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Weak interaction contribution to the inclusive hadron-hadron scattering cross sections at high pT

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Abstract

It is demonstrated that the strong power-like scaling violation in the transverse momentum distribution of inclusive hadron production, observed by CDF Collaboration in $\bar{p}p$ collisions at Tevatron is caused by contribution of weak interaction. At high energies this contribution is enhanced by the factor $(E/m_W)^2$, where E is hadron energy in c.m.s. and m_W is W-boson mass. The results of calculations are in good agreement with CDF data.

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The CDF Collaboration have measured the inclusive cross sections of charged hadron production at high transverse momentum p_T at $\bar{p}p$ collisions at c.m. energy 1.96 TeV [1]. Surprisingly the strong power-like scaling violation was observed at $p_T > 30$ GeV: at $p_T \approx 100$ GeV the data indicate that the scaling law $Ed\sigma/d^3p \sim 1/p_T^4$ is violated by two orders of magnitude. The scaling law $Ed\sigma/d^3p \sim 1/p_T^4$ for inclusive hadron production in hadron-hadron scattering was proved basing on very general grounds – the light-cone dominance of hard processes in strong interaction [2]. Therefore, the observation of the violation of the scaling law resulted to strong confusion. Theoretically the observed phenomenon was discussed in the paper by Albino et al [3]. The authors of Ref.[3] addressed the scaling violation to factorization breaking at high transverse momentum charged hadron production. Such explanation is not satisfactory: QCD has no scale parameters besides Λ_{QCD} and inclusive cross sections are infra-red stable in QCD. In principal there is the dimensional parameter in the problem in view – the energy of the collision. But, as it is well known [2],[4], the energy is related to the longitudinal size of the collision region, but not to the transverse size, which determines the cross section. In recent paper [5] an attempts were done to constract the models, describing the data, but as well as in [3] no success was achieved. At the same time the measurements of inclusive jet production [6],[7] demonstrate good agreement with scaling law and theoretical expectations.

In this paper it is shown, that the scaling law violation in inclusive cross sections of charged hadron production at high p_T, observed by CDF Collaboration, is well described by contribution of weak interaction. The idea is that weak interaction has the scale parameters – the masses of W and Z bosons. At high p_T the contribution of weak interaction to the inclusive cross section is strongly enhanced by the factor E^2/m_W^2, decreases with p_T as $1/p_T^2$ in comparison with strong interaction contribution which falls steeply with p_T. Moreover, the weak interaction contribution has a peak at $p_T = m_W/2$. Due to these circum stances the weak interaction contribution becomes compatible with strong ones at $p_T \gtrsim 30$ GeV. The weak interaction Lagrangian is the ones of the Standard Model:

$$
\begin{aligned}
L = \frac{g}{\sqrt{2}} \Bigg\{ & \left[W_\mu^+ \bar{u}\gamma_\mu \frac{1}{2}(1+\gamma_5)d + W_\mu^- \bar{d}\gamma_\mu \frac{1}{2}(1+\gamma_5)u \right] + \\
& + Z_\mu \frac{1}{\cos\theta_W} \left[\bar{u}\gamma_\mu \frac{1}{2}(1+\gamma_5)\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right)u + \right. \\
& + \bar{u}\gamma_\mu \frac{1}{2}(1-\gamma_5)\left(-\frac{2}{3}\sin^2\theta_W\right)u + \bar{d}\gamma_\mu \frac{1}{2}(1+\gamma_5)\left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W\right)d + \\
& \left. + \bar{d}\gamma_\mu \frac{1}{2}(1+\gamma_5)\left(\frac{1}{3}\sin^2\theta_W\right)d \right] + (u \to c,\ d \to s) \Bigg\} .
\end{aligned}
\tag{1}
$$

Here u and d are fields of u and d quarks, θ_W is the Weinberg angle,

$\sin^2\theta_W \approx 0.230$. The coupling constant g is equal

$$g^2 = \frac{e^2}{\sin^2\theta_W}, \qquad e^2 = \frac{1}{137} \tag{2}$$

The matrix element of weak interaction contribution to the inclusive cross section in $\bar{p}p$ collision is represented by the diagram of Fig.1

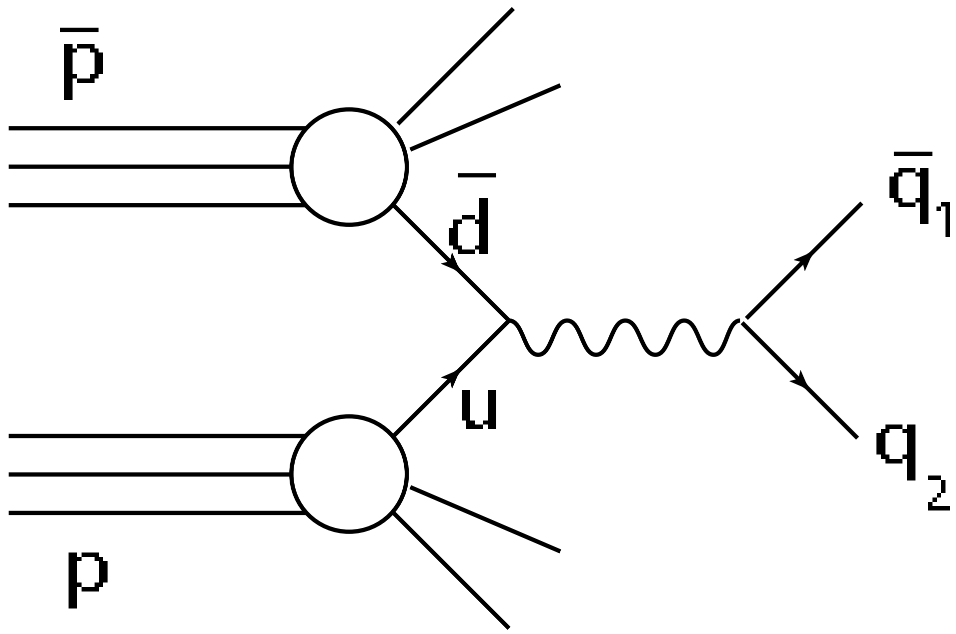

Fig.1 The diagram, describing the quark pair production at high p_T in case of W^+ exchange in annihilation channel.

There are also the diagrams, where $\bar{p}$ fragments into $u, \bar{s}, c$ and p – into $\bar{d}, c, \bar{s}$, correspondingly, as well the diagrams with W^- and Z in annihilation channel. (The contribution of W and Z exchange in t-channel is negligable.) In order to compare the results with CDF data let us calculate the inclusive cross section integrated over pseudorapidity

$$\eta = \frac{1}{2} \ln \frac{E + p_{\|}}{E - p_{\|}} \tag{3}$$

The contribution to the inclusive cross section of the diagram of Fig.1 is equal

$$E' \int \frac{d\sigma_{weak}}{d^3p'} d\eta' \bigg|_{|\eta'|<\eta} = \frac{9}{128} \, \frac{g^4}{(2\pi)^2} \, \frac{p_T}{E^5} \int \, \frac{dx_1 dx_2 dx_3}{x_1 x_2} \times$$

$$\frac{(x_1^2 + x_2^2)(1 + th^2\eta)}{\left(x_1 x_2 - \frac{m_W^2}{4E^2}\right)^2 + \frac{m_W^2 \Gamma_W^2}{16E^4}} \, \frac{1}{(x_1 + x_2) x_3 sech \, \eta - \frac{p_T}{E}} \, F_u(x_1) F_d(x_2) \times$$

$$\left\{ \sum_i \left[D_u^i(x_3) + D_d^i(x_3) + D_s^i(x_3) + D_c^i(x_3) \right] \right\} \quad (4)$$

Here E' and $p' = (p'_{\|}, \mathbf{p}_T)$ – are the energy and momentum of detected charged particle, E is the proton or antiproton energy in c.m.s., m_W and Γ_W are W mass and width , $F_u(x_1), F_d(x_2)$ – are u and d-quark distributions in proton, $D_u^i, D_d^i, D_s^i, D_c^i$ are the fragmentation functions of u, d, s, c quarks into i-th charged particle, the sum is performed over all charged particles. The integration domain in variables x_1, x_2, x_3 is restricted by

$$x_1 x_2 > \left(\frac{p_T}{E}\right)^2$$

$$(x_1 + x_2)x_3 sech\ \eta > \frac{p_T}{E}(1 + x_3 sech\ \eta) \qquad (5)$$

For estimation let us put $F_u(x) = c_d/x, F_d(x) = c_d/x, \sum_i D_u = 1/x$, where c_u, c_d are the effective constants, approximating quark distributions found by MSTW2008 [8] and CTEQ 6.6.M [9]. Similar definitions were used for other quark distributions. Assuming $p_T/E \ll 1$, we have from (4)

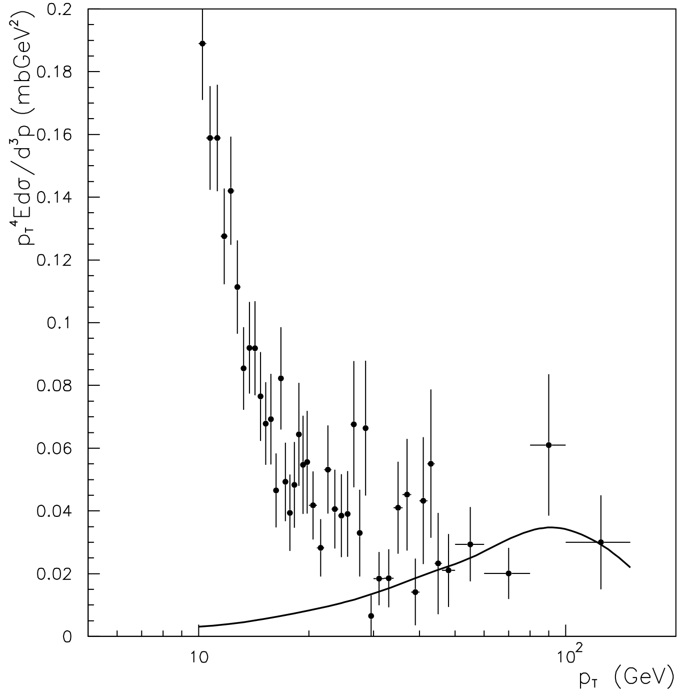

Fig.2 The inclusive cross section of charged particle production at $\bar{p}p$ collisions caused by weak interaction at c.m. energy 1.96 TeV in comparison with CDF data. It was chosen the same value of $\eta, \eta = 1$, as in CDF experiment.

$$E' \int \frac{d\sigma_{weak}}{d^3p'} d\eta' \bigg|_{|\eta'|<\eta} = \frac{9}{32} A(p_T) \frac{g^4}{(2\pi)^2} \left(1 + th^2\eta \right) \frac{E^2}{m_W^2 p_T^4} \ln \frac{E}{p_T} \times$$

$$\times \left\{ 1 - \frac{1}{1 - 4p_T^2/m_W^2} + 8 \frac{p_T^2}{m_W^2} + 32 \frac{p_T^4}{m_W^4} \ln \left| 1 - \frac{m_W^2}{4p_T^2} \right| \right\} \qquad (6)$$

$A(p_T)$ weakly depends on p_T and approximately is equal to 10. Eq.(6) is valid at all p_T with logarithmic accuracy, $\ln(E/p_T) \gg 1$, except the small interval near $p_T = m_W/2$, $p_T - m_W \sim \Gamma_W/4$. At high p_T (6) behaves as

$$E' \int \frac{d\sigma_{weak}}{d^3p'} d\eta' \bigg|_{|\eta'|<\eta} = \frac{1}{12} A \frac{g^4}{(2\pi)^2} \left(1 + th^2\eta \right) \frac{E^2}{p_T^6} \ln \frac{E}{p_T} \qquad (7)$$

The weak inclusive cross sections times p_T^4 is plotted on Fig.2 in comparison with experimental data of CDF Collaboration.

The fragmentation functions $D(x)$ at small x, which are poorely known, play an important role in the inclusive spectrum an high p_T. If instead the assumption $\sum_i D(x) = 1/x$, which was used in the calculation above, it would be $\sum_i D_i(x) = (1/x)^{1+\alpha}$, then in (6) would appear the additional factor $(E/p_T)^\alpha$. The measurements of inclusive cross sections at high p_T could give unique information about fragmentation functions at small x. The contribution of weak interaction to inclusive cross sections increase as $E^2 \ln(E/p_T)$ with collision energy. Therefore the measurements of inclusive cross sections at high p_T at LHC are very promisable.

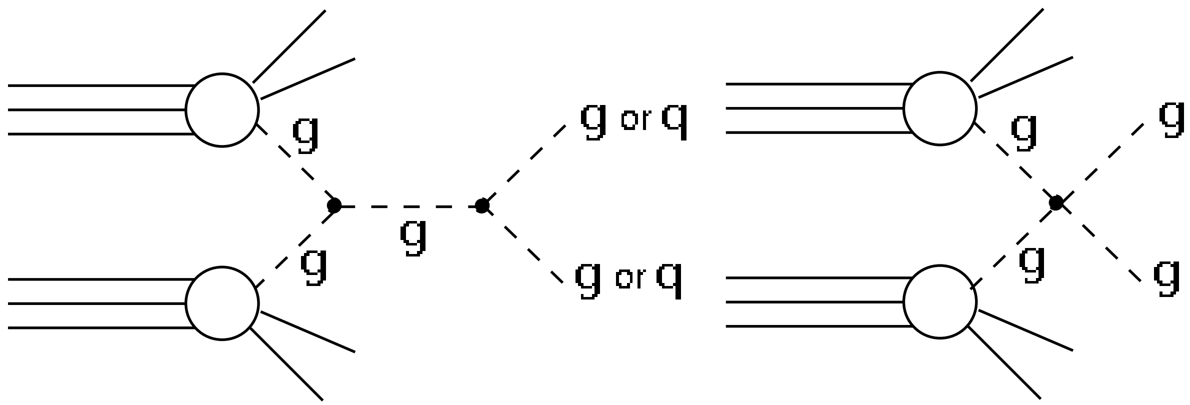

Fig.3 The diagrams representing the contributions to inclusive jets production due to gluon exchange.

Finally, let us now explain, why experimentally scaling violation is not observed in inclusive jet production [6],[7]. In this case in strong interaction mechanism the main role are playing the diagrams with gluon exchange, like ones presented on Fig.3 and the contribution of weak interaction is small in comparison with them.

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