Precision Timing with the CMS MIP Timing Detector

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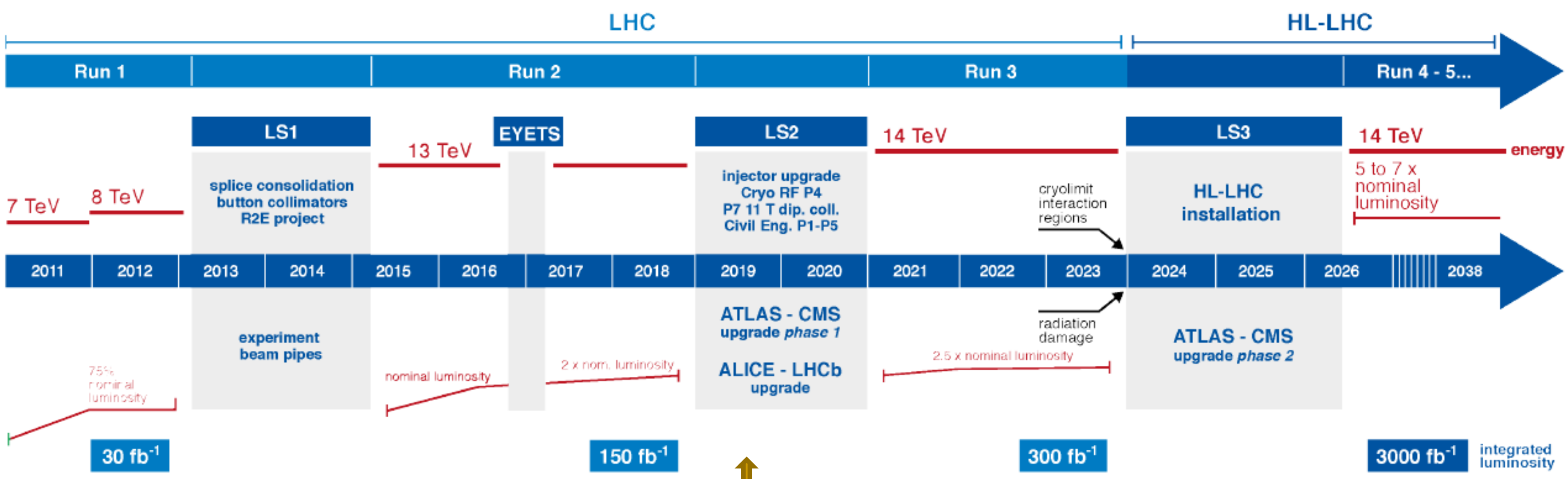
on behalf of the CMS Collaboration

PIC 2019 - Taipei


Large Hadron Collider
CMS
p
p
LHCb
ATLAS
ALICE

LHC / HL-LHC Plan



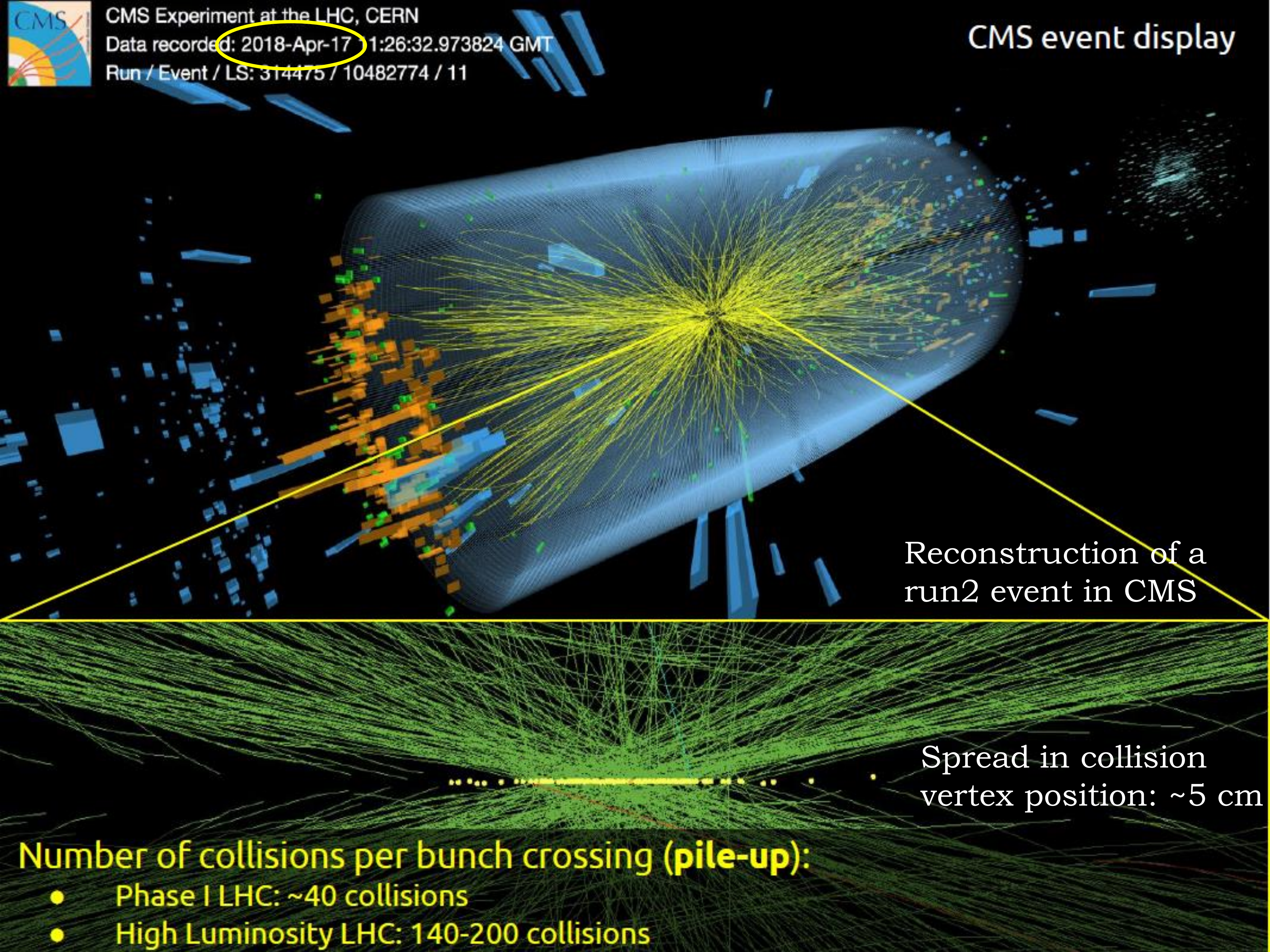
Higgs boson discovery

We are here.

	LHC	HL-LHC	
$E =$	7–14	14	TeV
$\mathcal{L}_{\text{peak}} =$	2	5–7.5	$\cdot 10^{34} \text{cm}^{-2}\,\text{s}^{-1}$
$\text{PU}_{\text{peak}} =$	40–60	**150–200**	
$\int \mathcal{L} =$	≥50	**250–320**	fb^{-1} /year
$\int \mathcal{L} =$	300–500	3000–4000	fb^{-1} total

Very challenging for event reconstruction.

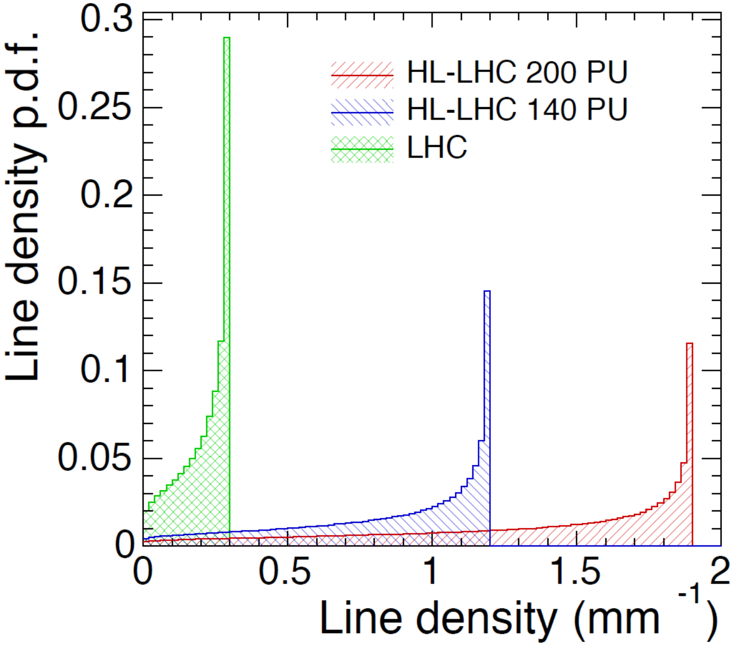
A ten times large dataset for physics and a real challenge for the detector radiation resistance.


CMS Experiment at the LHC, CERN
Data recorded: 2018-Apr-17 11:26:32.973824 GMT
Run / Event / LS: 314475 / 10482774 / 11
CMS event display
Reconstruction of a run2 event in CMS
Spread in collision vertex position: ~5 cm
Number of collisions per bunch crossing (pile-up):
• Phase I LHC: ~40 collisions
• High Luminosity LHC: 140-200 collisions

The HL-LHC challenge

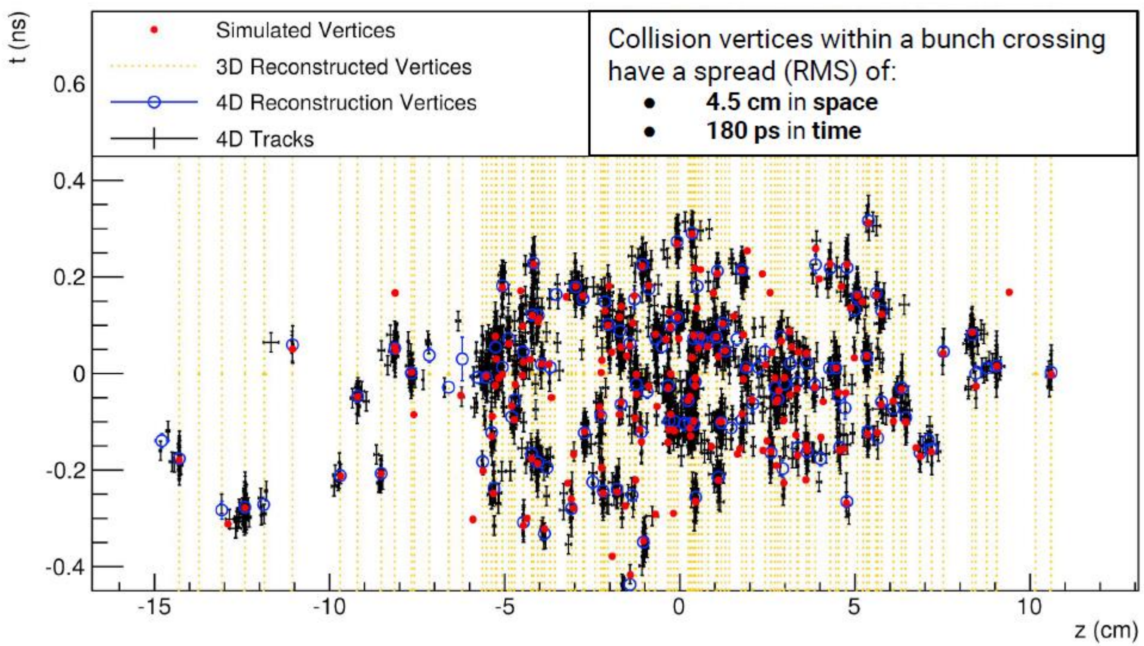
- Up to 5x higher vertex density
- Optimal cut at 1 mm for track-vertex compatibility
- Vertex density > 1 mm^{-1} means pile-up contamination and event reconstruction degradation

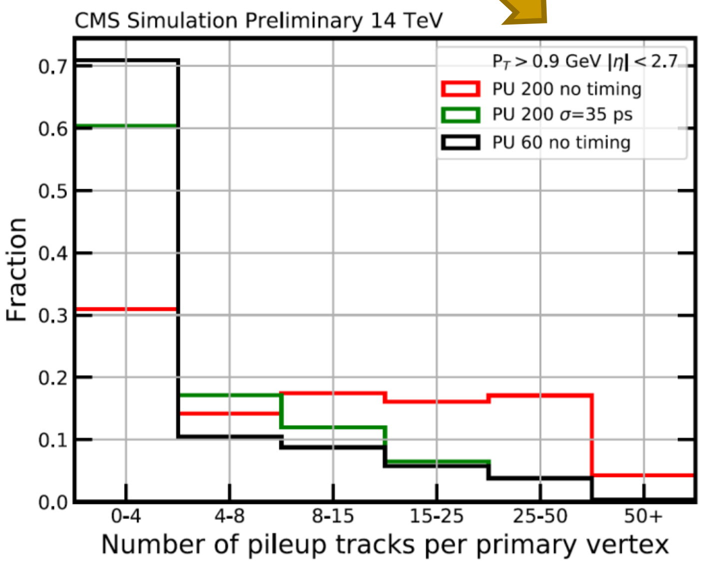
Probability density functions of the line density along the beam axis.



A Detector for MIP Timing

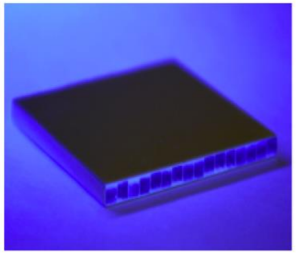
- Approach: time tagging tracks with 30-50 ps resolution
  - 3D → 4D vertex reconstruction
  - time compatibility for track-vertex association
- Goal: reduce the actual Phase2 pile-up to the current Phase1 size by slicing the beam spot in time slices.



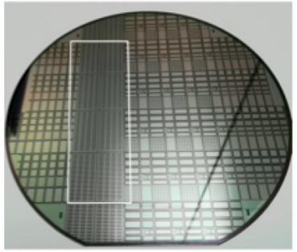


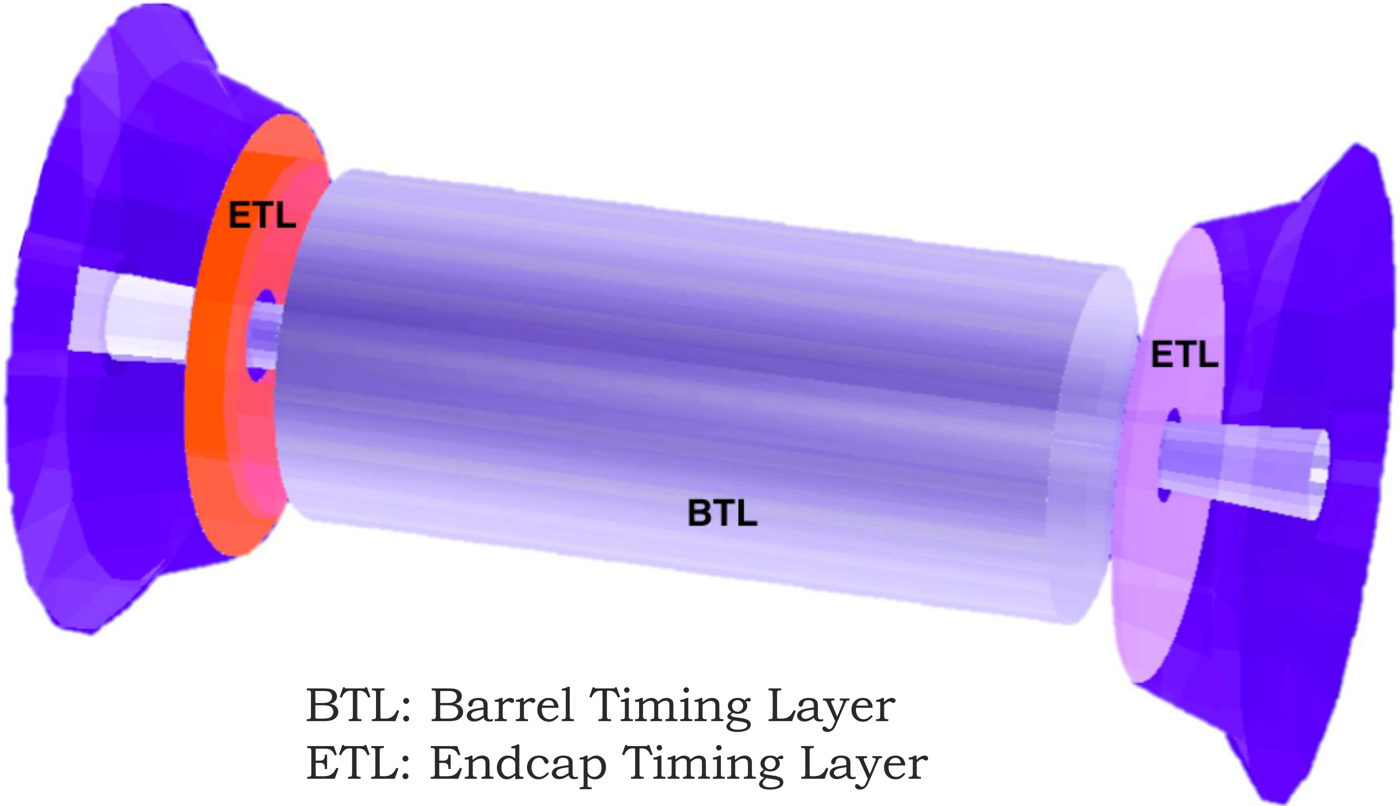
Design of the CMS MTD (Mip Timing Detector)

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2



ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2





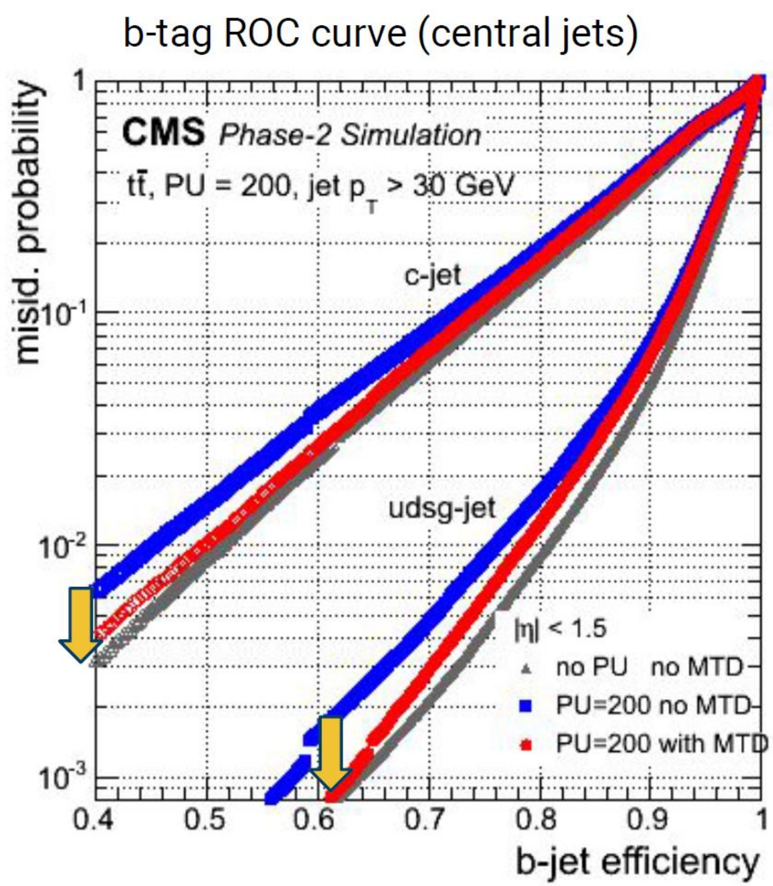
BTL: Barrel Timing Layer
ETL: Endcap Timing Layer

Improvement in the physics performance with the MTD

- Reconstruction performance
  - Higher b-tagging efficiency.
  - Improvement in identification and isolation of photons and leptons.
  - Better rejection of fake jets due to pile-up
  - Better missing transverse momentum resolution

- Signal yield gain in many Higgs decay channels.

- Velocity measurement from TOF: π/K and K/p discrimination for low p_T hadrons.



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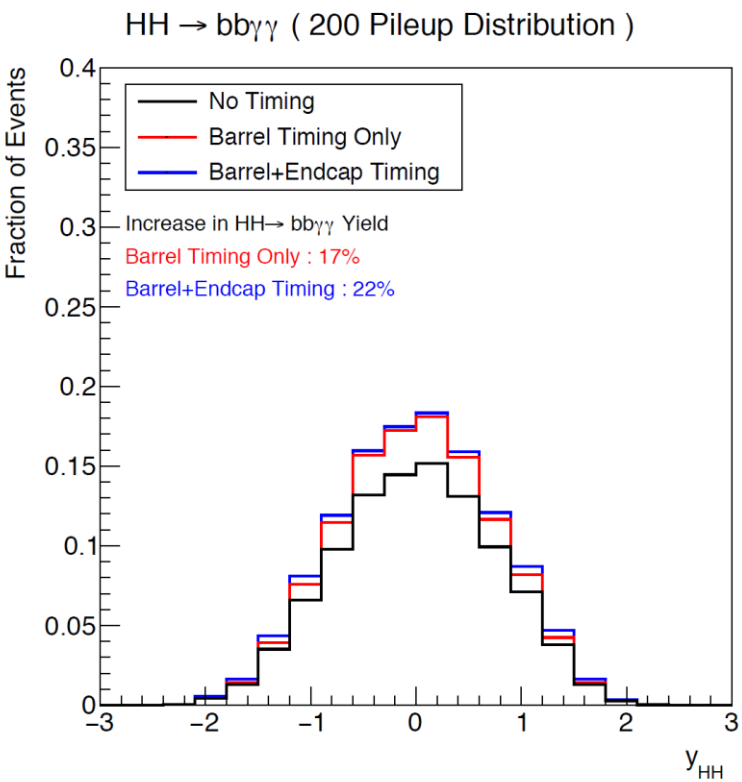
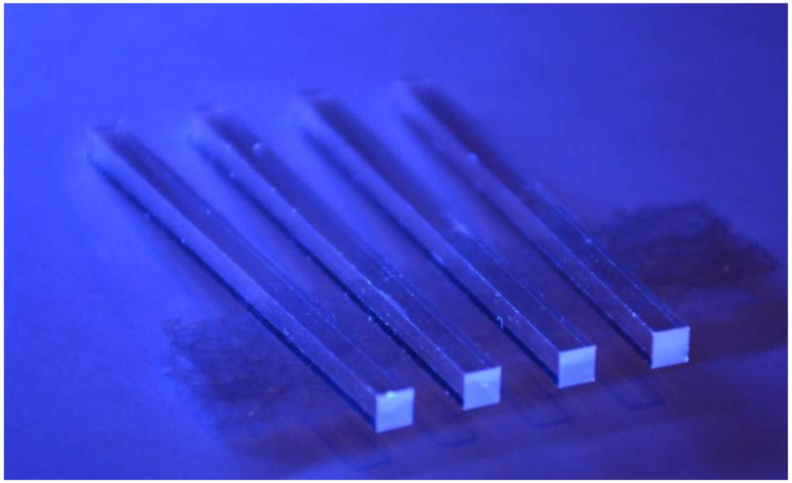
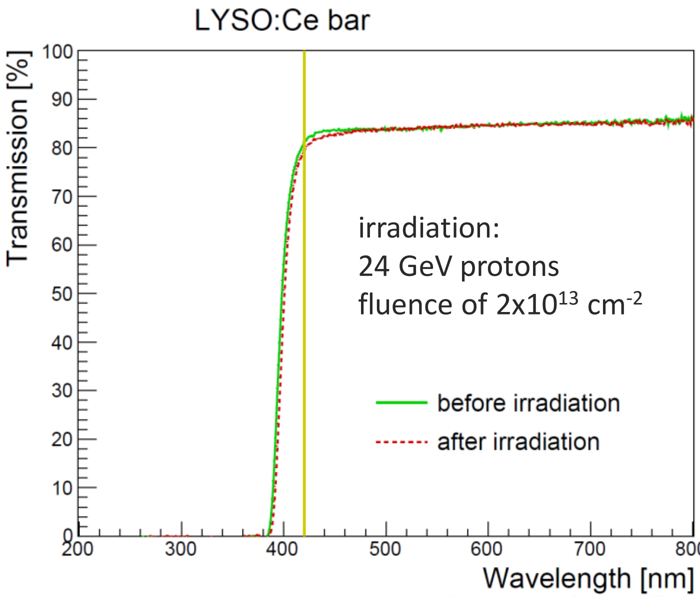


MTD barrel: sensor choice

- LYSO:Ce crystal as scintillator
  - Dense (>7.1 g/cm³)
  - High light yield (40000 ph/MeV)
  - Fast rise time O(100)ps and decay time ~40 ns
  - **Excellent radiation tolerance**

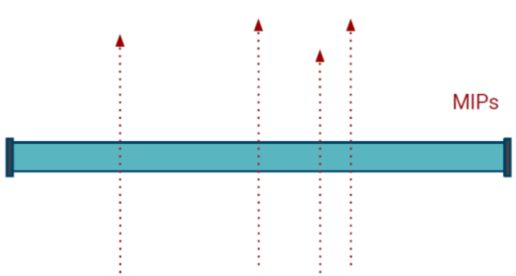


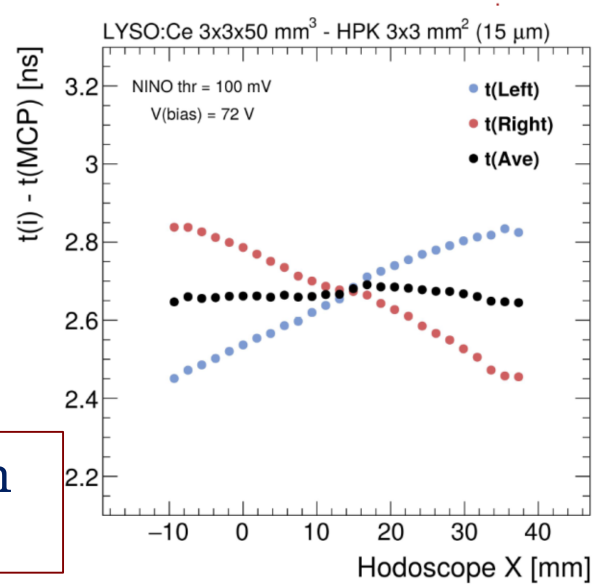


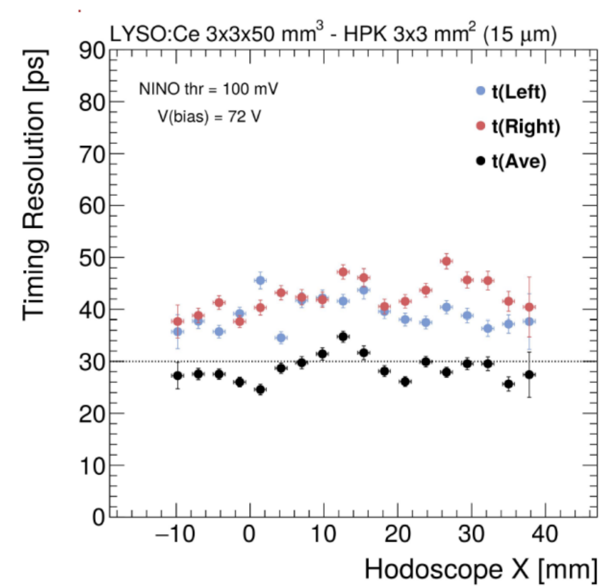
- Silicon Photomultipliers as photo-detectors
  - Compact, insensitive to magnetic fields, fast
  - High dynamic range
  - Good radiation tolerance
  - Good Photon Detection Efficiency at 420 nm: 20-40%

BTL sensor performance (test beam results)

- LYSO (3x3x57 mm) bars read-out by SiPMs at both ends → two different times (left and right) from each channel.
- Time is sensitive to the light propagation along bar.
- **Average time**: uniform response vs impact point, resolution improved and around 30 ps (matching requirements)
- **Time difference**: impact point along the bar with O(5 mm) resolution





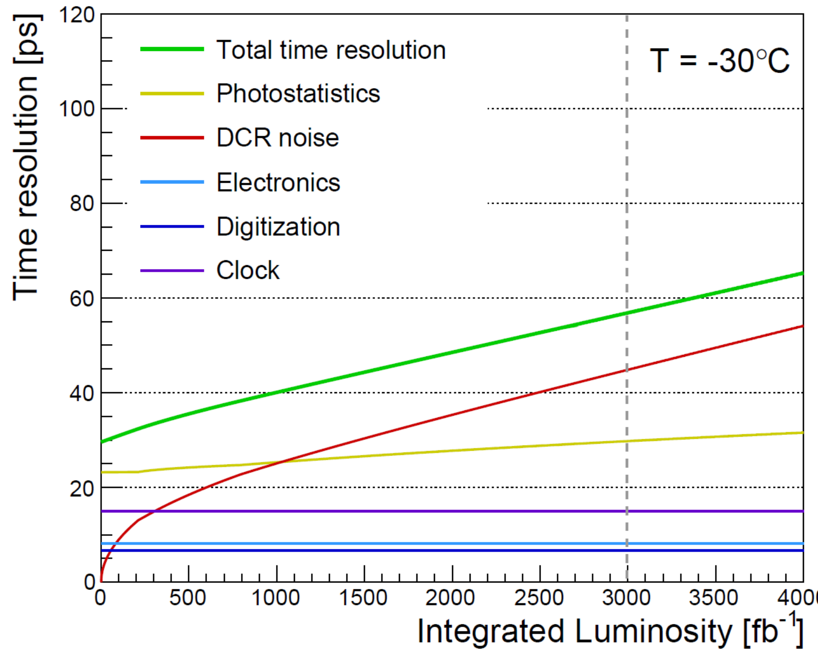


Average MIP deposition in LYSO bars ~ 4 MeV.

BTL timing performance

- Time resolution will degrade with the LHC integrated luminosity.
- Main contribution from Dark Count Rate due to the SiPM defects induced by irradiation.
  - Mitigation cooling at -30 °C
  - Possible mitigation with SiPM annealing during downtime.
- Degradation from photostatistics partially mitigated by tuning bias voltage (and therefore PDE).
- Other contributions are stable in time, not affected by irradiation.

$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR}$$



MTD Endcap: the radiation challenge

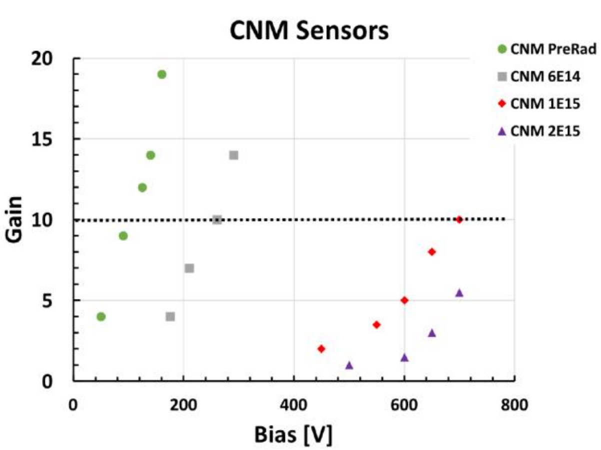
- Higher and non-uniform radiation dose in the Endcap region.
  - A factor 10 in the neutron flux comparing central barrel and outer Endcap
  - A factor 30 in integrated radiation dose.
- SiPM radiation hardness is not adequate for such high doses.
- **Low Gain Avalanche Detectors (LGADs)** will be use in Endcap.
  - Internal gain: 10-30

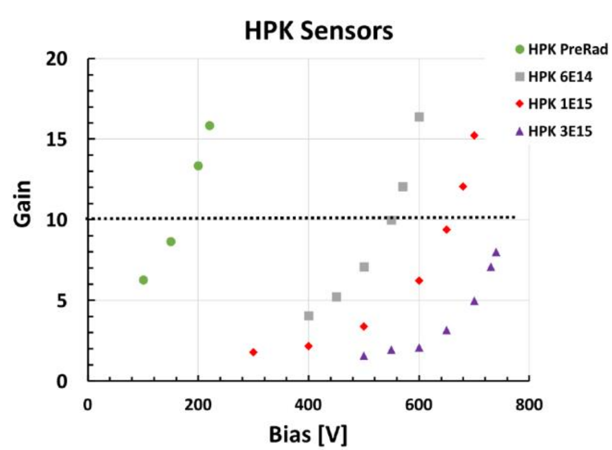
				3000 fb^{-1}	
Region	$\vert\eta\vert$	r (cm)	z (cm)	n_{eq}/cm^2	Dose (kGy)
Barrel	0.0	117	0	1.65×10^{14}	18
Barrel	1.15	117	170	1.80×10^{14}	25
Barrel	1.45	117	240	1.90×10^{14}	29
Endcap	1.6	127	304	1.5×10^{14}	19
Endcap	2.0	84	304	3.0×10^{14}	50
Endcap	2.5	50	304	7.5×10^{14}	170
Endcap	3.0	30	304	1.7×10^{15}	490

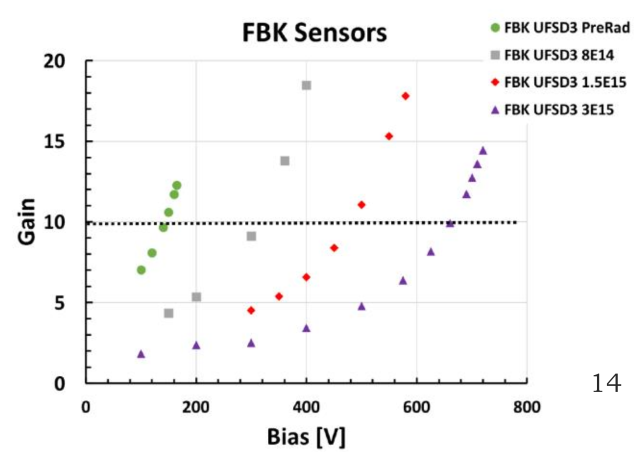
ETL sensor performance: radiation resistance

- The low gain is needed to allow segmentation and to keep the leakage current low. However the goal is to maintain a gain > 10 (resolution < 40 ps) until the end of HL-LHC.
- The gain decreases due to the irradiation: tuning of bias voltage to compensate gain loss.

Gain as a function of bias voltage for different neutron fluences for sensors manufactured by Centro Nacional de Microelectronica (CNM), Hamamatsu Photonics (HPK) and Fondazione Bruno Kessler (FBK).







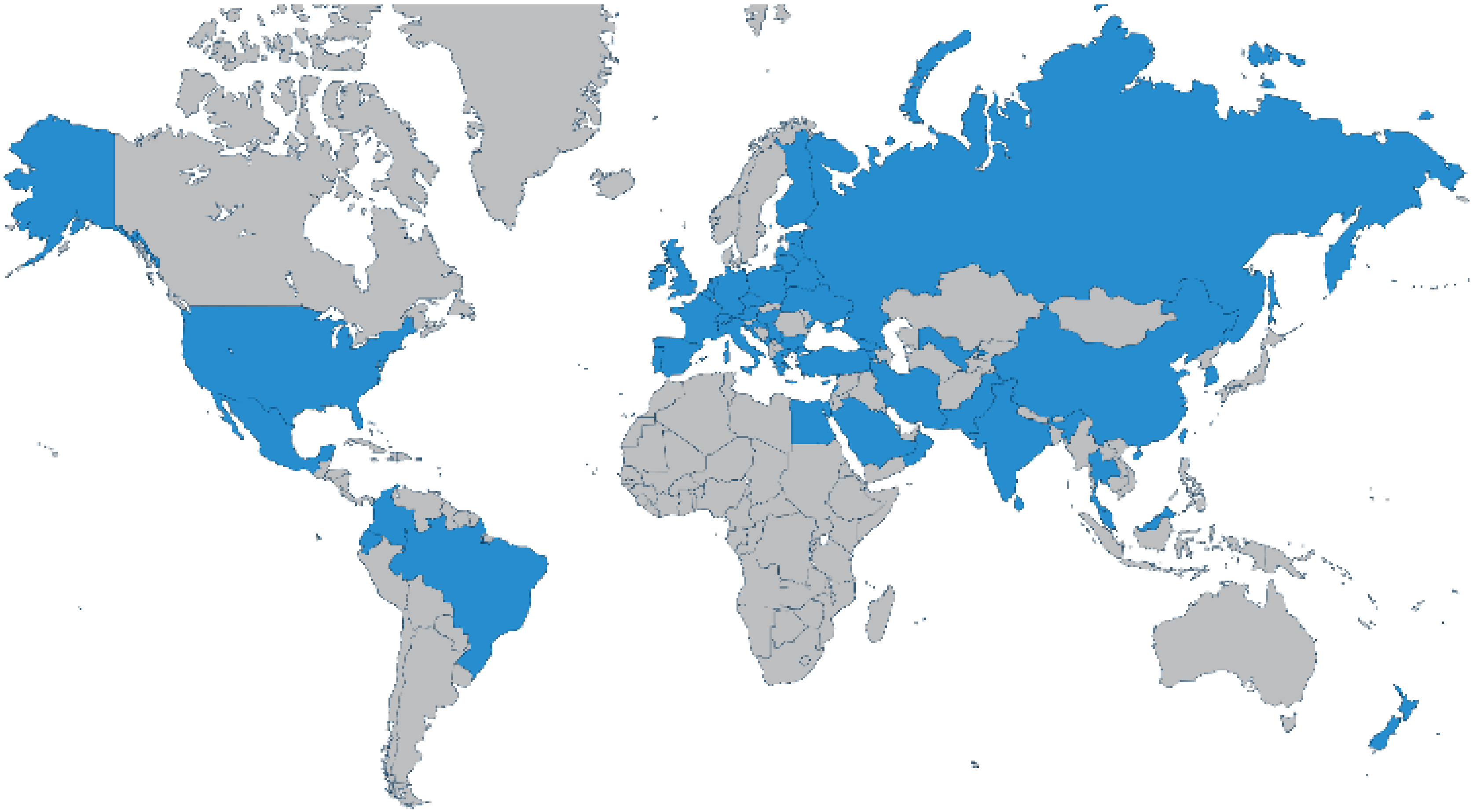
Conclusions

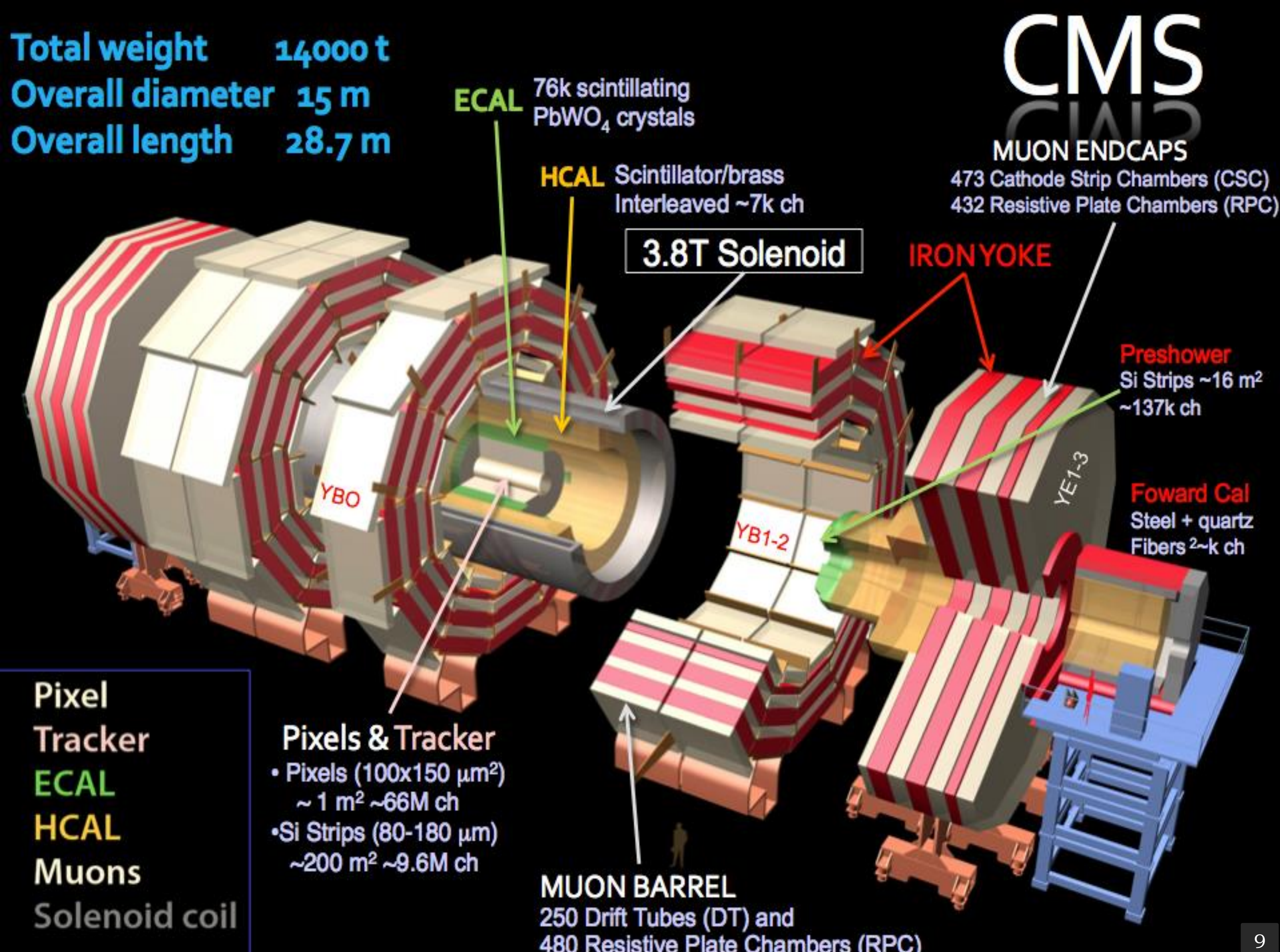
- CMS will upgrade the detector for the HL-LHC (2026-2036) → MTD: a new timing detector to mitigate harsh pile-up conditions.
- This detector will bring a completely new capability to CMS: the ability to measure precisely the production time of MIPs.
- **Barrel Timing Layer**: LYSO:Ce crystals with SiPM readout.
- **Endcap Timing Layer**: LGADs optimized for precision timing.
- Full CMS physics program will benefit: PU reduction, lepton and photon reconstruction, increase of effective luminosity, etc.
- Successful test beam campaign in progress: results show good agreement with expectation.
- A time resolution of 30 ps is achievable both in BTL and ETL; will degrade to only 40-60 ps at the end of HL-LHC.
- **MTD Technical Design Report** will be public in the next few weeks.

Backup

The CMS Collaboration

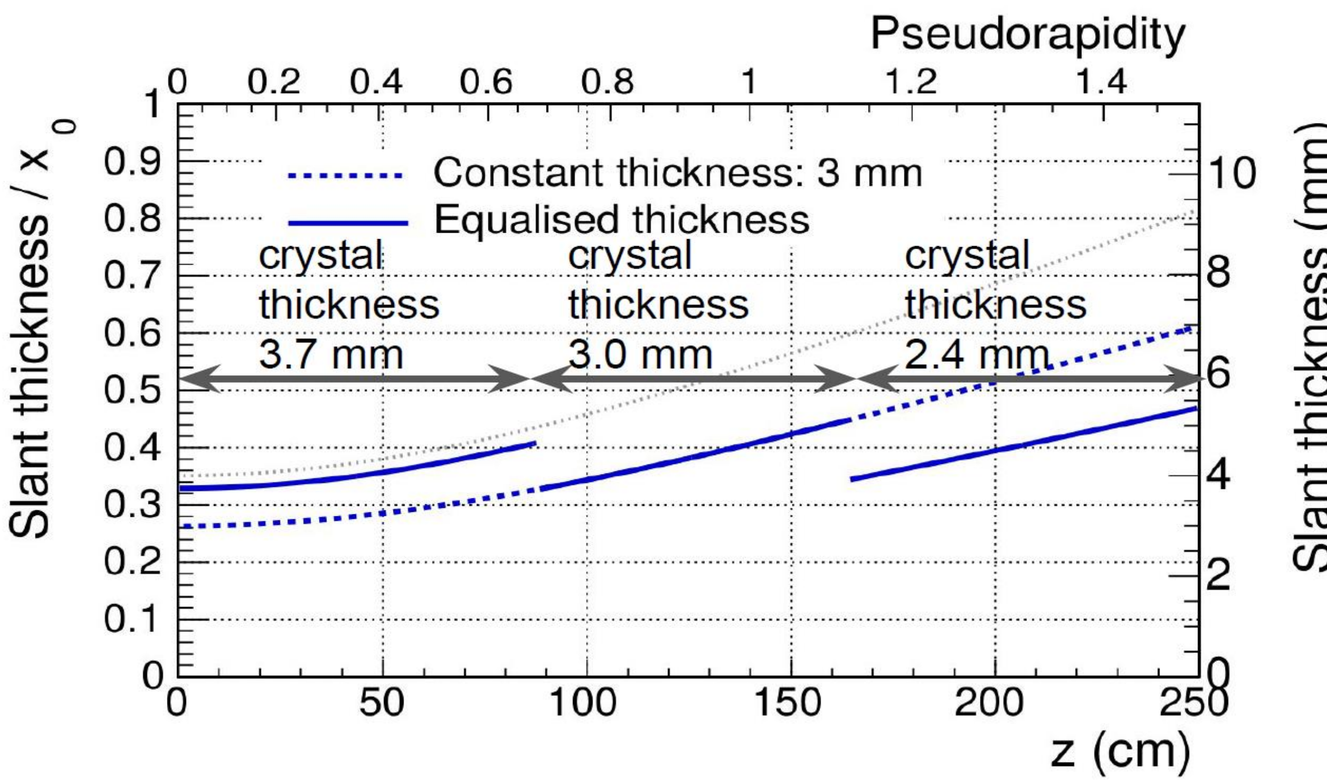
2942	1065	281	229	51
PHYSICISTS (1036 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS




CMS
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers 2~k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

Crystal bar thickness leveling

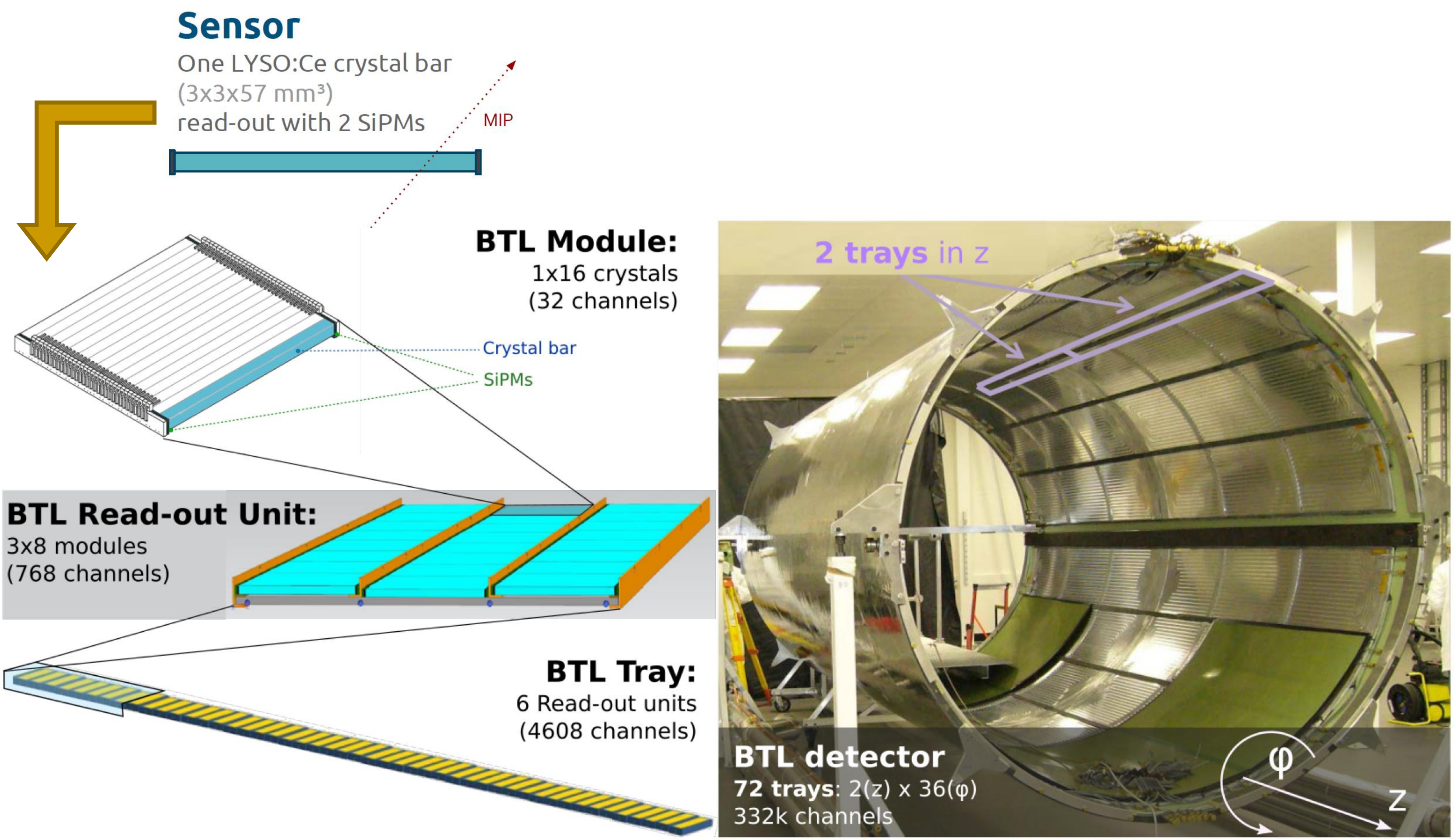
- Purpose is to achieve the best uniformity in energy deposit along the z-direction (beam-direction)
  - Reduce the crystal thickness along eta to compensate for the slant thickness actually crossed by the MIP in LYSO crystals
  - Energy deposit in crystal ∝ slant thickness



Crystal technical specifications

LYSO Crystal parameter	Specification	Spread (RMS)
Light output / end	> 6000 ph/MeV	$< 5\%$
LY(10ns)/LY(200ns)	> 20 %	$< 3\%$
LY(200ns)/LY(2000ns)	> 95 %	$< 3\%$
Decay time	< 43 ns	$< 3\%$
Rise time	< 200 ps	$< 3\%$
Density	> 7.1 g/cm^3	$< 2\%$
Refractive index	1.82	-
Radiation tolerance		
Loss of light output	$< 5\%$	$< 5\%$
Induced absorption coeff., μ_{ind}	< 3 m^{-1}	$< 5\%$
Dimensions	Specification	Tolerance
Length [mm]	57.0	+0.00/-0.03
Width [mm]	3.12	+0.00/-0.03
Height [mm]	3.75 / 3.0 / 2.4	+0.00/-0.03
Surface polishing	< 150 Å	

Layout of the Barrel Timing Layer



Low Gain Avalanche Detectors

Charge multiplication happens when the charge carriers are in electric fields above E ~ 300 kV/cm, when the electrons (and to a lesser extent the holes) acquire sufficient kinetic energy to generate additional e/h pairs.
The field value can be obtained by implanting an appropriate doping density (N_D ~ $10^{16}/cm^3$) that locally generates very high fields when depleted.

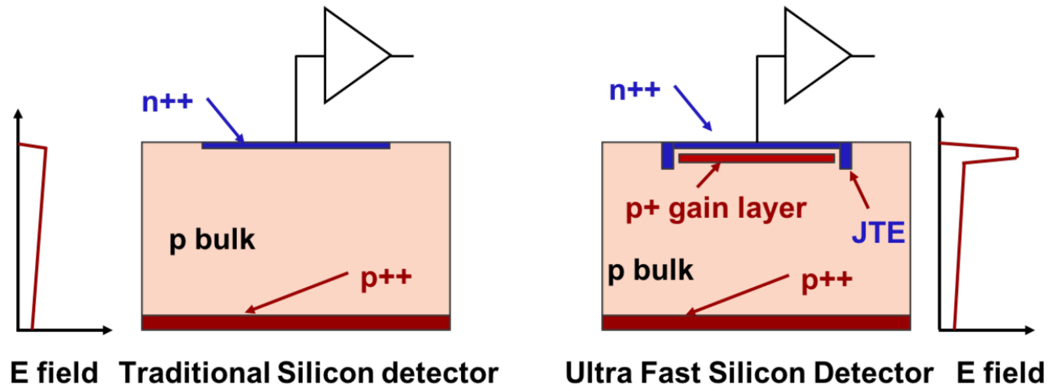
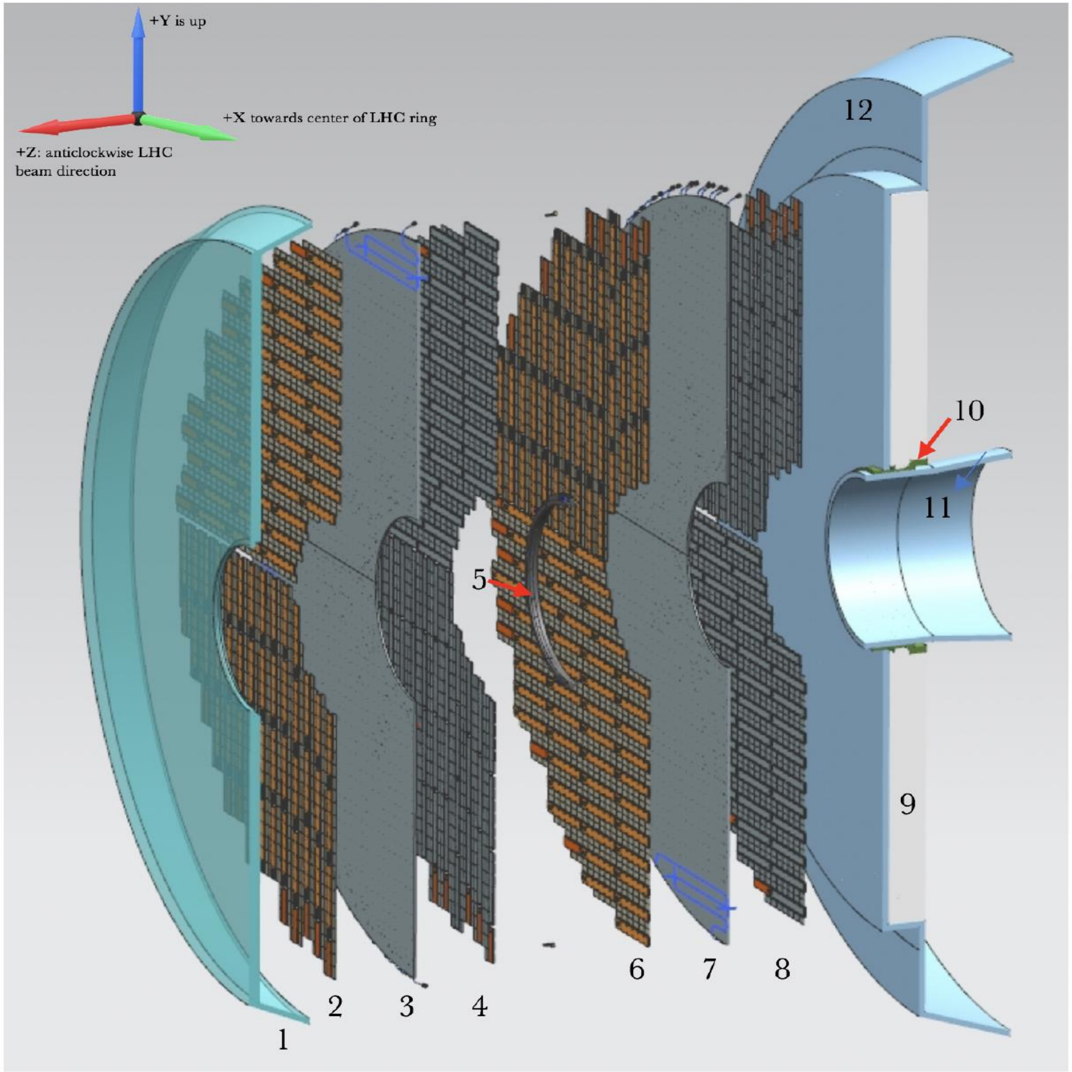


Figure 3.5: Cross-sectional diagrams comparing a standard silicon detector and a UFSD with an additional p implant providing the larger electric field needed for charge multiplication.

Layout of the Endcap Timing Layer



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen