CMS MTD Barrel Timing Layer: Precision Timing at the HL-LHC

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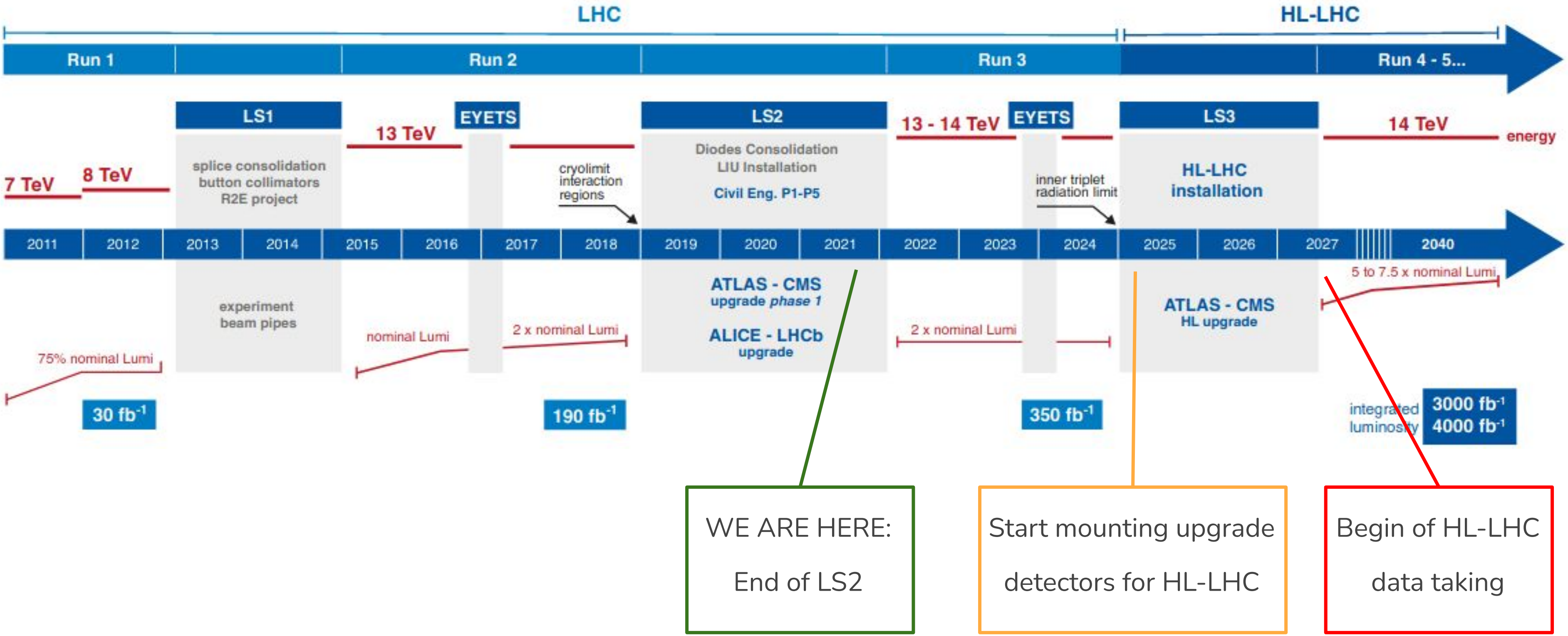
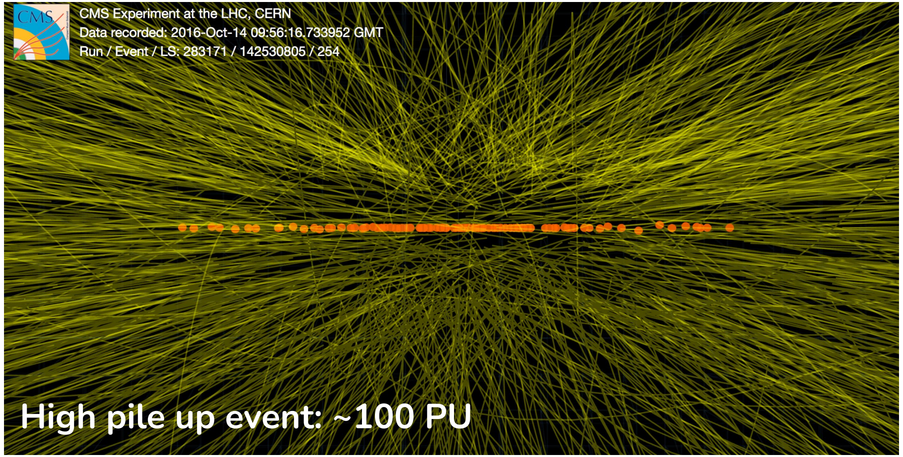
High Luminosity LHC: Schedule

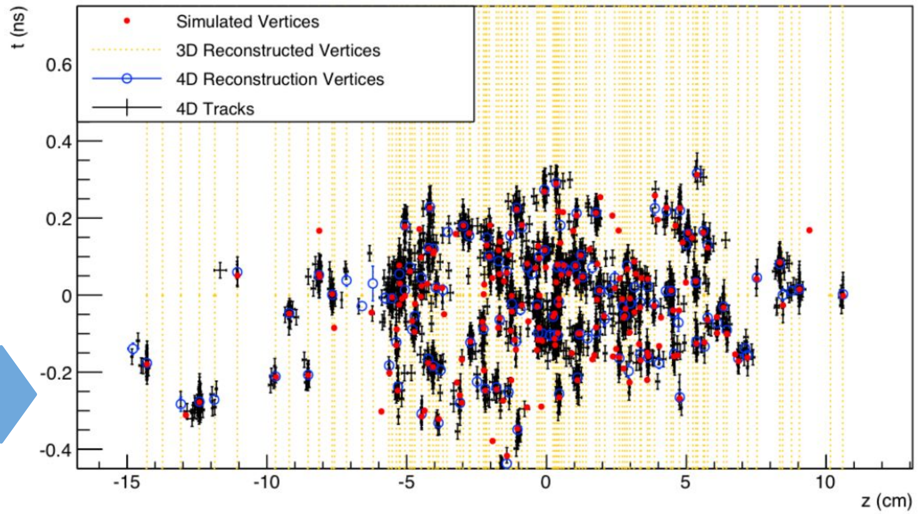


High Luminosity LHC: Challenges

- **High number of collisions per bunch crossing:**
    - Nominal scenario: $5\text{x}10^{34}$ $cm^{-2}s^{-1}$, ~140 PU
    - Ultimate scenario: $7.5\text{x}10^{34}$ $cm^{-2}s^{-1}$, ~200 PU

- **High pile up and radiation damage to detectors:**
    - Degradation of energy reconstruction and particle identification

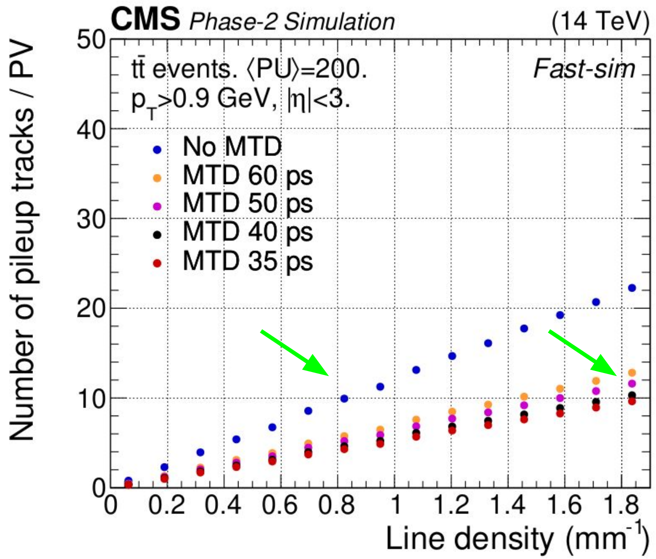




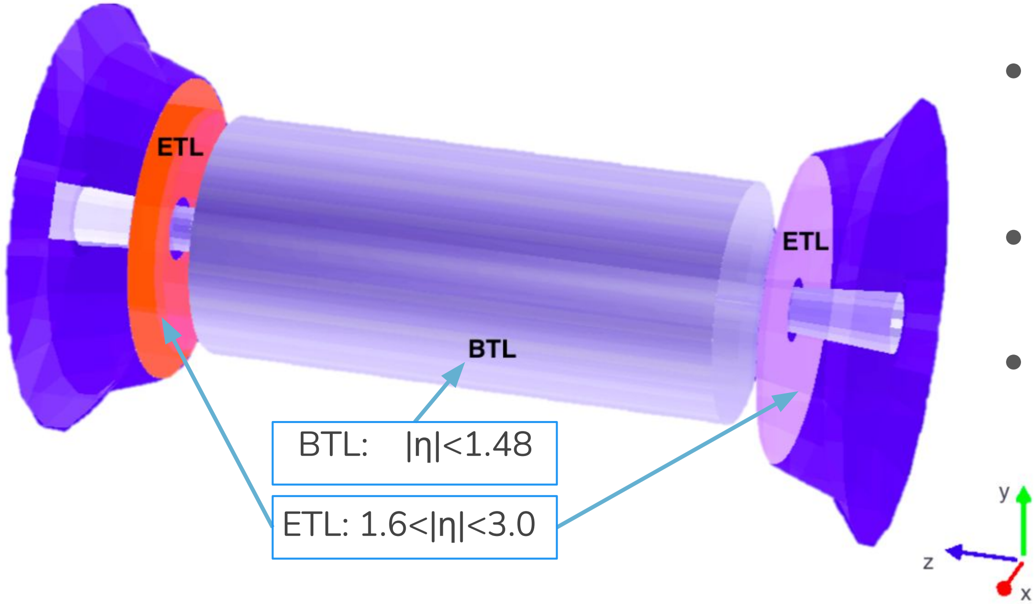
- **Timing information can be exploited to reject tracks** coming from the pile up → **Enable 4D reconstruction of vertices**

- **Proposed Minimum Ionizing Particle (MIP) Timing Detector (MTD):**
    - Provide 30-40 ps time resolution for MIPs (beginning of HL-LHC)

- **Impact on the CMS physics:**
  - Improve particle isolation, vertex identification (b-tagging, photons, long lived particles) and p_T^{miss} reconstruction
  - Time of flight (TOF) detector for charged particles identification, helping Heavy Ion Physics and Flavor Physics
- Recover the effective background conditions close to Phase-1 operations and **maintain excellent performance of CMS detector during HL-LHC**



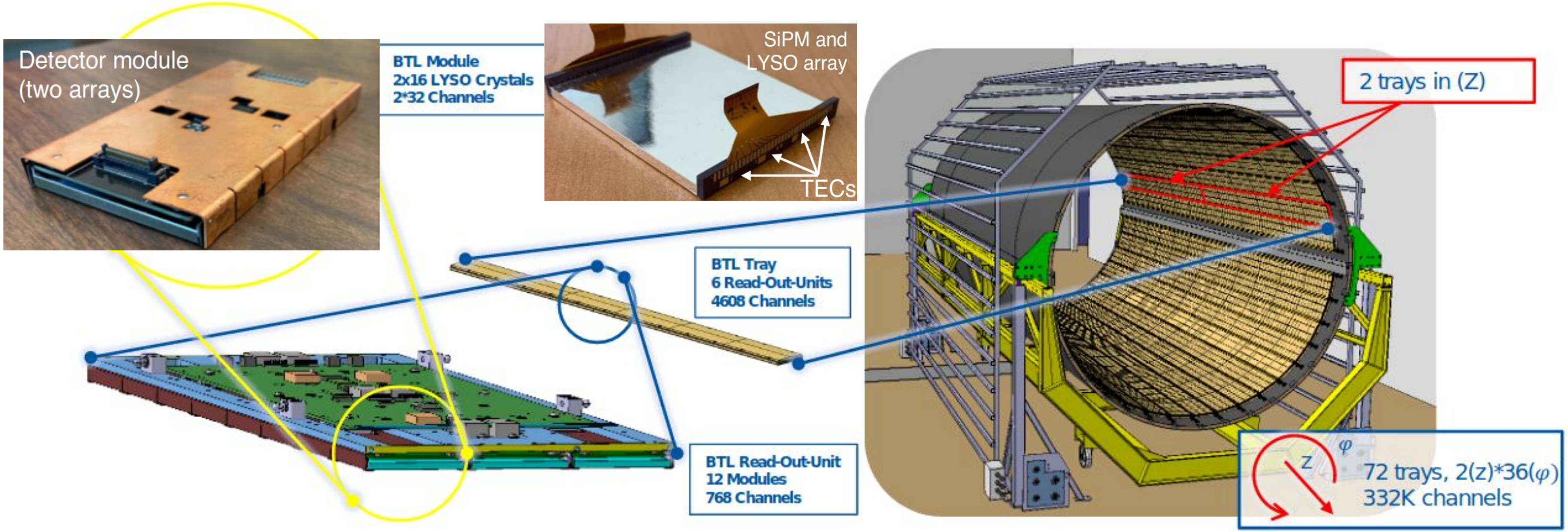
	Signal increase (%)		Expected significance	
Di-Higgs decay	BTL	BTL+ETL	No MTD	MTD
bbbb	13	17	0.88	0.95
$bb\tau\tau$	21	29	1.3	1.6
$bb\gamma\gamma$	13	17	1.7	1.9
bbWW			0.53	0.58
bbZZ			0.38	0.42
Combined			2.4	2.7



- **Split into two main sub-systems:**
  - Barrel Timing Layer (BTL)
  - Endcap Timing layer (ETL)
- **MTD is required to last throughout the HL-LHC era (~3000/fb)**
- **BTL and ETL will experience differing radiation dose through their lifetime** (FLUKA estimates):
  - BTL : 1.65×10^{14} - 1.90×10^{14} neq/cm^2
  - ETL : 1.50×10^{14} - 1.60×10^{15} neq/cm^2

- **Different technologies must be chosen:**
  - BTL : LYSO:Ce crystal bars coupled to SiPM readout
  - ETL : Si with internal gate (LGAD)

Barrel Timing Layer



- ➔ Thin (~40 mm), cylindrical layer housed in the Tracker/ECAL interface
- ➔ **Sensor technology: LYSO:Ce crystal scintillators read by SiPMs** at both ends
- ➔ **Read out by a dedicated ASIC, TOFHIR (Time-of-flight, High Rate)** chip which delivers precision timing information
- ➔ **Nominal operating temperature -45°C** to limit the noise induced time jitter

- ❏ Total active area of 38 m^2
- ❏ Z = 5.2 m, R = 1148 mm and $|\eta|<1.48$
- ❏ Total power requirement of ~30 kW
- ❏ -35°C with CO_2 and -10°C with thermo-electric cooler (TEC)

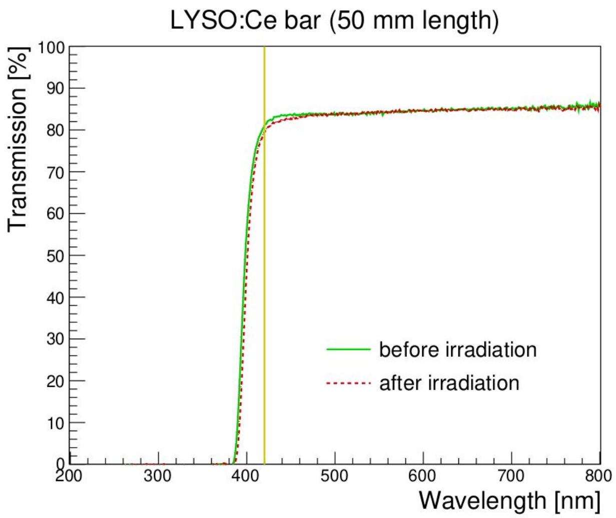
LYSO:Ce:

- ❑ High density (7.1 g/cm3): most probable value of energy deposit by a MIP ~ 0.86 MeV/mm
- ❑ High light yield (~ 40000 photons/ MeV)
- ❑ Fast scintillation rise time (< 100 ps)
- ❑ Short decay time (~40 ns)
- ❑ Non-hygroscopic

SiPMs:

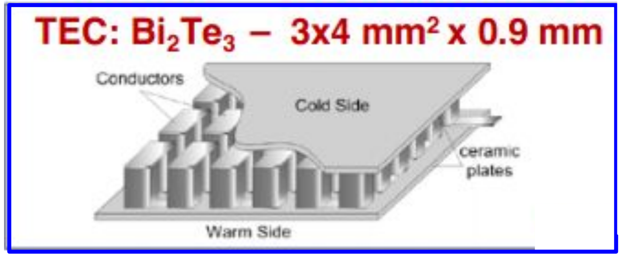
- ❑ Compact, robust and insensitive to magnetic fields
- ❑ Photo-detection efficiency (PDE): 20-40%, with optimal cell size of 15 μm
- ❑ Good radiation tolerance

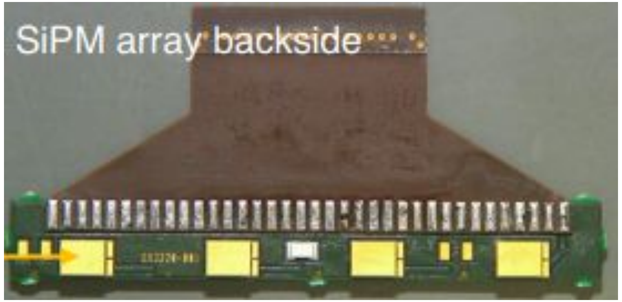
- **Crystals:**
  - **Dimension: ~3 x 3 x 57 mm^3** with η-dependent thickness
  - **Scintillation light at 420 nm** wavelength, matching SiPMs sensitivity
  - **Very high radiation tolerance**
    → verified with 24 GeV protons fluence of 2×10^{13} cm^{-2}

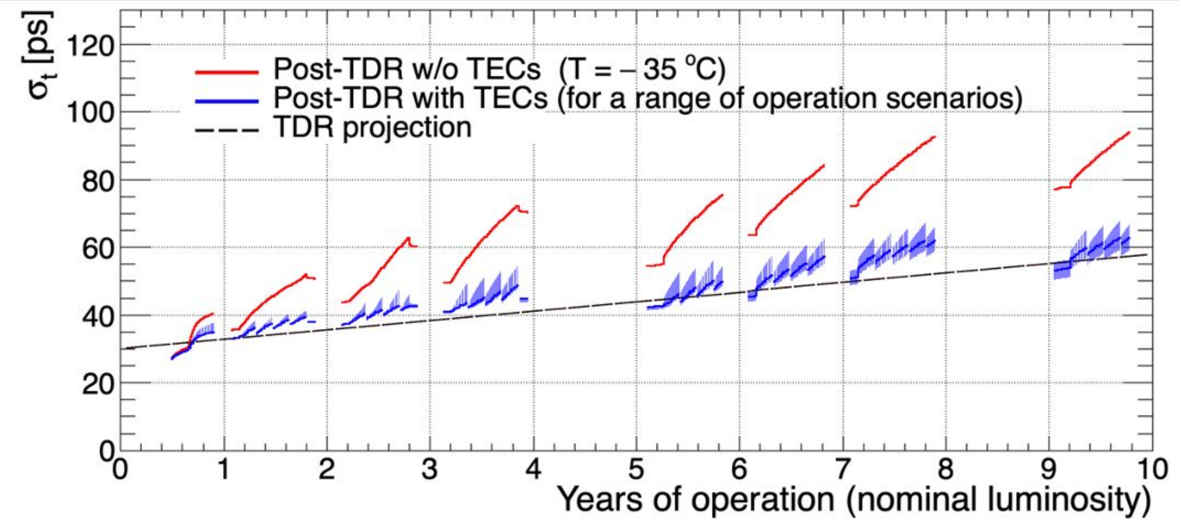


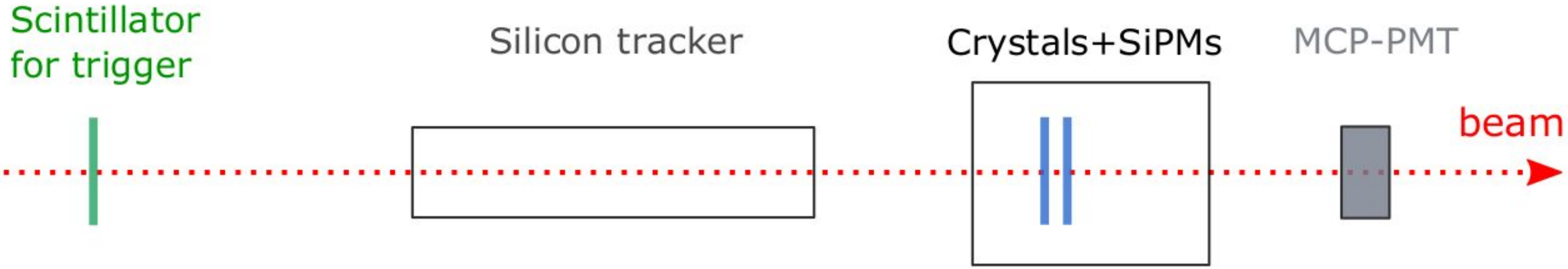
- **Challenges:**
  - ➔ Increase of dark count rate (DCR) with radiation damage and temperature
  - ➔ Linear drift of breakdown voltage with radiation

- **Solutions:**
  - ○ Dedicated noise cancellation circuit in the ASIC (TOFHIR)
  - ○ Annealing the SiPMs to about 40°C during shutdown
  - ○ Use thermoelectric coolers (TECs) to reduce SiPMs operating temperature





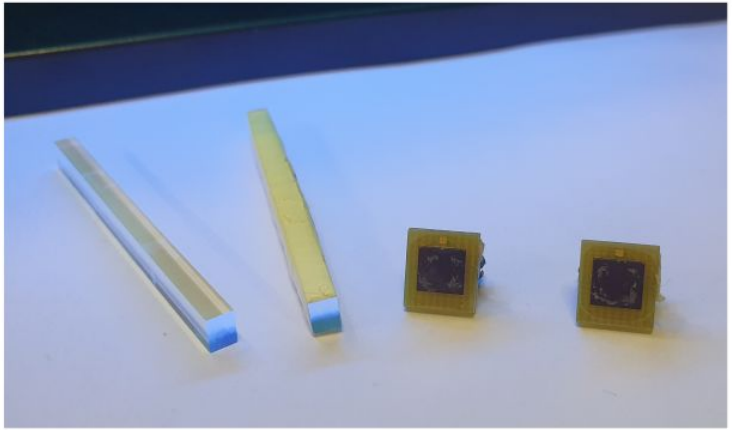




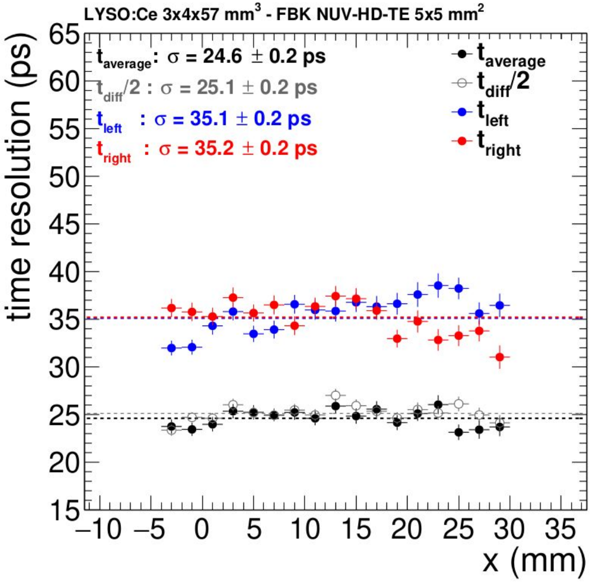
➔ Performed at Fermilab Test Beam Facility (FTBF), using 120 GeV protons

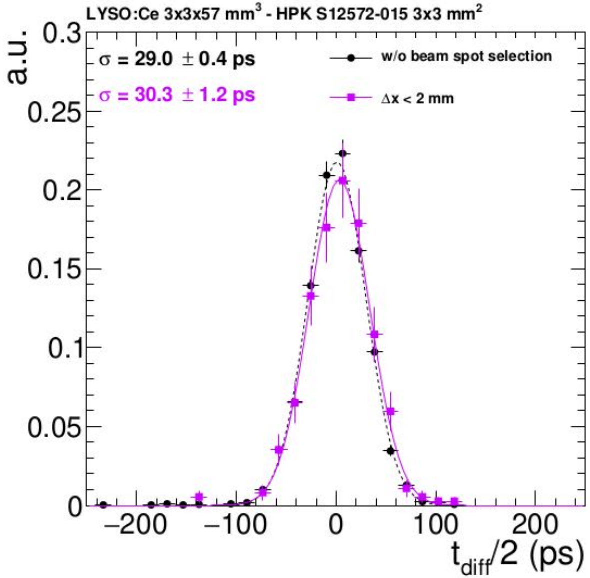
Setup:

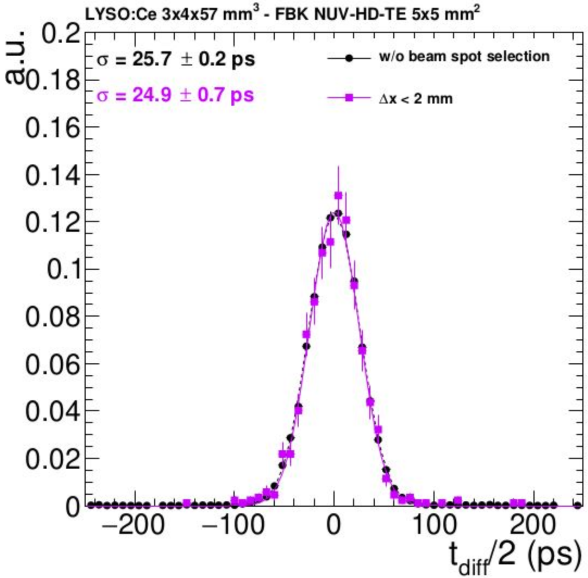
- ❏ Trigger based on a 10 cm^2 scintillation counter
- ❏ Silicon tracker telescope spatial information (X-Y)
- ❏ Micro Channel Plate (MCP) PMT for time reference
- ❏ LYSO:Ce + SiPMs (different prototypes) at 25°C, with ad-hoc read out electronics



JINST: 10.1088/1748-0221/16/07/P07023







Time resolution estimation:

- $(t_{left}+t_{right})/2 - t_{MCP} = t_{average}$
- $t_{left} - t_{right} = t_{diff}$
- $t_{left} - t_{MCP}$
- $t_{right} - t_{MCP}$

Test various SiPM prototypes:

- HPK S12572-015 (3x3 mm^2 area)
- FBK NUV-HD-TE (5x5 mm^2 area)

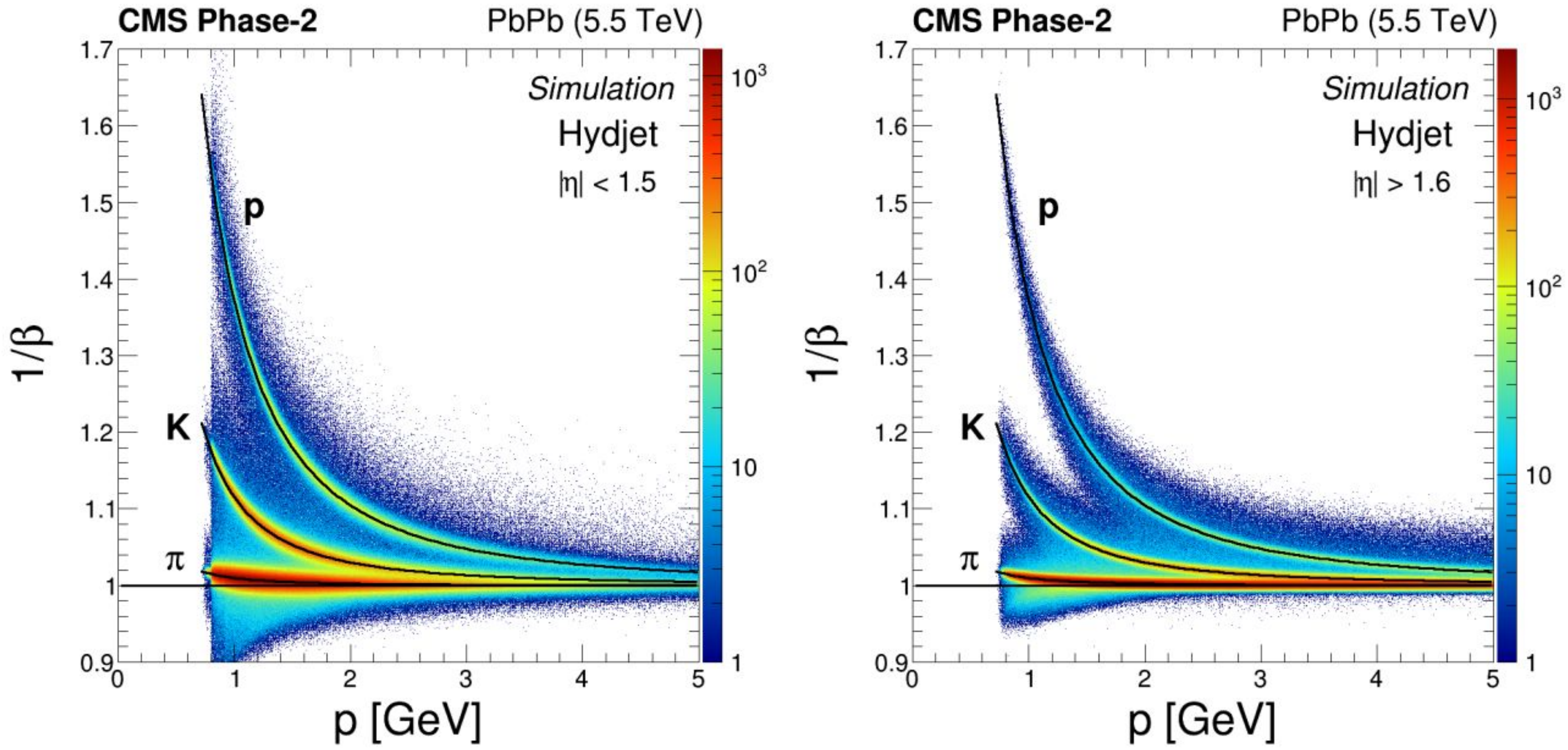
Target time resolution achieved

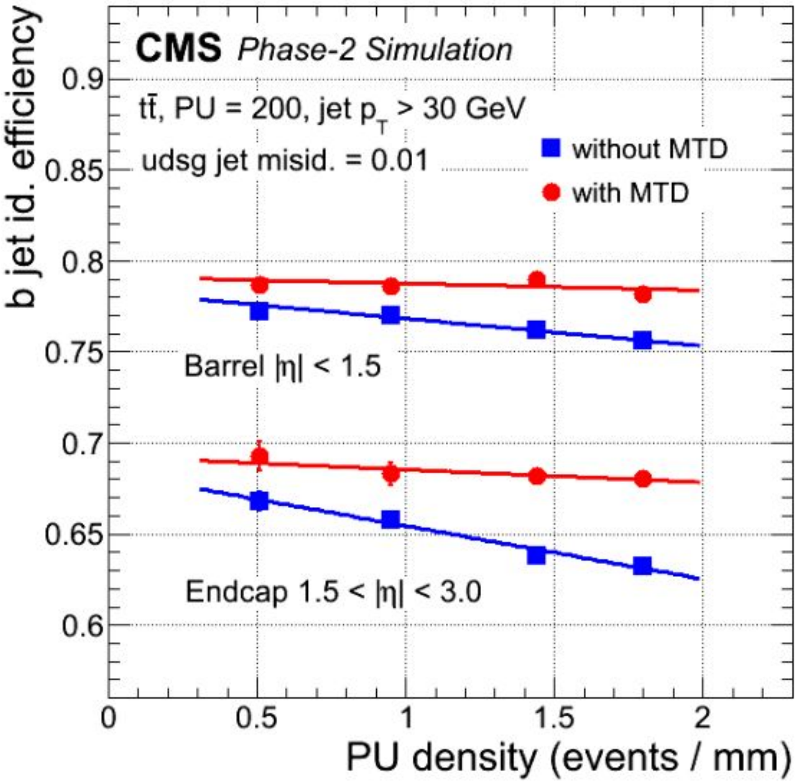
- Precision time measurements of MIP particles:
  - Help mitigating pileup during HL-LHC data taking
  - Improve particle isolation, vertex identification, p_T^{miss} reconstruction and time of flight measurement

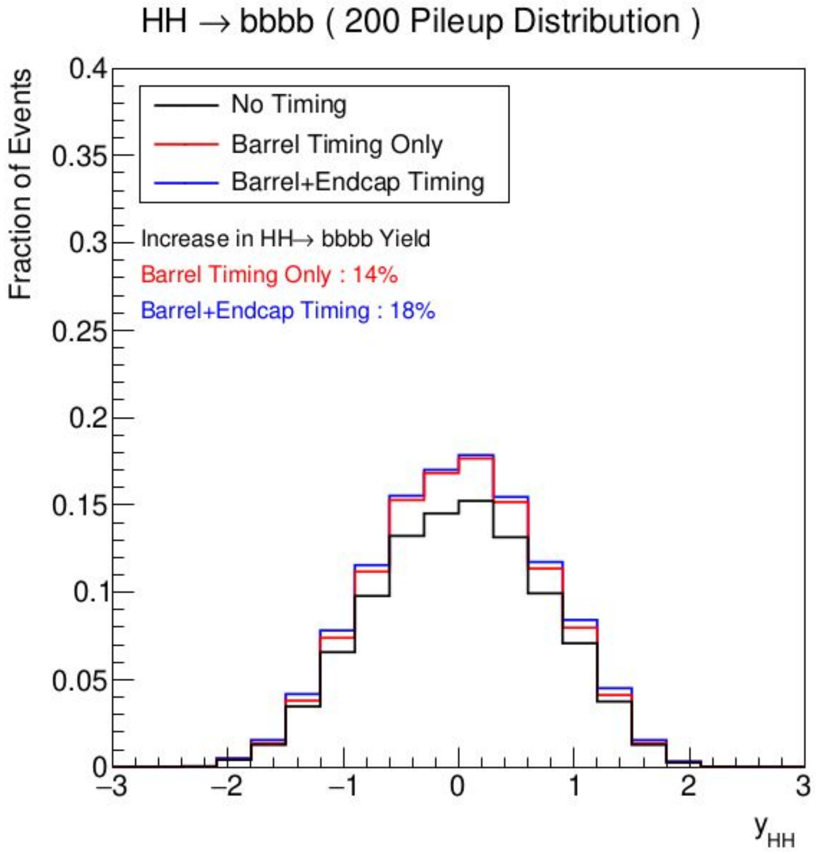
- Target time resolution of 30 ps has been achieved in test beam characterization of the current BTL sensor technology: LYSO:Ce readout by SiPMs

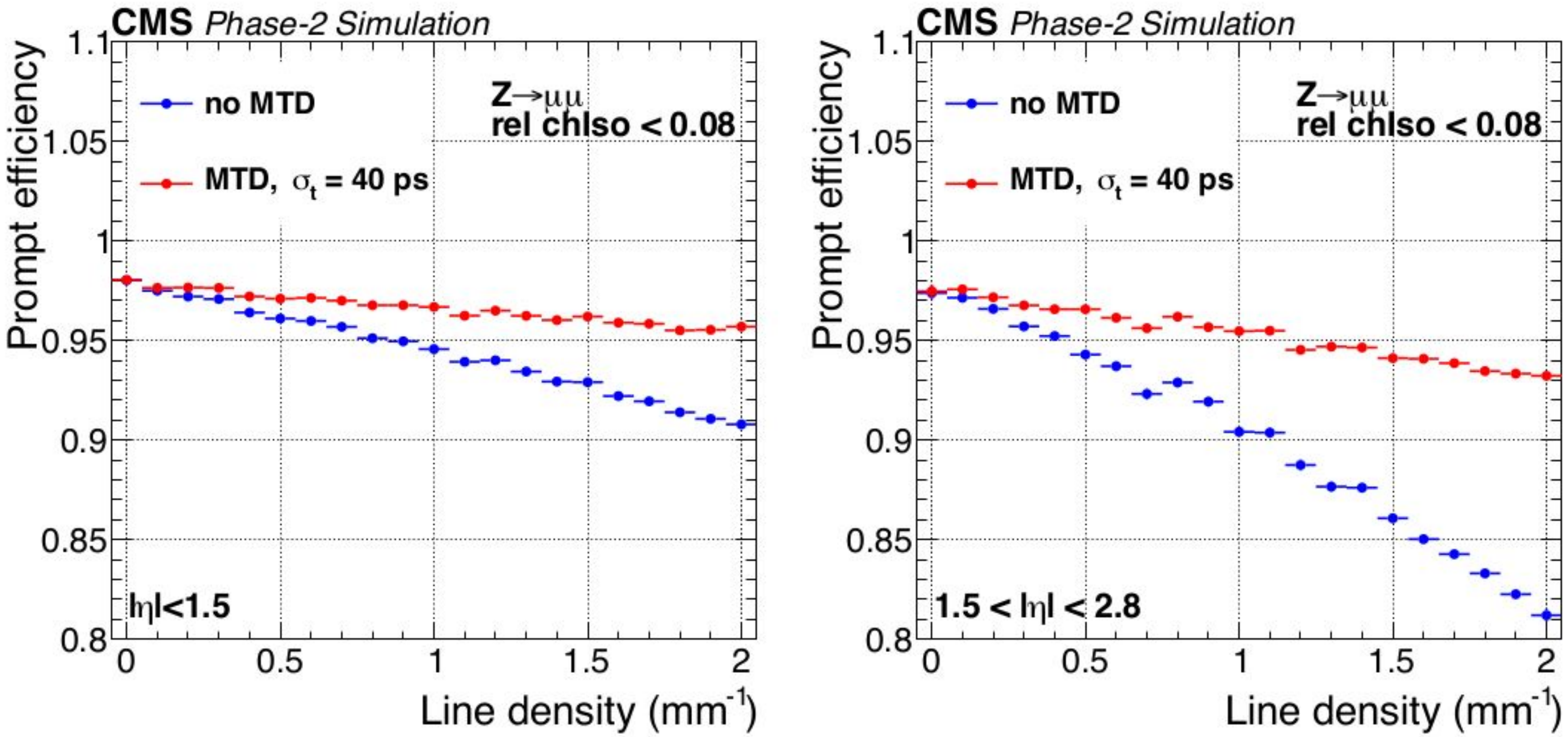
- Prototype testing ongoing :
  - Optimize end of life (end of HL-LHC operation) performance of BTL sensor modules with irradiated SiPMs, coupled to thermoelectric coolers
  - Test ASIC chip (TOFHIR) and readout unit

BACKUP


CMS Phase-2
PbPb (5.5 TeV)
Simulation
Hydjet
|η| < 1.5
p
K
π
1/β
p [GeV]
CMS Phase-2
PbPb (5.5 TeV)
Simulation
Hydjet
|η| > 1.6
p
K
π
1/β
p [GeV]


CMS Phase-2 Simulation
tt̄, PU = 200, jet p_T > 30 GeV
udsg jet misid. = 0.01
without MTD
with MTD
Barrel |η| < 1.5
Endcap 1.5 < |η| < 3.0
b jet id. efficiency
PU density (events / mm)


HH → bbbb (200 Pileup Distribution)
No Timing
Barrel Timing Only
Barrel+Endcap Timing
Increase in HH→ bbbb Yield
Barrel Timing Only : 14%
Barrel+Endcap Timing : 18%
Fraction of Events
y_{HH}



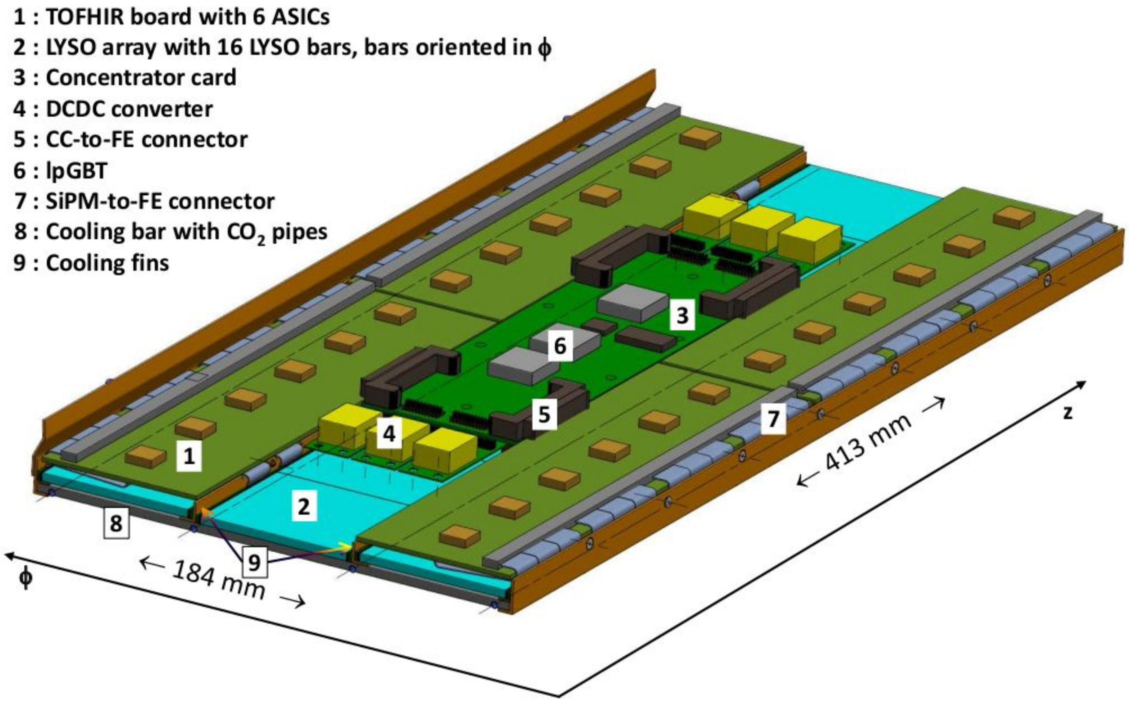
CMS Phase-2 Simulation
no MTD
MTD, σt = 40 ps
Z→μμ
rel chIso < 0.08
|η|<1.5
1.5 < |η| < 2.8
Prompt efficiency
Line density (mm⁻¹)
1.1
1.05
1
0.95
0.9
0.85
0.8
0
0.5
1
1.5
2

$\vert\eta\vert$ region	**0–0.7**	**0.7–1.1**	**1.1–1.48**
Readout unit ID within tray	1–2	3–4	5–6
Crystal thickness, t [mm]	3.75	3.0	2.4
$\langle t_{\text{slant}} \rangle$ **[mm]**	4.0	4.3	4.6
SiPM active area [mm^2]	11.2	9.0	7.2
$\langle \Phi_{\text{neq}}^{\text{tot}}(3000\ \text{fb}^{-1}) \rangle$ **[cm^{-2}]**	1.65×10^{14}	1.75×10^{14}	1.85×10^{14}

	Module	RU	Tray	Total
Channels (SiPMs)	32	768	4608	331776
Crystals	16	384	2304	165888
ASICs	1	24	144	10368
Modules	-	24	144	10368
Readout units (RU)	-	-	6	432
Trays	-	-	-	72

LYSO:Ce crystal parameter	Specification	Spread (rms)
Light output / end	> 6000 photons/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	< 15 nm	

SiPM parameter	Specification	FBK-NUV-HD	HPK-S12572	HPK-HDR2
Active area	–	~ 9 mm^2	~ 9 mm^2	~ 9 mm^2
Cell pitch	$< 20\ \mu$m	15 μm	15 μm	15 μm
Cell recovery time	< 10 ns	7 ns	8.5 ns	< 10 ns
Capacitance	< 600 pF	530 pF	295 pF	585 pF
Number of cells	> 20k	~ 40k	~ 40k	~ 40k
V_{br} ($-30\,°$C)	–	34.2 V	63.0 V	35.8 V
dV_{br}/dT	–	41 mV/ °C	59 mV/ °C	37 mV/ °C
$\delta V_{br}/10^{13}\ n_{eq}/cm^2$	≤ 0.2 V	< 0.1 V	0.2 V	< 0.1 V
DCR-T coefficient	–	1.76	1.90	1.79
ENF	< 1.1	< 1.05	1.07	< 1.05
Parameters after 3000 fb^{-1}				
Optimal OV	> 1V	1.6 V	1.5 V	1.2 V
PDE	–	15%	13%	23%
Current/device	–	1.32 mA	0.77 mA	1.30 mA
Static power consumption	≤ 50 mW	50 mW	50 mW	50 mW
Gain	$\geq 1.3 \times 10^5$	2.1×10^5	1.45×10^5	1.55×10^5
DCR/SiPM	–	42 GHz	37 GHz	55 GHz
PDE/$\sqrt{\text{DCR}}$	≥ 2.0	2.3	2.1	3.1



- TOFHIR (Time-of-flight, High Rate) ASIC chip:

  - Discrimination of the leading edges
  - Time measurement with a TDC

- 6 ASICs are mounted on a front end board

- 4 front-end boards plugged into a Concentrator Card:
  - Provide low voltage, bias voltage
  - 3 lpGBTs transfer data and control signals

- The ASICs, FE, CC, and associated power supplies constitute the RU, which supports 768 SiPMs