Precision Timing in the CMS MTD Barrel Timing Layer with Crystal Bars and SiPMs

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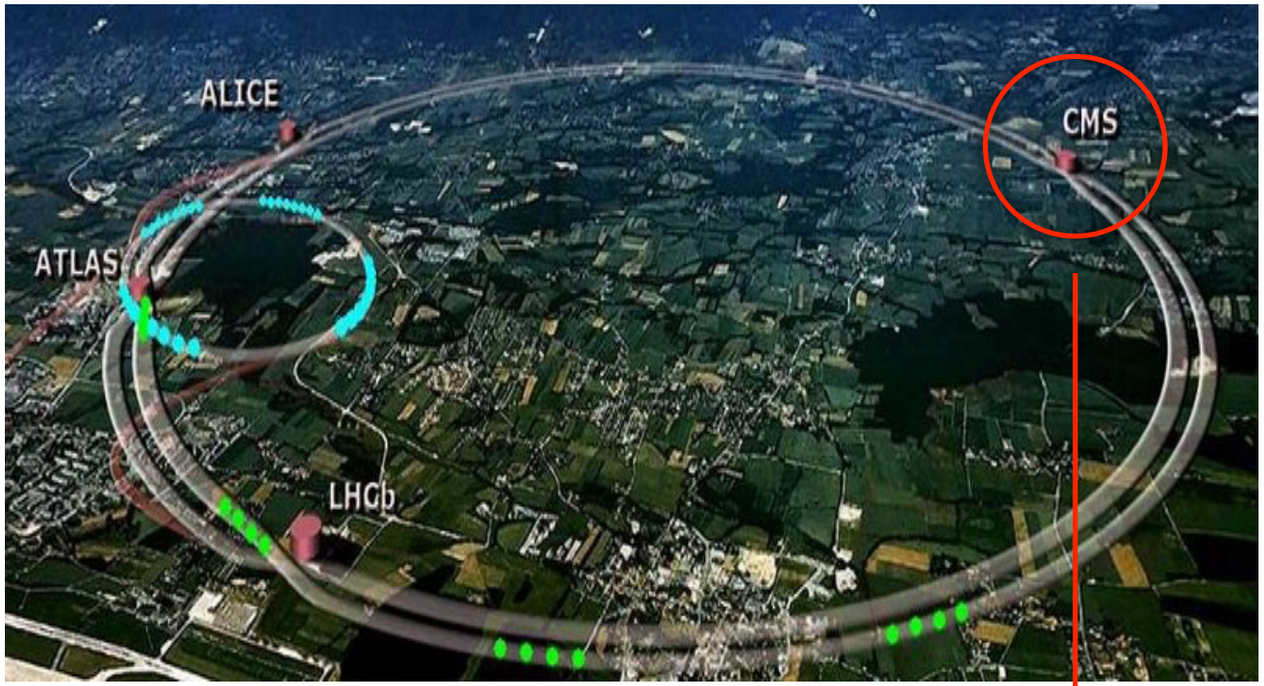
on behalf of the **CMS Collaboration**

SCINT2019 Conference, Sendai, Japan, 29 Sept. - 4 Oct. 2019

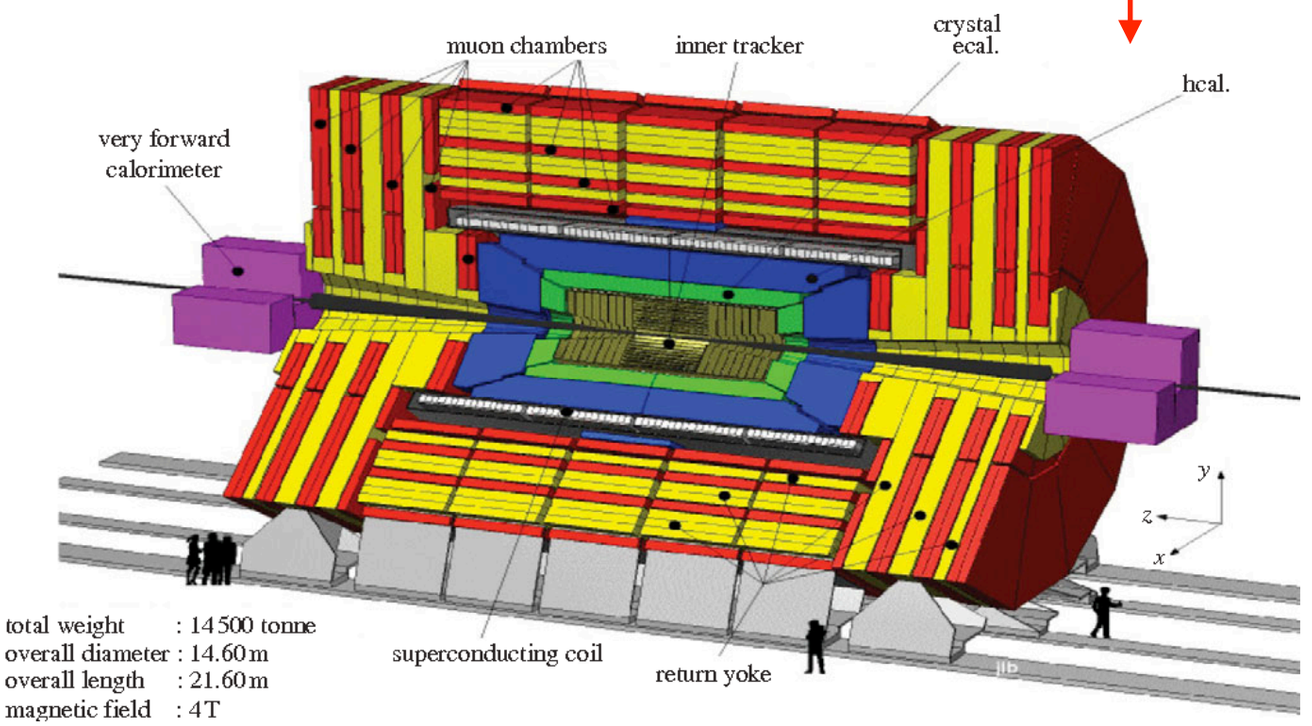
Large Hadron Collider and CMS

- LHC is the world's **largest and most powerful particle accelerator**
  - proton-proton collisions at 13 TeV
  - 4 experiments: ATLAS, ALICE, LHCb and **CMS**

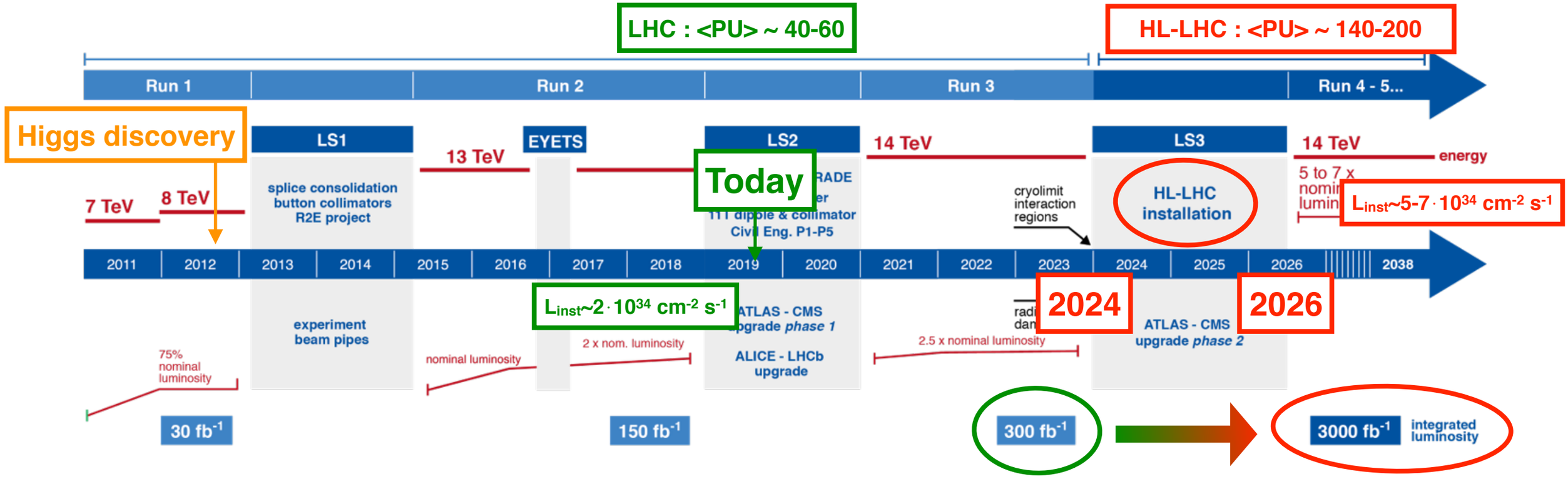


- Precise test of the Standard Model (SM) of fundamental interactions
  - e.g. Higgs Boson discovery and study of its properties

- Search for new physics beyond the SM
  - e.g. origin of dark matter in the universe, matter/antimatter asymmetry, neutrino masses



LHC and HL-LHC plans

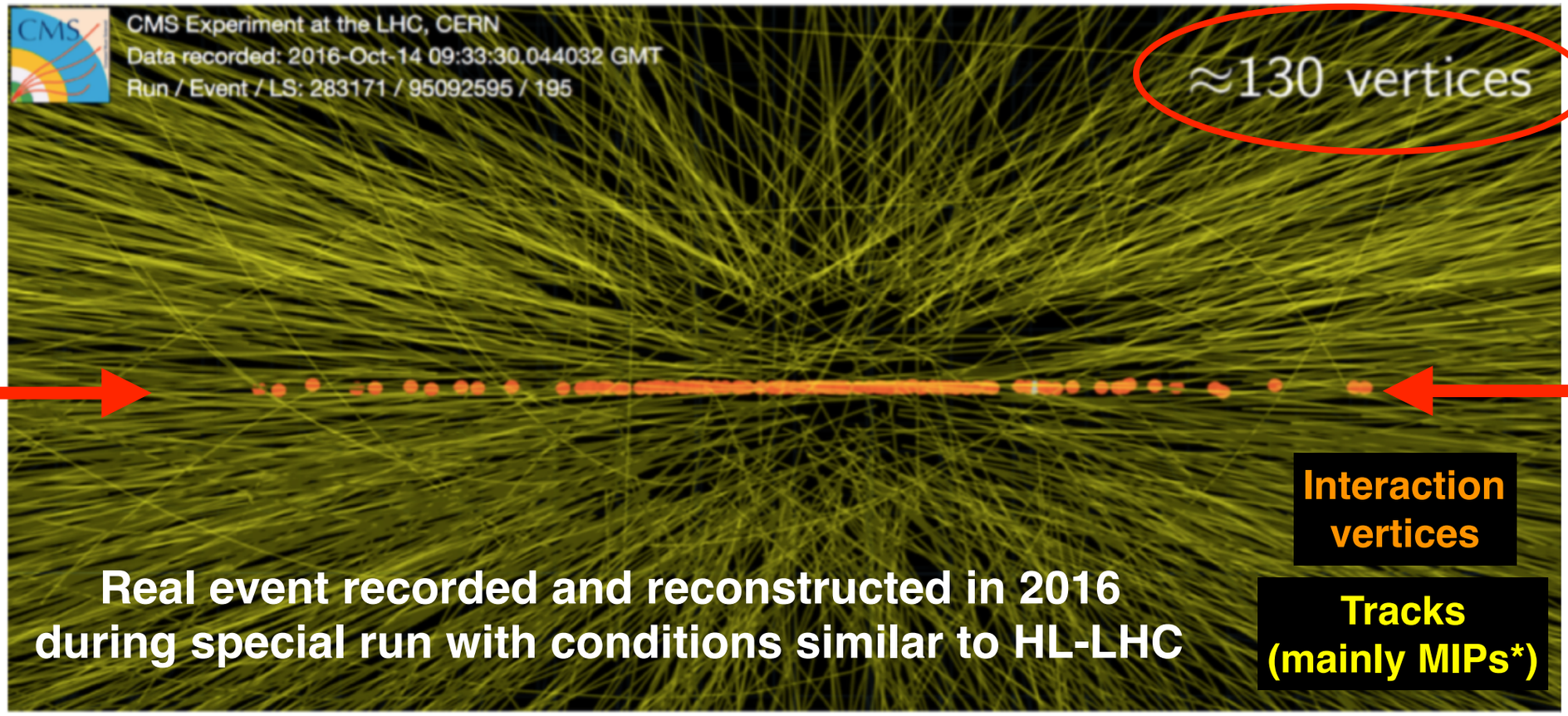


- HL-LHC: upgrade of LHC and injectors to increase instantaneous luminosity
  - 10X more data ⇒ **increased physics potential**
  - 5X more simultaneous pileup (PU) interactions
- CMS detector upgrade for HL-LHC conditions
  - sustain higher radiation levels
  - **mitigate impact on physics of higher pileup**

$$\frac{dN}{dt} \propto \mathcal{L}_{inst.} \times \sigma$$

rate of physics process | instantaneous luminosity | cross section of physics process

Example of HL-LHC pp collision



*Minimum Ionizing Particles

- Only **1 collision of physics interest** in >100 interactions simultaneously recorded every 25ns
- The rest are **pileup** interactions: **noise** for physics measurements

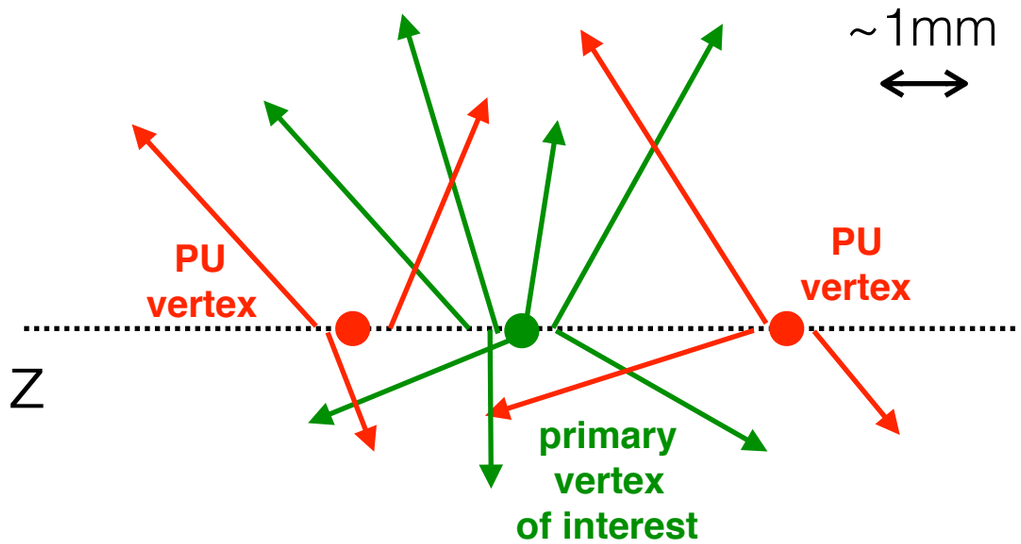
High Vertex Density at HL-LHC

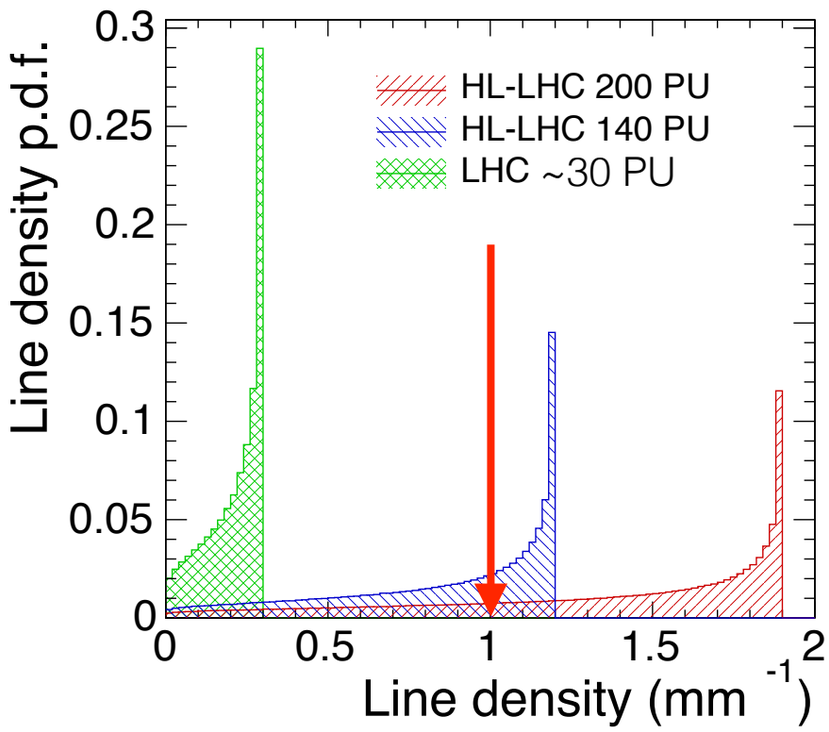
- Current global event reconstruction relies on track-vertex association <u>in space</u>
  - optimal z-cut at ~1mm for track-vertex compatibility

- At HL-LHC vertex density higher than 1 mm^{-1}
  - large number of **PU tracks incorrectly assigned** to primary vertex of interest
  - degradation in most event observables

- **Challenge**: keep current performance during HL-LHC phase
  - full physics program would benefit

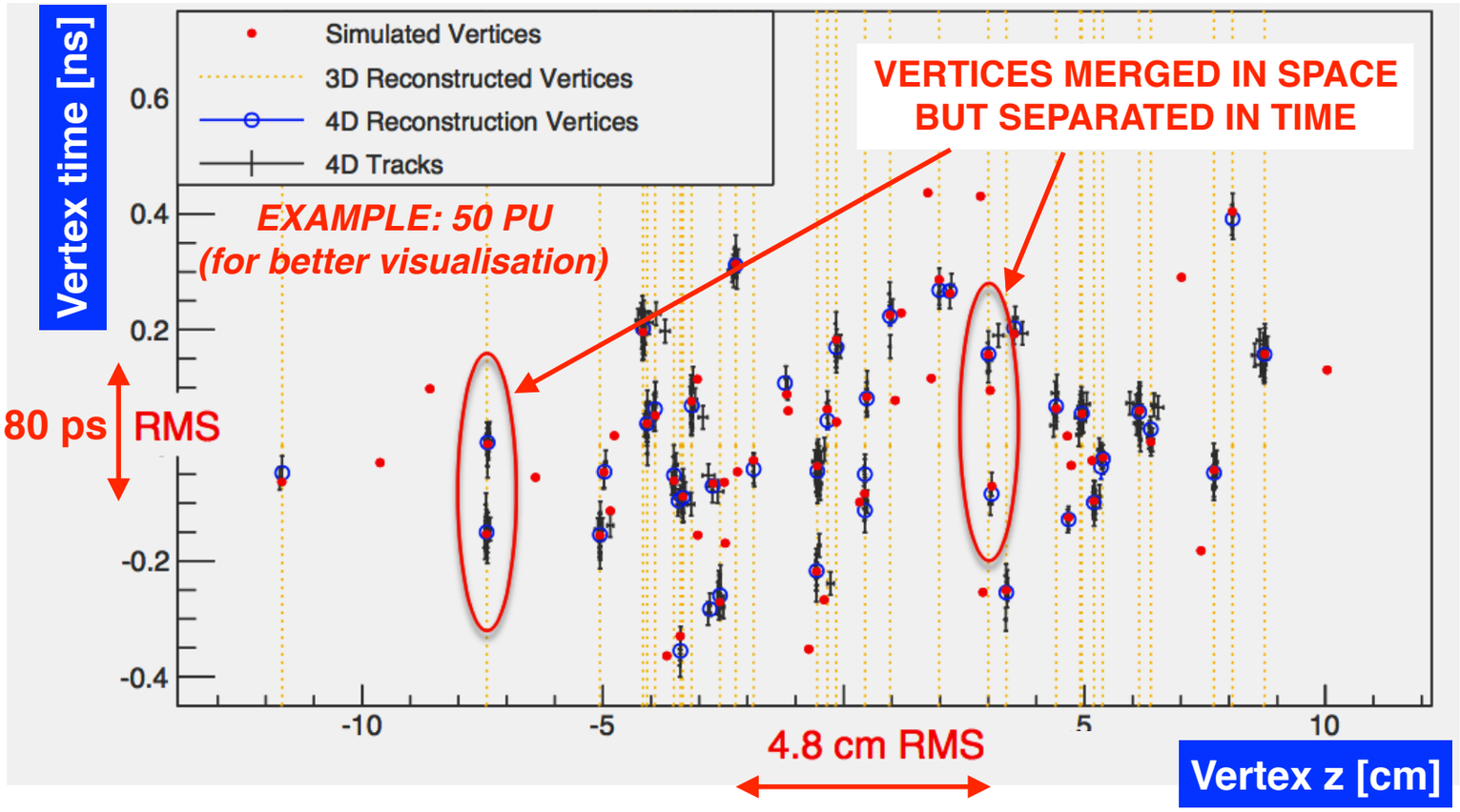
Example of track-vertex association





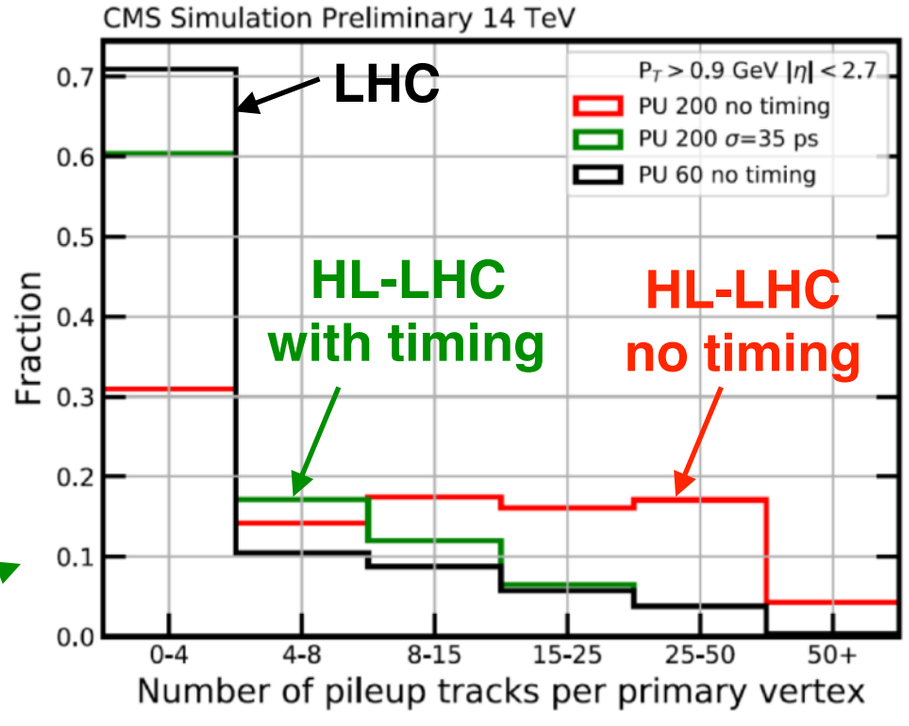
Precision Timing for Pileup Mitigation

Collision vertices within a bunch crossing



Basic Idea:
vertices merged in z
might be separated in time

PU tracks incorrectly associated to primary vertex of interest



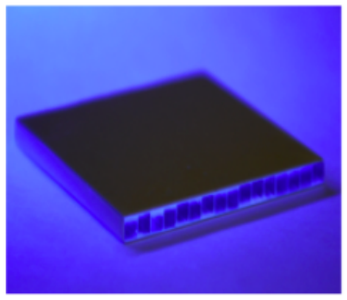
- Time spread of beam spot ~ 180 ps
  - better time resolution σ_t ⇒ better vertex separation
- **New detector** for MIP timing with **target resolution of 30-50 ps**
  - reduce pileup at HL-LHC ~ to current LHC levels

Design of the CMS Mip Timing Detector (MTD)

IN THIS TALK → **Barrel (BTL)**

BTL: LYSO bars + SiPM readout:

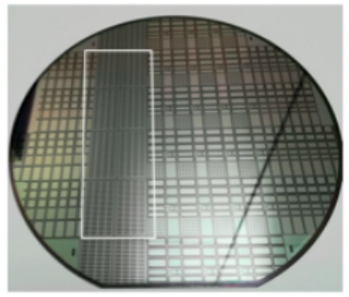
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2

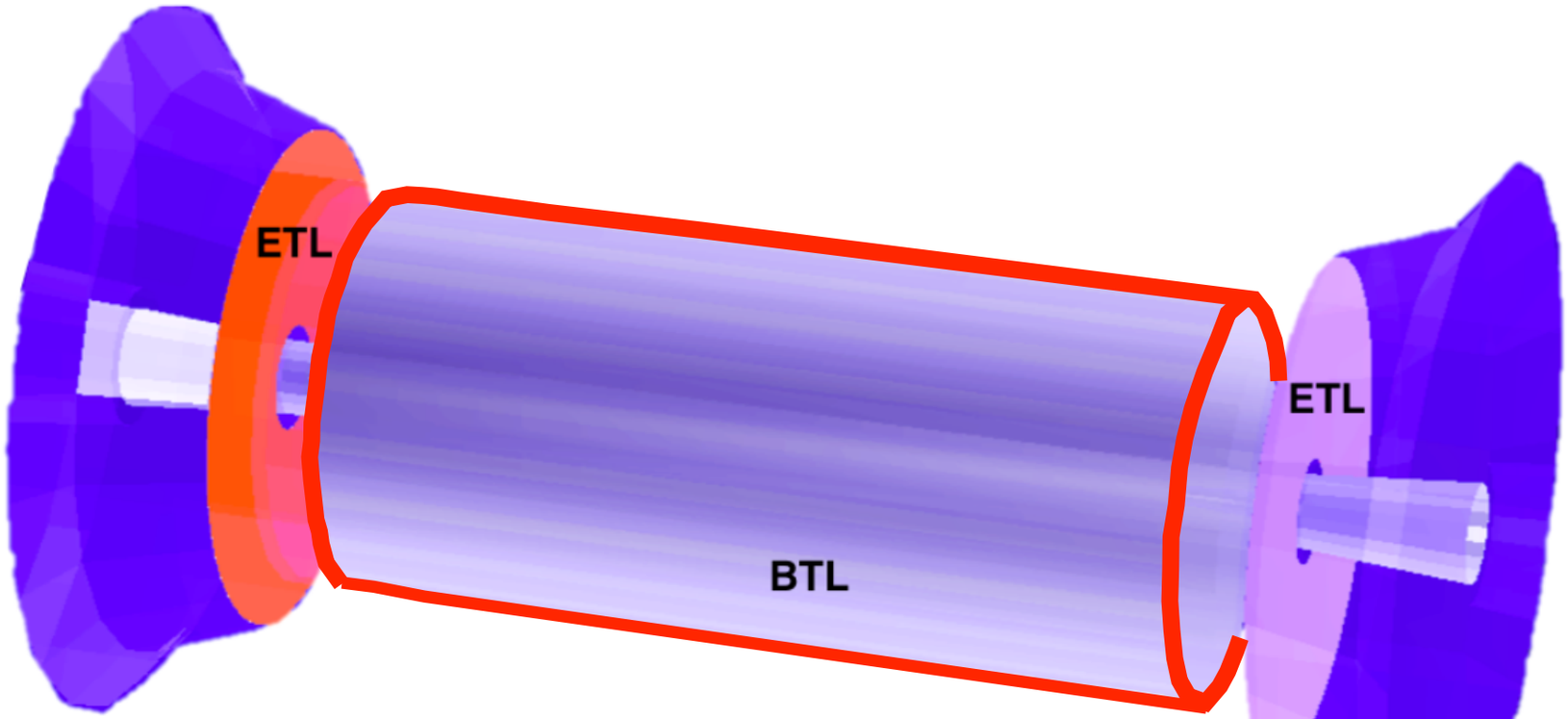


Endcaps (ETL)

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 $2x10^{15}$ n_{eq}/cm^2





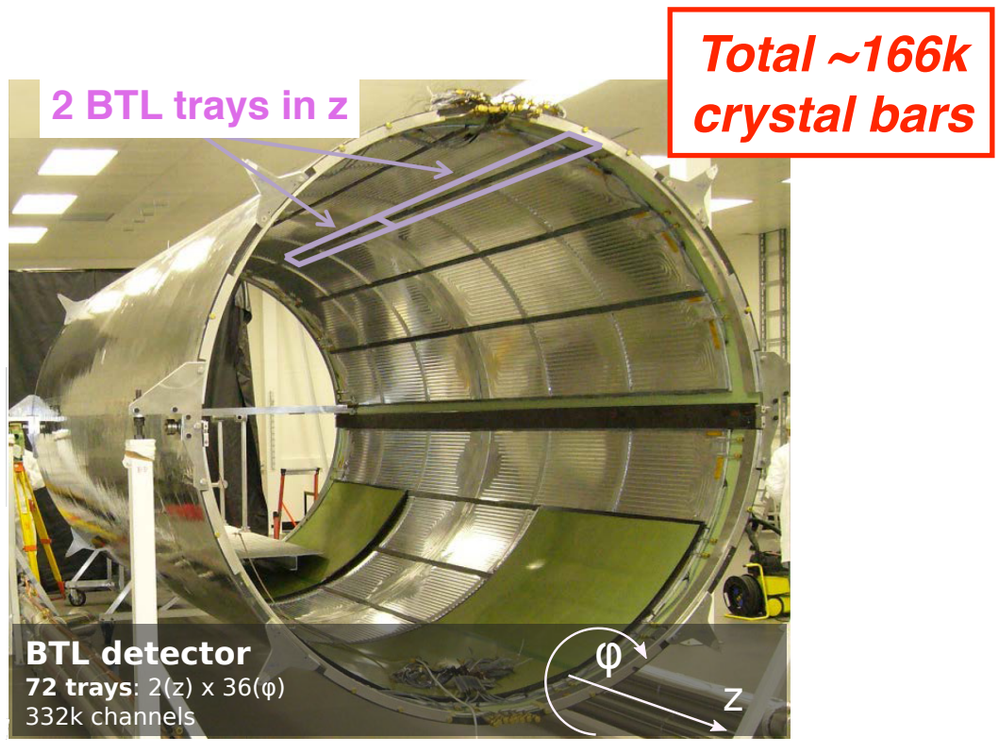
- ***Thin-layer between tracker and calorimeters***
- ***MIP sensitivity with time resolution of 30-50 ps***
- ***Hermetic coverage for $|\eta|<3.0$***

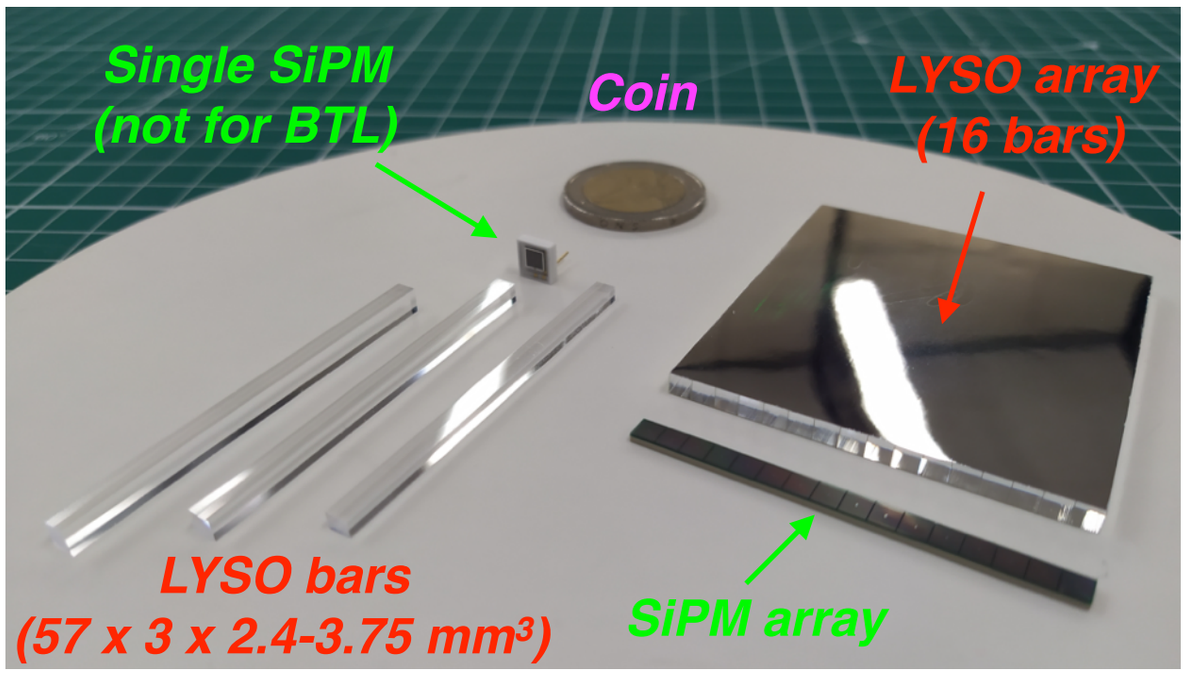
BTL Geometry and Sensors

- Cylinder (40mm-thin, ~1m radius) **integrated in tracker** support tube
  - share services and schedule with tracker

- **LYSO:Ce crystal bars** as scintillators
  - excellent radiation tolerance (no loss of transparency / light output at HL-LHC end)
  - dense (7.1 g/cm^3), bright (40k ph/MeV)
  - fast: rise time (~100 ps), decay time (~45 ns)

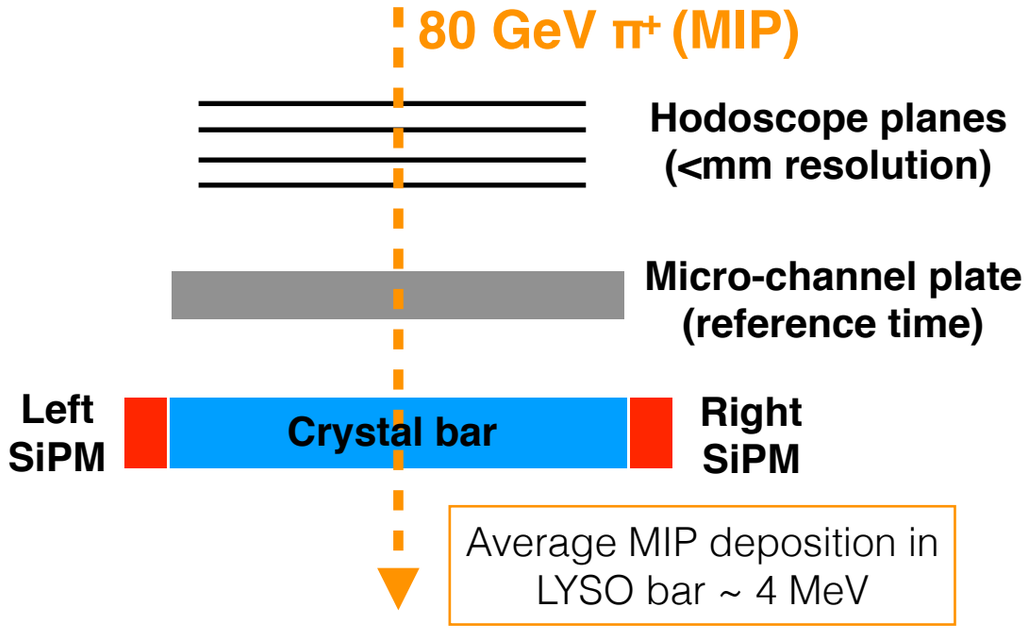
- **Silicon Photomultipliers** as photo-sensors (one SiPM per bar side)
  - compact, insensitive to magnetic fields, fast
  - good radiation tolerance
  - photo detection efficiency (PDE) at LYSO emission peak of 420 nm: 20-40%

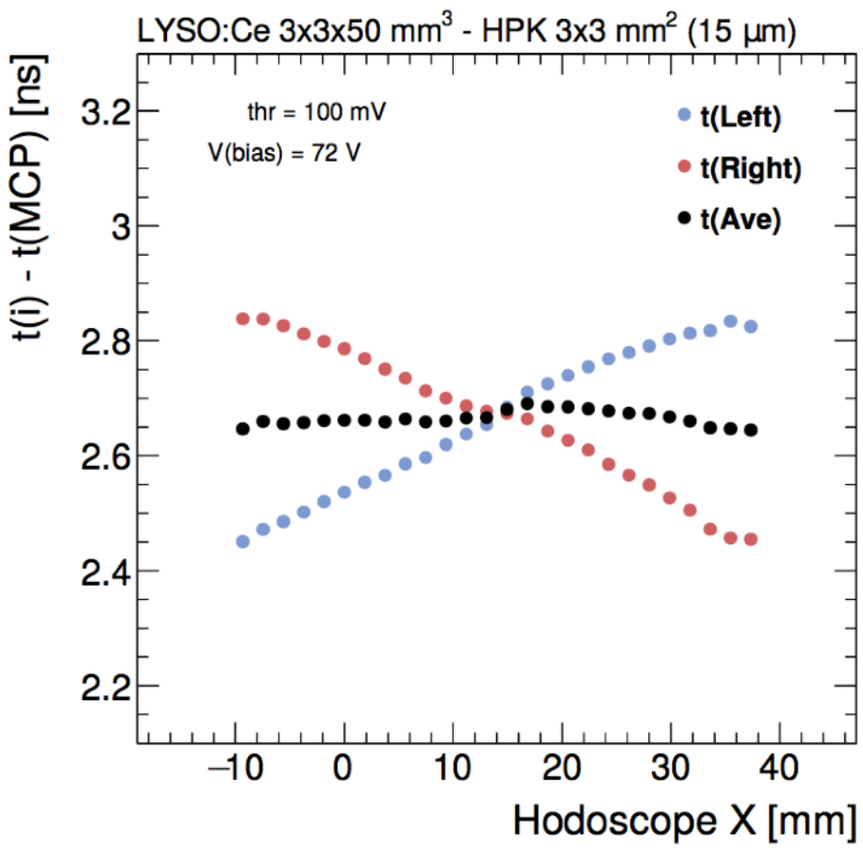


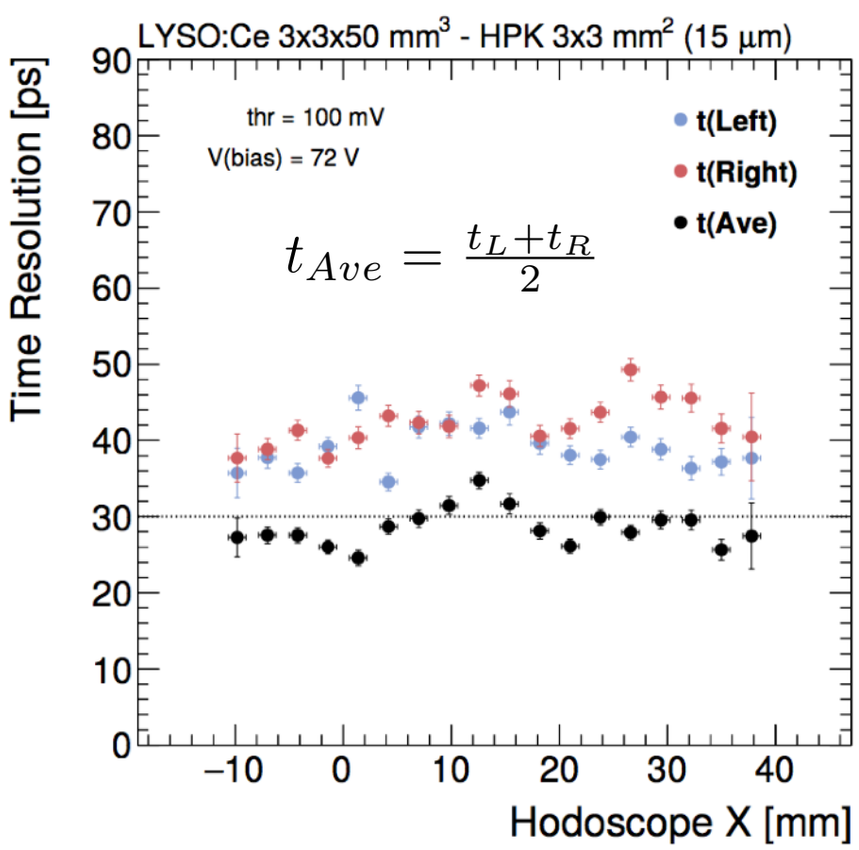


Test Beam Results

- Extensive R&D campaigns to prove target resolution
- Signal arrival time on SiPM proportional to distance
  - sensitive to light propagation in the bar
  - time difference: impact point along bar with <5 mm resolution
- Combination of two uncorrelated SiPMs per LYSO bar
  - **uniform time response** and **improved resolution (<30 ps)** across bar length





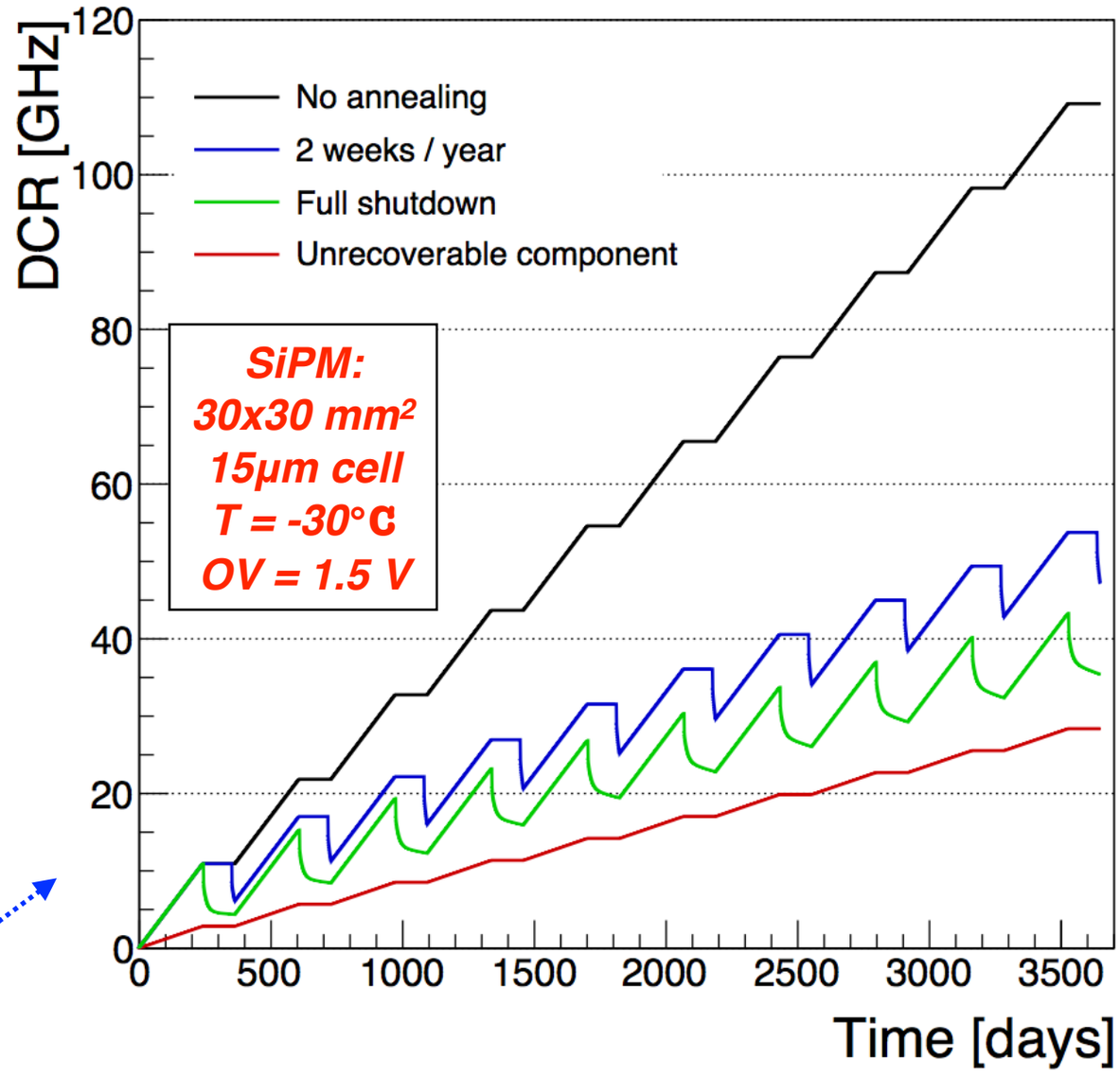


30 ps
TARGET RESOLUTION

Radiation Damage on SiPMs

- **Radiation creates defects in Si**
  ⇒ increase probability of thermal electron emission
  ⇒ Dark Current Rate (DCR)
  - increases power consumption
  - degrades time resolution

- DCR noise mitigation by
  - CO_2 cooling at -30°C
  - annealing of SiPMs at room temperature during shutdowns
  - lower SiPM bias voltage during operation



~3.5 V Decreasing OV=V_{bias}-V_{break} ~1.2 V

30-40% Decreasing PDE 15-20%

Timing Resolution

- **Timing resolution will degrade** with HL-LHC integrated luminosity
  - Photostatistics and noise terms dominate

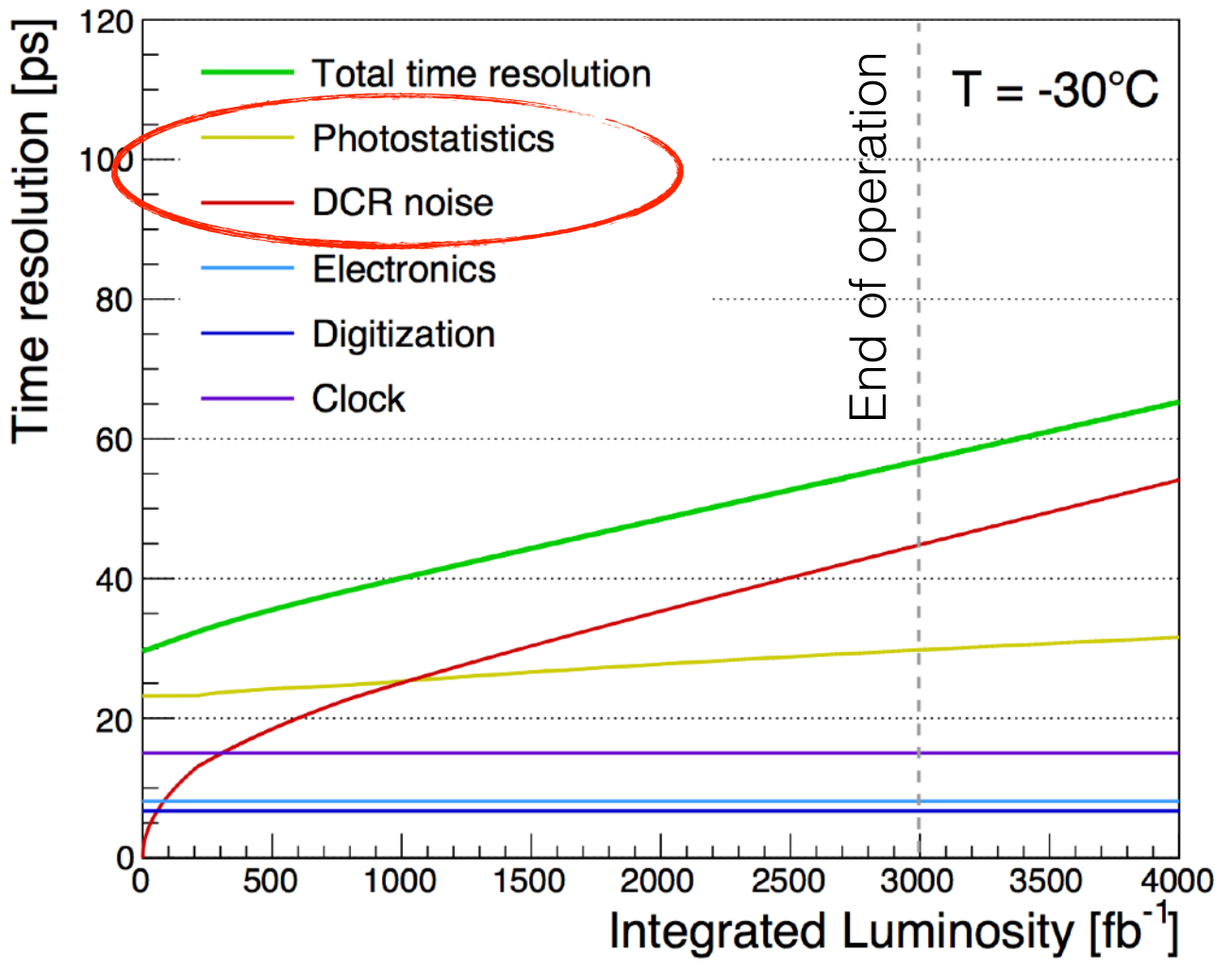
$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_{rise}\cdot\tau_{decay}}{N_{pe}}} \propto \sqrt{\frac{\tau_{rise}\cdot\tau_{decay}}{E_{dep}\cdot LY\cdot LCE\cdot PDE}}$$

$$\sigma_t^{DCR} \propto \frac{\sqrt{DCR}}{N_{pe}} \propto \frac{\sqrt{DCR}}{E_{dep}\cdot LY\cdot LCE\cdot PDE}$$

*LCE = Light Collection Efficiency

- Main properties to characterise quality of LYSO crystals
  - light output (LY · LCE)
  - rise time (τ_{rise})
  - decay time (τ_{decay})

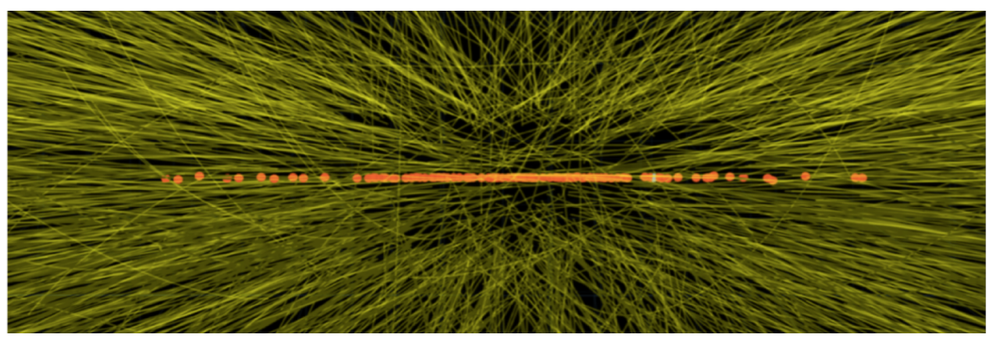
Expected evolution vs L_{int}



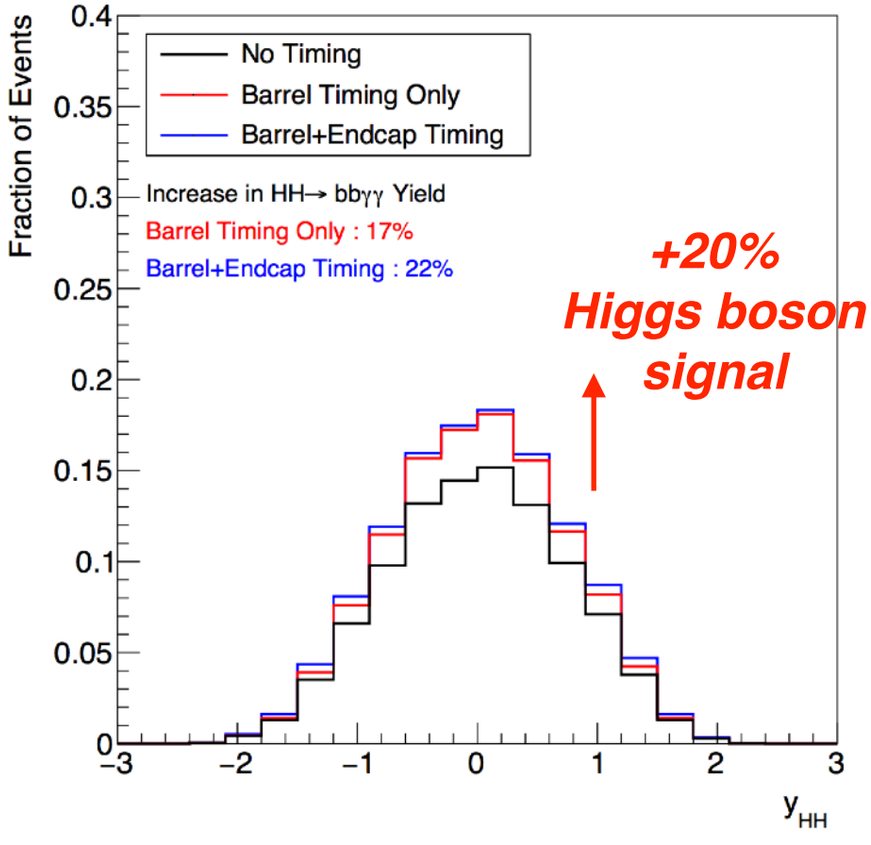
✤ **Time resolution between 30 and 60 ps during HL-LHC**

Outlook

- CMS upgrade for HL-LHC: new **MTD timing detector for charged particles**
  - target: 30-50 ps time resolution, hermetic coverage
- **Full** CMS physics program would benefit
  - mitigate harsh pileup conditions at HL-LHC
  - +20-30% effective luminosity
  - TOF particle ID, new searches for long lived particles
- Barrel Timing Layer: **LYSO:Ce crystal bars** with **SiPM** readout
  - well-established technologies thanks to past R&D
  - quality control on crystals and SiPMs from various vendors ongoing
- **MTD Technical Design Report** will be released in <u>few weeks</u>



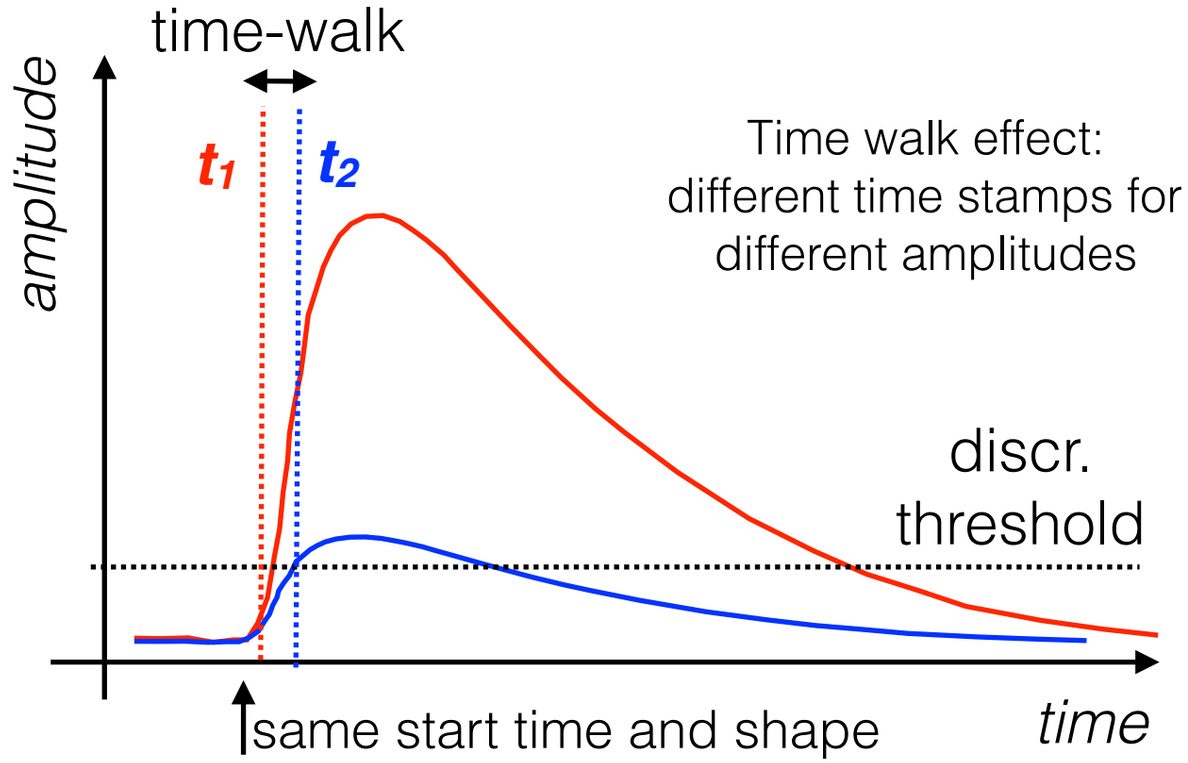
HH → bbγγ (200 Pileup Distribution)



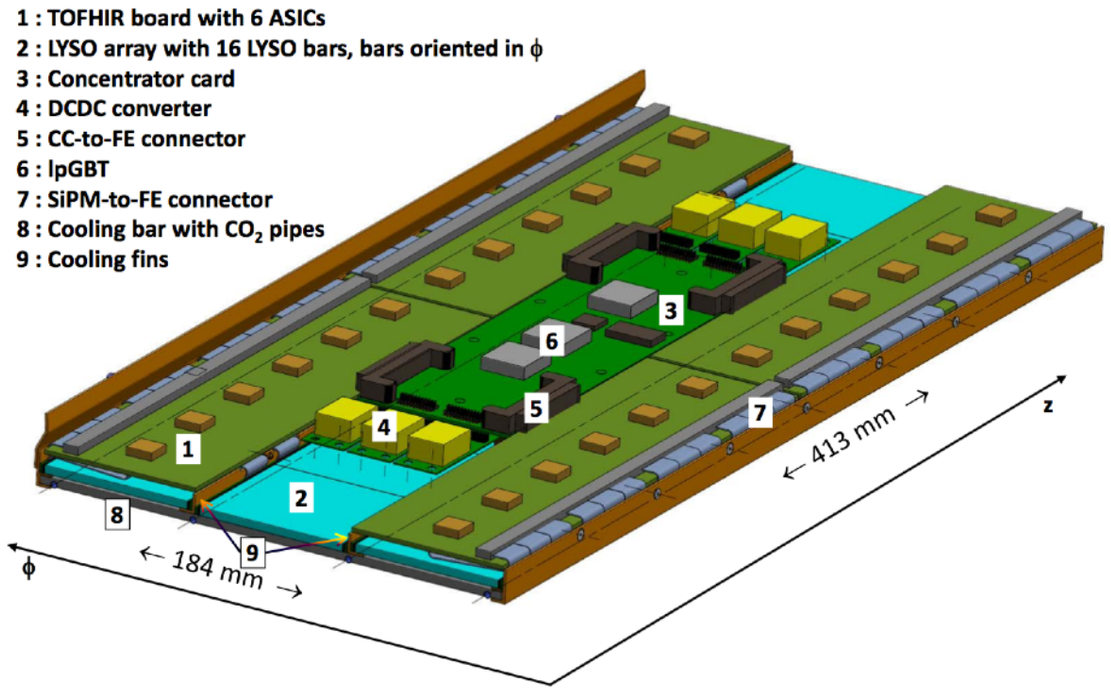
BACKUP

BTL Front-End Electronics

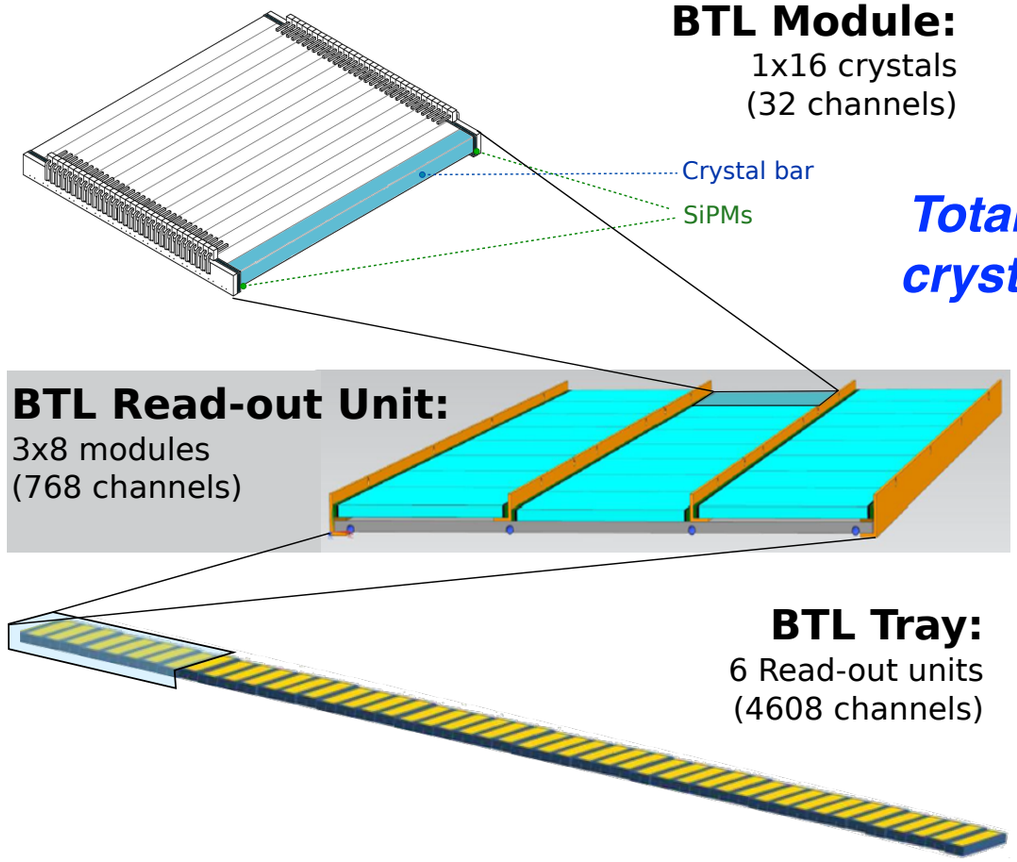
- Readout Electronics ASIC: TOFHIR2
  - based on TOFPET2 board used in LYSO TOF-PET applications
  - **fast**, adapted for **higher rates** and **radiation-hard**
  - leading-edge discriminator + TDC ⇒ time-stamp
  - amplitude measurement from QDC ⇒ time-walk correction
- Each board has 6 ASICs
  - each ASIC reads 32 SiPMS
- Testing of final prototypes in 2019-2020



Time walk effect: different time stamps for different amplitudes



BTL Geometry



- 40mm-thin cylinder, **integrated in tracker** support tube
  - sharing services and schedule with tracker detector
  - cannot be removed or serviced during entire lifetime of HL-LHC

- To cope with schedule/accessibility/ costs, use sensor technologies well-established and experienced by CMS
  - **array of LYSO:Ce crystal bars** (57 x 3 x 2.4-3.75 mm^3) oriented along φ direction
  - readout by **2 SiPMs** (one per bar side)