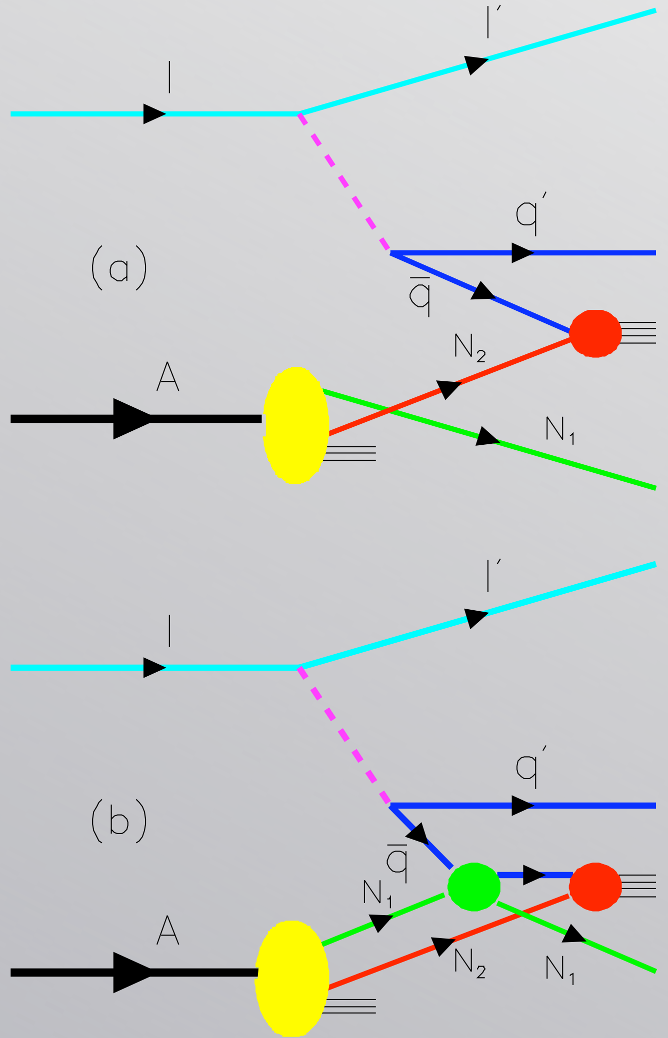
Hard Diffraction

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}



The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.

If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\overline{q}$ flux reaching N_2.

$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Reggeon Exchange

Phase of two-step amplitude relative to one step:

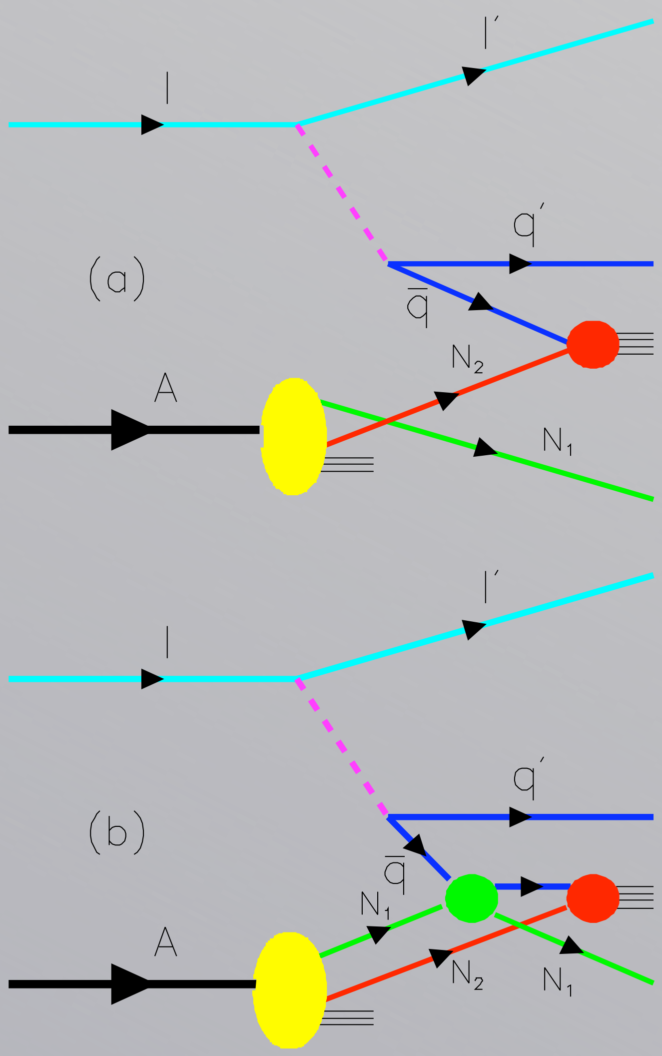
$$\frac{1}{\sqrt{2}}(1 - i) \times i = \frac{1}{\sqrt{2}}(i + 1)$$

Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

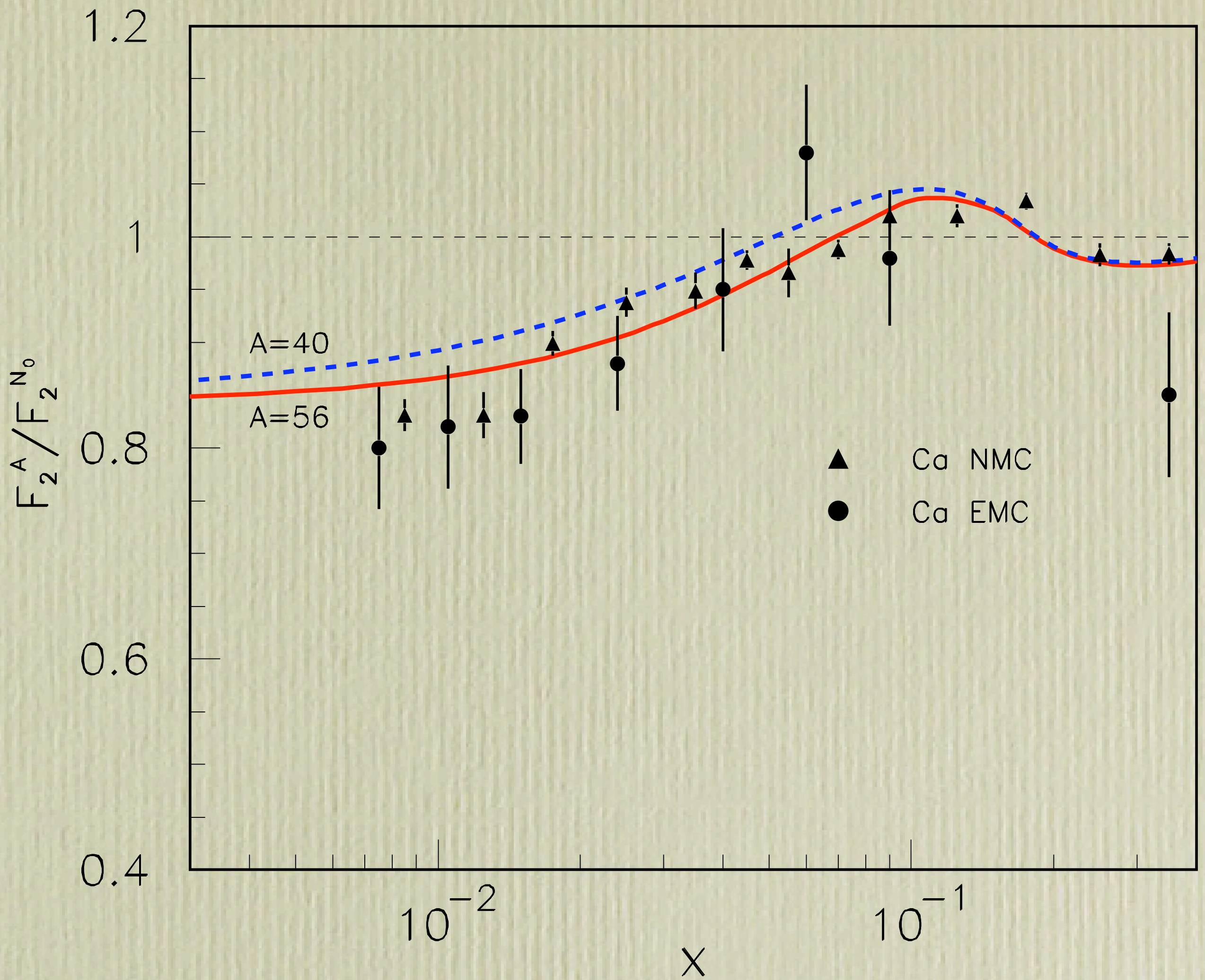
Different for couplings of $\gamma^*, Z^0, W^\pm$



The one-step and two-step processes in DIS on a nucleus.

If the scattering on nucleon N_1 is via $C = -$ Reggeon or Odderon exchange, the one-step and two-step amplitudes are opposite in phase, enhancing the $\bar{q}$ flux reaching N_2

$\rightarrow$ Antishadowing of the DIS nuclear structure functions



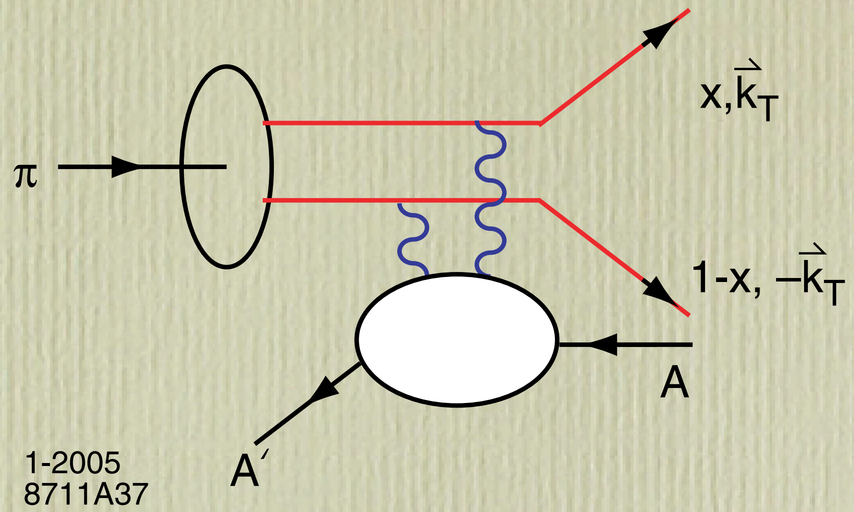
The nuclear shadowing and antishadowing effects at $\langle Q^2 \rangle = 1\ \mathrm{GeV}^2$

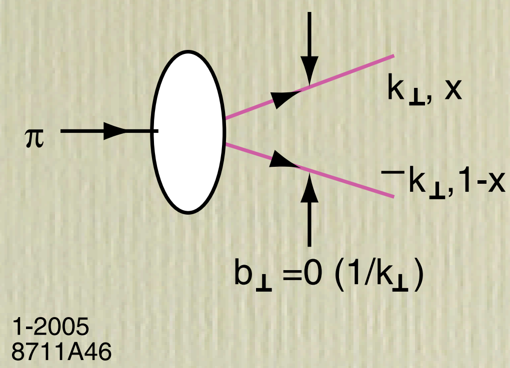
S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

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



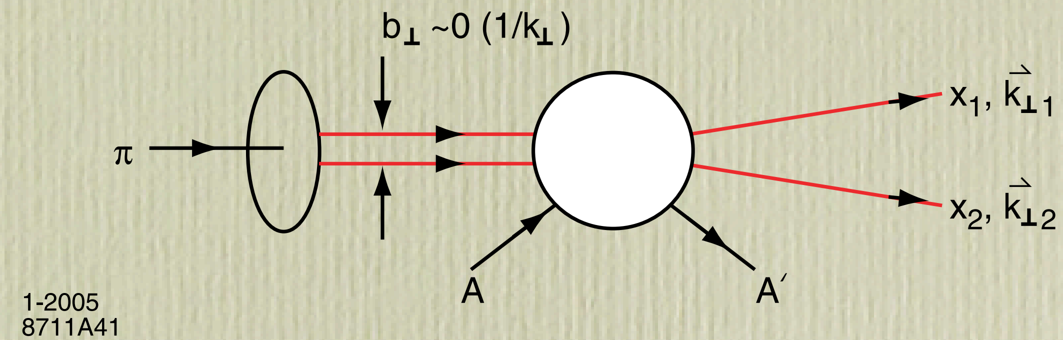


- Small Size Pion Valence Fock State
- Color Transparent
- E791 Fermilab Experiment

Use Diffraction to Resolve Hadron Substructure

- Measure Light-Front Wavefunctions
- AdS/CFT predictions
- Novel Aspects of Hadron Wavefunctions: Intrinsic Charm, Hidden Color, Color Transparency/Opaqueness
- Diffractive Di-Jet Production
- Nuclear Shadowing and Antishadowing
- New Mechanism for Higgs Production

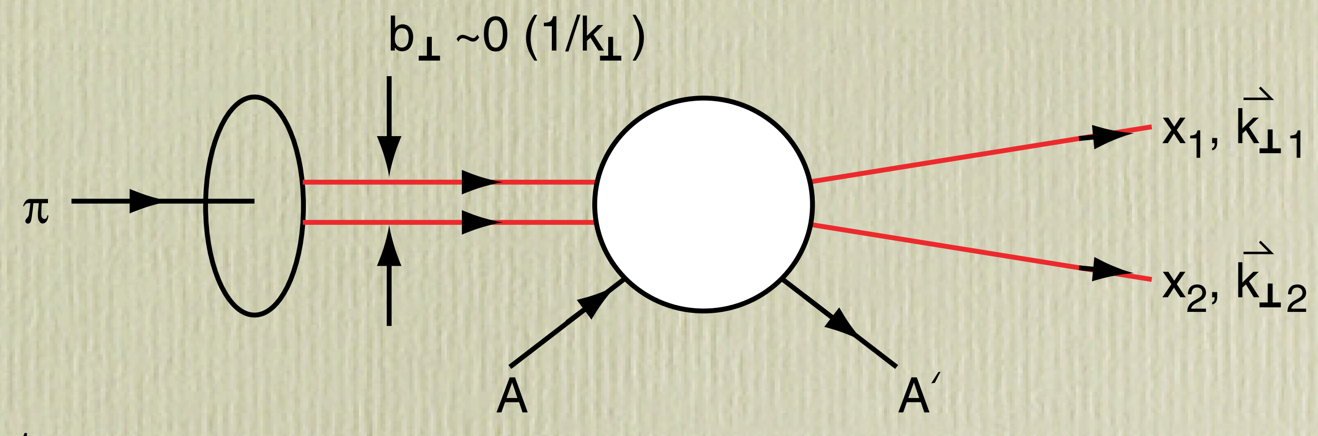
Diffractive Dissociation of Pion



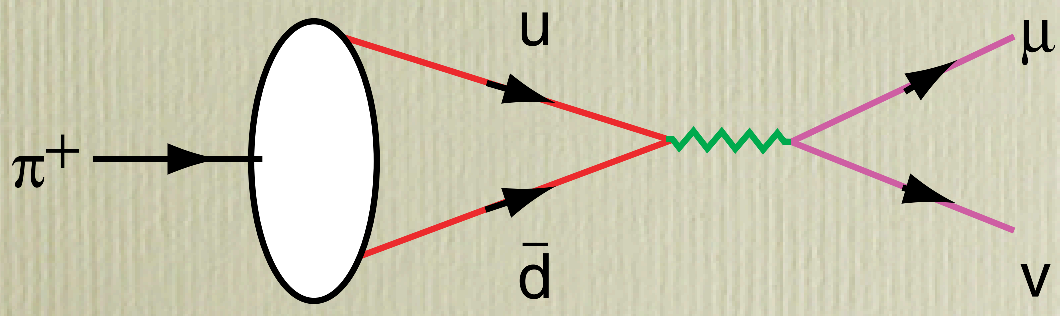
Measure Light-Front Wavefunction of Pion
Two-gluon Exchange
Minimal momentum transfer to nucleus
Nucleus left Intact

Hard Diffraction

Fluctuation of a Pion to a Compact Color Dipole State



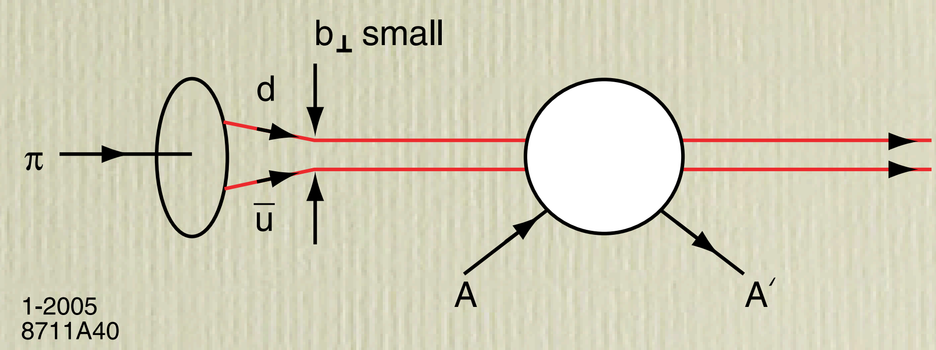
Color-Transparent Fock State For High Transverse Momentum Di-Jets



Same Fock State Determines Weak Decay

Fluctuation of a Pion to a Compact Color Dipole State

Small Size Pion Can Interact Coherently on Each Nucleon of Nucleus



$$M(\pi A \to JetJetA') = A^1 M(\pi N \to JetJetN')F_A(t)$$
$$d\sigma/dt(\pi A \to JetJetA') =$$
$$A^2 d\sigma/dt(\pi N \to JetJetN')|F_A(t)|^2$$
$$\sigma \propto \frac{A^2}{R_A^2} \sim A^{4/3}$$

Diffractive Dijet Cross Section Color Transparent

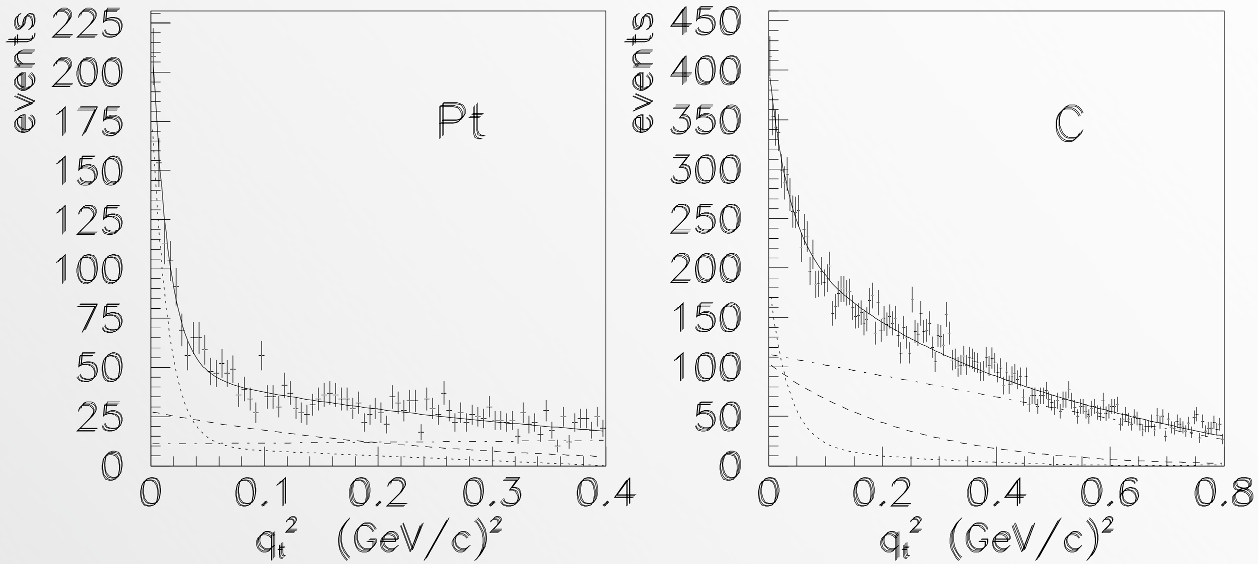
- **Fully coherent interactions between pion and nucleons.**
- **Emerging Di-Jets do not interact with nucleus.**

$$\mathcal{M}(\mathcal{A}) = \mathcal{A} \cdot \mathcal{M}(\mathcal{N})$$

$$\underline{\frac{d\sigma}{dq_t^2} \propto A^2 \quad q_t^2 \sim 0}$$

$$\underline{\sigma \propto A^{4/3}}$$

E791 Collaboration, E. Aitala et al., Phys. Rev. Lett. 86, 4773 (2001)



Verification of QCD Color Transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

k_t range (GeV/c)	α	α (CT)
1.25 $< k_t <$ 1.5	1.64 + 0.06 -0.12	1.25
1.5 $< k_t <$ 2.0	1.52 ± 0.12	1.45
2.0 $< k_t <$ 2.5	1.55 ± 0.16	1.60

α (Incoh.) = 0.70 ± 0.1

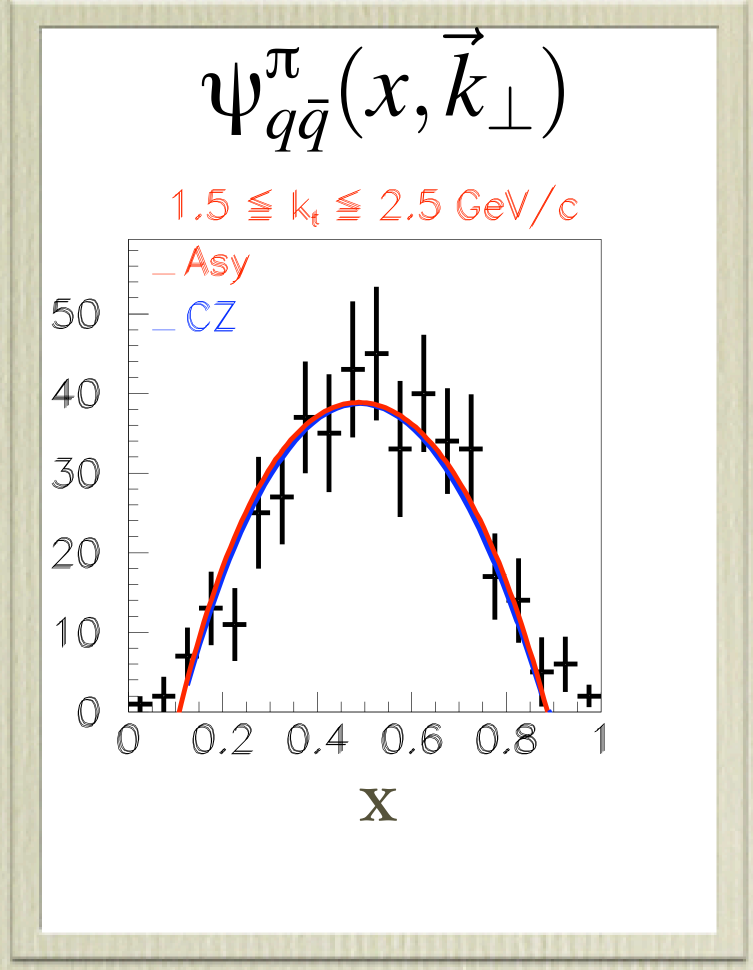
Conventional Glauber Theory Ruled Out

FermiLab E791
Ashery et al

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



Diffractive Dissociation of Pion into Di-Jets

- Verify Color Transparency
- Pion Interacts coherently on each nucleon of nucleus !
- Pion Distribution similar to Asymptotic Form Also:AdS/CFT
- Scaling in transverse momentum consistent with PQCD

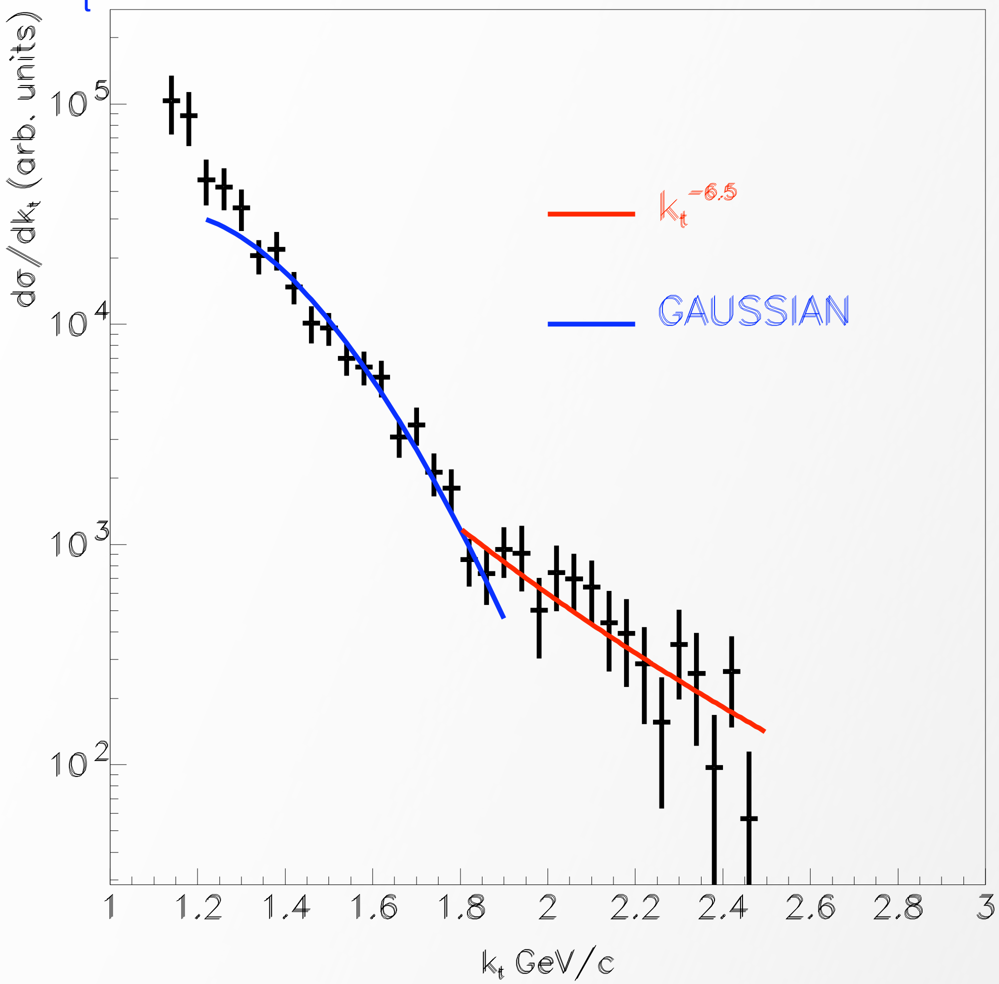
$$M \propto A, \ \sigma \propto A^2$$

$$\psi(x, k_\perp) \propto x(1-x)$$

THE k_t DEPENDENCE OF DI-JETS YIELD

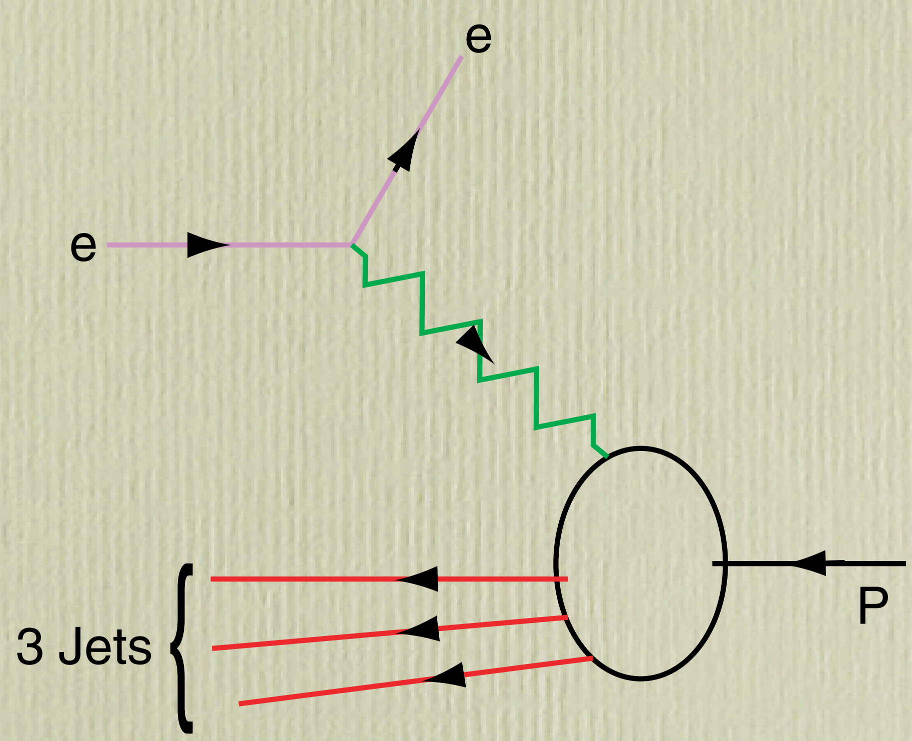
$$\frac{d\sigma}{dk_t^2} \propto \left|\alpha_s(k_t^2) G(x, k_t^2)\right|^2 \left|\frac{\partial^2}{\partial k_t^2}\psi(u, k_t)\right|^2$$

With $\psi \sim \frac{\phi}{k_t^2}$, weak $\phi(k_t^2)$ and $\alpha_s(k_t^2)$ dependences and $G(x, k_t^2) \sim k_t^{1/2}$: $\frac{d\sigma}{dk_t} \sim k_t^{-6}$



High Transverse momentum dependence consistent with PQCD/ AdS/CFT

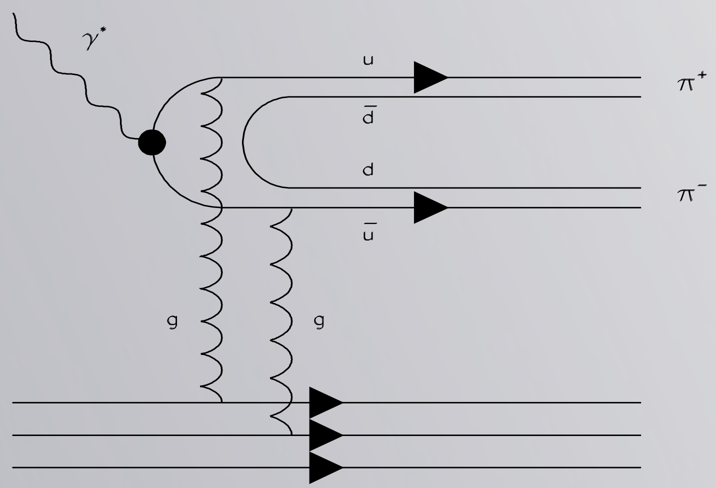
Coulomb Dissociate Proton to Three Jets at HERA



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

Hard Diffraction

Measure ratio of pion pairs to quark pairs in diffractive virtual photon interactions



The price: $\sigma_{2\pi} \;/\; \sigma_{2J} \;\sim\; k_t^{-4}, \quad \sim\; M^{-4}$

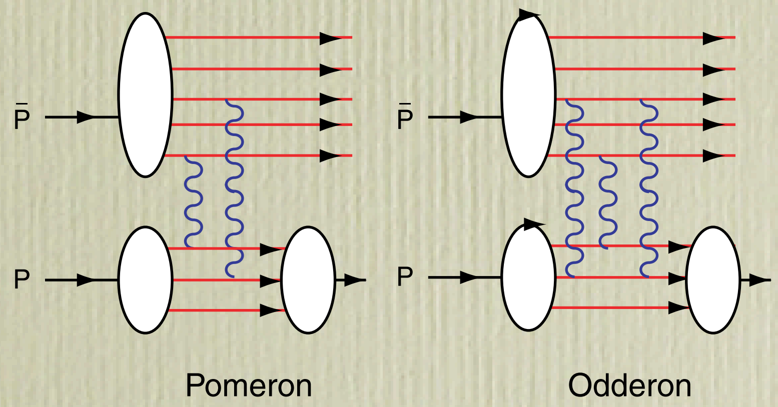
Pion quantum numbers ? **Longitudinal/Transverse ?**

Relation to pion Time-Like form factor ?

$$\frac{\sigma(\gamma^* + p \to 2\pi + p)}{\sigma(\gamma^* + p \to X + p)} \propto |F_\pi|^2$$

The Odderon

- Three Gluon Exchange
- Interference of 2-gluon and 3-gluon exchange leads to matter/antimatter asymmetries
- Asymmetry in jet asymmetry in $\gamma p \longrightarrow c\bar{c}p$
- Analogous to lepton energy and angle asymmetry $\gamma Z \to e^+e^-Z$
- Pion Asymmetry in $\gamma p \rightarrow \pi^+\pi^- p$

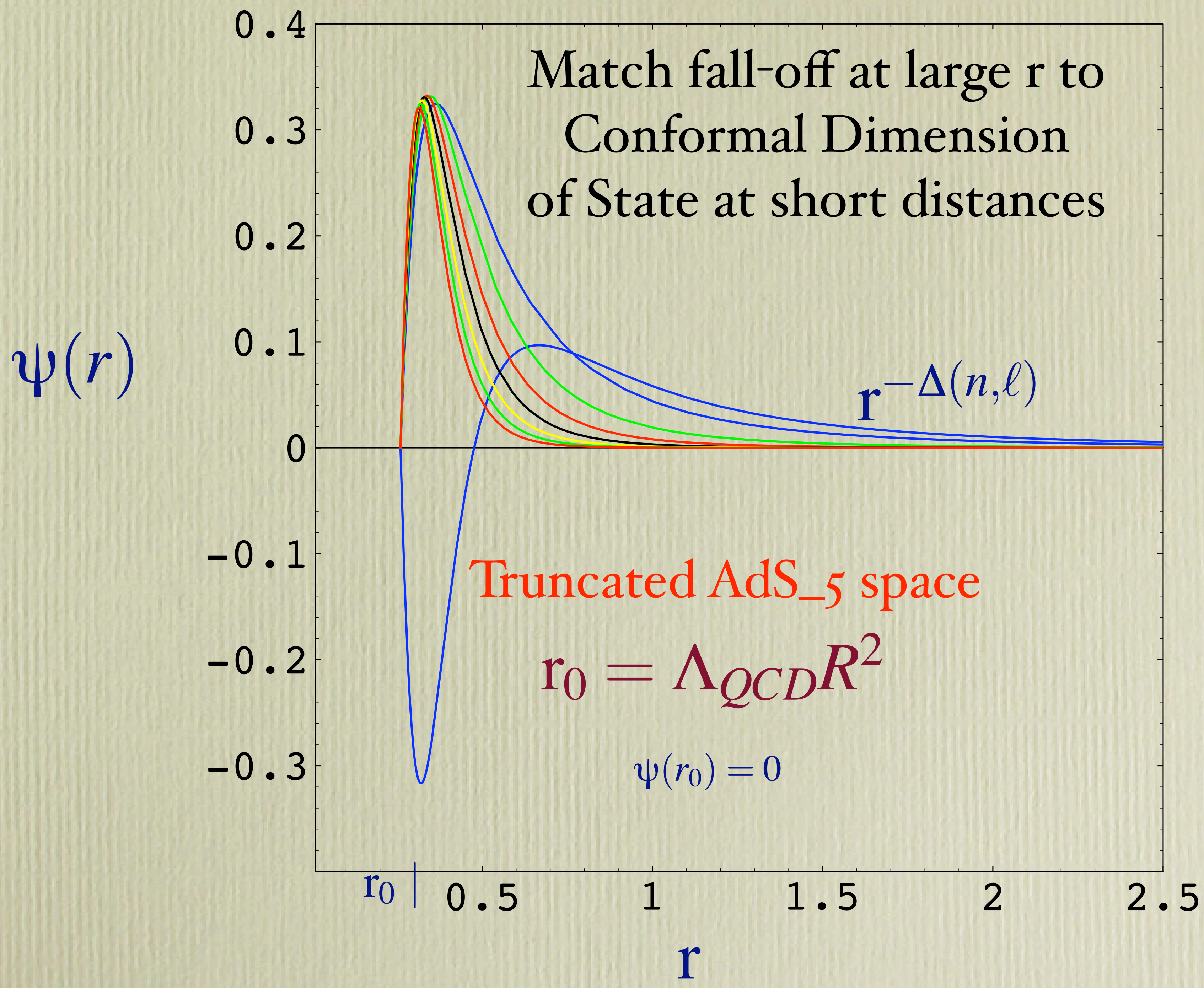


AdS/CFT and QCD

- 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

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


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

AdS/CFT Meson Spectroscopy

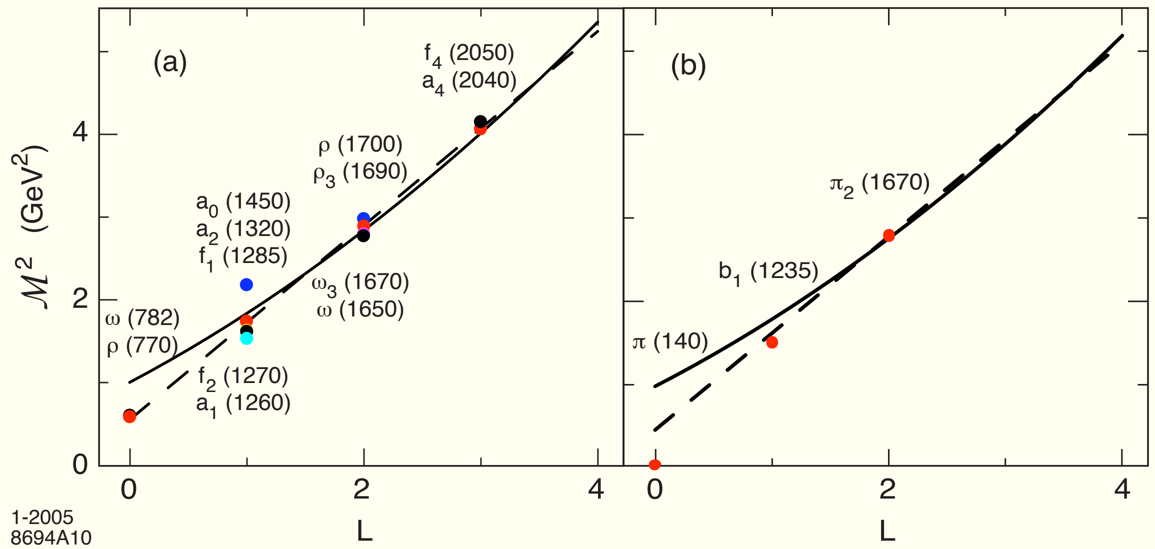


FIG. 1: Light meson orbital states for $\Lambda_{QCD} = 0.263$ GeV. Results for the vector mesons are shown in (a) and for the pseudoscalar mesons in (b). The dashed line has slope 1.16 GeV^2 and is drawn for comparison.

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

AdS/CFT Baryon Spectroscopy

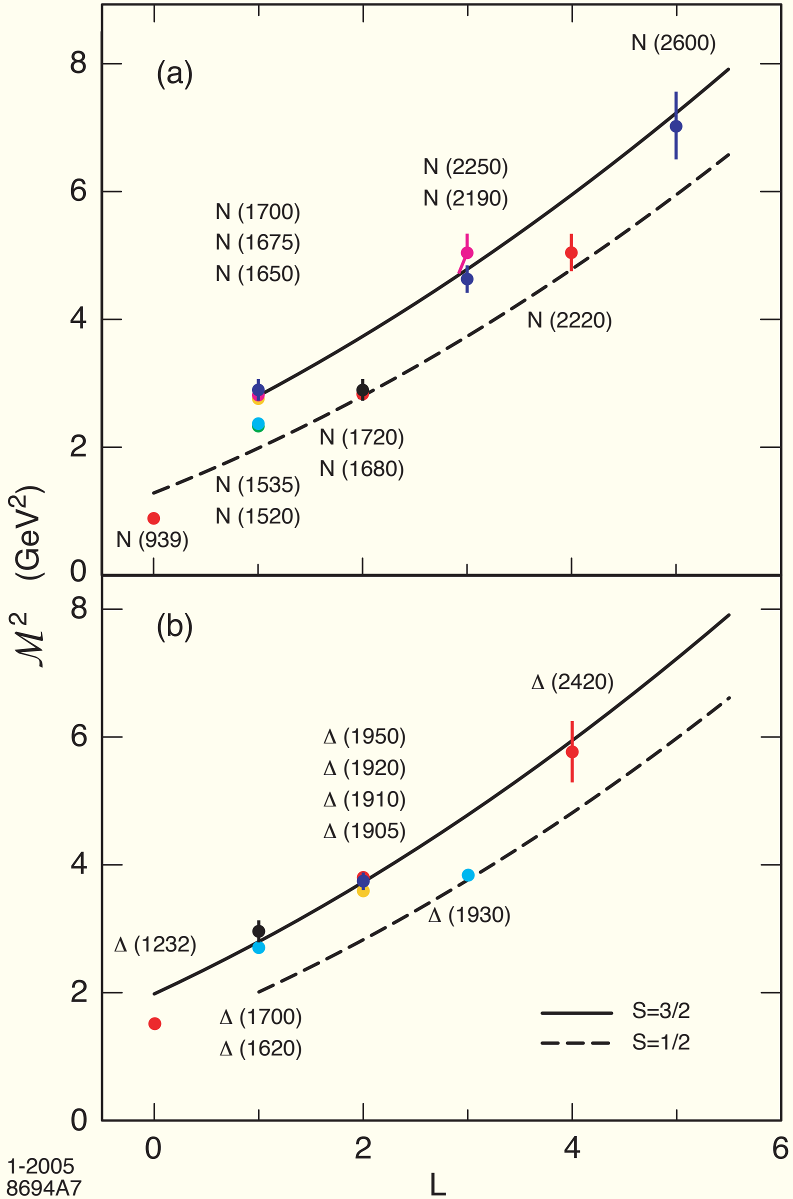


FIG. 2: Predictions for the light baryon orbital spectrum for $\Lambda_{QCD} = 0.22$ GeV. The lower curves corresponds to baryon states dual to spin-$\frac{1}{2}$ modes in the bulk and the upper to states dual to spin-$\frac{3}{2}$ modes.

One Parameter

$\Lambda_{QCD} = 0.22$ GeV

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

AdS/CFT

- 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

If we impose the condition:

$$\psi\left(x, |\vec{b}_\perp| = b_o\right) = 0, \tag{25}$$

then

$$\psi(x, b) = \gamma(x)\chi(b), \tag{26}$$

where $\gamma(x)$ is determined from the conformal invariance of the theory. In the conformal limit: $\gamma(x) = x(1-x)$. We obtain for $\psi(x, b)$

$$\psi(x, b) = Cx(1-x)\frac{J_\alpha(b\mathcal{M})}{b}, \tag{27}$$

The two-parton state including orbital angular momentum ℓ and radial modes is:

$$\psi_{n,\ell,k}(x, b) = B_{n,\ell,k}\; x(1-x)\frac{J_{n+\ell-1}\left(b\beta_{n-1,k}\Lambda_{QCD}\right)}{b}, \tag{28}$$

The figures show the model predictions for the two-parton wavefunction $\psi_n(x, \vec{b}_\perp)$, $n = 2$, as a function of x and $|\vec{b}_\perp|$ for $\ell = 0, k = 1$; $\ell = 1, k = 1$ and $\ell = 0, k = 2$ respectively. The normalization in the figures is arbitrary.

Holographic LFWF

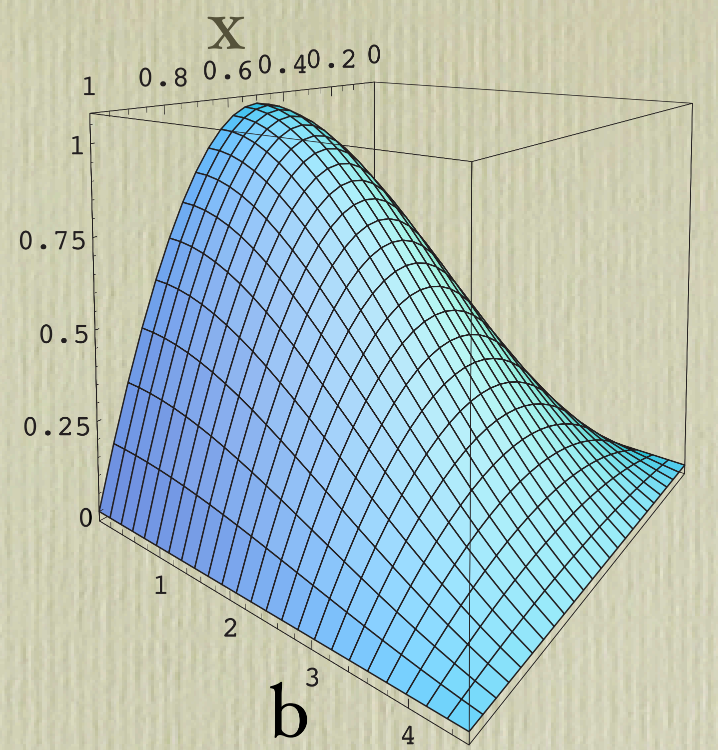


Figure 1: Ground state light-front wavefunction in impact space $\psi(x, b)$ for a two-parton state in a holographic QCD model for $n = 2, \ell = 0, k = 1$.

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

b = r

GdT & Sjb (preliminary)

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

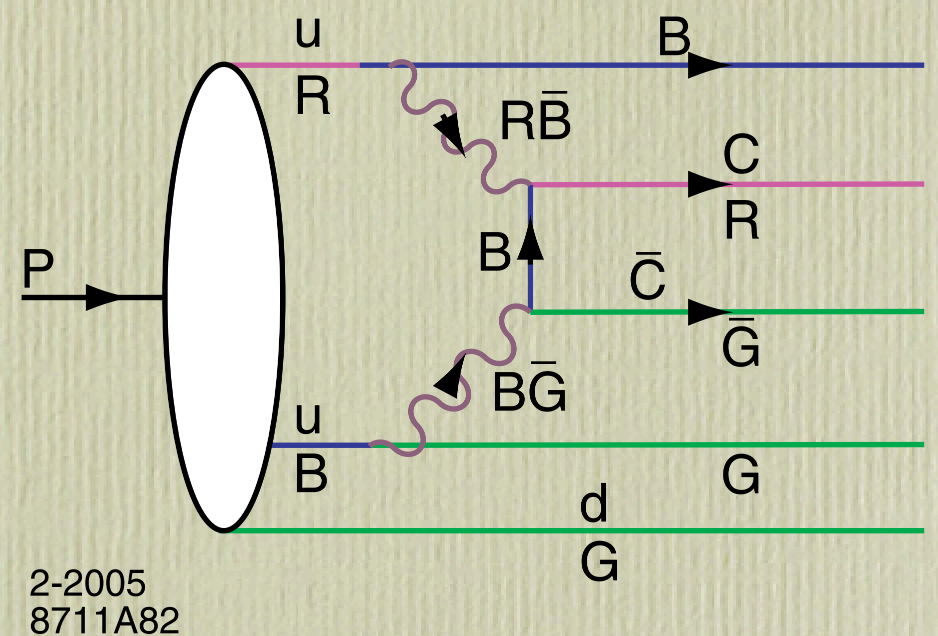
  $s(x) \neq \bar{s}(x)$

- "Intrinsic Charm": High momentum heavy quarks

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

- Orbital Angular Momentum Fluctuations - Anomalous Magnetic Moment

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

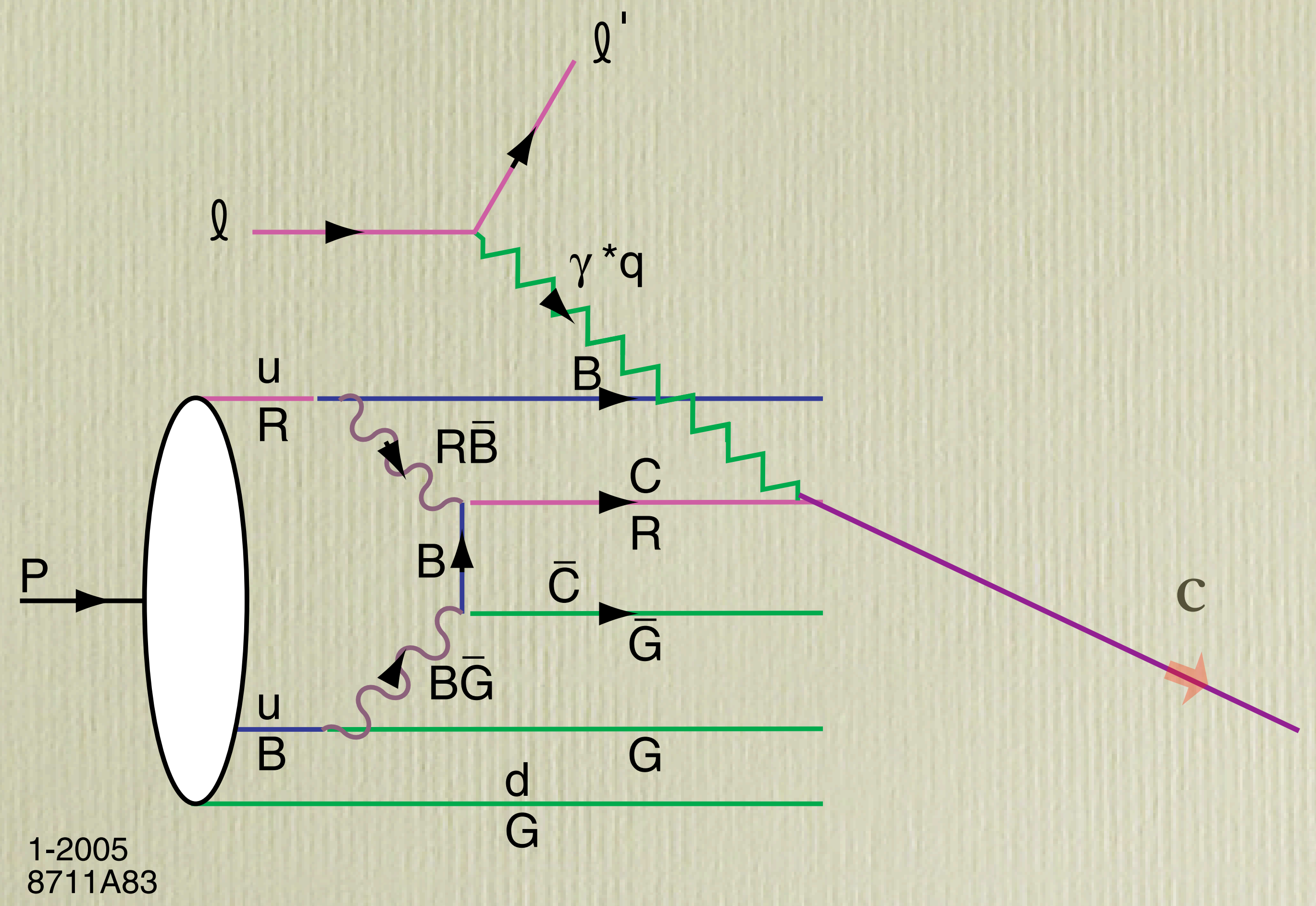
Distribution peaks at equal rapidity (velocity)

Therefore heavy particles carry the largest momentum fractions

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

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

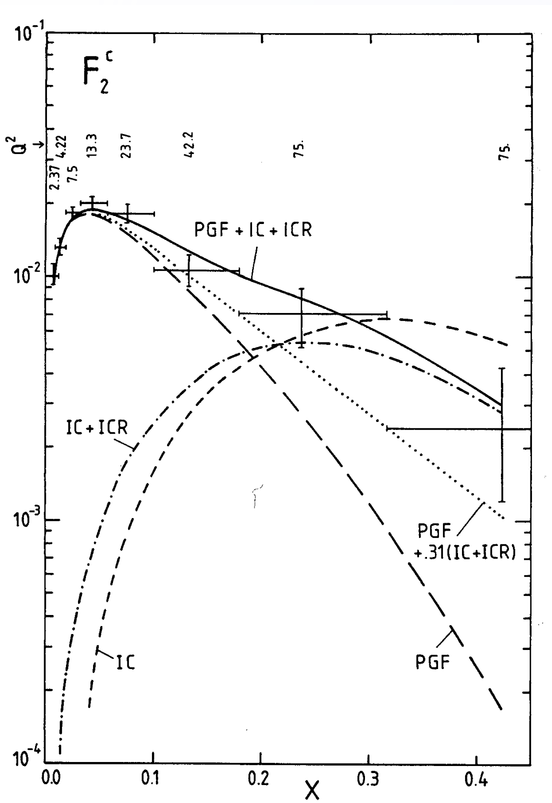
Measure c(x) in Deep Inelastic Lepton-Proton Scattering

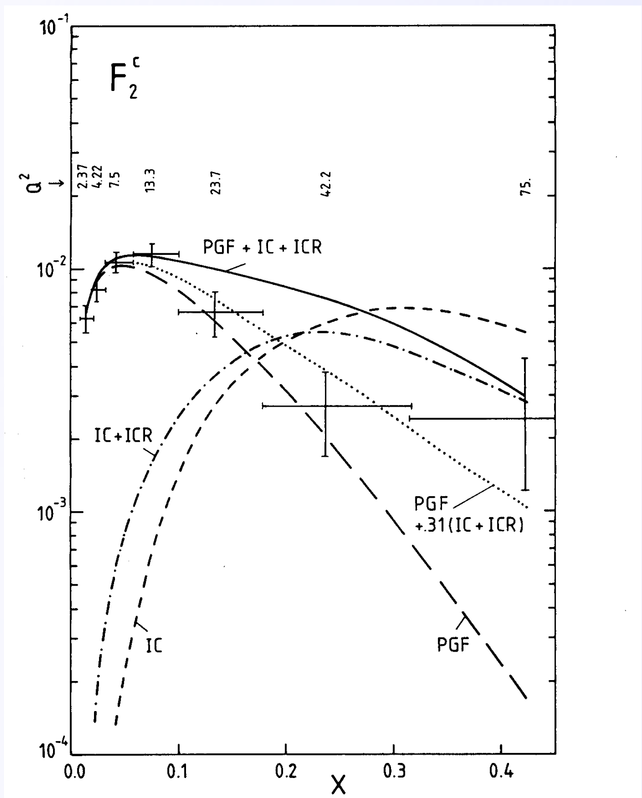


EMC Measurements of the Charm Structure Function

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

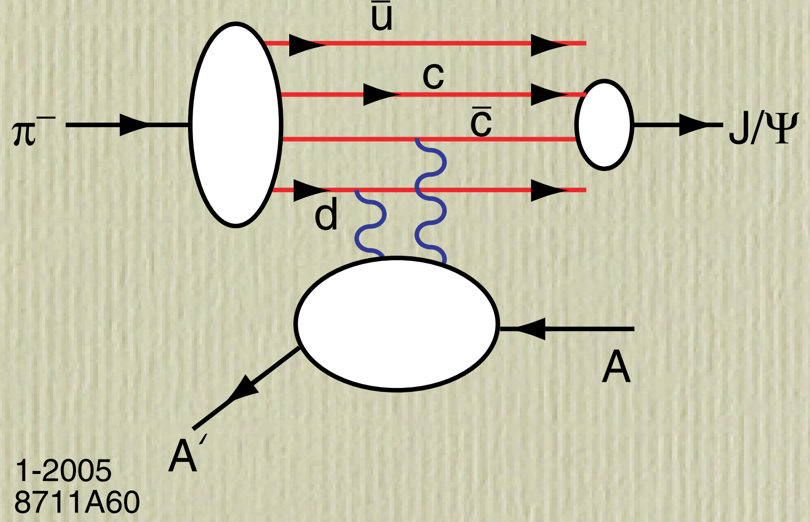


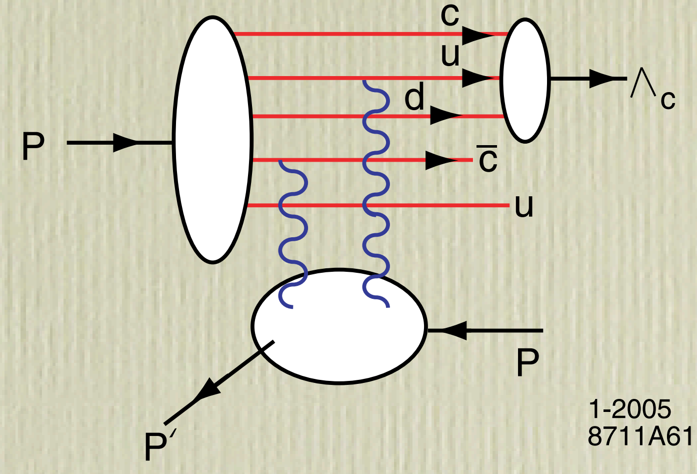


Analysis by
E. Hoffmann and R. Moore, Z. Phys. C 20, 71 (1983).

Photon Gluon Fusion Factor 30 too small

Diffractive Dissociation of Intrinsic Charm

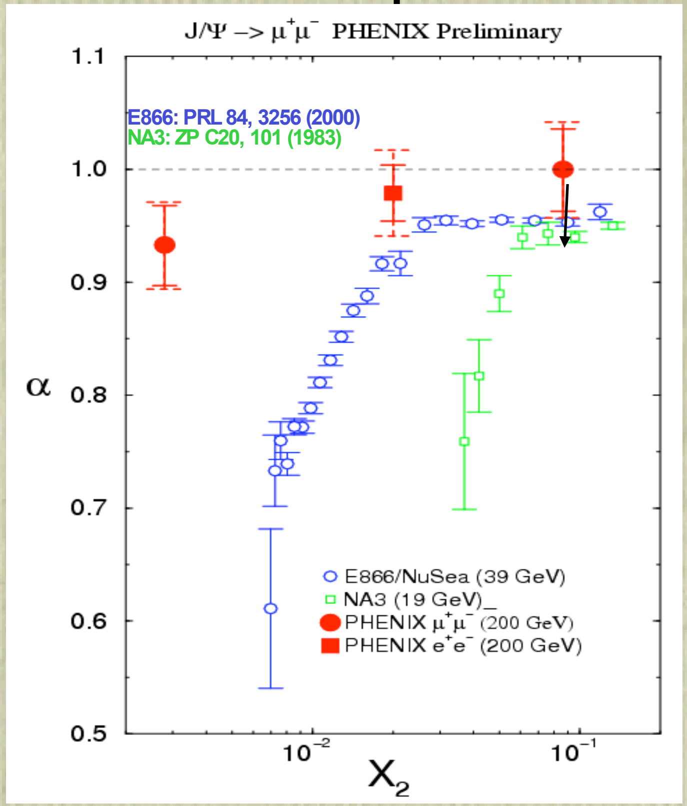


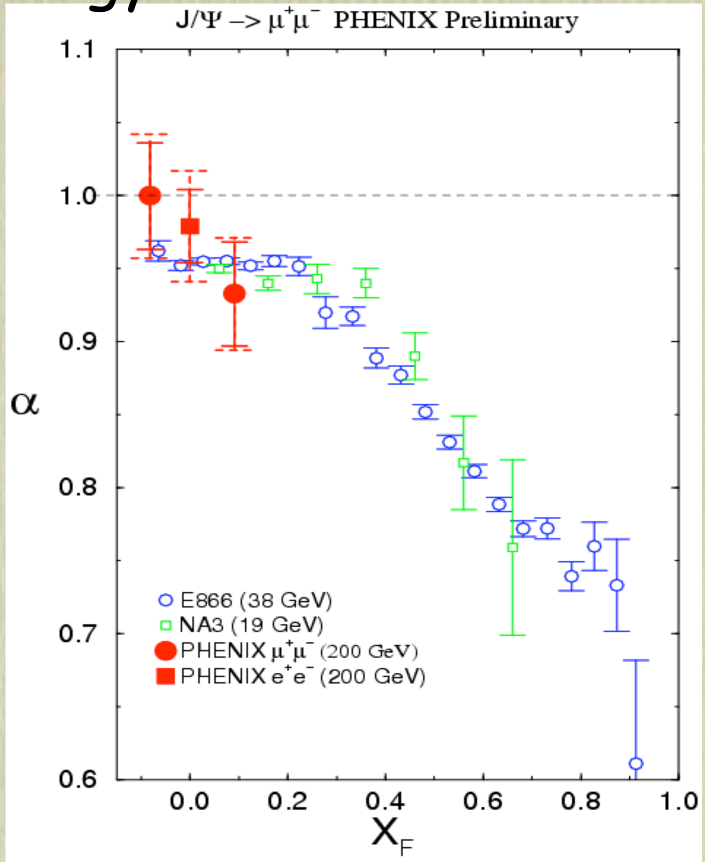


Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

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

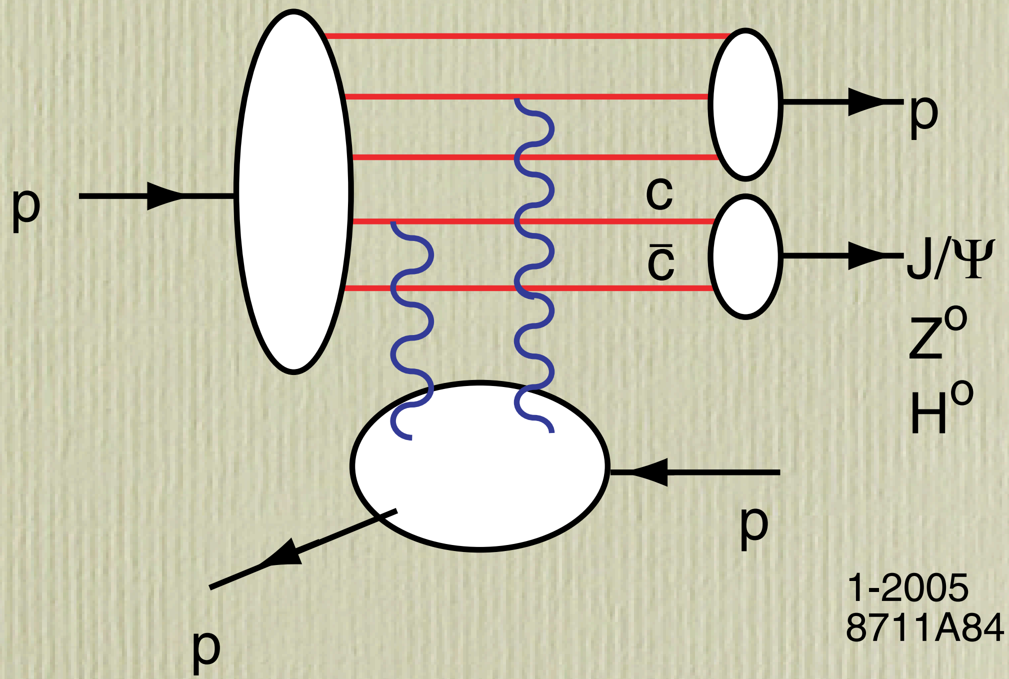
Will need another dAu run! (more pp data also)

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 $x_1 \sim x_F$ - expected to be weak at RHIC energy)

Intrinsic Charm Mechanism for Double Diffraction



$$p\,p \to J/\psi\, p\, p$$

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

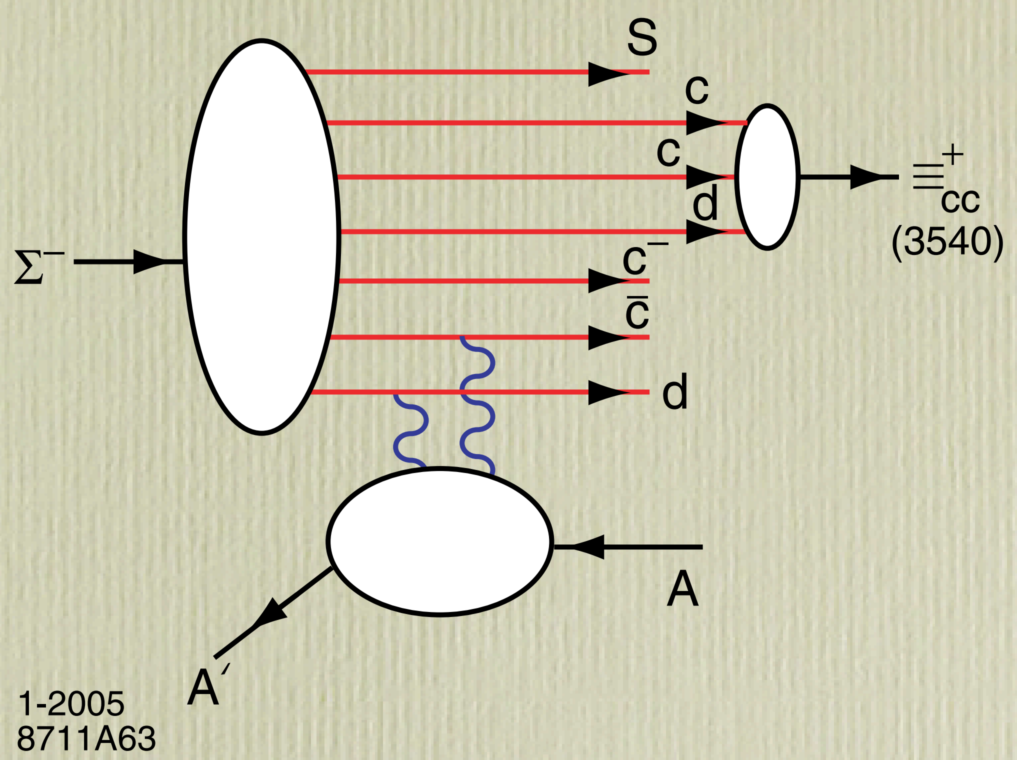
High x_F !

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

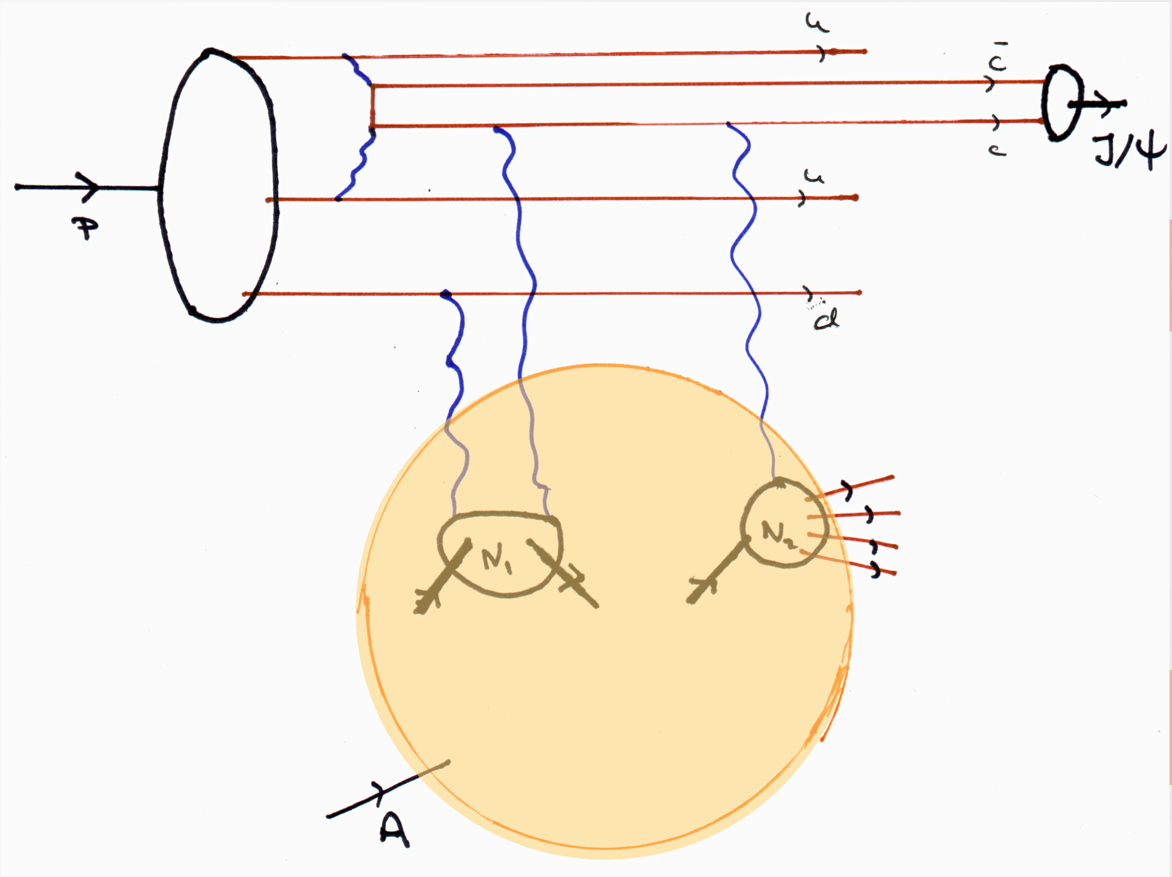
Collision produces color-singlet J/ψ through color exchange

Schmidt, Soffer, sjb

RHIC Experiment



Production of a Double-Charm Baryon



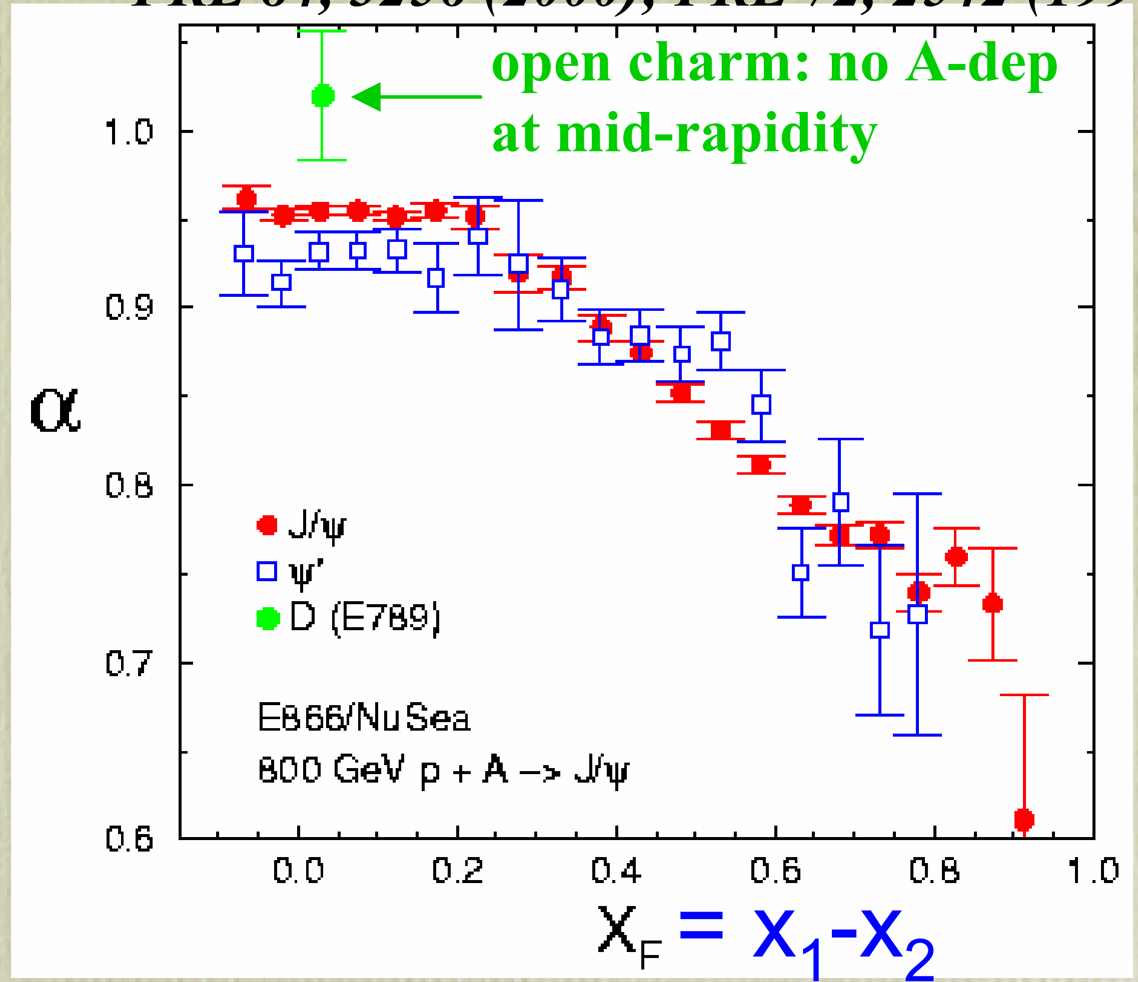
Shadowing of $pA \rightarrow J/\Psi X$

J/Ψ Production on Front Surface
No Absorption of Propagating J/Ψ
$\sigma(p + A \rightarrow J/\Psi + X) \propto A^{2/3}$

Elastic scattering of IC Fock state:
$|[uud]_{8_C}[c\bar{c}]_{8_C} > + N_1 \rightarrow |[uud]_{8_C}[c\bar{c}]_{8_C} > + N_1$
followed by:
$|[uud]_{8_C}[c\bar{c}]_{8_C} > + N_2 \rightarrow J/\Psi + X$
Depleted flux on downstream nucleons

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



Remarkably Strong Nuclear Dependence for Fast Charmonium

Hard Diffraction

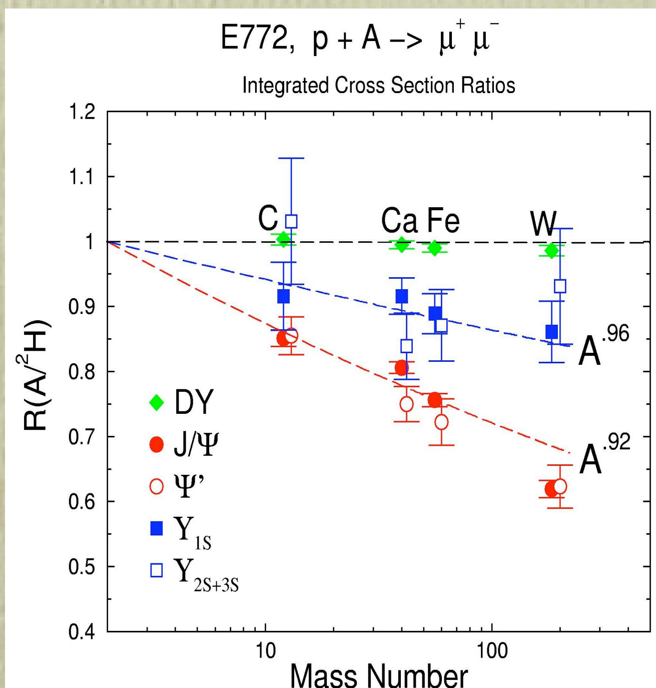
Nuclear effects in Quarkonium production

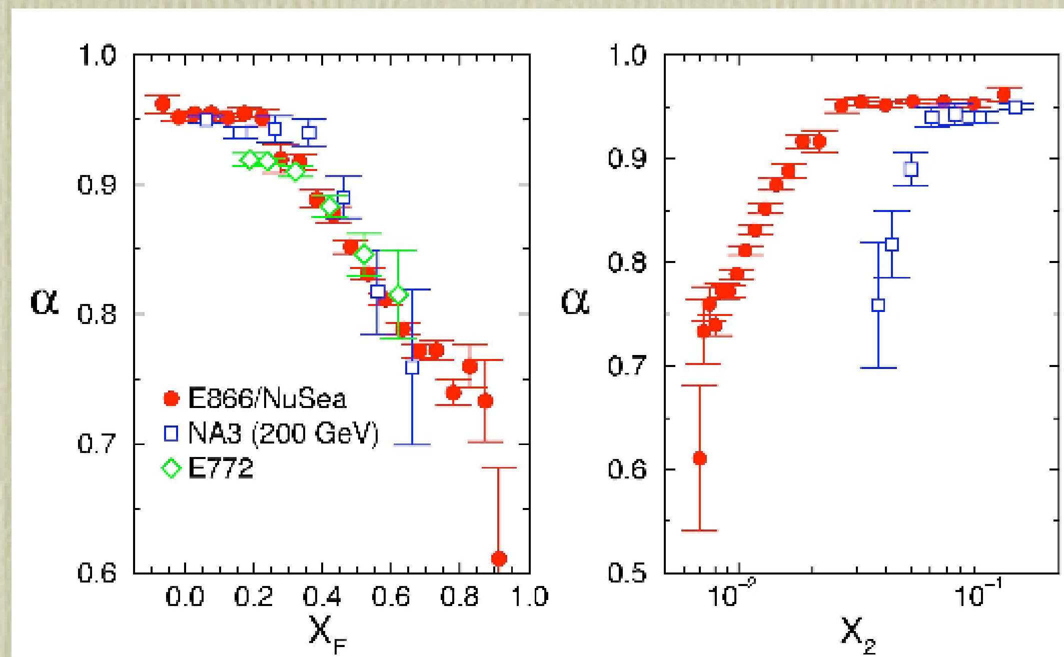
p + A at $s^{1/2}$ = 38.8 GeV

$\sigma(p+A) = A^{\alpha}\,\sigma(p+N)$

E772 data

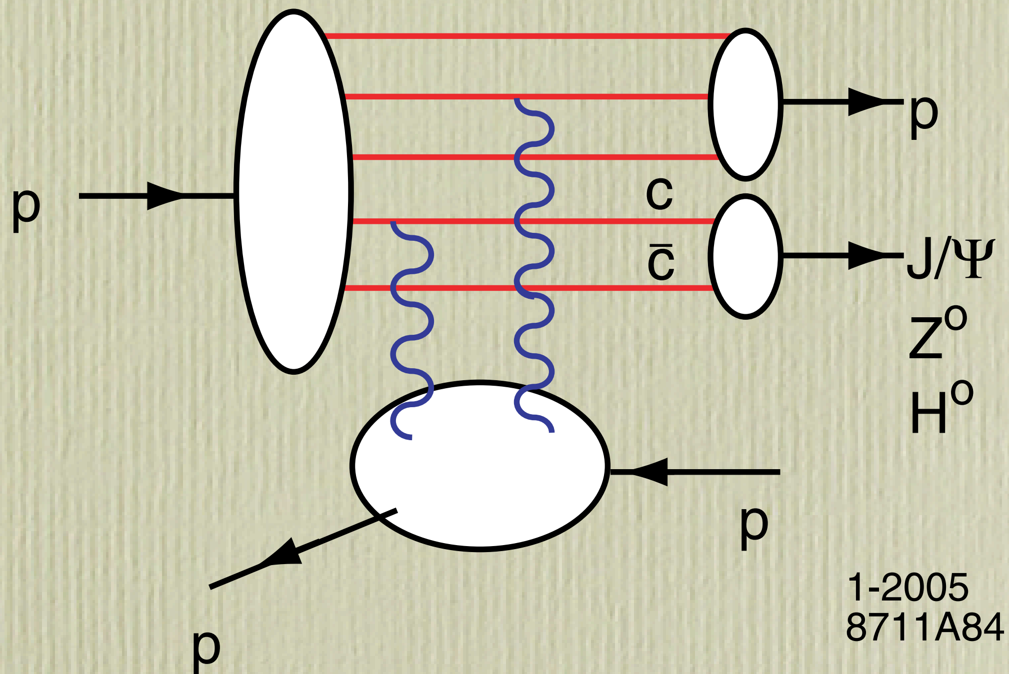
Strong x_F - dependence





Nuclear effects scale with x_F, not x_2 !!!

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 !

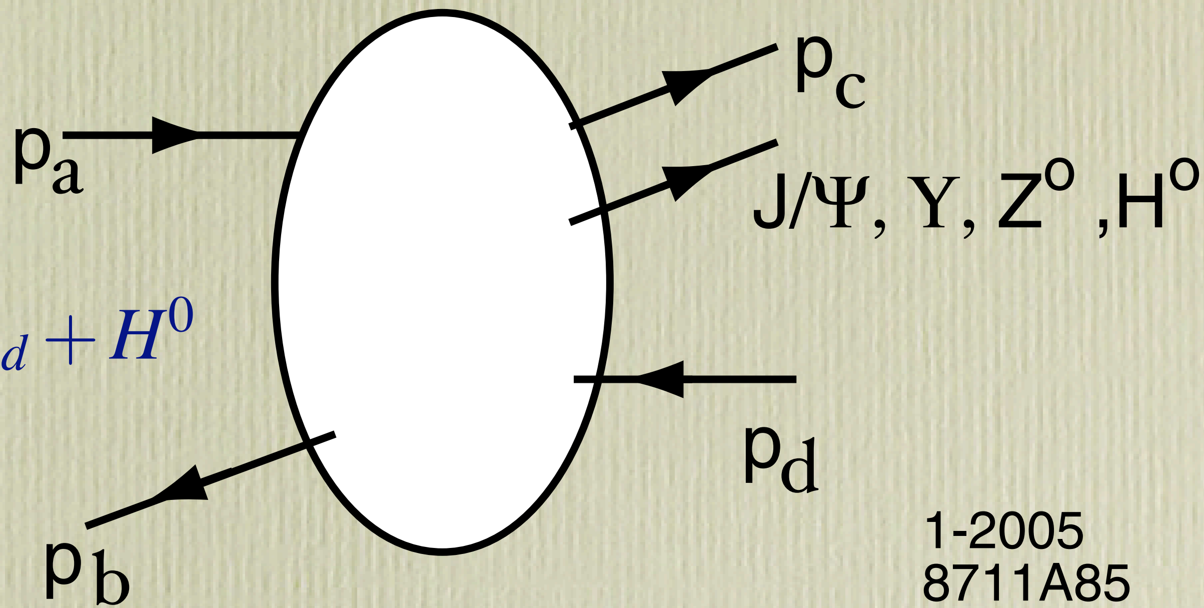
Intrinsic $c\bar{c}$ pair formed in color octet 8_C in proton wavefunction   Large Color Dipole

Collision produces color-singlet J/ψ through color exchange

Schmidt, Soffer, sjb

RHIC Experiment

Doubly-Diffractive Higgs Production



$p_a + p_b \rightarrow p_c + p_d + H^0$

$p_H^\mu = p_a^\mu + p_b^\mu - p_c^\mu - p_d^\mu$

Low transverse momentum protons p_c, p_d

Higgs appears in Missing Mass spectrum dN/dM^2

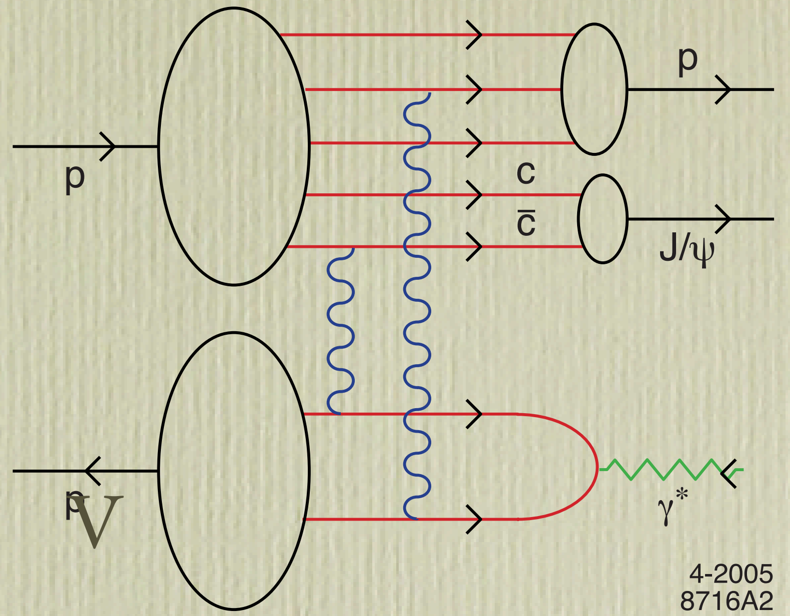
$M^2 = p_H^2$

Intrinsic Charm: Large range of Higgs momentum $x_F = p_H^z / p_a^z$

Extrapolate from doubly diffractive $J/\psi, \Upsilon, Z^0$ production

Soffer, Schmidt,sjb

New Test of Intrinsic Charm



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

Hard Diffraction

Higgs Production at High x_F

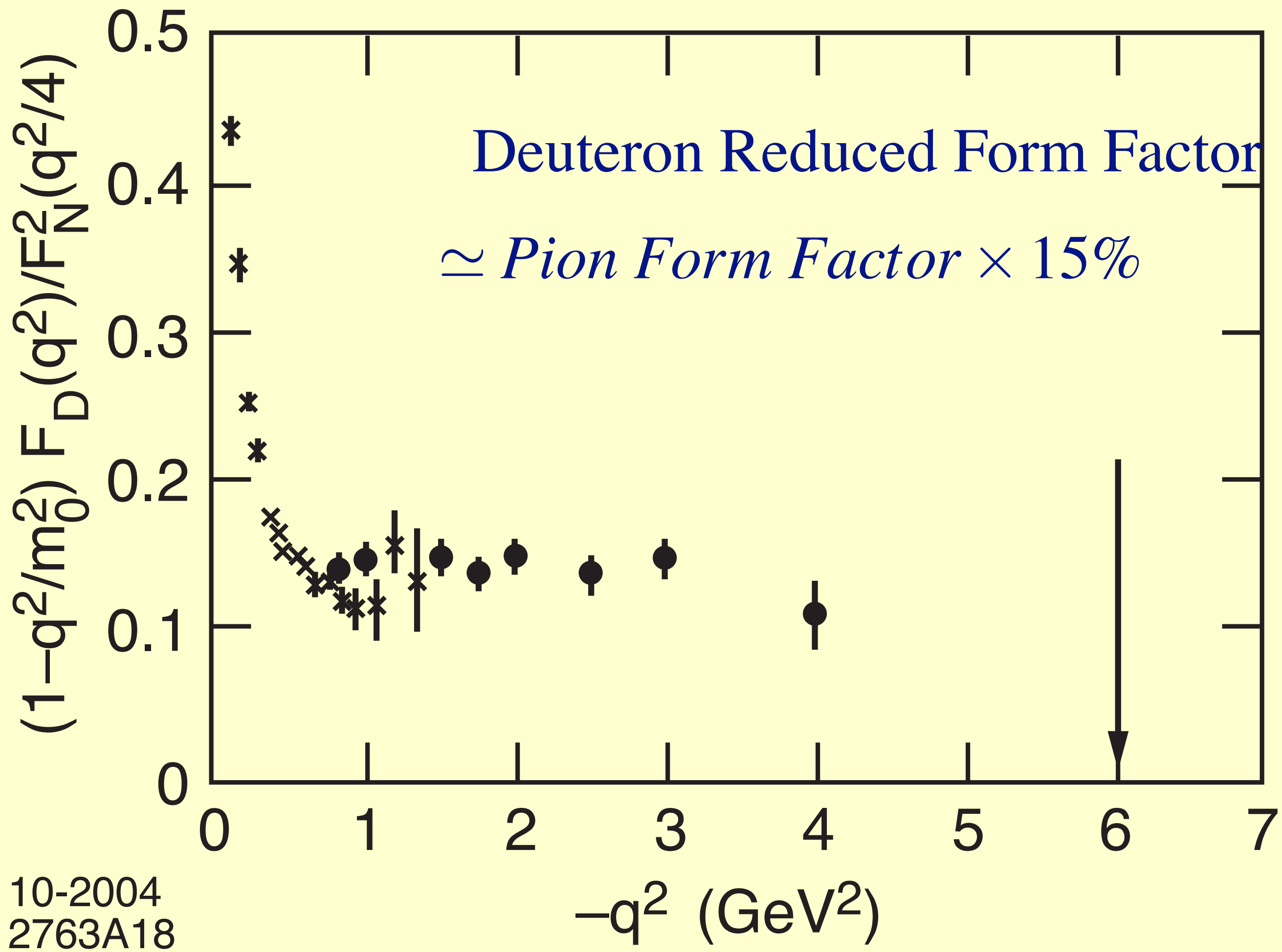
$$pp \to H^0 X$$

- Small transverse momentum
- Same x_F Distribution as Quarkonium
- Axial Detector?
- Intrinsic Charm and Bottom Couples to Higgs
- Higgs will carry high momentum fraction of projectile momentum

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



- 15% Hidden Color in the Deuteron

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 SSAs, Shadowing, Antishadowing
- Diffractive dijets/ trijets, doubly diffractive Higgs
- Novel Effects: Color Transparency, Color Opaqueness, Intrinsic Charm, Odderon