

2-2005  
8711A82

$|uudc\bar{c}\rangle$  Fluctuation in Proton  
 QCD: Probability  $\sim \frac{\Lambda_{QCD}^2}{M_Q^2}$

$|e^+e^-l^+l^-\rangle$  Fluctuation in Positronium  
 QED: Probability  $\sim \frac{(m_e\alpha)^4}{M_l^4}$

OPE derivation - M.Polyakov et al.

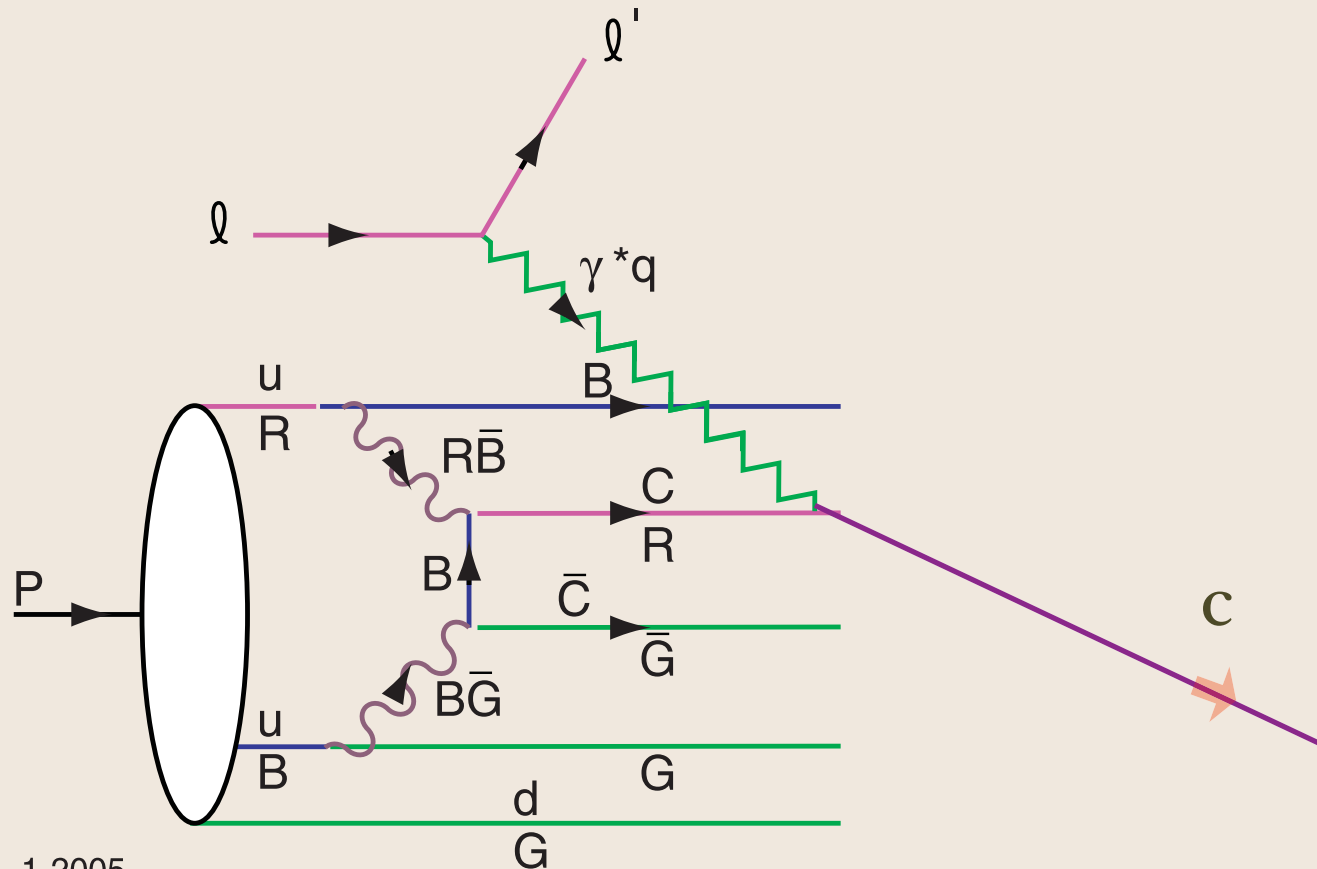
$c\bar{c}$  in Color Octet

High x charm

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

Anti-Shadowing & Novel  
 Phenomena in QCD

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



1-2005  
8711A83

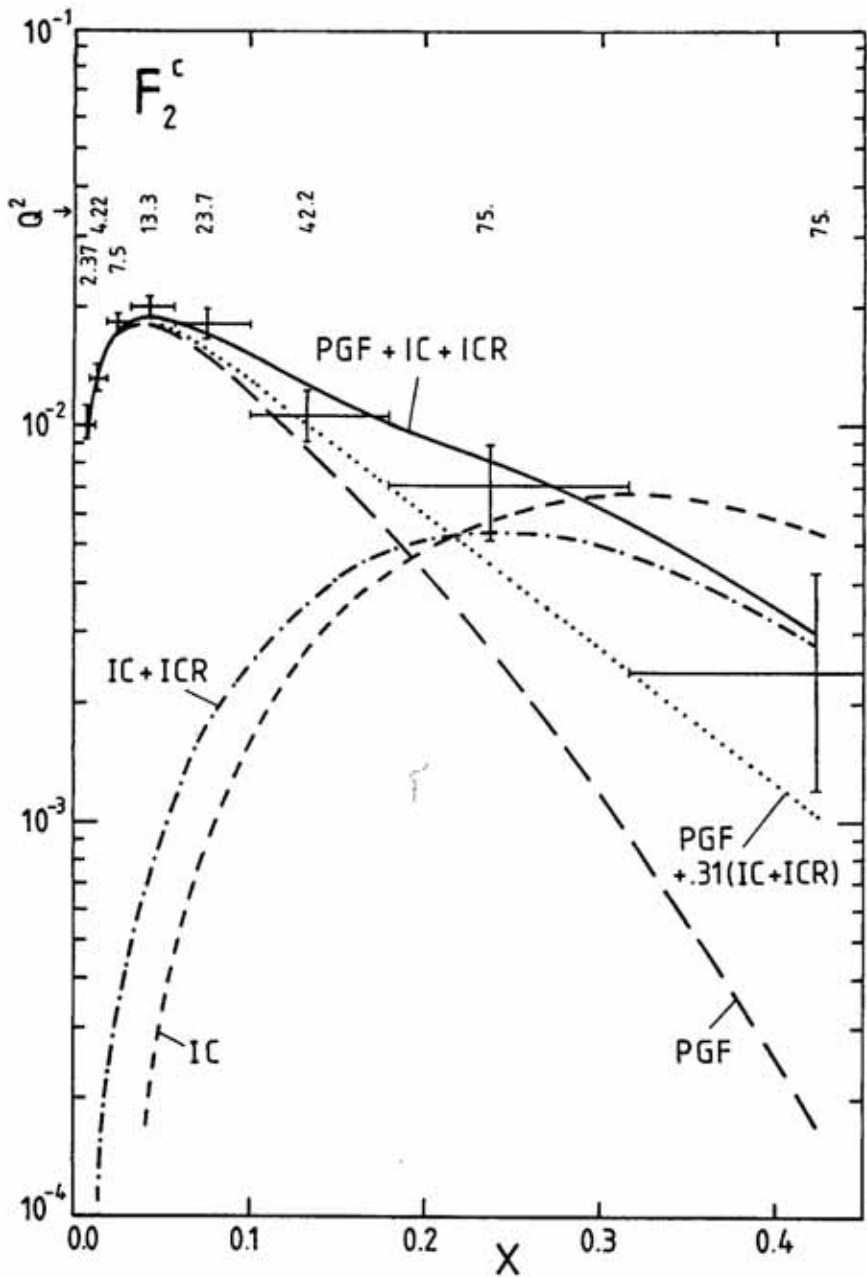
Hoyer, Peterson, SJB

Anti-Shadowing & Novel  
Phenomena in QCD

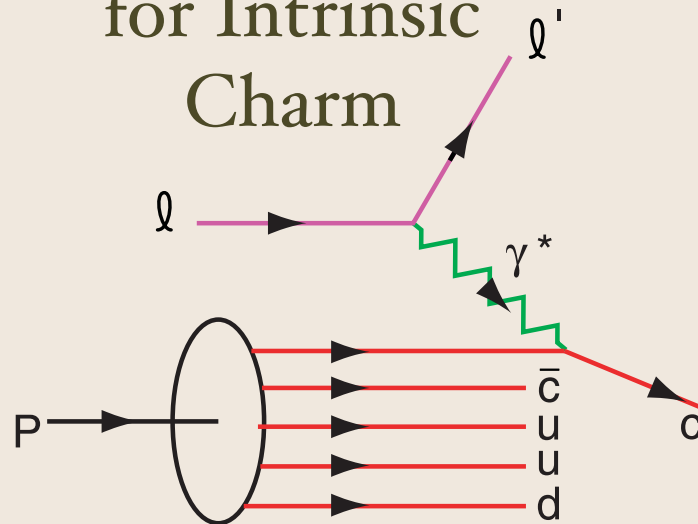
LANL  
I-18-06

# Measurement of Charm Structure Function

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



## Evidence for Intrinsic Charm



1-2005  
8711A59

Anti-Shadowing & Novel Phenomena in QCD

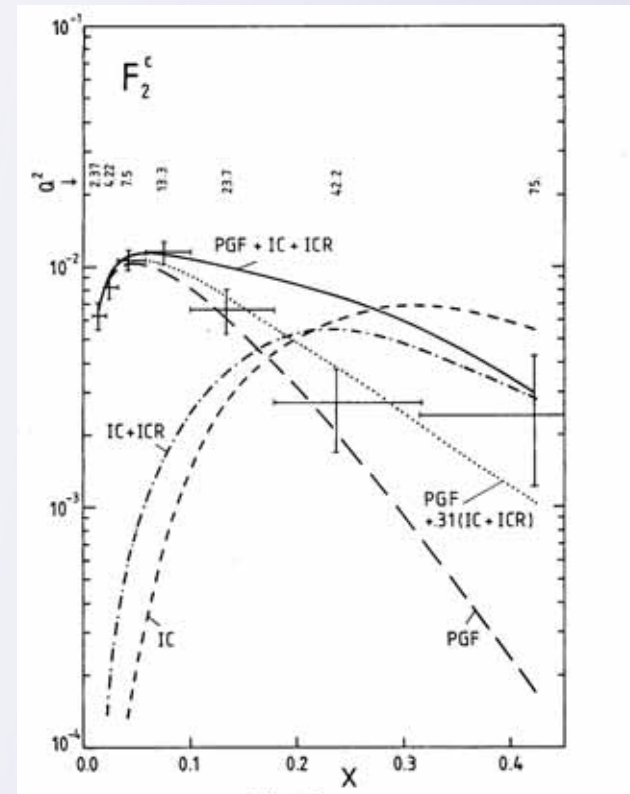
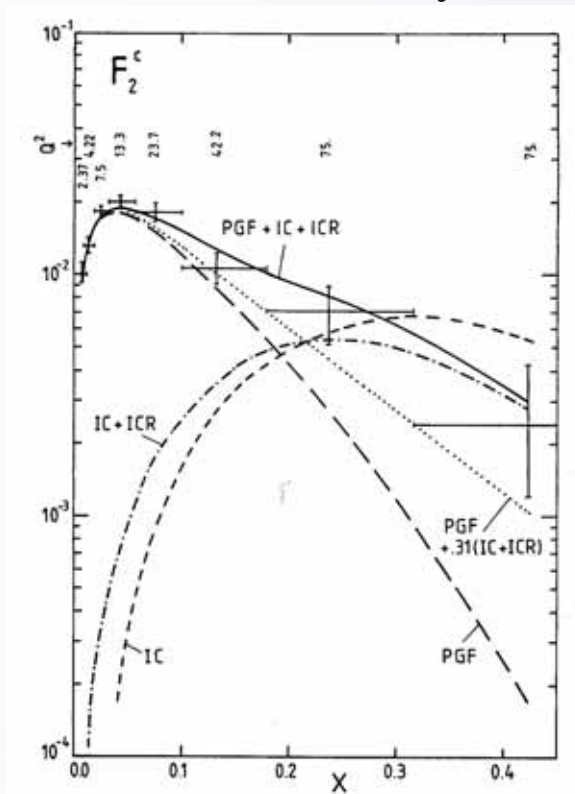
Analysis by

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

## 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  
→



Photon Gluon Fusion Factor 30 too small

Anti-Shadowing & Novel  
Phenomena in QCD

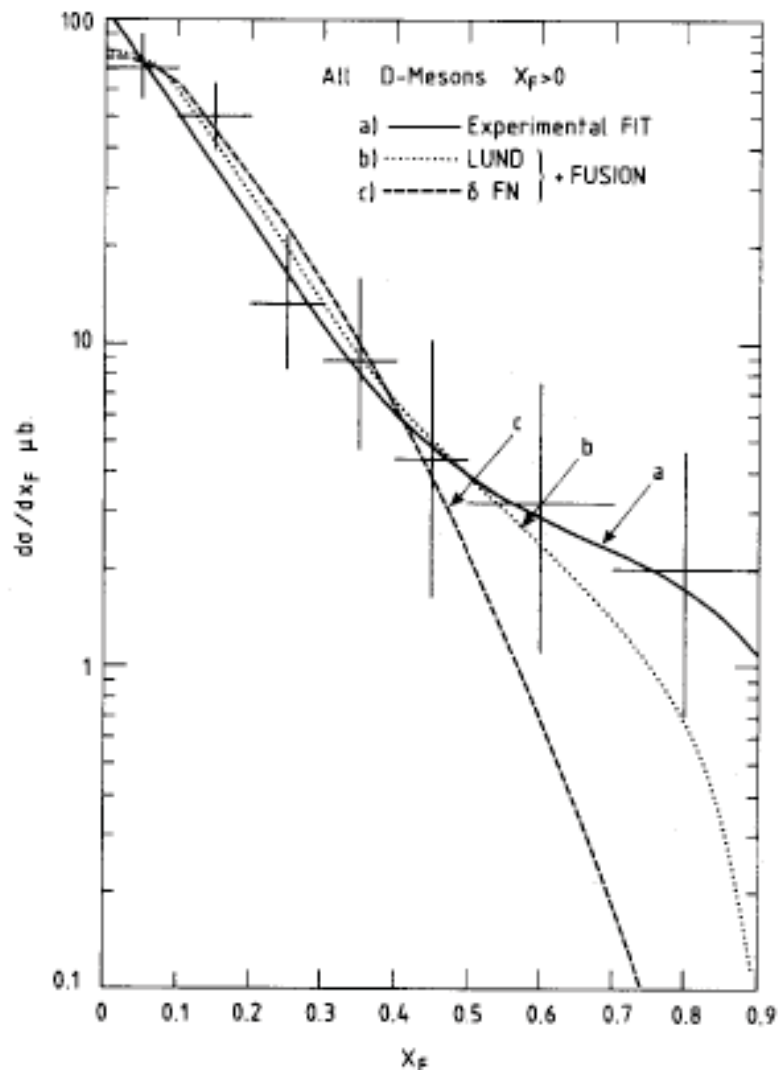
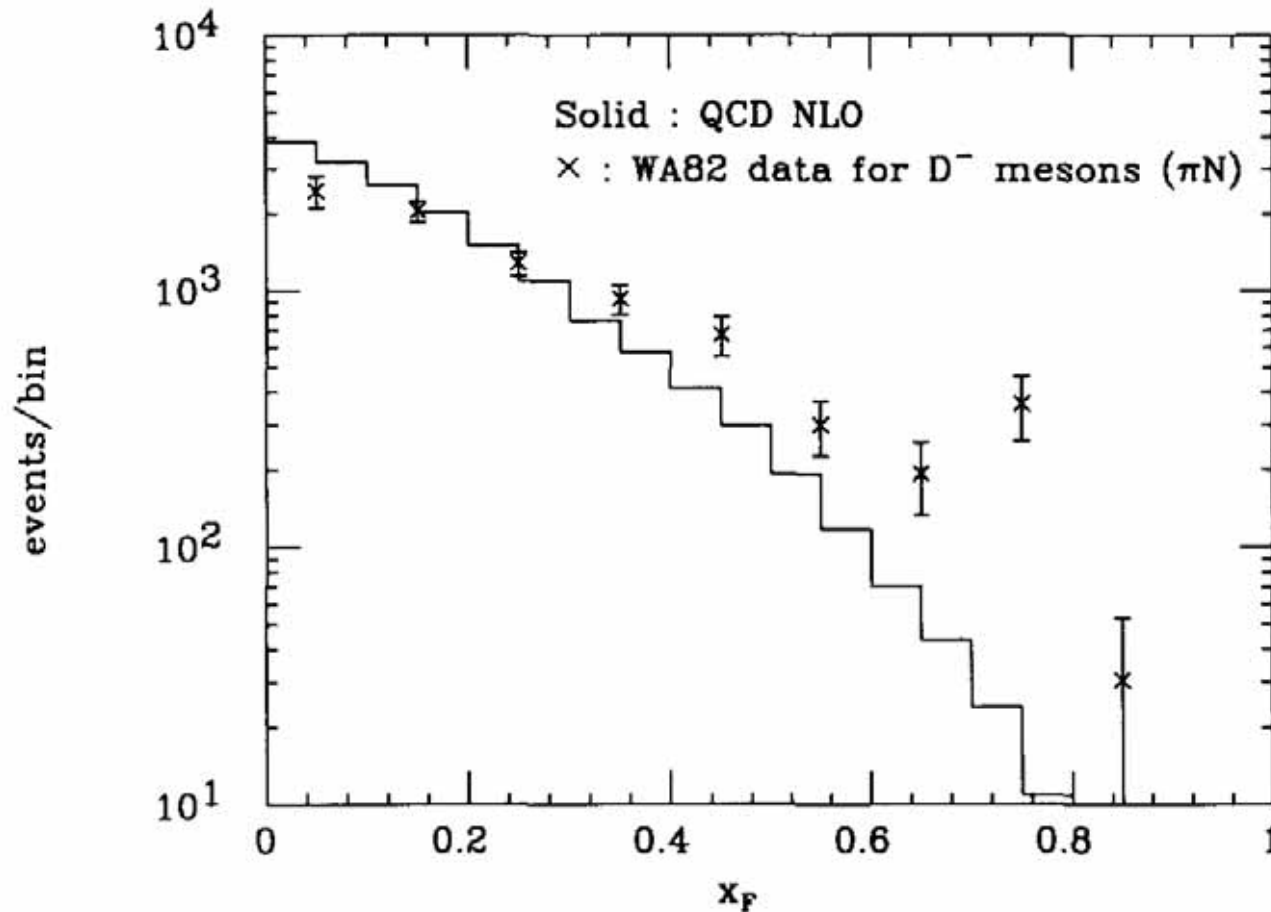


Fig. 1. The differential distribution  $x_F$  for all D mesons having  $x_F > 0$ . Curve (a) is the two-component fit to the data as described in the text. Curve (b) is the prediction of the Lund fusion calculation. Curve (c) is the prediction of the bare QCD fusion calculation ( $\delta$ -function fragmentation). Note that both theoretical curves have been normalised to the observed total cross section for  $x_F > 0$ .

M. Aguilar-Benitez et al.  
 [NA27 Collaboration],  
 “Inclusive Properties Of *D* Mesons  
 Produced In 360-GeV  $\pi p$  Interaction  
 Phys. Lett. B 161, 400 (1985).

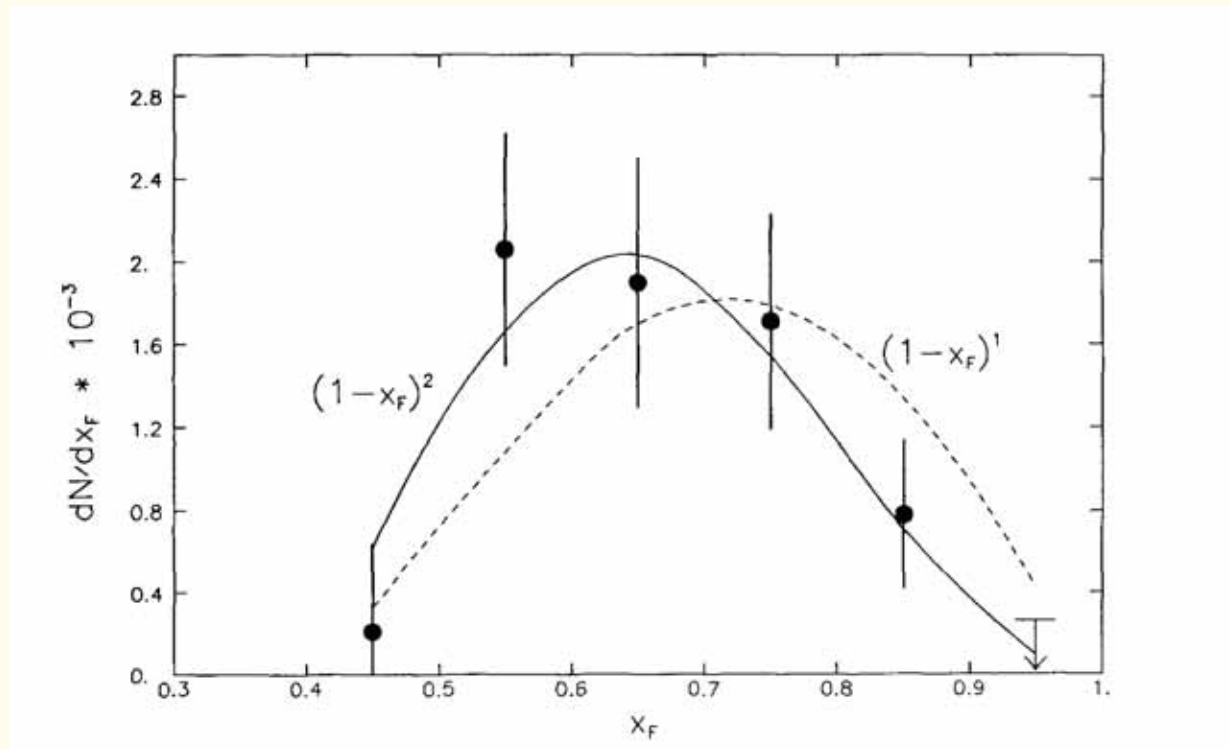
Anti-Shadowing & Novel  
 Phenomena in QCD



S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, “Heavy-Quark Production,”  
 Adv. Ser. Direct. High Energy Phys. 15, 609  
 (1998) [arXiv:hep-ph/9702287].

Anti-Shadowing & Novel  
 Phenomena in QCD

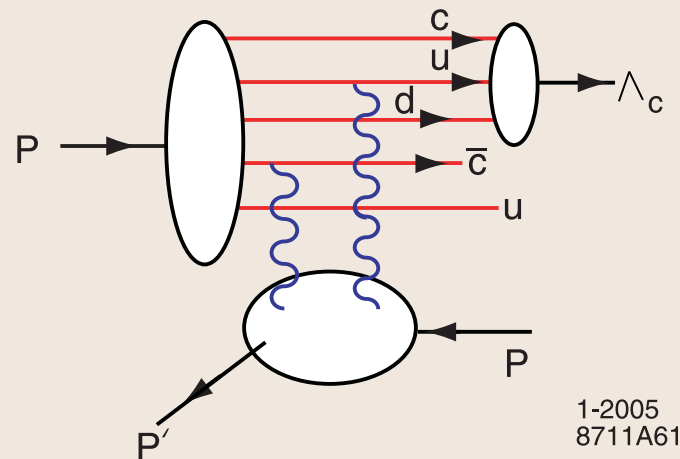
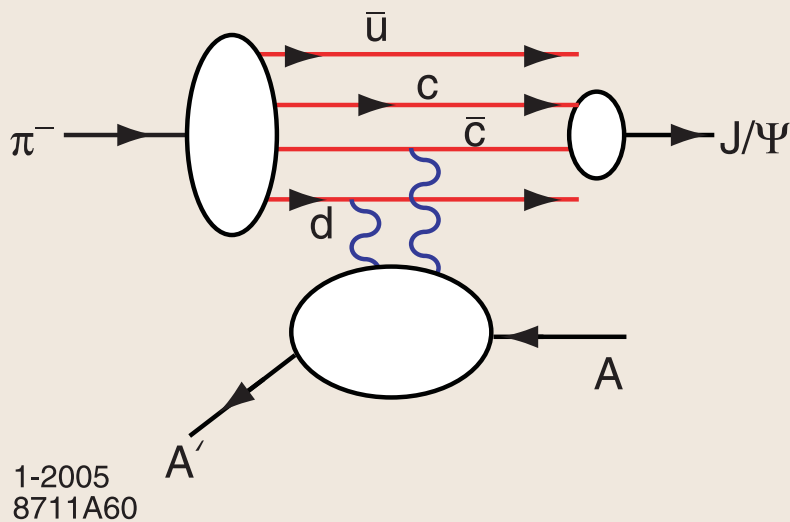
# Production of Charm Hadrons at the ISR



P. M. Chauvat et al. [R608 Collaboration],  
“Production of  $\Lambda_C$  With Large  $x_F$  At The ISR,”  
Phys. Lett. B 199, 304 (1987).

- EMC data:  $c(x, Q^2) > 30 \times \text{DGLAP}$   
 $Q^2 = 75 \text{ GeV}^2, x = 0.42$
- High  $x_F$   $pp \rightarrow J/\psi X$
- High  $x_F$   $pp \rightarrow J/\psi J/\psi X$
- High  $x_F$   $pp \rightarrow \Lambda_c X$
- High  $x_F$   $pp \rightarrow \Lambda_b X$
- High  $x_F$   $pp \rightarrow \Xi(ccd) X$  (SELEX)

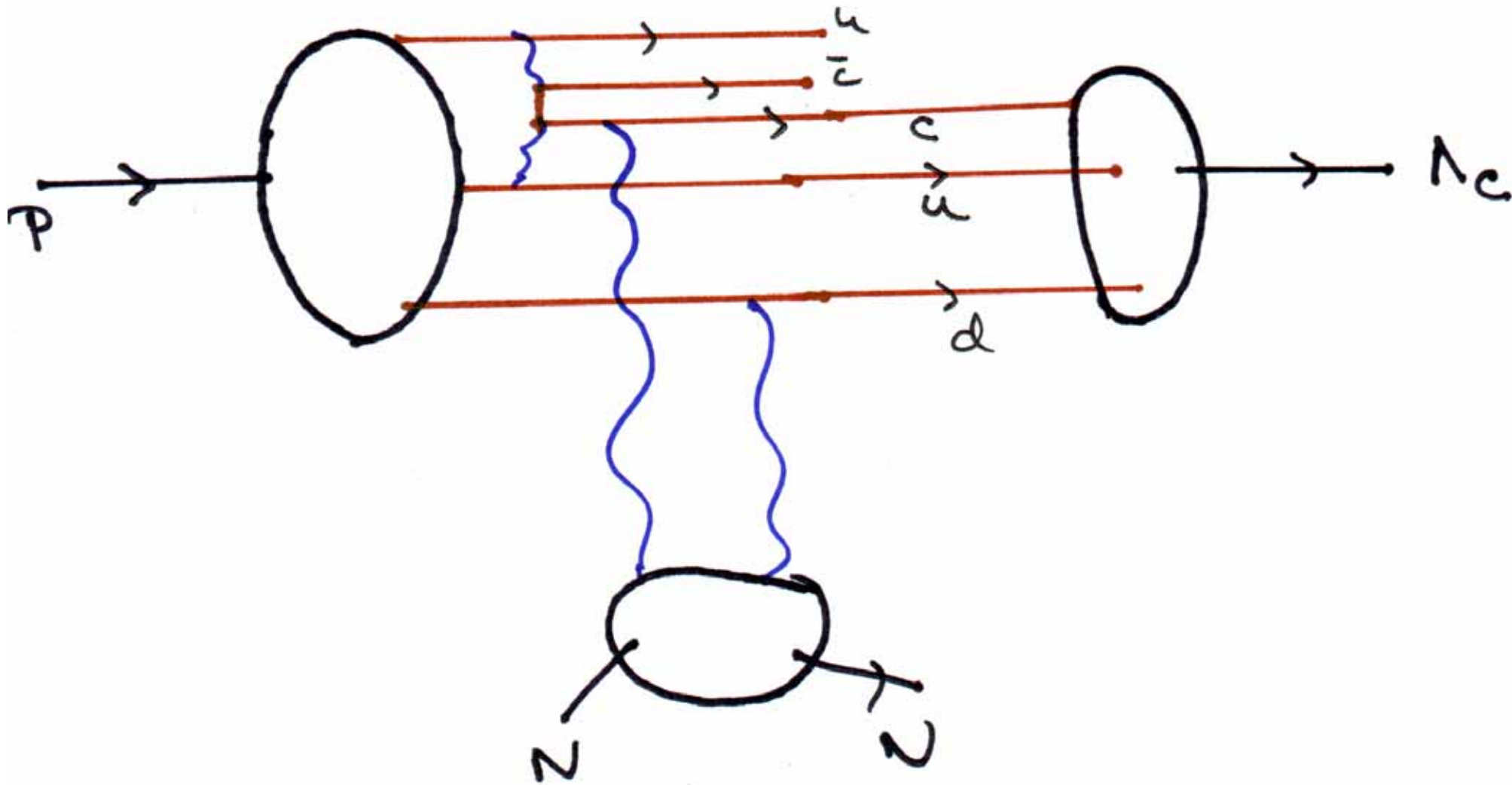
# Diffractive Dissociation of Intrinsic Charm



Coalescence of Comoving Charm and Valence Quarks  
Produce  $J/\psi$ ,  $\Lambda_c$  and other Charm Hadrons at High  $x_F$

$$p p \rightarrow p \Lambda_c X$$

## Diffractive Dissociation of Intrinsic Charm



Anti-Shadowing & Novel  
Phenomena in QCD

$$\pi A \rightarrow J/\psi J/\psi X$$

Intrinsic charm contribution to double quarkonium hadroproduction<sup>\*</sup>

R. Vogt<sup>a</sup>, S.J. Brodsky<sup>b</sup>

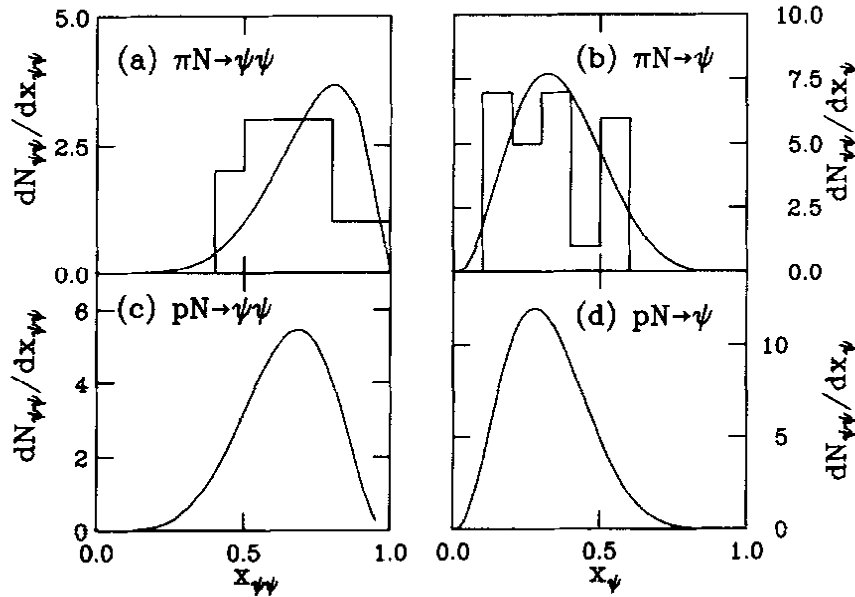


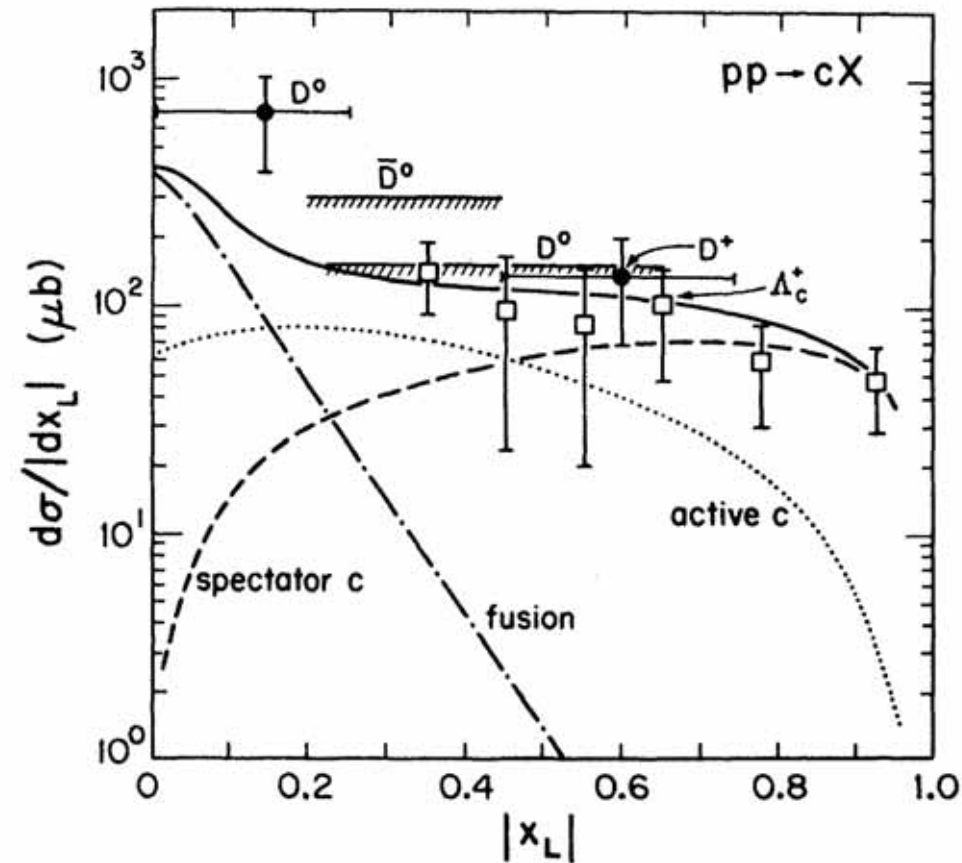
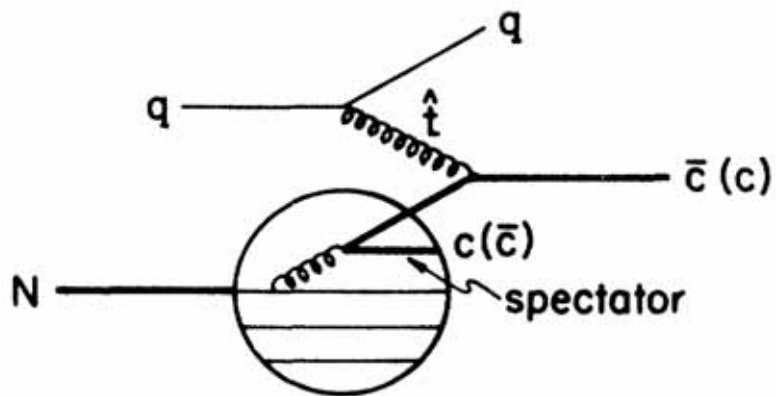
Fig. 3. The  $\psi\psi$  pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of  $J/\psi$ 's from the pairs are shown in (b) and (d). Our calculations are compared with the  $\pi^- N$  data at 150 and 280 GeV/c [1]. The  $x_{\psi\psi}$  distributions are normalized to the number of pairs from both pion beams (a) and the number of pairs from the 400 GeV proton measurement (c). The number of single  $J/\psi$ 's is twice the number of pairs.

The probability distribution for a general  $n$ -parton intrinsic  $c\bar{c}$  Fock state as a function of  $x$  and  $k_T$  written as

$$\frac{dP_{ic}}{\prod_{i=1}^n dx_i d^2 k_{T,i}} = N_n \alpha_s^4 (M_{c\bar{c}}) \frac{\delta(\sum_{i=1}^n k_{T,i}) \delta(1 - \sum_{i=1}^n x_i)}{(m_h^2 - \sum_{i=1}^n (m_{T,i}^2/x_i))^2},$$

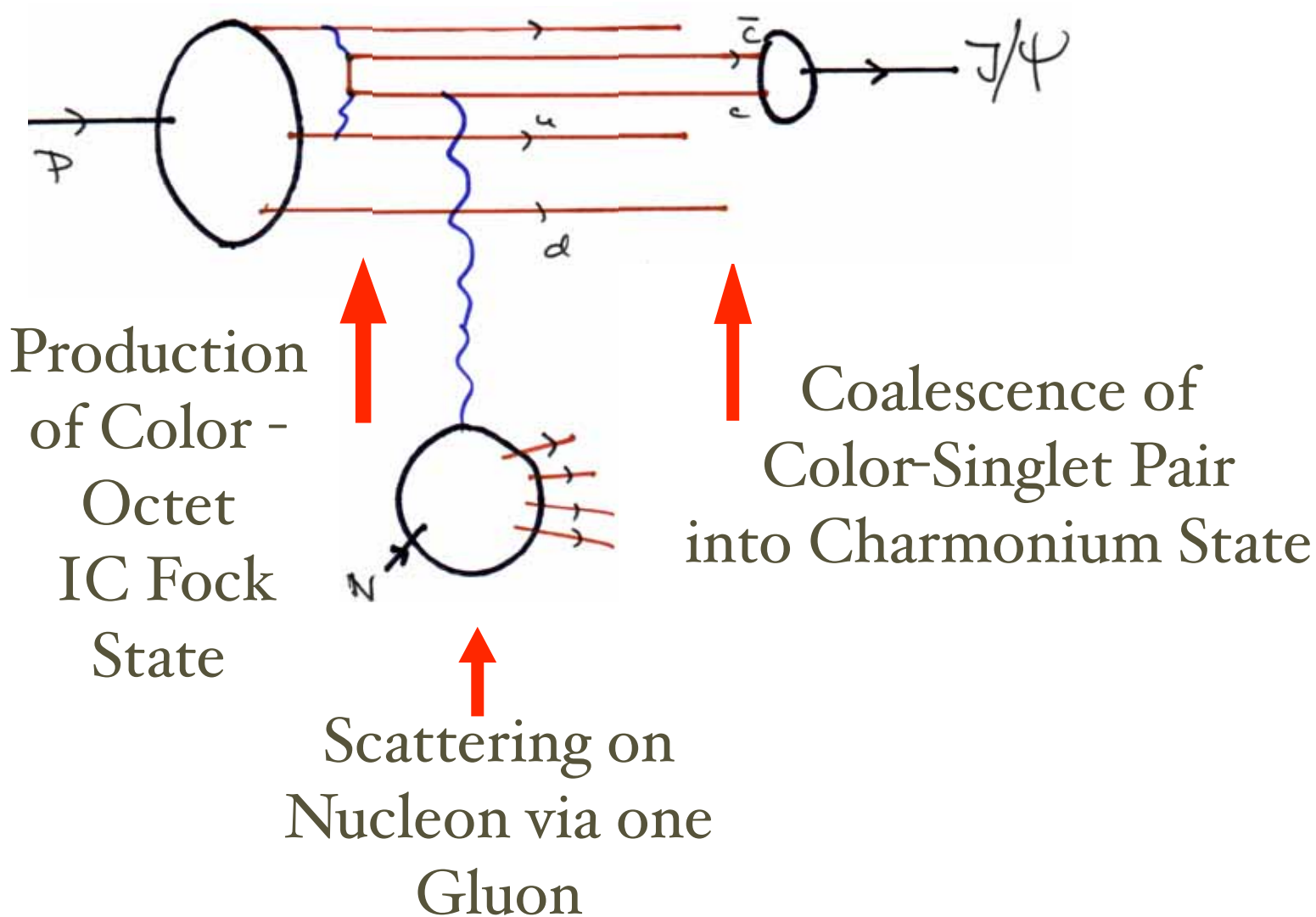
NA3 Data

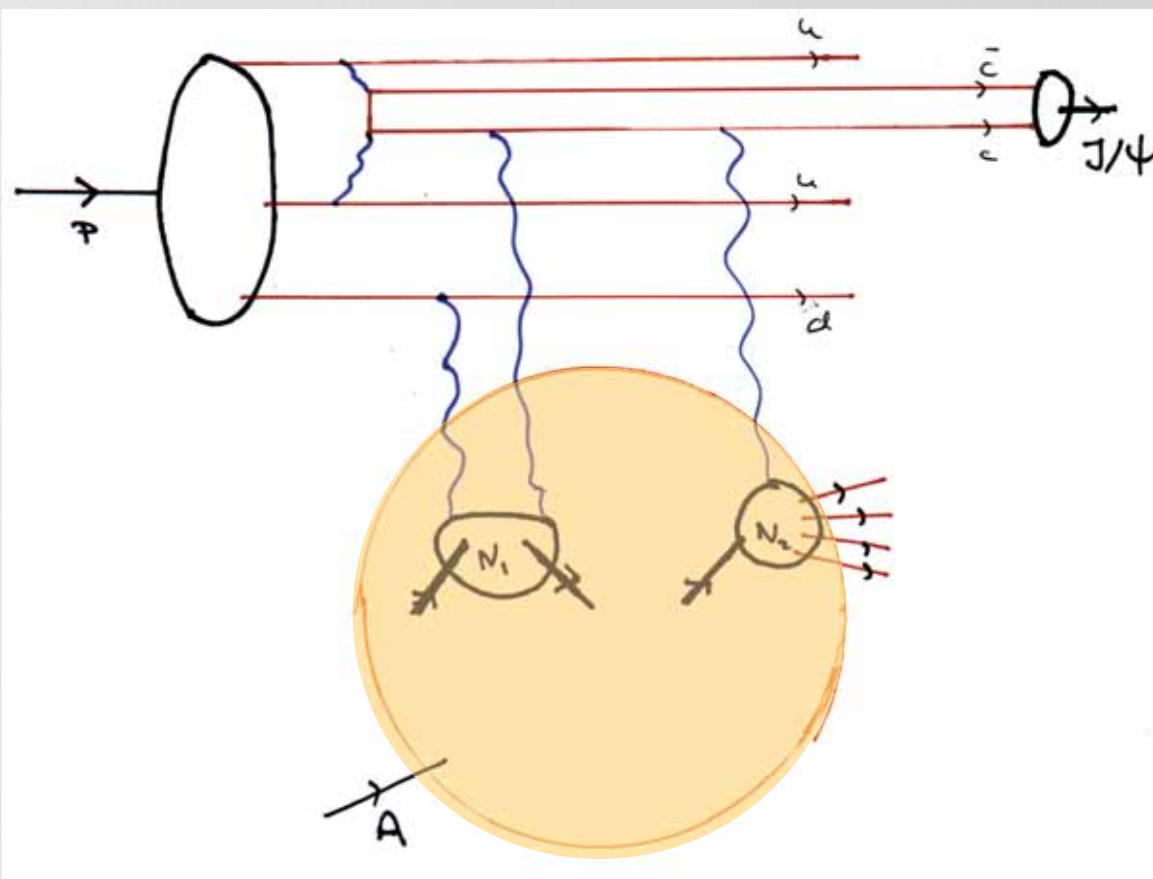
Anti-Shadowing & Novel Phenomena in QCD



Predictions for Inclusive Charm Production Distributions at the ISR. Assumes active and spectator charm distribution in proton patterned on IC, plus coalescence of valence and charm quarks.

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





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

$J/\Psi$  Production on Front Surface  
No Absorption of Propagating  $J/\Psi$

$$\sigma(p + A \rightarrow J/\Psi + X) \propto A^{2/3}$$

Elastic scattering of IC Fock state:

$$|[uud]_{8c}[c\bar{c}]_{8c} \rangle + N_1 \rightarrow |[uud]_{8c}[c\bar{c}]_{8c} \rangle + N_1$$

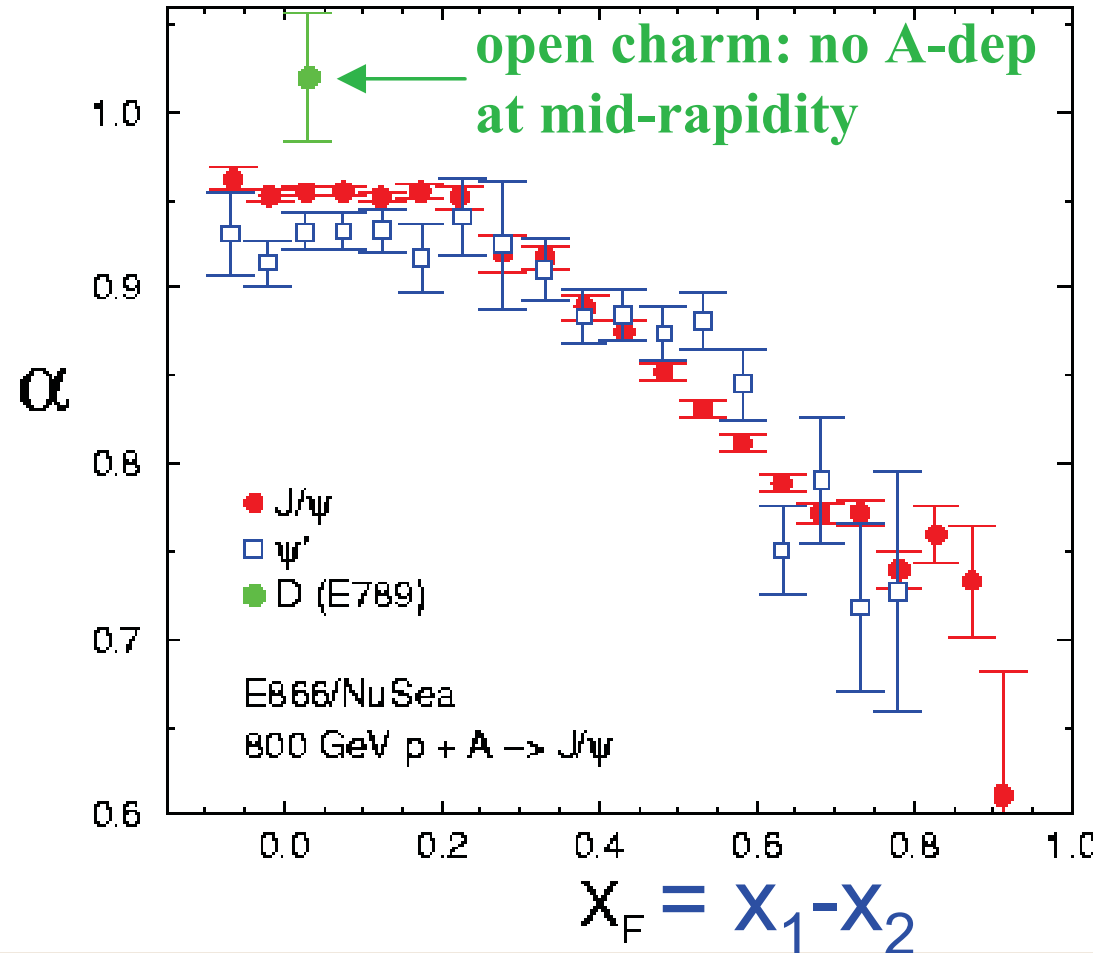
followed by:

$$|[uud]_{8c}[c\bar{c}]_{8c} \rangle + N_2 \rightarrow J/\Psi + X$$

Depleted flux on downstream nucleons

Anti-Shadowing & Novel  
Phenomena in QCD

800 GeV p-A (FNAL)  $\sigma_A = \sigma_p * A^\alpha$   
*PRL 84, 3256 (2000); PRL 72, 2542 (1994)*

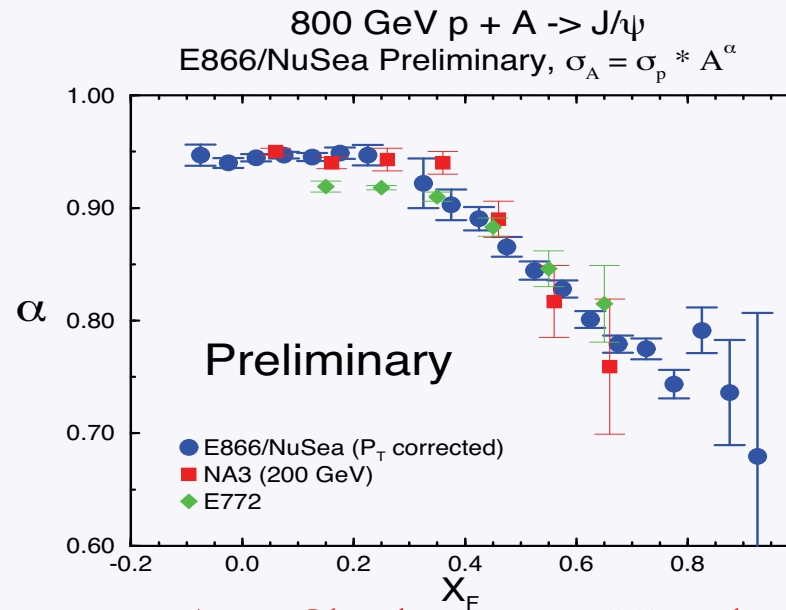
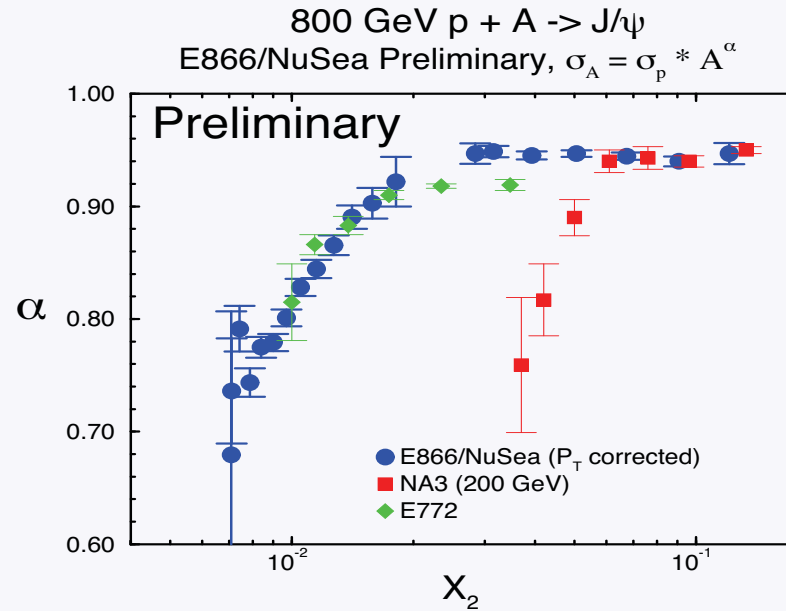


Remarkably Strong Nuclear  
 Dependence for Fast  
 Charmonium

M. Leitch

Anti-Shadowing & Novel  
 Phenomena in QCD

# $J/\psi$ Suppression Scales with $X_F$ not with $X_2$



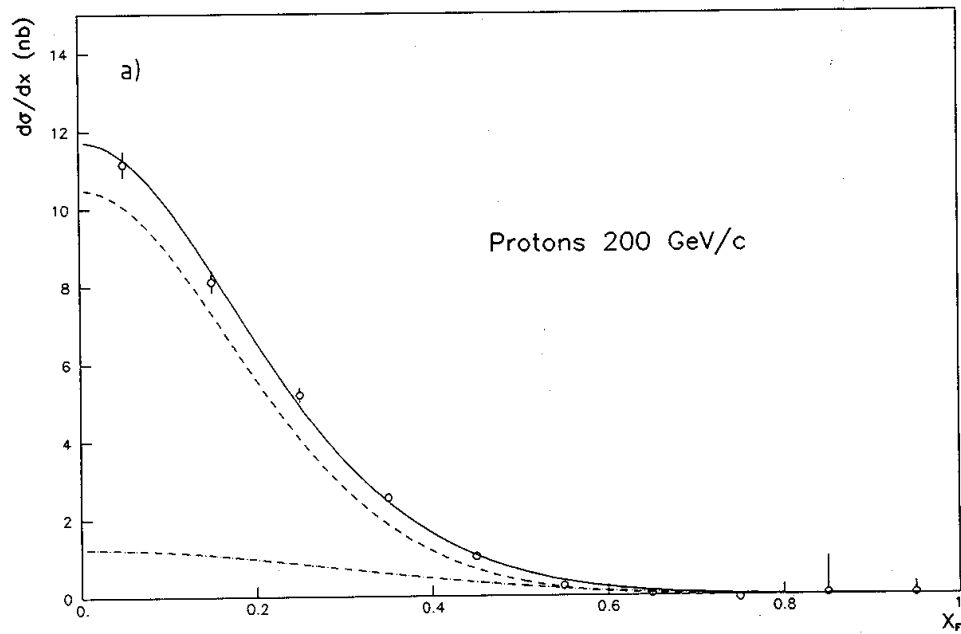
Anti-Shadowing & Novel  
Phenomena in QCD

# Nuclear Dependence of Quarkonium Production

NA3 data for  $\frac{d\sigma}{dx_F}(p(\pi)A \rightarrow J/\psi X)$ : hard  $A^1$  and “diffractive”  $A^{2/3}$  components

Diffractive contribution extends to large  $x_F$

$A^{\alpha(x_F)}$  not  $A^{\alpha(x_2)}$  : PQCD Factorization Violated!

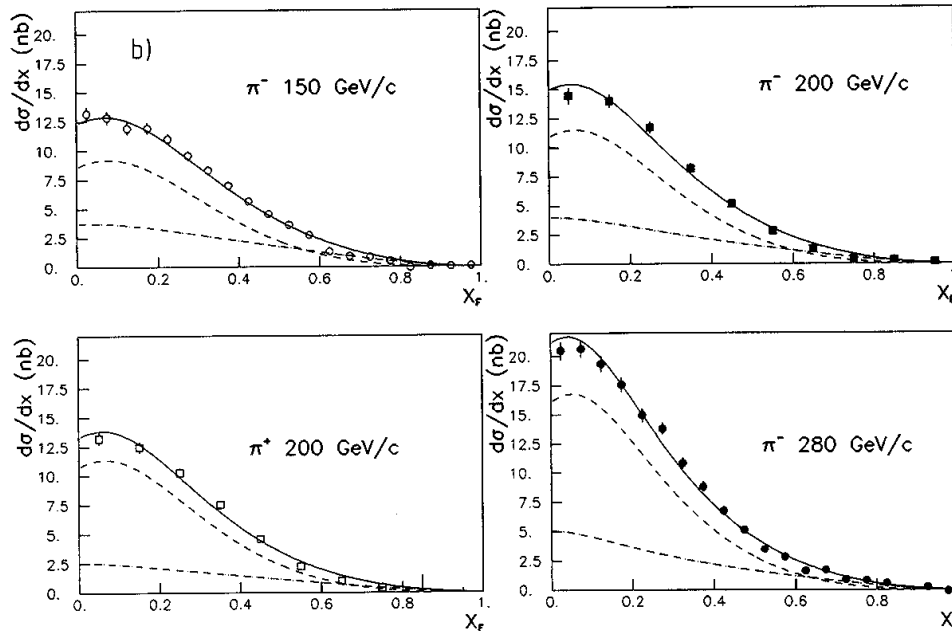


Hard Component  $\frac{d\sigma}{dx_F}(p(\pi)A \rightarrow J/\psi X)$

The fit:  $gg$  fusion (dashed)

$q\bar{q}$  fusion (dashed-dot)

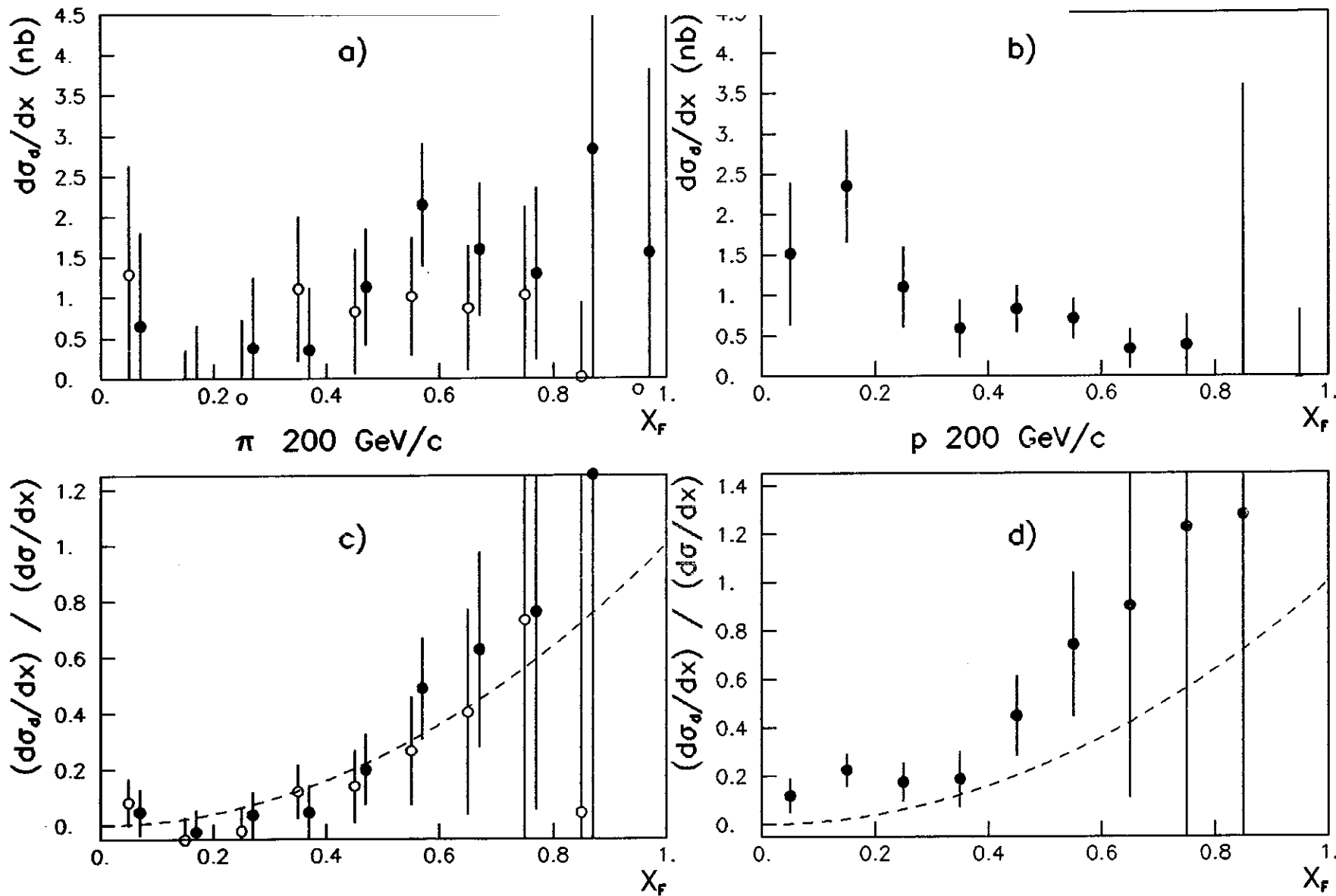
total (solid)



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Phenomena in QCD

NA3 COLLABORATION

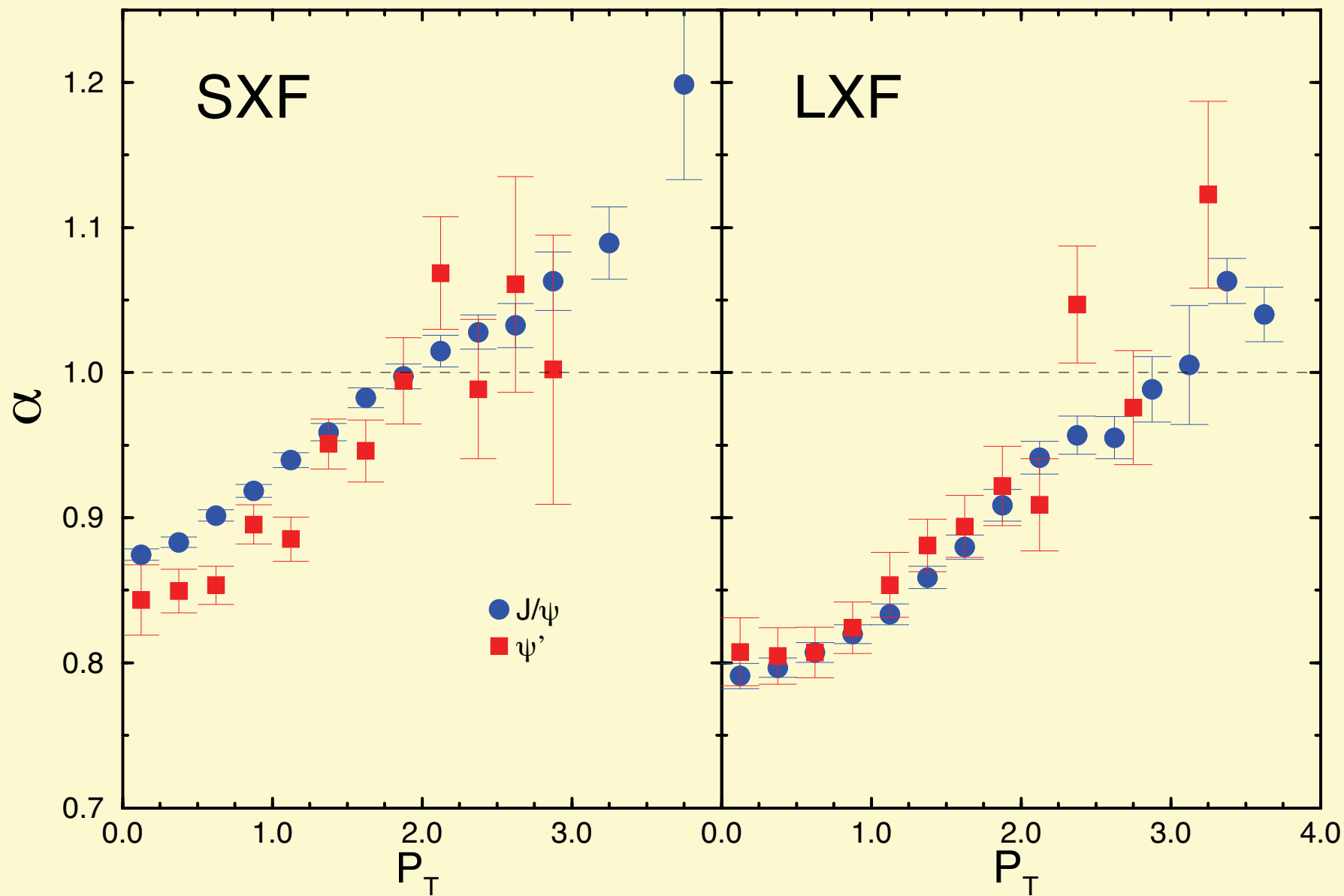
CERN-EP/83-86  
June 29th, 1983



Anti-Shadowing & Novel  
Phenomena in QCD

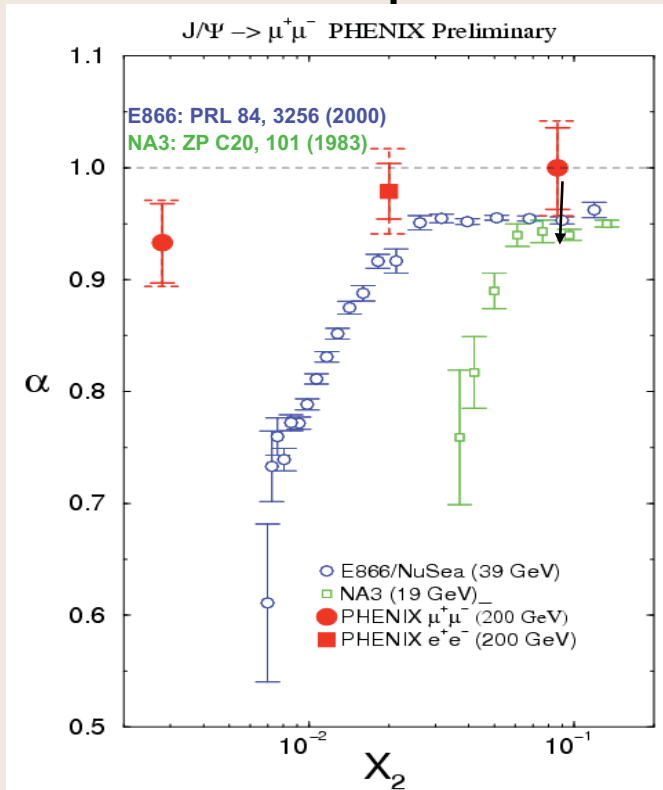
# 800 GeV $p + A \rightarrow J/\psi$

E866/NuSea Preliminary,  $\sigma_A = \sigma_p * A^\alpha$

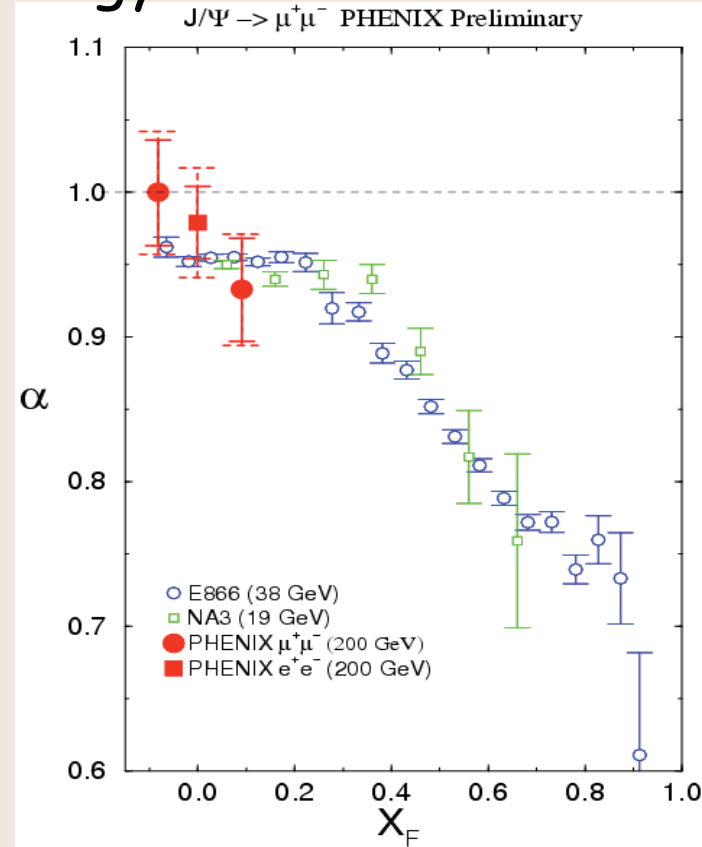


# J/ψ nuclear dependence vrs rapidity, $x_{Au}$ , $x_F$

## 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)

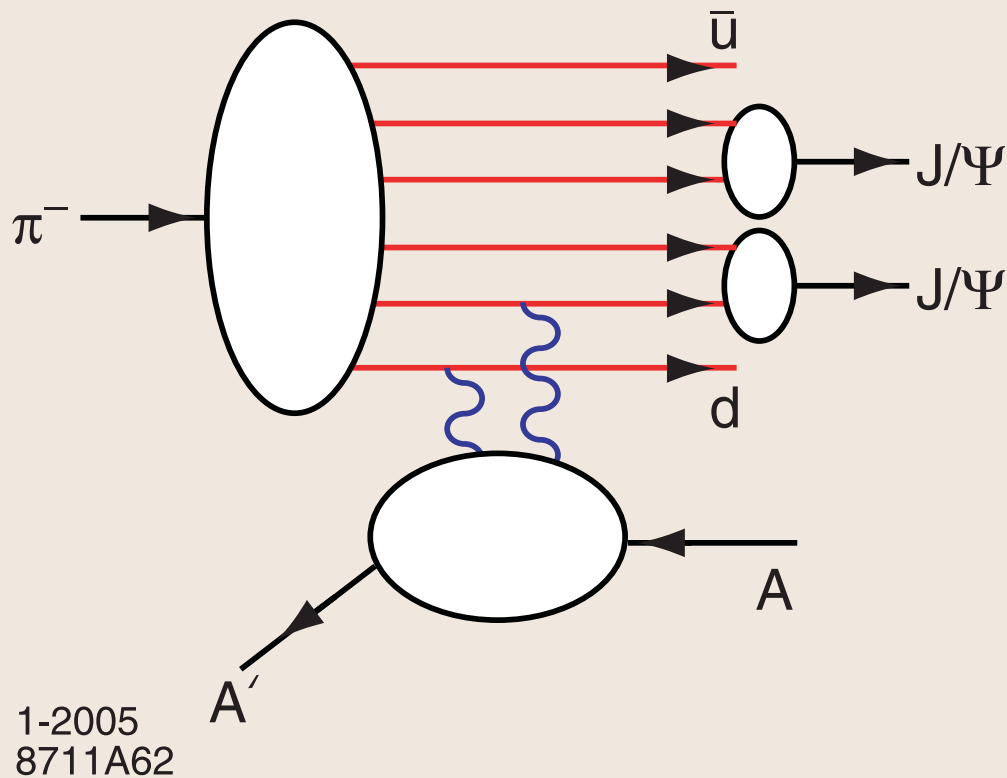
Not universal versus  $X_2$  : shadowing is not the main story.  
BUT does scale with  $x_F$  ! - why?  
(Initial-state gluon energy loss - which goes as  $x_1 \sim x_F$  - expected to be weak at RHIC energy)

M. Leitch

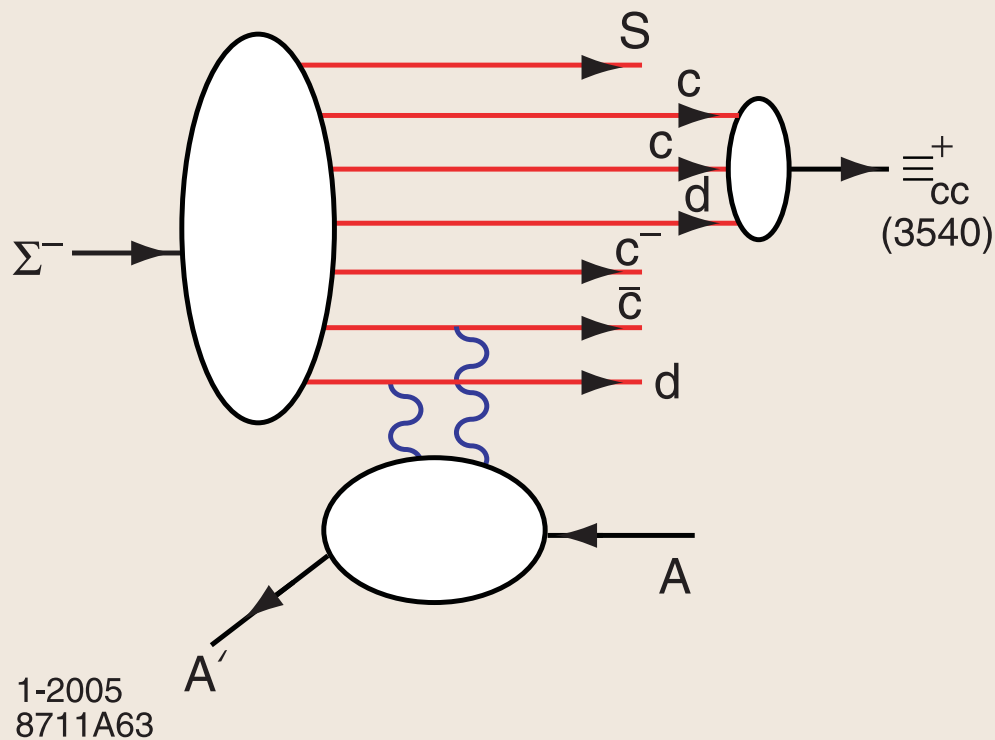
Anti-Shadowing & Novel Phenomena in QCD

- IC Explains Anomalous  $\alpha(x_F)$  not  $\alpha(x_2)$  dependence of  $pA \rightarrow J/\psi X$   
(Mueller, Gunion, Tang, SJB)
- Color Octet IC Explains  $A^{2/3}$  behavior at high  $x_F$  (NA3, Fermilab)  
(Kopeliovitch, Schmidt, Soffer, SJB)
- IC Explains  $J/\psi \rightarrow \rho\pi$  puzzle  
(Karliner, SJB)
- IC leads to new effects in  $B$  decay  
(Gardner, SJB)

# Production of Two Charmonia at High $x_F$



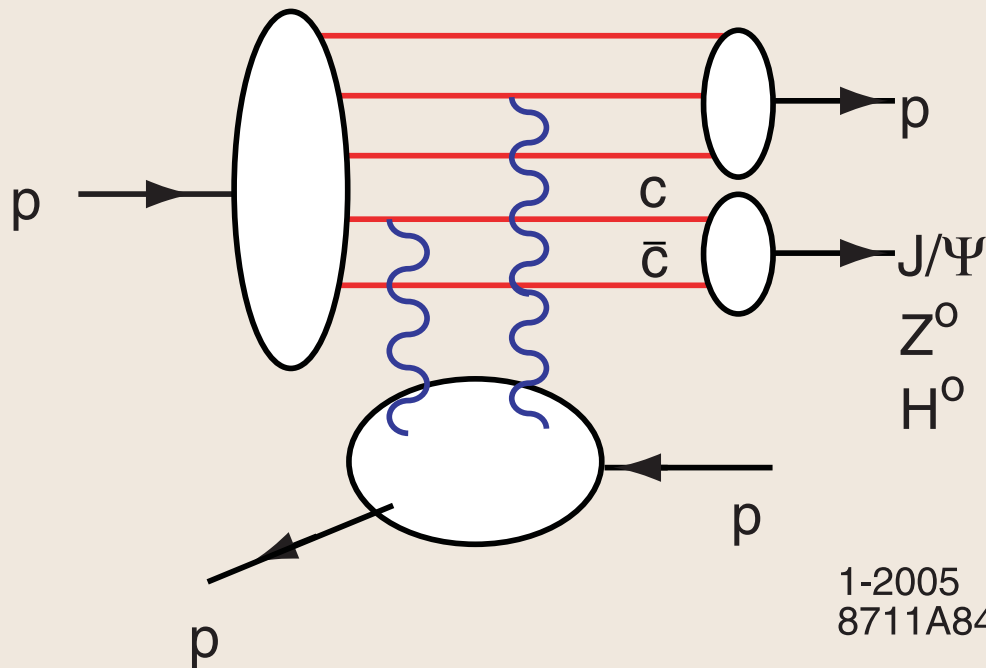
Anti-Shadowing & Novel  
Phenomena in QCD



## Production of a Double-Charm Baryon

Anti-Shadowing & Novel  
Phenomena in QCD

# Intrinsic Charm Mechanism for Double Diffraction



$$p p \rightarrow J/\psi p p$$

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

High  $x_F$  !

Kopeliovitch, Schmidt, Soffer, sjb

1-2005  
8711A84

Intrinsic  $c\bar{c}$  pair formed in color octet  $8_C$  in proton wavefunction Large Color Dipole  
Collision produces color-singlet  $J/\psi$  through color exchange

Anti-Shadowing & Novel Phenomena in QCD RHIC Experiment

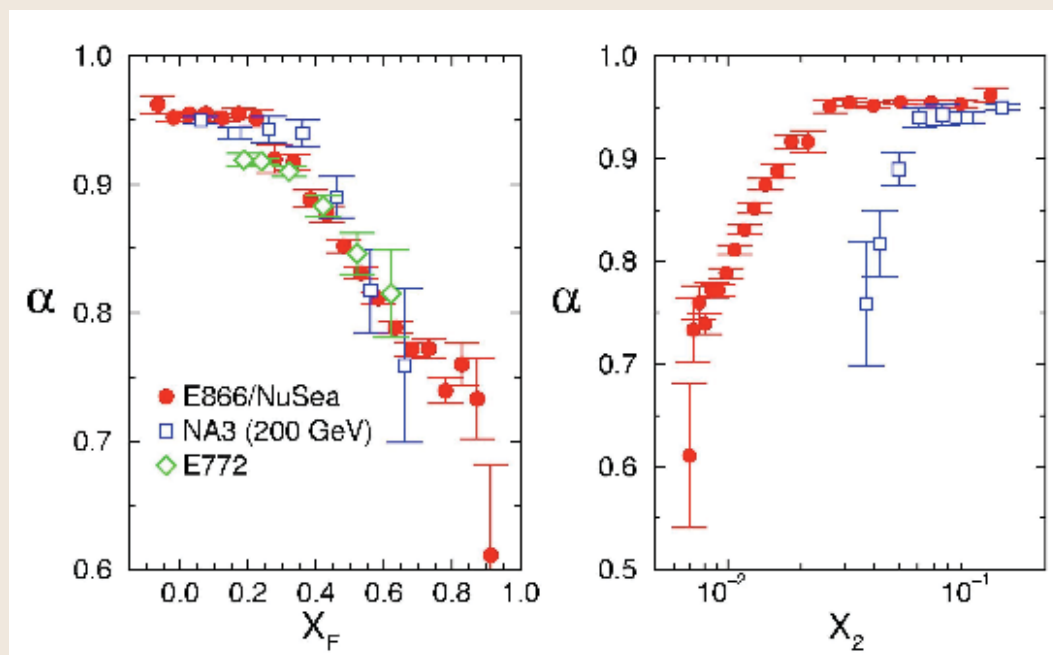
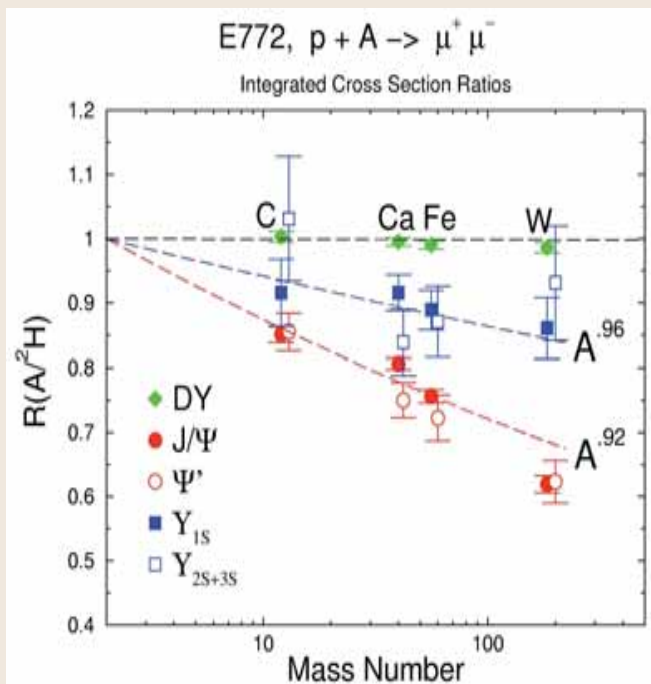
# Nuclear effects in Quarkonium production

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

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

E772 data

Strong  $x_F$  - dependence

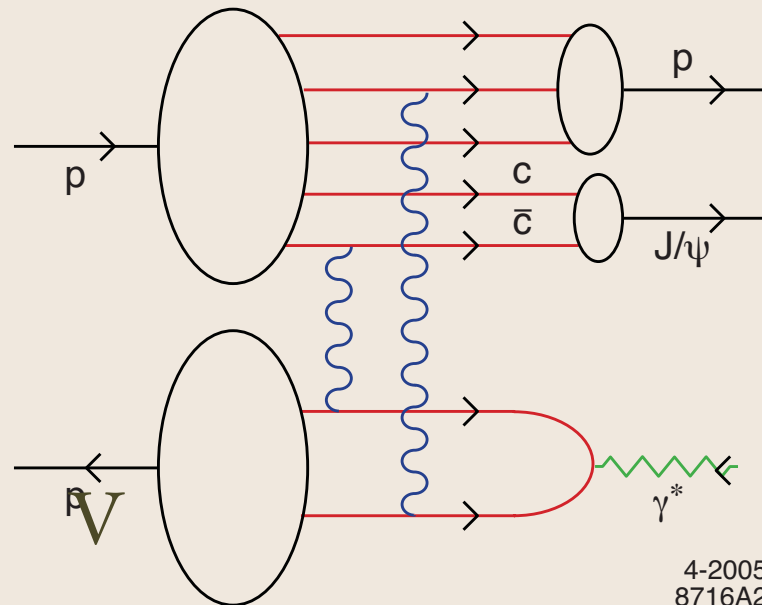


Nuclear effects scale with  $x_F$ , not  $x_2$  !!!

M.Leitch

Anti-Shadowing & Novel Phenomena in QCD

# New Test of Intrinsic Charm



## Doubly Diffractive DIS Reactions

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

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

Charm produced at high  $x_F$  and small  $p_T$

in **proton fragmentation region**

**Anti-Shadowing & Novel  
Phenomena in QCD**

# New Perspectives on QCD from AdS/CFT

- LFWFs: Fundamental description of hadrons at amplitude level
- QCD is Nearly Conformal
- Holographic Model from AdS/CFT : Confinement at large distances and conformal behavior at short distances
- Model for LFWFs, meson and baryon spectra
- Quark-interchange dominates scattering amplitudes

# Physics of 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 Opacity, Intrinsic Charm, Odderon**

Anti-Shadowing & Novel  
Phenomena in QCD

# Include Corrections to Handbag Diagram in DVCS

- Wilson line: Rescattering Corrections to Deep Inelastic Scattering

Hoyer, Marchal, Peigne, Sannino, sjb

- Diffractive DIS

- Single Spin Asymmetries

Hwang, Schmidt, sjb; Collins; X.Ji

- Shadowing, Antishadowing

Schmidt, Yang, Lu, sjb

- All Leading Twist

- Gauge Invariant (Also in LCG)

# QCD at The Amplitude Level

- Light-Front Fock Expansions
- LFWFs boost invariant
- Direct connection to form factors, structure functions, distribution amplitudes, GPDs
- Higher Twist Correlations
- Orbital Angular Momentum
- Validated in QED, Bethe-Salpeter
- AdS/CFT Holographic Model

# Essential to test QCD

- GSI antiprotons
- 12 GeV Jlab
- J-Parc
- BaBar/Belle: ISR, two-gamma, timelike DVCS
- RHIC/LHC Nuclear Collisions; LHCb
- photon-photon collider at the ILC (Zerwas)
- electron-proton, electron-nucleus collisions

# QCD Lagrangian

The diagram shows the QCD Lagrangian  $L_{\text{QCD}}$  enclosed in a red box. Labels with arrows point to various parts of the equation:

- gluon dynamics** points to the first term:  $-\frac{1}{4g^2} \text{Tr}(G^{\mu\nu} G_{\mu\nu})$
- quark kinetic energy + quark-gluon dynamics** points to the second term:  $\sum_{f=1}^{nf} i \bar{\psi}_f D_\mu \gamma^\mu \psi_f$
- mass term** points to the third term:  $\sum_{f=1}^{nf} m_f \bar{\psi}_f \psi_f$
- QCD color charge** points to the  $g^2$  in the denominator of the first term.
- field strength tensor** points to  $G_{\mu\nu}$  in the first term.
- covariant derivative** points to  $D_\mu$  in the second term.
- quark field** points to  $\psi_f$  in the second term.

$$\lim N_C \rightarrow 0 \text{ at fixed } \alpha = C_F \alpha_s, n_\ell = n_F / C_F$$

QCD  $\rightarrow$  Abelian Gauge Theory

Huet, sjb

# QCD

- Basic theory underlying all of hadron and nuclear physics
- Remarkable Phenomena: Confinement, Diffractive DIS, Chiral Symmetry Breaking, QGP, Hidden Color, Intrinsic Heavy Quarks, Color Transparency
- New Effects from orbital angular momentum + ISI and FSI --> SSA's
- QCD at the amplitude level: LFWFs
- New insights from conformal theory: ADS/CFT
- Conformal Template and Commensurate Scale Relations; Elimination of renormalization scale ambiguities
- Zero color limit
- DESY -- key role in QCD theory and experiment:
- Exploration of QCD just beginning!

# Outlook

- Only one scale  $\Lambda_{QCD}$  determines hadronic spectrum (slightly different for mesons and baryons).
- Ratio of Nucleon to Delta trajectories determined by zeroes of Bessel functions.
- String modes dual to baryons extrapolate to three fermion fields at zero separation in the AdS boundary.
- Only dimension 3,  $\frac{9}{2}$  and 4 states  $\bar{q}q$ ,  $qqq$ , and  $gg$  appear in the duality at the classical level!
- Non-zero orbital angular momentum and higher Fock-states require introduction of quantum fluctuations.
- Simple description of space and time-like structure of hadronic form factors.
- Dominance of quark-interchange in hard exclusive processes emerges naturally from the classical duality of the holographic model. Modified by gluonic quantum fluctuations.
- Covariant version of the bag model with confinement and conformal symmetry.