Precision Timing Calorimetry for High Energy Physics

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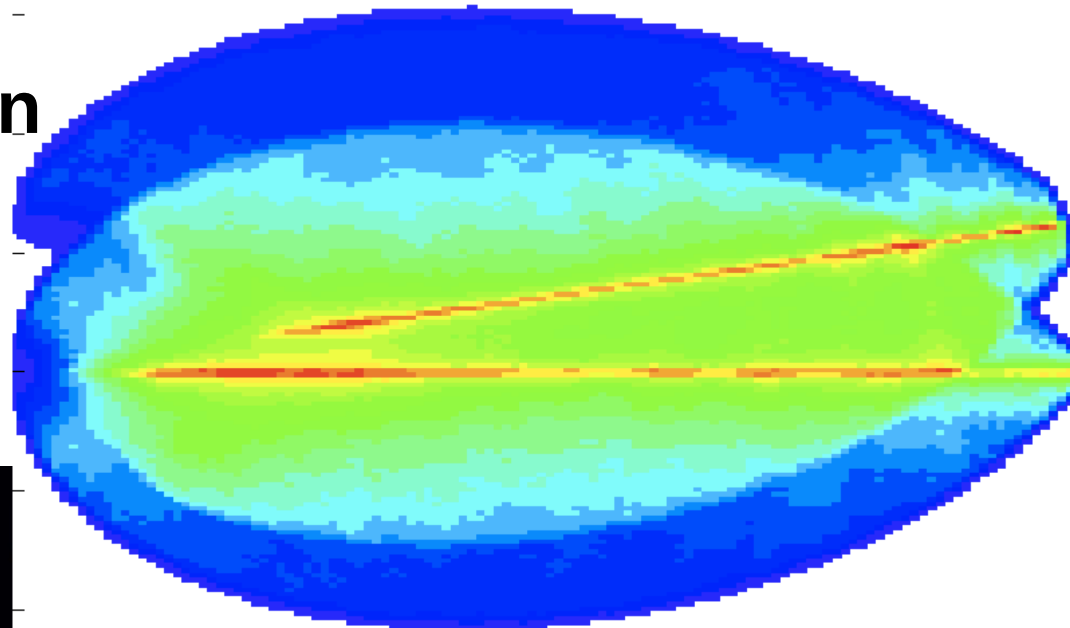
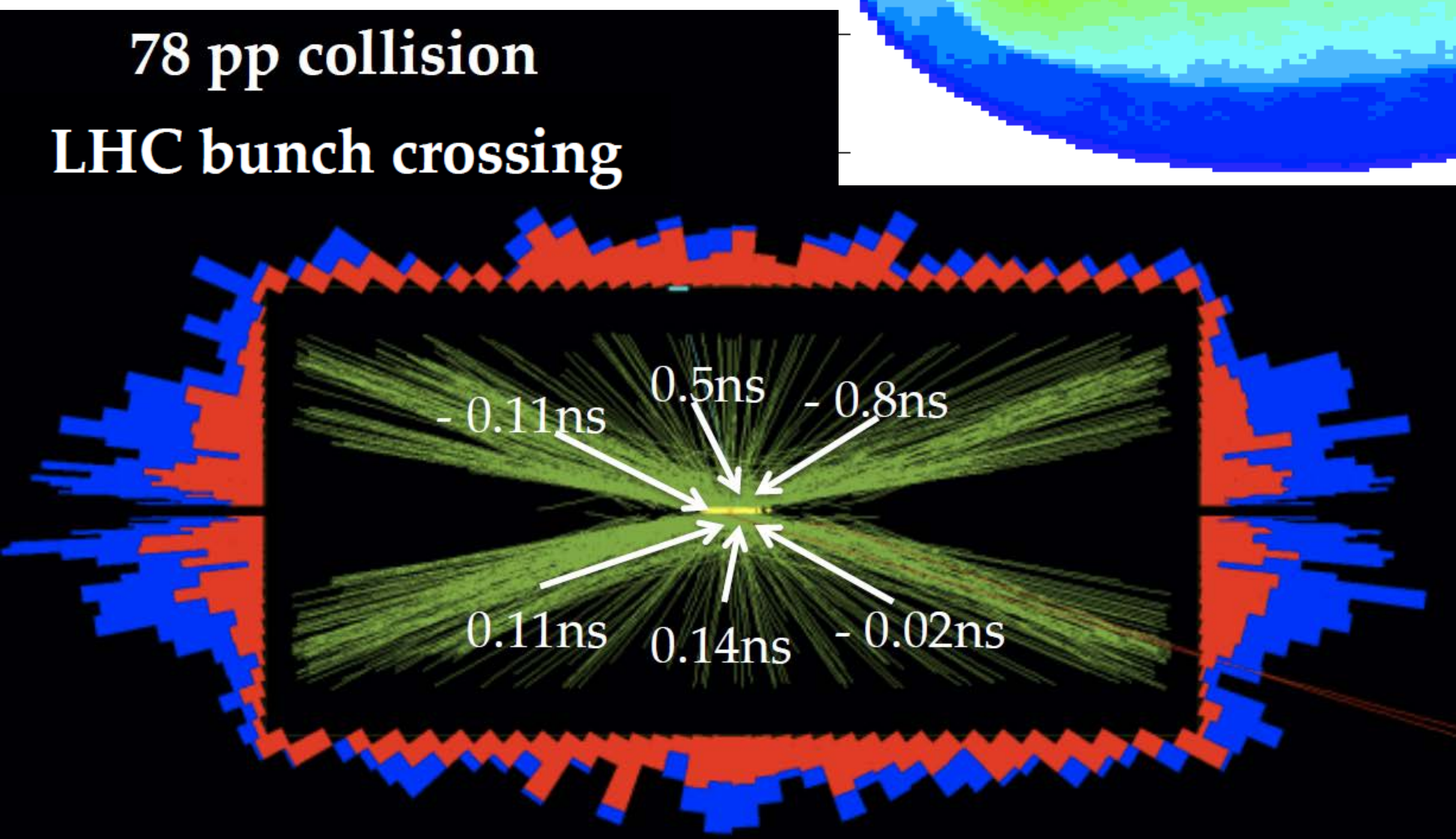
Precision Timing Calorimetry

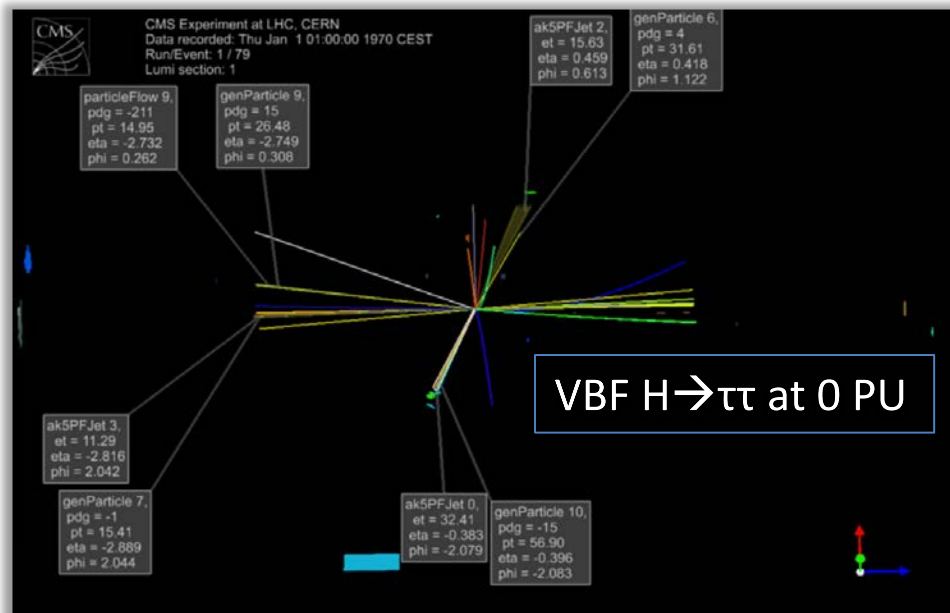
4D event reconstruction opens new territory in difficult experimental environments.

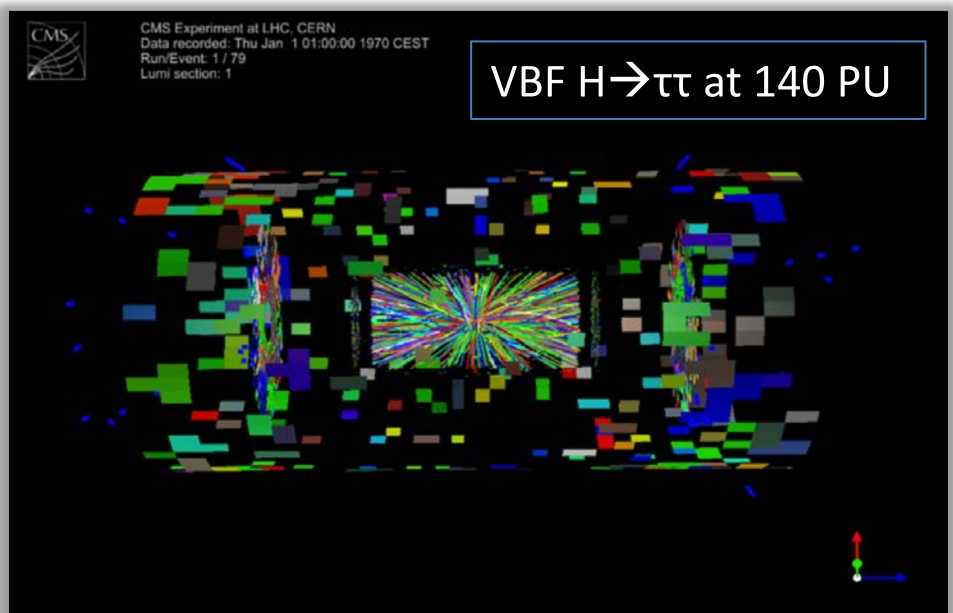




Challenges at HL-LHC

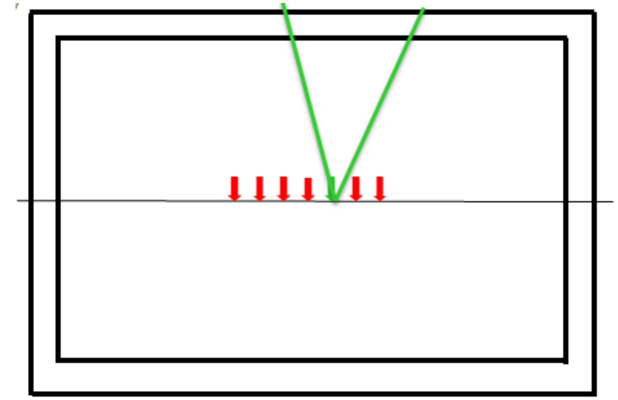
- Large samples needed to fully exploit LHC, goal : collect x10 more
  - <PU> ≈ 140 at HL-LHC ➔ 50nb/sec , collect 3000 fb^{-1}
- Some key signatures at HL-LHC
  - Higgs VBF and $W_L W_L$ scattering with forward jets, vertex identification for H→γγ
  - Searches in final states with MET from LSP
  - Precision studies of new physics which may be discovered at LHC

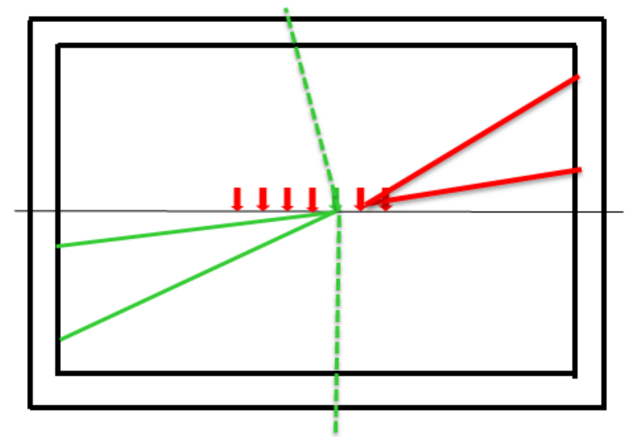


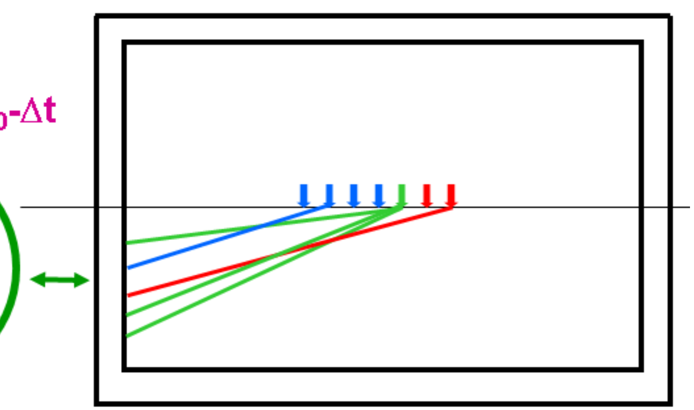


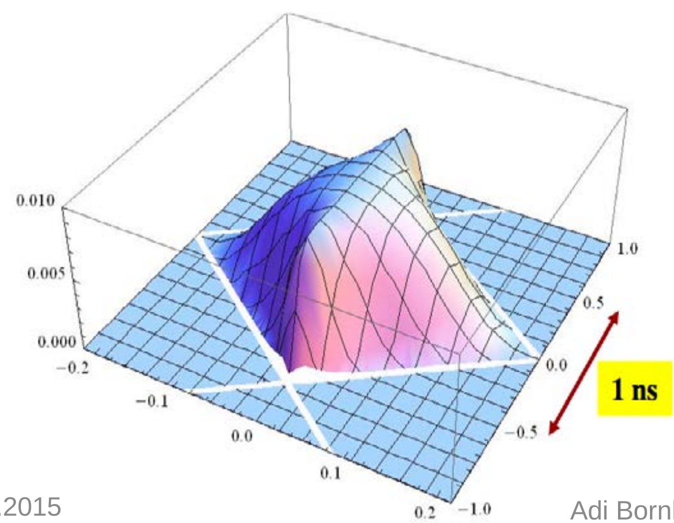
Precision timing at HL-LHC

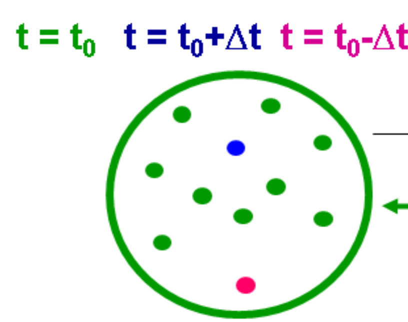
- **Target resolution of O (20-30 psec)**
  - **Allows reconstruction of H→γγ vertex and ~x10 pileup suppression**
- **Applications of timing information:**
  - ***Object level* : (e.g. identify forward PU jets for VBF Higgs, WW scattering)**
  - ***Hit level* : (e.g. timing-based cluster cleaning)**
  - ***Event level* (hard scatter vertex reconstruction, e.g. for H→γγ)**
  - **Separate spatially overlapping vertices that originate at different times**





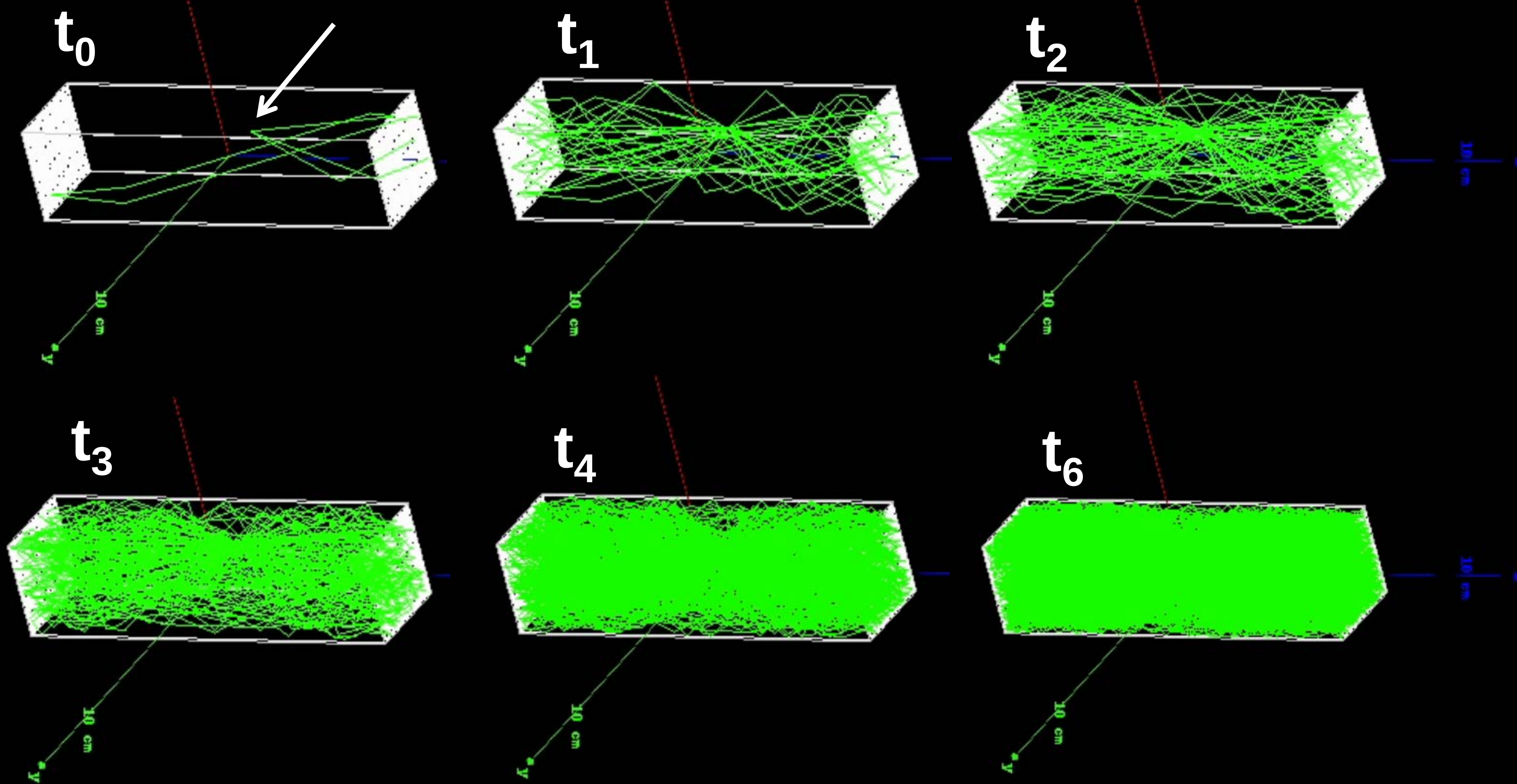






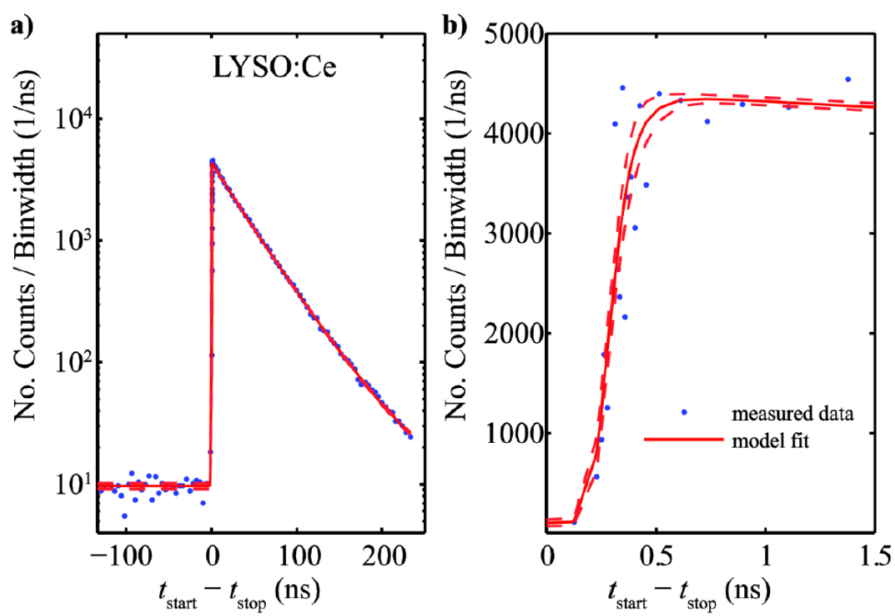
Photon Traces in LYSO Crystal

- For high energy showers in high light yield crystals, number of scintillation light yield is very large (>10^5 / GeV).
- Photon detection at one location in the crystal will be an averaged transit time spectrum



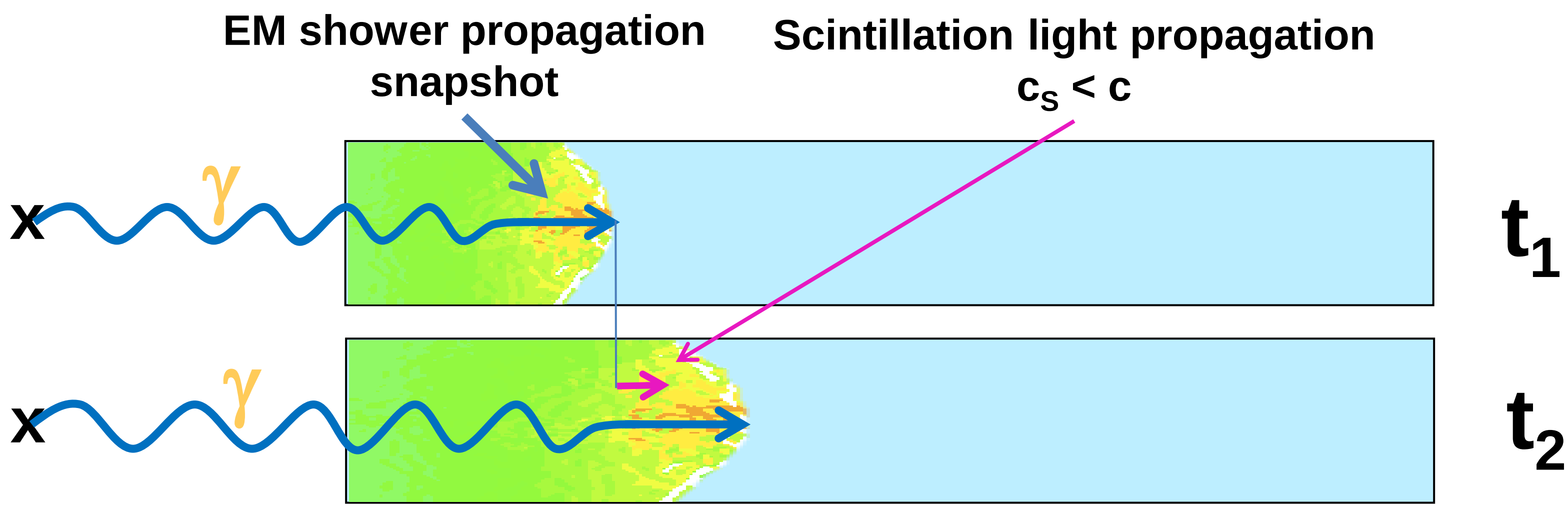
Scintillation Light Time Spectrum

- Scintillating crystals get often classified in fast and slow by their light output decay constants. This is often 10s of ns – PWO, LYSO : ~40 ns.
- Timing information is extracted from the leading edge of the signal – the rise time of the light output is important.
- LYSO scintillation light properties :
  - Light output rise time t_R < 75 ps, 35000 photons/MeV, t_D = 33 ns.
  - See : S Seifert, J H L Steenbergen, H T van Dam and D R Schaart, 2012 *JINST* 7 P09004. doi:10.1088/1748-0221/7/09/P09004

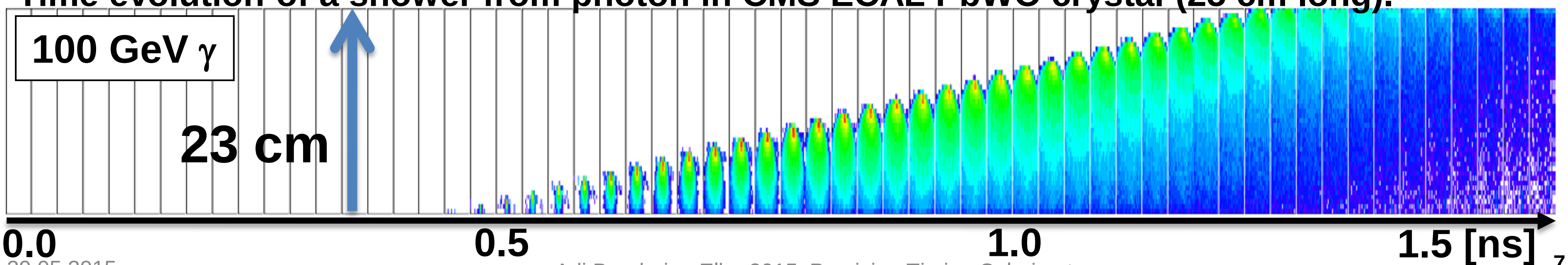


Optical Transit Time Spread

- Effect of the scintillation photon arrival at the photo detector we refer to as Optical Transit Time Spread.
- Experimental program to explore ultimate timing resolution, in particular the impact of the optical transit time spread.

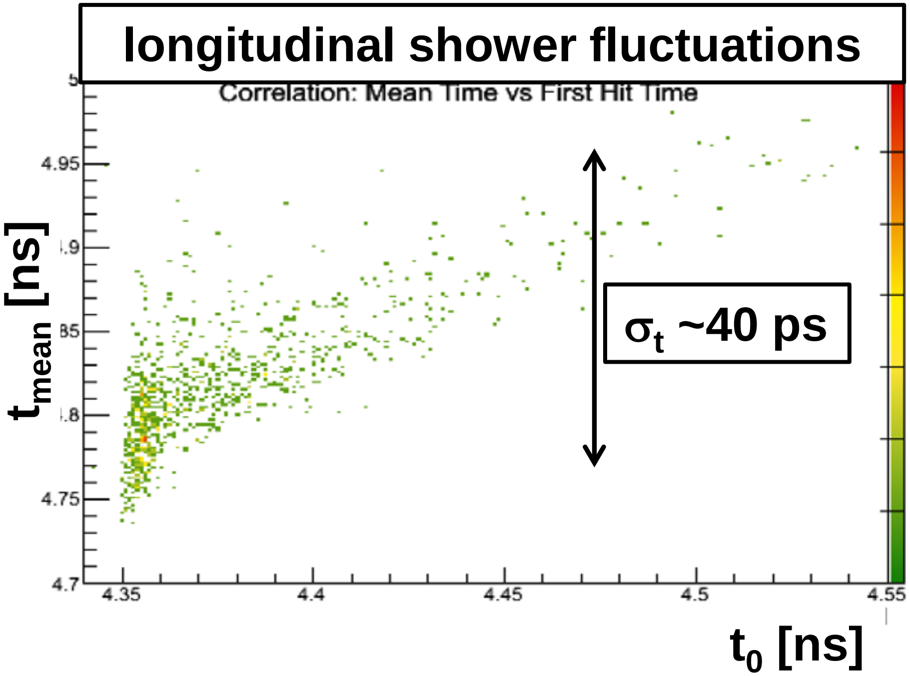


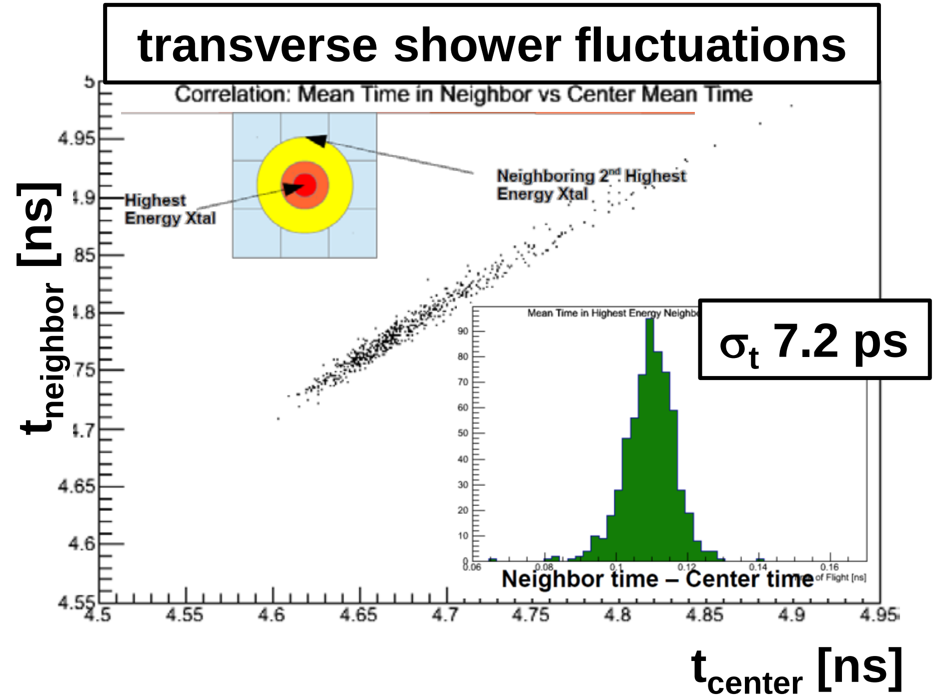
Time evolution of a shower from photon in CMS ECAL PbWO crystal (25 cm long).



Shower Fluctuations

- Utilizing the precise time of arrival requires association with a precise spatial information.
- Shower depth fluctuation may get partly compensated by light propagation to the photo detector.
- Shower fluctuations – in particular conversion depth for photons – need to be considered, relevant dimensions R_M and X_0 are order cm (30 ps).
- Shown here : GEANT hit time spectrum in a solid PbWO crystal matrix, 100 GeV photons.

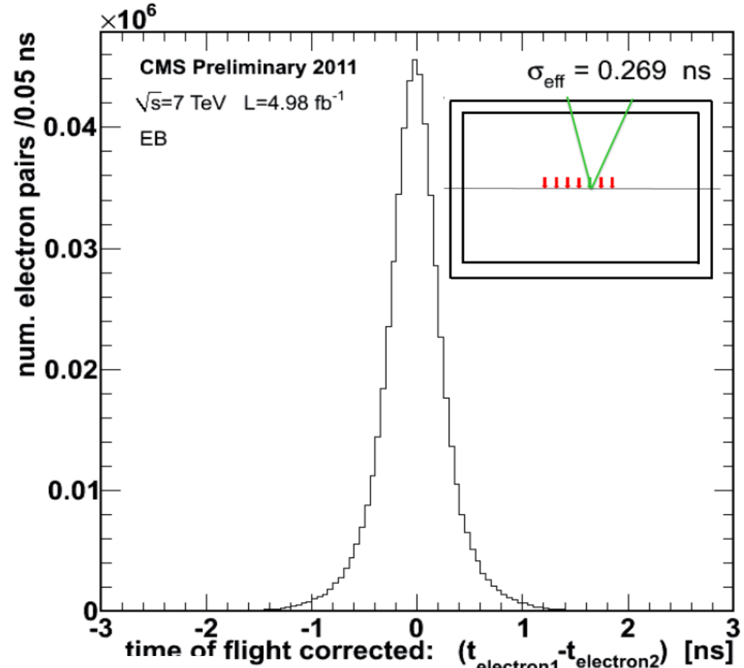


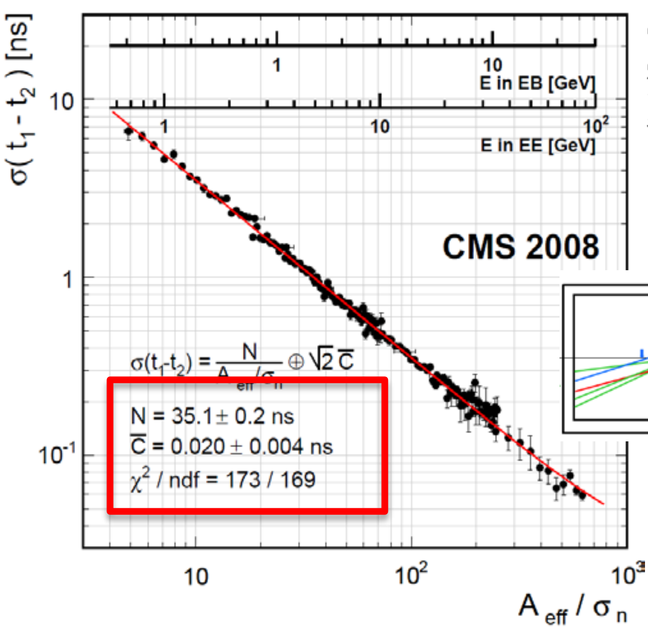


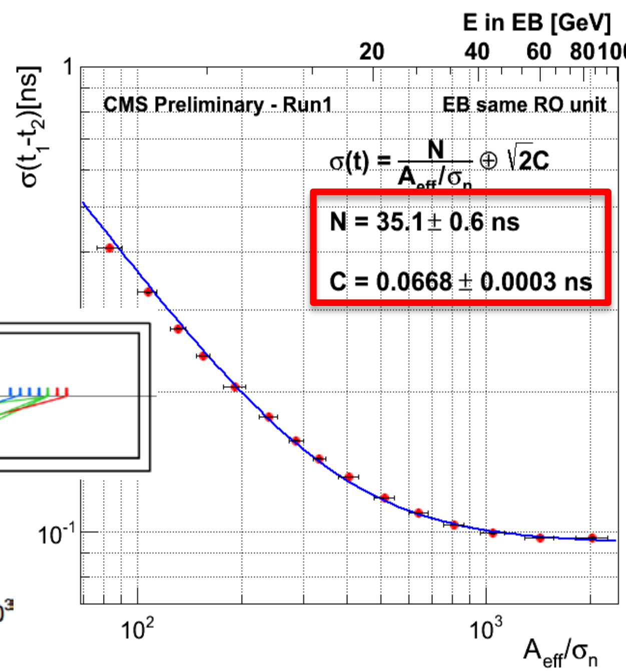
Timing Performance of CMS ECAL

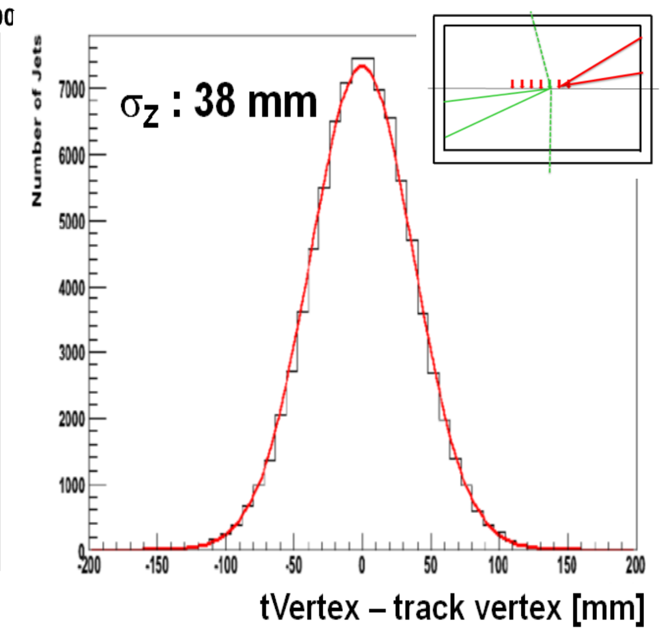
Large PbWO crystal calorimeter.
Results from pp collision data at LHC :

- **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.**



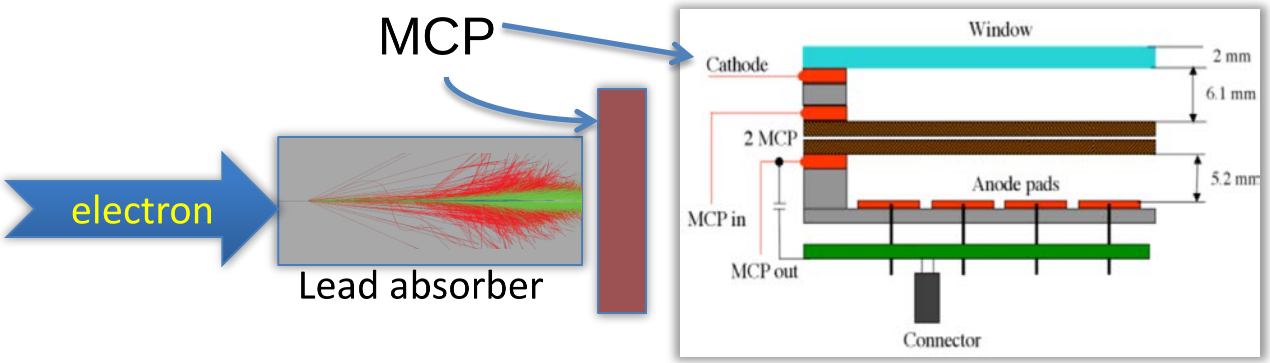


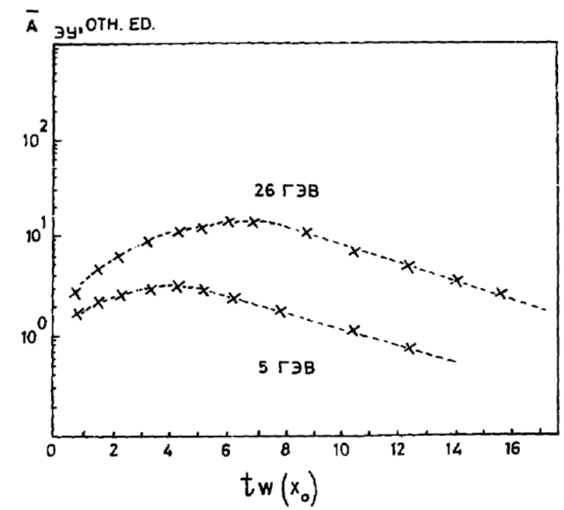




Fast timing with Microchannel Plates

- Starting point in exploring precision timing in calorimeters
  - Secondary emitter material as active element in a sandwich type calorimeter
  - First proposed: "*On possibility to make a new type of calorimeter: radiation resistant and fast*", A. I. Ronzhin et. al, preprint IFVE 90-99, 1990.

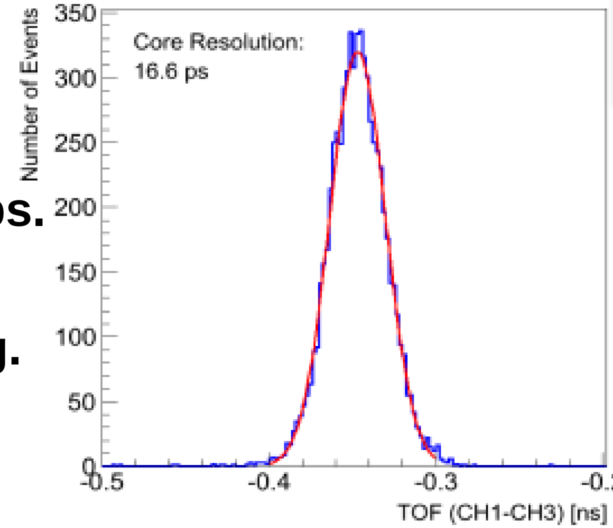




- Secondary particles from EM shower are detected by MCP
  - Signal is proportional to the number of secondaries → energy of parent
  - Most of secondary particles are low energy → MCP very efficient
  - MCP are intrinsically very fast → calorimeter with very fast timing

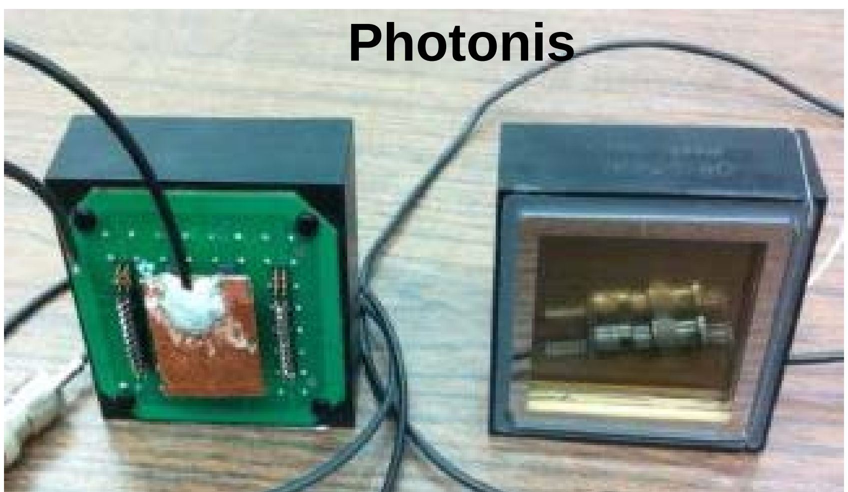
Photek 240 and Photonis MCP-PMT

- **TOF time resolution for protons between two MCPs (Photonis vs Photek) found to be ~17 ps.**
- **MCPs in SEC mode better than 40 ps.**
- **Includes 5 ps from readout (DRS4).**
- **MCPs serve as our reference timing.**



DRS4 boards
5 GSPS, 700 MHz

A. Ronzhin et. al. NIM A, Vol 749 p 65-73



25 μm pore size, 60x60mm^2 sensitive area, rise time~300 ps, SPTR~120 ps,

10 μm pore size, 41mm aperture, PC-MCP distance ~5mm, rise time~60 ps, SPTR~40 ps

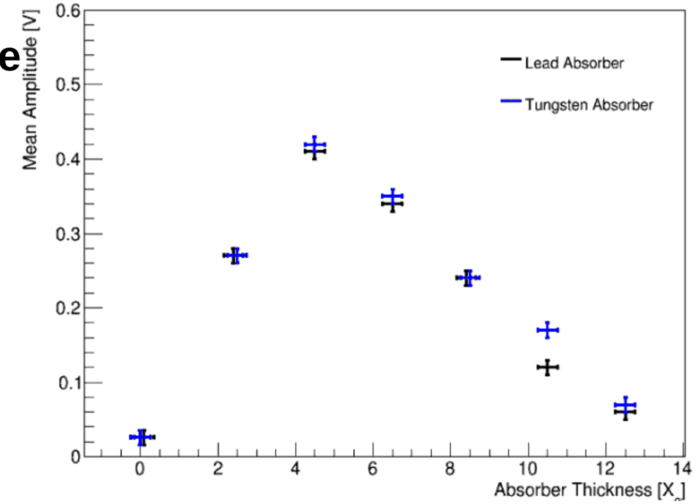
From single MIP to full showers with MCPs

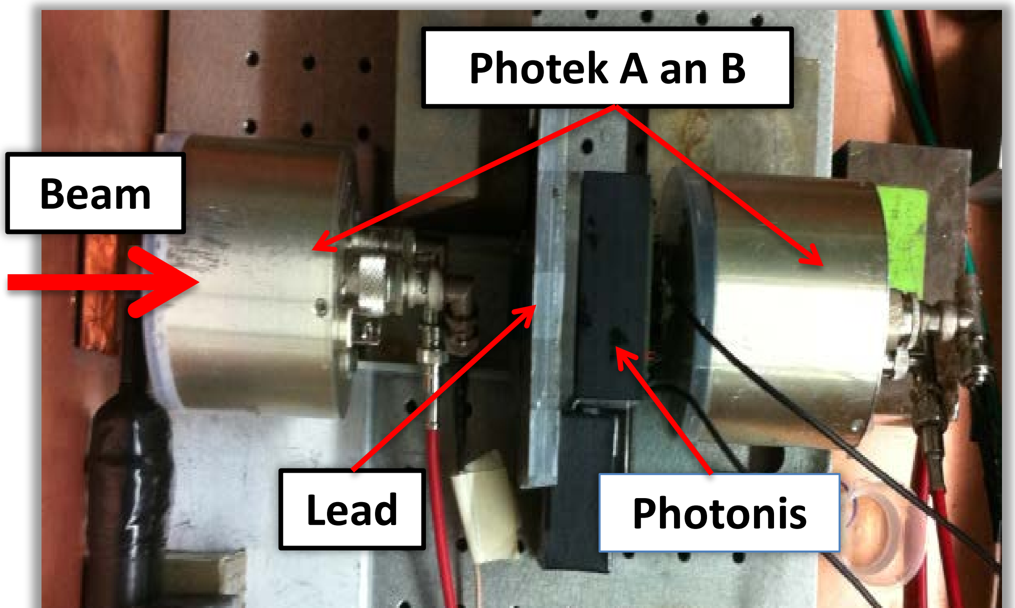
See poster presentation :

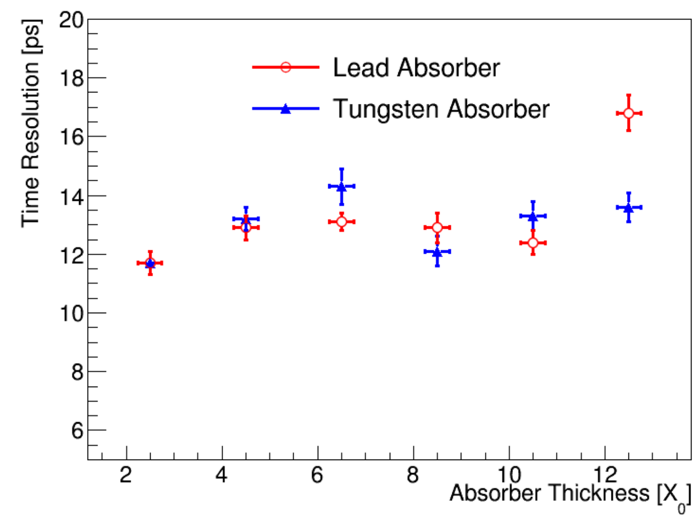
Fermilab: Sergey Los, Erik Ramberg, Erik Ramberg, CalTech: Artur Apresyan, Si Xie, Maria Spiropulu, U. Of Chicago: Heejong Kim

And forthcoming NIM paper (submitted) from the same authors.

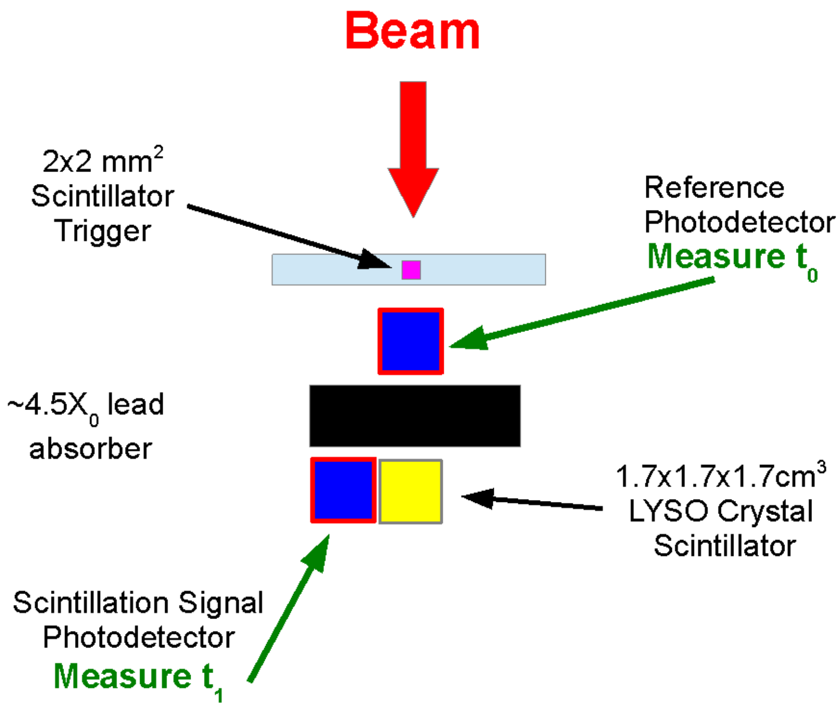
- **Measurements of shower profile with MCPs as active layer.**
- **Time resolution as a function of the shower depth : ~13 ps with Photek, <40 ps with Photonis.**
- **Time resolution among different transverse regions inside a shower : ~30 ps with Photonis**
- **To appear in NIM.**

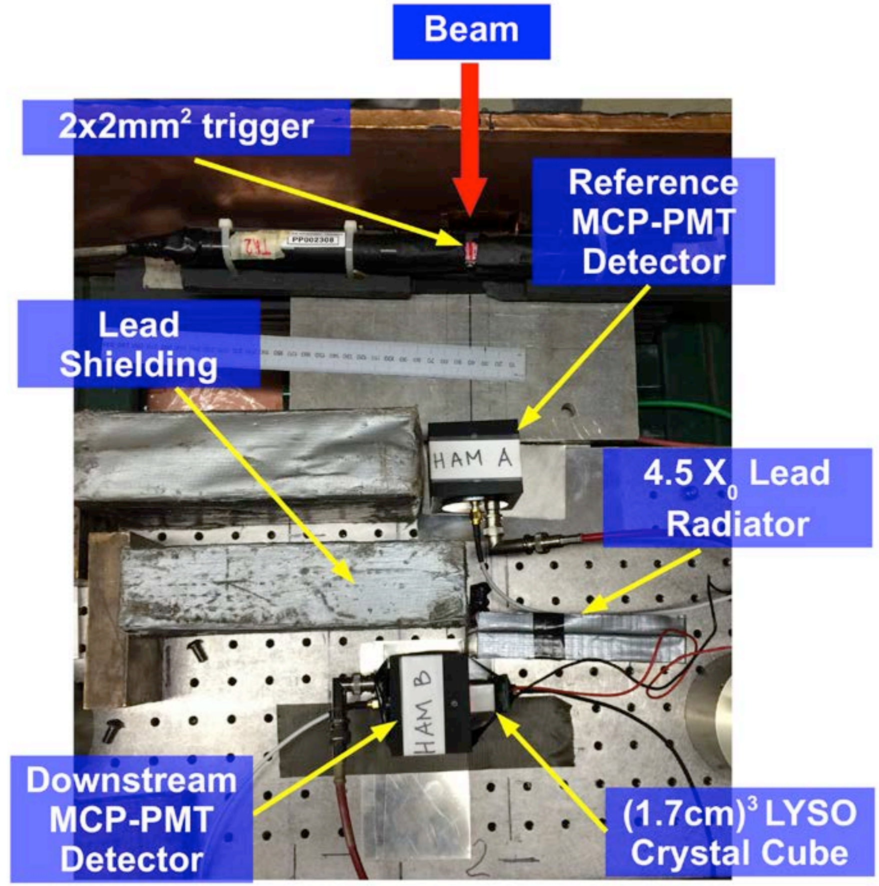






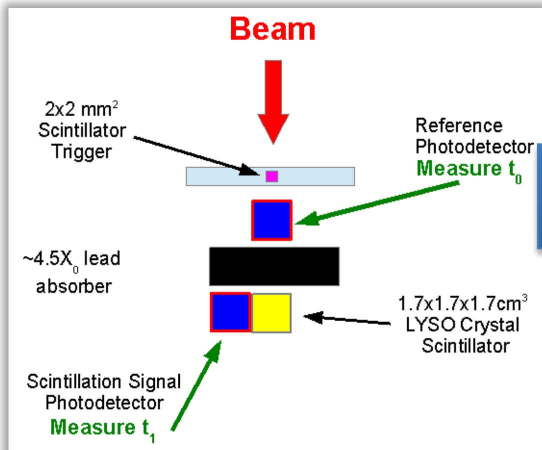
Experimental setup LYSO timing



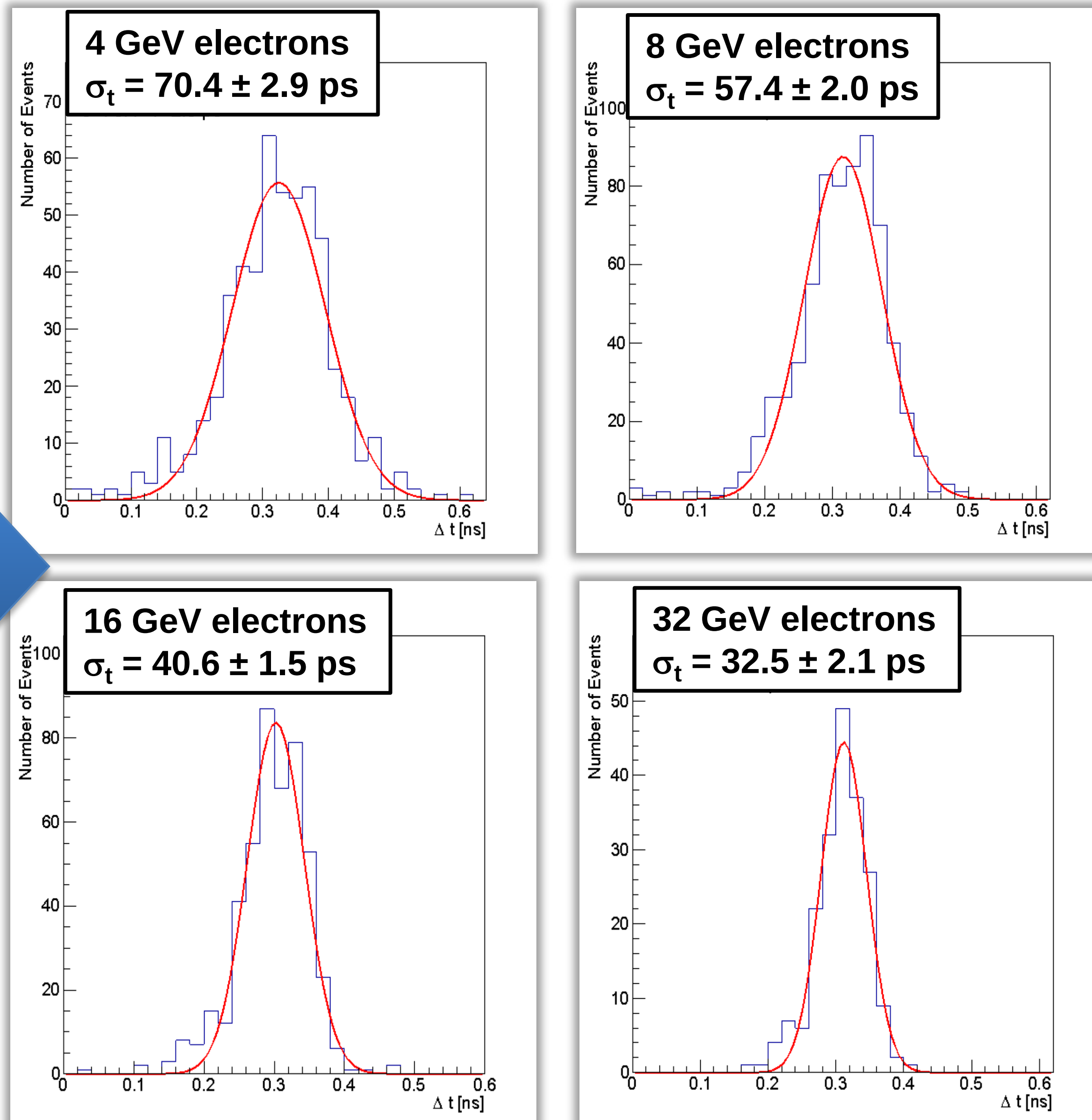


- **Study the effect of scintillation (of LYSO) on time resolution**
  - **Minimize the effect of optical transit by using a relatively small LYSO crystal (1.7cm x 1.7cm x 1.7cm cube)**

TOF Measurements (1.7 cm^3 LYSO)

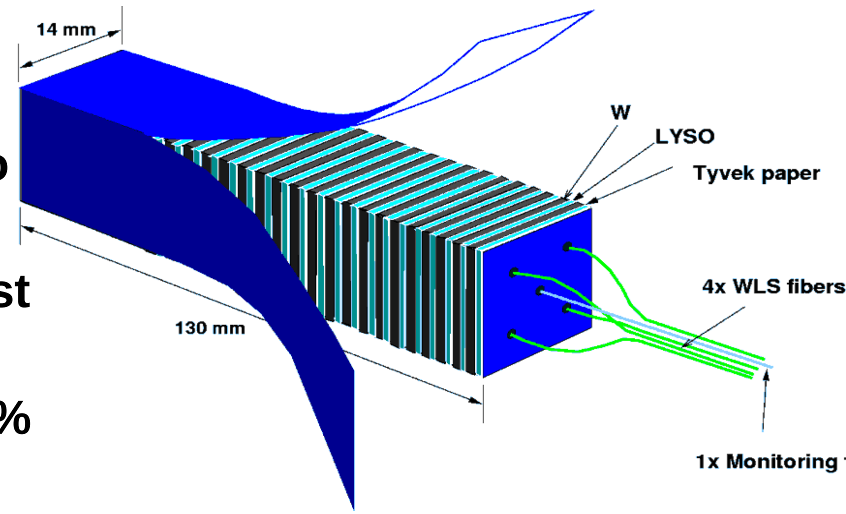


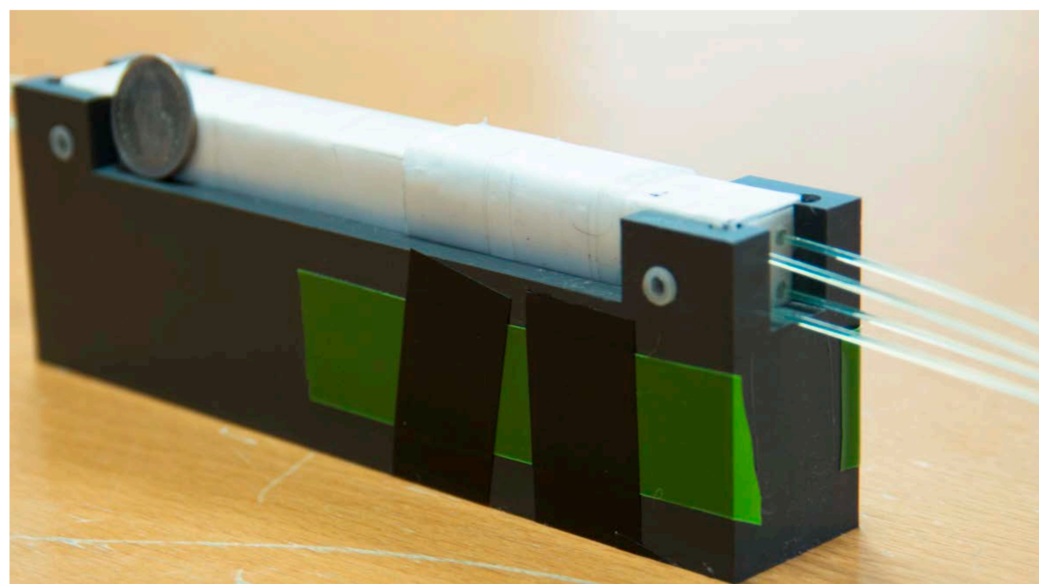
measure t_1-t_0



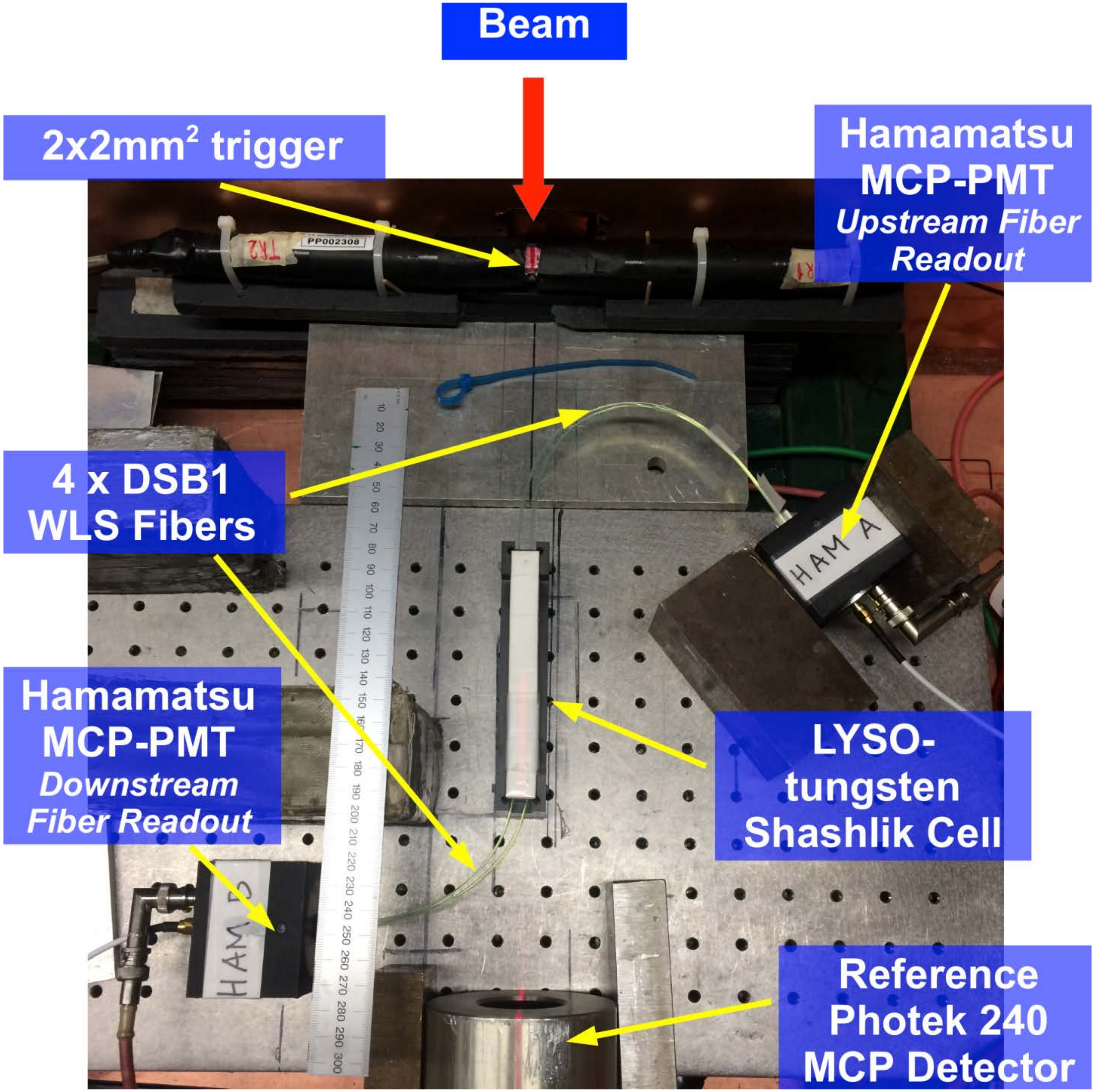
Increased Light Path Complexity

- **R&D for HL-LHC on LYSO/W Shashlik calorimeter.**
- **Radiation hard in HL-LHC environment up to 3 ab^{-1}, energy resolution of 10%/sqrt(E)$\oplus$1%.**
- **Resolution performance demonstrated in test beam on a 4x4 matrix.**
- **Radiation hardness of LYSO tested up to 80% of the required dose.**
- **Use single Shashlik cell to test timing performance with very complex light path.**

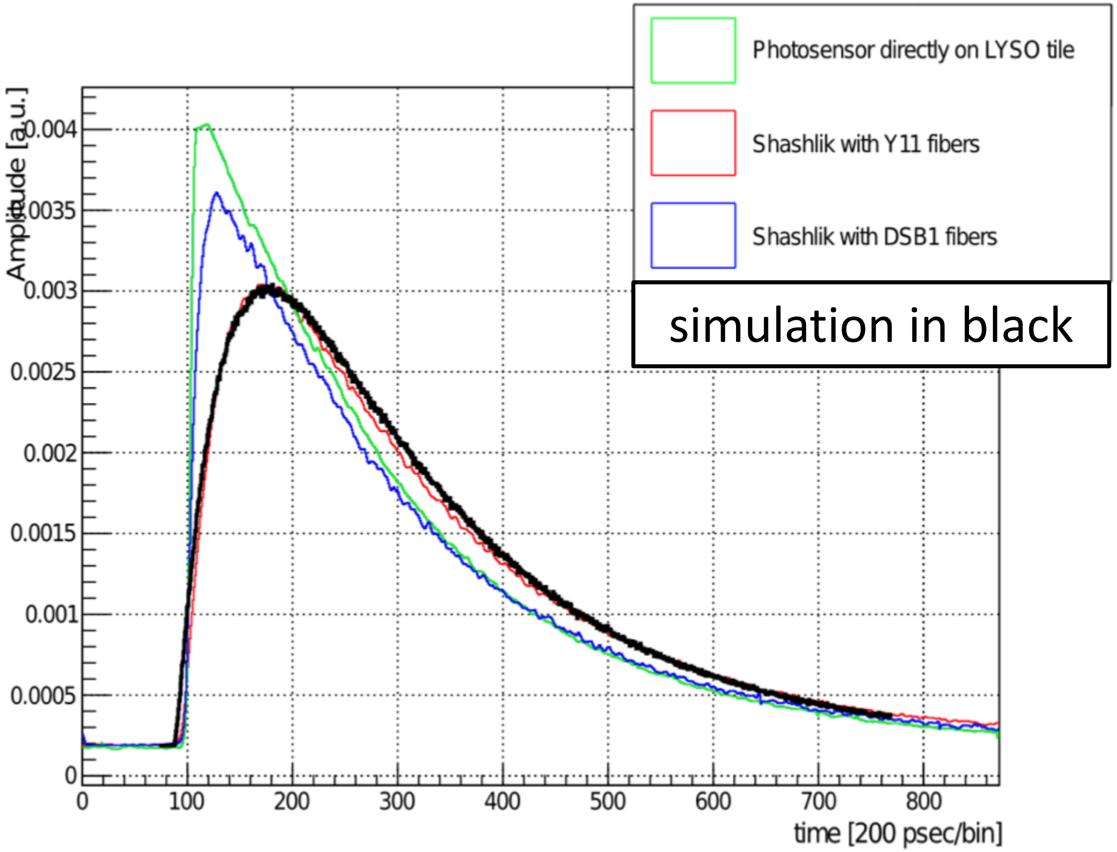




Beam Test Setup Shashlik Cell

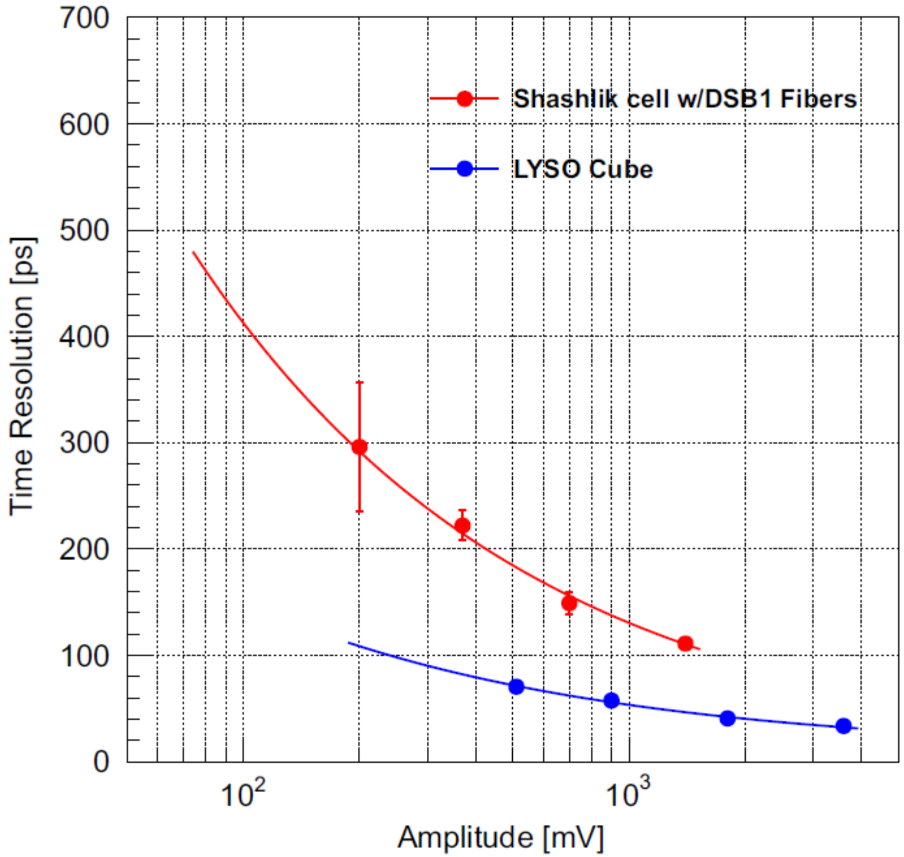


Wavelength Shifter Timing Properties



- **Pulse rise time of bare LYSO driven by MCP+DRS4, in Shashlik configuration by timing characteristics of the wavelength shifter.**
- **Ray tracing simulation of the full optical chain, including LYSO and WLS timing properties reproduces the measurement.**
- **No additional shaping of the pulse due to the complex light path.**

Shashlik Timing Performance

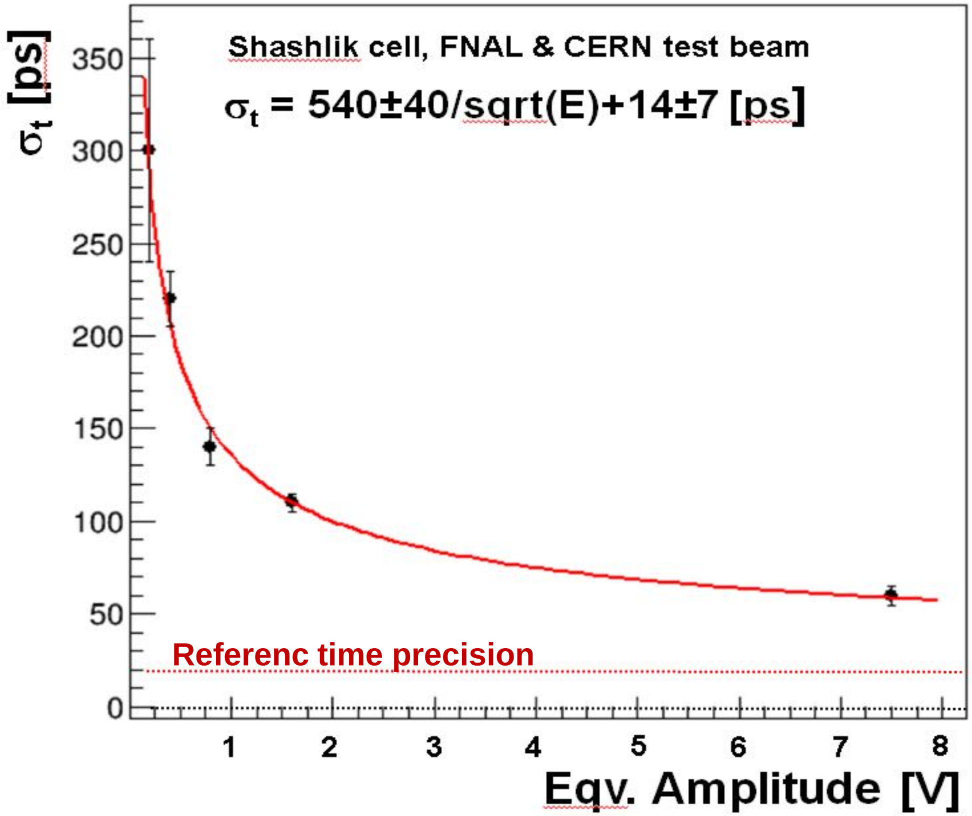


- **Performance of solid LYSO cube and LYSO/W scales with the rise time difference due to the WLS.**
- **Few 10 ps resolution achievable with LYSO based calorimeter, reaching ~32 ps at 32 GeV equivalent signal.**

NIM A, Vol 794 (2015) p 7-14

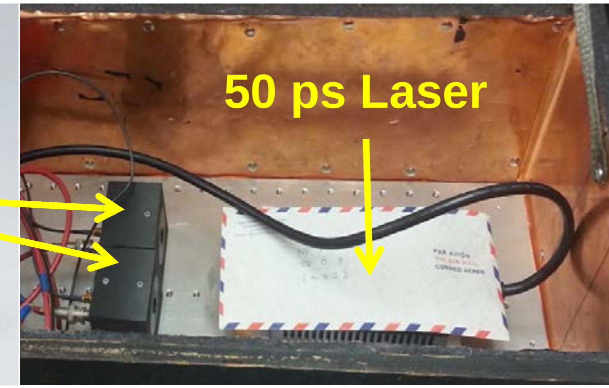
Current Systematic Limits

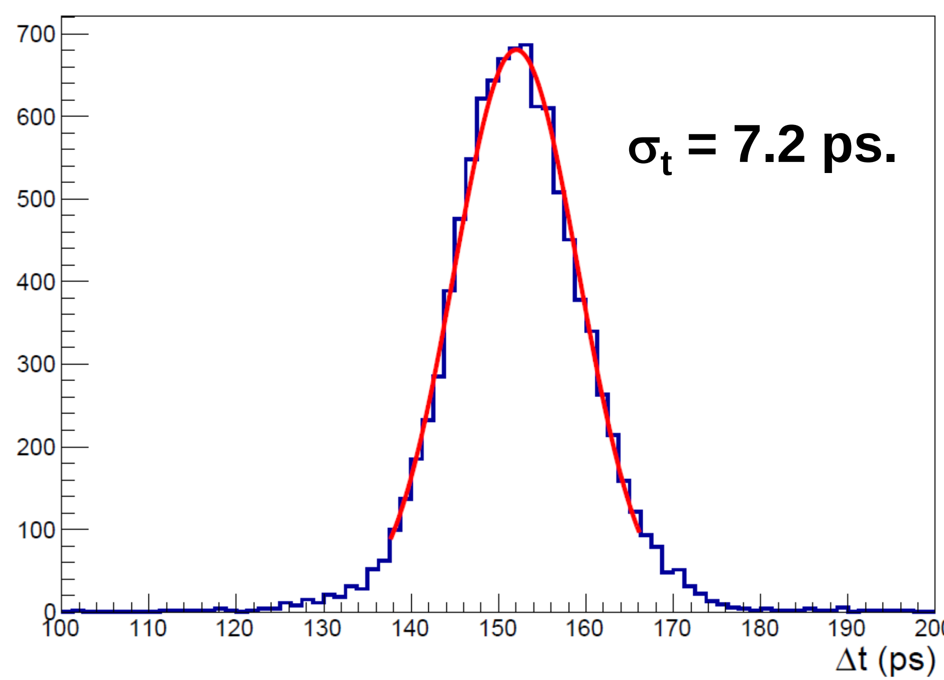
- **Extended measurement up to 150 GeV suggest that the systematic limit is small.**
- **Fit yields constant term compatible with the reference time resolution of around 15 ps.**



Light Sensing Performance

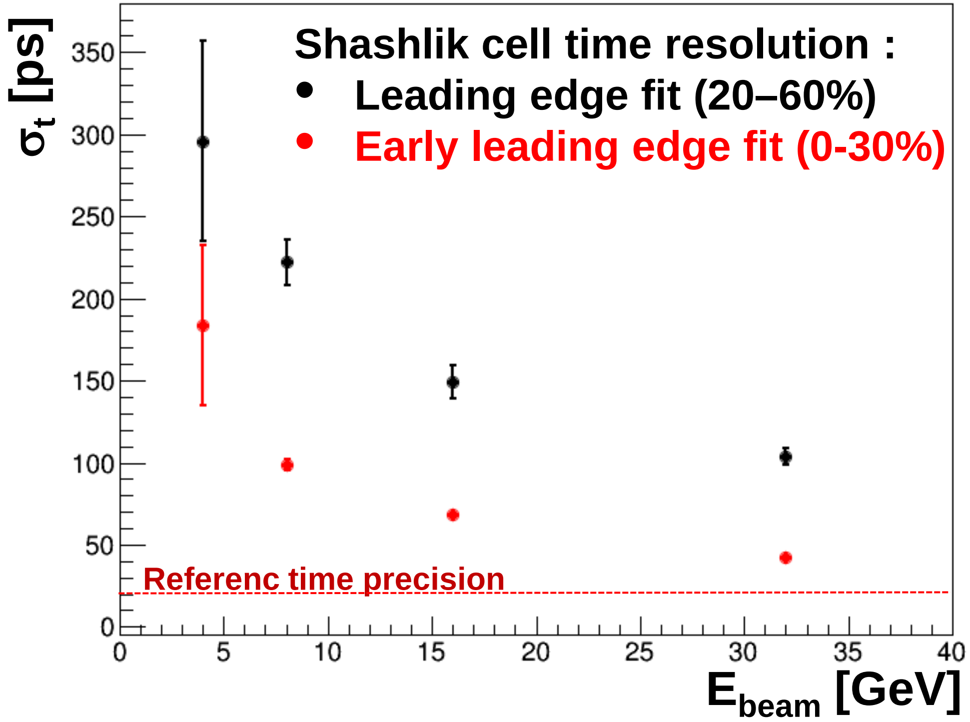
- Differential timing resolution of two MCPs read out with DRS4, illuminated with a 50 ps FWHM laser, DRS4 readout : σ_t = 7.2 ps.
- Hamamatsu MCP : IRF = 45 ps, TTS = 25 ps.
- Similar performance to MIP in a bare MCP.
- Multiphoton timing of MCP resolution approaches limit of readout chain.





Optimized Pulse Reconstruction

- **Extract timing from LYSO signal only from the initial ~2.0 ns of the pulse, fitting a linear function to 10 DRS samples of 200 ps.**
- **Further significant improvement of the performance down to 42 ps at 32 GeV with a reference time precision of about 20 ps.**
- **We observe ringing like noise in the MCP signal after a few ns. Not present with SiPMs.**



Next Steps

- **Crystals and MCPs as sensing elements in a sampling configuration.**

- **Will look at silicon sensors as well. Sensors suitable for calorimeters may not easily achieve 10 ps resolution – however large number of sensors may compensate this.**

- **Measure timing performance of 4x4 LYSO/W matrix.**

- **Move towards a MCP setup which covers entire showers to allow energy measurement.**

Summary

- **We measured the timing resolution of a LYSO/W Shashlik calorimeter cell to be 42 ps for 32 GeV electrons.**
- **The timing is extracted from the same scintillation light signal used for the energy measurement.**
- **We measure shower timing of high energy electrons with commercial MCPs at the level of 15 ps.**
- **We expect further improvement of the LYSO based measurements with a better understanding of the photo sensor characteristics.**
- **A large scale calorimeter with a time resolution of a few 10 ps for pile-up mitigation at HL-LHC seems achievable.**

Backup

Some Related Poster at this Conference

- **“Test beam results of micro channel plates in "ionisation mode" for the detection of single charged particle and electromagnetic showers “ , Speaker: Paolo Meridiani**
- **“Energy and time resolution for a LYSO matrix prototype of the Mu2e experiment”, Speaker : Simona Giovannella**
- **“Development of solar blind UV extended APD for readout of Barium Floride crystals”, Speaker : Prof. David Hitlin**
- **“Test and characterization of SiPMs intended as detector for the MEG high resolution timing counter”, Speaker : Marcello Simonetta**
- **“Fast Timing Detector R&D for the HL-LHC era”, Speaker : Dr. Sebastian White**
- **“State of the art silicon photomultipliers with LSO: Ce codoped Ca scintillators achieve 84ps coincidence time resolution for PET” Speaker : Mr. MYTHRA VARUN NEMALLAPUDI**