Precision timing calorimetry with the upgraded CMS ECAL

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CMS

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OUTLINE

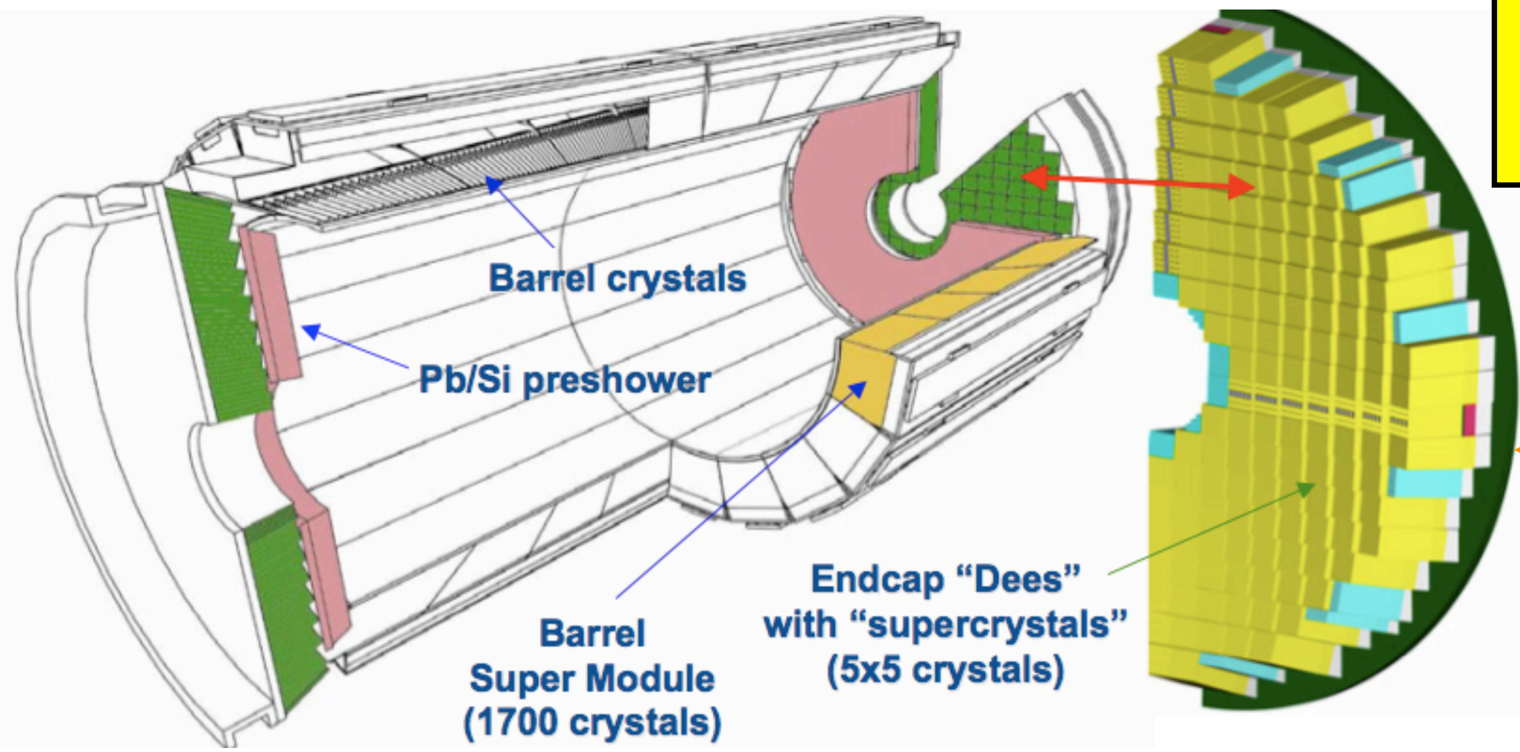
CMS ECAL: precision timing with $PbWO_4$ crystals

Physics at HL-LHC: precision timing and pile-up

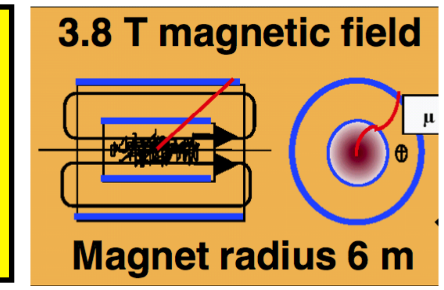
CMS ECAL barrel upgrade for HL-LHC
test beam results

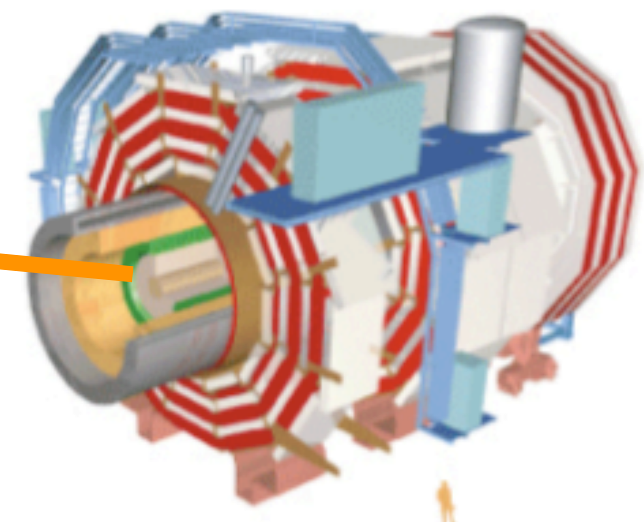
Summary

CMS ECAL



Tracker coverage $|\eta|<2.5$
ECAL placed inside the coil
Designed for 14 TeV,
$L=10^{34} cm^{-2}s^{-1}$, 500 fb^{-1}

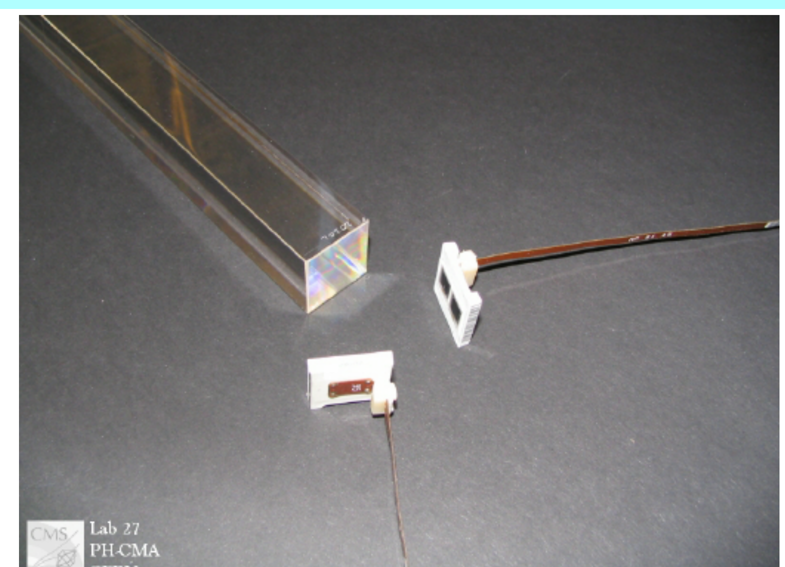




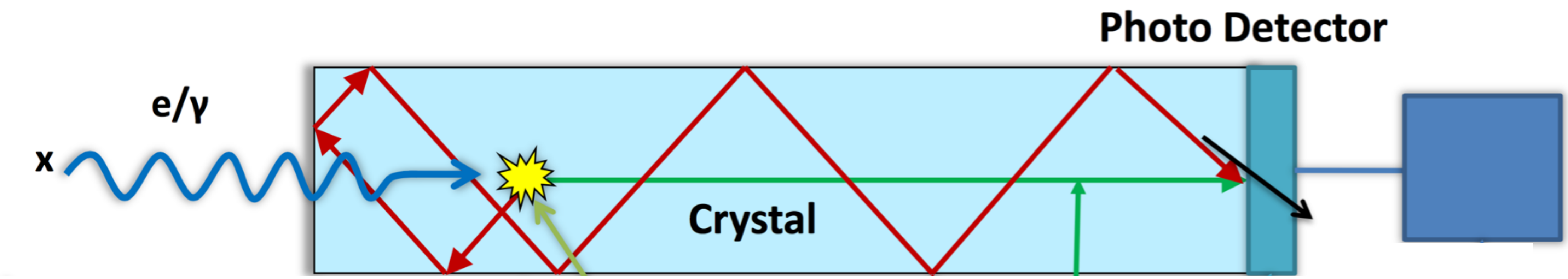
Homogeneous $PbWO_4$ crystals
Designed to optimise energy resolution: <1% at 60 GeV ($H\rightarrow\gamma\gamma$ discovery in 2012)
Barrel crystals: 2.2 x 2.2 x 23 cm^3 ($PbWO_4$ X_0=0.89cm)
Light yield 4pe/MeV on APD pair

No longitudinal segmentation:
cannot measure γ direction without interaction vertex position

Barrel - Avalanche Photo-Diodes (APD)
Gain: 50 QE ~ 75% @ λ_{peak}=420nm
$\Delta G/\Delta T$=-2.4%/°C $\Delta G/\Delta V$=3.1%/V



Precision Timing with Crystals



Several ingredients determine the time resolution of an electromagnetic shower in a homogeneous crystal calorimeter

- **Intrinsic EM shower fluctuations**

  longitudinal shower fluctuations

  optical transit time spread: scintillation rise/decay time, light propagation
- **Photodetector + electronics**

  photodetector: rise time, transit time

  noise: dark current, electronic noise
- **DAQ**

  clock distribution

TIMING WITH CMS ECAL

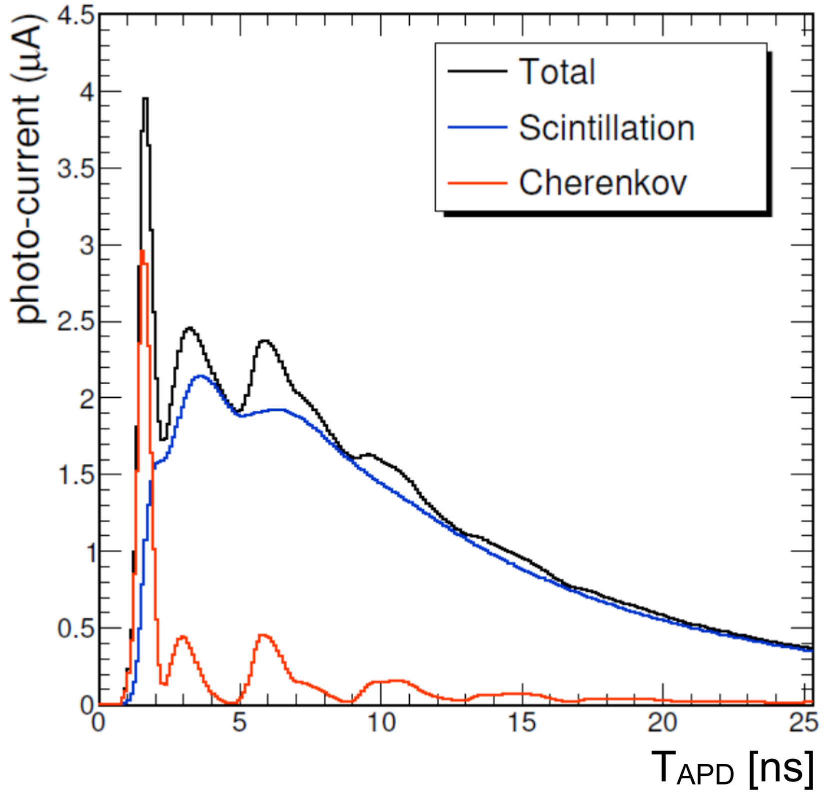
Original design requirements on ECAL timing to ensure good energy resolution

stability within 1ns

$PbWO_4$ is a fast scintillator

90% of light within 25ns

~10% contribution from Cherenkov

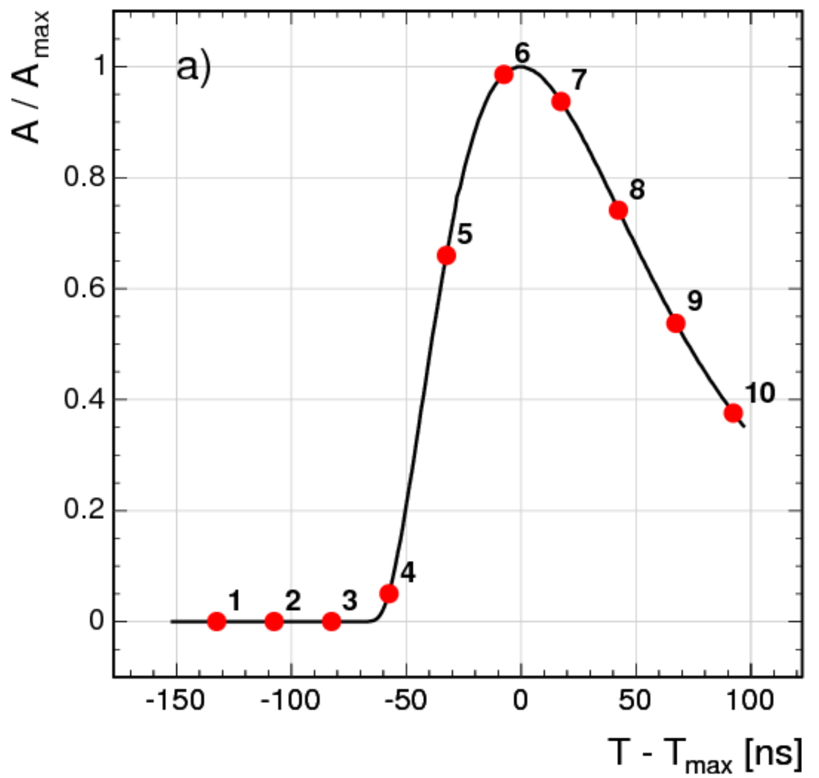


Timing information extracted from reconstructed pulse shape

electronics optimised for LHC Phase I conditions

43ns electronics shaping time

sampling at 40 MHz



Current ECAL Timing Performance

Test beam (2008)

- 2 crystals in the same EM shower: **20 ps constant term**

In-situ (Run1)

- 2 crystals in the same EM shower & same readout unit: **70 ps constant term**, degradation due to time calibration stability
- 2 crystals in different showers from Z→ee**: 150 ps constant term**, additional degradation from clock distribution

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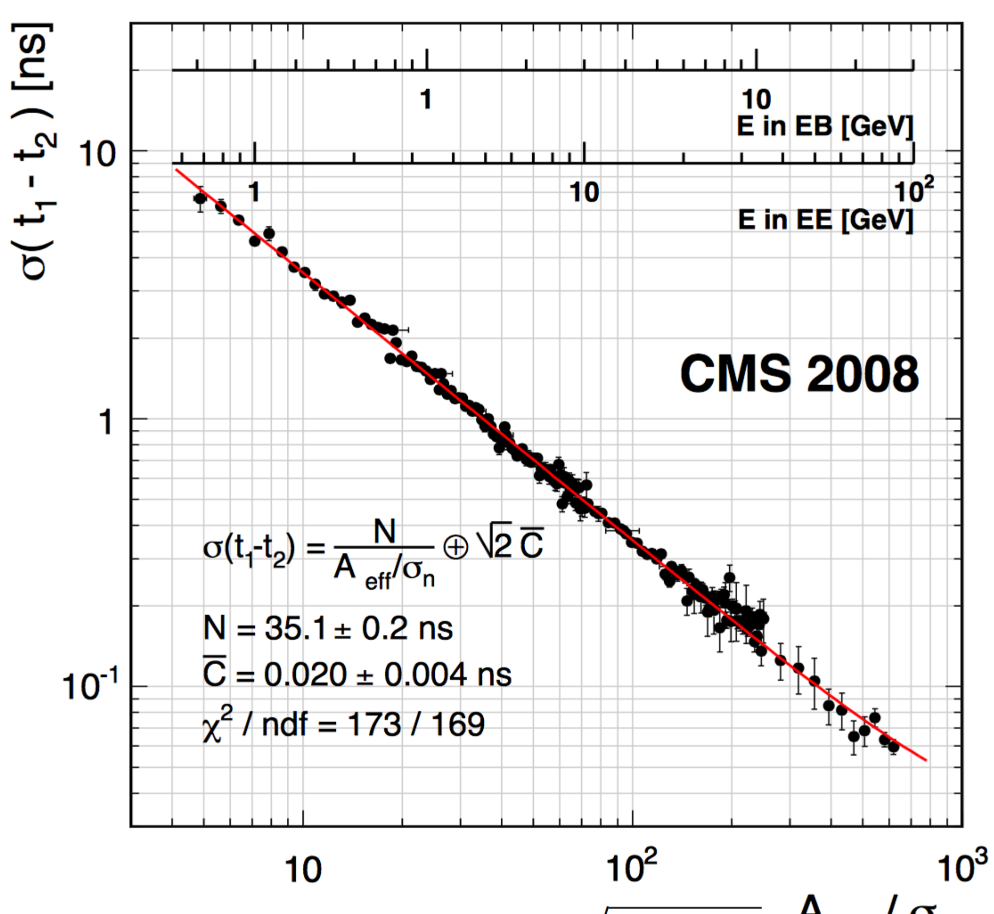
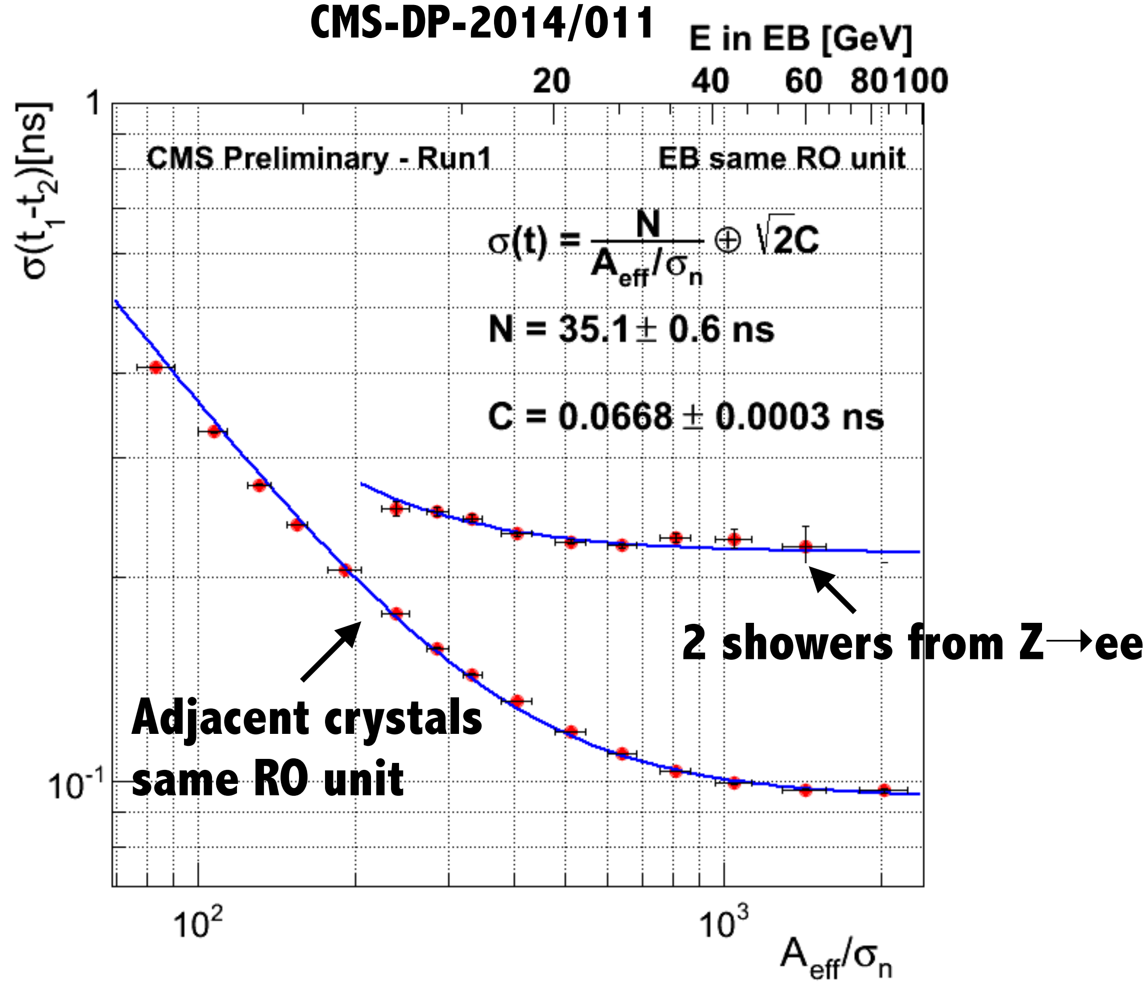


$$\sigma(t_1-t_2) = \frac{N}{A_{eff}/\sigma_n} \oplus \sqrt{2}\,\bar{C}$$

$$A_{\rm eff} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$$

CMS-DP-2014/011



$$\sigma(t) = \frac{N}{A_{eff}/\sigma_n} \oplus \sqrt{2}C$$

THE HL-LHC CHALLENGE

HL-LHC (>2026): **$L > 5E34 cm^{-2}s^{-1}$, $L_{int} > 300 fb^{-1}$ x year (target 3000 fb^{-1} in 10 years)**

radiation 1 order of magnitude worse then current LHC conditions

140-200 interactions per bunch-crossing

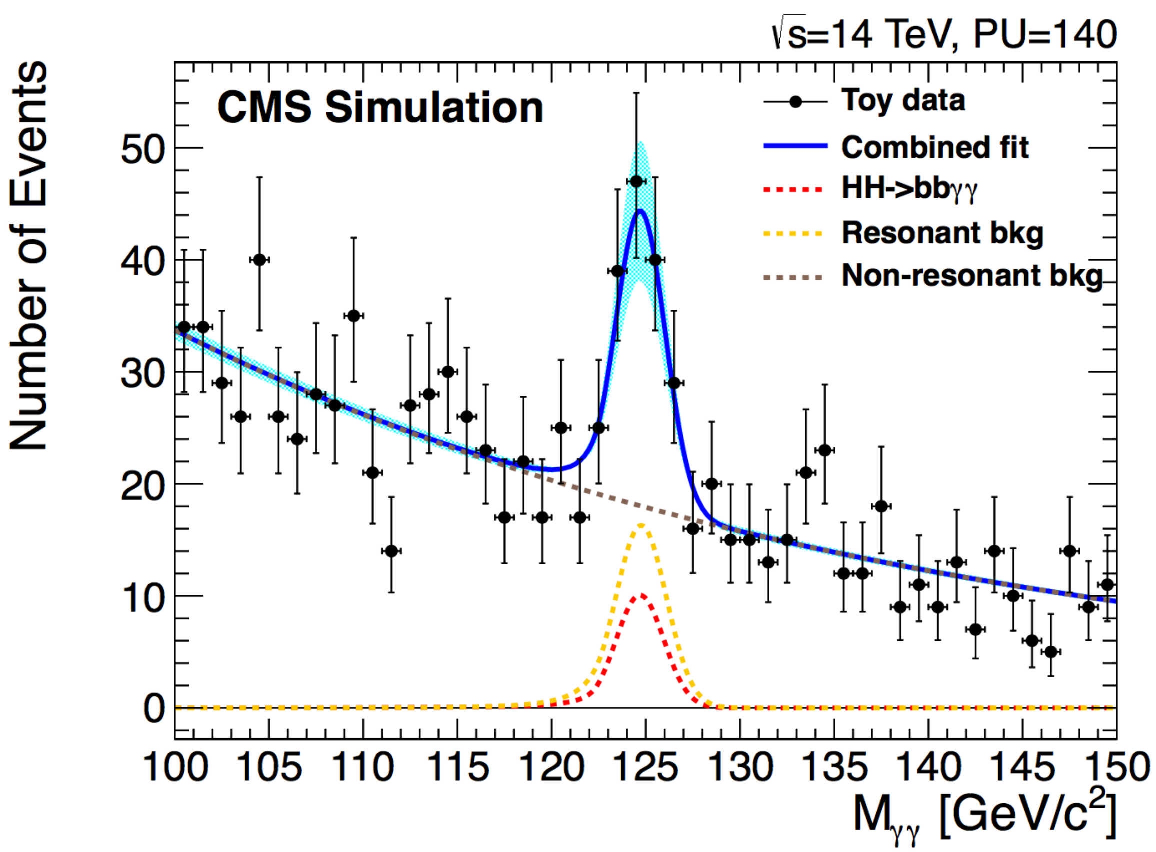
pile-up deteriorates object reconstruction: in a $\Delta R=0.4$ cone ~50 GeV from pile-up

HL-LHC challenge: precision physics with 200 pile-up events

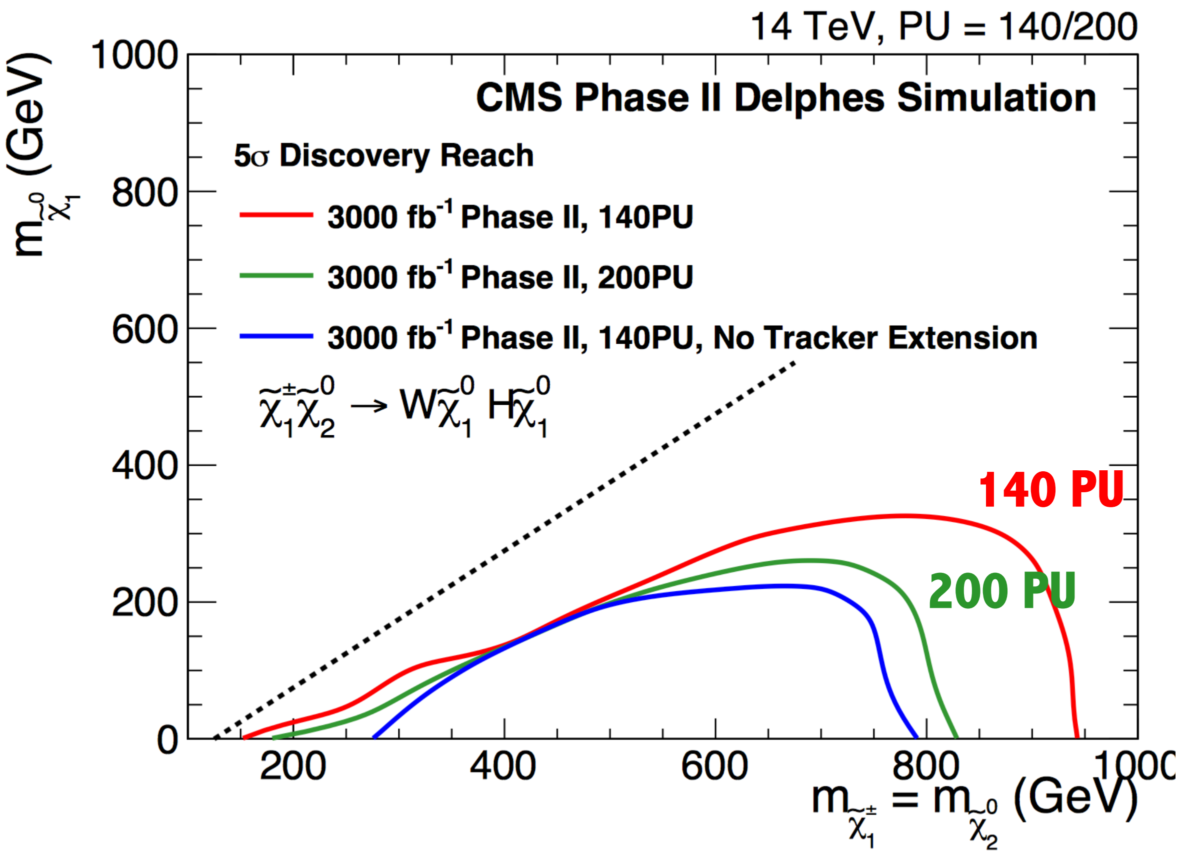
Higgs couplings precision 3-10%, access Higgs self-coupling (HH)

Extend sensitivity for BSM processes

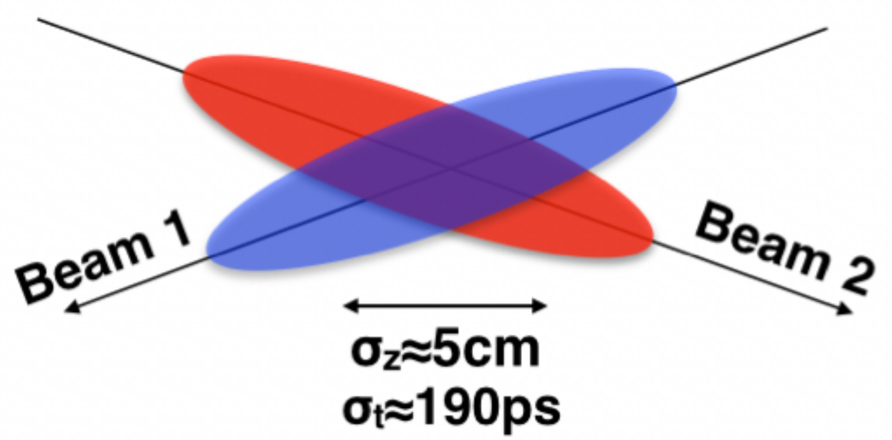
HH(bbγγ) @ 3000 fb^{-1}

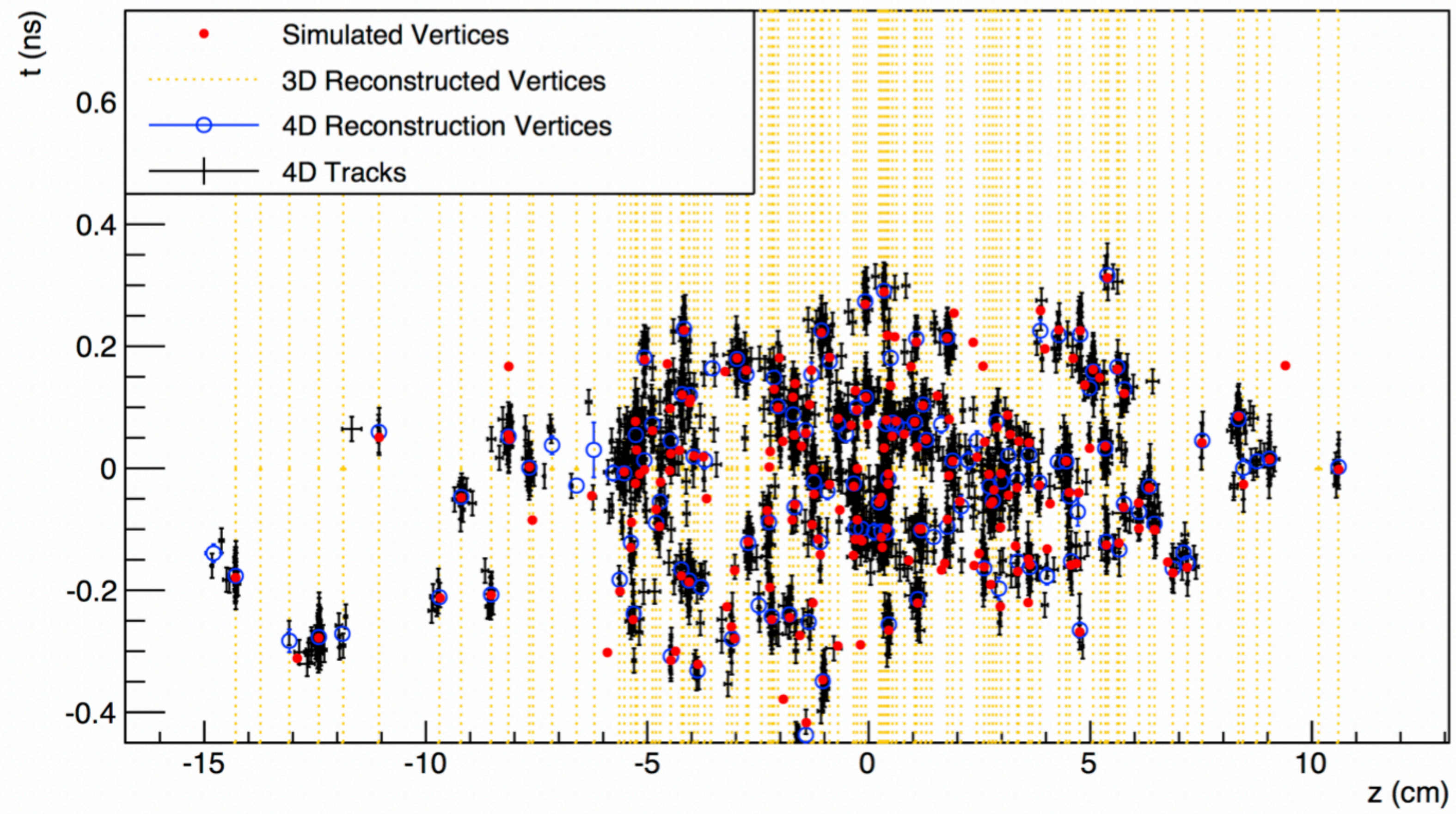


SUSY: $W^{\pm}H + E_T^{MIS}$



PRECISION TIMING @ HL-LHC





Pile-up vertices are spread along beam direction and time: precision timing for charged & neutral particles will be a key to reduce pile-up contamination

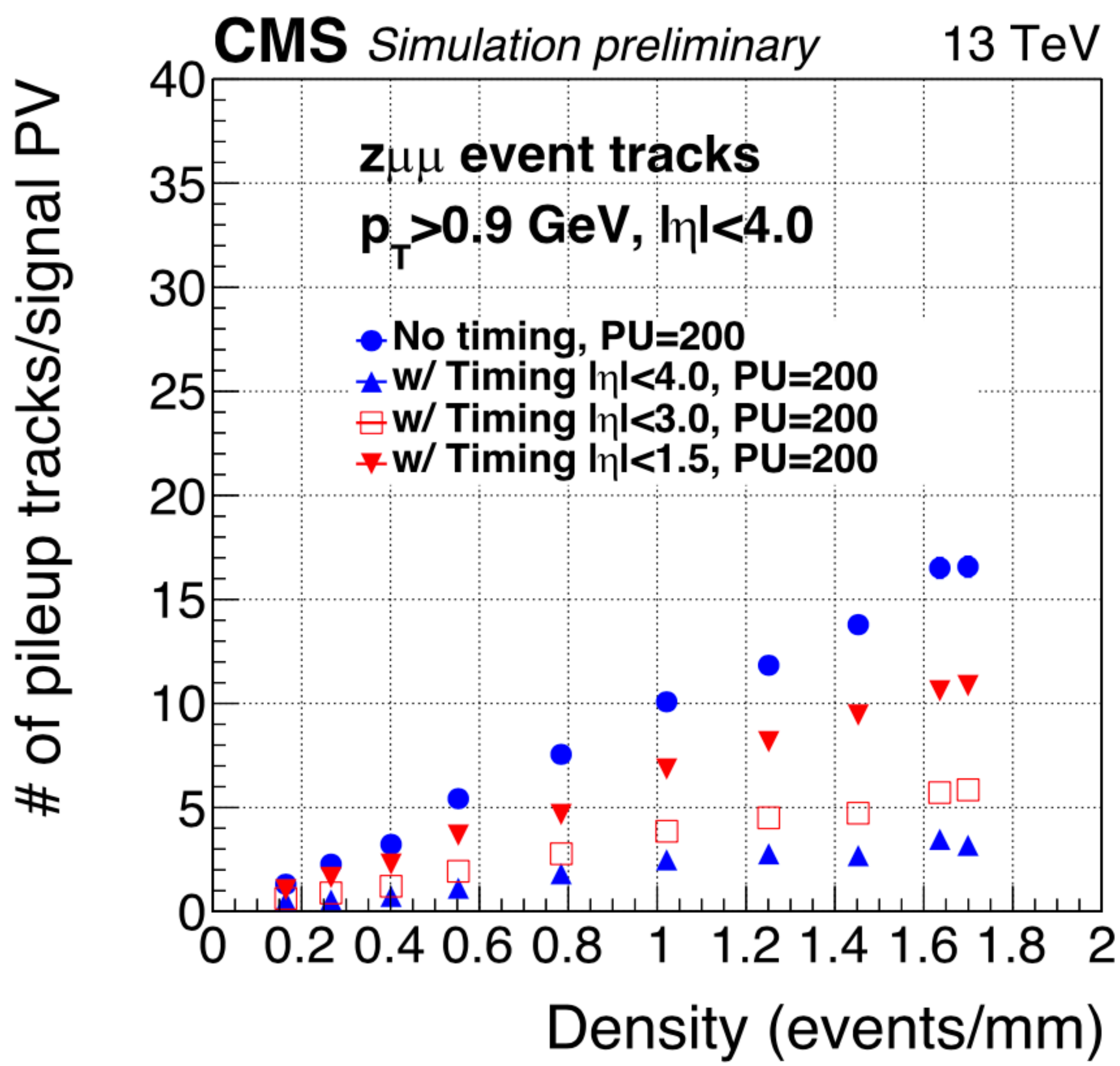
Track timing (<30ps) will allow full 4D (space+time) vertex reconstruction

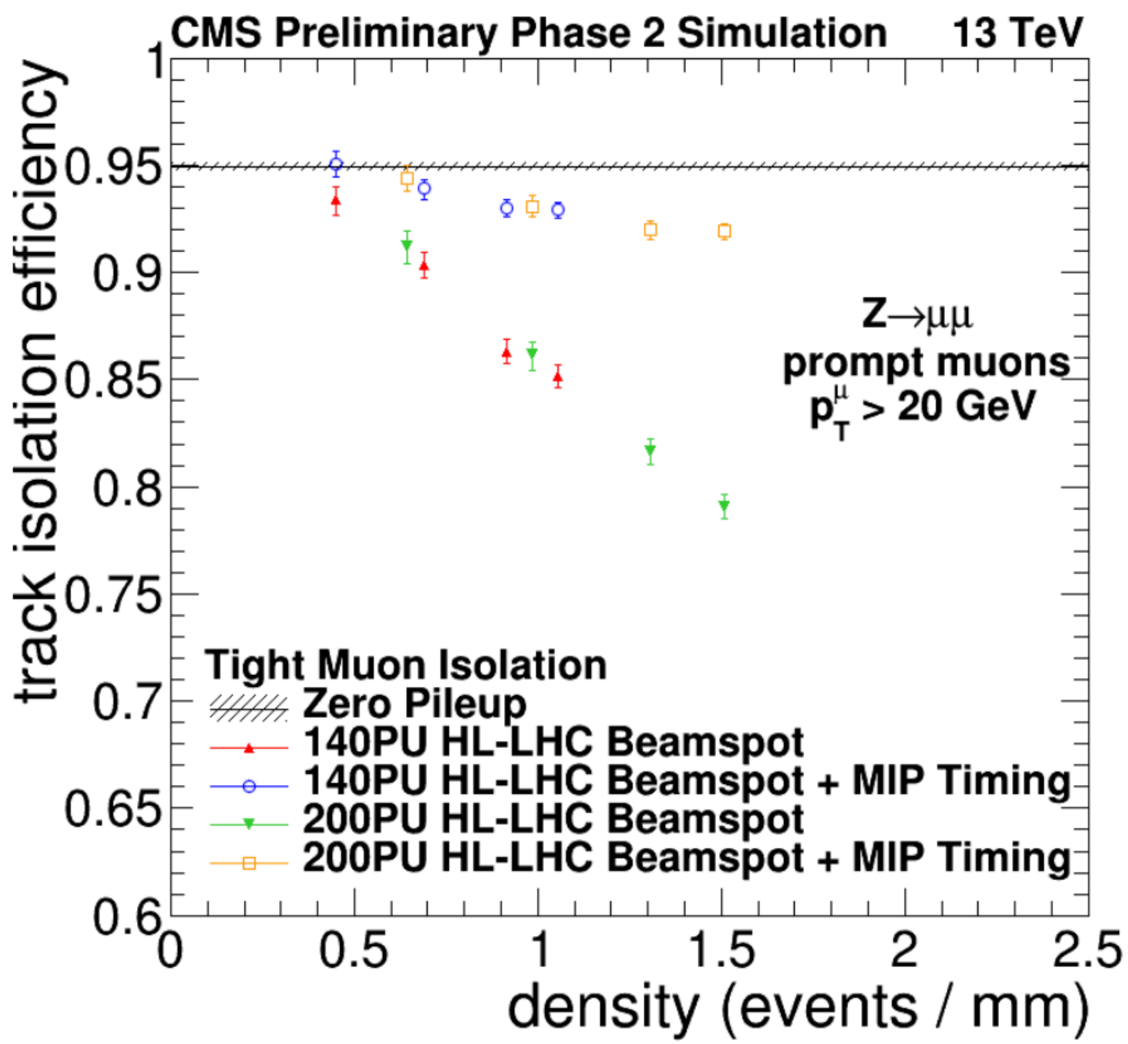
~ x10 reduction of vertex merging rate wrt 3D reconstruction @ PU200

CMS is considering a dedicated timing layer for MIPs with hermetic coverage $|\eta| < 3$ in front of calorimeters

Thin crystals+SiPM in the barrel, Si sensors with gain in the endcaps

PRECISION TIMING & PILE-UP



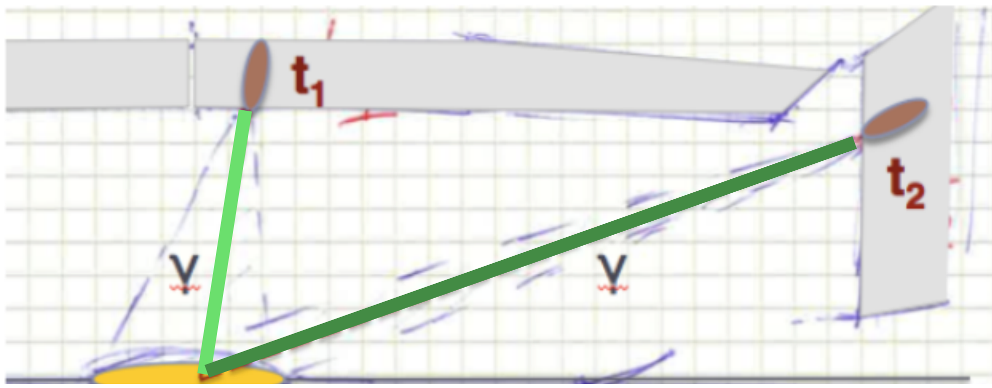


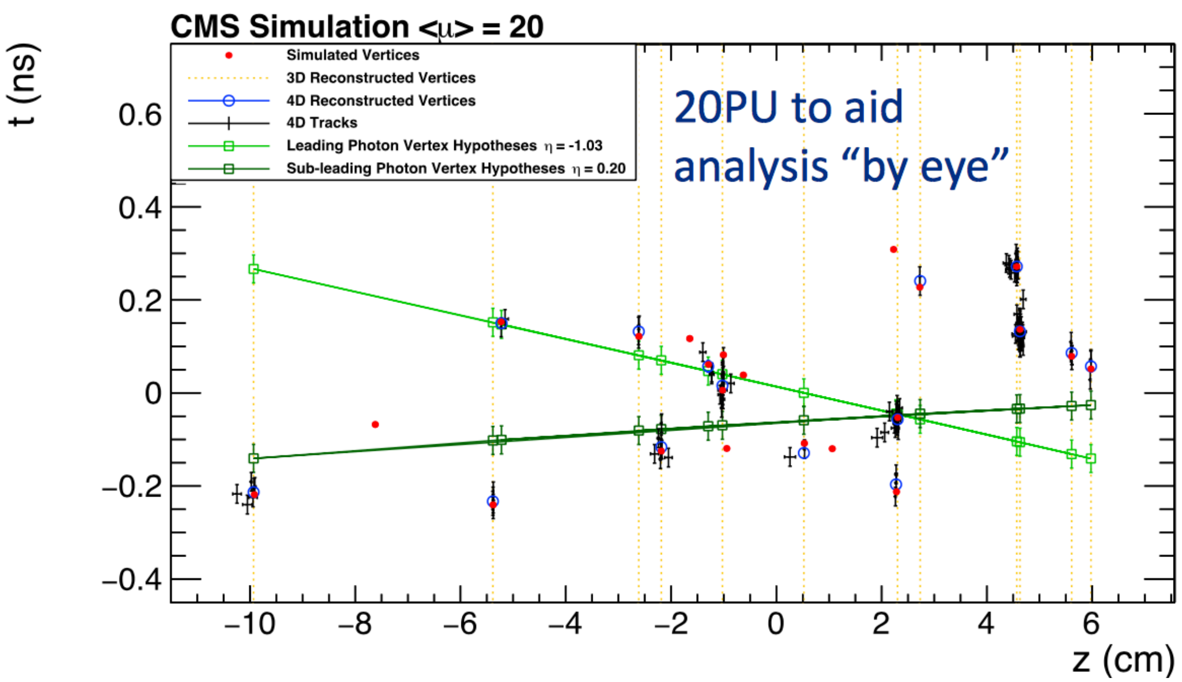
MIP Timing allows to reduce ~x5 spurious pile-up tracks

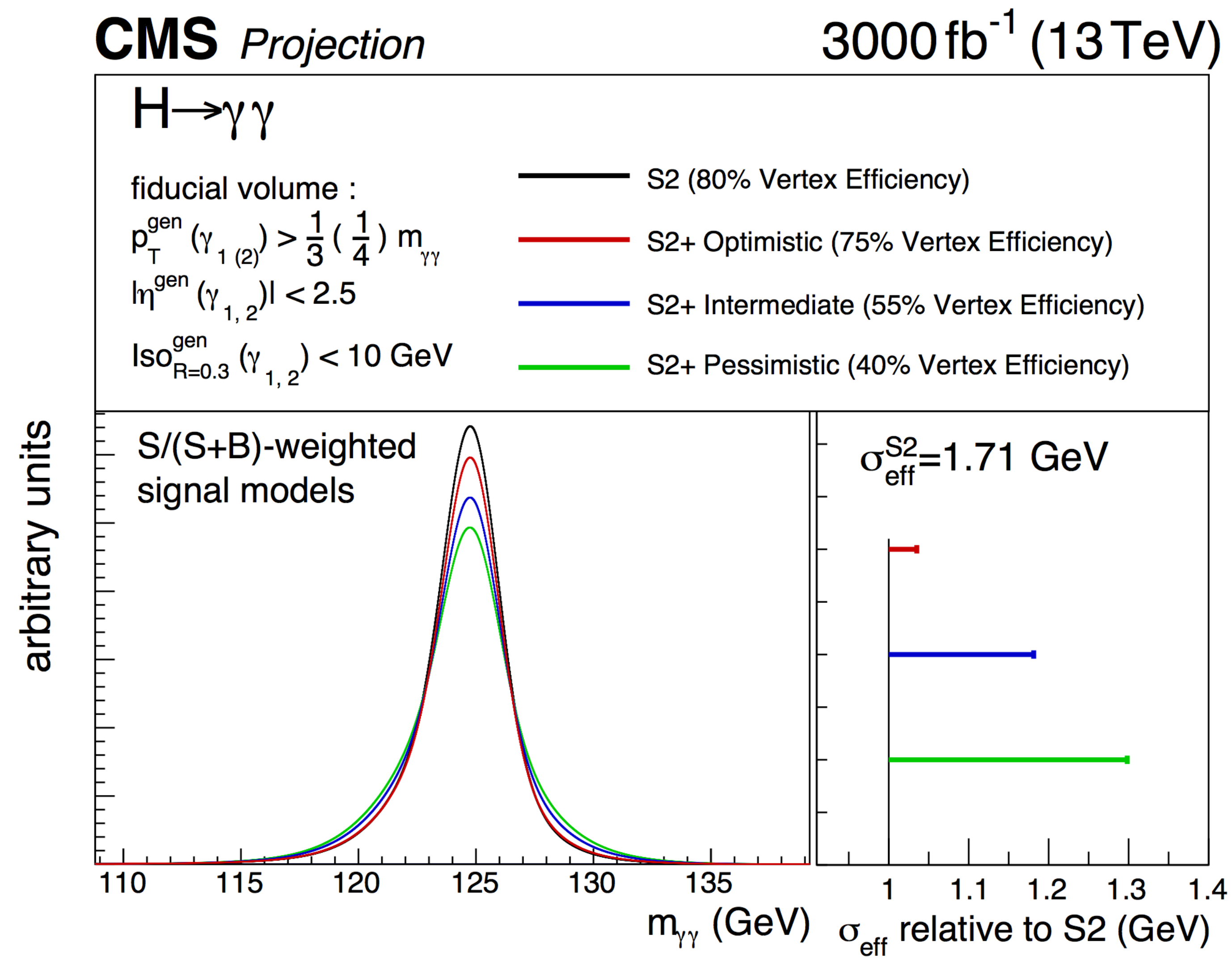
- track-vertex compatibility requirements both in space and time
- significant improvements for event reconstruction: isolation efficiency (e,μ,τ,γ), jet/MET resolution

Pile-up reduction also possible for photons if similar time resolution is achieved

PHOTON TIMING & H→γγ







Photon timing (<30ps) allows to determine di-photon interaction vertex position (and time)

Vertex currently determined using recoiling tracks properties. Efficiency ~80% with current pile-up LHC conditions, will become 30% @ PU200

ECAL+track precision timing allows to ~ keep current vertex efficiency @ PU200

ECAL BARREL UPGRADE

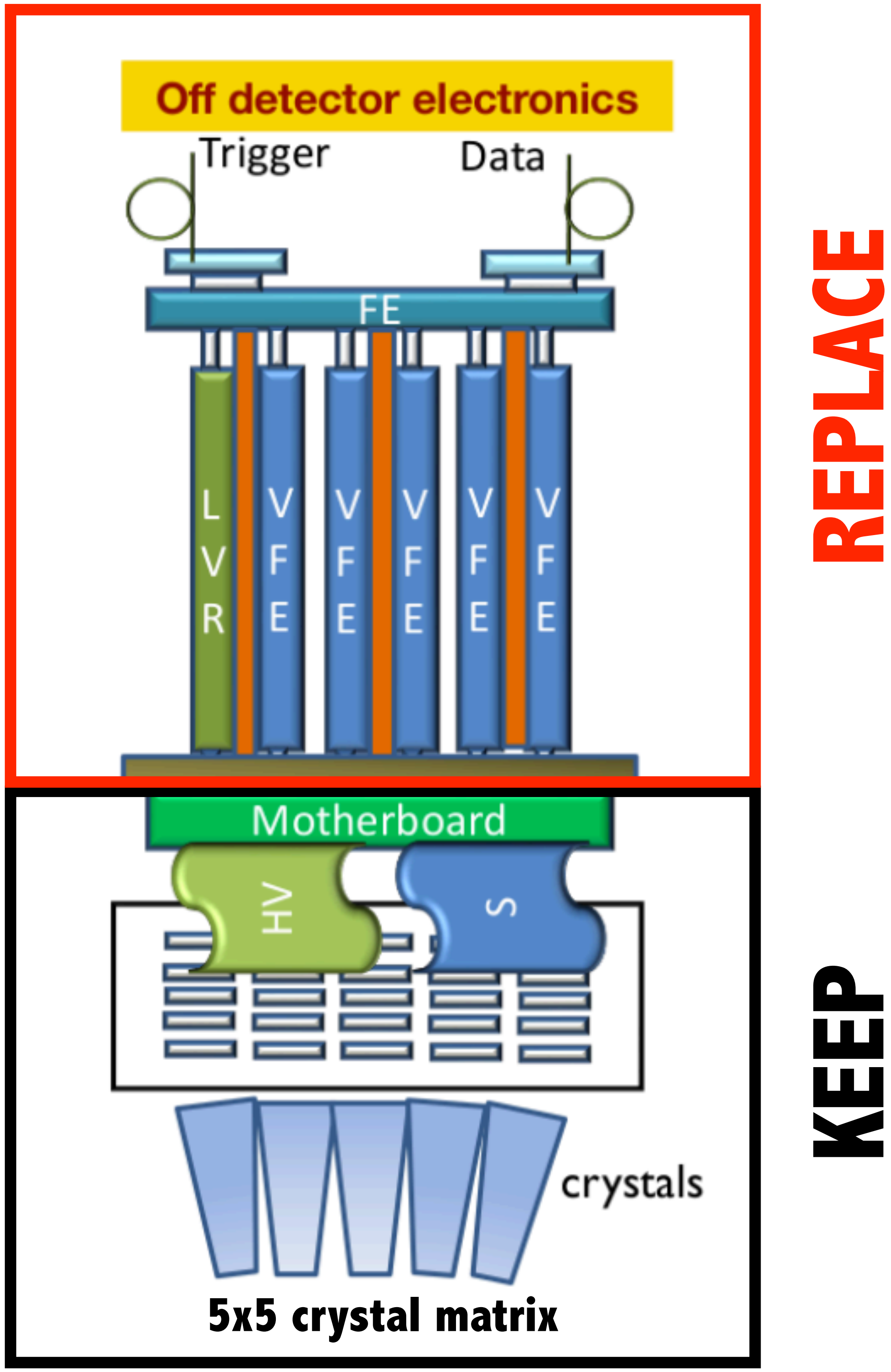
Upgrade necessary to cope with increased APD dark current, pile-up, trigger latency (12.5 μs) and L1 accept rate (750 kHz)

Operating temperature from 18°C to 9°C to reduce APD dark current

Keep crystals+APD, replace Very Front-End (VFE), FE and off-detector electronics

Profit of ECAL electronics replacement to optimise precision timing capabilities

- goal is to reach a time resolution <30ps for H→γγ photons (E>50 GeV)



UPGRADE EB ELECTRONICS & TIMING

Upgrade VFE based on dual gain Trans Impedence Amplifier (TIA)

- preserve a fast signal to optimise time resolution
- bandwidth cutoff (~35 MHz) imposed by APD/kapton impedance
- allow discrimination between scintillation and signals generated by hadron interactions in the APD (spike)

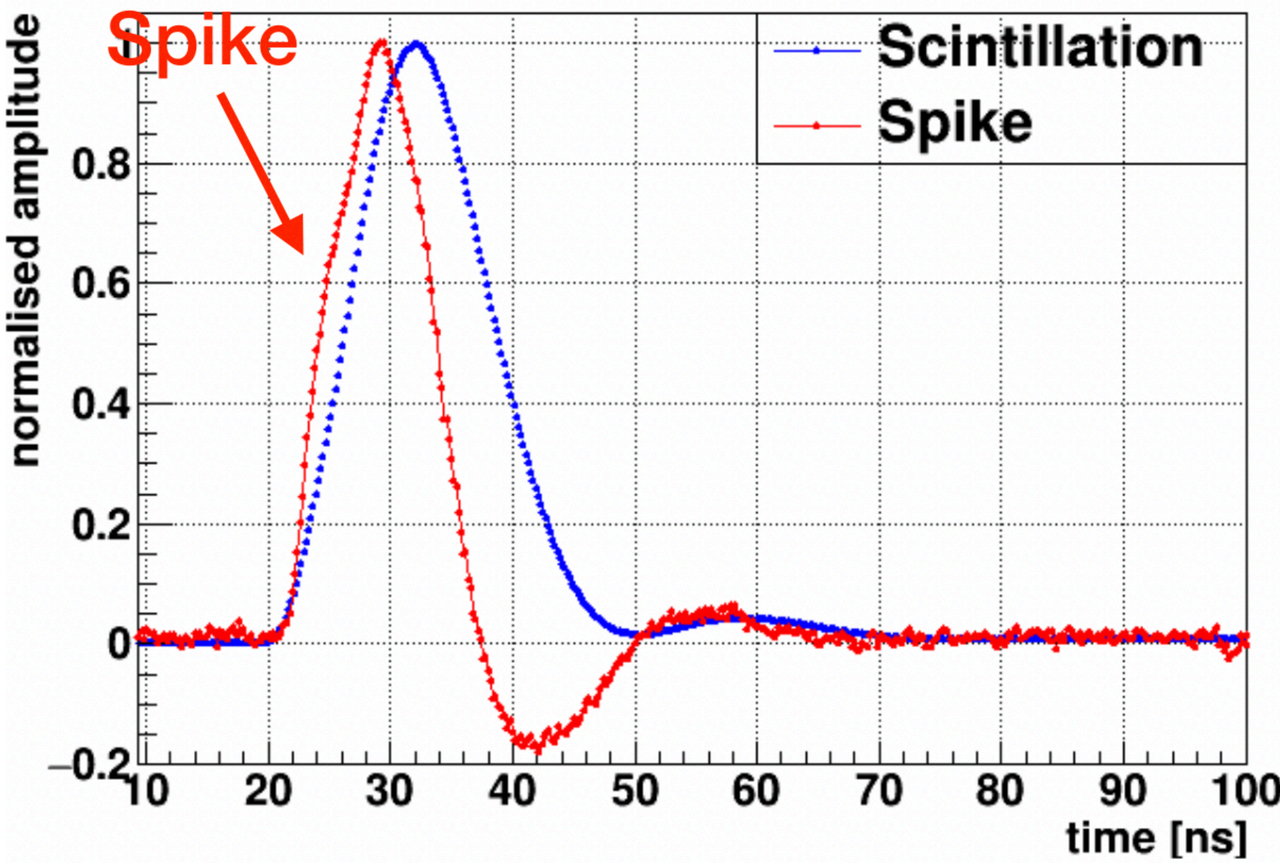
ADC sampling rate increased @ 160 MHz

- samples shipped to off detector electronics using high-speed optical links

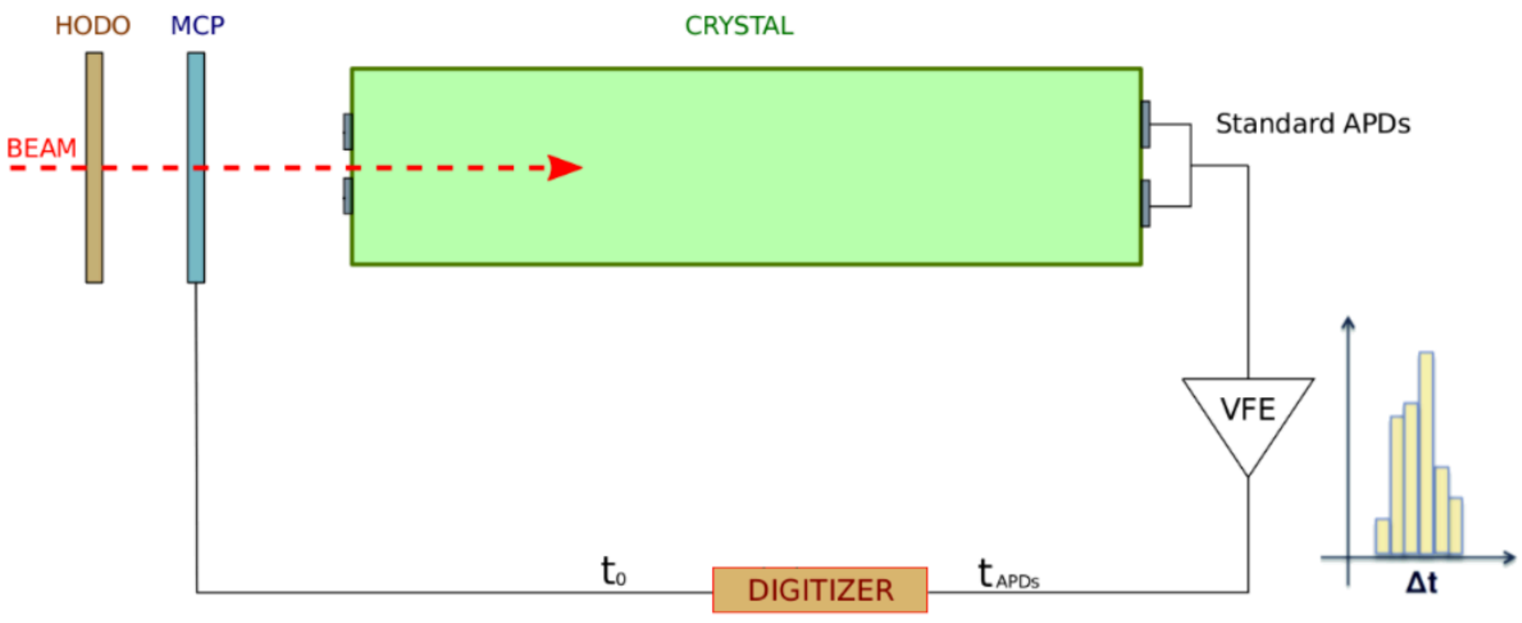
Clock distribution has a crucial role

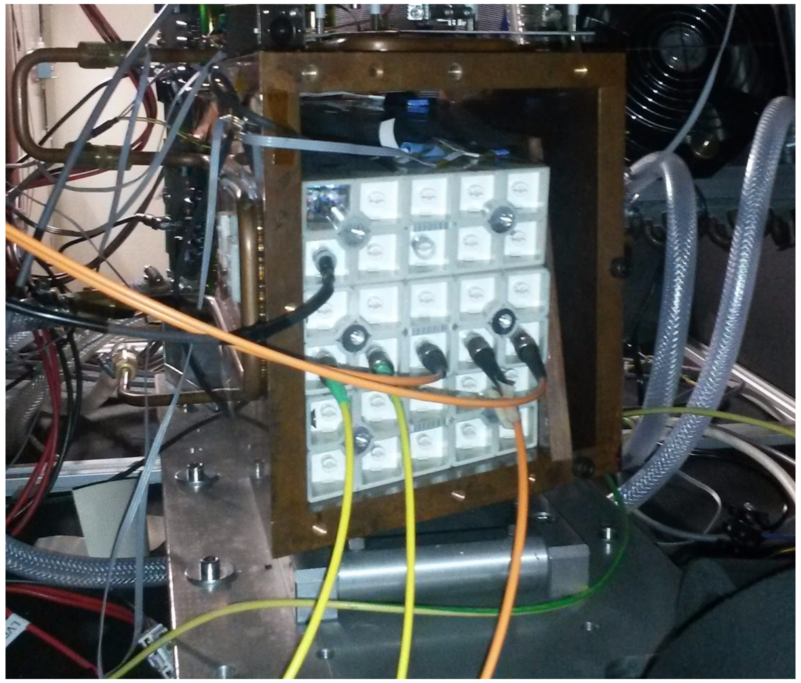
- need to ensure clock stability <10ps on a large distributed system

pulse shape in test beam with TIA (discrete components)



TEST BEAM STUDIES





Test beams performed in 2015,16 & 17 @ CERN SPS H4 to study intrinsic $PbWO_4$ timing capabilities

5x5 matrix of ECAL barrel crystals + APDs
different VFE electronics configuration
signals readout by a fast digitiser (CAEN V1742 5GS/s)
time extracted from a fit to the pulse shape
Micro-Channel Plate (MCP) detectors used as time reference (σ_t ~20 ps)

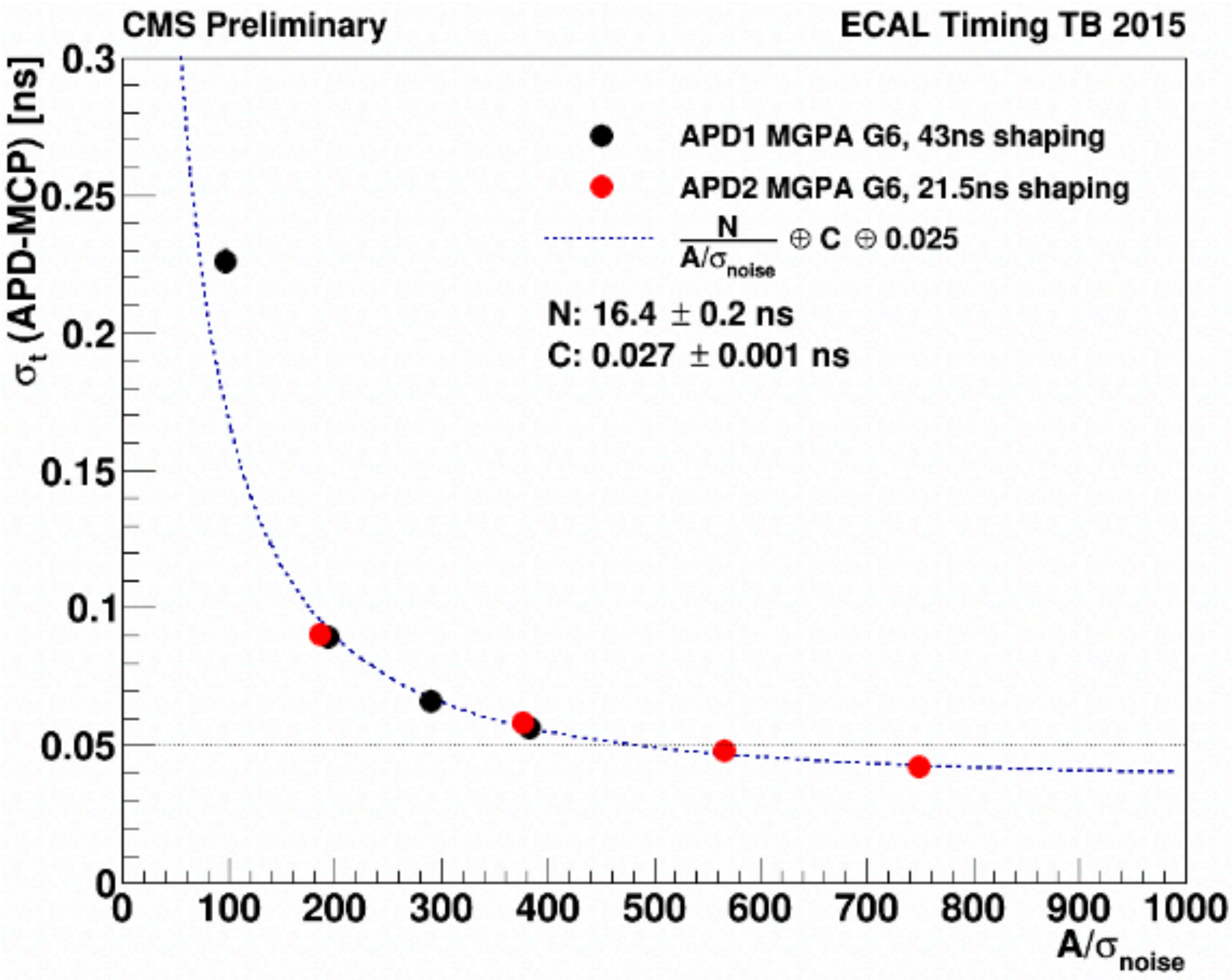
Test Beam 2015

APD + VFE electronics with standard (43 ns) and reduced (21.5 ns) shaping time

- 21.5 ns shaping time almost x2 A/σ_{noise}

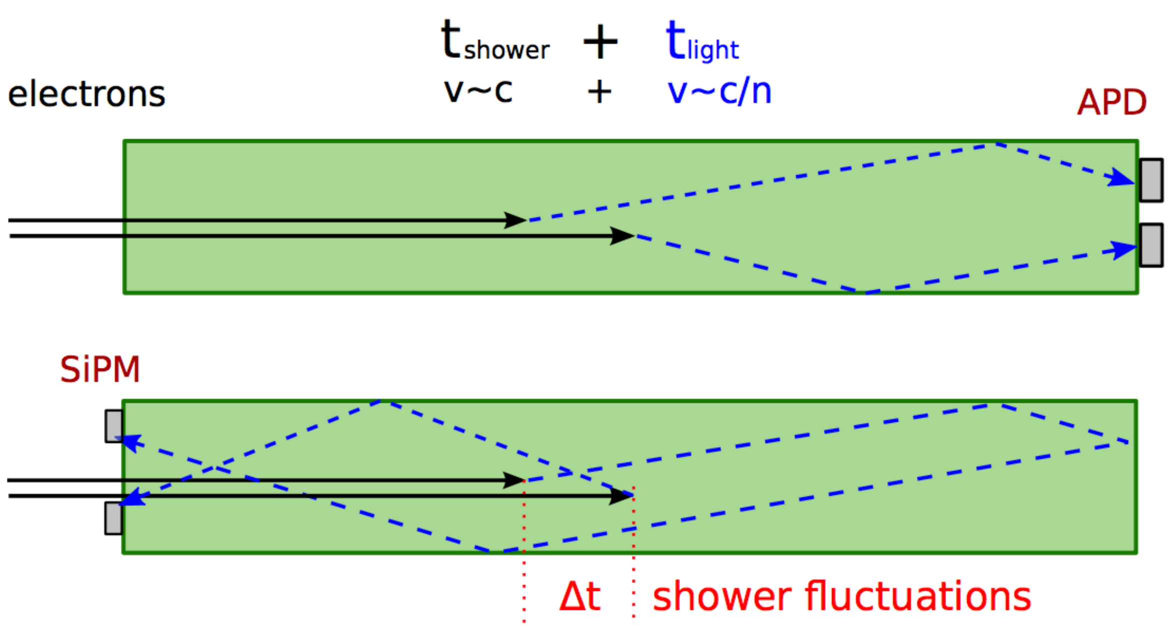
Additional noise from test beam custom electronics

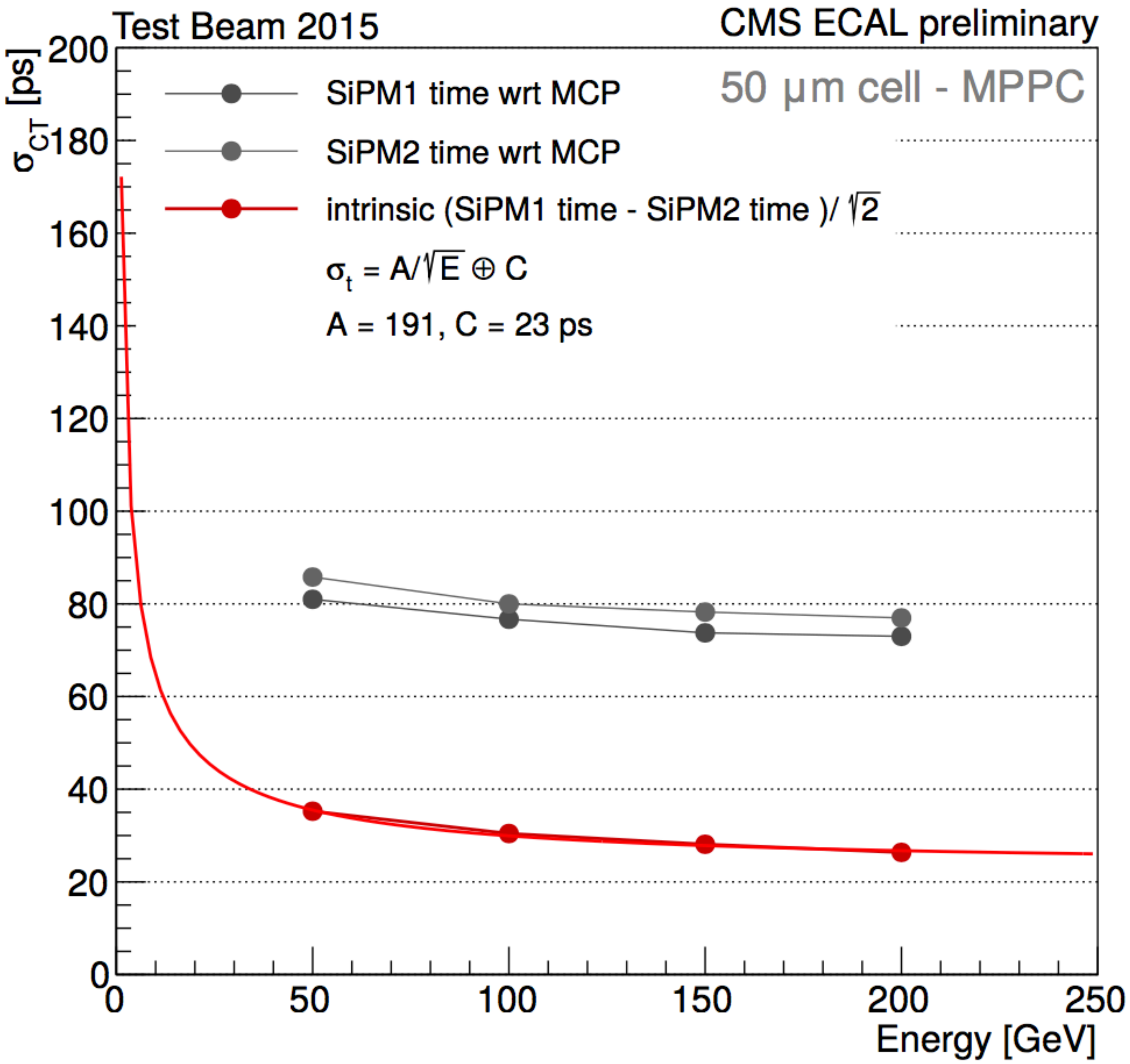
- in CMS: A/σ_{noise}~800 for a 50 GeV shower



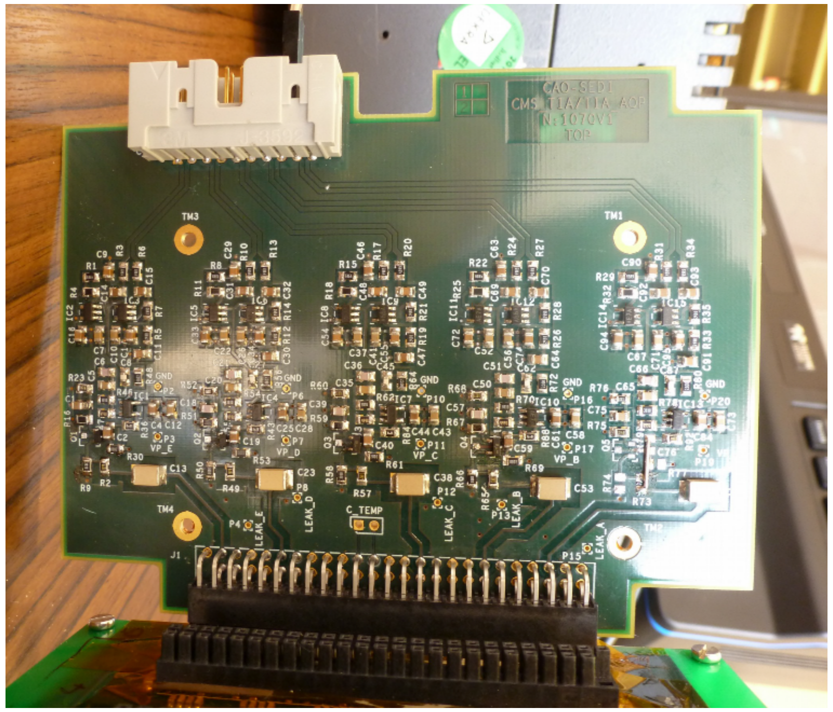
Test Beam 2015

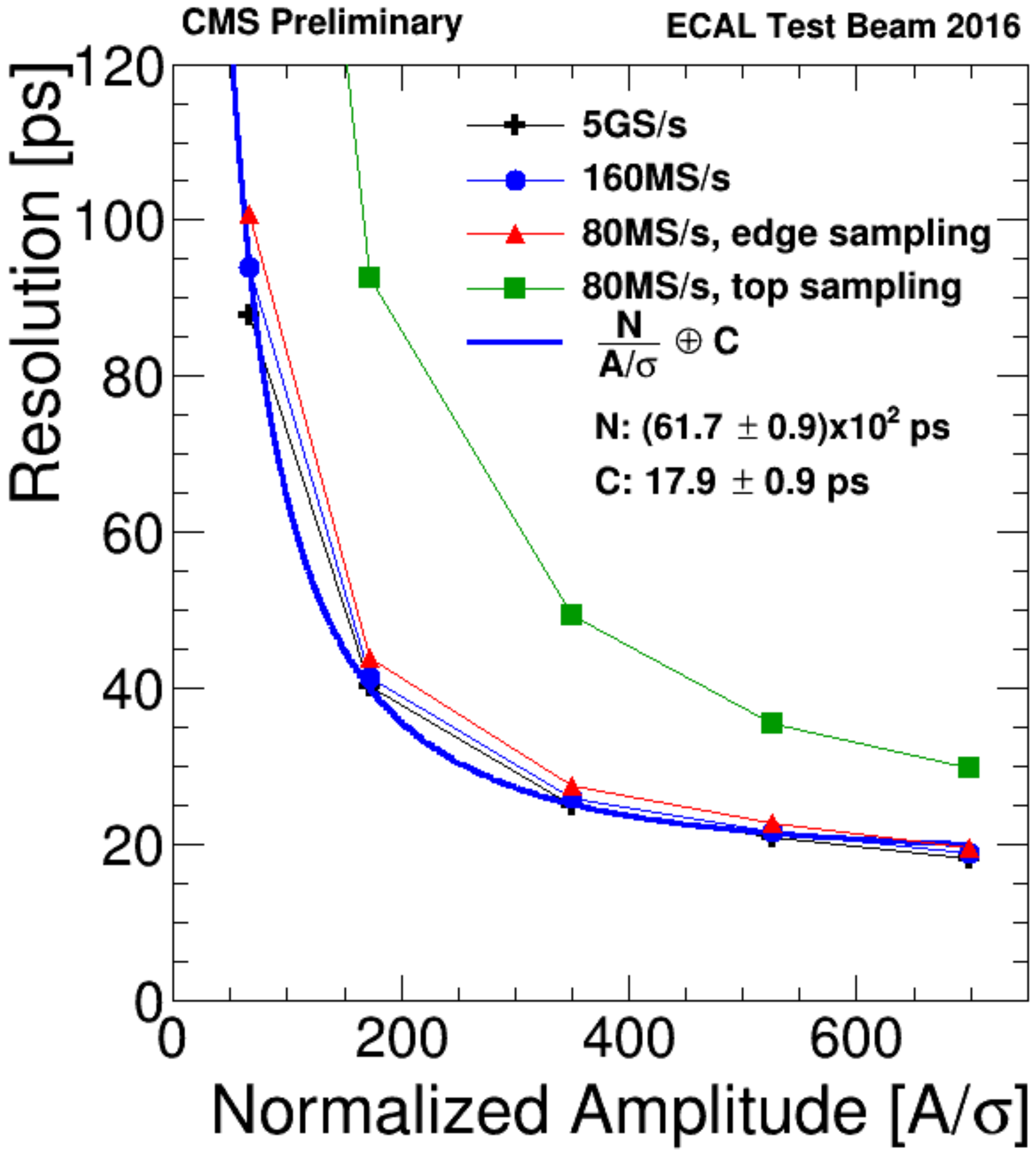
Readout using 2 SiPMs from the front face
resolution dominated by longitudinal shower fluctuations (~80 ps constant term)





TEST BEAM 2016





Prototype VFE with TIA implemented using discrete components

30ps resolution for A/σ = 250

- 25 GeV @ HL-LHC start (100 MeV noise)
- 60 GeV @ HL-LHC end (240 MeV noise)

Optimal performance already with 160 MHz sampling

Test beam with prototype TIA ASIC + integrated ADC in October

Summary

Precision timing will be a powerful tool to reduce pile-up contamination at HL-LHC

Upgraded CMS ECAL will enhance the timing performance to <30ps for $H \rightarrow \gamma\gamma$ photons

Prototypes tested in high energy beams meet specifications. Further tests are on-going

Additional capabilities of charged + neutrals timing @ HL-LHC with CMS are being investigated

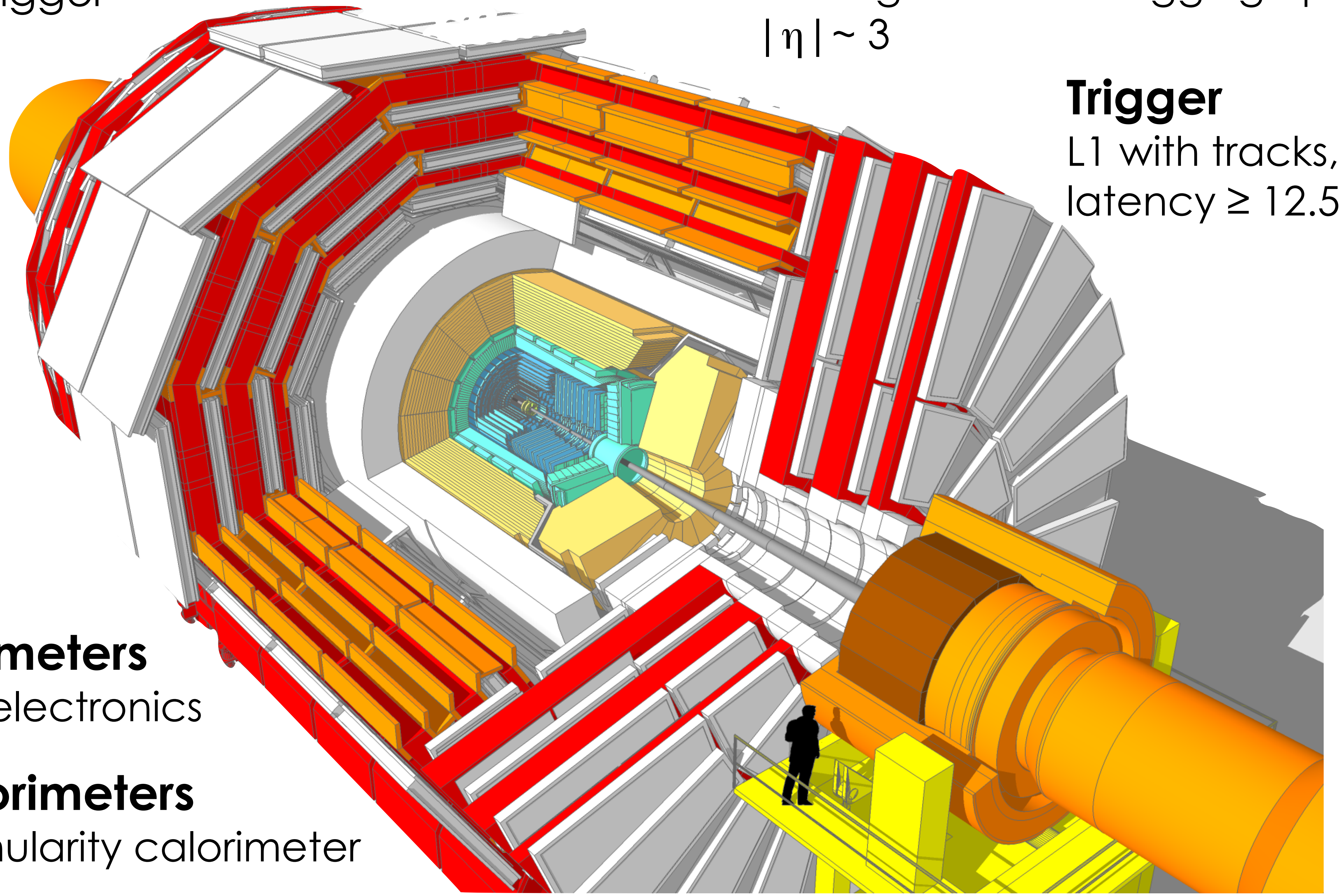
BACK-UP

CMS HL-LHC Upgrade Plan

Tracker
Coverage up to |η| ~ 4
Increased granularity
Tracks in L1 trigger

Muons
Complete coverage in fwd region |η|>1.6 (new GEM/RPC technology)
Investigate muon tagging up to |η| ~ 3

Trigger
L1 with tracks, 750 kHz, latency ≥ 12.5 μs



Barrel calorimeters
New readout electronics

Endcap calorimeters
New high granularity calorimeter