Proton Structure from High Energy Proton-Proton and Antiproton-Proton Elastic Scattering

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Abstract

Our phenomenological investigation of high energy pp and p̄p elastic scattering and study of the gauged Gell-Mann-Levy linear σ-model using path-integral formalism have led us to a physical picture of the proton structure. Namely, proton is a **Condensate Enclosed Chiral Bag**. Based on this picture, our prediction of pp elastic scattering at c.m. energy 7 TeV is discussed against the backdrop of recent measurements of elastic pp $d\sigma/dt$ at LHC by the TOTEM Collaboration at $\sqrt{s} = 7$ TeV.

Accelerator	$\sqrt{s}$	
CERN ISR	23 – 62 GeV	(pp)
Fermilab	27.4 GeV	(pp)
CERN SPS	546, 630 GeV	($\bar{p}p$)
Tevatron	1.8 TeV	($\bar{p}p$)

Models of Nucleon Structure

1. Skyrmion Model

2. MIT Bag Model

3. Little Bag Model

4. Topological Soliton Model

5. Chiral Bag Model, etc.

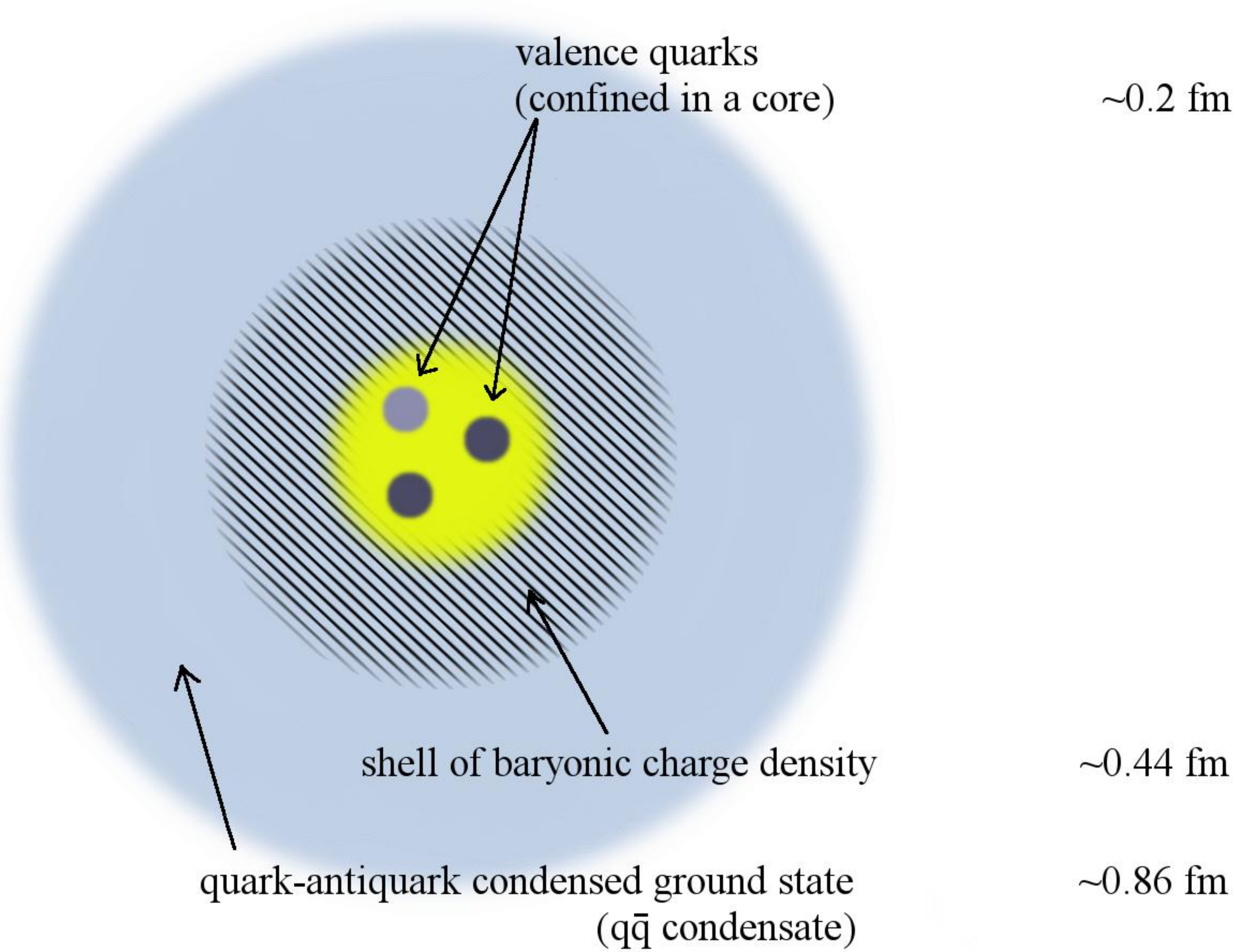


Fig.1. Physical picture of the proton – a Condensate Enclosed Chiral Bag

Gell-Mann-Levy linear σ-model

$$\mathcal{L} = \bar{\psi}\, i\, \gamma^{\mu}\partial_{\mu}\psi + \frac{1}{2}\left(\partial_{\mu}\sigma\, \partial^{\mu}\sigma + \partial_{\mu}\vec{\pi}\, \partial^{\mu}\vec{\pi}\right) - G\bar{\psi}[\sigma + i\, \vec{\tau}\cdot\vec{\pi}\, \gamma^{5}]\psi$$
$$- \lambda(\sigma^2 + \vec{\pi}^2 - f_{\pi}^2)^2$$

$$\sigma(x) + i\, \vec{\tau}\cdot\vec{\pi}(x) = \zeta(x)U(x), \qquad \zeta(x) = \sqrt{\sigma^2(x) + \vec{\pi}^2(x)}$$

Using right and left fermion fields:

$$\psi_{\mathrm{R}}(x) = \tfrac{1}{2}(1+\gamma^5)\, \psi(x), \qquad \psi_{\mathrm{L}}(x) = \tfrac{1}{2}(1-\gamma^5)\, \psi(x)$$

$$\mathcal{L} = \bar{\psi}_{\mathrm{R}}\, i\, \gamma_{\mu}\, \partial_{\mu}\psi_{\mathrm{R}} + \bar{\psi}_{\mathrm{L}}\, i\, \gamma^{\mu}\, \partial_{\mu}\psi_{\mathrm{L}} + \frac{1}{2}\partial_{\mu}\zeta\, \partial^{\mu}\zeta + \frac{1}{4}\zeta^2 tr\left[\partial_{\mu}U\, \partial^{\mu}U^{\dagger}\right]$$
$$-G\, \zeta\left[\bar{\psi}_{\mathrm{L}}U\, \psi_{\mathrm{R}} + \bar{\psi}_{\mathrm{R}}\, U^{\dagger}\, \psi_{\mathrm{L}}\right] - \lambda(\zeta^2 - f_{\pi}^2)^2$$

$$U(x) = \exp[i\, \vec{\tau}\cdot\frac{\vec{\varphi}(x)}{f_{\pi}}] \qquad (f_{\pi} \simeq 93\ \mathrm{MeV})$$

Hidden gauge symmetry

$$\mathcal{V}_\mu = -\frac{i}{2}\, g[\vec{\tau} \cdot \vec{\rho}_\mu + \omega_\mu]$$

Left gauge field $A_\mu^L(x)$ Right gauge field $A_\mu^R(x)$

$$\mathcal{L}_\mathrm{q} = \bar{\psi}_\mathrm{L}\, i\, \gamma^\mu \big(\partial_\mu + A_\mu^\mathrm{L}\big)\psi_\mathrm{L} + \bar{\psi}_\mathrm{R}(x)\, i\, \gamma^\mu \big(\partial_\mu + A_\mu^\mathrm{R}\big)\psi_\mathrm{R}$$
$$-G\, \zeta\, [\bar{\psi}_\mathrm{L}\, U\, \psi_\mathrm{R} + \bar{\psi}_\mathrm{R}\, U^\dagger\, \psi_\mathrm{L}]$$

$$\int d\psi \;\; d\psi^{\dagger} = e^{i\,\Gamma[U,\mathcal{V}]} \int d\psi^{0}\, d\psi^{0\,\dagger}$$

Action functional of the model:

$$e^{i\,W[U,\zeta,\mathcal{V},\psi,\psi^{\dagger}]}$$

$$= \frac{1}{\mathcal{N}} \int dU\, d\zeta\, d\psi^{0}\, d\psi^{0^{\dagger}} \cdot e^{i\,\Gamma_{WZW}[U,\mathcal{V}]+i\,S[U,\zeta,\mathcal{V}]+i\,S[\zeta,\psi^{0},\psi^{0^{\dagger}},\mathcal{V}]}$$

$$S[U,\zeta,\mathcal{V}] = \int d^4x\, \mathcal{L}_U(U,\zeta,\mathcal{V})$$

$$S\left[\zeta,\psi^{0},\psi^{0^{\dagger}},\mathcal{V}\right] = \int d^4x\, [\bar{\psi}^{0}\; i\,\gamma^{\mu}\left(\partial_{\mu}+\mathcal{V}_{\mu}\right)\psi^{0} \; + \frac{1}{2}\,\partial_{\mu}\zeta\,\partial^{\mu}\zeta$$

$$-G\,\zeta\,\bar{\psi}^{0}\psi^{0} - \lambda(\zeta^2 - f_{\pi}^{2})^2]$$

$\psi^{0}(x)$, $\psi^{0^{\dagger}}(x)$ transform only under the hidden symmetry

$$\zeta(x) = f_\pi$$

$$e^{iW[U,\zeta,\mathcal{V},\psi,\psi^\dagger]} \simeq \frac{1}{\mathcal{N}} \int dU\, e^{i\Gamma_{WZW}[U,\mathcal{V}] + iS[U,f_\pi,\mathcal{V}]} \int d\zeta\, d\psi^0\, d{\psi^0}^\dagger e^{iS[\zeta,\psi^0,{\psi^0}^\dagger,\mathcal{V}]}$$

The combined action $\Gamma_{WZW}[U,\mathcal{V}] + S[U,f_\pi,\mathcal{V}]$ describes the topological soliton of the nonlinear σ-model (NLσM).

Wess-Zumino-Witten action in simplest approximation:

$\Gamma_{WZW}[U,\mathcal{V}] = \int d^4x\, \mathcal{L}_{WZW}$, where $\mathcal{L}_{WZW} = g_\omega \omega_\mu B^\mu$

$$B^\mu = \frac{1}{24\pi^2} \epsilon^{\mu\nu\rho\sigma}\, tr[U^\dagger\, \partial_\nu U\, U^\dagger \partial_\rho U U^\dagger \partial_\sigma U]$$

Quark-scalar sector can provide ground state energy significantly lower than the energy of the non-interacting Dirac sea

$$\Delta E = \int d^3x \left[-\frac{1}{2}\left(\vec{\nabla}\zeta\right)^2 + v(\zeta) + 4\,\lambda\,\zeta^2\left({f_\pi}^2 - \zeta^2\right)\right] + E_{\rm g}^{KE}$$

$v(\zeta) = \lambda\,(\zeta^2 - f_\pi^2)^2$

The term $-\frac{1}{2}\int d^3x\left(\vec{\nabla}\zeta\right)^2$ can be very large.

If we take the ζ-field to be $f_\pi\,\theta(r - r_{\rm c})$, we find surface energy $-\frac{1}{2}\,f_\pi^2\,4\,\pi\,r_{\rm c}^2\,\delta(0)$ (infinitely negative).

With $\zeta(r)$ falling sharply from $\zeta(r) = f_\pi$ to $\zeta(r) = 0$, the mass of the soliton can be reduced by as much as ~600 MeV. This resolves a major problem of the topological soliton model.

Soliton mass ~ 1500 MeV (too large)
Nucleon mass = 939 MeV

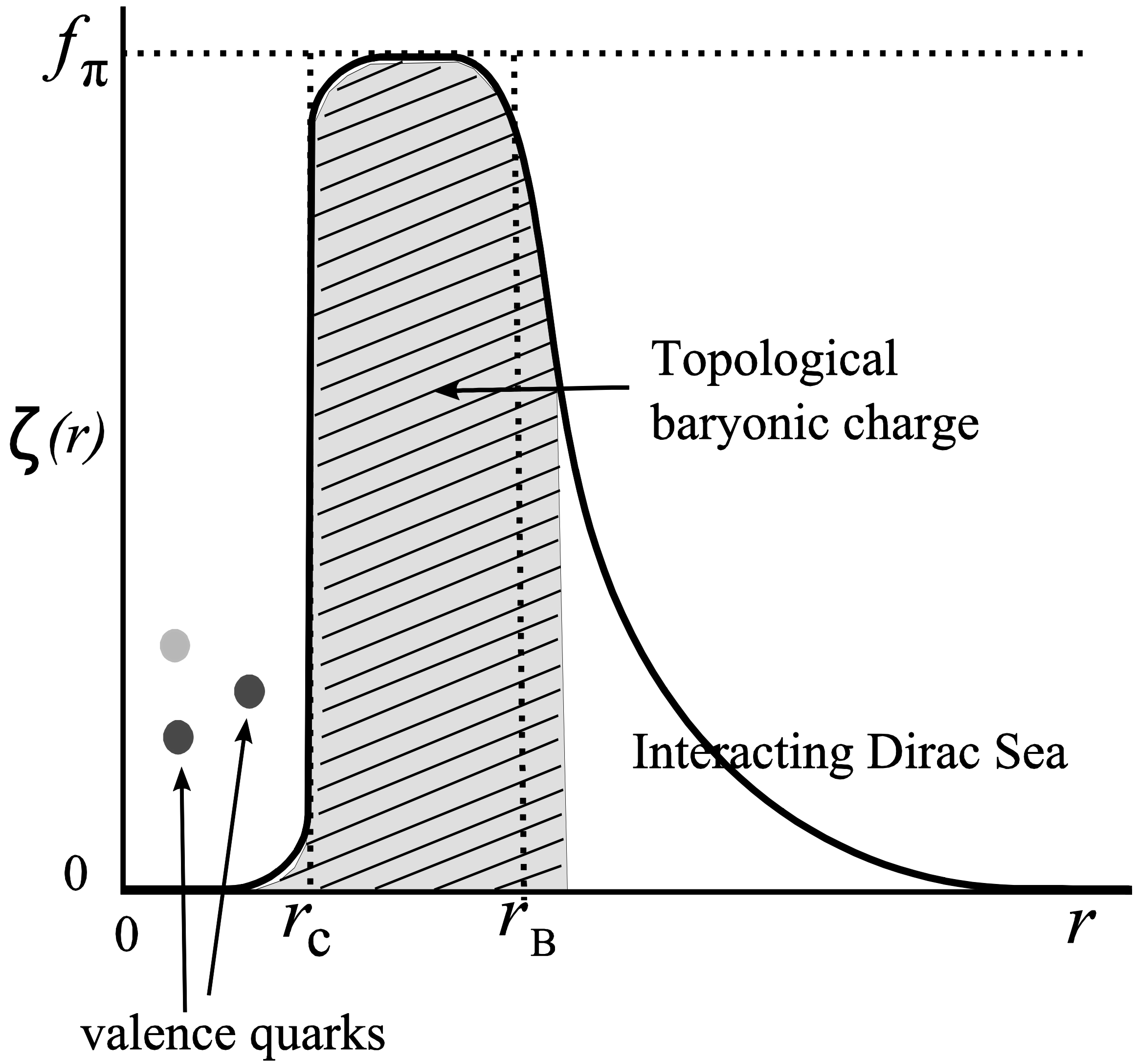
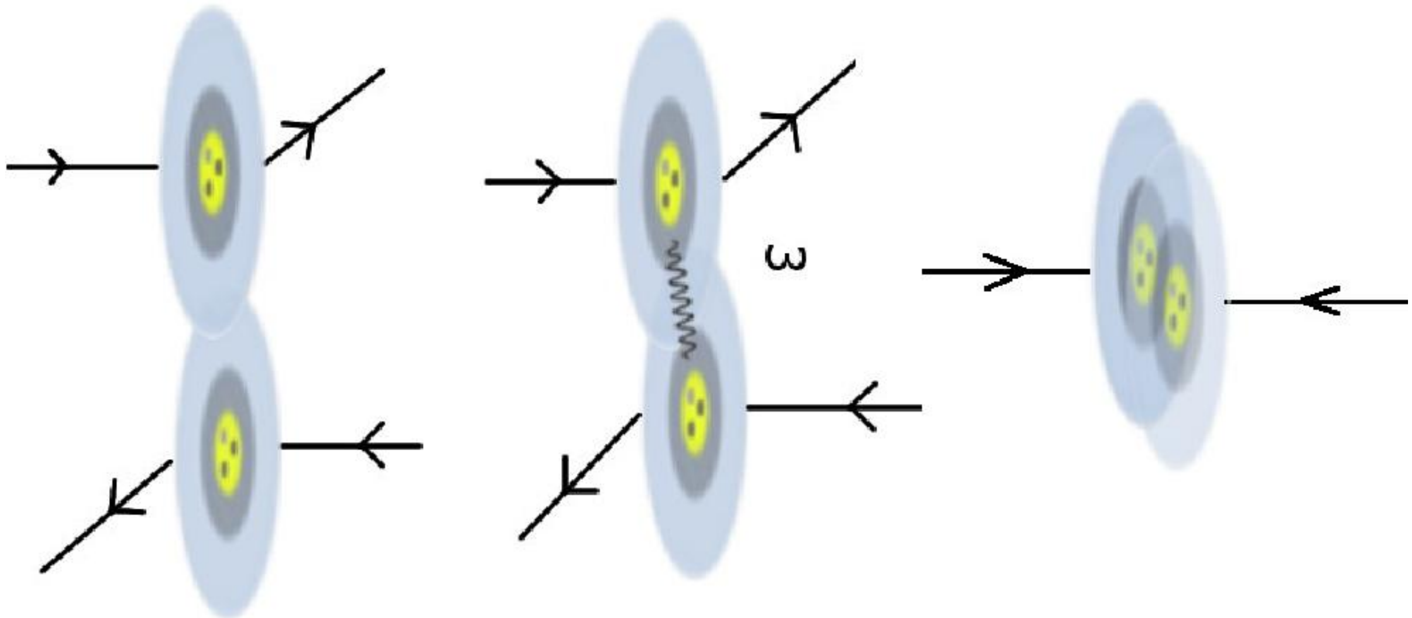


Fig. 2. The scalar field $\zeta(r)$ as a function of r.
r_C: radius of the core, r_B: radius of the baryonic charge density.



diffraction ω-exchange short-distance collision ($b \lesssim 0.1$ fm)

Fig.3. Elastic scattering processes

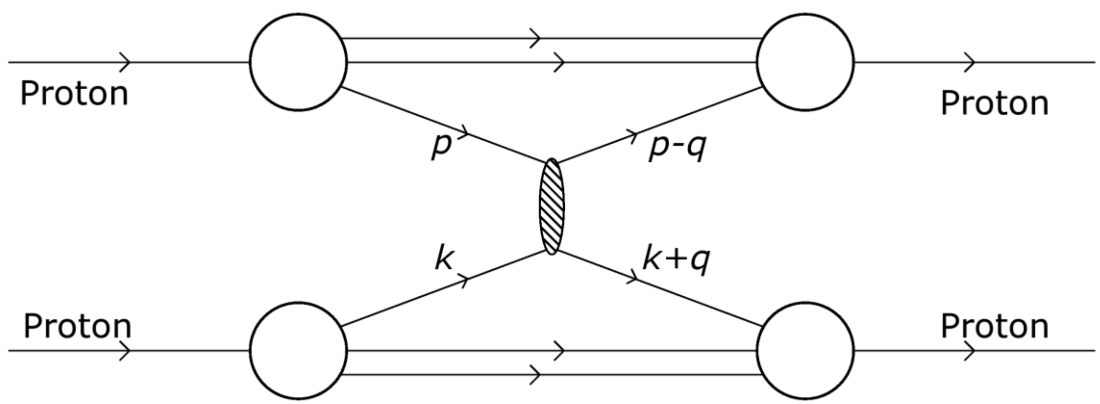
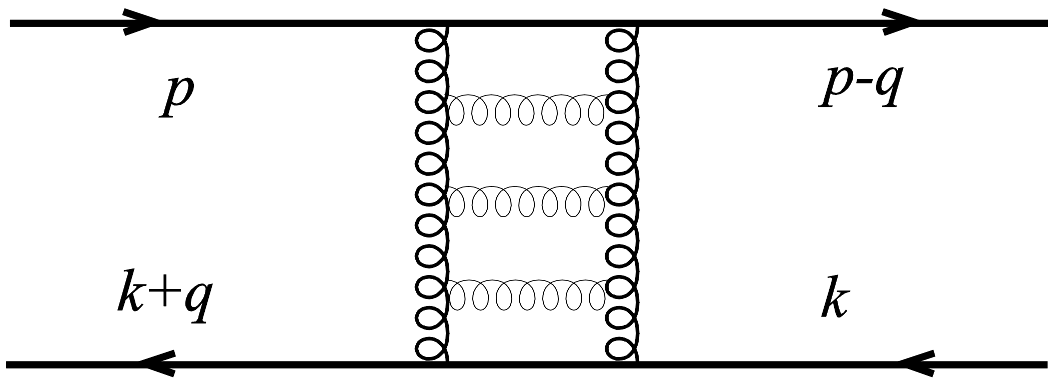
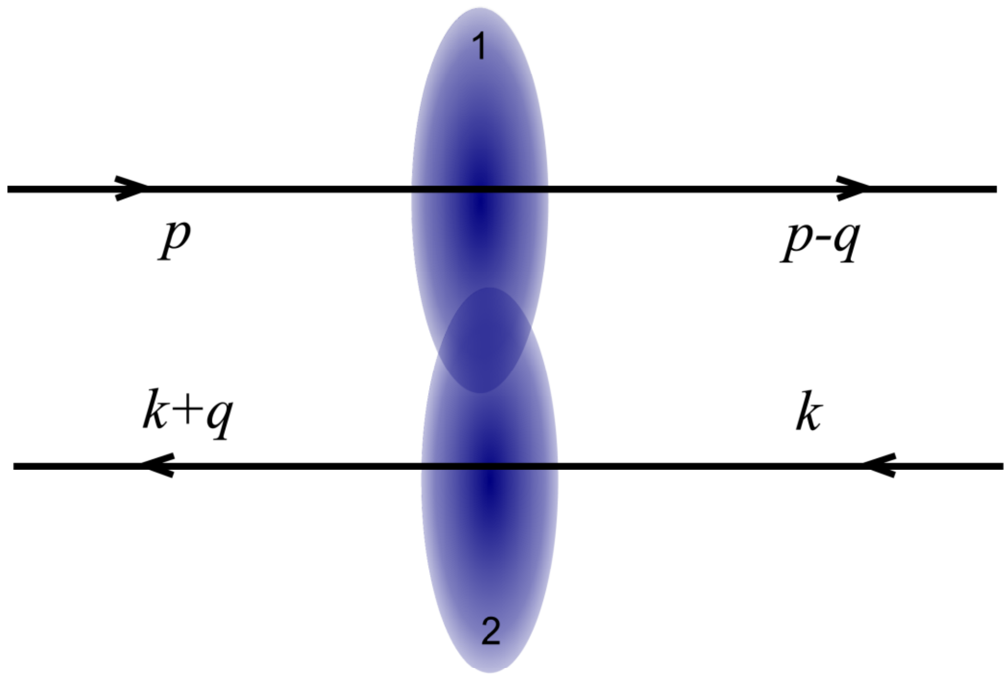


Fig.4. Hard collision of a valence quark from one proton with one from the other proton



a) exchange of gluons in the form of ladders



b) low-x gluon cloud of one quark interacting with that of the other

Figs. 5 a) and b): QCD processes for valence quark-quark scattering

Diffraction Amplitude

$$T_D(s,t) = i\,p\,W \int_0^\infty b\,db\;\; J_0(b,q)\;\; \Gamma_D(s,b)$$

$$\Gamma_D(s,b) = g(s)\left[\frac{1}{1+e^{(b-R)/a}} + \frac{1}{1+e^{-(b+R)/a}} - 1\right]$$

$$R = R_0 + R_1\left(\ln s - \frac{i\,\pi}{2}\right) \qquad\qquad a = a_0 + a_1\left(\ln s - \frac{i\,\pi}{2}\right)$$

$g(s)$: a complex crossing even coupling strength.

Diffraction amplitude - asymptotic properties

1. $\sigma_{tot}(s) \sim (a_0 + a_1 \ln s)^2$ (Froissart – Martin bound)

2. $\rho(s) \simeq \frac{\pi\, a_1}{a_0 + a_1 \ln s}$ (derivative dispersion relation)

3. $T_D(s,t) \sim i\, s \ln^2 s \;\; f(|t| \, \ln^2 s)$ (Auberson-Kinoshita-Martin scaling)

4. $T_D^{\bar{\mathrm{p}}\mathrm{p}}(s,t) = T_D^{\mathrm{pp}}(s,t)$ (crossing even)

Elastic scattering amplitudes due to ω-exchange, hard pomeron exchange and low-x gluon cloud-cloud interaction are given in our paper in the Proceedings of the EDS 2009 Conf. at CERN.

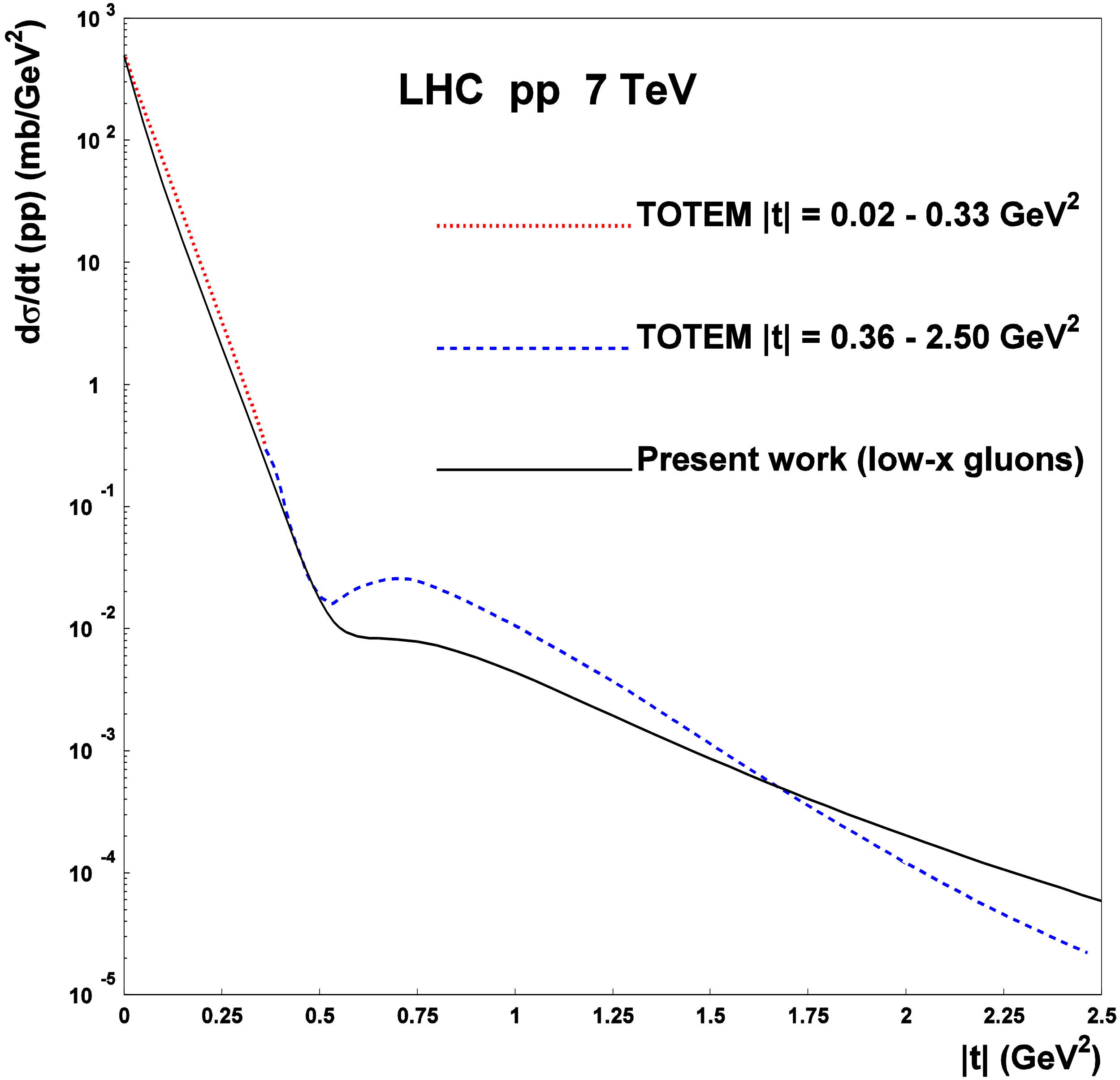


Fig.6. Comparison of our $d\sigma/dt$ prediction at $\sqrt{s}$ = 7 TeV with the TOTEM Collaboration measurements at LHC.

LHC $\sqrt{s}$ = 7 TeV

	Our results	TOTEM
σ_{tot}	97.5 mb	98.3 ± 3.0 mb
σ_{el}	19.8 mb	24.8 ± 1.4 mb
$\rho(t = 0)$	0.127	–
$B(t = 0)$	27.77 GeV^{-2}	20.1 ± 0.5 GeV^{-2}
$\frac{d\sigma}{dt}(t = 0)$	493.4 mb/GeV^2	503.7 ± 28.2 mb/GeV^2

Closing Comments

1. From our point of view, LHC and TOTEM have discovered the outer cloud of the proton. Why? Because our prediction for diffraction scattering, which originates from cloud-cloud interaction, agrees well with the experimentally measured differential cross sections in the small $|t|$ region.

2. The low energy nucleon models have led us to surmise correctly the chiral bag part of the proton structure.

3. Our investigation has shown that a single effective field theory model can describe the whole structure of the proton.

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