IL NUOVO CIMENTO Vol. 33 C, N. 4 Luglio-Agosto 2010
DOI 10.1393/ncc/i2010-10647-4

Colloquia: TOP2010

CMS status and first data

K. M. Ecklund on behalf of the CMS Collaboration

Department of Physics and Astronomy, Rice University - 6100 Main Street, Houston TX 77005, USA

(ricevuto il 2 Agosto 2010; approvato il 2 Agosto 2010; pubblicato online il 24 Settembre 2010)

Summary. — The Compact Muon Solenoid (CMS) experiment at CERN's Large Hadron Collider (LHC) has started to collect and analyze proton-proton collisions at $\sqrt{s} = 7$ TeV from the first physics run of the LHC. At the time of this meeting, CMS had collected a $17\,\text{nb}^{-1}$ of collision data, including small samples at lower energies of 0.9 TeV and 2.36 TeV. While these samples are too small for observation of top quark pair production, the results presented here demonstrate good detector performance and illustrate well-understood physics signatures that will lead in the near future to re-observation of the top quark at the LHC. Those signatures include jets, isolated muons and electrons from weak gauge boson decay, and separated secondary vertices from b-quark jets. With the capability to identify these signatures in collision data, CMS is poised for top physics studies from the first LHC physics run.

PACS 13.85.-t – Hadron-induced high- and super-high-energy interactions.
PACS 13.85.Ni – Inclusive production with identified hadrons.
PACS 13.85.Qk – Inclusive production with identified leptons, photons, or other nonhadronic particles.
PACS 13.87.-a – Jets in large-Q^2 scattering.

1. – CMS status

This workshop on top physics is coincident with the beginning of physics from the Large Hadron Collider (LHC) at CERN, which began colliding protons at the highest accelerator-produced energies in the past six months. In December 2009, the LHC produced proton-proton collisions at $\sqrt{s} = 0.9$ TeV and 2.36 TeV, followed by collisions at 7 TeV at the end of March 2010, just two months before this meeting. It was gratifying to finally see event displays from high-energy proton-proton collisions and positive press after the events of 2008. Since the initial collisions, luminosities have increased during the commissioning phase for the accelerator and experiments.

Through 26 May 2010, just before this meeting, the Compact Muon Solenoid (CMS) experiment recorded an integrated luminosity of $17.1\,\text{nb}^{-1}$, out of $18.8\,\text{nb}^{-1}$ delivered by the LHC for an efficiency of more than 90%. Figure 1 shows the integrated luminosity *versus* date. The peak instantaneous luminosity achieved at the end of this period was

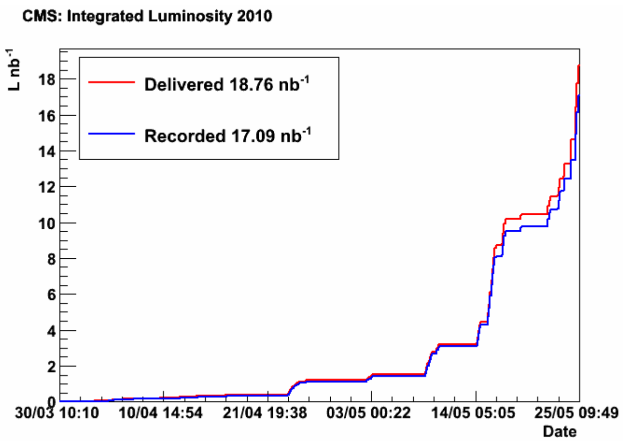

Fig. 1. – Integrated luminosity delivered to and recorded by the CMS experiment through 26 May 2010.

$2 \times 10^{29}\,\text{cm}^{-2}\,\text{s}^{-1}$ with eight colliding bunches. There is still a significant way to go towards the instantaneous luminosity goal of $10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$ for the first physics run, which is planned to continue through the end of 2011, with luminosity goals of $100\,\text{pb}^{-1}$ per experiment by the end of 2010 and $1000\,\text{pb}^{-1}$ total by the end of 2011(1).

One feature of fig. 1 is immediately apparent: the machine is very much in a commissioning phase, with an exponential growth for the luminosity. The detectors too are in a commissioning phase. The next section describes the detector performance during colliding beams.

2. – Detector performance

The Compact Muon Solenoid [2] is a general-purpose detector designed for high-p_T physics at LHC energies. From interaction point outward, CMS includes silicon pixel and strip tracking detectors with acceptance to pseudorapidities (η) less than 2.4, providing charged particle tracking and vertexing; a lead-tungstate crystal electromagnetic calorimeter ($|\eta| < 3$), for photon and electron identification; a brass-scintillator hadron calorimeter ($|\eta| < 3$) and quartz fiber forward calorimeter ($3 < |\eta| < 5$), for jet measurement combined with the electromagnetic calorimeter; a superconducting solenoid operated at 3.8 Tesla; and muon detection from muon systems in the central barrel (drift tubes and resistive plate chambers covering $|\eta| < 1.2$) and forward endcap (cathode strip and resistive plate chambers covering $0.9 < |\eta| < 2.4$). Signals from the calorimeters and muon systems provide triggering on high-p_T signatures. In early data taking these triggers are supplemented by beam-coincidence counters and scintillator wedges in front of the forward calorimeters for minimum bias triggering during low-luminosity running.

2˙1. *Tracking detectors*. – Figure 2 demonstrates a good understanding of the basic response of the silicon sensors used in the pixel and strip trackers. The cluster charge distribution shows very good agreement to Monte Carlo simulation for pixel sensors in

(1) The LHC design luminosity is $10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ with 2808 bunches at $\sqrt{s} = 14\,\text{TeV}$ [1].

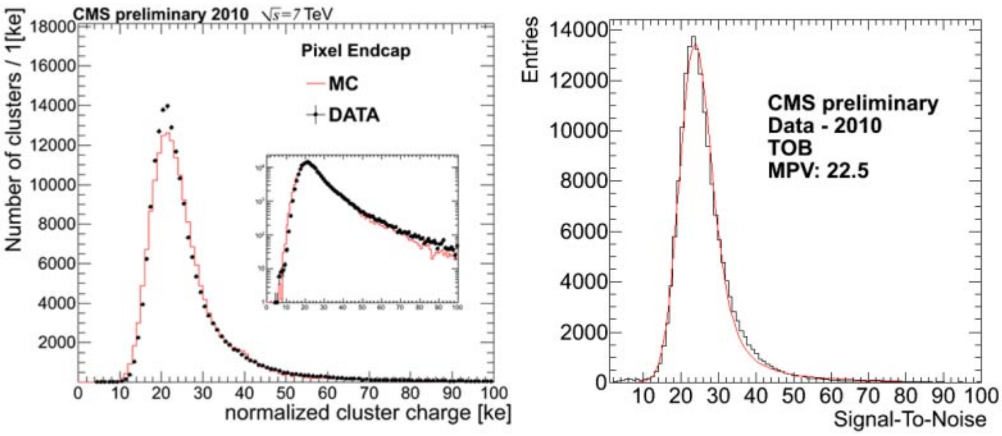

Fig. 2. – Cluster charge in the pixel endcap normalized to normal incidence (left) and signal-to-noise ratio for the barrel strip tracker (right).

both barrel and endcap regions. Likewise the strip modules have the expected signal-to-noise ratio, again in excellent agreement with simulation. CMS took advantage of the long cosmic running period in 2008–2009 to achieve this level of agreement [3, 4]. These results for collision data followed very quickly after beam collisions were recorded.

Tracking of charged particles is also well understood; detailed results from beam collisions are reported in ref. [5]. As examples, fig. 3 shows the number of sensor hits used per track and the primary vertex distributions from a single run. The later is dominated by the LHC beam size (0.25 mm transverse and 39 mm longitudinal) and is clearly seen to be offset with respect to the center of CMS.

CMS has reconstructed many well-known decays of light resonances to charged particles, demonstrating an understanding of the momentum scale by comparing the reconstructed masses to well-known values and an understanding of tracking uncertain-

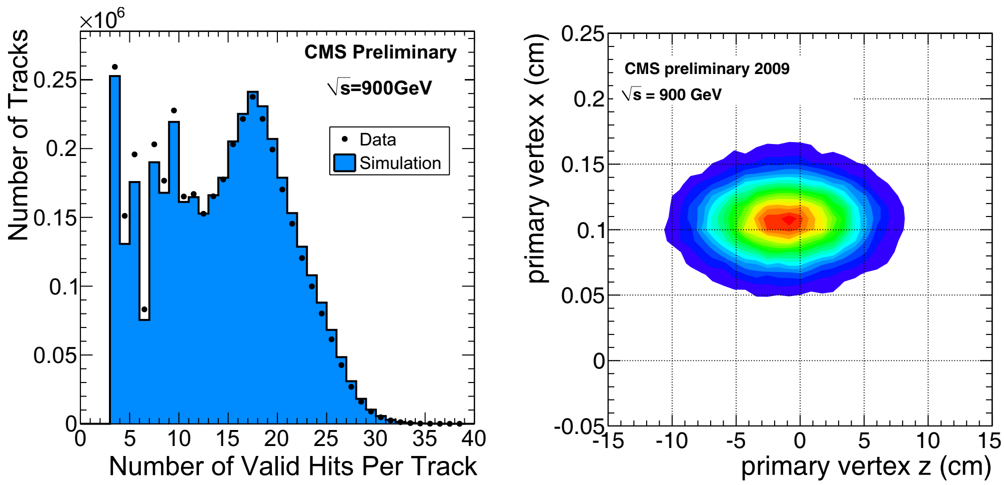

Fig. 3. – Tracking and primary vertex reconstruction in early CMS data.

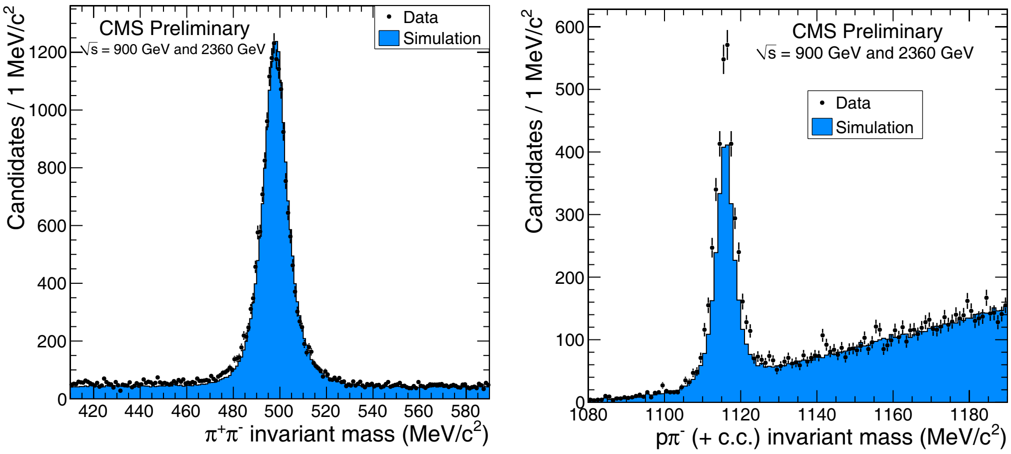

Fig. 4. – K^0_S and Λ invariant mass distributions. The PYTHIA based simulation is normalized to the observed K^0_S yield, showing a larger yield of Λ than predicted by simulation.

ties by comparing the mass resolutions to simulation. Using separated vertices, both $\Lambda \to p\pi^-$ and $K^0_S \to \pi^+\pi^-$ are clearly seen in fig. 4 [5]. When fit to double Gaussians (same mean), the masses are in good agreement with world averages [6], and resolutions match expectations from Monte Carlo simulation (see table I). By adding another track at an additional vertex in the cascade decay, the strange baryons $\Omega^- \to \Lambda K^-$ and $\Xi^- \to \Lambda\pi^-$ are also observed [7], at the expected masses. The cascade decay topology (primary vertex, secondary Ξ or Ω vertex, tertiary Λ vertex) is an excellent test of vertex reconstruction at centimeter length scales for the tracker.

At smaller length scales relevant to secondary vertices from b hadrons, CMS has developed several b-tagging algorithms. In early data, the performance of the 3D signed impact parameter is quite impressive [8]. Figure 5 shows the 3D impact parameter to the primary vertex and its significance for anti-k_T jets with $p_T > 40\,\text{GeV}$ and $|\eta| < 1.5$. At the time of this conference a number of doubly tagged QCD dijet events have been observed.

2·2. *Calorimeters*. – The CMS electromagnetic calorimeter has demonstrated agreement on the energy scale at the 1% level by reconstructing $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays in minimum bias (low p_T) data. Figure 6 shows the mass peaks for π^0 and η candidates in $0.43\,\text{nb}^{-1}$. The π^0 candidates must satisfy $p_T(\gamma) > 0.4\,\text{GeV}$ and $p_T(\gamma\gamma) > 1\,\text{GeV}$; for η candidates these cuts are increased to 0.5 and 2.5 GeV, respectively. The position and

TABLE I. – *Observed and simulated mass and mass resolution for Λ and K^0_S.*

	Mass (MeV)		PDG	Resolution (MeV)	
	Data	Simulation		Data	Simulation
Λ	1115.97 ± 0.06	1115.93 ± 0.02	1115.683 ± 0.006	3.01 ± 0.08	2.99 ± 0.03
K^0_S	497.68 ± 0.06	498.11 ± 0.01	497.61 ± 0.02	7.99 ± 0.14	7.63 ± 0.03

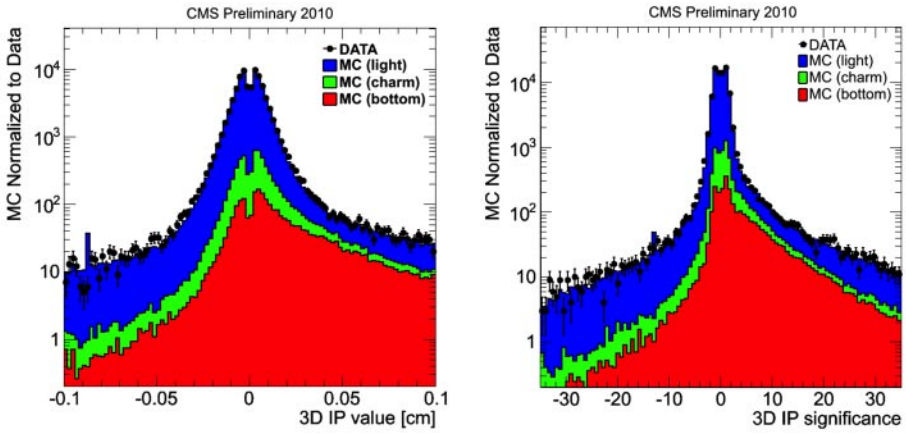

Fig. 5. – Three-dimensional impact parameter to the primary vertex (left) and significance (right) for $p_T > 40\,\mathrm{GeV}$ jets with $|\eta| < 1.5$.

widths of the mass peaks is in agreement with expectations from simulation. A dedicated high-level trigger collects such candidates for continuous calibration of the calorimeter.

The CMS hadronic calorimeter has also been commissioned, and the performance can be summarized by looking at jet reconstruction including the electromagnetic calorimeter and tracking detectors [9]. In all techniques the anti-k_T jet algorithm is used with $R = 0.5$ to form jets. Using a minimum bias sample, a sample of dijet events is selected, requiring back-to-back jets ($\Delta\phi > 2.1$) with $p_T > 25\,\mathrm{GeV}$ and $|\eta| < 3$. In fig. 7 the dijet mass distribution is compared to simulation for three jet reconstruction techniques: using calorimeters only, adding tracks, and an advanced particle flow technique that attempts to make optimum use of track information to correct measured jet energies.

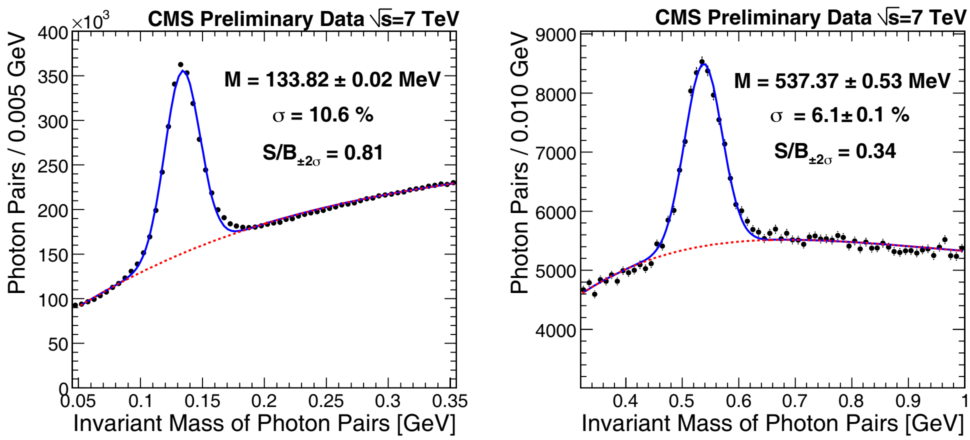

Fig. 6. – π^0 and η candidates in early CMS data.

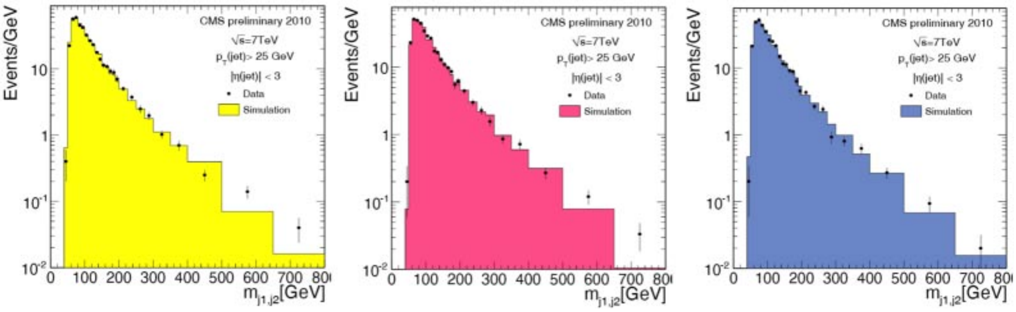

Fig. 7. – Left to right: dijet mass distributions for calorimeter only jets, calorimeter and track jets, and particle flow jets.

The missing transverse energy performance of the calorimeters is shown in fig. 8 for the calorimeter plus track jets. The distribution of the x and y component of the missing transverse energy compares well to simulation. The width of this distribution is plotted as a function of the sum of transverse energy, showing an expected resolution of 6 GeV for 100 GeV of ΣE_T and good agreement with simulation.

3. – Physics performance

With detector performance already well established, CMS is eagerly moving to physics analysis using early data sets and looking forward to rediscovering the standard model to establish the physics performance of the experiment while looking for new discoveries at the energy frontier. The first physics publications have already appeared at the time of the TOP2010 workshop.

3˙1. *Low-p_T physics.* – Using 1.1 μb^{-1} of data from the first hours of proton-proton collisions, CMS has measured the charged particle rapidity distribution using a tracking-based analysis [10, 11]. A minimum bias trigger from beam scintillation counters is combined with a requirement of 3 GeV of energy in the hadronic calorimeter and the

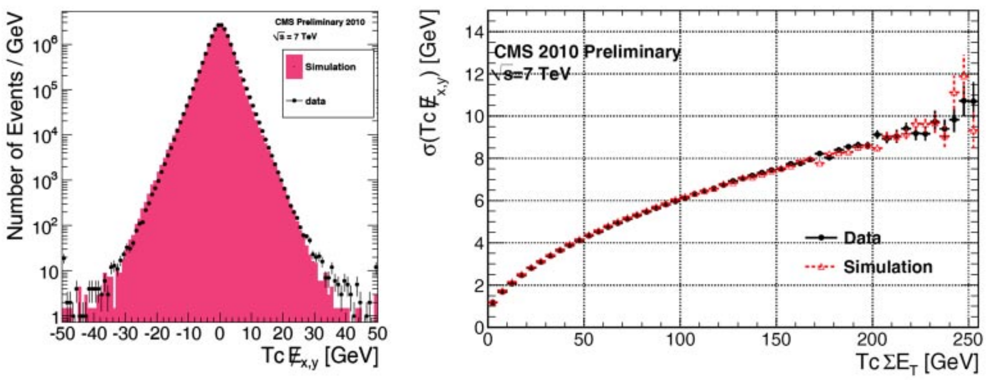

Fig. 8. – The x or y component of missing transverse energy for track plus calorimeter jets (left) and the resolution as a function of the transverse energy sum.

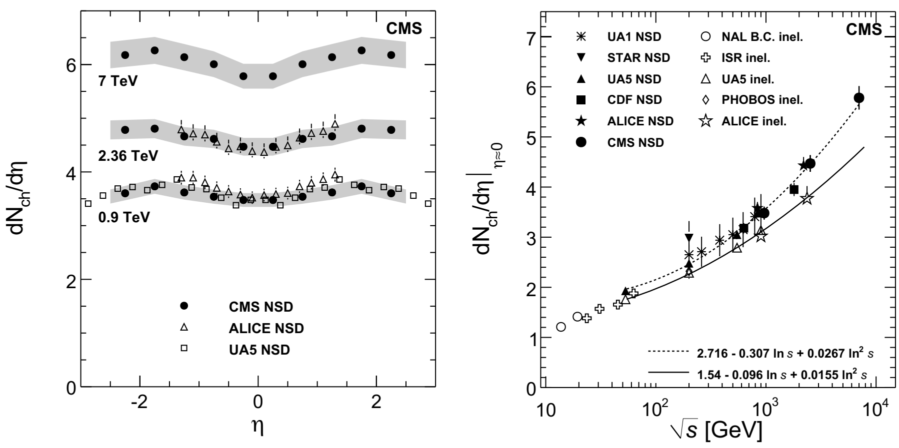

Fig. 9. – Charged particle multiplicity *vs.* pseudorapidity $\frac{dN}{d\eta}$ (left) and at $\eta = 0$ *vs.* $\sqrt{s}$ (right) in proton-proton collisions.

presence of a primary vertex. Three separate methods are used to count charged particle tracks using the pixel detector hits, pixel tracklets, and full tracks. A correction removes single-diffractive events. Figure 9 shows the differential distribution for three energies delivered by the LHC. The value at midrapidity is shown as a function of $\sqrt{s}$, with clear indications that the predicted trend from most models is exceeded at 7 TeV. These data and analysis suggest a new tune for the event generators is needed, especially as the high-p_T physics at the LHC will be done in an environment of multiple p-p interactions per beam crossing.

3·2. *High-p_T physics.* – CMS is also pursuing high-p_T physics with the available data. In 18 nb^{-1} of 7 TeV data, one expects the appearance of the electroweak gauge bosons. Analysis cuts carefully prepared on Monte Carlo samples have been applied to 1 nb^{-1} of data to look for $W \to e\nu$, $W \to \mu\nu$, $Z \to e^+e^-$, and $Z \to \mu^+\mu^-$ candidates. The leptons are required to have a track with $p_T > 20$ GeV and $|\eta| < 2.1$ pointing to matching hits in the electromagnetic calorimeter or muon systems as appropriate. Lepton candidates must be isolated from other track or calorimeter activity. Requiring large missing E_T, we expect of order 8 W candidates in 1 nb^{-1} and find 3 electron and 3 muon candidates. For the Z candidates the p_T cut is lowered to 10 GeV. One candidate is expected, and one $Z \to ee$ candidate is found (see fig. 10). Initial indications are that the W and Z cross sections are as expected.

4. – Outlook and conclusion

At a top physics workshop, I conclude looking forward to re-observation of the top quark by the LHC experiments. The luminosity performance is still on an exponential growth curve as the LHC is commissioned. With nearly 20 nb^{-1} recorded in the first two months, very soon the first top candidates will be recorded. The next two months leading up to the International Conference on High Energy Physics in Paris will likely bring some top candidates from both ATLAS and CMS, followed closely by cross section measurements.

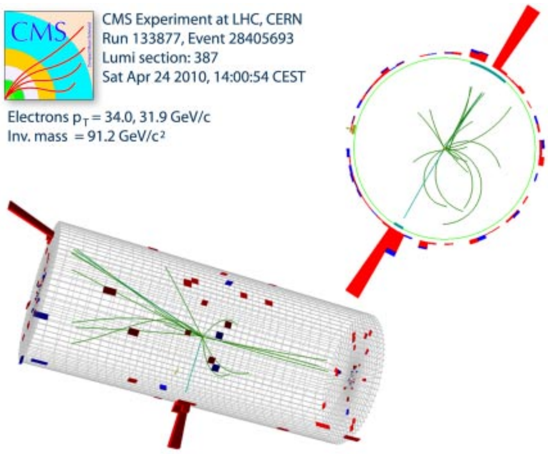

Fig. 10. – $Z \to e^+e^-$ candidate.

The CMS detector is performing well, already demonstrating excellent reconstruction of the many ingredients expected in a top signal: missing transverse energy, b tagging, leptons, and jets. Some of the success can be credited to an unexpected gift of time for the detectors to commission with cosmic rays and fully prepare for LHC beam collisions, but now with beam in the machine, the overall quality of the first results is impressive and bodes well for the future. Additional details of CMS performance were presented at this workshop [12], along with CMS strategies for data-driven background extraction [13] and jet measurement in top events [14].

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This contribution was supported by the U.S. Department of Energy grant DE-FG05-97ER41031.

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