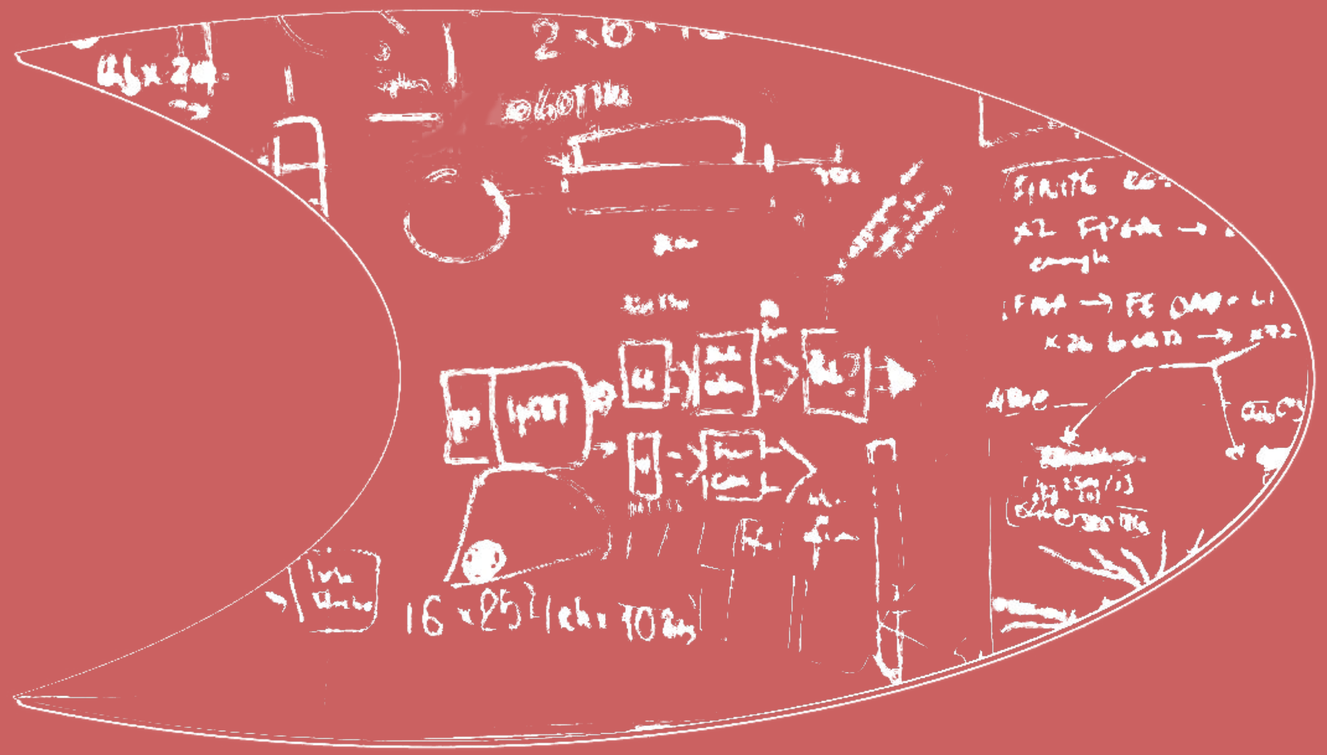
Performance of the BCM1F detector and plans for the HL-LHC upgrade

Mykyta Haranko

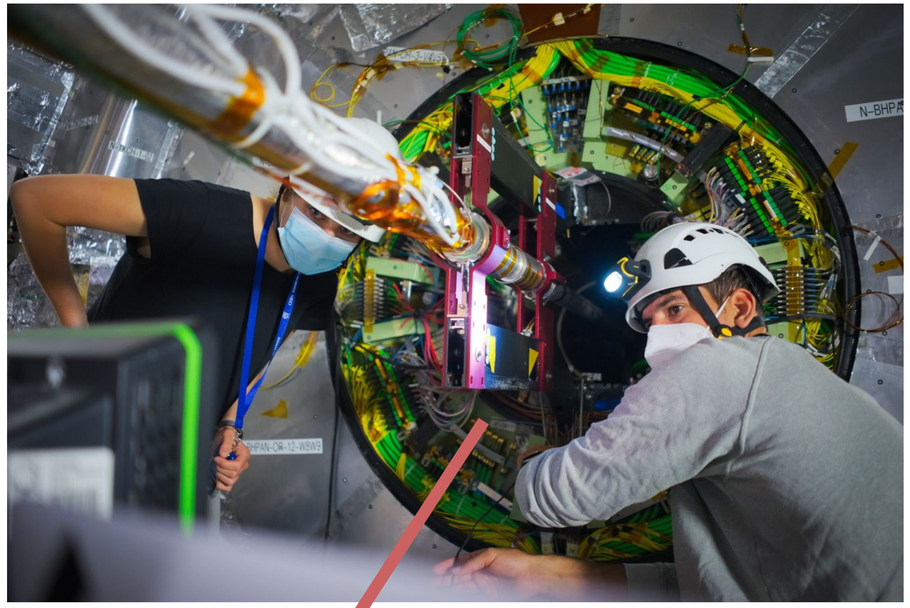
on behalf of the **CMS experiment**

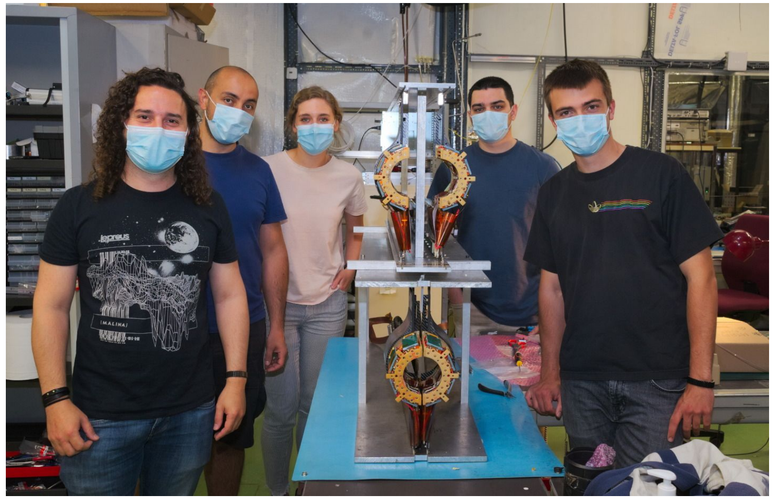
Rad Hard Beam Instrumentation Workshop
Zoom, 4th February 2022

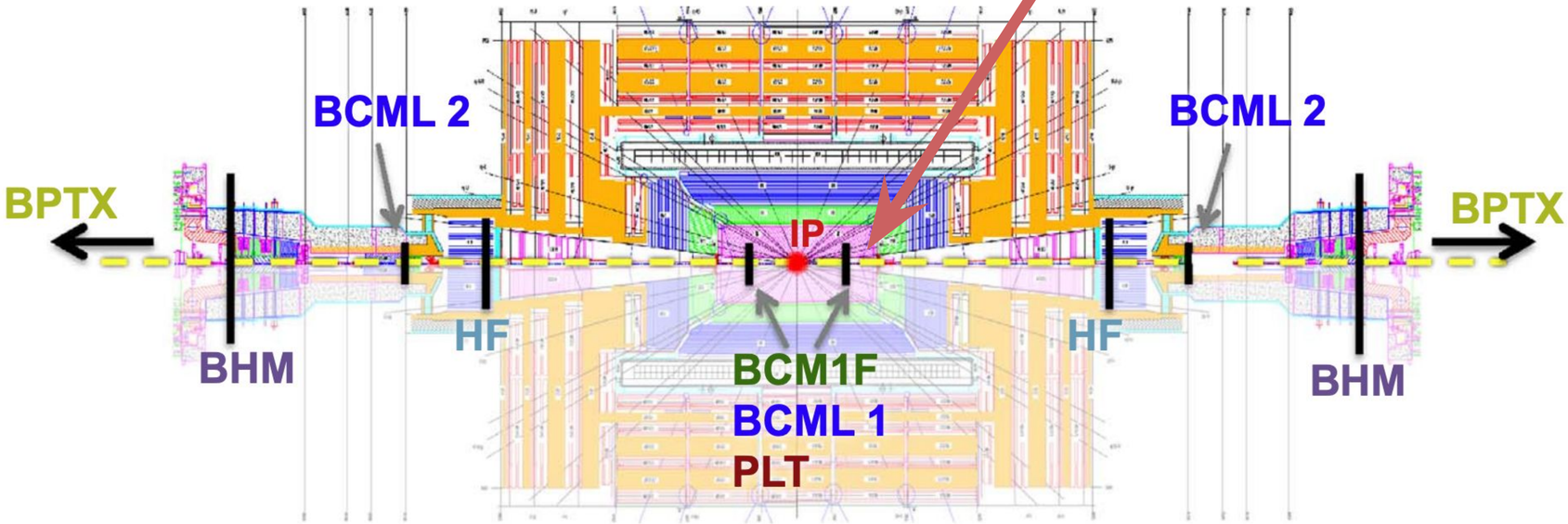


CMS BRIL Project

- Responsibilities of the **Beam Radiation Instrumentation and Luminosity (BRIL)** project of the **CMS experiment** are
  - Luminosity
  - 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 & simulation of that environment







BCM1F History

BCM1F first operation, 8 sCVD sensors (2007)

Fast ASIC, 24 sCVD sensors (2015)

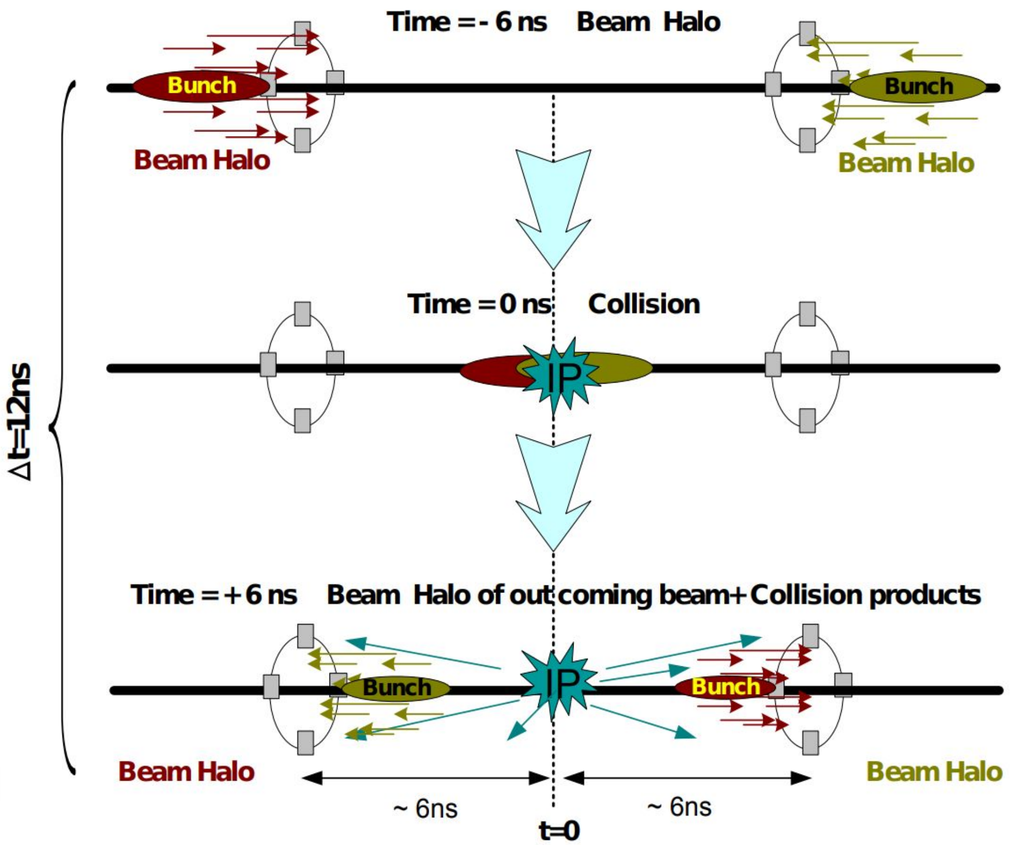
Mixed sensor installation (sCVD, pCVD, Si) (2017)

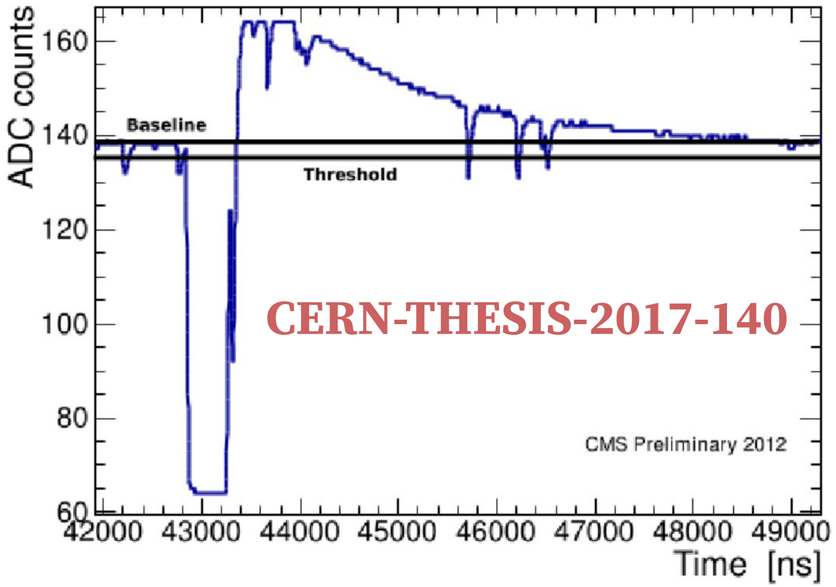
Run-3 installation, Si sensors (2021)

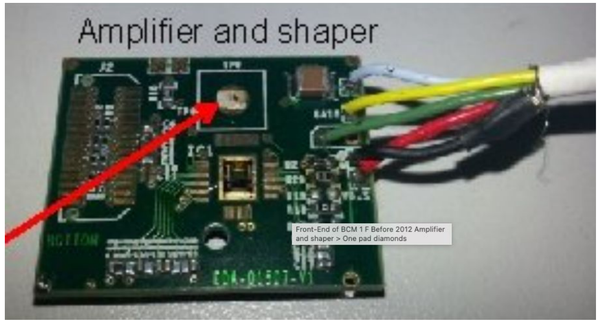
FBCM era (~ 2028 incl. schedule shift)

BCM1F v0

- **A total of 8** single-crystal chemical vapour deposition **(sCVD) diamond sensors**, 5mm x 5mm metallisation **operating since the first LHC runs**
  - Located at **Z +- 1.8 m** (12.5 ns separation between MIB and collision products)
- **BCM1F v0 has shown that**
  - Building of **stateless and fully independent** from all central CMS services luminometer is crucial
  - Fast ASIC is needed (LHC switching to 25 ns bunch spacing, long recovery after overdrive)
  - Optical conversion has to be moved of the “hot” volume

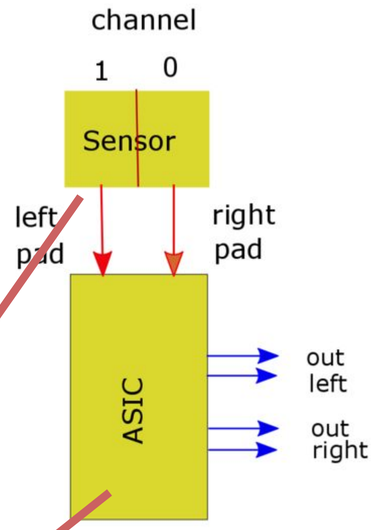


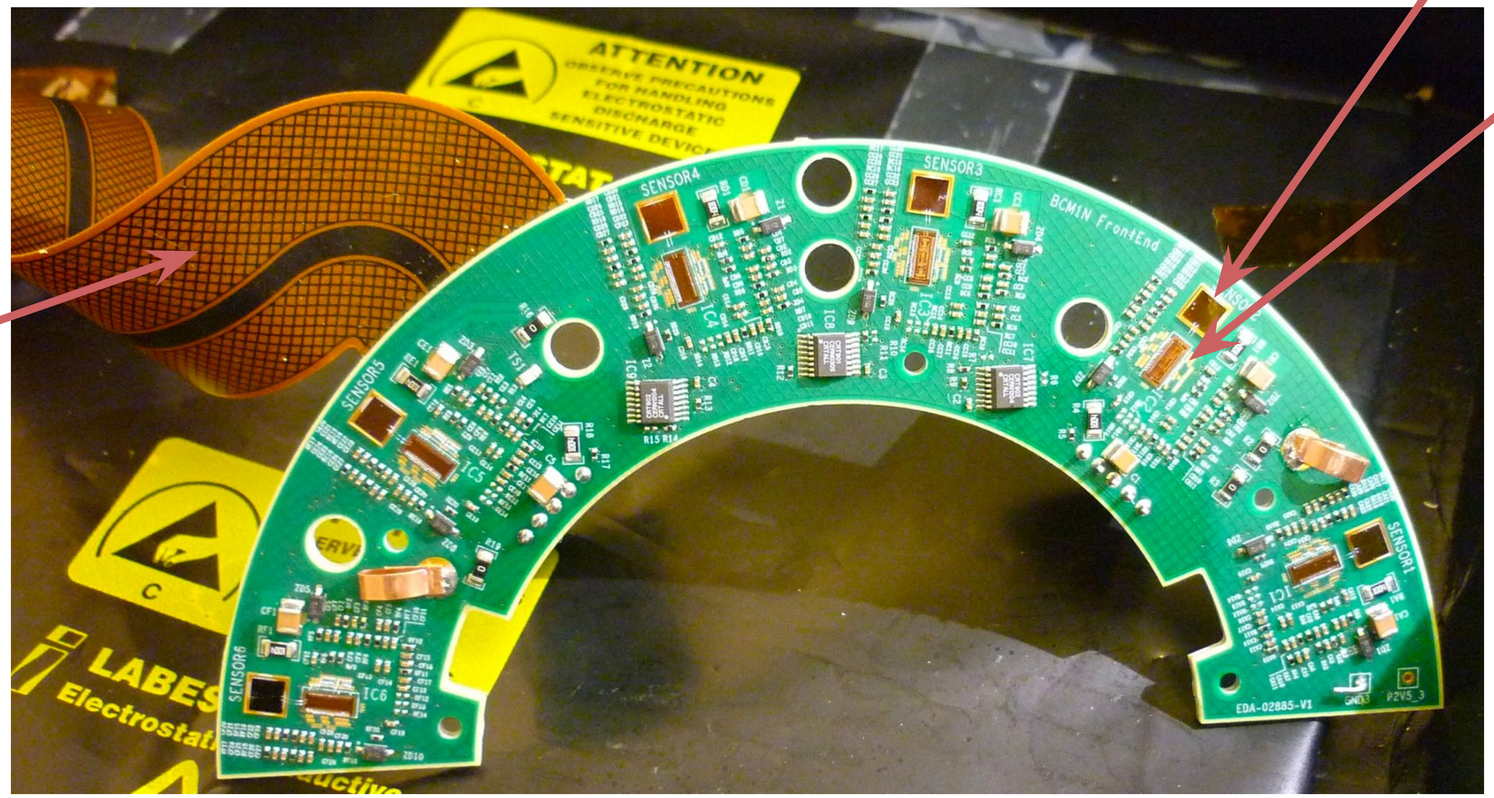




Upgraded BCM1F

- **24 single crystalline CVD diamond sensors** with **two pad** metallisation (**5 mm x 5 mm** with **25 um split**)
- New fast ASIC to resolve the issues identified previously
- Large PCB without connectors to minimise material budget
- Optical conversion is moved further from the interaction point

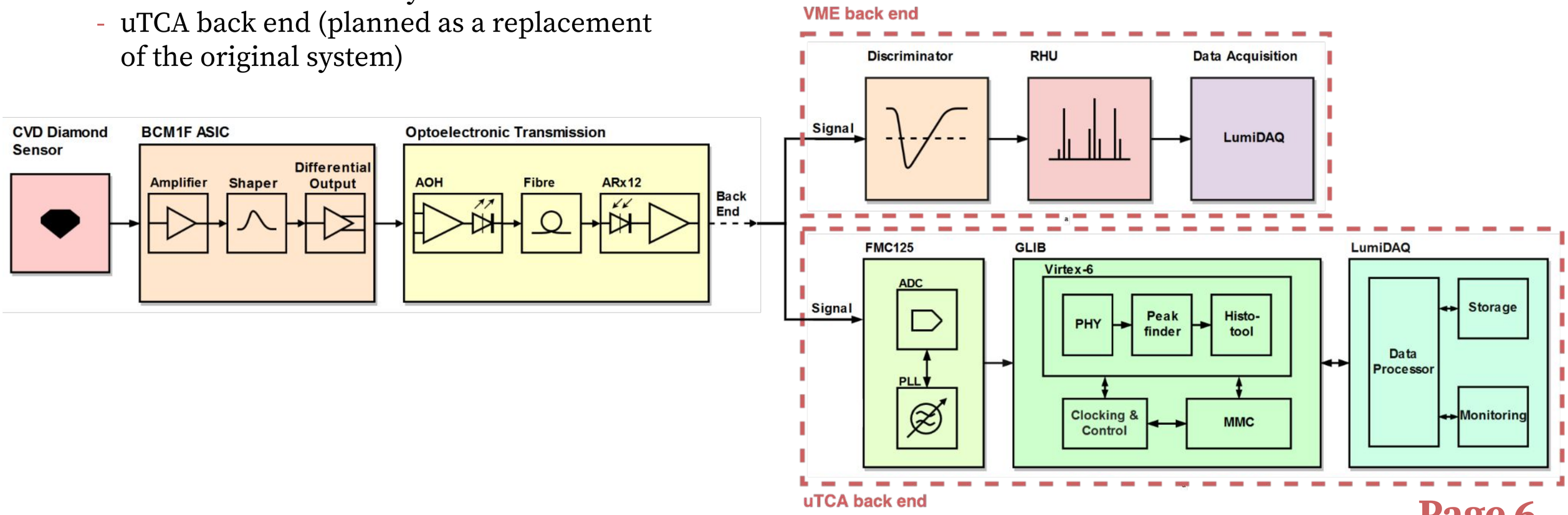




Part of the PCB

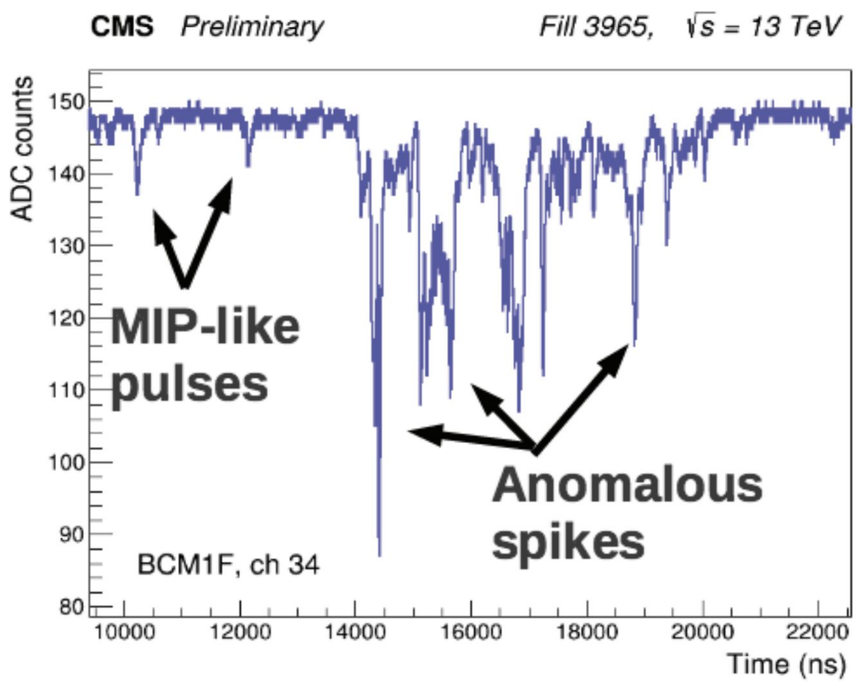
Electronics Chain

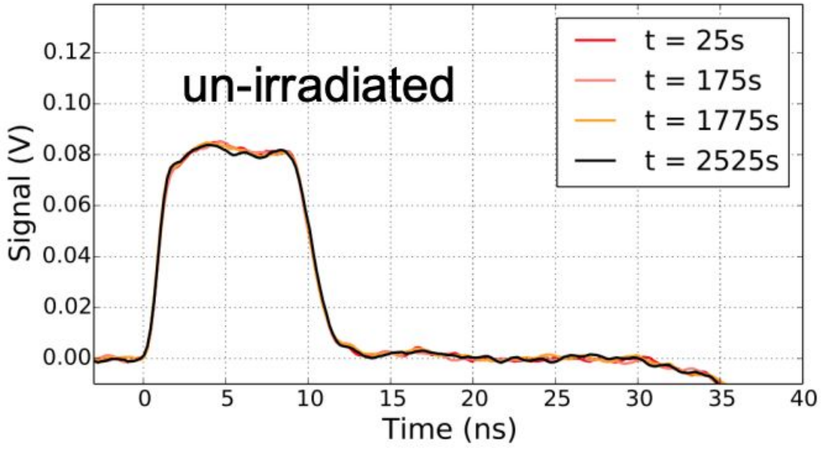
- **BCM1F ASIC** developed by **AGH UST** (Krakow) and **CERN** (Geneva) is the core of the front end
- Electrical analog pulses are converted into optical and sent to the service cavern
- Opto-electrical conversion in USC is followed by the duplication into two back-end systems
  - VME-based back-end system
  - uTCA back end (planned as a replacement of the original system)

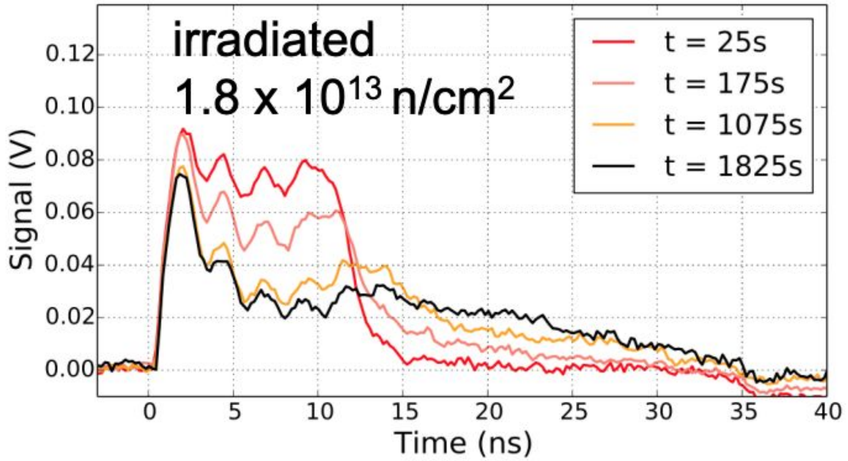


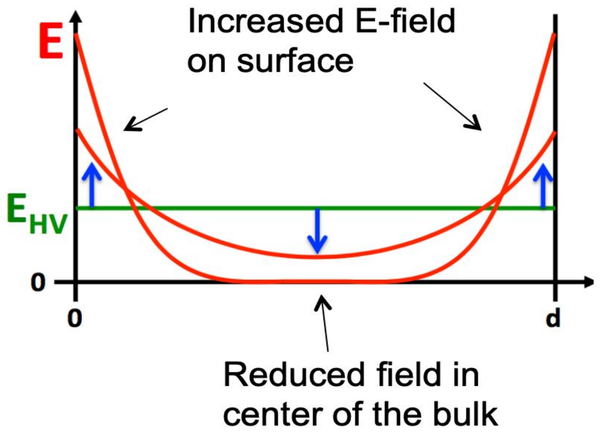
Sensor Choice

- **sCVD** diamond sensors were not performing as expected after irradiation
  - Erratic current was developing over time and caused tripping of a power supply
  - Initially resolved by reducing the applied voltage
  - TCT measurements have shown that in irradiated sCVD sensors E-field deforms with the build-up of electric charge in the bulk (trapped in neutral vacancies)





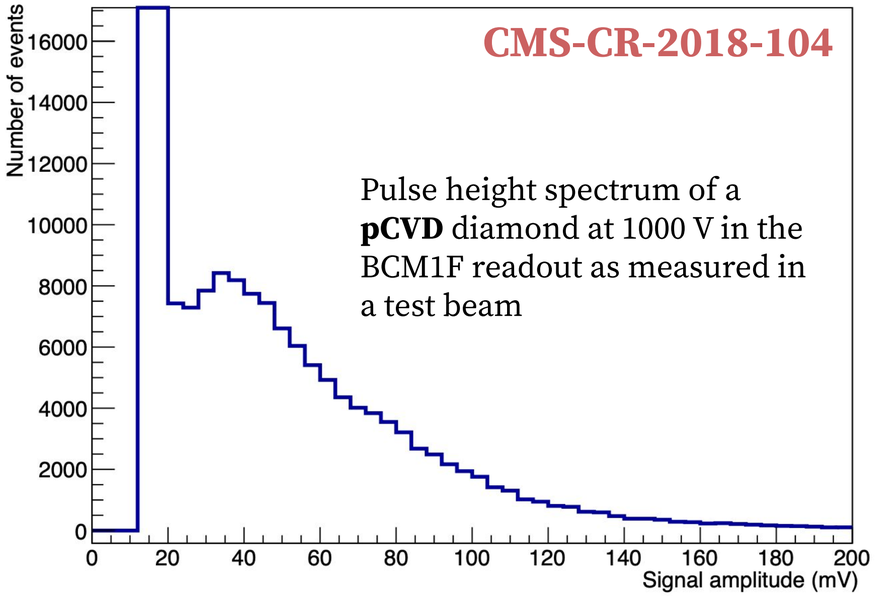




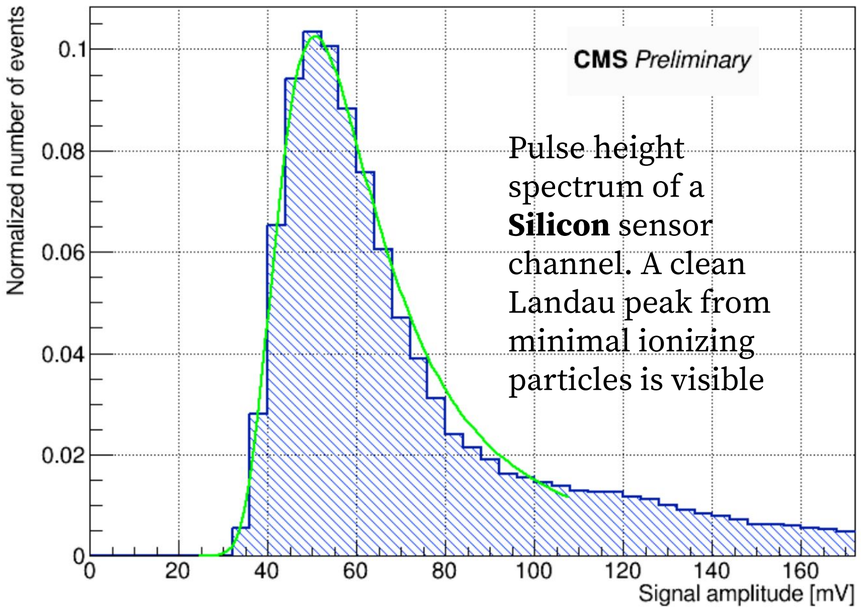
CERN-THESIS-2017-071

Sensor Choice

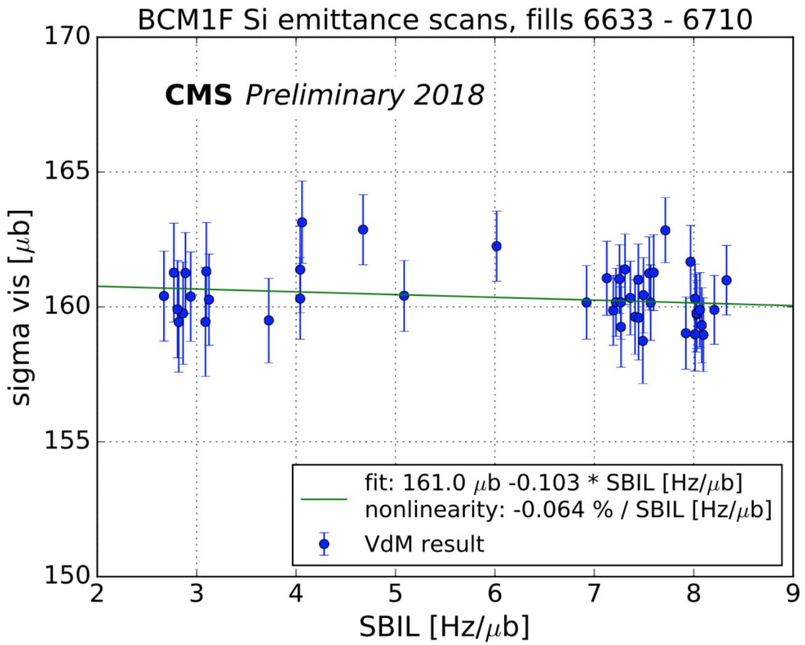
- A mix of **sCVD (4), pCVD (10)** and **Silicon (10)** sensors was installed in **2017**
  - Irradiated pCVD have shown much better stability compared to irradiated sCVD sensors
  - On the other side - harder to distinguish MIPs from noise and overall lower charge collection efficiency
- **Silicon** sensors have shown excellent performance
  - Separation of signal and noise and very good linearity
  - Radiation damage-induced leakage current (un-cooled sensors) caused the electronics to saturate in 2018



Pulse height spectrum of a **pCVD** diamond at 1000 V in the BCM1F readout as measured in a test beam



Pulse height spectrum of a **Silicon** sensor channel. A clean Landau peak from minimal ionizing particles is visible

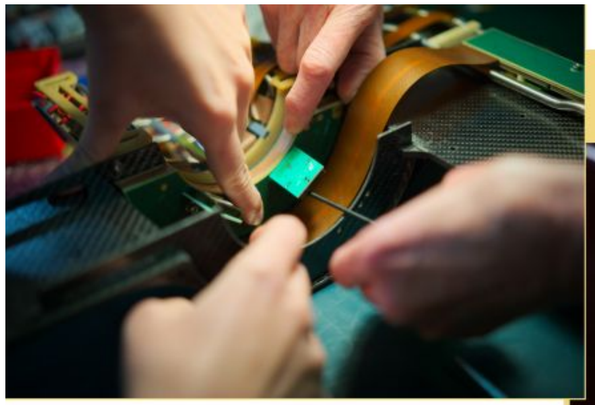


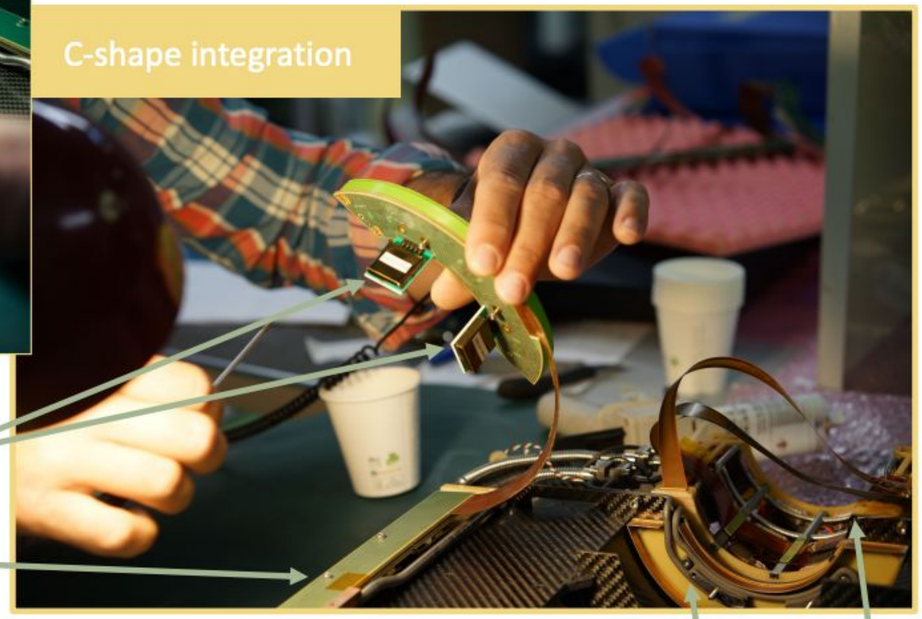
Linearity of **Silicon** sensor based luminosity measurement

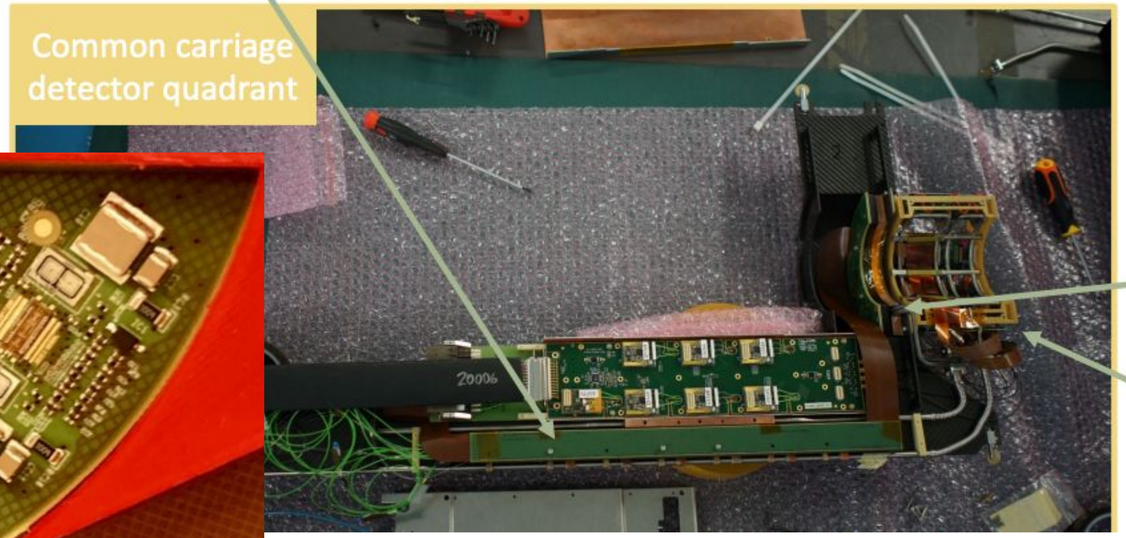
Sensor Choice

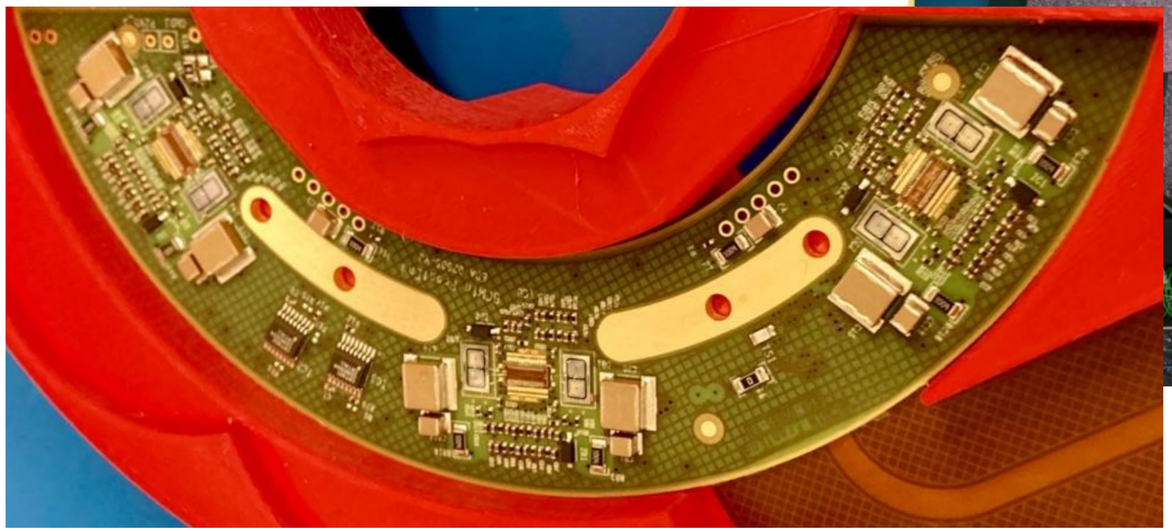
- **Run-3 BCM1F will consist of exclusively Silicon sensors**
  - AC-coupled sensors to protect electronics from leakage currents
  - PCB with active cooling
  - The system is **already installed and has been tested during the October 2021 LHC beam test**

Commissioning Poster - Link





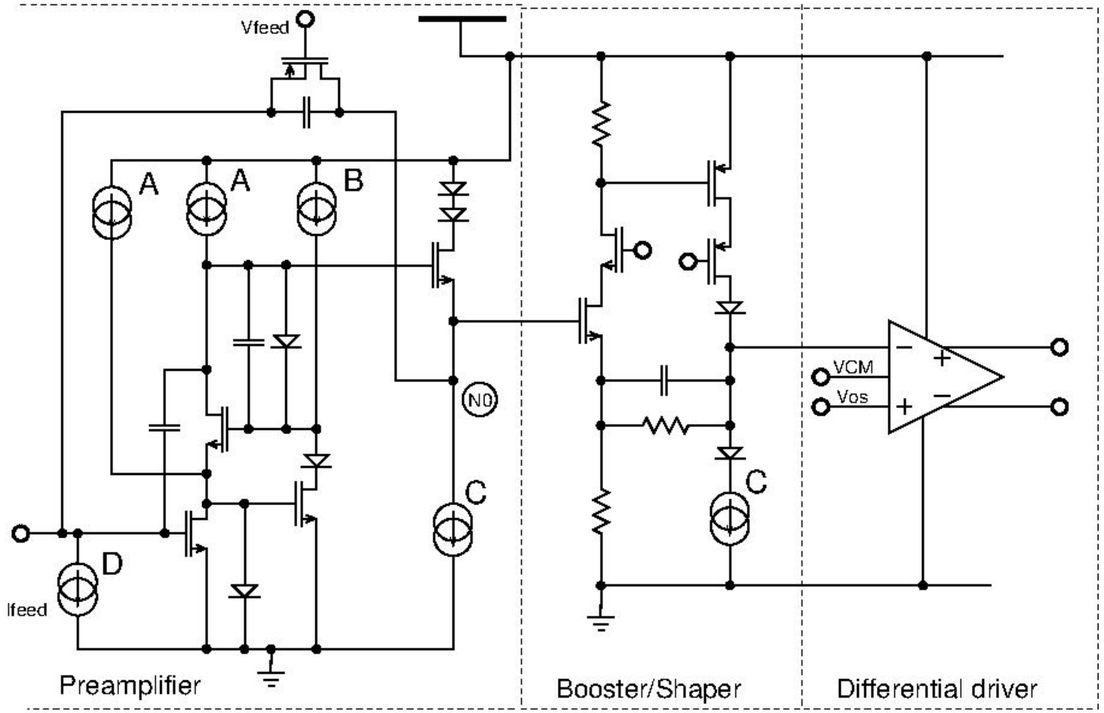


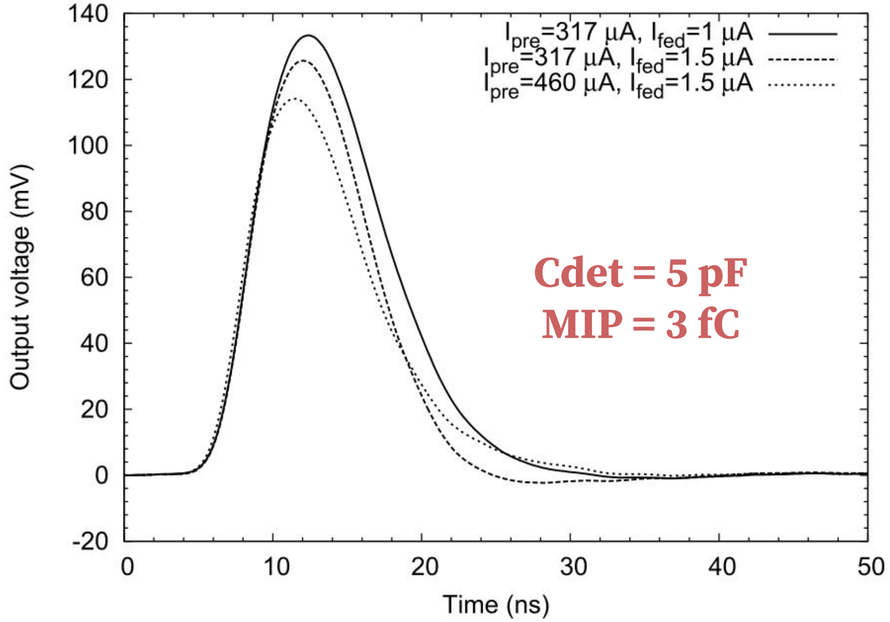


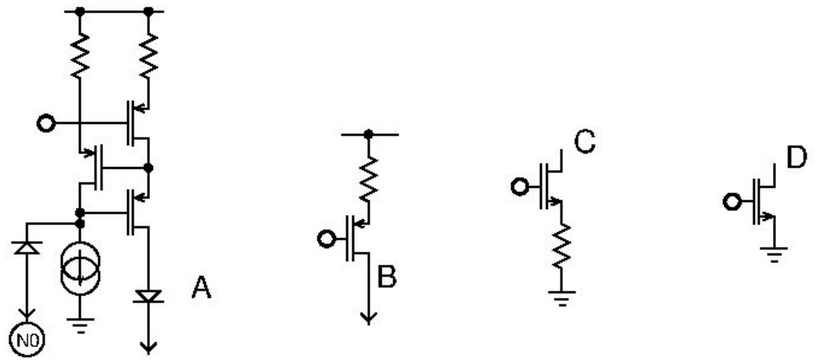
Front End ASIC

DOI:10.1109/TNS.2016.2575781

- Asynchronous front-end - BCM1F ASIC
  - **Short peaking time (7 ns - 9.4 ns) and FWHM (below 10 ns)** (key features allowing to preserve linearity at high counts)
  - Implemented in **IBM 130 nm** process (1.2 V nominal supply), supplied with **2.5 V**
  - Supply compatible with CMS driver for analog optical link
  - Supplying with elevated voltage allows for boosting of GBP which is important to get peaking time below 10 ns
- Preamplifier/shaper are based on the circuit from ABC130 chip *(IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 59, NO. 4, AUGUST 2012)*

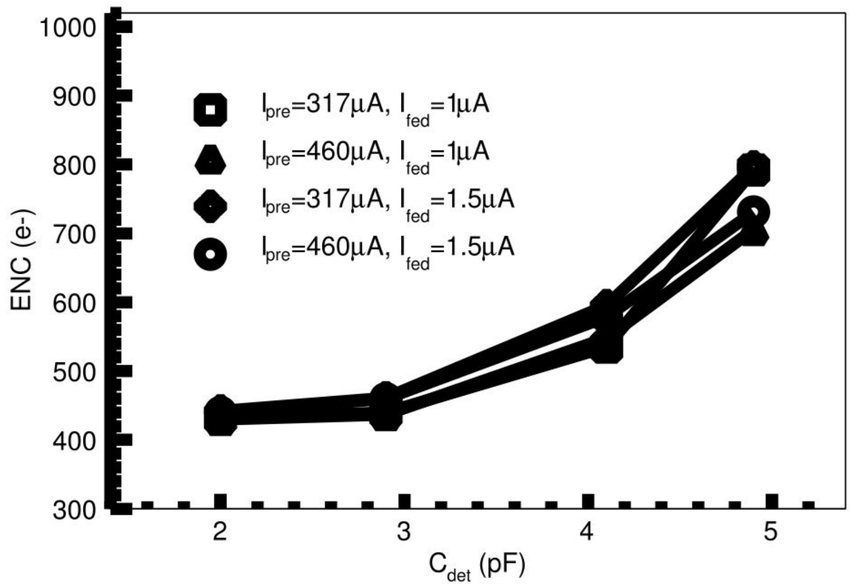


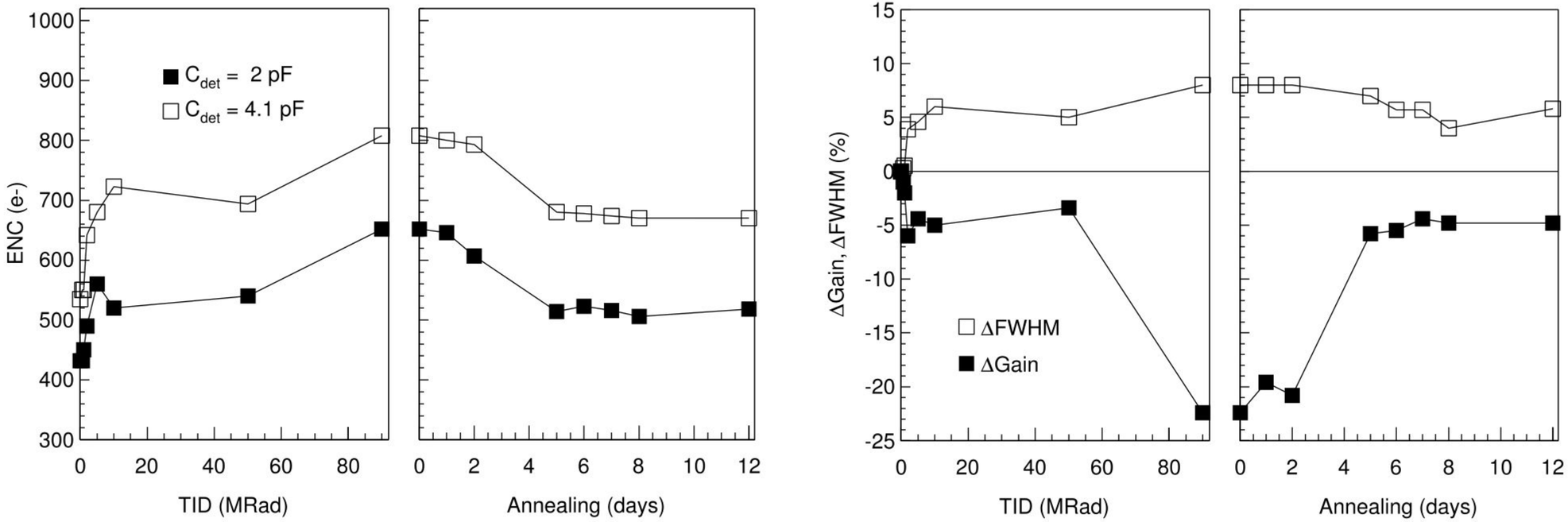




Front End Performance

- **Increase of ENC during irradiation** related to increase of 1/f noise in the input transistor (related to STI isolation)
- Effects understood and layout of the input transistor corrected later for ABCStar front end (not for BCM1F chip)
- More detailed description in **K.J.R. Cormier et al. 2021 JINST 16 P07061**

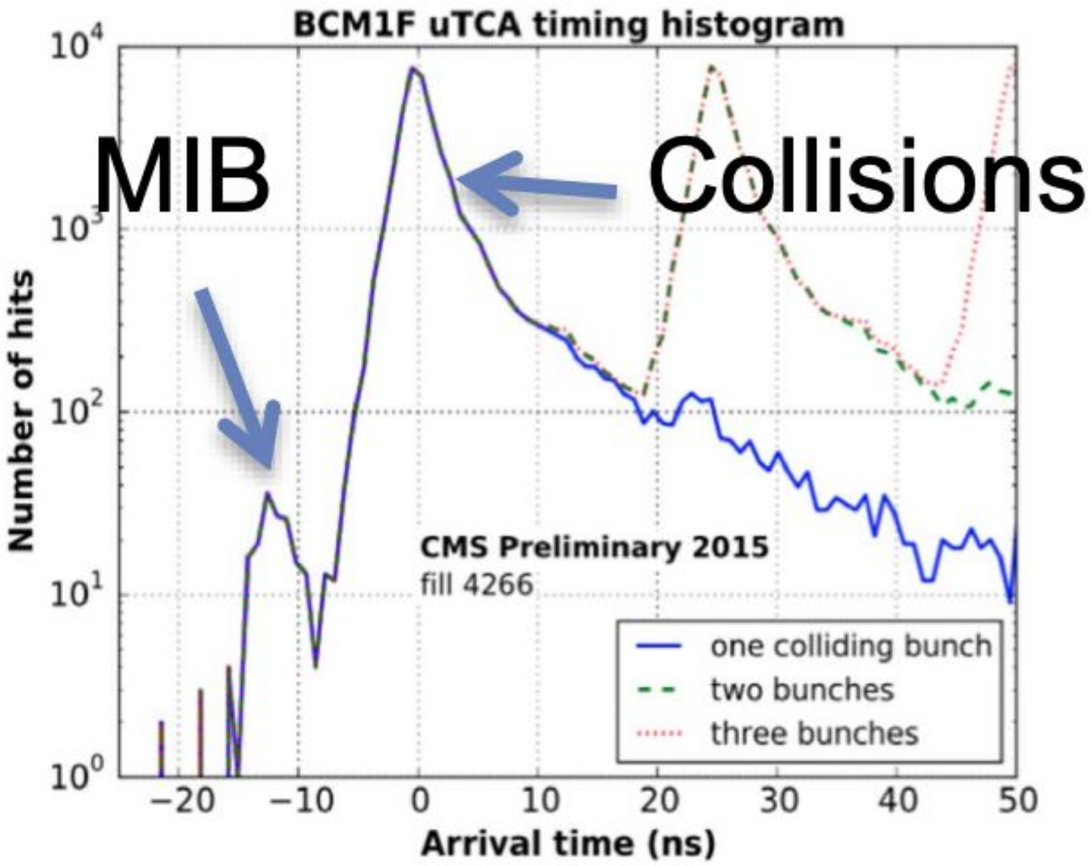




Back End Performance

- VME back end
  - Important luminometer and background monitor operating continuously
  - **Reliable and stable system**
  - **4 bins / BX** time resolution (12 points / BX using ADC)
  - **System becomes obsolete, becomes harder to maintain**

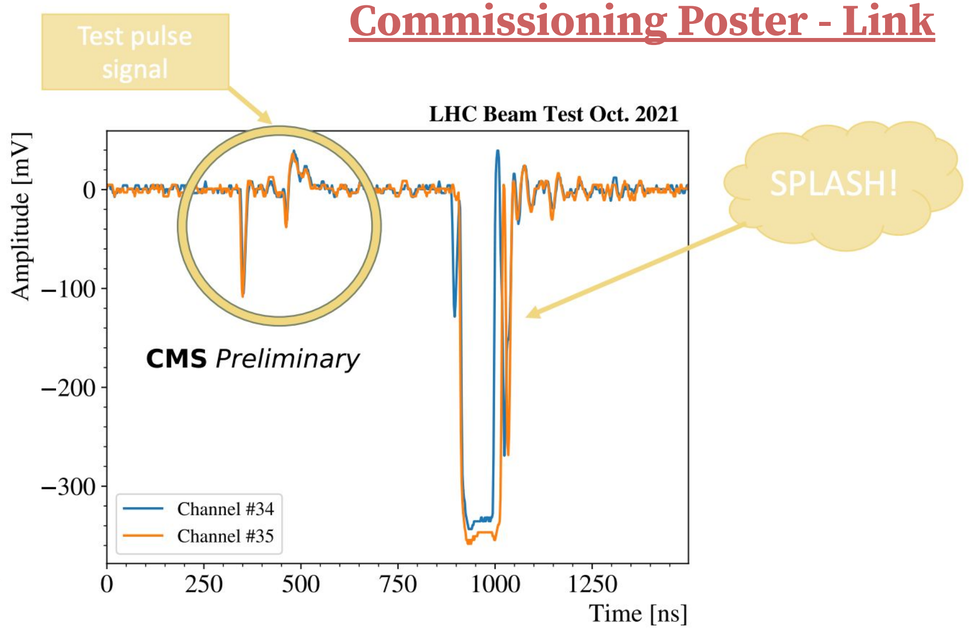
- uTCA back end
  - Increases processing power
  - Resolves the double hit front-end signals
  - **6 bins / BX** time resolution (30 points / BX in raw data acquisition mode)
  - Higher resolution to distinguish collision and MIB particle hits
  - **So far was not very stable, very high expectations for Run-3**

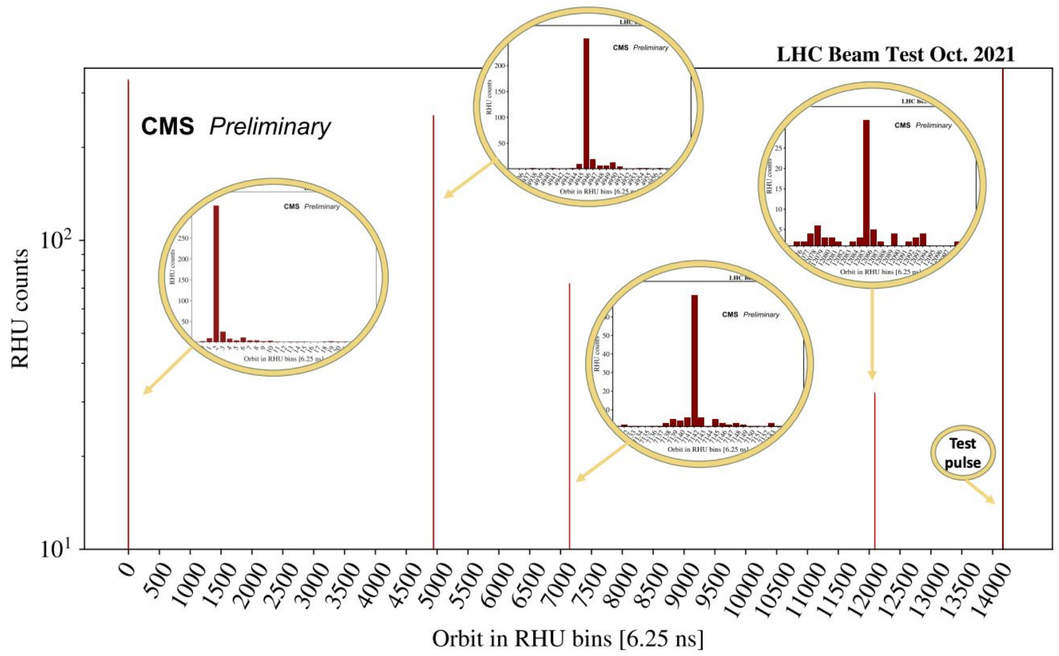


BCM1F Summary

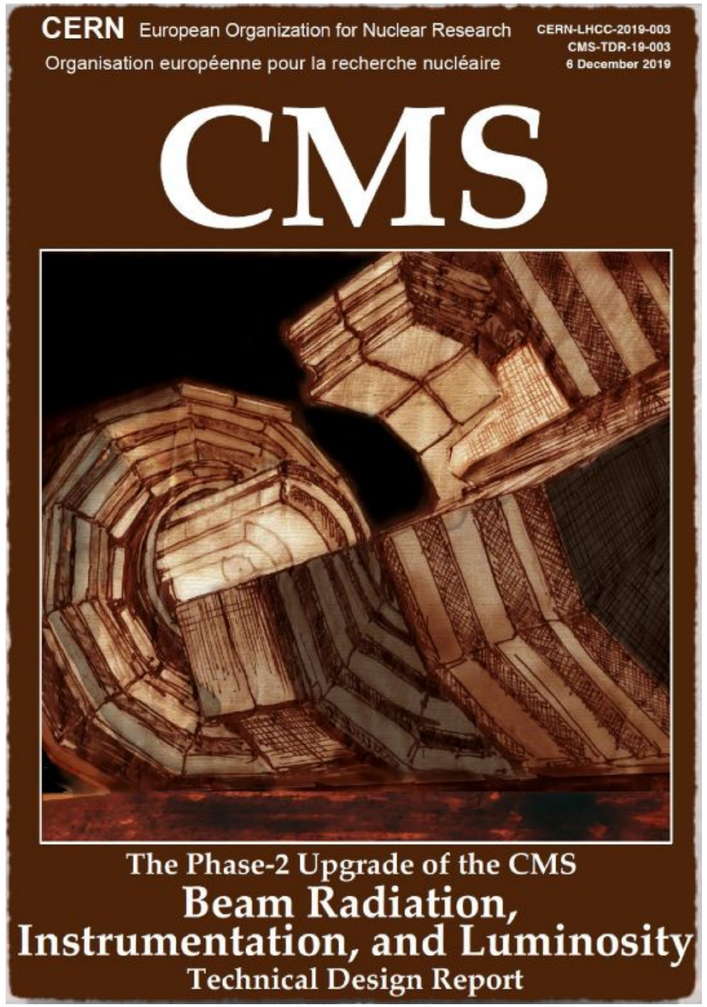
- **The Run-1 system has shown a necessity of having and independent luminometer**
- **The system has progressed a lot during Run-2**
  - Initial problems of unstable sCVD diamond sensors after some irradiation
  - Excellent stability after a refurbishment using pCVD diamond sensors
  - Very stable operation of the dedicated fast analog front end
  - **BIB measurement has been reliable the entire Run-2 and was a safety parameter for the operation of the CMS Tracker**
  - Prototype silicon diodes were qualified
    - Good linearity and hence luminosity performance
    - Limited longevity due to poor cooling
- **The Run-3 system is ready to go**
  - Actively cooled AC-coupled diode is designed for good linearity and stability to boost the luminosity measurement performance of BCM1F
- **The same system can not be re-built for HL-LHC**
  - Components for analog optical readout are not available anymore
  - A system using a digital front end is needed

Commissioning Poster - Link

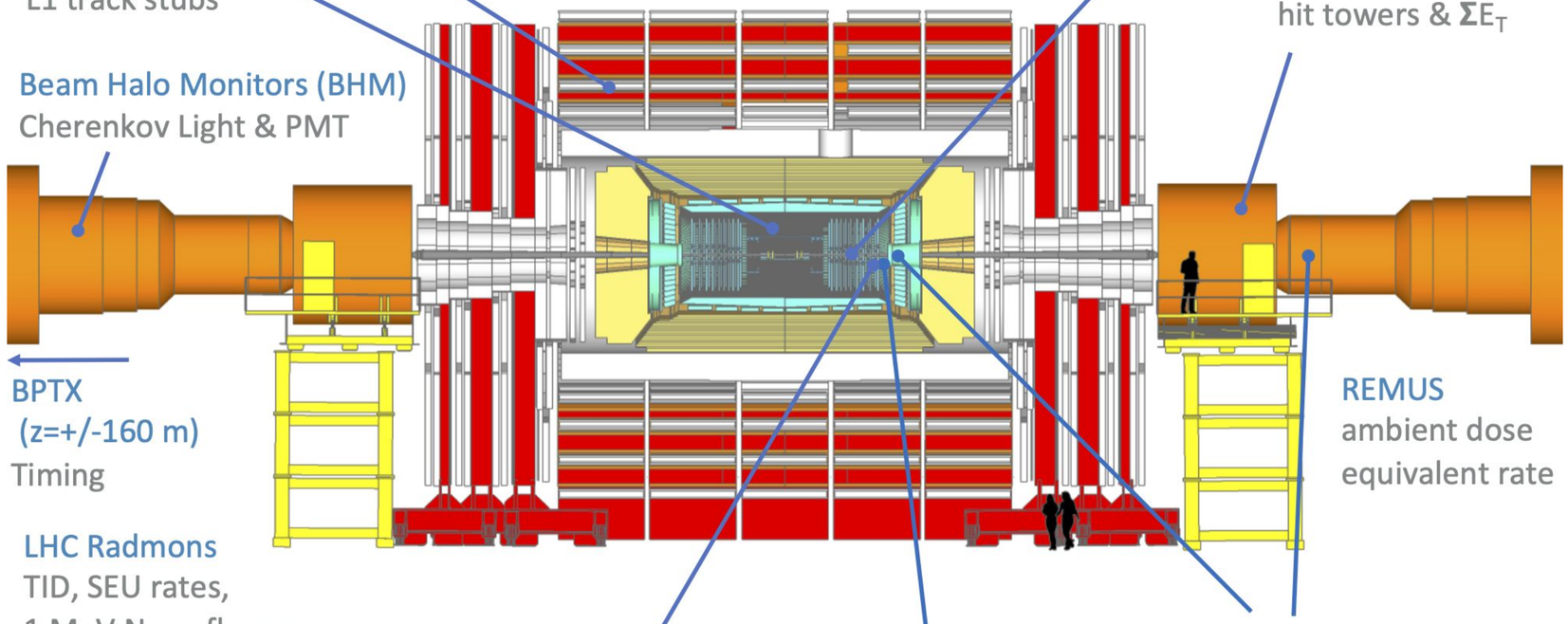




BRIL: 14 Technical Systems for HL-LHC



TDR is fully approved and public
(https://cds.cern.ch/record/2759074)



Muon Barrel (MB)
L1 trigger primitives

40 MHz scouting
L1 muons, tracks, calorimeter objects

Neutron Monitors
Gas filled proportional chambers

Tracker Endcap Pixel Detector (TEPX)
clusters & coincidences

Outer Tracker Layer 6 (OT L6)
L1 track stubs

Hadron Forward Calorimeter (HF)
hit towers & ΣE_T

Beam Halo Monitors (BHM)
Cherenkov Light & PMT

BPTX (z=+/-160 m)
Timing

REMUS
ambient dose equivalent rate

LHC Radmons
TID, SEU rates, 1 MeV N. eq fluence

Beams Conditions Monitor for Losses (BCML1,2)
Ionisation current in pCVD diamond and sapphire sensors

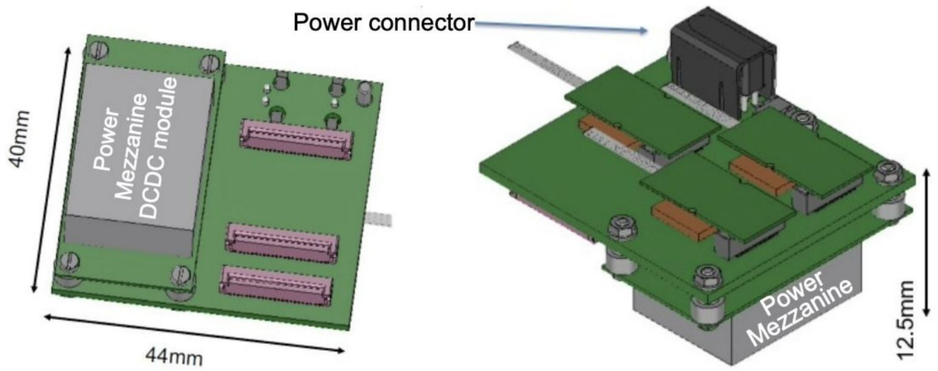
Neutron Spectrometer
SiPMs & Bonners spheres

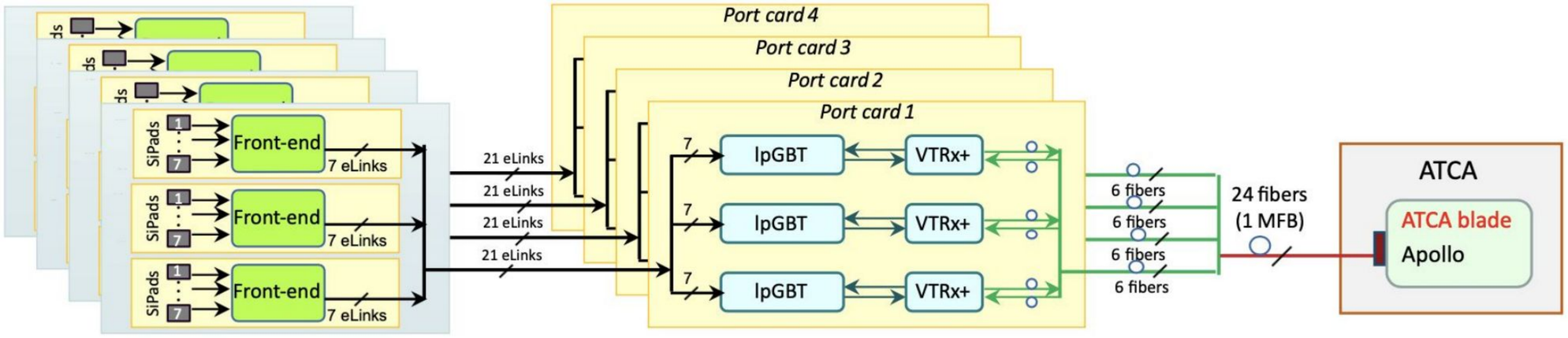
TEPX Disk 4 Ring 1 (D4R1)
clusters & coincidences

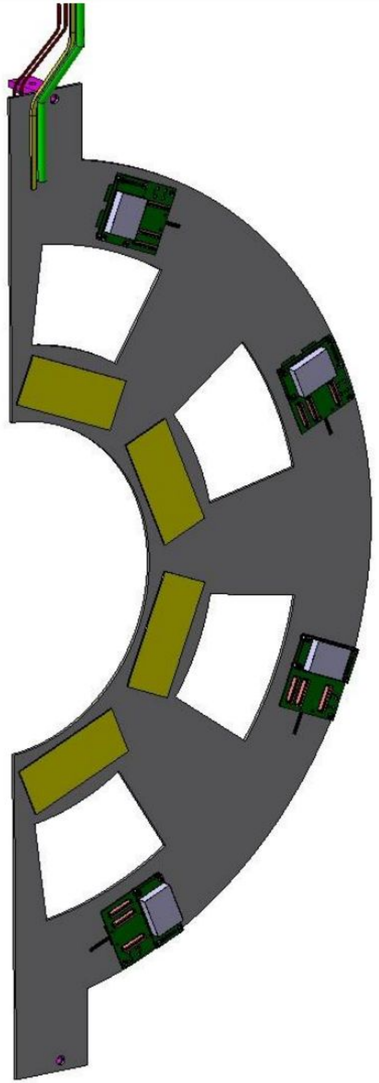
Fast Beam Condition Monitor (FBCM)
hits on Si pads

Fast Beam Condition Monitor (FBCM)

- FBCM is a direct successor of BCM1F and will help to retain the BCM1F capabilities for Phase-2, while also
  - Introducing a **modular design**
  - Re-using IT electronics as much as possible
  - Integrating with **Phase-2 CO_2 cooling** system
  - **Developing new, radiation tolerant 65 nm ASIC**



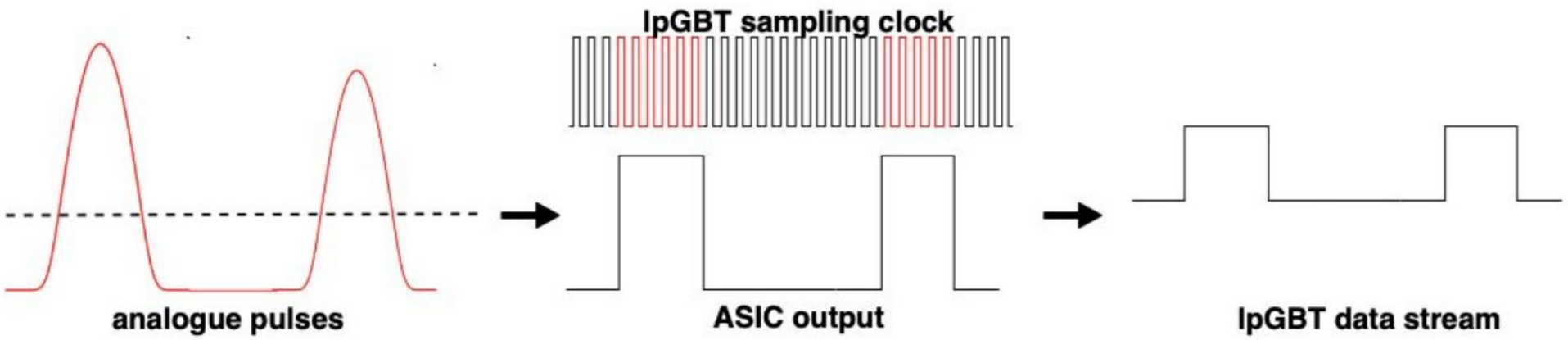




FBCM Design - ASIC

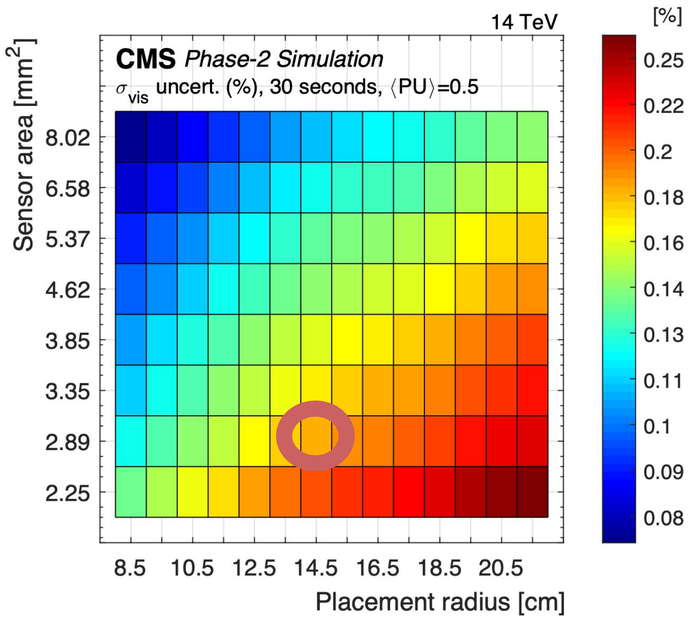
- **Baseline FBCM design (optimisation) presented in TDR**
  - Sensor size, granularity, basic geometry, read-out chain, services
  - Now need to move towards full specification and prototyping for EDR

- Work on **65 nm ASIC** to start in Q2 2022 along with electronics system (test-system, hybrids)
  - Quasi-final specs available
  - Semi-digital output starting at ToA and lasting ToT sampled by lpGBT
  - Integrated test pulse generator, programmable I2C registers
  - Rad-hard to **250 MRad & 3.5e15 1 MeV neq fluence**
  - Investigating several options for front-end power regulation

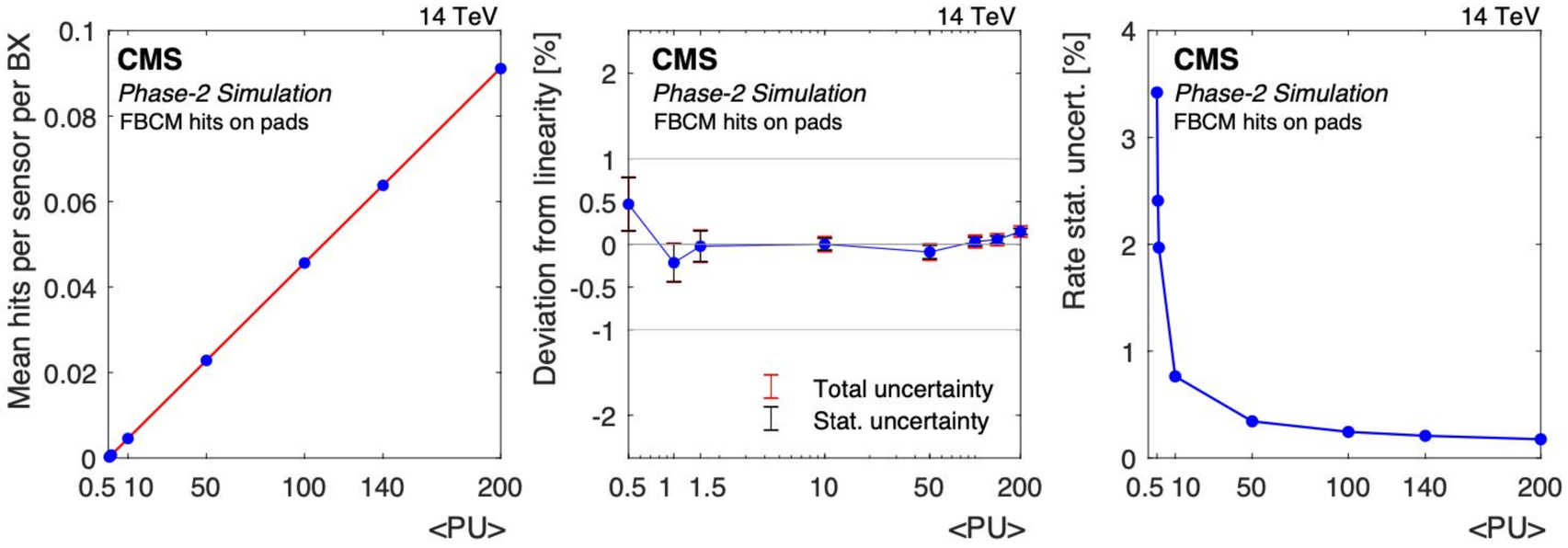


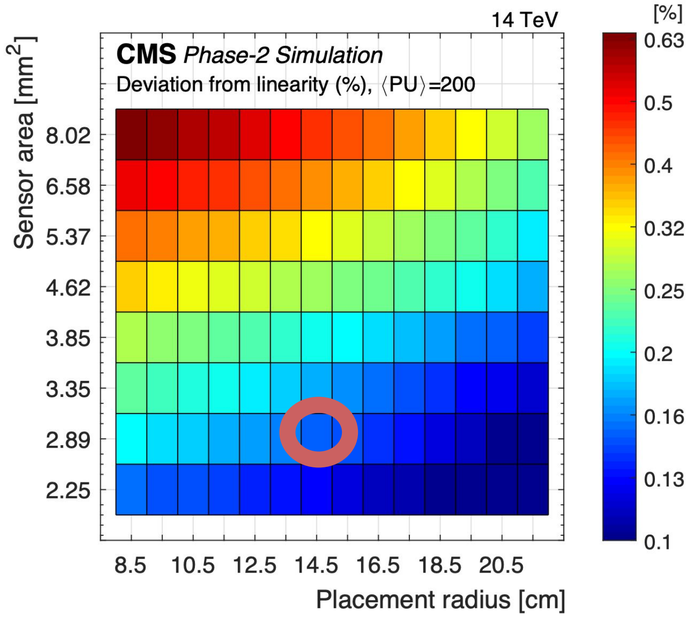
FBCM Design - Optimisation

- Extensive CMSSW simulation work to define sensor geometry
  - Studied baseline scenario of **2.89 mm² per pad at r=14.5 cm**
  - **Good statistical uncertainty** @ physics (PU200) and VdM (PU0.5) regimes
  - **Excellent linearity, no risk of zero-starvation**



σ_{vis} uncertainty (%) at <PU>=0.5

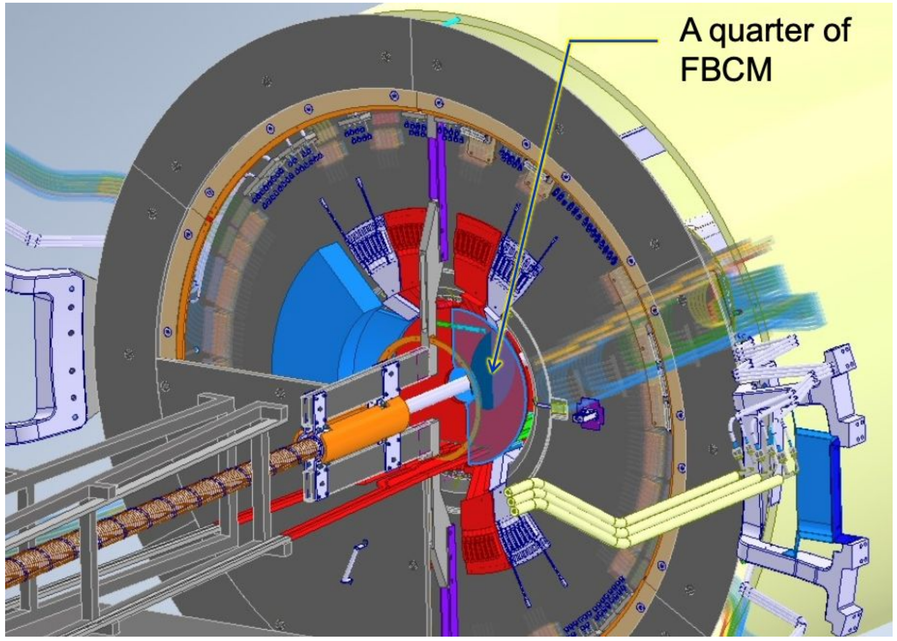


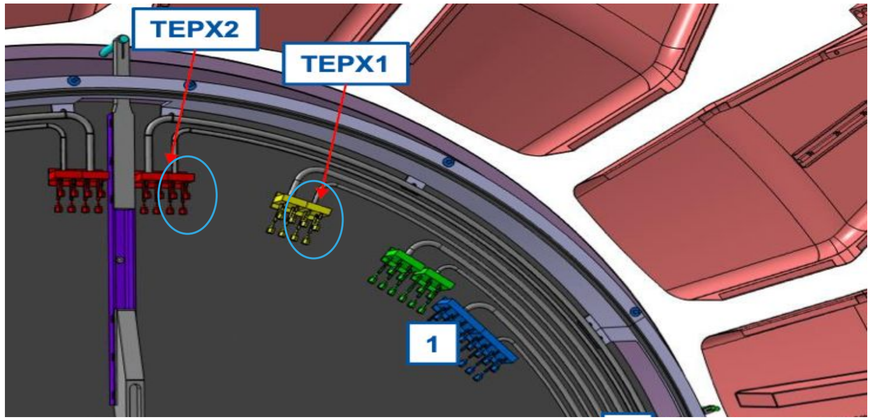


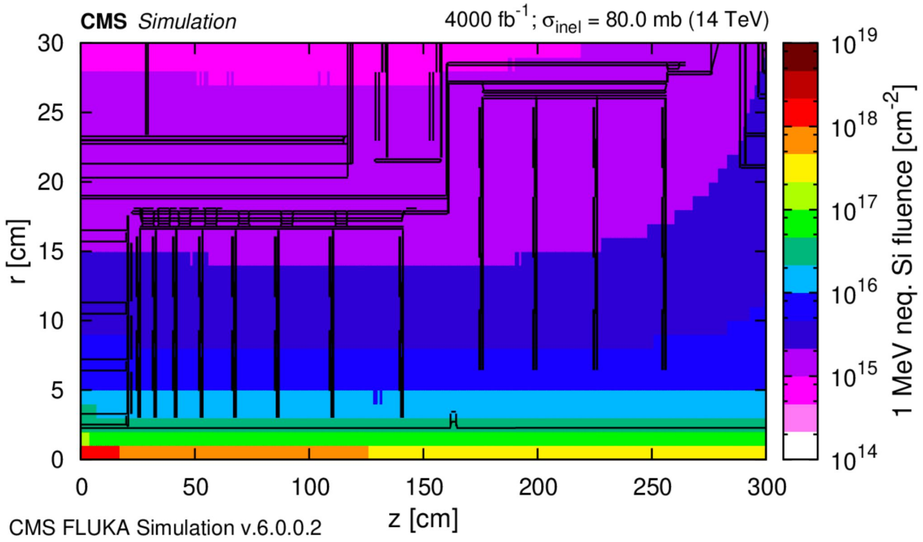
Deviation from linearity (%) at <PU>=200

FBCM Location and Services

- FBCM requires location close to the beam pipe and CO_2 cooling
  - In **close collaboration with Tracker colleagues**
  - Allows to profit from advanced IT design (mechanics, cooling, services)
  - See Georg's talk on CO2 cooling
- One FBCM quarter is
  - 4 IT port cards
  - **4 modules with 3 ASICs each**
- A total of 336 Si-pads
  - Radius between 8 and 30 cm
- Estimated power dissipation of 18 W per quarter

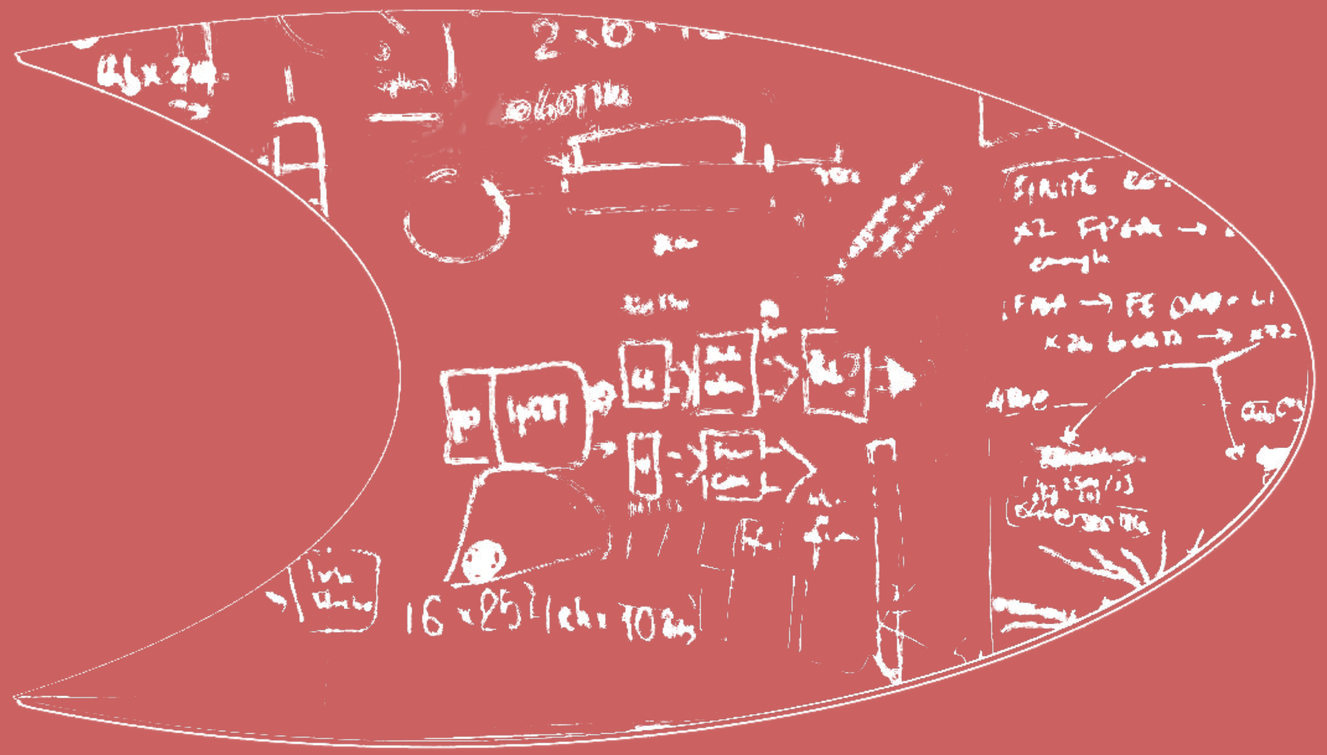






FBCM Summary

- For **CMS**, it is **crucial to retain an independent, stateless, asynchronous and fast online luminometer** for Phase-2 to provide **high-precision bunch-by-bunch** luminosity (& BIB) **at all times**
- Effectively it is an evolution of the present BCM1F concept
  - Benefiting from existing components and services as much as possible
  - Will be based on a dedicated ASIC
  - Tightly coupled to TEPX
- Provides orthogonal capabilities and systematics to all other CMS Phase-2 luminosity systems
- **The system is well-described in TDR and has been approved by CMS**

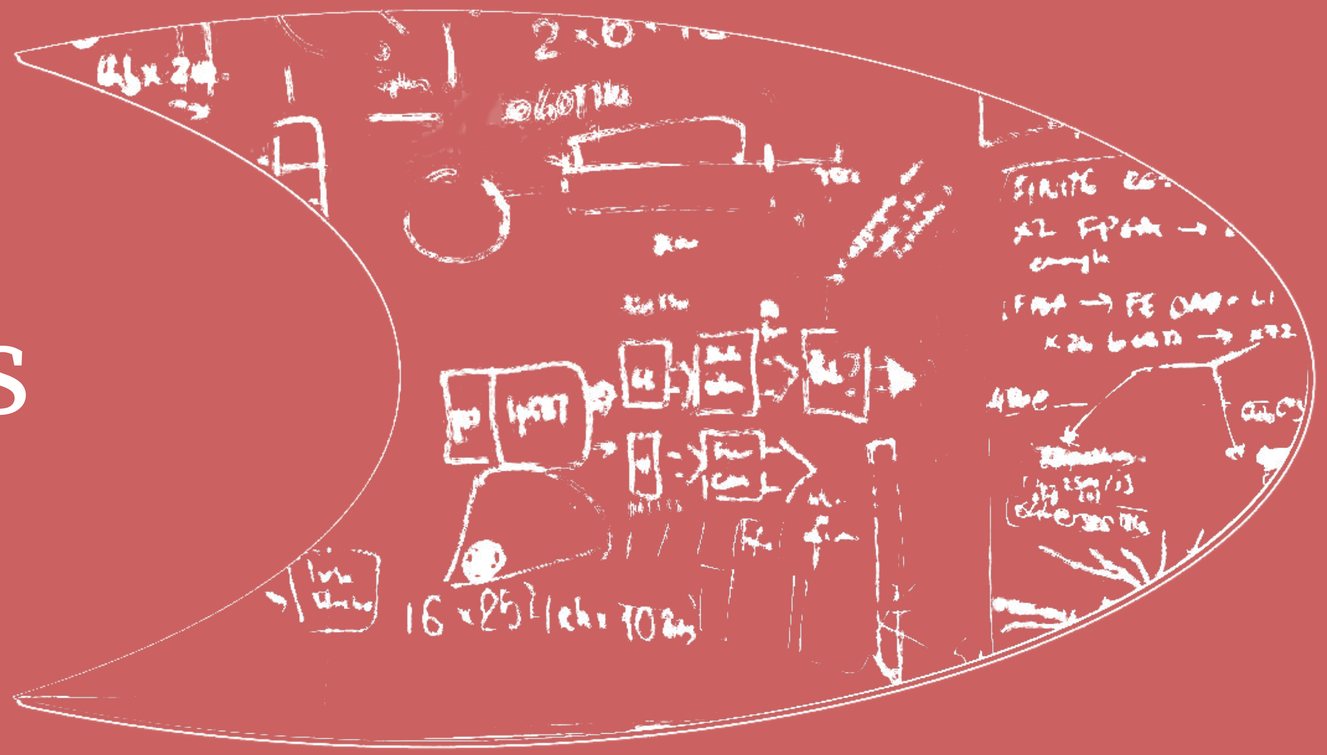


BRIL

CERN

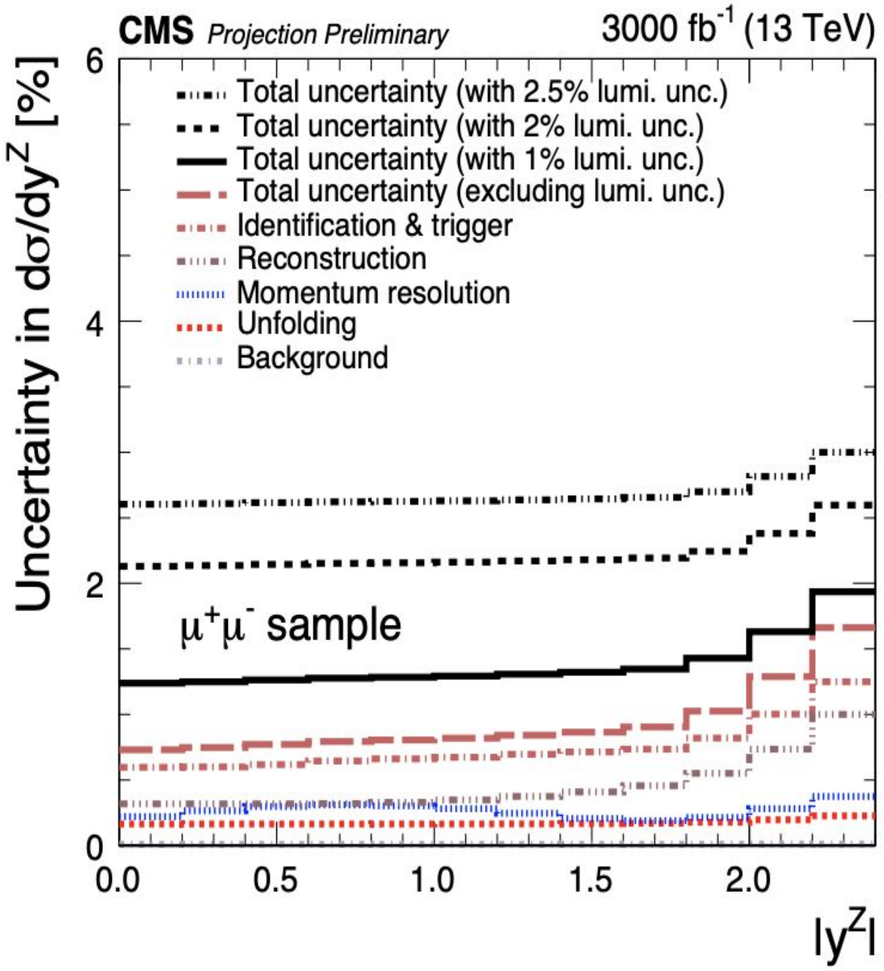
CMS

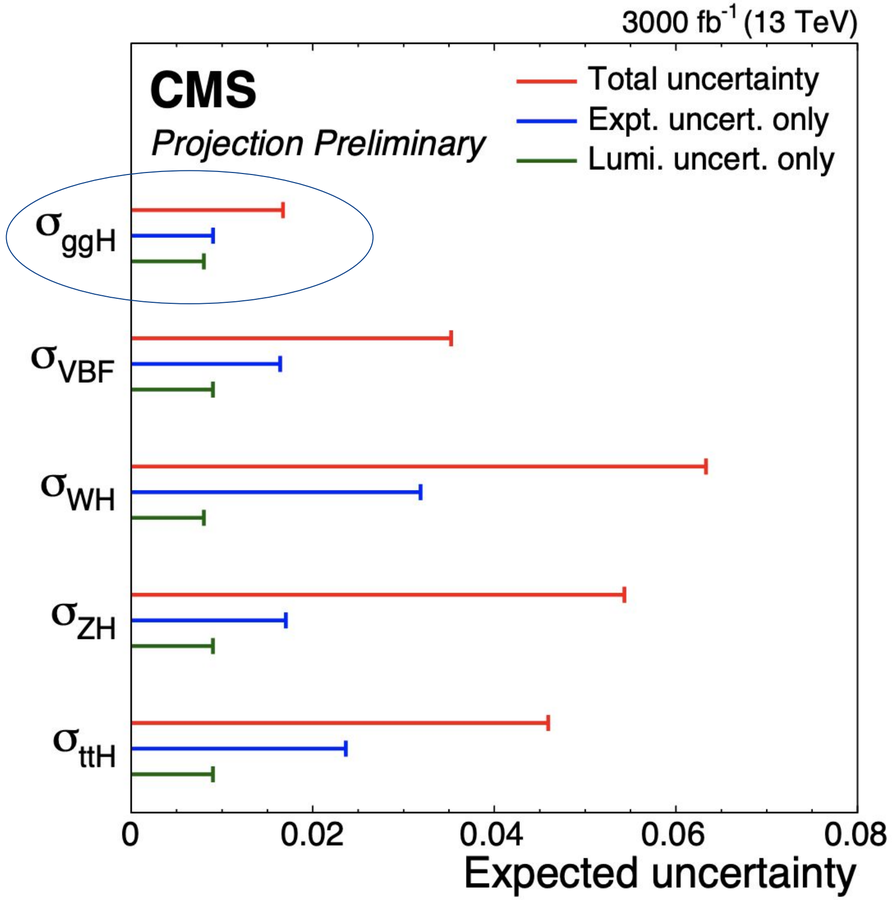
Extra Slides



Physics motivation for improved luminosity instrumentation

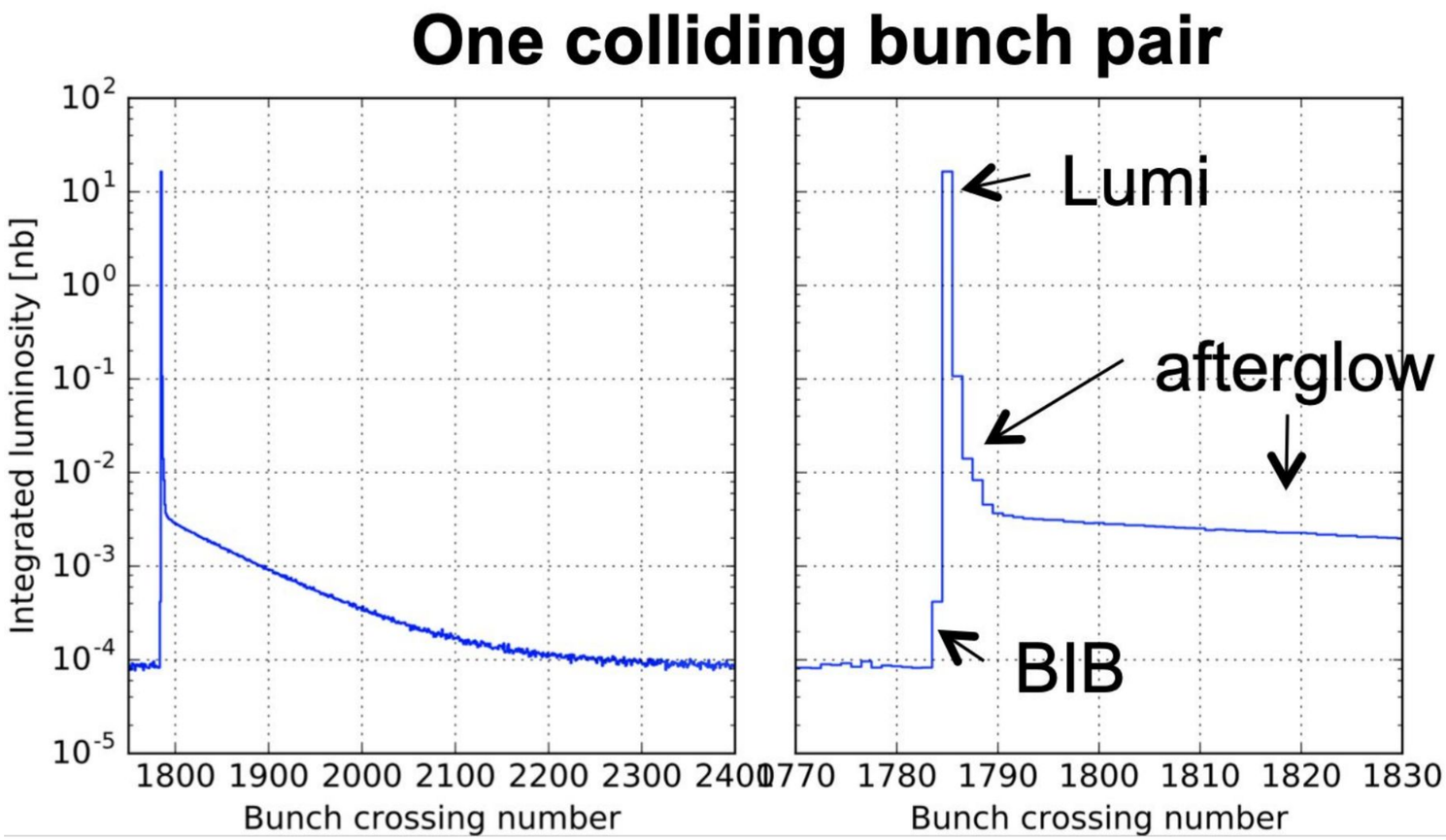
Luminosity uncertainty is dominant in key channels of physics interest



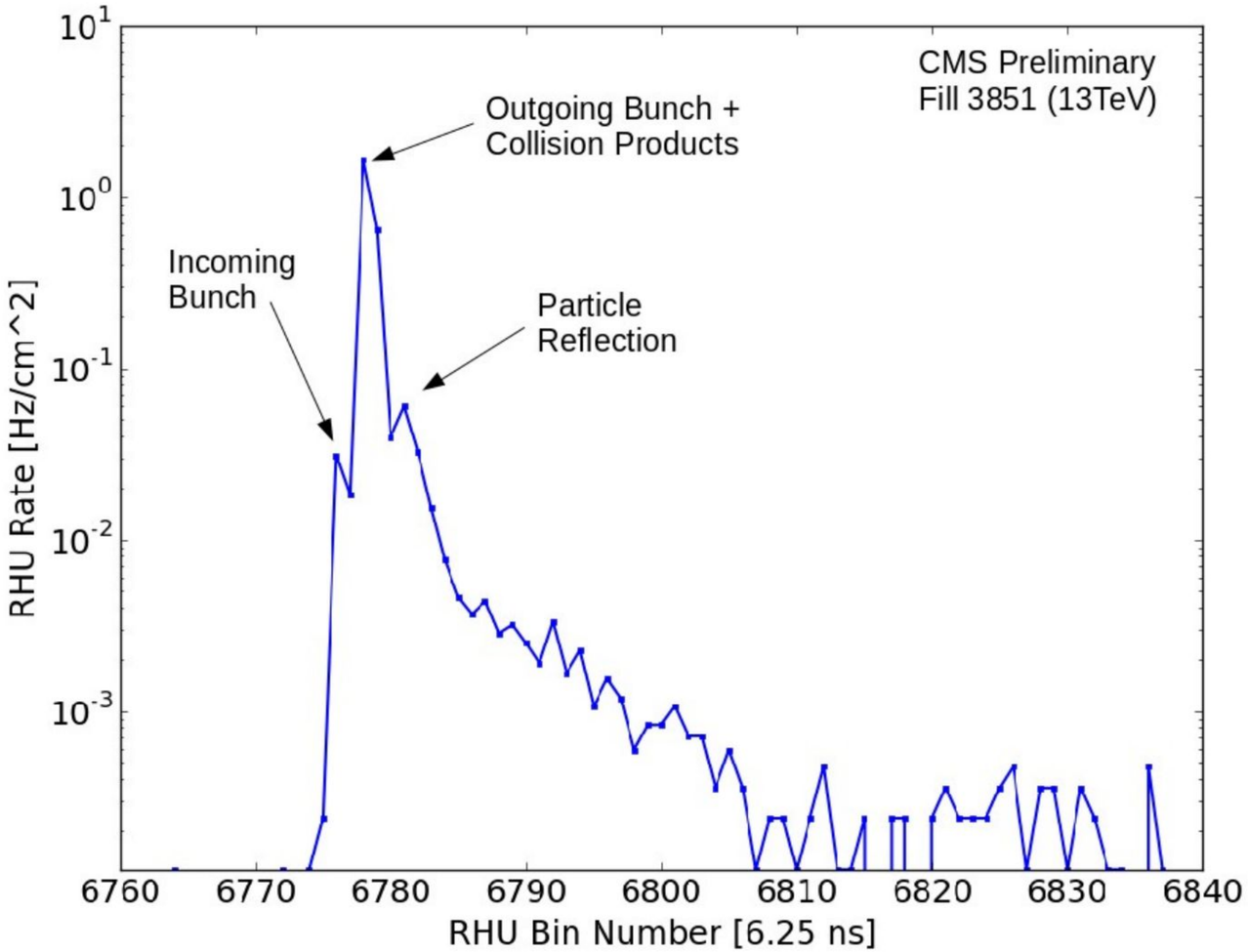


In the most precisely measured Higgs boson production process, gluon fusion (gg → H), and in Z boson production cross-section luminosity uncertainty will dominate the experimental uncertainty at HL-LHC even with the target 1% precision and will remain significant even when including the expected theoretical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

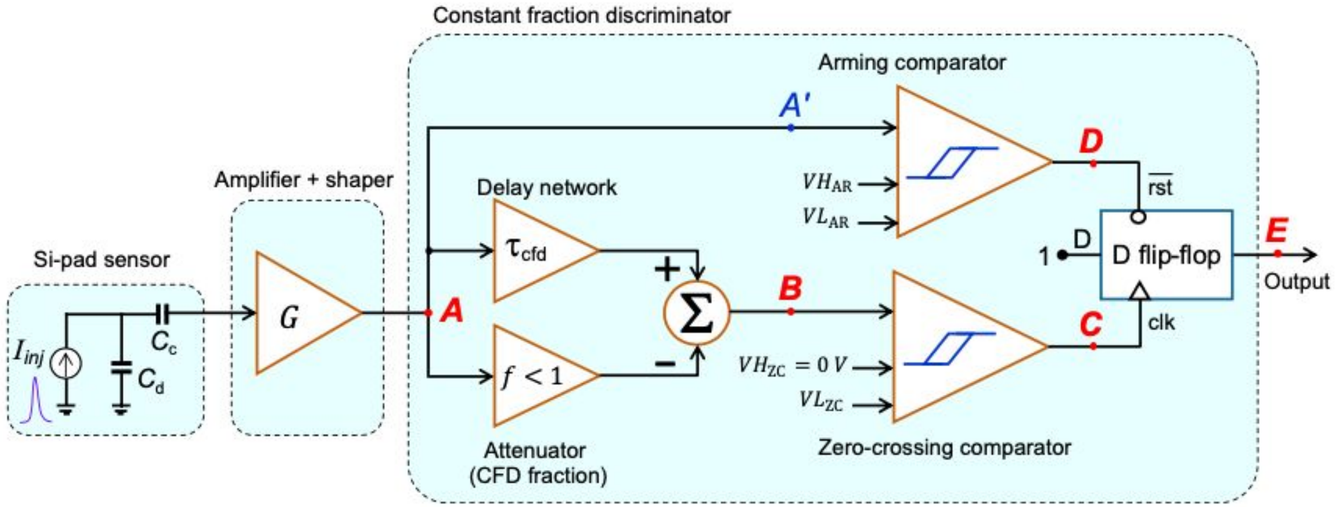
Afterglow of a single colliding bunch

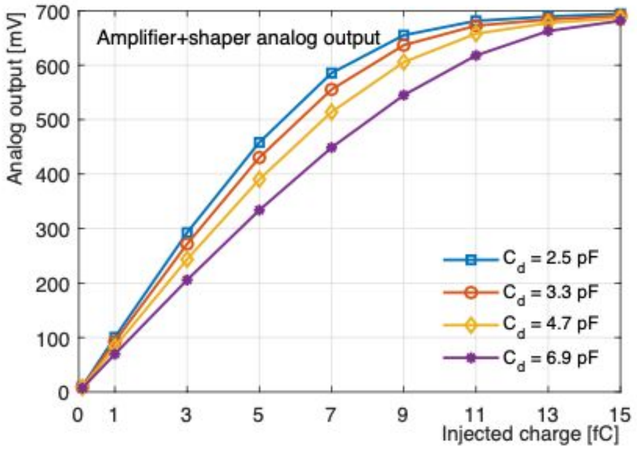


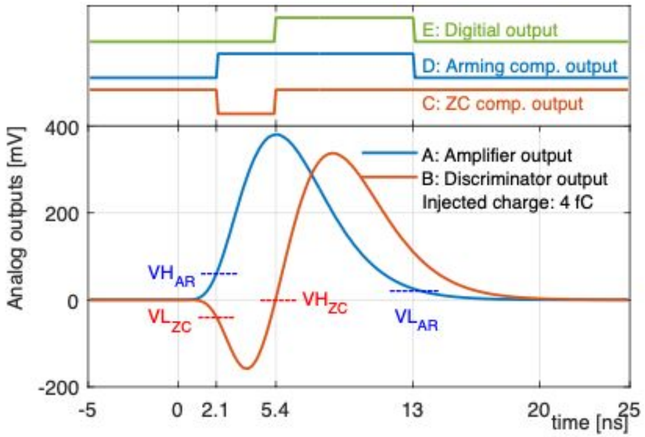
VME MIB


CMS Preliminary
Fill 3851 (13TeV)
Outgoing Bunch +
Collision Products
Incoming
Bunch
Particle
Reflection
RHU Rate [Hz/cm^2]
RHU Bin Number [6.25 ns]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
6760
6770
6780
6790
6800
6810
6820
6830
6840

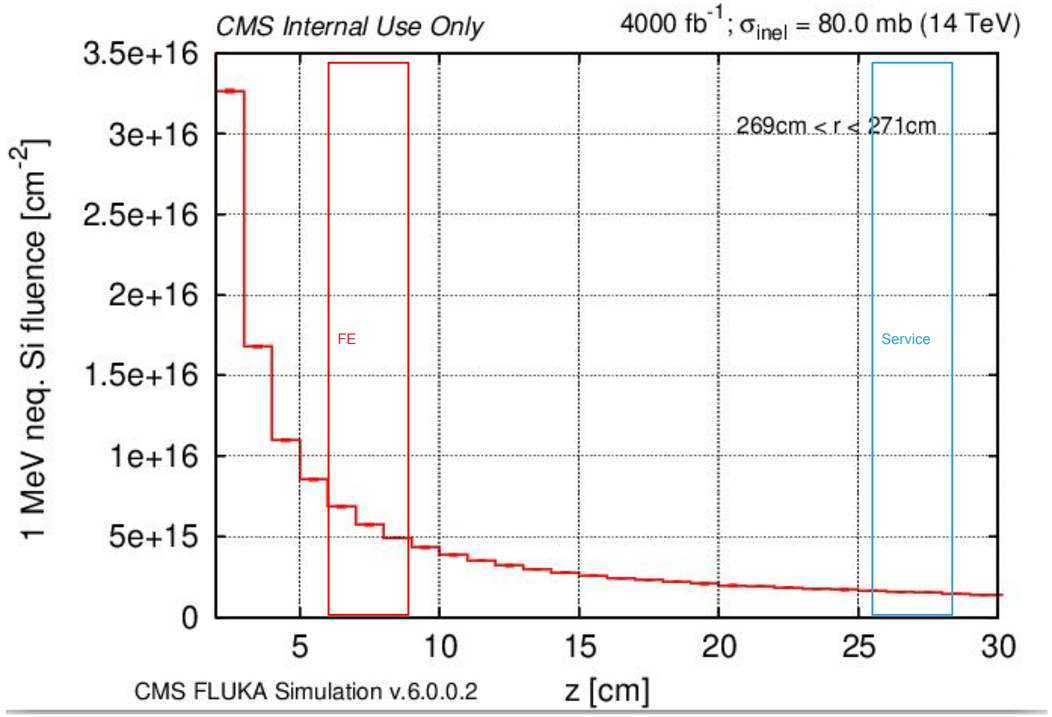
FBCM Potential CFD design



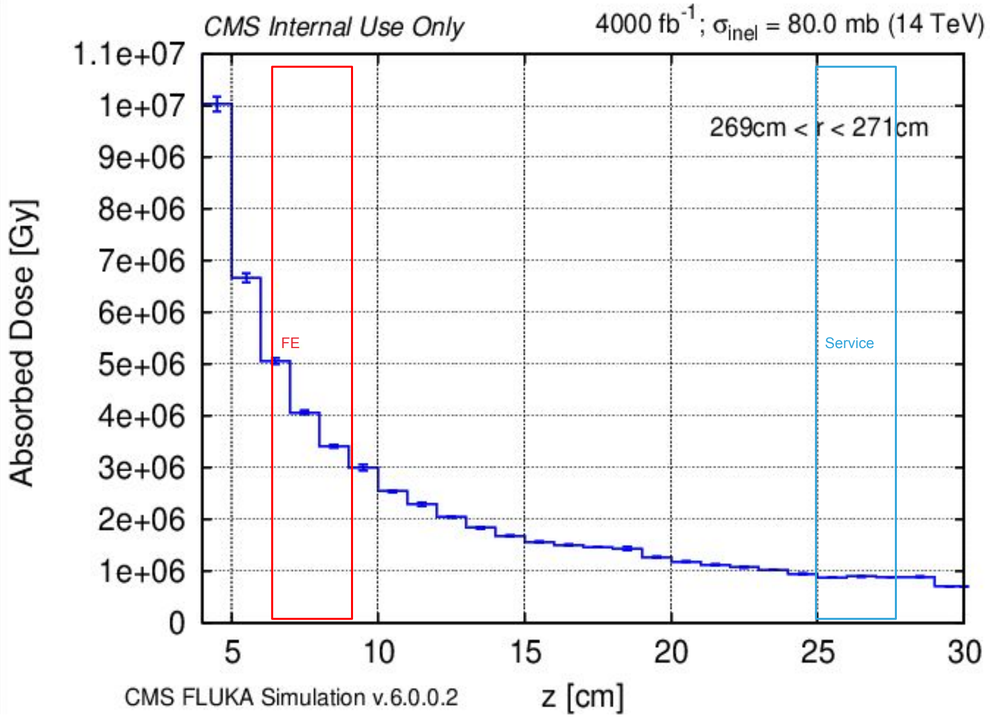




Radiation Levels

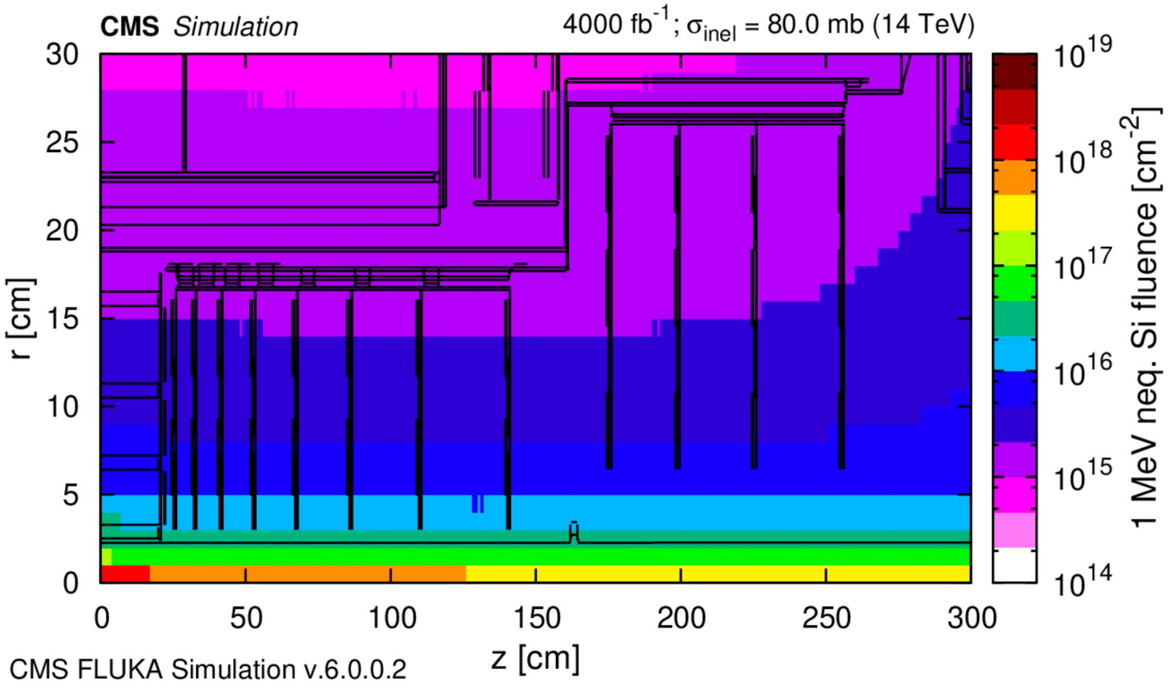


DD

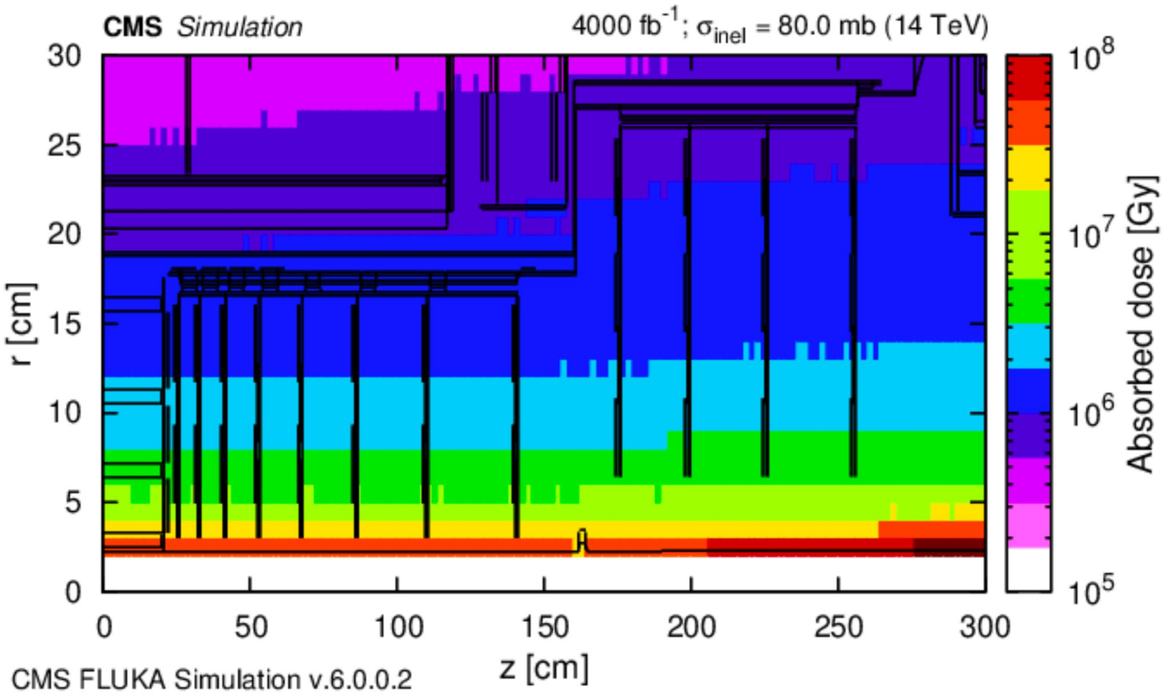


TID

Radiation Levels



Integrated particle fluence



Total Ionising Dose