

Intrinsic Heavy Quarks and other Novel QCD Phenomena at the LHC

- Heavy quarks carry high momentum fraction of proton's momentum
- Highly energy efficient
- Higgs production at high X_F
- Doubly diffractive Higgs Production $pp \rightarrow p + H + p$
- Inclusive Higgs production $pp \rightarrow H X$
- Extend to intrinsic heavy squarks, gluinos!

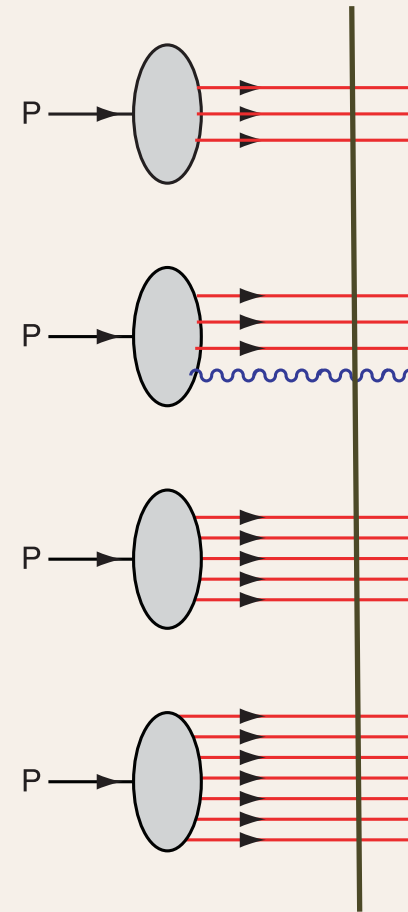
Hadrons Fluctuate in Particle Number

- Proton Fock States
 $|uud\rangle, |uudg\rangle, |uuds\bar{s}\rangle, |uudc\bar{c}\rangle, |uudb\bar{b}\rangle \dots$
- Strange and Anti-Strange Quarks not Symmetric
 $s(x) \neq \bar{s}(x) \quad \bar{u}(x) \neq \bar{d}(x)$
- “**Intrinsic Charm**”: High momentum heavy quarks
- “**Hidden Color**”: Deuteron not always $p + n$
- Orbital Angular Momentum Fluctuations - Anomalous Magnetic Moment

Light-Front Wavefunctions

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

$$\psi_n(x, k_{\perp}) \quad x_i = \frac{k_i^+}{P^+}$$

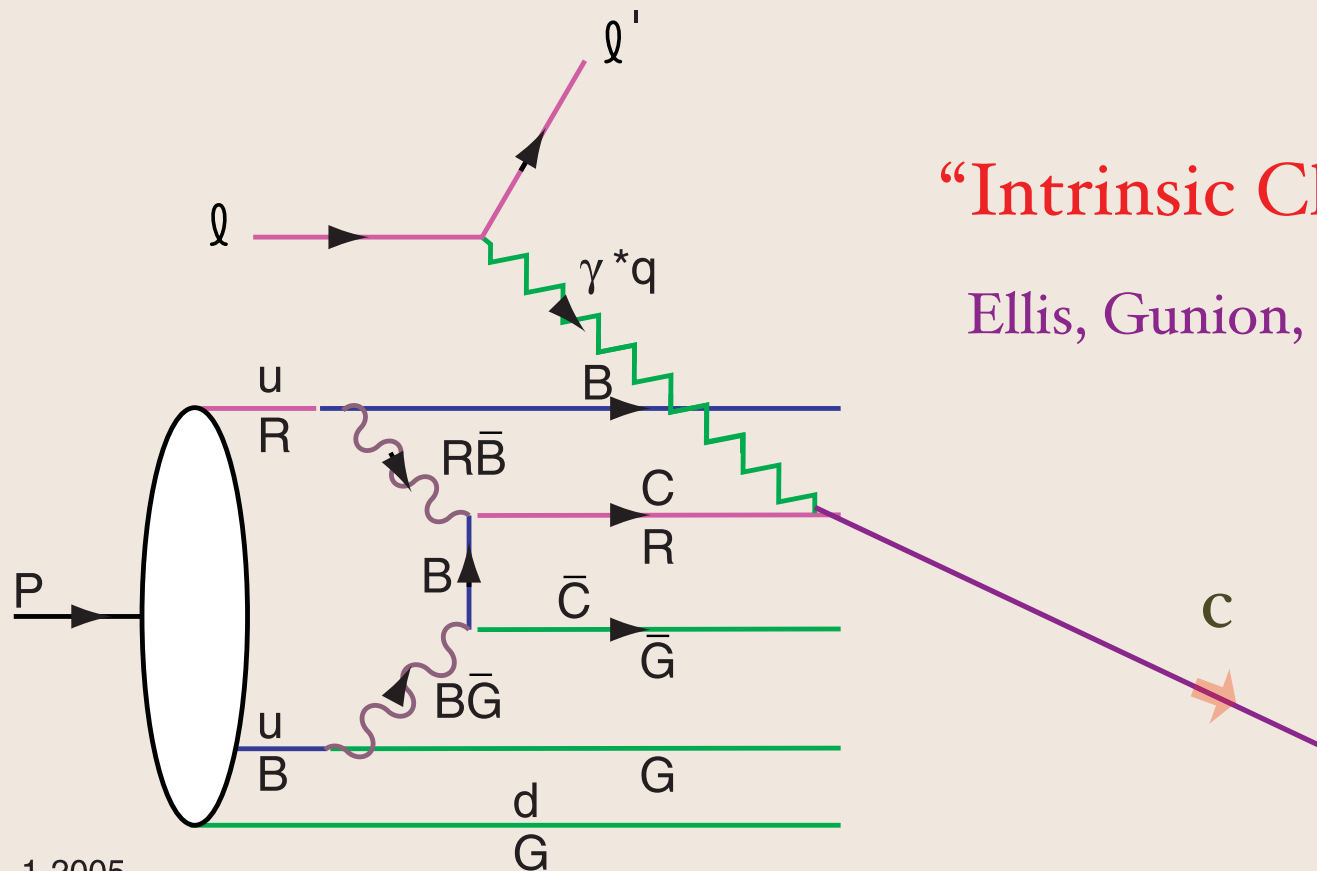


$$H_{LF}^{QCD} |\psi\rangle = M^2 |\psi\rangle$$

Invariant under boosts. Independent of P^μ

Anti-Shadowing & Novel
Phenomena in QCD

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



“Intrinsic Chevrolets”

Ellis, Gunion, Mueller, sjb

1-2005
8711A83

Hoyer, Peterson, SJB

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Measurement of Charm Structure Function

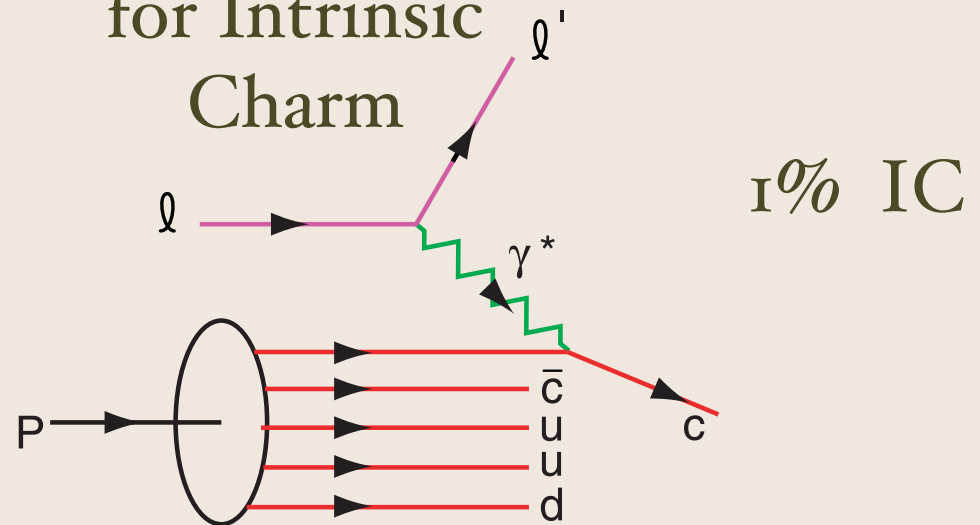
J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-GeV μ^+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

Photon Gluon Fusion Factor 30 too small!

Hoffman & Moore; Harris, Smith, Vogt

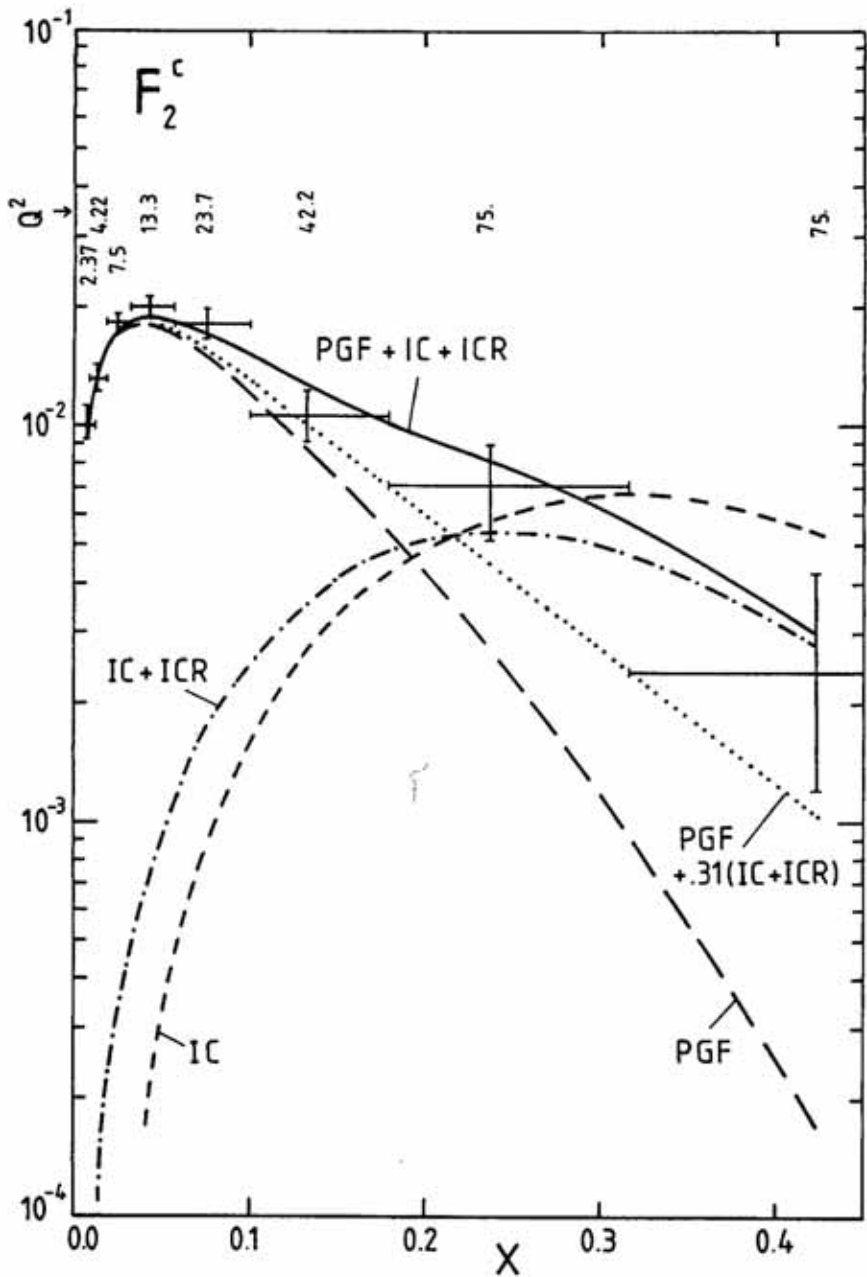
Evidence

for Intrinsic
Charm



1% IC

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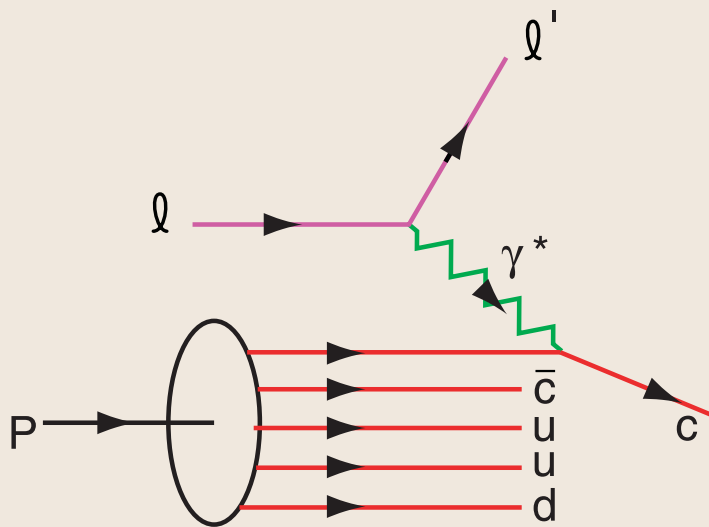


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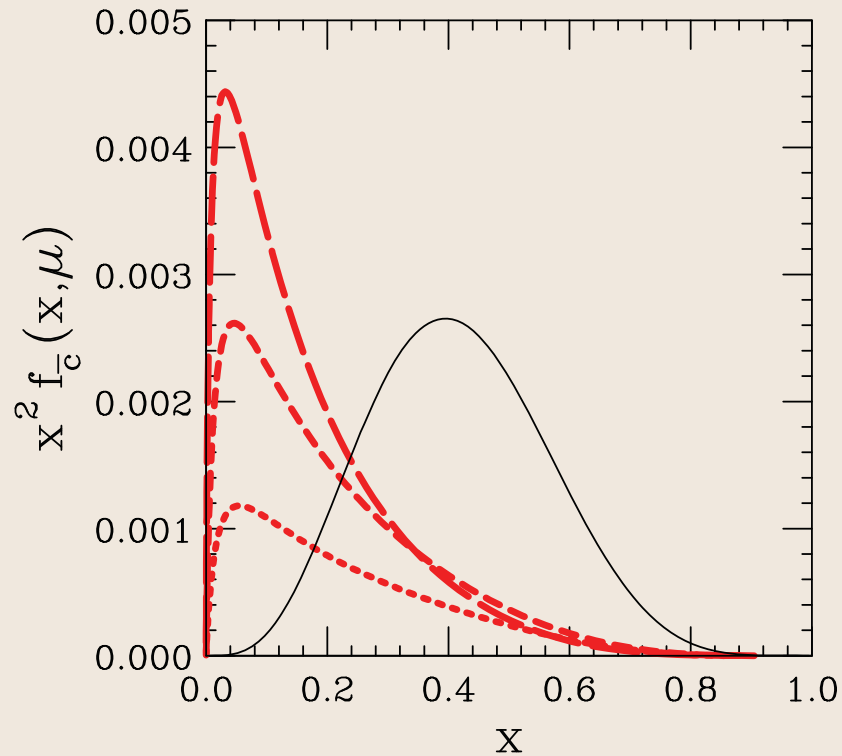
Novel QCD Phenomena at the LHC

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LIGHT-CONE MODELS FOR INTRINSIC CHARM AND BOTTOM.
 By [Jon Pumplin \(Michigan State U.\)](#), MSU-HEP-050816, Aug 2005. 15pp.
 e-Print Archive: [hep-ph/0508184](#)



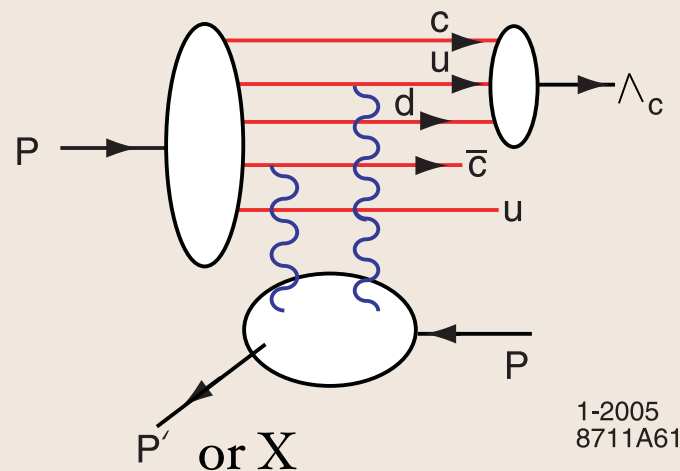
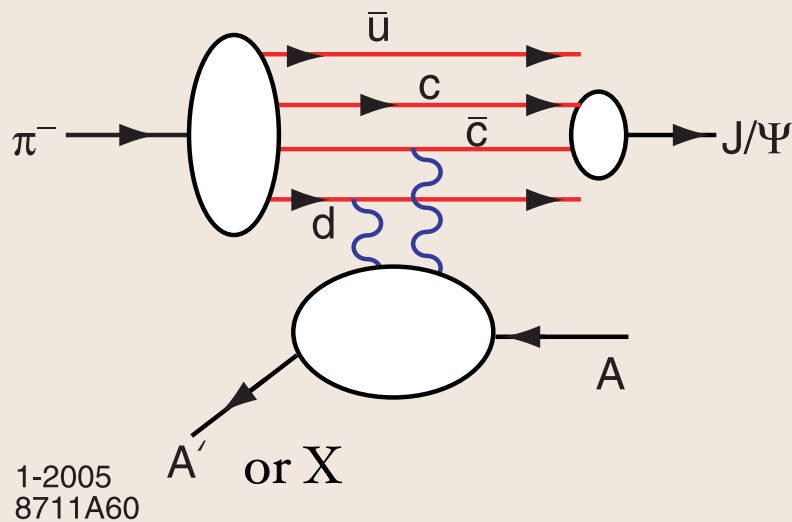
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Extrinsic vs. Intrinsic $c(x)$

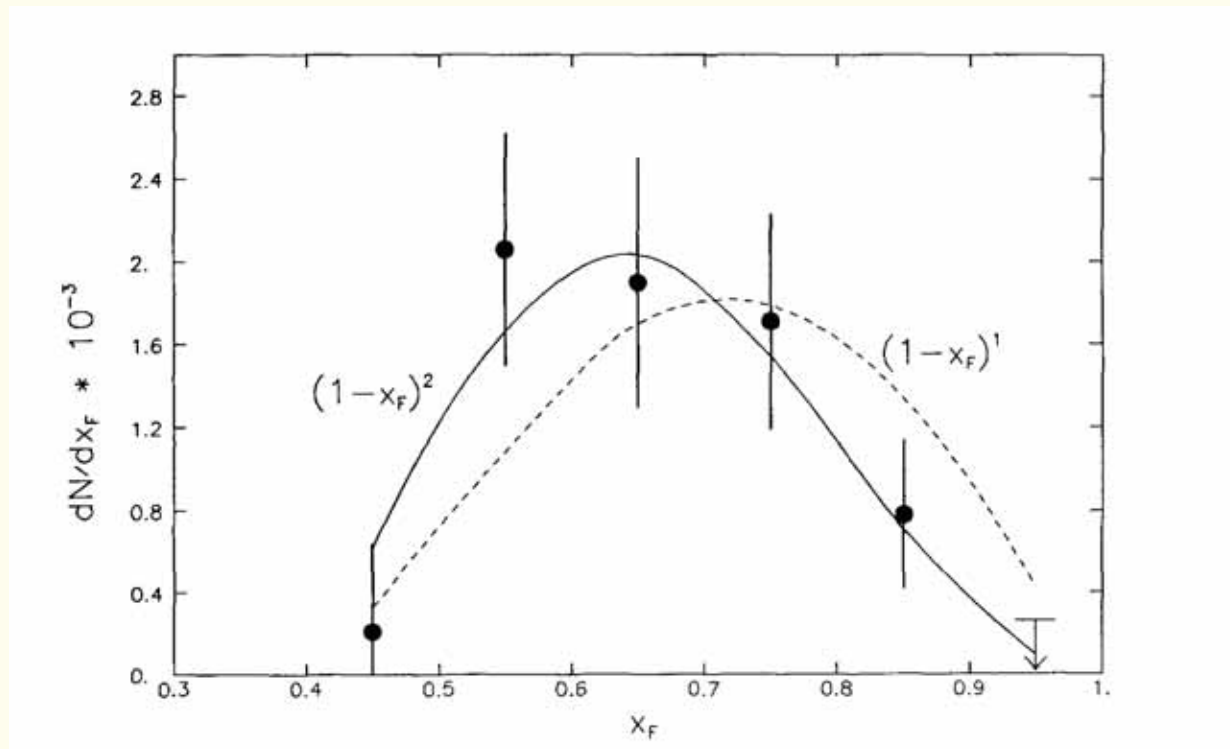
- EMC data: $c(x, Q^2) > 30 \times \text{DGLAP}$
 $Q^2 = 75 \text{ GeV}^2, x = 0.42$
- High x_F $pp \rightarrow J/\psi X$
- High x_F $pp \rightarrow J/\psi J/\psi X$
- High x_F $pp \rightarrow \Lambda_c X$
- High x_F $pp \rightarrow \Lambda_b X$
- High x_F $pp \rightarrow \Xi(ccd) X$ (SELEX)

Diffractive Dissociation of Intrinsic Charm



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

Production of Charm Hadrons at the ISR

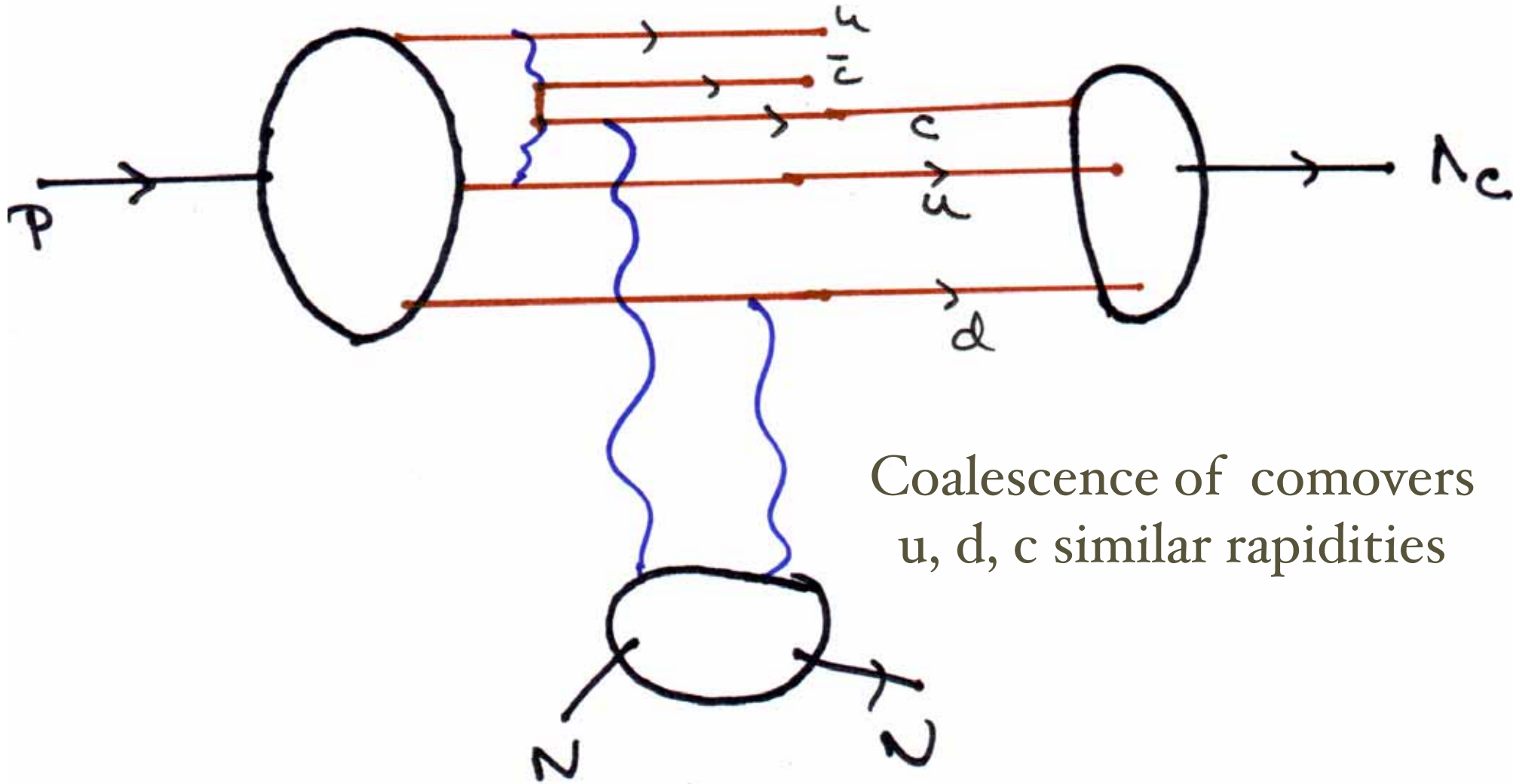


$$\frac{dN}{dX_F} (pp \rightarrow \Lambda_c X)$$

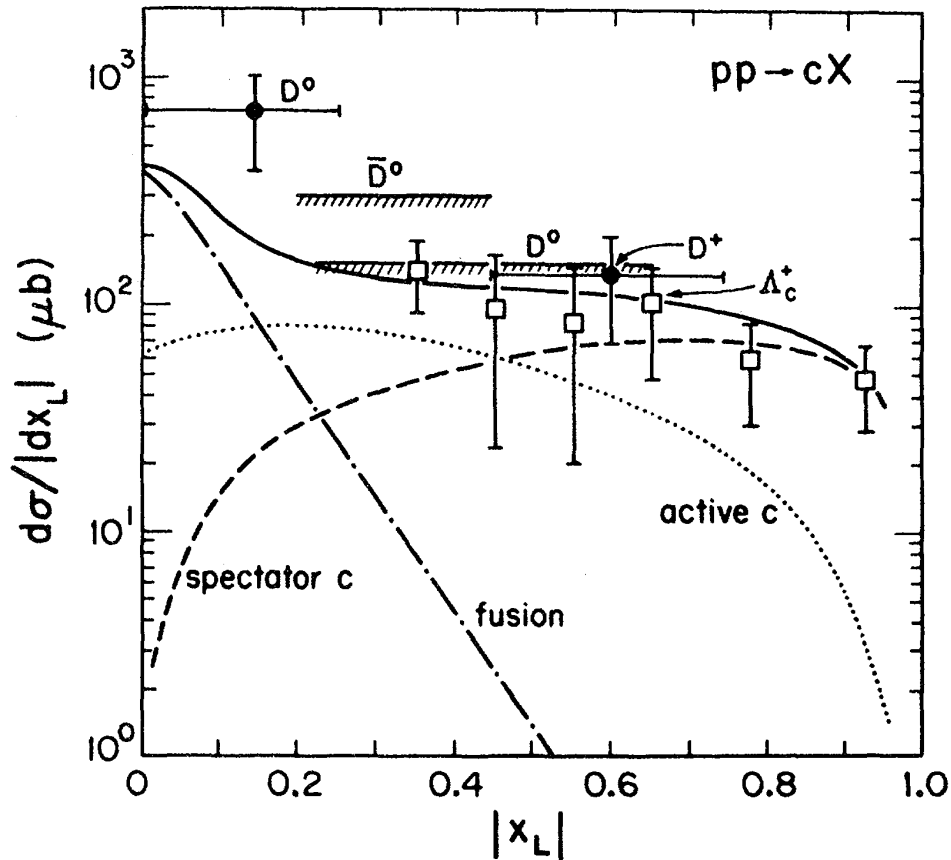
P. M. Chauvat et al. [R608 Collaboration],
“Production of Λ_c With Large x_F At The ISR,”
Phys. Lett. B 199, 304 (1987).

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

Diffractive Dissociation of Intrinsic Charm



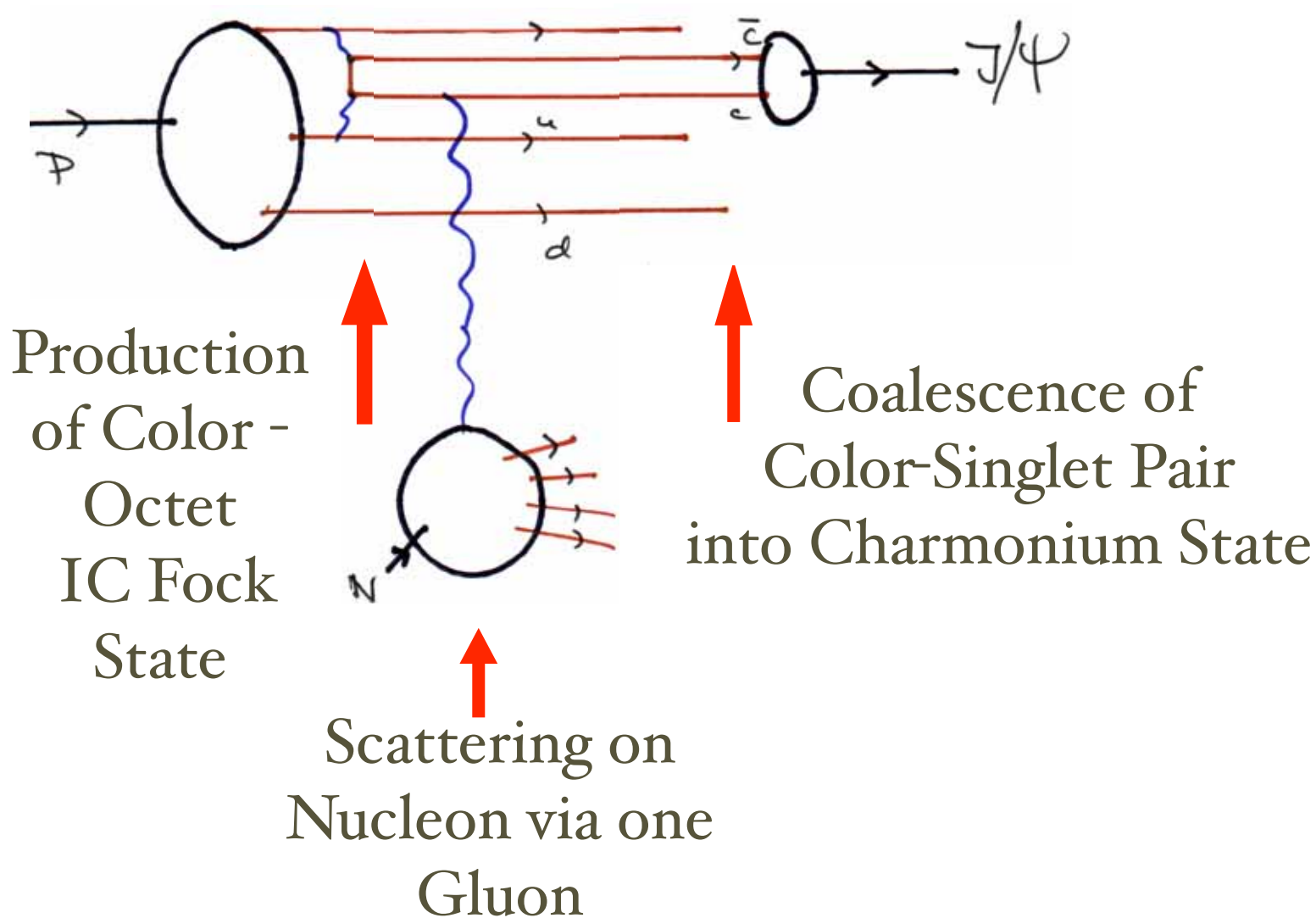
Coalescence of comovers
u, d, c similar rapidities



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

Systematic IC analysis: Gunion and Vogt

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.



Hard Component

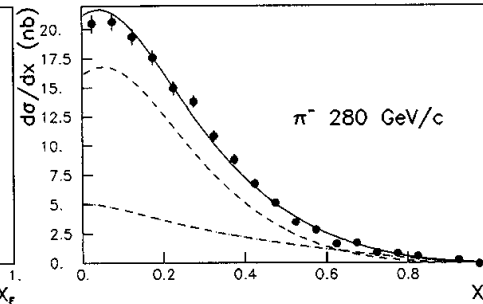
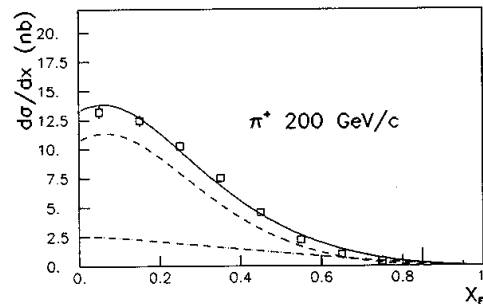
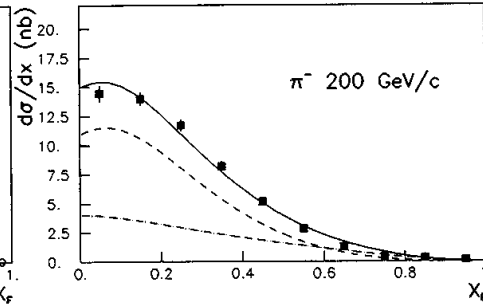
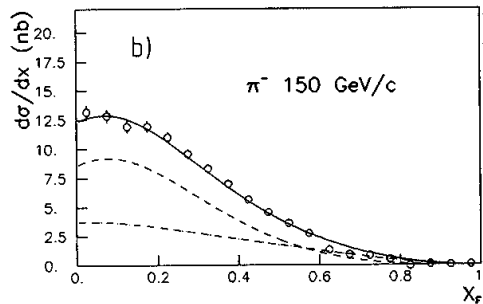
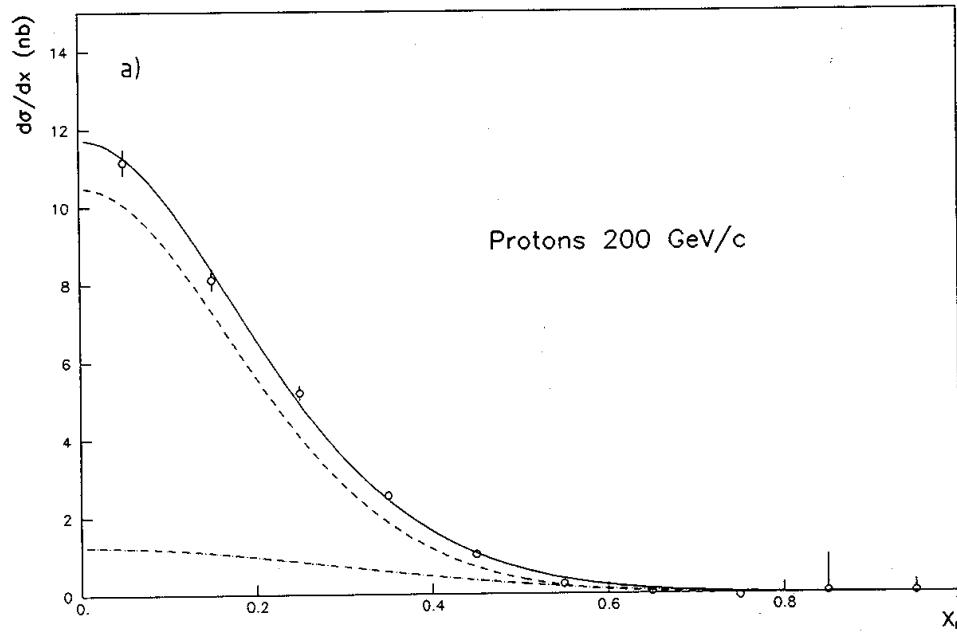
Hard Component $\frac{d\sigma}{dx_F}(p(\pi)A \rightarrow J/\psi X)$

The fit: gg fusion (dashed)

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

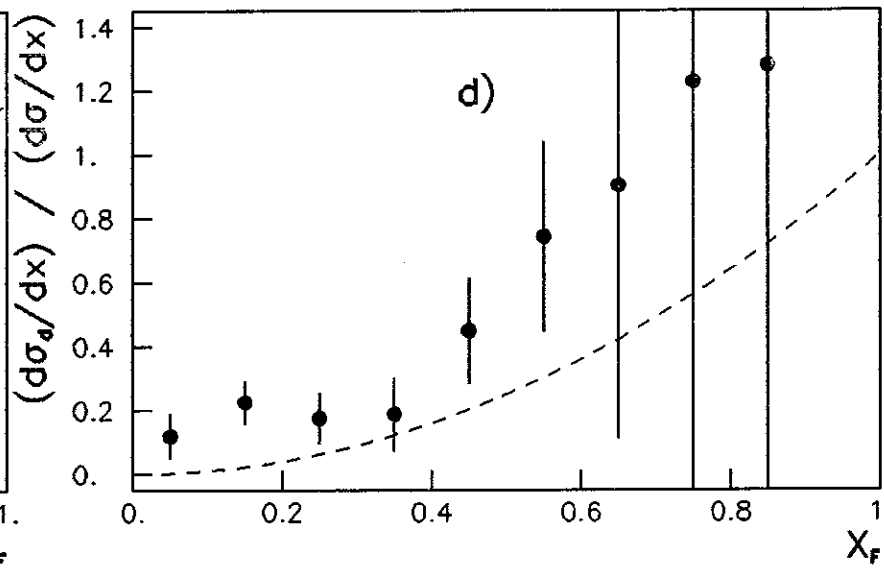
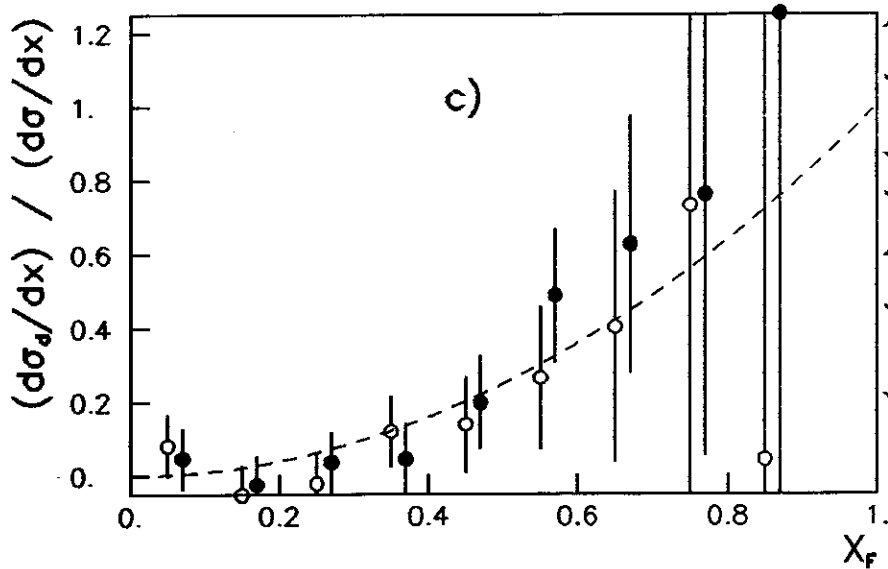
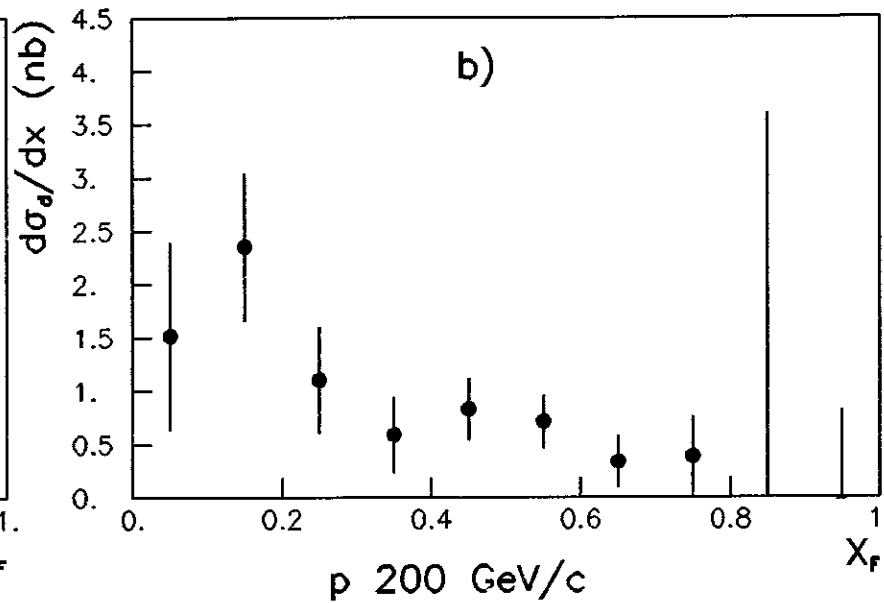
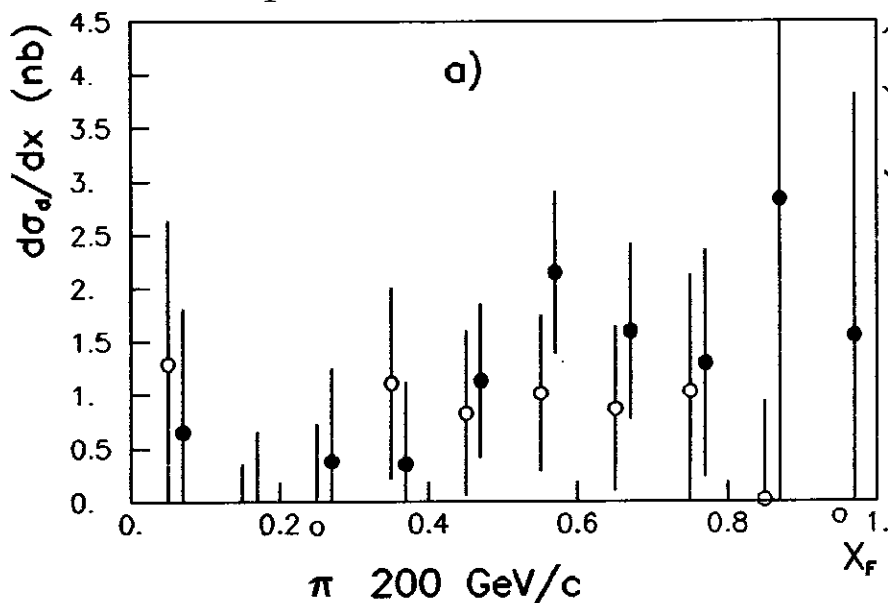
total (solid)

$$\frac{d\sigma}{dX_F}(pA \rightarrow J/\psi X) \propto A^1$$



$$\frac{d\sigma}{dX_F}(\pi A \rightarrow J/\psi X) \propto A^{2/3}$$

Remarkably flat



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!

VIOLATION OF FACTORIZATION IN CHARM HADROPRODUCTION.

By [P. Hoyer](#), [M. Vanttinen \(Helsinki U.\)](#), [U. Sukhatme \(Illinois U., Chicago\)](#),. HU-TFT-90-14, May 1990. 7pp.
Published in **Phys.Lett.B246:217-220,1990**

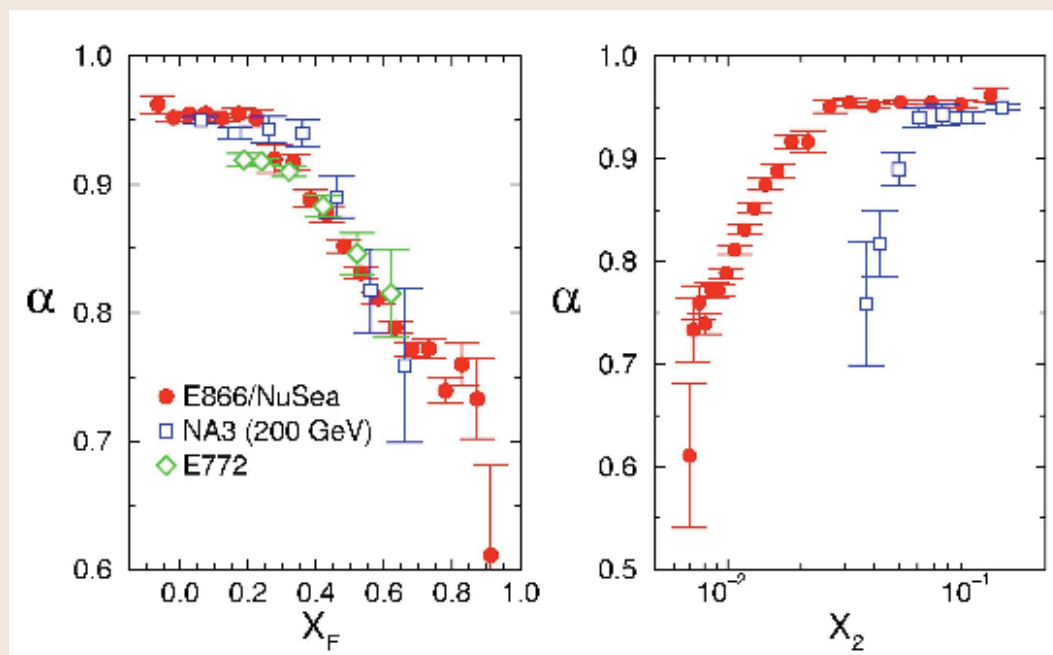
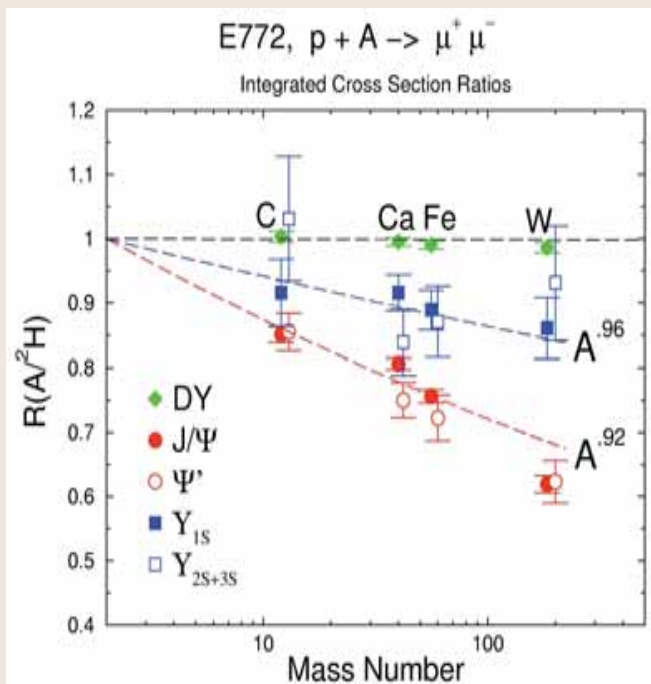
Nuclear effects in Quarkonium production

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

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

E772 data

Strong x_F - dependence



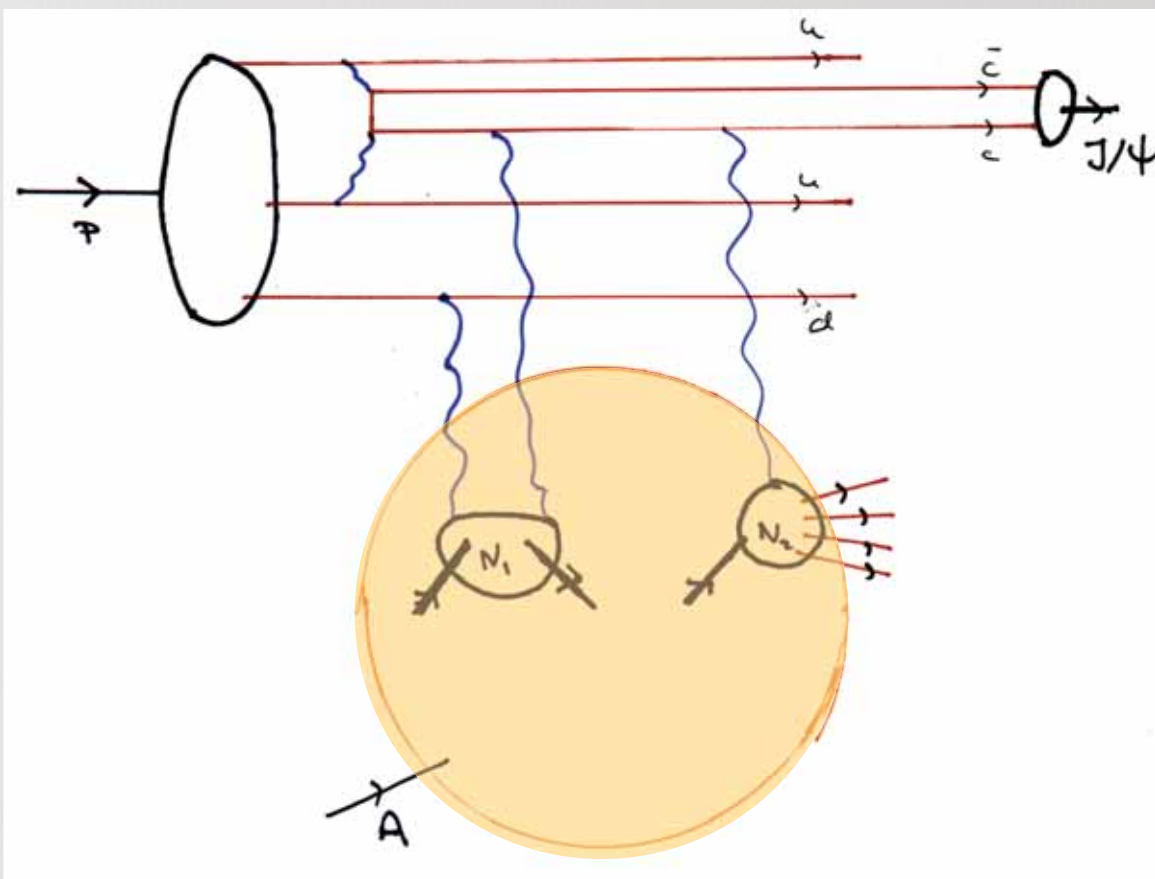
Nuclear effects scale with x_F , not x_2 !!!

M. Leitch

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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:

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

followed by:

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

Depleted flux on downstream nucleons

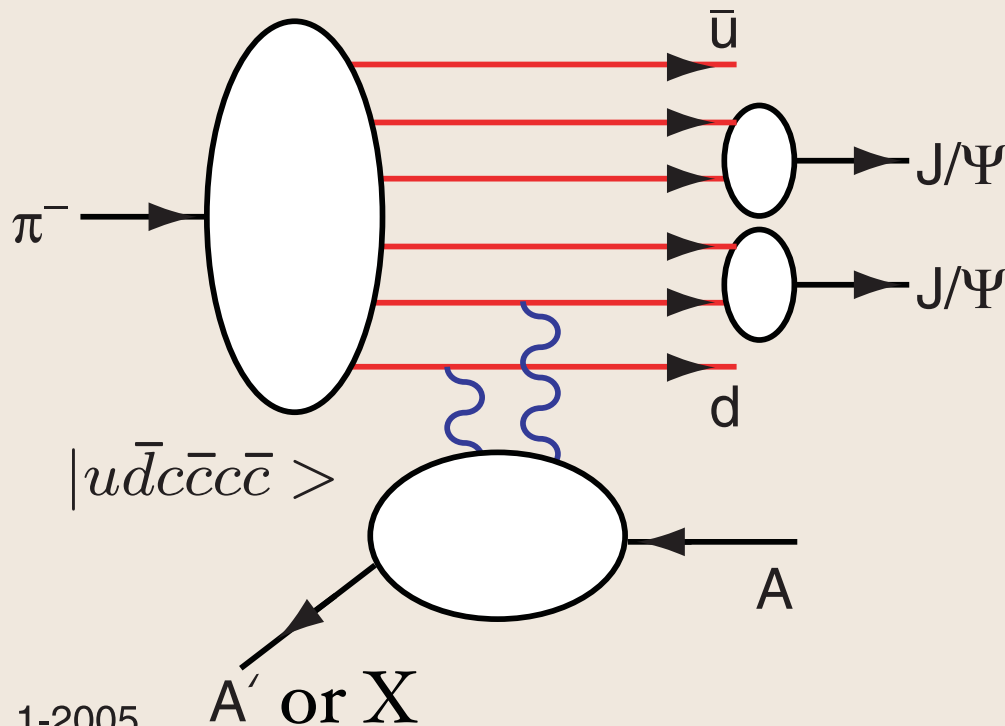
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- IC Explains Anomalous $\alpha(x_F)$ not $\alpha(x_2)$ dependence of $pA \rightarrow J/\psi X$
(Mueller, Gunion, Tang, SJB)
- Color Octet IC Explains $A^{2/3}$ behavior at high x_F (NA3, Fermilab)
(Kopeliovitch, Schmidt, Soffer, SJB)
- IC Explains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

Production of Two Charmonia at High x_F



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8711A62

Double IC Fock state of pion

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

Intrinsic charm contribution to double quarkonium hadroproduction^{*}

R. Vogt^a, S.J. Brodsky^b

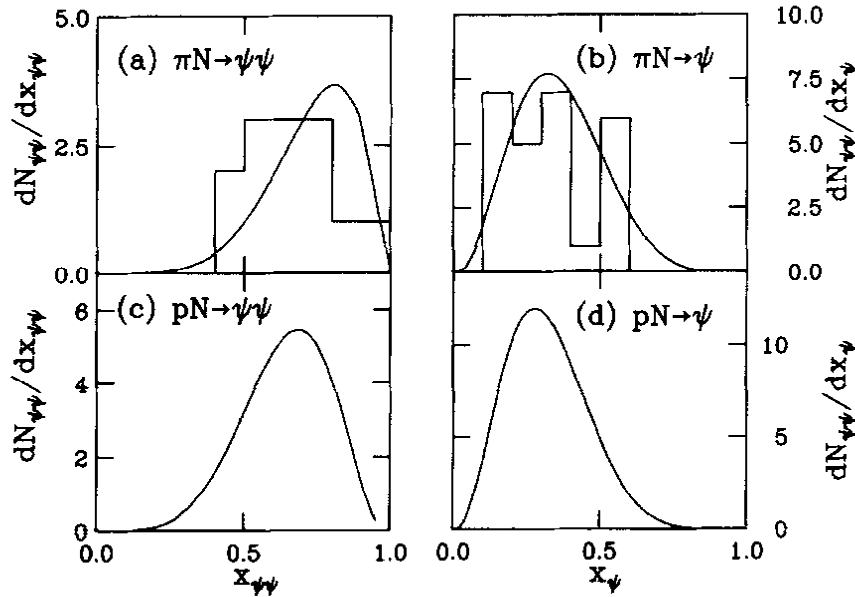


Fig. 3. The $\psi\psi$ pair distributions are shown in (a) and (c) for the pion and proton projectiles. Similarly, the distributions of J/ψ 's from the pairs are shown in (b) and (d). Our calculations are compared with the $\pi^- N$ data at 150 and 280 GeV/c [1]. The $x_{\psi\psi}$ distributions are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

NA3 Data

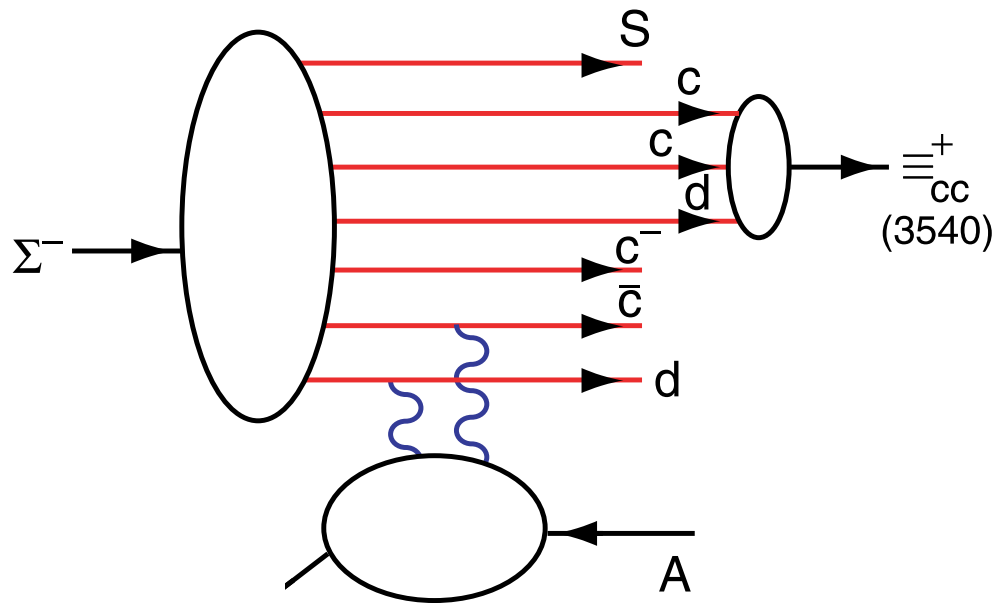
The probability distribution for a general n -parton intrinsic $c\bar{c}$ Fock state as a function of x and k_T written as

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

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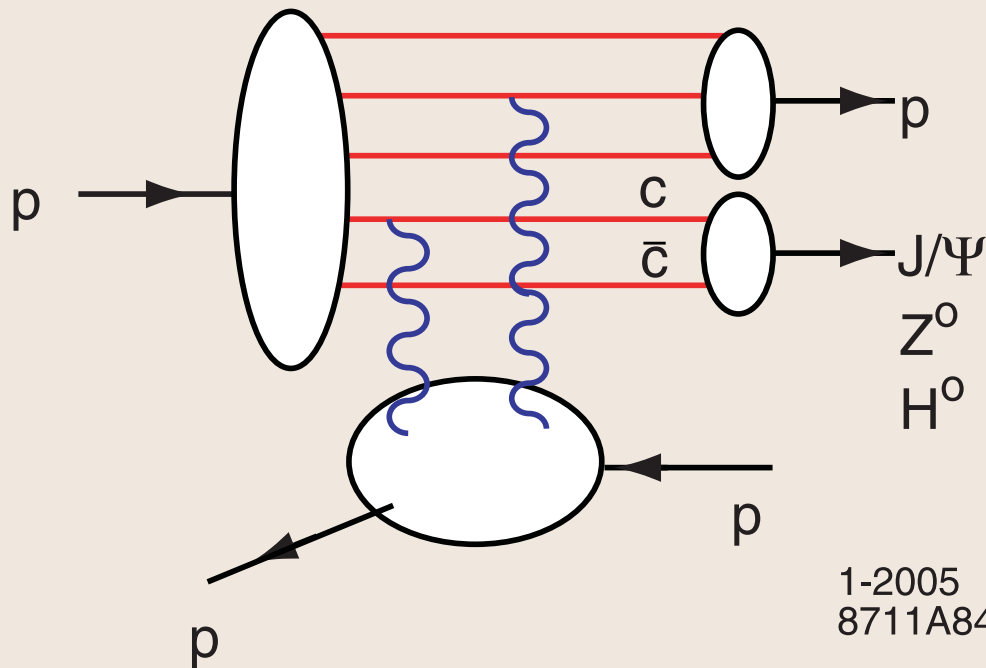
X

SELEX Measurements

$$\langle x_F \rangle \simeq 0.33$$

Production of a Double-Charm Baryon

Intrinsic Charm Mechanism for Double Diffraction



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

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

High x_F !

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8711A84

Kopeliovitch, Schmidt, Soffer, sjb

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

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Novel QCD Phenomena at the LHC

RHIC Experiment
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Advantage of Double Diffraction

$$pp \rightarrow p + H + p$$

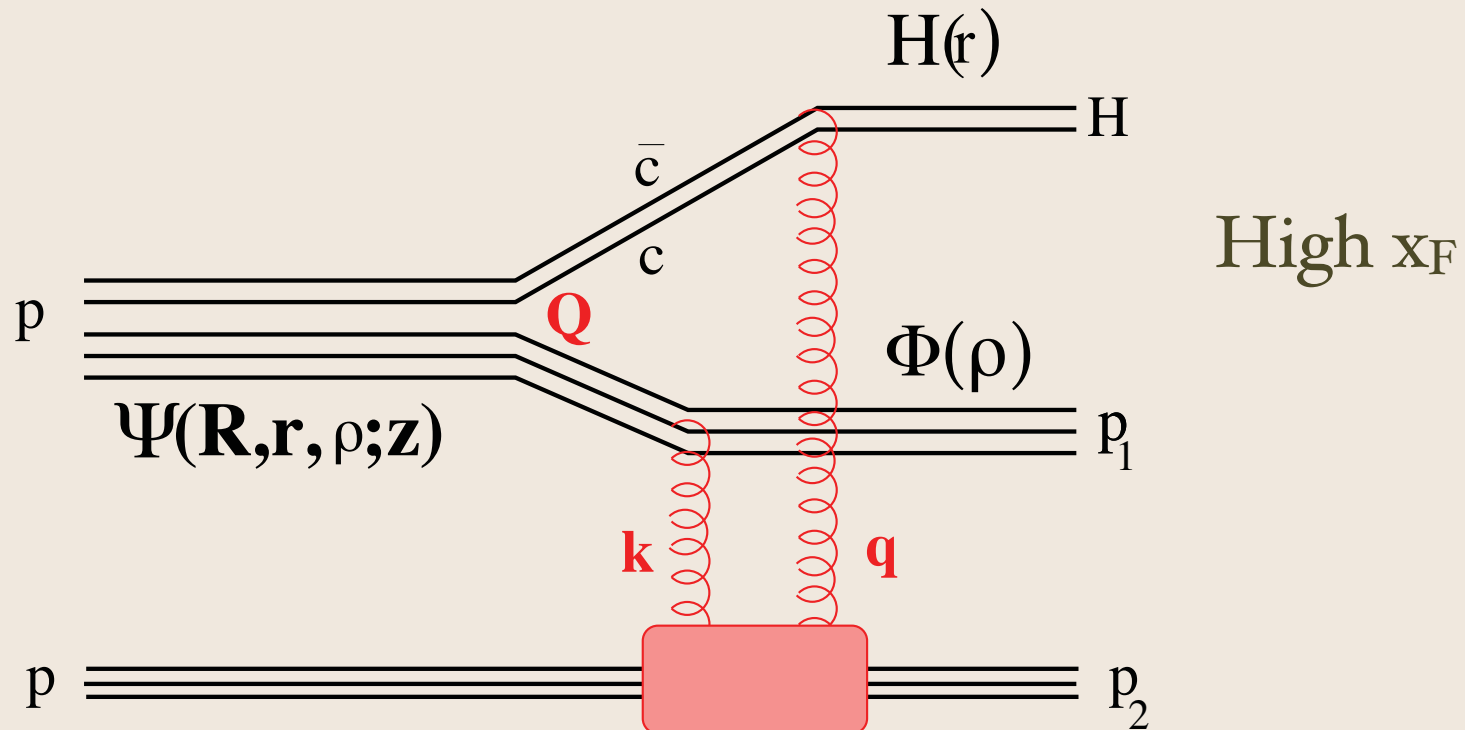
- Construct mass of Higgs from missing mass
- Independent of Branching Ratio
- Measure Branching Ratios

Small x_F

A. D. Martin, V. A. Khoze and M. G. Ryskin

Doubly Diffractive Higgs Production

$$pp \rightarrow p + H + p$$



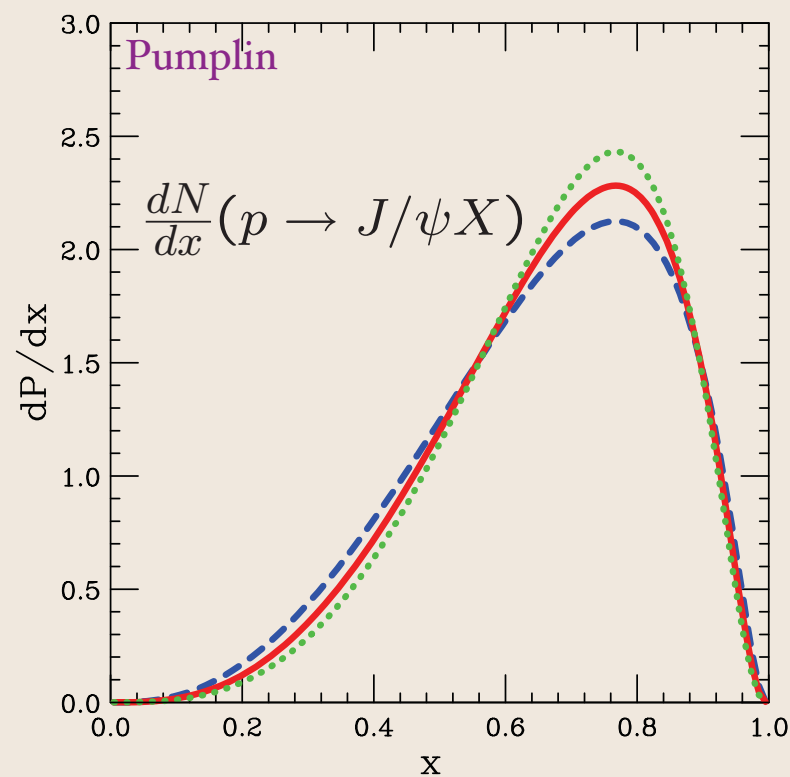
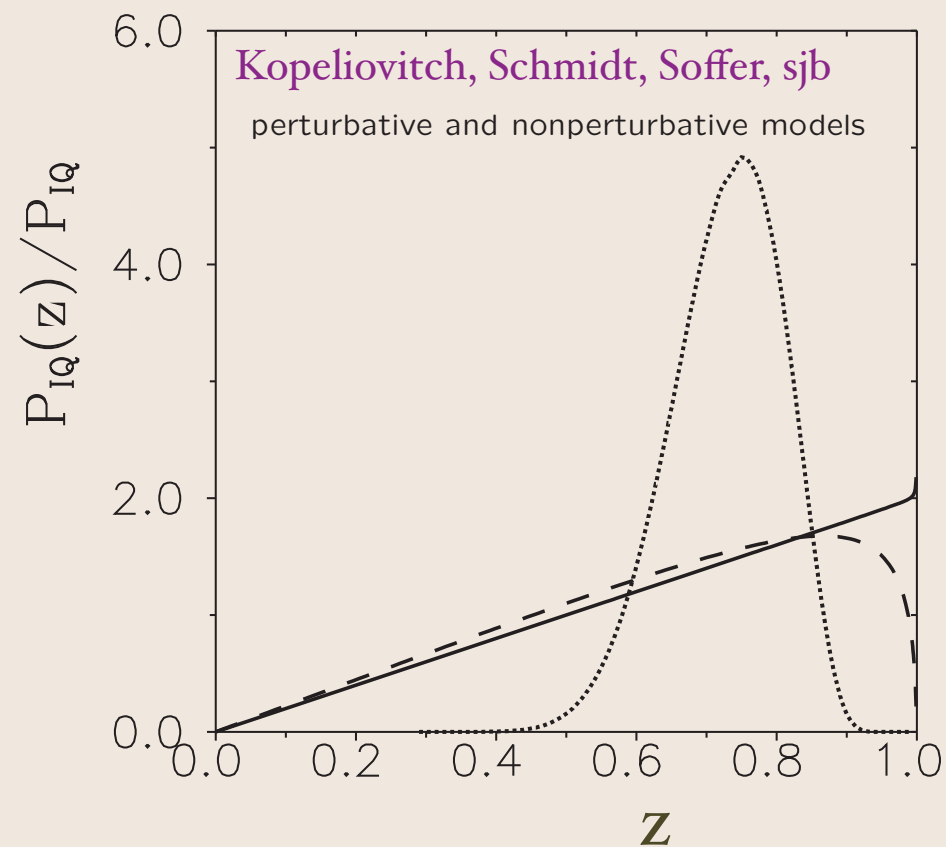
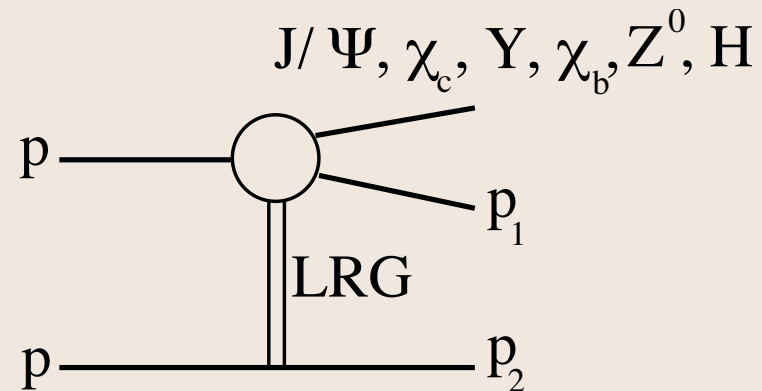
from IC, IB, IT

Kopeliovitch, Schmidt, Soffer, sjb

Doubly Diffractive Production

$$pp \rightarrow p + Z, \gamma, H + p$$

High x_F from IQ



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Tests of IQ

- Deep Inelastic Scattering $c(x,Q)$, $b(x,Q)$
- $pp \rightarrow \Lambda_b X$ Basile et al (ISR)
- $pp \rightarrow \Lambda_c D p$ associated production
- $pp \rightarrow Z^0 pp$

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- Inclusive Higgs production $pp \rightarrow H X$
- Extend to intrinsic heavy squarks, gluinos!

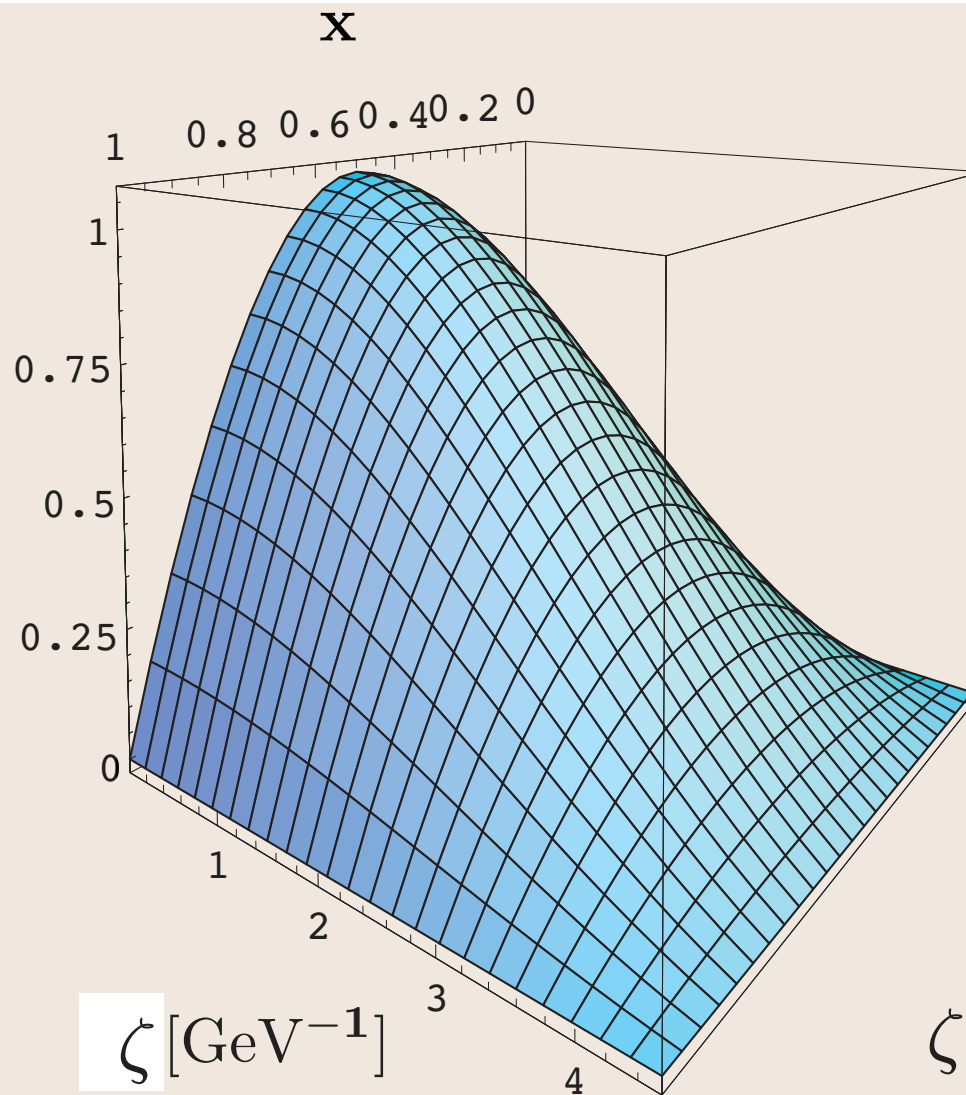
Other QCD Issues for LHC

- Renormalization Scale Setting: Eliminate ambiguity! Use same procedure as QED and EW
- BLM Scale absorbs nonconformal contributions; sets effective number of flavors. Satisfies RGE.
- Scale for three-gluon coupling has surprising dependence on gluon virtualities. Implications for heavy quark production
H. J. Lu Binger, sjb
- Non-conformal higher-twist contributions observed at RHIC
- Predictions from AdS/CFT for LFWFs, structure functions.
Polchinski, Strassler de Teramond, sjb

$$\sqrt{x(1-x)}\psi(\mathbf{x}, \mathbf{b})$$

Holographic Model

Guy de Teramond
SJB



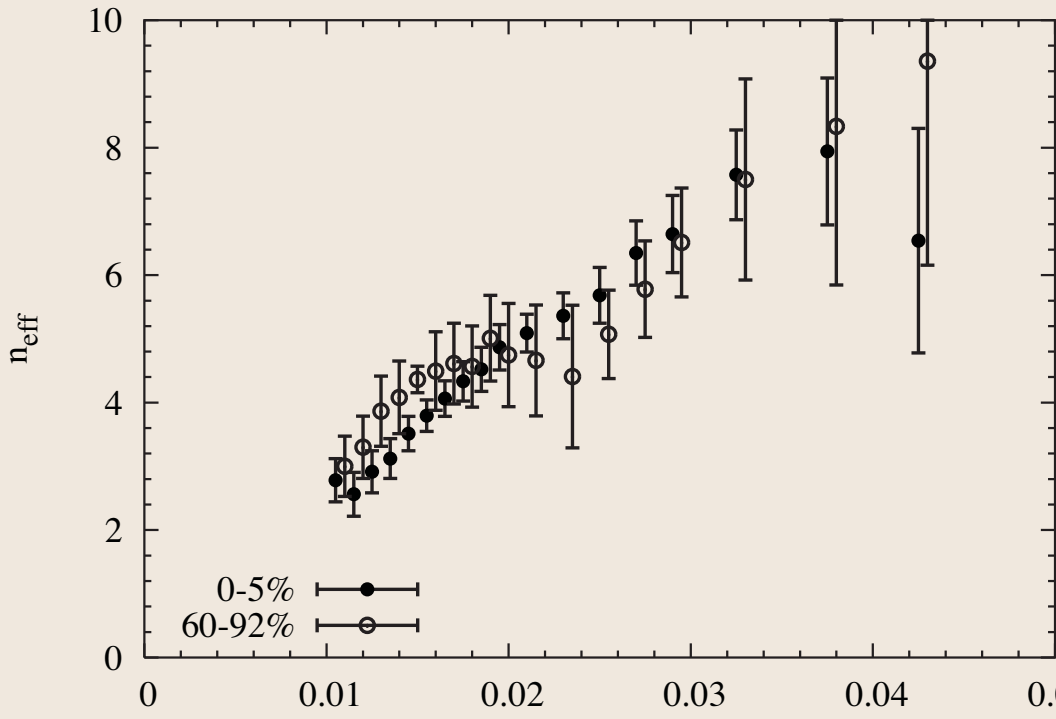
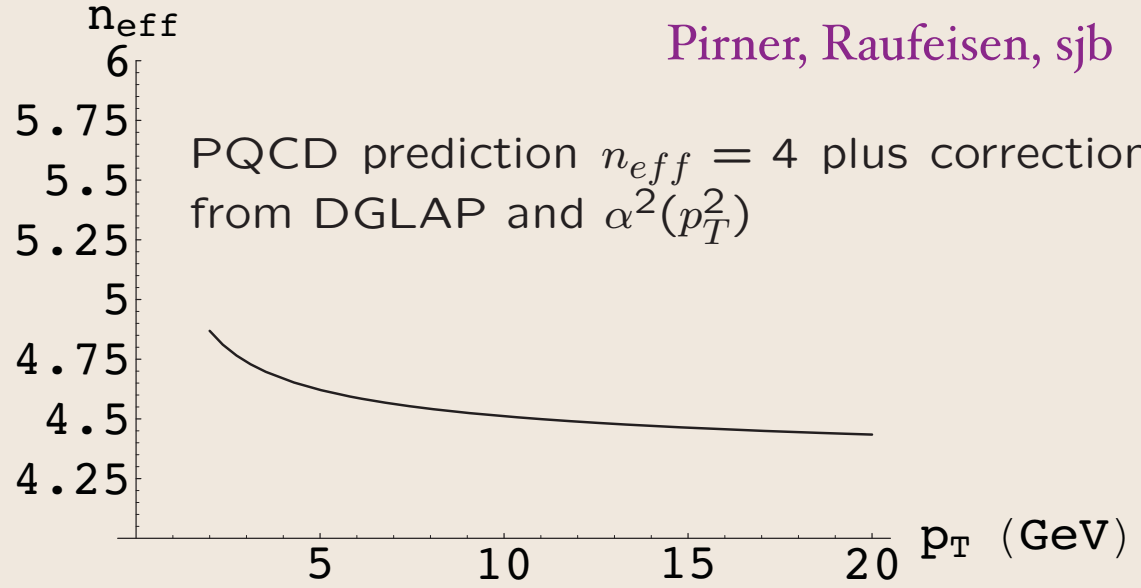
AdS/CFT
prediction for
meson LFWF

$$\zeta = b\sqrt{x(1-x)}$$

Two-parton ground state LFWF in impact space $\psi(x, b)$ for a for $n = 2, \ell = 0, k = 1$.

$$E \frac{d\sigma}{d^3p}(pp \rightarrow HX) = \frac{F(x_T, \theta_{CM})}{p_T^{n_{eff}}}$$

$$x_T = \frac{2p_T}{\sqrt{s}}$$



K. Adcox *et al.* [PHENIX Collaboration],
 "Single identified hadron spectra from $s(NN)^{1/2} = 130$ -GeV Au + Au collisions," Phys. Rev. C **69**, 024904 (2004) [arXiv:nucl-ex/0307010].

$$AA \rightarrow pX$$

Conventional wisdom wrong!
Evidence for Higher Twist Subprocesses

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Use BLM!

- Rigorous method: Satisfies Transitivity, all aspects of RG
- Preserves Conformal Template
- Physical Interpretation of Scales
- Correct Abelian Limit
- Eliminates unnecessary source of imprecision of PQCD predictions
- Commensurate Scale Relations: Fundamental Tests of QCD free of renormalization scale and scheme ambiguities
- BLM used in many applications, LGTH, BFKL, ...