中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

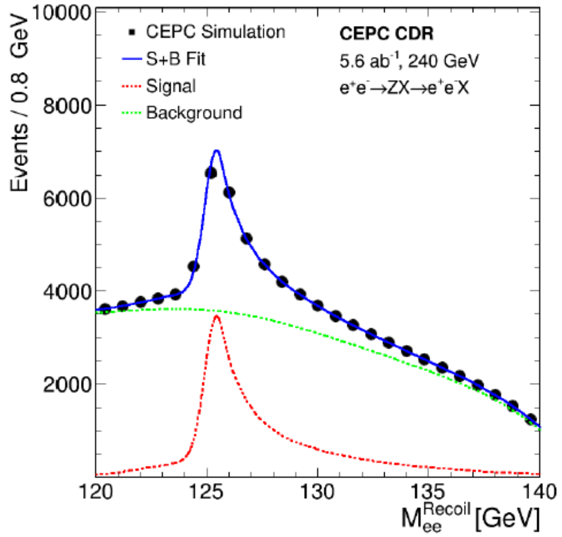
High-granularity Crystal Calorimeter: R&D status

Yong Liu (Institute of High Energy Physics, CAS),
on behalf of the CEPC Calorimetry Working Group

CEPC Day, Feb. 14, 2020

Based on the CHEF2019 talk, plus latest updates

Overview: motivations



- Background: future lepton colliders (e.g. CEPC)
  - Precision measurements with Higgs and Z/W
- Why crystal calorimeter?
  - Homogeneous structure
    - Optimal intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons: to improve Higgs recoil mass
    - Corrections to the Bremsstrahlung of electrons
  - Capability to trigger with a single photon
    - Flavour physics at Z-pole
    - Potentials in search of new physics, …
- Fine segmentation
  - Potentials in PFA for precision measurements of jets

High-granularity crystal ECAL

- Plenty of room for broad collaborations
  - New ideas proposed and discussed in a dedicated CEPC calorimetry workshop in March 2019
  - Need to identify key issues and technical challenges
- Key issues: optimization

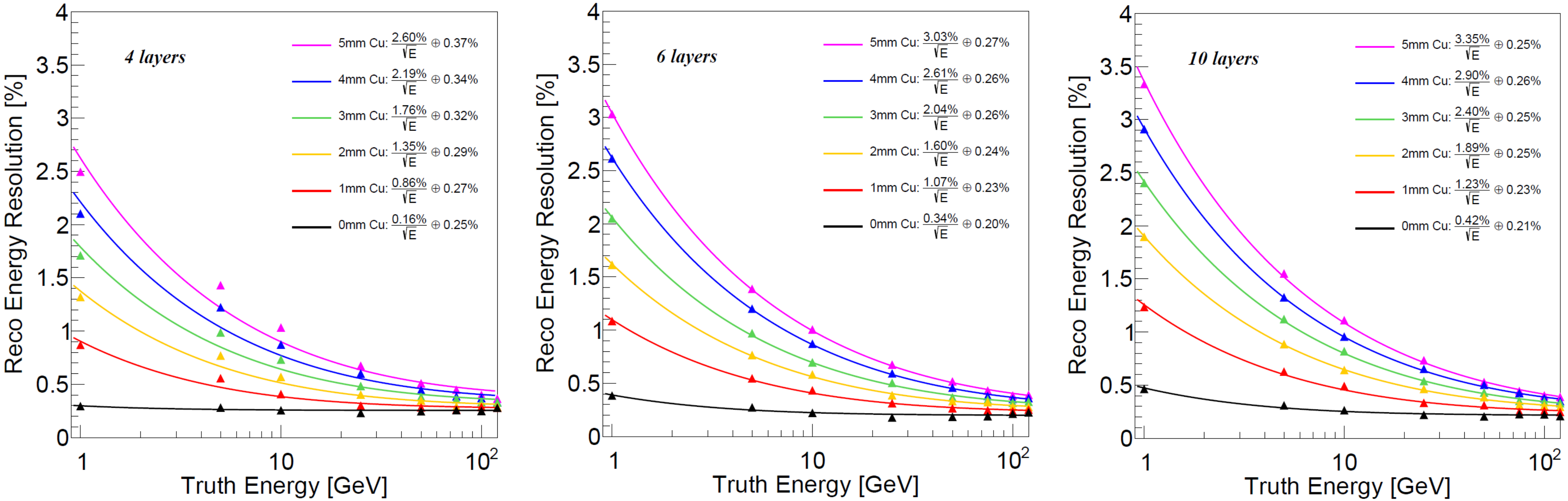
A non-exhaustive list

  - Crystal options: BGO, PWO, etc.
  - Segmentation: in longitudinal and lateral directions
  - Performance: single particles and jets with PFA
  - Impacts from dead materials: upstream, services (cabling, cooling)
  - Costing
  - Fine timing information

Longitudinal segmentations

Yuexin Wang (IHEP)

- Energy resolution with different numbers of sampling layers
  - 24X0 total depth for crystals in all scenarios

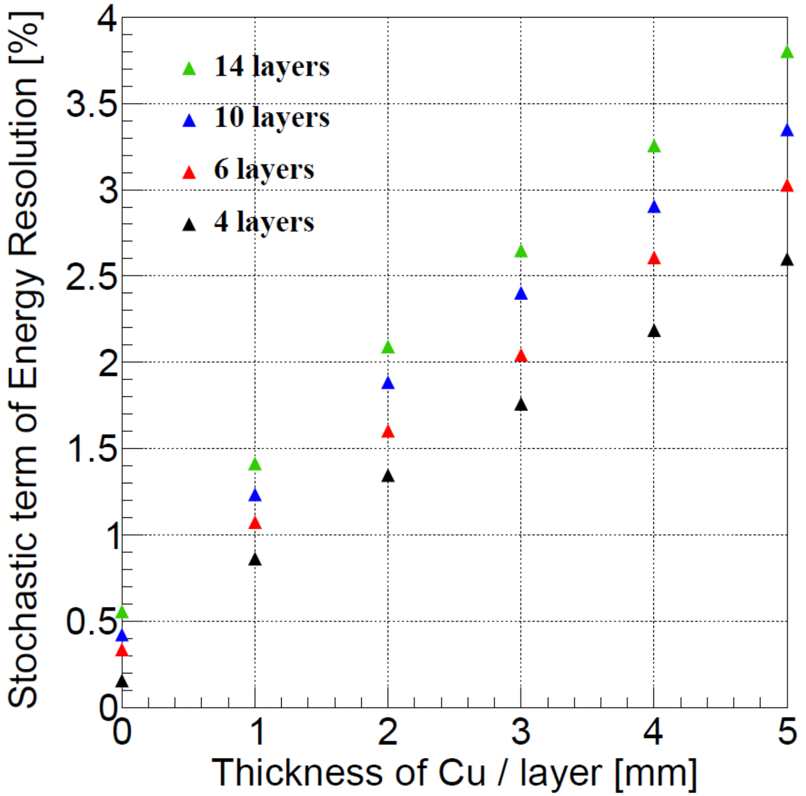


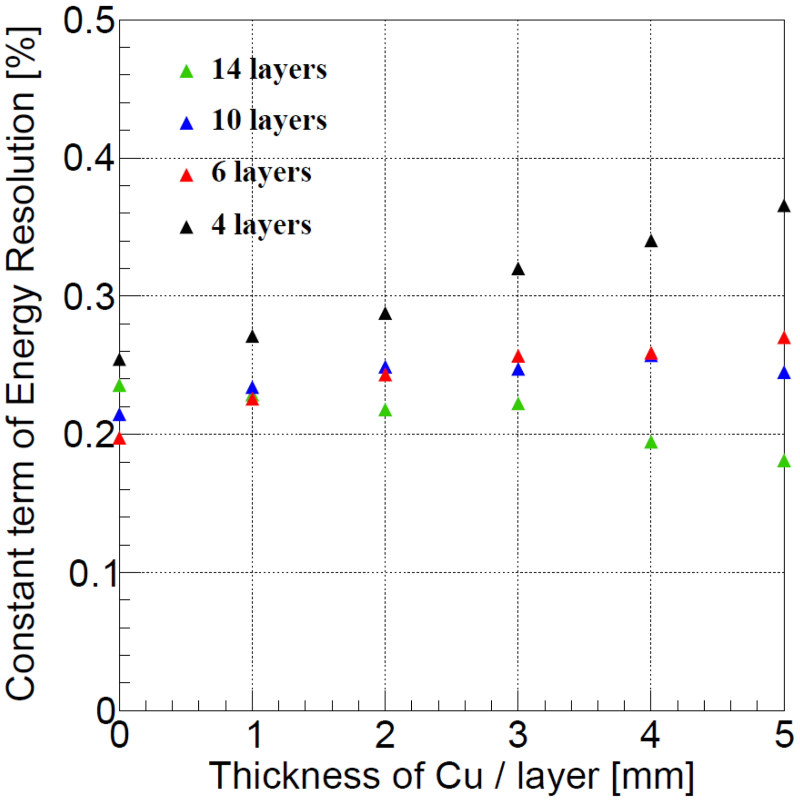
Note: digitization to be implemented; currently energy fluctuations (and leakages) dominate

Longitudinal segmentations

Yuexin Wang (IHEP)

- Stochastic and constant terms
  - Varying thickness of dead materials between layers (services as cooling, cabling, etc.)



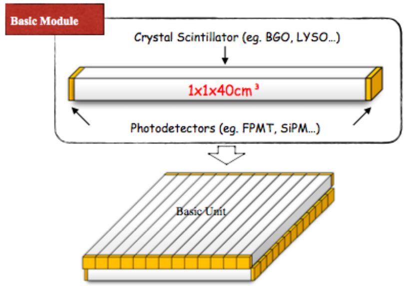


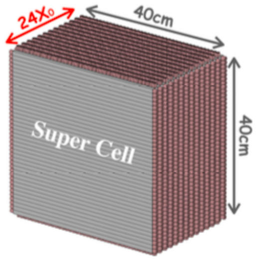
Note: digitization to be implemented; currently energy fluctuations (and leakages) dominate

Latest updates

Yuexin Wang (IHEP)

Reconstruction of Crystal ECAL



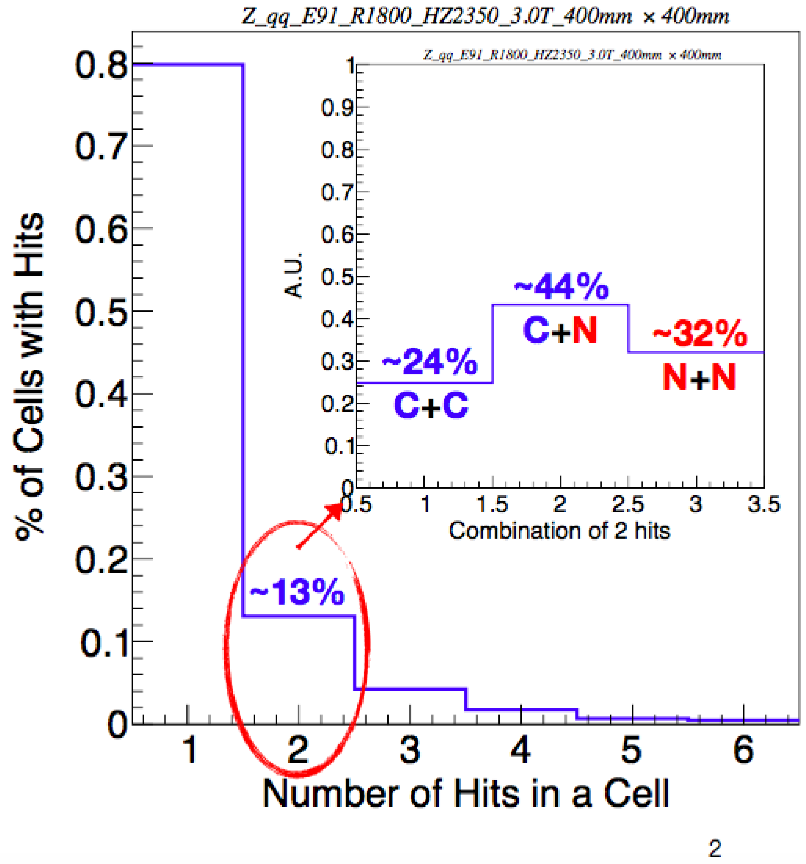


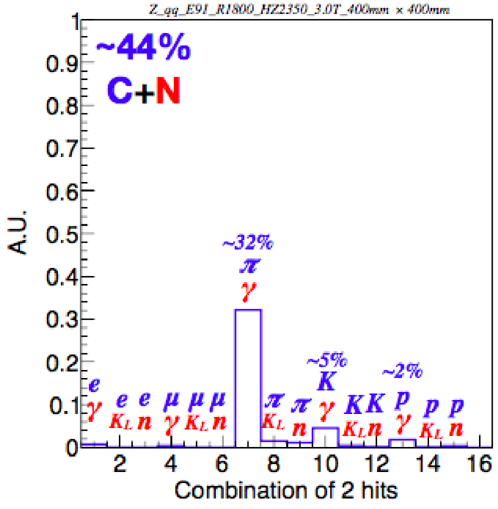
CEPC Baseline Geometry for ECAL (R=1.8m, L=4.7m), with $Z \rightarrow qq$ events

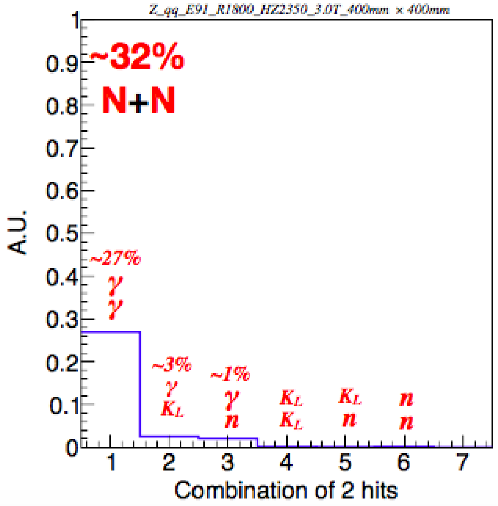
Investigated the multiple particles at in a jet at a super cell ($40 \times 40\ \mathrm{cm}^2$) surface

Multiplicity in a 40cm×40cm SuperCell

C: Charged particles
N: Neutral particles

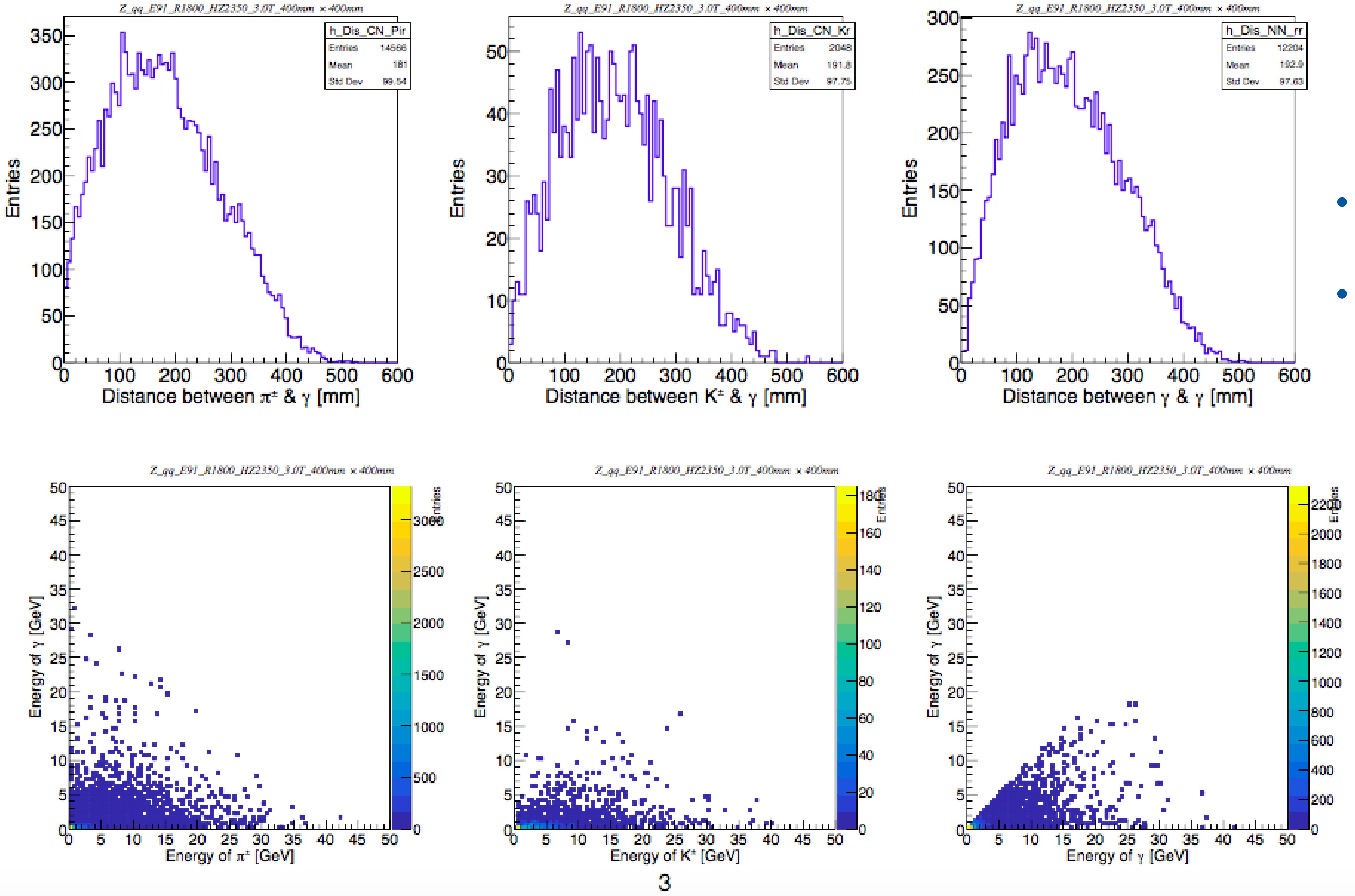






Distribution of Distance & Energy

Yuexin Wang (IHEP)



- Distance hereby depends on the detector geometry
- Plan to use angles of close-by particles, to be less dependent on geometry

Yuexin Wang (IHEP)

Next Step…

☞Reconstruction of Crystal ECAL

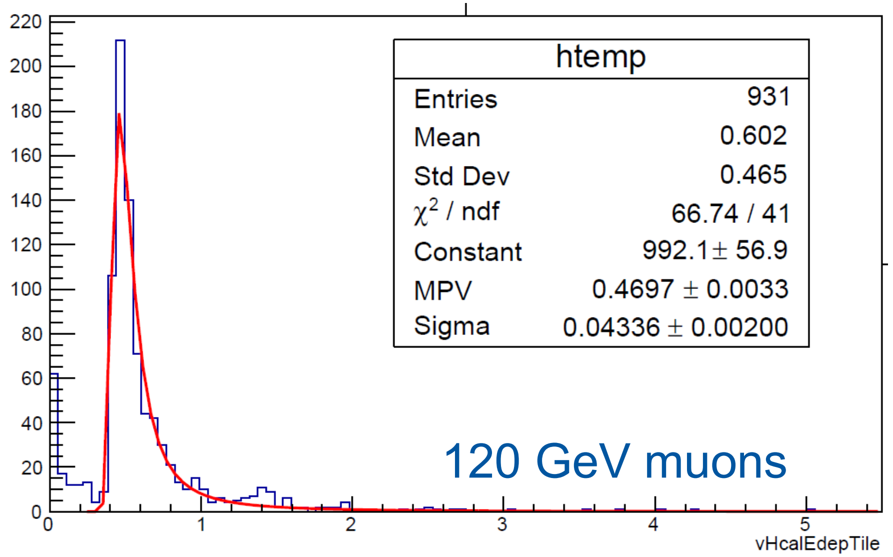
- *Simulation sample of di-particle*
- *Validation of Digitization (Energy & Time)*
- *Pattern study for reconstruction…*

- To generate two typical particles based on the jet information
- Digitisation (next 2 pages)

Digitizer in simulation for ECAL+HCAL

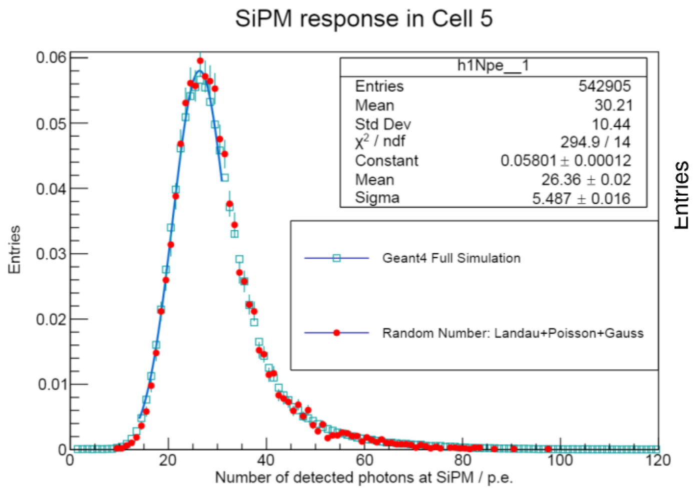
Geant4 version 10.5.0

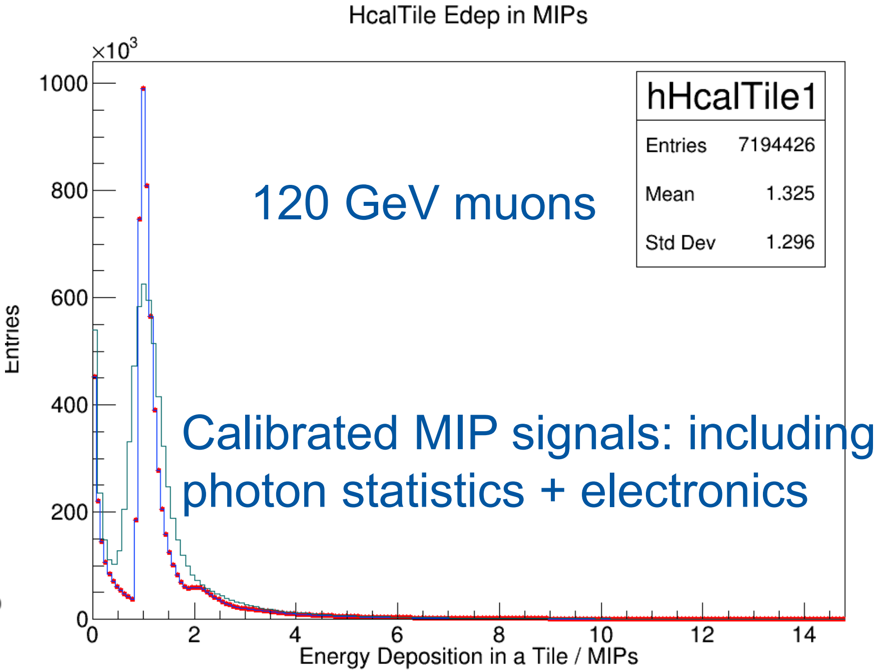
Energy Deposition in a scintillator



Energy Deposition / MeV

Digitizer can reproduce G4 full simulation with optical photons





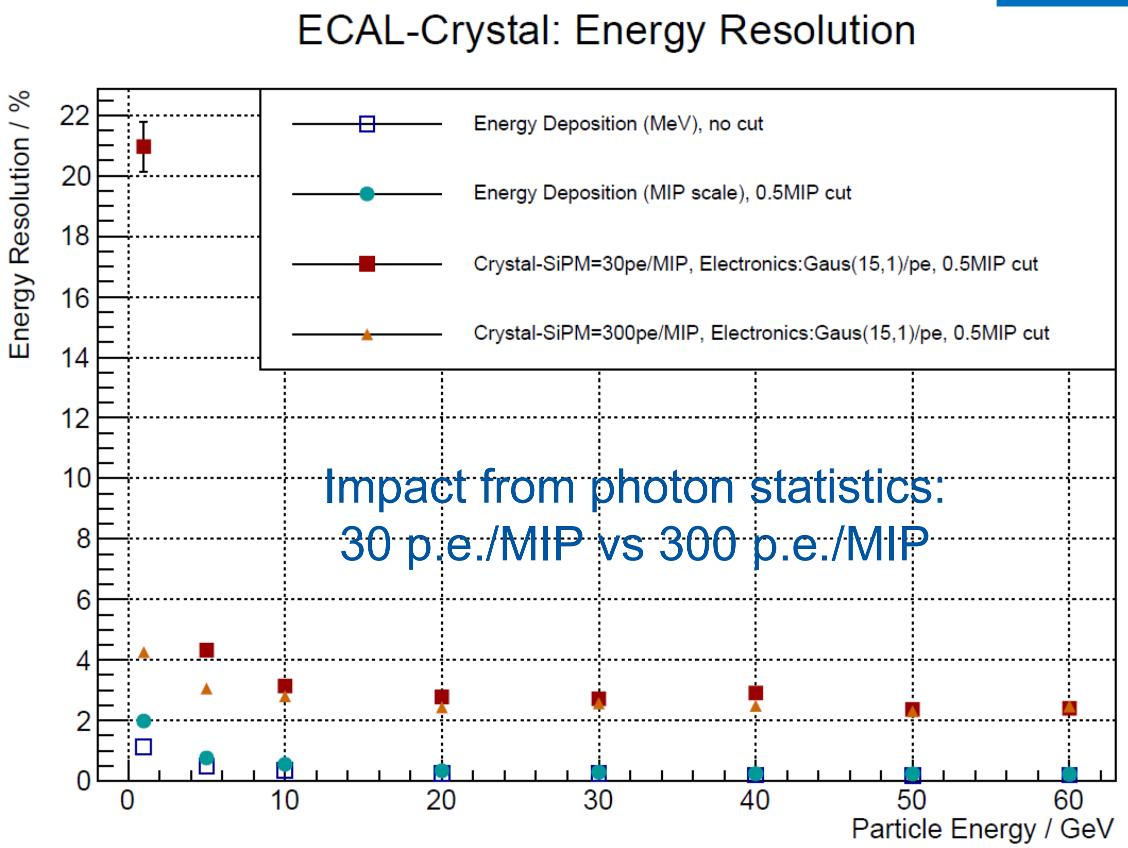
Calibrated MIP signals: including photon statistics + electronics

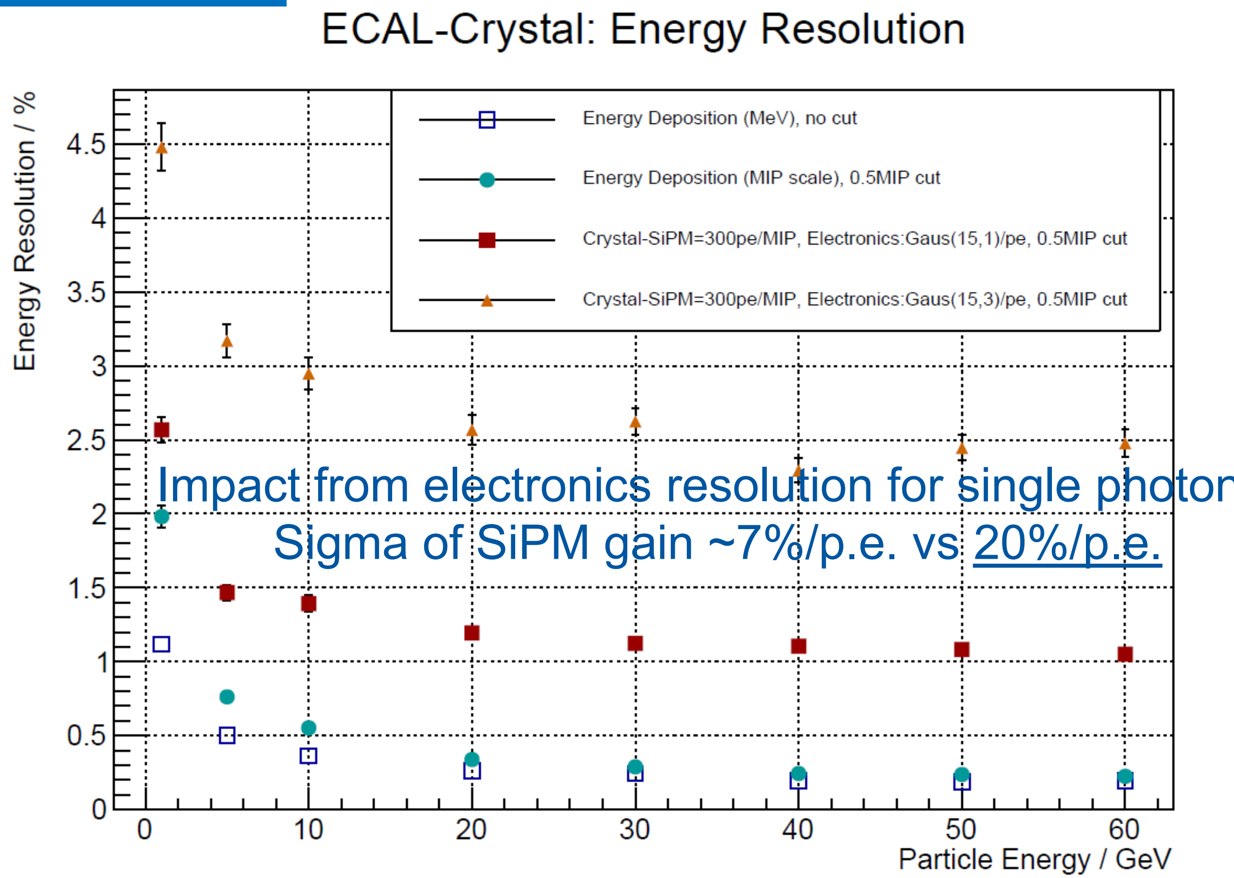
- Geant4 hit (energy deposition) → ADC signal in electronics (charge)
- Realistic factors that will impact energy resolution
  - Photon statistics: #photons/MIP, guided by Geant4 full simulation
  - Electronics resolution: #ADCs/photon
- Starting to implement this tool in the CEPC software

Digitizer in simulation for ECAL+HCAL

Geant4 version 10.5.0

MC samples: electrons





- Validation needs to be redone after implementing the digitiser

Crystal ECAL: technical challenges

A non-exhaustive list

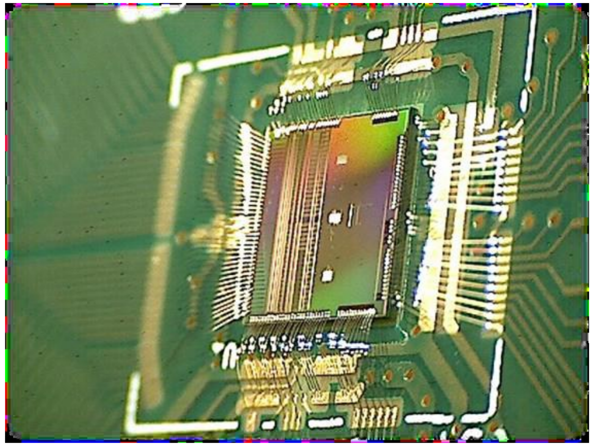
- Front-end electronics
  - Key for instrumentation of high-granularity calorimetry: examples from CALICE Si-W ECAL and CMS HGCAL
  - Multi-channel ASIC: high signal-noise ratio, wide dynamic range, continuous working mode, minimal dead time, etc.
- Cooling options
  - Power consumption (solid inputs from electronics)
  - Impacts of cooling structure to performance
- Calibration and monitoring systems
  - For SiPMs and crystals in the long term
- Scalable detector design: modules and mass assembly

Front-end electronics for SiPM readout

U. Heidelberg, IHEP

- ASIC for **SiPM readout**: “KLauS”, developed within CALICE collab.
  - Designed by U. Heidelberg (KIP)
  - Originally for CALICE scintillator-SiPM HCAL (AHCAL)
  - Promising candidate: 36-channel, low-power chip
    - Excellent S/N ratio: stringently required by high-dynamic SiPMs (small pixels)
    - **Continuous** working mode: crucial for circular colliders (no power pulsing)
  - Need to quantitatively verify its performance and power consumption

Wire-bonded Klaus5 chip



Klaus5 in BGA

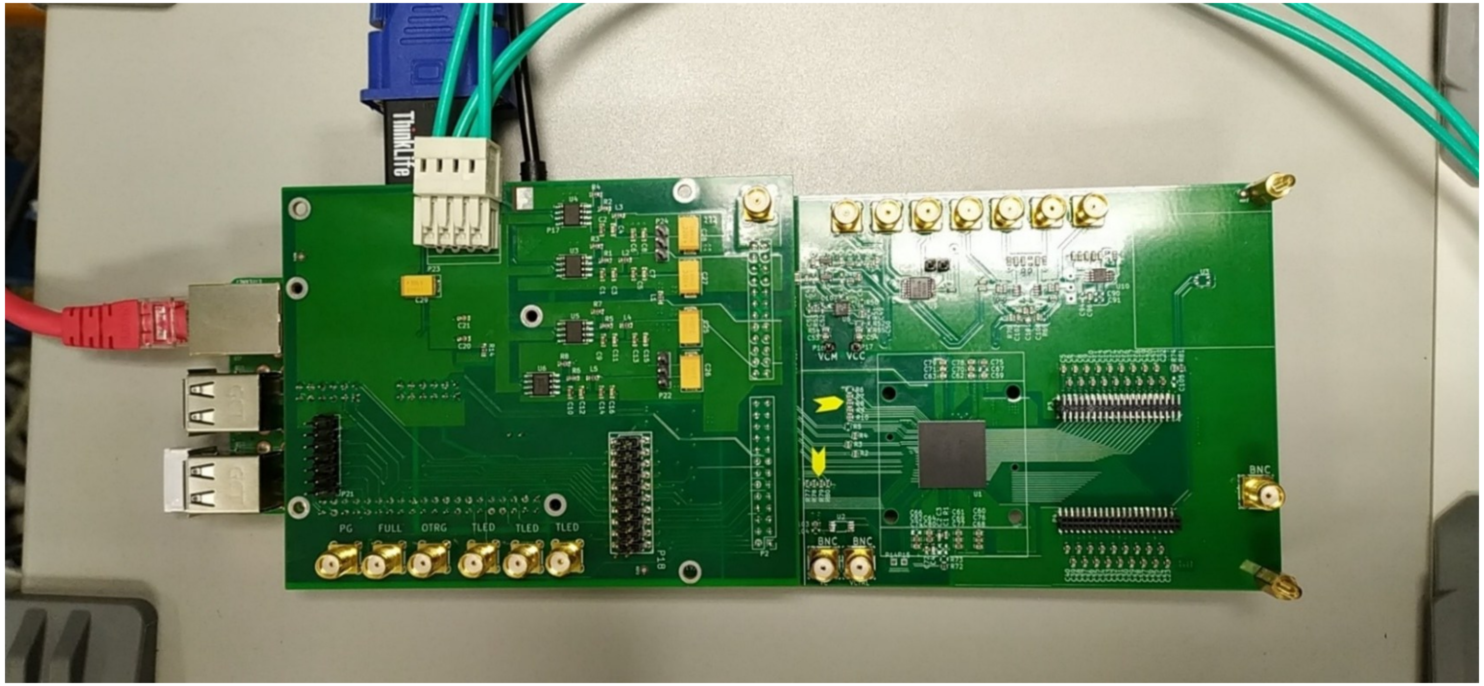
“Design and Tests of KLauS ASIC” in CALICE meeting at Mainz, 2018

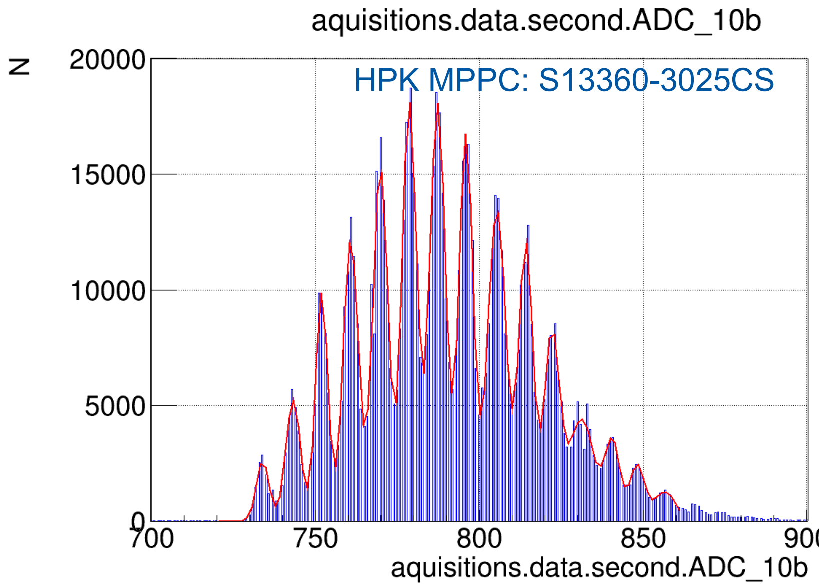
Challenge for ECAL: wide dynamic range (dense EM shower cores)

Front-end electronics for SiPM readout

U. Heidelberg, IHEP

- Test boards for KLauS-5 in BGA
  - Helpful discussions and support from Heidelberg colleagues
  - Boards produced after several iterations of designs/debugging
  - Boards tested first at Heidelberg and later at IHEP
  - Synergies with the JUNO-TAO

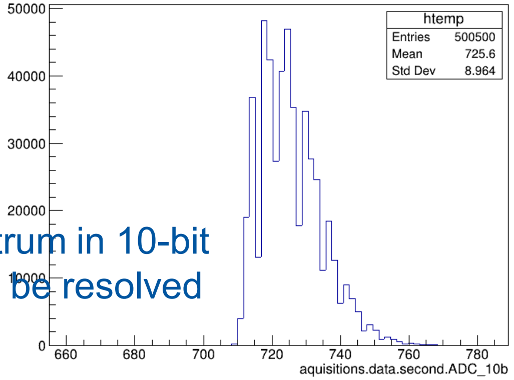




Klaus5: first tests with NDL-SiPM

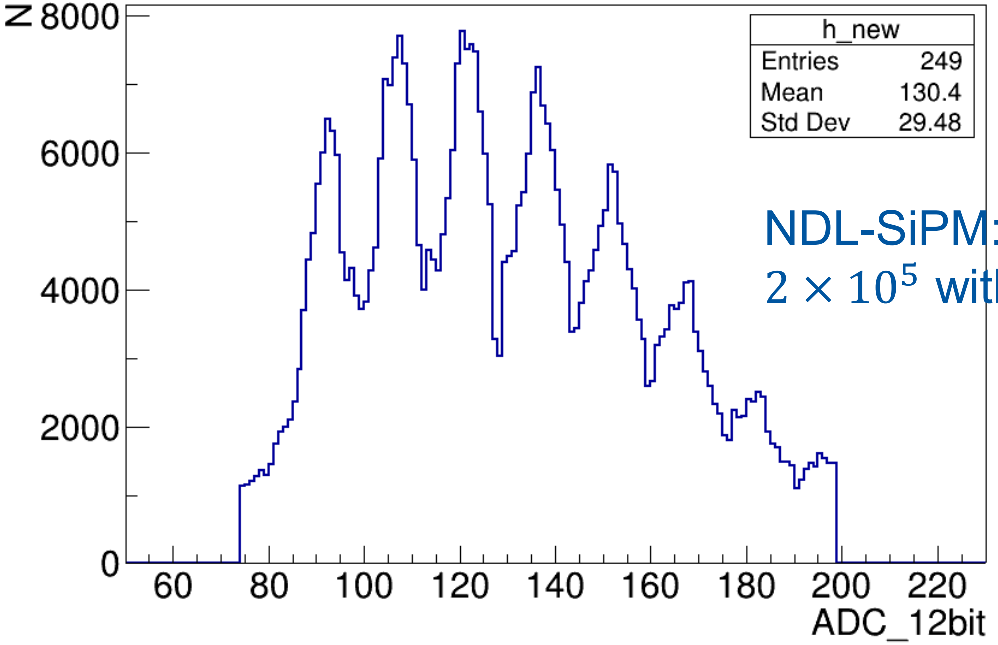
U. Heidelberg, IHEP

- NDL-SiPM: from Chinese vendor
  - Features: small pixel pitch (10μm or smaller) and high PDE
  - Need high S/N ratio in electronics to resolve single photons (small gain)



Single photon spectrum in 10-bit ADC mode: can not be resolved

Single photon spectrum in 12-bit ADC mode: after corrections



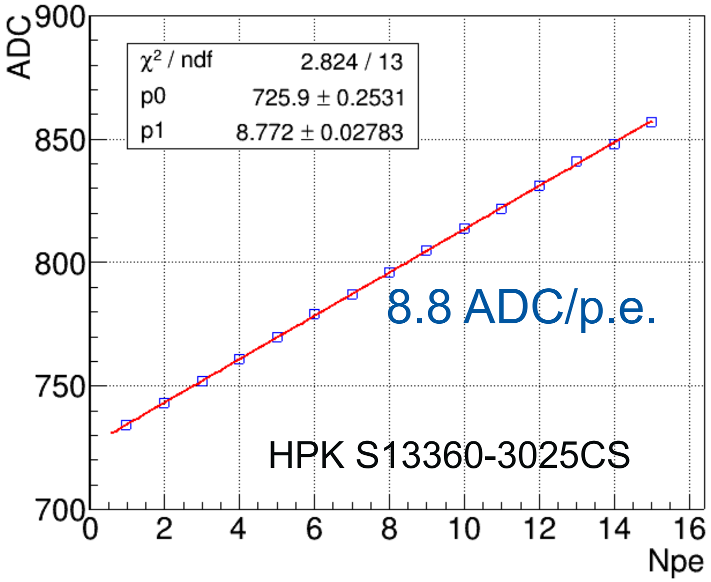
NDL-SiPM: nominal gain 2×10^5 with 10μm pixels

Klaus5: first tests on dynamic range

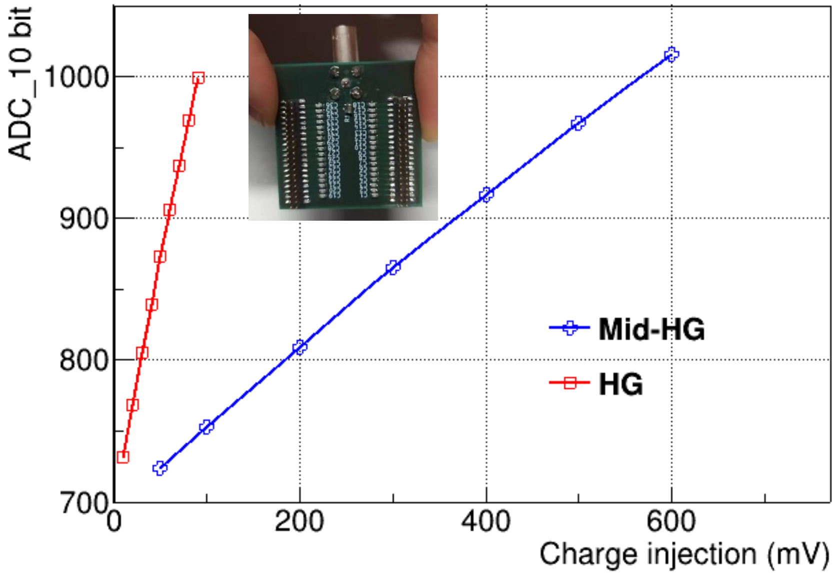
U. Heidelberg, IHEP

- High Gain modes: HG (1:1), Mid-HG (1:7)
- Low Gain modes: LG (1:40), Ultra-LG (1:100)

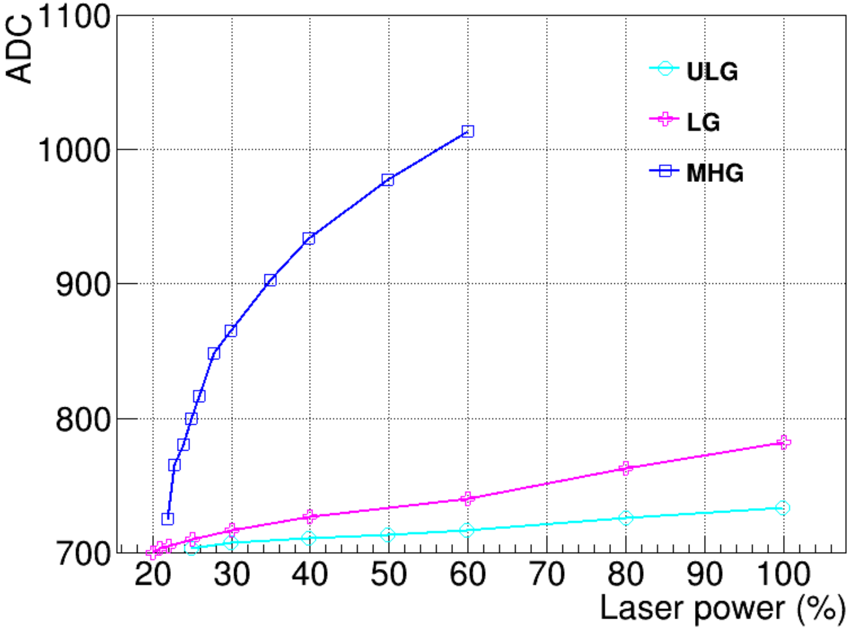
LED calibration in High Gain



Charge injection with HG and Mid-HG



Laser tests in Low Gain modes



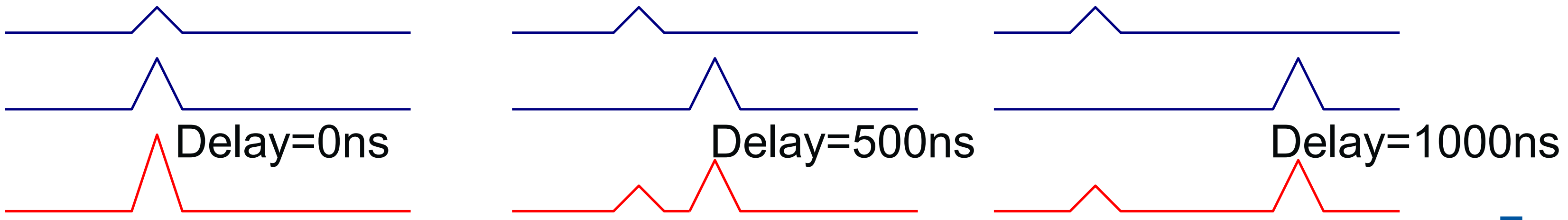
Maximum ~40 p.e. in the HG mode for HPK-SiPM (25μm); we can infer ~120 p.e. for NDL-SiPM (10μm)

In the ultra low gain mode, rough estimates are ~200 MIPs for HPK-SiPM, ~600 MIPs for NDL-SiPM (20p.e./MIP)

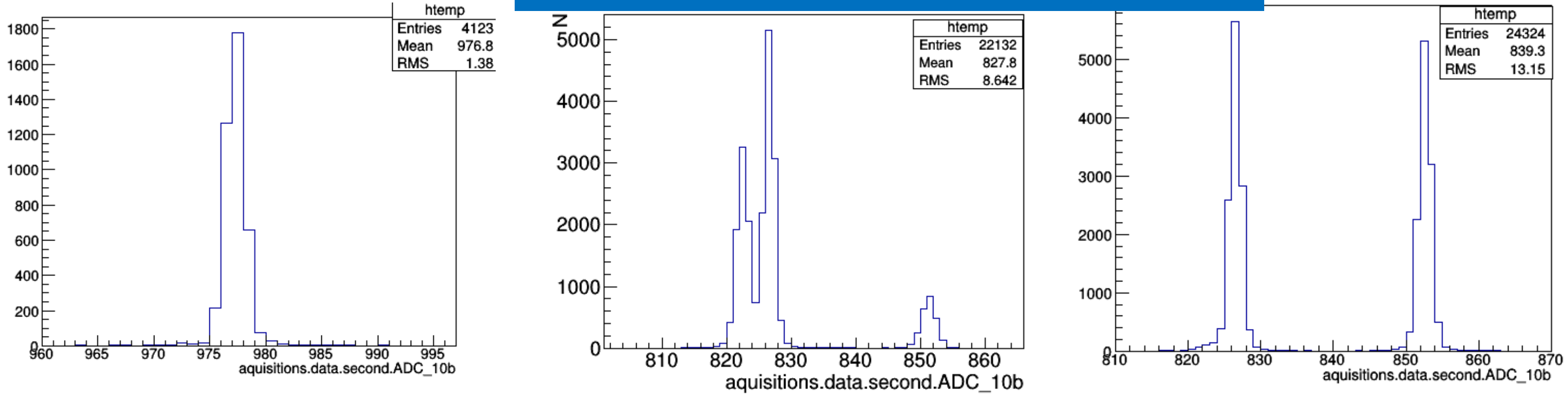
Klaus5: first tests on the dead time

Guofu Cao, Wenqi Yan (IHEP)

- Preliminary studies with charge injection
  - 2 close-by pulses, each 20 ns wide, with repetition rate 500 Hz
  - Scan the time interval between the pulses, 0-1000 ns
  - Tests show if time interval >700 ns, pulses can be well separated by Klaus5



Klaus5 ADC spectrum in various scenarios

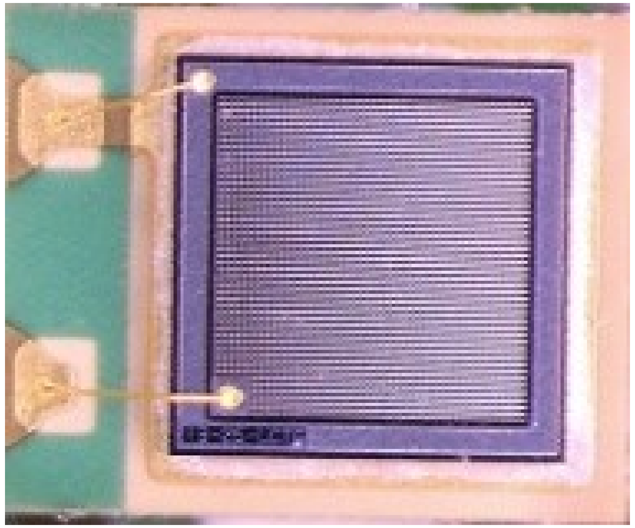


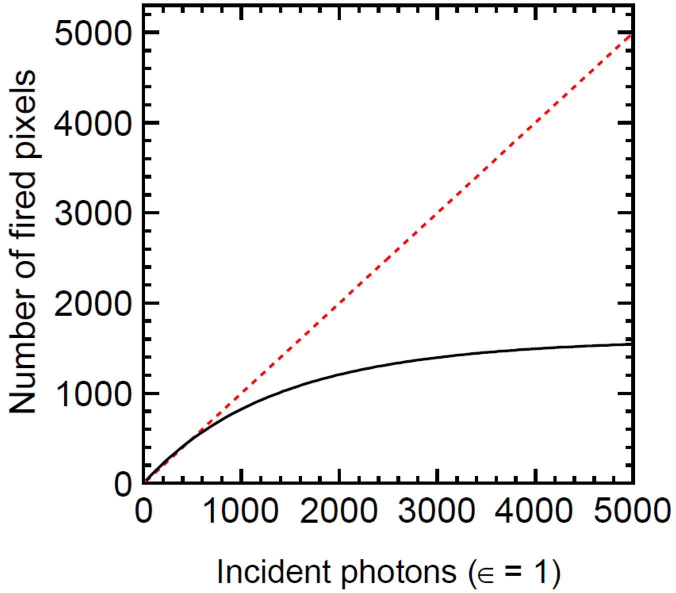
For a single channel, the chip can tolerate event rate > 1MHz

Note: 100kHz max. event rate estimated for CEPC at Z-pole with a factor of 3 as safety margin (CDR)

Crystal cell: dynamic range

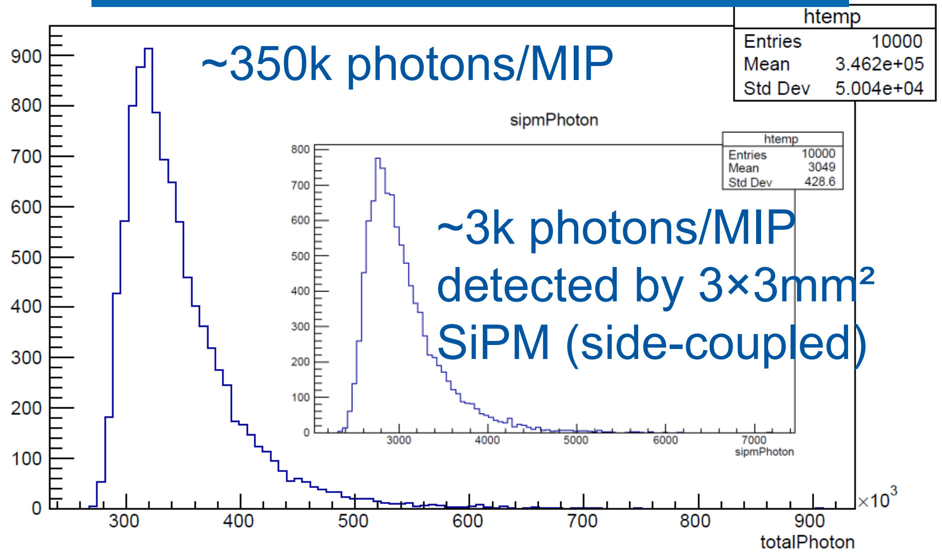
- Silicon Photomultiplier
  - Non-linear response due to finite #pixels (each as a binary counter)
- Crystal such as BGO produces (too) many photons
  - Stringent requirement on the readout: response linearity





arXiv:1510.01102

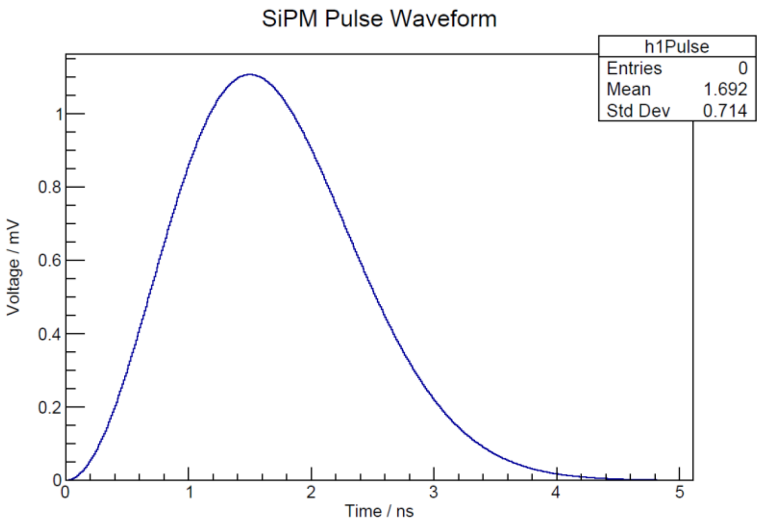
Geant4 simulation of BGO crystal



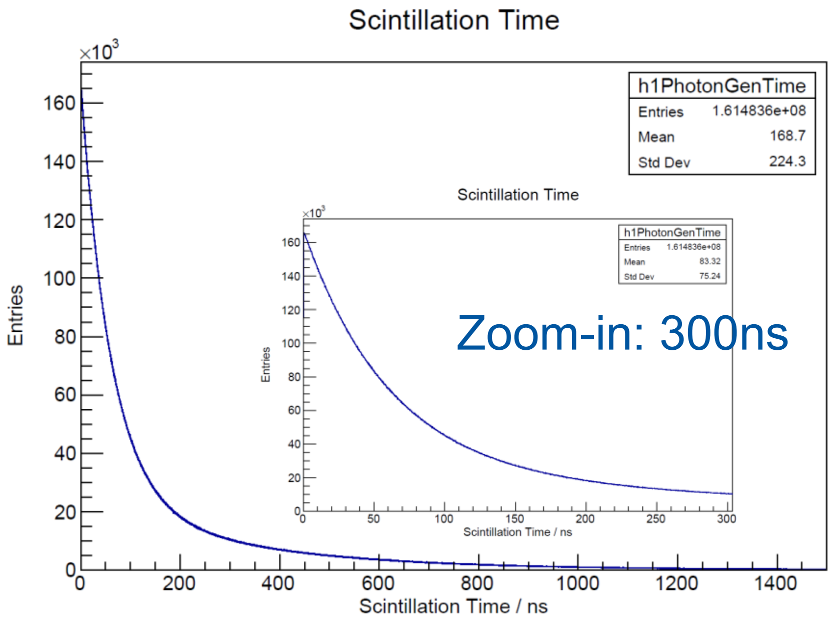
1 GeV muons passing through 45 mm BGO (~4X0) crystal bar (10×10×45 mm³)

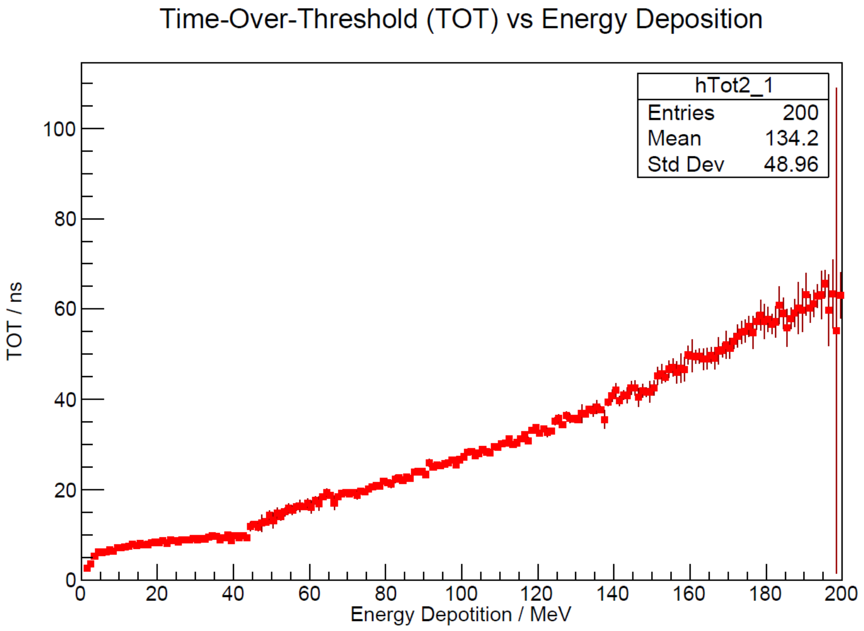
Crystal cell: dynamic range

- Geant4 full simulation of TOT with BGO crystal
  - Detailed properties of BGO: 8200 photons/MeV, time constants tau1=60ns, tau2=300ns
  - Linearity promising for larger signals
  - Non-linearity effects observed in some energy regions, besides small energy depositions



SiPM Single-Photon Pulse Waveform





Quantitative studies on the TOT non-linearity under way;
HGCROC chip for CMS-HGCAL project also provides this feature

CHEF2019 proceeding: to be submitted

PREPARED FOR SUBMISSION TO JINST

CALORIMETRY FOR THE HIGH ENERGY FRONTIER 2019 (CHEF2019)
25 - 29 NOVEMBER 2019
KYUSHU UNIVERSITY, FUKUOKA, JAPAN

High-granularity crystal calorimetry: conceptual designs and first studies

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Updates from US colleagues

- Increasing interests in the dual-readout of crystal calorimetry
  - Existing work on the PFA + dual readout with crystals
  - Interests to work in this direction
- More discussions foreseen at the Washington Workshop in April

Use of Particle Flow Algorithms in a Dual Readout Crystal Calorimeter

Stephen Magill

Argonne National Laboratory

Journal of Physics: Conference Series 404 (2012) 012048
doi:10.1088/1742-6596/404/1/012048

Abstract. The ability to grow clear, dense scintillating crystals presents an opportunity for development of a total absorption calorimeter that could contain multi-GeV hadrons in a detector volume similar to that of present-day calorimeters. With appropriate crystals and optimized readout elements, both scintillation and Cerenkov photons can be produced and detected separately. This dual readout approach allows one to selectively correct particle energies, resulting in significant gains in energy resolution $\rightarrow 20\%/\sqrt{E}$ or even better for hadrons. An R&D program is underway to 1) develop appropriate clear, dense crystals, 2) test innovative readout methods for both scintillation and Cerenkov light, and 3) provide test beam capability for crystal and readout sensor testing and simulation verification. As part of this effort, simulation studies have been done assuming a dual readout crystal calorimeter implementation for a future e^+e^- linear collider detector. By using the dual readout correction, corrections for magnetic field effects on low momentum charged hadrons, and particle flow techniques, substantial improvements in dijet mass resolution are obtained.

Summary and prospects

- High-granularity crystal ECAL
  - Aim to keep optimal energy resolution and PFA capability
  - Key issues for optimization and technical challenges (partially) identified
  - First studies initiated: simulation and various tests
- Prospects
  - Simulation studies with digitizer: crystal segmentation
  - **PFA performance for jets, to be evaluated**
  - Systematic studies on the Klaus5 performance with test boards
  - Further timing studies: TOA, TOT, etc.
- Welcome broader collaborations
  - Still at early design and R&D stage, many open issues

Thank you!