Precision Timing Analysis of July 2015 Test Beam Data

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Introduction:

The High-Luminosity LHC (HL-LHC) is expected to operate in instantaneous luminosity of 5×10^{34} cm^{-2} s^{-1} [1]. This high amount of luminosity causes the rate of simultaneous interactions per bunch crossing (pileup) to increase to 140-200. Accordingly, differentiating jets originating in the events of interest – such as those which come from Primary Vertex (PV) – from those produced in pileup interactions will be an integral part of data analysis and hardware triggering process. Measuring time of flight for a particle, in complementary to precision tracking methods, puts tight cuts on three-dimensional position of events which can significantly reduce pileup.

In this report, we have studied time resolution for July 2015 electron experiments primarily, and other experiments seconarily. First, we find a new method for extracting time resolution which provide us with a significantly better time resolution than previous method, for this year's experiment. Afterwards, we introduce a measure for computing noise-to-signal ratio and show how this measure scales with amplitude and time resolution. Then we compare recent laser experiment with the ones done before and make conclusions about MCP and SiPM behaviours.

Thereupon, we scrutinize the behaviour of wiggles in rising time and before rising edge of shashlik cell pulse, which is believed to affect time resolution notably. We then make conclusions about the source of these wiggles and finally examine some hypotheses for them.

Experimental Setup:

A picture of the experimental setup is shown in figure 1. The beam enters the box from left and hits the trigger counter. Then it goes into the shashlik calorimeter and finally passes through the reference detector which is produced by Photek (model PMT 240) [2]. The beam produces showers in the shashlik calorimeter [3] and the scintillation light is transferred through DSB1 fibers[4] into MCP-PMT photodetector produced by Hamamatsu (model R3809-52) [5]. The output voltage is attenuated before readout by DRS4 [6] as a DAQ system.

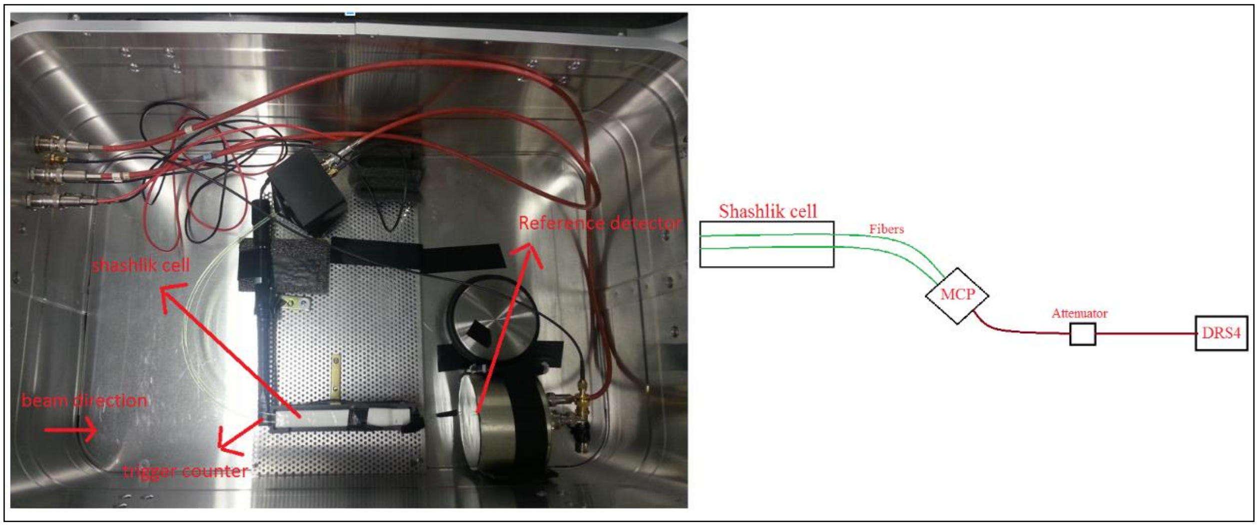


Figure 1. A photo of the experimental setup (left) and a schematic of how light transfers from shashlik cell to DRS4 (right)

Time Resolution:

Our chief goal is to find the best resolution for time-of-flight. To this end, timestamps for reference detector and shashlik cell pulses are needed to be extracted. In figure 2, sample pulses for reference, shashlik and trigger detectors with their fits are shown.

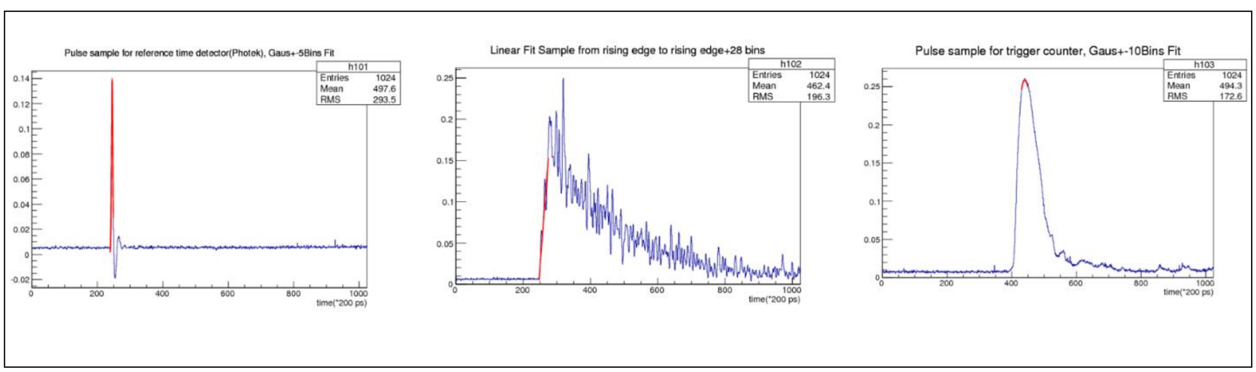


Figure 2. Sample pulse and fit for reference detector (left), shashlik cell (center), and trigger counter (right)

In these pulses, each bin in "X" axis corresponds to 200 ps and "Y" axis is voltage in units of Volts. The shape of shashlik pulses will be discussed later. In reference time pulse, we used a gaussian fit in an interval of 1 ns (5 bins) for each side of the X value corresponding to the maximum value of the function. For shashlik pulse, the first step is to find the rising edge. To that end, the algorithm starts from bin #1 to right in order to find the first bin of which 10 sequential right neighbors have values more than 10 times the RMS of the baseline noise. The algorithm now have found a bin which is somewhere in the risetime of the pulse. Rising edge is defined as the first minimum on the left side of the aforementioned bin (Figure 3).

As a timestamp for these kind of pulses, we performed linear fits from rising edge to different percentage of the maximum value in addition to fits from rising edge to various times after it, and the time at which the lines intersect with baseline are chosen as the timestamps. Usually, the best time resolution that we get is for the fit from rising edge to 32 bins (6.4 ns) after it with some cuts on all channels.

It is worth mentioning that in our previous work [3], an algorithm was introduced for finding the timestamp which resulted in a precise time resolution. However, for this experiment that algorithm does not end up with a good time resolution (Sample for both fits are shown in figure 4).

	Previous algorithm	Linear from RiseEdge to RiseEdge+6.4 ns
50 GeV	226 ± 4.9	139.8 ± 2.8
100 GeV	224.9 ± 5.1	140.9 ± 3.2
150GeV - 3kV supply Voltage- 10db Attenuator	196.1 ± 11.9	125.7 ± 6.8
150GeV - 2.95 kV supply Voltage- 6db Attenuator	235.4 ± 5.4	148.3 ± 3.8

Table 1.Time resolution using new and previous algorithms

Note that the time difference is not perfectly gaussian possibly due to behaviour of wiggles. Accordingly, the number of bins used to draw and the interval used to fit a gaussian function to the time difference affects the time resolution, sometimes significantly. **The reason is that ROOT 5.34 does NOT fit to data. Rather, it fits to the shape of pulse.**

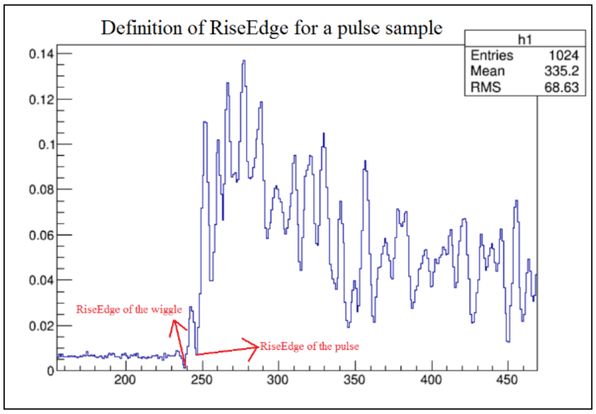


Figure 3. Definition of rise edge of the pulse and the wiggle

On the other hand, if one uses the new method for previous data, the time resolution would be worse. As can be seen from fit samples, **a reasonable guess is that wiggles in rising time affect significantly linear fits, hence time resolutions**. Moreover, fitting from rising edge to a relatively large time distance, practically, averages out the wiggles' jitter. It is notable that wiggles in rising

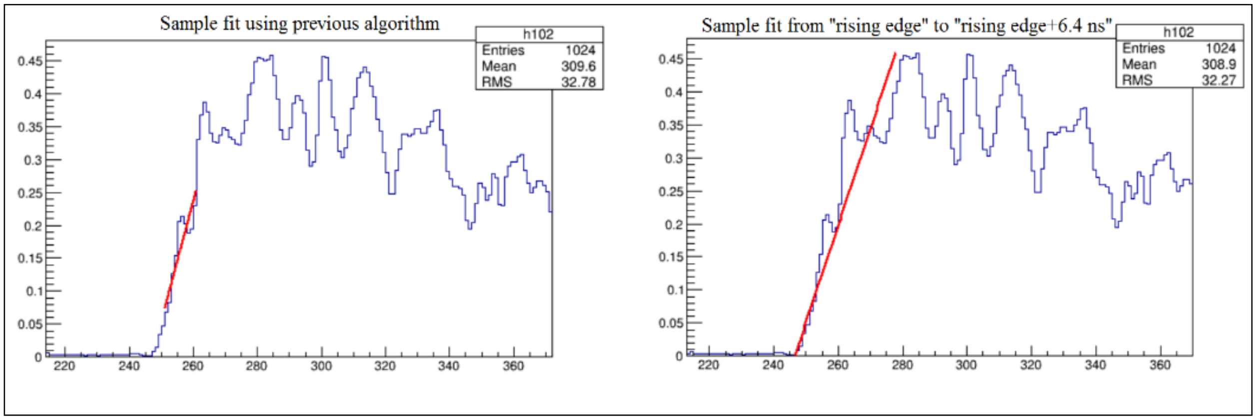


Figure 4. Sample fit for previous (left) and new (right) algorithms

time were less in last year's experiment. Wiggles are studied in more detail later in this report.

Exponential-Logistic Function:

In the meantime of finding time resolution, we have found a function to fit the whole pulse. This function is a multiplication of Logistic function [7] and an exponential function, and in spite of the function that was introduced before – in a "Physics in Medicine and Biology" paper [9] – it is differentiable infinite times (formula 1).

$$\mathrm{f}(x) = [3].\frac{e^{\frac{-(x-[0])}{[2]}}}{1+e^{\frac{-(x-[0])}{[1]}}}, \qquad [0],[1],[2], and\ [3]\ are\ free\ parameters \qquad (1)$$

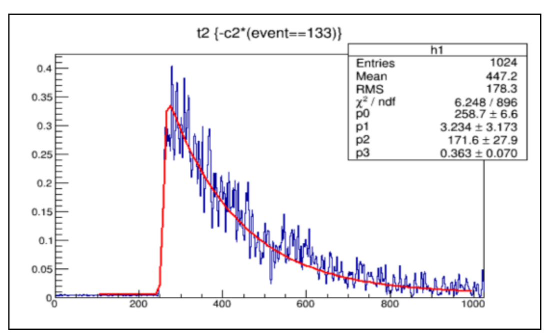


Figure 5. Sample fit of Exponential-Logistic function to shashlik cell pulse

The time resolution that we get using this function is not good enough. Nevertheless, this function has some benefits. For instance, fluctuations in this experiment are such large that maximum of the pulse does not precisely represent how many photons have hit the detector. This claim can be proved in figure 6.

There is a strong correlation between 3rd free parameter of the function – which somehow is equivalent to the height – and the integral of the pulse.

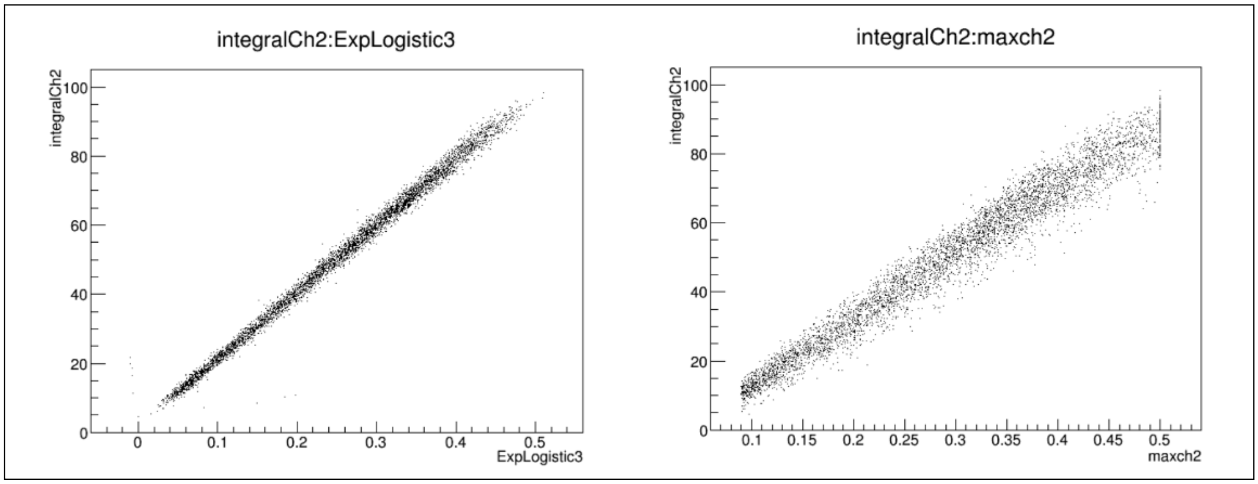


Figure 6. Correlation between the integral of shashlik cell with maximum of the pulse (right) and third free parameter of the Exponential-Logistic function fit (left)

Fluctuations in decay part:

How do the fluctuations in the decay part behave with respect to different energies? In order to find this, we fitted an exponential function with 3 free parameters from “rising edge +100 bins” to “rising edge +500 bins” (formula 2 and figure 7).

$$g(x) = [2] + e^{\frac{-(x-[0])}{[1]}}, \qquad [0], [1], and\ [2] are\ free\ parameters \tag{2}$$

This interval is divided into 8 equal intervals and the absolute distance to the fitted line is calculated and the average is reported in figure 8. Only 6 samples are used for calculation. For instance, in the “absolute fluctuation amplitude” plot, value of 50 GeV experiment for number 125 (=(100+150)/2) is 0.03. This shows that from “rising edge+100” to “rising edge+150” the absolute value of distance between the fitted function and pulse is calculated and averaged. This process is done for 6 samples and hence 0.03 is the average of (150-100)* 6=300 data.

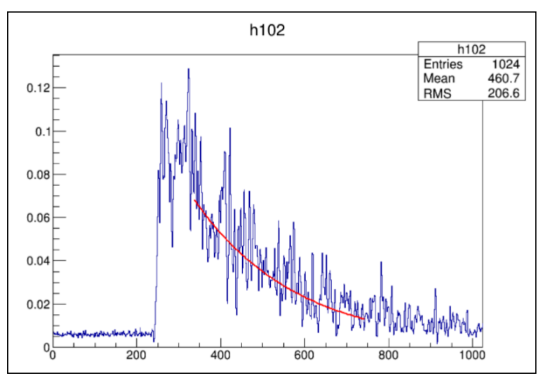


Figure 7. A sample fit of exponential function to decay part of shashlik pulse

"Raw amplitude of fluctuations" is the "absolute value" which is multiplied by the attenuation factor. From figure 8, it can be concluded that fluctuations decrease when going away from pulse's peak. In addition, the effect of attenuation on this parameter can be seen by comparing the two plots.

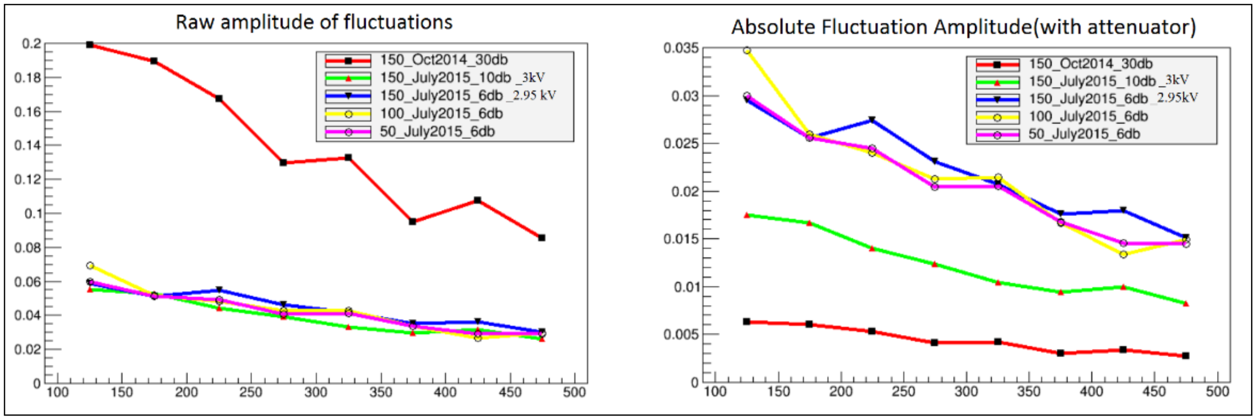


*Figure 8. Absolute (right) and raw -- amplified by attenuator factor -- (left) absolute amplitude of fluctuations with respect to the exponential fit in decay part of shashlik cell pulse. "X" axis represents time (*200 ps) after rising edge, and "Y" axis is the amplitude in Volts.*

Afterwards, we chose a single parameter for the fluctuations of each experiment. This parameter is the average of the aforementioned representatives of 8 intervals and is named "Fluctuation/Height" parameter. Figure 9 shows the relation between Fluctuation/Height

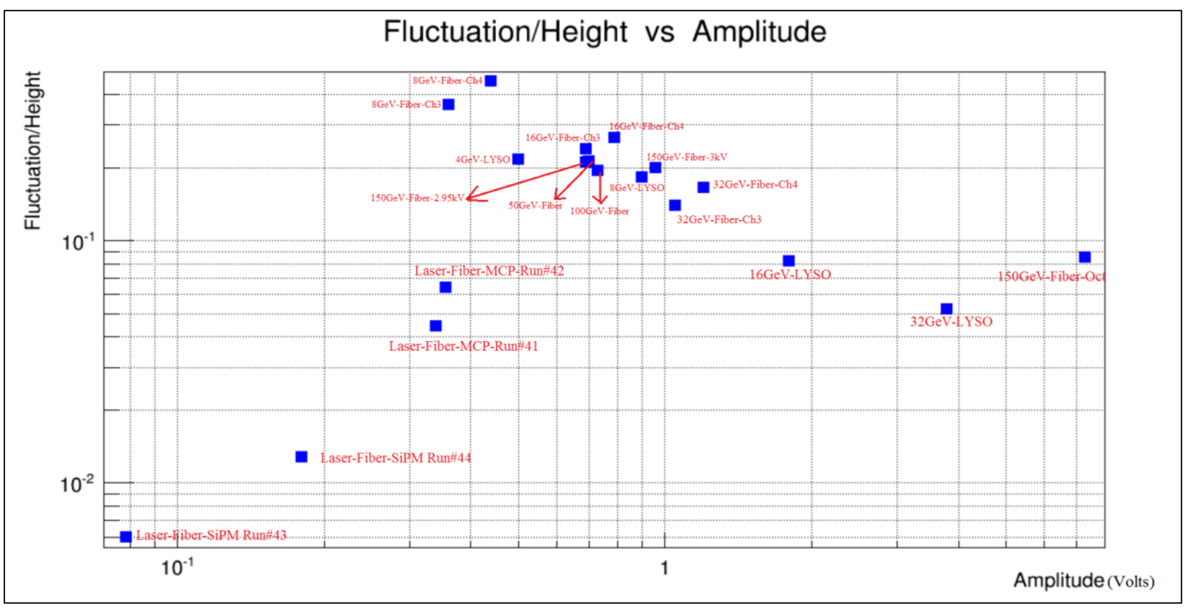


Figure 9. Fluctuation/Height parameter versus Amplitude for different experiments. If laser data is ignored, a correlation can be seen between these two variables.

parameter and amplitude. If laser data is ignored the correlation for electron experiments can be seen easily. It shows that the more amplitude is, the less Fluctuation/Height we have.

Another important plot is the relation between time resolution and Fluctuation/Height parameter and also amplitude.

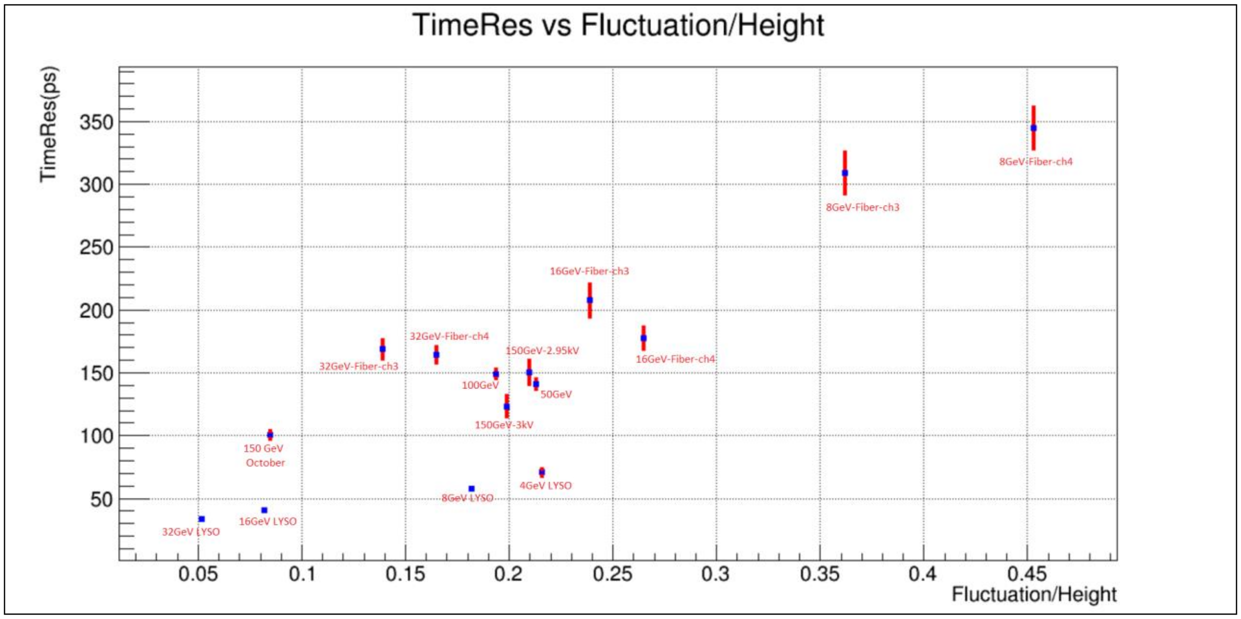


Figure 10.Time resolution versus Fluctuation/Height parameter for different electron experiments

It should be noted that time resolution for July 2014 experiments are extracted separately for each of the two MCPs. Therefore, the time resolution using both MCPs would be better roughly a factor of $\sqrt{2}$, assuming precise time resolution for reference detector. MCPs are used in all the data used in figure 10 and 11. Therefore, it seems that time resolution for MCPs scales with the amplitude rather than the energy of the particles. In other words, although in July 2015 we had the same 150 GeV experiment as the one done in October 2014 experiment, their time resolution differs dramatically. However, both of the experiments seemingly obey the trend of amplitude vs time resolution. In addition, from time resolution vs Fluctuation/Height parameter plot, both LYSO and fiber experiments seems to reach their best time resolution when their Fluctuation/Height parameter tends to zero.

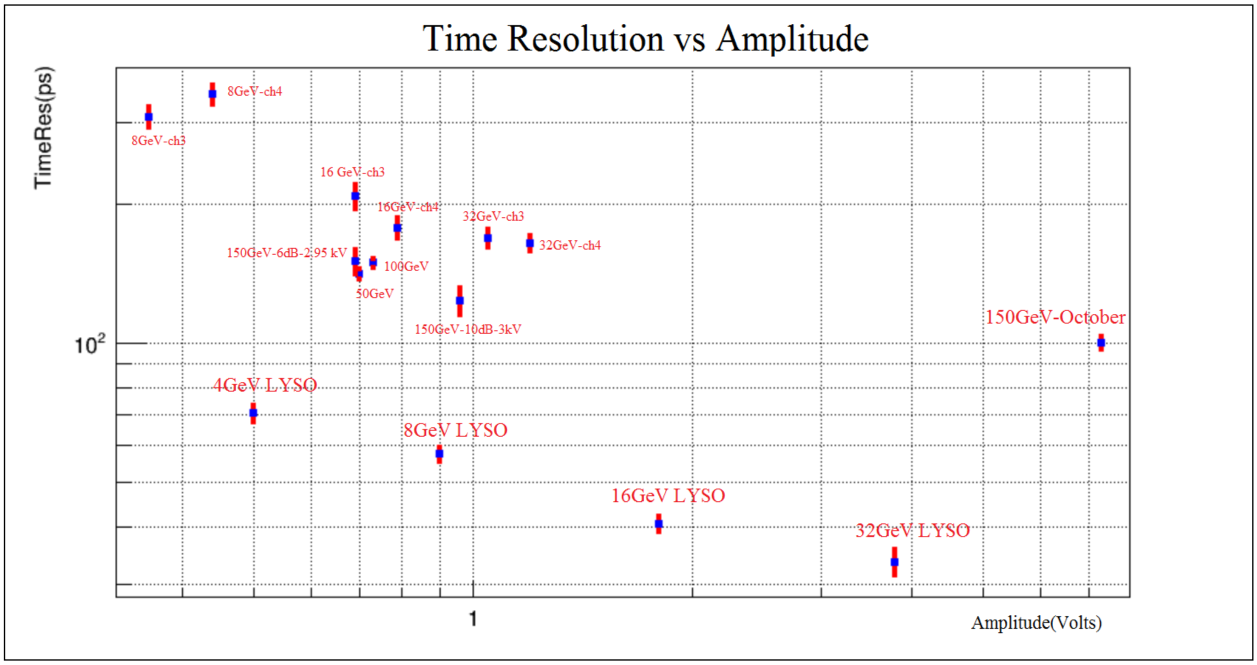
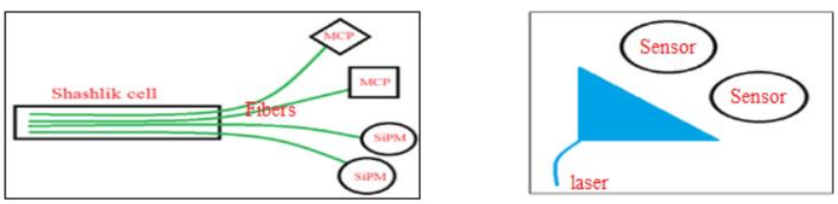


Figure 11. Time resolution versus Amplitude for different electron experiments

Recent laser data time resolution analysis:

As can be seen in figure 12, in our previous experiments, we achieved a time resolution of 7 ps between two MCPs for when laser is directly sent to them and 30 to 40 ps for when SiPMs are



	laser on shashlik using fibers(September 2015)	laser directly on sensor, 2 ns laser	Laser directly on the sensor, 50 ps laser
Time Resolution 2 MCPs	284.4 ± 18.3 ps	~7 ps (CERN, amp. x150000	~7 ps (CIT, ampl. ~0.4 V)
Time Resolution 2 SiPMs	45.4 ± 0.3 ps	To be done	~40 ps (Aashrita) ~30 ps (Cristian)

Figure 12. Data for laser experiment. MCP time resolution worsen dramatically. The schematic on top left shows how the light was collected through the fibers.

used instead. When laser is sent into shashlik cell and then transferred to sensors, as is done in September 2015, 284 ps is the best resolution that we get for MCPs and 45 ps is the best one for SiPMs. This shows that few changes in SiPMs time resolution is seen in contrast to MCPs of which time resolution worsen dramatically.

Study of wiggles in shashlik pulses:

In most of the pulses belonging to the shashlik cell, a couple of wiggles can be seen before the pulse reaches its maximum value. We have studied the properties of these wiggles and their effect on time resolution.

The shashlik pulses' shape:

When an electron enters the shashlik cell, it starts producing showers in both LYSO and Tungsten. However, scintillation process only occurs in LYSO crystals. Afterwards, scintillated light find its way into the fibers and another scintillation process happens in fibers, which changes blue light to green light and propagates spherically symmetric [8]. Then scintillated light undergoes total internal reflection until reaching MCP. Therefore, the shape of shashlik pulses are influenced by two scintillation processes.

Wiggles' properties:

In July 2015 experiment, as can be seen in figure 13, some wiggles exist in such a way that cannot be justified since, as was mentioned above, the shape should be a result of two scintillation processes. Even some of them happen before the rising edge which henceforth will be called "early wiggles". The algorithm to find early wiggles is similar to the algorithm for exploring the rising edge with a difference that this algorithm find the first 3 bins with values more than 5 times the RMS of the baseline noises rather than first 10 bins. Then the first local minimum on the left side is assigned as the rising edge of the early wiggle (figure 3). Figure 14 shows how far the early wiggles' rising edge can be from rising edge of the pulse. By definition, the difference between rising edge of the pulse and the early wiggle must be at least 3 bins and **hence the gap is nothing but a matter of definition.**

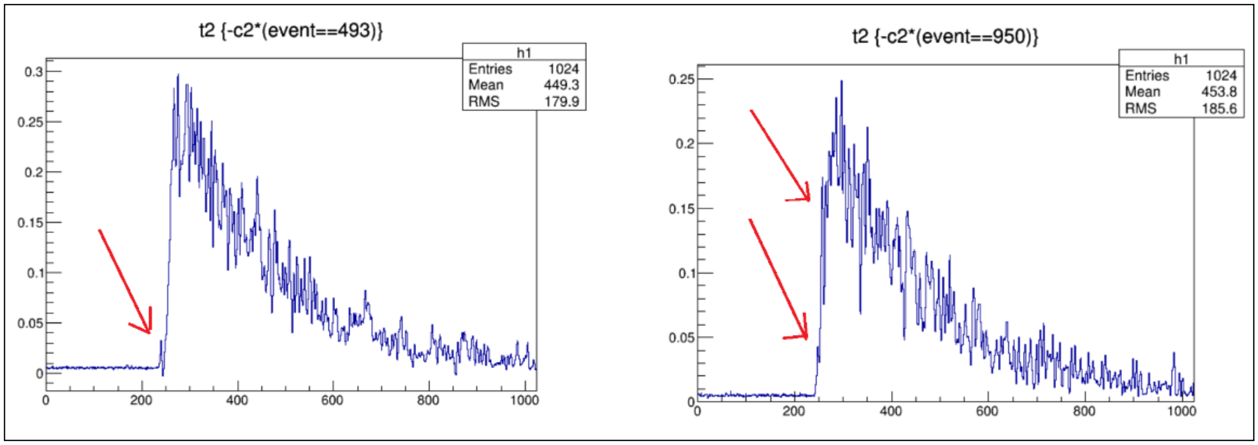


Figure 13.Wiggles in rising time (right) and before rising edge (left), which is called "early" wiggles

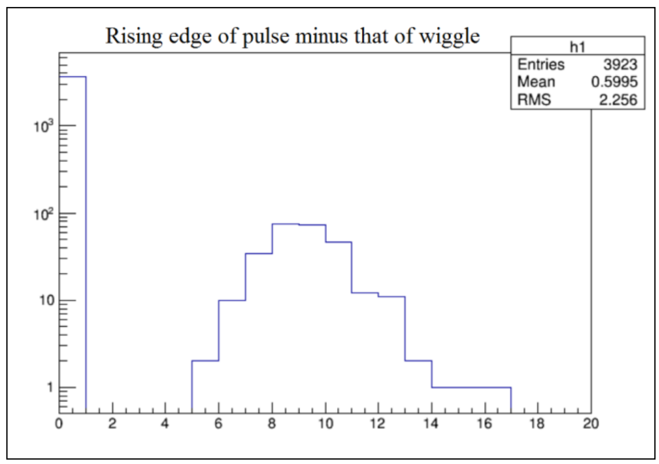


Figure 14.Rising edge of the pulse minus rising edge of the wiggle. Most of the pulses do not have early wiggles which results in "zero" for the "X" axis. Note the logarithmic scale in "Y" axis. The gap between zero and the bump is just a matter of definition.

Additionally, table 2 shows the early wiggles' height for this July's three runs plus a run for October 2014. "Raw height" is the absolute height which is corrected by a factor of attenuation. The primary goal was to investigate if these wiggles are added after attenuation (therefore have equal heights in spite of their different attenuation factor). Although the two July 150 GeV experiment have the same energy and different attenuator, their amplitude are not the same. The 10db and 6db experiments have 3kV and 2.95kV supply voltage of MCP-PMT, relatively. This little change in supply voltage is not negligible for gain and hence amplitude differences (figure 15). Therefore, **no conclusion is possible at the moment.**

"Early" wiggles' height	October 2014 150 GeV 30db attenuator (31.6 times decrease in voltage)	July 2015 150 GeV 10db attenuator (3.16 times decrease in voltage)	July 2015 150 GeV 6db attenuator (2 times decrease in voltage)	July 2015 100 GeV 6db attenuator (2 times decrease in voltage)	July 2015 50 GeV 6db attenuator (2 times decrease in voltage)
Absolute wiggles' average height:	Height=**0.0077** RMS=0.0031	Height=**0.0183** RMS=0.0149	Height=**0.0184** RMS=0.0161	Height=**0.0191** RMS=0.0154	Height=**0.0185** RMS=0.0162
Raw amplitude of the wiggles	Raw Height=0.2433	Raw Height=0.0578	Raw Height=0.0368	Raw Height=0.0382	Raw Height=0.0370
Wiggles' height Relative to amplitude:	Ratio=0.0503 RMS=0.0263	Ratio=0.0693 RMS=0.0565	Ratio=0.0567 RMS=0.0556	Ratio=0.0562 RMS=0.0572	Ratio=0.0528 RMS=0.0457
Number of events with early wiggles	16 out of 1555=>1.0%	101 out of 1469 =>6.9%	235 out of 3727 =>6.3 %	266 out of 3915 => 6.8%	297 out of 3965 =>7.5%

Table 2. Early wiggles' height and population for different experiments

Now we focus on the source of these early wiggles. The first result is that these **early wiggles do NOT come from attenuation process**. The reason is that, in the laser experiment which was done in September 2015, due to low amplitude of the laser pulse, no attenuator was used. However, early wiggles do exist in some of the pulses.

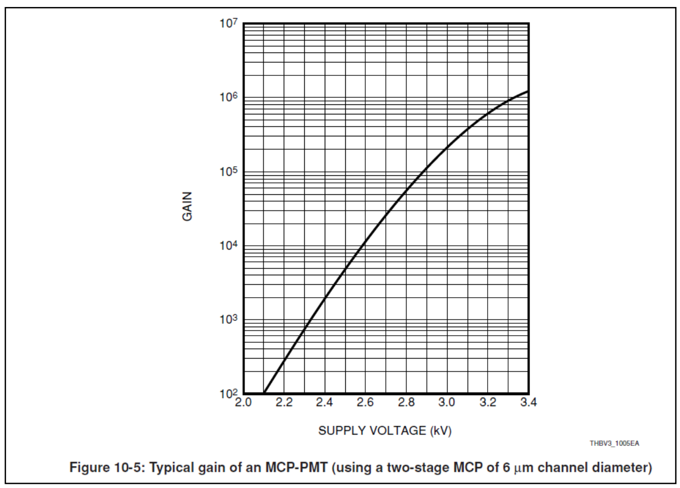


Figure 15. Typical gain of an MCP-PMT

The next certain result is that **DRS4 is not the source for early wiggles** on the grounds that early wiggles are seen ONLY in experiments where fibers are used. By looking at the data from last year's experiment [3], October 150 GeV electron experiment, July 2015 electron experiment, September 2015 laser experiment, and January 2015 laser experiment, whenever MCPs are used, **early wiggles exist in all fiber experiments and never exist in LYSO experiments**. Accordingly, early wiggles cannot come from DRS4 since this device cannot distinguish whether fibers are used or not.

The problem with wiggles' height analysis using table 2 is that their distribution is unknown, though seemingly exponential. The histograms of their distributions is shown in figure 17.

In addition, there is no significant correlation between early wiggles' bin – the time at which early wiggles happens – and their height. This statement can be concluded using figure 16.

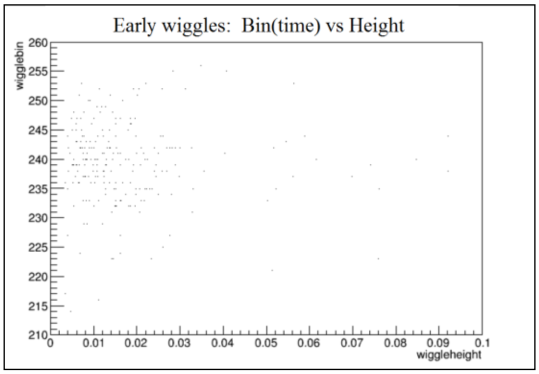


Figure 16. Early wiggles: Bin (time) vs Height. Time is measured with respect to "zero" out of 1024 bins.

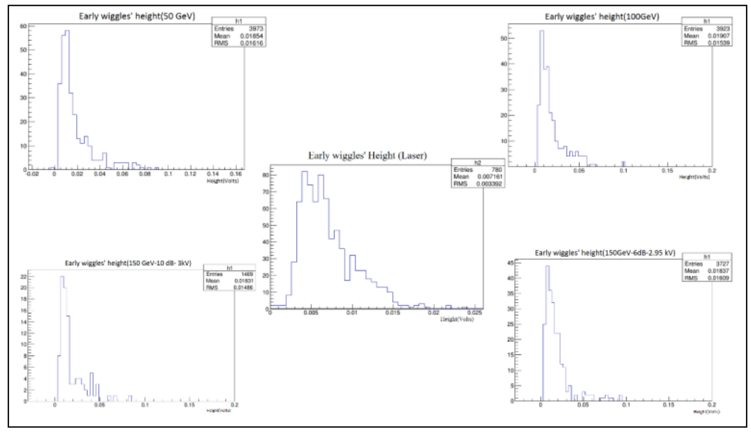


Figure 17. Early wiggles' height histogram for electron experiments with different energies and laser (center) experiment. The "X" axis is height in Volts.

Hypotheses:

One of the hypotheses for the reason behind these early wiggles is the "shielding problem". The cross section of a typical MCP-PMT [10] can be seen in figure 18. The photocathode of the MCP-PMT that was used in our experiments can absorb a wavelength range of 160 nm to 650 nm [5] which does not contain X-ray light (<100nm). Nonetheless, MCP itself can absorb X-ray photons and high energy electrons which come out of shashlik cell and go directly to MCP without hitting photocathode. The detection efficiency of MCP [13] is shown in table 3. Another hypothesis is that some UV photons get into the fibers and using total internal reflection, without scintillation in LYSO or fiber, directly strike the photocathode. This can be possible since DSB1 fibers are responsible to change blue light – and not UV light – to green light. Emission and Excitation spectrum of DSB1 fibers [4] and LYSO [11] are shown in figures 20 and 19, respectively.

Table 3: Detection Efficiency of MCP

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

Table 3. Detection Efficiency of MCP

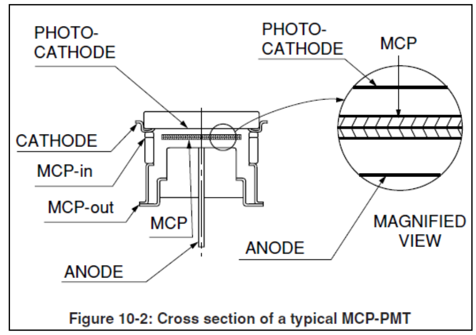


Figure 18. Cross section of a typical MCP-PMT

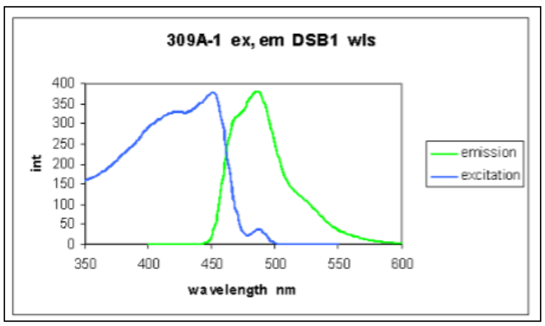


Figure 20. Emission and excitation of DSB1 fibers

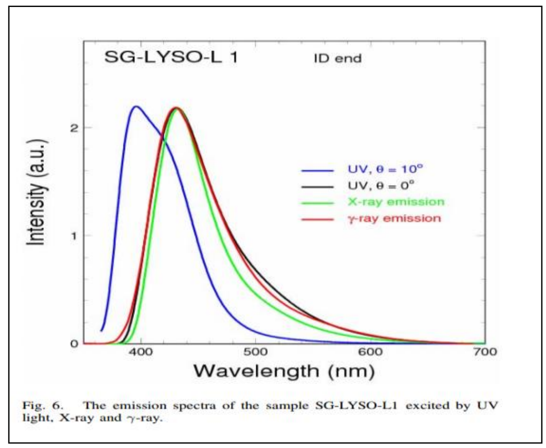


Figure 19.The emission spectra of the sample SG-LYSO-L1 excited by UV light, X-ray, and Gamma ray

Another observation is that although in July 2015 laser experiment 77.6% of the pulses had early wiggles, **if we replace MCP-PMT with SiPM no pulse have early wiggles.** However, this can be because of the relatively slow rise time of SiPMs. While MCP-PMTs' rise time are less than 200 ps[5] (=1 bin), SiPMs' rise time are usually around 1 ns[12](=5 bins) and thus early wiggles which usually have less than or equal to 5 bins significant voltages relative to noise may be ignored. Nevertheless, no certain deduction is possible at the moment.

Summary:

In this report, we introduced an algorithm which gives a better time resolution than previous one for July 2015 electron experiment. In addition, we introduced a function that fits all the shashlik cell pulse rather than a part of it and can be trustable for some analysis of the pulse shape. We introduced a measure, called Fluctuation/Height parameter, for computing the noise-to-signal ratio in the decay part of shashlik pulses. The parameter has correlations with amplitude and time resolution and the trend shows us that if we decrease this parameter we will get the best time resolution. In addition, the plots shows that time resolution scales with amplitude and not necessarily with the energy of the particles. For recent laser data, we achieved almost the same time resolution for when laser directly hit the SiPMs and when we get the light through the fibers from shashlik cell. On the other hand, if we use MCPs instead, the time resolution dramatically worsen.

In MCP pulses when fibers are used to collect the light in shashlik cells, some wiggles exist before rising edge and in rising time. We showed some evidences that these wiggles affect the time resolution. Moreover, by studying the features of "early wiggles" – the wiggles that occurs before rising edge – we concluded that the source for the wiggles are not from DRS4 data acquisition device nor from the attenuation process. Additionally, many properties of early wiggles are examined in this report. Finally, some hypotheses are inspected for the source of the early wiggles and some suggestions are introduced to remove them.

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[11]http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=4437128&url=http%3A%2F%2Fieeexplore.ieee.org%2Fstamp%2Fstamp.jsp%3Farnumber%3D4437128

[12] http://web.stanford.edu/~jbarral/Downloads/StageOption-Rapport.pdf chapter 3

[13] http://www.triumf.ca/sites/default/files/Hamamatsu%20MCP%20guide.pdf

Another work on timing studies by a FNAL summer student in 2012:

https://eddata.fnal.gov/lasso/summerstudents/papers/2012/Madisen-Holbrook.pdf

MCP vs SiPM:

http://indico.cern.ch/event/397937/contribution/7/attachments/798262/1094109/mcpvssipm.pdf