New Heavy Gauge Boson Searches with CMS

M. Malberti, on the behalf of the CMS Collaboration

Abstract New heavy gauge bosons, like W' and Z', are foreseen by several extensions of the Standard Model. The large luminosity and center of mass energy available at the LHC will allow to probe such bosons with masses above 1 TeV already in the very first period of data taking. Here the sensitivity to searches for new gauge bosons with the CMS experiment is discussed. These studies are based on detailed detector simulation with realistic start up conditions and are focused on possible early discoveries. The expected CMS discovery/exclusion potential as a function of luminosity is presented as well.

Keywords: Gauge bosons, BSM

1 Introduction

The Standard Model (SM) successfully describes the fundamental fermions and their interactions through gauge bosons. However, far to be considered a complete theory, it leaves many open questions (e.g. the naturalness and hierarchy problem, the dark matter problem...), for which a number of models, introducing new symmetries, new interactions or new dimensions, have been proposed. New heavy neutral (Z') or charged (W') gauge bosons appear in several extensions of the Standard Model, such as Left-Right Symmetric Models (LRSM) [1], E_6 based GUTs (giving rise to Z'_ψ, Z'_ξ, Z'_η) [2], Little Higgs Models [3], Extra Dimensions [4]. Moreover, the Altarelli Reference Model [5], also known as Sequential Standard Model (SSM), is often considered as a benchmark by experimentalists: in this model, the new heavy gauge bosons $Z'(W')$ are considered as heavy carbon copy of the corresponding SM ones, $Z(W)$, with the same coupling constants.

M. Malberti
INFN Milano-Bicocca, Piazza della Scienza 3, I-20126, Milano, Italy,
e-mail: martina.malberti@mib.infn.it

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Current limits by the Tevatron experiments CDF and D0 exclude new heavy gauge bosons up to about 1 TeV, depending on the model assumed. At the Large Hadron Collider (LHC), the large luminosity (10^{34} cm^{-2} s^{-1} designed luminosity, and $\sim 10^{32}$ cm^{-2}s^{-1} in the initial phase) and the large center of mass energy of 14 TeV will allow a good potential for new gauge bosons searches already with the very first data, i.e. with luminosity of the order of 100 pb^{-1}. In this paper the discovery potential of the Compact Muon Solenoid (CMS) experiment is discussed. The central feature of CMS is a superconducting solenoid, providing a 4 T magnetic field. Both the inner tracker and the calorimeters are contained within the solenoid. The tracker consists of silicon pixel and strip detectors. The electromagnetic calorimeter (ECAL) is made of $PbWO_4$ scintillating crystals and it is surrounded by a brass/scintillator sampling hadron calorimeter. Muons are measured in gas chambers embedded in the iron return yoke. Besides the barrel and endcap detectors, CMS has extensive forward calorimetry. A detailed description of the CMS experiment can be found in [6].

The discussion is focused on analyses based on detailed simulations of the CMS detector, assuming realistic start-up calibration and alignment conditions. Emphasis is given to analysis strategies relevant for an early data-taking.

2 Events selections and backgrounds in leptonic searches

Leptonic channels $Z' \to l^+l^-$ and $W' \to l\nu$, with electrons or muons in the final state, provide the cleanest signatures for new gauge bosons searches at hadron colliders.

2.1 $Z' \to l^+l^-$ signature and backgrounds

$Z' \to l^+l^-$ events are characterized by two high (O(TeV)) transverse momentum leptons with opposite charge. $Z' \to e^+e^-(Z' \to \mu^+\mu^-)$ are selected by requiring events passing an electron (muon) trigger and two well reconstructed and isolated electrons (muons) within the detector acceptance, $|\eta| <2.5$ for electrons and $|\eta| <2.4$ for muons [7,8]. The main background is represented by SM Drell-Yan events, while minor contributions come from $t\bar{t}$, W+jets, γ+jets, as shown in Fig. 1.

Table 1 summarizes the production cross section times the branching ratio of $Z' \to e^+e^-$ for two different values of the SSM Z' mass and the corresponding number of events expected within the detector acceptance for an integrated luminosity of 100 pb^{-1}.

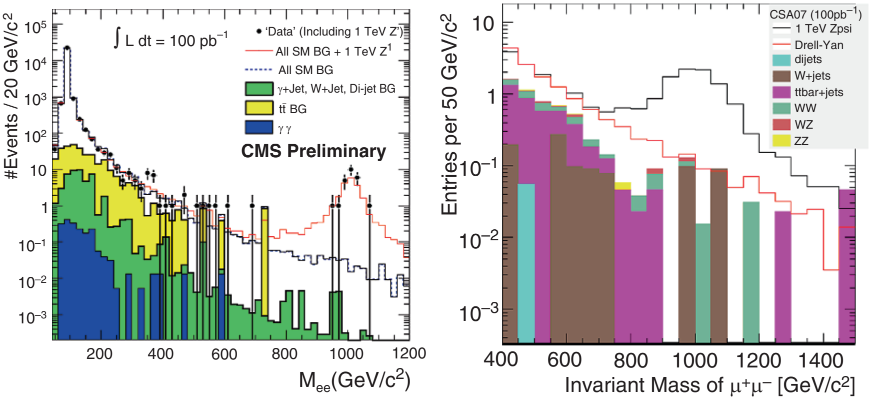


Fig. 1 Invariant mass distribution for a $Z' \rightarrow ee$ (left) and $Z' \rightarrow \mu\mu$ (right) with M = 1 TeV. The main backgrounds from Standard Model processes are also shown

Table 1 Production cross section times branching ratio for $pp \rightarrow Z' \rightarrow e^+e^-$ and number of events expected in 100 pb^{-1} with both leptons within the detector acceptance

SSM Z'	M = 1000 GeV	M = 2000 GeV
$\sigma\times$ BR (fb)	458	20
n. of events in 100 pb^{-1} with 2 electrons in $\lvert\eta\rvert$ <2.5	38	1.8
Drell-Yan background	M > 600 GeV	M > 1600 GeV
$\sigma\times$BR (fb)	50	0.76
n. of events in 100 pb^{-1} with 2 electrons in $\lvert\eta\rvert$ <2.5	4	0.07

2.2 $W' \rightarrow l\nu$ signature and backgrounds

$W' \rightarrow l\nu$ events present a straightforward signature, with one high p^T lepton and missing transverse energy (MET) due to the neutrino; moreover, as the boson transverse momentum is expected to be small, the lepton and the MET are almost balanced in the transverse plane. This signature is identical to the SM $W \rightarrow l\nu$ one, that represents an irreducible background. Other sources of backgrounds, giving much smaller contributions, are $t\bar{t}$, Drell-Yan, di-bosons and di-jet events in which one jet is misidentified as a lepton and the other is mismeasured giving rise to missing transverse energy. Beyond the trigger and lepton identification requirements, two dedicated selections can be applied in order to enhance the signal in the high p^T region. They exploit the W' kinematics: the angle between the lepton and the MET has to be close to 180° and their transverse energy must be balanced (this is accomplished by requiring $0.5 < E_l^T/MET < 1.5$). The transverse mass spectrum ($M^T = \sqrt{2E_l^T E_\nu^T(1 - cos\phi_{l-MET})}$, where ϕ_{l-MET} is the angle between the lepton direction and the MET direction in the transverse plane) of the lepton–neutrino pair is shown in Fig. 2 for the electron channel, normalized to an integrated luminosity of 100 pb^{-1} [9].

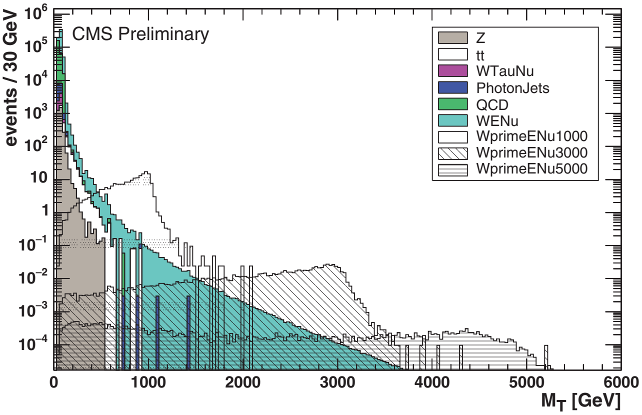


Fig. 2 Transverse mass distribution of $W' \to e\nu$ events for three different W' mass values and main backgrounds

3 Electron and muon reconstruction at high energies

The reconstruction of electrons and muons at high energies presents several experimental issues. Electrons are reconstructed as energy deposits in the electromagnetic calorimeter linked to a track in the tracker. The identification criteria, based on the shape of the electromagnetic shower, track matching and isolation, are robust against start-up conditions and are optimized for high energy electrons, in order to keep a high efficiency (∼80%) and to guarantee a low rate of jets faking electrons.

An important issue related to the energy measurement at very high energy is related to the saturation of the ECAL electronics, that occurs for energy deposits of 1.7 TeV (3 TeV) in one single crystal in the barrel (endcaps). The energy can be, however, efficiently recovered by using the energy deposits in the crystals surrounding the saturated one, with a resolution of about 10% for 1 TeV electrons [10].

Concerning the muon reconstruction, the Muon System and Tracker alignment plays an important role, because it has a large impact on the mass resolution: for a 1 TeV (2 TeV) Z', the mass resolution is 7–8% (10%) for a misalignment scenario corresponding to 100 pb^{-1} [8], nearly doubled with respect to ideal conditions (Fig. 3). Misalignment doesn't affect efficiency, which is around 94% for di-muons.

There are two important issues that are specific of the TeV muon reconstruction: the first is the low bending in the magnetic field at such high energies that requires a very precise measurement of the position, and the second one is the high probability of bremsstrahlung. Dedicated algorithms have been developed in order to get the best performances in terms of efficiency and resolution.

Lepton reconstruction and identification efficiencies will be measured using the so called "Tag and probe" method [11], which exploits Drell-Yan events: in events containing two electron (muon) candidates, one lepton is reconstructed with tight criteria and used as "tag", the second one is identified as "probe"; in this way, a sample of high purity probes can be selected and used to measure efficiencies. In

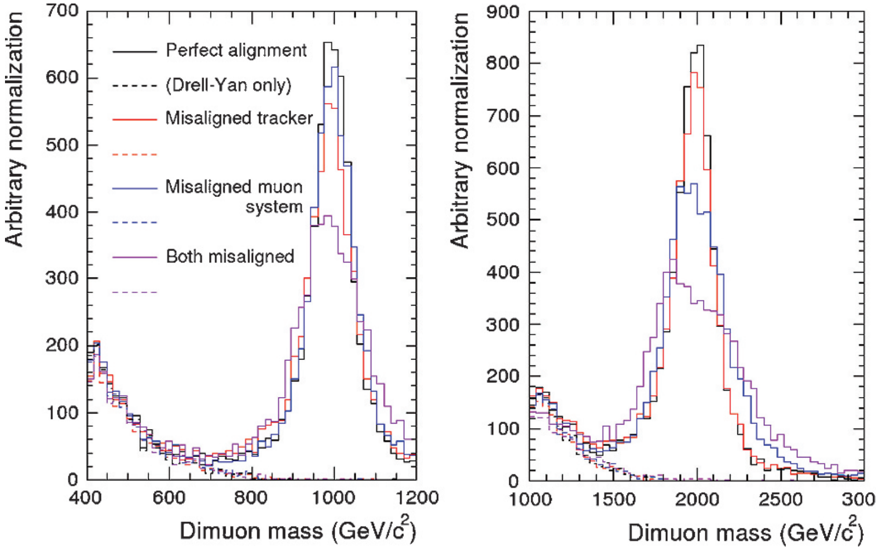


Fig. 3 Di-muon Invariant mass spectra for 1 TeV and 2 TeV SSM in different alignment conditions

the case of high energy leptons, the method will be applied in two different mass regions: at the Z pole (in a region 70 GeV $<$ M(ll) $<$ 110 GeV) and in the high invariant mass range (e.g. M(ll) $>$ 200 GeV). The first one, thanks to the tight mass cut, is characterized by high purity, but allows to probe lepton transverse momentum ranges only up to about 150 GeV and requires a MC based extrapolation to high energies; the second one, on the contrary, covers higher momentum ranges, but is affected by larger backgrounds. Both will be used for cross checks and to reduce systematic errors.

4 Background determination and uncertainties

New heavy gauge boson searches are characterized by small SM backgrounds, that anyway must be understood carefully in order to establish the significance of events found in the signal region. It is desirable, especially in a start-up scenario, to determine backgrounds from the data themselves whenever possible. In particular, data driven techniques have been studied for $t\bar{t}$ and QCD background.

The $t\bar{t}$ background can be determined with two approaches: one is the b-tag method, exploiting events containing exactly one b-tagged and two b-tagged jets, in order to measure simultaneously the b-tagging efficiency and the total number of $t\bar{t}$ events; the second one is the e-μ method, exploiting events with one electron and one muon, with appropriate corrections for acceptances and electron/muon efficiencies [7]. These methods have been tested on simulated datasets containing signal and background events, showing a good agreement between the extracted number of $t\bar{t}$ events and the one expected from the simulation (Fig. 4).

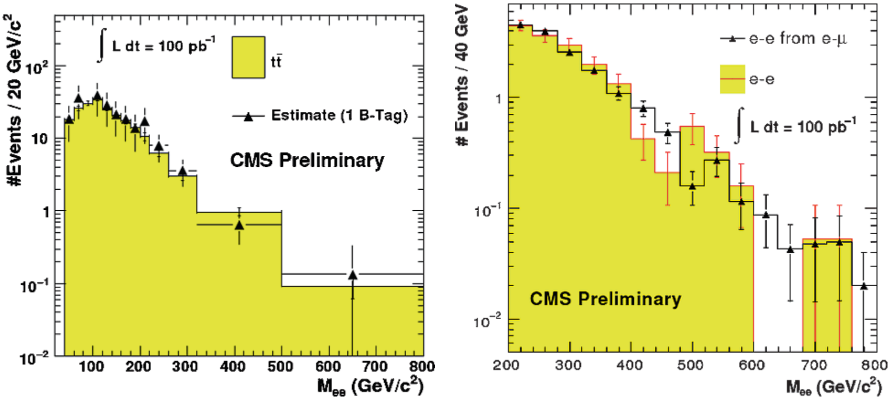


Fig. 4 $t\bar{t}$ background to $Z' \rightarrow ee$ events estimated using the b-tag method (left) and the $e-\mu$ method (right)

The QCD background, is almost negligible, but can be controlled using different techniques. For $Z' \rightarrow ee$ events, it can be obtained by measuring the lepton fake rate, i.e the probability that a jet fakes a lepton, on jet triggered events. In the case of $Z' \rightarrow \mu\mu$ searches, the use of same-sign di-leptons has been considered, exploiting the fact that no charge correlation between two lepton candidates is expected in events containing jets faking electrons. In $W' \rightarrow e\nu$ searches, a technique already applied at Tevatron, has been investigated: it uses a sample of non-isolated electrons and normalizes the transverse mass spectrum in the low, background dominated, transverse mass region.

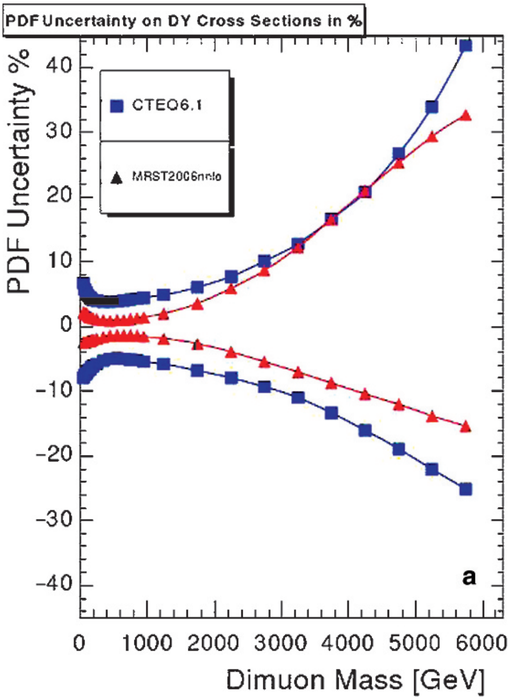
SM Drell-Yan and W events , which constitute the most important and irreducible backgrounds to Z' and W' respectively, will be controlled by normalizing the simulation to the Z peak or W transverse mass peak. Several theoretical uncertainties have been considered, like PDFs (see Fig. 5), renormalization and factorization scales, higher order QCD and QED corrections [7, 8].

5 Expected significance and exclusion limits

The CMS experiment is expected to have a very good potential for searches of new neutral gauge bosons even with low integrated luminosities. A discovery, in the di-electron or di-muon channel, is possible up to masses of about 1.5 TeV for a SSM Z' and 1.2 TeV for a Z'_ψ with an integrated luminosity of 100 pb^{-1} (Fig. 6).

The $W' \rightarrow e\nu$ discovery sensitivity is shown in Fig. 7 and indicates that a discovery is possible up to W' masses of about 2.2 TeV with an integrated luminosity of 100 pb^{-1}. Systematic effects such as uncertainties on the detector calibration (2% on the electron energy scale, 10% on the MET), backgrounds (10%), luminosity (10%) and PDFs (10%) are taken into account. In case no discovery is possible, an

Fig. 5 PDF uncertainties on the absolute Drell–Yan cross section as a function of the di-muon mass [8]



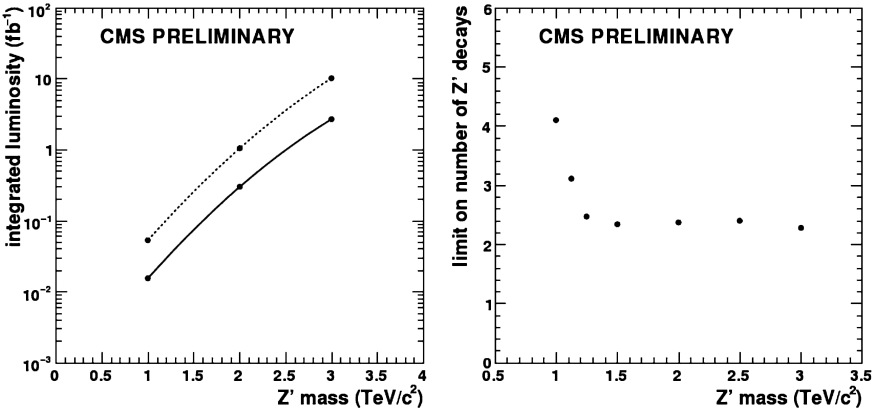


Fig. 6 Left: Integrated luminosity needed to reach a 5σ significance in the electron channel as a function of resonance mass for two different models, Sequential Standard Model (full line) and Z'_ψ (dashed line). Right: Expected 95% CL limit on the number of events as a function of the resonance mass

exclusion limit can be set up to W' masses of about 2.5 TeV with 100 pb^{-1}. For comparison the current best limit from the D0 experiment in the electron channel is 1 TeV with about 1 fb^{-1} [12]. Increasing the integrated luminosity up to 100 fb^{-1}, the CMS exclusion potential rises up to about 4.5 TeV (Fig. 8).

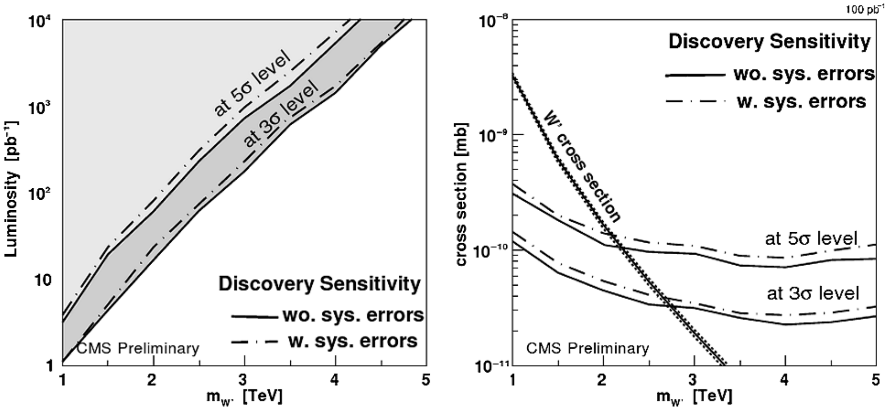


Fig. 7 Discovery potential of $W' \to e\nu$ as a function of the mass and of the integrated luminosity

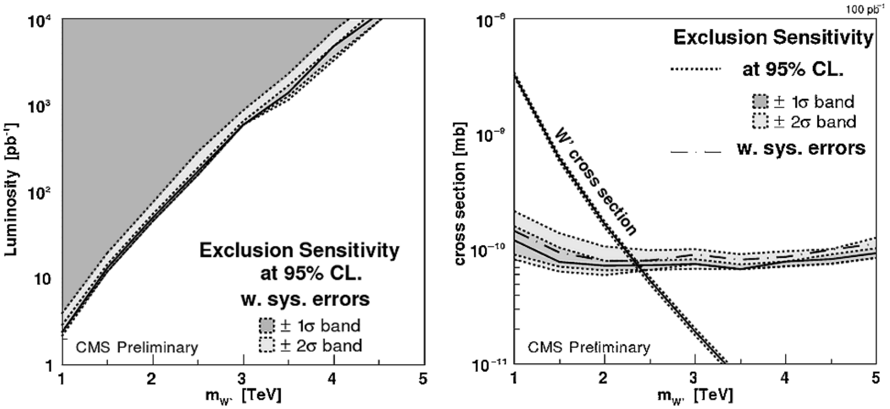


Fig. 8 Exclusion sensitivity as a function of the mass and of the integrated luminosity

6 Searches in the di-jets channel

Beyond leptonic searches, searches involving jets measurements are feasible. Di-jet events are sensitive to new physics and, for example, the di-jet ratio has been found to be a useful observable to search for the evidence of a new resonance [13]. The di-jet ratio is defined as the ratio between the number of di-jet events with $|\eta| < 0.7$ and the number of events with $0.7 < |\eta| < 1.3$. Spin 1 gauge bosons, as well as other spin 1/2 or spin 2 resonances, have more isotropic angular decays than QCD (Fig. 9–left) and the di-jet ratio is larger than for QCD events. Figure 9 shows the di-jet ratio as a function of the di-jet mass: a signal can be observed with 100 pb^{-1} for masses around 2 TeV, while with higher integrated luminosities the di-jet ratio is expected to be useful in order to determine the resonance spin.

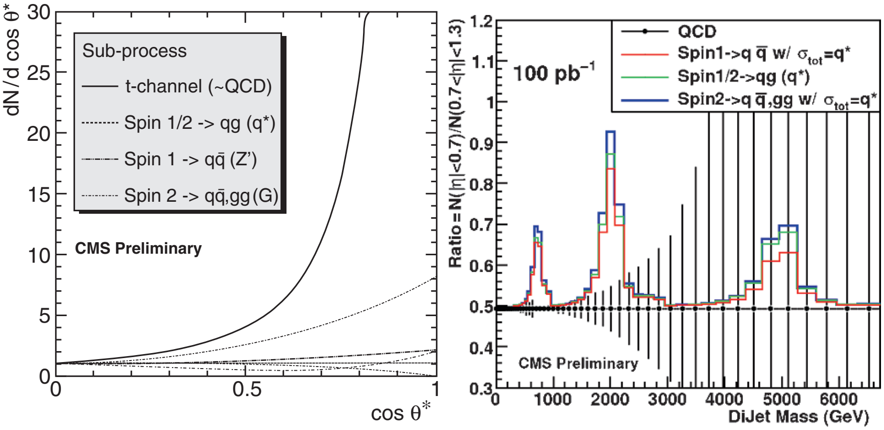


Fig. 9 Left: angular distribution of resonances compared to the angular distribution of QCD events. Right: Di-jet ratio as a function of di-jet mass

7 Conclusions

The potential of the CMS experiment for new heavy neutral or charged gauge bosons searches has been presented. Analysis strategies have been defined to be ready for real data, including realistic start-up detector conditions. A good sensitivity, probing the region above 1 TeV, is reachable already with integrated luminosities of about 100 pb^{-1}.

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