Diffractive W boson production at the LHC

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Abstract

Diffractive W boson production and background processes, photoproduction and inclusive W production, are discussed. Standard cuts for W are introduced and searches for additional cuts are summarized. The old HERA method of the W rapidity reconstruction ($E - p_z$ balance) is reported as not working in the LHC case. Studies for method involving p_{T} balance are introduced as a possible solution. Reproduced resultes of K. Golec-Biernat at the generator level are shown.

Contents

1 Introduction

The W boson production has been studied carefully for a long time. In this work we would like to investigate thefeasibility of diffractive W production measurement at ATLAS. There are some significant differences between non-diffractive and diffractive W boson production channels. One can think about finding phase space regions in which clean signature of the diffractive W might be visible. Furthermore, the measurement of W boson production asymmetry in the diffractive pp collisions is a valuable method to determine details of the parton distribution in the proton such as: the $d_{val}(x)/u_{val}(x)$ ratio for large x or the sea quark isospin symmetry at small x values.

Aim of studies, which are supposed to be summarized by this report, was to check the feasibility of (mentioned above) diffractive W production asymmetry measurement:

- find suitable MC generators,
- recognize background sources,
- define selection criteria,
- find ways to remove background,
- propose method to reconstruct W rapidity.

1.1 Kinematic variables

In this paper several kinematical variables are used. To ensure full understanding it is recommended to become acquainted with the definitions.

rapidity

$$y = \frac{1}{2} * \ln(\frac{E + p_z}{E - p_z}) \tag{1}$$

where E stands for energy and p_z is longitudinal momentum of a particle.

pseudorapidity

$$\eta = -\ln(\tan\frac{\theta}{2}) \tag{2}$$

where θ is an azimuthal angle of a particle.

x fraction of the p momentum carried by the incident quark.

For a massless particles rapidity might be considered as a comparable value with pseudorapidity. Unfortunately, it is no longer true for the W boson with its mass about $80 GeV/c^2$. For the basic control plots pseudorapidity was used, for all W related analysis rapidity was used.

1.2 The W boson production asymmetry[1]

The W boson production asymmetry in rapidity is defined as follows:

$$A(y) = \frac{d\sigma_{W^+}(y) - d\sigma_{W^-}(y)}{d\sigma_{W^+}(y) + d\sigma_{W^-}(y)} \tag{3}$$

where $d\sigma_{W^\pm}(y)$ is a cross section for $W^\pm$ production in function of rapidity. The *A(y)* is plotted at the right side of the figure 1. For inclusive W production one should expect a U-shaped, symmetrical with respect to zero, rapidity line (dashed one at the plot). For processes involving the pomeron exchange (diffractive ones) other characteristic is expected (solid line at the plot). The value of the *A(y)* should vanish smoothly for negative rapidity assuming that the diffractive proton goes in this direction. The grey area on the plot represents rapidity gap, in which there should be no particles detected.

From the measurements of the W asymmetry in pp collisions, the $\frac{d_p(x)}{u_p(x)}$ [2] ratio can be extracted as:

$$\frac{d_p(x)}{u_p(x)} \approx \frac{1 - A(y)}{1 + A(y)} \tag{4}$$

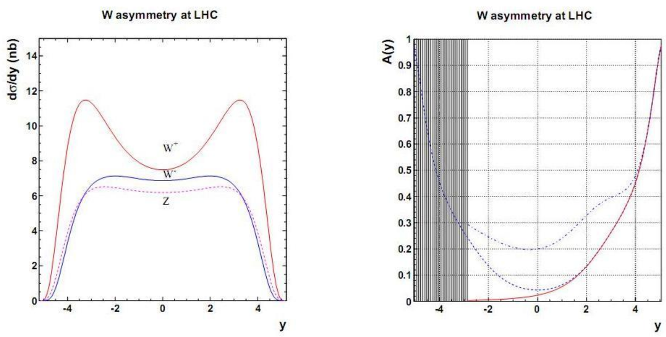

Figure 1: Left: the $W^\pm$ boson cross section in function of rapidity; right: the W asymmetry in pP collisions (solid line) together with the asymmetry in the pp collisions (dashed line). The dashed area marks rapidity gap. Details in the text.

[1] By Krzysztof Golec-Biernat, EPS Conference, Krakow, Poland, July 2009.

[2] Ratio of d and u valence quarks in the proton as a function of x.

2 The W production channels

2.1 Diffraction

In the diffractive case, the standard inclusive parton distributions in pp collisions are replaced by diffractive parton distributions. The single diffraction event can be then interpreted as a proton - pomeron (pP) collision, where pomeron is a vacuum quantum number object.

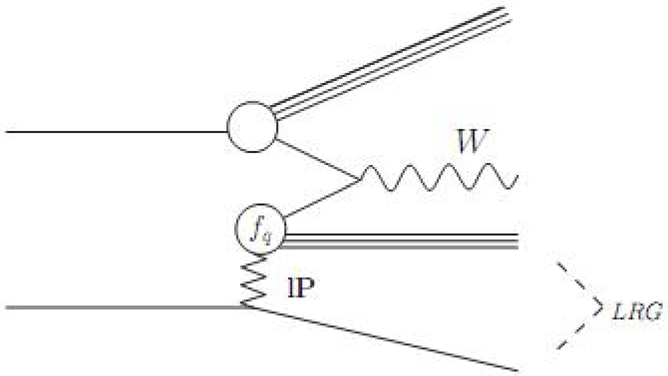

Figure 2: Diffractive $W^{\pm}$ production diagram

As it is shown at the figure 2, one of the colliding protons emits a pomeron which is interacting with one of the second proton‘s quarks. The W boson produced in this way decay subsequently into a lepton and a corresponding neutrino. The Large Rapidity Gap (lack of particles) is expected to be seen in the direction of diffractive proton.

2.2 Background

2.2.1 Photoproduction

The event with the W boson resulting from photoproduction should be considered as a significant background process. That is because of an almost identical signature that it might leave in a detector. One should worry especially about the Large Rapidity Gap existence in this channel, as it is one of the main features that can help distinguish between the diffractive and inclusive W production.

2.2.2 Inclusive W production

The inclusive W production is the main source of a background in the discussed analysis. The leading order diagrams for this process are shown at the figure 4. All variables distributions (e.g. total multiplicity, charge particles multiplicity...) plotted as a function of (pseudo-) rapidity should be symmetric.

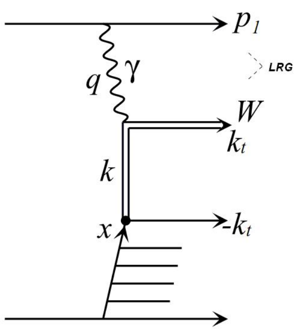

Figure 3: The $W^{\pm}$ boson photoproduction diagram

3 Monte Carlo generators

Unfortunately, different W boson production channels demand different Monte Carlo generators. Well known, multipurpose generator, Pythia can simulate neither diffractive W boson production nor photoproduction. Therefore, Pomwig and MadGraph/MadEvent were used.

3.1 Pomwig[3]

Pomwig generates diffractive events involving single or double pomeron exchange. Pomwig works by replacing the photon flux coming from electrons in Herwig by a pomeron flux that was measured at HERA. The photon structure function is similarly replaced by a pomeron structure function. Pomeron emission from a proton can then be simulated within Herwig by requesting an electron as the incoming beam particle together with the Pomwig structure functions. This electron is converted into an outgoing proton by Pomwig and the pomeron appears as a photon in the event record. This leads to a surprising looking lepton-photon-proton vertex in the event record, but the observable final state particles are correct.[4]
Process id 11450 was selected ($pp \to W^{\pm} \to l\nu_l,\quad l = e, \mu, \tau$) and the underlying events simulation was turned on. The incoming beams were set to energy of 5 TeV in the CM frame each.[5].

[3] http://www.pomwig.com/

[4] Text taken from the https://twiki.cern.ch/twiki/bin/view/AtlasProtected/PomwigForAtlas page (8 IX 2009).

[5] The beams energy in the CM equal 2×5 TeV was used in every MC generator as a default setting.

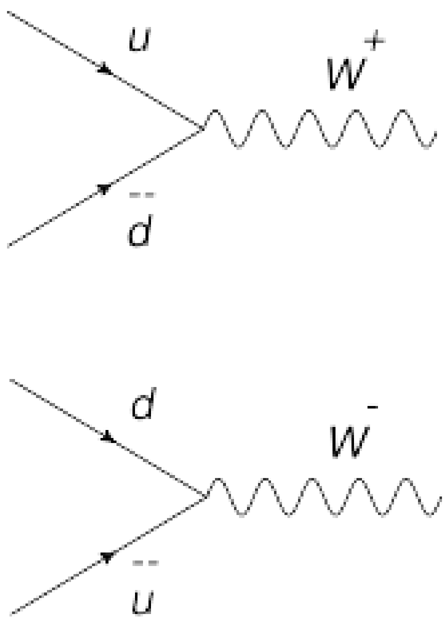

Figure 4: The leading order diagrams for the inclusive $W^{\pm}$ boson production

3.2 MadGraph/MadEvent[6]

MadGraph / MadEvent is a software that is able to generate amplitudes and events for any process (with up to 9 external particles) in any model. In this analysis Standard Model settings were used. Others implemented are as follow: Higgs effective couplings, MSSM, the general Two Higgs doublet model. An easy to use mechanism of creating extended models is provided. MadGraph with its web page interface for the process generation and Feynman's diagrams generations is intended to prepare steering files which might be used in MadEvent. An efficient simulation may be performed on the web clusters or at the local machines. MadEvent, however, is not able to simulate the whole chain which leads to the final state particles. As a consequence, additional MC generator has to be used to perform parton showering and further hadronization.

MadGraph/MadEvent was used to generate the W photoproduction ($p\gamma \rightarrow W^{\pm}j$). The obtained data were hadronised in the Pythia MC generator which was built-in to the ATLAS ATHENA framework (the most current version of ATHENA at that moment was 15.2.0).

[6]http://madgraph.hep.uiuc.edu/

3.3 Pythia[7]

Pythia, the well known, multipurpose MC generator, was used in two ways:

- to simulate hadronization and parton showering for data coming from MadEvent,
- for inclusive W boson generation:
  msub 2 1 ($f_i f_j \to W^{\pm}$) process was used,
  W boson decay channels to leptons were switched on.

3.4 Summary

It the table number 1 obtained results of cross sections estimation are presented. Three different MC generators were used to simulate three different processes. In the last column relative values in respect to the diffractive cross section are presented. It can be seen that photoproduction is a negligible process and therefore it was skipped in further analysis.

MCGenerator	Process	Cross section	Ratio
Pomwig	$pp \to W^{\pm} \to l\nu_l$	1.94 nb	1
Pythia	$pp \to W^{\pm}$	35.2 nb	≈ 18
MadGraph	$p\gamma \to W^{\pm}j$	10.7 pb	≈ 0.005

Table 1. Cross sections

[7] http://home.thep.lu.se/~torbjorn/Pythia.html

4 MC data analysis

4.1 Standard cuts

The standard cuts that are used to select events involving W boson production are as follow:

- lepton isolation under condition $\Delta R = \sqrt{\Delta\eta^2 + \Delta\theta^2} \leq 0.4$
  (there should be no other particles in the cone of radius 0.4 surrounding selected lepton),
- lepton‘s $E_T > 20$ GeV,
- missing $p_T > 20\ \frac{GeV}{c}$.
- (π - $\angle$(p_{Tlep}, p_{Tmiss})) $<$ 1 rad
  (an assumption of back to back decay in the W rest frame).

Moreover, additional cuts for geometrical acceptance of a detector should be applied. In this work ATLAS@LHC characteristics were taken into account:

- for leptons: $|\eta| < 2.5$ (ATLAS inner tracker cut),
- for hadrons: $|\eta| < 5.0$ (ATLAS calorimeter cut).

4.2 Additional W selection method

Results of cuts mentioned in paragraph 4.1 are presented on figures 5 and 6. Data samples were normalized to the same luminosity. It is clearly visible that they are not sufficient and therefore additional studies were performed in order to find a kinematic region in which the signal to background ratio is at satisfying level.

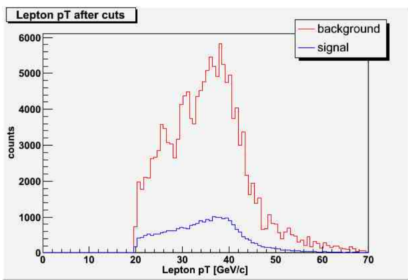

Figure 5: Lepton‘s p_T after cuts

Since proton-Pomeron interactions should leave asymmetric signal in the detector many different cuts were studied in order to select signal from a background. The best results were obtained for an asymmetry in E_T defined as:

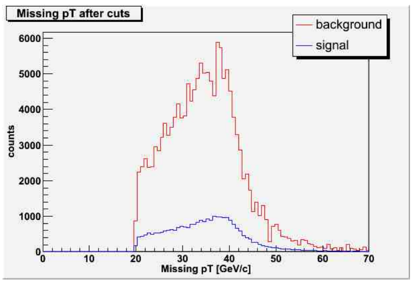

Figure 6: Missing p_T after cuts

$A_{E_T} = (\sum_{2.5<\eta<5.0} E_T - \sum_{-5.0<\eta<-2.5} E_T)/(\sum_{2.5<\eta<5.0} E_T + \sum_{-5.0<\eta<-2.5} E_T)$

A result of this cut is presented on the figure 7. A red solid line, which represents a background, behaves as expected in a symmetric way. For the signal data there is a clearly visible raise of the counts for $A_E <$ - 0.9. In this region the signal is bigger than the expected background.

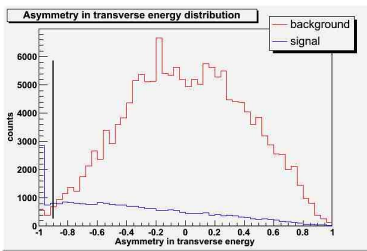

Figure 7: Asymmetry in transverse energy distribution

Second idea was to use ATLAS Forward Detectors (FD) in order to detect the diffractive proton. There are two FD (their acceptances are given):

- RP240 (ALFA) $0.02 < \zeta < 0.2$,
- RP420 $0.002 < \zeta < 0.02$.

Where $\zeta = (E_P - E_{P'})/E_P$ is a relative energy loss of the diffractive proton. It occurs (figure 8) that diffractive events are within acceptance of the Forward Detectors. By using the FD one can significantly improve the signal to background ratio.

Finally, two additional cuts (with respect to the inclusive ones) for events with diffractive W production were obtained.

4.3 Theory signal data reproduction

It was interesting to check whether it is possible to reproduce the Golec-Biernat's results at the MC Generator level. The crucial plot of asymmetry in the W boson production is

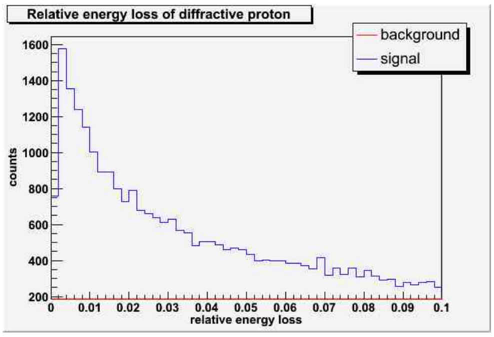

Figure 8: Relative energy loss of diffractive proton

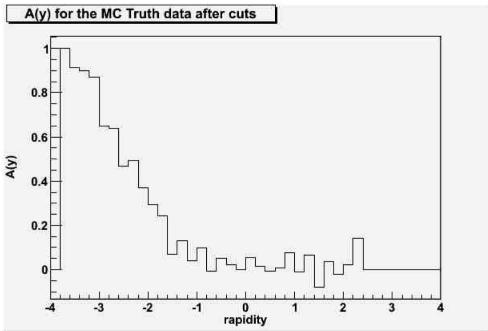

Figure 9: Asymmetry for signal data taken from MC.

shown at the figure 9. Inclusive W cut plus a requirement of proton in Forward Detectors were applied.

A shape of the curve fits to theoretical predictions. However, this asymmetry is plotted versus rapidity of the W boson. In the real life experiment one can expect only information about lepton and the missing transverse energy. Therefore, further studies were devoted to finding a method of the W boson rapidity determination.

4.4 Rapidity measurements

4.4.1 The HERA method

The first guess was to use a method which was used in HERA@DESY - so called "E - p_z" balance:

$$\sum E - p_z = 2E_0 \tag{5}$$

where $E_0$is an initial particle energy. The sum was calculated for all visible particles in final state without any geometrical cuts (figure 10) and with ATLAS geometrical cuts (figure 11). The first result shows that in principle it is possible to extract correct information from this formula. However, after applying geometrical cuts one destroys completely this behavior. The HERA method is not working because of very different

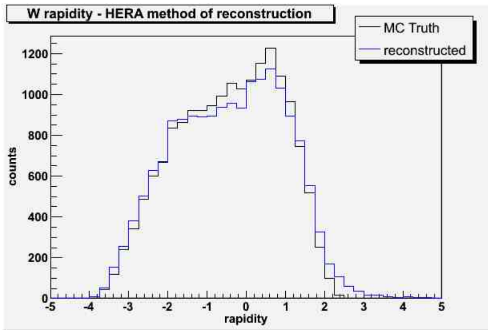

Figure 10: The W boson rapidity via the HERA method without geometrical cuts

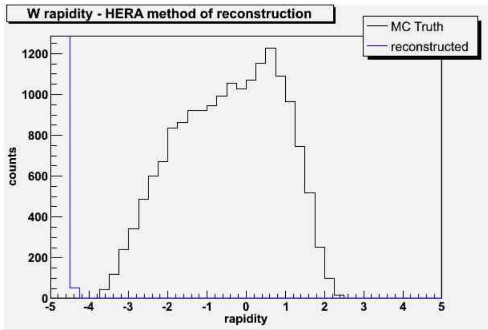

Figure 11: The W boson rapidity via the HERA method with geometrical cuts

kinematic conditions in ep (HERA) and pp (LHC) colliders. The proton remnant which is going in the $|\eta|>5.0$ is no longer visible in the detectors, but carries huge of E - p_z contribution. Therefore, another method of obtaining the W boson rapidity was studied.

4.4.2 The Tevatron method

Another method of obtaining the W boson rapidity is based on calculating its invariant mass squared:

$$M_W^2 = (E^{lepton} + E^{\mu})^2 - (\vec{p}^{lepton} + \vec{p}^{\mu})^2 \quad (6)$$

and extracting from this formula neutrino's p_z. This equation, however, has two solutions for this value. Difficulties with deciding which is the correct one were encountered. A few ideas were studied (e.g. selecting solution closer/further to lepton, averaging, weighting by distance in rapidity to lepton etc.) without success.
Then, two very recent papers[8] connected with the inclusive W boson production at Tevatron were found. It occurred that the ambiguity in determination of the correct solution can be resolved on statistical basis. Each solution is weighted with a factor (extracted on the MC basis) depending on the decay angle between the lepton (electron) and the

[8] A) A. Bodek et. al. Phys. Rev D 77 (2008) 111301
B) CDF Collaboration (T. Aaltonen et. al.) Phys. Rev. Lett. 102 (2009) 181801

proton in the W rest frame and the W production cross section (calculated in NNLO) as a function of W rapidity ($\frac{d\sigma_W(y)}{dy}$).
Although the method seems to be successfully working at the Tevatron case, studies for ATLAS has not yet been done due to the lack of time. Implementation of this method in ATLAS conditions requires much more work.

5 Summary

Diffractive W boson production at the LHC has been studied and it seems to be an interesting process to work on. Special cuts were found in which signal to background ratio is at satisfying level. Additional improvements can be made by using ATLAS Forward Detectors at 240m and 420m. Theoretical predictions for the W boson production asymmetry (in diffractive processes) can be seen at the MC generator level, however method of the W boson rapidity reconstruction requires further studies.