QCD Highlights from CDF (and D0)

Giorgio Bellettini
Dipartimento di Fisica and INFN, Pisa
Fermilab
giorgiob@fnal.gov

Abstract We review a number of hadron physics results at the Fermilab Tevatron collider, paying special attention to some anomalies observed recently in vector boson events with associated jets.

Introduction

The main features of hadron interactions were studied with priority in the early times of the Tevatron collider. The results from those times will stay for always in the Particle Data Book. A revival of interest on them can be expected when the analysis of minimum bias data collected in a few runs at reduced Tevatron energies of 300 and 900 GeV, just before the shutdown of the collider, will be performed by CDF and D0. The 900 GeV data of CDF will be the largest statistics of minimum bias ever collected at hadron colliders. We shall mention only a few classical QCD measurements which were continued during the Tevatron Run II (2001-2011). At this point in time hadron jets are the primary objects of interest in searches on heavy flavor, vector boson, top quark and searches for New Physics. Most of my talk will discuss measurements of jet properties in associated vector boson production.

Physics results from D0 and CDF

The running strong coupling constant $\alpha_s$ and the point-like quarks Taking advantage of the wide and rather uniform coverage of their calorimeter, the D0 Collaboration has measured the inclusive jet cross section over a large range of polar angle and transverse momentum. Their recent data are displayed in Fig. 1 [1]. These data can be interpreted by convoluting structure functions of the primaries and parton-parton scattering amplitudes with $\alpha_s$-dependent couplings, as depicted in Fig. 2. The coupling constant $\alpha_s$ can thus be measured.

To illustrate the running of $\alpha_s$, D0 data are merged with previous HERA measurements and plotted as a function of transverse momentum $p_t$ in Fig. 3 [2].

Production of jets at small center of mass angles $\theta^*$ is dominated by gluon exchange amplitudes, which generate a cross section as $d\sigma/d\cos\theta^* \simeq 1/(1 - \cos \theta^*)^2$ with a Rutherford-like
dependence on $\theta^*$. A possible new interaction at a higher energy scale $\Lambda$ can be tested by assuming an additional four fermion point-like interaction amplitude. This amplitude would generate in the cross section a term as $d\sigma/d\cos\theta^* \simeq 1/\Lambda(1 + \cos\theta^*)^2$, thereby smoothing the forward angular dependence. It became customary to display the angular cross section as a function of $\chi = (1 + \cos\theta^*)/(1 - \cos\theta^*)$ rather than of $\theta^*$ directly, since this makes the distribution more sensitive to a possible $\Lambda$-dependent term, as illustrated in Fig. 4. Assuming the less favorable interference sign between the contact and the QCD interaction amplitudes, the D0 analysis excludes $\Lambda < 2.58$ TeV at 95% c.l. [3].

**Searches for new particles** New heavy particles decaying into two quarks are expected in many models, like those which predict a new intermediate boson $Z'$. The result of a search for a $t - \bar{t}$ resonance in the $m_{t\bar{t}}$ spectrum by CDF using the of 106 pb$^{-1}$ integrated luminosity collected in run1 is shown in Fig. 5. The inset shows a simulation of a narrow, vector-like $Z'$ resonance of mass 500 GeV/c$^2$. These early data left room for hopes. However, the CDF search for di-quark resonances in run2 gave negative results in the $t - \bar{t}$ spectrum as well as in any other dijet channel. The inclusive dijet mass distribution with 1.13 fb$^{-1}$ excludes bumps up to $m_{jj} \sim 1.25$ TeV/c$^2$ [5] (Fig. 6). The limits obtained on a number of exotic processes are also shown in Fig. 6.

The features of additional jets in W, Z production events are now raising great interest. Observing a second intermediate boson decaying into two jets in these events is the natural training lane towards the search for associated production of a light Higgs boson, as $W(Z)H \rightarrow W(Z)bb$. The integral jet production rate above a 30 GeV energy cut in Z+jets events measured by CDF is shown in Fig. 7 [5]. While the leading order calculation predicts less rate and requires a normalization factor of 1.46 in order to fit the data, the NLO calculation fits well the entire distribution. Since the simulation of jet production in W events is very similar to production in Z events, this agreement gives confidence on the simulation of the features of the QCD background in a search for diboson events.

In a search for light Higgs $\rightarrow b\bar{b}$ the ultimate background will b-jets production by non-resonant QCD processes. Simulating reliably this background is of utmost importance. Tagging of a secondary vertex due to late decay of beauty hadrons has been exploited since a long time for assigning b-flavor to jets. CDF has developed a technique by which b-jet flavor tagging is improved by measuring the mass of the track system associated to delayed vertices within a jet. However, such secondary vertices can be generated also by charmed hadron decays. Also, because of decays of unstable hadrons and of measurement errors (‘fakes’), light jets can feature secondary vertices as well. Given the dominance of light flavor and gluon jets in inclusive production, fakes can produce a very significant tag rate. Fig. 8 shows the simulated vertex mass distribution of b and lighter quark vertices and a CDF fit to the vertex mass of b-tagged jets in Zjj data in 7 fb$^{-1}$, in terms of b-signal and background [7].
larger mass of b-vertices can be used to improve the purity of b tagging. The measured b-jet rates fit reasonably well with theory expectation in terms of relative rates to total Z production and to inclusive Z+jets:

\[ \frac{\sigma(Z + b)}{\sigma(Z)} = (2.84 \pm 0.29 \pm 0.29) \times 10^{-3} \]  

(1)

to be compared with theory expectations varying between $2.3 \times 10^{-3}$ and $2.8 \times 10^{-3}$ depending on the $Q^2$ scale,

\[ \frac{\sigma(Z + b)}{\sigma(Z + j e t s)} = (2.24 \pm 0.24 \text{stat} \pm 0.27 \text{syst}) \times 10^{-2} \]  

(2)

to be compared with theory expectations between $1.8 \times 10^{-2}$ and $1.9 \times 10^{-2}$. We expect jet production dynamics to be very similar in W+jets as in Z+jets. Therefore one is confident in simulation of jet production in W events as well. This is the jet production Standard Model picture on which the search for rare diboson processes and for possible new phenomena in W with final state jets is based.

Finding dibosons in fully leptonic final states is relatively easy. CDF observation of $ZZ \rightarrow llll$ in 4 charged leptons (Fig. 9) dates from 2009 [8]. The statistics is not very large, but the $ZZ$ component is clear. Of course, the four charged leptons final state provides the clearest signature for $ZZ$ production. If one studies final states with jets, WZ, WW pairs mix with $ZZ$ and generate an inclusive signal. This inclusive diboson signal has the largest rate and was the first to be observed by CDF in the sample of large $E_{t,\text{miss}} + 2$jets, where the prime contribution is from $Z \rightarrow \nu \bar{\nu}$ (also W leptonic decays generate $E_{t,\text{miss}}$ when the charged lepton is not detected). The $jj$ invariant mass in this sample [9] is shown in Fig. 10. More recently, associated $W/Z \rightarrow jj$ production in events with a charged lepton and $E_{t,\text{miss}}$ was also observed [10], as shown in Fig.11 ($Z \rightarrow ll$ events contribute to these events when a lepton escapes detection).

The slightly inaccurate fit in Fig. 11 to the distribution around $m_{jj} = 150$ GeV triggered CDF to a deeper study of this process above $m_{jj} = m_Z$. Events with exactly two $E_l > 30$ GeV jets were selected and $P_{T,jj} > 40$ GeV of the jet pair was required in order to allow a more reliable background calculation. The result of this analysis is shown in Figs. 12a and 12b [11]. The expected rate was simulated according to the SM cross sections for the known processes (inclusive W+jets being the dominant background, as listed in the inset), but the fit to the spectrum was poor. A bump of over $3 \sigma$ significance about 40 GeV wide around $m_{jj} = 145$ GeV was left unexplained. The rate in the bump corresponds to a cross section of $3.1 \pm 0.8$ pb, i.e. to a $3.3 \sigma$ effect.

When confronted with the problem of understanding this anomaly, one is troubled by the limited information available on hadron jets. Jets are defined by a cone algorithm and their energy is integrated within some range of pseudorapidity-azimuthal angle ($\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} =$...
0.4 in this analysis). Corrections for detector defects, out-of-cone energy losses, in-cone energy contributed by underlying event are applied only in average. When aiming to spectroscopy of hadron jet systems, we suffer because with this definition jet energy resolution is too poor. Jet energy calibration should be personalized and be flavor specific for optimal discrimination of signal versus background. A new state may decay into a pair of light quark jets, s-jets, c-jets, b-jets. Background jets have their own flavor composition, often with dominance of gluon jets. Therefore signal/background would depend on flavor, and flavor tagging would allow separate studies in flavor channels. Combining separate analyses in different flavor channels would improve the overall S/B discrimination. Hopefully, personalized corrections will be possible in future experiments.

In absence of more detailed information, several important checks were made on data of this spectrum. The b-tag rates for jets in the bump and in adjacent \( m_{jj} \) ranges, at \( m_{jj} < 120 \text{ GeV} \) and \( m_{jj} > 160 \text{ GeV} \), were compared and found to be the same within statistical errors. The overall mass of the W+jj system was studied. Although the fit to the SM contribution was not perfect (Fig. 13), no evidence for a mother resonance was found [12].

The same \( m_{jj} \) distribution was studied by D0 [13] who did not see any evidence for a bump (Fig. 14). The p-value for a bump at 145 GeV with cross section as large as 3 pb is \( < 10^{-3} \). Fitting for a bump, D0 finds a cross section \( \sigma_{D0} = 0.4 + 0.8 - 0.4 \text{ pb} \), consistent with 0 within 0.5\( \sigma \). This is 2.5\( \sigma \) apart from the CDF value of 3.1 \( \pm 0.8 \text{ pb} \), with a 0.6\% probability of being consistent with it. On comparing directly the event rates of the two experiments, CDF (Fig. 15) concluded that they are not fully incompatible [14]. In the range \( 120 < m_{jj} < 300 \text{ GeV} \), both CDF and D0 see a \( \sim 4 \sigma \) rate excess above SM simulation. The D0 excess is 200 \( \pm 50 \) events, CDF excess is 370 \( \pm 70 \) events. The difference is 170 \( \pm 86 \) events, about 2\( \sigma \). At the time being, CDF is increasing the statistics of the measurement to the full available integrated luminosity and searching for the anomaly in other channels where the effect, if it is real, should also appear.

A step forward in the hunt for the light Higgs boson is studying b-jets in W/Z events. The process \( W(Z)+bb \) with two b-jets produced incoherently in association to a W or Z boson is an irreducible background for the process \( W(Z)H \rightarrow l\nu b\bar{b} \). A step in this direction is made by CDF searching for heavy flavored jet pairs in W/Z events (Fig. 16). Charm is tagged with an efficiency of \( \sim 6 \% \), beauty with an efficiency of \( \sim 40 \% \). Because of the larger rate of WW production than WZ, the observed 3\( \sigma \) excess is mostly due to \( W \rightarrow cs \). However, some rate is also contributed by \( Z \rightarrow b\bar{b} \) [15]. A search for exclusive beauty jets will come next.

Conclusions

We have discussed D0 and CDF results in jet production and the search for new particles at the TeVatron. In order to fully exploit the jet internal structure one must compare data
to jet fragmentation theory. In addition, the job for theorist would include interpreting the kinematical structure of multi-jet states. These are hard jobs since these phenomena are in part non-perturbative. It must be faced since we must expect that the branching ratios of new states of higher and higher mass into multi-jets will become dominant. We will be forced to tackle multi-jets spectroscopy. One can advocate a vital role of theory in this project. In a joint effort between experimentalists and theorists, the role of hard interaction theory will be of prime importance.

References


**Figures**

Figure 1: D0 inclusive jet cross-section as a function of transverse momentum and rapidity [1].

Figure 2: First order diagram illustrating the dependence of the parton scattering amplitudes on $\alpha_s$ in [1].
Figure 3: Running of $\alpha_s$ from HERA to Tevatron energies, including the run 2 D0 data [2].

Figure 4: Expected difference from pure Rutherford and QCD scattering in the $\chi$ distribution of jet pairs due to the onset of a new point-like interaction between partons [3].

Figure 5: The $t\bar{t}$ spectrum observed by CDF at the end of run 1 (points) compared to the standard model predictions (thick dashes). The inset shows a simulation of a narrow, vector like resonance of mass 500 $GeV/c^2$ [4].
Figure 6: At left, inclusive dijet mass distribution measured by CDF in run 2 with $1.13fb^{-1}$ integrated luminosity; at right, CDF limits on the production of exotic particles decaying into two jets [5].

Figure 7: Jet multiplicity distribution in Z+jets events by CDF [6]. While the leading order calculation requires a normalization factor of 1.46 in order to fit the data, the NLO calculation fits well.
Figure 8: At left, simulated mass distribution of secondary vertices in b-jets, c-jets and light quark jets in CDF; at right, fit to the mass distribution of secondary vertices in Zjj events in terms of b jets and of various backgrounds [7].

Figure 9: Two-by-two pairings of the 4 charged leptons in CDF ZZ search, showing dominance of the diboson process over background [8].
Figure 10: CDF observation of the diboson signal WW/WZ/ZZ in the sample of large invisible transverse energy and jets [9].

Figure 11: $W/Z \rightarrow jj$ signal observed by CDF in events with a charged lepton and $E_{t,\text{miss}}$ [10].
Figure 12: a), dijet mass distribution in lepton, missing $E_t$ and exclusive two jets events up to 300 GeV. b) Distribution after subtracting the known SM contributions [11].

Figure 13: Distribution of the lepton + missing $E_t$ + ij mass in the sample of [12].
Figure 14: Dijet mass distribution by D0 in the lepton, missing Et and exclusive two jets events after subtracting all SM contributions except dibosons. The dotted histogram represents the expected signal from a resonance at 145 GeV with cross section as large as suggest by CDF [13].

Figure 15: CDF comparison of the rates observed at $m_{jj} \approx 120$ GeV by their experiment and by D0 (left), and distribution of the rate difference (right) [14].
Figure 16: Mass distribution of heavy flavored dijets in W/Z events. Charm is tagged with a \( \sim 6\% \) efficiency, beauty with a \( \sim 40\% \) efficiency. The distribution is fitted with a WW + WZ contribution with a p-value of 0.12\% (a 3\( \sigma \) evidence) [15].
Figure 17: Inclusive jet distribution as a function of mass, indicating that quark jets dominate over gluon jets at large mass [16].