Precision luminosity measurement at CMS with the Pixel Luminosity Telescope

Teilchenphysik Seminar - TU Dortmund

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The Standard Model

Spin-1/2 *fermions*:

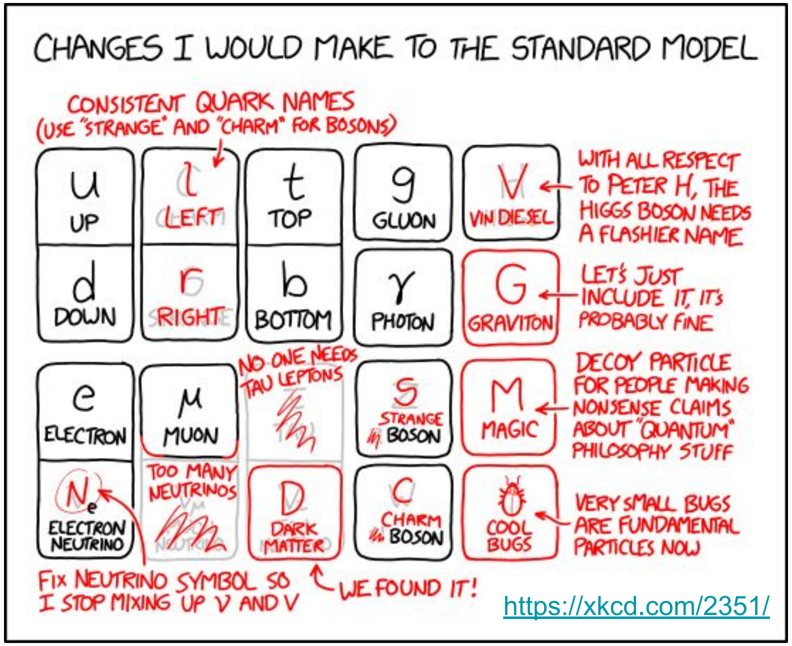
Wavefunction antisymmetric under exchange of two particles

- Quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$
  - *q* participate in EM, weak, strong interactions
- Leptons: $\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{pmatrix}$
  - *L* participate in EM, weak interactions
  - ν_L participate in weak interactions

Spin-1 *gauge bosons*:

Wavefunction symmetric under exchange of two particles

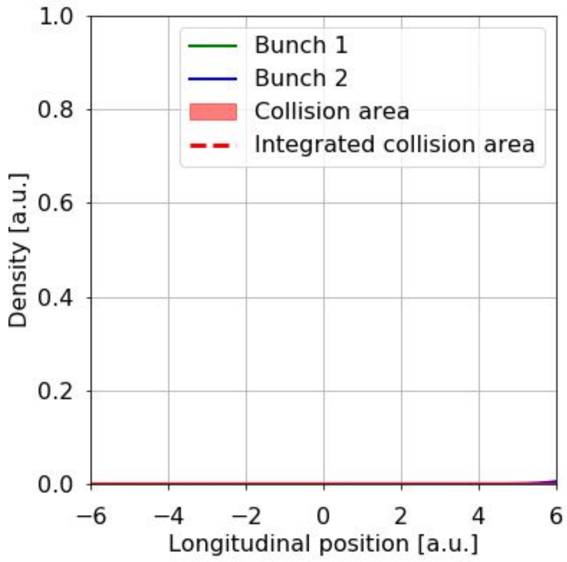
- Photon (γ)
  - Mediates EM interactions
- Weak vector bosons (Z^0, $W^\pm$)
  - Mediates weak interactions
- Gluon (*g*)
  - Mediates strong interactions

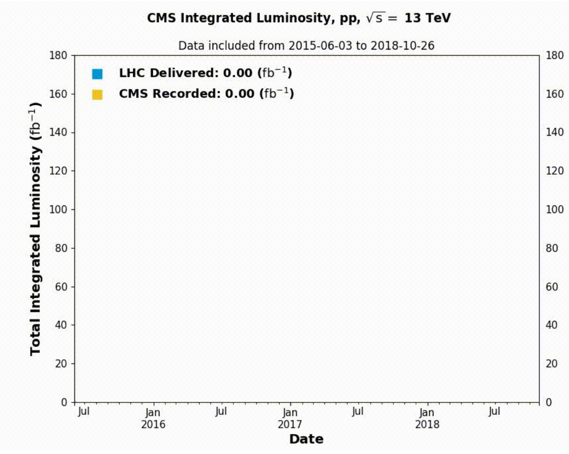


https://xkcd.com/2351/

Luminosity at the LHC

- What is luminosity?
  - Average number of "interactions" when "bunches" of protons cross
    - At the LHC, groups of ≈100 billion protons collide as often as 25 million times per second
    - ≈30 proton interactions for each crossing ("pileup")
  - Quantifies the ability to produce a certain number of interactions
    - Proportionality factor between rate of interactions and the cross-section
    - e.g. $dN/dt = \mathcal{L}_{peak} \cdot \sigma_{Higgs} \approx (0.02\ \text{pb/s})(50\ \text{pb}) = 1\ \text{/s}$
  - "Instantaneous" luminosity aggregated into "integrated" luminosity
    - Amount of data produced in a certain period of time
- Why is it important?
  - Monitoring of accelerator performance
    - Optimization of beam parameters
  - Detector operation during data-taking
    - Instantaneous luminosity determines trigger "selectiveness"
  - Integrated luminosity needed for physics analyses
    - Yields expected frequency of each type of interaction
      - e.g. $N = \mathcal{L}_{int}^{day} \cdot \sigma_{Higgs} \approx (500\ \text{pb}^{-1})(50\ \text{fb}) = 25\text{e}3$
    - Particularly important for cross-section measurements





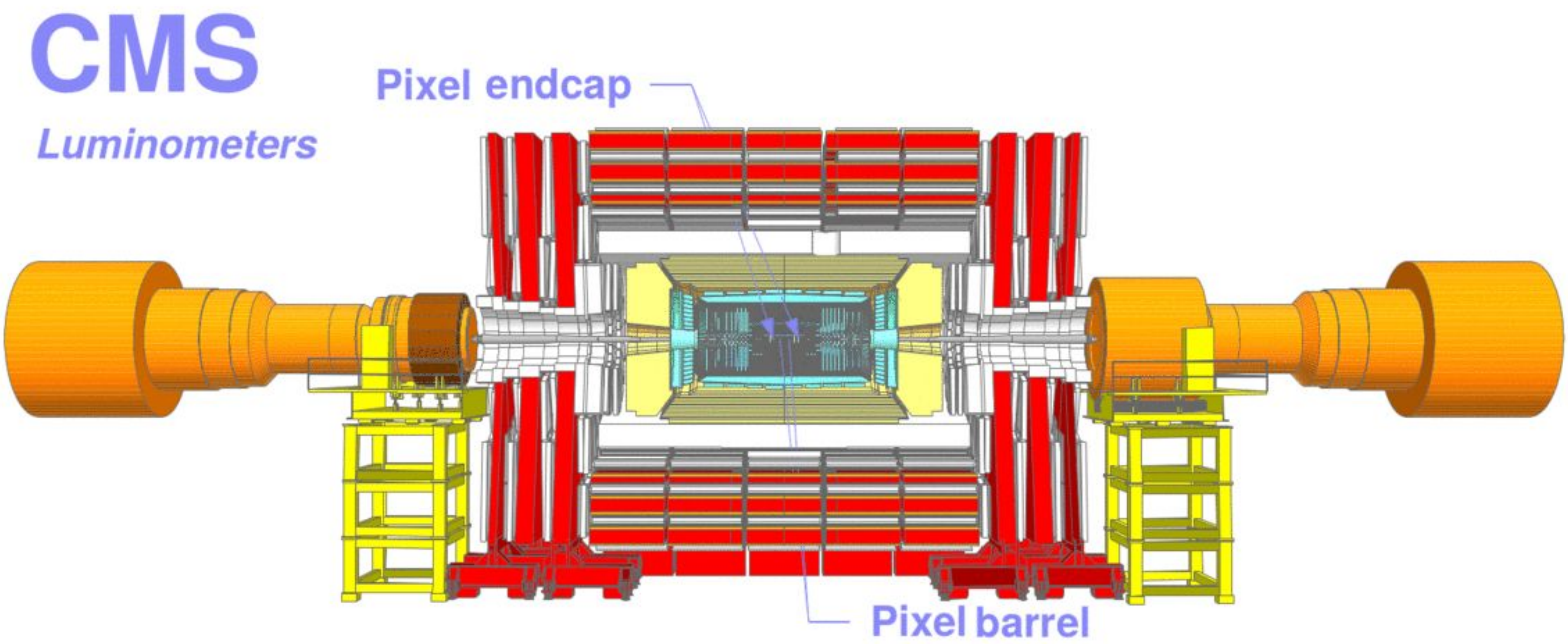
Luminosity measurement

- Recording and processing data from each luminometer
    - Absolute luminosity calibration and corrections

First CMS Lumi journal publication (Eur. Phys. J. C 81 (2021) 800):
Precision luminosity measurement in proton-proton collisions at $\sqrt{s}$= 13 TeV in 2015 and 2016 at CMS

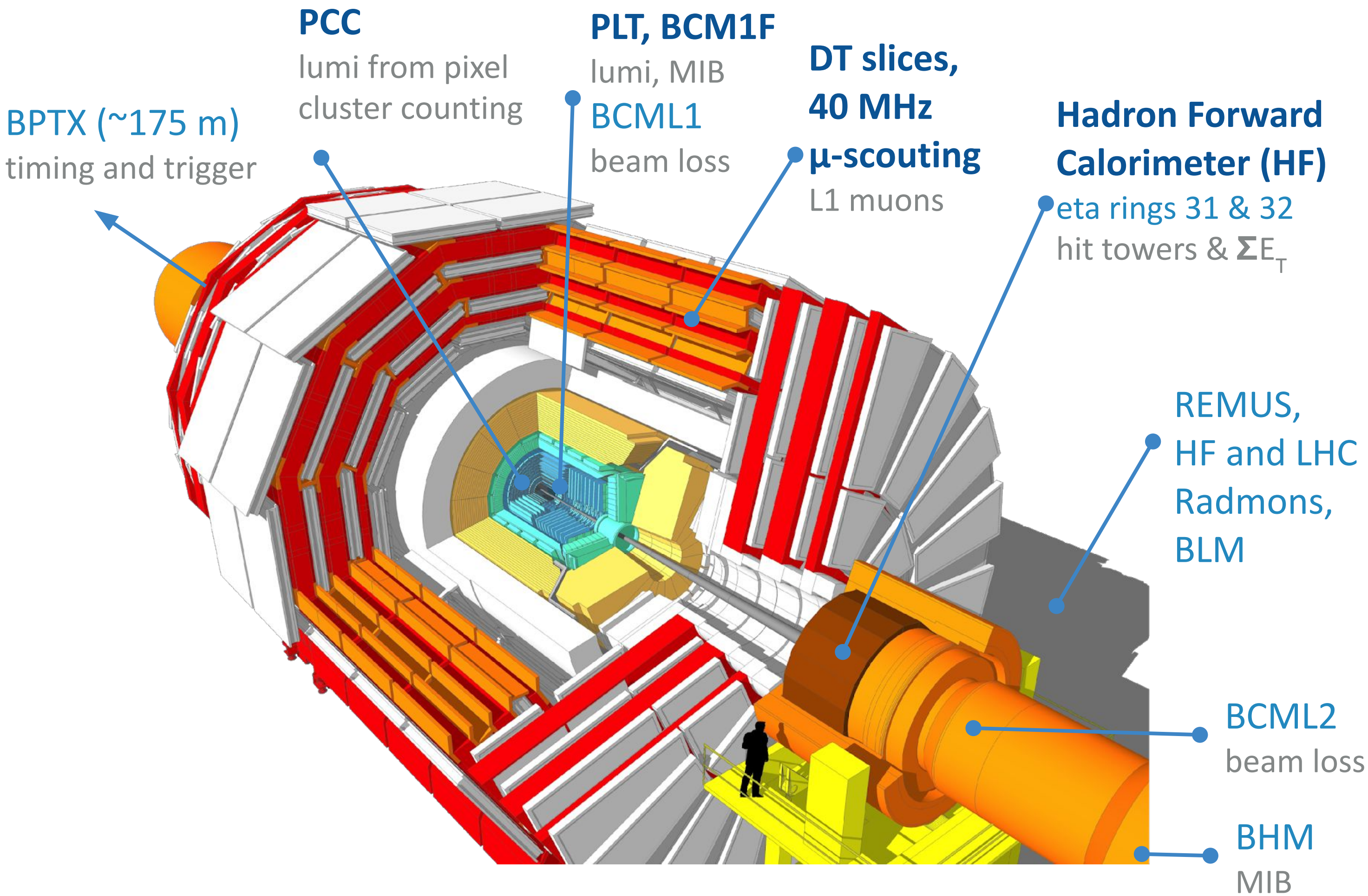
Luminometers at CMS

- Dedicated luminometers: PLT, BCM1F
- CMS sub-detectors used for lumi measurement: Pixel, HF, DT

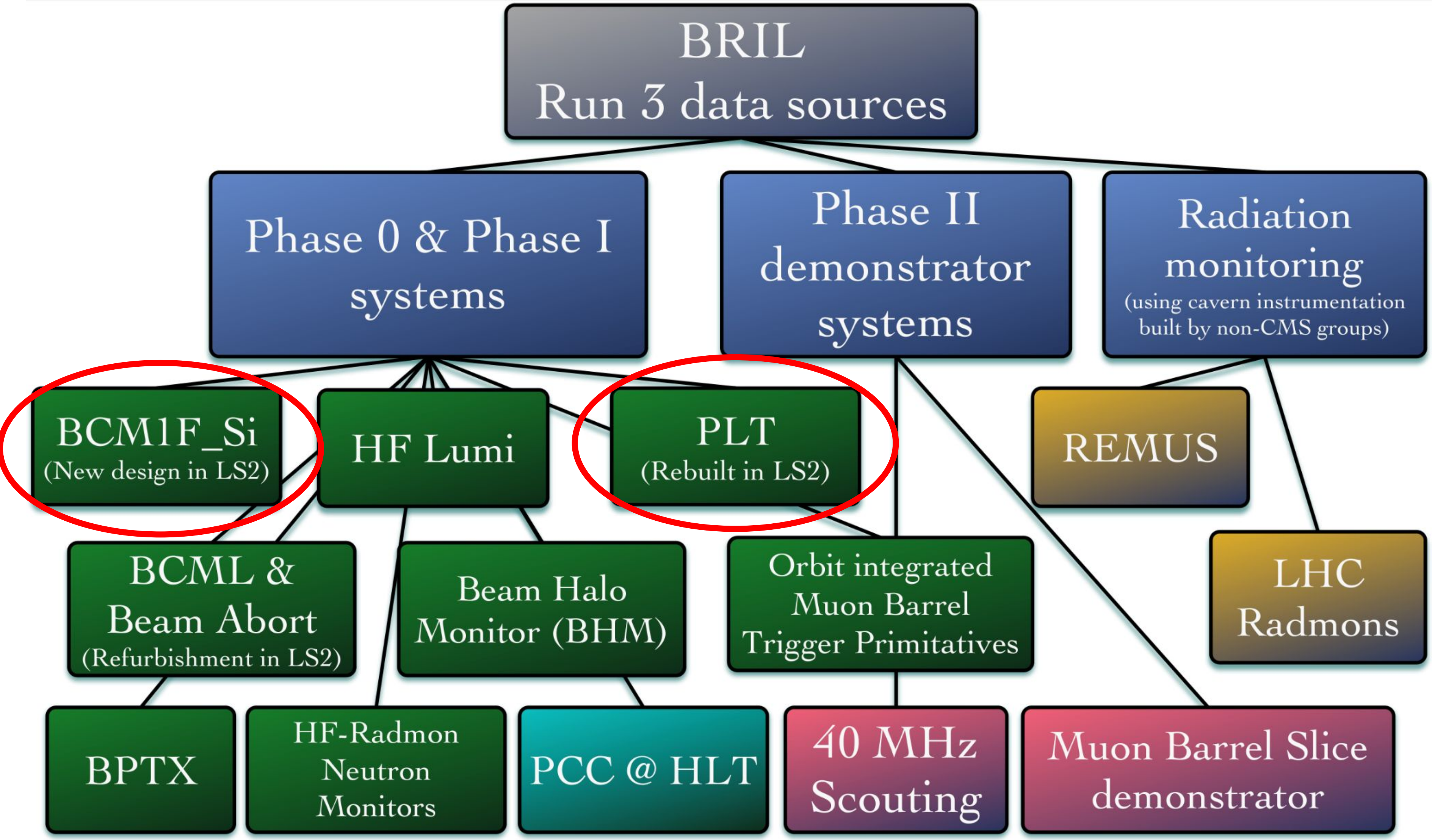


CMS BRIL Project

- Beam Radiation, Instrumentation, and Luminosity
  - Luminosity measurement, beam condition monitoring, radiation monitoring and simulation, etc

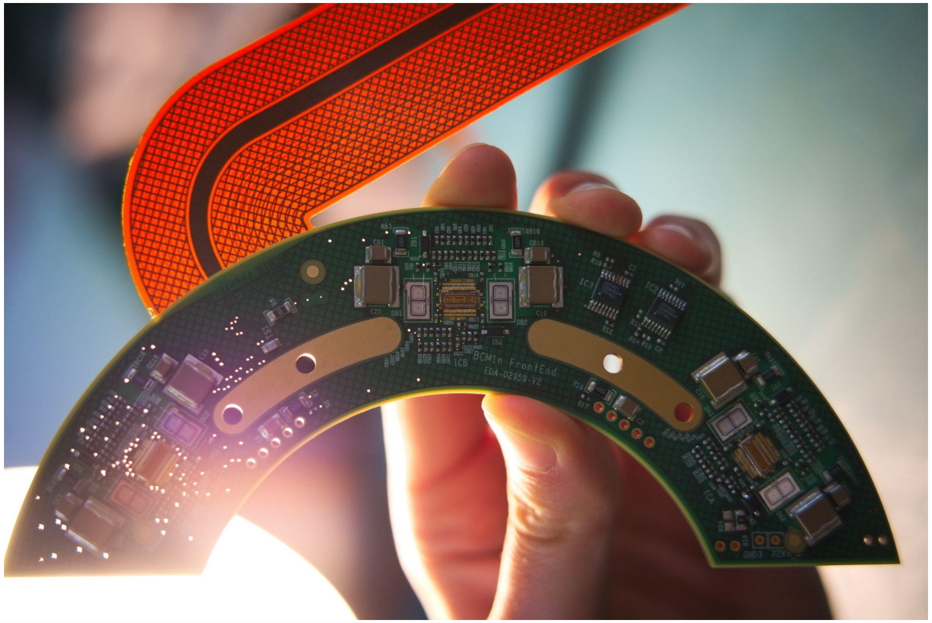


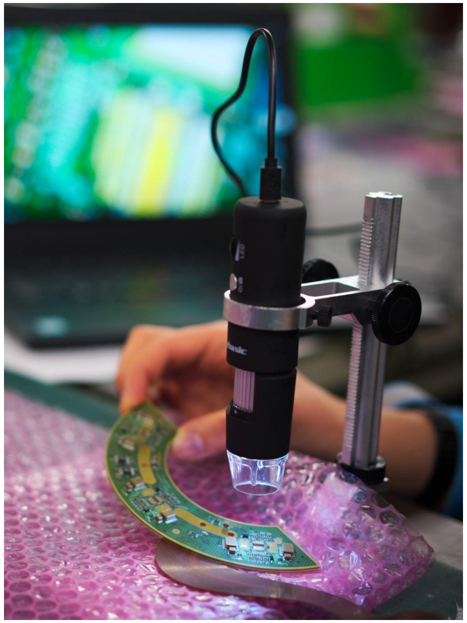
CMS BRIL Project [Run 3]



Fast Beam Condition Monitor (BCM1F)

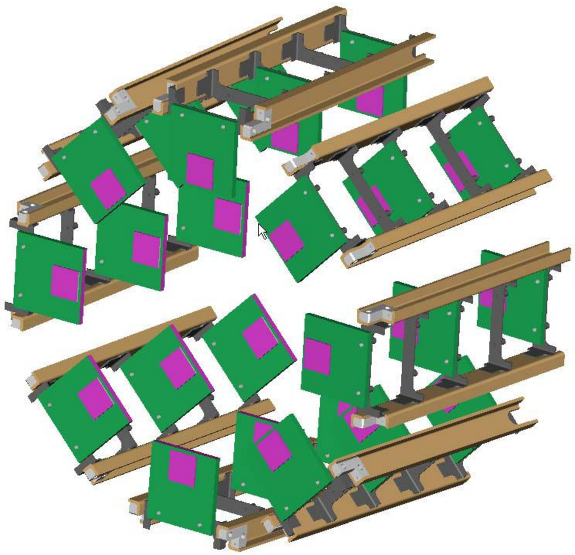
- Silicon pad detector dedicated to luminosity and background measurement
  - Installed in CMS in 2015 for LHC Run2 and rebuilt for LHC Run 3 data taking
  - New version implements CMS Phase-2 silicon sensor prototypes and active cooling
- Four C-shape PCBs arranged into two rings at each side of CMS
  - Six double-pad silicon sensors per C-shape
  - Located z = ±1.8 m from the interaction point and radius = ~6 cm
- Real-time histogramming with 6.25 ns per-bin
  - Allows separation of incoming machine-induced background and collisions

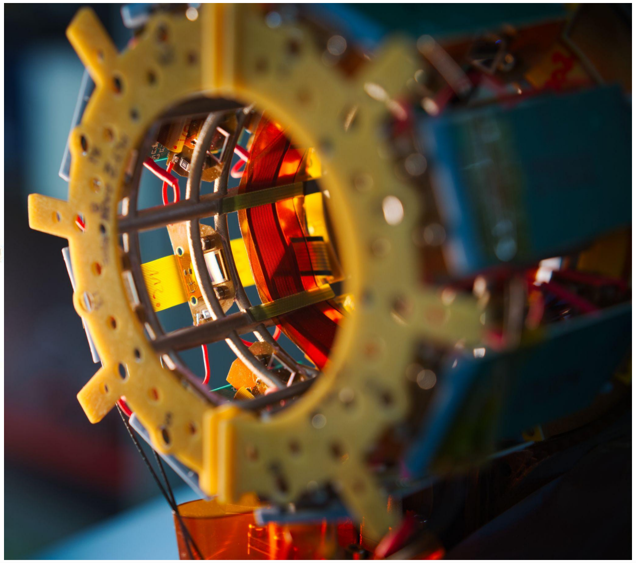


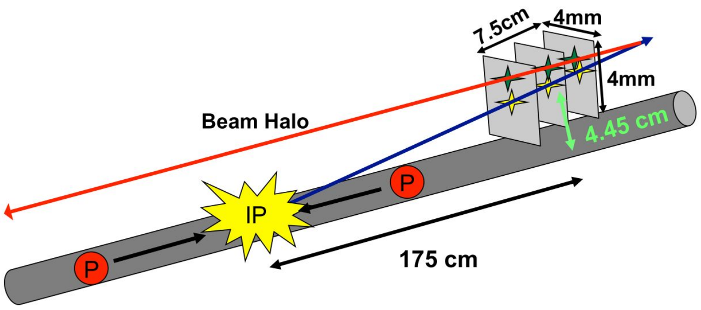


Pixel Luminosity Telescope (PLT)

- Silicon pixel detector dedicated to luminosity measurement
  - Installed in CMS in 2015 for LHC Run2 and rebuilt for LHC Run 3 data taking
  - New version implements three CMS Phase-2 silicon sensor prototypes
- Arranged into 16 channels or “telescopes”
  - Three sensor planes per telescope
  - Same readout chips (ROCs) as CMS Phase-0 Pixel detector (PSI46v2)
  - 7.5 cm in length
- Triple-coincidences from “fast” readout (40 MHz): primary luminosity measurement
- Full pixel data (~3 kHz): used for track-reconstruction studies





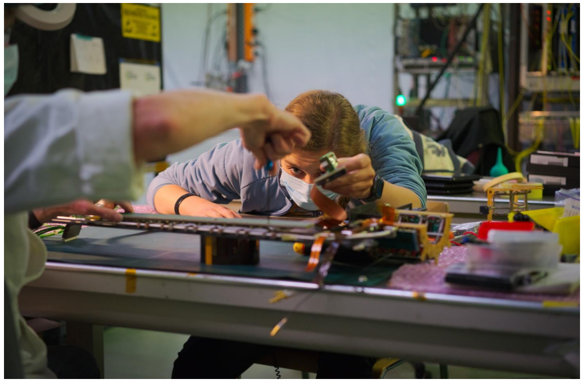
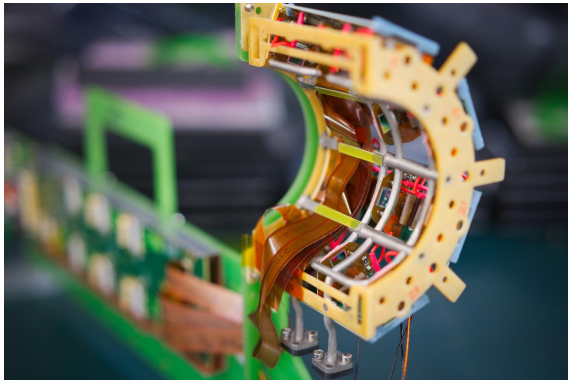


BRIL LS2 Activity

More photos: https://cds.cern.ch/record/2765247

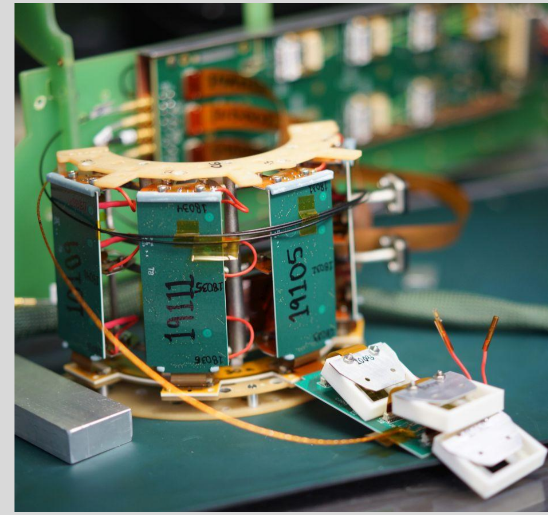
- Production of new components
- Sensor production and characterization with Sr-90
- Assembly and integration
- Stress-testing under thermal cycles (PLT)
- Troubleshooting and repairs...

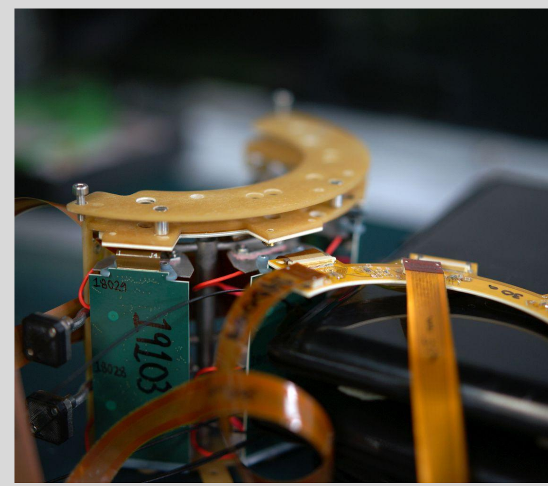


Q06 Status

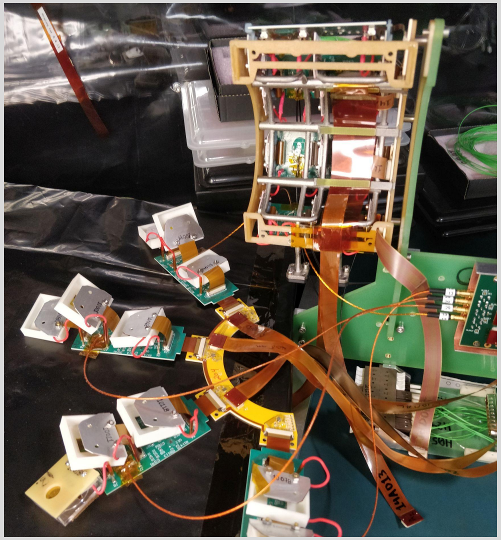
- [2021-03-22] Installed in freezer to replace Q07
  - Immediate issue with “H29”
    - Analog flex cables were swapped when OMB was remounted
  - H13 ROCs *unresponsive* to Δvana
  - After cassette assembly, this quadrant was only tested ~4-5 times
- [2021-03-26] Infamous “Friday 26th LCDS Massacre”
  - Investigation and repair was expected to be nearly identical as Q07
  - Bypassing H13 telescope did not recover functionality (strongly indicates LCDS failure)
  - Port card 14030 replaced with 19105 (tested 100% the day before)
    - Extracted 14030 post-mortem: H13 LCDS fatality confirmed
    - 19105 did *not* recover H13 functionality! 😭
    - Again, bypassing H13 telescope did not recover functionality
      - Strongly indicates LCDS failure
    - In addition, bypassing the port card revealed a fully-functional H13 telescope!
      - Strongly indicates LCDS failure

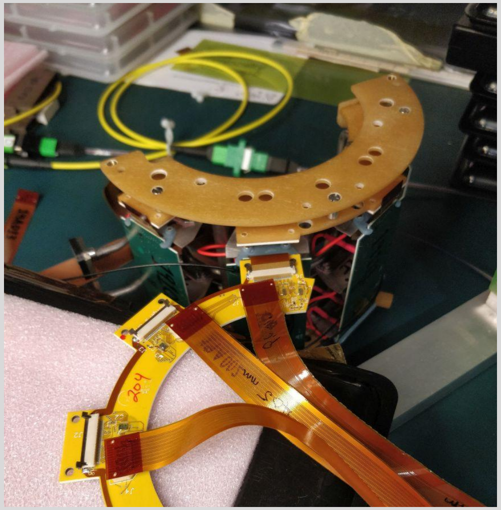




Q06 Status

- [2021-03-26] Infamous “Friday 26th LCDS Massacre” (cont.)
  - Port card 19105 replaced with 19106 (tested 100% *immediately* before replacement)
    - Same story!
    - Extracted 19105 post-mortem: H13 LCDS fatality confirmed
    - 19106 did not recover H13 functionality! 😱
    - Again, bypassing H13 telescope did not recover functionality
      - Strongly indicates LCDS failure
    - Again, bypassing the port card revealed 100% H13 telescope!
      - Strongly indicates LCDS failure
- [2021-03-29] Exhaustive investigation of H13
  - No issues whatsoever identified
  - Unable to reproduce or “trigger” LCDS failure
  - Temporarily installed type 2 port card recovered H13!
    - Not secured with screws

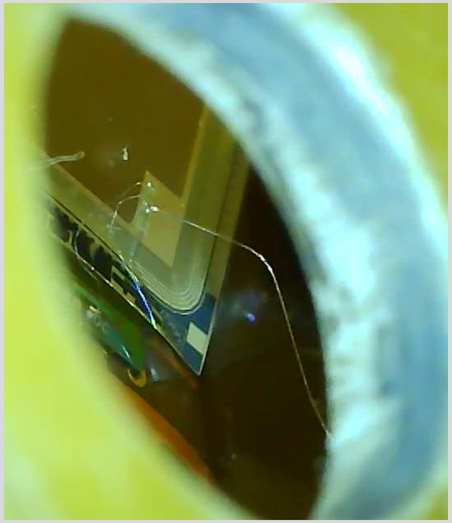


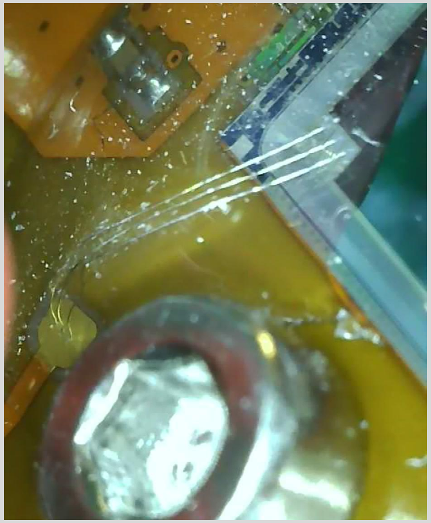


Q06 Status

- [2021-03-30] Decided to proceed with port card replacement
  - Port card 19106 replaced with 19102 (last remaining 100% spare*)
    - Brought H13 back to life!!! 🎉
    - All quadrants 100% functional again!!!
      - Many many thanks to C.Farrow!!!
  - Investigation inconclusive
    - Remaining hypothesis: mechanical stress due to screws
    - Q06 port card is currently not fastened to cassette

PLT Source Testing

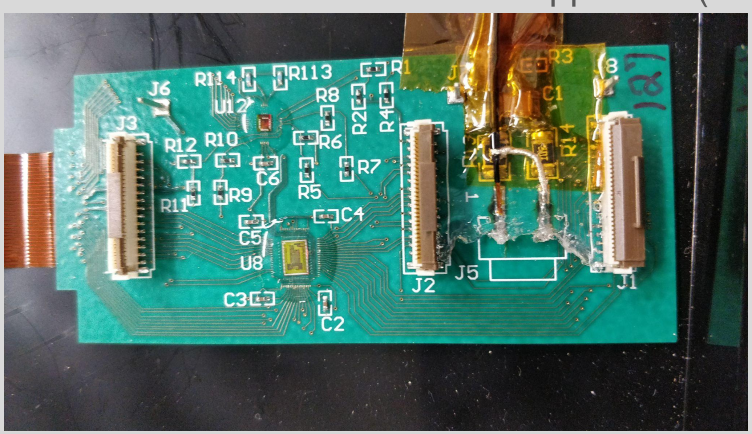


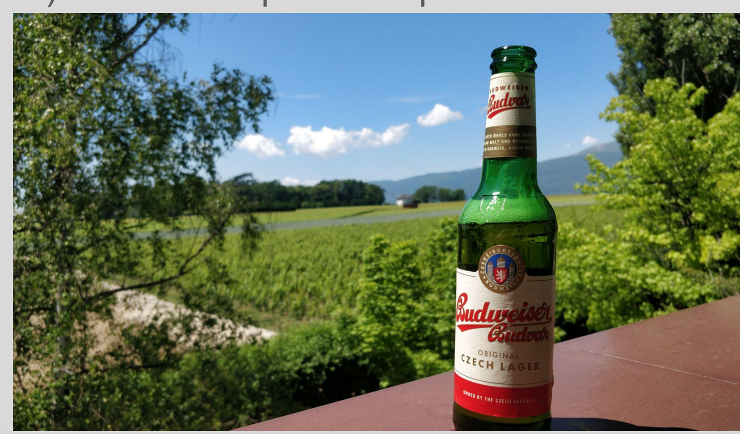


- Q05
  - Source tested on 2021-04-06
  - No issues to report
- Q08
  - [2021-05-06] **HUB05 ROC0**
  - Visible HV wire bond damage
  - Consistent with receiving no HV bias
- Q06
  - [2021-05-07] **HUB29 ROC2**
  - No indication of wire bond damage (but wire bonds encapsulated in Si potting)
  - Consistent with receiving no HV bias
    - No noticeable current draw from this sensor plane (IV scan using CAEN)
- Q07
  - [2021-05-07] **HUB21 all ROCs**
  - Investigation identified an HDI (19116) issue
    - No measurable HV on HDI pins & micro-coax core discontinuous from live wire
  - HV micro-coax cable was replaced and HDI HV functionality recovered
  - [2021-05-12] Repaired HDI reinstalled in Q07

Q08/Right-1/Capricciosa

- [2021-06-07] Source test: All 100% except HUB13
  - [2021-06-11] After *extensive* investigation
    - HV can be measured on HUB13 HDI HV pins [if cable is bent in a specific way]
    - C.Farrow noticed that solder was missing from the interior of the micro-coax connector
    - After applying the solder, a continuity test showed good connectivity regardless of bending
    - Si potting was applied, 24hr later…
  - [2021-06-16] HDI was mounted and *no current draw for HUB13* :'(
    - HDI dismounted again, HV functionality was 100% good!
      - Si potting "disrupted" for measurements. Re-apply Si potting...?
    - **[lots of intermediate tests and heart attacks omitted for brevity]**
      - It's been a "beer for lunch" kind of Tuesday
    - HV issue was tracked down to the CAEN HV module*
      - Issue disappeared (HV HUB13 functional again) when attempted to reproduce observation



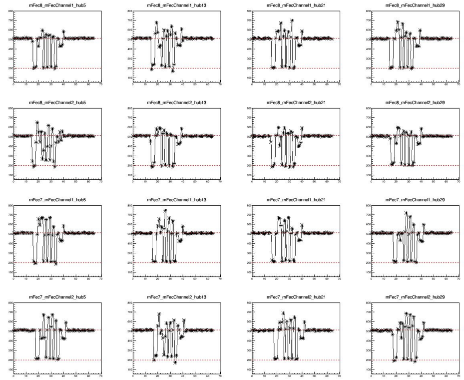


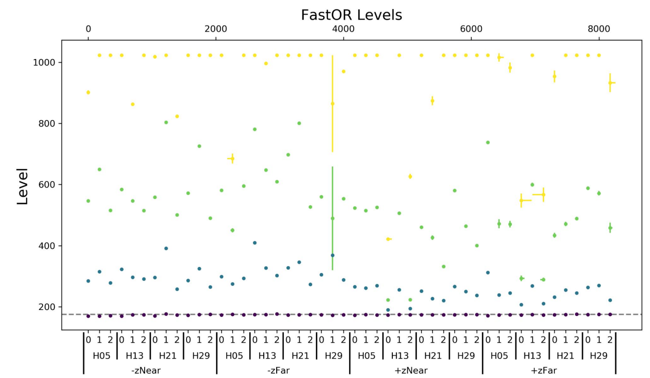
BRIL LS2 Activity

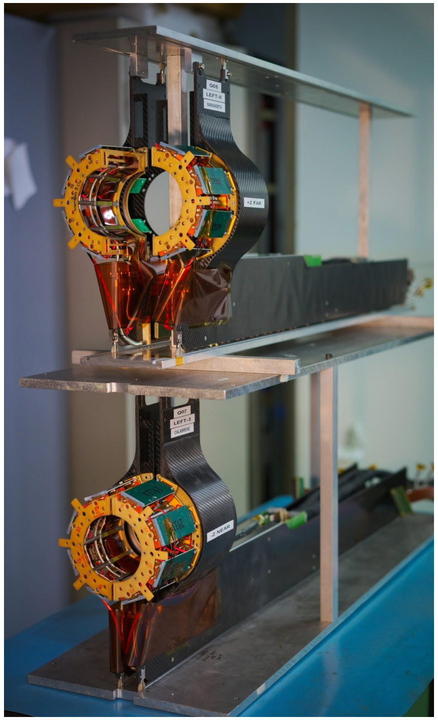
More photos: https://cds.cern.ch/record/2777045

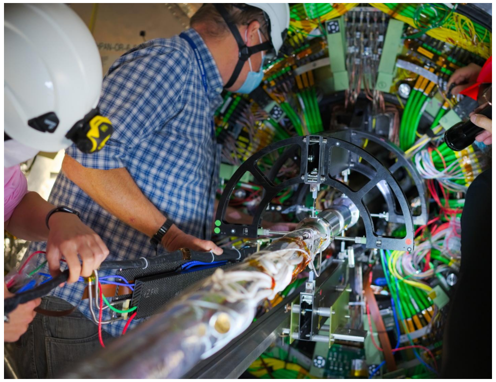
- Transport
- Installation
- Checkout

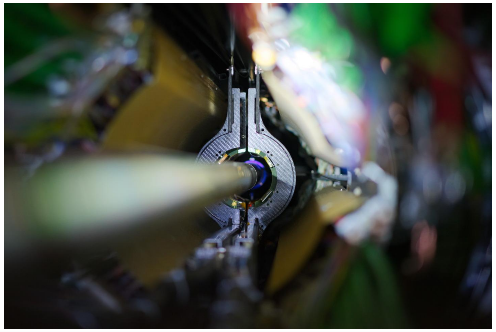
[News article on CMS website](#)
[News article on CERN website](#) ([CERN Bulletin](#))





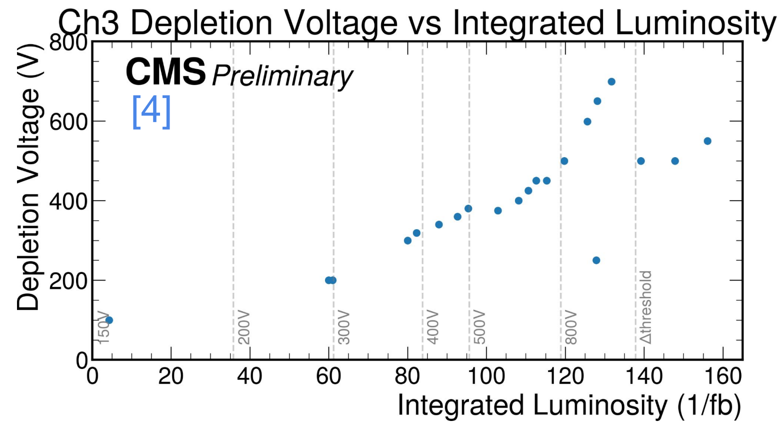


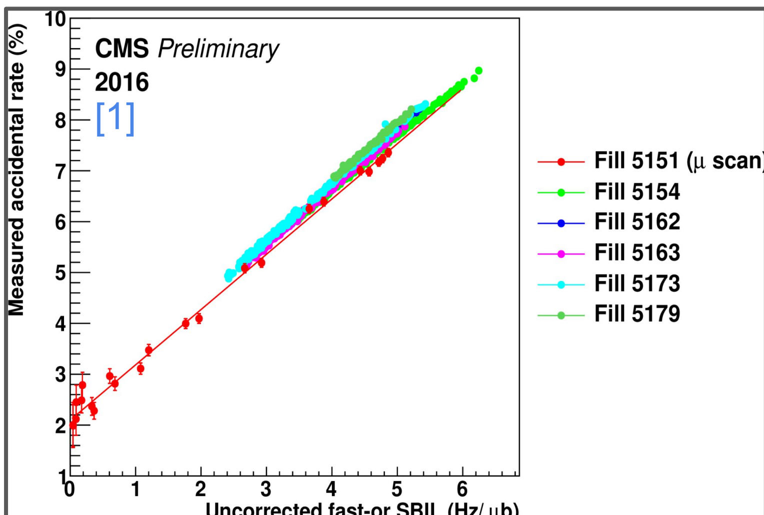


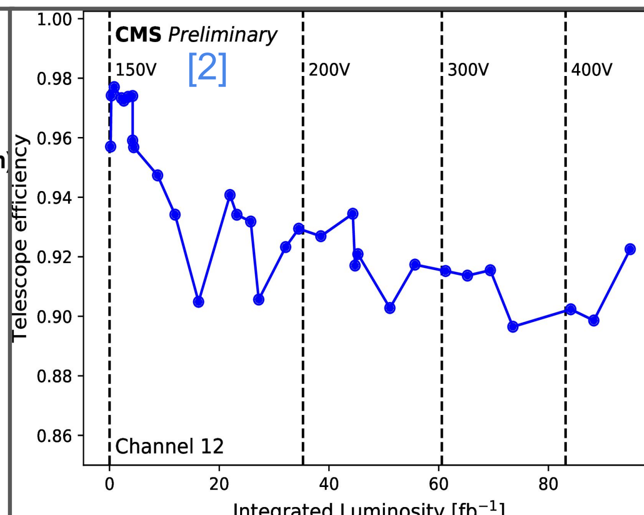


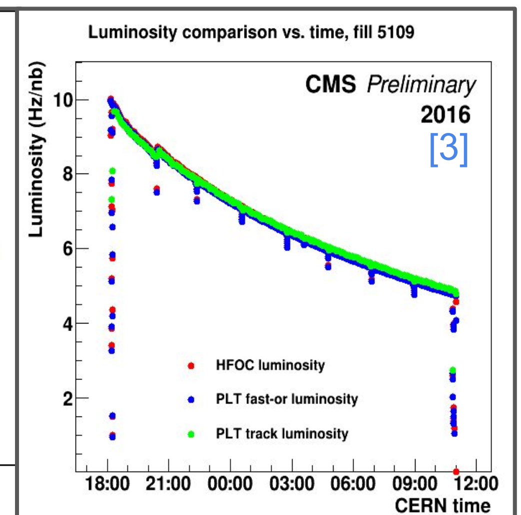
PLT performance during Run 2

- [1] Accidentals
  - Fraction of “background” tracks vs SBIL
- [2] Efficiency
  - Fraction of tracks with a “missing” hit
- [3] Luminosity using track data
  - Can reduce contribution from accidentals
- [4] Depletion voltage
  - Minimum HV bias at which sensors are efficient



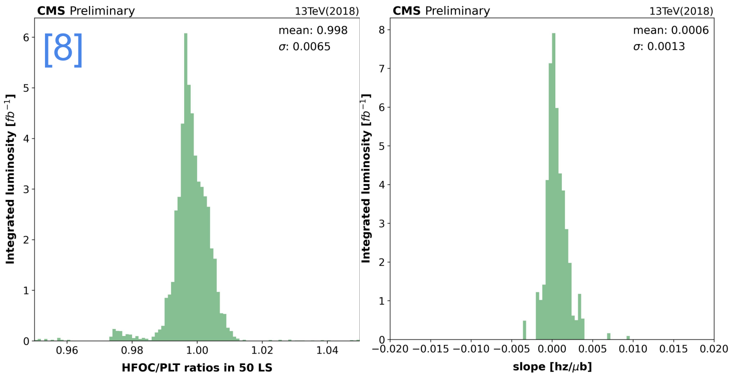


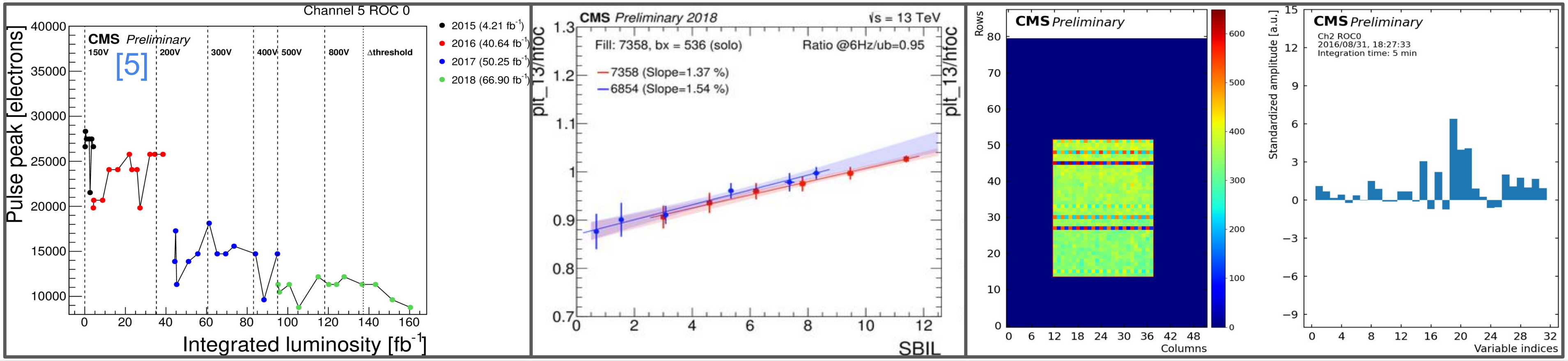




PLT performance during Run 2

- [5] Pulse Heights
  - Amount of charge deposited by particle traversing sensor
- [6] High-pileup performance
  - Linearity behavior of PLT vs HFOC at very high SBIL
- [7] Occupancy-based DQM
  - K-means ML to identify dead pixels, decoding errors, etc
- [8] Cross-detector linearity & stability uncertainty
  - Histogram ratio and slope distributions





LHC pilot beams

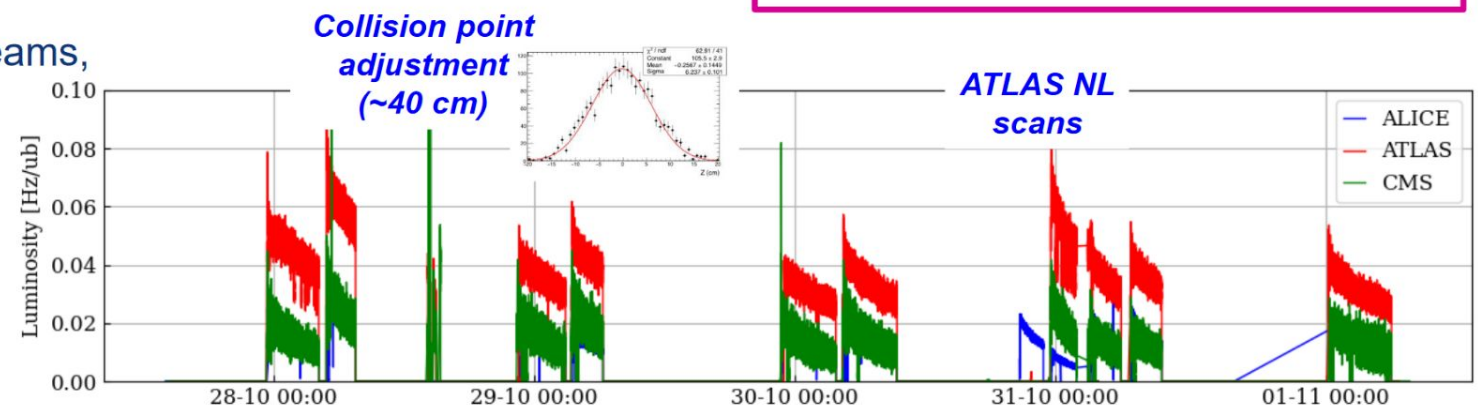
morning_plots.lumi.png

Stable beams with great frictions

- Collisions for experiments.
  - Request for a few periods of ~6+ hours.

5 nights of stable beams, close to 40 hours

4 bunches of 7-8E10 p per beam to avoid parasitic collisions



Unknown CMS physicist

We apologize for our optimistic planning, as clients you had to be patient with us...

LHC Beam Test

17

LHC pilot beams


LHC pilot beams

- [2021-10-19] First splash events!
- [2021-10-26] First collisions!
- [2021-10-29] Preliminary Run 3 PLT masks deployed
- [2021-10-30] VcThr Scan
  - Optimized VcThr for all channels in -zFar and adjusted their BX alignment as much as possible

```
$ ./bin/histfile_showbxfine /scratch/workloop_data/Data_Histograms_20211025.140947_V2.dat 10000 | grep --extended-regexp '\[2375\]|\[2376\]'
[2375]: 0.005 0.005 0.007 0.006 0.170 0.002 0.008 0.118 0.001 0.000 0.000 0.000 0.000 0.001 0.000 0.000
[2376]: 0.353 0.682 0.659 0.137 0.003 0.000 0.055 0.001 0.346 0.438 0.681 0.673 0.054 0.581 0.570 0.570
$ ./bin/histfile_showbxfine "$(ls -t /scratch/workloop_data/Data_Histograms_202110* | head -1)" | grep --extended-regexp '^\[1235\]|^\[1236\]'
[1235]: 0.001 0.003 0.003 0.003 0.000 0.000 0.000 0.392 0.001 0.000 0.000 0.000 0.001 0.000 0.000 0.000
[1236]: 0.428 0.731 0.704 0.269 0.510 0.605 0.613 0.000 0.659 0.707 0.692 0.672 0.697 0.614 0.571 0.573
```

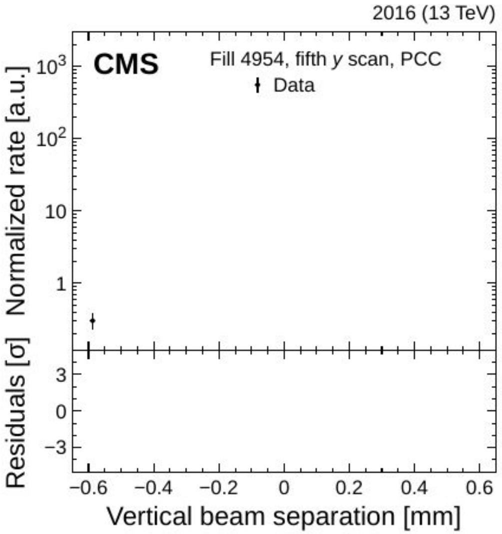
- [In progress] Automation of detailed PLT per-fill DQM
- [In progress] Preliminary Run 3 PLT σ_{vis} calibration

Absolute luminosity calibration and corrections

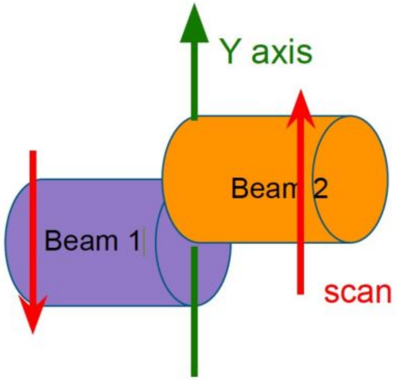
- Determination of the visible cross section: σ_{vis} (normalization)
- Measurement and correction for stability and linearity (integration)

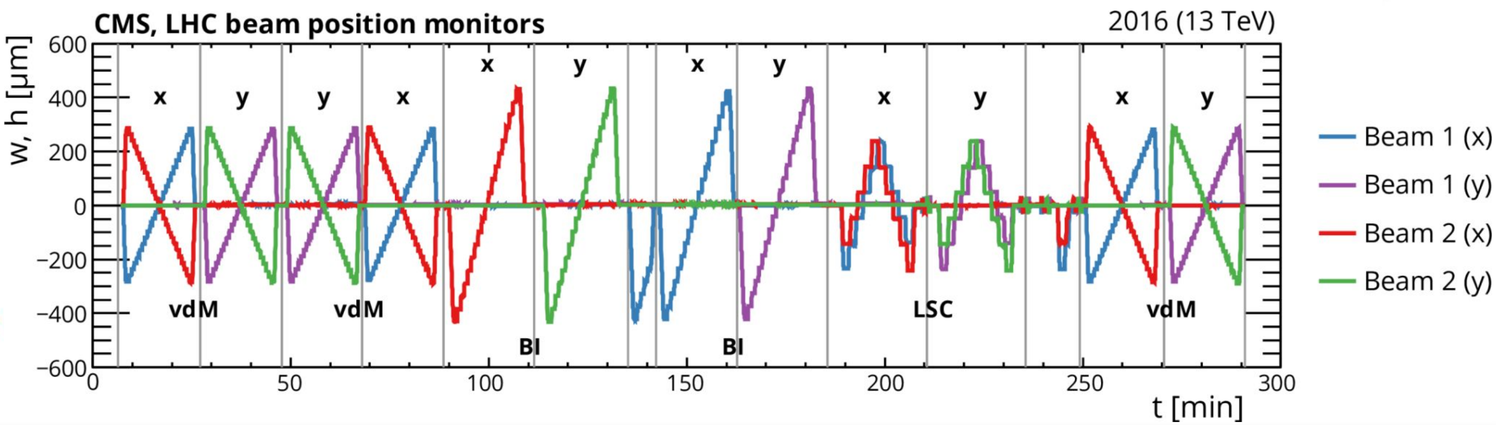
Determination of σ_{vis} (normalization)

- van der Meer (vdM) method
  - Allows absolute luminosity calibration from beam parameters
    - Visible cross-section (σ_{vis}) related to detector acceptance
  - Beams are separated and scanned across each other in special fill
    - Very low pileup conditions
    - "vdM", "offset", "imaging", "length scale" scans
  - Measurement of rate as a function of beam separation
    - Size of the beam overlap region can be determined and the absolute luminosity calculated
- Emittance scans
  - Quick scan (7-9 steps) at the beginning and end of fills

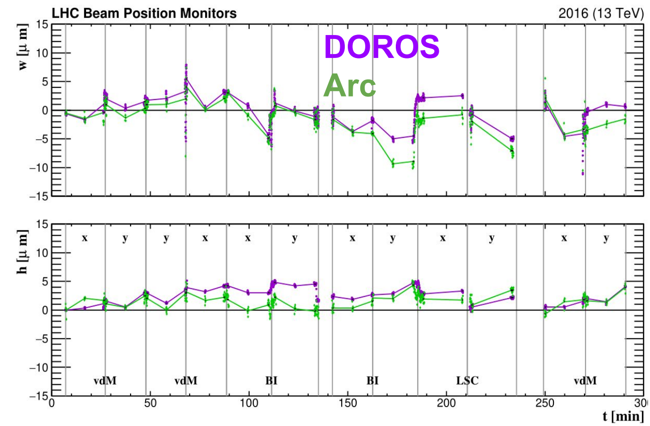


$$\sigma_{\text{vis}} = \frac{R_0}{N_1 N_2} \frac{2\pi \Sigma_X \Sigma_Y}{f_{\text{LHC}}}$$

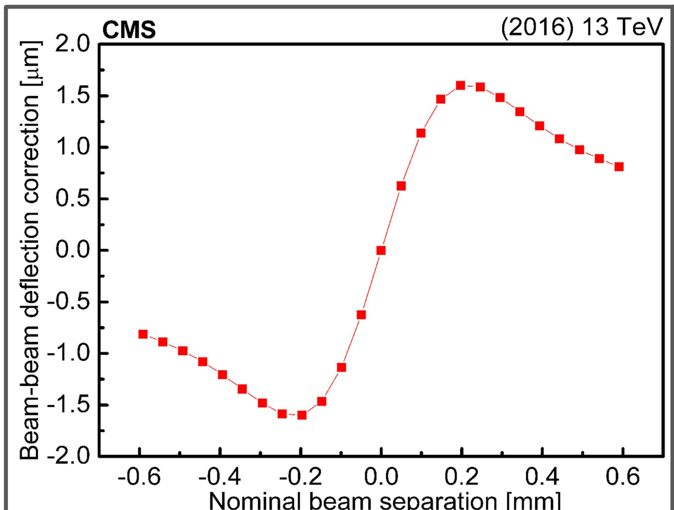


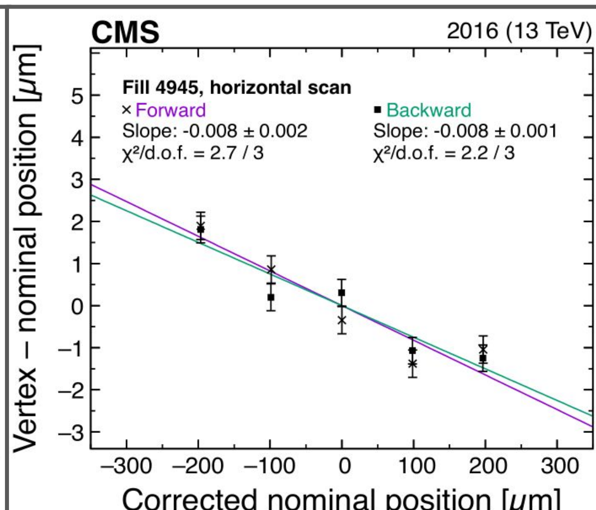


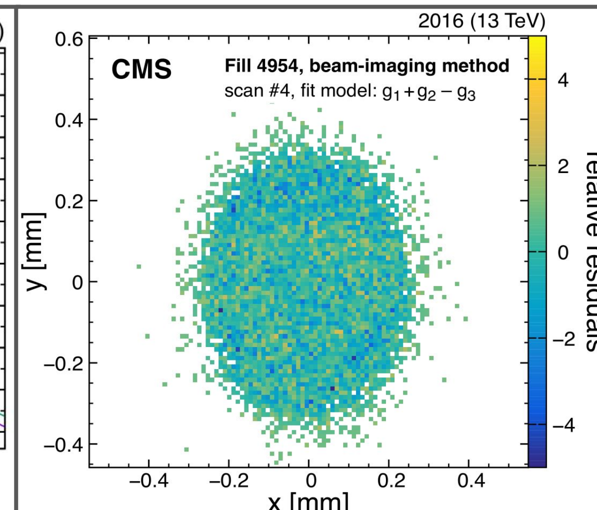
Determination of σ_{vis} (normalization)



- Orbit drift corrections
  - Potential bias from beam positions monitors (DOROS, Arc BPM)
- Beam-beam effects
  - EM interaction (deflection & shape) between colliding buches
- Length scale calibration
  - Δ(beam separation $_{\text{LHC magnets}}$, beam separation $_{\text{actual}}$)
- Transverse factorizability
  - Non-factorizability of X and Y components measured and corrected with the beam-image method
- Other corrections
  - beam current calibration and spurious charge 👻🛰️

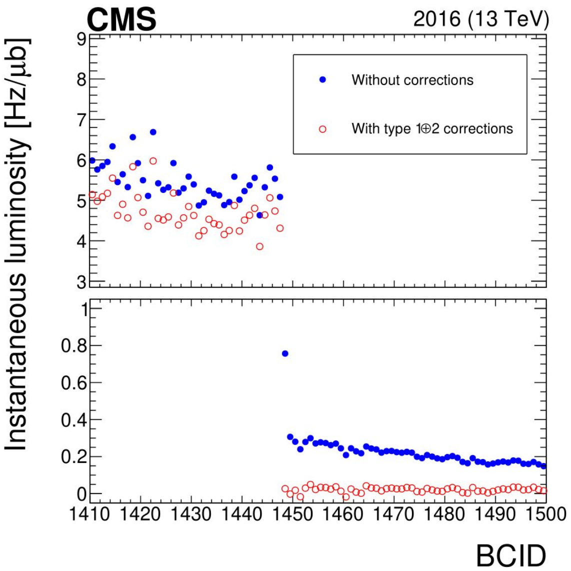


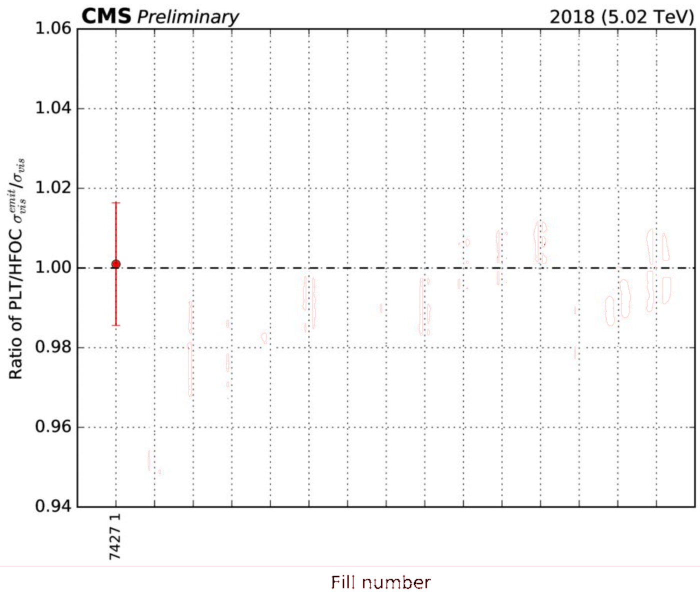


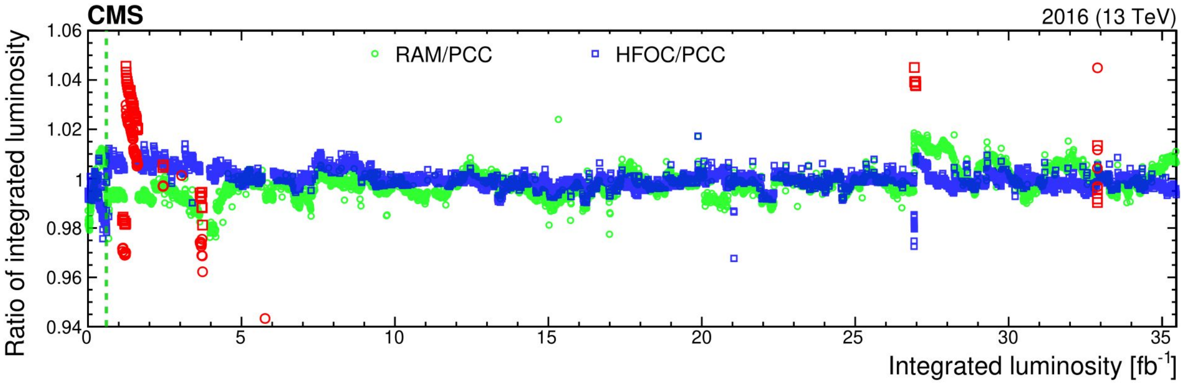


Stability and linearity (integration)

- Corrections for typical LHC physics running conditions
- Rate corrections
  - Efficiency & Non-linearity
    - Reduced response, noise from radiation damage
  - Out-of-time pileup corrections
    - From electronics spillover and material activation (“afterglow”)
- Linearity and Stability
  - Determined from comparisons between luminometers







Total 2015-2016 correction and uncertainty

- Normalization uncertainty
  - Uncertainty in the absolute luminosity scale (σ_{vis}) determined from vdM scan procedure
  - Dominant: beam position monitoring, transverse factorizability, beam-beam effects
- Integration uncertainty
  - Uncertainty associated with σ_{vis} variations over time (stability) and pileup (linearity and out-of-time rate corrections)

Source	Impact on σ_{vis} [%] 2015	2016
Ghost and satellite charge	+0.2	+0.3
Orbit drift	+0.6–1.0	+0.2–1.0
Residual beam position corrections	+0.3–1.1	+0.2–0.9
Beam-beam effects	+0.6	+0.4
Length scale calibration	−0.4	−1.3
Transverse factorizability	+0.8–1.3	+0.6

LUM-17-003

$$\int \mathcal{L}dt = \frac{1}{\sigma_{vis}} \int R(t)dt$$

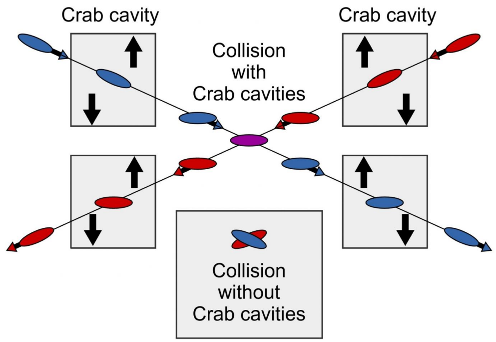
Source	2015 [%]	2016 [%]	Corr
Normalization uncertainty			
Bunch population			
Ghost and satellite charge	0.1	0.1	Yes
Beam current normalization	0.2	0.2	Yes
Beam position monitoring			
Orbit drift	0.2	0.1	No
Residual differences	0.8	0.5	Yes
Beam overlap description			
Beam-beam effects	0.5	0.5	Yes
Length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

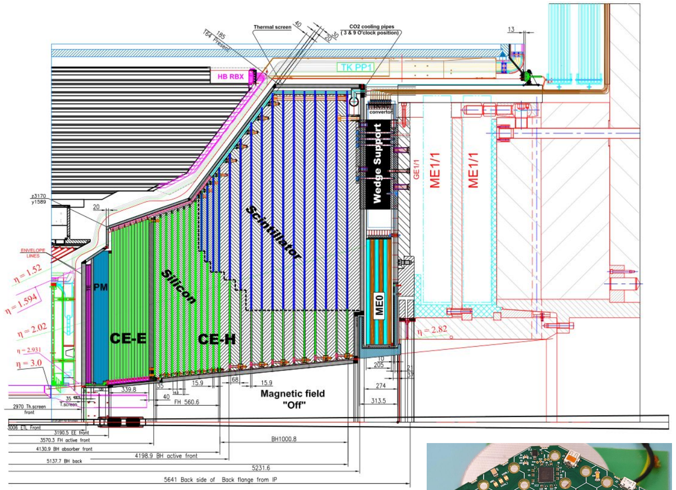
1.0%

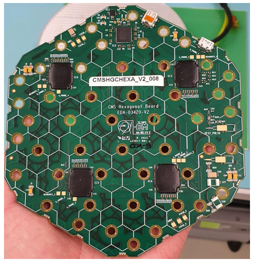
0.7%

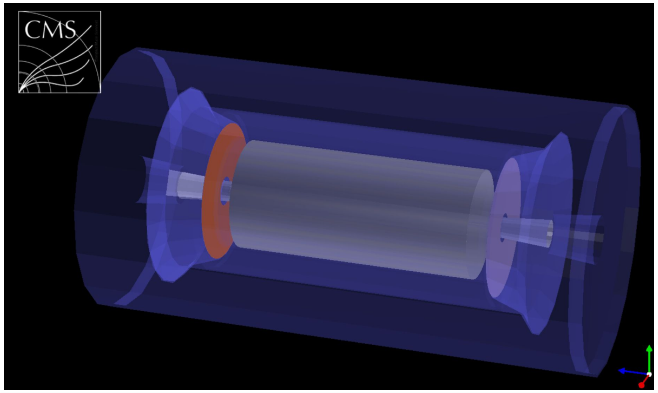
High-Luminosity LHC

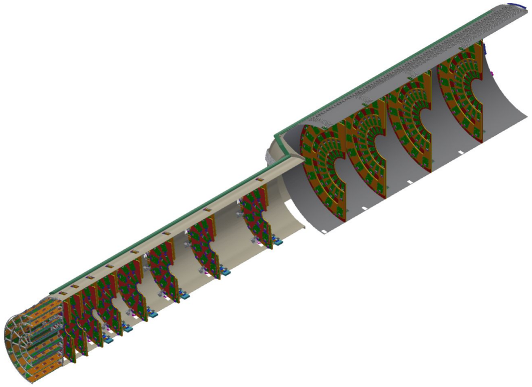
- Increase in luminosity ~10x LHC's design value
  - Large data sample size -> improves studies of rare processes
  - 12 T quadrupole magnets to focus beams at IPs
  - Crab cavities to optimize crossing angle at IPs
- Upgrade of CMS detector systems
  - Colossal amount of ongoing work to update systems able to operate at HL-LHC conditions
  - Replacement of Pixel and Tracker (input to L1 trigger)
  - Replacement of End-Cap Calorimeter (HGCAL)
  - MIP Precision Timing detector (30 ps resolution)
  - Overhaul of the Trigger and DAQ systems
    - Event rate: 100 kHz -> 750 kHz
    - Permanent storage: 1 kHz -> 7.5 kHz





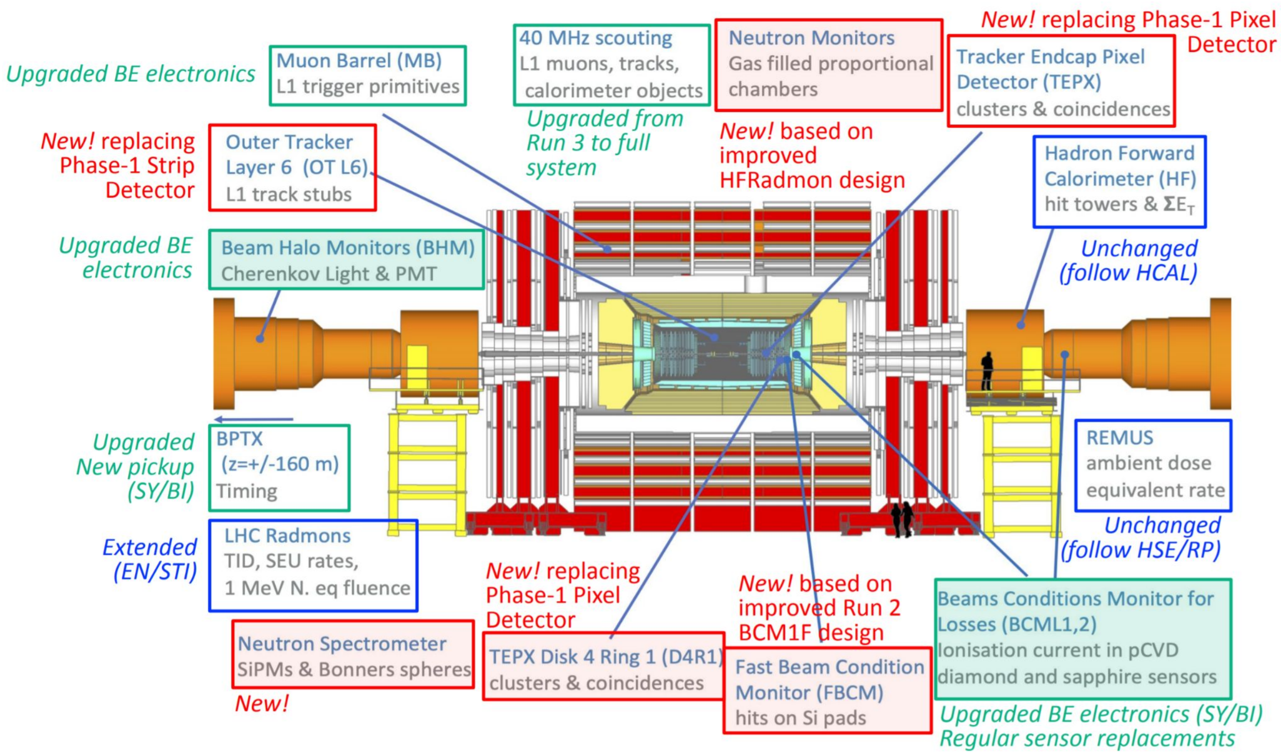






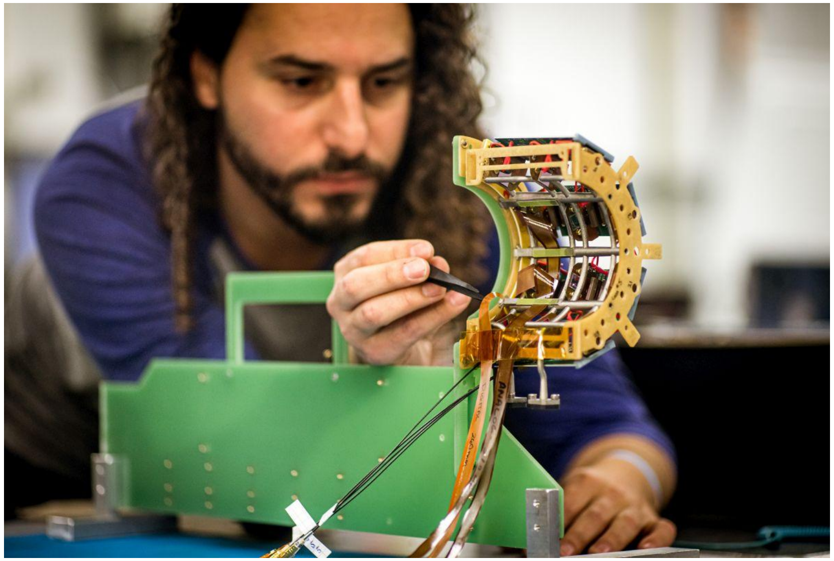
Luminosity measurement at HL-LHC

- Large contribution from luminosity uncertainty in precision SM measurements
  - ≈1% lumi uncertainty required to become comparable to other experimental uncertainties
- Target: redundant and diverse detectors with excellent linearity and stability
  - Tracker Endcap Pixel Detector (TEPX) Disk 4 Ring 1 (D4R1)
  - Fast Beam Conditions Monitor (FBCM)
  - Muon barrel detector and 40 MHz scouting



Summary

- Luminosity measurement is very involved and important for the collaboration
  - It requires multiple redundant and robust luminosity detectors
  - The new PLT detector has been successfully installed and being commissioned for Run 3
- The van der Meer scan method is crucial
  - Determine the overall normalization and systematic uncertainties associated with integrated luminosity
- The HL-LHC presents challenging conditions for new lumi detectors and lumi measurement techniques

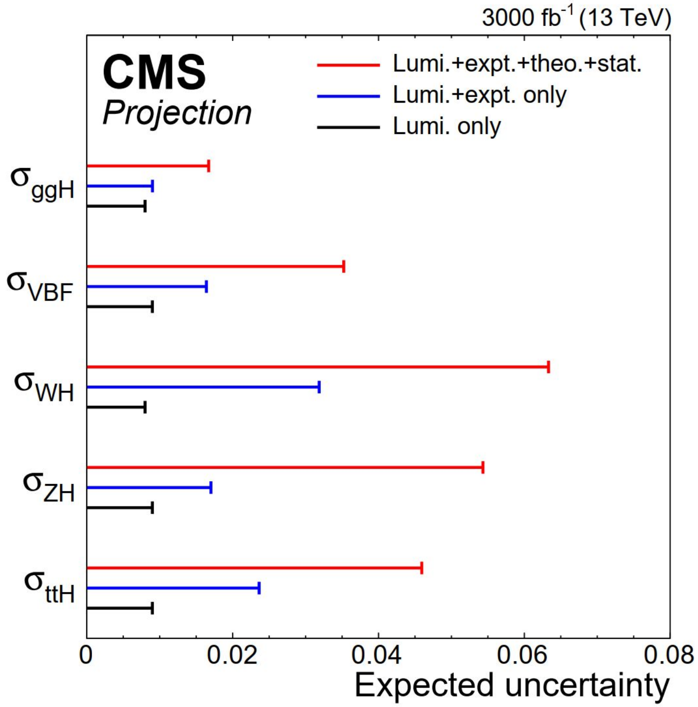


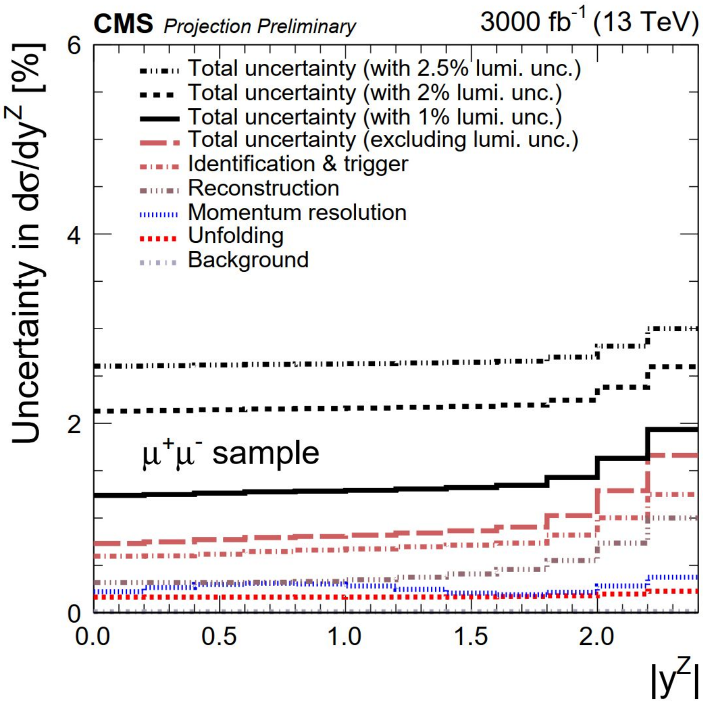
References/Info

- CMS website: Illuminating! Counting LHC collisions with CMS
- CMS website: The installation of the BRIL luminometers: Preparing for bright Run 3
- LPC: General information about luminosity calibration at the LHC
- Precision luminosity measurement in proton-proton collisions at $\sqrt{s}$= 13 TeV in 2015 and 2016 at CMS
- The Phase-2 Upgrade of the CMS Beam Radiation, Instrumentation, and Luminosity Detectors: Conceptual Design

Backup

High-precision lumi measurement at HL-LHC





Proposed CMS Lumi Systems for HL-LHC

- Diverse detector technologies and counting methods, orthogonal systematics, redundancy!
- Already in use during Run 2:
  - Hadron Forward (HF) calorimeter (3.15 < |eta| < 3.5)
    - 2 algorithms for luminosity measurement:
      - Tower Occupancy (HFOC)
      - Transverse Energy sum (HFET)
  - Radiation and Environment Monitoring Unified Supervision (REMUS) monitors
    - Radiation Monitoring System for the Environment and Safety (RAMSES) subsystem used for luminosity systematics

	Available outside stable beams	Independent of TCDS	Independent of foreseeable central DAQ downtimes	Offline luminosity available at LS frequency (bunch-by-bunch)	Statistical uncertainty in physics per LS (bunch-by-bunch)	Online luminosity available at ~1s frequency (bunch-by-bunch)	Statistical uncertainty in vdM scans for σvis (bunch-by-bunch)	Stability and linearity tracked with emittance scans (bunch-by-bunch)
FBCM hits on pads	✓	✓	✓	✓	*0.037%*	✓	*0.18%*	✓
D4R1 clusters (+coincidences)	✓	✓	✓	✓	*0.021%*	✓	*0.07%*	✓
HFET [sum ET] (+HFOC [towers hit])	✓	*if configured*	*if configured*	✓	*0.017%*	✓	*0.23%*	✓
TEPX clusters (+coincidences)	*if qualified beam optics*	✗	*if configured*	✓	*0.020%*	✓	*0.03%*	✓
OT L6 track stubs	*not anticipated*	✗	*if configured*	✓	*0.006%*	✓	*0.03%*	✓
MB trigger primitives via back end	✓	✗	✗	✓	*0.25%*	✓	1.2%	✓
40 MHz scouting BMTF muon	✓	✗	✗	✓	*0.96%*	✓	4.7%	✓
REMUS ambient dose equivalent rate	✓	✓	✓	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*

precision luminometers (FBCM, D4R1, HFET/HFOC, TEPX, OT L6)

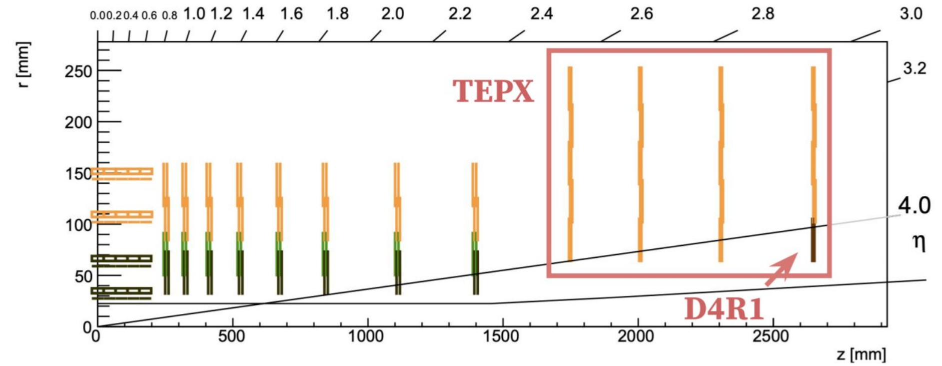
independent of any central CMS service (FBCM, D4R1, HFET/HFOC)

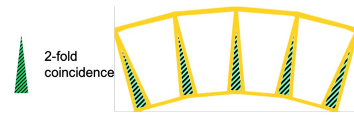
at least one of them shall be available 100% of the time

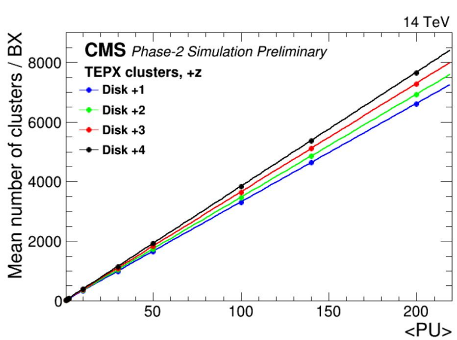
independent measurements (MB trigger primitives, 40 MHz scouting, REMUS)

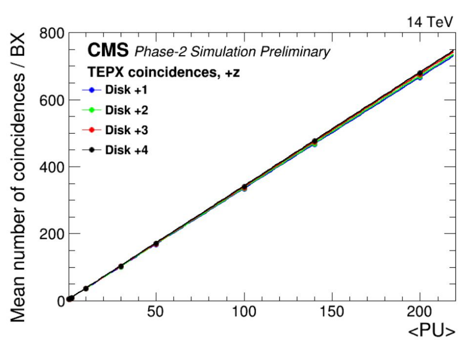
Tracker Endcap Pixel Detector (TEPX)

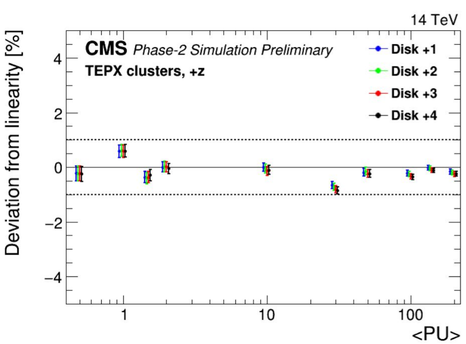
- TEPX 63 < r < 255 mm, 175 < |z| < 265 cm
  - D4R1 lies beyond $|\eta| = 4$
- 800 M pixels over an area of 2 m^2
- Designed for 10^3 kHz → low occupancy
- TEPX luminosity
  - real time Pixel Cluster Counting on FPGA
  - dedicated unbiased trigger (75 kHz)
  - module geometry allows coincidence measurement
    - handle for calibration and systematics

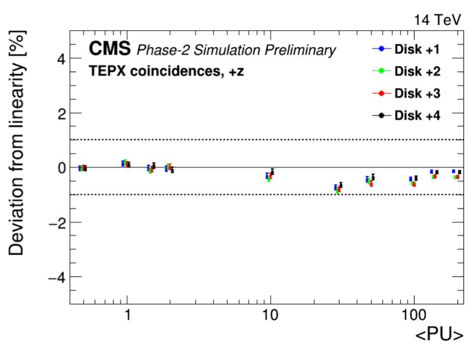






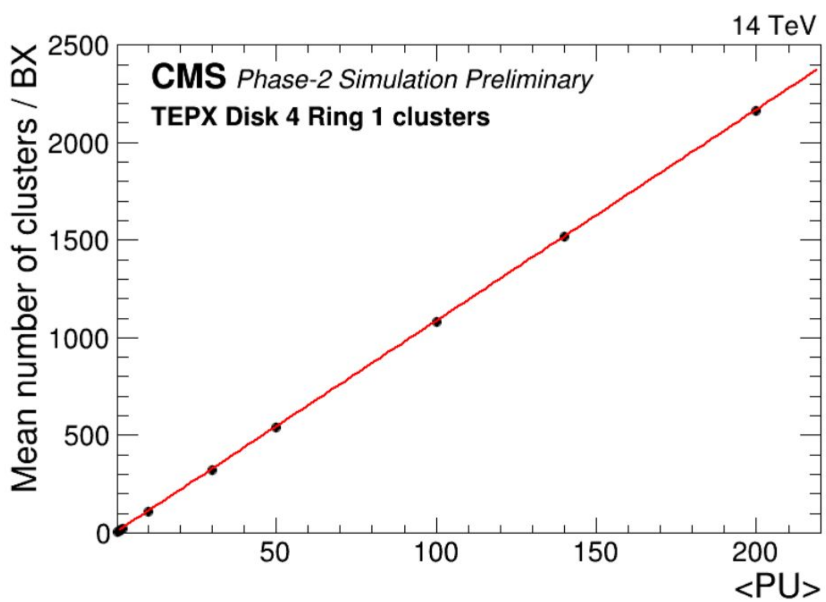


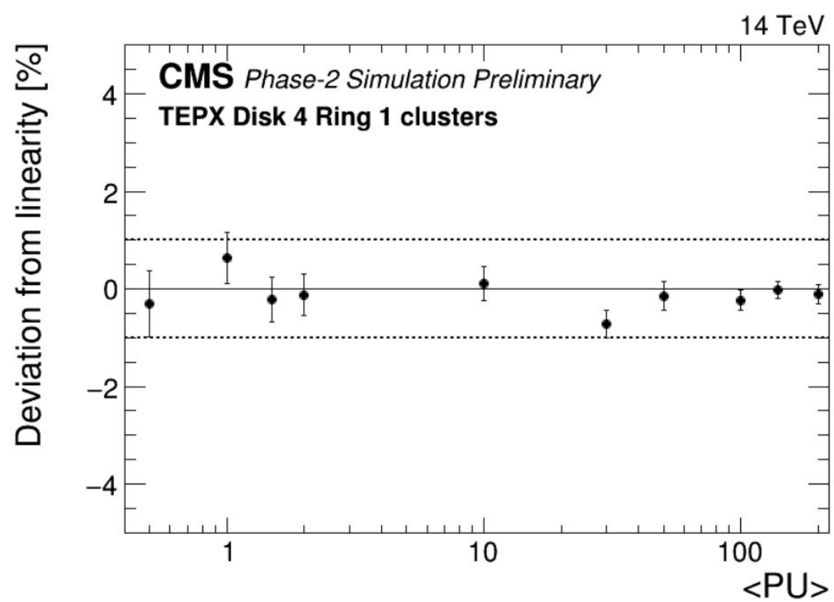




Disk 4 Ring 1 (D4R1)

- D4R1 operated exclusively by BRIL
- Higher trigger rate (750+75 kHz) and smaller surface (190 mm^2)
  - Similar performance as TEPX
- Beam-induced background measurement
  - Needs at least 30 empty bunch crossings to decrease albedo and out-of-time particle contribution
  - Only the first bunch in a train or unpaired bunches





Fast Beam Conditions Monitor (FBCM)

- Proposal to locate close to bulkhead (behind disk 4 of TEPX)
  - 8 < r < 30 cm, 277 < |z| < 290 cm
- 4 quarters, 84 silicon-pad (expect 300um, 2.89 mm^2) sensors/quarter
- Luminosity measurement using zero-counting algorithm
- BIB measurement exploiting info of the time-of-arrival (ToA) and time-over-threshold (ToT) of hits with a sub-ns resolution at the rate of 40 MHz