CEPC TDRrd ECAL Updates

Yong Liu (IHEP) for the CEPC TDRrd ECAL team

CEPC Reference Detector TDR Weekly Meeting

November 12, 2024

Overview on updates

- CEPC Detector Ref-TDR Topical Discussion
  - Agenda on Nov. 7, 2024: https://indico.ihep.ac.cn/event/24102/
  - TDR ECAL chapter: structure and documenting (next pages)

- CEPC ECAL Weekly Meeting on TDRrd
  - Agenda on Nov. 8, 2024: https://indico.ihep.ac.cn/event/23982/
  - SiPM and electronics: linearity specifications and studies (for feedback to IDRC)
  - Mechanics and cooling: update on cooling pipe arrangement
  - Beam induced backgrounds: impacts to EM performance (results still preliminary)
  - Crystal granularity studies → *Talk (Nov. 5, 2024) by Shengsen SUN*

Work plan on TDRrd ECAL chapter (updated)

- A first draft in late Nov. or early Dec. would include
  - General ECAL requirements
  - ECAL technical options: SiW-ECAL, ScW-ECAL, crystal
  - Performance: single-particle EM performance, two-particle separation power
  - Crystal calorimeter prototyping and beamtests
  - SiPM and readout electronics specifications
  - Beam-induced backgrounds: hit rates and impacts to performance
  - Mechanics and cooling: preliminary designs and FEA results, CF prototypes
- Studies to address technical challenges: to be continued after TDRrd draft
  - Impacts to ECAL performance: temperature variations and radiation damages
  - Calibration schemes: Bhabha/di-muon events with colliding beams; in-situ calibration system

TDR ECAL chapter: updated structure

Remarks: always keep a local (up-to-date) version in case of any outage

Chapter 7 Electromagnetic calorimeter

(Editor: Yong Liu)

7.1 General introduction

(Contacts: Haijun, Jianbei, Yong)

Motivations and general requirements on the electromagnetic calorimetry (ECAL) sub-detector system for CEPC

- Jet energy resolution
- Particle-flow paradigm
- High granularity calorimeters

7.2 ECAL technical options

A brief overview of PFA-oriented calorimetry and technical options explored within the CALICE collaboration within last 20 years.

7.2.1 Silicon-tungsten sampling calorimeter

(Contact: Huaqiao Zhang)

- Brief introduction on the SiW-ECAL design
- Physics prototype and performance in beamtests
- Engineering prototypes and technical challenges
- Synergies with CMS-HGCAL: silicon modules

7.2.2 Scintillator-tungsten sampling calorimeter

(Contact: Yunlong Zhang)

- Brief introduction on the ScW-ECAL design
- Physics prototype and performance in beamtests
- Technological prototype and beamtests

7.2.3 High-granularity crystal calorimeter

(Contact: Yong Liu)

7.2.4 ECAL baseline option for the CEPC reference detector

- Criteria in 3 major aspects (physics performance and potentials, cost and technical readiness level
- Conclusion on the ECAL baseline option
- Considerations on ECAL alternative/backup options: open questions that remain to be addressed towards a final detector for CEPC

7.3 ECAL overall design and performance studies

- Detector design: a few schematics
- Technical specifications: a summarised table with some paragraphs as supporting materials

7.3.2 Performance studies in simulation

(Contact: Fangyi Guo)

- A brief introduction to CyberPFA for ECAL recontruction (with cross reference to the "Software" chapter)
- Single-particle EM performance: response linearity and energy resolution
- Two-particle separation power with varying distance

7.3.3 Electronics

(Contact: Jinfan Chang)

- Front-end ASIC for SiPM-readout in ECAL: design and schematics
- Other considerations for ECAL electronics and cross reference to the "Electronics" chapter

7.3.4 Mechanics and cooling

(Contact: Shaojing Hou, Jiebing Yu)

- Mechanics design for barrel and endcap regions: main structures, modules, FEA results
- Cooling design and simulation studies
- Assembly and integration with other sub-detectors

7.4 Technical challenges and dedicated R&D activities

7.4.1 A list of key issues and technical challenges

Followed by R&D activities to address key issues and challenges

7.4.2 R&D activities on crystal, SiPM and readout ASIC

- Crystal uniformity
- SiPM dynamic range
- SiPM-readout ASIC dynamic range
- Timing resolution

7.4.3 Prototype and beamtests: key issues that have been already addressed

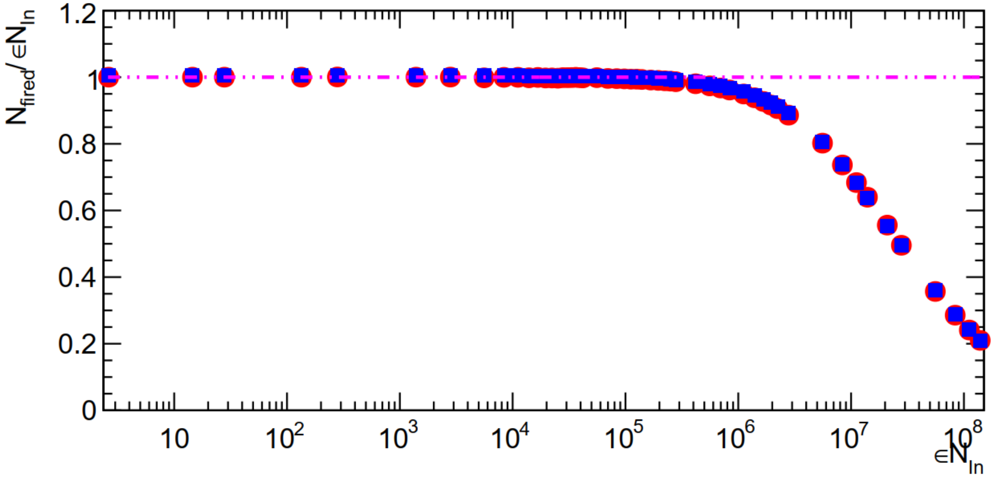
- Crystal calorimeter prototype development
- Beamtests at CERN and DESY
- Open questions beyond the prototype

7.4.4 Beam-induced backgrounds

- Estimates of hit rates and data throughput
- Simulation results of TID and NIEL

SiPM and electronics: linearity specification

- SiPM response linearity to BGO scintillation light: simulation studies done
  - Need to quantify more details from existing studies
- Front-end electronics linearity
  - Work plan: to be modelled in the ECAL digitisation
  - Target: ASIC non-linearity effect should be smaller than SiPM non-linearity
  - "HGCROC": a state-of-art chip for CMS HGCAL, considered as a first reference



Including BGO scintillation and pixel recovery effects

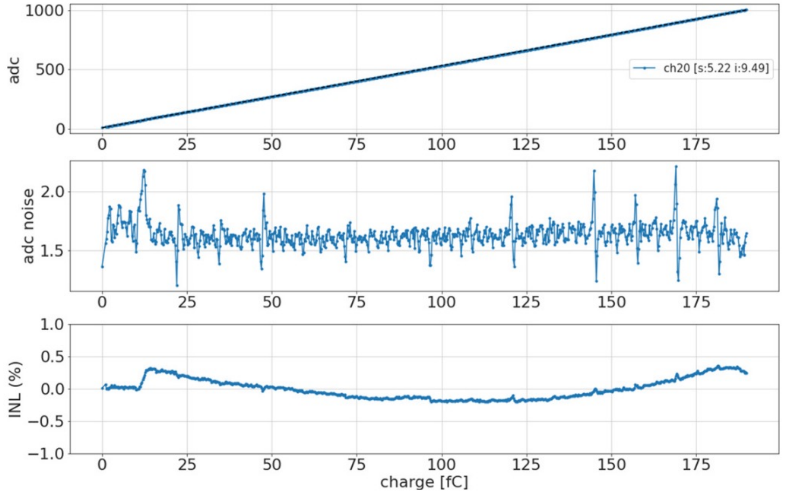
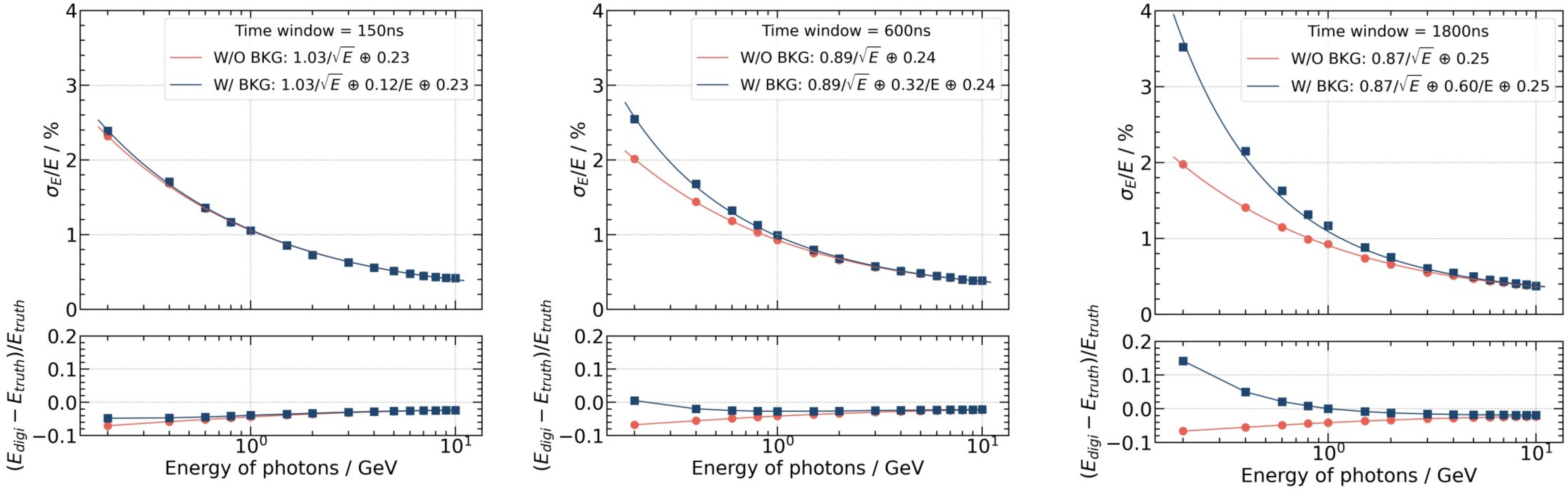


Figure 2. ADC characterisation. Top: charge conversion in ADC units versus injected charge. Middle: noise in ADC units for each charge. Bottom: integral non linearity (INL).

Backup Slides

Beam backgrounds: impact to EM performance

- Beam-induced backgrounds at 50MW Higgs mode
  - Varying ECAL time window: 150 ns – 1800 ns
  - Significant contribution to noise term, but results are still preliminary
  - Fitting method needs to be updated



SiPM and readout electronics: a first set of specs

SiPM parameters

Parameters	NDL-SiPM (EQR06)	NDL-SiPM (EQR10)	HPK S14160-3010PS
Pixel pitch	6um	10um	10um
Num. of pixels in 3x3mm	244,719	90,000	89,984
Gain	8E4	1.7E5	1.8E5
Operational Voltage	Vb + 8V (Vb=24.5V)	Vb + 12V (Vb=24.5V)	Vb + 5V (Vb=38V +/- 3V)
Peak PDE	30% (at 420nm)	36% (at 420nm)	18% (at 460nm)
Typical DCR	2.5 MHz	3.6 MHz	700 kHz
Inter-pixel Crosstalk	12%	Not specified in data sheet	<1%
Terminal Capacitance	45.9pF	31.5 pF	530pF

Blue: data sheet
Green: measurement
Red: no information

SiPM-readout electronics: first specs

Parameters	NDL-SiPM (EQR06)	NDL-SiPM (EQR10)	HPK S14160-3010PS
Charge per 1 p.e.	12.8 fC	27.2 fC	28.8 fC
Threshold (10 p.e.)	128 fC	272 fC	288 fC
1 MIP (200 p.e.)	2.56 pC	5.44 pC	5.76 pC
Max. charge: 3000 MIPs	7.68 nC	16.32 nC	17.28 nC

IDRC recommendations to calorimetry (1)

- *"The innovative technologies selected for the baseline ECal and HCal present both opportunities and challenges. It is essential to maintain steady progress in prototyping and simulation to demonstrate their feasibility and readiness, along with finalizing specifications. One aspect that must be monitored and perfected is the reproducibility of glass scintillators."*

- Work Plan
  - Continue data analysis of crystal calorimeter prototype beamtests
    - Aim for publications as journal papers (CERN, DESY) in Nov. – Dec.
  - Specifications on SiPM and readout electronics
    - Dedicated discussions with electronics colleagues started in Nov. 1
    - Aim for finalising a set of specs in coming 2-3 weeks after discussions and iterations

IDRC recommendations to calorimetry (2)

- *"Design choices should be thoroughly justified by physics goals achieved with simulation of a full detector model. Alternative parameter choices should be considered and evaluated for physics outcomes. For example, ECal crystals of 1 cm (transverse) x 2 cm (depth) would reduce channel count and cost. Does it impact physics performance? "*
- *"Some specific performance issues that would be interesting to more fully understand. These include higher energy π^0 reconstruction, which may benefit, for example, from a staggered bar arrangement or finer granularity in the first few layers. Also electron ECal resolution when the bending of electrons match the 12 degree incline angle. Does this impact electron measurements?"*

- Work Plan
  - Calorimetry software team first focuses on performance comparison with crystal transverse granularities: 10x10 mm versus 15x15 mm (ongoing studies)
  - Other recommendations remain to be discussed to come up with a more detailed plan for the given constrained timeline

Suggestions from IDRC members

- Tommaso Tabarelli de Fatis (Università di Milano Bicocca)
  - Following up on our discussion after your talk yesterday, I would like to suggest that you try to simulate the response of a a detector with
    - 0.5 (side) x 1 (depth) x ~40 cm in the first 4 layers (~4 X0)
    - 1.0 (side) x 1 (depth) x ~40 cm in the next 16 layers
    - 2.0 (side) x 1 (depth) x ~40 cm in the last 8 layers
  - This would give the same total number of SiPMs, but improve the granularity for pi0/gamma separation.
  - Another option would be to stick to 1x1 cm^2 bars, to ease production, but stagger them by 0.5 cm in each second layer. This might require 0.5 cm side bars at the two ends.
- James Brau (U. Oregon)
  - Different longitudinal granularity for long bars: e.g. cross section of 1x2 cm^2 with coarser longitudinal segmentation (a factor of 2 less)

Preliminary report of IDRC Review: ECAL part (1)

- General remarks
  - *Findings: The electromagnetic calorimeter (ECal) and hadronic calorimeter (HCal) teams are strong and productive. They are generally making good progress on their technologies.*
- Comments
  - *The ECal team recognizes that they have several challenges in front of them to bring their chosen technology to maturity. They should sustain steady progress addressing these including:*
    - *Developing and perfecting the Particle-flow algorithms including the effective pattern recognition and minimization of ambiguity issue;*
    - *Dealing technical issues (ASICs, hermiticity, minimized power, mass production) with the very large number of channels in the very finely grained concept;*
    - *Successfully overcoming beam-induced backgrounds and radiation damage;*
    - *Understanding the impact of design choices on the performance to define specifications for the SiPMs linearity, crystal granularity and uniformity, readout threshold and noise, calibration needs;*
    - *Developing and optimizing the in-situ calibration system.*

To address technical challenges (1)

- *"Developing and perfecting the Particle-flow algorithms including the effective pattern recognition and minimization of ambiguity issue"*
- Work Plan: joint efforts with software team
  - This suggestion is related to further optimisations of the particle-flow algorithm CyberPFA.
  - The work plan include the performance evaluation with the full detector geometry (including both barrel and endcaps) and also the tracking performance, especially its matching with calorimeter clusters.
  - Besides, the calorimeter calibration for the jet energy scale needs in-depth studies, to ensure correct reconstruction of the Z and H boson masses in a consistent way.

To address technical challenges (2)

- *"Dealing technical issues (ASICs, hermiticity, minimized power, mass production) with the very large number of channels in the very finely grained concept."*
- Work plan: joint efforts with electronics, software, mechanics teams
  - This is related to the general detector design for ECAL, optimisation and validation, including mechanics, cooling, embedded electronics and their integration.
  - ASIC development requires joint efforts of CEPC electronics team, while keeping an eye on DRD6/7 collaborations on new calorimetry-specific ASIC developments.
  - Modularity is a major prerequisite to demonstrate mass production capability. We plan to further optimize and validate modular designs for barrel and endcaps, and would also need to propose protocols on Quality Assurance and Quality Control (QA/QC) for key components, including crystals, SiPMs, ASICs, mechanics, cooling, etc.
  - Further studies on integration of modules and cooling (in barrel and endcaps) is planned.

To address technical challenges (3)

- *"Successfully overcoming beam-induced backgrounds and radiation damage."*
- Work plan: joint efforts with software and MDI teams
  - This is related to simulation studies of beam-induced backgrounds and modelling of radiation damages to crystals and SiPMs.
  - Key information is needed from the MDI team: mappings of **TID (Total Ionisation Dose)** and **NIEL (Non-Ionisation Energy Loss**) in ECAL (esp. in ECAL endcaps), which is a crucial input for study radiation damages to crystals and SiPMs
  - Based on ongoing developments of modelling (including TID vs crystal transparency, NIEL vs SiPM noises), we plan to quantify the impacts of radiation damage to the EM performance and also to the cooling system design (e.g. SiPM operational temperature)
  - We also plan to further study extra hits from beam-induced backgrounds and evaluate their impacts to EM performance by mixing calorimetric signals and backgrounds. This would also be related to the optimization of ECAL time window for signal readout.

To address technical challenges (4)

- *"Understanding the impact of design choices on the performance to define specifications for the SiPMs linearity, crystal granularity and uniformity, readout threshold and noise, calibration needs."*
- Work plan: joint efforts with software and electronics teams
  - SiPM noise, linearity, readout threshold and crystal uniformity have been extensively studied in the lab and in simulation. We would need to prepare a comprehensive summary of these results and thus define specifications, which would be also an input to the SiPM-readout chip design.
  - Crystal granularity: longer crystal bars (60cm) and coarser transverse granularity (15x15mm) were already tested in beams. Granularity would also impact the PFA performance, which is being investigated by the software team. Other granularity designs were suggested by some IDRC members via separate messages, which require further discussions with the software team.
  - Calibration needs: we plan to study calibration precision to meet the specifications.

To address technical challenges (5)

- *“Developing and optimizing the in-situ calibration system.”*
- Work plan: joint efforts with electronics and software teams
  - In-situ calibration system in general would be indispensable to the success of ECAL that can finally achieve optimal EM performance
  - Bhabha and di-muon events at CEPC would be ideal for ECAL calibration. We would need to estimate typical numbers of events and running times that are required to achieve the calibration precision
  - The calibration system needs to “remove” beam-induced backgrounds that could be mixed in the events in the pile-up way.
  - We may need to monitor and correct the crystal transparency and SiPM noises due to radiation damages. Furthermore, the instantaneous radiation damage to crystals and SiPMs during beam injection may also need to be monitored and corrected by the in-situ calibration system.
  - A detailed design would need to be discussed with the electronics team.

Preliminary report of IDRC Review: ECAL part (2)

- Comments
  - *There are ECal issues that need clarification such as*
    - *The 0.1 MIP ECal threshold is chosen based on a balance between S/N and dynamic range - a more quantitative explanation of this is missing from presentation;*
    - *SiPM dynamic range and linearity needs specification;*
    - *The noise levels of the ECal including SiPMs and readout electronics;*
    - *Anticipated level of crystal degradation with time, and its impact on physics performance;*
    - *Homogeneity of MIP detection efficiency.*

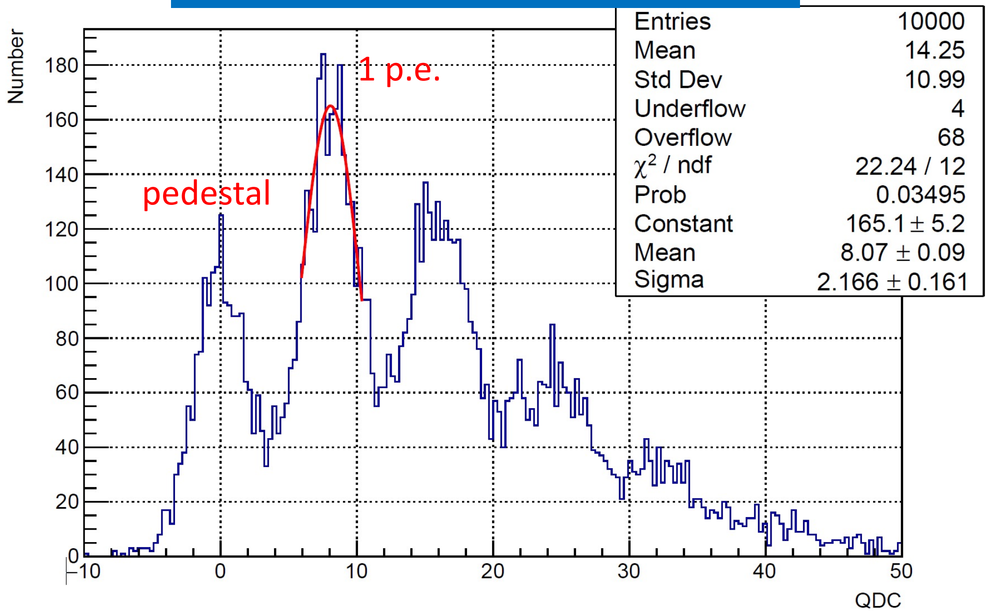
Feedback

- *“The 0.1 MIP ECal threshold is chosen based on a balance between S/N and dynamic range - a more quantitative explanation of this is missing from presentation.”*
    - There have been many extensive studies (simulation, measurements). Need to summarise results.
- *“SiPM dynamic range and linearity needs specification.”*
    - There have been many extensive studies (simulation, measurements). Need to summarise results.
- *“The noise levels of the ECal including SiPMs and readout electronics.”*
    - Tested in the lab and beamtests.
- *“Anticipated level of crystal degradation with time, and its impact on physics performance”*
- *“Homogeneity of MIP detection efficiency”*

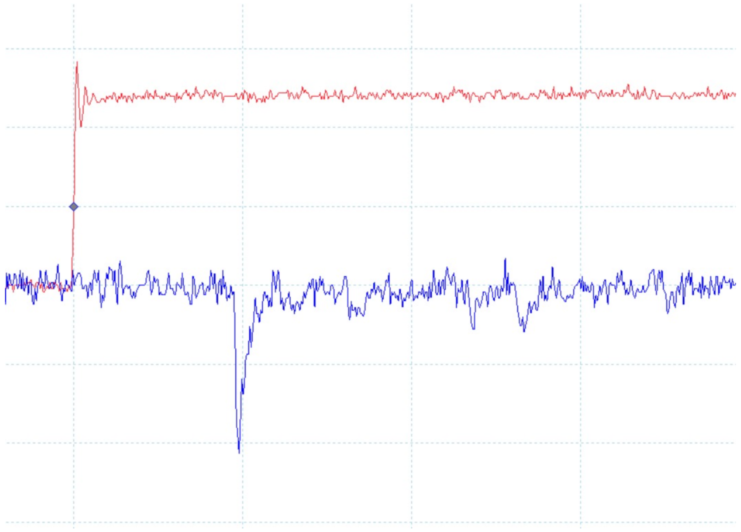
SiPM noise level

- Feedback to “*The noise levels of the ECal including SiPMs and readout electronics.*”

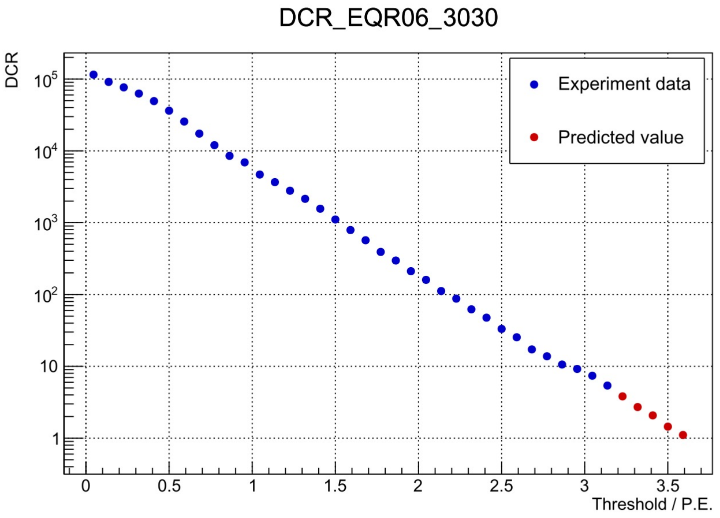
NDL EQR06 11-3030D-S



Typical Single Photon Waveform



Noise Rate vs. Threshold

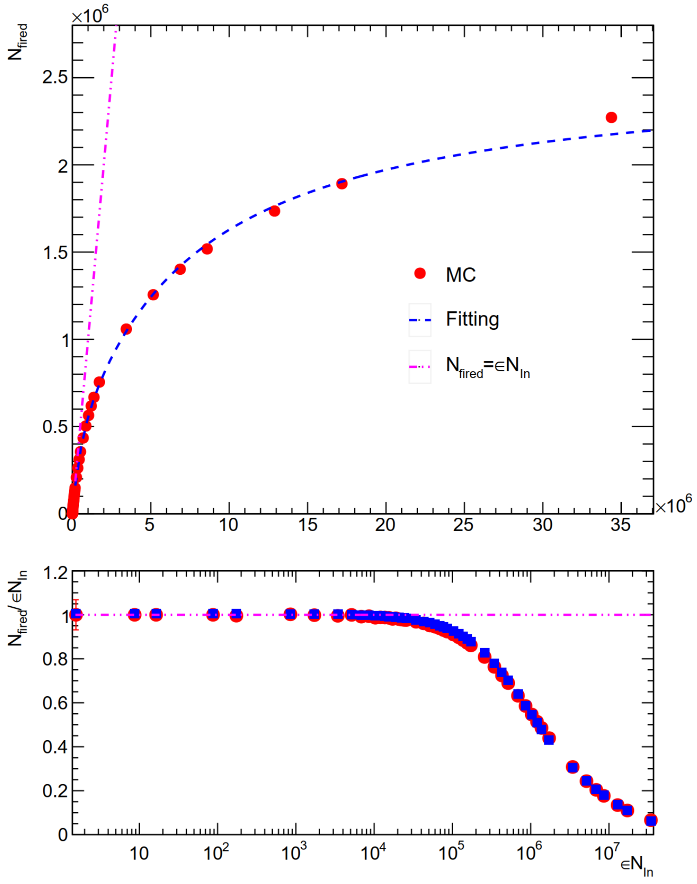


- NDL-EQR06 is the target SiPM option for crystal ECAL
  - 6 μm pixel pitch, 3×3 mm^2 active area
  - High pixel density (244720 pixels), narrow pulse shape (~10 ns)
  - Negligibly low noise expected at 0.1 MIP (10 p.e.) threshold

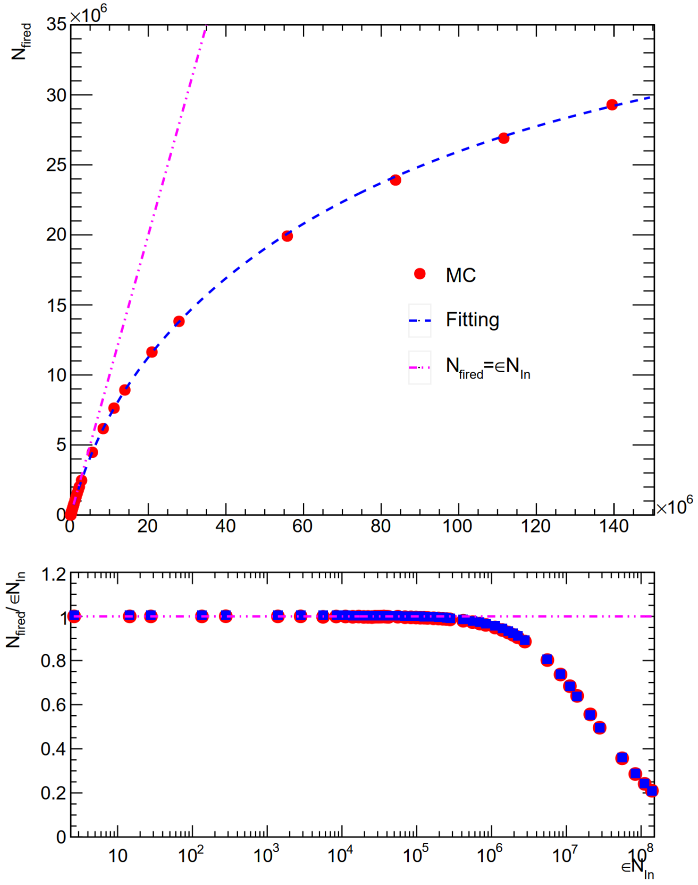
SiPM response to BGO scintillation

- Feedback to *"SiPM dynamic range and linearity needs specification."*

HPK S14160 3010PS



NDL EQR06-11-3030D-S



A Monte Carlo model to simulate the SiPM response to BGO(40x40x1cm) scintillation light. The model includes both BGO and SiPM properties.

SiPM	Pixel Pitch (μm)	Active Area (mm^2)	Nominal pixel counts	PDE (%) $\lambda = \lambda_p$
HPK S13360-6025PE	25	6.0x6.0	57600	25%
HPK S14160-3010PS	10	3.0x3.0	89984	18%
NDL EQR06 11-3030D-S	6	3.0x3.0	244719	30%

The SiPM option selected for crystal ECAL

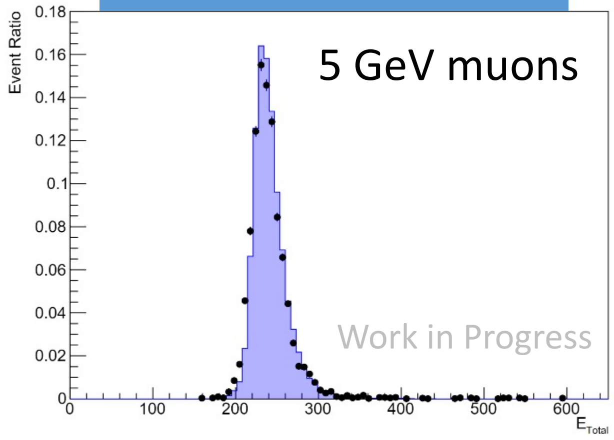
SiPM	Max. photon counts	5% non-linearity
HPK S13360-6025PE	57600	19592
HPK S14160-3010PS	89984	53747
NDL EQR06 11-3030D-S	244719	1106210

We would need to formulate specifications based on these studies

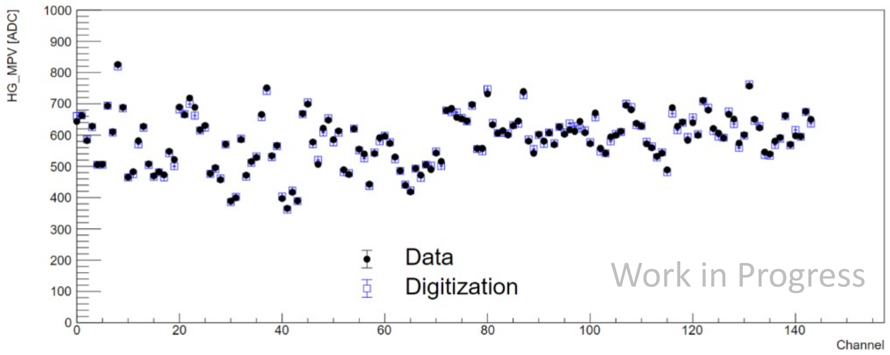
MIP response uniformity: channel-wise and run-wise

- Crystal calorimetery prototype in 5 GeV muon beam: MIP calibration, validation of digitisation

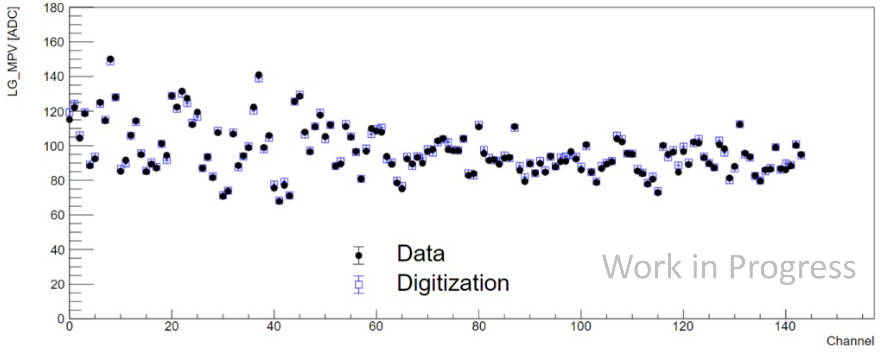
Energy Spectrum (Esum)



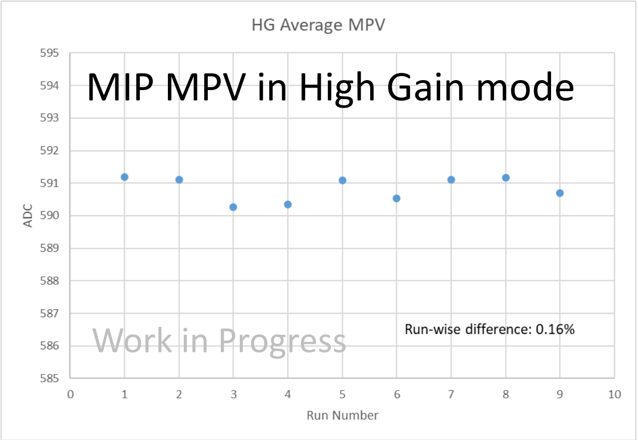
MIP calibration per channel (HG mode)



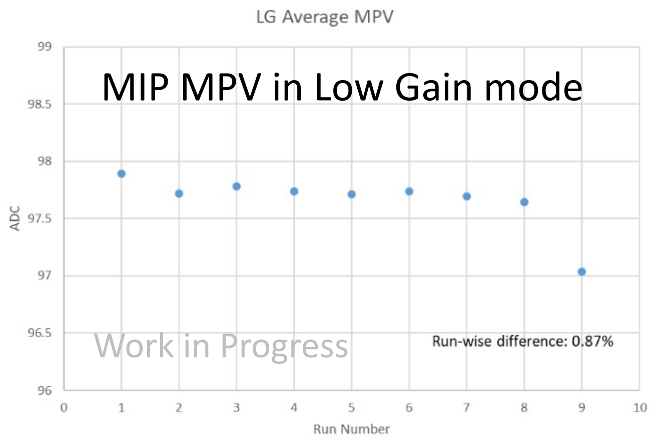
MIP calibration per channel (LG mode)



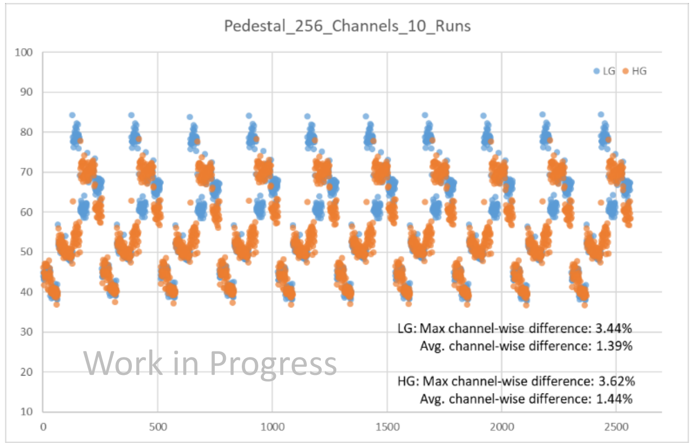
Calibration stability: MPV-HG vs. RunID



Calibration stability: MPV-LG vs. RunID

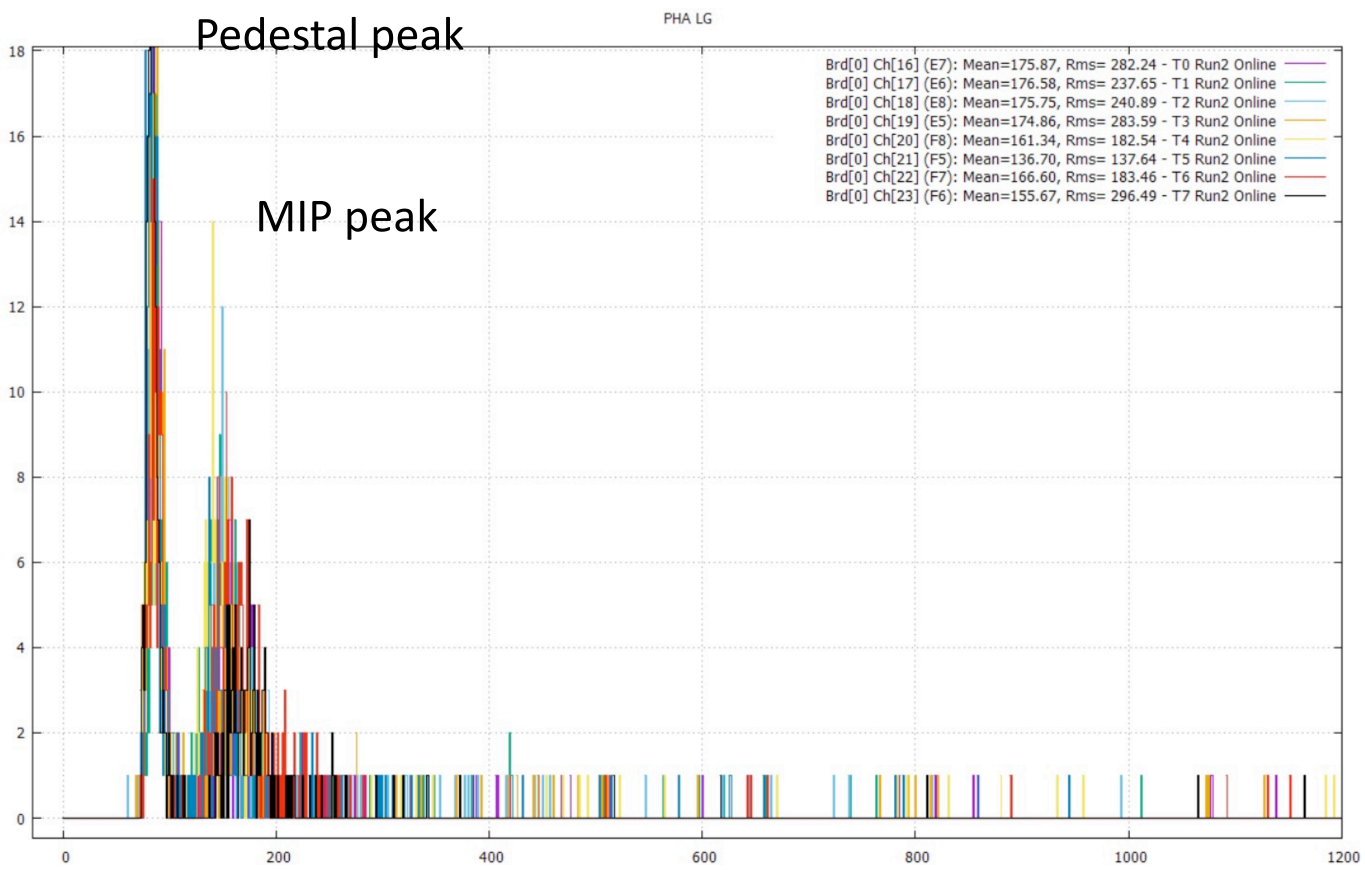


Pedestal stability: Mean vs. RunID



Crystal calorimeter prototype in beamtests

- *The noise levels of the ECal including SiPMs and readout electronics*



The crystal calorimeter prototype used commercially available ASICs. The S/N ratio is promising and barely noises besides pedestals

We would need to discuss with electronics team for further evaluation with custom-made designed ASIC in planning