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Precision Timing Calorimeter for High Energy Physics

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Outline

- High Energy Physics motivation for pursuing precision timing in calorimeters
- Physical processes that affect precision timing (TOF resolution)
- Experimental beam test results (FTBF, CERN)
  - LYSO-based sampling calorimeter
  - LYSO-Tungsten Shashlik calorimeter
- Laser tests at Caltech
- Summary

Physics Motivation for Precision Timing

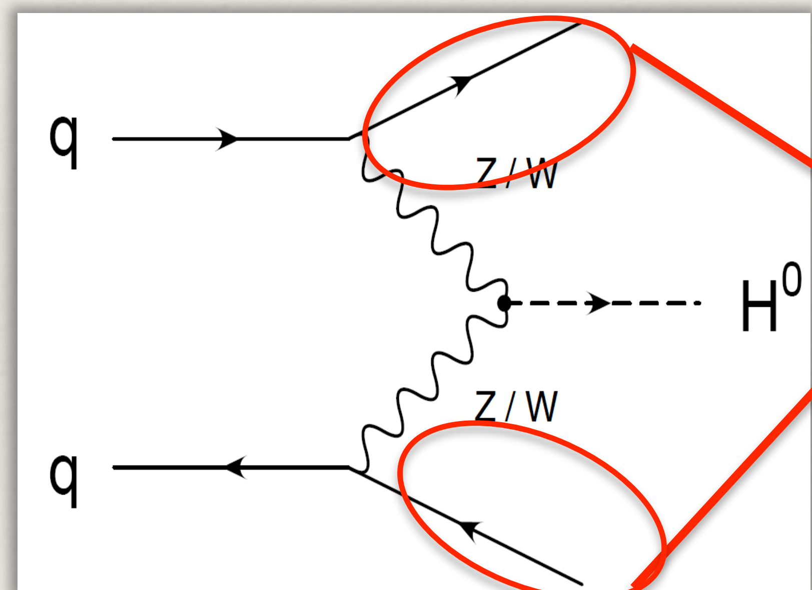
High-Luminosity Large Hadron Collider (HL-LHC)

collect more data (3 ab^{-1}) ⇒ higher instantaneous luminosity ⇒ higher average primary interaction per bunch crossing (PU)

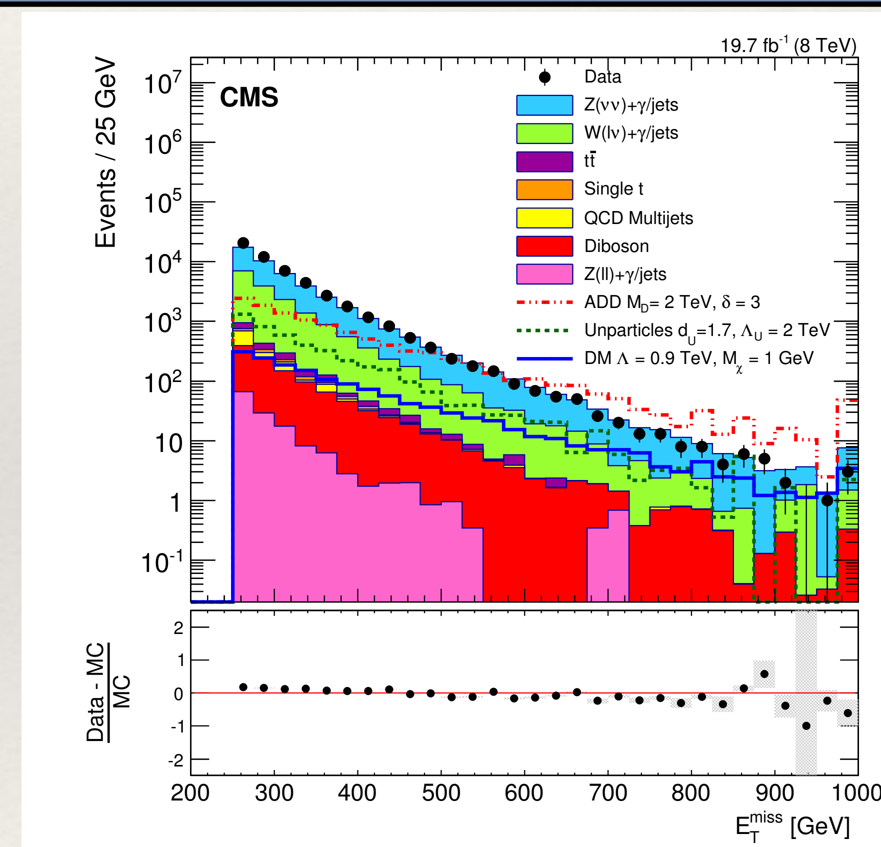
Goals

<u>Precise measurements of Higgs properties</u>:
- couplings, tensor structure, rare decay
- role in EW-SB ($W_L W_L$ scattering)

<u>Explore signals of new physics</u>:
- Supersymmetry, DM direct production
- Many analyses require <u>jets</u> and <u>MET</u>



forward jets



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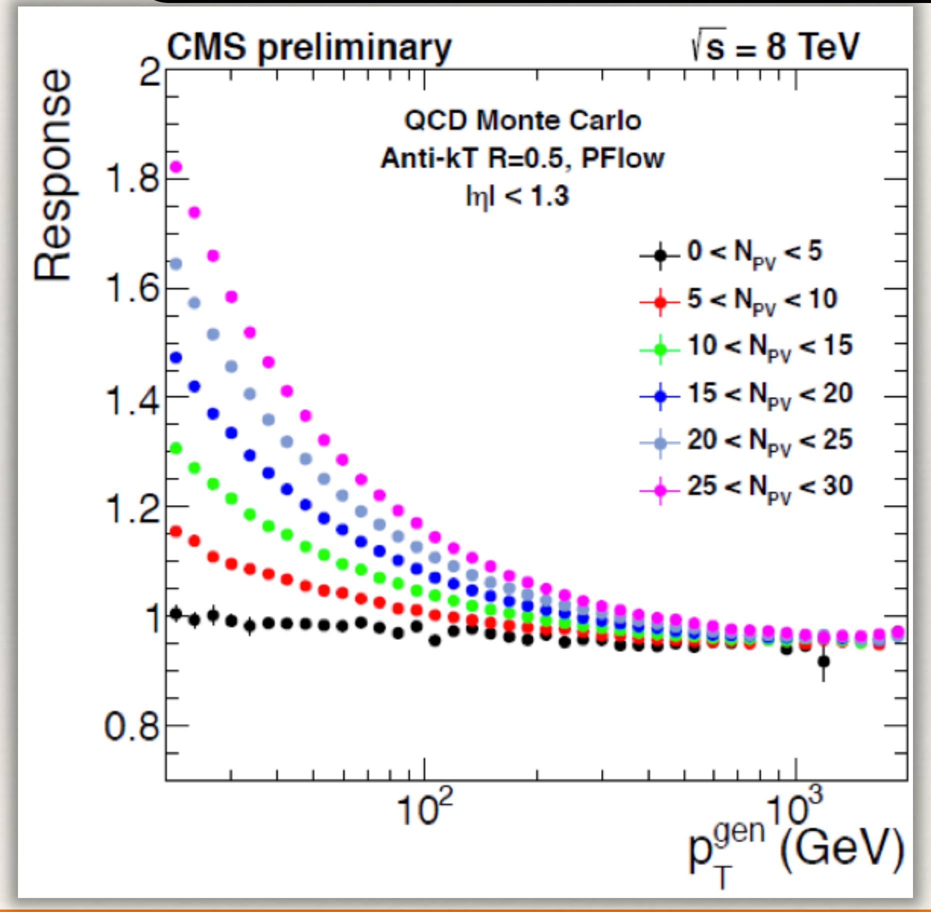
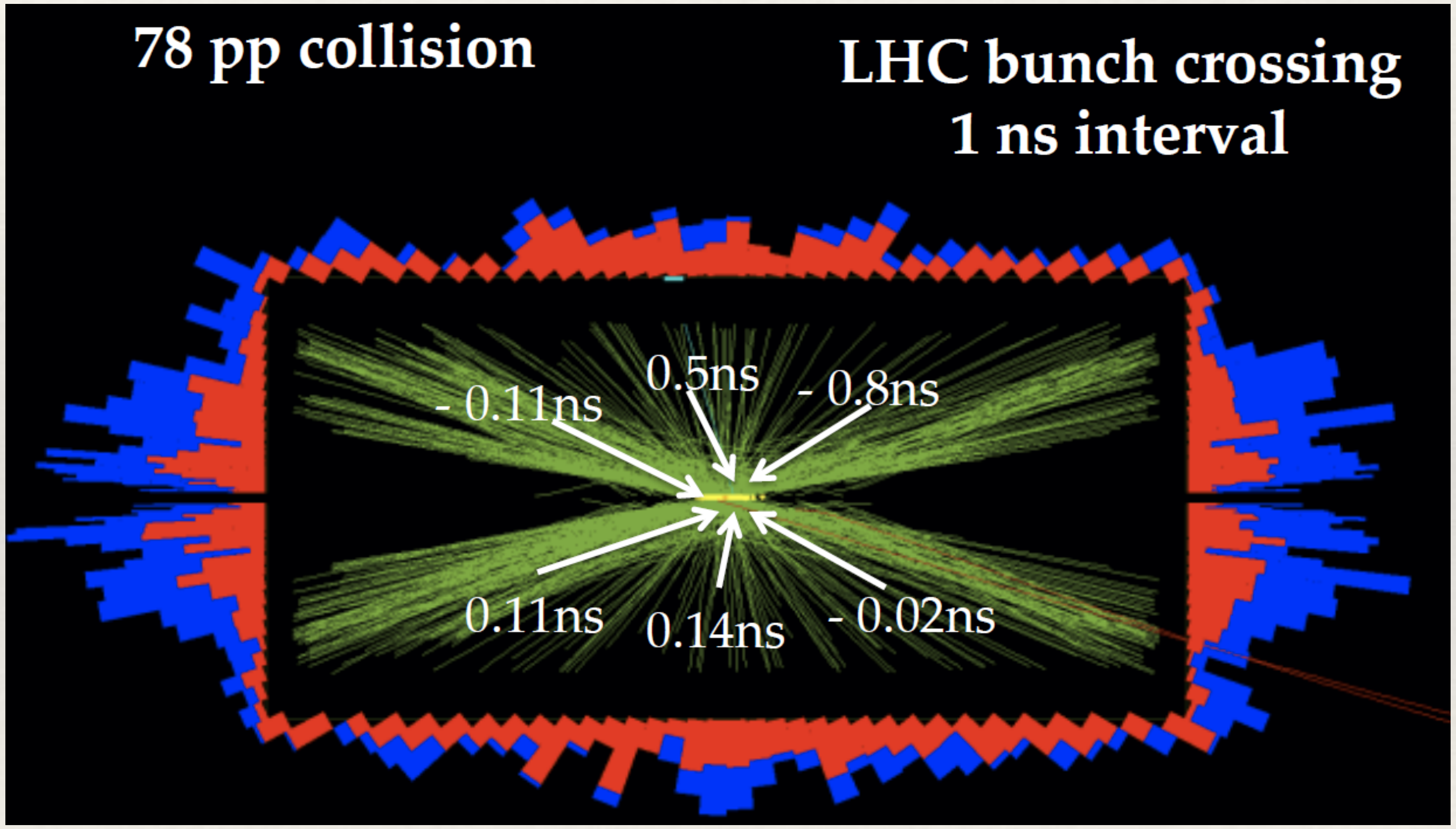
Physics Motivation for Precision Timing

Challenges

<u>Collect more data to increase LHC reach</u>:

- Pileup interactions up to 140
- Key measurements will be affected by this harsh environment





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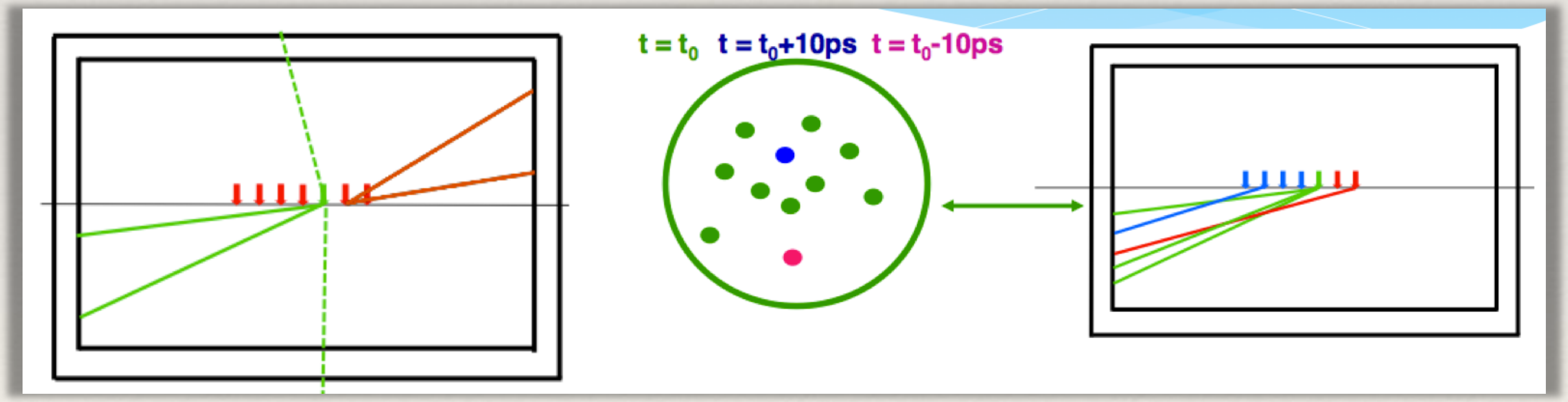
Precision Timing Calorimeters

Calorimeter with time resolution of the O(20-30) ps

- Allows a $H \rightarrow \gamma\gamma$ vertex reconstruction with approximately 1 cm resolution
- Reduces pileup (PU) energy by a factor of 5-10

Possible physics applications of timing information

- *Object level*: identify forward PU jets (improve VBF higgs and WW scattering)
- *Single hit level:* e.g timing-base ECAL clustering cleaning
- Spatially separate overlapping vertices that corresponds to different time



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Precision Timing Using Crystal

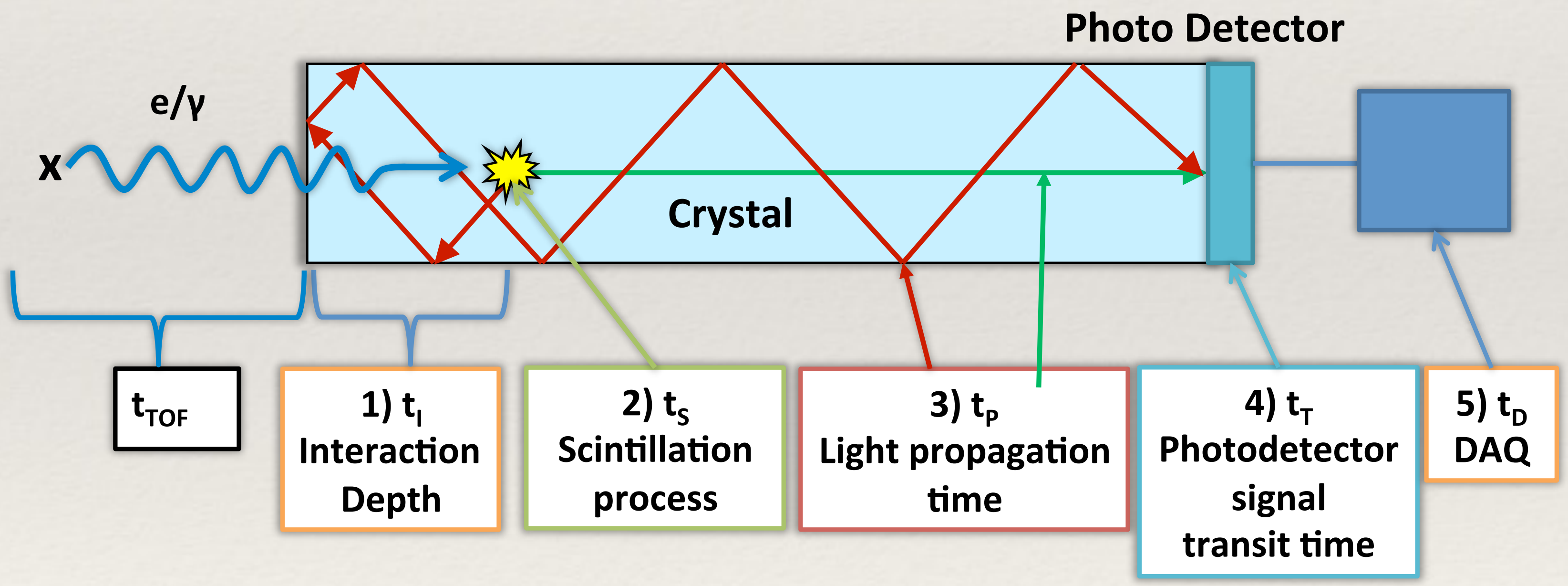
TOF resolution driven by a number of different effects

- Main effects can be approximately factorize
- EM shower development (t_I): shown to be **less than 13 ps**
  (A. Ronzhin et. al. NIM-A, vol 749 p.65-73, new paper accepted by NIM-A)

We focus our studies on **scintillation** and **transit time (t_S and t_T)**

Setup allows to control:

Photodetector jitter (t_P) at the 10 ps level and DAQ resolution (t_D) to about 6ps



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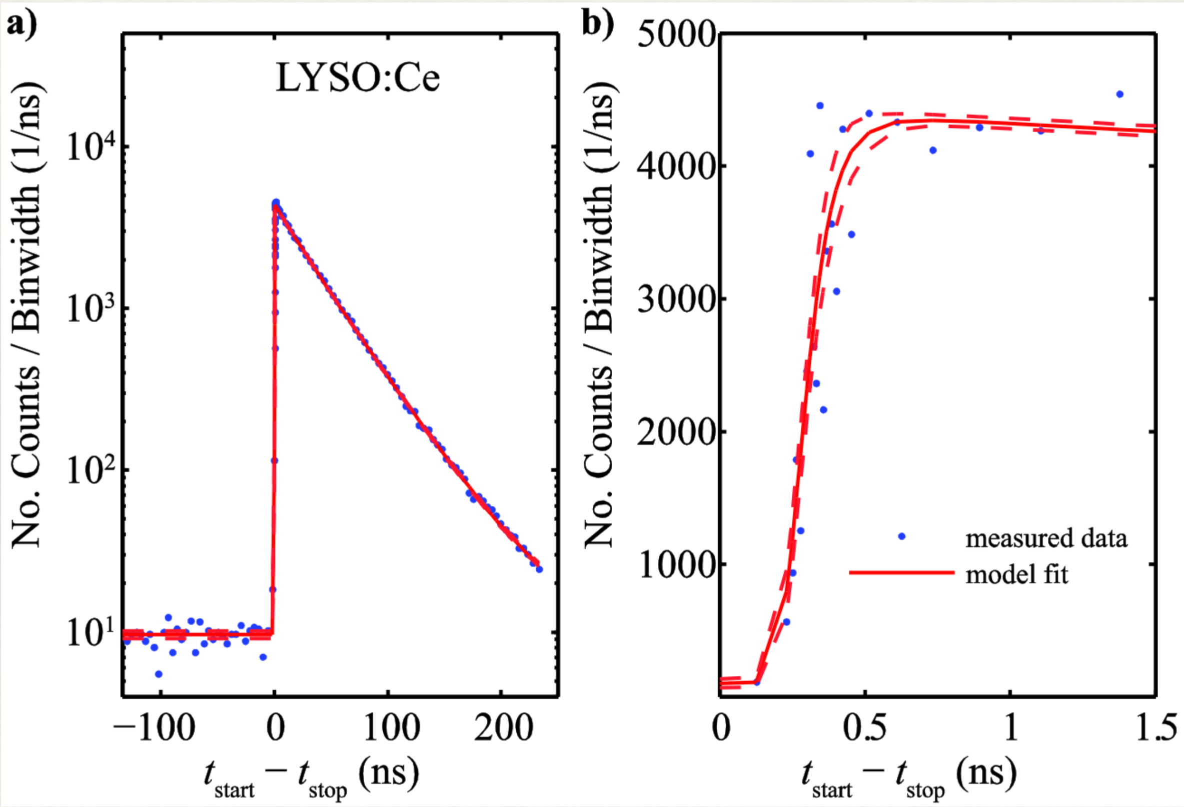
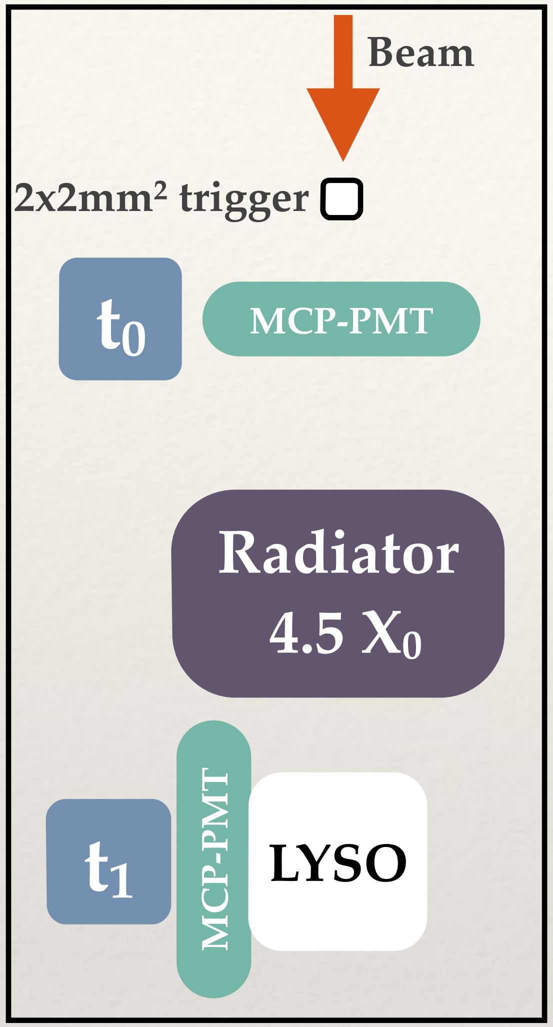
Scintillation Light Time Spectrum

- Scintillating crystals are often classified according to its time decay constant (τ_d). This is of the order of **tens of ns; PWO, LYSO ≈ 40 ns**
- In a calorimeter: timing information is obtained from the leading edge of signal; thus the **rise time of the light** output is the key quantity
- LYSO scintillation light properties:
  - Light output rise time t_R **< 75 ps - Light yield ≈ 35,000 photons/MeV**

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



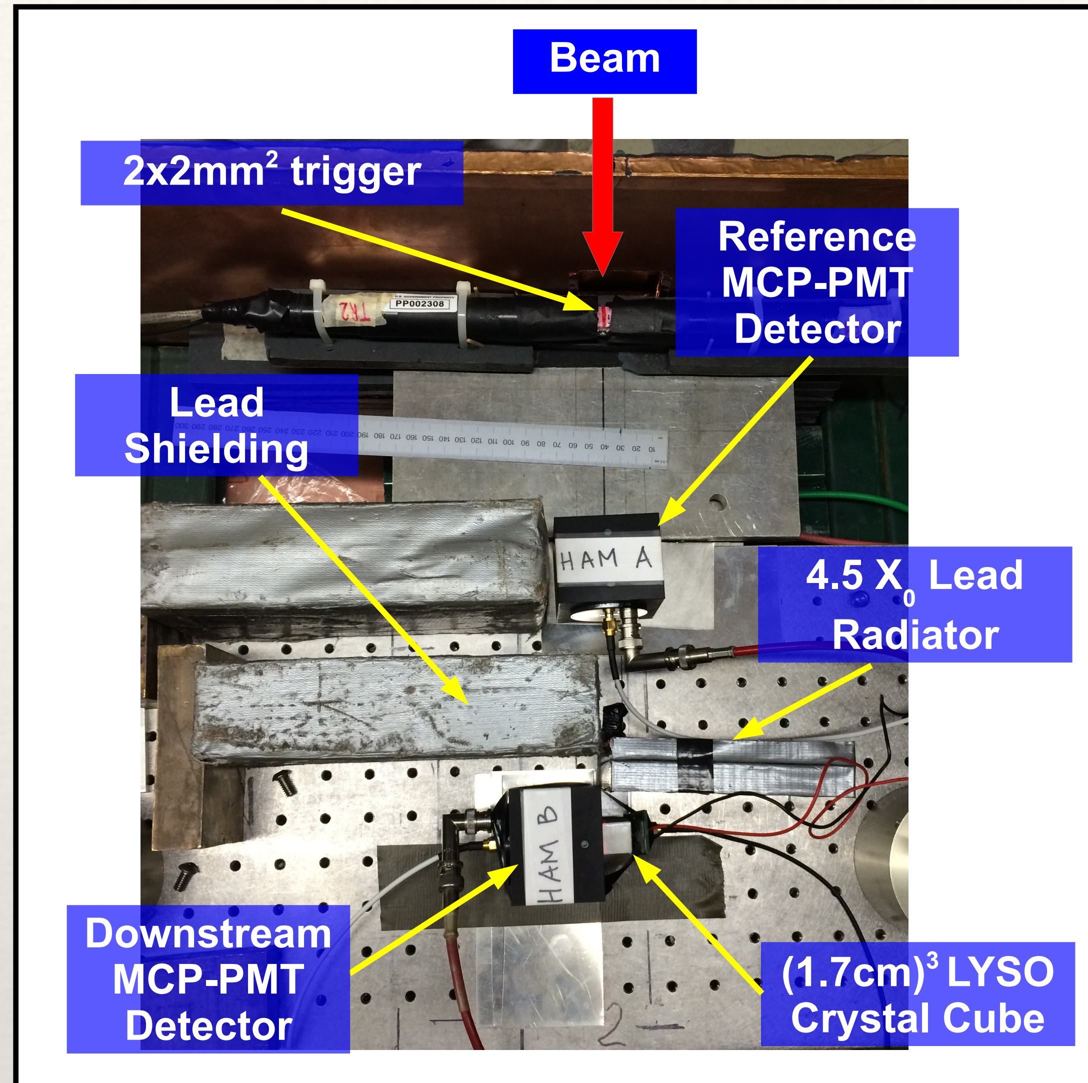
LYSO-based Sampling Calorimeter



All measurements were carried out using electron beams

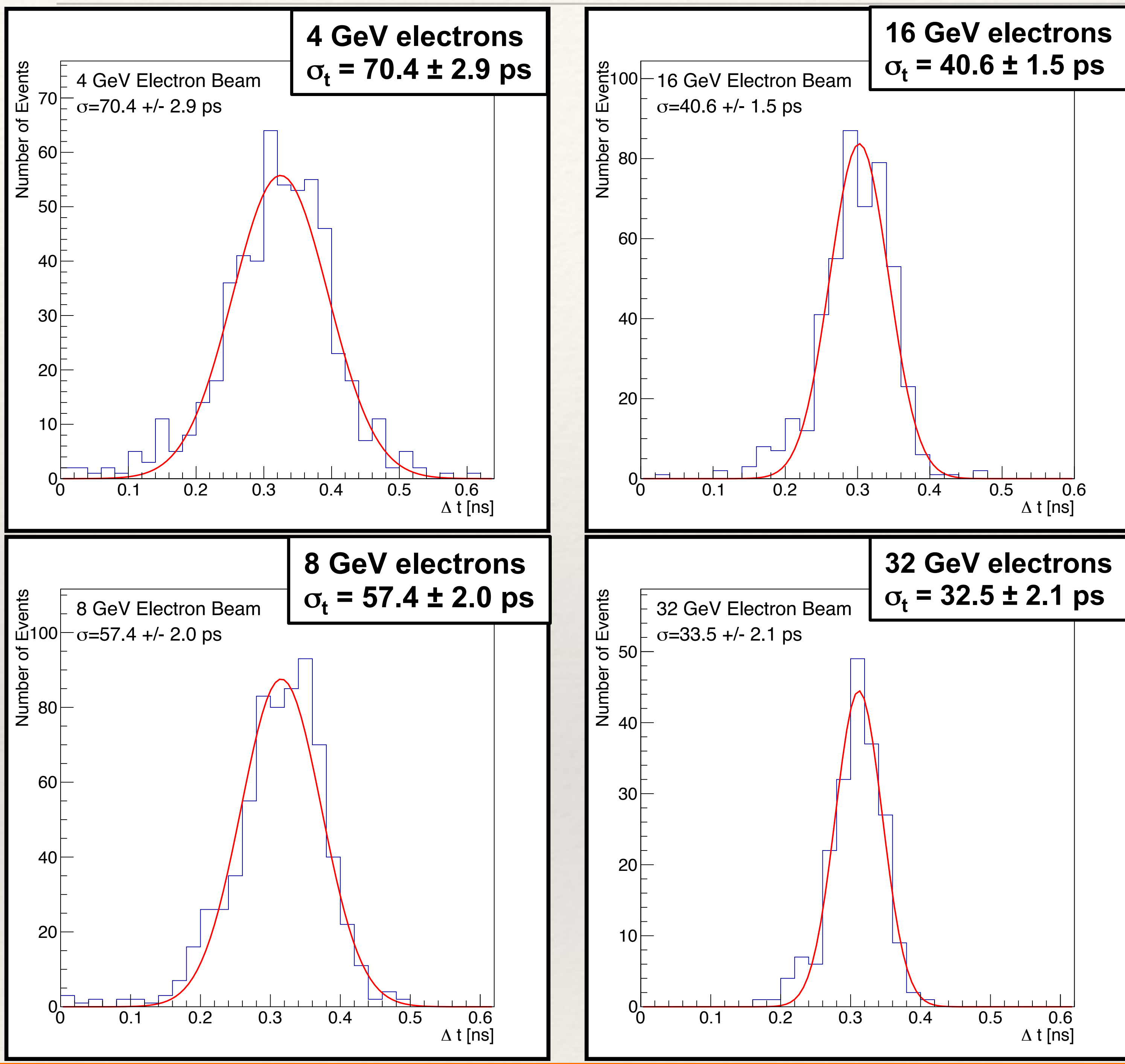
All measurement carried out at the Fermilab Test Beam Facility (FTBF)

DAQ = DRS4 wave digitizer + laptop



Goal: **study the effect of scintillation light by reducing optical transport.**
Electromagnetic Shower developed in the lead radiator, then sampled by the LYSO crystal
TOF = t_1 - t_0 (1)

LYSO-based Sampling Calorimeter Results



- Measure **TOF resolution** for different electron energies (4, 8, 16, 32 GeV)
- Measure **33 ps TOF resolution** for 32 GeV electrons
- **TOF resolution**: width of gaussian fit to the TOF distribution (**σ**)

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NIM-A, vol 794 p. 7-4.
doi:10.1016/j.nima.2015.04.013

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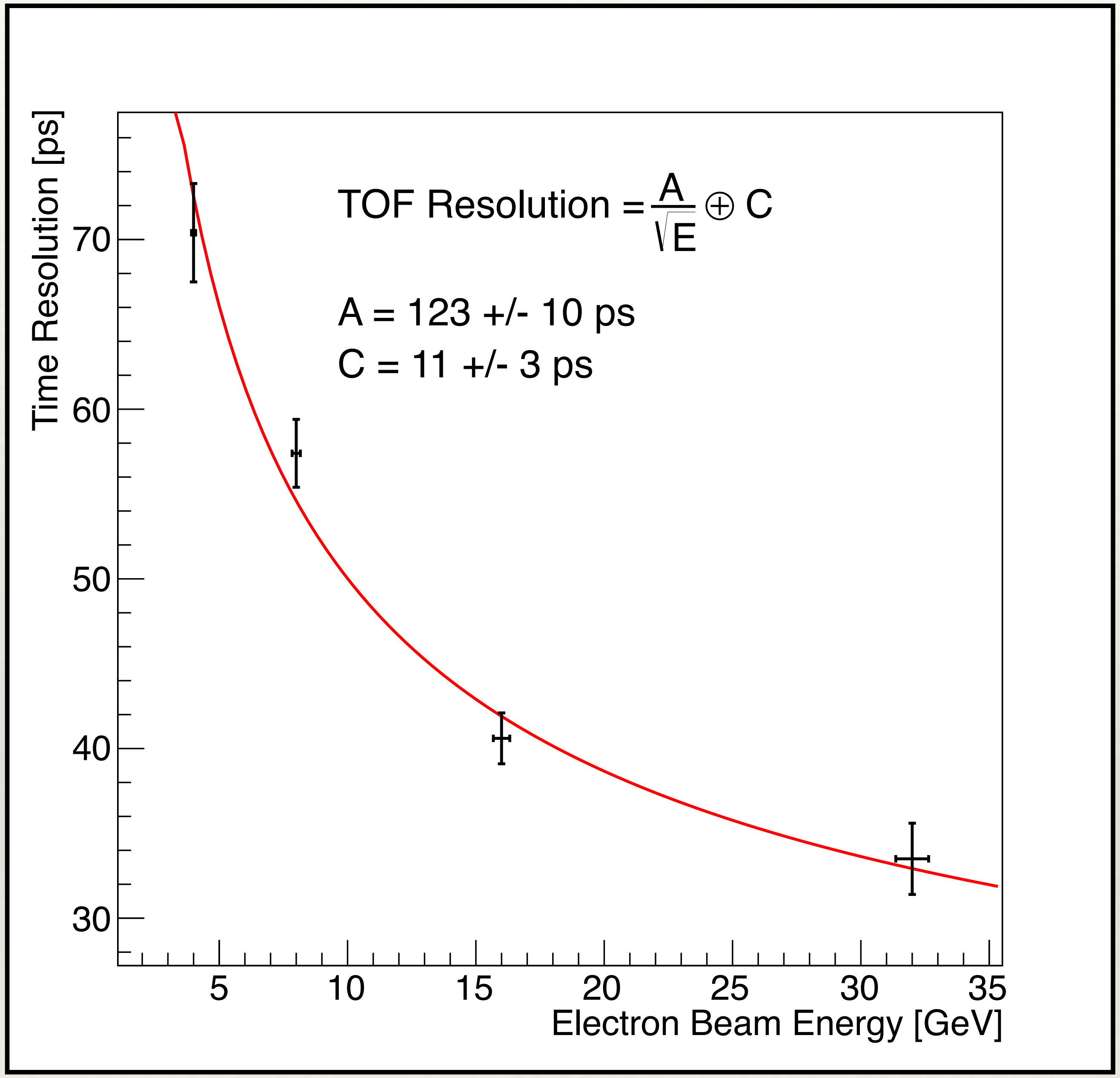
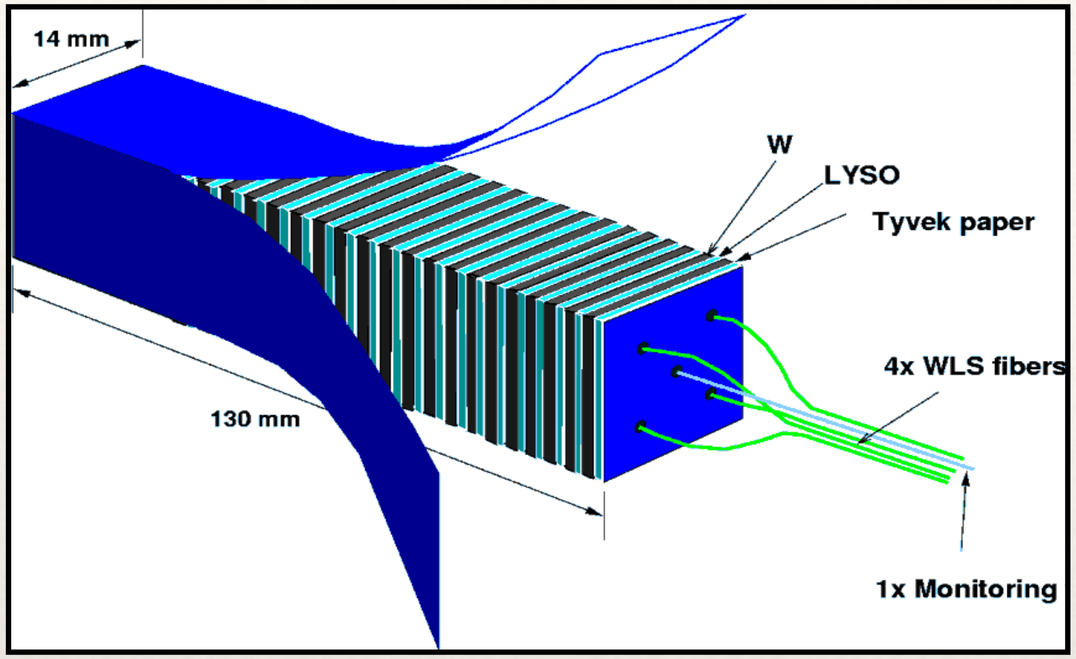
LYSO-based Sampling Calorimeter Results II



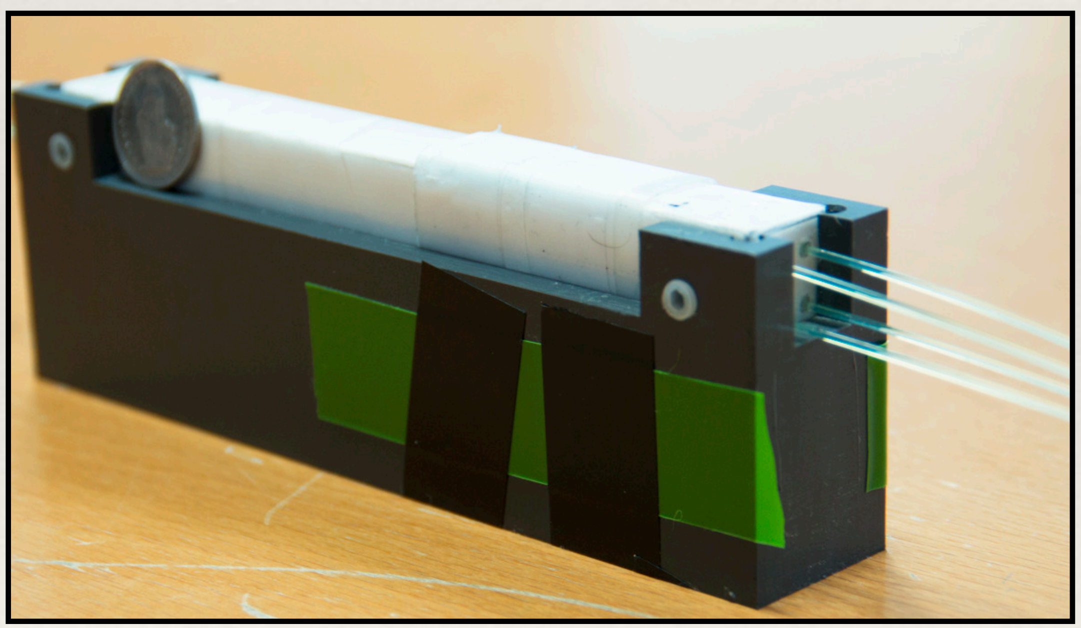
- Observe a **1/√E behavior** for **TOF resolution**
- Fit the TOF resolution distribution to the superposition of an stochastic term and a constant term
- **Summary:** **<u>20-30 ps TOF resolution goal is achievable</u>** for ~50 GeV e/γ objects; provided enough light collection

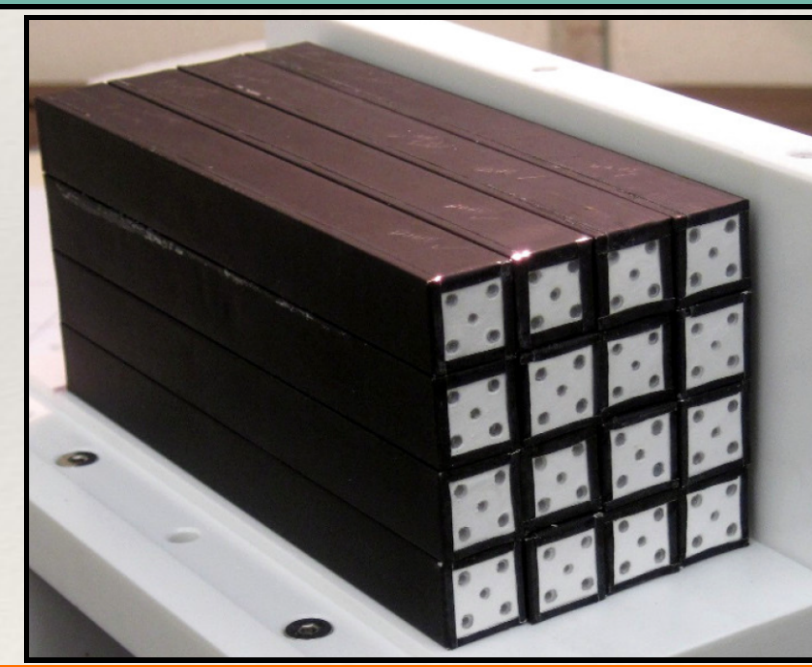
NIM-A, vol 794 p. 7-4.
doi:10.1016/j.nima.2015.04.013

Increased Light Path Complexity

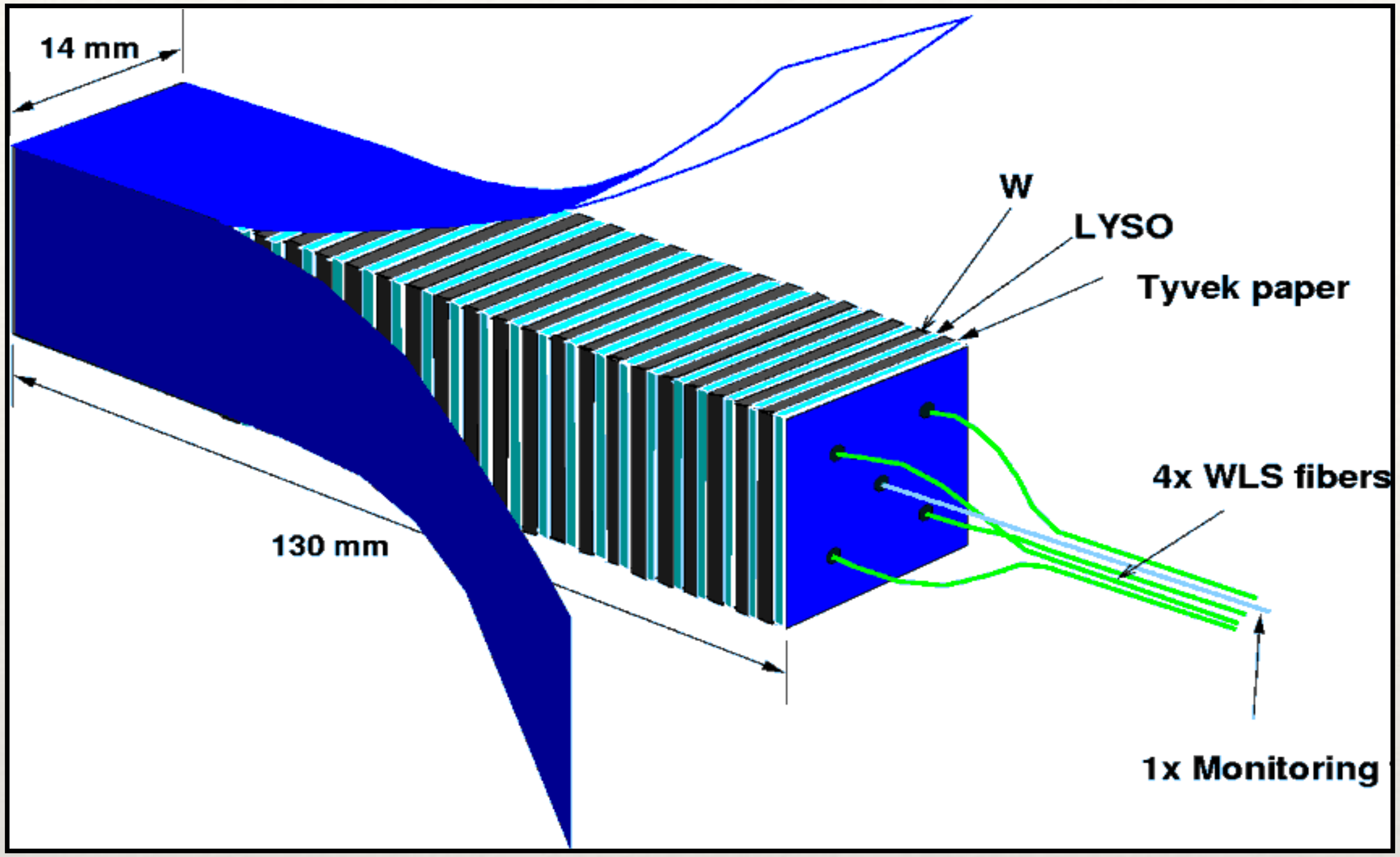


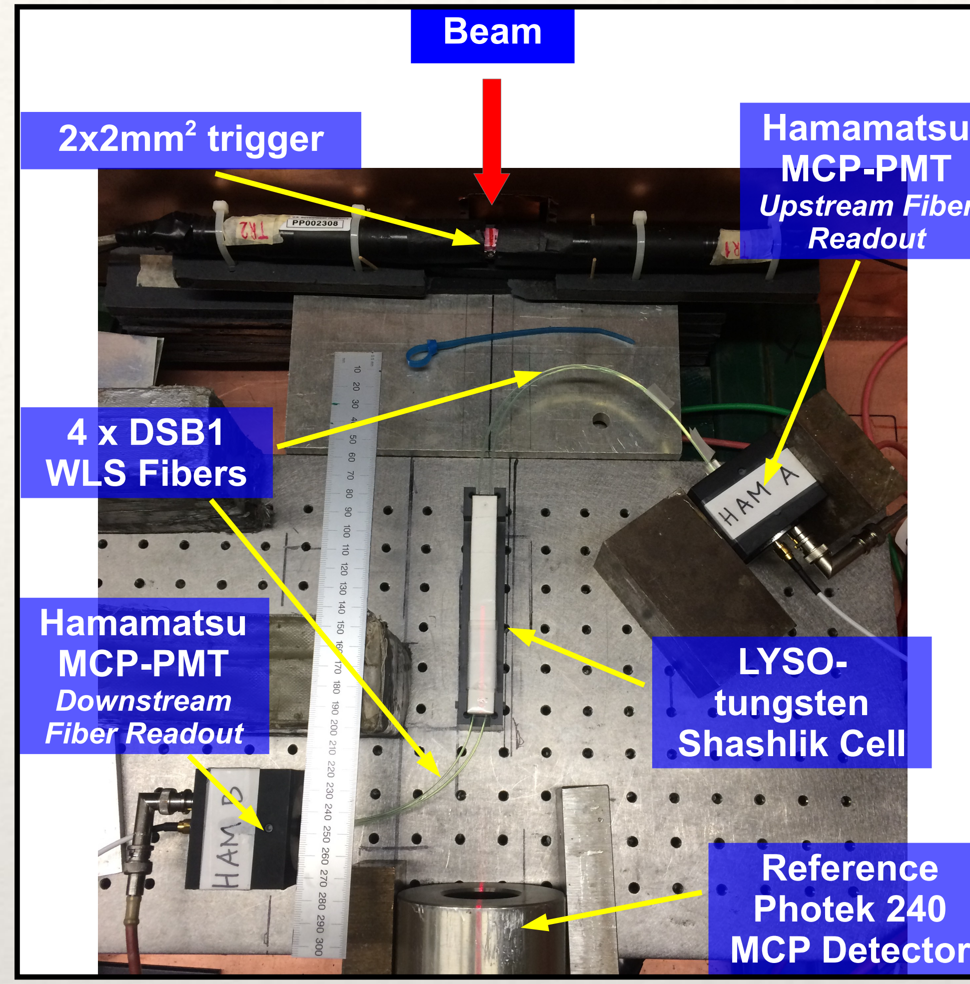
- R&D for HL-LHC on LYSO/W shashlik calorimeter
- Radiation hard in HL-LHC up to 3 ab^{-1}
- Energy resolution of $10\%/\sqrt{E} \oplus 1\%$
- Energy resolution performance shown in test beam on a 4x4 matrix
- Use single shashlik cell to test timing performance





LYSO-Tungsten Shashlik Calorimeter





Goal: study the effect of optical transit by increasing the distance traveled by the light

Goal: measure the TOF resolution using WLS fiber and side readout (a la sampling calorimeter)

Build single shashlik module with WLS fibers and MCP-PMT readout

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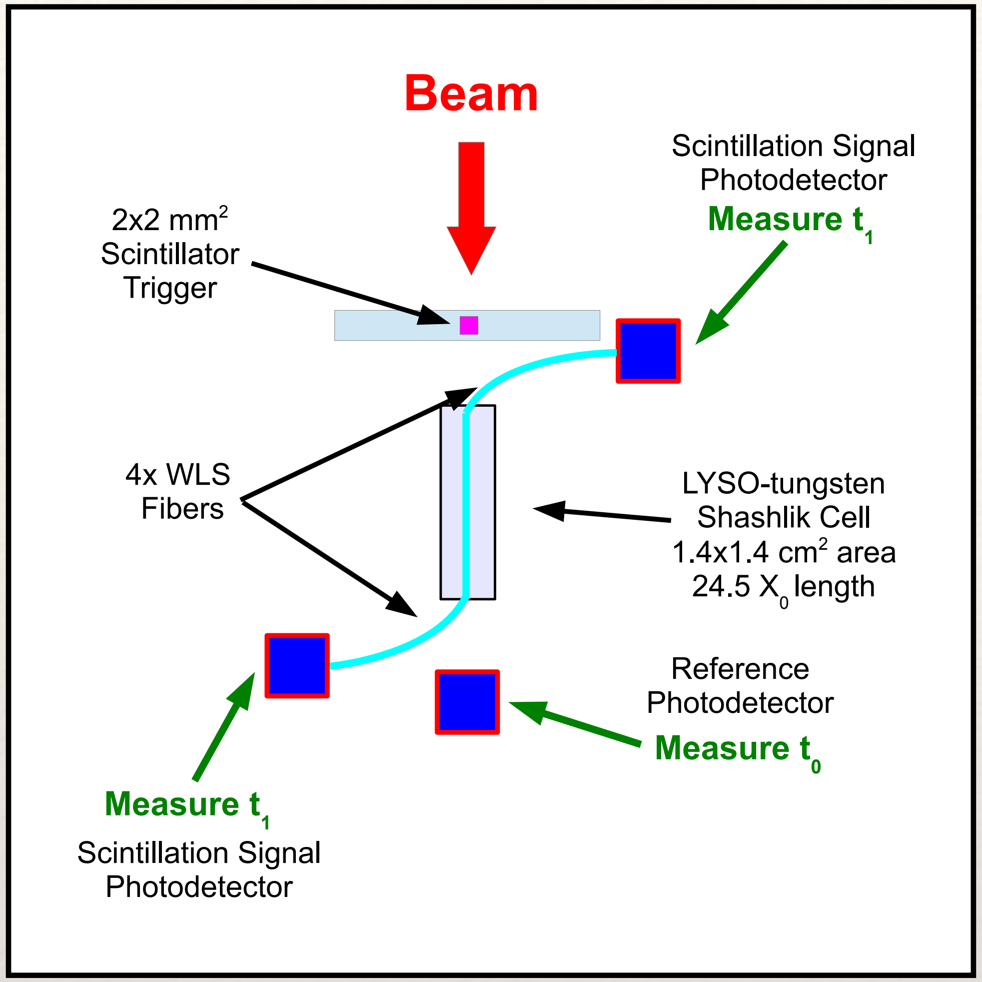
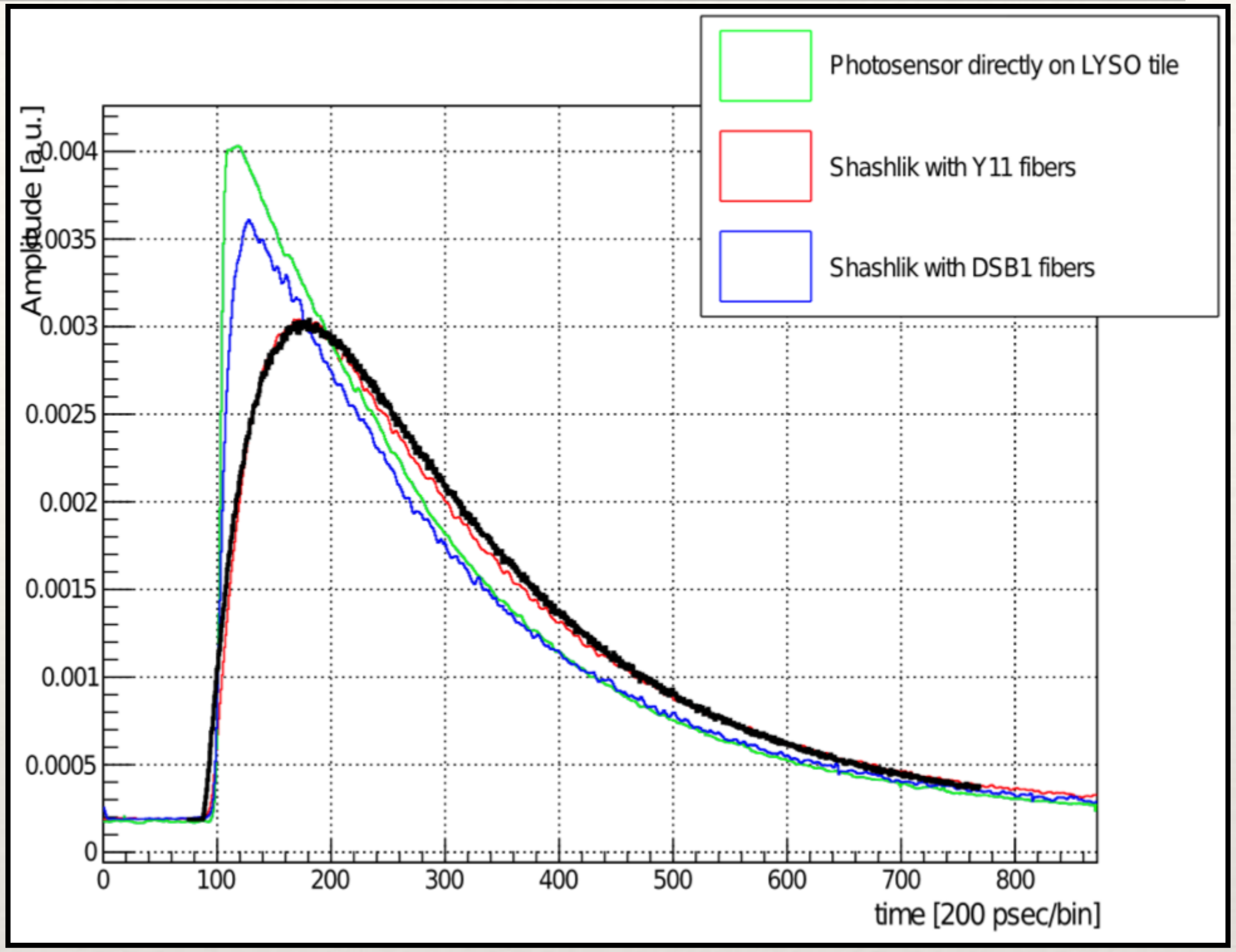
Shashlik WLS fibers Readout Results I





Test the response of different WLS fiber, **particularly the rise time**.

Measure rise times to be ~7.1 ns and ~2.4 ns for the Y11 (kuraray) and DBS1 WLS fibers respectively.

In terms of TOF resolution **the faster (DBS1) fiber performs better**.

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doi:10.1016/j.nima.2015.04.013

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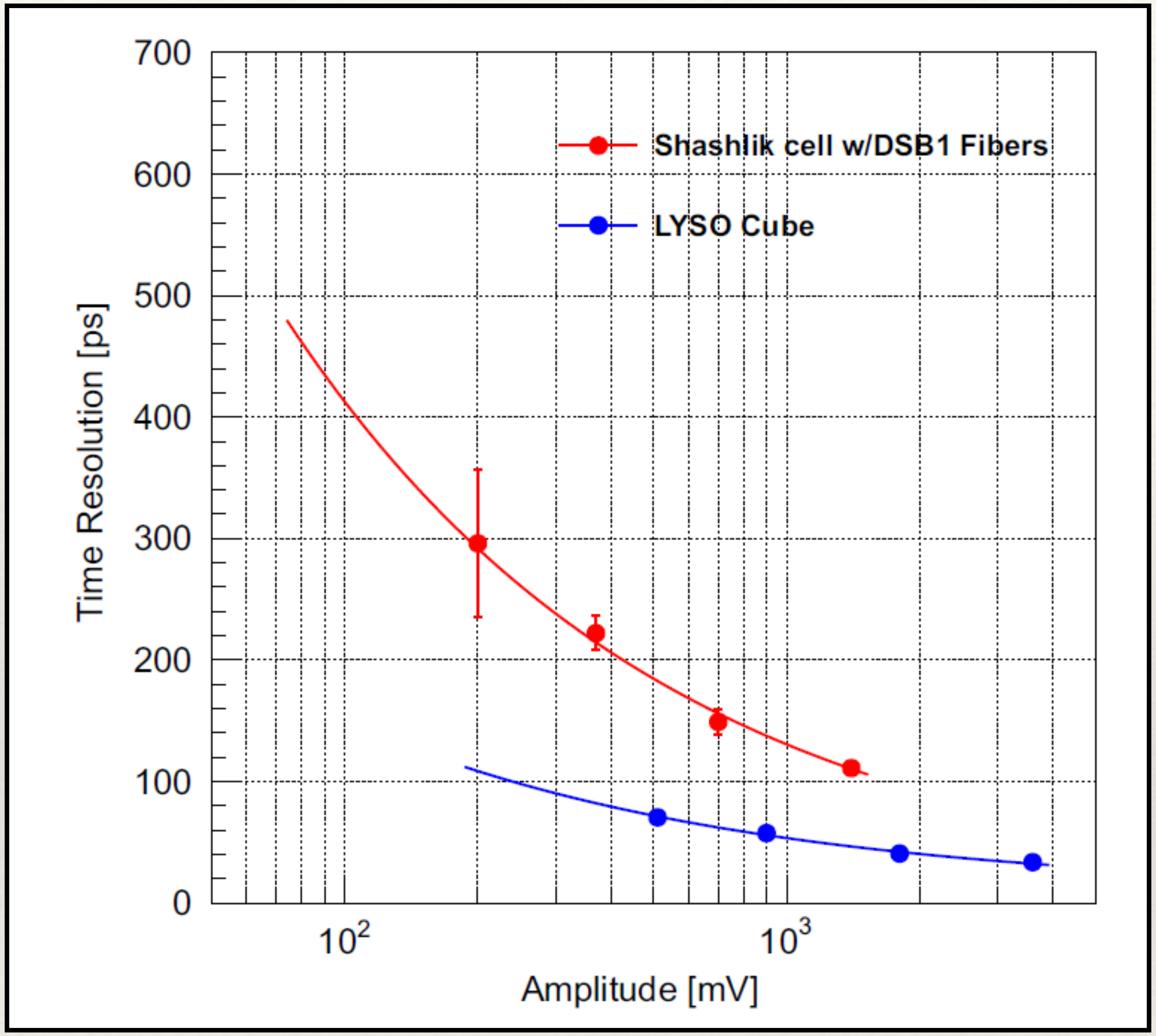
Shashlik Timing Performance



- Performance of LYSO based calorimeters scales with rise time
- Main difference is due to WLS
- **Summary**: few tens of ps TOF resolution is achievable using LYSO bases calorimeters for e/γ objects of ~ 100 GeV

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doi:10.1016/j.nima.2015.04.013

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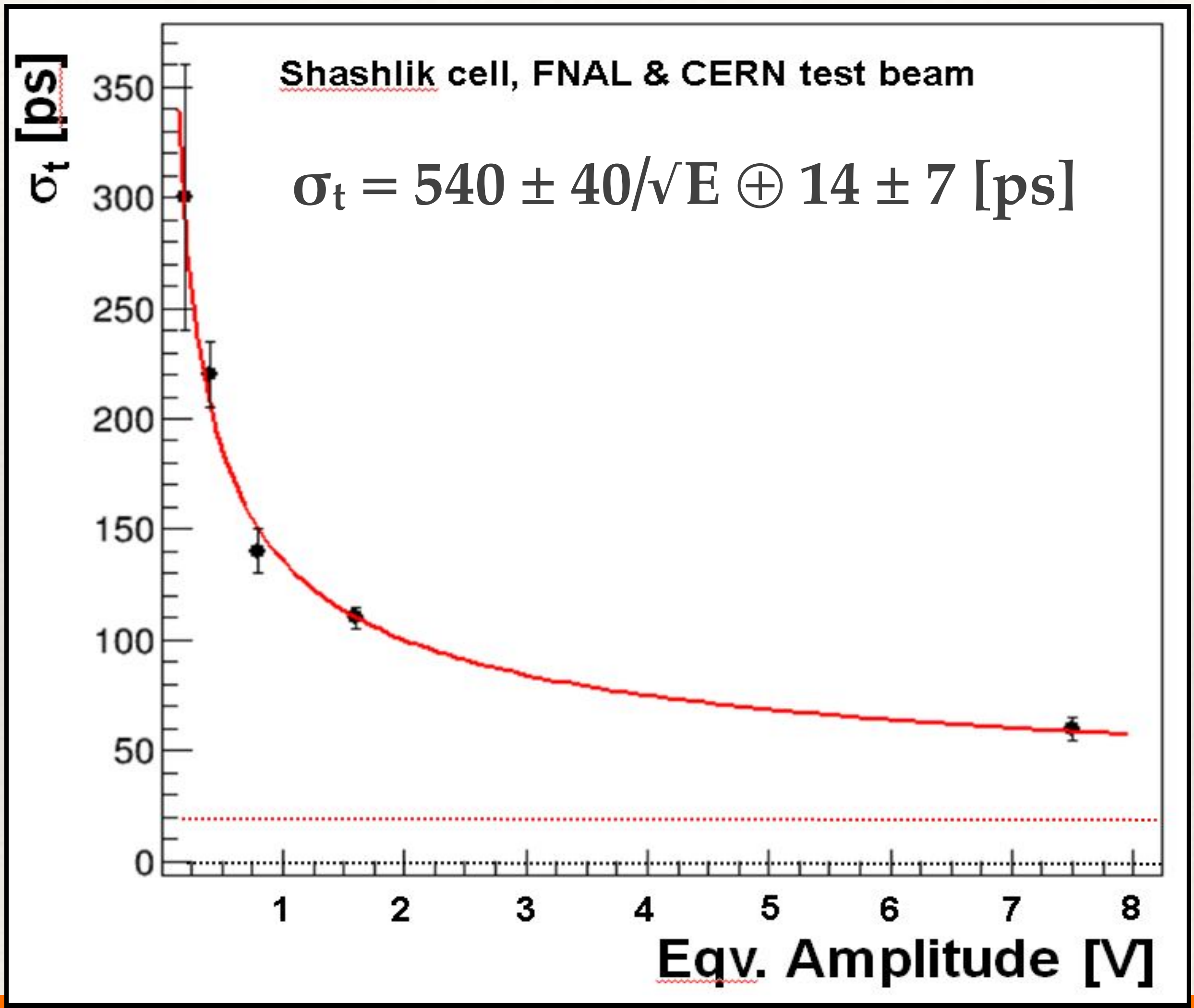
Current Systematic Limits

- Extended measurement up to 150 GeV suggests that systematic limit is of the order of 10 ps
- Fit yields constant term compatible with reference time resolution of 15 ps



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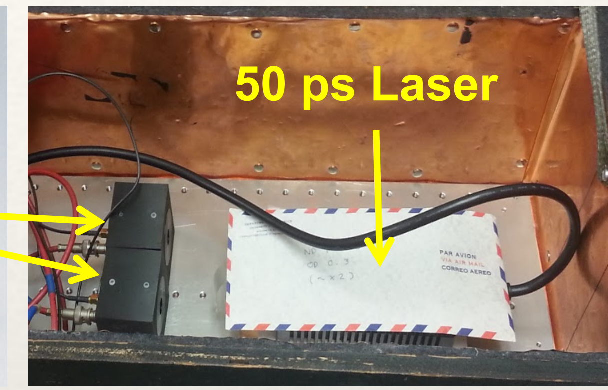
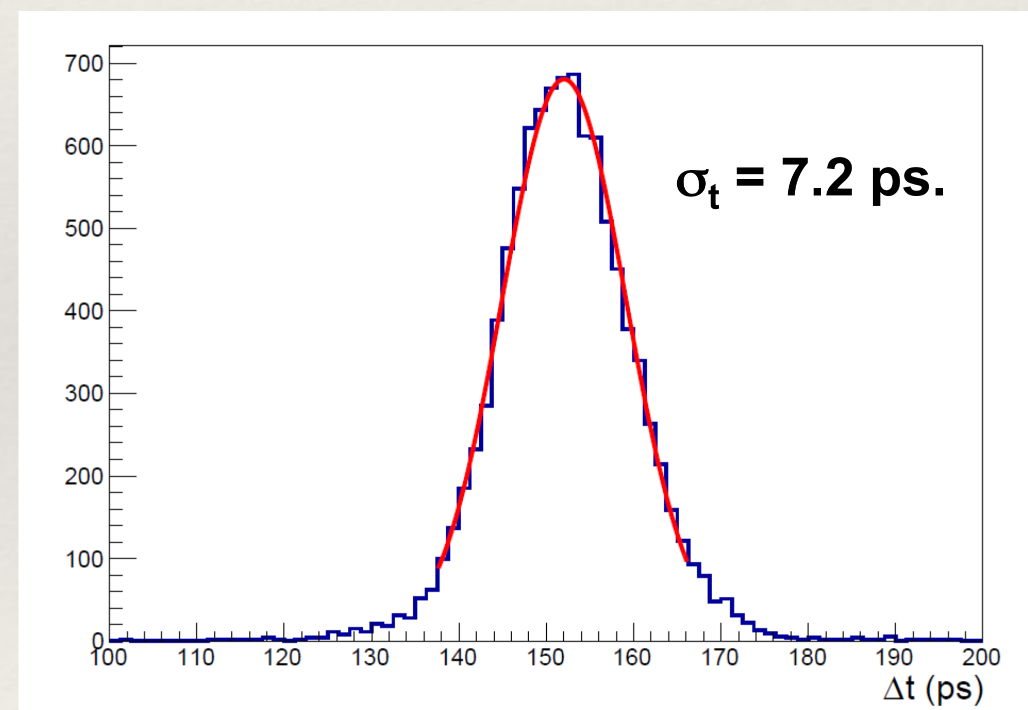
Light Sensing Performance

- Differential time resolution of two MCP-PMTs
- DRS4 read out
- Illuminated with a 50 ps FWHM laser
- $\sigma_t = 7.2$ ps
- Multi-photon timing performance of MCP-PMT approaches read-out limit

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





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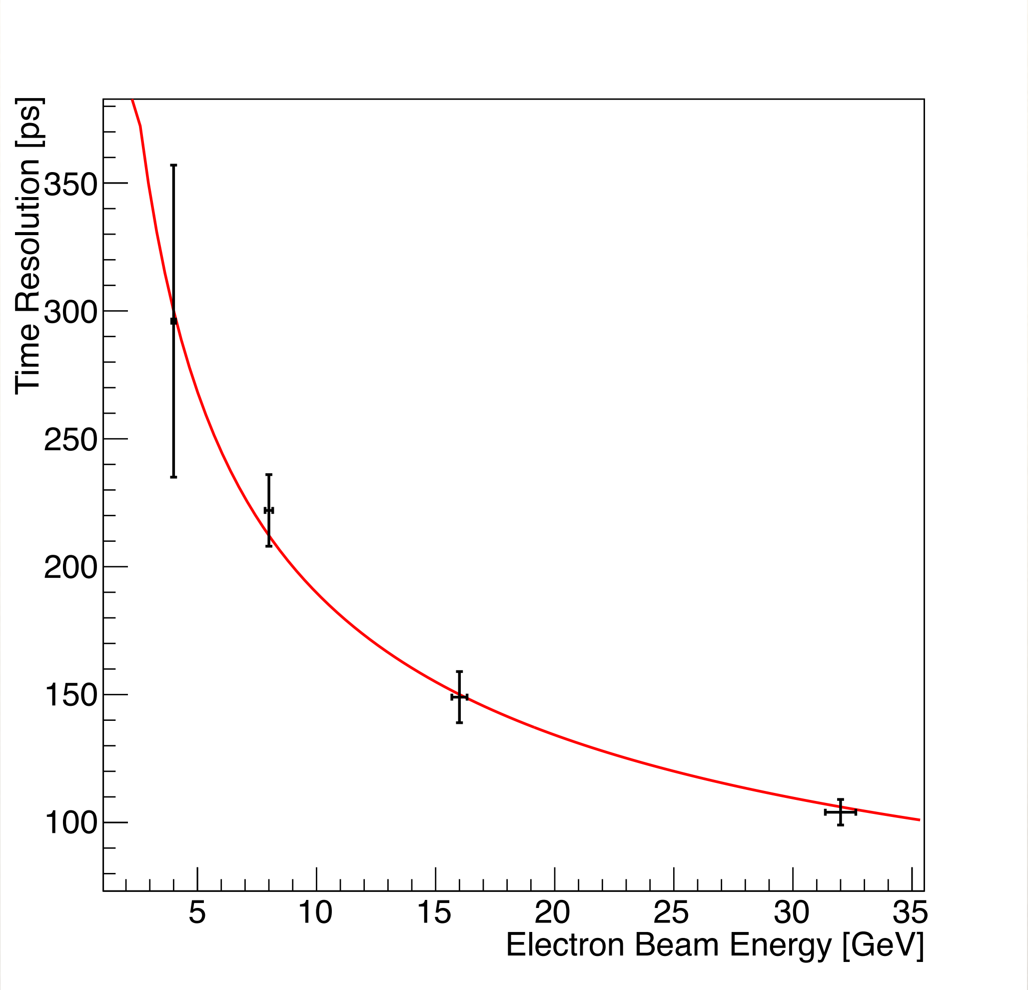
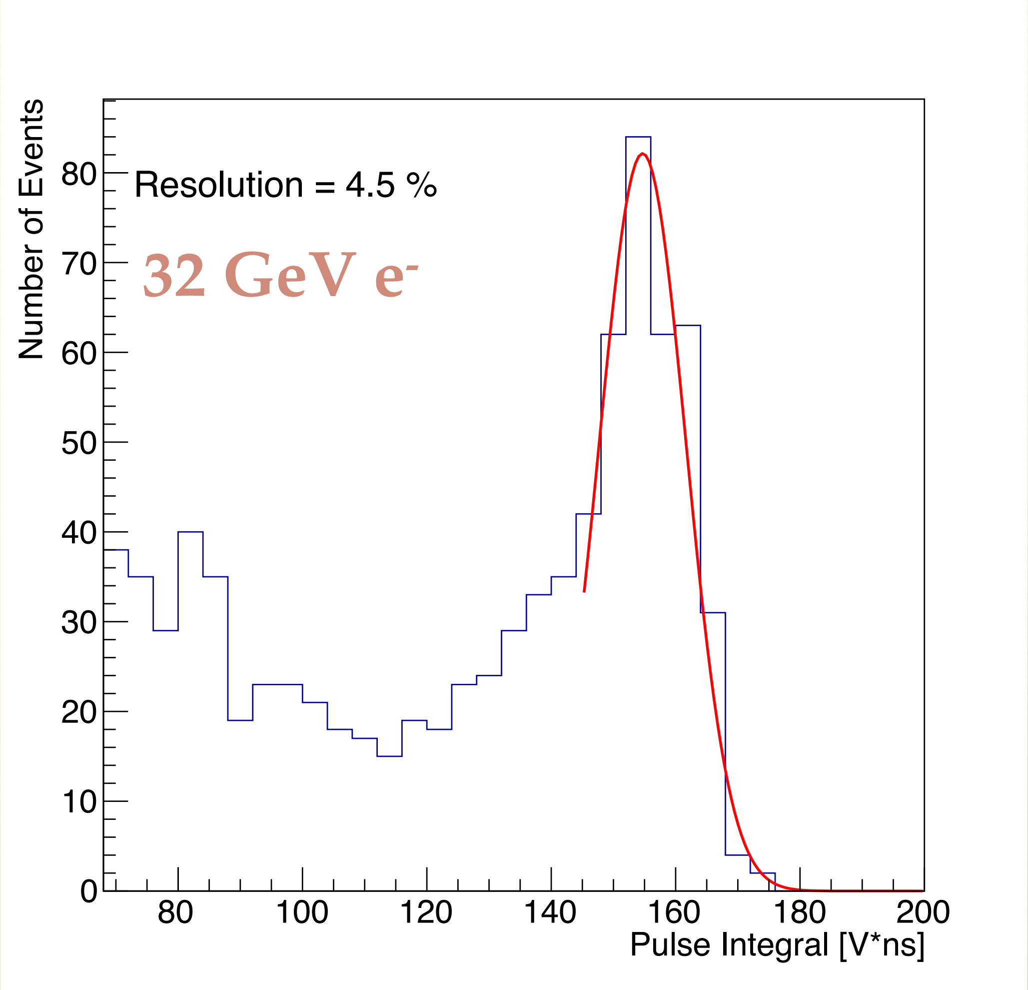
Summary

- Carried out measurement in beam test with standalone LYSO-based sampling and LYSO-Tungsten Shashlik calorimeter prototypes.
- The 20-30 ps TOF resolution goal is achieved using a LYSO-based sampling calorimeter with MCP-PMT and DRS4 read out.
- Study the optical transit time effect on TOF resolution by using different WLS fiber readout and by direct optical coupling to sides of the Shashlik cell.
- Measure ~50/100 ps TOF resolution for a single Shashlik cell using side/WLS(DBS1) read out
- A large scale calorimeter with a time resolution of few tens of ps for pileup mitigation seems achievable

Backups

Shashlik WLS fibers Readout Results II





Use same TOF algorithm as in the LYSO-sampling calorimeter.

Measure a **~4.5% energy resolution** using a single shashlik cell readout by WLS fiber and MCP-PMTs

Observe a 1/√E behavior for the **TOF resolution,** measure ~100 ps time resolution for 32 GeV e^-

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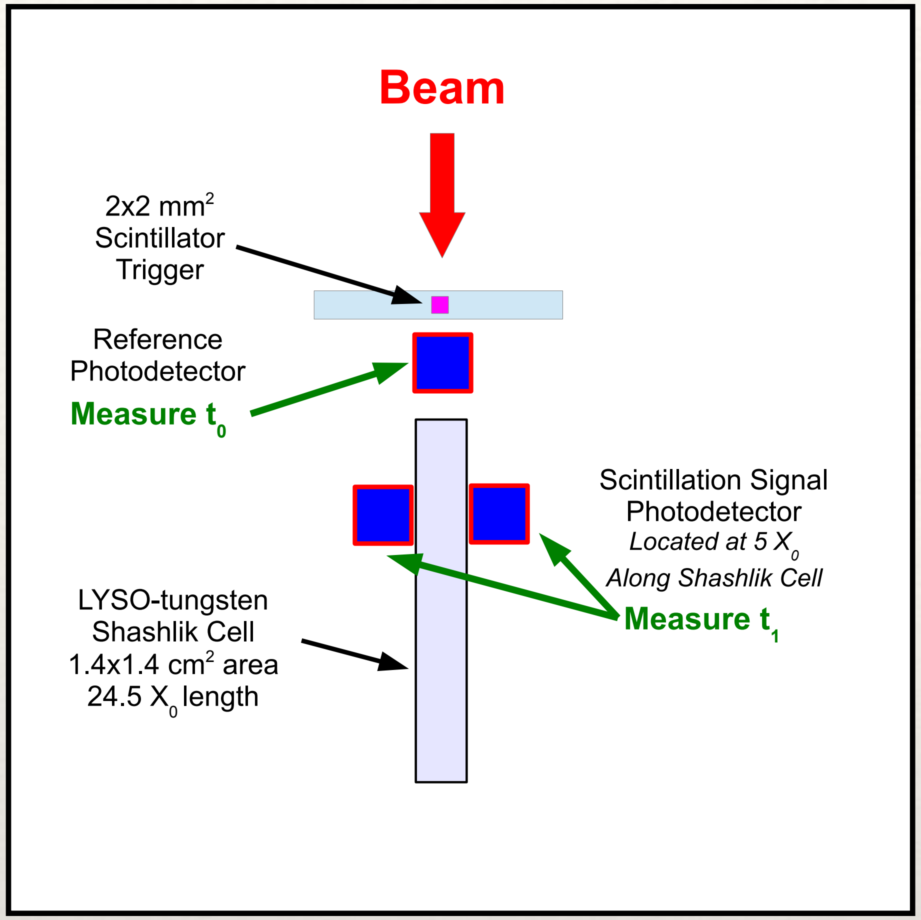
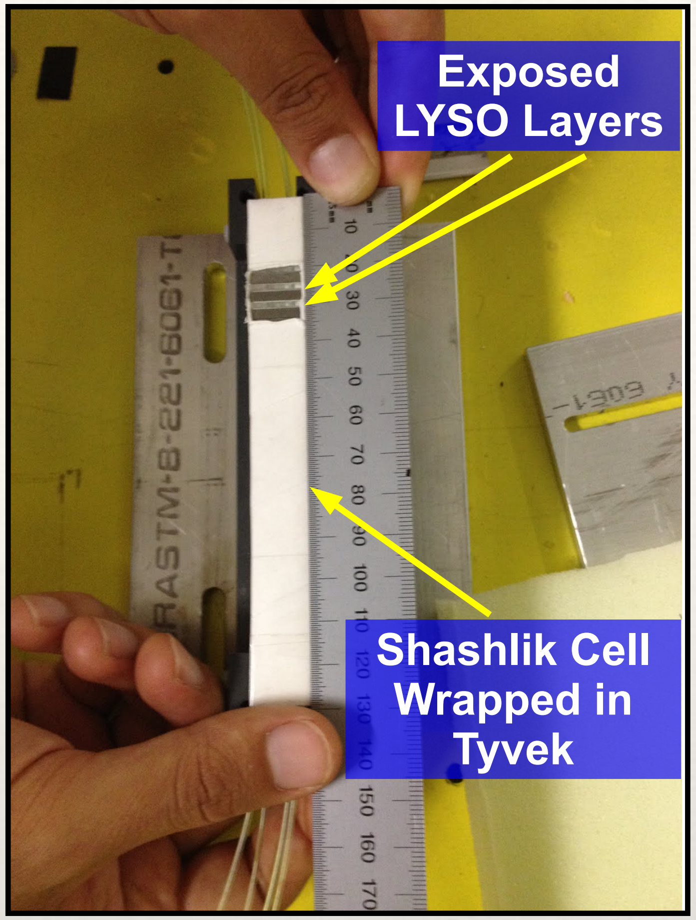
Shashlik Side Readout





Alternative timing readout: direct coupling of photodevice to the edges of the shashlik cell. Decreases transit time; Exposing two LYSO tiles

Similar approach as a sampling calorimeter by **direct optical coupling of MCP-PMTs at ~5X_0**.
Reduces transit time jitter with at the expense of collecting less light.
Energy measurement obtained with WLS fibers

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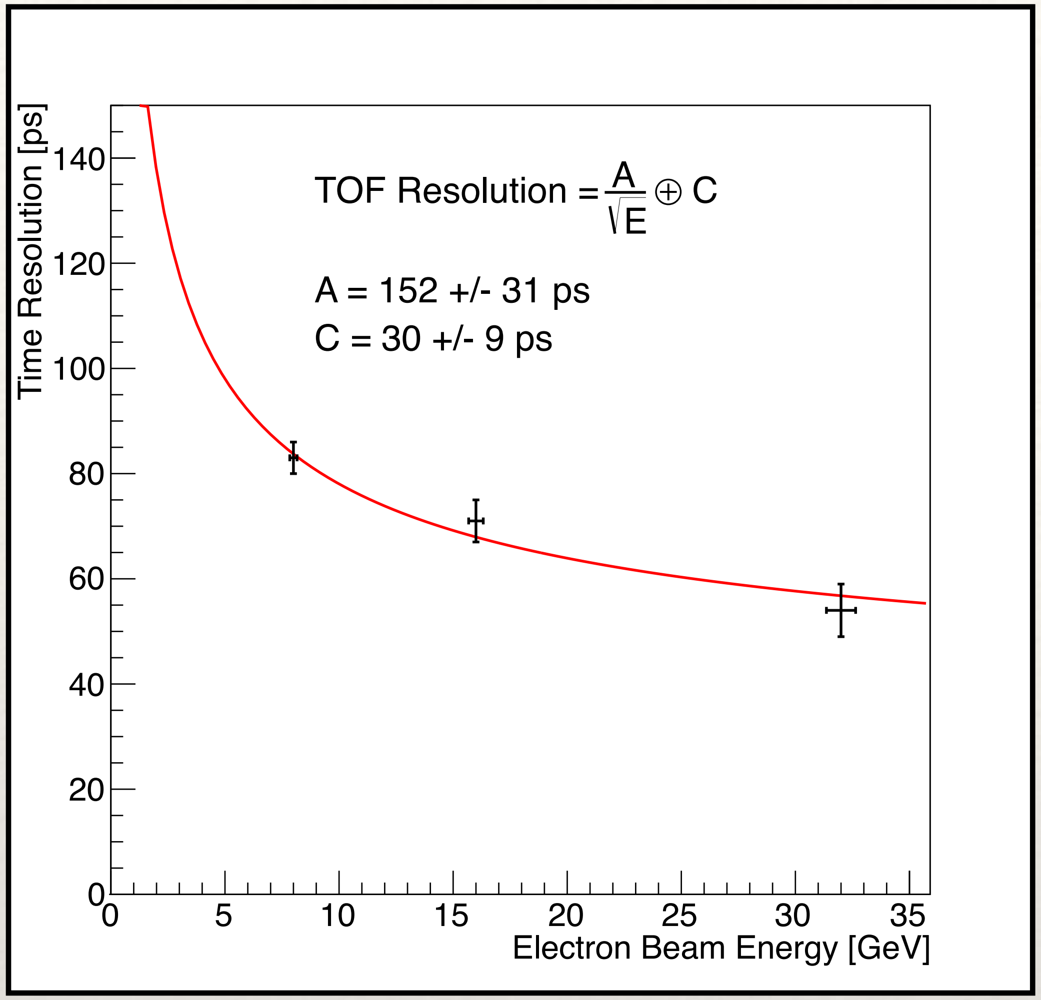
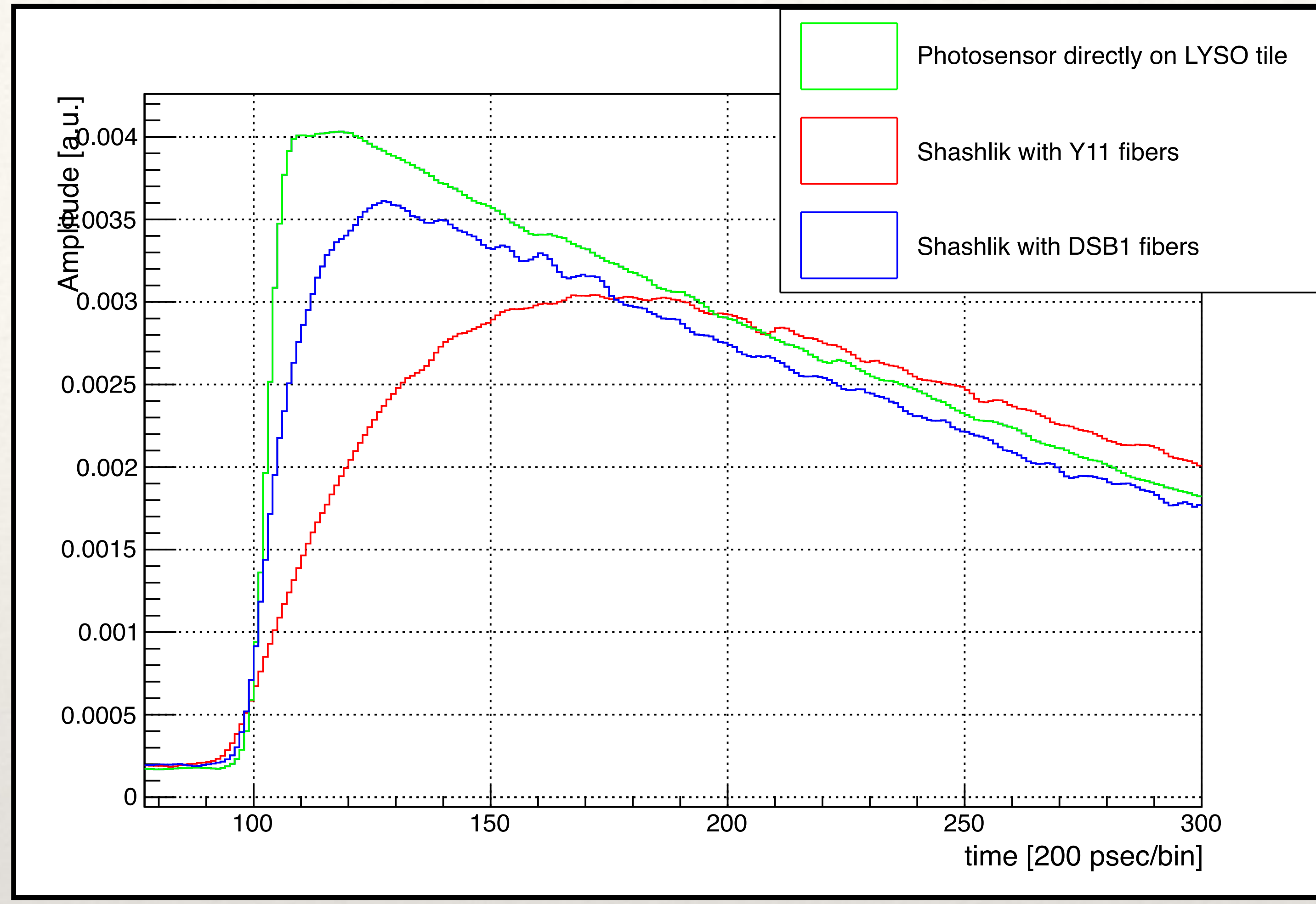
Shashlik Side Readout Results





Measure a faster rise time from direct side coupling readout compared to that of the WLS fibers.

Observe a $1/\sqrt{E}$ behavior for the **TOF resolution,** measure ~50 ps time resolution for 32 GeV e^-

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Hamamatsu MCP-PMT R3809U-50

http://www.hamamatsu.com/resources/pdf/etd/R3809U-50_TPMH1067E10.pdf

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

Photek 240

http://www.photek.com/pdf/datasheets/detectors/DS006_Photomultipliers.pdf

Ability to survive up to 3000 fb^{-1}, and to 2035

- predicted neutron fluence of about 10^{16} n/cm2 in forward regions (CMS)
- ionizing dose up to 150 Mrad in CMS electromagnetic calorimeter (η~3)

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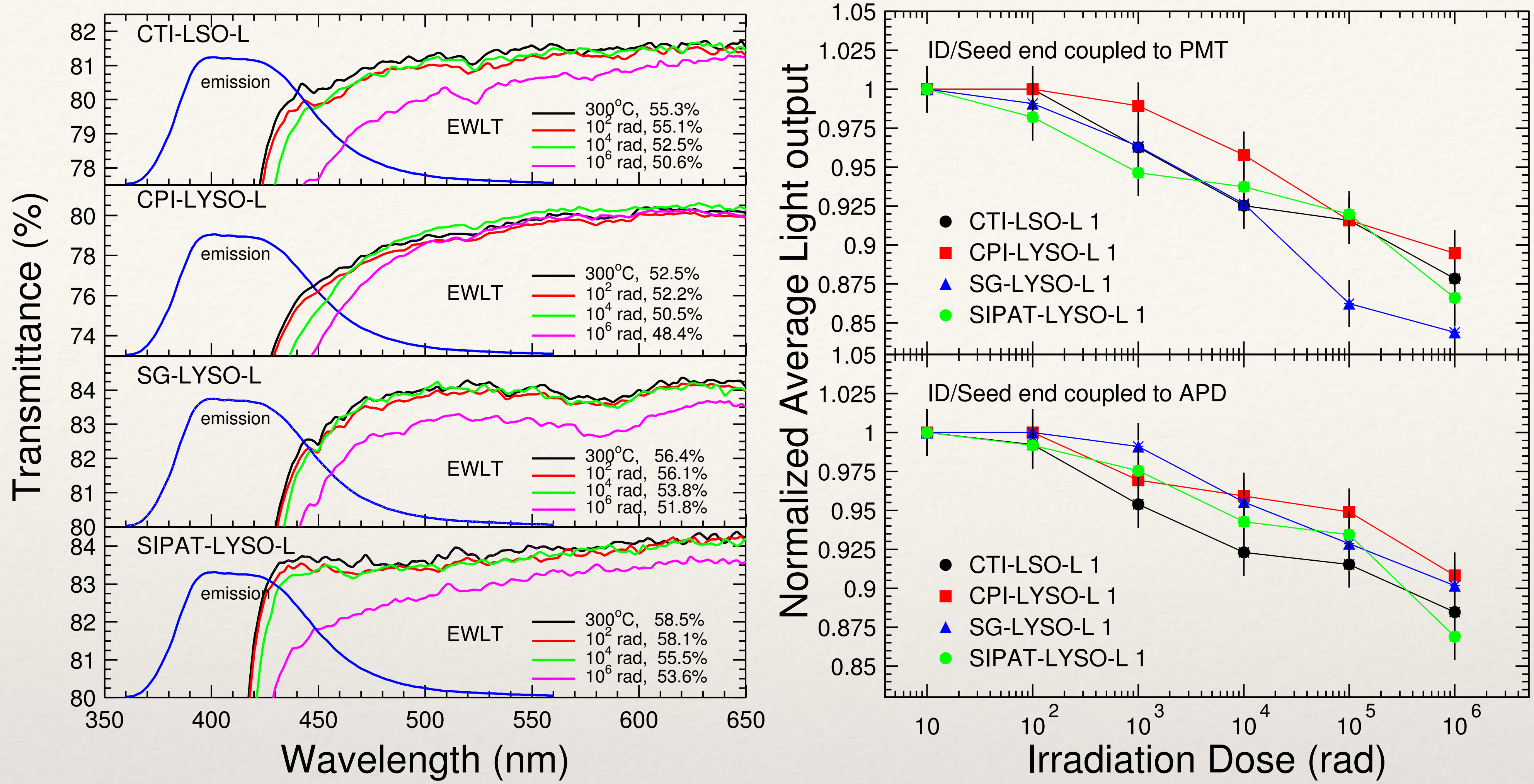

Figure 9. Left: The longitudinal transmittance spectra are shown as a function of wavelength in an expanded scale together with the photo-luminescence spectra for four LSO and LYSO samples before and after the irradiation with integrated doses of 10^2, 10^4 and 10^6 rad. Right: The normalized light output is shown as a function of the integration dose for four long LSO and LYSO samples with PMT (top) and APD (bottom) as the readout devices.

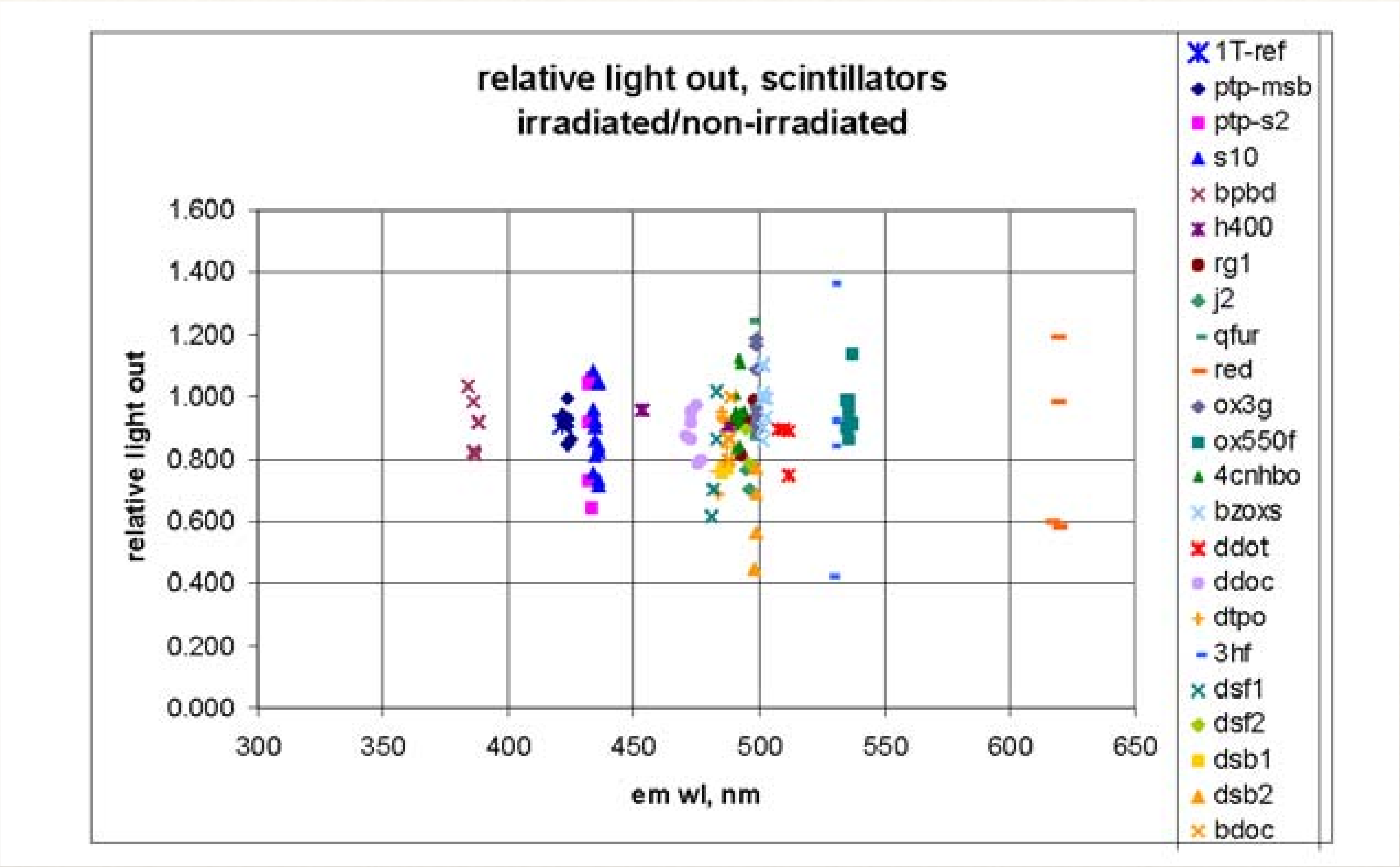

Figure 9. Measurement of the scintillation efficiency of small 1-inch by 1-cm thick samples of scintillator materials exposed to 1Mrad of ^{60}Co irradiation. What is plotted is the ratio of light yield after irradiation to before irradiation for samples as a function of their maximum emission wavelength. The results indicate that for these very small samples, recovery to 90% of original efficiency occurs for essentially all materials. As such these measurements are not particularly informative. More definitive studies are required of actual detector materials (tiles and fibers in needed lengths) in order to draw meaningful conclusions.