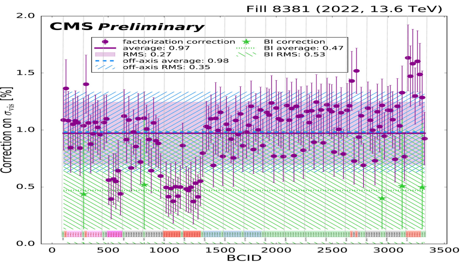
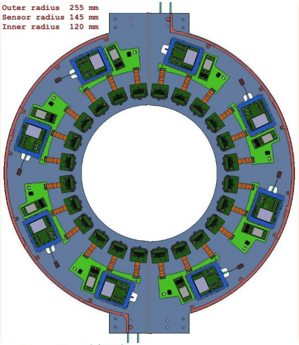
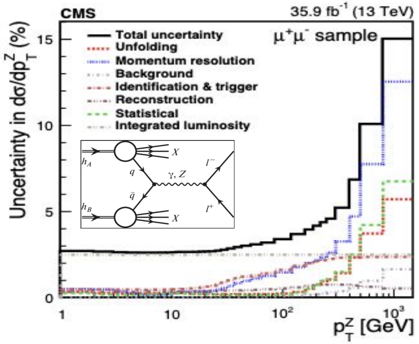


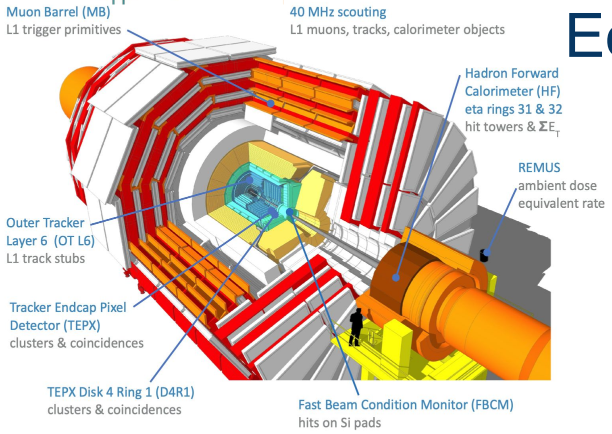
Precision luminometry for tests of the Standard Model at (HL-)LHC

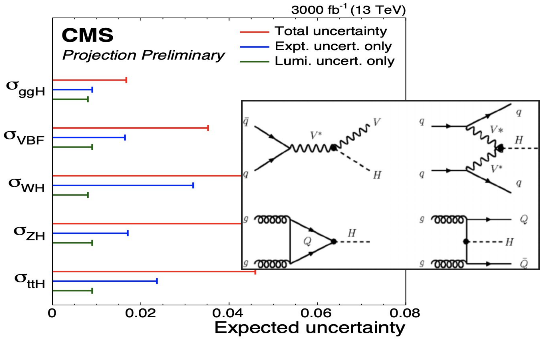


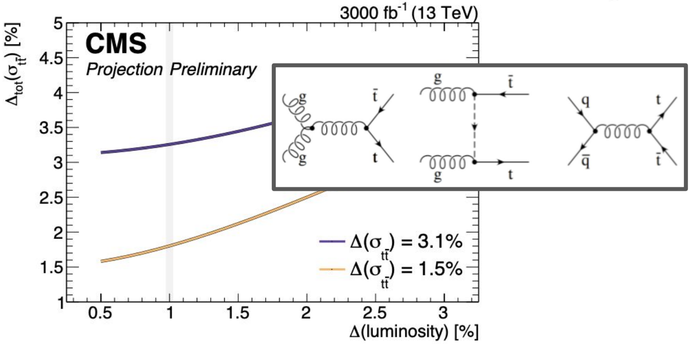


Gabriella Pásztor

Eötvös University, Budapest







Outline

Physics motivation: test of the Standard Model

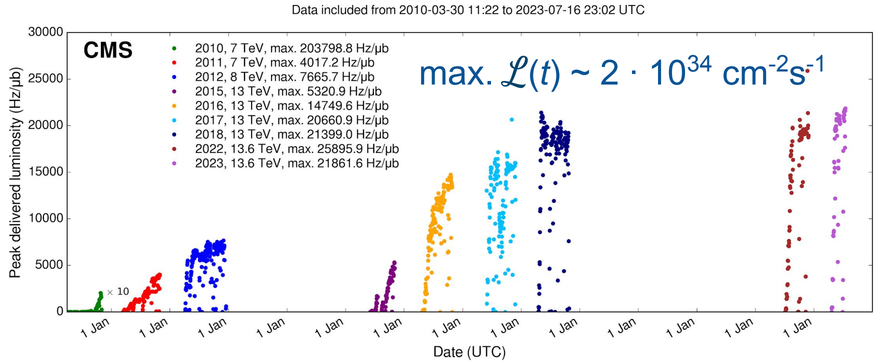
Methodology

Attacking the leading uncertainties

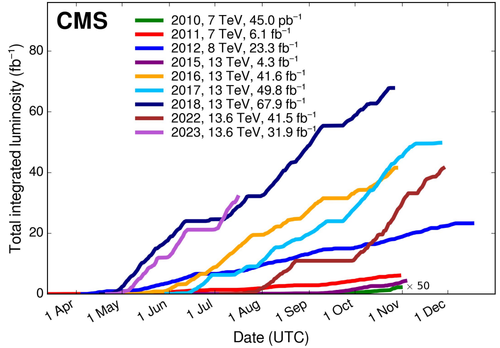
- Understanding beam-beam interactions
- Improved techniques for precision calibration - highlights
  - Orbit movements
  - Transverse non-factorization of the beam particle density
  - Z boson counting

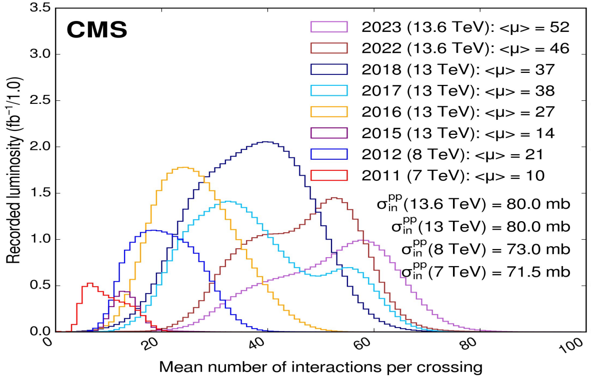
Luminosity instrumentation and the CMS phase-2 detector upgrade

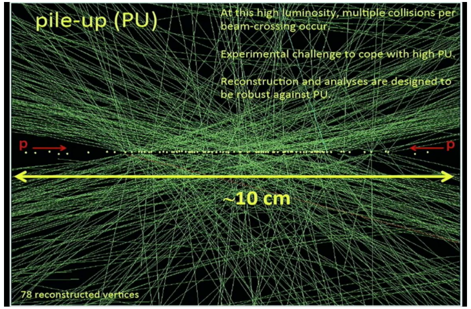
Luminosity



- Quantifies interaction rate at colliders
- Time-dependent "instantaneous" luminosity:
  $R_X(t) = \mathcal{L}(t) \cdot \sigma_X$
  - Feedback to accelerator, detector operation
- Integrated luminosity over time: $L_{int} = \int \mathcal{L}(t) dt$
  - Necessary to normalize physics measurements to derive cross sections
- Bunches can be different:
  single bunch instantaneous luminosity (SBIL): $\mathcal{L}_b(t)$
  - max. ~ 7 Hz/μb = $7 \cdot 10^{30}$ cm^{-2}s^{-1}
- Multiple interactions per bunch crossing
  - Event pile up ~ 50







How luminosity affects LHC program?

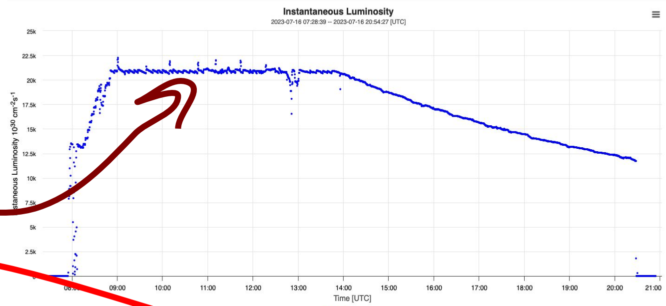
Test of the Standard Model
- precise cross sections (σ) measurements
- compare to model predictions and other experiments

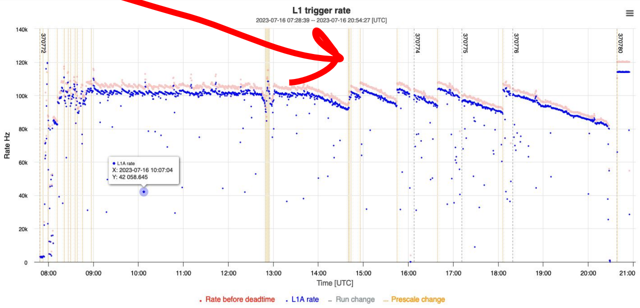
Quest for New Physics beyond the Standard Model
- discovery → measure σ
- no signal → put limit on maximal σ allowed by the results

$$\sigma = \frac{N_{obs} - N_{bkg}}{A \varepsilon L_{int}}$$

LHC physics goals require a precision around ~1%

- Real-time (online) 2-5% bunch-by-bunch (BbB) measurement
  - Assist beam optimisation, **luminosity levelling**
  - Optimisation of detector operations, e.g. **fast online "trigger" selection**
- Ultimate 1% with final calibration and corrections offline
  - Luminosity uncertainty still dominant in key channels of physics interest (e.g., Drell-Yan, top quark pair, and Higgs studies)
  - … but **subdominant in most analyses**

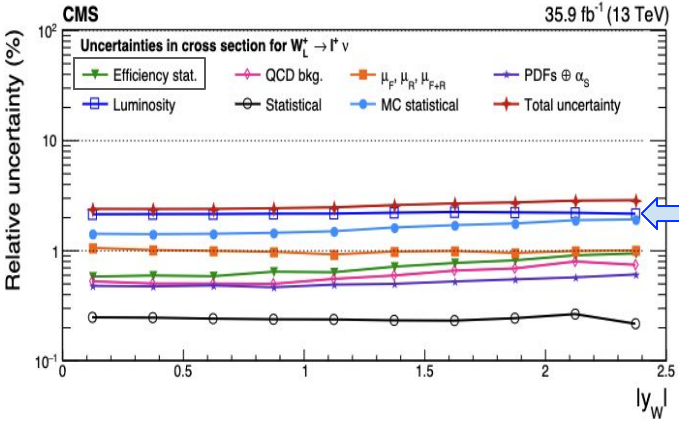


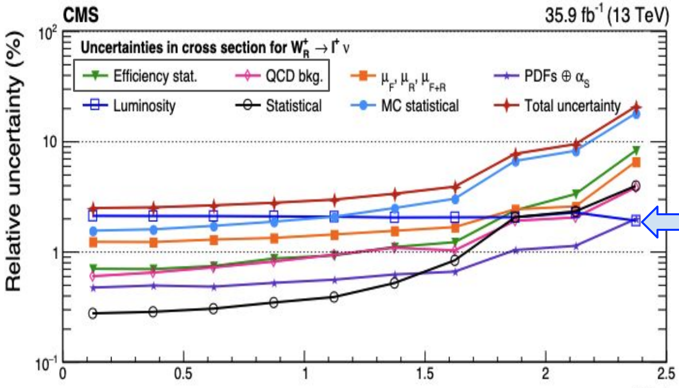


Final ("precision") uncertainty / year: 1.6% (2015), **1.2% (2016)**
Current preliminary uncertainty / year: 2.3% (2017), 2.5% (2018), **1.4% (2022)**
Run 2 (2015-2018) preliminary combined: 1.6%

Impact of luminosity precision

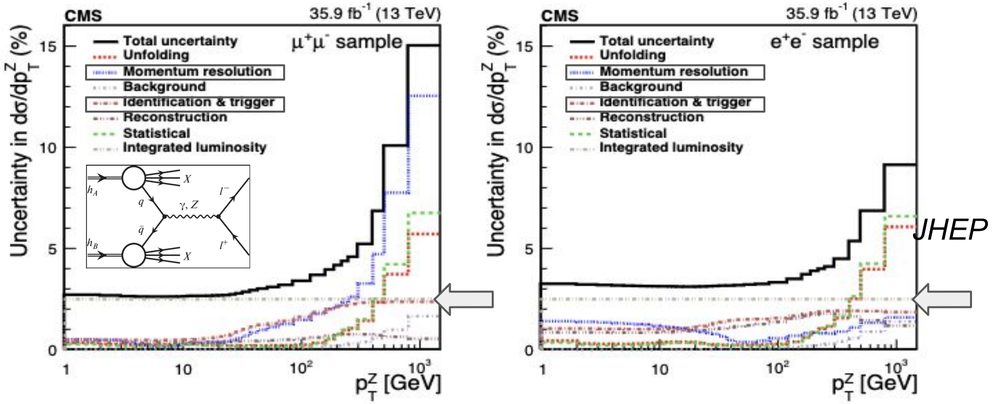
Polarized W production cross section





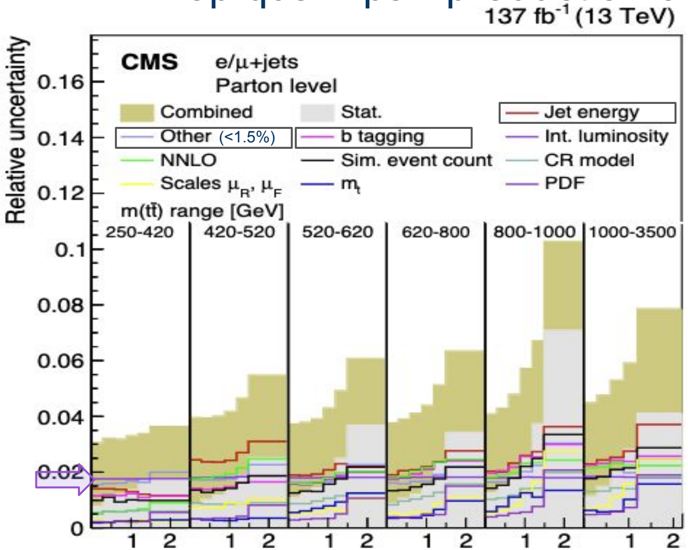
Phys.Rev.D 102 (2020) 9, 092012

Z production cross section



JHEP 12 (2019) 061

Top quark pair production cross section



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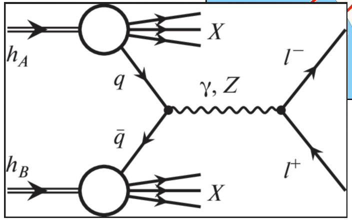
JHEP 08 (2023) 204

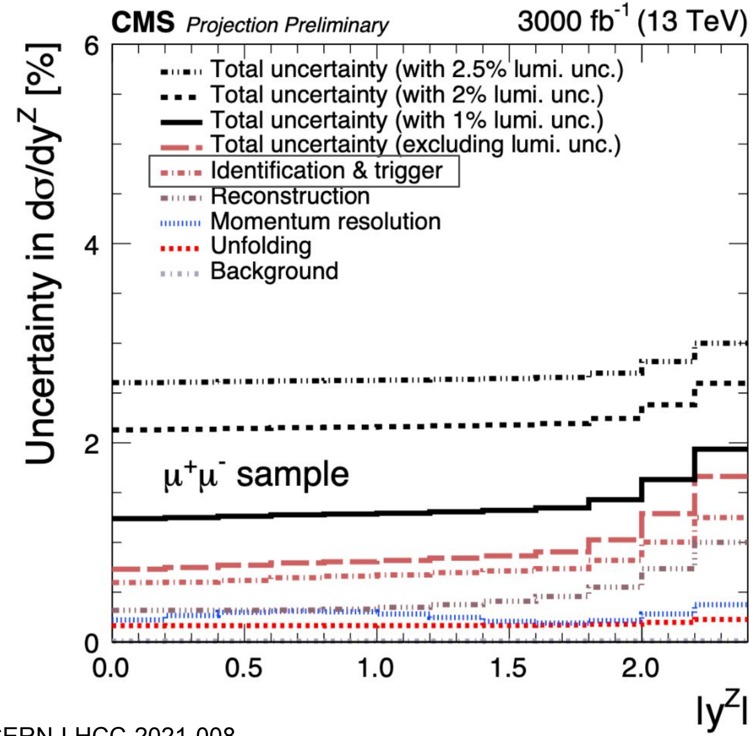
1.21 fb^{-1} (13.6 TeV)

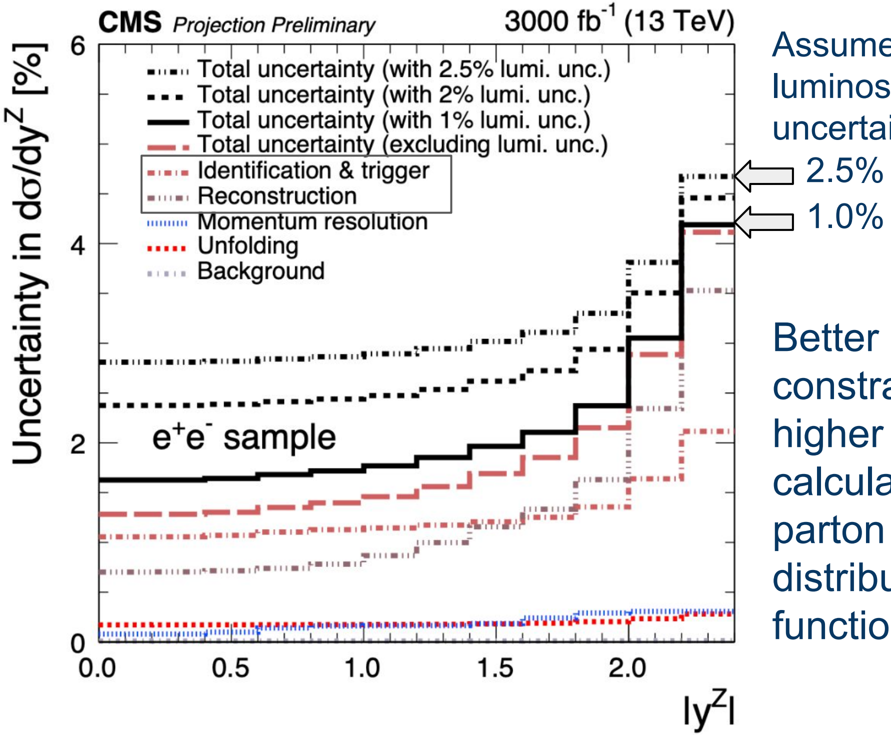
Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.6
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.5
ME scale, backgrounds	0.2
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Top quark p_T	0.5
tW background	0.7
t-channel single-t background	0.4
Z+jets background	0.3
W+jets background	<0.1
Diboson background	0.6
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.5
Integrated luminosity	2.3

Drell-Yan lepton pair production at HL-LHC



Assuming Run-2 systematics for other experimental contributions



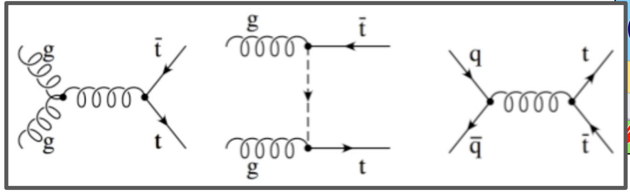


Assumed luminosity uncertainty

Better constraints on higher order calculations, parton distribution functions

CERN-LHCC-2021-008

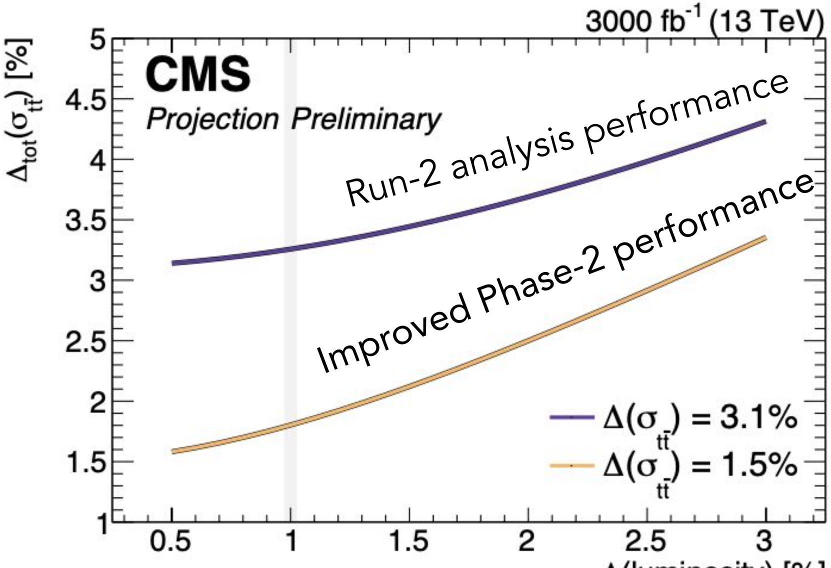
Top quark pair production at HL-LHC



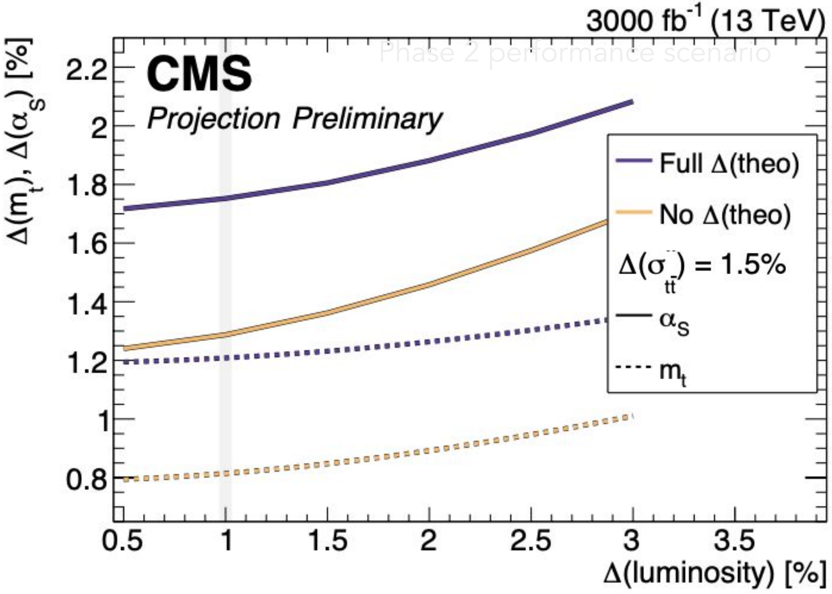
Two scenarios considered for other experimental uncertainties

- Run 2 → total uncertainty on cross-section excluding luminosity: 3.1%
- Phase 2 performance with improved lepton ID (0.5%/lepton), top pT modelling (⅓), jet energy scale (~½), other (½) → total uncert. excluding luminosity: 1.5%

Production cross-section



Top quark pole mass & strong coupling constant



CERN-LHCC-2021-008

Higgs boson properties at HL-LC

Phase 2 scenario with improved detector performance
Assuming target 1% luminosity precision reached

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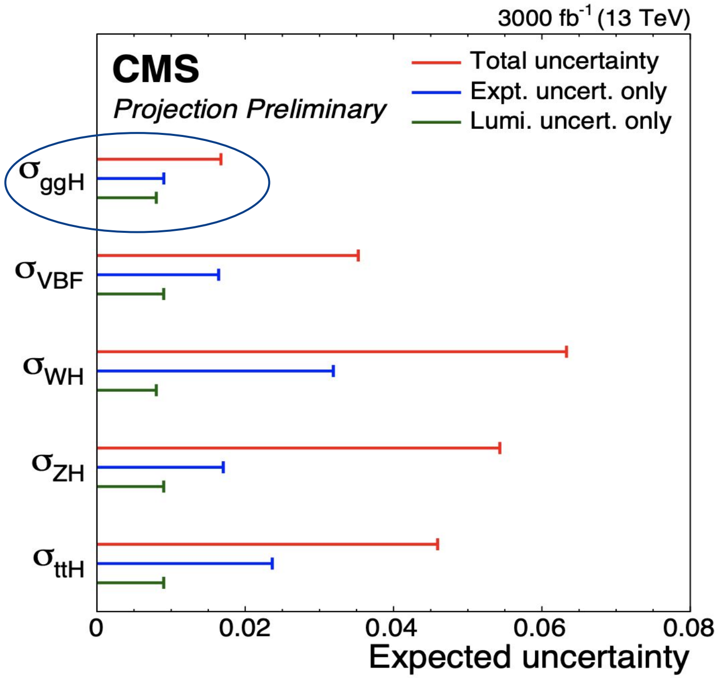
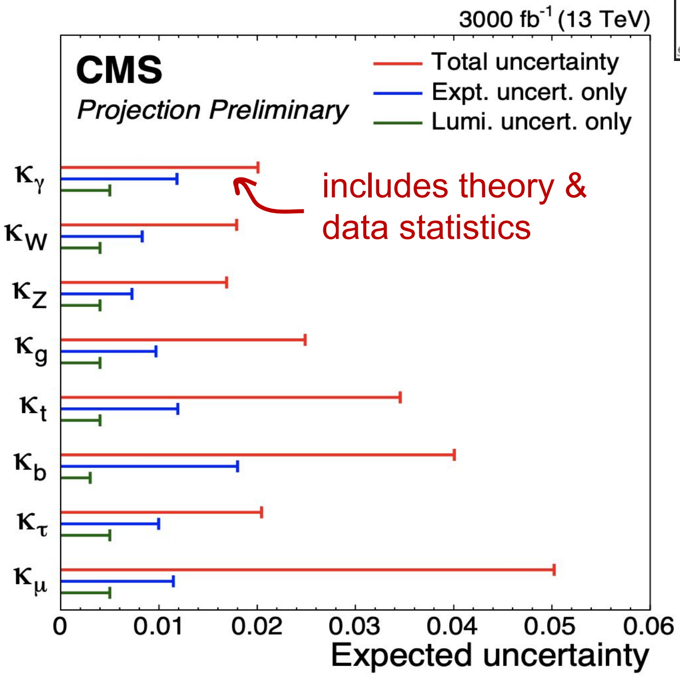
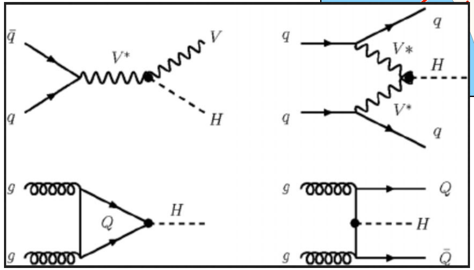






In the most precisely measured Higgs boson production process, gluon fusion (ggH), luminosity uncertainty will dominate the experimental uncertainty at HL-LHC even with the target 1% precision and will remain significant even when including the expected theoretical uncertainties

Data statistical uncertainties in cross sections 0.8% (ggH), 2.6% (VBF), 4.6% (WH), 3.9% (ZH), 1.8% (ttH), in coupling modifier parameters ~1%

Luminosity measurement strategy

$$R(t) = \mathrm{d}N\,/\,\mathrm{d}t = \mathcal{L}(\mathrm{t}) \cdot \sigma$$

Absolute calibration

- Identify luminometers with ~linear rates
- Convert measured rates to luminosity using a calibration constant:
  visible cross-section (σ_{vis})
- Measure rate and luminosity in-situ from beam parameters in well-controlled environment: van der Meer (vdM) transverse beam-separation scans
  (well-separated bunches, PU<1)
  → derive visible cross-section
- Main challenge: corrections for various systematic effects

Integration over time and bunches

- Calculate "integrated" luminosity in physics conditions for a given time period: $L = \int R(t)\,\mathrm{d}t\ /\ \sigma_{vis}$

  → stability of instrumentation in time (aging, operating conditions,...)

- Extrapolation of σ_{vis} to physics conditions *(PU up to 70 in Run 2/3, bunch trains)*

  → linearity of detector & counting method

- Out-of time effects (e.g., from activation of detector material, electronic time walk, late particles…)

Luminometer calibration

Luminosity from beam parameters for a single bunch crossing

$$\mathcal{L} = f_{\text{rev}} N_1 N_2 \int \rho_1(x,y)\rho_2(x,y)\,\mathrm{d}x\mathrm{d}y = f_{\text{rev}} \frac{N_1 N_2}{2\pi\Sigma_x\Sigma_y}$$

Bunch intensities

Bunch particle density distributions in transverse plane

Effective bunch overlap widths in x and y transverse directions

Assumes transverse factorisation of bunch particle density distributions: $\varrho_i(x,y) = \varrho_{x,i}(x) \cdot \varrho_{y,1}(y)$

In a calibration fill optimised for best precision

- Measure head-on luminosity from beam parameters ($\mathcal{L}$) using Van-der-Meer (VdM) transverse beam separation scans (or beam - gas imaging in LHCb)
- Measure luminometer head-on rate (R_0)
- Define the calibration constant as $\sigma_{vis} = R_0 / \mathcal{L}$

Typical conditions in VdM fills

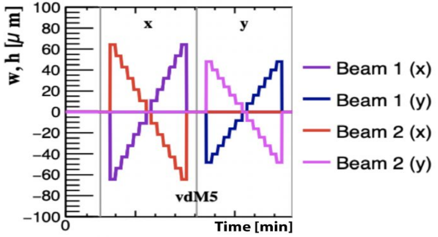
- low inst. luminosity & PU
- single, well-separated bunches (no trains!) to minimize long-range beam-beam interactions
- large transverse beam size (large β*) w.r.t. vertex resolution
- zero crossing angle

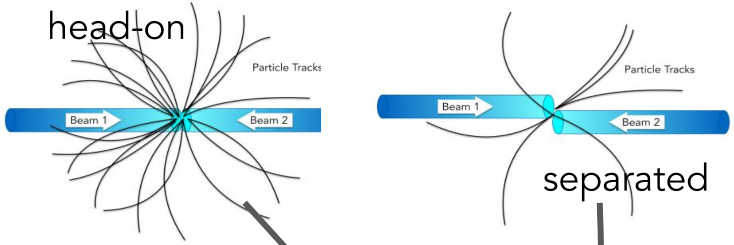
σ_{vis} determination with vdM method

- Rate for different transverse beam separations Δx, Δy for $\pm 6\sigma_{beam}$ in fine steps
- Bunch overlap widths Σ_x, Σ_y given by normalised integral
- Fit functions vary: g, g+g, poly×g, etc.
- Visible cross-section

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y}{N_1 N_2 f_{rev}} \cdot R_0$$

- Ingredients to measure
  - Bunch intensities N_1, N_2
  - Background affecting R_0
  - Length-scale & orbit movements affecting separation Δx, Δy, and thus Σ_x, Σ_y
  - Non-factorisation of beam particle densities $\varrho_{1,2}(x,y)$
  - Beam-beam interactions affecting bunch shape and separation





Pixel cluster counts in zero bias data

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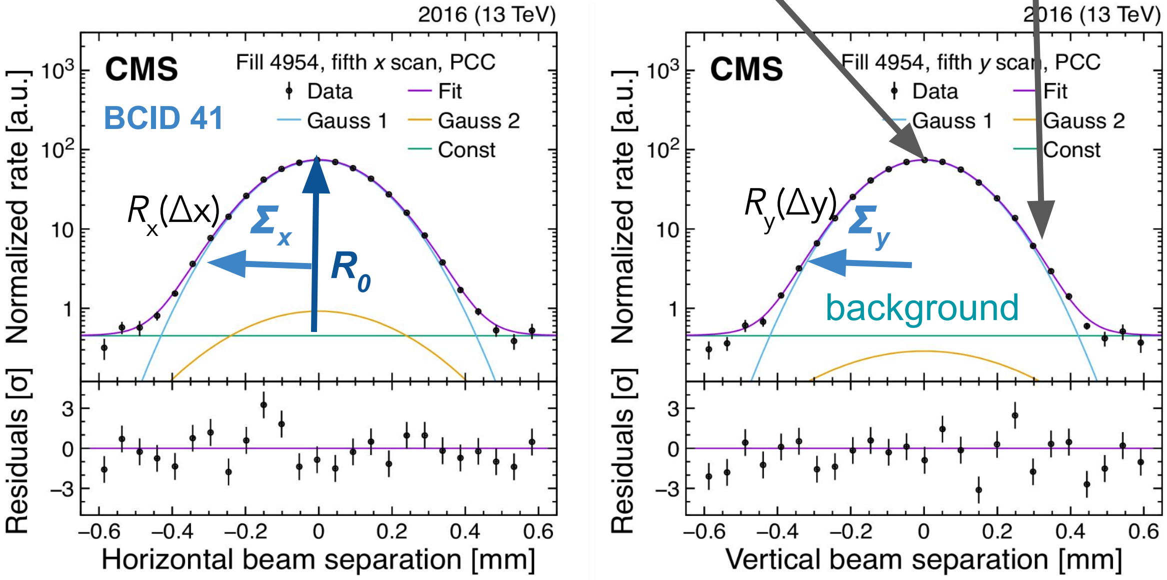

Width ~ Integral / Peak: $\Sigma_x = \int R_x(\Delta x)d(\Delta x) / (\sqrt{2}\sqrt{\pi}\cdot R_x(0))$

Luminosity uncertainties

Source	Correction (%)	Uncertainty (%) 2022 (preliminary)	Uncertainty (%) 2015, 2016 (final)
Calibration			
Beam current	3.4	0.2	0.1
Ghost and satellite charges	0.4	0.2	0.2
Orbit drift	0.1	0.1	0.2, 0.1
Residual beam positions	0.0	0.3	0.8, 0.5
Beam-beam effects	1.0	0.4	0.5
Length scale	-1.0	0.1	0.2, 0.3
Factorization bias	1.0	0.8	0.5
Scan-to-scan variation	-	0.5	
Bunch-to-bunch variation	-	0.1	0.6, 0.3 (combined for scan-to-scan, bunch-to-bunch, cross-detector consistency)
Cross-detector consistency	-	0.4	
Integration			
HFET OOT pileup corrections		0.2	0.3, 0.4
Cross-detector stability		0.5	0.6, 0.5
Cross-detector linearity		0.5	0.5, 0.3
Calibration		1.2	1.3, 1.0
Integration		0.8	1.0, 0.7
Total		1.4	1.6, 1.2

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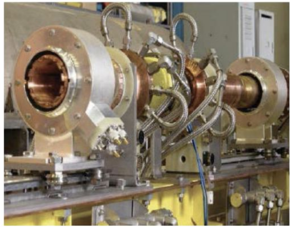
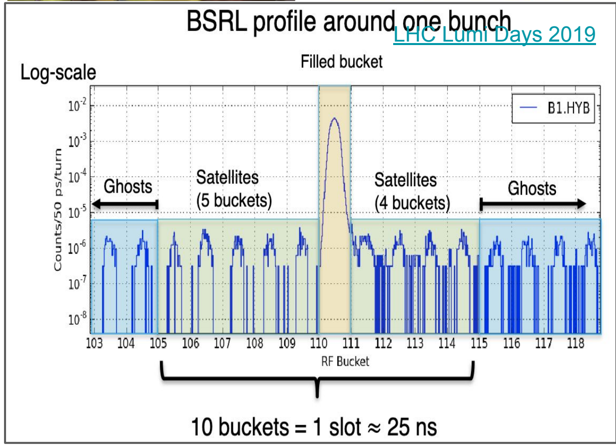
Provided by LHC beam instrumentation





$$n^j = \frac{n^j_{\mathrm{FBCT}}\left(1 - f^j_{\mathrm{sat}}\right)}{\sum_j n^j_{\mathrm{FBCT}}} N_{\mathrm{DCCT}}\left(1 - f_{\mathrm{ghost}}\right)$$

Luminosity uncertainties

Source	Correction (%) 2022 (preliminary)	Uncertainty (%) 2022 (preliminary)	Uncertainty (%) 2015, 2016 (final)
Calibration			
Beam current	3.4	0.2	0.1
Ghost and satellite charges	0.4	0.2	0.2
Orbit drift	0.1	0.1	0.2, 0.1
Residual beam positions	0.0	0.3	0.8, 0.5
Beam-beam effects	1.0	0.4	0.5
Length scale	-1.0	0.1	0.2, 0.3
Factorization bias	1.0	0.8	0.5
Scan-to-scan variation	-	0.5	0.6, 0.3 (Scan-to-scan, Bunch-to-bunch, Cross-detector consistency combined)
Bunch-to-bunch variation	-	0.1	
Cross-detector consistency	-	0.4	
Integration			
HFET OOT pileup corrections		0.2	0.3, 0.4
Cross-detector stability		0.5	0.6, 0.5
Cross-detector linearity		0.5	0.5, 0.3
Calibration		1.2	1.3, 1.0
Integration		0.8	1.0, 0.7
Total		1.4	1.6, 1.2

Major contributions of ELTE team

Strong collaboration between experiments and machine experts to tackle common systematics

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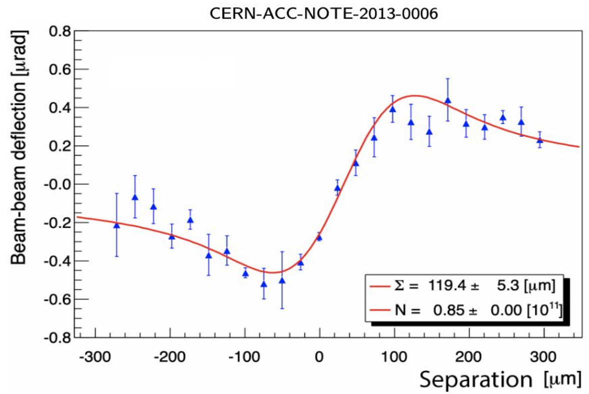
Beam-beam (BB) interactions

Electromagnetic interaction between the charged particles of the beams
→ all particles perturbed (only few collide!), trajectory change due to non-linear force:

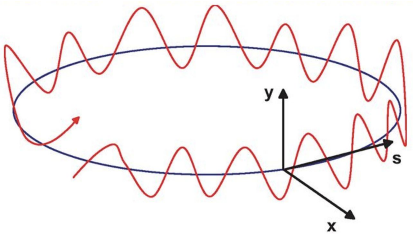
$$F_{\perp} = \pm \frac{Ne^2(1+\beta_{rel}^2)}{4\pi\epsilon_0 r}\left(1-\exp\left[-\frac{r^2}{2\sigma^2}\right]\right)$$



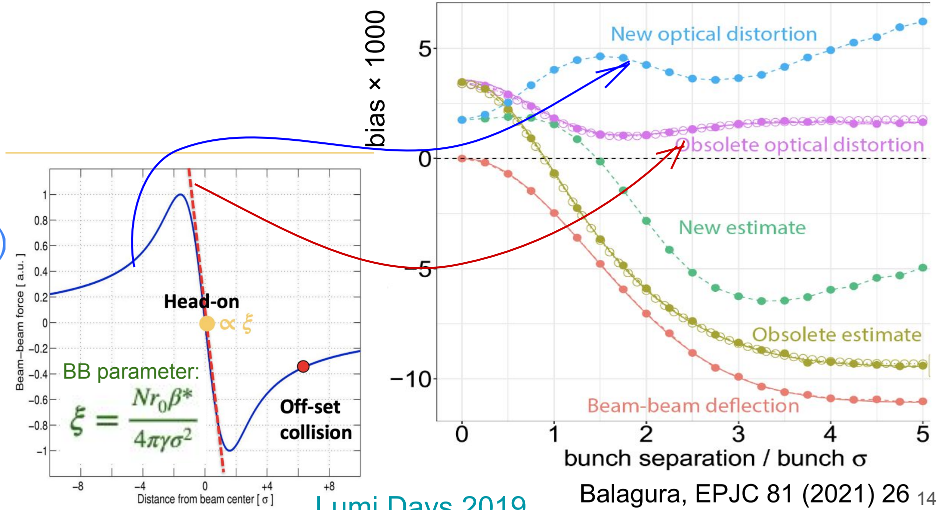
- Affects beam separation: **"beam-beam deflection"**
  - coherent effect on a bunch
  - estimated analytically using Bassetti–Erskine formula
- Distorts the bunch sizes, shapes: **"optical" or "dynamic-beta" effect**
  - incoherent effect on single particles
  - modifies bunch overlap area, thus measured rates in luminometers
- Also changes the betatron tunes (tune shift & spread: $\Delta Q \propto \xi$), causes particle losses, emittance blow up…

Model with multiparticle simulations:
B*B & COherent Multibunch Beam-beam Interaction (COMBI)

After Run 2: large correction to previous calculation based on linear approximation (lumi results before 2019 biased by ~1%)



betatron tune => # of transverse oscillations of a particle in one revolution around the ring (Q_x=64.31, Q_y=59.32 for pp at top energy)



Lumi Days 2019

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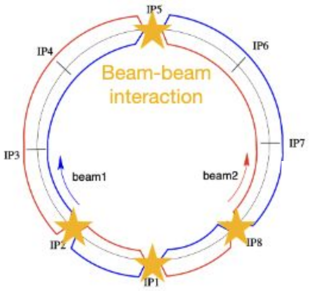
Beam-beam interactions

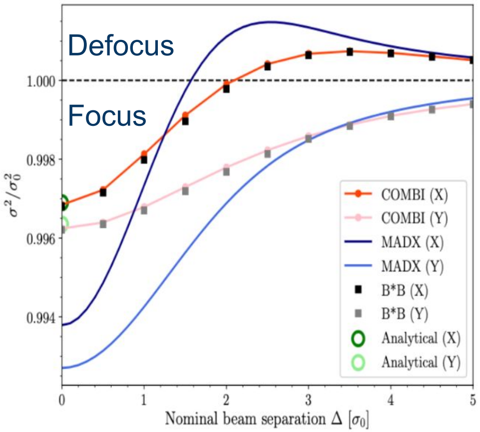


LHC working group (LLCMWG) effort
→ correction scheme, uncertainty estimation prescription

Per-bunch input to calculate luminosity bias $\mathcal{L}/\mathcal{L}_0(\Delta \mid \xi_R, q_x, q_y)$

- Luminometer based transverse bunch width (assuming round beams with equal sizes: $\sigma_R^2 = \Sigma_x\Sigma_y/2$)
- Bunch intensity (assuming $N = N_1N_2/2$)
- Beam parameters: β^*, Q_x, Q_y, E_b
- Number of collisions per orbit (→ tune shift, effective fractional tunes q_x, q_y)

Uncertainties due to Q_x, Q_y, β^*, non-Gaussian, non-round, non-equal sized & charged bunches…



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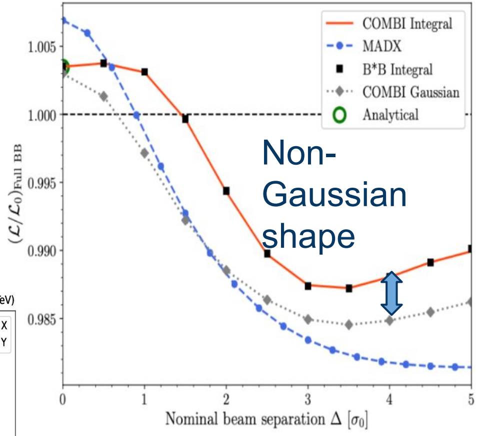

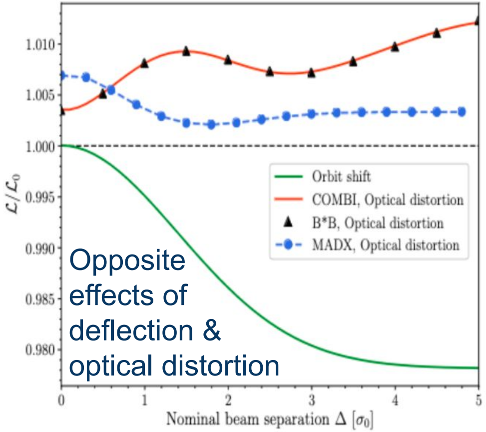

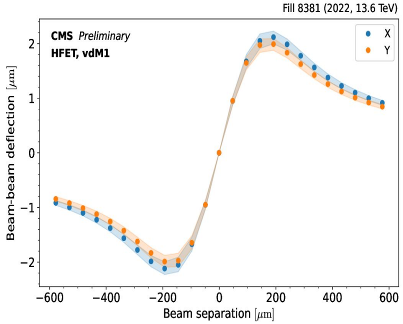

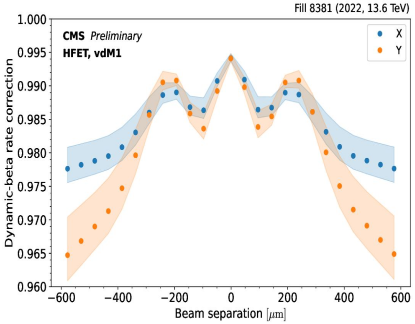

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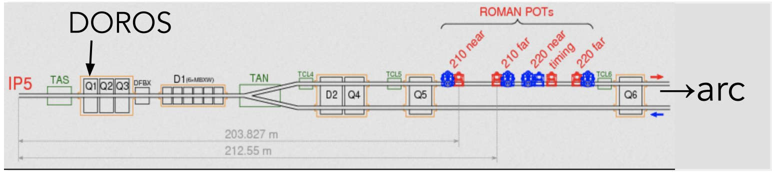
Orbit drift from nominal position



- Measured by beam position monitors (BPMs)
- Correct nominal beam positions & separations (Δx, Δy)
- "Arc" BPMs in LHC arcs adjacent to experiments
  - Their data transformed to beam positions at the interaction points (IPs) using LHC optics model
- Diode Orbit and Oscillation (DOROS) BPMs at Q1 triplet quadrupoles 21.5 m from the IP
- Average Beam 1 & Beam 2 orbit tracked by the movements of the luminous region ("beam spot") at the IPs via reconstructed vertex positions by the tracking detectors
- All orbit measurements are integrated over all bunches
- Orbit drifts have many origins, e.g.,
  - **Beam-beam deflection** (affects separated colliding bunches)
  - **Magnetic non-linearities** (systematic "hysteresis")
  - Slow "random" orbit drifts (assumed to be **linear** between head-on measurements before and after scans)
  - Orbit jitters (instabilities with few 10s of seconds characteristic time)

Measured linear orbit drift wrt. nominal orbit during *head-on* collisions (before, in the middle, and after scans)

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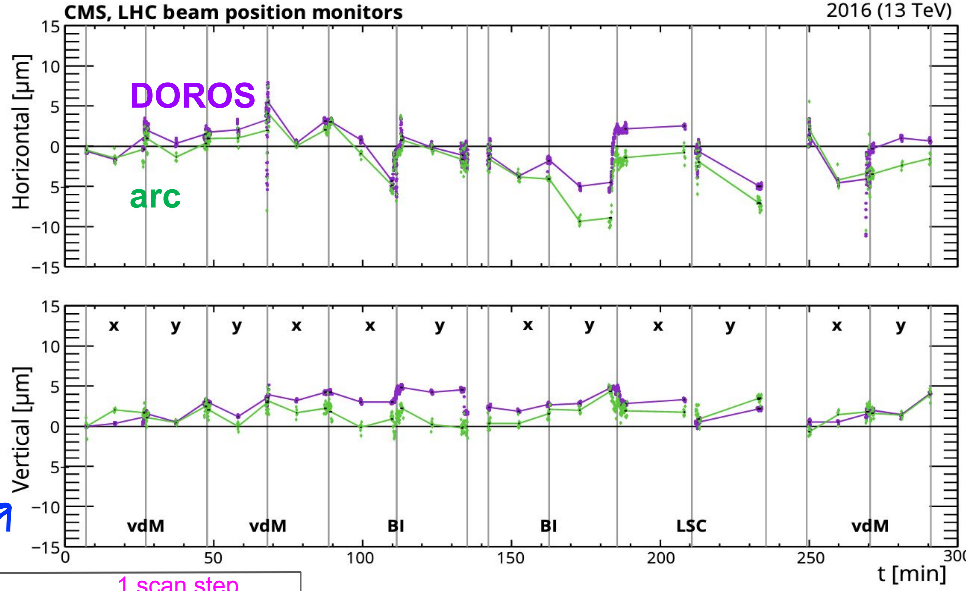

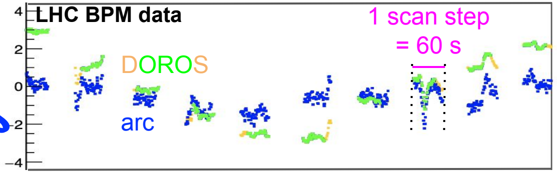

Measured orbit drift wrt. nominal orbit per second

“Residual” orbit drifts and magnetic non-linearities

Systematic residual orbit drifts observed in BPM data:

Residual = BPM - α·**Nominal**
- β·**BBdeflection**
- **linearOD**

- BPM length scale (α) wrt LHC nominal positions from corrector magnet currents
- Beam-beam deflection corrected by a geometric factor to account for the BPM distance from the IP and scaled (β) to account for non-colliding bunches and BPM instrumental effects

Possible source: **magnetic non-linearities**
- All experiments observe similar effects
- Dedicated measurements performed in Run 3 and by magnet experts in the lab (CERN-ACC-NOTE-2022-0013) showing consistent results

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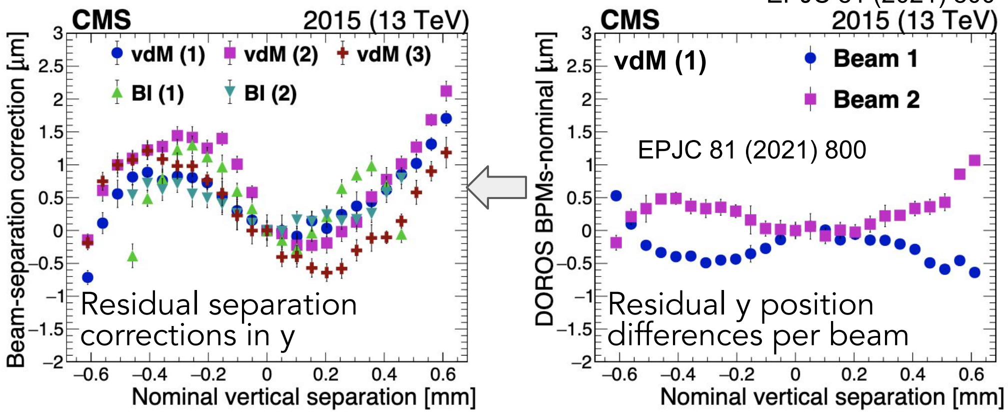
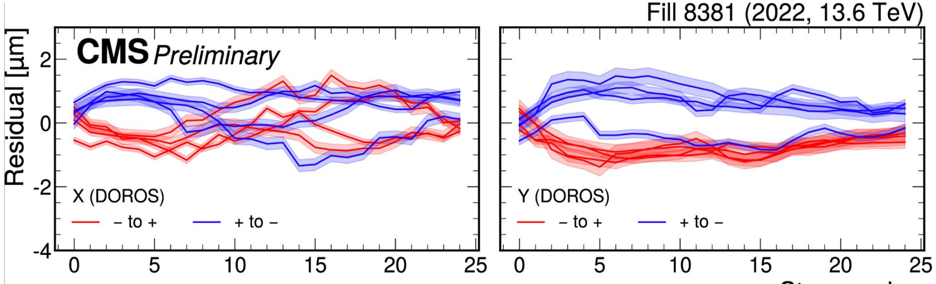
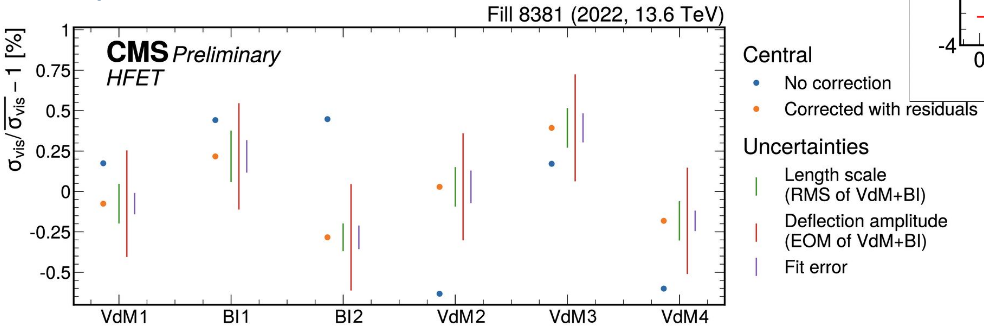




CMS-PAS-LUM-22-001

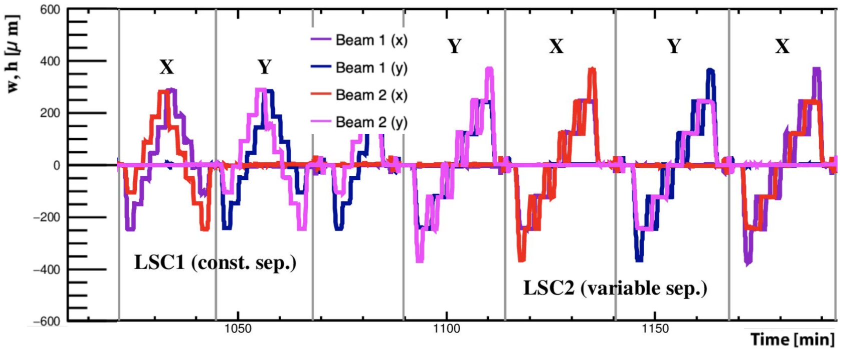


Correction improves consistency of measured visible cross section values from scan to scan

Transverse length scale (LS) calibration

CMS-PAS-LUM-18-002

- Scale factor between nominal displacement from LHC dipole corrector magnet currents to actual displacement in tracker reference frame using luminous region (beamspot) position from reconstructed vertices
- Special scans performed to move the beamspot position
  - Beams moved together in equidistant steps with constant (non-zero) beam separation to measure average B1&B2 LS
    - Fast, allows to measure back & forth
  - One beam moved in equidistant steps with the other beam performing 3-step mini-scans around it to determine the head on position, having thus variable beam separation during the scan
    - Provides per beam LS
- Main difficulty: orbit drift (OD) during the scans



Adjusts Σ_x, Σ_y

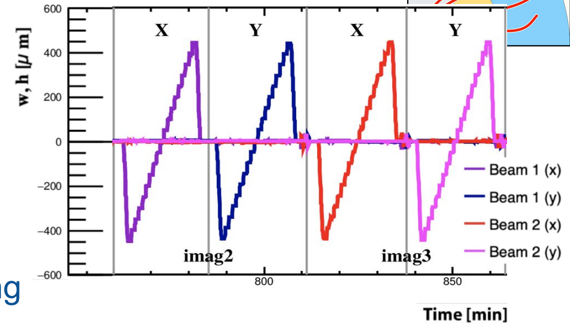
OD correction:

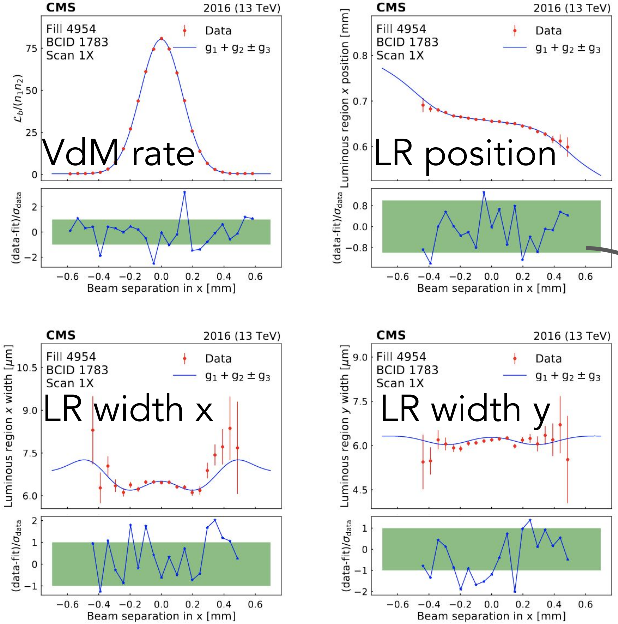
- Correct nominal positions using beam position monitor (BPM) data
- BPM length scale enters
- Few steps, possible large effect of "random" shifts / jumps

LS correction can reach -1%
Typical uncertainty 0.2-0.3%

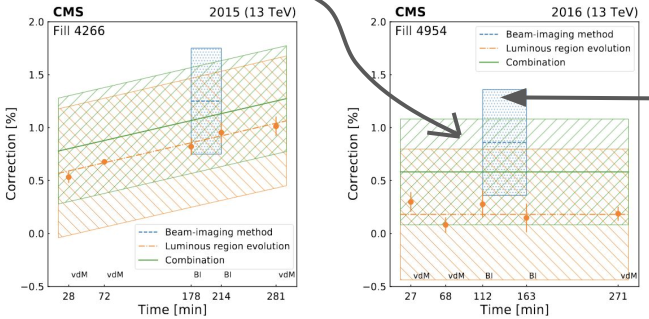
Transverse beam particle density factorisation

- Even with beam tailoring in the LHC injection chain, the VdM assumption of $\varrho_i(x,y) = \varrho_{x,i}(x) \cdot \varrho_{y,1}(y)$ not exact
- Various methods developed to measure the effect and derive bunch shapes using reconstructed vertex position distributions
  - Beam imaging using a special scan with a stationary beam scanned by the other
  - Luminous region analysis exploiting the 3D beam spot reconstruction (position, widths, tilts) and vdM rates - does not need dedicated scan, "continuous" monitoring

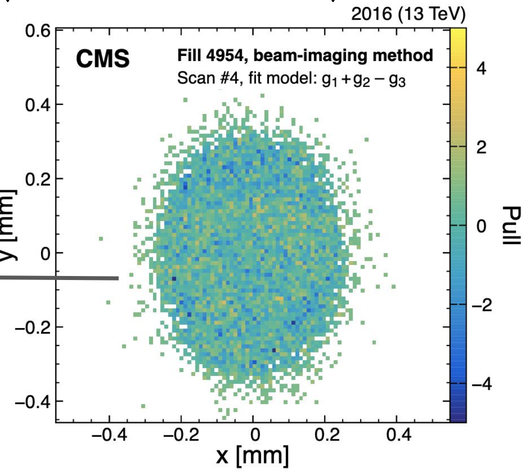




- Good agreement between methods
- Time dependence observed
- Vertex data available only for small number of bunches



Simultaneous fit of the 4 scans to determine the bunch shapes (G1 + G2 - G3 model)



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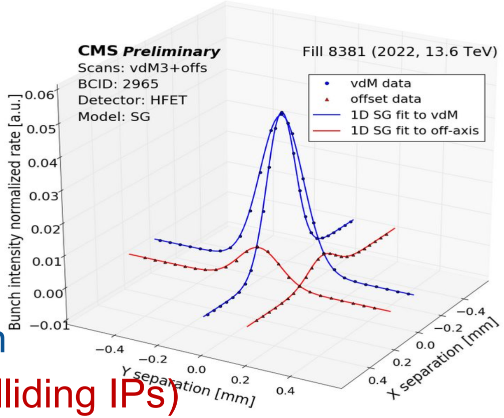
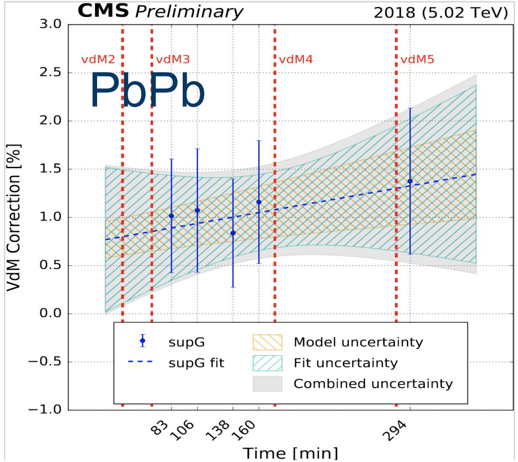
Transverse beam overlap shape factorisation

- Factorisation effects can change from bunch to bunch (& in time)
- Study directly the overlap area from luminometer rates
- Simultaneous analysis of VdM & offset/diagonal scans
  - Similar to LHCb pioneered 2D scan analysis
  - Orbit drifts during extended data taking need to be controlled
  - Applicable in PbPb collisions where beam size similar to vertex resolution
- First evidence for bunch family dependence (PS Booster ring, number of colliding IPs)





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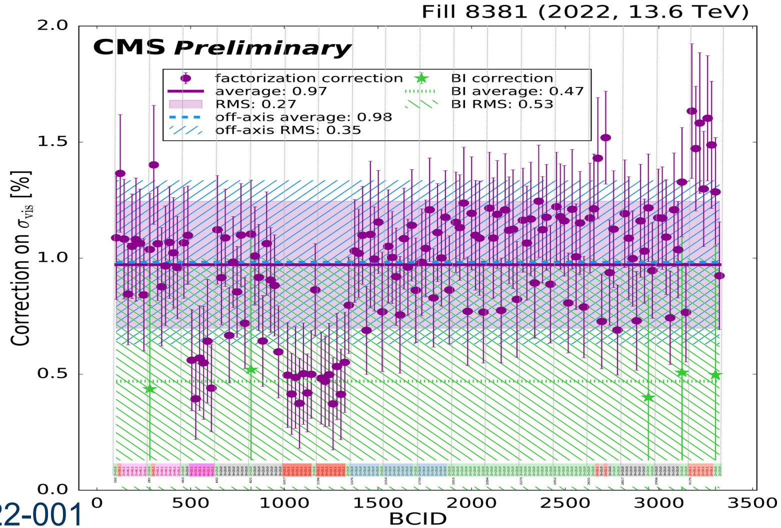
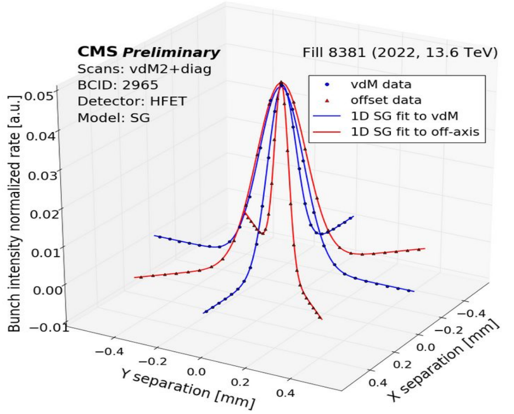
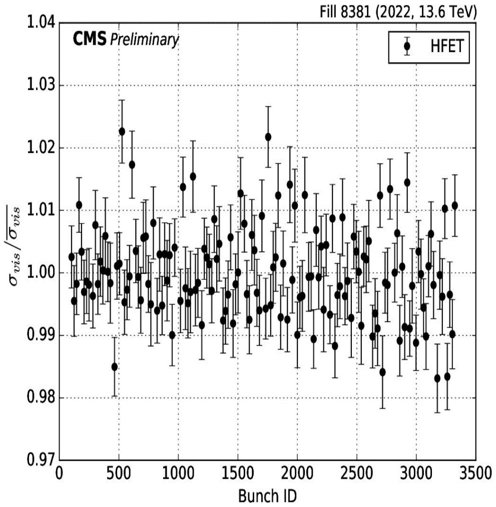


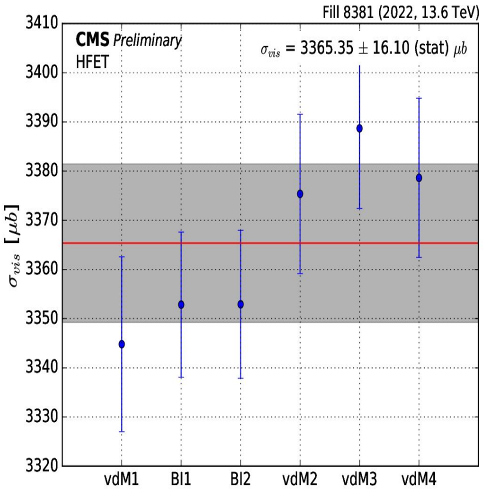
CMS-PAS-LUM-22-001



Probing uncorrected / unknown effects

Bunch-by-bunch and scan-to-scan variation of calibration constant

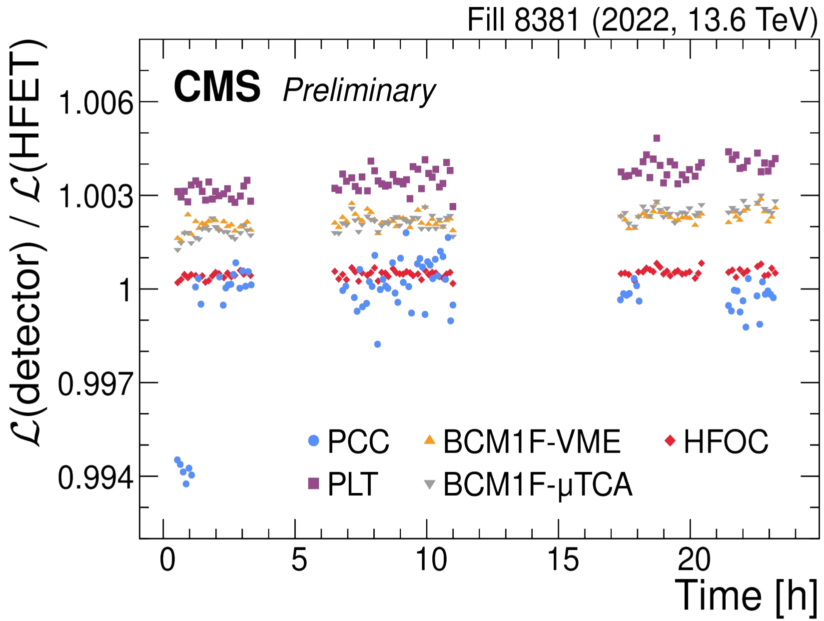




CMS-PAS-LUM-22-001

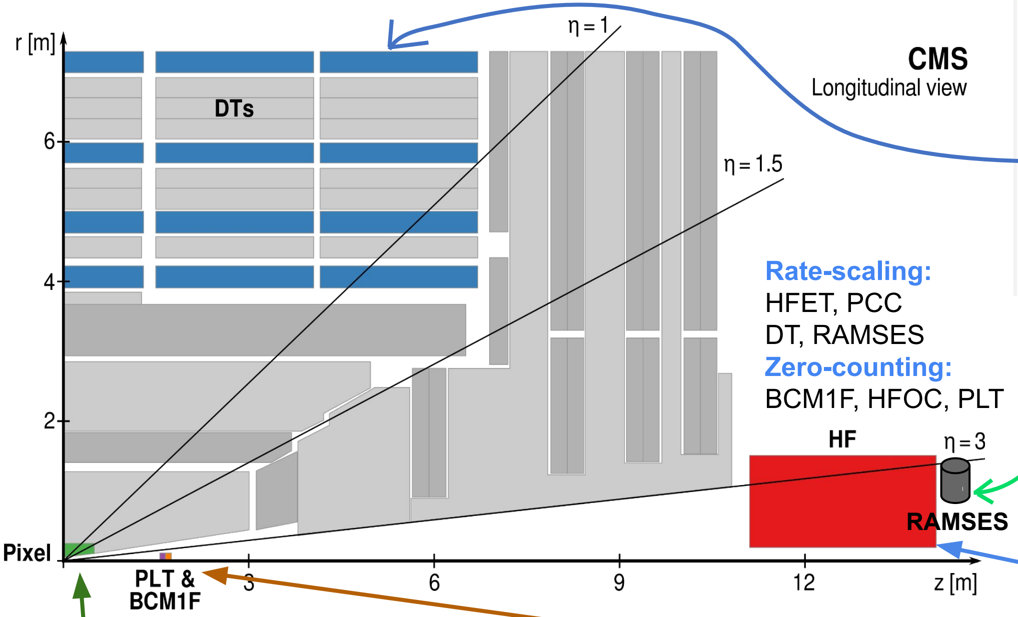
Measures beam-dependent uncorrected effects

Luminosity cross-detector comparison in non-scanning periods of a vdM fill

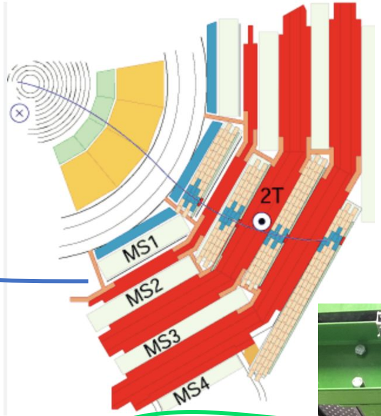


Essential to have several, independently calibrated luminometer to check for unknown instrumental biases

Luminometers in CMS



Rate-scaling:
HFET, PCC
DT, RAMSES
Zero-counting:
BCM1F, HFOC, PLT

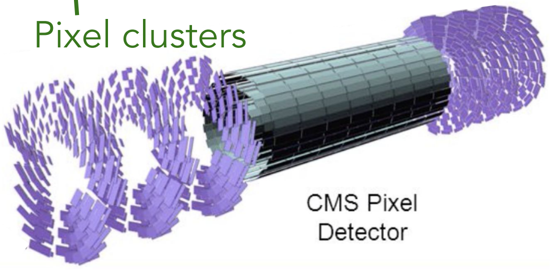


Muon Drift Tubes (DT):
L1 trigger primitives
(stubs, orbit integrated)

6 independently calibrated, bunch-by-bunch luminometer using varied technologies + 2 orbit-integrated reference systems

HFOC: Hit towers (occupancy)
HFET: sum(E_T)

Pixel clusters

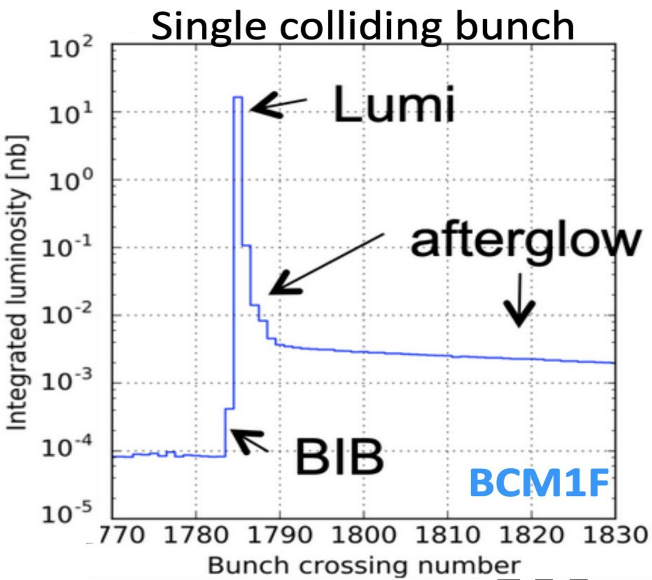


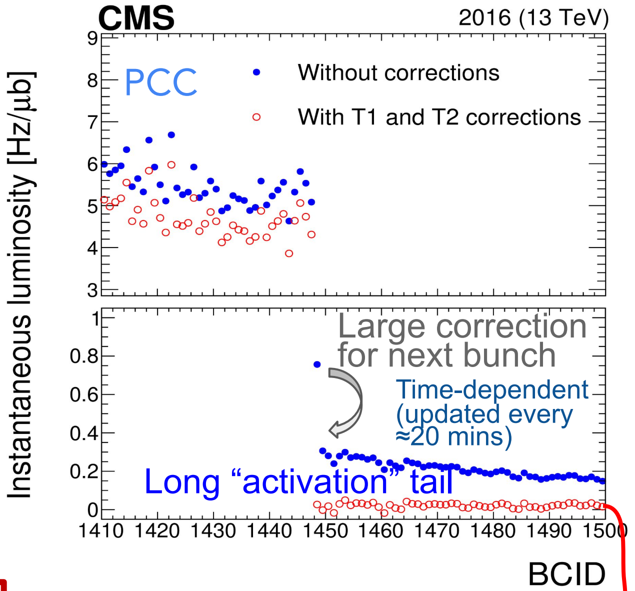
PLT: 3-fold coincidences in Si pixel telescope
BCM1F: hits on Si pads

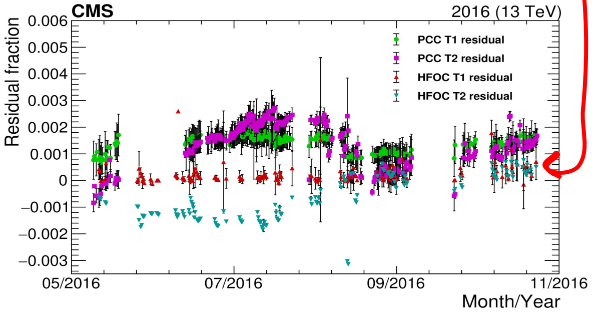
Phase-2 DT & 40 MHz scouting demonstrator systems in Run 3

Luminosity uncertainties

Source		PCC:
Calibration		
Beam current		
Ghost and satellite charges		
Orbit drift		
Residual beam positions		
Beam-beam effects		
Length scale		
Factorization bias		
Scan-to-scan variation		
Bunch-to-bunch variation		
Cross-detector consistency		
Integration		
HFET OOT pileup corrections	0.2	0.3, 0.4
Cross-detector stability	0.5	0.6, 0.5
Cross-detector linearity	0.5	0.5, 0.3
Calibration	1.2	1.3, 1.0
Integration	0.8	1.0, 0.7
Total	1.4	1.6, 1.2







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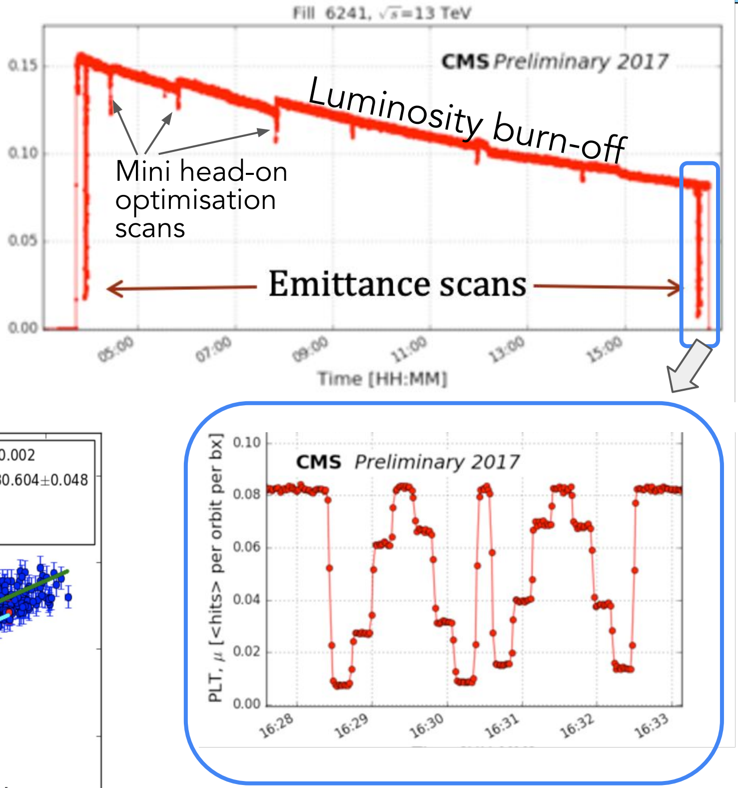
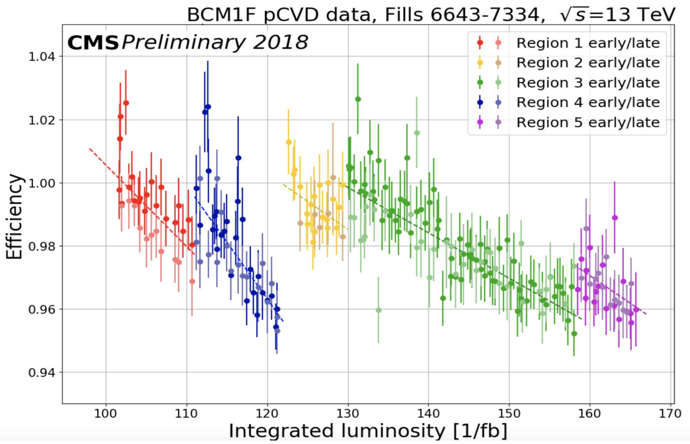
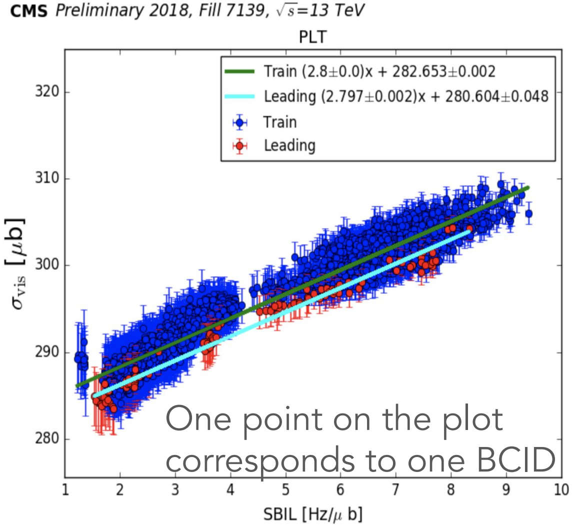
Emittance scans: mini-vdM scans in physics fills

- Fast luminosity scans with small ~3σ_b maximum separation with 7-15 points of 10 s each
- Less precise than VdM scans due to uncorrected biases, used for relative measurements in similar conditions
- Study time dependence of luminometer response → efficiency monitoring
- Different SBILs from bunch to bunch and at start and end of fill → measure (non-)linearity



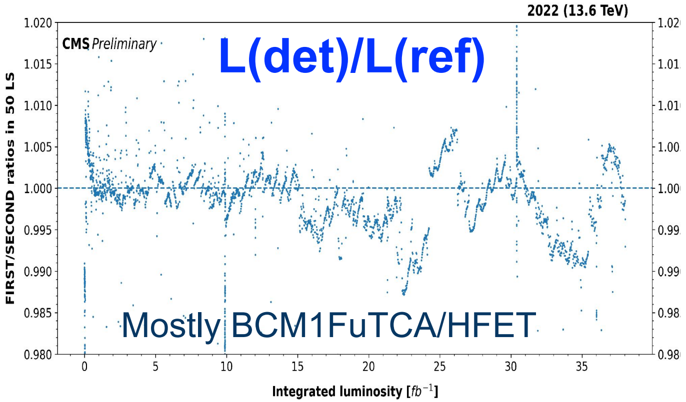


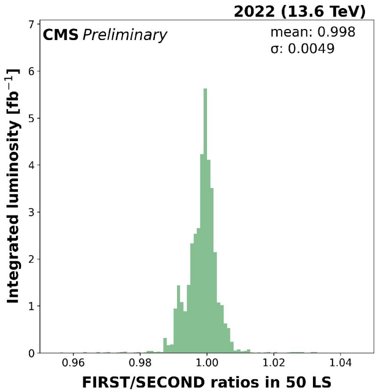


Integration systematics: stability & linearity

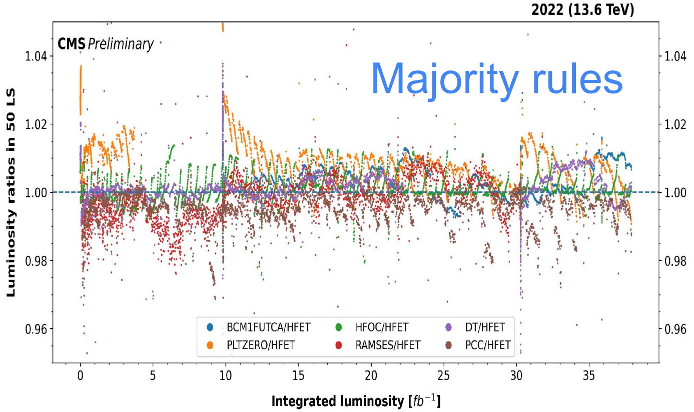
Compare independently calibrated luminometer measurements

CMS-PAS-LUM-22-001

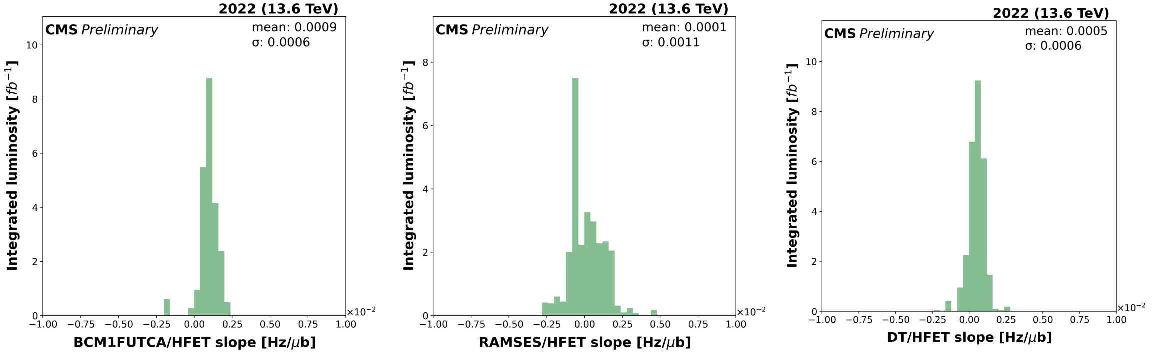




First, each BbB luminometer
- independently vdM calibrated
- corrected for out-of-time effects
- linearity and efficiency monitored & corrected using short vdM-like "emittance" scans



Slope of L(det)/L(ref) vs. L(ref)

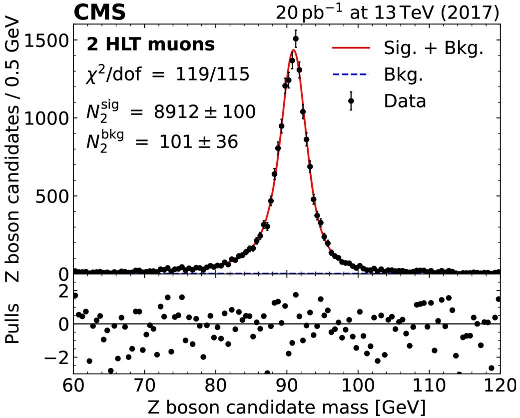


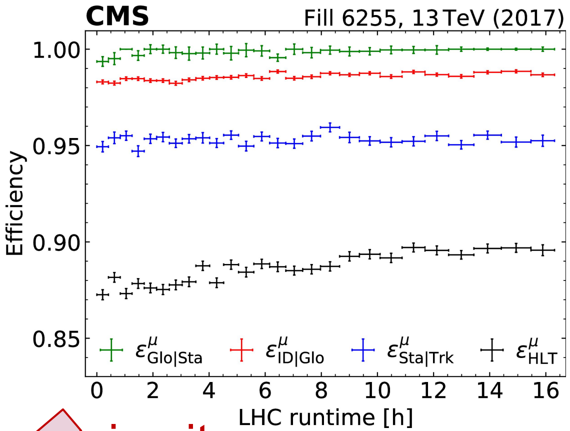
Typical stability uncertainty: 0.5-0.6%

Typical linearity uncertainty: 0.5%

Z counting for luminosity integration

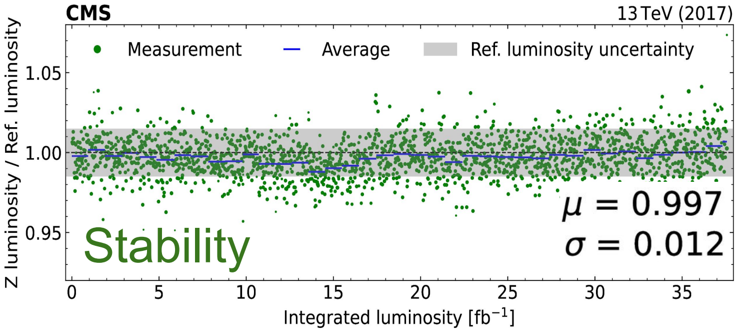
- Self-calibrating measurement (muon efficiency from same data)
- $\sigma(N_{highPU}/N_{lowPU})$ = 0.5% in 2017
- Need close-by vdM calibration at least once for each collision energy with few 100 pb^{-1} low PU data

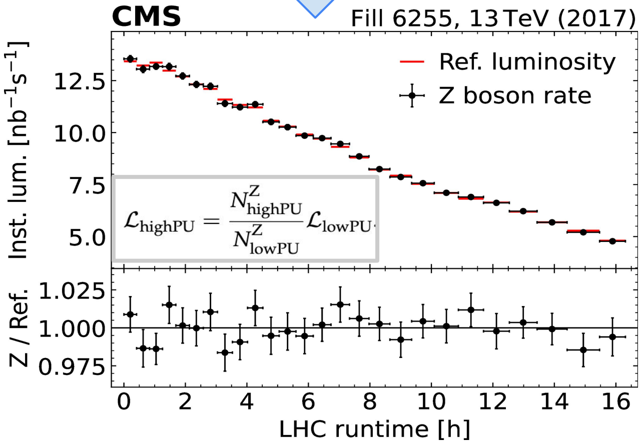


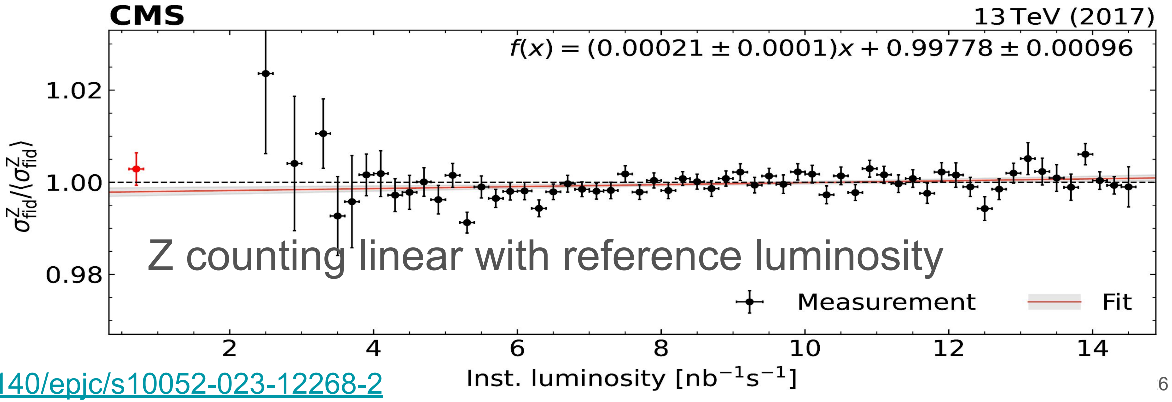


Z→μμ count

in-situ muon efficiency







10.1140/epjc/s10052-023-12268-2

Luminosity uncertainties

Source	2022 (preliminary) Correction (%)	2022 (preliminary) Uncertainty (%)	Uncertainty (%) 2015, 2016 (final)
Calibration			
Beam current	3.4	0.2	0.1
Ghost and satellite charges	0.4	0.2	0.2
Orbit drift	0.1	0.1	0.2, 0.1
Residual beam positions	0.0	0.3	0.8, 0.5
Beam-beam effects	1.0	0.4	0.5
Length scale	-1.0	0.1	0.2, 0.3
Factorization bias	1.0	0.8	0.5
Scan-to-scan variation	-	0.5	} 0.6, 0.3
Bunch-to-bunch variation	-	0.1	}
Cross-detector consistency	-	0.4	}
Integration			PCC:
HFET OOT pileup corrections		0.2	0.3, 0.4
Cross-detector stability		0.5	0.6, 0.5
Cross-detector linearity		0.5	0.5, 0.3
Calibration		1.2	1.3, 1.0
Integration		0.8	1.0, 0.7
Total		1.4	1.6, 1.2

State-of-the-art in 2018 at the end of Run 2 ~2.5%

~ factor 2 improvement!

Getting close to target precision of 1%

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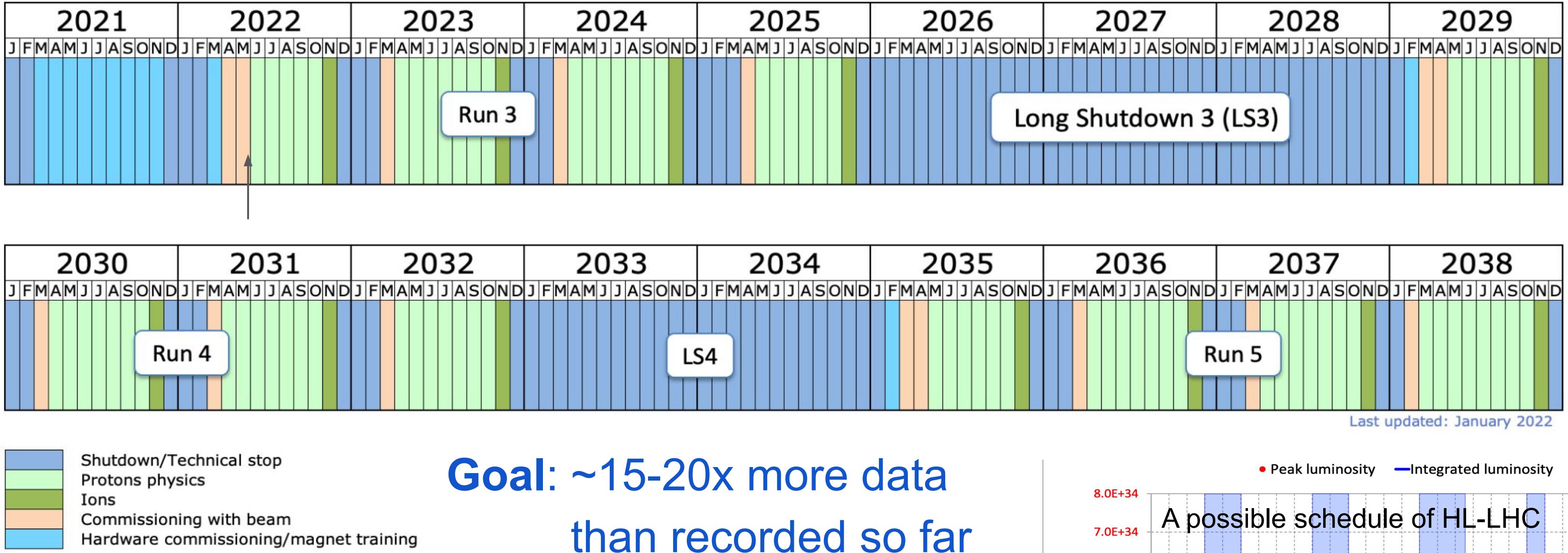
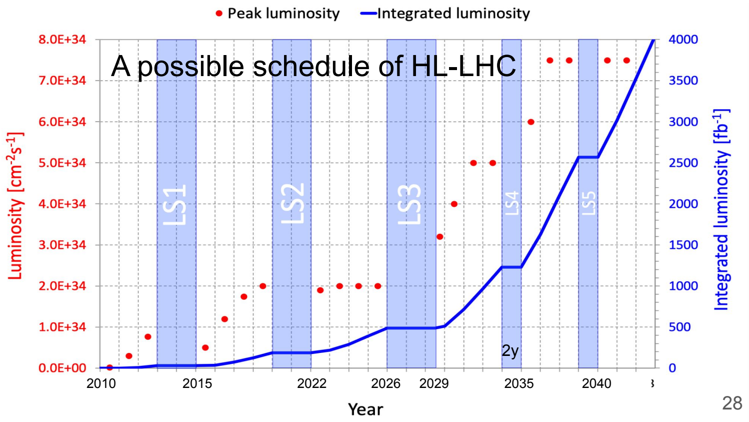
HL-LHC schedule and challenges



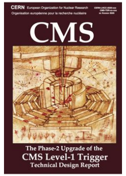
Goal: ~15-20x more data than recorded so far



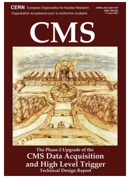
Challenges

- **High-radiation environment**: replace tracker & endcap calorimeter
- **High pileup up** to ‹μ›=140-200, **high particle multiplicity**: improve granularity, use timing information
- **Extended physics reach**: enlarged acceptance in |η|
- **High data rate**: upgrade trigger and DAQ

The CMS Phase-2 Upgrade

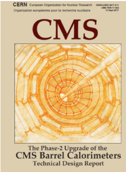


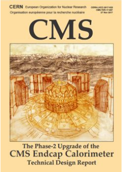
Level-1 Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1 Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



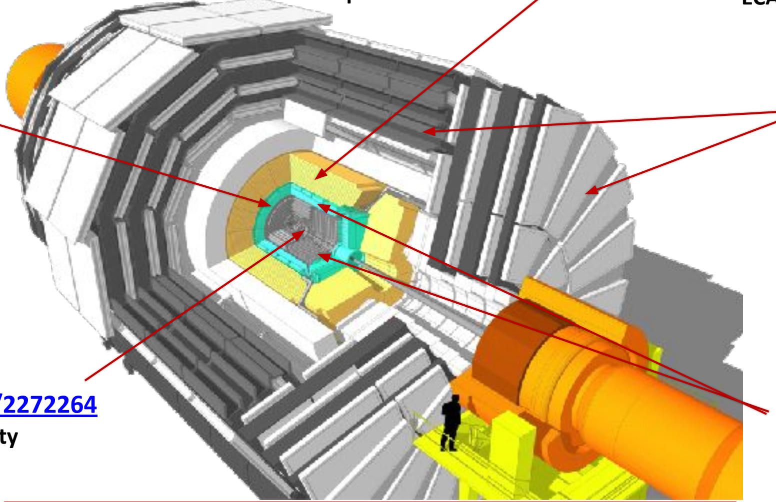
DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL single crystal granularity readout at 40 MHz with precise 30 ps timing for e/γ at 30 GeV
- Spike rejection
- ECAL and HCAL new Back-End boards

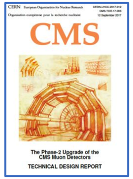


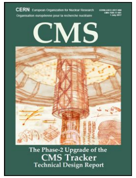


High-Granularity Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/Cu-W/SS



Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC BE electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

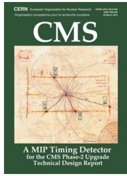


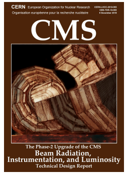


Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Extended coverage to $\eta \simeq 4$
- Design for tracking in L1 Trigger

MIP Timing Detector
https://cds.cern.ch/record/2667167

Precision timing with:
- Full coverage to $\eta \simeq 3$
- 30-50 ps time resolution for MIPs
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes





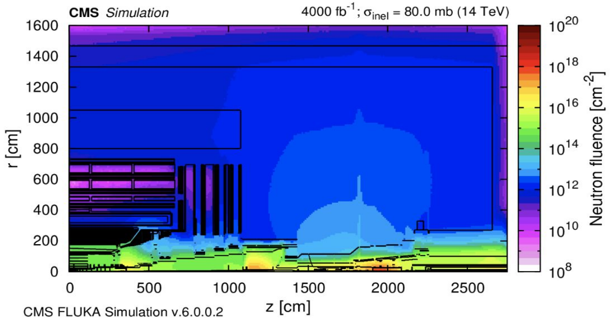
Beam Radiation Instrumentation and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors

Approved in 2022
14 technical systems

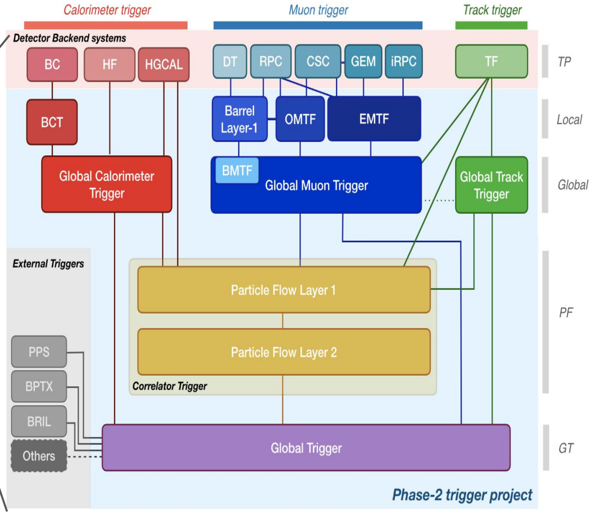
SS: stainless steel, FE: front end, BE: back end,
MIP: minimum ionizing particle,
SiPM: Silicon Photomultiplier

Main features of CMS Phase-2 upgrade

- New **silicon pixel and strip tracker** with higher granularity and larger coverage (|η|<4)
- New "imaging" **high-granularity endcap calorimeter**
- **Extended muon coverage** in forward region (|η|<2.8), new **high-granularity GEM detectors**
- **Precision timing** by dedicated **MIP timing detectors** with 30-50 ps resolution (|η|<3) supplemented by improved timing information from muon detectors and calorimeters
- **Upgraded electronics** with higher bandwidth



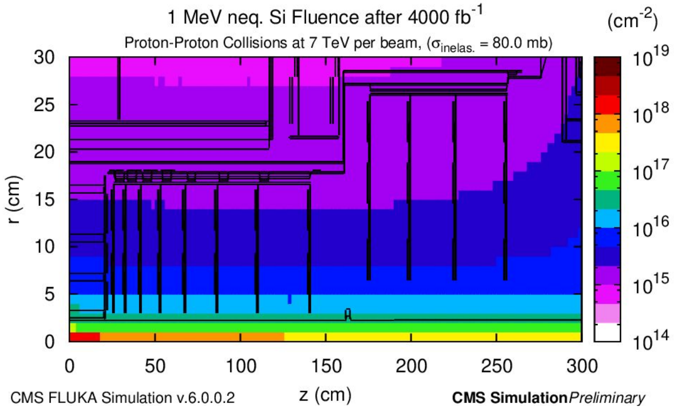
- Fully reconstructed p_T > 2 GeV tracks & particle-flow at level-1 trigger, increased rate (750 kHz) and latency (12.5 µs), 40 MHz scouting
- High-level trigger with heterogeneous architecture,7.5 kHz output rate*[1]

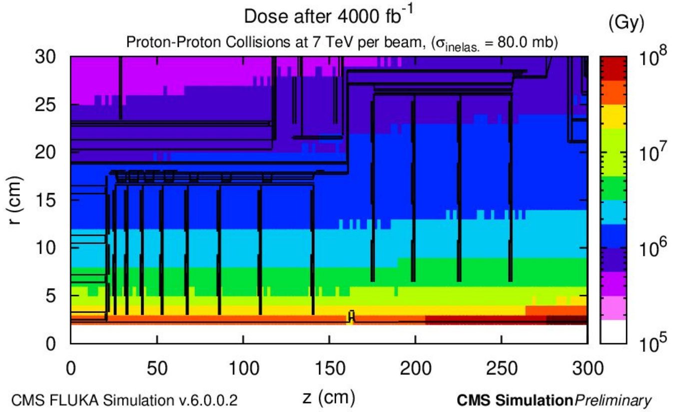


Upgrade in full swing, first full phase-2 detector installed

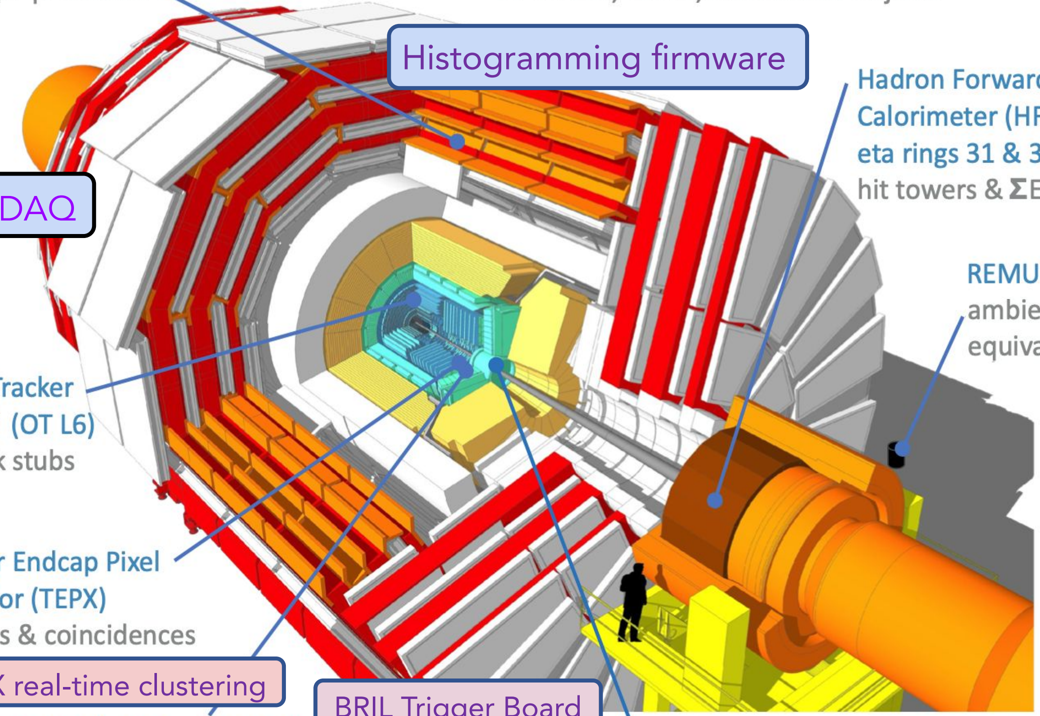
Luminosity measurement at HL-LHC

- 1% target precision for integrated luminosity per year in very demanding conditions
  - event pile-up up to 140-200 at 40 MHz
  - 10 years of data taking to collect >3000 fb^{-1} data
    - neutron fluences ~10^{16} cm^{-2} in forward pixel tracker
    - total ionizing dose ~10^{7} Gy
- Measure pileup distributions, i.e. bunch-by-bunch luminosity for simulation
- Real-time feedback with ~2% precision for luminosity levelling
  - from 17 to (5-7.5) · 10^{34} $cm^{-2}s^{-1}$ with β^*, crossing angle, beam separation adjustments
- Manage non-linearity inherent in every luminometer, as well as train effects
  - extrapolating current luminometer linearity performance to HL-LHC → 2-3% uncertainty
- Minimize long-term efficiency loss using radiation hard instrumentation
- Understand the beam properties with improved instrumentation





BRIL SUBSYSTEMS
for bunch-by-bunch Phase-2 luminometry



CERN-LHCC-2021-008

Pillars of luminometry

1. Consumer of *CMS subsystem data* (much like the trigger)
2. Dedicated BbB luminometer: FBCM
   - Independent, under full control of BRIL
   - Luminosity & BIB outside stable beams
   - Simple, reliable, high precision
   - Unique asynchronous / sub-BX timing capabilities
     - Time structure of beams
     - Orthogonal systematics
   - Proven technology (Run-2 BCM1F)
   - Pragmatic, reuses existing components, while new ones, especially FE ASIC is designed to fulfil only BRIL requirements
3. Principle of *maximum commonality*
   - Histogramming firmware for subsystem backends
   - Run control and data acquisition, independent of CMS

Robust system of diverse technologies and counting methods with different systematics

Luminosity architecture

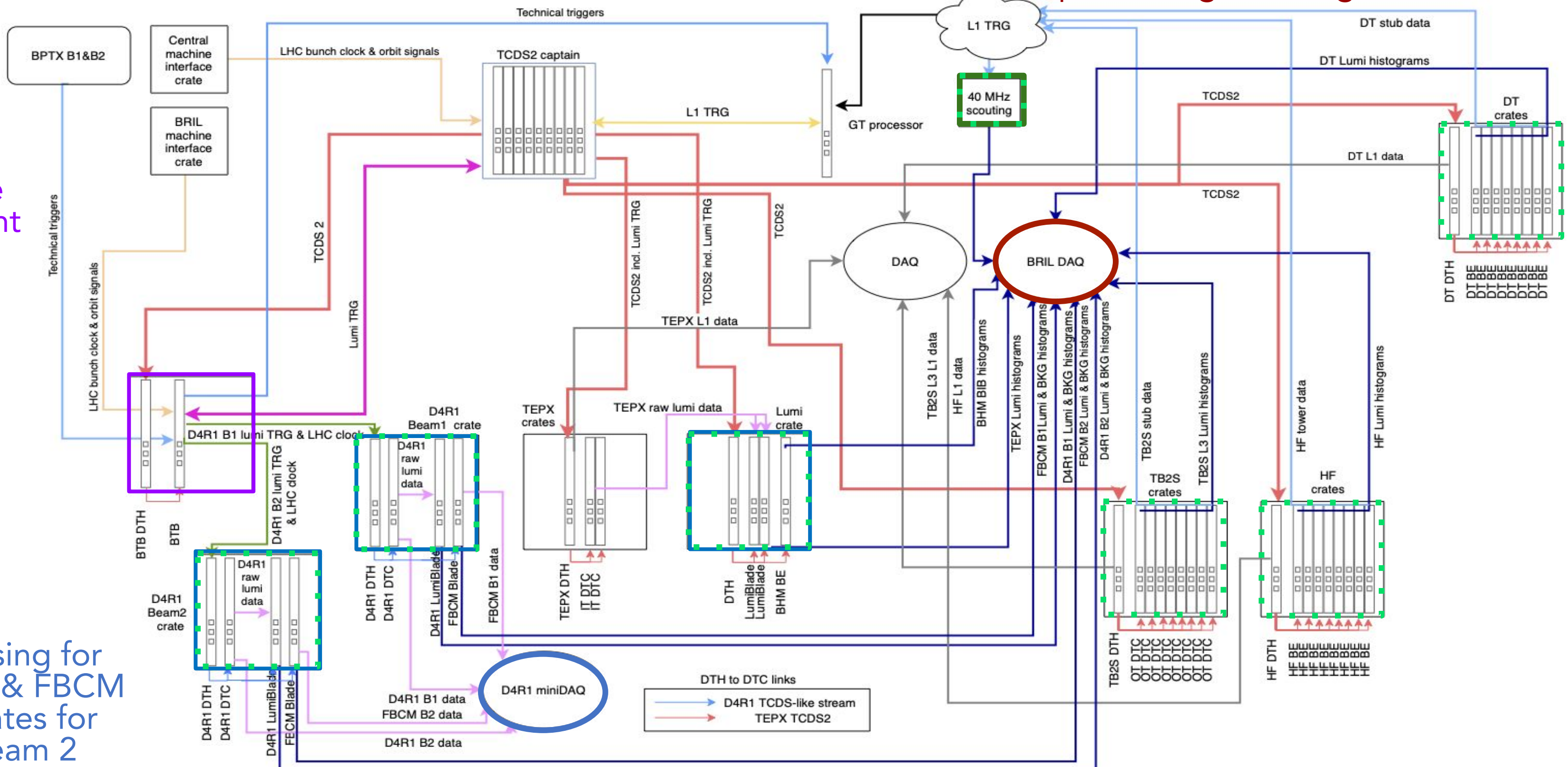
Scouting HW with histogramming FW installed

BRIL data acquisition
Run control, histo data readout / processing / sharing

Clock signal to BRIL systems, special scheme for independent operation of D4R1 & FBCM

Trigger generation for TEPX (D4R1)

Encode BPTX Beam 1 & 2 discriminated signal for GT

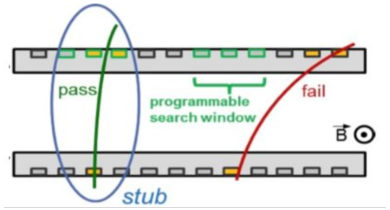


Data processing for TEPX, D4R1 & FBCM [separate crates for beam 1 & beam 2 for D4R1 & FBCM on different clocks]

Histogramming firmware installed at subsystem back ends

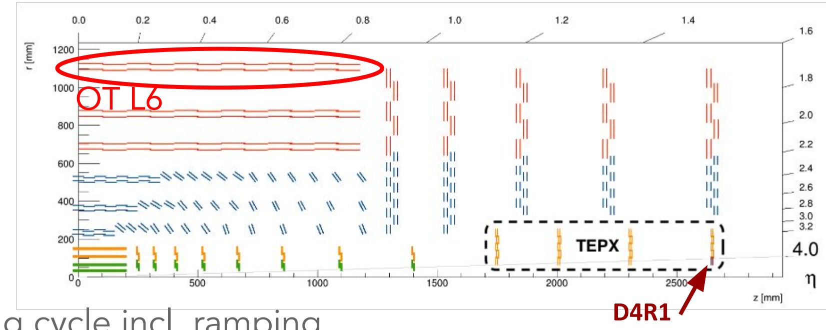
Updated from CERN-LHCC-2021-008

Tracker Luminosity



Tracker Endcap Pixel Detector

- Real-time Pixel Cluster Counting (PCC) on 2 m^2 of Si @ 75 kHz
- 2- & 3-fold coincidence counting for calibration & monitoring
- Data split in pixel back end, luminosity events sent to dedicated processor board for real time cluster reconstruction and counting

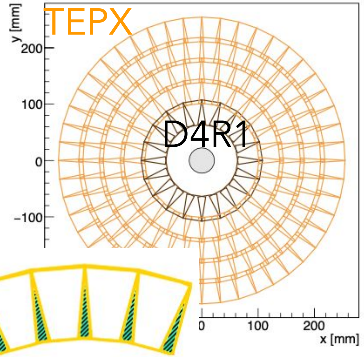


Disk 4 Ring 1

- Fully independent (including services), operated by BRIL
- Always on → provides beam-induced background and luminosity measurements during machine development, commissioning, filling cycle incl. ramping
- Full trigger bandwidth for BRIL: 825 kHz at PU200, 2-4 MHz at low PU

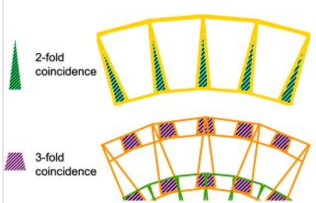
Outer Tracker Layer 6 - best statistical power

- Histogramming instances at OT back end count stubs from 12 modules each at 40 MHz during stable beams using dynamical error handling

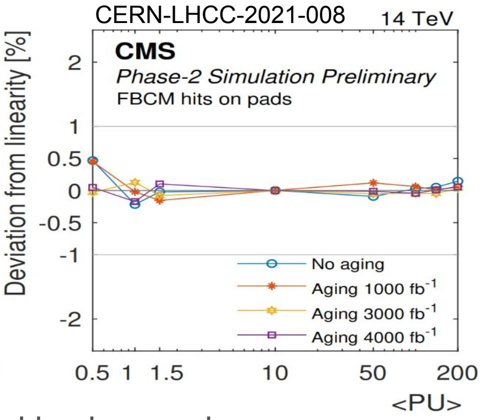


BRIL Trigger Board

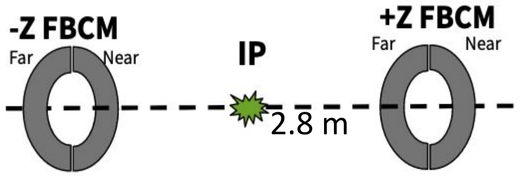
- Clocking infrastructure for FBCM / D4R1
- Unbiased luminosity triggers for TEPX / D4R1
- Forwards beam 1 and beam 2 signals from Beam Pickup Timing Experiment (BPTX) To Global Trigger (GT)

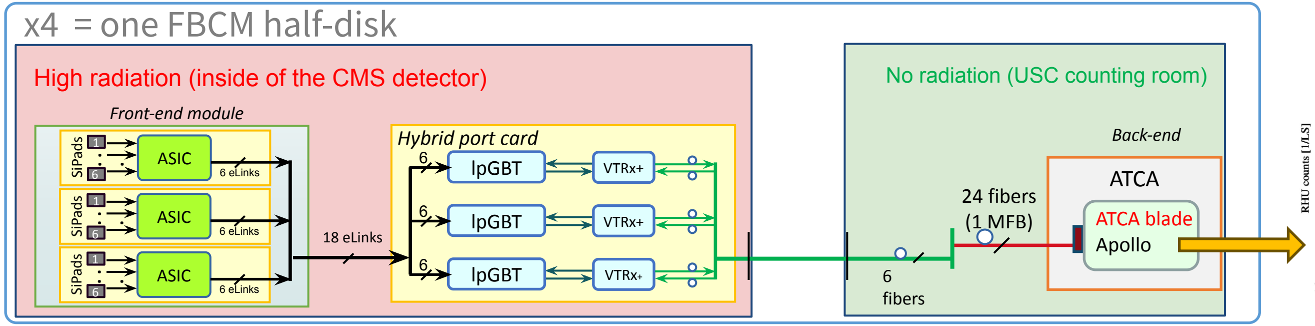


Fast Beam Conditions Monitor (FBCM)

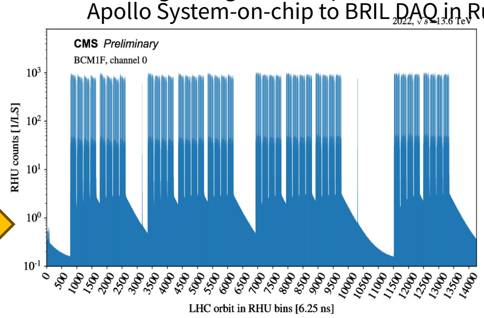


- Stand-alone luminometer under full control of BRIL
- Independent of CMS services (DAQ, TCDS, run control, magnet status)
- Available outside stable beams (additional safety, e.g. tracker high voltage interlock)
- Inspired by Run 2 BCM1F concept: based on Si-pad sensors with fast front-end ASIC
- Adapting Phase-2 Inner Tracker (IT) electronics components
- Triggerless readout with sub-BX timing to study time structure of beams and beam-induced background
- 288 Si-pad sensors of 2.89 mm^2 at r = 14.5 cm arranged on 4 half-disks, with modular design
- Two option for sensors: 290 um 2-pad (Run-3 BCM1F) or 150 um 6-pad (lower S/N, more rad hard, common GND ring to limit sensitive volume, produced on IT wafers)
- Location behind Disk 4 of the TEPX in the Tracker cold volume
- **Good statistical precision, excellent linearity, no significant degradation with aging**





Example (Run3 data) of the aggregated per bunch crossing histogram as expected to be read out from Apollo System-on-chip to BRIL DAQ in Run 4



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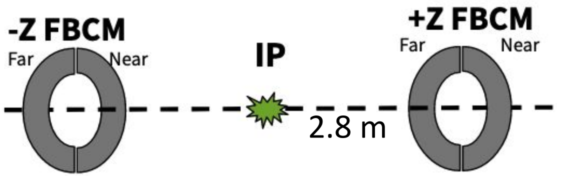
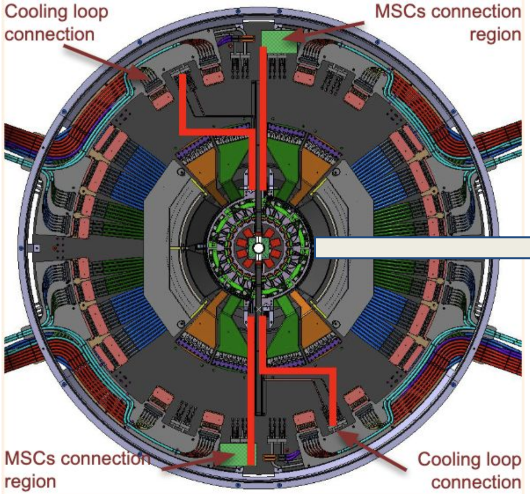
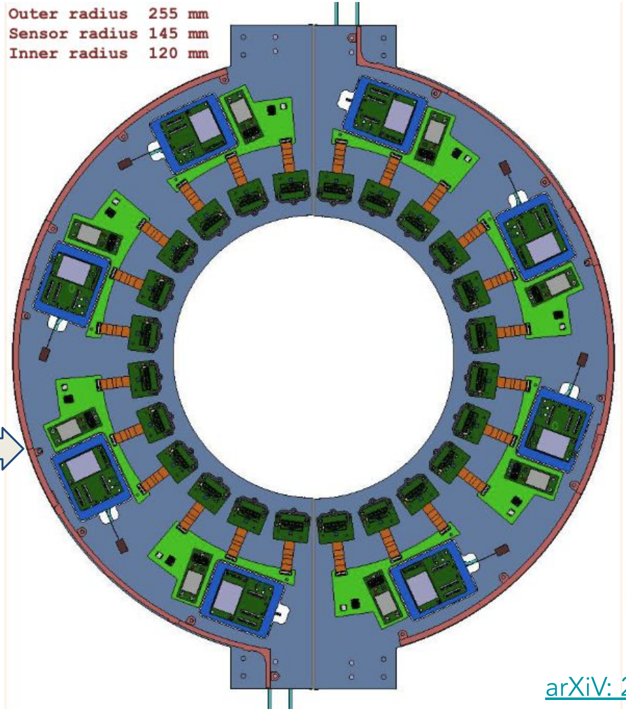
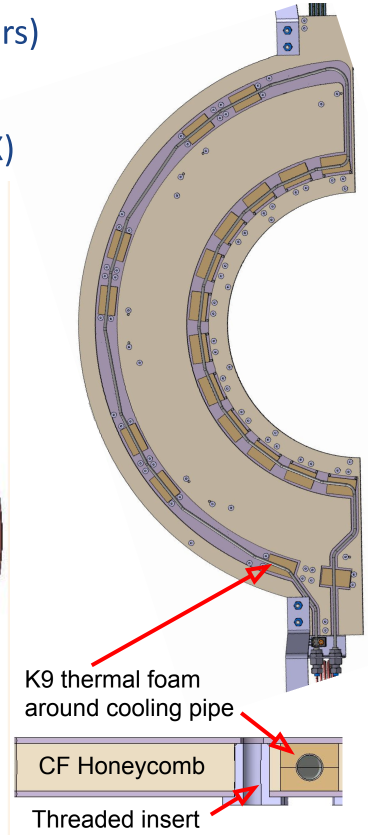
Fast Beam Condition Monitor design

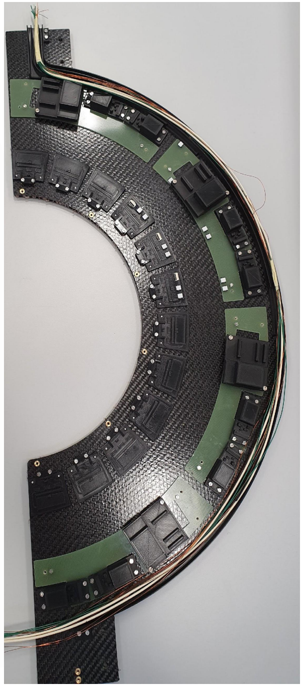


- 2x2 identical half disks at 2.8 m from IP with 12 modules each
- Mechanics follows CMS inner tracker design (materials, manufacturing, vendors) with minor modifications
- Independent, dedicated BRIL ring connected to the Tracker Endcap Pixel (TEPX) detector cooling manifold









Mechanical mockup

arXiV: 2402.03971

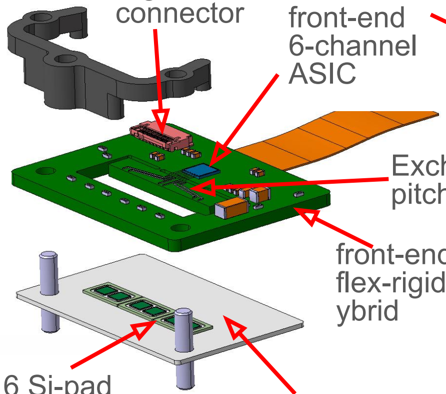
CF: carbon fiber

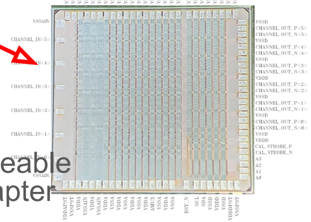
FBCM half-disk

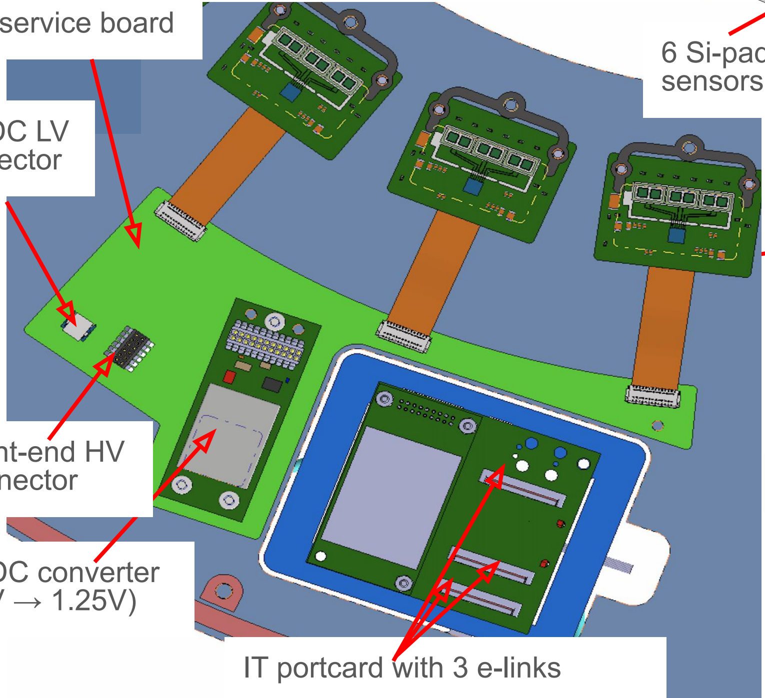
- 6-channel ASIC optimised for fast time response & low noise, qualified to place production order
- Service boards at higher radius provide power, control, and read out for 3 front-end modules each

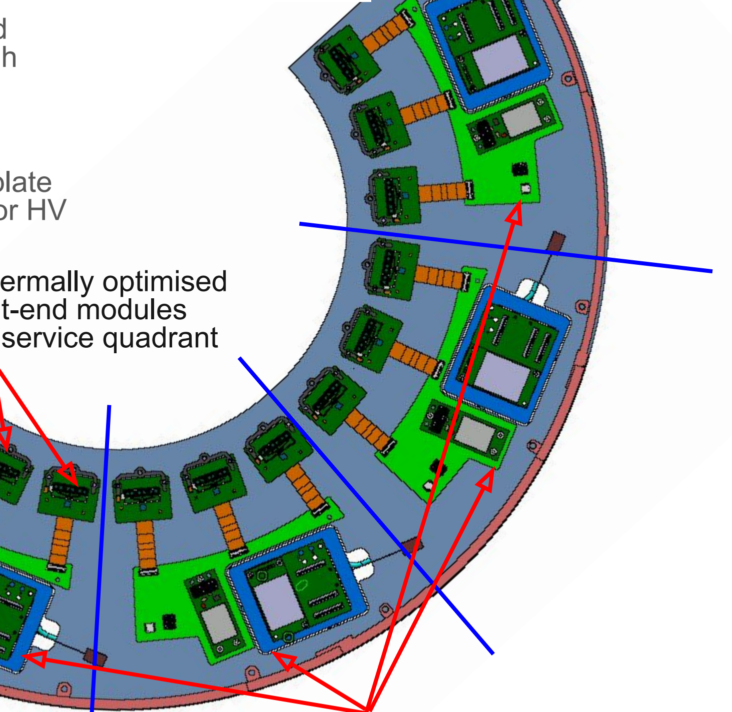
LV: low voltage, HV: high voltage, bPol12V: CERN-developed DC-DC converter, AlN: Aluminum-Nitrid

JINST 19 (2024) 02, C02026







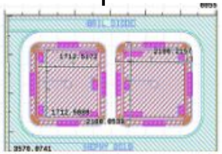


arXiV: 2402.03971

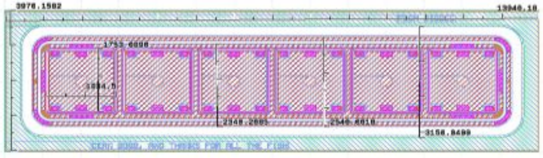
FBCM read out

1) Si-pad sensors, n-on-p

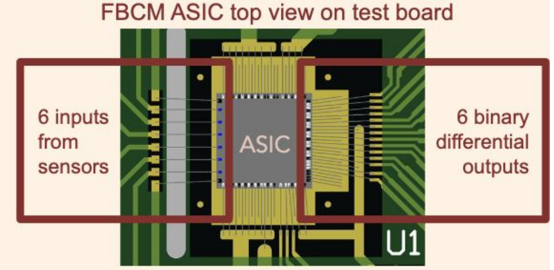
Send analog LV signal pulse via short, low-capacitance bonds

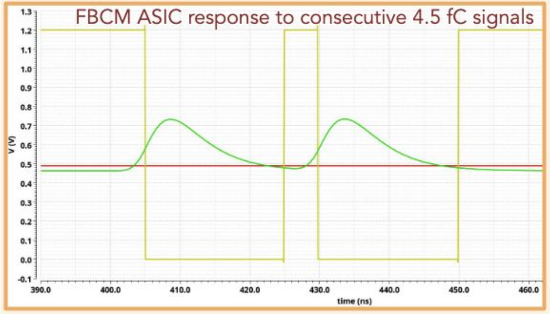


3* 2-pad, 290 um thick



6-pad, 150 um thick





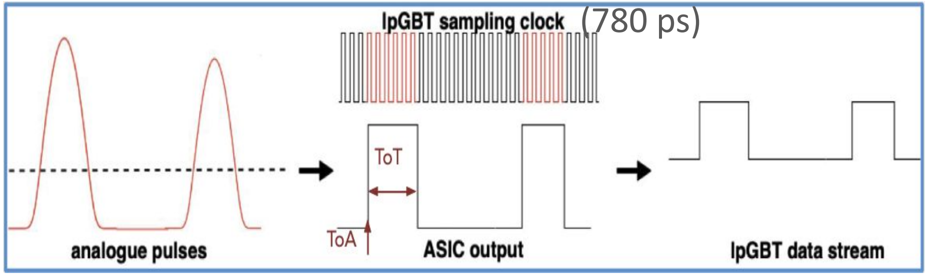
2) FBCM23 front-end ASIC

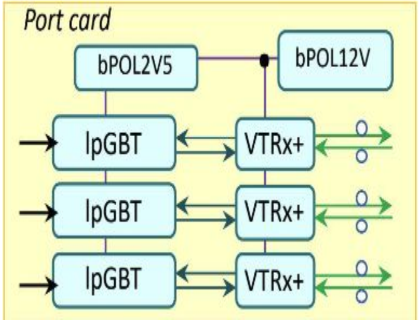
- 65 nm, radiation hard
- 3x3 mm^2, wire-bonded
- 6 channels, SLVS output
- Triggerless asynchronous read out
- Electronic noise < 800 e^- ENC
- Adjustable peaking time (4-8 ns)
- Timewalk below 5 ns
- Linearity up to 6 fC
- **Fast amplifier and comparator**
  - Fast return to baseline after hit with multiple MIPs (150 fC)
  - Double-hit resolution after discrimination 25 ns
- Expected dose 200 Mrad, fluence $2.5 \cdot 10^{15}$ n_{eq}/cm^2
- SEU-protected I^2C register block

First test beam measurement in April

3) IT portcard

lpGBT transceiver samples binary signal, packs into frames, and outputs via VTRx+ electro-optical interface





4) ATCA-standard back-end Apollo FPGA board

- Unpacks data
- Measures ToA and ToT
- Aggregates data to sub-bunch-crossing histograms

SLVS = Scalable Low-Voltage Signal
SEU = Single Event Upset (bitflip)
lpGBT = Low Power GigaBit Transceiver
VTRx+ = Versatile Link Plus Transceiver

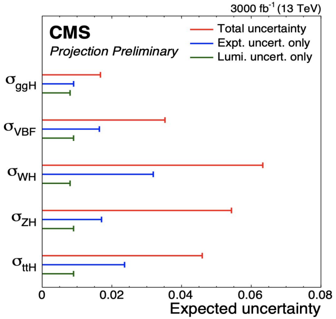
Capabilities of Phase-2 luminometers

	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	✗	✗	*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*

Chapter 5 of the BRIL Phase-2 TDR

Orthogonal instrumentation systematics!

Precision luminosity determination



… required by EW and top physics at (HL-)LHC

… challenging (and a lot of fun!)

… necessitates

- good understanding of beam physics 10.1140/epjc/s10052-023-12192-5
- excellent quality of beam instrumentation to determine bunch intensity & shape, orbit position, etc.
- luminometer data quality rigorously monitored (development of machine learning based tools, e.g. for CMS Pixel Luminosity Telescope (PLT) 10.1140/epjc/s10052-023-11713-6
- refined techniques to calculate corrections for the absolute calibration of the luminometer visible cross sections 10.1140/epjc/s10052-021-09538-2 CMS-PAS-LUM-22-001 10.1140/epjc/s10052-023-12268-2

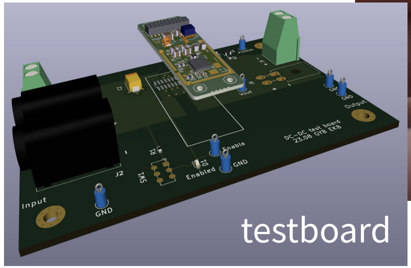
The requirements at HL-LHC even more severe CERN-BE-2022-001 CERN-LHCC-2021-008

→ development of dedicated luminometer, FBCM (incl. ELTE, Uni Debrecen) arXiV: 2402.03971

→ adaptation of various CMS sub-systems for lumonimetry

The goal of 1% luminosity precision at HL-LHC is challenging

but in our reach



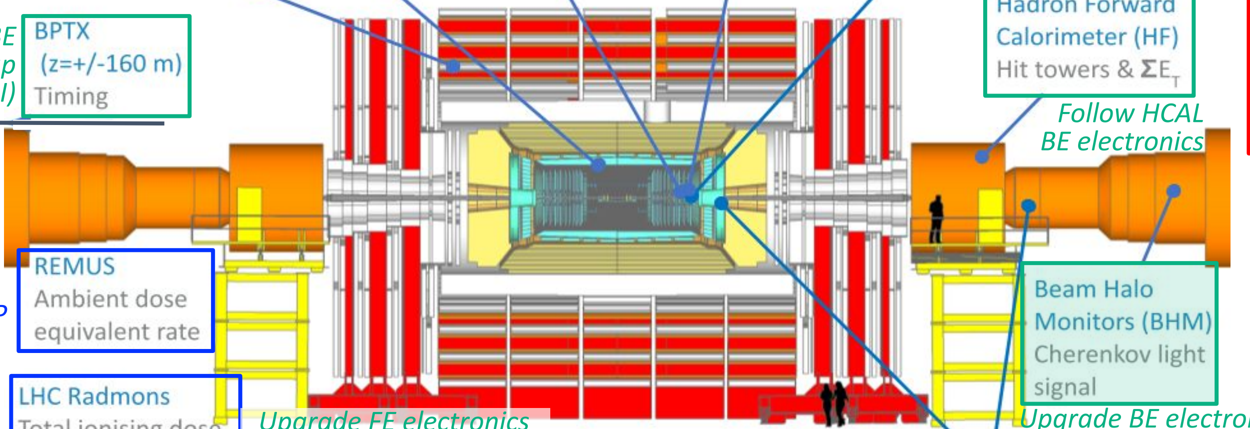
testboard


DC-DC bPOL12V front

Extra

Beam Radiation, Instrumentation and Luminosity project

15 technical systems for radiation monitoring, beam timing and abort, beam-induced background, and luminosity measurements



New
Outer Tracker Layer 6 (OT L6)
L1 track stubs

Tracker Endcap Pixel Detector (TEPX)
Clusters & coincidences
New

TEPX Disk 4 Ring 1 (D4R1)
Clusters & coincidences
New

New
Fast Beam Condition Monitor (FBCM)
Hits on Si pads

Follow Muon BE electronics to full BbB
Muon Barrel (MB)
L1 trigger primitives

Upgrade BE New pickup (SY/BI)
BPTX
(z=+/-160 m)
Timing

Hadron Forward Calorimeter (HF)
Hit towers & ΣE_T
Follow HCAL BE electronics

Follow HSE/RP
REMUS
Ambient dose equivalent rate

Beam Halo Monitors (BHM)
Cherenkov light signal
Upgrade BE electronics (following HCAL)

More monitors Follow EN/STI
LHC Radmons
Total ionising dose
SEU rates
HE hadron fluence
Thermal n fluence
1 MeV n eq fluence

Upgrade FE electronics
Gas-Filled Proportional Counters (GFPC v1 / LHC Radmon)
Neutron fluence

New
TetraBall
Unfolded neutron spectrum

40 MHz scouting
L1 muons, tracks, calorimeter objects
Upgrade to full system

Beams Conditions Monitor for Losses (BCML1 and BCML2)
Ionisation current in pCVD diamond and sapphire sensors
Upgrade BE electronics (SY/BI)
Regular sensor replacements

New
Bonner Sphere Spectrometer (BSS)
Unfolded neutron spectrum

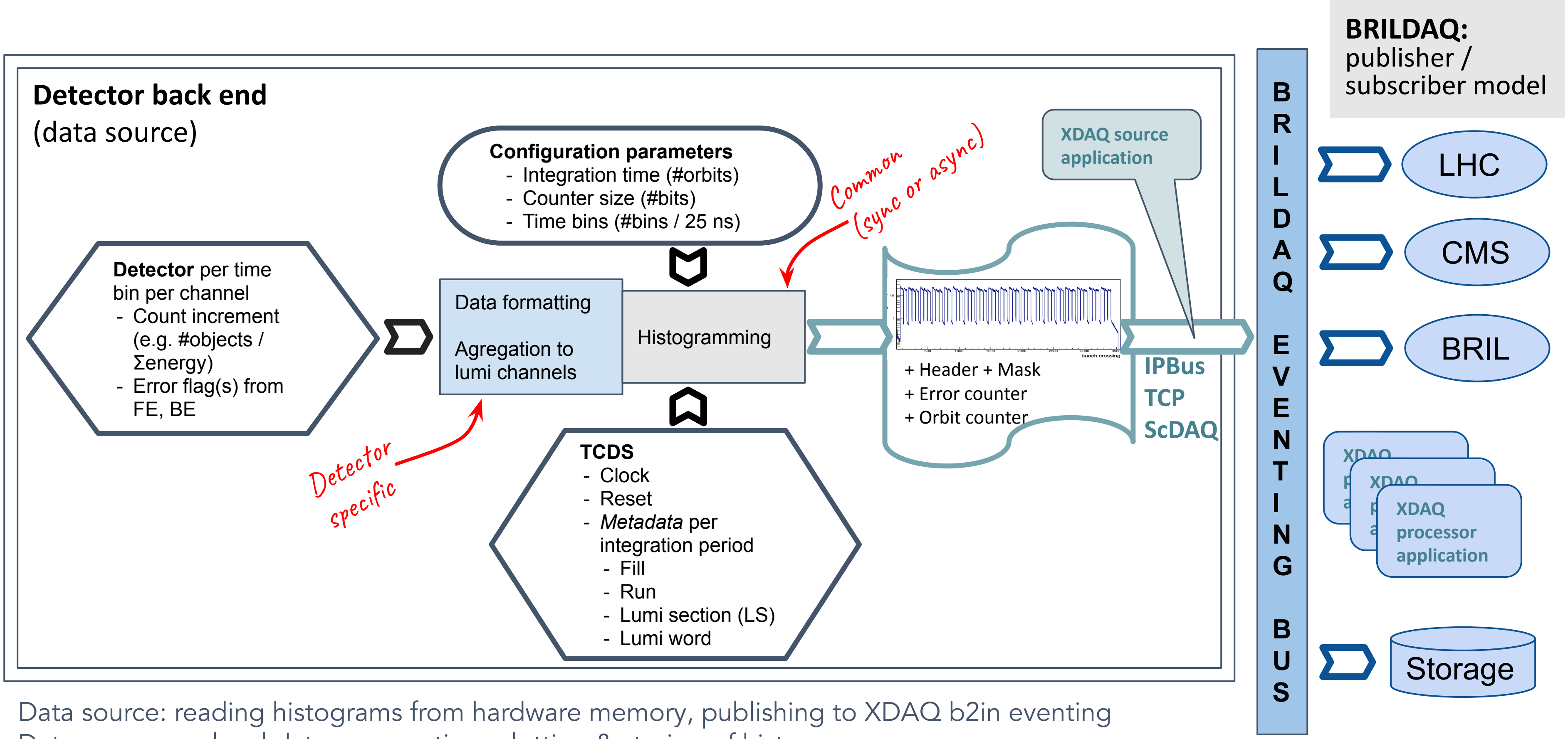
New
BRIL Trigger Board (BTB)
- Generates independent luminosity triggers
- Encodes beam 1 & 2 discriminated signals from BPTX for Global Trigger
- Generates TCDS2-like control stream based on LHC clock for D4R1 and FBCM

BRIL Data Acquisition (BRILDAQ)
- Independent run control
- Read out and process luminosity histograms, calibration and monitoring data
- Share data real-time
- Database of BRIL information for physics

Architecture design with CMS DAQ
Follow evolution of XDAQ platform

Link to TDR

Histogramming and BRIL DAQ



Data source: reading histograms from hardware memory, publishing to XDAQ b2in eventing
Data processor: local data aggregation, plotting & storing of histograms

Luminometry from Run 2 to Phase 2

Natural progression from Run 2

- ➢ Successful construction of two detectors during LS2
- ➢ Participation in Run 3 demonstrator systems with Phase-2 histogramming firmware
- ➢ Semi-online PCC in Run 3

Luminometry (counting method)	Run 2	Run 3	Phase-2	New Phase-2 features
Hits on semi-conductor sensors (pulse height, timing)	BCM1F (pCVD+Si, via VME BE)	BCM1F (Phase-2 Si, via μTCA BE): real-time pulse height	**FBCM** (Phase-2 Si and BE)	More channels
Hit calorimeter towers	HFOC (via dedicated BE FW)		Potentially ATCA BE	Potentially amplitude
Calorimeter E_T sum	HFET (via dedicated BE FW)		Potentially ATCA BE	—
Track stubs	PLT (3x coincidences on telescope)	Rebuilt PLT	**OT L6** (2x coincidences on TB2S)	More channels
Pixel clusters	Phase-1 pixel tracker (offline)	Phase-1 pixel tracker (at HLT, in BRILDAQ)	**TEPX D4R1**	More channels, 2x & 3x coincidences at overlaps
Muon barrel L1 trigger primitives	DT orbit-integrated per 23 s	Demonstrator BbB with histogramming FW	MB Phase-2 BE	BbB per 1 s
Trigger objects via 40 MHz scouting	μ candidates (demonstrator)	μ candidates (Phase-1 system with histo FW)	Full Phase-2 system	Access also to calorimeter & track objects
Ambient dose equivalent rate (orbit-int per 1 s)	REMUS (via LHC Timber)	REMUS (in BRILDAQ)		—

Central paradigm: maximum commonality

Since conception of BRIL, **strengthen the use of common components in data acquisition and analysis of BRIL instrumentation**

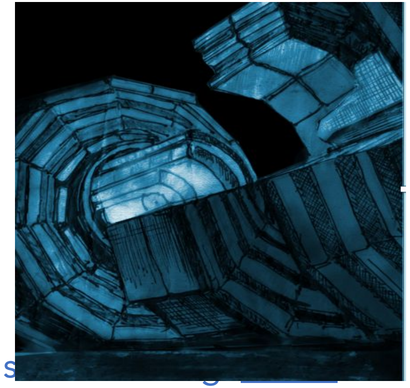
Common

- triggering (BRIL Trigger Board: generate unbiased triggers for TEPX & D4R1, BPTX signal to CMS Global Trigger)
- readout back-end electronics (e.g., use Apollo and Serenity boards for BRIL luminosity systems)
- histogramming module for all luminometers
- data acquisition = BRILDAQ
  - Read out and process luminosity histograms, monitoring and calibration data
    - Luminosity data processed in ATCA back end with system-on-chip processors
    - Read out via control network through gigabit Ethernet
      - subsystems need to give sufficient bandwidth for (small) BRIL data volume
      - work with DAQ group to define architecture
    - Injected to BRILDAQ infrastructure
  - Independent run control system
  - Database providing all necessary information for physics analyses

⤇ More on common histogramming FW & BRILDAQ: J. Benitez

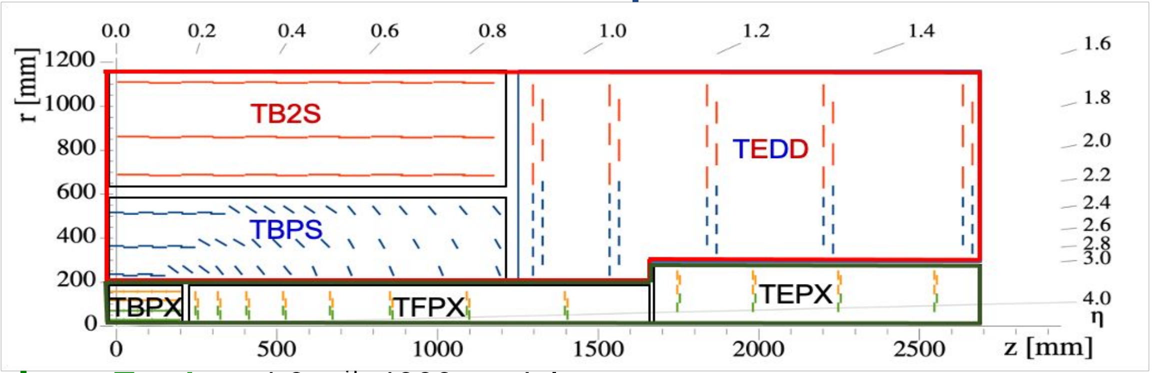
Summary of CMS Phase-2 strategy

- BRIL deliverables include
  - radiation and neutron monitoring (LHC Radmons, REMUS PMIs, GFPCs, Bonner-sphere neutron spectrometers),
  - beam instrumentation: abort (BCML) and timing (BPTX),
  - beam-induced background (BHM, EMTF, TEPX D4R1, FBCM) and luminosity measurements
- Aim to reach (2%) 1% precision on (real-time) ultimate luminosity measurement
  - Optimal exploitation of data from existing subsystems
    - TEPX and BRIL-operated D4R1 with pixel cluster and coincidence counting
    - Strip Tracker OT L6 twofold coincidence counting
    - Hadron Forward (HF) calorimeter with 2 algorithms
    - Muon Barrel (DT+RPC) backend and 40 MHz trigger scouting systems providing muon information
      - 40 MHz scouting extendable to track and calorimeter objects
  - Construction of a fully independent, always-on luminosity detector with asynchronous, s
  - This strategy enables CMS to have 3 (almost) ideal luminometers, and in total 5 independently calibrated bunch-by-bunch measurements, plus additional handles on stability and linearity using different detector technologies and counting methods with orthogonal systematics
- Rich network of collaborations with CMS subsystems, CMS technical coordination, CERN departments, and LHC-wide working groups, the paradigm of maximum commonality of HW/FW/SW components, reliance on proven technologies, and a natural evolution from Run 2 to Phase 2 will help to make these plans a reality

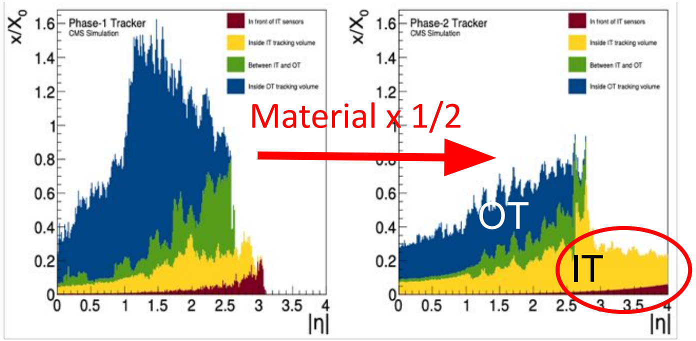


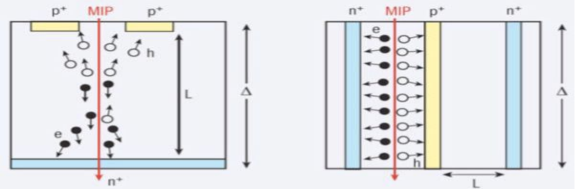
https://cds.cern.ch/record/2272264

Silicon Pixel & Strip Tracker: 25xLHC readout channels



10x more radiation hard
Higher coverage of pixel detector to |η|<4



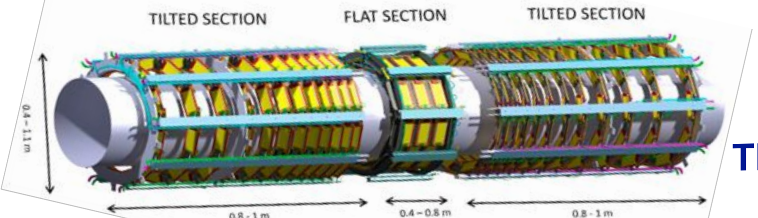


Inner Tracker: 4.9 m^2, 4000 modules

- 2G hybrid micropixels of 25 µm x 100 µm
- n-in-p type Si sensors of 150 µm thickness (3D @ TBPX1)
- C-ROC in CMOS 65 nm (CERN RD53): v1 under thorough tests
- Focus on module prototype tests, QC procedures

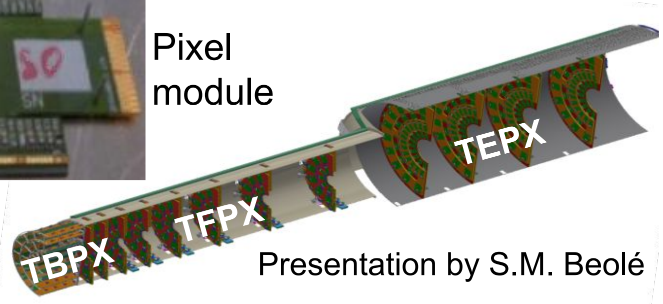
Outer Tracker: 190 + 25 m^2, 13200 modules,

- 43M microstrips + 170M macropixels
- **Input to L1 trigger at 40 MHz**



TBPS Layer 1

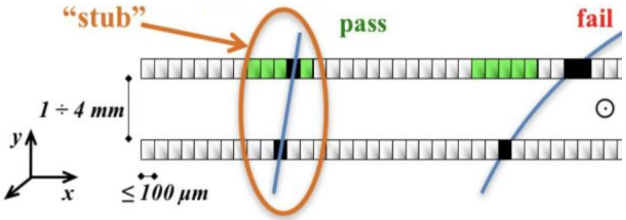
Pixel module



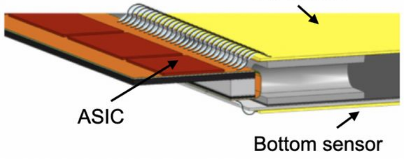
Presentation by S.M. Beolé

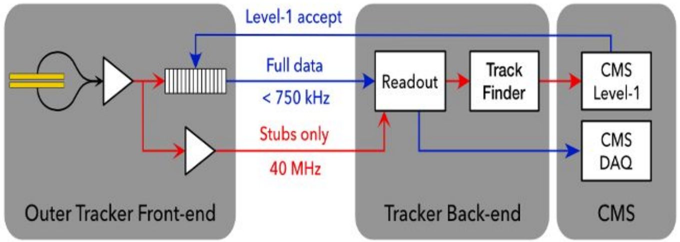
Outer Tracker

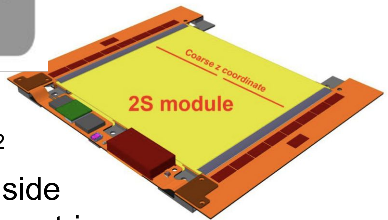
- pT discrimination via hit correlation (“stubs”) in sensors of double-sided modules
- Flex hybrid to get data from both sensors to a single ASIC
- Different sensor spacing for different detector regions + tunable correlation windows
- Associate track to stubs from OT layers and extract track pT for triggering at L1
- Exploring possibility to reconstruct displaced tracks
- **OT in production mode**: 30% of sensors produced, ASICs in production or ready for it, hybrid design completed
- Preparing extensive integration tests and test beams



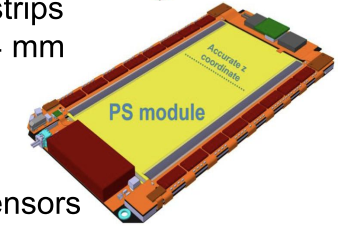
p_T modules







10 x 10 cm^2
2 sensors / side
5 cm x 90 μm strips
spacing: 1.8 / 4 mm



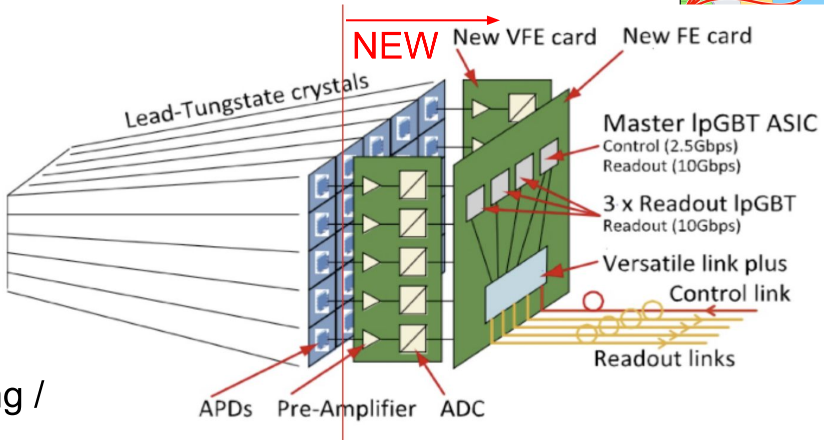
5 x 10 cm^2
2 strip + 1 pixel sensors
960 x 2.5 cm x 100 μm strips
960 x 32 x 1.5 mm x 100 μm pixels
spacing: 1.6 / 2.6 / 4 mm

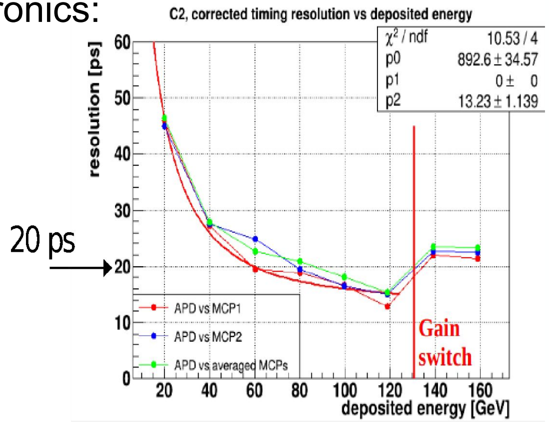

Four modules mounted successfully on a ladder, no significant change in leakage current levels and noise

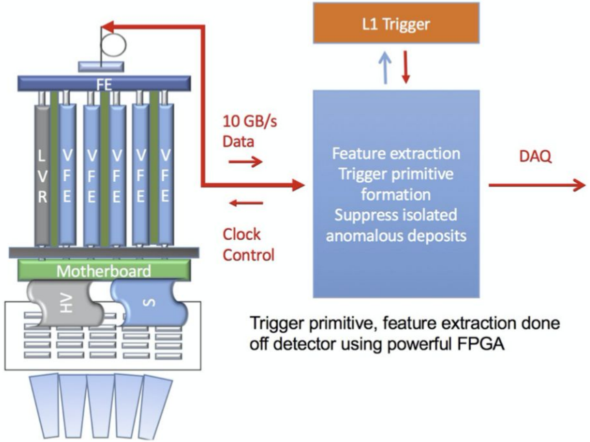
Barrel calorimeter

https://cds.cern.ch/record/2283187

- $PbWO_4$ crystals and Avalanche Photodiodes (APDs) kept
- **FE electronics to be replaced**
  - 30 ps time resolution for 30 GeV e/γ
  - Single crystal readout (instead of 5x5) at 40 MHz (no latency)
  - New Very Front End (VFE) removes spikes (anomalous signals due to particles hitting the APD directly)
- 9° C operating temperature (from 18 C) to mitigate APD aging / radiation damage
- 2021 Oct testbeam with prototype electronics: good linearity, E and time resolutions
- VFE ASICs (CATIA v2 & LiTE-DTU v2) pre-production: good performance, last design modifications done
- HCAL new BE, common with ECAL



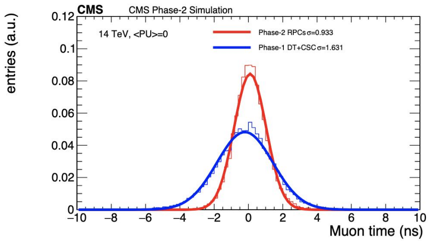


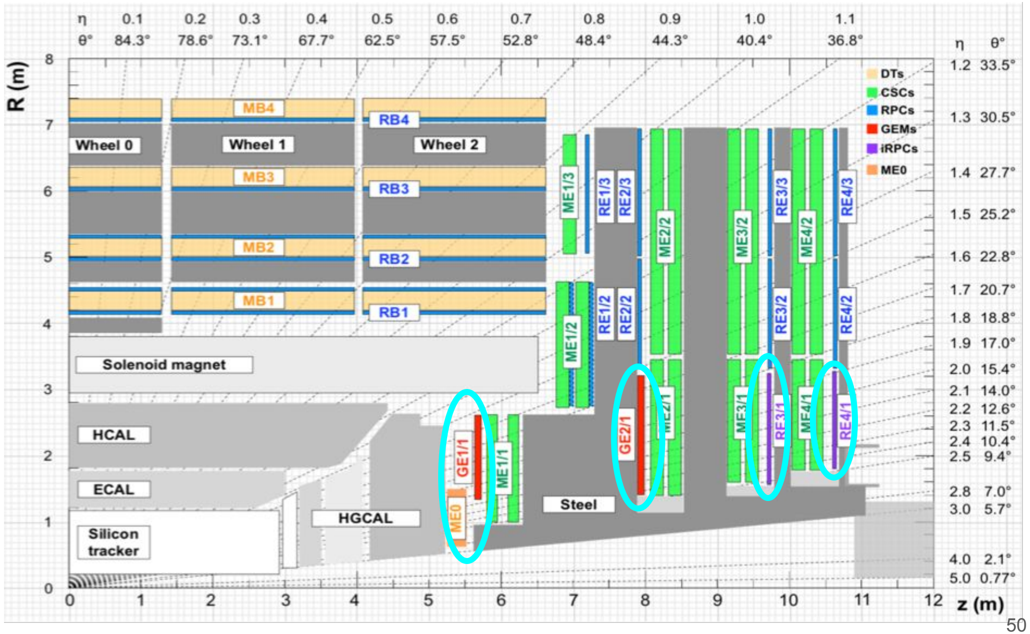


https://cds.cern.ch/record/2283189

Muon detectors

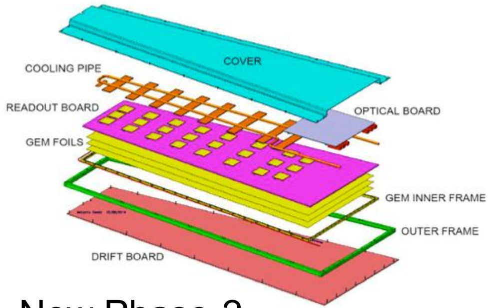
- Existing **DT**, **CSC**, **RPC** detectors with upgraded electronics
  - cope with ~10x higher rates and improve performance
  - improve RPC trigger hit time resolution from 25 ns to 1.5 ns
- New detectors in challenging (high rate, high background) forward region
  - increase redundancy and extend coverage to |η| = 2.4 - 2.8
  - enhance tracking performance
  - allow bending angle measurement at trigger level
- Gas Electron Multiplier chambers
  - **GE1/1** (LS2), **GE2/1** (2024/25 & 2023/24 (E)YETS): 50+100 m^2 of 2-layer triple-GEM
  - **ME0** (LS3): 60 m^2 of 6-layer triple-GEM
- Improved RPC
  - **RE3/1, RE4/1** (2024/25 EYETS)



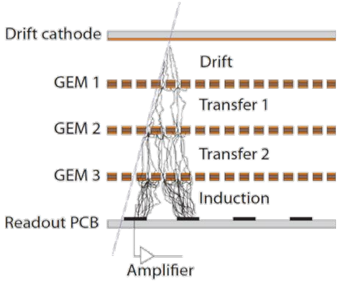


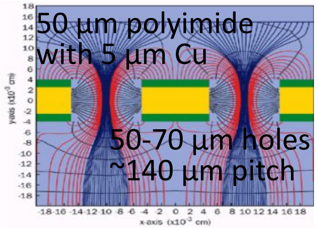
Posters by S. Mohamed, M.R. Kim

Muon detectors: first stage completed in LS2

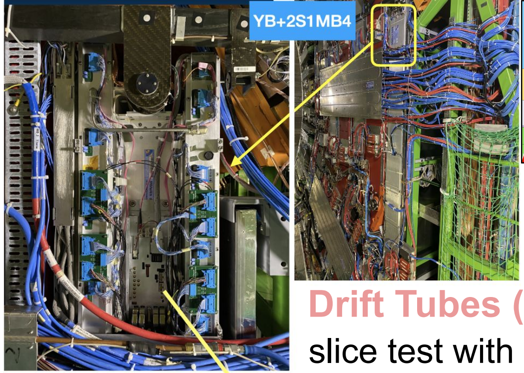


New Phase-2 technology

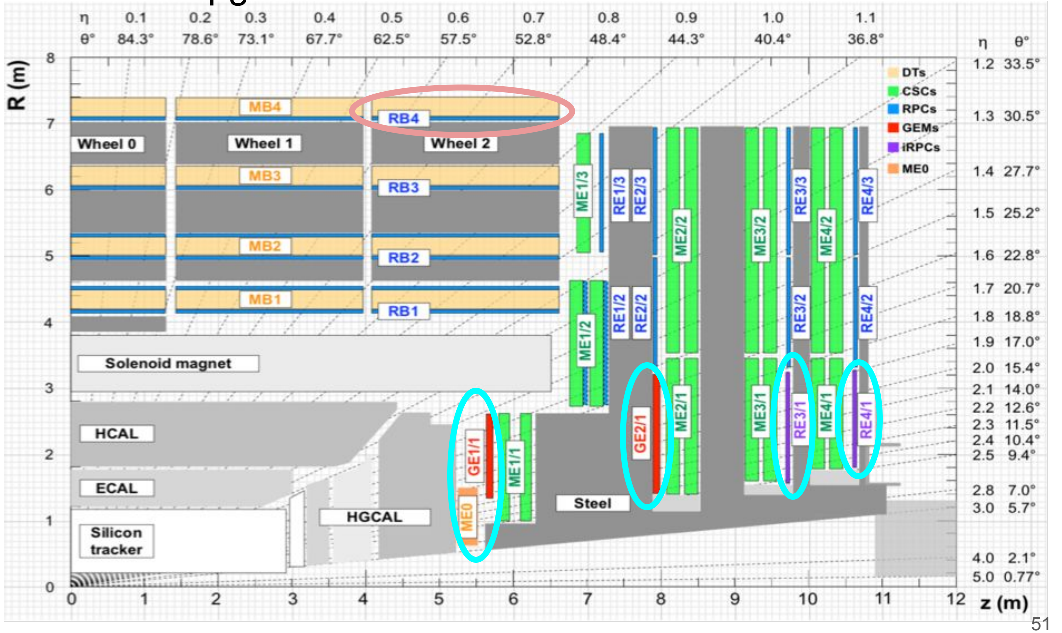




- **GE1/1** installed (2x36 SCs of 2 triple-GEMs), good performance in 2021 Oct beam test
- One slice of endcap equipped with new **GE2/1, RE3/1, RE4/1** chambers
- CSC on-detector electronics upgraded



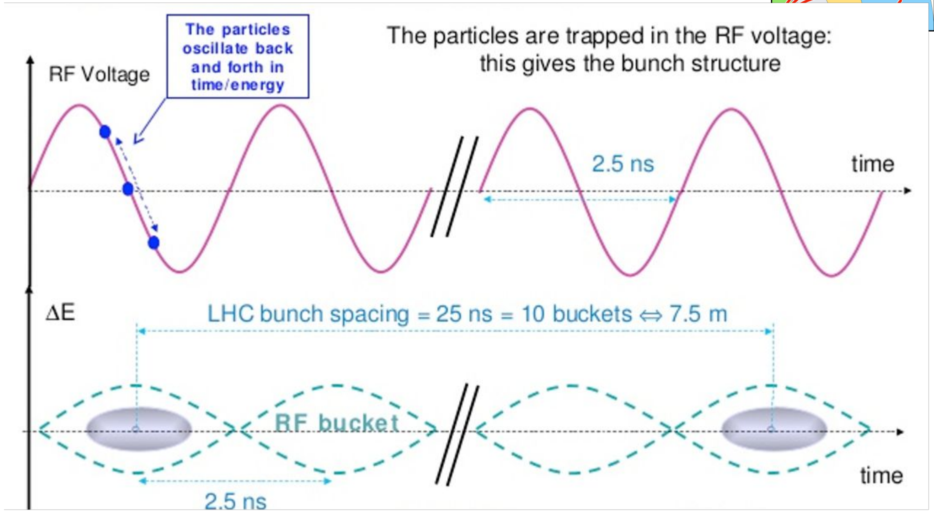
Drift Tubes (DT) slice test with Phase-2 on-board electronics

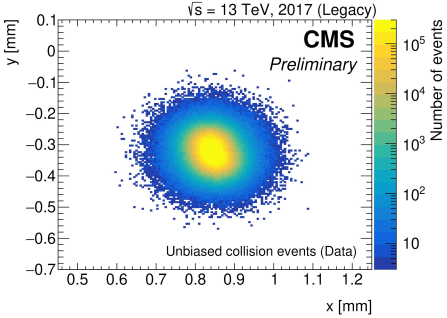


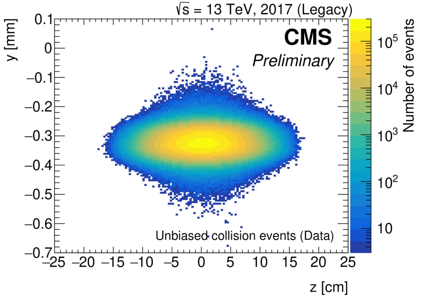
LHC details

LHC operations

- Bunched beams accelerated by RF cavities
- f_{RF} synchronised to movement of bunches (LHC: f_{RF} = 400.8 MHz @ full energy)
  - Longitudinal focusing
  - LHC: 3-4.5 cm bunch length
- Dipole magnets keep particles on ~circular orbit with alternating arcs and straight sections
- Quadrupole magnets focus the bunches to tiny cross-sections
  - LHC: 10-16 μm in transverse bunch size
- LHC parameters
  - 3564 bunch locations spaced by 7.5 m (every 10th RF bucket)
  - Collisions at every $10/f_{RF}$ ~ 25 ns
  - 1 orbit takes $1/f_{rev}$ = 1/11245 Hz ≈ 90 μs

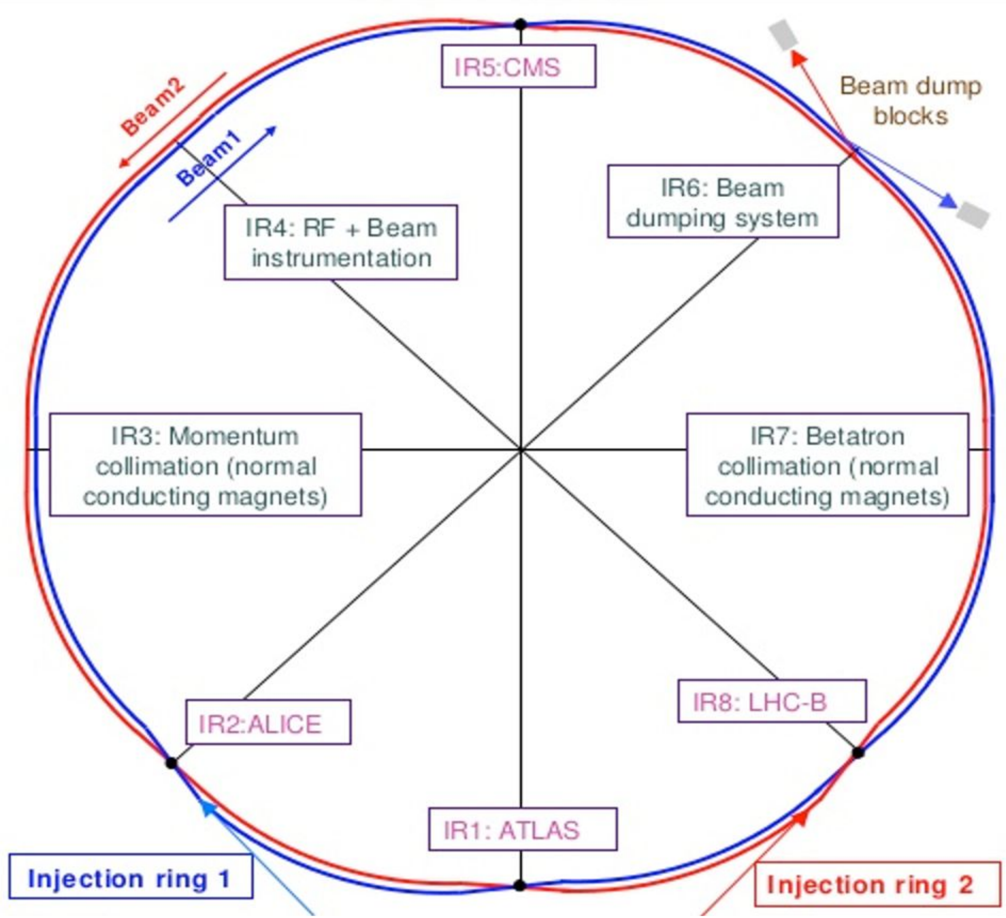






LHC ring & beam instrumentation

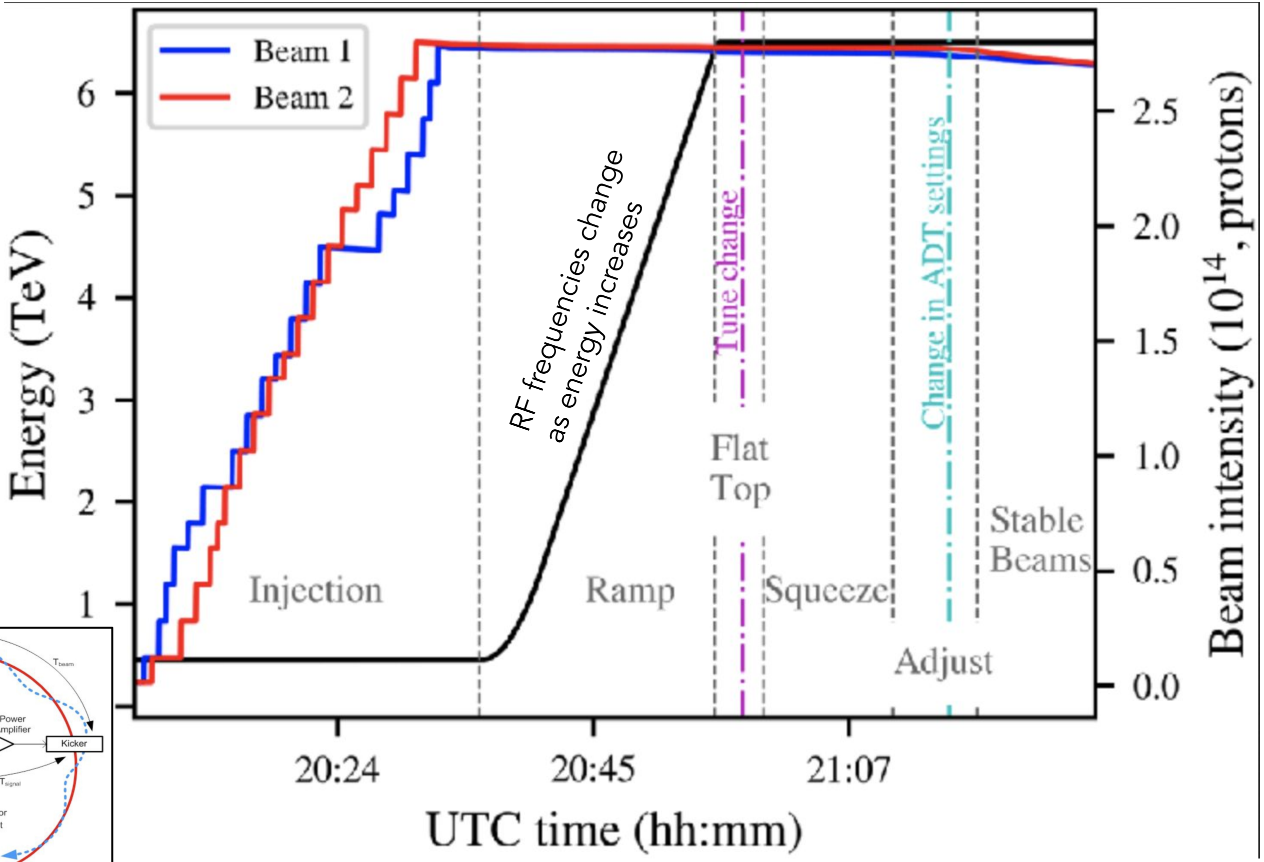
- Insertion Regions (IR) at straight sections (~528 m)
- Injection from the SPS at 450 GeV beam energy close to IR2 (ALICE) and IR8 (LHCb)
- Acceleration by RF cavities around IR4 to reach collision energy (13.6 TeV in Run 3)
- Beam collimation at IR3 and IR7
- Collisions at 4 Interaction Points (IP1: ATLAS, IP2: ALICE, IP5: CMS, IP8: LHCb)
- Beam dump system at IR6
- Arcs equipped by superconducting magnets to bend, focus, and correct the orbits of the beams

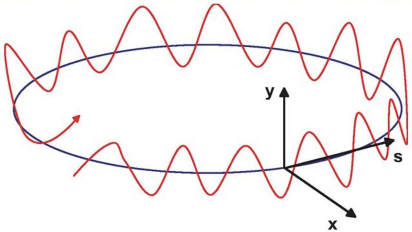


The LHC filling cycle

Complex sequence of actions to fill the LHC and prepare for stable collisions takes >1 hour

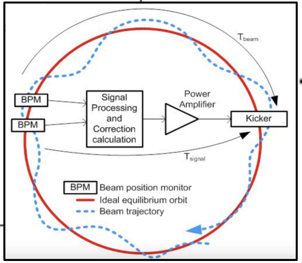
RF frequencies of two beams locked





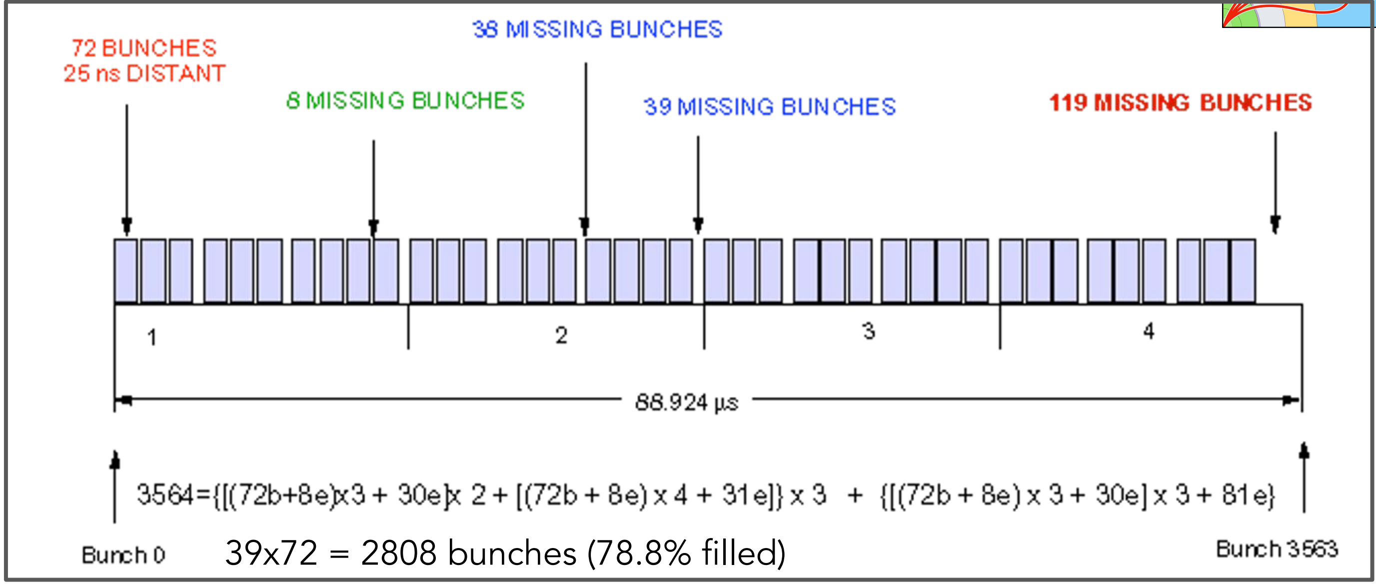
Number of transverse oscillations of a particle in one revolution around the ring is called the betatron tune (Q_x=62.31, Q_y=60.32 during pp collisions at top energy), with (Q_x, Q_y) = (62.28,60.31) at injection (450 GeV) energy at HL-LHC.

Transverse oscillations can be controlled by a damping system. ADT = LHC transverse damper

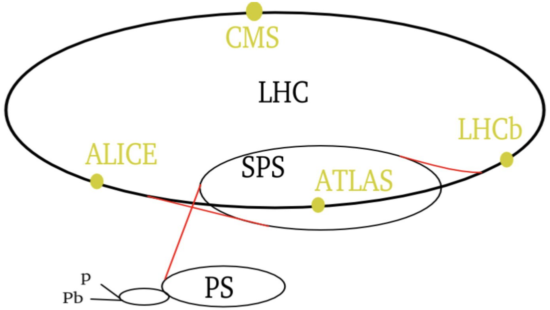


Filling scheme with bunch trains (an example)

- 72 bunches from PS to SPS in one go → bunch trains
- Variable spacing to accommodate rise times of injection and extraction magnets ("kickers") in PS, SPS and LHC

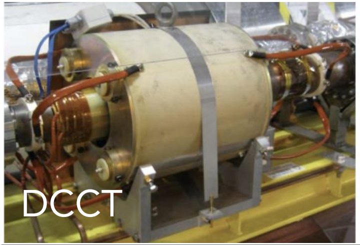


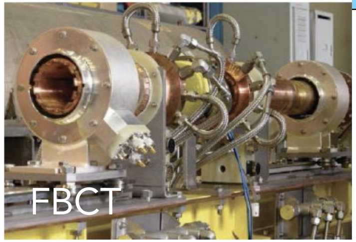
- Empty bunches also useful to determine beam backgrounds, pile-up and detector noise
- Unique numbering scheme: Bunch Crossing IDentifier (BCID)
- LHC can run with a large variety of filling schemes

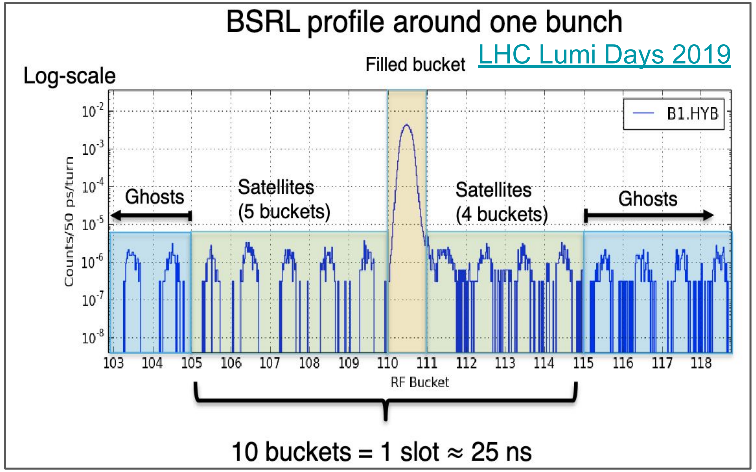


Bunch intensity measurements (N_1,N_2)

- DC Current Transformers (DCCT) / Beam Current Transformer - DC (BCTDC): Total charge per beam including bunched and unbunched charges
- Fast Beam Current Transformers (FBCT), a wall current transformer: Relative bunch intensities including charges outside the filled bucket (satellites), but not to the unfilled bunches (ghosts) due to bunch charge limit
- Beam Quality Monitors (BQM), a wall current monitor designed to measure longitudinal bunch parameters such as bunch length and phase: sum of 20 samples of (uncalibrated) intensity per filled bucket (i.e. not affected by satellites)
- Longitudinal Density Monitors (LDM) / Beam Synchrotron Radiation - Longitudinal (BSRL): Longitudinal beam profile to determine satellite and ghost charges with a time resolution of 90 ps (integrated over 5 minutes)
- IP8 beam - gas imaging (BGI): Ghost charges by comparing rates for empty - empty and empty - filled bunch crossings







$$n^j = \frac{n^j_{\mathrm{FBCT}}\left(1 - f^j_{\mathrm{sat}}\right)}{\sum_j n^j_{\mathrm{FBCT}}} N_{\mathrm{DCCT}}\left(1 - f_{\mathrm{ghost}}\right)$$