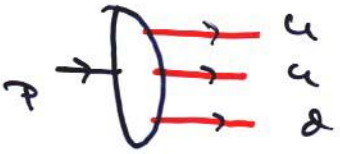
Theory Tools

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



- interpolate between hadronic and QCD degrees of freedom
- Light-Front quantization
- gauge coherence
  - * Color filter; color transparency
  - * diffraction; rapidity gaps
- effective charges $\alpha_s(Q^2)$
  - * commensurate scale relations
- conformal aspects of QCD
  - * infrared fixed point
  - * dimensional counting rules
  - * AdS/CFT correspondence
- Abelian limit ($N_C \to 0$).

Predictions from conformal QCD:
+ $AdS_5 \times S^5$ + large N_c

large Q^2
Form Factors

$$F(Q^2) \sim \left(g_{YM}^2 N_c\right)^{\frac{(n-1)}{2}} \left(\frac{\Lambda_0}{Q}\right)^{2n+|h_i|-2}$$

$$F_2(Q^2)/F_1(Q^2) \sim \left(\frac{M\Lambda_0}{Q^2}\right)$$

mod logs, anom. dim.

$$\mathcal{M}(Q^2)_{AB\to CD}$$

Polchinski - Strassler

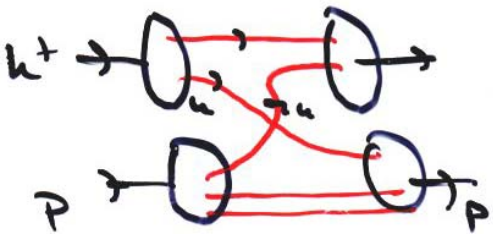
$$\sim \frac{\left(g_{YM}^2 N_c\right)^{\frac{1}{4}(n_\tau-2)}}{N_c} \left(\frac{\Lambda_0}{Q}\right)^{n+|h_i|-4}$$

← QIM

$$n_\tau = n_A + n_B + n_C + n_D$$

BF, MMT

- Non-perturbative derivation
- large N_c : QIM dominant



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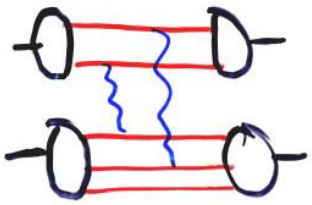


Suppressed at large N_c

Nuclear Chromodynamics

Nuclei provide new testing ground for QCD

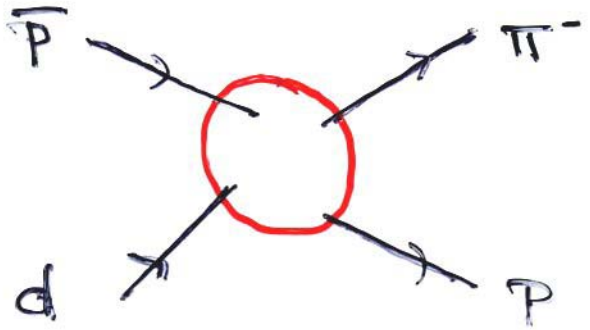
nuclear properties:

- pQCD predicts for nuclear amplitudes
- $F_d(Q^2)$, $\gamma d \to np$
- hidden color
- nuclear-bound quarkonium

nuclear environment

- Shadowing, anti-shadowing ← not in Ψ_A!
- jet energy loss
- tests of factorization
- color transparency,
- nuclear-coherent reactions
- nuclear dissociation of hadrons

Important hard exclusive process



$$\frac{d\sigma}{dt} = \frac{1}{s^{12}} F(t/s)$$

conformal prediction

Reduced amplitude formalism

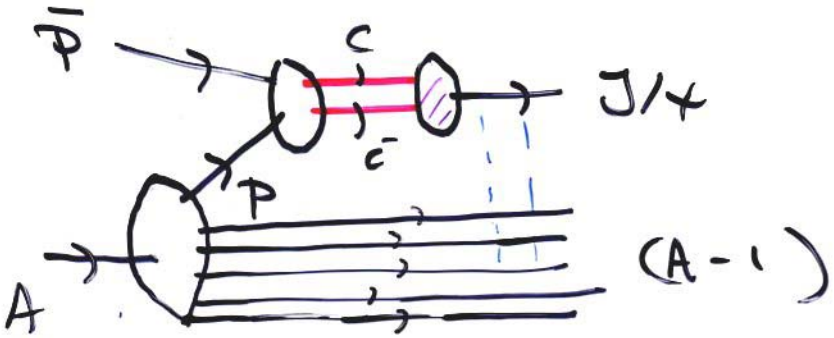
Crossing to $pp \to d\pi^+$

$\pi^+ d \to pp$

Hidden color

$$\bar{p} A \to \left[J/\psi (A-1) \right] \to \mu^+\mu^- (A-1)$$

Form charm inside of nucleus

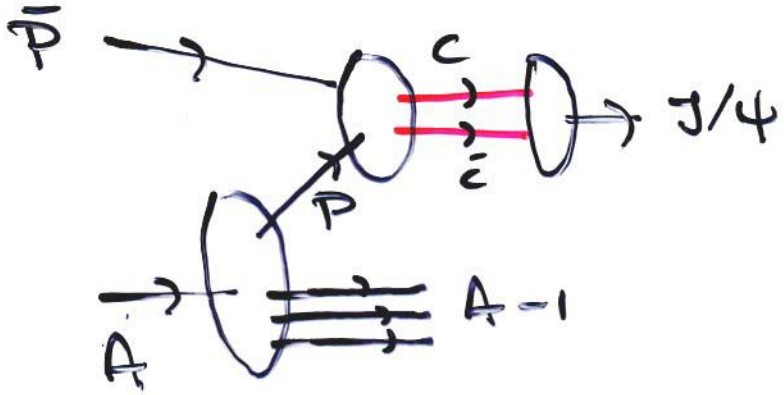


+ inelastic

mass change ?

- Place J/ψ in center of nucleus at low v_{rel}
- $\sigma \sim Z\sigma_N$? (small part of $\bar{p}$ cs.)
- strong enhancement via Fermi-motion
- Subthreshold production (Y possible!)
- nuclear bound quarkonium via
- QCD Van der Waals
- Modify J/ψ mass, width, decays
- $J/\psi \to p\pi$: final state absorption

Use $\bar{p}A \to J/\psi(A-1)$ to measure relativistic nuclear wavefunction



$$x = \frac{p^+}{p_{A^+}}$$

- measures $\frac{dN}{dx\, d^2k_\perp} = |\psi_{p/A}(x, k_\perp)|^2$

Blankenbecler Gunion, SJB

- measure absorption of $\bar{p}$ color transparency?

- measure absorption of J/ψ in nucl. matt. different for $J/\psi \to \bar{p}p$ vs $\ell^+\ell^-$?

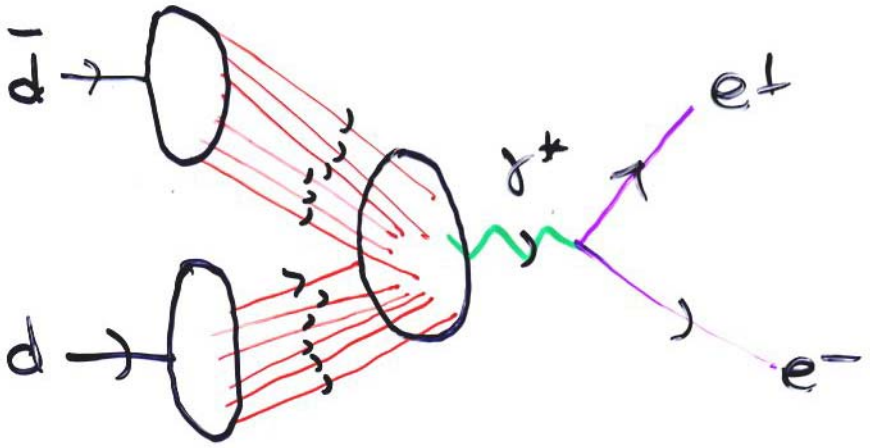
Store antideuterons at GSI

Study complete nuclear annihilation

$d\bar{d} \to \pi^+\pi^-, K^+K^-, p\bar{p}, \Lambda\bar{\Lambda}, \Lambda_c\bar{\Lambda}_c$

$\gamma\gamma, e^+e^-$

$p\bar{p}\, J/\psi, \quad p\bar{p}\, D\bar{D}$



crossing ↓

deuteron f.f.

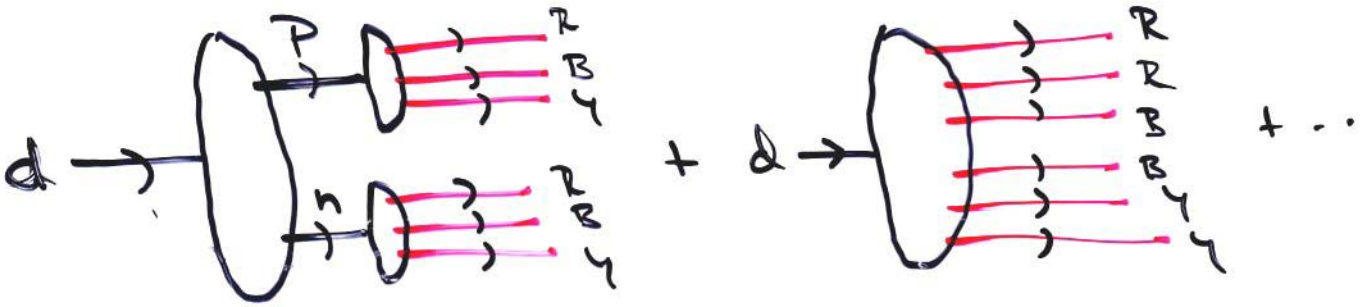
$ed \to e'd'$

pQCD: $F_d(Q^2 = s) \sim \frac{1}{s^5}$ large coupl.

Hidden color enhancement.

Six-quark deuteron wavefunction

contains "hidden color" components



5 color singlet combinations

$$3_c \times 3_c \times 3_c \times 3_c \times 3_c \times 3_c$$

$$= 1_c + 1_c + 1_c + 1_c + 1_c + \cdots$$

equal weight as $b_i^i \to 0$.

Large, J_i, BB

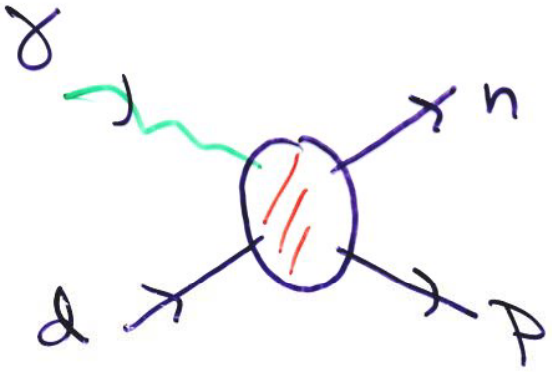
Needed to understand normalization of $Q^5 F_d(Q^2)$

Farrar et al

Deuteron

Photodisintergretion

$$\gamma d \to n p$$



1 + 6 + 3 + 3

= 13

PQCD predicts (modulo logs)

$$\frac{d\sigma}{d\cos\theta_{cm}} \Rightarrow \frac{1}{s^{11}} F(\theta_{cm})$$

Conformal Prediction

Hidden color

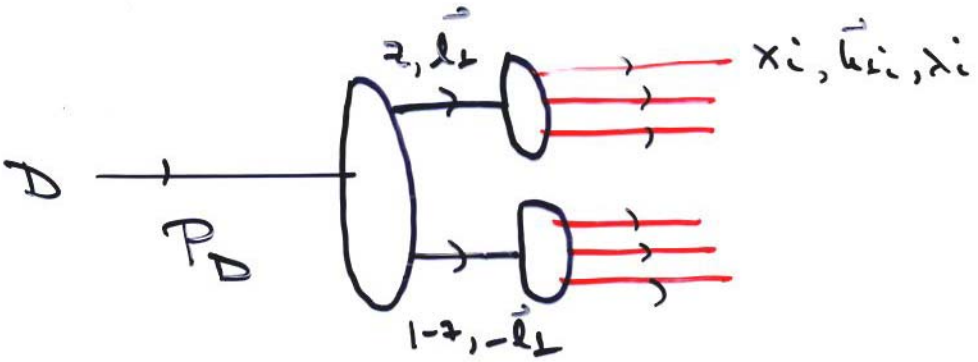
Cluster decomposition theorem

C. Ji + SJB
J. Nagy (Lowell)

$$\lim_{BE\to 0} \psi^D_{uud\,udd}(x_i, \vec{k}_{\perp i}, \lambda_i) = \int_0^1 dz \int d^2\ell_\perp \, \psi^d_{(z,\ell_\perp)}$$

$$\times \; \psi^{\uparrow}_{uud}\left(x_i/z, \vec{k}_{\perp i} - \frac{x_i}{z}\vec{\ell}_\perp, \lambda_i\right)$$

$$\times \; \psi^{n}_{uud}\left(\frac{x_i}{1-z}, \vec{k}_{\perp i} + \frac{x_i}{1-z}\vec{\ell}_\perp, \lambda_i\right)$$



combine
l.c. time ordering
take BE→0.

$$\sum_{i=1}^{6} x_i = 1 \;, \quad \sum_{i=1}^{6} \vec{k}_{\perp i} = 0$$

$$\sum_{i=1}^{2} \frac{x_i}{z} = 1 \;, \quad \sum_{i=1}^{3} \vec{k}_{\perp i} - \frac{x_i}{z}\vec{\ell}_\perp = 0$$

Proof simple since l.c. energies are additive

F.T. : Lunde + Noyes

Duality

$\sum$ hadron degrees of freedom

= QCD (q, g) degrees of freedom

* Bloom Gilman duality in DIS @ fixed W^2

QCD : $q(x) \sim (1-x)^3$ $\uparrow \to \uparrow$

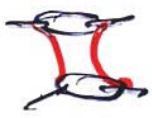
$(1-x)^5$ $\uparrow \to \downarrow$

no DGLAP evolution of

fixed $W^2 = Q^2 \frac{(1-x)}{x}$

$(1-x)^p \Rightarrow F_2(Q^2) \sim \left(\frac{1}{Q^2}\right)^{p+1}$

* $\sum$ meson exchange = $q\bar{q}$ exchange



Outstanding Spin Problems

* 1. A_{NN} in $\frac{d\sigma}{dt}(pp \to pp)\Big|_{90°}$

$\sqrt{s} = 5$ GeV

ANL, BNL

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

e+e−

* 3. $pp \to \psi' X$ at high p_T

Longitudinal Pol.

CDF

* 4. $\pi N \to \mu^+\mu^- X$ angular corr.

CP, NA10

* 5. $F_2(Q^2) / F_1(Q^2) \neq \frac{C}{Q^2}$

$Q^2 > 3$ GeV^2 Jeff Lab

Polarization studies in $\bar{p}p$

Single spin asymmetries:

transversity in Drell-Yan !

P_y : G_E/G_M in time-like domain

:

Highly sensitive to QCD dynamics

at amplitude level.

FSI / ISI mechanisms

ANN in $\bar{p}p$!

Summary — Novel Aspects of QCD

* New insights into Fundamental QCD Mechanisms

* Manifestation of point-like quark, gluon interactions
  gauge theory, coherence

* Simple Scaling laws - Counting Rules
  - conformal aspects of QCD ⇔ AdS/CFT

* "Color-Transparency" $\pi A \to$ Jet Jet X
  - fluctuating color structure of hadrons

* Final State - Gluon Interactions
  - SSA, Diffractive DIS
  - DIS not determined by WFs alone!

* Nuclear Effects
  Hidden Color! Gluon Avalanche!
  Shadowing - Antishadowing
  q-G Plasma!

* Light-Front Quantization { Relativistic Quantum Mechanics

Summary : Anti-protons $E_{Lab} \leq 15$ GeV

→ New window to QCD

- novel effects, hadron structure, dynamics
- remarkable nuclear effects, color transparency

- $\bar{p}p \to e^+e^-, \gamma\gamma, M\bar{M}, B\bar{B}$
- $\bar{p}d \to$ hidden color, reduced amplitude

- Exotic charm effects
  $\bar{p}c\bar{c}p$, $u\bar{u}d\bar{c}\bar{s}$
- Intrinsic charm, threshold effects
- polarization important, SSA, G_E/G_M
- anti-deuteron beams
- anti-hydrogen

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
- Hard Exclusive Processes
- Reduced Nuclear Amplitude
- Exotic States

Nuclear Chromodynamics

⇒ Scientific revolution

- Confined / PQCD predictions for hard nuclear amplitudes
- Hidden color
- Reduced nuclear amplitudes
- Nuclear bound quarkonium
- Color Transparency
- Shadowing / Anti-shadowing
- :