Dear review team,

Thank you for the feedback and the thoughtful set of questions. We have prepared answers for all the questions, which we provide below.

We are ready to discuss these responses in our breakout session today.

Chris, on behalf of the US-MTD management team

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Dear MTD team,

We appreciate the large amount of work to prepare the MTD documentation, including the high quality presentations both seen at the plenary today and expected at the breakout session tomorrow.

1. As discussed at lunch today, with the spirit of helping sharpen the overall presentation for CD-1, we have assembled a list of questions at a google doc [NB: CCN - do not use, use this private doc here], which we would request to be addressed tomorrow in the dedicated presentations, if they are not already. This will reduce tomorrow evening questions to a small/negligible amount.

> We will do as much of this as we can tonight.

2. In addition, we would find it useful to hear **an extended presentation (20') at the breakout session to explain in detail the rationale of the time resolution "numbers" quoted in KPPs**.

> David Stuart will prepare this. We have struggled with this in the last few months as we have developed our KPPs. We'd like to discuss with the committee their suggestions on how best to articulate this.

3. Finally, with regards to committee "findings", **we would appreciate a short-list prepared by each presenter in order to summarize it collectively and precisely during the closeout.**

> We will each do this. We will provide these summaries by the middle of the afternoon..

Thanks again, and looking forward to continued discussions tomorrow.

Best regards,
Adam, Greg, Maurice, Stefano

General questions

Requirement on the MTD Timing resolution value

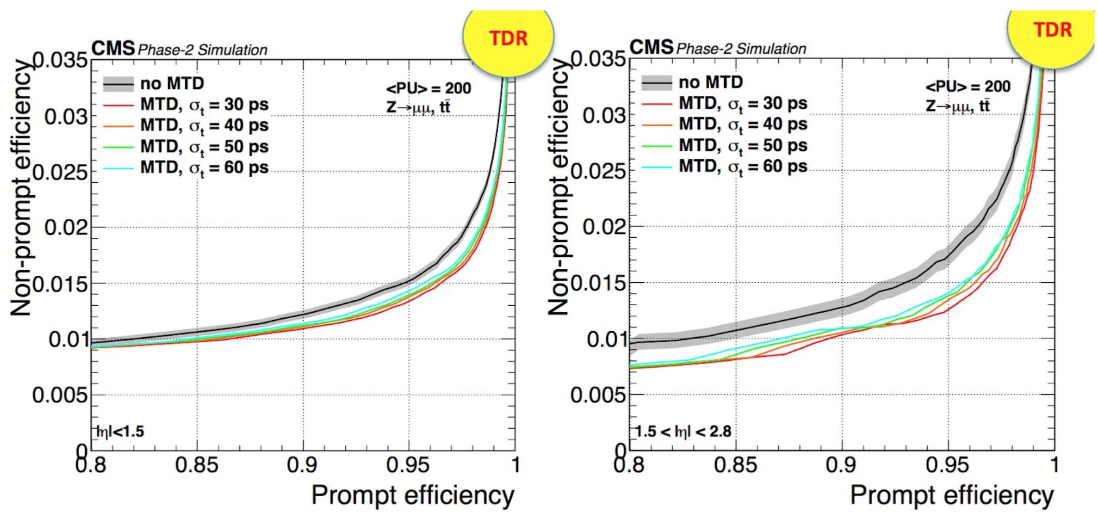
4.The MTD physics-engineering requirements are to achieve “sufficient resolution to disambiguate
spatially-coincident vertices”. For CD-2, it will be necessary to be quantitatively explicit to specify acceptance criteria for each component.

To be specific, please include the following points:

4.1. Basic physics plots motivating the choice of 40, 60 ps for the various running periods;

David will address this in his talk.

4.2. Can these plots be shown separately for tracks pointing to the Barrel versus the one pointing to the EndCap, i.e. what is the relative contribution of the two detectors for physics? Are the timing resolution for BTL and ETL the same?



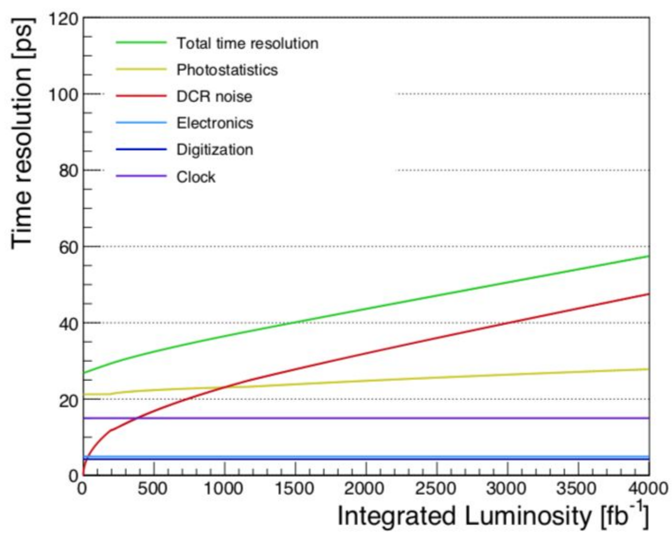
At a constant background efficiency of 12% the muon efficiency is improved by 5% in the barrel @ 40ps and 8-9% in the endcap. At 60 ps resolution this is degraded to 3-4% and 6-7% respectively. The improvement from timing is larger in the endcap per track than in the barrel, but most massive physics is produced centrally, which means the dominating physics impact in searches or single-parameter measurements will be from the barrel. In differential measurements or b-physics the endcap plays an equal role to the barrel. The degradation in physics performance if only 60ps is achieved is about 50% of the nominal improvement from MTD.

4.3. Does the simulation that demonstrates the conceptual design is sufficient include effects from the full system, including the module resolution, jitter in clock distribution all the way through the chain from TTC all the way to the FE ASIC, etc.?

BTL Timing Resolution Breakdown -- **all are included in the simulation**:

CMS clock distribution	15 ps
Digitization	6 ps
Electronics	7 ps
Photo-statistics	25 – 35 ps
Noise (SiPM dark counts)	negligible at startup, 50 ps after 4 000 fb^{-1}

These values are evolved in terms of integrated luminosity as in the plot that follows:

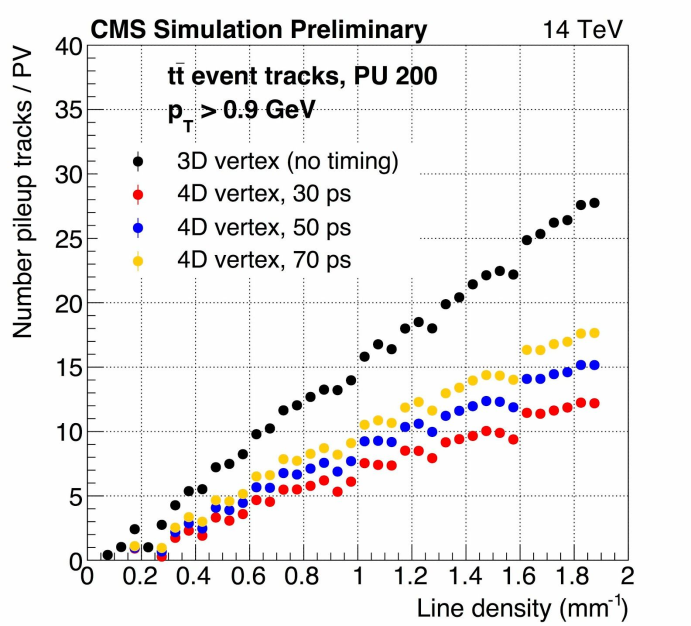


The values of the clock jitter from the machine are estimated by the CMS timing distribution group and are in common use by all subsystems, but the resolution is dominated by the DCR.

For ETL similar inputs are used but they are summed in quadrature into a single resolution term that is used in the simulation. The 35ps sensor jitter (@2000/fb), 40 ps ASIC jitter, and clock distribution jitter are summed in quadrature and used to develop the expected two-hit timing resolution per track.

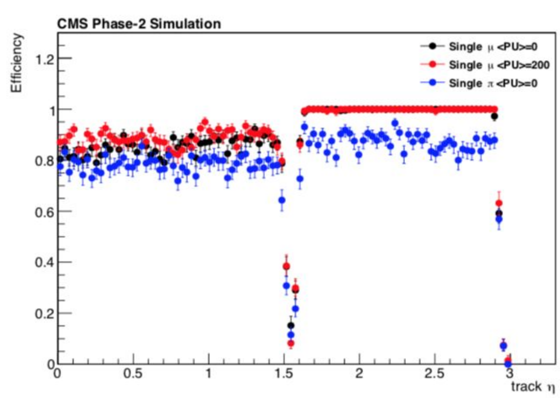
4.4. During running time the performance of the detector will deteriorate due to increase effect of radiation. This looks to be happening in the whole BLT region already at 2000/fb while for the ETL looks to be concentrated at the highest eta regions. What is the implication on physics? Is the degradation of other parts of the full system included in the simulation? In other words, what is the impact on physics if you cannot reach < 40 ps but you instead satisfy < 60 ps?

If only 60ps is achieved system wide from beginning of life then the benefit of MTD in pileup rejection remains but is reduced by a factor of 50% compared to the projections shown in the MTD TDR which are for 40ps. This follows directly from the degradation in the amount of pileup tracks rejected from the primary vertex, as shown below.



4.5. Present to us the MTD coverage in the BTL and ETL regions. This do not look to be 100% but more 85% or less. Have been these acceptance values folded in the evaluation of the reconstructed plot in the TDR?

This efficiency map (for pions) is used as input to the fast simulation of the MTD from which our high level physics results are derived.



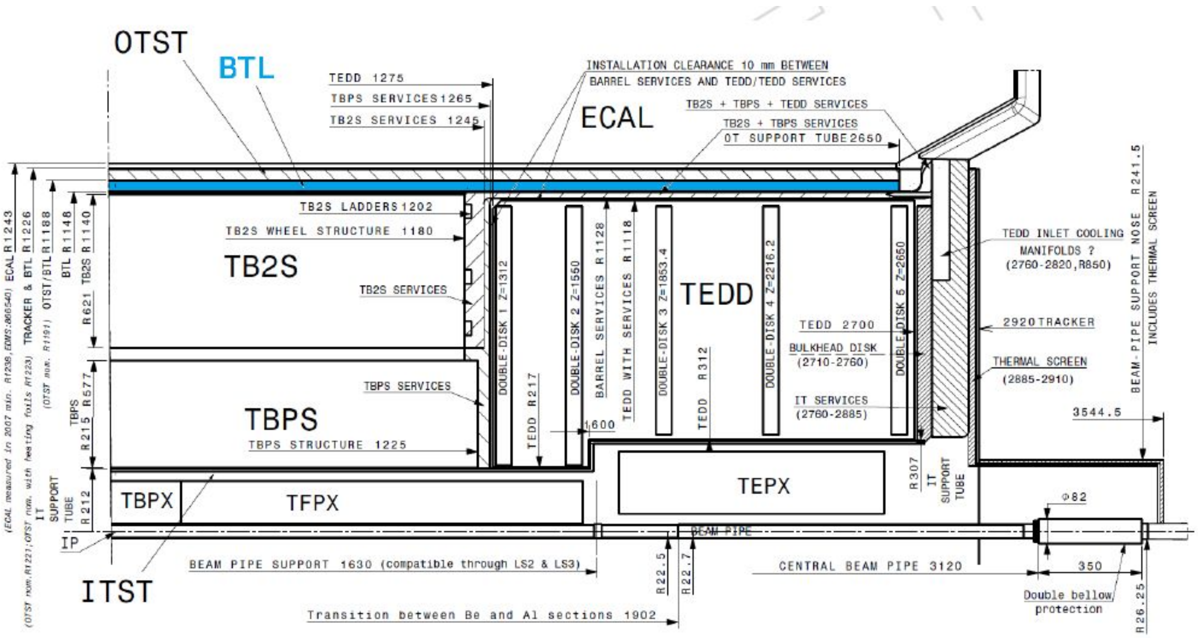


Figure 2.1: BTL integration within CMS.

The Tracker Support Tube (OTST) has a length of 5.3 m. The BTL trays cover a length of 4.96 m. The outer edge of the BTL tray corresponds to eta ~1.5 which is the edge of the acceptance of the ECAL barrel.

5. Silly questions for Technology choice and Value engineering

5.1. What are the timing resolution that CMS can reach without the MTD? Is the ETL really needed in the EndCap regions? What is the capability provided by the HGCAL detector itself?

EM showers are measured in the barrel and EM and high energy hadronic showers in the endcap calorimetry with resolution of 30ps. MIP timing is only provided by the MTD, therefore extending the improvements in physics object reconstruction to the barrel and endcap region.

5.2. What is exactly the neutron moderator positioned below the ETL and why, if any, the ETL is not positioned “behind” the moderator. In this way, we expect the neutron flux on the ETL to be reduced and the ETL could work in synergy with the HGCAL reconstruction.

The neutron moderator provides protection of the tracker detector and the ETL from the neutrons produced in the HGCAL [ie. “backsplash”]. Therefore, the ETL needs to be on the side towards the interaction point.

5.3. Does barrel MTD invalidate crab crossing as an accelerator option? What is the risk that the crossing scheme spoils the performance of the barrel MTD?

No MTD does not invalidate the advantages of crab-crossing, neither does any crab-crossing scenario obviate the benefit provided by MTD. Rather, MTD increases the options available to the accelerator to deliver luminosity since the beamspot can be manipulated in both its z and time profiles. Examining even extreme accelerator optics configurations (“crab kissing”), the change in the time spread of the beamspot is marginal compared to standard optics. Therefore MTD is still highly effective regardless of crab cavity configuration.

6. Calibration technique and impact on Time resolution

While we have seen in your presentations a lot of technical discussion of detector performance issues and separation of the different contributions for the timing resolution, we have not found any discussion of a calibration technique in situ to disentangle the contribution related to the channel-to-channel T0 alignment.

6.1 Is there a pulsing or laser system that provide the capability of reconstructing and following the T0s at a level of < 30 ps RMS in the BTL or ETL system for all running period?

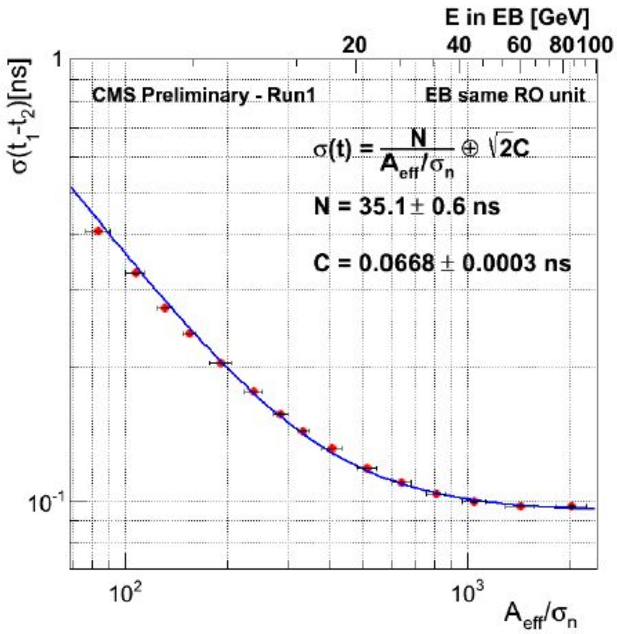
There is no laser system. The T0 calibration is done with physics events, see below. The amplitude response is followed with the MIP peak and with the natural LYSO radioactivity peak.

In the high-frequency domain above the PLL loop bandwidth (100 kHz to 100 MHz), the effects will be canceled by back-end and on-detector PLLs. The lpGBT ASIC used in both the BTL and the ETL on-detector electronics has a PLL with a loop bandwidth around a few MHz. Furthermore, there will be an additional PLL in the ETROC ASIC. The specification and the architecture of this PLL is still under study.

If the baseline solution with lpGBT clock distribution does not meet the differential jitter requirements, a pure clock will be distributed via a separate clock distribution tree.

6.2 Is there a physics process that can constitute a simple calibration IN-SITU of such offsets? 10 ps time differences correspond to 1.5 mm cable differences or delay in electronics components.

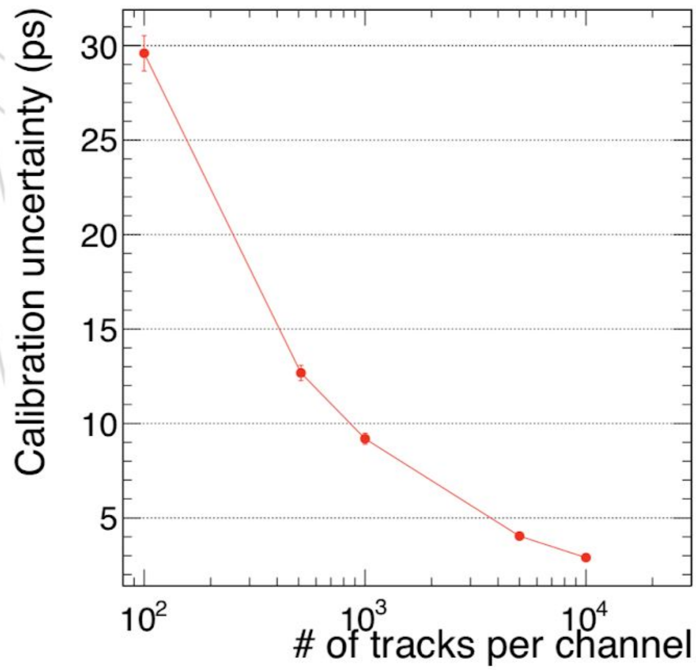
We do a physics calibration by equalizing the mean time response in each channel. This method has been employed successfully with the CMS ECAL during LHC run 1 and 2. It was estimated that for MTD less than one hour of data taking are sufficient to accumulate sufficient statistics to do a single channel calibration. CMS ECAL achieved a local time resolution around 70 ps with this method.



A similar strategy will be deployed for MTD. The time offsets of the MTD channels can be inter-calibrated using all the tracks collected by the CMS high level trigger. The distribution of the reconstructed time at the vertex — i.e. after TOF correction — of these tracks has an RMS spread of approximately 200 ps, primarily determined by the time spread of the luminous region, as the additional spread due to the sensor resolution is marginal compared to the beam spot time spread. The mean time of this distribution over many events provide the reference calibration points.

To illustrate the method, we show results from a full simulation study for the BTL. Similar conclusions, appropriately scaled for the occupancy and channel count, apply to the ETL as well. As illustrated in this Figure, the median of the distribution provides a reference calibration point with an uncertainty of about 9 ps for 1000 tracks and of less than 3 ps for 10000 tracks, where the uncertainty is the spread between the injected time offset and the estimated time offset from the truncated mean of the distribution.

At an allocation high-level trigger rate of 1 kHz and an average occupancy of 5% for 200 pileup events, this amount of tracks will be collected respectively in around 20 or 200 s in each channel, thereby providing the possibility of frequent and granular calibrations. These calibration constants can be made available for the prompt reconstruction of the events, which in the current CMS operation starts within 24 hours of the data-taking.



6.3 Where are timing offsets (e.g., from different fiber lengths) accommodated in these systems?

The timing offsets are coming from calibrations and stored in the online Database, and they enter in the reconstruction stage at the HLT and offline levels.

6.4 An error on this alignment or a not-clear calibration procedure can wash out a great performant detector.

For the purpose of associating a track to hit in the timing detector, the spatial alignment is not critical. The average hit density is below one track per 10 cm2, while the resolution of the track extrapolated to the MTD is of the order of 1 mm or better depending of the pT. For the purpose of the time-of-flight correction, the precision of the track reconstruction is dominated by the tracking precision (Section 5.3.1). Hence, also in this case, the requirement on the MTD alignment is not stringent. The spatial alignment will be based on the match between tracks extrapolated to the MTD and the hits in the MTD, similarly to the alignment technique adopted in the tracker. By combining the information from many tracks, the precision of this method is much better than the spatial resolution of the MTD sensors and is not a limiting factor. This procedure can be repeated in time, to monitor systematic movements relative to the tracker.

7. BOE-cost and risks

7.1 From the point of view of BOEs, schedule and risk we have really appreciated the organisation of the BOE section that is clear to read and full of details. However, as discussed in the open section, we believe that the central cost and the risk associated to the LYSO procurement is overly aggressive. The Mu2e learning phase demonstrated that Chinese producers have a monopoly on the LYSO salt price so that if different producers cannot be identified, the best evaluation will be to use SICCAS producer as central value, we suggest to use the difference between SICCAS and the cheapest non-Chinese vendor as a value for contingency. Add a risk on the risk register that the price could doubled and use a central probability value of 5-10%.

We have received 8 responses to the RFQ:

Company	**Country**	**Option C [kCHF]**
Crystal Photonics Inc	USA	3842
Simcrystals Technology Co.,Ltd.	China	3444
JT crystal technology Co., Ltd.	China	2563
Zecotek		2194
Hypercrystal Co.	Taiwan	3173
Tianle Photonics Co., Ltd.	China	2092
SIPAT Co.		2512
Shanghai Institute of Ceramics, CAS	China	3094

The average of all 8 responses is 2864 kCHF. This is the number we use in the US costing. We assume an EU of M3, which translates to a ±15% uncertainty.

We acknowledge that there are several ways one can use the responses to the RFQ process to arrive at an estimate to use in the costing. Taking the straight average is simplest. Further, we are evaluating crystals from all 8 vendors, with no a priori preference towards any of the 8, hence the simple average is a good approach here.

We already have a risk to account for a market effect like a tariff:

ID: RT-402-8-33-D

Title: BTL - Difficulties procuring LYSO from international suppliers

Summary: If LYSO becomes the subject of high tariffs from a specific country, then the increased cost jeopardizes project budget and/or delays jeopardize QC testing schedule and all subsequent dependent activities.
Probability: 10%
Cost impact: 200 - 450 - 700k
Schedule impact: 3-6-9 months
Explanation: Considering an overall investment from the US of ~$900k. Assuming a 50% tariff means a cost impact of 450k, with some guessed range ±250k.

We know this needs to be updated in that our investment in LYSO is ~$1.1M, rather than 900k. We will do this before the IPR in June.

Further, if we are confronted with export controls originating in China in retaliation towards a US tariff, the procurement could go through CERN or one of our Chinese collaborators.

From the technical point of view we see two risks that have not being considered for the BTL and that we suggest here to discuss:

- Since BTL cannot be substituted it is important to consider the two following points:
    - 7.2 A clear measurement of MTTF for SiPMs and all electronics component should be evaluated and measurement carried out before CD-2;
      This will be done on the prototyping stage, where the performance of individual components and the readout unit as a whole will be performed.
      This is addressed for SiPMs below.
    - 7.3 Evaluation of the effect of radiation induced noise on the performance should also be carried out. Explained below.
      We plan to subject prototype and pre-production concentrator cards to repetitive temperature changes as well as irradiate the cards and test them to estimate the effect of the aging on the concentrator cards. Once front-end boards as well as readout test electronics is ready to measure the performance of the readout unit - tests will be done to measure the radiation induced noise on the electronic components (this will be done within international MTD effort)

- 7.4 For cost profile. Is there anything you can change in your scope if the DOE funding profile will change?

  We have scope (up and down) options that we have described in CMS-doc-xxxxx.
  We can discuss the timing of our CORE contributions to the MTD in negotiation with the MTD Resource Manager. The details of this would depend on the details of the time profile.

8. Project efficiency / labor / schedules

- 8.1 Page 17 Chlebana: Why is BTL module schedule serial? (e.g., at a single site: produce module batch 01, integrate modules +electronics, test; then produce module batch 04, integrate modules + electronics, test; then produce…)

  The assembly at UVa and Caltech is done in parallel. The sequence of assembly steps assumes the same people will be doing the sequential steps (produce modules + integrate modules + testing) and can be completed in the available time. We can increase throughput by having more people work on the assembly and change the sequence, having the same people focus on one stage of the assembly process. We can use this option in case we have to increase throughput. .

- 8.2 Is there a significant cost/risk benefit to reduce the number of BTL module production sites from 2 (CalTech + UVa) to 1? (+ 1 international site)

  We want to have two production sites in the US in order to reduce the risk on one site having problems and to be able to maintain the necessary production throughput in the US. The hardware costs for establishing a BTL module production site is about 121k$ which includes the cost for the pick and place robot + stencil printer + DAQ test stand. If we only had one site, we would have to increase production so the labor costs would be similar as for having two sites.

- 8.3 Same question for ETL module production sites: FNAL + UNL. How much overlap will there be with Tracker production at FNAL?

  .

  The Tracker production and the ETL assembly will have separate facilities and not interfere with each other. We do not expect significant overlap for the wire bonding resources. The wire bonding for the ETL can be done in a concentrated short interval and the sub assemblies can be set aside until ready for the next step. We note that the wire bonding required for ETL modules is relatively simple compared to that for similar silicon sensor modules with approximately 50 bonds per ASIC with a simple pattern.

  Reducing from two U.S. ETL assembly sites to one would result in relatively little cost savings, primarily the cost of a DAQ and environmental chamber and the difference in cost between a wire bonding technician at FNAL and UNL for the 20% of the assembly done at FNAL. This savings is estimated to be less than $100k. There would be a significant increase in risk as a result of having only one site in the U.S.

- 8.4 Will the non-US assembly sites also use the same procedures and design?
  Yes

- 8.5 How much correlation in the BTL/ETL test stands can be exploited?

The BTL+ETL System Testing L4 area was specifically devised as a joint task to ensure coherence between testing for barrel and endcap. The test stands will include environmental chambers, for which the designs will be shared between BTL and ETL. The backend interfaces will also be similar for ETL and BTL. As the BTL testing will occur first, the ETL tests will be informed by BTL testing and may reuse much of the same hardware. System testing will also include joint vertical system tests between available BTL and ETL components.

- 8.6 Uncosted labor. Should only include labor actually needed to deliver the scope. Sounded like objective KPP is where all uncosted labor is. (Neu's MTD overview slide 35 says contributed labor is not in line with other projects because most of it is there for OPP)

  There is a bit of an understanding, see the next question about the comment regarding contributed labor and oKPPs.

  Slide 35 of CN's talk was meant to say that when examining the labor associated with satisfying our tKPPs specifically (BTL SiPM, BTL CC, BTL Assembly, ETL FE ASIC, ETL Assembly) the ratio of costed to uncosted is similar to OT and CE.

	Uncosted	Total	Uncosted/Total
MTD	20.14	46.71	0.431
OT	76.21	181.11	0.421
CE	38.99	127.48	0.306

- 8.7 Question for 8AM on uncosted labor in MTD:
  It was claimed that the large amount of MTD uncosted labor is only there for meeting objective and not for KPP. Can you give a breakdown of the uncosted labor that is only there for objective and if removed would have no impact at all on KPP? What FTE's in what institutes and what years?

  There was a misunderstanding:
  - We have WBS areas which complement our work towards our tKPPs but are not essential to completing our deliverables
    - BTL LYSO, ETL LGADs, BTL and ETL System Testing
  - These are not strictly associated with oKPPs
  - These areas are included in our WBS and labor estimates to reflect that we have participation in these areas but are mostly pd/students by design
    - Participation in BTL LYSO QC for training of 1-2 pd/students from UVa, Caltech

- Pd/student participation in LGAD sensor R&D in FY19,20 at Kansas
- System Testing for both BTL and ETL, driven by pd and students

Here is our labor summary down to L4:

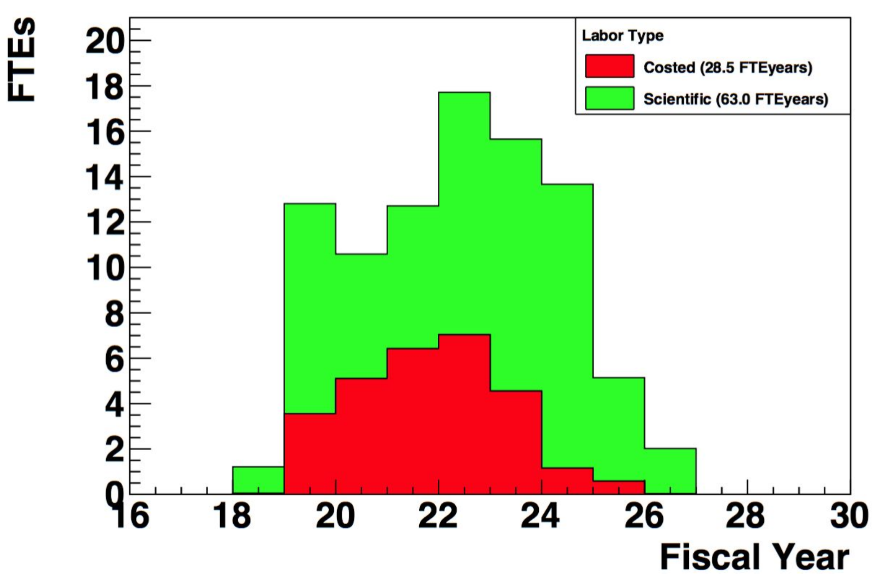
WBS Area	Contributed FTE	Total FTE	Contributed / Total (%)
Management	15	15	100
BTL – LYSO	1.67	1.67	100
BTL – SiPM	0	3.05	0
BTL – CC	0	2.91	0
BTL – System Testing	3.47	3.58	97
BTL - Assembly	4.83	10.95	44
BLT - I&C	5.02	6.02	83
ETL – LGAD	2.19	2.19	100
ETL – ASIC	1.43	12.78	11
ETL – System Testing	3.58	3.58	100
ETL - Assembly	13.88	17.02	82
ETL- I&C	11.96	12.77	94
Total	63.03	91.52	69

The ETL Assembly task stands out with a large amount of contributed labor. Some of this is due to the physicist labor that is needed for the R&D and prototyping, but we also identified an error in our estimate -- this contributed labor number includes senior faculty acting in a supervisory role over the assembly team at UNL, in both the prototyping and production phases, which were over estimated in the FTE appropriate for that supervision.

We do not have the plots per-institute time profile at our fingertips but we will make it. Summary of the uncosted labor for each institute:

Resource Name	Labor (hours)	Labor (FTE-years)
CD1-v2-DR-402.8 402.8 TL - Timing Layer	111428	63.02
Graduate student— contributed (uncosted) labor at Average University	40280	22.78
California Institute of Technology	5839	3.30
University of Kansas	4036	2.28
Kansas State University	2222	1.26
University of Nebraska	12442	7.04
University of California - Santa Barbara	10276	5.81
University of Virginia	5465	3.09
Particle Physicist Experimental Uncosted	10249	5.80
Fermi National Accelerator Laboratory	10249	5.80
Particle Physics Experimental Research Associate Uncosted	6237	3.53
Fermi National Accelerator Laboratory	6237	3.53
Postdoc — contributed (uncosted) labor at Average University	31591	17.87
California Institute of Technology	7268	4.11
University of Kansas	1472	0.83
University of Nebraska	10968	6.20
University of California - Santa Barbara	6183	3.50
University of Virginia	5700	3.22
Scientist — contributed (uncosted) labor at Average University	22351	12.64
California Institute of Technology	3315	1.88
University of Nebraska	2150	1.22
University of California - Santa Barbara	10256	5.80
University of Virginia	6630	3.75
Undergraduate student — contributed (uncosted) labor at Average University	720	0.41
University of Kansas	720	0.41

402.8-TL Costed and Scientific Labor



9. Specific technical questions

BTL-LYSO

- 9.1 Choice of Double readout. Flatter resolution along tile but failure rate x 2. If one side dies resolution increases by x 1.4

  The main reason to use two SiPMs on a bar-like crystal is the better performance and uniformity. A side effect is that the time resolution can still be maintained at sqrt(2) times the resolution if one of the two SiPMs has a fault. It is more robust than single SiPM channels.

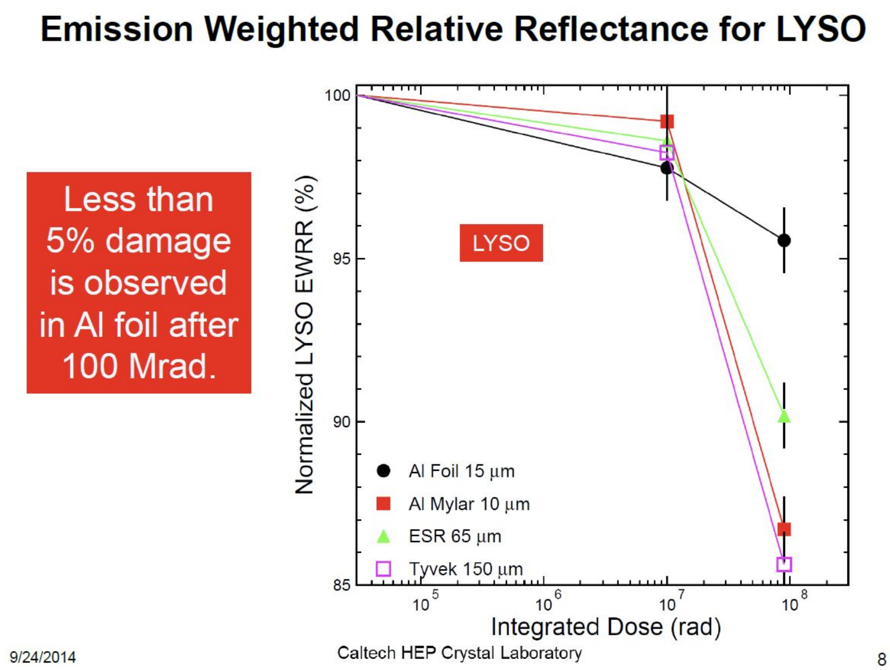
  Our experience with HCAL is that the SiPMs do not fail during operation, so that does not pose much risk.

- 9.2 Problems of wrapping. Who does this? what is the final option? You said that producer is going to do it. Is inside the RFQ? Are the SiPMs glued at the crystals' producing firm? Is this a plus or a minus for the schedule? You reduce manpower usage by you add risk of shipment, manipulation of SiPMs and time.

  The wrapping is done by the manufacturer. We are currently negotiating use aluminium foil as wrapping with ESR or $BaSO_4$ as reflector between crystal and aluminium. This is part of the RFQ.
  Currently, the module and tray assembly includes the gluing procedure of the SiPM on the crystal. The manpower estimates are derived from the procedure used by the CALICE collaboration. We will discuss with SiPM manufacturers if they can do the gluin for us. iBTL collaborators have experience with this from building R&D PET scanners.

- 9.3 R&D on wrapping rad-hardness is important. Measurement of transparency changes at Caltech? Tyvek (or ESR) start loosing reflection power is this being done/planned?

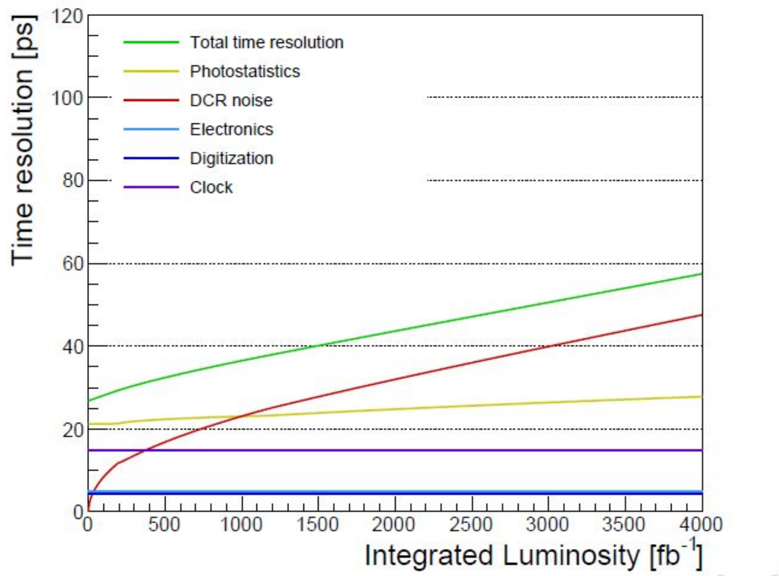
  Different wrappings have been tested at CALTECH.
  Measurement of radiation hardness of wrapping :



At 100 kGy little degradation was found. BTL is expected dose at end of life is 25 kGy.

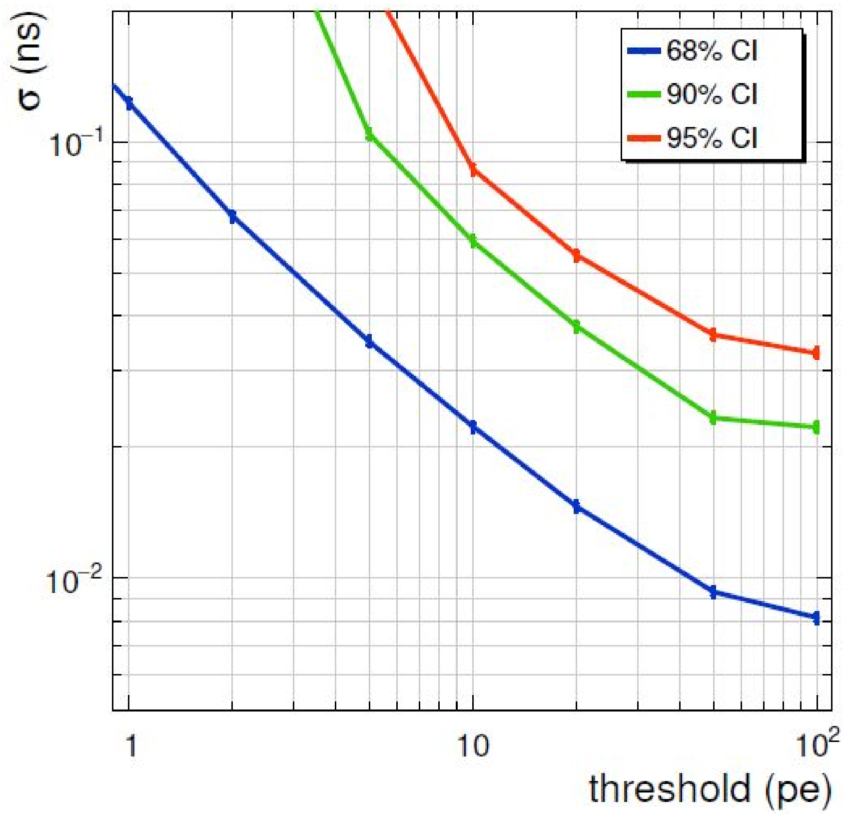
- 9.4 Effect on time resolution related to the instantaneous TID (rad/hour). From your 25 kGy after 10 years, we can derive 2.5 kGy per year i.e., 0.5 Gy/hour. Measurement of assembled BTL with MIP during irradiation should be performed before going to further. The noise induced from the scintillating tile can deteriorate the timing resolution.

  We intend to do such measurements with a final spec prototype. LYSO has been irradiated to much higher doses and its radiation hardness is fully sufficient.
  SiPMs have been irradiated to the doses the BTL will operate at and the DCR has been measured. It is used in the calculation of the expected BTL performance vs dose.
  See plot below from the TDR :



- 9.5 What is the background occupancy on the LYSO crystals? Show existing data and show where the threshold will be set.

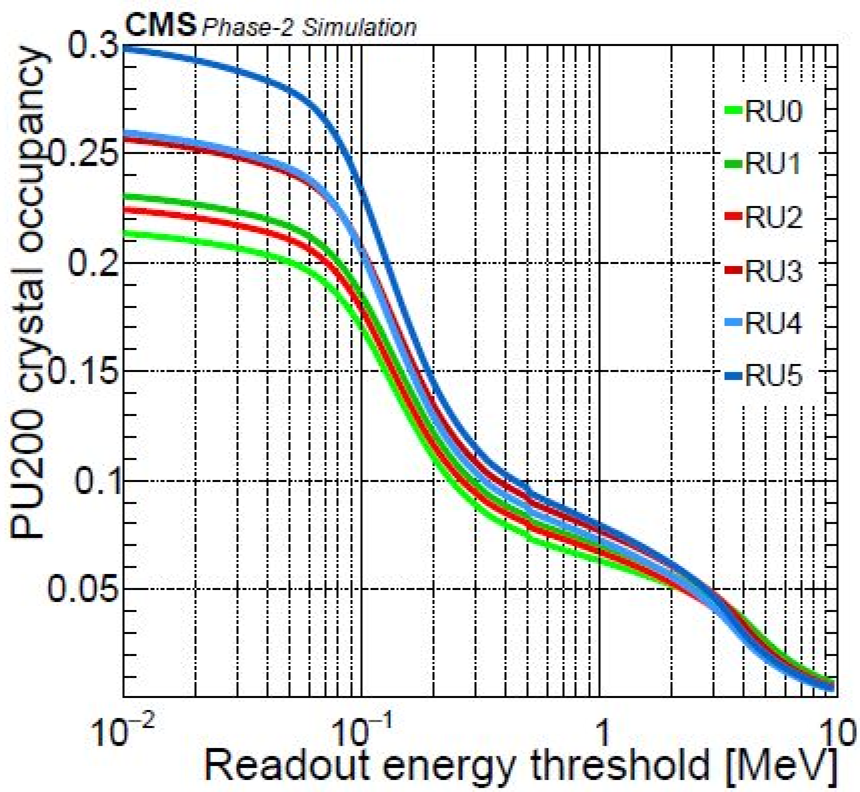
The dominant background is from the DCR in the SiPM
Regarding the background from low energy pile up activity in LYSO :
The PU contribution is less than 10 ps for a threshold of 20 pe. We will operate at a higher threshold than that.



Regarding the radiation induced background in LYSO from Renyuan Zhu :
The question is about the effect on readout noise induced by background radiation. We measured radiation induced readout noise in LYSO crystals of 25 x 25 x 200 mm [1] about ten years ago. The conclusion is "The equivalent readout noise induced by the radiation dose expected at the CMS barrel and endcaps is 0.2 MeV and 1.0 MeV for LSO/LYSO crystals of 25 x 25 x 200 mm." The result thus is negligible for CMS BTL LYSO crystals after scaling the noise down by sqrt of the crystal volume, assuming that crystal's light output is unchanged. Such a measurement is later used as one of the radiation hardness specifications for Mu2e CsI crystals.

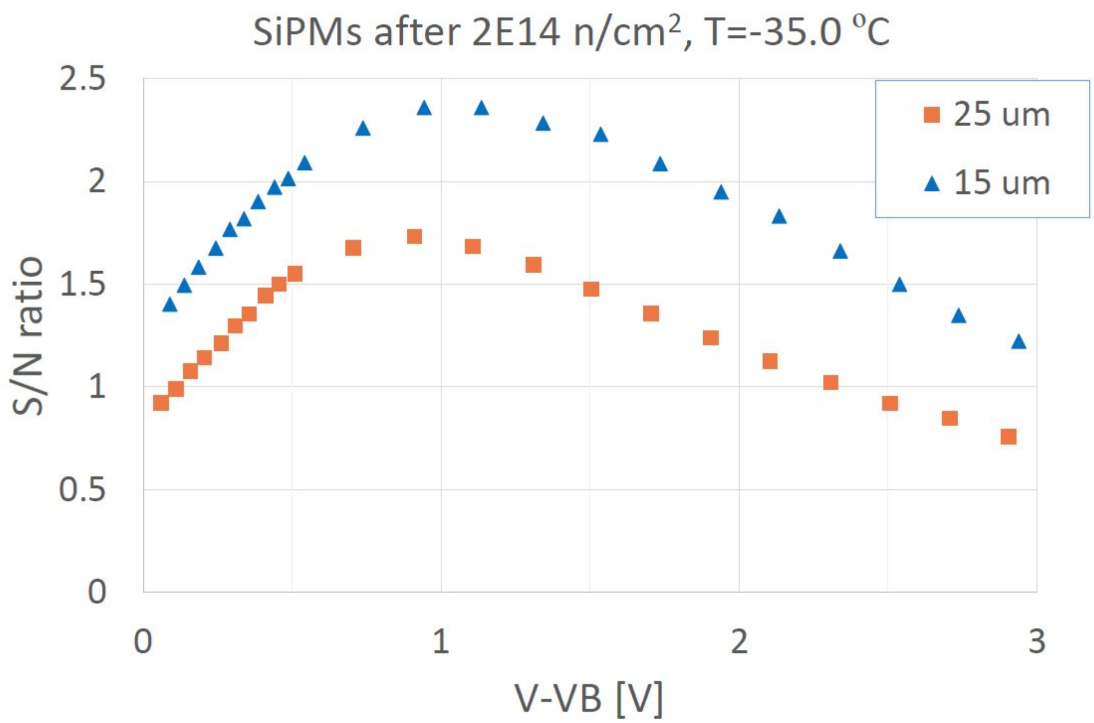
[1] http://www.hep.caltech.edu/~zhu/papers/09_NSSCR_gamma.pdf

All these effects are incorporated in the occupancy plot we show in the TDR. At a threshold of 1 MeV the vast majority of these low energy signals is suppressed in the ASIC which has dedicated mechanism to suppress high rate low amplitude random hits - the DCR suppression circuit.



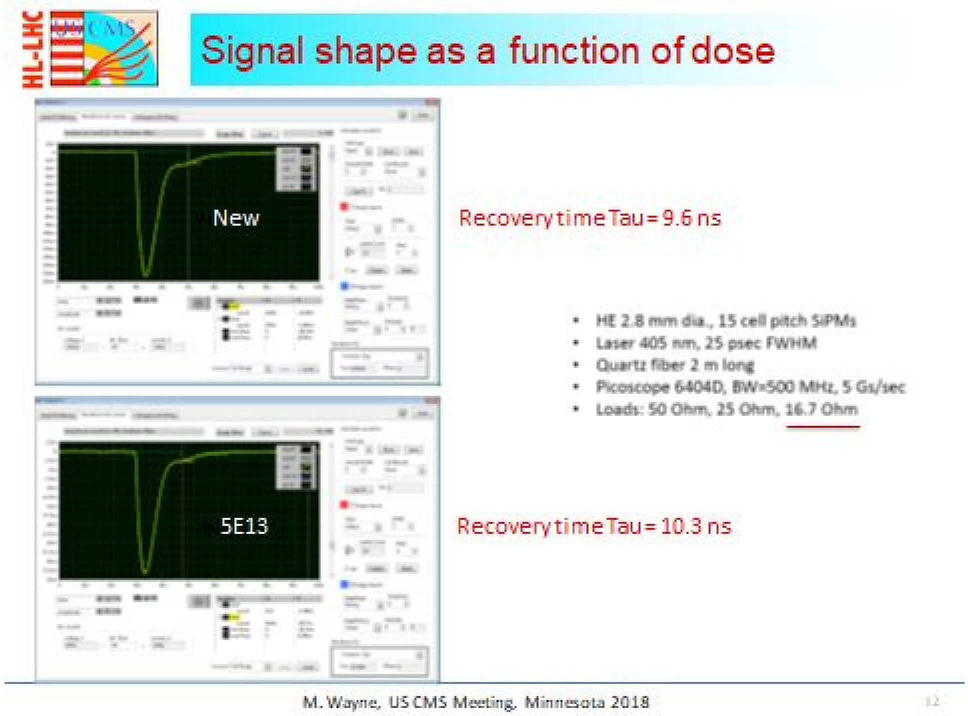
10. BTL-SIPMs

- 10.1 Pixel choice. Why 15 and not 30 um (or 50)?. There is a compromise between dynamic range, DCR, radiation hardness and PDE. PDE suggest to go to larger pixel size. It is quite likely that 50 um may be more radiation herd for timing applications. They have higher gain and faster rise of the PDE with voltage, hence they can operate at lower overvoltage and the DCR is a strong function of overvoltage, even stronger at lower temperatures
  We compared the performance of HPK 15 um vs 25 um pixel size, at a few different doses up to 2E14. The 15 um devices had better signal/noise at lower temperature (-35 degrees for our test) and also had a better reduction of dark current as the temperature is decreased. The 25 um devices exhibited high cell occupancy and self-heating effects for doses > 2E13. (Plots and a summary slide are available)



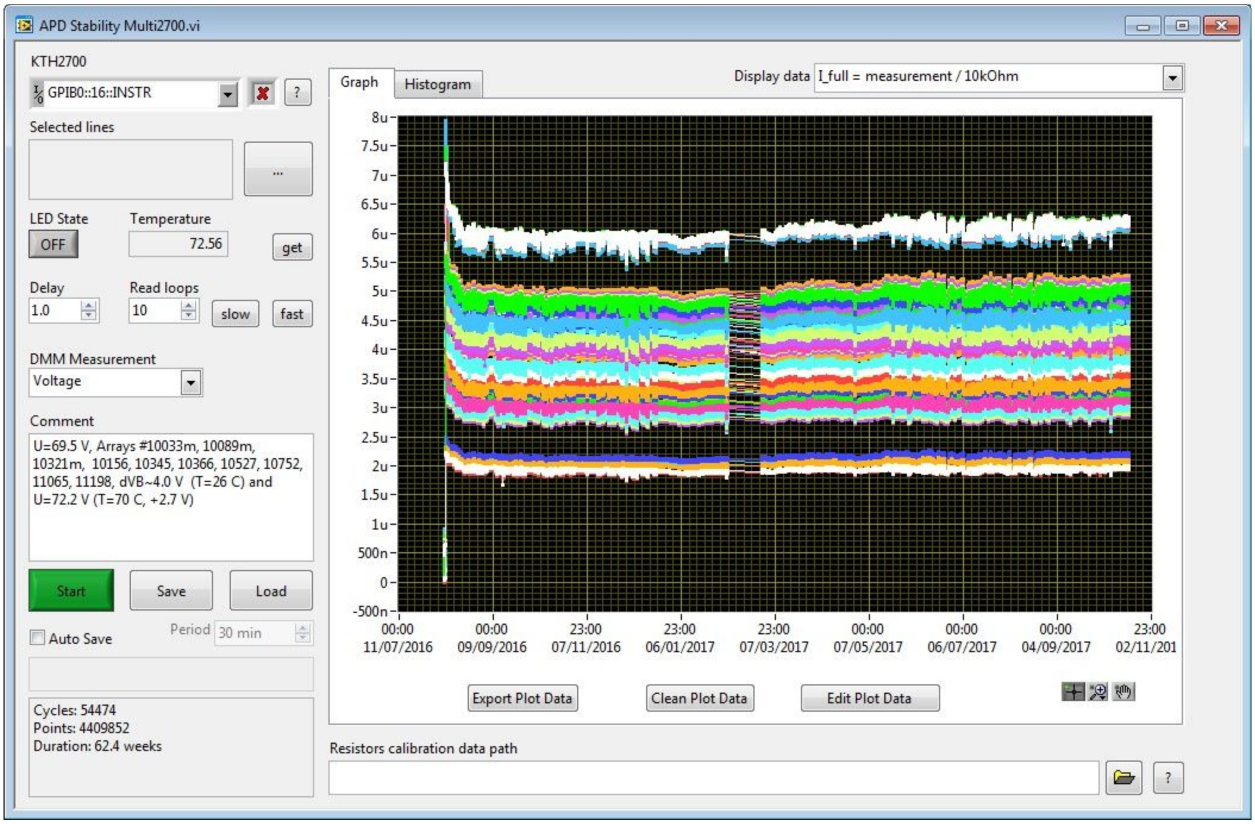
- 10.2 Radiation hardness of LYSO and SiPMs have been eveluated for calorimetric applications. It is not obvious if they apply to the timing measurements, which may be sensitive to different features (like induced phosphorence), which were not of concern for calorimetry.
  A number of beam tests have been done over the past couple of years. Timing results are consistent with our understanding of LYSO+SiPM. But we can look into this issue in more detail.
  The driving feature of the LYSO is the large light yield. The rise time of the LYSO is much faster (<50 ps) than the shaping time of the SiPM+ASIC. Possible pulse shape changes of the LYSO are not expected to alter the rise time of the LYSO. The induced phosphorescence (see answer from Renyuan) is not large in magnitude.

- 10.3 Radiation hardness of optical glue may be an issue. Radiation resistance of different technologies of quenching resistors (metal vs polysilicone) may be an important factor.
  We have irradiated SiPMs with different coatings, as well as separate samples of glass windows and epoxies/resins. We have studied the pulse shape of the SiPM after irradiation, and saw no significant difference, indicating no damage to the quenching resistors. But will follow up with the vendors.



- 10.4 SiPM vendors: HPK and FBK. Why not SENSL?
  We decided to limit our number of vendors to two, and chose the two we have been working with most closely over the past few years. Both vendors have produced promising SiPMs under consideration by BTL.
- 10.5 QA for SiPMs Is this really necessary or is only accademia? Could we reduce the impact here. Hamamatsu is going fine but also most of the other good producers. Can this be reduced to a smaller number without losing effectiveness? This could help for Labour.
  We plan to test all channels at -30 degrees. Not at all clear if HPK will do that, or even be willing to do the tests we plan. Also, there is the question of cost.
- 10.6 Do SiPMs need to be batch qualified for rad tolerance, following COTS guidelines?
  From all of our experience (including a year of operation in HE), the effects of radiation are very uniform from channel to channel. So it should be sufficient to test a small subsample after irradiation.
- 10.7 What instead is missing is an effort on evaluating MTTF in standard condition and after irradiation. This is important since there are 331 kchannels and there is not possibility to substitute the channels. MTTF to be evaluated for 151 ktiles, probability of 1 out of 2 dying. I.e. number of dead SiPMs ==> 2 x Nsipm= Dead Tiles

  For HCAL we did an accelerated aging test on 80 channels of HPK SiPM. They were continuously operated at 70 degrees for 62 weeks. This is the equivalent of roughly 30 years operation at room temperature. There were no failures. A similar study was done for both HE and HB, 80 channels in each case.



- 10.8 How can the PDE reach such a good level with 15 um pixel? Explain.
  There are likely several factors, but our understanding from HPK is the main improvement is in the "geometric factor", i.e. the sensitive area of each pixel.
- 10.9 Is the final choice you are carrying out with or without VIAS?
  We still have two options under consideration: using wire bonds like was done for HCAL, or using TSV (through silicon vias).
- 10.10 In the last part of the run, reducing bias will reduce the DCR but also PDE thus losing light yield and deteriorating resolution from 40 up to 60 ps. Is there a practical limit of current you need to keep during running? What is the guideline? Is there a method to check the gain during running? When operating such a large number of channel? peak-peak determination?
  Yes, there is a power limit (50 mW per channel). One can check the gain while running. As long as one can resolve the photopeaks, then the separation between them gives the gain. If not, there are statistical methods involving the peak over the width.
  We also consider to implement a the ability to measure the breakdown voltage. With this and the amplitude of the MIP - which is a known energy deposit - we can calculate the gain.

11. BTL-INTEGRATION

- 11.1 Any BTL ASIC risks?

  The risk due to a late arrival of the ASIC is accounted for in the risk register. A prototype of the ASIC exists and has been demonstrated to achieve design performance. The ASIC is on schedule as of now. There are two more ASIC development cycles of which the second one is entirely meant for fixing possible issues, no development is expected for this last cycle.

  The BTL FE ASIC (TOFHIR) is a deliverable from LIP in Lisbon.

- 11.2 Production issue. Where the crystals are going to be tested? ICMS? Will they check LY, LRU and shape? What is the dominating term of the resolution you will use for QC control?
  Crystal vendor evaluation is underway at Rome. For pre-production and production QC, the LY and and the time resolution of each matrix are the most important figures of merit to measure.The dominating terms in time resolution are LY and decay time and they both factor in the time resolution measurement. These two measurements (LY and TR) can be done simultaneously by dry coupling a 16 channel crystal array to a reference SiPM array.

  The dimensions of the matrices can be measured but this likely will be done by the manufacturer, since they will need to satisfy the tolerance specification we give them.

  We do not yet have a formal commitment from an international partner to complete the QC testing on the pre-production and production LYSO crystals. However, it is likely that these activities will happen at Rome as well. Another partner in Beijing has also expressed interest in participating in the LYSO QC. These commitments are being formalized in the preparation of the Step 2 UCG package for iMTD.

- 11.3 Concentrator? Do they have DC-DC converters? What about rad-hardness due to TID and B-Field?
  Yes, the readout unit will have 6 DCDC converters to provide the power to the board components and power to front end cards. The same DCDC converters will be used in the entire CMS phase 2 project, and thorough tests including magnetic field and rad hardness will be performed by ETH to ensure that the DCDC converters perform per expectations.

  These DCDC converters are a CERN deliverable.

- 11.4 What is the expected flow of the parts: Where the crystals/SiPMs are shipped to, how they are tested/ what is done to them, where they go next etc… Our suggestion would be:
    - Given huge number on channels and relative insensitivity to failure even at ~1% level
    - Given maturity and high quality of the products it makes little sense to test the components
    - Send the Sipms to crystal vendor and ask them to glue the crystals and Sipms
    - Do QA for the final product
      In fact for the LYSO we plan to rely on the QAQC from the vendor and do sample tests on a wider range of parameters and only measure the amplitude response to a radioactive source. Currently the flow of components is : LYSO from vendor to Rome, test there, send to assembly center. SiPM to CERN, test there, send to assembly center. Then gluing SiPM to LYSO at assembly center.
      If we were to do the gluing by the SiPM vendor, we would test the SiPMs with the crystal attached. This would require some changes to the test setup but this can be done.
      We are currently exploring the schedule and cost implications of outsourcing this step to industry.

12. ETL-ETROC

- 12.1 Interested to see details on jitter assumptions of external clock distribution (iCMS deliverable), as well as the clock distribution jitter inside the ETROC

  We will explain this in the parallel session talk (Ted Liu), which will also show the impact of worse than expected system clock jitter distribution.

- 12.2 Re: opportunity of using the ALTIROC. What system changes are needed in case of using ALTIROC. How late could these be changed?

  Changing the frontend ASIC to use the ALTIROC will require significant geometry changes for the modules, also impacting the design of the support services etc: the ALTIROC has a 15x15 channel matrix instead of 16x16 at 1.3x1.3mm^2 pixel size, so the size of chip would be different. The LGAD design then would needs to follow ATLAS. It would also impact the readout as the ALTIROC TDC window is only 2.5ns while the ETROC has 6.25ns, to allow Particle ID for slower moving particles. Also moving to the ALTIROC would require increasing our power budget in ETL. Our current thinking is that we will make a judgment on the ALTIROC opportunity before CD-2, that is, at the time of having the evaluation of ETROC1 and the full simulation results of the ETROC2 prototype.

- 12.3 What are the dates for ETROC ASIC design reviews?

The original design review for ETROC1 was scheduled for March 2019. Due to the recent TDR writing and preparation for director review, the ETROC1 design review is moved to May 2019. By then, we will have the initial testing results of ETROC0 (chips arrived CERN this week). The ETROC1 design is so far on track to be ready for submission in June 2019. The actual submission date will be decided once we have the testing results of ETROC0 in May.

For ETROC2 and ETROC3:   two months before the submission schedule in P6.

- 12.4 Summary of schedule risks

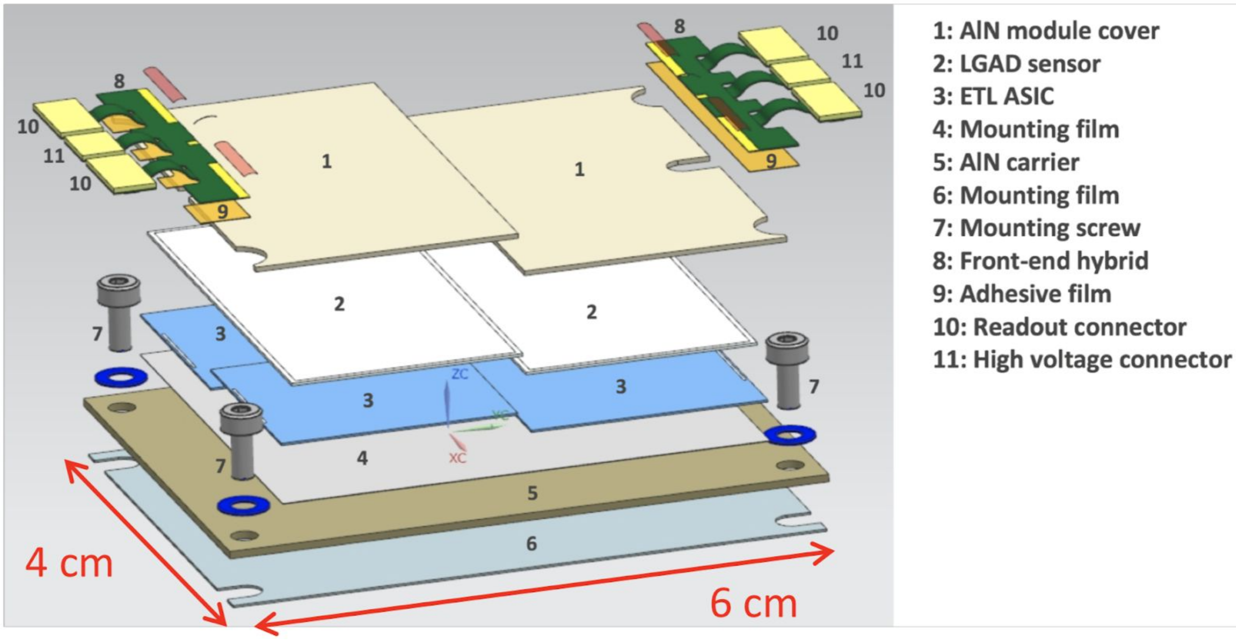
  I will discuss the ETROC risks in my BO session talk.

- 12.5 Interested to understand the differences between CFD vs LE discriminations

  This will be discussed in the parallel session talk. The information is also available in the CDR, see Fig. 6.51 and the Table in the text.

- 12.6 Does the design allow for replacement of radiation damaged inner modules without replacing the whole thing? Can you point to a few drawings?

  The modules are mounted with screws and one-sided tacky film, hence we maintain the ability to replace individual modules. In order to replace a module, the Dees will be dismounted from the nose of HGCal, brought up to the lab on the surface, and laid down for ease of access to components. Service cabling that runs from outside to in between the service hybrids will be disconnected, and modules replaced and reconnected. The detailed engineering workflow for this procedure is currently being developed. We show below an image of a module that shows the screws used to tighten the modules onto wedges, The second image shows the layout of modules on wedges. Service hybrids are shown in orange, and modules are in between service hybrids.



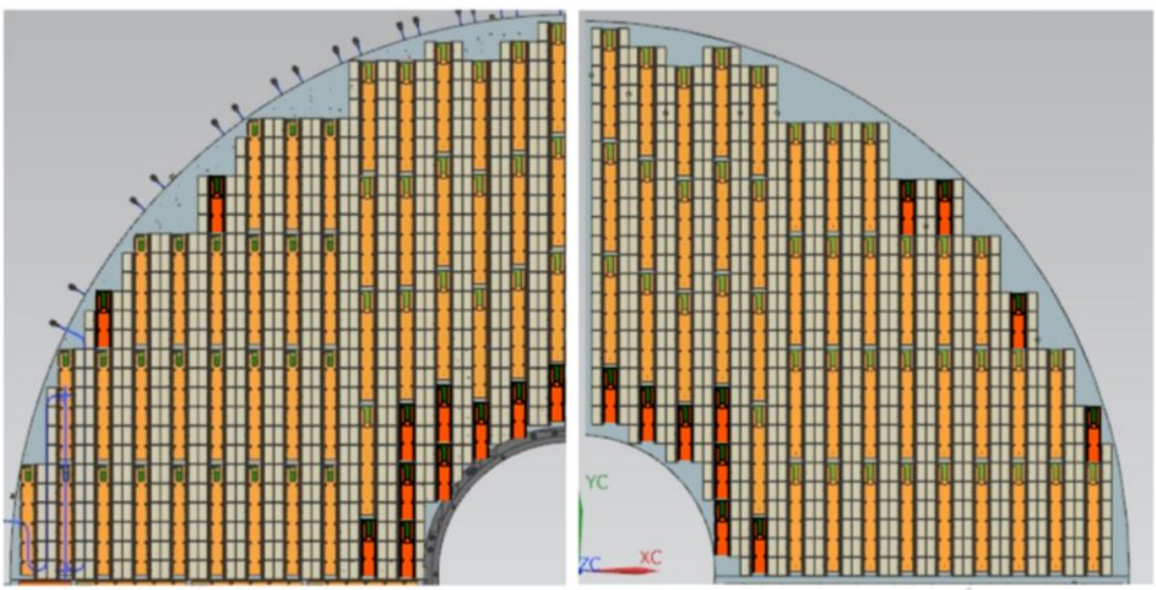


Figure 3.68: Layout of the modules and service hybrids on an ETL wedge, showing the placement on the front and back faces (right and left images), where the left image is viewed facing toward the IP and the right image is viewed facing away from the IP. The full-sized service hybrids are shown in orange and the half-sized service hybrids are shown in red. The LGAD sensors, shown as the gray rectangles, are assembled as either 1-sensor or 2-sensor modules, as described in Section 3.4. Examples of 1-sensor modules are seen at the edges of the front face, while 2-sensor modules are used to cover the central region.

- 12.7 ASIC talk should clarify Why does ASIC production take 1 year?

The ASIC production period includes ordering of the final wafers, waiting for their reception, and extensive QC testing on wafer before submission for bump-bonding.

13. Previous Director's Review recommendations (Apr 2018): have these been addressed?

Yes, we have responses for these comments and recommendations.

- 13.1 BTL - comments: measurement of slow moving particles. How does this work?
  Time measurement is used to measure velocity. i/beta is a classic use in particle ID.

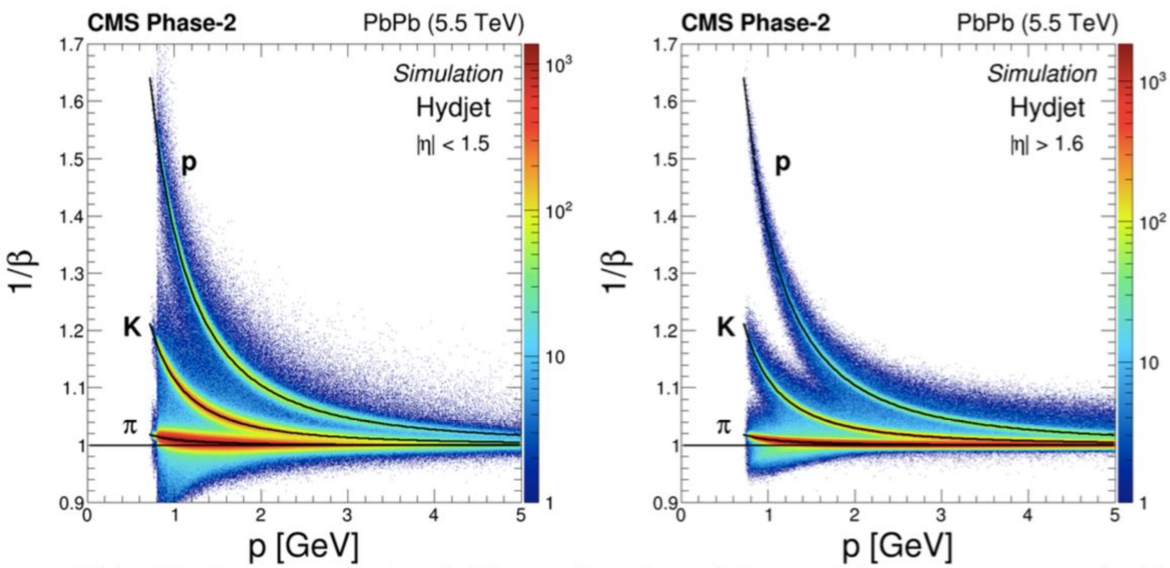
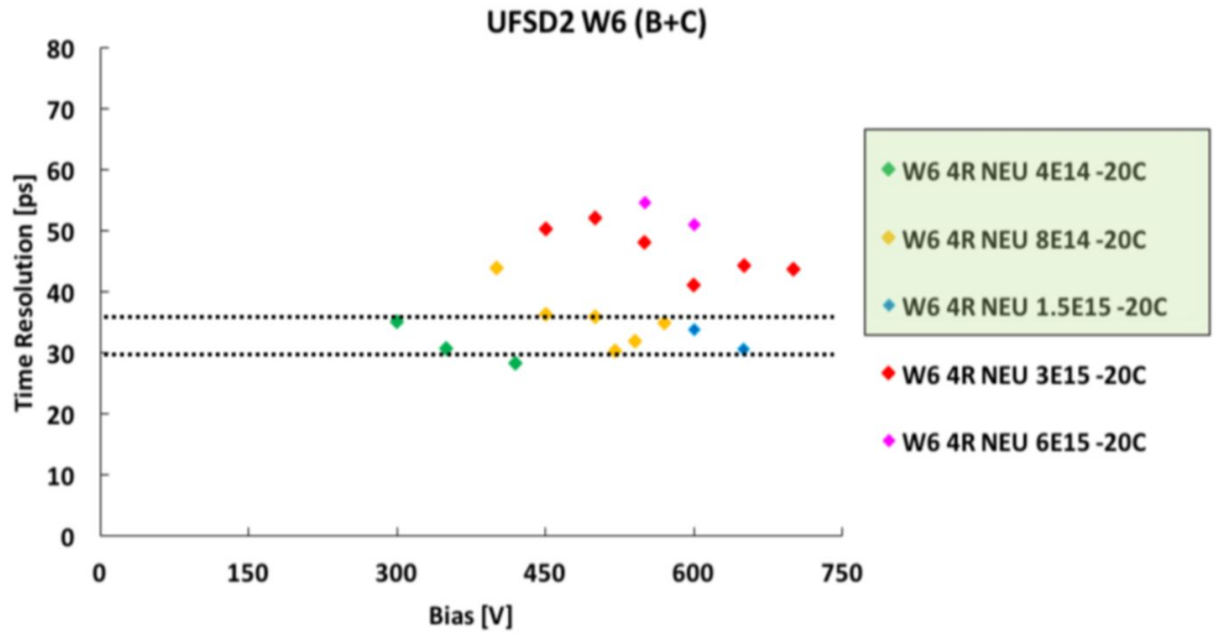
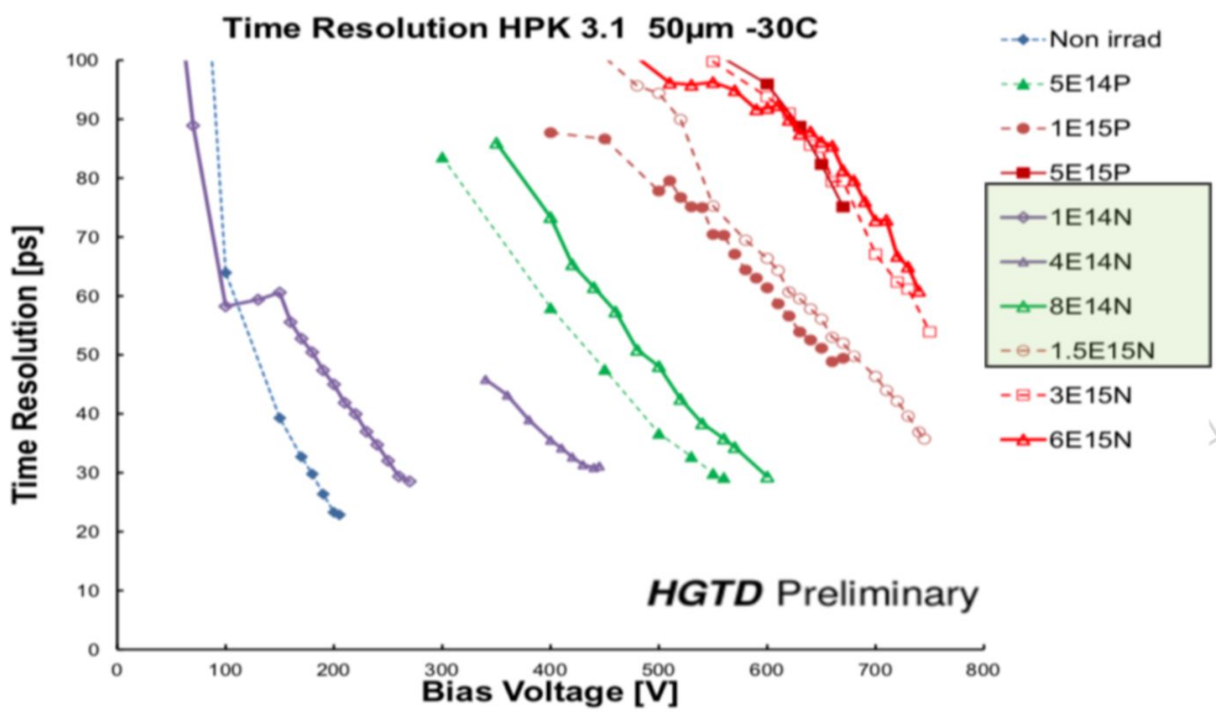


Figure 5.24: The inverse velocity ($1/\beta$) as a function of the particle momentum, p, for BTL ($|\eta| < 1.5$) and ETL ($|\eta| > 1.6$) in HYDJET PbPb simulation at 5 TeV.

- 13.2 BTL - comments: system test for the ability of reaching 30 ps time resolution in large and distributed system have to be planned before large scale production.
  Yes, we have already contacted the international CMS MTD BTL leaders to ensure the coordination of such large system tests.
- 13.3 ETL - comments: R&D of the sensors for exploring new doping strategies. Has this been done yet?
  New sensors produced by FBK using carbon doping, and those from HPK do indeed show improved radiation tolerance with timing resolution measured to be around 40 ps up to 1.5e15 n/cm2. Images below illustrate these results.

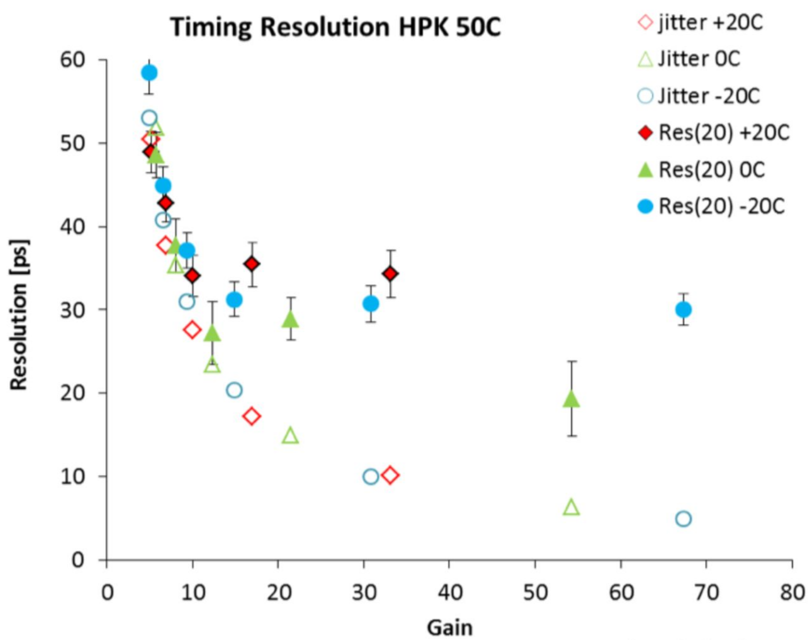




- 13.4 ETL - comments: LGAD reduced signal along the time. Solution: bias increase + preamp?
  The gain of about 10 allows us to reach time resolution of 30 ps, as shown in the image below. The bias voltage can be raised in order to maintain high gain, and this dependence is shown in the second figure below.

Additionally, the ETROCs of the modules at the highest eta which are subjected to the highest fluences, can be operated at a higher power setting for the pre-amp to recover some of the degradation of the resolution.

Highest eta modules (not many) could run with higher power for preamp, to recover some of the resolution degradation. Bias increase for LGAD helps too (up to a point). Can be replaced as well (small cost).



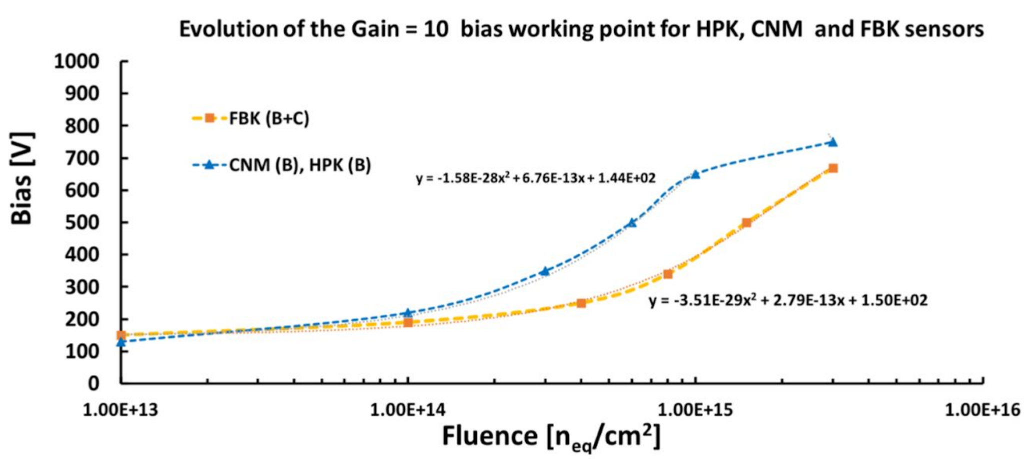


Figure 3.10: Bias voltage needed to maintain a gain of 10 as a function of fluence for sensors from HPK, CNM, and FBK.

- 13.5 ETL - comments: no information presented on output bandwidth and no specifications provided on the aggregator ASIC.

The output bandwidth is small (for L1A readout), 160Mbps to 320Mbps. The “aggregator” ASIC is the lpGBT.

- 13.6 ETL - recommendation: By CD-2 firmly establish the pulse shape variations with radiation dose
  This has been studied in testbeam and LGAD simulation and these pulse shapes were inputs to the ETROC design as Ted describes in his talk.
- 13.7 BTL/ETL - recommendation: By CD-2, optimize US CMS contributions and the US CMS cost share for the project to maximize the overall project effectiveness. This optimization should be considered jointly for the BTL+ETL
  We’ve done this. Our USMTD scope was endorsed by the USCMS Phase 2 Advisory Board and presented to DOE at the PEMP Notable briefing in December 2018.