**Color scheme:**

**Blue: answers to questions**

**Green: new text quotation. Also bold it. This needs to be one tab separated from the answers and new line.**

**Paste the standard paragraph response, thank reviewers blablabla**

Reviewer #2: Please consider reviwing the following remarks:  
P(age)#L(ine)#  
Abstract:  
The efficiency and timing resolution before irradiation were found to be 100% and 30-40 ps, respectively. A "no-response" area between pads ………..  
The sensors are divided in 'efficient' part, and no response area. This leads to 100% efficiency but it is misleading if the concept is not clarified (as the geometrical efficiency is not this value).

**Changed to “The signal detection efficiency and timing resolution in the sensitive areas”**

P2L58 … pile-up contamination ….  
I would consider a different adjective…………..

**Changed to “in order to overcome the event reconstruction challenges posed by  the high rate of concurrent collisions per beam crossing.”**

P3L67 …. We also compare the uniformity of 50 and 80 m LGAD sensors, as well as the HPK and CNM sensors irradiated to an equivalent neutron flux of 6 1014 n/cm2. Detailed measurements of irradiated HPK sensors were presented in Ref.  
of 50 and 80 m thick LGAD sensors ……  
…. As well as…   
Here you put in the same sentence two different comparison (thickness and manufacturer) which I found confusing.

**Changed the sentence by breaking into two.**

Need to copy paste the actual new text

. an equivalent neutron flux of 6 1014 n/cm2…   
The unit of flux are n/cm2/s. This is integrated flux.

**Changed flux to fluence**

Paste the new text sentence

P2L102 The primary beam (bunched at 53 MHz) consists 102 of high energy protons (120 GeV) at variable intensities between 1 and 300 kHz.  
Incomprehensible. Thought Hz is frequency, not intensity.

**Simplified the sentence, and added clarification that all the measurements presented in this paper were taken with the primary beam.**

Paste the new text sentence

Figure 4: Photographs of the HPK 50D-PIX 22 array sensor (top left), the CNM-W9HG11 22 array sensor (top right), the 50D-GR single sensor (bottom left), and the CNM W11LGA35 single sensor (bottom right) are shown.  
….. , the 50D-GR single sensor…….                     
……., the HPK 50D-GR single sensor …………

**Done according to reviewer’s suggestion.**

P6L129 ……. with a different p+ dose of the gain layer to study the optimal parameters of the charge multiplication mechanism.  
I do not think you are studying the optimal parameters for charge multiplication (could e.g. maximum gain….), but rather the parameters functional to time resolution.

**Changed to “for fast timing detectors”**

Put the new sentence here

P7L161 …. about 130 W per channel.   
I hope it is much less!

**We have corrected it to say 130 mW per channel.**

P8L184 … The above choices of timestamp reconstruction algorithms used are motivated by the result of a dedicated study of different timestamp reconstruction algorithms for each of the three readout boards.  
The choice of the above timestamp reconstruction algorithms was motivated by the result of a dedicated study of various algorithms for each of the three readout boards.

**Done**

P9L209 … timing resolution …  
… time resolution …..

**Done**

P9L212 …. is the same for all runs and requires that  the signal amplitude is between 160 mV and 320 mV….  
This information is redundant as the mip signal, or a signal calibration, is not provided.

We have changed the sentence to say:

**“…requires that the signal is consistent with a minimum ionizing particle corresponding to amplitude values in the range between 160 mV and 320 mV.”**

P9L213 … The signal selection for LGAD boards was optimized for each board individually, by selecting the MIP signal peak fitted with a Landau function.   
What does this mean? The signal selection here is not distinguishing real events from noise?

The text has been changed to:

**“Signal events in LGAD sensors  are selected such that they are above the noise levels listed for each board in Sec. 4.  ”**

**Add the noise level for UCSC board to section 4.**

P10L237  
Fig. 5 Can explain the error bars? Why they are bigger for the CNM sensor, and bigger in the y-coordinate, and increasing with it?

The statistics accumulated with the HPK 50D-PIX sensor was the largest among various sensors we tested in these measurements, hence the plots with this sensor have the smallest statistical uncertainties. The measurements presented in the upper and lower panels of this figure were obtained from different datasets and therefore do not have the same statistical uncertainties. The reason that the error bars grow with increasing Y-coordinate is due to the fact that beam is more centered at low Y-coordinate, and hence there are more events at lower values of the Y-coordinate.

Add something in the caption about this to make him happy.

P10L239 … impacts its timing ….  
… impacts on its timing ….

**Done.**

P10L241 …. Is fit to a Landau …..  
…. Is fitted to a Landau …..

**Done.**

P11 Figure caption.  
Figure 7: t measurement across the X- and Y-axes of the HPK 50D-PIX sensor mounted on the FNAL board. The scans of pixels 1 and 2 along the X-axis, and pixels 1 and 3 along the Y-axis are shown. The pixel numberng scheme is defined in Fig. 4.  
Why the caption does not mentions the CNM sensor?

We have added the the CNM sensor added to caption as follows:

Add the new text

P10L249 … A possible explanation for this effect is a small difference in the rise time of the pulses that originate from the passage of particles in the metallized and non-metallized areas……  
Too much hand-waving. Is the rise time difference well identified? I would no try to give explanation of the effect before verification.

Yes, the rise time difference is well identified. We have recently confirmed this effect with test beam measurements using FBK LGAD sensors, which also have single channels partially covered with metal.

**We should quantify the rise time difference. CHECK WITH NICOLO ABOUT THE EFFECT IN SIMULATION.**

P11L254 The results for the CNM sensor also show hints of this behavior, though the larger statistical uncertainties make it less significant.  
They seem to go in the other direction (concerning the effect of metal), or not?

After further discussion among the authors, we have confirmed that there is no metalized area in the CNM sensor, and we believe that the feature alluded to in the original text is unconvincing. Therefore we have changed the sentence to:

“The CNM sensor does not contain metalized areas on its surface and we do not observe the same effect.”

P11L270 … We define the width of the \no-response" area as the distance between the half-maxima of the two  fitted S-curves, as shown in Fig. 9.   
This definition contradicts the statement before that the sensors are 100% efficient (excluding the interdetector region). The area between the 100% to 50% efficient is obviously not fully efficient. But with the current definition, it is part of the active sensor area. This must be corrected.  
Besides, if a definition of the inter-detector region should be chosen, the 0.5 value is not good, as it should be chosen a value high enough to be used in experimental condition (90%, 95%, ???).

**XXXX**

It’s a good point. We should choose 90% then. Check with Nicolo and Hartmut.

Fig. 9 Some of the not efficiency points (0%) for both ch1 and 2 are significantly higher than 0. What is the noise hit occupancy for these sensors?

We know that in a small fraction of events (<1%) the reconstructed position of the track is wrong. The points outside the sensor area in these plots actually had hit the sensor. These events are not a result of noise in the LGAD sensor.

Add sentence to text

Fig. 10: same comments as above.

Please see the answer above.

P18L342 …. The distribution of the  t between the reference timestamp and the timestamp from the HPK 50D-PIX sensor is shown in Fig. 16. We observe no significant changes in the behavior of the  t as the temperature varies.  
It does look like there is a shift in the x-direction of about 1mm from high to low temperatures? Is it possible?

Admit in the text that there is a shift. Plots need to be remade such that the boundaries are the same on Figs 15-17.

Figure 16 and 17: please use the same markers in the two figures for corresponding temperatures.

**Colors and markers need to be fixed in one of the plots to correspond to the other one.**

P21L367 .. The distribution on the right of Fig. 18 shows that the amplitude under the aluminum (periphery) is about 2.5 times larger than that without aluminum (center).  
How does it compare with the pre-irradiation spectra?

Unfortunately, we didn’t have unirradiated sensors at the FNAL test beam campaign. However, measurements were presented on page 12 of Nicolo Cartiglia’s talk at RD50 meeting in Krakow:

<https://indico.cern.ch/event/637212/contributions/2608659/attachments/1471224/2276633/Cartiglia_BeamTest_FNAL.pdf>

A similar effect, but of much lesser magnitude (~10%) is observed in the pre-irradiated device.   
  
  
  
  
  
  
  
Reviewer #3: Dear authors, dear editor,  
The manuscript addresses the timing resolution of LGAD sensors measured in beam tests. These detectors are foreseen for both CMS and ATLAS after phase II upgrade for precise timing measurements and are currently very intensively studied. The presented work certainly importantly adds to understanding of their operation and their performance (different manufacturers, electronics, geometries analysed). The amount of data and the work done is impressive.   
However, I have several issues that need to be addressed before the paper can be recommended for publication. They are listed below.   
  
With best regards,  
  
Your reviewer  
  
MA - major remark that needs to be addressed  
MI - minor remark that needs to be addressed  
OP - optional remark or comment from reviewer  
  
Abstract:    
"…factor of 2.5 when" ->  at lower voltages should be less so "… of up to a factor of 2.5 …"

**DONE**

Experimental setup  
L88: MI - "electronic time resolution"  it is not clear to me what you mean by that. Please make it clearer.

**The definition of the electronic time resolution is added to the text.**

L102: MI - "at variable intensities between 1 and 300 kHz" - it is not clear what the intensity refers to.

**This sentence has been changed, also at the request of the other reviewer.**

L109-L114 : MI - the  detailed description of trigger board is in a way to detailed as not all terms can be explained in enough details such as "front end board". I would prefer a simpler statement. It is not crucial for the remainder of the paper. In this context I think Fig.3 isn't needed, particularly for an already lengthy paper.

**While we do see your point, the custom board was indeed critical to establish the synchronized readout of two independent DAQ systems, those of pixels and V1742. Only due to the achieved synchronous readout the precision tracking was possible, hence we think the board deserves to be mentioned in some detail. A similar readout board could have implemented in other facilities, to achieve similar goals. There is a similar telescope being built now at CERN, where they intend to use a similar system.**

LGAD Sensor Properties  
MA: Table 1 is not referenced in the text. It is vital to list also the information about the gain of the detectors at given voltage, current, and break down voltage. It would help the reader to understand manuscript better. There has been no mentioning of the difference between the dose of W9HG11 and W11LGA35 from CNM. Are these two different only in geometry or also in dose?

**Ask Nicolo and Hartmut if these numbers make**

L131 : MI - Are they also identical in thermal budget ?  
Readout Electronics  
L161 : MI - "power consumption of the board is about 130 W …" . is  130 W a typo? This is hard to believe.

**Indeed, thank you for catching it. Typo is fixed now.**

Timestamp Reconstruction  
L176 : MI -  "decay time" is not an appropriate wording, maybe "fall time"…

**Decay time is a commonly used term for describing the time taken for the amplitude of a pulse to decrease from e.g. 90% to 10%, and is used throughout the literature. We prefer to keep this terminology.**

L194 : MI - "… by a linear function…" -> "… by linear dependence of timestamp on pulse height"

**Done**

Sensor Studies and Analysis  
L215 : MA  - The Landau function doesn't accurately describe the data. The spectra are broadened by noise and also by fluctuations in multiplication/gain. Therefore convolution of Gaus+Landau would be more accurate. Can you comment on uncertainty arising from this in your analysis?

**XXXX**

We can fit it to the gaus(x)landau and check the difference…

L227 : MA - What are the gains at these voltages?

**XXXX**

Can we look this up from other plots?

L229-233 : MA -  What was the cut on LGAD signal to be considered as a signal (can be expressed in charge or gain fraction)?  If the cut is very low you may end up with 100% efficiency, but with very high noise occupancy, which would be unacceptable at real experiment. A value of noise occupancy would be also welcome.

**The electronic noise was measured using dedicated runs with no particles, and data collected using random triggers. The RMS of the amplitude of noise was measured to be 1.2 mV on FNAL boards. The cut used in the efficiency plots is at 20 mV, well above the noise level.**

Your answer is fine. Do not list signal selection cuts.

But we should add it to the text and say that we did it.

Figure 5: MA - How did you determine the error bars? Why are they larger for W9HG11 (bottom right plot)?

Error bars are evaluated as Clopper–Pearson intervals for calculating binomial confidence intervals. They are larger for the CNM sensor since there was much more data collected for the 50D-PIX sensor.

Add sentence on Clopper-Pearson into the text.

L241 : MA - Can you show the fit of Landau to the data? This goes hand in hand with the previous comment in L215.

**XXXX**

Yes, we should show one of these fit examples.

Figure 6 : MA - Why is uncertainty of HPK smaller than for CNM? Can you convert MPV[V] into gain/charge? This conversion would be welcome already earlier in the text.

**Same comment as above about uncertainties.**

**Think about the MPV into gain question.**

L247 : OP - I think the reason for this difference in timestamp can be different signal formation in the  electrode for hit positions. The resistivity of n++ layers in not the same as that of Al electrodes, hence the difference in rise time. This holds for the section from L303-308.

**XXXX**

Sure, it can be that. We even say that. Maybe we can be more quantitative about the rise time?

L256/Figure 8 : MA - It is a absolutely necessary to present the reader with the gain values for the data in Fig. 8 in order to mislead the reader into believing that HPK in "intrinsically better"- see a comment L227. The difference is already in average electric fields achieved for both sensors, gain and also in capacitances.

**XXXX**

Yes. The table in the end should be sufficient.

L268 : MI - This looks like a ROOT code - please write erf full form. "floated in the fit" is colloquial - "were free parameters of the fit" is better

**DONE**

Figure 12 - OP:  Is it clear why time stamp is negative for 50D-PIX device in the gap region?

**To clarify: this is not a plot of a time-stamp of a single detector, but rather the Δt=t1-t0 between the reference timestamp  in Photek 240 MCP-PMT (t0) and the timestamp of the LGAD sensors (t1). Due to different cable lengths used during different device testing, the absolute value of Δt is not relevant. Therefore, all measurements are calibrated such that the central, flat part of these plots aligns with the Δt=0. As a result, some of the points will appear negative.**

Figure 14 / L318-322 - MA: What is Landau fluctuations limit for the 80 um sensor timing resolution? It seems that more charge for 80 um detector (although at lower gain) compensates for longer rise time and Landau fluctuations.  Can you show also "constant function" fit to data, so that it would be more evident?

**Quote and check with Nicolo.**

Figure 15 - section 6.5 : MA -  There is one significant piece of information missing for the reader. It is true that lowering the temperature increases the gain (impact ionization depends strongly on temperature, also mobility), but also the breakdown voltage. Vbd shifts to higher values for larger temperatures hence higher gain at lower temperatures can be compensated by larger applied bias at higher temperatures. Hence, similar or only slightly worse resolutions can be obtained at 20C for non-irradiated sensors.

**Quote and check with Nicolo. If it is true, we add a sentence.**

**Also, add in the text that we need low temperature in LHC for irradiation.**

L355 : MA - There is no mentioning (even in a single sentence) of what radiation does to the LGADs nor citations to previous works on LGAD radiation hardness.

**Should do.**

L358-359 : MA - missing citation for spectrum and flux.

**Citiation for Ljubljana reactor?**

Figure 18 : MA -  What is the gain? What is the bias voltage of the W11LGA35 device?

**Just do it**

L368 : MA - 2.5 times at what voltage?

**Just do it.**

L372 : MA - Looking at Fig. 4, I would say that the whole active area of HPK50D is without metallization.

**Indeed, this is correct, the single channel HPK sensors do not have any metalized area.**

L374 : MA - Please give the gain values - not only voltages. How close are the applied voltages to breakdown voltages?

**Just do it**

Figure 20 : OP - Is the data set size for CNM detector smaller, hence larger uncertainty?

**XXXX**

L390 : OP - Do you have any idea how is this possible?

**Should rephrase in the paper that this is faster rise time, not that signals are earlier.**

L391 : MI - The decrease of timing resolution for CNM at higher voltages can only be due to increase of noise, hence jitter, as Fig. 21 shows the increase of MPV. Please mention this or even better give the relative increase of noise.

**Measure the noise in the two runs.**