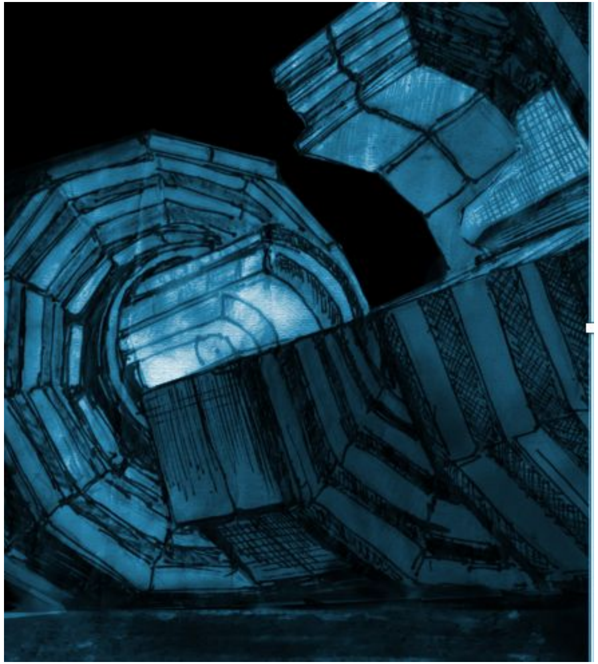


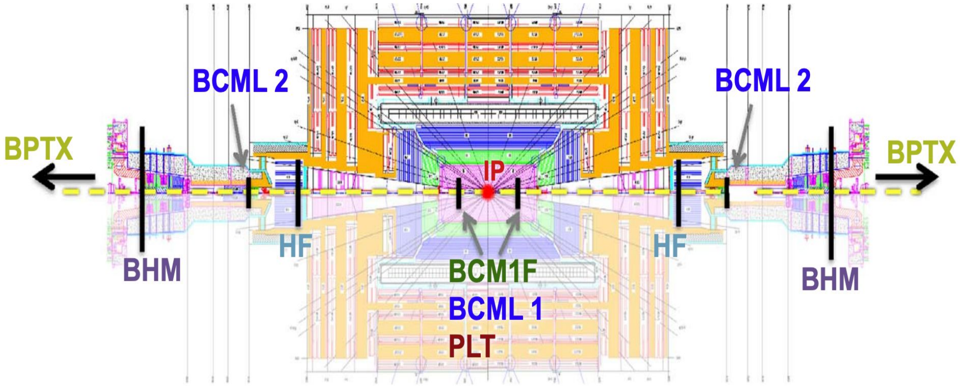
G. Auzinger on behalf of the CMS Collaboration

# High-precision luminosity instrumentation for the CMS detector at the HL-LHC

VCI 2022, Feb. 21st to 25th 2022

# Luminosity measurement in CMS

- Is the responsibility of the Beam Radiation Instrumentation & Luminosity (BRIL) Project
  - Formed in 2013 to collect smaller systems under one roof
  - Deliverables include:
    - Luminosity ← this presentation
    - Monitoring of beam-induced background (BIB)
    - Active protection from dangerous beam loss events (beam abort)
    - Relative beam timing and technical triggers
    - Monitoring of radiation environment in the CMS cavern & radiation simulation

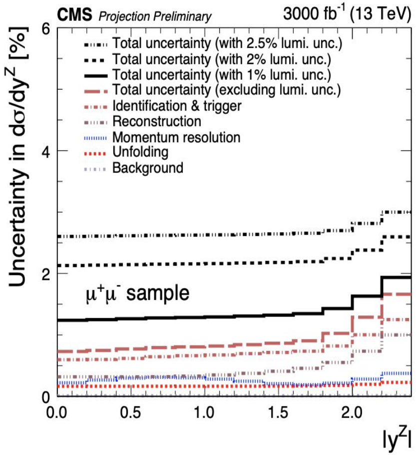

- Operating a series of beam- and luminosity instrumentation independently from central services since the beginning of CMS
- A relatively small project with very diverse responsibilities

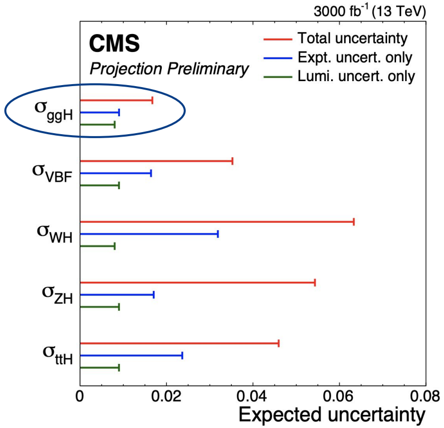
# High-Luminosity LHC & physics motivation for improved luminosity instrumentation

- High-Luminosity LHC will increase instantaneous luminosity w.r.t nominal by a factor of 7.5 ($5\times10^{34}$ $cm^{-2}s^{-1}$)
- Maximum Pile-up of 200
- Many changes to beam optics
  - CRAB cavities
  - Bigger collimator apertures
  - Different $\beta^*$
  - Luminosity levelling
- Will make precision luminosity extremely challenging
  - Thus requires a series of redundant, complimentary & independent luminometers

Luminosity uncertainty is dominant in key channels of physics interest

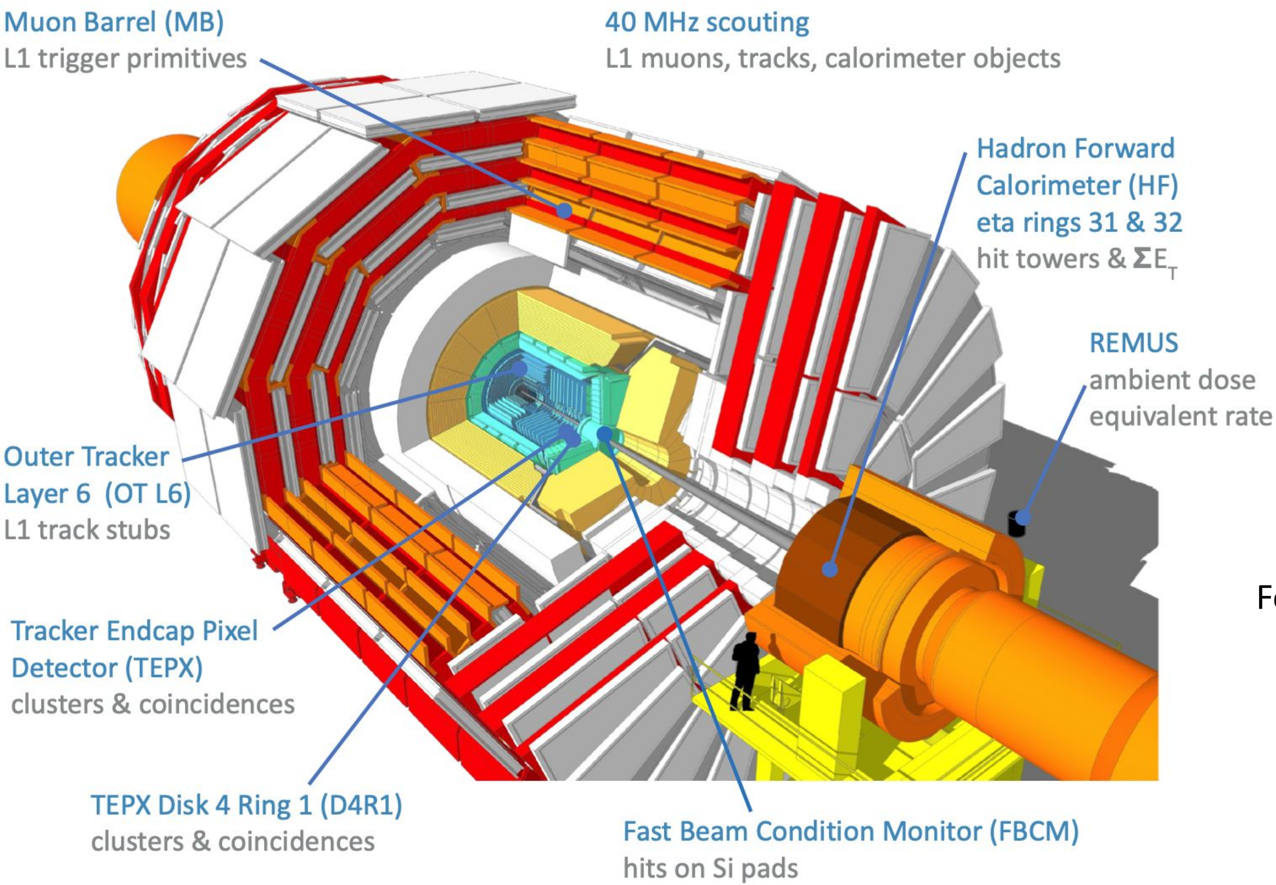
Examples from Drell-Yan, top and Higgs measurements




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

# BRIL - CMS SUBSYSTEMS
# for bunch by bunch PHASE II LUMINOSITY



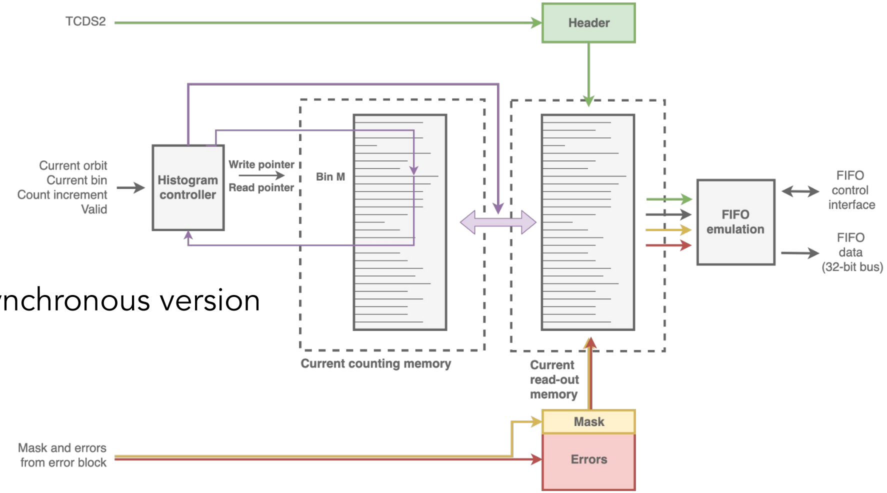

1. Phase II luminosity will become a consumer of CMS subsystem data, much like the trigger and DAQ
2. In addition, build a dedicated subdetector, FBCM, a simple, reliable and independent high precision luminometer
   - orthogonal systematics to other CMS subsystems
   - sub-BX time resolution
   - bunch-by-bunch luminosity
   - beam-induced background measurement
   - fully independent operation

For HL-LHC, aim for:

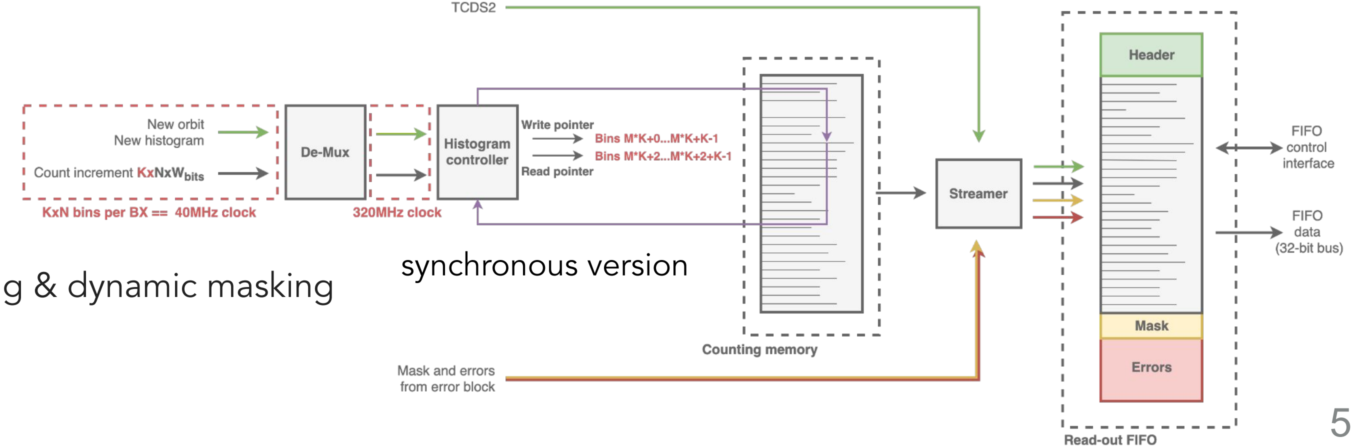
- Luminosity uncertainty
  - < 1% offline
  - < 2% online

# Generic BRIL histogramming FW

- For HL-LHC BRIL will become a consumer of subsystem data
  - To either be counted (histogrammed, BX-by-BX) directly in the respective back-end
  - Or requiring dedicated real-time processing (TEPX, D4R1)
  - Counts are to be integrated during so-called 'lumi-words' lasting 1 second
- Two kinds of data:
  - Synchronous (with 40 MHz bunch clock): OT stubs, muon stubs,...
  - Asynchronous (triggered read-out, random): TEPX clusters, scouting muons,...
- In order to facilitate integration, BRIL is developing a generic drop-in FW block to perform histogramming
  - Synchronous & asynchronous versions with standardised interfaces
  - To be used by all BRIL data sources in HL-LHC
  - Provides error handling & dynamic masking




asynchronous version

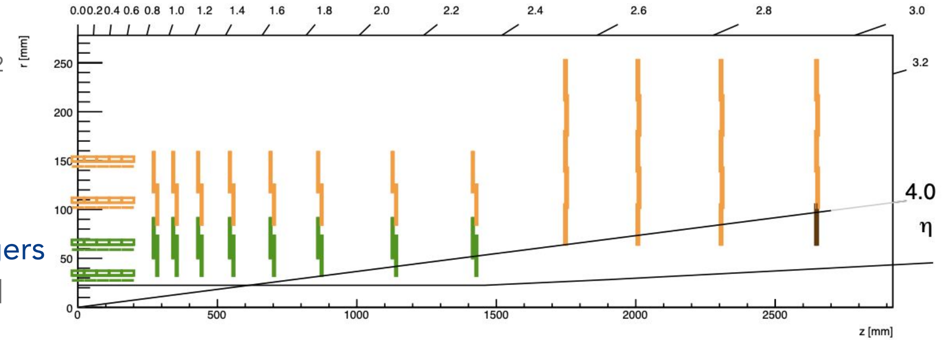



synchronous version

# TEPX

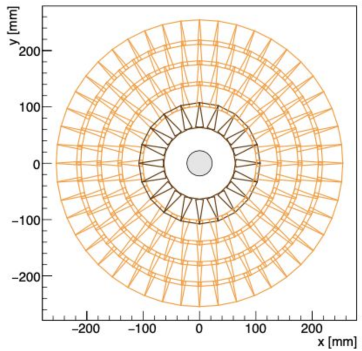
## Tracker End-Cap Pixel Detector (TEPX)

- 4 disks x 5 rings per side - sensitive area of more than 2 $m^2$
- Always on for qualified beams
- Operated by the Tracker Project
    - 750 kHz physics triggers
    - 75 kHz of additional & independent luminosity triggers
    - Lumi events sent to dedicated lumi processor board
- Stat. uncertainty for pixel cluster counting: ~ 0.095% / BX / s for physics at PU200
- 2- and 3-fold coincidence counting: additional tool for monitoring / calibration



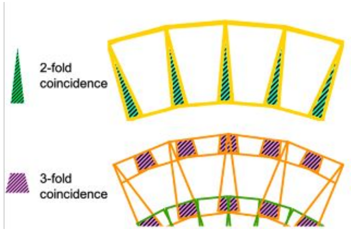

## TEPX Disk 4 Ring 1 (D4R1)

- Operated exclusively by BRIL, still benefiting from the tracker infrastructure
- Always on when safe - operated on LHC clock outside of stable beams
- Full trigger bandwidth dedicated to luminosity: up to 1 MHz at PU200 and 2 MHz (possibly 4 MHz) in low pile-up conditions
- Stat. uncertainty ~ 0.1% / BX / s for physics at PU200
- Ability to measure beam-induced background




## BRIL Responsibilities

- Development of a dedicated real-time pixel cluster counting firmware
- Development of dedicated clocking & triggering infrastructure
- Development of real-time processing, analysis algorithms for luminosity and BIB

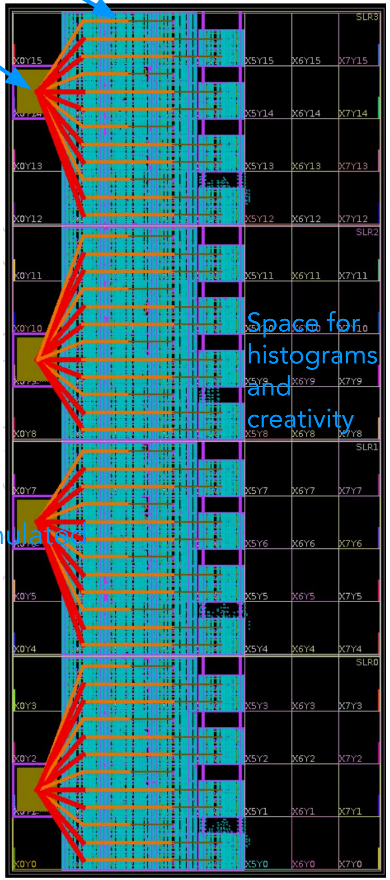


# Highlights of TEPX and D4R1 development

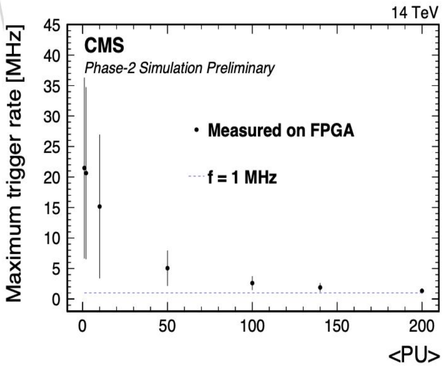
- Geometrical TEPX clustering algorithm per CMX Pixel Read-out Chip (CROC)
  - Successful implementation of 192 clustering instances on a VU13P FPGA (more than required by current TEPX baseline; no timing violations, 40% of FPGA logic, 15% of BRAM memory)
  - Excellent agreement with CMS offline clustering algorithm (<0.01% difference)
- Special clocking scheme enabled by an extra node in clock distribution tree for independent D4R1 operation to allow BIB measurement during LHC ramps
  - So-called 'BRIL Trigger Board' prototype firmware developed and principle validated
  - All basic components (RD53A, lpGBT, Xilinx FPGAs, Silicon Lab PLLs) tested to be able to follow the ramping LHC clock without loss of PLL or transceiver locks
  - Phase error <10 ps, negligible for D4R1 front end with a ToT sampling period of 25 ns

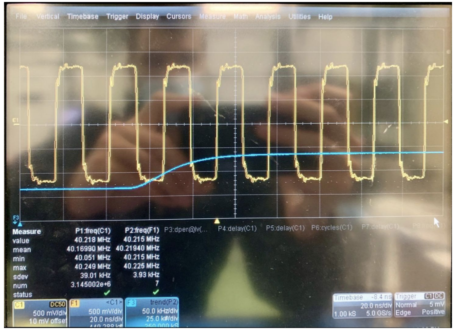
Clustering modules

25 Gbps links

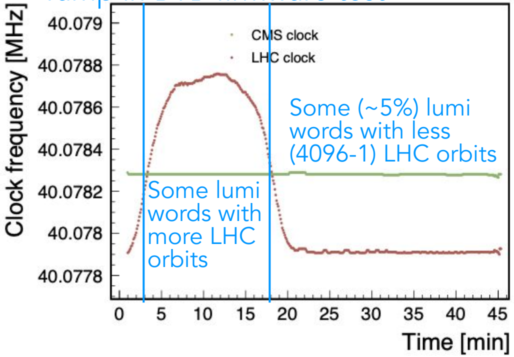



VU13P



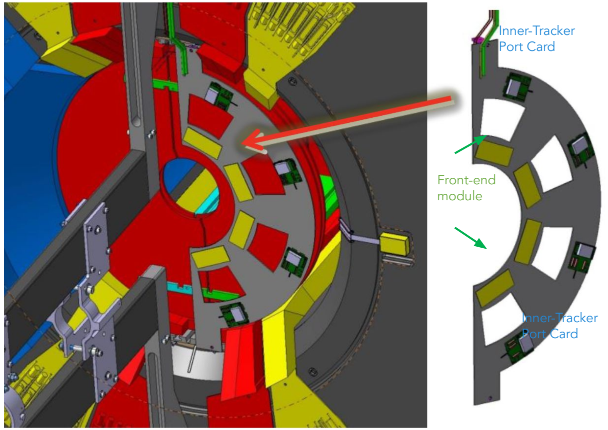
Measured clock frequencies during simulated ramp in BTB firmware test

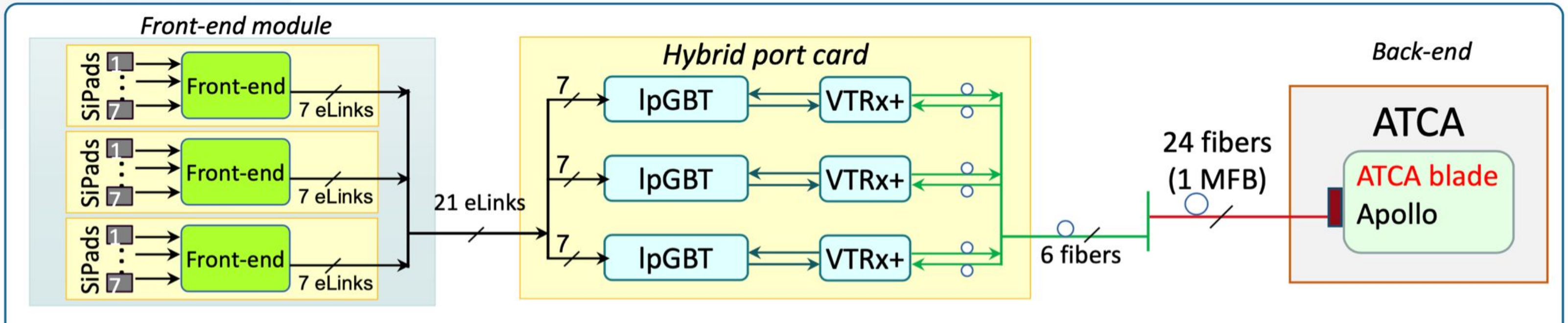


# Fast Beam Condition Monitor (FBCM) concept

- Silicon pad sensors behind TEPX & close to the beam-pipe
- Front end compatible with Tracker opto-electronics (lpGBT & VTRX+) and all services (cooling, powering, readout)
- Triggerless, asynchronous ASIC with few hundred ps time resolution
  - double hit resolution compatible with efficient BX-by-BX measurement
  - Semi-digital output starting at time-of-arrival and lasting time-over-threshold
- ASIC design
  - To be developed by CERN EP/ESE in 2022 - specifications finalized
  - Modular front-end architecture: front-end modules & remote service-electronics (opto + power) for improved longevity
  - Readout using spare Inner Tracker services (supporting a total of 12 ASICS)
  - 7 channels/ASIC ⇒ 84 sensors per quarter for a total of 336 individual channels

A quarter of a FBCM as an illustration

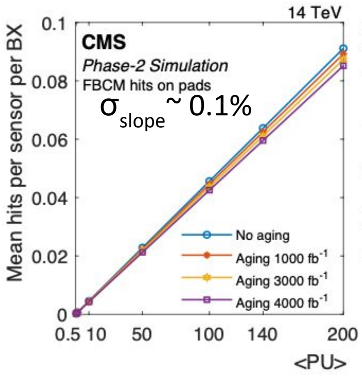


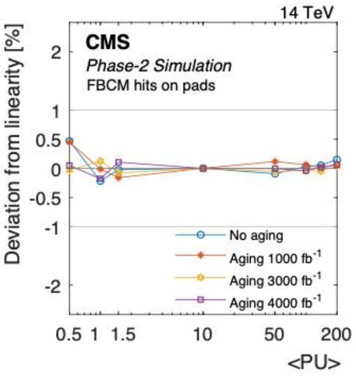



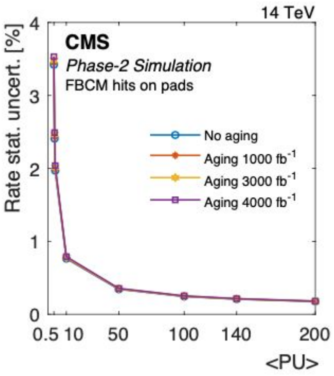

*Architecture of a quarter of FBCM*

# FBCM parameter optimization

- Luminosity algorithm based on zero counting
- Detector design optimisation based on statistical uncertainty vs. linearity* and a pragmatic frontend design
  - Simulated using CMSSW and preliminary ASIC characteristics (to be fine-tuned during ASIC development)
- Baseline described in the TDR:
  - sensor size: 2.89 $mm^2$
  - location: r =14.5 cm & z = 283.5 cm
  - Frontend ASIC with ~ 12ns FWHM pulses

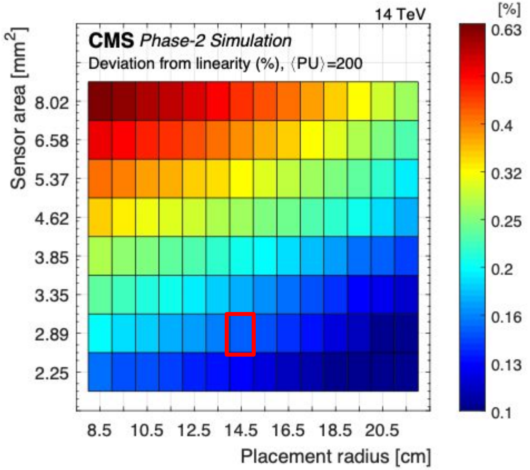


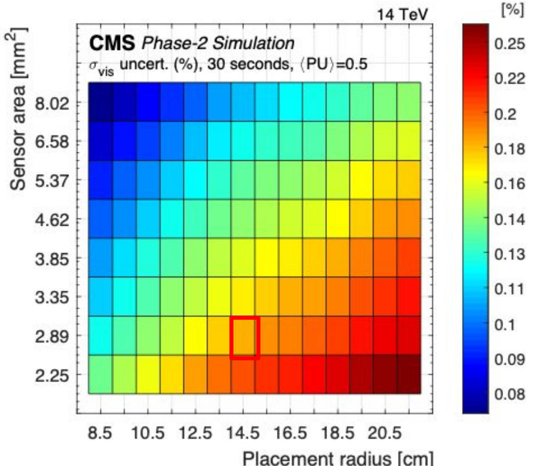



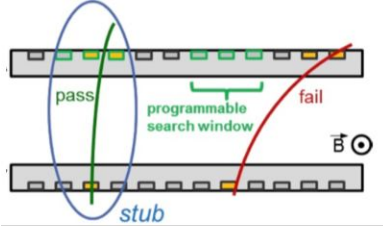

- Measurement of beam-induced background for BCIDs of single and 1st bunches in the train

*as a function of pile-up



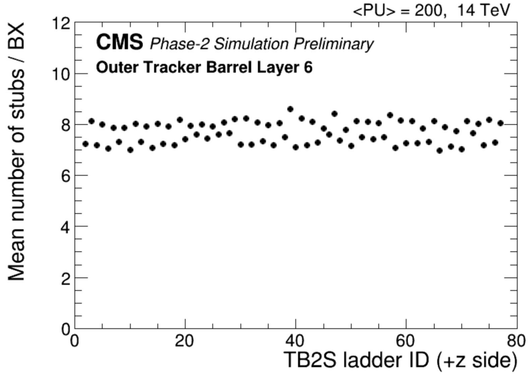



# Outer Tracker Layer 6



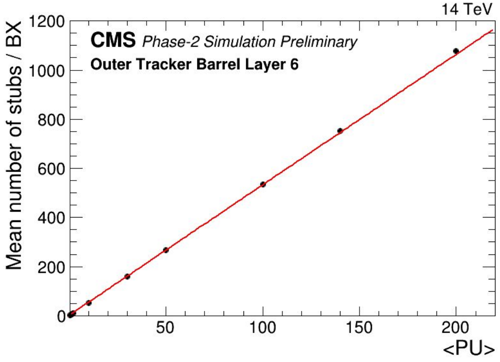

## Motivation

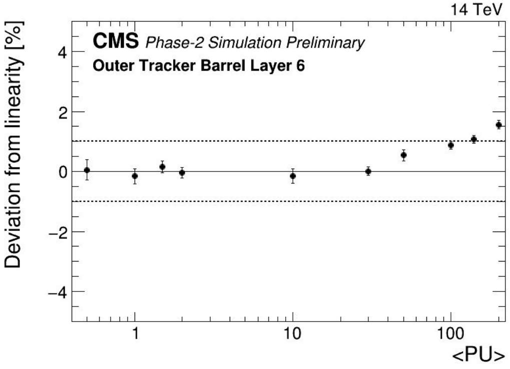
- Outer Tracker provides two-sensor coincidences (stubs) for the L1 Track Trigger at 40 MHz during stable beams
- Transmitted through the Outer Tracker back-end
- Only histogramming module needs to be added to existing OT tracker back-end firmware to be able to count stubs (BX-by-BX)
- Layer 6 stubs have shown to be linear with pile-up in simulation
- Highest statistical power of all BRIL systems




## Implementation baseline

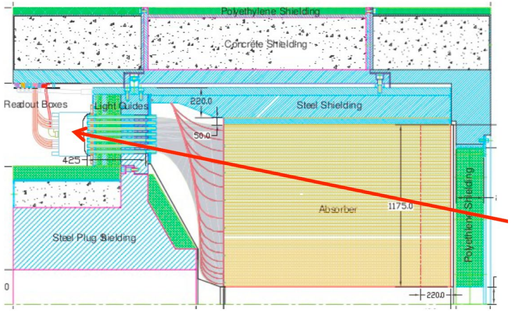
- 6 generic histogramming modules per OT back-end card
  - 12 modules (1 ladder) per histogram
- Relatively small (but non-negligible) resource utilisation
  - VU9P / 6 histograms: 0.5% of LUT and 2.4% of BRAM
- Read out via slow control interface (control network) ~ 500 kBits/s per board
- Error handling: dynamically exclude failing and include recovered modules from histogramming - to be fully developed

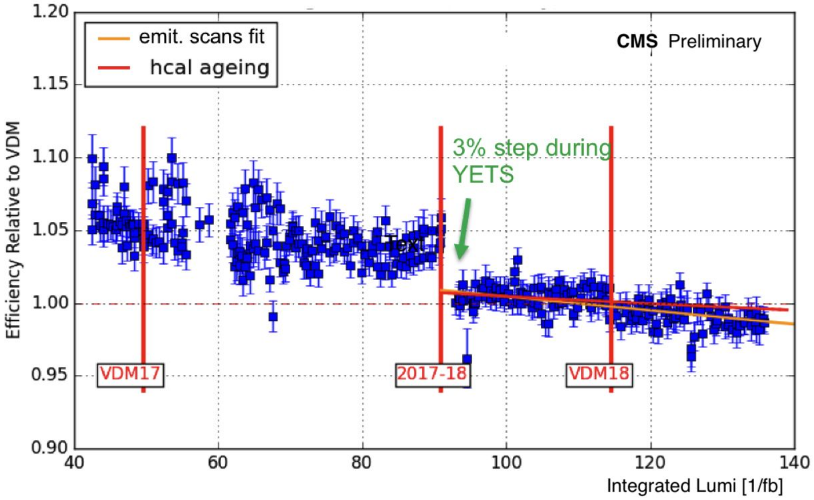


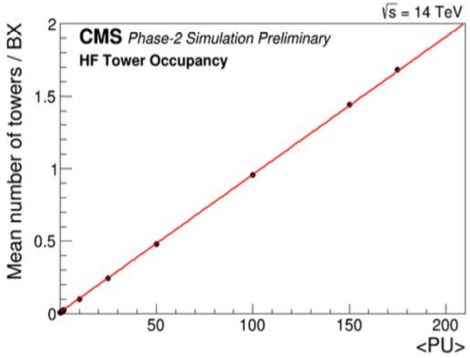



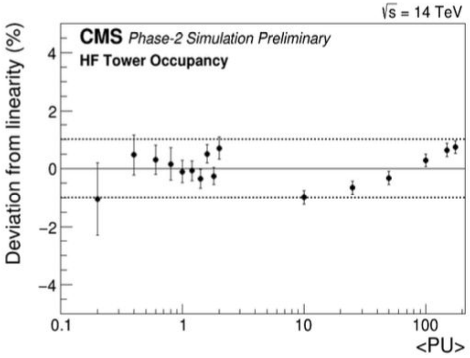
# Hadron Forward Calorimeter (HF)

- Already the backbone of BRIL Luminosity measurement in Runs 2 & 3
- No significant change foreseen for HL-LHC
- Two luminosity algorithms: HF transverse energy sum (HFET) and HF occupancy (HFOC)
- Rings 31 & 32 ($3.15 < |\eta| < 3.5$) give best linearity
  - Studied using samples that include the latest HGCAL geometry & aging of 1000 $fb^{-1}$
- For HFOC some non-linearity at high PU previously observed, but understood



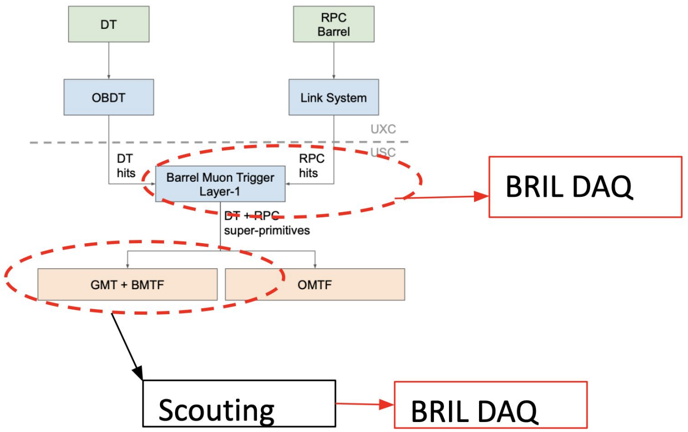



# Muon Barrel back-end and 40 MHz scouting

Muon Barrel Trigger Primitives

- Synchronous 40 MHz BRIL histogramming firmware to be installed in the Barrel Muon Trigger Layer-1
- FW included for Run 3 Slice Test (demonstrator)
- Stat. precision: 1.2% / bunch / s at PU200



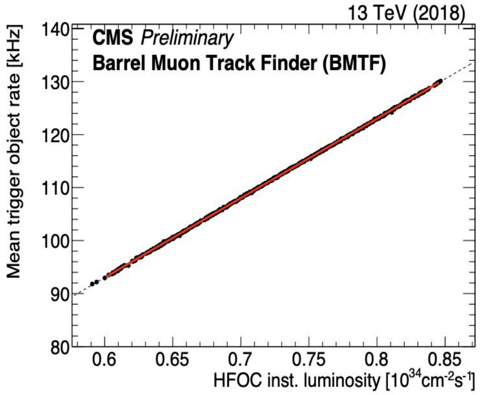

Barrel Muon Track Finder (Drift Tubes + Resistive Plate Chambers) muon candidates accessible via 40 MHz scouting system

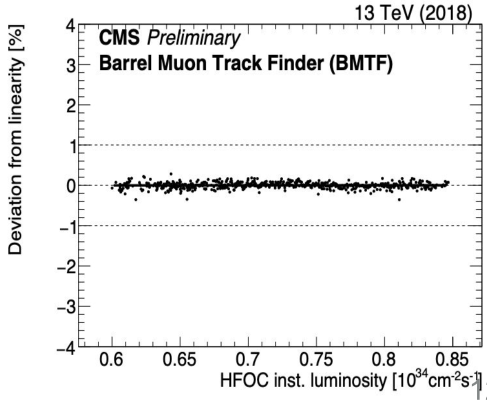
- System for real-time processing/recording/histogramming of L1 primitives via spare L1 Trigger output fibers
- Asynchronous histogramming FW to be installed (data not clock-synchronous)
- Offline performance studied in 2018 data samples
  - Stat. precision: 4.6% / bunch / s at PU200
  - Excellent linearity and negligible background
- Real-time histogramming demonstrator foreseen for Run 3

EndCap Muon Track Finder muon candidates

- Stat. precision: 1.9% / bunch / s at PU200
- Sub % *linearity* requires more study
- Interesting prospects for measurement of high-radius beam-induced-background and also cavern background

Scouting can be extended to track & calo objects in Phase 2



# Performance comparison & considerations

Summary of the performance characteristics and capabilities of the proposed luminosity systems.

| | 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* |

# Summary

- The HL-LHC presents a unique challenge for CMS and requires improved luminosity precision to increase physics performance
- BRIL has developed a comprehensive plan to exploit a host of different and independent data sources across CMS to provide:
  - Complementary luminosity measurements with different systematics
  - two systems under full control of BRIL
- Major proof-of-concept tests have been successfully completed and summarised in the recently approved & published BRIL Technical Design Report
- The project is working towards final engineering designs and algorithms