



Luminosidad de alta precisión en el experimento CMS del LHC

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<https://link.springer.com/content/pdf/10.1140/epjc/s10052-021-09538-2.pdf>

Eur. Phys. J. C (2021) 81:800
<https://doi.org/10.1140/epjc/s10052-021-09538-2>

THE EUROPEAN
PHYSICAL JOURNAL C



Regular Article - Experimental Physics

Precision luminosity measurement in proton–proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS

CMS Collaboration^a

CERN, 1211 Geneva 23, Switzerland

Received: 5 April 2021 / Accepted: 9 August 2021 / Published online: 9 September 2021
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Abstract The measurement of the luminosity recorded by the CMS detector installed at LHC interaction point 5, using proton–proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016, is reported. The absolute luminosity scale is measured for

rather results from a variety of uncorrelated sources of systematic uncertainty with typical magnitudes of 0.1–0.5%. In this paper, we report the precise determination of the absolute luminosity at the CERN LHC interaction point (IP) 5 using data from proton–proton TeV collected in 2015 and 2016. The physics program at the LHC that can precisely test the validity of predictions, e.g., cross sections of weak gauge bosons [4,5] or top understanding of the luminosity is systematic uncertainty in these measurements. The luminosity measurement is also uncertainty 1.5–3%.



Public CMS Luminosity Information

- Overview
- Other public luminosity information
- Run 3 annual charts of luminosity
 - 2022 proton–proton collisions at 13.6 TeV
- Run 2 annual charts of luminosity
 - 2018 proton–proton collisions
 - 2018 lead–lead collisions
 - 2017 proton–proton collisions
 - 2017 proton–proton reference run
 - 2016 proton–proton collisions
 - 2016 proton–lead collisions
 - 2016 low-energy proton–lead collisions
 - 2015 proton–proton collisions
 - 2015 proton–proton reference run
 - 2015 lead–lead collisions
- Multi-year plots
- Run 1 annual charts of luminosity
 - 2013 proton–lead 5.02 TeV/nucleon collisions
 - 2013 proton–proton 2.76 TeV collisions
 - 2012 proton–proton 8 TeV collisions
 - 2011 proton–proton 7 TeV collisions
 - 2011 lead–lead 2.76 TeV/nucleon collisions
 - 2010 proton–proton 7 TeV collisions

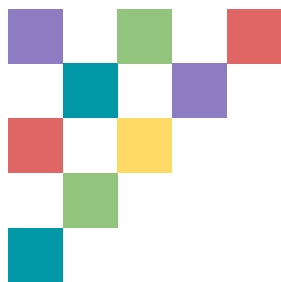
<https://bit.ly/3DbSScQ>

CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

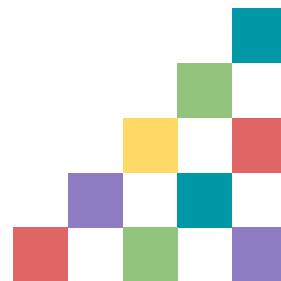
CMS

The Phase-2 Upgrade of the CMS
Beam Radiation, Instrumentation
and Luminosity Detectors
Technical Design Report

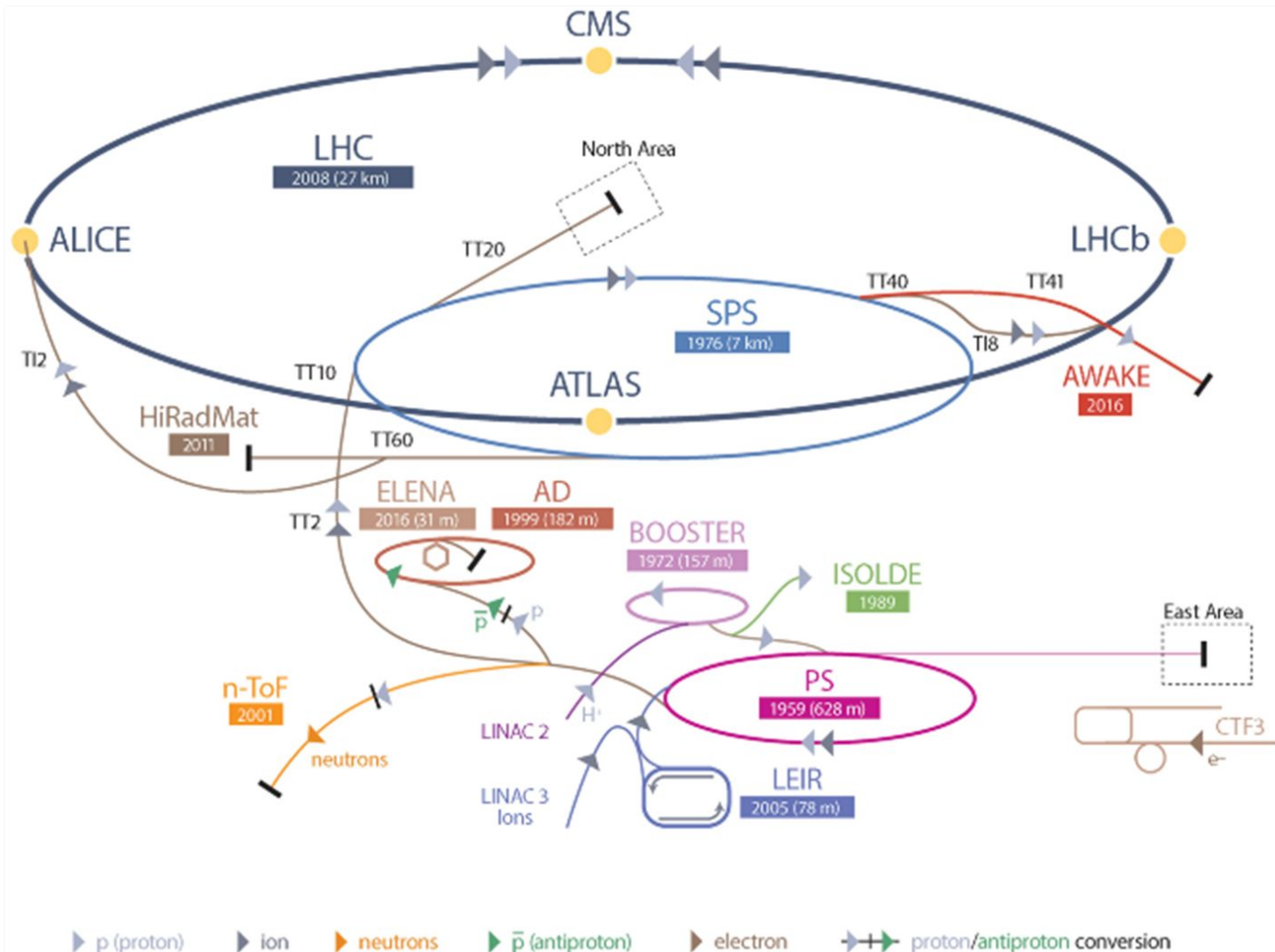
<https://cds.cern.ch/record/2759074/files/CMS-TDR-023.pdf>



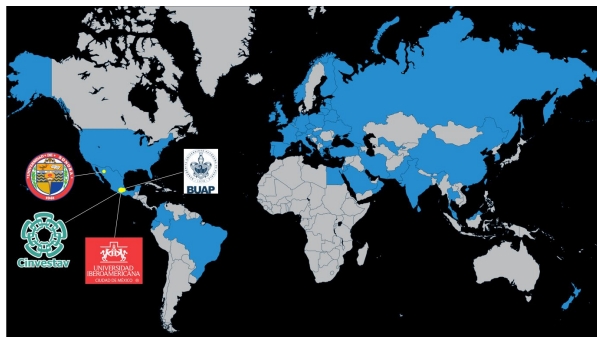
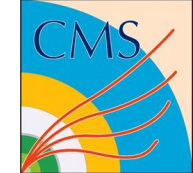
Introducción



EL LHC



El experimento CMS del LHC



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS

Pixel ($100 \times 150 \mu\text{m}^2$) $\sim 1 \text{ m}^2 \sim 66\text{M}$ channels
Microstrips ($80\text{--}180 \mu\text{m}$) $\sim 200 \text{ m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying $\sim 18,000 \text{ A}$

MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER

Silicon strips $\sim 16 \text{ m}^2 \sim 137,000$ channels

FORWARD CALORIMETER

Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)

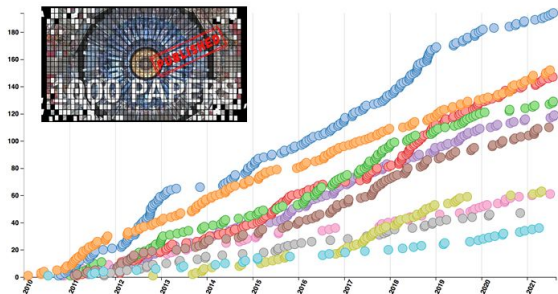
$\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)

Brass + Plastic scintillator $\sim 7,000$ channels

Show all Total Exotic Standard Model Supersymmetry Higgs Top Heavy Ions
B and Quarks Forward and Soft QCD Beyond 2 Generations Detector Performance

1058 collider data papers submitted as of 2021-08-06



Luminosidad 101

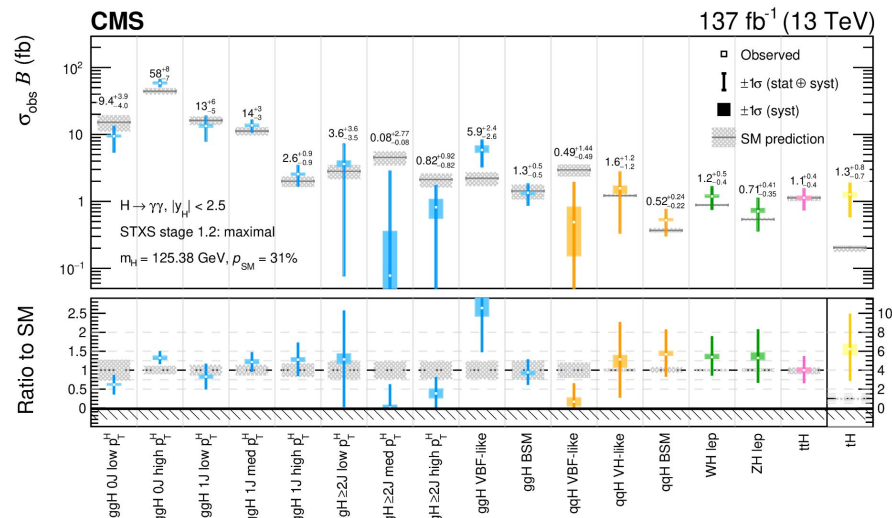
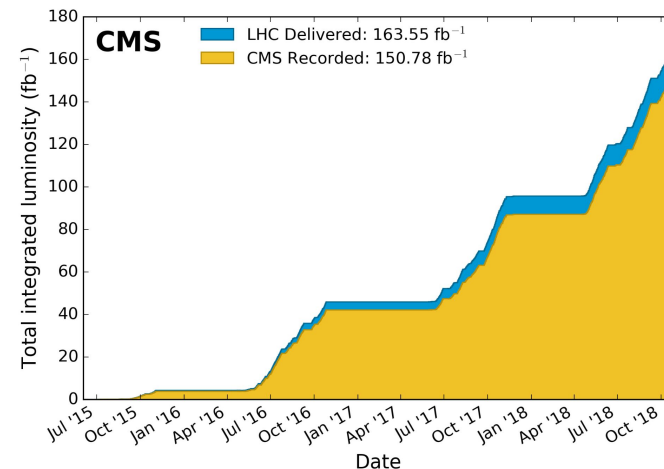
La **luminosidad instantánea** es una medida del número de colisiones por unidad de área por unidad de tiempo ($\mathcal{L}$).

La **luminosidad integrada** es el número total de colisiones por unidad de área (L).

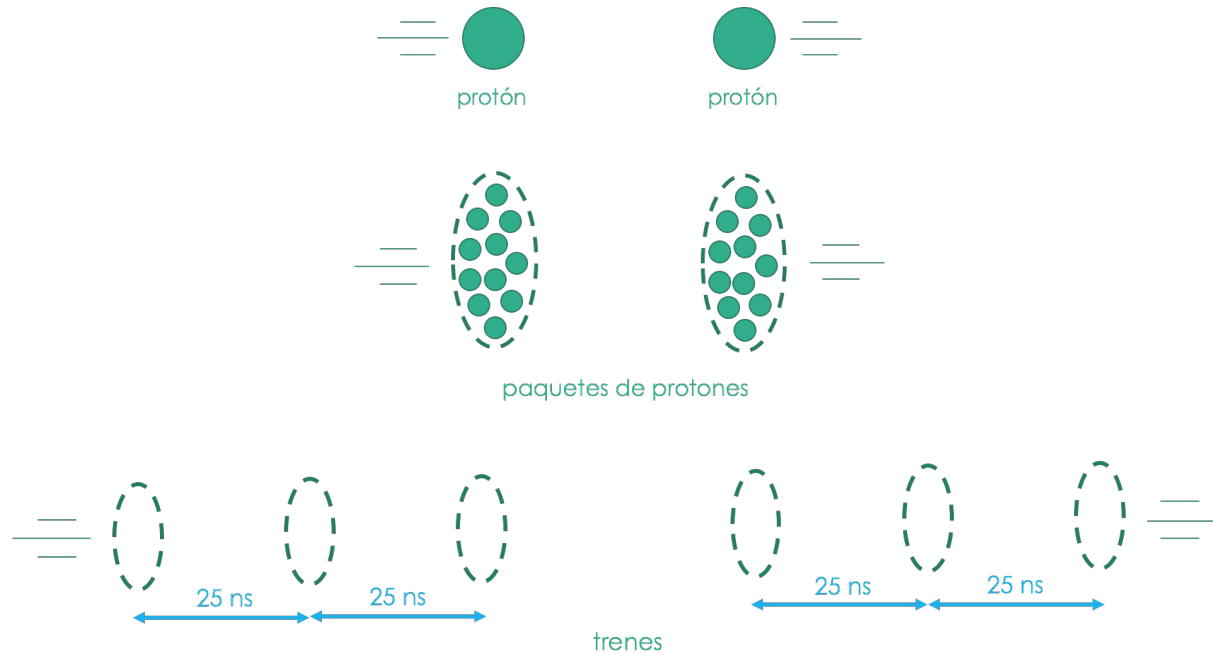
Es un parámetro esencial para todo análisis de física en experimentos de altas energías:

$$\sigma = \frac{N}{L}$$

↙ sección eficaz del proceso a estudiar
 → número de eventos observados



Luminosidad 101



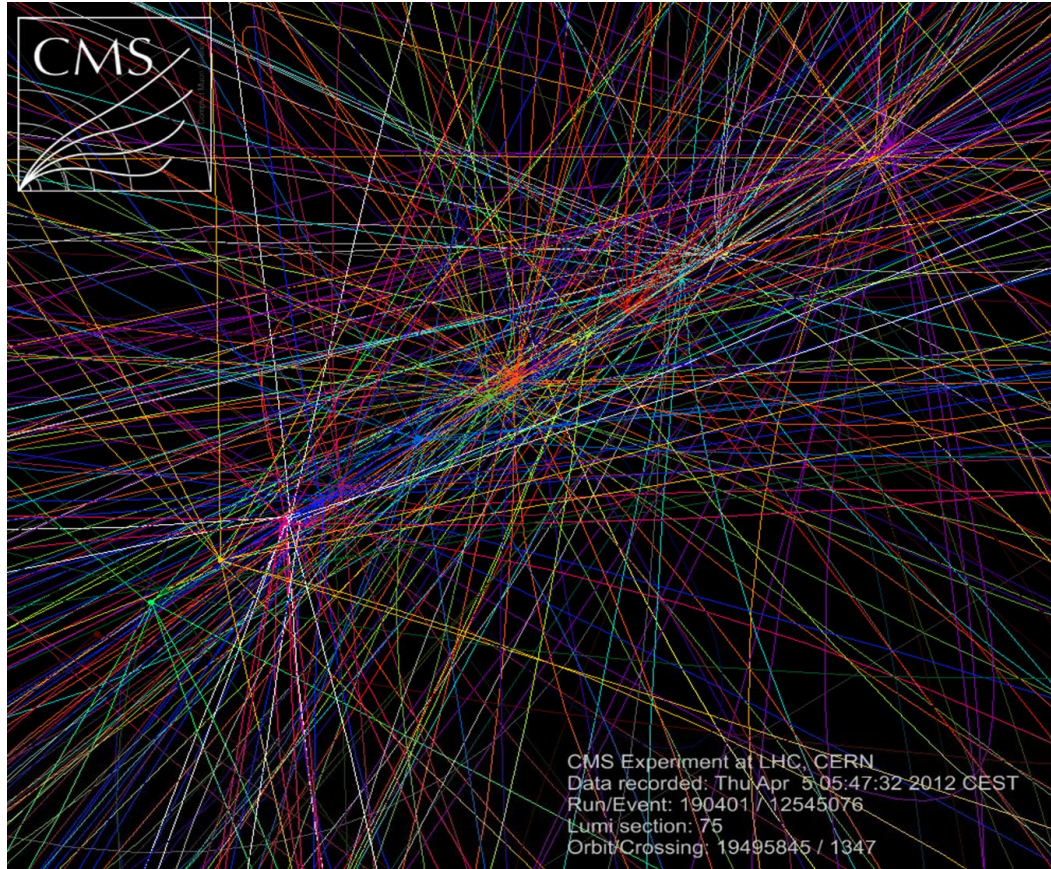
Luminosidad instantánea entregada:

$$\mathcal{L} = \frac{N_1 N_2 f n_b}{4\pi \sigma_x \sigma_y}$$

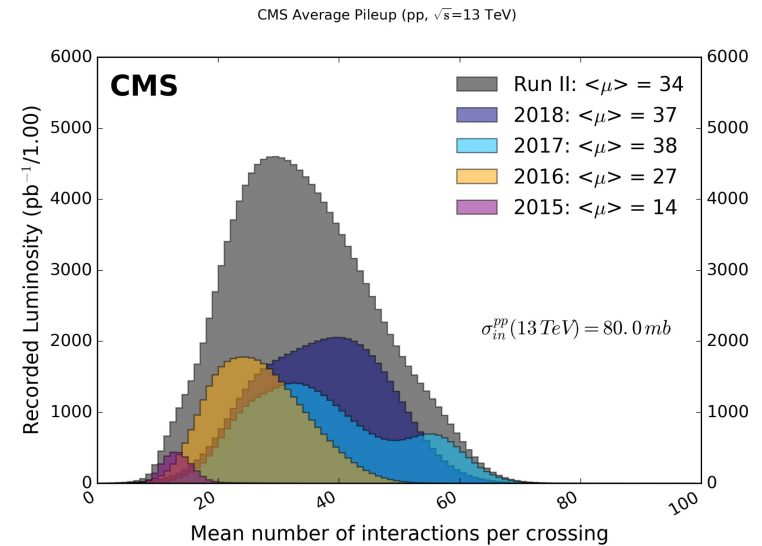
Diagram illustrating the components of the luminosity formula:

- N_1 : Número de protones por paquete (Number of protons per bunch)
- N_2 : Número de protones por paquete (Number of protons per bunch)
- f : Frecuencia del LHC (LHC frequency)
- n_b : Número de paquetes (Number of bunches)
- σ_x : Horizontal beam size
- σ_y : Vertical beam size

Luminosidad 101



Evento vs Colisión



Pileup (PU)

Luminosidad 101

¿Cómo se determina la luminosidad **registrada**?

La tasa de un observable dado se puede convertir a una medición de luminosidad usando una cantidad conocida como la **sección eficaz visible**.

$$R(t) = \frac{dN}{dt} = \mathcal{L}_{\text{inst}} \sigma_{\text{vis}}$$

Dadas las condiciones nominales en las que opera el LHC, la transferencia de la constante de calibración requiere un *luminómetro* cuya **linealidad** pueda medirse con precisión entre varios órdenes de magnitud tanto en luminosidad instantánea como en PU.

La luminosidad de cada paquete se debe medir de forma individual:

- **Online:** publicando a CMS y al LHC “en tiempo real” para retroalimentar las condiciones de operación.
- **Offline:** perfil de PU, eficiencia de reconstrucción.

$$L = \int \frac{R(t)}{\sigma_{\text{vis}}} dt$$

Luminosidad integrada -> requiere **estabilidad** de operación durante todo el periodo de toma de datos

Medida usando escaneos Van der Meer (VdM) en donde los haces se desplazan en la dirección transversal.

$$\sigma_{\text{vis}} = \frac{2\pi \Sigma_x \Sigma_y R_0}{N_1 N_2 f}$$

Σ_x, Σ_y — superposición entre haces
 R_0 — tasa durante colisiones centrales
 N_1, N_2 — número de protones por paquete (*bunch intensity*)
 f — frecuencia del LHC

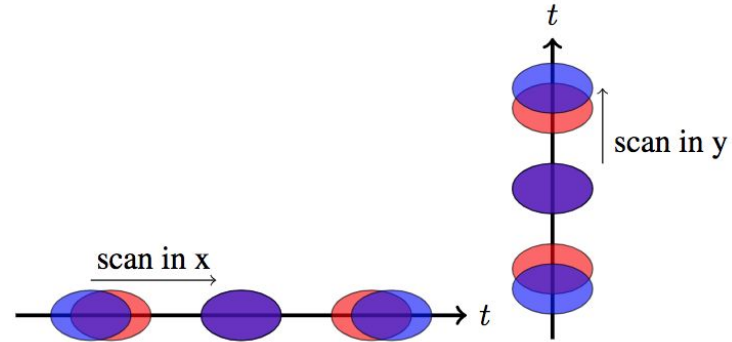
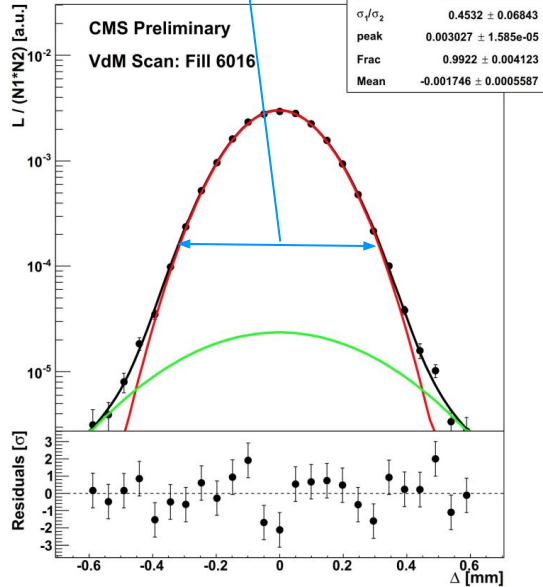
Condiciones especiales para los haces con **PU por paquete máximo de 0.5** y paquetes con mayor separación.

Depende de la instrumentación del LHC.

Escaneos Van der Meer

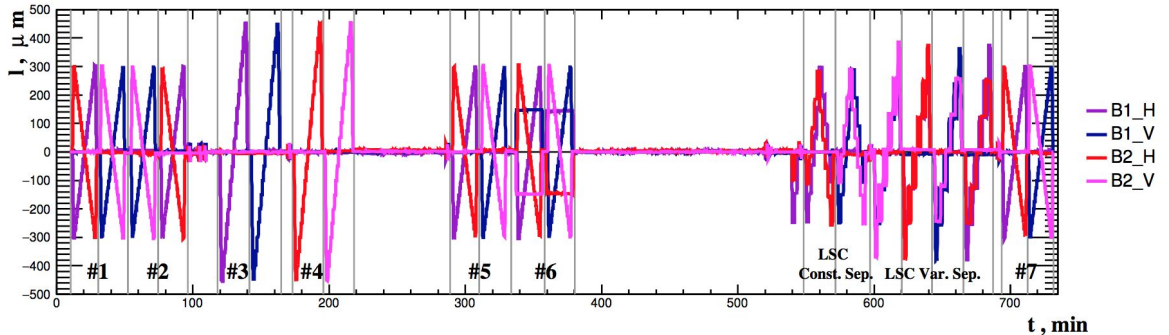
$$\sigma_{\text{vis}} = \frac{2\pi \Sigma_x \Sigma_y R_0}{N_1 N_2 f}$$

Scan 1: X-plane BCID 1783



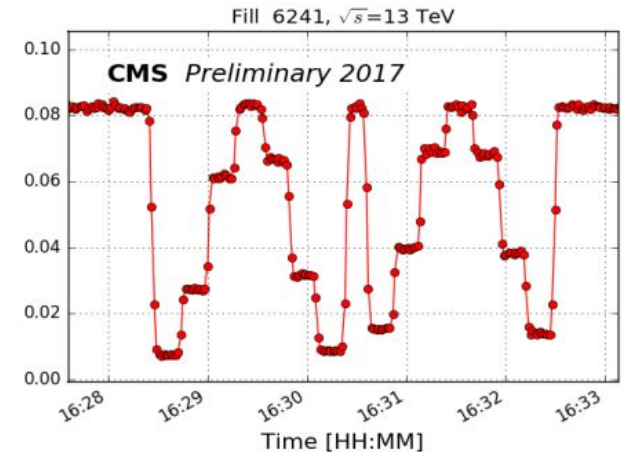
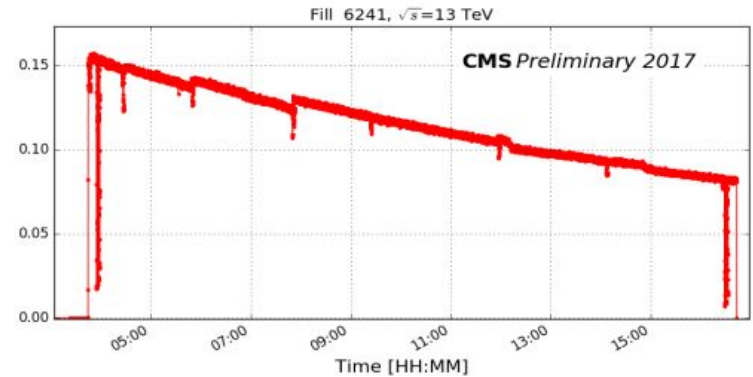
En un escaneo VdM, la separación entre los haces varía en las direcciones x y y, y el perfil de luminosidad que resulta se ajusta para determinar el ancho de la superposición de los haces.

DOROS beams position in VdM Scan with Fill6016

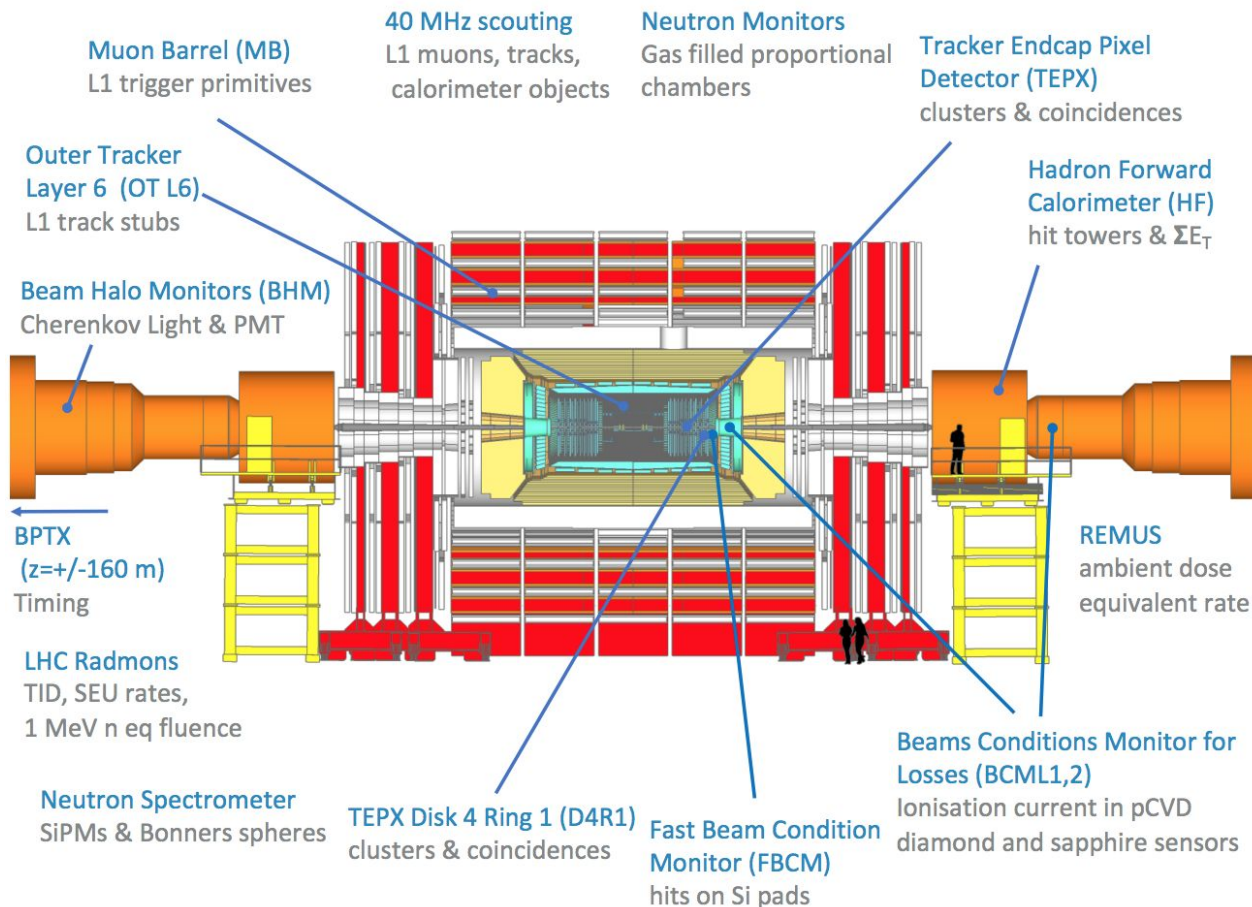
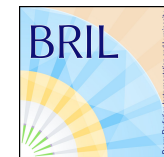


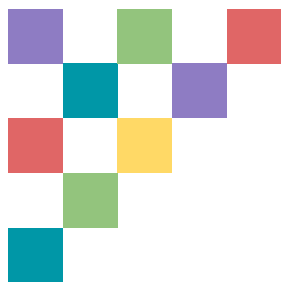
Emittance scans: mini escaneos VdM

- Escaneos rápidos de luminosidad al inicio y fin de cada *fill*.
- Entre 7 y 9 puntos, de 10s de duración cada uno.
- Menos precisos que los escaneos de VdM, pero útiles para hacer mediciones relativas.
- Útiles para estudiar la **dependencia temporal** de la respuesta de los luminómetros.
- **SBILs distintas al inicio y final de cada fill**, y variaciones en SBIL de paquete a paquete → útiles para estudiar y corregir efectos de **linealidad**.



El Proyecto BRIL @ CMS





Luminosidad en el LHC



Luminosidad en la Corrida 2 del LHC

2015-2016

Durante la Corrida 2, los principales luminómetros fueron:

- **Pixel detector** => pixel cluster counting (PCC)
- **HF** => occupancy (channels over threshold)
- **PLT** => coincidencias triples
- **BCM1F** => corriente inducida en los sensores de diamante
- **DT** => número de muones

$$\begin{aligned}\langle N_{\text{observables}} \rangle &= \langle N_{\text{observables/interaction}} \rangle \langle N_{\text{interactions}} \rangle \\ &\equiv \langle N_{\text{observables/interaction}} \rangle \mu,\end{aligned}$$

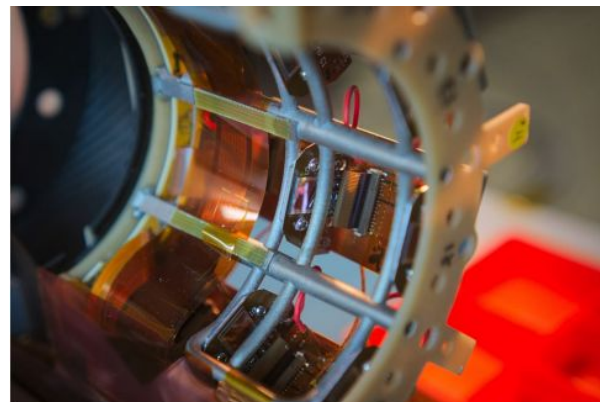
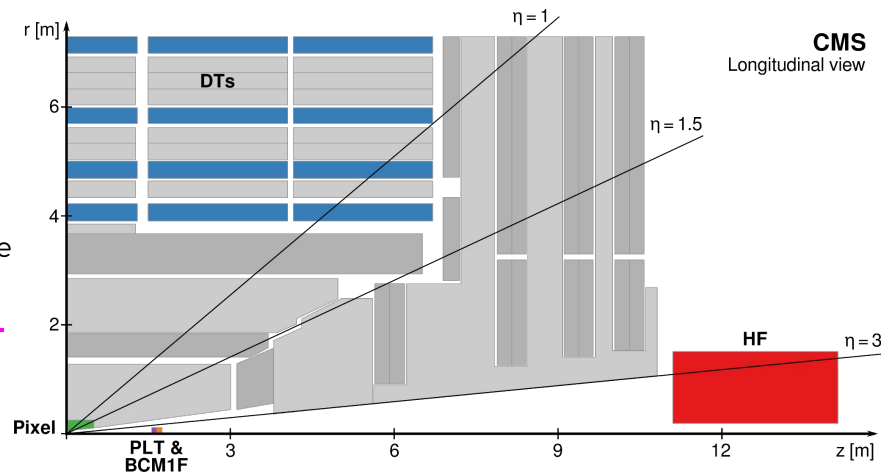
Rate-scaling

$$\mathcal{L}_b = \frac{\langle N_{\text{observables}} \rangle}{\langle N_{\text{observables/interaction}} \rangle} \frac{v_r}{\sigma} \equiv \langle N_{\text{observables}} \rangle \frac{v_r}{\sigma_{\text{vis}}}.$$

Zero-counting

$$\langle f_0 \rangle = \sum_{k=0}^{\infty} \frac{e^{-\mu} \mu^k}{k!} p^k = e^{-\mu(1-p)}.$$

$$\mathcal{L}_b = \mu \frac{v_r}{\sigma} = -\ln \langle f_0 \rangle \frac{1}{1-p} \frac{v_r}{\sigma} \equiv -\ln \langle f_0 \rangle \frac{v_r}{\sigma_{\text{vis}}}.$$



Luminosidad en la Corrida 2 del LHC

2015-2016

Fig. 17 The luminosity measurements from PCC, HFOC, and RAMSES are compared as a function of the integrated luminosity in 2016. Comparison among three luminometers facilitates the identification of periods where a single luminometer suffers from transient stability issues. The ratios that are plotted in red contain invalidated data. The dashed line delineates the vdM calibration (fill 4954)

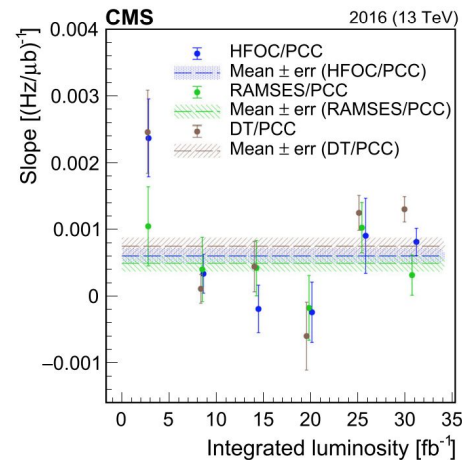
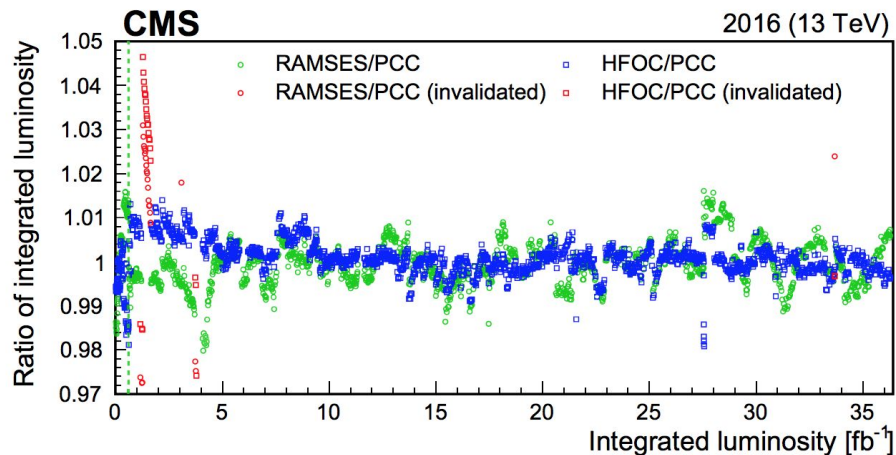
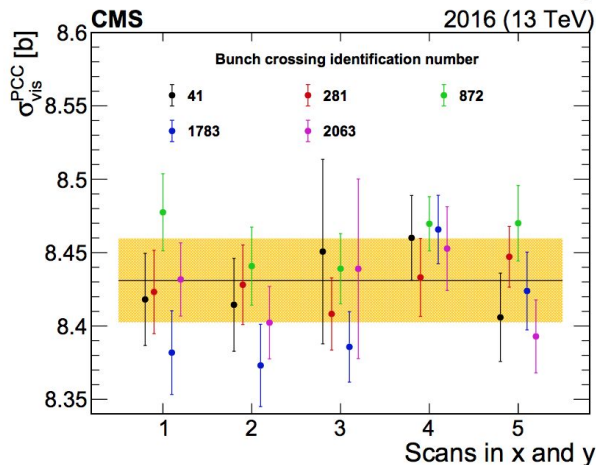


Fig. 19 Linearity summary for 2015 (upper) and 2016 (lower) at $\sqrt{s} = 13$ TeV. The slopes are plotted for each detector relative to PCC. The markers are averages of fill-by-fill slopes from fits binned in roughly equal fractions of the total integrated luminosity through the year. The error bars on the markers are the propagated statistical uncertainty from fitted slope parameters in each fill, which are weighted by integrated luminosities of each fill. The dashed lines and corresponding hatched areas show the average from the entire data set and its uncertainty

Luminosidad en la Corrida 2 del LHC

2015-2016



2015:
2.27 fb⁻¹

2016:
36.3 fb⁻¹

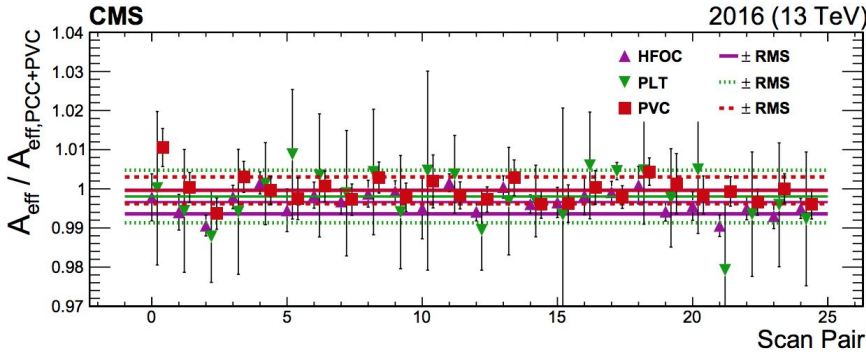


Table 4 Summary of contributions to the relative systematic uncertainty in σ_{vis} (in %) at $\sqrt{s} = 13$ TeV in 2015 and 2016. The systematic uncertainty is divided into groups affecting the description of the vdM profile and the bunch population product measurement (normalization), and the measurement of the rate in physics running conditions (integration). The fourth column indicates whether the sources of uncertainty are correlated between the two calibrations at $\sqrt{s} = 13$ TeV

Source	2015 (%)	2016 (%)	Corr
Normalization uncertainty			
<i>Bunch population</i>			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
<i>Beam position monitoring</i>			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
<i>Beam overlap description</i>			
Beam-beam effects	0.5	0.5	Yes
Length scale calibration	0.2	0.3	Yes
Transverse factorizability	0.5	0.5	Yes
<i>Result consistency</i>			
Other variations in σ_{vis}	0.6	0.3	No
Integration uncertainty			
<i>Out-of-time pileup corrections</i>			
Type 1 corrections	0.3	0.3	Yes
Type 2 corrections	0.1	0.3	Yes
<i>Detector performance</i>			
Cross-detector stability	0.6	0.5	No
Linearity	0.5	0.3	Yes
<i>Data acquisition</i>			
CMS deadtime	0.5	< 0.1	No
Total normalization uncertainty	1.3	1.0	–
Total integration uncertainty	1.0	0.7	–
Total uncertainty	1.6	1.2	–

Corrida 3

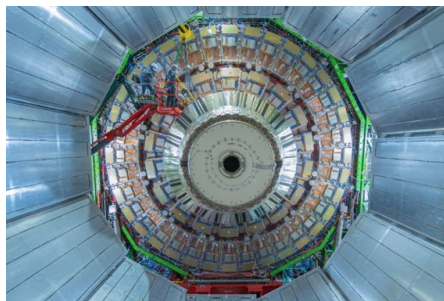
2022-2024

Long shutdown 2 (LS2): 2019 – 2021

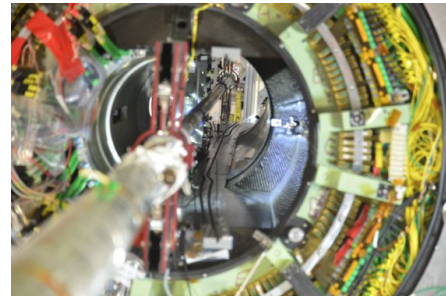
Corrida 3: inició en julio de 2022 y el objetivo es recolectar el doble de la luminosidad integrada de la Corrida 2.



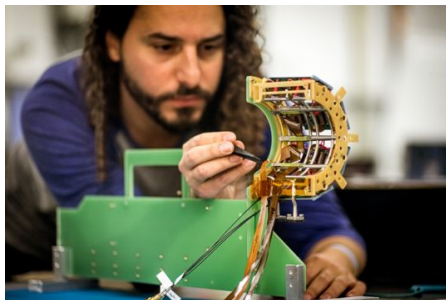
Instalación de un nuevo *beam pipe*



Instalación del detector GEM (Fase-2)



Instalación de la nueva *Barrel Pixel Layer 1*



Reemplazo de los detectores PLT y BCM1F

+ *Muon demonstrators,*
...

Corrida 3

2022-2024

LHC Page1 Fill: 7920 E: 6800 GeV t(SB): 01:10:43 05-07-22 17:57:51

PROTON PHYSICS: STABLE BEAMS

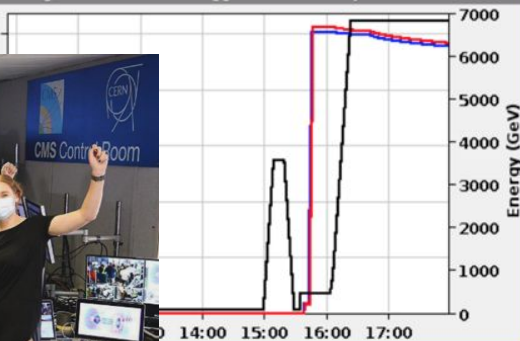
Energy: 6800 GeV I B1: 2.31e+11 I B2: 2.35e+11

Inst. Lumi [(ub.s)⁻¹] IP1: 4.38 IP2: 0.33 IP5: 4.47 IP8: 0.00

FBCT Intensity and Beam Energy

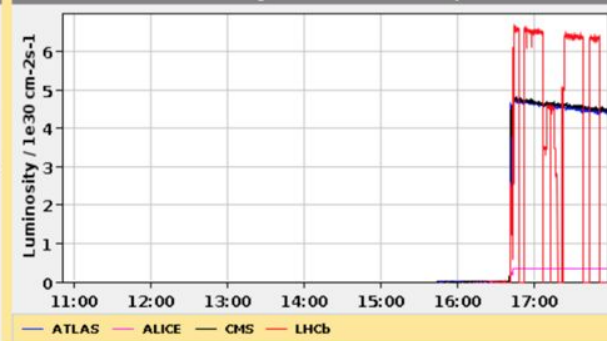
Updated: 17:57:49

2.5E11

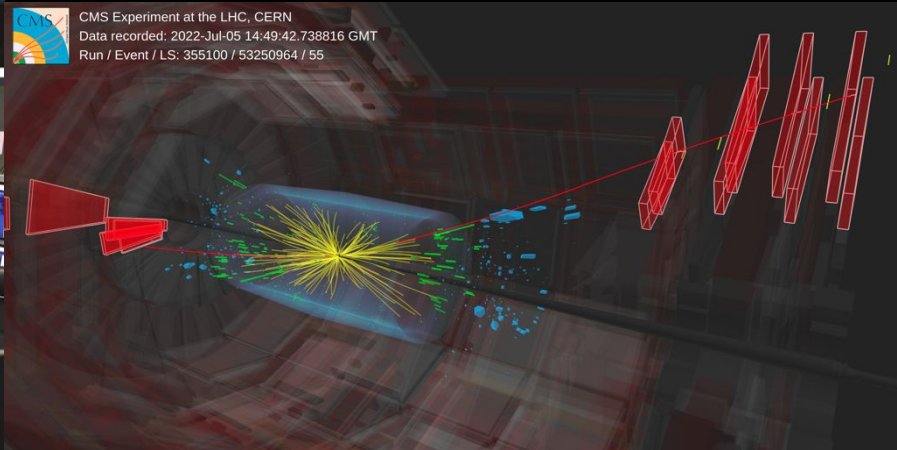


Instantaneous Luminosity

Updated: 17:57:51



CMS Experiment at the LHC, CERN
Data recorded: 2022-Jul-05 14:49:42.738816 GMT
Run / Event / LS: 355100 / 53250964 / 55

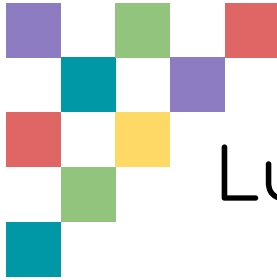


CMS



The Phase-2 Upgrade of the CMS
**Beam Radiation, Instrumentation
and Luminosity Detectors**
Technical Design Report

Luminosidad en el HL-LHC



EL HL-LHC

Actualizaciones a:

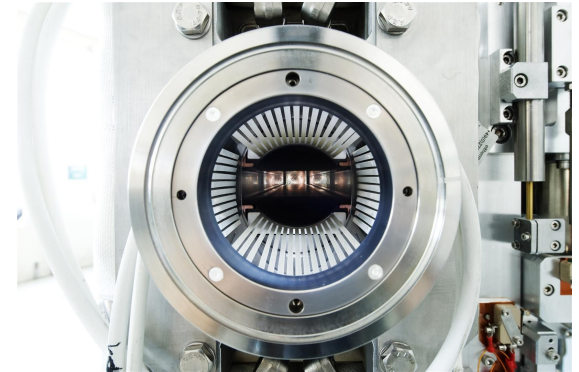
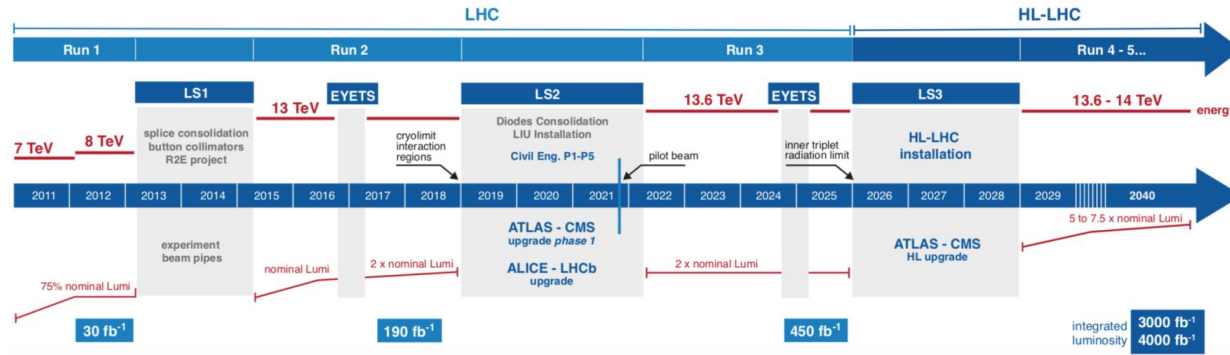
- Cadena de aceleradores.
- Cuadrupolos y “óptica” de los haces.
- *Crab cavities*.
- Sistema de protección del acelerador (colimadores).
- Líneas de transmisión superconductoras.
- ...



The Linac4 accelerator.
(Image: Maximilien Brice/CERN)



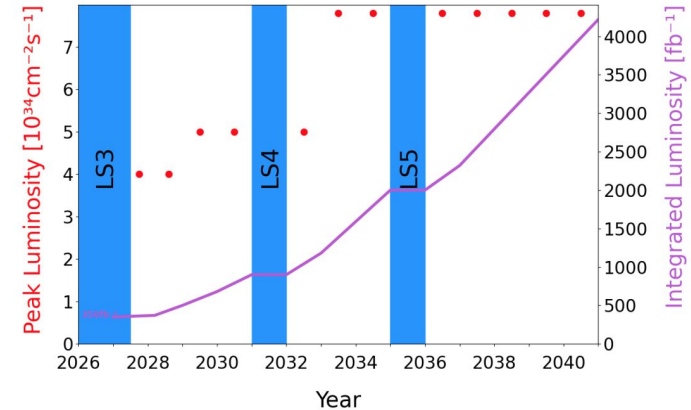
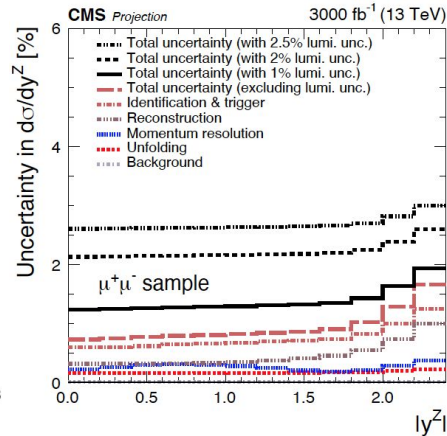
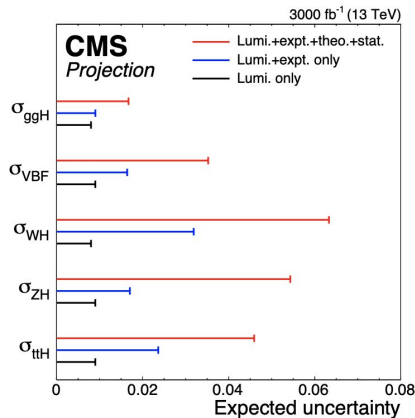
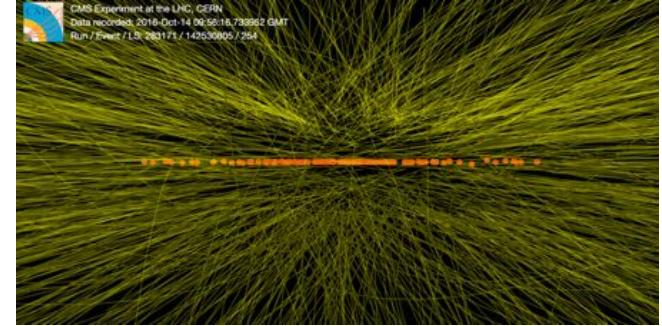
Assembly of the first crab cavity.
(Image: Julien Ordan/CERN)



LHC collimator.
(Image: Claudia Marcelloni/CERN)

Mediciones de precisión de luminosidad en la era del HL-LHC

- Se espera que el HL-LHC opere a una luminosidad instantánea base de $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ con un PU promedio de 140.
 - Máximo esperado: $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ y PU promedio de 200.
- El alto PU y el ambiente extremo de radiación esperado hace que los detectores tengan que ser mejorados para mantener su desempeño.
- Una medición precisa de la luminosidad es clave para el programa de física del HL-LHC, ya que se ha convertido en una de las incertidumbres dominantes de muchos análisis.
 - Mediciones de luminosidad paquete-por-paquete.
 - Objetivo: incertidumbre de 1% offline (2% online).



Clave para la precisión: redundancia

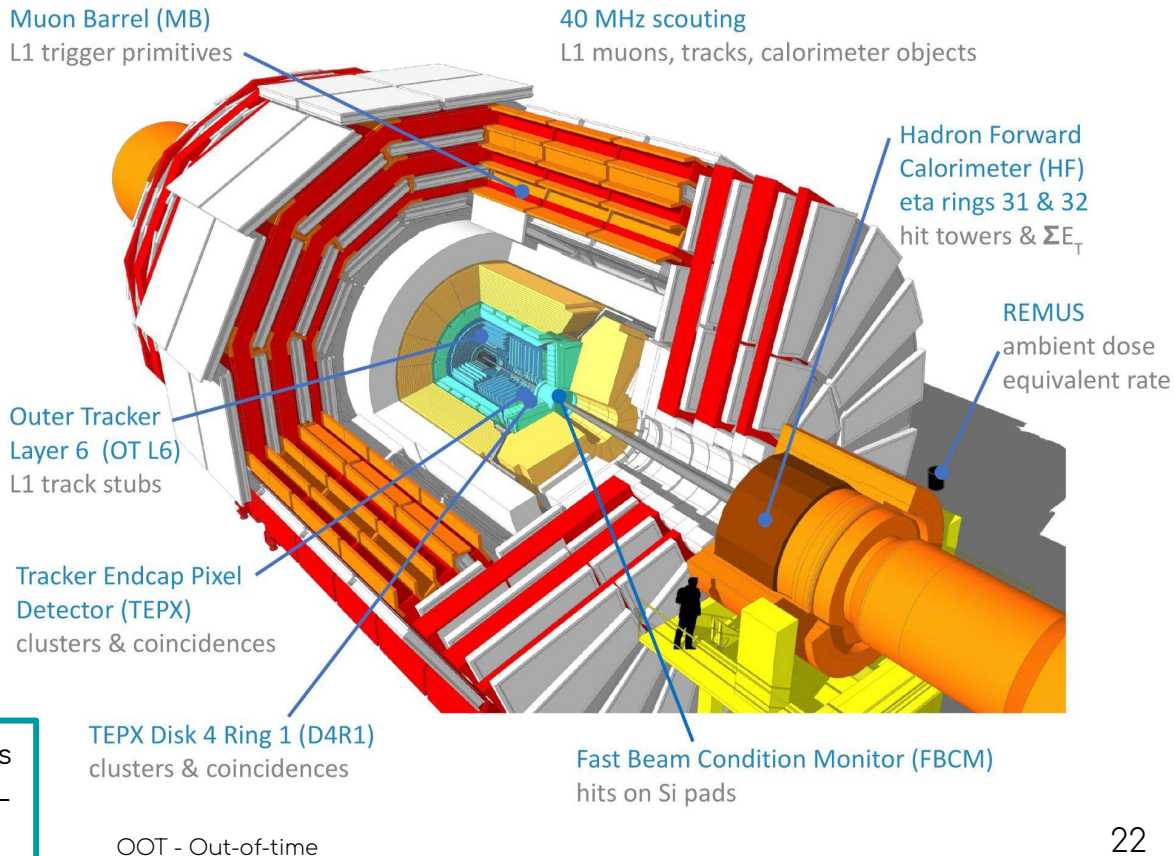
En la Fase-2 BRIL planea utilizar varios subsistemas de CMS, así como un luminómetro independiente.

- La experiencia durante la Fase-1 nos ha mostrado la importancia de tener múltiples sistemas para medir la luminosidad para tener redundancia y minimizar los sesgos originados por efectos de un mismo detector:
 - Efectos de sincronización (OOT).
 - Linealidad.
 - Estabilidad operacional.

Emittance scans para monitorear la eficiencia y la linealidad de cada luminómetro

Tecnologías y métodos de conteo diversos, sistemáticos distintos

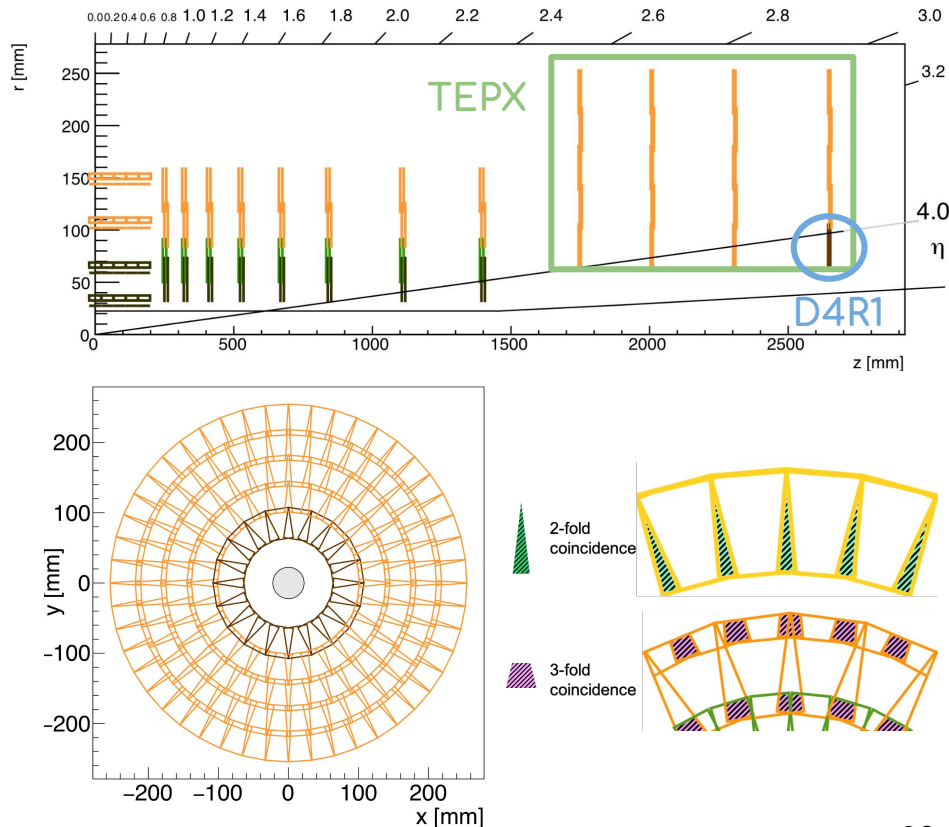
Componentes comunes en la adquisición de datos y en el análisis para todos los subsistemas de BRIL (e.g. histogramas, BRILDAQ)



Tracker Endcap Pixel Detector (TEPX)

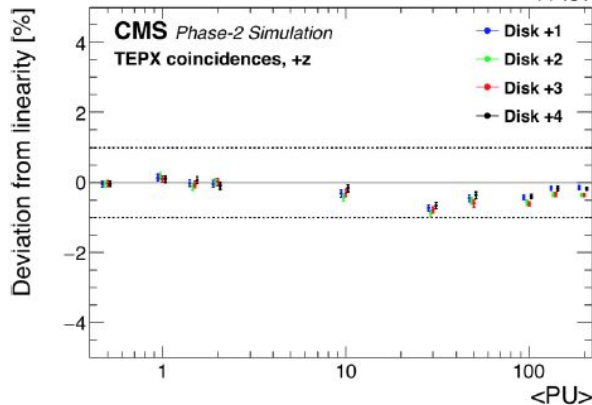
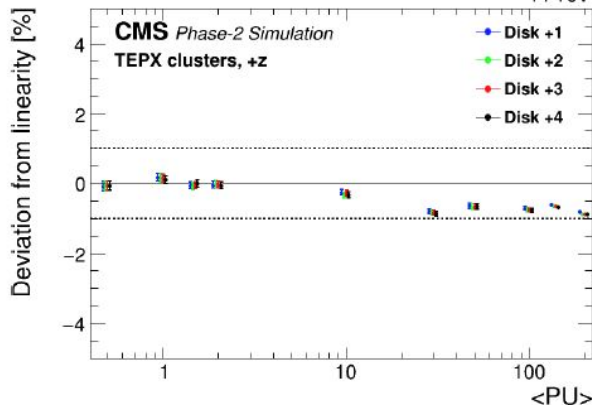
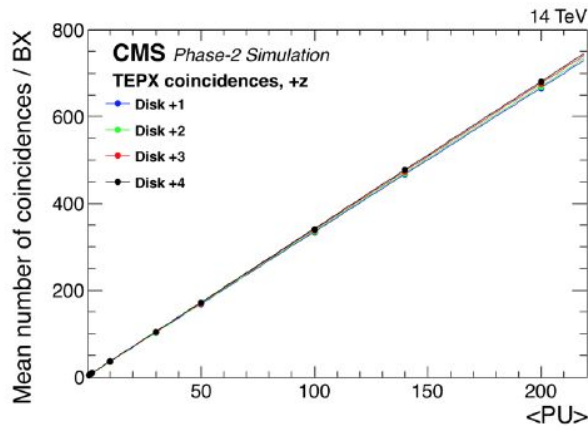
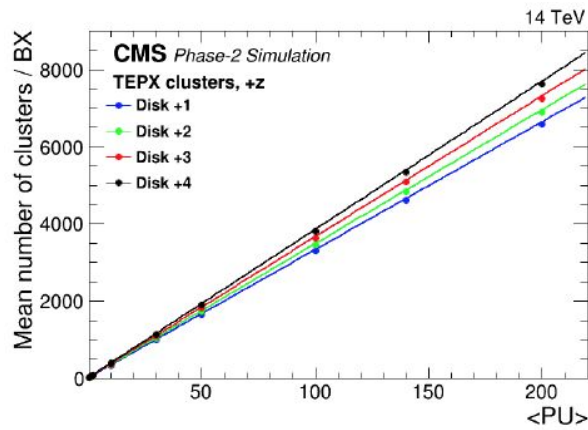
Descripción

- Se instalará en la región externa del Tracker.
 - 4 discos dobles cada uno conformado por 5 anillos, en cada lado de CMS.
 - Para asegurar hermeticidad, módulos consecutivos se traslapan. Esto permite reconstruir dobles y triples coincidencias, las cuáles son menos sensibles a contaminación por ruido o por *fakes*.
 - Debido a la baja utilización de recursos de la electrónica, TEPX puede usarse simultáneamente para tracking y para luminosidad.
 - 750 kHz triggers para física.
 - 75 kHz triggers para luminosidad durante corridas de física.
 - Bandwidth completo durante escaneos VdM.
 - Disponible durante '*qualified beams*'.
-
- **Disk 4 Ring 1 (D4R1)** no es útil para tracking.
 - Operado exclusivamente por BRIL.
 - Bandwidth completo para luminosidad.
 - Da información de BIB y puede utilizarse durante el ciclo completo del LHC.



Tracker Endcap Pixel Detector (TEPX)

Desempeño esperado



La linealidad entre los escenarios de PU de 0 y 200 para clusters y coincidencias fue evaluada usando simulaciones.

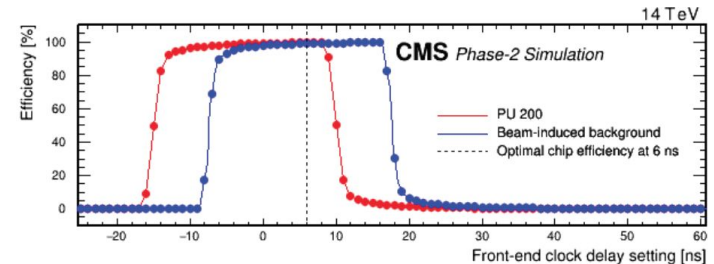
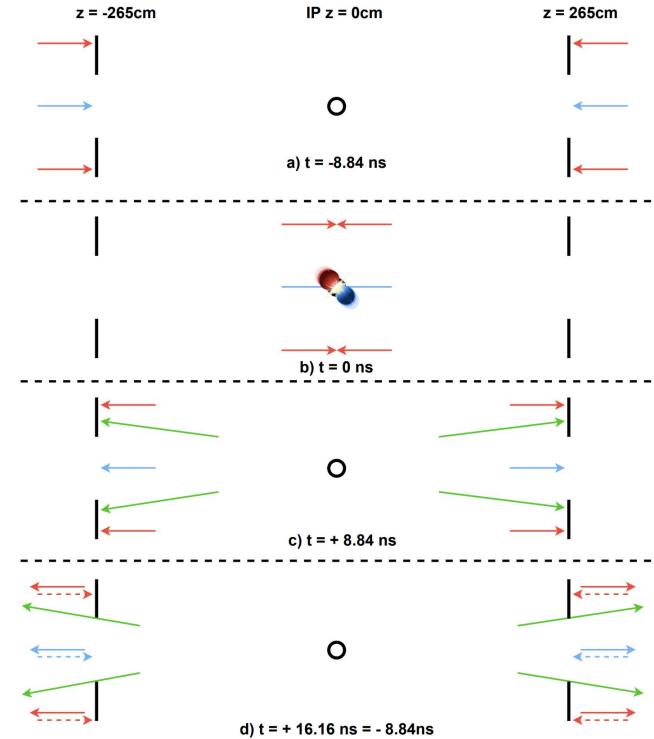
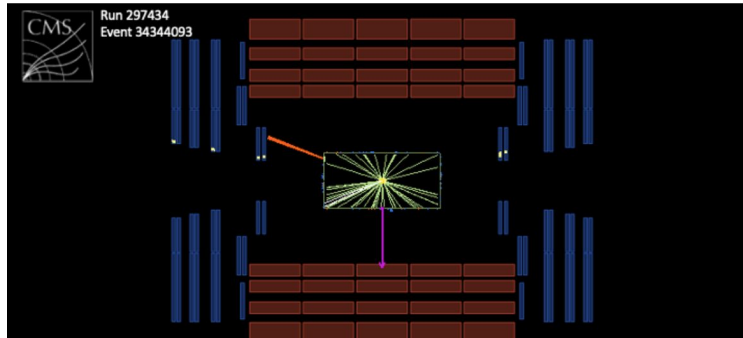
Desviaciones dentro de 1% a lo largo de todo el rango.

Incertidumbre estadística para PCC:
0.095%/BX/s para PU200

TEPX Disk 4 Ring 1 (D4R1)

Beam-induced background

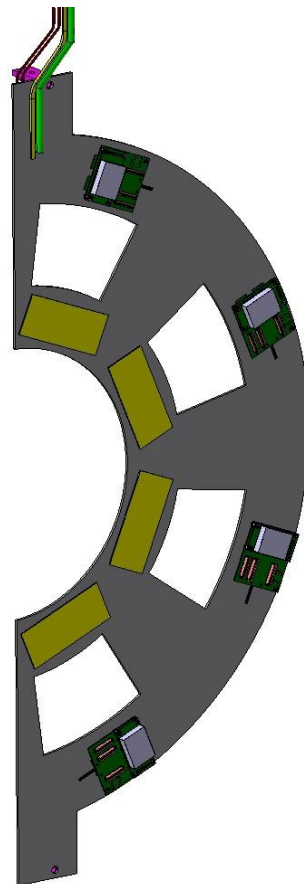
- BIB se origina de dos formas: 1) interacciones *beam-gas*, y 2) *beam-halo*.
- Solamente el primer paquete del tren o paquetes 'desparejados' se utilizarán para medir el BIB.
 - Contaminación importante de productos de colisiones.
 - Se necesitan al menos 30 cruces vacíos para disminuir la contribución de partículas OOT.
- Los módulos del D4R1 tienen que ajustarse para ver el BIB un cruce antes de los productos de las colisiones.
- Se evaluó la resolución utilizando simulaciones, dando resultados prometedores.



Un luminómetro independiente: FBCM

Motivación & Diseño

- FBCM: Fast Beam Conditions Monitor
- En las Corridas 2/3, los luminómetros independientes fueron PLT & BCM1F.
- Características principales:
 - Bajo el control completo de BRIL.
 - Independiente de los servicios centrales de CMS (DAQ, TCDS, RC, magnet status).
 - Medición de luminosidad & BIB fuera de 'stable beams'.
 - Puede ser un candado adicional de seguridad para CMS (Interlock Tracker HV).
 - Mediciones de luminosidad independientes, redundantes y complementarias.
- Estará basado en sensores de silicio con un chip rápido en el FE (ASIC en proceso de diseño).
 - Dividido en cuatro secciones, cada una cubriendo una mitad en ambos lados del detector.
 - Tamaño y ubicación de los sensores fueron optimizados utilizando simulaciones.
 - Se ubicará detrás del último disco de TEPX.
 - Compartirá los servicios y líneas de enfriamiento con TEPX.
 - En el diseño debe considerarse no poner en riesgo a TEPX.



Un luminómetro independiente: FBCM

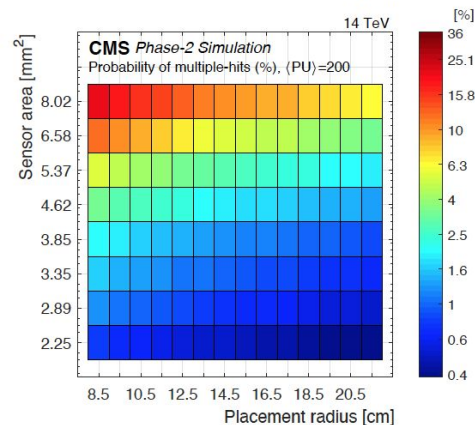
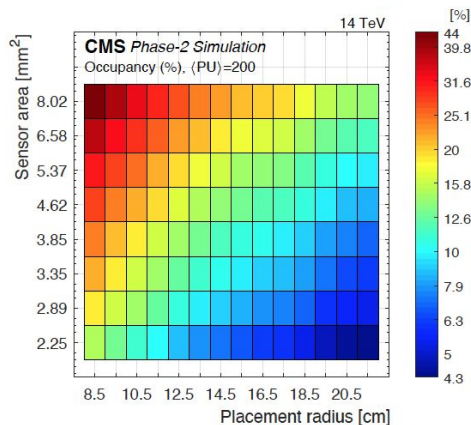
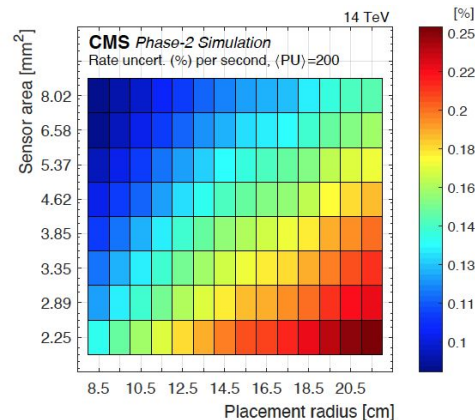
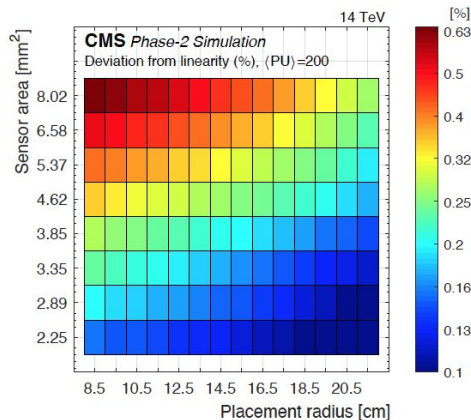
Optimización del diseño

Consideraciones:

- FBCM utilizará el algoritmo zero-counting algorithm.
- Buena precisión estadística.
- Excelente linealidad.

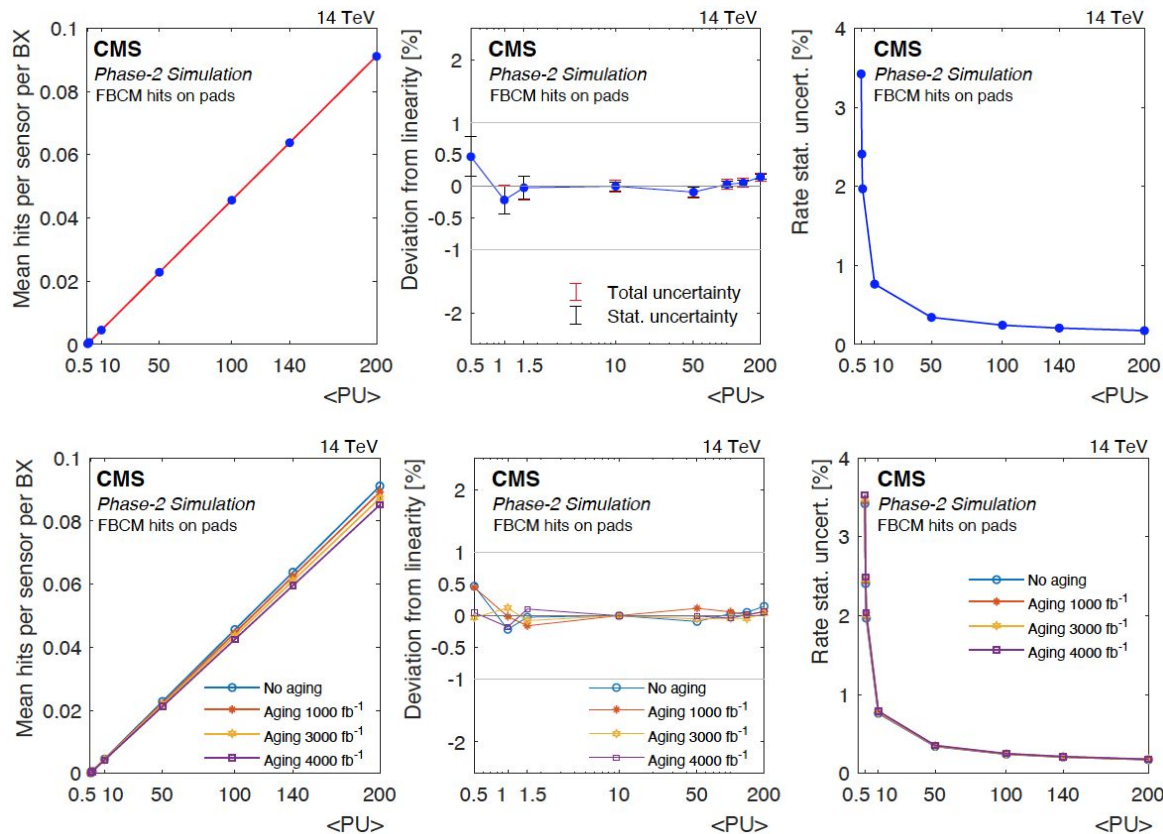
TDR baseline scenario: 2.89 mm^2 at $r = 14.5 \text{ cm}$.

336 sensores.



Un luminómetro independiente: FBCM

Desempeño esperado



Incertidumbre estadística para PU200 de $\sim 0.2\%/BX/s$.

Efectos del envejecimiento tomando en cuenta tres escenarios de luminosidad integrada. Desviación de un comportamiento perfectamente lineal dentro de 0.5% para PU200 en todos los escenarios.

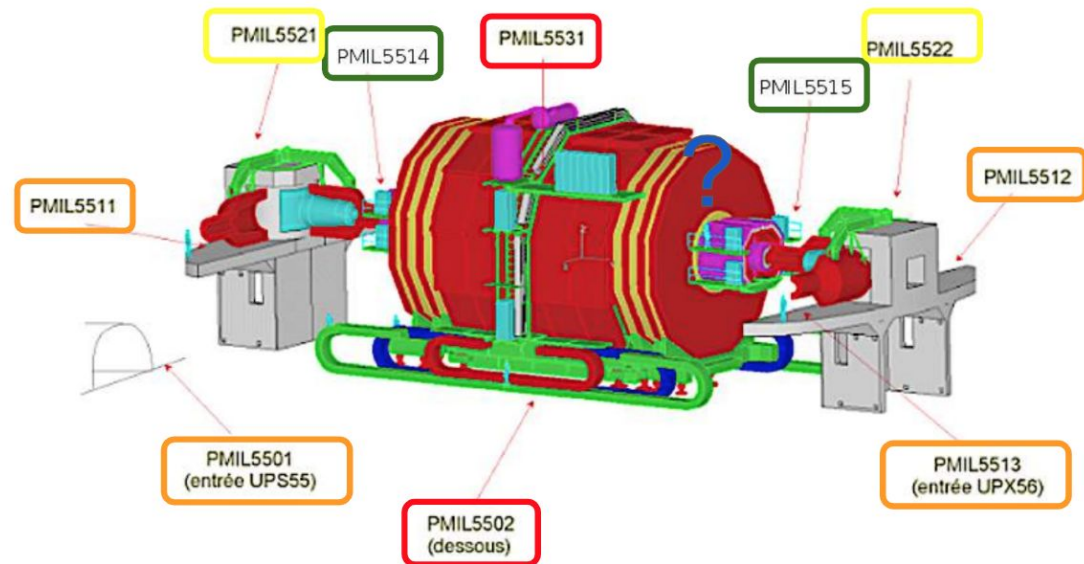
REMUS: Radiation and Environmental Unified Supervision

Uso para luminosidad

Detectors at P5

- 8+2 detectors in Run 2
- 2 additional detectors in Run 3

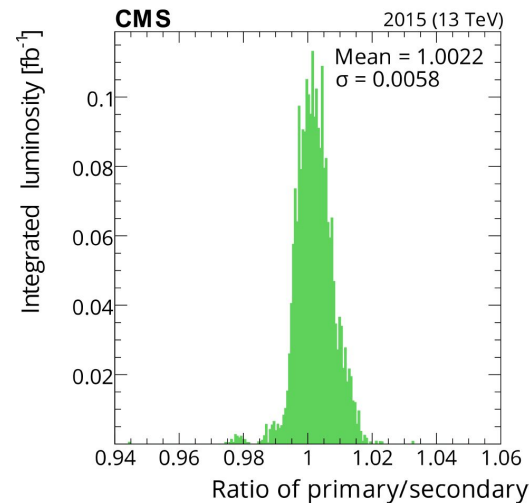
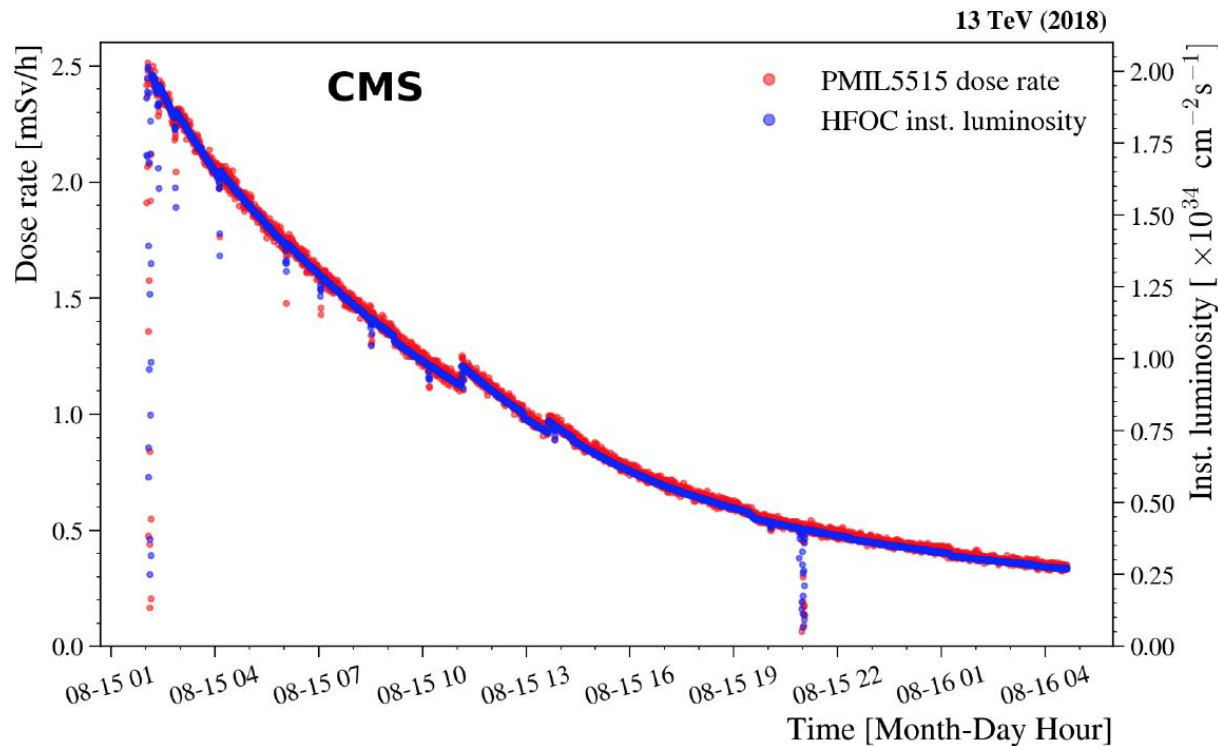
- Monitor radiation levels (ambient dose equivalent rates)
- Alarm functions
- Long-term data logging



- : Installed a little bit later in Run 2. Located closer to the IP. Used for luminosity cross check due to higher rates.
- : Close to the cavern walls. Similar dose levels among them
- : Located at very end of the cavern. Lower exposition
- : Installed below CMS structure(02), and among electronics racks (31) low and rare measurements
- : Requested for Run 3

REMUS: Radiation and Environmental Unified Supervision

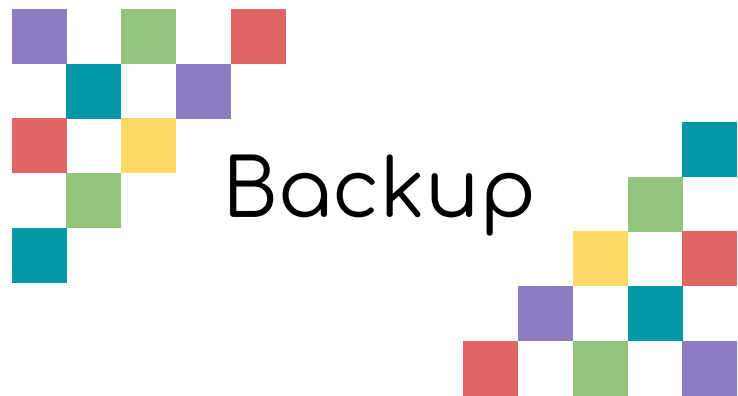
Uso para luminosidad



Resumen



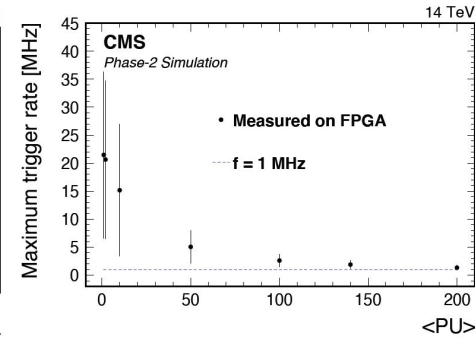
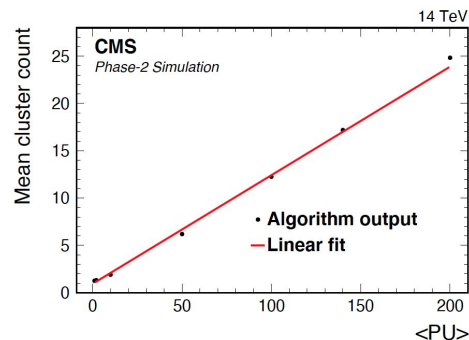
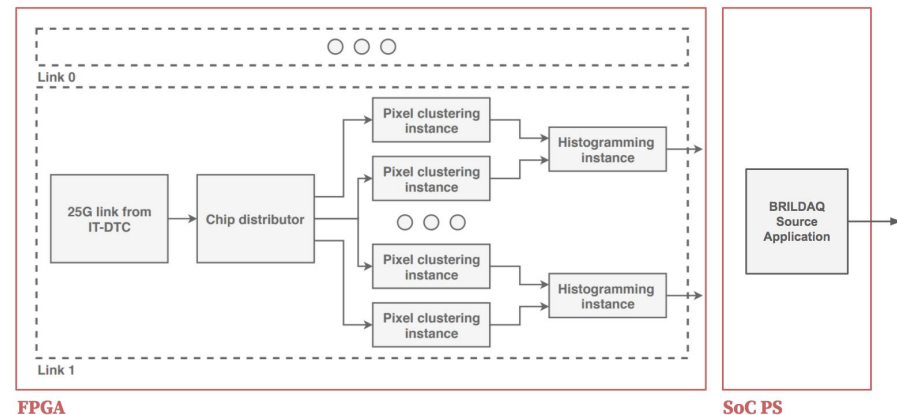
- La luminosidad es un parámetro fundamental para CMS, tanto para los análisis de física como para retroalimentación rápida al LHC.
- El proyecto BRIL es responsable de monitorear las condiciones de los haces, de medir la radiación en la caverna del experimento, y de la operación de los detectores que miden la luminosidad.
- La Corrida 2 fue enormemente exitosa. El LHC logró superar la luminosidad instantánea máxima proyectada al momento de su diseño.
 - CMS ha logrado medir la luminosidad de los primeros dos años de dicha corrida con una precisión nunca antes alcanzada en un colisionador de hadrones.
- En el HL-LHC BRIL pretende alcanzar una precisión del 1% (2%) offline (online).
 - Como parte de la estrategia se utilizarán subsistemas de CMS y un luminómetro independiente.
 - El TDR resume con detalle los planes para la Fase-2 y marca el camino a seguir para las revisiones de ingeniería.



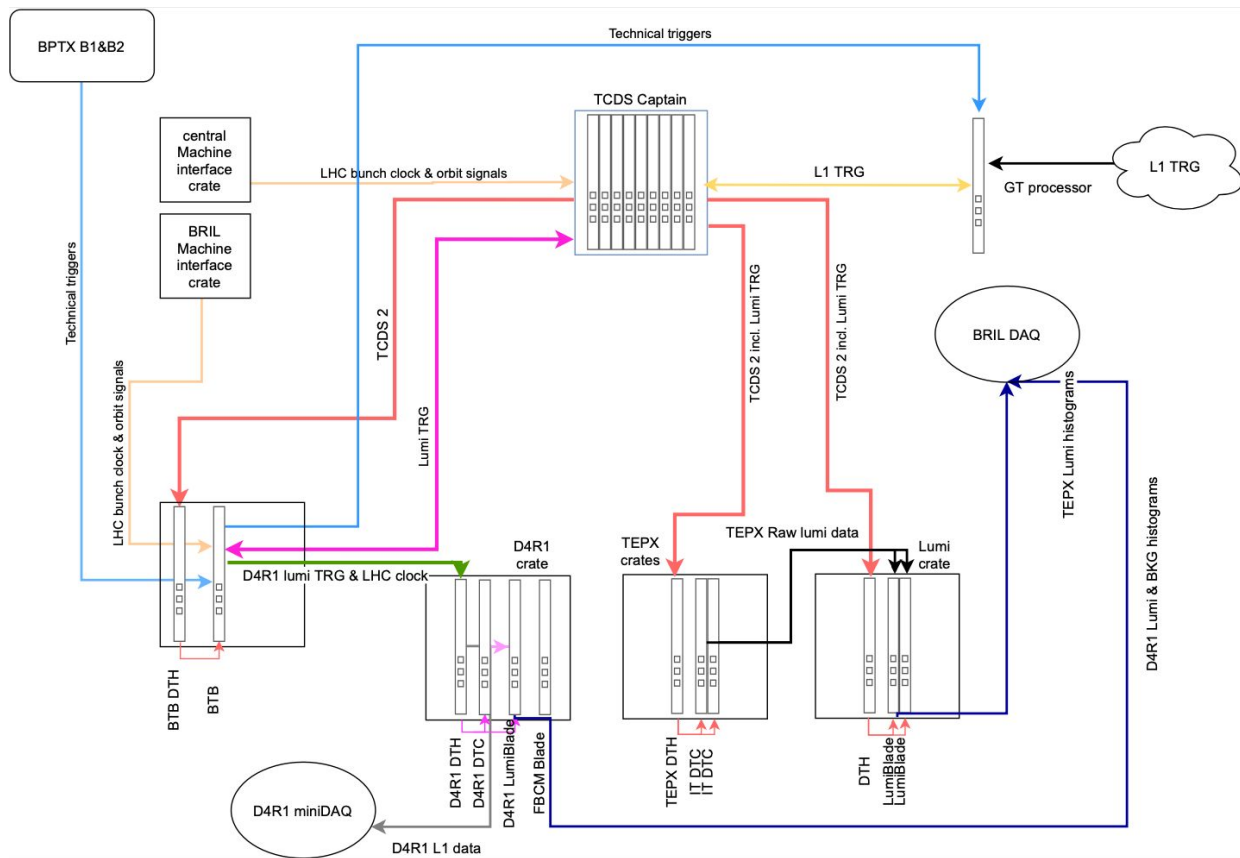
Tracker Endcap Pixel Detector (TEPX)

Pixel Cluster Counting on FPGA

- Same processing architecture for TEPX and D4R1.
- Targeting real-time pixel cluster counting on FPGA - performed per event per chip.
- Histogramming:
 - Cluster counts will be grouped per quarter ring.
- Prototype pixel cluster counting algorithm has been developed.
 - Two hits form a cluster if they touch horizontally, vertically or diagonally (single corner touch).
 - Position and size of clusters are not calculated.
 - Charge (ToT) information is not used.
 - Verified against the CMS offline reconstruction algorithm.
- Measured maximum event rate.
 - Satisfies D4R1 rate requirements and can sequentially process data from multiple chips for the rest of TEPX (e.g. 2 chips per instance).
 - Can handle very high rates during VdM.
- Adequate resource utilization such that additional features could be implemented.



Tracker Endcap Pixel Detector (TEPX) BRIL Trigger Board (BTB)



<= Trigger and data flow for the Phase-2 TEPX system (lumi centered)

The BTB will generate independent luminosity triggers for the TEPX system and distribute them via the central TCDS2 system.

It will also:

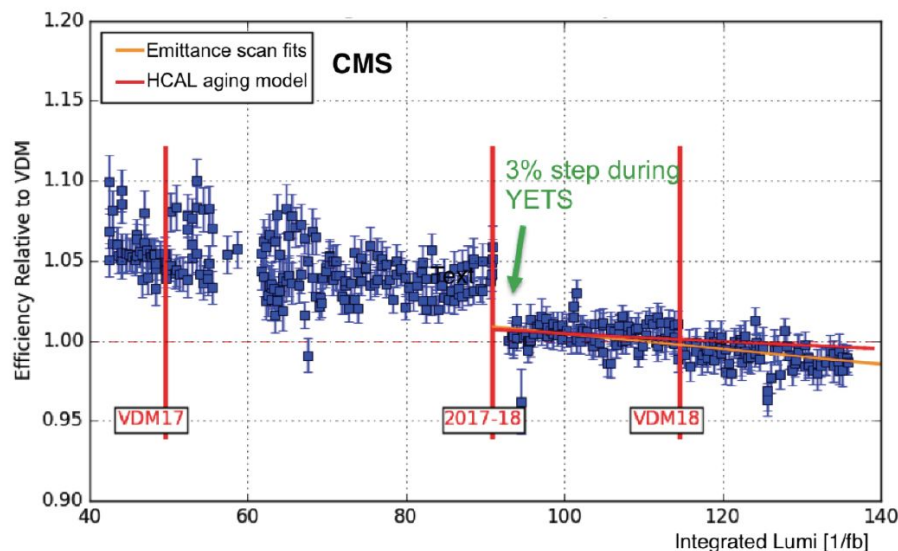
- Generate a TCDS2-like control stream based on the LHC clock for D4R1 as it can be used during the LHC ramp.
- Encode beams logical signals from the BPTX system into a high-speed serial optical data link and synchronize them with TCDS2.

Prototype BTB firmware developed and tested on Serenity.

Hadron Forward Calorimeter (HF)

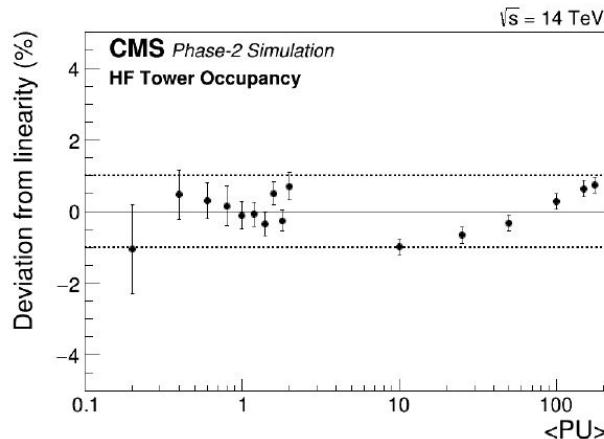
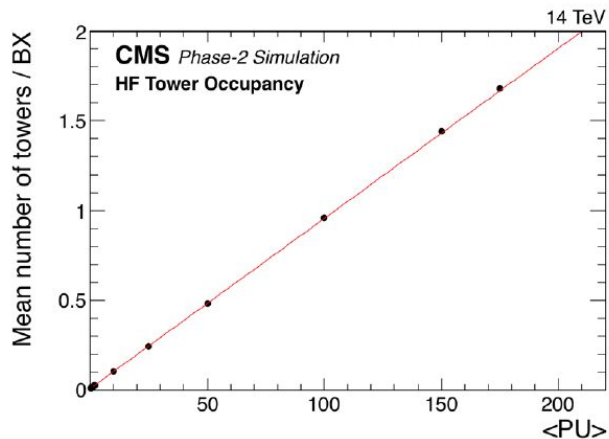
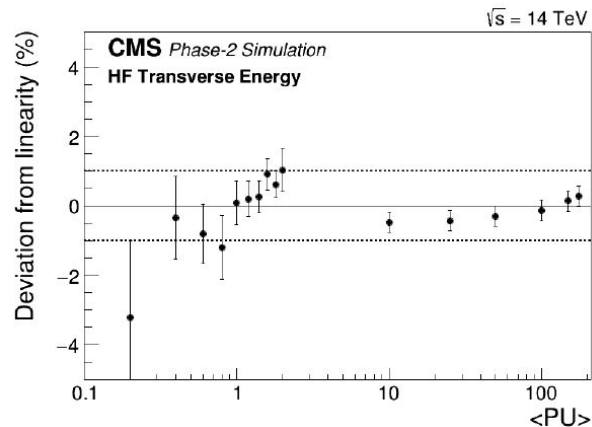
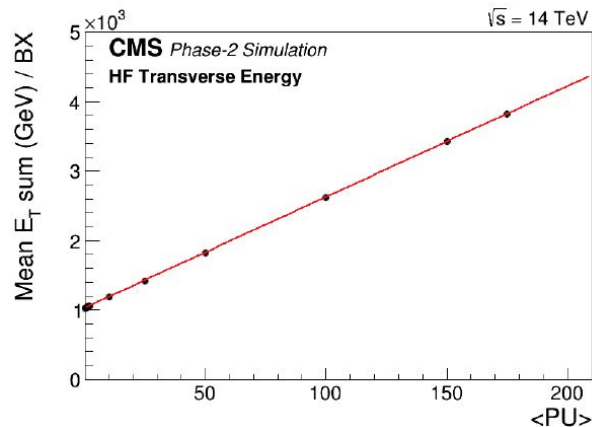
Overview

- One of the main luminometers in Run 2.
 - No significant changes foreseen for Phase-2.
- Two algorithms, using a limited number of calorimeter towers (η rings 31 and 32) corresponding to $3.15 < |\eta| < 3.50$, are used to measure luminosity:
 - HFOC uses “zero-counting” to track the fraction of bunch crossings with no energy depositions above a threshold.
 - HFET measures the sum of deposited transverse energy per bunch crossing.
- Main features of HF as a luminometer:
 - Full 40 MHz readout rate.
 - Online & offline luminosity measurements.
 - Available outside stable beams.
 - Independent of central CMS DAQ.
 - Independent of cooling.



Hadron Forward Calorimeter (HF)

Expected performance



Simulations used to evaluate linearity in occupancy and mean transverse energy sum, including the aging effects of 1000 fb^{-1} integrated luminosity.

Deviations from linear behaviour within 1% across the full pileup range.

Statistical precision for PU200:

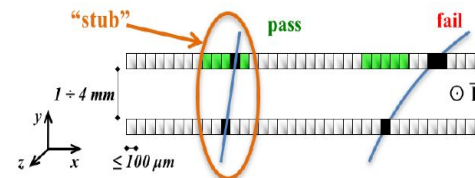
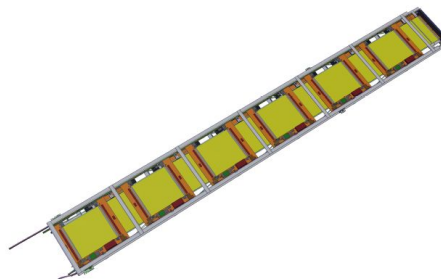
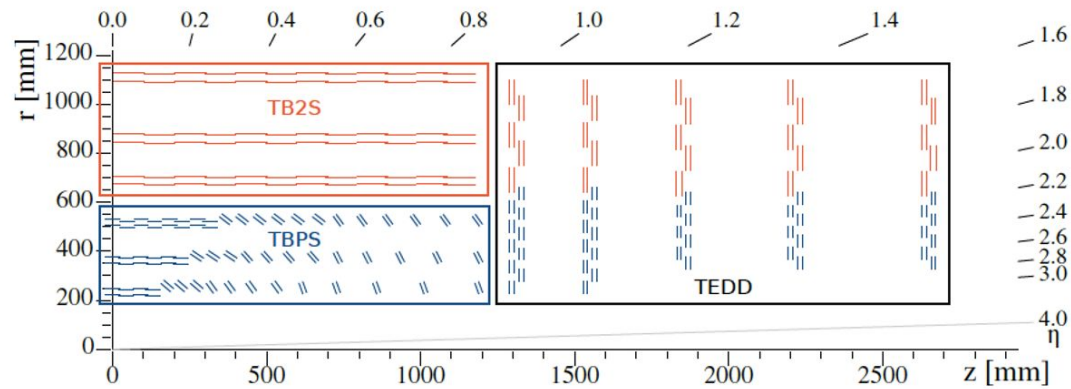
0.08%/BX/s for HFET

0.32%/BX/s for HFOC

Outer Tracker (OT)

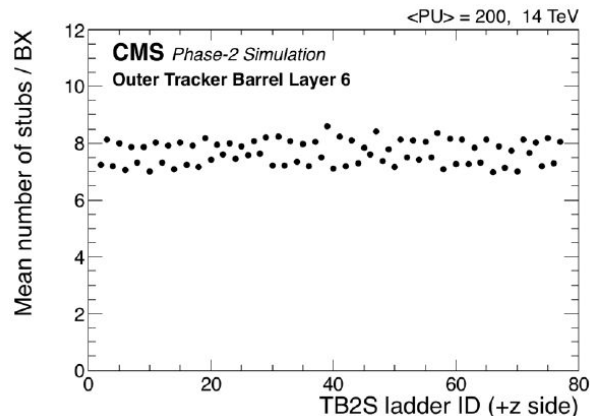
Overview

- Layout consists of 6 barrel layers and 5 endcap disks.
 - Layer 6 has 76 ladders on each half of CMS with 12 modules each
- Provides track stubs (two-hit coincidences on closely separated sensors) at 40 MHz.
 - Stub reconstruction is performed by the front-end ASIC.
- Available during stable beams.
- Histogramming module needs to be added to existing OT tracker firmware.
 - Stub information is received by DTC backend boards where the BRIL firmware module will be installed and will tap into this data stream.
 - 1 ladder per histogram (152 total).
 - Could be doubled if resources allow.
- Error handling to be fully developed.
 - Dynamically exclude failing modules from histogramming and include recovered ones.

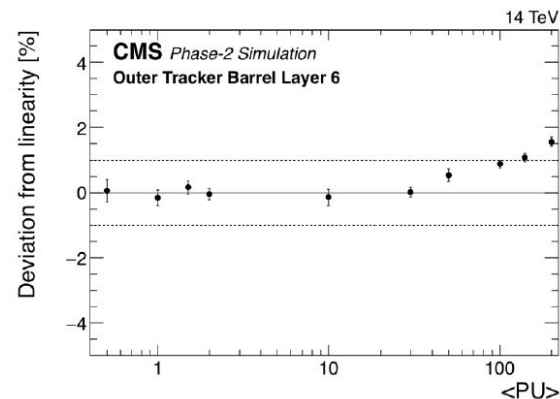
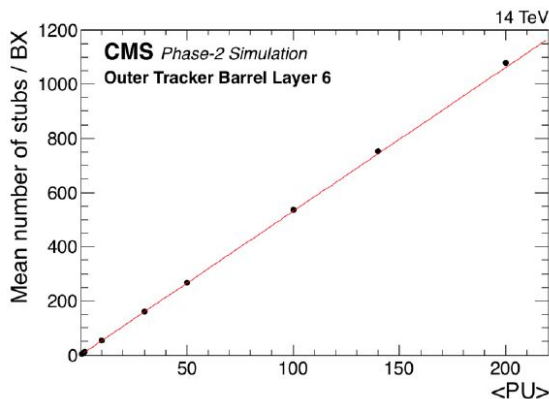


Outer Tracker (OT)

Expected performance



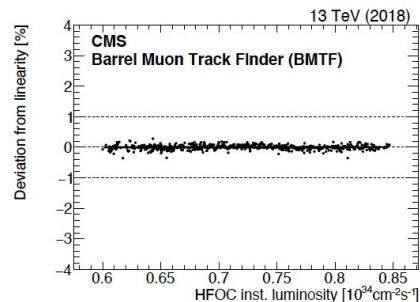
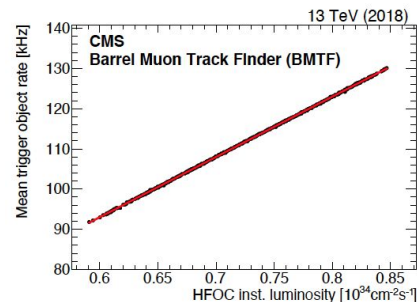
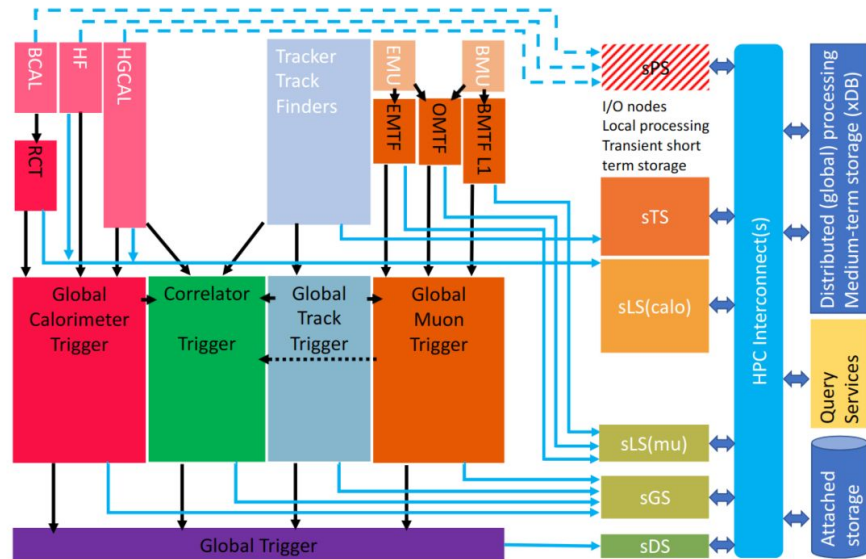
- Detector simulations, including effects from front-end electronics, were used to evaluate the linearity of the mean number of stubs in the pileup range between 0 and 200.
- Layer 6 in the barrel shows the best linearity using the current stub selection, with a deviation of less than 1.5% up to a pileup of 200.
- Simulations show that for PU 200 the maximum total rate is 1078 stubs per event under physics conditions. Considering a 40 MHz readout rate, this translates into a statistical precision of **0.03% / BX / s**
-> Most statistically powerful luminometer!



40 MHz Scouting

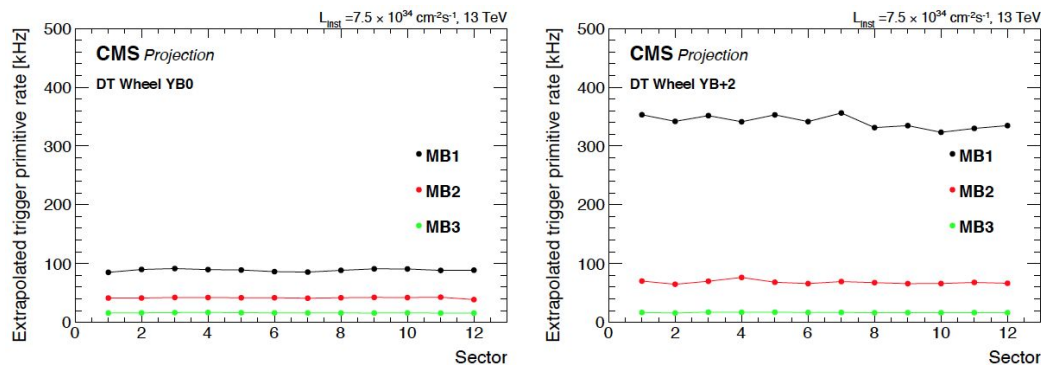
Overview

- The scouting system captures L1 trigger objects generated by different L1 layers using spare, high speed, optical links.
 - Useful for monitoring, algorithm development, and physics studies with high statistics.
- For Phase-II, BRIL firmware will be installed in the Global/Local Scouting boards to record L1 objects.
 - Barrel Muon Track Finder (BMTF) -> histograms with per bunch info.
 - BMTF was used for Run 2 luminosity measurements (orbit- and LS-integrated rates), with excellent linearity and small backgrounds, useful for systematic evaluations.
 - Extended demonstrator in Run 3 provides access to BMTF muon candidates or best 8 global muons, as well as calorimeter information.
- Possibility to expand to EMTF (for BIB) and to other objects (e.g. track counting).



Muon Barrel (MB) System Overview

- Hits from DT and RPC detectors will form muon track segments or trigger primitives per DT chamber at L1.
 - Valid data during squeeze, when DAQ is in configured state.
 - These have already been studied in Run 2 and rates extrapolated to HL-LHC conditions.



- Trigger and readout electronics will be replaced for Phase-II, allowing bunch crossing identification through improved timing resolution.
- BRIL histogramming firmware will be installed in the back-end processor firmware and access primitive data in parallel to CMS L1 trigger.
 - Streamed at 40 MHz.
 - Histograms: primitive counts per bunch crossing per second.
 - Run 3 demonstrator (YB+2, sector 12) runs BRIL histogramming firmware.

Muon Barrel (MB) System

Expected performance

Performance of trigger primitives as luminosity observables was done using Run 2 data.

Dependence of total rate on the instantaneous luminosity recorded by HFOC is found to be linear with very small deviations, all within 1%.

-> No background corrections applied to DT primitives.

To estimate the statistical precision, the total orbit integrated rate is obtained from extrapolations and found to be 17 MHz.

-> 0.61 primitives/BX

1.2%/BX/s statistical uncertainty at PU200

