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Early Standard Model physics and early discovery strategy in CMS

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Abstract

Although hadron colliders like the LHC are constructed for exploring new physics at higher energies, data-sets will be largely dominated by Standard Model processes. Especially in the early stage of running, it will be important to understand this overwhelming Standard Model continuum prior to any dedicated search for new physics. This paper covers CMS perspectives for early Standard Model physics and early discovery of new processes. It is shown how key Standard Model processes can be measured at low integrated luminosity. Plans for early discovery of physics beyond the Standard Model with 1 fb^{-1} or less are then discussed.

1 Introduction

The term “early physics” is often used as the startup of LHC is approaching. Does it refer to a small number of signal events? To the first days of running? Or to a small integrated luminosity? In this paper, what will be described is “the physics we plan to do with the first 1 fb^{-1}” with the CMS detector. It corresponds roughly to what we hope will be the physics of the first year of LHC.

Of course, drawing plans for early studies and establishing strategies for early discoveries is challenging as unexpected issues will unavoidably show up. In that sense, the results that will be presented might look optimistic. Nonetheless, systematics are considered in a realistic scenario for a working detector just after commissioning. This means the detector is supposed to be completed, including the endcaps of the electromagnetic calorimeter and the silicon pixel detector, that the tracking system is only roughly aligned (to about 100μm), and that the calorimeter is not fully calibrated (to 1.5% for ECAL and 5% for HCAL)[1]. Systematic uncertainties on quantities like the jet energy scale or the b-tagging efficiency are also supposed to be large.

The physics of the Standard Model will be illustrated in section 2 by some chosen work about B mesons, W bosons and top quark physics. Then, some hints about what can be done in the context of the search for new physics will be given in section 3.

2 Early Standard Model physics

While the W and Z inclusive cross-sections at parton level are predicted at the 3% level, and while the $t\bar{t}$ pair production is predicted with a precision of 10%, the prediction of the charge multiplicity in minimum bias events suffers from a 50% uncertainty [2]. This uncertainty can be removed with a few 10^4 events, which only corresponds to 15 minutes of good data taking. The main difficulties come from the beam background, which has a characteristic angular dependence, from the pile-up which depends crucially on the bunch-crossing density, and from the tracking efficiency. Studies have shown that the tracking efficiency does not suffer from the tracker alignment, as long as it is accounted for in the tracking algorithm [3]. Tracker misalignment only affects momentum resolution, and therefore has only an impact on the $\mathrm{dN/dp_T}$ differential charge multiplicity. The residual uncertainty depends on the jet momentum but is reduced to less than 1% in the low Pt region, which is already enough to distinguish between models.

In the same spirit, it will be very important to study the structure of underlying events[4]. To do that, benefit is taken from both the prescaled single-jet trigger and from a Minimum-Bias trigger based on the forward hadron calorimeter. Jets are constructed from the charged particles using a simple clustering algorithm and then the direction of the leading charged particle jet is used to isolate the transverse regions with respect to the jet axis. The transverse region is almost perpendicular to the plane of the hard 2-to-2 scattering and is therefore very sensitive to the underlying event. Key quantities that are studied are the density of charged particles, $dN/d\eta d\phi$ and the average charged PT_{sum} density, $dPT/d\eta d\phi$. To avoid biases from detector effects like charged jet energy calibration, charged track inefficiencies and charged track fake rates, the ratio between the observables for $p_T > 0.9GeV/c$ and $p_T > 0.5GeV/c$ are considered. These ratios (e.g. figure 1), which are sensitive to differences between different models and/or different tunings, are also nicely free from the systematic effects enumerated above, and basically don’t need to be corrected when comparing to the corresponding generator level observables. The central region of Drell-Yan muon-pair production events can also be used to study the same quantities.

Drifting to another field, B physics will be already very active in the first phase of running. The ability to trigger at HLT on B mesons based either on soft muons or on displaced vertices (after a L1 jet trigger) will result in a fairly large dataset of interesting events. Already at 1 fb^{-1}, the measurement of the inclusive B cross-section will be dominated by systematics, with an expected 20% precision. More specific studies are therefore possible.

The decay $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ is of particular interest, since it allows to study many properties of the B_s^0 system, such as the lifetime difference between the two weak eigenstates [5]. A large part of the background can be rejected already at the High-Level trigger, by selecting non-prompt J/ψ decaying into muons. About 10’000 signal events are expected with 1 fb^{-1}, which allows a measurement with a precision of 20%.

We move now to the study of weak bosons. The inclusive processes $pp \rightarrow W + X$ and $pp \rightarrow Z + X$, with

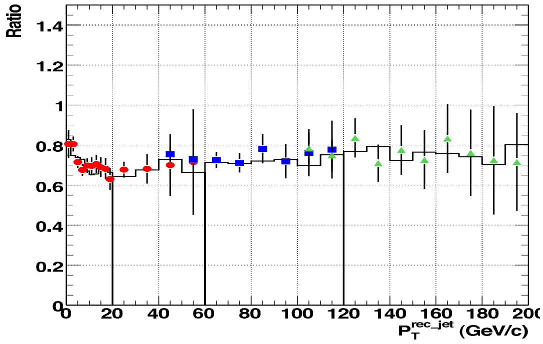

Figure 1: Ratio between average charged PT_{sum} density with $p_T > 0.9$GeV/c and $p_T > 0.5$GeV/c versus the transverse momentum of the leading charged particle jet; points correspond to the raw (uncorrected) reconstruction level profiles; histograms correspond to the generator level profiles for the events passing the reconstruction level selection [4].

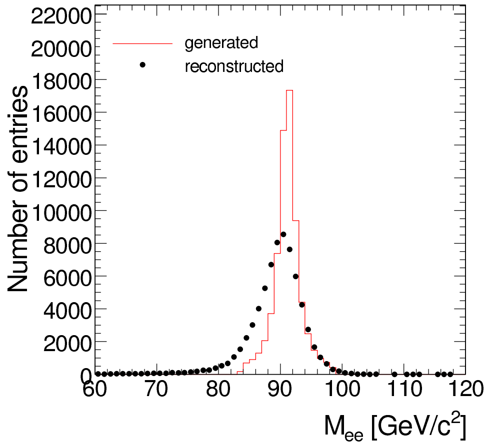

Figure 2: Reconstructed and generated Z mass distribution with all selection cuts [8]. The normalization is arbitrary.

the subsequent decay of W and Z into leptons have relatively large cross sections and rather simple signatures. The leptonic final states from these processes will play an essential role during the first stages of the LHC, where it can be used to calibrate the detector, to establish identification criteria and to estimate detector efficiencies (figure 2). The selection has to be performed by a set of robust and simple selection criteria that minimize systematics while ensuring a good efficiency and a good purity [6]. In a conservative scenario assuming a non-optimal detector and leading-order estimates, the systematic uncertainties on the rate measurement are found to be 2.3% for $Z \rightarrow \mu^+\mu^-$ and 3.3% for $W \rightarrow \mu\nu$. Similar performances have been demonstrated for decays into electrons [7]. A measurement of the luminosity from these rates with a 5% accuracy seems therefore feasible.

One last subject that cannot be escaped in this short overview of the early physics of the Standard Model is the study of top quarks. The initial goal is to measure the total $t\bar{t}$ cross-section. This will open the road to more sophisticated studies like mass measurement, single-top production, polarization or search for FCNC. The analysis should rely on a robust, cut-based selection. For a hadronic $t\bar{t}$ system, this can be achieved by requesting between six and eight jets, with two b-tagged jets amongst them, a transverse energy above 30 GeV and a total transverse energy in the calorimeters above 148 GeV [9].

In the semi-leptonic channel (figure 3), a clean signal can be obtained. Existing studies implement a complex selection strategy, that allows to target the top mass with a better understanding of detector effects [10]. A combined likelihood variable is used to select one muon from the list of reconstructed muons. The jets are reconstructed from the combined electromagnetic and hadronic calorimeter deposits and clustered with the Iterative Cone algorithm using an opening angle of 0.5 rad. The event selection

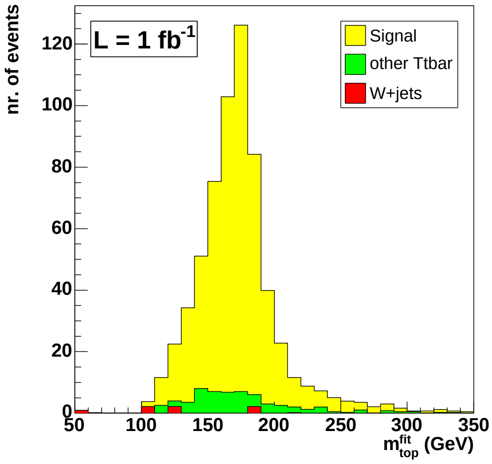

Figure 3: Reconstructed transverse mass for the top quark in semi-leptonic decays with 1 fb^{-1} of data and including the expected contribution of background processes [10].

then consists of a series of sequential cuts on kinematic or topological variables. A first pre-selection criterion reduces the amount of events to a manageable number by requiring, in addition to the lepton, at least four reconstructed jets with a transverse energy larger than 10 GeV and with a pseudo-rapidity in the range of the tracker. For the remainder of the event selection several variables are examined, resulting in a definition of some simple criteria. The event is required to have at least 4 jets after applying the primary vertex constraint with a calibrated transverse energy exceeding 30 GeV. Of these four jets, two have to be b-tagged. The four leading jets should not overlap to reduce ambiguities in the jet energy scale calibration procedure. The selected lepton candidate must have a transverse momentum larger than 20 GeV/c. This selection is then complemented by topological probability cuts based on a kinematic fit of the event.

For the startup, a simpler selection that stops before applying any b-tag selection criteria already potentially reaches a s/b of 1.7 for a significance above 80. Dedicated studies are being developed in that direction.

3 Early discovery strategy

When it's about the search for new physics, the early phase of running becomes more challenging. Signals are often small, and a prior good understanding of the background is mandatory. The search for "Higgs-like" deviations in data will nevertheless be performed for various possible topologies since the beginning. The primary goal will be to set exclusion limits since discovery is almost out-of-reach with 1 fb^{-1} or less. One of the exceptions is the $H \rightarrow WW \rightarrow l\nu l\nu$, where a 5σ signal can be observed if the Higgs boson mass is $165\mathrm{GeV/c}^2$, with only 1 fb^{-1} and considering the corresponding systematic uncertainties (figure 4). The key aspect of all the early searches is the control of background from data. This is achieved in the search for $H \rightarrow WW \rightarrow l\nu l\nu$ by defining normalization regions [11] for each source of background. If similar cuts are used to define the signal and the normalization regions, most systematic errors will cancel in the efficiency ratio. Moreover the efficiency ratio is better controlled than the predictions for the single efficiencies. For example, a normalization region for WW can be defined by requiring the angle between the two leptons $\phi_{ll} < 140$deg. and the invariant mass of the two leptons $m_{ll} > 60GeV$, keeping all other selection cuts unchanged. The error on the theoretical prediction of the ratio between the number of WW events in the signal and in the normalization region is expected to be small compared to the other sources of uncertainty. Only the $e\mu$ final state is considered in order to reduce the contribution of Drell-Yan and WZ. Figure 5 shows the ϕ_{ll} distributions for the different processes in this normalization region.

In some cases, the possible signature is striking even at low luminosity. This is the case for some SUSY scenarios where generic signatures of cascade decays with leptons, jets and missing transverse energy are large [12]. Signal and background can be disentangled with a series of cuts on observables that carry some discrimination power. These observables include the three leading jet transverse energies and pseudo-rapidities, the leading and next-to-leading muon transverse momentum, the missing transverse

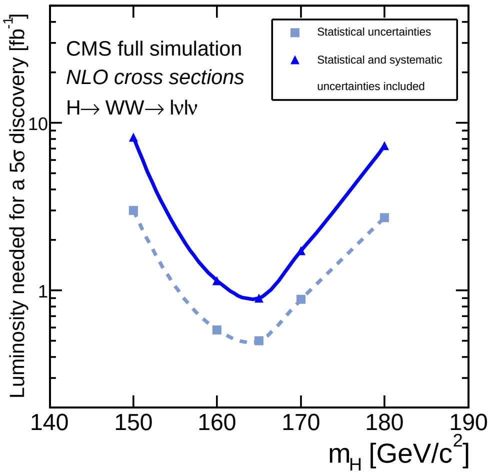

Figure 4: Integrated luminosity needed for a 5σ discovery as a function of different Higgs-boson masses for the H → WW channel [11] .

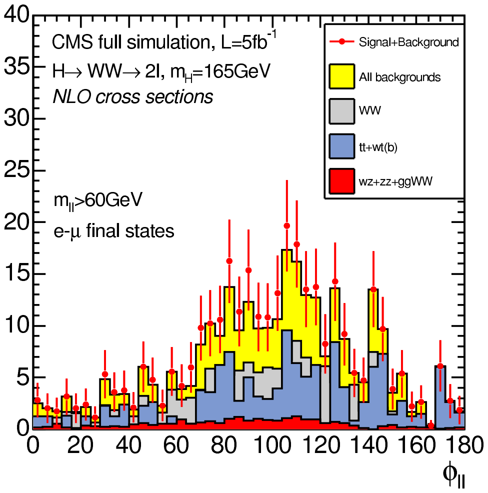

Figure 5: Distribution of the angle between the leptons in the transverse plane for the signal and the different backgrounds, for an integrated luminosity of 10 fb^{-1} . The WW normalization region is considered, with all signal cuts applied but $m_{ll} > 60 GeV$. Only electron-muon states are kept [11].

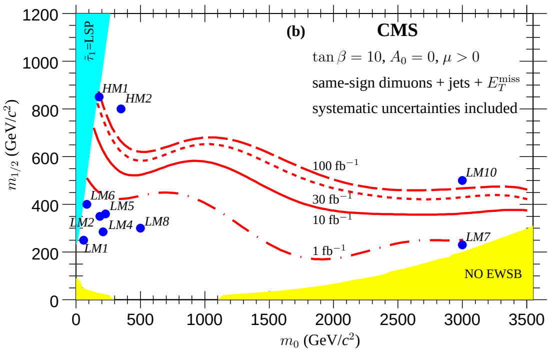

Figure 6: Dimuon 5σ CMS reach contours in the (m_0 , $m_{1/2}$) plane, including systematic uncertainties [13].

energy, and various jet and muon isolation variables. The strategy is to find a set of selection cuts that optimize the significance with which the null hypothesis (only standard model backgrounds) is expected to be excluded in the presence of signal.

Figure 6 shows that most of the low-mass SUSY benchmark points (LMx) can already be addressed with 1 fb^{-1} by looking at same-sign leptons accompanied by jets and missing transverse energy.

Other clear signatures include those from heavy neutral gauge bosons decaying either leptonically or hadronically. Using signal and background shapes only, and taking into account realistic detector misalignment scenarios and various sources of systematic uncertainties, the discovery reach for a representative set of Z models was found to be in the range between 1.9 and 2.8 TeV/c^2 for an integrated luminosity of 1 fb^{-1} [13]. It should be possible to enter a yet unexplored mass region above 1 TeV/c^2 at the earliest stages of data taking, with an integrated luminosity of only 0.1 fb^{-1} and non-optimal alignment of the tracker and the muon detectors. Full simulation and reconstruction of signal and background processes have been used, which included expected alignment precision and pile-up of minimum bias collisions, and examined trigger and reconstruction efficiencies.

4 Conclusion

The initial phase of running will be crucial for CMS. The High-Level trigger and the detector will have to be understood. The Standard Model processes will have to be measured. The search for new physics will start.

The CMS collaboration is getting ready for that fascinating period, by validating the software, training people and preparing data analysis while building the detector. Many Standard Model studies and some searches beyond the Standard Model are possible in the early phase of running. This is also made possible by the great flexibility of our trigger system. In all cases, much care has to be taken to use robust selection criteria and analysis methods to avoid biases due to the large systematic uncertainties that we will have at the beginning.

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