Luminosity measurement at CMS.
(Вимірювання світимості для експерименту CMS.)

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28 January 2022, Geneva, CERN

Дякую!

Дорогі вчителі, дякую вам за ваш час, за вашу зацікавленість і мотивацію розвиватися!

За те що хочете навчати нове покоління і оновлюєте програму навчання!

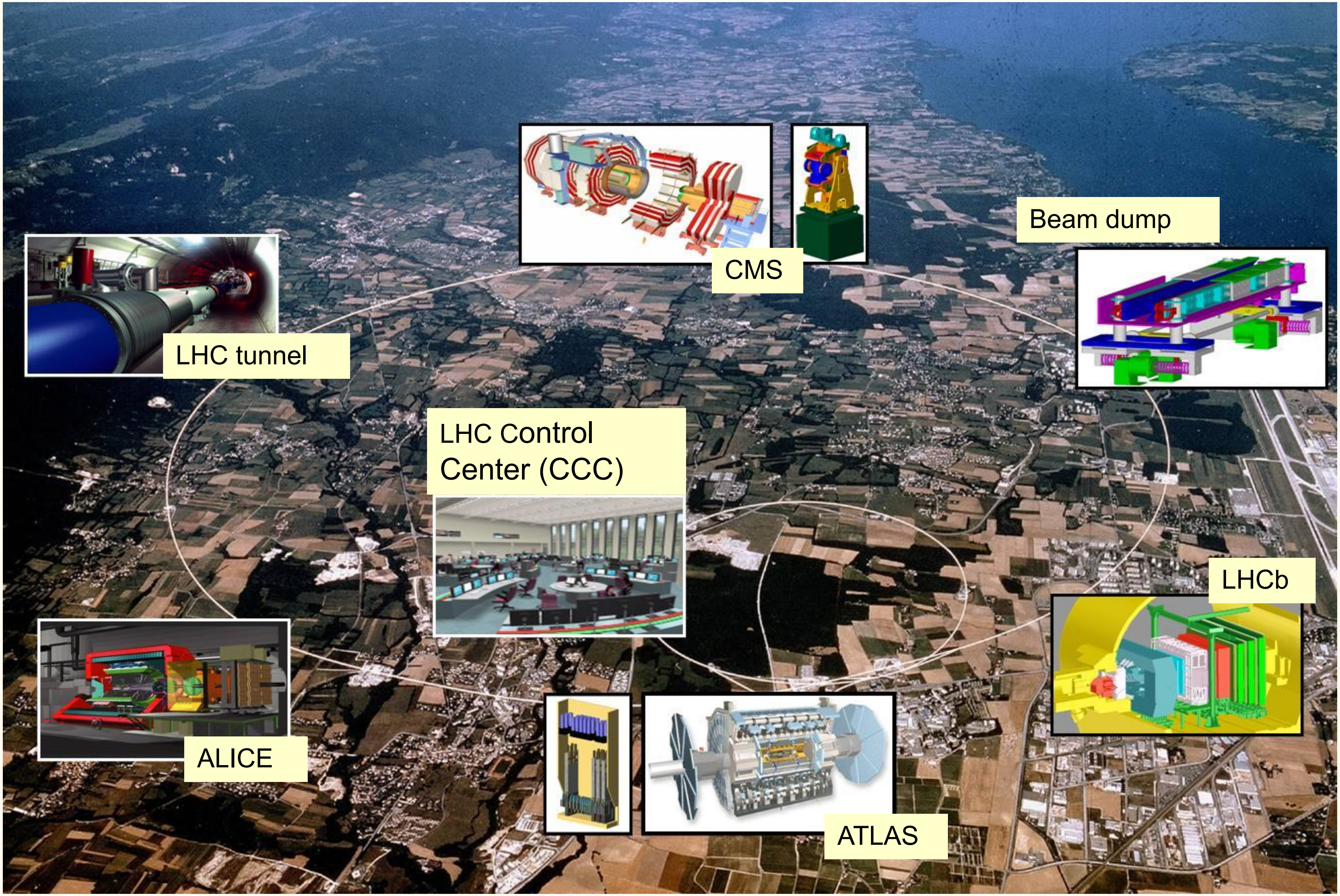
Завдякі вам буде більше зацікавленіх физикою молодих людей!

Outline

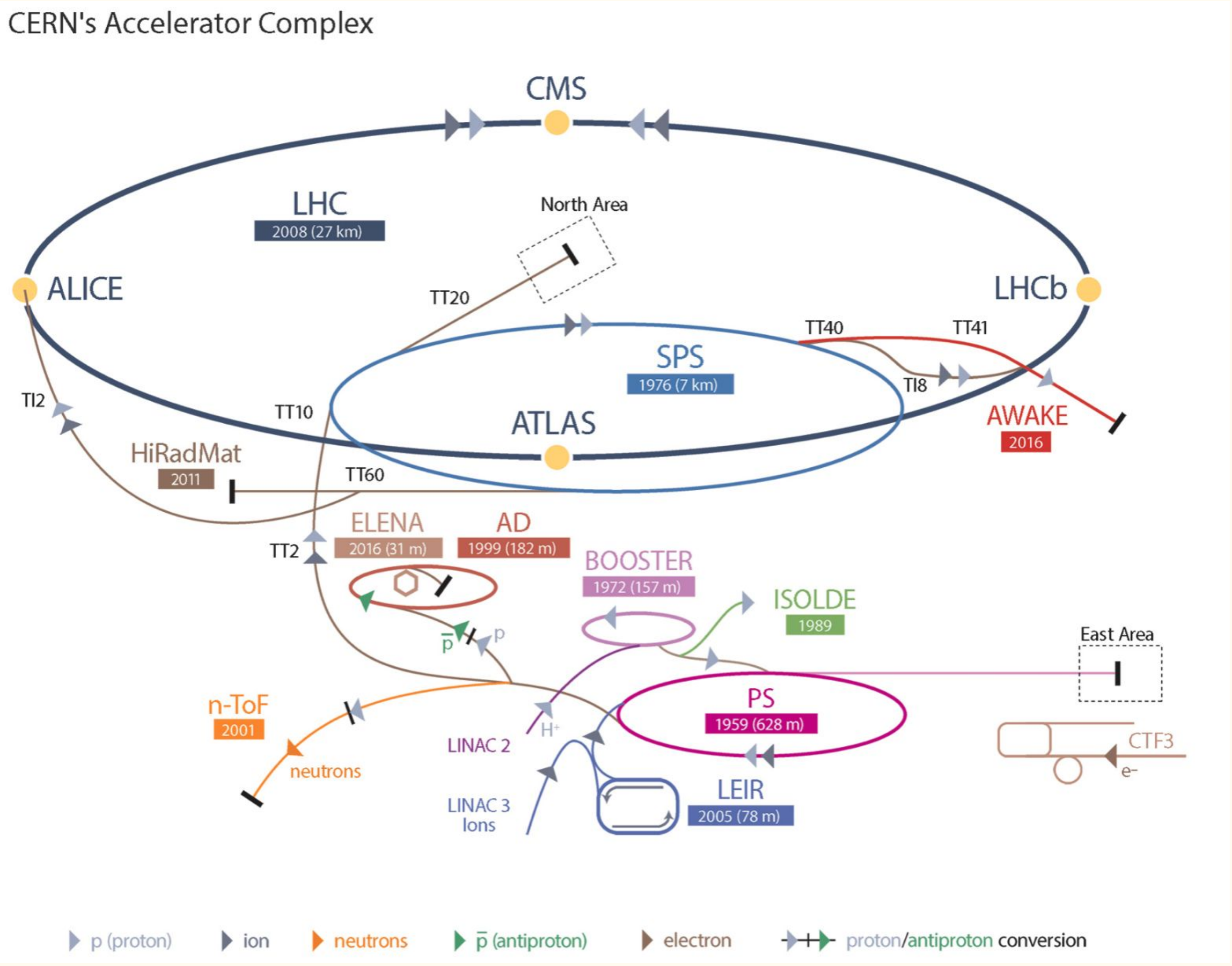
- Ланцюг прискорювачів CERN і LHC.
- Експеримент CMS.
- Структура пучків частинок на LHC.
- Вимірювання світимості.
- Онлайн-детектори світимості.
- Калібрування світимості:
  - поправки;
  - стабільність і спеціальне сканування світимості.
- 3D інтерактивна модель CMS детектора.

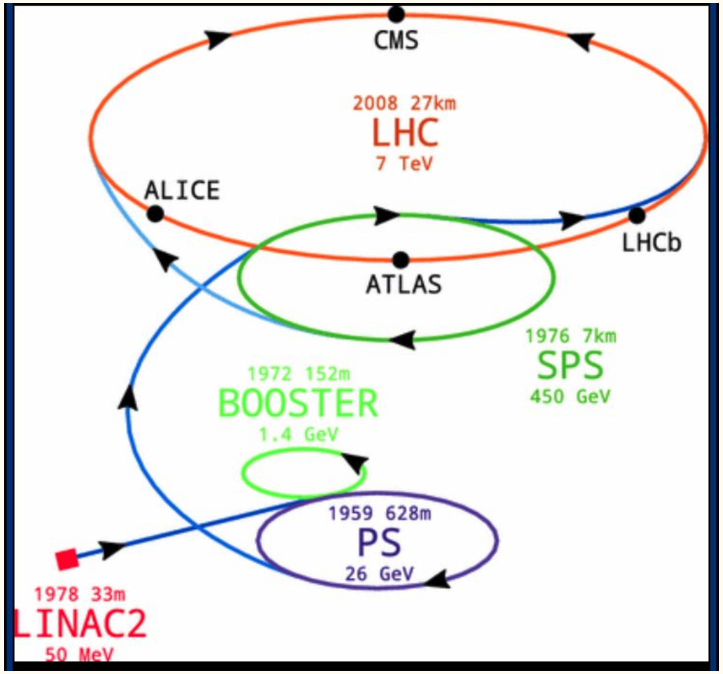
- CERN accelerators chain and LHC.
- CMS experiment.
- Particle beams structure at LHC.
- Luminosity measurements.
- Online luminosity detectors.
- Luminosity calibration
  - Corrections;
  - Stability and special emittance scans.
- 3D interactive model of CMS detector.

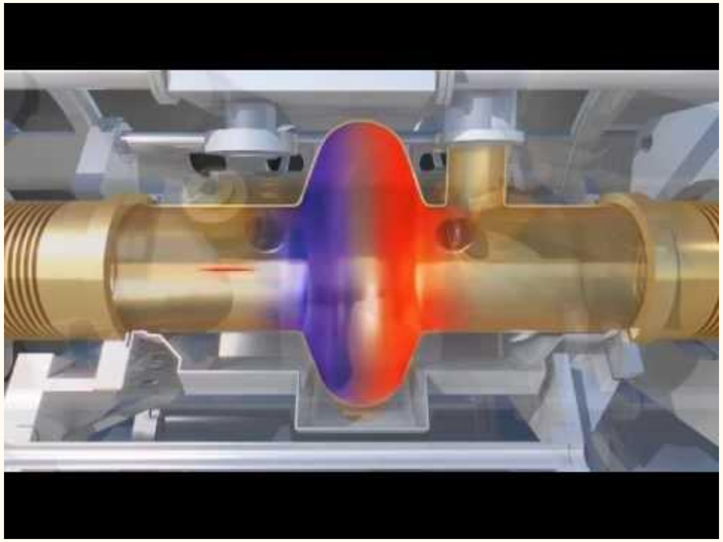
LHC — proton-proton collider, $\sqrt{s}_{max} = 14$ TeV



CERN is accelerator complex!



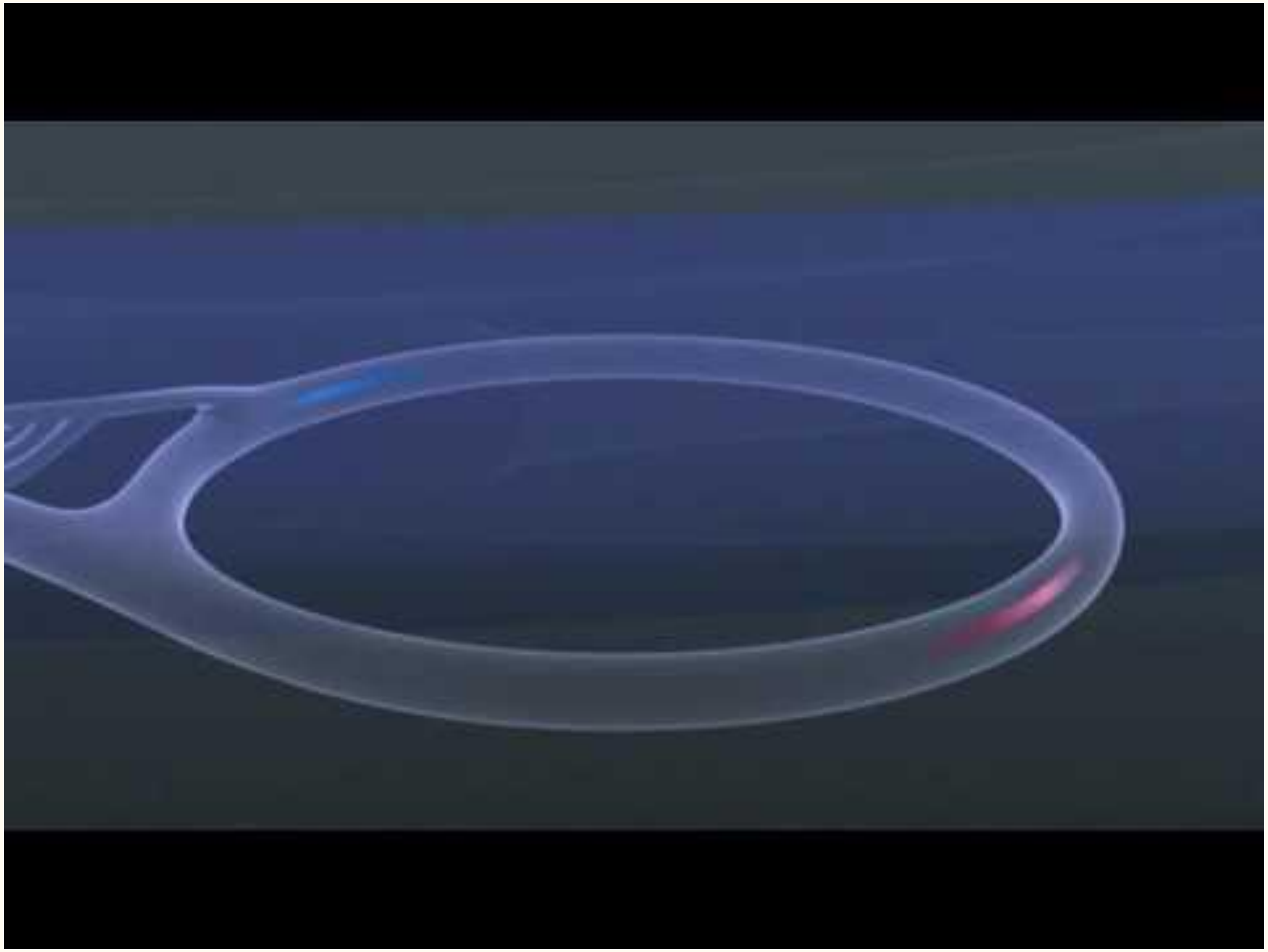


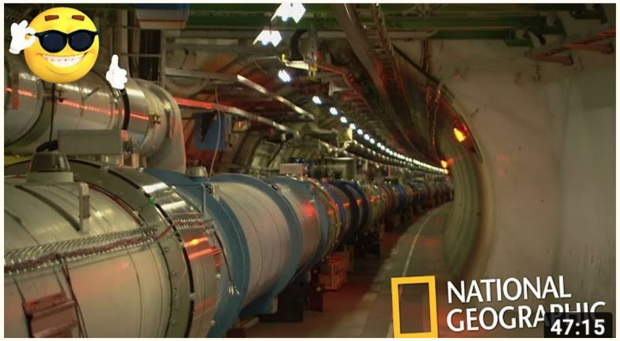


https://youtu.be/RDdPuL-uOQc

видео!

More about CERN and LHC





National geographic
видео с русской озвучкой!

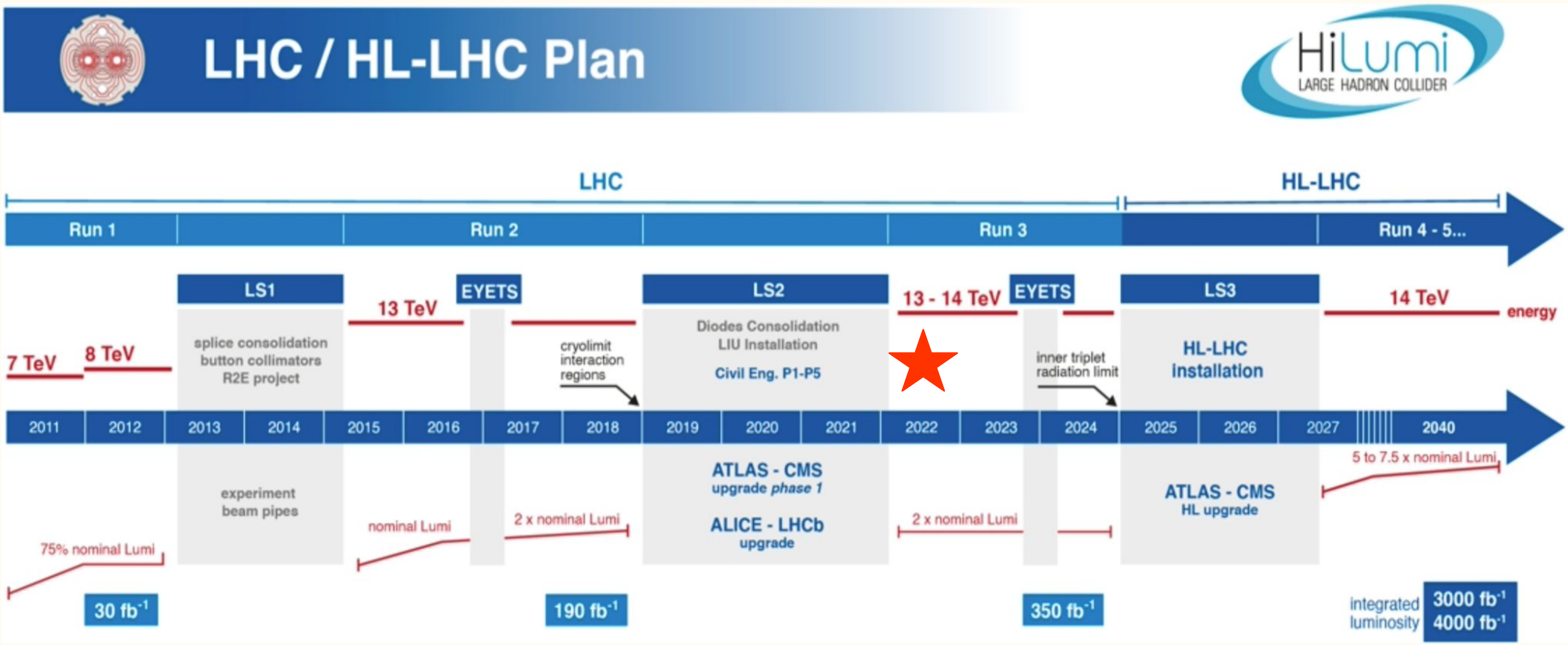
https://youtu.be/ETWPnOOE1LQ

видео!

https://www.youtube.com/watch?v=FLrEghnKncA

What is LHC Run 1 - Run 2 - Run 3 … and High Lumi LHC (HL-LHC)?

- LHC construction: 1998 - 2008, first collisions took place in 2010.
- First era of data taking -- LCH Run 1 -- started in 2011.
- Second era -- LCH Run 2: 2015 - 2018.
- Today we are at the beginning of Run 3!



4th July 2012
Higgs discovery

LHC Run 2, 2015-2018

- Energy per beam:

  6.5 - 7 TeV
- The beam:

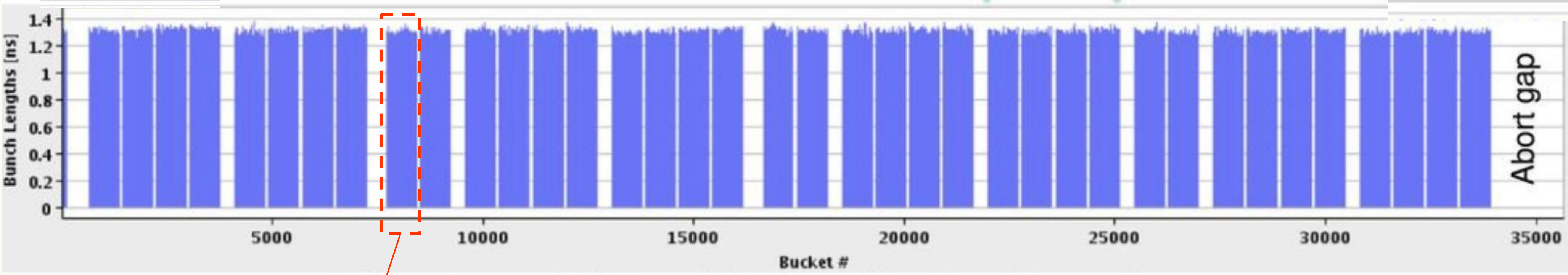
  ~2800 proton bunches

  $\sim 10^{11}$ protons per bunch
- **Bunch spacing 25/50 ns**
- Beam width: ~20 um

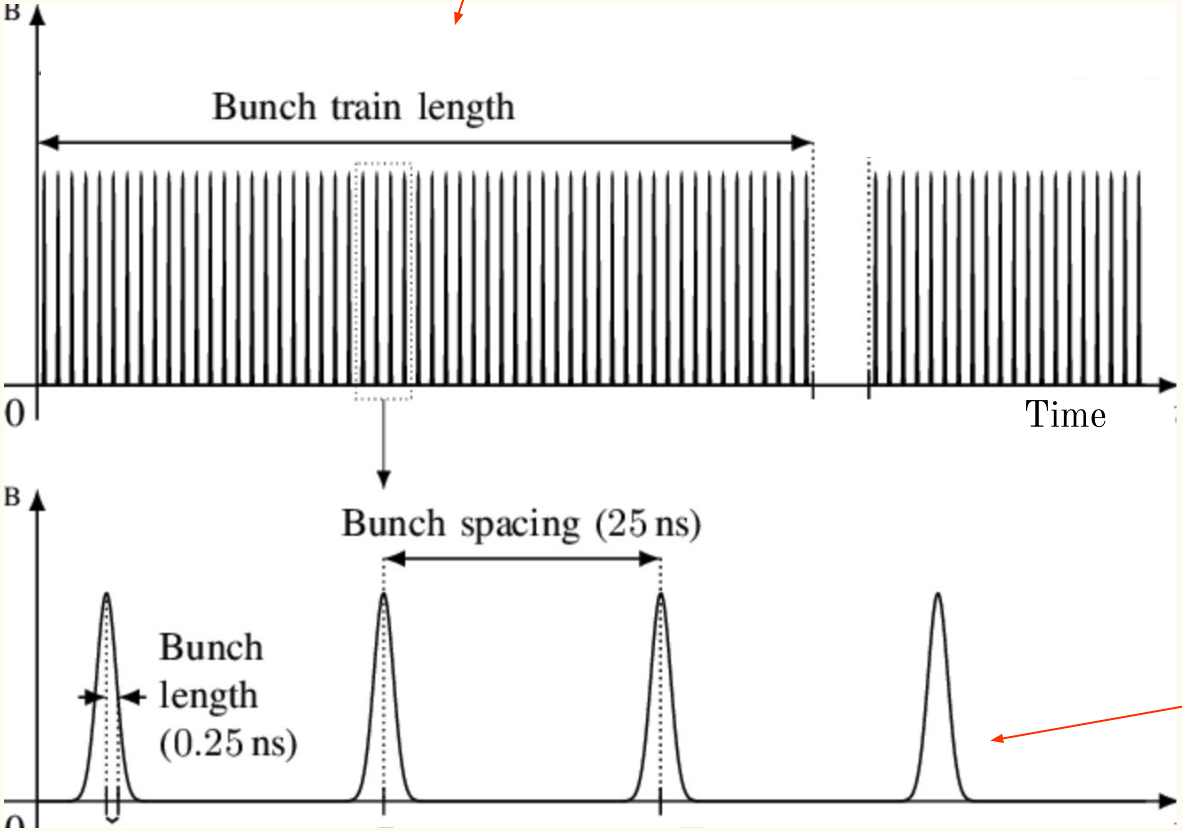
Each 10th RF bucket filled → 25 ns

More about LHC beam structure

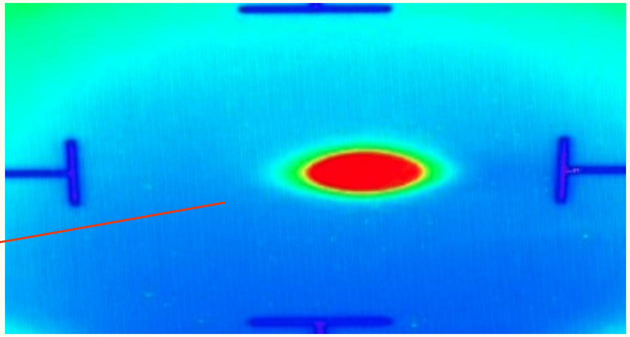
One LHC orbit (89 μsec length, 89000 ns / 2.5 ns = 35600 RF buckets):



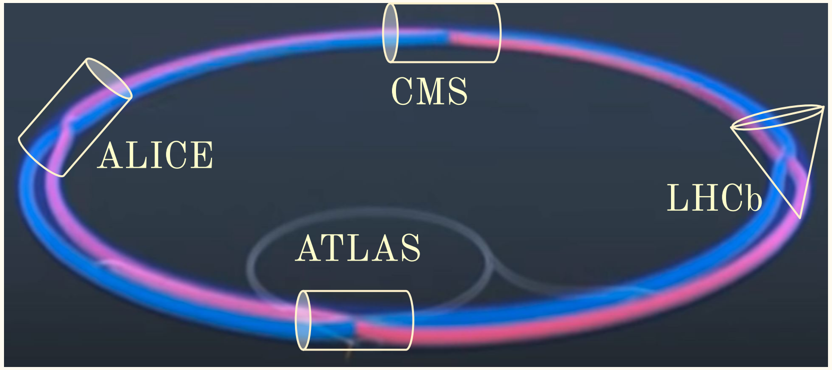
One bunch train example

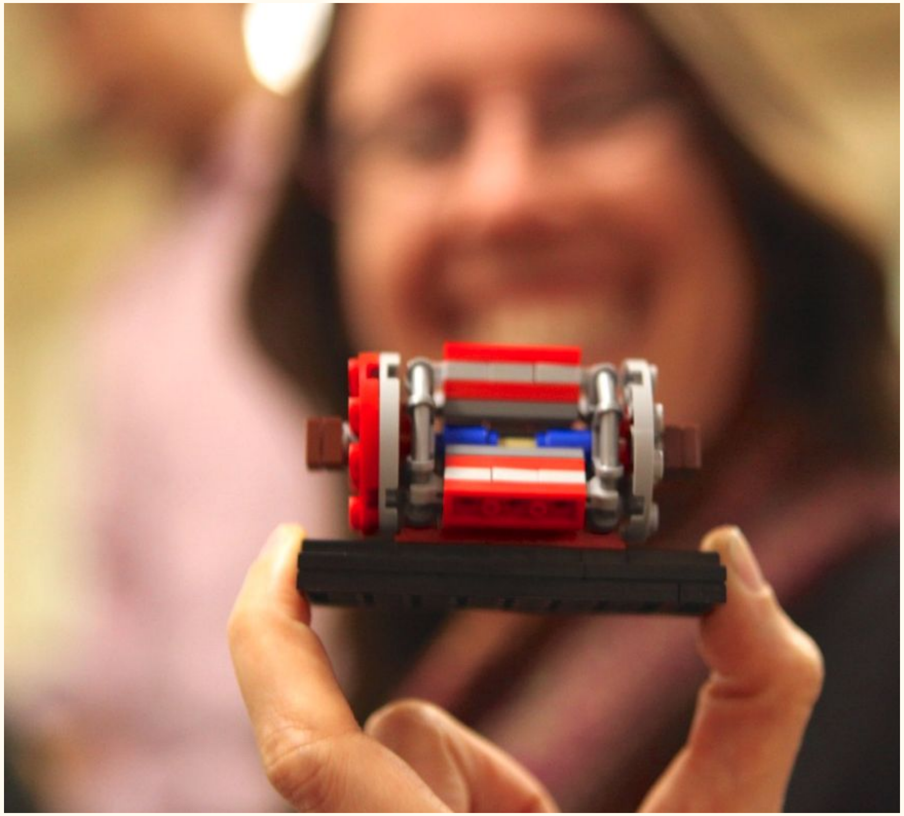


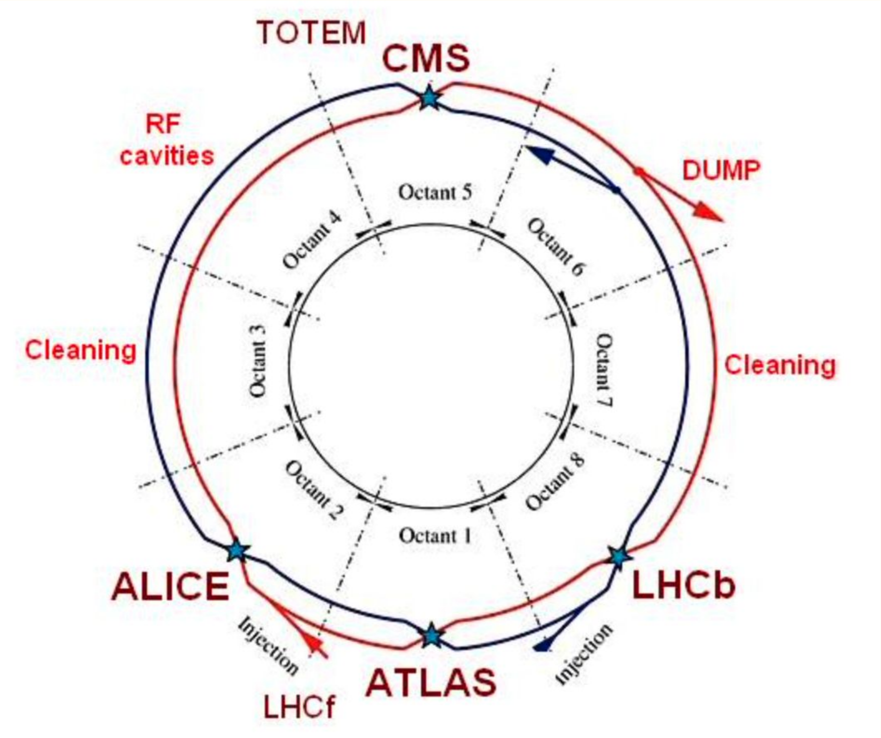
One bunch profile, shape in XY plane:

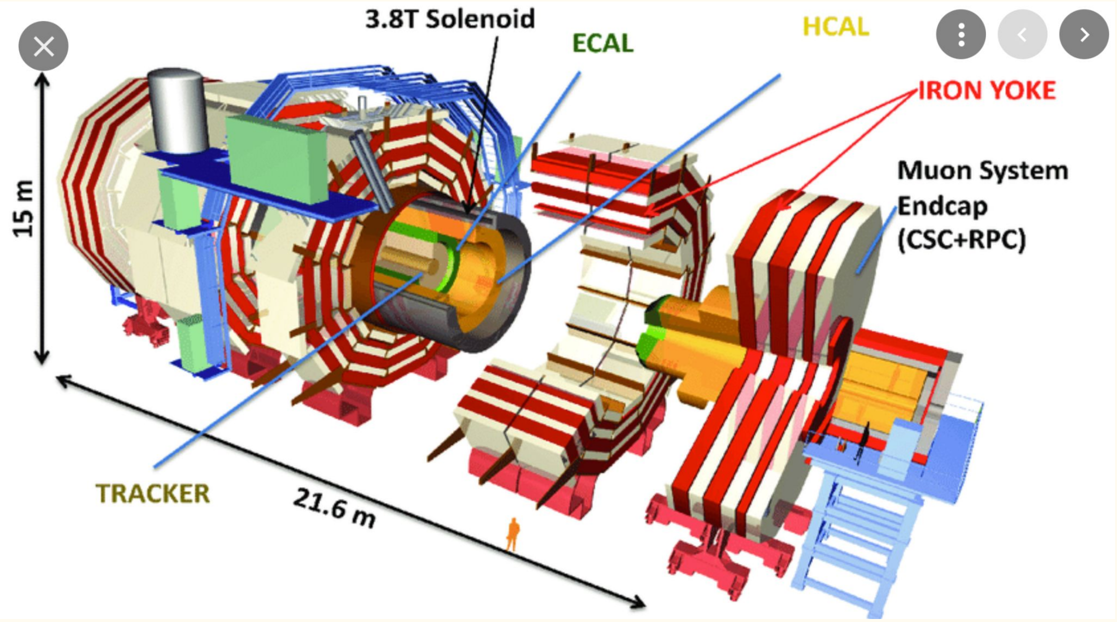


How do we see collisions?

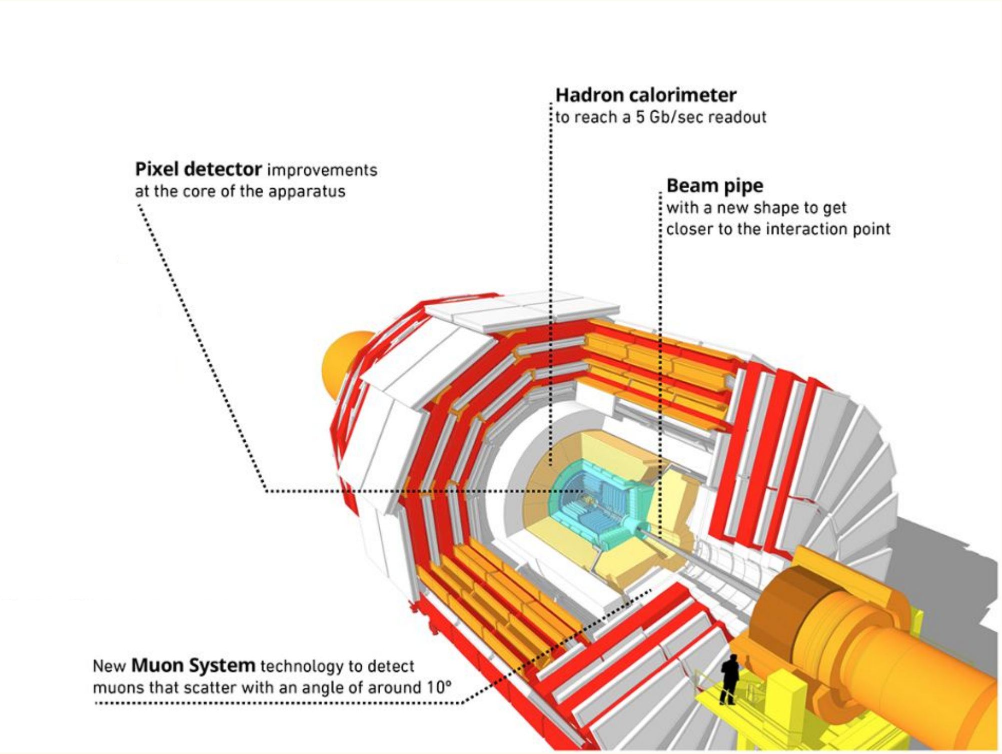


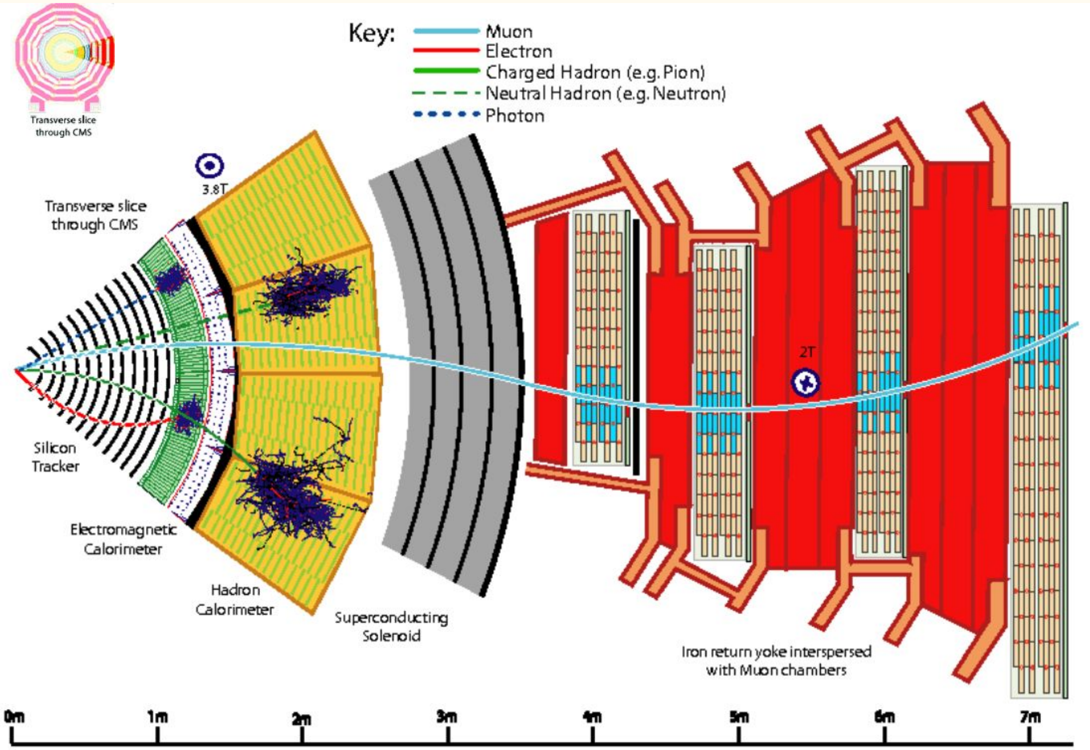


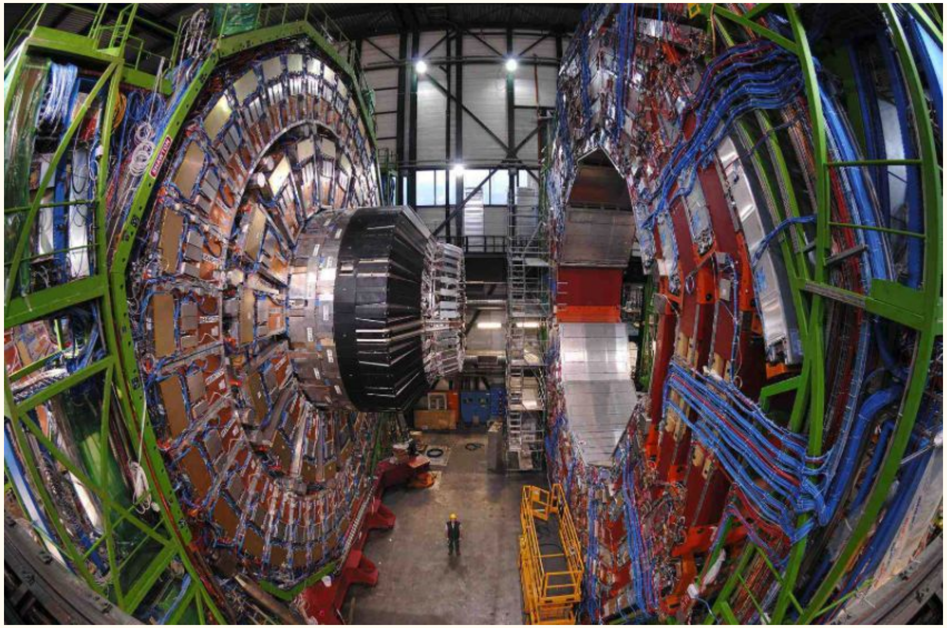




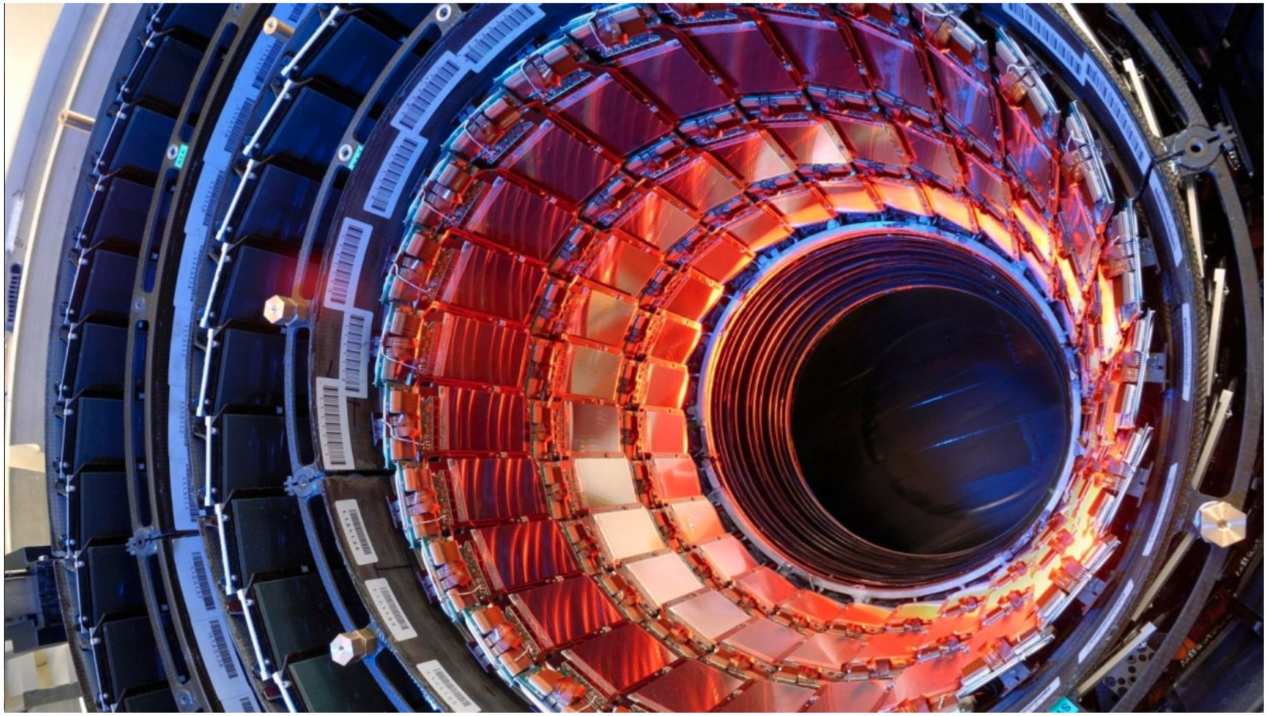
CMS detector



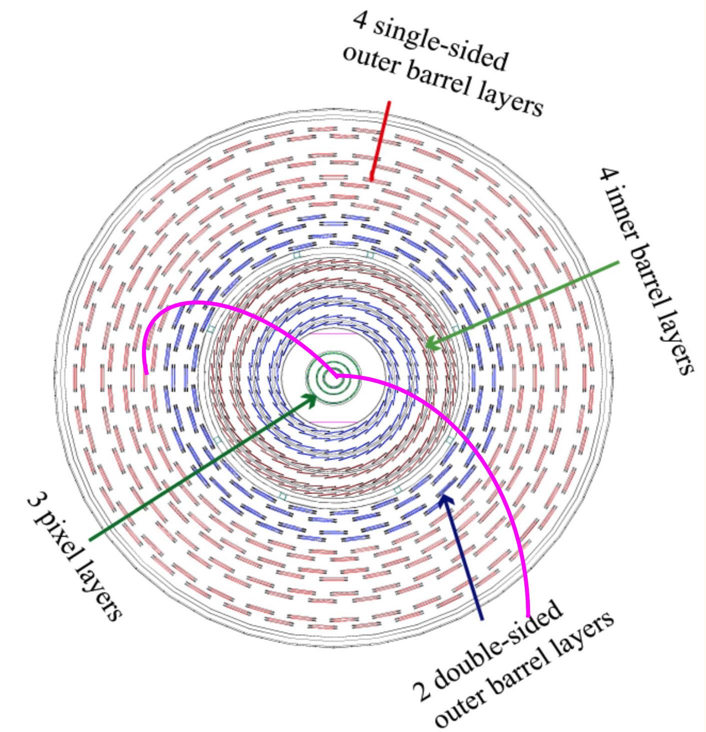




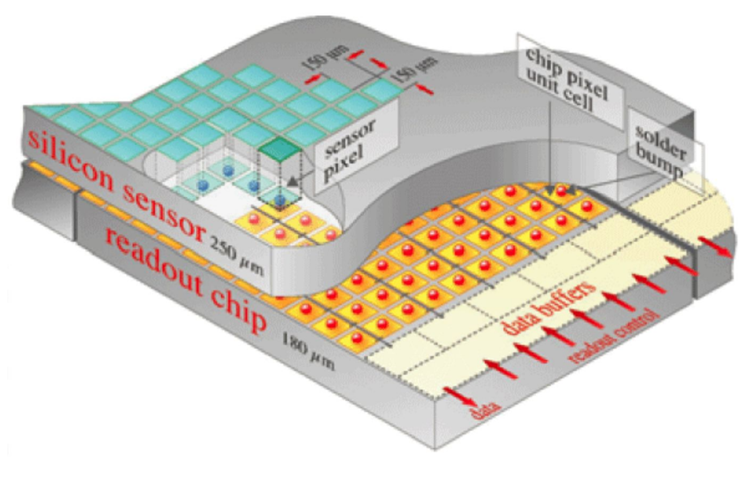
CMS pixel and tracker detectors



CMS Tracker showing silicon strips detectors in the barrel module.



CMS Tracker layers shown in the plane perpendicular to the beam.



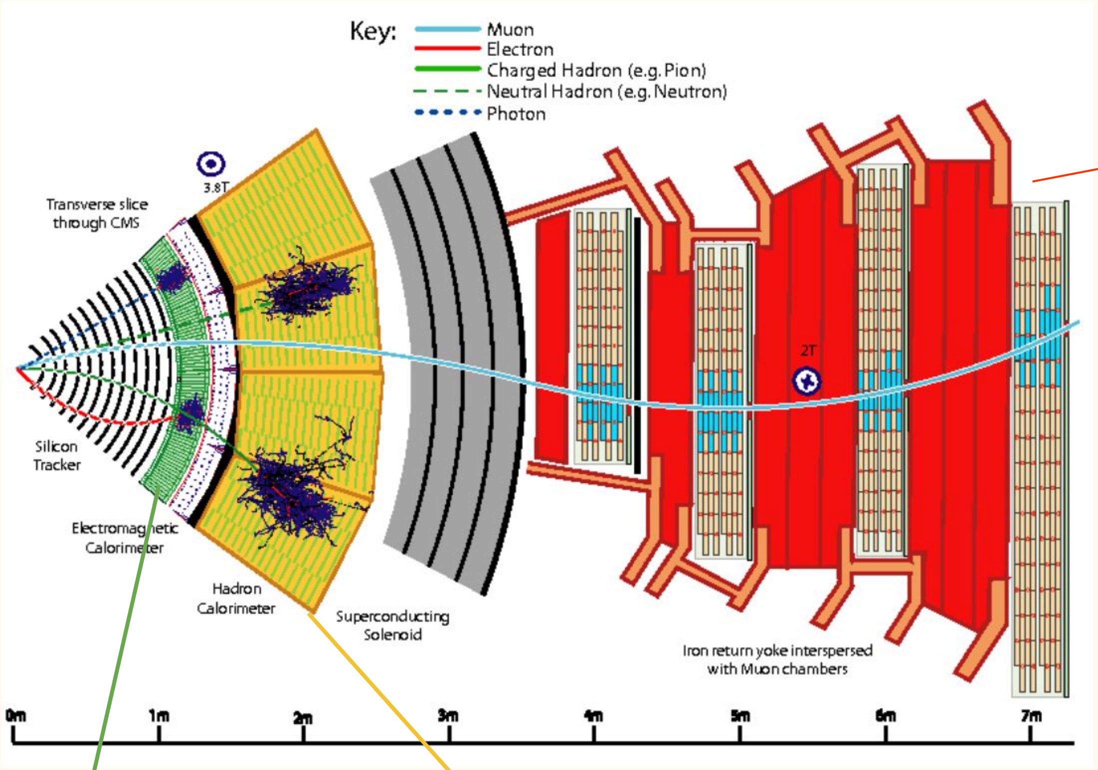
CMS silicon pixel detector

Silicon pixel detector has 3 layers: 4cm, 7cm and 11cm from beam center. Each pixel is 100µm by 150µm, about two hairs widths. 10 million particles per square centimetre per second.

The tracker silicon strip detector consists of four inner barrel (TIB) layers, six concentric layers of the outer barrel (TOB). Finally two endcaps (TEC) close off the tracker.

Each module consists of three elements: a set of sensors, its mechanical support structure and readout electronics.

CMS calorimeters and muon system



CMS = "Compact Muon Solenoid": muons is one of CMS's most important tasks.

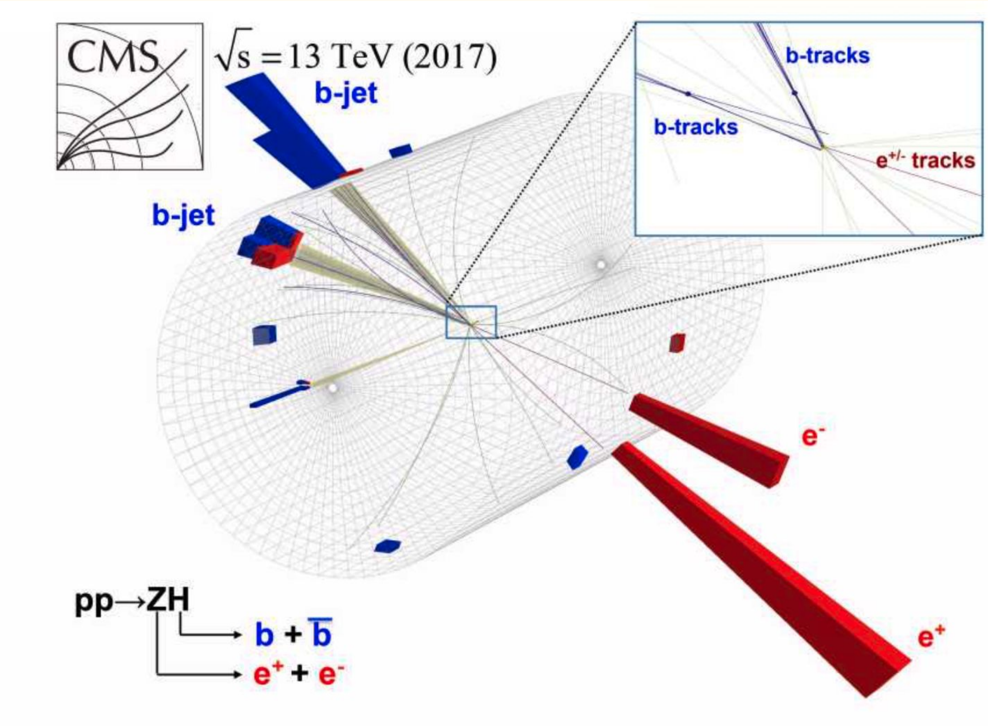
One of the clearest "signatures" of the Higgs Boson is its decay into four muons.

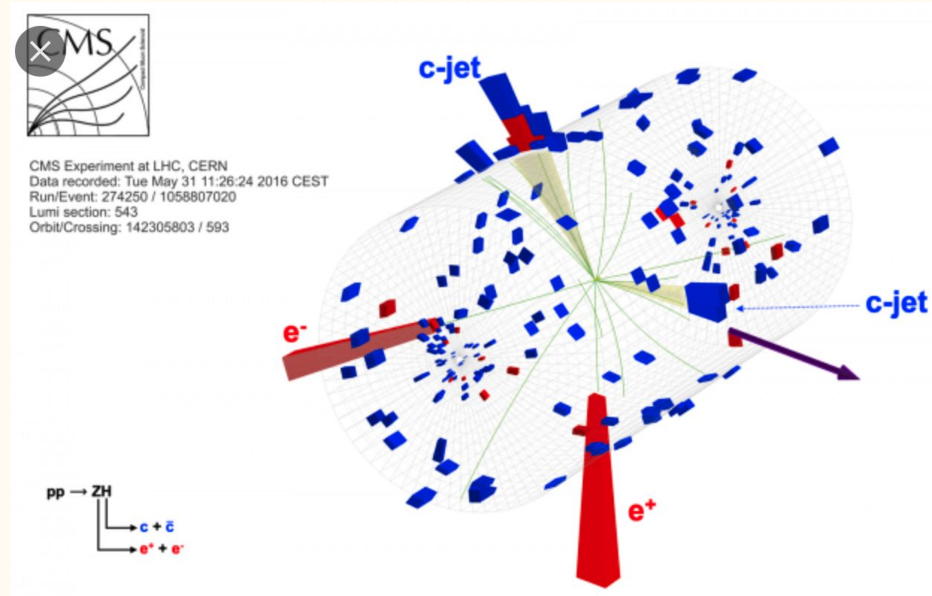
In total there are 1400 muon chambers: 250 drift tubes (DTs) and 540 cathode strip chambers (CSCs) track the particles' positions.

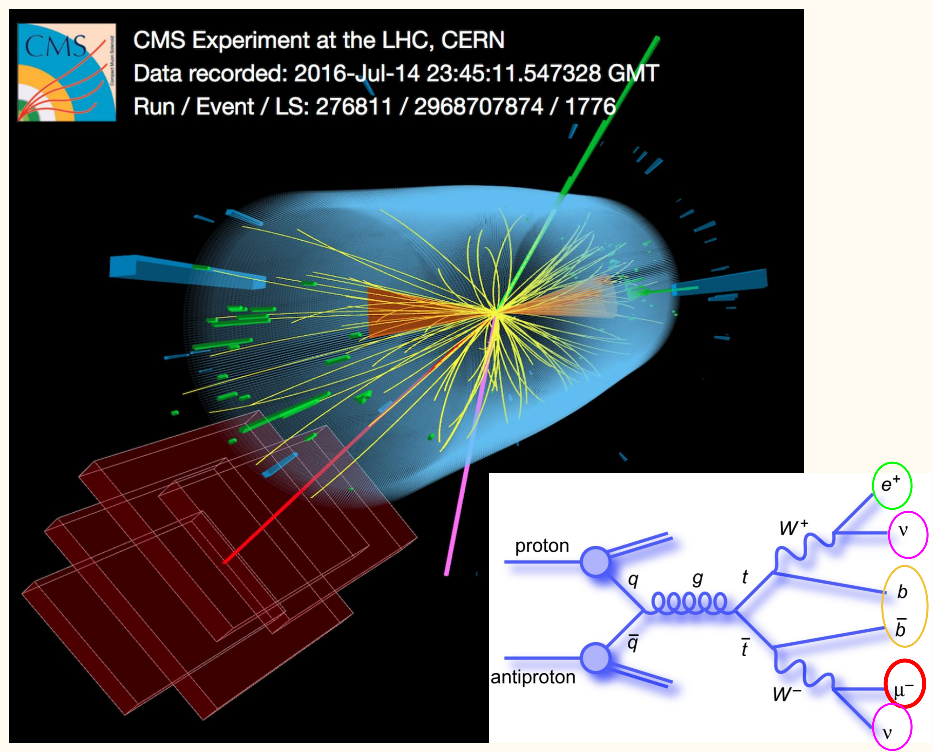
The Electromagnetic Calorimeter (ECAL) measures the energy of electrons and photons by stopping them completely.

Hadrons, which are composite particles made up of quarks and gluons, fly through the ECAL and are stopped by the outer layer called the Hadron Calorimeter (HCAL).

Can CMS record all collisions?

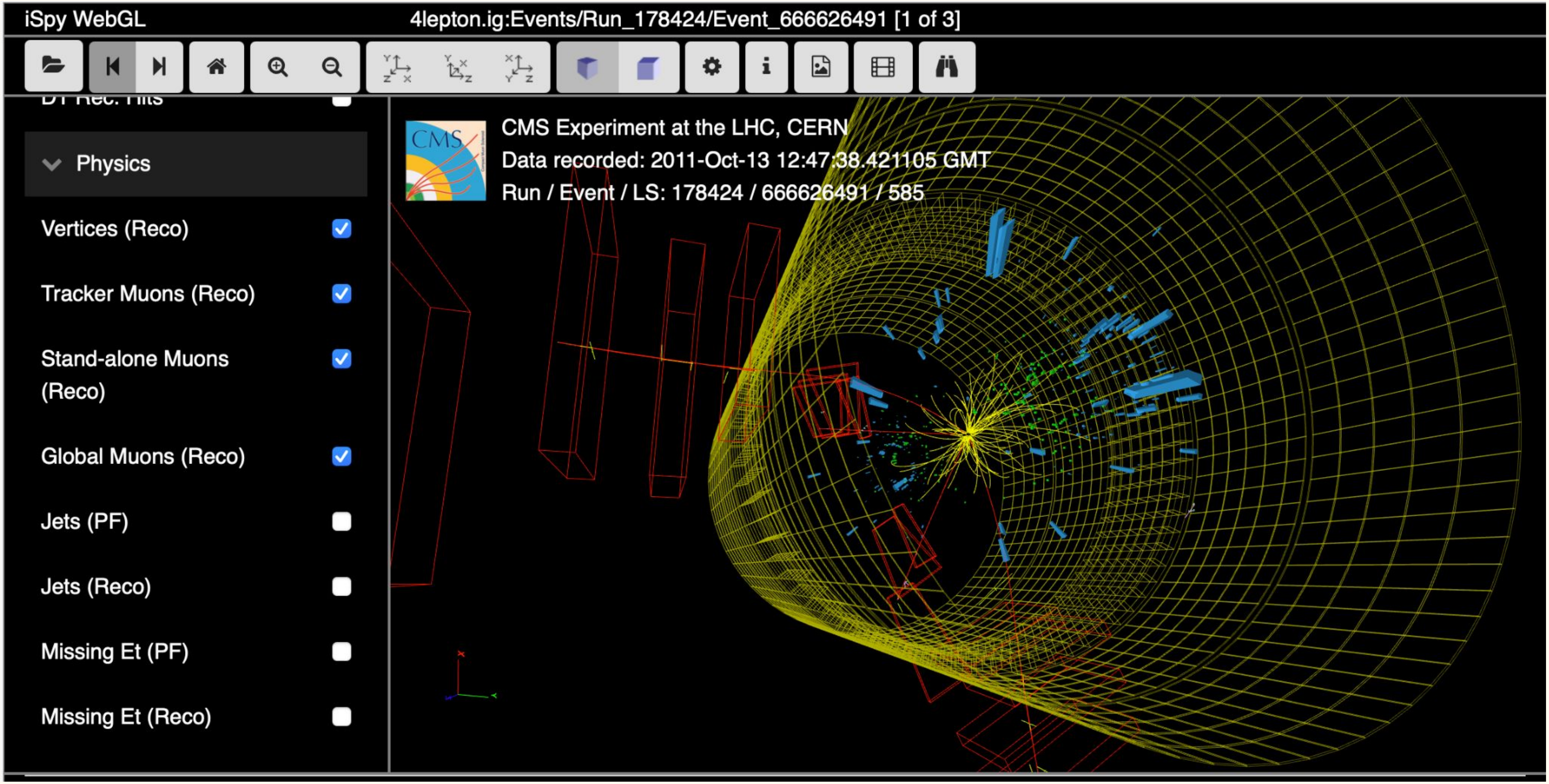






- These CMS event displays shows just some examples of recorded collisions.
- Not all collisions are recorder due to processing time and time needed to readout detectors
- **Trigger system** based on interesting signals in the detectors decides which events to record.

3D interactive CMS detector



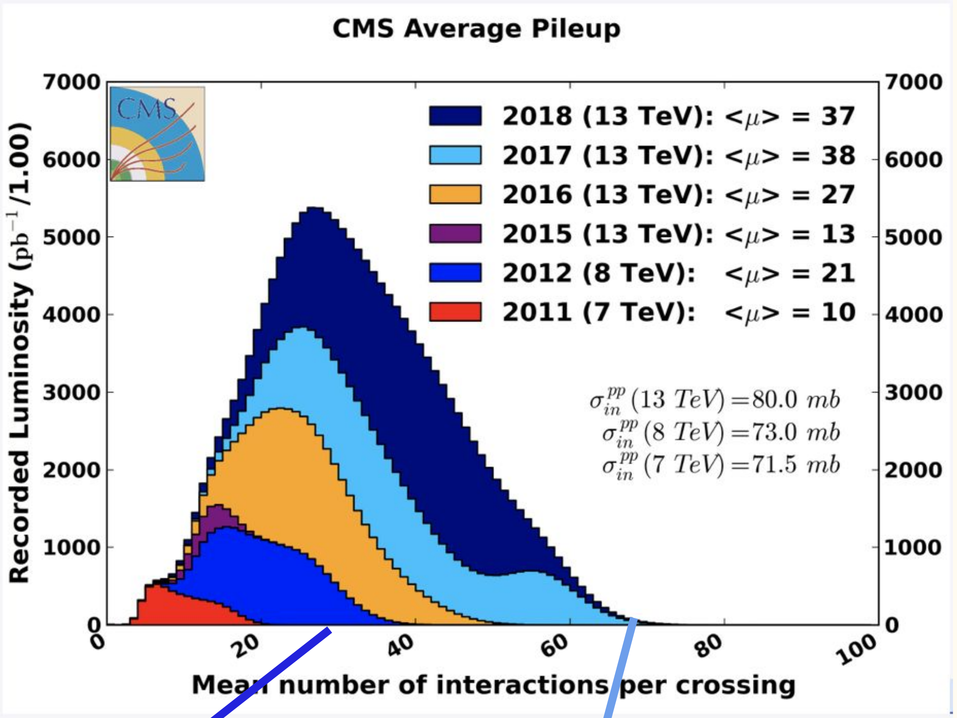
https://opendata.cern.ch/visualise/events/cms
https://www.i2u2.org/elab/cms/event-display/#

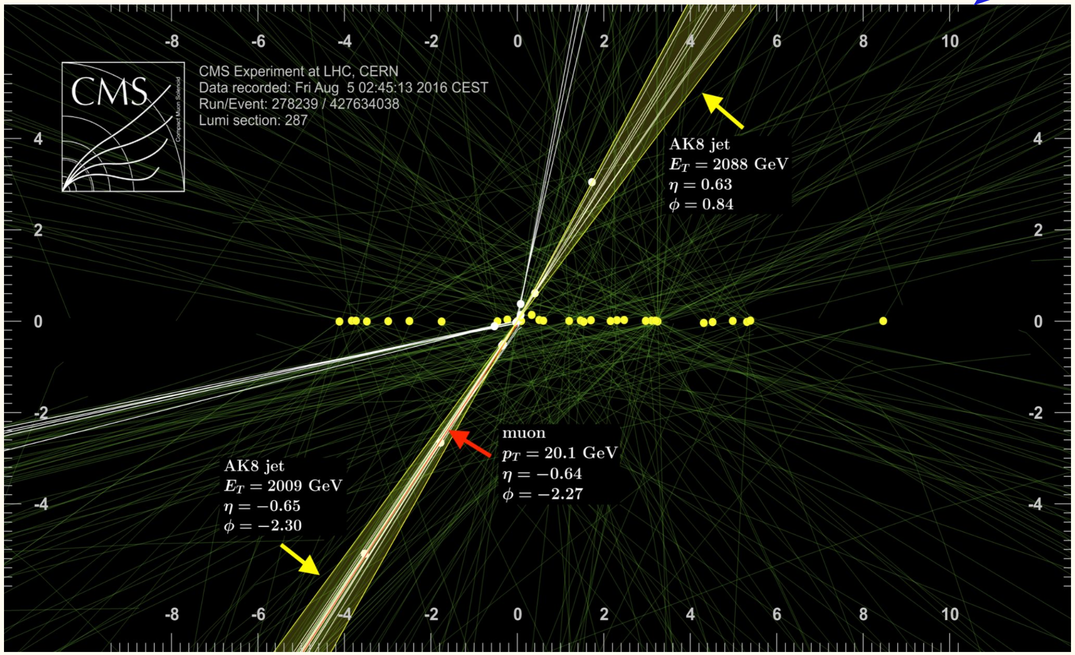
Спробуйте самі!

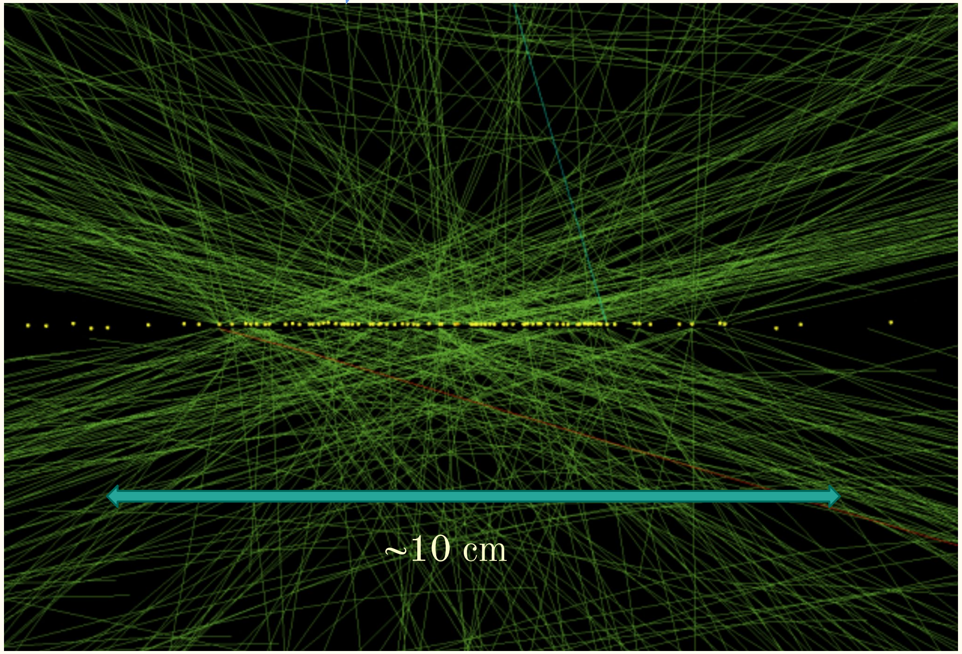
Pileup

Number of primary vertices in one pp collision.

Is pileup 35 and 70 so different???







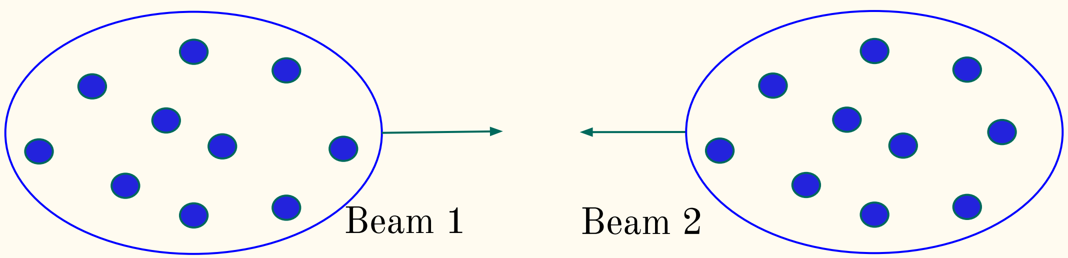
Luminosity

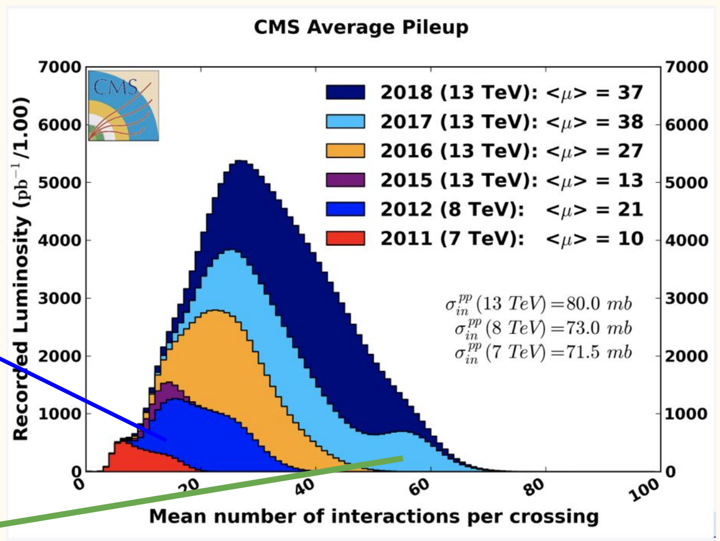
What is luminosity $\mathcal{L}$?

→ **Proportionality factor between cross section σ_p and number of interactions per second $\frac{dR}{dt}$**

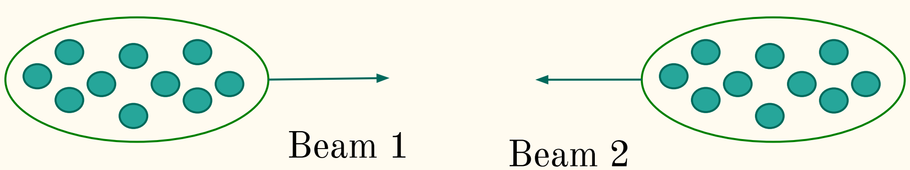
$$\frac{dR}{dt} = \mathcal{L} \times \sigma_p \qquad (\rightarrow \quad \text{units}: \ \text{cm}^{-2}\text{s}^{-1})$$

Lower luminosity collison



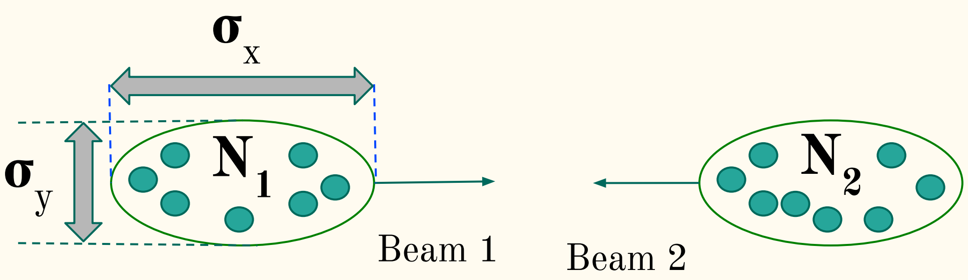


Higher luminosity collison



Luminosity formula

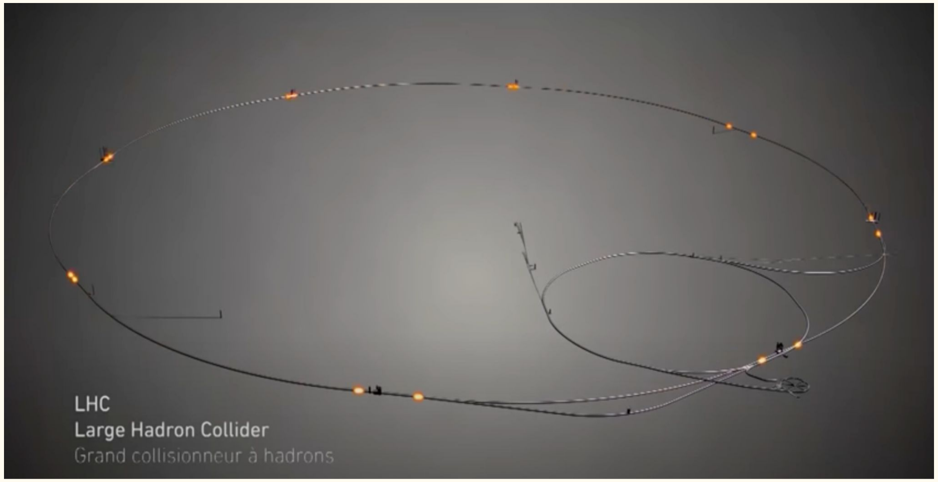
For one collision:



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

Beam size in X and Y (about 15µm): $\sigma_{x,y}$
Number of protons in Beam 1,2: $\mathbf{N_{1,2}}$

For LCH collisions:



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

LHC revolution frequency: f=11kHz
Number of bunches in LHC (about 2800): $\mathbf{n_b}$

Example

Rare interactions and cross section

- **Cross section σ measures how often a process occurs**
- **Characteristic for a given process**
- **Measured in:** $barn = b = 10^{-28} m^2$ $(pb = 10^{-40} m^2)$

  More common: $barn = b = 10^{-24} cm^2$ $(pb = 10^{-36} cm^2)$

  We have for the LHC energy:

  $\sigma(pp \rightarrow X) \approx 0.1\ b$ **and**

  $\sigma(pp \rightarrow X + H) \approx 1 \cdot 10^{-11}\ b$

  $\sigma(pp \rightarrow X + H \rightarrow \gamma\gamma) \approx 50 \cdot 10^{-15}\ b = 50\ fb$ **(femtobarn)**
- **VERY rare (one in 2 10^{12}), need many collisions ...**

Calculations for the LHC

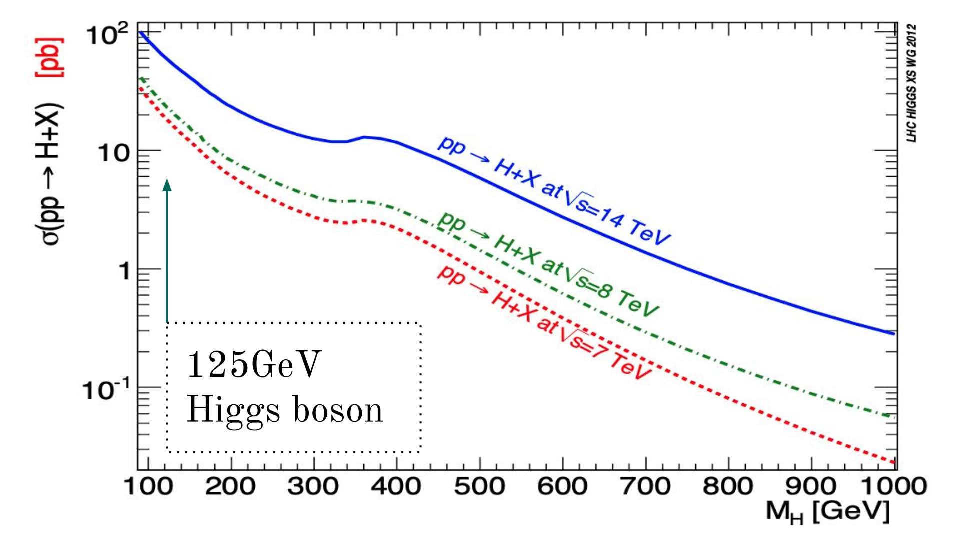
- $N_1 = N_2 = 1.15 \times 10^{11}$ **particles/bunch**
- $n_b = 2808$ **bunches/beam**
- $f = 11.2455$ kHz, $\phi = 285\ \mu$**rad**
- $\beta_x^* = \beta_y^* = 0.55$ m
- $\sigma_x^* = \sigma_y^* = 16.6\ \mu$m, $\sigma_s = 7.7$ cm

$$\mathcal{L} = 1.200 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$$

$$\frac{dR}{dt} = \mathcal{L} \times \sigma_p$$

For small cross certain processes we need high luminosity to see some events!

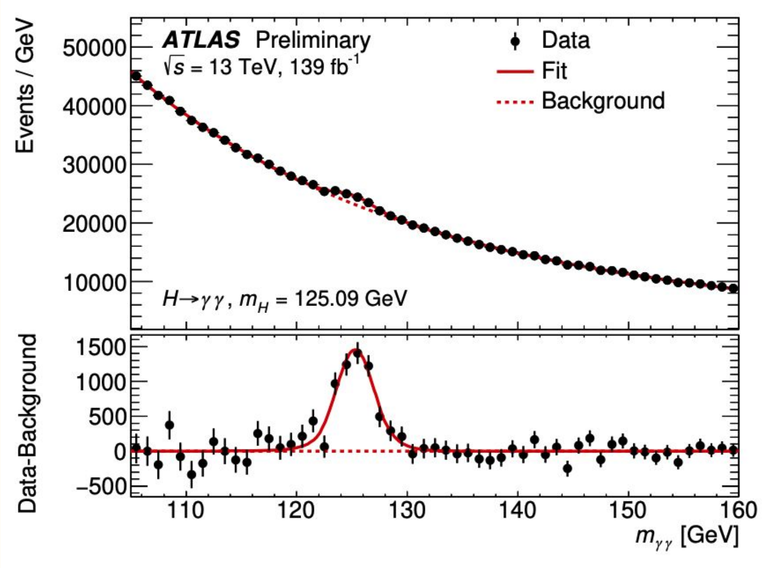
Why do we want to collide at higher energy?

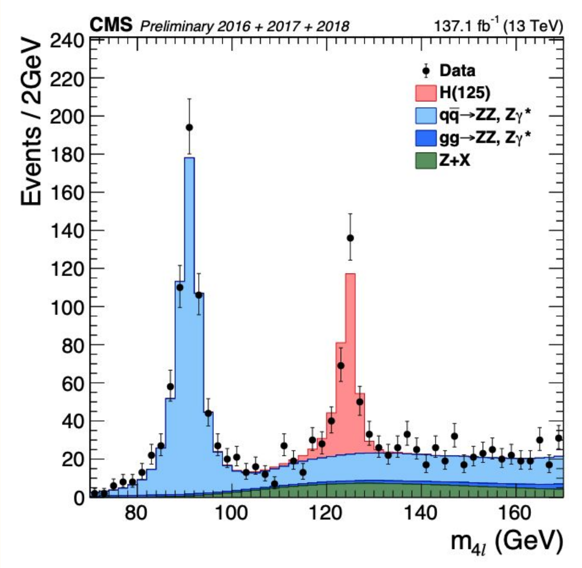


What really counts: Integrated luminosity

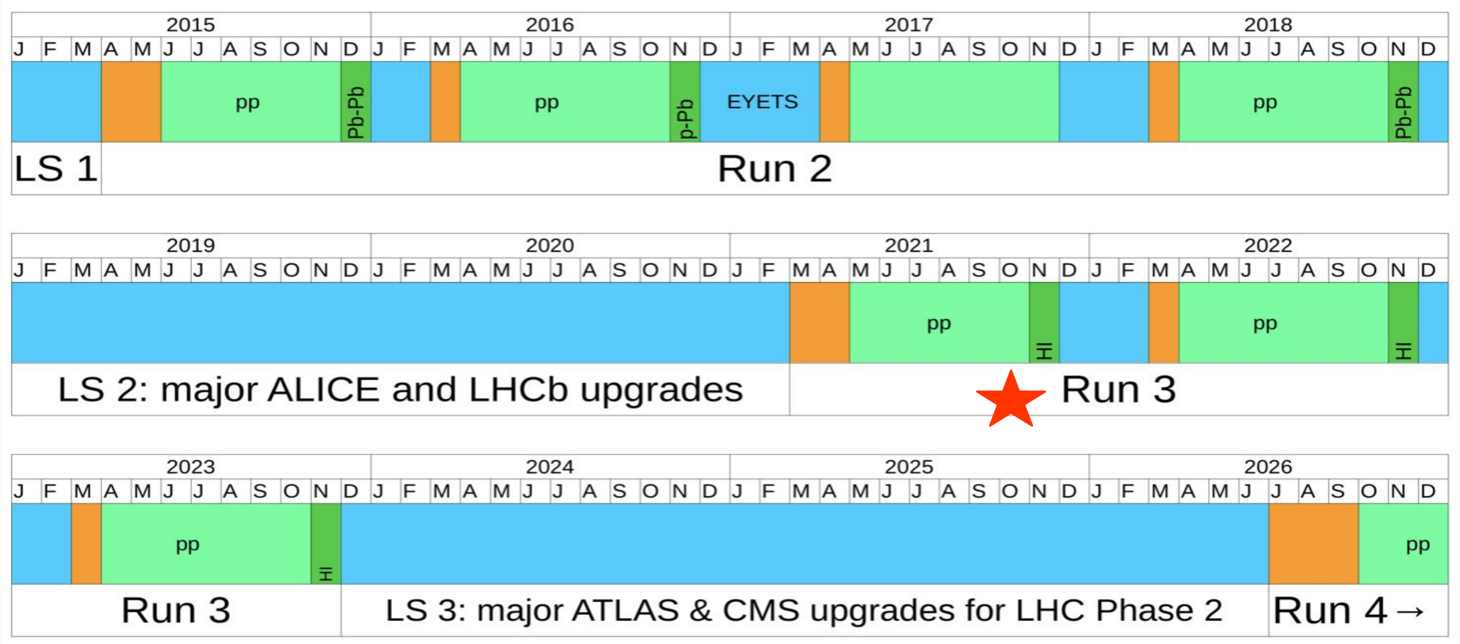
- $\mathcal{L}_{\text{int}} = \int_0^T \mathcal{L}(t)dt$
- $\mathcal{L}_{\text{int}} \cdot \sigma_p = \int_0^T \mathcal{L}(t)dt \cdot \sigma_p =$ **total number of events observed of process** p
- **Unit is:** cm^{-2}**, i.e. inverse cross-section**
- **Often expressed in inverse barn**
- **1 fb^{-1} (inverse femto-barn)** **is** $10^{39}cm^{-2}$
- **for 1 fb^{-1}: requires** 10^6**s at L** $= 10^{33}cm^{-2}s^{-1}$
- **Assume:**
  - **You have accumulated 20 fb^{-1} (inverse femto-barn)**
  - **You are interested in** $\sigma(pp \to X + H \to \gamma\gamma) \approx$ **50 fb (femtobarn)**
  - **You have 20 fb^{-1} · 50 fb = 1000**
  - **You have 1000 events of interest in your data !!**

Full data 2015 - 2018:

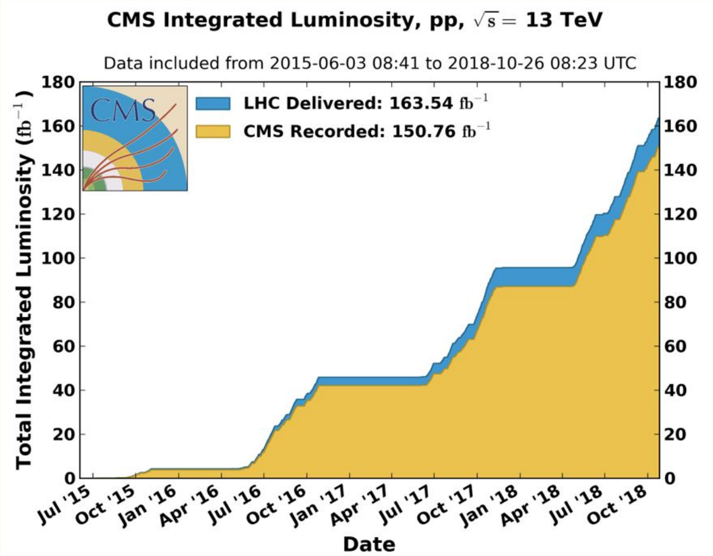


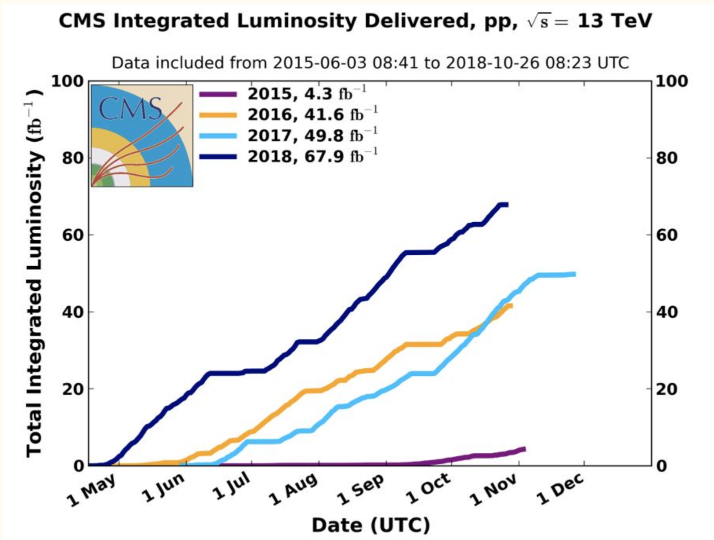


Run 2 and Run 3 timelines



Run 2 luminosity





(see more here)

LHC plans for Run 3

Run 3 will start in last week of March, 2022.
The energy will be 6.8 TeV per beam, so 13.6 TeV centre-of-mass energy.

The current schedule foresees a 3 year run, but there will be very likely an extra year (2025).

Hope to get ~30 fb^{-1} in 2022, then 80 fb^{-1} per year. So 270 fb^{-1} at the end of Run 3. PU will be ~ 53.
We will at least double and, with some luck, maybe triple the Run 2 pp luminosity.

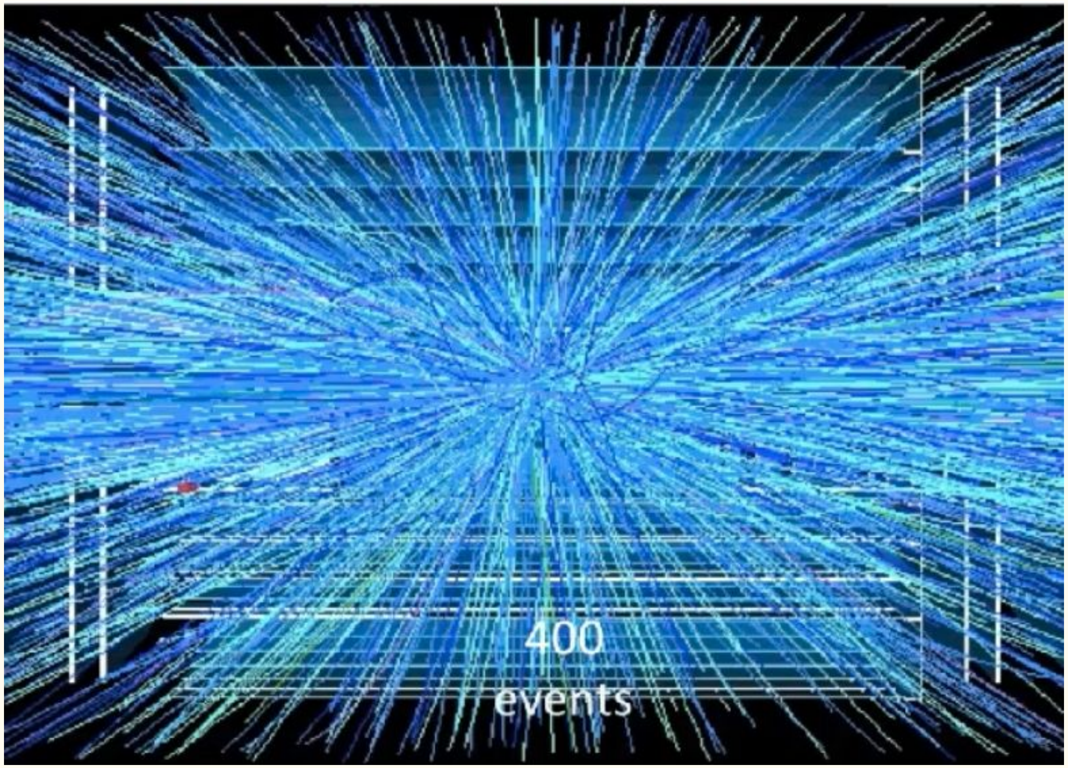
Detector	Target [fb^{-1}]	Run 3 baseline [fb^{-1}]	Run 3 + 1 year [fb^{-1}]		Leveled luminosity [$10^{34} cm^{-2} s^{-1}$]
ATLAS & CMS	**160**	190	270		2
LHCb	**25**	20	28		0.15 - 0.2
ALICE	**0.2**	0.13	0.18		0.0013

Preliminary numbers ... work in progress

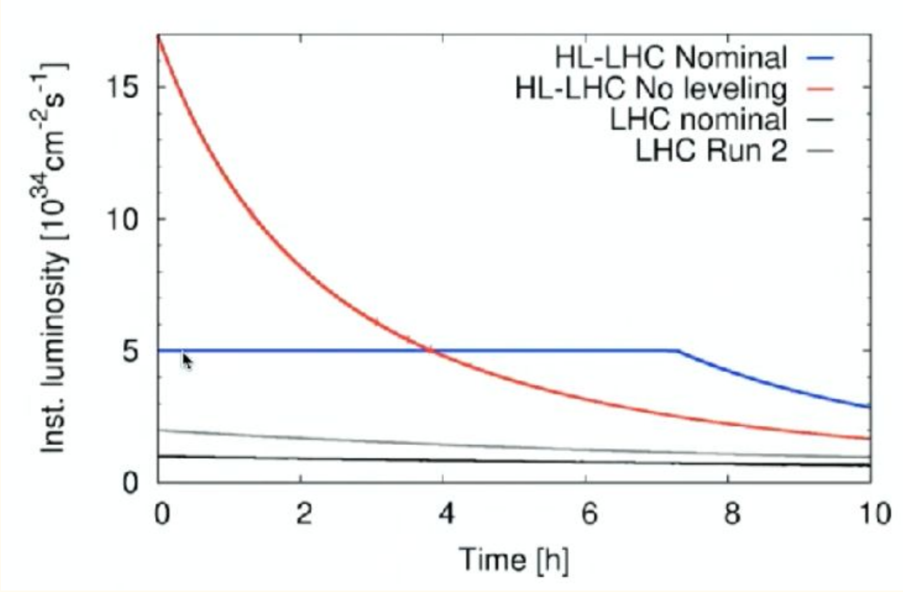
High Lumi LHC (HL-LHC)

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)
Beam energy in collision [TeV]	7	7
N_b	1.15E+11	2.2E+11
n_b [12]	2808	2760
Beam current [A]	0.58	1.1
Half Crossing angle [μrad]	142.5	250
Minimum β^* [m]	0.55	0.15
ε_n [μm]	3.75	2.50
Total loss factor R0 without crab-cavity	0.836	0.342
Total loss factor R1 with crab-cavity	-	0.716
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2} s^{-1}$]	-	1.70E+35

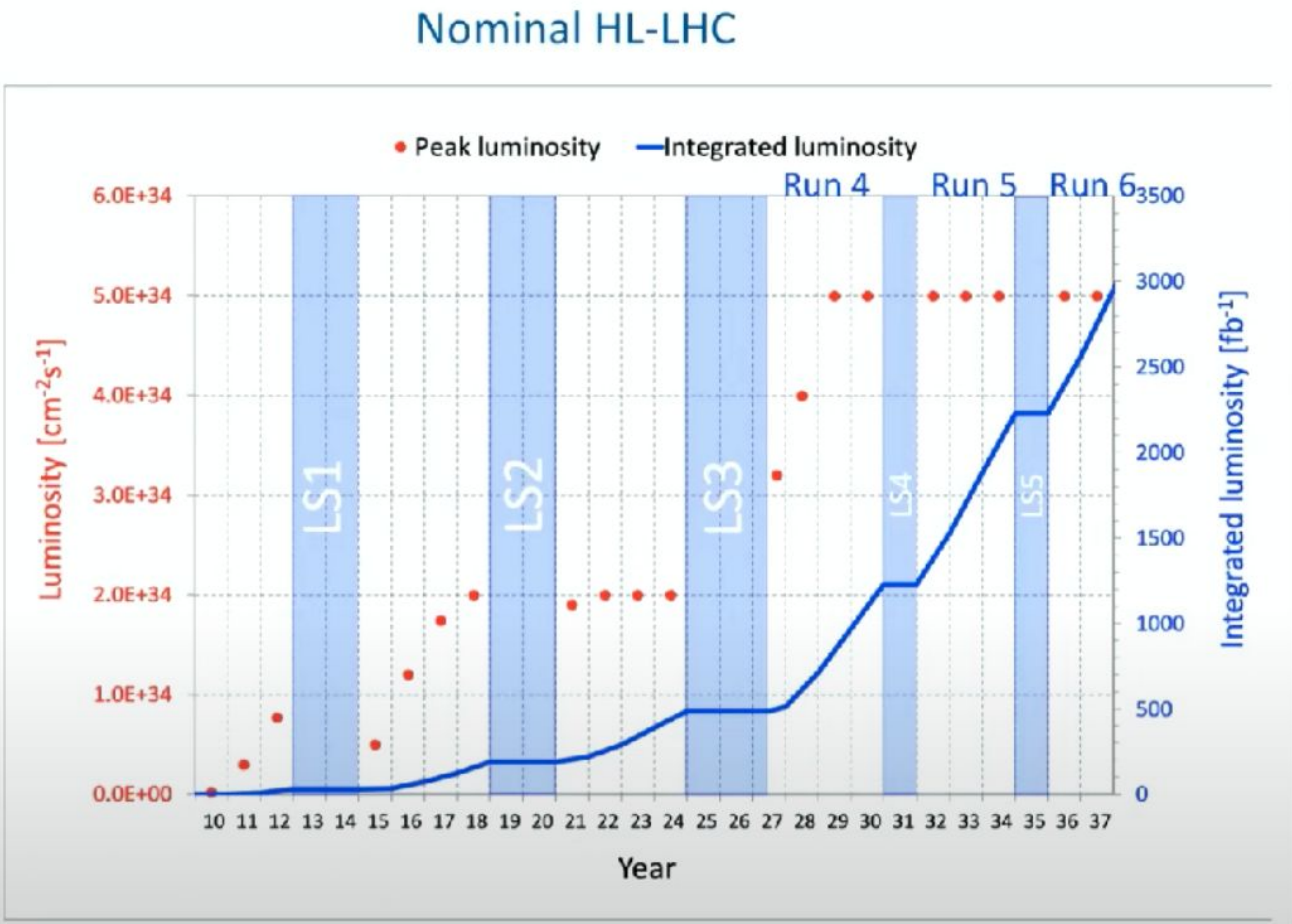
- With more intense and more focused bunched LHC can get to the pileup of 400 in HL-LHC!
- Proton collisions will look like heavy ion collisions!
- New strategy for operations: luminosity leveling.



Level at $5x10^{34}$ $cm^{-2} s^{-1}$
corresponds to ~140 pile up interactions



HL-LHC projection



Luminosity detectors

- for integrated luminosity measurement
- but also for online luminosity measurement

Luminometers of the CMS experiment

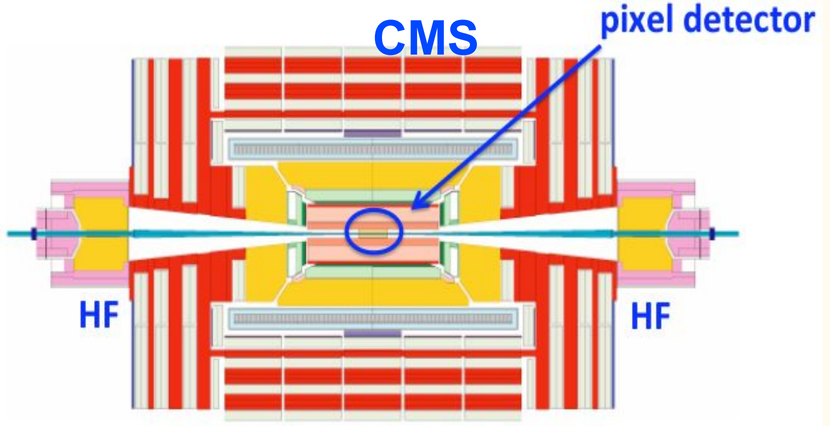
- **Any detector, which can provide particles hit rates can be used as a luminometer.**
- **A luminometer with a linear response produces a signal that is proportional to the instantaneous luminosity.**
- In the CMS following Luminometers are used:

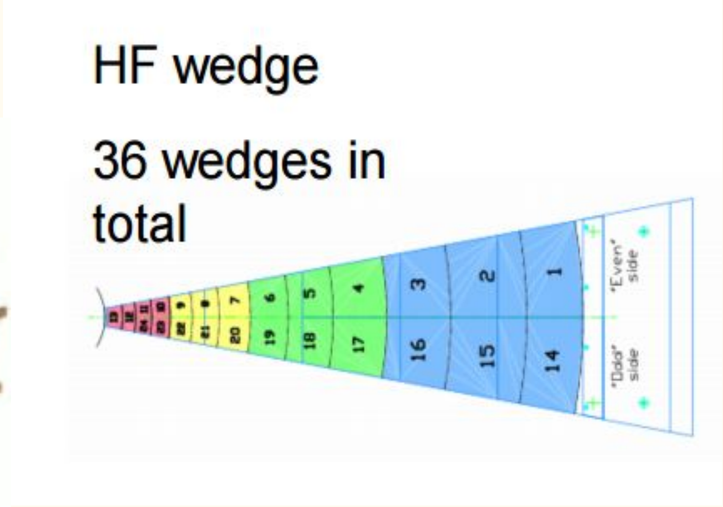
- Pixel Detector

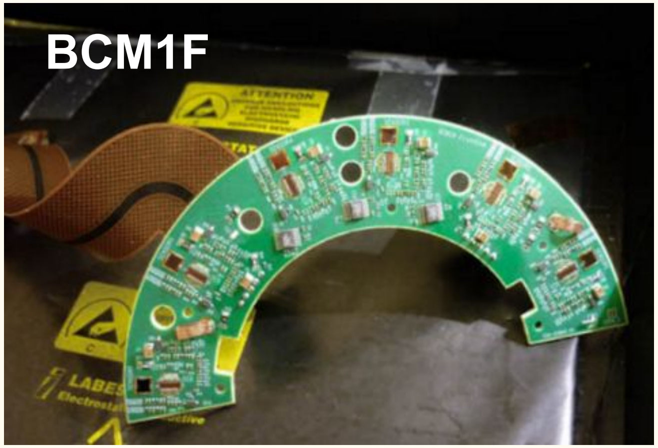
- Forward calorimeter (HF)

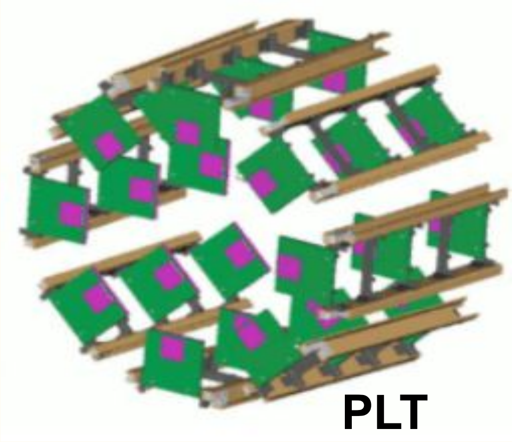
- Fast Beam Conditions Monitor (BCM1F)

- Pixel Luminosity Telescope (PLT)

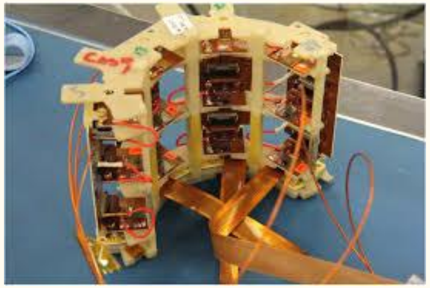






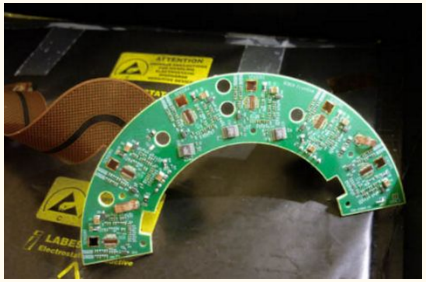


Unique inner carriage



4 PLT telescopes on titanium alloy SLM cassette

+



6 BCM1F sensors and dedicated ASICs mounted on PCB

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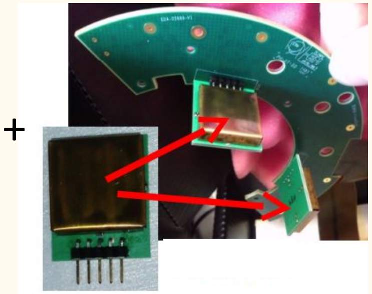
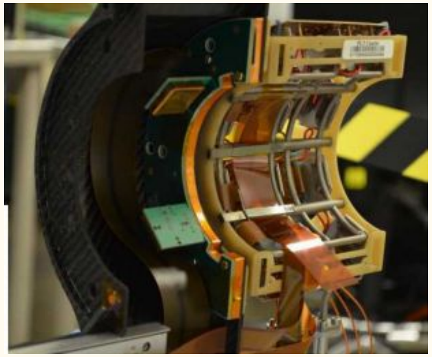
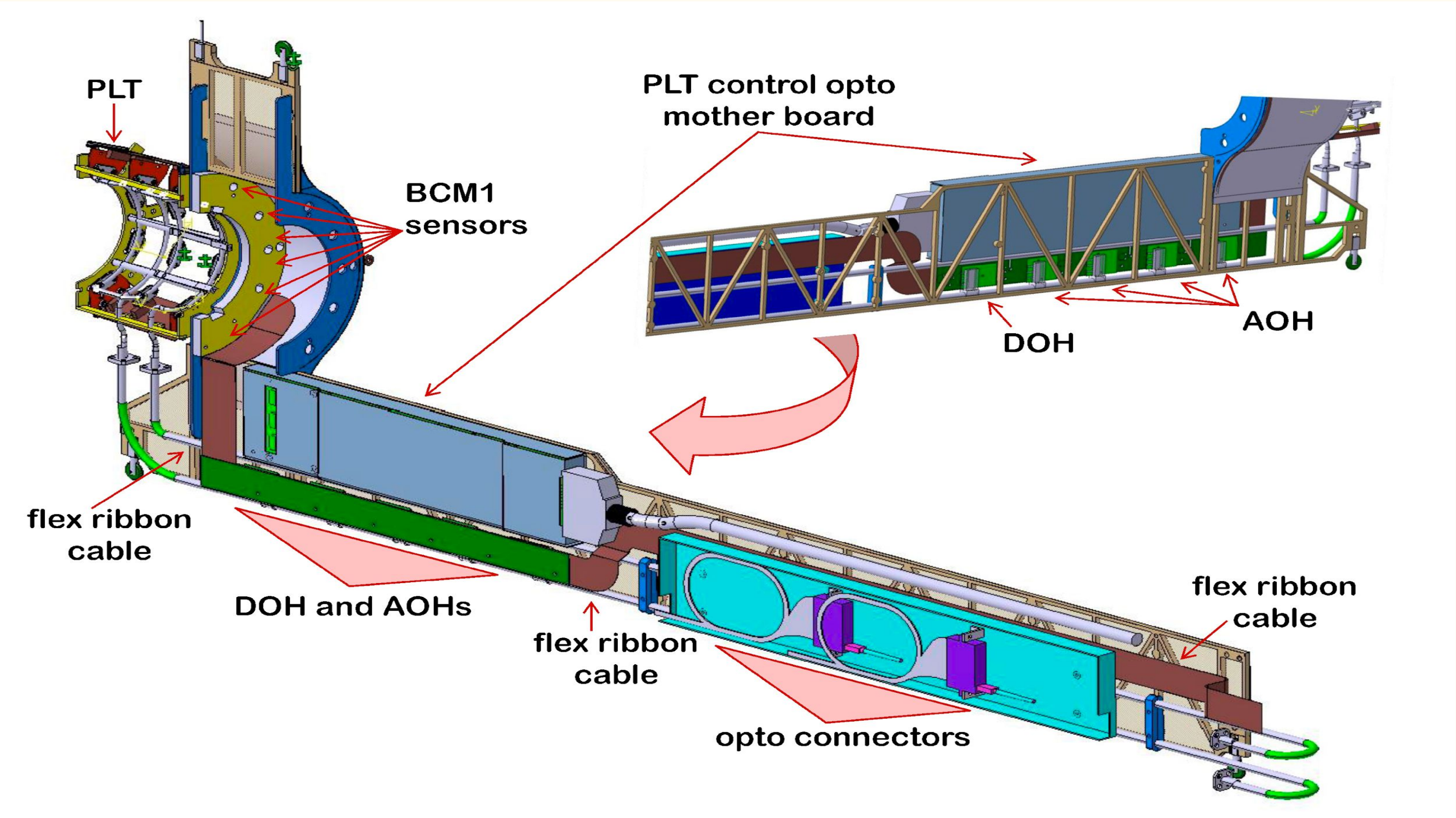


BCM1L traces soldered onto PCB (C-shape)

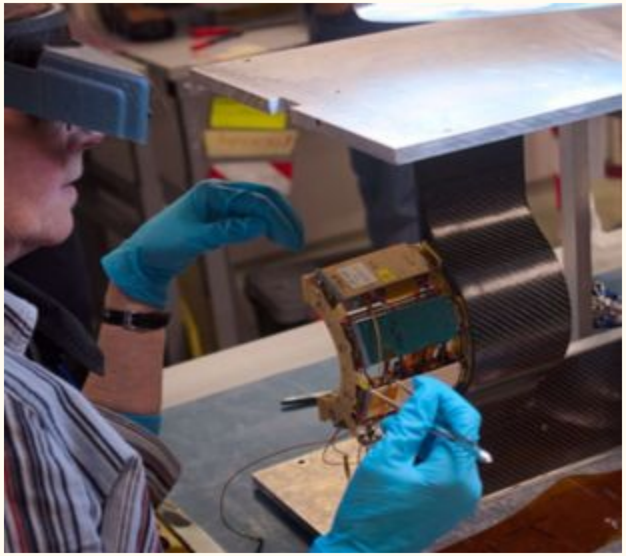
=

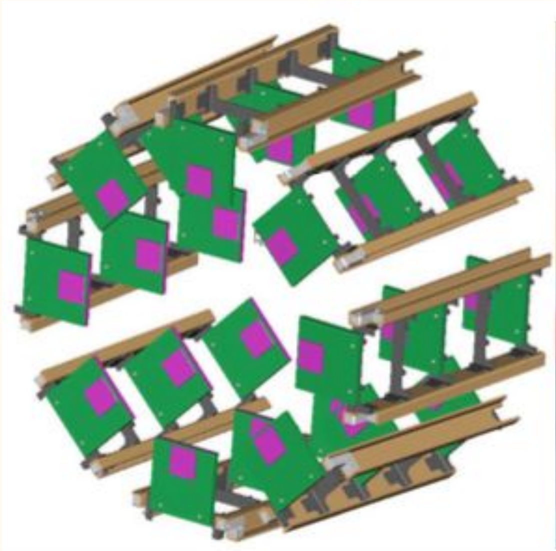


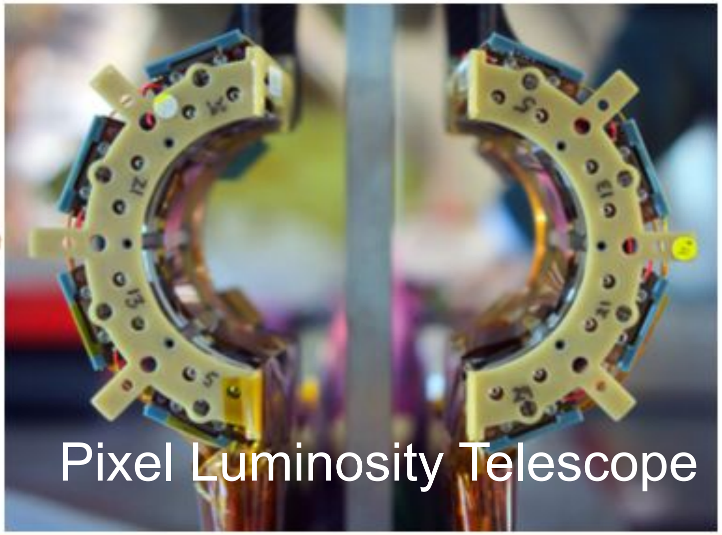


- Specifications
- Sensors
- Electronics
- Readout
- Cooling
- Design
- Support structure and shape which fits with uther CMS detectors
- Testing
- Installation
- Calibration
- Operations
- Data analysis
- Performance optimization

Detector assembly and tests in the laboratory

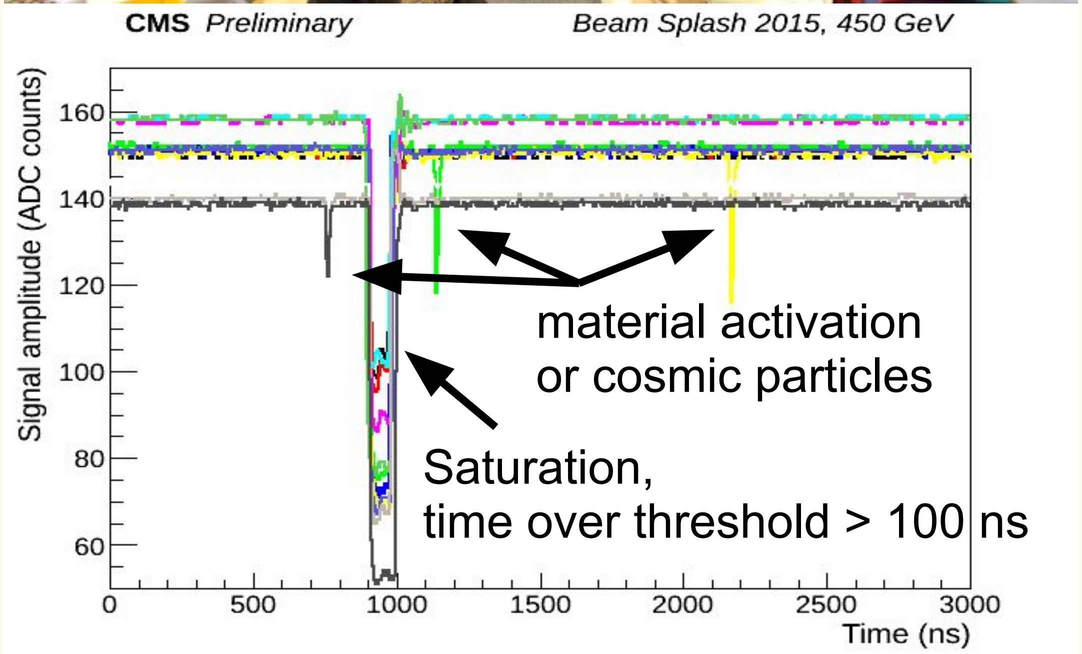






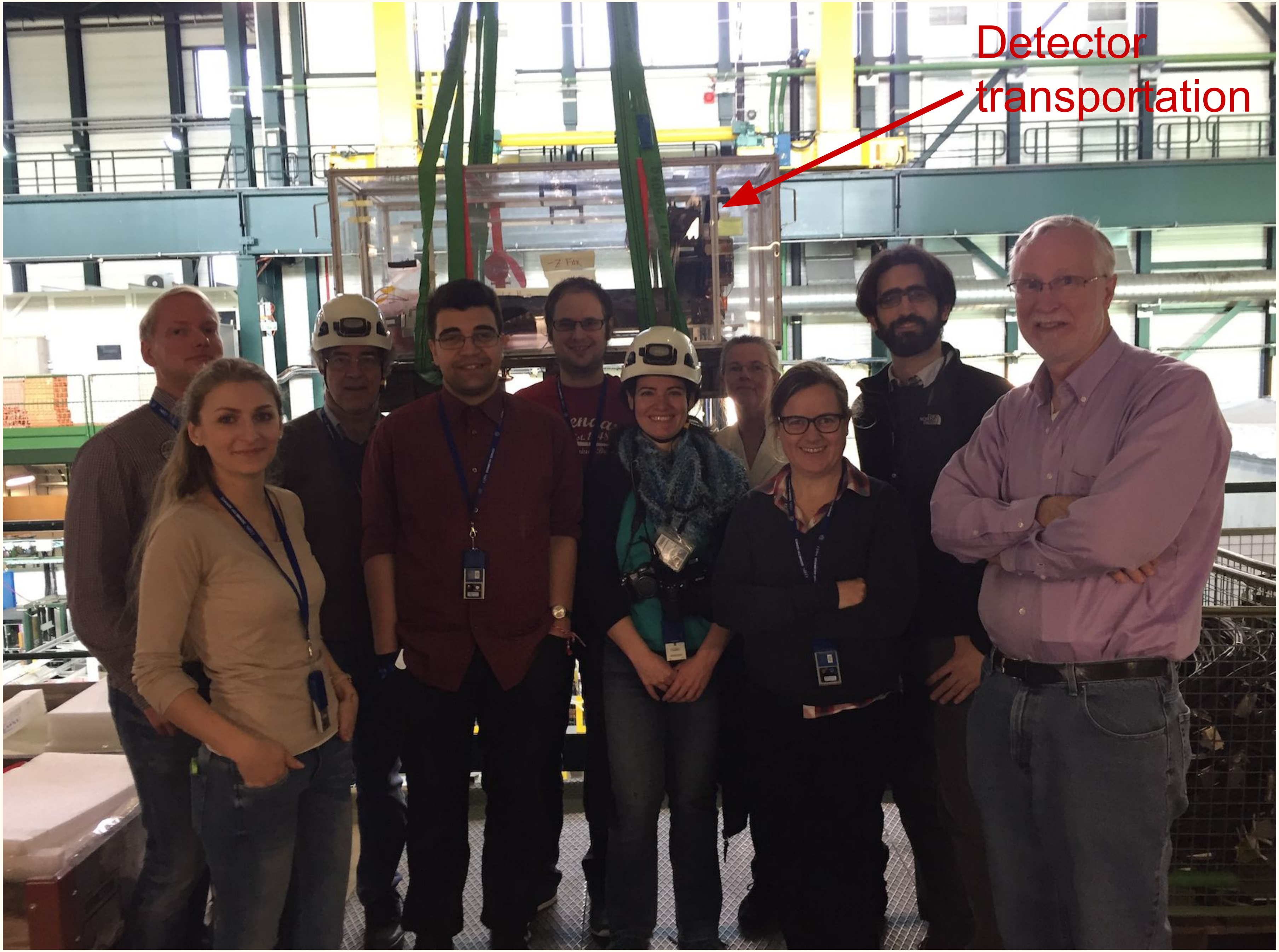
Happy BRIL team before installation 2015

Easter present 2015: beam splashes at LHC!



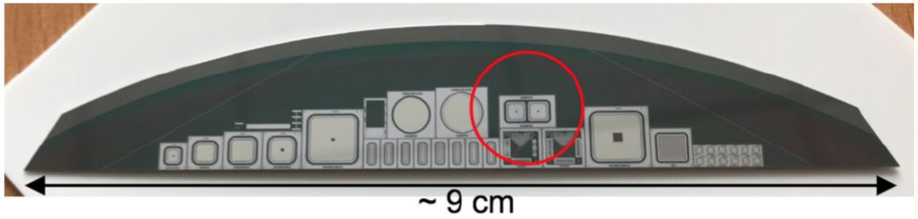
- Splash event: a single bunch is dumped in a collimator just upstream of the experiment.
- Since many particles cross the sensor simultaneously the signal amplitude saturates.
- First data recorded by the VME ADCs: the response of diamond sensors in splash events.

Before installation (2017)



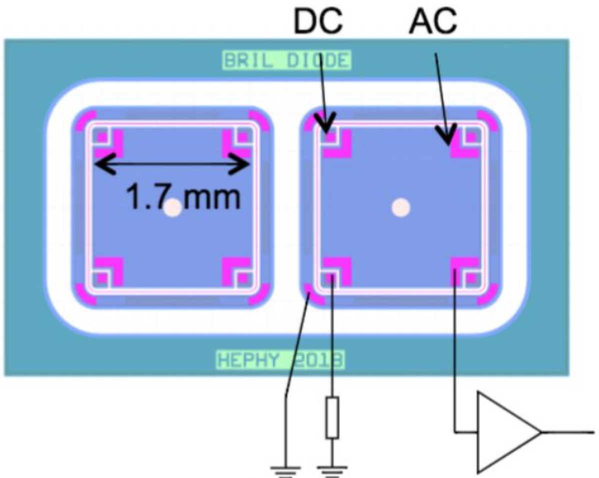
New generation of the detectors

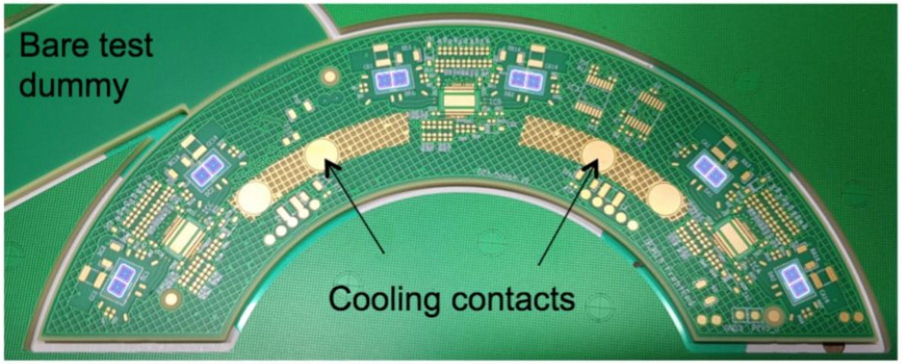
BCM1F for Run3

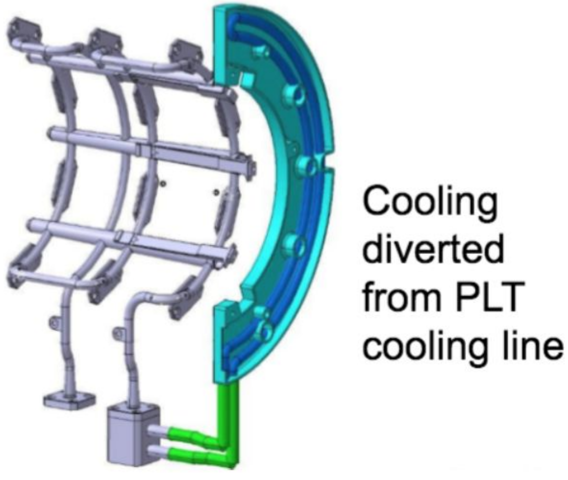


[Planning talk]

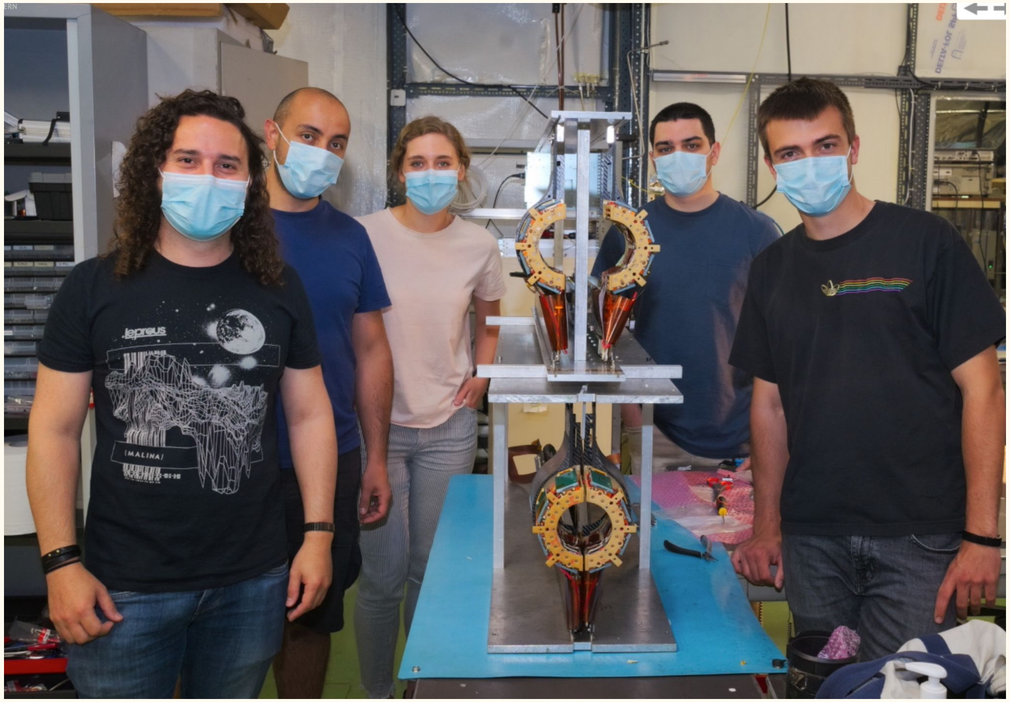
- Desired Si sensors, but no leakage current into FE-ASIC
  - AC coupling
- New sensor design: AC coupled double diodes, external bias resistor.
- First batch with recent HGCal sensor production.
- PCB features active cooling and various other improvements

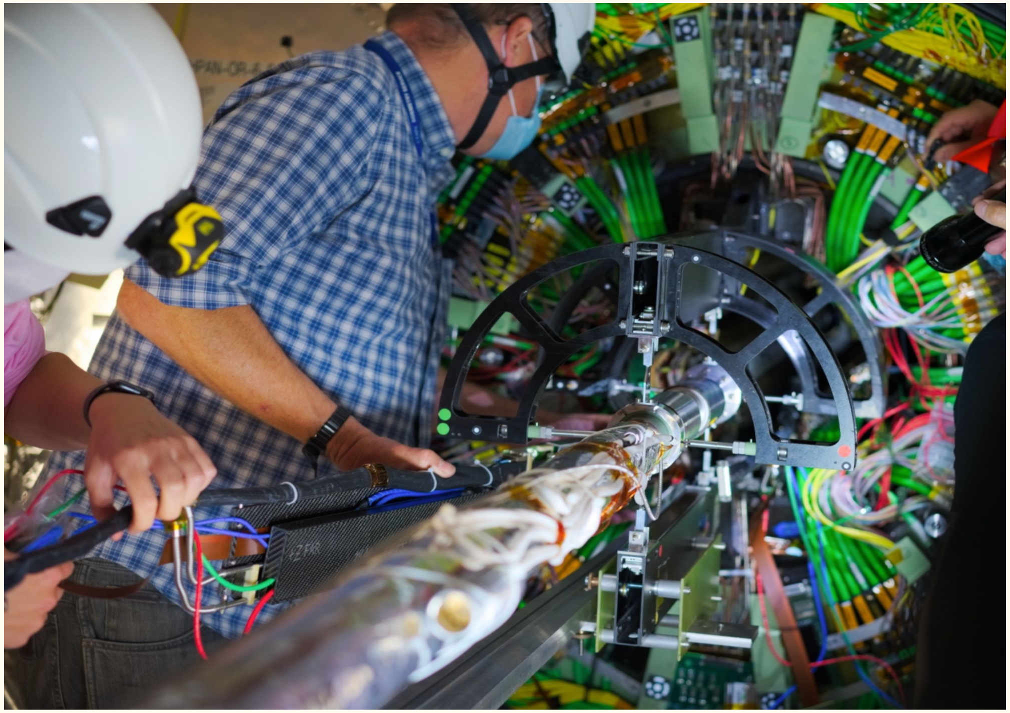


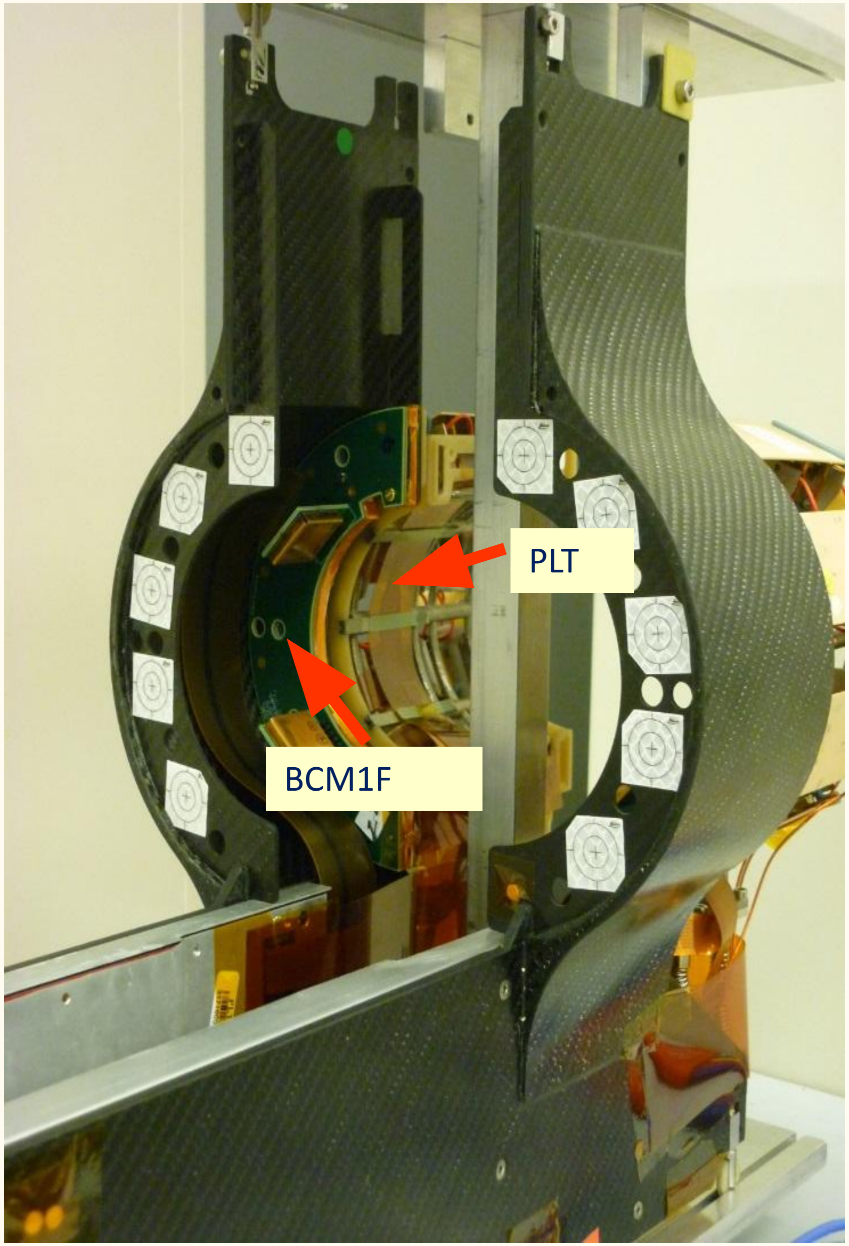




Installation 2021

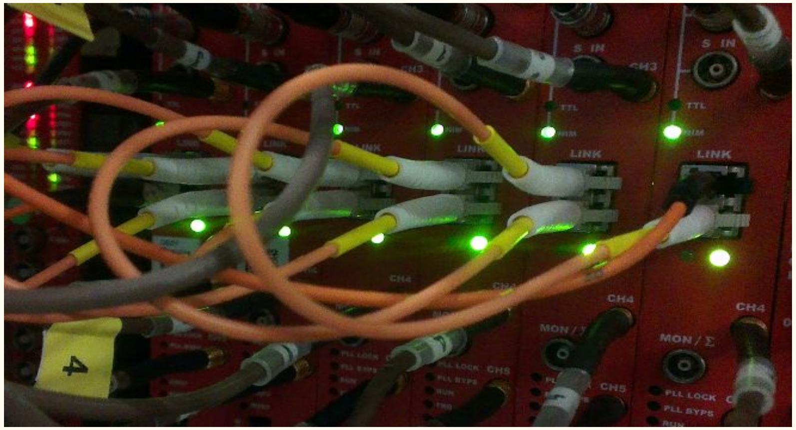


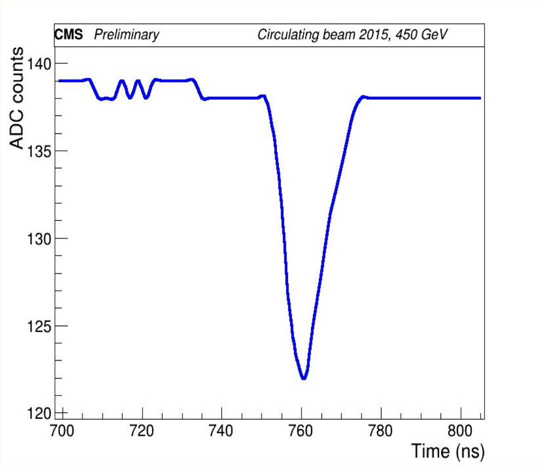




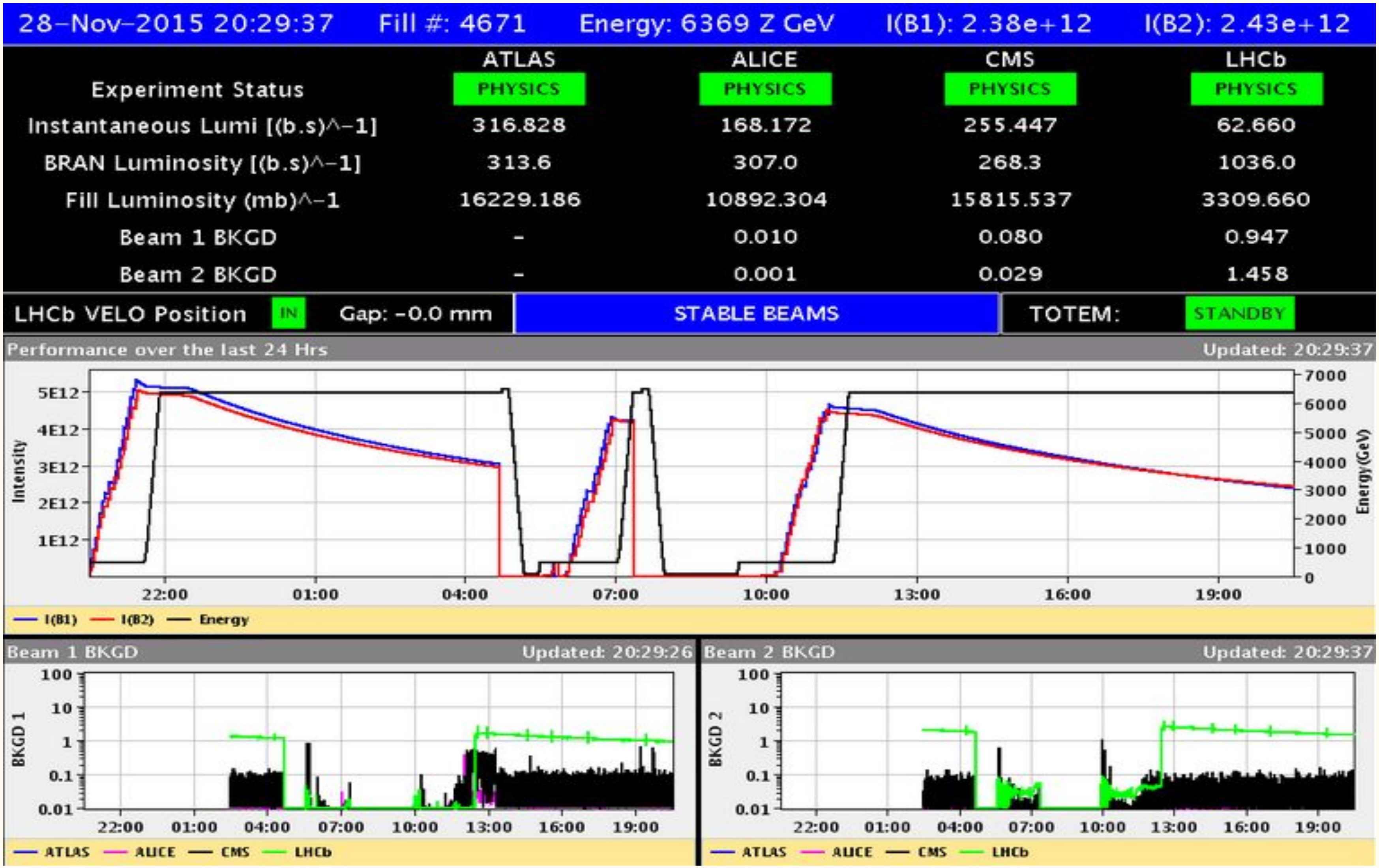
Part of the back-end

- 48 channels of BCM1F are served by CAEN v1721 ADCs:
    - 8 channels 8 bit 500 MS/s Digitizer (2 ns sampling time);
- Custom made RHU modules.
    - Histograming units recording every collision for online luminosity measurement.



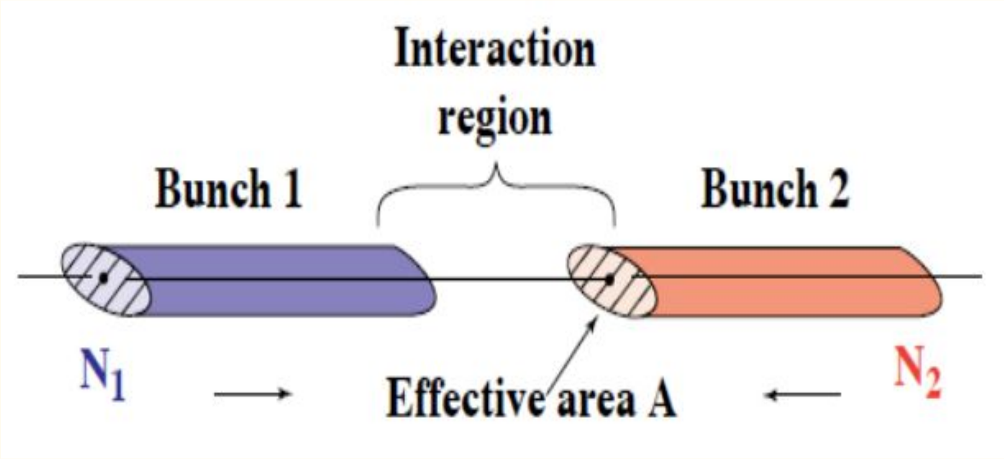


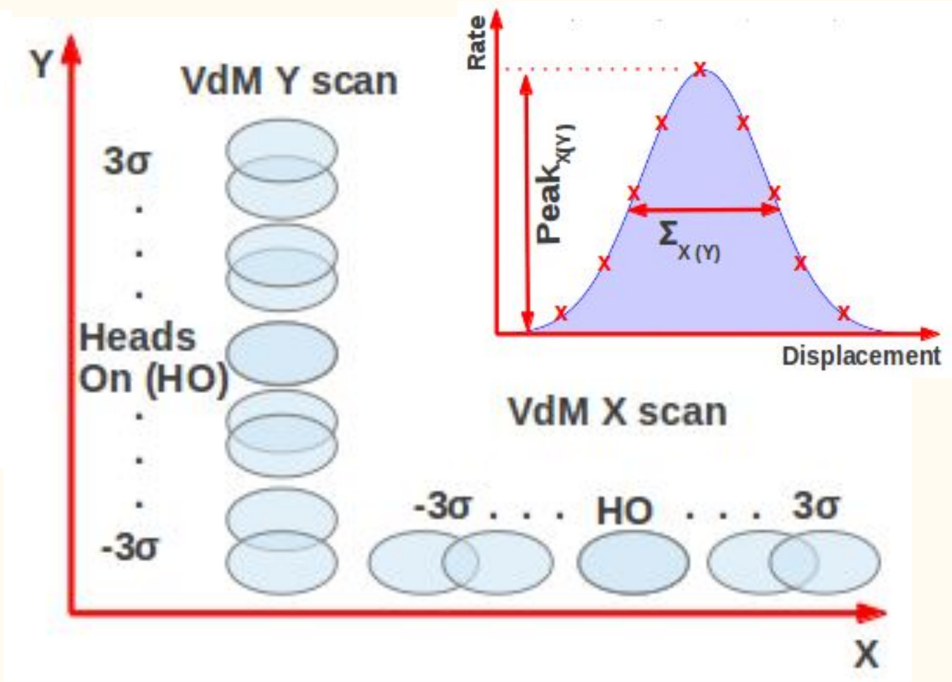
ONLINE Luminosity and Background measurements



Luminosity calibration

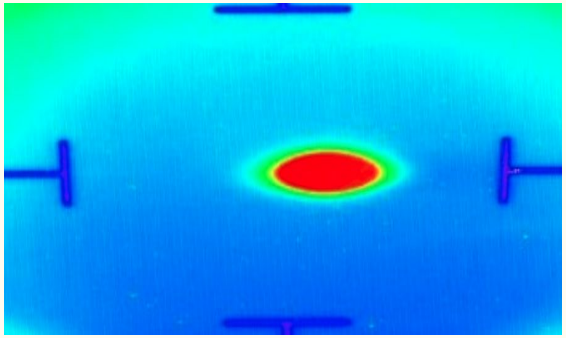
Calibration of the luminometers





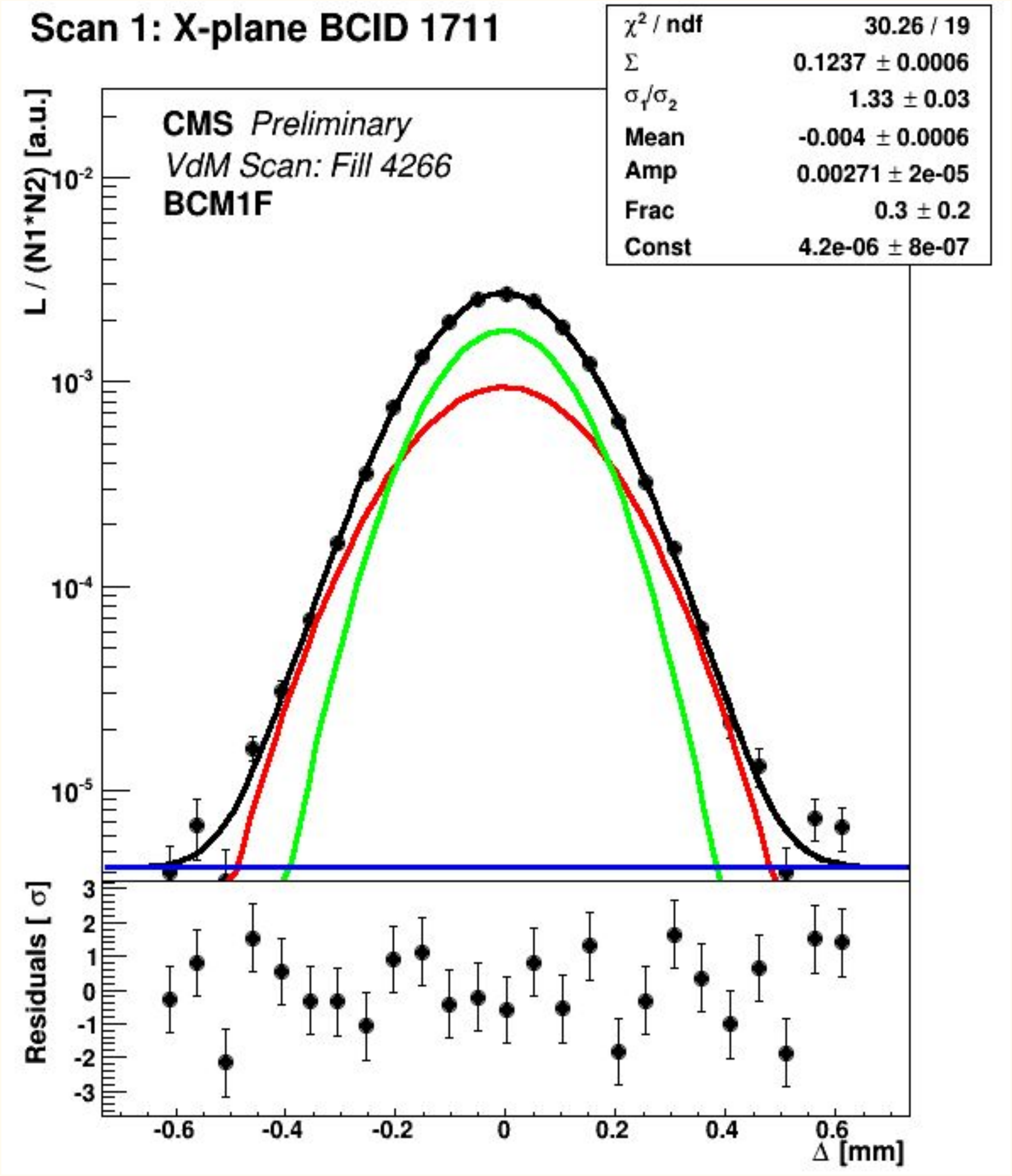
$$L = N_1 N_2 f n_b / A_{eff},$$

where N_1, N_2 - number of protons in beams 1 and 2, f - LHC orbit frequency, n_b - number of colliding bunches, A_{eff} - effective area.



- ***Van der Meer scan method*** proposed by Simon van der Meer: determine A_{eff} by measuring rates as a function of the beams displacement. Scans obtained in X and Y planes separately.

Visible cross section measurement



- Analysis framework is used to fit beam overlap and calculate visible cross section - the effective cross-section seen by the luminometer:

$$A_{eff} = 2\pi \Sigma_1 \Sigma_2,$$

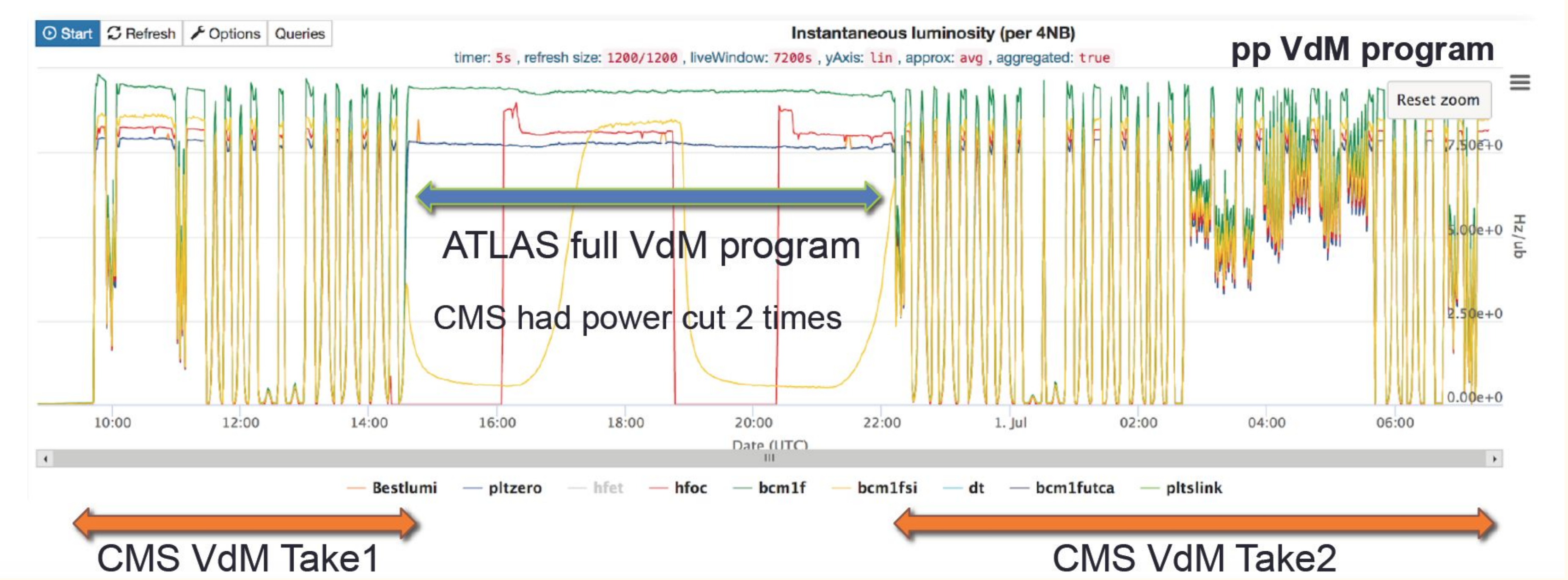
$$\sigma_{vis} = \frac{2\pi \Sigma_X \Sigma_Y}{N_1 N_2 f n_b} \left(\frac{Peak_X + Peak_Y}{2} \right).$$

- The distribution is fitted with a Double Gaussian + Constant fit

- σ_{vis} is the important quantity, since it is used than for the data taking fills as the cross section from which the actual luminosity is measured.

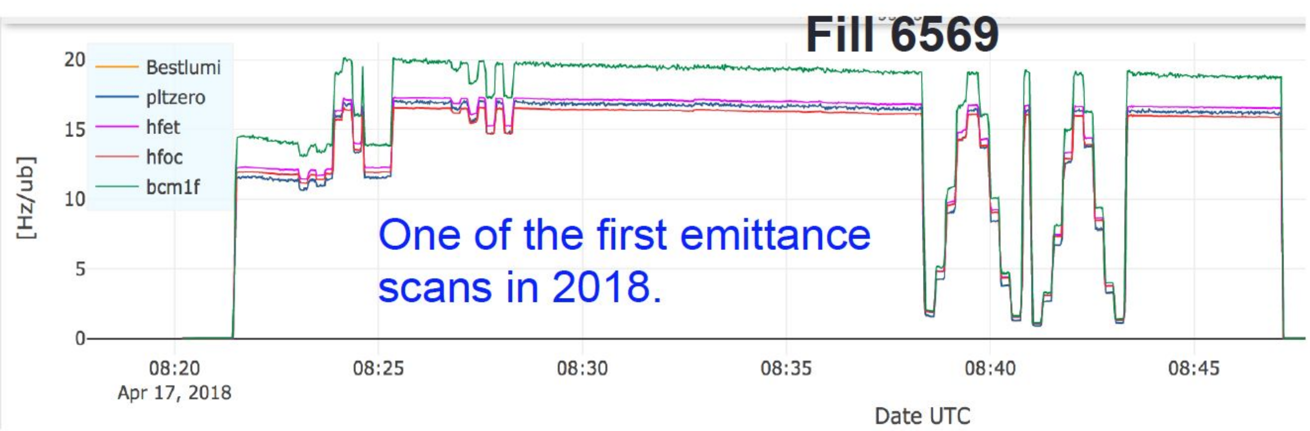
Example of the Van der Meer scans program

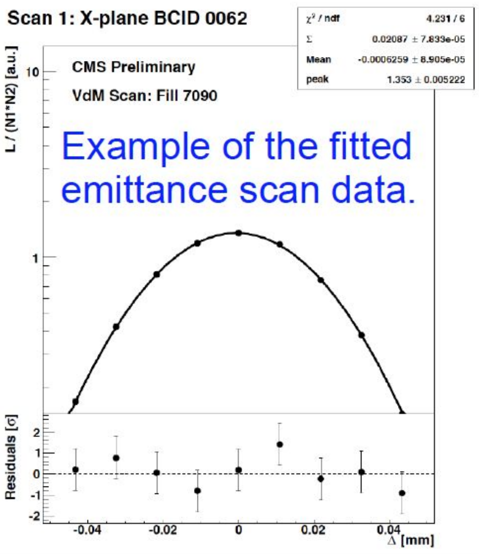
- **Very complete pp VdM program, Fill 6868, July 2018:**
  - 7 pairs of VdM scans (3 pairs are Imaging scans with one beam fixed), 2 offset scans, 5 emittance scans;
  - length scale calibration with fixed and alternating separation;
  - 2 super separation measurements of background.



Special emittance scans for performance monitoring

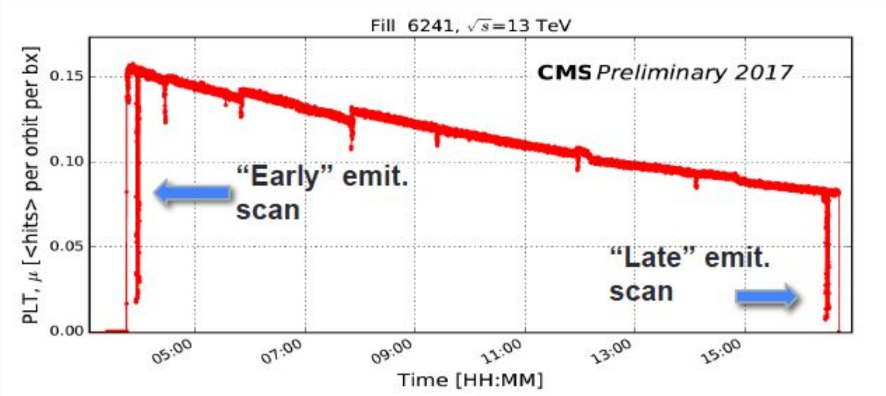
- From 2017 CMS is using emittance scans – mini Van der Meer scans performed in 9 steps of beam separation.
- In 2017 it was demonstrated that emittance scans are powerful tools to monitor the detector performance.
- In 2018 from the first days with beams in the LHC emittance scans were used to cross check performance of the luminometers and correct calibrations for online purposes.
- Excellent online web-monitors allowed to display updating in real time luminosity in control room and accessible remotely.

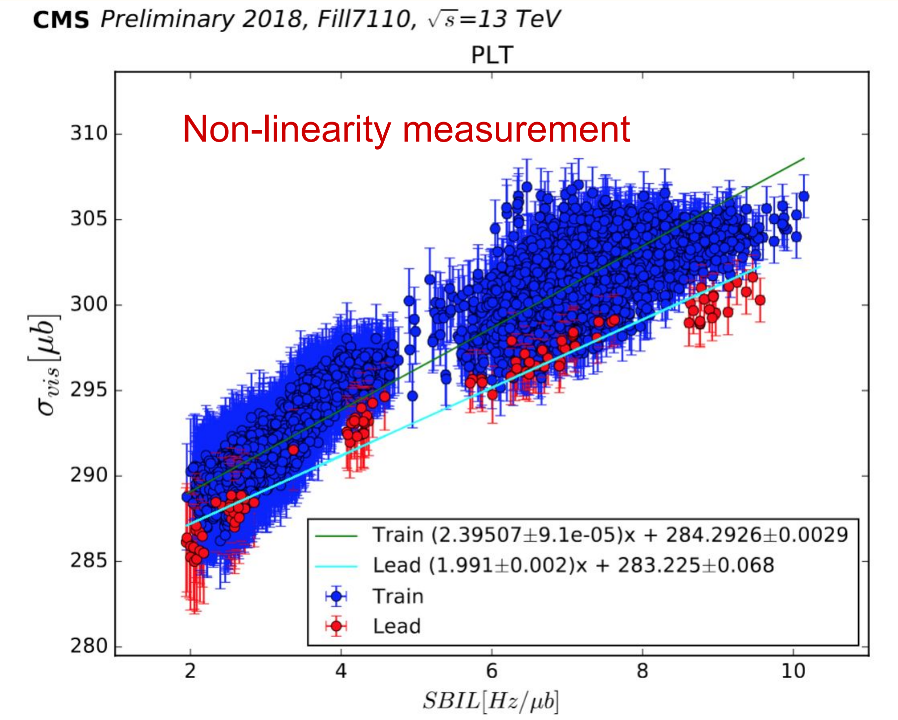


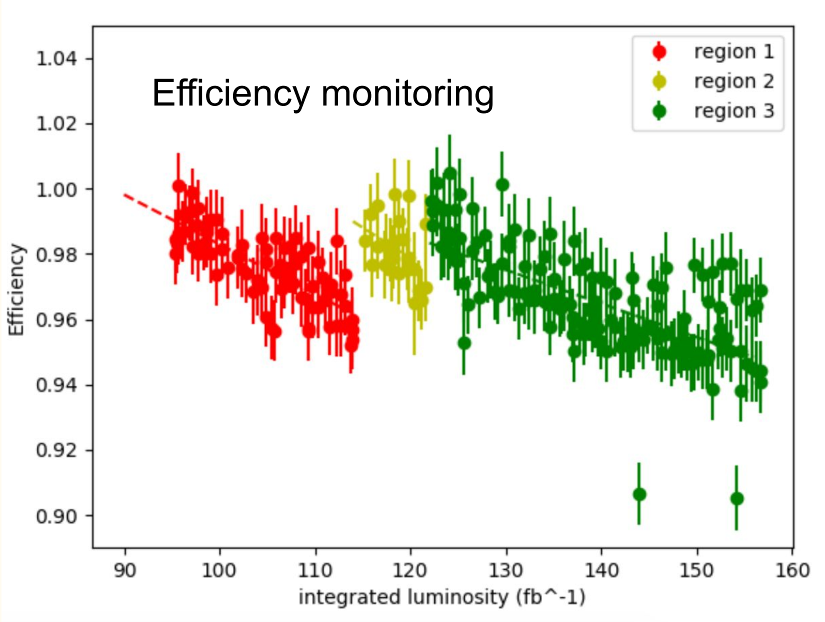


Application of emittance scans

- Wide range of Single Bunch Instantaneous Luminosity (SBIL) is covered in each LHC fill -> Emittance scans early in the fill and towards the end of the fill allow for non-linearity measurement of online luminometers in each fill.
- Through the whole year emittance scans are employed to track the performance of the detectors and correct for efficiency drops.







Дякую за увагу!

Давайте подивимось 3D модель CMS!

https://indico.cern.ch/event/1107838/timetable/

ONLINE Ukrainian Teacher Programme

24 Jan 2022, 17:00 → 28 Jan 2022, 20:00 Europe/Kiev

Zoom (CERN)

Daria Ternova (CERN), Oleksandr Yurov, Jeff Wiener (CERN)

Description This is the first ONLINE Ukrainian Teacher Programme. It features talks and virtual visits delivered via Zoom that include ample opportunities for teachers to interact with the lecturers and discuss open questions.

Please note: The timetable is shown in the timezone of Ukraine, which is one hour ahead of Geneva. (This means a session that starts at 5pm in Ukraine starts at 4pm in Geneva.)

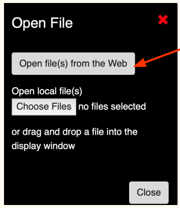
ONLINE Ukrainian Teacher Programme:
https://indico.cern.ch/e/UATP22online

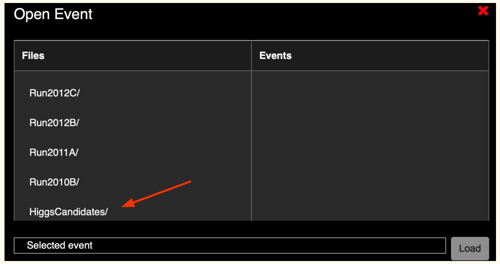
Contact jeff.wiener@cern.ch

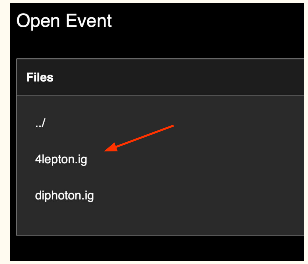
FRIDAY, 28 JANUARY

17:00 → 20:00 **Session 5**

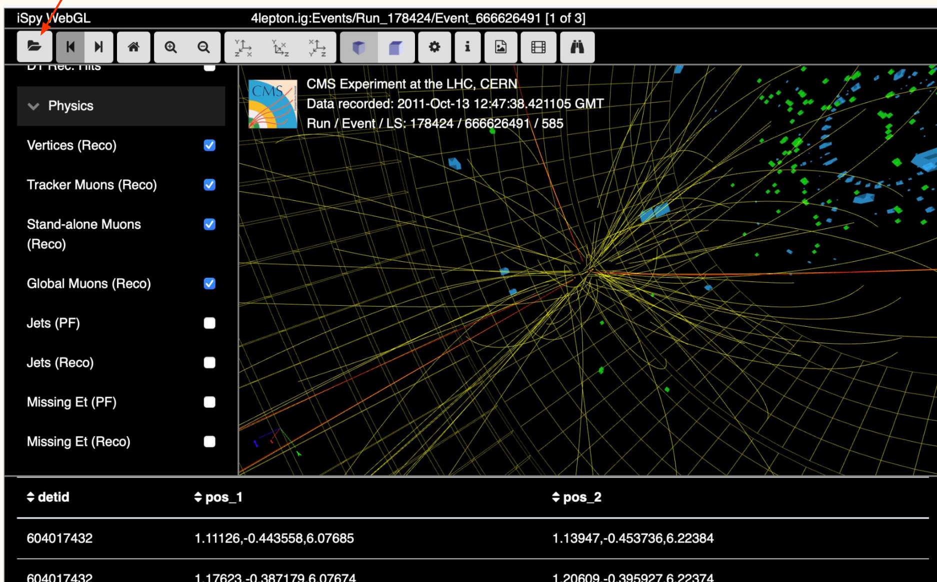
3D interactive CMS detector



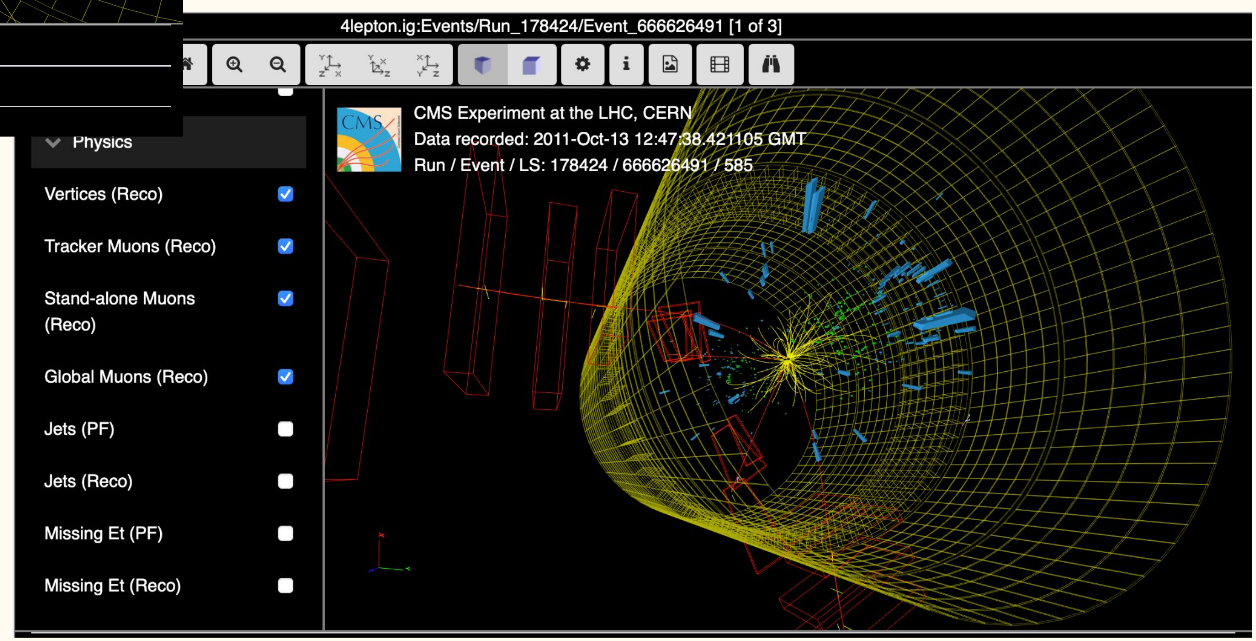


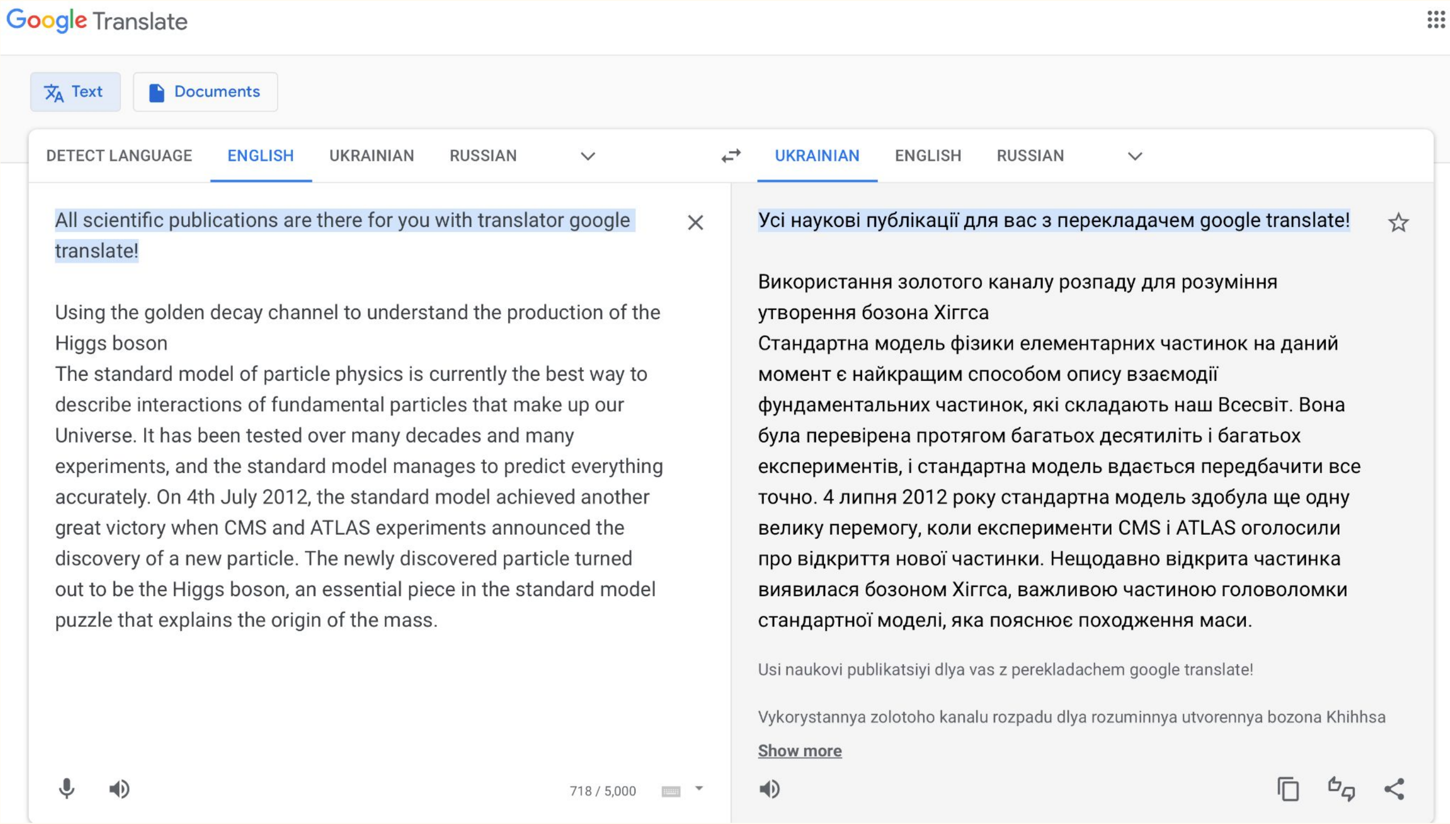


Спробуйте самі!



https://opendata.cern.ch/visualise/events/cms
https://www.i2u2.org/elab/cms/event-display/#

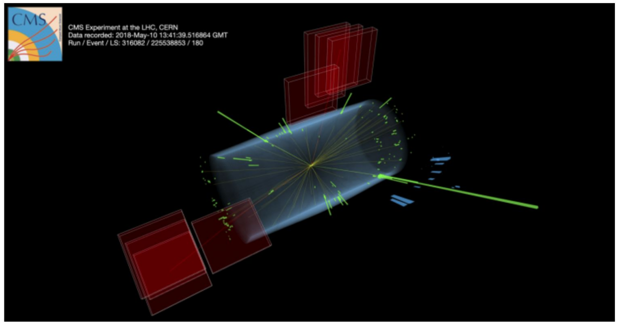




Спробуйте самі!

https://translate.google.com

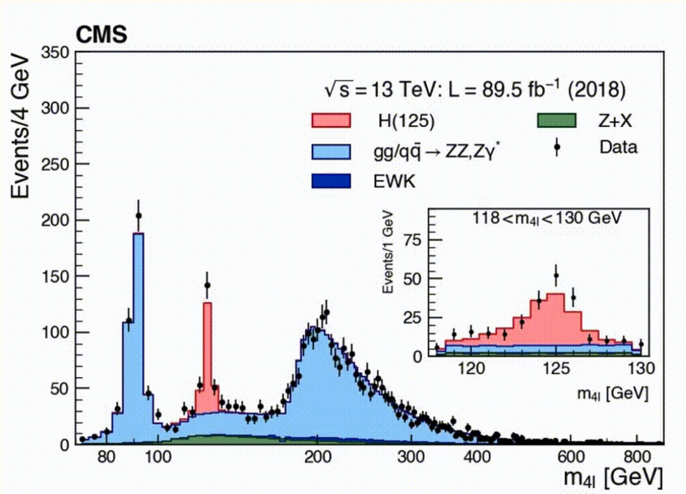
By CMS Collaboration



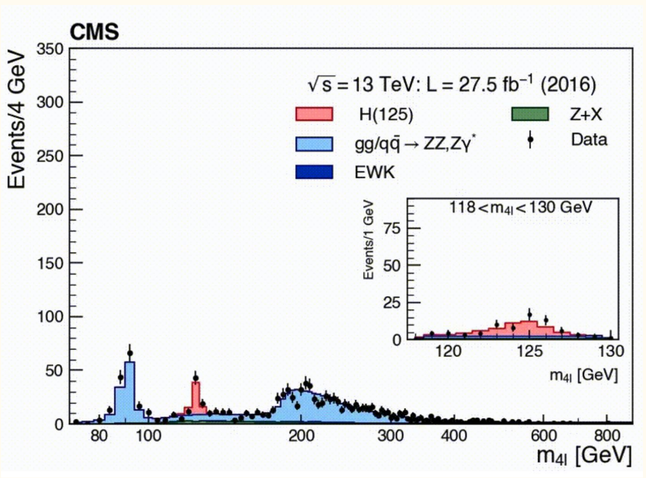
Using the golden decay channel to understand the production of the Higgs boson

The standard model of particle physics is currently the best way to describe interactions of fundamental particles that make up our Universe. It has been tested over many decades and many experiments, and the standard model manages to predict everything accurately. On 4th July 2012, the standard model achieved another great victory when CMS and ATLAS experiments announced the discovery of a new particle. The newly discovered particle turned out to be the Higgs boson, an essential piece in the standard model puzzle that explains the origin of the mass.

Full Run 1 + Run 2



Run 1 alone



https://cms.cern/news/using-golden-decay-channel-understand-production-higgs-boson

Links and literature

LHC: https://home.cern/science/accelerators/large-hadron-collider

CERN Animation of CERN accelerator network: https://youtu.be/RDdPuL-uOQc

CMS News: https://cms.cern/cms-updates?field_article_type_target_id=382

Higgs boson https://home.cern/science/physics/higgs-boson

Higgs boson PDG https://pdg.lbl.gov/2019/reviews/rpp2018-rev-higgs-boson.pdf

Higgs article CMS: https://cms.cern/news/using-golden-decay-channel-understand-production-higgs-boson

Luminosity Werner Herr, Particle Colliders, CAS 2012, Granada
https://indico.cern.ch/event/173359/contributions/275970/attachments/218796/306434/luminosity_slides.pdf

CMS detector homepage: https://cms.cern/detector

HL-LHC by F.Moortgat https://www.youtube.com/watch?v=s0toLfMFTlU

Top quarks mass https://home.cern/news/news/physics/run-top-quark-run

Muons: https://indico.cern.ch/event/426323/contributions/1048167/attachments/907573/1281134/muon.pdf

LCH page 1: https://op-webtools.web.cern.ch/vistar/vistars.php

How to make your own cloud chamber: https://home.cern/news/news/experiments/how-make-your-own-cloud-chamber

Scoollab: https://scoollab.web.cern.ch

Cosmic Pi https://indico.cern.ch/event/555003/attachments/1305253/1951255/Cosmic_Pi_talk_ideasquare_070716.pdf