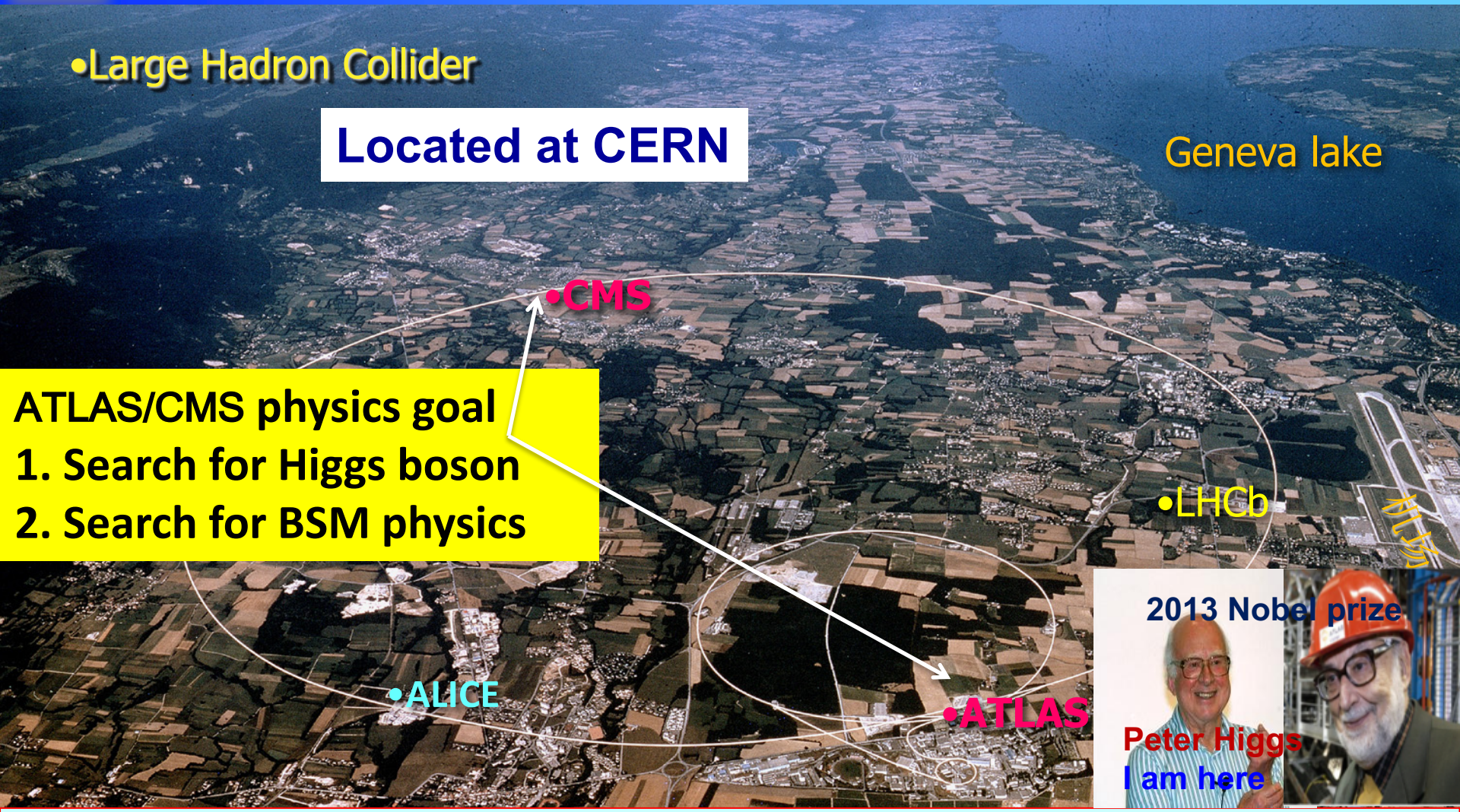
CMS upgrade

Huaqiao Zhang (IHEP)

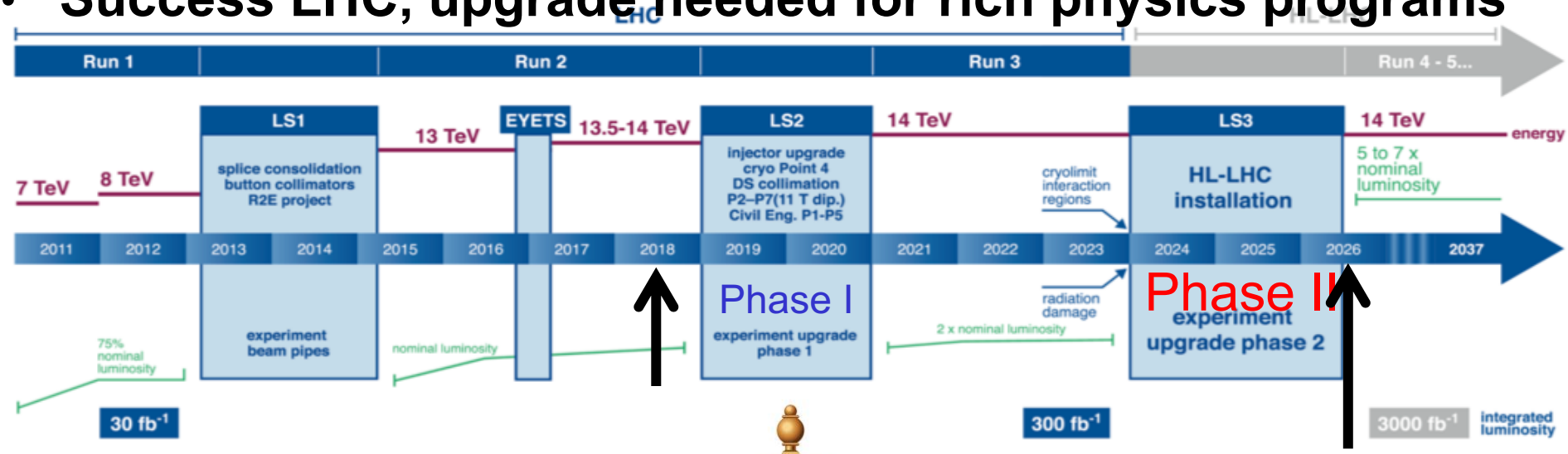
Large Hadron Collider (LHC)

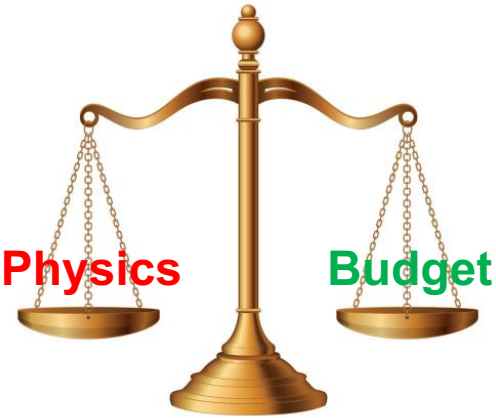


- 27km, 100m underground, ¼ in Switzerland, ¾ in France
- Designed Ecm 14TeV(14×10^{12}eV) for p–p collisions

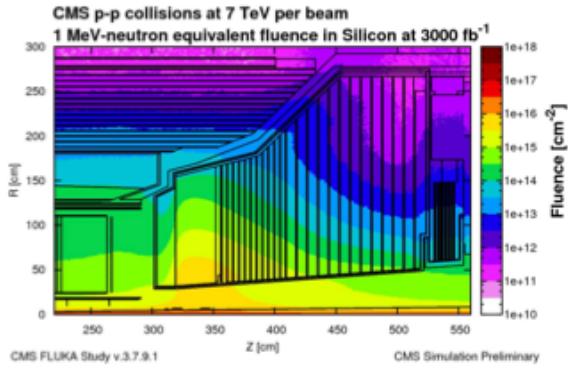
LHC operation Roadmap

- **Success LHC, upgrade needed for rich physics programs**

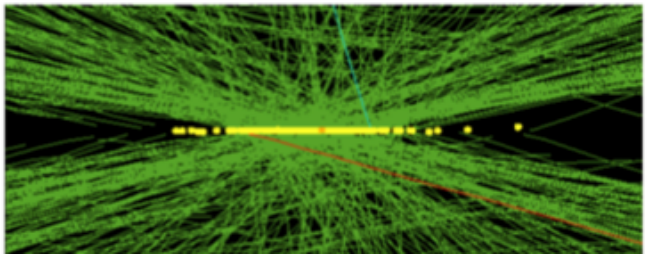




Radiation damage



Pileup challenge



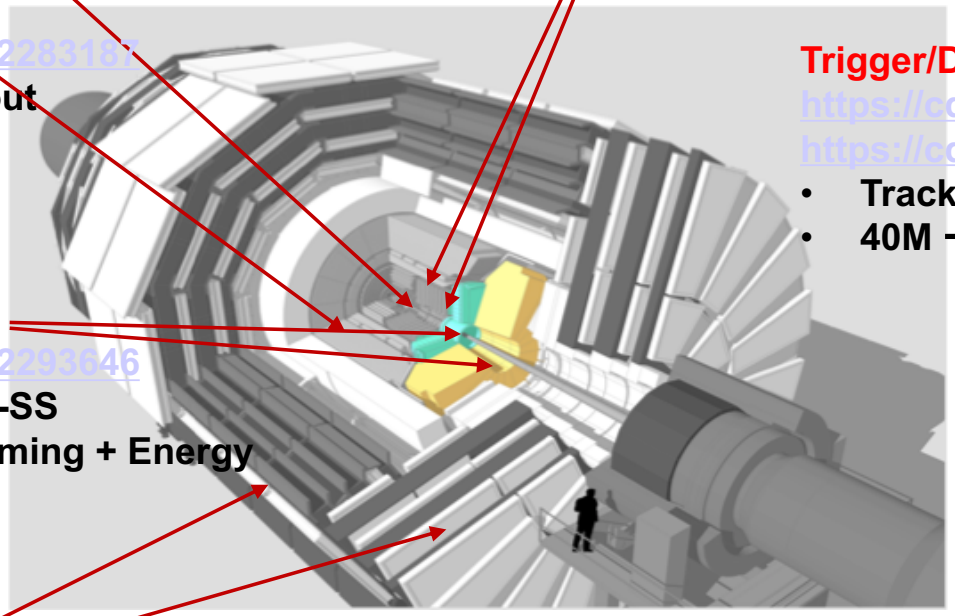
Event rates capability

Overview of CMS phase II upgrade

Tracker: https://cds.cern.ch/record/2272264
- Si-strips and Pixels increased granularity
- Tracking in L1-Trigger
- Coverage extended to |eta|~3.8

MIP Timing detector:
https://cds.cern.ch/record/2296612
- ~30ps timing resolution
- Barrel: Crystals + SiPMs
- Endcap layer: LG Avalanche Diodes

Barrel Calorimeter:
https://cds.cern.ch/record/2283187
- New ECAL/HCAL readout



Trigger/DAQ:
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1
- 40M → 750k(PF-like) → 7.5k

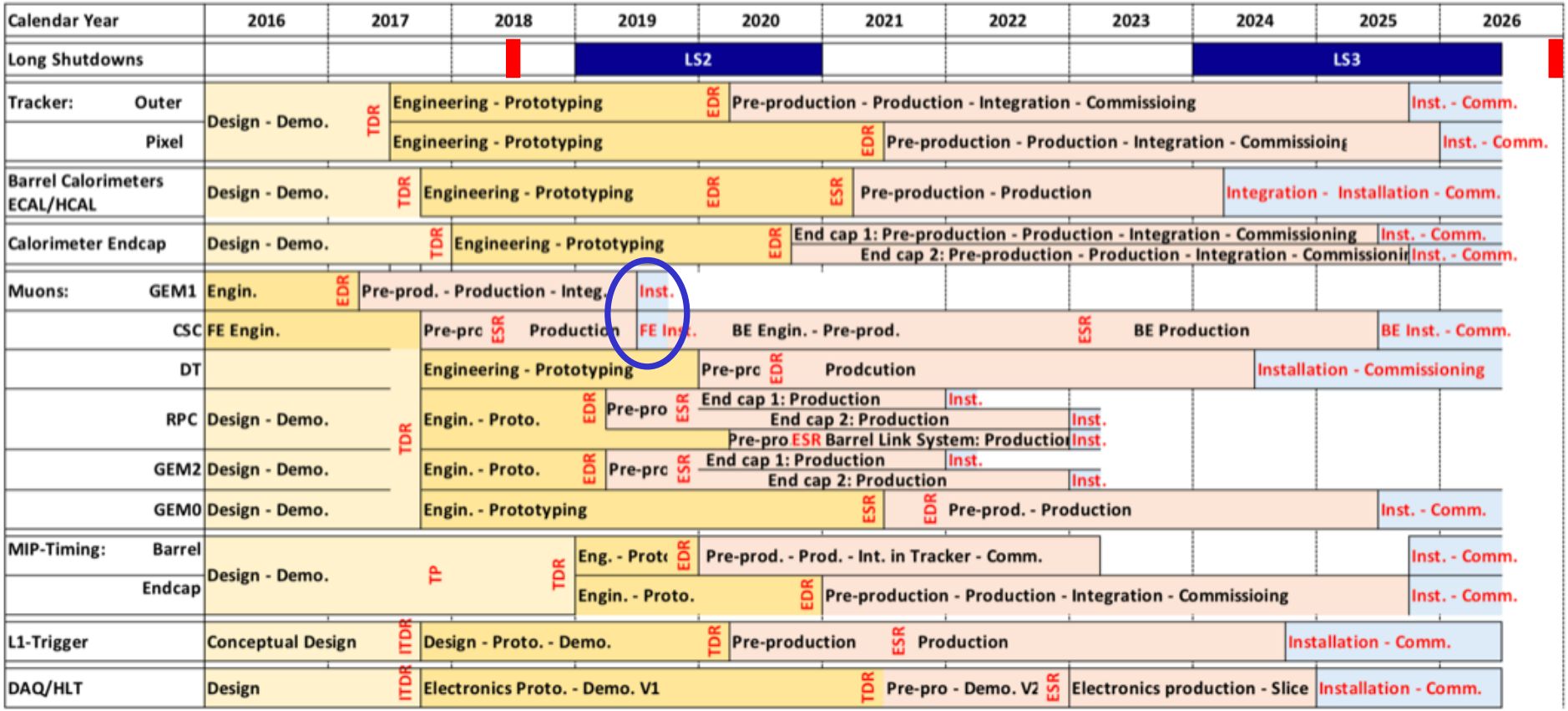
Calorimeter Endcap:
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D position + precise timing + Energy

Muon system: https://cds.cern.ch/record/2283189
- New FE/BE readout for DT/CSC
- New GEM/RPC 1.4 <|eta|<2.4
- Coverage extended to |eta|~3

Beam/Luminosity and common Infrastructure
https://cds.cern.ch/record/2020886

Timeline of CMS phase II upgrade

- LS2 (2019-2020):
  - GE1 and CSC FE for inner endcap disk 1-4
  - Beam pipe/magnet infrastructure
- LS3 (2024-2026): All other projects



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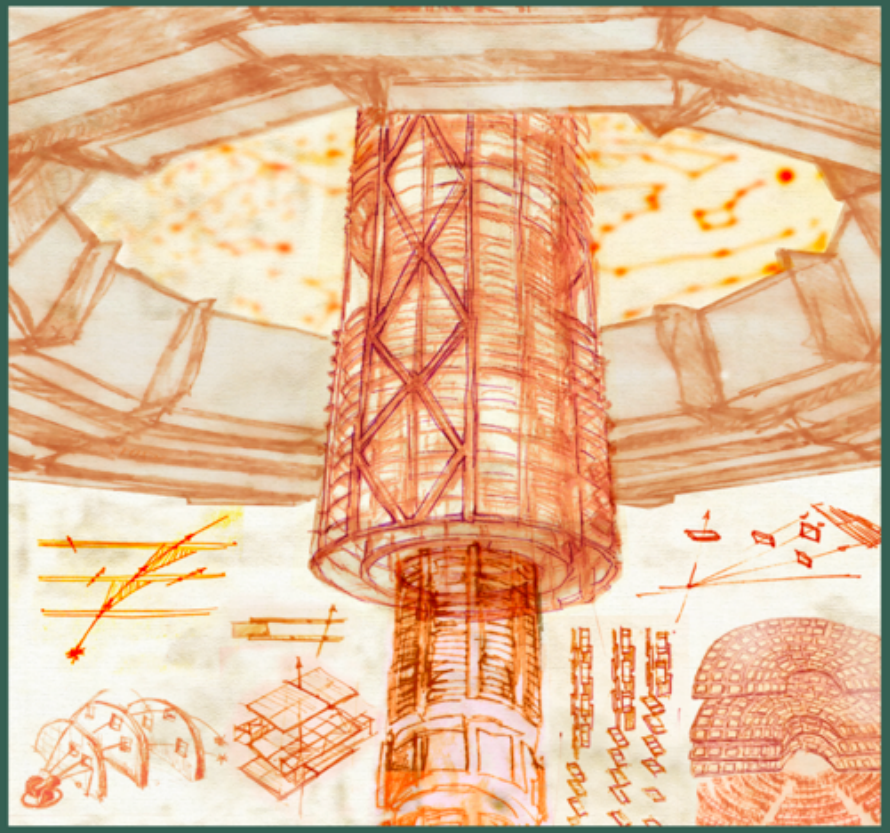
CERN-LHCC-2017-009
CMS-TDR-17-001
1 July 2017

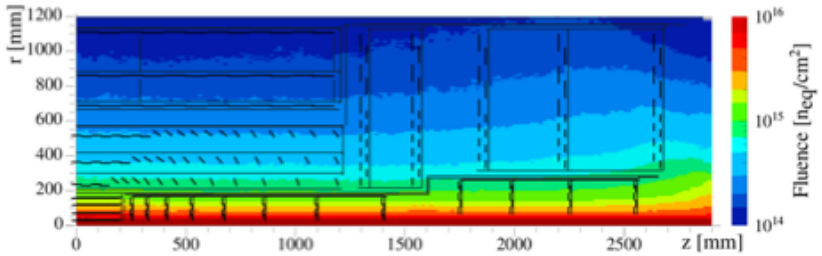
CMS

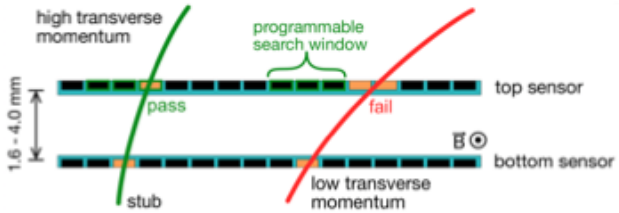


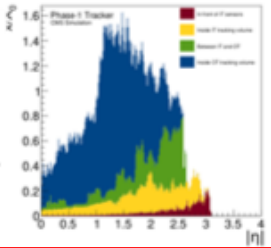
The Phase-2 Upgrade of the CMS Tracker Technical Design Report

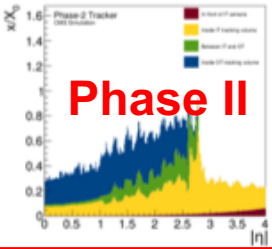
CMS Phase II Tracker design

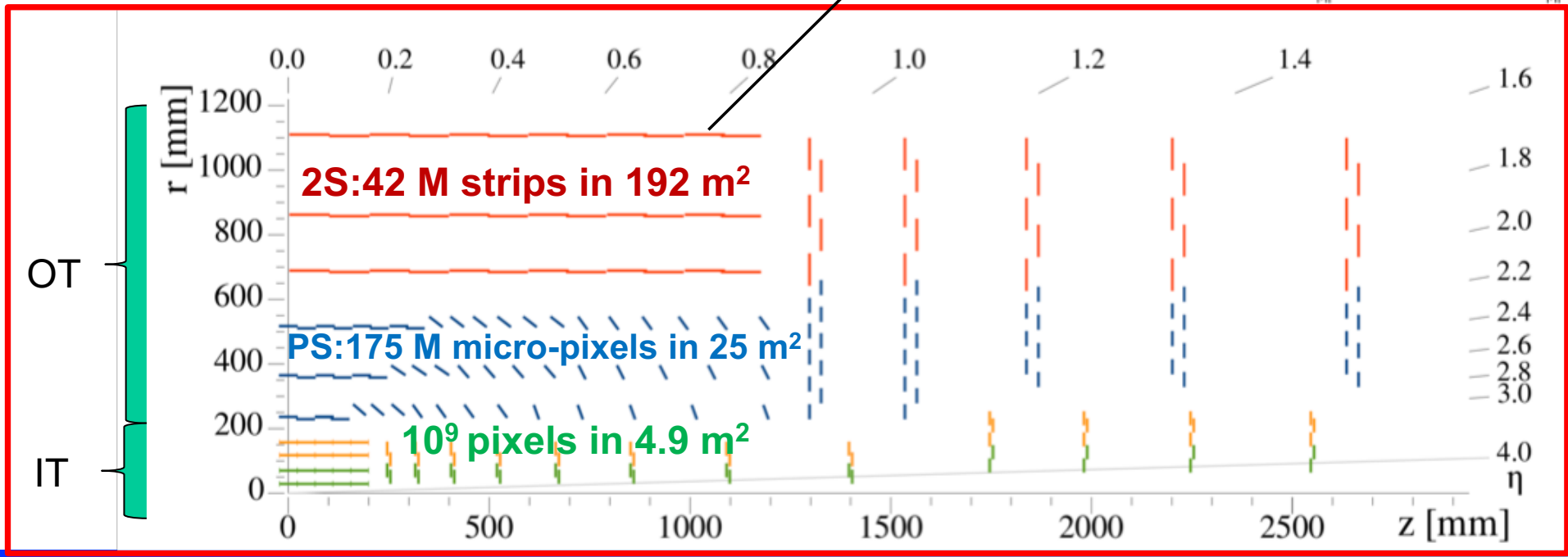
- Radiation: ~2.3*10^{16} MeV neq/cm^2
- 40 MHz input for L1-Trigger
- Increased granularity
  - OT Si-sensors ≃ 200μm thick - 90/100μm pitch - 2.5/5cm strips - 1.5 mm macro-pixels in inner layers
  - IT Si-silicon sensors ≤ 150μm thickness - 50x50 to 25x100μm² - large pixels in outer layers?
- Tilted 3 layers of inner OT
- Extend coverage |eta|<3.8
- Reduced material









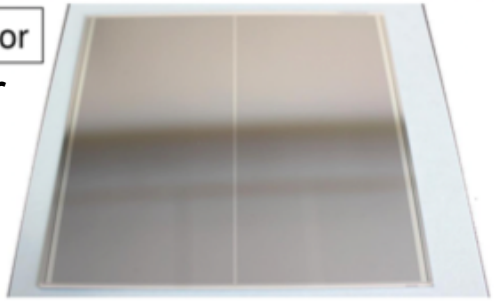


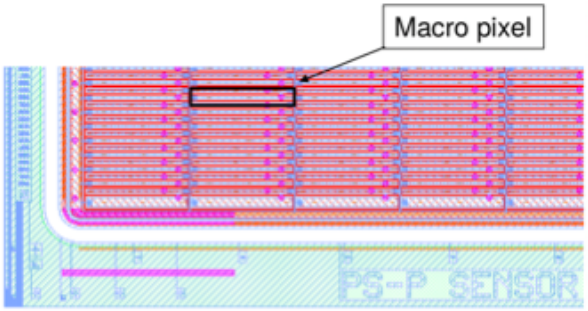
Phase II Silicon tracker sensor

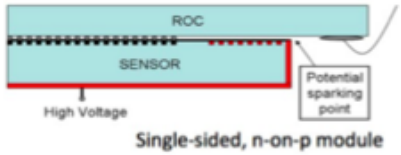
Sensor R&D

Outer Tracker: N-in-p planar sensor

- 200-240 micron active layer
- Bias ~800 V
- 3 different sensors
  - 2S: 10*10 cm2, 2032 strip, AC read-out by CBC, noise ~1000e
  - PS-s:5*10 cm2, 1920 strips, AC read-out by SSA, noise ~700 e
  - PS-p: 5*10 cm2, 30208 macro pixels, DC readout by MPA, noise ~175 e

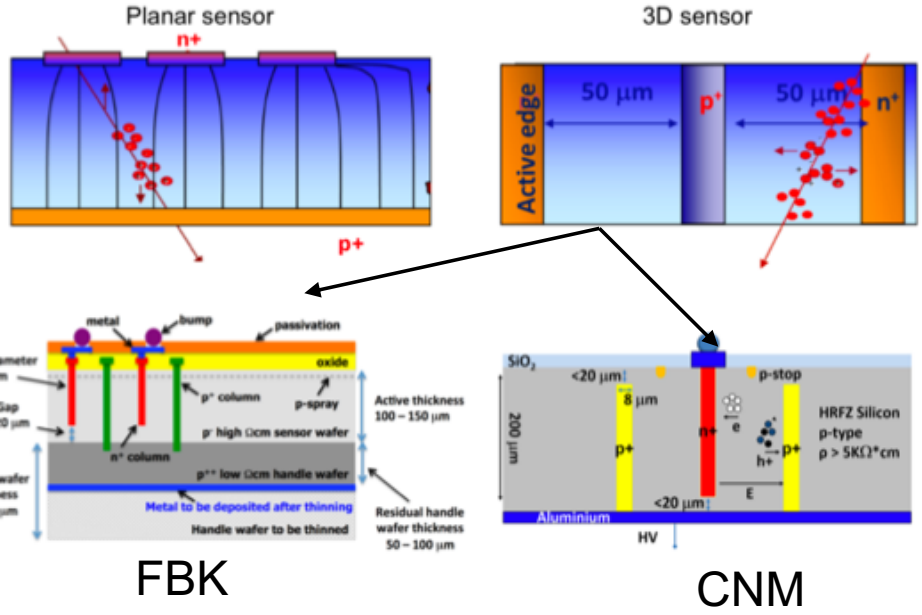






Inner tracker:

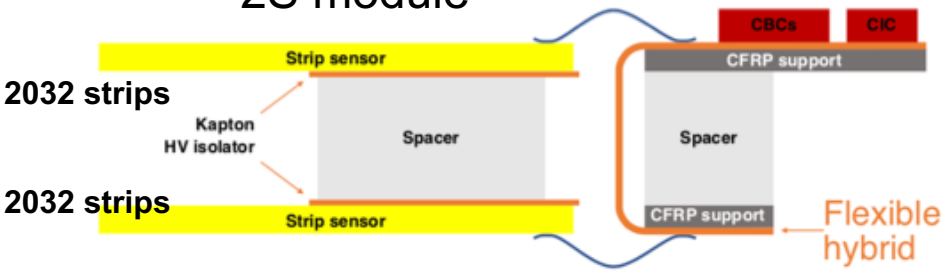
- Planar sensors: radiation hardness to be demonstrated, low signal
- 3D sensors: complex fabrication, high capacitance



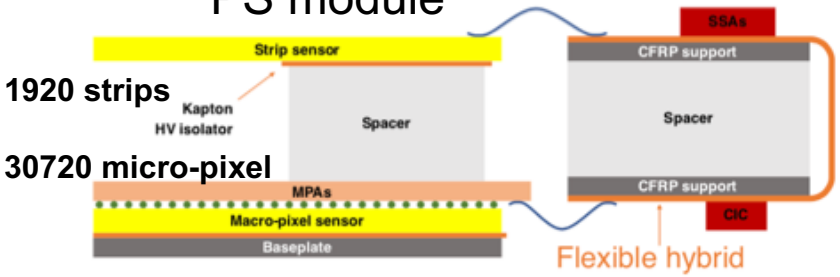
Many R&D efforts still ongoing, Global effort of silicon project at LHC

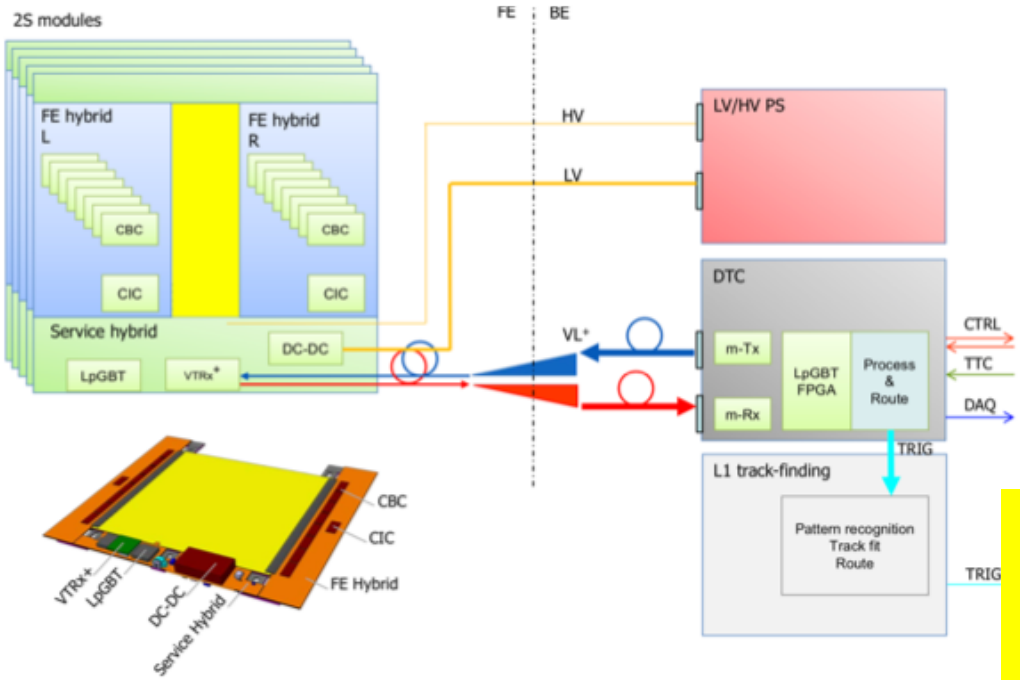
Outer tracker readout

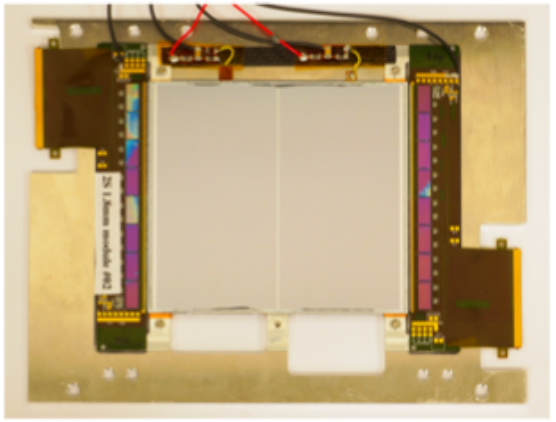
2S module



PS module



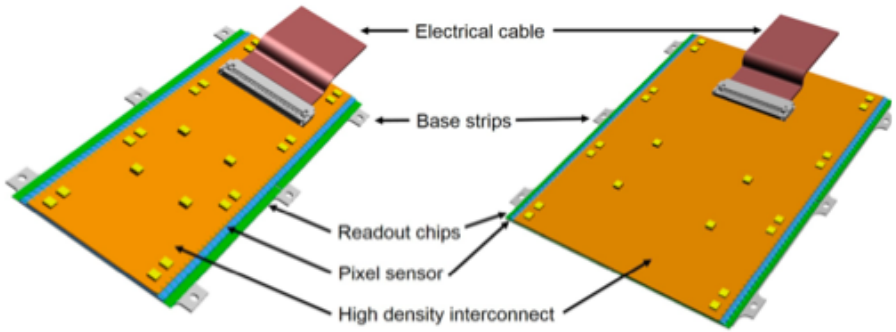




- Trigger data: 80%
- LpGBT: transfer data and distribute clock/control signal
- Filp-chip bump bonding for FE ASICs

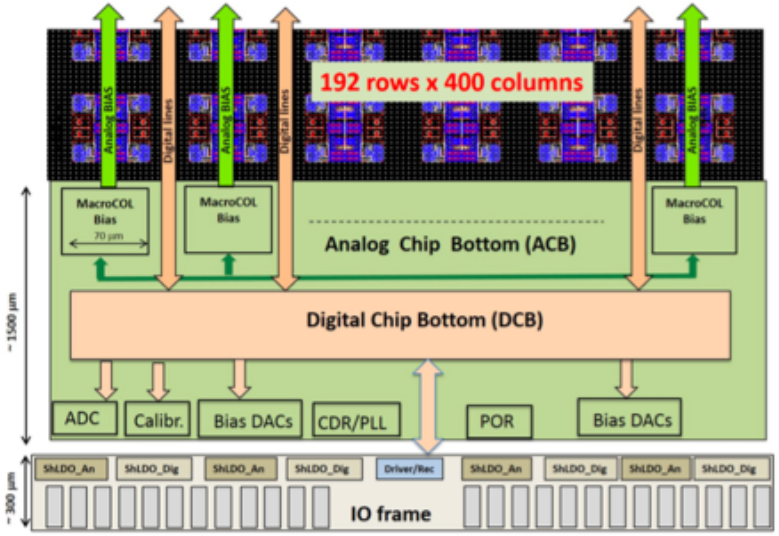
- **CBC3 available and fully functional**
- **MPA/SSA full size chip received**
- **CIC specs finalized**
- **lpGBT expect for users in 2018**
- **DC-DC powering**
- **Hybrids: new orders**

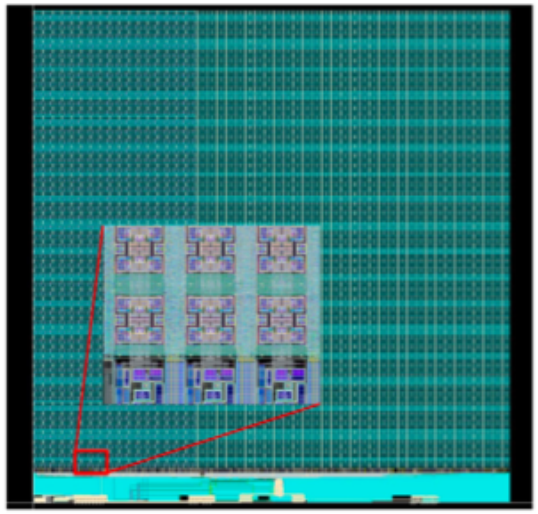
Inner Tracker readout



1*2(L) and 2*2(R) modules

Technology	65 nm CMOS
Chip size	22 mm × (16.4 mm + 2 mm)
Pixel size	50 × 50 μm^2, 25 × 100 μm^2
Number of pixels	144 320
Detector capacitance	< 100 fF (200 fF for edge pixels)
Detector leakage current	< 10 nA (20 nA for edge pixels)
Detection threshold	< 600 e-
In-time threshold	< 1200 e-
Hit rate	< 3 GHz/cm^2
Noise hit occupancy	< 10^{-6}
Charge resolution	4 bit ToT (Time over Threshold)
Pixel region organization	2 × 2 pixels (alternatively 4 × 1 or 4 × 4)
Hit buffer depth (2 × 2 region)	≥ 8 (for 12.5 μs latency)
Hit loss (dead-time + buffer loss)	< 1% at 3 GHz/cm^2
Trigger rate	≤ 1 MHz
Readout data rate	1–4 links at 1.28 Gb/s = max. 5.12 Gb/s
Radiation tolerance	500 Mrad, 1 × 10^{16} n_{eq}/cm^2 at −15 °C
SEU affecting whole chip	< 0.05/hr/chip at 1.5 GHz/cm^2 particle flux
Power consumption at max. hit/trigger rate	< 1 W/cm^2 including SLDO losses
Temperature range	−40 °C to +40 °C



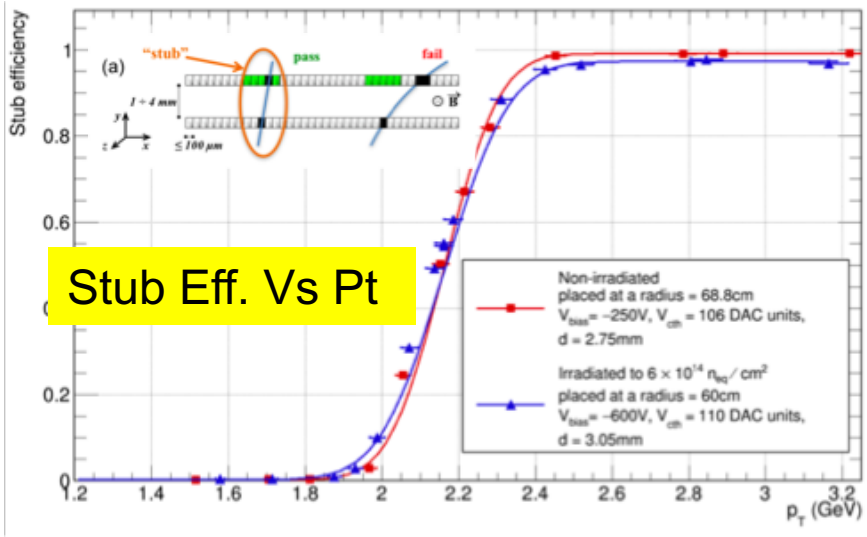


ASIC chip developed by RD53 collaboration for both ATLAS and CMS detectors

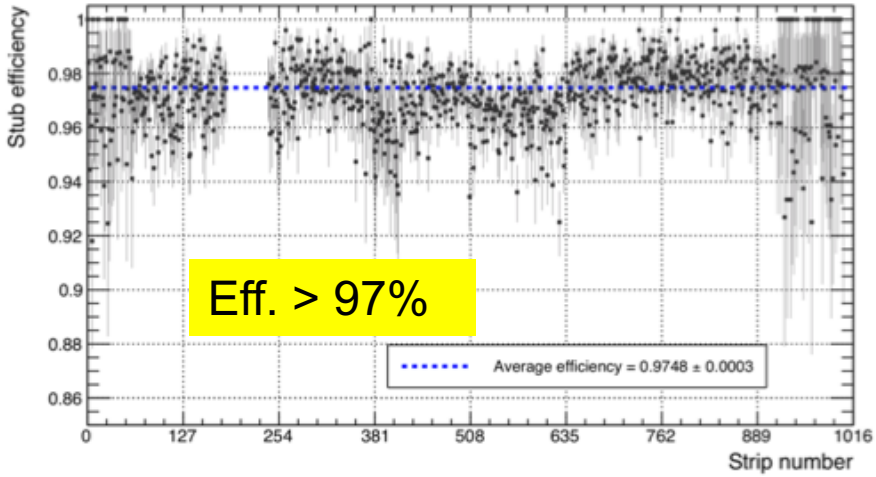
Functional overview and detailed layer out of the demonstrator chip

Phase II Tracker performance

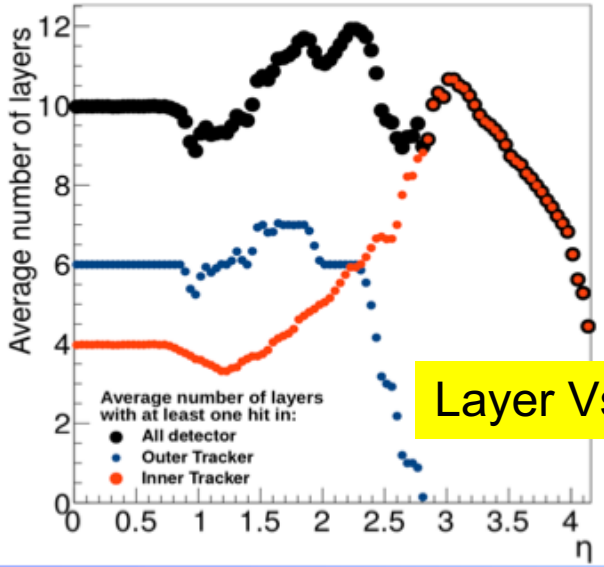
- Tracking efficiency is robust w.r.t. radiation and pileup



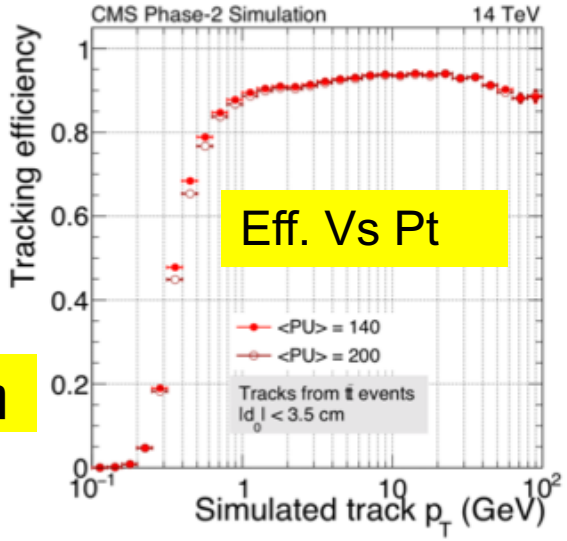
Stub Eff. Vs Pt



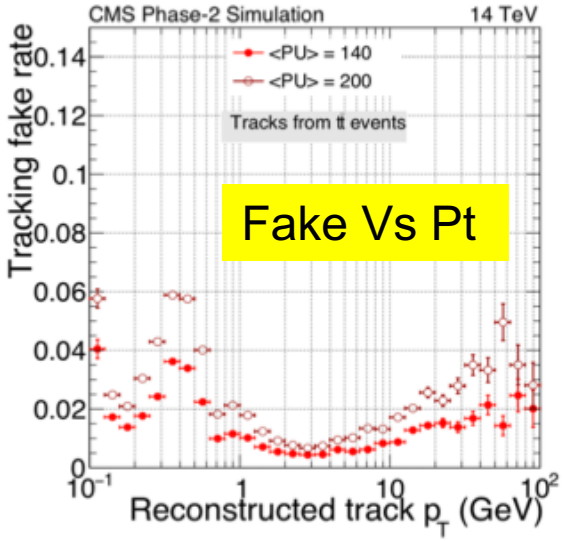
Eff. > 97%



Layer Vs η



Eff. Vs Pt



Fake Vs Pt

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CERN-LHCC-2017-023
CMS-TDR-019
9 Apr 2018

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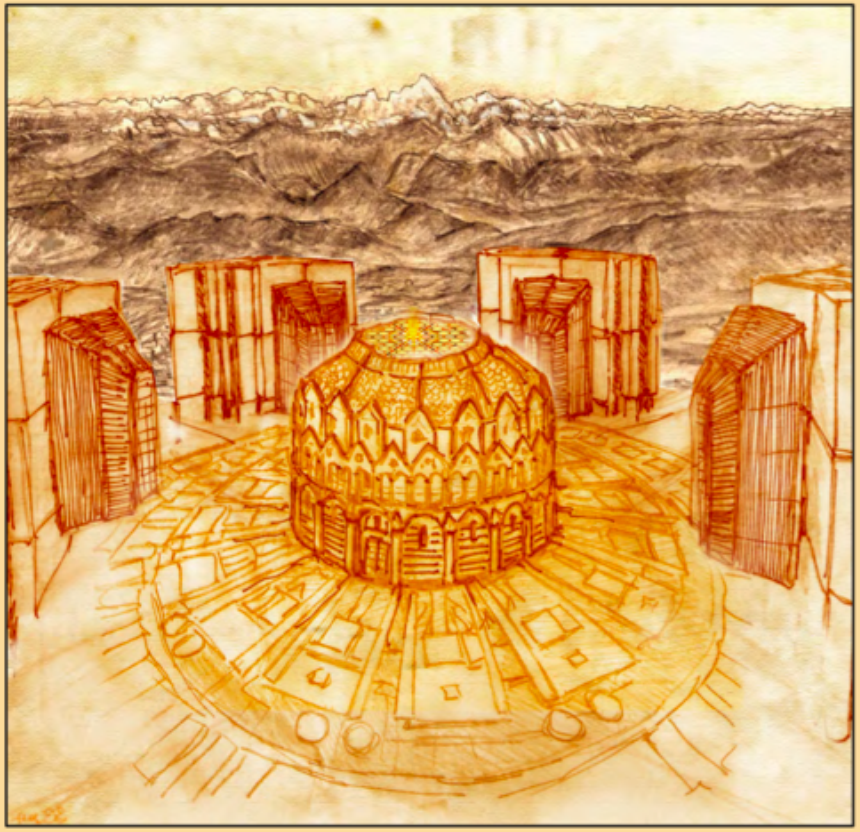

The Phase-2 Upgrade of the
CMS Endcap Calorimeter
Technical Design Report

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CERN-LHCC-2017-011
CMS-TDR-17-002
12 Sept 2017

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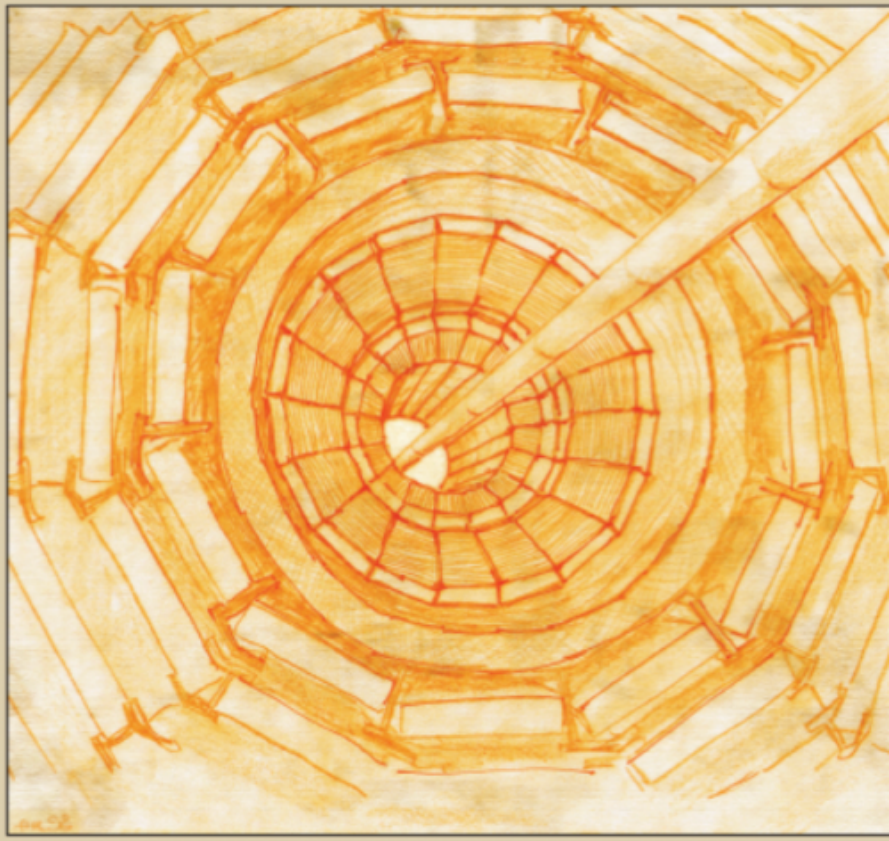
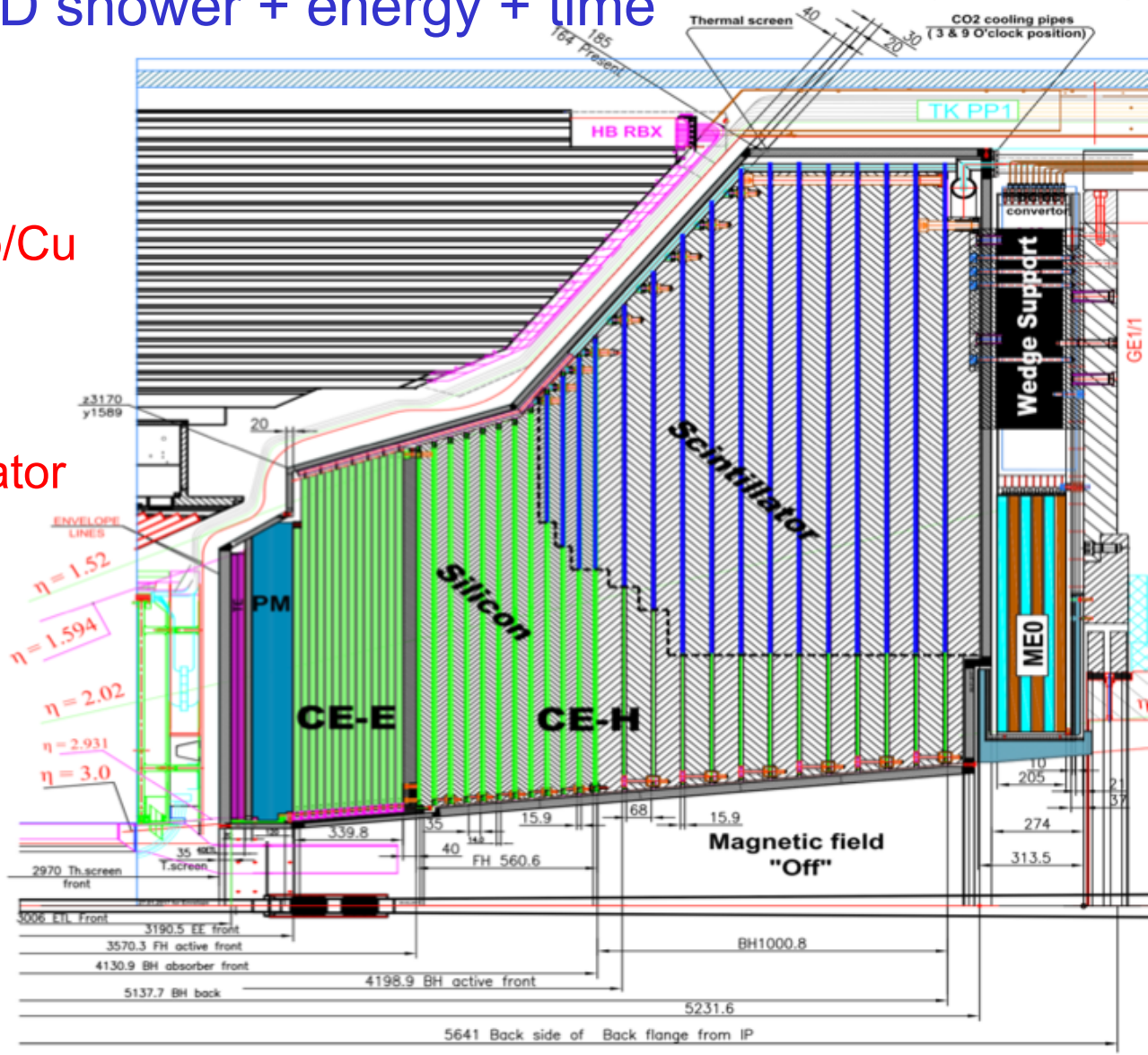


The Phase-2 Upgrade of the
CMS Barrel Calorimeters
Technical Design Report

The Phase II EndCap Calorimeter Overview

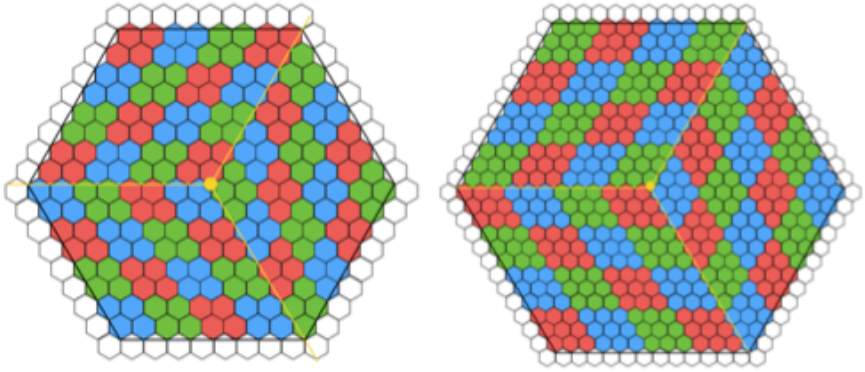
- New Calorimeter: 3D shower + energy + time
  - Ecal + Hcal
- Ecal (CE-E)
  - 28 layers Si + W/Pb/Cu
  - 25 X_0 & ~1.3λ
- Hcal (CE-H)
  - 24 layers Si/Scintillator

  + Stainless Steel
  - ~8.5λ
- Total Silicon:
  - 600 m^2
- Total scintillator
  - 500 m^2
- 6 M Channels

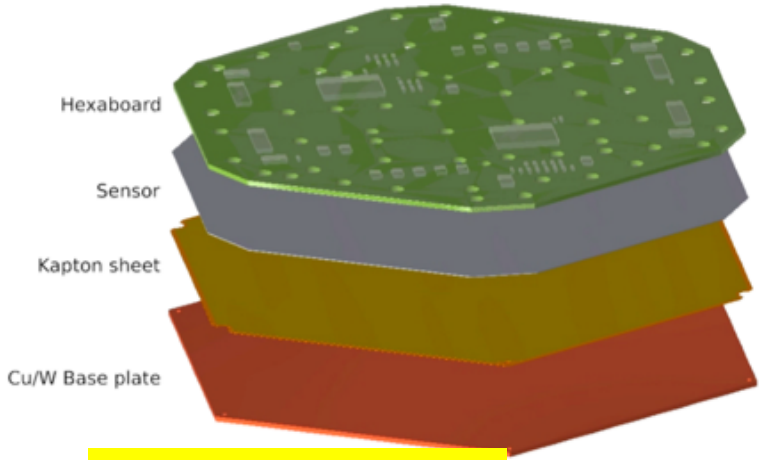


The HGCal design

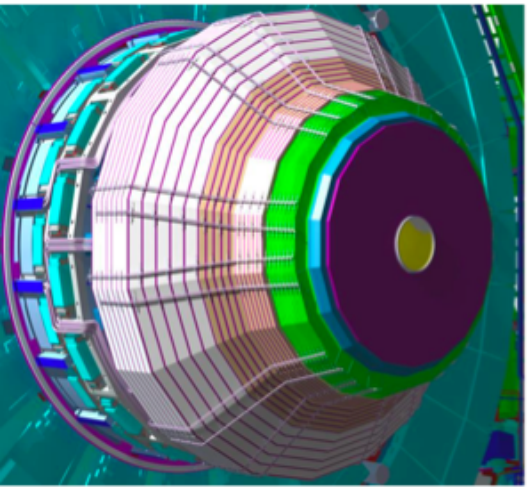
8inch, 1.18cm^2(192) / 0.52cm^2(432)

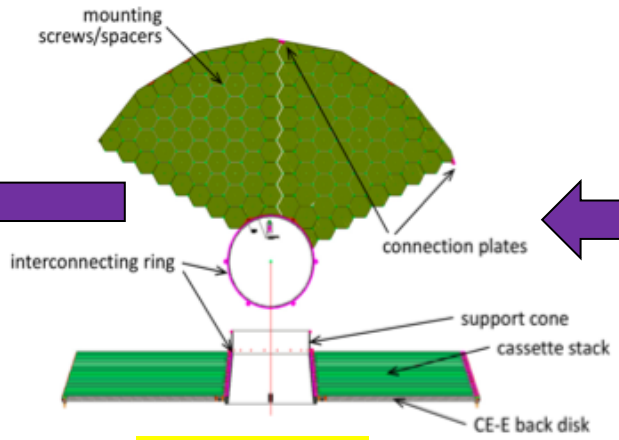


Sensors (Hexagon)

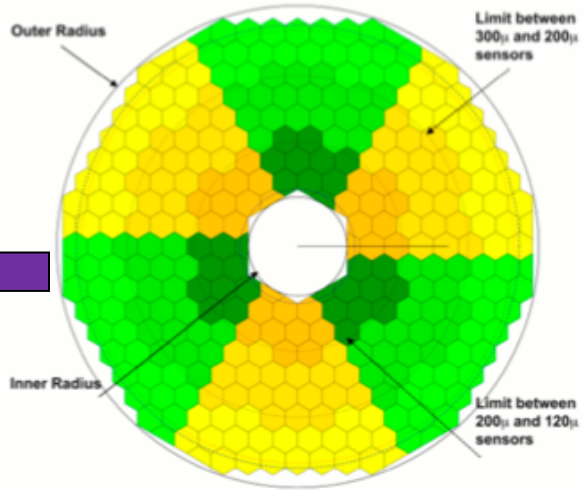


Module Assembly



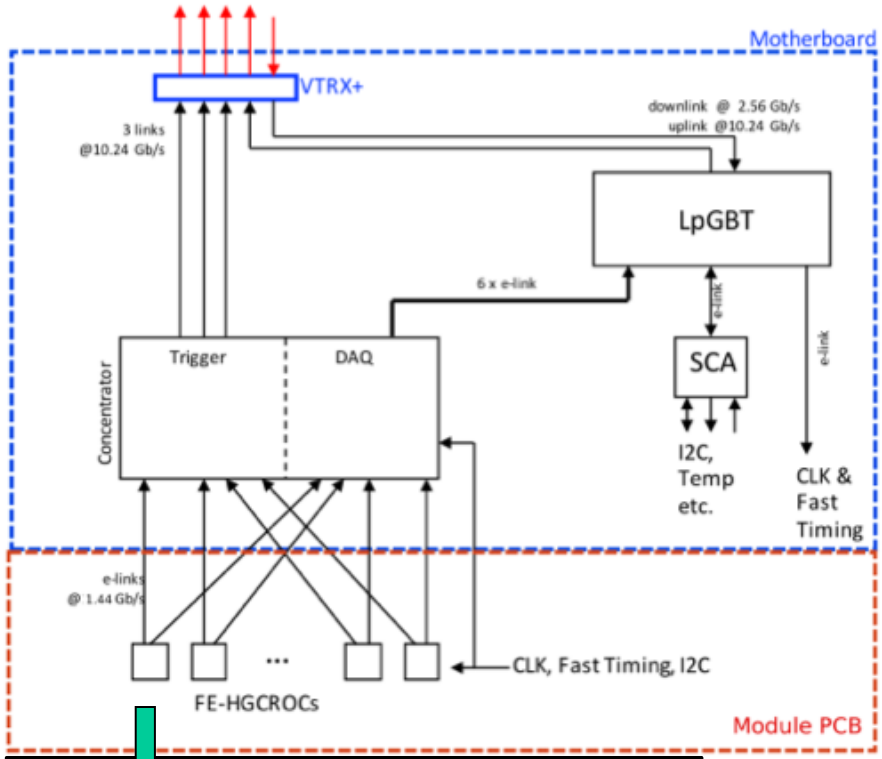


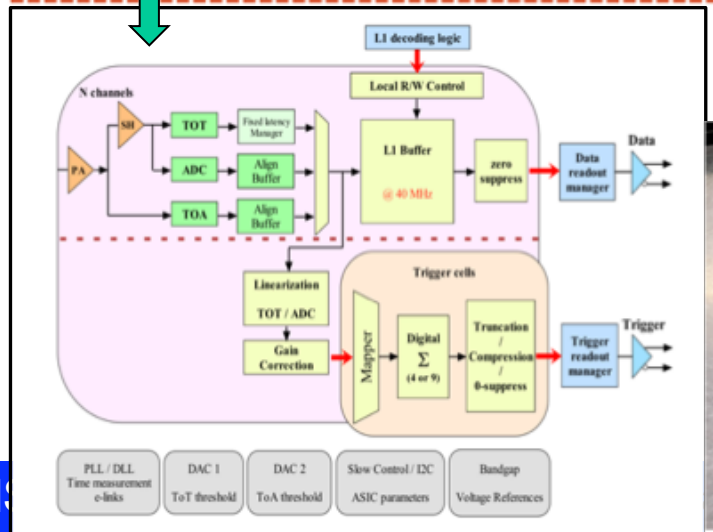
Stacking

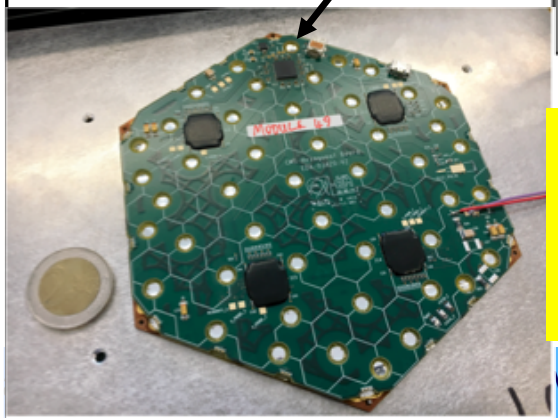


Tiling

HGCal readout

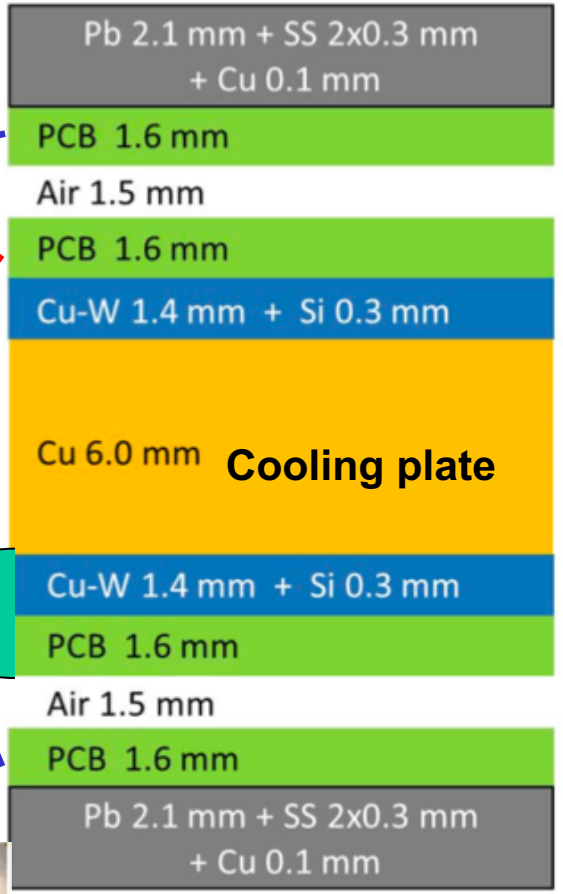






Motherboard

Module PCB

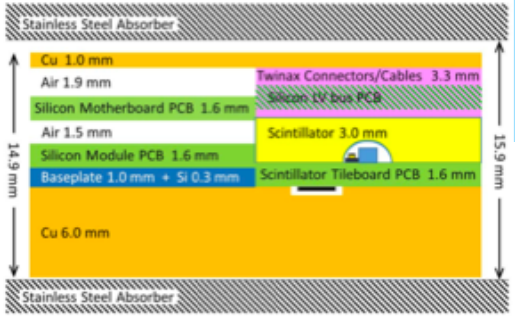


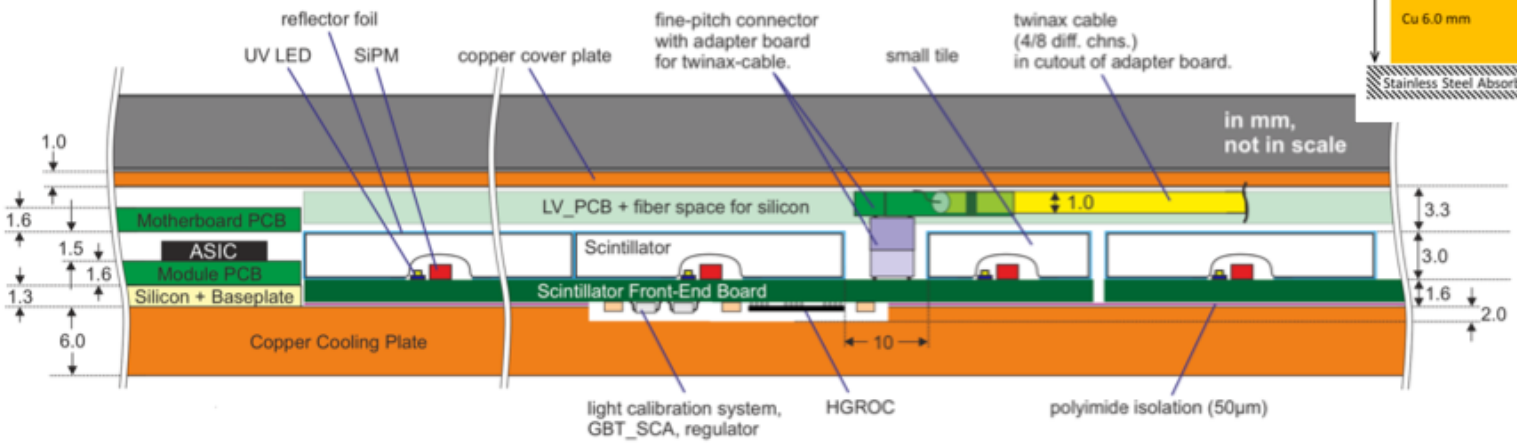
FE developed from SKIROC

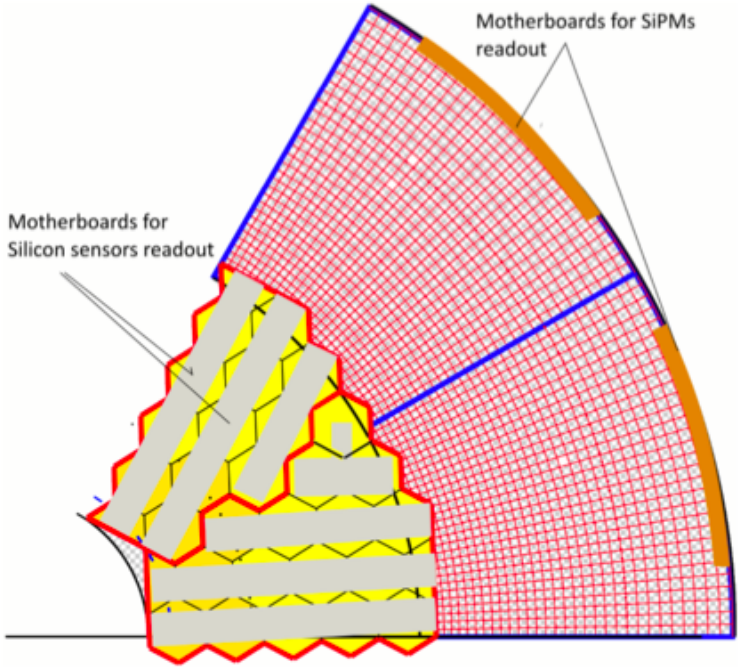
HGCROC V1 is under test

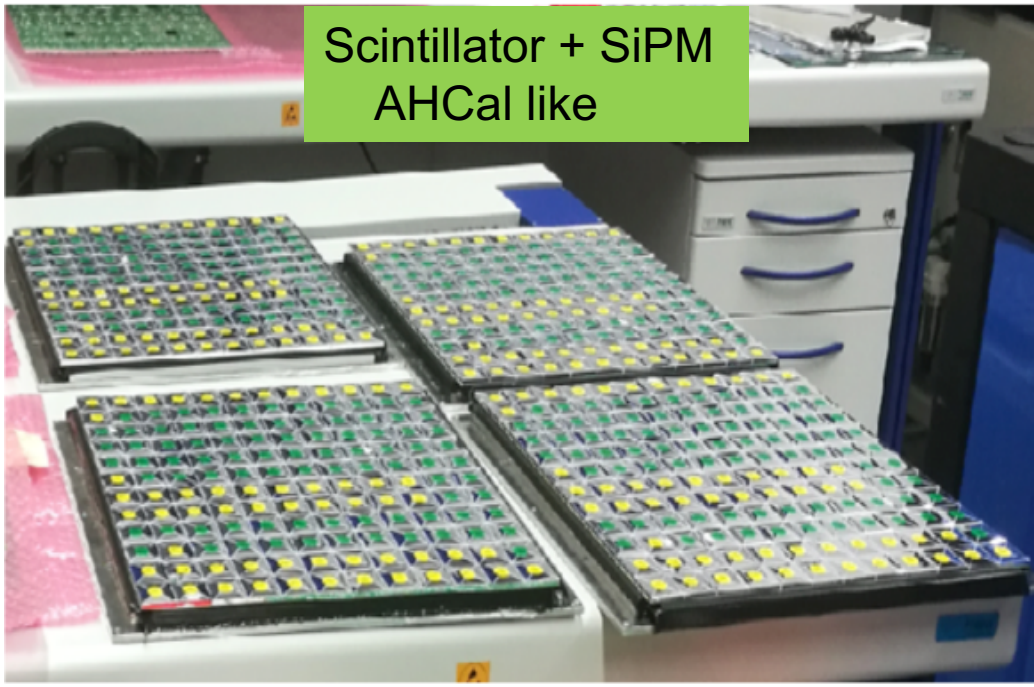
Final version expected in 2019

HGCal hadronic calor



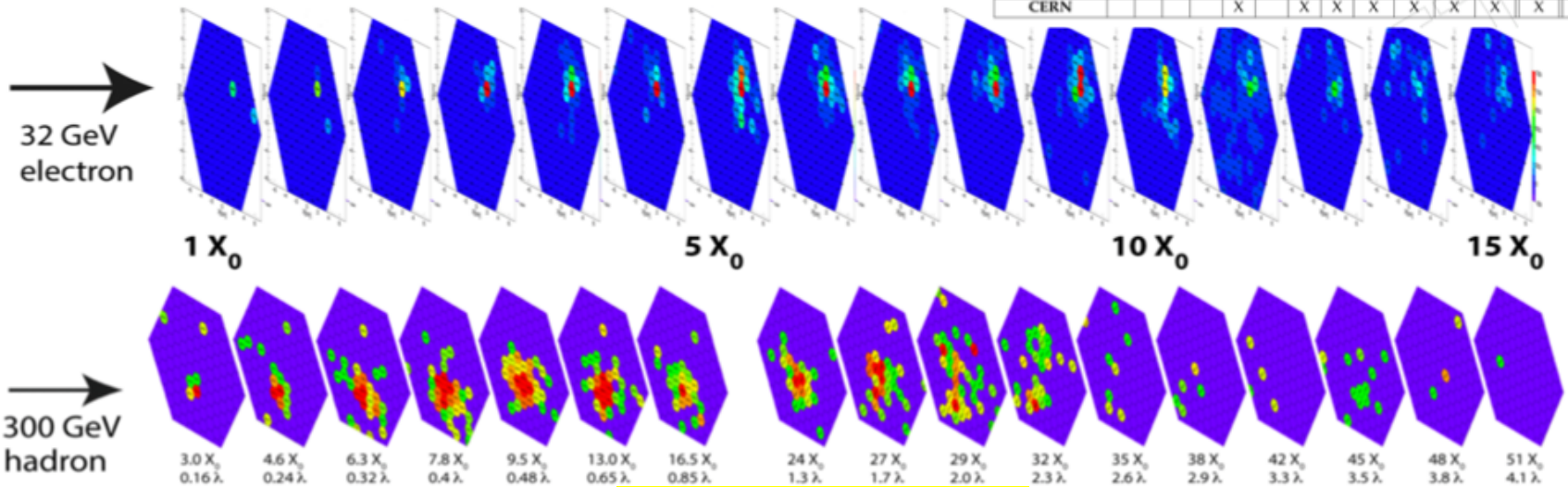




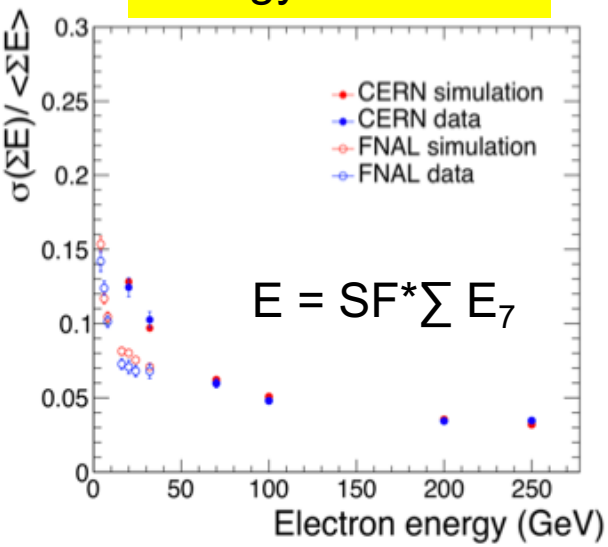


HGCal performance from beam test

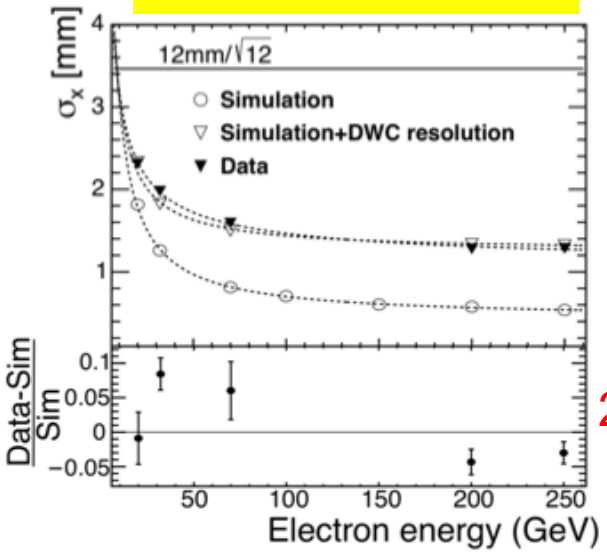
	e^-												π^-	p^+	μ^-
Energy (GeV)	4	6	8	16	20	24	32	70	100	150	200	250	125	120	30-120
FNAL	X	X	X	X	X	X	X							X	
CERN					X		X	X	X	X	X	X	X		X



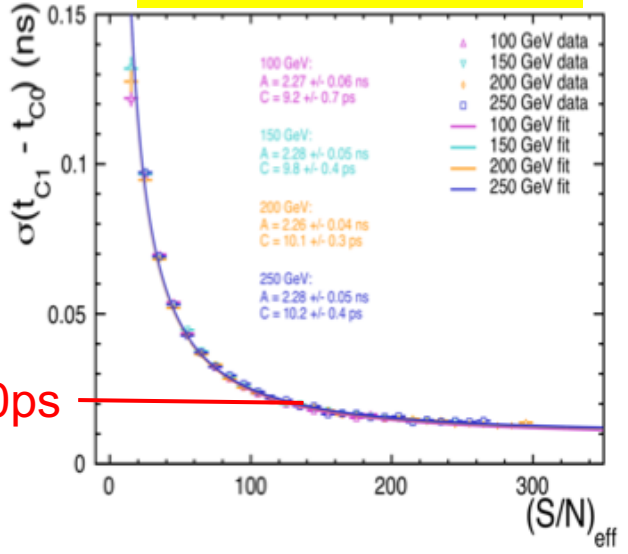
Energy resolution



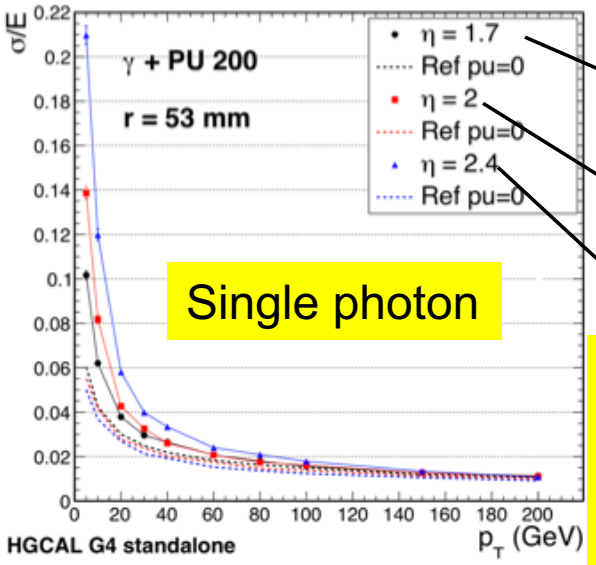
Position resolution



Timing resolution



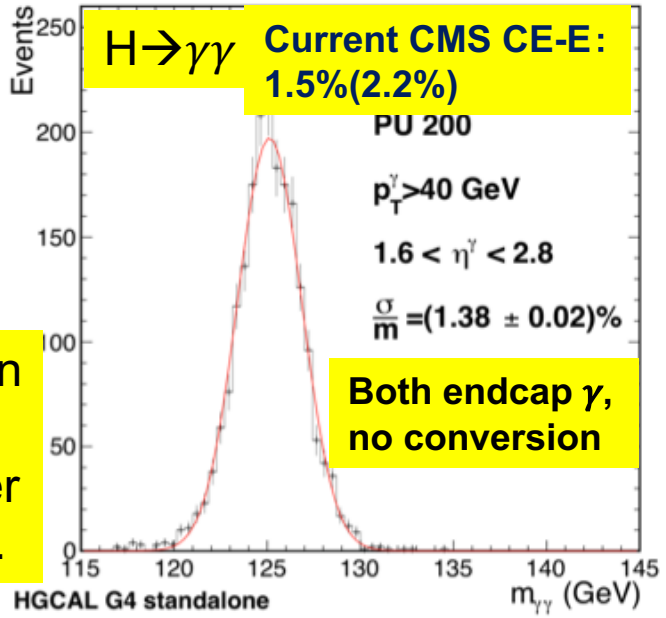
Energy resolution (not-optimal)

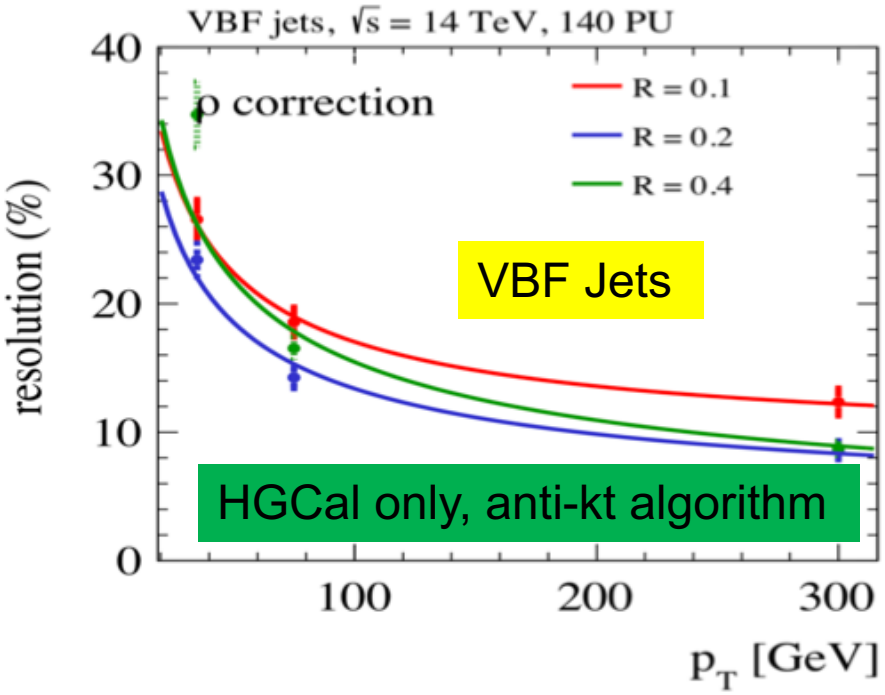


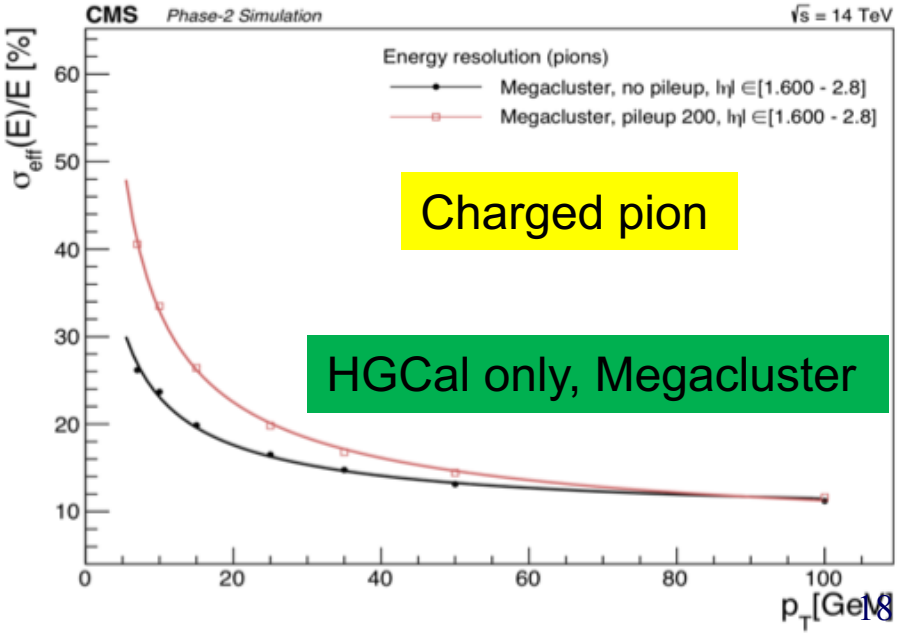
Single photon

Si (um)	stochastic	const
300	23/√E %	0.5%
200	25/√E %	0.5%
100	27/√E %	0.5%

Comparable energy resolution
Lots of potential:
timing, 3D shower, trigger
backpointing, pileup prof.

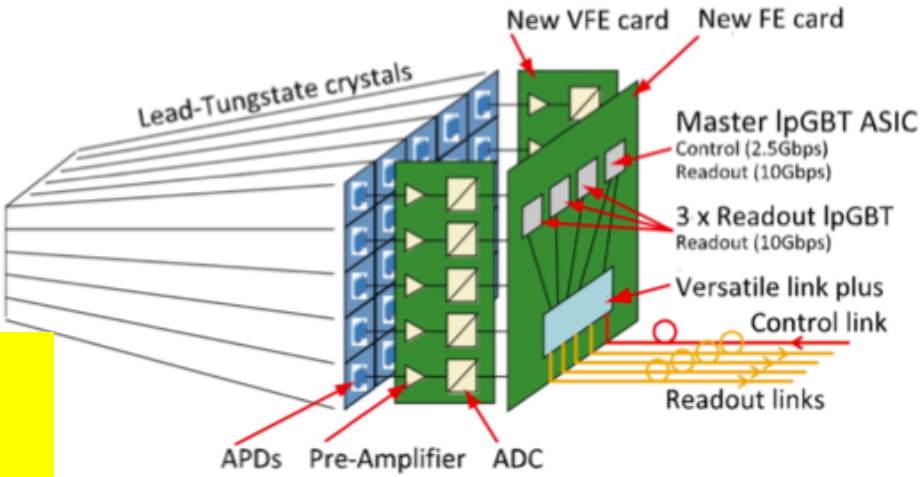






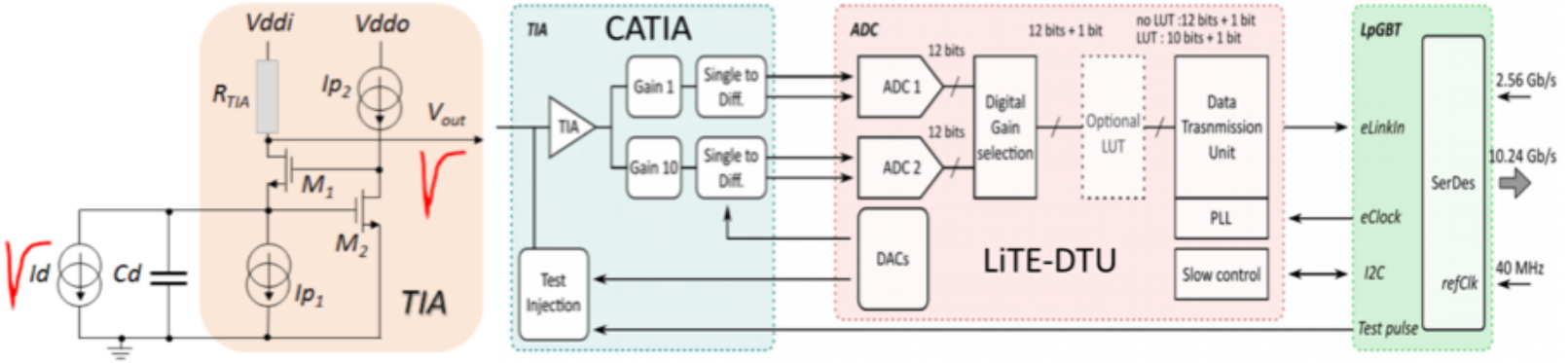
Phase II barrel calorimeter overview

- Upgrade electronics only (very robust detector)
  - VFE 20ns peaking time, 160MHz sampling, 30ps resolution@30GeV e/γ
  - 40 MHz readout capability
  - FE with 10 GB lpGBT ASIC
- Operate at 9°:
  - mitigate APD aging



VFE:
- TIA: V0-ASIC concept demonstrated
- CATIA: full features 2018 (TSMC)
- LiTE-DTU: submission Nov. 2018

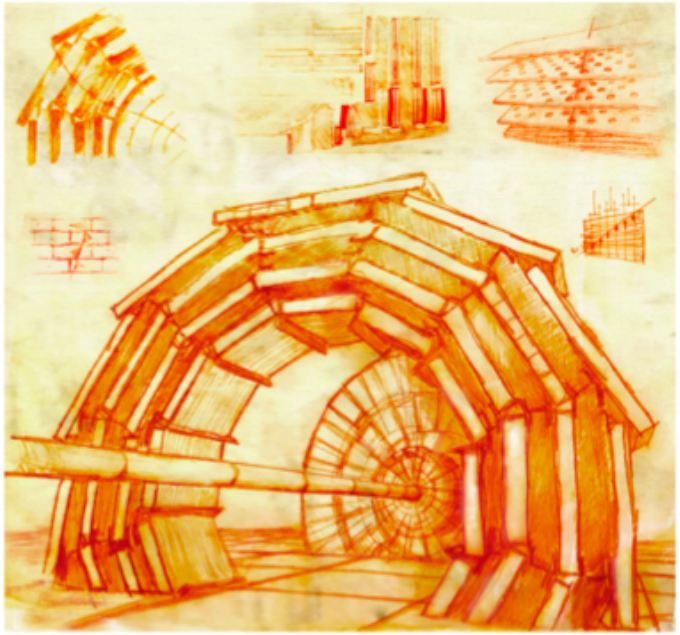
FE: demonstrator in 2018



CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

CERN-LHCC-2017-012
CMS-TDR-016
12 September 2017

CMS



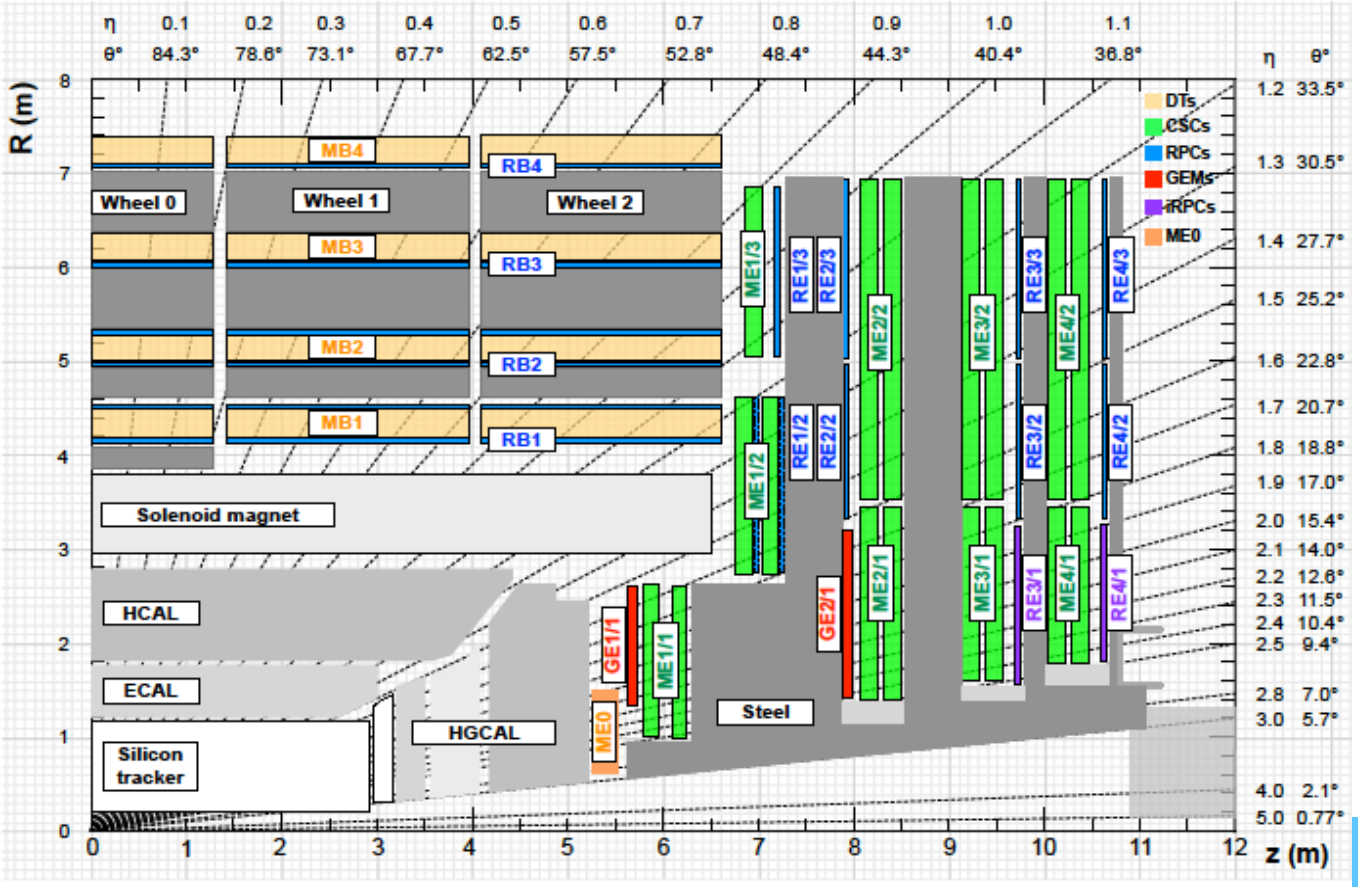
CERN-LHCC-2017-012 / CMS-TDR-016
11/02/2018

The Phase-2 Upgrade of the CMS Muon Detectors

TECHNICAL DESIGN REPORT

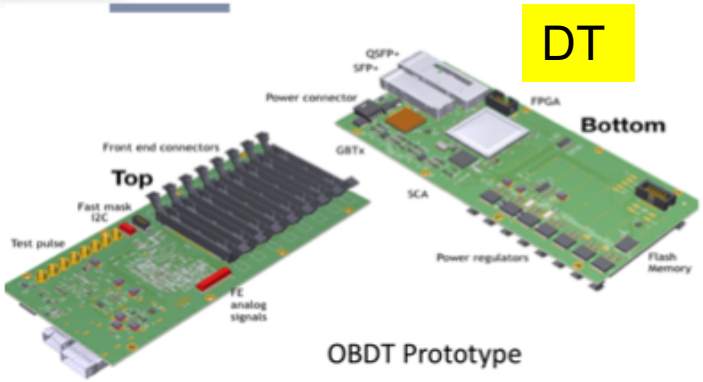
Phase II Muon upgrade overview

- Drift Tube (barrel): 40 MHz readout with improved z/t -precision
- Resistive plate chamber (barrel): readout with improved t-precision
- Cathode Strip chamber (Endcap): ME234/1 readout with higher bandwidth and latency, replace ME1 with higher radiation hard components
- New stations: GEM1/GEM2; iRPC3/iRPC4, 1.6<|η|<2.4; ME0, 1.15 <|η|<3



Status of muon upgrades

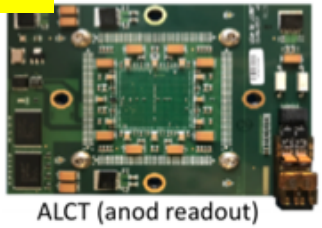
DT



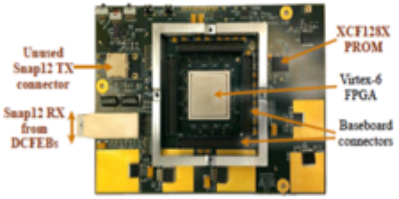
OBDT Prototype

CSC


DCFEB (cathod readout)

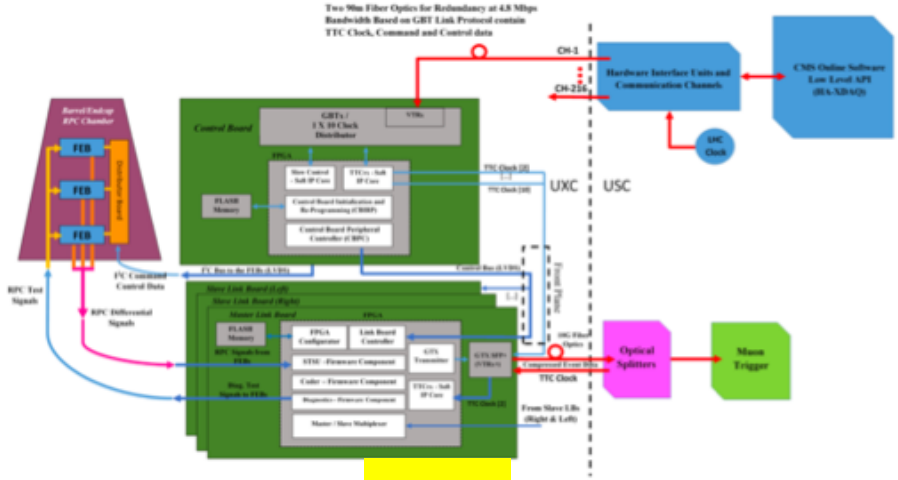

ALCT (anod readout)


LVDB (low voltage)

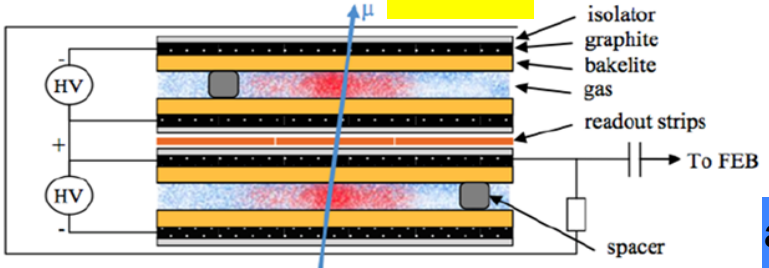


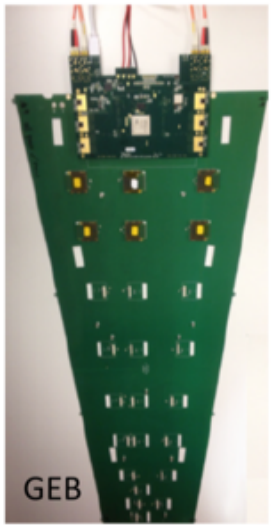
OTMB

Prototyping of board/detector

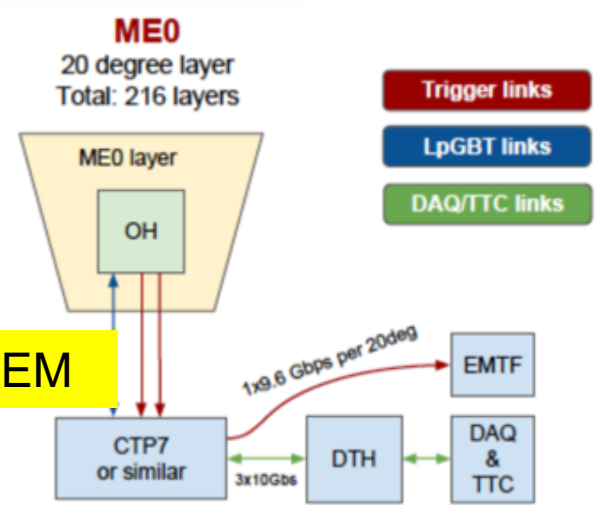


RPC

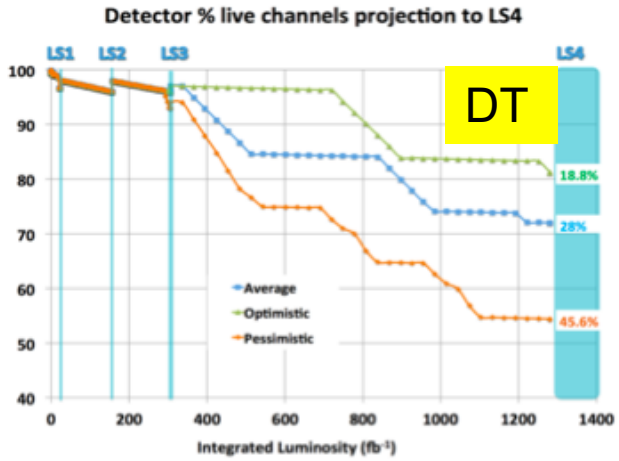


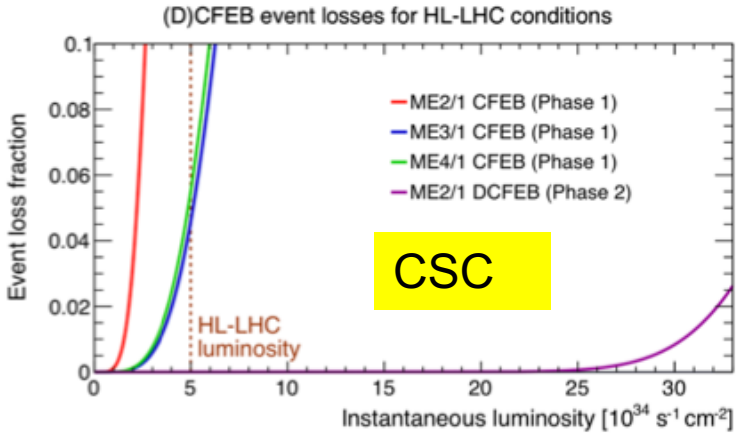


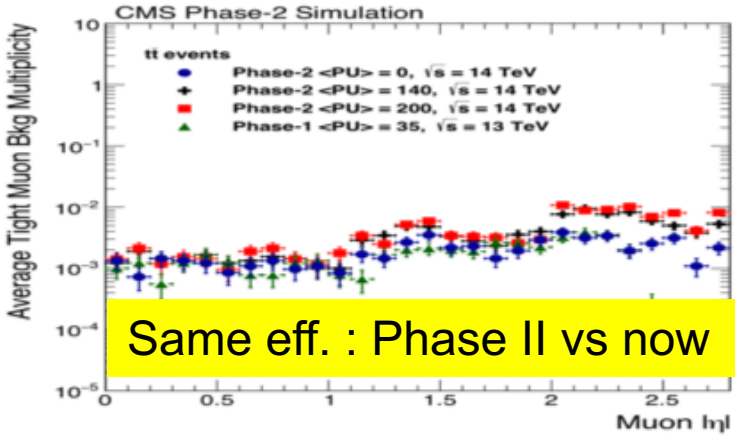
GEM

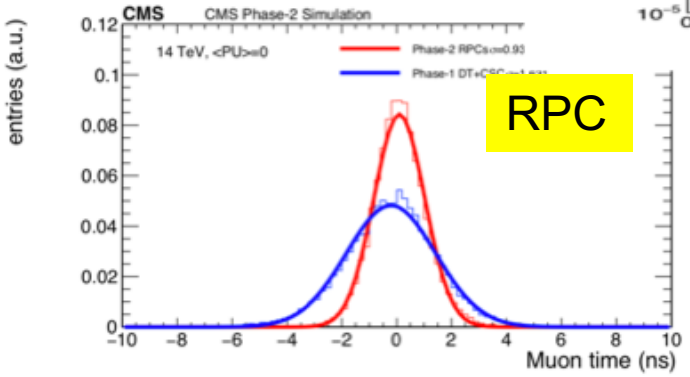


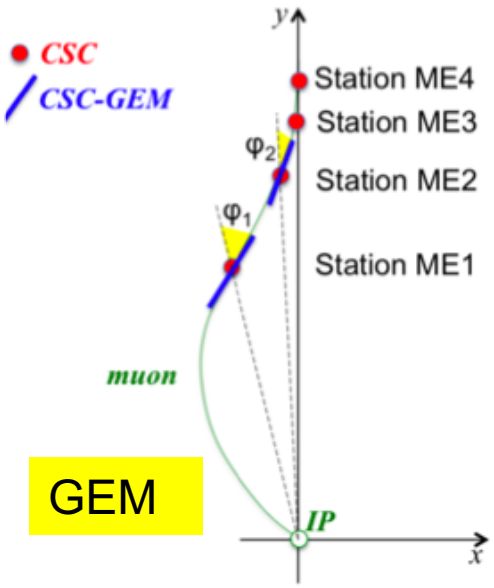
Expect improvement from muon upgrade











LHCC-P-009
27 November 2017

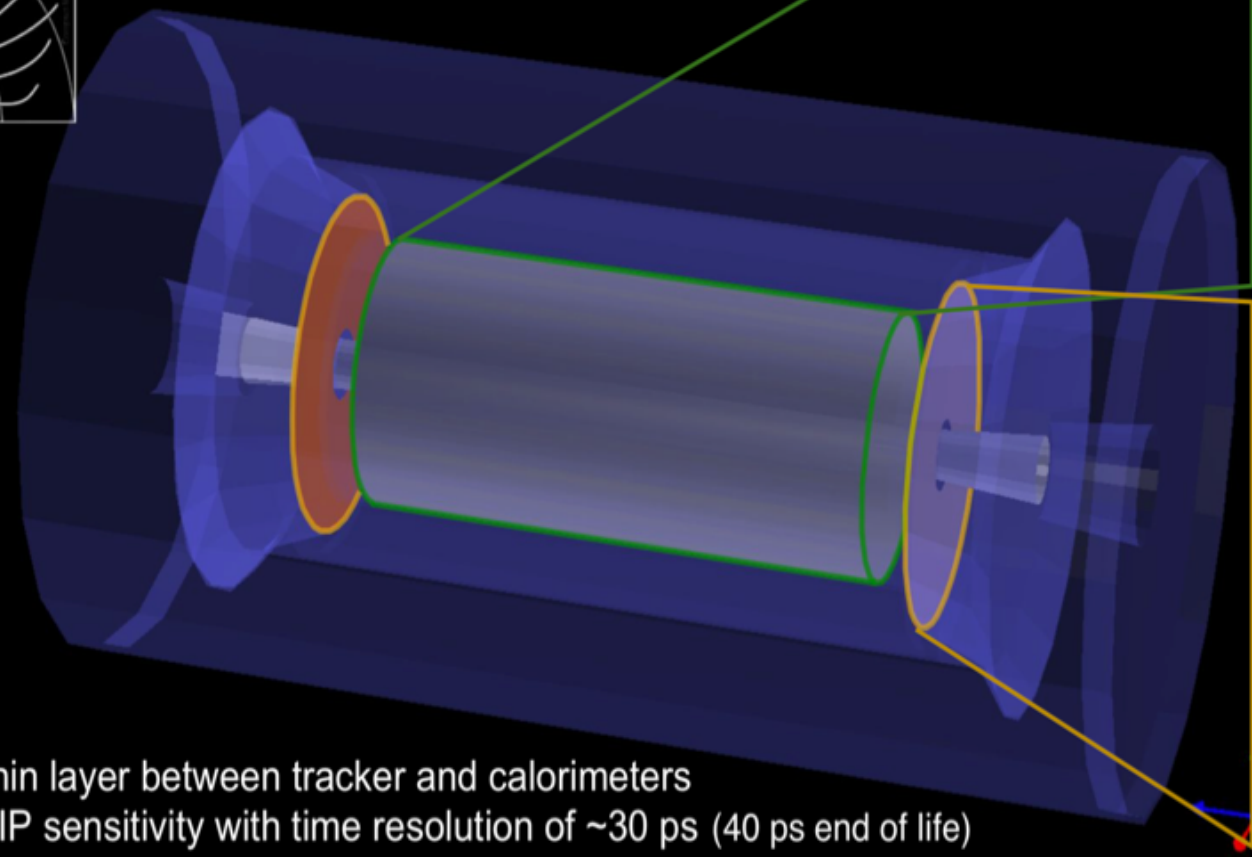
TECHNICAL PROPOSAL FOR A MIP TIMING DETECTOR IN THE CMS EXPERIMENT PHASE 2 UPGRADE

CERN-LHCC-2017-027 / LHCC-P-009
04/05/2018

Mip Timing Detector overview

Calorimeter upgrades:

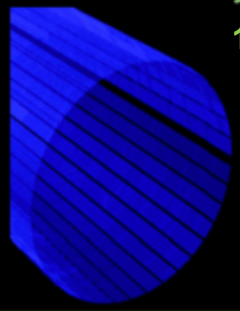
- Precision timing of **showers**
- Provide precision timing on high energy photons in ECAL Barrel
- All photons and high energy hadrons in HGCal Endcap

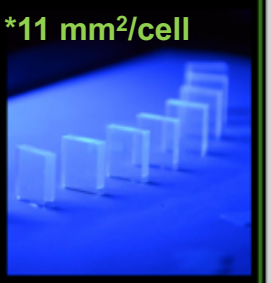


BARREL

TK/ECAL interface ~ 25 mm thick
Surface ~ **40** m^2
Radiation level ~ $2x10^{14}$ n_{eq}/cm^2
Sensors: **LYSO crystals + SiPMs**

11*11 mm^2/cell

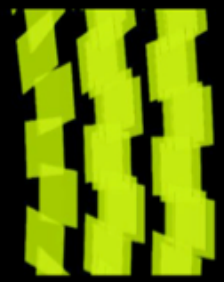


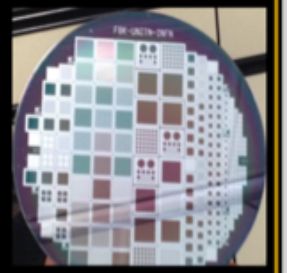


ENDCAPS

On the CE nose ~ 42 mm thick
Surface ~ **12** m^2
Radiation level ~ $2x10^{15}$ n_{eq}/cm^2
Sensors: **Si with internal gain (LGAD)**

1*3 mm^2/cell

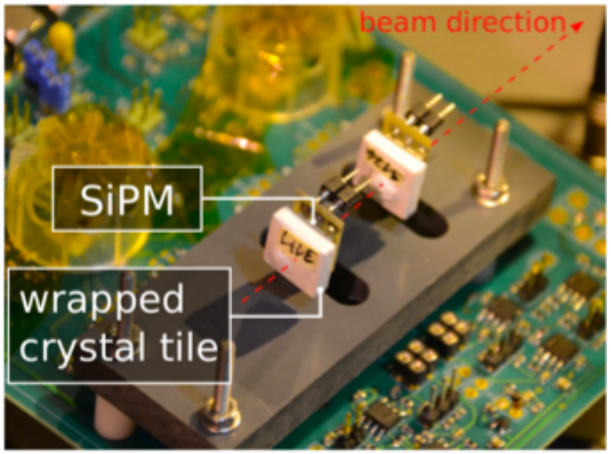


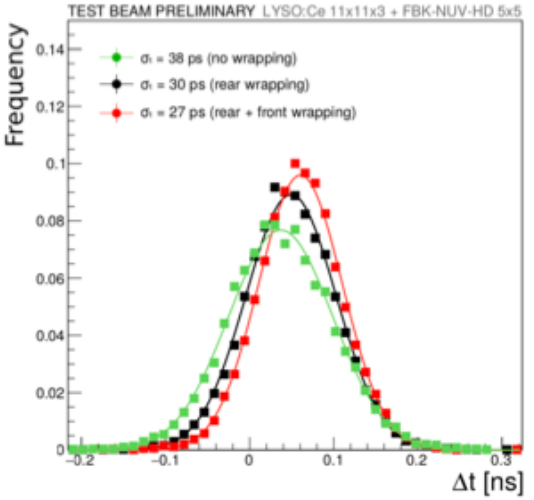


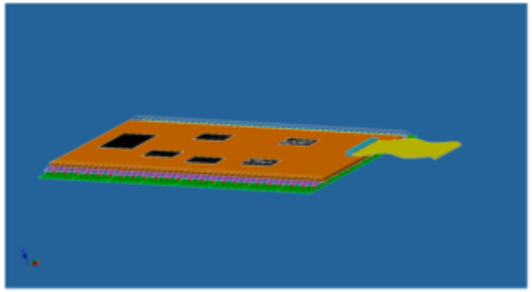
- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps (40 ps end of life)
- Hermetic coverage for $|\eta|<3$

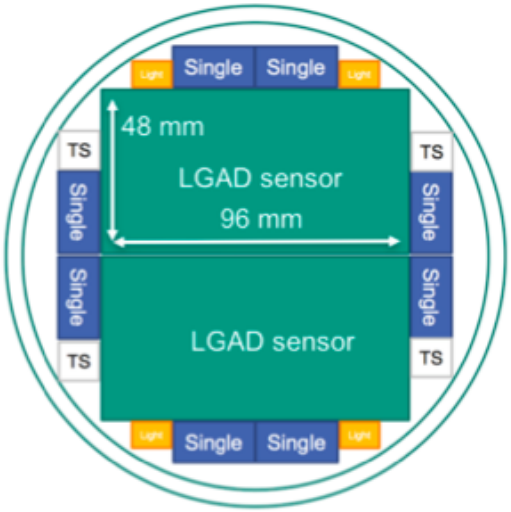
R&D of MTD

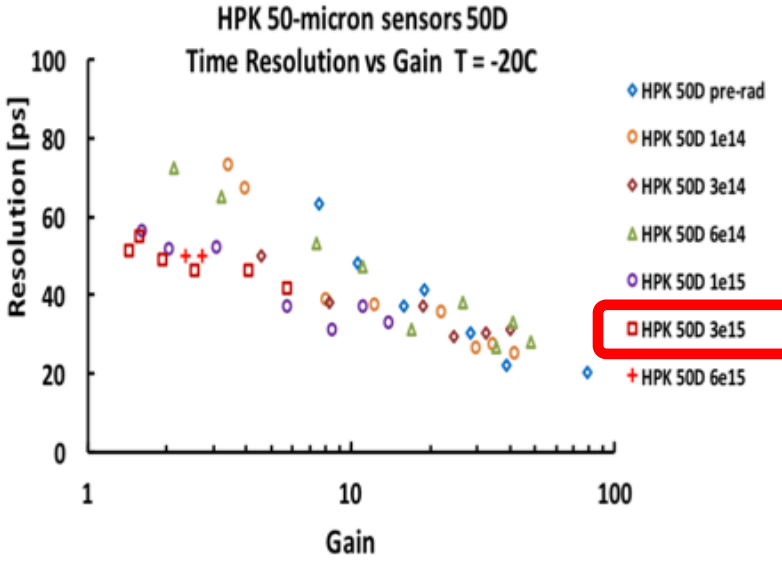

LYSO:Ce crystals w/o wrapping
Teflon wrapped


beam direction
SiPM
wrapped
crystal tile


TEST BEAM PRELIMINARY LYSO:Ce 11x11x3 + FBK-NUV-HD 5x5
Frequency
σt = 38 ps (no wrapping)
σt = 30 ps (rear wrapping)
σt = 27 ps (rear + front wrapping)
Δt [ns]

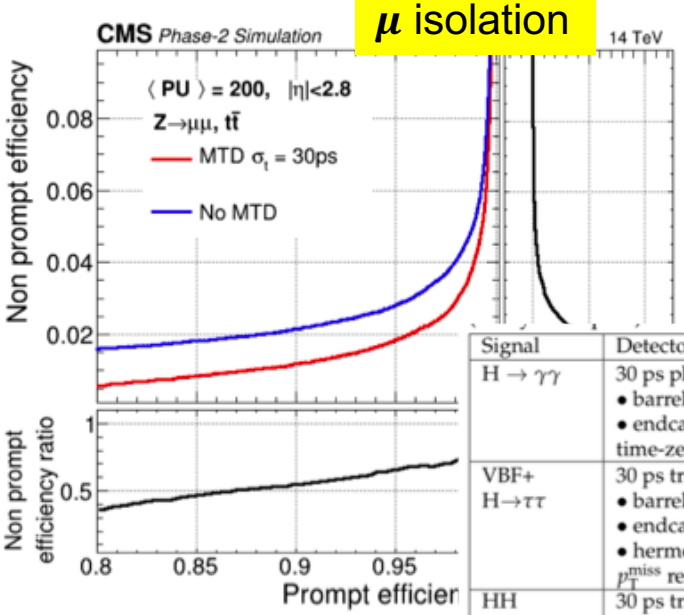



Single
Single
Light
TS
48 mm
LGAD sensor
96 mm
LGAD sensor

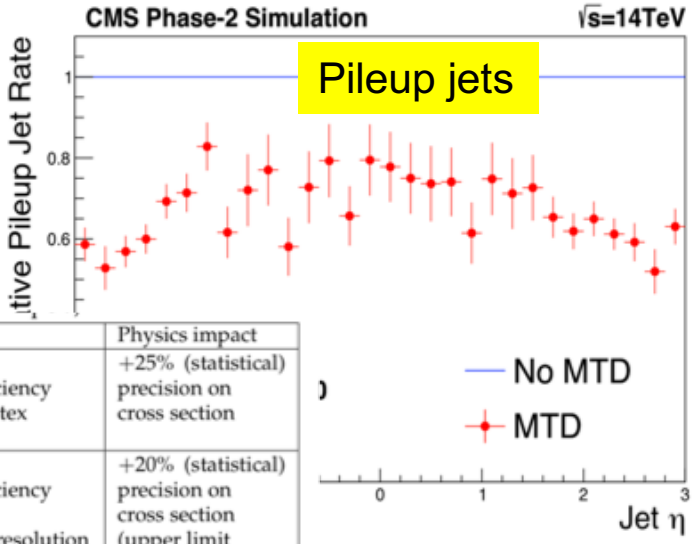

HPK 50-micron sensors 50D
Time Resolution vs Gain T = -20C
Resolution [ps]
Gain
HPK 50D pre-rad
HPK 50D 1e14
HPK 50D 3e14
HPK 50D 6e14
HPK 50D 1e15
HPK 50D 3e15
HPK 50D 6e15

Expected improvement with MIP timing detector

μ isolation

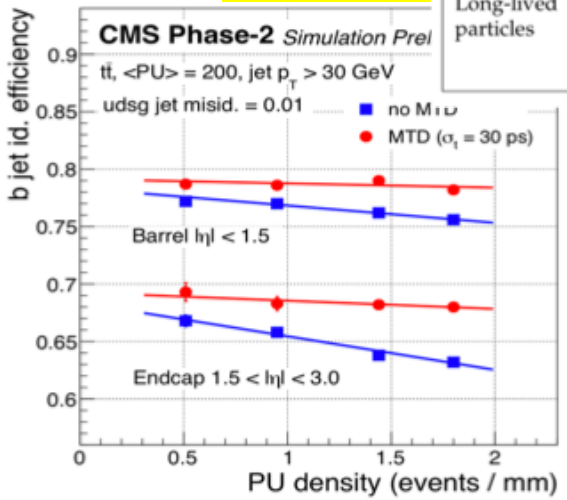


Pileup jets

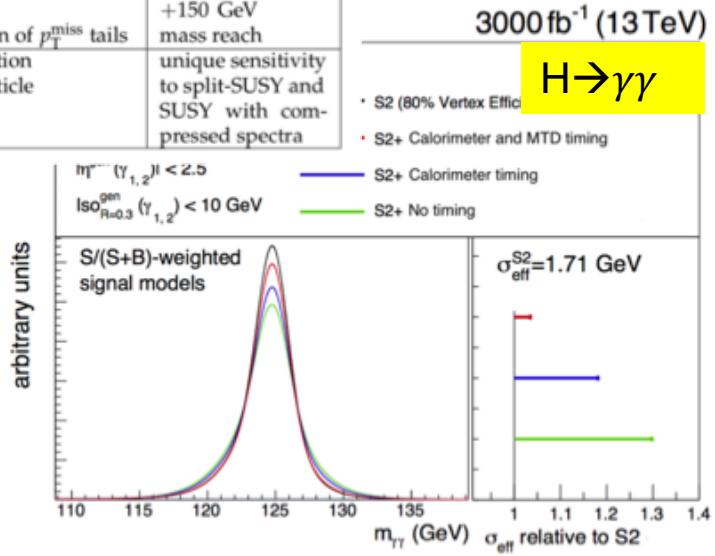


Signal	Detector requirement	Analysis impact	Physics impact
$H \to \gamma\gamma$	30 ps photon and track timing • barrel: central signal • endcap: improved time-zero and acceptance	$S/\sqrt{B}$: +20% - isolation efficiency +30% - diphoton vertex	+25% (statistical) precision on cross section
VBF+ $H \to \tau\tau$	30 ps track timing • barrel: central signature • endcap: forward jet tagging • hermetic coverage: optimal p_T^{miss} reconstruction	$S/\sqrt{B}$: +30% - isolation efficiency +30% - VBF tagging +10% - mass (p_T^{miss}) resolution	+20% (statistical) precision on cross section (upper limit or significance)
HH	30 ps track timing • hermetic coverage	signal acceptance : +20% b-jets and isolation efficiency	Consolidate HH searches
$\chi^{\pm}\chi^{0} \to W^{\pm}H+p_T^{miss}$	30 ps track timing • hermetic coverage: p_T^{miss}	$S/\sqrt{B}$: +40% - reduction of p_T^{miss} tails	+150 GeV mass reach
Long-lived particles	30 ps track timing • barrel: central signature	mass reconstruction of the decay particle	unique sensitivity to split-SUSY and SUSY with compressed spectra

B-tagging



H→$\gamma\gamma$



CERN-LHCC-2017-013
CMS-TDR-017
September 12, 2017

The Phase-2 Upgrade of the CMS Level-1 Trigger

Interim Technical Design Report

CMS Collaboration

CERN-LHCC-2017-013 / CMS-TDR-017
01/02/2018

CERN-LHCC-2017-014
CMS-TDR-018
12 September 2017

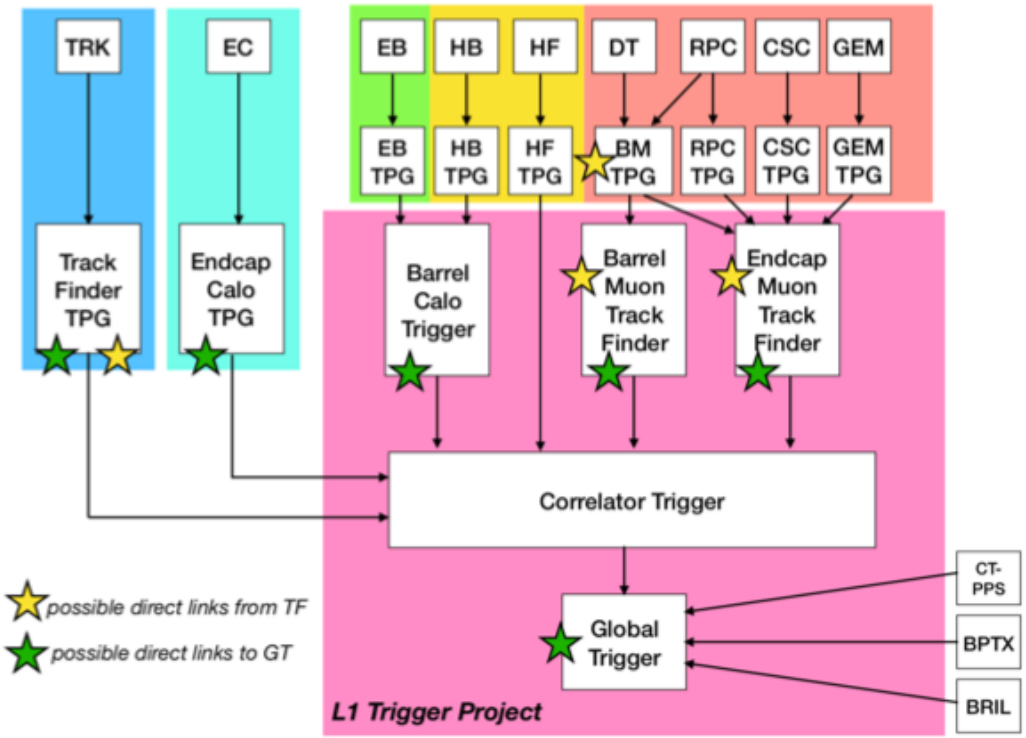
The Phase-2 Upgrade of the CMS DAQ

Interim Technical Design Report

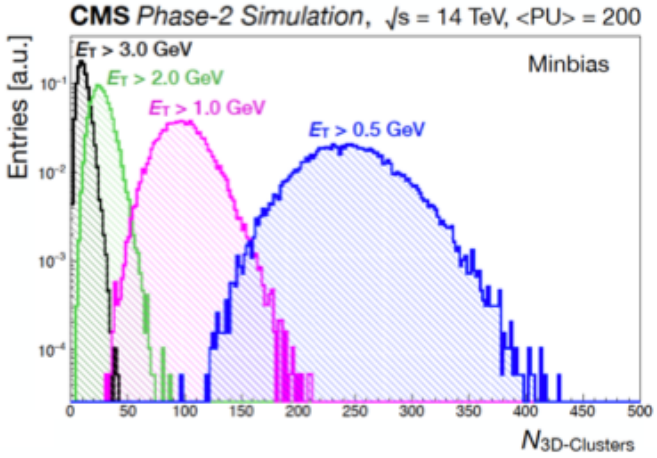
CMS Collaboration

CERN-LHCC-2017-014 / CMS-TDR-018
09/02/2018

- L1-Trigger
  - Tracks in trigger @ 40 MHz
  - >50 Tb/s input
  - 12.5 us latency
  - Accept rate: 500kHz/750 kHz @ 140 PU/200 PU



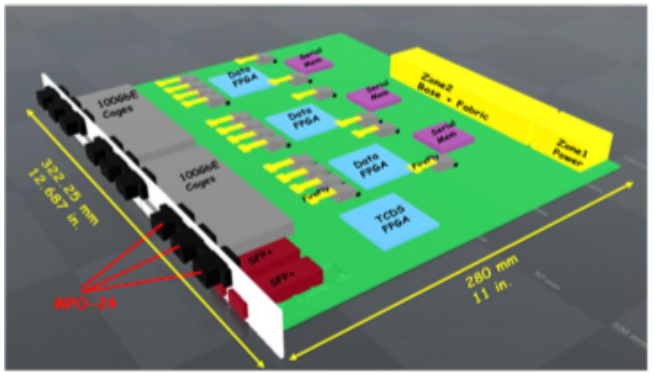
New firmware and new ideas to handle challenging trigger:
PF @ L1, 3D calor clusters

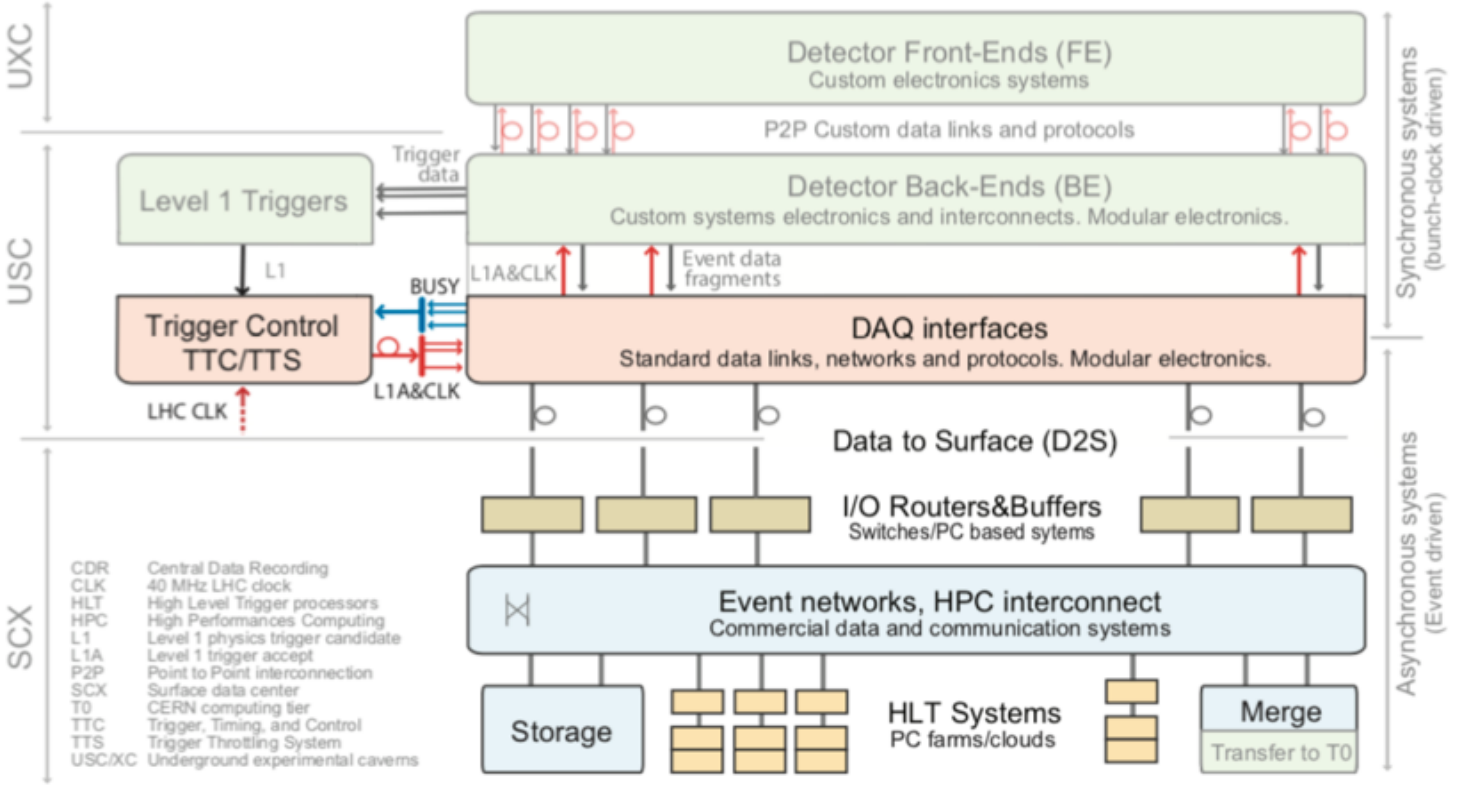


DAQ and HLT

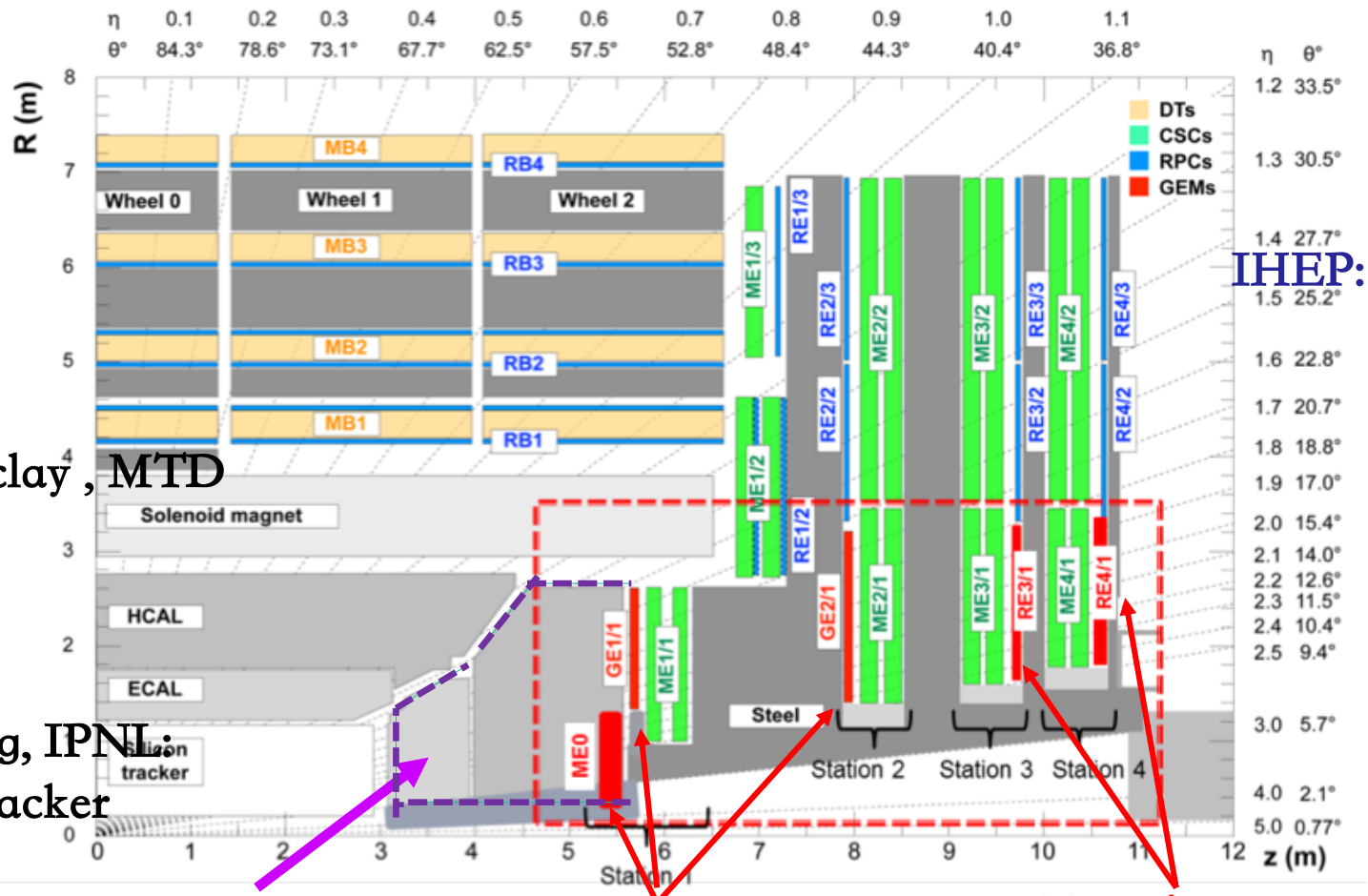
- New TCDS high speed serial distribution of precise clock and multiple triggers data steam
- Systems interface with DTH ATCA boards
- HLT output at 7.5 kHz, 4.5 MHS06 for 500 kHz (140 PU) in LS3 plus 4.7 MHS06for 750 kHz (200 PU) staged to LS4

First ATCA DTH prototype in Q4 2018





French/Chinese in CMS Phase II upgrade



CEA-saclay , MTD

Strasburg, IPNL: Tracker

IHEP: HGCal

LLR:electronic/mechnic…

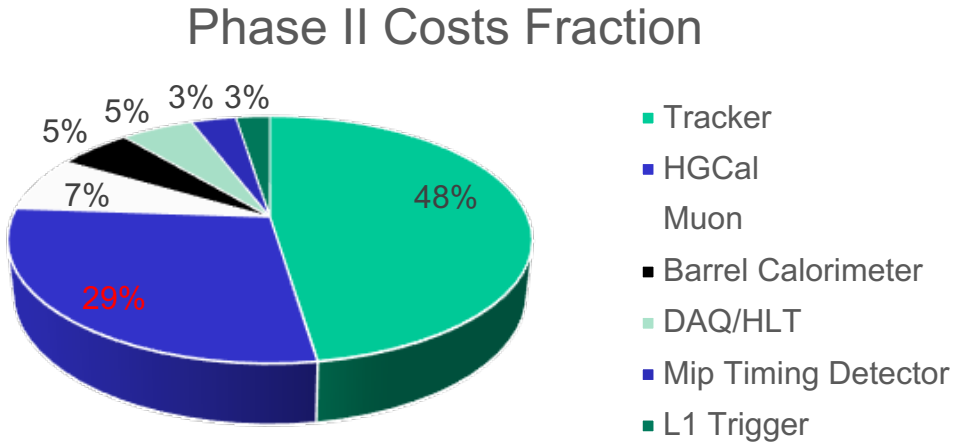
PKU, GEM GE1/1, GE2/1+ME0

THU/IPNL, Glass mRPC RE3/1+RE4/1

IHEP: L1-Trigger

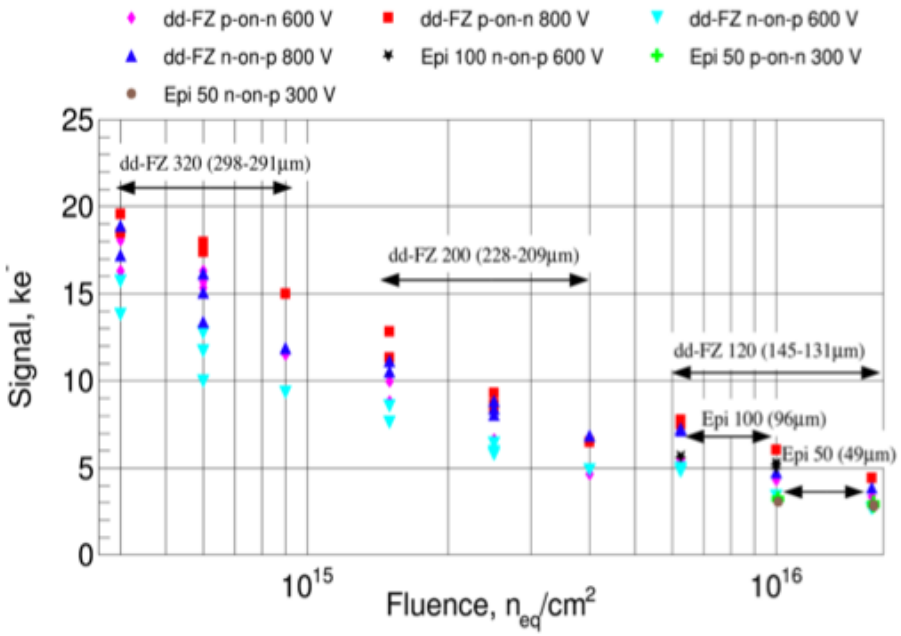
Summary

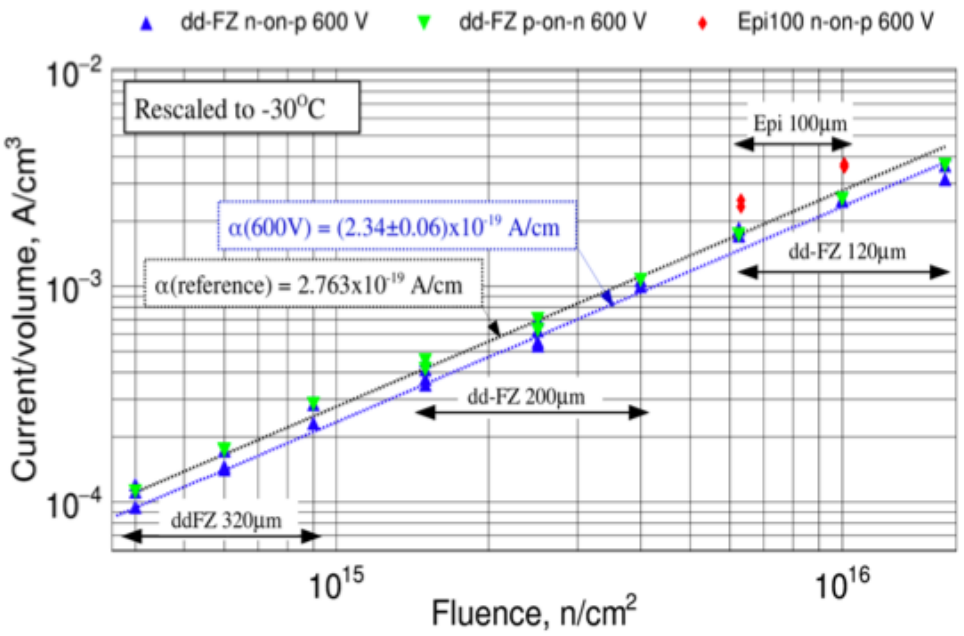
- CMS Phase II upgrades have been approved by LHCC/UCG and CERN RB recently
  - L1-Trigger, DAQ/HLT and MIP Timing Detector TDRs is coming
- Production MoU expected to be proceed in coming RRB
- Progress being developed
  - Key components such as silicon sensor, gas detectors
  - Electronics such as various FE ASICS, lpGBTs
  - Improvements to detector performance/physics outcome
- France/Chinese collaborate on CMS upgrades



backup

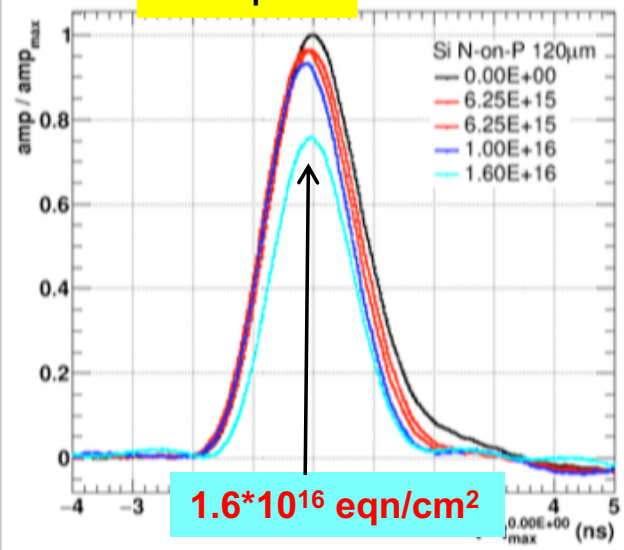
Silicon sensor radiation tests



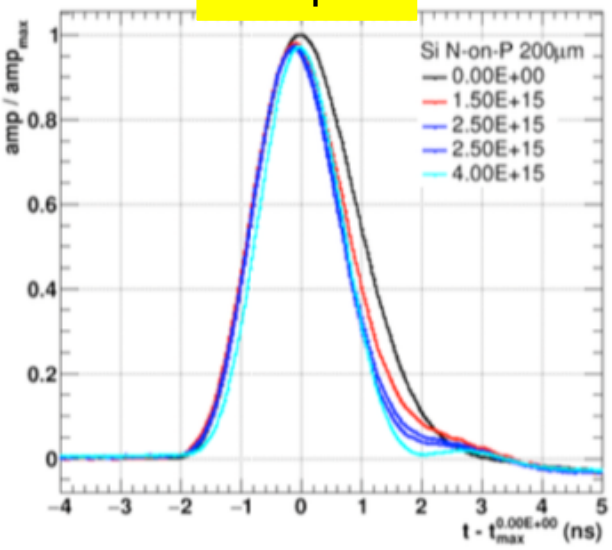


Silicon sensor irradiation tests

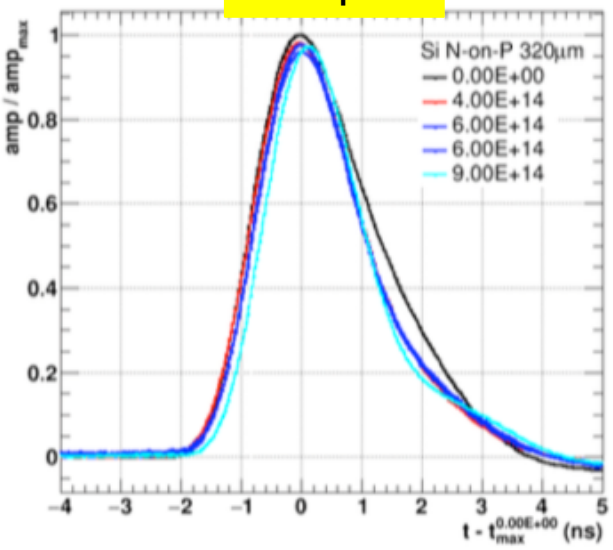
120 µm



200 µm



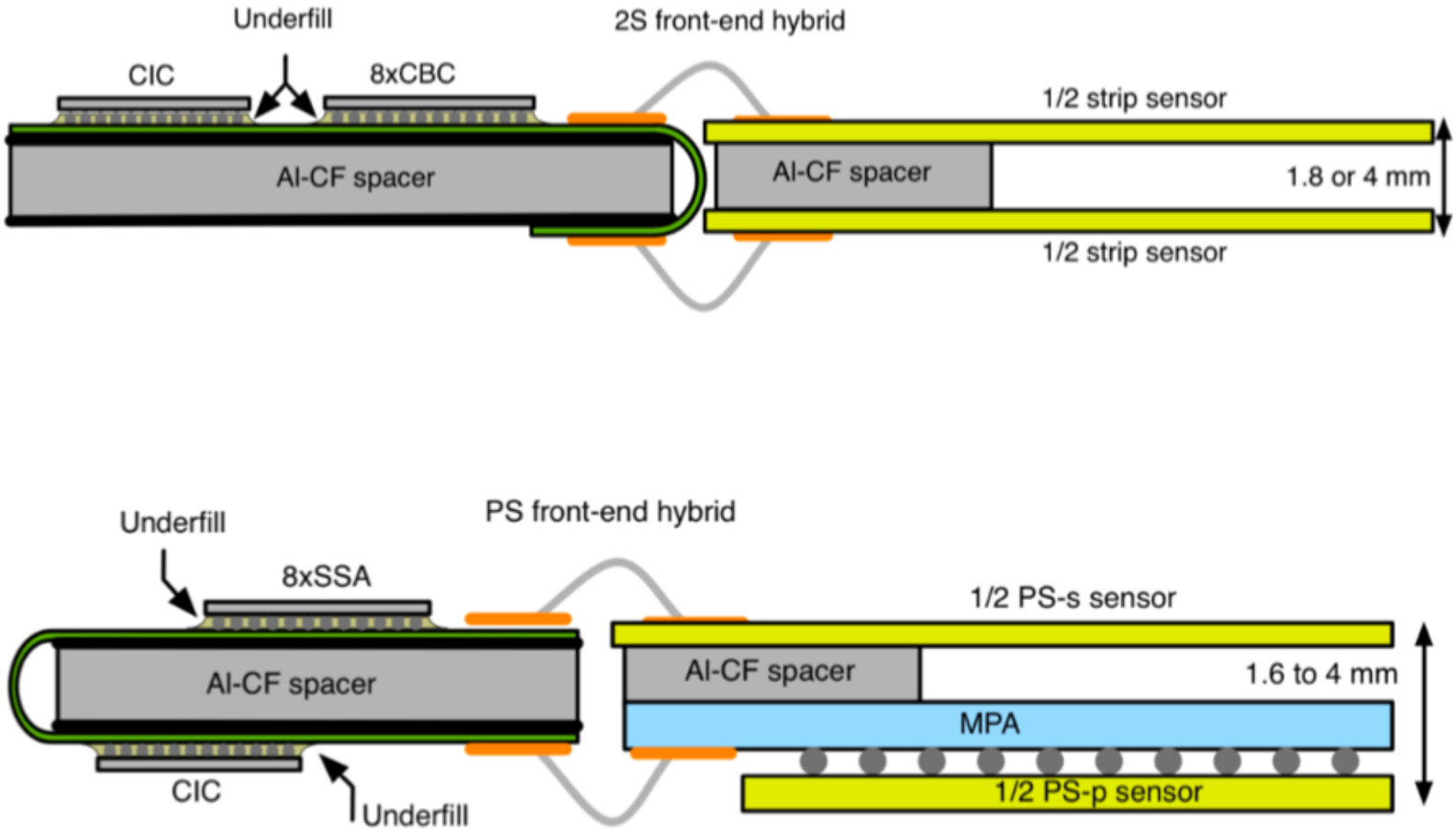
320 µm

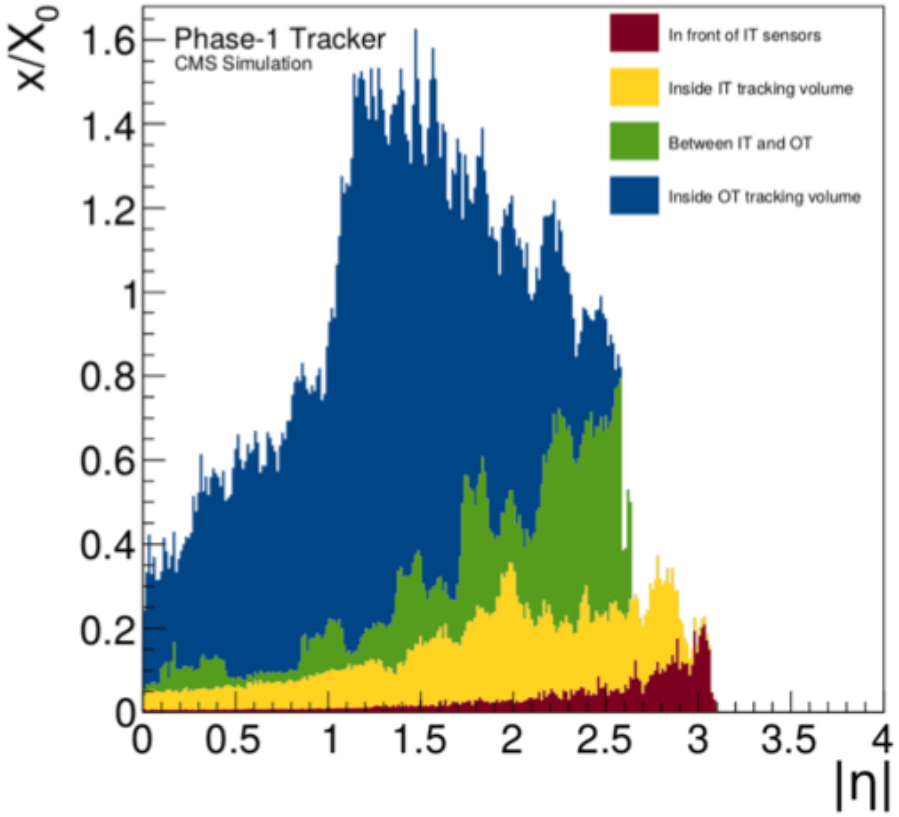


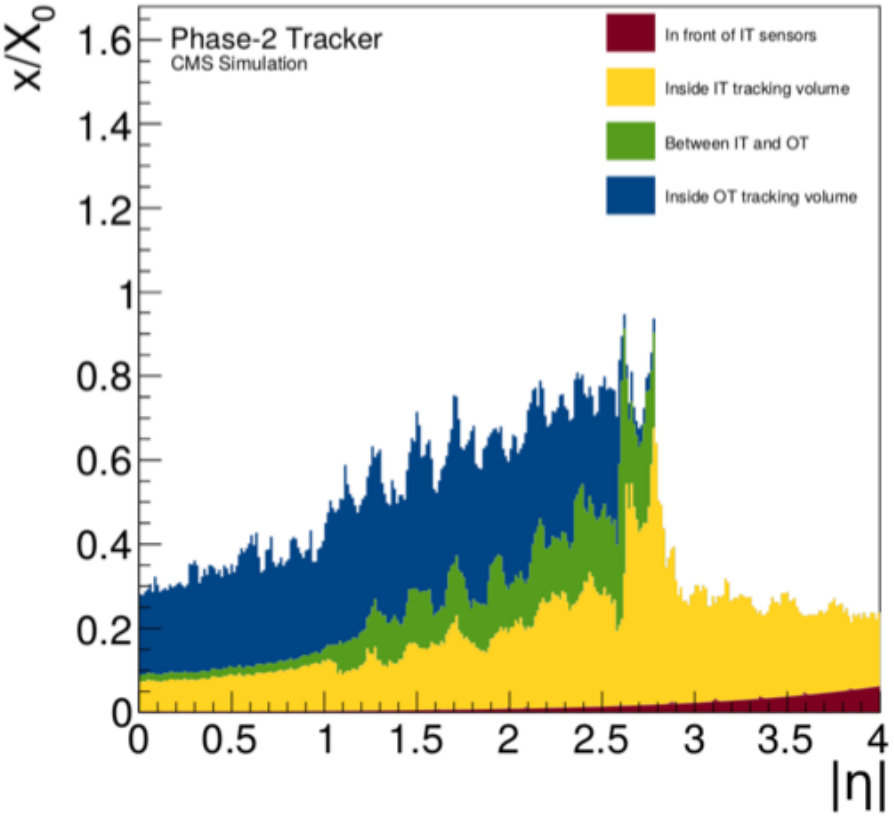
- Si N-on-P sensor produced by Hamamatsu
- 120, 200, 320 um tested
- Neutron radiation up to $1.6*10^{16}$ 1MeV n/cm^2(120um)
- Beam and Sr^{90} tests give consistent results

Pulse shape after radiation changed marginally

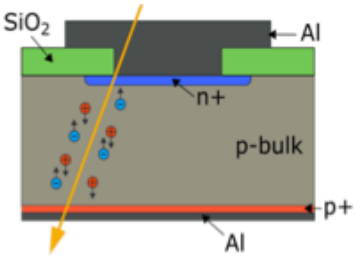
Out tracker module



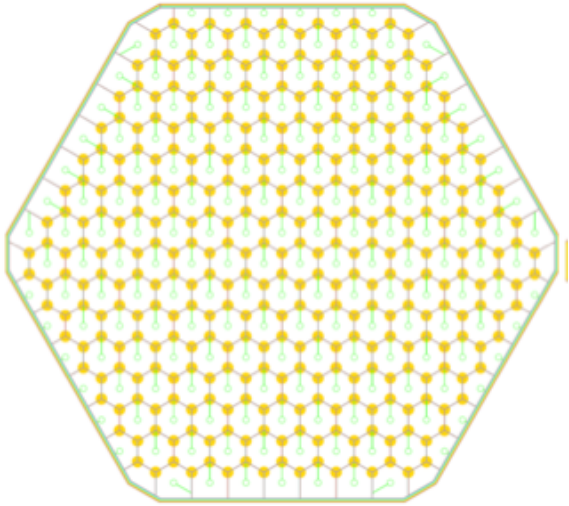

Phase-1 Tracker
CMS Simulation
In front of IT sensors
Inside IT tracking volume
Between IT and OT
Inside OT tracking volume
x/X0
|η|


Phase-2 Tracker
CMS Simulation
In front of IT sensors
Inside IT tracking volume
Between IT and OT
Inside OT tracking volume
x/X0
|η|

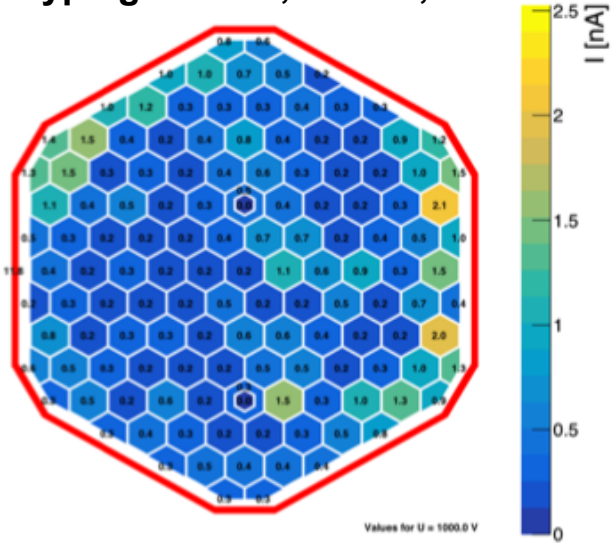
Silicon sensors



8'' baseline design

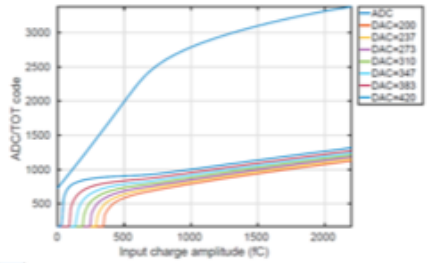


Prototyping HPK 6'', 300um, 1000V bias

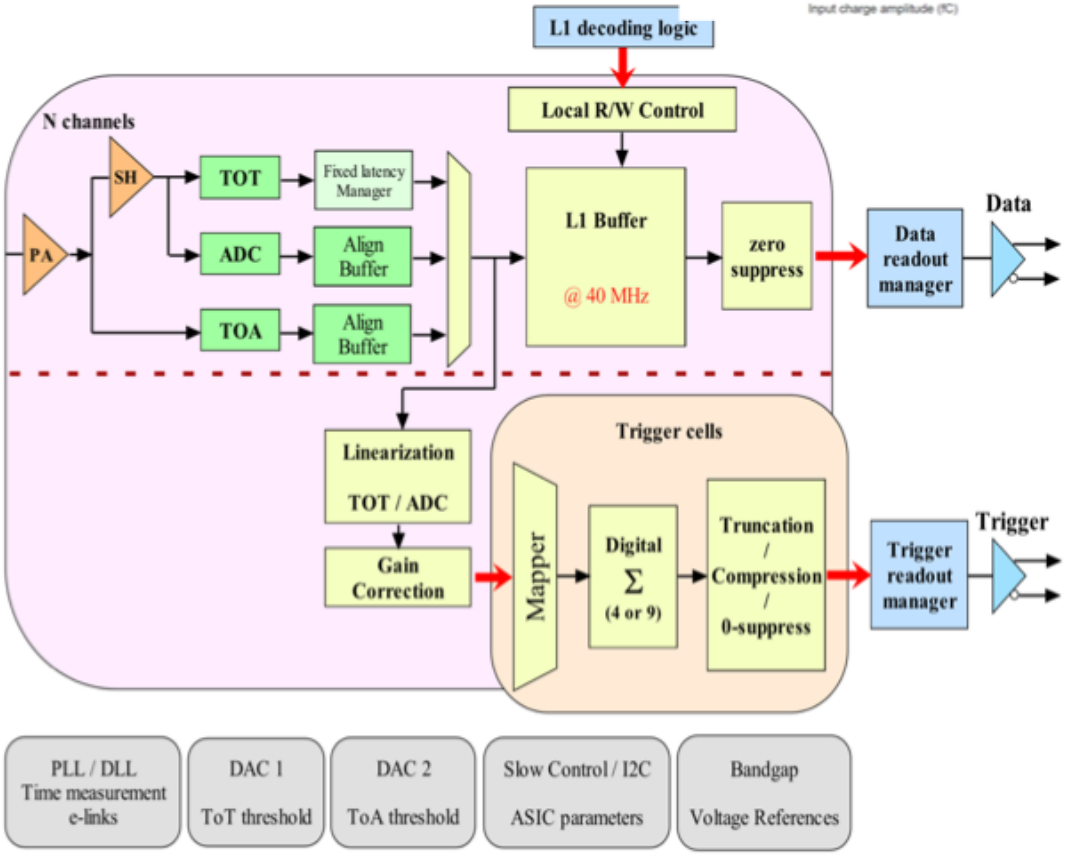


Active thickness (μm)	**300**	**200**	**120**
Area (m^2)	245	181	72
Largest lifetime dose (Mrad)	3	20	100
Largest lifetime fluence (n_{eq}/cm^2)	0.5×10^{15}	2.5×10^{15}	7×10^{15}
Largest outer radius (cm)	≈180	≈100	≈70
Smallest inner radius (cm)	≈100	≈70	≈35
Cell size (cm^2)	1.18	1.18	0.52
Initial S/N for MIP	11	6	4.5
Smallest S/N(MIP) after 3000 fb^{-1}	4.7	2.3	2.2

Silicon part Front End readout



- Requirements (not a full list)
  - Radiation hard (of course)
  - Low noise: <2500e
    - Including sensor leakage current noise
  - Shape time: <20 ns
    - Sensor pulse Shape is 1-2 ns
  - Dynamic Range 0.2fC -10 pC
    - High gain for < 100 fC
    - ToT for ~100 fC – 10 pC
  - Low power: ~20 mW/channel
    - total ~ 100kW for 6M channels
  - <100 ps time resolution per cell
  - 36 bunch crossings latency



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See details from Christophe de La Taille's slides

- 60 ps time resolution ➔ 2 cm position resolution for $|\Delta\eta_{\gamma\gamma}|<0.8$