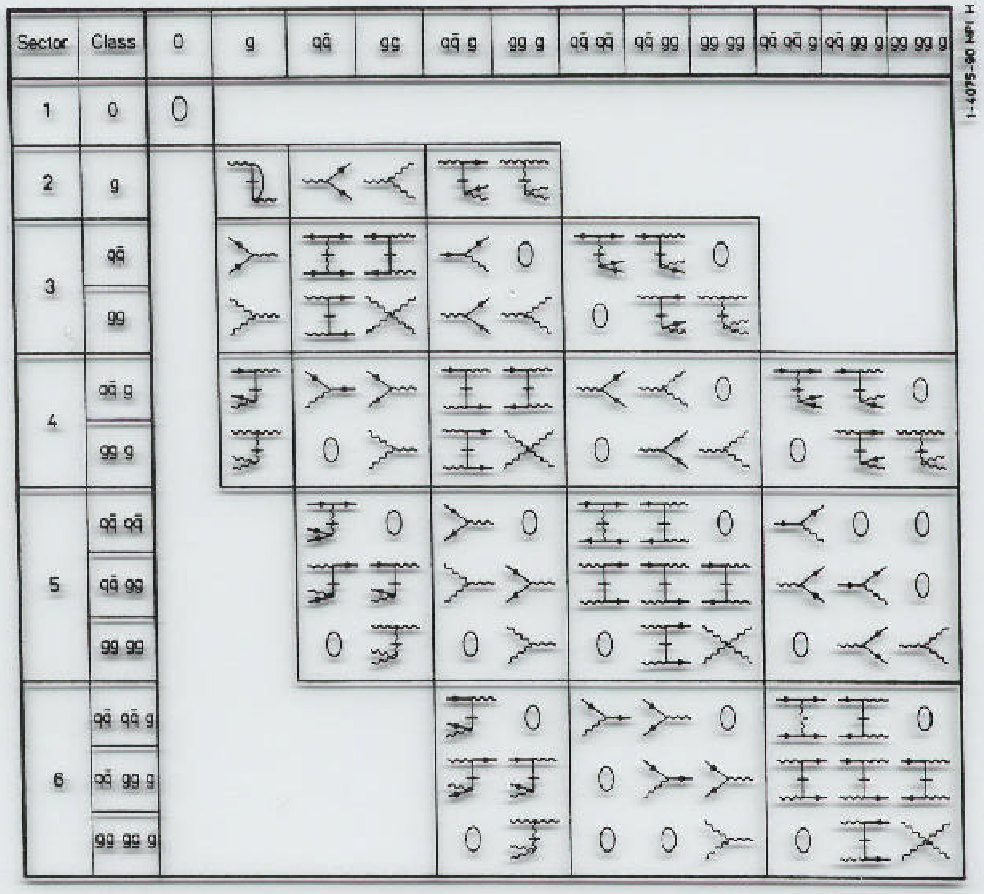
QCD (3+1)

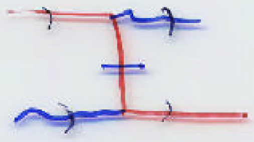


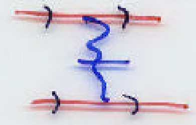
DLCQ: $\langle n | H_{LC}^{I} | m \rangle$

$$\left(M^2 - \sum_n \frac{k_\perp^2 + m^2}{x} \right) \psi_n = \sum_m \langle n | H_{LC}^{I} | m \rangle \psi_m$$

PBC: $k^+ = \frac{2\pi}{L} n \quad , \quad \vec{k}_\perp = \frac{2\pi}{L_\perp} \vec{n}_\perp$

H_{LC}^{QCD} : New 4-pt interactions





$$\frac{\gamma^+}{k^+} \qquad\qquad \gamma^+ \frac{1}{(k^+)^2} \gamma^+$$

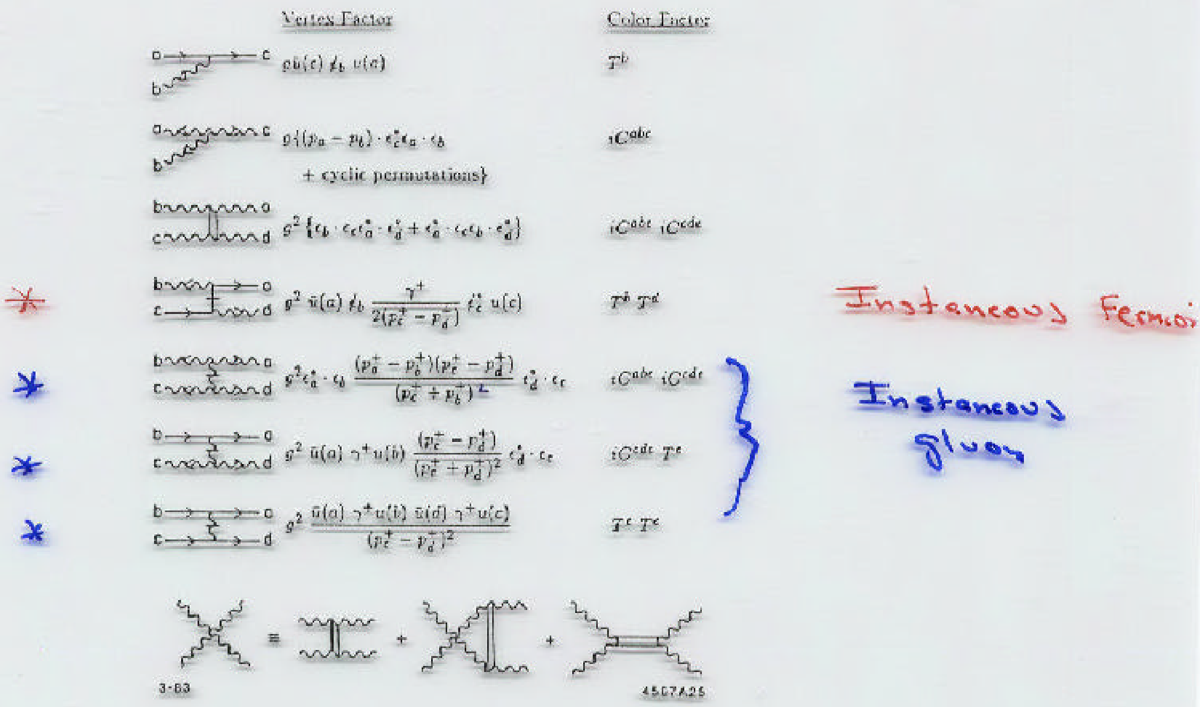
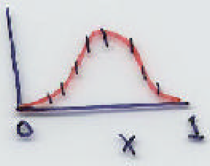


Figure 54. Graphical rules for QCD in light-cone perturbation theory.

For 1+1 Theories, K cuts off Fock states

$$x_i = \frac{k_i^+}{P^+} = \frac{n_i}{K} = \left\{ \frac{1}{K}, \frac{2}{K}, \dots \frac{K-1}{K} \right\}$$

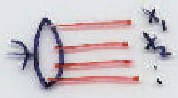
$\psi(x_i)$



Sample states at finite resolution

continuum limit: $K \to \infty$.

For fixed K: finite # partitions $\sum_i n_i = K$.



$x_i = \frac{n_i}{K}$

QED (1+1): No dynamical photons in $A^+ = 0$ gauge

$V =$

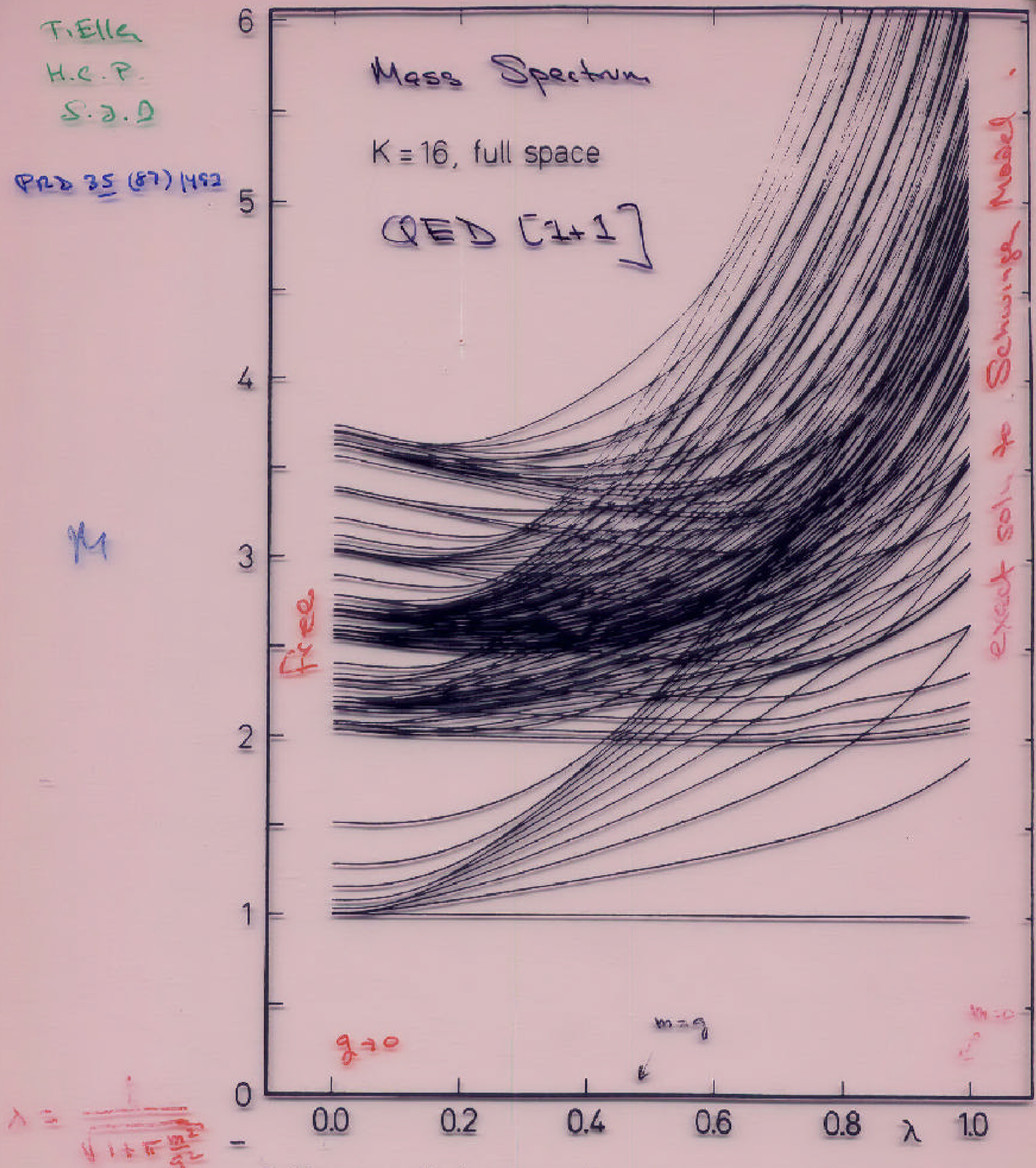
$$= \frac{g^2}{\pi} \left[\frac{1}{(k^+ - l^+)^2} - \frac{1}{(k^+ + m^+)^2} \right]$$

From normal ordering:

$$\frac{g^2}{\pi} \sum_{m=1}^{n^+} \frac{1}{m^2}$$

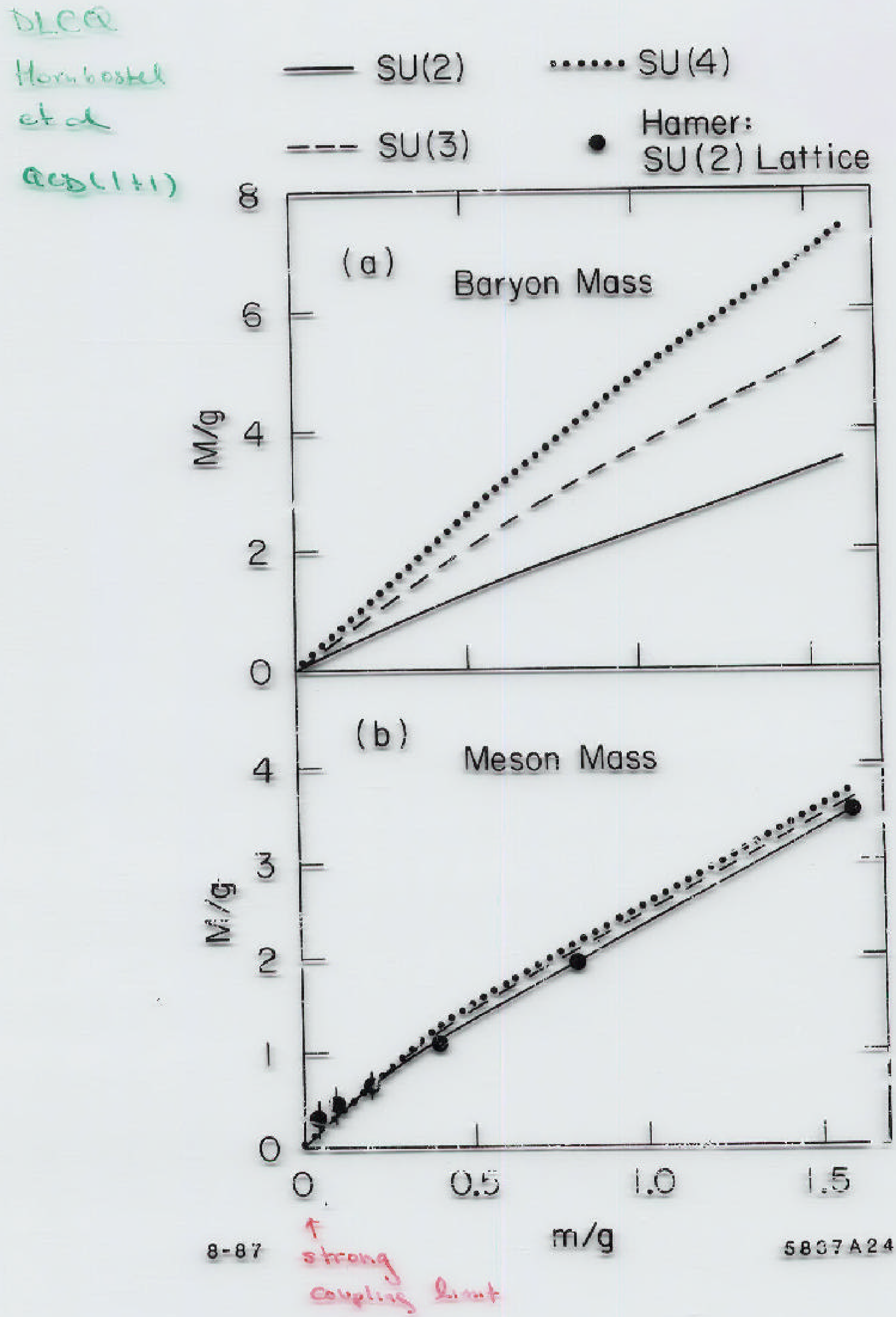
T. Eller
H.C.P.
S.J.B.

PRD 35 (87) 1492



6. *The renormalized spectrum of invariant masses.* — The invariant masses M_i/M_1 as calculated with the full Fock space of the massive representation for $K = 16$ is plotted versus *all values* of the coupling constant λ. — Note the qualitatively different parts of the spectrum. Many quasi-crossings are not resolved graphically despite the small step in the calculation, $\Delta\lambda = 0.01$.

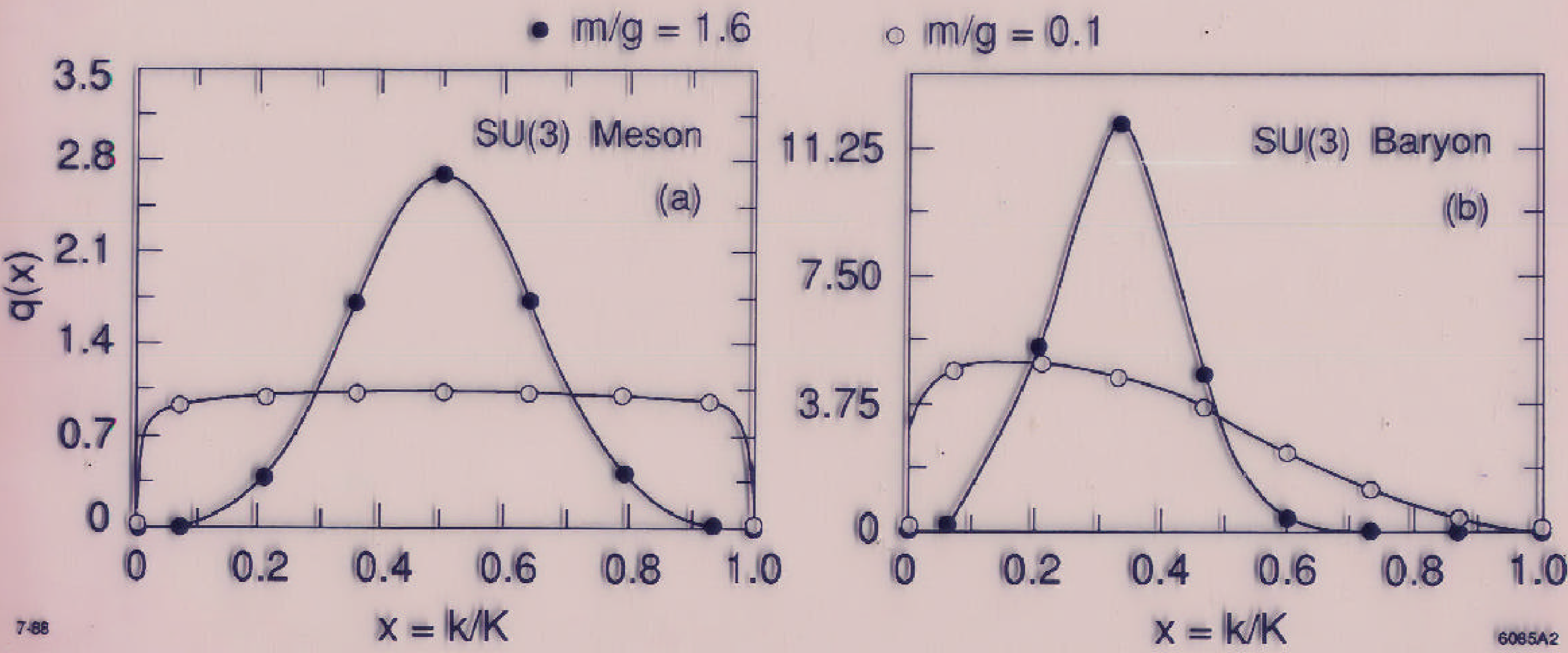
Prob $q\bar{q}q\bar{q} \lesssim 10^{-4}$


DLCQ
Hornbostel
et al
QCD(1+1)
SU(2)
SU(4)
SU(3)
Hamer:
SU(2) Lattice
(a)
Baryon Mass
M/g
(b)
Meson Mass
M/g
0
0.5
1.0
1.5
m/g
8-87
5837A24
strong
coupling limit
g→∞

QCD(1+1)

Hornbostel, Pauli, SJB

DLCQ



analytic: Einhorn

"Exact" Solution

to

QCD [1+1]

Hornbostel

Pauli, SJB

Burkhardt

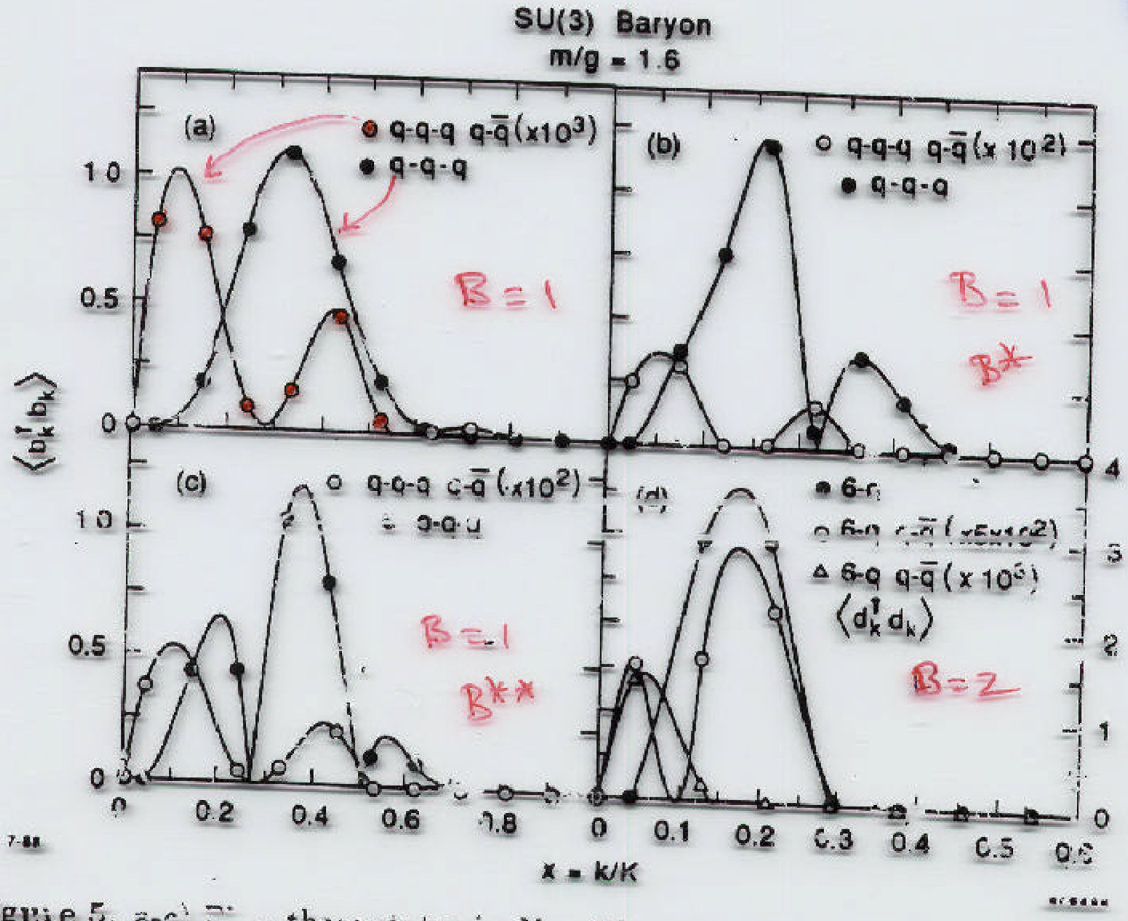


Figure 5. a-c) First three states in $N = 3$ baryon spectrum, 2K=2… d) First $B = 2$ state.

DLCQ (3+1)

See also
Pauli, Wertgarten, Wölz
Perry, Glazek

{ Calculations for a renormalizable quantum field theory model

{ Simplified Yukawa model with Pauli-Villars regularization

Bouchut
Feyet + Sourles
Chang + Yan
Burkardt, Langnau

{ Invariant mass cutoff to regulate phase space

$$\sum_i \left(\frac{k_\perp^2+m^2}{x}\right)_i < \Lambda^2$$

SJB, McCartor, Hiller

M_0 ⟶ dynamical fermion

Analytic soln for non dynamical fermion

μ ⟶ μ_1 ⟶ bosons
PV

H.C. Pauli
SJB

DLCQ (3+1)

Periodic boundary conditions

$$-L < x^- < L \quad , \quad -L_\perp < x, y < L_\perp$$

$\Rightarrow$ Discrete momenta:

$$p_i^+ = \frac{\pi}{L} n_i \quad , \quad \vec{p}_{\perp i} = \frac{\pi}{L_\perp}(n_{xi}, n_{yi})$$

$$P^+ = \frac{\pi}{L} K \quad , \quad \Sigma_i n_i = K$$

$$x_i = \frac{p_i^+}{P^+} = \frac{n_i}{K} > 0$$

* Fock state number limited by K,

$$\sum_i \frac{m_i^2 + p_{\perp i}^2}{x_i} < \Lambda^2 \quad \text{limits } n_x, n_y$$

* Continuum limit $K \to \infty$

Application to Yukawa theory (3+1)

Hiller, McCartor, SJB

Hiller
McCartor
SJB

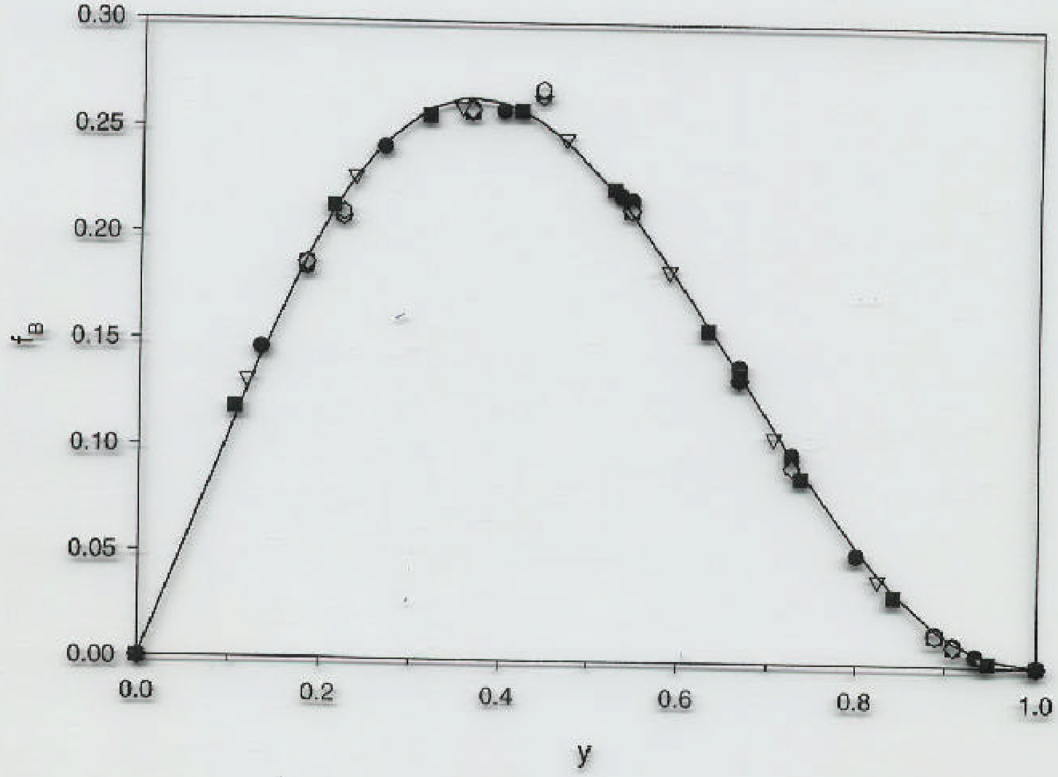


Figure 1: The boson distribution function f_B at various numerical resolutions, with $\langle :\phi^2(0): \rangle = 1$, $\Lambda^2 = 50\mu^2$, and $\mu_1^2 = 10\mu^2$. The solid line is the parameterized fit.

Structure Function $F_B(y)$
for Fermion eigenstate

$M = \mu$, $< : \phi^2(0) : > = 1$

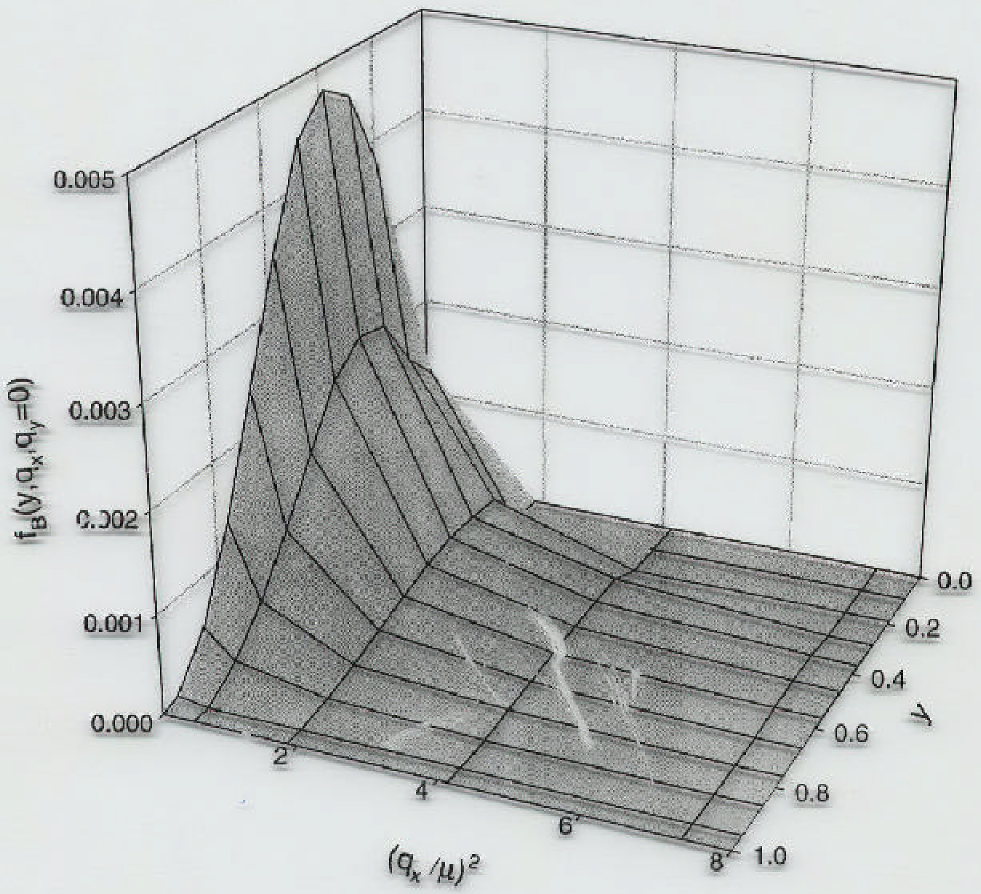


Figure 8: The boson distribution function $f_B(y, \mathbf{q}_\perp)$ with $K = 21$, $N_\perp = 7$, $\langle :\phi^2(0): \rangle = 1$, $\Lambda^2 = 25\mu^2$, and $\mu_1^2 = 10\mu^2$. The transverse momentum is varied with q_y fixed at zero.

$f_B(y, q_{\perp x}, q_{\perp y} = 0)$

summed over all Fock states

4/62

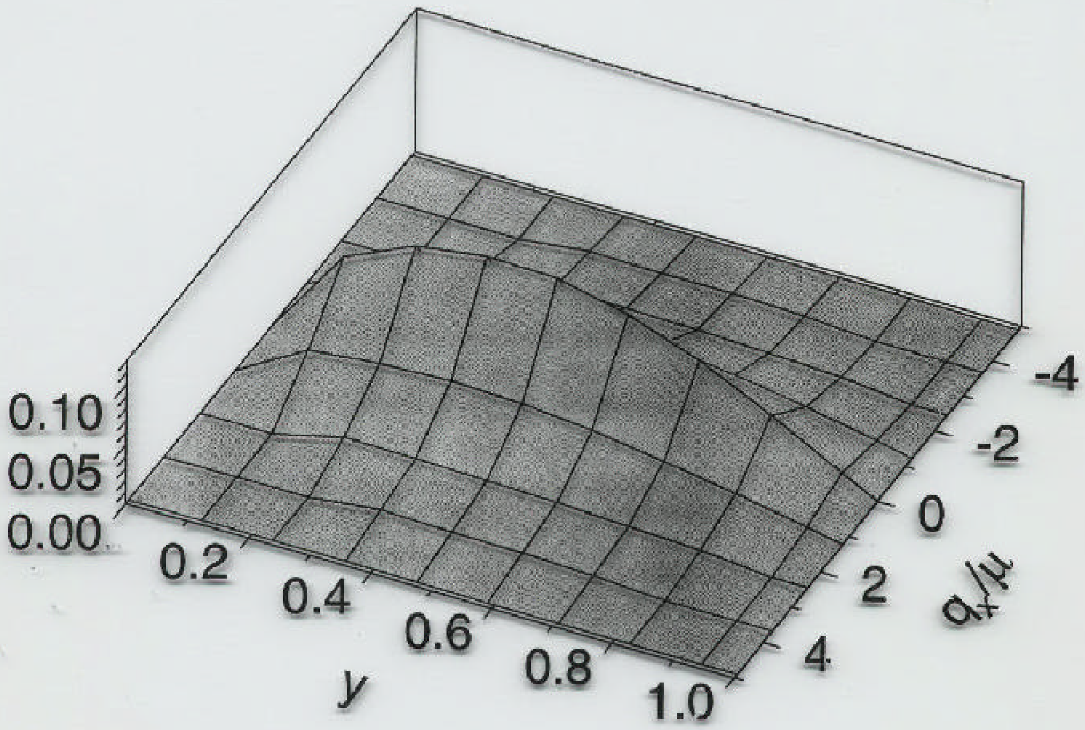
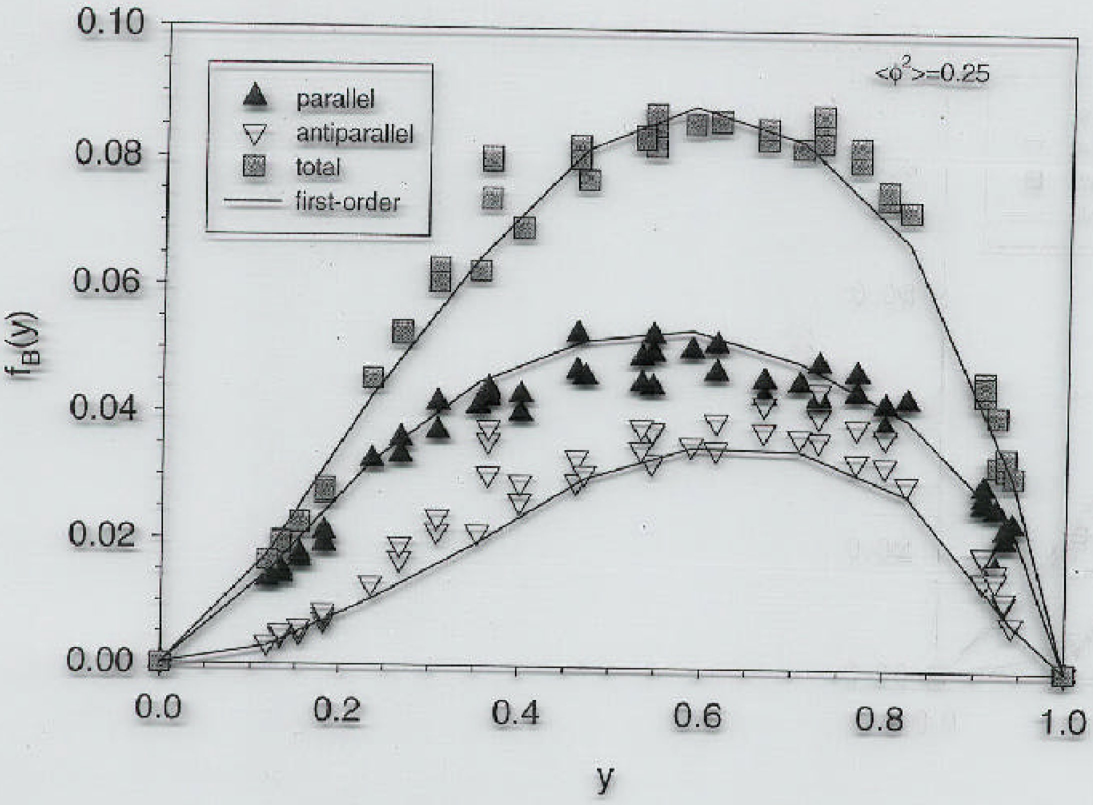


Figure 4: The one-boson amplitude $\psi^{(1,0)}$ as a function of longitudinal momentum fraction y and one transverse momentum component q_x in the $q_y = 0$ plane. The parameter values are $K = 17$, $N_\perp = 4$, $\mu_1^2 = 10\mu^2$, $\Lambda^2 = 50\mu^2$, and $\langle :\phi^2(0): \rangle = 1$.

$\psi(y, q_x, q_y = 0)$

lowest Fock state.



0.10
0.08
0.06
0.04
0.02
0.00
$f_B(y)$
parallel
antiparallel
total
first-order
$<\phi^2>=0.25$
0.0
0.2
0.4
0.6
0.8
1.0
y

DLCQ (3+1)

* Model shows good convergence

* Reliable calculation of

  { structure functions, matrix elements
  distribution amplitudes, etc.

* PV regularization renders theory finite

  ⇒ broken SUSY regularization

* Encouraging for QCD (3+1)

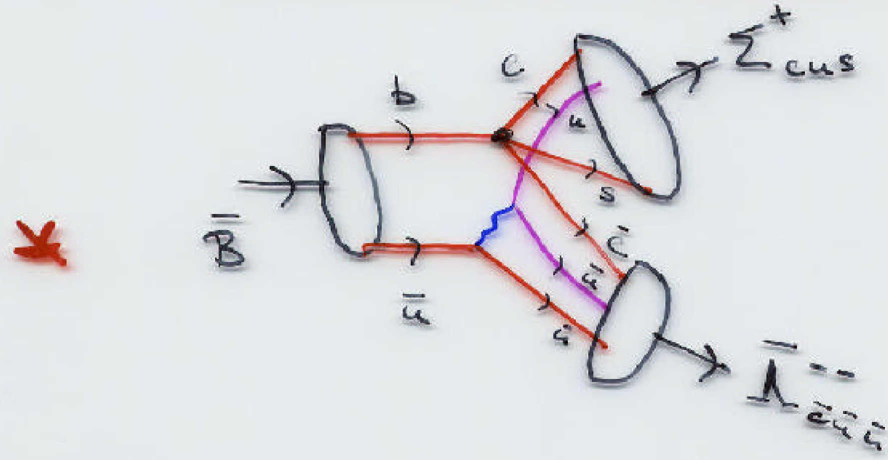
  - Feynman gauge formulation of the

    P. Srivastava, SJB

  - Chiral properties?

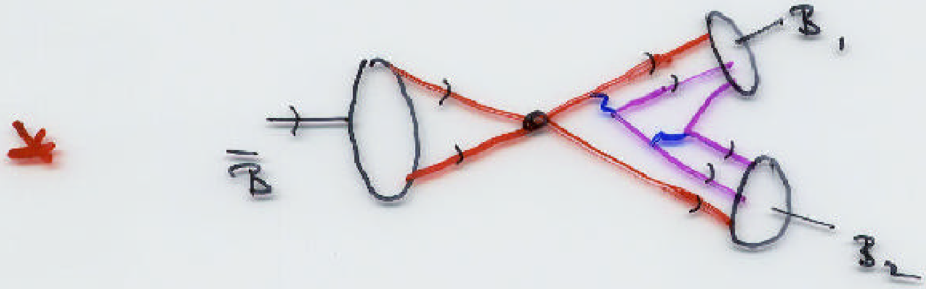
  - Heavy Quarkonium application
    color octet component

Apply PQCD to $B \to$ Baryon Pairs



"Non-Factorizable"

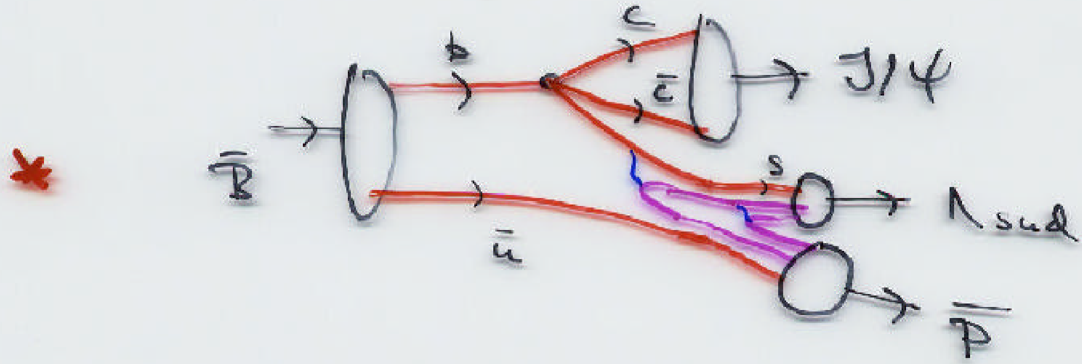
α_s^1 order!



"Annihilation"

Similar to timelike $F_p(Q^2)$

novel helicities

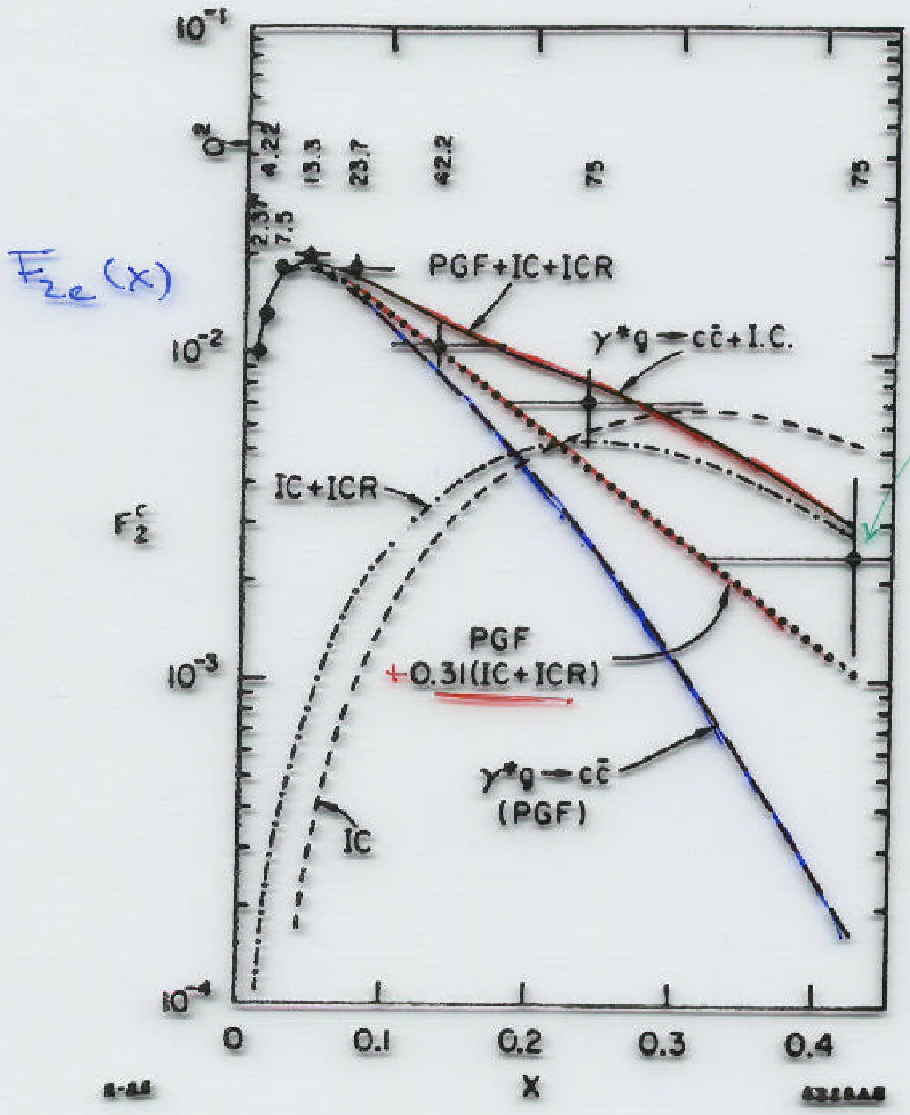


Low mass dibaryons

Navarra SJB

Study new bound states

$(\Lambda \bar{p})$ $(\Lambda J/\psi)$ $(\bar{p} J/\psi)$



$Q^2 = 75$ GeV^2

$x_{Bj} = 0.42$

Hoffman + Moore

* Smith, Vogt, Ho

EMC data

Prob (IC)

$\cong$ { 0.3% HM

1.0% Su

Steffens,

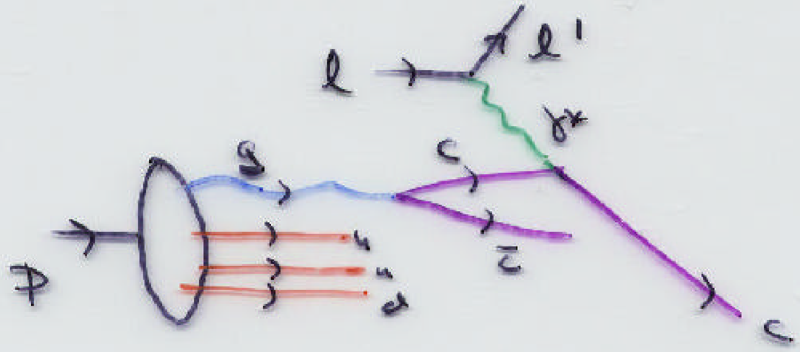
Melnitchouk

Thomas

(variable quark mass scheme)

CBM for IC

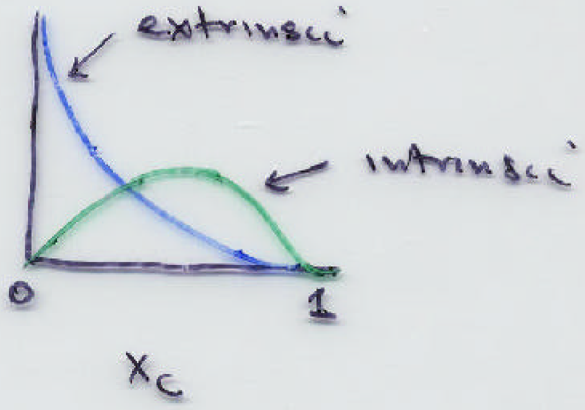
Two Contributions to Sea Quark Distributions



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

1 gluon irreducible

intrinsic
initial state for DGLAP evolution



$Q^2 \gg 4m_c^2$

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

Vogt

Thomas
Soss

SJB, Hoyer, Sakai.
Peterson

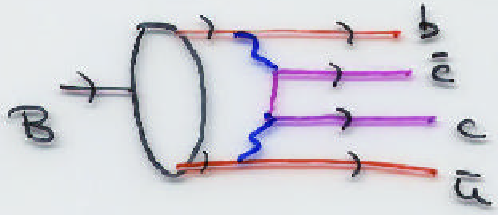
Ingelman & Thunman

Higher Particle-Number Fock States

— required by relativity, q.f.t.

Example: **Intrinsic Charm in B**

Hoyer, Peterson, Sakai, SJB

$\psi_{b\bar{c}c\bar{u}/B}$: 

$$\langle x_Q \rangle \sim \frac{\mu_B^2}{m_Q^2}\, \alpha_s^4(\mu_B^2)$$

color octet $c\bar{c}$

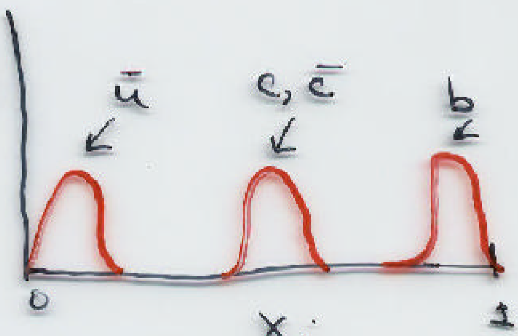
* OPE analysis by Franz, Polyakov, Shifman

* EMC measurement of IC in proton

$P_{c\bar{c}/p} \sim 1\%$

Harris, Smith, Vogt

* $\psi_{b\bar{c}cu/B}(x_i, \vec{k}_{\perp i})$ peaks at

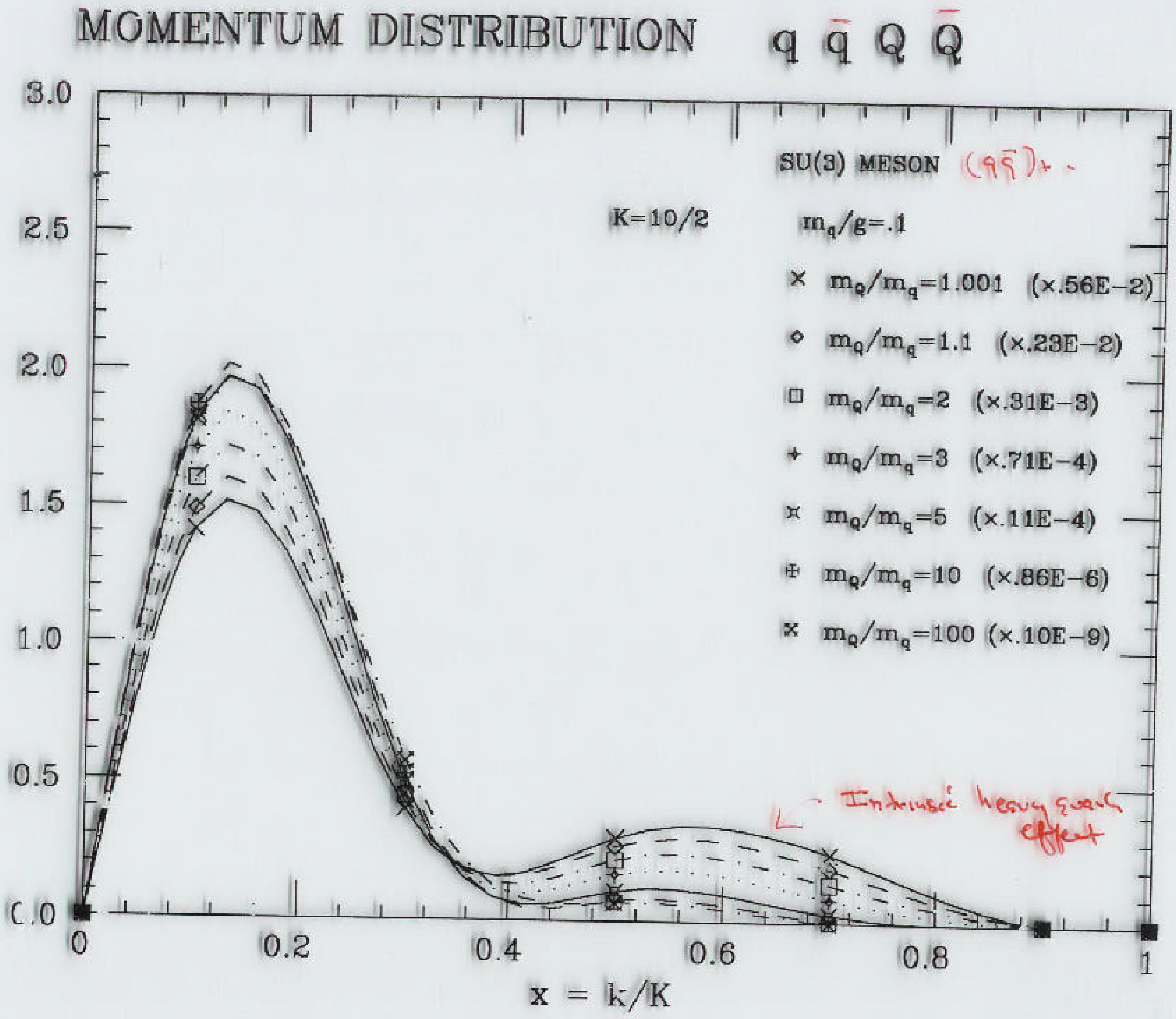


How

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

$P_{c\bar{c}/B} \sim 4 \times P_{c\bar{c}/p}$!

QCD(1+1)



DLCQ

Hornbostel + SJB

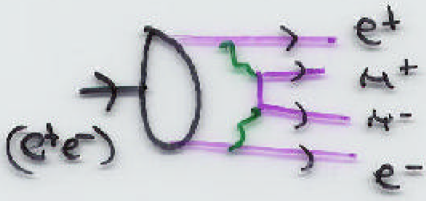
Possible new source ?

s, c, b

Color - Octet Intrinsic Charm

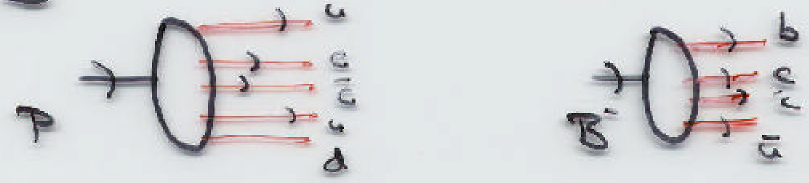
S. Gardner
+
SJB

QED:



$$P_{rob} \sim \left(\frac{\mu_{Bohr}}{m_{\mu^+\mu^-}}\right)^4 \times \alpha^4$$

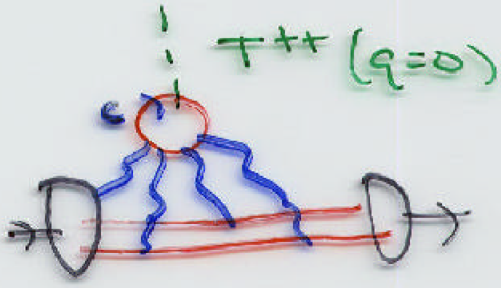
QCD



Only suppressed by $\frac{1}{m_{c\bar c}^2}$ if color octet

Franz et al:

$\langle x_{c\bar c}\rangle_H \Rightarrow$



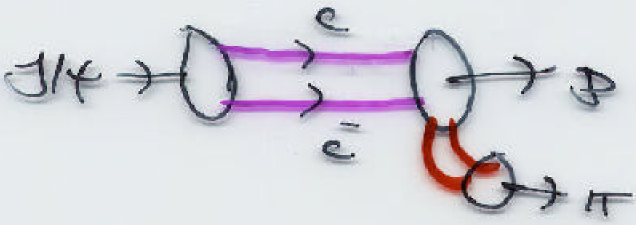
$$T^{++} \Rightarrow \frac{G^{+\nu}\, G^{+\mu}\, G_{\mu\nu}}{m_c^2} \leftarrow [A_\mu, A_\nu]$$

∴ $\text{Prob} \sim \alpha_s^4 \, \frac{\mu^2_{Bohr}}{m_{Q\bar Q}^2}$ for color octet

$\frac{1}{m_r} = \frac{1}{m_1} + \frac{1}{m_2}$: $\mu^{B}_{Bohr} \sim 2\,\mu^{\pi}_{Bohr}$ More IC in B!

Consequences of Intrinsic Charm

* $J/\psi \to \rho\pi$, $\psi' \not\to \rho\pi$



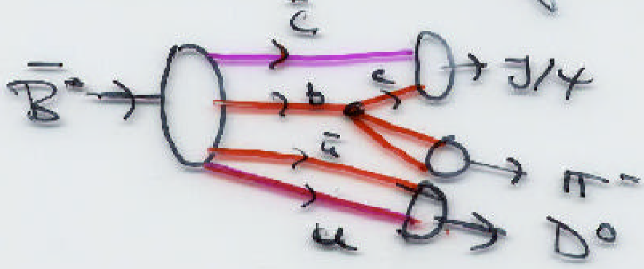
Karliner
SJB

* $\Upsilon \to J/\psi\, X$ spectrum — Hoo

* $\pi p \to D^{\pm} X$, $\Sigma p \to \Lambda_c X$

Hoyer et al

Consequences for B-decays



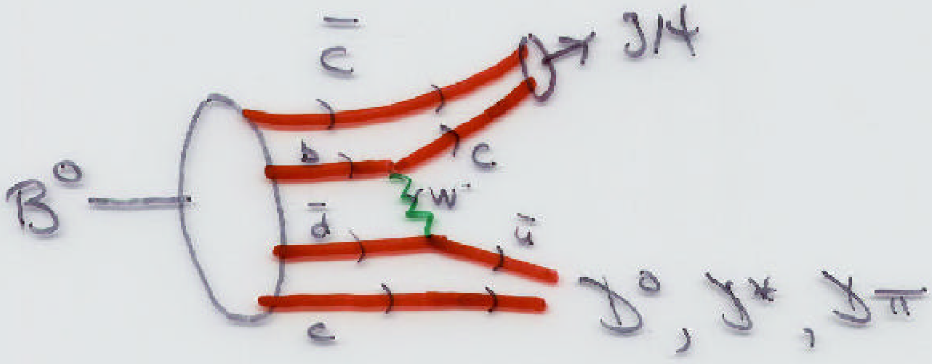
Hoo

CLEO, Belle
bump at low $P_{J/\psi}$

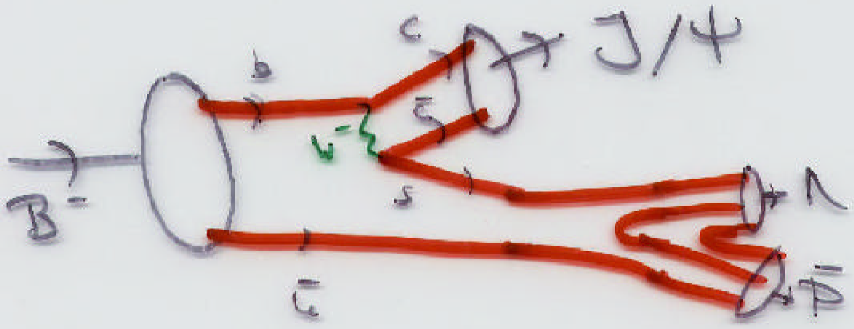
Leading CKM

Evasion of CKM!

Gardner
SJB



Great
Hou

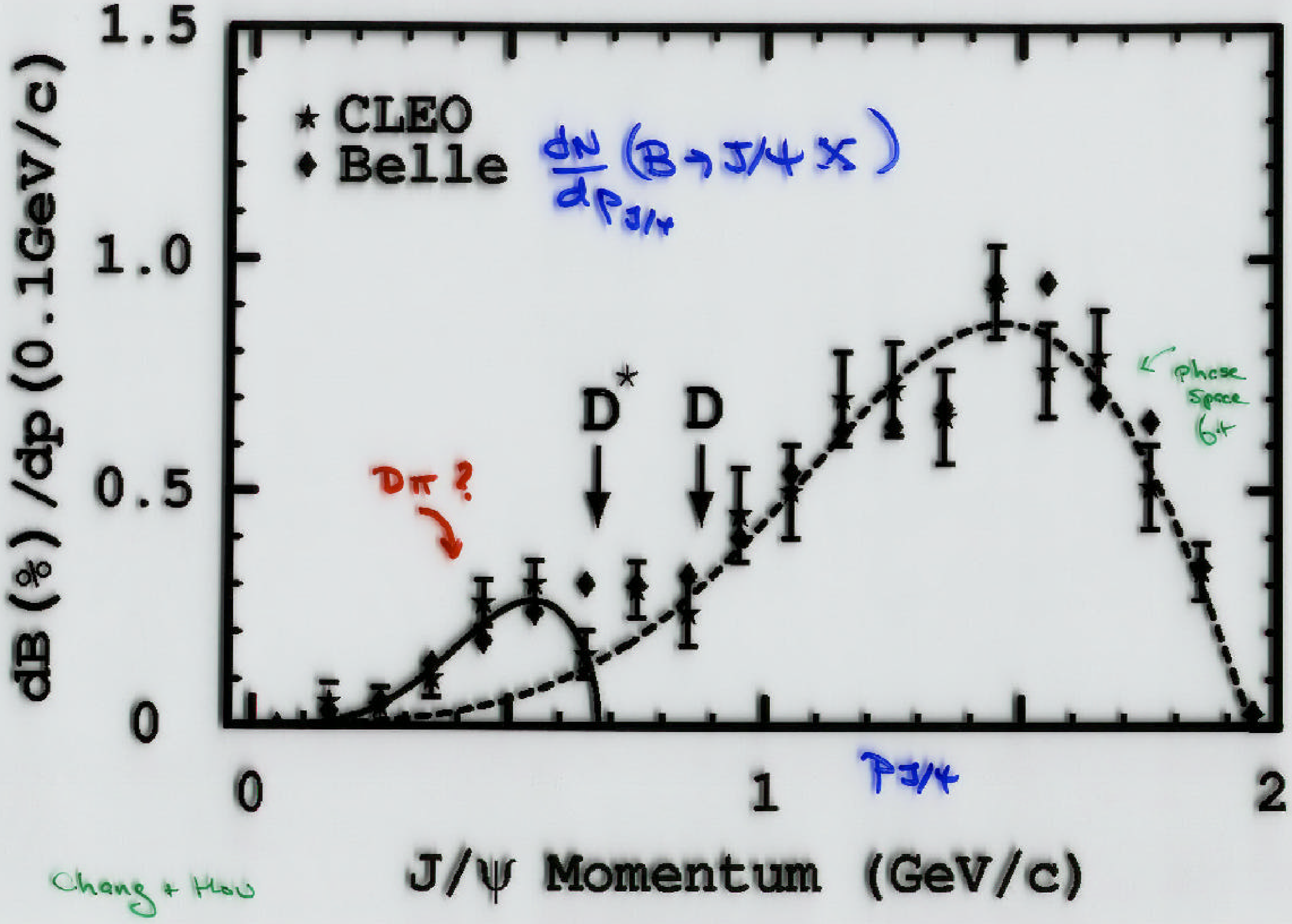


Navarra
SJB

* Both produce bump in M_X spectrum
~ 2 GeV

* $B \to \eta' k$

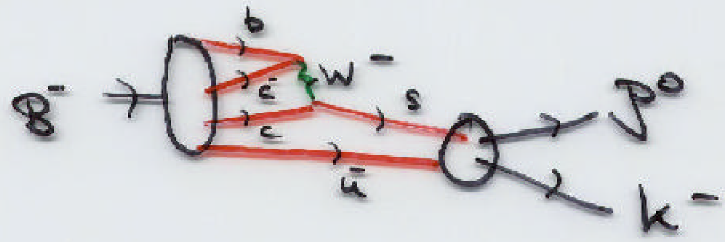
$$|\eta'\rangle = (\,)|gg\rangle + (\,)|gc\bar{c}\rangle + \ldots ?$$



1.5
1.0
0.5
0
dB (%) /dp (0.1GeV/c)
CLEO
Belle
dN/dp J/ψ (B → J/ψ X)
D*
D
Dπ ?
phase space fit
0
1
2
p J/ψ
J/ψ Momentum (GeV/c)
Chang + Hou

Use color-octet intrinsic charm to evade the CKM Hierarchy

S. Gardner + SJB

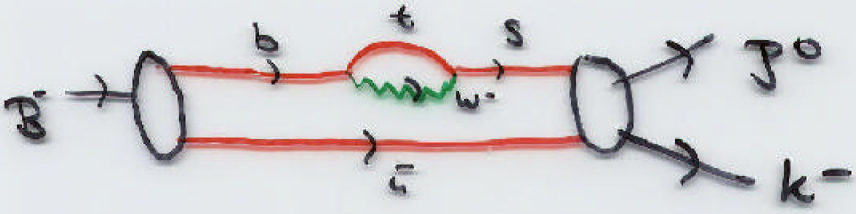


(s very fast)

New pattern of exclusive decays

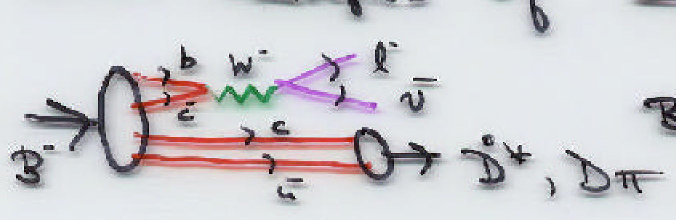
Enhances rate

Interferes with standard contributions



Other examples of IC in B decays

Chang + Hou



Massive lepton pairs

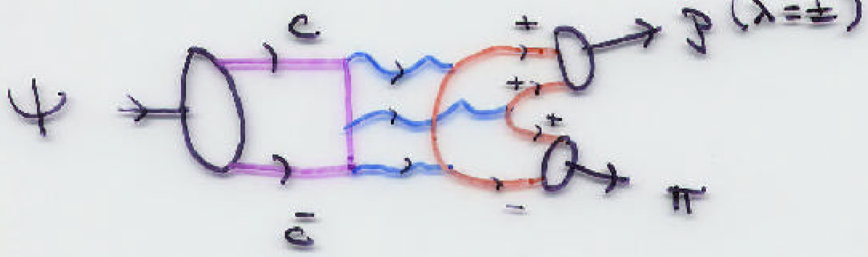
↑ Seen at CLEO? bump at low $p_{J/\psi}$

The "$J/\psi \to \rho\pi$" Puzzle and Intrinsic Charm

SJB + M. Karliner

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

$$B[\psi'(2S) \to \rho\pi] < 3.6 \times 10^{-5}$$



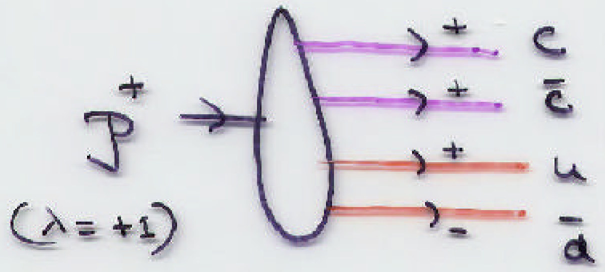
PQCD: $B[\psi' \to \rho\pi] < \frac{1}{50}$ expected rate

$Q\bar{Q} \to \rho\pi$ suppressed by "hadron helicity cons."

Same problem: KK^*

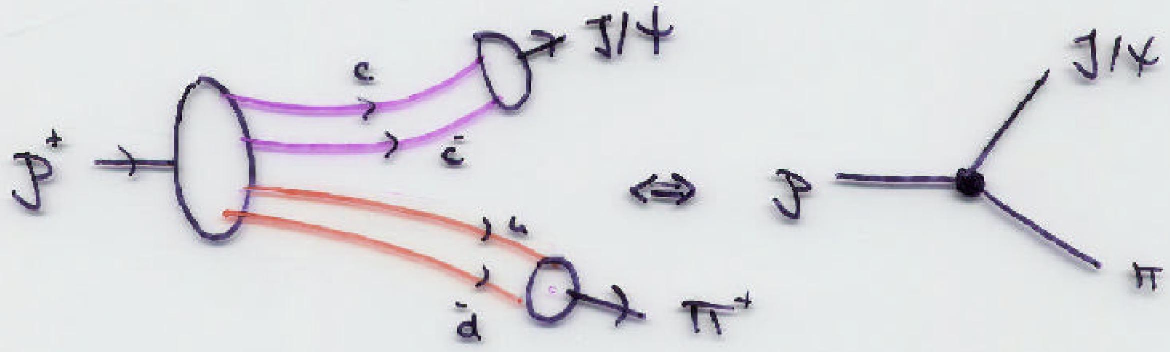
SJB, G.P. Lepage
S.F. Tuan

Intrinsic charm of p : $|u d \bar{d} c \bar{c}\rangle$



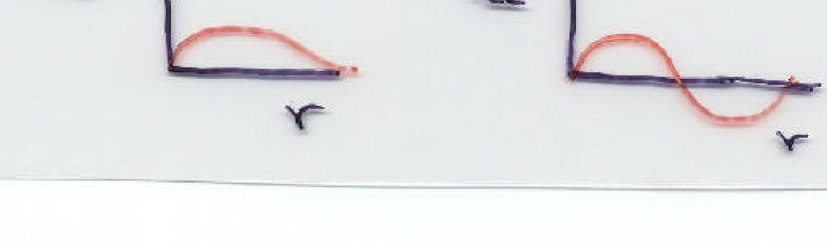
minimizes off-shellness

$\therefore$ close match to $J/\psi\ \pi^+$



suppressed coupling to $\psi'(2S)$

because of node in radial $c\bar{c}$ w.f.



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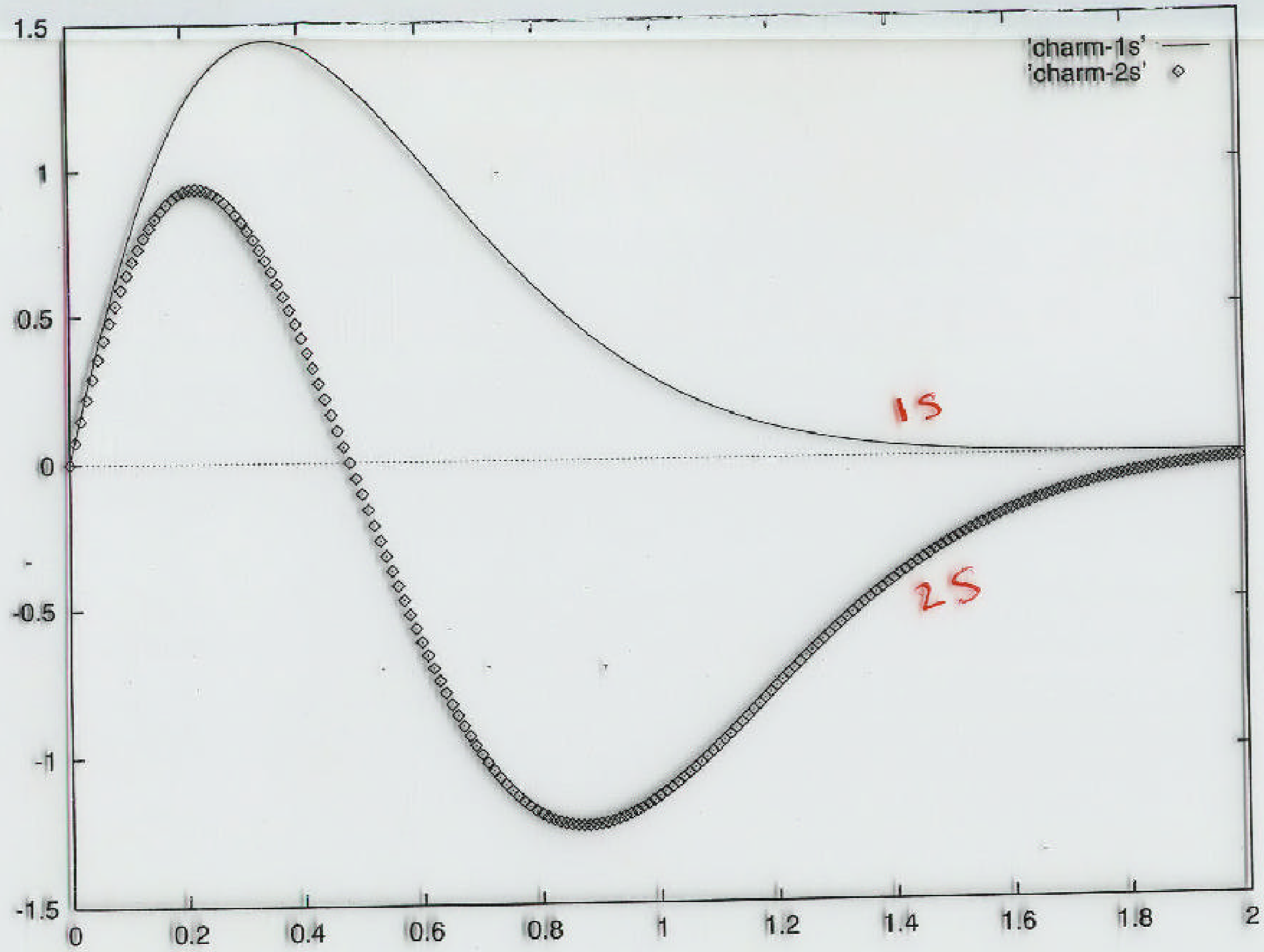


Conformal Symmetry and Baryon Distribution Amplitudes

V. Braun, S. Derkachov,
A. Manashov, G. Korchemsky

$$q\uparrow q\uparrow q\uparrow \;\Rightarrow\; \phi_{\Delta}^{\lambda=3/2}(x_i,\mu^2)$$

$$q\uparrow q\downarrow q\uparrow \;\Rightarrow\; \begin{cases} \phi_{N}^{\lambda=1/2}(x_i,\mu^2) \\ \phi_{\Delta}^{\lambda=1/2}(x_i,\mu^2) \end{cases}$$

$$\sum_{i=1}^{3} x_i = 1$$

$$\phi_{N,\Delta}^{\lambda=1/2}(x_i,\mu^2) = x_1 x_2 x_3 \sum_{N=0}^{\infty} \varphi_N^{\mu_0} \left[\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right]^{\gamma_N} \times \left\{ P_N(1-2x_3) \pm P_N(1-2x_1) \right\}$$

scalar diquark

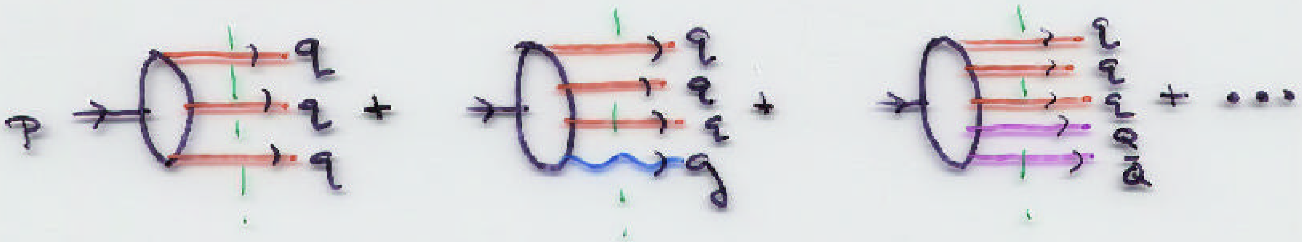
$(\uparrow \; \downarrow) \quad \uparrow$

1 2 3

Jacobi Polynomials $P_N^{(1,3)}$

expansion in conformal polynomials

Light-Cone Fock Representation of Hadrons



$|p\rangle = \sum_n |n\rangle \, \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$

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

- Explicit solutions using "DLCQ" — QCD(1+1), "collinear" QCD
  SJB, Pauli, Hornbostel, Antonuccio, Dalley

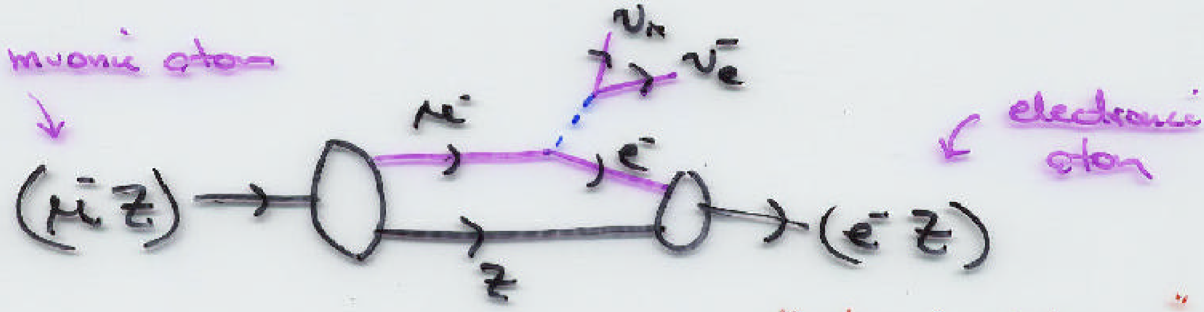
- Calculate structure functions — $q(x)$, $g(x)$, $Q(x)$, Spin-dependence

- Calculate Regge behavior using "ladder relations" — $x \to 0$, BFKL, Spin-dependence
  Mueller, SJB, Antonuccio, Dalley

- $x \to 1$ constraints — Lepage, SJB, Burkardt, Sch

- Properties of heavy quark sea — $s(x) \neq \bar{s}(x)$
  extrinsic vs intrinsic
  physics of $\Delta\Sigma$, anomaly
  Bass
  Hoyer, Ma, Schmidt, SJB, Schlumpf

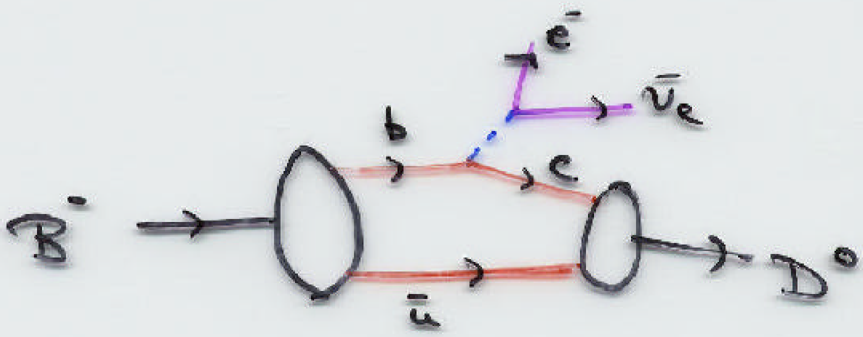
Atomic Physics Analog of B, D decay



"atomic alchemy"

* observe sudden emergence of moving atom !

Greub, Wyler, SJB



Semi-leptonic B decay

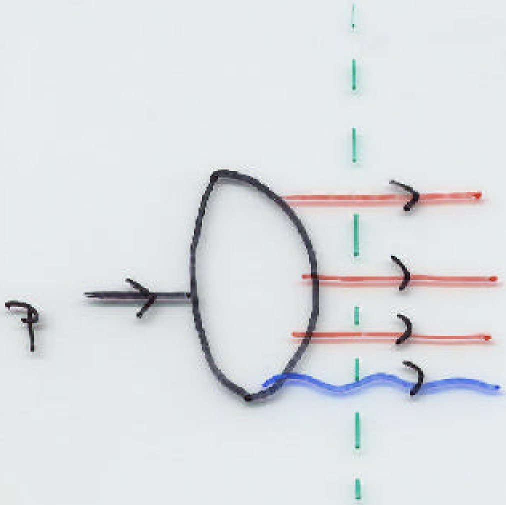
* Calculations require Ψ_B, Ψ_D at large and soft momenta

* Abelian Correspondence Principle — Huet, SJB

$$QCD \xrightarrow[N_C \to 0]{} QED$$

Light-Cone Wavefunctions in QCD

Essential quantities for QCD calculations
at amplitude level



$x_1, \vec{k}_{\perp 1}, \lambda_1$

$$x_i = \frac{k^+_i}{p^+} = \frac{k^0_i + k^z_i}{p^0 + p^z}$$

Fixed $\tau = t + z/c$ "light-cone time" Dirac

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

$$\sum_{i=1}^{n} x_i = 1 \ , \quad \sum_{i=1}^{n} \vec{k}_{\perp i} = \vec{0}_\perp$$

* Relativistic representation of hadrons in terms of quark and gluon degrees of freedom.

Summary

* Exact Formula For $B \to l \bar{\nu} M$
  - Higher Fock States required for Lorentz Inv
* PQCD Analysis of Exclusive B-decays
  - Rigorous Factorization Formulae for some contributions
  - Analyzable contributions controlled by Sudakov suppression
  - α_s Freezes in IR
* Light-cone wavefunctions + Distribution Amplitudes
  - Computable using DLCQ, non-pert methods
  - Measurable in $\gamma\gamma \to M\bar{M}$, Diff. dissoc
* Intrinsic Charm and Strangeness
  - Evasion of CKM
  - Novel Consequences