Luminosity measurement and Hit Efficiencies in ATLAS

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Abstract

The luminosity is a key component of an accelerator. The precision of the luminosity measurements is crucial for a lot of aspects of the ATLAS physics program. Measurement of the luminosity with the track-counting method requires high and stable track efficiencies which relies on stable and high hit efficiencies. The goal of this study is to determine if the hit efficiencies in the ATLAS silicon detectors are high and stable in 2015-2016.

Contents

1. Introduction

An accurate measurement of the luminosity is a key component of the ATLAS physics program. The importance of this, lies to the fact that luminosity's uncertainty affects many precision measurements and limits some others as an additional component of the systematic error. It's really crucial for a lot of processes like the cross section measurements, the evaluation of background levels and the determination of the sensitivity to the signatures of new phenomena.

The luminosity can be measured from the beam parameters, as follow:

$$L = \frac{n_1 n_2 n_b f_r}{2\pi \Sigma_x \Sigma_y} \quad (1)$$

where $n_1 n_2$ is the bunch-population product, n_b is the number of colliding bunch pairs, f_r is the LHC revolution frequency and Σ_x and Σ_y are the horizontal and vertical beam size, which are measured directly during a pair of orthogonal van der Meer (beam-separation) scans.

Regarding the importance of the luminosity it's obvious that we need a more precise value than the one we can obtain directly from the machine parameters, Σ_x and Σ_y. To measure the luminosity we can use a lot of methods/algorithms.

One of them is the track-counting method. It's obvious that high and stable track efficiencies are nedded, which relie on high and stable hit efficiencies.

During this project we tried to figure out if the correction factor applied to the track-counting luminosity in 2016, comes from hit inefficiencies. We studied the time and layer dependece of hit efficiencies for the ATLAS detector, using data from 2015,2016 and 2017. The runs we chose are low pile-up runs, to eliminate the fake trucks, since they contribute at high pile-up and cannot be used to measure hit efficiencies reliably.

2. Theory

2.1. Luminosity - calculation methodology

Luminosity gives us a measure of how many collisions we have in an accelerator per second. The luminosity L for any process can be expressd as

$$L = \frac{R}{\sigma} \quad (2)$$

where R is the event rate and σ is the cross section for every process. Now if we expand this formula for the inelastic interactions, the luminosity is given by:

$$L = \frac{R}{\sigma} = \frac{\mu n_b f_r}{\sigma_{inel}} = \frac{\epsilon \mu n_b f_r}{\epsilon \sigma_{inel}} = \frac{\mu_{vis} n_b f_r}{\sigma_{vis}} \quad (3)$$

where μ is the number of inelastic pp collisions per bunch crossing, n_b is the number of colliding bunch pairs, f_r is the LHC revolution frequency and ϵ is the efficiency of the luminosity detector including the acceptence. In the final form, μ_{vis} is the number of visible (detected) collisions per bunch crossing and σ_{vis} is the visible cross section.

Scince μ_{vis} is a directly measurable quantity, all the components of the nominator in Eq.(3) are known. If we know the σ_{vis} we are able to calculate the luminosity L, for each time interval.

2.2. Track-counting luminosity algorithms

There are a lot of methods/algorihms to determine the σ_{vis} and one of them is the track-counting method. σ_{vis} can be determined from Eq.(3) as we know the luminosity L and the μ_{vis}.

The primary calibration technique to determine the σ_{vis} is the Van der Meer scans.

The beam conditions during vdM scans are different from those in normal physics operation, with lower bunch intensities and only few tens of widely spaced bunches circulating. These conditions are optimized to reduce various systematic uncertainties in the calibration procedure. During a vdM run the beams are sweeped transversely across each other so the beam profile can be measured.

These runs and the calibration of σ_{vis}, take place at given time, but the obtained value is applicable for the entire year.

Figure 1 shows the correction factor applied to the track-counting Luminosity, during 2016.

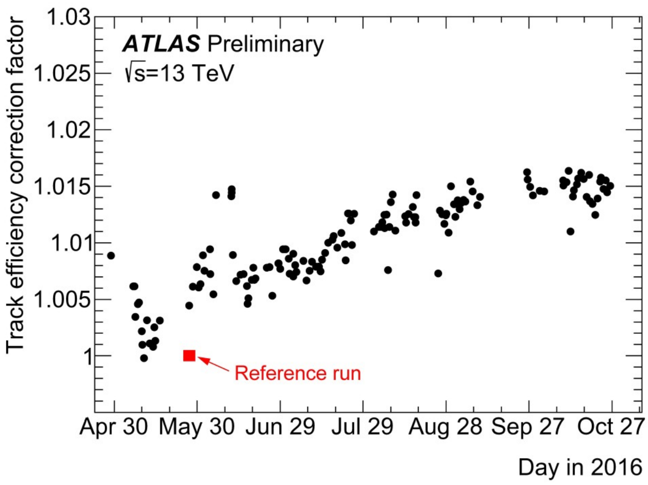

Figure 1: Correction Factor Applied to the Track-Counting Luminosity,2016

This correction factor applied to the track-counting luminosity due to time-dependent effects on the track reconstruction and selection efficiency over 2016. We studied if the reason for decrease in track efficiency is a decrease in hit efficiency.

2.3. Hit efficiency

Hit efficiency is the number of hits per expected hit, where inactive modules and chips are taken into account. It can be expressed as:

$$hit_{eff} = \frac{measured\ hits}{expected\ hits} = \frac{measured\ hits}{measured\ hits+outliers+holes} \qquad (4)$$

Figure 2 shows the independent layers of a detector where the measured hits, the holes and the outliers are illustrated.

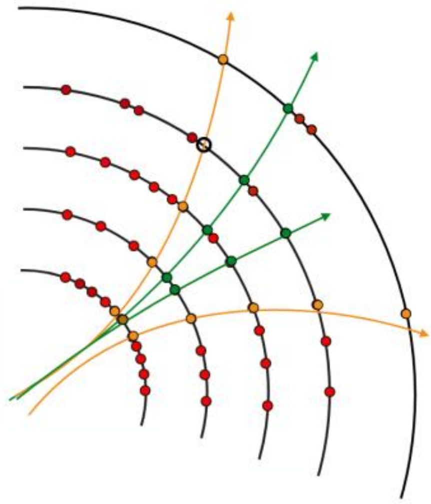

Figure 2: Hits and tracks in a detector: The spots are the hits and the arrows are the tracks. The spots on the trakcs are the measured hits. In the upper yellow track there is a hole (open circle). In the lower yellow track the outliers are illustrated.

A hole is counted when a hit is expeted in an active sensor located in the track trajectory between the first and the last hit assosiated with this track, but no such hit found. If the corresponding sensor is known to be inactive and therefore not expected to provide a hit, no hole is counted. An outlier is a hit which is linked to the track but it's too far away to be considered as a hit.

2.4. ATLAS Inner Detector

The Inner Detector (ID) is contained within a cylindrical envelope , within a solenoidal magnetic field of 2T. It consists of three independent but complementary sub-detectors, the Pixel layers, the silicon microstrip (SCT) layers and the transition radiation straw tube layers (TRT). To be noticed that in this report there is no study for the TRT layers. Figure 3 shows the ID layout.

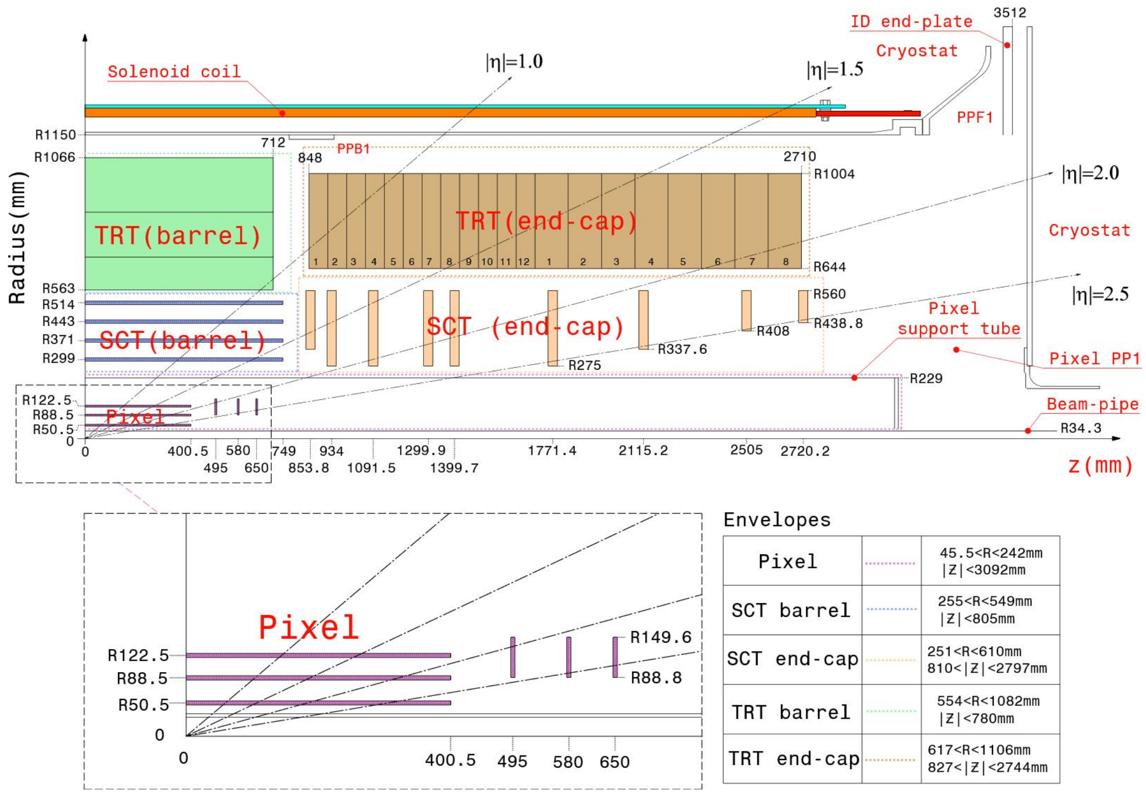

Figure 3: Plan view of a quarter-section of the ATLAS inner detector, showing each of the major detector elements with its active dimensions and envelops.

The pixel sensors are arranged in three barrel layers and two end-caps each with three disk layers. The SCTs sensors are arranged in four coaxial cylindrical layers in the barrel region and two end-caps each containing nine disk layers.

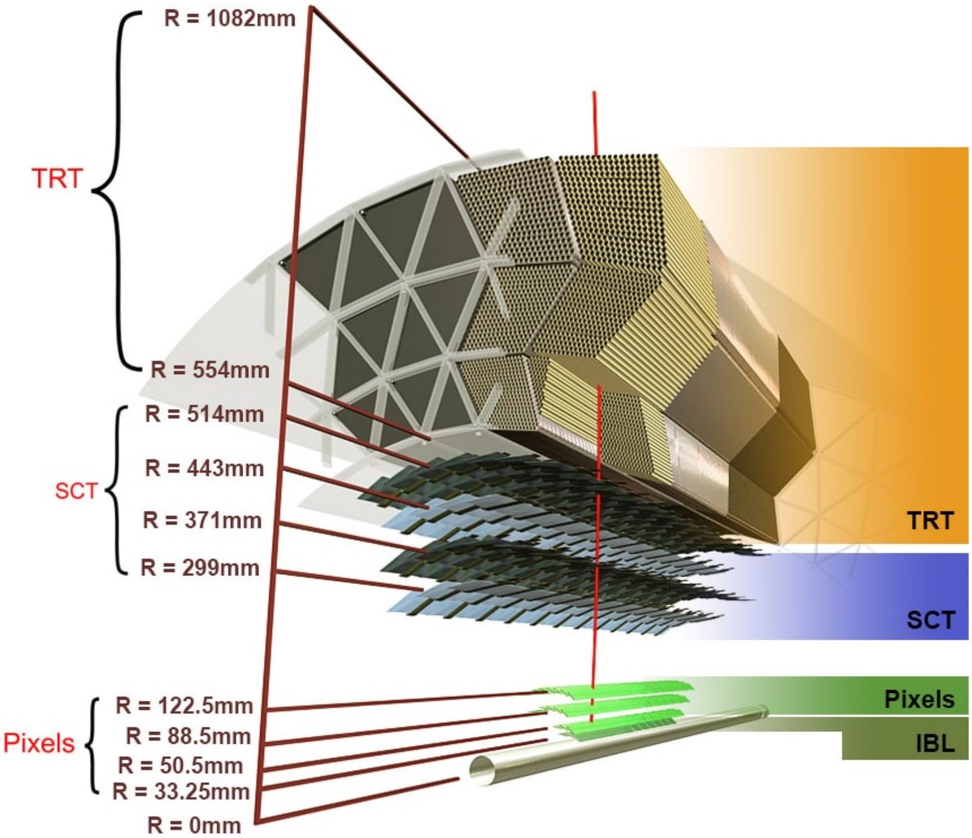

Figure 4: Schematic view of (a) the ATLAS detector, with (b) a detailed layout of the Inner Detector (ID), including the new Insertable B-Layer (IBL).

Figure 4 shows the sensors and the structural elements from another point of view, including pixel layer IBL (Inner Barrel Layer), which was added in 2015.

2.4.1. Pixel and SCT Modules

The Pixel and SCT consist from modules and each module consists form chips . There are 1744 modules in the pixel detector and 4088 modules in the SCT. During the operation some of the modules or the chips may break. For instance in 2017, the percentence of the non -working modules is 2.2% for the Pixel and 1.3% for SCT. Figure 6 illustrates a map of modules status, where the red spots are the inactive modules.

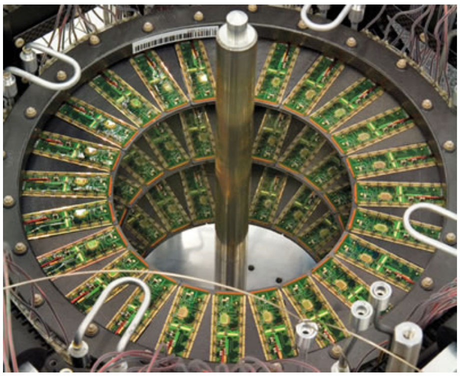

Figure 5: End-cap Pixel modules

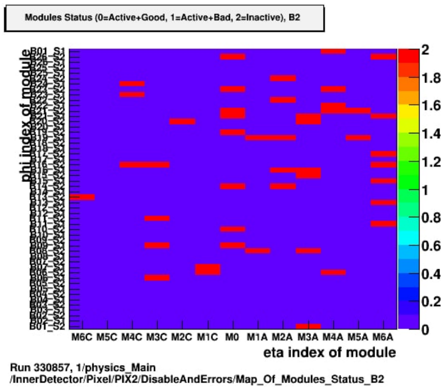

Figure 6: Map of Module Status

2.5. Possible Reasons for Hit Inefficiecy

Summurising there are four possible reasons for hit inneficiency.

1. Component (module or chip) is known to be not working, therefore a hit is not expected and it is not contained in the denominator.

2. Component working but inefficient e.g. due to radiation damage

3. Tracking lost the hit (outlier)

4. Component (module or chip) is not working but software does not know.

Reasons 2-4 are measured in this study.

3. Datasets and technical details

The data we used are pp collisions at 13 TeV. All of the runs are low-pileup runs, in order to reduce the sensitivity to fake tracks. They are form 2015,2016 and 2017 and Table 1 contains detail information about them.

Table 1: Details for the used runs

year	run number	date	lumi (1/nb)	soft. rel.	$<\mu_{peak}>$
2015	267358	Jun 10	78.244	20.7.8.6	0.00286
2015	277081	Aug 25	1.054	20.7.8.6	0.694
2015	282457	Oct 18	13.5	20.7.8.6	0.221
2016	299315	May 17	20.7	20.7.6.2	0.457
2016	299390	May 18	42.7	20.7.6.2	0.582
2016	308979	Sep 20	$29.511 *10^{-3}$	20.7.8.1	0.0387
2016	308982	Sep 20	$8.025*10^{-3}$	20.7.8.1	0.00274
2016	309010	Sep 20	$50.819*10^{-3}$	20.7.8.1	0.00492
2016	309039	Sep 22	$136.3*10^{-3}$	20.7.8.1	0.00864
2016	309074	Sep 22	$46.4*10^{-3}$	20.7.8.1	0.00283
2017	330857	Jul 27	54.1	21.0.31	1.1
2017	330874	Jul 28	0.731	21.0.31	1.1

Two things must be clarified about these runs.

- During the project we found out that the runs of September 2016 (red color), which are these that we are interested in, were reconstructed with defferent software than the others. Specifically they are ALFA-runs and they have different setting than the normal runs and consequently we couldn't use them to compare the hit efficiencies with the other runs. Regarding the lack of data due to the low pile-up as well as the limited time we had during this summer student program, we were unable to find others,not special runs from this period.

  So despite the motivation of this project we were forced to focus more on the time and layer dependence of hit efficiency.

- From software release 21.0.30 onwards, the software was improved to account for dead chips, so that if a chip (a module consists of 16 chips) is dead this does not count as hole. The only runs which have newer software realease than 21.0.30 are the runs from 2017 (blue color). That means that we can expect higher hit efficiency for these runs.

4. Results

4.1. Layer Dependence

The layer dependence of the hit efficiency of the run:299315 of 2016, is calculated. Figure 7 illustrates this dependence first for the barrel and then for the two end caps.

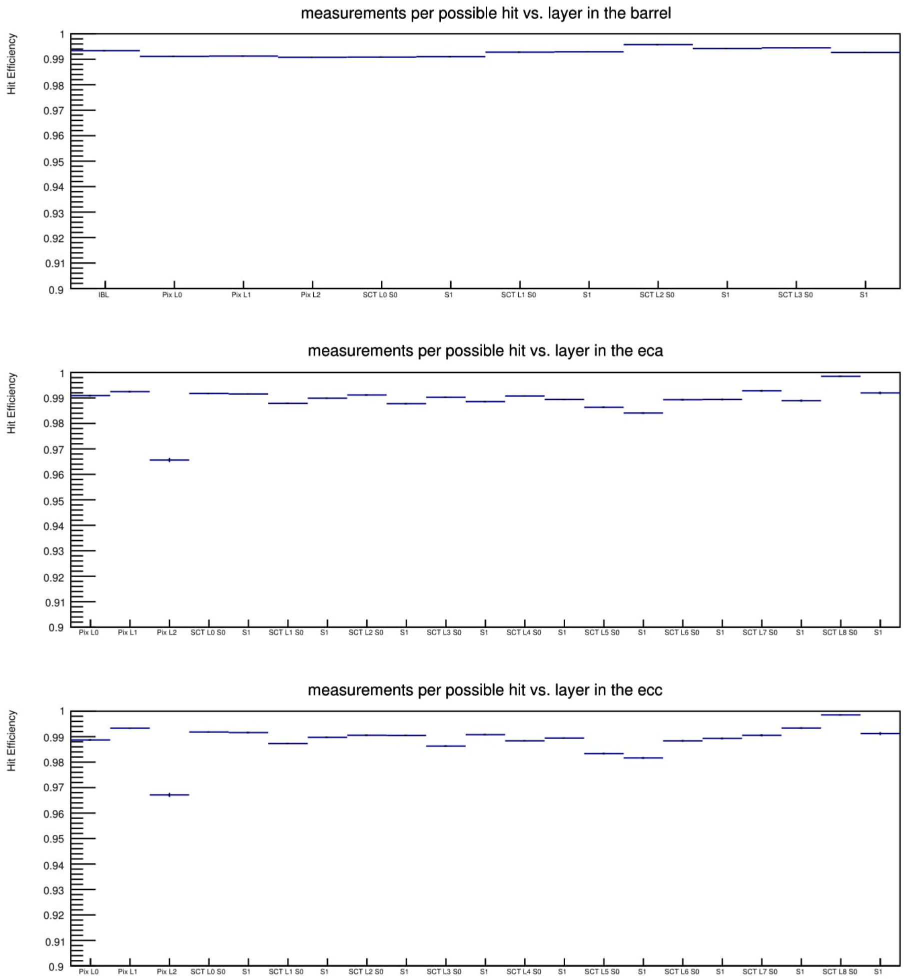

Figure 7: Layer dependence of Hit Efficiency. Hit efficiency's values are in the y-axis. The different layers are in the x-axis, starting from the inner layer (IBL for barrel and Pixel L0 for the end caps) and continute to the outer layers.

First of all, it is evident that the hit efficiency mostly is around 99% for nearly all layers of barrel and end-caps. However, the efficiency is only 96.5 % in the Pixel L2 in the end-caps, 2.5% lower than the others. We check if it is happening only in this run, or the same behavior repeats during the years, by creating the time dependence histograms for the runs we have from 2015,2016 and 2017.

In addition we observe that the plots for end-cap A and end-cap C are almost identical, with a difference less than 0.5% so in the rest of the talk only results for the end-cap A will be presented. The result for end-cap C can be found in the Appendix.

4.2. Time Dependence

4.2.1. Barrel

The time dependence, through the years 2015,2016 and 2017 , of the hit efficiency is calculated. Figures 8 and 9 show how the hit efficiency changes versus the run number. The first three runs are from 2015, the next two from 2016 and the last two from 2017. For pixel, as well as for SCT, each one of the layers in the barrel is shown.

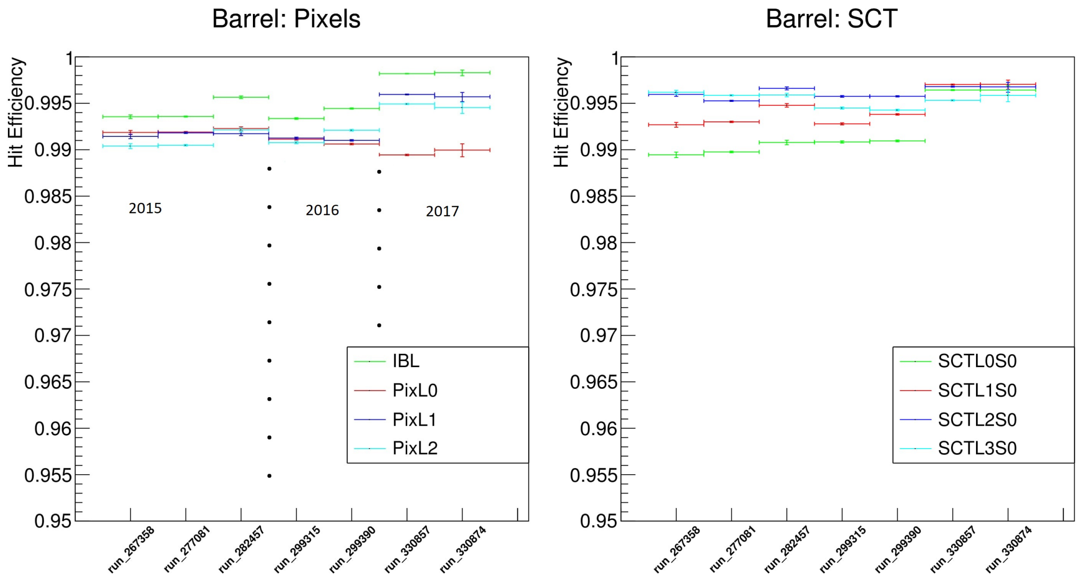

Figure 8: Barrel Hit efficiency versus run number

First of all, it is evident that the hit efficiency is stable around 99% throught these three years. However, we notice a different behavior in some of the layers.

The Pixel IBL has the highest efficiency of all layers. This is logical considering that IBL is a new insertable layer and the radiation damage is less comparing to the others. Additionaly this layer it's constracted with higher resistance to the radiation damage.

The Pixel Layer 0, is the only layer where the hit efficiency is slightly decreasing with time (0.2%). This also may be explained form it's position in the detector, as it is the inner layer and the radiation damage is obviously higher.

For Pixel in the other three layers ,a "jump" of +0.5% is observed for the runs 330857 and 330874 of 2017, compared to 2015 and 2016. This is expected, due to the update of the software after the realeas 21.0.30 which is explained in section 3. After the update the software knows about the dead chips, so they don't count as a hole.

4.2.2. End-Cap A

The time dependence, through the years 2015,2016 and 2017 , of the hit efficiency is calculated. Figures 9 shows how the hit efficiency of the SCT changes versus the run number. The left plot is for the first four disks of the end-cap. The right plot is for the five outer disks. Figure 11 shows how the hit efficiency of the Pixel changes versus the run number. In all the plots the first three runs are from 2015, the next two from 2016 and the last two from 2017. For SCT, first of all, the hit efficiency is mostly around 99%.

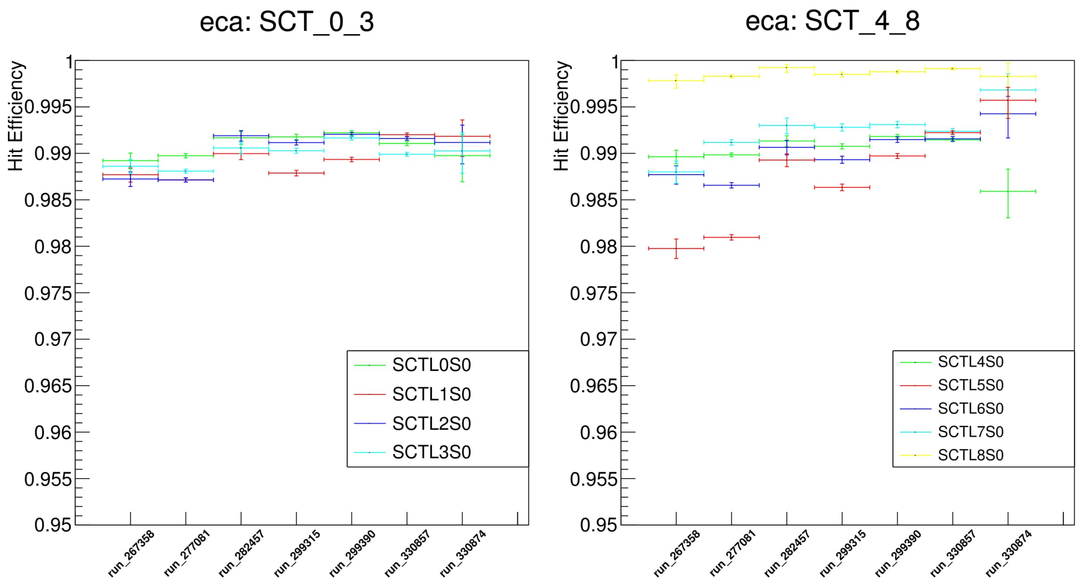

Figure 9: End-cap A, SCT, Hit efficiency versus run number

Apart form this, we notice that in early 2015 , runs 267358 and 277081, the efficiency is lower (1%) but since late 2015 its good. We try to explain whether the cause is the number of dead modules. This behavior is more intense in the disk 5 of SCT so we check the phi dependence of the inactive modules in this disk. Specifically we compare the phi plot for the runs 277081 and 282457. 282457 is the last run of 2015 where the efficiency is higher, in Fig.10.

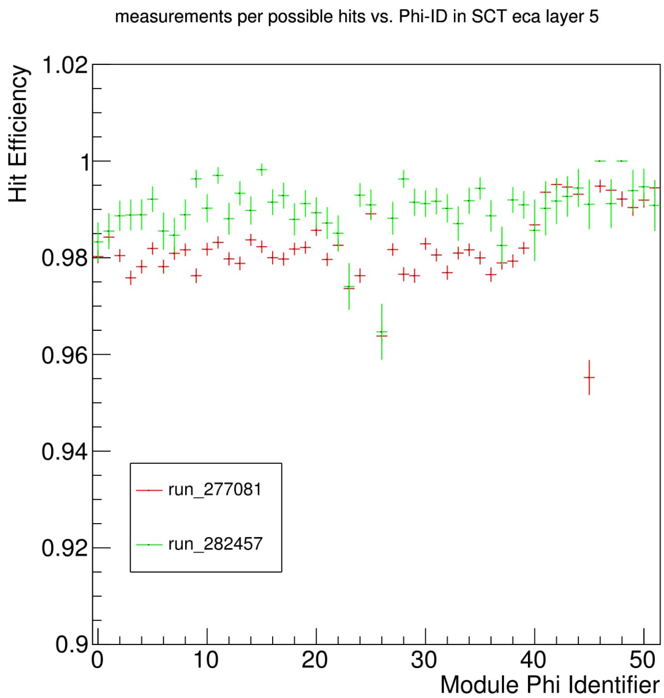

Figure 10: End-Cap A, SCT, disk 5 : Phi dpenedence of Hit efficiency

Accoring to Figure 10, only for Phi region 40-50 there is no remarkable difference between these two runs . For Phi 0-40 we notice a difference but we don't know the reason. Consequently, we are unable to explain this behavior.

Figure 11, in the next page, shows the time dependence for the Pixel detector layers.

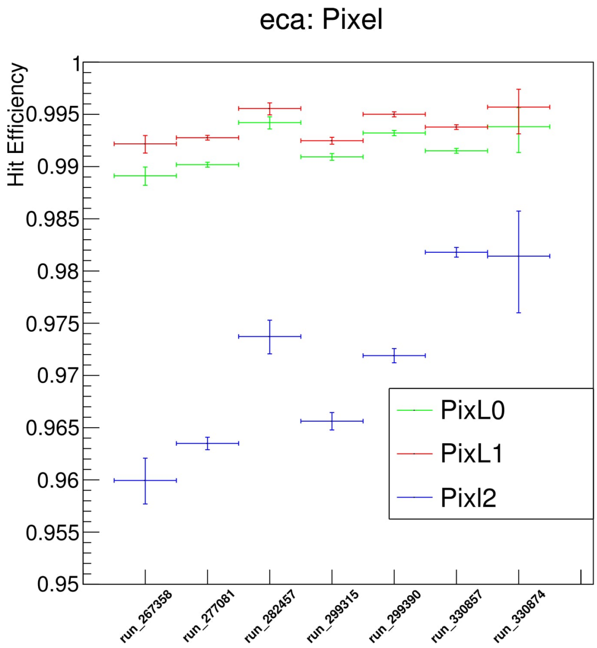

Figure 11: End-cap A, Pixel, Hit efficiency versus run number

From Figure 11 we can confirm that the inefficiency (2.5%) we notice in Pixel Layer 2 at the end caps in Fig.7, is repeated in all the runs. We must underline that in 2017 the efficiency, even in this layer, is better (inefficiency 1-1.5%). Once more we try to explain this, by checking the number of dead modules.

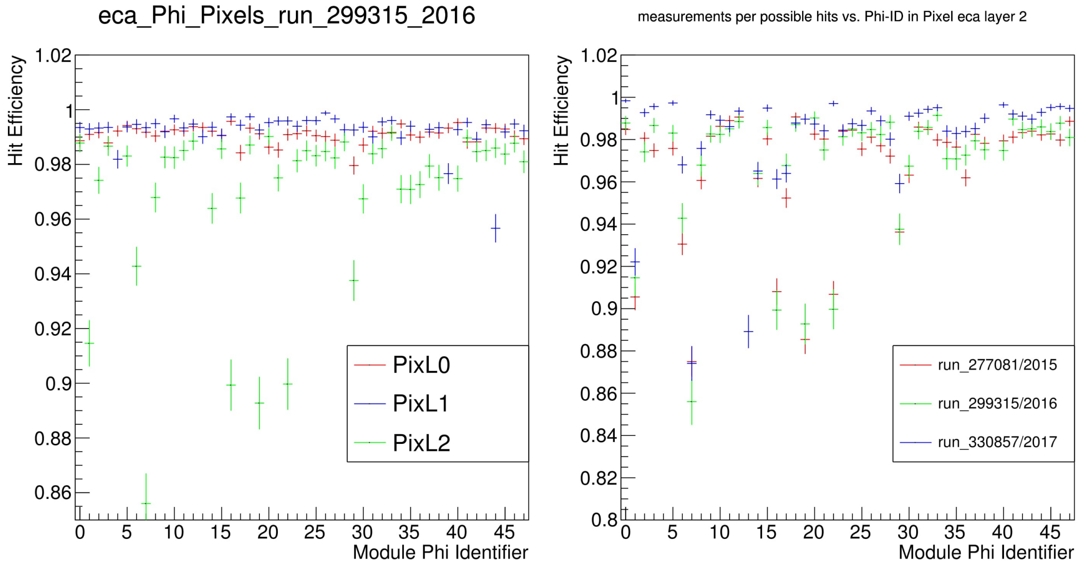

Figure 12: End-Cap A, Pixel: Phi dpendence of Hit efficiency. In the left is ilustrated only the run: 299315 of 2016. In the right are illustrated one run from each year.

The left plot in Fig.12, illustrates the phi dependece ony for the run 299315 of 2016. It's easily noticed that in Pixel Layer 2 we have high inefficiencies concentrated in particular Phi regions.

According to the right plot in Fig.12, this is observed in every run. However, in the run of 2017 (blue), the hit efficincey is more stable and higher comparing to the other years, due to the software update. For instance, for Phi 19 and 22 the efficiency for 2017 is 99 % ,while for 2015 and 2016 is only 90%.

Summurising we can strongly assume that the inefficincies in Pixel Layer 2 of the end-caps, lie on the number of the inactive modules and chips, but to be completely sure we need more research.

5. Summary

The stability of tracking efficiency versus time is important for luminosity measurement. Stable trackig efficiency relies on stable hit efficiencies. In this report we studied the hit efficiency in Pixel and SCT during the years 2015-2017. We tried to find out wheather it is stable and high.

We have observed that the efficiency is mostly 99% . Additionally the highest efficiencies appear in 2017 for most cases, probably due to the update of the software realease used for the reconstruction. Furthermore, inefficiencies noticed in the End-caps at Pixel Layer 2 (2.5%) and at SCT disk 5 (1%). The cause were for the first one probably the number of dead modules. For the second one we couldn't find out the reason.

5.1. Future research

Unfortunately we were unable to compare the hit efficiencies under the exact same software conditions for the various years. In order to do this we need to reconstruct all the data, including the ALFA runs from end of 2016, with the same software settings, and then redo this measurement. In particular, for checking the hypothesis that the 2017 hit efficiencies in pixel L2 are better due to taking into account dead chips, all data need to be processed with software 21.0.30 or later.

Alternatively we can try to make this measurement in all physics runs using muons in Z $\rightarrow$mumu events since they can be used to measure the hit efficiency reliably also in high-pileup runs.

A. Appendix: End- cap C Hit Efficiencies Plots

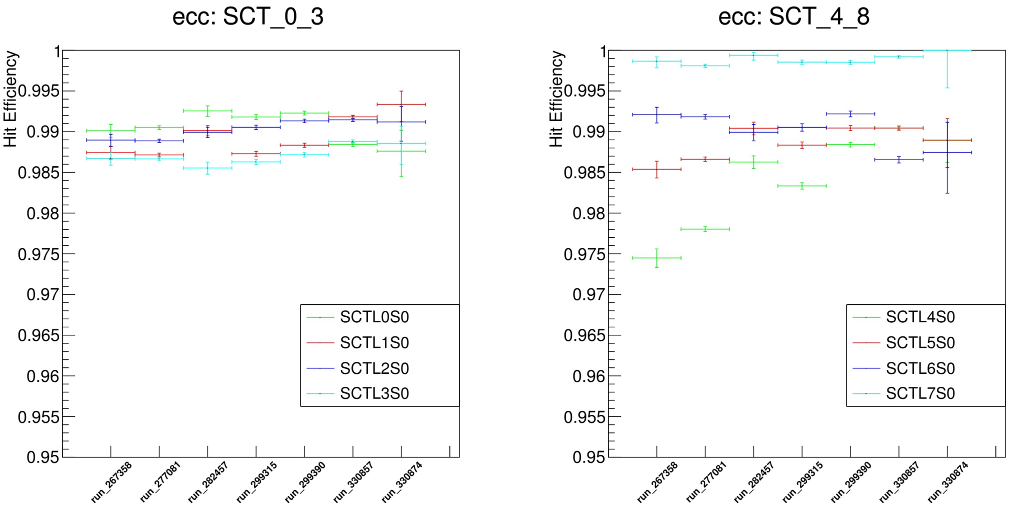

Figure 13: End-cap C, SCT, Hit efficiency versus run number

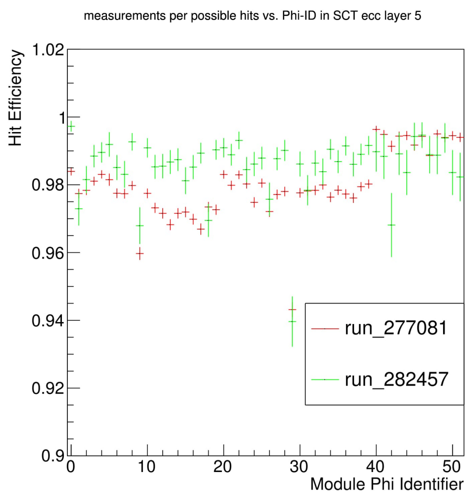

Figure 14: End-Cap C, SCT, disk 5 : Phi dpenedence of Hit efficiency

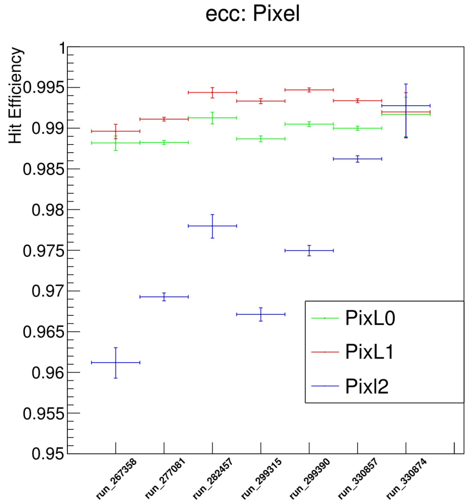

Figure 15: End-cap C, Pixel, Hit efficiency versus run number

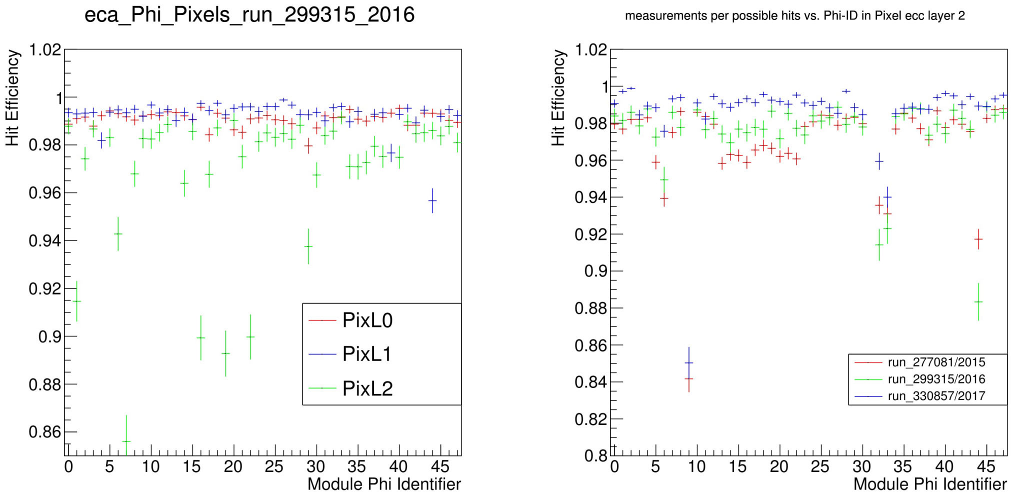

Figure 16: End-Cap C, Pixel: Phi dpendence of Hit efficiency. In the left is ilustrated only the run: 299315 of 2016. In the right are illustrated one run from each year.

References

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