Vol. 29 (1998) *ACTA PHYSICA POLONICA B* No 5

A PRECISE PARTON LUMINOSITY MONITOR AT LHC AND APPLICATIONS FOR THE $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ SEARCH*

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(Received February 25, 1998)

A new approach to determine the LHC luminosity is investigated. Instead of employing the proton–proton luminosity measurement, we suggest to measure directly the parton–parton luminosity. It is shown that the electron and muon pseudorapidity distributions, originating from the decay of W^+, W^- and Z^0 bosons produced at 14 TeV pp collisions (LHC), constrain the x distributions of sea and valence quarks and antiquarks in the range from $\approx 3 \times 10^{-4}$ to $\approx 10^{-1}$ at a Q^2 of about 10^4 GeV^2. Using this information one can relate the rate of $l^\pm$ events to the quark and antiquark luminosity at the LHC. Furthermore, it is demonstrated that other $q\bar{q}$ related scattering processes like $q\bar{q} \to W^+W^-$can then be predicted accurately. This continuum production is an important background process for the resonant signature $H \to W^+W^- \to l^+\nu l^-\bar{\nu}$. It is shown that precise prediction of this background enhances the discovery potential for the Standard Model Higgs in the W^+W^- decay channel for 120 GeV $\leq m_H \leq$ 500 GeV.

PACS numbers: 12.38. Qk

1. Introduction

The future CERN Large Hadron Collider (LHC) [1] will collide protons at a centre-of-mass energy of 14 TeV. These collisions will reveal the behaviour of fundamental particles of matter at distances/energies never studied before. The aim is to produce high energy, but also a high luminosity of $\mathcal{L}_{\text{Design}} = 10^{34}$ s^{-1}cm^{-2}. The expected initial luminosity of 10^{33} s^{-1}cm^{-2} will result in

* Presented at the Cracow Epiphany Conference on Spin Effects in Particle Physics and Tempus Workshop, Cracow, Poland, January 9–11, 1998.

about 10 fb^{-1} per year. It is worth pointing out that already at this initial luminosity the event rate of weak bosons is huge: about 10^6 $W^{\pm} \to \ell^{\pm}\nu$ per day and about 500 $W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ per day! The non-resonant W^+W^- production is especially important as it is the dominant background for the Standard Model Higgs search in the $H \to W^+W^-$ decay channel [2].

Besides the Higgs search (one of the main goals at the LHC) the interpretations of essentially all proposed measurements will require a good knowledge of the parton distribution functions at the relevant Q^2 and the collected integrated luminosity.

The parton distribution functions $\mathrm{f}(x, Q^2)$, where x is the fractional parton momentum ($x = p_{\mathrm{parton}}/E_{\mathrm{beam}}$) of the relevant types of valence and sea quarks (or antiquarks) and gluons at the considered Q^2 of the reaction, are actually determined from experimental observables in deep-inelastic lepton–hadron scattering at fixed target and HERA experiments as well as from Drell–Yan lepton pair production processes at hadron colliders [3]. These results, obtained at different Q^2, have then to be extrapolated to the relevant Q^2 scale of process at LHC. While the x distributions of the valence quarks are already quite well constrained, uncertainties for the x distributions of sea quarks and antiquarks and gluons remain important. As a result of these structure function uncertainties, combined with the unknown contributions from higher order QCD corrections, total cross section predictions of W^+, W^- and Z^0 boson production at 14 TeV pp collisions (LHC), vary currently between 10–20%.

Moreover, the uncertainty in the evaluation of the luminosity has to be added. The traditional methods to determine the proton–proton luminosity are size and intensity measurements of the beams at the interaction point, as well as event rates of processes with previously measured or calculable cross sections like elastic proton–proton scattering [4] and QED processes like $pp \to ppe^+e^-$ [5]. Unfortunately, precise measurements of the above processes, especially at high luminosity, are very difficult. Both omni-purpose experiments, ATLAS [6] and CMS [7], consider a luminosity accuracy of $\pm 5\%$ as their goal [8].

Consequently, current estimates of the achievable accuracies for signal and background processes at the LHC appear to be somewhat depressing. This is especially the case when these uncertainties are compared with the possible small statistical errors for many LHC measurements or the current knowledge of quark and lepton couplings to $W^{\pm}$ and Z^0 bosons.

2. Weak boson production

Experiments at the LHC will study the interactions between fundamental constituents of the proton, the quarks and gluons, at energies where these partons can be considered as quasi free. Consequently the important quantity is the parton–parton luminosity at different values of x_{parton} [9] and not the traditionally considered proton–proton luminosity. We thus propose a new approach to measure the LHC luminosity: using $W^\pm$ and Z^0 boson production to constrain the quark/antiquark structure functions and luminosities.

Assuming collisions of essentially free partons, the production of weak bosons, $u\bar{d} \to W^+ \to \ell^+\nu$, $d\bar{u} \to W^- \to \ell^-\bar{\nu}$ and $u\bar{u}(d\bar{d}) \to Z^0 \to \ell^+\ell^-$ are in lowest order understood to at least a percent level. Moreover it is a well known fact that the $W^\pm$ and Z^0 production rates at the LHC, including their leptonic branching ratios into electrons and muons, are huge and provide clean and well measurable signals. With the well known $W^\pm$ and Z^0 masses, possible x values of quarks and antiquarks are constrained from $M^2_{W^\pm,Z^0} = s x_q x_{\bar{q}}$ with $s = 4E^2_{beam}$. The product $x_q x_{\bar{q}}$ at the LHC is thus fixed to $\approx 3\times 10^{-5}$. The rapidity distributions of the weak bosons are directly related to the fractional momenta x of the quarks and antiquarks. Consequently, the observable pseudorapidity distributions of the charged leptons from the decays of $W^\pm$ and Z^0 bosons are also related to the x distributions of quarks and antiquarks. The shape and rate of the lepton pseudorapidity distributions provide therefore the key to precisely constrain the quark and antiquark structure functions and their corresponding luminosities.

TABLE I

Examples of estimated weak boson production cross sections at the LHC for three different sets of structure functions using PDFLIB and PYTHIA programs [13,14]. In all cases the leptonic branching ratios into electrons and muons are included.

Weak boson cross sections ($\sqrt{s}$ = 14 TeV)			
	$\sigma \times BR$		
Reaction	MRS(A)	CTEQ 2L	GRV 94 HO
$u\bar{d} \to W^+ \to \ell^+\nu$	20.18 nb	17.32 nb	21.58 nb
$d\bar{u} \to W^- \to \ell^-\bar{\nu}$	14.24 nb	12.63 nb	15.40 nb
$u\bar{u}(d\bar{d}) \to Z^0 \to \ell^+\ell^+$	3.246 nb	2.854 nb	3.456 nb
$q\bar{q} \to (Z^*,\gamma^*) \to \ell^+\ell^+$ ($M_{\ell\ell}$=150-200 GeV)	9.71 pb	8.98 pb	10.26 pb
$q\bar{q} \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	3.53 pb	3.30 pb	3.63 pb

The production of $pp \to W^+$, W^- and Z^0 and their identification using the leptonic decays have been discussed extensively in the literature [10]. In particular, these reactions provide clean sources of isolated high p_t electrons or muons, and due to their high rate, are often considered as a clean and excellent calibration tool at the LHC [11]. However, previous studies concluded that their use as a luminosity monitor is limited to relative luminosity measurements only [12]. The reason for these rather pessimistic conclusions is based on the predicted cross section variations using different sets of structure functions [13]. The size of these cross section variations is as large as 10–20% as can be seen from Table I. The cross section predictions as well as the following simulation results are obtained using the PYTHIA Monte Carlo program [14]. These cross section variations for single $W^{\pm}$, Z^0 production are strongly correlated with the cross section predictions for other $q\bar{q}$ related processes. As an example, the corresponding cross sections for the reaction $q\bar{q} \to W^+W^-$ are also given in Table I. Thus, even without looking at further details, the uncertainties for multi boson production cross sections at the LHC are reduced to about 5-10% if event rates are estimated relative to the production rates of single $W^{\pm}$, Z^0 events. Furthermore such relative measurements reduce also errors from branching ratios and detection efficiency uncertainties.

For the following studies, the MRS(A) structure function set [13] is used as reference system. Figure 1a shows the expected rapidity distribution of W^+ and W^-, which directly reflect the difference between the x distributions of the u, d valence quarks and the sea quark or antiquarks. For small $W^{\pm}$ rapidities, corresponding to $x_{1,2}$ values of $\approx 6 \times 10^{-3}$, most $W^{\pm}$ originate from the annihilation of sea quark–antiquarks and only small differences between W^+ and W^- are expected. For larger rapidities the $W^{\pm}$ originate from the annihilation of quarks and antiquarks with very different x values. For example, to produce a $W^{\pm}$ at a rapidity of about 2.5, one finds the corresponding $x_{1,2}$ values of the quark and antiquark to be $x_1 \approx 0.1$ and $x_2 \approx 3 \times 10^{-4}$. As the proton is made of two valence u quarks and one valence d quark the W^+ production is much more likely than the W^- production at large rapidities. Figure 1b shows the pseudorapidity distributions of the charged leptons originating from the $W^{\pm}$ decays. Because of the V–A interaction, the differences between the pseudorapidity distributions of ℓ^+ and ℓ^- especially at large η values are larger than the ones for the W^+ and W^-. The reason is that the left handed lepton (ℓ^-) is emitted preferentially in the direction of the incoming quark and the right handed anti-lepton (ℓ^+) is emitted opposite to the quark direction. Thus the observable charged lepton pseudorapidities reflect not only the x distributions of quarks and antiquarks but allow also to some extent a distinction between valence and sea quarks at a given x.

As mentioned above we want to demonstrate that the dynamics and event rates of weak boson production at the LHC accurately constrain the quark and antiquark structure functions and their corresponding luminosity.

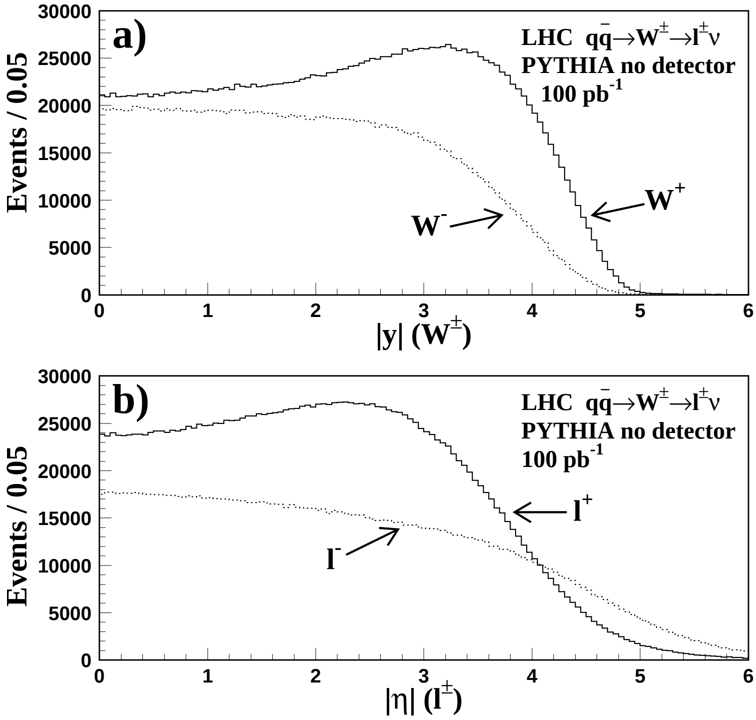

Fig. 1. Expected rapidity (pseudorapidity) distribution of $W^\pm$ (a) and $\ell^\pm$ (b) originating from the reaction $q\bar{q} \to W^\pm \to \ell^\pm\nu$ at the LHC ($\sqrt{s} = 14$ TeV and the MRS(A) structure functions [13]). The assumed luminosity of 100 pb^{-1} corresponds to about one day of data taking with a luminosity of 10^{33} sec^{-1} cm^{-2}.

For this purpose simple event selection criteria are used (for details see [15] and [16]). These criteria closely follow the design characteristics of the CMS experiment [7].

3. Using the W$^\pm$ and Z^o production to constrain the q and $\bar{q}$ structure functions

We now study the effects of different structure function parametrizations on the measured $\ell^\pm$ pseudorapidity distributions ($q\bar{q} \to W^\pm \to \ell^\pm\nu$), and on the reconstructed Z^0 rapidity distribution ($q\bar{q} \to Z^0 \to \ell^+\ell^-$).

At the LHC, in contrast to proton–antiproton colliders, the antiquarks have to come from the sea. Thus, the pseudorapidity distribution of the positive charged leptons, $u\bar{d} \to W^+ \to \ell^+\nu$ contains the information about the sea $\bar{d}$-quarks and the valence or sea u-quarks. The negative charged leptons, $d\bar{u} \to W^- \to \ell^-\bar{\nu}$ carry consequently the information about the sea $\bar{u}$ quarks and the valence or sea d quarks. The rapidity distribution of charged lepton pairs, from $Z^0, (Z^*, \gamma^*) \to \ell^+\ell^-$, provide the information about the sum of sea $\bar{u}$ and $\bar{d}$ quarks and the corresponding valence and sea quarks. Consequently, the combination of the different observable lepton pseudorapidity distributions should provide some sensitivity to the u, d, $\bar{u}$ and $\bar{d}$ parton densities over a large x range. The question is how well q and $\bar{q}$ structure function can be constrained from the observable weak boson rapidities. For this purpose the different $\ell^\pm$ cross sections are studied relative to a reference structure function, arbitrarily chosen to be the MRS(A) set.

The fraction of weak bosons which are produced from the annihilation of valence quarks and low x antiquarks increases strongly with increasing rapidity. The valence quark x distribution is already quite well constrained. The main difference between the various structure functions comes from the sea q and $\bar{q}$ parametrizations especially at low x. Thus precise measurements of the charged lepton pseudorapidity distributions from $W^\pm$ decays and the rapidity distribution of the Z^0 events constrain the low x domain of $\bar{u}$ and $\bar{d}$.

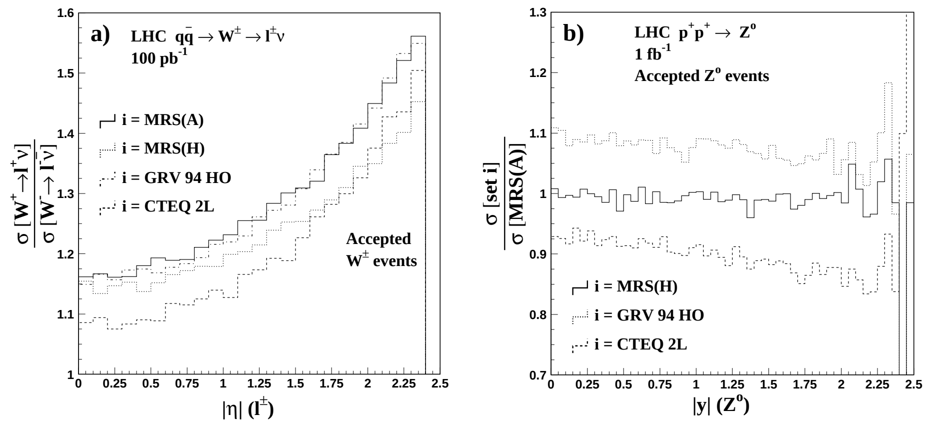

Fig. 2. a — the ratios of the accepted cross sections $\sigma_{u\bar{d}\to W^+\to\ell^+\nu}/\sigma_{d\bar{u}\to W^-\to\ell^-\bar{\nu}}$ as a function of the lepton pseudorapidity for four different structure functions [13]; b — rapidity dependence of the reconstructed Z^0 cross section for different sets of structure functions relative to the one obtained from the MRS(A) parametrization.

The sensitivity of the measurable lepton rapidity distribution to the different sets of structure functions is shown in figure 2. Figure 2a) shows the observable ratio of the ℓ^+ to ℓ^- event rates for three different sets of structure functions and an integrated luminosity of 100 pb^{-1}. The difference between the various low-x sea quark parametrizations are thus reflected in the observable lepton pseudorapidities. Consequently, the shape of the $\ell^\pm$

pseudorapidity distributions provide a strong constraint on the underlying x distribution of quarks and antiquarks with x between $\approx 3 \times 10^{-4}$ and $\approx 10^{-1}$. The differences of about 5-10% between these sets should be compared with the statistical precision, which is smaller than 1% per bin for an integrated luminosity of only 100 pb^{-1} (corresponding roughly to one day of data taking at the initial LHC luminosity of $10^{33}\text{s}^{-1}\text{cm}^{-2}$). Figure 2b) shows the ratio of the predicted Z^0 cross sections from different structure functions relative to the reference MRS(A) set. The expected Z^0 event rates are roughly a factor of 10 smaller and the errors shown in this figure correspond to about 10 days of data taking. Other figures with the rapidity dependence of the $\ell^{\pm}$ cross section predictions from different sets of structure functions are shown in reference [15] and [16].

Having demonstrated that the $\ell^{\pm}$ pseudorapidity distributions, originating from weak boson decays, are very sensitive to details of the quark and antiquark x distributions one can now relate the rate of $\ell^{\pm}$ events in a selected pseudorapidity interval to the quark and antiquark luminosity at the given x. Obviously, if the shape of the pseudorapidity distribution is accurately known, the $\ell^{\pm}$ event rates need to be measured only for a small pseudorapidity interval, where a large number of "clean" events can be selected.

4. Precise predictions of $q\bar{q} \rightarrow W^+W^-$

Once the quark and antiquark luminosity at $Q^2 \approx 10^4$ GeV^2 and in the x range between $\approx 5\times10^{-4}$ and 10^{-1} are constrained from the single boson production, very accurate theoretical predictions for cross section ratios like $\sigma(q\bar{q} \rightarrow W^+W^-)/\sigma(q\bar{q} \rightarrow W^{\pm})$ should be possible. The justification is that similar higher order QCD corrections for $q\bar{q}$ scattering processes at different Q^2 like $q\bar{q} \rightarrow W^+W^-$ can be expected and moreover that the Q^2 dependence should in principle be calculable. For example, the total cross section predictions for the process $pp \rightarrow W^{\pm}$ differ by about 15% if the CTEQ 2L and the MRS(A) parametrizations are used (see Table I). However, using the process $\sigma(q\bar{q} \rightarrow W^{\pm})$ as a reference process, one can relate the cross section in question, i.e. $\sigma(q\bar{q} \rightarrow W^+W^-)$, to the reference reaction $\sigma(q\bar{q} \rightarrow W^{\pm})$. Comparing now the prediction for the relative cross sections between CTEQ 2L and the MRS(A) one finds that the difference is reduced to $\approx 7.5\%$.

As a next step, the parametrizations of the $q, \bar{q}$ structure functions, especially at low x, should be adjusted such that the observed $\ell^{\pm}$ pseudorapidity distributions are described. We do not expect any principle problem of measuring the shape and the rate of the charged lepton pseudorapidity distribution with a $\pm1\%$ accuracy. Thus even small differences for the

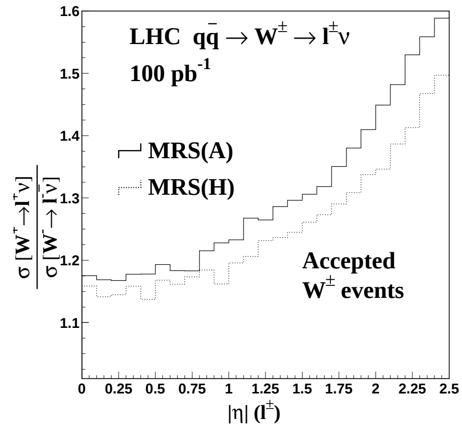

Fig.3

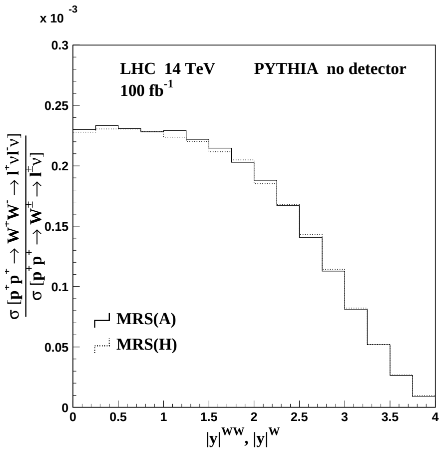

Fig.4

Fig. 3. Detectable charged lepton cross section ratio, $\sigma_{u\bar{d}\to W^+\to\ell^+\nu}/\sigma_{d\bar{u}\to W^-\to\ell^-\bar{\nu}}$, as a function of the lepton pseudorapidity for the MRS(H) and MRS(A) structure function parametrizations.

Fig. 4. The cross section ratio $\sigma_{pp\to W^+W^-}/\sigma_{pp\to W^\pm}$ as a function of the rapidity of the W boson or the WW-system for MRS(H) and MRS(A) structure function parametrizations.

sea quark parametrization, like those shown in figure 3 between MRS(A) and MRS(H), should be detectable. One could thus use the difference in cross section for the two sets as a pessimistic limitation of the proposed method. Differences between relative cross section predictions for different $q\bar{q}$ scattering processes and the two parametrizations indicate therefore the size of the remaining uncertainties. For example the cross section ratios $\sigma(q\bar{q} \to W^+W^-)/\sigma(q\bar{q} \to W^\pm)$ are 4.74×10^{-4} for MRS(A) and 4.76×10^{-4} for MRS(H) (see figure 4). Other $q\bar{q}$ scattering processes like $\sigma(q\bar{q} \to W^\pm Z^0)/\sigma(q\bar{q} \to W^\pm)$ show similar stability with predicted ratios of 1.78×10^{-4} for MRS(A) and 1.79×10^{-4} for MRS(H).

Following the above procedure, i.e. constraining the $q, \bar{q}$ structure functions and the corresponding parton luminosities, the event rate of weak boson pair production appears to be predictable with a much better accuracy than the previously considered optimistic goal of $\pm5\%$.

The possibility to detect the Standard Model Higgs in the reaction $pp \to H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ has recently been investigated by Dittmar and Dreiner [2] [17]. The authors studied especially the mass region 155 GeV $\leq m_H \leq$ 170 GeV, which is difficult to cover with the so-called "golden signature" $pp \to H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$. The new signature appears to give 5 σ signals for an integrated luminosity of less than 5 fb^{-1}. They indicated also that for mass regions above 250 GeV or below 130 GeV a signal with large statistical significance can be obtained. However the signal to background ratio drops below a value of 0.15. Thus, in order to distinguish the resonant production $pp \to H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ from the continuum production of W^+W^-X events with a 5 σ significance, a systematic uncertainty of less than 3% is required. Following the method outlined in this paper, a precise WW prediction should be possible, allowing Higgs detection over the mass region between 120 GeV and 500 GeV. This is especially important since measuring different Higgs decay channels will be important in order to improve our knowledge of the exact nature of the Higgs.

5. Outlook

We have not investigated the achievable theoretical accuracies, but believe that many theoretical uncertainties, like the $\alpha_s(Q^2)$ uncertainties or still unknown higher order QCD corrections, contribute in very similar ways to the single and pair production of weak bosons. Furthermore, the experimental possibility to measure the x distributions of sea and valence quarks and the corresponding luminosities to within $\pm 1\%$ should encourage our theoretical colleagues to match this experimental accuracy.

Finally, we argue that the gluon x distribution and the corresponding gluon luminosity can also be constrained in a similar way from accurate measurements of the rapidity distribution of gluon dominated scattering processes, like $q\bar{q} \to Z^0 g$. The feasibility of this approach, where the leptonic Z^0 decays provide an excellent signature and should allow the selection of essentially background free Z^0–jet events, has been presented by F. Behner at EPS 97 in Jerusalem [18].

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