Novel QCD Phenomena in Anti-Proton Collisions

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Presented at

The International Workshop on Physics with Antiprotons at GSI

GSI-Darmstadt June 4-9, 2002

Jointly organized by the European Graduate School Copenhagen-Giessen and GSI.

The transparencies specifically addressing antiproton physics are
Part 1: 6–10;
Part 2: 4–5, 14, 15, 19;
Part 3: 3, 4, 10–14;
Part 4: all;
Part 5: 1–9, 12–19, 22–25;
Part 6: all

Main Topics:

1. The theory and main features of exclusive antiproton reactions.

2. QCD color transparency in quasi-elastic antiproton reactions.

3. Unusual features of physics at the charm threshold. I particularly emphasized the possibility of a large threshold effect at the second charm threshold where the baryons remain intact, as in the $\bar{p}p \to$ charm $\bar{p}p$ reaction. The threshold regime may be enhanced by an eight- quark $uud\bar{u}\bar{u}dc\bar{c}$ resonance due to attractive QCD van der Waals effects. There is in fact evidence for a similar degenerate resonance in $pp \to$ charm pp reactions. The predicted cross section at $p_{lab} = 15\ GeV/c$ is 1 μb. Strong spin correlations and anomalous color transparency effects are also predicted.

4. The reduced amplitude formalism for exclusive $\bar{p}$ deuteron reactions.

5. Single spin asymmetries in antiproton in inclusive Drell-Yan reactions.

6. Effects of intrinsic charm in antiproton reactions.

7. Features of open charm production in antiproton annihilation.

8. A possible physics program with an anti-deuteron beam.

9. Crossed deeply virtual Compton scattering as a key measure of hadron structure in QCD

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"Probing Matter with Anti-Matter"

Quantum Chromodynamics

$$\mathcal{L}_{QCD} = -\frac{1}{4} G_{\mu\nu}^2 + \sum_f \bar{\Psi}_f (i \not{D} - m_f) \Psi_f$$

* In principle, QCD explains all of hadron, nuclear physics

* Confined quarks and gluons!

* Large range of experimental tests of PQCD

  Precision limited due to theoretical uncertainties

* Composition of hadrons – just beginning

QCD ($N_c = 3$)

Non-Abelian Yang-Mills gauge theory

3-gluon, 4-gluon couplings

* Invariant under $SU(3)_c$ rotations

$$q_i(x) \Rightarrow U_{ij}(x)\, q_j(x)$$

Abelian Correspondence Principle

P. Huet
SJB

* $\lim_{N_c \to 0} \mathrm{QCD}(N_c) = \text{'QED'}$

$$\alpha_{QED} = C_F\, \alpha_{QCD} \quad \underline{\text{fixed}}$$

$$C_F = \frac{N_c^2 - 1}{2 N_c}$$

* Hadrons $\Rightarrow$ Atoms

* Nuclei $\Rightarrow$ Molecules

Quantum Chromodynamics

* Remarkable Theory

$$\mathcal{L}_{QCD} = -\frac{1}{4} G_{\mu\nu}^2 + \bar{\psi}(\not{D} - m)\psi$$

* In principle explains all of nuclear, hadron physics

* Confined quarks and gluons!

* extraordinary range of experimental tests
  - leading twist, PQCD predictions

* but many profound questions
  - experimental anomalies

* Core subject of particle/nuclear physics
  - Like atomic physics —

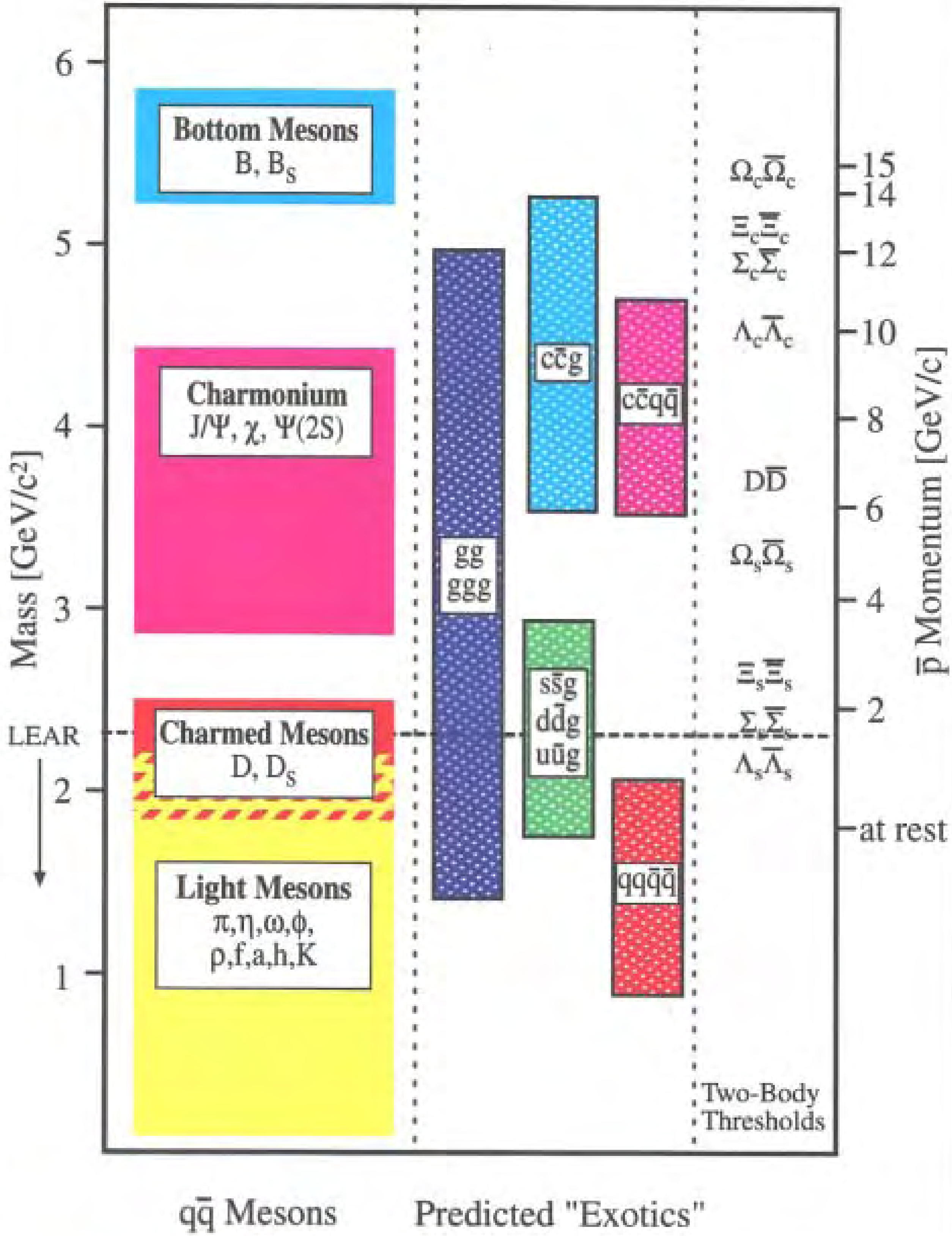
    { new phenomena waiting to discovered, explored

Study of QCD just beginning!

Novel Phenomena

- Hidden color
- Color Transparency
- Intrinsic Charm
- Spin Anomalies
- QCD Van der Waals Int.
- Diffraction: Pomeron / Odderon
- Exotica

Mesons and Exotics



Ulrich Wiedner

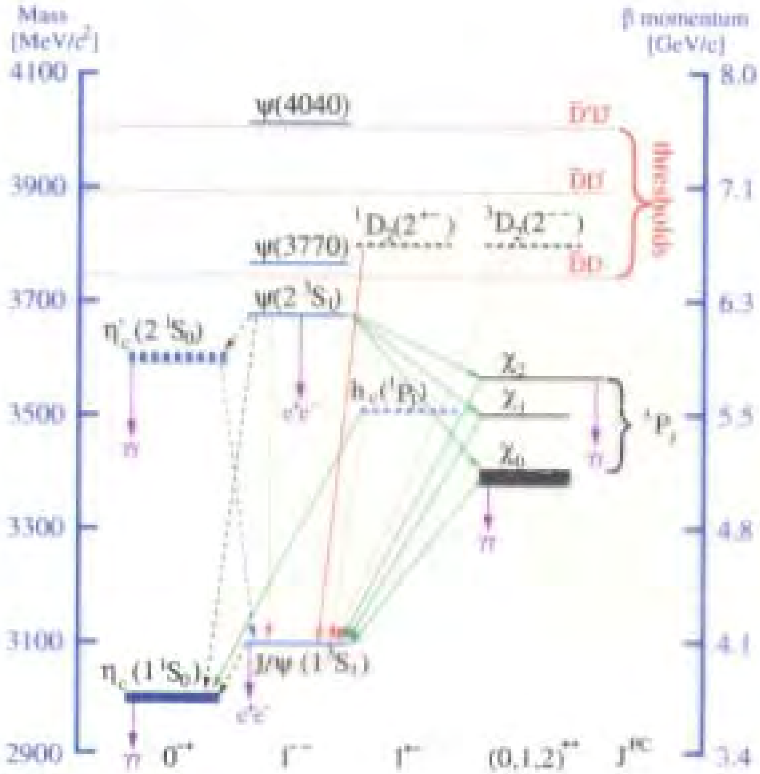


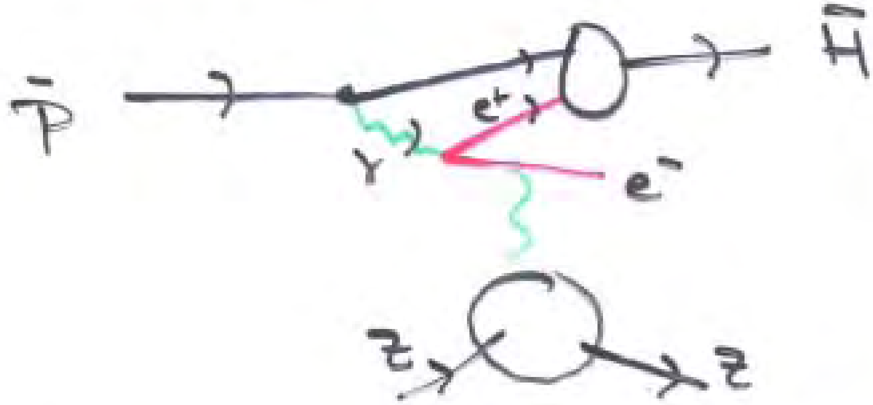
Figure 2.4. Charmonium states and their decay modes. Undiscovered and poorly known states are marked by dashes.

Anti-protons : $E_{\bar{p}}^{lab} < 15$ GeV

- Window to proton structure
- Total Annihilation to New Flavors
- Tests via Crossing
- Color Transparency Tests
- QCD Van der Waals
- Nuclear-Bound Quarkonium
- How Exclusive Processes
- Reduced Nuclear Amplitudes
- Exotic States

GSI:

$\boxed{\text{Beams of Anti-Hydrogen!}}$



(15 GeV beam)

coalescence of $\bar{p}e^+$

Munger
Schmidt
SJB

LEAR, FNAL
Discovery

extract neutral beam
precise energy

⇒ Precision Measurement of
Anti-Lamb Shift possible $2P_{1/2} - 2S_{1/2}$
using level crossing in $\vec{E}, \vec{H}$ fields

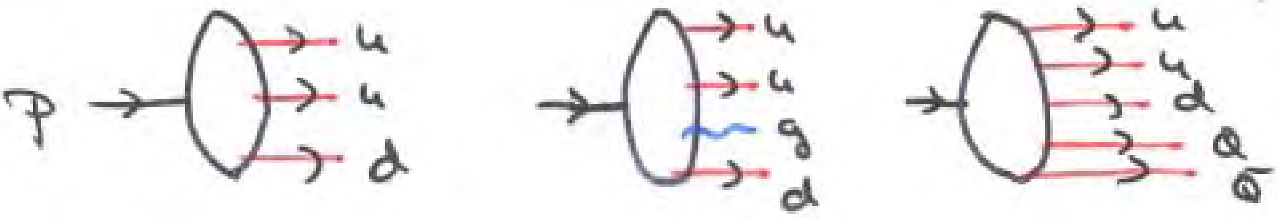
B. T. Robinson, C. Munger

Induce hfs transitions?

In relativistic quantum field theory:

$|\,\text{hadron}\rangle \sim$ sum over fluctuations

{ particle number
+
configurations:
color, size, helicity



large p_T exclusive processes only see ψ_{val}

$b_\perp^i \sim O\left(\frac{1}{p_T}\right)$

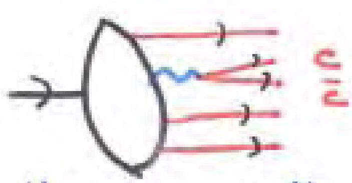
$\Rightarrow$ color transparency

gluon distrib.
(intrinsic + extrinsic)

"intrinsic" and "extrinsic"
$s, \bar{s}$
$c, \bar{c}$
$b, \bar{b}$

$\ln Q^2/m_c^2 : c(x) = \bar{c}(x)$

$\frac{1}{m_c^2} : c(x) \neq \bar{c}(x)$

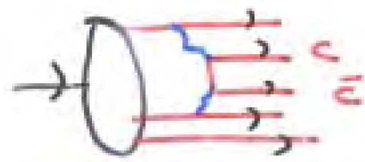


"extrinsic"

$g \to c\bar{c}$

$\bar{x}_c < \bar{x}_g$

soft



"intrinsic"

multi-connected

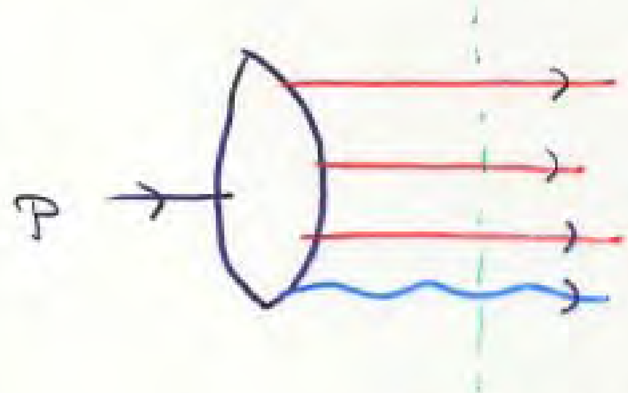
$\bar{x}_c \sim \frac{m_{c\perp}}{\sum m_\perp}$ hard!

Light-Cone Wavefunctions

and QCD Phenomena

Non-Perturbative QCD

$\{\Psi_n\}$: translation: hadrons $\Rightarrow q, g$



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

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

fixed $\tau = t + z/c$ Dirac

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

free q, g basis

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

"Light-cone Fock expansion"

boost invariant Frame-indep.

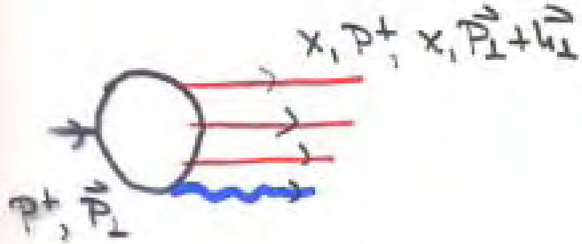
* Given $\{\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\}$

wavefunction known for $\underline{\text{all}}$ $\underline{P^\mu}$!

relative coordinates

$$|P^+, \vec{P}_\perp\rangle = \sum_n \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) \prod_j \frac{1}{\sqrt{x_j}}$$
$$|x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i\rangle$$

absolute coordinates



In equal-time theory (instant form)

boost's mix with interactions

changing $\vec{P} \to \vec{P}'$ as complicated

as solving $H|\Psi\rangle = E|\Psi\rangle$

L.C. wfs $-\left\{\begin{array}{l}\text{rest frame} \\ P^+ \infty \\ \text{Frame-independent!}\end{array}\right.$

J^z conservation for each LC Fock comp.

X Ji

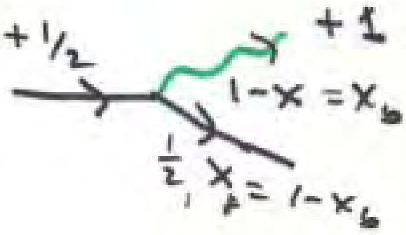
$$J^z_{(n)} = \sum_{j=1}^{n} S^z_j + \sum_{j=1}^{n-1} l^z_j$$

Hwang
Ma
Schmidt
SJB

Only $\underset{\sim}{(n-1)}$ relative l^z_j !

$$J^z \, |\psi^{\uparrow}_{\lambda_f, \lambda_b}\rangle = \tfrac{1}{2} \, |\psi^{\uparrow}_{\lambda_f, \lambda_b}\rangle$$

Helicity retention at $x_b \to 1$



$$|\psi^{\uparrow}_{1/2, 1}|^2 \sim \frac{1}{(1-x_b)^2} \varphi^2$$

SJB + GPL

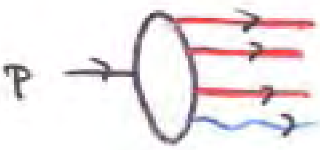
Burkardt, Schmidt, SJB

* Quark, gluon structure of hadrons:

  central focus of QCD

* Light-cone Fock expansion:

  rigorous repn of quantum field theory



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

gauge-invariant measures

$$q(x,Q^2) = \sum_n \int^{m_n^2<Q^2} |\Psi_n(x_i,k_{\perp i},\lambda_i)|^2 \, \pi d^2k_{\perp i}\, dx_i \; \delta(x_i - x_q)$$

⇒ parton distributions, inclusive process

$$\phi(x_i,Q^2) = \int^{m_n^2<Q^2} \pi d^2k_{\perp i} \; \Psi_{val}(x_i,k_{\perp i},\lambda_i)$$

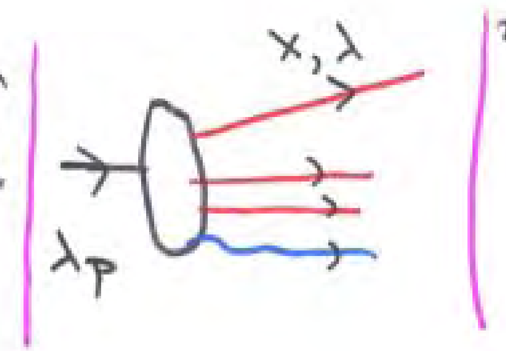
⇒ distribution amplitude, exclusive proc

Ψ_n: { fluctuations in particle number, size
helicity, flavor, momentum correlations

Light-Cone Wavefunctions

encode all helicity, transversity distributions

$$q_{\lambda/\lambda_p} = \sum$$



$$q_{\lambda/\lambda_p}(x, \Lambda) \quad \begin{cases} \text{transversity: density matrix} \\ \text{light-cone helicity} \end{cases}$$

$$= \sum_{n,q} \int \left| \psi^{(\Lambda)}_{n,\lambda_p}(x_i, \vec{k}_{\perp i}, \lambda_i) \right|^2 \prod_{j=1}^{n} dx_j \prod_{j=1}^{n} d^2 k_{\perp j}$$

$$\delta\left(\sum_i^n x_i - 1\right) \delta\left(\sum_i^n \vec{k}_{\perp i}\right)$$

$$\delta(x - x_q)\, \delta_{\lambda, \lambda_q}$$

Factorization
Light-cone Scheme

$$\Theta(\Lambda^2 - \mathcal{M}_n^2)$$

$\tau = t + z/c$

Dirac
Bjorken, Kogut, Soper
Lepage + SJB
Pauli + SJB

Equation of motion

$$i\frac{\partial}{\partial\tau}|\Psi_H\rangle = P^-|\Psi_H\rangle = \frac{M_H^2 + \vec{P}_\perp^{\,2}}{P^+}|\Psi_H\rangle$$

$$H_{LC} = P^- P^+ - P_\perp^2 \qquad P^+, P_\perp \text{ kinematical}$$

$$\boxed{H_{LC}\,|\Psi_H\rangle = M_H^2\,|\Psi_H\rangle}$$

⇒ eigenvalue problem for LC Hamiltonian

Insert complete set of H^0_{LC} color-singlet eigenstate

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

$$\sum_n \langle m|H_{LC}|n\rangle\langle n|\Psi_H\rangle = M_H^2\,\langle m|\Psi_H\rangle$$

DLCQ

⇒ Heisenberg matrix form of eigenvalue problem

$$|\Psi_H\rangle = \sum_n |n\rangle\langle n|\Psi_H\rangle = \sum_n |n\rangle\,\psi_{n/H}(x_i, \vec{k}_{\perp i}, \lambda_i)$$

⇒ LC Fock expansion of eigenstate $|\Psi_H\rangle$

$p^{\pm} = p^0 \pm p^z$

Light-Cone Quantization of QCD

(Dirac: Front Form)

Quantize at fixed $\tau = t + z/c$, $A^+ = 0$

$$P^- = i \frac{\partial}{\partial \tau} \; ; \; P^+ , \vec{P}_\perp \quad \text{kinematical}$$

$$\mathcal{L}_{QCD} \Rightarrow H^{LC}_{QCD} = P^- P^+ - \vec{P}_\perp^{\,2}$$

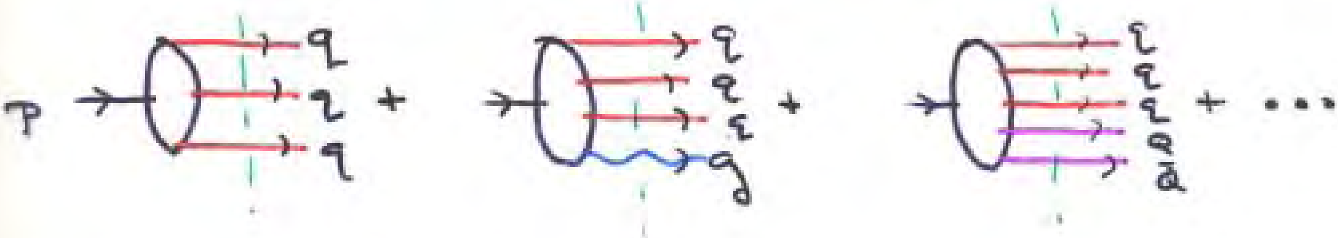
$$\boxed{H^{LC}_{QCD} \, | \Psi \rangle = \mathcal{M}^2 \, | \Psi \rangle}$$

eigenvalues of H^{LC}_{QCD} $\begin{cases} \text{bound state} \\ \text{continuum soln's} \end{cases}$

eigenfunctions of H^{LC}_{QCD} $\begin{cases} \text{wavefunctions} \\ \text{scattering states} \end{cases}$

- * independent of P^+, $P_\perp$!
- * J_z conserved
- * Minkowski space, no fermion doubling
- * Direct connection to physics
- * vacuum trivial (possible zero modes)

Light-Cone Fock Representation of Hadrons



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

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

- 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, Schmidt

- Properties of heavy quark sea — $s(x) \neq \bar{s}(x)$
  extrinsic vs intrinsic
  physics of $\Delta\Sigma_1$, anomaly
  Pauli
  Kogan, Ma, Schmidt, SJB, Schlumpf

Discretized Light-Cone Quantization

– program for solving quantum field theory

Heisenberg

* $\boxed{\text{Diagonalize } H_{LC}!}$

SJB + H-C Pauli
Eller, Hornbostel
Burkardt, Thorn
Hiller, McCartor

$$H_{LC}|\Psi\rangle = M^2|\Psi\rangle$$

$$\langle n|H_{LC}|m\rangle\langle m|\Psi\rangle = M^2\langle n|\Psi\rangle$$

$|n\rangle$: e.states of H^0_{LC}

* Periodic, anti-periodic boundary conditions

$$k_i^+ = \frac{2\pi}{L} n_i \quad , \quad P^+ = \frac{2\pi}{L} K$$

$$\sum_i n_i = K \quad , \quad n_i > 0$$

LFTD: Wilson, Perry, Glazek

finite matrix repn of QFT

Review: SJB, Pauli, Pinsky

Connection to M-theory: Susskind, Klebanov, Antonuccio et al

Hiller
McCartor
SJB

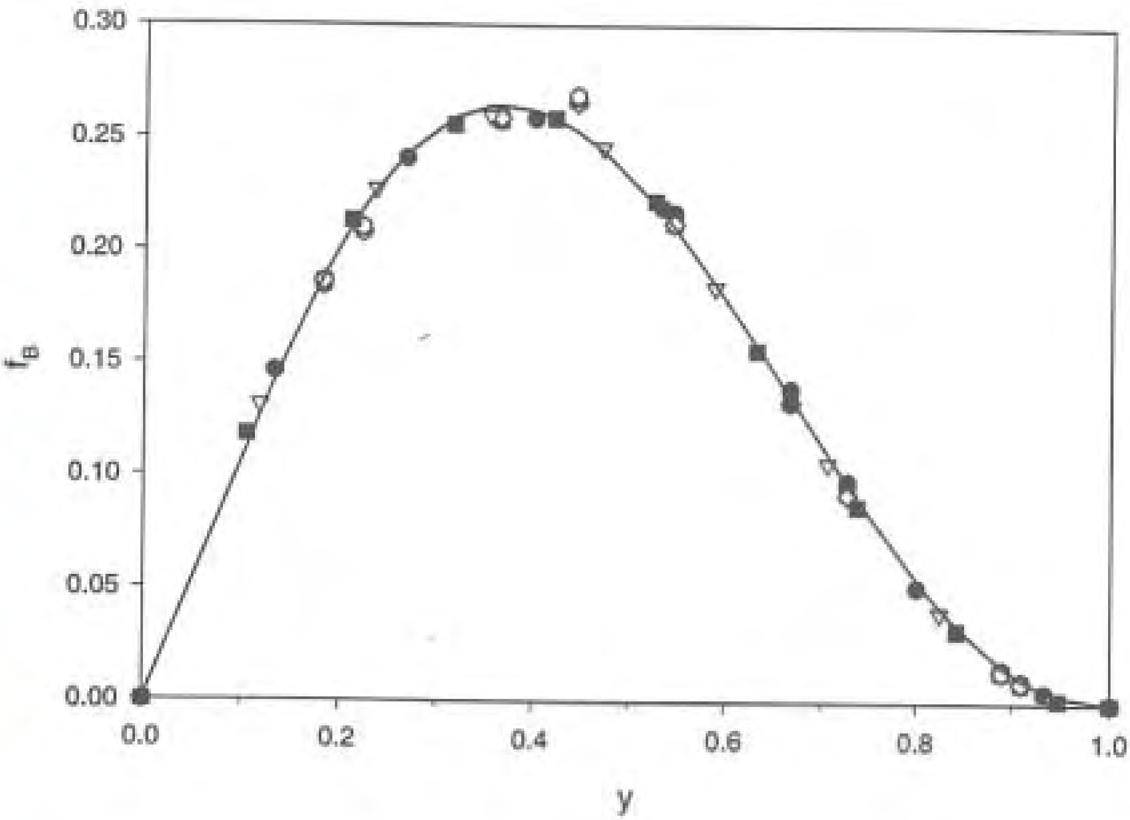


Figure 1: The boson distribution function f_B at various numerical resolutions, with $\langle :\phi^2(0): \rangle = 1$, $\Lambda^2 = 50\mu^2$, and $\mu_1^2 = 10\mu^2$. The solid line is the parameterized fit.

Structure Function $f_B(y)$
for Fermion eigenstate

$M = \mu$, $\langle : \phi^2(0) : \rangle = 1$

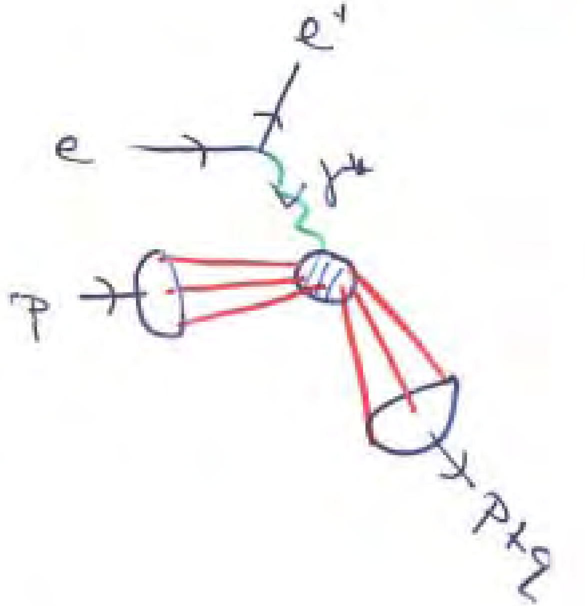
Form Factors at large momentum transfer

SJB + G.P. Lepage

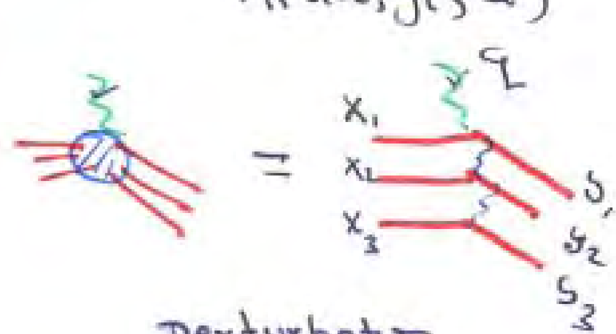
Duncan + Mueller

Factorization of soft and hard dynamics

↑ e.g. quark confinement



$T_H(x_i, y_i, Q)$



perturbation theory

⇒ hard scattering

$$\Rightarrow \quad F_p(Q^2) = \int_0^1 \pi\, dx_i \int_0^1 \pi\, dy_i \; \phi_p(x_i, Q)\; T_H \; \phi_p(y_i, Q)$$

$$* \quad F_p^1(Q^2) \sim \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^2 \qquad \left(T_H \sim \left(\frac{1}{Q^2}\right)^{n-1} \cdot f(x_i, y_i)\right)$$

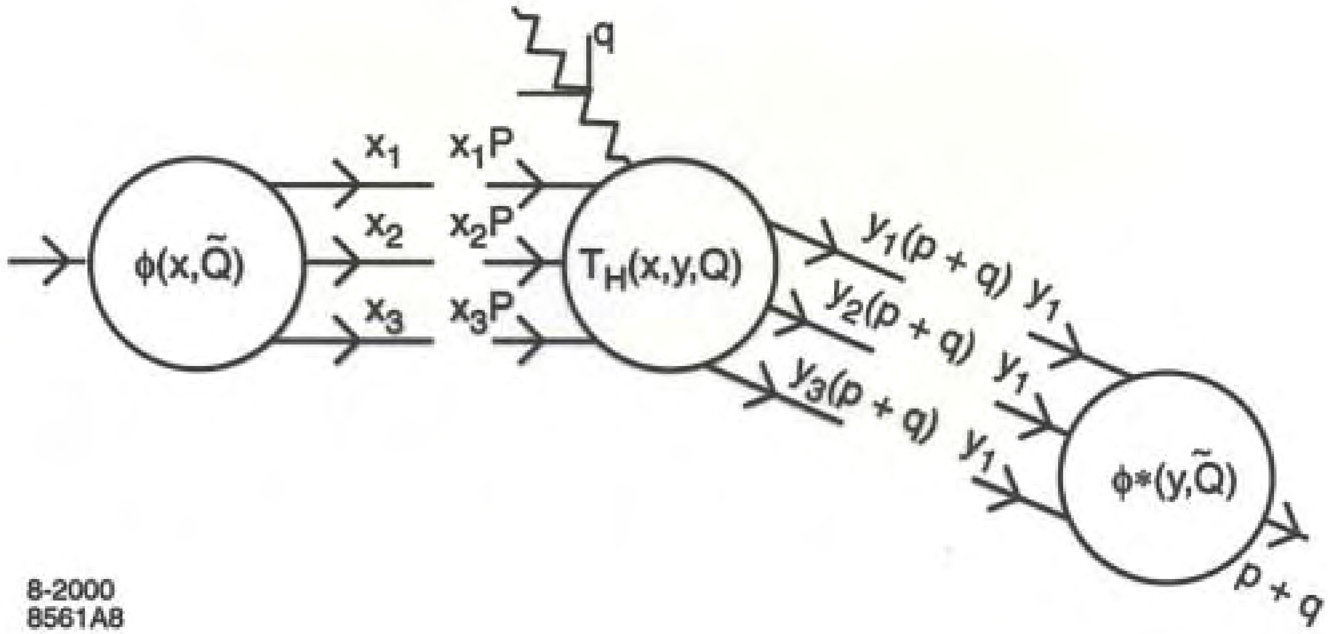
$*$ Had. helicity conserved: $F_2/F_1 \sim \frac{1}{Q^2}$

$$* \quad \phi_p(x_i, Q) = \int^{Q^2} \pi\, d^2k_{\perp i}\; \psi_{val}(x_i, k_\perp)$$

non-pert. universal

$$\simeq \phi(x_i, b_\perp = 1/Q)$$

controls normal.



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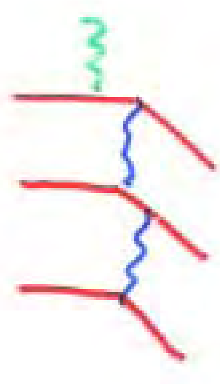


$$\frac{\alpha_s^2(Q^*)}{Q^4}$$

high $Q^2 = -q^2$

$Q^2 \gg \langle k_\perp^2 \rangle$

T_H

ϕ

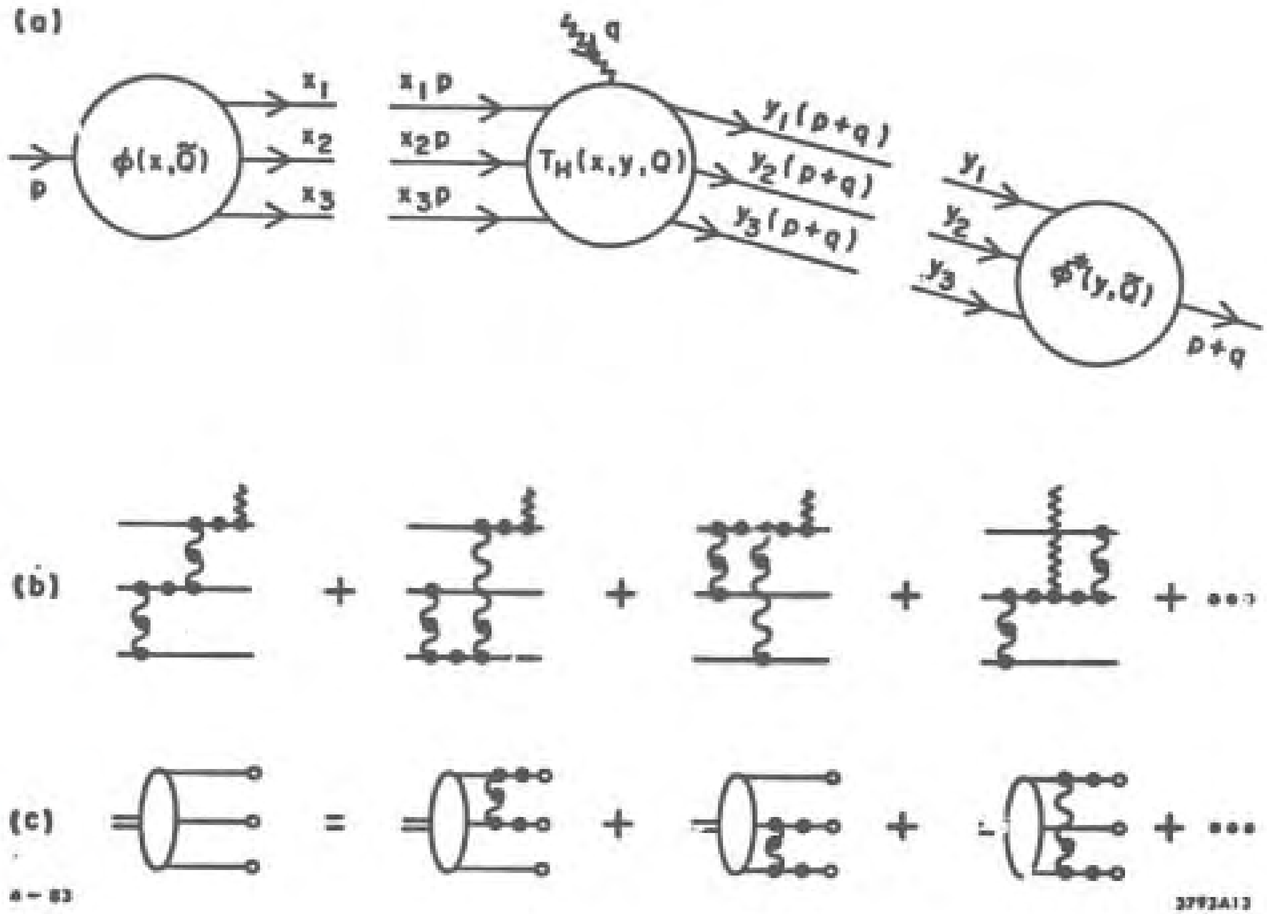


Figure 19. (a) Factorization of the nucleon form factor at large Q^2 in QCD. (b) The leading order diagrams for the hard scattering amplitude T_H. The dots indicate insertions which enter the renormalization of the coupling constant. (c) The leading order diagrams which determine the Q^2 dependence of the distribution amplitude $\phi(x, Q)$.

Calculation of proton form factor in PQCD

Lepage + SJB

Chernyak + Zhitnitsky

Radyushkin

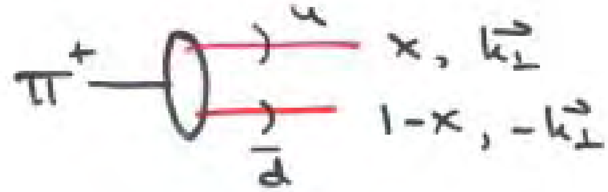
Mueller, Duncan

Feynman endpoint: Kroll et al

G.P. Lepage
SJB

Pion Distribution Amplitude

$$\phi_\pi(x,Q^2) = \int \frac{d^2k_\perp}{16\pi^2}\, \psi^{(Q)}_{q\bar{q}/\pi}(x,\vec{k}_\perp)$$



$$\sim \psi_{q\bar{q}/\pi}\left(x,\, b_\perp \sim O\left(\tfrac{1}{Q}\right)\right)$$

$$\phi_\pi(x,Q) = \int \frac{dz^-\, P_\pi^+}{4\pi}\, e^{ixP_\pi^+ z^-/2}$$

$$\langle 0|\bar{\psi}(0)\frac{\gamma^+\gamma^5}{2\sqrt{2n_c}}\psi(z)|\pi\rangle^{(Q)}\Big|_{z^+=\vec{z}_\perp=0}$$

$P\exp\int_0^1 ds\, i g\, A(sz)\cdot z = 1$ in $A^+=0$ gauge

$$= \int \frac{dk^-}{2\pi}\, \psi_{BS}(k,p)$$

obeys: OPE, RGE, Evolution Eq.

$\phi_M(x_i, Q)$

Hadron Distribution Amplitude

- key non-perturbative input to hadronic exclusive processes at large momentum transfer

Rigorous results

$$\phi(x_i, Q) \equiv \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-n\gamma_n/2\beta_0}$$

$$\int \prod_{i=1}^{n} \{d^2k_\perp^{(i)}\, \Theta(Q^2 - M_n^2)\}\, \delta^{(2)}(\Sigma k_\perp^{(i)})\, \psi^{val}(x_i, k_\perp^{(i)})$$

$$\phi_M(x_i, Q) = x_1 x_2 \sum_n a_n\, C_n^{3/2}(x_1 - x_2) \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n/2\beta_0}$$

Lepage SJB Efremov Radyushkin

non-perturbative input

from conformal symmetry

$$\zeta(Q^2) = \frac{1}{2\pi}\int^{Q^2} \frac{d\ell^2}{\ell^2}\, \alpha_s(\ell^2)$$

deviations from conformal symmetry

$$e^{-\gamma_n \zeta(Q^2)} \Rightarrow \left(\ln Q^2/\Lambda^2\right)^{-\gamma_n/2\beta_0}$$