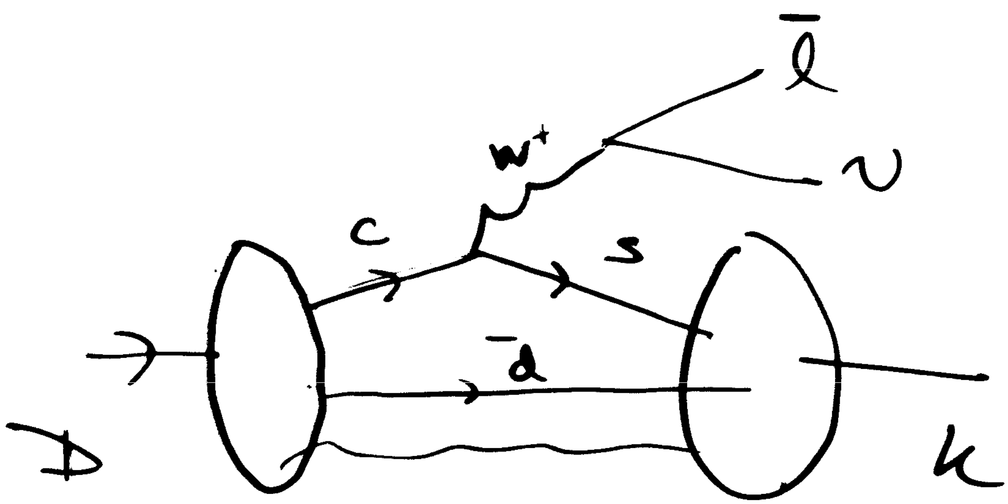
Light-Cone Wavefunctions:

B, D

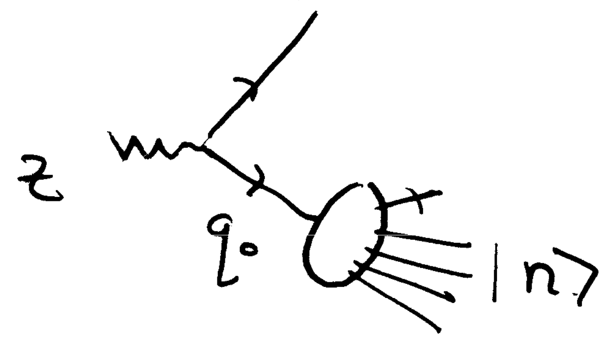
exclusive decays



S&B
Szczepaniak
Henley

Jet hadronization in LCQ

(heuristic)



$$|q_0\rangle = \sum_n |n\rangle\langle n|q_0\rangle$$

$|q_0\rangle$ ← e. state of H^0_{LC}

$|n\rangle$ ← e. state of H_{LC} ← IR, UV regulated

Interesting to study in 1+1 theories
collinear QCD

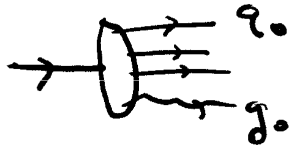
Hadronization at amplitude level!

Proposal for DLCQ

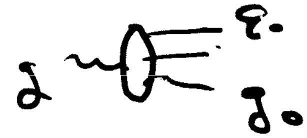
SJB
J. Hiller

Pre-diagonalization

Diagonalize H_{LC} for q, g

q 

$\{\psi_n\}$

g 

Regulate IR + UV:

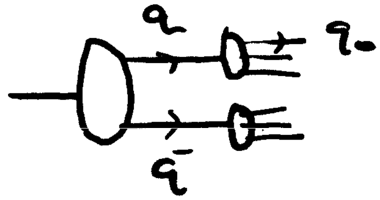
$$\lambda^2 < \Delta\mathcal{M}^2_n < \Lambda^2$$

$$\Delta\mathcal{M}^2_n = \sum_{i=1}^{n} \frac{m_i^2 + \vec{k}_{\perp i}^2}{x_i} - M_q^2$$

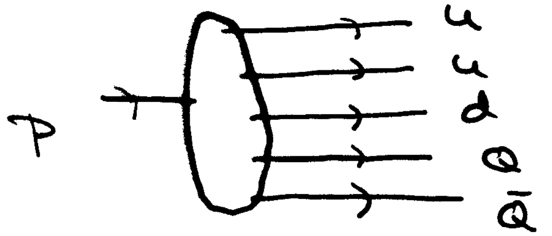
Then use $\{q, g\}$ basis to diagonalize hadrons

Control
$x \to 0$
Ladder Relations
Antonuccio, Dalley
[illegible]

q_0 are "extrinsic" quarks

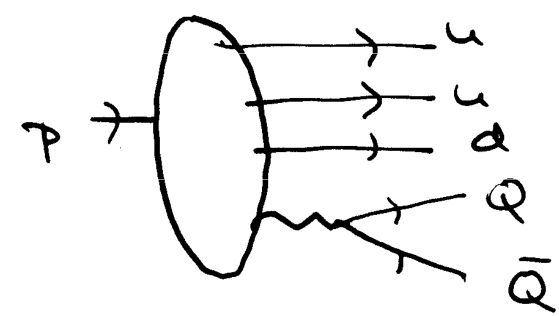


__Two__ contributions to heavy quark sea!



$Q = s, c, b, t$

=

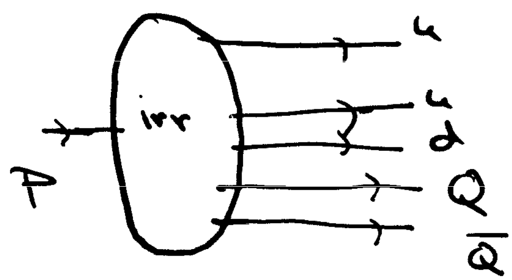


"__extrinsic__"

subconstituents of gluon

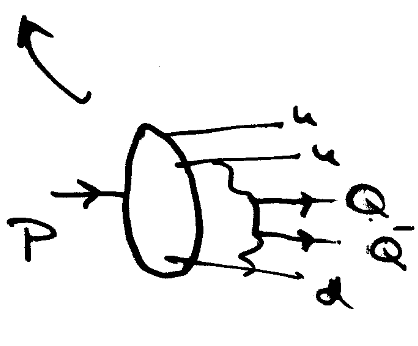
DGLAP evolution

+



"__intrinsic__"

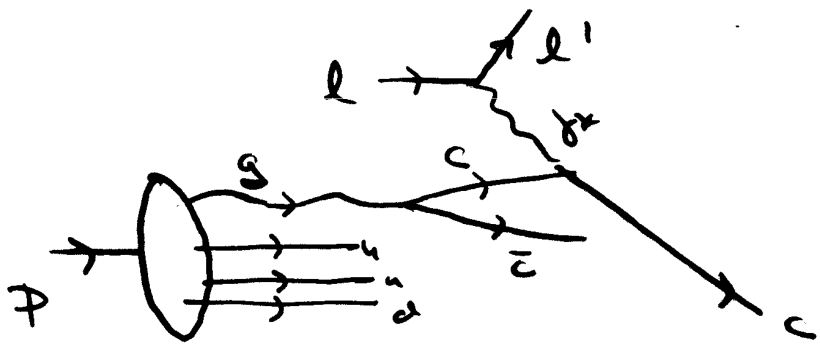
1 gluon __irreducible__



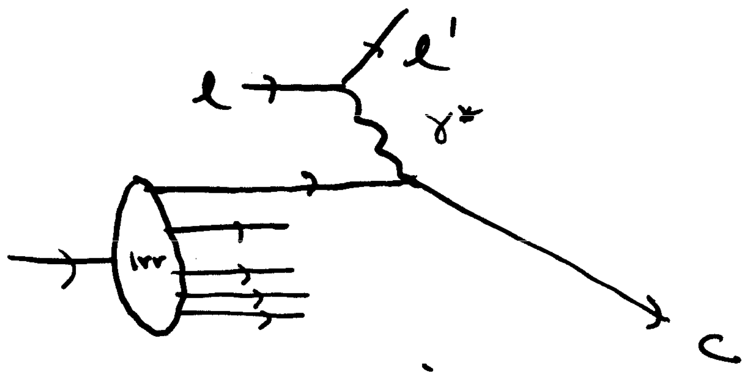
+ ...

(Physical gauge)
$A^+ = 0$

Two Contributions to Sea Quark Distributions



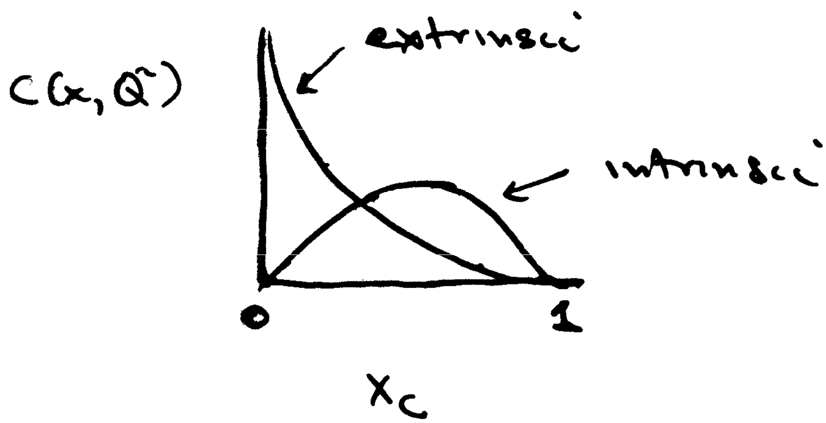
extrinsic = photon-gluon fusion $g\gamma^* \to c\bar{c}$



1 gluon irreducible

intrinsic

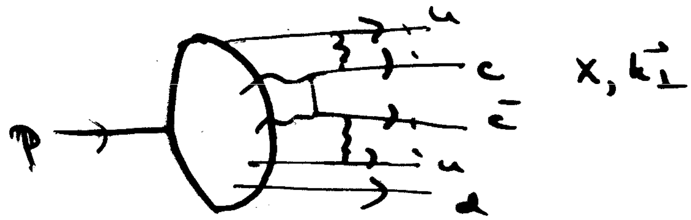
initial state for DGLAP evolution.



$Q^2 \gg 4m_c^2$

$c_I \propto \frac{1}{m_c^2 R^2}$

Intrinsic



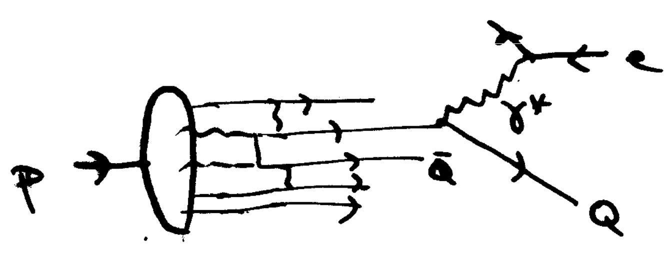
$$\sum x_i = 1$$
$$\sum \vec{k}_{\perp i} = 0$$

$$\psi_{uudc\bar{c}}(x, k_\perp) \sim \frac{\Gamma(x, k_\perp)}{M_p^2 - \sum_{i=1}^{5} \frac{m_i^2 + k_{\perp i}^2}{x_i}}$$

wavefunction maximal at equal velocity (rapidity)

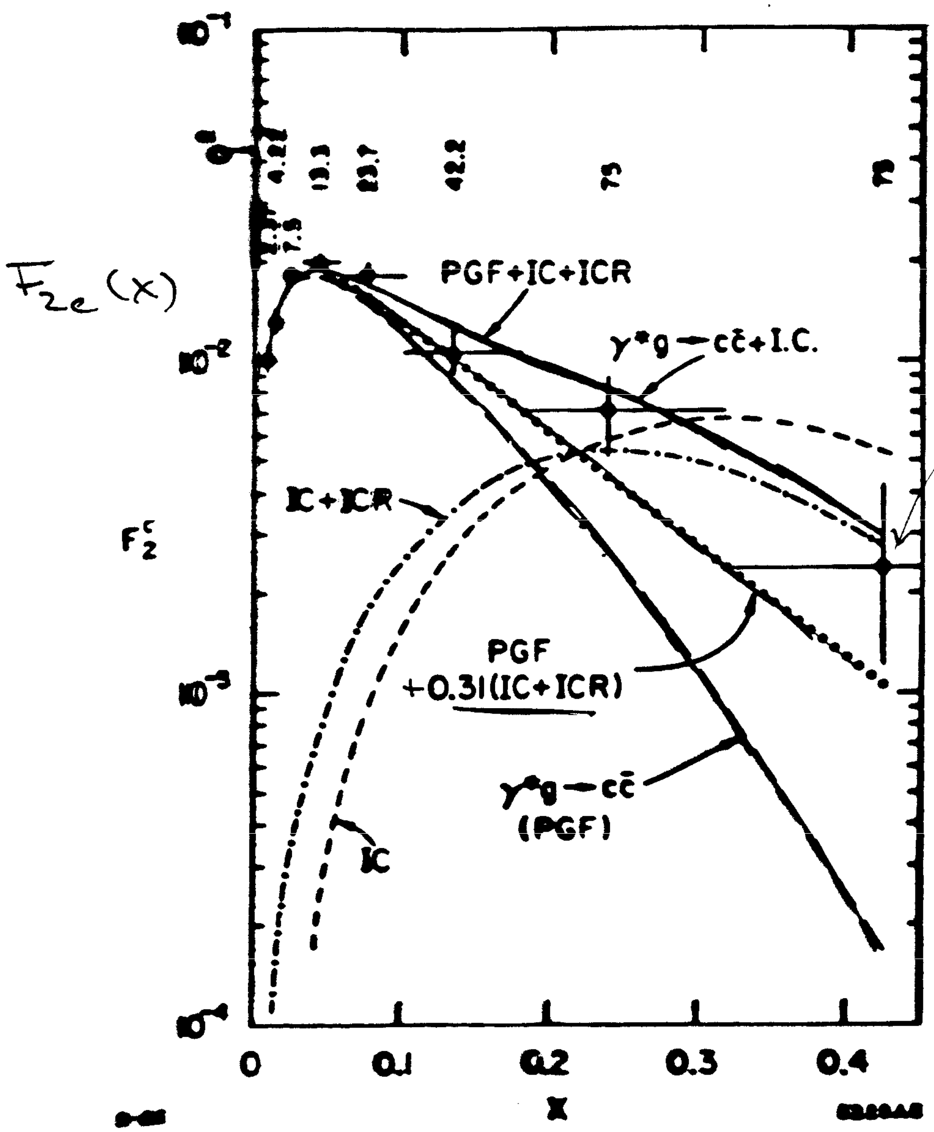
$$x_i = \frac{m_{i\perp}}{\sum_i m_{i\perp}}$$

∴ Heavy quarks tend to have largest momentum



intrinsic heavy quark structure function

enhancement factor $\frac{X}{1-e^{-X}}$, $X = \frac{\pi C_F \alpha_V}{\beta}$



$Q^2 = 75\ GeV^2$

$x_{Bj} = 0.42$

Hoffman + Moore

Smith, Vogt,

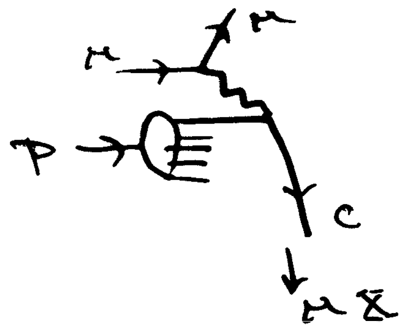
EMC data

Prob (IC)

$\cong \begin{cases} 0.3\% \\ 1.0\% \end{cases}$

Charm Puzzles

* Charm Structure Function



EMC

$c(x,Q^2) \cong 30$ PQCD !

$(\gamma^* g \to c\bar{c})$

$x = .42$

$Q^2 = 75\ GeV^2$

* $\pi N \to J/\psi\, J/\psi\, X$ NA3

x_F

$\frac{d\sigma}{dx_F}$ only observed at $x_F > 0.4$!

* $\pi N \to J/\psi\, X$ NA3

$$\frac{d\sigma}{dx_F} = A^{.98} \frac{d\sigma}{dx_F}^{PQCD} + A^{.77} \frac{d\sigma}{dx_F}^{Diff}$$

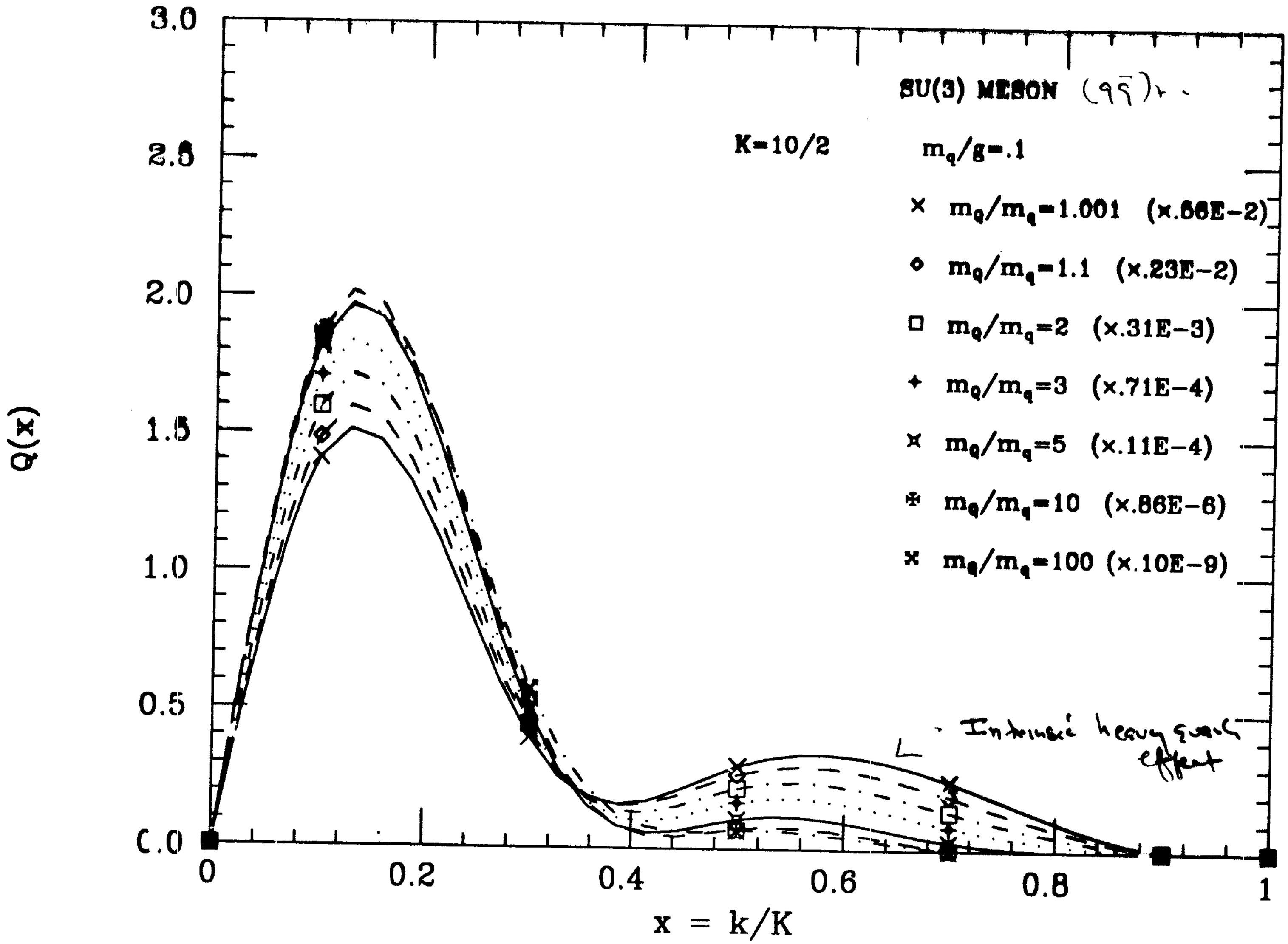
$A^{\alpha(x_F)}$ not $A^{\alpha(x_2)}$ ~ flat in x_F !

Violates PQCD factorization!

Hoyer, Sukhatme, Vanttinen

QCD(1+1)

MOMENTUM DISTRIBUTION $q \bar{q} Q \bar{Q}$



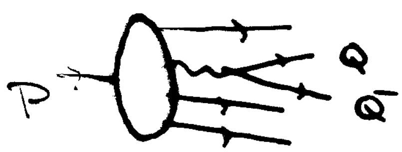
DLCQ

Hornbostel + S

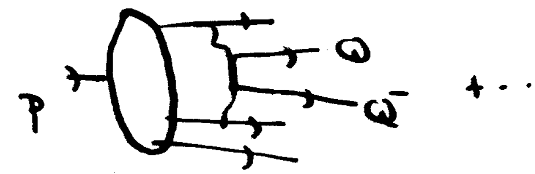
Possible new source of s, c, b quarks at large x ≈ 1

Heavy Sea in Nucleon

Distinguishing characteristics:



+



extrinsic — intrinsic

$P_{ext}(M^2_{Q\bar{Q}} > 4M_Q^2)$ — $P_{int}(M^2_{Q\bar{Q}} > 4M_Q^2)$

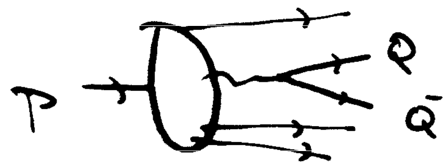
probability (high momentum probe) $\sim \frac{\alpha_s}{\pi} \log \frac{M^2_{Q\bar{Q}}}{4m_Q^2} P_g$ — $\sim \frac{\alpha_s^2}{R^2 M^2_{Q\bar{Q}}} P_{gg}$

(R ↑ interquark separation)

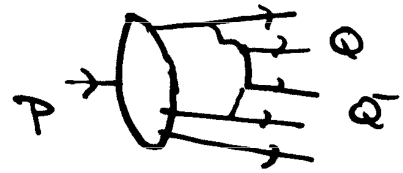
x_Q dist: $\langle x_Q \rangle < \langle x_g \rangle$, $(1-x_Q)^{5 \text{ to } 7}$ — $\langle x_Q \rangle \sim \frac{m_{Q\perp}}{\Sigma m_\perp}$, high x_Q!

Distinguishing Properties $\quad Q = s, c, b, t$

extrinsic

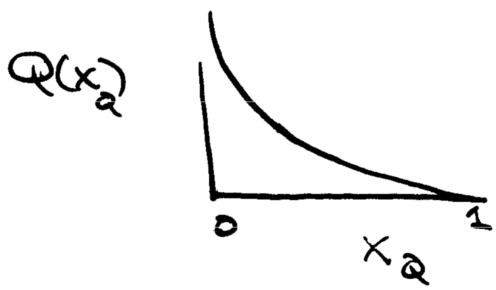


intrinsic



$Q_{ext}(x) \sim (1-x)\, g(x)$

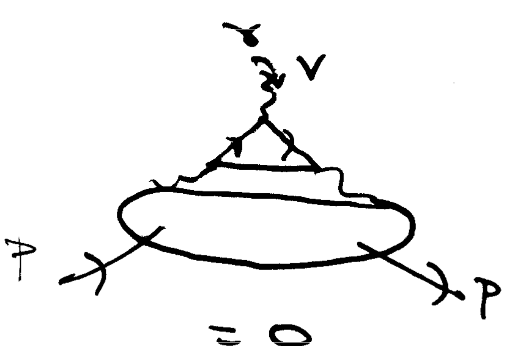
$\sim \frac{1}{x^{\alpha}} (1-x)^{5-7}$



$Q(x) \cong \bar{Q}(x)$

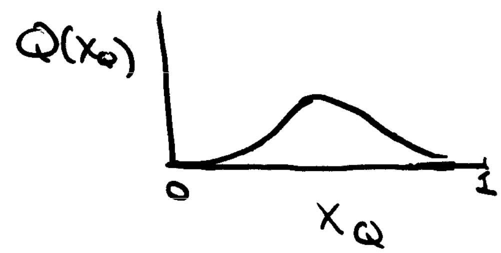
---

zero contribution to vector current



$Q_{int}(x)$:

peaks at $x_Q \sim \frac{m_{\perp Q}}{\sum m_{\perp}}$

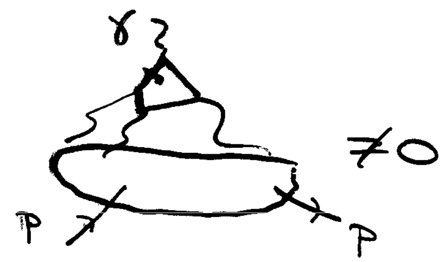


$Q(x)$ and $\bar{Q}(x)$ can be different!

---

non-zero contribution vector current

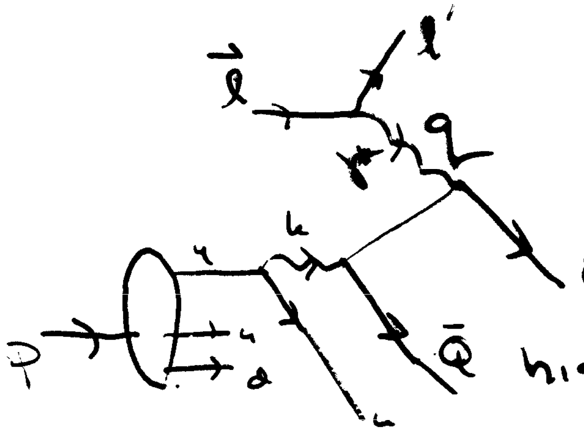
e.g. strange contribution to μ_p



S.J.B.
I. Schmidt
B.-Ma

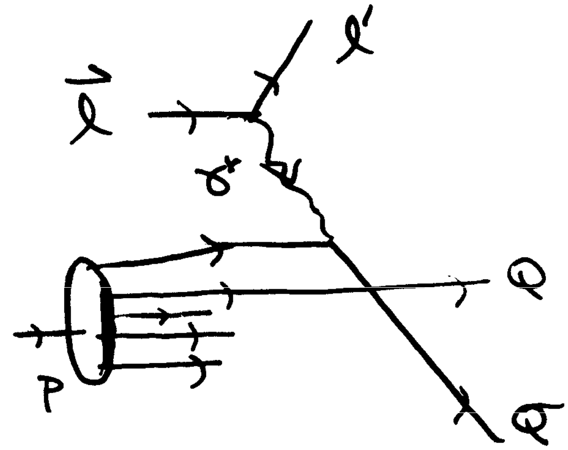
Distinguishing Characteristics

Axial Current and Polarized DIS



three high p_T jets!

SJB + I. Schmidt



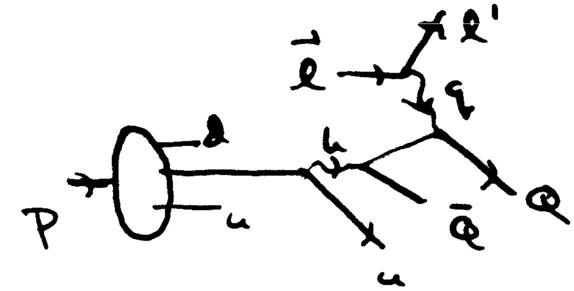
one jet between ls

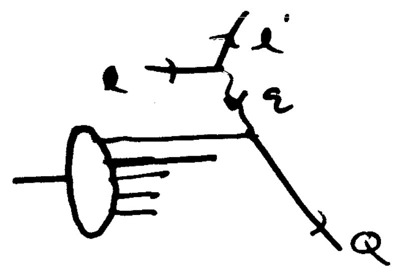
extrinsic	intrinsic
$Q^2 \gg \lvert k^2\rvert \gg 4 m_{\bar{Q}}^2$	$Q^2 \gg 4 m_{\bar{Q}}^2$
$\Delta Q = \Delta \bar{Q}$	$\Delta Q \neq \Delta \bar{Q}$!
$\Delta Q_{TOT} = -\frac{\alpha_s}{2\pi} \Delta g$	ΔS negative from $p \to K \Lambda$
"anomaly contribution"	$\Delta \bar{S} = 0$
($A^+ = 0$ gauge)	$\Delta Q_{TOT} \propto \frac{1}{R^2 m_Q^2}$
ΔQ_{TOT} independent of m_Q^2! $Q^2 \gg \lvert k^2\rvert \gg 4 m_Q^2$	

∴ Two contributions to E-J Sum Rule

high Q^2

Extrinsic | **Intrinsic**





$Q^2 = -q^2$

$$\Delta s^{ext}_{TOT} = -\frac{\alpha}{2\pi}\,\Delta q \qquad \Delta Q_{int} \neq \Delta \bar{Q}_{int}$$

$\Delta\bar{Q}_{ext} = \Delta Q_{ext}$

$$\Delta c^{ext}_{TOT} = -\frac{\alpha}{2\pi}\,\Delta q \qquad \Delta Q_{int} \sim \frac{1}{M_Q^2 R^2}$$

$$\Delta b^{ext}_{TOT} = -\frac{\alpha}{2\pi}\,\Delta q \qquad \frac{\Delta s_{int}}{\Delta c_{int}} \sim \frac{m_c^2}{m_s^2}$$

if $\underline{Q^2 \gg k^2 \gg 4m_Q^2}$ $\qquad$ $\underline{Q^2 \gg 4m_Q^2}$

Phenomenology: Perhaps roughly equal!

Look at x_Q-dist (x_c range)

jet recoiling against l

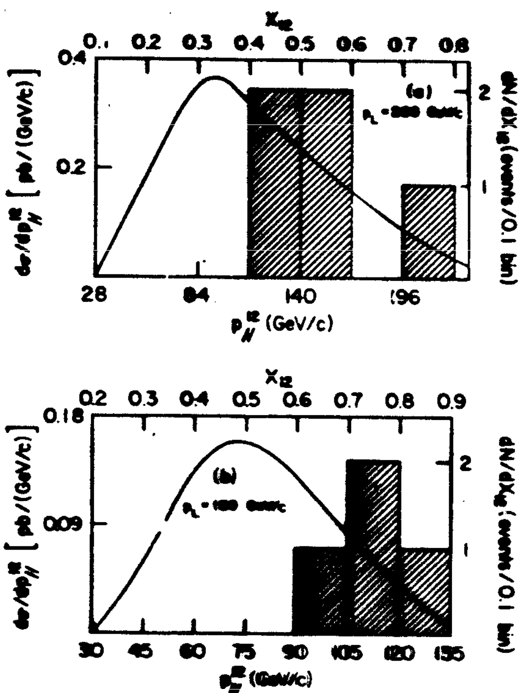
Note: resolution dependence!

Production of Two J/ψ

$\pi p \to J/\psi \; J/\psi \; X$

all events

Total $x_F \gtrsim 0.4$!



$P_{Lab} =$ 280 GeV/c

$P_{Lab} =$ 150 GeV/c

FIG. 5. The calculated longitudinal differential cross section $d\sigma/dp_{\parallel}^{12}$ for the J/ψ pair in $\pi p \to JJX$ at (a) $p_L = 280$ GeV/c and (b) $p_L = 150$ GeV/c, with experimental data. The scales for the experimental events are to the right of the figure.

NA3 data

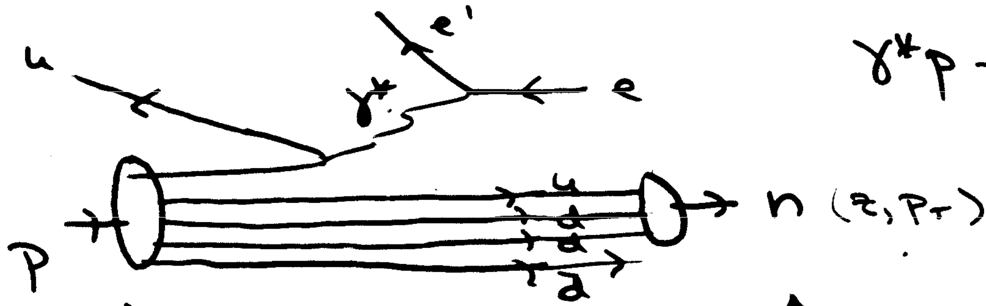
(Li + Liu)

$$\frac{d\sigma}{dx_{12}} (\pi p \to \psi_1 \psi_2 X)$$

Light-Cone Wavefunctions and "Fracture Functions"

Veneziano
Trentadue

$\gamma^* p \to n X$



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

$$\otimes$$

$$\psi^{(n)}_{n'}(x_i, k_{\perp i}, \lambda_i)$$

parton distrib at amplitude level

Coalescence at amplitude level

$$\mathcal{M}^\mu \sim \langle p | J^\mu(0) | n \, u \, \bar{d} \rangle$$

extension of F.F.

SJB + M. Karliner

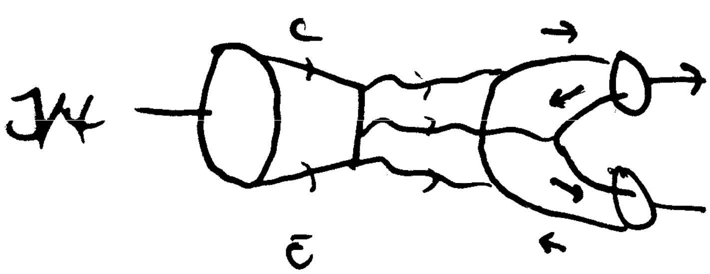
$J/\psi \to \rho\pi$ Puzzle

* $B[J/\psi \to \rho\pi] = 1.28 \pm 0.10\,\%$

largest two-body hadronic decay!

* PQCD: $J/\psi \to PV$ <u>suppressed</u> by helicity conservation

SJB, Tuan, Lepage



$\rho(\lambda=+)$
$\pi(\lambda=0)$
no go!

↑
$c\bar{c}$ annihilate at $b_\perp \sim O\left(\frac{1}{m_c}\right)$

ref PDG 6-92

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

$BR(J/\psi \to K^+K^-) = 2.37 \pm 0.31 \times 10^{-4}$

not suppressed! → $\rho\pi = 1.28 \pm 0.10 \times 10^{-2}$

→ $K^+K^{-*} = 5.0 \pm 0.4 \times 10^{-3}$

$BR(\psi' \to K^+K^-) = 1.0 \pm 0.7 \times 10^{-4}$

$\rho\pi < 8.3 \times 10^{-5}$ (90% c

$K^+K^{-*} < 1.8 \times 10^{-5}$ (90% c

Expect suppression of vector + pseudoscalar

ψ' okay

J/ψ disaster!

* Strong violation of hadron helicity conservation

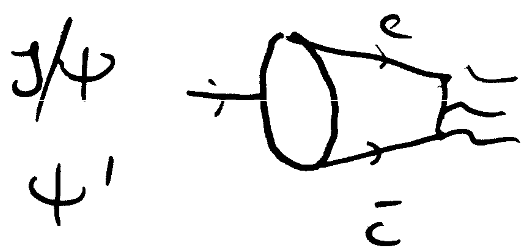
* Extremely fast quenching of $\rho\pi$, KK^* signal

see: Chiueh + Tornqvist.

PQCD : $c\bar{c}$ annihilation

Expect $\Gamma_{ns} \propto |\psi_{ns}(\vec{0})|^2$

$$\frac{\Gamma_{2S}}{\Gamma_{1S}} \sim \frac{\Gamma_{\psi' \to \ell\bar{\ell}}}{\Gamma_{\psi \to \ell\bar{\ell}}}$$



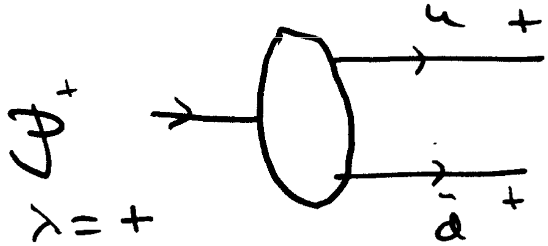
However $\psi' \to \rho\pi$

never observed!

$$B_{\psi' \to \rho\pi} < \frac{1}{50} \text{ PQCD expect.}$$

↑

$< 3.6 \times 10^{-5}$



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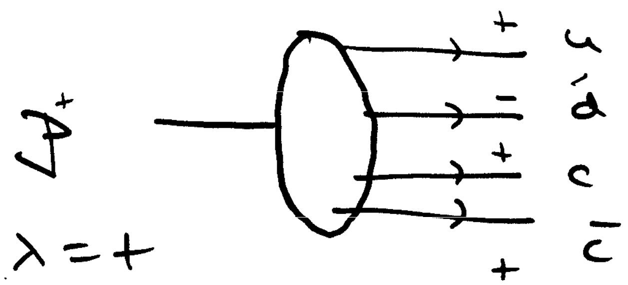
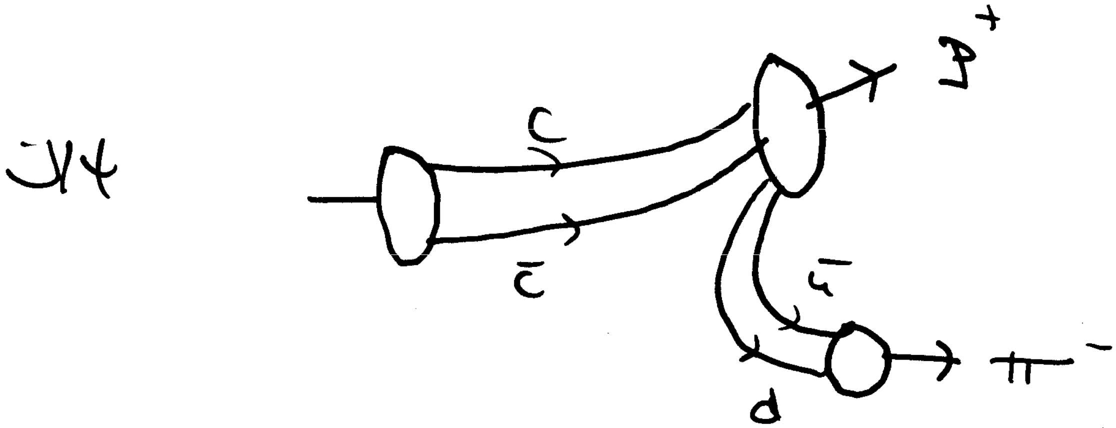


minimize

M^2

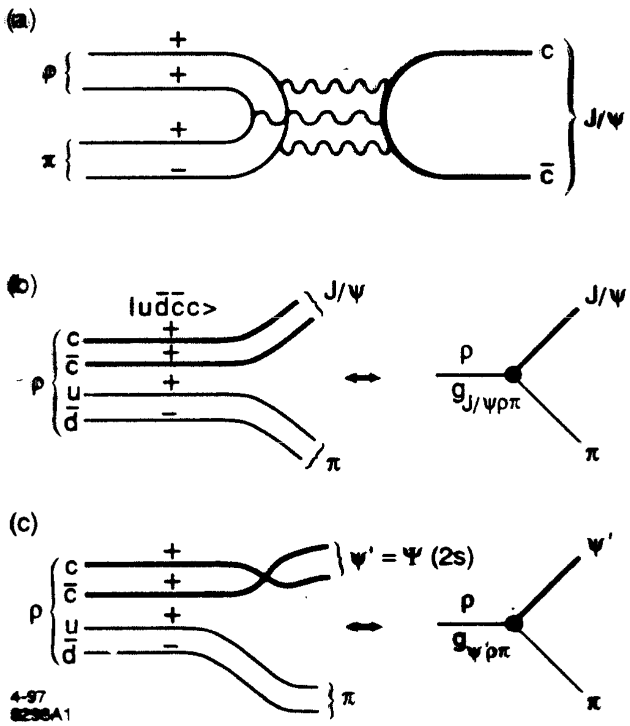
$p \sim J/\psi\ \pi$



Overlap integral

ψ' suppressed!

p: no radial node



usual PQCD annihilation

cc̄ rearrangement ∃ J/ψ π

radial node

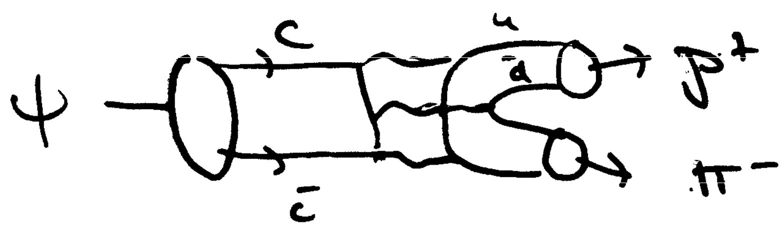
suppressed ∃ ψ' π coupling

$\rho\pi$ Puzzle

[1S] $J/\psi \to \rho\pi$ 1.28 ± 0.10 %

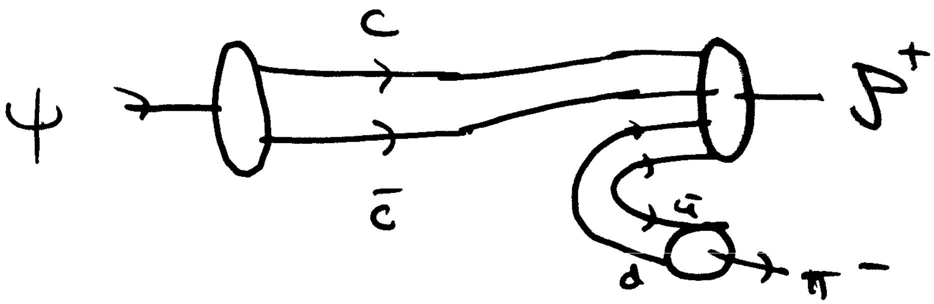
[2S] $\psi' \to \rho\pi$ $B < \frac{1}{50}$ expectations!

$< 3.6 \times 10^{-5}$



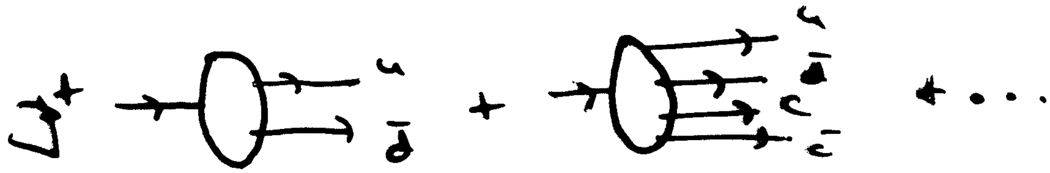
$\Gamma \sim |\psi_{nS}(0)|^2$

SJB
M. Karliner



$\psi' \not\to \rho\pi$ suppressed (radial node)

rearrange $c\bar{c}$ into 4-quark Fock state of ρ



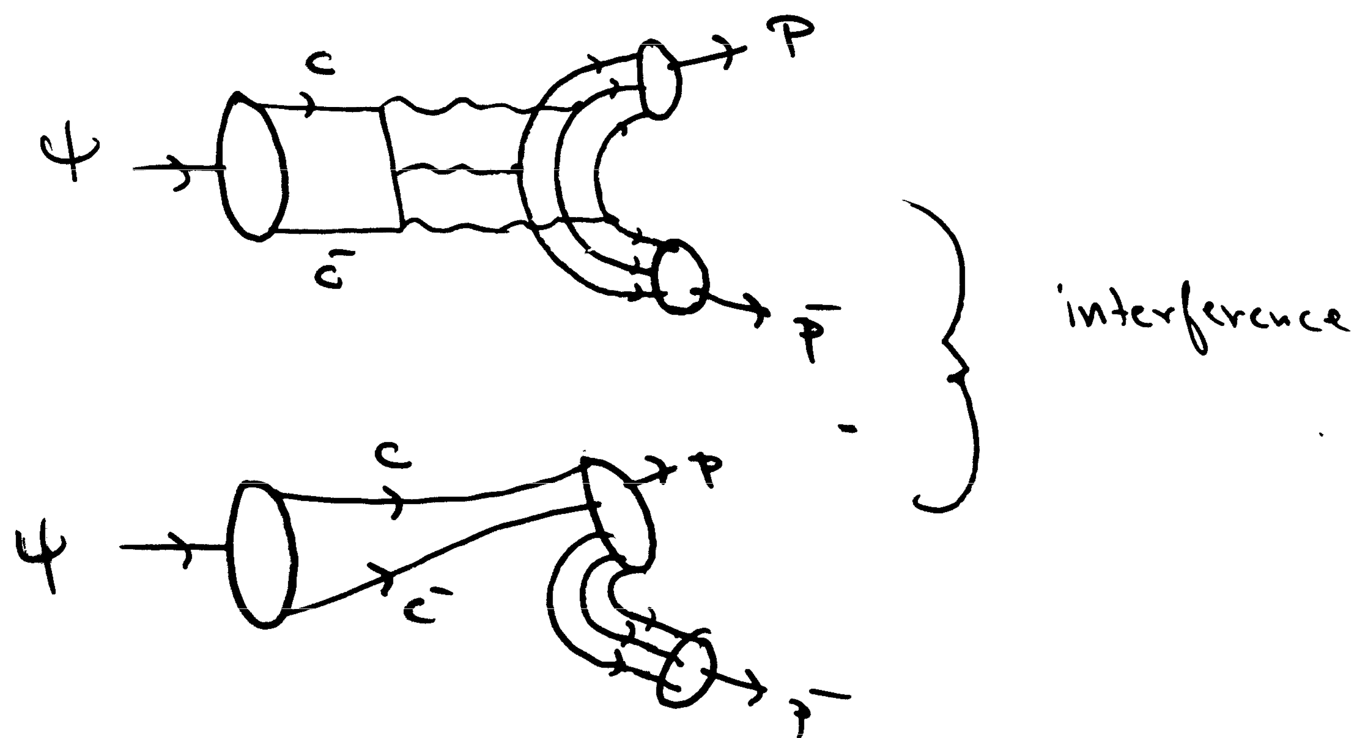
↑ no radial node

Intrinsic charm in light-hadrons

$P_{Q\bar{Q}} \sim \frac{1}{m_{Q\bar{Q}}^2} \alpha_s^2(m_{Q\bar{Q}}^2)$ scaling $s\bar{s} : c\bar{c} : b\bar{b}$

$\Rightarrow \phi \to \rho\pi$ vs $\psi \to \rho\pi$

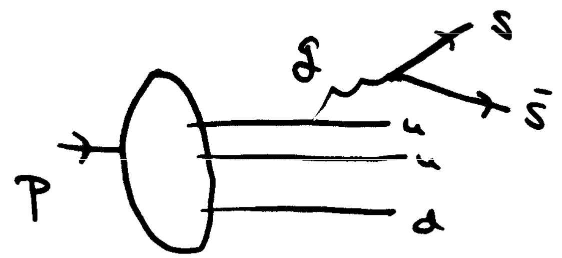
Rearrangement plus Annihilation



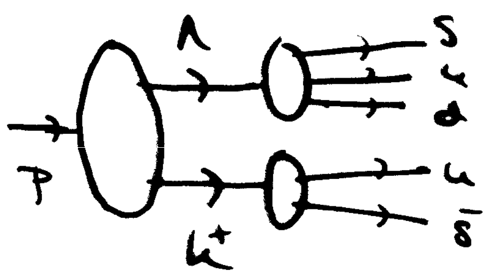
complicates B, Υ decays.

Anti-symmetry of the strange sea

$$s(x) \stackrel{?}{=} \bar{s}(x)$$



yes!



no!

Thomas et al
SJB + Ma
Nielsen
Navarra
et al

In KΛ model

s helicity opposite to p helicity

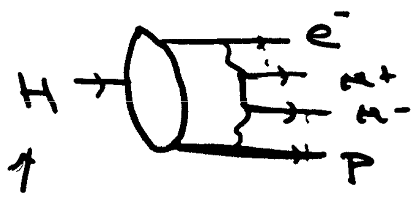
SJB, DQ Ma

$$\boxed{s(x) \neq \bar{s}(x)}$$ probes new physics

a) * non-perturbative QCD effect

* K–Λ fluctuations

* QED analog:



hydrogen

Coulomb distortions

Opposite charges have low V_{rel}

$\Rightarrow$ asymmetric μ^+, μ^-

$\langle x_{\mu^-} \rangle > \langle x_{\mu^+} \rangle$

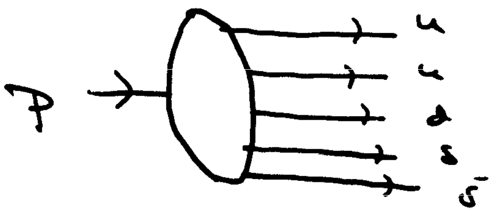
b) * non-perturbative hadronization q jets

$D_{p/s} \neq D_{\bar{p}/s}$

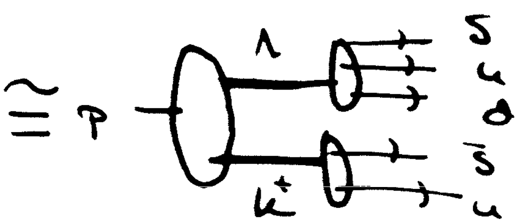
c) * coalescence effects

d) * $\Delta s \neq \Delta \bar{s}$

e) * discriminate intrinsic vs extrinsic contributions



"intrinsic strangeness"



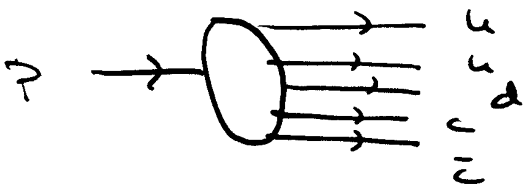
asymmetric distributions

$\langle x_s \rangle > \langle x_{\bar{s}} \rangle$

helicity of s antialigned!

minimum $\mathcal{M}^2$ dominant

$\Delta s < 0$, $\Delta \bar{s} = 0$



"intrinsic charm"

$\langle x_c \rangle$, $\langle x_{\bar{c}} \rangle$ large

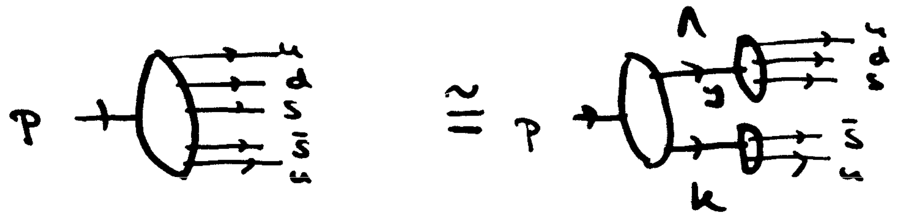
minimum $\mathcal{M}^2$ dominant $\Rightarrow$

$$P_{Q\bar{Q}} \sim \frac{1}{\mathcal{M}^2_{Q\bar{Q}}}$$

$\Rightarrow$ {
- $c(x,Q)$, $b(x,Q)$ at large x
- J/ψ, $\psi\psi$, Λ_c, Λ_b at large x_F
- $J/\psi \to \rho\pi$ puzzle
- HERA anomaly.

Model for Intrinsic Strangeness

SJB + Bo-Qiang Ma
SLAC-PUB-7126
PL



$\times \qquad \ell = 1$

$$s(x) = \int_x^1 \frac{dy}{y} \, f_{\Lambda/K^+\Lambda}(y) \; q_{s/\Lambda}\left(\frac{x}{y}\right)$$

$$\Psi(x_i, k_{\perp i}) = \begin{cases} A \; e^{-\mathcal{M}^2/2\alpha^2} \\ A \; (1 + \mathcal{M}^2/\alpha^2)^{-p} \end{cases}$$

$p = 3.5$

$$\mathcal{M}^2 = \sum \frac{k_\perp^2 + m^2}{x}$$

estimate: $P_{K\Lambda} \sim 4$ to 15% : $\langle x_s \rangle > \langle x_{\bar{s}} \rangle$

$K\Sigma$, $K^*\Lambda$ negligible

$\Delta S_s = -\frac{1}{3} P_{K\Lambda} \qquad \Delta S_{\bar{s}} = 0$

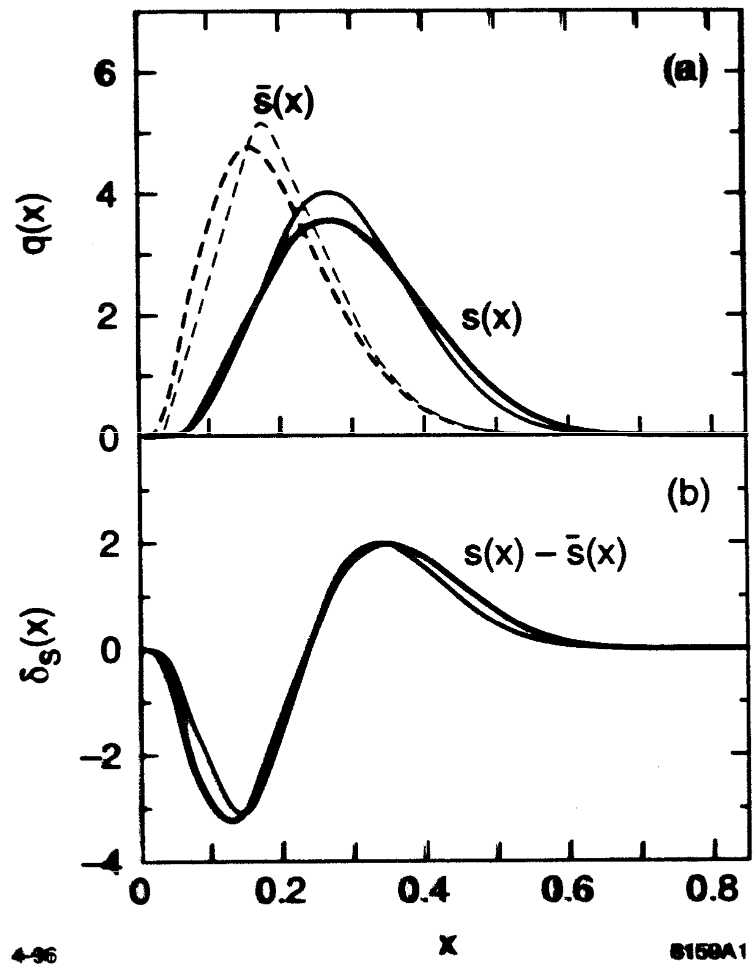
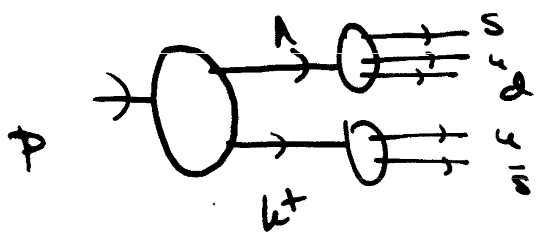


Figure 1: The momentum distributions for the strange quarks and antiquarks in the light-cone meson-baryon fluctuation model of intrinsic $q\bar{q}$ pairs, with the fluctuation wavefunction of $K^+\Lambda$ normalized to 1. The curves in (a) are the calculated results of $s(x)$ (solid curves) and $\bar{s}(x)$ (broken curves) with the Gaussian type (thick curves) and power-law type (thin curves) wavefunctions and the curves in (b) are the corresponding $\delta_s(x) = s(x) - \bar{s}(x)$. The parameters are $m_q = 330$ MeV for the light-flavor quark mass, $m_s = 480$ MeV for the strange quark mass, $m_D = 600$ MeV for the spectator mass, the universal momentum scale $\alpha = 330$ MeV, and the power constant $p = 3.5$, with realistic meson and baryon masses.

If $\quad G_{s/p}(x) \neq G_{\bar{s}/p}(x)$

Then $\quad D_{p/s}(z) \neq D_{\bar{p}/s}(z)$

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

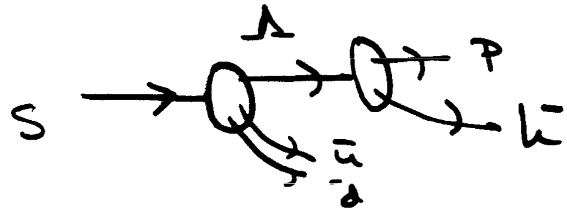


$$G_{s/p}(x) > G_{\bar{s}/p}(x)$$

at large x

↖ lowest mass intermediate state

∴

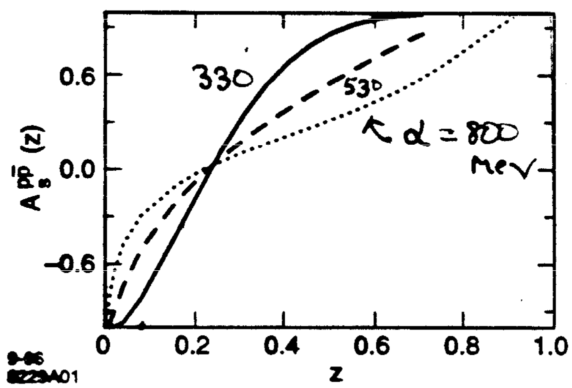


$$D_{p/s}(z) > D_{\bar{p}/s}(z)$$

at large z

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

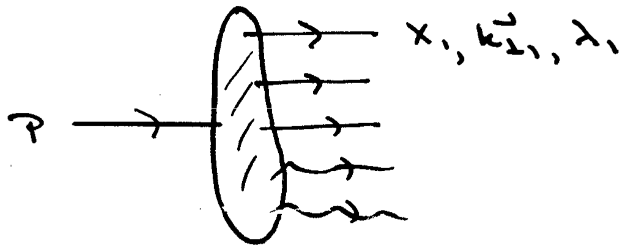
$$\underset{\text{c.c.}}{=} \frac{G_{s/p}(x) - G_{\bar{s}/p}(x)}{G_{s/p}(x) + G_{\bar{s}/p}(x)}$$



Model for $A_s^{p\bar{p}}(z)$ $\Psi = C e^{-\mathcal{M}^2/2\alpha^2}$

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

Role of LC Wavefunctions in QCD



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

* Precise realization of Quark Parton Model

* Representations of { Leading Twist + Non-Leading Twist } Structure Functions

* Representations of Exclusive Amplitudes including Form Factors, Weak Trans. Amplit.
  from low to high Q^2

* Definition of Higher-Twist Coefficient Functions

* Derive Factorization Theorems ($A^+=0$ gauge)
  Evolution Equations, R.G.E.

* Translation of Hadron to $q+g$ degrees of freedom

* Novel Effects: Color Transparency
  Intrinsic gluons, heavy quarks

Summary / Outlook

QCD + LCQ ⇒

relativistic many-body theory

boost-invariant

trivial vacuum

symmetry breaking { zero modes; $m_V \neq m_L$ ← Burkardt

DLCQ ⇒

complete solns to quantum field theory!

Spectrum, scattering states, $\psi_n(x_i, k_{\perp i}, \lambda_i)$

exclusive, inclusive m.e., OPE

new directions → B-decays, fragmentation, $Z_{LC} = \sum_n e^{-M_n^2/PT}$

Novel QCD Phenomenology

Summary:

Two contributions to heavy quark sea!

* LC. wavefunctions, analysis
* high x_c EMC data
* $\Delta q = \Delta q_{\text{intrinsic}} + \Delta q_{\text{extrinsic}}$
  ↑ anomaly
* $\Delta q_{Int} \neq \Delta \bar{q}_{Int}$, $q(x)_{int} \neq \bar{q}_{int}$

* hadroproduction at large x_F, A-dep, !
* HERA: proton fragmentation
* coalescence: leading particle effects
* asymmetric hadronization

$c\bar{c}$ { Charm + strangeness together: crucial probe of hadron structure