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“REDISCOVERING” THE STANDARD MODEL AT CMS

DAN GREEN
CMS Dept., Fermilab, Batavia Il. 60510, USA
dgreen@fnal.gov
For the CMS Collaboration

The Large Hadron Collider (LHC) began 7 TeV C.M. energy operation in April, 2010. The CMS experiment immediately analyzed the earliest data taken in order to “rediscover” the Standard Model (SM) of high energy physics. By the late summer, all SM particles were observed and CMS began to search for physics beyond the SM and beyond the present limits set at the Fermilab Tevatron. The first LHC run ended in Dec., 2010 with a total integrated luminosity of about 45 pb^{-1} delivered to the experiments.

Keywords: Large Hadron Collider, CMS, Standard Model, Beyond the Standard Model

1. Introduction

The CMS experiment is one of two general purpose detectors which have begun data taking at the LHC located at CERN. The performance of the CMS detector, software and physics analyses has been documented elsewhere[1,2]. A complete description of CMS has also been published[3].

While the LHC accelerator was being installed and commissioned, CMS used the cosmic ray flux of muons to accomplish a preliminary detector commissioning of many of the subsystems, both alignment and calibration[4]. Indeed, those data were also used to contribute to knowledge of the charge ratio of atmospheric muons[5]

On March 30, the LHC machine began to deliver proton-proton collisions to CMS. Data at 0.9, 2.36 and 7 TeV were obtained. The first data run of the LHC ended in December, 2010 with more than 45 pb^{-1} of integrated luminosity delivered to the experiments. This first run of the LHC enabled CMS to fully commission the detector for physics analyses.

Because a new accelerator was commissioned in an unexplored energy regime with a new detector, the first task of CMS was to “rediscover” all the particles contained in the SM. The matter particles are quarks and leptons. The quarks come in three generations of doublets: u, d, c, s, t and b. The charged leptons are e, μ and τ, while the neutral leptons are the corresponding three neutrinos. The force carriers are the gluons, photons, W^+,W^- and Z. The range of cross sections that are spanned in order to observe all SM particles covers about nine orders in magnitude, going from the total inelastic cross section down to the top pair cross section. This impressive dynamic range was covered by CMS in only five months of data taking.

2. Tracking Systems

CMS has built a state of the art tracking system which records the positions and vector momenta of the charged particles produced in the interactions. The tracking system consists of silicon pixels and silicon strips immersed in the 3.8 T magnetic field produced by the CMS solenoid. Details of the performance of the tracking system are available elsewhere[6].

The first CMS results were derived using open triggers which passed the total inelastic cross section and covered the production of charged particles, mostly u and d quarks[7,8]. Data at 0.9, 2.36 and 7 TeV were published on the number of charged particles per unit of rapidity and the mean transverse momentum, p_t, of those particles. These results were necessary input to the tuning of the Monte Carlo models which are used to describe these processes. More low momentum particles were found than were predicted by extrapolating tunes from the Tevatron experiments. This excess necessitated the retuning of the Monte Carlo models for a description of 7 TeV p-p interactions.

The specific ionization of the charged tracks was also recorded, which was used to separate pions, kaons and protons with momenta of a few GeV. Very quickly, using the tracker to find secondary decay vertices, Ks, Λ, Ξ, and Ω states were seen which "rediscovered" the s quark. Later, with shorter distances between the production and decay vertices becoming detectable, D and D* decays were found, which identify states containing c quarks. Finally, B^o, B^+, B_s states were observed, tagging the mesons containing a b quark. An event with a primary vertex and two candidate b decay vertices is shown in Fig.1. Finding all these states at the already well established mass and width[9], serves to commission the tracking system for physics analyses. All the quarks were then commissioned except for the top quark, which had to wait for a larger accumulated integrated luminosity.

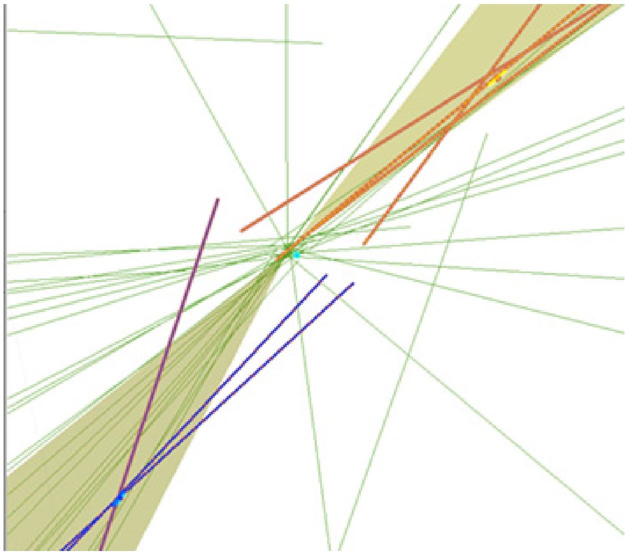


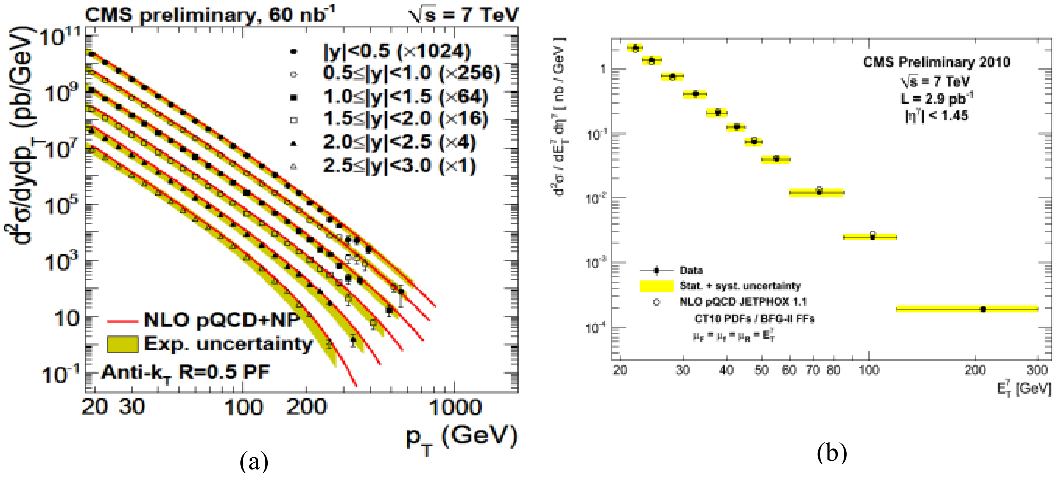
Fig. 1. The tracking system performance in a candidate event containing a b quark pair. The ellipses indicate the estimated spatial errors on the primary and the two secondary vertices.

3. Calorimetry

The CMS detector has fine grained calorimetry. Immediately after the first data was taken, neutral pions were observed by way of their two photon decay final state. The eta soon followed and the energy scale and energy resolution of the electromagnetic calorimeter was thus cross checked against calibrations found previously in particle test beams. The calibrated energy scale for neutral energy deposits was determined to ~ 1 % in the early data taking. Isolated photons balancing a recoil jet were seen later. These events were used to validate the jet energy scale.

Jets were observed soon after data taking started, showing that quarks and gluons from the SM were being observed in the calorimetry. The two jet sample was used, assuming no final state transverse momentum, to cross calibrate the calorimetry and to establish the energy resolution of the calorimetry for jets. Typical fractional energy resolution values are 5-10 % depending on p_t. The cross section for jets and photons[10] as a function of p_t is shown in Fig. 2. This data establishes the commissioning of CMS for isolated photons and gluons.

The calorimeters are also the crucial devices used to measure the missing transverse energy, MET, which is the energy which would be needed to be added to make the measured final state transverse energy zero. In CMS the MET is determined using both the calorimeters and the tracking system. Tracking offers a superior measurement of low momentum charged particles with respect to calorimetry, so that both systems are used synergistically.



(a) (b)

Fig. 2. The cross section for jets (a) and prompt photons (b) at 7 TeV as a function of the jet p_t and the photon E_t

The Gaussian "core" of the fractional MET resolution is $\sim 50\% / \sqrt{\sum E_t}$, where the sum is over all particles in the final state. CMS managed to provide a quite clean MET measurement, near the irreducible scale set by electroweak W and Z production processes which contain real MET due to final state neutrinos, by carefully "cleaning" spurious calorimeter signals and by using the tracking in concert with the calorimetry. Since MET is the signal for neutrinos escaping the detector, CMS was thus commissioned for these particles of the SM.

Electrons are commissioned in CMS by combining a charged track with a calorimetric energy deposit. The energy deposit is required to be isolated (no nearby energy) and to match the track in position and momentum. Using these selection criteria a rather pure sample of electrons can be found, where the rate of fake electrons is kept at the 0.001 level or below.

4. Muon Systems

The muon detectors in CMS were well aligned using cosmic ray events prior to data taking with proton collisions. Good alignment of the muon detectors allowed CMS to identify muons up to 1 TeV in momentum in the cosmic ray data set. Upstream “halo” from the LHC accelerator scraping was also used to align the muon detectors located at small angles to the incident beams.

Muons were required to be isolated, similar to the electron requirement. Muons are measured in CMS in the tracking system and, redundantly, in a standalone set of muon detectors. The redundant measurements were used to establish the muon momentum and position resolutions and to set the absolute momentum scale. The muon resolution is ~ 1% at 10 GeV, ~ 2 % at 100 GeV and ~ 10% at 1000 GeV.

The resonances observed in events with final state lepton pairs are “standard candles” whereby the resolution and energy scale of the leptons can be determined. A composite plot of the mass spectrum for di-muons is shown in Fig. 3. The observed resonance range from ~ 1 GeV to the ψ, the Y, and finally the Z[11,12]. In some real sense this plot shows graphically how CMS has recapitulated the course of high energy physics over the last fifty years during the first rediscovery phase of the data taking.

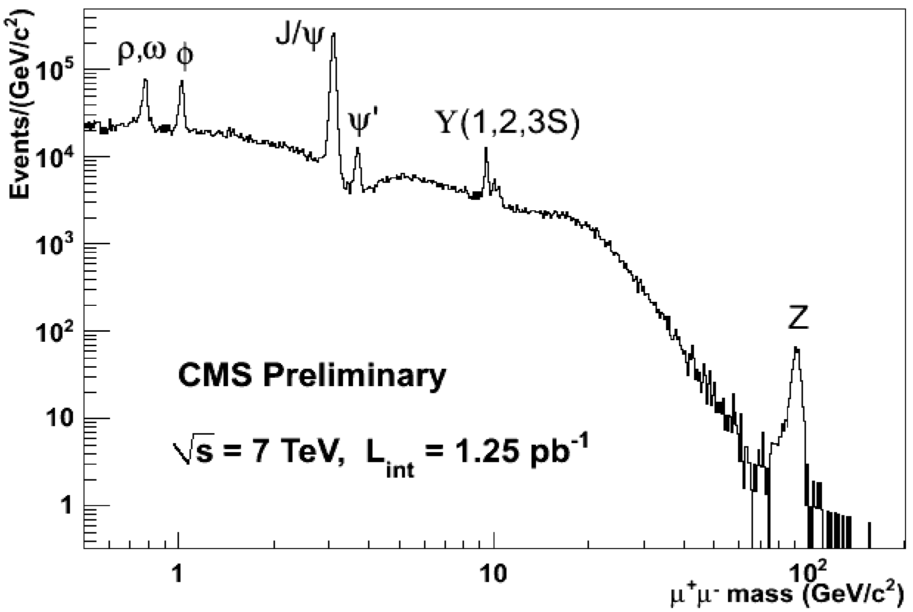


Fig. 3. The dimuon data collected by CMS. The resonances which are visible rance from up/down quark anti-quark states at low mass, to strange quark resonances, charm quark and bottom quark states. Note the upsilon spectroscopy is well resolved. Finally the Z state is observed at 91 GeV.

The very good lepton momentum resolution allows CMS to resolve the complete set of spectral lines for both the ψ and the Y. The very clean Z is used in CMS in a "tag and probe" exercise, where a very tightly defined "tag" lepton is used to explore if a "probe" lepton partner is found. In this fashion the lepton trigger, reconstruction and identification efficiencies have been determined for both electrons and muons.

5. W and Z Bosons

The remaining particles in the SM to be commissioned at CMS are the tau lepton, the W and the top quark. The Z has already been shown. The tau was found and identified in the di-tau decay of the Z resonance where one tau decayed into a lepton plus neutrinos and the other tau decayed into a pion(s) plus neutrinos. The existence of a low background Z resonance with a substantial tau decay branching fraction makes the tau commissioning possible.

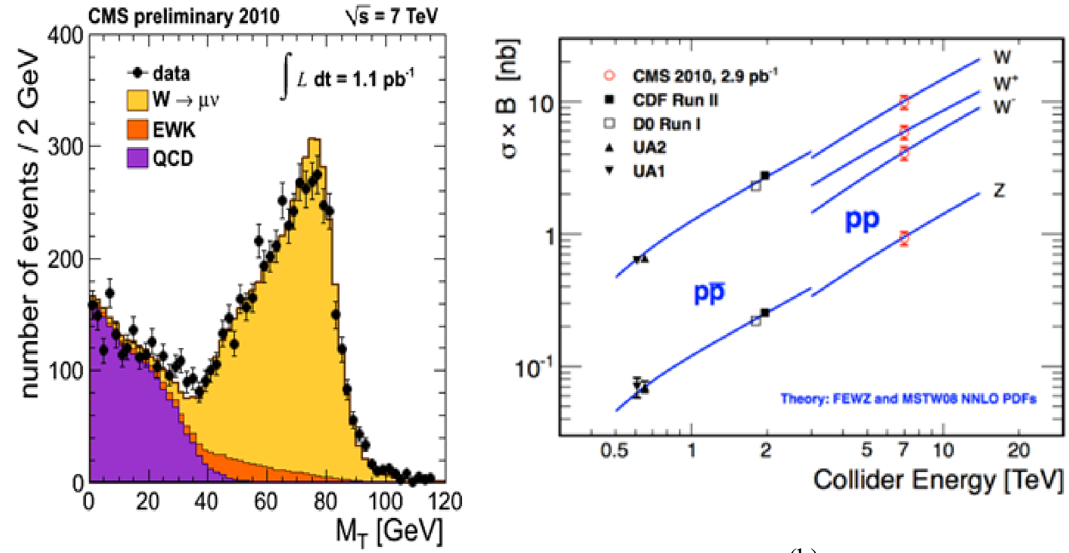
For the W commissioning, the decay mode used is that into a lepton plus a neutrino. This technique uses the lepton commissioning already achieved from the di-lepton resonance data and the neutrino commissioning completed already using the MET data samples from total inelastic events and b quark semileptonic decays.

Taken together, the transverse mass, M_t, is computed. This is the mass of the lepton – MET system computed in the transverse plane alone. The distribution of Mt for isolated muons in events with a substantial measured MET is shown in Fig. 4. A clear Jacobean peak due to W production is seen, over a small background. The cross section derived from the extracted signal is also shown in Fig. 4 along with data[12] from other hadron collider experiments. The agreement with the predicted value is quite good, which confirms that CMS has commissioned the W bosons.

6. Top at CMS

The last particle of the SM which was commissioned by CMS was found in the summer of 2010 – the top quark. The top decays almost totally into the W + b final state. The W can decay either into a lepton plus a neutrino or into two quark jets. In CMS two final states were studied, one with two leptons plus two b jets plus MET and the other with a lepton plus four jets (2 b jets) plus MET. In both cases a clean top signal was observed[13].

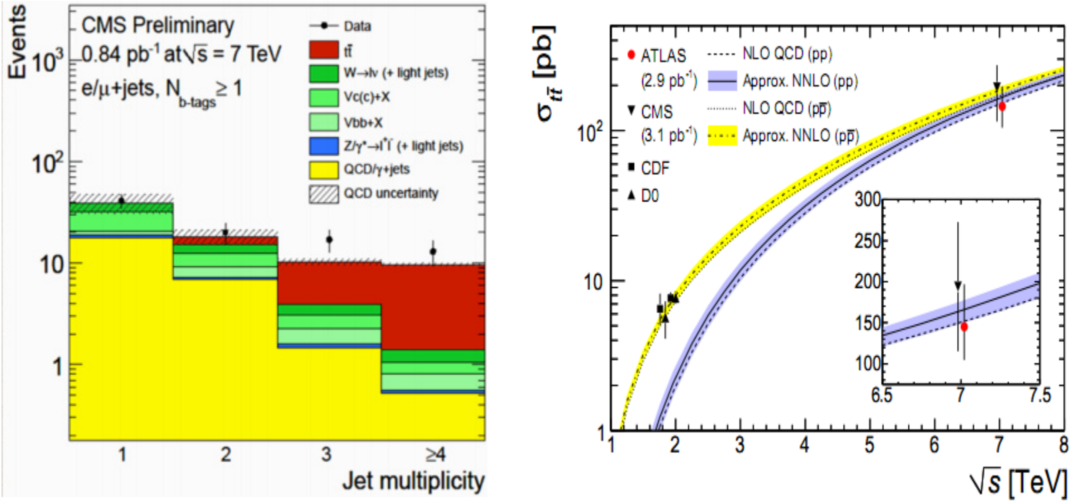
The data from CMS for the single lepton signature are shown in Fig. 5. A b jet, identified by a displaced secondary vertex (Fig. 1), is required in order to reduce the W plus jets background. For four or more jets, the top pair signal clearly dominates all backgrounds.



(a)

(b)

Fig. 4. The distribution of transverse mass for W candidate events containing a muon and missing transverse energy (a). The cross sections for W and Z production from CMS data on 7 TeV proton-proton collisions and lower energy data on proton-anti-proton collisions (b).



(a)

(b)

Fig. 5. The jet multiplicity for top pair candidate events containing a muon or electron and at least one jet with at least one jet tagged as a b quark (a). The cross section for top production as a function of C.M. energy (b).

The extracted signal cross section is also plotted in Fig. 5 in comparison to lower energy data. The agreement with the expectations of the Monte Carlo models is again quite good.

7. Beyond the SM

Having thus rediscovered all the elements of the SM, it becomes plausible for CMS to begin to look beyond. The process of rediscovery has given confidence that the detector is functioning well with performance levels at or beyond their design values.

At a C.M. energy of 7 TeV, for gluon induced processes, the LHC has a parton luminosity which is a factor ~ 10,000 times higher than the Tevatron for producing masses 1 TeV and above[14]. Therefore, for these mass scales, CMS can already set limits which explore new territory since the integrated parton luminosity of the LHC now exceeds that of the Tevatron.

The strongly produced states are the first candidates to be studied for physics beyond the SM. In Fig. 6 is shown the behavior of di-jets when searching for new "contact" interactions which are generic new physics signatures at a mass scale far above the mass range of the data in question[15,16]. Clearly, CMS limits are set which exceed those set by Tevatron experiments.

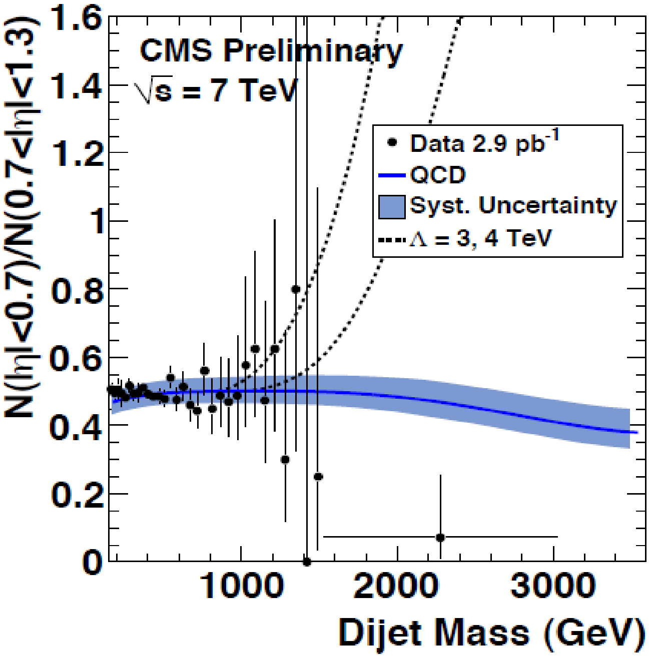


Fig. 6. CMS search results for contact interactions in jet data. Limits on the contact scale already exceed Tevatron limits.

There is a plethora of conjectured new physics which has been proposed over the last twenty years. CMS will now begin to search for evidence of this new physics. The final state used in a given search is defined by the integrated luminosity delivered by the LHC. It starts with the strongly produced particles. On possibility studied by CMS is that of lepto-quarks, a composite of leptons and quarks as might be expected in unified theories. No such signal has yet been seen [17,18] with mass limits already beyond those set at the Tevatron.

A specific model of new physics is that of Supersymmetry (SUSY). It is expected that squarks and gluinos, since they carry color, will be strongly produced at the LHC with fairly large cross sections. In specific models, the gluino may be long lived, giving a spectacular signature. Unfortunately this search in CMS has yielded a negative result so far[19].

Supersymmetric squarks and gluinos, with masses ~ 1 TeV may be produced with pb level cross sections. Assuming R parity, they would make a series of decays cascading to the lightest, stable, supersymmetric particle (LSP), which implies a decay signature of jets from the decay products and MET from the escaping LSP. Given that CMS has nowcommissioned jets and MET, as described above, limits can be set in specific SUSY models with some confidence. The expected limits for 100 pb^{-1} of integrated luminosity, are shown in Fig. 7. Clearly, very soon CMS will make a substantial improvement on the existing SUSY model limits from the Tevatron and LEP experiments.

8. Conclusions

The CMS experiment has begun data taking in April, 2010. A rapid set of analyses have been made which have allowed CMS to fully "rediscover" the SM, whereby all the particles of the SM have been cleanly identified and commissioned. The success of this program has enabled CMS to begin searches for physics beyond the SM with confidence that the detector is well understood and the analysis tools are robust. Operating at 7 TeV in 2010 and above that energy in 2011, CMS will explore new territory at the mass scale of 1 TeV and above where the new physics is expected to exist.

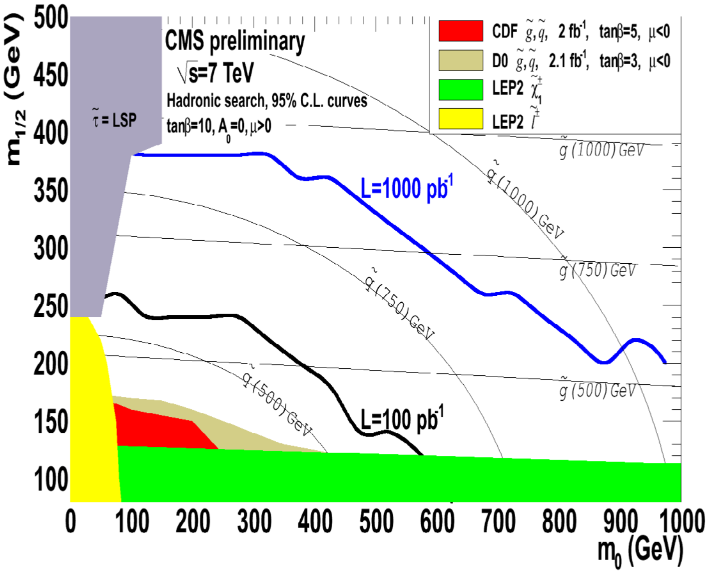


Fig. 7. Expected limits on SUSY parameters from CMS for 100 and 1000 pb^{-1} of data at 7 TeV compared to existing limits from the LEP and Tevatron experiments.

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