Experience with the CMS tracker operations

CEPC workshop
IHEP Beijing

Patrick L.S. Connor
on behalf of the CMS Collaboration

Deutsches Elektronen-Synchrotron
Hamburg

13 November 2018

Introduction.

Calendar
CMS in a nutshell
The CMS tracker
Silicon modules

Introduction

Outline

1. Basics of CMS tracker
2. Operations & calibrations
3. Upgrade

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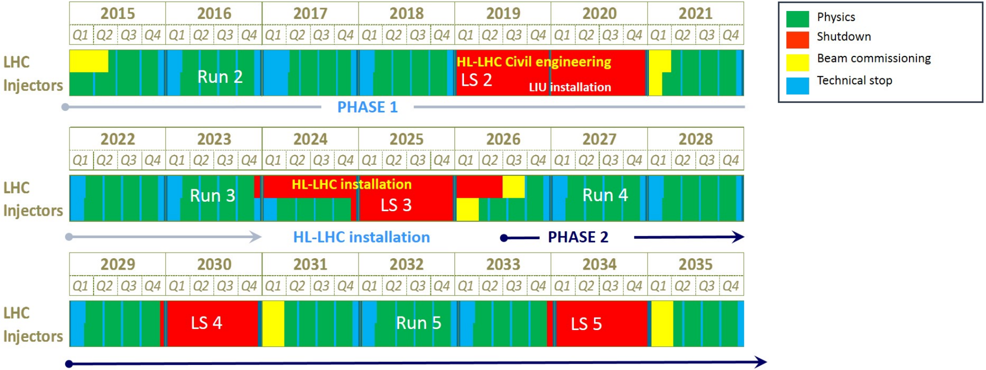
1. Basics of CMS tracker
2. Operations & calibrations
3. Upgrade

Goal

- Illustrate ageing of the detector
- Highlight some lessons
- Show (if) effects on performance

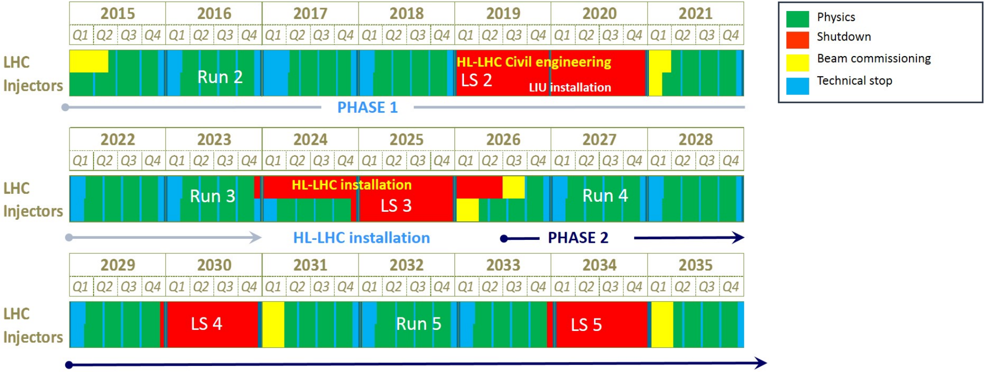
$\longrightarrow$ so that CEPC can benefit from this experience

Calendar



(Figure from [1])

Calendar



(Figure from [1])

Today

- Already one upgrade of the pixel tracker (phase-0 $\rightarrow$ phase-1)
- End of Run 2 (pp collisions are over, currently HI collisions)
- Full upgrade of the tracker for Run 2

CMS in a nutshell

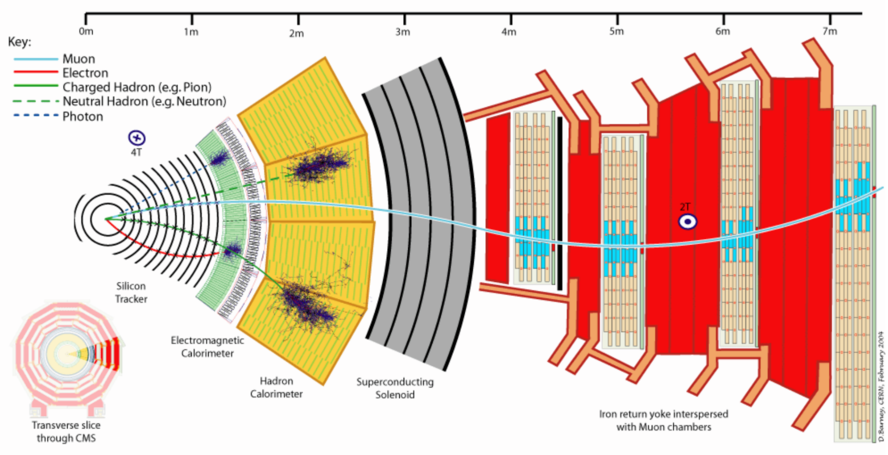


Figure from [2]

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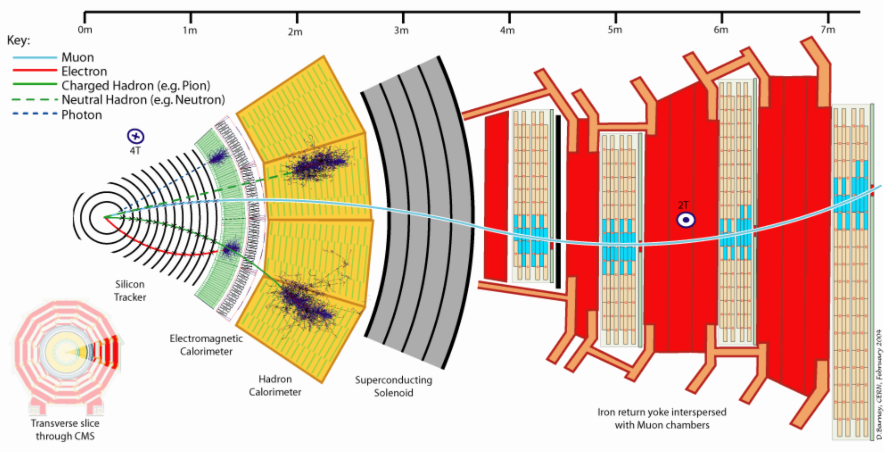


Figure from [2]

Tracking system

- **Central tracking system**
- Muon chambers

The CMS tracker

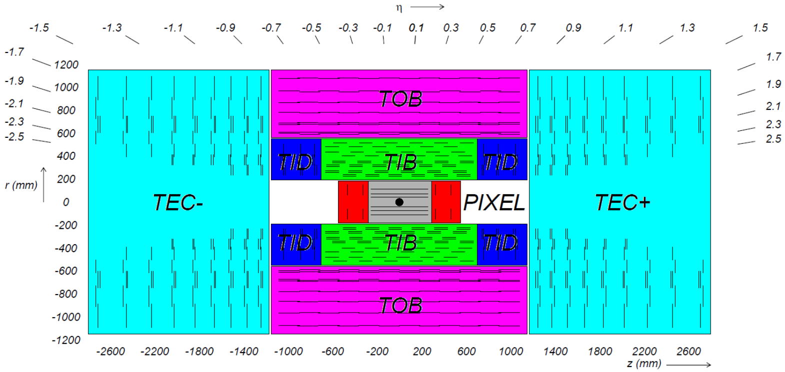


Figure from [3]

Pixel

PXB PXF

Strip

TIB TID TOB TEC

The CMS tracker

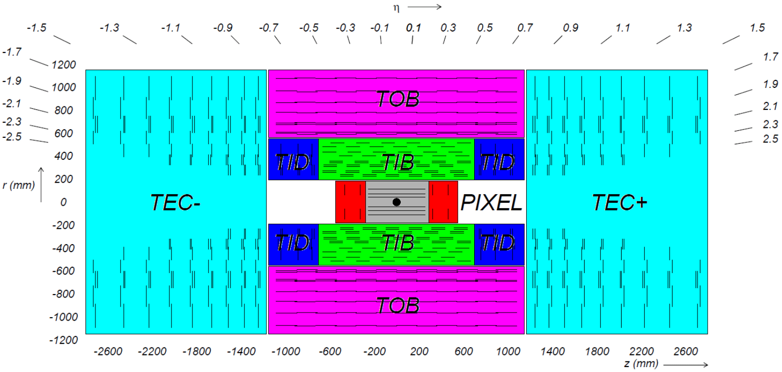


Figure from [3]

Pixel

PXB PXF

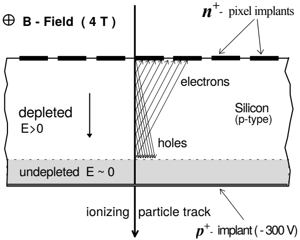
Strip

TIB TID TOB TEC

A few key figures

	#modules	#channels
Pixel (0)	1440	$\sim 66M$
Pixel (1)	1852	$\sim 125M$
Strip	15 148	$\sim 9.3M$

Silicon modules



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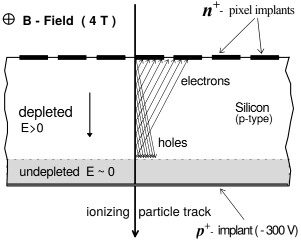
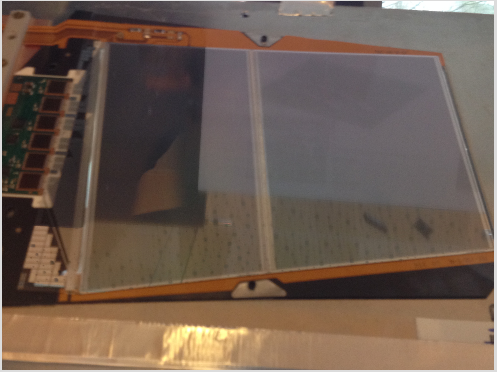
Silicon modules



(Figure from [1])

Strip module



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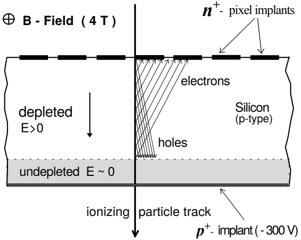

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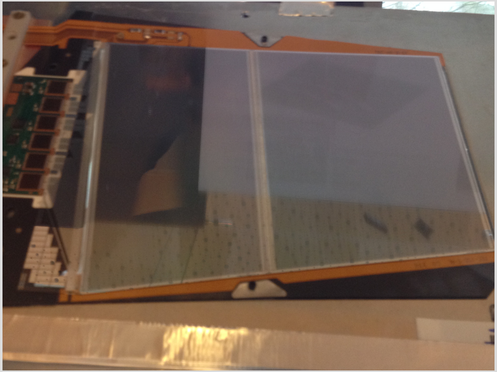
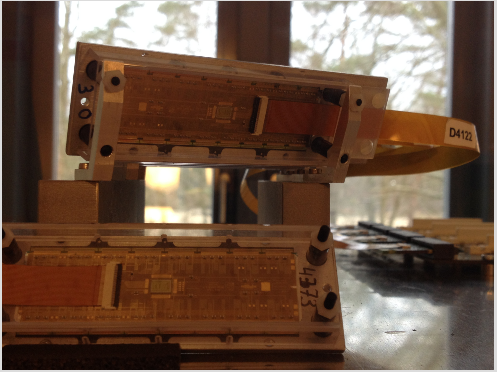
Strip module



Pixel module



Ops & Calibrations.

Signal calibration
Timing
Hit efficiency
Bias voltage
Radiation damage
Bad components
Alignment

Ops & Calibrations

Online operations in a nutshell

- Run coordination with LHC and other experiments.
- Intervention on the detector in case of issue with operations & acquisition.
- Shifters relay 24:7

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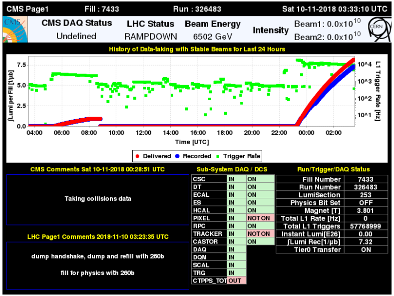
LHC Vistar

Even accessible for non-CMS collaborators
$\longrightarrow$ `https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHCCMS`



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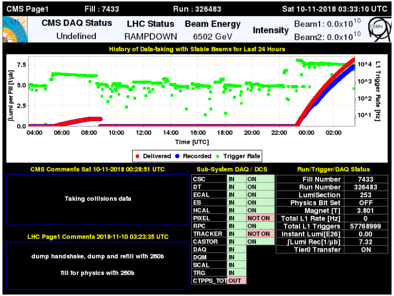


In this talk

Daily routine not covered here, we rather **focus on calibration and long-term evolution of the tracker.**

Signal calibration

Pixel

Gain calibration

- Module response

$\longrightarrow$ Local injection of signal and measurement at the output

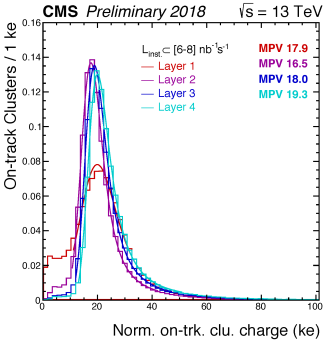
Signal calibration

Pixel

Gain calibration

- Module response

⟶ Local injection of signal and measurement at the output



(Figure from [4])

ROCs in L1

Different design to face the radiation.

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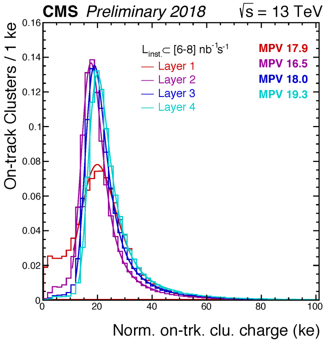


(Figure from [4])

ROCs in L1

Different design to face the radiation.

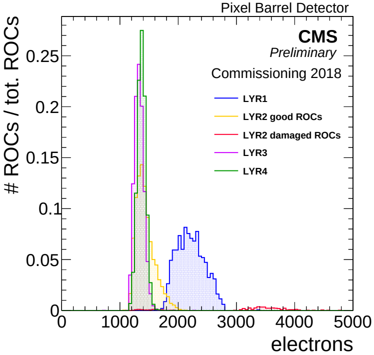
Thresholds

Defines when a module "sees" a particle

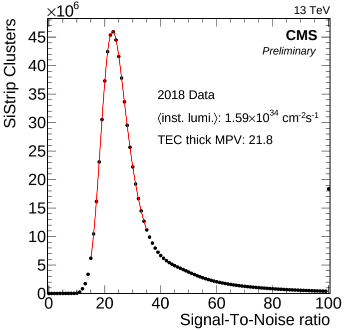
⟶ shown above for pixel barrel

L1 Different modules ⟶ suppress cross-talk

L2 Damaged modules ⟶ issue with DCDC converters



(Figure from [5])

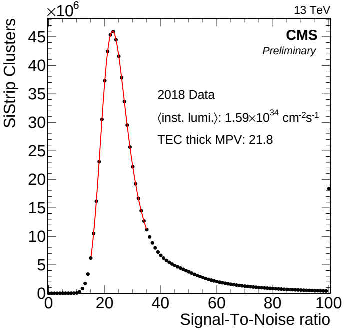


Signal calibration

Strip

Gain calibration

- Module response
- **Ageing of cables**



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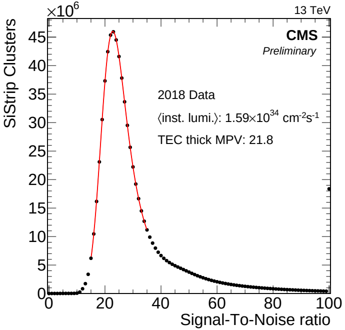
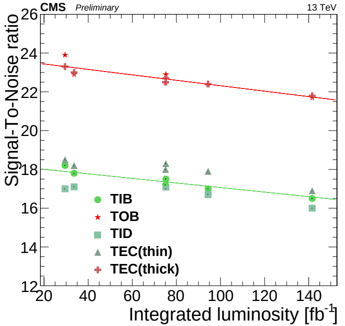
Tracking

- Seed must have $S/N > 5$
- Additional hits must have $S/N > 3$

Signal calibration

Strip





(Figures from [6])

Gain calibration

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- **Ageing of cables**

Tracking

- Seed must have $S/N > 5$
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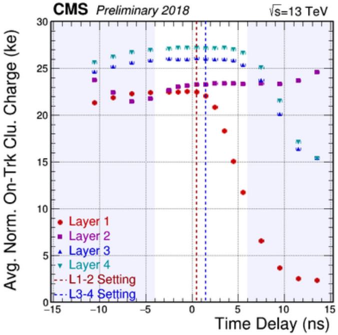
2018 performance

MPV estimation from fit to Landau $\otimes$ Gaussian:

	TIB	TID	TEC	TOB	TEC
thickness		340		500	
MPV	16.5	16.0	16.9	21.7	21.8

S/B is corrected for the path length inside silicon.

Timing

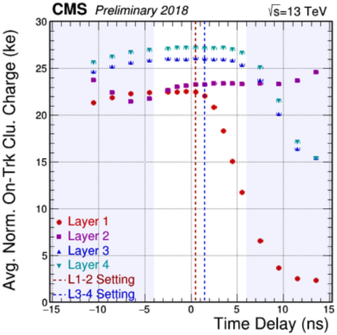


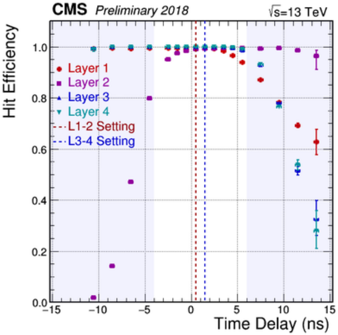
Issue

- LHC delivers collisions every $25\ \mathrm{ns}$.
- Fiber cables of different lengths.
- L1/L2 and L3/L4 sit on the same clock distribution.
- Chips have different processing times.

$\longrightarrow$ need to synchronise the signal among the layers

NB: also need to synchronise the tracker with the rest of the detector (not discussed here)





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Hit efficiency

For each module as

$$\epsilon = \frac{N_{\text{observed hits}}}{N_{\text{predicted hits}}}$$

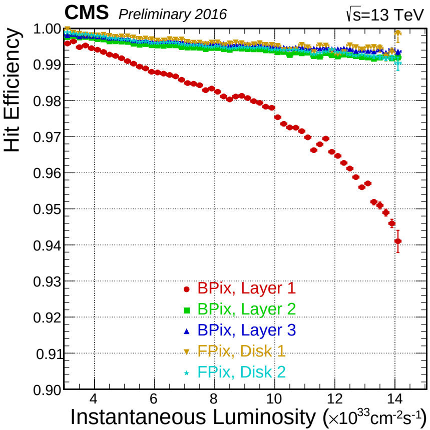
where tracks are traversing the modules within $1\ \mathrm{mm}$ around the expected hit.

Hit efficiency

Pixel

Nota bene

Different x-axis ranges!



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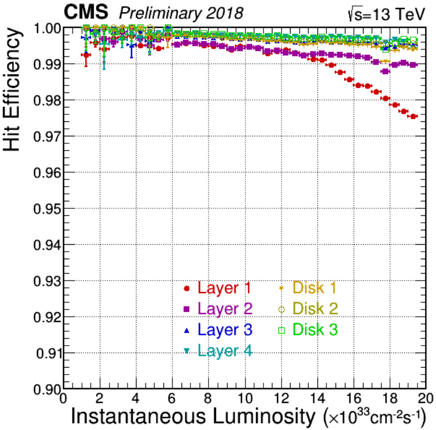

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Hit efficiency

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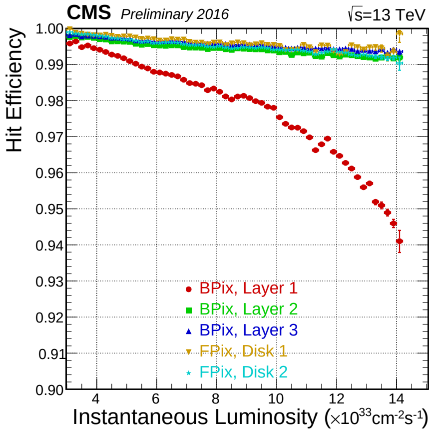

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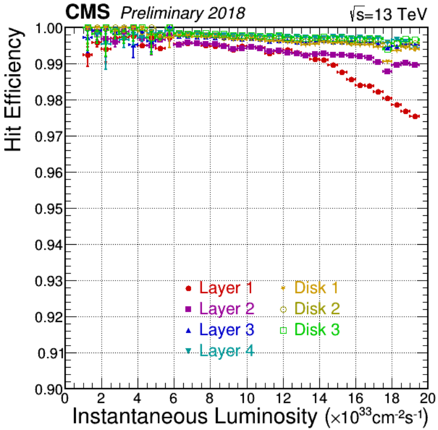

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From Phase-0 to Phase-1

- All modules were changed
- New design for Layer 1

Hit efficiency

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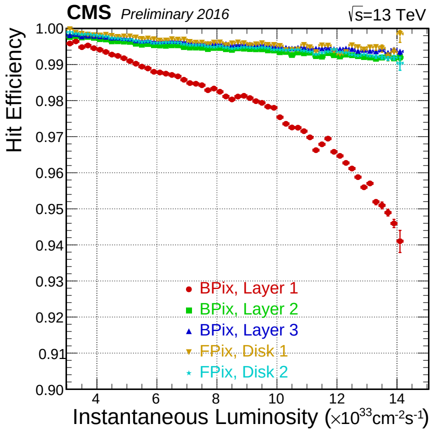

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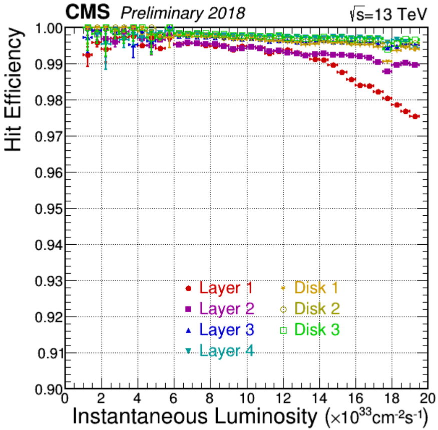


(Figure from [8])

From Phase-0 to Phase-1

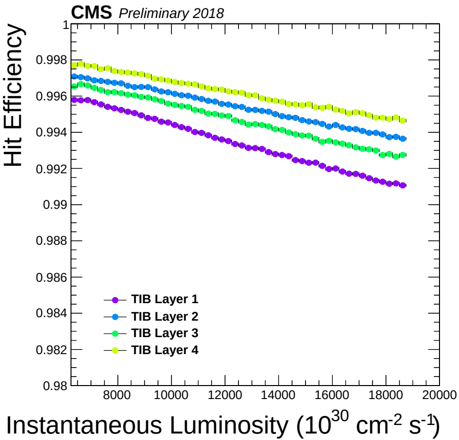
- All modules were changed
- New design for Layer 1

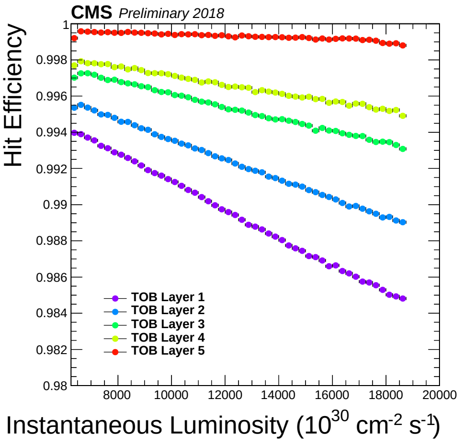
Layer 1 in pixel barrel

Replace it all for Run 3

Hit efficiency

Strip





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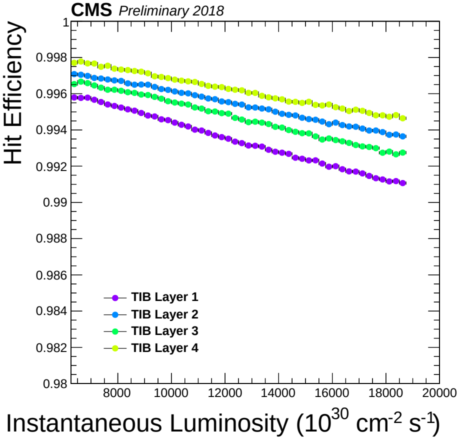
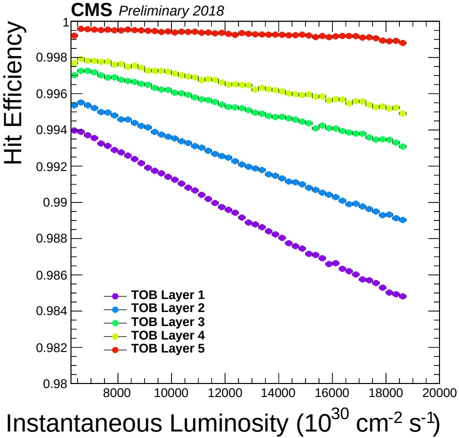


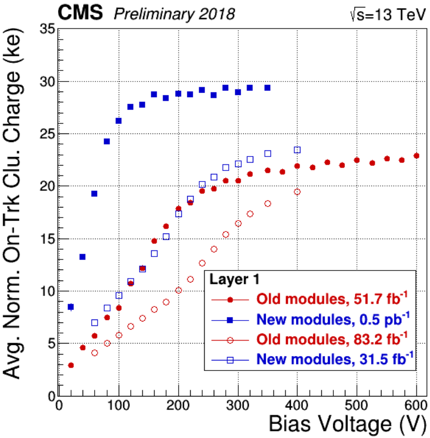


(Figures from [6])

Decrease with luminosity

- Larger occupancy in the modules $\longrightarrow$ HIPs (tracker inefficiency)
- Thick modules suffering more than thin modules $\longrightarrow$ greater chance for interaction

Bias voltage



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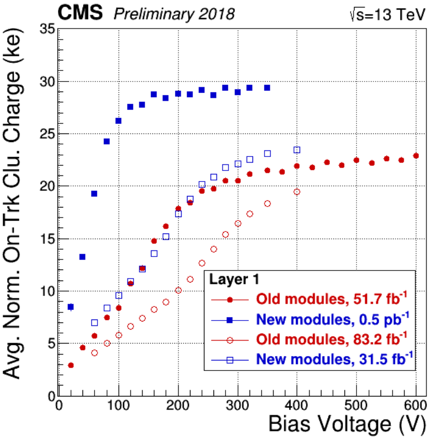


(Figure from [4])

Bias voltage

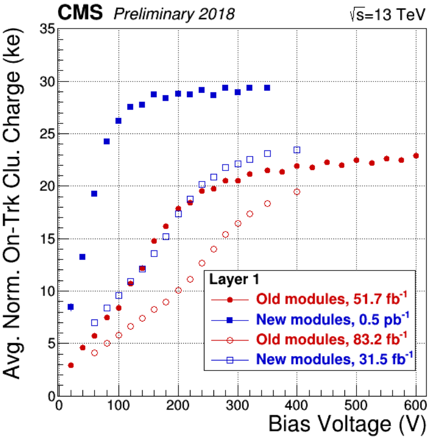
Bias (voltage) scan

Determine HV

$\longrightarrow$ optimal configuration of depletion zone

- Full bias scans are performed during ramp-up fills (4-5 hours)
  $\longrightarrow$ a few times a year
- Mini bias scans with selected modules are performed regularly to monitor
  $\longrightarrow$ every $4-5\ \mathrm{fb}^{-1}$

Bias voltage



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Issue with DCDC converters

When restarting stuck modules, electronic can get damaged due to a weakness in the electronics.

- Eight damaged modules in 2017.
- Six of them replaced for 2018.

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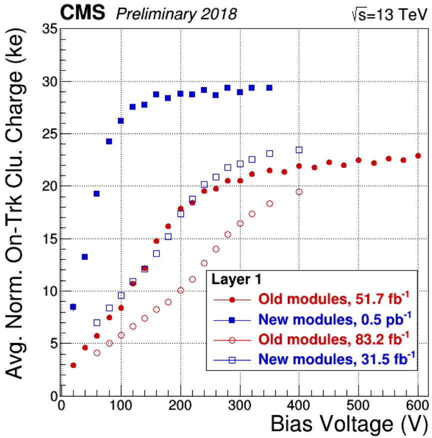

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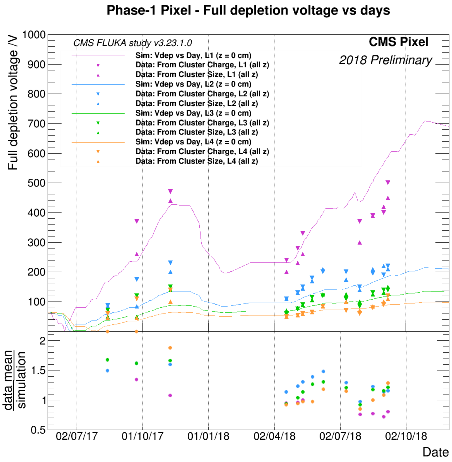
Radiation effects

Sensor's structure gets less regular & more complex...

Radiation damage

Pixel



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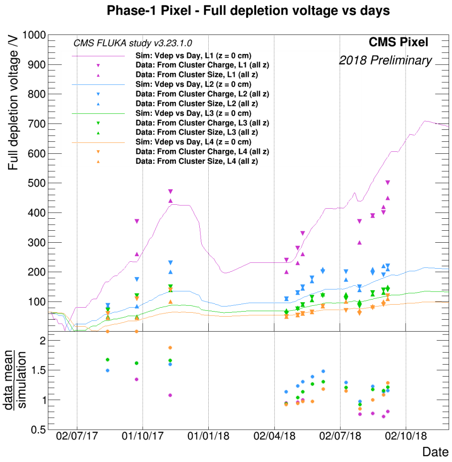

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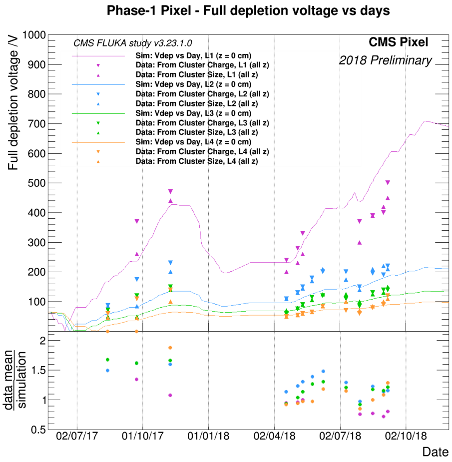
Conditions

- The closer to the IP, the more the drift of electrons in the module is affected.
- We update several times a year the description of the drift.
- Either increase of bias voltage or annealing.

Radiation damage

Pixel



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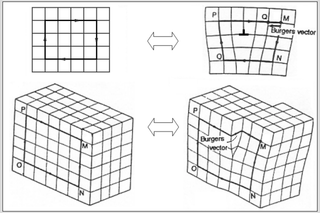
Annealing



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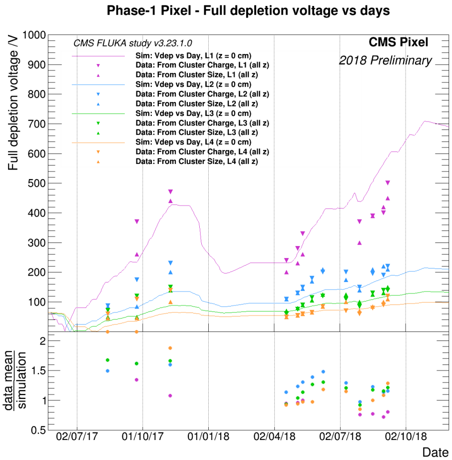

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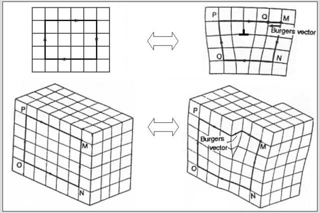

(Figure from [9])

Hamburg model

Full depletion not so well defined anymore in L1...

Conditions

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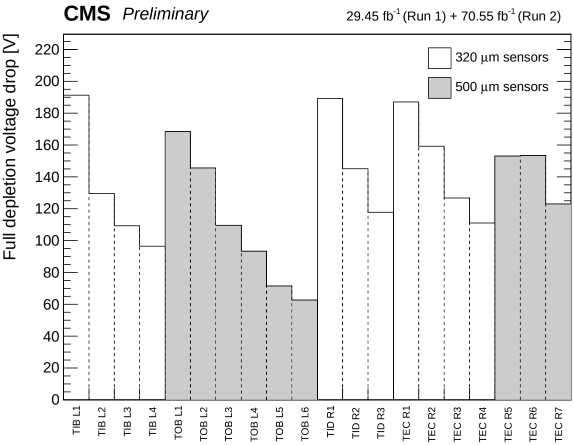
Radiation damage

Strip



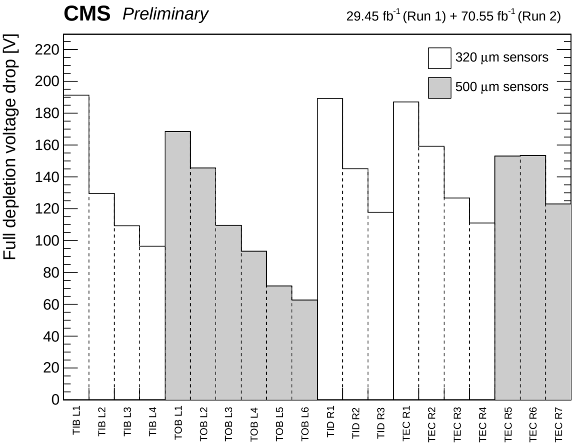
(Figure from [6])

Configuration

External voltage in strip fixed to $300V$.

Radiation damage

Strip



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Configuration

External voltage in strip fixed to $300V$.

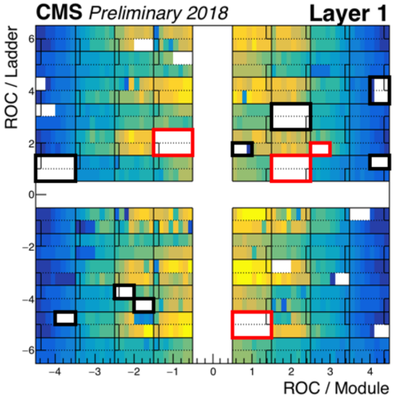
Effect of radiation in strip tracker

Result from September 2017.

- Effect decreases with distance to IP.
- External thick layers are more affected than internal thin layers.

$\longrightarrow$ no need to change the voltage throughout Run 1 and Run 2.

Bad components



(Figure from [4])

Issues

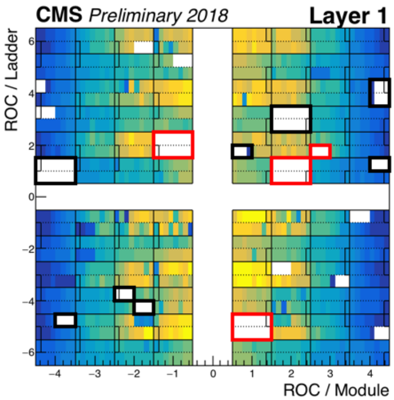
- White non-squared regions show stuck TBM(Single-Event Upset).
- Squared regions show regions damaged by DCDC converter issue.

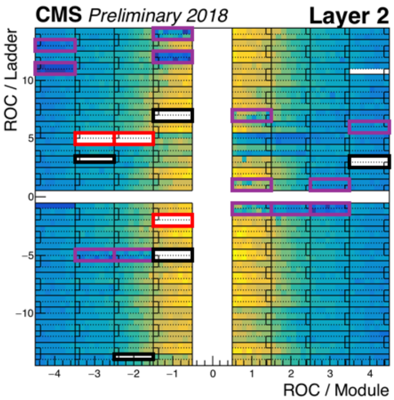
Legend

Blue-yellow nuances show occupancy.

- Several modules left from 2017
- New bad components in 2018

Bad components





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Legend

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- Several modules left from 2017
- New bad components in 2018
- The functional ROCs, connected to the broken DCDC converters in 2017, which show the higher level of noise are marked inefficient in reconstruction

Alignment
In a nutshell

Purpose
Reach $\sigma_{\text{align}} \approx \sigma_{\text{hit}} \sim \mathcal{O}(10\ \mu\text{m})$.

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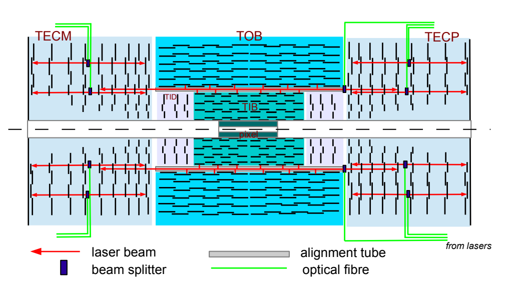
Laser Alignment System



(Figure from [10])

- Can be used to align high-level mechanical structures
- However difficulties with diffraction effects on mirror and exact positions of LAS components.

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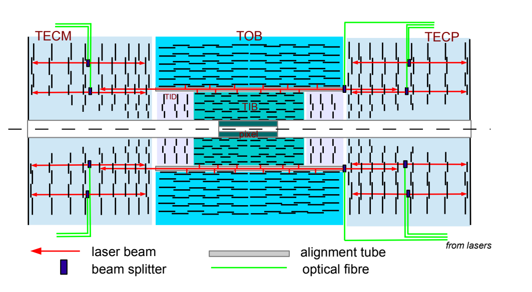
Reach $\sigma_{\text{align}} \approx \sigma_{\text{hit}} \sim \mathcal{O}(10\ \mu\text{m})$.

Laser Alignment System



(Figure from [10])

- Can be used to align high-level mechanical structures
- However difficulties with diffraction effects on mirror and exact positions of LAS components.

Track-based high-precision alignment

- $\mathbf{p}$ ($\mathbf{q}$) stands for the alignment (track) parameters,
- $\mathbf{m}$ ($\mathbf{f}$) stands for the measurements (predictions),
- and σ stands for the uncertainties.

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \left(\frac{m_{ij} - f_{ij}(\mathbf{p},\mathbf{q}_j)}{\sigma_{ij}} \right)^2$$

$\longrightarrow$ need **cosmic & resonance tracks** against weak modes [11, 12, 13, 14, 3]

Alignment

Vertexing performance

Primary Vertex

- Consider only vertices with at least 4 tracks.
- Reconstruct a vertex with $N-1$ tracks.
- Check impact parameter with Nth track.

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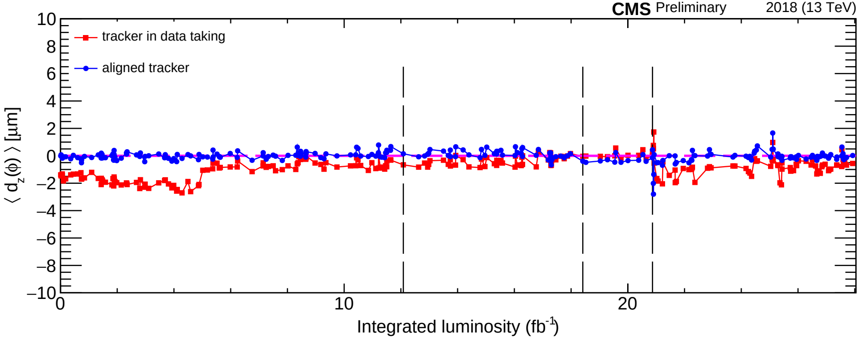
Figure

- Comparison of sets of alignments corrections during data taking and after high-precision alignment.
- Vertical lines corresponds to updates of pixel calibration.
- 80 sets of alignment corrections for high-precision alignment.

$\longrightarrow$ residual effects absorbed in the alignment and constant performance over time.



(Figure from [3])

Upgrade.

Structure

Material budget

Track finder

Upgrade

	LHC						HL-LHC
	Run-I		Run-II		Run-III		
E_{CM}[TeV]	7-8	LS1	13	LS2	14	LS3	14?
L [$cm^{-2}s^{-1}$]	$7{\cdot}10^{33}$		$\geq 1{\cdot}10^{34}$		$\geq 2{\cdot}10^{34}$		$\sim 5{\cdot}10^{34}$
<PU>	~21		≥25		≥50		≥140
$\int L{\cdot}dt$ [fb^{-1}]	~30		≥150		≥300		~3000

year	…	12	13	14	15	16	17	18	19	20	21	22	23	24	25	+10 years
CMS tracker	Phase-0						Phase-I							Phase-II		

(Modified figure from Benedikt Vormwald)

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(Modified figure from Benedikt VORMWALD)

Plans

- For Run 3, plan is only to change the first layer in barrel pixel.

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CMS tracker	Phase-0						Phase-I							Phase-II		

(Modified figure from Benedikt VORMWALD)

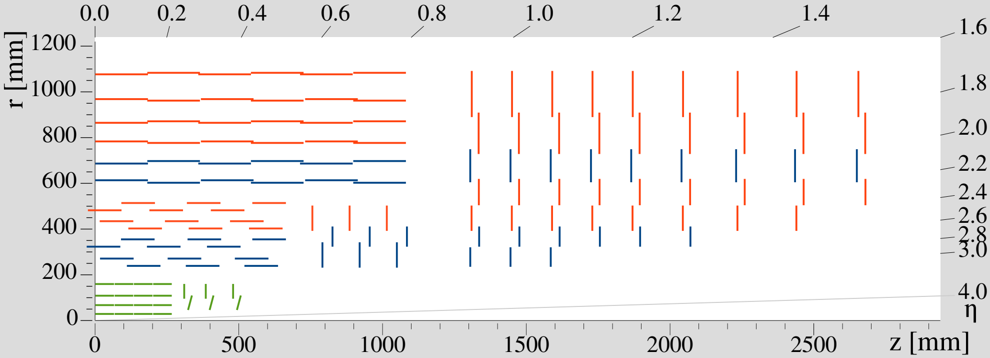
Plans

- For Run 3, plan is only to change the first layer in barrel pixel.
- Discussing in the next slides the *phase-II upgrade* for HL-LHC.

Structure

(Figures from [1])

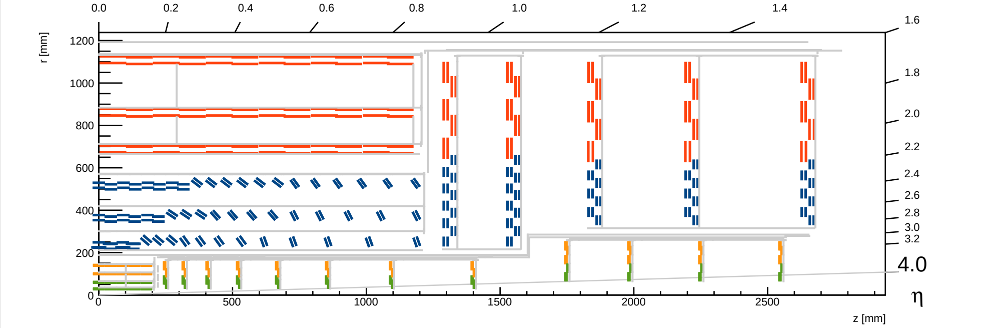
Phase-1



Structure

(Figures from [1])

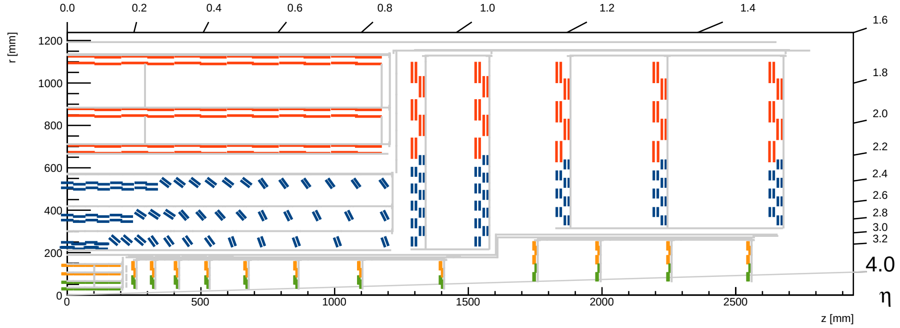
Phase-2



Structure

(Figures from [1])

Phase-2



Upgrade of the CMS detector

The *whole* silicon tracker has to be changed!

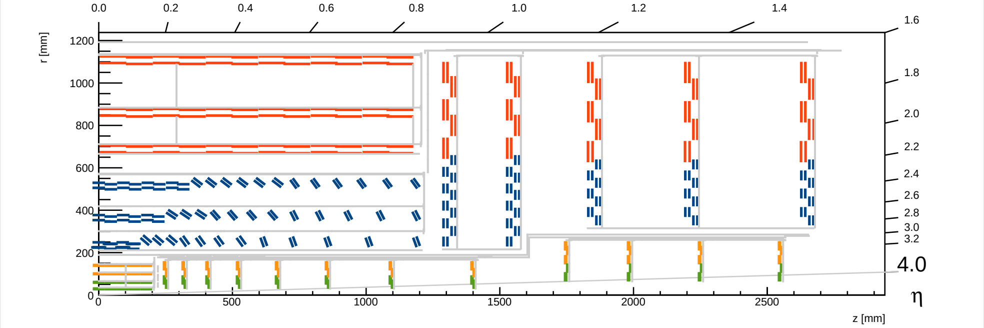
inner tracker pixel modules

outer tracker double-sensor modules

Structure

(Figures from [1])

Phase-2



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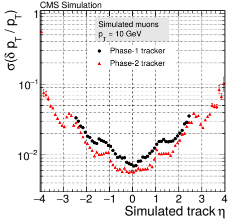
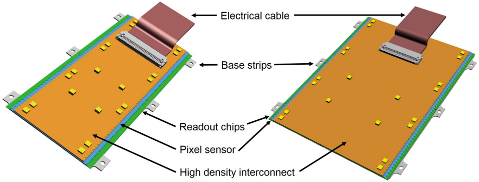


Structure

Inner tracker



Pixel modules

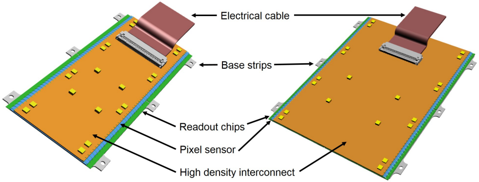
sensor area $16.4 \times 22.0\ \mathrm{mm}^2$

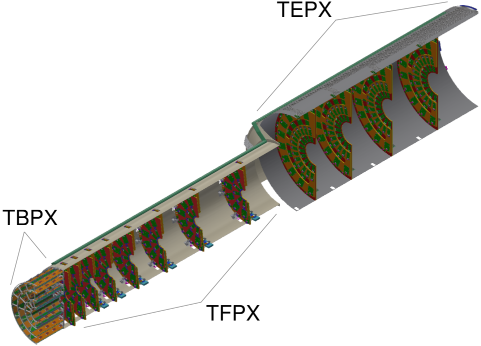
pixel size $25 \times 100\ \mu\mathrm{m}^2$ or $50 \times 50\ \mu\mathrm{m}^2$

$\longrightarrow$ factor 6 smaller pixels than currently!

Structure

Inner tracker





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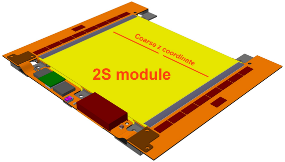
Structure

Outer tracker

Double-strip modules (2S)

sensor area $10 \times 10\ \mathrm{cm}^2$

strip size $5\ \mathrm{cm} \times 90\ \mu\mathrm{m}$



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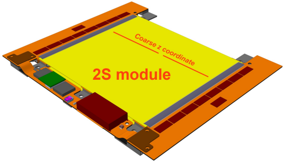

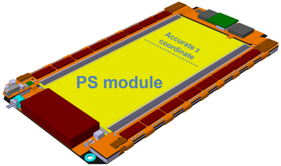

Macropixel-strip modules (PS)

sensor area $5 \times 10\ \mathrm{cm}^2$

strip size $2.35\ \mathrm{cm} \times 100\ \mu\mathrm{m}$

macropixel size $1.467\ \mathrm{mm} \times 100\ \mu\mathrm{m}$

(Figures from [1])

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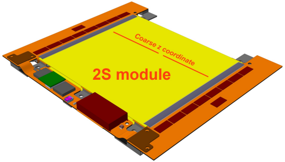

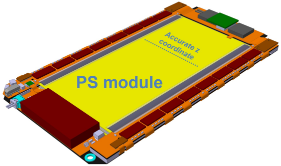

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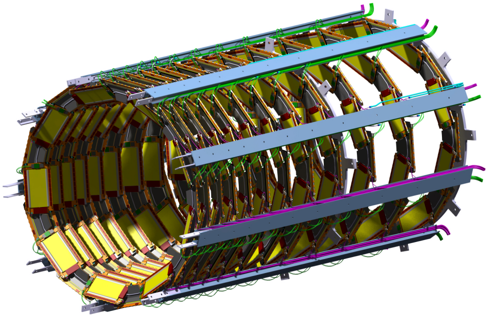
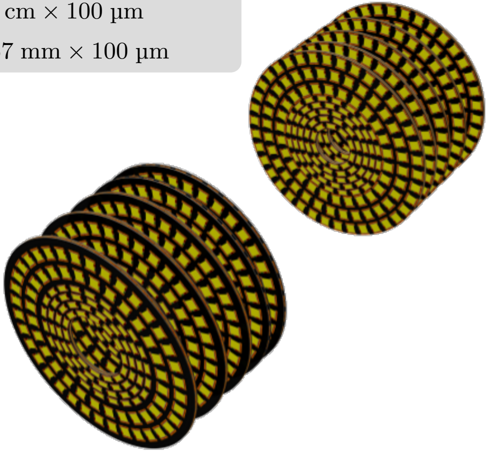
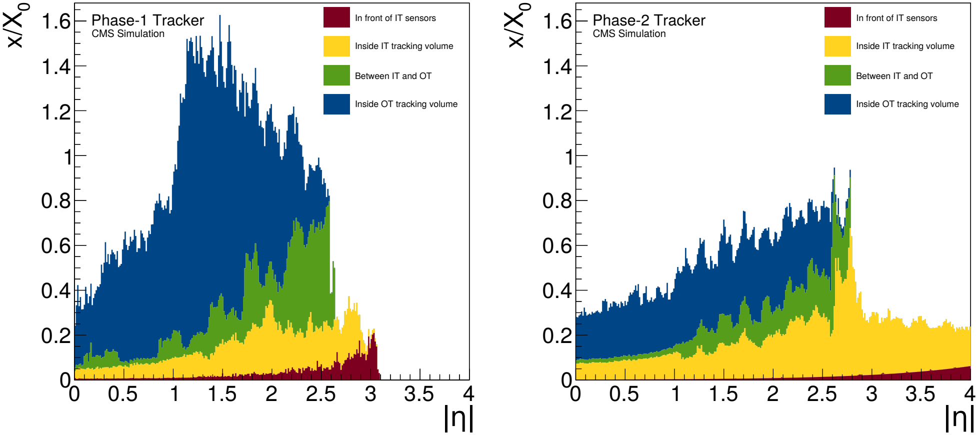




Material budget



(Figures from [1])

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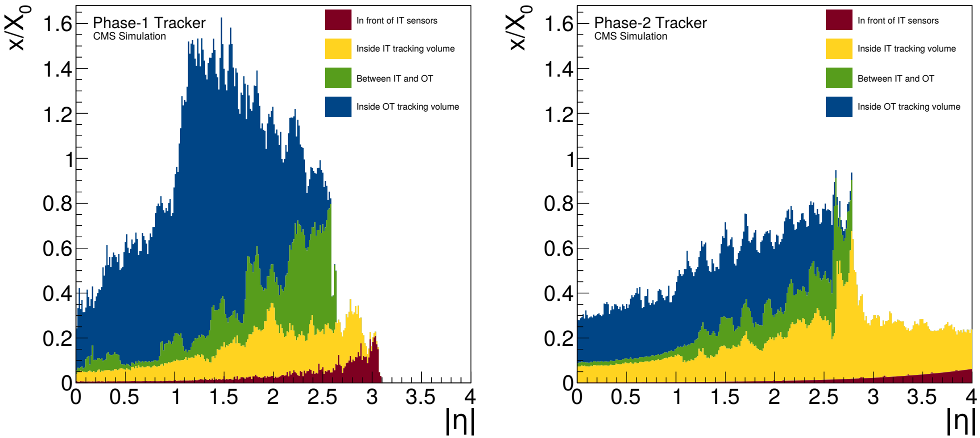


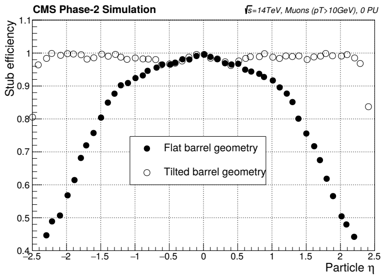
(Figures from [1])

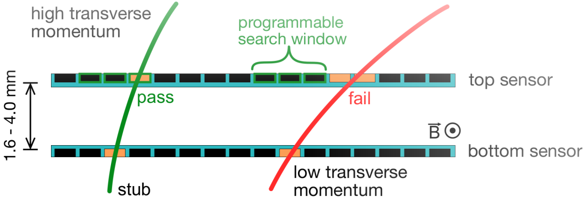
Improvement

- Less layers
- Tilted modules

Track finder

Principle





(Figures from [1])

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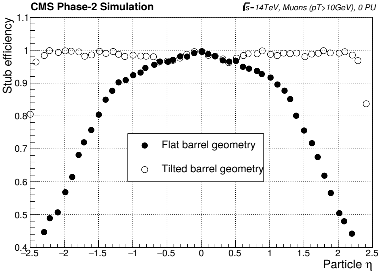

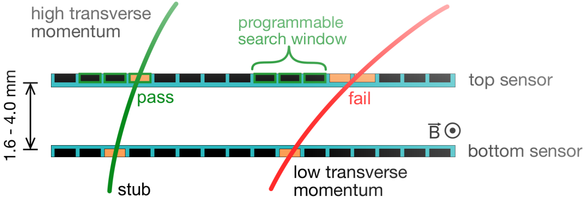

(Figures from [1])

Principle

- Modules in outer tracker are double sided with one common chip
  $\longrightarrow$ « p_T modules »
- Fast tracking can be performed
  $\longrightarrow$ trigger on tracks with $p_T > 2\ \mathrm{GeV}$

Summary & Conclusions.

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  - completely new detector with new modules;
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  - tilted modules;
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非常感谢!

Back-up.

Pixel Tracker

Layer	#TBM/module	#cores/TBM	#channels/core	#ROCs/channel
1	2	2	2	2
2	1	2	2	4
3/4	1	2	1	8

Strip Tracker

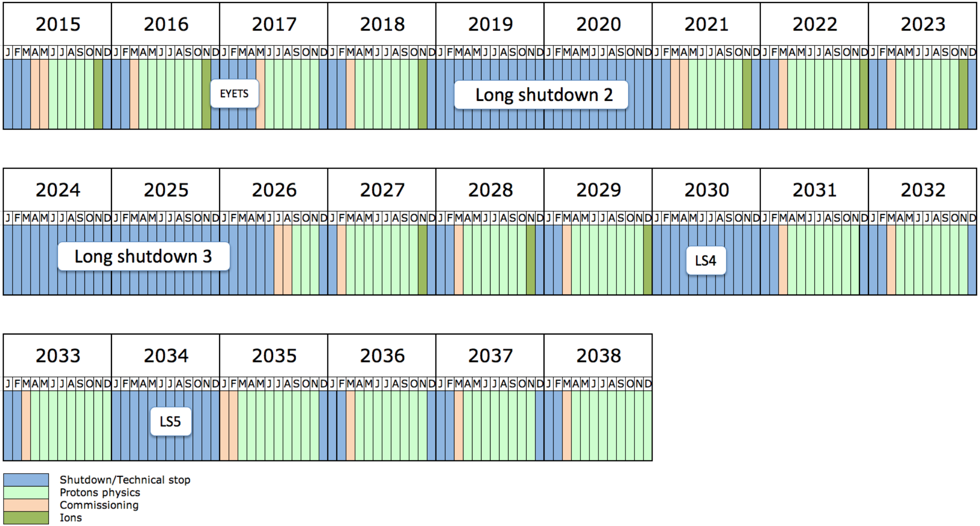
Layer	Radius /mm	Type	#Modules	Pitch /μ	Strips
TIB 1	250	double-sided	336	80	768
TIB 2	340	double-sided	456	80	7768
TIB 3	430	single-sided	552	120	7512
TIB 4	520	single-sided	648	120	7512
TOB 5	610	double-sided	504	122/183	768/512
TOB 6	696	double-sided	576	122/183	768/512
TOB 7	782	single-sided	648	183	512
TOB 8	868	single-sided	720	183	512
TOB 9	965	single-sided	792	122	768
TOB 10	1080	single-sided	888	122	768

Strip Tracker

Layer	Radius /mm	Type	#Modules	Pitch /μ	Strips
TID 1	277	double-sided	144	$81 \ldots 112$	768
TID 2	367	double-sided	144	$113 \ldots 143$	768
TID 3	447	single-sided	240	$124 \ldots 158$	512
TEC 1	277	double-sided	144	$81 \ldots 112$	768
TEC 2	367	double-sided	288	$113 \ldots 143$	768
TEC 3	447	single-sided	640	$124 \ldots 158$	512
TEC 4	562	single-sided	1008	$113 \ldots 139$	512
TEC 5	677	double-sided	720	$126 \ldots 156$	768
TEC 6	891	single-sided	1008	$163 \ldots 205$	512
TEC 7	991	single-sided	1440	$140 \ldots 172$	512

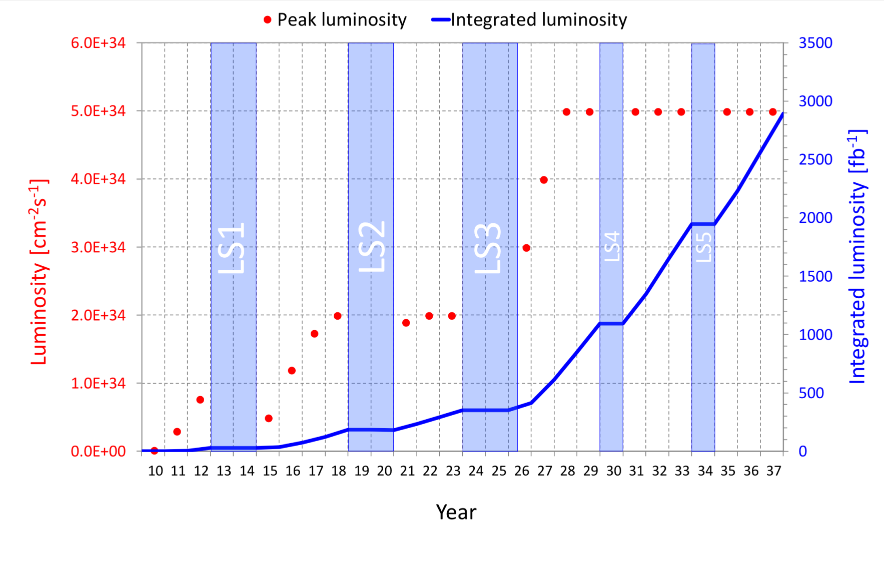
LHC schedule

Operation calendar



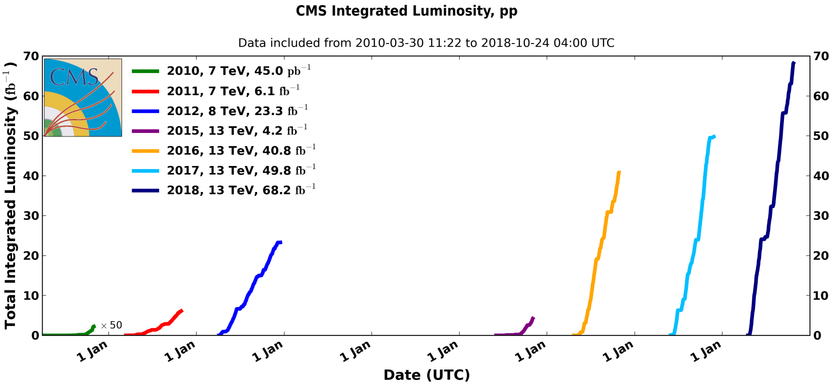
LHC schedule

Delivered luminosity



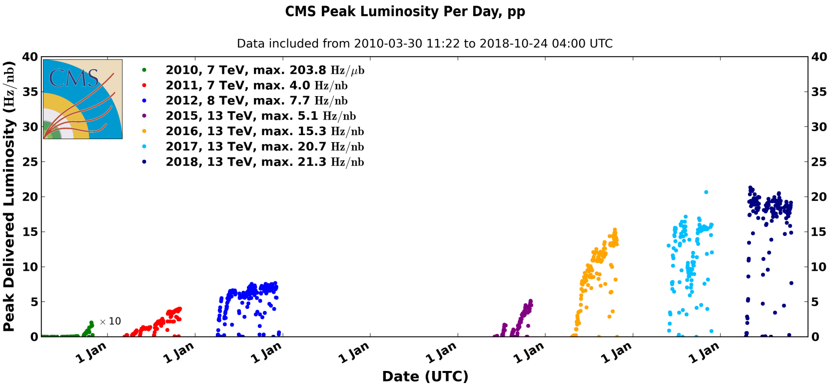
CMS Run-II I

Luminosity



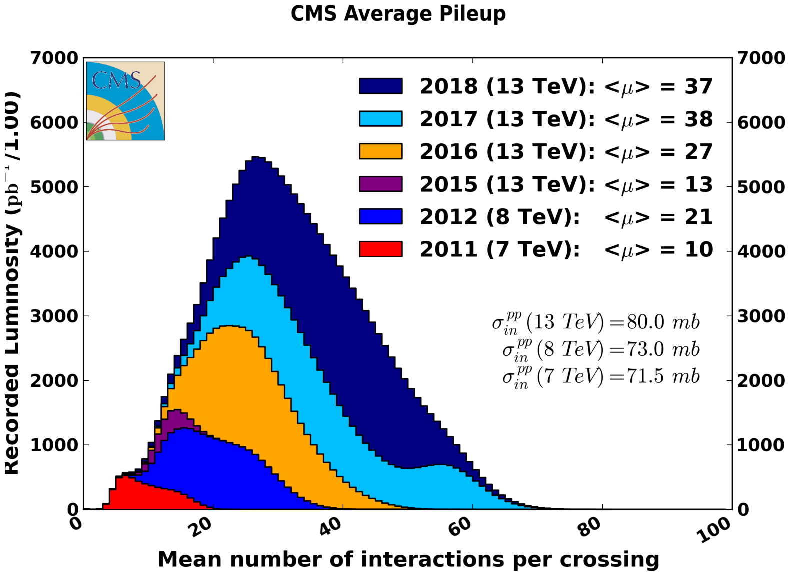
CMS Run-II II

Luminosity

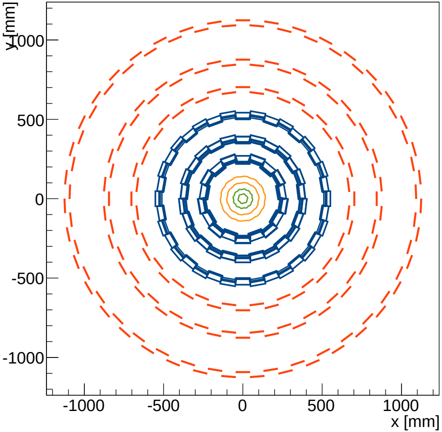


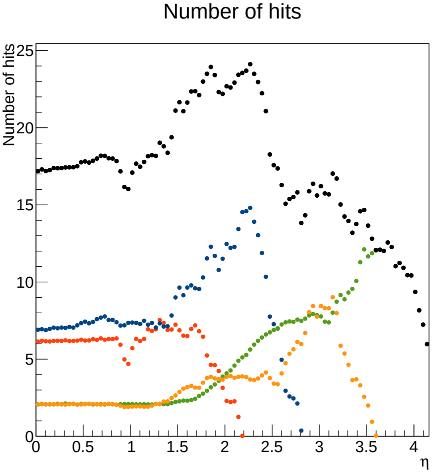
CMS Run-II

Pile-up



Upgrade





- Minimum bias per bunch crossing: 140
- Integrated luminosity: 3000 fb^{-1}
- Number of tracks used for material: 3000
- Number of tracks used for geometry: 50000
- Irradiation α parameter (at reference temperature 20 °C): $4.28\times10-17$ A/cm

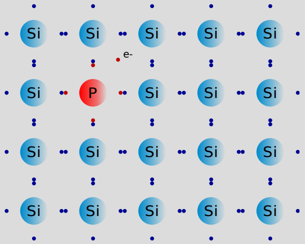
http://cms-tklayout.web.cern.ch/cms-tklayout/layouts-work/recent-layouts/OT614_200_IT404/index.html

Semi-conductor material

Key property

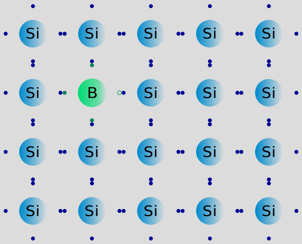
Valence band close to *conduction* band
$\longrightarrow$ excited electrons may induce a **current**

n-doped (donor)



Additional electrons can populate the conduction band.

p-doped (acceptor)

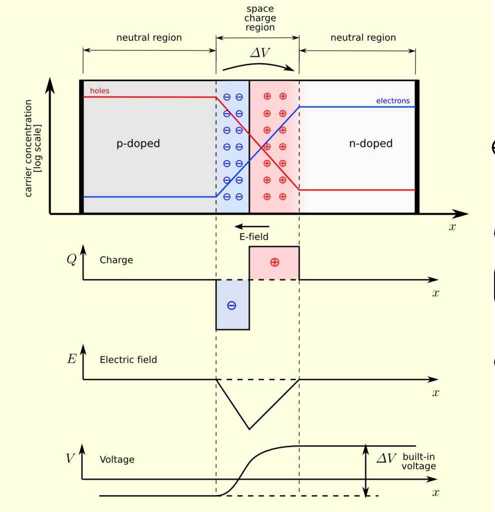


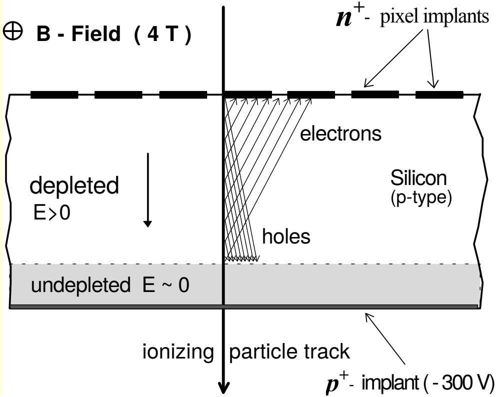
Electrons can fall in the holes.

pn-junction

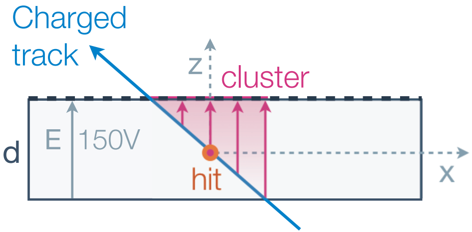
A "natural" *depletion zone* appears around the contact surface.

np-junction


space charge region
neutral region
neutral region
ΔV
holes
electrons
p-doped
n-doped
carrier concentration [log scale]
x
E-field
Q
Charge
x
E
Electric field
x
V
Voltage
ΔV built-in voltage
x

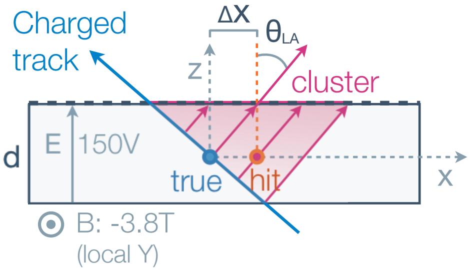

B - Field (4 T)
n^+- pixel implants
electrons
depleted
E>0
Silicon
(p-type)
holes
undepleted E ~ 0
ionizing particle track
p^+- implant (- 300 V)

Particle detection



Use in particle physics

A signal is induced when a particle crosses the junction.
$\longrightarrow$ increase depletion zone with external electric field



Working in magnetic field

Displaced hit
$\longrightarrow$ Lorentz drift

Tracking resolution

The resolution on the momentum is determined by the following formula:

$$\left|\frac{\sigma_p}{p}\right|^2 = \left(\frac{a_n p_T}{0.3BL_T^2}\right)^2 \sigma_X^2 + \left(\frac{0.06}{B\beta}\right)^2 \frac{1}{X_0 L_T \sin\theta} \quad (1)$$

where

- $a_n = \sqrt{\frac{720}{n+4}}$ is a typical parameter of the current configuration (n is the index of the layer),
- B is the strength of the magnetic field in Tesla,
- L_T the length of the tracker in metres,
- p_T the transverse momentum in GeV,
- θ the polar angle,
- σ_X the spatial resolution of the devices in metres,
- and X_0 the characteristic length of the material.

It means that at low energy, the momentum resolution is limited by the *multiple scattering* while at high energy, it is limited by the determination of the curvature (the uncertainty from the polar angle is negligible).

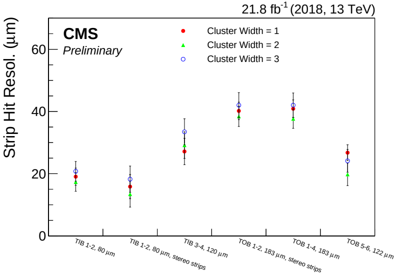
Bethe-Bloch formula

Quoting from `http://meroli.web.cern.ch/Lecture_landau_ionizing_particle.html`

- It is well known that the Bethe-Bloch formula describes the average energy loss of charged particles when travelling through matter, while the fluctuations of energy loss by ionization of a charged particle in a thin layer of matter was theoretically described by Landau in 1944.
- Protons, pions and other types of charged particles, which are in most cases close to MIPs, all produce approximately Landau-distributed spectra when traversing the matter.

L. Landau, On the Energy Loss of Fast Particles by Ionization, J. Phys. USSR 8 (1944) 201.

Hit resolution



The strip hit resolution is computed by using hits in overlapping modules of the same layer ("pair method").
Tracks are selected with the following cuts:

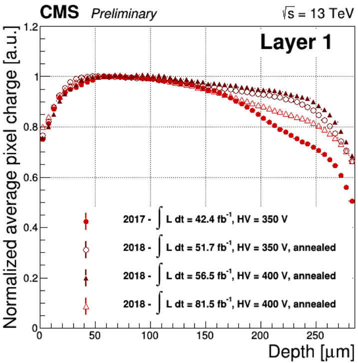
- $p_T >$ 3 GeV ;
- number of hits $>=$ 6;
- χ^2 probability $>= 10^{-3}$;

Hit pairs are selected by requiring:

- at most 4 strips cluster width;
- Clusters that are of the same width in both the modules;
- Clusters that are not at the edge of the modules;
- Predicted path (distance of propagation from one surface to the next) $<$ 7 cm; i.e. only pairs within the same layer are allowed;
- Error on predicted distance in the bending coordinate between the two hits $<$ 25 microns

Strip Hit resolution derived with the pair method by selecting pairs of hits in different types of overlapping sensors and for different cluster widths expressed in units of number of strips.

Annealing



For non irradiated, fully depleted detector, the pixel charge profile (normalised average pixel charge as a function of the production depth) is expected to be flat as detector is fully efficient and all charge is collected, while for irradiated detector the losses are expected due to the trapping of carriers. The losses are larger for the charges released further from the readout plane.
The selection requirements include:
Tracks with $p_T > 3$ GeV

- $Q_{\text{cluster}} < 1000$ ke
- size in 4 $<=$ y
- $N_{\text{residuals}} < 100$ m

The normalised average pixel charge as a function of the production depth in the silicon substrate is shown for Layer 1 of the Barrel Pixel detector at the end of 2017 (HV $=$ 350 V), at the beginning of 2018 data taking (HV $=$ 350 and 400 V) and after 30.0 fb^{-1} of data is collected in 2018.

- During 2017 EYETS, the Barrel Pixel detector was held at the temperature $T > 10°$ for 53 days
$\longrightarrow$ The beneficial effect of the annealing during this period is clearly visible in the flattening of the pixel charge profile.
- At the beginning of 2018 data taking, the charge collection was additionally increased in Layer 1 by raising the bias voltage from 350 V to 400 V.

Acronyms I

PXB PiXel Barrel. 9, 10

PXF PiXel Forward. 9, 10

TEC Tracker End-Caps. 9, 10, 21–23

TIB Tracker Inner Barrel. 9, 10, 21–23

TID Tracker Inner Disk. 9, 10, 21–23

TOB Tracker Outer Barrel. 9, 10, 21–23

CEPC Chinese Electron Positron Collider. 3, 4

CMS Compact Muon Solenoid. 3, 4, 15–17, 52–55, 66–69

DCDC Direct-Current to Direct-Current. 18–20, 31–34, 41, 42

EYETS Extended Year End Technical Stop. 86

HI Heavy Ion. 5, 6

HIP Highly-Ionising Particle. 29, 30

HL-LHC High-Lumi LHC. 49–51

Acronyms II

HV High Voltage. 31–34

IP interaction point. 35–40

LAS Laser Alignment System. 43–45

LHC Large Hadron Collider. 15–17, 24, 25

MPV Most Probable Value. 21–23

PV Primary Vertex. 46, 47, 66–69

ROC Read-Out Chip. 18–20, 41, 42, 71

SEU Single-Event Upset. 41, 42

TBM Token-Bit Manager. 41, 42, 71

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