Mip Timing Detector for CMS at HL-LHC

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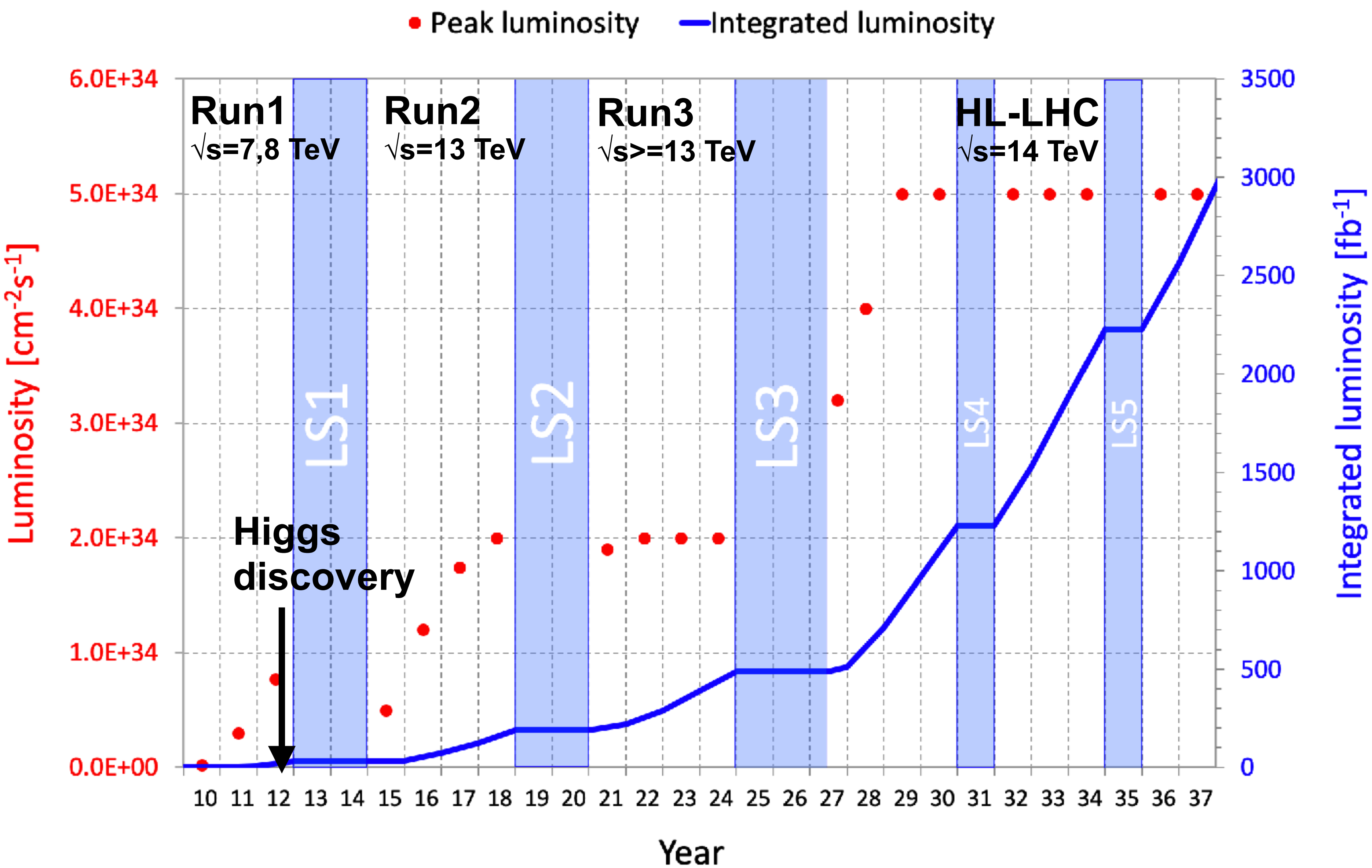
Outline

- HL-LHC physics, motivation for a precision timing detector and physics impact
- The MTD design
- Timing with LYSO scintillating crystals: the Barrel Timing Layer

HL-LHC



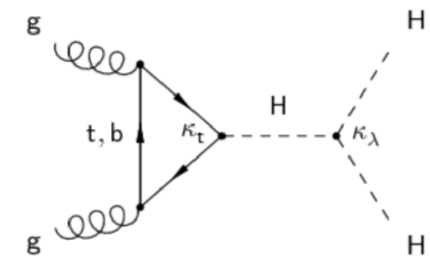
HL-LHC after LS3 (>2027): instantaneous luminosity increased beyond 5E34 cm^{-2} s^{-1}, ~300 fb^{-1} per year (~same luminosity collected in Run1+Run2+Run3), $\sqrt{s}$=14 TeV

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

PHYSICS AT HL-LHC

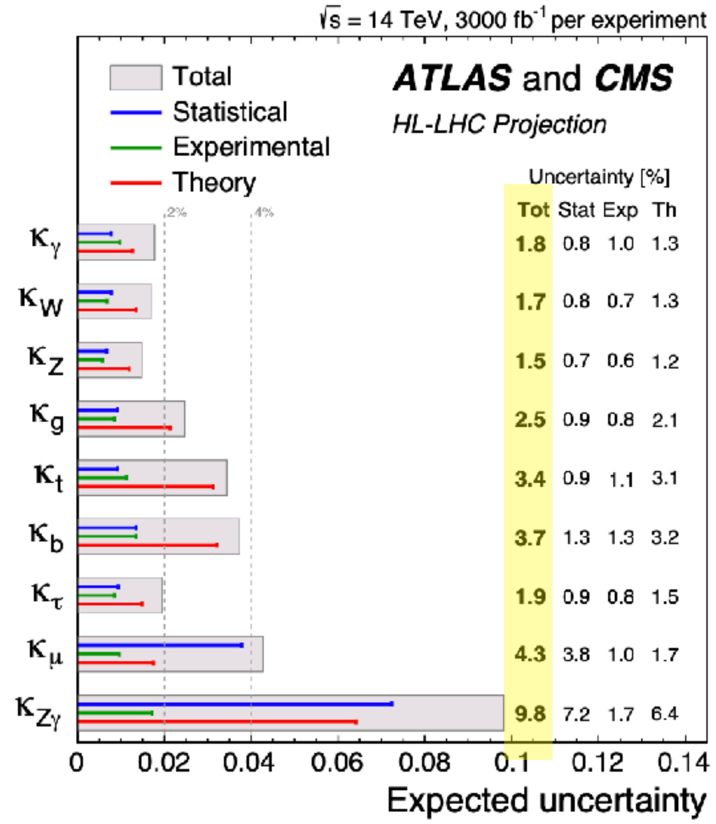
Exploit ultime LHC physics potential, with >3000 fb^{-1}

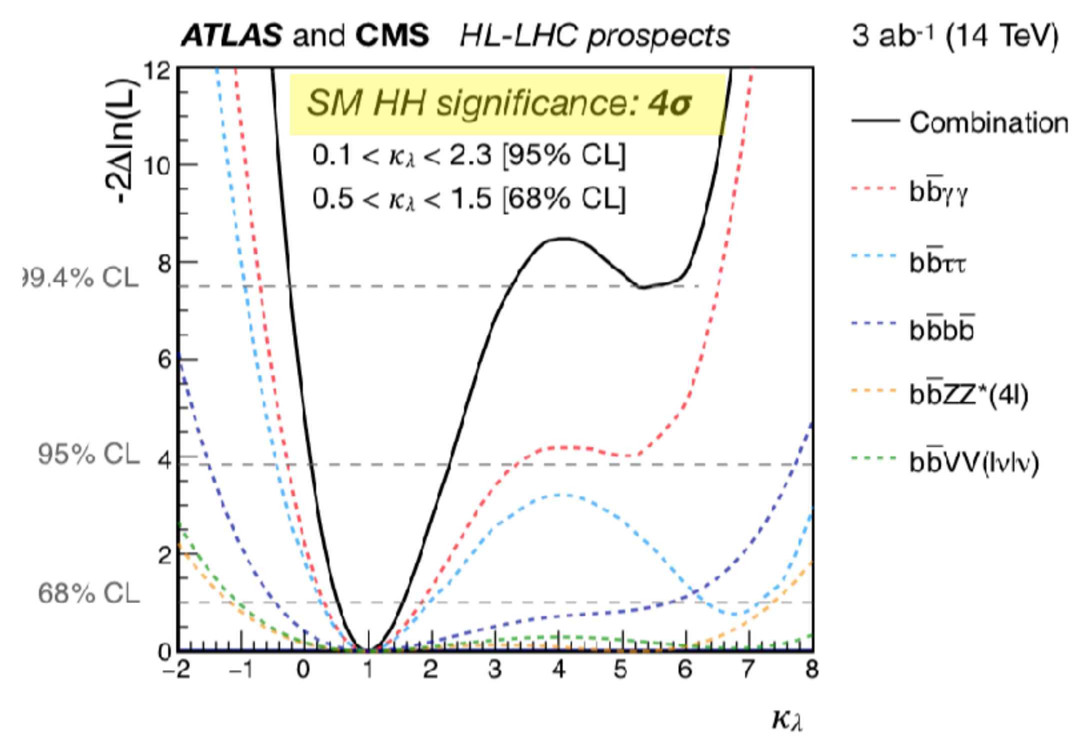
Ultimate precision for some Higgs couplings at few %



Higgs physics

- **couplings precision measurements**
- **Higgs self-coupling** from HH production



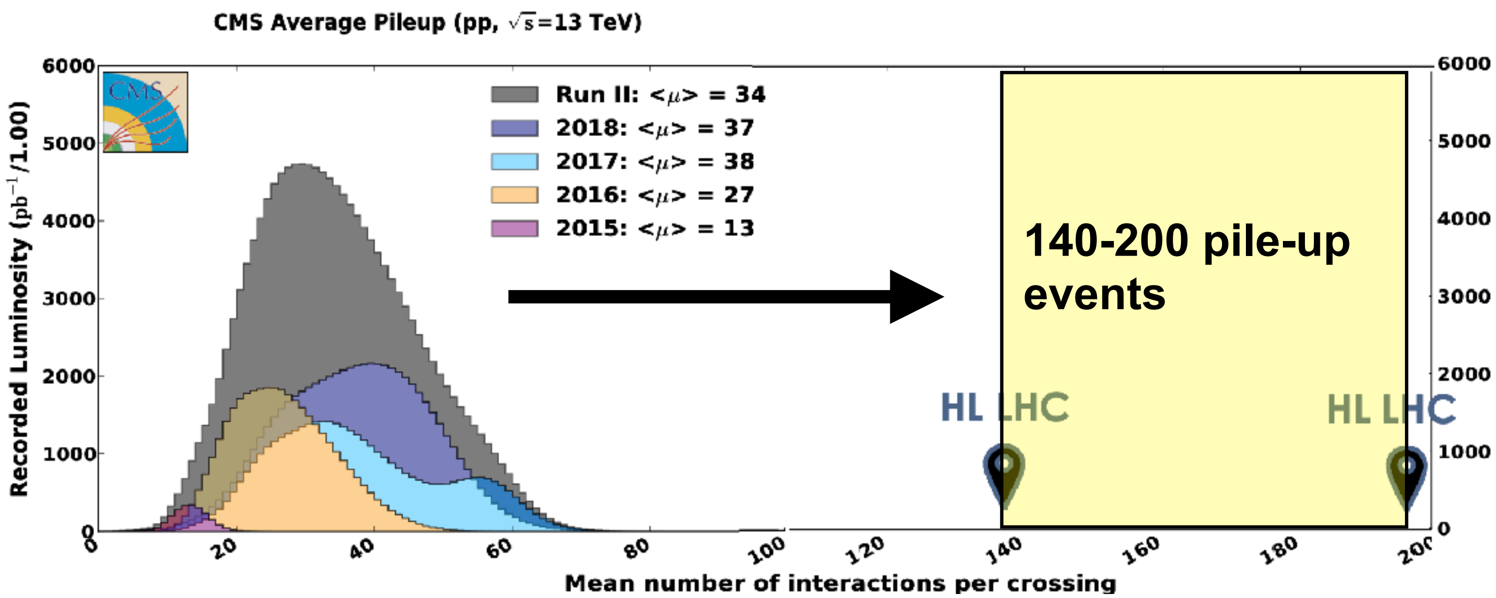


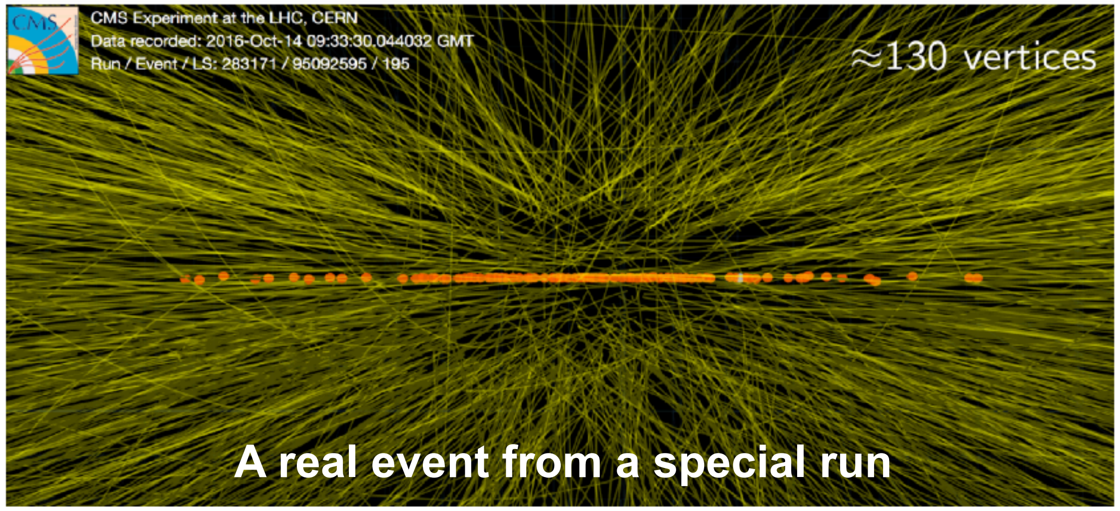
BSM direct searches: leave no stone unturned

- No sign of BSM so far. New physics not in the explored mass range or more weird
- **Novel ideas to explore regions so far not covered (long lived, low mass…)**

Indirect search for BSM: precision measurements in SM, Top or B-physics

THE CHALLENGE OF HL-LHC

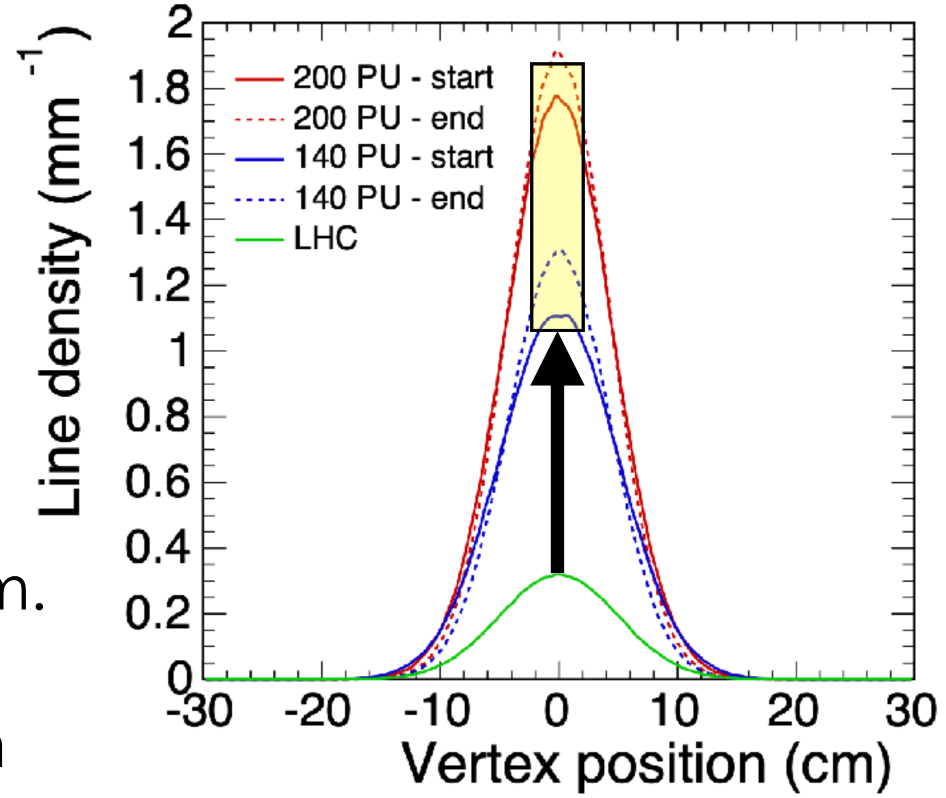




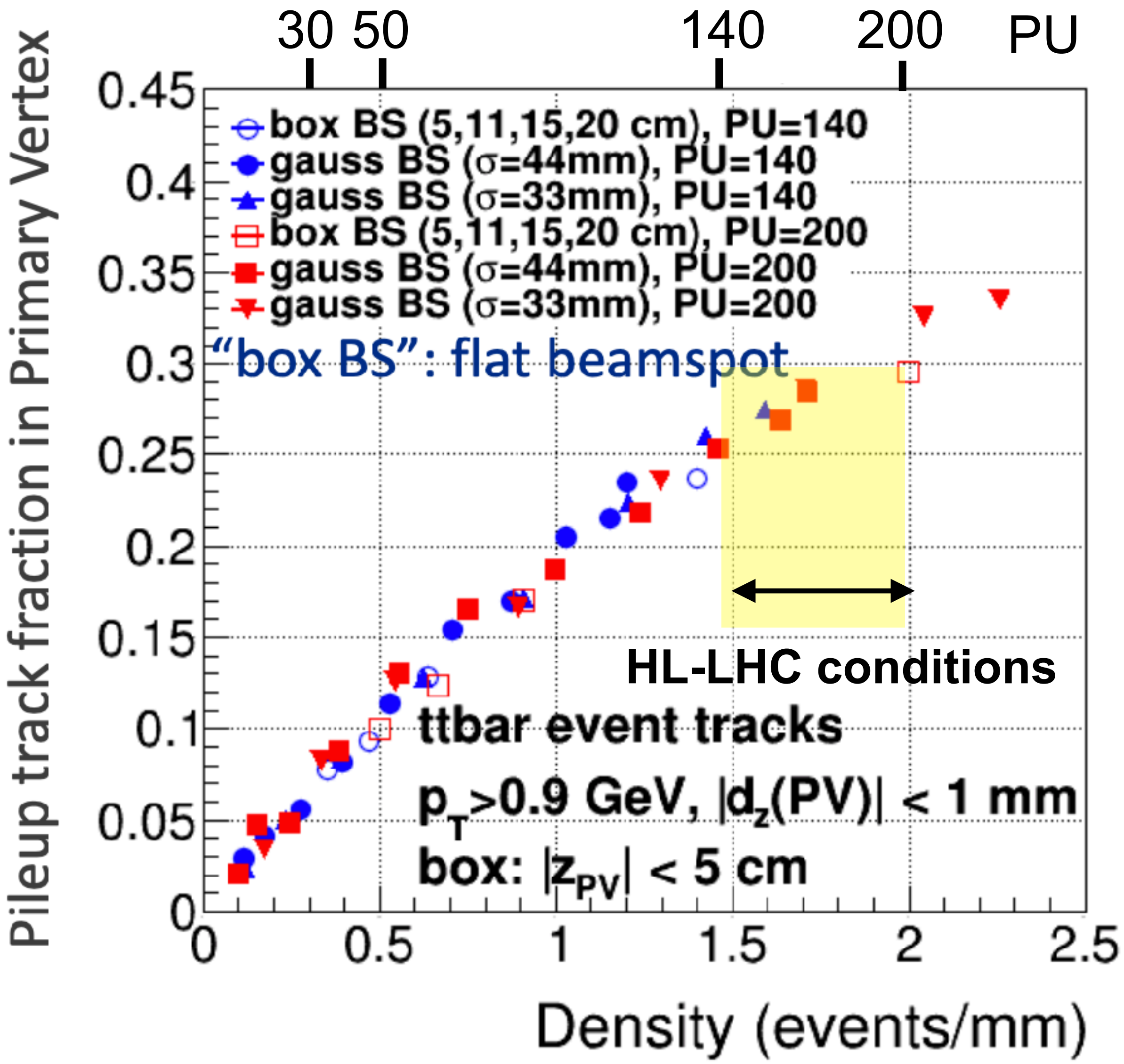
Challenging PU conditions at HL-LHC.

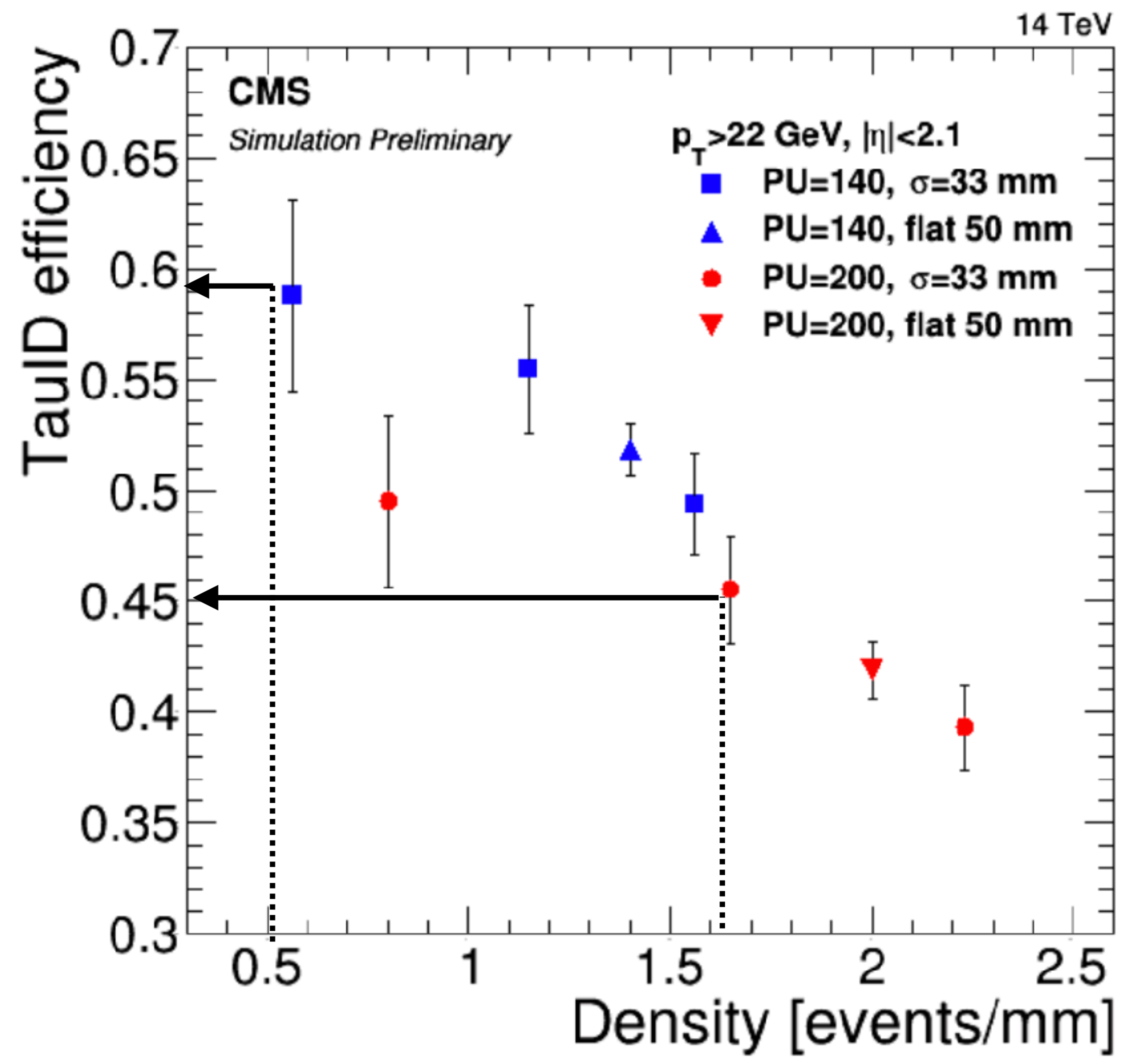
Increase in inst lumi comes with higher number of interactions per bunch-crossing

- 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**



EFFECT OF PILE-UP IN EVENT RECO



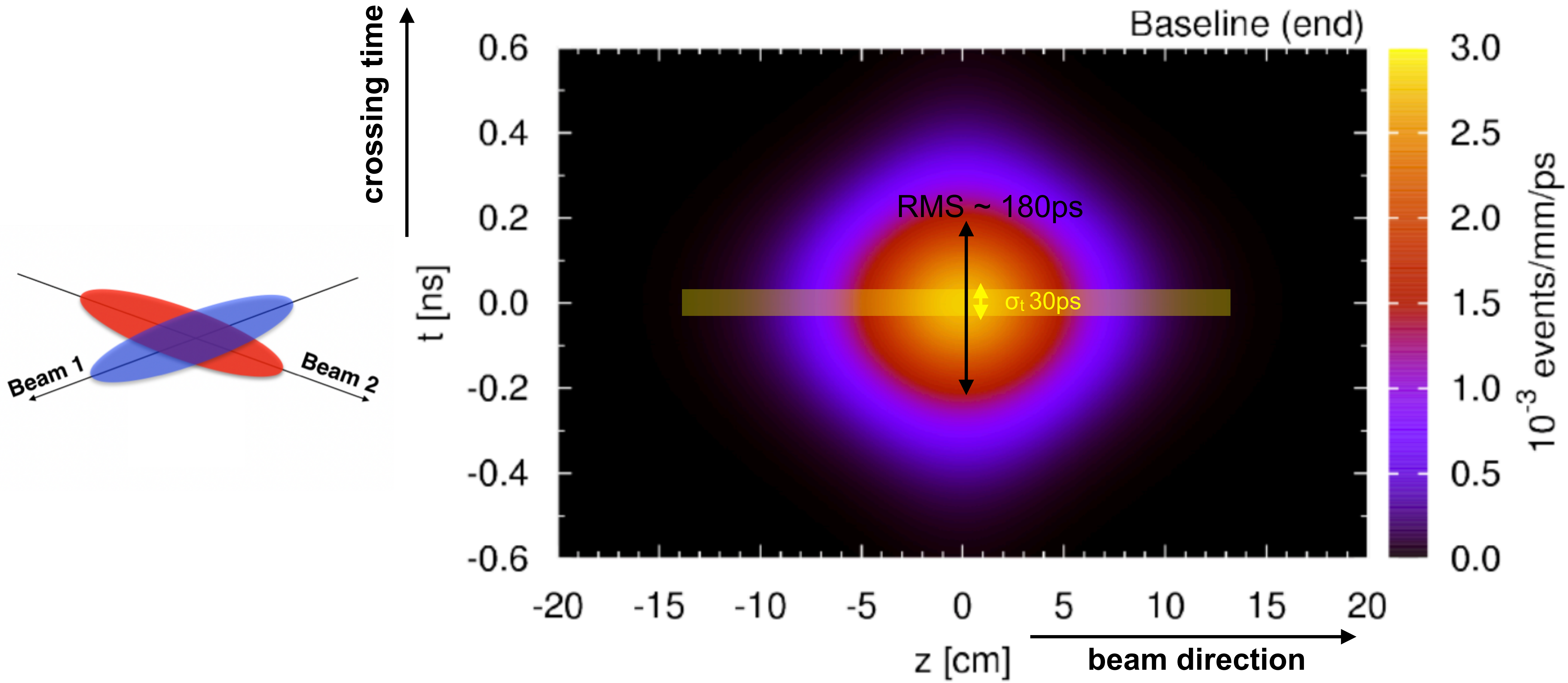


Fraction of **pile-up tracks associated to the hard-scattering event can reach up to 30% at PU200 conditions. Track based informations will be no longer PU free**

Significant impact on object reconstruction from PU contamination: e.g. τ lepton identification efficiency reduced by 20-30%

Similar effects also for global quantity (eg missing E_T). **Performance reduction impacts at analysis level, reducing gain from luminosity increase**

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

CMS UPGRADE FOR HL-LHC

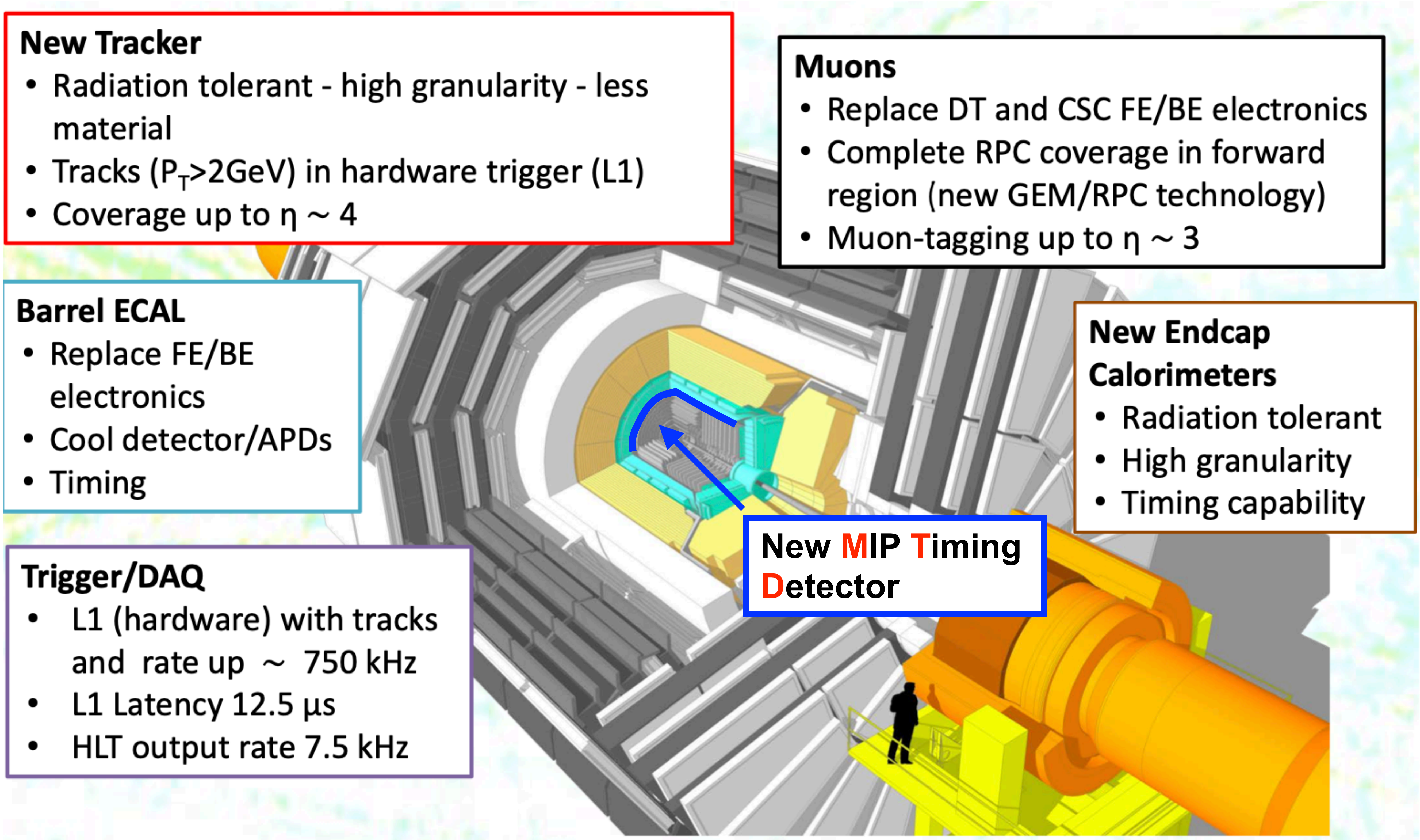
INFN
Istituto Nazionale di Fisica Nucleare

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

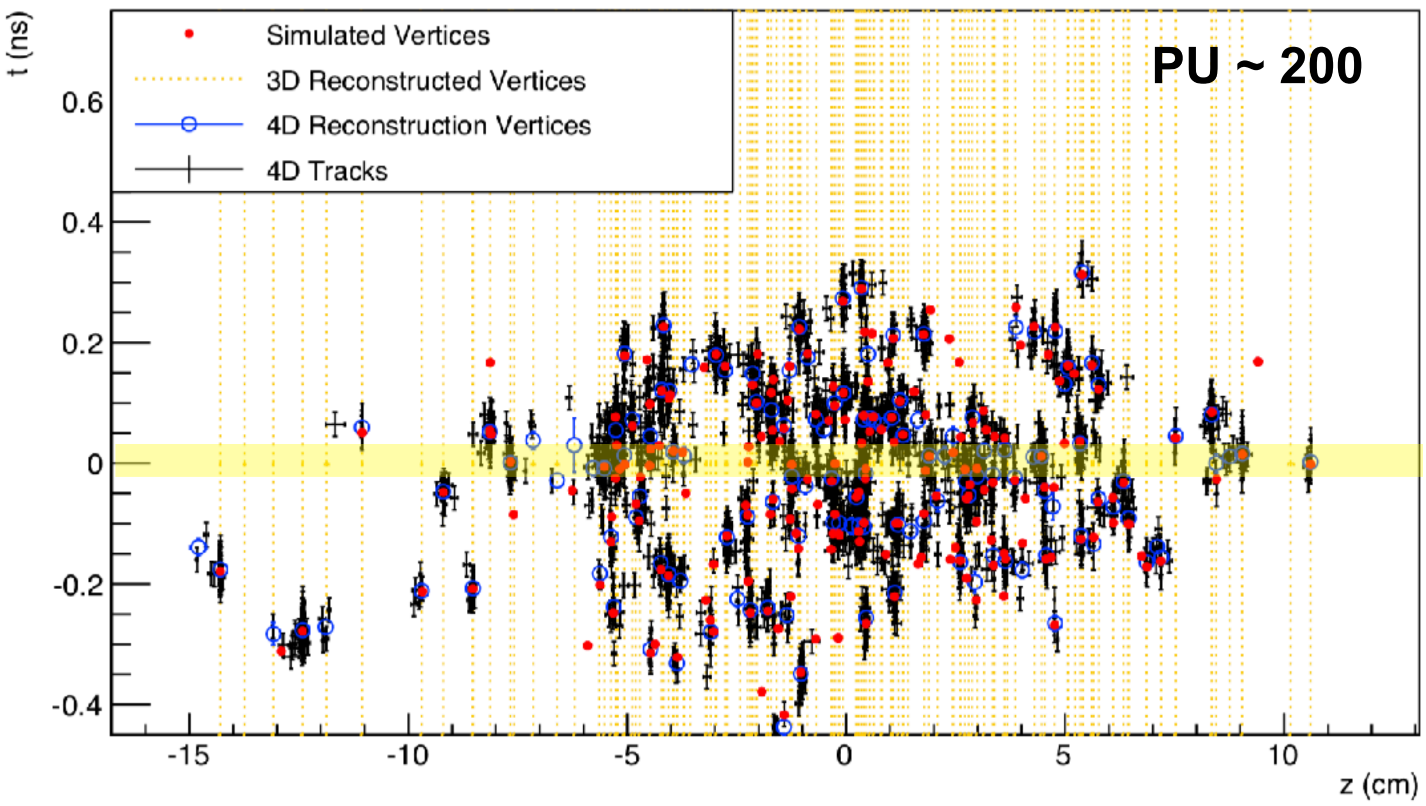
Barrel ECAL
- Replace FE/BE electronics
- Cool detector/APDs
- Timing

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



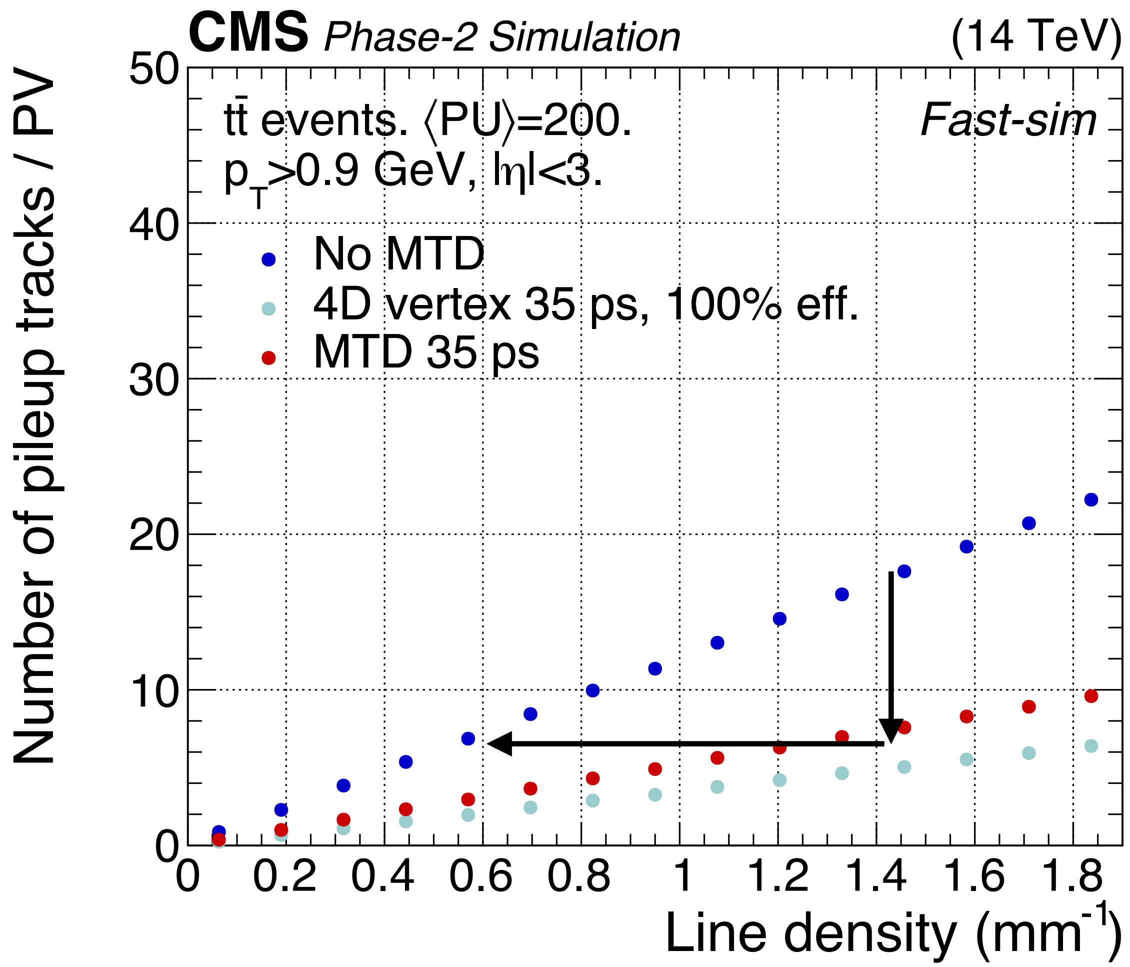
Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz

Change Of Paradigm: 4D Tracking



High precision timing (~30ps) for tracks

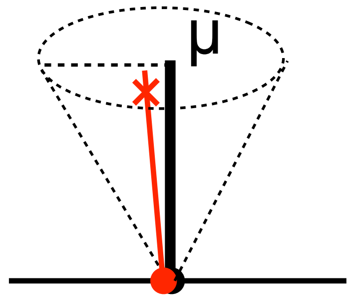
- Can reconstruct vertex not only in space but also time
- timing (time-of-flight) can also be exploited for particle ID (BSM searches and flavour physics)



Track-vertex association using track timing

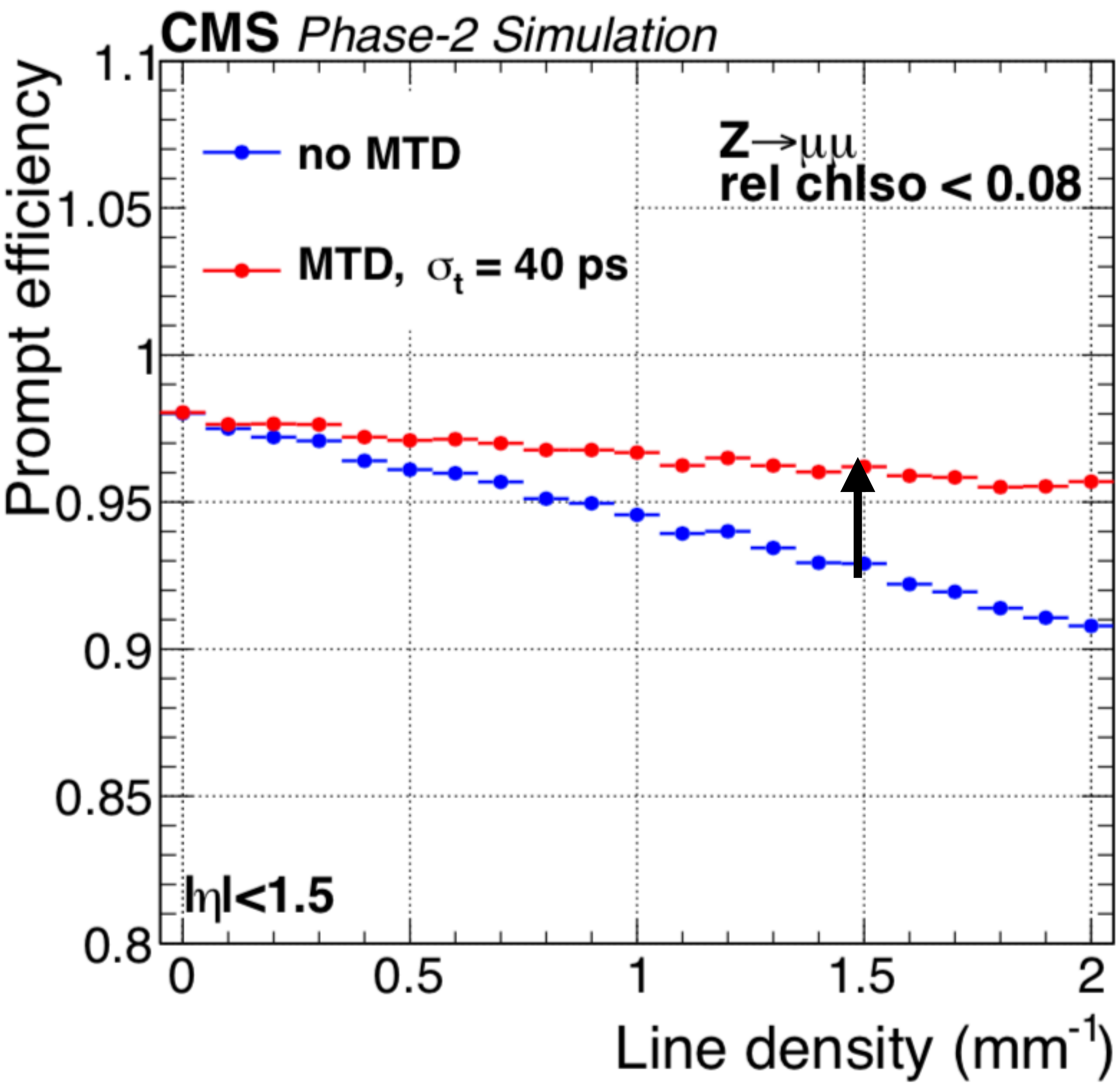
- **3-5 reduction of PU contamination** using also time at vertex information eg $|\Delta t(\text{track-vertex})| < 3\,\sigma_t$
- PU contamination per vertex reduced to current LHC conditions

MTD IMPACT: LEPTON ID

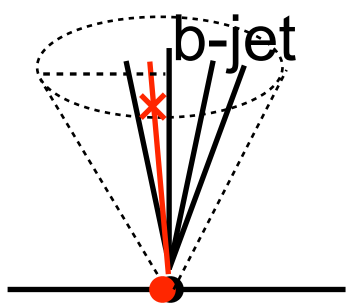


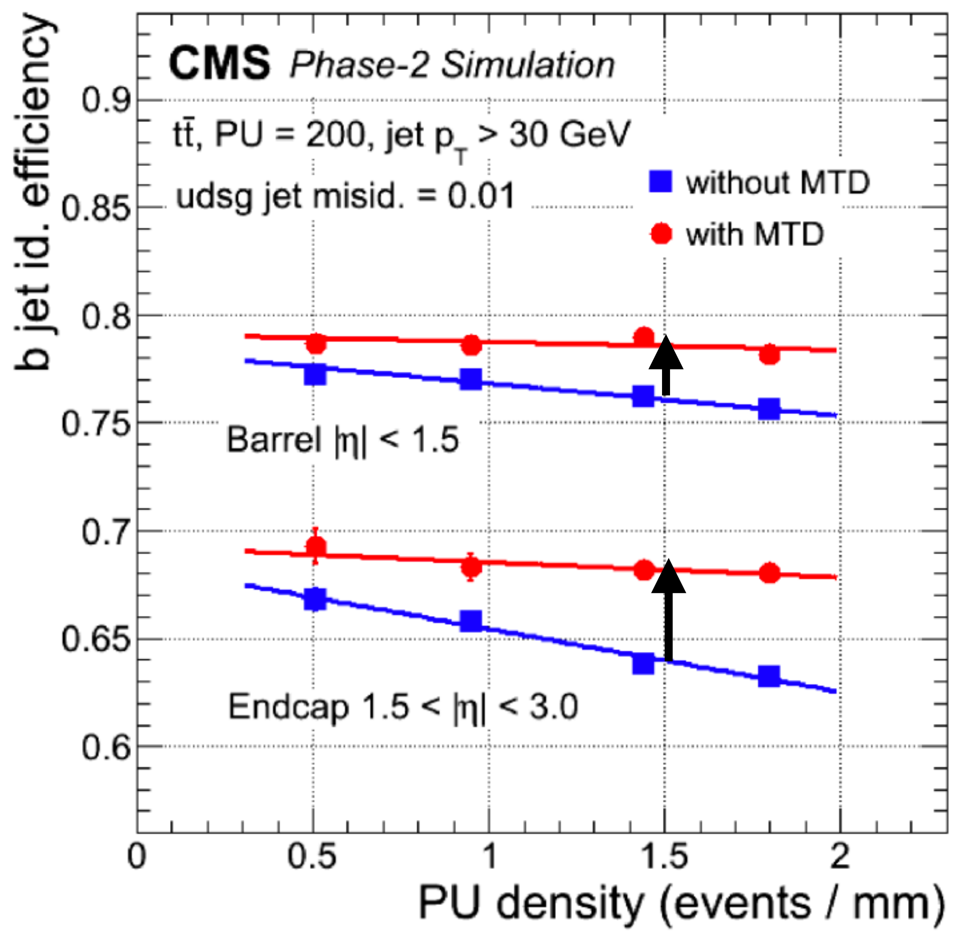
Simplest (yet effective) application: lepton isolation

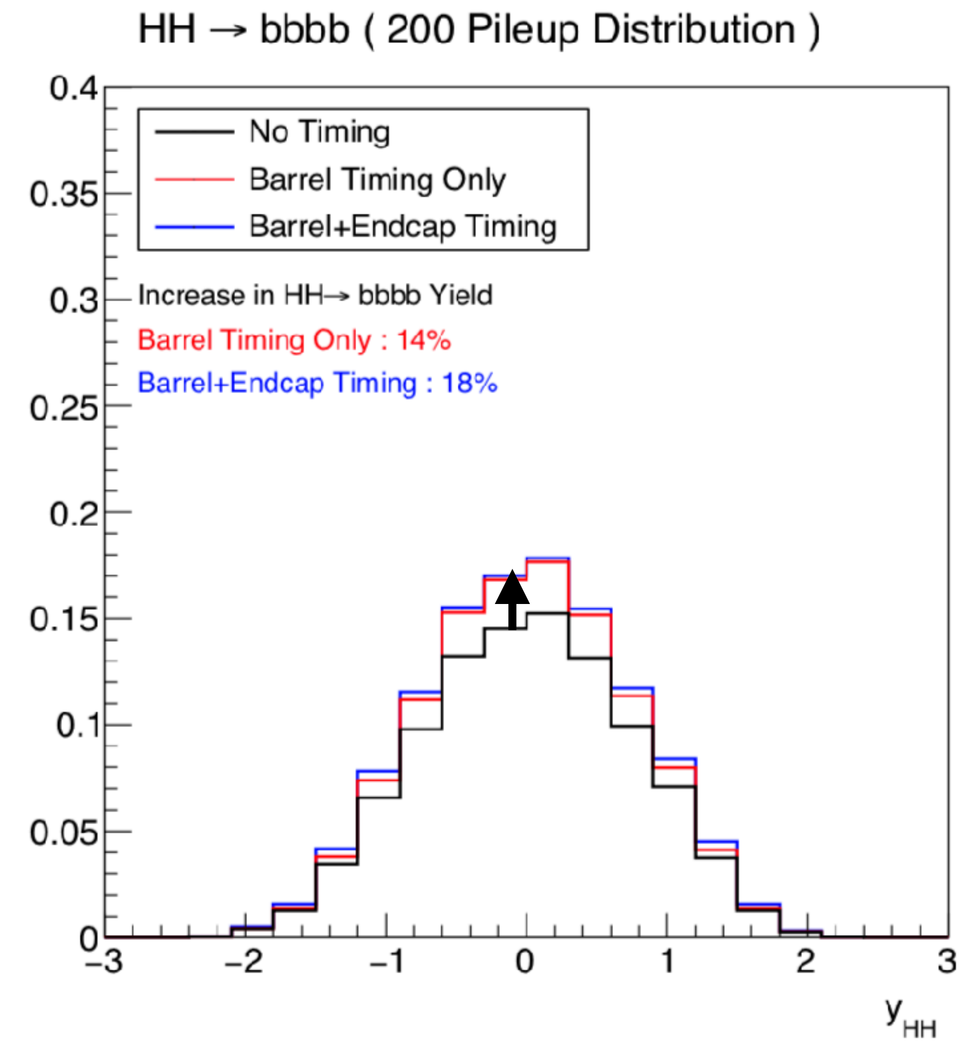
- Isolated leptons main probes at LHC in several final states (eg. H→ZZ→4l, H→$\tau\tau$, …)
- Reduction of PU contamination in isolation cone: **gain up 15-20% for lepton identification**



MTD Impact: B-Tagging



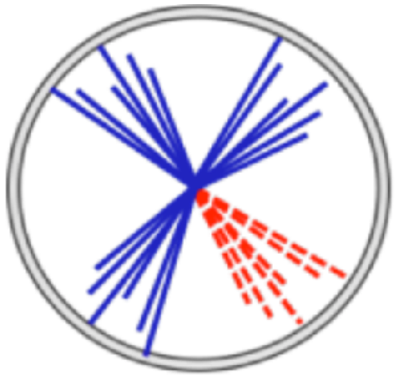


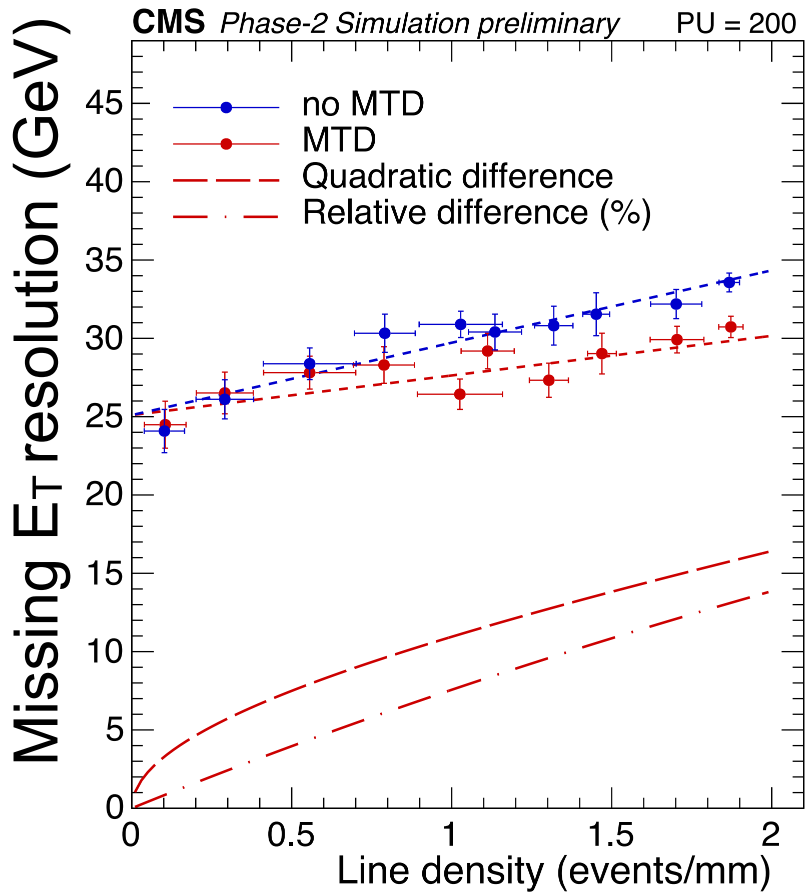


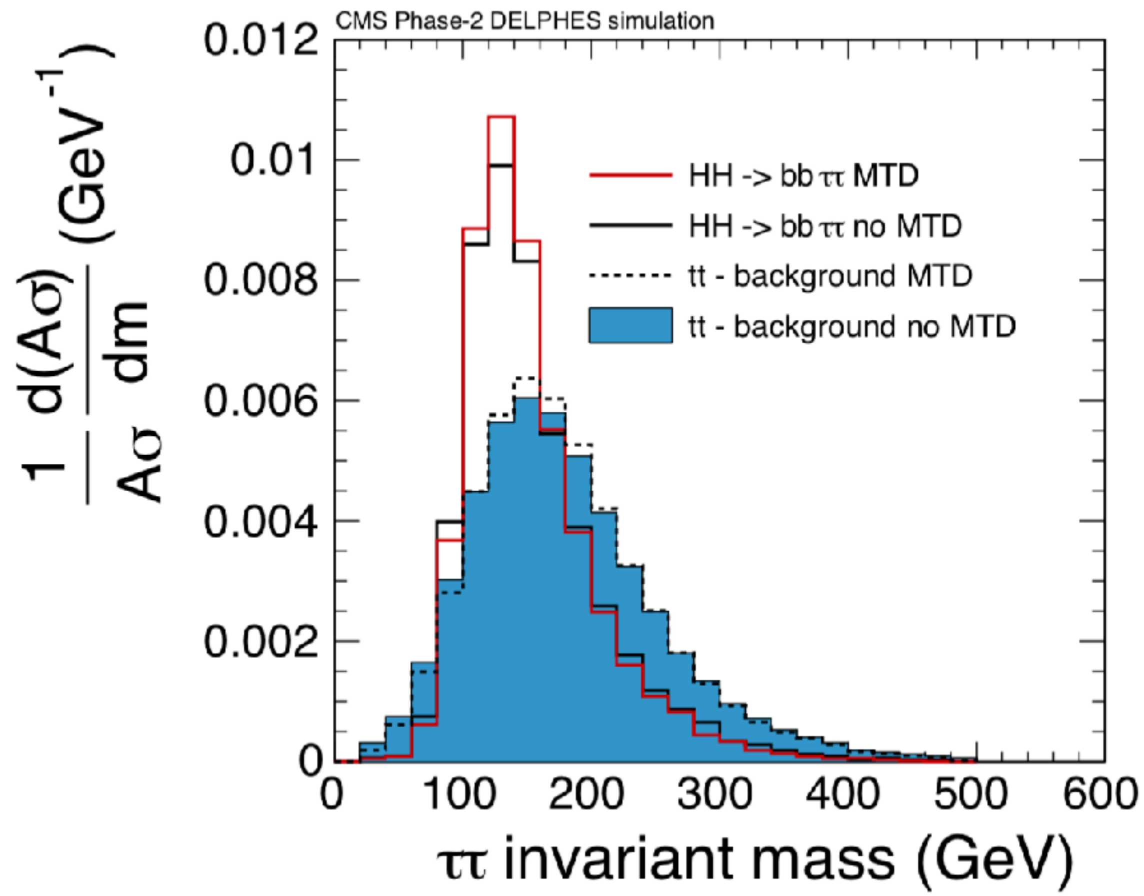
Reduction of PU contamination helps to maintain performance at high pile-up for more complex algorithms, such as identification of displaced jets, aka b-tagging

Significant acceptance gains (~20%) when looking at final states with several b (e.g. HH→bbbb, HH→bbɣɣ)

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. $H\rightarrow\tau\tau$) or searches (e.g. SUSY)

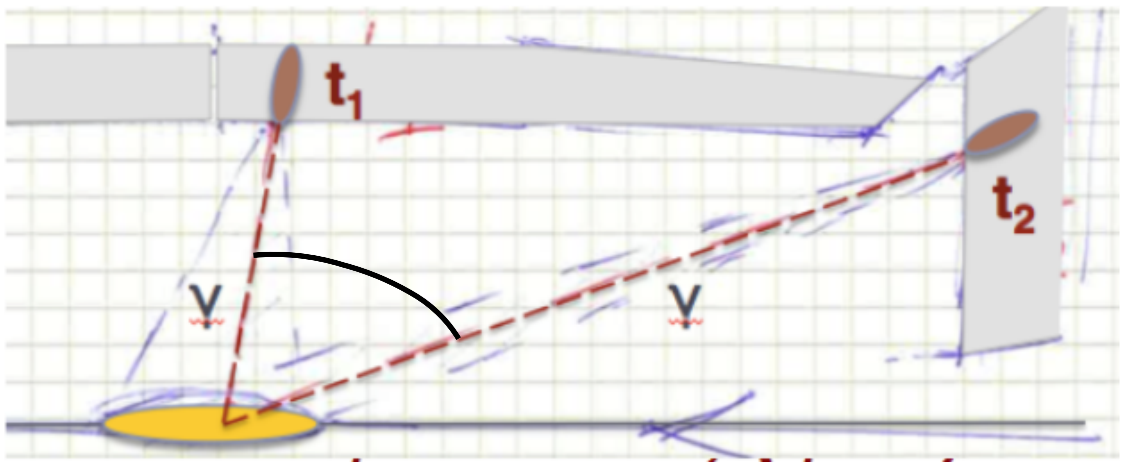
TRACK + NEUTRAL TIMING

Track-timing complements timing capabilities in upgraded CMS calorimeters

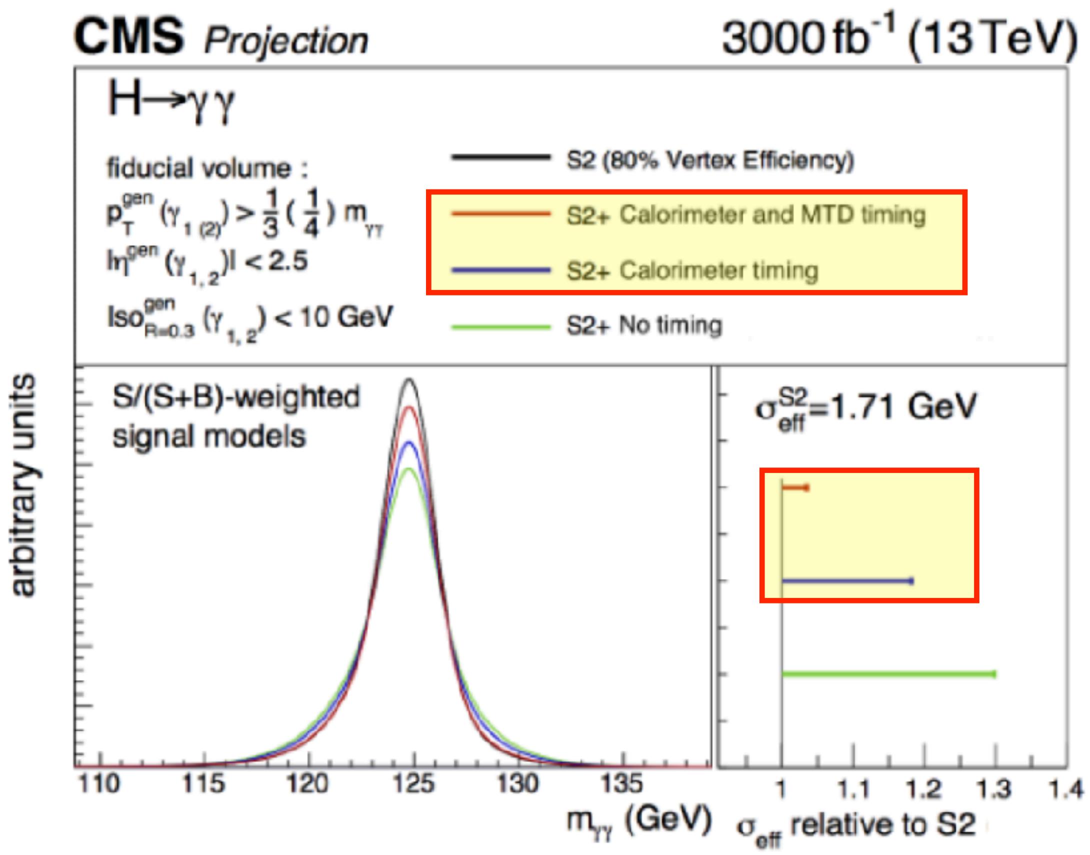
- Barrel: ECAL upgraded electronics, precise timing for γ ~30ps above E>40-50 GeV
- Endcap: new HGCAL, precise timing for γ ~50ps above p_T>3-4 GeV

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



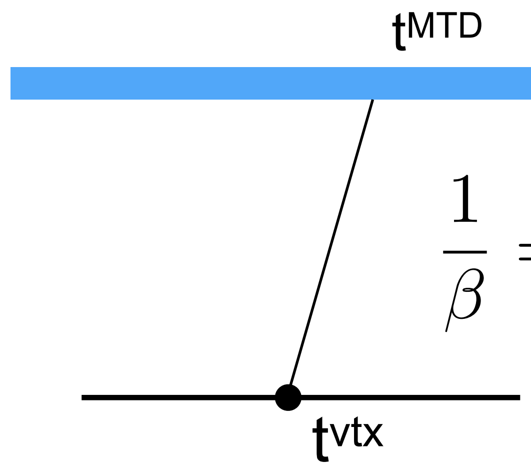
PU Mitigation At Analysis Level

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

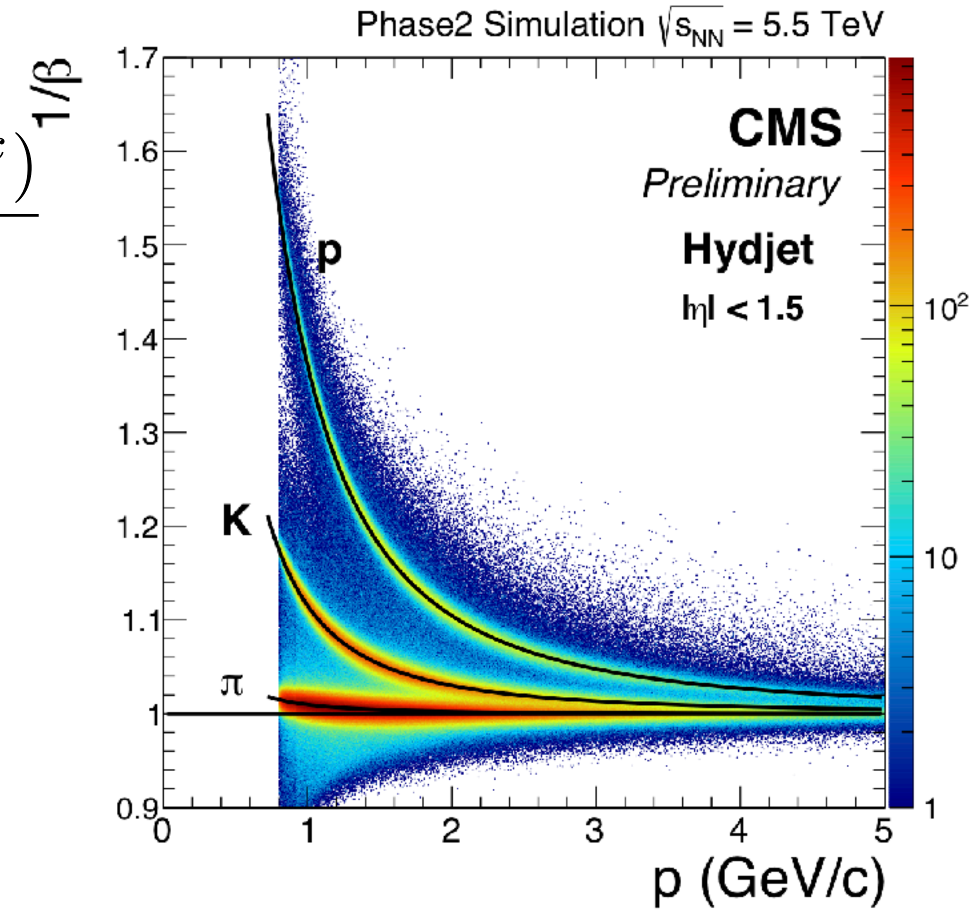
For many channels, **the gain is equivalent to 25-30% increase of integrated luminosity**

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



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

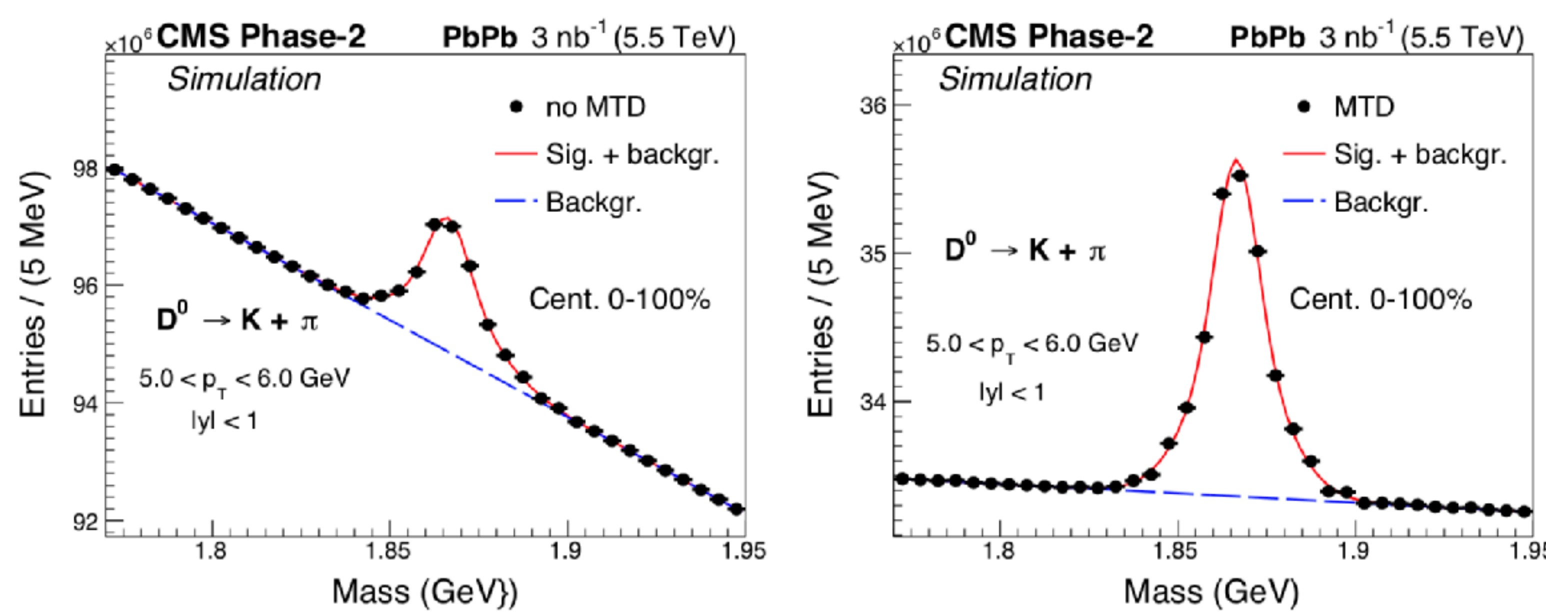


New capability for CMS:
Time-of-flight particle identification (TOFPID)

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

Example of TOFPID:

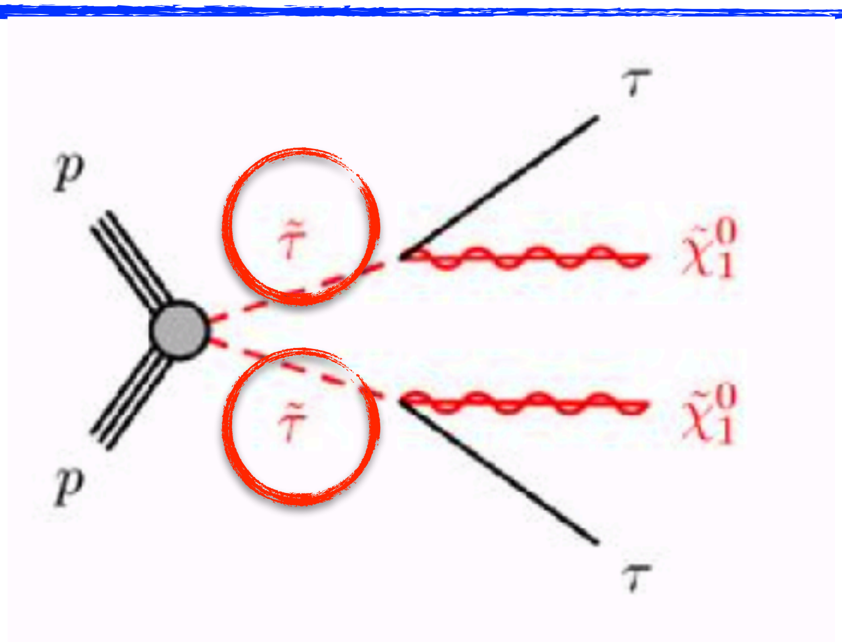
– **reduction of combinatorial background of a factor ~3** for D→K+**π** in PbPb events
– Expect gains in general for flavour physics: e.g. B→K*(→K**π**)μμ



TOFPID: BSM

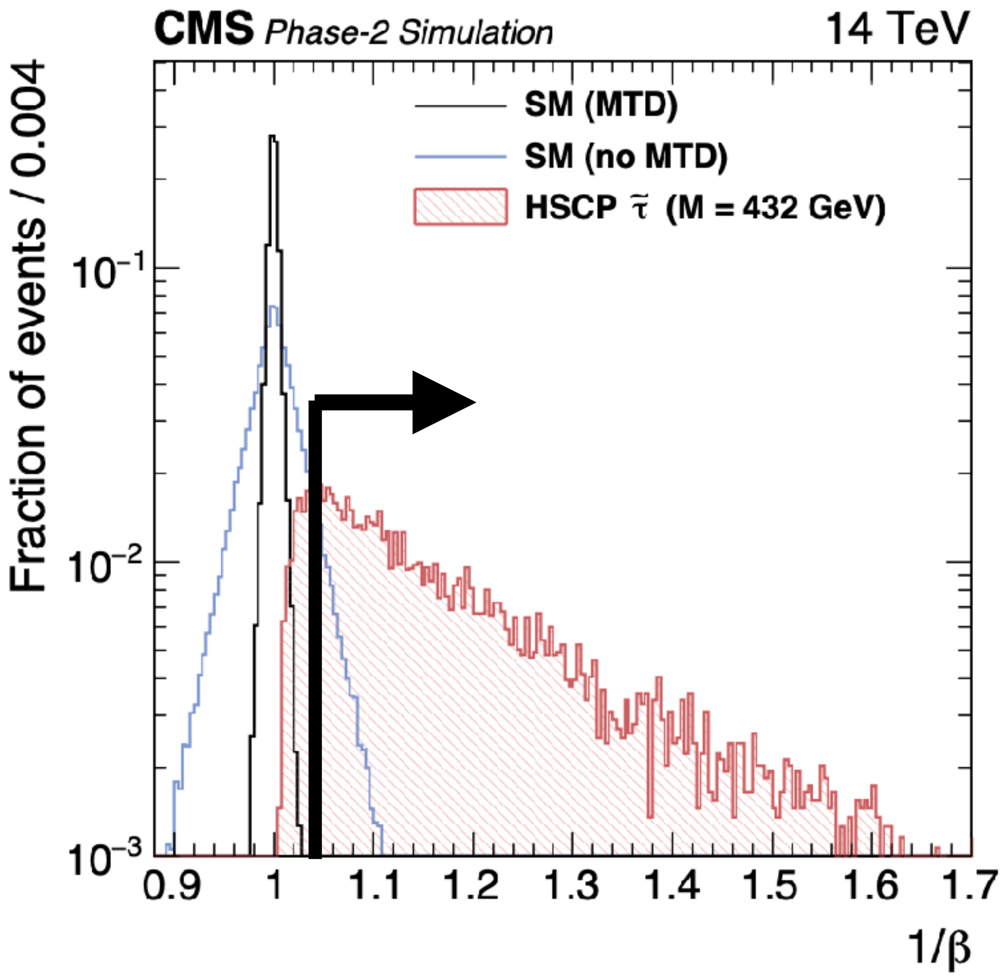
TOFPID can also be applied in BSM searches, eg heavy stable charged particle (staus, gluinos,…)

– a new handle in addition to dE/dX

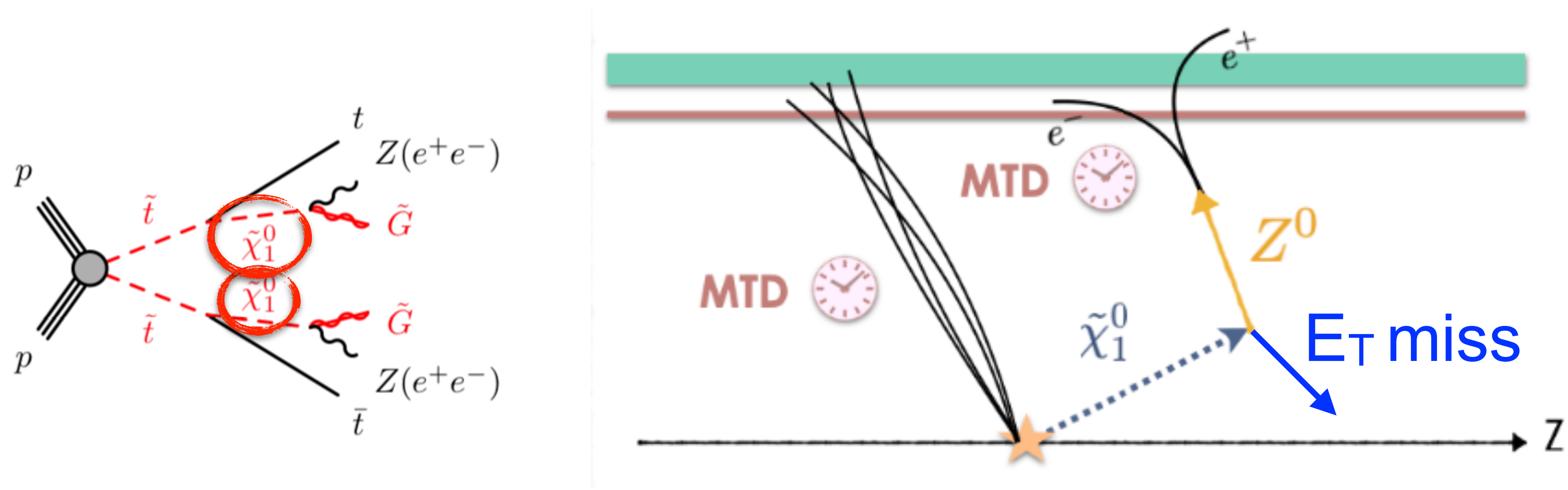


1/β resolution improved by 1 order of magnitude

large reduction of SM background → signal acceptance gain



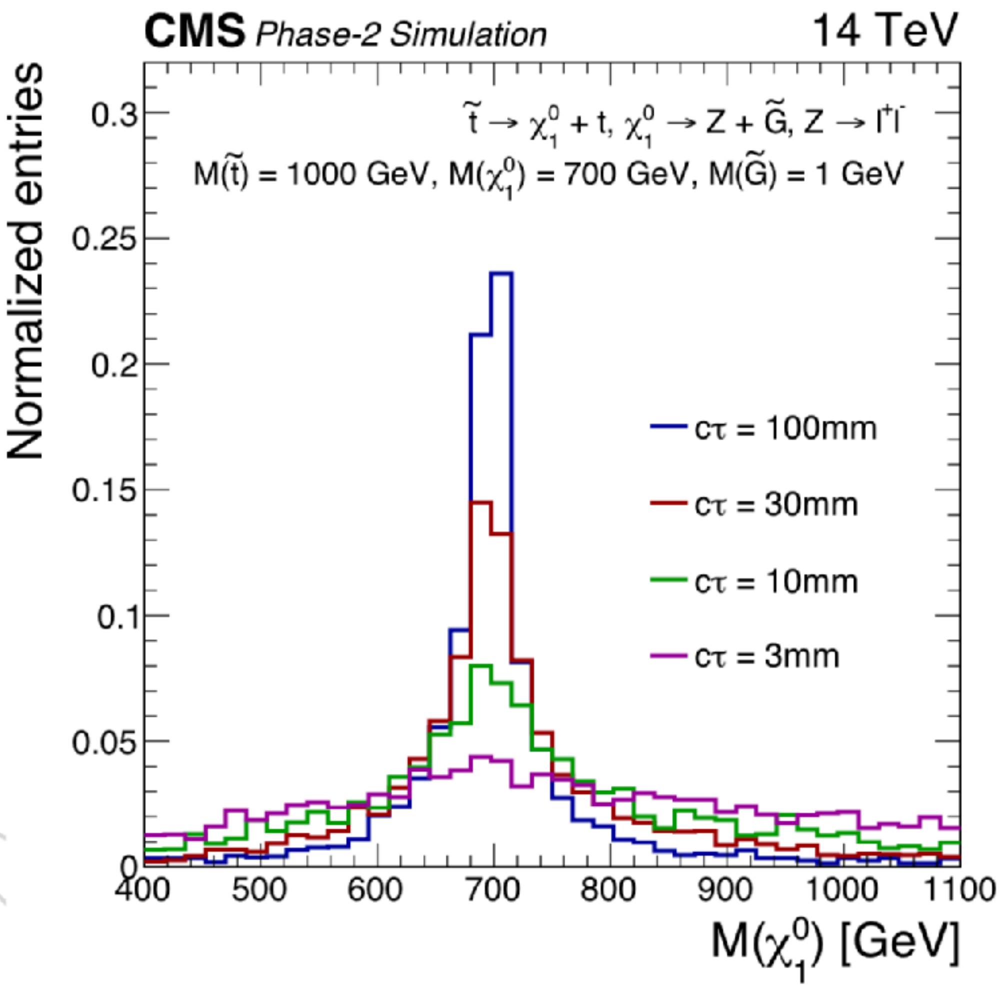
BSM: Displaced Objects



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



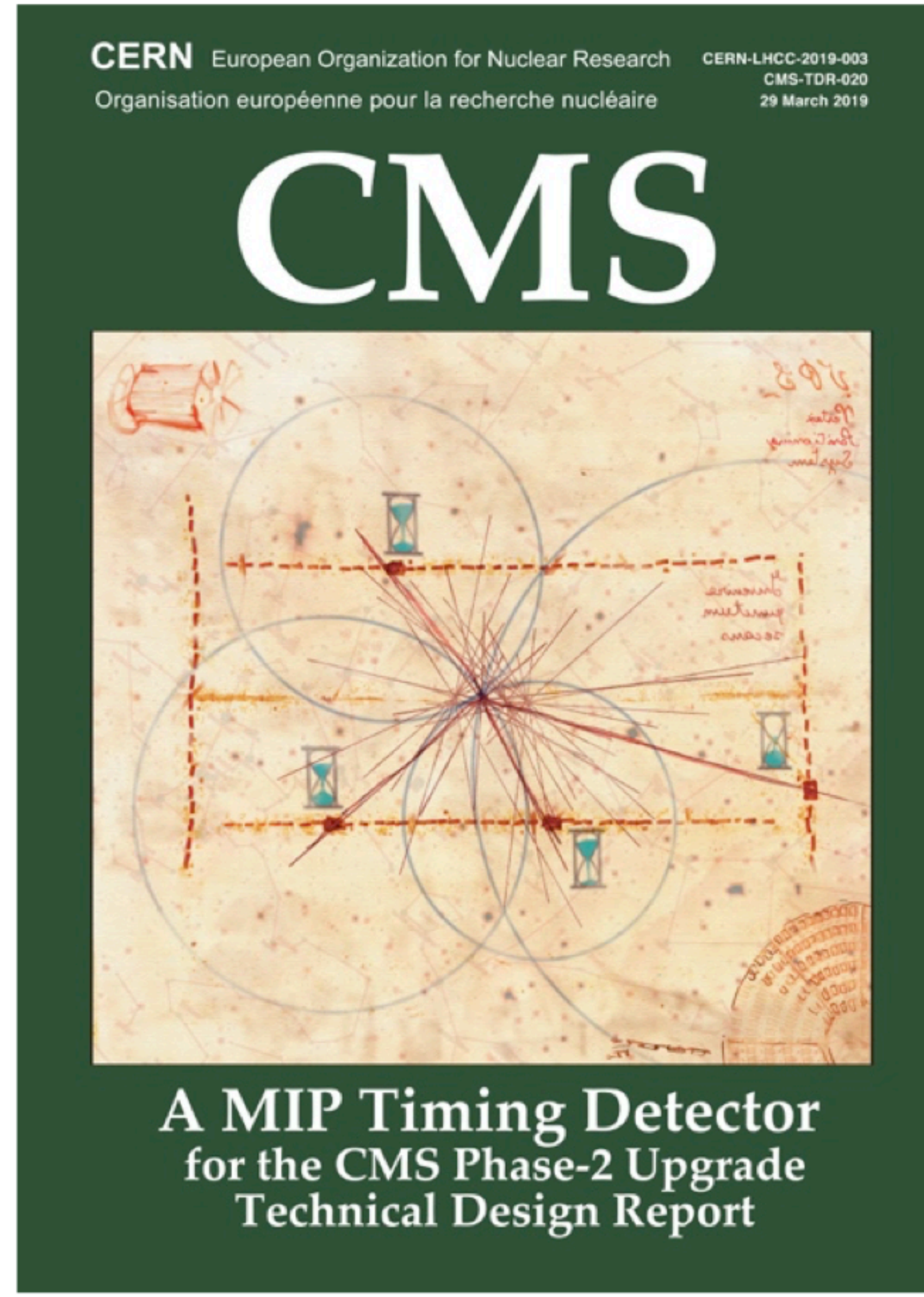
The CMS MIP Timing Detector

MTD project approved by CERN research board at the end of 2019

- Culmination of an R&D phase started in 2013, exploring various technologies for timing

Several italian institutions involved

- MiB, Rome, Padova, Torino
- Rome has responsibility for qualifying LYSO crystal vendors and crystal QA/QC during construction phase



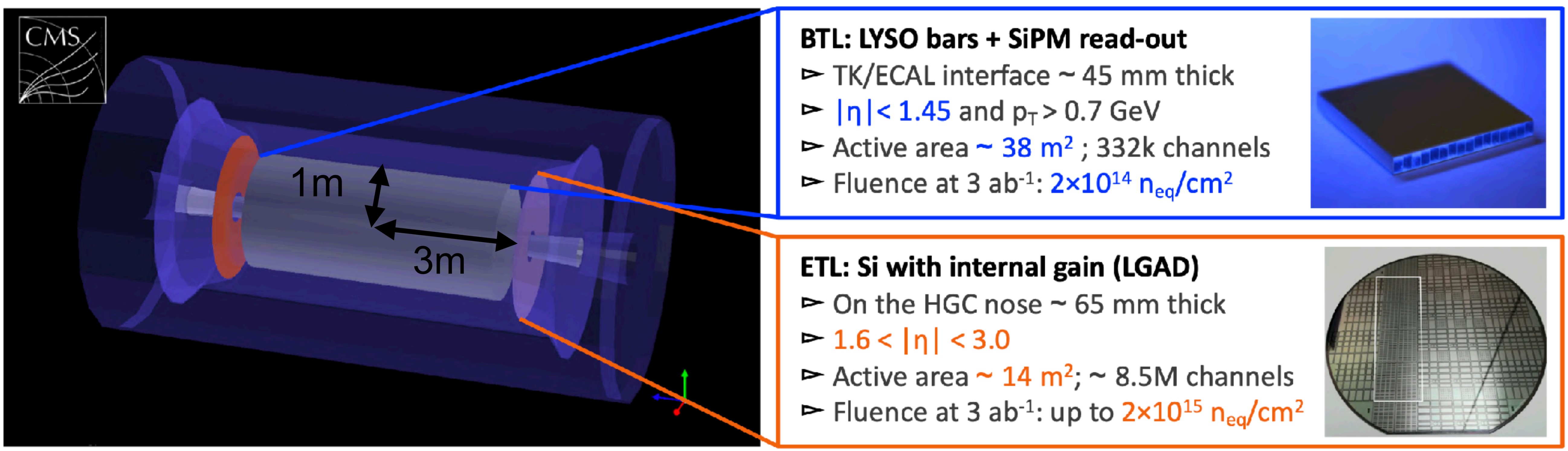
https://cds.cern.ch/record/2667167

MTD DESIGN

Ideal solution: a 4D capable tracker, but technology not yet mature enough. R&D ongoing for future colliders

CMS solution: 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, power consumption/channel count



BTL Technology

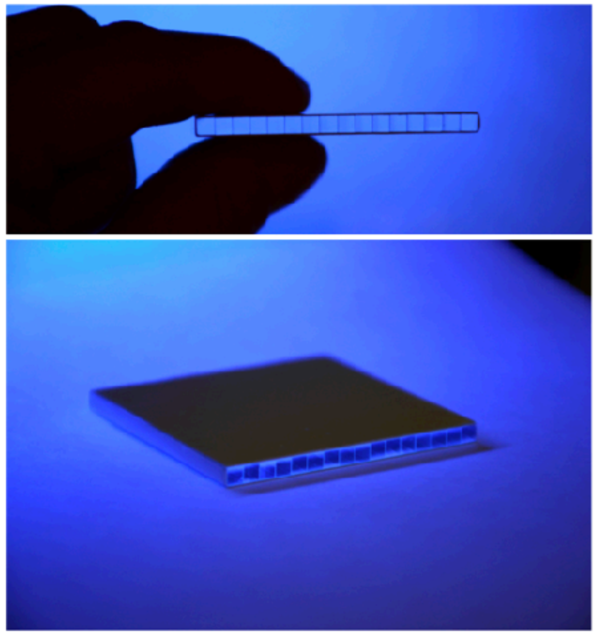
Lutetium-Yttrium orthosilicate, Cerium doped crystals (LYSO:Ce)

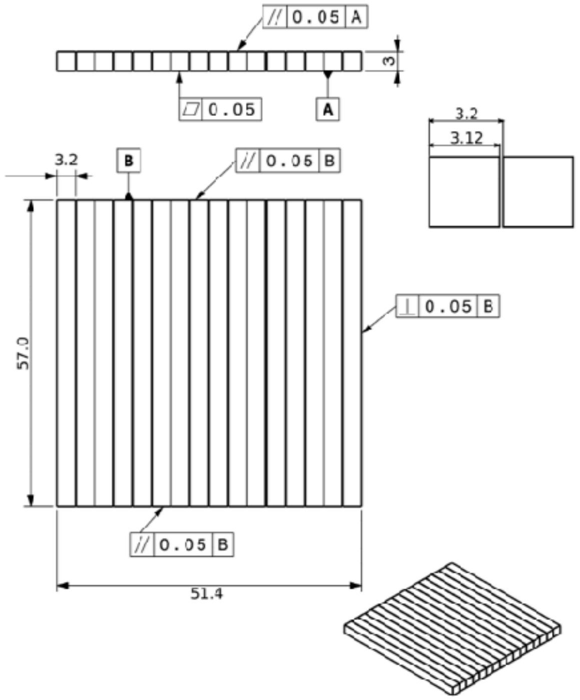
- High light yield (40k photons/MeV)
- Fast (40ns decay time)
- Dense (7.1 g/cm^3), MIP deposit 4.2 MeV on average in BTL
- commercially available from several vendors (PET)
- Excellent radiation hardness up to tens of kGy

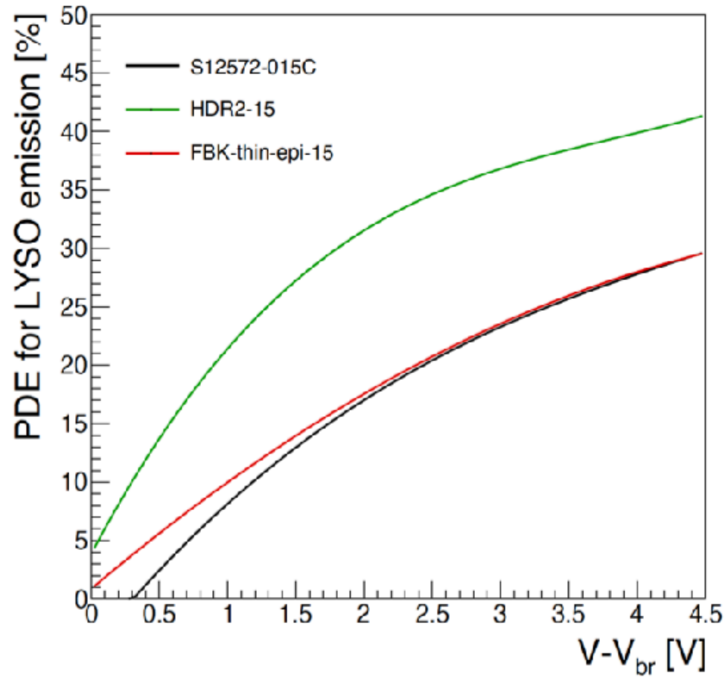
Silicon Photomultipliers as photosensors

- Compact (SiPM+package ~1mm), fast, insensitive to magnetic field
- Photo detection efficiency PDE @ 420 nm (20-40%)
- SiPM active area (~9 mm^2), match LYSO transverse size
- Optimal SiPM cell size compromise between PDE and radiation tolerance: 15μm
- High intrinsic gain: 1.5 - 4 x 10^5

LYSO:Ce matrix 1x16

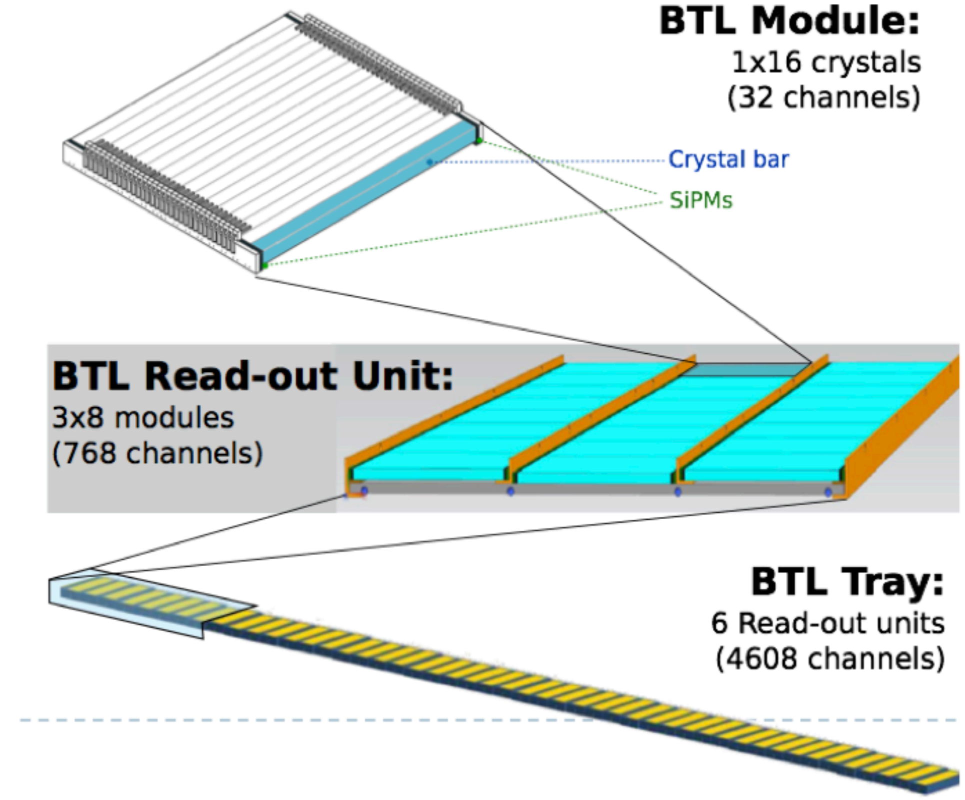


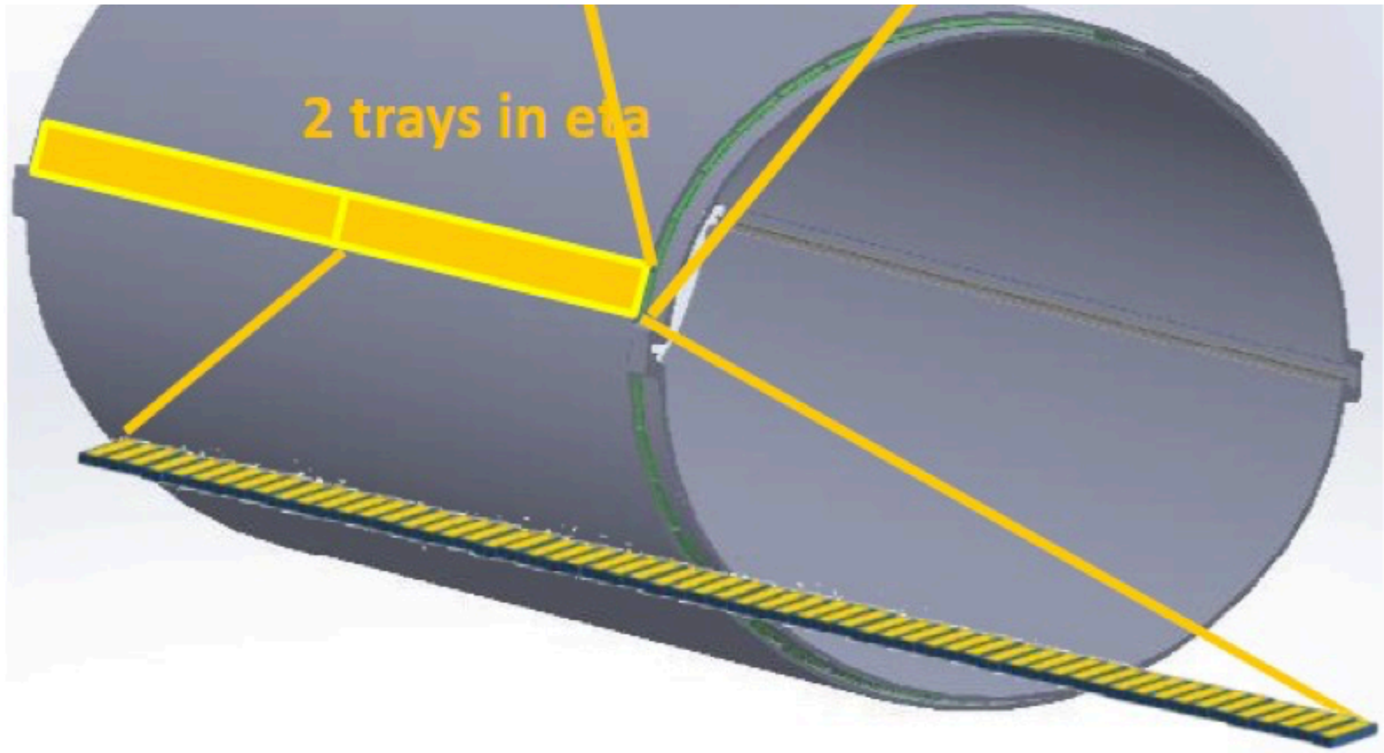


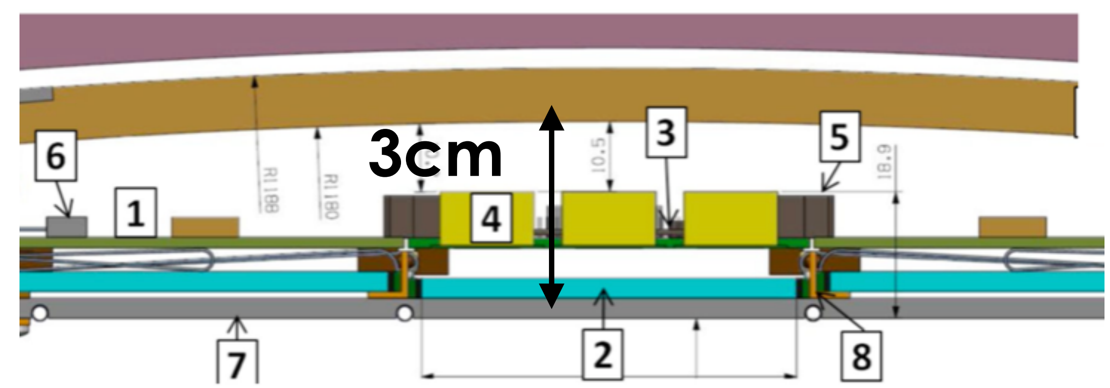


BTL LAYOUT

- 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





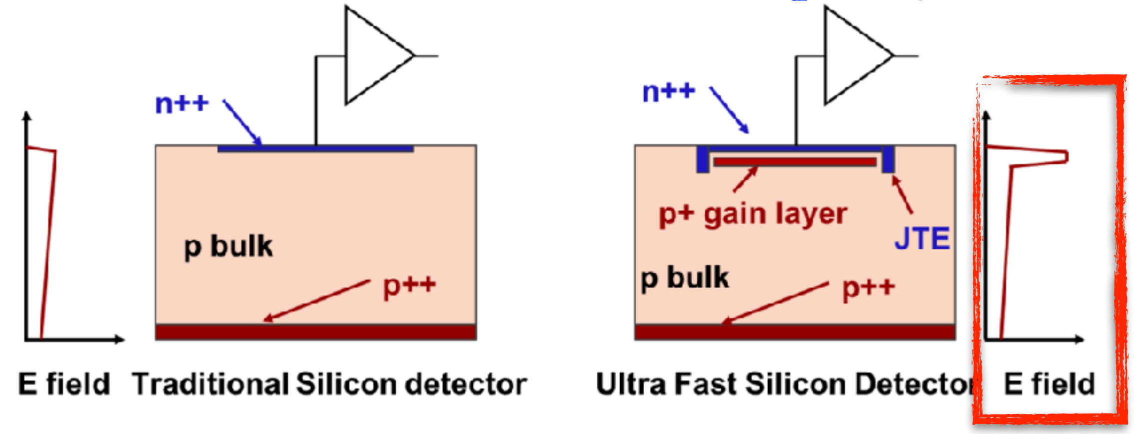


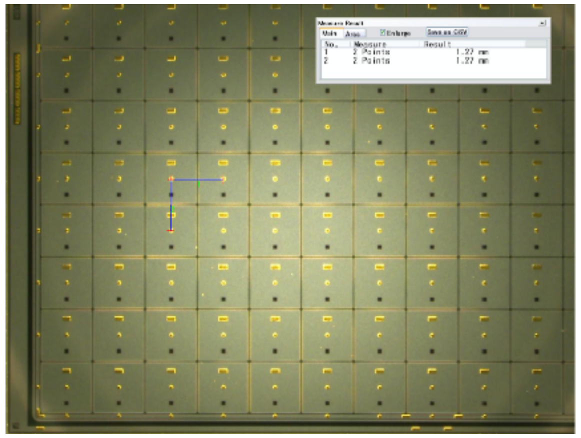
ETL TECHNOLOGY

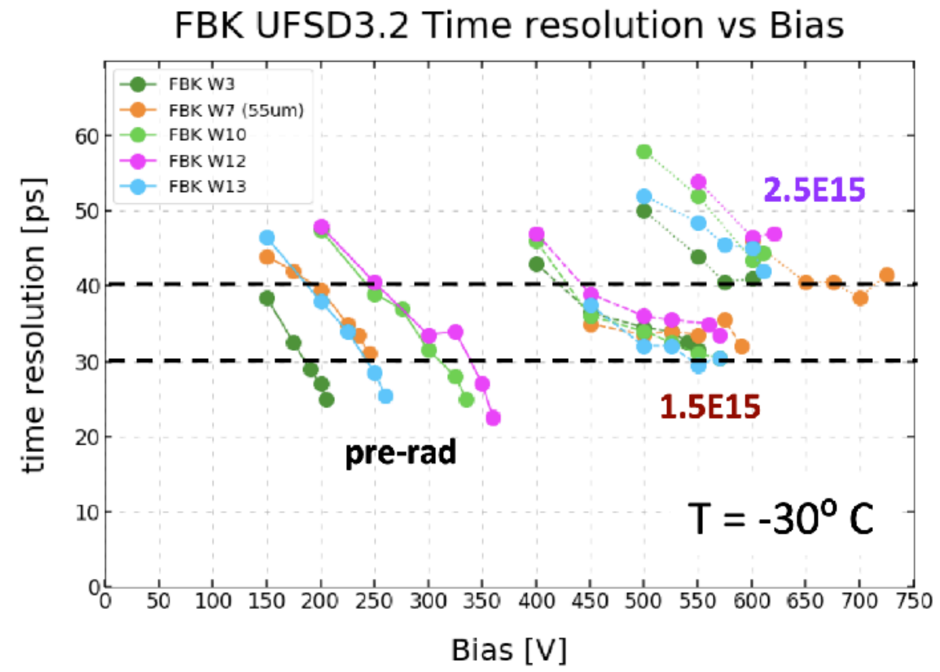
Low gain avalanche silicon detectors (LGAD)

- Moderate internal gain (5-50) thanks to a dedicated gain layer: increase signal slew rate (dV/dt) keeping low noise
- 50μm thickness
- Pixelated array: fill factor ~85% for ~2mm^2 pixel
- Operating voltage (reverse bias) up to ~700V
- Radiation tolerance demonstrated up to 2E15 n_{eq}/cm^2

Same technology also chosen for ATLAS HGTD

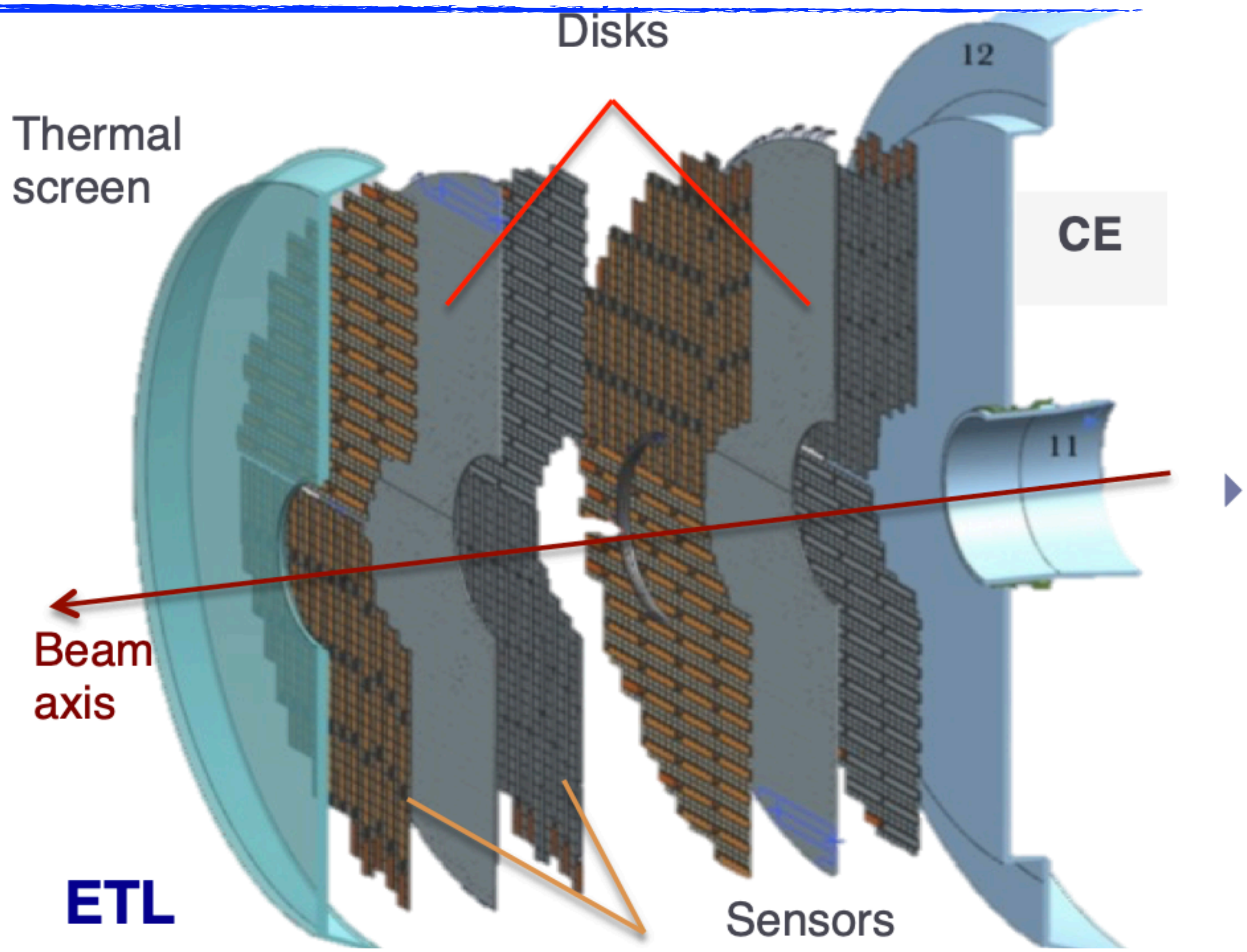


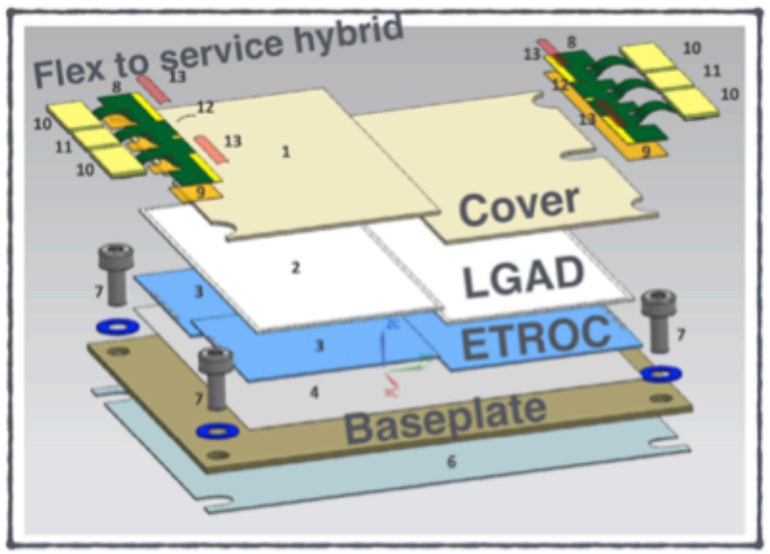


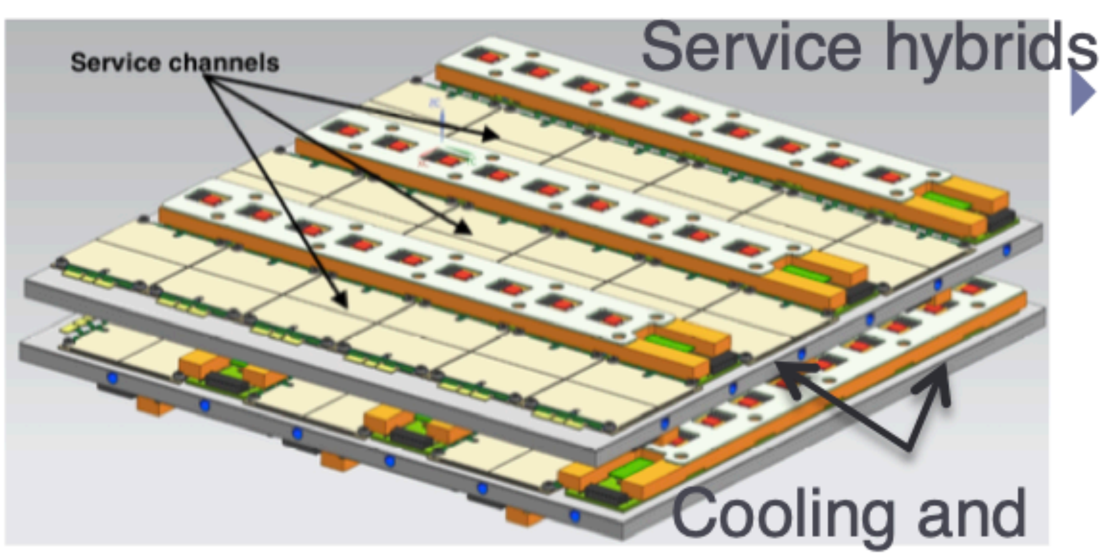


ETL Layout

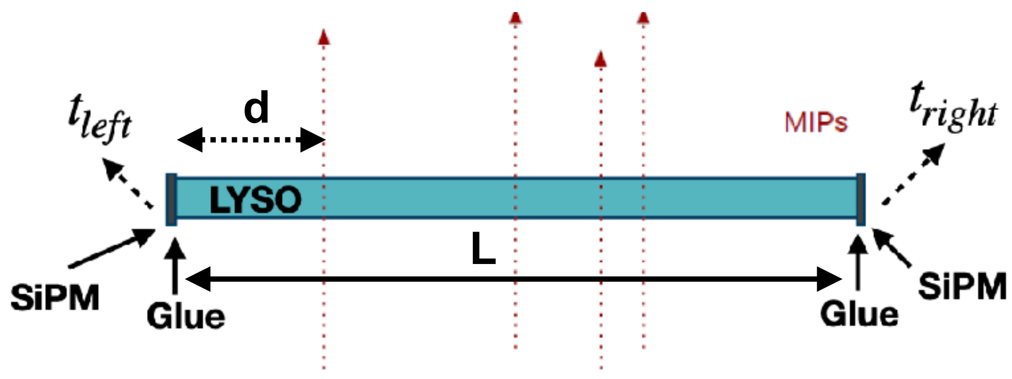
- Basic unit: array of 16x32 LGADs, pad size 1.3 x 1.3 mm^2
  - Sensor bump bonded to 2 readout chips
- 2 disks per endcap: staggered module layout on each side of each disk
- 2 hits per track: 30ps throughout HL-LHC
- Coverage 1.6<|η|<3, 8.5M channels



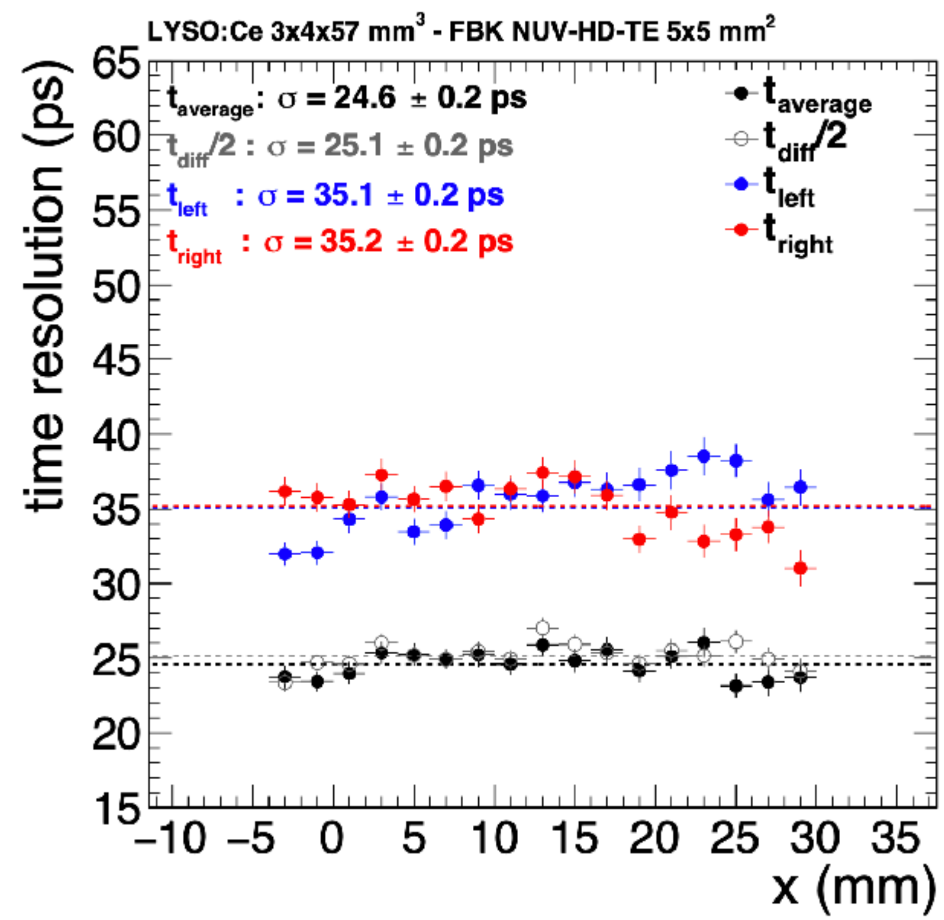




BTL Sensor: Test Beam Performance

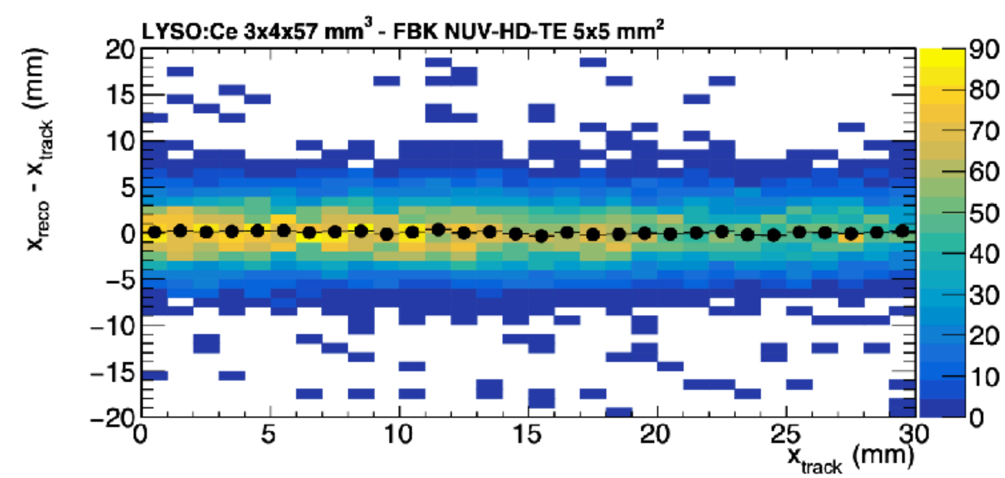


$$t_{left} = d/v$$
$$t_{right} = (L-d)/v$$
$$1/v \simeq 15\text{ps/mm}$$



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
  - $\sqrt{2}$ gain compared to a single measurement
- From time difference $t_{diff} = t_{left}-t_{right}$ charged particle impact position can be measured (~3mm resolution)

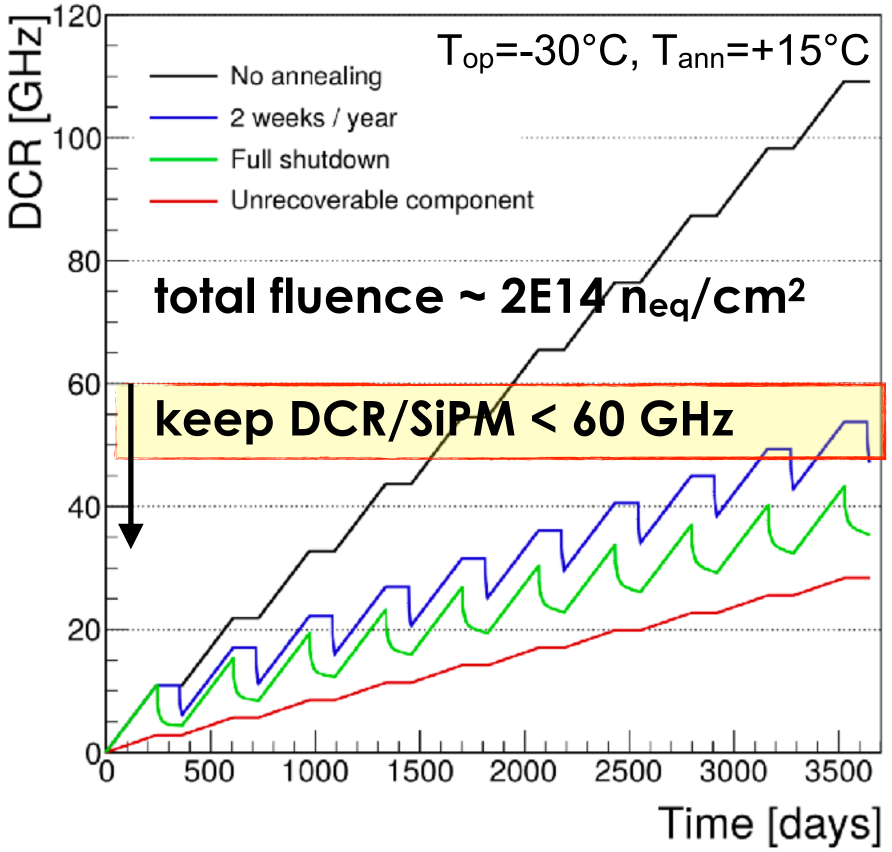


Test beam studies confirm BTL expected performance: time resolution <30ps

BTL Time Resolution

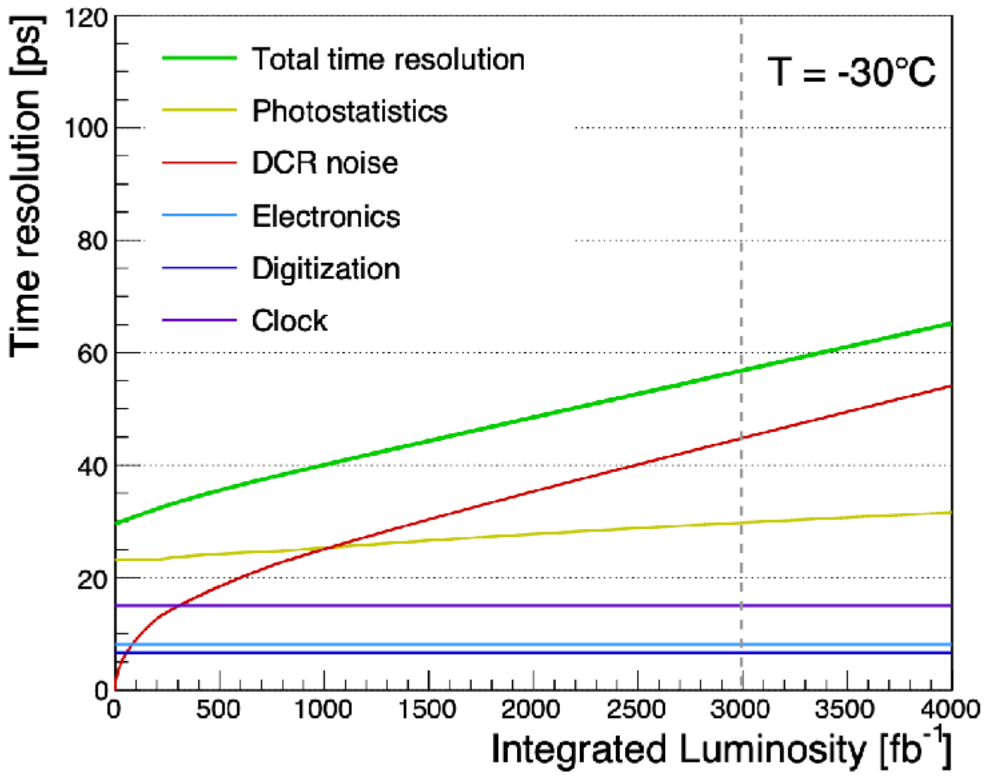
SiPM dark current increase due to radiation damage throughout HL-LHC

- Low temperature: DCR reduced by ~1/2 every 10 °C, operating temperature < -30°C (CO_2 cooling)
- Annealing during shutdown
- Increase of dark current limits also the SiPM operating voltage (limited power budget)
- Possibility to use small thermoelectric coolers on the SiPM package under discussion



Time resolution <60ps after 3000 fb^{-1}

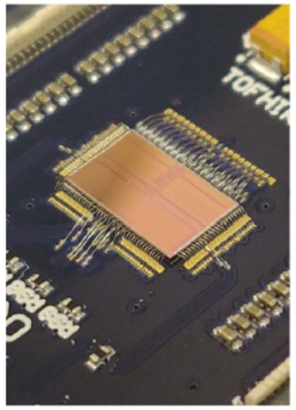
- Contribution from DCR noise becomes the largest contribution after 1000 fb^{-1}
- Photostatistics dominant contribution at the begin of operations
- Electronics+clock distribution contribution ~ 15ps

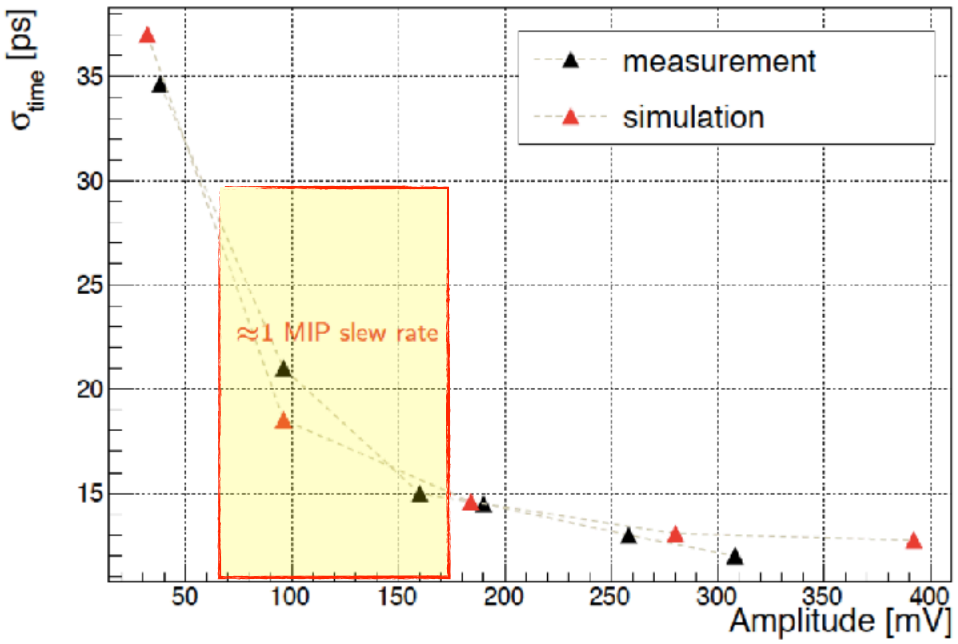


A new ASIC developed: TOFHIR

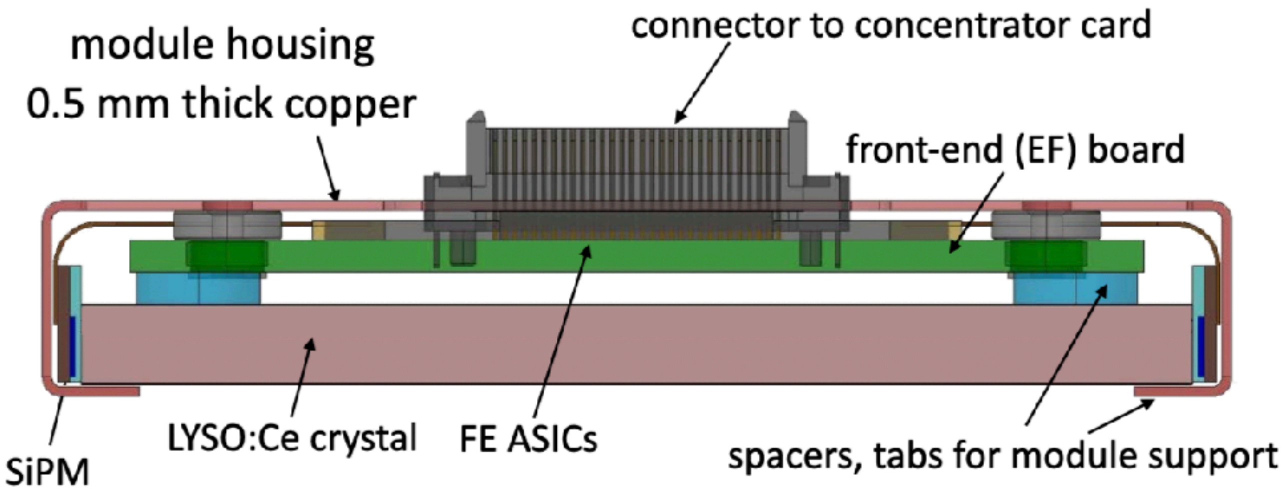
Time Of Flight at HIgh Rate

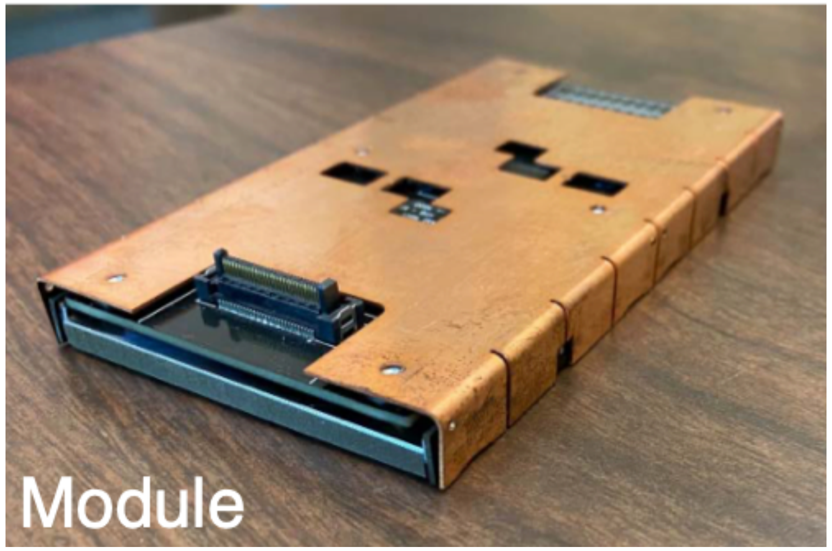
- Analog+digital ASIC, based on TOFPET2, radiation hard technology (TSMC CMOS 130nm)
- DCR noise cancellation
- High hit rate: 2.5 MHz MIP hits/channel
- Power consumption: 15 mW/channel



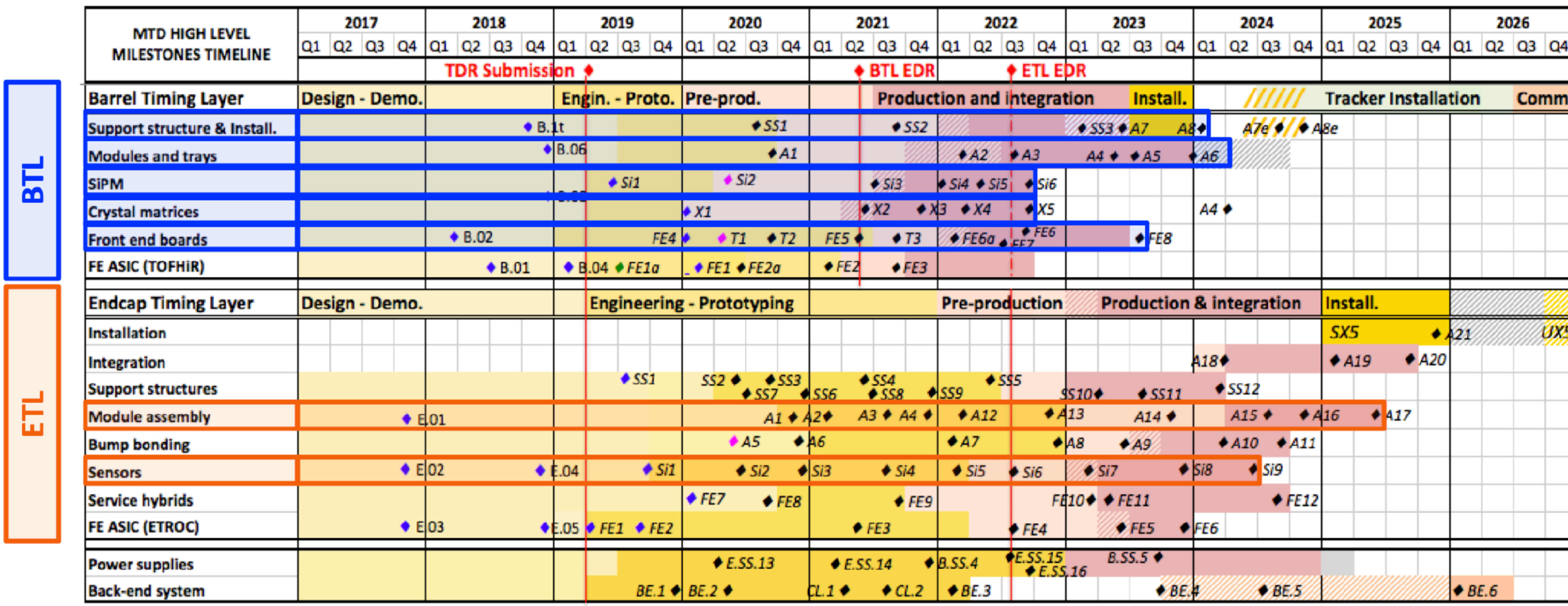


BTL module designed to minimise the distance between SiPM and ASIC





MTD SCHEDULE



Schedule is very tight for BTL as installation should start before tracker

– BTL integration 2022-2023, installation to start at the end of 2023, before LS3

– Market surveys ongoing for LYSO and SiPMs, towards the final tender+order (fall 2021)

ETL schedule a bit more relaxed, can be installed either on surface or in the cavern after lowering HGC

– ETL integration 2023-2024, installation (on surface) 2025 during LS3

Steady progress despite COVID, small delays not impacting the critical path

LYSO Characterisation In Rome

Last step of LYSO vendor selection started 2 weeks ago in Rome

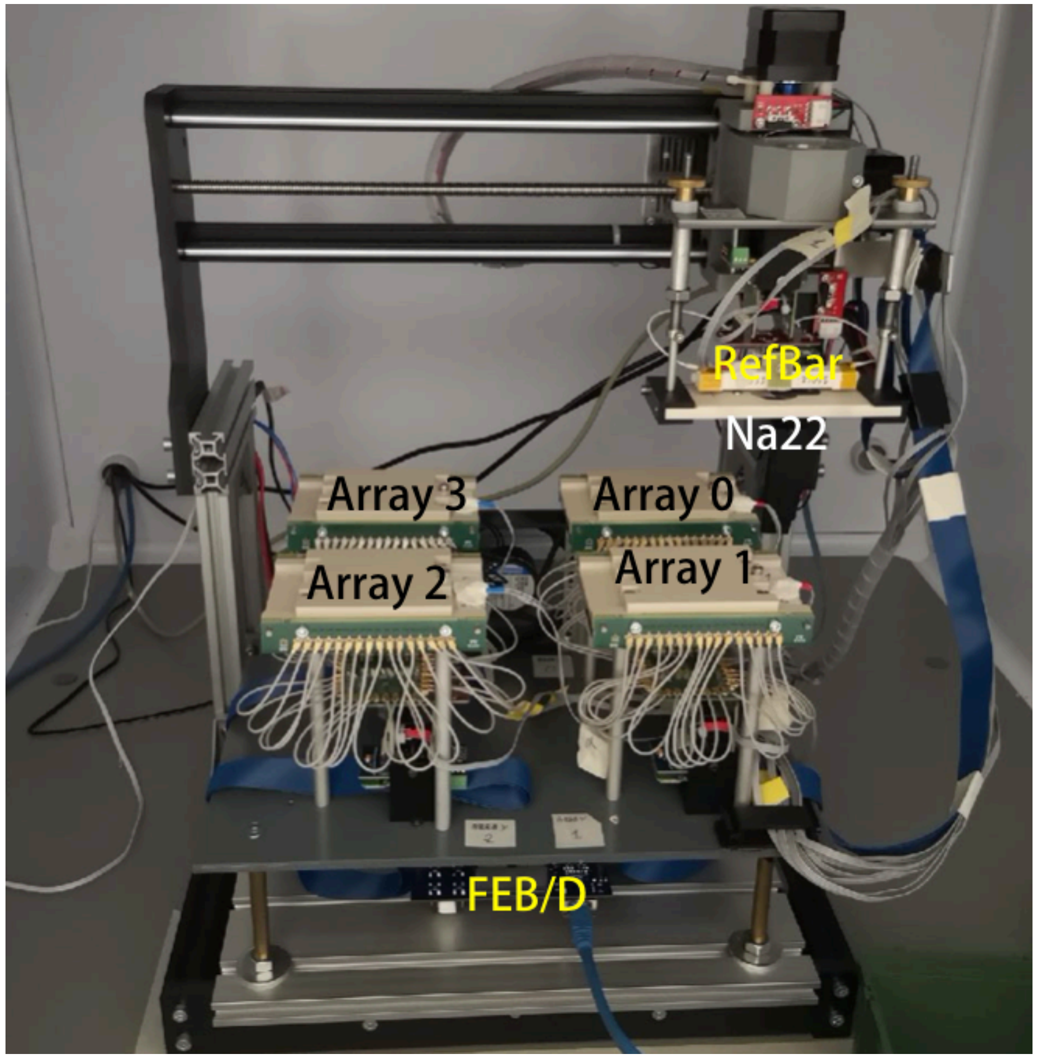
- LYSO is a “commercial" product (PET), several producers worldwide
- Now measuring about 300 arrays + 200 crystals from 9 vendors

QA/QC during production will also be performed in Rome

Custom measurement benches developed for characterisation of LYSO up to -30°C

Single LYSO crystals and arrays qualified in terms of

- light yield, decay time, time resolution, optical cross-talk (in arrays) measured using radioactive sources
- dimension, density, planarity (array) and uniformity



SUMMARY

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

- Significant improvements on several observables from PU mitigation with precision timing (~30ps resolution)
- Physics gains for many final states are equivalent to ~25% more luminosity (few years of additional running of HL-LHC)
- New powerful handles for BSM (in particular LLP searches) and heavy flavour physics

MTD quickly moving into integration phase after several years of R&D

- Novel detector technologies adopted for barrel and endcap, new ASICs developed, addressed several design challenges
- Several italian groups are leading this effort since the very beginning of the project
- 2021 a key year for the project