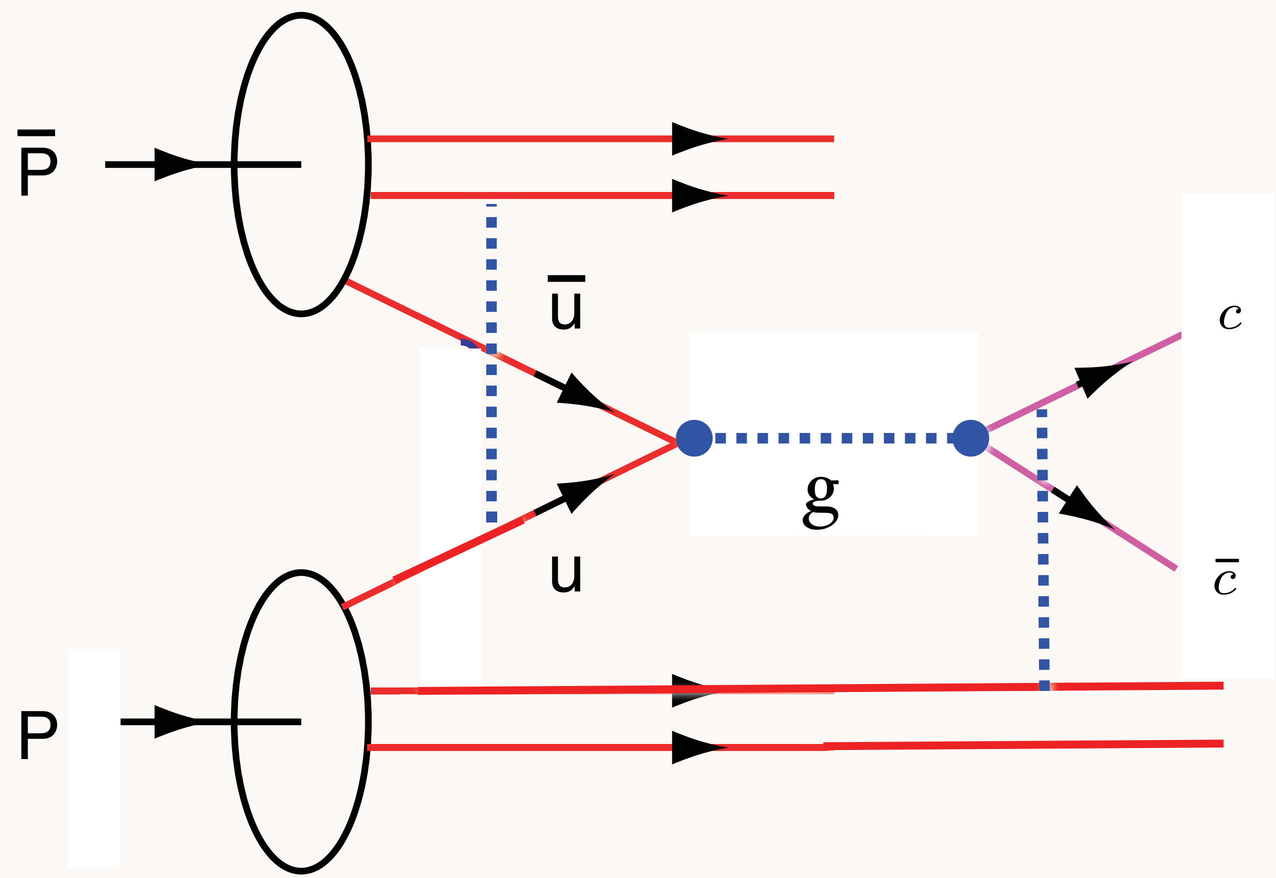
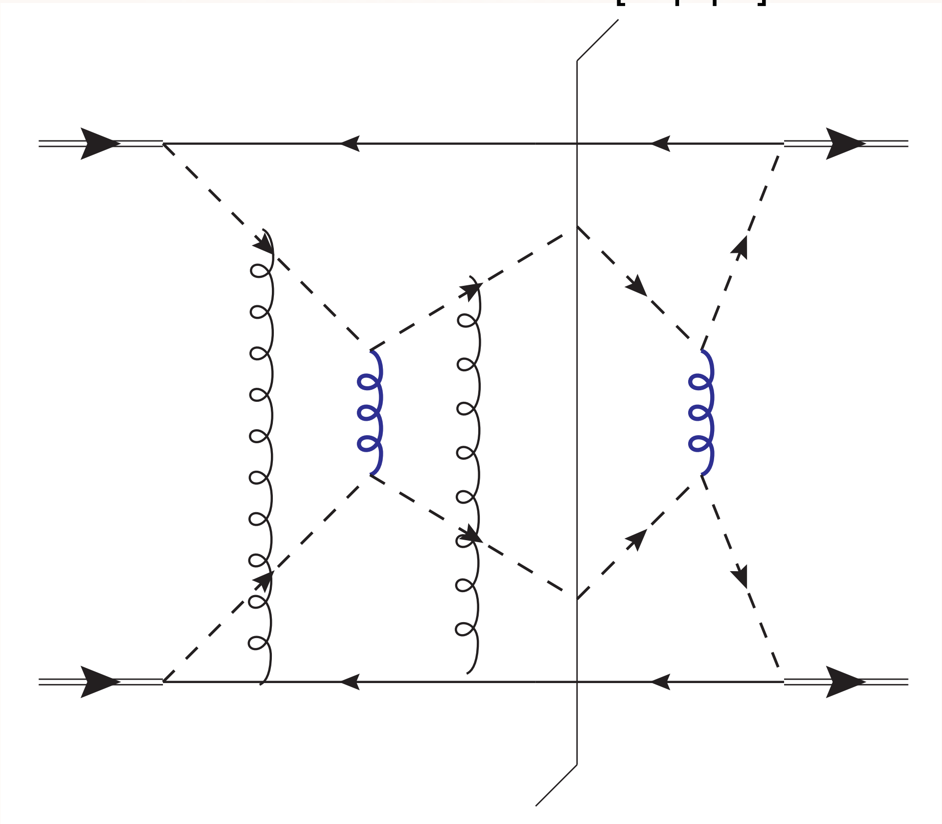


Problem for factorization when both ISI and FSI occur!

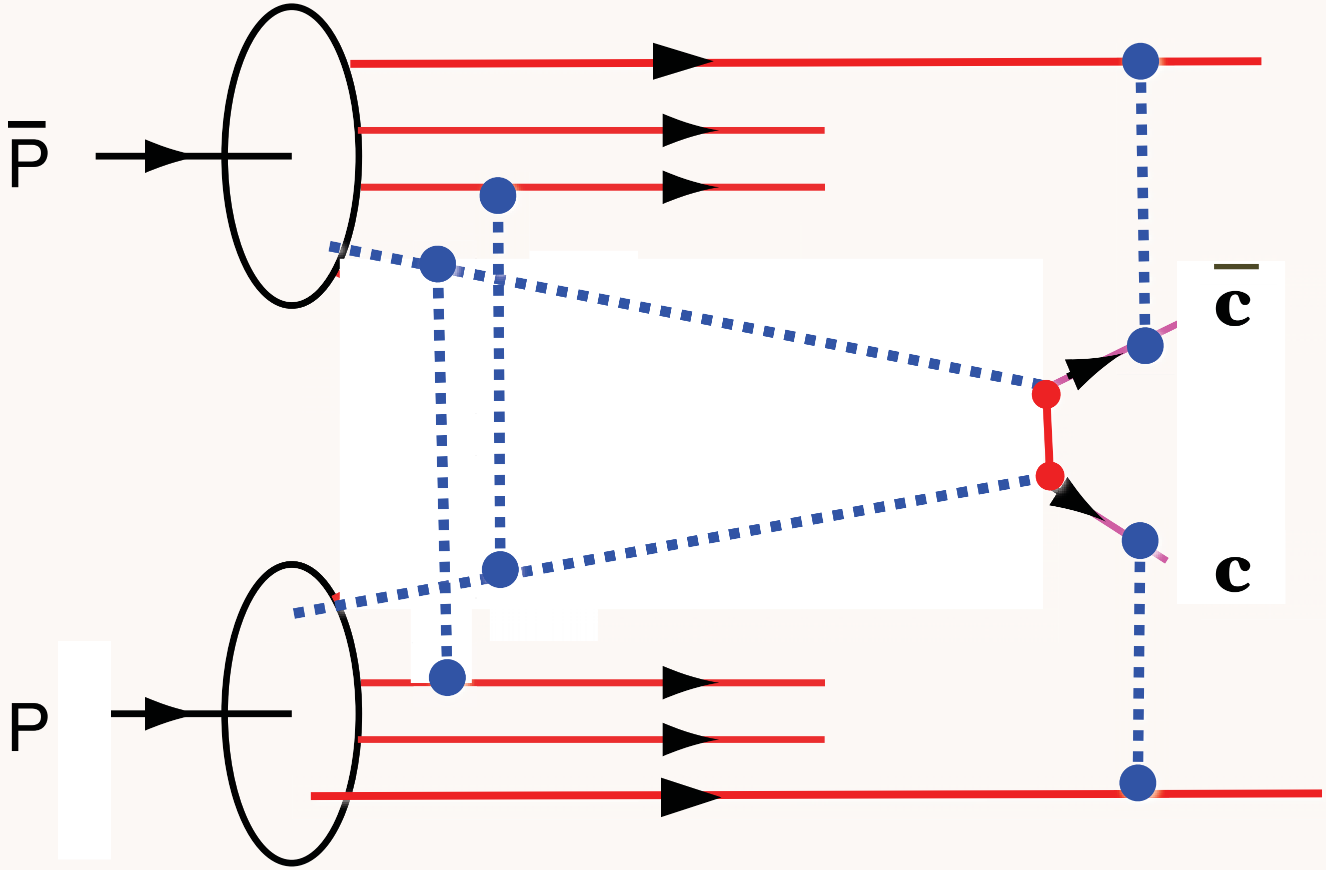
Factorization is violated in production of high-transverse-momentum particles in hadron-hadron collisions

John Collins, Jian-Wei Qiu . ANL-HEP-PR-07-25, May 2007.

e-Print: **arXiv:0705.2141** [hep-ph]



The exchange of two extra gluons, as in this graph, will tend to give non-factorization in unpolarized cross sections.

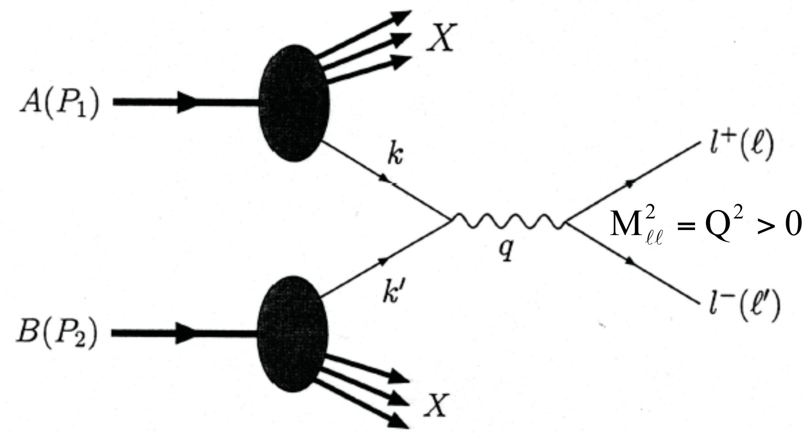


$\cos 2\phi$ **correlation for quarkonium production at leading twist from double ISI**

Enhanced by gluon color charge
Also possible FSI

The Drell-Yan process

- process complementary to DIS
- cross section directly related to parton distribution functions
- no fragmentation functions involved
- all valence quarks will contribute in anti-proton annihilation
- wealth of (spin)-observables



$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \frac{\nu}{2}\sin^2\theta\cos 2\phi$$

$$\nu \propto \sum_q e_q^2 \frac{h_1^\perp \bar{h}_1^\perp}{f_1 \bar{f}_1}$$

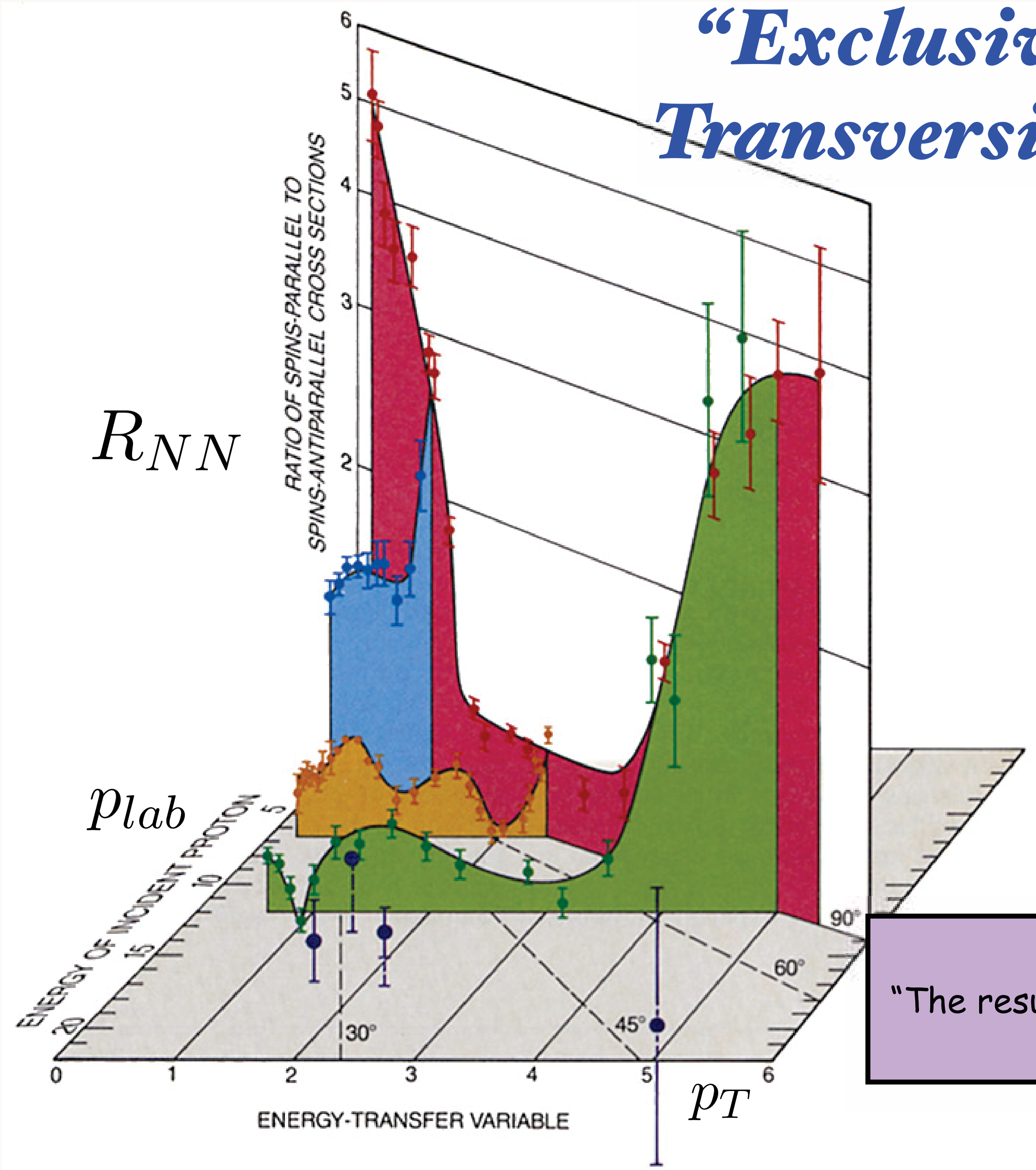
$$A_{TT} \propto \frac{\sum_q e_q^2 \left(h_1 \bar{h}_1\right)}{\sum_q e_q^2 \left(f_1 \bar{f}_1\right)}$$

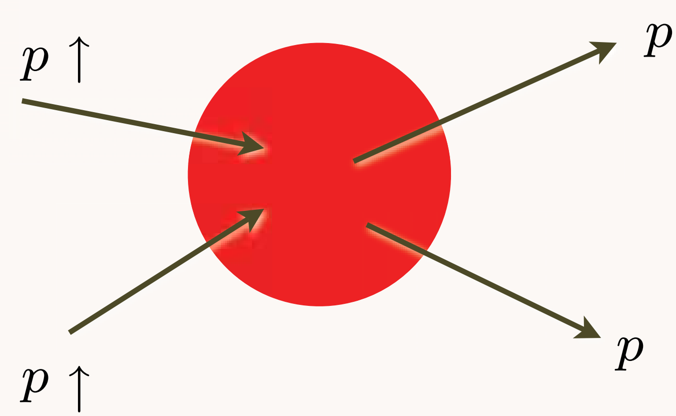
Transversity Test

B. Seitz

Spin Correlations in Elastic $p - p$ Scattering

"Exclusive Transversity"





polarization normal to scattering plane

Ratio reaches 4:1 !

A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

"Exclusive Transversity"

A. Krisch, Sci. Am. 257 (1987)
"The results challenge the prevailing theory that describes the proton's structure and forces"

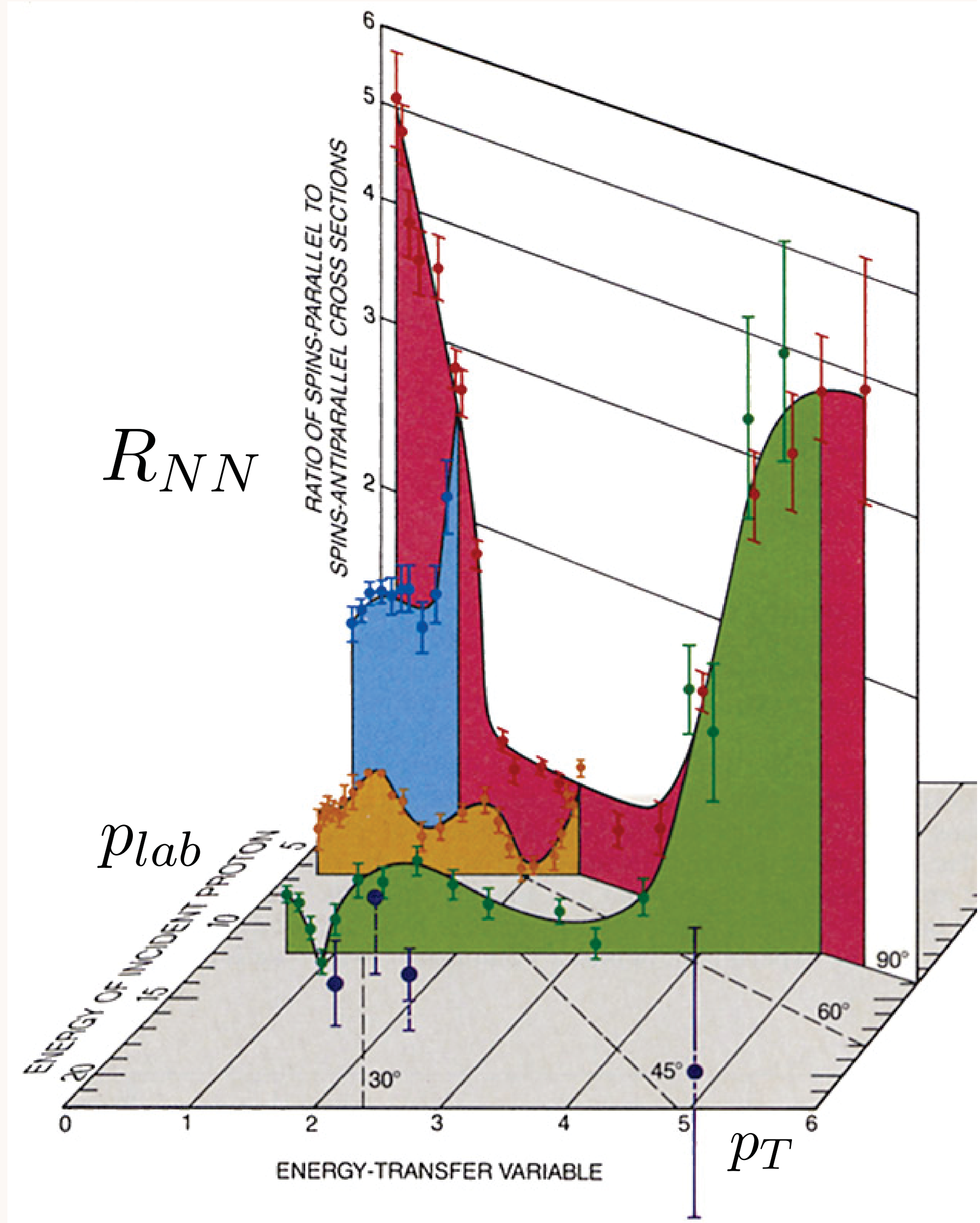
Spin-dependence at large-P_T ($90°_{cm}$):

Hard scattering takes place only with spins ↑↑

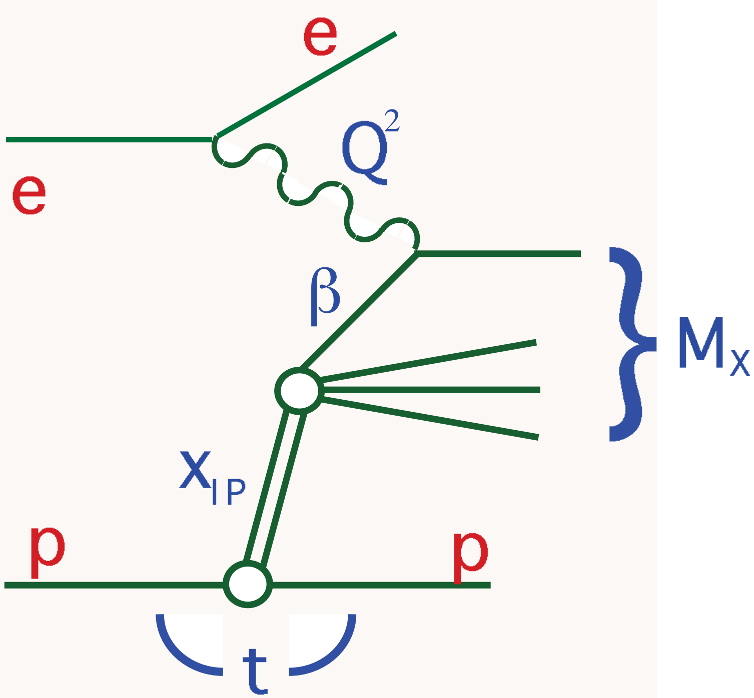
Coincidence?: Quenching of Color Transparency

Coincidence?: Charm and Strangeness Thresholds

Alternative: Six-Quark Hidden-Color Resonances



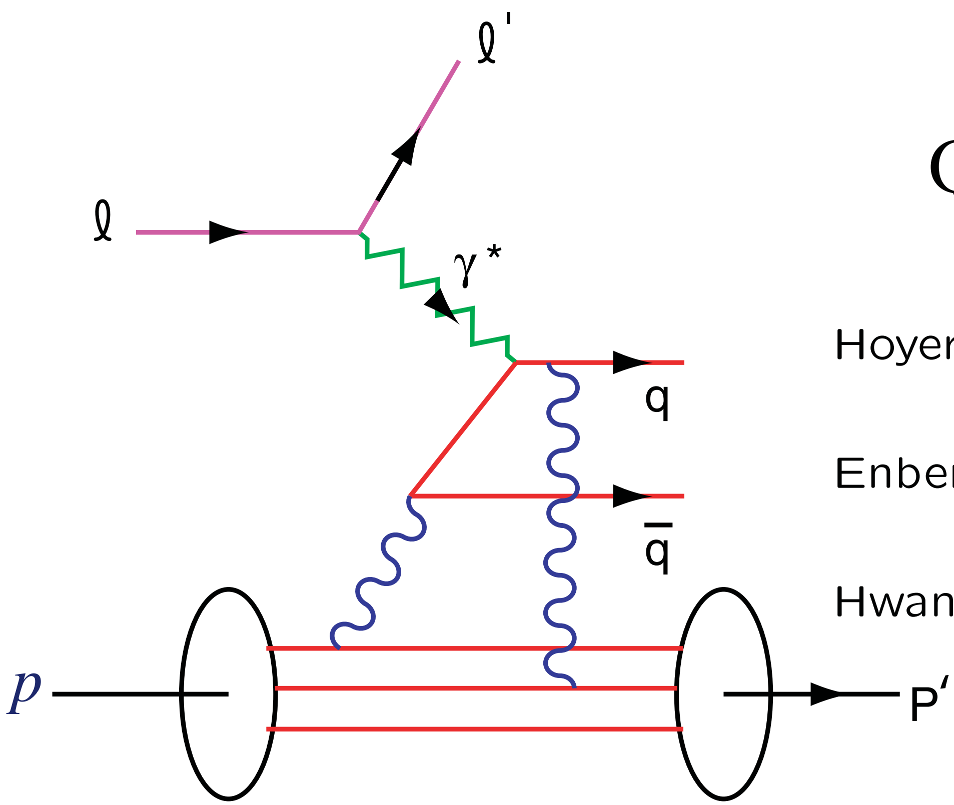
Remarkable observation at HERA



10% to 15% of DIS events are diffractive !

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

Final-State Interaction Produces Diffractive DIS



Quark Rescattering

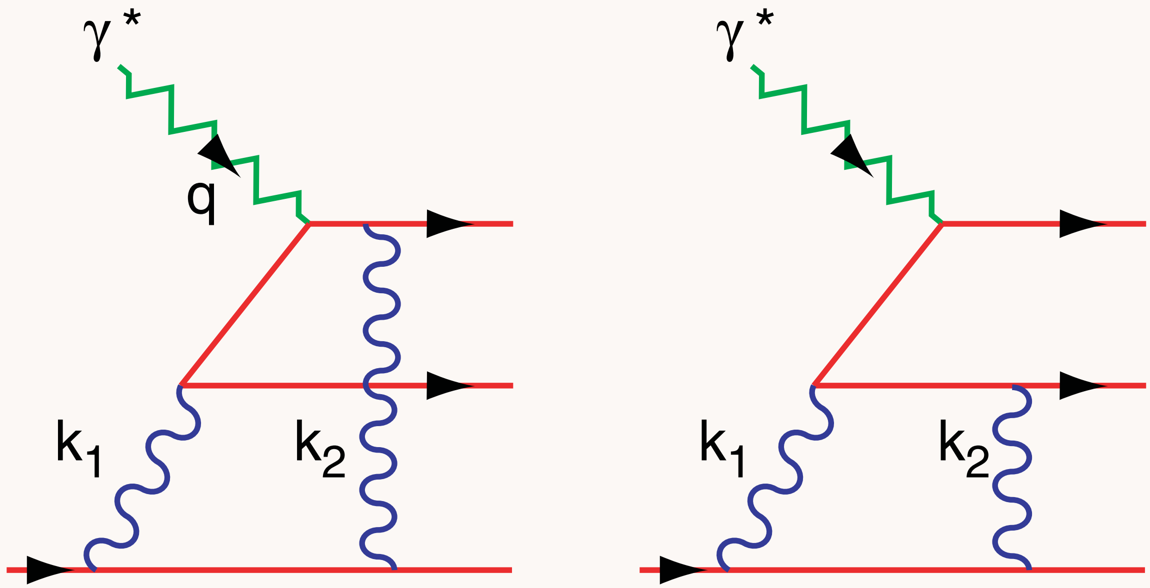
Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

Hwang, Schmidt, SJB

Low-Nussinov model of Pomeron

Final State Interactions in QCD



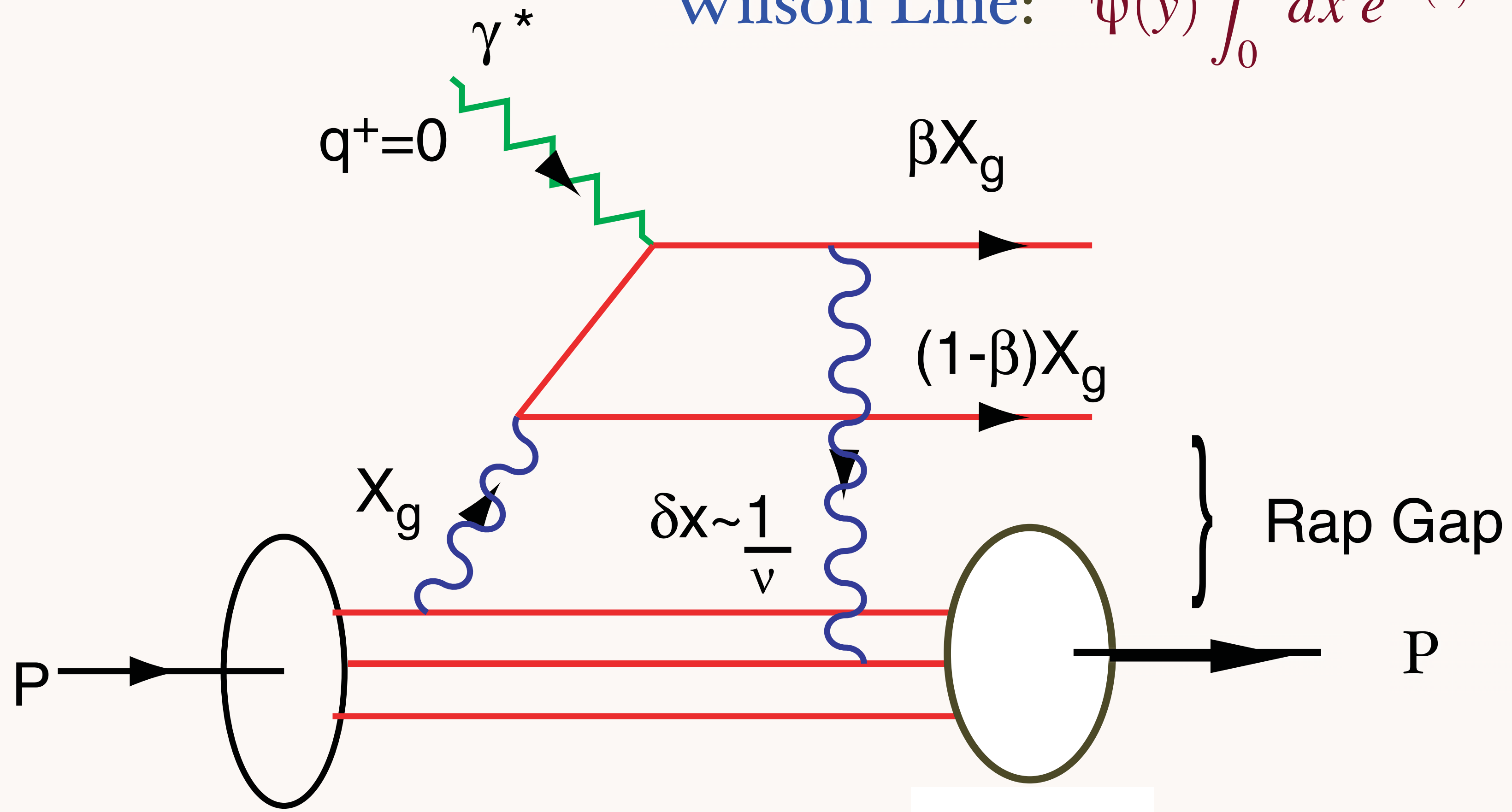
Feynman Gauge   Light-Cone Gauge

Result is Gauge Independent

Hoyer, Marchal, Peigne, Sannino, sjb

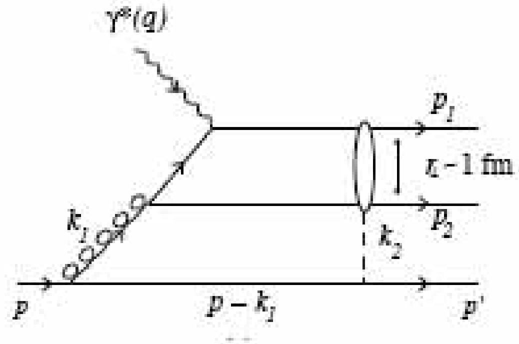
QCD Mechanism for Rapidity Gaps

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



Reproduces lab-frame color dipole approach

- 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)

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.

Consequences for DDIS

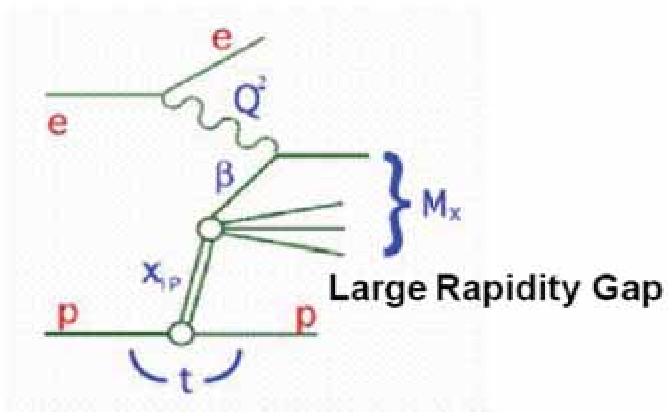
- Underlying hard scattering sub-process is the same in diffractive and non-diffractive events
- Same Q^2 dependence of diffractive and inclusive PDFs (remember: hard radiation not resolved)
- and same energy (W or x_B) dependence

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

Also describes: vector meson leptoproduction BGMFS

- 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 $[f_{g/p}(x_B, Q^2)]^2$

Diffractive Structure Function F_2^D



Diffractive inclusive cross section

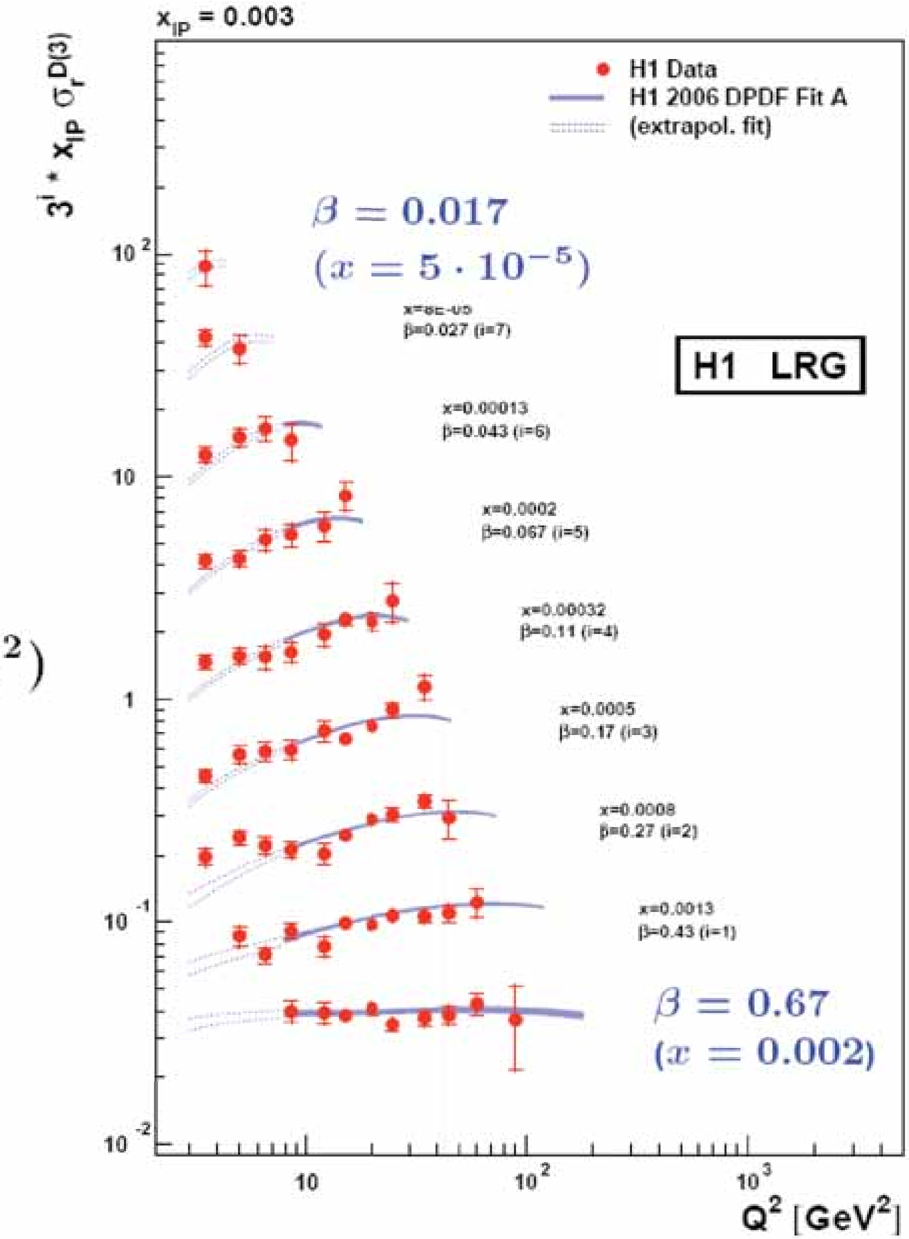
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\,d\beta\,dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P},\beta,Q^2)$$

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

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

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

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



Diffractive Hadron-Hadron Hard Collisions

PHENIX + Forward Tag

- Single diffractive + high P_T
- Double diffractive + high P_T
- Heavy quarks diffractive
- Lepton pair diffractive (Berman, Levy, Yan 1969)
- Nuclear dependence $\sigma(pA \to J/\psi X) \propto A^{2/3}$ at high x_F

Bartels, Goulianis, Mueller, BFKL, Kovchegov, Maor, Khoze, Peigne, Gay Ducati Kopeliovitch, Schmidt, sjb

“Dangling Gluons”

Bodwin, Lepage, sjb
Hoyer, Marchal, Peigne, Sannino, sjb

- Diffractive DIS
- Non-Unitary Correction to DIS: Structure functions are not probability distributions
- Nuclear Shadowing, Antishadowing
- Single Spin Asymmetries -- opposite sign in DY and DIS
- DY $\cos 2\phi$ correlation at leading twist from double ISI-- not given by standard PQCD factorization
- Wilson Line Effects persist even in LCG
- Must correct hard all subprocesses for initial and final-state soft gluon attachments -- Ji gauge link, Kovchegov gauge

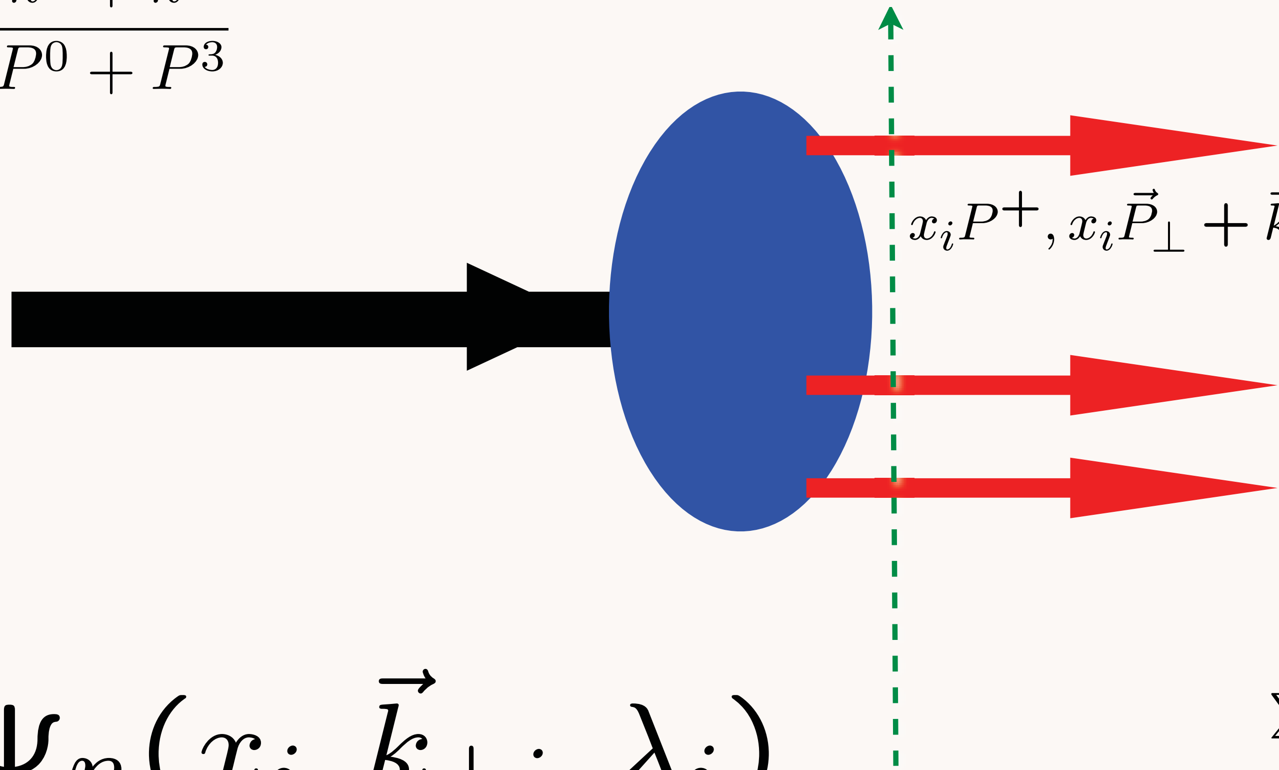
Challenging Conventional Wisdom

- **Renormalization scale is ambiguous**
- **Initial and final-state interactions are power suppressed in a hard QCD reaction**
- **Heavy quark distributions derive exclusively from gluon splitting**
- **Nuclear parton distributions are universal**
- **Hadroproduction at large transverse momentum derives exclusively from 2 to 2 scattering subprocesses**

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

Fixed $\tau = t + z/c$

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



$P^+, \vec{P}_\perp$

$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

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

$\sum_i^n x_i = 1$

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

Invariant under boosts! Independent of P^μ

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

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

The Light Front Fock State Wavefunctions

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

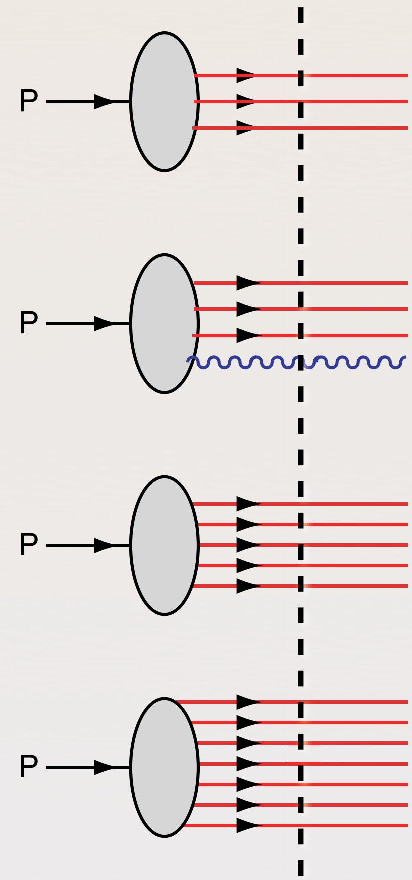
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

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

are boost invariant.

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



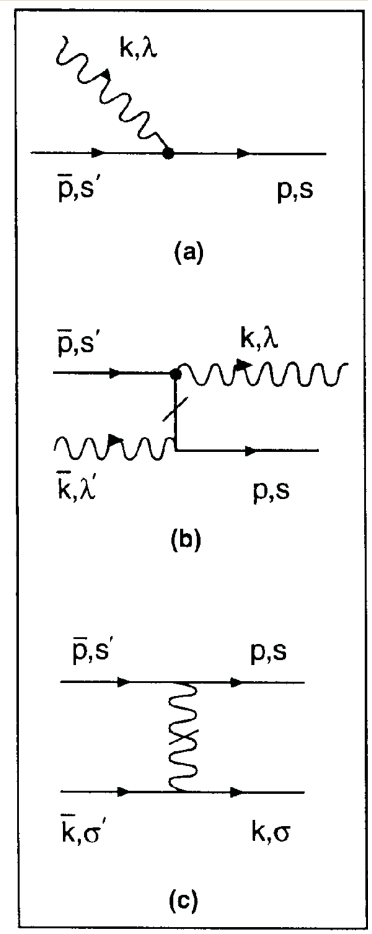
Intrinsic heavy quarks, $\bar{s}(x) \neq s(x)$

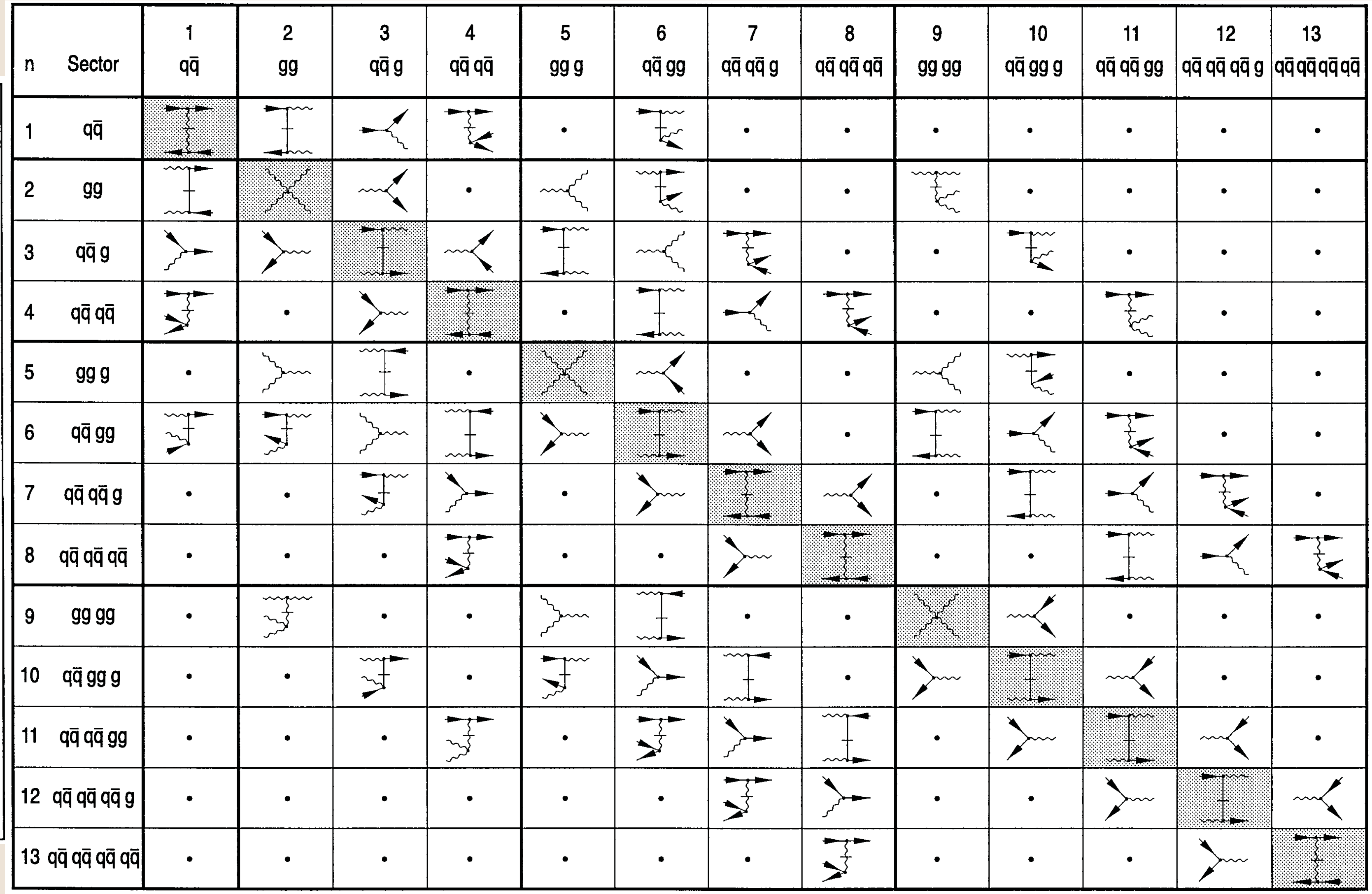
$\bar{u}(x) \neq \bar{d}(x)$

Fixed LF time

Light-Front QCD Heisenberg Equation

$$H^{QCD}_{LC}|\Psi_h\rangle = \mathcal{M}^2_h\,|\Psi_h\rangle$$

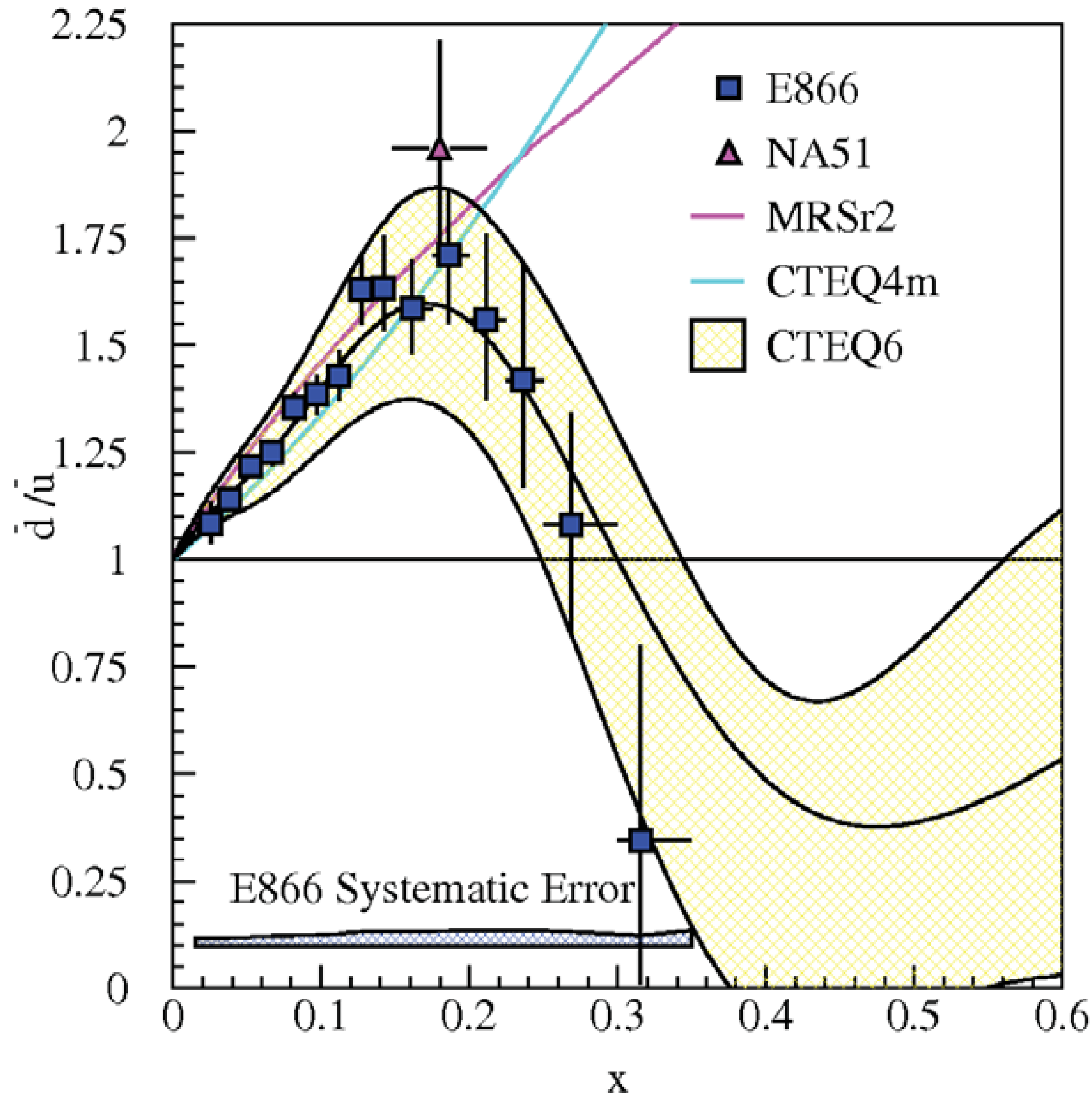




Light Antiquark Flavor Asymmetry

- Naïve Assumption from gluon splitting:

- E866/NuSea (Drell-Yan)

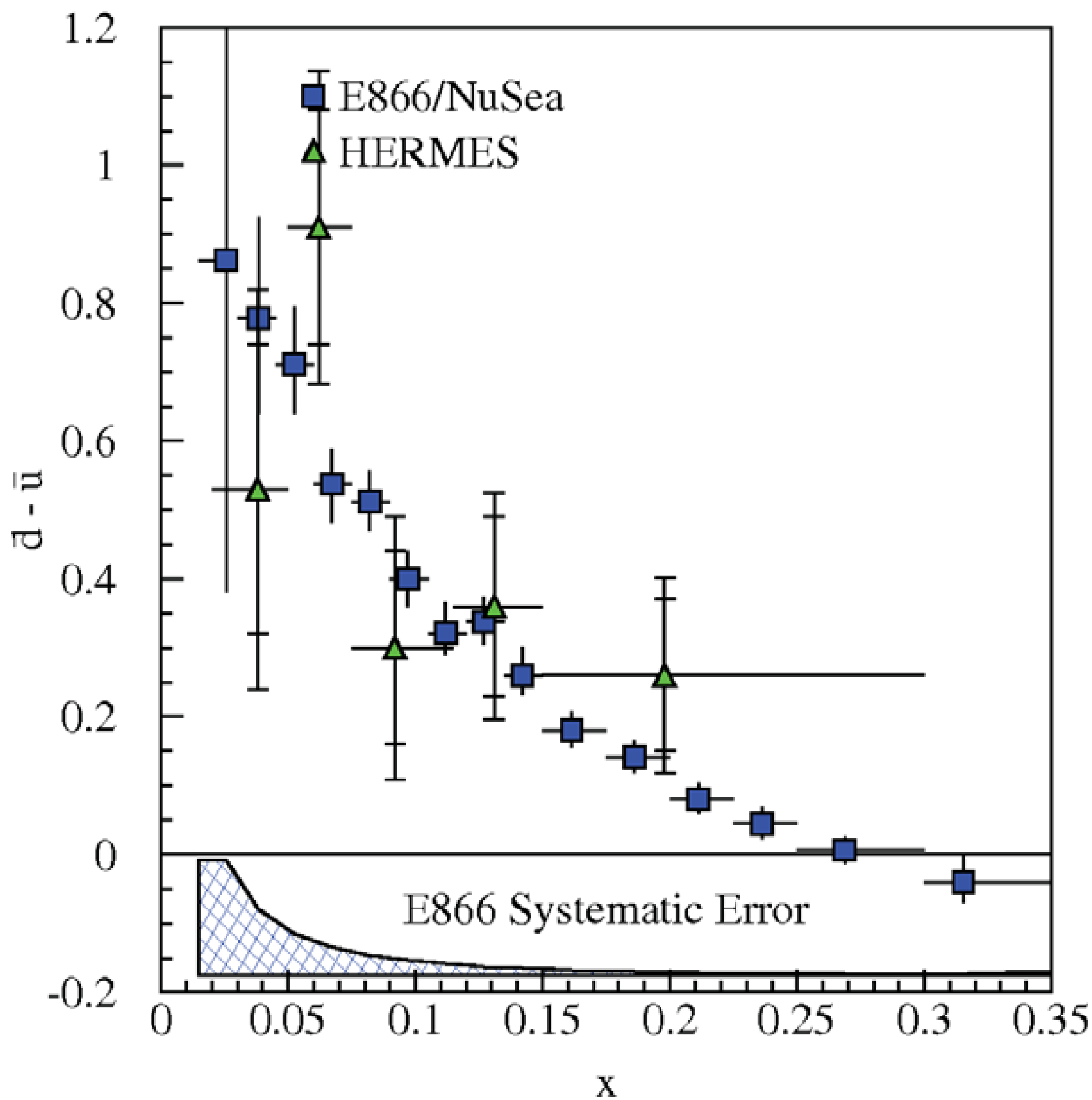


Proton Structure: By What Process Is the Sea Created?

- A proton with 3 valence quarks plus glue **cannot** be right at any scale!!

$$\bar{d}(x) = \bar{u}(x) = \bar{q}(x)$$

- $\bar{d} - \bar{u}$
  - Symmetric sea via pair production from gluons subtracts off
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference



Paul E. Reimer

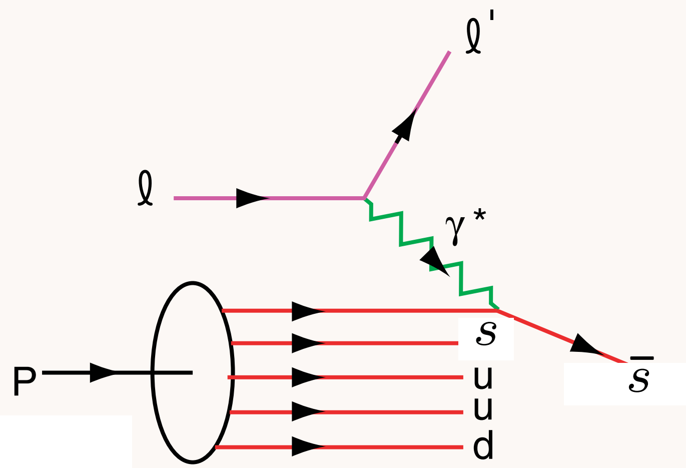
$$\bar{u}(x) \neq \bar{d}(x)$$

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

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

$$\bar{s}(x) \neq s(x) \qquad ep \rightarrow e'KX$$

$$|uuds\bar{s} > \simeq |\Lambda(uds)K^+(\bar{s}u) >$$



Strangeness Asymmetry

The strange and anti-strange distributions of the proton need not be $s(x,Q^2) \neq \bar{s}(x,Q^2)$; this asymmetry reflects fundamental nonperturbative aspects of the proton's structure.

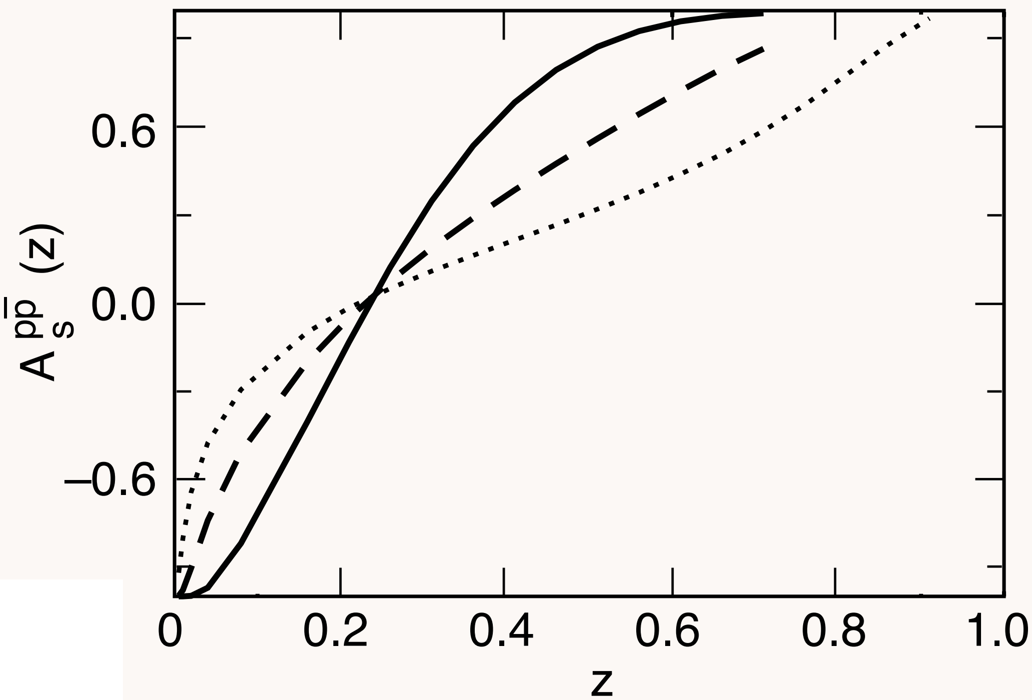
Meson-Baryon fluctuations produce asymmetry

Compare $D(s\bar{c})$ and $D(\bar{s}c)$
in proton fragmentation region at the EIC

Compare protons versus anti-proton in $\bar{s}$ current quark fragmentation

$$D_{s\to p}(z) \neq D_{s\to \bar{p}}(z)$$

Tag s quark via high x_F Λ production in proton fragmentation region.

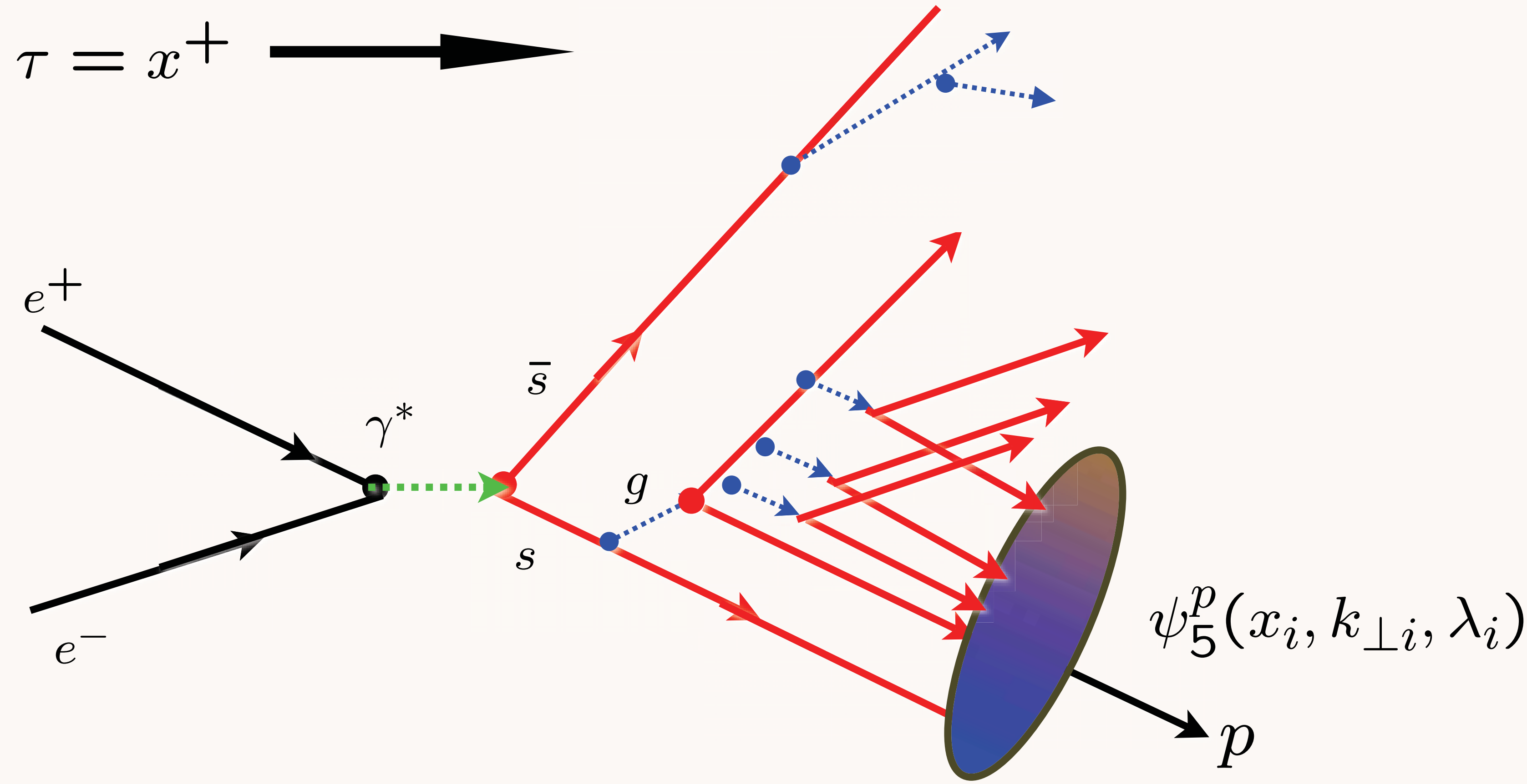


B.Q. Ma and sjb

$$A_s^{p\bar{p}}(z) = \frac{D_{s\to p}(z) - D_{s\to \bar{p}}(z)}{D_{s\to p}(z) + D_{s\to \bar{p}}(z)}$$

Consequence of $s_p(x) \neq \bar{s}_p(x)$ $\quad |uuds\bar{s}> \simeq |K^+\Lambda>$

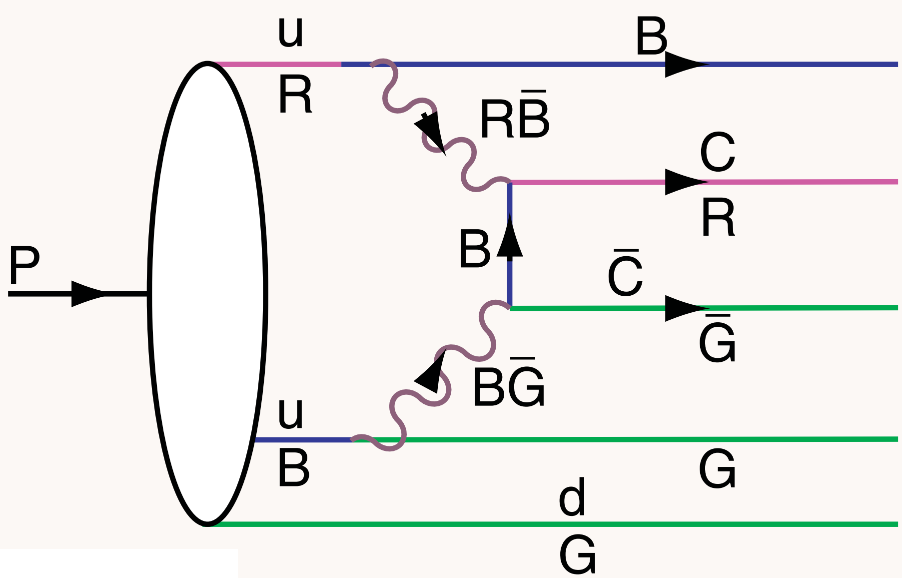
Hadronization at the Amplitude Level



Higher Fock State Coalescence $|uuds\bar{s}>$

Asymmetric Hadronization ! $D_{s\to p}(z) \neq D_{s\to\bar{p}}(z)$

B-Q Ma, sjb



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

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

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

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

OPE derivation - M.Polyakov et al.

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

$c\bar{c}$ in Color Octet

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

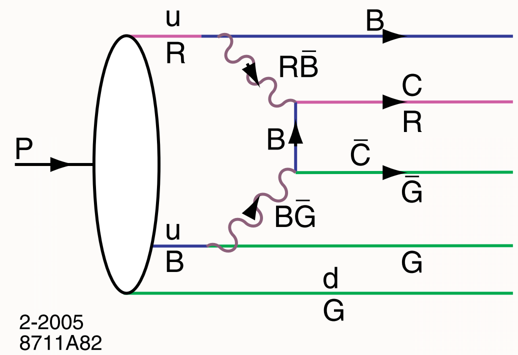
$$\hat{x}_i = \frac{m_{\perp i}}{\sum_j^n m_{\perp j}}$$

High x charm!

Hoyer, Peterson, Sakai, sjb

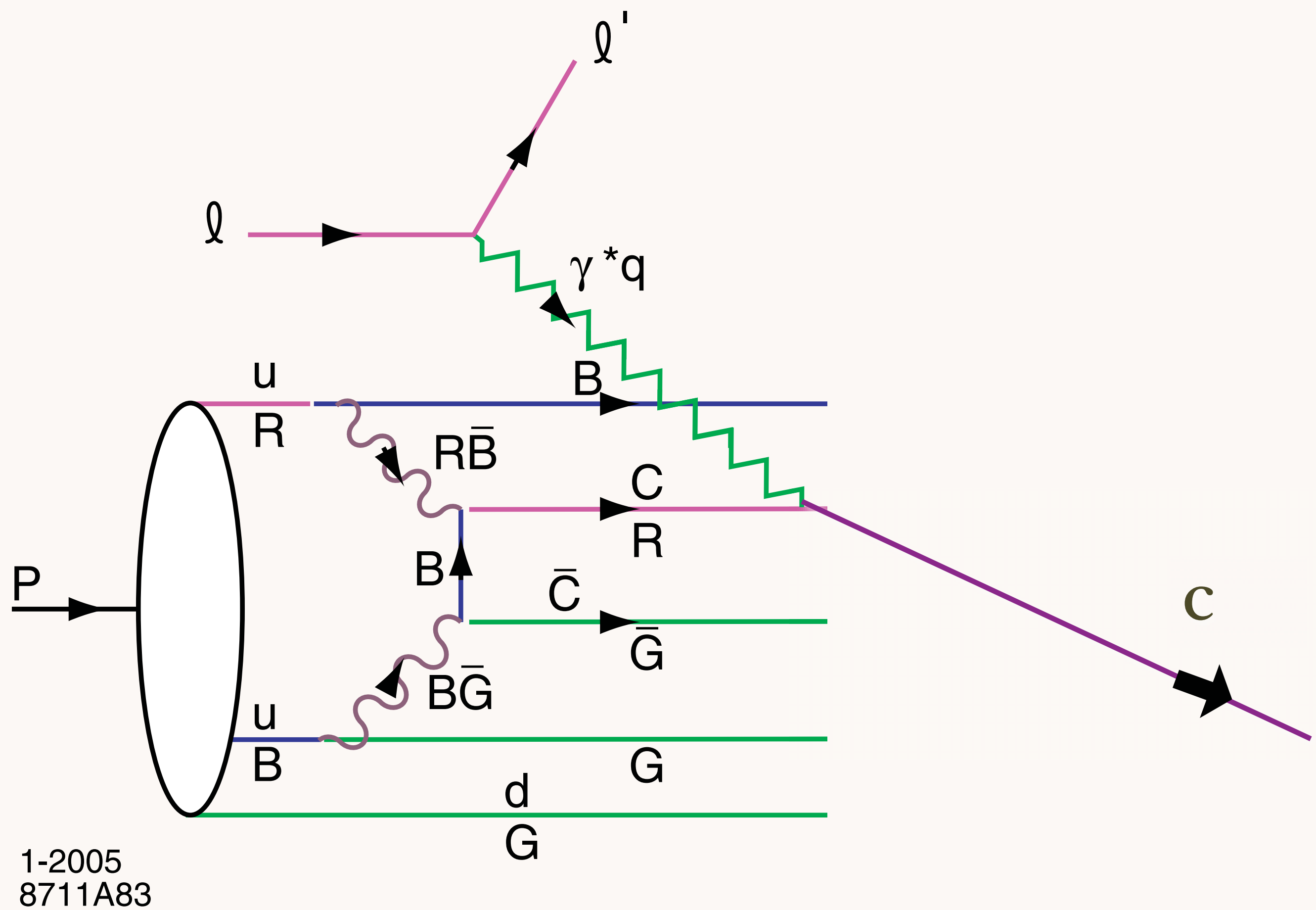
Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



- Rigorous prediction of QCD, OPE
- Color - Octet + Color - Octet Fock State!
- Probability $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- Large Effect at high x
- Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)
- Severely underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)
- Many empirical tests

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

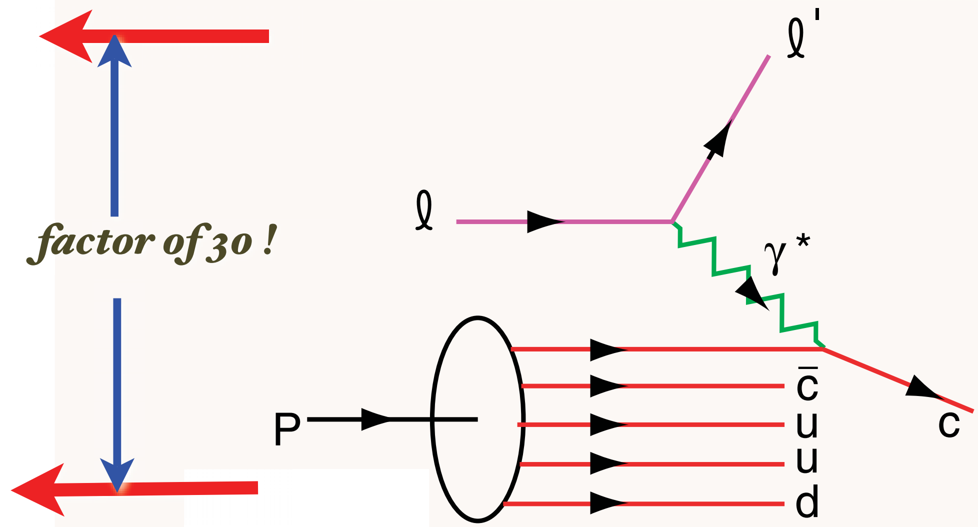


Hoyer, Peterson, SJB

Measurement of Charm Structure Function

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

First Evidence for Intrinsic Charm



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

- 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)

Model similar to Intrinsic Charm

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

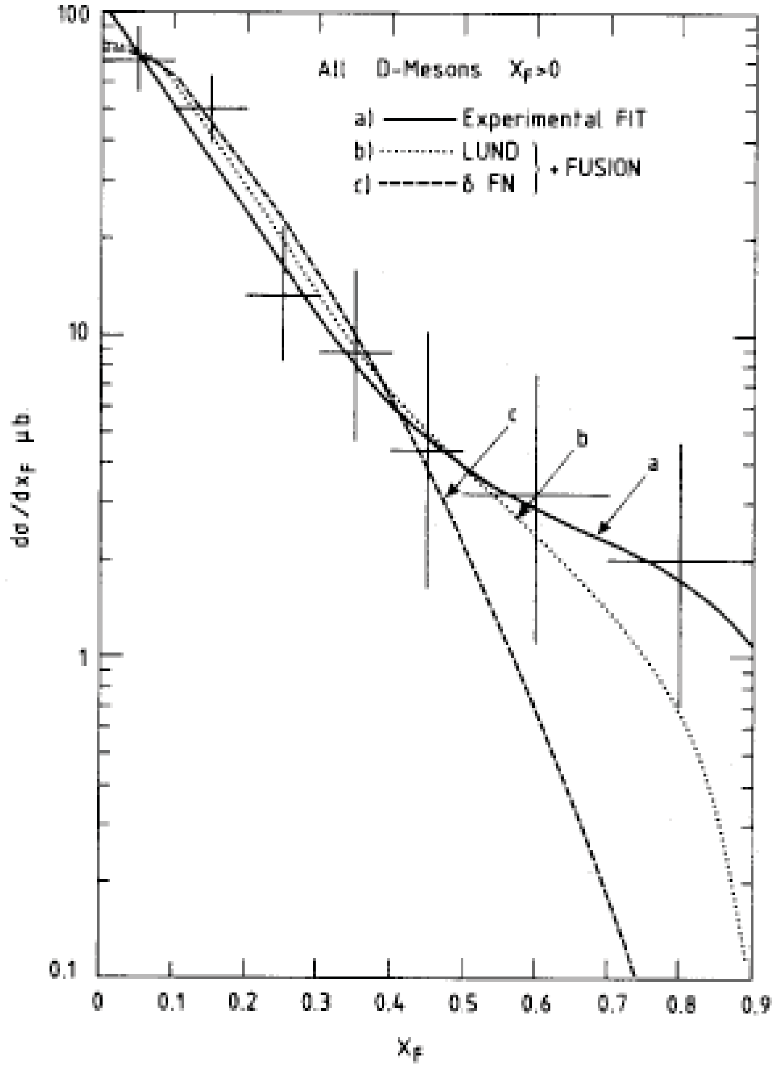
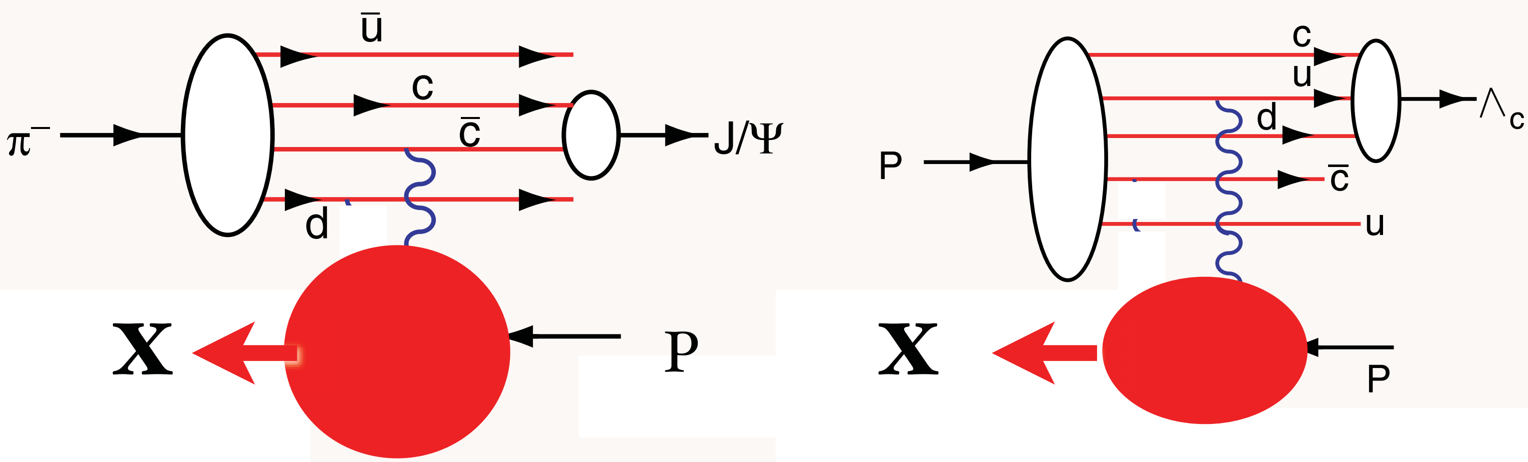


Fig. 1. The differential distribution x_F for all D mesons having $x_F > 0$. Curve (a) is the two-component fit to the data as described in the text. Curve (b) is the prediction of the Lund fusion calculation. Curve (c) is the prediction of the bare QCD fusion calculation (δ-function fragmentation). 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 πp Interaction
Phys. Lett. B 161, 400 (1985).

Leading Hadron Production from Intrinsic Charm

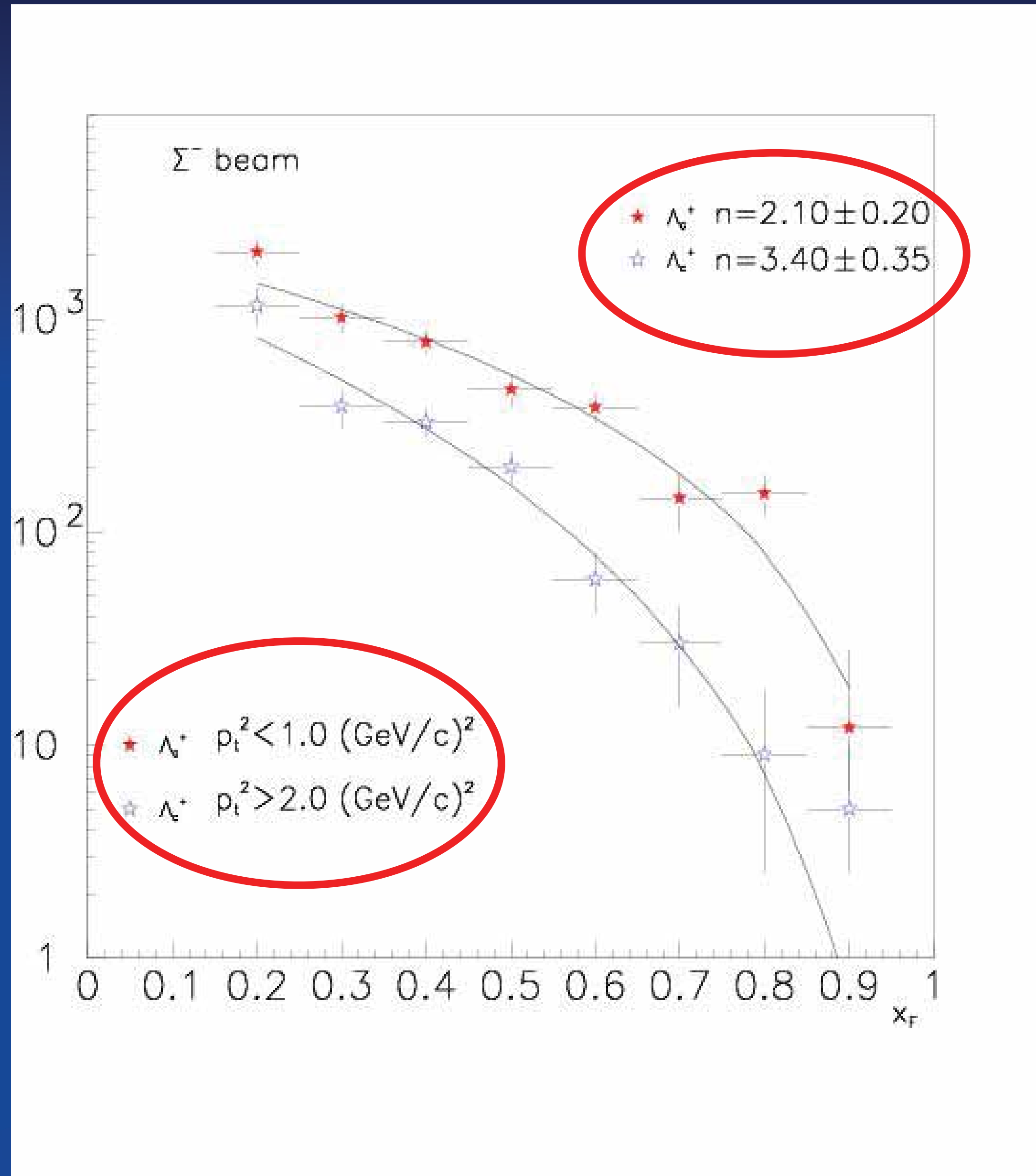


Coalescence of Comoving Charm and Valence Quarks Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

SELEX Λ_c^+ Studies – p_T Dependence

- Λ_c^+ production by Σ^- vs x_F shows harder spectrum at low p_T - consistent with an intrinsic charm picture.

(Vogt, Brodsky and Hoyer, Nucl. Phys. B383,683 (1992))

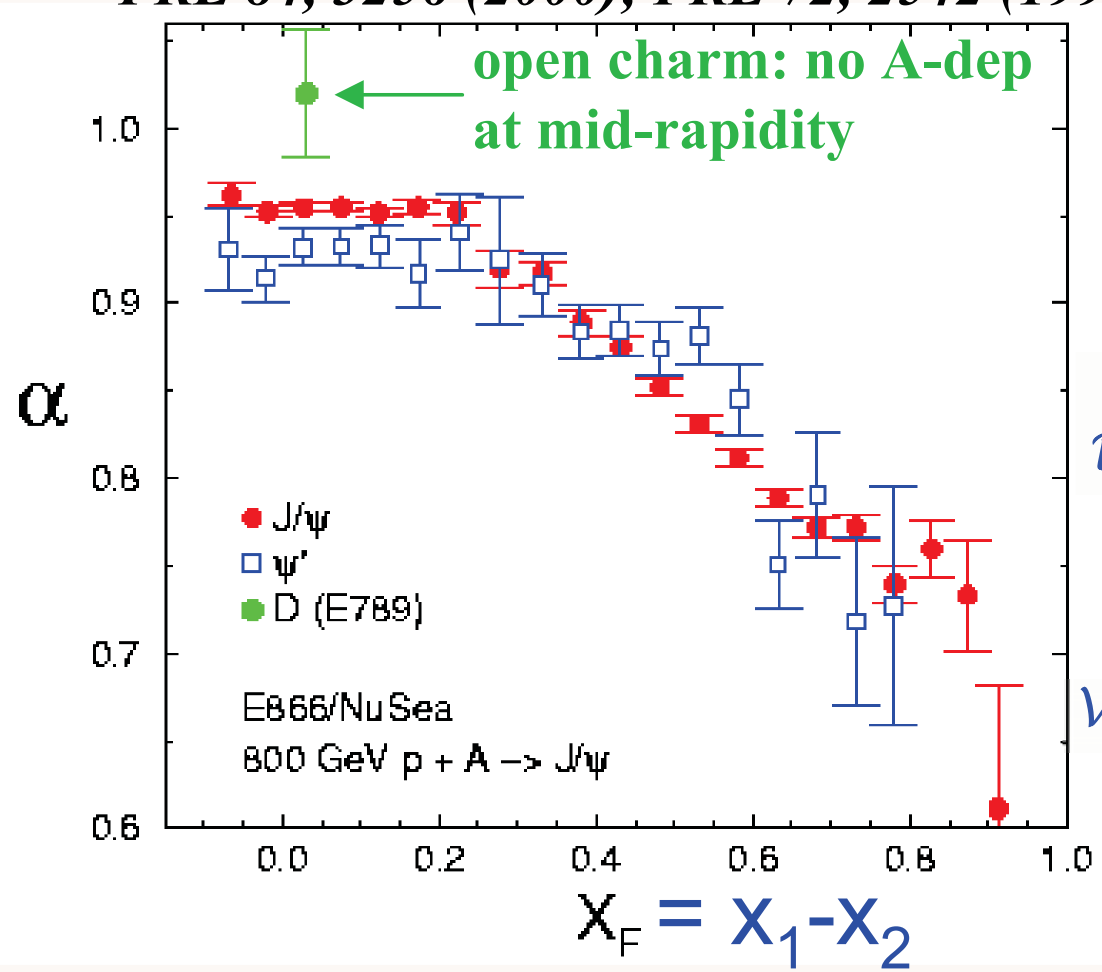


M. Leitch

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

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

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$



Remarkably Strong Nuclear Dependence for Fast Charmonium

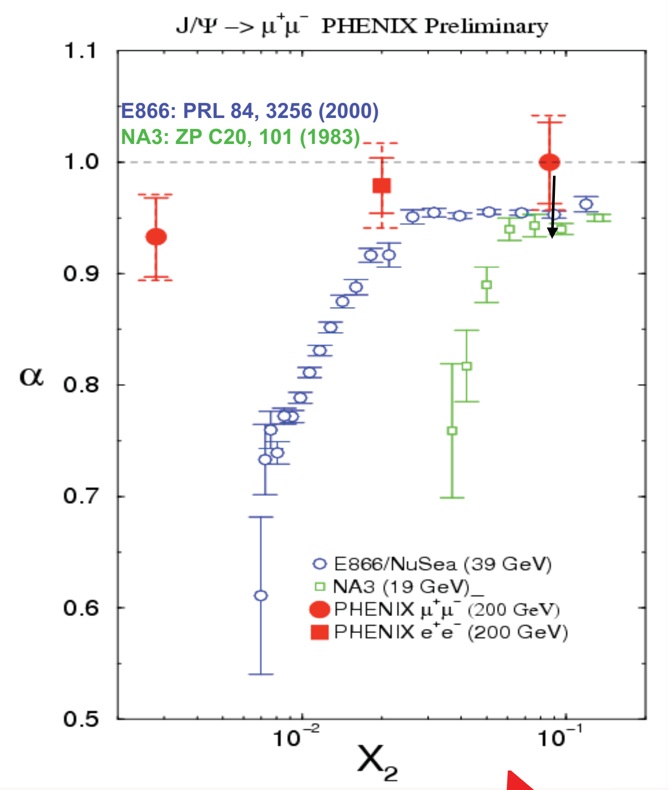
Violation of PQCD Factorization!

Violation of factorization in charm hadroproduction.
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

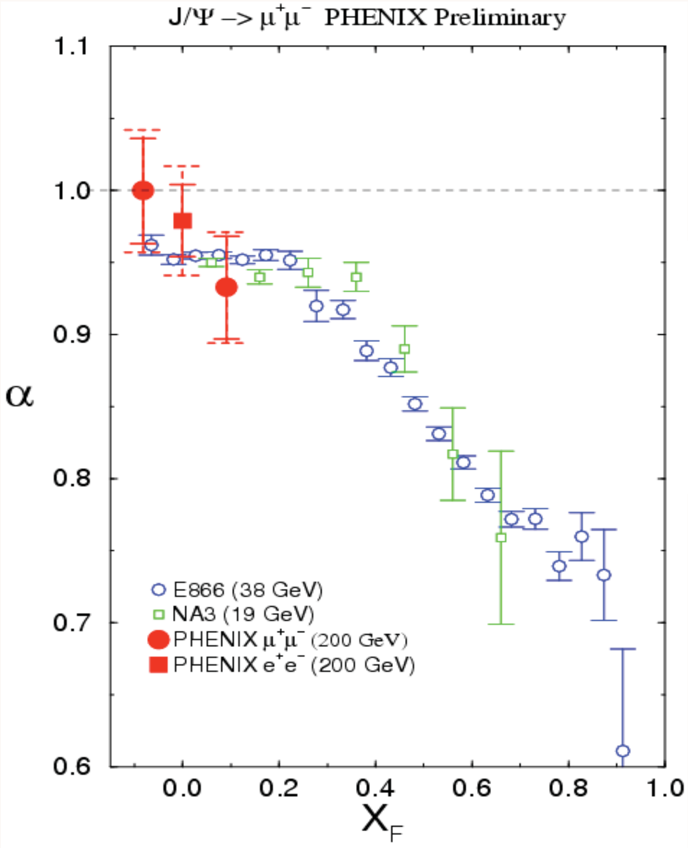
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F

M.Leitch

PHENIX compared to lower energy measurements



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



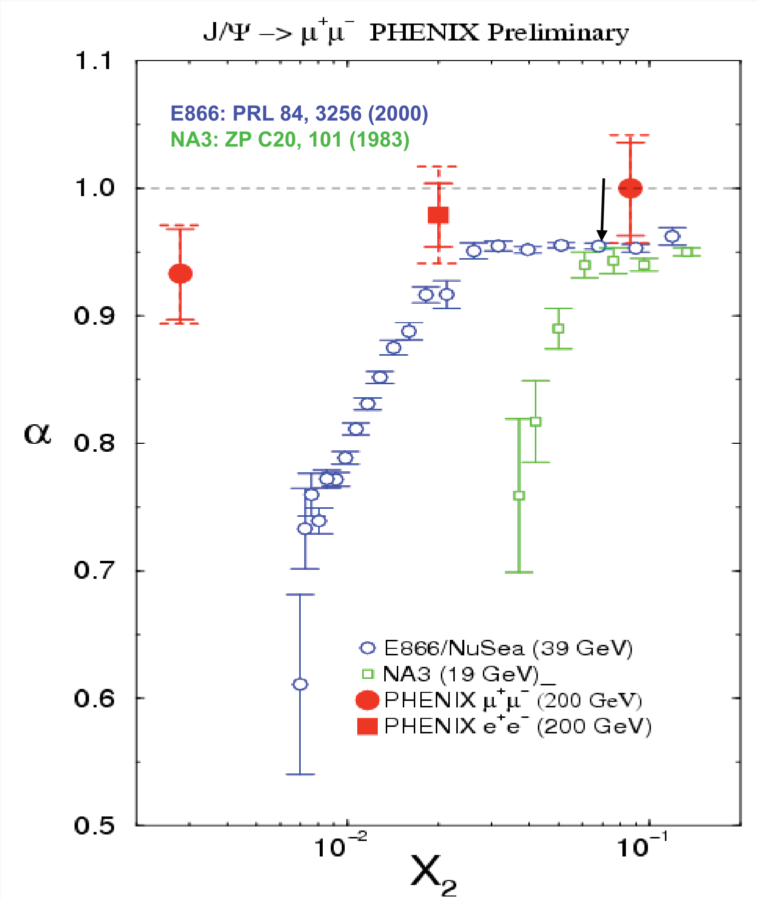
Huge "absorption" effect

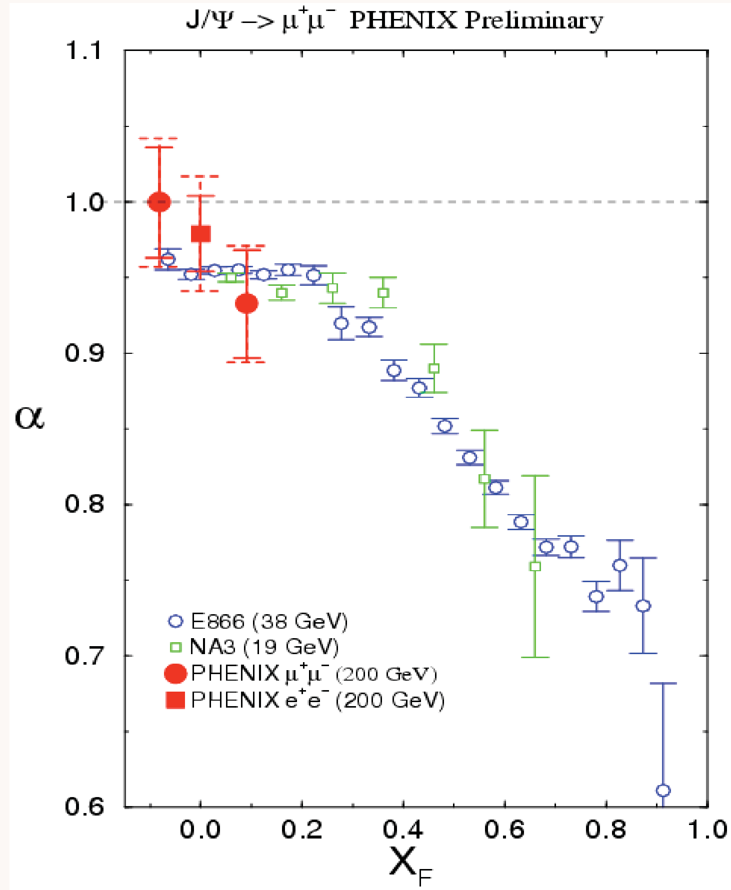
Violates PQCD factorization!

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Hoyer, Sukhatme, Vanttinen

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) \qquad \sigma_A = \sigma_p \times A^{\alpha}$$

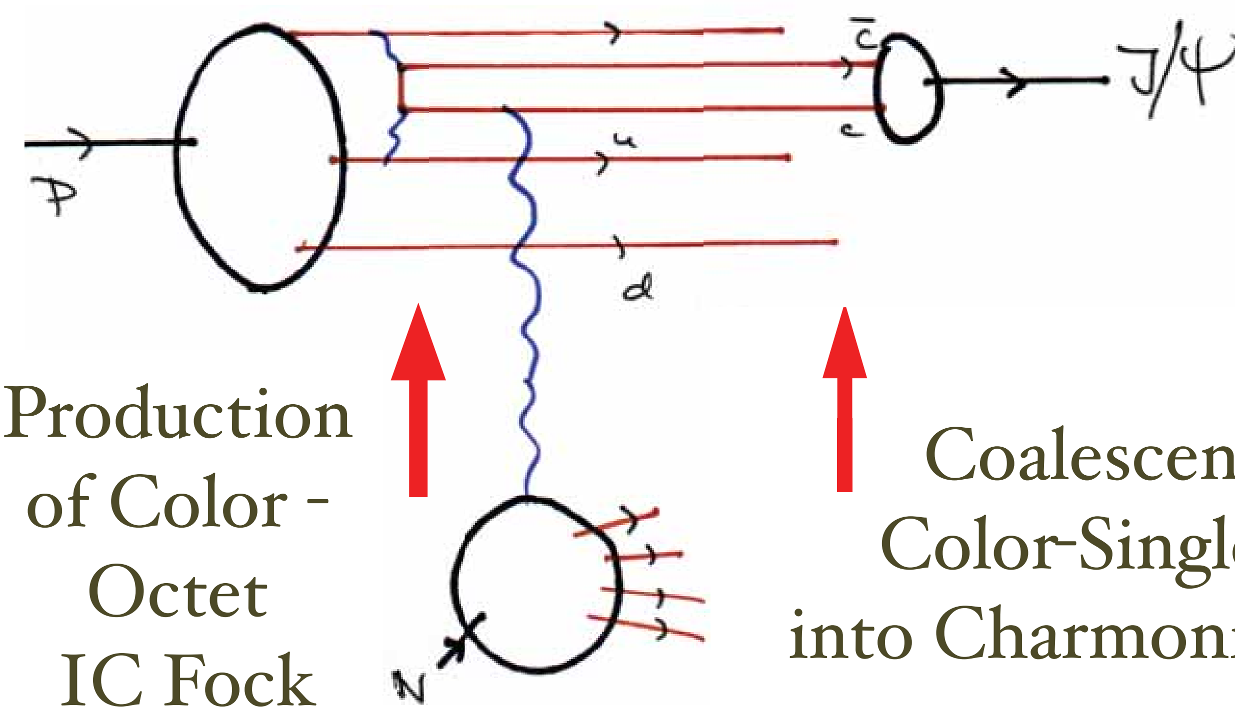




Key question for RHIC:

$$\frac{d\sigma}{dx_F}(A_1 A_2 \to J/\psi X) \qquad \sigma_{A_1 A_2} = \sigma_p \times A_1^{\alpha_1} \times A_2^{\alpha_2}$$

Vary centrality



Production of Color - Octet IC Fock State

Coalescence of Color-Singlet Pair into Charmonium State

Scattering on Nucleon via one Gluon

In nuclear case, Color-Octet IC Fock state absorbed on front surface

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

$$\frac{d\sigma_1}{dx_F}$$

x_F

$$\frac{d\sigma}{dx_F}(\pi A \to J/\psi X)$$

J. Badier et al, NA3

Two Components

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3}\frac{d\sigma_{2/3}}{dx_F}$$

A^1 component

Identify with Fusion

Conventional PQCD subprocesses

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

J. Badier et al, NA3

$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^1 \frac{d\sigma_1}{dx_F} + A^{2/3} \frac{d\sigma_{2/3}}{dx_F}$$

$A^{2/3}$ component

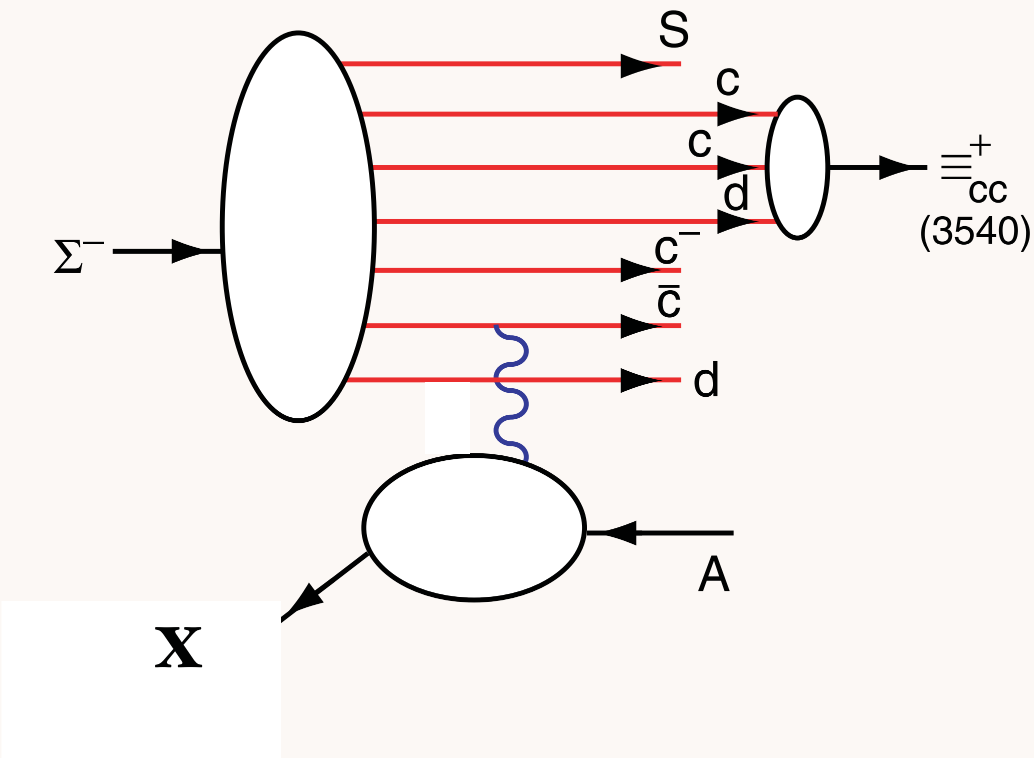
$pA \to J/\psi X$

Identify with IC

High x_F

Remarkably Flat Distribution

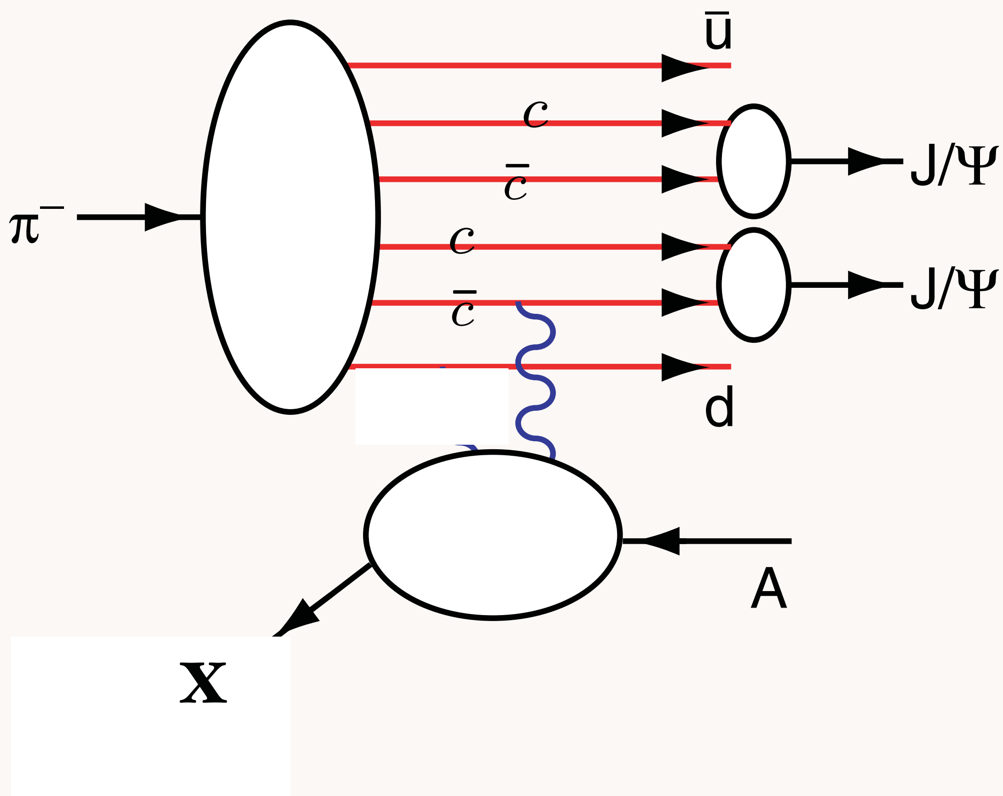
Excess beyond conventional PQCD subprocesses



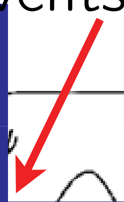
Production of a Double-Charm Baryon

SELEX high x_F $\quad < x_F > = 0.33$

Production of Two Charmonia at High x_F



All events have $x^F_{\psi\psi} > 0.4$!



Excludes `color drag' model

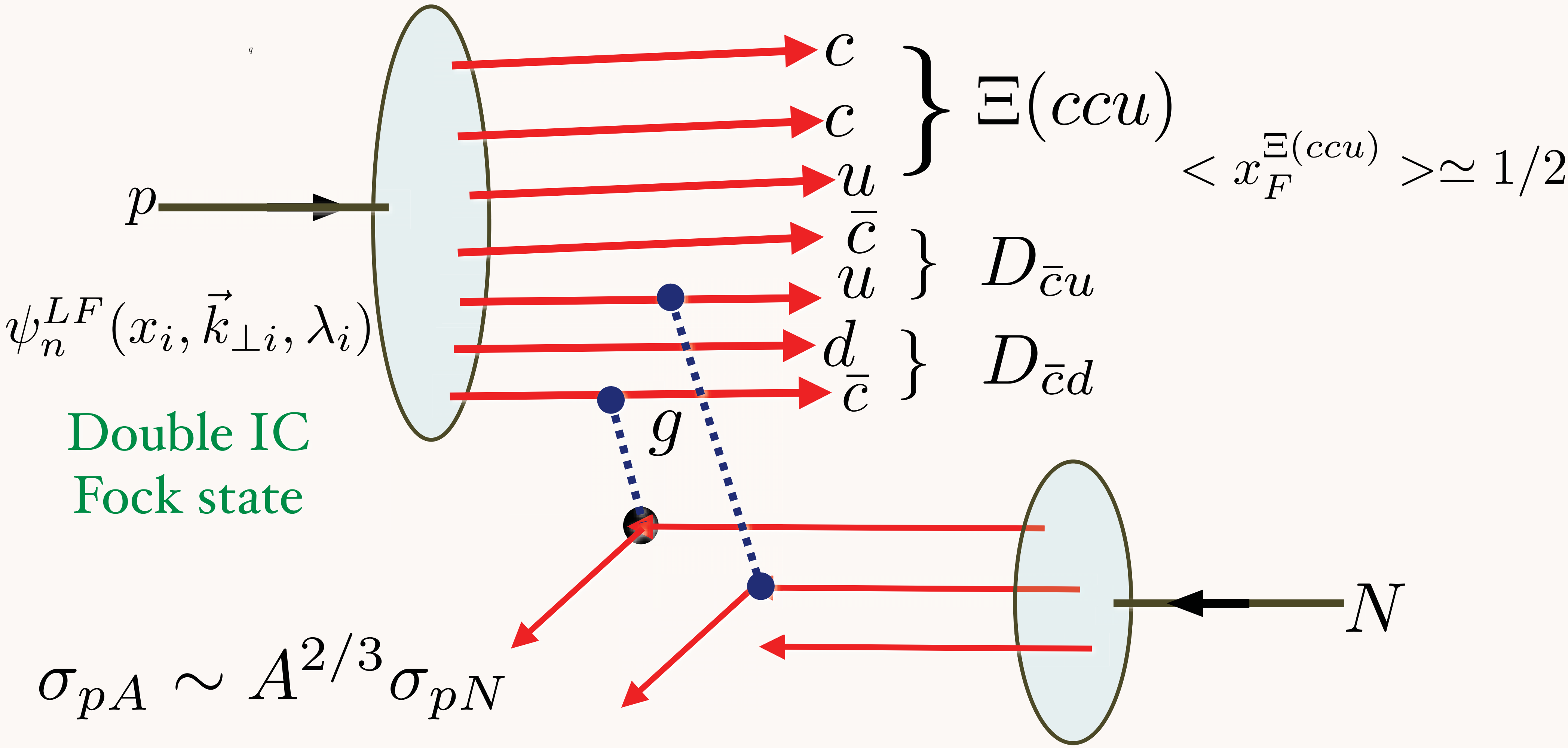
$\pi A \rightarrow J/\psi J/\psi X$

NA3 Data

Study Forward Fragmentation of Proton

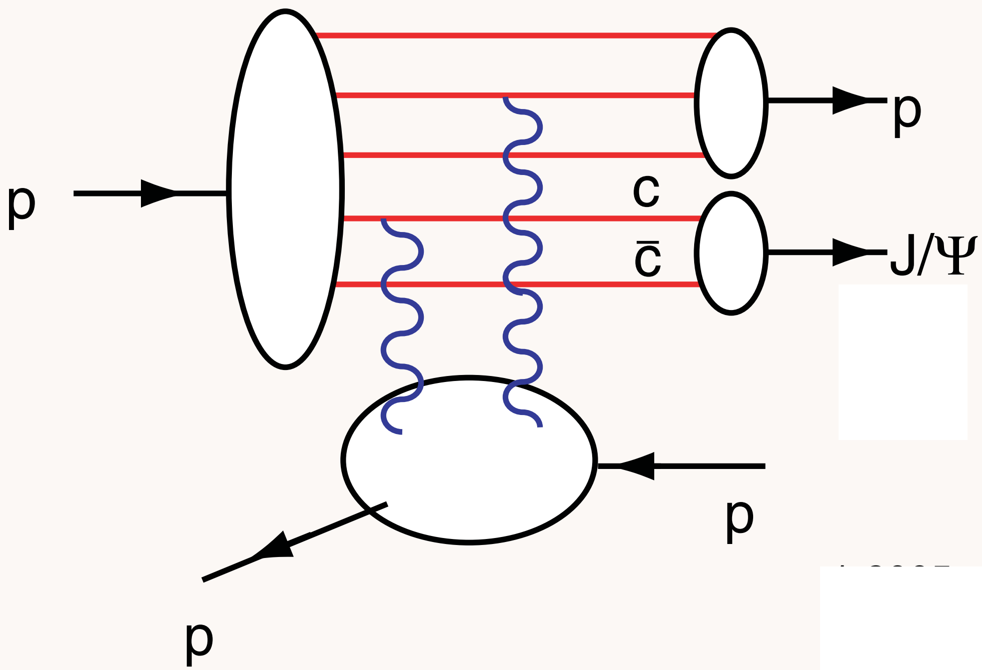
"Heavy Hadron Factory"

$$p\ A \to \Xi^{++}(ccu)\ D^0_{\bar{c}u}\ D^-_{\bar{c}d}\ X$$



Kopeliovich, Schmidt, Soffer, sjb

Intrinsic Charm Mechanism for Exclusive Diffraction Production



$$pp \to p + J/\psi + p$$

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

Produces $(C = -)$ $J/\psi, \Upsilon$

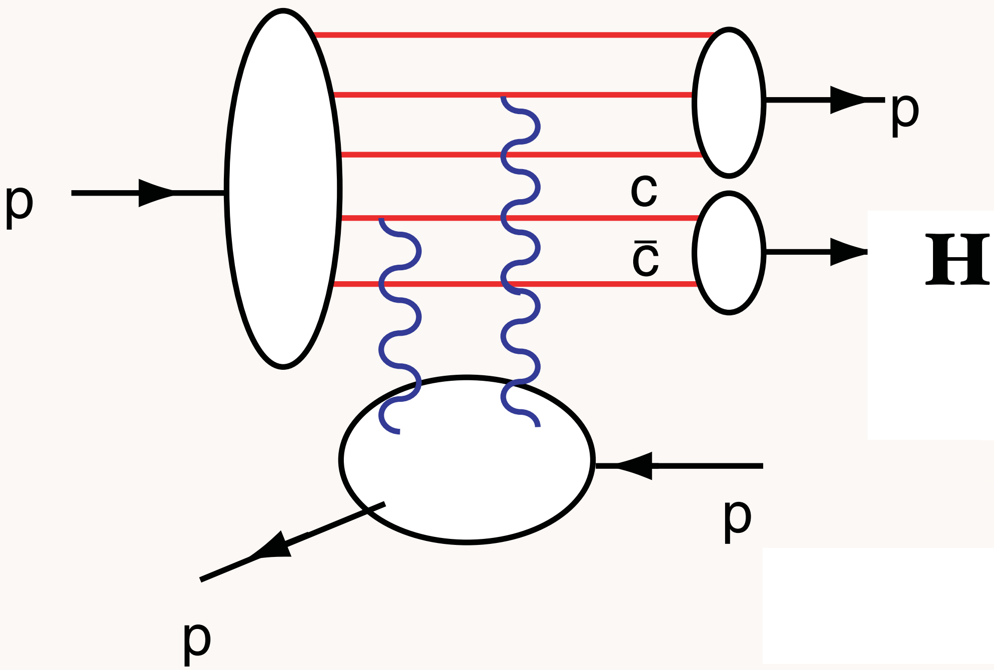
Same IC mechanism explains $A^{2/3}$ high x_F J/ψ hadroproduction

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

RHIC Experiment

Intrinsic Charm Mechanism for Inclusive and Exclusive Diffractive High-X_F Higgs Production



$$pp \to HX$$

$$pp \to p + H + p$$

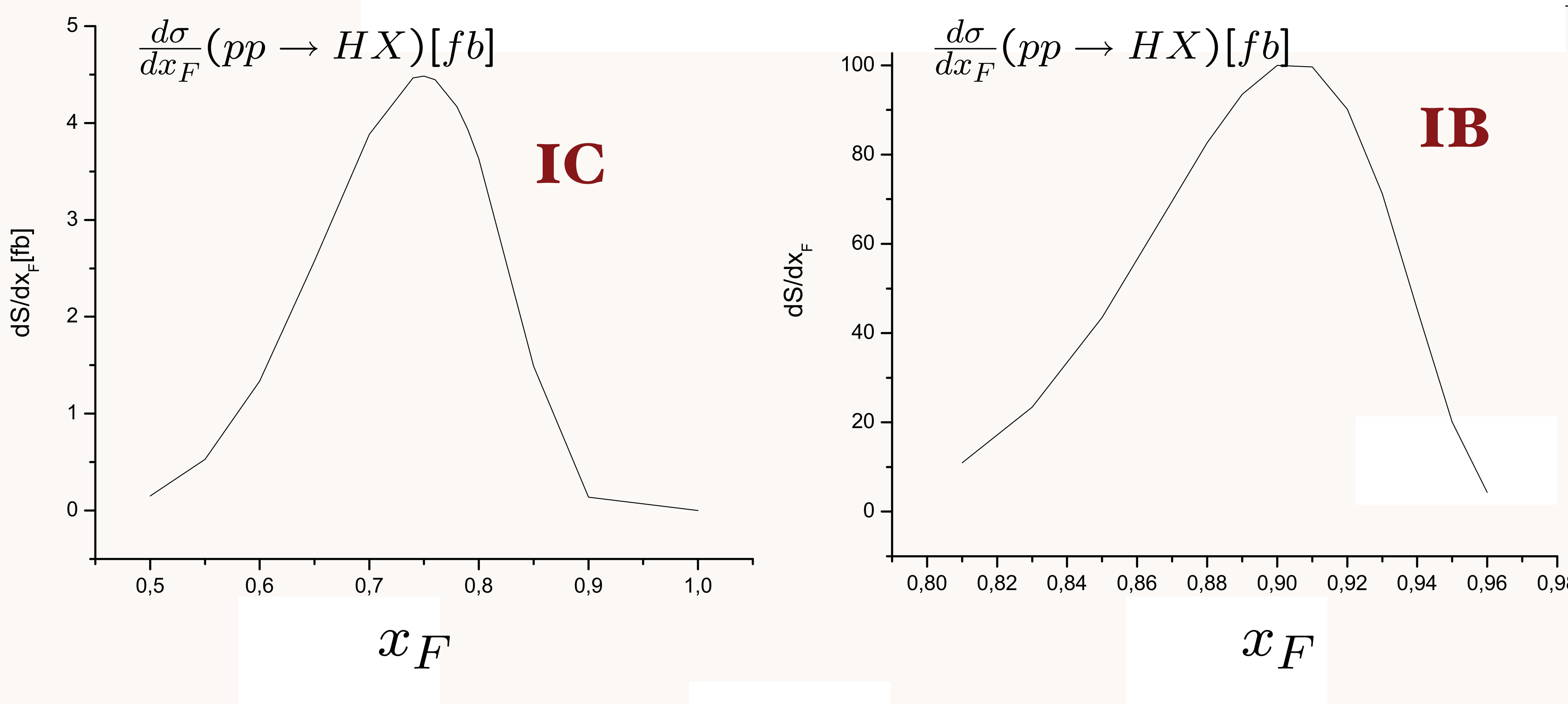
Also: intrinsic bottom, top

Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Higgs can have 80% of Proton Momentum!

Kopeliovitch, Schmidt, sjb

Intrinsic Charm and Bottom Contribution to Inclusive Higgs Production



- 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)

Color Opaqueness

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

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

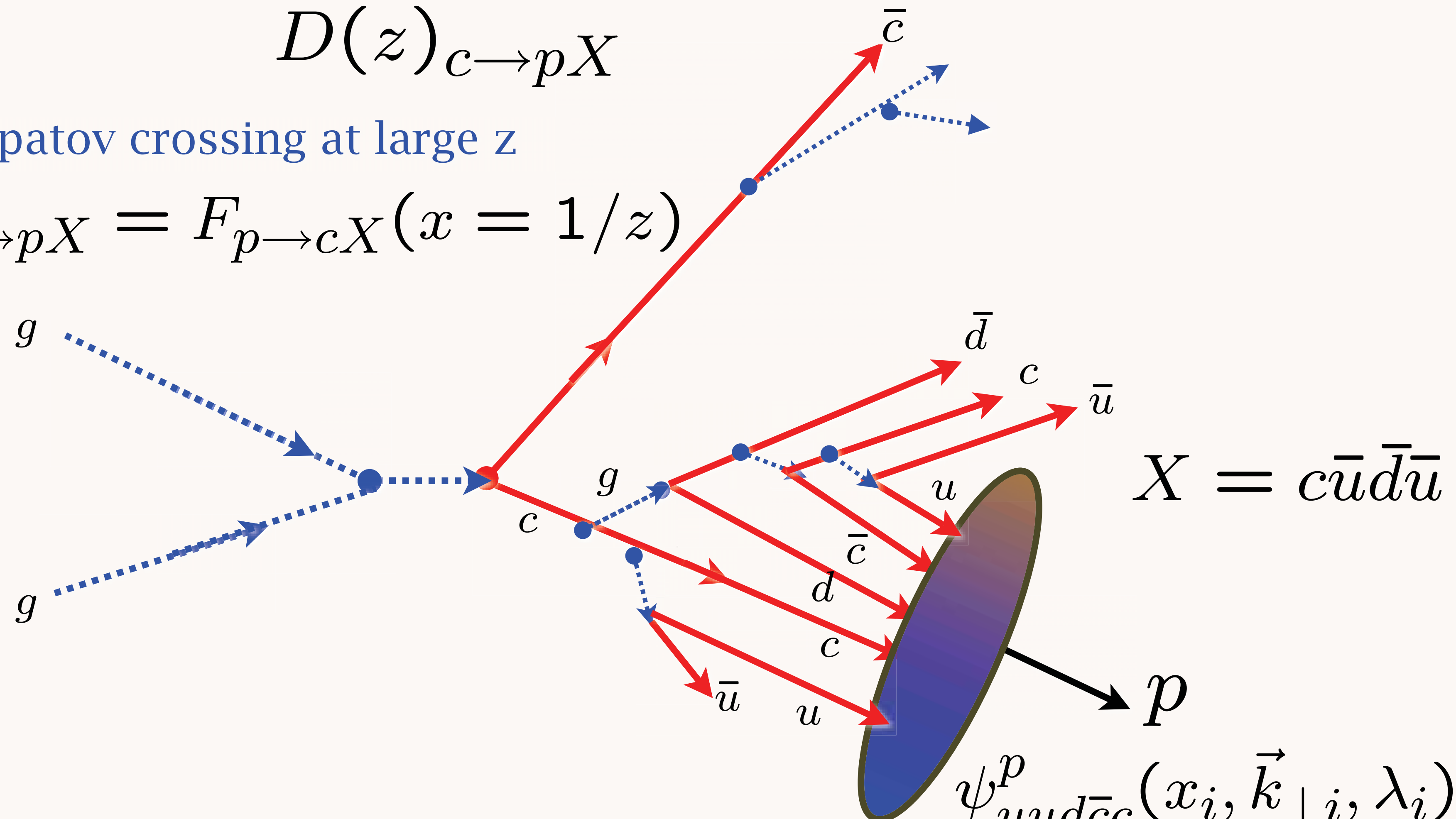
Higgs production at x_F = 0.8

Timelike Test of Charm Distribution in Proton

$$D(z)_{c \to pX}$$

Gribov-Lipatov crossing at large z

$$zD(z)_{c \to pX} = F_{p \to cX}(x = 1/z)$$



Intrinsic charm model:
predict proton at same rapidity as charm quark: high z

$$z_i \propto m_{\perp i} = \sqrt{m_i^2 + k_\perp^2}$$

$$e^+e^- \to B_c\overline{B_c}$$

$$e^+e^- \to D_s\overline{D_s}$$

$$e^+e^- \to J/\psi\eta_c$$

Novel Form-Factor Zeroes for Heavy Hadron Pairs

$$S_z = 0$$

C. Ji, sjb   Phys.Rev.Lett.55:2257,1985

J/ψ polarization at high P_T:

Problem for NRQCD and Color-Octet Models

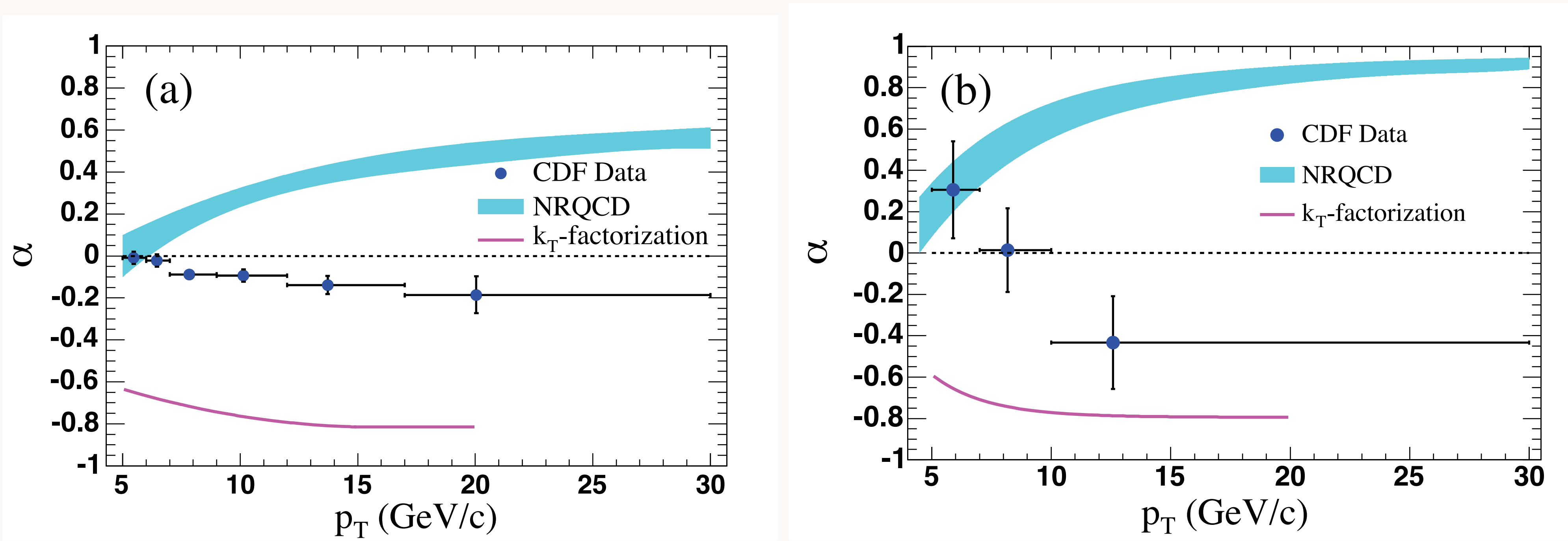
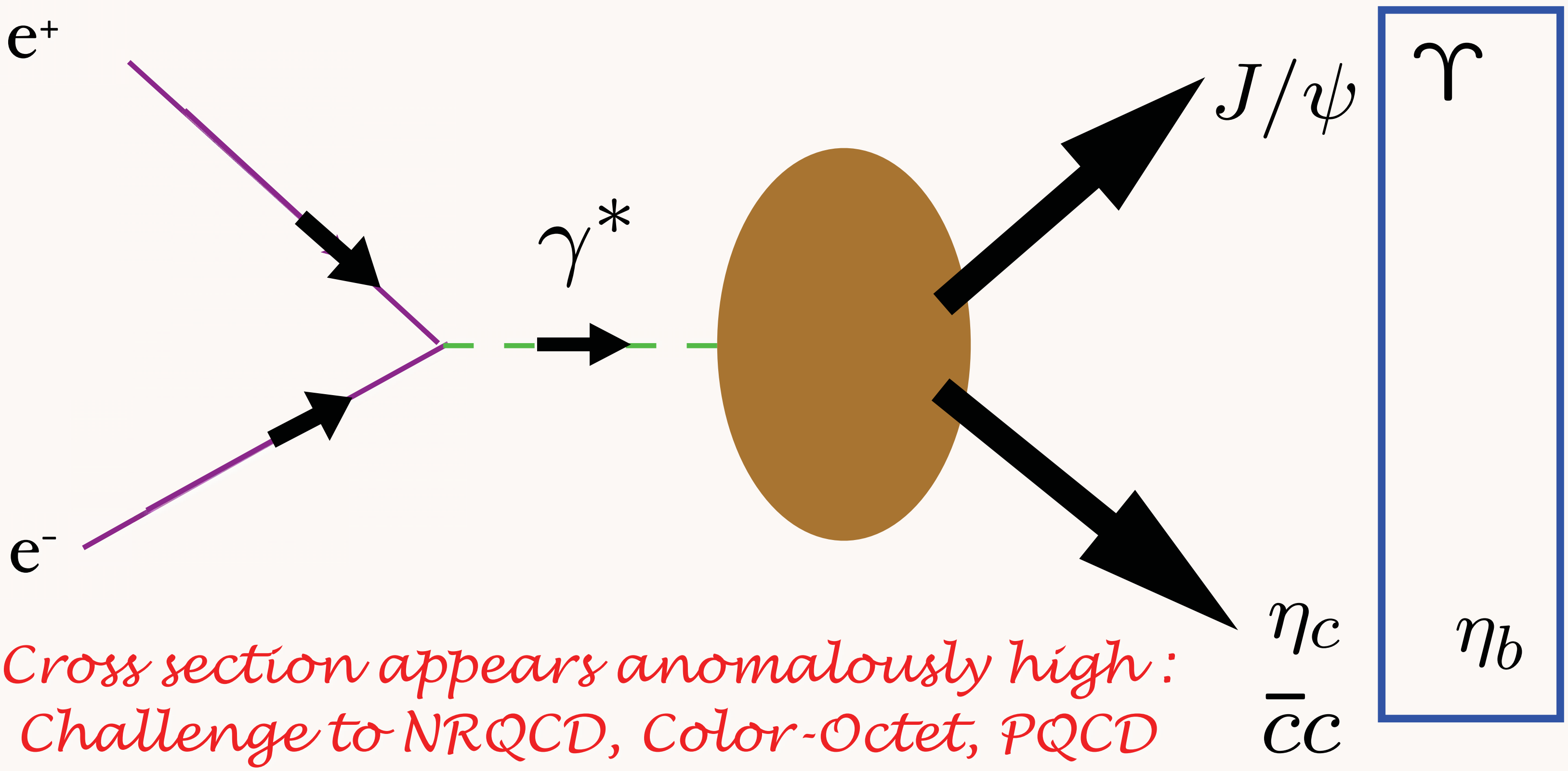


FIG. 3: Prompt polarizations as functions of p_T: (a) J/ψ and (b) $\psi(2S)$. The band (line) is the prediction from NRQCD (the k_T-factorization model [9]).

Polarizations of J/ψ and $\psi(2S)$ Mesons Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

Quarkonium Production

High energy B factory



Cross section appears anomalously high :
Challenge to NRQCD, Color-Octet, PQCD

New results by Bodwin et al,
Sterman, et al (threshold enhancement)

Heavy Quark Anomalies

$J/\psi \to \rho\pi$ puzzle

BR = 1.27 +/- 0.09 %

Largest two-body decay channel

Violates hadron helicity conservation

ψ' almost never decays to $\rho\ \pi$ $< 8.3 \times 10^{-5}$

Solution: Intrinsic charm Fock states in ρ, π

Karliner, sjb