Precision Timing with the CMS MTD Barrel Timing Layer for HL-LHC

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On behalf of the CMS Collaboration

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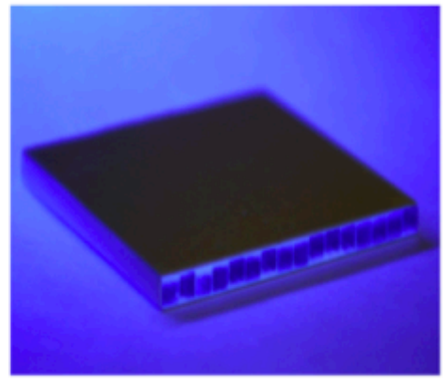
Overview of CMS MIP Timing Detector

Barrel Timing Layer (BTL)

BTL: LYSO bars + SiPM readout:

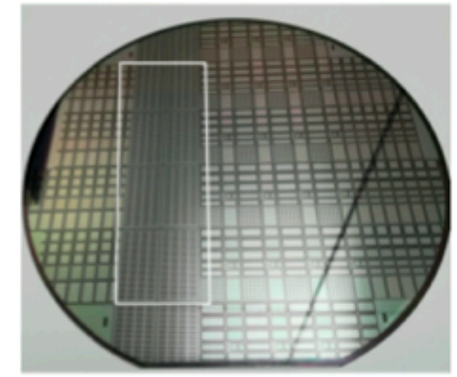
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2×10^{14} n_{eq}/cm^2

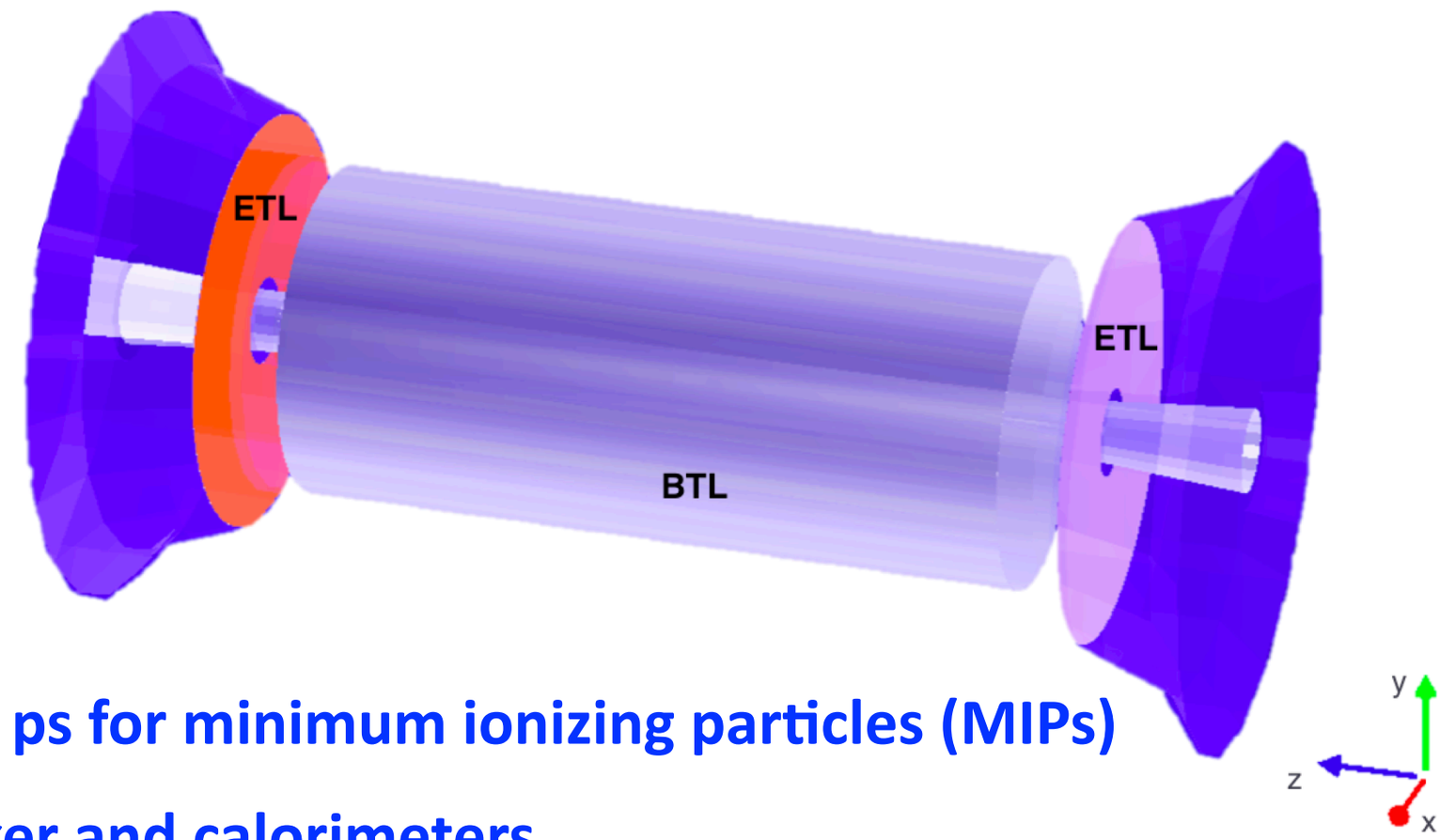


Endcap Timing Layer (ETL)

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 2×10^{15} n_{eq}/cm^2



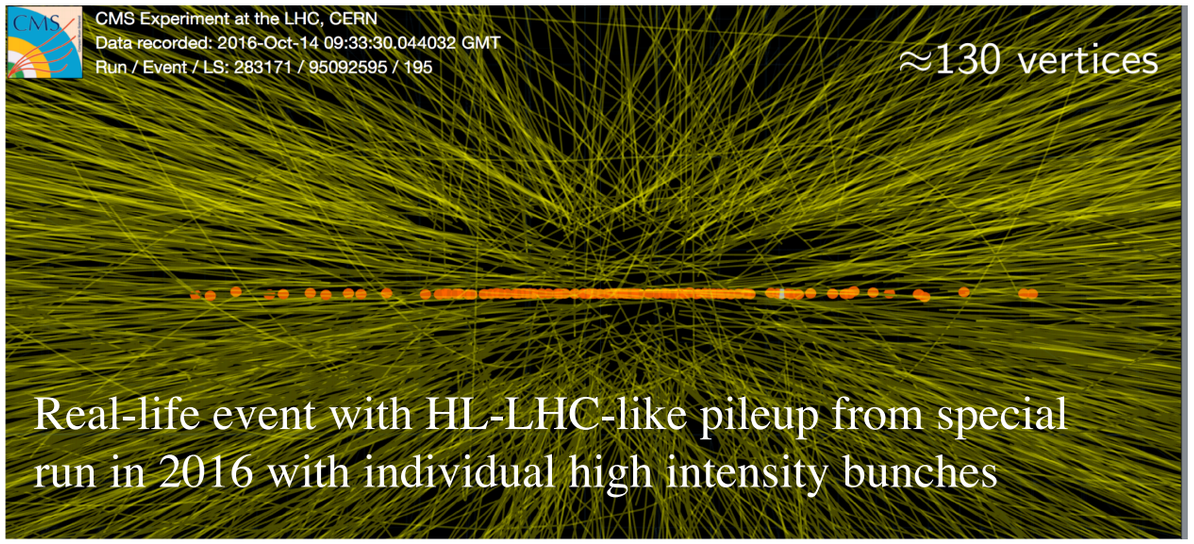


- **Time resolution of 30-50 ps for minimum ionizing particles (MIPs)**
- **Thin layer between tracker and calorimeters**
- **Hermetic coverage for $|\eta| < 3.0$**

MTD TDR CMS-TDR-020

CMS MIP timing detector: pileup mitigation

- Phase-II upgrade: maintain excellent detector performance under high pileup of 140-200 collisions per bunch crossing, and severe radiation environment at HL-LHC
- MTD will be added to CMS to help meet the high-pileup challenge.

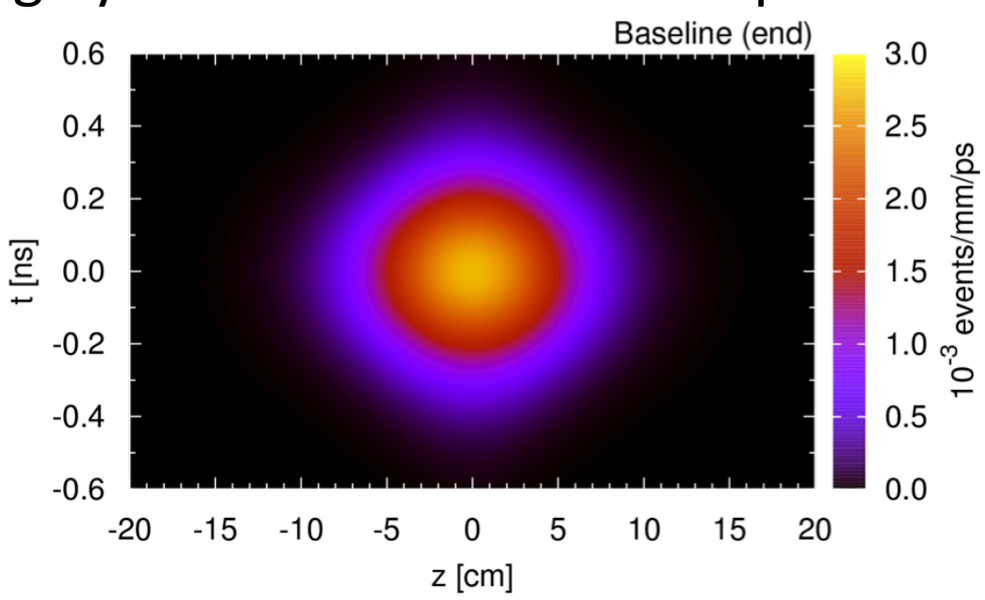


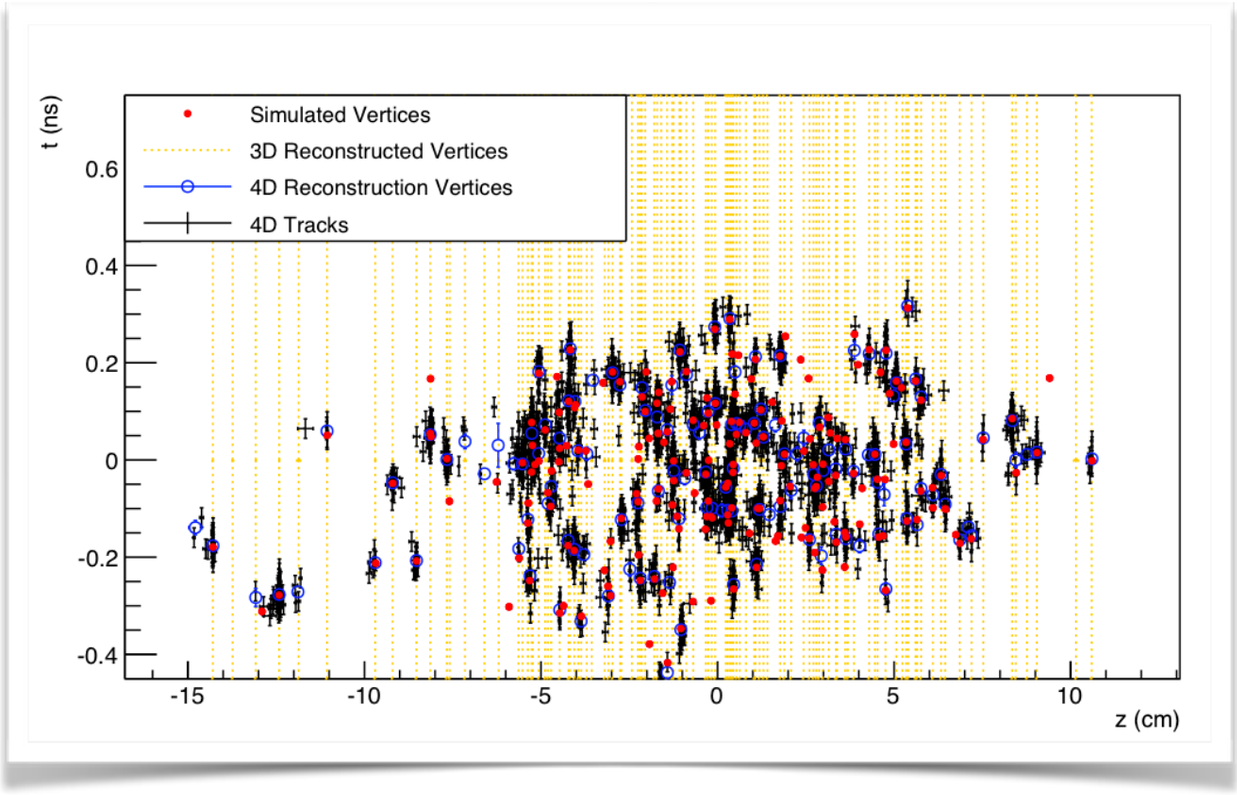
Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches

4D (x,y,z,t) vertex reconstruction:

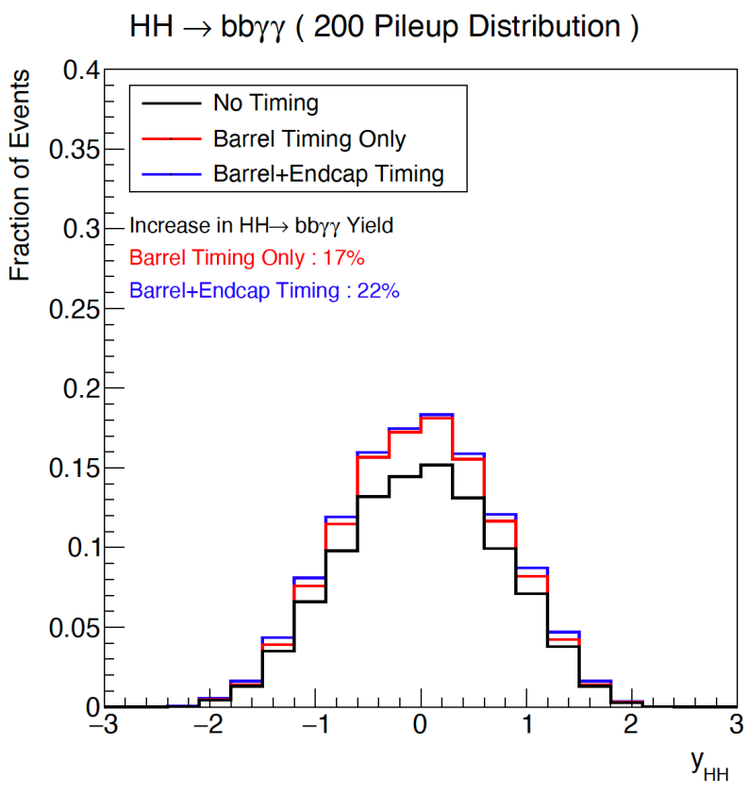
- Vertex merging reduced from 15% to 1% in 200 PU scenario
- Disentangle overlapping vertices in space with precision timing.

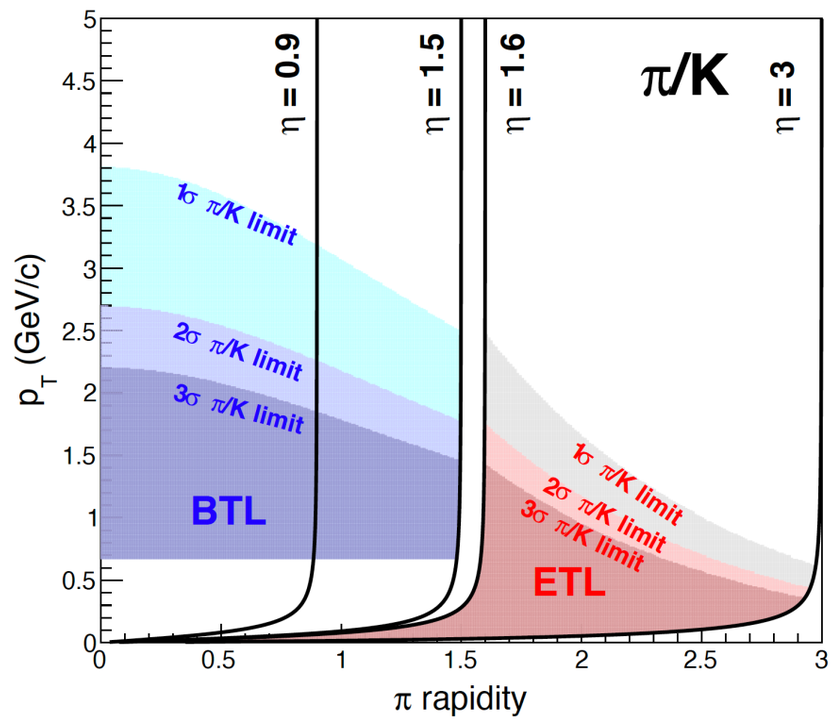
Beam spot: time spread of 180 - 200 ps, largely uncorrelated with the spread in z

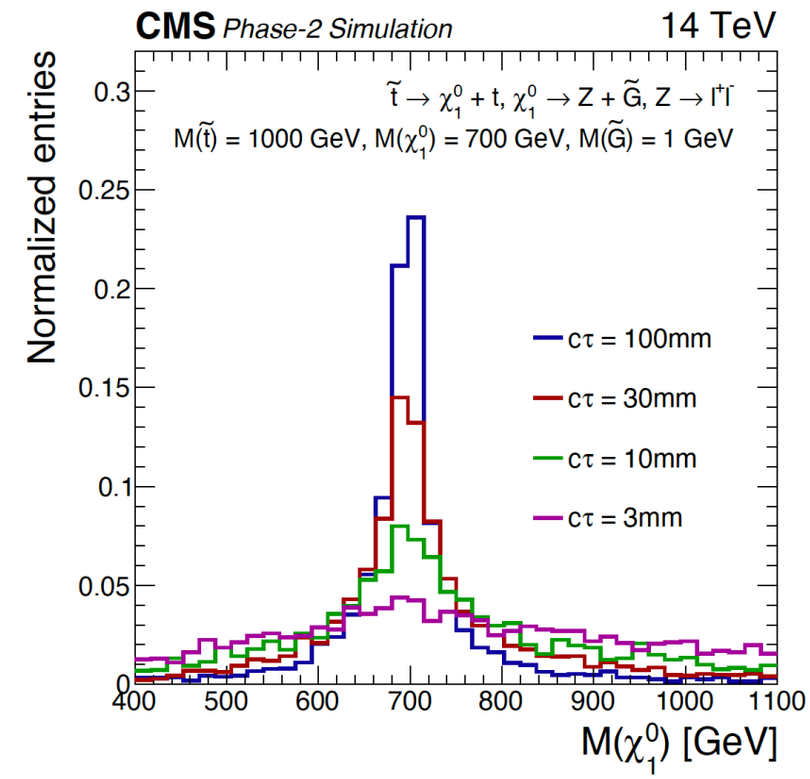




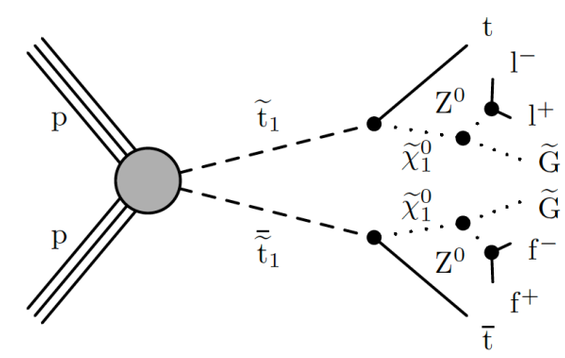
CMS MIP timing detector: expand physics reach at HL-LHC







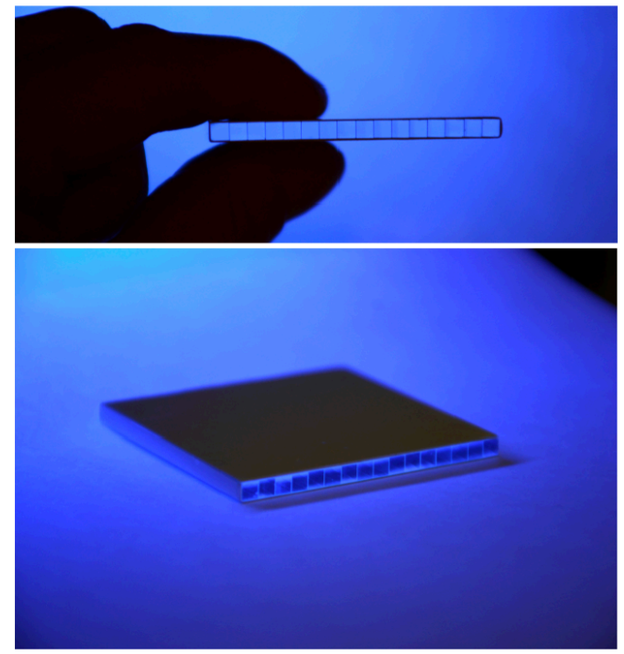
- Reduction of pile-up enhances quality of particle reconstruction
  - 10 - 20% gain in di-Higgs significance
- Particle ID for low p_T hadrons, new reach for Heavy Ion Physics:
  - π/K separation up to 2 GeV, p/K separation up to 5 GeV
- Mass reconstruction of the long-lived particles

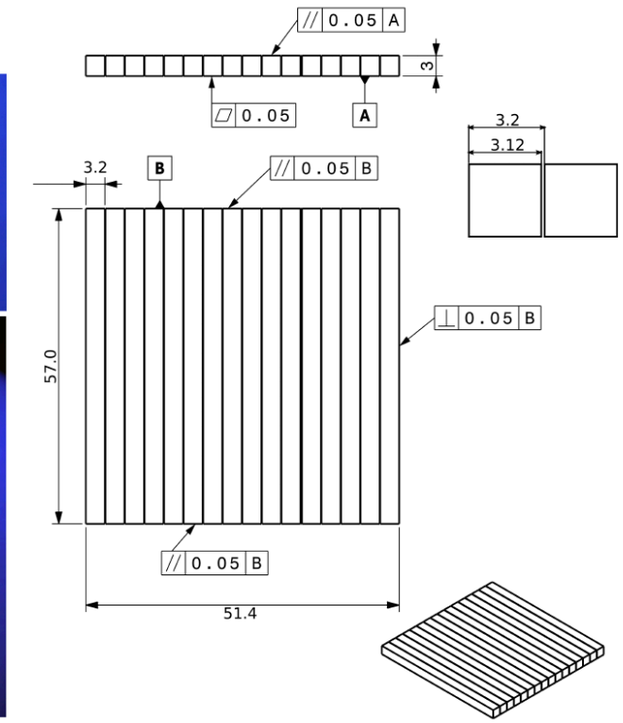


BTL sensor design - LYSO:Ce

Lutetium-yttrium orthosilicate crystals activated with cerium (LYSO:Ce) as scintillator $3 \times 3 \times 57\ mm^3$.

LYSO:Ce matrix 1x16

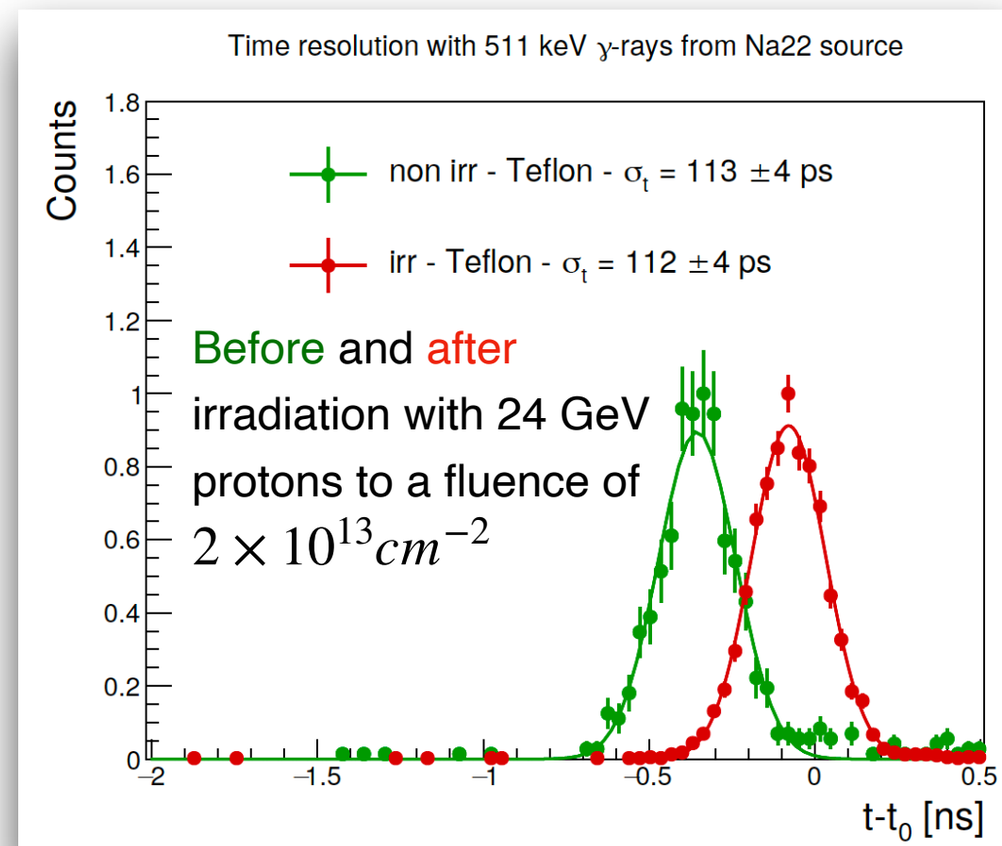




Stochastic fluctuations in the time-of-arrival of photons detected at the SiPM:

$$\sigma_t^{photostatistics} \propto \sqrt{1/N_{p.e.}} \propto \sqrt{1/(E_{dep} \times LY \times LCE \times PDE)}$$

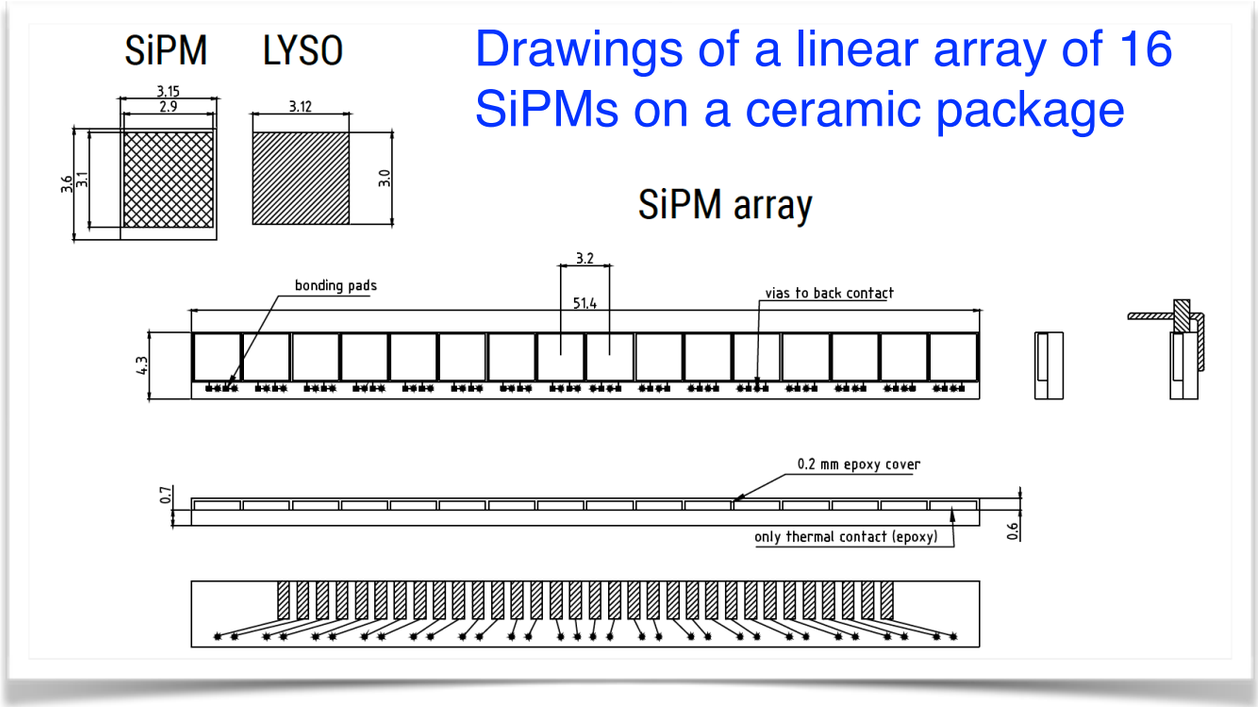
- Dense (7.1 g/cm³): a MIP deposits **E_{dep} ~4.2 MeV** including impact angle (0.86 MeV/mm)
- Bright: light yield (LY) ~40k photons/MeV.
- Excellent radiation tolerance



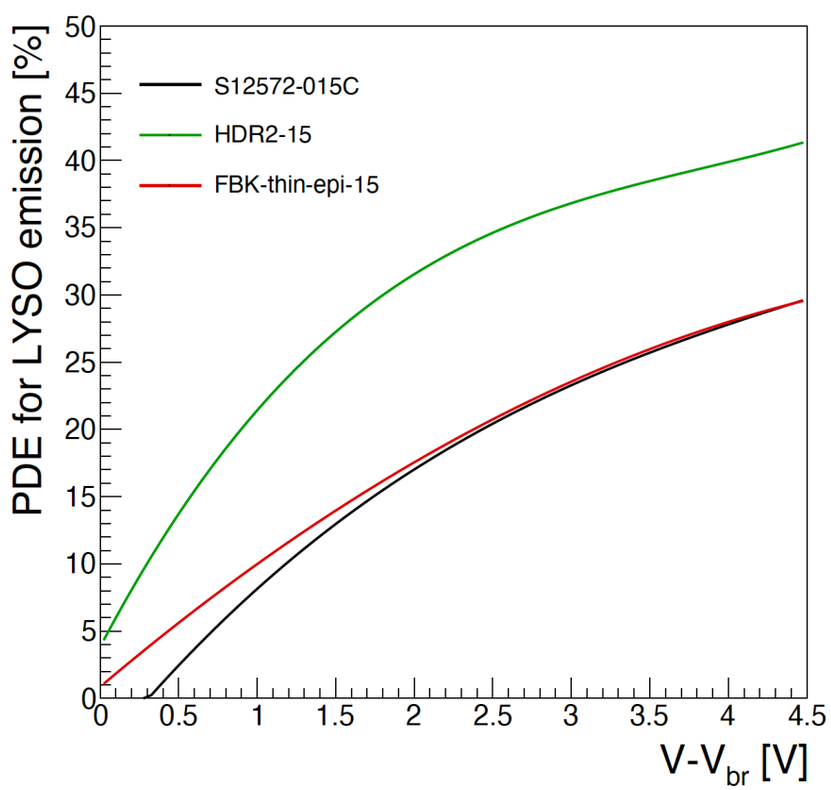
BTL sensor design - SiPM

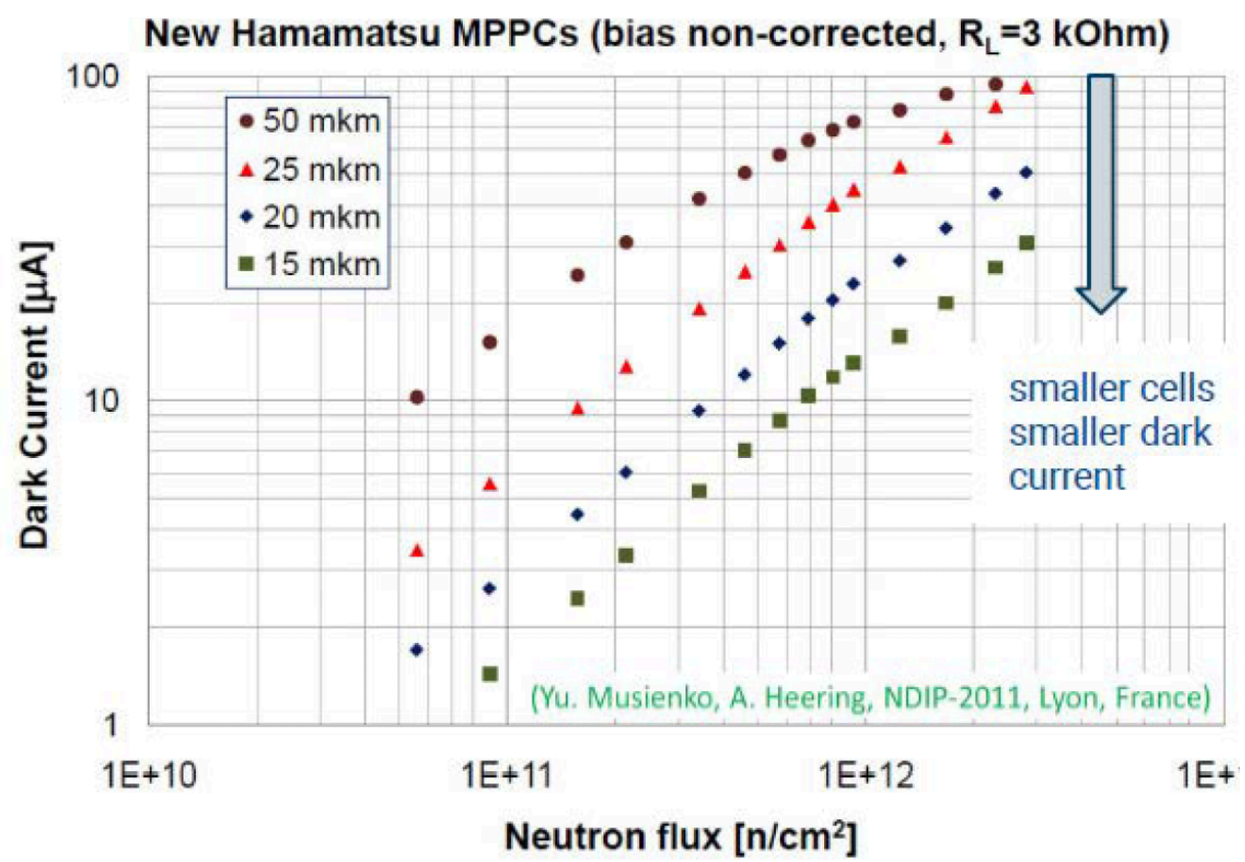
Silicon Photomultipliers as photo sensors

- Compact, fast (single photon resolution of 100 ps), insensitive to magnetic fields, radiation hard
- SiPM active area of 9 mm^2, coupled to LYSO using glue: light collection efficiency (LCE) 15%
- Optimal SiPM cell size: 15 µm, balance between radiation tolerance and photon detection efficiency
- Gain: $1.5 - 4 \times 10^5$
- Photo detection efficiency (PDE) : 20-40%



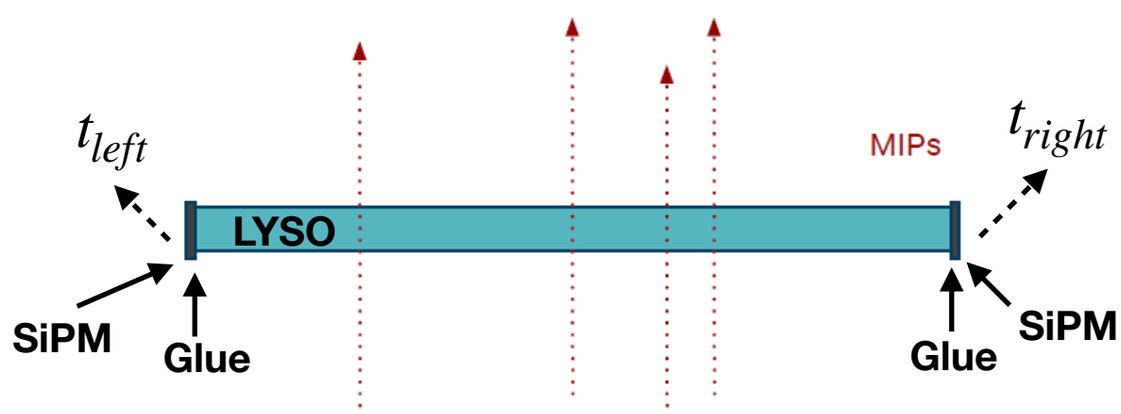
Drawings of a linear array of 16 SiPMs on a ceramic package

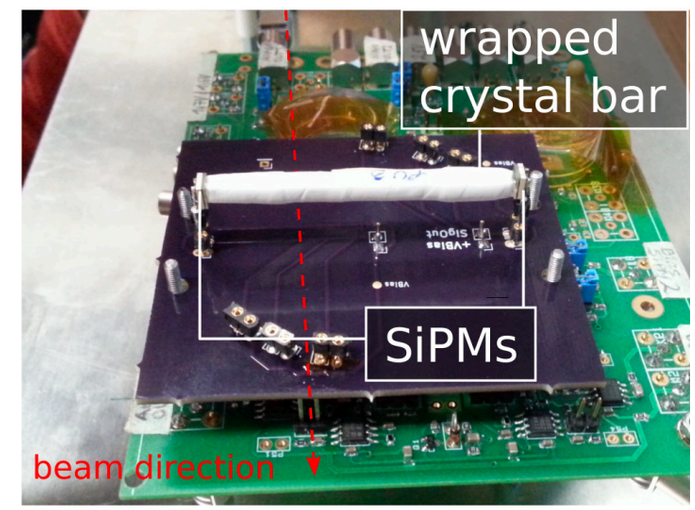


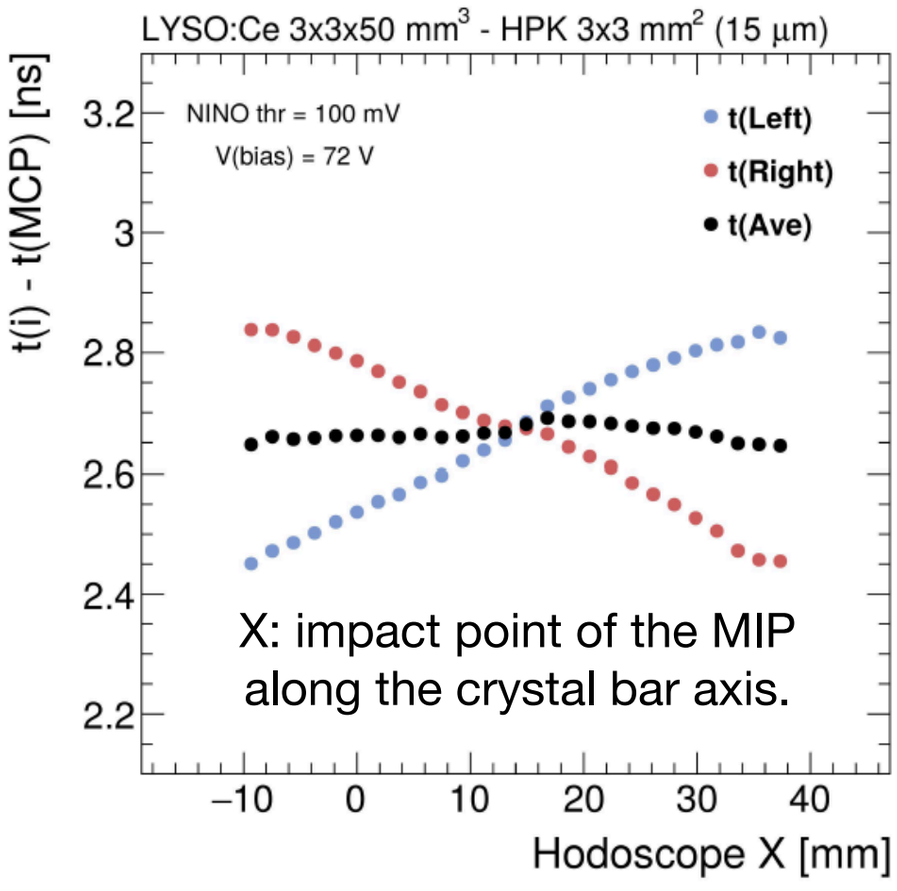


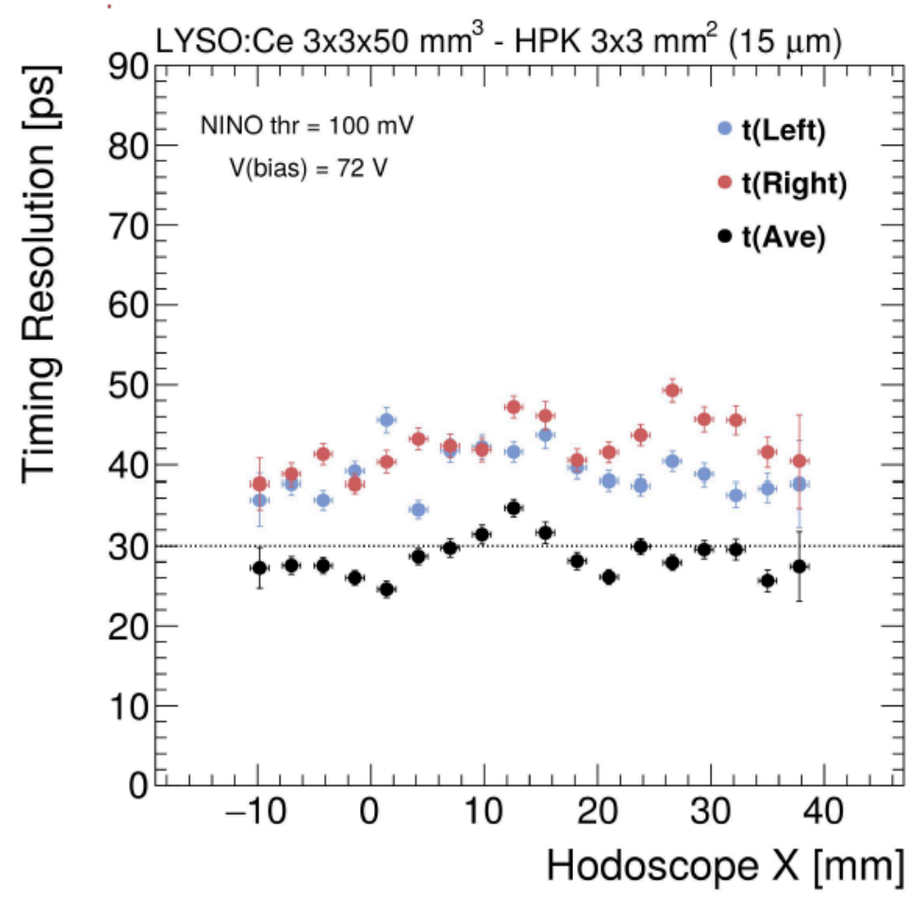
BTL sensor performance in test beam

- Timestamp of a MIP traversing BTL: $t_{Ave} = (t_{left} + t_{right})/2$
- Achieved 30 ps time resolution per BTL sensor before irradiation
- Uniform time response and resolution across sensor area





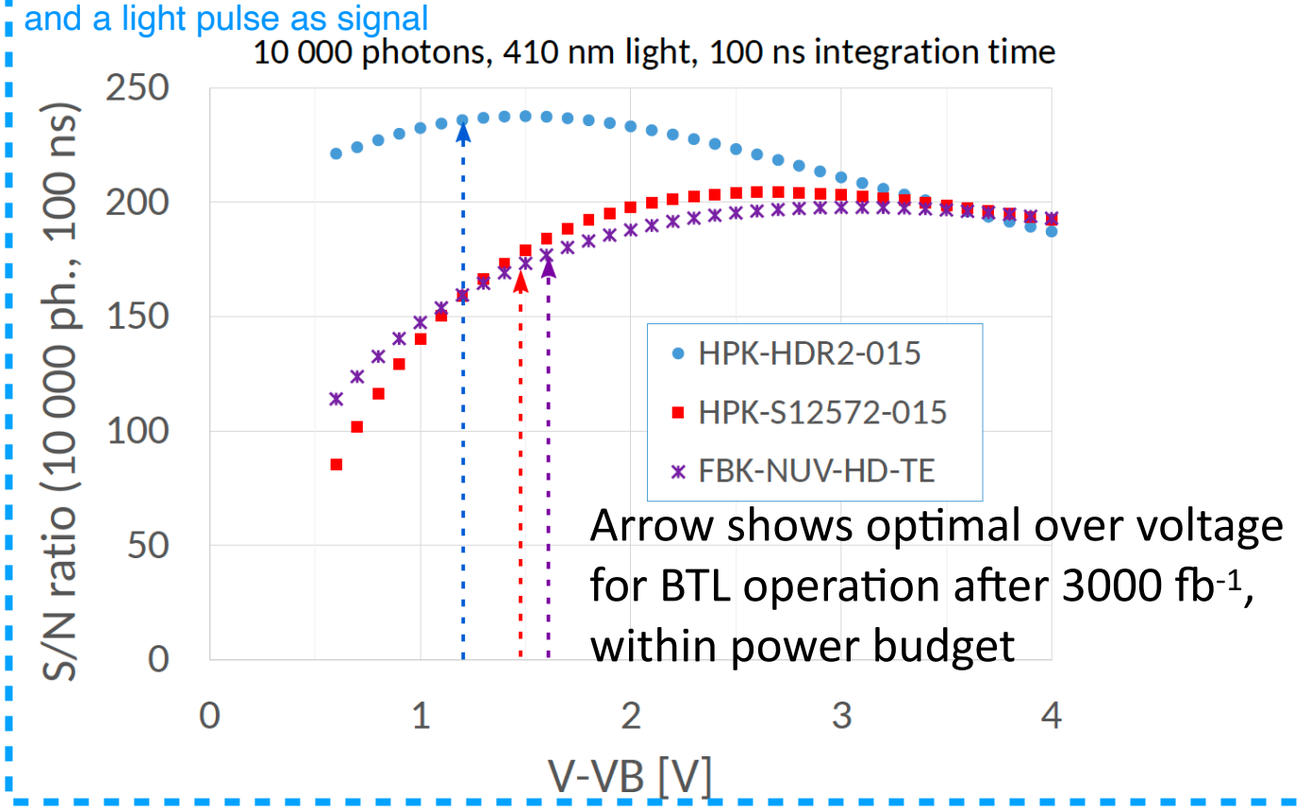




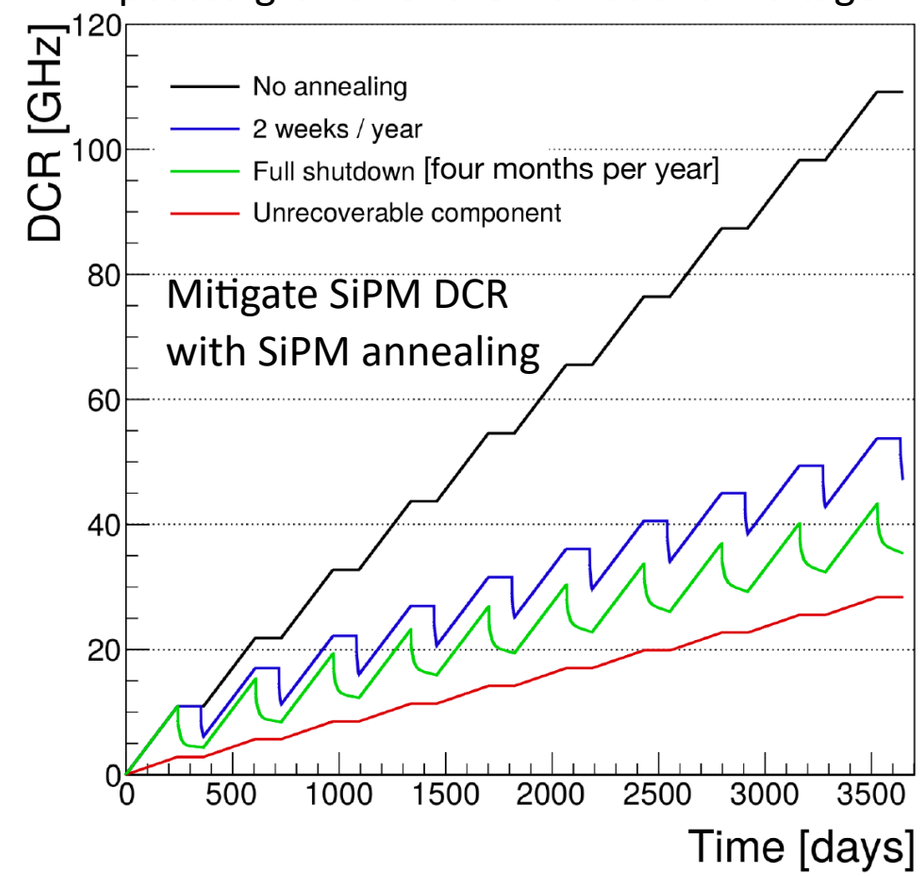
SiPM dark count rate noise mitigation

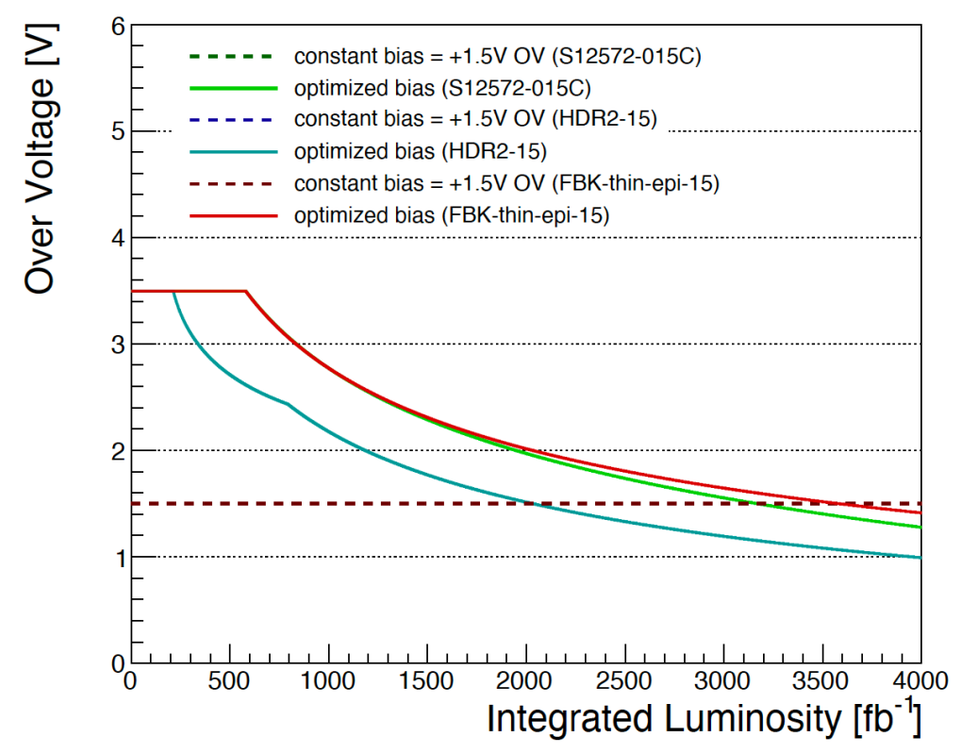
- Dark count rate (DCR) noise contributes to ~50 ps on time resolution after 3000 fb^{-1}
  - Radiation damage increases SiPM DCR up to 55 GHz
- DCR noise mitigation:
  - CO_2 cooling SiPM temperature to -30(-35) °C
    - DCR decreases by a factor 1.8 every 10 °C .
  - Annealing of SiPMs at 20 °C during shutdowns
  - Optimizing SiPM operating point
  - Dedicated noise cancelation circuit in front-end ASIC

Signal-over-noise (S/N) ratio measured using irradiated SiPMs (irradiated to neutron fluence $2.1 \times 10^{12}\ n_{eq}/cm^2$) with DCR linearly scaled to $3 \times 10^{14}\ n_{eq}/cm^2$, and a light pulse as signal



Expected growth of the DCR at over-voltage 1.5 V

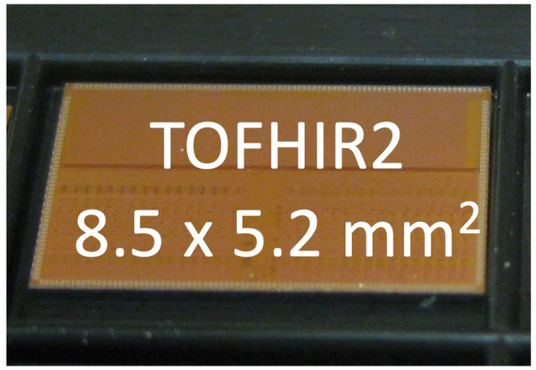




BTL TOFHIR ASIC: Time Of Flight at HIgh Rate

Challenges:

- Reduce impact of DCR noise and pileup
- High rate (2.5 MHz MIP + 5 MHz low E hits/channel)
- Dynamic range variation: decrease of p.e. during operation
- Power budget 15mW/channel



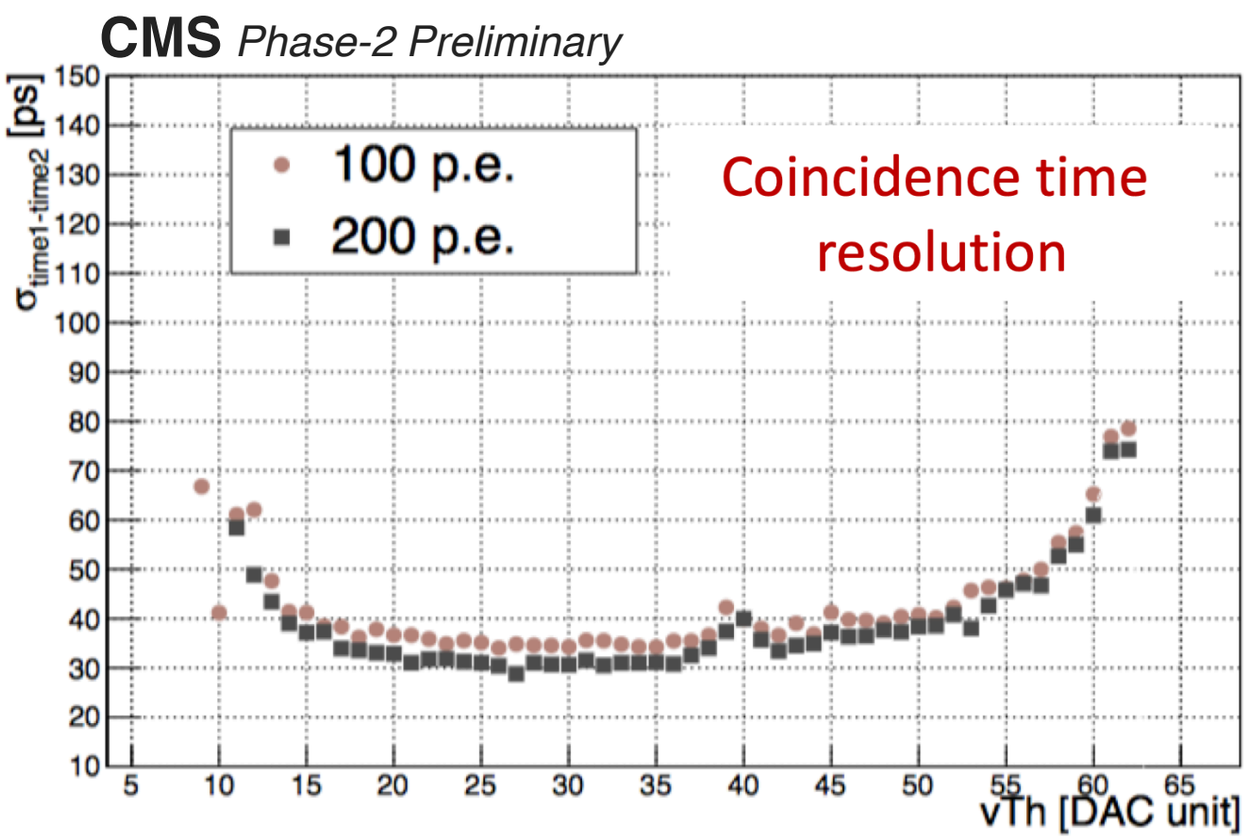
TOFHIR versions:

- TOFHIR1 (UMC 110 nm): available, enabled system level testing
- TOFHIR2 (TSMC 130 nm): new frontend design, DCR noise cancellation circuit
  - First MPW submission Feb 2020
    - ASIC received May 2020 and under testing since July 2020
  - Next MPW submission and engineering run in Q1 2020 and Q2 2021
    - May shift because of COVID knock-on effects

Ted Liu's talk at ACES 2020: https://indico.cern.ch/event/863071/contributions/3738906/

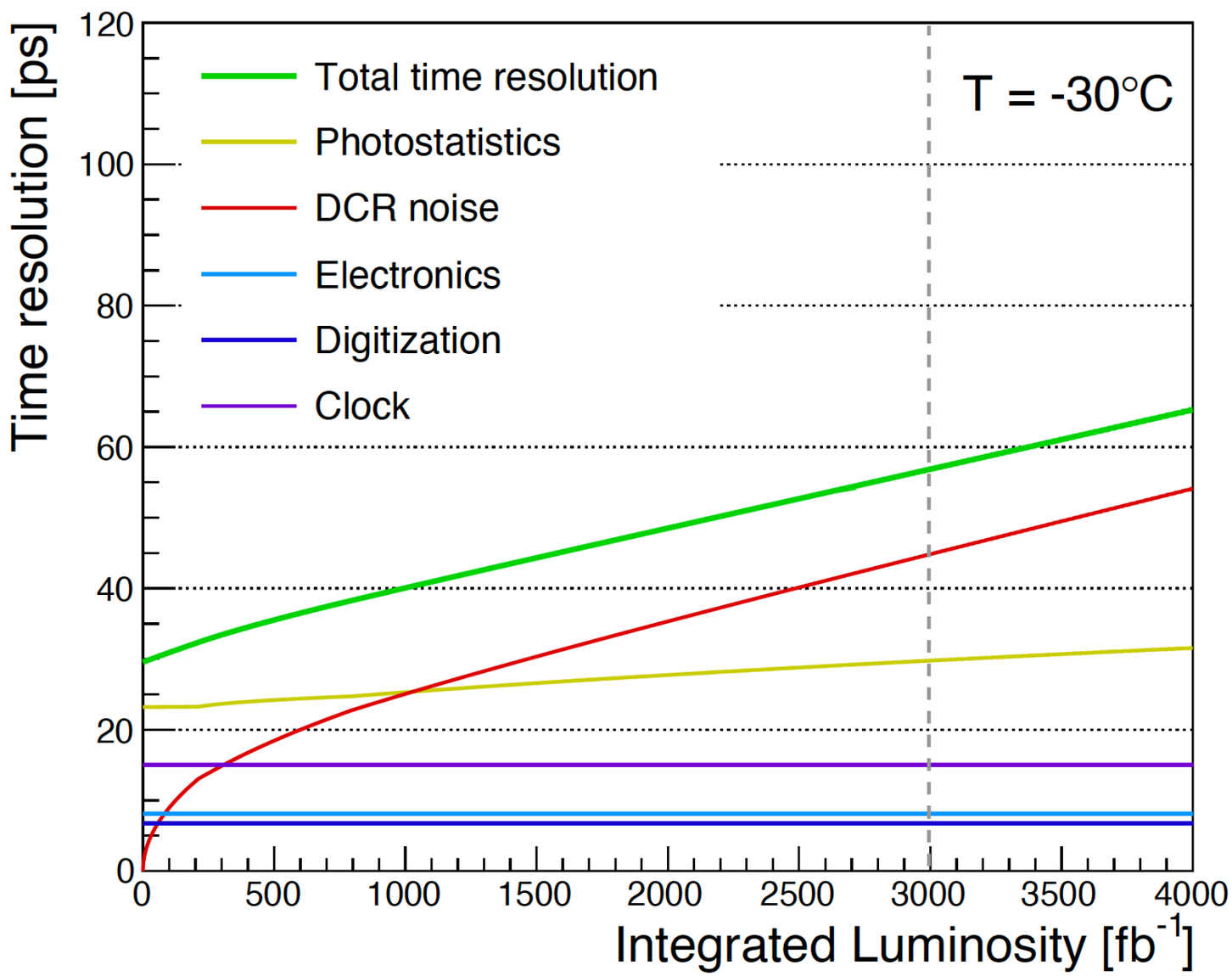
TOFHIR1 single channel σ_t ~21 ps with laser pulse of 200 p.e.

- *Same slew rate as 8k p.e. LYSO pulses*
- *Adding LYSO photo-statistics contribution resolution of 31 ps (before SiPM irradiation) expected*



Terms contributing to time resolution

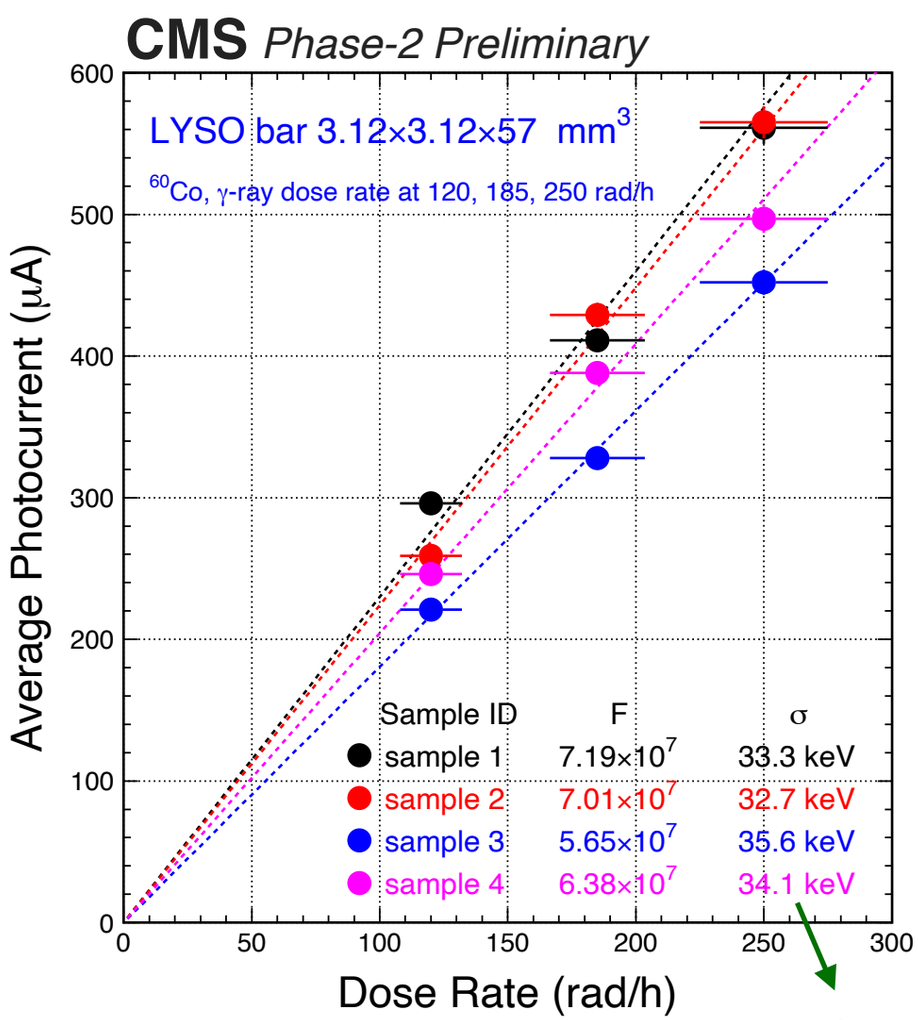
- Photostatistics and DCR noise contributions dominate timing resolution



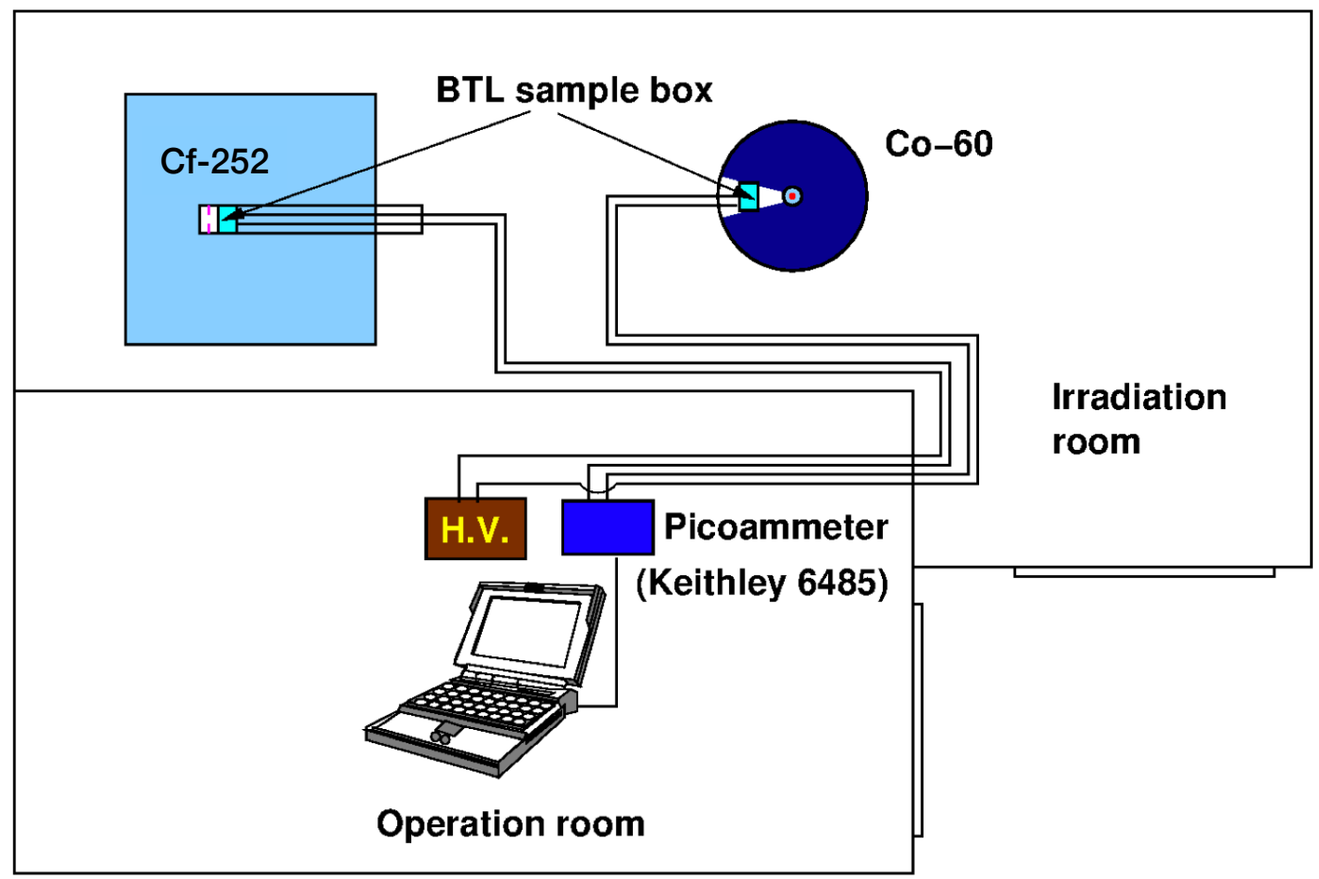
- Photostatistics: 25 - 35 ps, stochastic fluctuations in the time-of-arrival of photons detected at the SiPM
- DCR noise: < 60 ps after 3000 fb^{-1}
- Electronics: 7ps
- Digitization: 6 ps
- Clock distribution: 15 ps

Study of in-time and out-of-time pileup contributing to time resolution

- **Negligible readout noise** induced by gamma-ray (192 rad/h) and neutron flux (3.17×10^6 [$1\ MeV\ n_{eq}\ cm^{-2}s^{-1}$]) at @BTL |η|=1.45 expected at HL-LHC: **less than 10 ps and 2 ps** contribution to total time resolution of the BTL sensor performance.



Schematic for the experimental setup

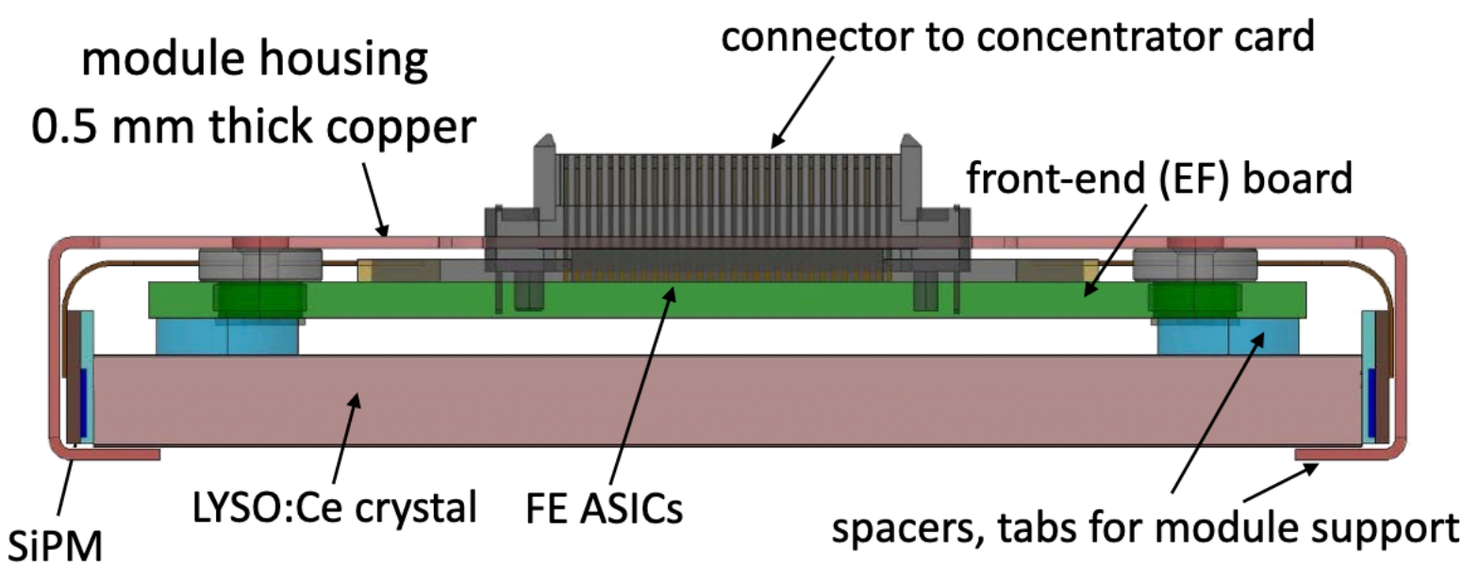


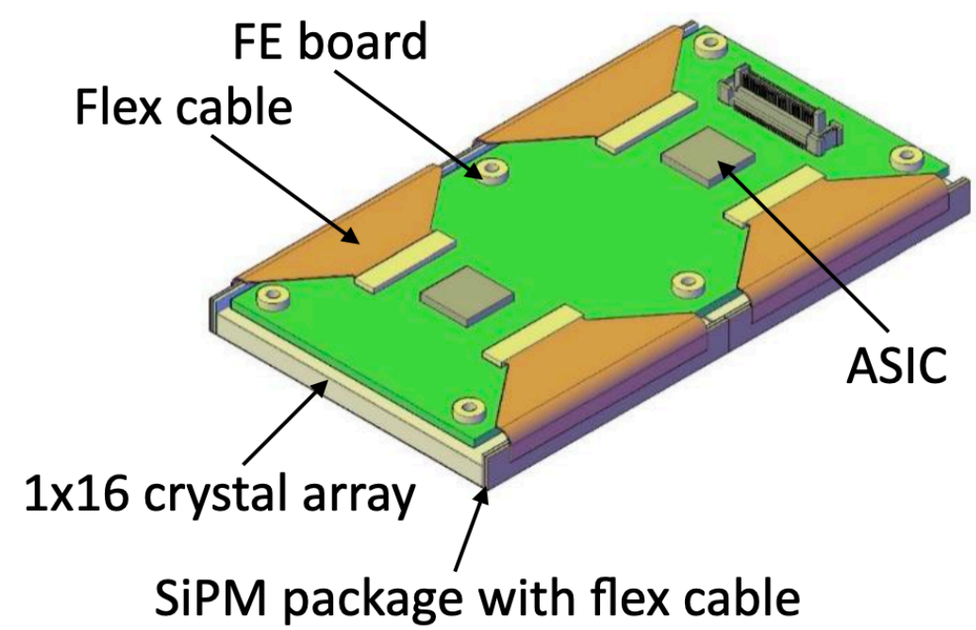
Negligible compared to MIP signal of 4.2 MeV

BTL module design

Motivation of the BTL module design:

- Minimize distance between the SiPM's and ASICs for best possible signal integrity
- Encapsulate variability of the dimensions of the module components
- Simplify tray assembly

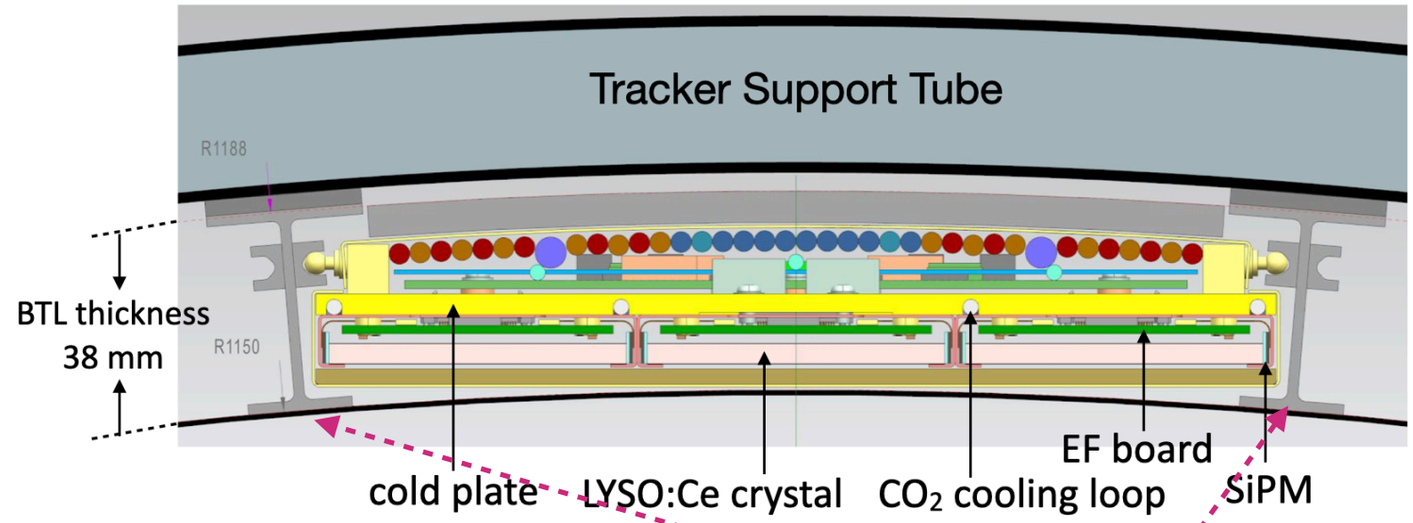


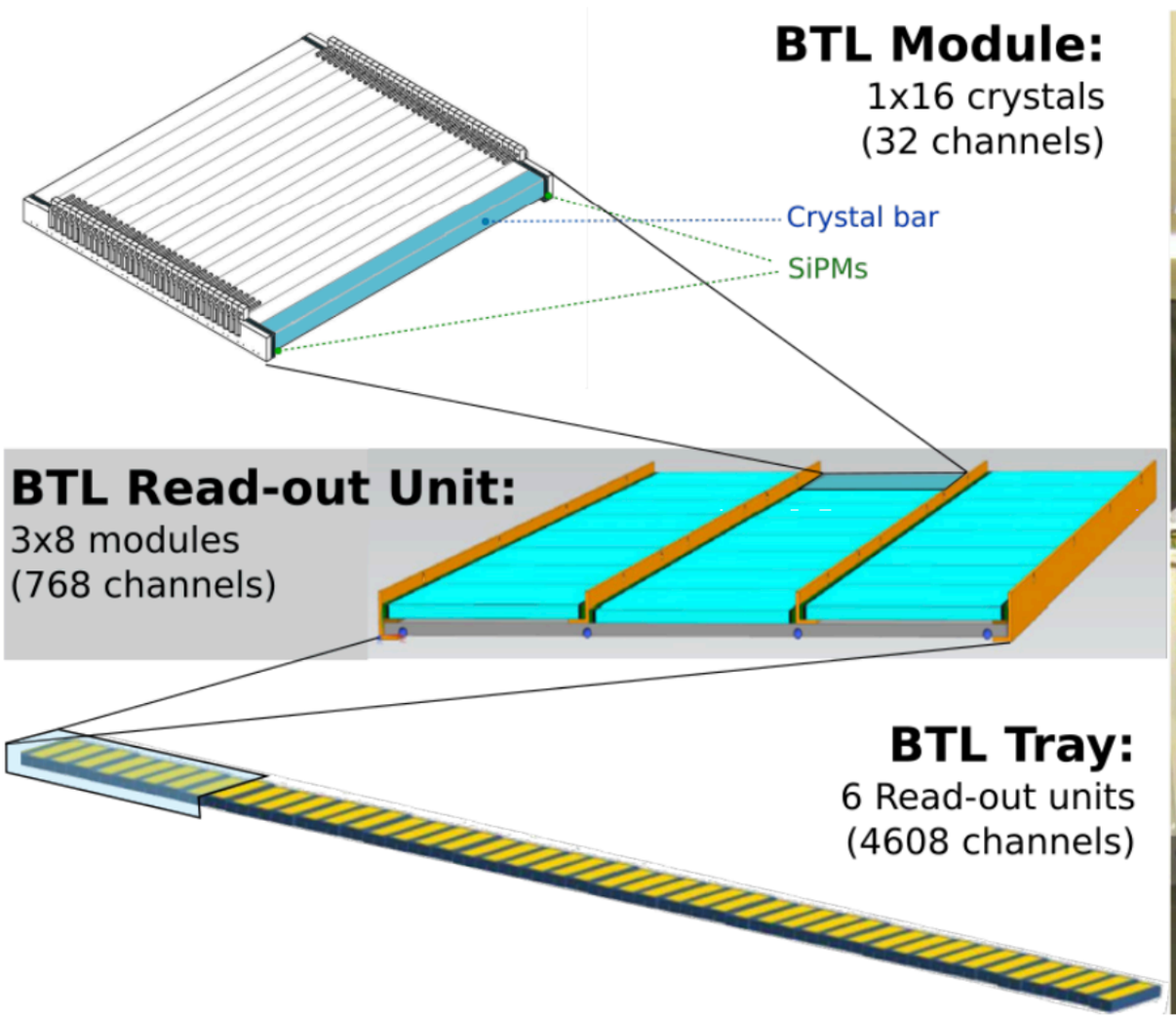


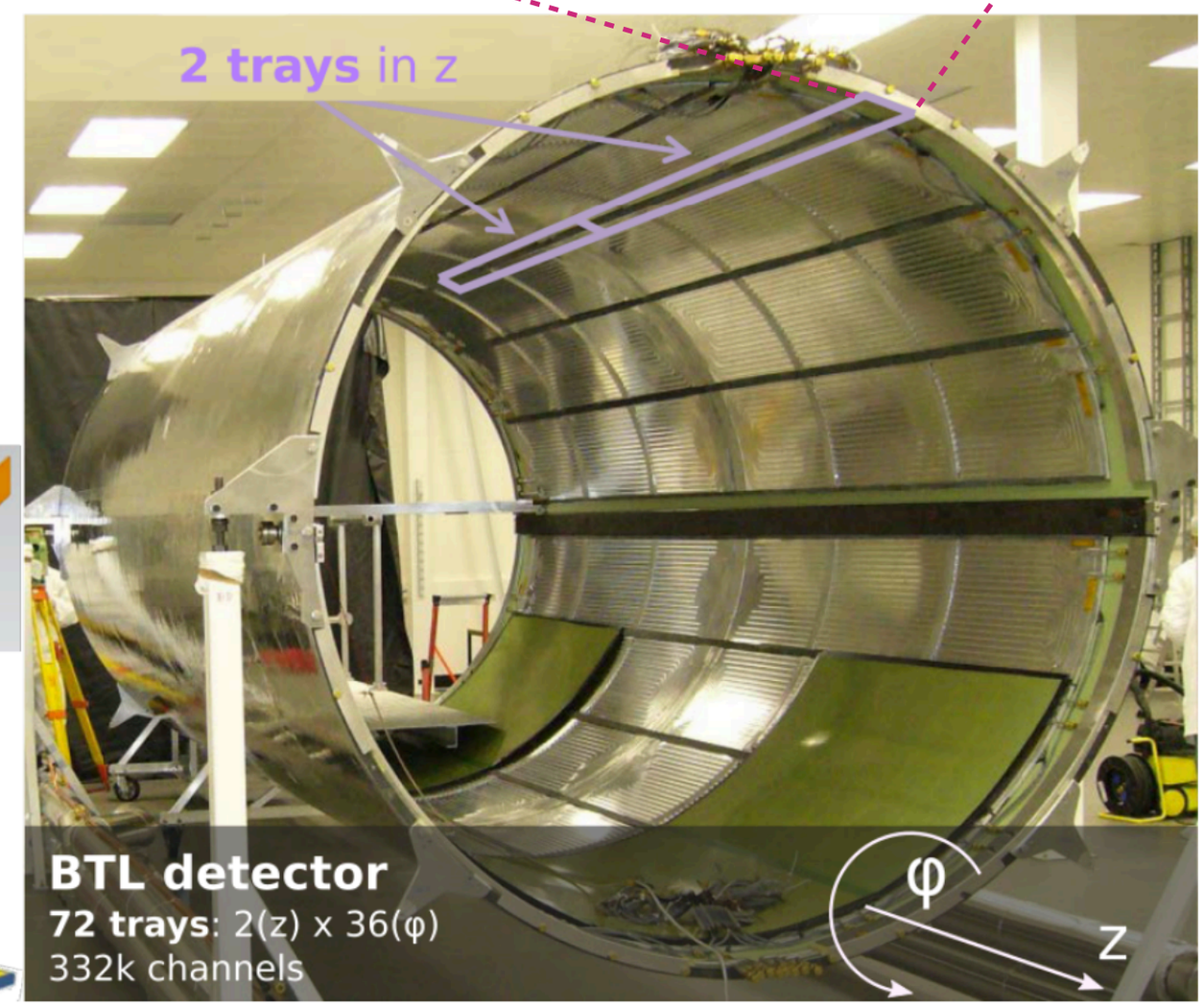
Schematic view of R-ϕ cross section of BTL module

BTL layout

- Coverage: |η| < 1.45
- Surface ~38 m²
- 332k channels
- BTL detector mounted on inner surface of Tracker Support Tube





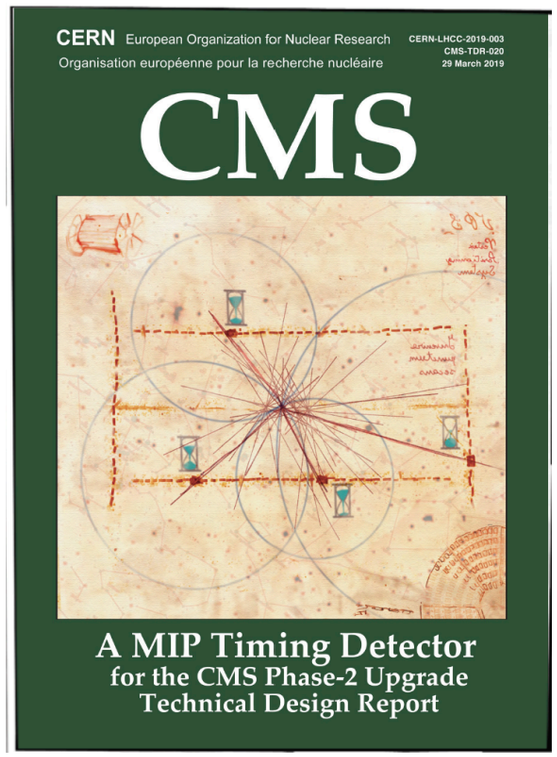


Summary

- CMS phase-2 upgrade will include a new MIP timing detector with a time resolution of 30-50 ps to mitigate harsh pile-up condition at HL-LHC

- The CMS Barrel Timing Layer will be based on LYSO:Ce crystals read out with SiPMs

- Expand CMS HL-LHC physics reach: enhancement of physics object reconstruction, open up new territory in CMS Heavy Ion Physics and long lived particle search



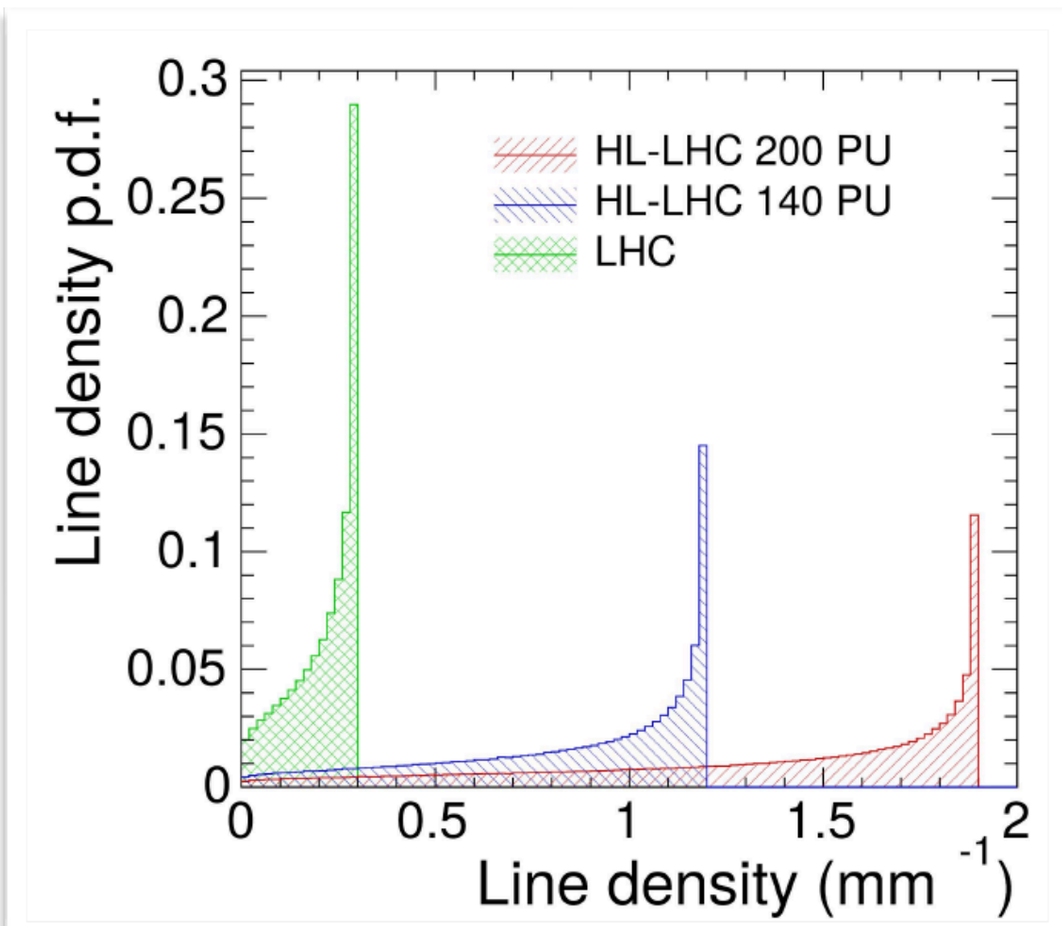
CMS-TDR-020

Backup slides

CMS MIP timing detector and pileup mitigation

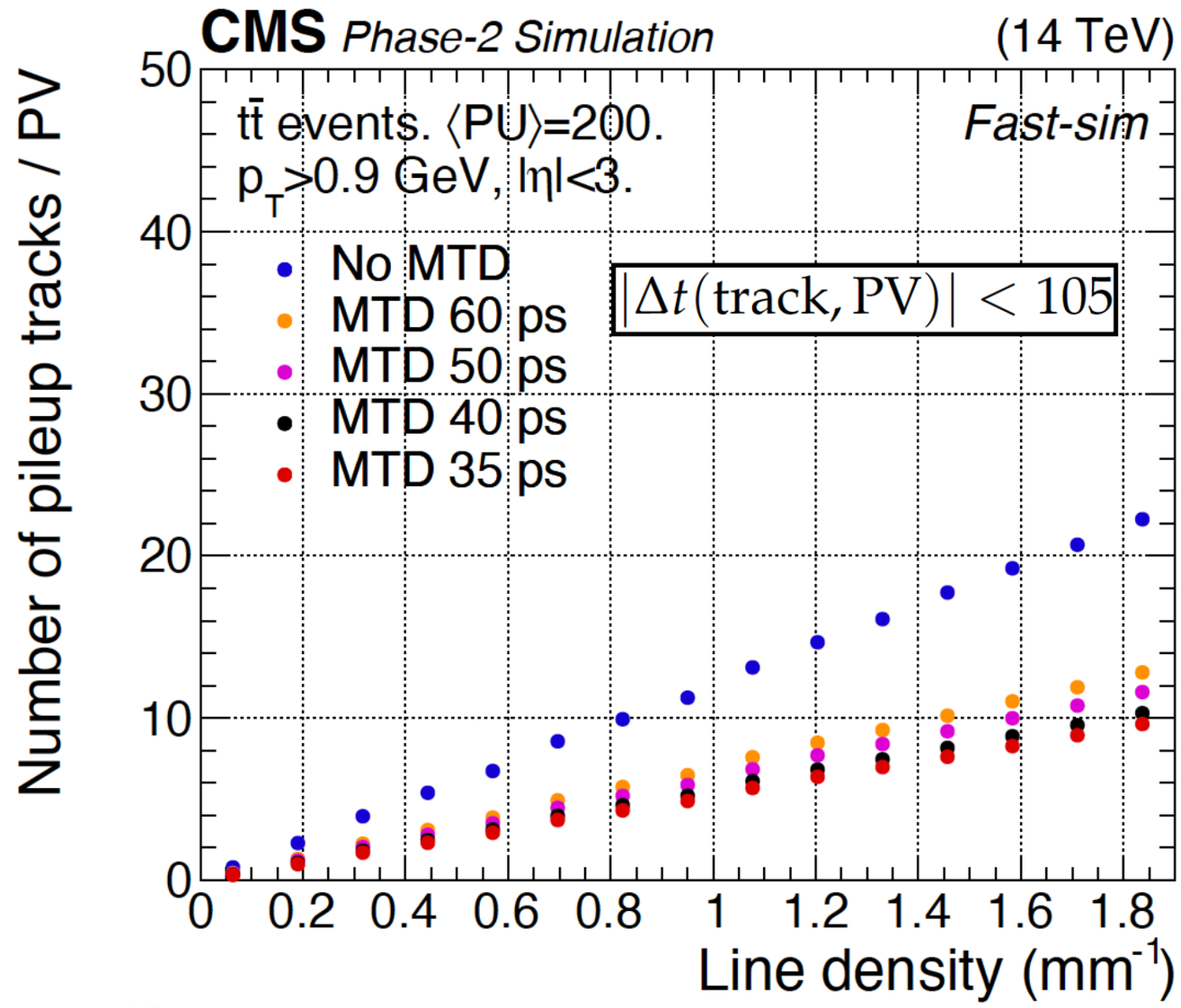
Line density of the collision vertices at LHC and HL-LHC

- e.g. peak density for 200 PU: 1.9 collisions/mm

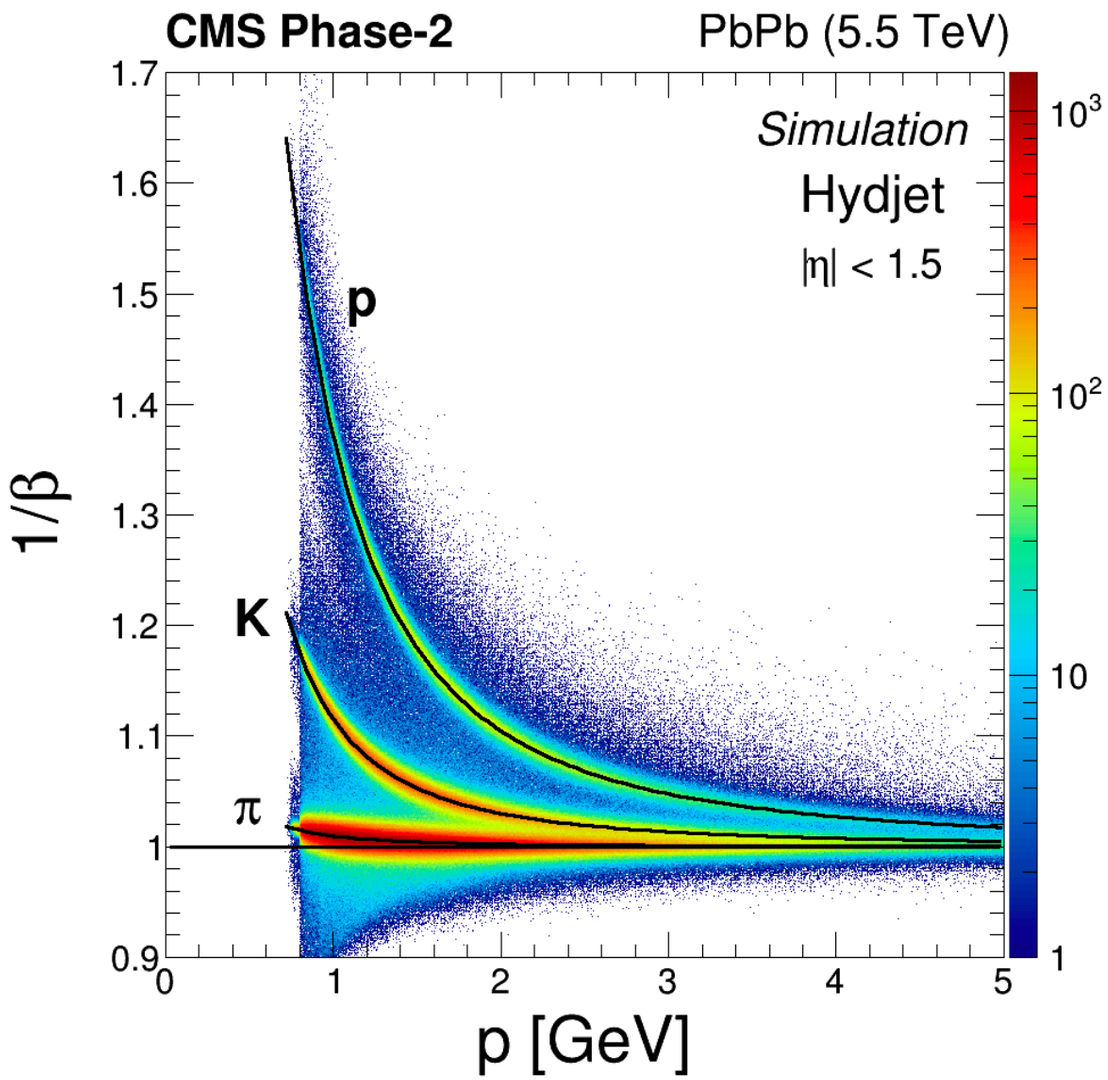


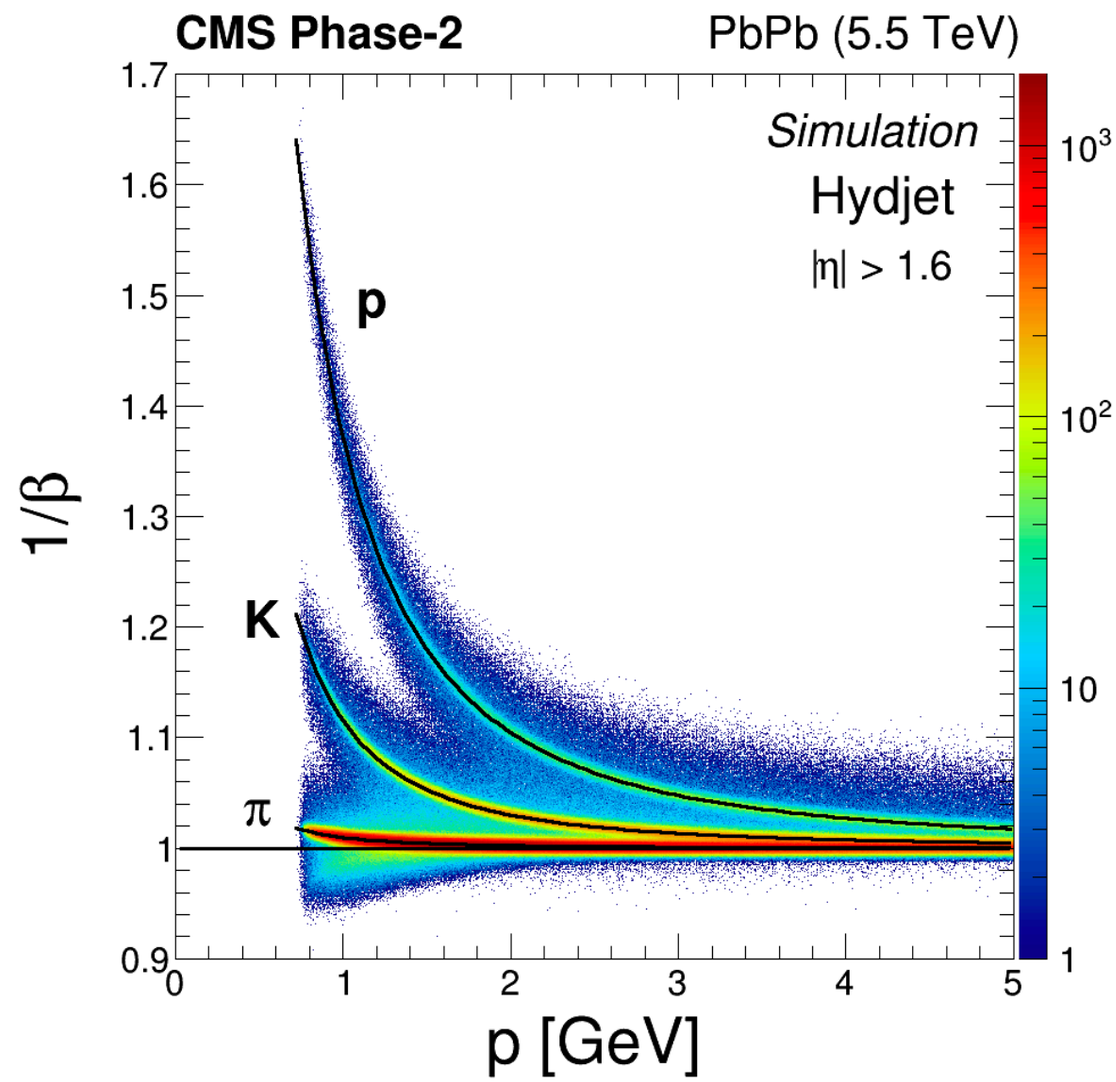
Reduction of pileup tracks incorrectly associated to the primary vertex:

- reduced from ~20 to ~10 with MTD at line density of 1.9 collisions/mm.



Particle ID with MTD





$$\frac{1}{\beta} = \frac{c(t_0^{\mathrm{MTD}} - t_0^{\mathrm{evt}})}{L}$$

L: path length of a track from the beam line to the MTD.

t_0^{MTD} : particle arrival time is provided by the MTD hit

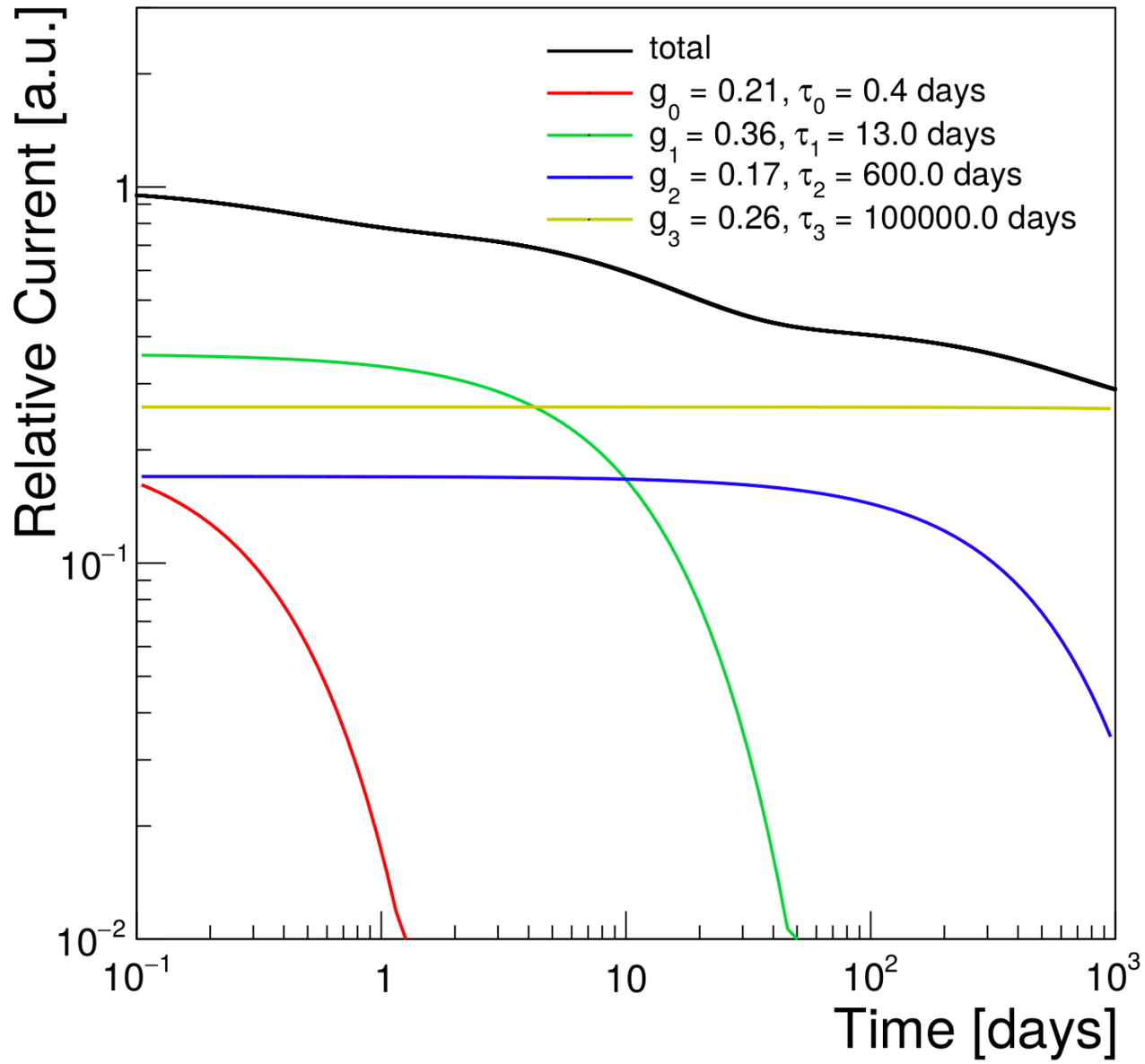
t_0^{evt}: common event start time,

taken to be the time of the most populated 4D vertex

MTD: Radiation doses and fluences

Region	$\lvert\eta\rvert$	r (cm)	z (cm)	3000 fb^{-1}		1.5×3000 fb^{-1}	
				n_{eq}/cm^2	Dose (kGy)	n_{eq}/cm^2	Dose (kGy)
Barrel	0.0	116	0	1.65×10^{14}	18	2.48×10^{14}	27
Barrel	1.15	116	170	1.80×10^{14}	25	2.70×10^{14}	38
Barrel	1.45	116	240	1.90×10^{14}	32	2.85×10^{14}	48
Endcap	1.6	127	303	1.5×10^{14}	19	2.3×10^{14}	29
Endcap	2.0	84	303	3.0×10^{14}	50	4.5×10^{14}	75
Endcap	2.5	50	303	7.5×10^{14}	170	1.1×10^{15}	255
Endcap	3.0	31.5	303	1.6×10^{15}	450	2.4×10^{15}	675

SiPM Annealing



$$I_{\mathrm{dark}}^{\mathrm{irr}}(t) = I_{\mathrm{dark}}^{\mathrm{irr}}(0) \sum_i g_i e^{-\tau_i/t}$$

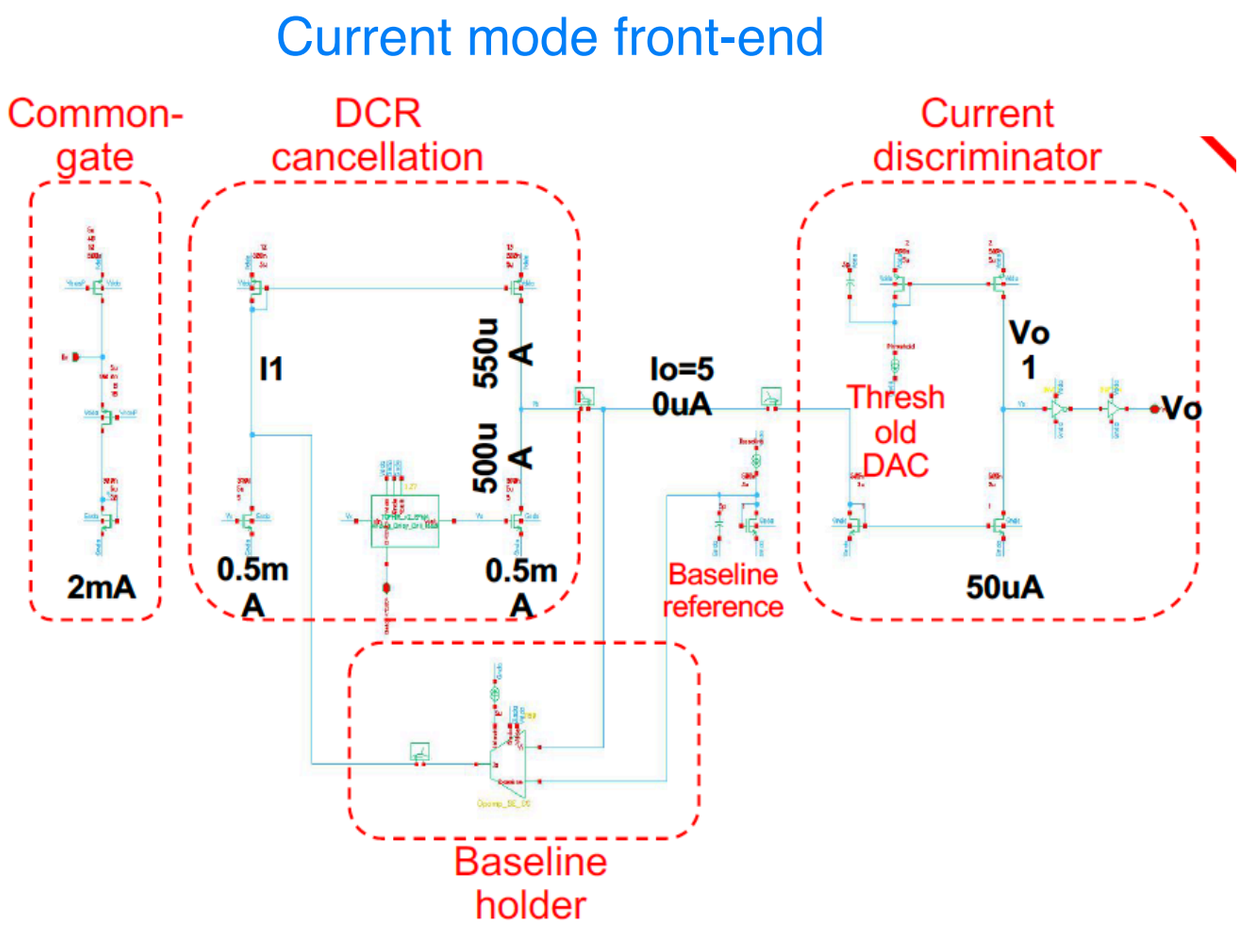
SiPM end-of-operation specifications

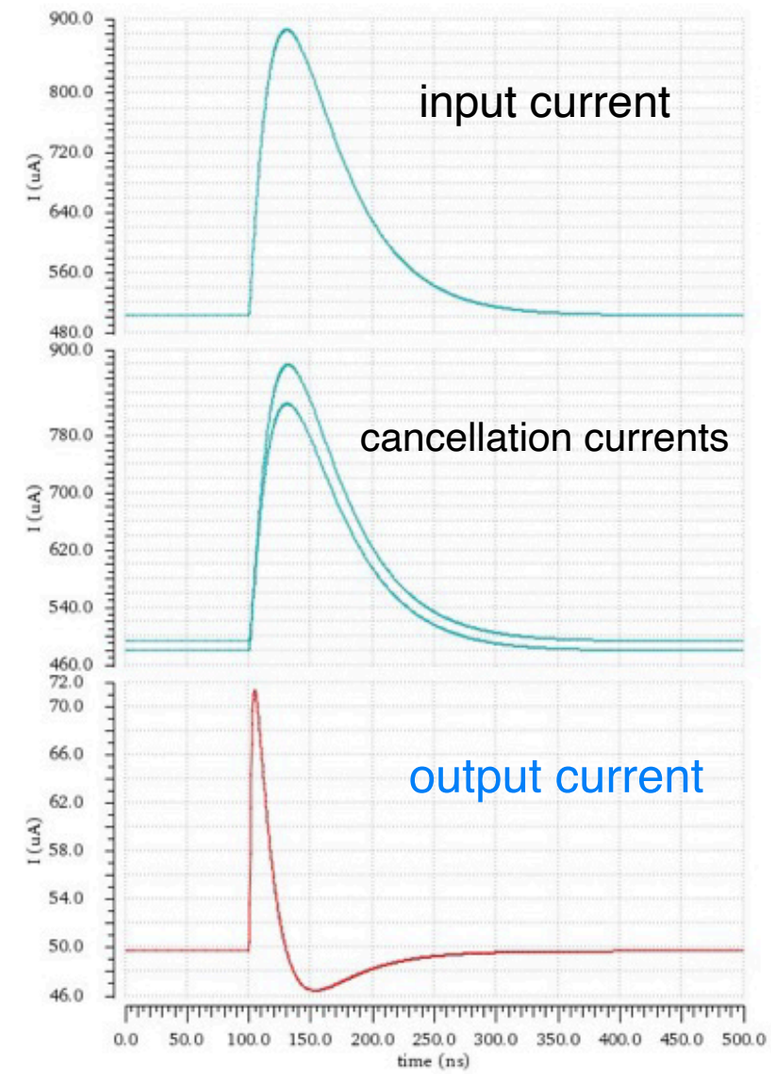
SiPM parameter	Specification	FBK-NUV-HD	HPK-S12572	HPK-HDR2
Active area	–	$\sim 9\ \mathrm{mm}^2$	$\sim 9\ \mathrm{mm}^2$	$\sim 9\ \mathrm{mm}^2$
Cell pitch	$< 20\ \mu\mathrm{m}$	$15\ \mu\mathrm{m}$	$15\ \mu\mathrm{m}$	$15\ \mu\mathrm{m}$
Cell recovery time	< 10 ns	7 ns	8.5 ns	< 10 ns
Capacitance	< 600 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
$\delta V_{br}/10^{13}\ n_{eq}/\mathrm{cm}^2$	≤ 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/$\sqrt{\mathrm{DCR}}$	≥ 2.0	2.3	2.1	3.1

TOFHIR DCR cancellation

Mitigate DCR noise and baseline fluctuations

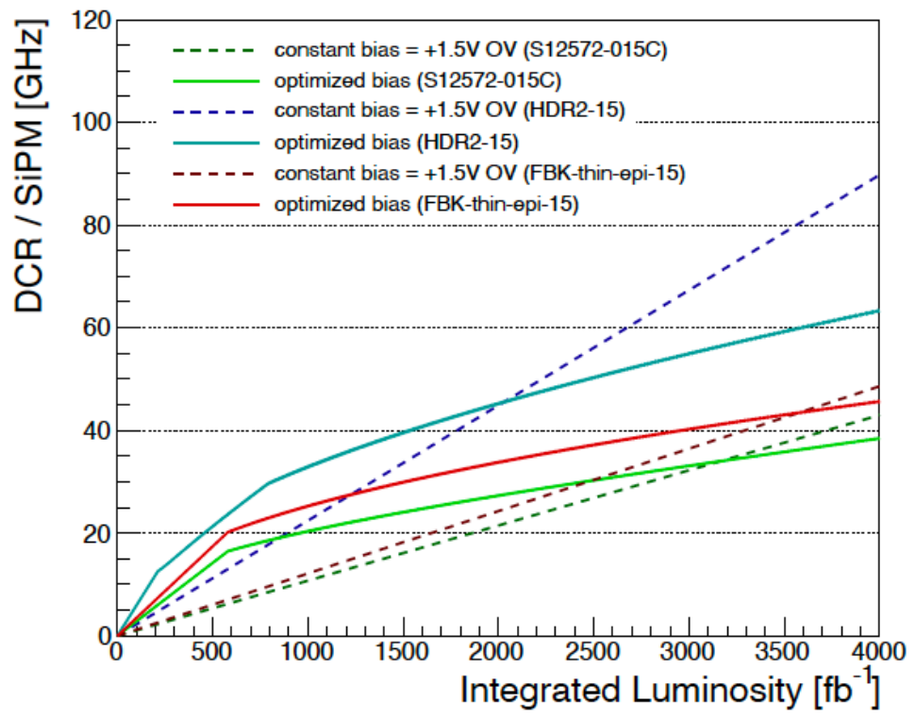
- *At the highest DCR the time resolution expected to improve by a factor 3.5*
- *Inverted and delayed pulse added to the original pulse, delay line is approximated by a RC net*
- *Short output pulse (< 25 ns)*

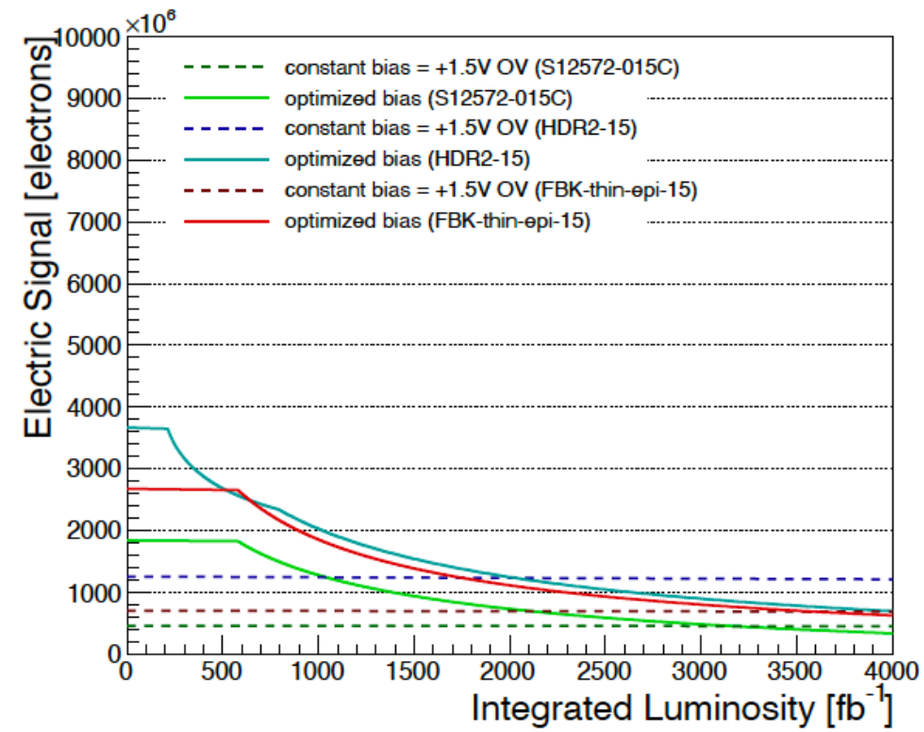


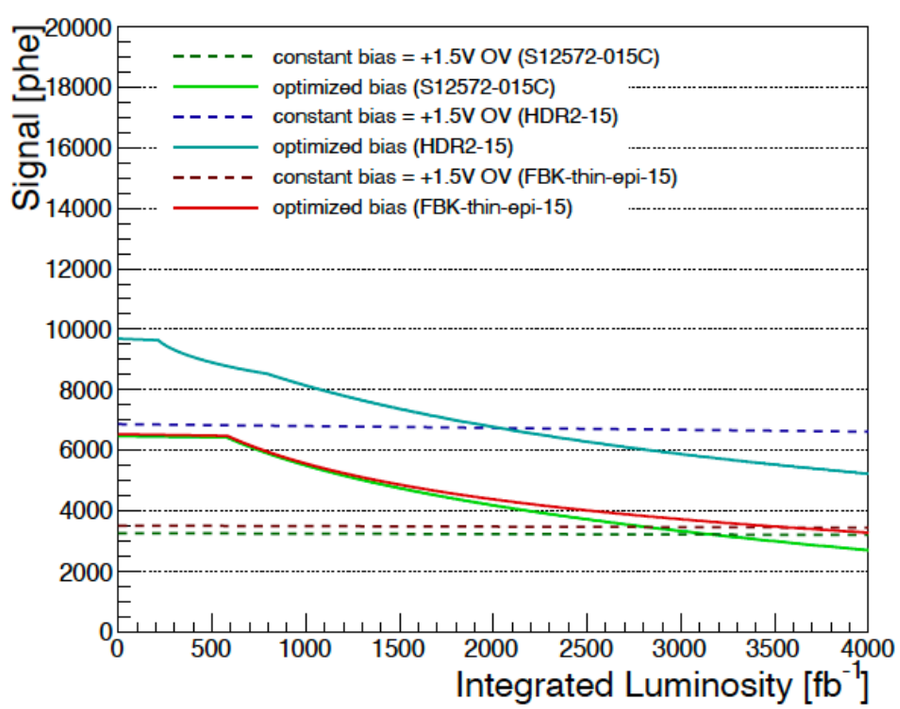


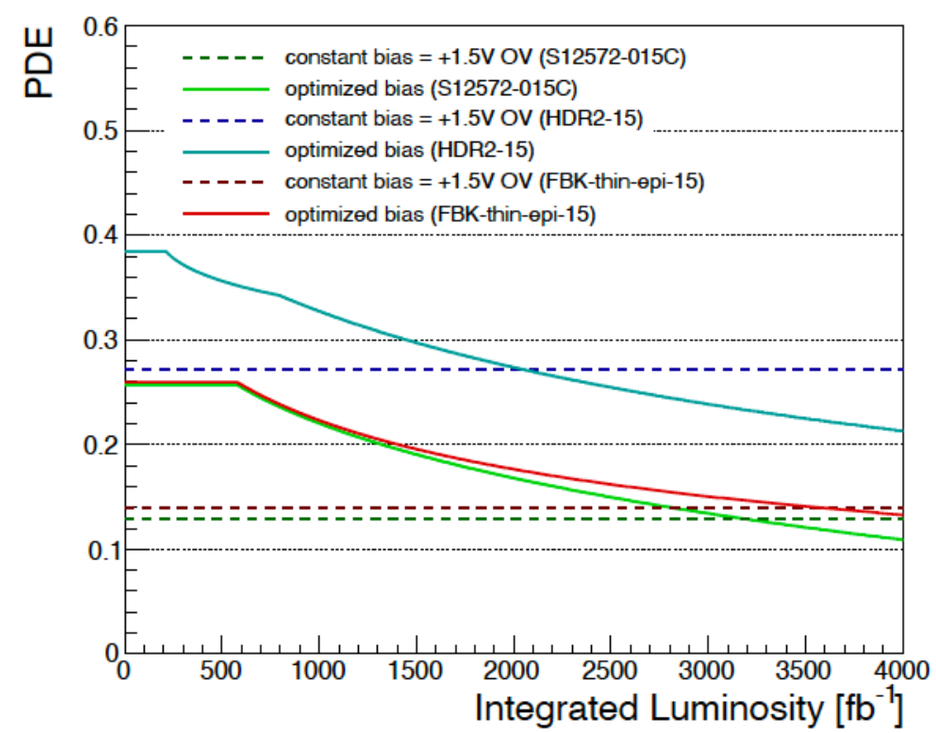
Reference Ted Liu's talk at ACES 2020: https://indico.cern.ch/event/863071/contributions/3738906/

Evolution of SiPM operating parameter during HL-LHC life time







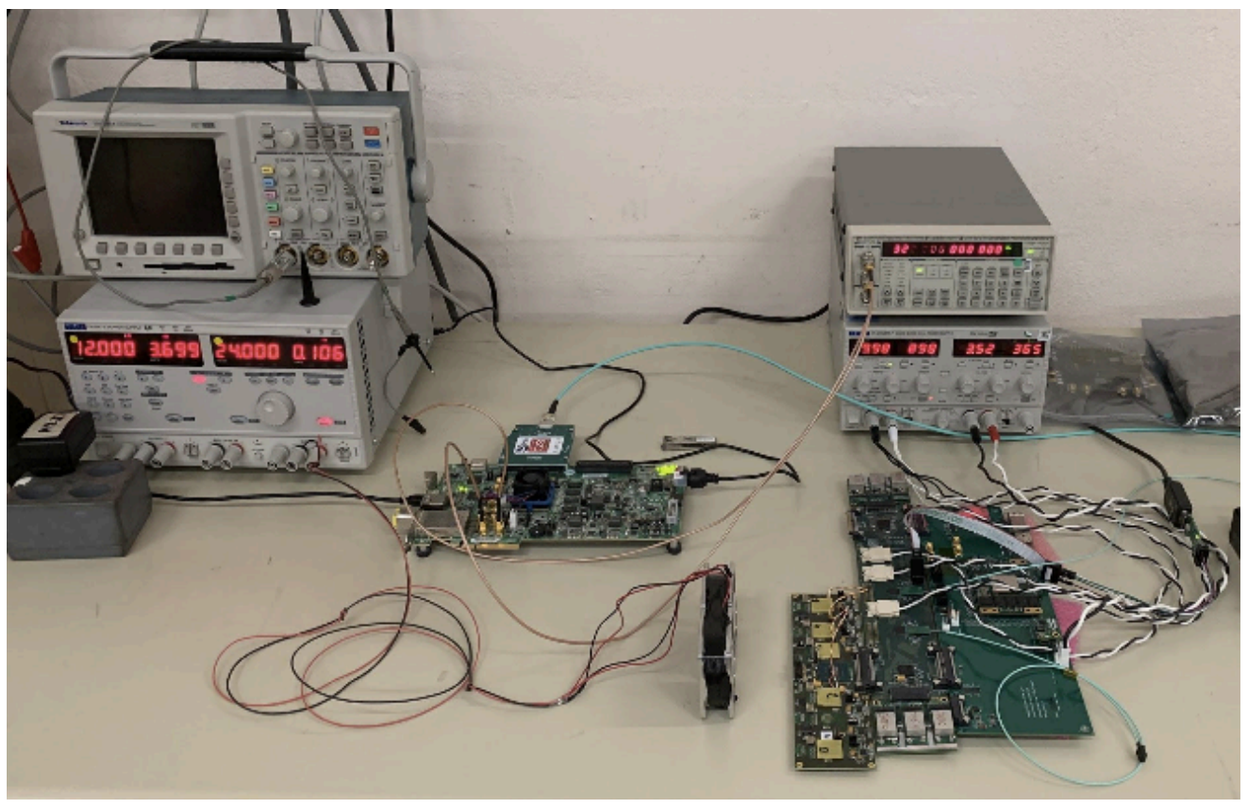


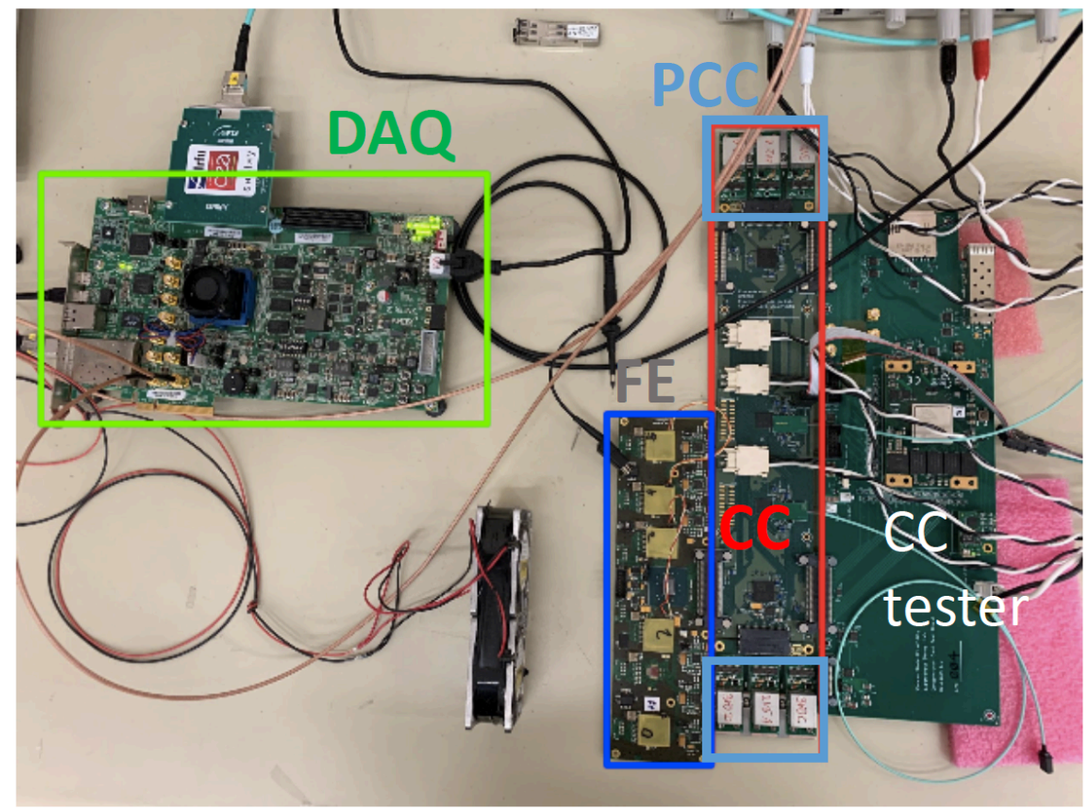
BTL Readout Unit

- **Readout unit (RU):** 768 SiPM channels, 24 modules
  - 4 Front-end cards, one concentrator card, two Power Convertor Cards

Reference: Ted Liu's talk at ACES 2020: https://indico.cern.ch/event/863071/contributions/3738906/

Integration of RU prototype1 with backend DAQ is being carried out at CERN





BTL construction model