PHYSICS BEYOND THE STANDARD MODEL IN CMS AT THE START OF THE LHC

Norbert Neumeister

Department of Physics, Purdue University, West Lafayette IN, USA

Abstract

While the Standard Model of Particle Physics has been well tested and verified with high precision within the current energy limits of present day colliders, there are several reasons to expect that the Standard Model is an incomplete theory and that new phenomena should appear at the TeV energy scale. The Large Hadron Collider (LHC) is in its final stage of commissioning and first collisions are expected by mid-2008. The CMS detector is a general purpose experiments at the LHC and will be used to search for signatures of new Gauge Bosons, Extra Dimensions and other processes beyond the Standard Model. The potential of CMS to observe possible new physics at this new energy frontier and the challenges and strategies for these searches are discussed. The focus will be on searches for new physics with the initial data collected at the LHC.

1 Introduction

The Compact Muon Solenoid (CMS) experiment [1] is one of the two general-purpose experiments, which will operate at the LHC and is currently in the construction phase at CERN. Its prime goals are to explore physics at the TeV scale and to study the mechanism of electroweak symmetry breaking. The LHC is designed to provide proton-proton collisions with a luminosity of up to 10^{34} cm^{-2}s^{-1} and a center-of mass energy of 14 TeV. Here we will focus on a start-up luminosity of $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}.

High-mass resonances decaying into lepton or photon pairs provide some of the most important discovery potentials beyond the Standard Model at the LHC. They are predicated in numerous models. Extra dimension models [4, 5, 6] propose ways to solve one of the most fundamental problems of the Standard Model – the hierarchy problem. Basically all extra dimension models predict new resonances that can be accessible at the LHC.

In order to extract the new physics at an early stage of LHC, the key point is to understand the detector and any unanticipated limitations as soon as possible. Since both the machine and the detector comprise new challenges, it is essential to concentrate on signatures, which can be understood already with a partially commissioned detector and only a few pb^{-1} of data. The main signatures of interest for discoveries of new physics are high momentum leptons, photons, jets and missing transverse energy. The CMS detector was designed with a flexible, robust and redundant muon system. Therefore dimuons are an ideal signature for the initial phase of research at the LHC. We will discuss the search for dimuon resonances as an example for a search for new physics in the first data-taking phase with a rather low luminosity.

2 Dimuon Searches

Many scenarios beyond the Standard Model are expected to manifest themselves through modications in the mass spectrum of high-mass dimuon pairs. The experiments at the LHC are going to be the first opportunity to search for new resonances in a mass range signicantly larger than 1 TeV/c^2 .

We discuss the potential of the CMS experiment to discover a representative set of additional heavy neutral gauge bosons Z' (spin 1) predicted by grand unified theories [3], as well as gravitons $G^\star$ (spin 2) arising in the Randall-

Sundrum (RS) model of extra dimensions [5, 6]. Two different Z' models are considered: Z_{SSM} within the Sequential Standard Model (SSM), which has the same couplings as the Standard Model Z^0 and is often used as a benchmark by experimentalists and Z_ψ, arising in $E6$ and $SO(10)$ GUT groups. The RS model suggests that excited massive graviton states are strongly coupled to ordinary particles (not suppressed below the Planckian scale like for the ordinary graviton in the usual description of gravity) and can signicantly contribute to the Standard Model processes above the fundamental scale. The ability to test experimentally the RS predictions depends on the model parameter $c = k/\bar{M}_{\mathrm{Pl}}$, which controls the coupling of the RS graviton to ordinary particles: both graviton production cross section and its decay width scale as c^2. The RS model graviton can decay in the dilepton, dijet or diboson channel. In the dilepton case the signature would be a series of narrow resonances in the dilepton invariant mass distribution. Here we focus on the CMS discovery potential for the *start-up luminosity* $\mathcal{L} = 10^{32}\ \mathrm{cm}^{-2}s^{-1}$. To include systematic uncertainties in a realistic way we use the description of the detector alignment and calibration expected at the early stages of data-taking.

The dimuon decay is a golden channel for Z' and $G^\star$ discoveries. In both cases the dominant background arises from Drell-Yan lepton pair production, whereas contributions from $t\bar{t}$ and from vector boson pair production are significantly smaller and are highly suppressed by selection cuts. The momentum resolution of the detector plays a key role in separating the signal from the background. The accurate momentum reconstruction of very high-p_T (TeV) muons is challenging because of catastrophic energy loss and severe electromagnetic showers in the muon system. The CMS muon reconstruction algorithms have been optimized to deal with this problem.

Once a new high-mass resonance is discovered, its observables can be used in the attempt to identify the theoretical framework to which it belongs. The measurement of the forward-backward asymmetries of leptonic decay products, both at the resonance peak and off the peak, is a powerful tool to identify a Z'. Spin discrimination of new heavy resonances based on an unbinned likelihood ratio statistic incorporating the angles of the decay products typically require more signal events than one could hope to collect with the initial LHC luminosity and are therefore not discussed.

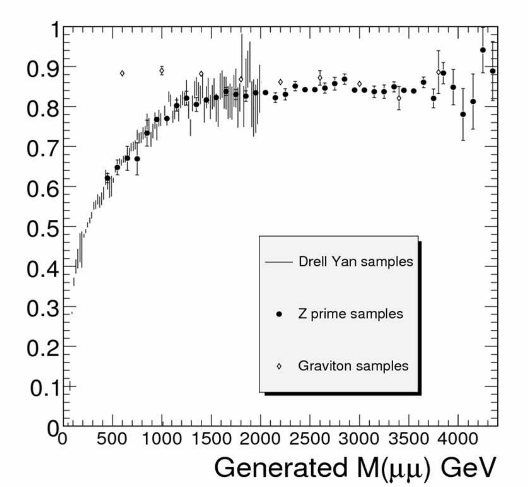

Figure 1: *Overall selection and reconstruction efficiency for Drell-Yan (bars), Z_{SSM} (closed circles), and $G^{\star}$ (open circles) dimuon events as a function of the $\mu^+\mu^-$ invariant mass.*

2.1 Event Selection and Acceptance

In order to select efficiently a pure sample of high-mass dimuon candidates, the following requirements are imposed:

- The event passes the logical OR of single-muon and dimuon non-isolated trigger paths.
- It contains at least one pair of oppositely-charged muons reconstructed offline.
- The transverse momentum p_T of each muon track in a pair is larger than 20 GeV/c.
- Both muons are isolated in the tracker.

The overall selection efficiency, including acceptance effects, is shown in Fig. 1. Efficiencies for Drell-Yan and Z' dimuon events are very similar: they increase from about 50% at 200 GeV/c^2 to about 80% at 2 TeV/c^2. Efficiency

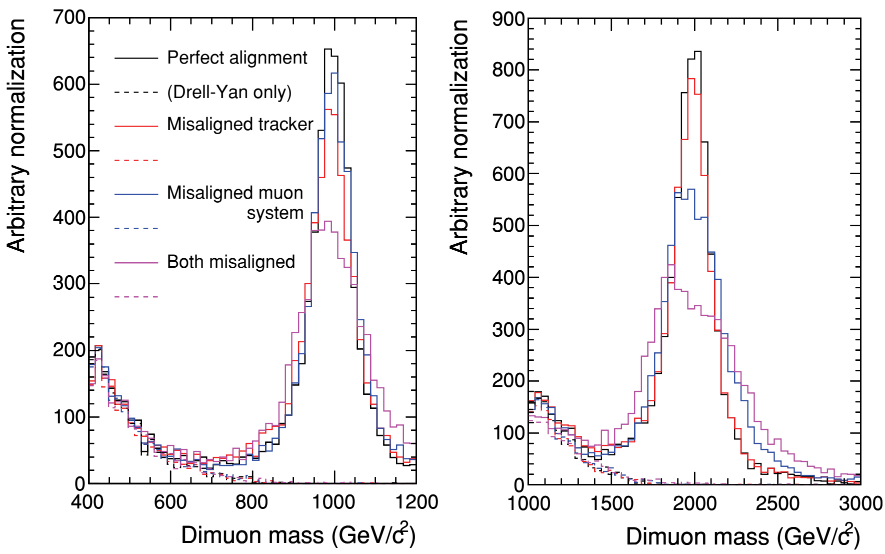

Figure 2: *Dimuon invariant mass spectra for 1 and 2 TeV/c^2 Z_{SSM} resonances and the Drell-Yan background for different alignment scenarios: using ideal alignment of both the silicon tracker and the muon system; assuming ideal alignment for one detector and applying the misalignment expected at the initial stages of the data taking to the other one; and for the case when both detectors are misaligned. All histograms within each panel represent the same events under different misalignment scenarios, and are therefore normalized to the same (arbitrary) integrated luminosity.*

for $G^\star \to \mu^+\mu-$ events is close to 90% at masses below 1 TeV/c^2, in accordance with a high geometrical acceptance in this region.

Once a sample of candidate events is selected, a search for new particles is performed by comparing the observed invariant-mass distribution of opposite-sign muon pairs, $M_{\mu\mu}$, with that expected from Standard Model processes for $M_{\mu\mu} > 200$ GeV/c^2. If more than one dimuon candidate can be formed in the selected event (in the absence of pile-up, this happens in less than 1% of events), the one with the highest value of $M_{\mu\mu}$ is used.

The geometrical acceptance for the signal and backgrounds is determined by the acceptance of the muon system used to identify muons. The fraction of

Drell-Yan $\mu^+\mu^-$ events with both muons within the full geometrical acceptance of the CMS muon system ($|\eta| < 2.4$) increases from 56% at an invariant mass of 200 GeV/c^2 to about 95% at very high masses. The acceptance of $Z' \to \mu^+\mu^-$ events is very similar to that of the Drell-Yan dimuons, whereas the acceptance of $G^\star \to \mu^+\mu^-$ events is noticeably higher: the difference is as big as 25% at the mass values of a few hundred GeV/c^2 and gets smaller with increasing mass. The explanation of this difference lies in the different production mechanisms for Z' bosons and $G^\star$. At leading order, the only production mechanism for Z' bosons is the quark-antiquark scattering, $q\bar{q} \to Z' \to \mu^+\mu^-$. Gravitons are produced mainly via the $gg \to G^\star \to \mu^+\mu^-$ gluon-gluon fusion process at lower masses, while the $q\bar{q} \to G^\star \to \mu^+\mu^-$ contribution dominates at higher masses. The dimuons produced via quark-antiquark processes have on average lower acceptance than the ones produced via gluon-gluon fusion. This is due to the presence of forward events where a high-momentum valence quark interacts with an antiquark to produce a resonance boosted along the z-axis, resulting in lower acceptance. In addition, there is a small difference arising from the different angular distributions for the decay products of spin-1 Z' bosons and spin-2 $G^\star$.

2.2 Invariant Mass Resolution and Detector Misalignment

The precision of reconstructed dimuon masses, and therefore the statistical significance of a possible resonance peak, would be impaired by imperfect alignment of the silicon tracker and the muon system. Small curvatures of high-momentum tracks are poorly constrained if the alignment of sensor positions is uncertain, a situation we expect to improve with data. To study the influence of misalignment effects on detector performance and the resulting physics reach, tools to displace and rotate the silicon tracker modules and muon chambers at the reconstruction level were implemented in the reconstruction software. To describe the expected misalignments and their improvement with time and integrated luminosity, several misalignment scenarios were developed in the CMS reconstruction framework and subsequently used in performance studies. These scenarios simulate the detector alignment expected to be achieved with 10 and 100 pb^{-1} of integrated luminosity.

The dimuon mass spectra for 1 and 2 TeV/c^2 Z_{SSM} resonances and the corresponding Drell-Yan background are shown in figure 2, illustrating the

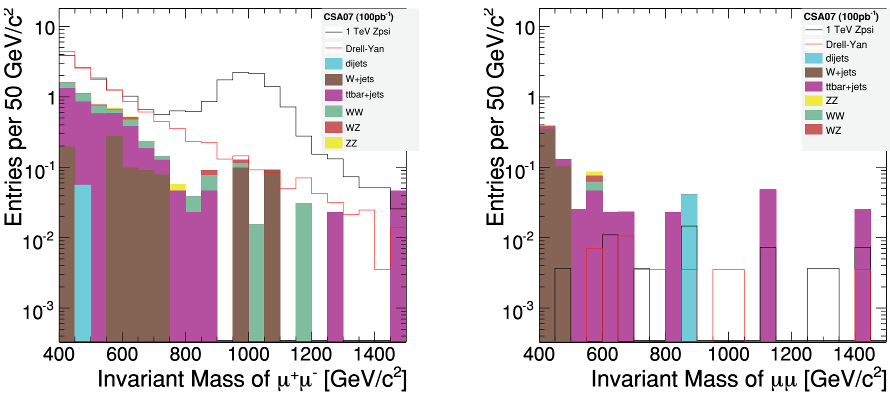

Figure 3: *Invariant-mass distributions for opposite-sign (left) and same-sign (right) dimuons from* 1 *TeV*$/c^2$ Z_ψ *and different background sources expected for* $L_{int} = 100\ pb^{-1}$ *after applying all event-selection criteria. The spectrum is shown in the mass range* $400 < M_{\mu\mu} < 1500\ GeV/c^2$*. All histograms except for Drell-Yan and* Z_ψ *are stacked.*

relative importance of tracker alignment and muon system alignment in the expected alignment scenarios. The effect of muon alignment has a stronger dependence on momentum at these scales because long lever arms are needed to resolve small track curvatures. While the expected misalignment smears the distribution of the signal peak, the shape of the Drell-Yan mass spectrum remains largely unaffected.

2.3 Backgrounds

The dominant (and irreducible) source of background to new high-mass dimuon resonances is the Drell-Yan production of muon pairs, $pp \to \gamma^*/Z^0 \to \mu^+\mu^-$. In addition to the Drell-Yan production a variety of backgrounds from other sources have been studied. Invariant-mass distributions for opposite-sign and same-sign dimuons from different background sources passing all selection criteria and weighted to correspond to an integrated luminosity of 100 pb^{-1} are shown in figure 3 in comparison with the mass spectrum expected for a 1 TeV$/c^2$ Z_ψ. In the mass range $M_{\mu\mu} > 400$ GeV$/c^2$, the most significant background after the Drell-Yan is $t\bar{t}$. The dijet background is strongly suppressed by the

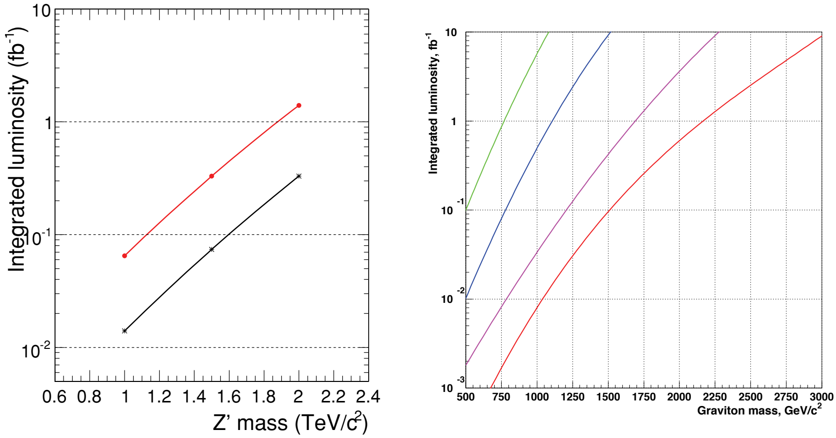

Figure 4: *Integrated luminosity needed to reach* 5σ *significance* ($S_{\mathcal{L}} = 5$) *as a function of the mass of the resonance for a)* Z_ψ *(top) and* Z_{SSM} *(bottom), and b) RS gravitons with the coupling constant c of (from top to bottom)* 0.01, 0.02, 0.05, *and* 0.1.

soft isolation cut, whereby the sum of the p_T of all tracks around each muon in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ is required to be less than 10 GeV/c. The remaining admixture of dijet events can be evaluated in data from samples of same-sign and opposite-sign events rejected by the isolation cut. Another useful control sample for studies of misidentified and mismeasured muons is the sample of same-sign dimuons passing all selection criteria. Non-Drell-Yan backgrounds can be further suppressed by muon-quality cuts, jet-veto criteria, missing-E_T cuts, requirements that the two muons be back-to-back in the plane transverse to the beam direction and originate from a common vertex, and others.

2.4 Discovery Potential

The fitting procedure and the significance estimators described in [2)] are used to evaluate the CMS discovery potential for new high-mass resonances in the dimuon decay mode. The integrated luminosity needed to reach 5σ significance as a function of the mass of the resonance is shown in figure 4 for a) two studied Z' models and b) Randall-Sundrum gravitons with various values of the model parameter c.

An unbinned likelihood fitter with a fitting function very similar to that of the signal-significance technique is used to set limits in the absence of a

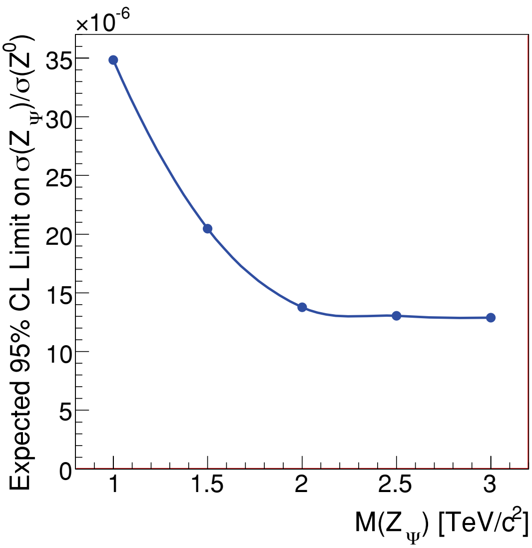

Figure 5: *Expected 95% CL limits on the ratio* $(\sigma(pp \to Z') \cdot \mathcal{B}(Z' \to \mu^+\mu^-))/(\sigma(pp \to Z^0) \cdot \mathcal{B}(Z^0 \to \mu^+\mu^-))$ *as a function of* Z' *mass, assuming no signal events present in the sample.*

signal. Limits on the number of signal events are set using the same likelihood-ratio-based discriminant, and then translated to the limits on the ratio of cross sections for production of new resonances relative to Z^0 production. Expected limits for Z' bosons are shown in figure 5, for the detector alignment expected to be achieved with 100 pb^{-1} of integrated luminosity.

The main sources of systematic uncertainties are expected to be a) theoretical uncertainties (parton distributions, higher-order corrections, etc.), b) uncertainties arising from an imperfect knowledgeof the detector (alignment, calibration, magnetic field), and c) uncertainties in the fitting procedure (background shape, functional forms of pdfs, mass resolution, etc.). Evaluation of these uncertainties and of their impact on the signal observability is discussed in [2].

3 Conclusions

The initial phase of running will be crucial for CMS. All sub-detectors have to be understood and calibrated and the Standard Model processes have to be measured. The CMS collaboration is in the process of getting ready for this exciting period, by validating the software and preparing data analysis while installing and commissioning the detector. It has been demonstrated that signals of new physics could already be discovered with an integrated luminosity of about 1 fb^{-1}. Dilepton signatures are one of the most promising signatures for the search for new physics in the initial phase of the LHC.

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