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Two Scales of the Hadronic Structure

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These are preliminary lecture notes, intended only for distribution to participants
Two scales of the hadronic structure

Search for clean signatures in the data

Bogdan Povh
• Introduction
• Diffractive cross section is surprisingly small
• Hadronic cross sections rise slowly
• Diffractive cone hardly shrinks with energy
• Gluon shadowing is weak
• Conclusion "anschaulich"
The first evidences for the smallness of the gluonic clouds come from the ISR-experiments but they have been formally interpreted within the Regge-phenomenology with no connection to hadronic structure (small triple pomeron coupling)
I will reinterpret the data in a less formal way, showing that the weakness of diffraction is related to smallness of gluonic clouds. I will argue that the radius of the gluonic spots suggested by data is about 0.3 fm. This is small as compared to the confinement radius of 1 fm (in fact one has to compare these numbers squared)
Introduction

Theoretically small $r_0 = 0.3$ fm is not a surprise.

1. Lattice-calculation
2. Instanton-liquid model
3. Quark model with gluons of $m_g = 0.8$ GeV
Introduction

Any high energy reaction via the strong interaction carries the information on the size of the gluon cloud. But, in general, cannot be unambiguously interpreted.

Diffraction seems to be the unique way to probe directly the gluonic structure of hadrons.
At high energies and large $M_x$ diffraction is dominated by gluon bremsstrahlung.

Colorless exchange
At low energies the neutral object is $q\bar{q}$ exchange (Regge exchange) but the cross section drops with energy $\sim s^{-1/2}$ and $M_x$ dependence

\[ \frac{d\sigma_{dd}}{dM_x^2} \propto \frac{1}{M_x^3} \]

The gluon bremsstrahlung gives different $M_x$ dependence because the gluon is a vector particle

\[ \frac{d\sigma_{dd}}{dM_x^2} \propto \frac{1}{M_x^2} \]
Diffraction

The $1/M^2$ mass distribution at fixed $s$ and $t$ is the signature of gluon bremsstrahlung.

Analogy to photon bremsstrahlung

$$\frac{d\sigma}{d\omega} \propto \frac{1}{\omega},$$

$$M_x^2 \propto \frac{1}{\omega} \rightarrow \frac{d\sigma_{dd}}{dM_x^2} \propto \frac{1}{M_x^2}$$

in spite of the difference of photon and gluon.
Diffraction
Diffractive

Inclusive cross section for the reaction $pp \rightarrow pX$ at ISR
\[
\frac{d^2 \sigma}{dM_x^2 dt} \approx \left( g_{pp}^P(t) \right)^2 \left( \frac{s}{M_x^2} \right)^{n=1} \frac{\sigma_{PP}(M_x)}{M_x^2}
\]

\[\ln \left( \frac{s}{M_x^2} \right) = \text{rapidity gap}\]

P: Pomeron

scaling

 gluon bremsstrahlung

\((g_{pp}^P)^2 \sim \sigma_{tot}\)
Diffraction

\[ \sigma_{Pp}^{tot} = \left( \frac{M_x^2}{s} \right)^n \left( g_{pp}^P(t) \right)^2 M_x^2 \frac{d^2 \sigma}{dM_x^2 dt} \approx 2mb \]

naïve expectation:

\[ \sigma_{Pp}^{tot} \approx \frac{9}{4} \sigma_{pp}^{tot} \approx 50mb \]

The Pomeron-proton total cross section
The gluon cloud of the valence quark is small.

\[ r_0^2 = 0.1 \text{ fm}^2 \]

Neither the single gluon comes far from the quark nor two gluons can couple to the color singlet if they are more than 0.3 fm apart.
Similar results are obtained in diffraction in DIS from the H1 and ZEUS data by Hauptmann und Soper.

\[ r_0 = 0.2 \text{ fm} \]
Proton-proton cross section

Schematic total cross sections of pions, kaons, protons/antiprotons and photons on the proton
Proton-proton cross section

\[ \sigma_{tot} \propto R^2 \]

The transverse distances between the quarks are independent.
The s dependence comes from the gluon bremsstrahlung.

\[ R^2(s) = R_0^2 + nr_0^2 \]

\[ x = \left( \frac{1}{2} \right)^n x_0 \quad n = \ln \frac{x_0}{x} / \ln 2 \]

\[ R^2(s) = R_0^2 + \frac{1}{\ln 2} r_0^2 \ln \frac{x_0}{x} \approx R_0^2 + r_0^2 \ln \frac{s}{s_0} \approx R_0^2 \left( \frac{s}{s_0} \right)^\varepsilon \]

\[ \varepsilon = \frac{r_0^2}{R_0^2} \]
Proton-proton cross section

Our model: Kopeliovich, Potashnikova, bp and Predazzi

\[ \sigma_{tot} = \sigma_0 + 3 \frac{9}{4} C \cdot r_0^2 \left( \frac{s}{s_0} \right)^\Delta \approx \sigma_0 \left( \frac{s}{s_0} \right)^\varepsilon \]

\[ \sum_n \sigma_{qN}^n = \sum_n \frac{1}{n!} \left[ \frac{4\alpha_s}{3\pi} \ln \frac{s}{s_0} \right]^n \frac{9}{4} C \cdot r_0^2 \]

\[ \Delta = \frac{4\alpha_s}{3\pi} = 0.17 \]

\[ B_n = \frac{2}{3} \left< r_{ch}^2 \right> + \frac{n r_0^2}{2} \]

\[ B = \frac{2}{3} \left< r_{ch}^2 \right> + 2\alpha' \ln \frac{s}{s_0} \]

Our prediction: \( \alpha' = \frac{\alpha_s}{3\pi} r_0^2 = \frac{\Delta}{4} r_0^2 = 0.1 GeV^{-2} \) 

Experiment: \( \alpha' = 0.25 GeV^{-2} \)
Proton-proton cross section

Differential cross sections of elastic pp and pp scattering.

Imaginary part of partial amplitude as a function of the impact parameter.
Proton-proton cross section

\[ \sigma_{\text{tot}}(\text{mb}) \]

\[ B_{\text{el}}(\text{GeV}^{-2}) \]

pp (solid circles) and \( \bar{p}p \) (open circles) cross sections at \( s^{1/2} > 10 \text{ GeV} \)

elastic slope and our predictions
Photoproduction of $J/\psi$

It is good to have a hadron-proton elastic scattering far away from the unitary limit.

\[ \gamma^* + p \rightarrow J/\psi + p \]

$\Delta$ and $\alpha'$ agree with our parameters before the unitary correction.
Photoproduction of J/$\psi$

Differential cross sections for the exclusive photoproduction of J/$\psi$. 
Photoproduction of J/ψ

Values of the slope $b$, of the $t$ distribution, plotted as a function of $W$.

$$B = B_0 + 2\alpha' \ln \left( \frac{s}{s_0} \right) = B_0 + 4\alpha' \ln \left( \frac{W}{W_0} \right)$$

$\alpha' = 0.1$
\[ \varepsilon = 0.2 \]
Figure 1: $\lambda_{\text{eff}}$ as a function of $Q^2$. The estimate for the ZEUS REGGE97 and ZEUS QCD 01 parametrizations are also shown.
Gluon shadowing

Boost

Reduction of the gluon density by $x$
PQCD gives huge shadowing.

Observed small.

For shadowing one needs also transverse overlap.
Chew-Frautschi plot
The Regge trajectory simulates the collective effect of exchanging all members of a family of particles. When $t$ is negative it is the square of the momentum transferred in the exchange. Positive $t$ is the squared mass of the physical particles of spin 1, 3, 5,...
Conclusion "anschaulich"

For linear potential (string) gives $m^2 \sim J$

\[
\alpha'_{\rho} = \frac{1}{2\pi\kappa} = 0.9 \text{GeV}^{-2}
\]

\[
\kappa = \frac{1 \text{GeV}}{\text{fm}}
\]

naive expectation for $\alpha'_P = \frac{4}{9} \times 0.9 \text{GeV}^{-2} = 0.4 \text{GeV}^{-2}$

measured $\alpha'_P = 0.1 \text{GeV}^{-2}$

$\kappa_P = 8 \text{GeV/fm}$
Backup Slides
Color glass condensate = gluon shadowing as function of $k_\perp$

One would expect:

$$\frac{G_A}{A \cdot G_N}$$
\[
M_x^2 = \frac{k_T^2}{x(1-x)} + \frac{m_h^2}{1-x}
\]

\[
M_x^2 = \frac{k_T^2}{\omega / E_h} = \frac{k_T^2}{\omega} \cdot E_h
\]

\[
dM_x^2 \propto \frac{d\omega}{\omega^2}, d\omega \propto \omega^2 dM^2 \propto \frac{dM^2}{M^4}
\]

\[
\frac{d\sigma}{d\omega} \propto \frac{1}{\omega} \rightarrow \frac{d\sigma}{dM^2} \propto \frac{1}{M^2}
\]
**Photoproduction of J/ψ**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$J/ψ → μ^+μ^-$</th>
<th>$J/ψ → e^+e^-$</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$</td>
<td>0.67 ± 0.03 ± 0.05</td>
<td>0.695 ± 0.021 ± 0.028</td>
<td>Fits to $\sigma \propto (W/90\text{GeV})^x$</td>
</tr>
<tr>
<td>$W$ range</td>
<td>$30 &lt; W &lt; 170 \text{ GeV}$</td>
<td>$35 &lt; W &lt; 290 \text{ GeV}$</td>
<td></td>
</tr>
<tr>
<td>$b_0 (\text{GeV}^{-2})$</td>
<td>$4.23 ± 0.07^{+0.10}<em>{-0.12}^{+0.085}</em>{-0.051}$</td>
<td>$4.11 ± 0.08^{+0.33}<em>{-0.09}^{+0.08}</em>{-0.16}$</td>
<td>Fits to Eq. (2)</td>
</tr>
<tr>
<td>$\alpha'_B (\text{GeV}^{-2})$</td>
<td>$0.098 ± 0.037 ± 0.040 ± 0.001$</td>
<td>$0.128 ± 0.037^{+0.008}_{-0.025} ± 0.005$</td>
<td></td>
</tr>
<tr>
<td>$\alpha'_B(0)$</td>
<td>$1.198 ± 0.011 ± 0.015$</td>
<td>$1.204 ± 0.015^{+0.004}<em>{-0.013}^{+0.008}</em>{-0.008}$</td>
<td>Fits to Eq. (1)</td>
</tr>
<tr>
<td>$\alpha'_B (\text{GeV}^{-2})$</td>
<td>$0.099 ± 0.023 ± 0.020$</td>
<td>$0.136 ± 0.031^{+0.008}_{-0.020}$</td>
<td></td>
</tr>
<tr>
<td>$t$ range</td>
<td>$-t &lt; 1.8 \text{ GeV}^2$</td>
<td>$-t &lt; 1.25 \text{ GeV}^2$</td>
<td></td>
</tr>
</tbody>
</table>

Measurements of $\delta$, $b_0$, $\alpha'$ and $\alpha(0)$ obtained separately from the electron and muon decay channels.