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

Francesca M. Addesa (Princeton University)
on behalf of the CMS-MTD collaboration

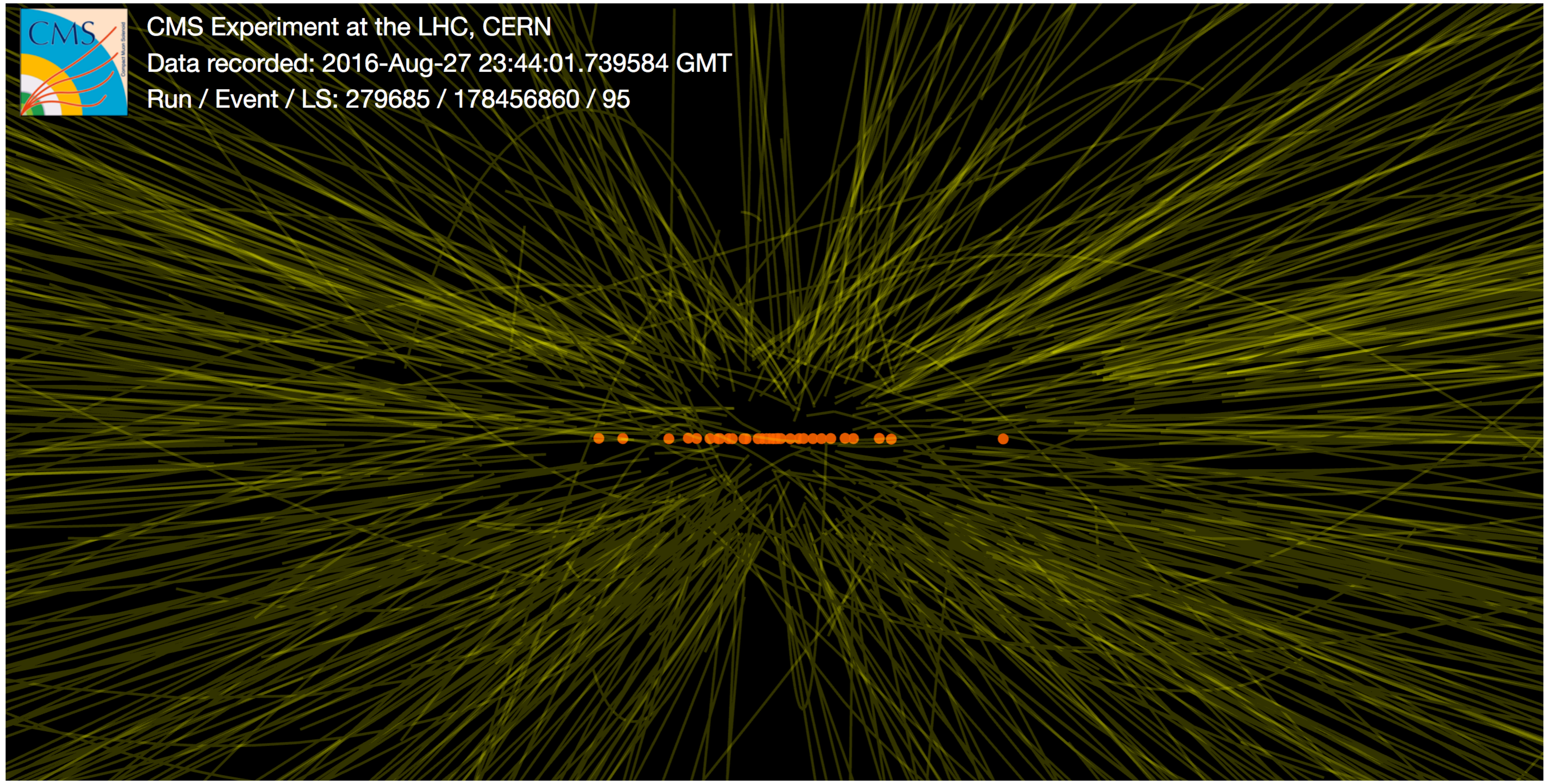
Towards HL-LHC

Major challenges wrt LHC:

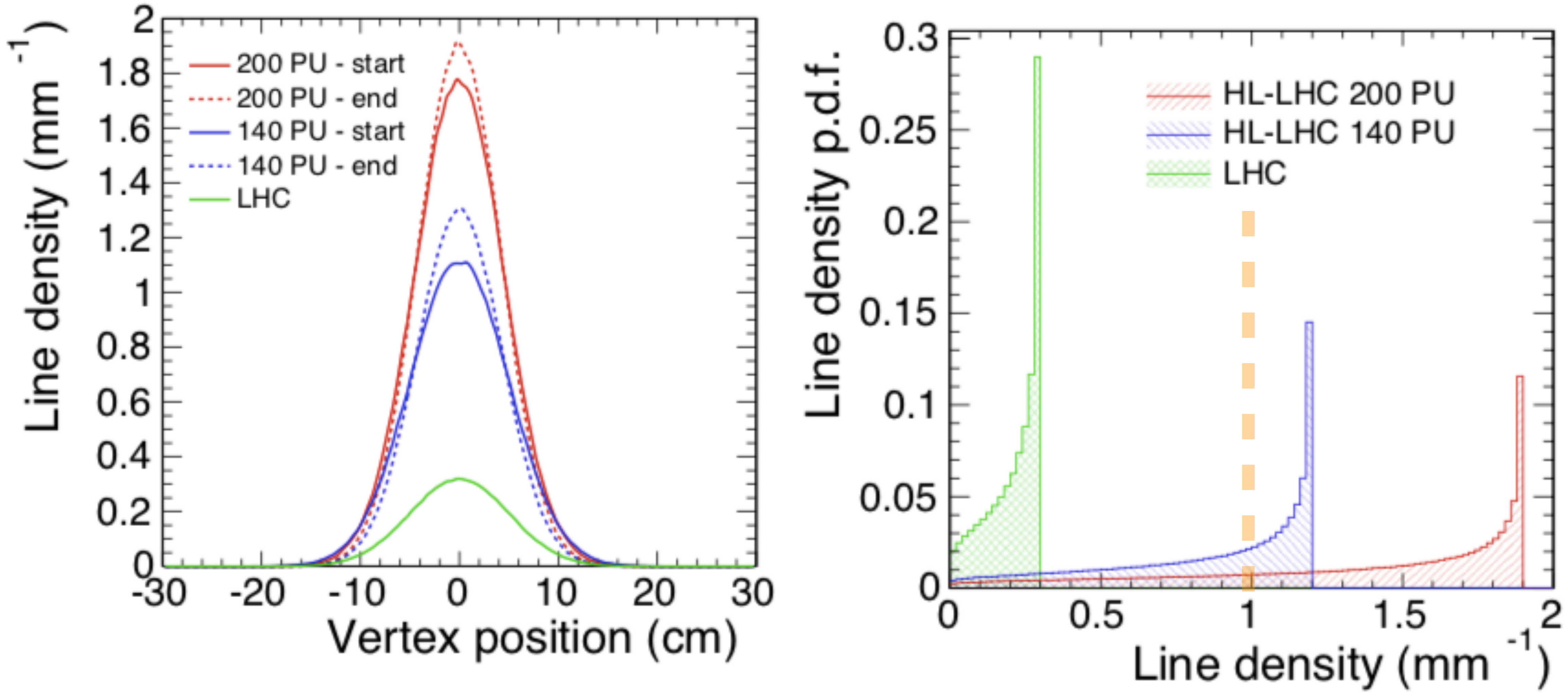
- x 3 - 4 instantaneous luminosity ▶ up to x 5 pileup (PU) interactions
- x 10 integrated luminosity ▶ radiation damage of detector components

▶ Experiment Upgrades

PILEUP Impact @HL-LHC



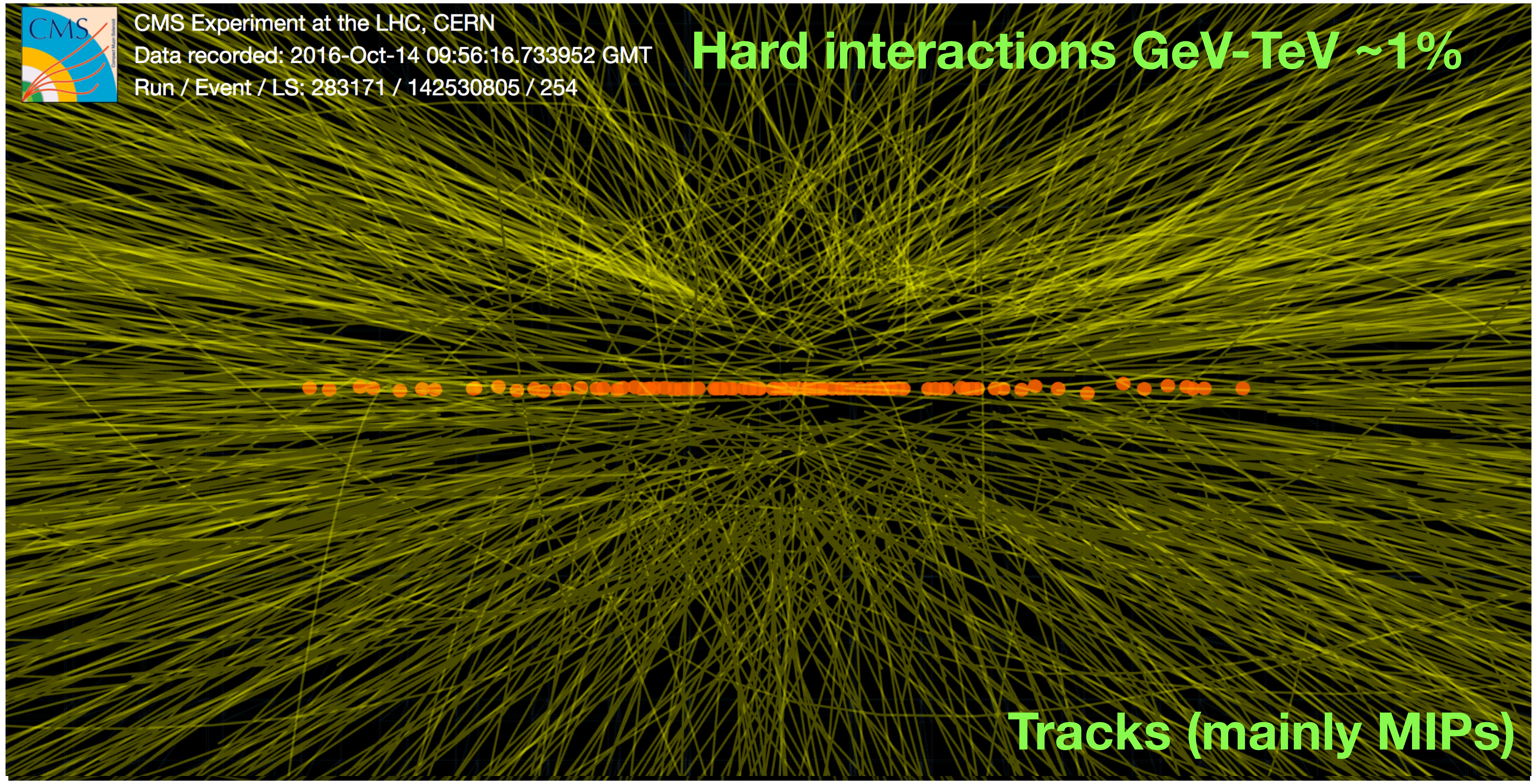
RUN 2: 40-60 interactions per bunch crossing



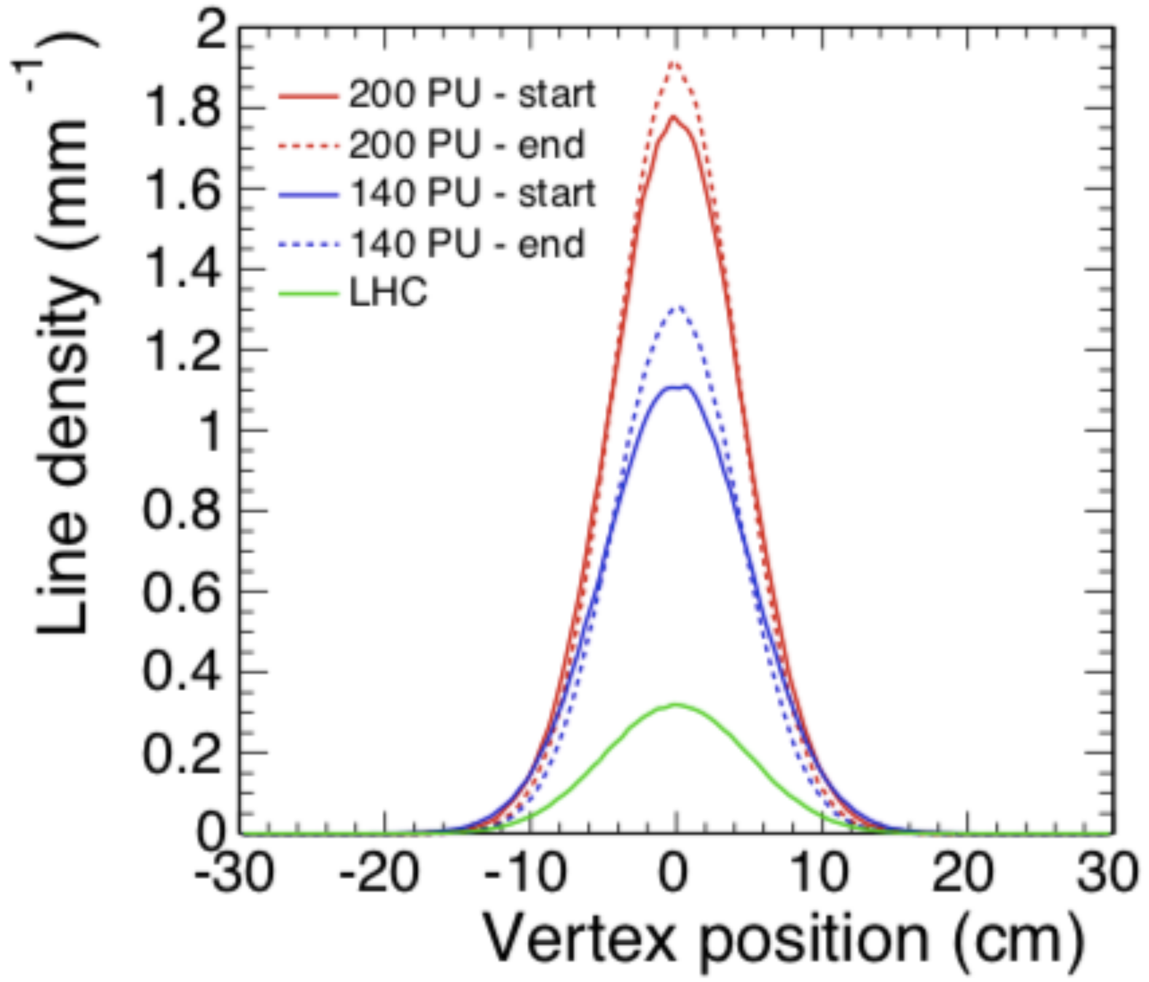
In CMS, PU mitigation relying on the high granularity of the tracking subdetectors and dedicated algorithms combining their information. Due to growing spatial overlap of tracks and energy deposits, in the transition from 140 to 200 pileup events (**Line density >1 mm^{-1}**) reduced efficiency of tracks-vertex association.

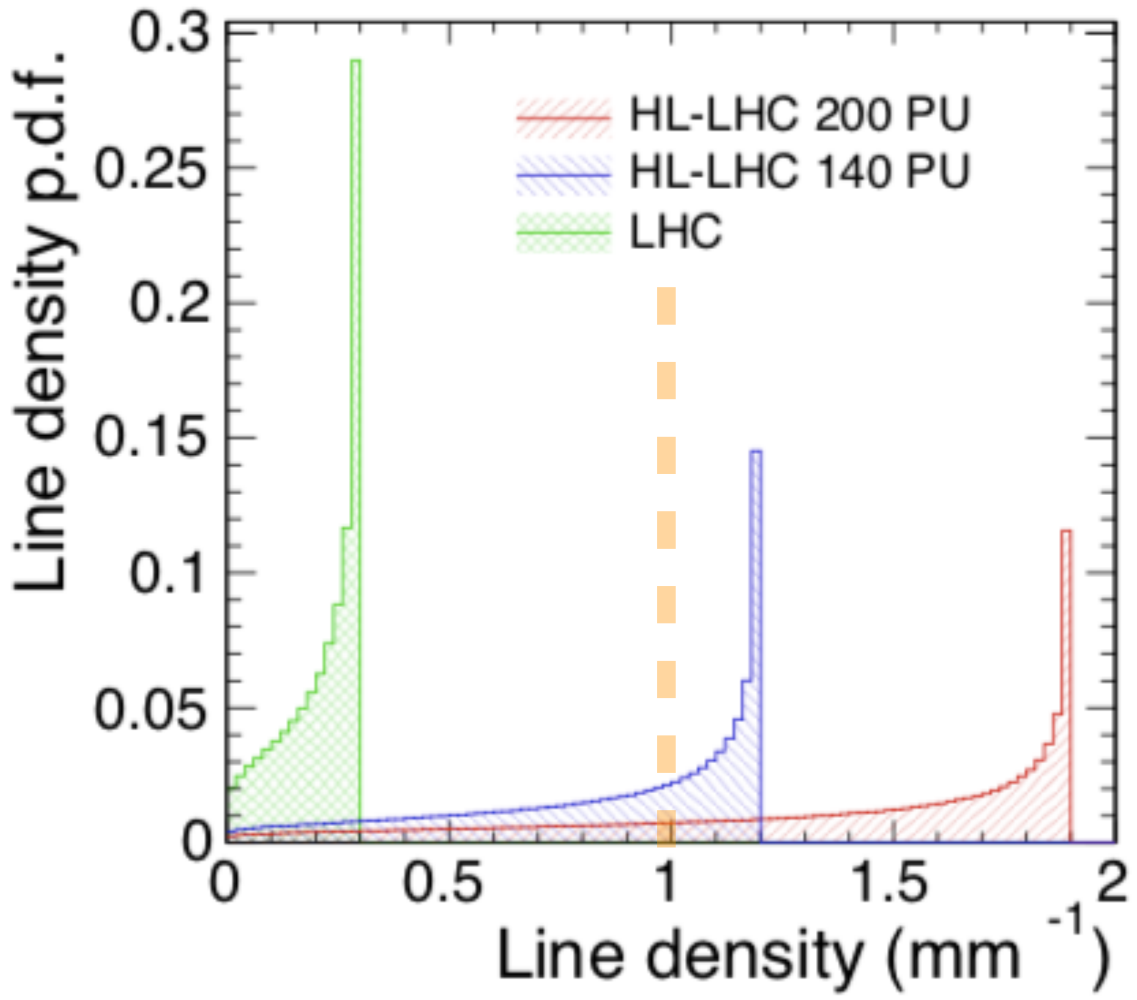
Misidentification, degradation of reconstruction efficiency and energy resolution

PILEUP Impact @HL-LHC



HL-LHC: 140-200 interactions per bunch crossing

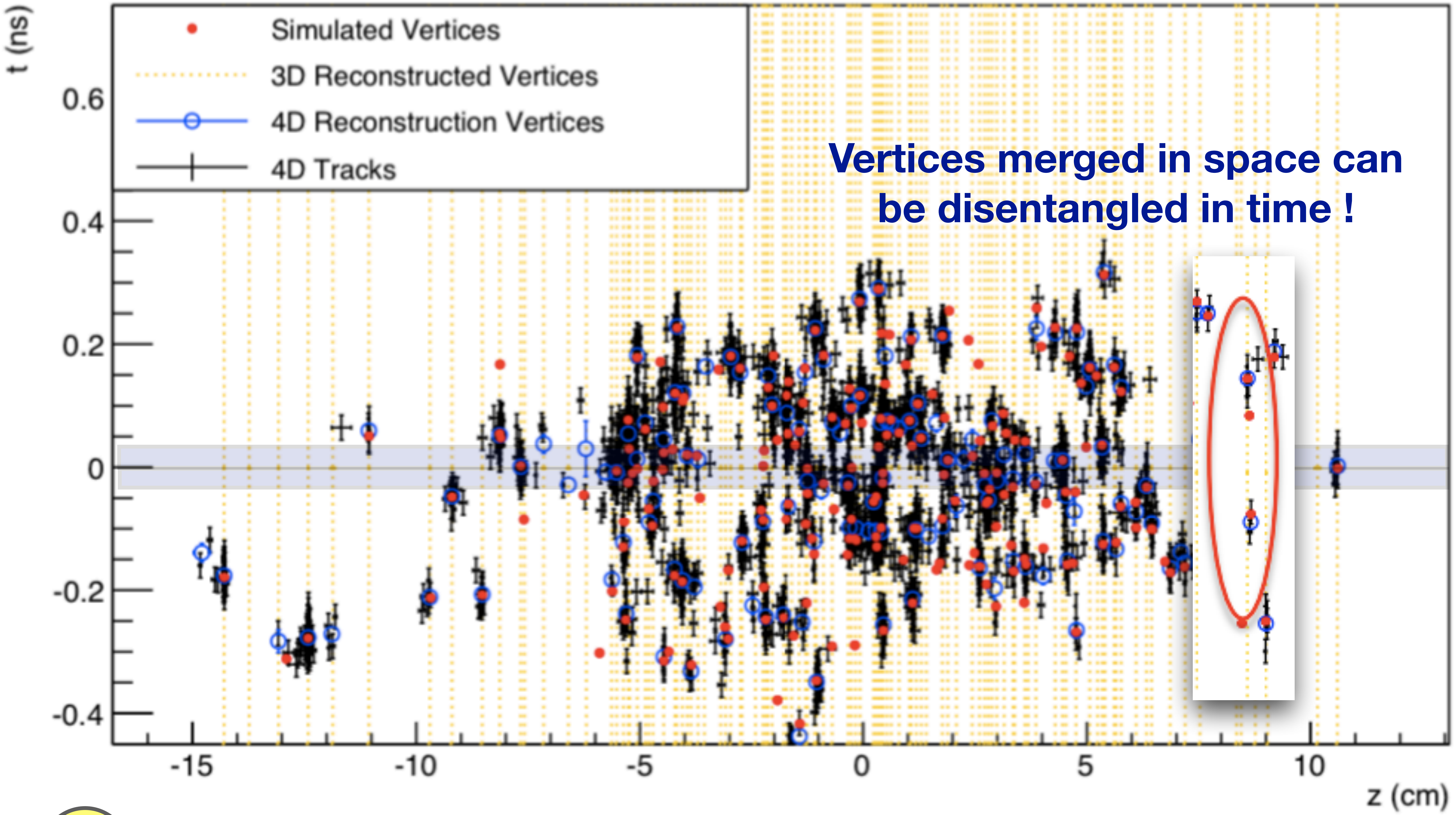




In CMS, PU mitigation relying on the high granularity of the tracking subdetectors and dedicated algorithms combining their information. Due to growing spatial overlap of tracks and energy deposits, in the transition from 140 to 200 pileup events (**Line density >1 mm^{-1}**) reduced efficiency of tracks-vertex association.

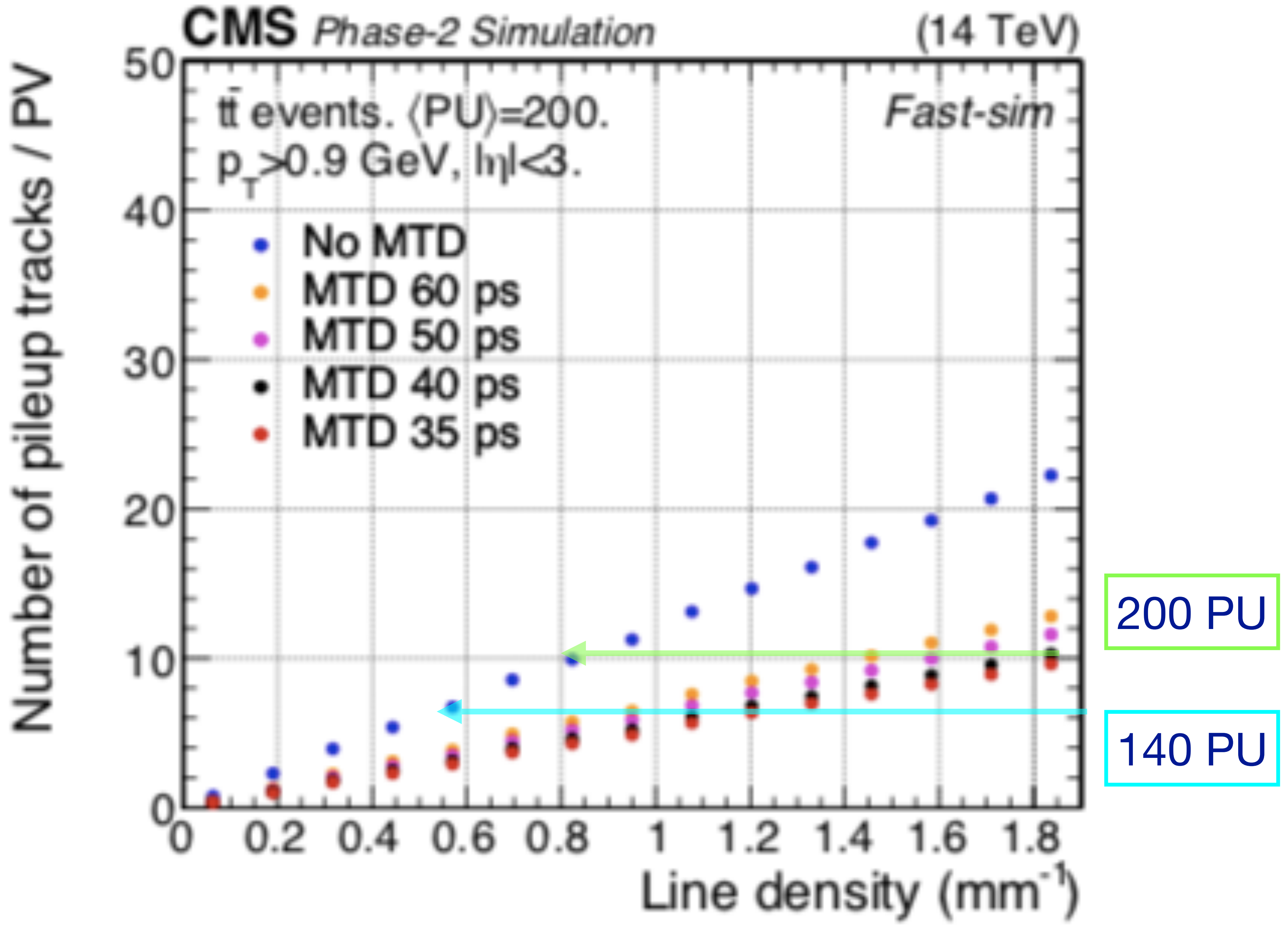
Misidentification, degradation of reconstruction efficiency and energy resolution

CMS strategy for PU mitigation



Time tagging charged particles (Mips) with Time resolution ~ **30-40 ps** corresponding to slicing the beam spot in consecutive time exposures of the same duration

Restoring PU levels close to RUN 2 scenario with **40-60 collisions**/frame



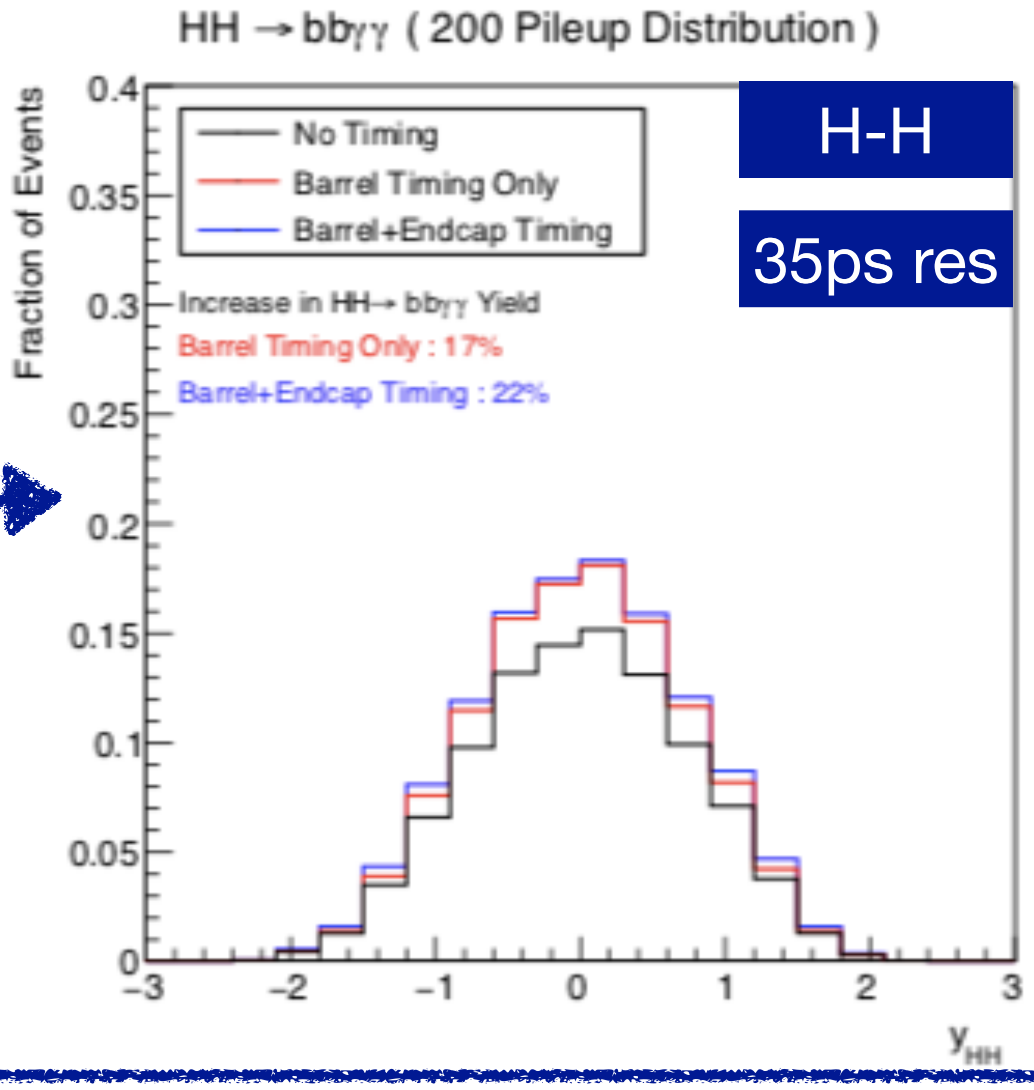
Exploiting the interaction vertices distribution along the beam (4.5 cm RMS) corresponding to 180-200 ps RMS in the time domain

Physics performance with MIP Timing Detector (MTD)

Vertex merging reduced from 15% using 3D-PF vertex reco to 1% with 4D-PF vertex reco. Phase I track purity restored.

Identification, reconstruction and resolution of physics objects improved (b-tagging, lepton isolation, MET)

Statistical precision and sensitivity improvement in many processes of interest for the HL-LHC program



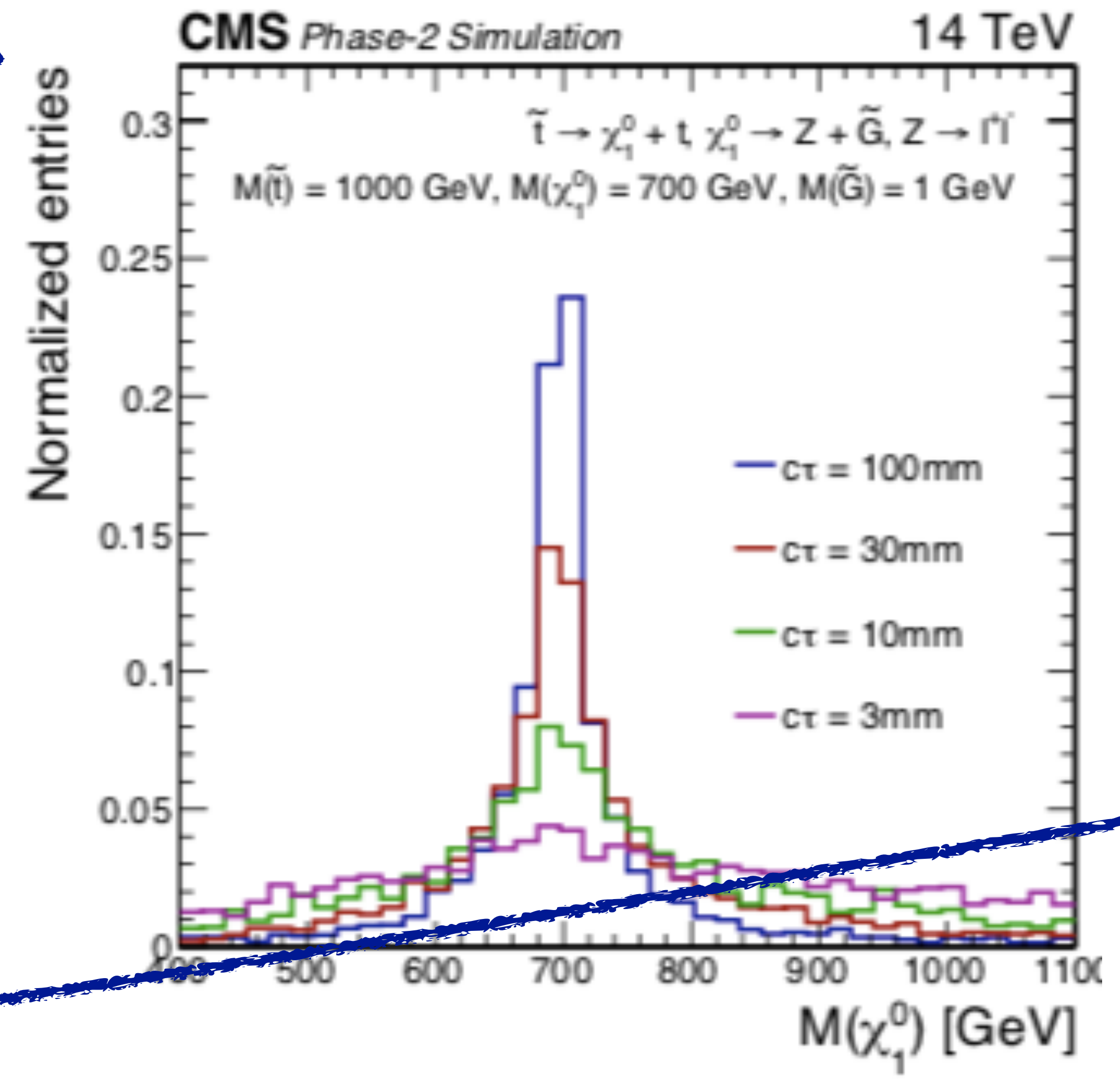
Channel	No MTD	ETL Only	BTL Only	MTD
	50 ps BTL, 50 ps ETL			
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.36	1.44	1.50
$bb\gamma\gamma$	1.70	1.72	1.78	1.80
Combined	2.31	2.37	2.47	2.53

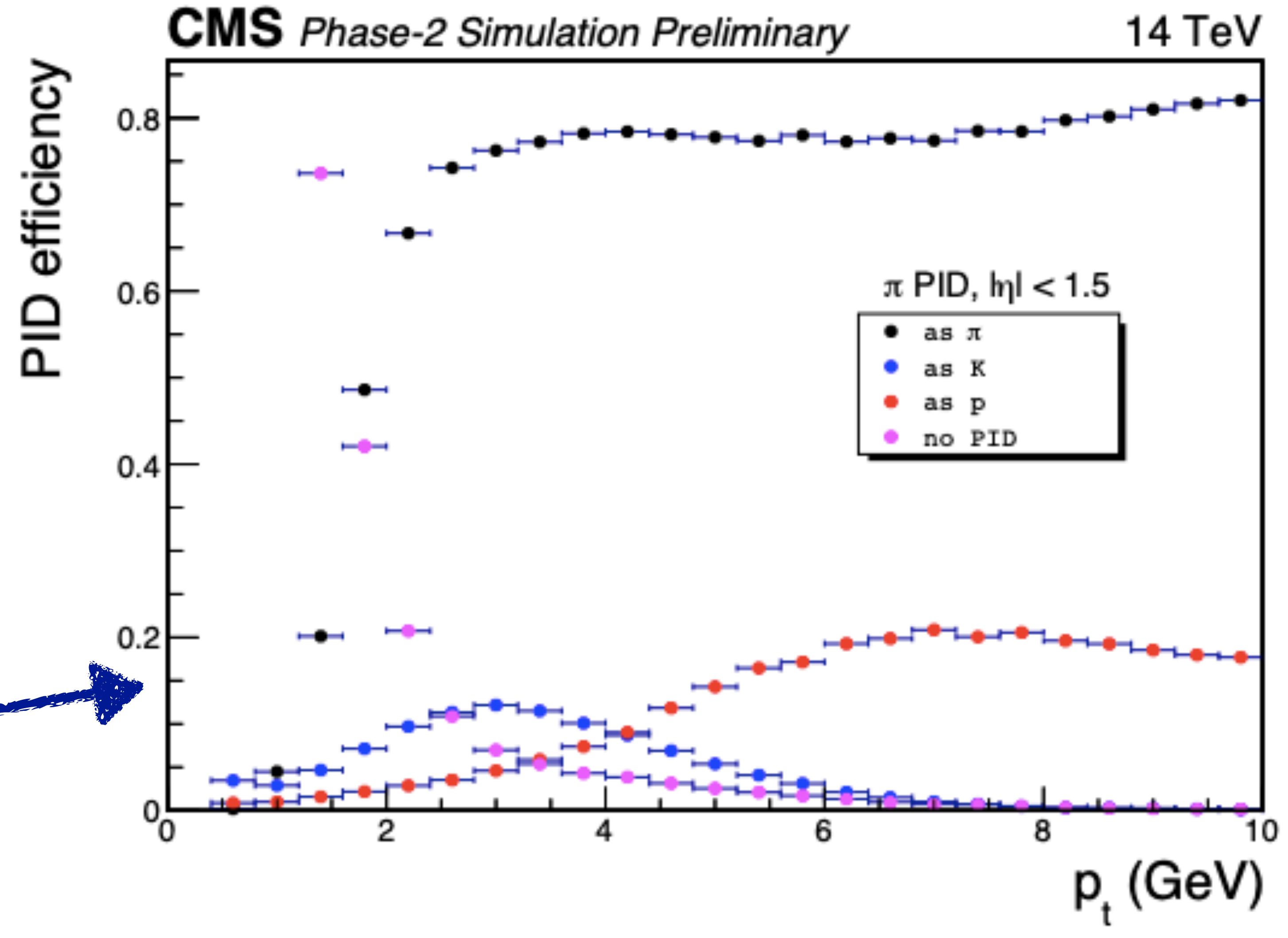
+ bbWW, bbZZ. 2.63

+20% signal yield

MTD also adding new capability to CMS:

- Potential for direct measurement of LLP mass by reconstruction of the time of displaced vertices
- PID of low Pt charged hadrons through TOF measurement (High impact for heavy ions physics)





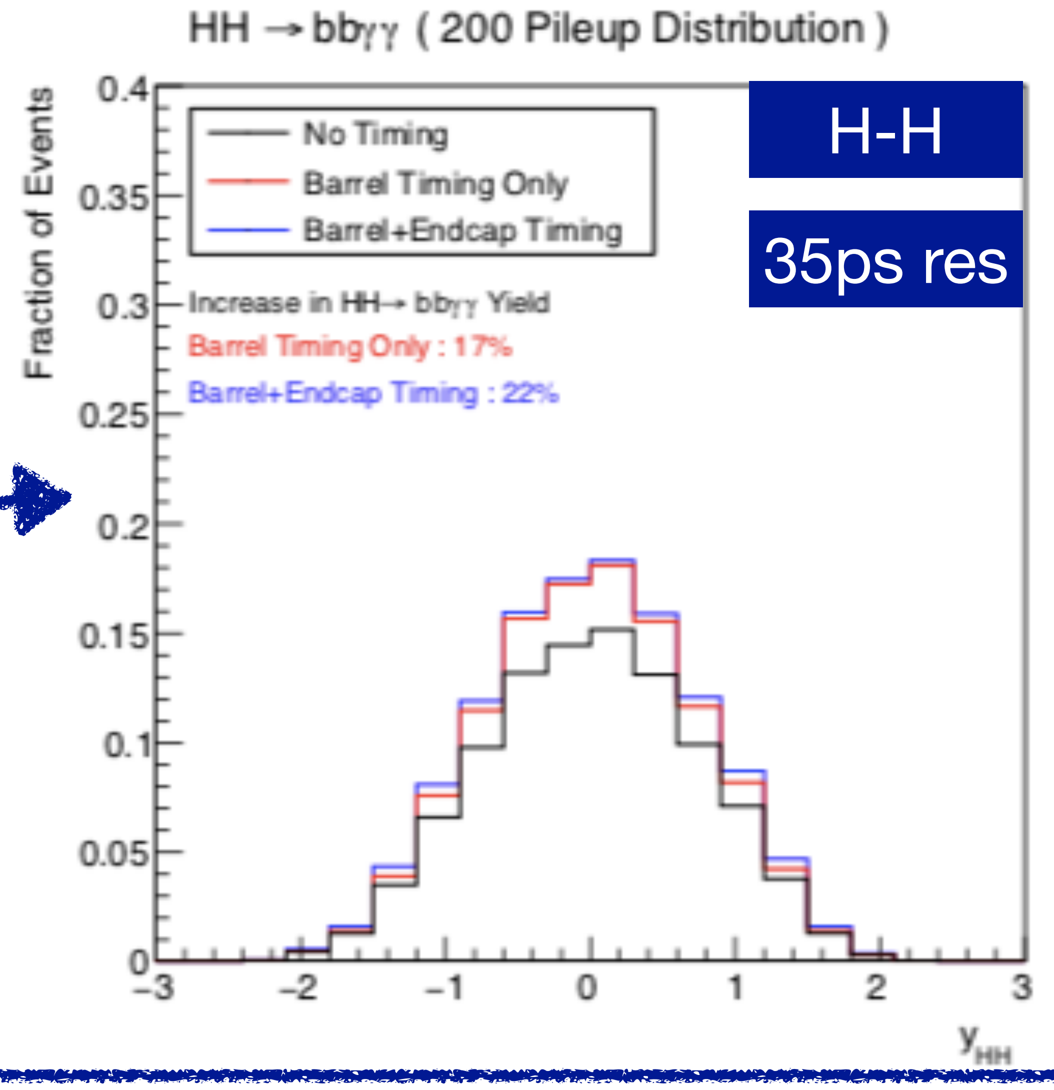
Physics performance with MIP Timing Detector

L. Soffi's talk
Today 12.20

Vertex merging reduced from 15% using 3D-PF vertex reco to 1% with 4D-PF vertex reco. Phase I track purity restored.

Identification, reconstruction and resolution of physics objects improved (b-tagging, lepton isolation, MET)

Statistical precision and sensitivity improvement in many processes of interest for the HL-LHC program



50 ps BTL, 50 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.36	1.44	1.50
$bb\gamma\gamma$	1.70	1.72	1.78	1.80
Combined	2.31	2.37	2.47	2.53

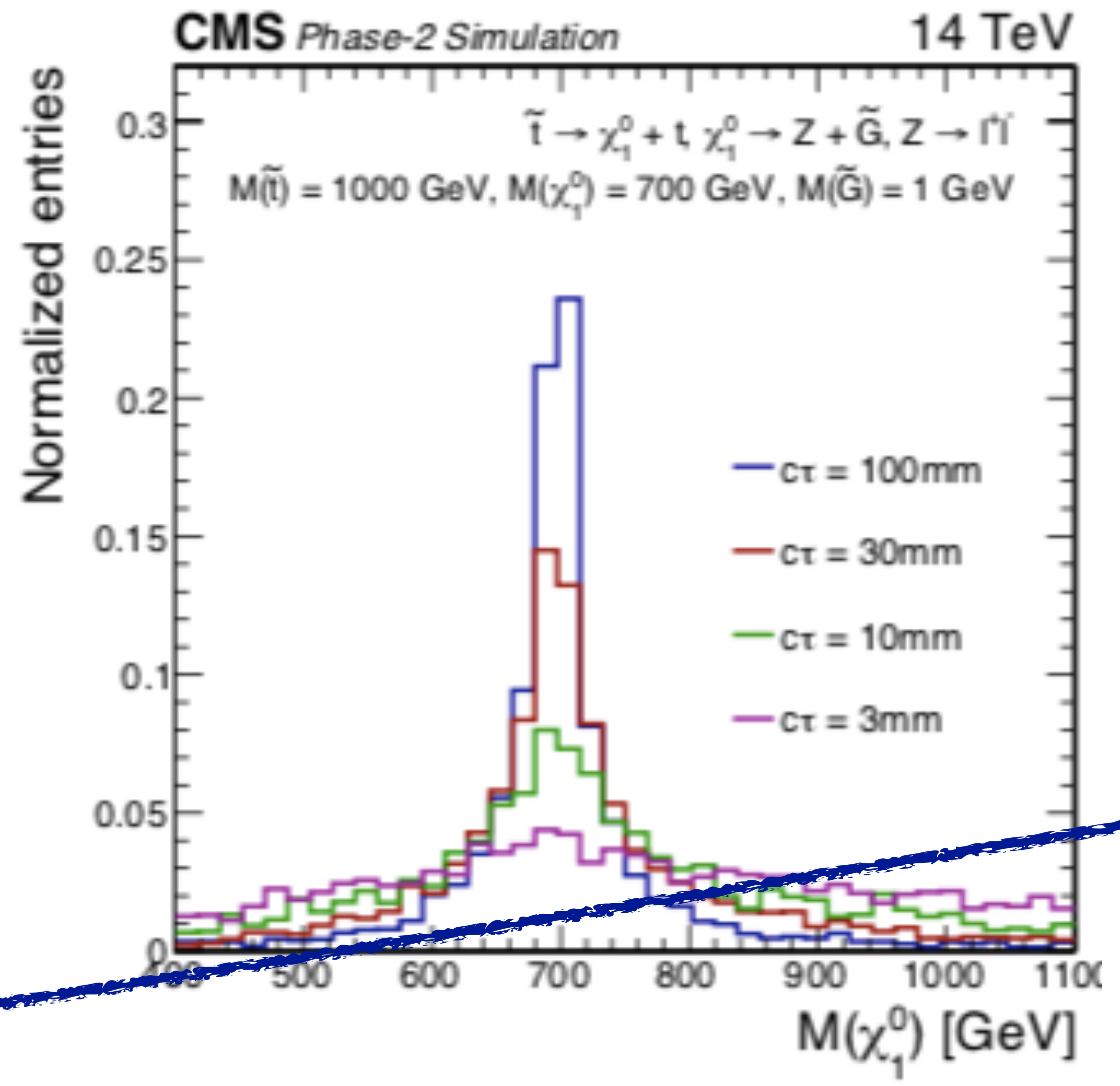
+ bbWW, bbZZ. 2.63

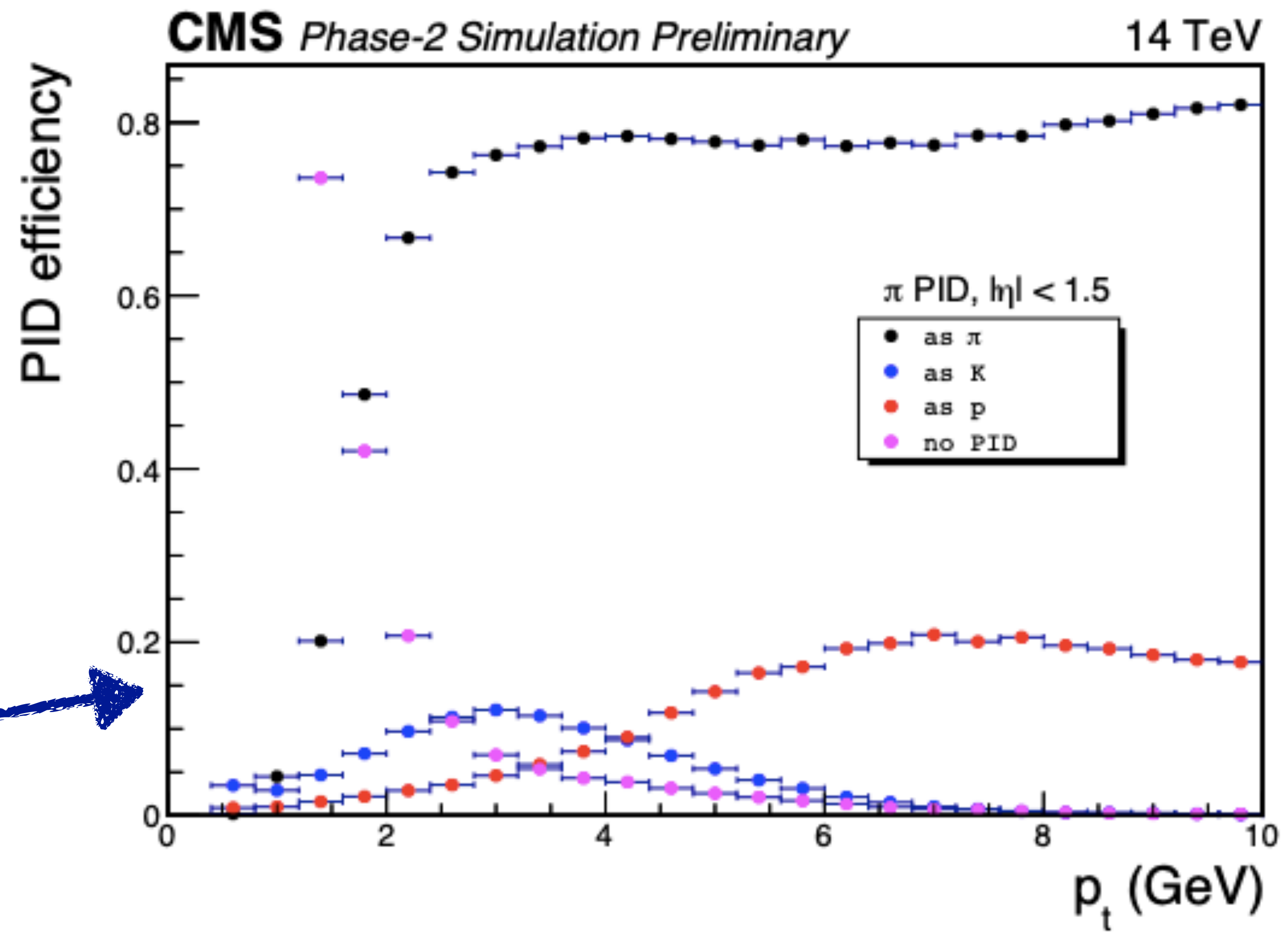
+20% signal yield

MTD also adding new capability to CMS:

- Potential for direct measurement of LLP mass by reconstruction of the time of displaced vertices

- PID of low Pt charged hadrons through TOF measurement (High impact for heavy ions physics)

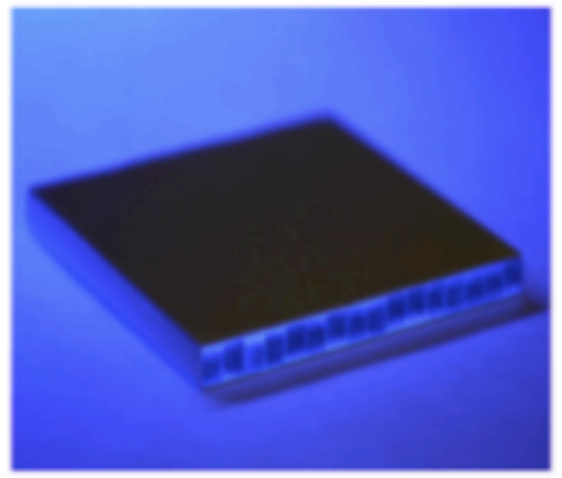




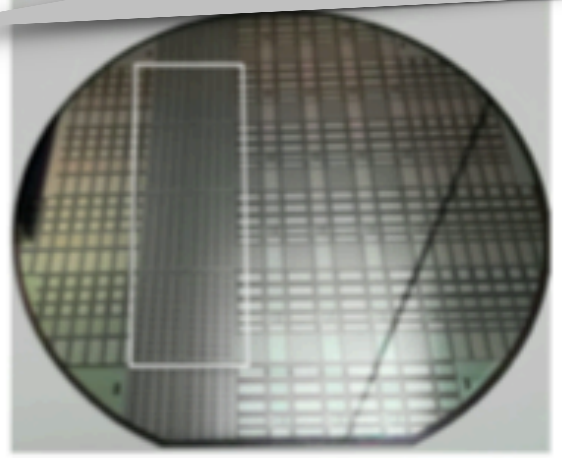
MIP Timing Detector

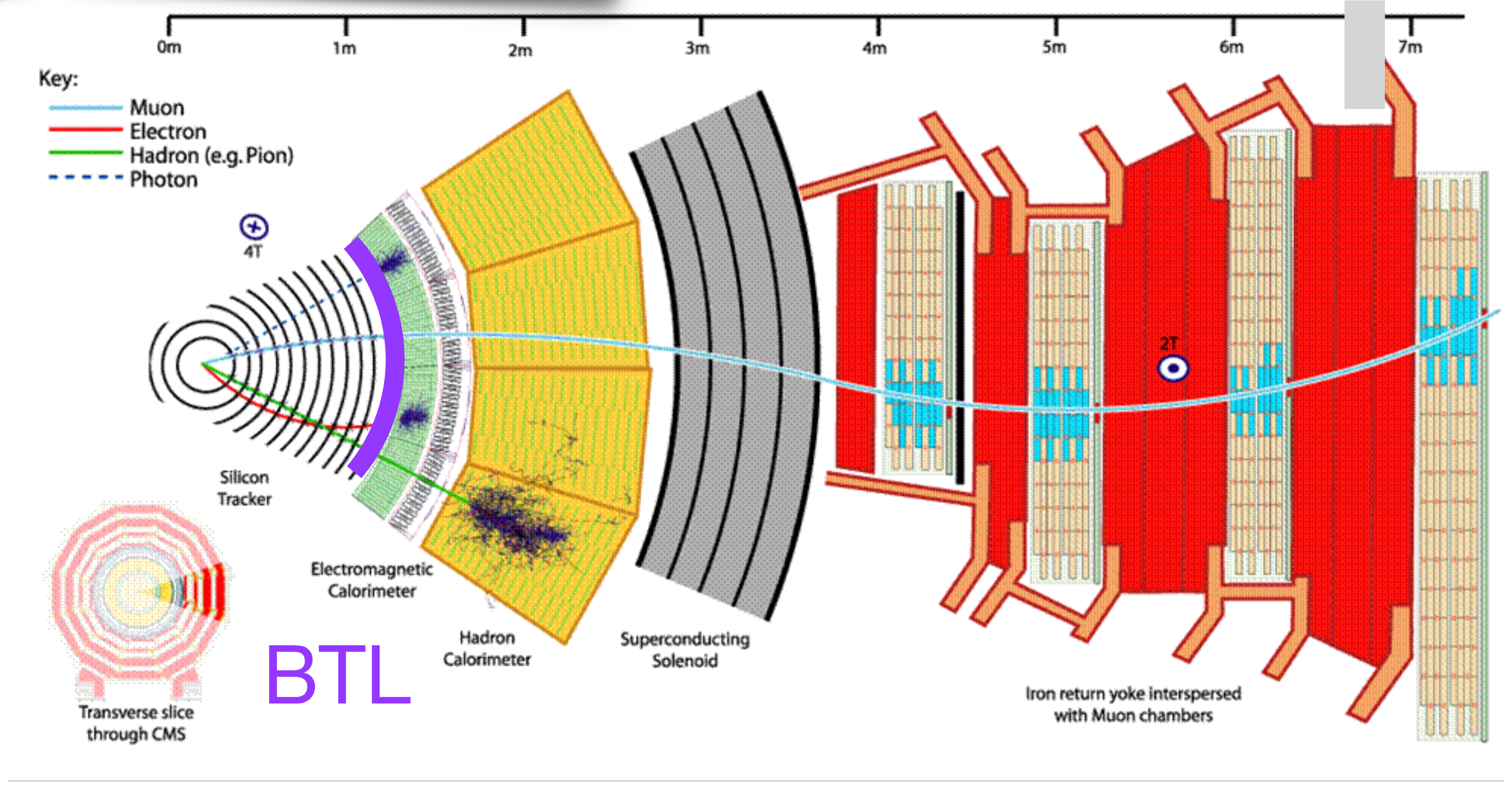
M. Tornago's talk

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m²; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n_{eq}/cm^2

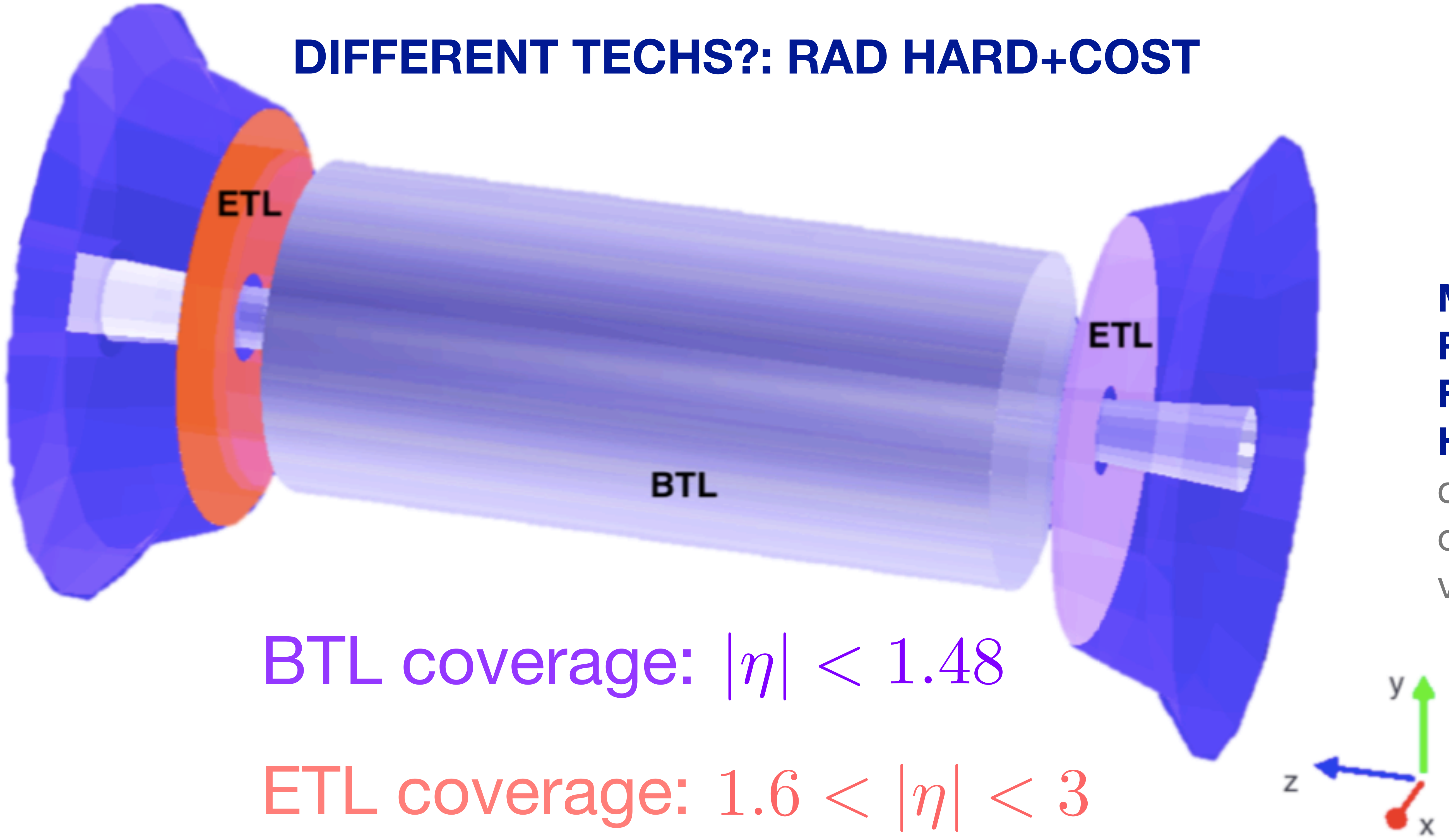


ETL: Si with internal gain (LGAD):
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m²; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2x10^{15} n_{eq}/cm^2





DIFFERENT TECHS?: RAD HARD+COST



BTL coverage: $|\eta| < 1.48$

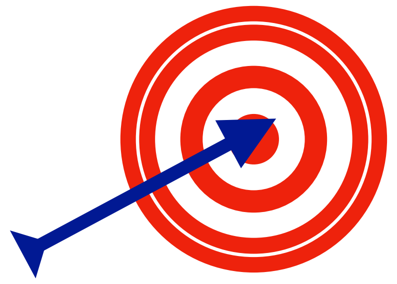
ETL coverage: $1.6 < |\eta| < 3$

MTD DELIVERED MEASUREMENT

Raw: Time of arrival of the Mip on the MTD

Final: Track time at the collision vertex

How: matching the track to MTD hits cluster and correcting the MTD time measurement for the TOF obtained using the track length and the particle velocity



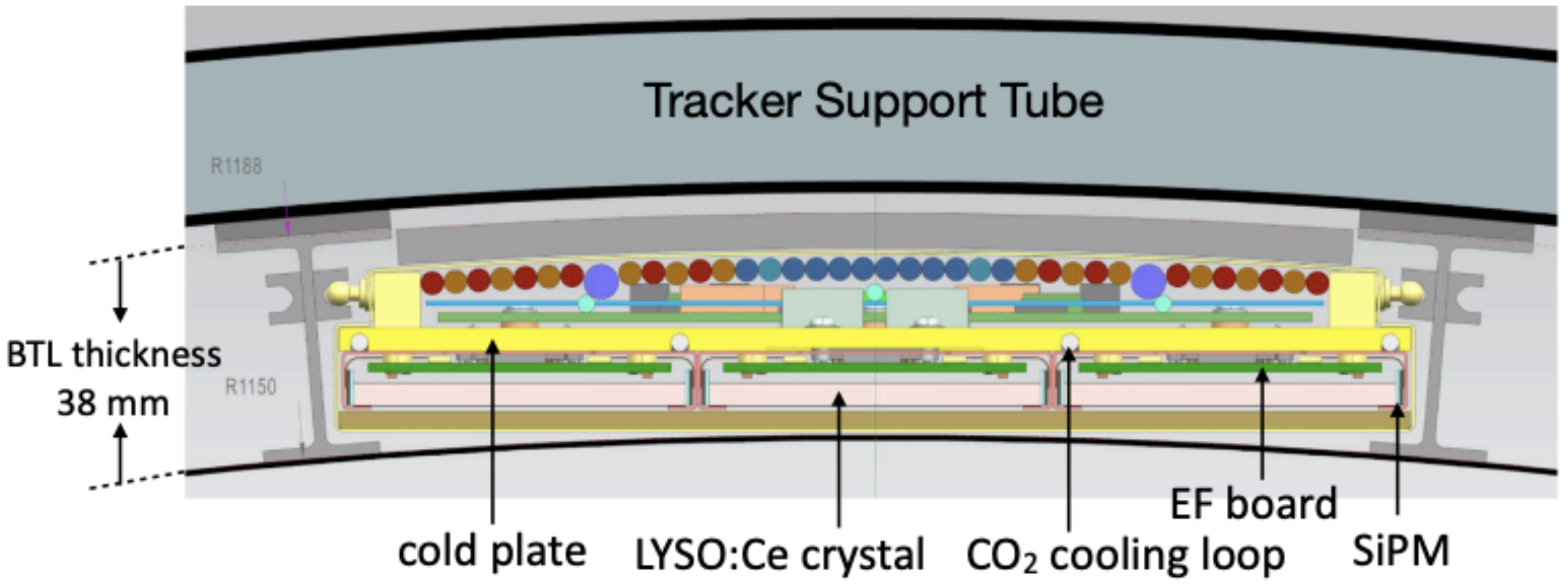
TIME RESOLUTION:

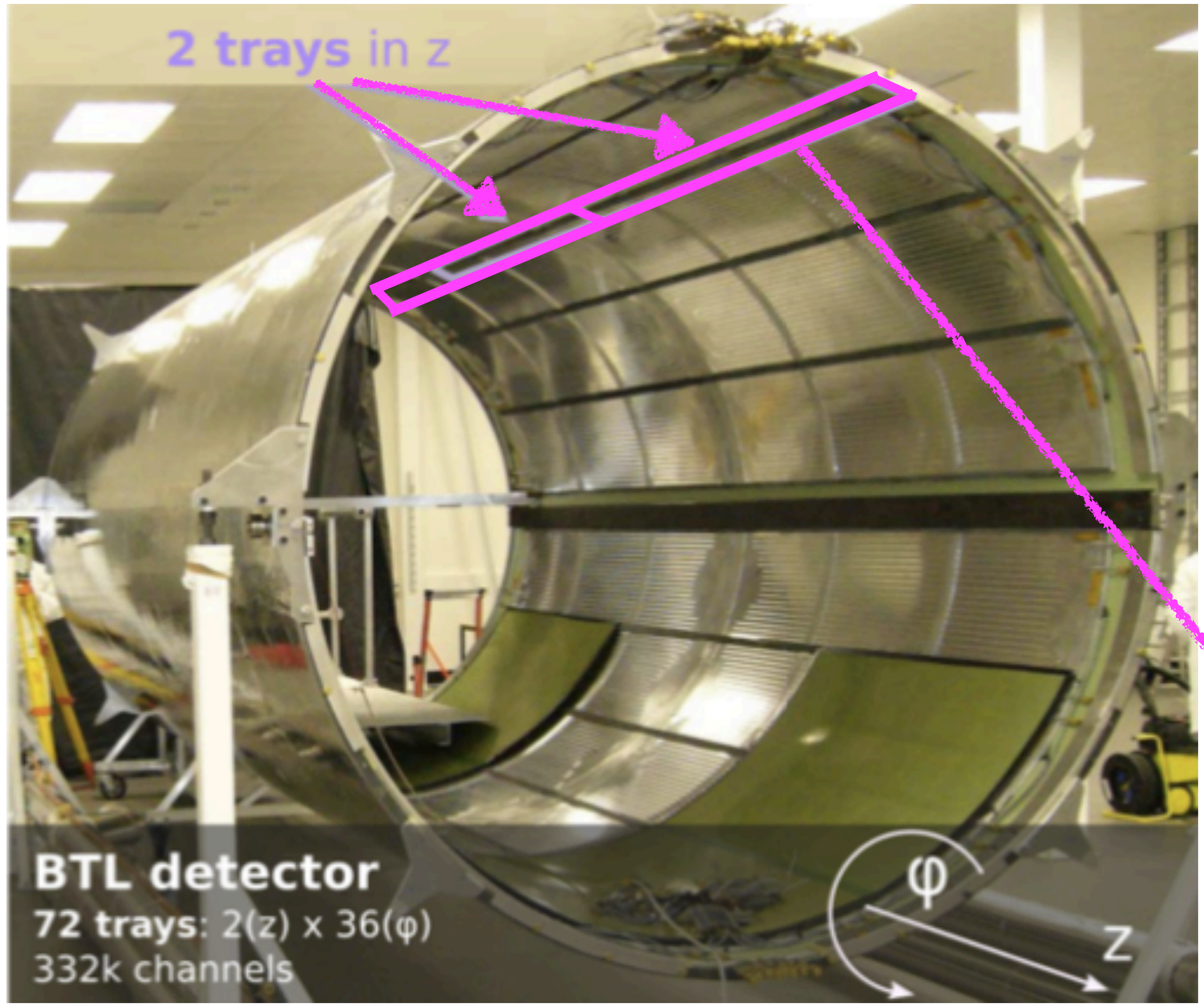
30-40 ps Begin Of Operation (BOO)

<70ps EOO End Of Operation (EOO, 3000 fb^{-1})

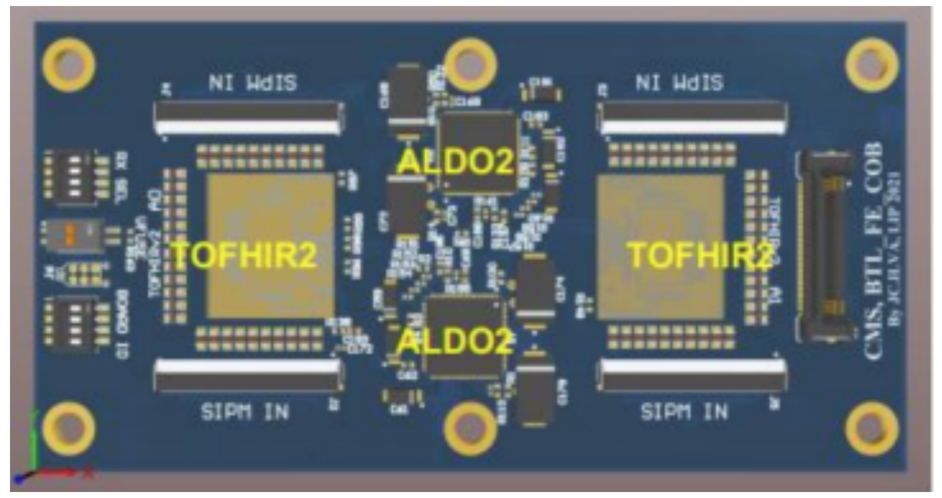
Barrel Timing Layer (BTL)

T= -35°C with CO_2 cooling



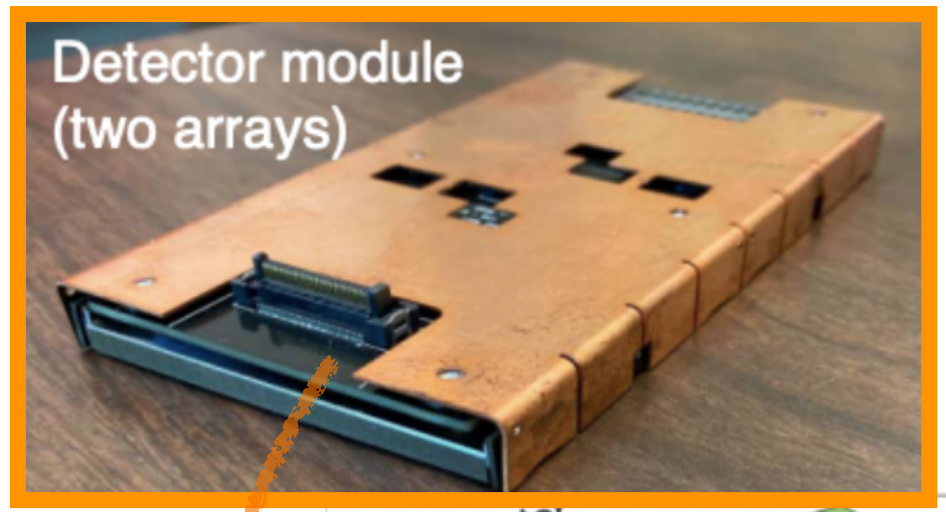


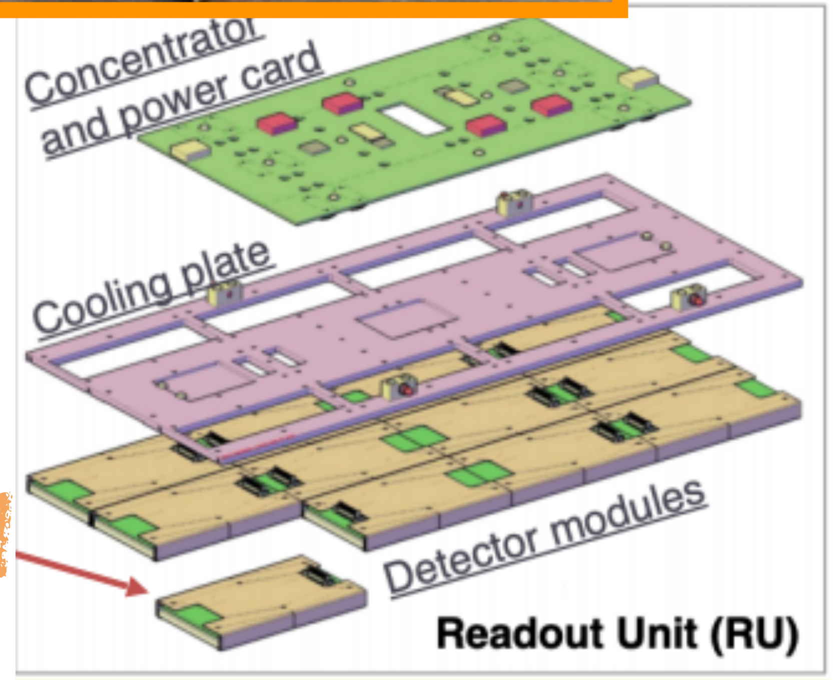
+

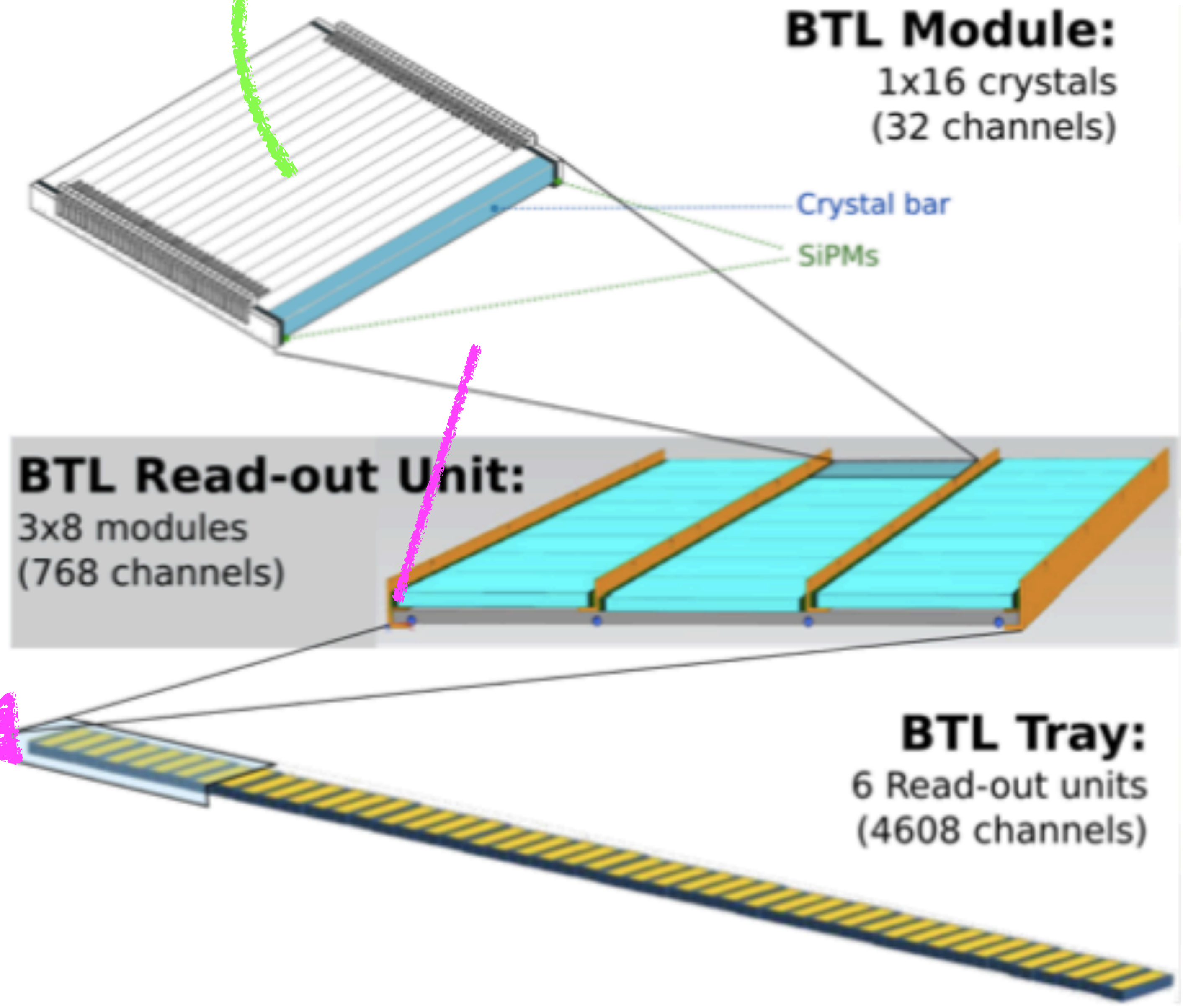


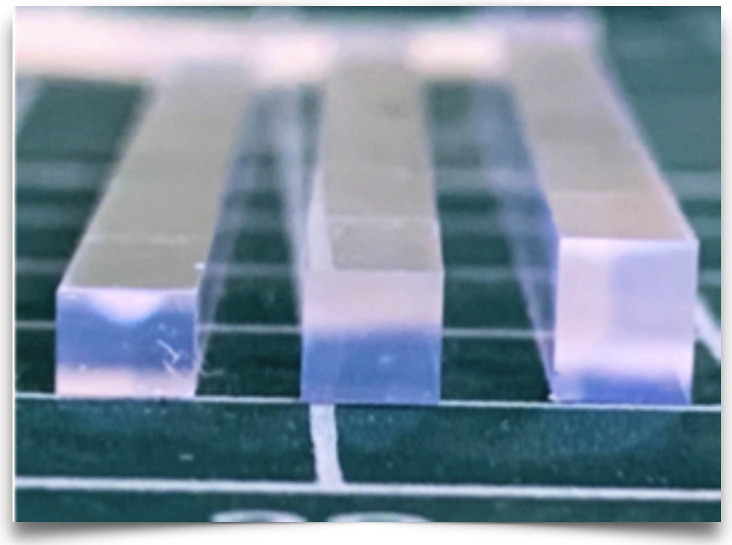
TOFHIR ASIC

=









Type	t (mm)	|Eta|
1	3.75	0-0.7
2	3	0.7 - 1.1
3	2.4	1.1 - 1.5
L=56.2 mm. w=3.12 mm		

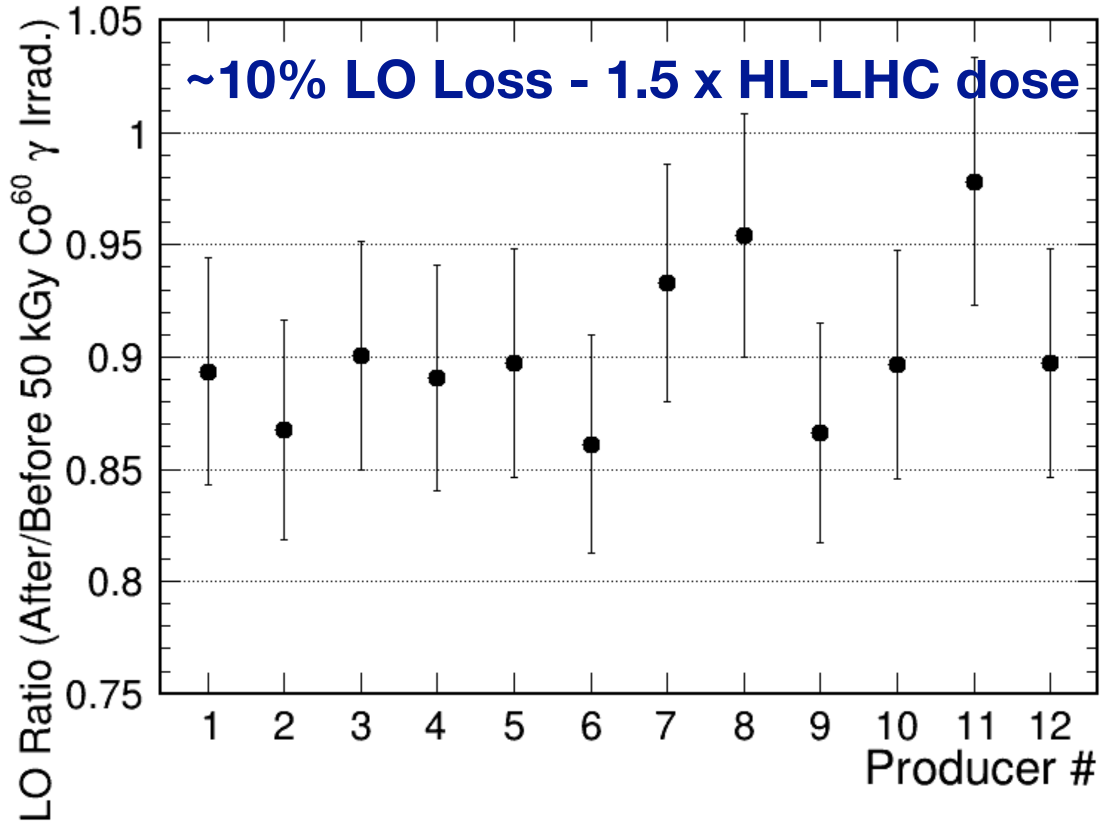
BTL sensors: LYSO:Ce crystals & SiPMs

LYSO:Ce crystals

- Well established technology (PET)
- Fast scintillation kinetics:
  - rise time ~100 ps
  - decay time ~ 40 ns
- Radiation hard proven up to:
  - 50kGy with γ from ^{60}Co source
  - 3×10^{14} 1MeV neq/cm^2
- High Light Yield: 40000 γ/ MeV

Comprehensive study of LYSO:Ce crystals from 12 producers performed to identify potential BTL suppliers and set the QA/QC requirements for the production stage.

- Optical transmission, photoluminescence
- Light output (LO), decay time (τ)
- LO/τ (figure of merit timing)
- Light yield temperature coefficient
- Decay time temperature dependency (low T)
- γ radiation resistance



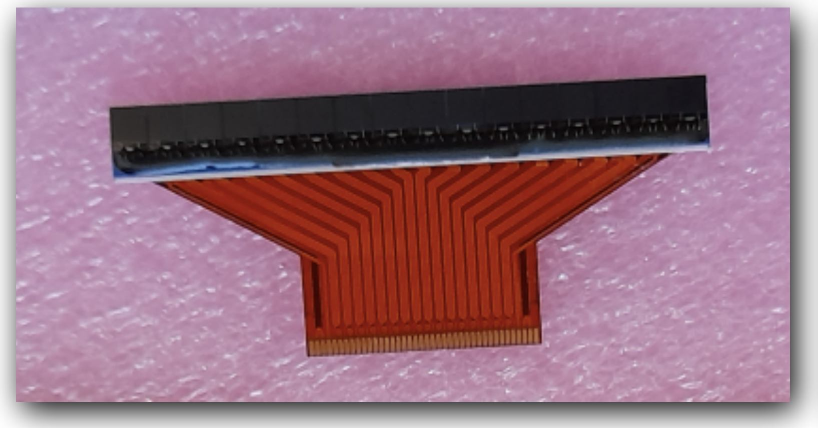
https://arxiv.org/abs/2205.14890

TENDER SUBMISSION BY THE END OF THE YEAR

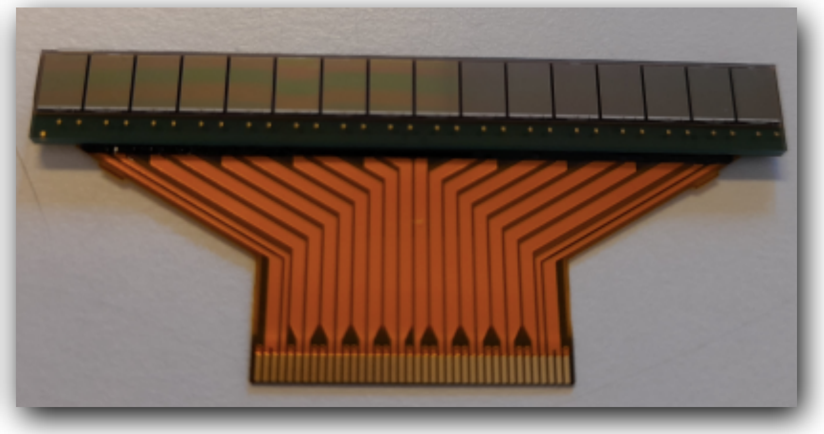
SiPMs

- Well established technology
- Compact and robust
- Insensitive to magnetic fields
- Fast recovery time <10 ns
- High dynamic range (10^5)
- PDE@Lyso emission peak 20-40%
- Radiation hard proven up to:
  - to 2×10^{14} 1MeV neq/cm^2

FBK, 20 µm thin glass enc



HPK, 300 µm silicon resin enc.

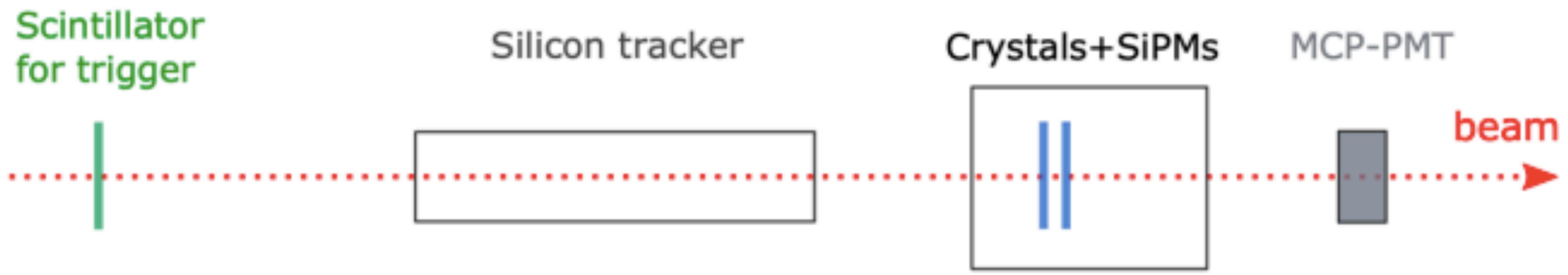


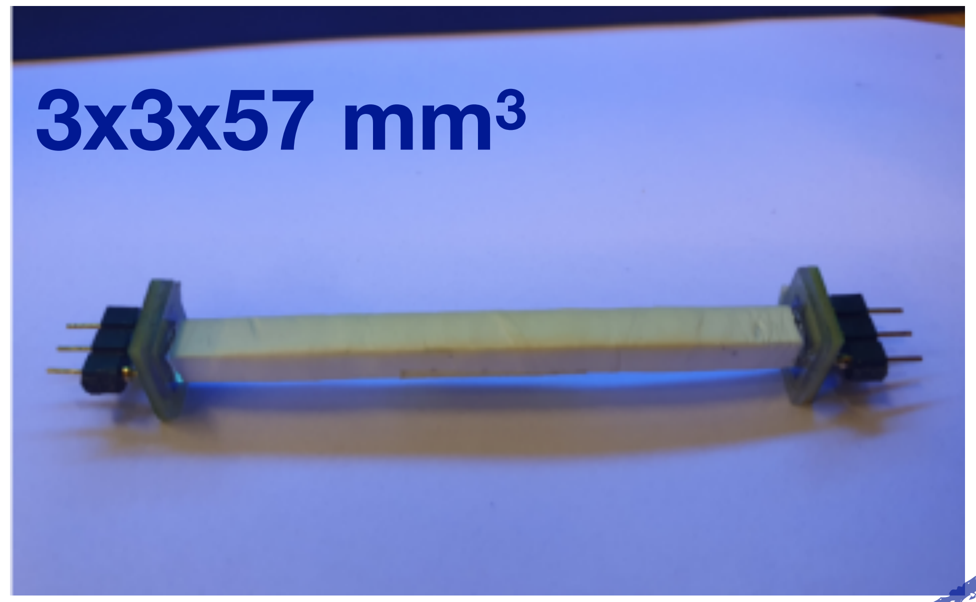
TENDER SUBMISSION: SPRING 2023

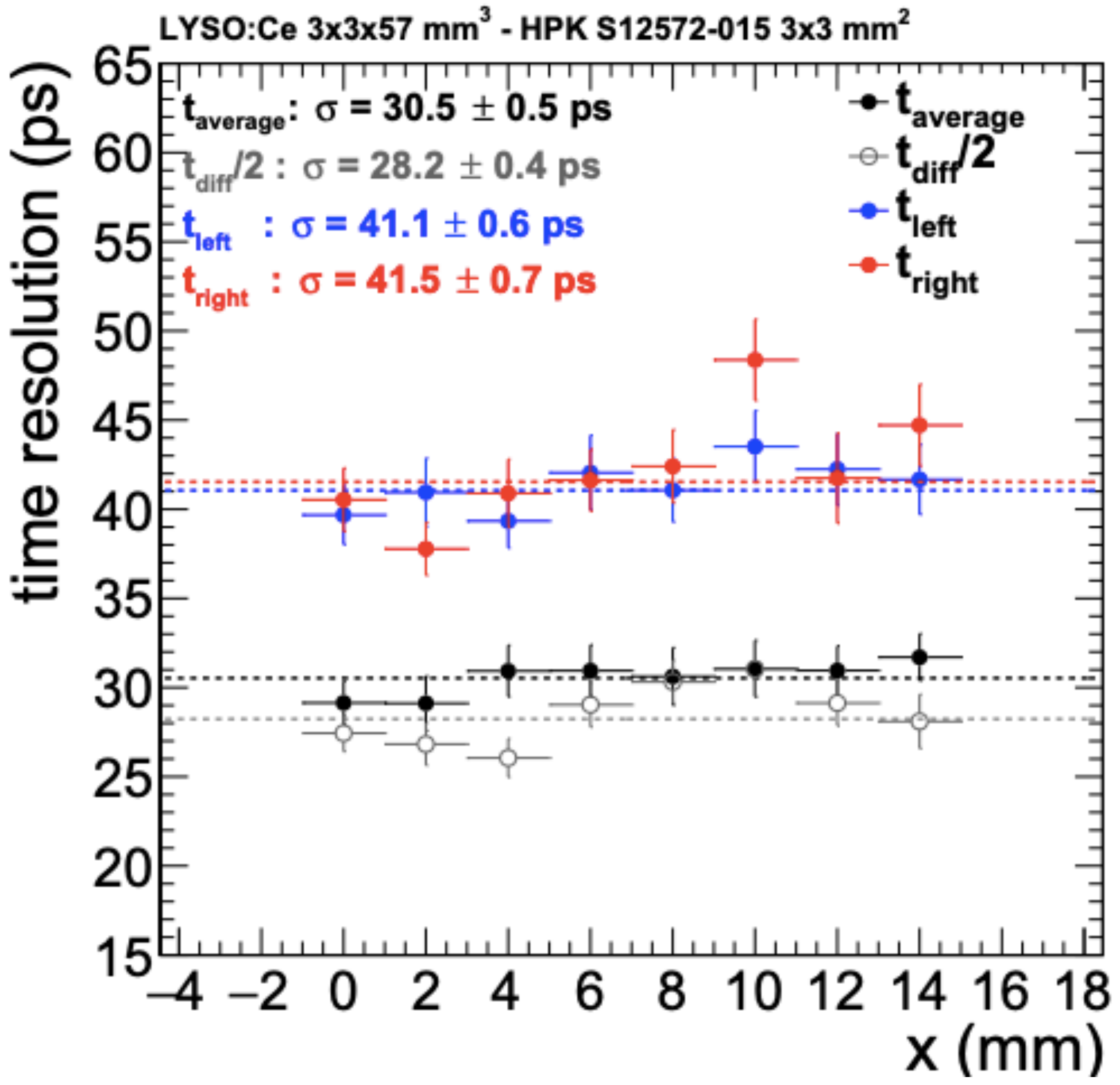
(optimized prototype testing on going)

BTL unirradiated sensors: beam test results

120 GeV proton beam - FERMILAB (FTBF)



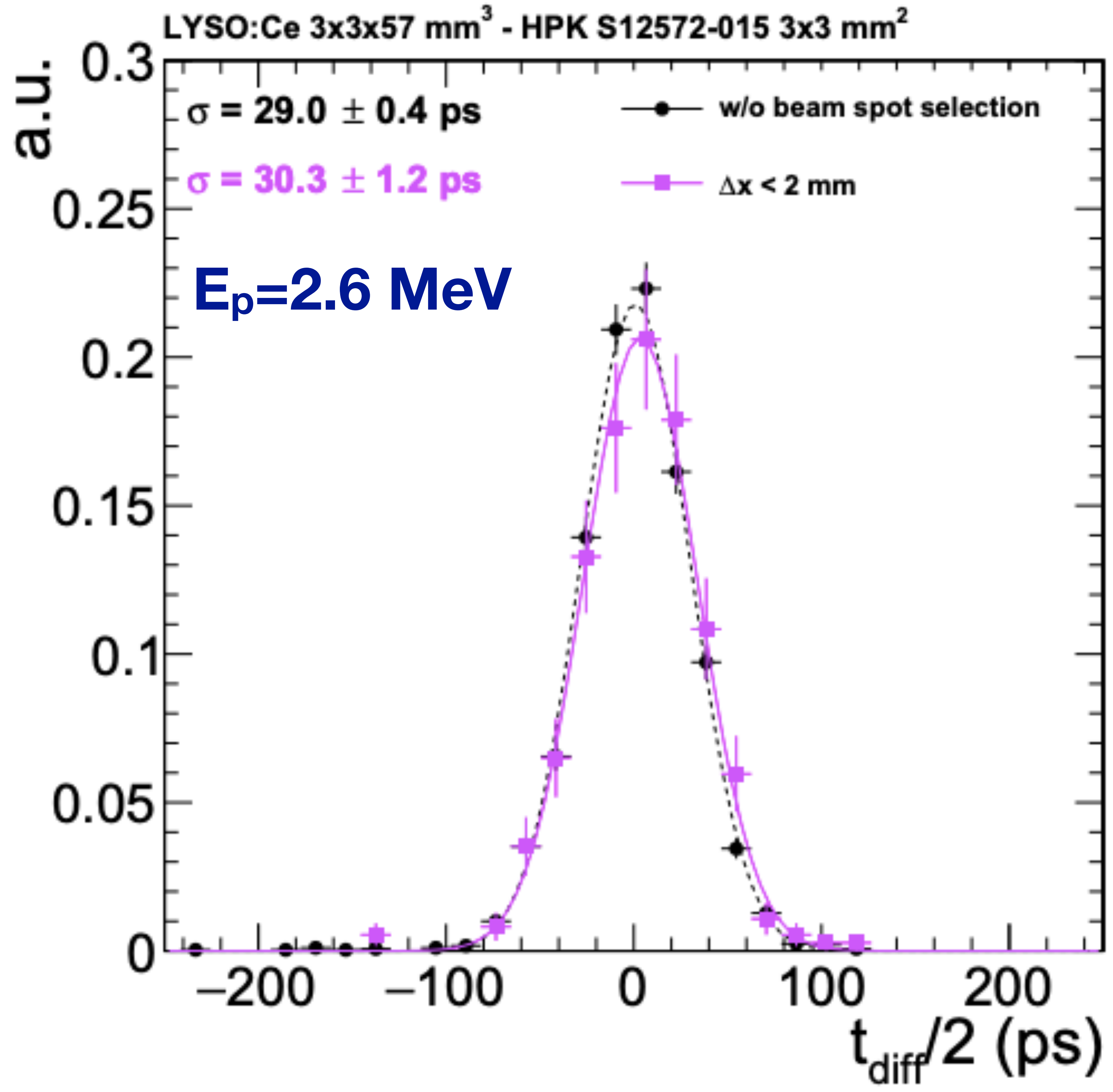




Factor √2 improvement in σ_t by double sided readout

NB: Double ended readout also enabling track position determination with res. O(mm)

Unirradiated sensors



σ_t can be extrapolated to ~22 ps for 4.2 MeV (<E_p> Mip in BTL) and to **~30 ps** when considering elec., clock, digi. contribution to σ_t. **BTL performance BOO demonstrated!**

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

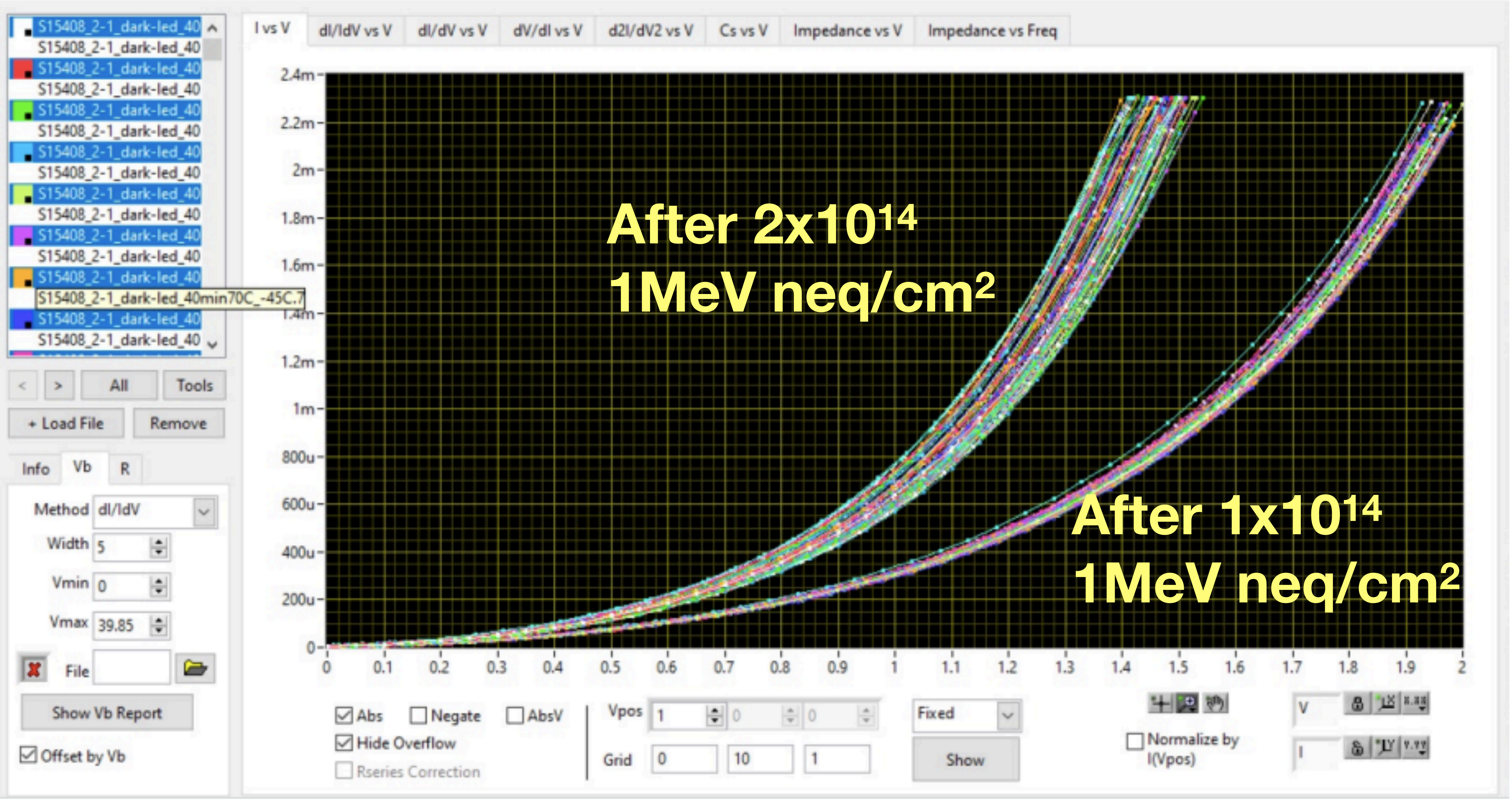
BTL performance evolution I

$$\sigma_{\mathrm{t}} = \sigma_{\mathrm{clock}} \oplus \sigma_{\mathrm{digi}} \oplus \sigma_{\mathrm{ele}} \oplus \sigma_{\mathrm{phot}} \oplus \sigma_{\mathrm{DCR}}$$

DCR

Dark Count Rate. Single SiPM's cell firing due to thermally produced electrons. Dark count signal and signal from LYSO:ce scintillation indistinguishable.

Radiation induced silicon defects increasing the DCR probability. Aka DCR growing with integrated luminosity



After 1000 fb^{-1} main driver for:

- **Time jitter** ▶ $\sigma_{\mathrm{DCR}} \propto \sqrt{\mathrm{DCR}}/\mathrm{N_{pe}}$
- **Power consumption**

To meet BTL target resolution EOO:

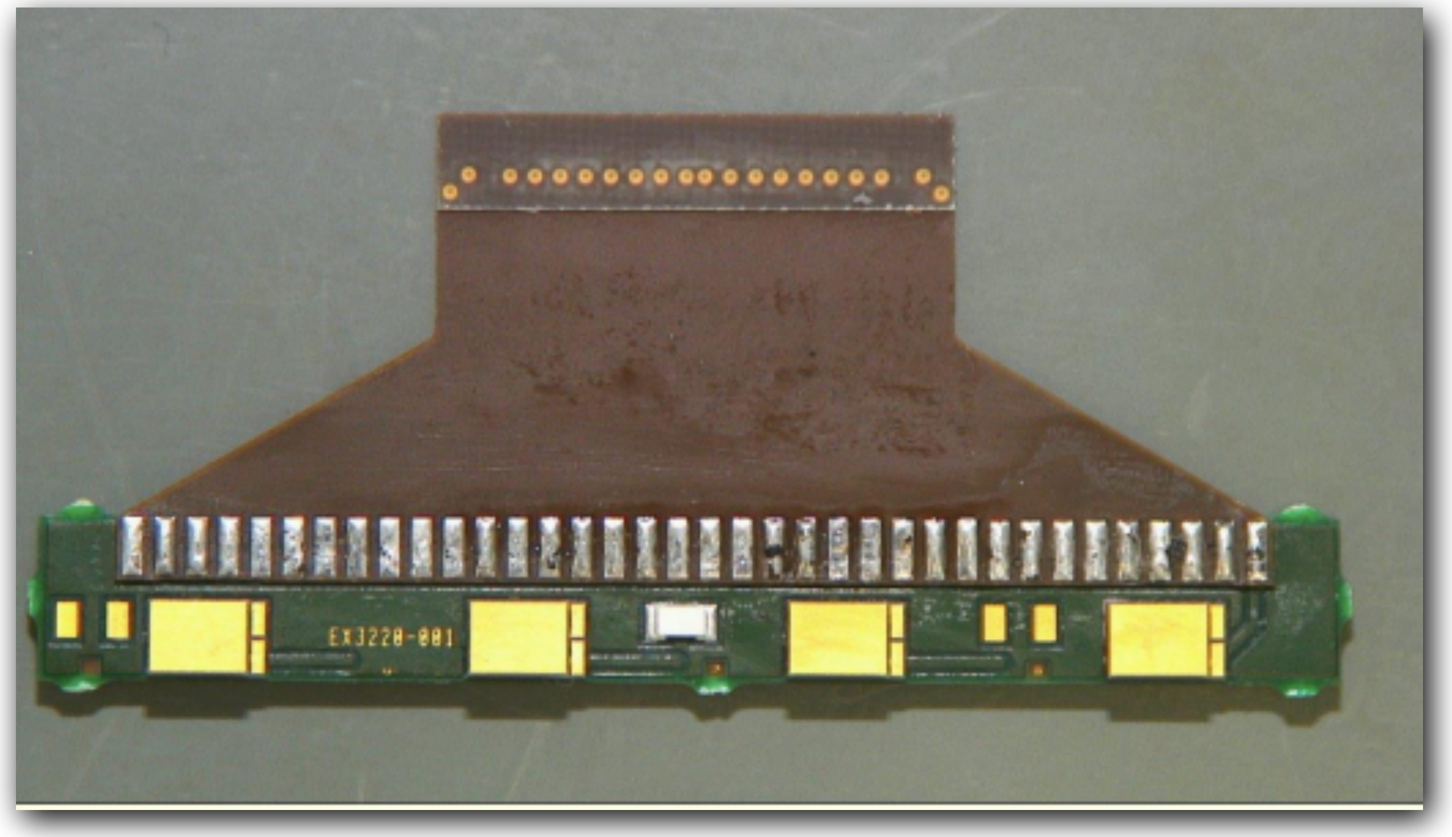
DCR< 35-55 GHz ▶ ACTION NEEDED!

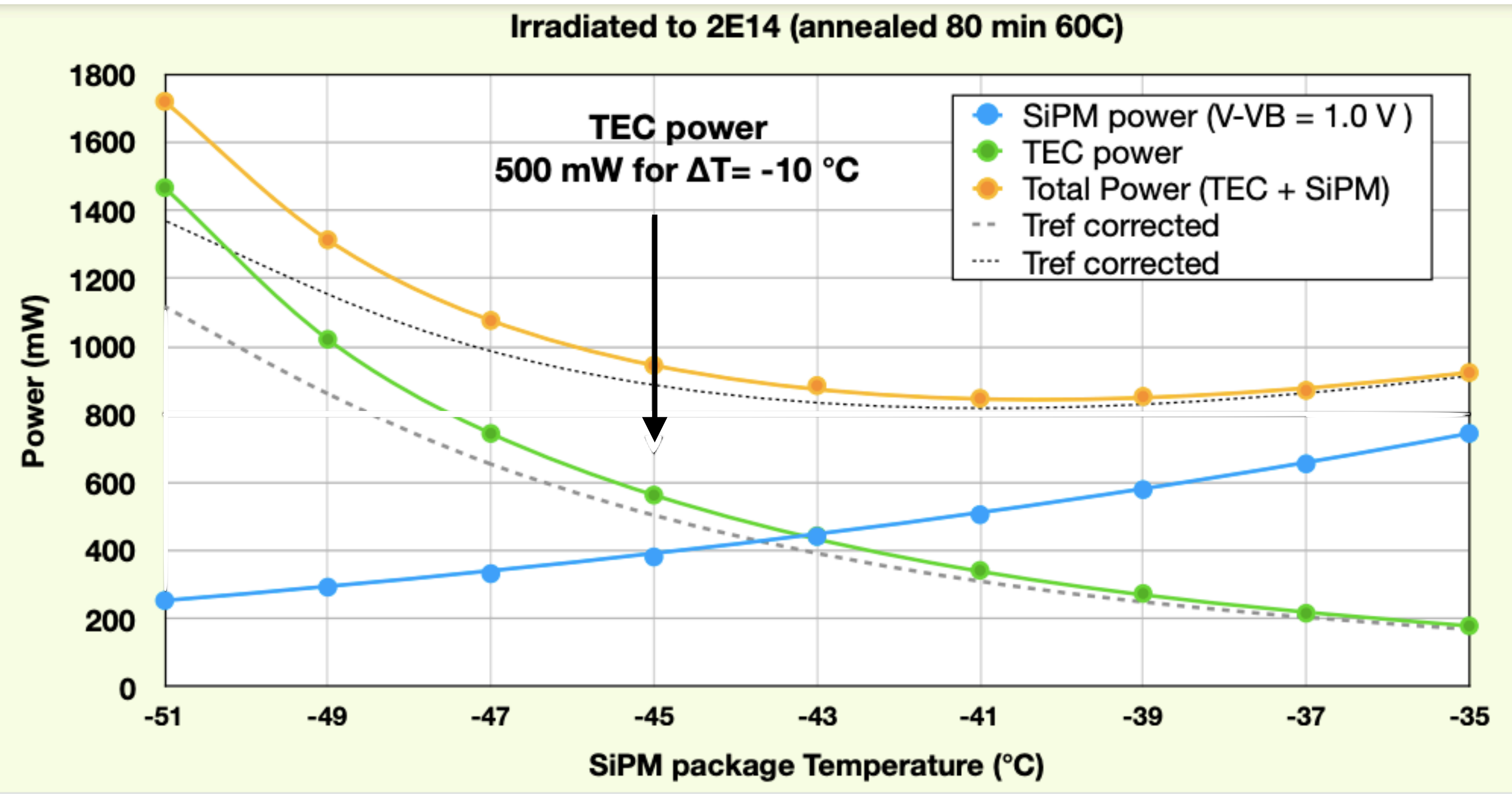
BTL performance evolution II

DCR FEATURE	ACTION	GAIN
Increasing with V_{ov}	Lowering V_{ov}, optimizing S/N ratio	**~ factor 2 less DCR**
Increasing with the temperature ~x 2 every 7-10°C	Further lowering SiPM's T to **-45°C** using Thermoelectric coolers (TEC)	**~ factor 2-3 less DCR**
increasing with radiation damage	Annealing at room +40 °C during machine shutdown	**~ factor 2 less DCR**
	Noise filtering with signal processing technique DLED in TOFHIR	**~ factor 2 lower σ_{DCR}**

BTL performance evolution II

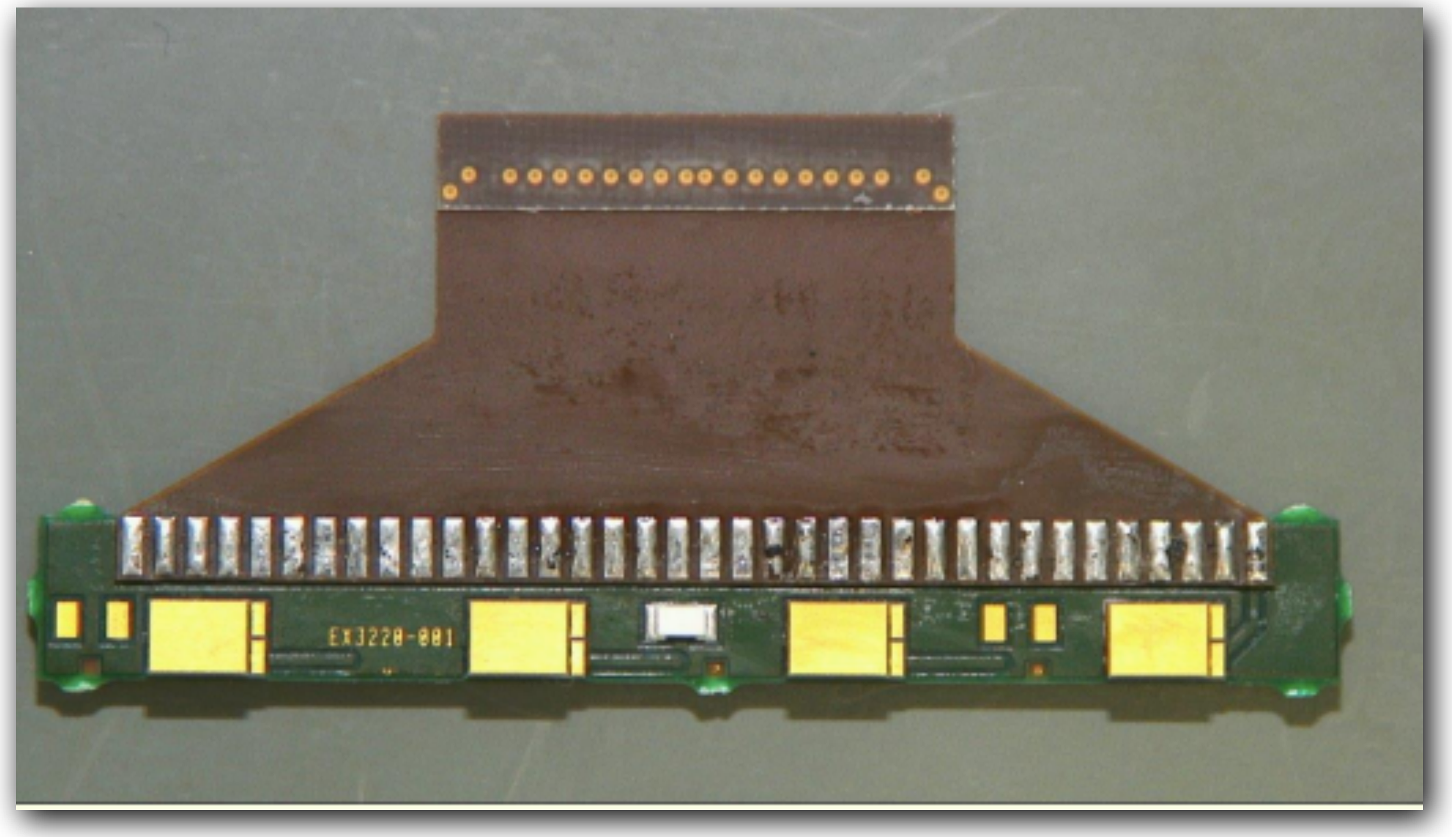
DCR FEATURE	ACTION	GAIN
Increasing with V_{ov}	Lowering V_{ov}, optimizing S/N ratio	**~ factor 2 less DCR**
Increasing with the temperature ~x 2 every 7-10°C	Further lowering SiPM's T to **-45°C** using Thermoelectric coolers (TEC)	**~ factor 2-3 less DCR**
increasing with radiation damage	Annealing at room +40 °C during machine shutdown	**~ factor 2 less DCR**
	Noise filtering with signal processing technique DLED in TOFHIR	**~ factor 2 lower σ_{DCR}**

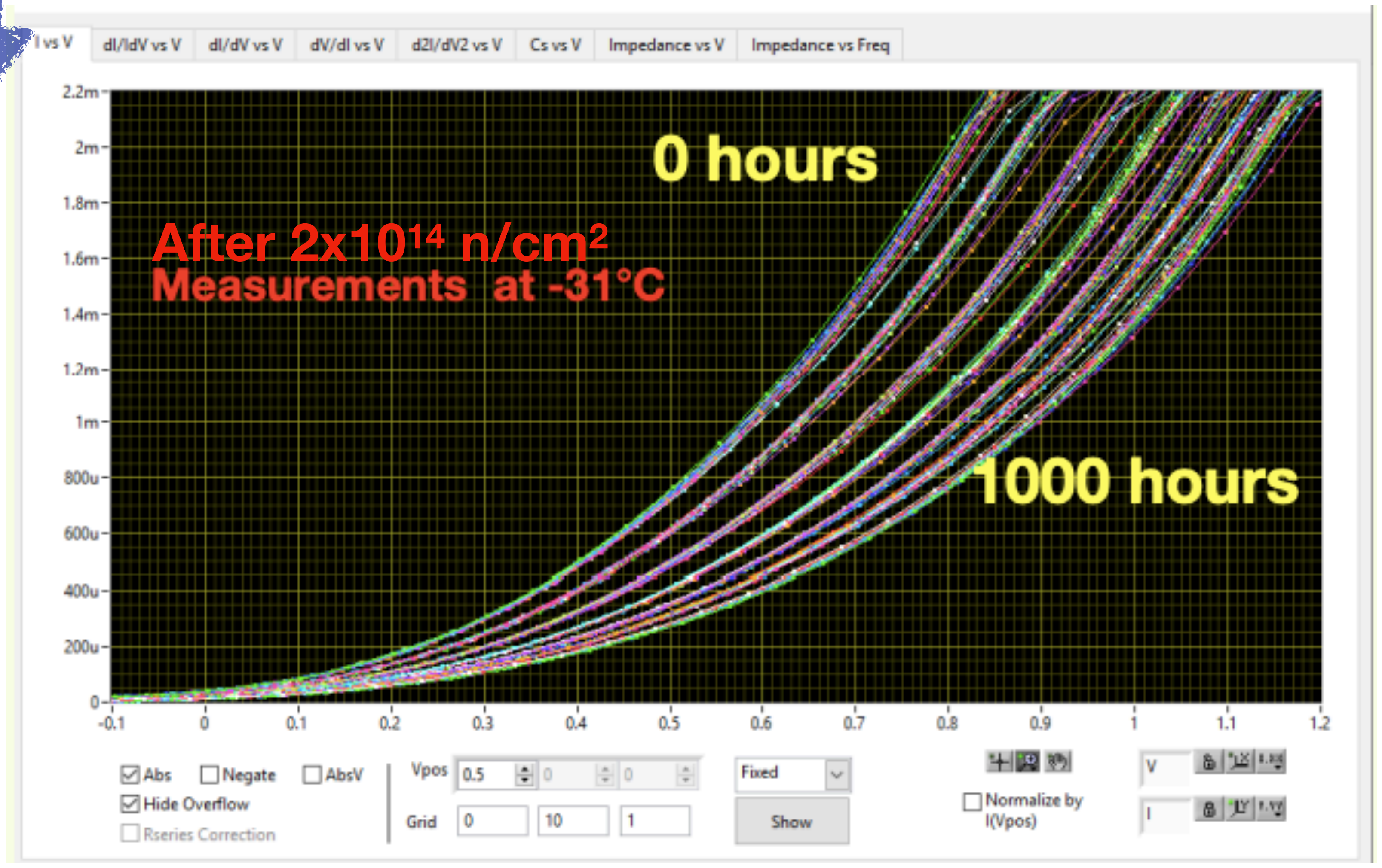




BTL performance evolution II

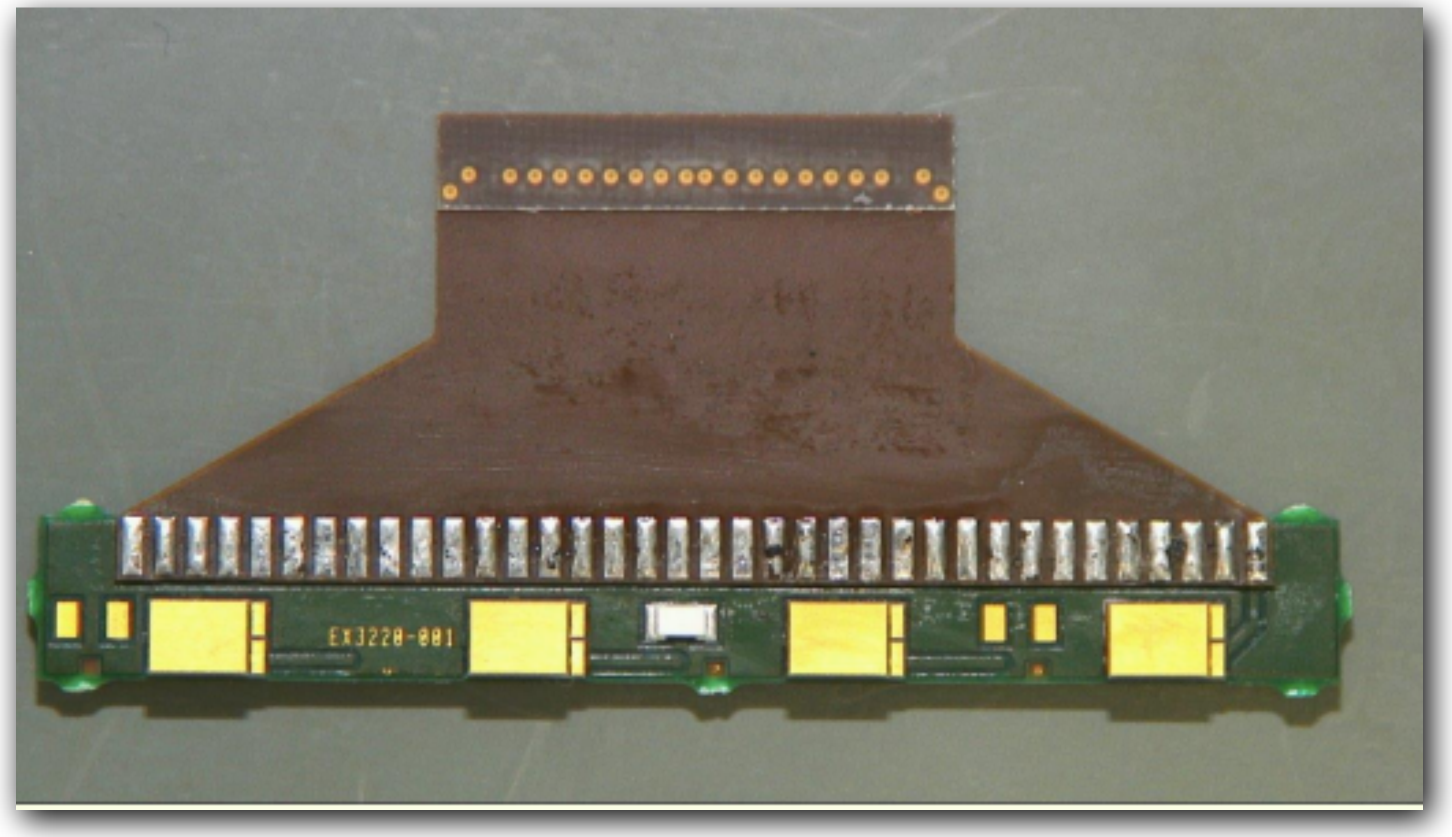
DCR FEATURE	ACTION	GAIN
Increasing with V_{ov}	Lowering V_{ov}, optimizing S/N ratio	~ factor 2 less DCR
Increasing with the temperature ~x 2 every 7-10°C	Further lowering SiPM's T to **-45°C** using Thermoelectric coolers (TEC)	~ factor 2-3 less DCR
increasing with radiation damage	Annealing at room +40 °C during machine shutdown	~ factor 2 less DCR
	Noise filtering with signal processing technique DLED in TOFHIR	~ factor 2 lower σ_{DCR}

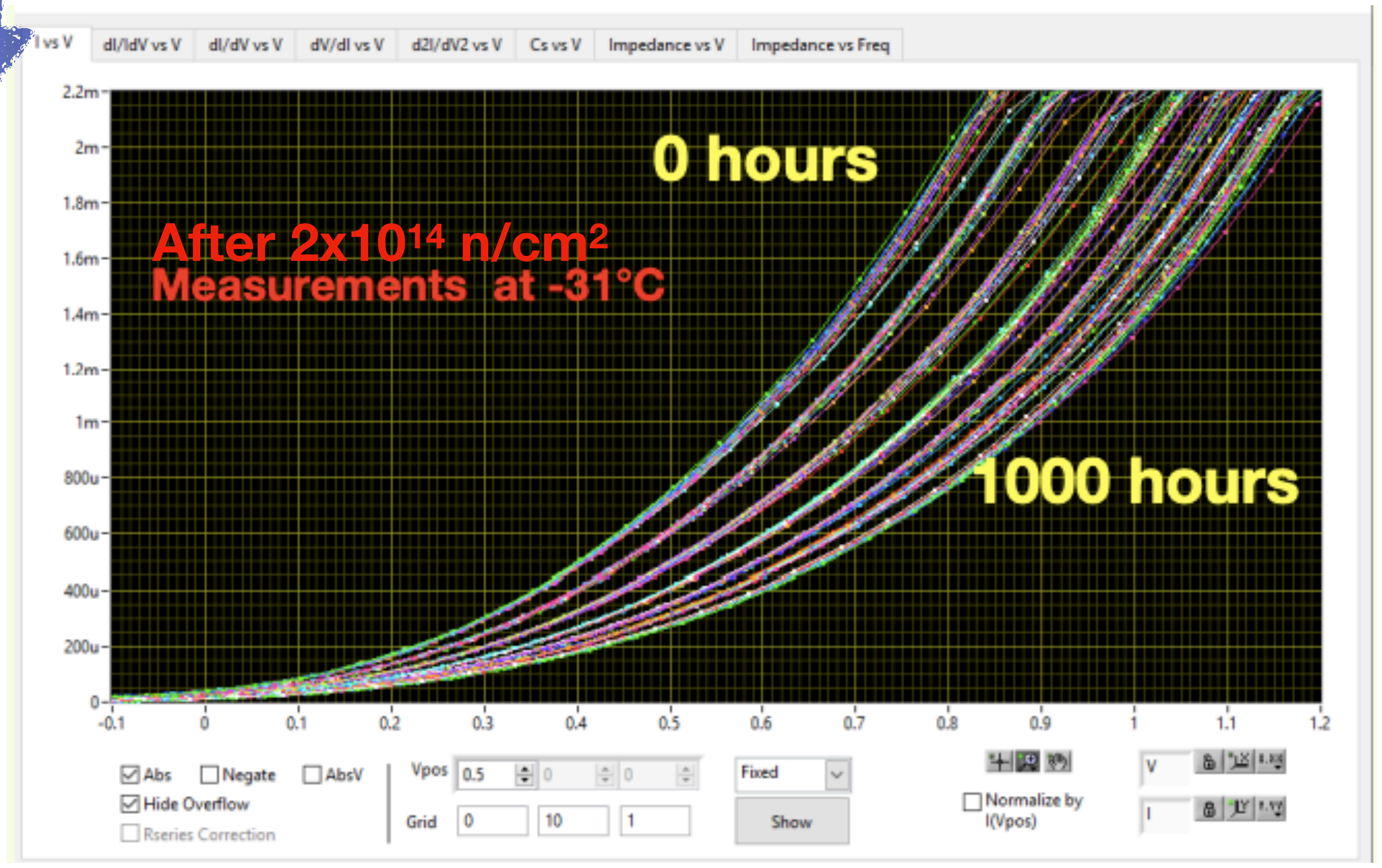


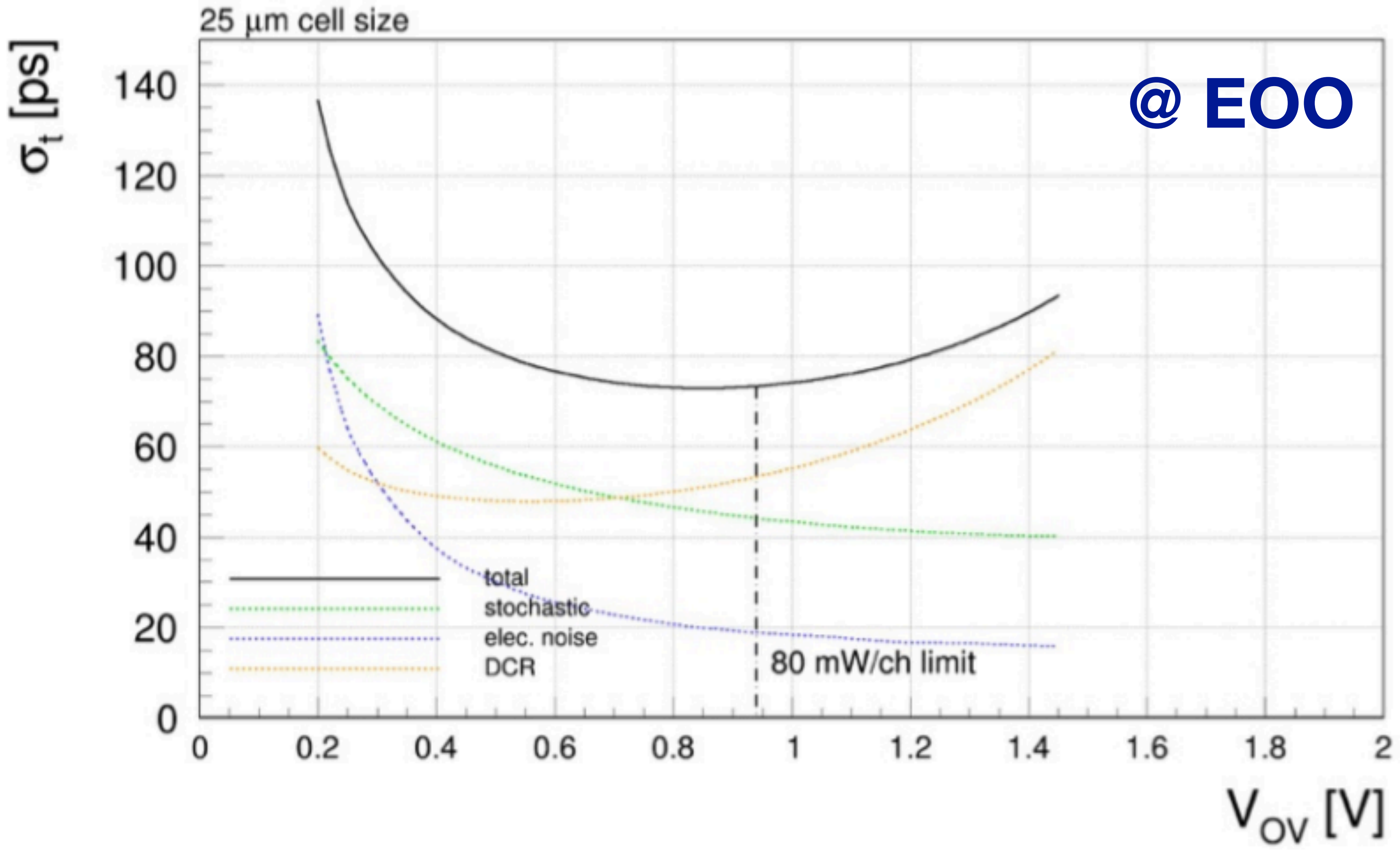


BTL performance evolution II

DCR FEATURE	ACTION	GAIN
Increasing with V_{ov}	Lowering V_{ov}, optimizing S/N ratio	**~ factor 2 less DCR**
Increasing with the temperature ~x 2 every 7-10°C	Further lowering SiPM's T to **-45°C** using Thermoelectric coolers (TEC)	**~ factor 2-3 less DCR**
increasing with radiation damage	Annealing at room +40 °C during machine shutdown	**~ factor 2 less DCR**
	Noise filtering with signal processing technique DLED in TOFHIR	**~ factor 2 lower σ_{DCR}**





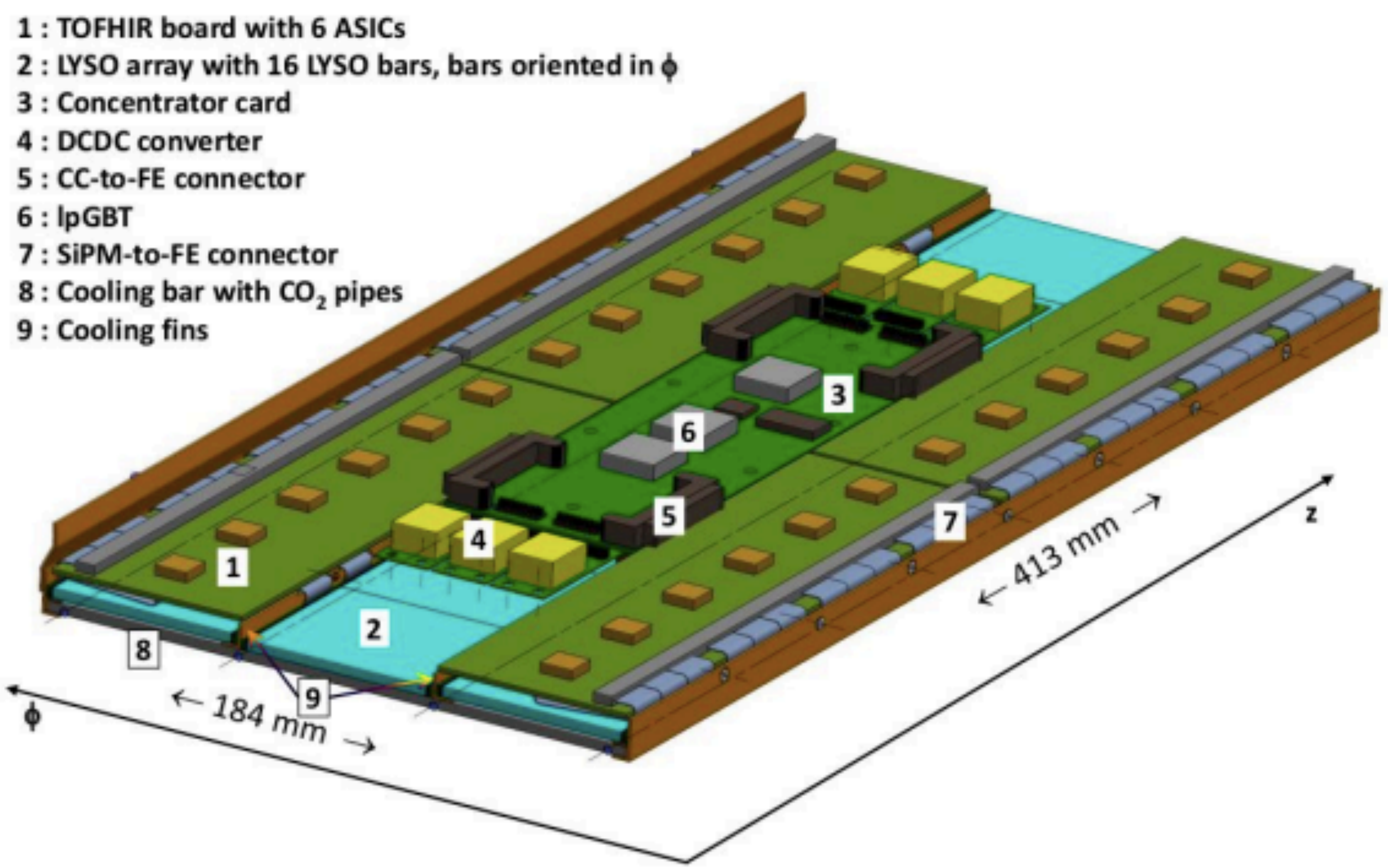


Conclusions

- CMS Mip Timing Detector (MTD) for Time aware charged particle tracking to help pileup mitigation during HL-LHC:
  - Recovering detector performance close to phase I level. Gain in several searches of the HL-LHC program.
  - Adding new capabilities to CMS, e.g. reconstruction of the time of displaced vertices for direct measurement of neutral LLPs mass.
- BTL target time resolution of 30 ps achieved during on beam characterization of unirradiated sensor prototypes.
- Sensor optimization is in progress to meet the TDR target EOO resolution (<70ps). Performance validation of optimised sensors expected in fall/beginning of next year
- In parallel, system tests are ongoing to validate the full electronics readout chain and thermal performance. Test of a fully populated readout unit successfully completed

BACK UP

BTL READOUT ELECTRONICS



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

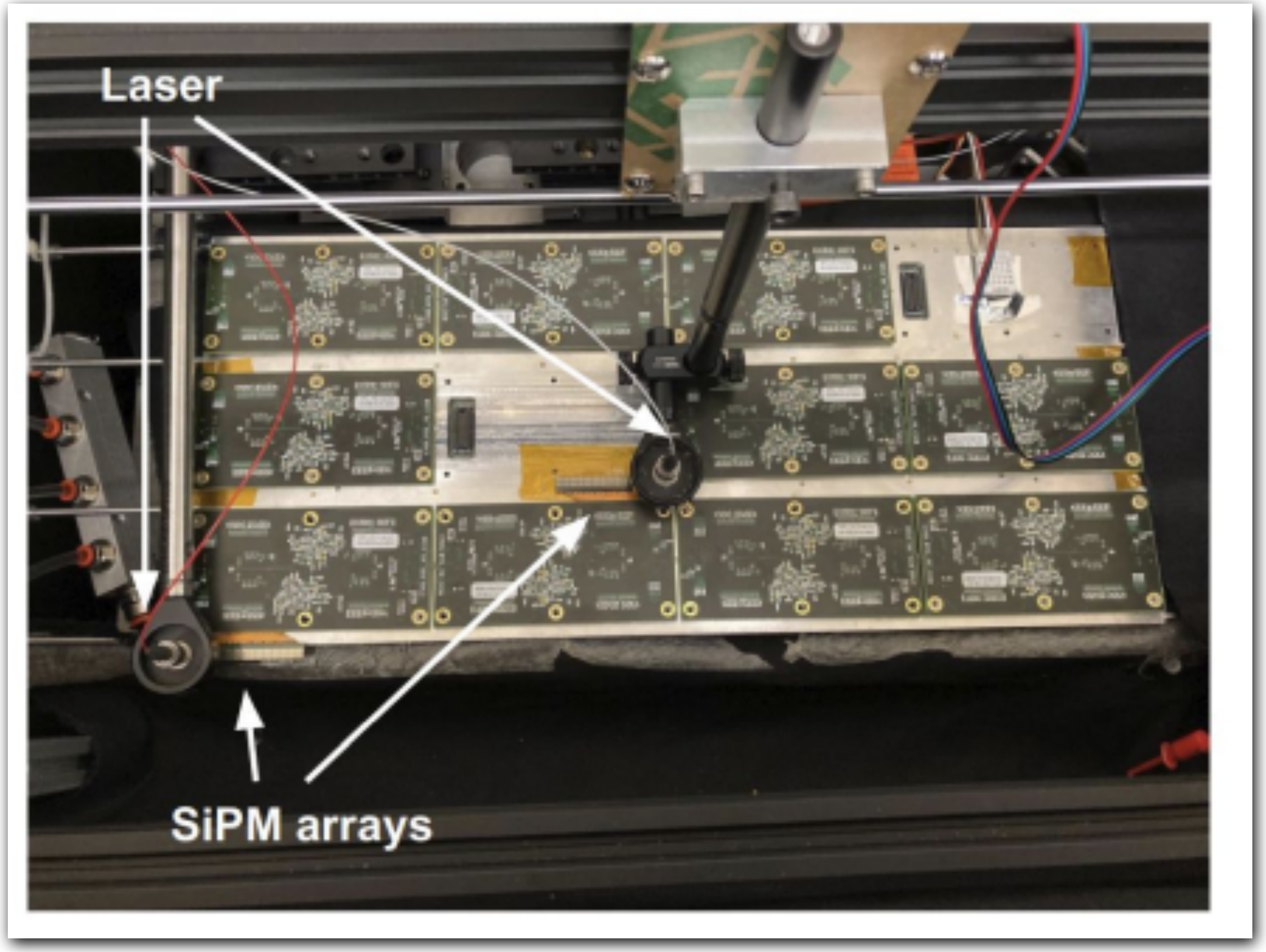
  - Discrimination of the leading edges
  - Time measurement with a TDC

- 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

READOUT UNIT TESTS



Almost fully populated readout unit (24 LYSO:Ce arrays) successfully tested.

- Good noise uniformity for different FE board
- No evidence of a dependence of the noise from the position on the Concentrator Card (CC)
- No evidence of a dependence of the noise term from the degree of population of the CC

multiple LYSO+SiPM assembled modules inside copper housings testing with UV laser on going