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

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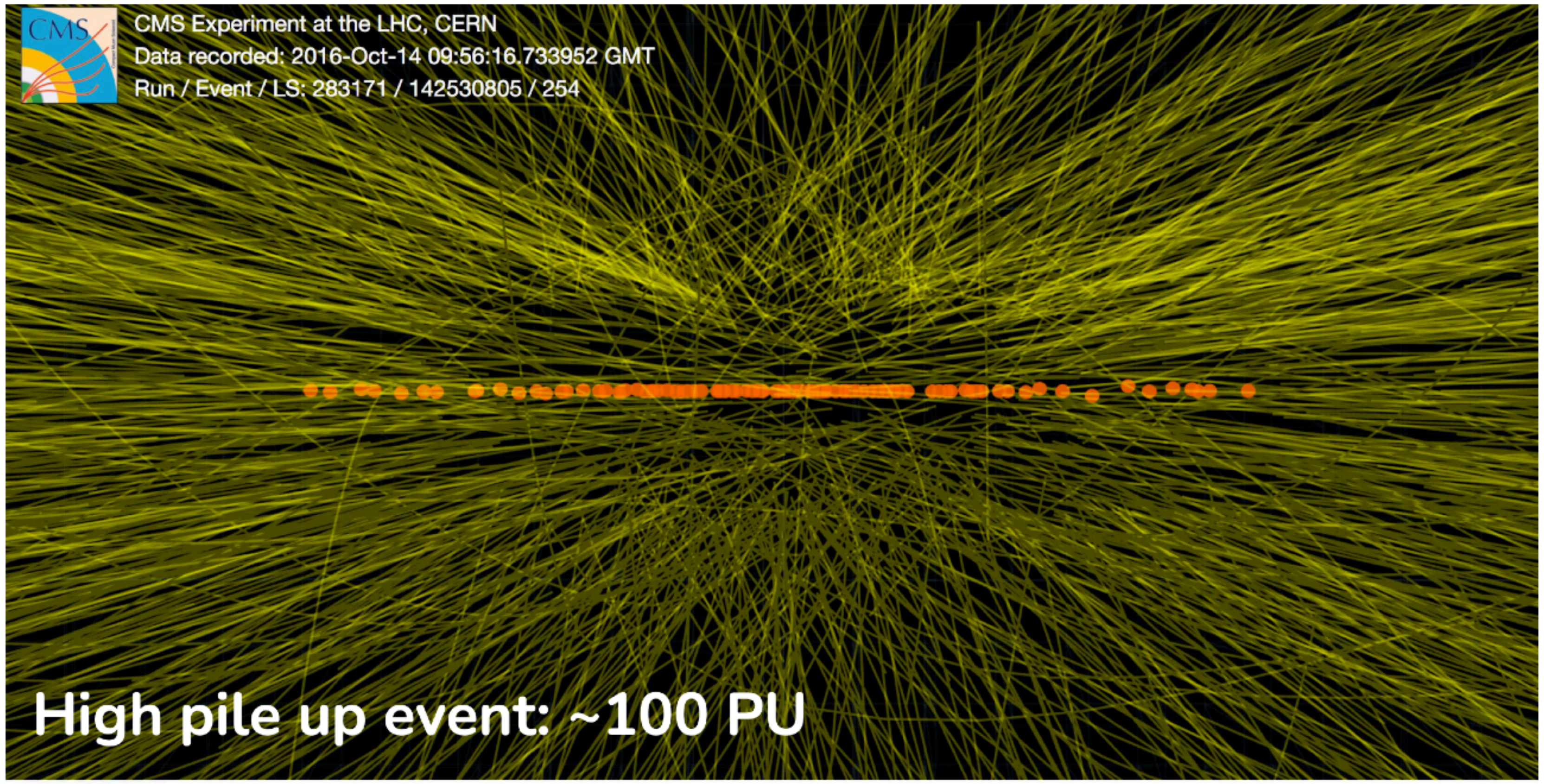
The HL-LHC Challenge

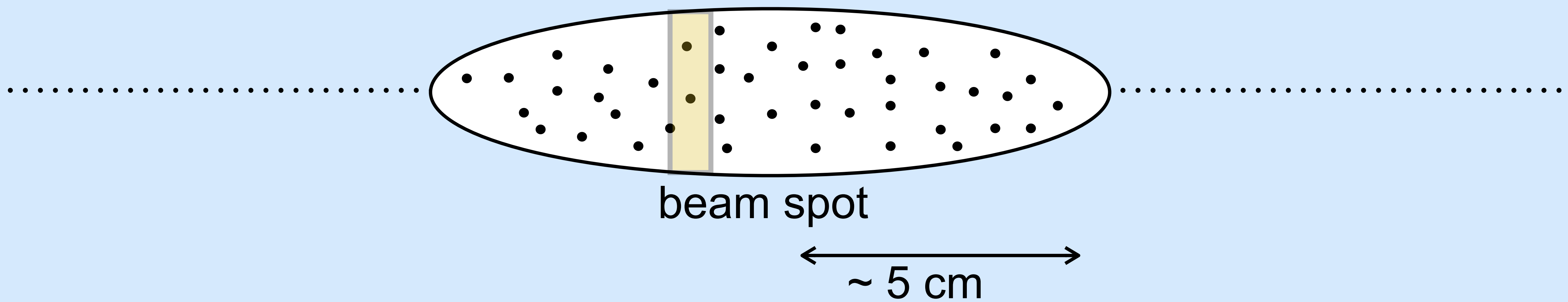
- **After 2027 luminosity** of LHC **will be increased** to enhance the potential for discoveries
  - **x5 - x7.5 present instantaneous luminosity**
  - **From 40 to 200 concurrent interactions**
- **Detectors to be upgraded** to cope with higher radiation and pileup
- **Significant issue from increased track occupancy**
  - **Additional handles to mitigate impact of pileup needed**



4D Reco: Benefits from Timing

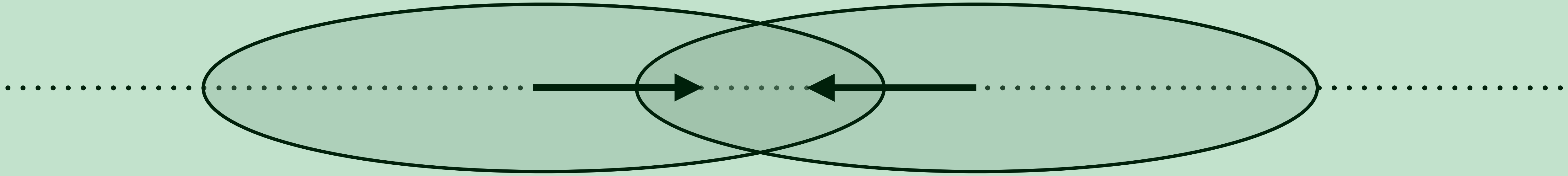
Reduction of pileup contamination by **exploiting timing of particles**

3D: vertexing consistent with primary vertex within a slice in z.



4D with addition of timing info: it selects particles consistent with primary vertex within a slice in time.

30 ps resolution in time ⟺ additional O(6) rejection factor



bunches cross in ~ 200 ps

4D Reco: Benefits from Timing

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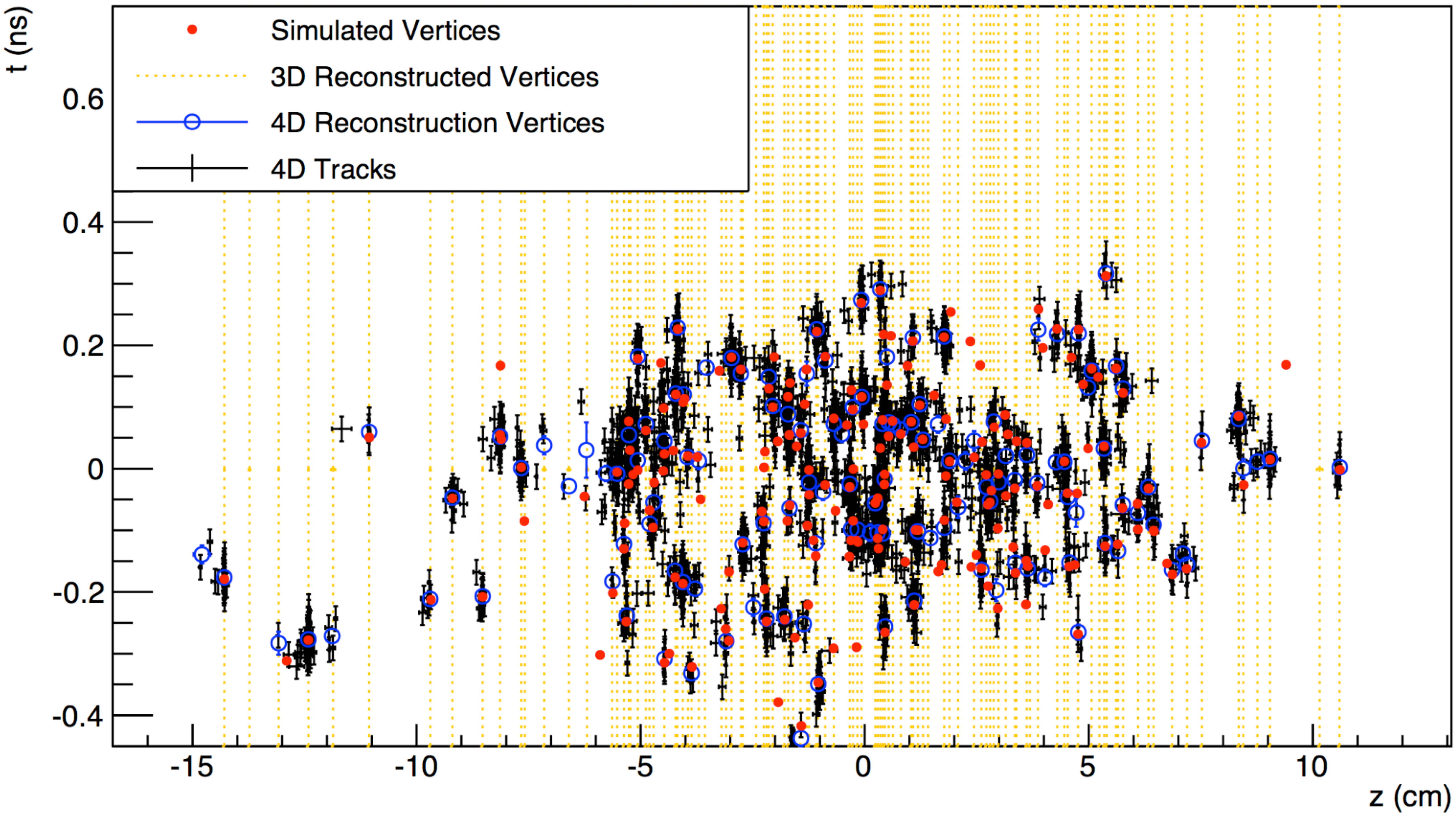
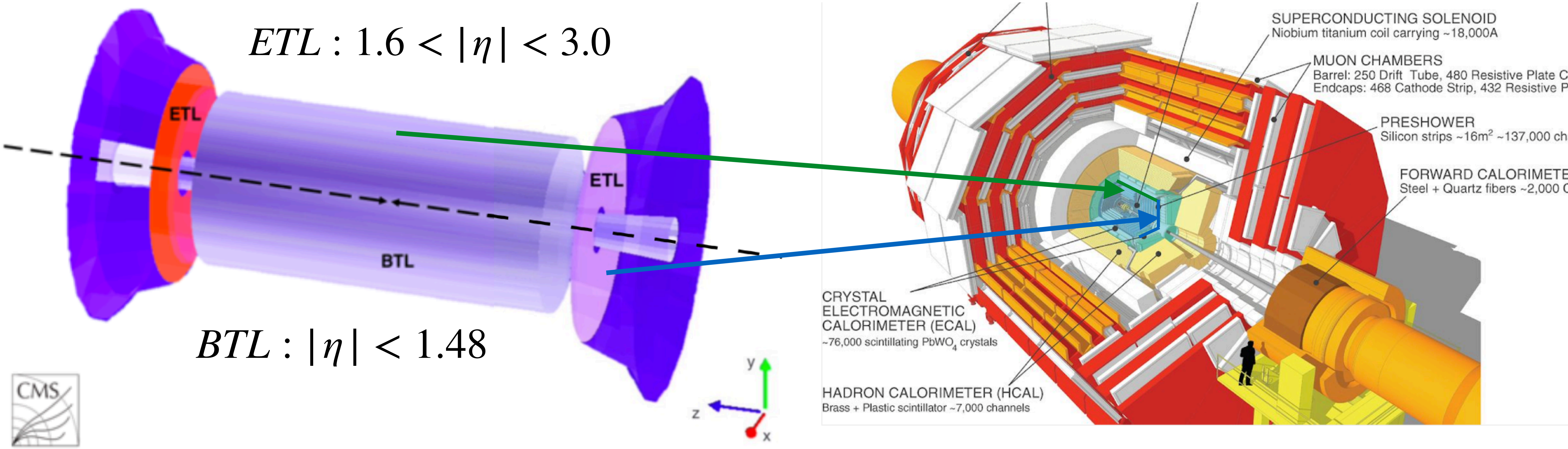


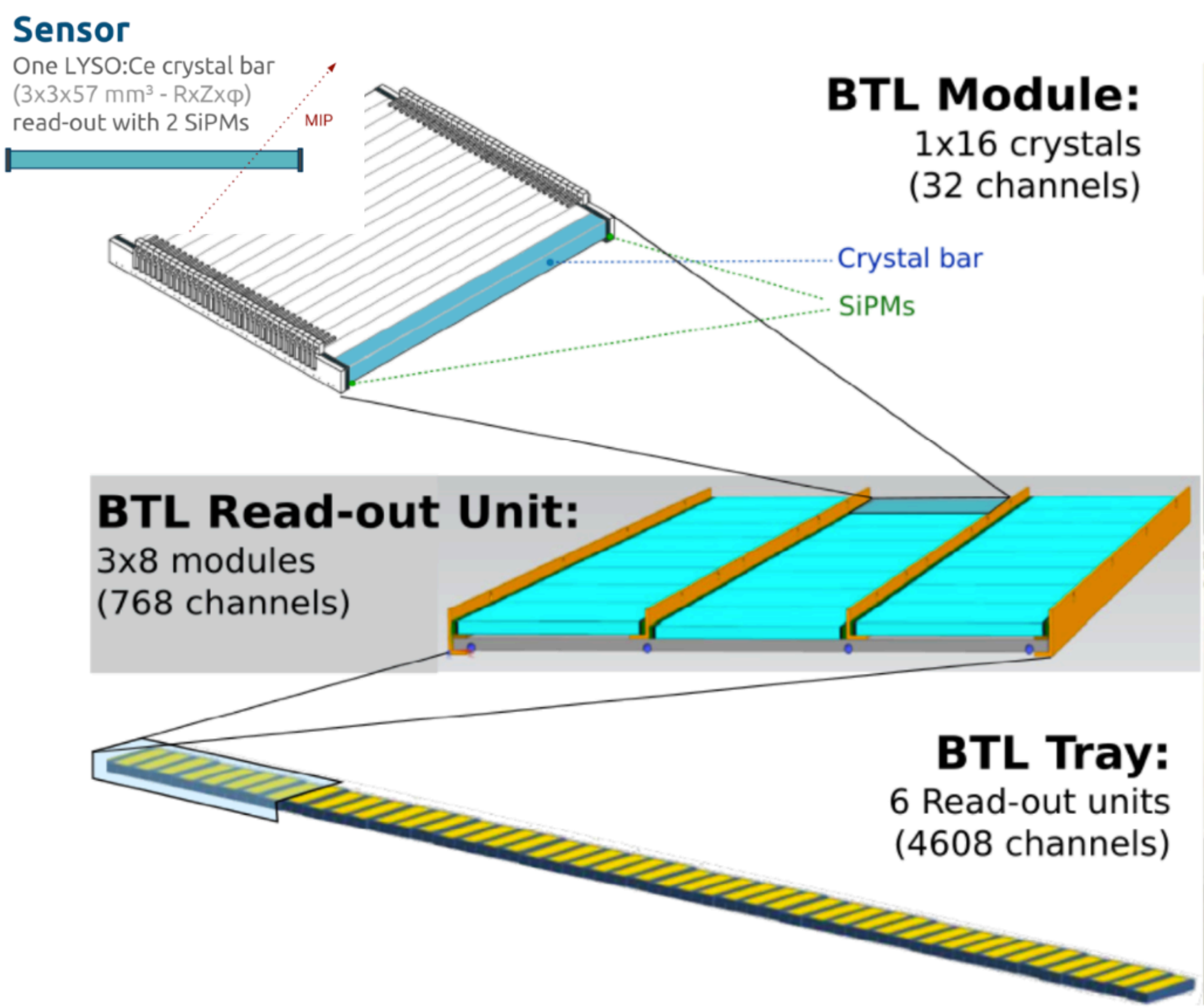
CMS MIP TIMING DETECTOR

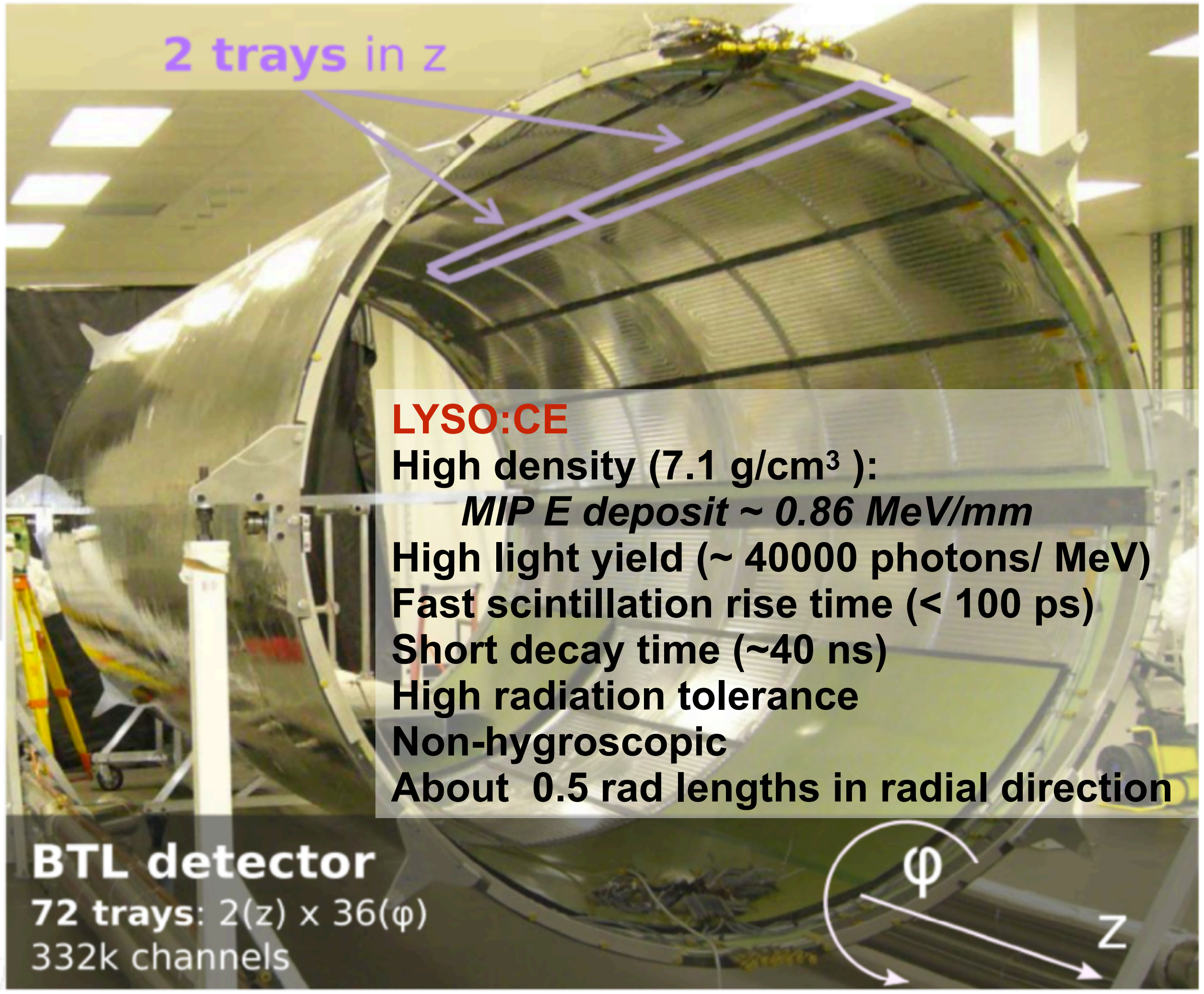
- **CMS proposes to build a Minimum Ionizing Particle (MIP) Timing Detector (MTD):**
  - Measurement of timing of charged tracks
    - 30-40 ps time resolution for MIPs (beginning of HL-LHC)
- **Different technologies, depending on radiation**
  - ***Barrel*** (fluence ~ 10^{14} neq/cm^2) LYSO:Ce crystal bars coupled to SiPM
  - ***Endcap*** (fluence ~ 10^{15} neq/cm^2) Low Gain Avalanche Diodes with ASIC readout



BARREL: REQUIREMENTS AND CHOICES (I)

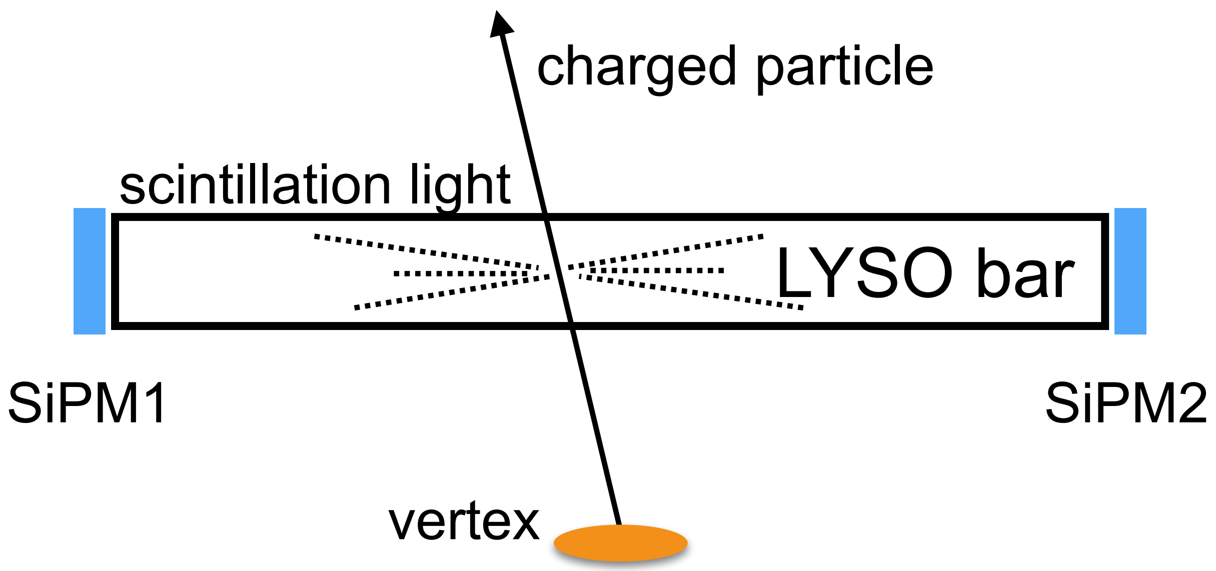
- **Fast and high light yield sensors:** use of 3 × 3 × 57 mm^3 LYSO bars (Lutetium Yttrium Orthosilicate crystal bars doped with Cerium)
- **Minimize radial size and impact on full CMS detector design:** use volume and tracker support tube, also for cooling
- **Simple geometry:** trays with crystals aligned in ϕ direction

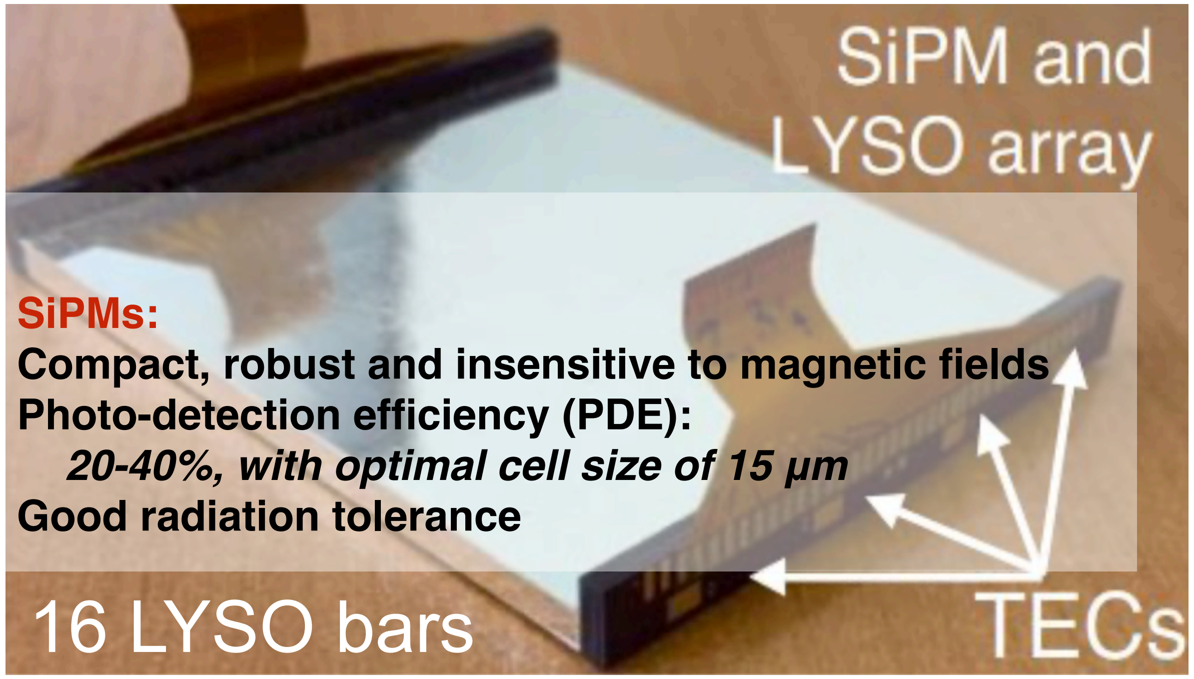




BARREL: REQUIREMENTS AND CHOICES (II)

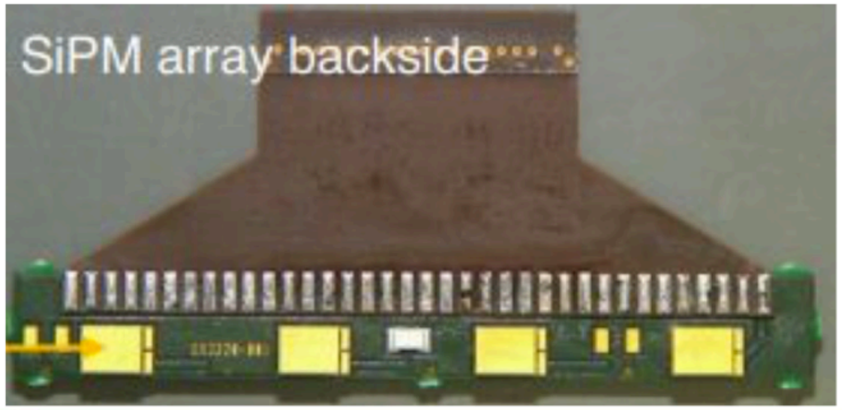
- Scintillation light measured with a pair **of Silicon Photomultipliers (SiPMs), one at each end of the crystal bar**
  - **Minimization of active area and power budget**
  - **Maximization of resolution** ($\sqrt{2}$ improvement)
  - **Determination of track position** with O(mm) resolution
- Operations at **-45^{0}C to reduce impact of dark count noise**
- **SiPMs read by ASIC (TOFHiR)** for analog processing and digitiz.
  - Noise cancellation using **baseline restoration algorithm**



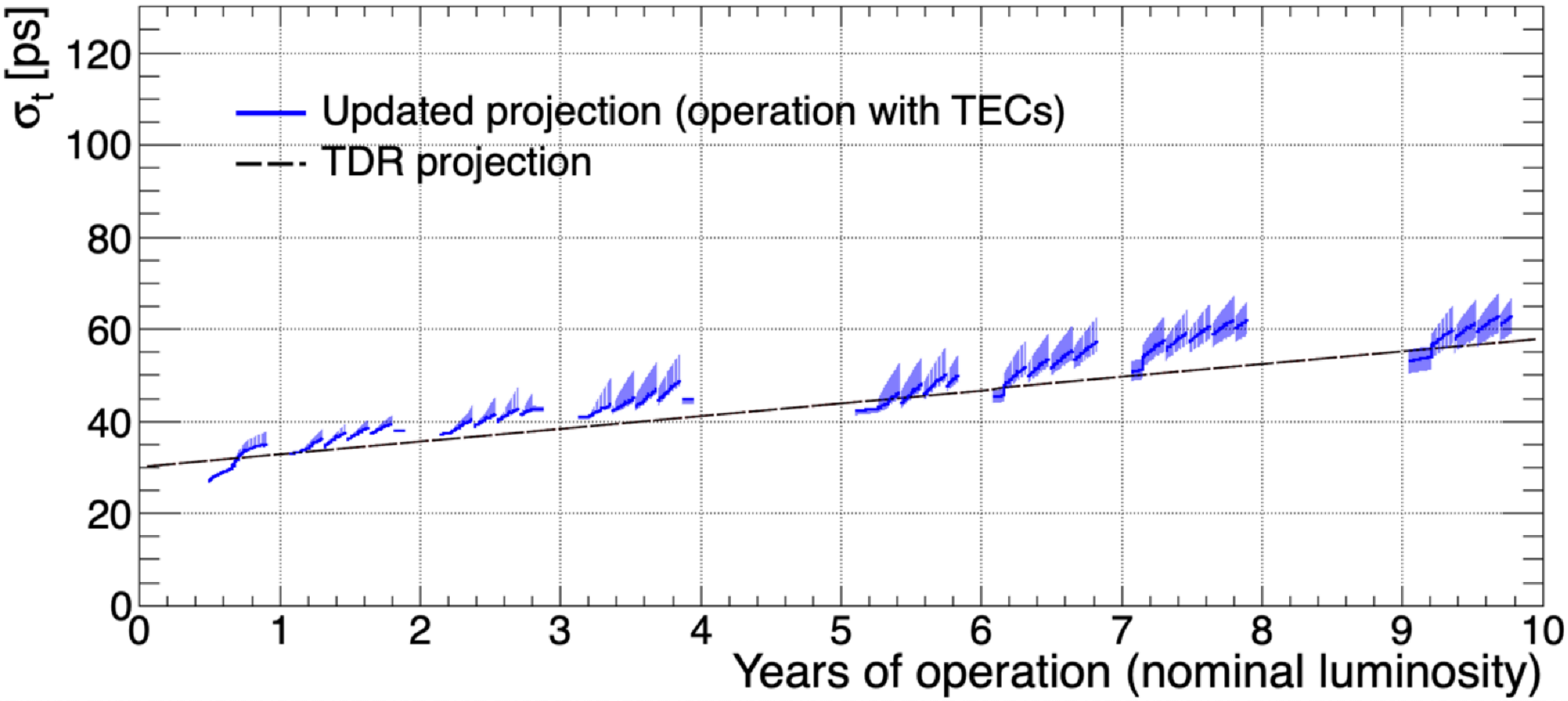


RECENT IMPROVEMENT IN DESIGN: TEC

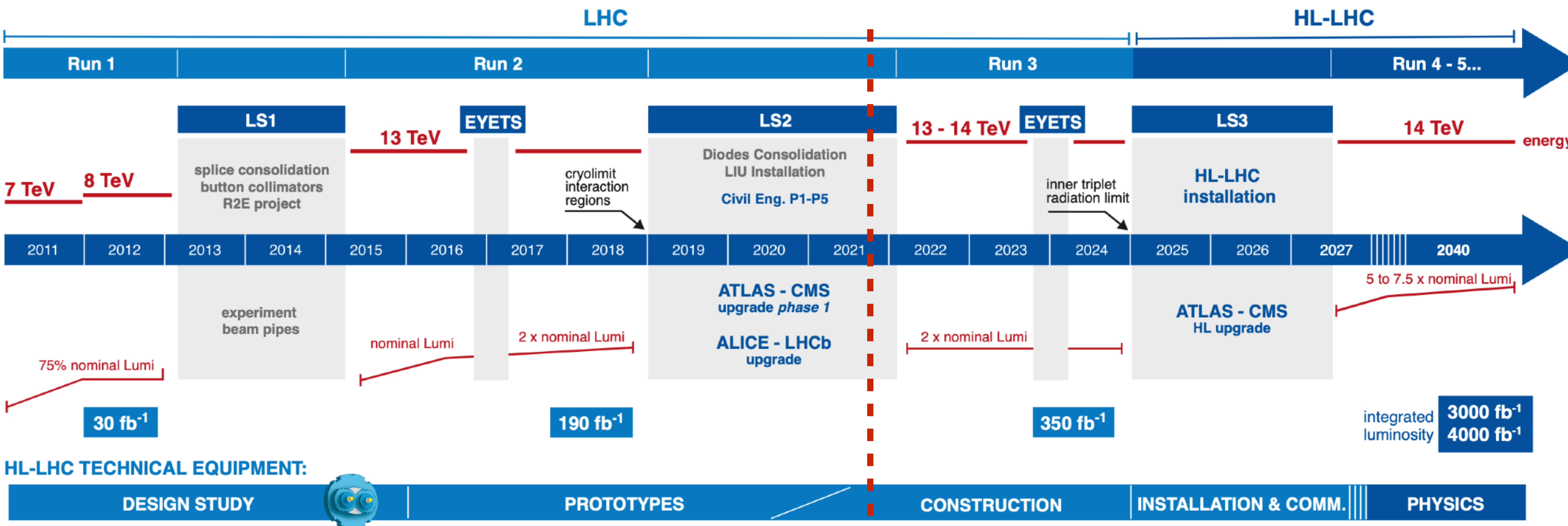
- **Two handles to mitigate impact of SiPMs dark count rate due to large radiation budgets**
  1. Reduce temperature
  2. Annealing of SIPMs

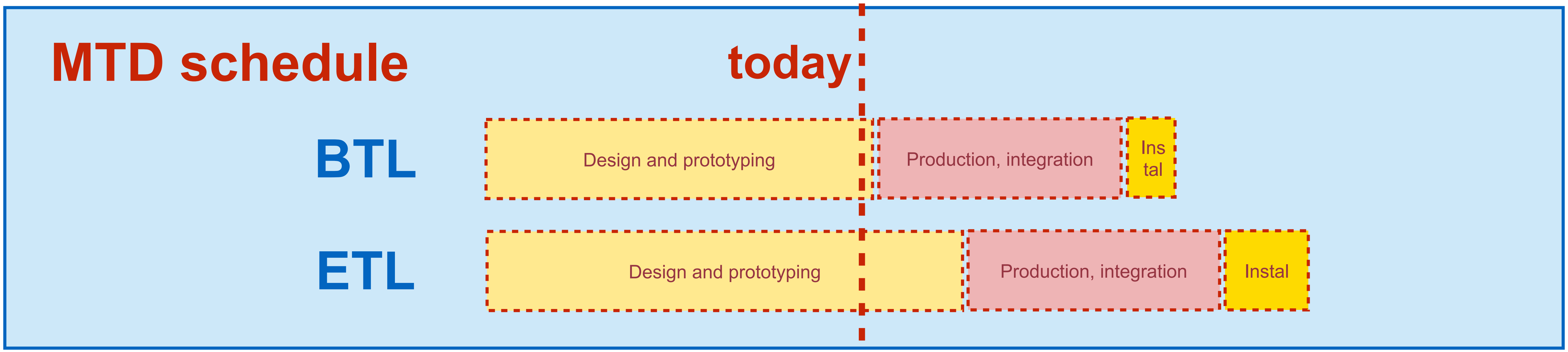


- **Added Thermoelectric Coolers (TEC) coupled to SiPMs**



WHERE WE ARE NOW

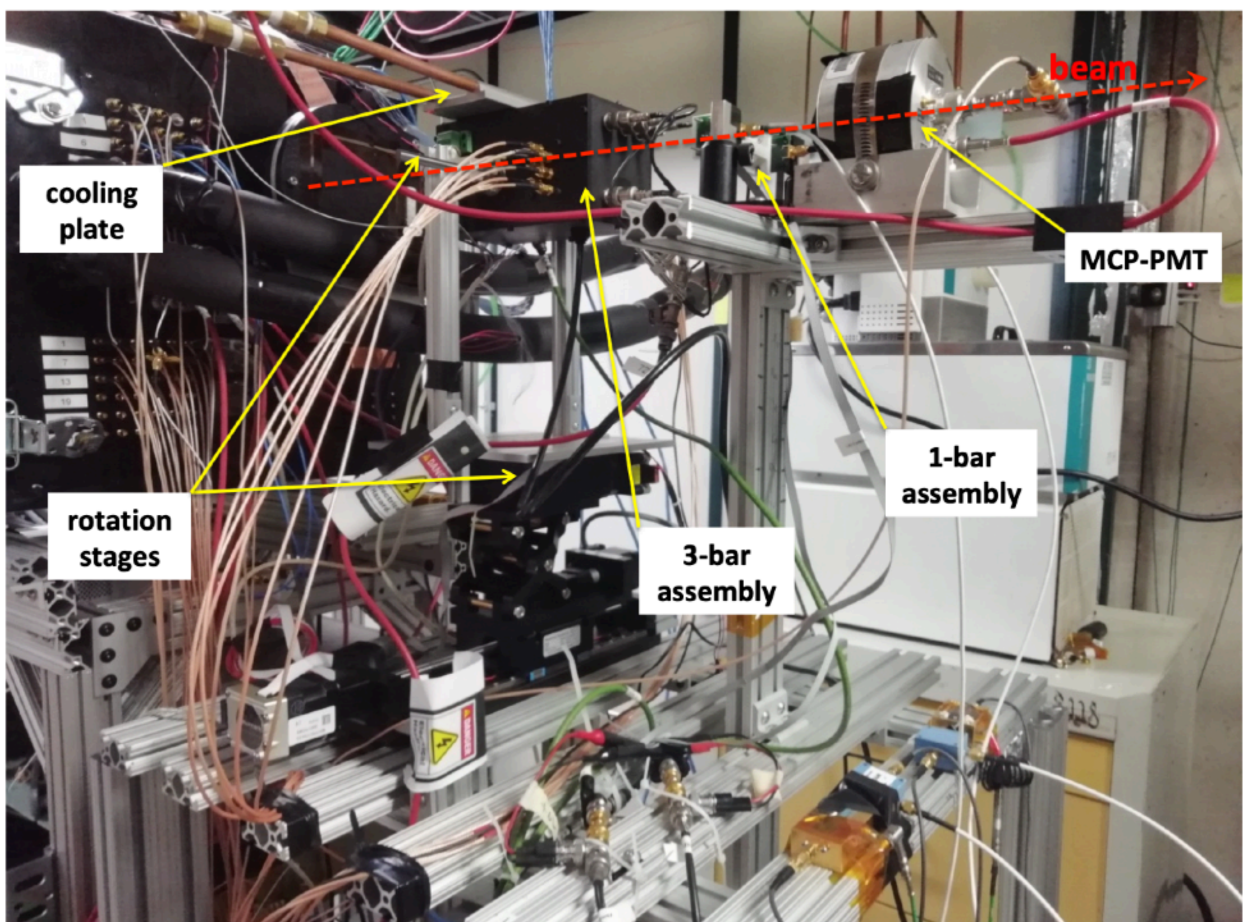




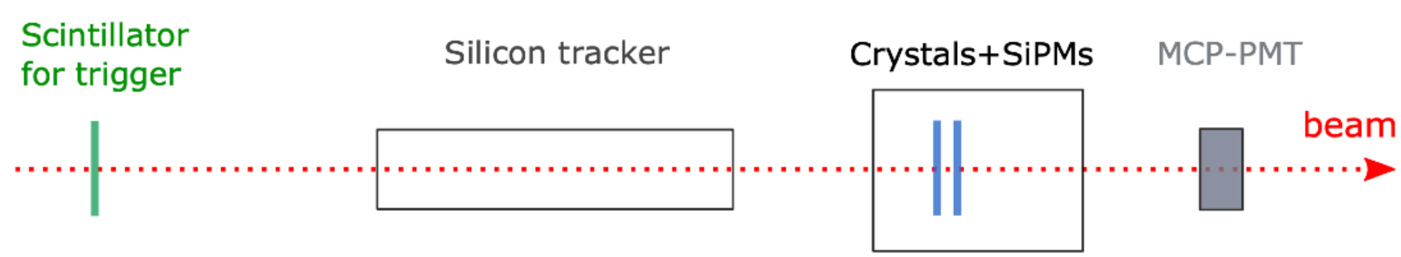
***A different timescale for BTL and ETL**: BTL to be installed prior to the Tracker Installation, ETL assembling can exploit the full Long Shutdown 3 period and installation after High Granularity Cal.*

TestBeam at Fermilab: Layout

- Testbeam 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

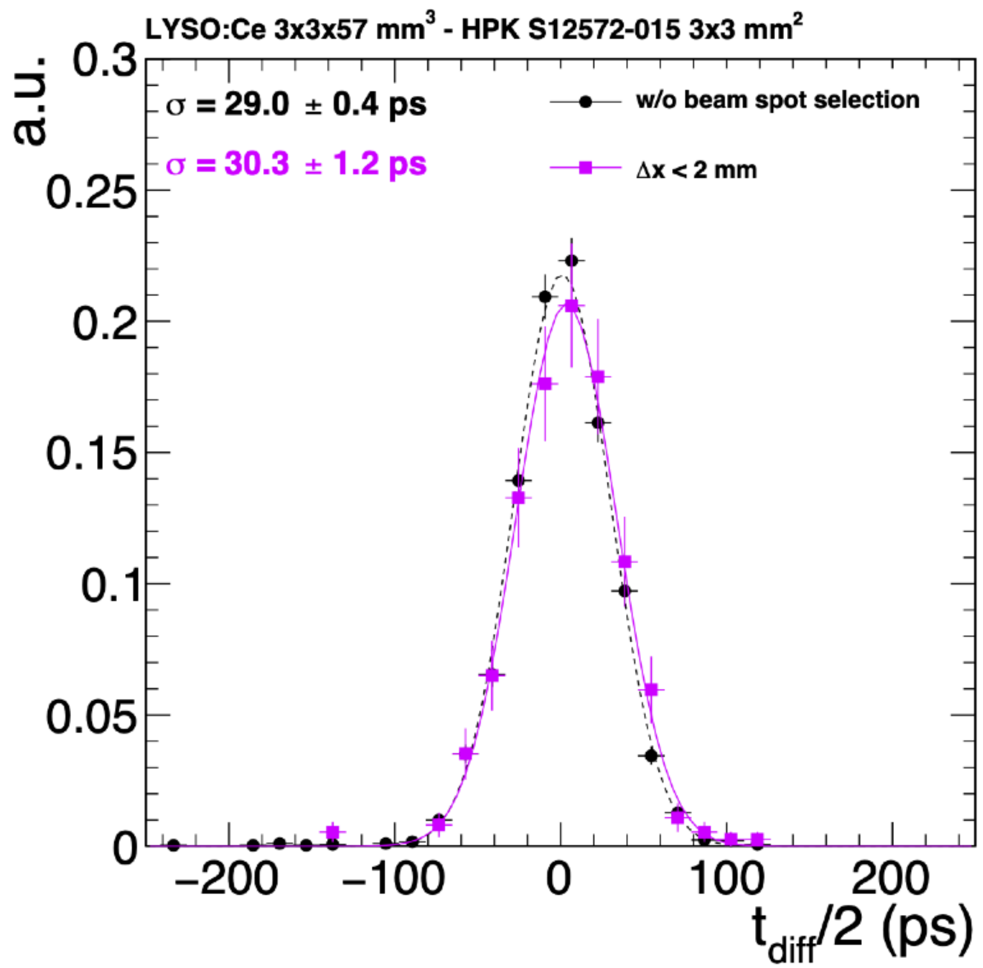


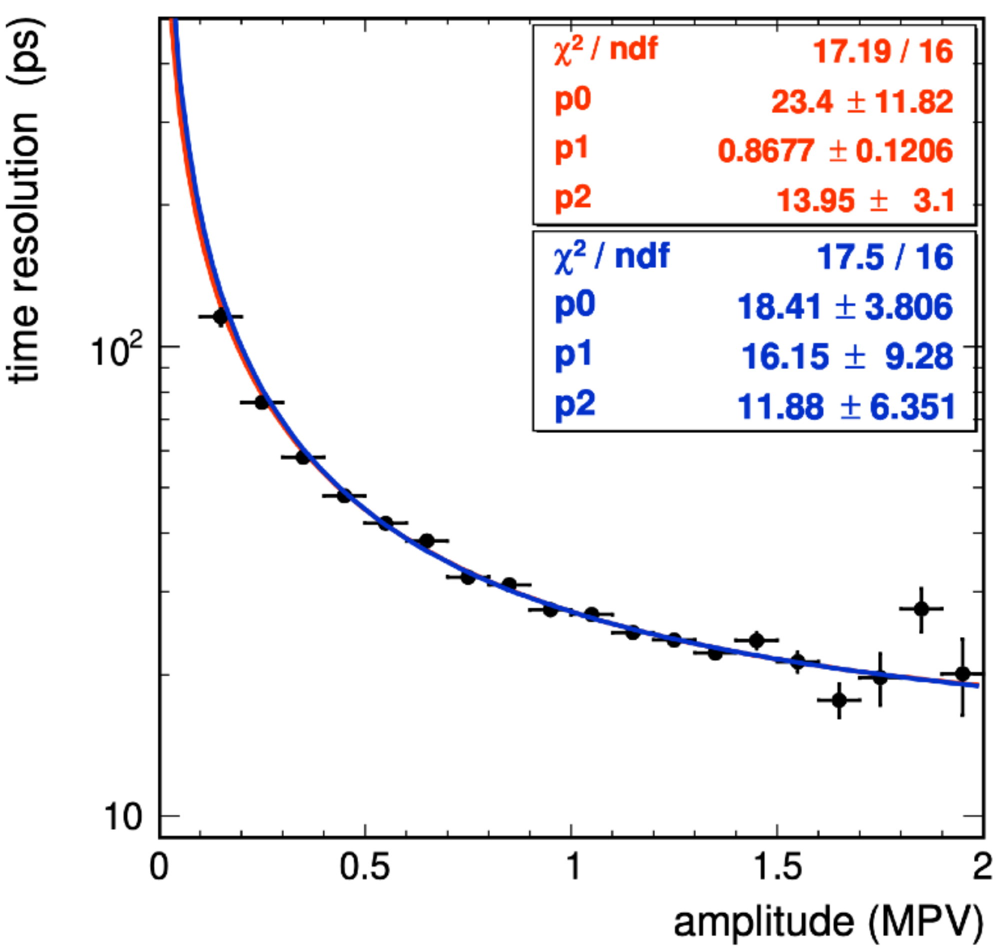
JINST: 10.1088/1748-0221/16/07/P07023



TestBeam: Time Resolution

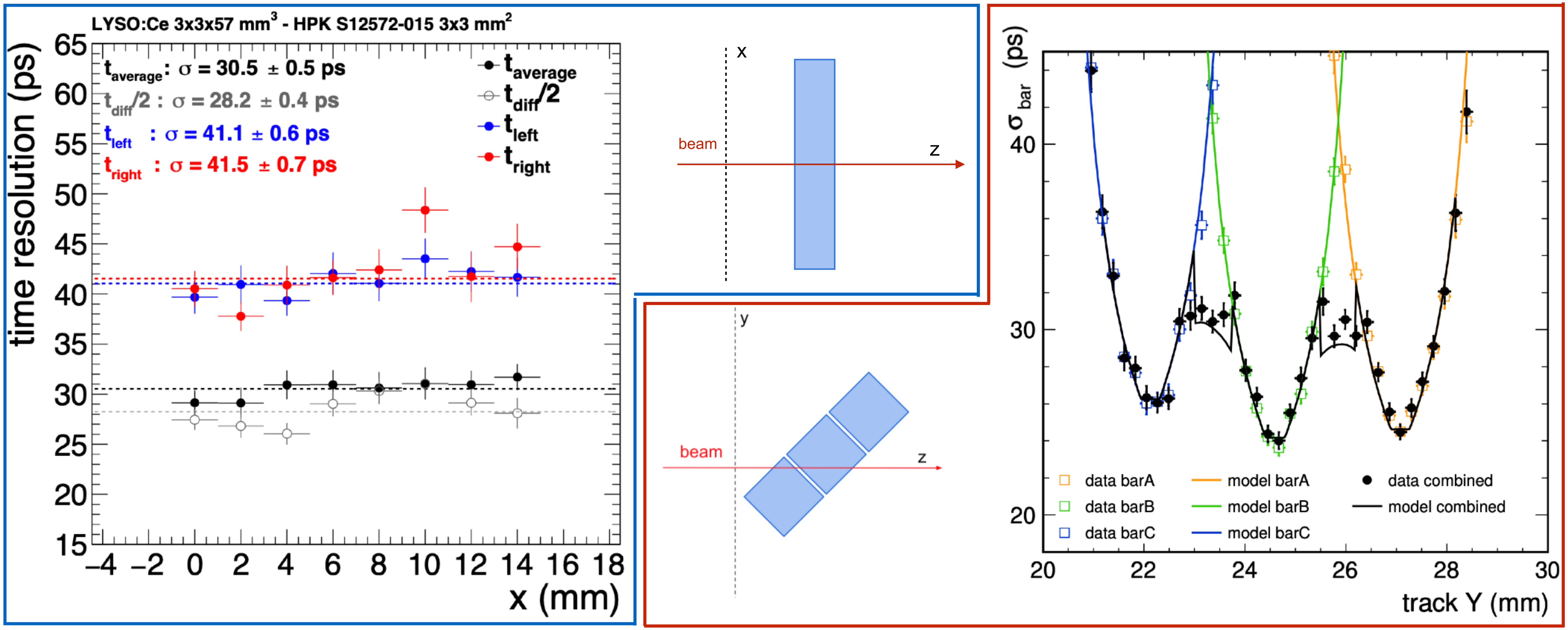
- Estimated as $\sigma_{t_{average}}$ and $\sigma_{t_{diff}}/2$ where
  - $\Delta t_{bar} = t_{average} - t_{MCP} = (t_{left} + t_{right})/2 - t_{MCP}$ and $\sigma_{t_{average}} = \sqrt{\sigma^2_{\Delta t_{bar}} - \sigma^2_{t_{MCP}}}$
  - $t_{diff} = t_{left} - t_{right}$
- **Resolution** for MIP **below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





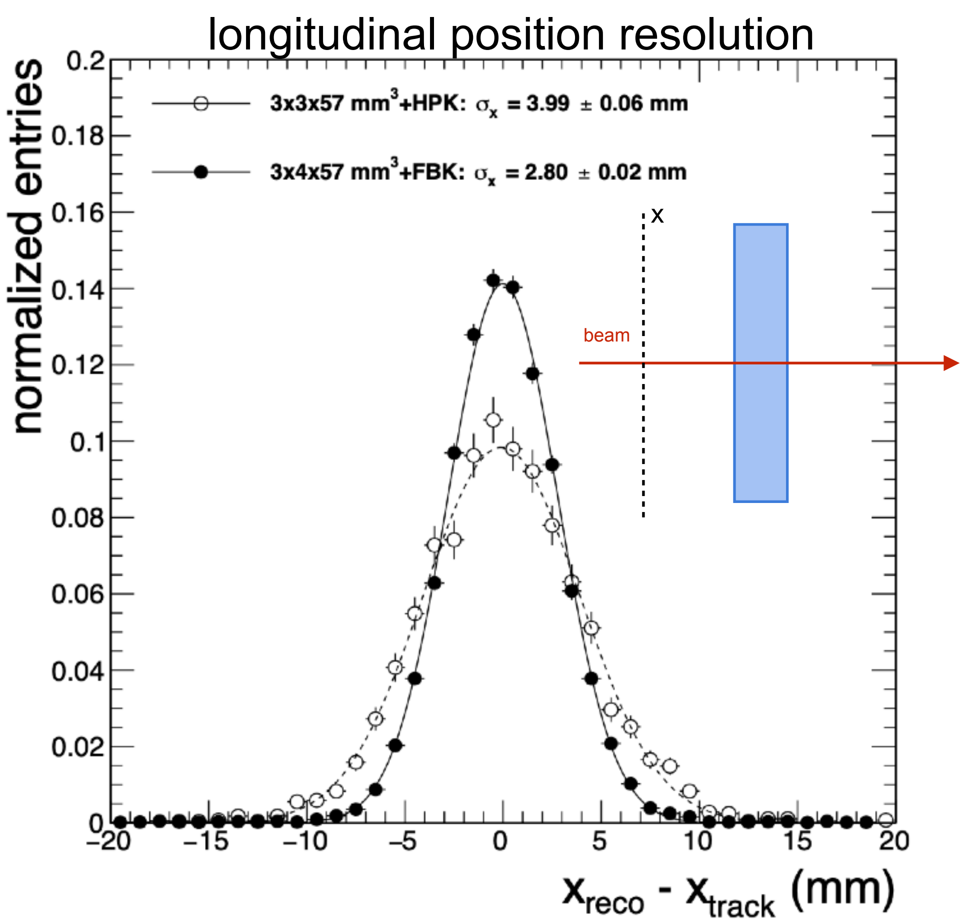
TestBeam: Uniformity of Response

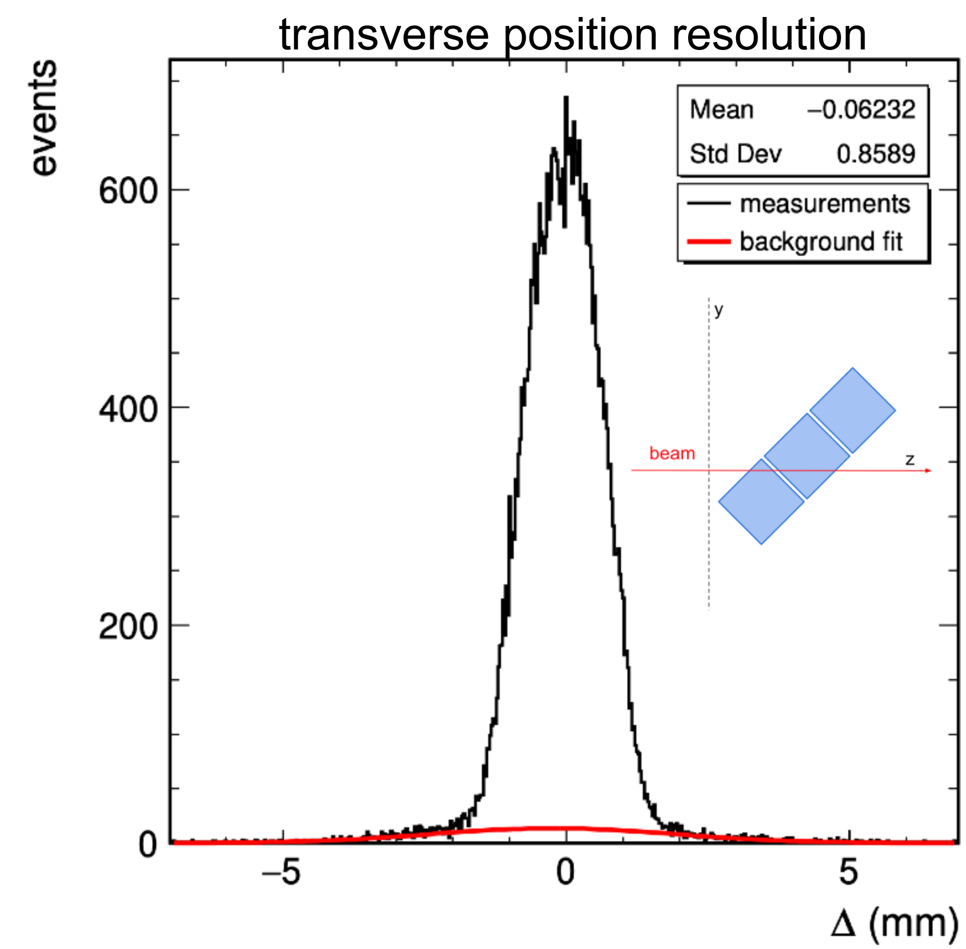
- **Uniform response and resolution** along the bar
- **Effect of gaps negligible** if gap < 200 μm
  - expect gap ~ 80 μm for final bar arrays



TestBeam: Spatial Resolution

- **Position of the track can be determined**
  - Along the bar by measuring $t_{diff} = t_{left} - t_{right}$
  - For tracks hitting more than a crystal (important for low-p_t curved tracks in CMS) with an average weighted with E deposits
- **σ ~ 3-4 mm (longitudinal) and <1 mm (transverse for 45^0 tracks)**
  - Representing another position measurement added to tracker ones

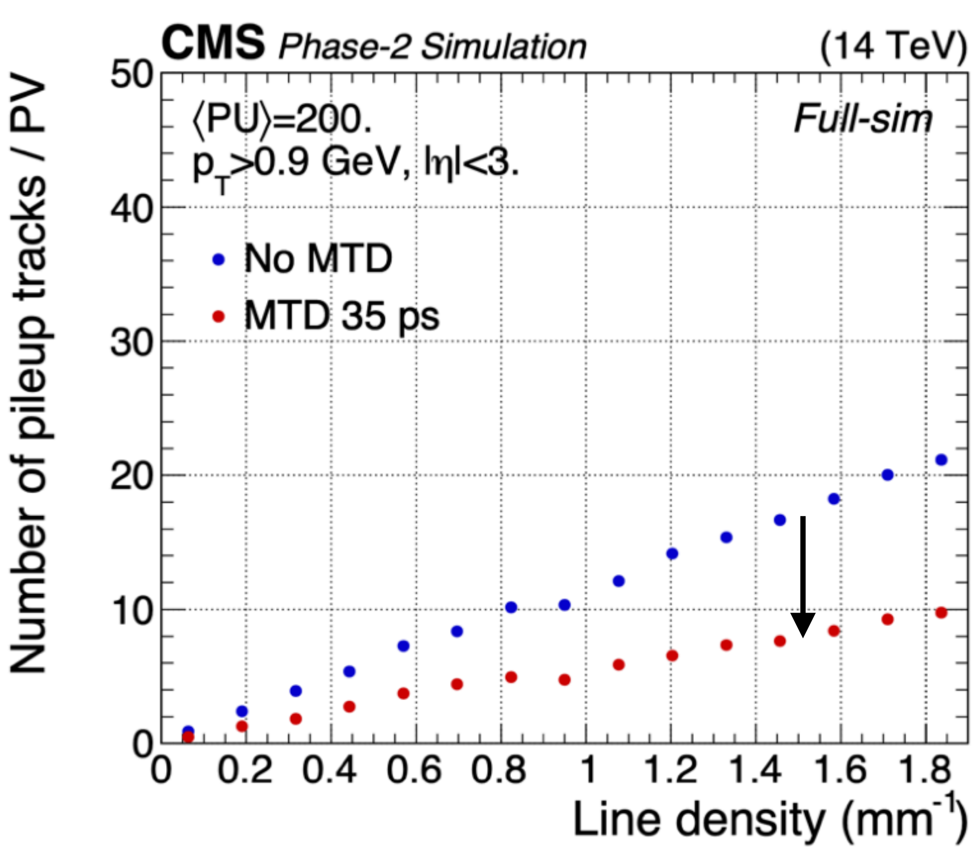




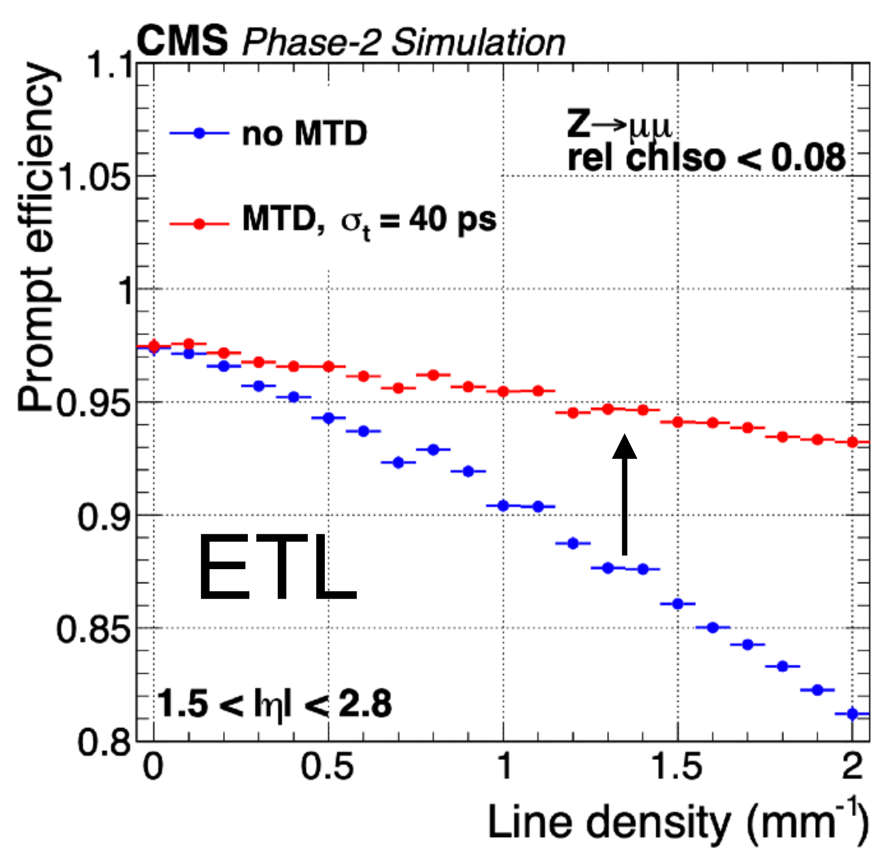
Physics Performance in Reco

- **Pile-up:** average track reduction of ~2.4
- **Lepton isolation:** efficiency gains 3% (BTL) 6% (ETL) for high pT muons at PU200 line density. Larger at low pT
- **B-tagging:** efficiency improvements 3% (BTL) 6% (ETL)
- **Time-of-flight PID:** π/K separation up to ~2.5 GeV, K/p up to ~5 GeV

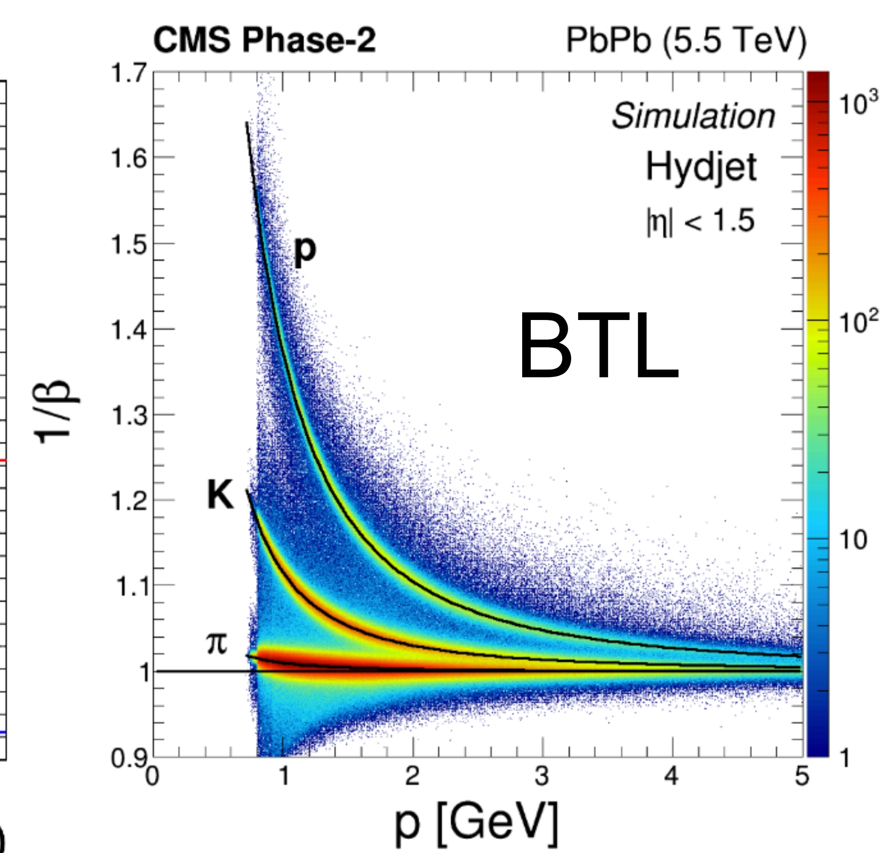
Pileup rejection



Isolation



PID



Impact in Physics Analysis: Higgs

- **Gains for complex final states such as HH**
  - **several improvements** in reconstruction contribute (including tau reconstruction and b tagging)
  - **significance increases ~12% , equivalent to ~25% increase in luminosity**

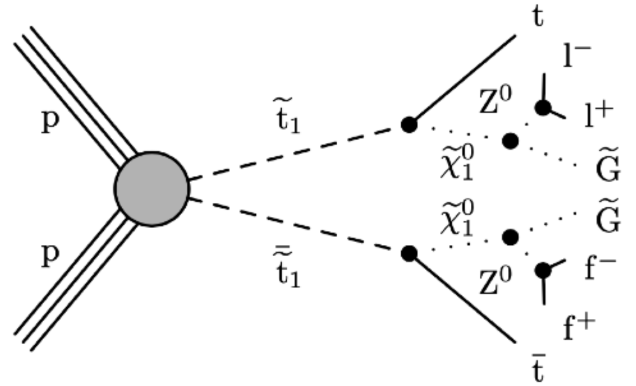
Assuming a 35ps time resolution

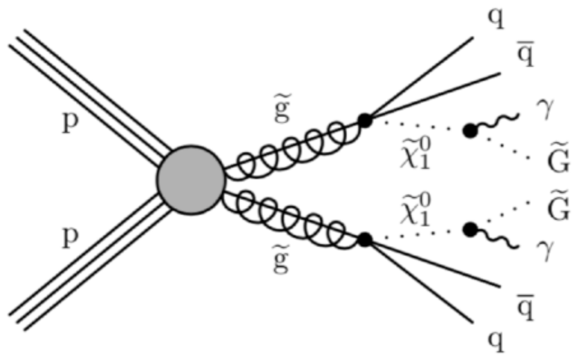
	Signal increase (%)		Expected significance	
Di-Higgs decay	BTL	BTL+ETL	No MTD	MTD
bbbb	13	17	0.88	0.95
$bb\tau\tau$	21	29	1.3	1.6
$bb\gamma\gamma$	13	17	1.7	1.9
bbWW			0.53	0.58
bbZZ			0.38	0.42
Combined			2.4	2.7

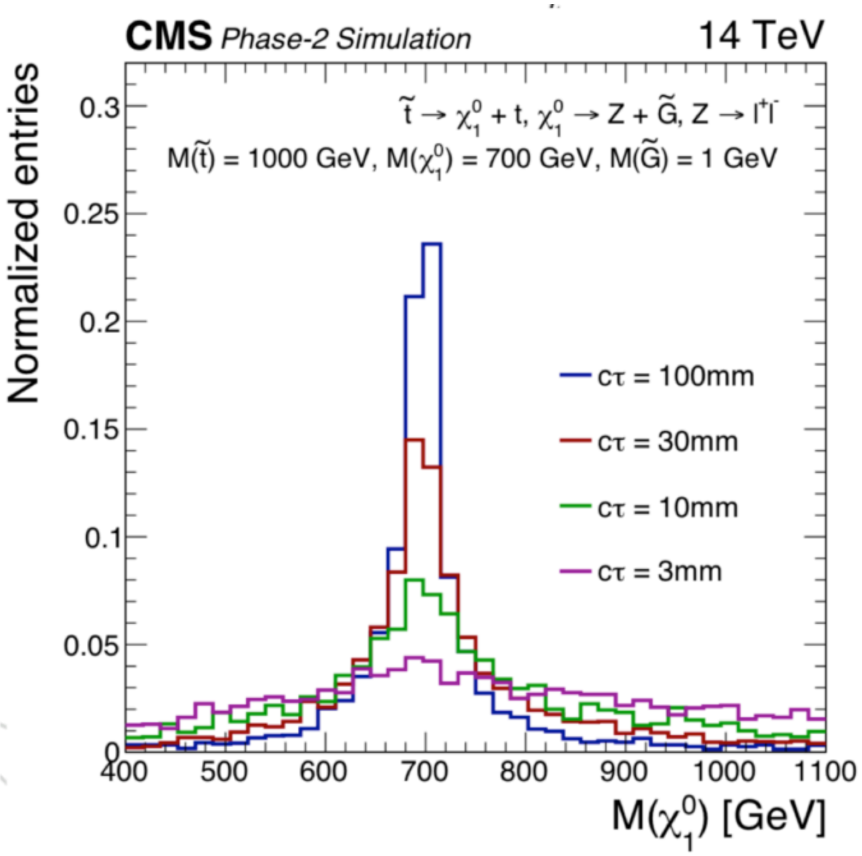
IMPACT IN PHYSICS ANALYSIS: LONG-LIVED

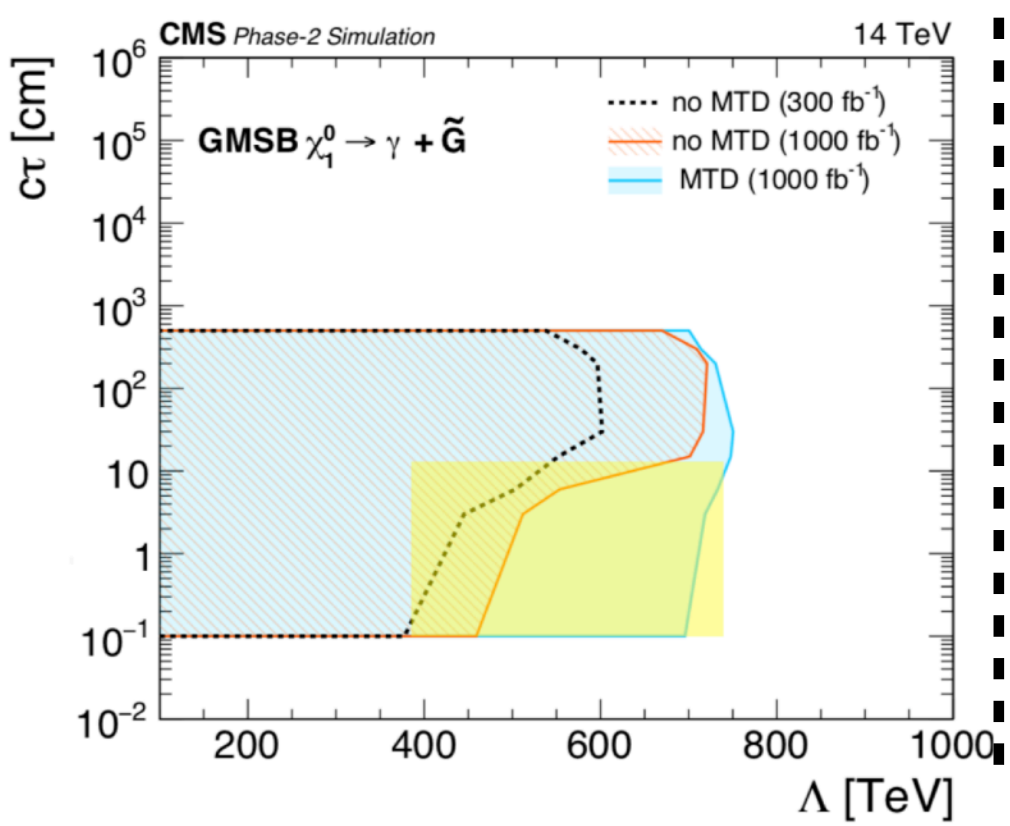
Neutralino in Z/γ G (gravitino)

- **with Z**: β from displaced decay vertex time ⇒ χ_0 mass reconstruction
- **with γ**: TOF improvement via 4D vertex recon.



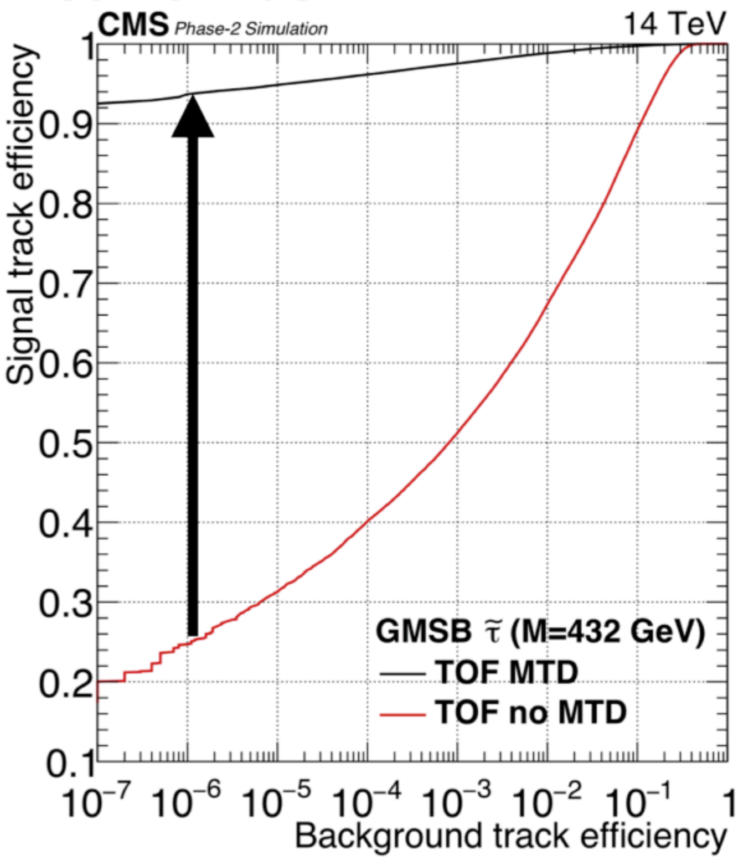






Heavy stable charged particles

β resolution improved by 1 order of magnitude



CONCLUSIONS

- **CMS MIP timing detector exploits timing of charged tracks** to **mitigate impact of pile-up** at HL-LHC conditions
  - **30-40 ps resolution** at start of HL-LHC degrading to 60 ps at the end
  - **Improvements in reconstructed objects using 4D reco** and LHC conditions recovered
  - **Benefits** in several areas of physics (e.g. **HH and Long-lived**)
- **Barrel sector based on LYSO:Ce crystals coupled to SiPMs**
  - Recent **addition of thermoelectric coolers** in design
  - Design and prototyping being completed, **production starting soon**
- **Recent results at testbeams are encouraging**
  - Confirmed **better than 30 ps baseline resolution and uniformity**
  - **Determination of track position** with O(mm) resolution
  - **Details in JINST paper**: 10.1088/1748-0221/16/07/P07023

BACKUP

READOUT UNIT (768 SIPMS)

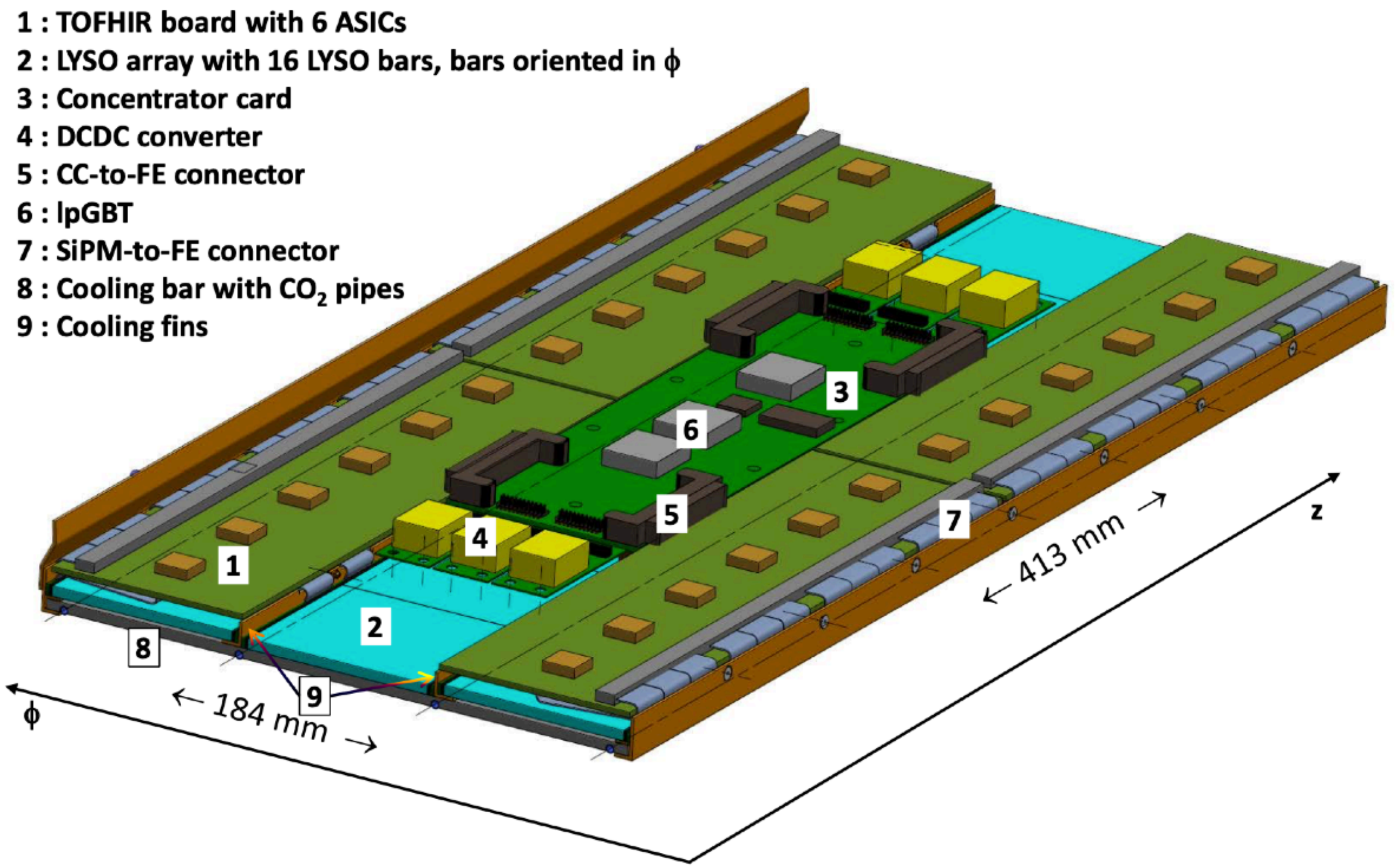


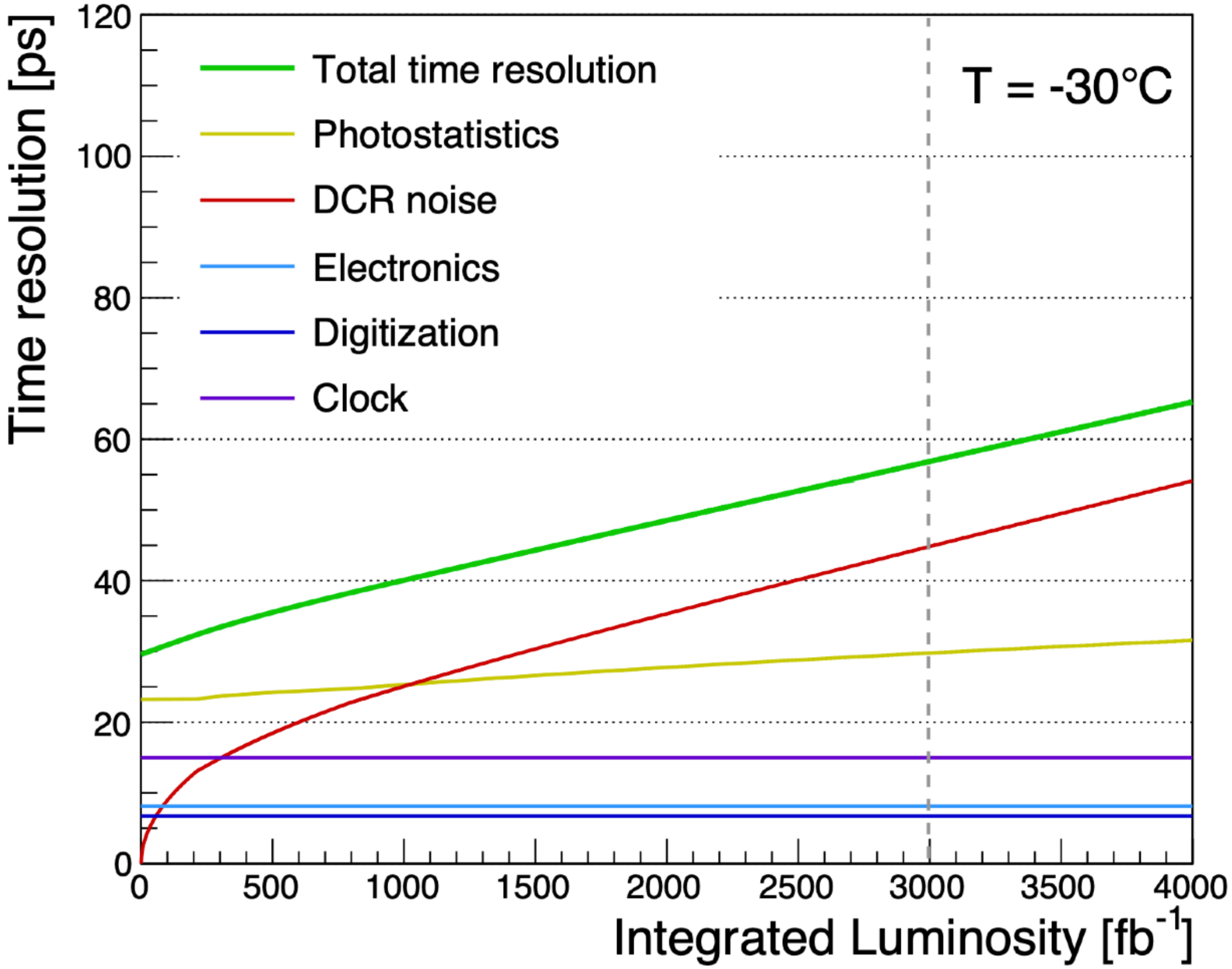
Table 2.1: Summary of the BTL modularity and channel count. The number of items in each module, readout unit and tray are shown.

	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

Contributions to Resolution

$$\sigma_t^{\mathrm{BTL}} = \sigma_t^{\mathrm{clock}} \oplus \sigma_t^{\mathrm{digi}} \oplus \sigma_t^{\mathrm{ele}} \oplus \sigma_t^{\mathrm{phot}} \oplus \sigma_t^{\mathrm{DCR}}$$

$$\sigma_t^{\mathrm{phot}} \propto \sqrt{\frac{\tau_r \tau_d}{N_{\mathrm{phe}}}} \propto \sqrt{\frac{\tau_r \tau_d}{E_{\mathrm{dep}} \cdot \mathrm{LY} \cdot \mathrm{LCE} \cdot \mathrm{PDE}}}$$



Impact on Physics Analysis: Summary

Signal	Physics measurement	MTD Impact
HH	**+25%** gain in signal yield → Consolidate searches	Isolation, b-tagging, MET
H→γγ H→4leptons	**+25%** statistical precision on xsecs → Couplings	Isolation, Vertex identification
VBF+H→ττ	**+30%** statistical precision on xsecs → Couplings	Isolation VBF tagging, MET
EWK SUSY	**40%** reducible background reduction → +150 GeV mass reach	MET
Compressed SUSY	Extended reach from acceptance gains for low p_T isolated leptons	Isolation
Long Lived Particles (LLP)	New handles for selection → Unique discovery potential	β_{LLP} from timing of displaced vertices
Heavy Ion	Large combinatorial background reduction for charmed hadrons ID	PID