Precision Timing Calorimetry with the upgraded CMS Crystal ECAL

TIPP 2017

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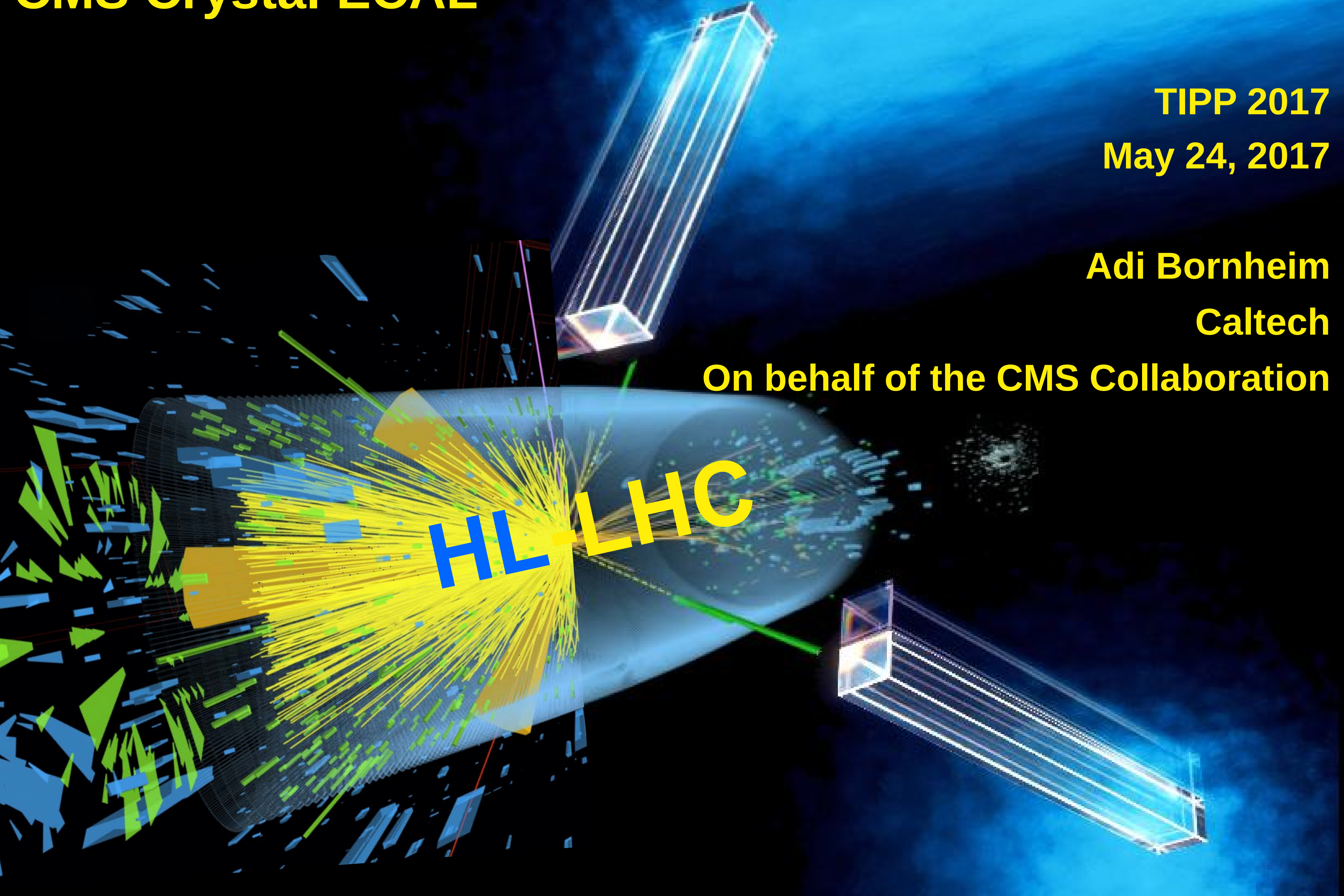
Adi Bornheim

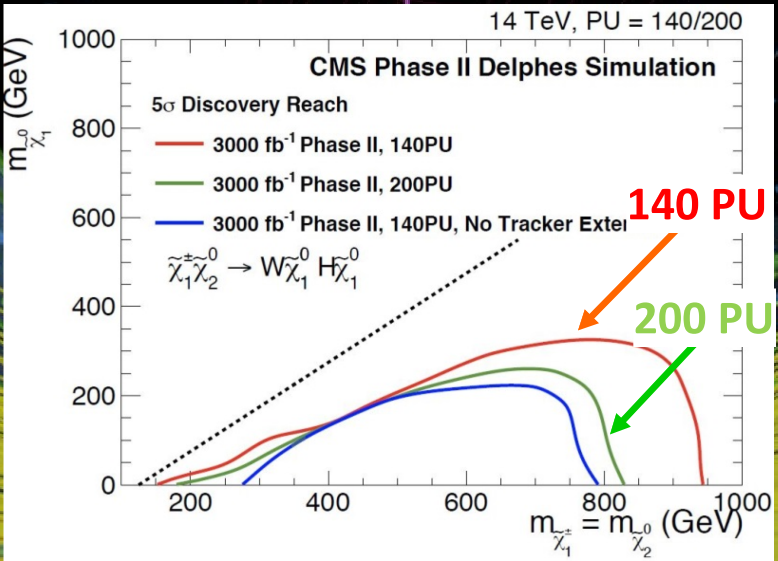
Caltech

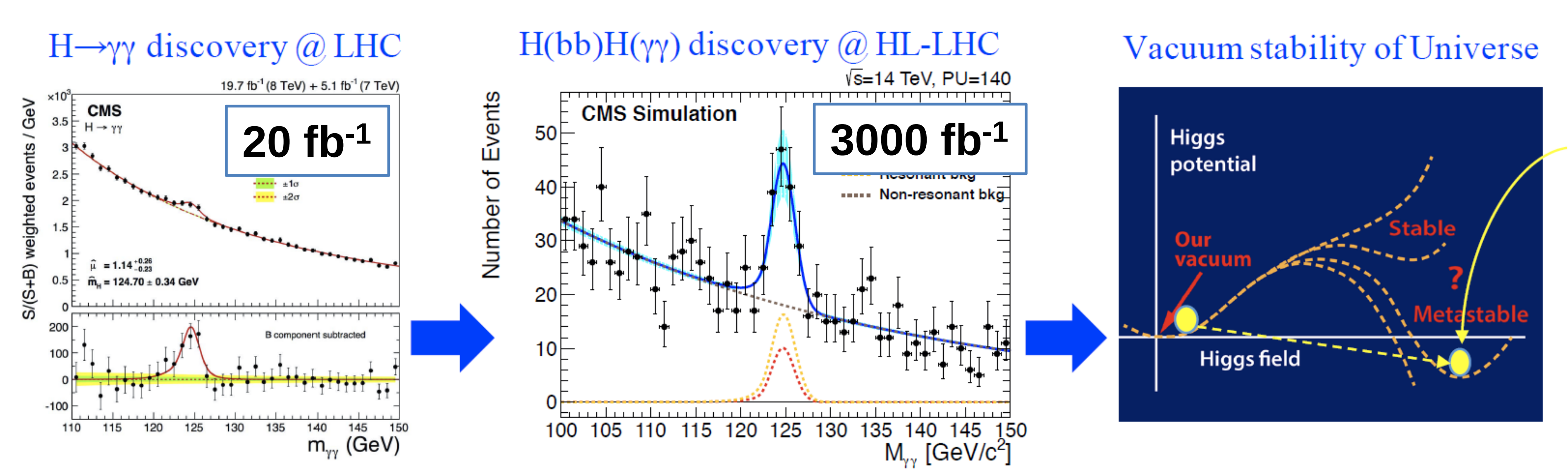
On behalf of the CMS Collaboration



The Challenge of HL-LHC

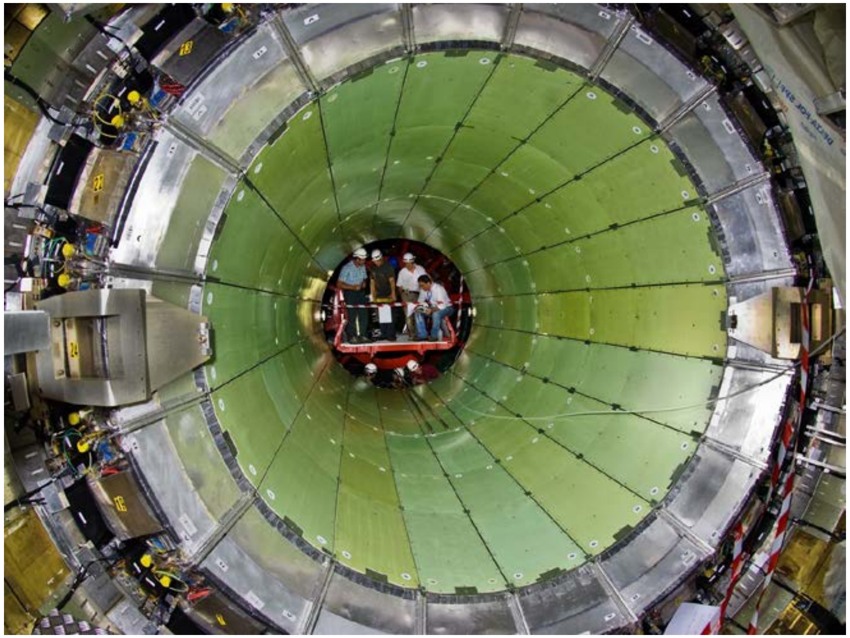
- HL-LHC will accumulate 3 ab^{-1} of p-p collisions to achieve its physics goal.
- This will require operation at 200 collisions per bunch crossing.
- Achieving physics performance very challenging at these PU rates.

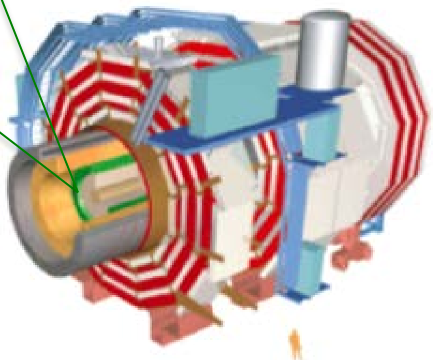




CMS ECAL

- **Homogeneous, compact, hermetic, fine grain $PbWO_4$ crystal calorimeter**
  - **Emphasis on energy resolution**
  - **No longitudinal segmentation**
  - **See presentation by C.-M.Kuo**
- **Barrel (EB) :**
  - **$|\eta| < 1.48$**
  - **36 Super Modules: 61200 crystals**
  - **($2.2 \times 2.2 \times 23$ cm^3) ~$26X_0$**
- **Phase II Upgrade of the ECAL :**
  - **New readout electronics with faster shaping and digitisation, full readout at 40 MHz and accommodating up to ~12 μs trigger latency.**
  - **Lower temperature (8 ^{O}C or less).**
  - **See presentation by P. Barria and poster by F. Meng.**
- **CMS Characteristics:**
  - Tracker coverage: $|\eta| < 2.5$;
  - CMS Magnetic field: B = 3.8 T
  - ECAL fully contained inside the coil

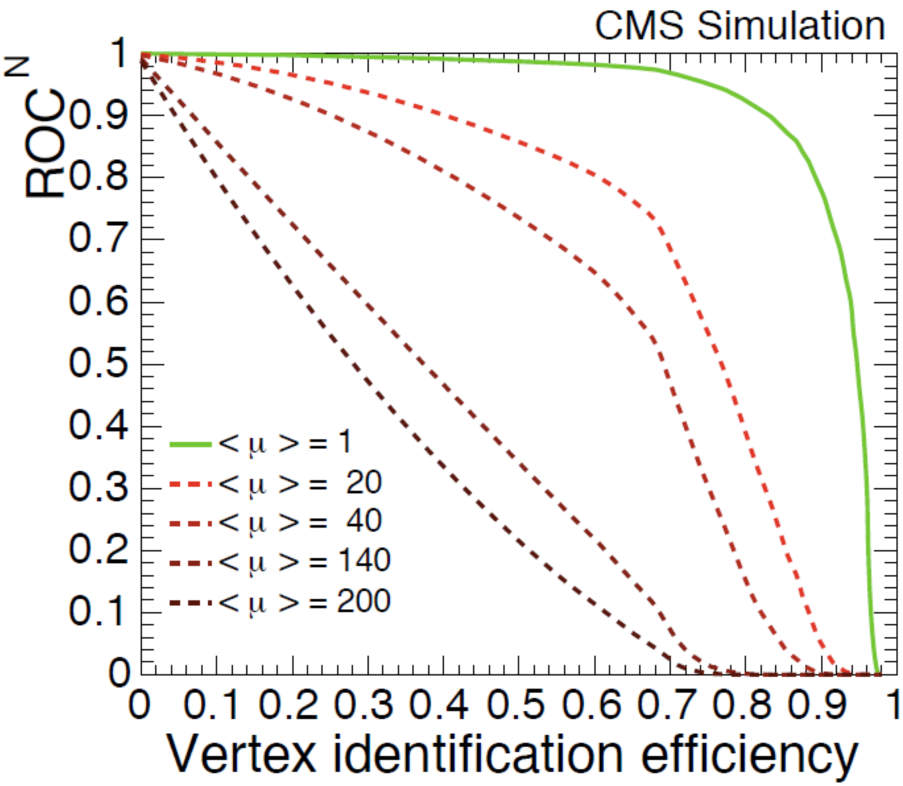




Photon Timing in H→γγ

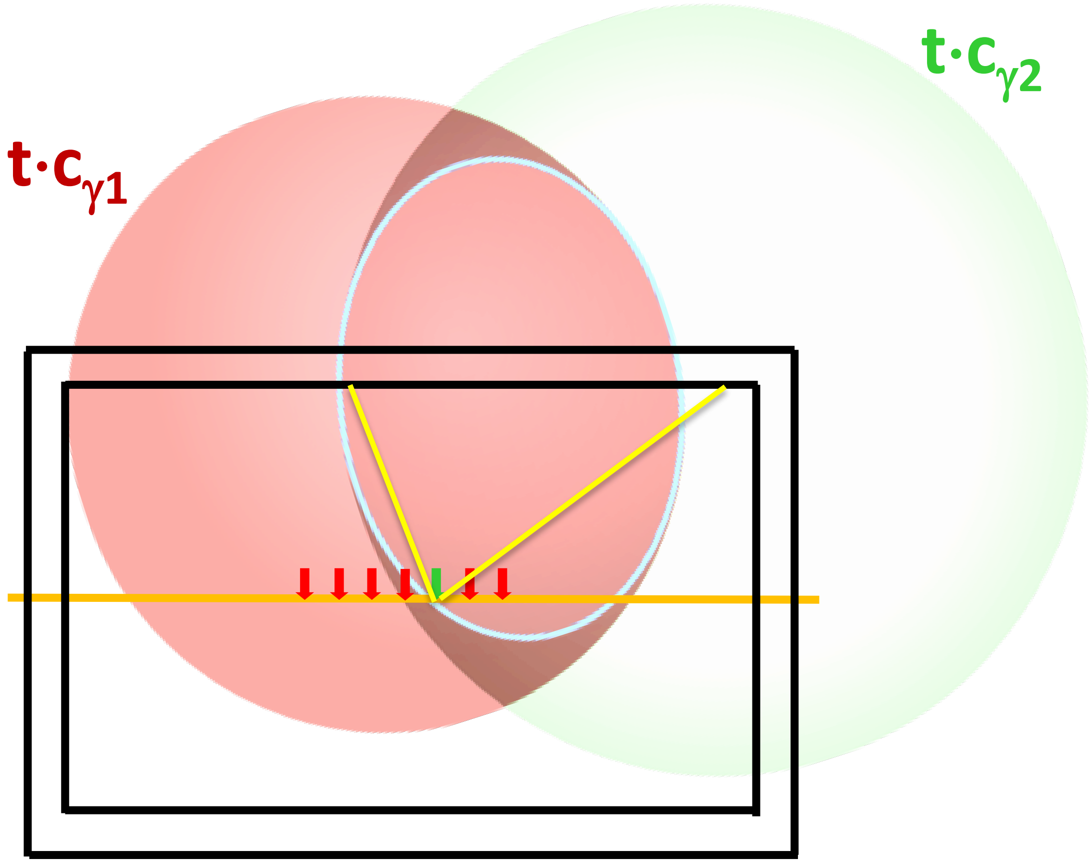
- $H\to\gamma\gamma$ important mode for precision Higgs physics.
- Clean signal with large visible cross section makes it a key driver for measurements of Higgs production and decays dynamics.
- Standard candle for di-Higgs to $bb\gamma\gamma$.

- Vertex ID uses Σp_T to find hard vertex.
- At HL-LHC, many PU vertices with high Σp_T.
- With a timing measurement for two photons, can calculate the z and t location of the vertex.



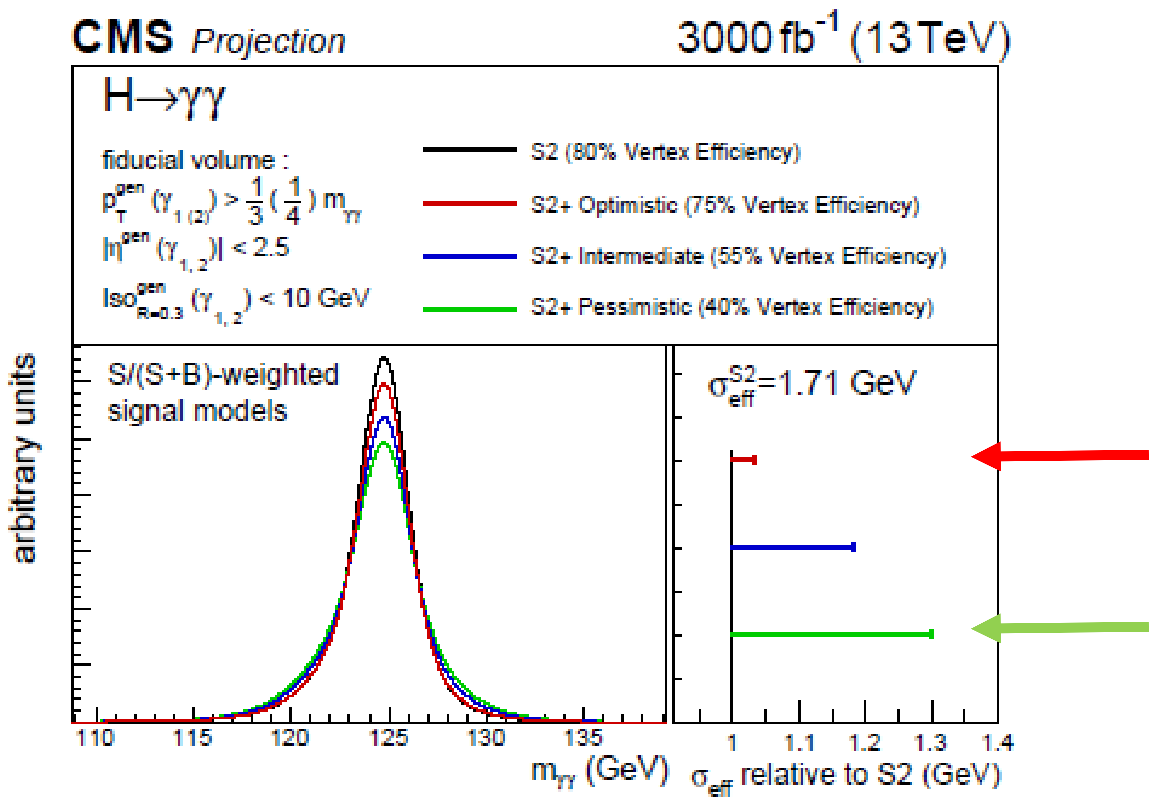
4D Triangulation with Photon Timing

- With two time and position measurements eg. from two photons and with the constraint from the beam axis x and y location, the vertex x and t can be calculated analytically.
- Equivalent to GPS with two satellites.



Physics impact of Photon Vertexing

- **$H \rightarrow \gamma\gamma$ primary vertex selection efficiency reduced from 80% in current LHC data to 40% at 140 PU and even further at 200 PU.**
- **Dramatic reduction of effective mass resolution, equivalent to a loss in effective luminosity for statistically limited measurements.**
- **Precision timing in the ECAL, combined with precision timing tags on tracks, will recover with deterioration almost fully.**



CMS ECAL Upgrade for HL-LHC

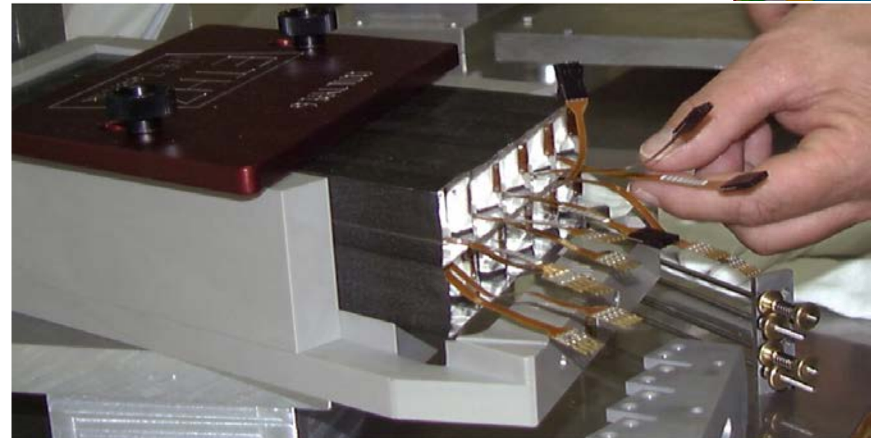
- **$PbWO_4$ crystal matrix, APDs & overall mechanical structure will remain unchanged.**

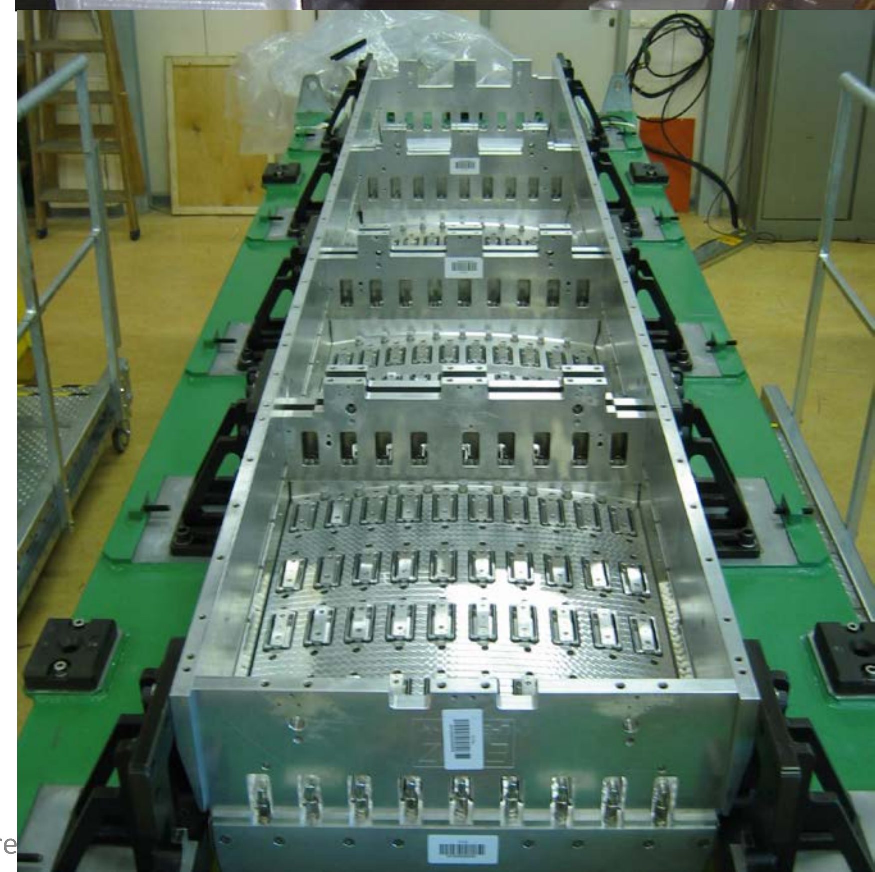
- **The frontend and very frontend electronics readout will be replaced:**
  - **satisfy increased trigger latency requirement (up to 12.5 s), L1 accept rate (750 kHz)**
  - **cope with increased APD dark current, better identification of beam induced APD noise and higher data rates.**

- **APD/cable impose effective bandwidth cutoff at around 35 MHz.**

- **Trans Impedance Amplifier (TIA) based very front end readout ensures optimal exploitation of ECAL timing capabilities.**

- **Talk of P. Barria, poster of F. Meng**



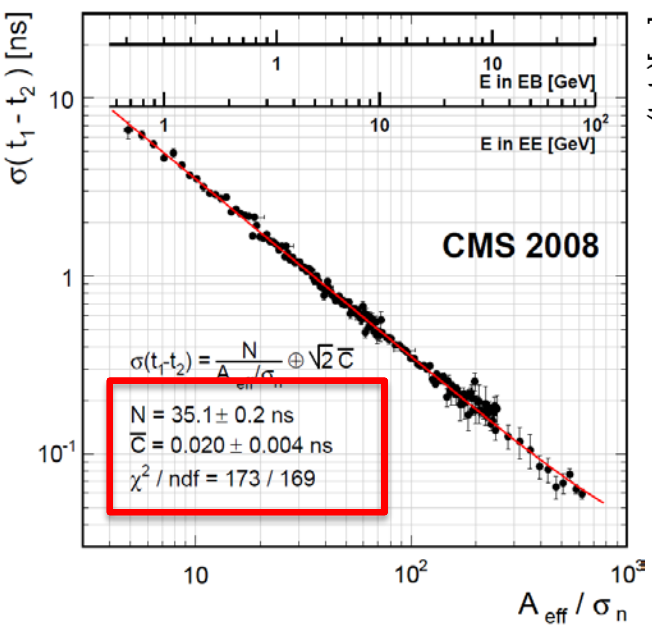


Timing Performance current CMS ECAL

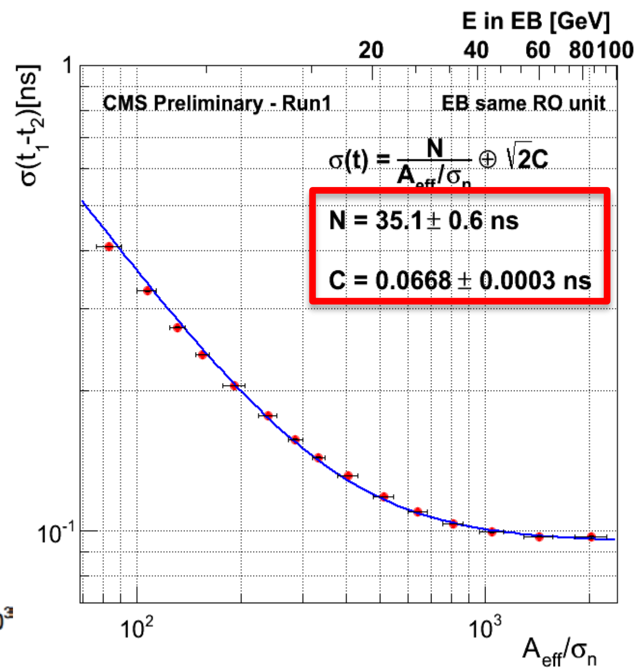
Results from test beams and pp collision data at LHC :

- Electron showers from Z→ee decay Δt_{TOF} : ~270 ps, single channel : ~190 ps, without path length correction : ~380 ps
- Constant term of resolution : ~20 ps in test beam, ~70 ps in situ (same clock).
- Studies on jet timing vertex resolution suggest very promising performance.

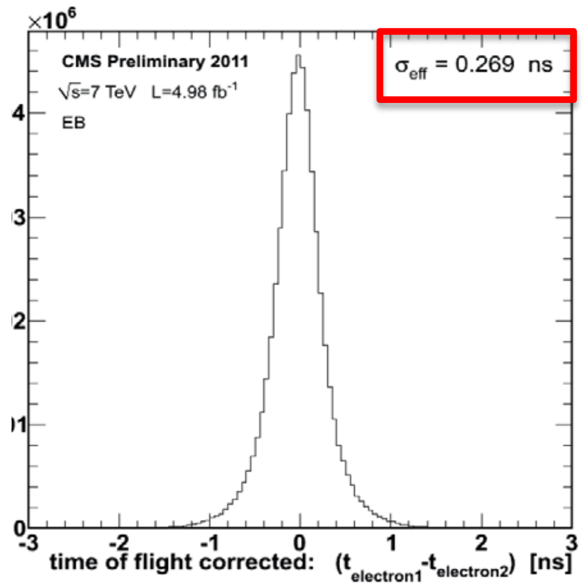
Test Beam



In-situ, cluster



In-situ, Z→ee



Scintillation Light Time Spectrum

- **Timing information is extracted from the leading edge of the signal – the rise time of the light output is important.**
- **Crystal scintillators feature intrinsic signal rise times of few 10 ps. For $PbWO_4$ 60 ps have been measured in a cube of 2x10x10 mm^3 .**
- **S. E. Derenzo, M. J. Weber, W. W. Moses and C. Dujardin. "Measurements of the intrinsic rise times of common inorganic scintillators." IEEE TNS, 47:860-864, 2000.**

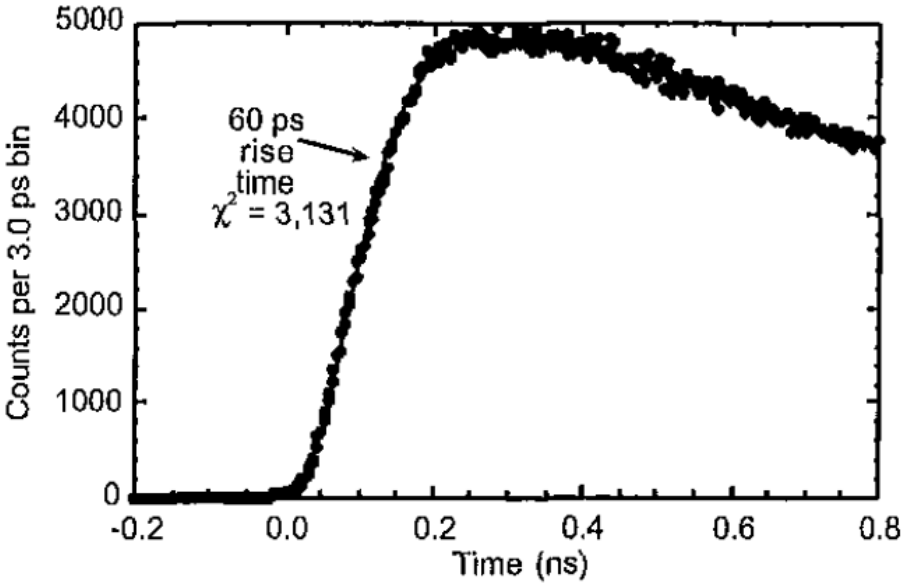
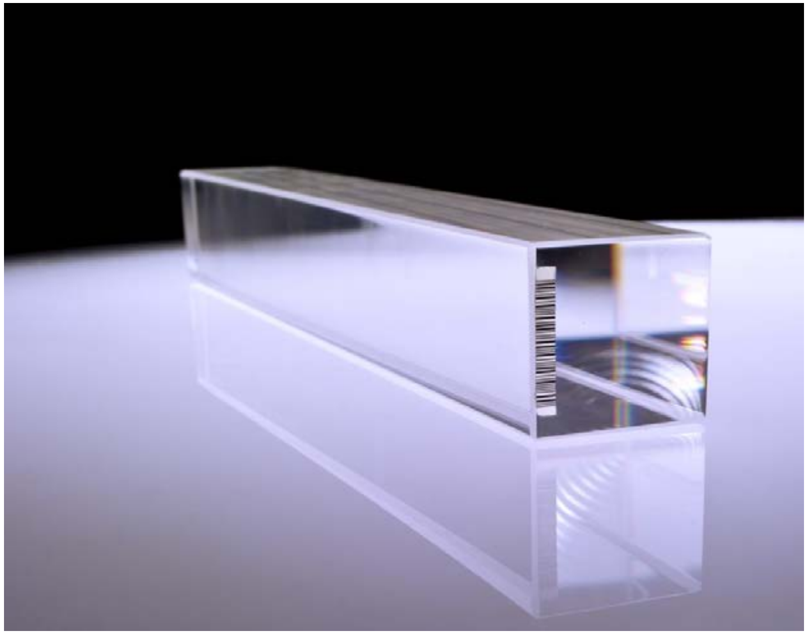
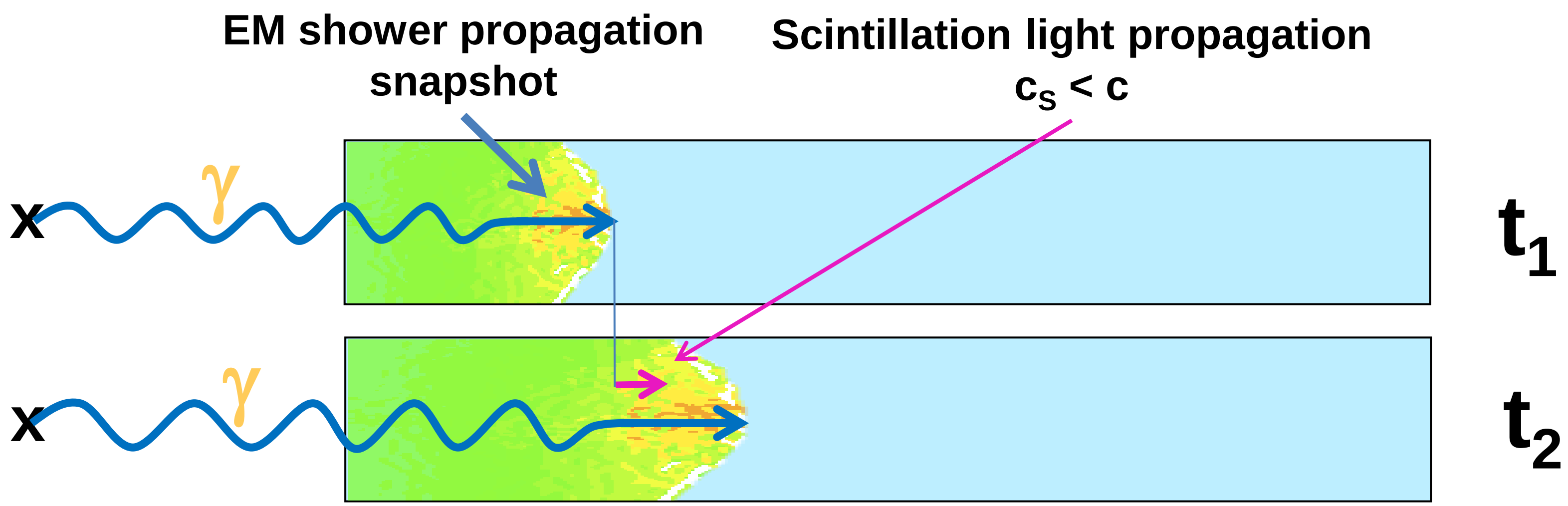


Figure 7: $PbWO_4$ 2 x 10 x 10-mm painted black on five sides. Best fit rise time is 60 ps.

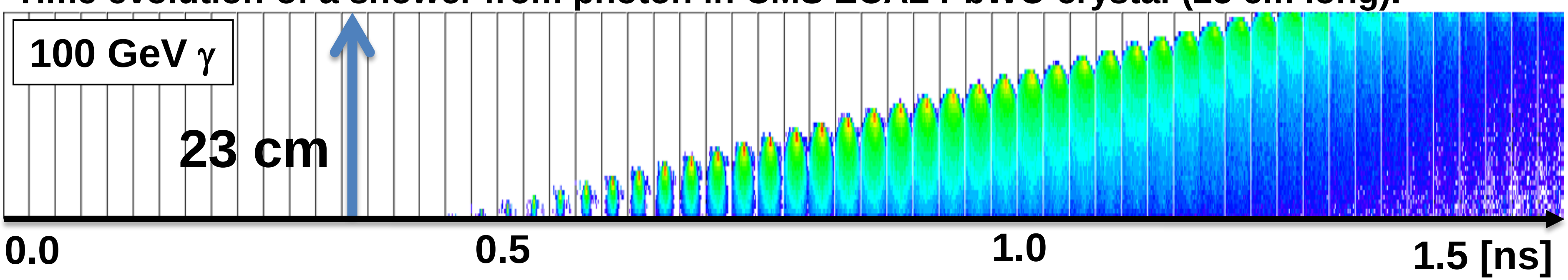


Optical Transit Time Spread

- Scintillation light propagation through the crystal takes time and causes dispersion of the pulse shape.



Time evolution of a shower from photon in CMS ECAL PbWO crystal (25 cm long).



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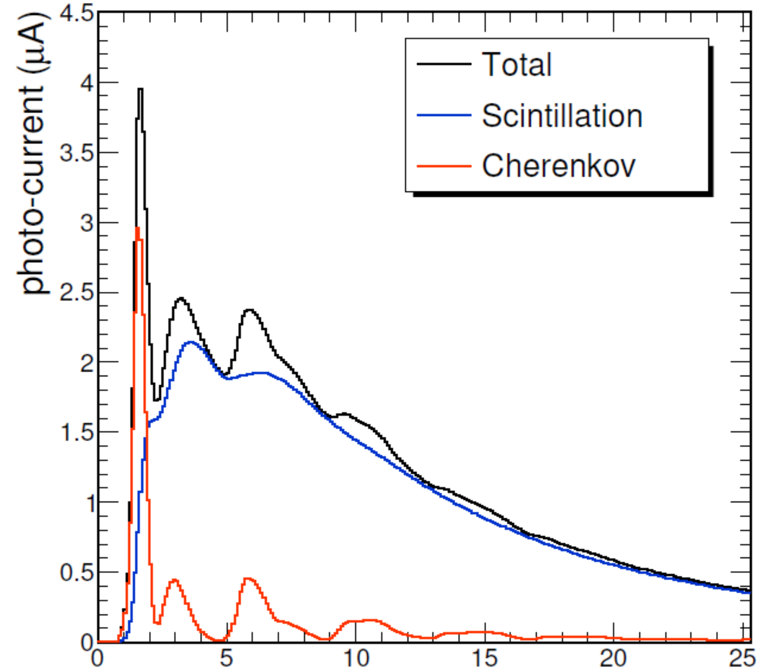
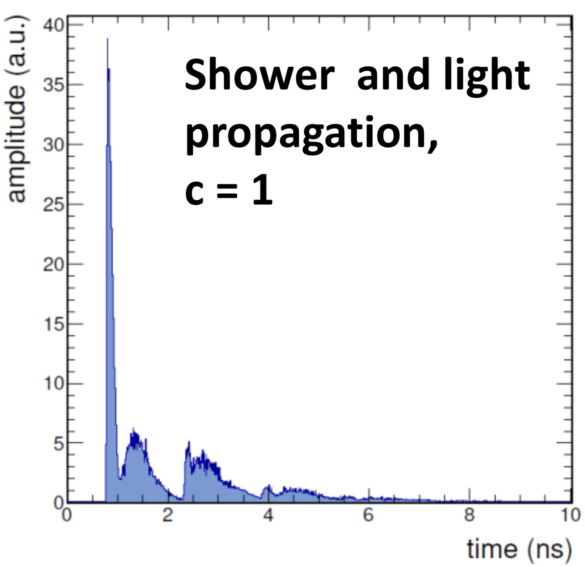
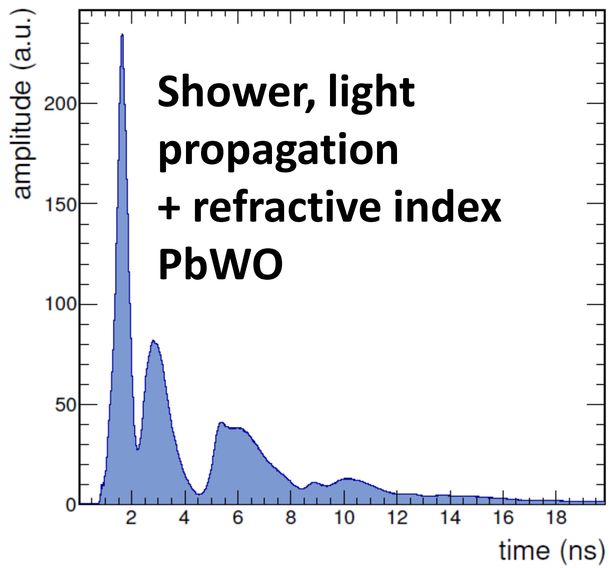
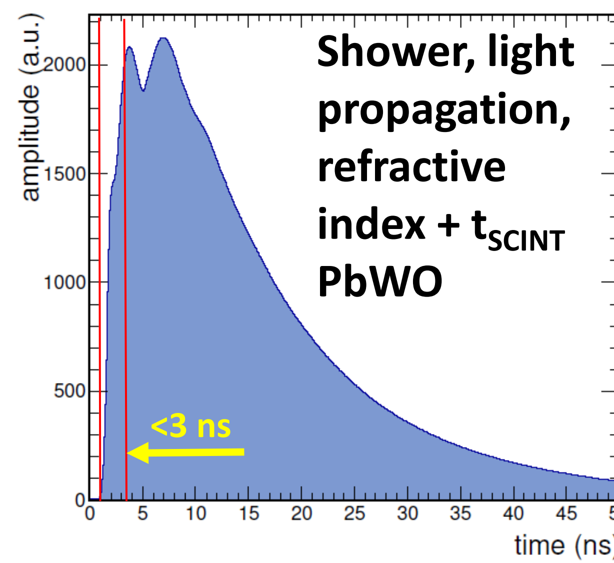
CMS $PbWO_4$ Light Timing Structure

- CMS ECAL MC studies for Phase II upgrade.
- Light extraction at one end of the crystal.
- Precise understanding of the pulse shape needed to optimize readout electronics.
- APD/cable impedance will be the limiting factor.



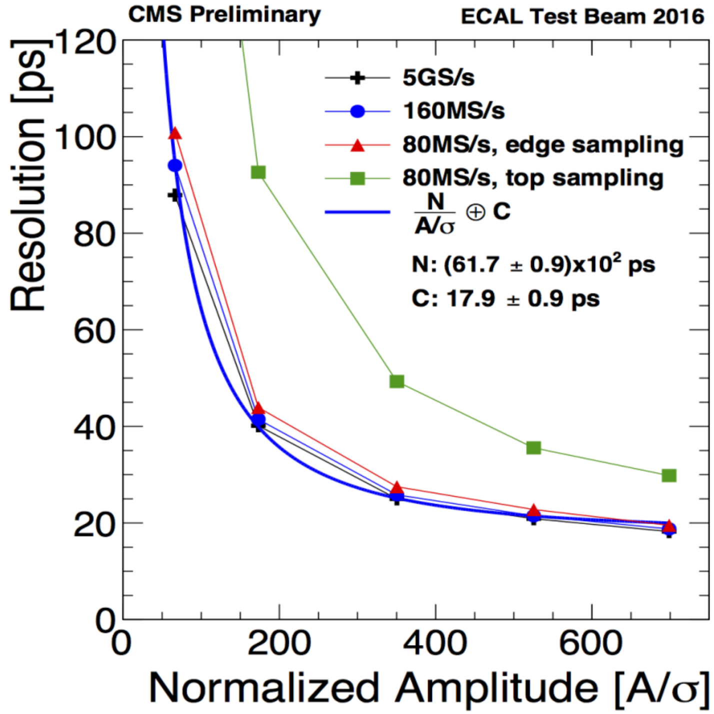






Test Beam Results

- CMS ECAL crystal matrix with TIA prototype, digitized at 5 GHz.
- Offline reduction of sampling rate to explore minimal digitization rate satisfying our specs. Baseline design now assumes 160 MHz.
- Timing extracted from template fit to the pulse shape similar to the pulse reconstruction in CMS.
- Micro-Channel-Plate sensor as timing reference for the incoming beam particle.



- Initial results on this prototype meet design specs.
- 30 ps resolution @ A/σ = 250.
  - Equivalent to 25 GeV photons (@100 MeV noise, HL-LHC start),
  - 60 GeV (@240 MeV noise, HL-LHC end)
- Test with advanced prototype with integrated ADC in June 2017.

Summary

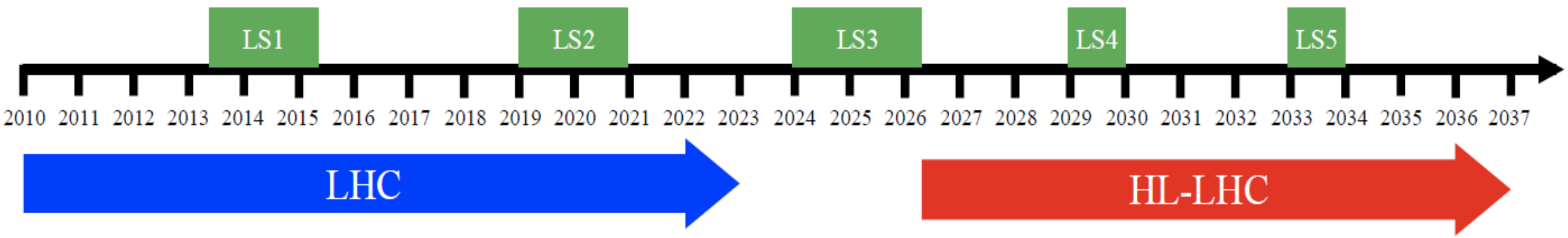
- **CMS ECAL Phase II upgrade will enhance the timing performance of the detector to about 30 ps for photons from Higgs decays.**

- **Prototypes of readout tested in high energy beams meet the design goals.**

- **Additional precision timing capability enhancements of CMS detector being investigated.**

Backup

HL-LHC Schedule



LHC

$E = 7\text{-}14$ TeV

$L = 1 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

<PU> ~ 40-60

$\geq 50\ \mathrm{fb}^{-1}$ per year

$300\text{-}500\ \mathrm{fb}^{-1}$ total

HL-LHC

$E = 14$ TeV

$L = 5 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

<PU> ~ 140

$250\ \mathrm{fb}^{-1}$ per year

$3000\ \mathrm{fb}^{-1}$ total