Precision timing with the MIP timing detector in Phase 2 CMS

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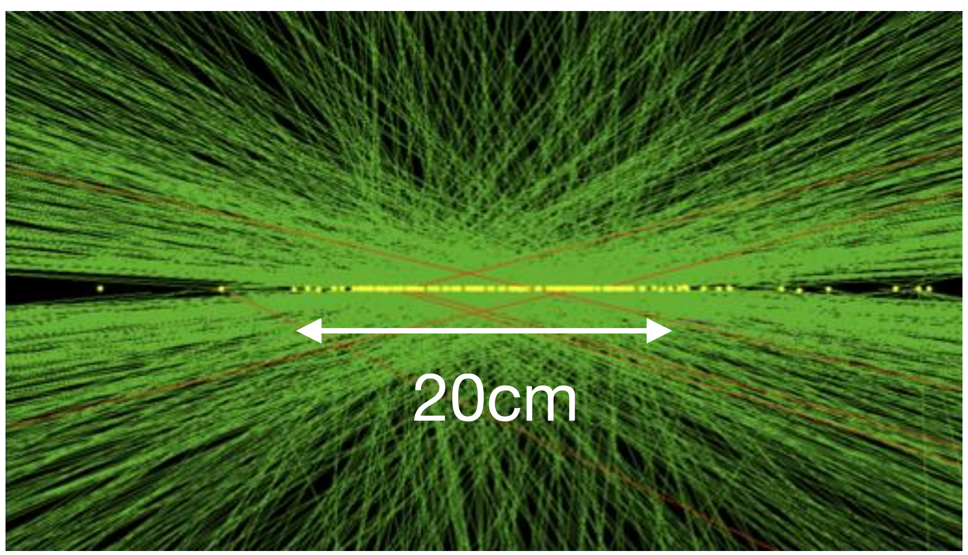
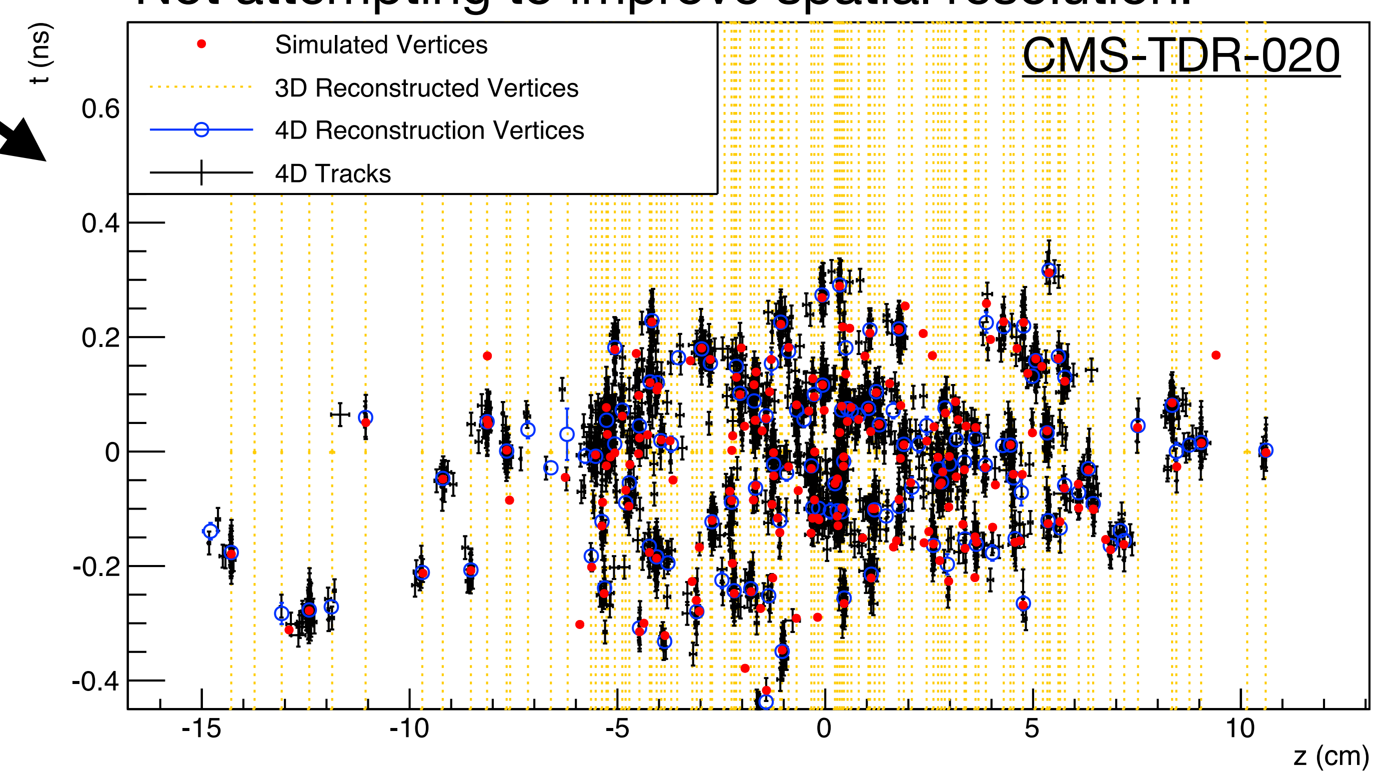
On the importance of vertex timing

- High Luminosity ➝ large number of pileup interactions, from <μ>=38 at the end of Run 2 to <μ>=200
- 200 vertices - how to disentangle them?
  - Tracker provides great spatial resolution, but **vertices will merge** if too close (separation <0.3mm)
  - Collisions are **spread in time** (~200ps) thanks to the LHC beam bunch structure
  - Resolve spatially overlapping vertices with precision timing of charged tracks ➝ maintain physics performance that relies on pileup suppression
- CMS target: **time stamps with 30-50ps resolution for every track**



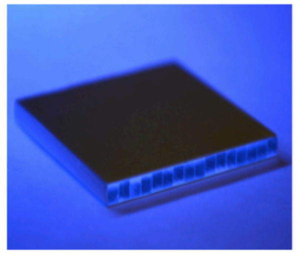
Tracks and vertices at the HL-LHC, the (probably) most shared illustration about high pileup

Timing allows to distinguish vertices at same x, y, z. Not attempting to improve spatial resolution!

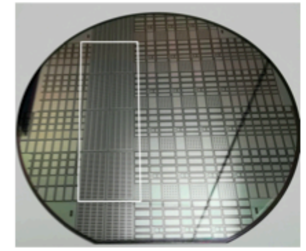


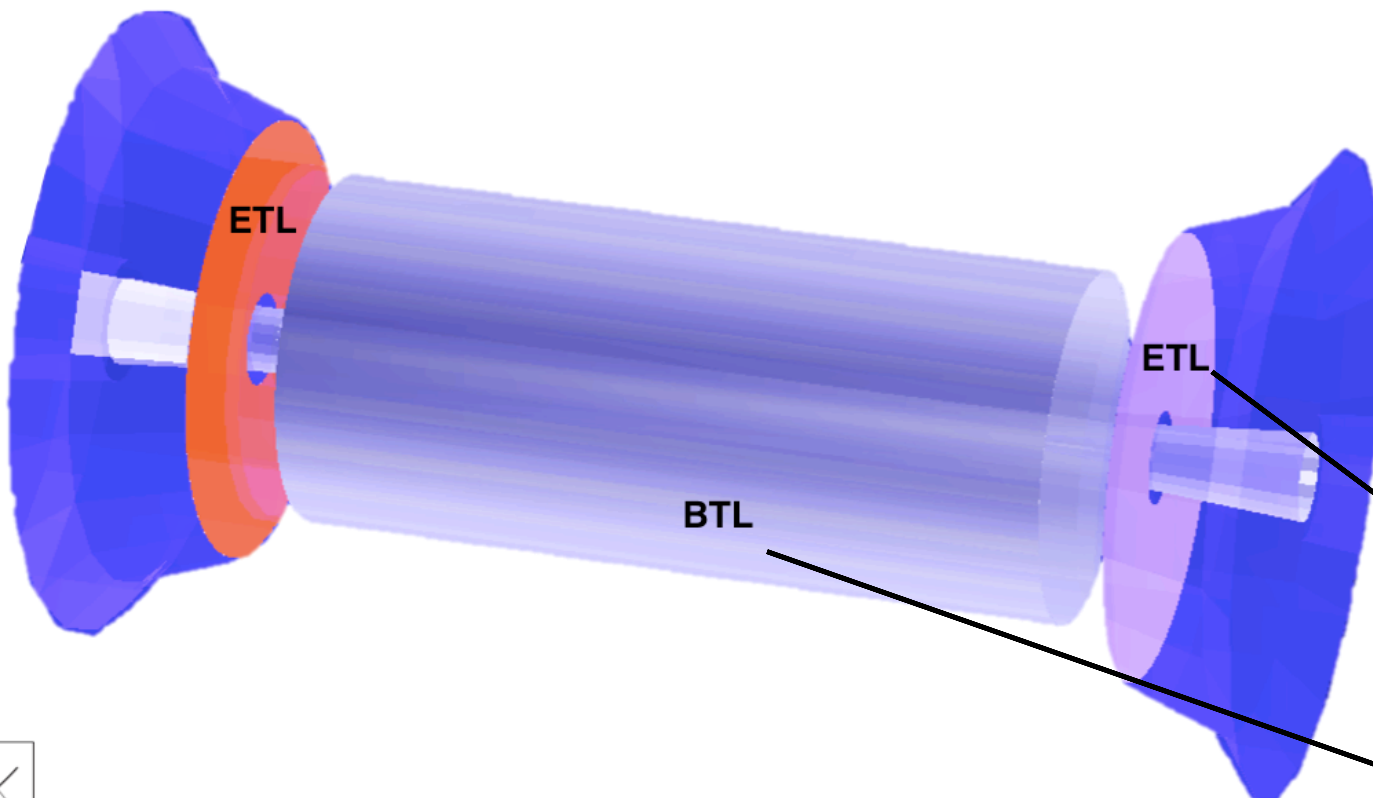
The MIP Timing Detector in CMS

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 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2

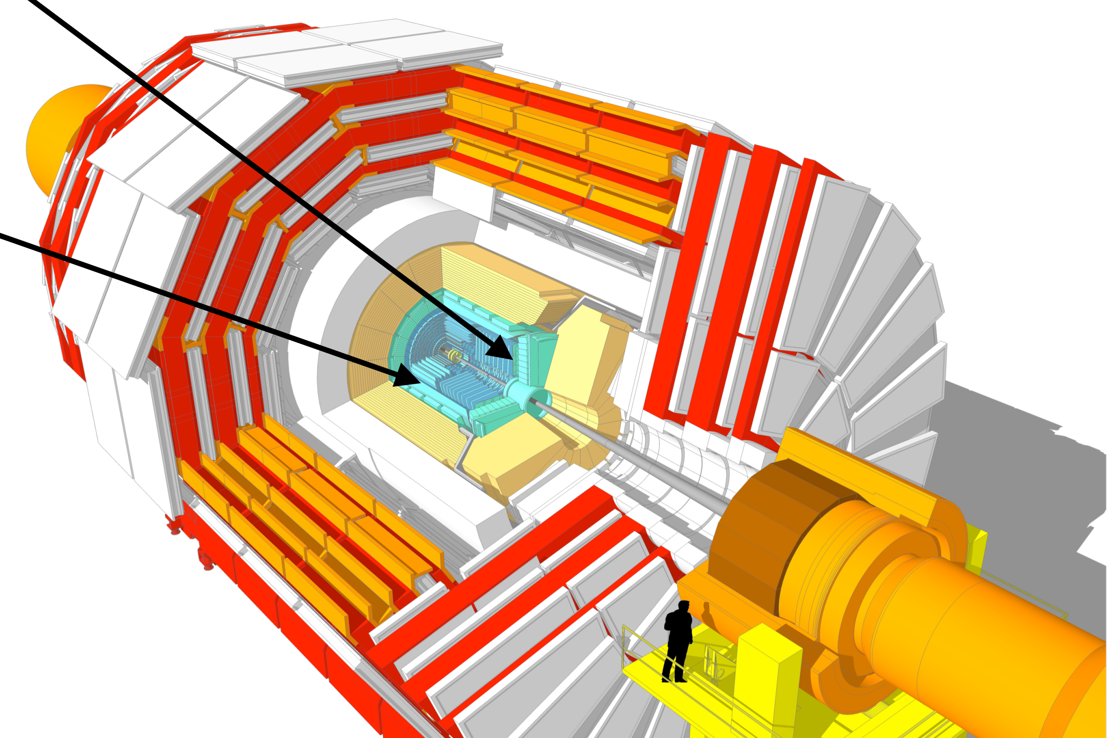


ETL: Si with internal gain (LGAD):
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2





(Almost) hermetic coverage up to |η|<3.0



Limited space available within CMS:
- **Barrel timing layer** (BTL) sits in the barrel tracker support tube
- **Endcap timing layer** (ETL) on CE nose in front of HGCal

Barrel and Endcap Timing Layers

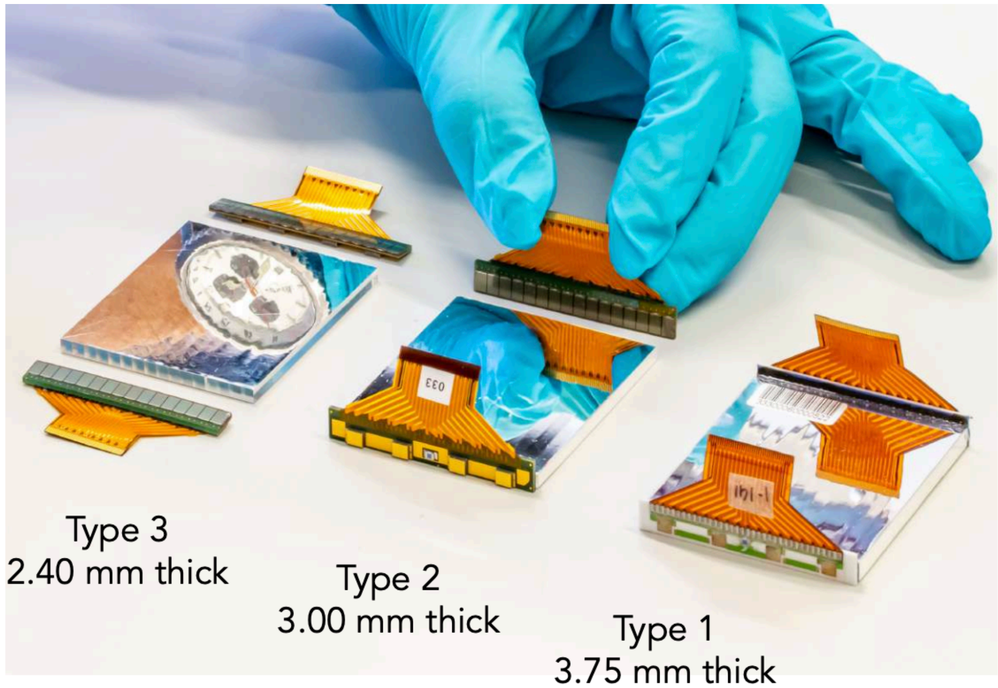
CMS-TDR-020

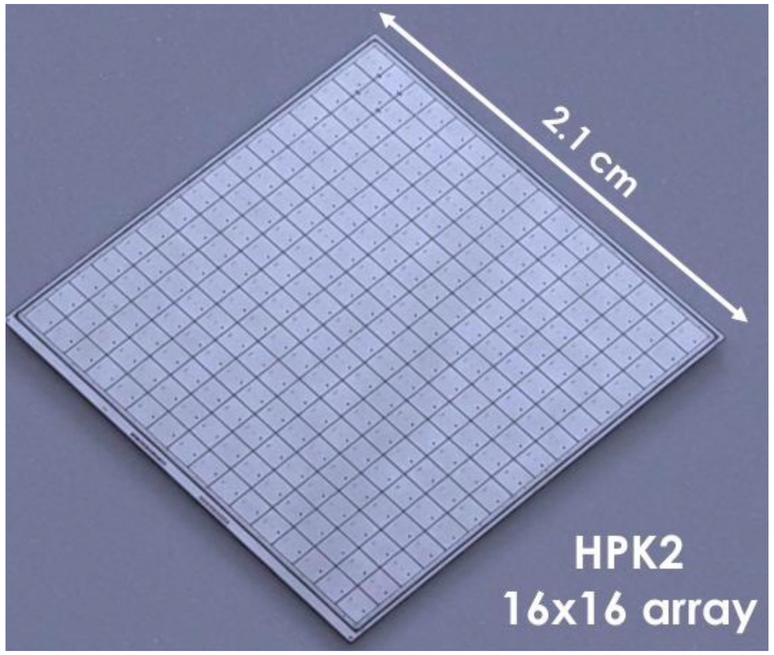
Radiation dose and expected fluence for BTL and ETL

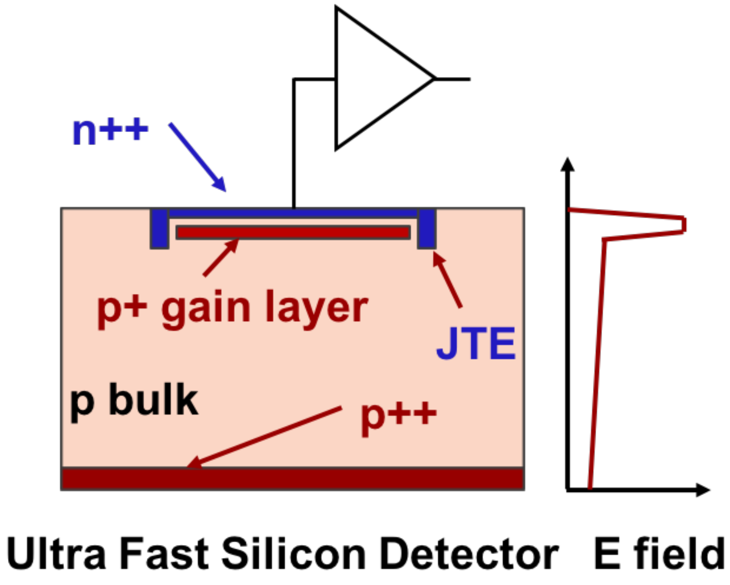
Region	$\|\eta\|$	r (cm)	z (cm)	3000 fb^{-1} n_{eq}/cm^2	3000 fb^{-1} Dose (kGy)	1.5×3000 fb^{-1} n_{eq}/cm^2	1.5×3000 fb^{-1} Dose (kGy)
Barrel	0.0	116	0	1.65×10^{14}	18	2.48×10^{14}	27
Barrel	1.15	116	170	1.80×10^{14}	25	2.70×10^{14}	38
Barrel	1.45	116	240	1.90×10^{14}	32	2.85×10^{14}	48
Endcap	1.6	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

BTL technology:
- **LYSO** crystal bars with **SiPM** arrays glued to both ends
- Proven, radiation hard technologies with good time resolution

ETL technology:
- **Low Gain Avalanche Diodes** (LGAD): Silicon → radiation hard for high |η|
- Thin sensors with small pixel size (= low capacitance)



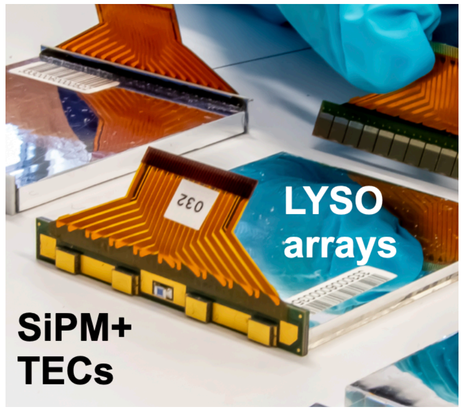




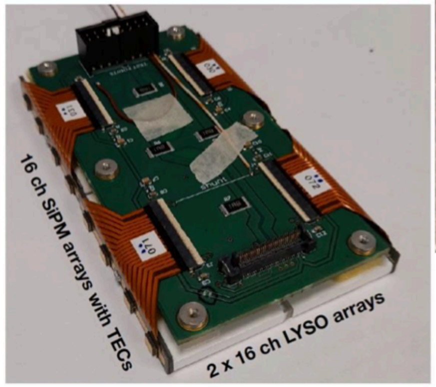
BTL design

- BTST houses BTL (1600 kg)
- 2x16 LYSO bars packaged into BTL module, 12 modules + FE electronics form one readout unit
- 72 trays in BTST structure → 166k LYSO bars, **332k readout channels**
- Assembly procedures and mechanical structures are well advanced and **moving towards production / installation**

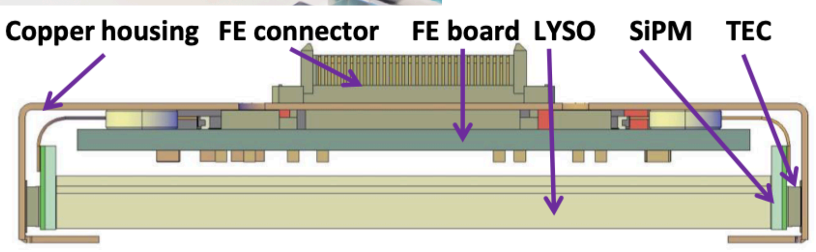
BTL sensor module

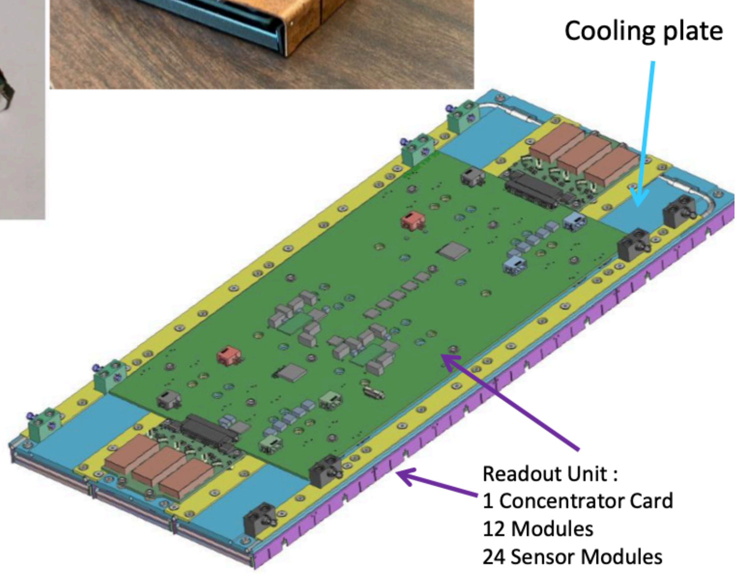


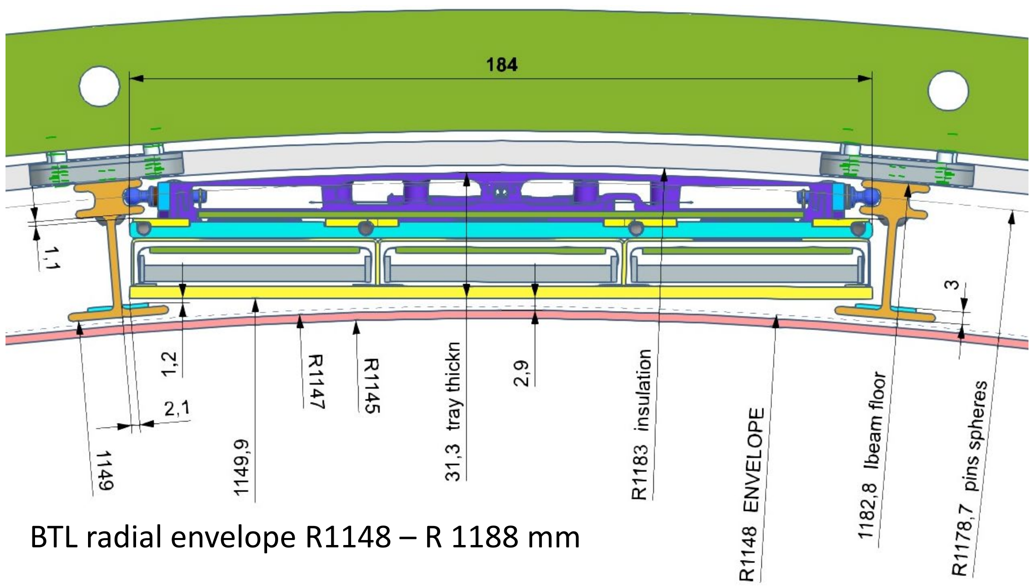
BTL module



BTL detector module





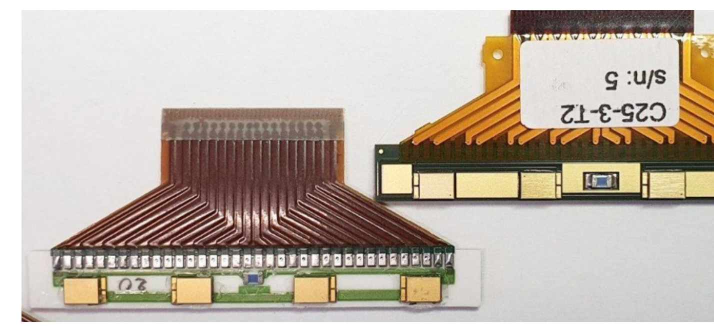


BTL radial envelope R1148 – R 1188 mm

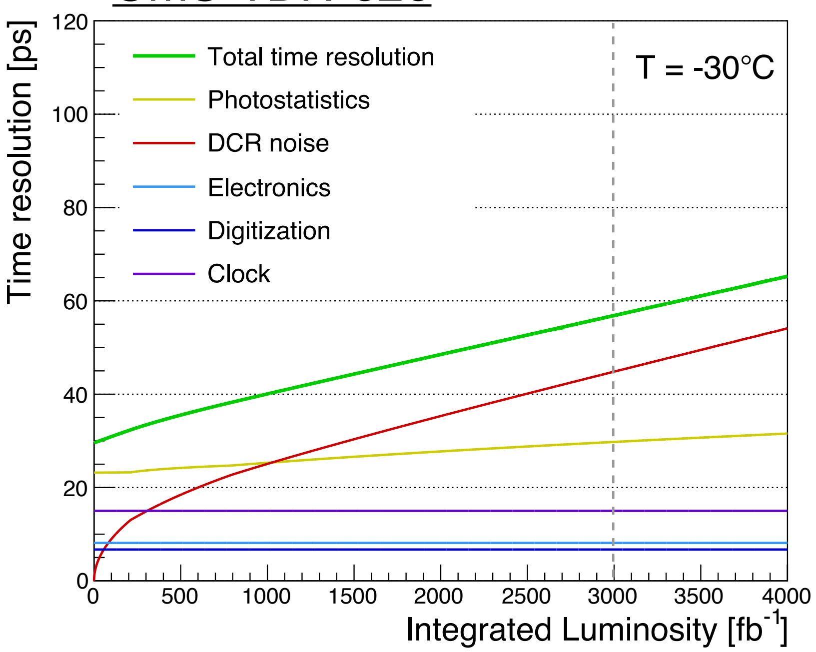
BTL time resolution

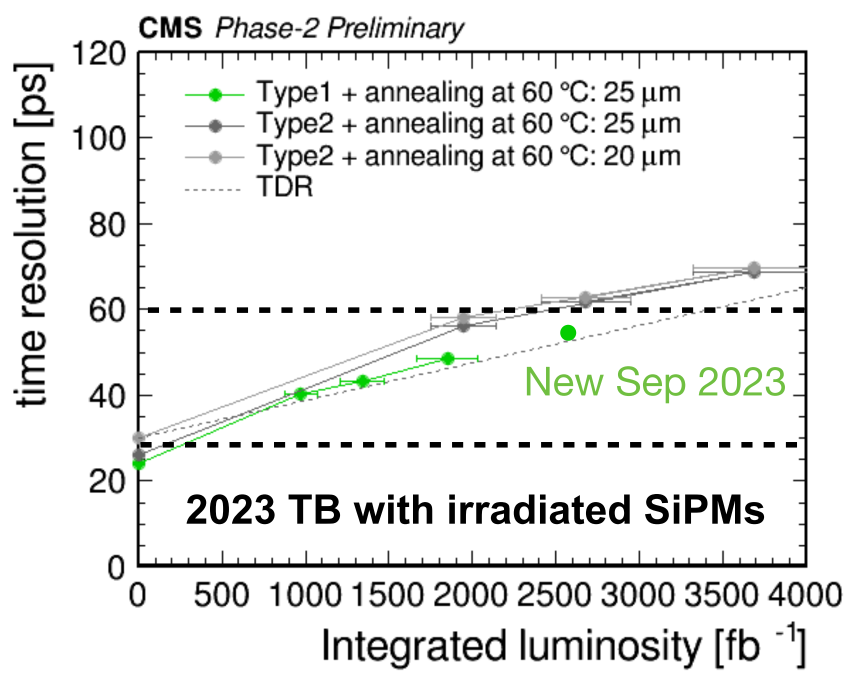
$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR}$$

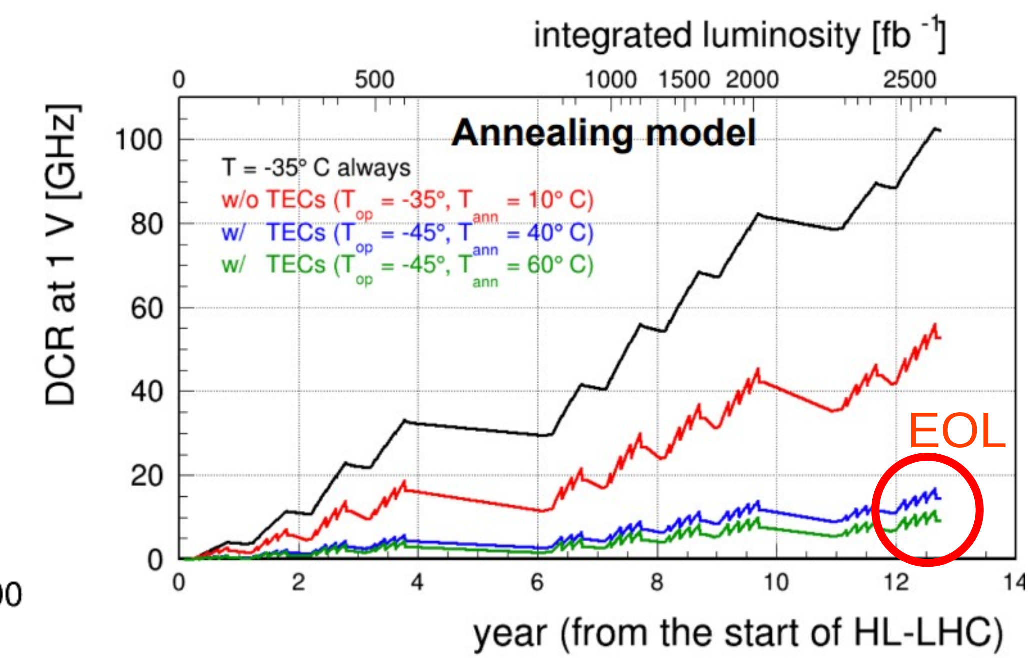
- **Clock, digitization and electronics noise terms sub-dominant** except at startup
- Photostatistics: depends on MIP energy, geometry, crystal light yield, photon detection efficiency of SiPM
- Dark Count Rate: Coming from SiPM, dominating source over time. **Cold operation and warm annealing** crucial to maintain physics performance
- Strong effort to achieve TDR time resolution of 30-70ps over BTL life time
  - Improved light yield thanks to (uniformly) thicker LYSO bars, 3.75mm
  - DCR limitation thanks to improved **thermal management** through TECs
- Proceeding towards **production with design that meets TDR targets**



CMS-TDR-020

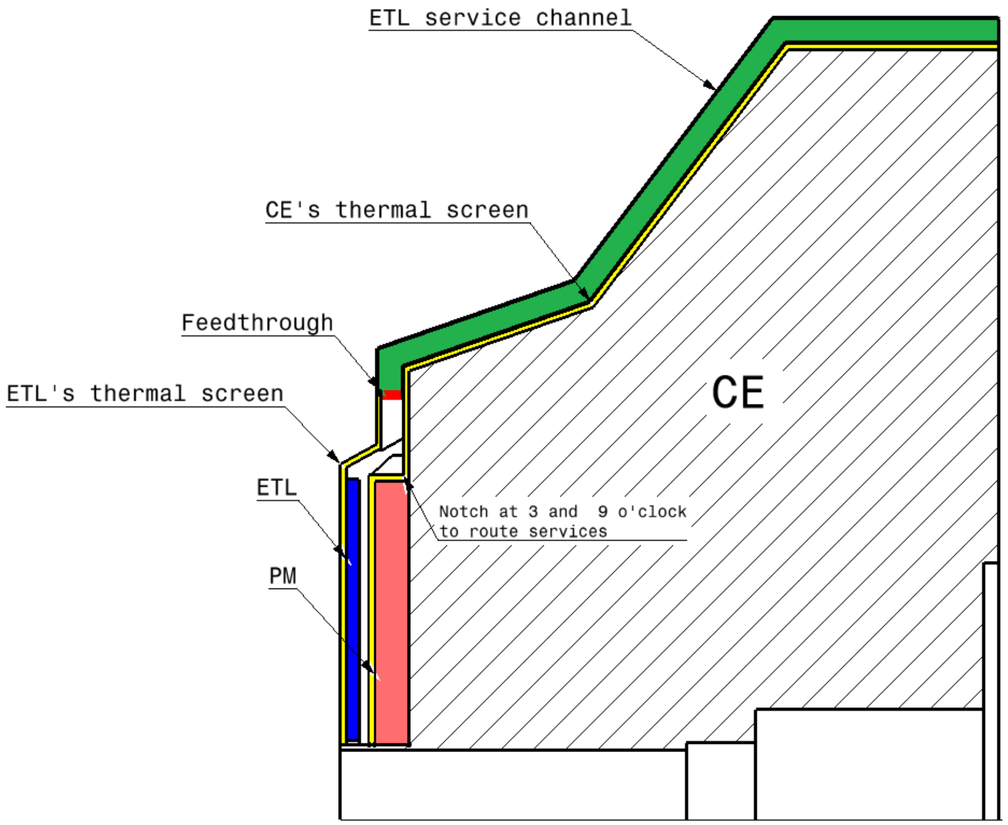


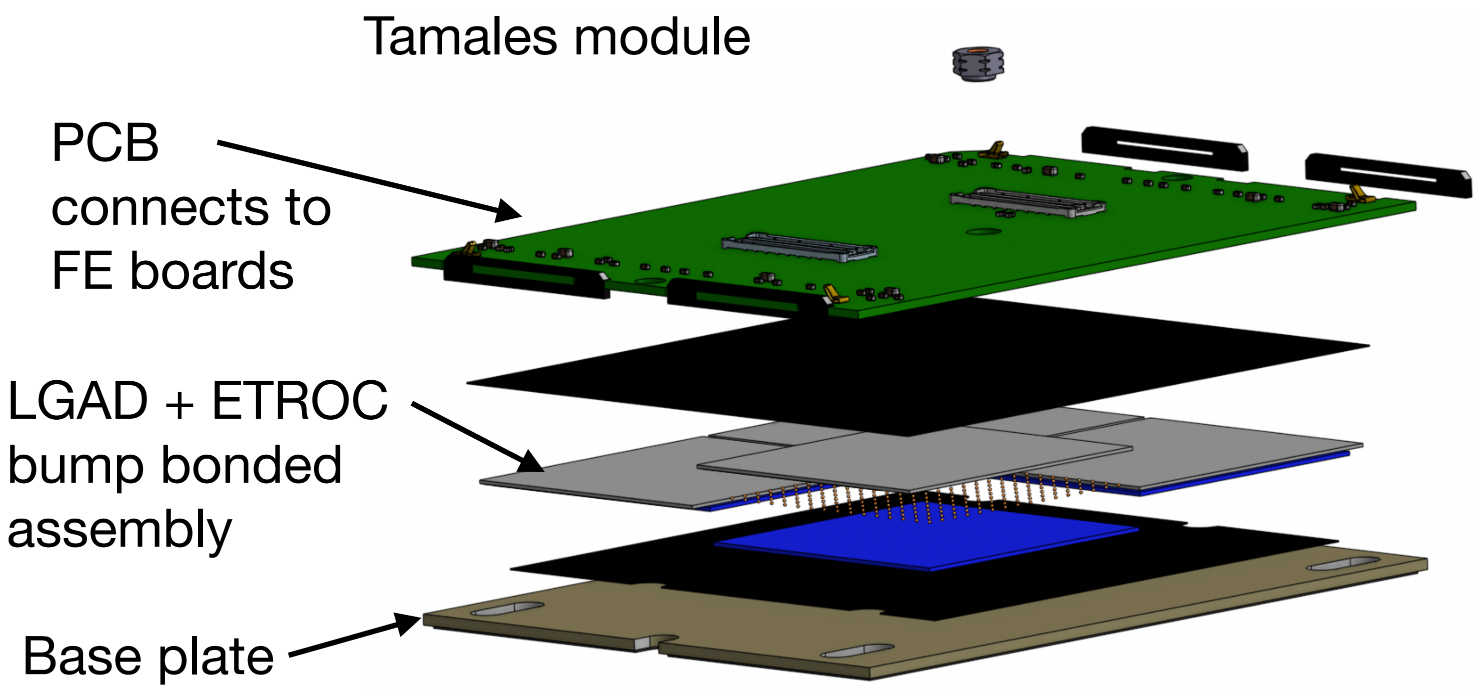


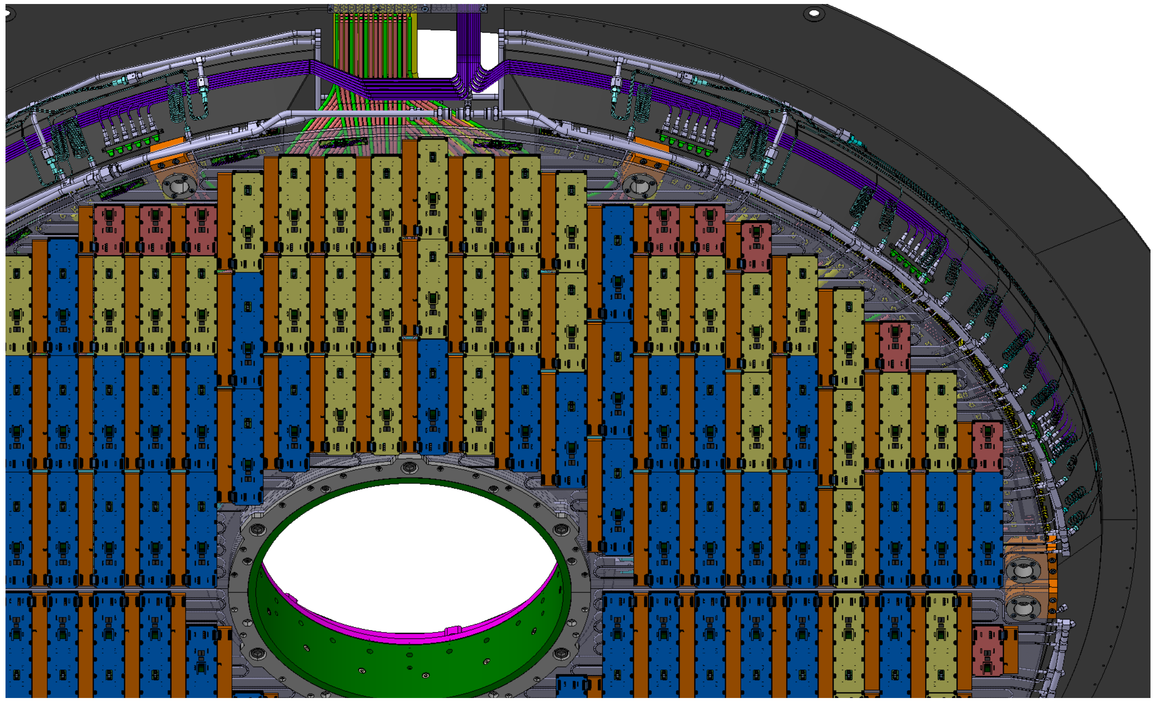


ETL design

- ETL will sit on the CE nose in front of HGCal
  - Installation can happen later than BTL, timelines are shifted
- **Two aluminum disks** populated with "tamales" modules on both sides, resulting in close to 100% fill factor
- 50ps time resolution per hit, **2 hits per track** → 35ps time resolution
  - Dominated by LGAD + readout ASIC analog part





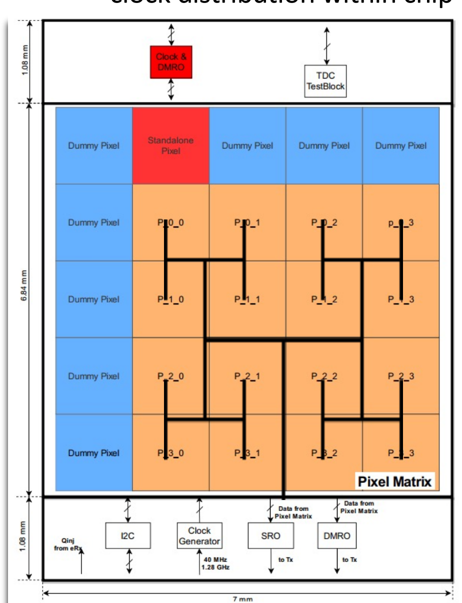


ETL status

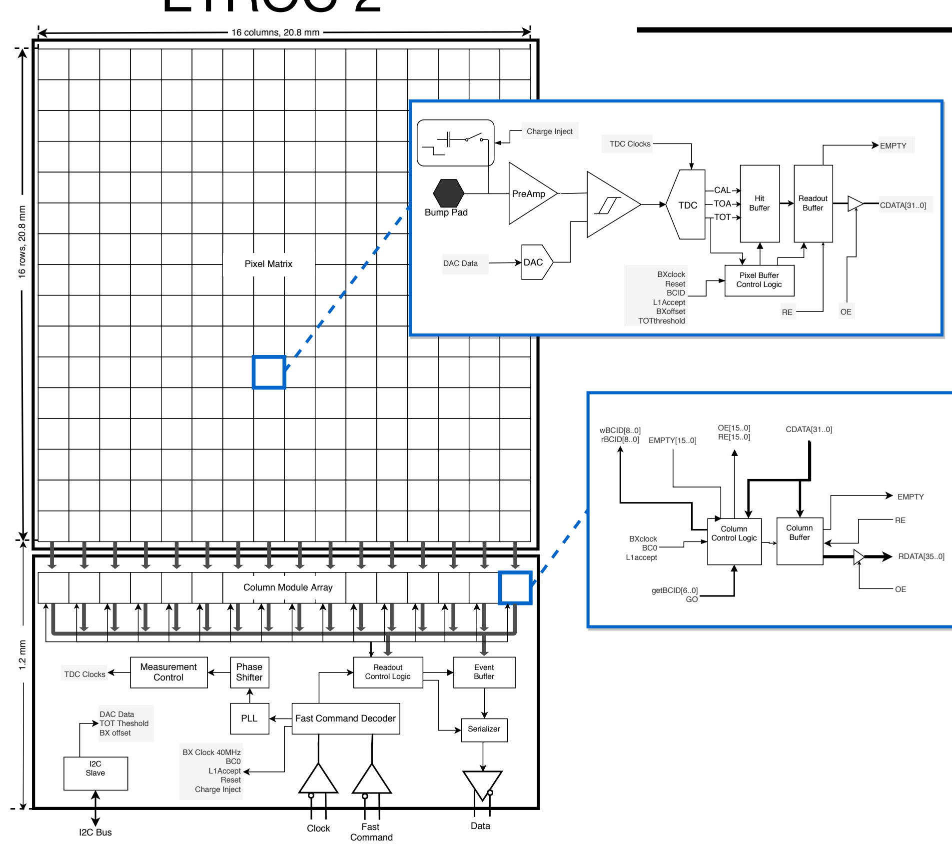
- First full size, **16x16 pixel prototype of the ETL readout ASIC** (ETROC2) is being studied successfully
  - ETROC1 confirmed <50ps single hit time resolution
  - Currently reproducing results with full size chip at various beam facilities
- **First slice tests of ETL** have been successfully carried out using IR laser
  - Tests with electrons and MIPs to follow in coming months

ETROC 1 clock tree

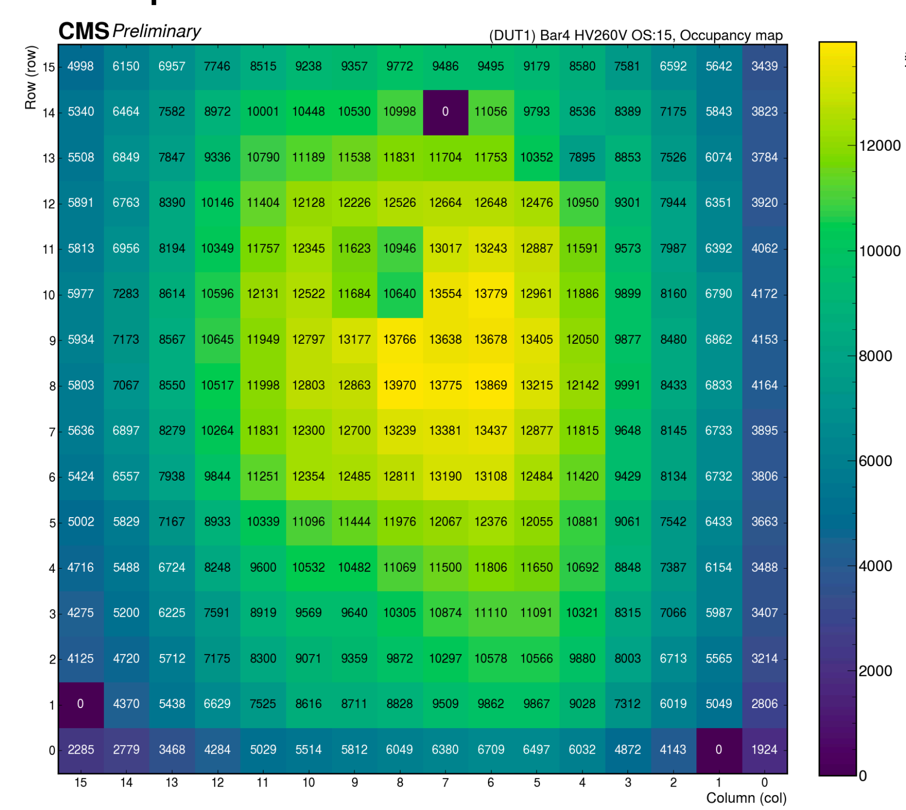
ETROC1 4x4 H-tree clock distribution within chip



ETROC 2



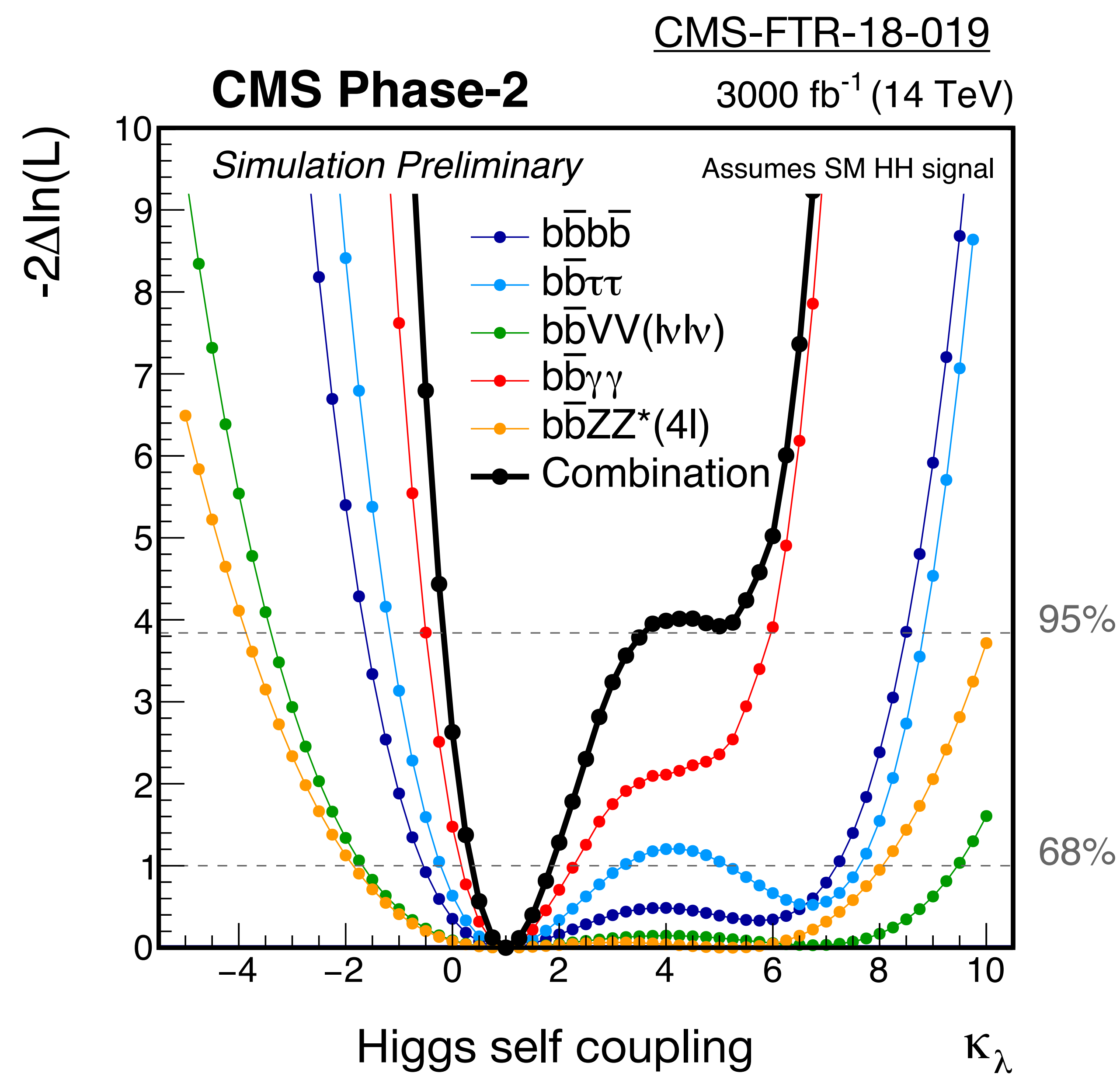
Occupancy for 16x16 pixels in test beam



Details: arXiv:2011.01222

Physics impact

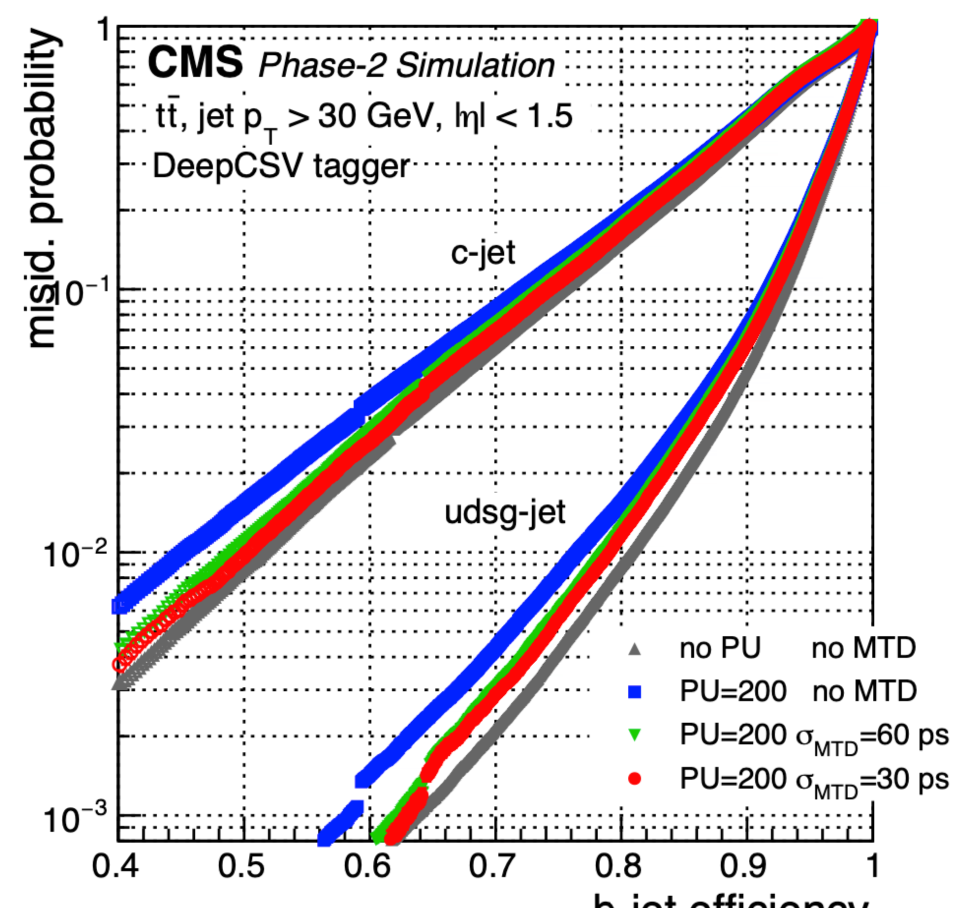
- **Improvements** in lepton isolation, jet flavor tagging, particle ID **propagate to any physics analysis**
- **Observation and measurement** of di-Higgs production essential for understanding of **Higgs mechanism**
  - Timing layer increases expected significance of SM HH production by ~15%
  - Full potential certainly not yet exploited
- The **timing layer** (and other Phase 2 upgrades) will play a major role in our ability to **discover new physics at HL-LHC!**



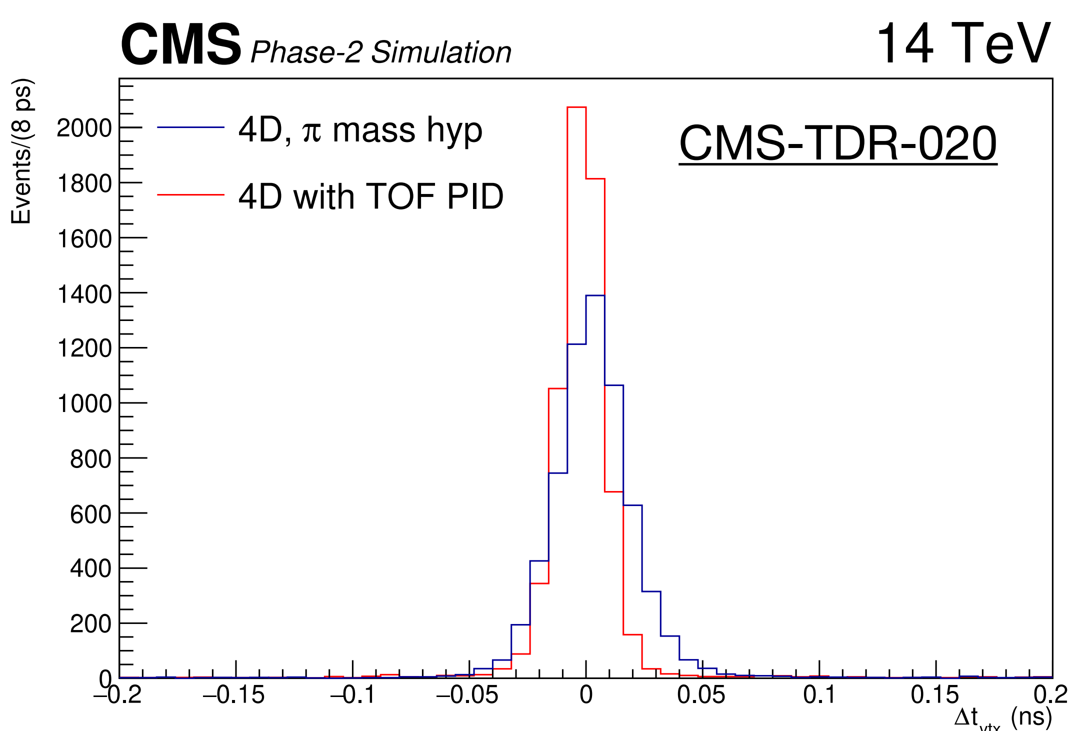
4D Tracking and Vertexing

- One timing layer with limited spatial resolution (e.g. 1.3x1.3 mm^2 pixels in ETL)
  - **Extend tracks with matched MTD hits** for time association
- **Vertex clustering and fitting in 4D** depends on mass hypothesis of MIP
  - For 1m path: Δt(K-π) = 400ps for p_T = 1 GeV; Δt(K-π) = 4ps for p_T = 100 GeV
  - Studies ongoing on best algorithm to fully exploit timing potential
  - General expectation: **O(10)ps vertex resolution**
- PU suppression from MTD will **greatly impact physics performance**, e.g. flavor tagging

b-tagging in Phase 2



CMS-TDR-020



Vertex time resolution

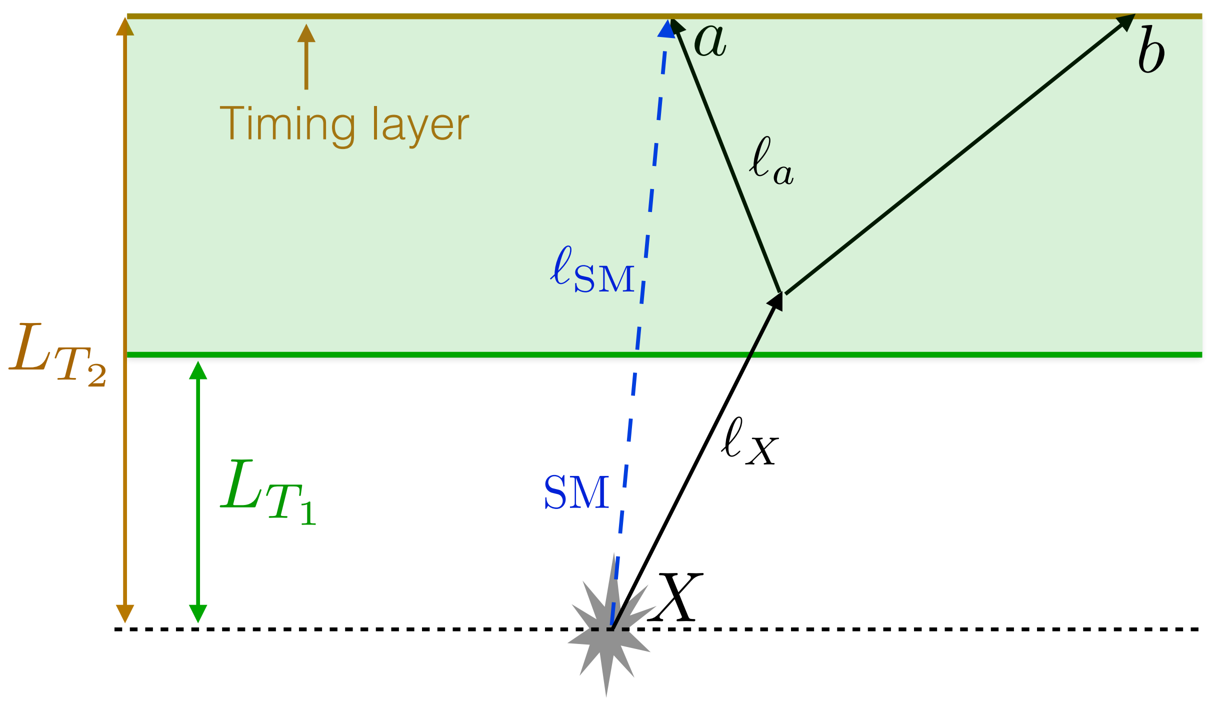
New exotic particle searches

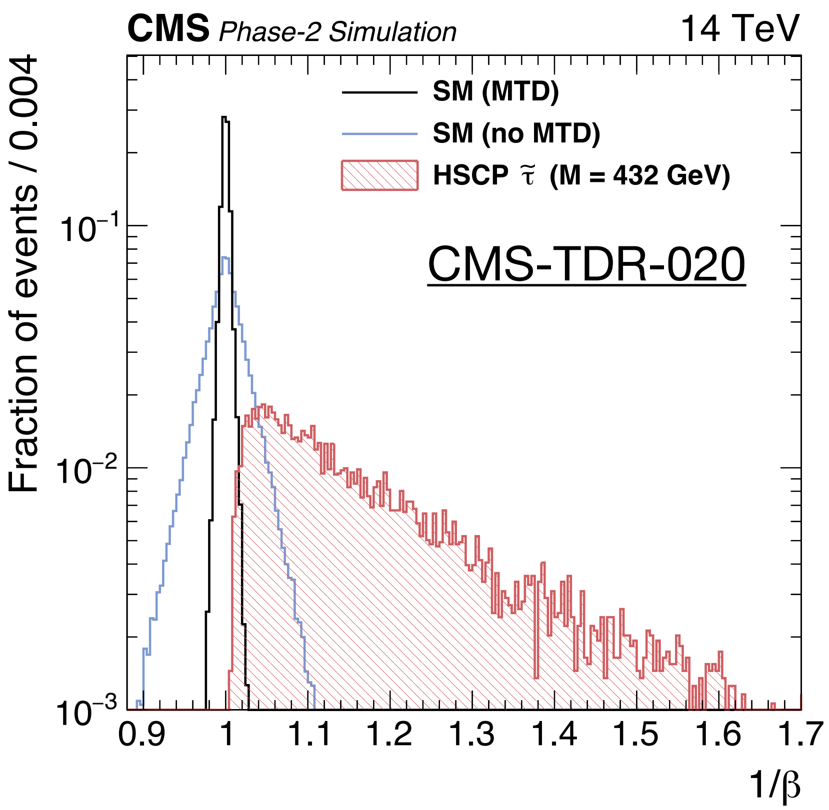
Time delayed particles from slowly moving BSM particles

- **Delayed jets** with better time resolution than currently possible
- **Delayed electrons** from HNL decays, removing inefficiencies of displaced tracks
- Inclusion of timing into HLT for generic searches

$$\Delta t^{i}_{\mathrm{delay}} = \frac{\ell_X}{\beta_X} + \frac{\ell_i}{\beta_i} - \frac{\ell_{\mathrm{SM}}}{\beta_{\mathrm{SM}}}$$

PRL 122.131801



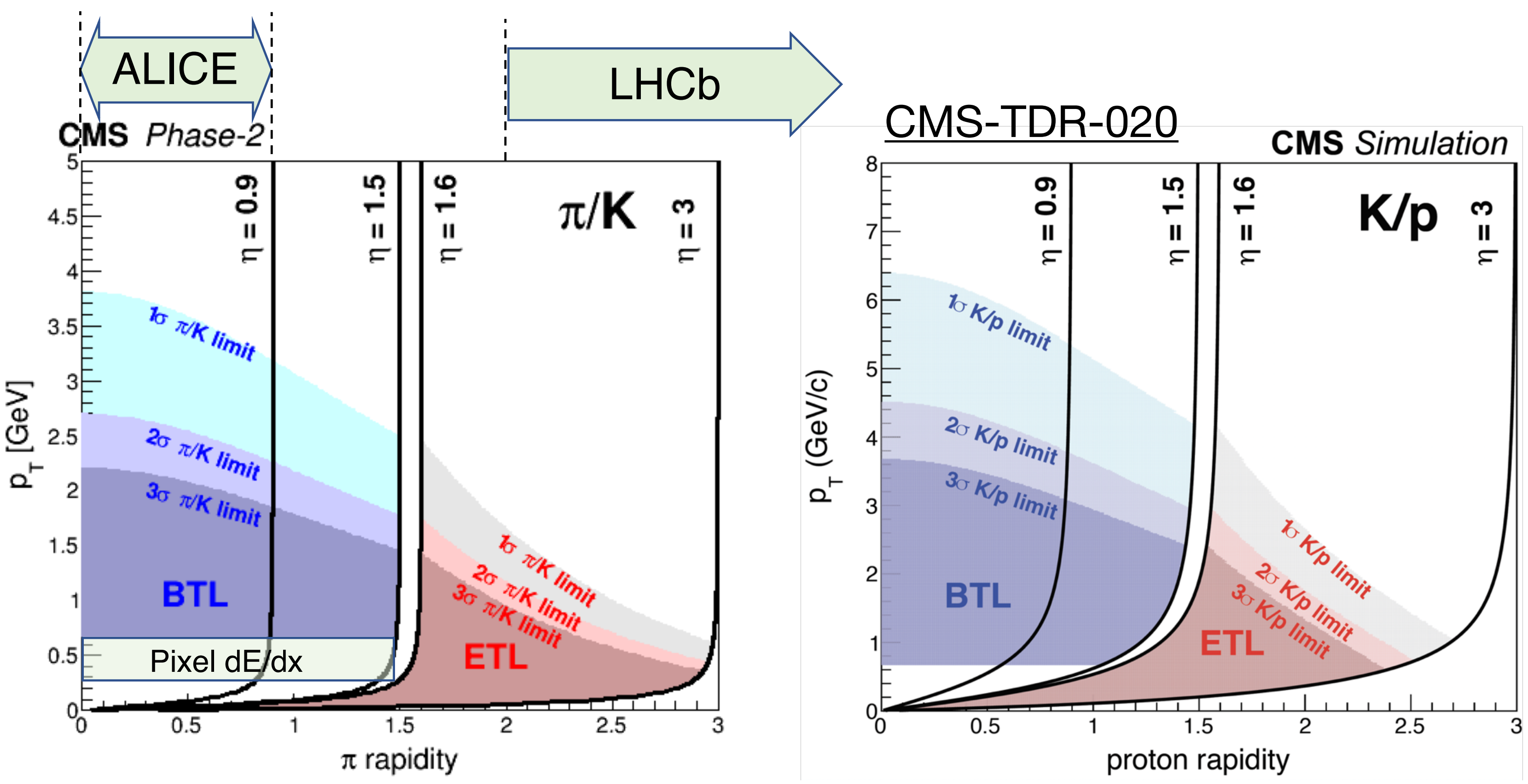


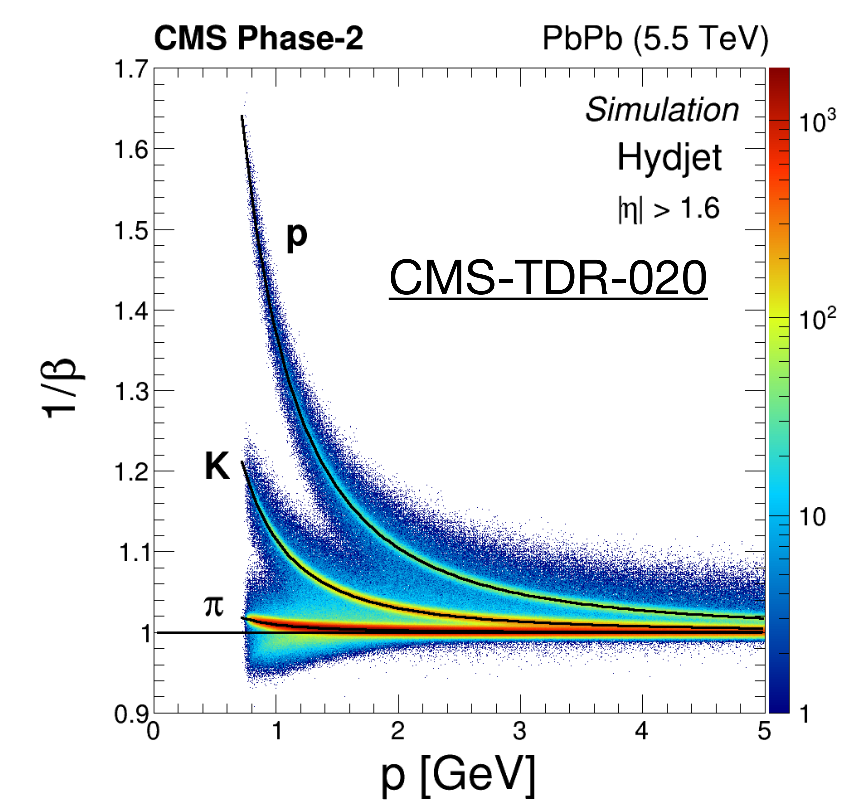
1/β reconstruction for heavy stable charged particles (HSCP)

- **HSCP identification** currently relies on pixel dE/dx
- TOF enabled 1/β measurements allow mass reconstruction of potential signal
- Relies on **robust vertex time reconstruction**

Physics of Quark Gluon Plasma

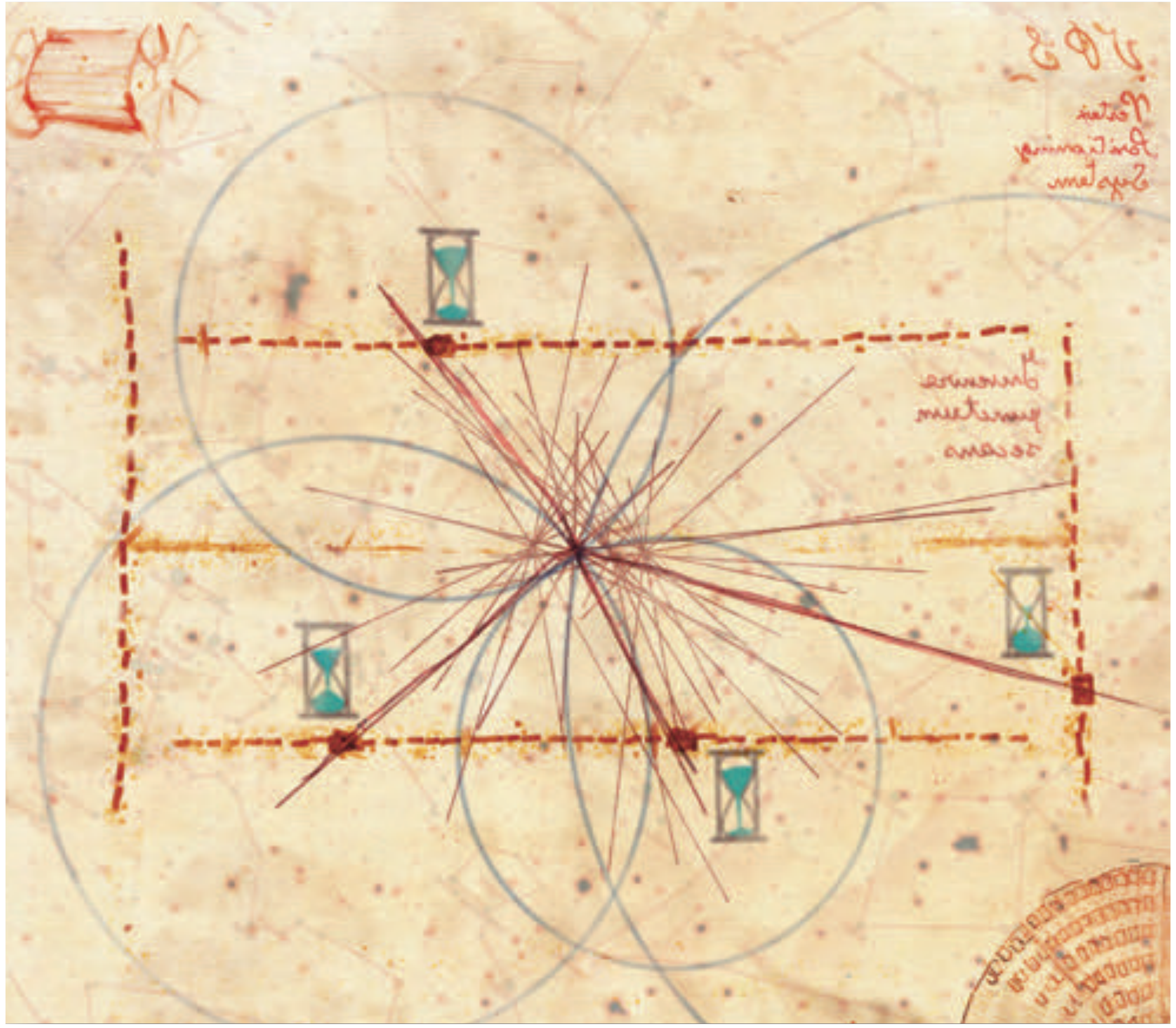
- No complication of vertex disambiguation in PbPb collisions, $\frac{1}{\beta} = \frac{c(t_0^{\mathrm{MTD}} - t_0^{\mathrm{evt}})}{L}$,
- Measurements of heavy flavor particles of interest to study evolution of QGP
- MTD will allow **separation of K and π up to 2.5 GeV** in mid-rapidity, coverage down to p_T ~ 0 GeV
- Alice and LHCb have complementary PID capabilities, but CMS only detector with **almost hermetic PID coverage**
  - Resolve ambiguities left from Alice Run 2 results on Λ_c to D^0 ratio ➝ relies on improved S/B in D^0 ➝ K π decay channel





Summary and Outlook

- CMS MIP timing detector is progressing and will meet TDR performance
- Barrel timing layer starting production now, installation starts in 2025
- Endcap timing layer in last prototyping phase, installation to start in 2027
- Track and vertex **timing will have great impact on CMS physics program**
- Timing detectors will play **major roles in future (collider) experiments**
  - Multiple timing layers in silicon tracker for “real” 4D tracking
  - PID in EIC detectors
  - BIB suppression in muon collider



BACKUP

CMS as QGP detector

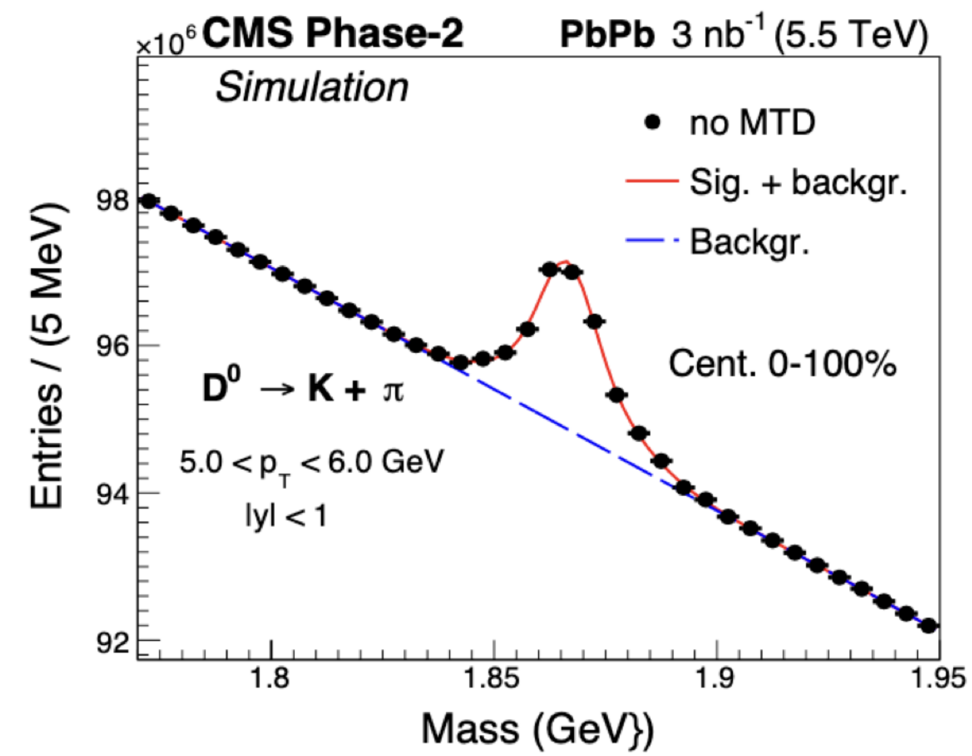
A rich program by CMS and MTD at HL-LHC

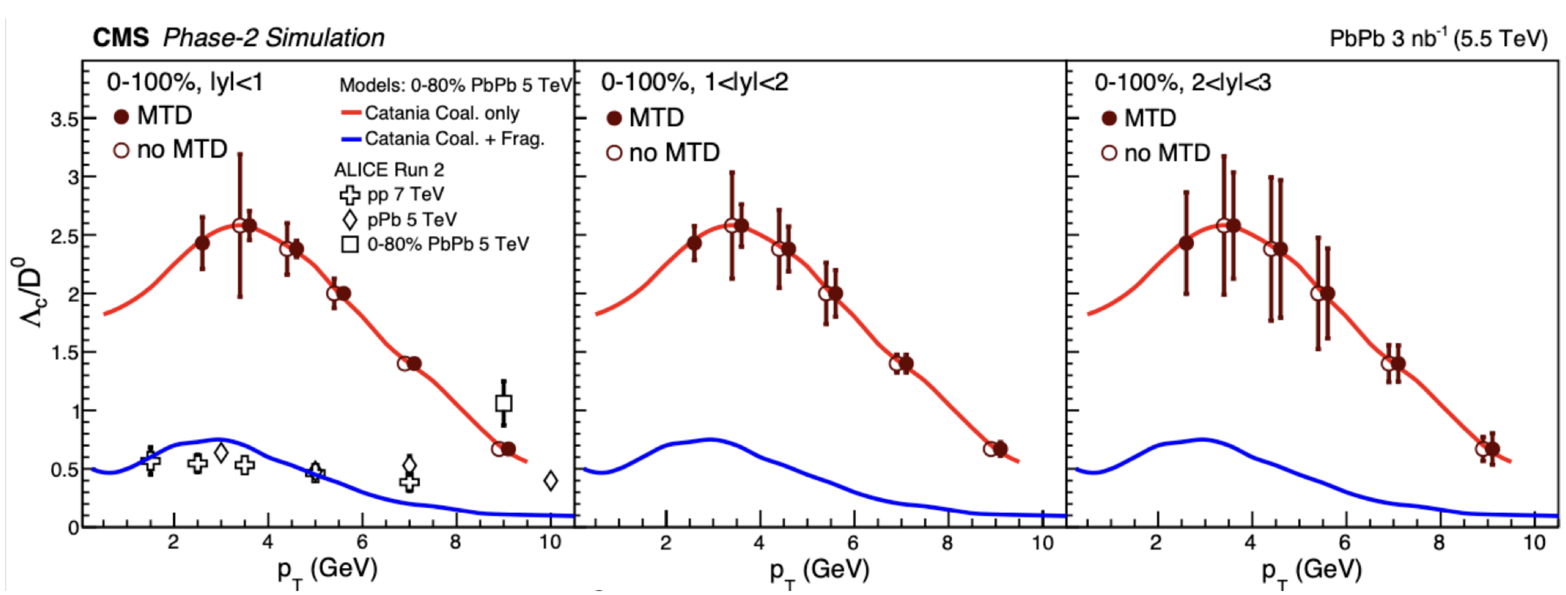
Unique science goals	Key observables
QGP medium response to parton energy loss	• Jet-hadron correlations to $\Delta r>1$ with PID
(3+1)D heavy flavor dynamics and hadronization in QGP	• HF baryon/meson yields and collective flow (v_n) vs y, p_T
Fluctuations and transport of conserved quantum charges in QGP	• Long-range PID two-particle correlations in Δy and $\Delta\phi$ • Charge balance function to $\lvert\Delta y\rvert>2$ • High-order cumulants (C_4) vs y_{max}
Origin of collectivity in small system	• LF and HF collective flow (v_n)
Mechanism of light nuclei production over wide phase space	• Light nuclei yields and collective flow (v_n) vs y and p_T

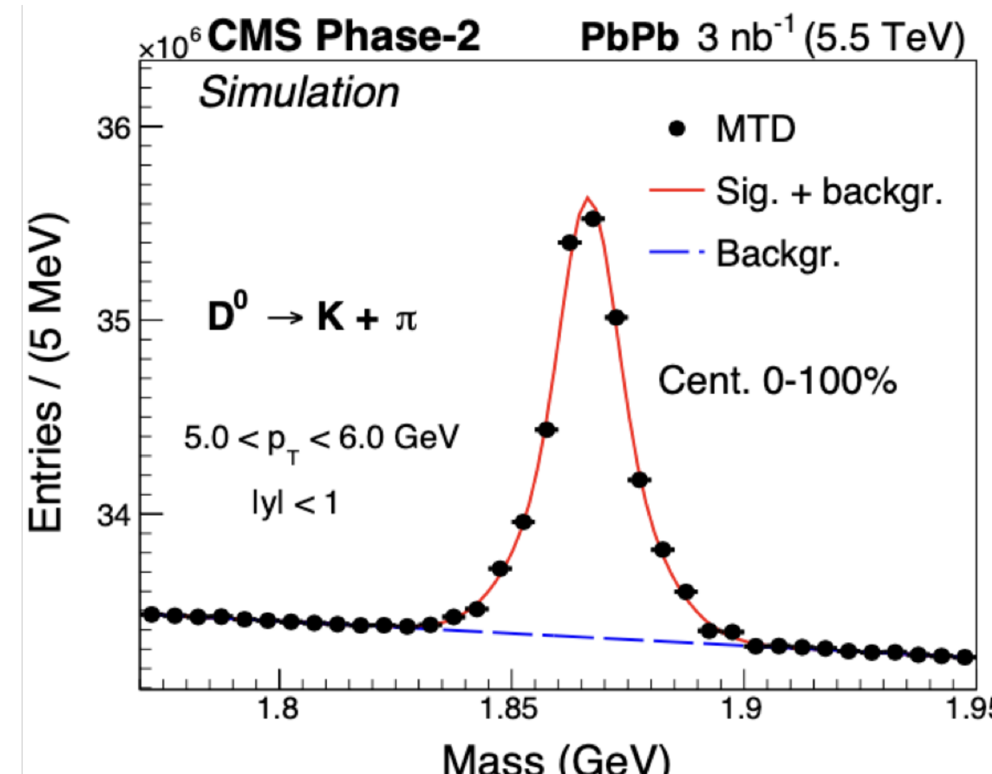
⋮

and be prepared for surprises!

- The Λ_c to D^0 yield ratio in PbPb collisions serves as an important probe of quark coalescence or recombination mechanism in a hot and dense QGP

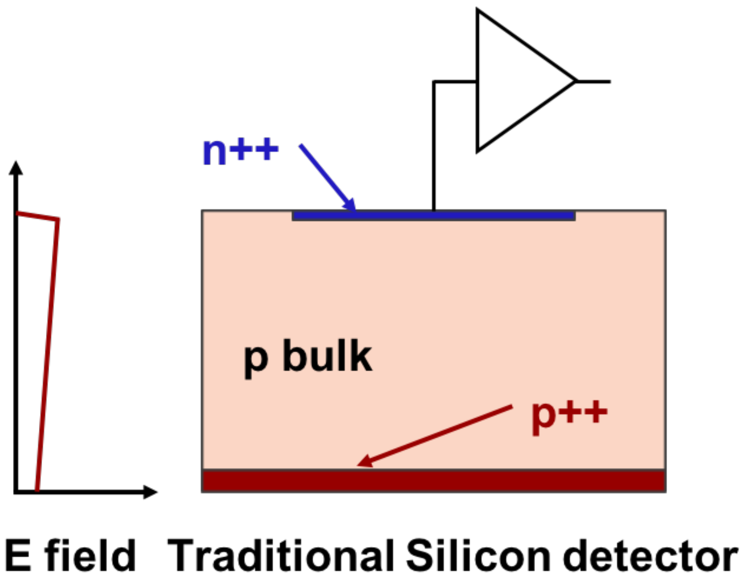


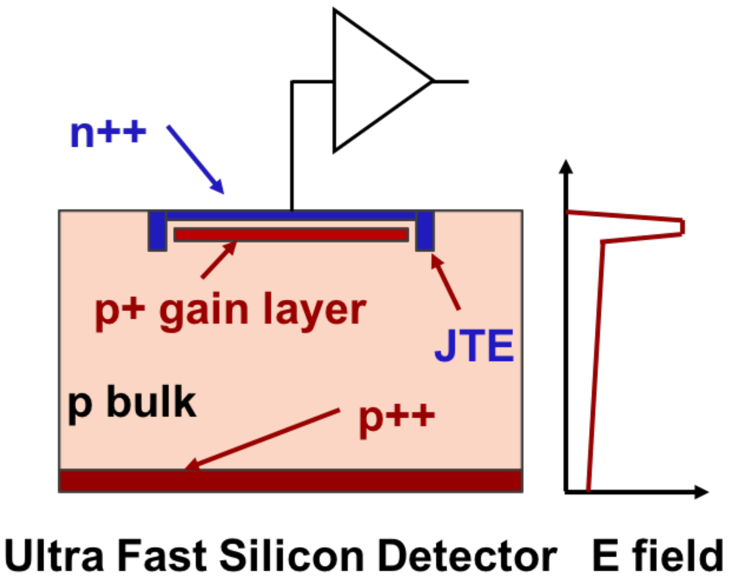




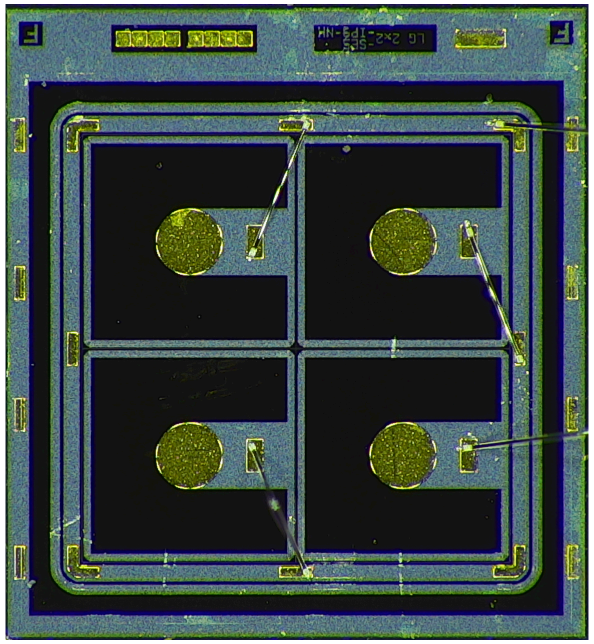
Ultrafast Sensors

- **Low Gain Avalanche Diodes** (LGAD): Additional gain layer (multiplication implant)
  - Internal gain proportional to bias voltage
  - Low / moderate gain ~10: **low noise, fast slew-rate** (~70mV/ns) **and fast rising pulse** (O(100)ps rise time)
  - Thin sensors: **50µm depletion region**
  - Junction Termination Extension (JTE) reduces electric field at perimeter of pads, resulting in **no-gain inter-pad gaps.** Need to be sufficiently small for large coverage.
- 1.3 x 1.3 mm^2 pixels: moderate capacitance (~3pF)
- Moved from 16x32 pixel sensor to 16x16 to increase production yield



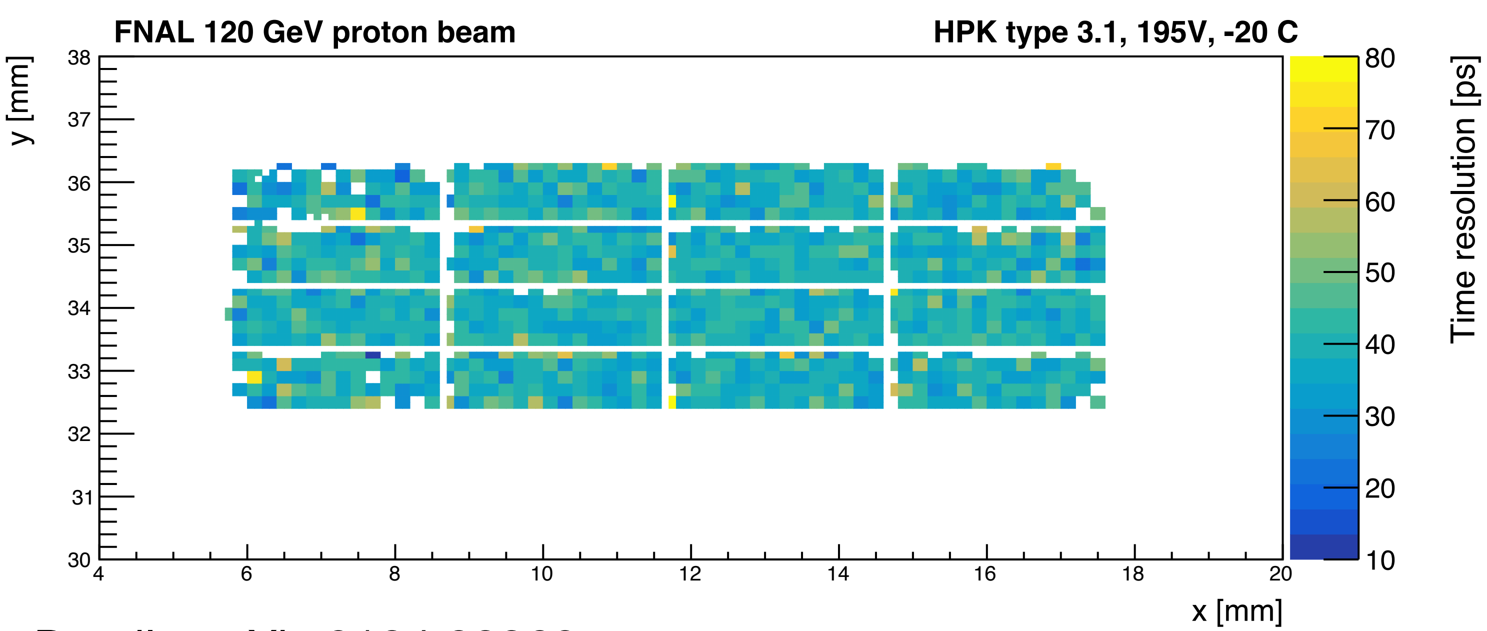


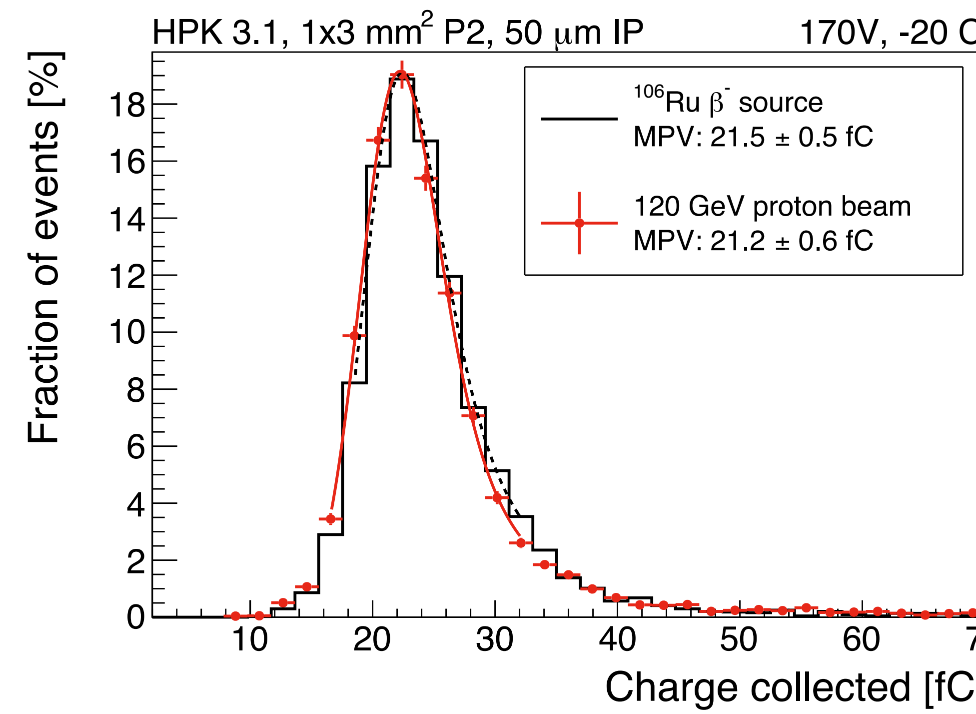
4x4 pixel prototype, Hamamatsu



Sensor performance

- HBK prototypes, 4x4 pixel arrays with 1x3mm^2 pixel size
- **Uniform time resolution** for entire active area of pads observed in test beam
    - Intrinsic **sensor resolution 30ps**
- Remarkable good agreement of collected charge measurements in test beam and beta source
- Test beam measurements **confirm laser TCT measured size of inter-pad gap** (non-active area), gaps < 80µm specified for ETL
- Verified that **MIP response can be predicted from CV probe station measurements →** highly important for large scale production uniformity testing!





Details: arXiv:2104.08369

LGAD radiation tolerance

- Irradiated sensors to 8×10^{14} and 1.5×10^{15} n_{eq}/cm^2 (expected after $3000fb^{-1}$)
- Bias voltage needs to be increased to maintain gain after irradiation
- Characterization of irradiated sensors shows 40ps time resolution until expected end of life at the end of HL-LHC
- Safe operations according to specs possible with bias <12V/µm, verified in test beam