Contributions from weak-interaction channels to inclusive hadron spectra at TeV energies

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Abstract – At the FERMILAB TEVATRON and CERN LHC accelerators partonic processes reach such a high energy region, where the weak interactions could enter into consideration in the hadron yields through the opening of resonant W and Z exchange diagrams. We investigate these contributions to inclusive charged hadron production in $p + p$ and $p + \bar{p}$ reactions at a few TeV energies, and compare our results to existing CDF and CMS data. We perform a leading order perturbative QCD calculation and include electroweak channels to estimate the order of magnitude of charged hadron excess. The energy dependence of hadron production and the fine structure of transverse momentum distributions are investigated. As expected, in $p + \bar{p}$ collisions electroweak channels yield much larger contribution, than in $p + p$ collisions. However, these types of contributions remains close to be negligible at the available accelerator energies.

Introduction. – The first year of successful run of CERN Large Hadron Collider resulted enormous amount of data in $p + p$ collisions at energies $\sqrt{s} = 2.36, 7$ TeV. The preliminary data of the ALICE \cite{1}, ATLAS \cite{2} and CMS \cite{3} collaborations on inclusive charged hadron production display the extension of transverse momentum spectra well measured up to 100 GeV/c or even beyond. These results complement results from the CDF Collaboration at FERMILAB TEVATRON. They reported \cite{4,5} the inclusive charged hadron distribution measured up to $p_T \approx 50 - 100$ GeV/c at $\sqrt{s} = 1.96$ TeV collision energy. With increasing luminosity and running time we can expect sufficiently large number of recorded events at LHC so that the inclusive hadron spectra will be measured up to transverse momenta of couple of hundred GeV with high precision. Thus all contributions beyond standard channels based on strong interaction particle production will be revealed, if they have small but non-negligible effect.

Inclusive hadron production at high transverse momenta is used to be calculated in the framework of perturbative quantum chromodynamics (QCD) improved parton models, which reproduces the well known scaling properties of the measured hadron spectra, namely $E^d \sigma / dE \propto p_T^{-n}$, where $n \approx 5$. When electroweak channels from W and Z boson exchange start to give noticeable contributions then one would expect the above scaling to be violated because of the resonance structure of the heavy boson exchange. This violation appears at half of the bosonic mass values at jet levels, but shifted down to lower momentum values in hadronic spectra as a consequence of jet fragmentation.

In this letter we address a general question. The motivation of our work is to quantify the role of electroweak channels in inclusive hadron production. Recently, the CDF collaboration \cite{4} reported a very strong scaling violation in inclusive charge hadron spectra at high transverse momentum, which triggered considerable theoretical interest. In Ref. \cite{6} the fragmentation functions have been investigated carefully, and no means have been found to explain these CDF data. In another effort the inclusion of electroweak channels were proposed to explain the CDF data \cite{7}. Here we report the outcome of our attempt to repeat this calculation. Although we make several approximations, we carefully investigate their possible effect and
conclude that both at TEVATRON and at LHC the yield of the electroweak channels remains below the per cent level as compared to the yield of the strong processes.

In the meantime, the CDF collaboration published a paper with reanalyzed data on inclusive hadron spectra [5], invalidating their earlier findings. The strong scaling violation reported before almost entirely disappeared, although the new data stop at smaller transverse momentum value \( p_T \leq 50 \text{ GeV}/c \), than the firstly reported dataset \((p_T \leq 100 \text{ GeV}/c)\). Also recently, the CMS collaboration has published their data at \( \sqrt{s} = 7 \) TeV and no strong violation was reported. Thus, it seems that strong scaling violations do not appear in the inclusive hadron spectra at current colliders. Nevertheless, we believe that for future reference it is useful to publish our quantitative predictions with the electroweak production channels also taken into account.

**Pure perturbative QCD framework.** The inclusive hadron spectra is determined in the perturbative QCD improved parton model [8]:

\[
\begin{align*}
\left( \frac{d\sigma}{dt} \right)_W &= \frac{g^4}{64\pi^2} |V_{ab}|^2 |V_{cd}|^2 \frac{\hat{s}^2}{(\hat{s} - m_W^2)^2 + m_W^2 \Gamma_W^2} \\
&\times f_{a/p}(x_a, Q^2) f_{b/p}(x_b, Q^2) D_{h/c}(z_c, Q^2_F) \frac{\hat{s}}{\pi z^2_c} \\
&\times \left( \frac{d\sigma}{dt} \right)_0 (\hat{s} + \hat{t} + \hat{u}),
\end{align*}
\]

where all reactions with \( u, d, s \) or \( c \) quarks in the incoming or outgoing channels are summed over. Here \( f_{a/p} \) denotes the parton distributions function of parton \( a \) in the proton, and \( D_{h/c} \) is the fragmentation function of hadron \( h \) emerging from parton \( c \). For factorization scales we use \( Q = \kappa p_T \) and \( Q_F = \kappa p_T \), with \( \kappa = 1 \) as default. We use the MSTW2008 parton distribution functions [9] and the KKP fragmentation functions [10] for our leading order (LO) calculation.

**Estimating the weak-interaction contributions.** Here we estimate the order of magnitude of the weak-interaction contributions by using a leading order calculation in the parton model. The dominant W boson exchange channels are \( q_a \bar{q}_b \rightarrow W^\pm \rightarrow q_c \bar{q}_d \), as illustrated by Fig. 1. We neglect Z boson exchange and t-channel diagrams. This is justified by the fact that the coupling of Z to quarks is smaller than the W coupling, and t-channel diagrams are suppressed as compared to the resonant s-channel contributions. We also neglect photons, as these do not posses a resonance structure, therefore their contribution is also expected to drop rapidly with \( p_T \).

The Born-level cross section for the partonic subprocess shown in Fig. 1 is

\[
\left( \frac{d\sigma}{dt} \right)_W = \frac{g^4}{64\pi^2} \left| V_{ab} \right|^2 \left| V_{cd} \right|^2 \frac{\hat{s}^2}{(\hat{s} - m_W^2)^2 + m_W^2 \Gamma_W^2},
\]

where \( \hat{s} \) and \( \hat{u} \) are the partonic Mandelstam variables, \( m_W \) and \( \Gamma_W \) are the mass and width of the W boson, \( V \) is the CKM matrix, and \( g^2 = e^2/\sin^2\theta_W \) is the weak coupling. Since the main contribution comes from \( \hat{s} \) values close to the W mass, we can use the weak coupling measured at the vector boson mass, neglecting the running of the electroweak coupling, which has weaker momentum dependence, than \( \alpha_s \). Thus we use \( \alpha(M_Z^2) = 1/127.9 \), and the weak mixing angle \( \sin^2\theta_W(M_Z^2) = 0.231 \) (see [11]).

**Difference between pp and p\bar{p} collisions.** Considering usual strong interaction production channels the hadron yields are very similar in pp and p\bar{p} collisions. The slight deviation in the parton distribution function for valence and sea quarks will generate a very small difference in the production of charged hadrons.

In earlier investigation of on-shell W\(^\pm\) and W\(^-\) production, an asymmetry has been found [12], which strongly depends on the \( d - \bar{d} \) asymmetry in proton distribution functions. Similar effect appears in weak boson mediated parton-parton scattering. We expect a larger contribution from W\(^\pm\)-channels in p\bar{p} collisions relative to the yield in pp collisions because in the \( \bar{p} \) the weight of valence antiquark is much larger than the the weight of the sea antiquarks in \( p \).

**Numerical results.** We calculate hadron production for p+\bar{p} collisions at \( \sqrt{s} = 1.96 \text{ TeV} \), and compare the numerical results to the CDF data [4, 5]. We repeat the investigation in our pQCD based calculation at 7 TeV in p+p collisions and compare the numerical results to CMS data. The factorization scale dependence was investigated by varying the \( \kappa \) values between 1/2 and 3/2. Figure 2 and 3 display the obtained results. The data points are from CMS [3], and CDF [4, 5] respectively, which are close to the pQCD LO predictions.

Our results indicate that weak channel contribution is more than three orders of magnitude smaller than strong channel contributions. The choice of the scales do not influence significantly this result.

One would expect a bump in the jet spectrum at \( p_T \approx m_W/2 \) from the decay of W bosons, and a bump in the hadron spectrum at somewhat lower momenta, due to fragmentation of quarks to lower momentum hadrons. Indeed our calculation of the weak-interaction contribution reproduces this feature.
As mentioned earlier, the weak-interaction contribution should be considerably higher in $p + \bar{p}$ collisions than in $p + p$. To investigate this difference, we made calculations at different center of mass energies. We define the ratio:

$$R_{pp/pp} = \frac{\left( E \frac{d^3\sigma}{dp^2} \right)_W (p + \bar{p} \to h^\pm + X)}{\left( E \frac{d^3\sigma}{dp^2} \right)_W (p + p \to h^\pm + X)}, \quad (3)$$

and plot this quantity on Fig. 2. During this study, we fix $\kappa = 1$. The main difference in the curves for different $\sqrt{s}$ energy values is that in higher energy collisions the ratio $R_{pp/pp}$ is smaller. This can be readily understood by the increasingly larger weight of the gluon in the proton with decreasing partonic momentum fraction $x$ because the higher the collision energy, the smaller $x$ contribute to the produced hadron with the same transverse momentum. The ratio increases with increasing $p_T$ due to the increasing valence quark contribution, coming from the higher momentum fraction part of the parton distribution functions.

We also define the ratio of the weak and strong interaction contributions in $p\bar{p}$ collisions:

$$R_{W/S} = \frac{\left( E \frac{d^3\sigma}{dp^2} \right)_W (p + \bar{p} \to h^\pm + X)}{\left( E \frac{d^3\sigma}{dp^2} \right)_S (p + \bar{p} \to h^\pm + X)}. \quad (4)$$

We investigate the dependence of this ratio on the collision energy and the transverse momentum. Our result are displayed on Fig. 5. We also used $\kappa = 1$ here. As expected, the ratios have a peak at somewhat lower transverse momenta than $M_{W}/2$. The ratio is higher in lower energy collisions because of the dominance of gluons at small $x$, discussed above.

We study the sensitivity of the above results on the scale choice $\kappa$, and find that varying $\kappa$ between 1/2 and 3/2 makes the ratios vary a few ten percents (which is the usual sensitivity of leading order QCD results on the factorization scale). The main conclusion, namely the negligibility of weak interactions, remain the same.

**Conclusion.** — We have investigated the inclusive hadron production in $pp$ and $p\bar{p}$ collisions at FERMILAB TEVATRON and CERN LHC, including strong and weak-interaction channels. We have performed a LO calculation to obtain an estimate on the hadron excess from weak channels.

Our parton model calculation confirms the usual practice of neglecting weak interaction contributions when calculating hadron spectra, in $pp$ and $p\bar{p}$ collisions at collision energies accessible with present technology. The weak-interaction contribution is always orders of magnitude smaller.

We expect that repeating our analysis at next-to-leading order accuracy would lead to similar conclusion especially for the ratios $R_{pp/pp}$ and $R_{W/S}$ where the effect of the NLO K factors cancel to a large extent.

A naive estimate of comparing the running couplings at the momentum scales involved, namely $(\alpha_{EW}/\alpha_s)^2 = O(10^{-1})$ is still an overestimate of the ratio on Fig. 5, because of the dominance of gluon channels in hadron production.

Fig. 2: (Color online.) Contributions to inclusive average charged particle yield from strong (upper red band) and weak (bottom blue band) interaction channels in $pp$ collisions at $\sqrt{s} = 7$ TeV energy. The scale uncertainty of the strong and weak interactions is indicated by the bands. Experimental data are from the CMS Collaboration [3].

Fig. 3: (Color online.) Contributions to inclusive charged particle yield from strong (upper red band) and weak (bottom blue band) interaction channels in $pp$ collisions at $\sqrt{s} = 1.96$ TeV energy. The scale uncertainty of the strong and weak interactions is indicated by the bands. Experimental data are from the CDF Collaboration [5].
Fig. 4: (Color online.) The ratio of weak-interaction contributions in $p + \bar{p}$ to $p + p$ collisions at different $\sqrt{s}$ energy values.

Fig. 5: (Color online.) The ratio of weak-interaction contributions to QCD contributions in $p + \bar{p}$ collisions at different $\sqrt{s}$ energy values.

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