

Leading proton production in ep and pp experiments: how well do high-energy physics Monte Carlo generators reproduce the data?

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Abstract

The simulation of leading-proton production at high-energy colliders as obtained by the HERWIG, LEPTO and PYTHIA Monte Carlo generators is analysed and compared to the measurements of HERA and fixed-target experiments. The discrepancies found between real data and Monte Carlo events could be responsible for inaccurate simulation of particle multiplicities and hadronic final states, which could eventually generate problems in computing the Standard-Model backgrounds to new physics at the LHC collider.

1 Introduction

The production of final state baryons carrying a large fraction of the available energy but a small transverse momentum (leading baryons) is crucial for a deep understanding of strong interactions beyond the perturbative expansion of QCD. Indeed, in high-energy collisions, the QCD-hardness scale decreases from the central, large p_T region, to the soft, non-perturbative hadronic scale of the target-fragmentation region. Therefore, the measurement of leading baryons in the final state of high-energy collisions allows to gather information on the non-perturbative side of strong interactions.

Another reason of interest in leading-baryon production comes from the fact that the energy carried away by the leading baryon(s) produced in a high-energy collision is not available for the production of the central-hadronic system. Therefore, the leading-baryon spectra should be well simulated for a proper accounting of the hadronic multiplicities and energies, e.g. at the LHC collider where an appropriate simulation of these quantities will be the ground for a reliable calculation of the Standard-Model backgrounds to new physics.

Here we will review the data on the production of leading protons and compare them to the most popular Monte Carlo generators available.

2 The data and the Monte Carlo generators used for the comparison

2.1 The proton-proton data

Although the experimental data on leading-proton production are scarce, a few measurements in a large x_L range are available, where x_L represents the fractional longitudinal momentum of the proton. In proton-proton collisions, leading-proton production has been studied both at the ISR [2, 3] and in fixed-target experiments [4–6]. The x_L spectra measured in fixed-target experiments are shown in Fig. 1a-c,e.

2.2 The ep data

Cross sections for the production of leading protons were also measured at the HERA collider [7–9]. More recently, the ZEUS Collaboration made a new measurement [10] of the cross-section for the semi-inclusive reaction $ep \rightarrow eXp$ in deep-inelastic scattering using 12.8 pb^{-1} of data collected during 1997. The single-differential cross sections, $d\sigma_{ep \rightarrow eXp}/dx_L$ and $d\sigma_{ep \rightarrow eXp}/p_T^2$, and the double-differential cross section, $d^2\sigma_{ep \rightarrow eXp}/dx_L dp_T^2$, were measured in the kinematic range $Q^2 > 3 \text{ GeV}^2$ and $45 < W < 225 \text{ GeV}$, where W is the total mass of the hadronic system. The protons were measured using the leading-proton spectrometer (LPS) [11] in the range $x_L > 0.56$ and $p_T^2 < 0.5 \text{ GeV}^2$, where p_T is the scattered-proton transverse momentum.

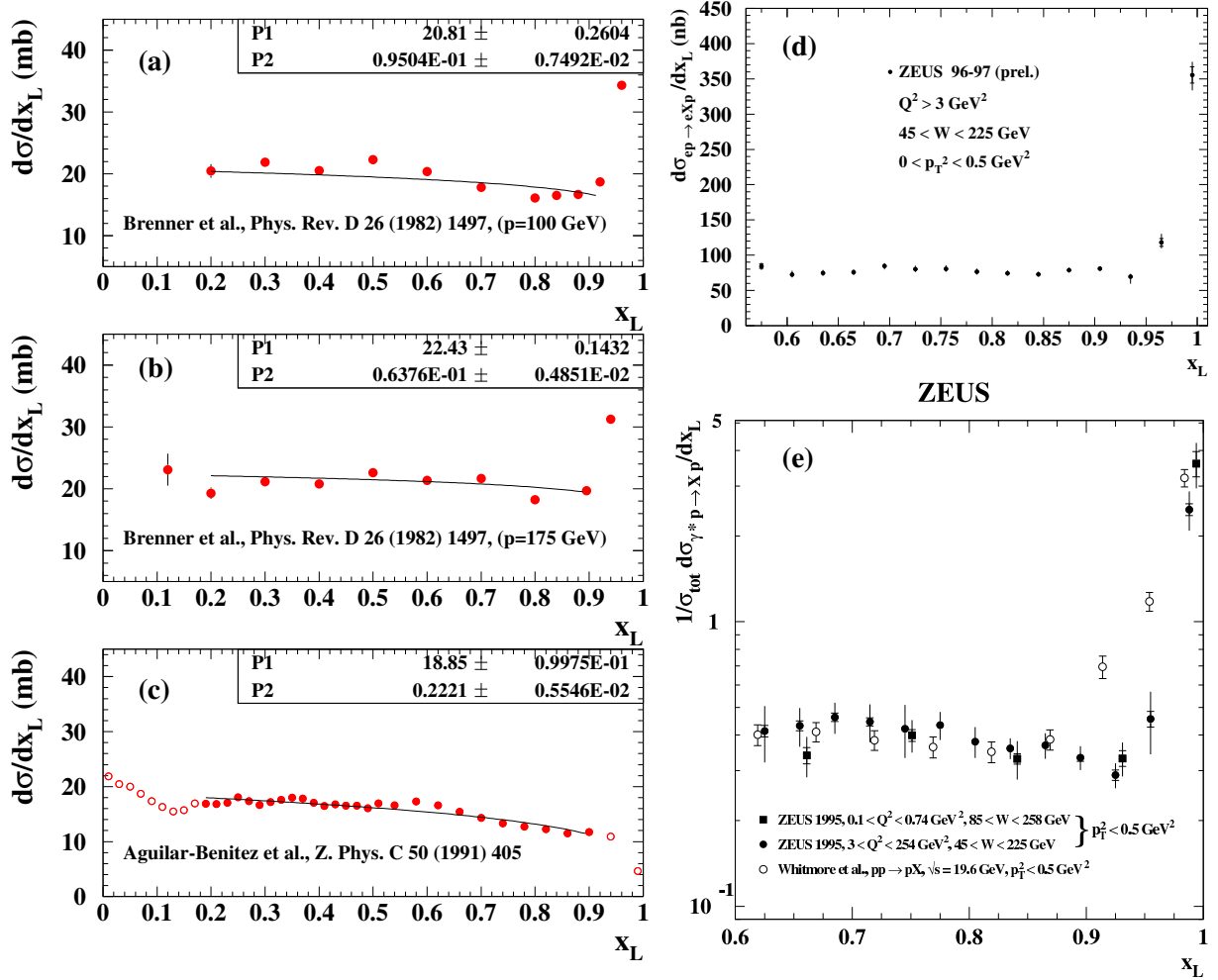


Fig. 1: Differential cross sections $d\sigma/dx_L$ measured in fixed-target experiments (a, b, c and e) and by the ZEUS Collaboration [9, 10] (d, e).

2.3 The Monte Carlo generators

Large samples of Monte Carlo ep events were generated to be compared to the data. The LEPTO generator was used either with the MEPS or the ARIADNE packages; in the latter case the diffractive component of the cross section was simulated using the Soft Color Interaction model. Events were also generated with HERWIG. Since this Monte Carlo does not simulate diffractive events, the POMWIG generator was used to account for the single diffractive events, and the SANG generator to account for the diffractive events in which the scattered-proton dissociates in a higher-mass hadronic system.

Proton-proton events at the LHC center of mass energy (14 TeV) were generated with PYTHIA.

3 Discussion

3.1 The x_L spectrum

Figure 1a, b and c show the $d\sigma/dx_L$ obtained by the fixed target experiments [4–6] which measured leading protons in a wide range of x_L . The cross section for such events shows a peak for values of the final-state proton momentum close to the maximum kinematically allowed value, the so-called diffractive peak. Below the diffractive peak the cross section is lower and consistent with a flat one. In this region, under the assumption of Regge factorisation [12], the fraction of events with a leading proton is expected to be approximately independent of the energy and type of the incoming hadron. The lines superimposed

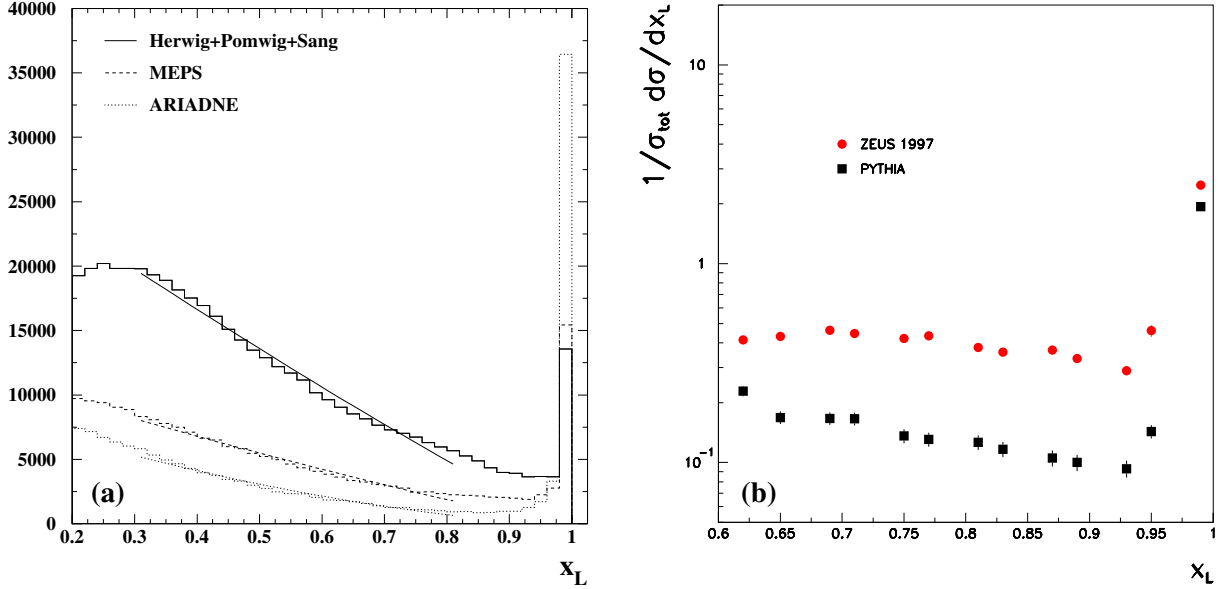


Fig. 2: (a) Differential cross section $d\sigma_{ep \rightarrow eXp}/dx_L$ generated with LEPTO, with MEPS or ARIADNE, and with HERWIG+POMWIG+SANG Monte Carlos; (b) Comparison between the normalised differential cross section $1/\sigma_{tot} d\sigma_{pp \rightarrow Xp}/dx_L$ simulated with PYTHIA and $1/\sigma_{tot} d\sigma_{ep \rightarrow eXp}/dx_L$ measured by the ZEUS Collaboration [9].

to the data are the results of fits in the range $0.1 < x_L < 0.9$ to the function $(1 - x_L)^\alpha$ that is commonly used to characterise the longitudinal distributions of leading particles. The values of α obtained are 0.1, 0.06 and 0.22 respectively for Fig. 1a, b and c. Fig. 1d shows the preliminary $d\sigma/dx_L$ obtained by ZEUS. Below the diffractive peak the cross section is again consistent with a flat one, i.e. $\alpha \sim 0$. A comparison between the normalised cross section $1/\sigma_{tot} d\sigma/dx_L$ obtained by the fixed-target data [6] and by the ep data is shown in Fig. 1e. For $x_L < 0.9$ the fraction of events with a leading proton is indeed consistent for the pp and the ep data set.

The x_L distributions of the simulation of the HERA events are shown in Fig. 2a. Already at first glance, the difference w.r.t. the data is evident, since the spectra are much more populated at low x_L in the Monte Carlo than they are in the data. Indeed, the fits to the same functional form as for the data give $\alpha = 1.0$ for LEPTO-MEPS, $\alpha = 1.4$ for LEPTO-ARIADNE and $\alpha = 1.0$ for HERWIG+POMWIG+SANG.

In Fig. 2b the x_L distribution obtained from the simulation with PYTHIA of pp events at the LHC center of mass energy (14 TeV) is compared to the ZEUS data. As discussed previously, according to the vertex factorisation hypothesis, the fraction of events with a leading proton is expected to be consistent in the ep and in the pp case. The simulation appears to approximately agree with the data in the diffractive peak region but is not able to describe the data neither in shape nor in normalisation in the region outside the diffractive peak.

In general we conclude that the fraction of beam energy carried away by the leading proton in the Monte Carlo is on average much smaller than in the data, with the consequence that the energy available in the simulation for the production of the central-hadronic system is correspondingly larger than in nature.

3.2 The p_T^2 spectrum

Although the p_T^2 distribution of the leading proton is less important for the hadronic final states than the x_L distribution, it is interesting to investigate how well the generators can reproduce it.

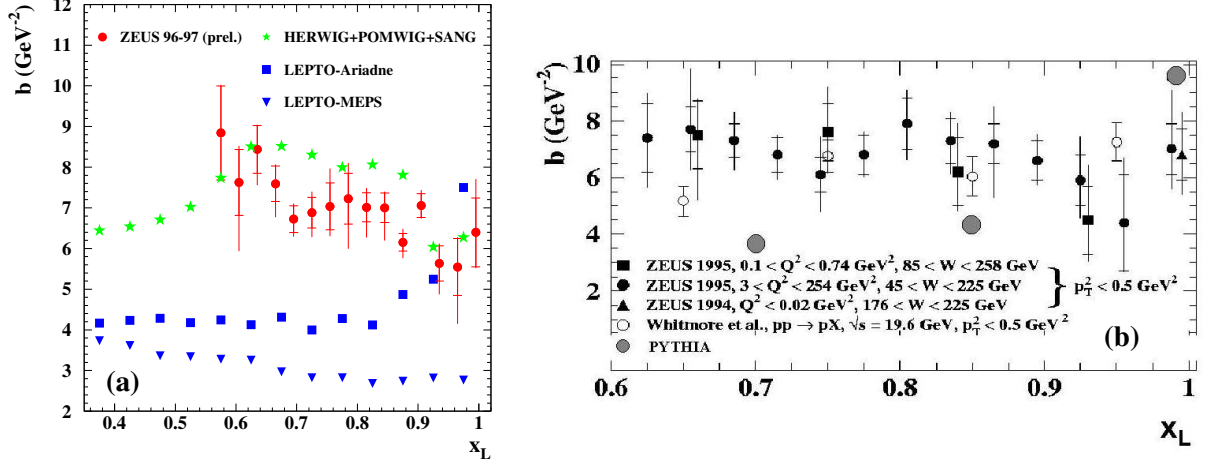


Fig. 3: The slope-parameters b obtained from a single-exponential fit to the differential cross section $d\sigma_{ep \rightarrow eXp}/dp_T^2$ ($d\sigma_{pp \rightarrow Xp}/dp_T^2$ for PYTHIA pp sample) to the function $A \cdot e^{-b \cdot p_T^2}$ in each of the x_L bins shown. (a) The red dots are the ZEUS preliminary data [10], while the other symbols represent the results of the Monte Carlos described in the picture; (b) The grey dots are the pp events simulated with PYTHIA, while the other symbols are the data described in the picture.

In Fig. 3a the red dots show the values of the slope-parameter b obtained from a single-exponential fit to the function $e^{-b \cdot p_T^2}$ in each of the x_L bins of the ZEUS $d\sigma/dp_T^2$ measurement. The b slopes obtained by a similar fit performed on the simulated events in the ep case and in the pp case are also reported in Fig. 3a and Fig. 3b, respectively. In the pp case the extracted b -slopes have been corrected for the expected shrinkage of the diffractive peak.

The b -slopes values resulting from the fit to the p_T^2 distribution of the HERWIG+POMWIG+SANG sample appear to be in the right ball park.

The LEPTO generator shows too small b -slope values, smaller than those of the data by approximately 3 GeV^{-2} . In the case the matrix-element parton showers are used to generate the events, since the dependence of b on x_L is similar to that of the data, it is conceivable to fix the difference by tuning the primordial k_T of the generation. If the ARIADNE package is used instead, it seems quite difficult to improve the situation in a similar way, since the generated b values increase with x_L , a feature that is not seen in the data.

The b -slopes values resulting from the fit to the p_T^2 distribution of the PYTHIA pp sample are approximately consistent with the ZEUS data in the diffractive peak region, but lower than the data again by approximately 3 GeV^{-2} in the region outside the peak.

3.3 Reweighting of the PYTHIA leading proton spectrum

A sample of pp proton events generated with PYTHIA has been used to simulate the many interactions per bunch crossing (pile-up events) occurring at the LHC luminosities in a recent study on the diffractive production of a Higgs boson at the LHC [13]. The simulated leading proton spectrum has been reweighted both in x_L and in p_T^2 with the following function, calculated for each x_L bin of Fig. 2b:

$$f(x_L) = [-37.22 + 135.1 \cdot x_L - 148.5 \cdot x_L^2 + 54.3 \cdot x_L^3] \cdot \frac{e^{-b_{ZEUS}t}}{e^{-b_{PYTHIA}t}} \cdot \frac{b_{ZEUS}}{b_{PYTHIA}},$$

where $b_{ZEUS} = 7 \text{ GeV}^{-2}$ and $b_{PYTHIA} = 4.4 \text{ GeV}^{-2}$. The polynomial form in x_L is the result of a fit to the ratio ZEUS/PYTHIA of the differential cross sections $1/\sigma_{tot} d\sigma/dx_L$ of Fig. 2b; thus $f(x_L)$ provides the number of simulated leading protons to be consistent with the ZEUS data.

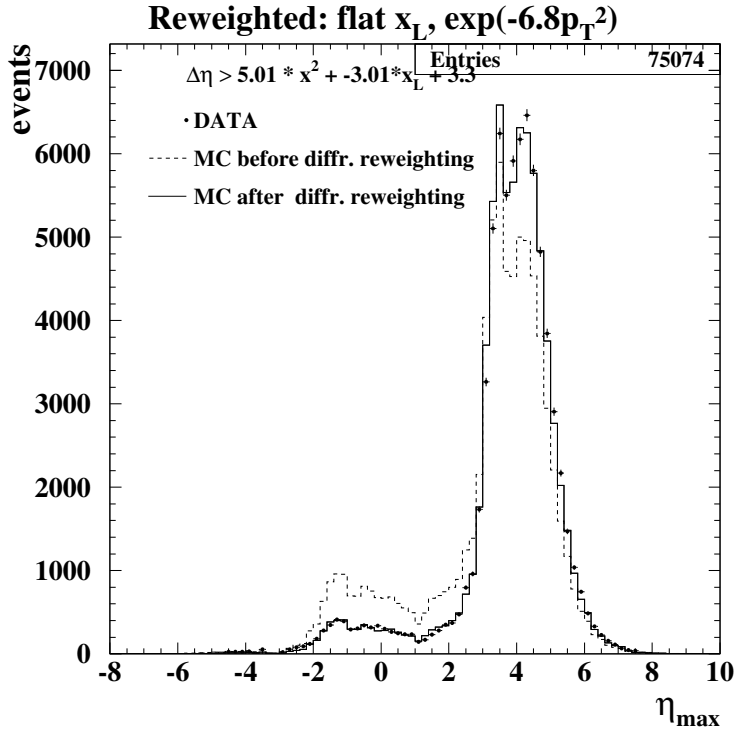


Fig. 4: The η_{max} distribution of the ZEUS data [10] (dots) and of the LEPTO-MEPS Monte Carlo obtained with the default x_L and p_T^2 distributions (dashed-line histogram). The MC distribution after reweighting to a flat x_L and to $e^{-6.8p_T^2}$ is shown by the full-line histogram.

3.4 The fraction of diffractive — large-rapidity gap — events w.r.t. the total

One way to identify a diffractive event produced in ep or pp interactions is to search for a large-rapidity gap (LRG) in the pseudorapidity distribution of the particles produced. In ZEUS, a diffractive-LRG event was tagged by $\eta_{max} < 2$, where η_{max} corresponds to the pseudorapidity of the most forward (i.e. proton direction) energy deposit in the calorimeter exceeding 400 MeV. The η_{max} distribution for ZEUS DIS events with $Q^2 > 3 \text{ GeV}^2$ is shown by the dots in Fig. 4. The two regions of non-diffractive events (with η_{max} between 2 and 8) and of diffractive events (which distribute at η_{max} values below 2) are clearly distinguishable.

The LEPTO-MEPS events were passed through the standard simulation of the ZEUS trigger and detector, and through the same reconstruction and analysis programs as the data. The η_{max} distribution of the MC events after such processing is shown by the dashed histogram in Fig. 4. We note that the diffractive events with $\eta_{max} < 2$ generated with the Soft Color Interaction algorithm in LEPTO-MEPS are more than twice those found in the data. Therefore, the Soft Color Interaction algorithm, as implemented in the LEPTO generator, fails to describe the data in the range of the ZEUS-LPS detector, i.e. $x_L > 0.56$.

4 Summary

The data on leading-proton production in ep and pp scattering have been compared to the most popular Monte Carlo generators available to simulate high-energy physics events. This exercise has revealed that the simulation of the leading-proton momenta, both longitudinal and transverse to the beams, does not reproduce the properties of the data. In particular, the x_L distribution of the leading protons would be made more close to that of the data if a proper accounting of the energy available for the hard-scattering process could be achieved.

Although the HERWIG generator has been successful in simulating many features of high-energy physics final states, it does not contain the diffractive component of the cross section, and the x_L spectrum it produces is far from being almost flat, as seen in the data.

The Soft Color Interaction model in its standard implementation in LEPTO is producing twice the fraction of diffractive-LRG events seen in the ZEUS data at $x_L > 0.56$, therefore distorting in a significant way the multiplicities and hadronic energies present in real events.

The PYTHIA Monte Carlo has been used to simulate pp events at the LHC center of mass energy (14 TeV), and then also compared to ep data. The generator has been shown to reproduce the longitudinal and transverse momentum of the data in the diffractive peak region; however, it underestimates both the cross section and the p_T^2 -slopes at lower values of the scattered proton momentum, contradicting the hypothesis of vertex factorisation, which is supported by the data.

All the above arguments generate some concern that the hadronic multiplicities of the MC generators taken into account here have been tuned consistently and that they can produce an accurate simulation of the final states of the Standard-Model processes at the LHC energies.

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