Precision Timing Detectors at Hadron Colliders

PRISMA+ Colloquium

Mainz

Adi Bornheim

Caltech

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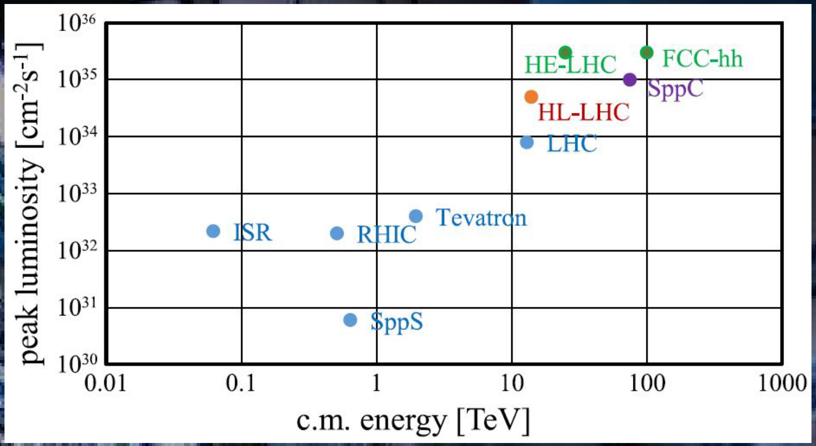
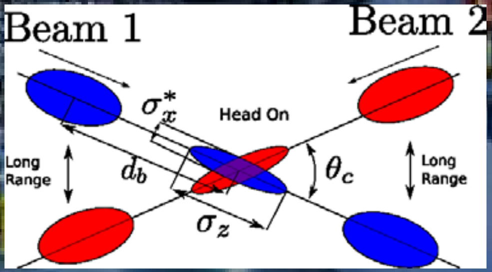
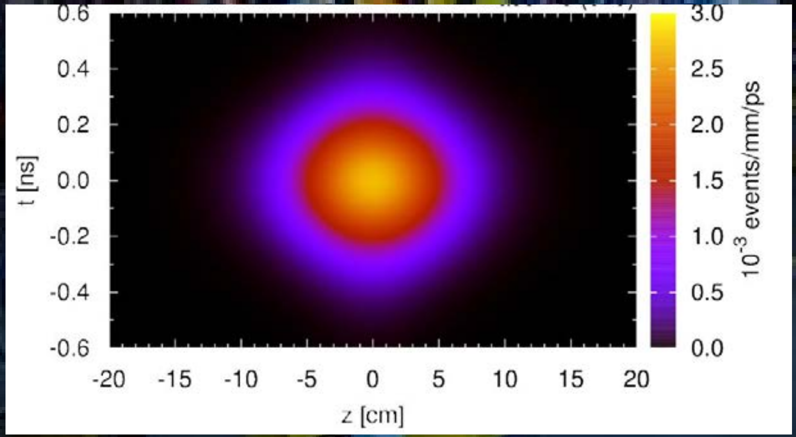
Hadron Colliders

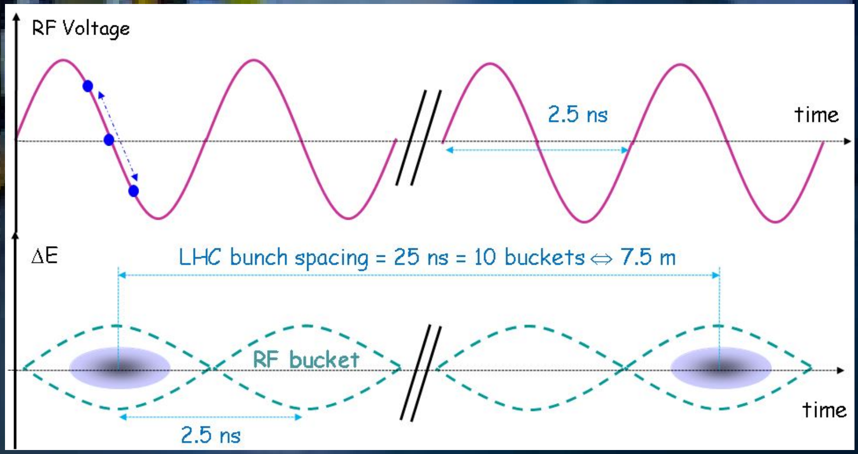
- Tool of choice at the “energy frontier” in particle physics.
  - Discovery reach driven by CM energy, high luminosity important too.
  - At LHC : Also precision physics, HI physics, …



- Technology implies that “luminous region” has macroscopic dimensions.
  - At LHC : Particle collisions spread out over a region of about 20 cm - 180 ps.

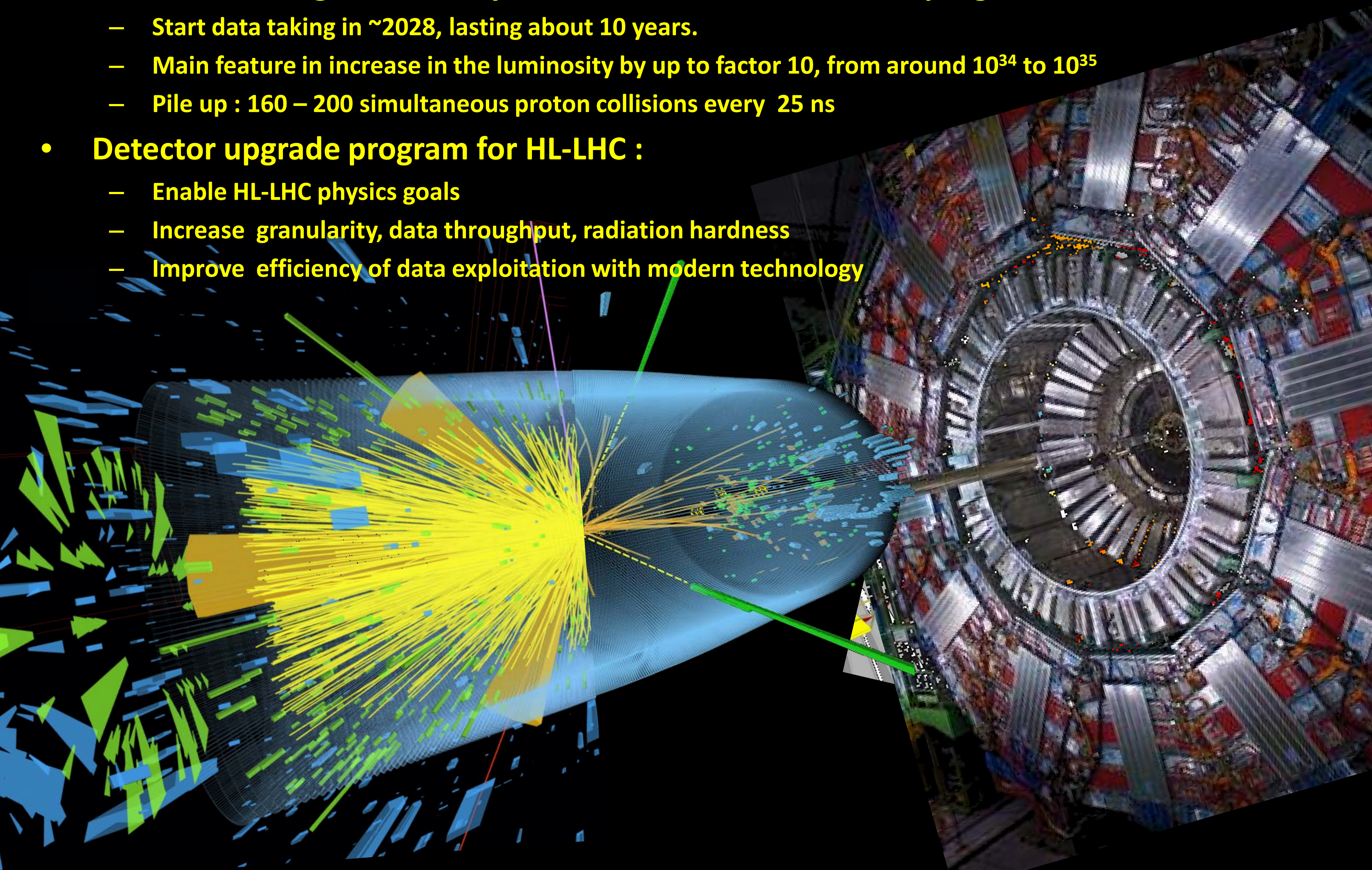






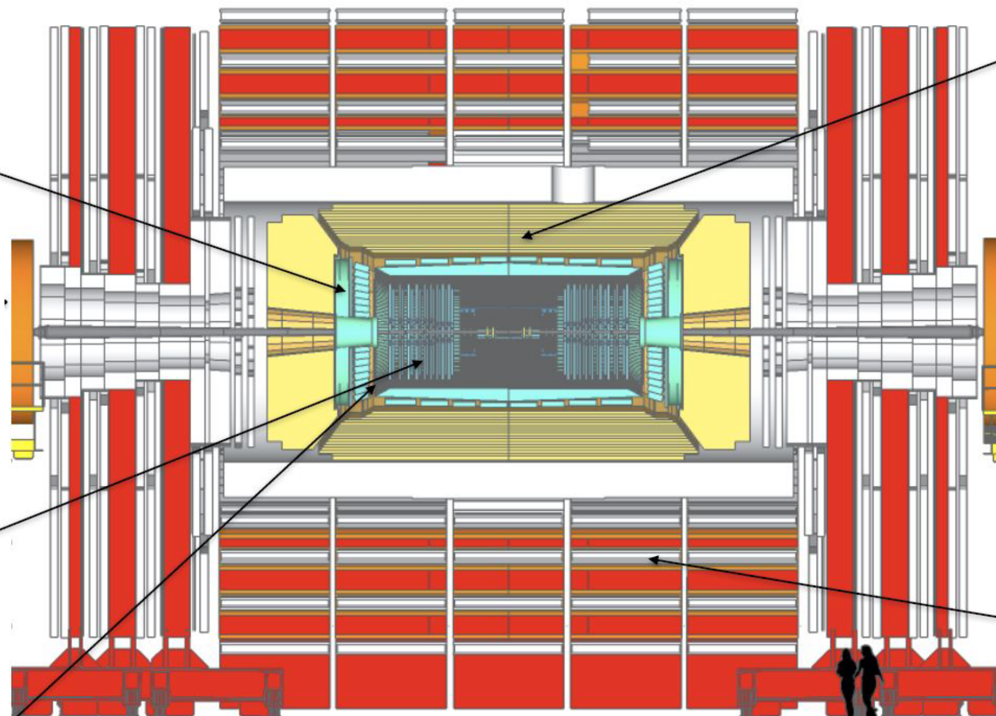
HL-LHC & Phase 2

- HL-LHC is the high luminosity extension of the current LHC program.
  - Start data taking in ~2028, lasting about 10 years.
  - Main feature in increase in the luminosity by up to factor 10, from around 10^{34} to 10^{35}
  - Pile up : 160 – 200 simultaneous proton collisions every 25 ns
- Detector upgrade program for HL-LHC :
  - Enable HL-LHC physics goals
  - Increase granularity, data throughput, radiation hardness
  - Improve efficiency of data exploitation with modern technology

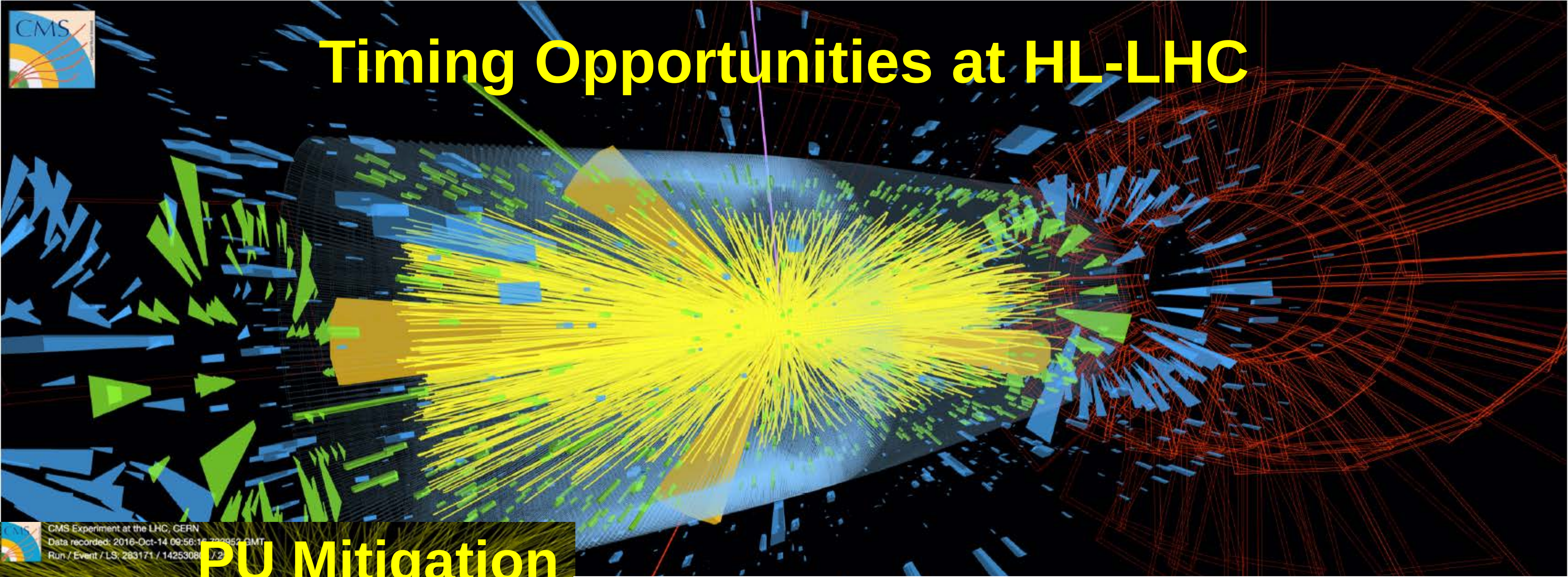


CMS Detector & Phase 2 upgrades

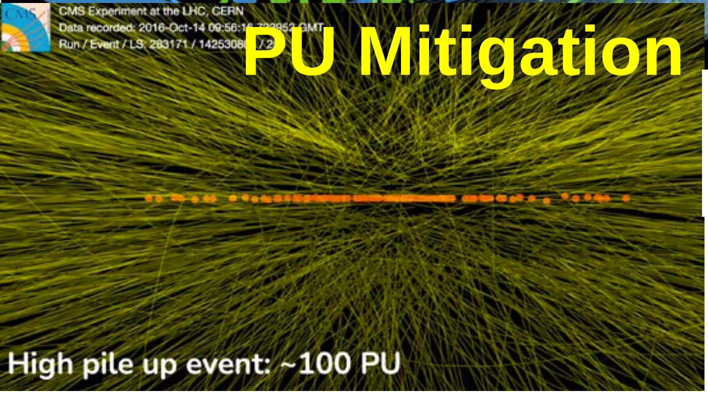
- 15 m / 50 ns tall, 23 m / 77 ns long
- Calorimeters will have precision timing
- Dedicated MIP timing detector
- Trigger will have (some) precision timing information

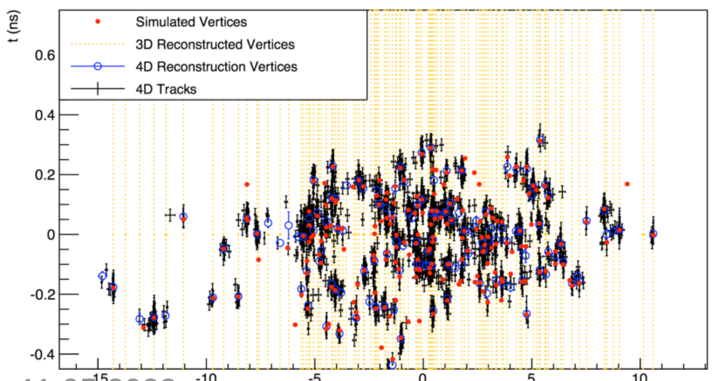


Timing Opportunities at HL-LHC

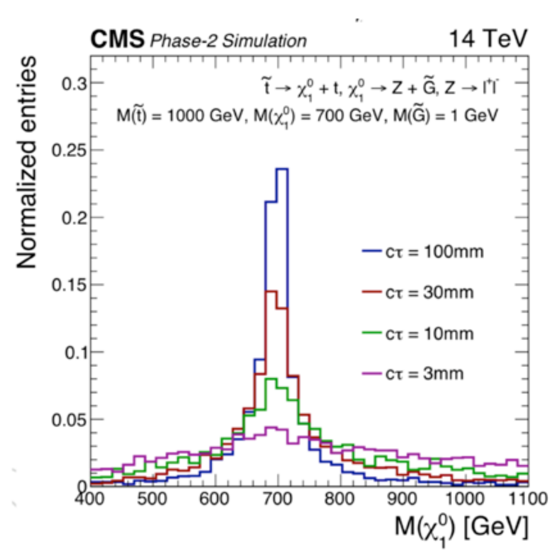


PU Mitigation

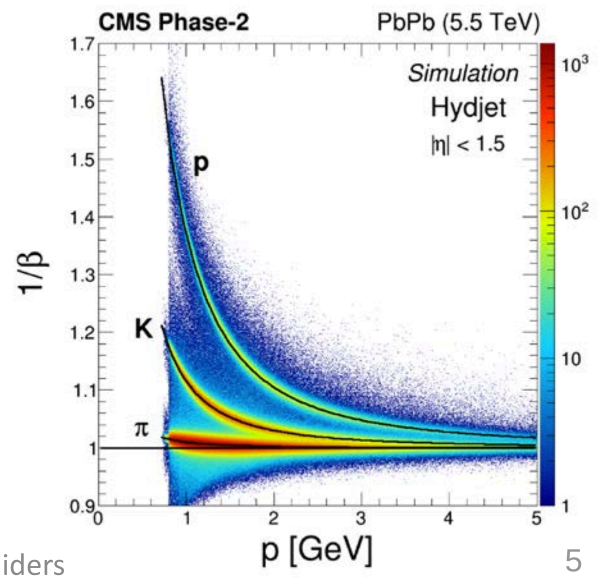




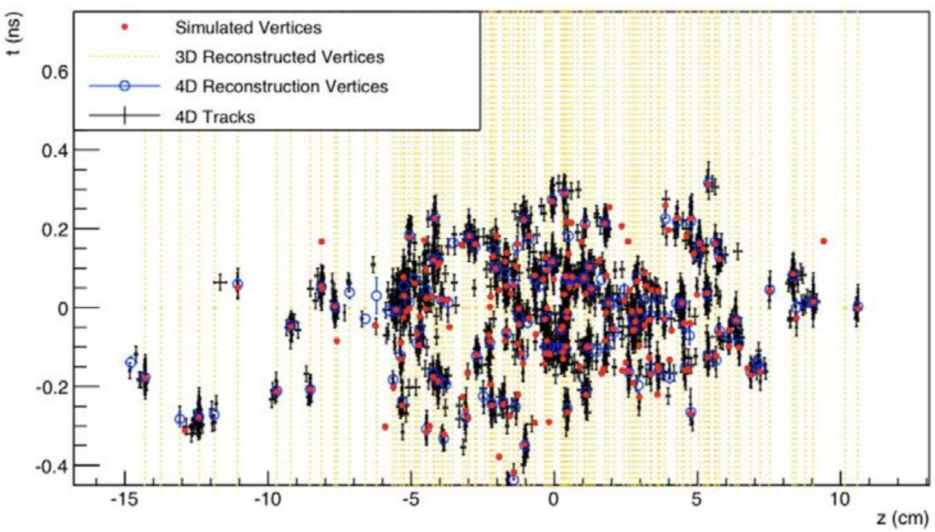
New physics reach



Improved reconstruction



- At high PU, density of tracks in space increases wrong assignment of low-pT tracks to vertices.
- Time tagging tracks, enable 4D reconstruction of vertices.
- Assign tracks and physics objects to their proper vertices, enhancing reconstruction.
- Utilizing timing from MTD, not yet from calorimeters.
- Not yet utilizing advanced reconstruction techniques.



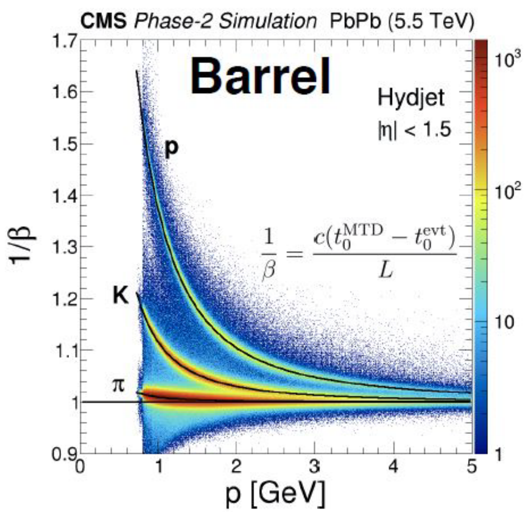
HH production sensitivity (sigmas) at 3 ab^{-1}

Channel	No MTD	$\langle\sigma_t\rangle$ 35 ps	$\langle\sigma_t\rangle$ 50 ps	$\langle\sigma_t\rangle$ 70 ps
bbbb	0.89	0.95	0.94	0.93
bbττ	1.3	1.58	1.48	1.44
bbγγ	1.7	1.85	1.83	1.81
bbWW	0.53	0.579	0.576	*0.53(*)*
bbZZ	0.38	0.423	0.418	*0.38(*)*
Combined	**2.4**	**2.71**	**2.63**	**2.57**
Luminosity gain	-	+26%	+20%	+14%

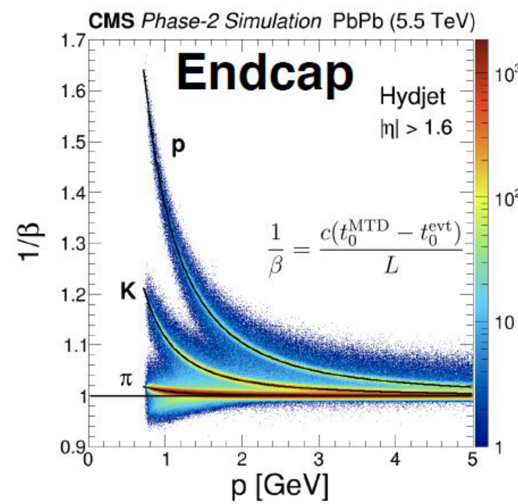
Improved Reconstruction

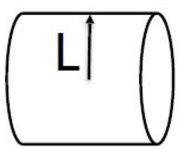
- **Improved particle ID, extending usable range to higher pT compared to Tracker.**

CERN-LHCC-2019-003

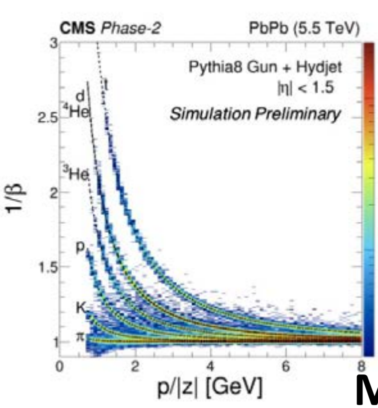


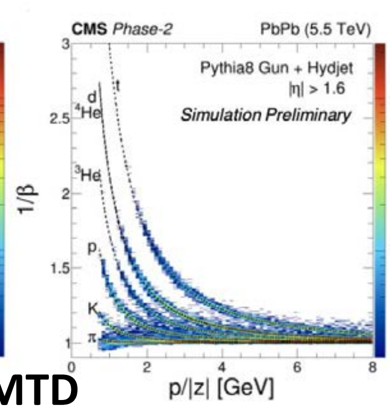
MTD



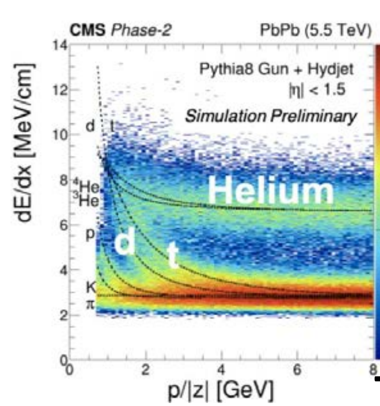


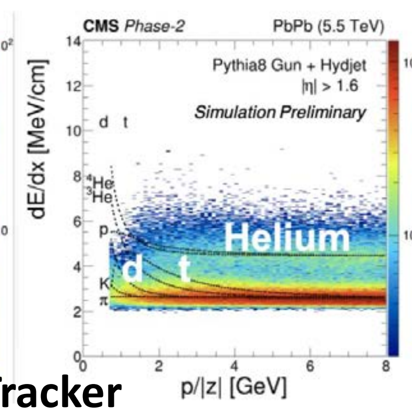
Experiment	η coverage	r (m)	σ_T (ps)	r/σ_T (x100) (m x ps^{-1})
CMS	IηI < 3.0	1.16	30	3.87
ALICE	IηI < 0.9	3.7	56	6.6
STAR	IηI < 0.9	2.2	80	2.75





MTD

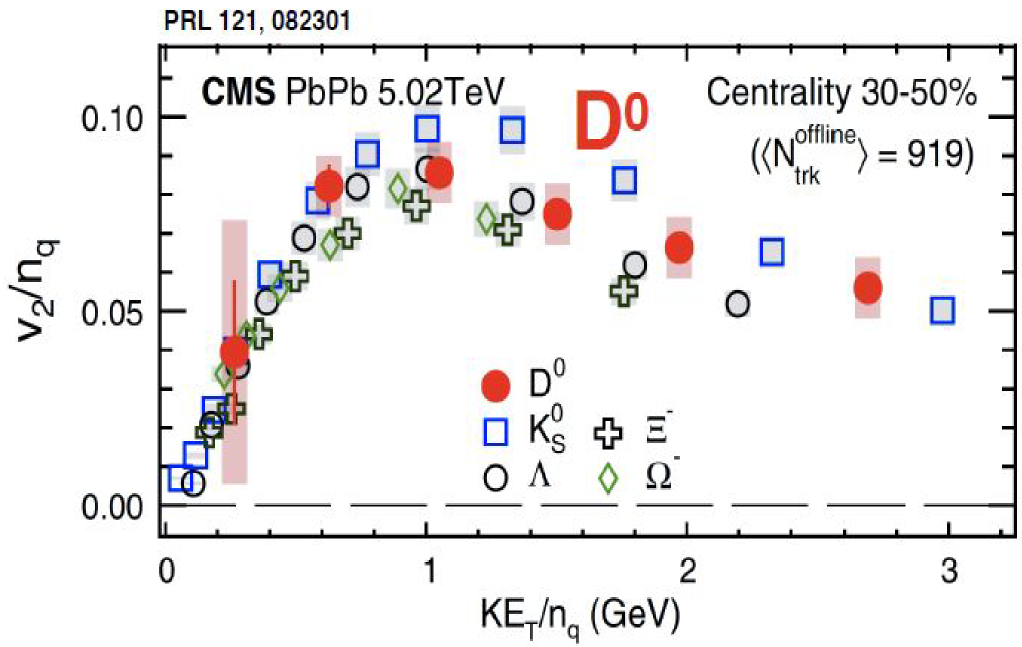


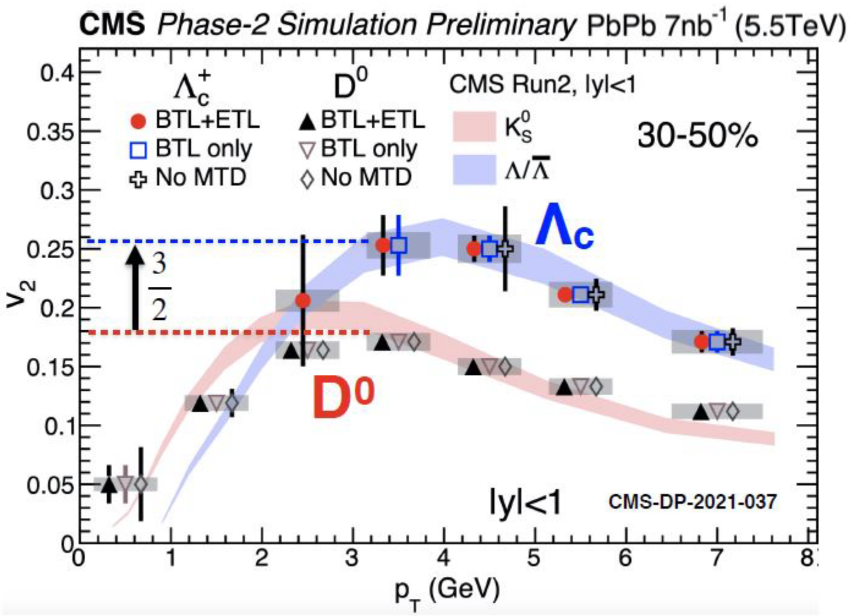


Tracker

Impact on HI physics

- **Physics application of PID in Heavy Ion physics : Measurement of v2.**
- **Extended acceptance from MTD**



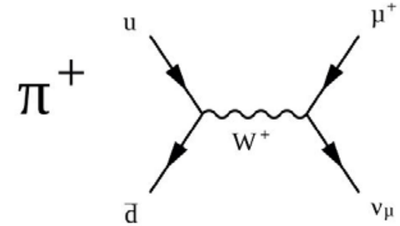


- MTD will allow to derive the v_2 of charm baryons and to measure precisely the N_q-scaling of v_2 in the charm quark sector:

$$v_2(\Lambda_c) = \frac{3}{2}\, v_2(D^0)?$$

Long Lived Particles

- **Long lived particles (LLPs) are an area of intense activity on searches at LHC.**
- **Long live times can be due to :**



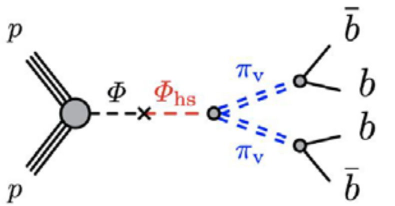
e.g. $\pi^\pm \rightarrow \mu^\pm \nu_\mu$ ($c\tau_0$ ~ 7.8m)

small coupling

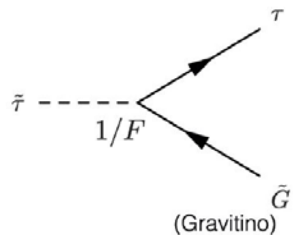
$$\frac{1}{\tau} = \frac{f_\pi^2 |V_{ud}|^2}{256 \pi m_\pi} \left[\frac{g^2}{M_W^2} \frac{m_\mu}{m_\pi} (m_\pi^2 - m_\mu^2) \right]^2$$

heavy mediator

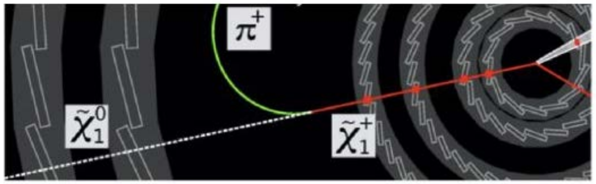
compressed spectra



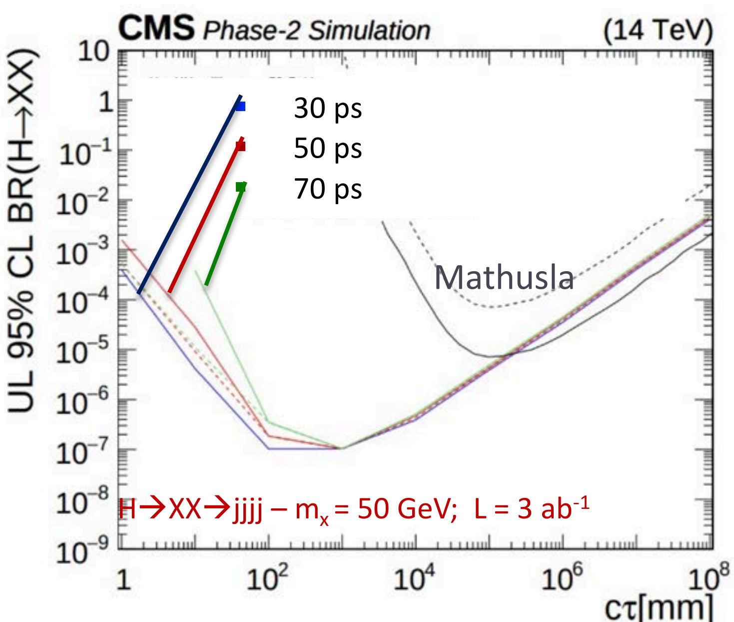
Feeble coupling to SM (Higgs portal to hidden sectors)

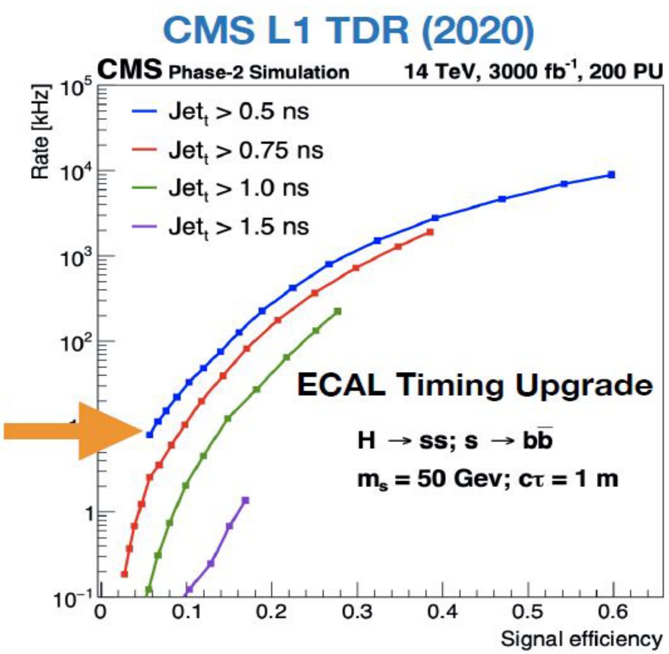


Scale suppression (Gauge mediated SUSY)

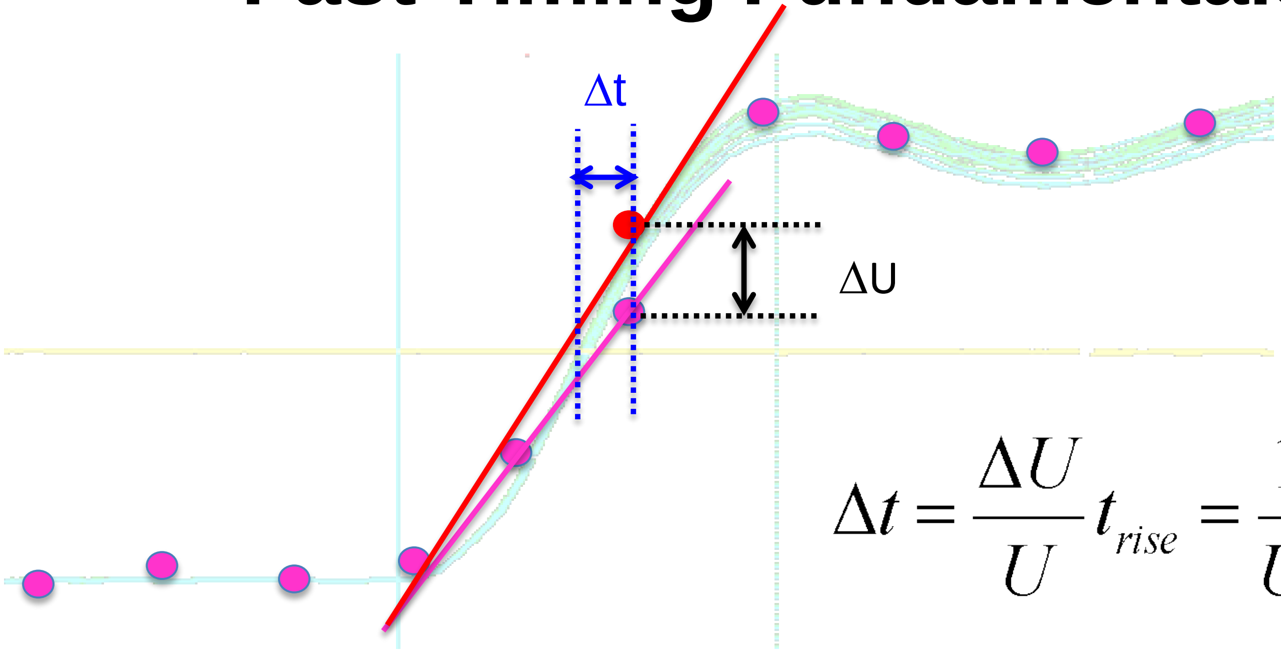


Phase space suppression (SUSY)





Fast Timing Fundamentals

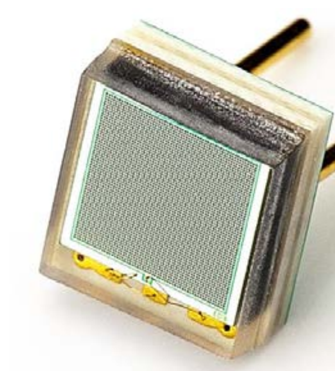


$$\Delta t = \frac{\Delta U}{U} t_{rise} = \frac{1}{U} \frac{\Delta U_i}{\sqrt{n_{samples}}} t_{rise}$$

For good time resolution, need:

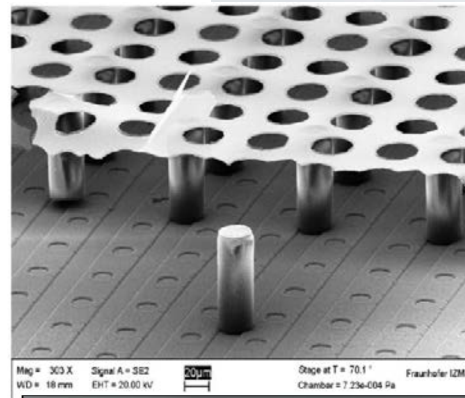
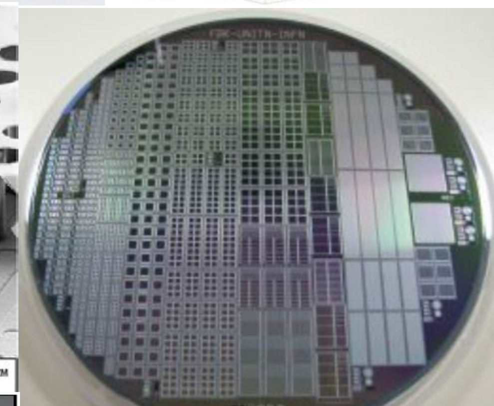
1. **fast rise time (t_{rise}) ⇒ primary signal rise time (scintillation : LYSO ~30 ps, Silicon sensors ~1ns)**
2. **low Signal-to-Noise (DU/U) ⇒ primary signal amplitude : LYSO 30k photons/MeV (1.07 MeV/mm MIP) , Si sensors ~30k e/h pairs in 300 μ for a MIP**
3. **more time samples ($n_{samples}$)**
4. **signal integrity matching timing needs (pulse shapes, linearity, etc.)**

Sensor Technology

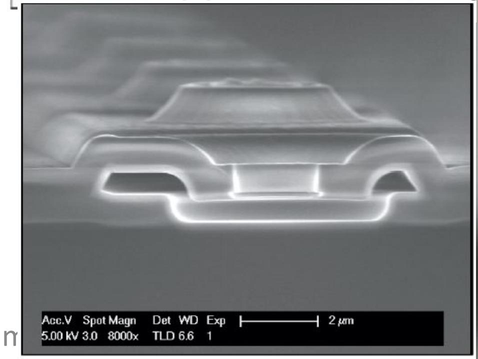



- **Photo sensors :**
  - **PMT : ~ns rise time, very good S/N**
  - **SiPM/APD : Rapid technology evolution**
  - **MCP-PMT : Fast pulses**
  - **Cherenkov light**
  - **Streak camera : sub ps**
  - **Pump-probe technology : fs**


- **Semi-conductor sensors :**
  - **Silicon : Very common in HEP**
  - **CdTe : Large primary signal**

- **Gas based sensors :**
  - **Micromegas : Micro fabrication**
- **Advanced sensors :**
  - **TIPSY, Quantum Dots, Nano-wires**

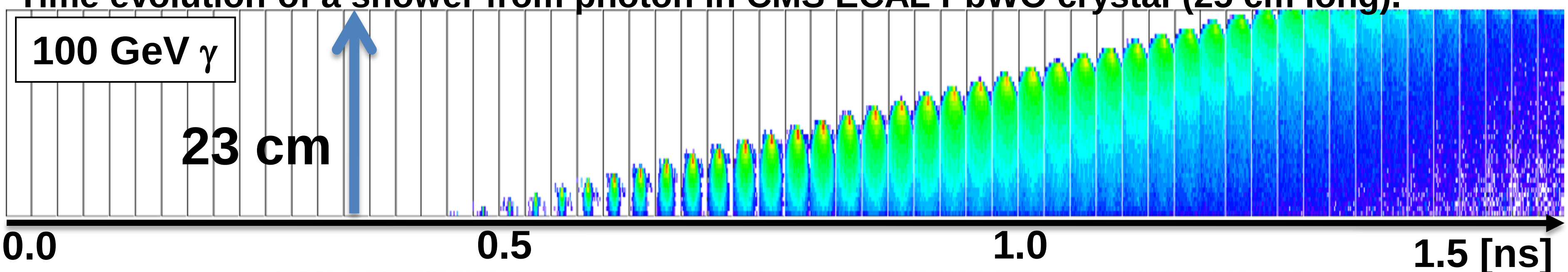


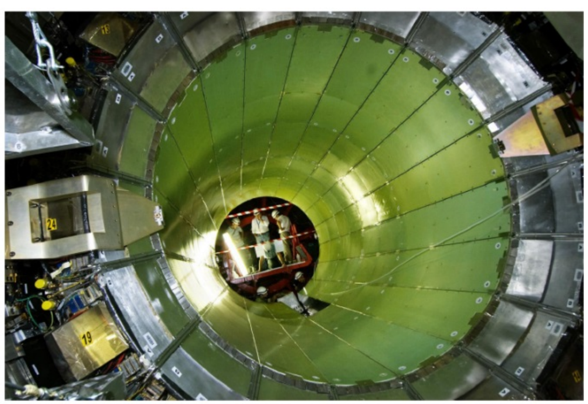

– **But : HEP detectors are complex systems, more than just sensors.**

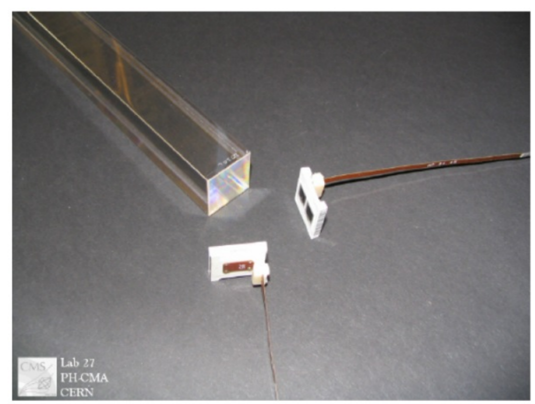
Precision timing with scintillators

- Scintillators have several features ideal for timing : Uniform, large raw signal yield, fast, very radiation hard.
- Effect of the scintillation photon arrival at the photo detector we refer to as Optical Transit Time Spread.

Time evolution of a shower from photon in CMS ECAL PbWO crystal (25 cm long).





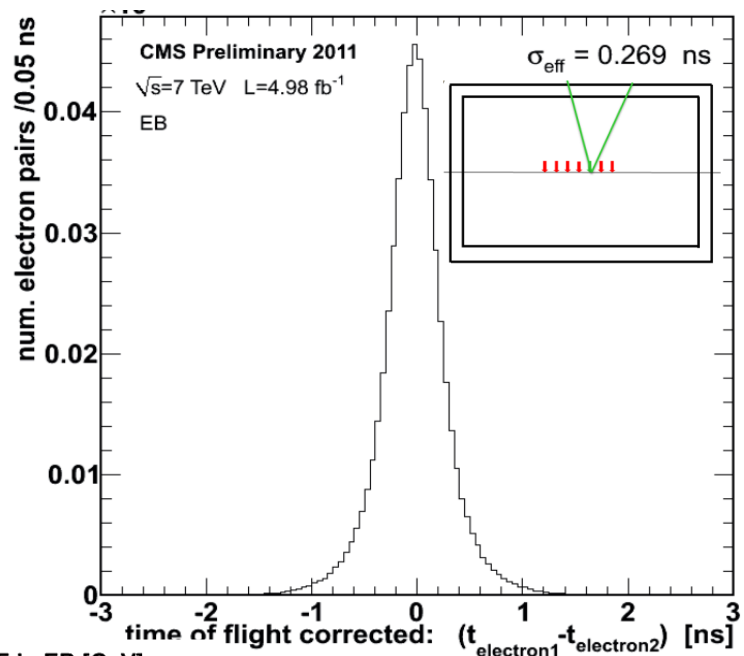


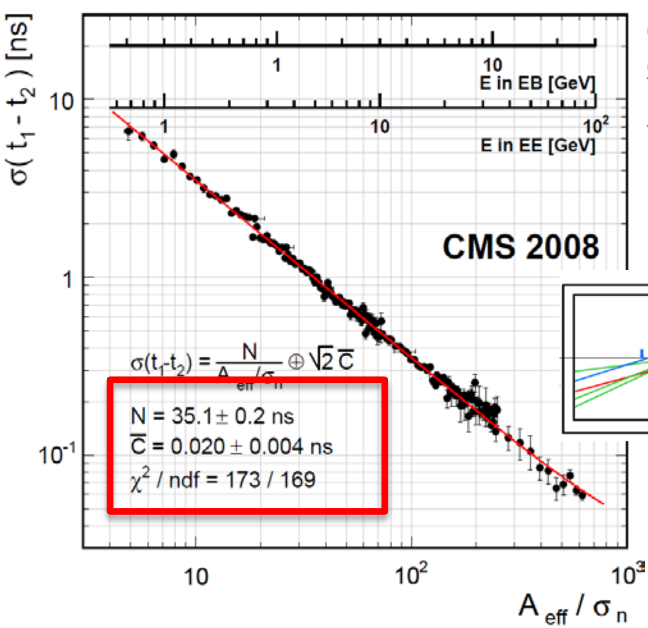
Timing Performance of CMS ECAL

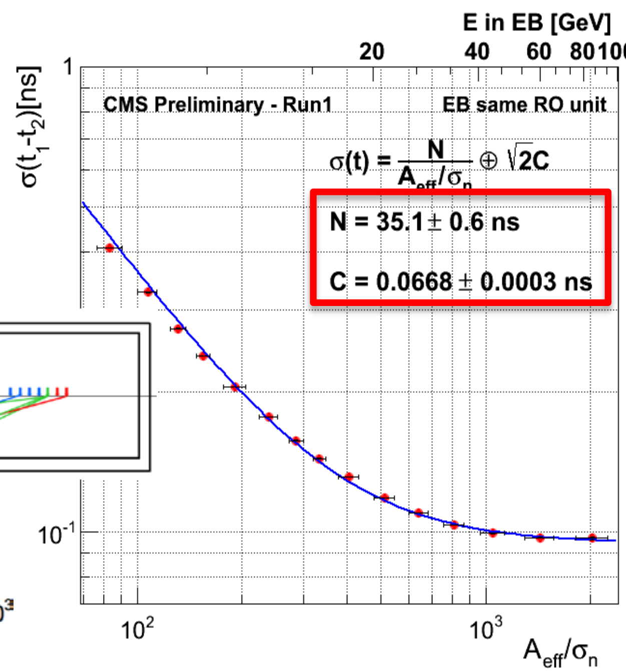
Large PbWO crystal calorimeter.

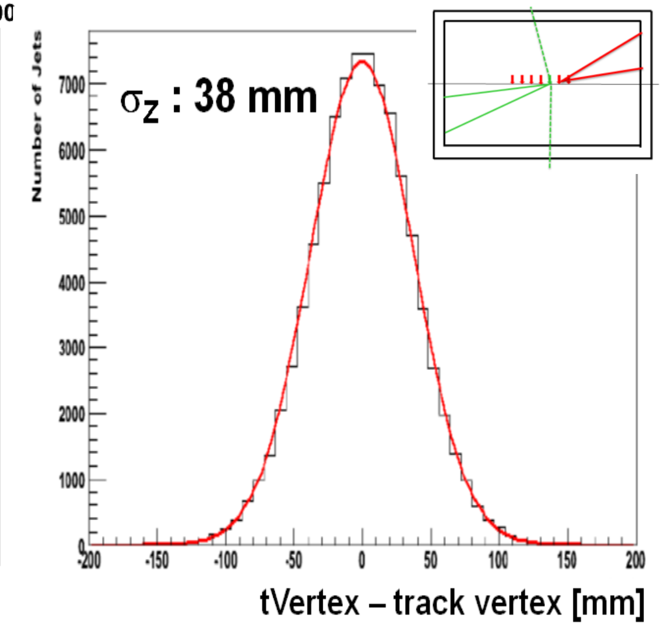
Results from pp collision data at LHC :

- **Electron showers from Z→ee decay Δt_{TOF} : ~270 ps, single channel : ~190 ps**
- **W/o path length correction : ~380 ps**
- **Constant term of resolution : ~20 ps in test beam, ~70 ps in situ (same clock).**
- **Studies on jet timing vertex resolution suggest very promising performance.**



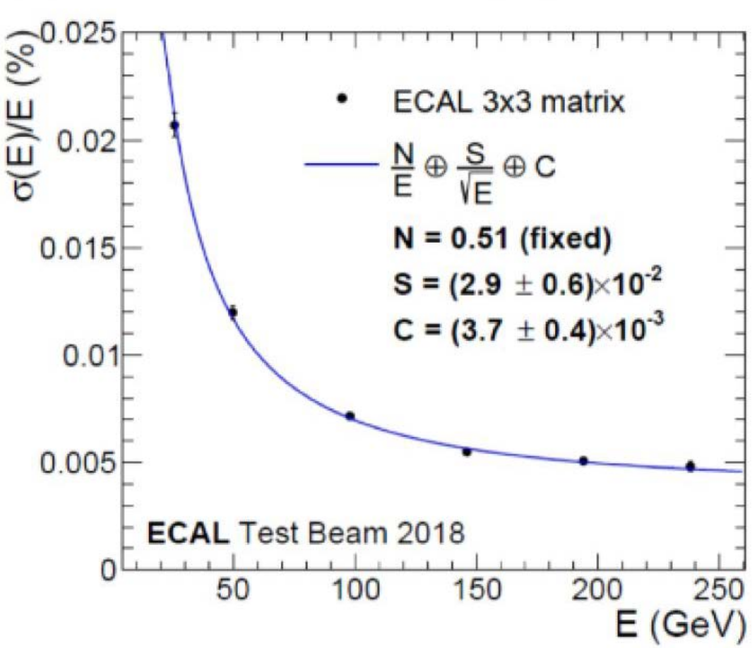


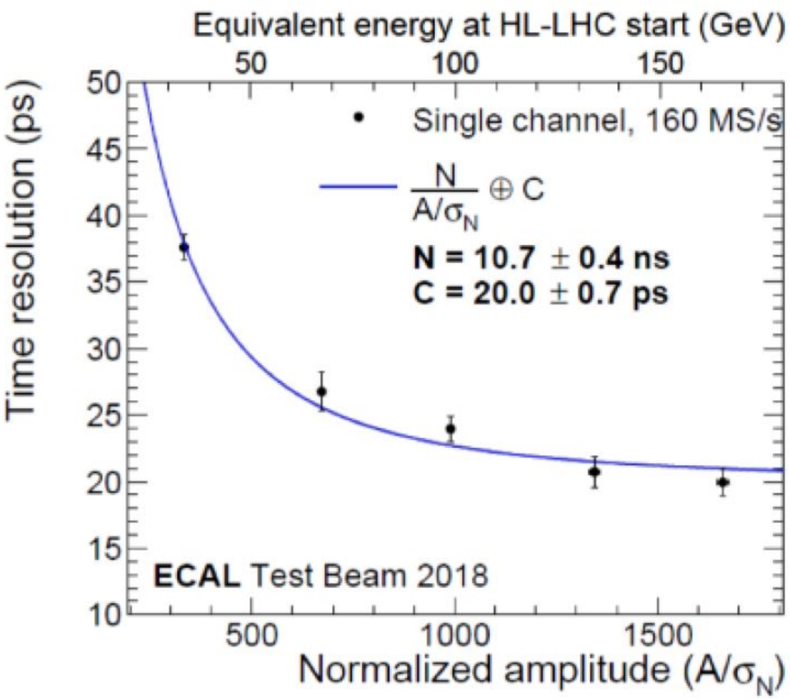




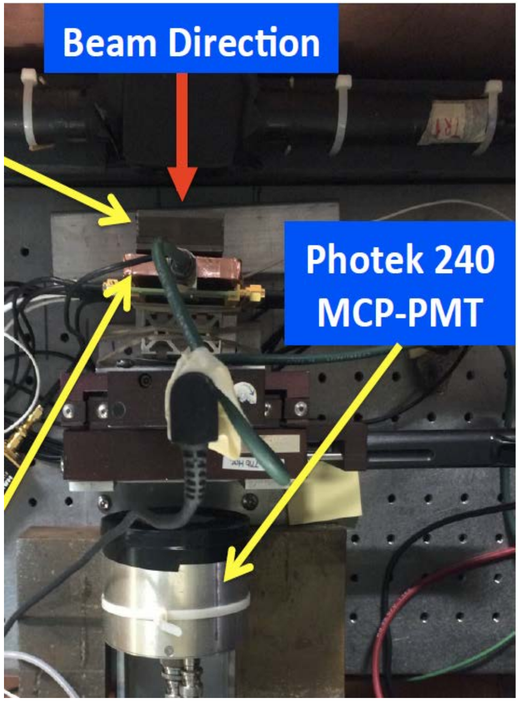
CMS ECAL Phase 2 Timing

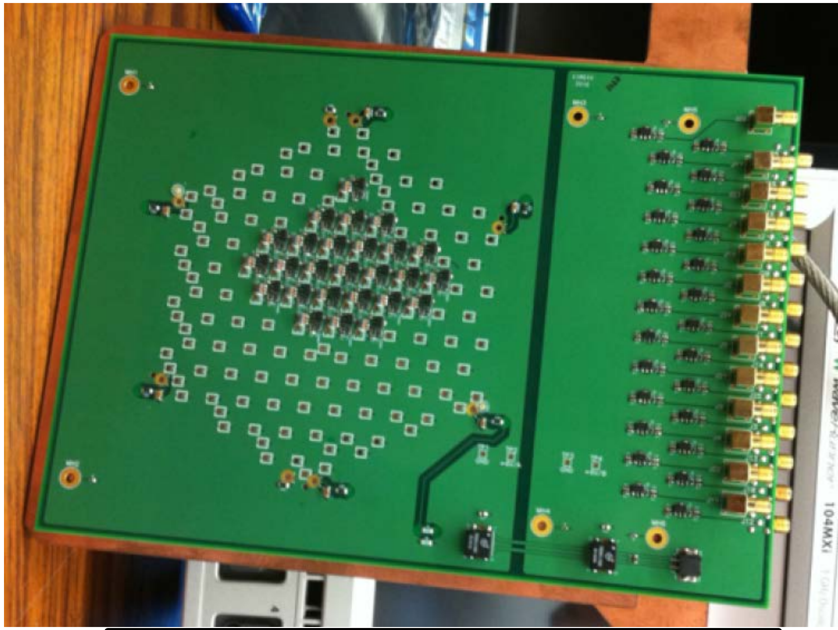
- Phase 2 upgrade of ECAL will feature precision timing readout :
  - 30 ps time resolution for high energy clusters.
- Information available at L1 trigger.
- Achieve by replacing front end electronics, dedicated ASIC.
  - Upgrade of electronics was necessary to cope with trigger rates.
- Improved pulse shape allows better suppression of intrinsic noise of photo detector.



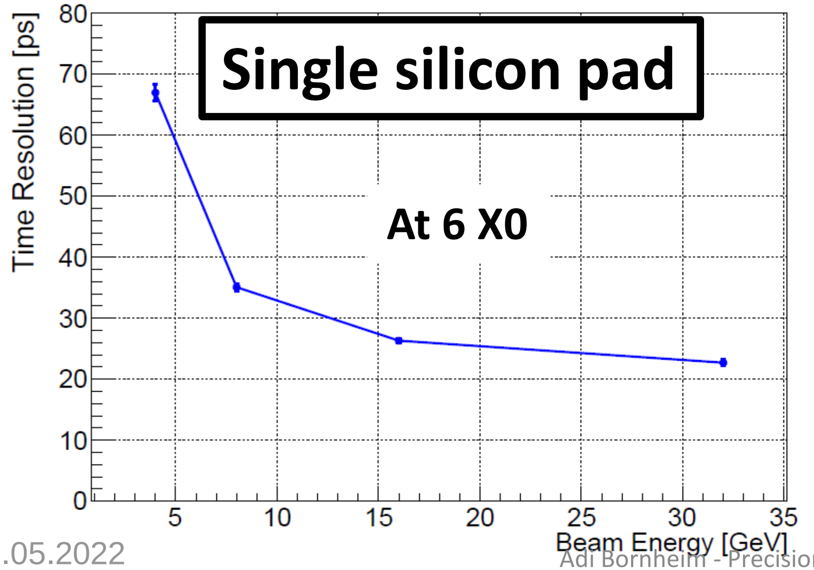


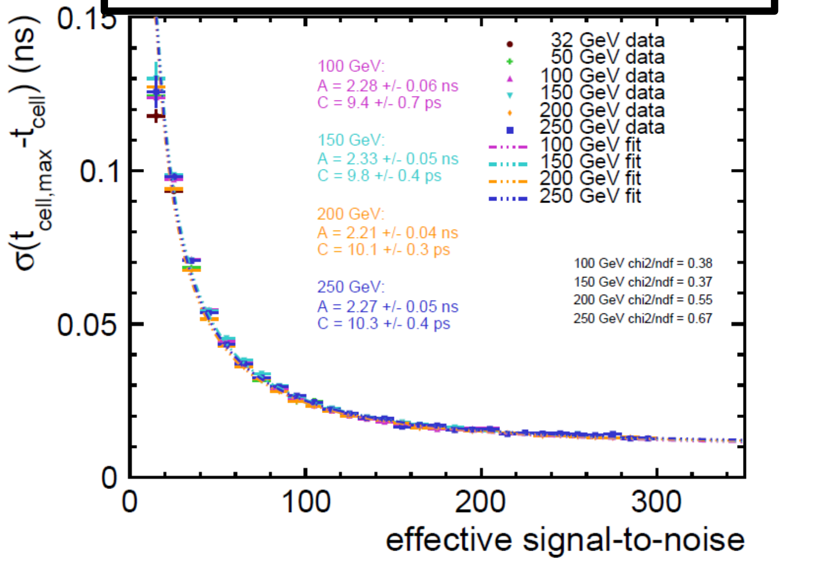
Silicon Shower Timing





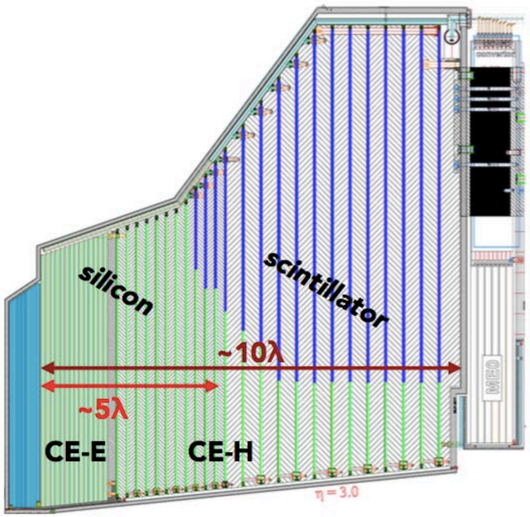
Silicon sensor, 128 pads

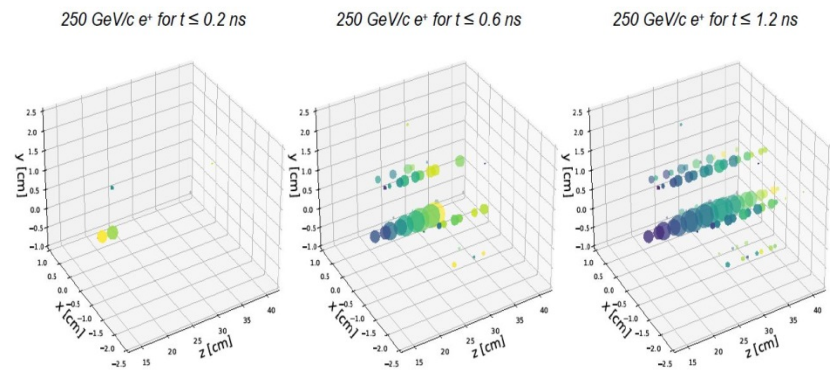




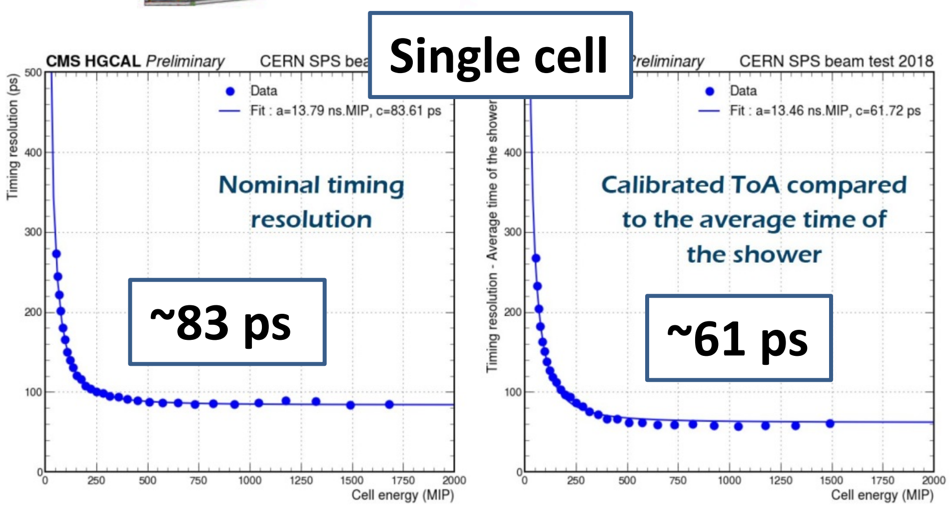
HGCAL Timing

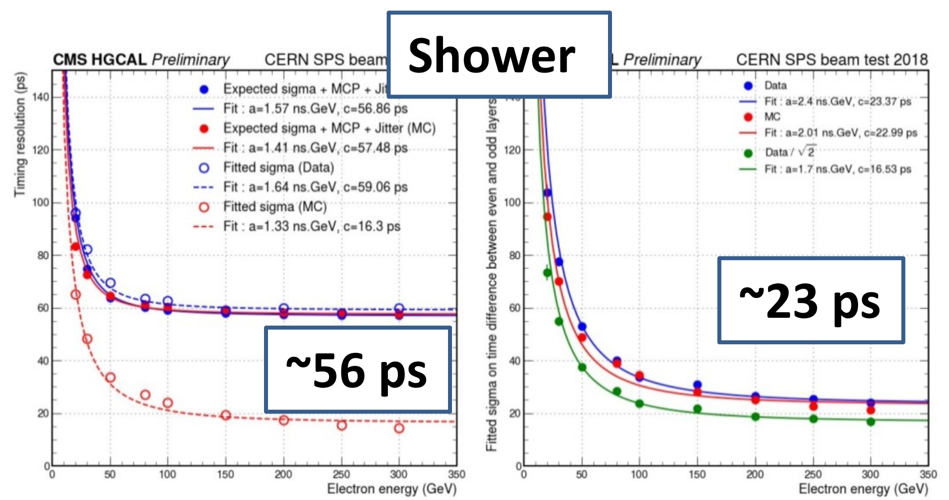
- CMS endcap replacement - HGCAL will feature precision timing capabilities.
- HGCAL : High Granularity Calorimeter – Silicon/Scintillator "pixels"
- Cell size 0.5/1.0 cm, >6m channels, 640 m^2 (Si); 240k channels, 350 m^2 (Scint)



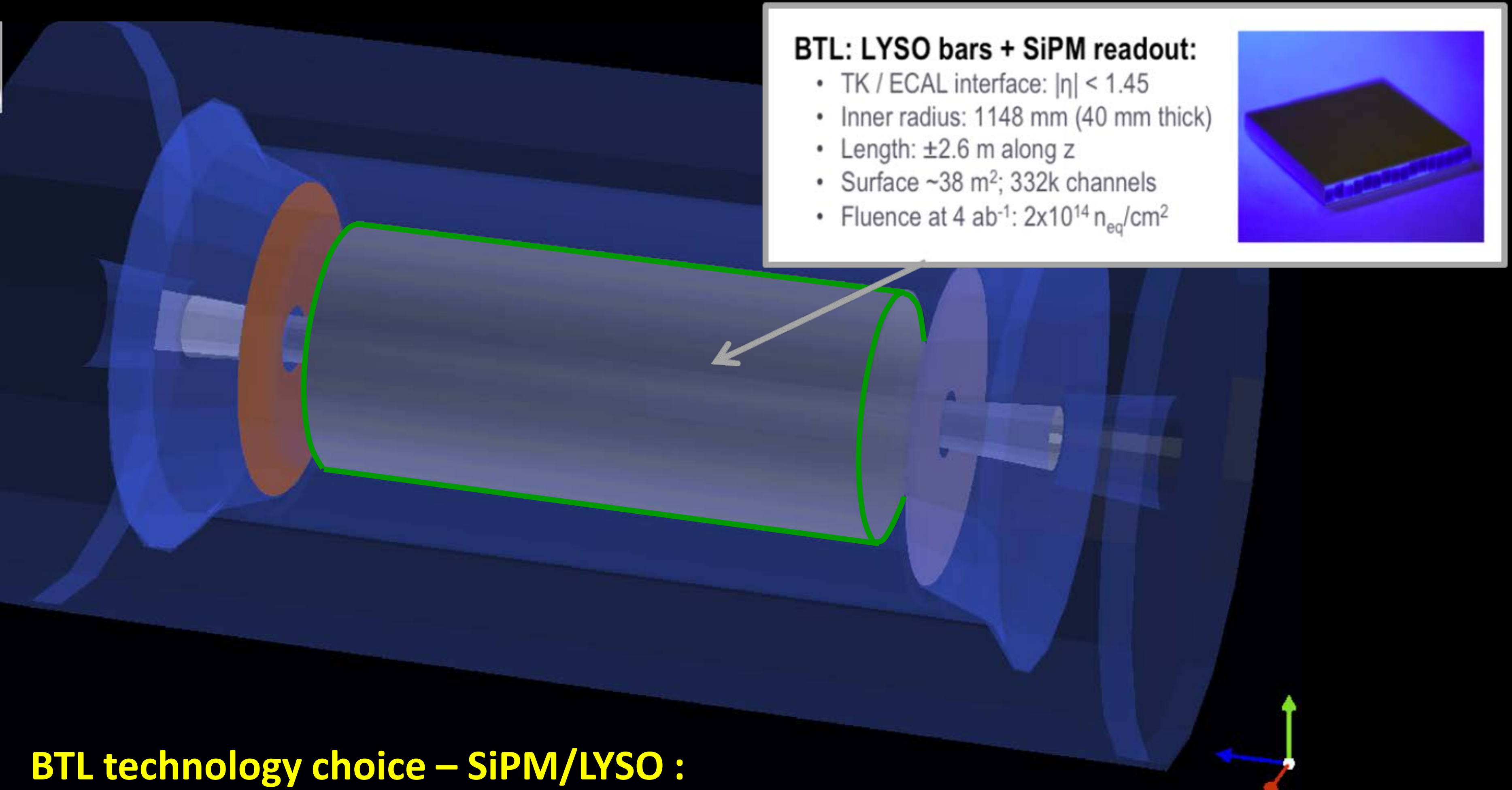


Timing development of an electromagnetic shower in HGCAL prototype





The CMS Barrel Timing Layer

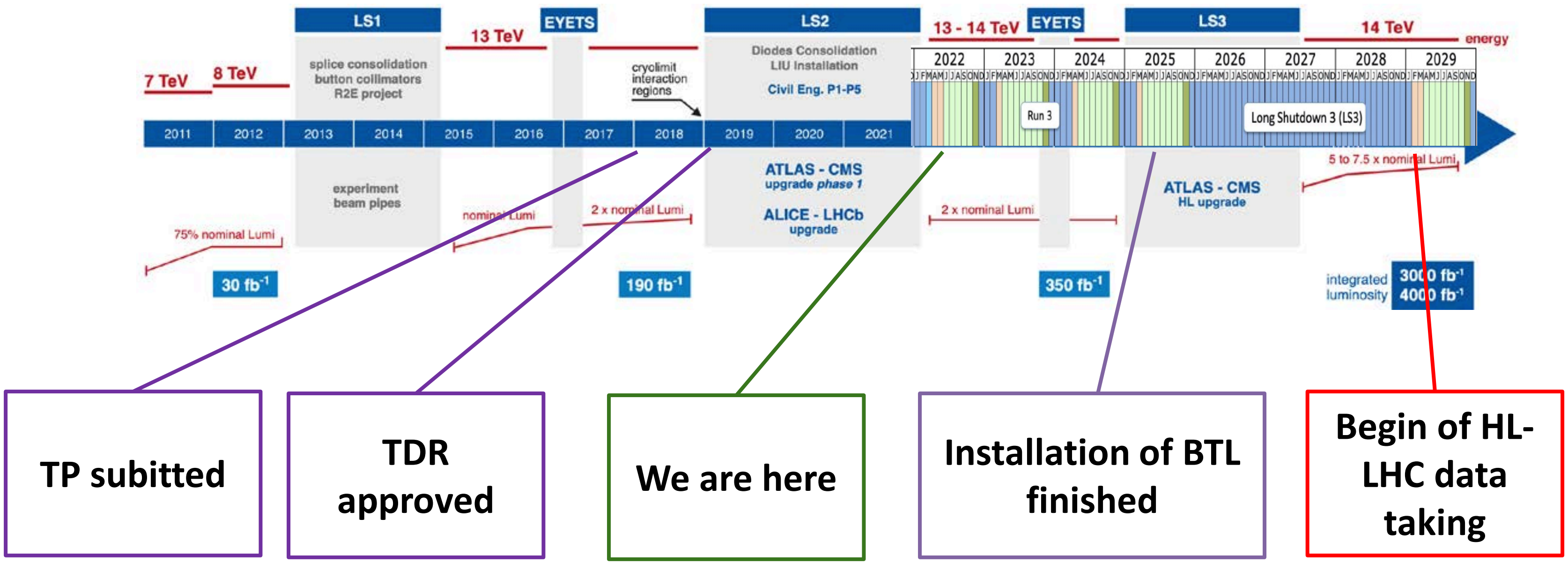


BTL technology choice – SiPM/LYSO :

- **Timing performance <20 ps with MIPs in LYSO/SiPM demonstrated.**
- **Radiation hardness established at the required level.**
- **Extensive experience with SiPM in CMS & LYSO in HEP & PET**
- **Cost effective mass market components**

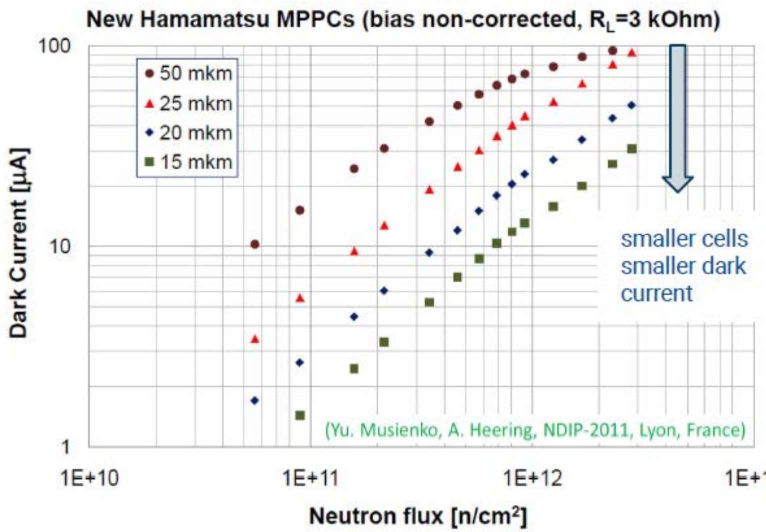
Design constraints

- Time resolution 30-40 ps at the start of HL-LHC, <60 ps up to 3000 fb^{-1}.
  - Requires additional measures to maintain EOL performance.
- Radiation levels for BTL after 3000 fb^{-1} :
  - Fluence 1.65 – 1.9 × 10^{14} n_{eq}/cm^2 , Dose : 18-32 kGy
- Maintenance free operation inside the tracker cold volume.
  - Requirement to run SiPMs below -30 C to limit dark count rate (DCR).
- Cover ~38 m^2 of area at the outer circumference of the CMS tracker.
- Schedule constraints of HL-LHC :

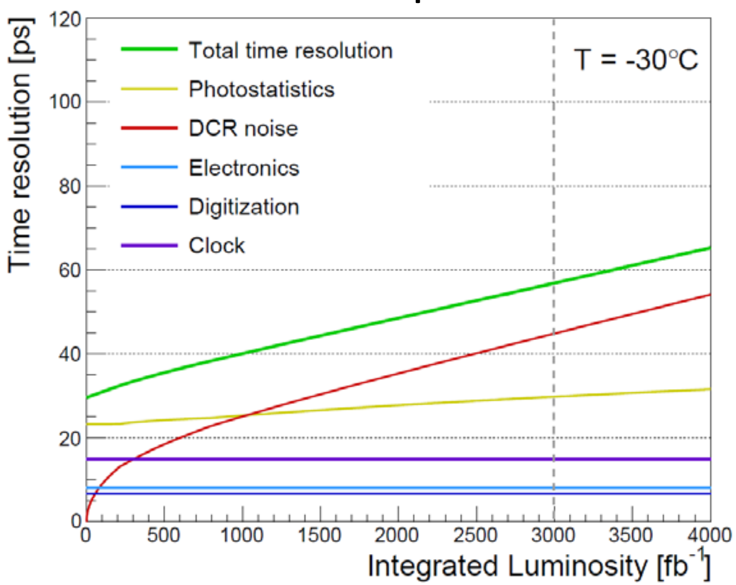


MTD Barrel Sensor

- Maximize slew rate to optimize performance.
- LYSO crystals as scintillator
  - Excellent radiation tolerance
  - Bright (40k ph/MeV)
  - Fast rise time O(100ps), decay time ~40 ns
- Silicon Photomultipliers as photo-sensors
  - Compact, insensitive to magnetic fields, fast
  - For un-irradiated SiPMs, smaller pixels lower DCR.
  - For irradiated SiPMs, testing larger pixels.
  - High dynamic range, rad tolerant
  - Photo Detection efficiency : 20-40%
- High aspect ratio geometry :
  - Enhance light collection efficiency (~5 %)
  - Minimize SiPM area / Crystal area
  - Reduce power consumption
  - Better timing performance



Resolution <60 ps @ 3 ab^{-1}

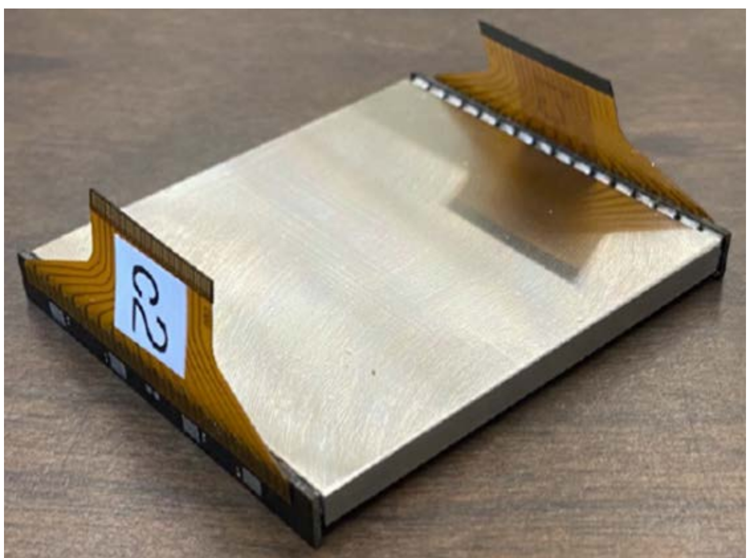


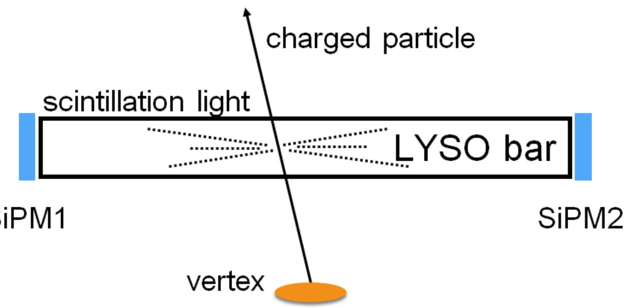
Sensor geometry choice

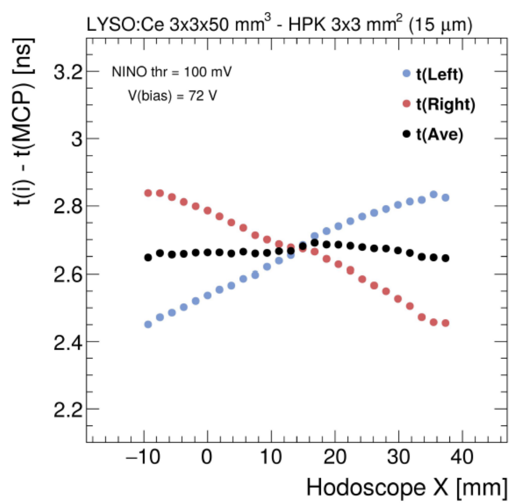
- **Scintillation light measured with a pair of Silicon Photomultipliers (SiPMs), one at each end of the crystal bar**
  - **Minimize impact point position dependency**
  - **Minimization of active area and power budget**
  - **Maximization of resolution ($\sqrt{2}$ improvement)**
  - **Determination of track position with O(mm) resolution**

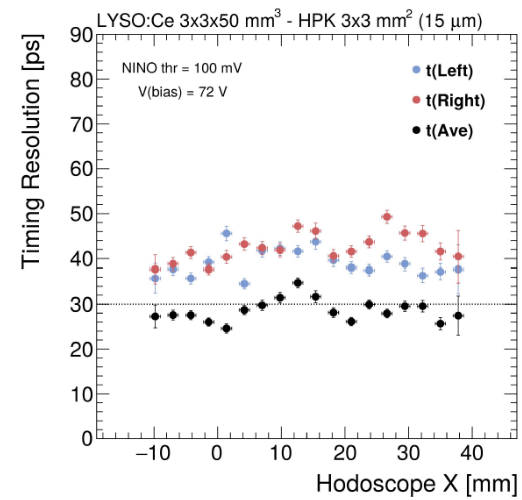
BTL module :

- **16 LYSO bars, read out by 32 SiPMs,**
- **Size 51 x 57 mm, thickness 2.4, 3.0, 3.75 mm**



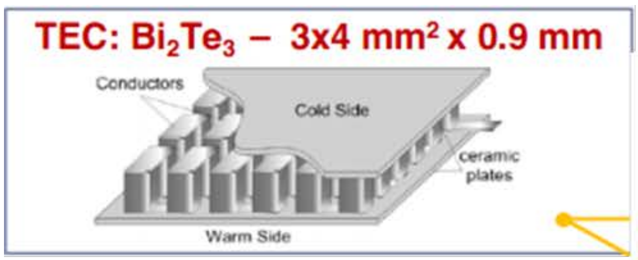


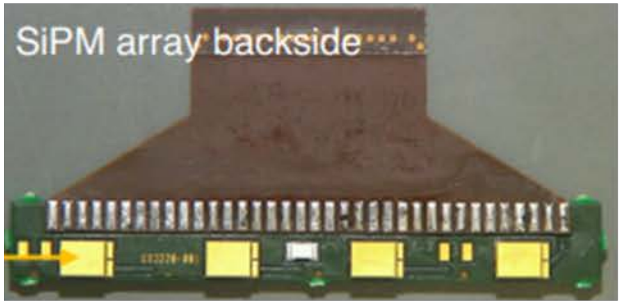


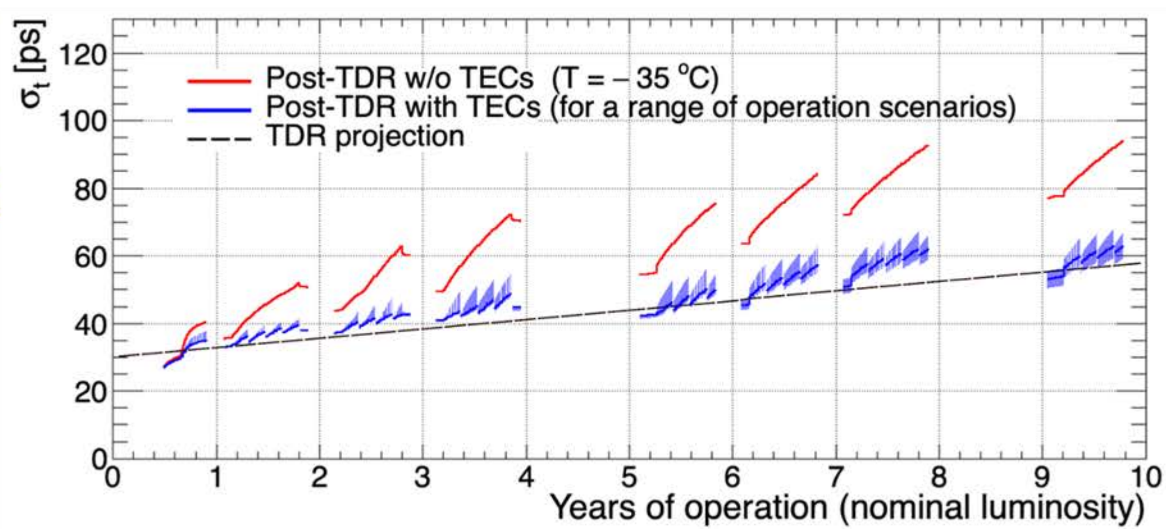


Further Design Improvements

- Two handles to mitigate impact of SiPMs dark count rate (DCR) due to large radiation budgets :
  - Reduce temperature
  - Annealing of SIPMs
- Added Thermoelectric Coolers (TEC) coupled to SiPMs :
  - Reduce operational temperature from -35 °C (CO_2) to -45 °C (CO2 + TEC).
  - Allow annealing in situ during detector maintenance at +40 °C

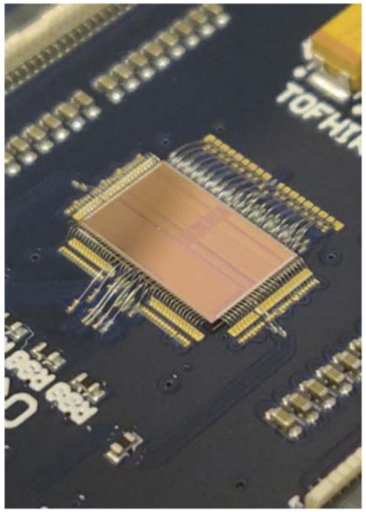




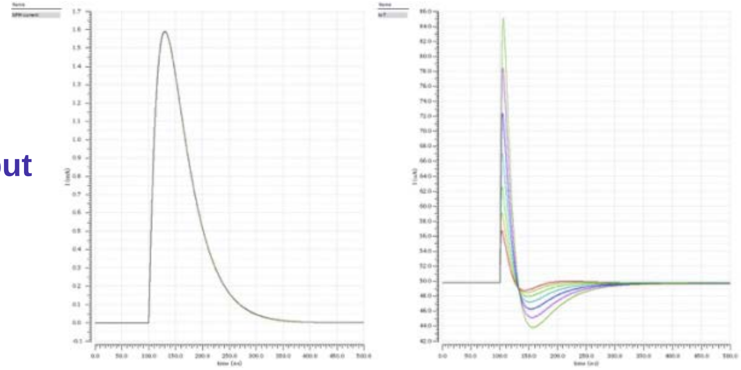


DCR Mitigation with the BTL ASIC

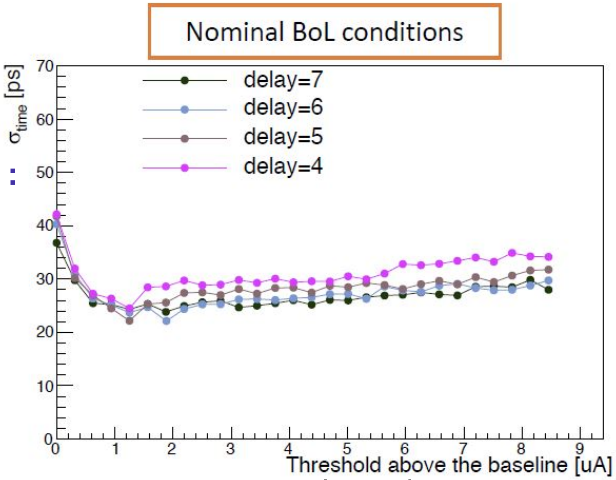
- Dedicated readout ASIC (TOFHIR) is being developed for BTL.
  - Derived from TOFPET ASIC developed for PET applications.
- Key feature is a noise suppression filter :
  - Inverted and delayed pulse subtract from the input pulse
  - Restores baseline at the rising edge of the pulse.
- Improves time resolution by about a factor 2 at EOL.

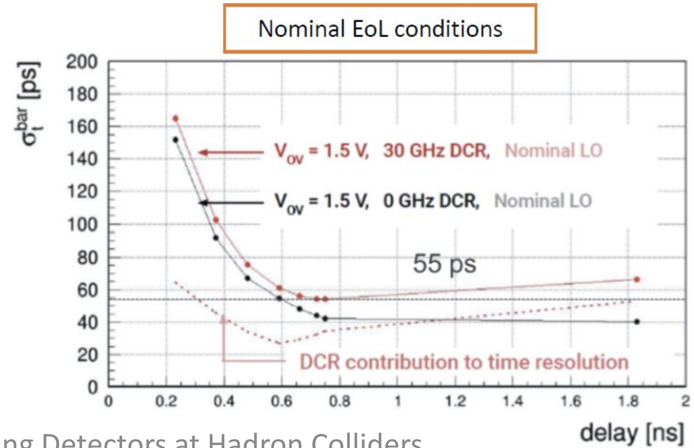


Simulation of TOFHIR DCR cancelation
Left : Input pulse
Right : Pulse after subtraction of delayed input pulse



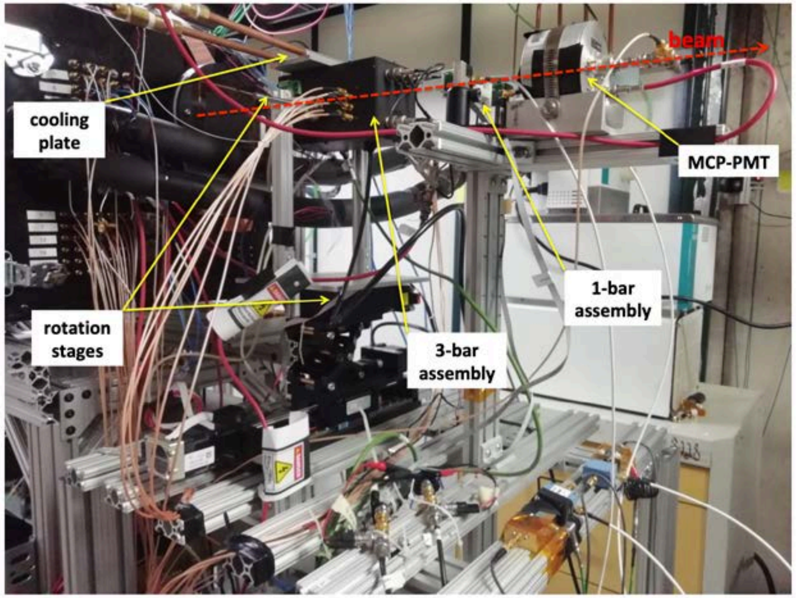
Measurements :

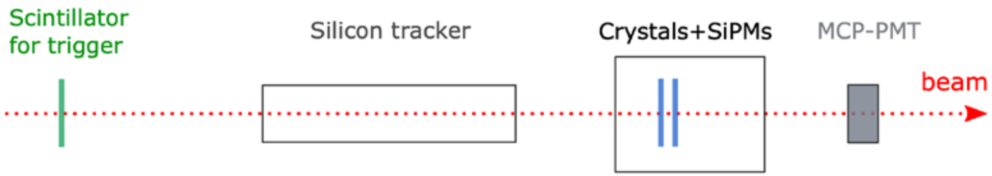


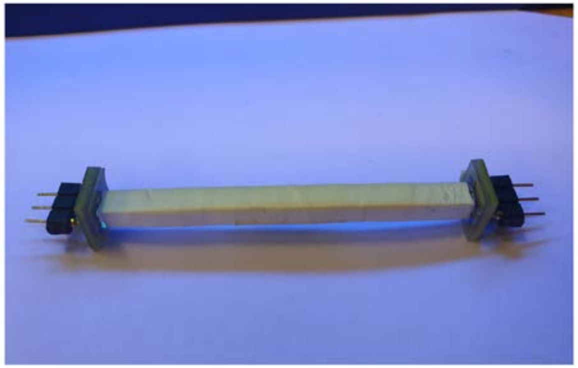


BTL Performance in Test Beam

- Test beam to test resolution and uniformity of LYSO crystals
- 120 GeV protons beam.
- Silicon tracker telescope to measure proton position and Micro Channel Plate-PMT (MCP-PMT) used as reference time
- Two different SIPMs tested (HBK and FBK). Box at 25^{0}C
- Layout allowing rotation of crystals vs direction of beam
- Recent test beams at PSI and CERN with TOFHIR readout and irradiated SiPMs, analysis ongoing.

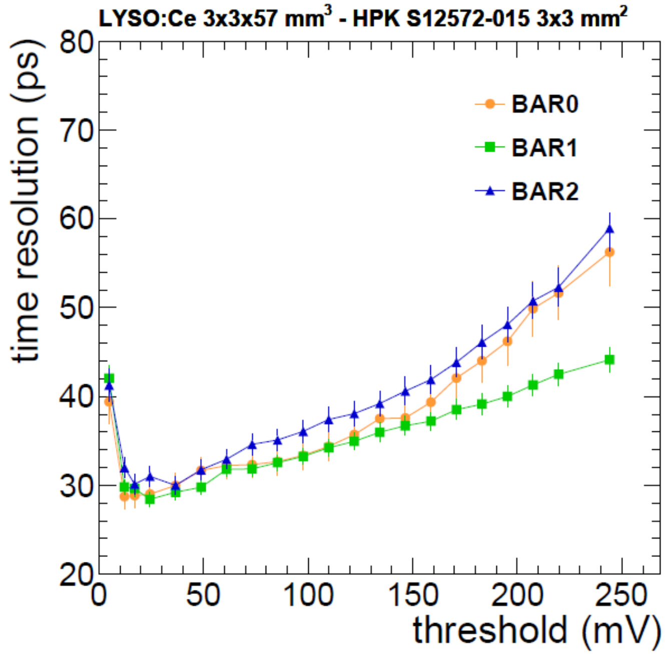






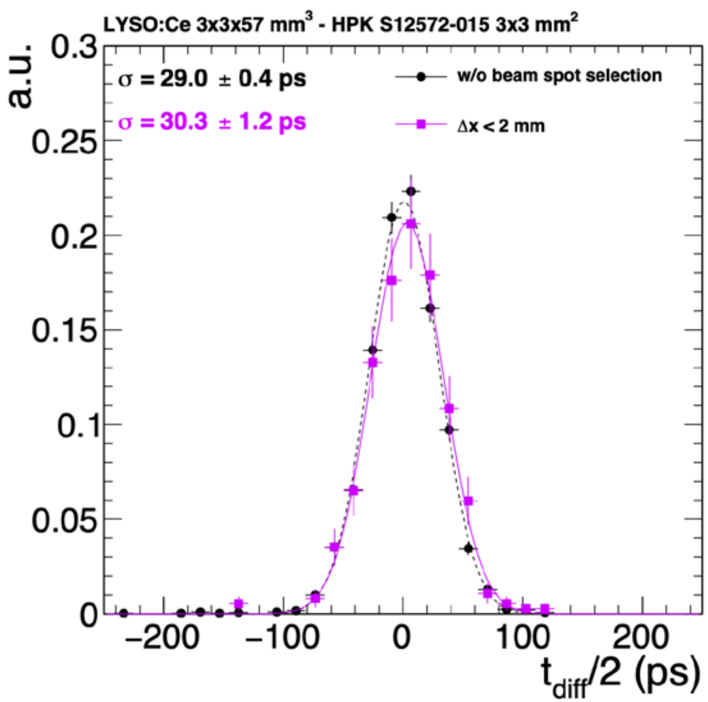
BTL Timing Measurement

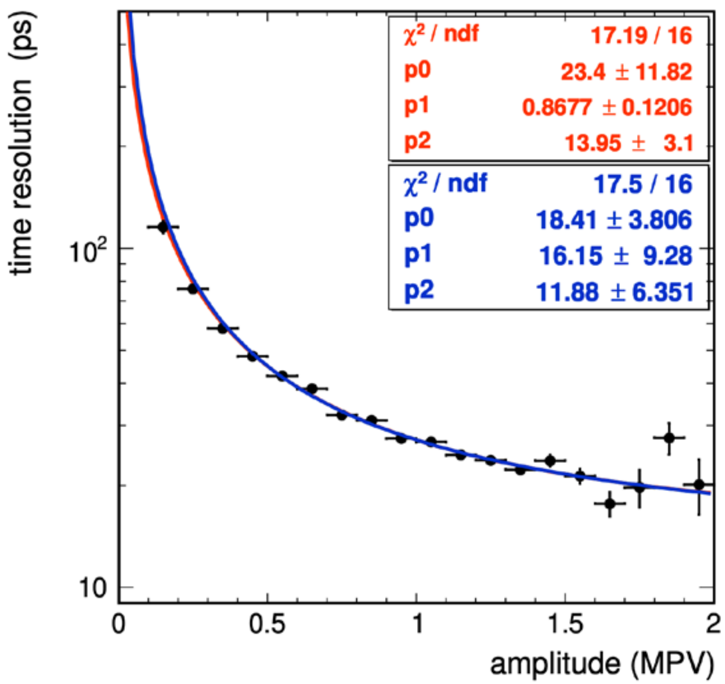
- In FNAL test beam shown , timing extracted from the leading edge of SiPM pulse.
- At low thresholds, timing resolution improves with increasing threshold due to larger S/N.
- At larger thresholds, timing resolution deteriorates as fluctuations on the arrival time of the Nth photon add more jitter.
- In case of BTL, minimum varies as DCR add noise. Optimal threshold in the range of 50 photo electrons.
  - Note : ~160k scintillation photons, ~9k PE



Time resolution

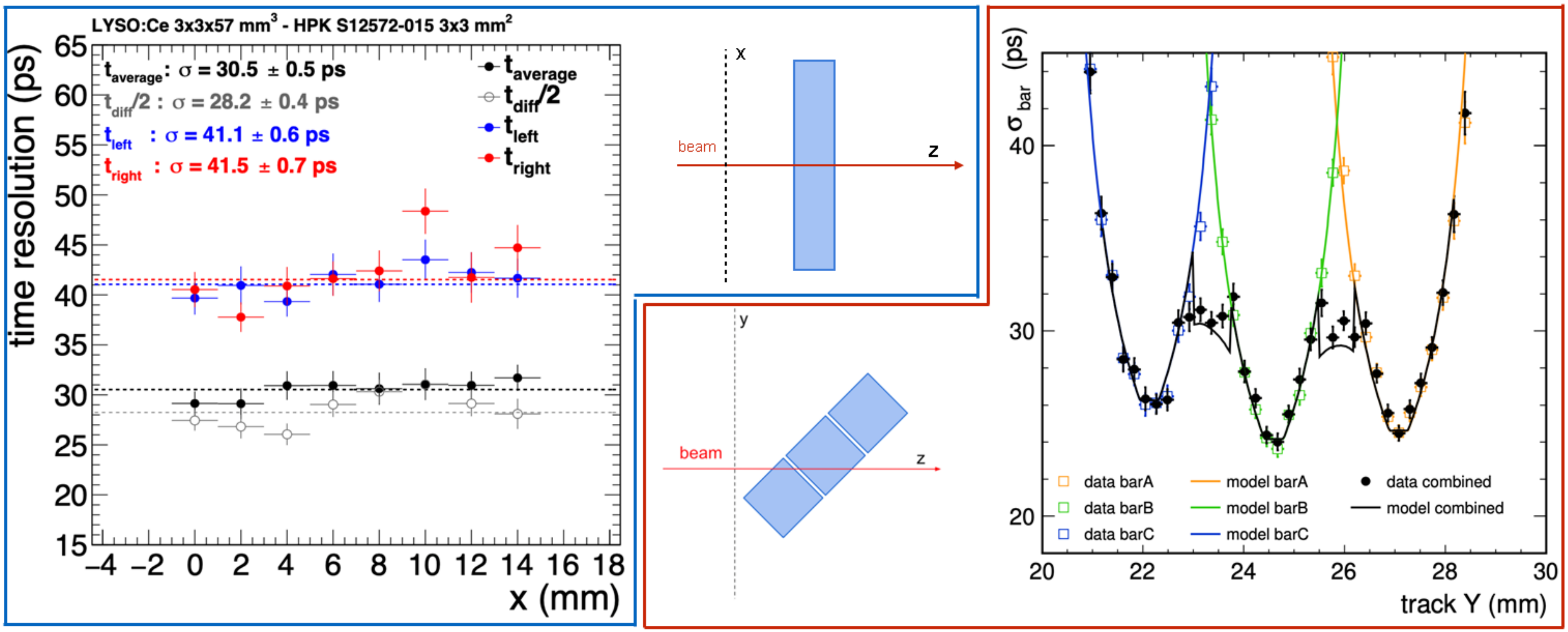
- Estimated as $\sigma_{t_{average}}$ and $\sigma_{t_{diff}}/2$ where
  - $\Delta t_{bar} = t_{average} - t_{MCP} = (t_{left} + t_{right})/2 - t_{MCP}$ and $\sigma_{t_{average}} = \sqrt{\sigma^2_{\Delta t_{bar}} - \sigma^2_{t_{MCP}}}$
  - $t_{diff} = t_{left} - t_{right}$
- Resolution for MIP below 30 ps
- Improves with increased light output and, for sufficiently high thresholds, scales with the inverse of the square root of amplitude





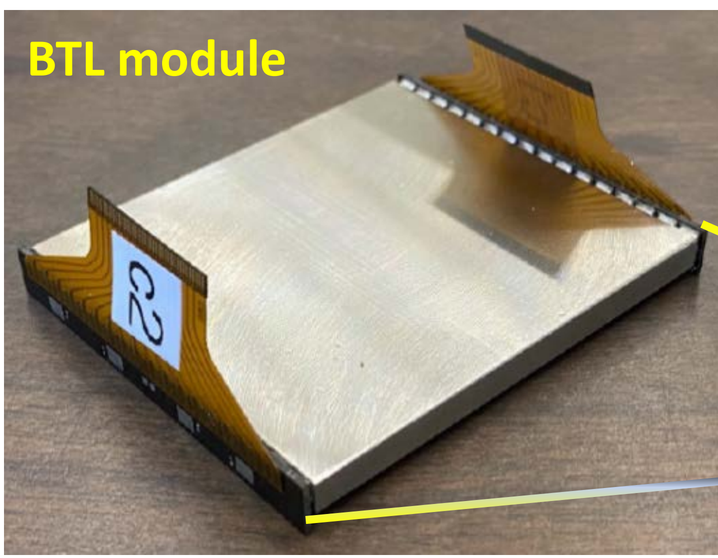
Sensor Uniformity

- In the detector, particles will cross LYSO bars at broad range of impact angles depending on their pT.
  - LYSO bar thickness varies along eta in three groups (2.4, 3.0, 3.75 mm) to equalize effective path length.
- Uniform response and resolution along the bar :
  - Effect of gaps negligible if < 200 μm, expect gap ~ 80 μm for final bar arrays

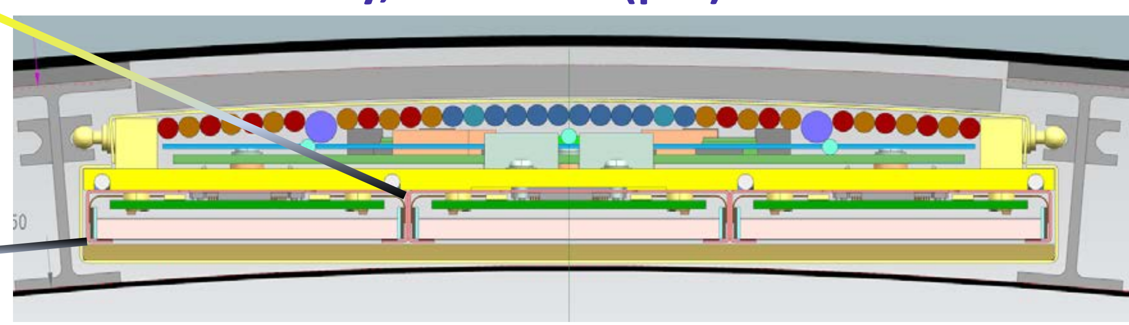


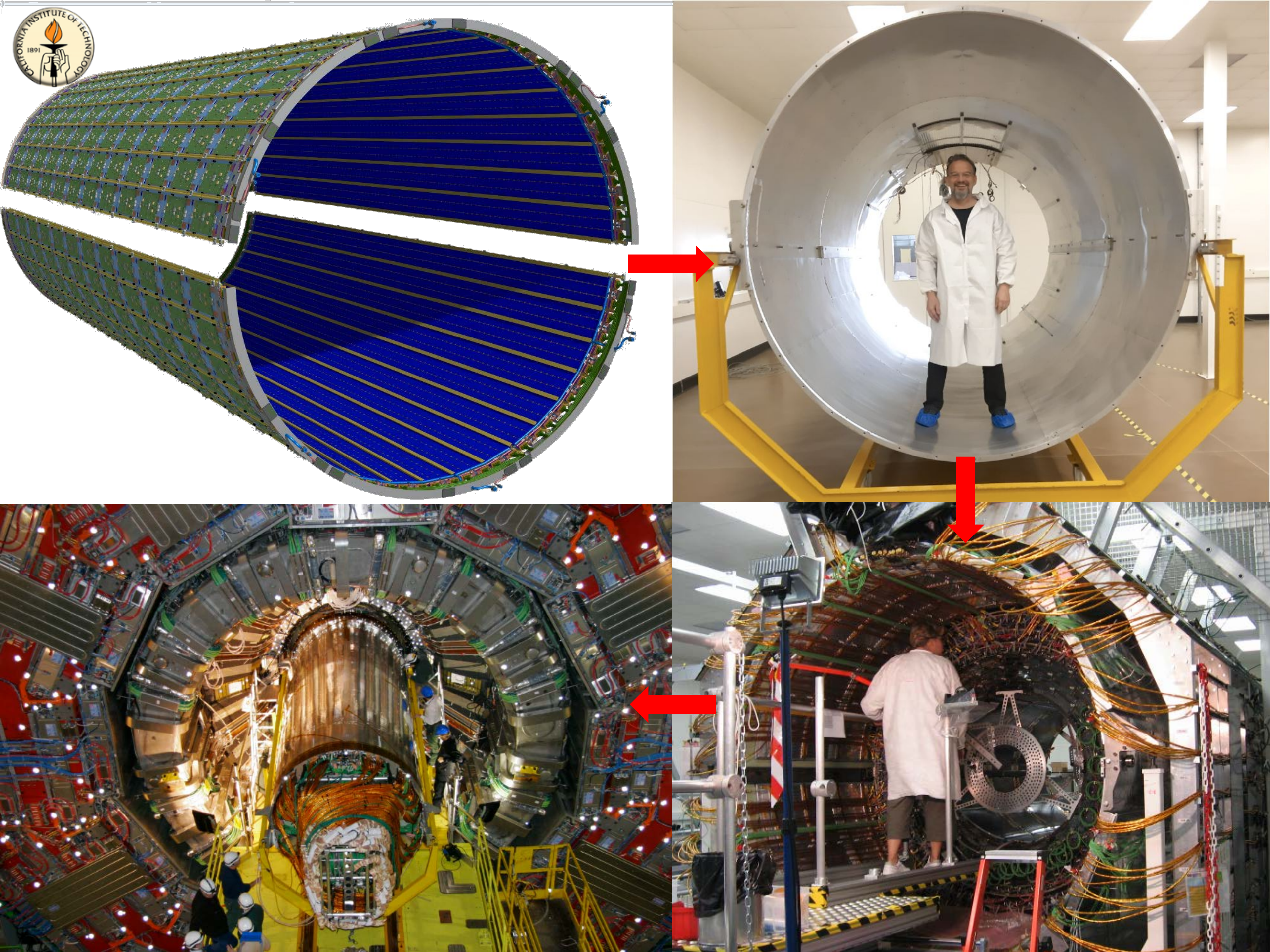
BTL Layout & Design

- BTL attached to inner wall of Tracker Support Tube
- Cold volume shared with Tracker
- BTL Segmentation :
  - 72 trays (36 in $\phi \times 2$ in η)
  - 331k readout channels, 165k LYSO bars, organized in 10368 modules, 6 Readout Units per tray.
  - Tray dimensions : 250 x 18 x 2.5 cm
  - Module dimensions : 51x57 mm^2



BTL tray, transvers (phi) cross section

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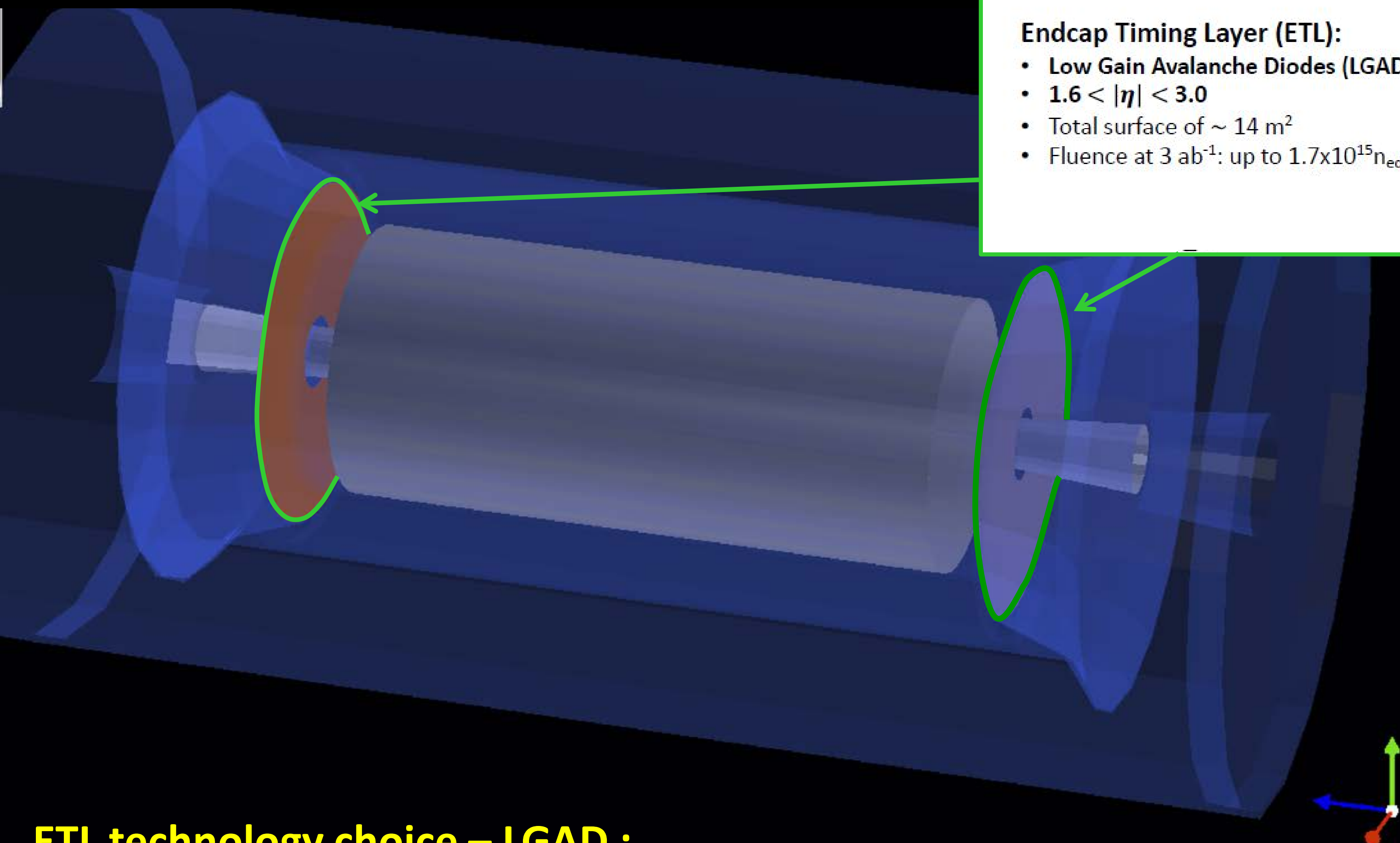
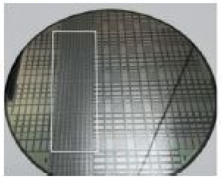
The CMS Endcap Timing Layer



Endcap Timing Layer (ETL):

- **Low Gain Avalanche Diodes (LGADs)** with ASIC readout
- **$1.6 < |\eta| < 3.0$**
- Total surface of $\sim 14\ m^2$
- Fluence at 3 ab^{-1}: up to $1.7 \times 10^{15} n_{eq}/cm^2$



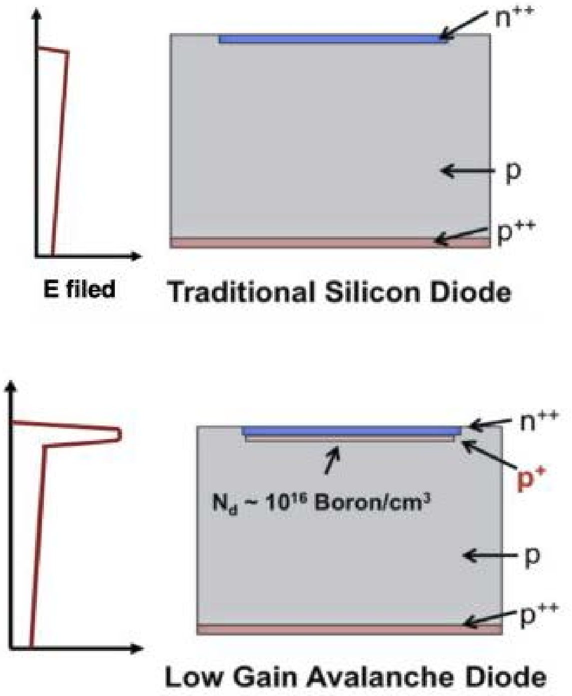
ETL technology choice – LGAD :

- **Very resilient against radiation**
- **Typically 30 ps time resolution per timing layer**
- **Employing technology from tracking detecors**

Timing with LGAD

LGAD technology:

- p^+ gain layer implanted underneath n++ electrode
  - High located electric field (E > 300 kV/cm)
  - charge multiplication
  - Moderate internal gain 10 – 30 to maximize signal/noise ratio
- Sensor Requirements:
  - Pad size of few mm^2 determined by occupancy and read-out electronics (pad capacitance ~ 3 – 4 pF)
  - Gain and breakdown uniformity
  - Low leakage current
  - Provide large and uniform charge, > 8 fC when new and > 5 fC at the highest irradiation fluence
  - No-gain distance between adjacent pads < 50 µm



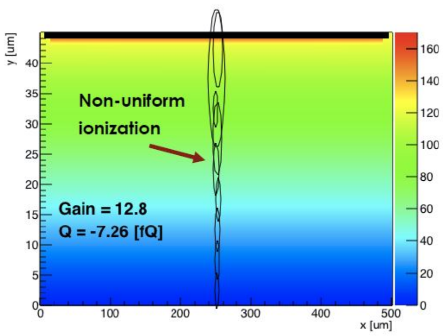
The final sensor:

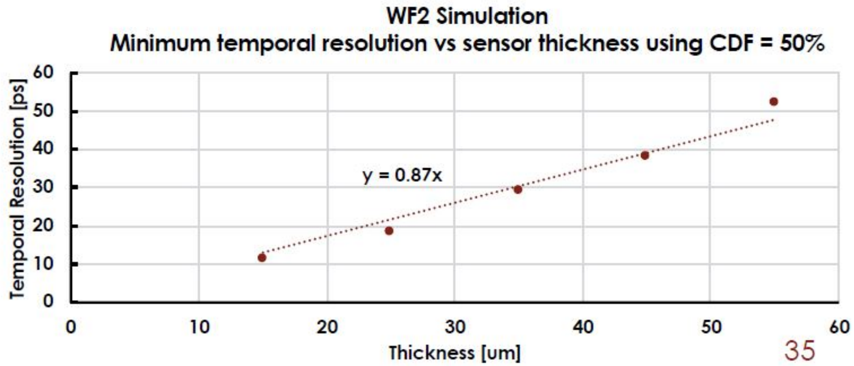
- 16x16 pad array with 1.3x1.3 mm^2 pads

Intrinsic limitation :

Landau fluctuations

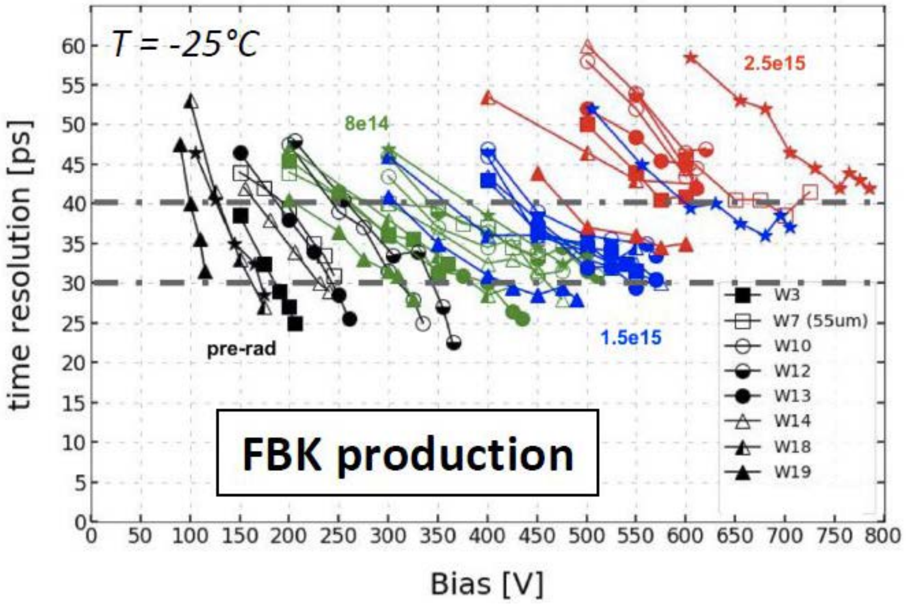
in the signal creation process :

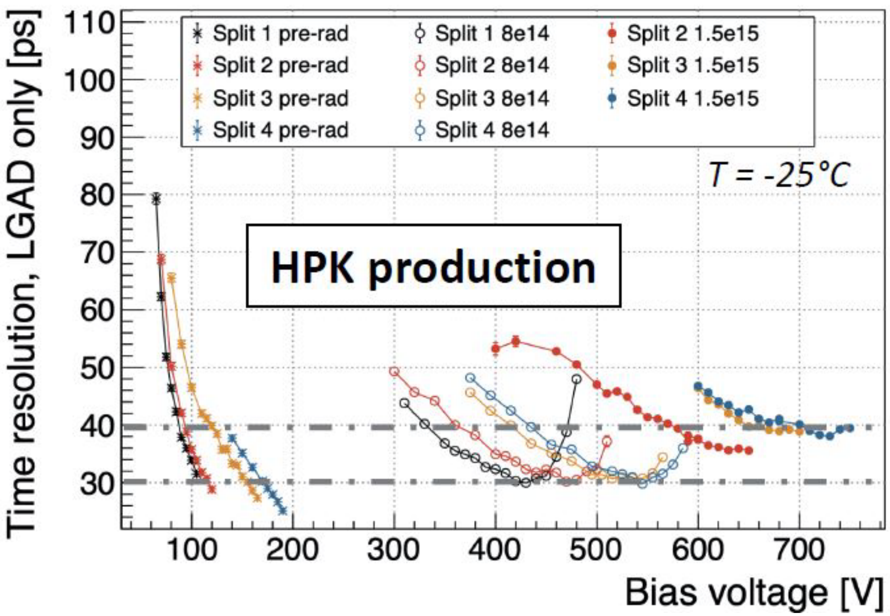




LGAD Performance

- Laboratory setups in Torino and FNAL based on a Sr^{90} β-source
- Sensor performances are benchmarked using very fast low noise electronics
- Both FBK and HPK sensors achieve a time resolution < 40 ps up to $2.5 \times 10^{15}\ n_{eq}/cm^2$
  - With both the latest FBK and HPK production, ETL able to avoid performance degradation even in its innermost part
  - Results might change with ELT ASIC. Additional resolution contribution from
- ASIC, discussed later

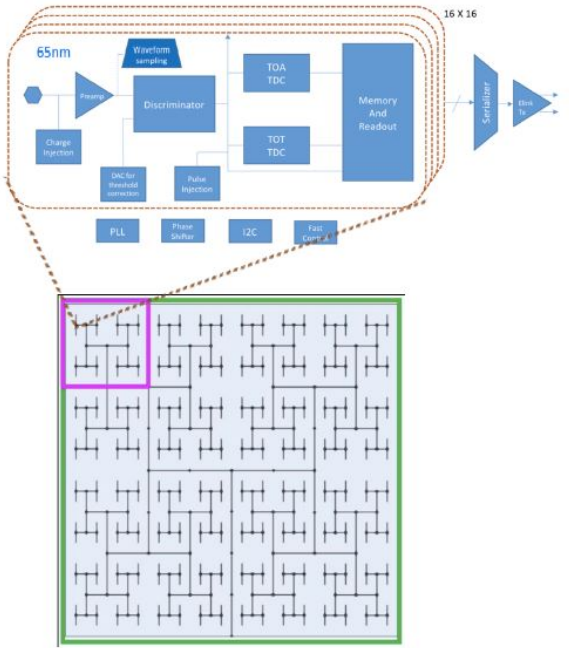




ETROC

Endcap Timing Layer Read-Out Chip (ETROC) is the ETL read-out ASIC

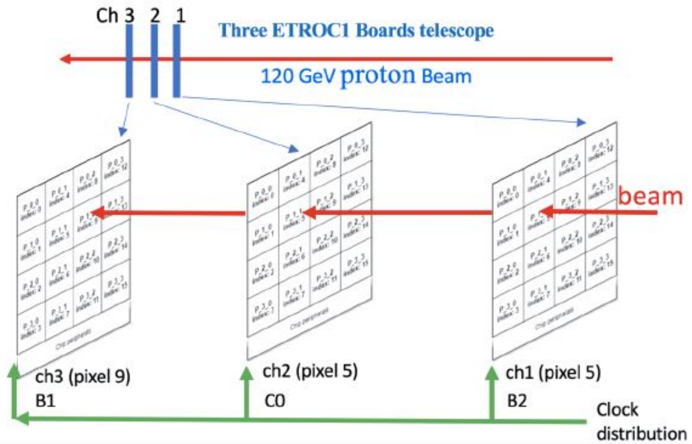
- **Time resolution < 50 ps per single hit**
- **Power budget: 1W/chip, 3mW/channel**



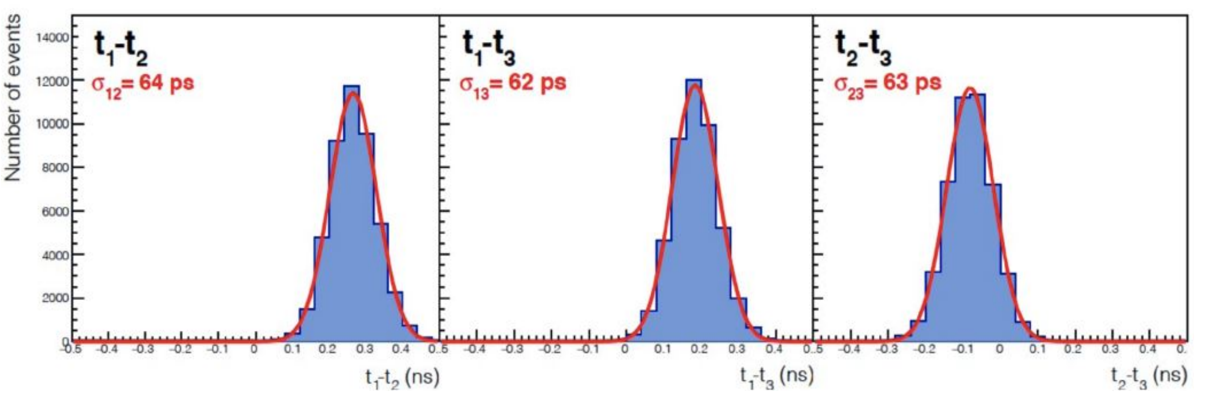
Three prototype version before the full-size 16x16 chip:

- **ETROC0 : single analog channel**
- **ETROC1 : full front-end with TDC and 4x4 clock tree**
- **ETROC2 : design in progress: full functionality + full size**

Test beam results with ETROC1 meet specs

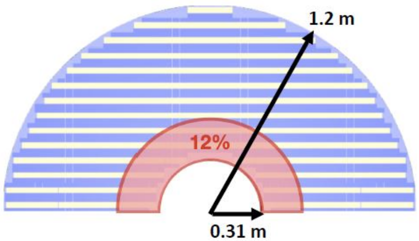


$$\sigma_i = \sqrt{(\sigma_{ij}^2 + \sigma_{ik}^2 + \sigma_{jk}^2)/2} \sim \textbf{42-46 ps}$$

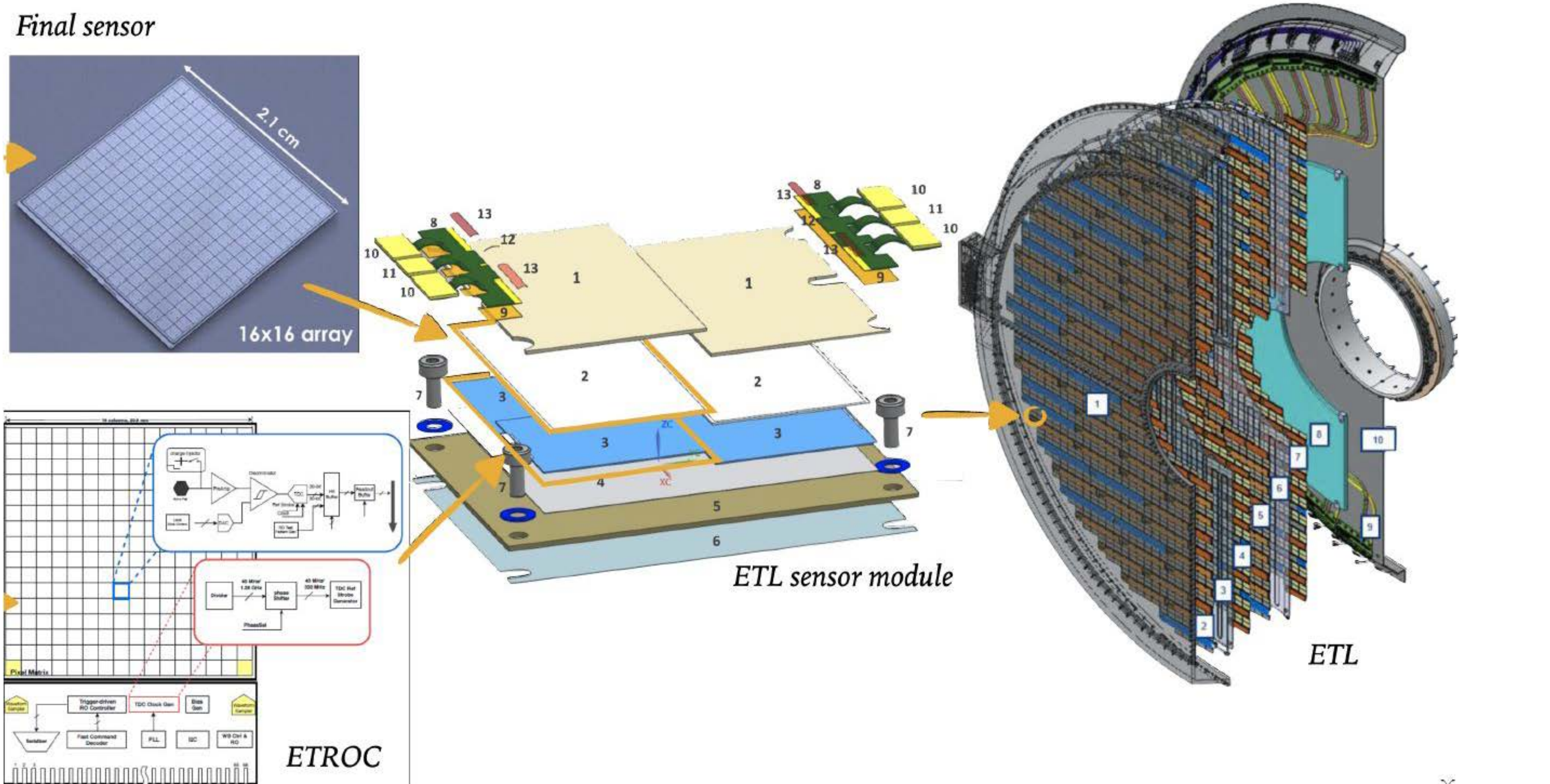


ETL

- **Embedded in neutron moderator in front of HGCAL, 200 Kg, thickness 42 mm, out radius about 1.2 m, 8M channels.**
- **Radiation level up to >10^{15}**
- **Two layers of LGAD, achieving a combined 30 ps BOL, <60 ps EO**



Radiation fluence expected in ETL, in red the region > $1x10^{15}$ n_{eq}/cm^2

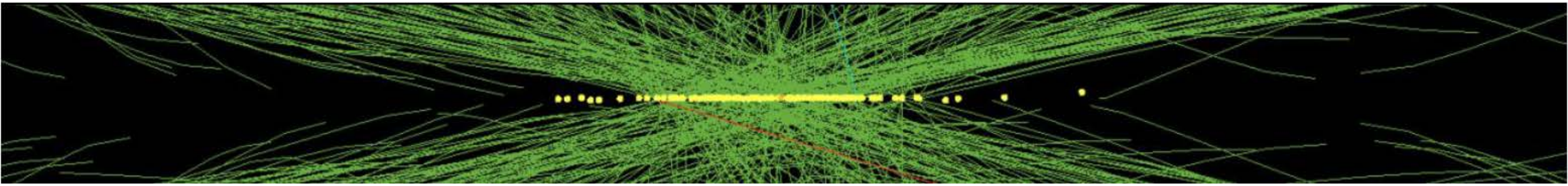


Summary

- Hadron colliders continue to be prominent tools in particle physics
  - Detectors need to evolve to harvest physics potential

- Timing will have high impact on the HL-LHC physics program
  - TOF for particle ID, 4D reconstruction, LLP signatures
  - Enhance statistical significance of Higgs analysis by reducing effective pile-up

- CMS timing upgrade well advanced :
  - Transitioning from last prototype rounds to pre-series stage.
  - Design choices and concepts confirmed in lab and beam tests.
  - Detector production scheduled to start in 2023.



Backup