Silicon sensor probing and studies of the muon p_T scale uncertainty at CMS

Supervisors:
Dr. Leonard Spiegel
Dr. Pushpa Bhat

Student:
Carmen Giugliano

Istituto Nazionale di Fisica Nucleare

Italian Summer Internship

Rome wasn't built in a day.

Contents

Introduction

To search for the Higgs boson , to address the open questions of Standard Model and to search evidence of new physics beyond the standard model a machine able to explore the so called TeV scale is necessary.
The Large Hadron Collider (LHC) has been specifically built to study the TeV frontier, indeed it provides to the acceleration and to the collision of protons and heavy nucleus such as Pb at energy scales never explored before.
The Compact Muon Solenoid experiment at the LHC is designed to hints new physics and to understand better the Standard Model. CMS can be considered like a technology masterpiece for its duties that made possible to see it like a detector in a detector. All these stuff undergoing to a series of upgrades since suffer the effect of radiations. To probe the detectors and to enrich the knowledge, physicists non only takes data from the collisions but they also use Cosmic rays and try to process millions of data developing tools and improving the data analysis.
In few steps the present work is done in this way:

- In the first Chapter it is going to explain briefly all the CMS detectors.
- In the second Chapter it is going to talk about the new Forward PIXel upgrades and in particularly the procedures to test wafer sensors provided by Sintef.
- In the third Chapter it is going to talk about the development of a workflow that allows to study the muons momentum scale uncertainty at high p_T values.

Chapter 1

The Compact Muon Solenoid detector

The Compact Muon Solenoid experiment is one of the four great experiments at the p−p accelerator LHC. It is a so-called "general-purpose" experiment since its main goal is to explore physics at the TeV energy scale from the Standard Model measurements to the Higgs and new physics searches.
CMS has a compact design because of it is small for its enormous weight, about 14.000 tonnes for 15.00 meters of diameter and 28.7 meters of length (Fig 1). It

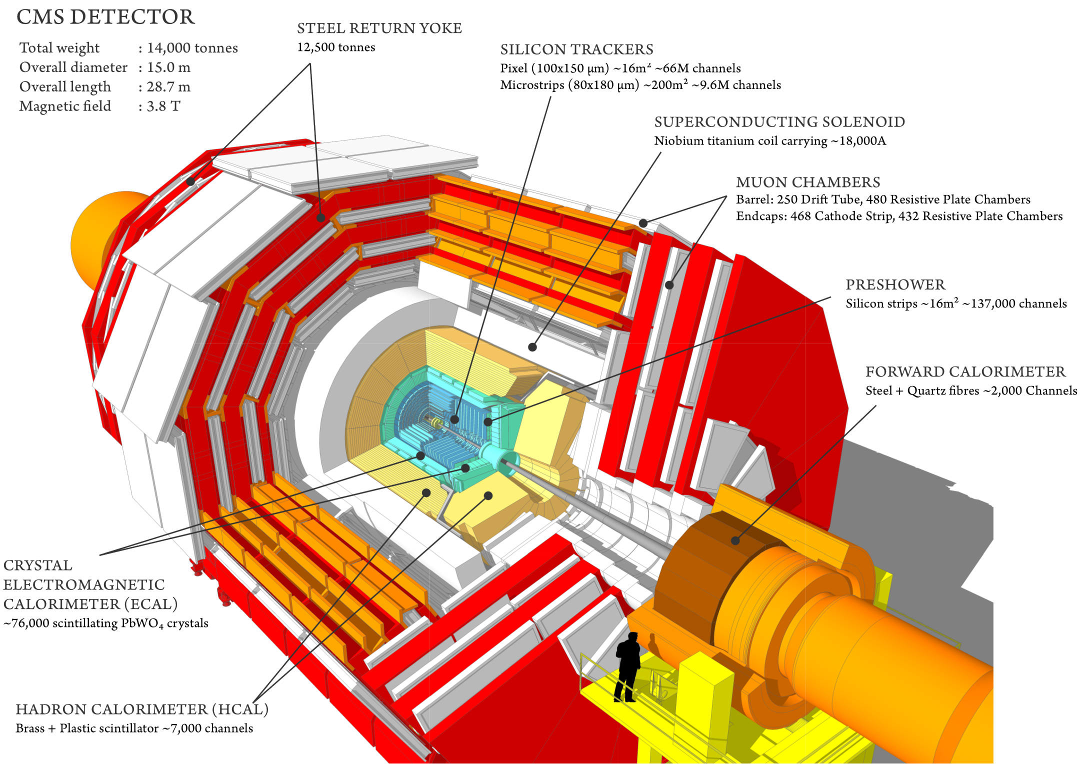


Figure 1.1: CMS 3D view.

takes its name from the huge superconducting solenoid which generates an internal magnetic field of 3.8 Tesla, about 10^5 times the magnetic field of the Earth.

1.1 The CMS Layout

The overall layout of CMS is shown in fig 1.1: The CMS detector has cylindrical

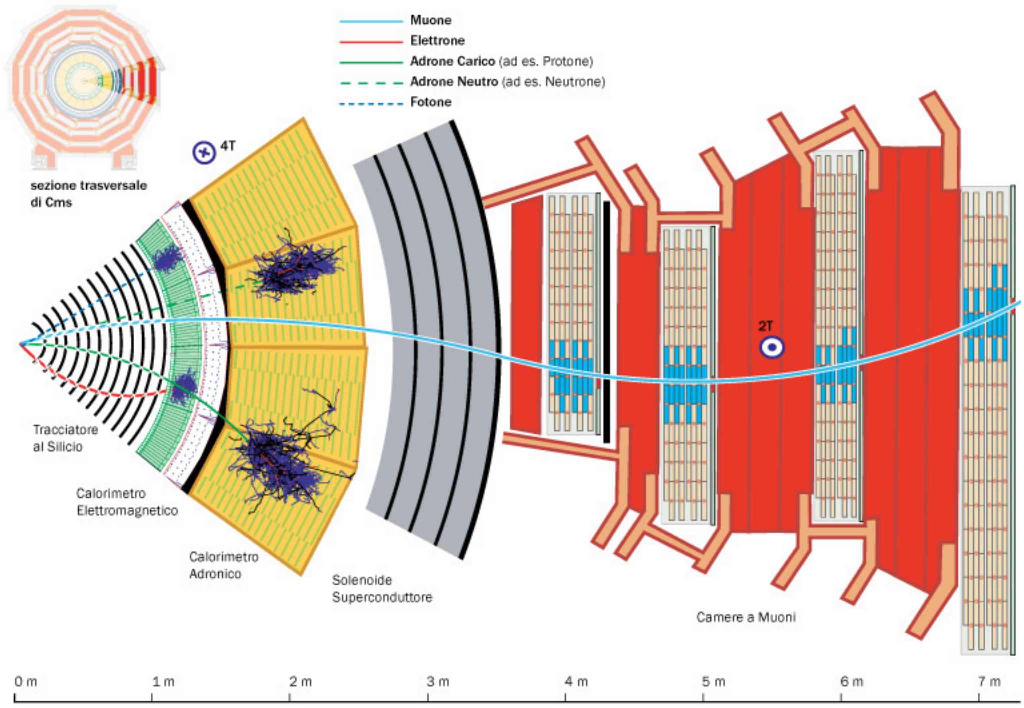


Figure 1.2: Transverse slice of CMS.

symmetry with respect to the beam axis. It is made up of by several layers of detectors centered on the interaction point. From the inner to the outer part of the detector we have:

- **The tracker system**: designed to provide a precise and efficient measurements of the trajectories of charged particles emerging from the LHC collisions. The CMS tracker consist of a silicon pixel detector and a silicon strip detector 1.1.
  - Pixel detector: silicon pixel detector is used for accurate measurement of the vertex, it provides a two-dimensional measurements of the hit position in the module planes.
  - Strip detector: silicon strip detector which is used for accurate track reconstruction, it is composed of four sub-detectors: the Tracker Inner and the Outer Barrels (TIB an TOB), the tracker Inner Disks (TID), and the Tracker Endcaps (TEC)
- **The Electromagnetic Calorimeter (ECAL)**: for accurate electron and photon energy measurement.
- **The Hadronic Calorimeter (HCAL)**: crucial for energy measurements of jets and missing energy, provides energy measurements for charged and neutral hadrons. Thanks to the tracker it manages to distinguish between charged and neutral.

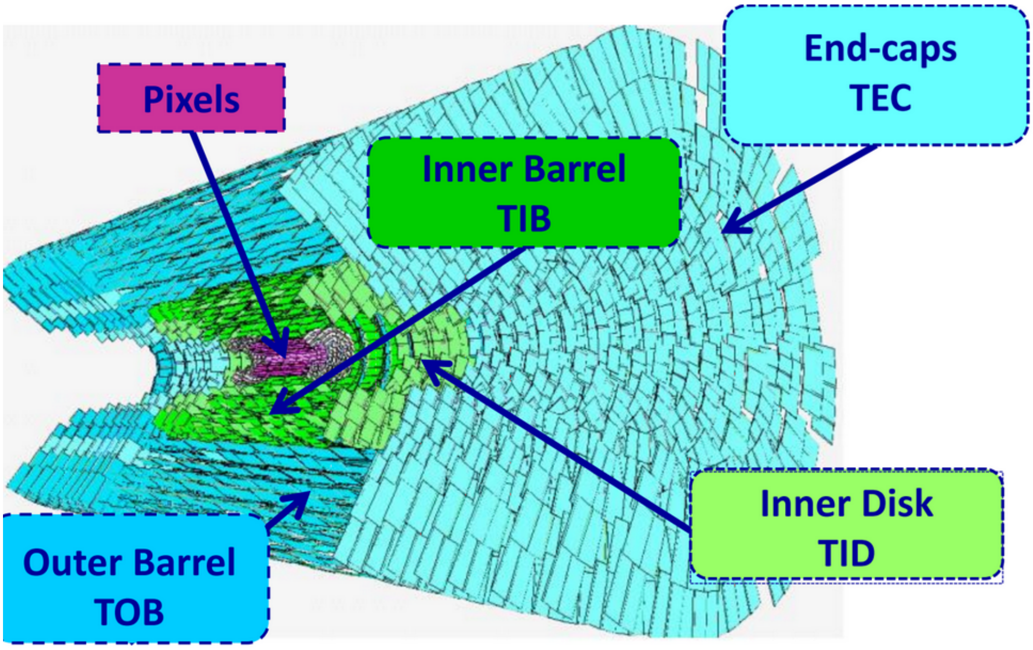


Figure 1.3: Tracker system.

- **The Superconducting Solenoid**: the coil generating an internal constant magnetic field of 3.8 Tesla in the direction of the beam axis.
- **The return yoke**: interspersed with the Muon system, sustain the structure and it is studied to allow magnetic field lines of the solenoid.
- **The Muon system**: designed to have the capability of reconstructing the momentum and charge of muons over the entire kinematic range of the LHC. CMS uses three types of particle detectors for muon identification:
  - Drift Tube detectors;
  - Resistive Plate Chambers;
  - Cathode Strip Chambers.

1.2 Coordinate system at CMS

The coordinate system adopted by CMS has the origin centered at the nominal collision point inside the experiment, the x-axis pointing to the center of the LHC, y-axis pointing upwards, perpendicular to the LHC plane, and the z-axis along the anticlockwise-beam direction. Using a polar coordinate system we could introduce η, the pseudorapidity, defined as:

$$\eta = -\ln\tan\frac{\theta}{2}$$

where θ is the polar angle.

Chapter 2

Silicon Sensor Testing

CMS is undergoing to a series of upgrades. The next step in 2017 is an upgrade of the pixel detectors since they suffer the radiation. USA is responsible of the endcaps forward pixels. The goal has been to keep FPIX documentation on the CMS docdb (private) server `https://cms-docdb.cern.ch`
so at the very beginning we used a prototype to become familiar in operating the Cascade probe station and handling silicon sensor wafer.

2.1 FNAL Instrumentation:

- Keithley 487 Picoammeter (guard ring, GPIB22);
- Keithley 486 Picoammeter (active area, GPIB21);
- Keithley 237 Voltage source (chuck, GPIB30);
- HP4284A LCR meter (GPIB17);
- Thorlabs TSP01 temperature and humidity data logger (USB);
- Cascade Summit 12000AP Probe Station;

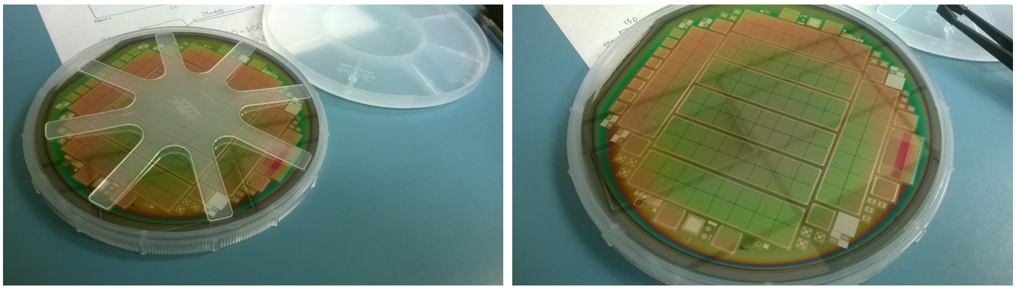
2.2 Sintef Phase I Wafer

In the figs 2.1 is shown the new prototype provided by Sintef with a larger than usual diameter of 150mm. A large diameter means that the detector can lodge till to 8 sensor (fig 2.2.1).

2.2.1 Wafer batches

Wafer batches are dicided in this way:

- A $1 - 99$ (prototypes)
- B $101 - 199$
- C $201 - 299$
- D $301 - 399$
- E $401 - 499$ If necessary



(a) (b)

Figure 2.1: Sintef Prototype.

Since Sintef provides IV measurements for sites 4-12 and CV measurements for site 4, and their measurements tend to agree with our own (plus the quality of the sensors appears to be high), the plan is to spot check a semi-random selection of 10 wafers per batch.

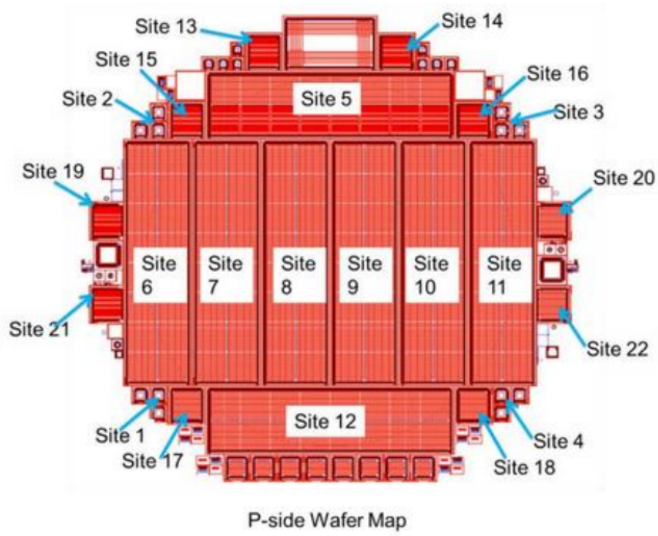


Figure 2.2: Wafer Map

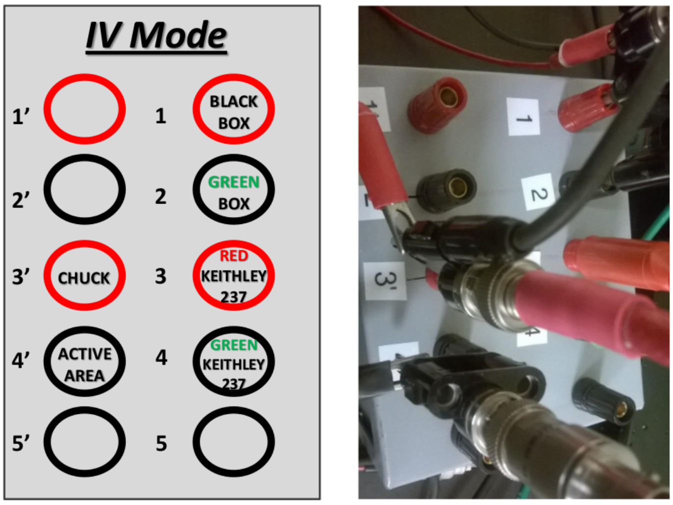
- Sites 1-4: diodes;
- Sites 5-12: 2X8sensors;
- Sites 13-18: 1X1 sensors;
- Sites 19-22: slim edge sensors

Site 1 is used to set the reference for the wafer map and also for the "needle landing" VI. Starting with the site 1-4 diodes allows the operator to make adjustments to the needle heights and positions before the first 2X8 sensor (site 5) is measured. The complete set of measurements including setup time takes about 1 hour per wafer. Each measurement results in an XML files and all of the XML files are uploaded to the P5 conditions database. The Sintef measurements are also converted from the provided Excel format to individual XML files and uploaded to the database.

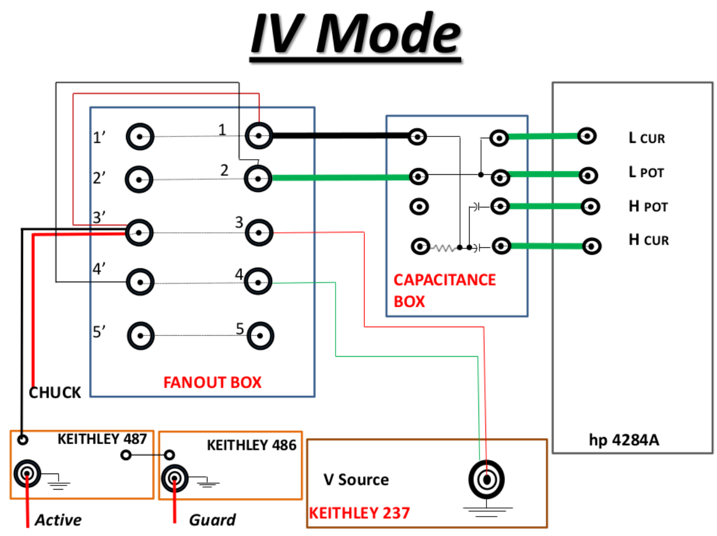
Thanks to the Needle Landing VI it is possible to land the Needles to the active and to the guard areas. When the Needle scratch the area we can close this VI and open the Automated VI. In the Automated VI we can set the name of the folder in which we want to save our data, the name of the prototype, the name of the operator , the type and the parameters for the measurement. Then we check to save and we run choosing the different type of measurements. The Manual VI allows us to see the behavior of the measurements plotting IV and CV data and to save data in a XML file for each measurement.

2.2.2 Schematic for IV measurements:

In the following scheme there is the correct configuration that allowed us to make IV Measurements:



(a)



(b)

Figure 2.3: IV Block Scheme.

IV Measurement Parameters

- Measurements sites: 1-4, 5-12;
- Maximum Voltage: 600 V;
- Step Size: 10V;
- Time Delay between measurements: 2s;
- Compliance current: 50μA
- Safe mode (measurements stop once the compliance current is reached).

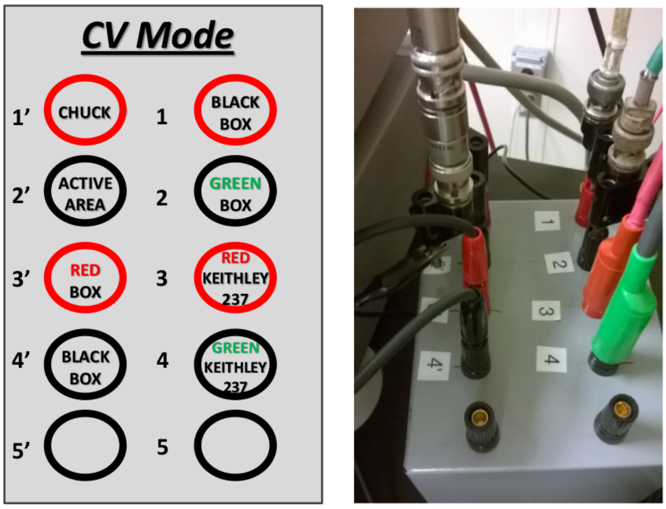
2.2.3 Schematic for the CV measurements

In the following scheme there is the correct configuration that allowed us to make CV Measurements:

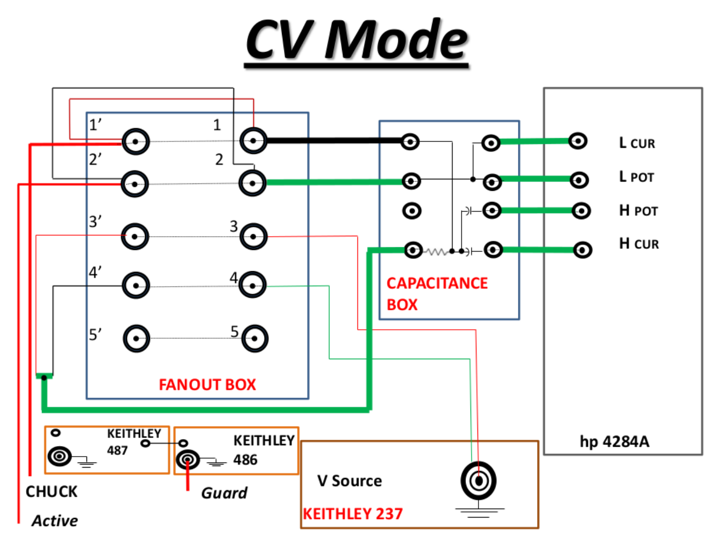
CV Measurement Parameters

- Measurements sites: 1,5;
- Maximum Voltage: 350V;
- Step Size: 10V;
- Time Delay between measurements: 5s;
- LCR frequency: 10KHz.

In the fig 2.2.3 we show the CV measurement in the site 9 of the Sintef_A18 prototype.
We tested the device measuring how capacitance change when voltage change.
Capacitance fall with increasing bias voltage because increases the lenght of the depletion zone and arrives, since for the limited shape of the device, at the minimum value that is the plateau value. We also made measurements at different frequencies, it appears that we are not in the quasistatic conditions so next step will be agree with other CMS groups about the frequency to utilize during next run.



(a)



(b)

Figure 2.4: CV Block Scheme.

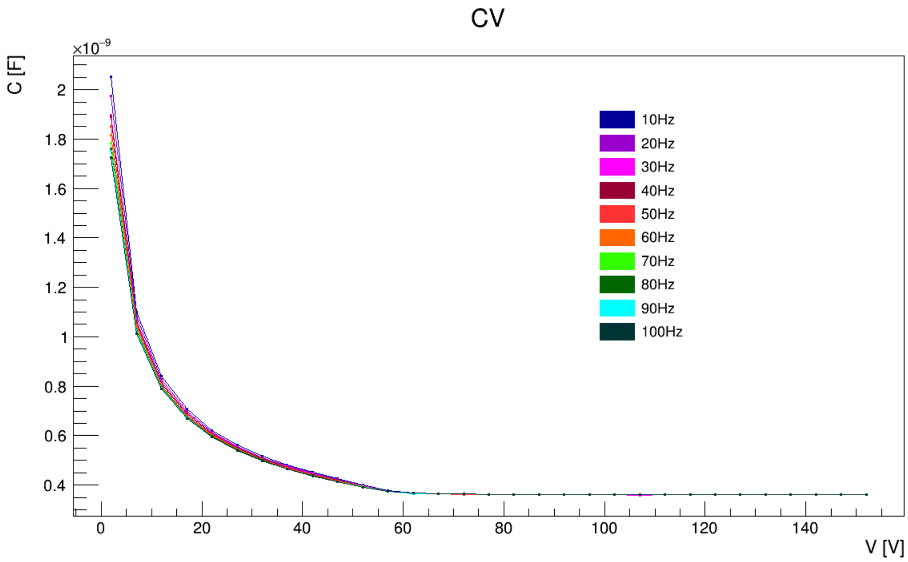


Figure 2.5: CV Measurement.

Chapter 3

Cosmic Muon p_T analysis at High energy

For searches beyond the Standard Model with the Compact Muon Solenoid (CMS) Detector, a detailed understanding of systematic uncertainty in the transverse momentum (p_T) scale of the detector is necessary. So to probe the detector performances when there is not beam we use cosmic ray muons. We could analyze muons by two different methods: the *1-leg reconstruction* or *Cosmic end point method* and the *2-leg reconstruction*. The first one consist in the study of the μ^+ and the μ^- distribution, the latter consist in the splitting in two part of a single track of a cosmic muon that pass through CMS, so with this method we are going to have an upper and a lower part. From last cosmic ray muon [1] studies,we know that within the barrel of CMS, there is a 5% uncertainty in the p_T scale of muons at 1000 GeV. While this uncertainty is negligible for low energy muons, at high energies, such as in the search for massive new particles (e.g., Z), the 5% uncertainty must be addressed.
We have to underline that within CMS, the p_T of muons is measured using the radius of curvature of the muons path. At high momentum, the muon scale becomes less certain. This uncertainty is believed to arise from a weak mode within the detector. At high p_T (grater than 200 GeV) the uncertainty on the $\frac{1}{p_T}$ bias is about 0.05 c TeV given by cosmic endpoint method (5% uncertainty on momentum scale at 1 TeV) valid only for barrel. At the moment our assumption is that:

$$p_T = p_T^* \left(1 \pm 0.05 \left(\frac{P_T^*}{1000}\right)\right)$$

So our aim was to study the p_T difference between upper and lower parts of cosmic muons at high p_T .

3.1 Use of the Alignment Validation Tool

We started to work with the CMS Alignment Validation Tool, All-In-One Meta Validation Tool, provided by the CMS Alignment Validation Group [2]. This tool allowed us an easy, fast and parallelized validation and comparison of any set of alignments. At the very beginning we studied the Run2015B cosmics using different conditions to fit the tracks: hp 1368 and PCL alignment. The former Aligns all the pixel modules the latter is an automatic process that aligns the most important degree of freedom (36 total degrees of freedom for 6 structures) as data comes in.

3.1.1 The workflow

With this tool we can at the first: Define the Alignment conditions, then define the values for validation parameters and at the end define which of the defined validation to run on which of the defined alignments.

3.1.2 The general procedure:

- Log into lxplus:
  `ssh user@lxplus6.cern.ch`
- Create a rekease area:
  `cmsrel CMSSW_7_4_6`
  `cd CMSSW_7_4_6/src`
  `cmsenv`
- Check out the package: `git cms-addpkg Alignment/OfflineValidation`
  `scram b -j 12`
- Copy the dataset into `Alignment/OfflineValidation/python` i.e.:
  `cp /afs/cern.ch/user/h/hroskes/public/tracksplitting/Dataset_CRAFT_cff.py .`
- Copy the configuration file, [1]
- Run the command:
  `validateAlignment.py -c test.ini -N <name of the folder where the output goes > -m`
  - This creates a root file on eos:
    `/store/caf/user/$USER/AlignmentValidation/<name specified with -N>`
- It is also possible to run:
  `validateAlignment.py -c test.ini -N <name of the folder where the output goes> -n`
  This command just creates the files, and then you can run them manually.
- Run all the validation jobs: `all the *.sh files besides TkAlMerge.sh`
  The last one creates 313 plots.

If you do not have access to eos because you are not a CERN Resident you have to change all the path in the .sh files.

3.2 p_T studies

At this point we changed the range in the plot about the p_T but we saw that there were no entries for high values of p_T so we tried to extend the analysis to include pre-2015 cosmic ray runs.

[1] The configuration file is the central point to define properties of the validation session.

3.2.1 Research dataset

We found previous cosmic Dataset in the `https://twiki.cern.ch/twiki/bin/view/CMS/TkAlignment` page. There we found different types of dataset and we chose among them following these criteria:

- AOD Format;
- RECO CRAFT;
- Last version;
- Exclude smaller dataset.

The results can be seen in the fig 3.2.1:

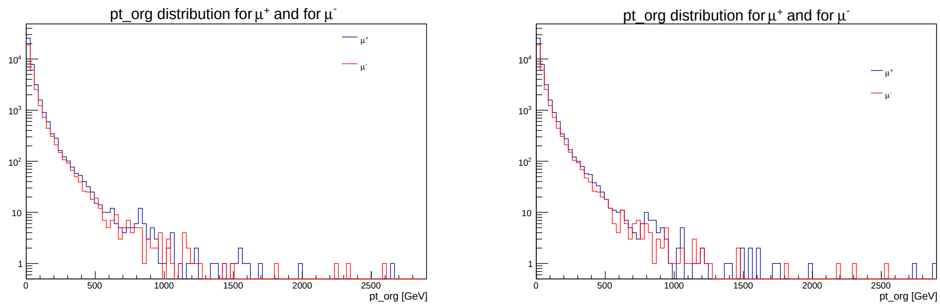
year	Web Site	Dataset	N. Of Events	globalTag	Runs
2009	https://twiki.cern.ch/twiki/bin/view/CMS/CRAFT09AnalysisInfo	/Cosmics/CRAFT09-v1/RAW	500 M	GR09_31X_V5P::All	108479-111146
2010	https://twiki.cern.ch/twiki/bin/view/CMS/GlobalRunTrackerAlignment2010#CRAFT10_February_2010	/Cosmics/Commissioning10-v3/RAW	300 M	GR10_P_V2COS::All	127476- 127764
2011	https://twiki.cern.ch/twiki/bin/view/CMS/TrackerAlignment2011#Summary_of_CRAFT11_Datasets	/Cosmics/Commissioning11-TkAlCosmics0T-v1/ALCARECO	1 M	TrackerAlignment_GR10_v5_offline	158028-158383
2012	https://twiki.cern.ch/twiki/bin/view/CMS/TrackerAlignment2012#COSMICS_DATASET_during_2012_coll	/Cosmics/Commissioning12-TkAlCosmics0T-v1/ALCARECO	2 M	GR_P_V30	186785-189146
2014	https://twiki.cern.ch/twiki/bin/view/CMS/TkAl2014Datasets	/Cosmics/Commissioning2014-TkAlCosmics0T-PromptReco-v4/ALCARECO	0.6 M	GR_P_V30	229514-229713
2015	https://twiki.cern.ch/twiki/bin/viewauth/CMS/TkAl2015Datasets#CRAFT15_3_8_T_cosmics	/Cosmics/Commissioning2015-TkAlCosmics0T-04Jun2015-v1/ALCARECO	10.9 M	FT_R_74_V15B	238443-239517

Figure 3.1: Dataset list from 2009 to 2015.

Unfortunately we verified that the tool cannot read previous data and what is major, that we cannot make a single total list since in the years, starting from 2008 to now, CMS had had different types of alignments with rotations, twists and global movements that changed for each year and so for each dataset. So for what we have said it becomes really difficult or even impossible create a single rule to calculate the best muon p_T . At this point we decided to analyze all the current dataset:
/Cosmics/Commissioning2015-TkAlCosmics0T-04Jun2015-v1/ALCARECO

Plot

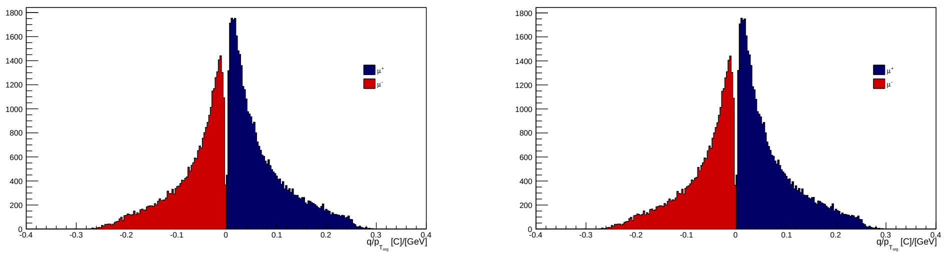
Here we report all the plot about the study on the muon p_T (Figs 3.2):



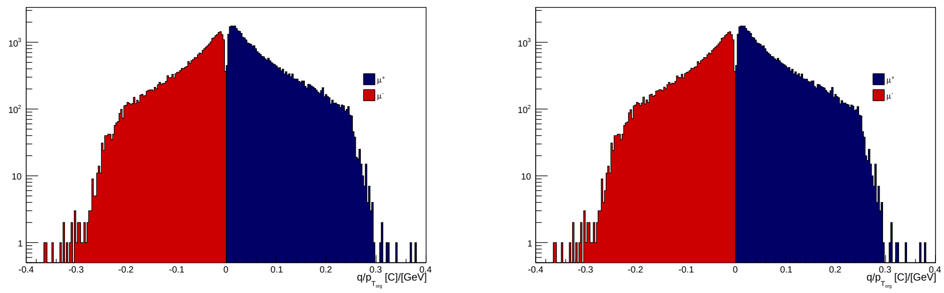
(a) *PCL* (b) *hp1368*

Figure 3.2: p_T distribution for both of the two types of alignments.

As we can see we had passed from 10M data to 72thousand of events for both the two alignment data. At the first we verified the cosmic end point method working on the q over p_T _org variables (Figs 3.3):



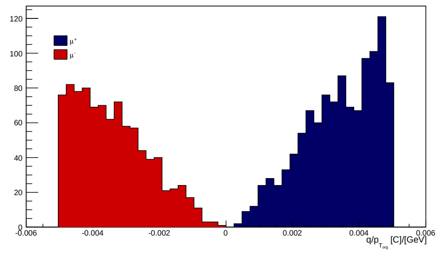
(a) *PCL* (b) *hp1368.*



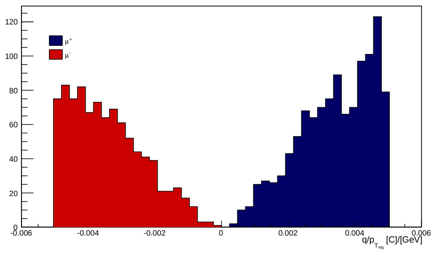
(c) *logy PCL* (d) *loy hp1368*

Figure 3.3: q/p_T distribution

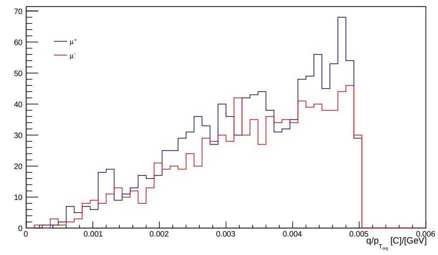
Looking at the muons distribution we expected a grater μ^+ distribution than μ^-, indeed we can see that we have the 32% more μ^+ than μ^-. At this point we asked for p_T grater than 200 GeV and we obtained the plots in Figs 3.4, where we could see that for both of the alignment there were 22% μ^+ more than μ^-. Again, the main problem is that we had few entries at high p_T : We also tried to see if there were some differences among the two distribution flipping and normalizing them but we didn't found many differences. So we tried to use the 2-leg reconstruction method working with the variables



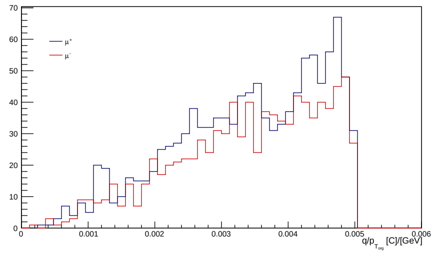
(a) *PCL*



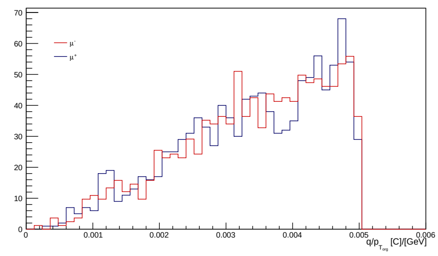
(b) *hp1368*



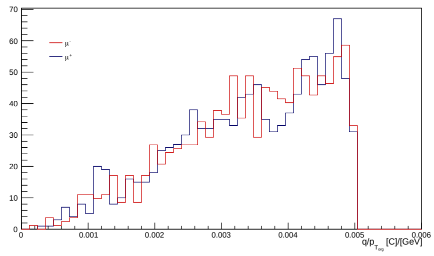
(c) *flipped PCL*



(d) *flipped hp1368.*



(e) *normalized PCL*

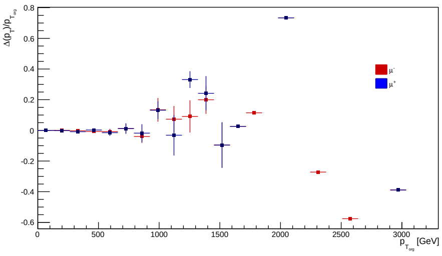


(f) *normalized hp 1368*

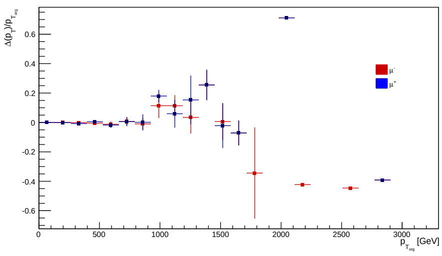
Figure 3.4: q/p$_T$ studies on p$_T$>200.

$$\frac{\Delta(p_T)}{p_T} = \frac{p_{T_{upper}} - p_{T_{lower}}}{p_T}$$

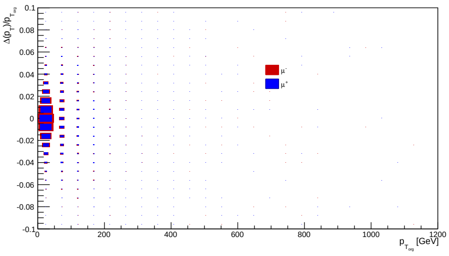
But since we had few entries we could not say much except that the distribution for each type of alignment seems centered around zero (see also fig **??**).



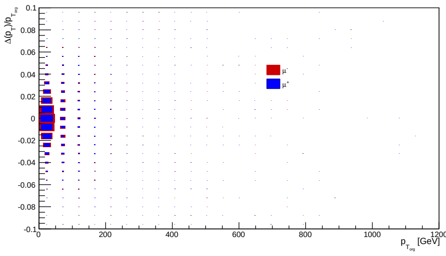
(a) *PCL*



(b) *hp1368*



(c) *Box PCL*



(d) *Box hp1368*

Figure 3.5: $\Delta(p_T)$ over p$_T$ distribution box plot

Conclusions

We worked both on the hardware and software part at the CMS experiment.
For the former part we keep documentation to analyze silicon sensor using the Cascade Probe Summit Station, for the latter we were interested in the muon p_T studies. We developed a workflow to analyze most recent CRAFT data starting from the use of a Tool provided by the Alignment Group. What we found at this time is that our is just a preliminary analysis since there where a lot of problems coming from the use of the Alignment Validation Tool: first of all the muon p_T used in that Tool is calculated with a fit just on the tracker. This is a problem because we know that if we work at high p_T value the best fit on the muon p_T is given by considering the muon's system information. Particularly when the p_T is grater than 400 GeV a "global" fit is three times better than a fit on the tracker only. Then we have to say that the low statistic not allow us to make a deep analysis, for that next planning step is a meeting with the CMS Muon POG convener to better understand what is possible to do in order to increase the number of "good data".

Bibliography

[1] https://twiki.cern.ch/twiki/bin/viewauth/CMS/MuonReferenceResolution

[2] https://twiki.cern.ch/twiki/bin/viewauth/CMS/TkAlAllInOneValidation