Detecting Photons for Fast Timing

-

Calorimeter Precision Timing

Workshop on "Timing detectors for PPS"

CERN

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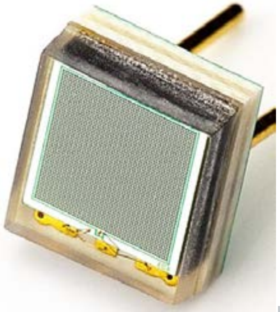
Caltech

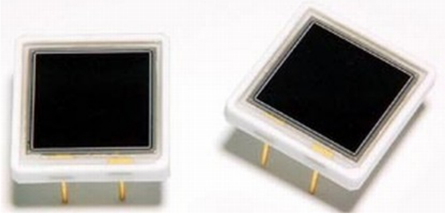
Outline

- Photon detection – Photon detectors
- Precision Timing Applications for HL-LHC.
- Precision Timing with Calorimeters
  - SEC
  - Scintillator
- Summary

Photo Sensors

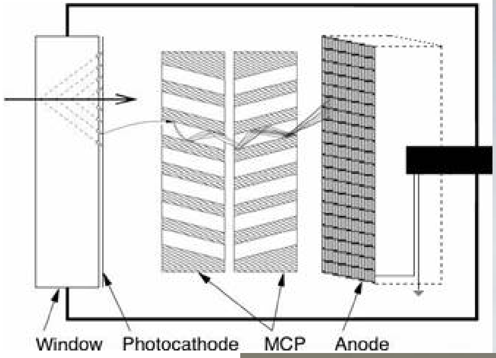
- PMT : typically ~ns rise time, setups with a few 100 ps possible



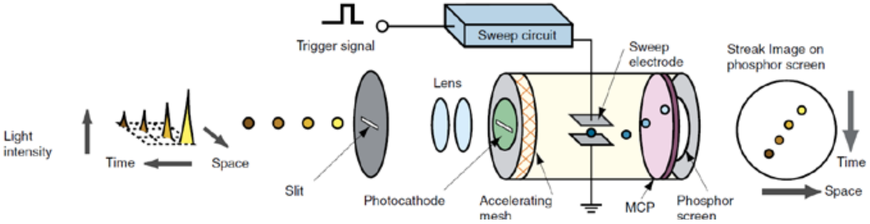


- Semi-conductor based (SiPM, APD, ..) : time resolution ~100 ps

- MCP-PMT : few ps resolution for charged particles



- Streak camera : sub ps

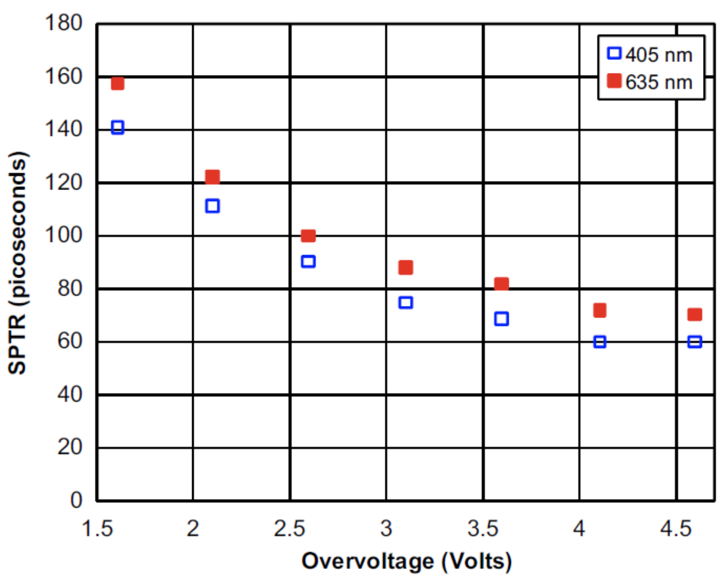


Limit for precision timing ?

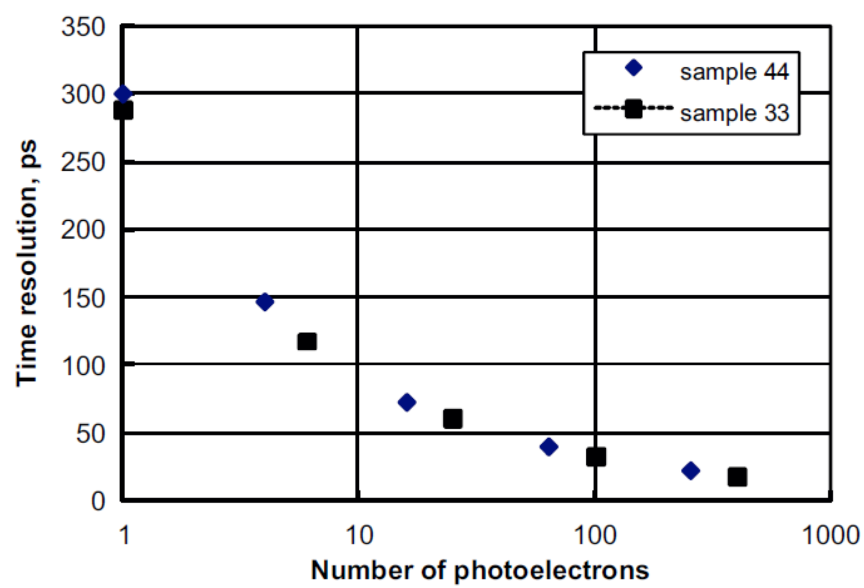
Single-Photon / Multi-Photon

- **To achieve good time resolution need fast rising, large signals, small jitter and low noise.**
- **Signals consisting of many, synchronous photons improve the precision of the averaged signal.**

A. Ronzhin et al. / Nuclear Instruments and Methods in Physics Research A 616 (2010) 38–44



1x1 mm SiPM

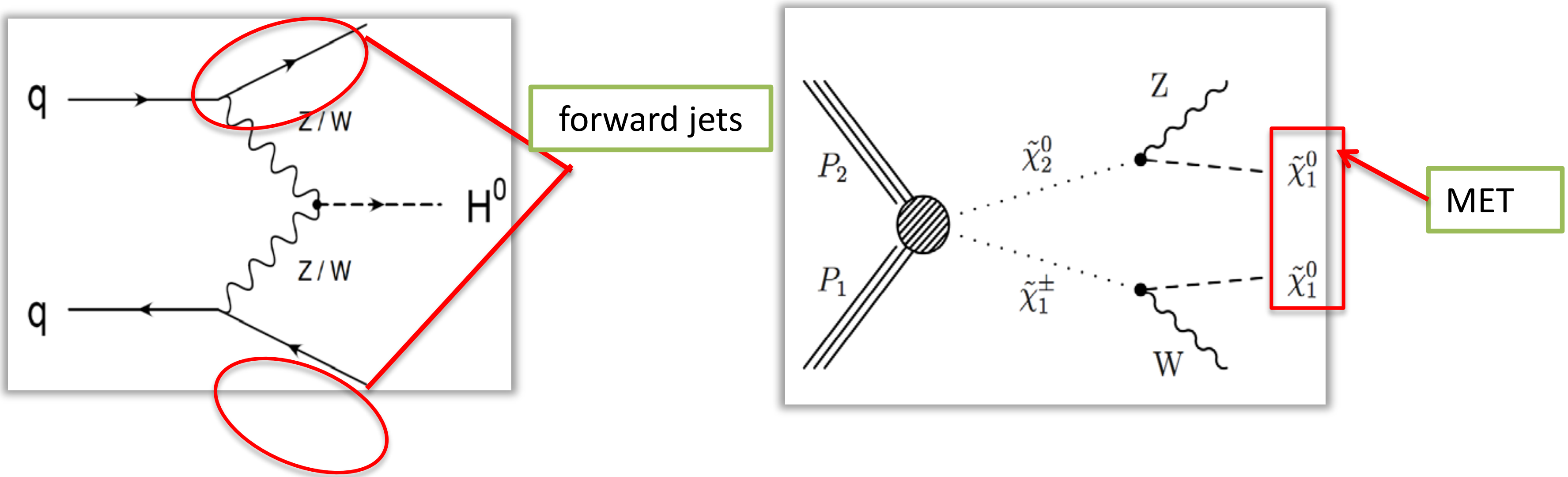


3x3 mm SiPM

Goals of the HL-LHC

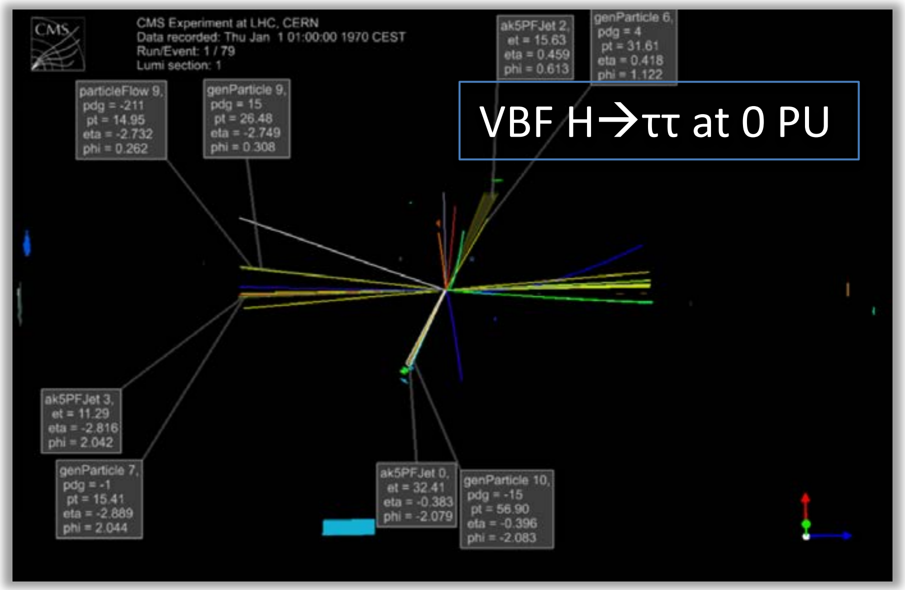
- **A fundamental scalar boson has been found**
  - **The study of the Higgs boson will continue to be a central element**
  - **Precise measurements of the Higgs couplings, tensor structure, rare decays**
  - **Role of the Higgs in EWK SB through $W_L W_L$ scattering**

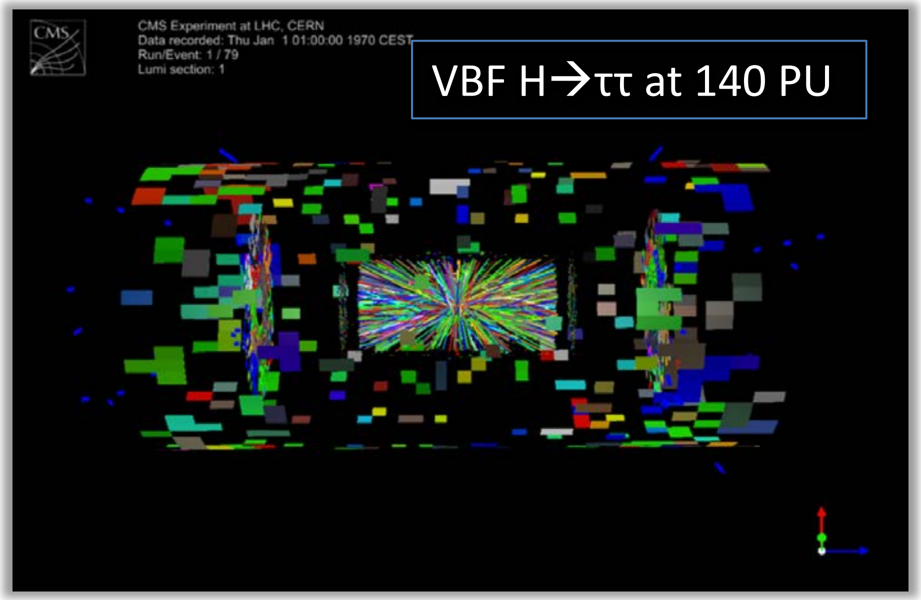
- **Possibly exploration of new physics found at LHC**
  - **Or significant extension of exclusion reach for various BSM scenarios**



Challenges at HL-LHC

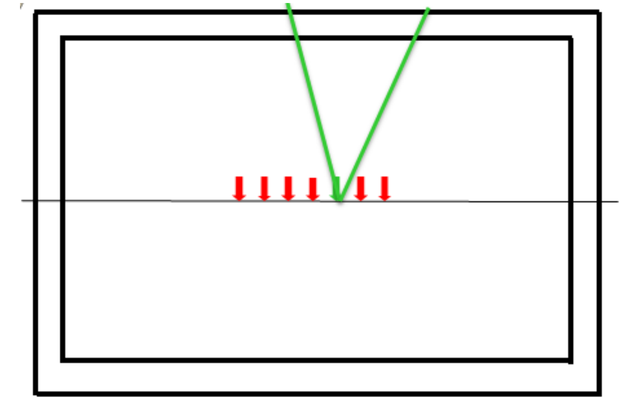
- **Large samples needed to fully exploit LHC, goal : collect x10 more**
  - **<PU> ≈ 140 at HL-LHC → 50nb/sec , collect 3000 fb^{-1}**
- **Some key signatures at HL-LHC**
  - **Higgs VBF and $W_L W_L$ scattering with *forward jets, vertex identification* for H→γγ**
  - **Searches in final states with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

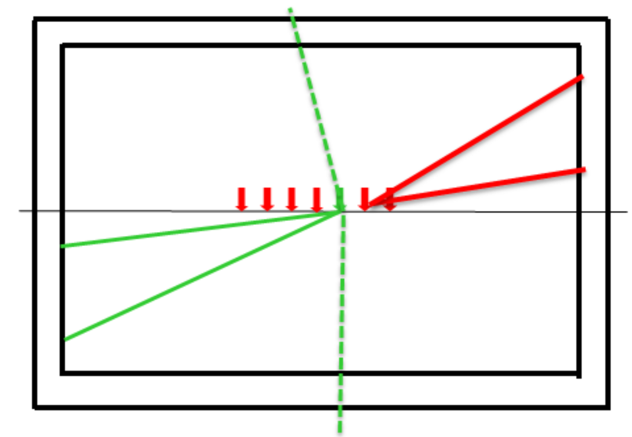


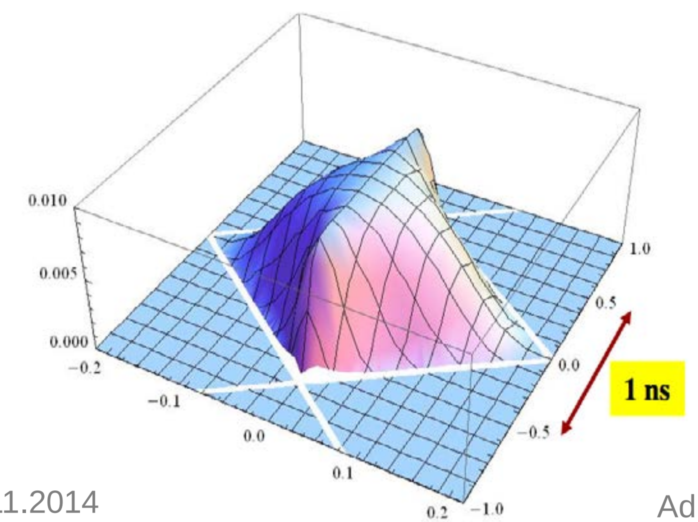


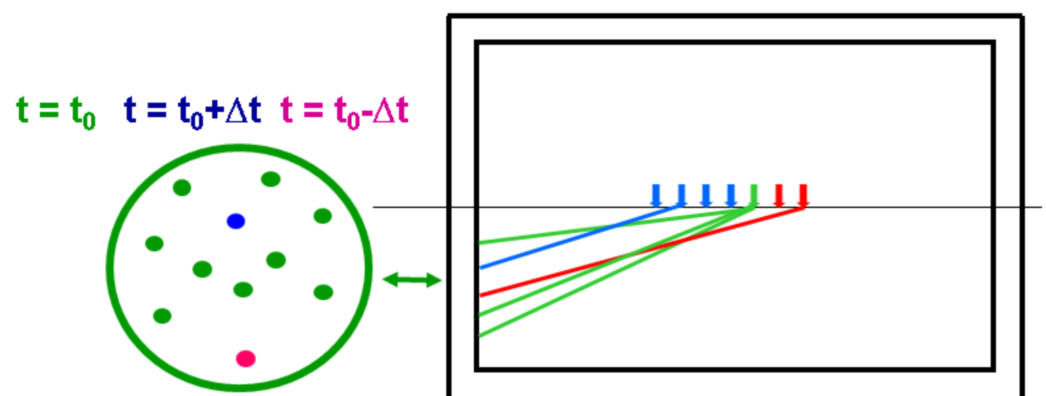
Precision timing at HL-LHC

- ➢ **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**





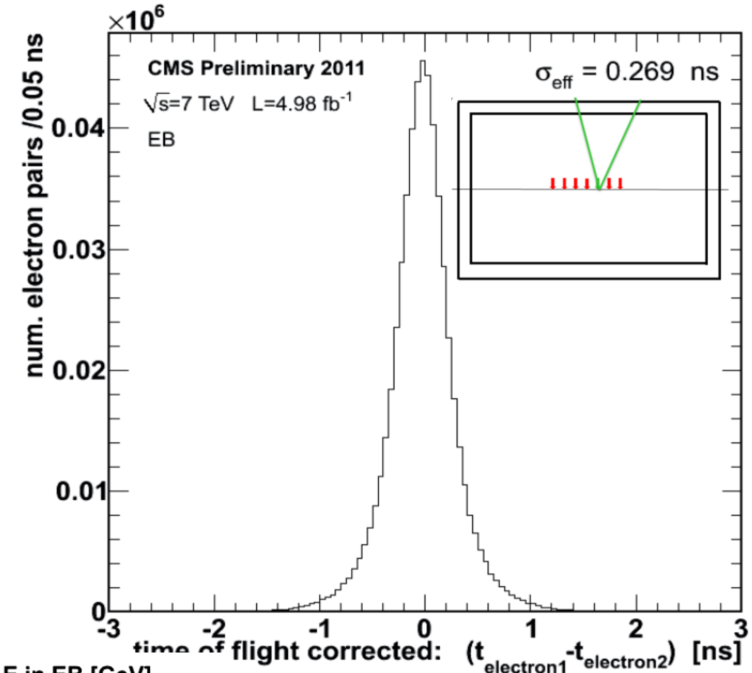


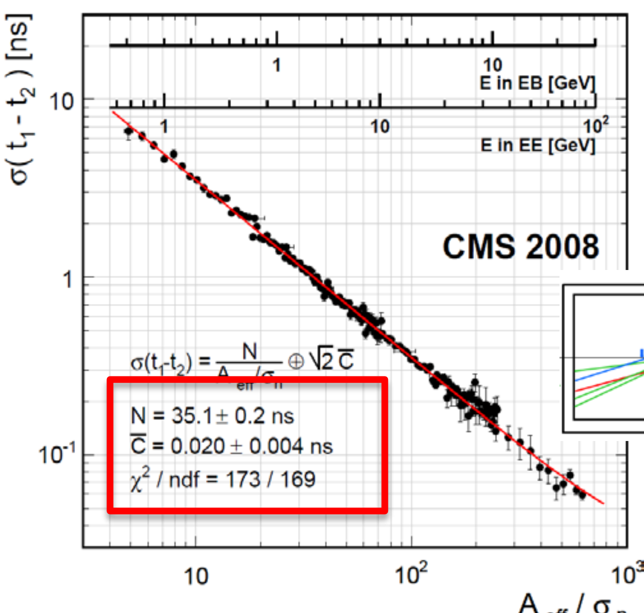


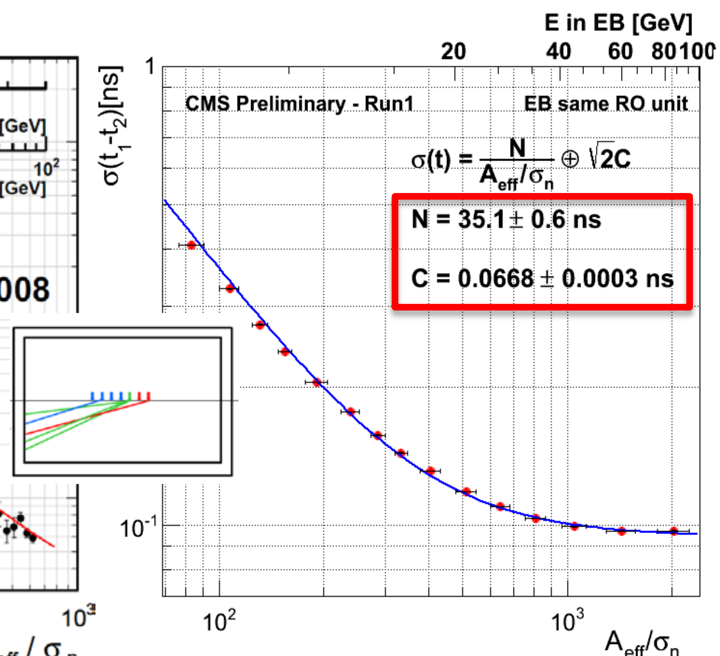
Timing Performance of CMS ECAL

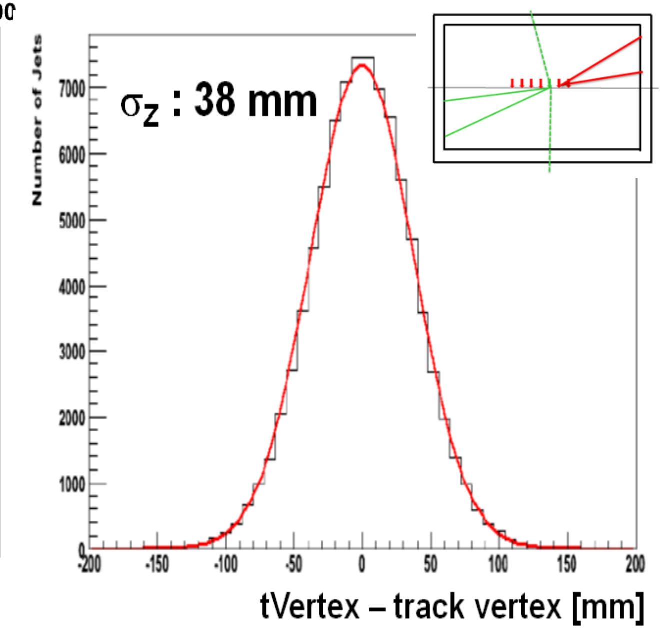
Results from pp collision data at LHC :

- **Reconstruct time of two 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.**

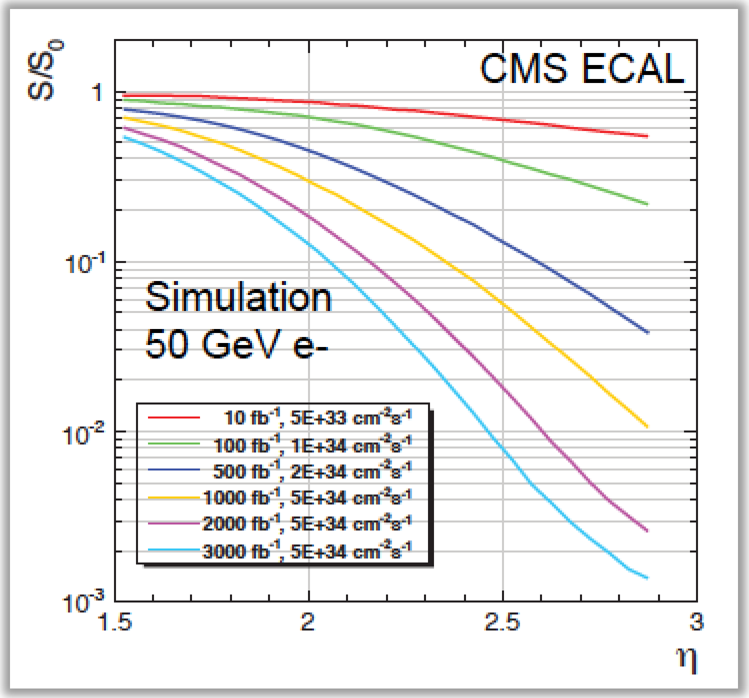


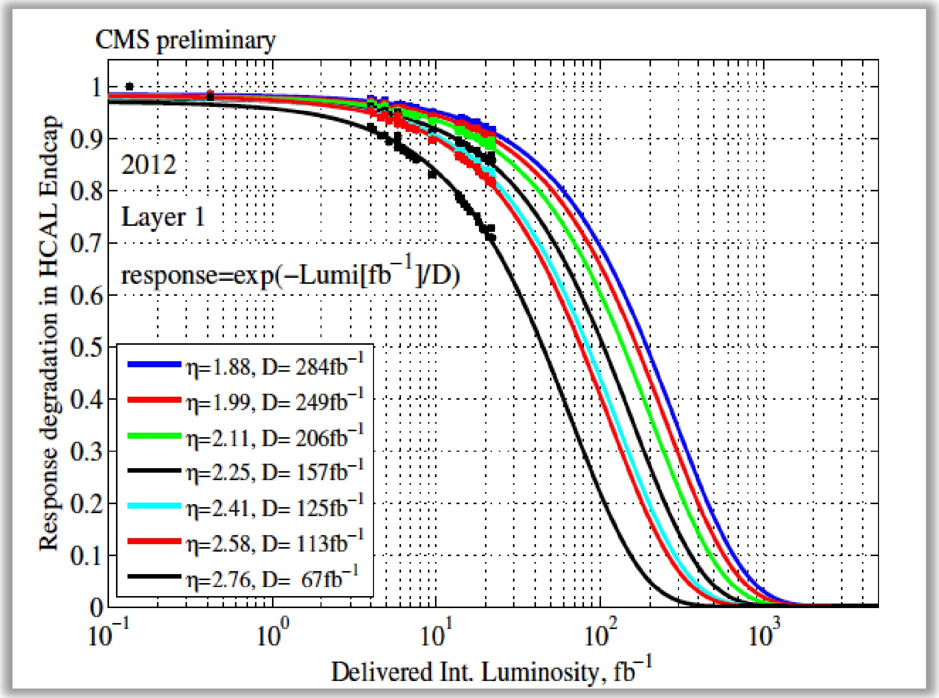






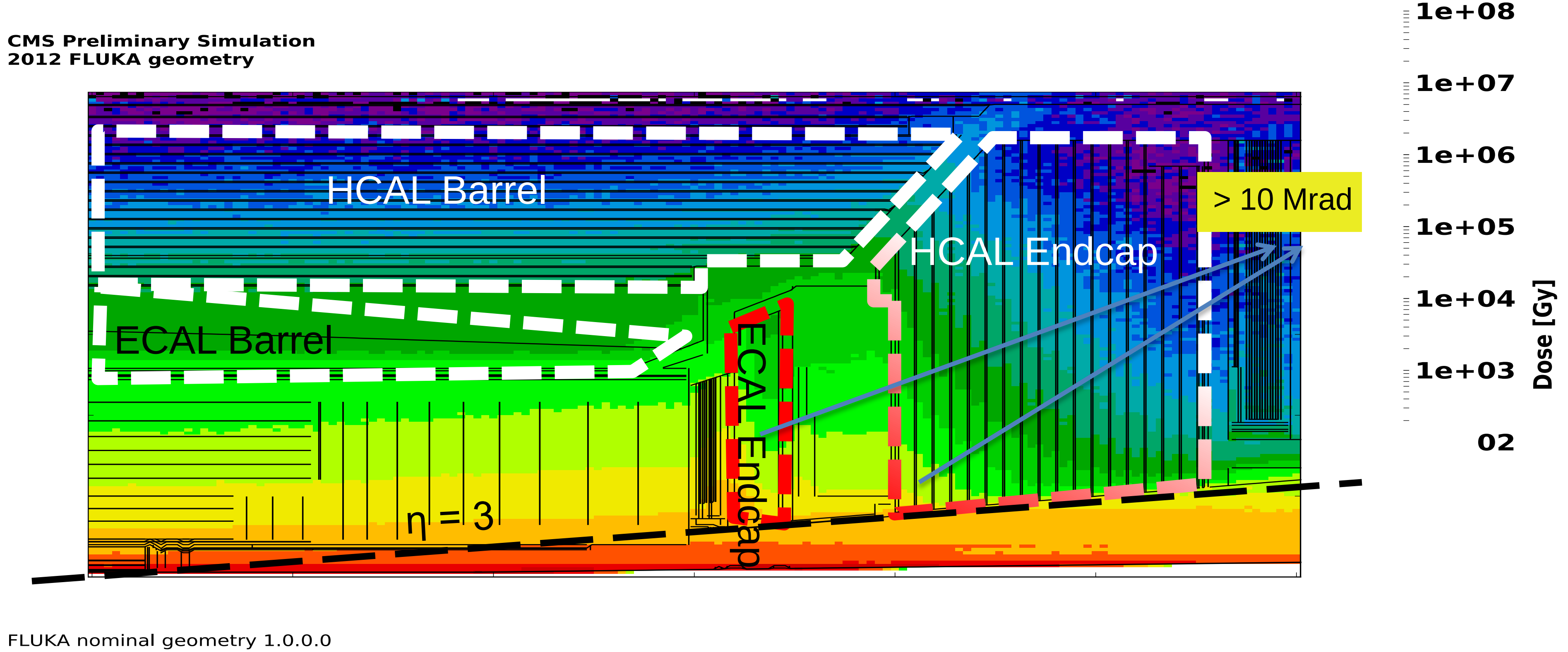
CMS forward calorimeters in HL-LHC





- Extensive studies of radiation damage
  - Both in test exposures and using the ~30fb^{-1} of CMS data
  - Compared with CMS simulations and radiation model
- Have to replace the CMS endcap (1.5<|η|<3.0) calorimeters
  - Barrel ECAL / HCAL and HF (3.0<|η|<5.0) **can** survive 3000 fb-1
  - **Replace ECAL and HCAL endcaps before HL-LHC (i.e. after L=300-500fb^{-1})**

CMS calorimeters in HL-LHC

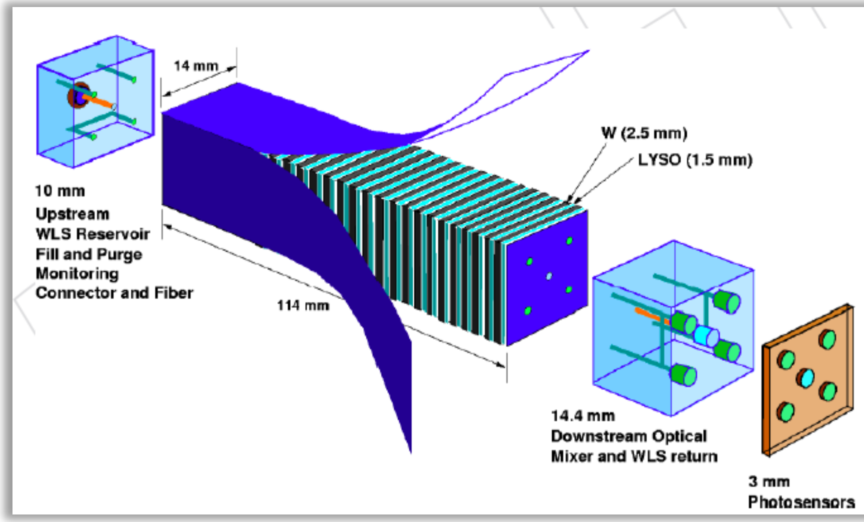


Phase 2 Upgrades Strategy

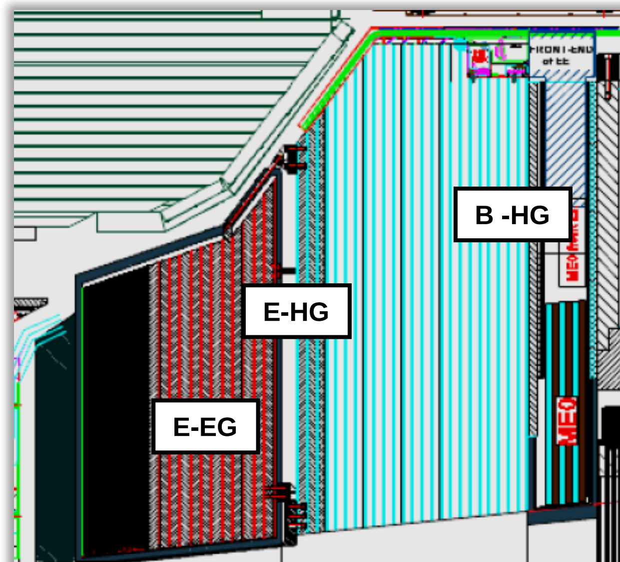
- **Maintain performance at extreme PU**
- **Sustain rates and radiation doses**

Endcap options : Shashlik & HGCal

- W-absorber, LYSO (CeF_3)scintillator
- Compact (~11cm long), small Moliere radius (13.7mm), high granularity ($14mm^2$) to mitigate pileup
- High light yield for good e/γ energy resolution ~10%/√E
- Readout with capillaries filled with liquid WLS
- Readout options being evaluated now, GaInP or SiPM

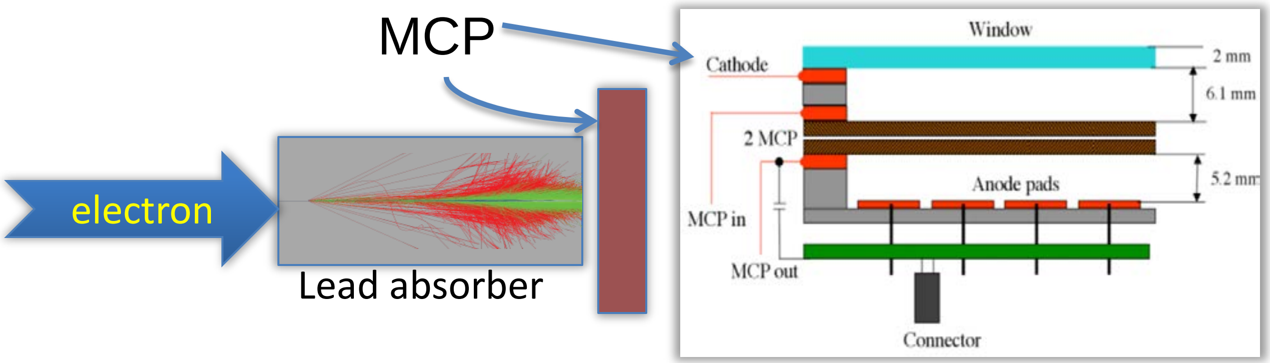


- ECAL (E-HG): ~33 cm, 25 X_0, 1λ:
  - 30 layers of Si separated by 0.5/0.8/1.2 X_0 of alternating W, lead/Cu
- HCAL (H-HG): ~60 cm, 3.5λ:
  - 12 planes of Si separated by 40 mm of brass
- Back HCAL (B-HG) as HE re-build 5.5λ
- ΔE/E ~ 25%/√E;
  - 3D shower reconstruction
  - Use shower topology to mitigate PU effect



Fast timing: secondary emitter

- 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.



MCP detection efficiency from Hamamatsu catalog

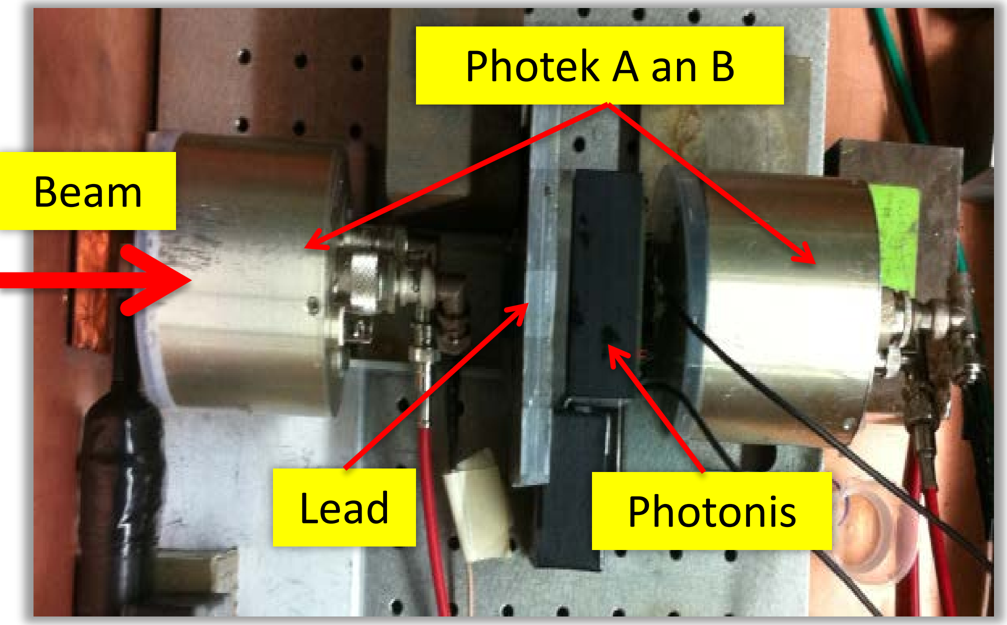
Types of Radiation	Energy or Wavelength	Detection Efficiency (%)
Electron	0.2 keV to 2 keV	50 to 85
	2 keV to 50 keV	10 to 60
Ion (H^+, He^+, Ar^+)	0.5 keV to 2 keV	5 to 58
	2 keV to 50 keV	60 to 85
	50 keV to 200 keV	4 to 60
UV	300 Å to 1100 Å	5 to 15
	1100 Å to 1500 Å	1 to 5
Soft X-ray	2 Å to 50 Å	5 to 15
Hard X-ray	0.12 Å to 0.2 Å	to 1
High energy particle (ρ, π)	1 GeV to 10 GeV	to 95
Neutron	2.5 MeV to 14 MeV	0.14 to 0.64

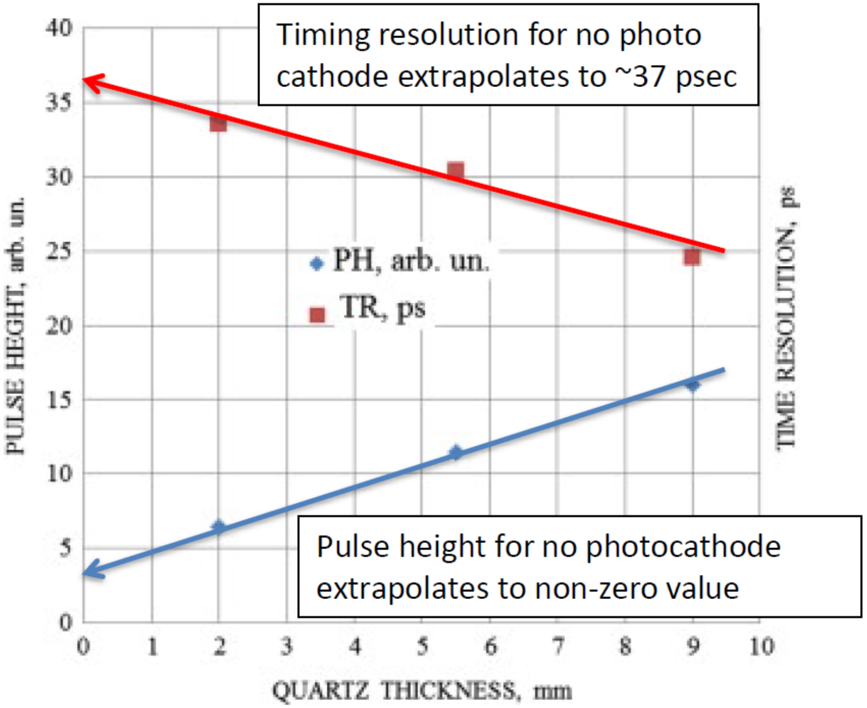
- Secondary particles from EM shower are detected by MCP
  - Signal is proportional to the number of secondaries → energy of parent
  - Most of secondary particles are low energy → MCP very efficient
  - MCP are intrinsically very fast → calorimeter with very fast timing

Precision Timing with Secondary Emission

- Time resolution with commercial MCP, extrapolated to device with no quartz window : ~40 ps.
- Signal creation in MCP layer, referred to as secondary emission (SEC).
- Initial tests yield indeed 40 ps in SEC mode.

⇒ Thin layer detector with sufficient timing resolution for HL-LHC.

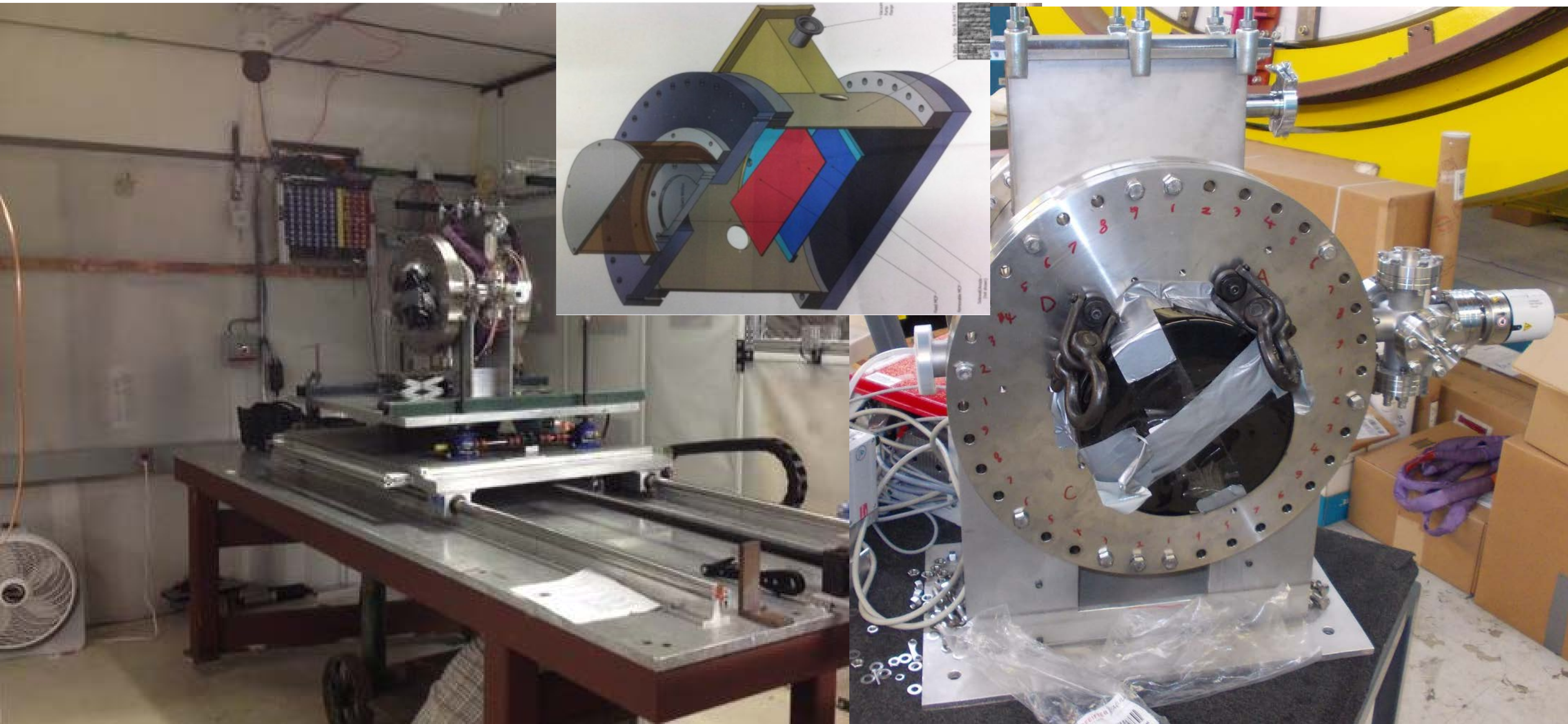




A. Ronzhin et. al. NIM A, Vol 749 p 65-73

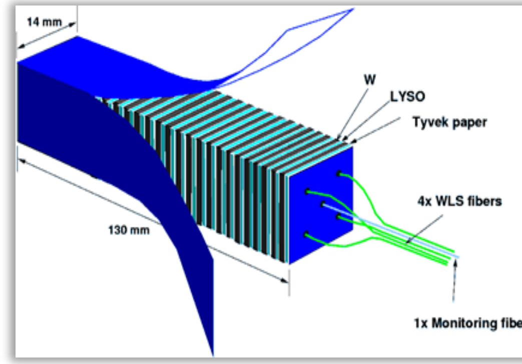
Secondary Emission Calorimeter

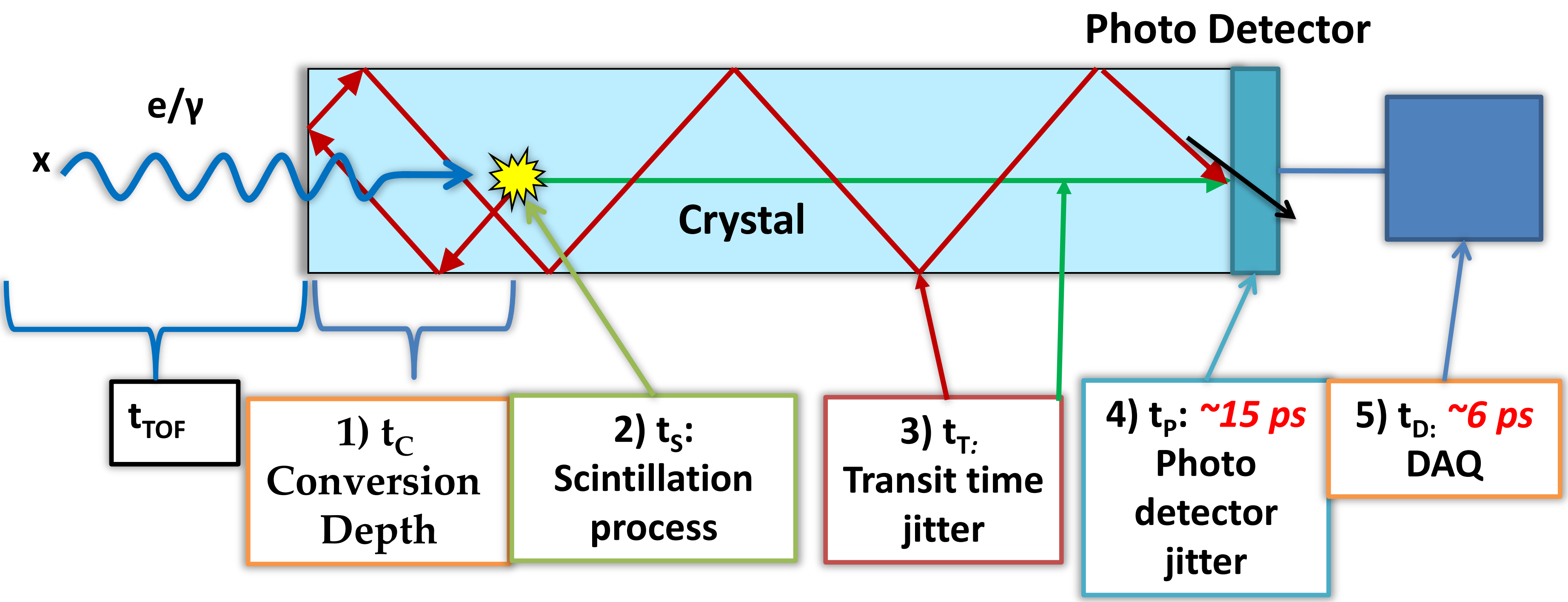
- Tungsten / MCP sampling calorimeter in a vacuum vessel.
- PSEC4 readout, LAPPD MCP layer.
- First beam test last week with one MCP layer live.
- Option for a shower max timing layer in LHC detectors.



Precision timing with crystals

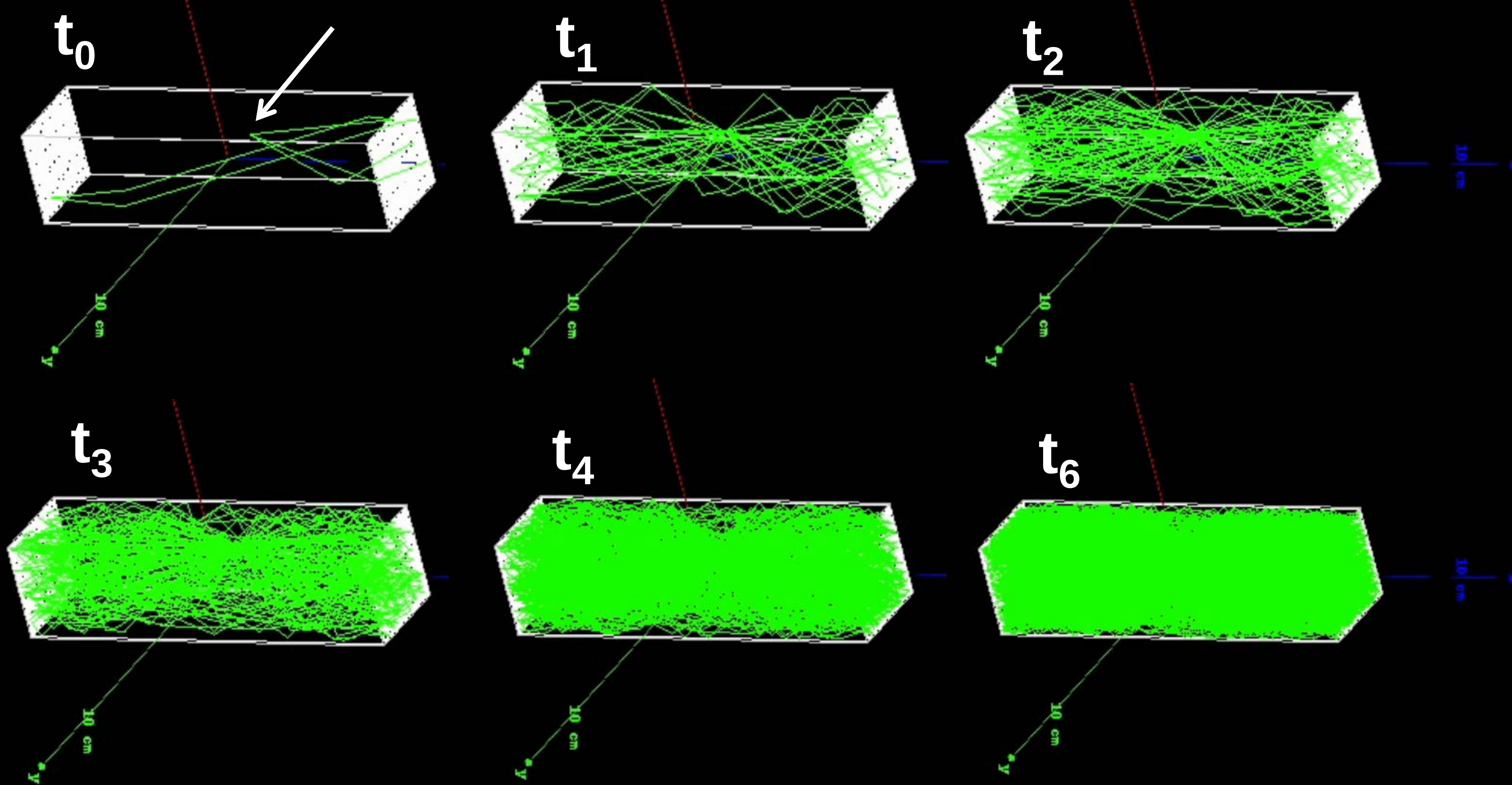
- Main ingredients can be factorized
- *NIM* A *749* (2014) p 65-73 :
  - In the same paper we studied the effects of t_P and t_D: ~15 ps (MCP-PMT) and 6 ps (DRS4)
- Studies of t_S and t_T





Photon Traces in LYSO Crystal

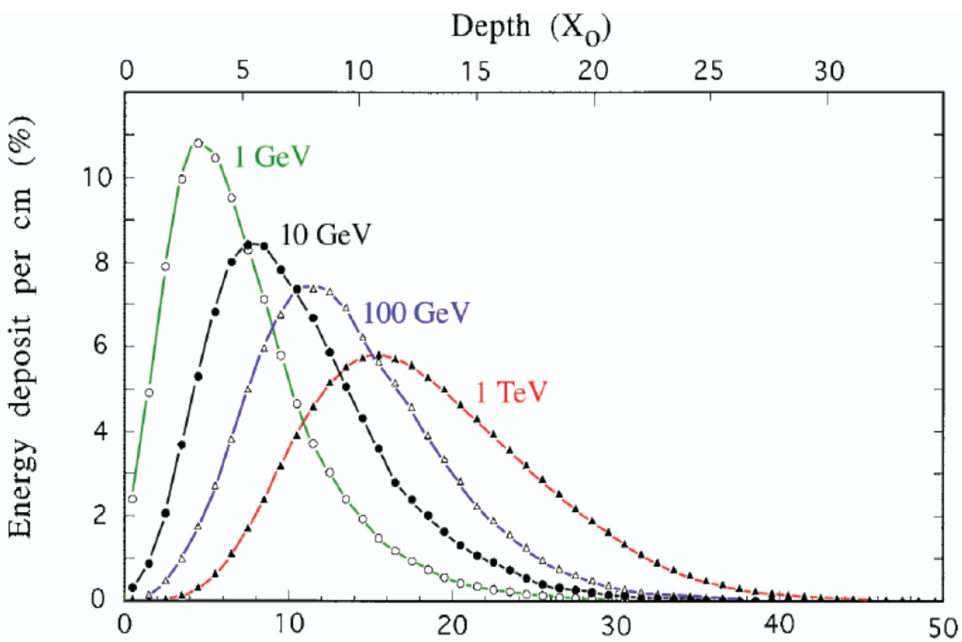
- For high energy showers in high light yield crystals, number of scintillation light yield is very large (>10^5 / GeV).
- Photon detection at one location in the crystal will be an averaged transit time spectrum



Shower Shape and Size

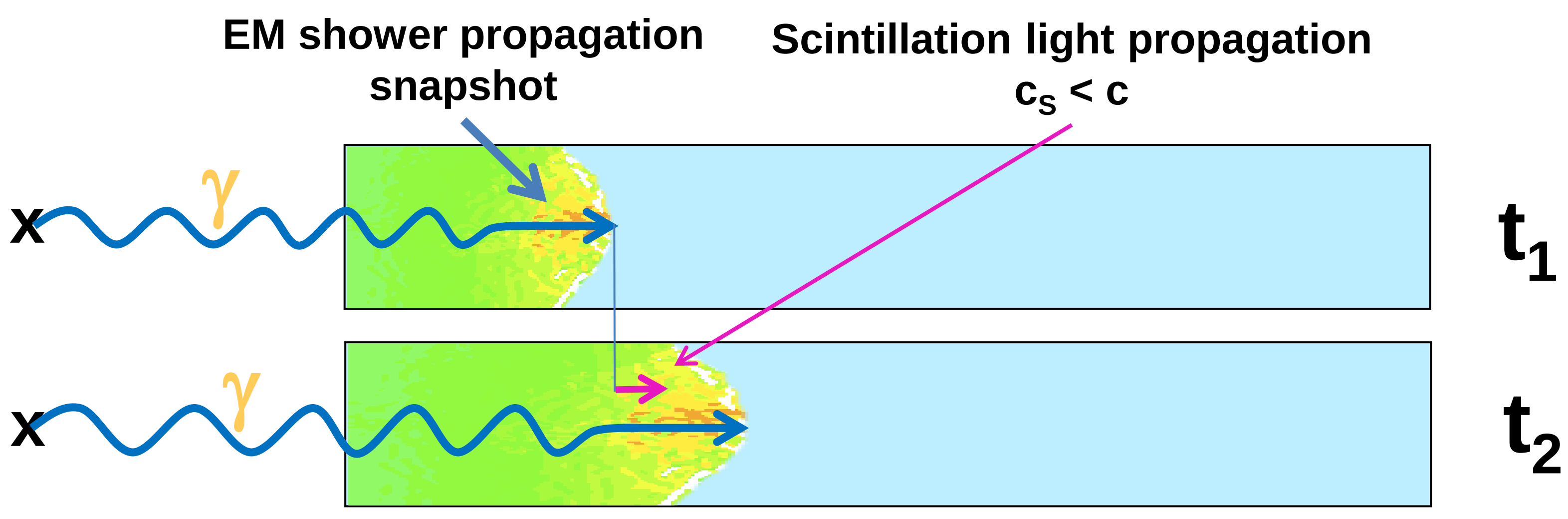
- Size of the shower given by radiation length X_0. We use 1.7 cm, 10 cm and 20 cm LYSO crystals as well as 1.5 mm thick LYSO plates.
- In dense scintillators X_0 is of the order 1 cm. LYSO crystals : 1.2 cm.
- From simulation studies : Shower fluctuations in 100 GeV photon showers cause fluctuation of the mean shower time of the order of few 10 ps, dominated by the conversion depth.
- Mean shower depth varies by several X_0 as a function of energy.

⇒ Shower propagation takes 100s of ps.

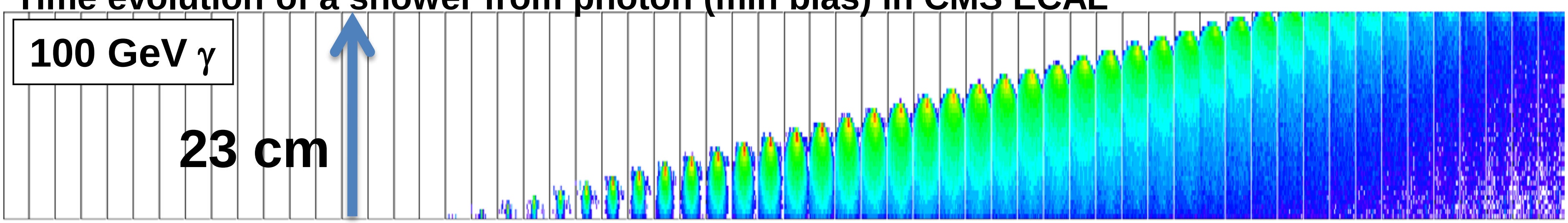


Optical Transit Time Spread

- **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 (min bias) in CMS ECAL



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 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**

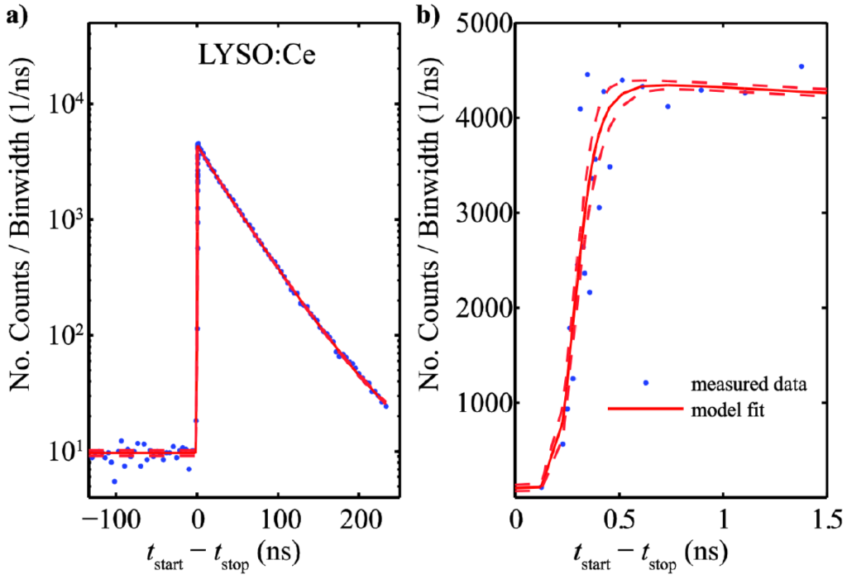


Photo Detector Timing Performance

- Typical timing performance parameters of photo detectors are the rise time, single photon timing jitter, n-photon timing jitter.
- As we measure signals with many photons there may be additional factors typically not quoted by manufactures – like the 100000-photon timing jitter.
- Part of our program is to characterize the timing performance of various photo detectors.
- We are considering PMTs, SiPMs, MCPs, HAPDs. Rise times of faster devices may be smaller than transit time spread.

Hamamatsu MCP-PMT

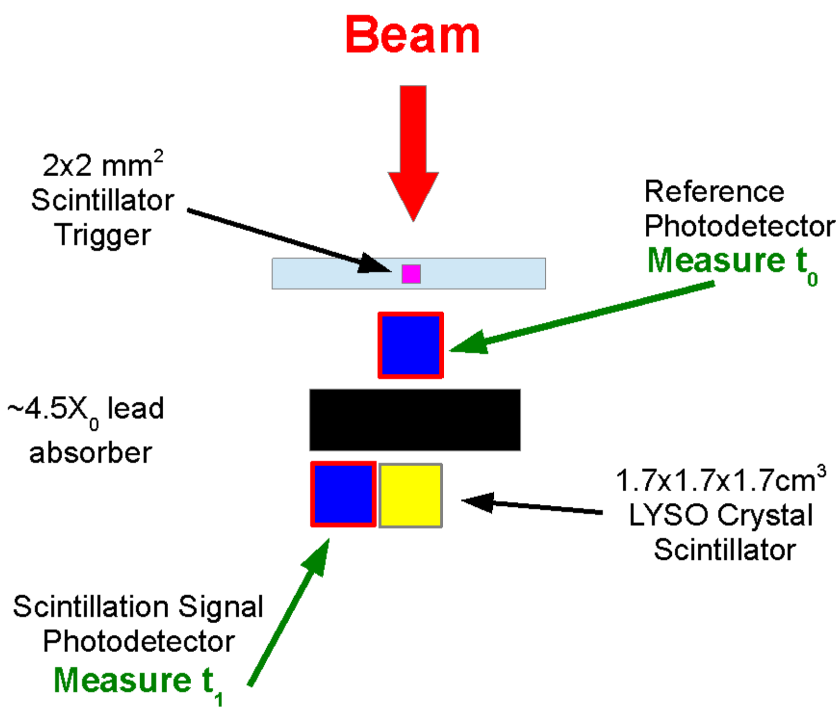
Rise Time [G]	150	—	ps
Fall Time [H]	360	—	ps
I.R.F. (FWHM) [I]	45 [J]	—	ps
T.T.S. (FWHM)	—	25 [K]	ps

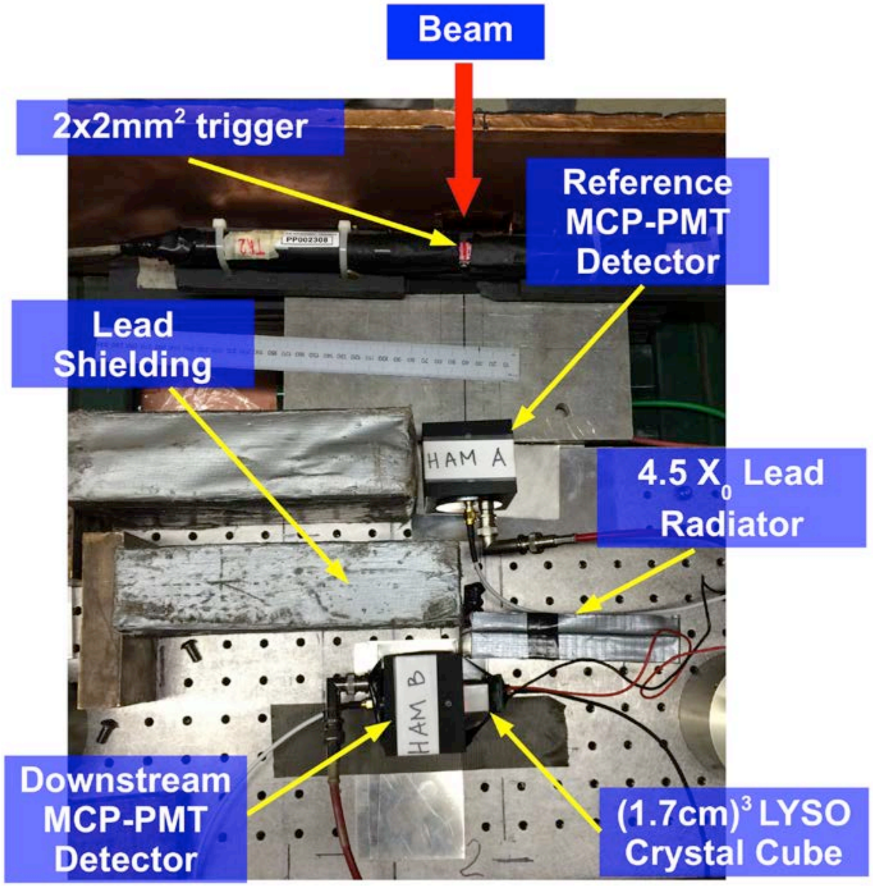
Precision timing with crystals

- With the secondary emission setup we showed that
  - Timing resolution of the MCP-PMT (t_P) is about 11 ps
  - The electronic time resolution of the (t_D) DAQ system is about 6 ps
  - Time of arrival of the front of an electromagnetic shower can be determined with a precision < 20 ps.
  - we conclude that the associated time scale t_C does not contribute significantly to the time resolution of our experimental setup.

- To complete the characterization of the TOF resolution
  - Focus on contributions due to fluctuations in the scintillation process (t_S), and in the optical transit (t_T) to the photodetector.

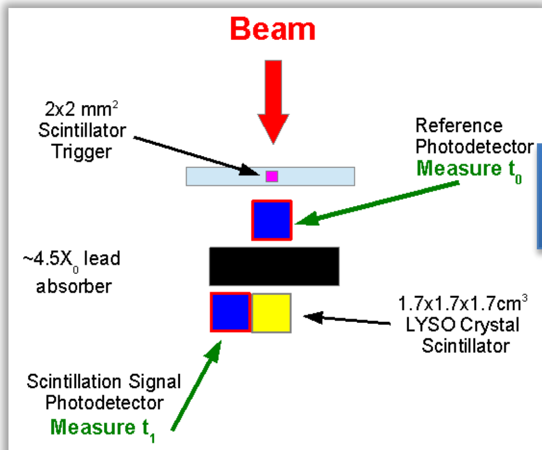
Experimental setup: Scintillation Time t_S



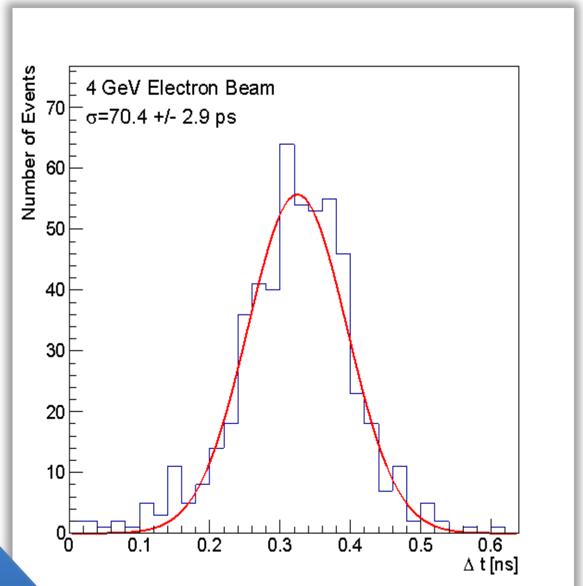


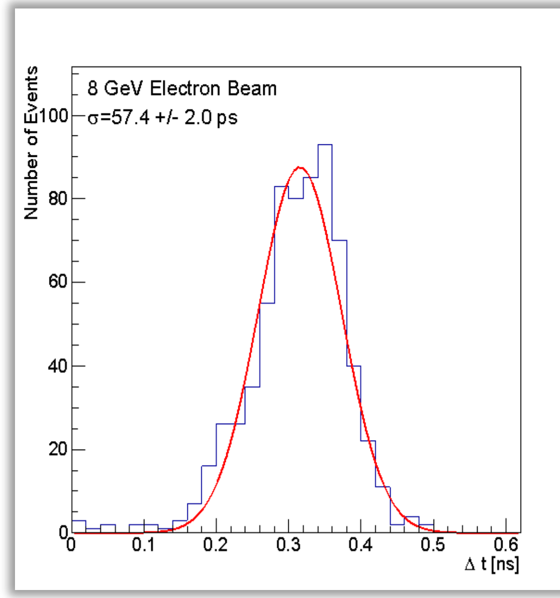
- Study the effect of scintillation (of LYSO) on time resolution
  - Minimize the effect of optical transit by using a relatively small LYSO crystal (1.7cm x 1.7cm x 1.7cm cube)

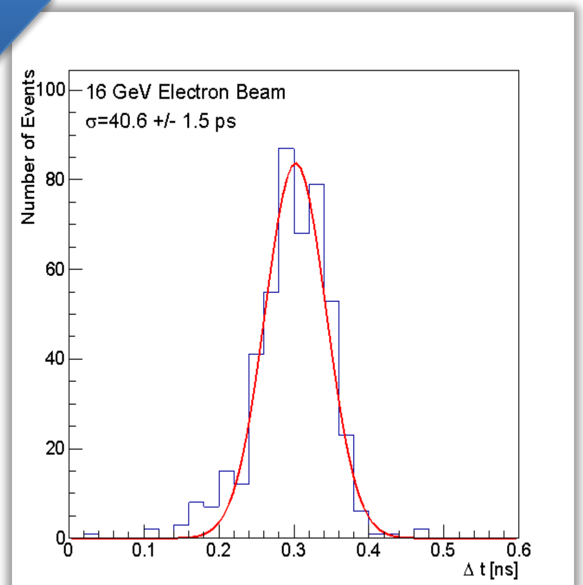
TOF Measurements (1.7 cm³ LYSO)

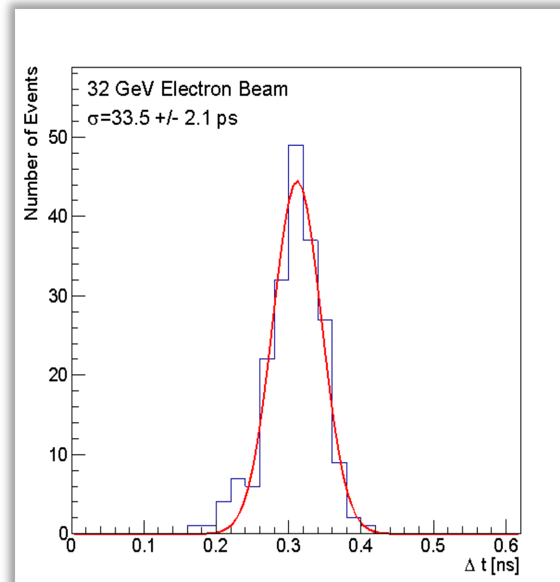


measure t_1-t_0

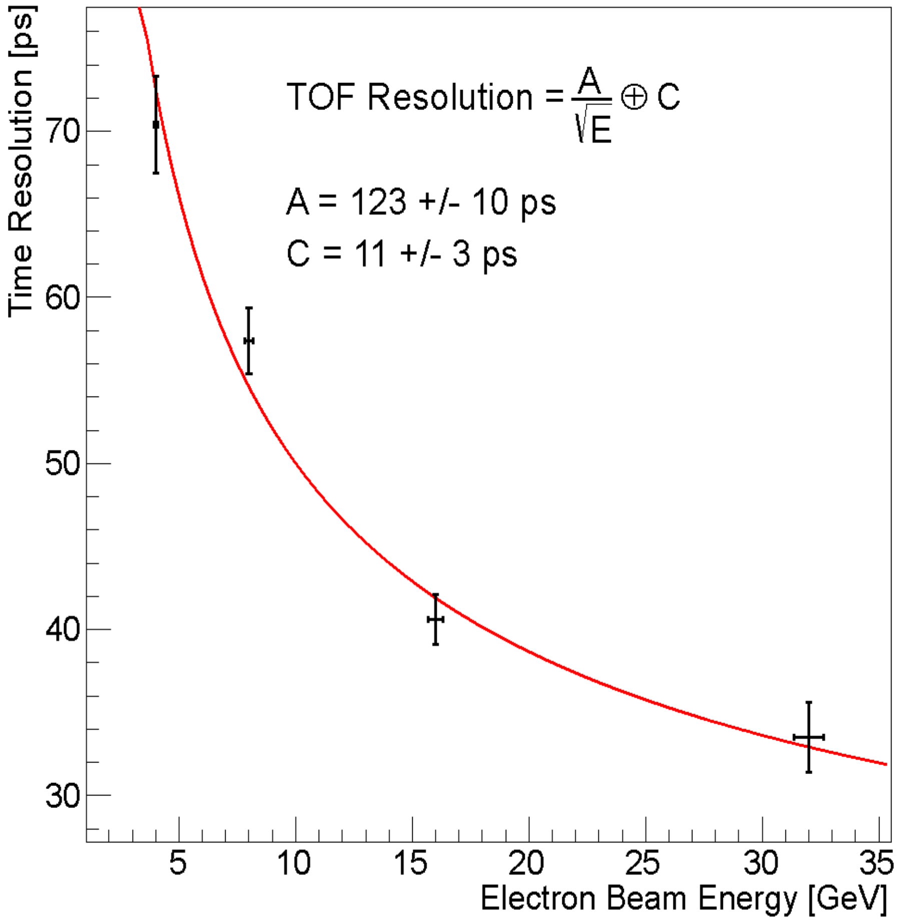






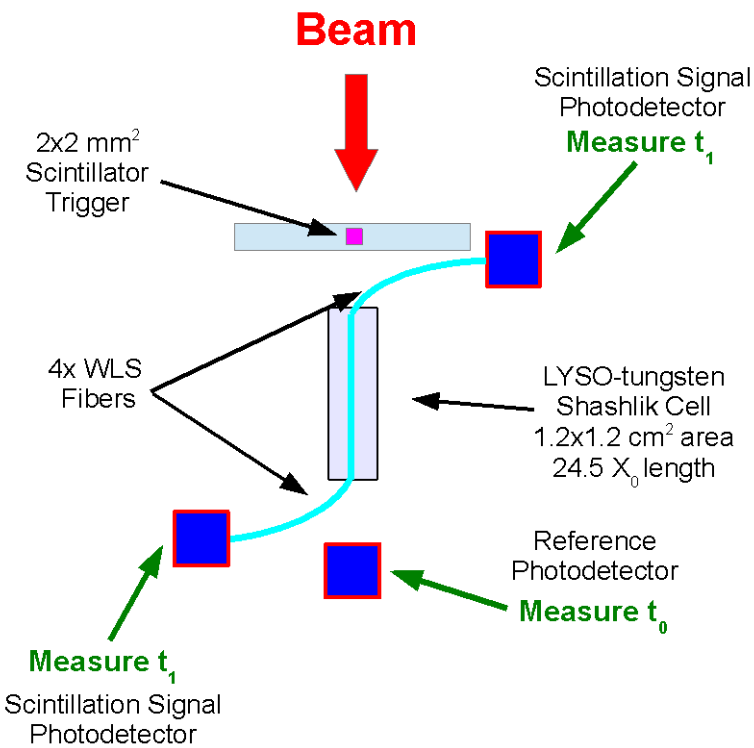


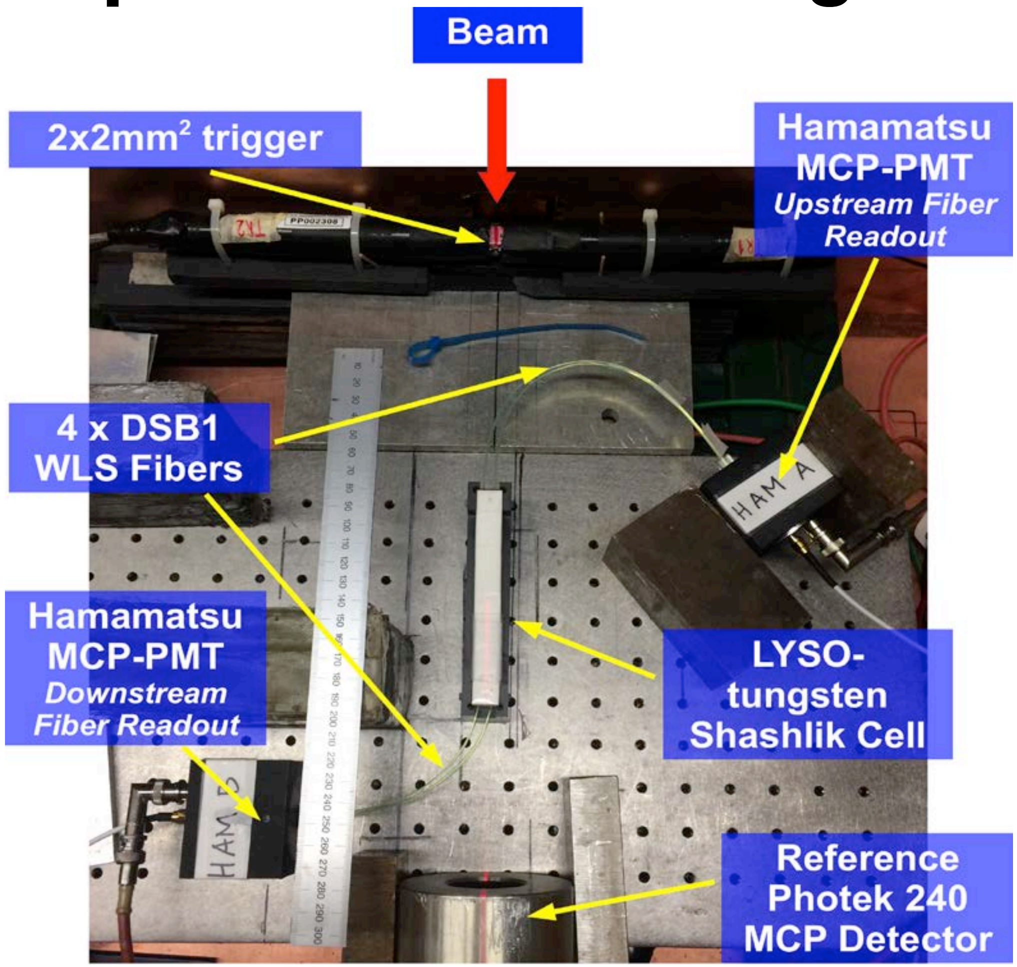
Time resolution : LYSO cube



- **Note: Energy contained in the cube is a small fraction of beam energy**
- **MCP coupled to LYSO cube via ~0.8 cm cookie. Fraction of scintillation light captured is small.**
- **Subtracting the contributions from DAQ, PMT and trigger size: t_S<20 ps**

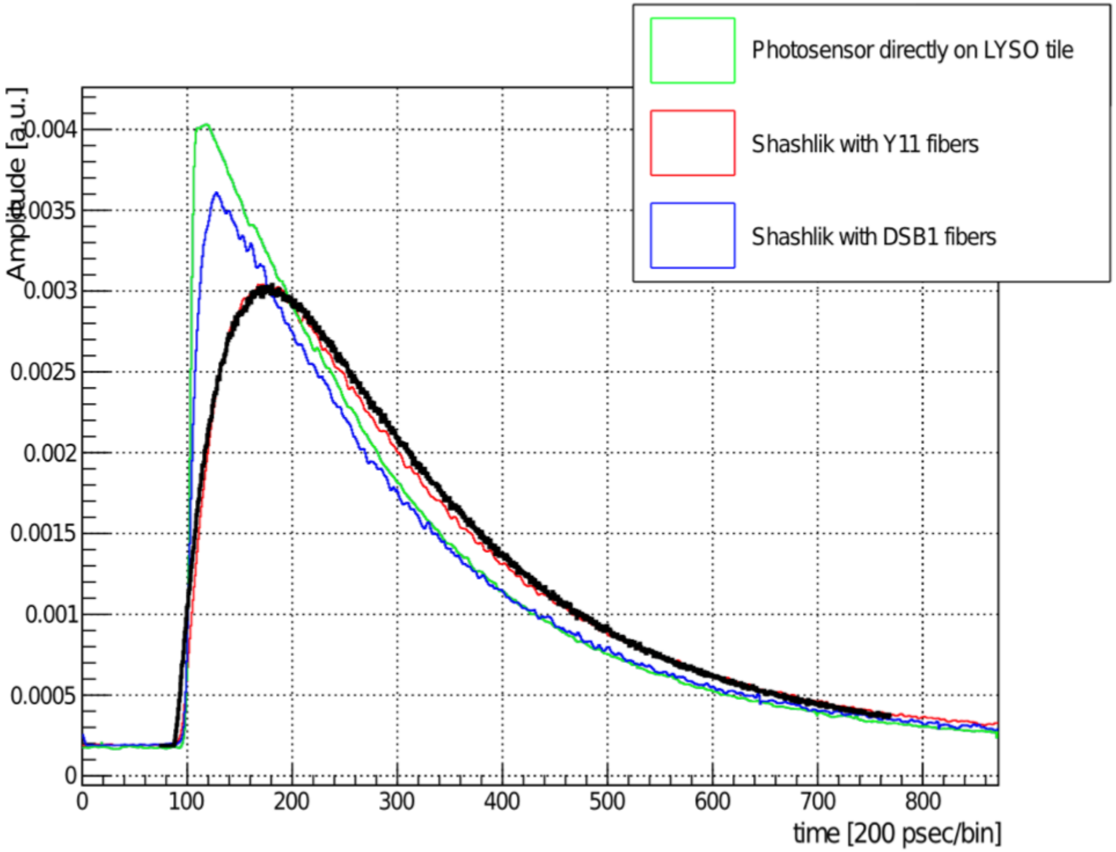
Experimental setup: Shashlik Timing

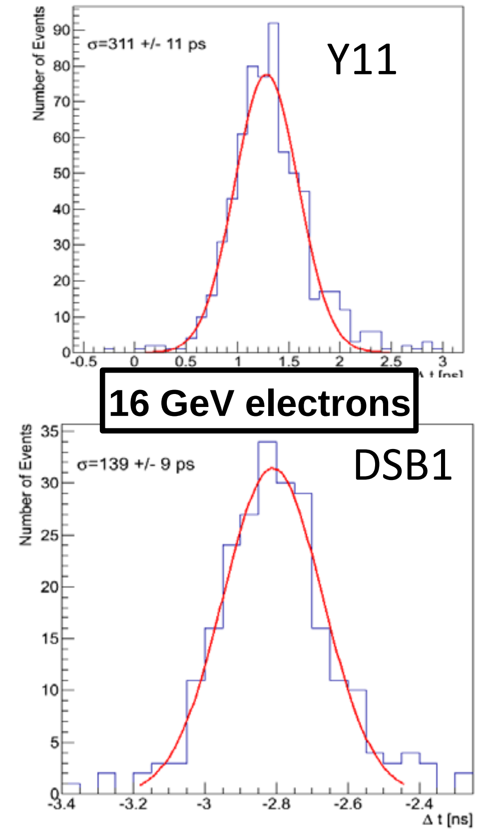




- **Maximize optical transit time jitter: read Shashlik cell fibers**
  - **WLS fiber readout further modulates the pulse: study the effect**

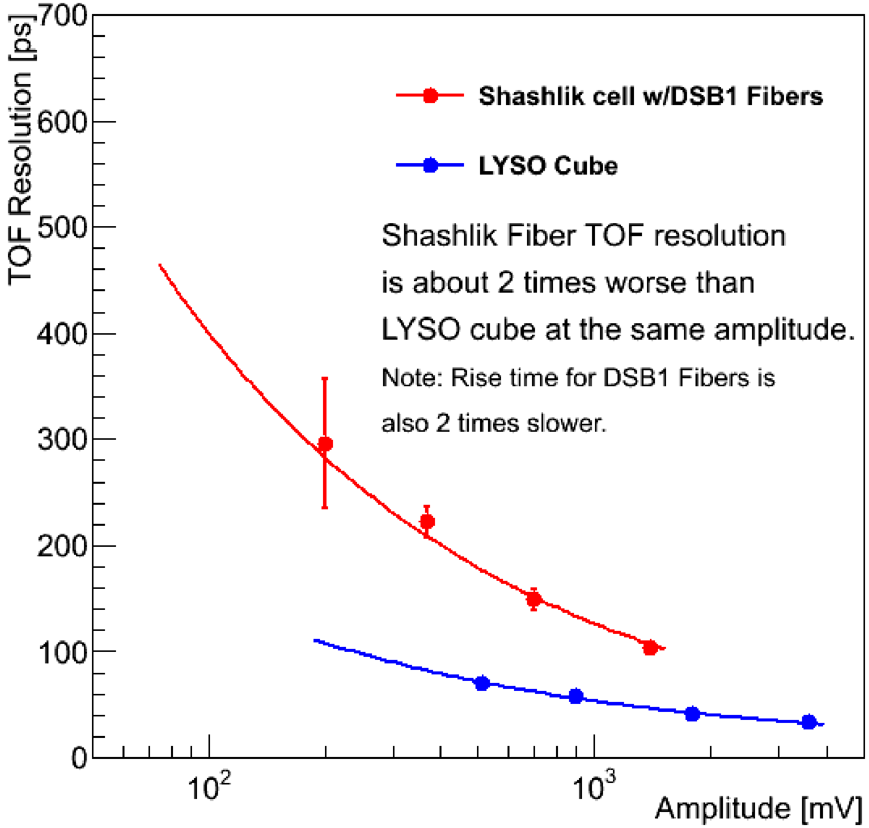
Impact of the WLS material





- Compare pulse shapes of different WLS materials : Y11 vs DSB fibers provided by Randy Ruchti
  - Significantly faster rise time with DSB (~2.4 ns) compared to Y11 (~7.1 ns).
- From detailed MC simulation and ray tracing : Pulse shape can be described by WLS time constant and scintillation decay constant.
- Timing resolution expected to scale accordingly.

Time resolution Shashlik



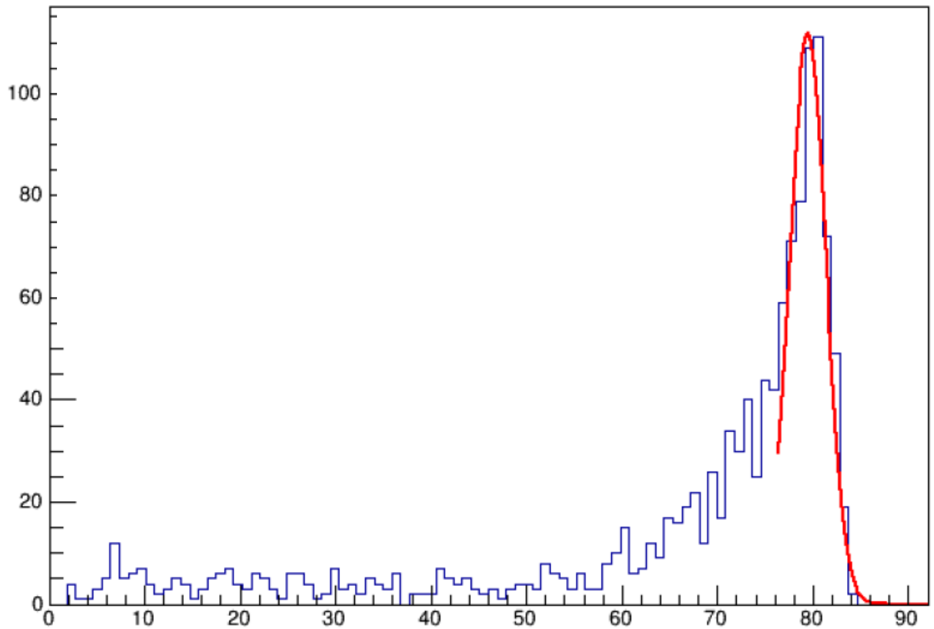
- Observe 1/√E dependence of time resolution
- Performance difference can be attributed to WLS rise time.
- Contributions from reference time measurement etc.:~20 ps
- Few 10 psec resolutions shown to be achievable with Shashlik setup
- Effects of optical transit time jitter sub-dominant at current performance.

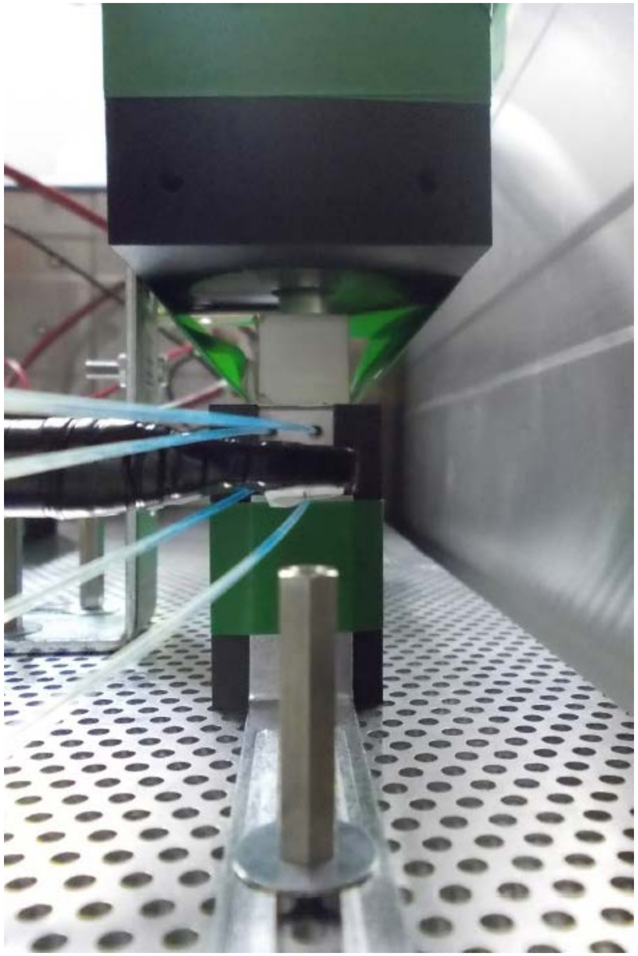
Future plans

- **Optimize light output onto photo detector:**
  - **Shorter WLS fibers, thicker fibers & alternative light extraction**
  - **Test capillaries with fast WLS as soon as available**
- **Better time reference:**
  - **Need order few ps tag on the incoming particle**
- **Use full matrix to ensure shower containment:**
  - **Relative time resolution among adjacent channels.**
- **Optimize pulse reconstruction.**
  - **Current results use rising edge only: pulse shape fits found to gain 10% to 20% performance.**
- **SiPM/GaInP photosensors**
  - **Optimization of the PCB board in collaboration with FNAL experts**

Future – In Stock

- Recent test beam at CERN at higher energy and cleaner beam.
- Energy resolution from Shashlik compatible with single cell resolution of a 4x4 prototype.
- Time resolution scaling as expected.





Summary

- Precision Timing can play a significant role in PU mitigation @HL-LHC.
- LYSO based detectors – as eg. a LYSO/W Shashlik calorimeter - can achieve a time resolution of order 10 ps.
- Strategy : Benefit from large number of photons to improve timing precision.
- New type of calorimeter (SEC) under development at FNAL, in collaboration with UChicago and FNAL