Precision Timing at HL-LHC with the CMS MIP Timing Detector

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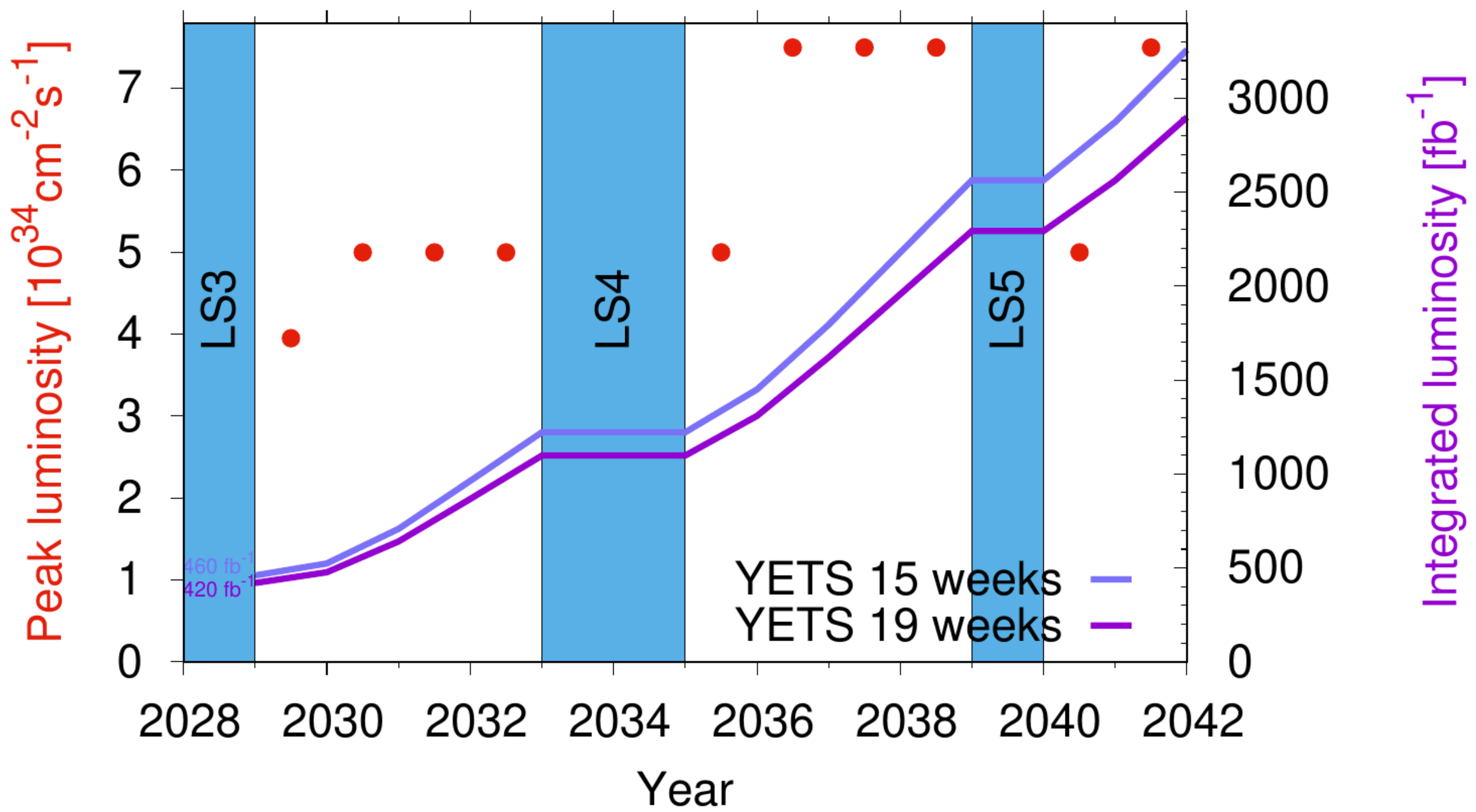
TIPP 2023 4th September 2023

Outline

- HL-LHC: motivation for a precision timing detector and challenges
- The CMS MIP Timing Detector
  - Timing with LYSO + SiPMs: the Barrel Timing Layer
  - Timing with LGADs: the Endcap Timing Layer

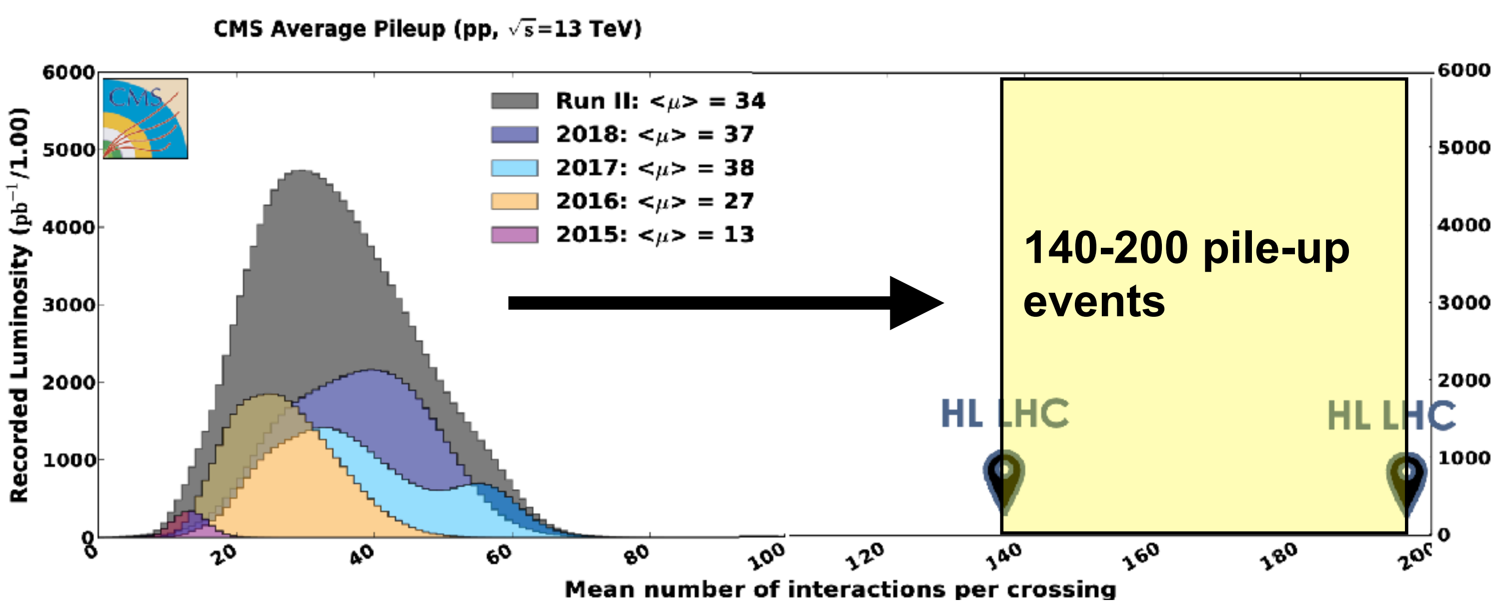
HL-LHC

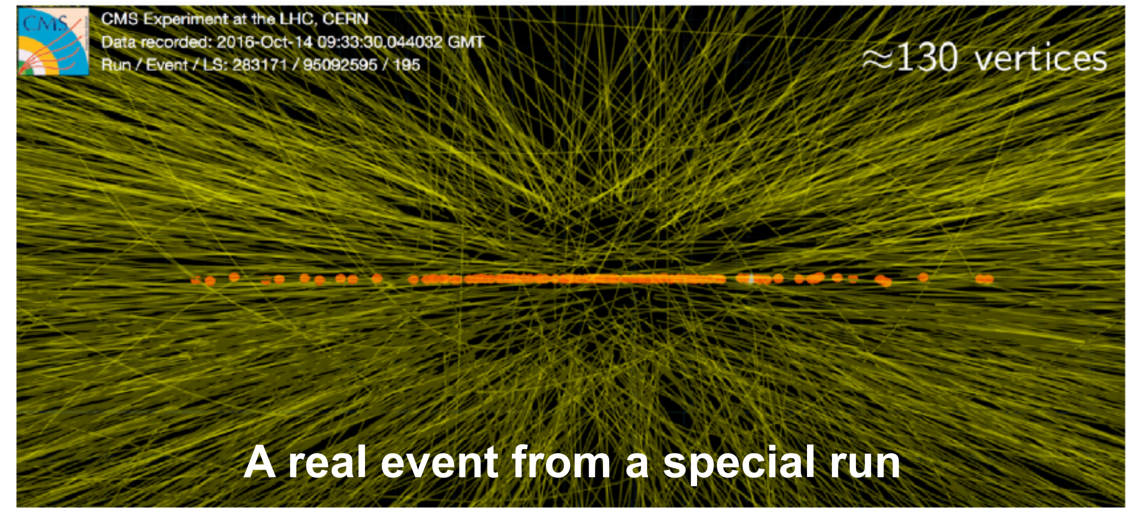


HL-LHC after LS3 (>2028): instantaneous luminosity increased beyond 5E34 cm^{-2} s^{-1}, ~300 fb^{-1} per year (~same luminosity collected in Run1+Run2+Run3), $\sqrt{s}$=14 TeV

Goal: **at least 3000 fb^{-1} after 10 years of operation**

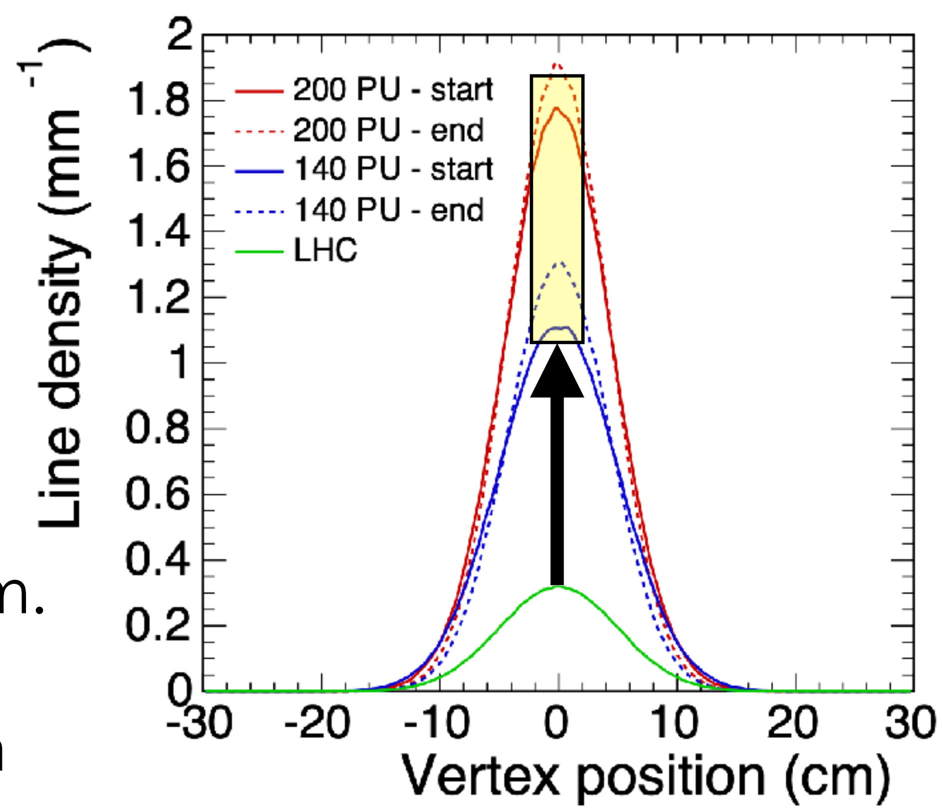
THE CHALLENGE OF HL-LHC



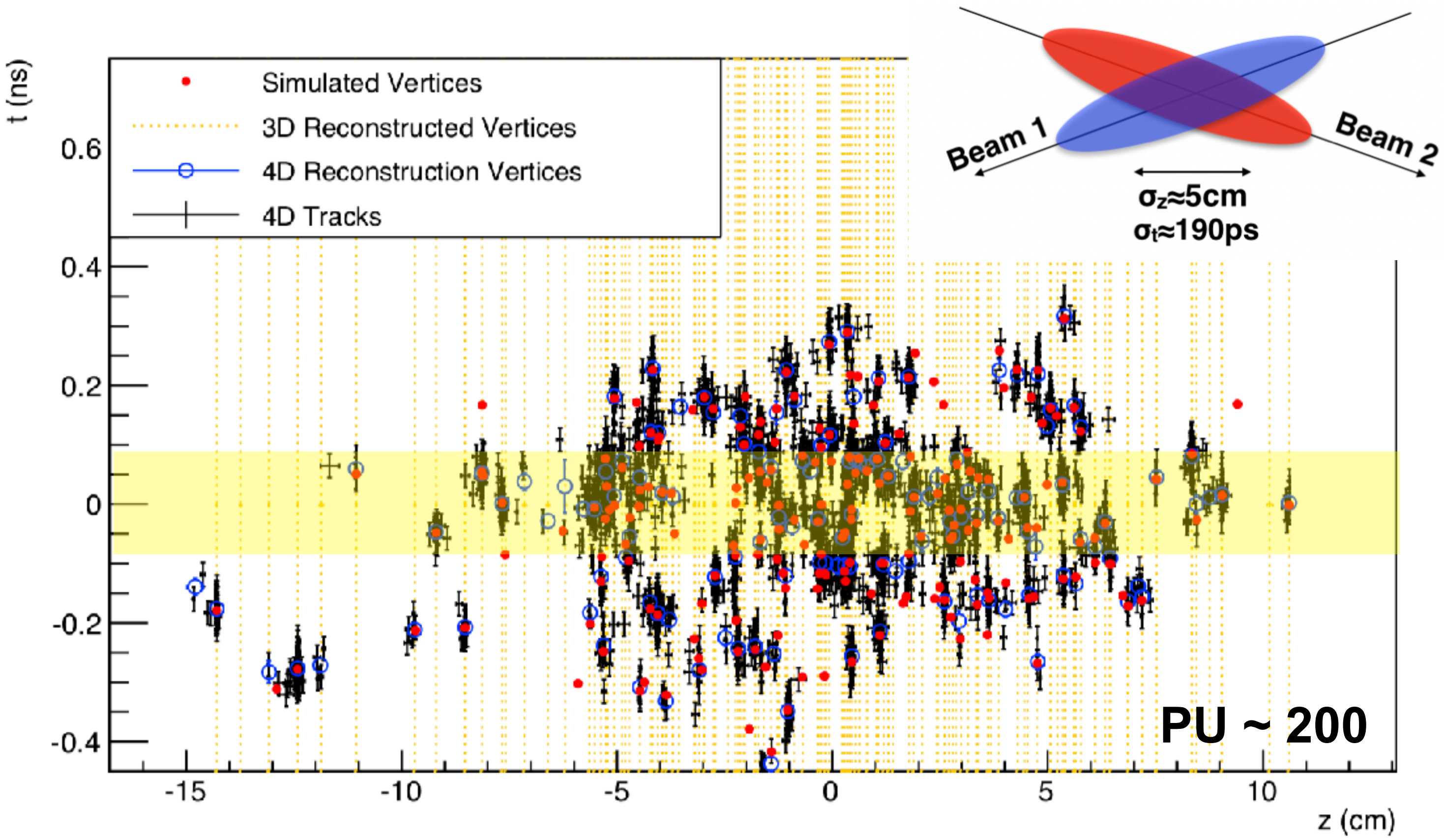


Challenging PU conditions at HL-LHC: increase in inst lumi comes with higher number of interactions per bunch-crossing

- Thousands of tracks, calorimeters clusters, etc to be associated with respective production vertex
- Event density >1.5mm^{-1} (x 5-7 compared to LHC) will challenge tracker spatial resolution
- Track-vertex association: now done requiring |dz|<1mm. PU contamination deteriorates event reconstruction
- New idea for PU mitigation: **exploit beam spread also in time**

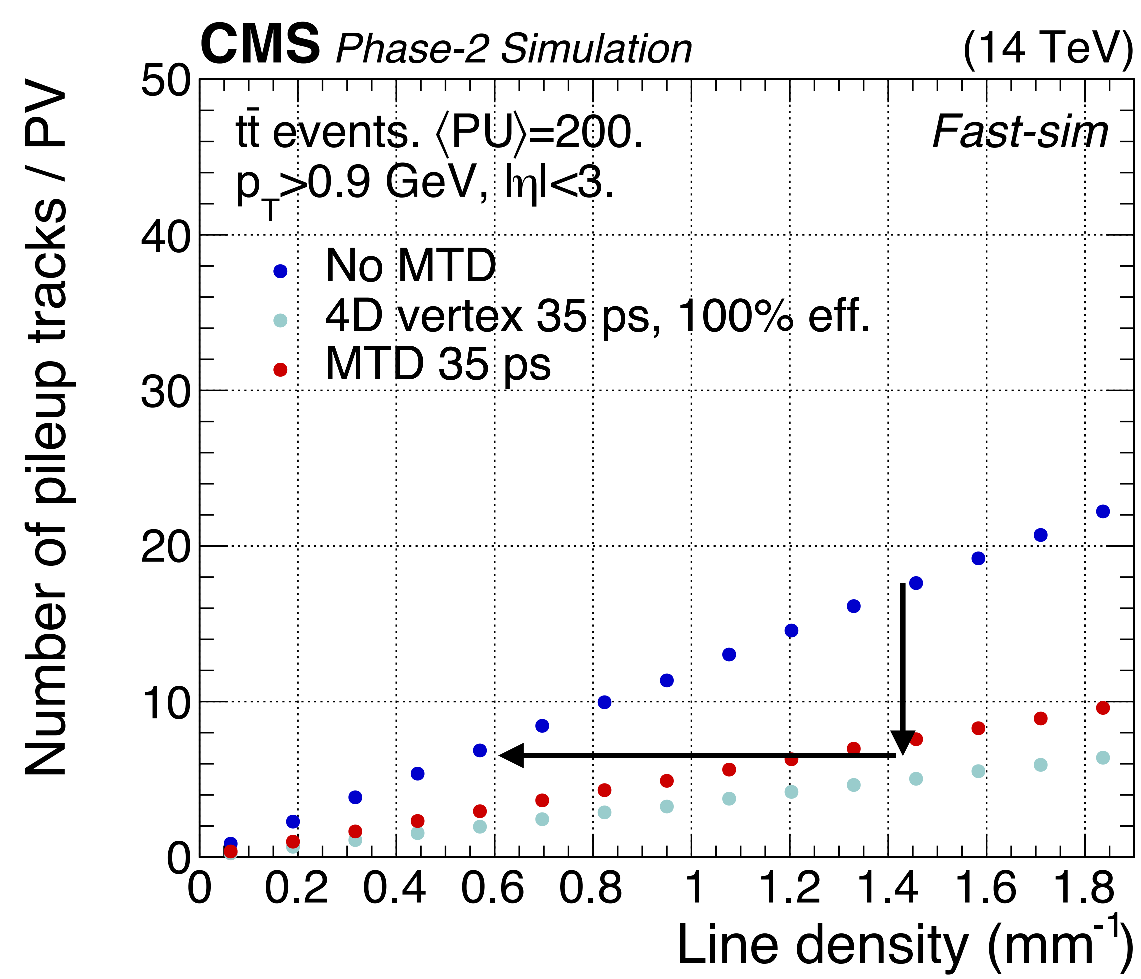


Change Of Paradigm: 4D Tracking



Precision timing (~30ps) for tracks

– Reconstruct vertex not only in space but also time



Track-vertex association using track timing

– **3-5 reduction of PU contamination** using also time at vertex information eg $|\Delta t(\text{track-vertex})| < 3\,\sigma_t$

– PU contamination per vertex reduced to current LHC conditions

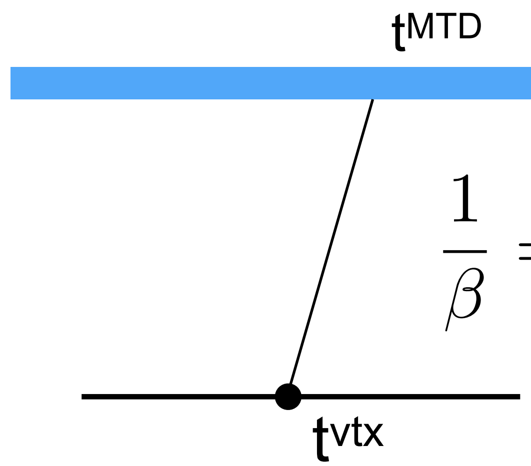
PU Mitigation At Analysis Level

Improvements on event reconstruction from timing impact at analysis level across the full HL-LHC physics program, leveraging on gains on several observables and physics objects

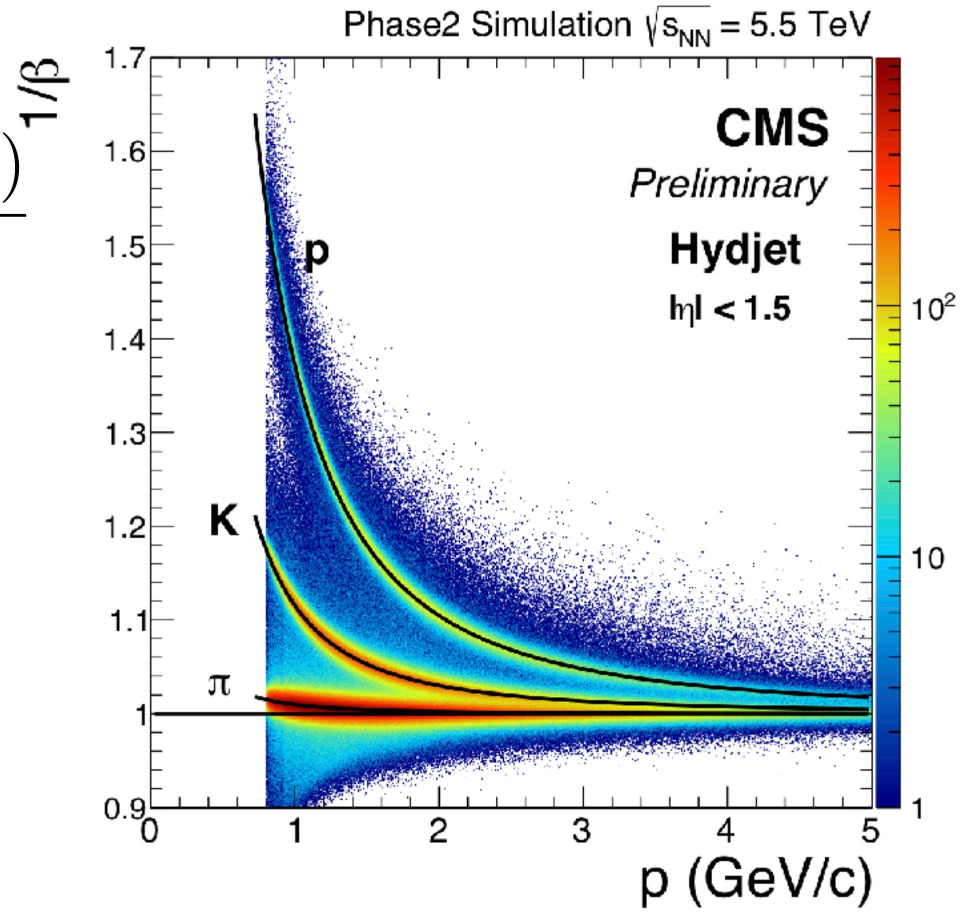
For many channels, **the gain is equivalent to 25-30% increase of integrated luminosity**

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

TOFPID: Flavour Physics & BSM



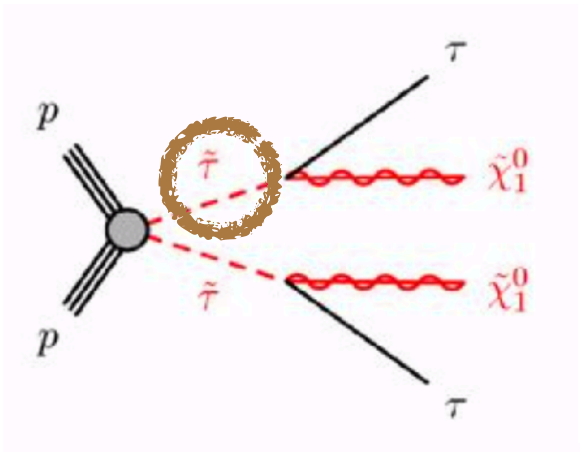
$$\frac{1}{\beta} = \frac{c(t^{MTD} - t^{vtx})}{L}$$

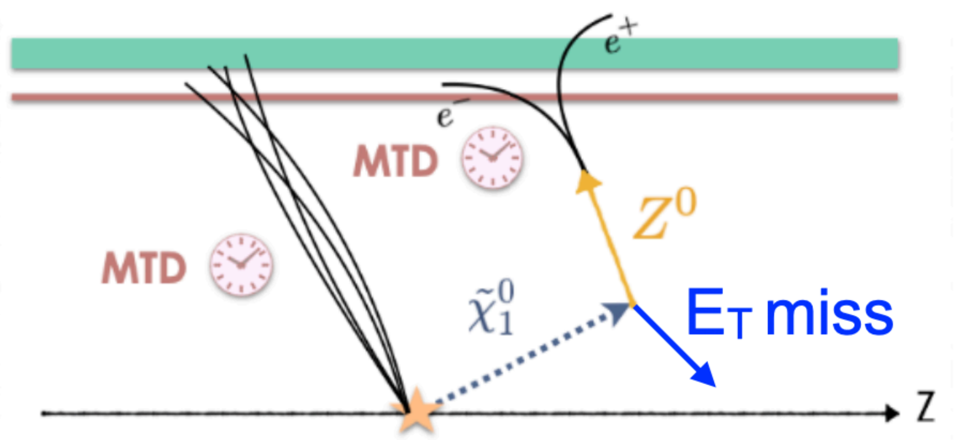


New capability for CMS:
Time-of-flight particle identification (TOFPID)

π/K separation up to 2-3 GeV and K/p separation up to 5 GeV

Timing can also be applied in BSM searches, eg:
- heavy stable charged particles (staus,…)
- long-lived neutral particles
- …

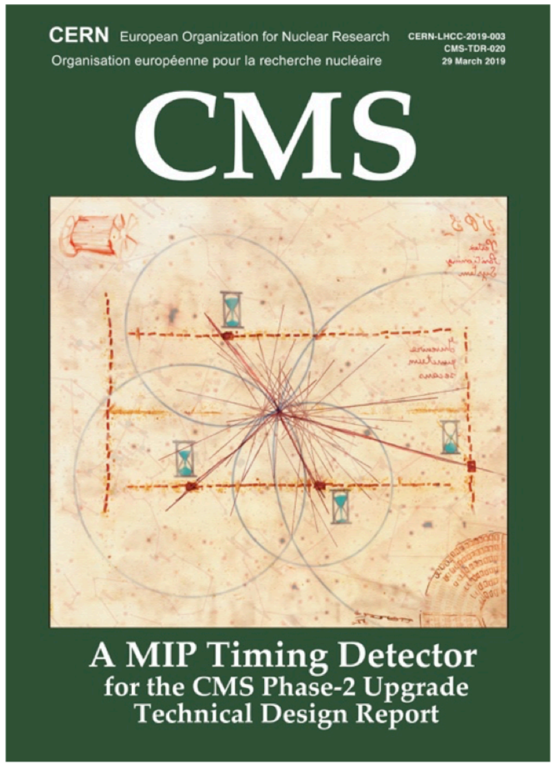




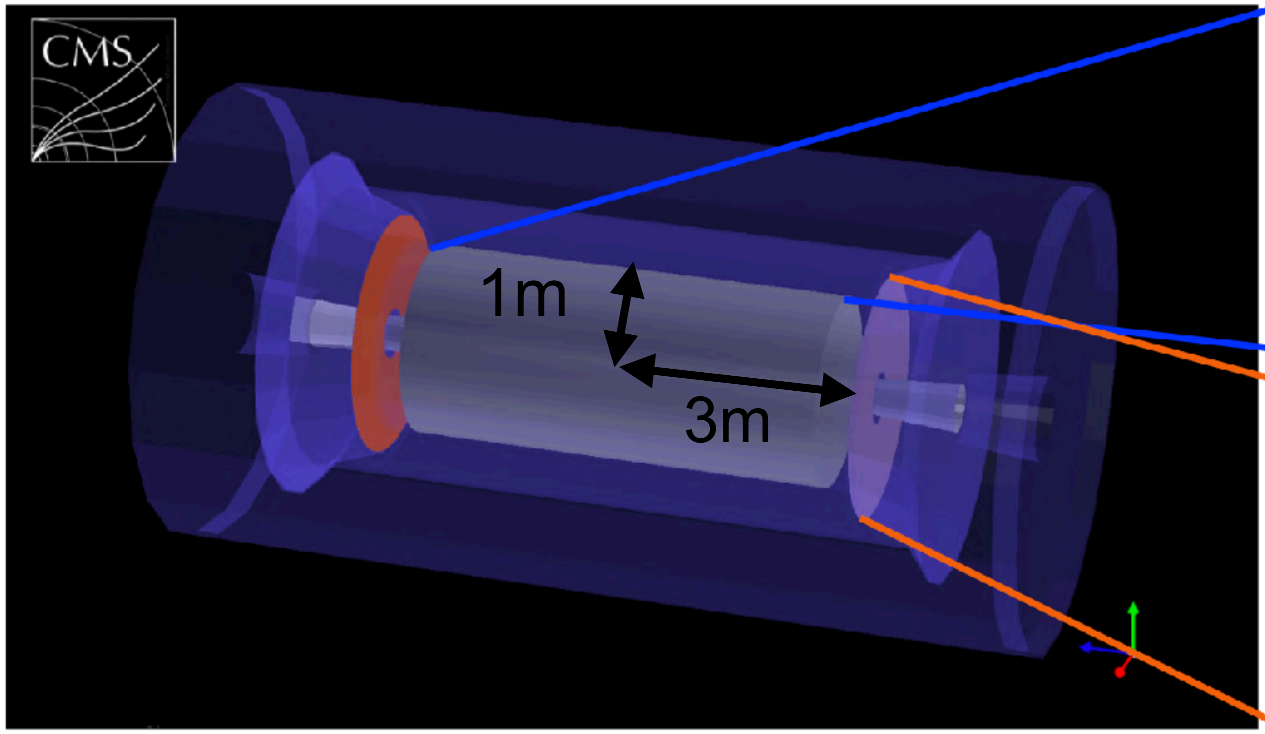
CMS MIP TIMING DETECTOR

CMS MTD: 2 thin timing layers for charged particles installed between tracker and calorimeters

- Almost hermetic coverage for $|\eta|<3$
- Different technologies adopted for barrel and endcap: choice driven by radiation hardness, cost/area/channel, power consumption, schedule
- MTD project approved by CERN research board at the end of 2019

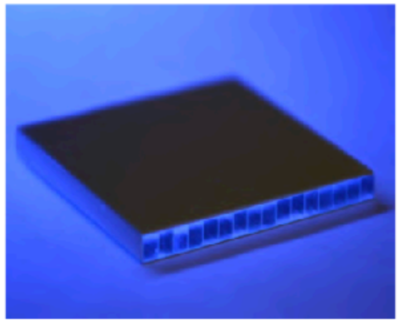


https://cds.cern.ch/record/2667167



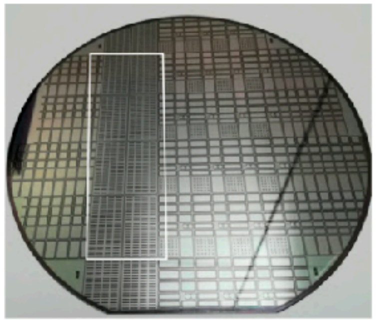
BTL: LYSO bars + SiPM read-out

- TK/ECAL interface ~ 45 mm thick
- $|\eta|< 1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: $2\times10^{14}\ n_{eq}/cm^2$



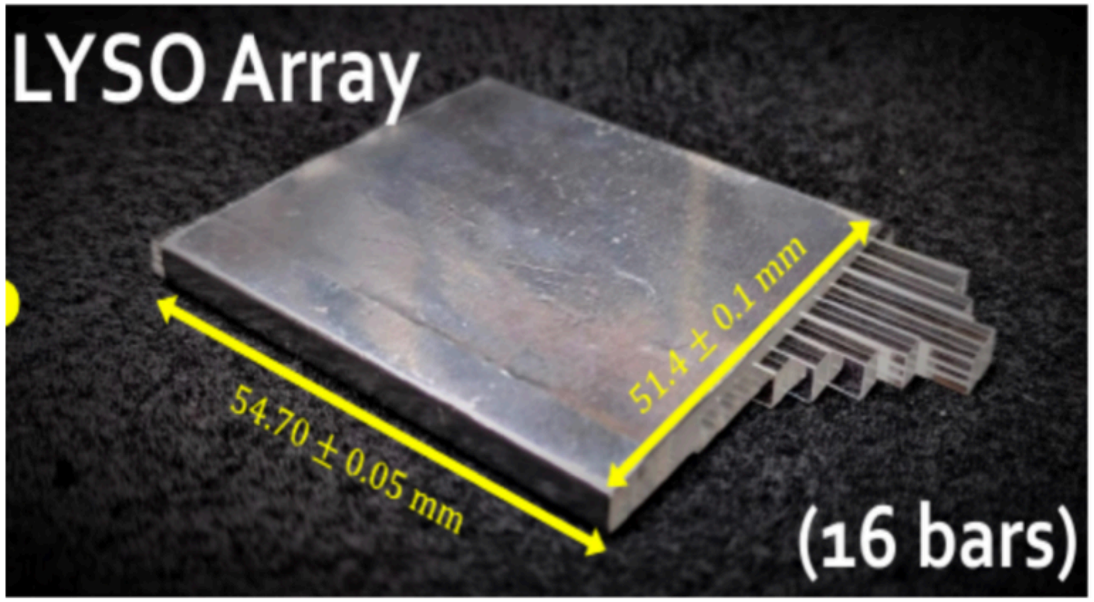
ETL: Si with internal gain (LGAD)

- On the HGC nose ~ 65 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to $2\times10^{15}\ n_{eq}/cm^2$



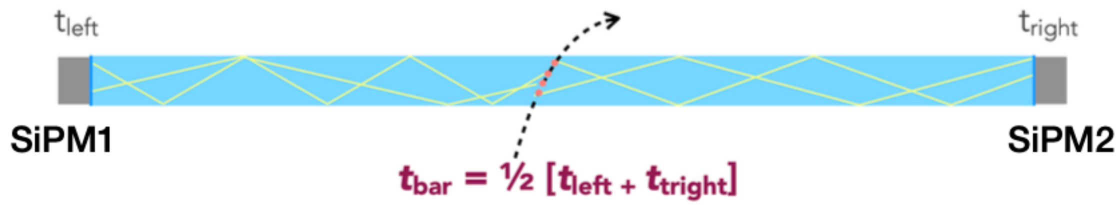
BTL: Technology And Design

Lutetium-Yttrium orthosilicate, Cerium doped crystals (LYSO:Ce)
- High light yield (40k photons/MeV), fast (40ns decay time)
- Dense (7.1 g/cm^3): MIP deposit 4.2 MeV on average in BTL
- Excellent radiation hardness up to tens of kGy



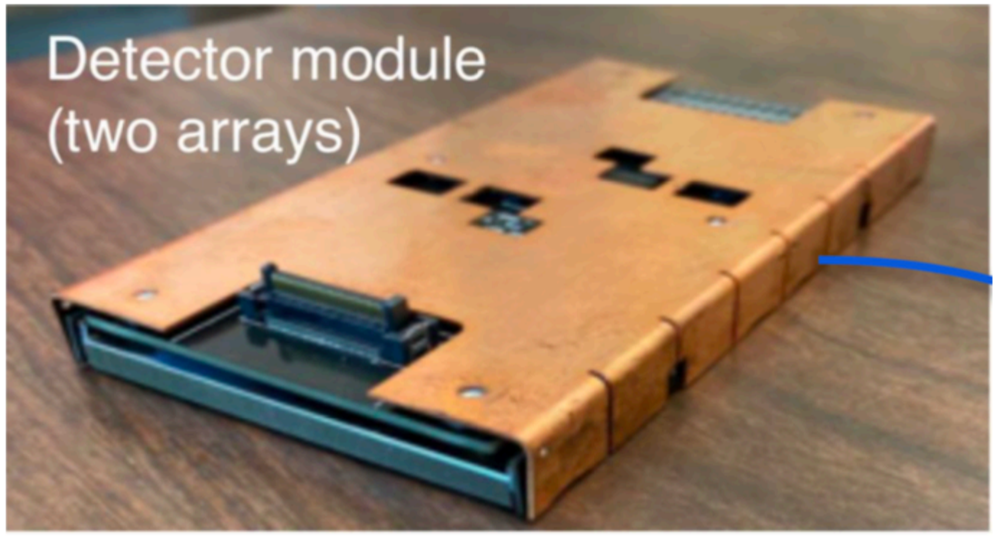
Silicon Photomultipliers
- Compact, fast, insensitive to magnetic field
- Photo detection efficiency (PDE) @ 420 nm 30-50%

Double-ended SiPM readout
- Improve resolution by $\sqrt{2}$
- Average time response independent from impact point



Detector module
- 16 LYSO bars glued to 2 SiPM arrays (~165k crystals)
- Dedicated ASIC (TOFHIR2) for signal processing

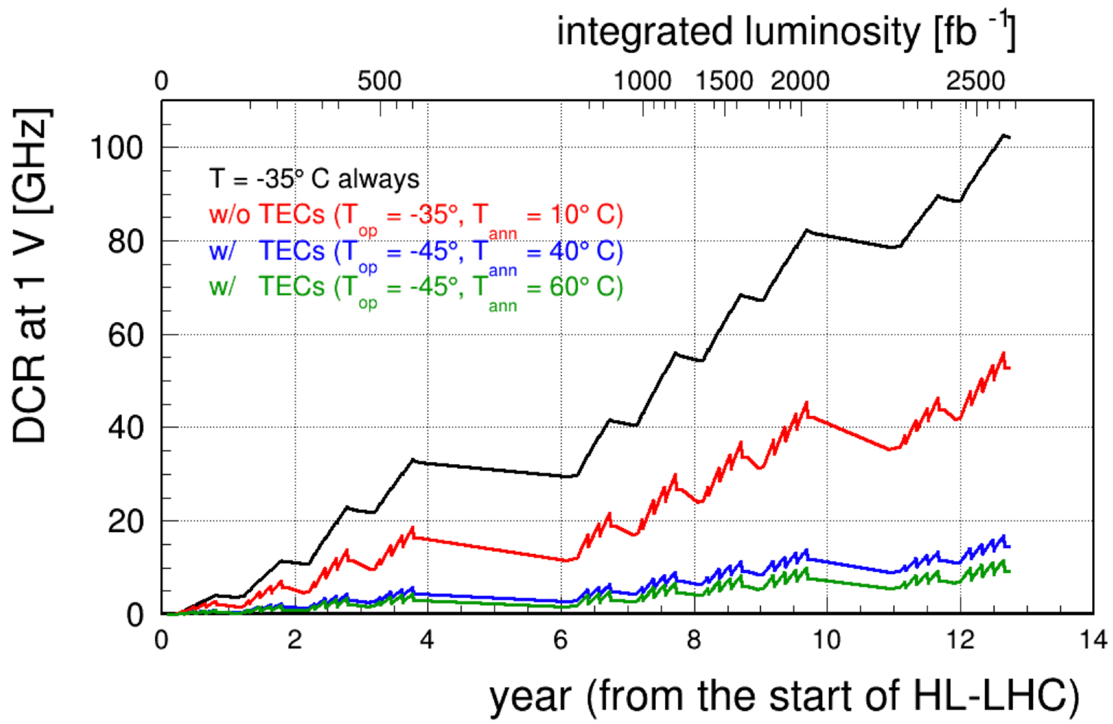
Major challenge: S/N reduction over BTL lifetime
- SiPM Dark Count Rate (DCR) increasing up to O(10) GHz after 3000 fb^{-1} (2E14 n_{eq}/cm^2)



BTL Challenge: Improve S/N

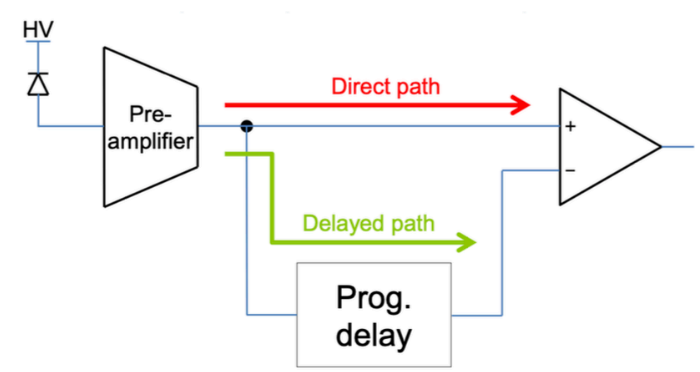
Cold operations + annealing

- CO_2 cooling at -35°C + additional cooling (**-45°C**) using **Thermo-electric coolers** (TECs) integrated in the SiPM package (DCR ~ x2 every 10°C)
- **In-situ annealing cycles** (+60°C) during machine shutdown (reverse TEC bias)



TOFHIR: high electronics gain + noise filter

- **DLED**: sum inverted and delayed signal
  - preserve fast rising edge while cancelling correlated noise

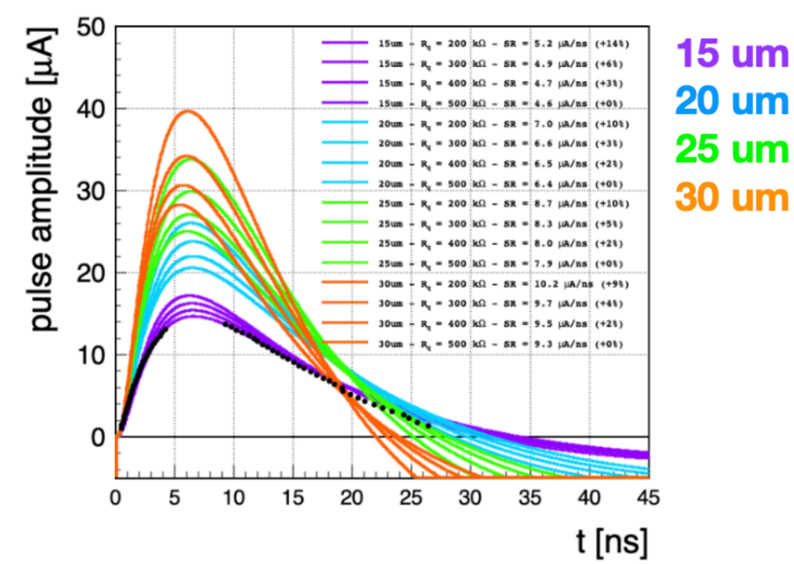


Large signal from SiPMs

- **SiPMs with larger cell size** (15→30μm)
  - Steeper signal → lower impact of electronics noise
  - Larger PDE → improvements for photo statistics and DCR resolution contributions

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

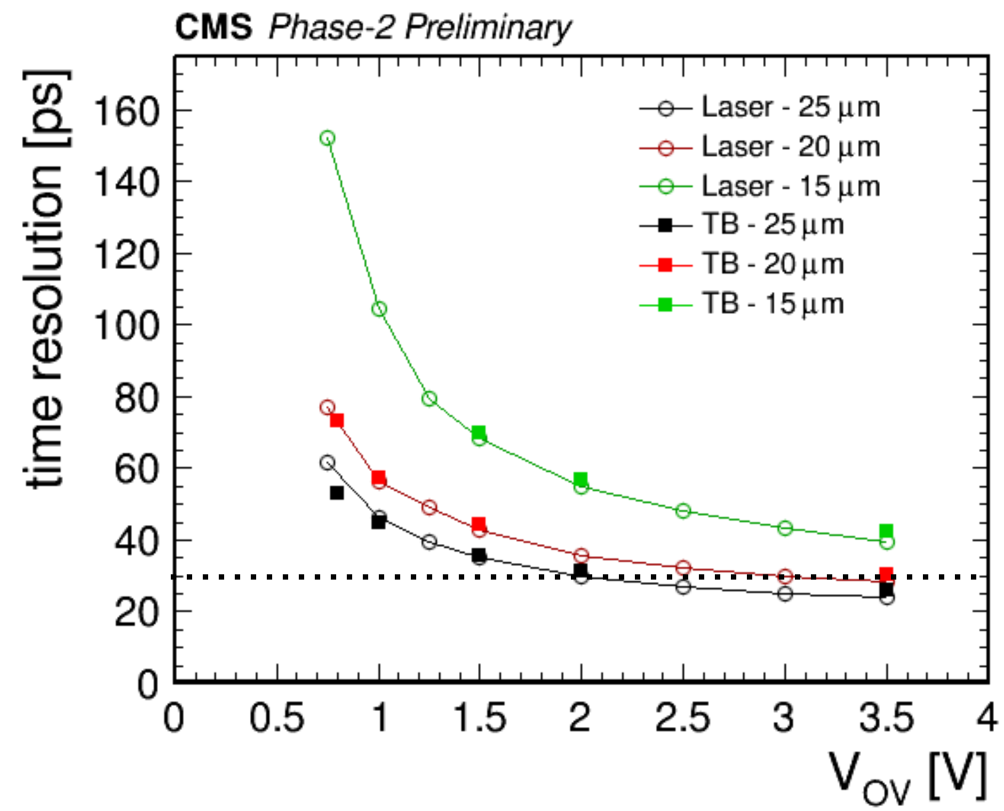
dominates at EoO



BTL PERFORMANCE VALIDATION

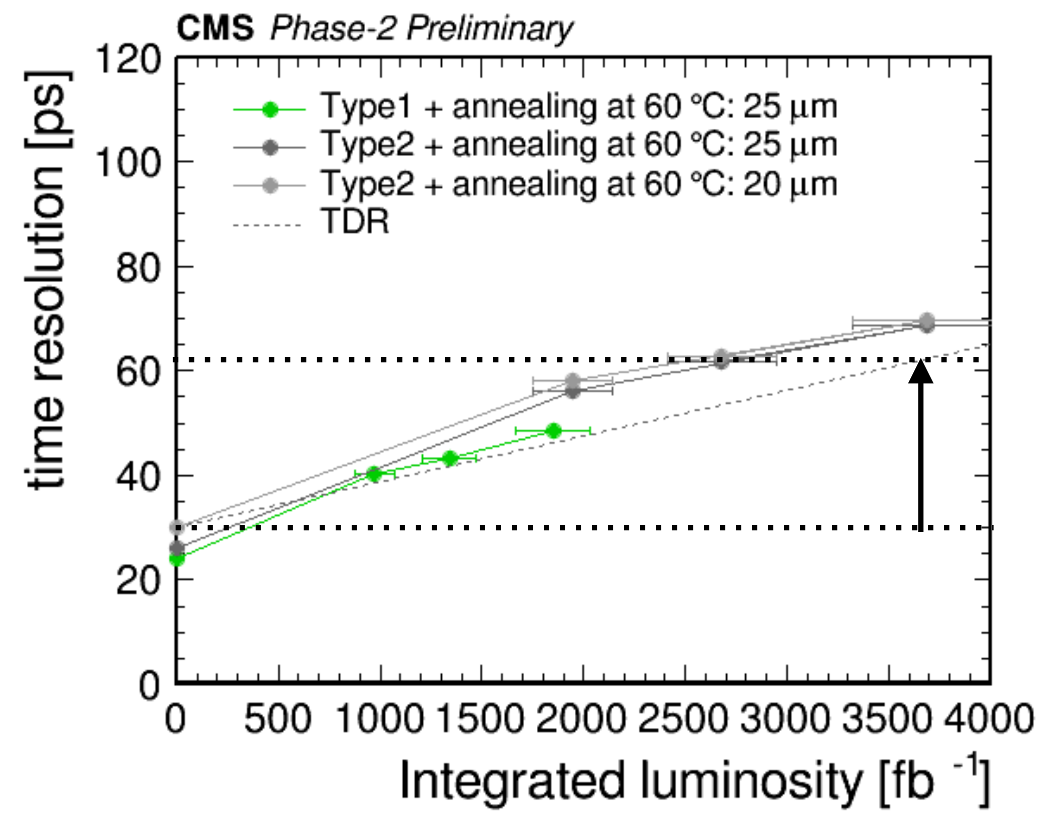
Extensive study of sensor prototypes in laboratory with UV laser and MIPs at test beam

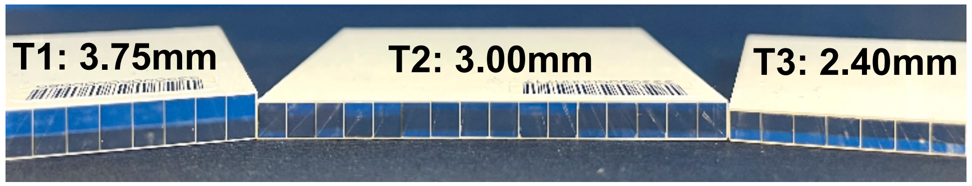
- **BTL time resolution at startup measured at ~30ps**



Performance over entire HL-LHC operations validated with beam

- Tested sensor prototypes irradiated at full fluence with final TOFHIR ASIC
- **EoO performance ~65ps**, close to TDR expectations
- Final detector configuration chosen: **25μm cell SiPMs + 3.75mm thick (Type1) LYSO**

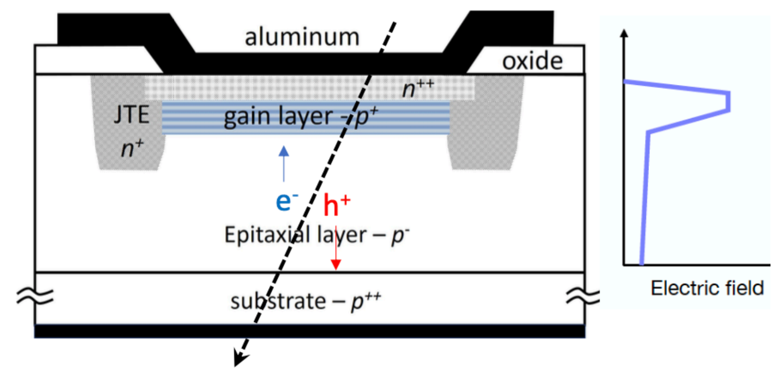


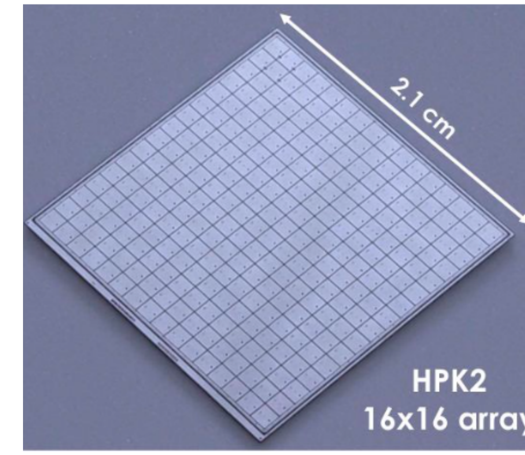


ETL: Technology and Design

50 μm thick planar low-gain avalanche silicon diode (LGAD)

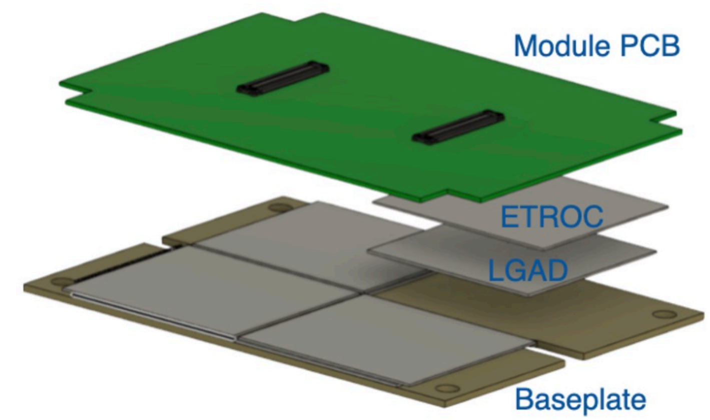
- highly doped thin gain layer, moderate gain (10-30) to improve S/N ratio
- 16x16 array, pad size 1.3x1.3 mm², inter-pad <50μm
- charge collected >8 fC until EoO



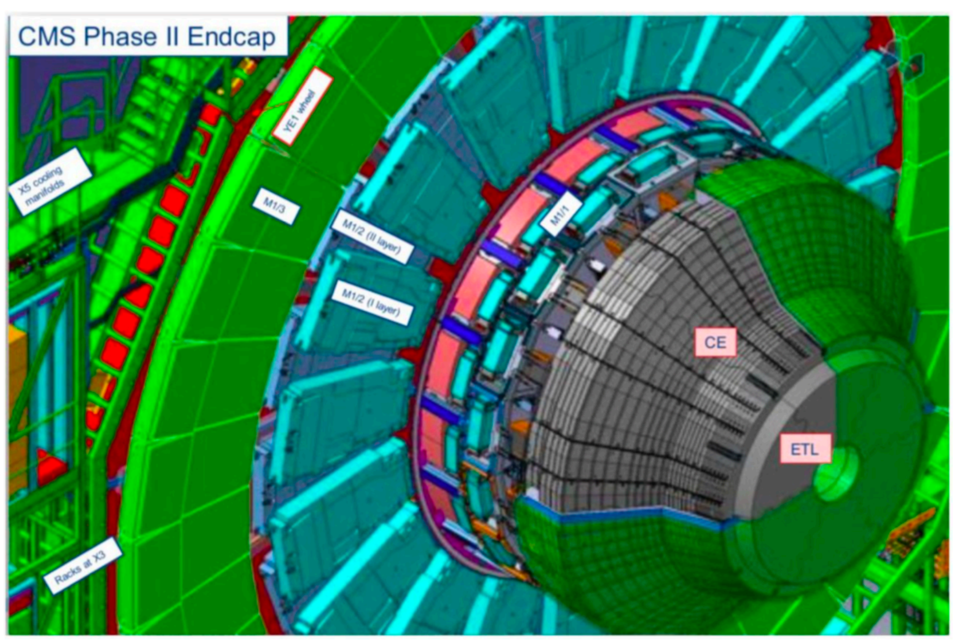


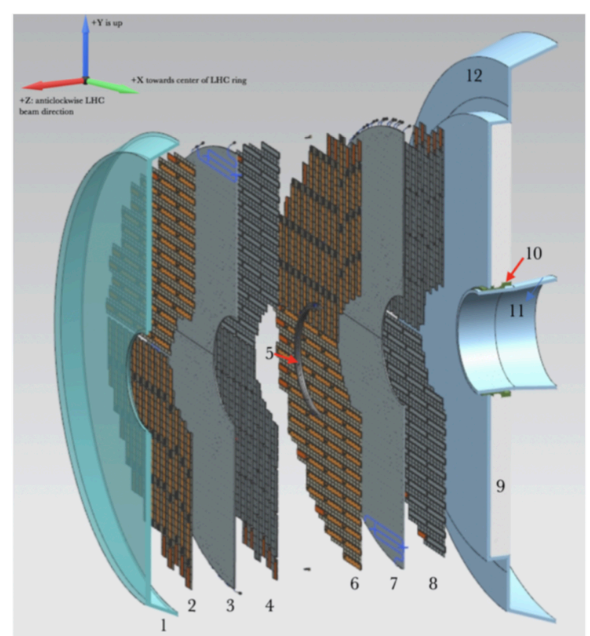
Sensor bump bonded to readout ASIC (ETROC)

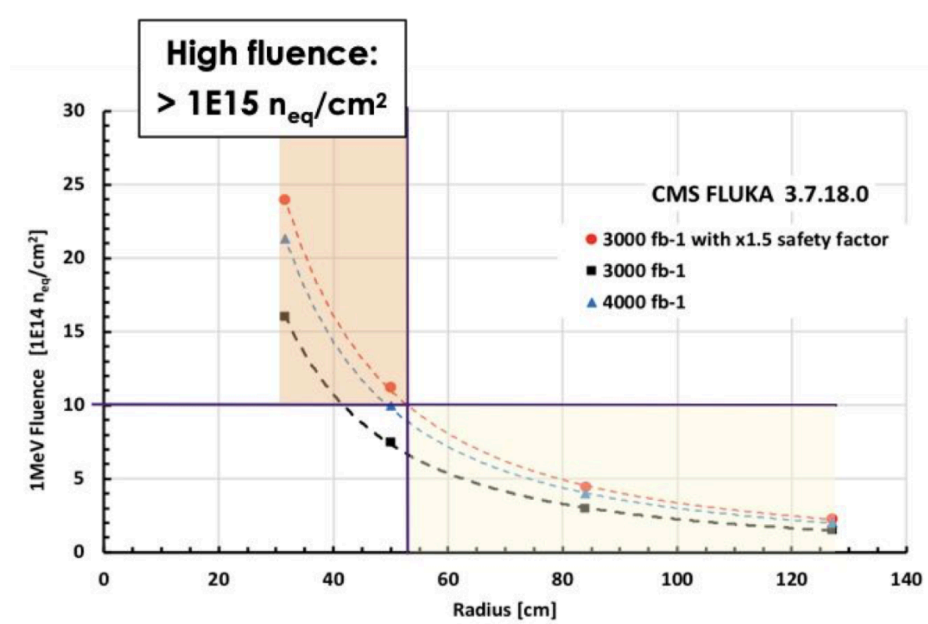
- Modules assembled as 2 double-sided disks on each endcap
- Each disk provides large geometrical acceptance (~85%), 2 disks to ensure 2 hits/track
- ~8000 modules on 2 endcaps, 8.5M channels
- **Target time resolution: 50ps/hit, 35ps/track**



~12% of ETL will be exposed to fluence >1E15 n_{eq}/cm^2







ETL: Towards Final Sensor Design

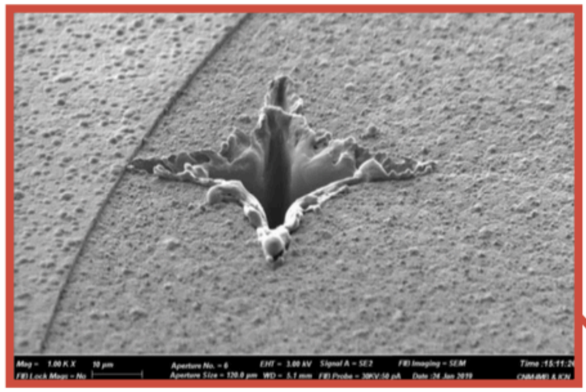
Worked with multiple vendors to optimise ETL sensor design

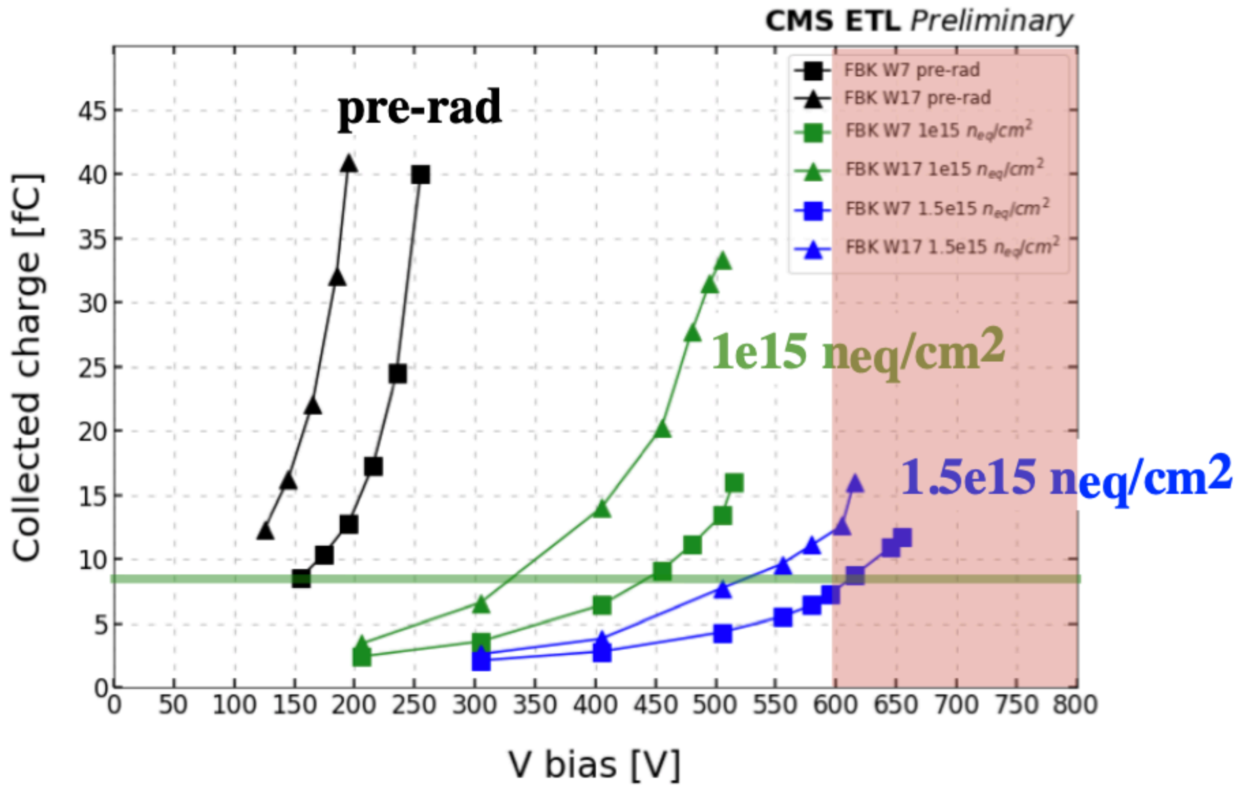
- Market survey concluded, tender to be issued in Q4/2023

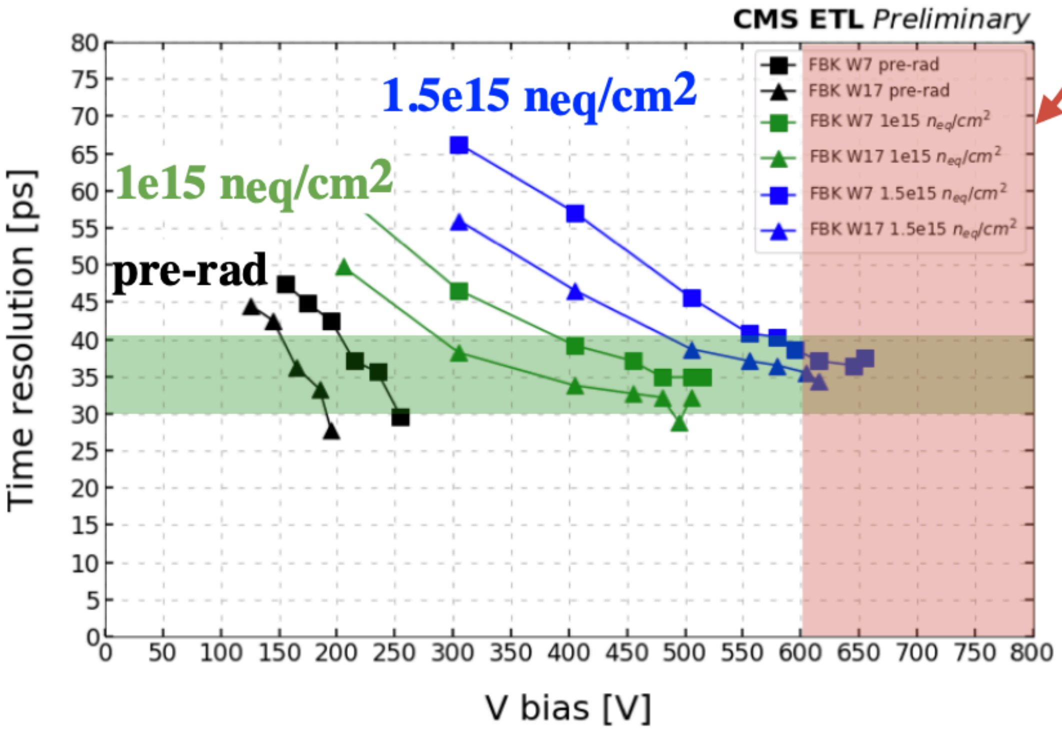
Example of MS samples performance: FBK (55 microns thick) sensors measured with a Sr90 source setup

- Bare sensors $\sigma_t \sim 30$ps
- Timing performance after irradiation recovered increasing bias voltage within safe limits (<11.5 V/µm)

Single event burnout at high E-field from rare large ionising events







ETL PERFORMANCE VALIDATION

Full size 16x16 array tested on beam with custom electronics

– intrinsic σ_t ~ 30ps

Realistic readout tested: LGAD + ETROC1 (4x4)

– σ_t ~ 45ps, first full system DAQ

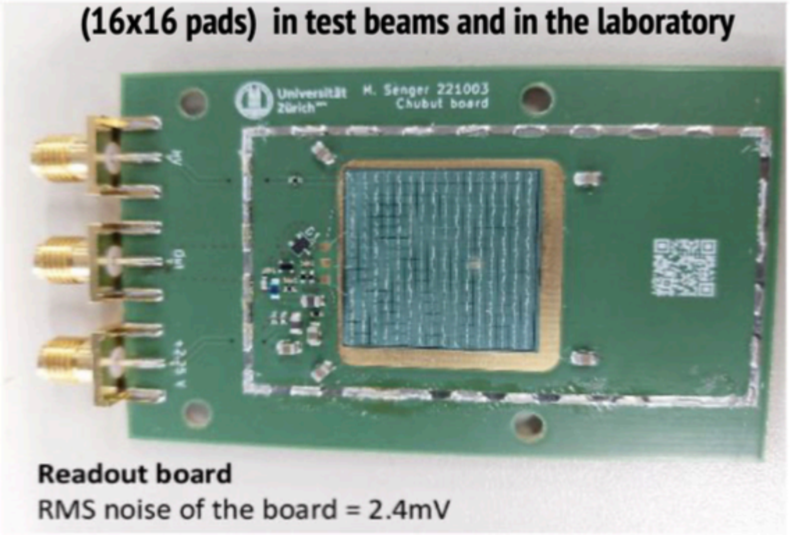
ETROC2 (full size ASIC 16x16) currently under test

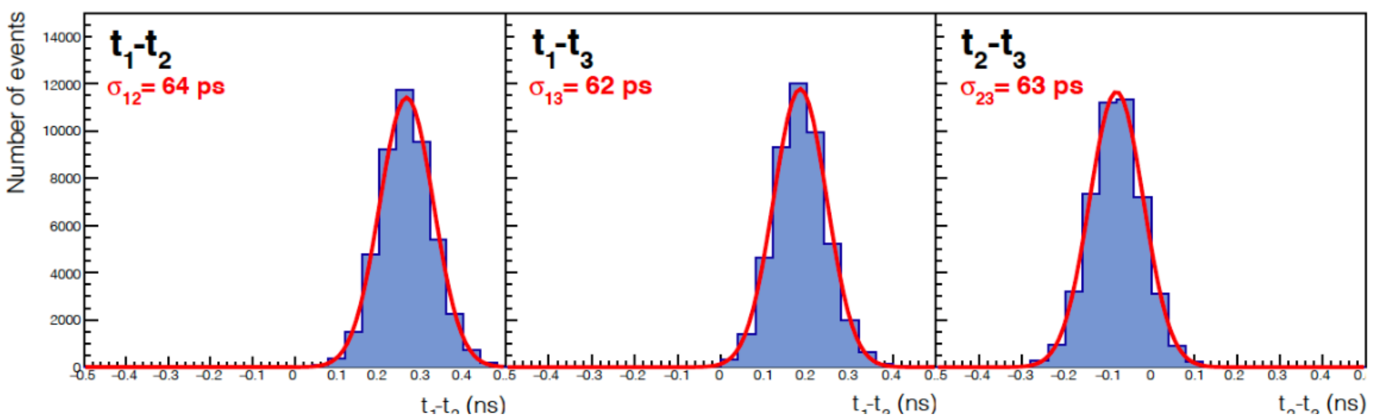
– Received Jun2023, all looks good

– Test beam of LGADs+ETROC2 to start in Sep2023

– Aim to submit the final chip (ETROC3) in 2024

UZH-UCSC board used to stress test the final sensor (16x16 pads) in test beams and in the laboratory

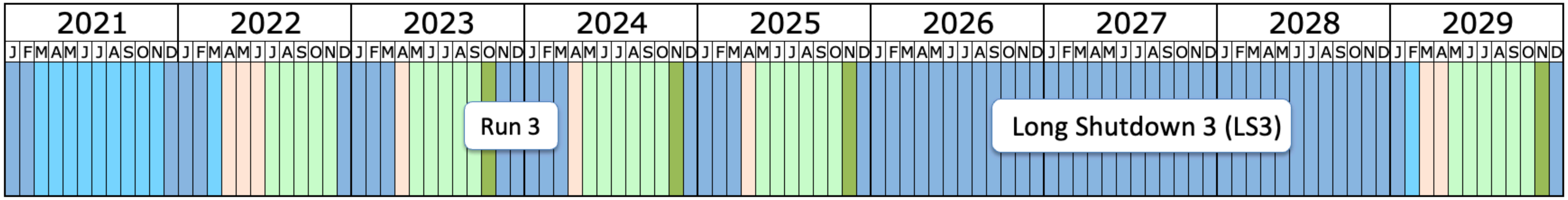




LGAD+ETROC1 resolution is 42-46 ps from TDC digital outputs

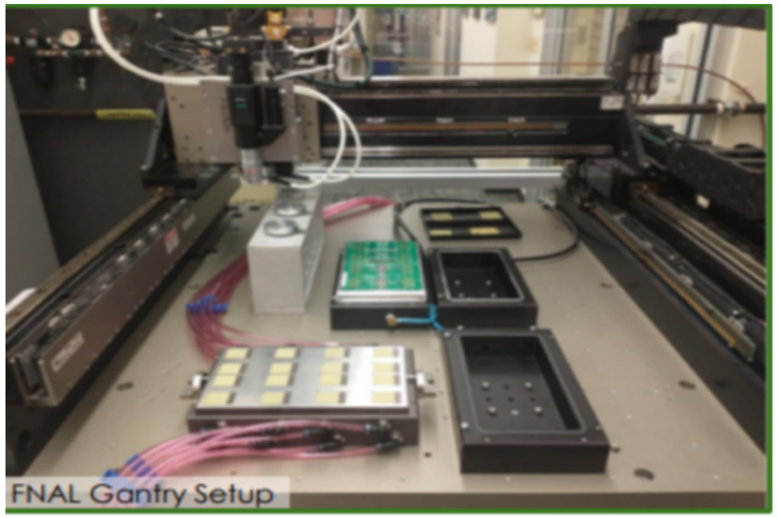
$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)}$$

MTD SCHEDULE



BTL: tight schedule, first detector to be installed inside the tracker support tube
- Now pre-production: finalising assembly tools and final integration tests
- 4 assembly centres. Assembly to start in Q2/2024
- Final installation in the Tracker support tube by Q3/2025

ETL: more relaxed schedule, can be installed either on surface or inside the cavern
- Now finalising the prototyping: focussing on ETROC2 validation, sensor procurement, module design and assembly procedures, integration tests
- 3 assembly sites established, 1 being setup, more under discussion. Assembly scheduled to start during 2025



SUMMARY

MTD: a major asset for the overall CMS physics programme at HL-LHC

- **Physics gains for many final states**, in some cases **equivalent to ~25%** more luminosity (few years of additional running of HL-LHC)
- **New powerful handles** for BSM and heavy flavour physics

MTD: mature design, moving into integration phase after several years of R&D and extensive prototyping

- **Novel detector technologies** adopted for barrel and endcap, **new ASICs** successfully developed, **addressed several design challenges**
- **Performance validated with beam for BTL and ETL**, close to TDR expectations
- **Now gearing up for assembly**: finalising tools and procedures, detector construction to start in 2024 with BTL

CMS Upgrade For HL-LHC

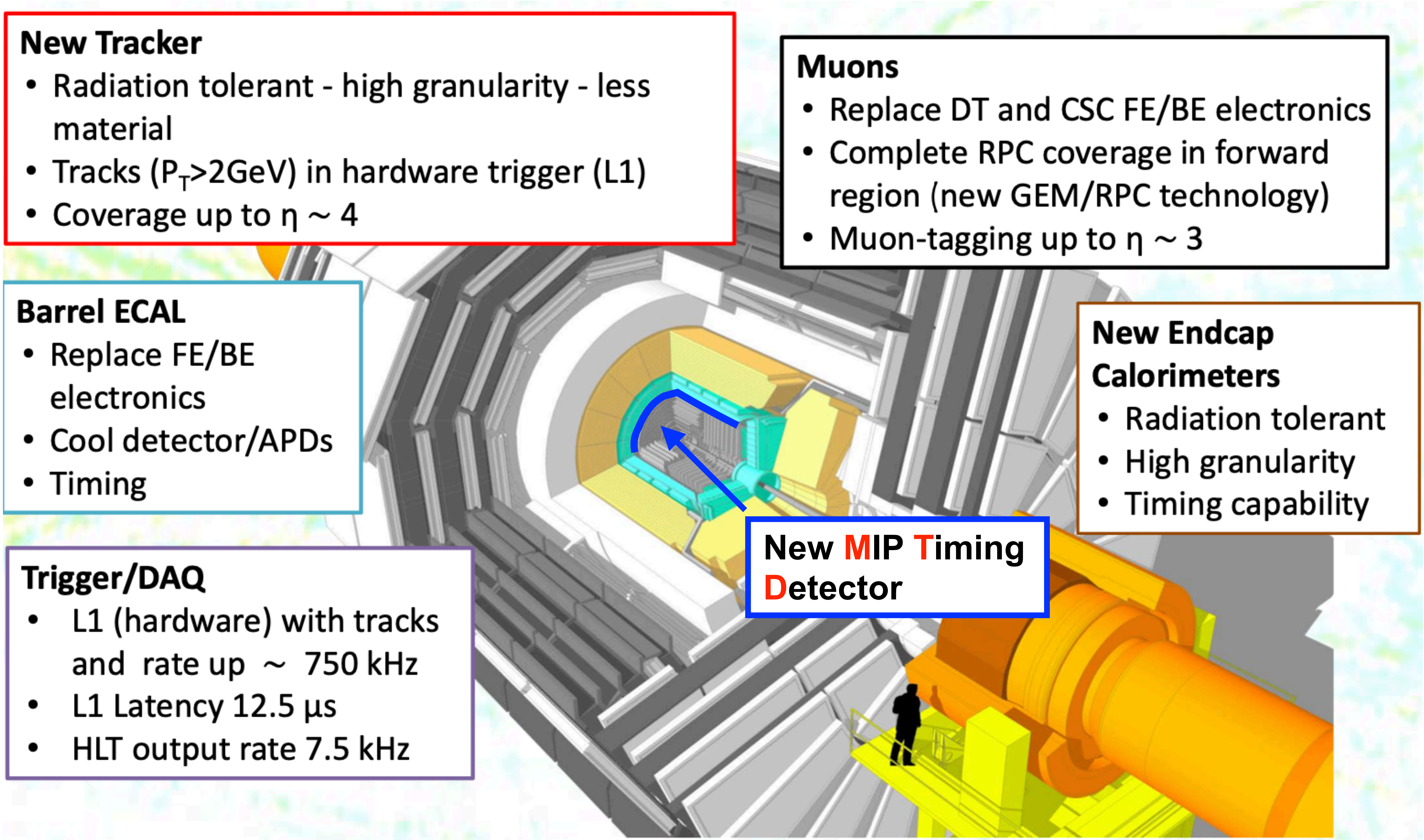
New Tracker
- Radiation tolerant - high granularity - less material
- Tracks (P_T>2GeV) in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT and CSC FE/BE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Muon-tagging up to η ~ 3

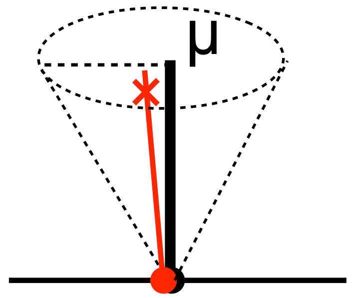
Barrel ECAL
- Replace FE/BE electronics
- Cool detector/APDs
- Timing

New Endcap Calorimeters
- Radiation tolerant
- High granularity
- Timing capability

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz

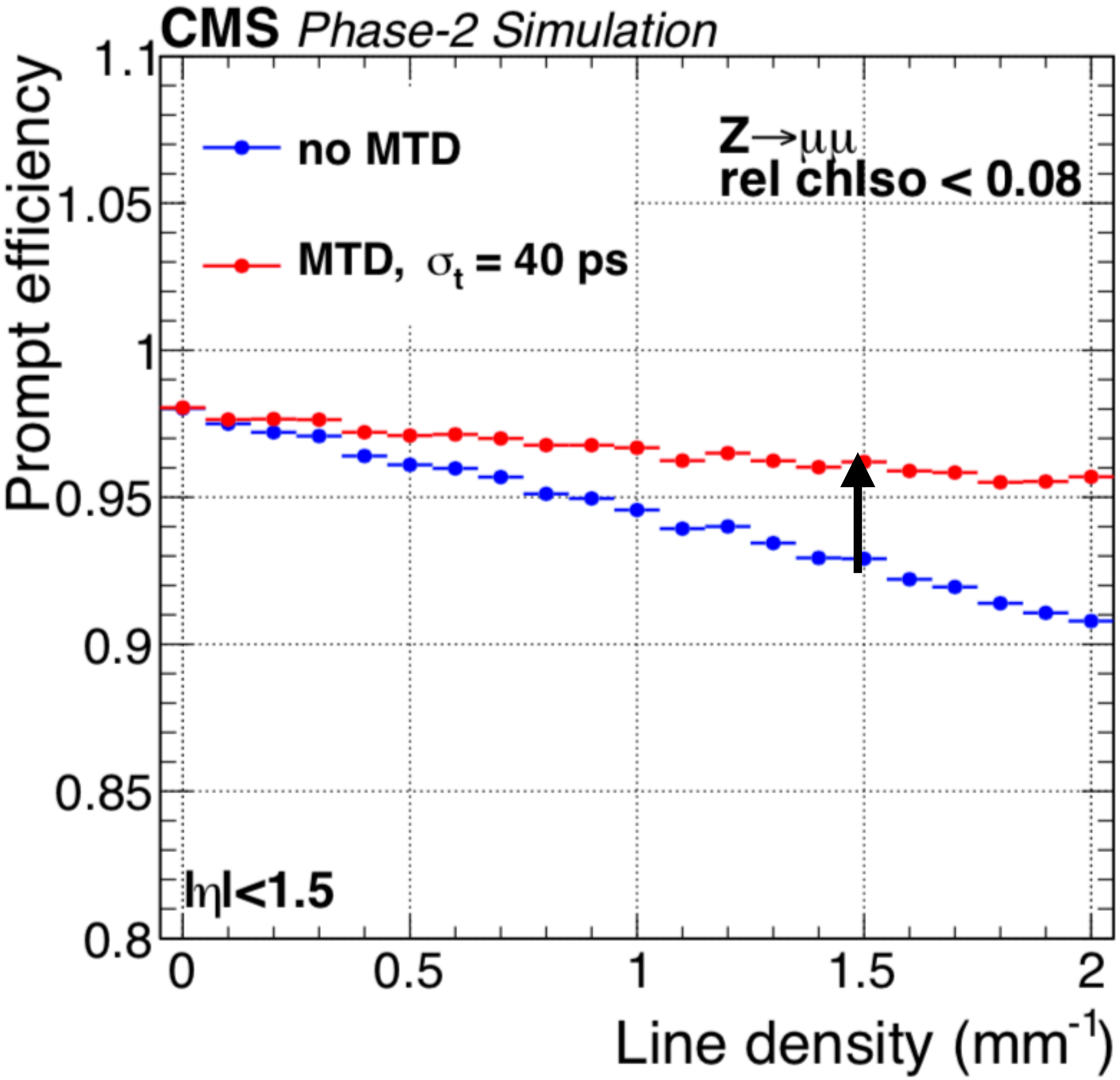


MTD Impact: Lepton ID

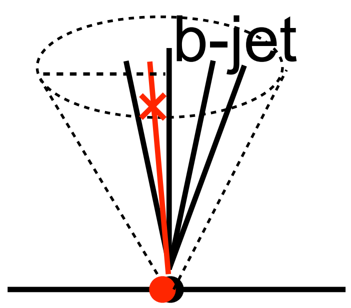


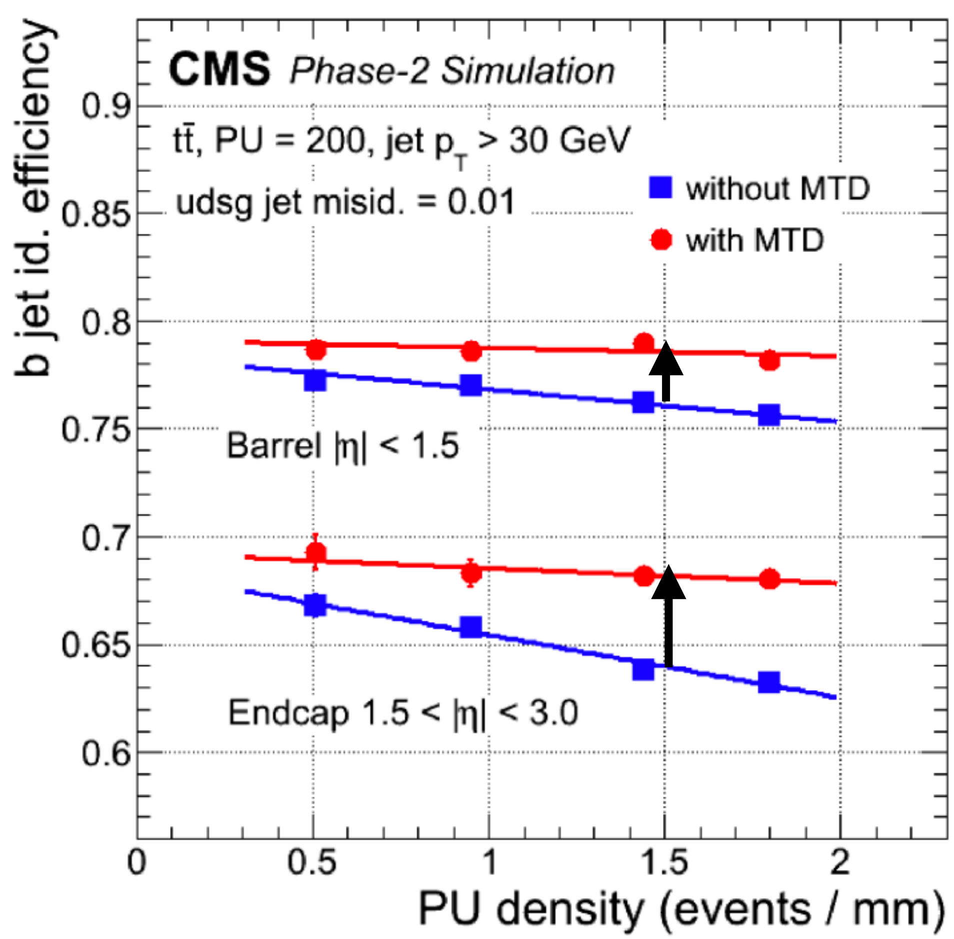
Simplest (yet effective) application: lepton isolation

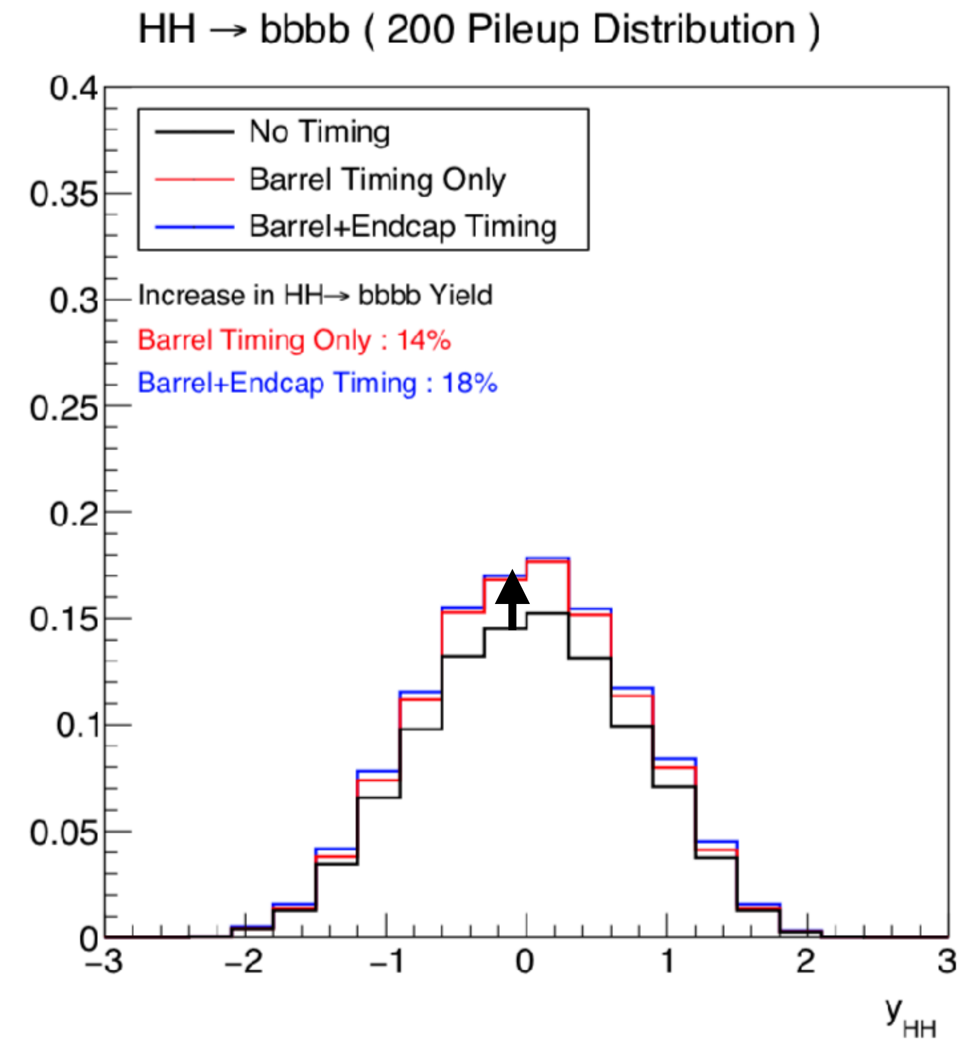
- Isolated leptons main probes at LHC in several final states (eg. H→ZZ→4l, H→$\tau\tau$, …)
- Reduction of PU contamination in isolation cone: **gain up 15-20% for lepton identification**



MTD Impact: B-Tagging



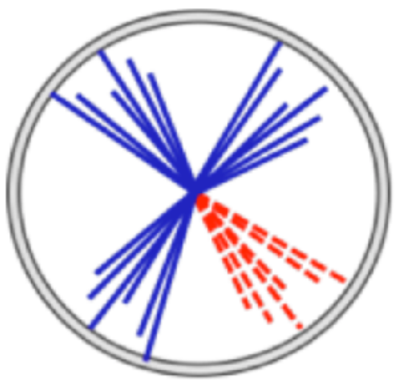


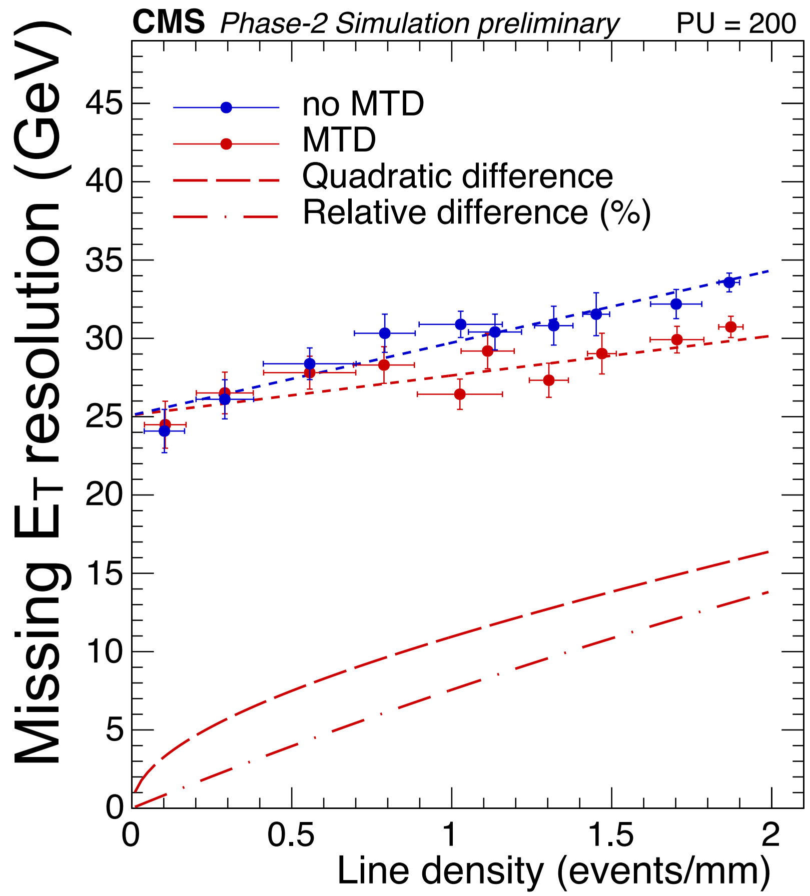


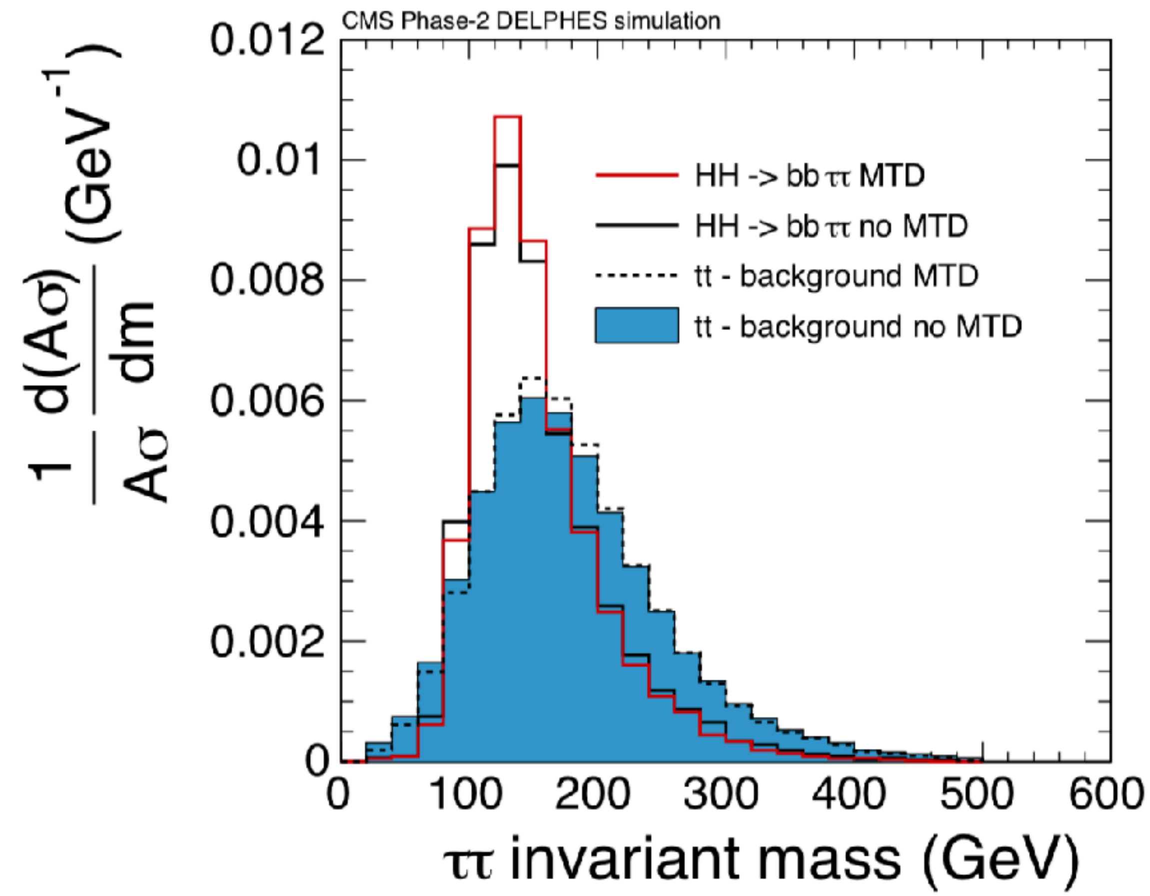
Reduction of PU contamination helps to maintain performance at high pile-up for more complex algorithms, such as identification of displaced jets, aka b-tagging

Significant acceptance gains (~20%) when looking at final states with several b (e.g. $HH \to bbbb$, $HH \to bb\gamma\gamma$)

MTD Impact: Missing E_T







Also gain in resolution for global event properties, such as momentum balance in the transverse plane, missing transverse energy

Improvements eg. for reconstruction of invariant mass for events with neutrinos (e.g. H→$\tau\tau$) or searches (e.g. SUSY)

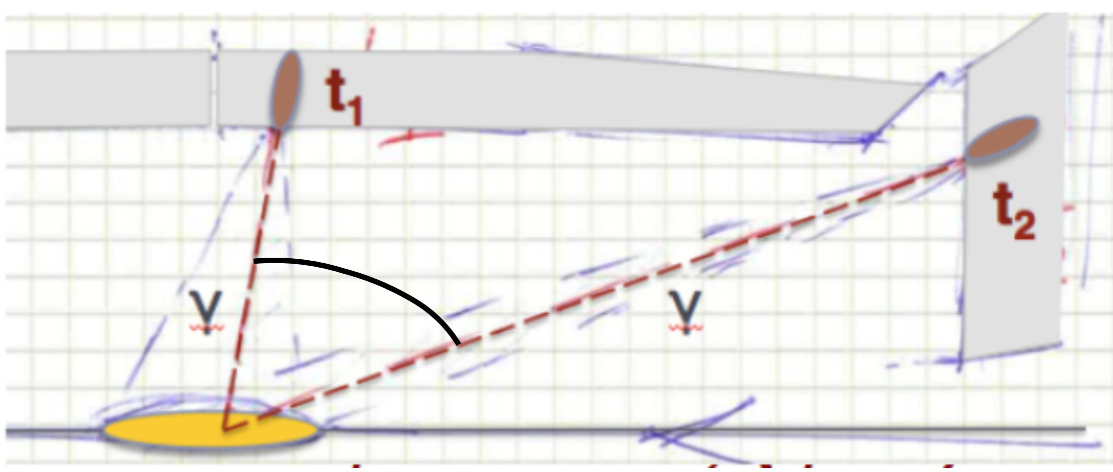
Track + Neutral Timing

Track-timing complements timing capabilities in upgraded CMS calorimeters

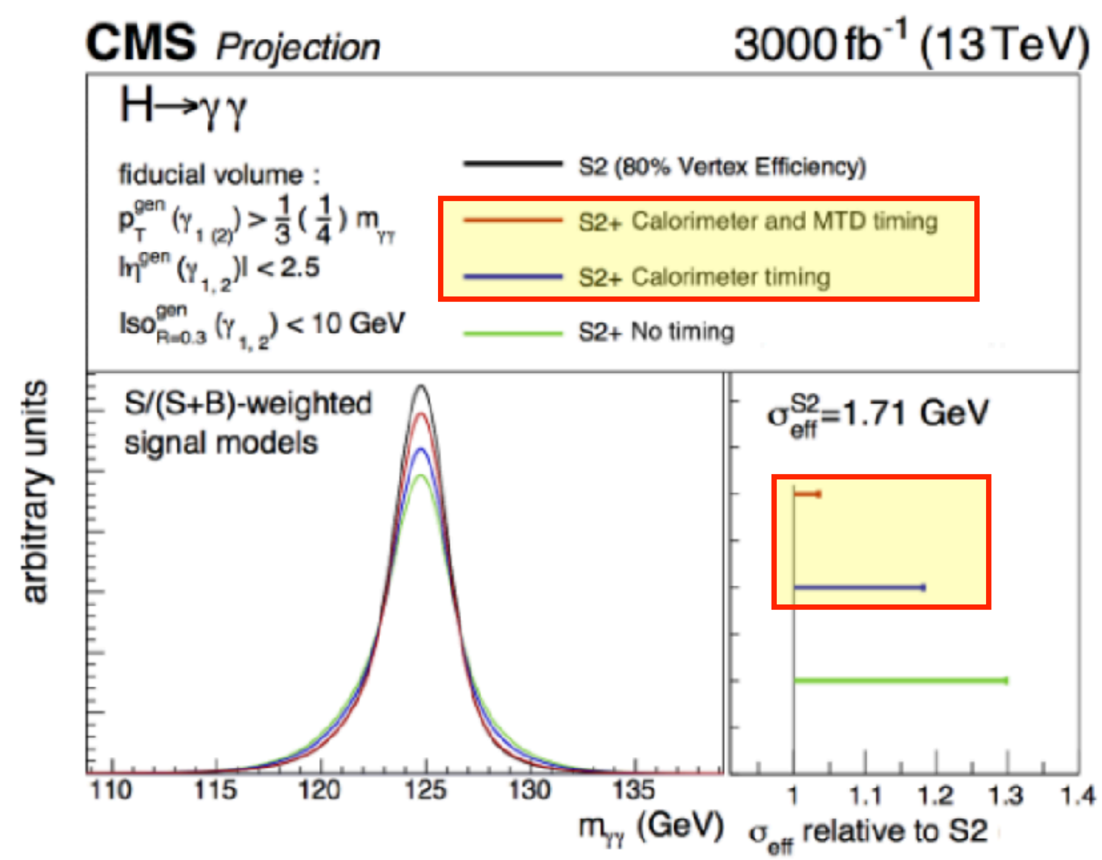
- Barrel: ECAL upgraded electronics, precise timing for γ ~30ps above E>40-50 GeV
- Endcap: new HGCAL, precise timing for γ ~50ps above p_T>3-4 GeV

Track+neutral timing can be combined in PU robust particle flow algorithms (being developed)

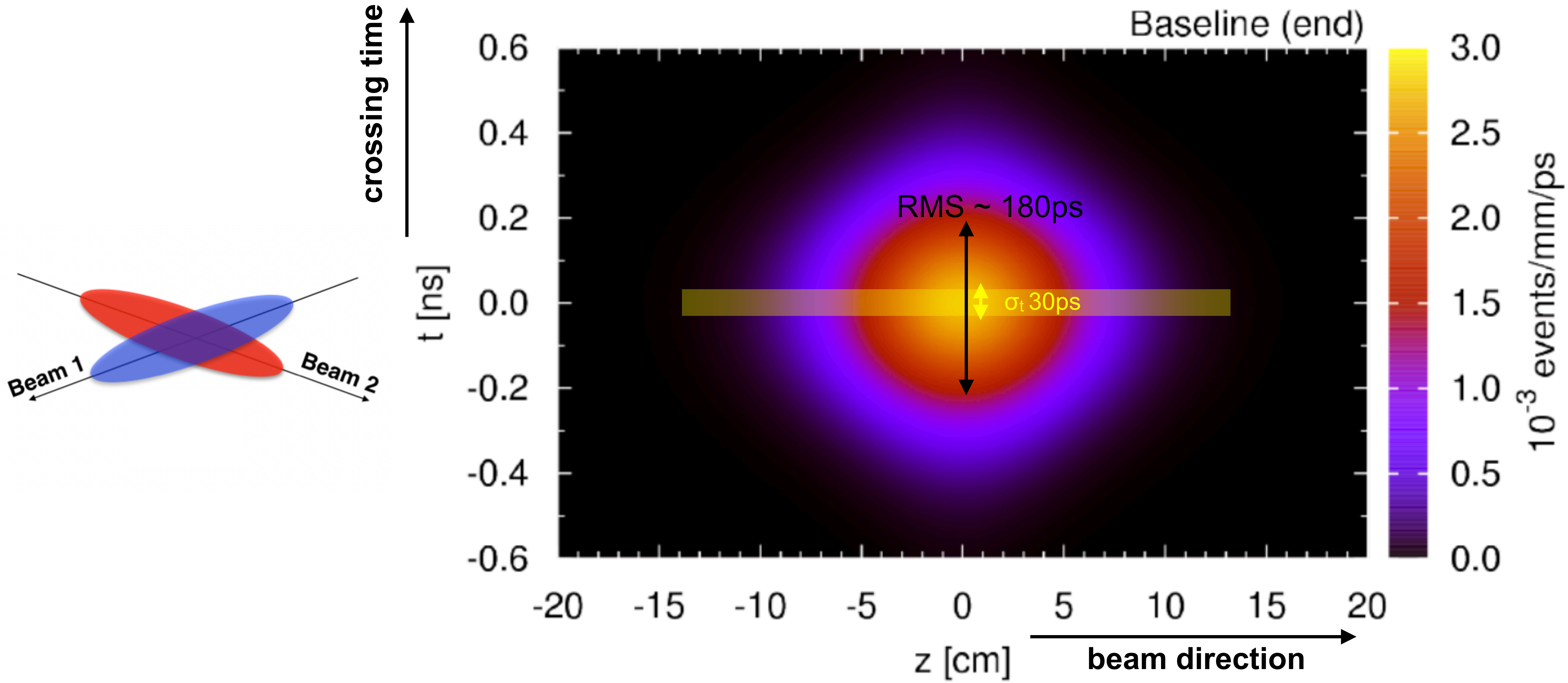
Another example: identify H→γγ production vertex using the track+ECAL timing information without a "pointing" calorimeter



ECAL photon time + vertex time from MTD recover ~80% vertex identification efficiency, similar to LHC current performance



Beam Spot Spread



Bunch crossing extends in space (along the beam direction) and time

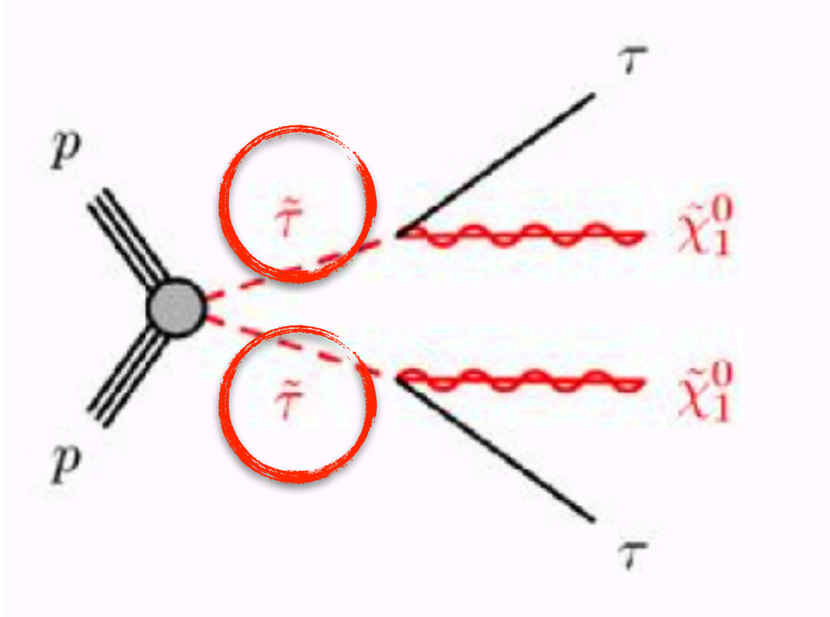
Nominal LHC optics: RMS in space ~5cm, in time ~ 180ps

If beam spot can be sliced in ~30ps time exposures, pile-up in a single exposure drops to current LHC pile-up levels

TOFPID: BSM

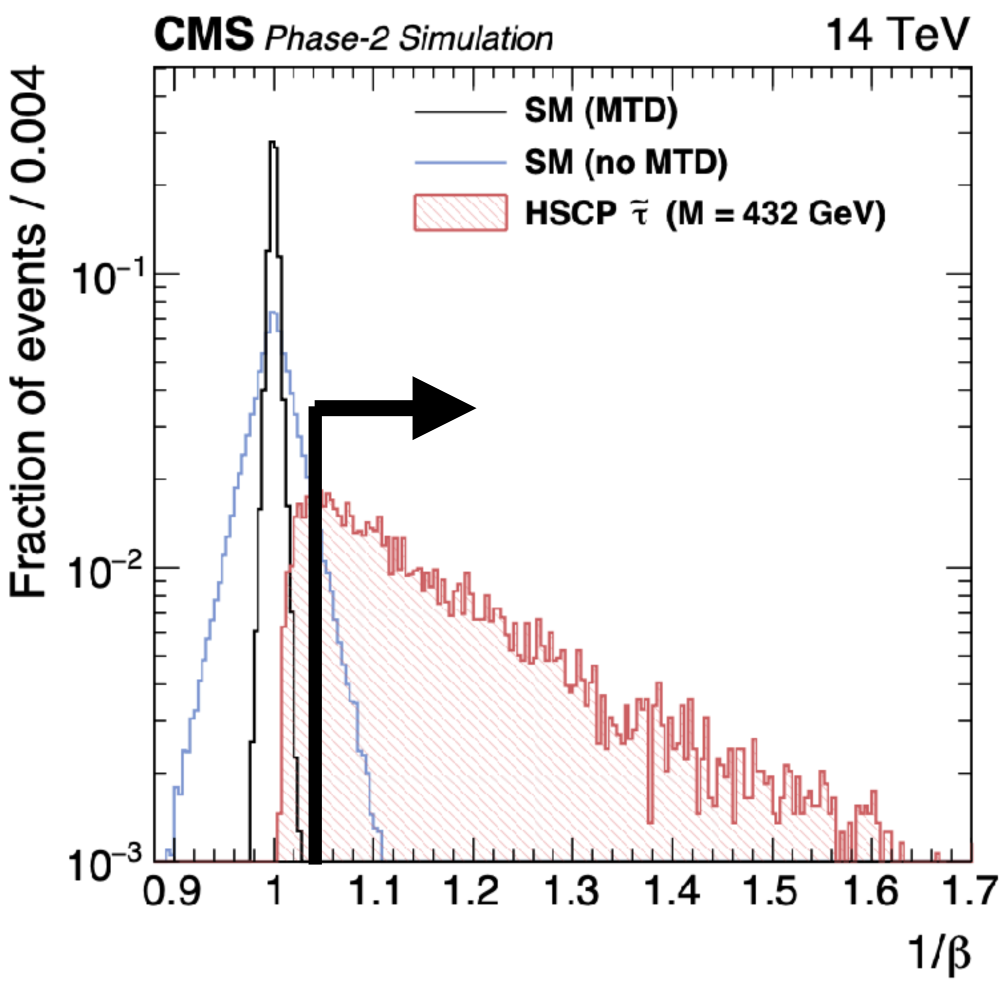
TOFPID can also be applied in BSM searches, eg heavy stable charged particle (staus, gluinos,…)

– a new handle in addition to dE/dX

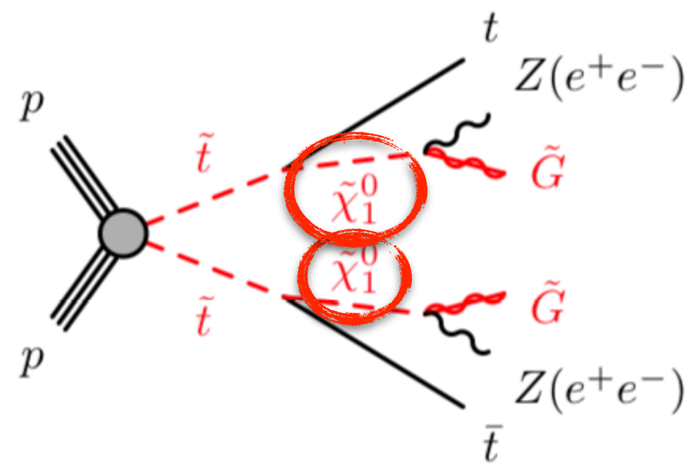


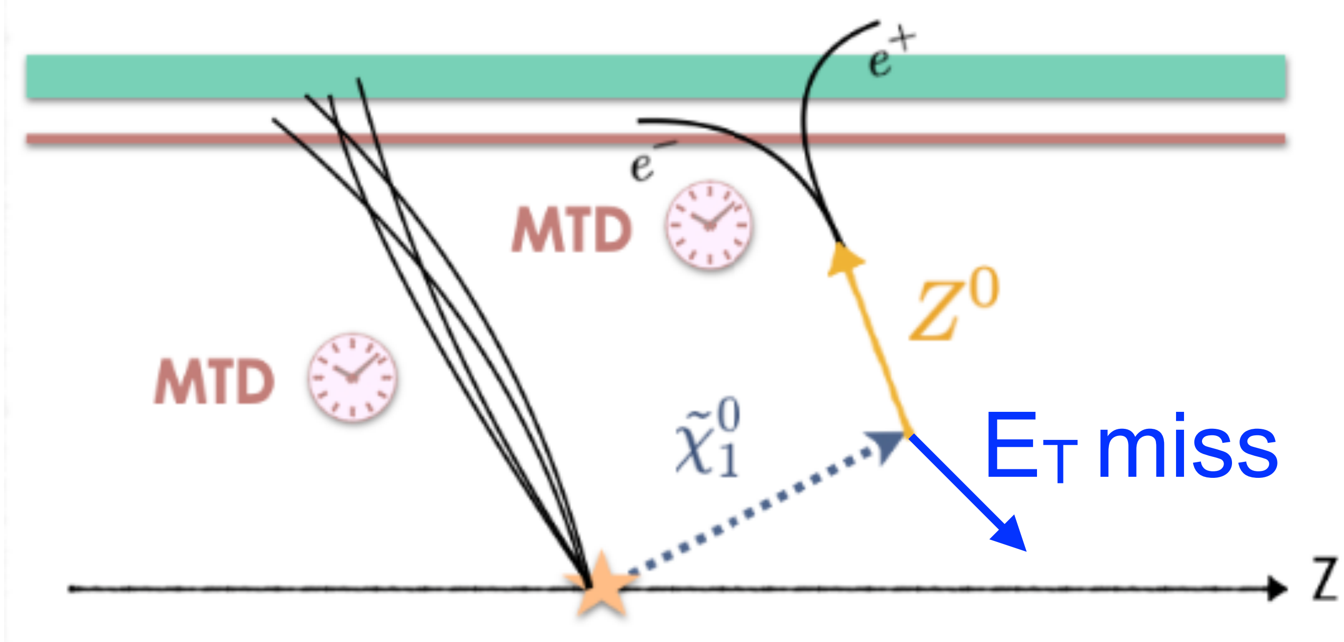
1/β resolution improved by 1 order of magnitude

large reduction of SM background → signal acceptance gain



BSM: DISPLACED OBJECTS

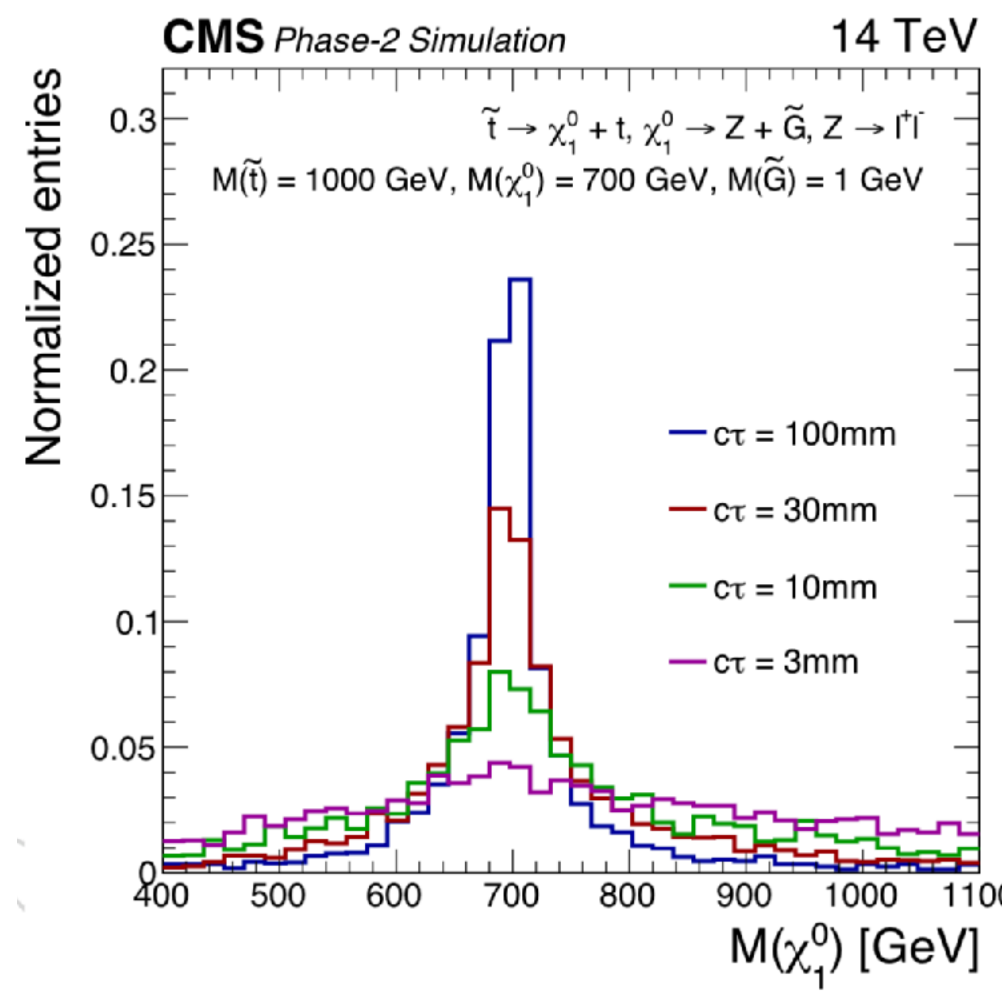




Eg: long lived neutral particle, neutralino, decaying into Z+gravitino (E_T miss)

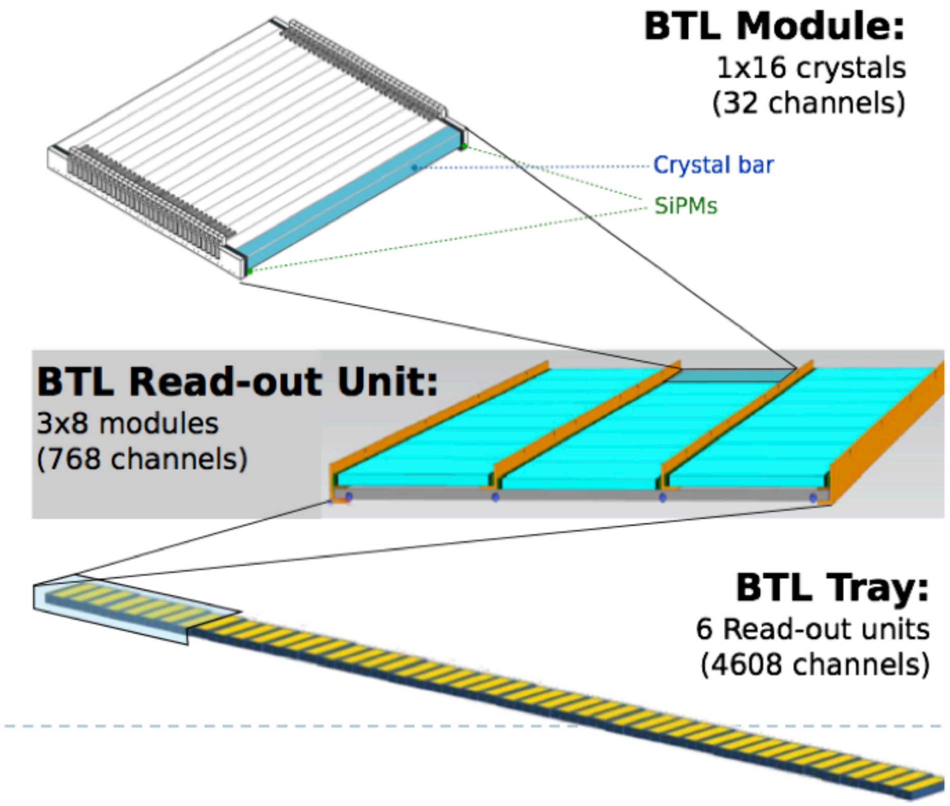
Can close kinematics measuring $\beta_{neutralino}$ from displaced vertex time (better resolution for longer decay distance)

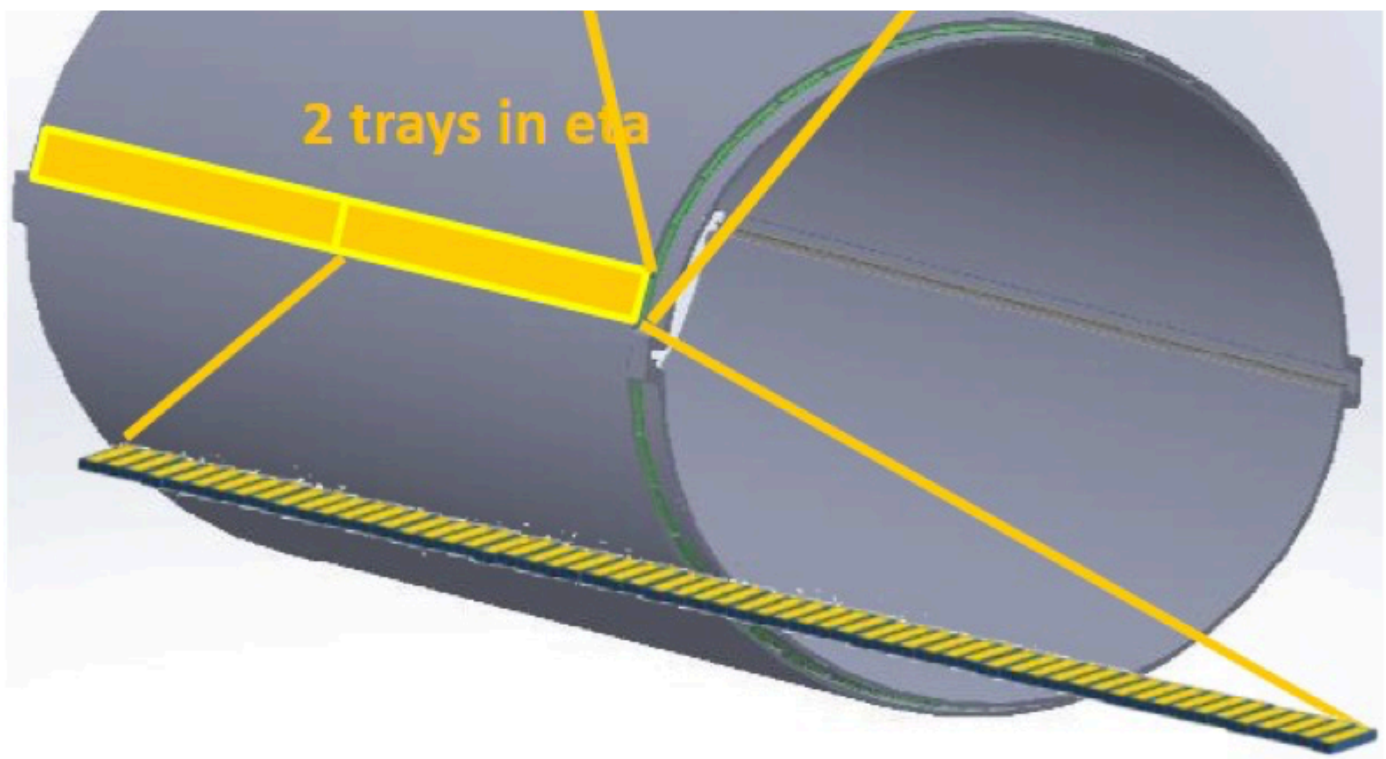
Neutralino mass can be reconstructed

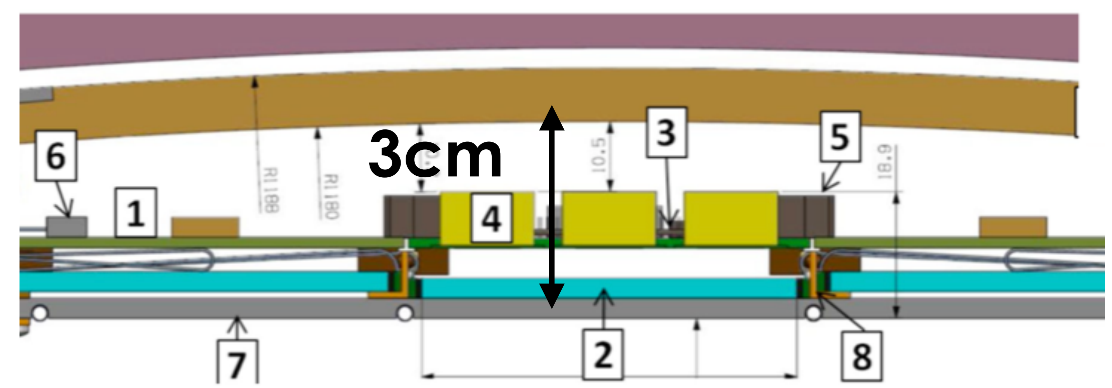


BTL LAYOUT

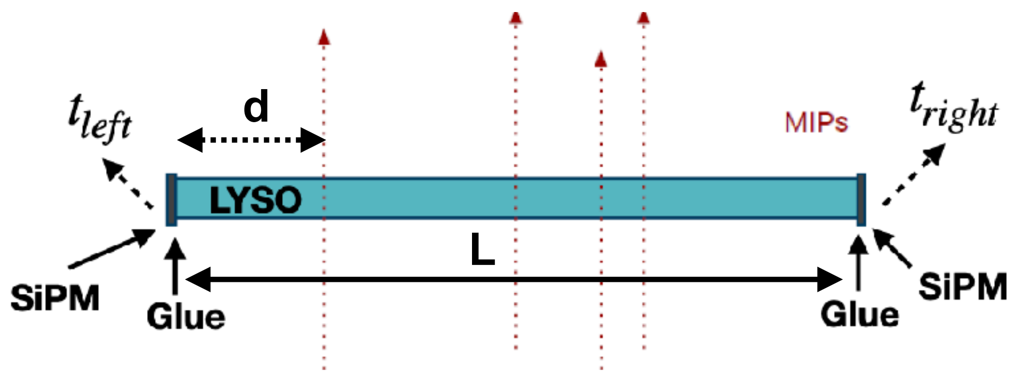
- Basic unit: array of 16 LYSO crystals (57mm length, 3.2mm pitch, 3 different thickness vs η) + 2 SiPM linear arrays on both ends
- 72 trays on the inner surface of the tracker support tube, ~38m^2
- Coverage $|\eta|<1.45$, 332k channels



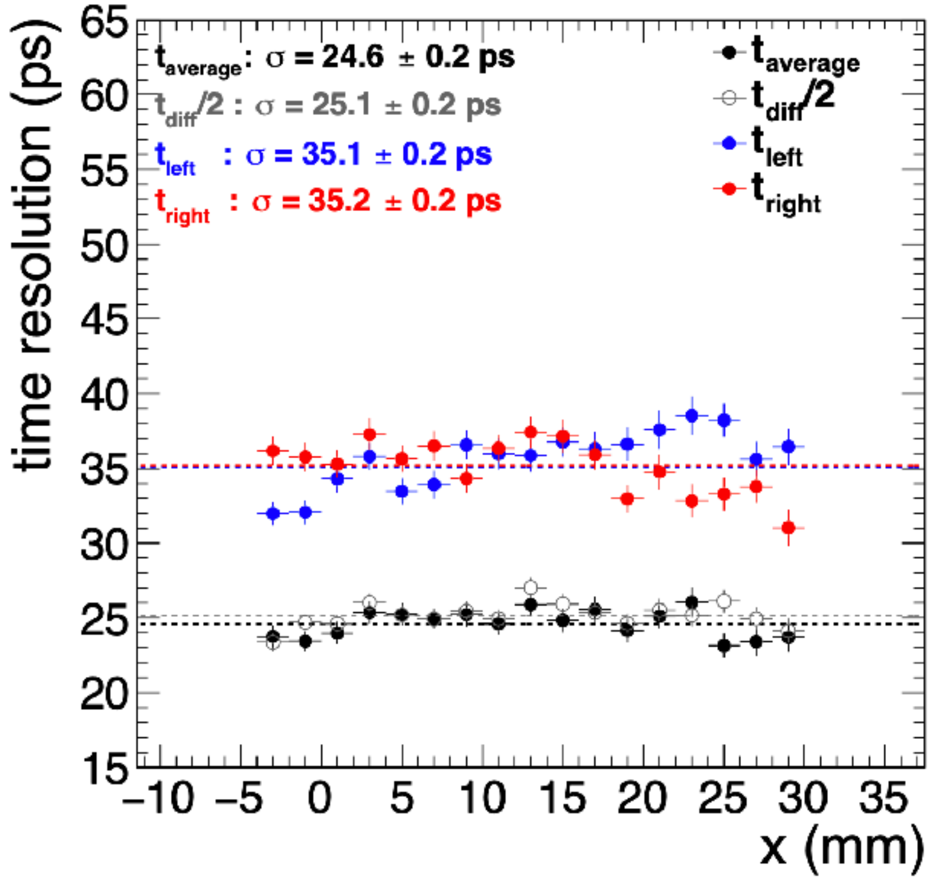




BTL Sensor: Test Beam Performance

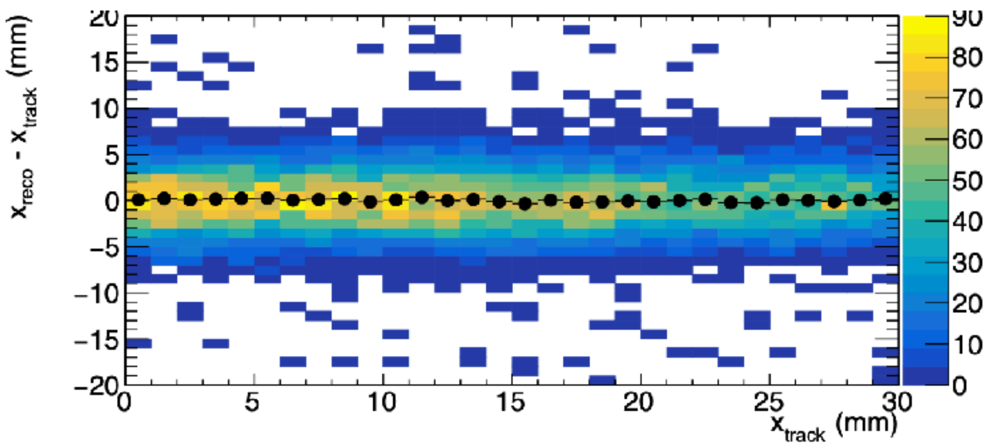


$$t_{left} = d/v$$
$$t_{right} = (L-d)/v$$
$$1/v \simeq 15\text{ps/mm}$$



SiPM readout on both ends of the LYSO bar

- 2 independent time measurements, t_{left} and t_{right}
- Average time $t_{ave} = (t_{left}+t_{right})/2$ provides optimal time measure independent of particle impact point
  - √2 gain compared to a single measurement
- From time difference $t_{diff} = t_{left}-t_{right}$ charged particle impact position can be measured (~3mm resolution)



Test beam studies confirm BTL expected performance: time resolution <30ps