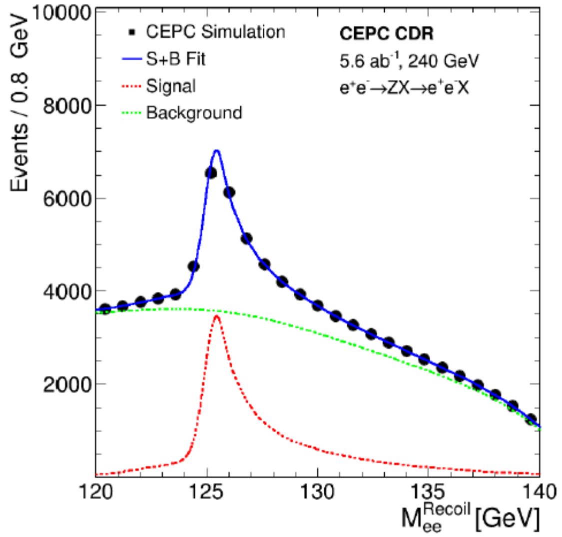
High-granularity Crystal Calorimeter: R&D status

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

CEPC Physics and Detector Plenary Meeting
May 6, 2020

Motivations: reminder



- 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
  - PFA capability for precision measurements of jets

High-granularity crystal ECAL: reminder

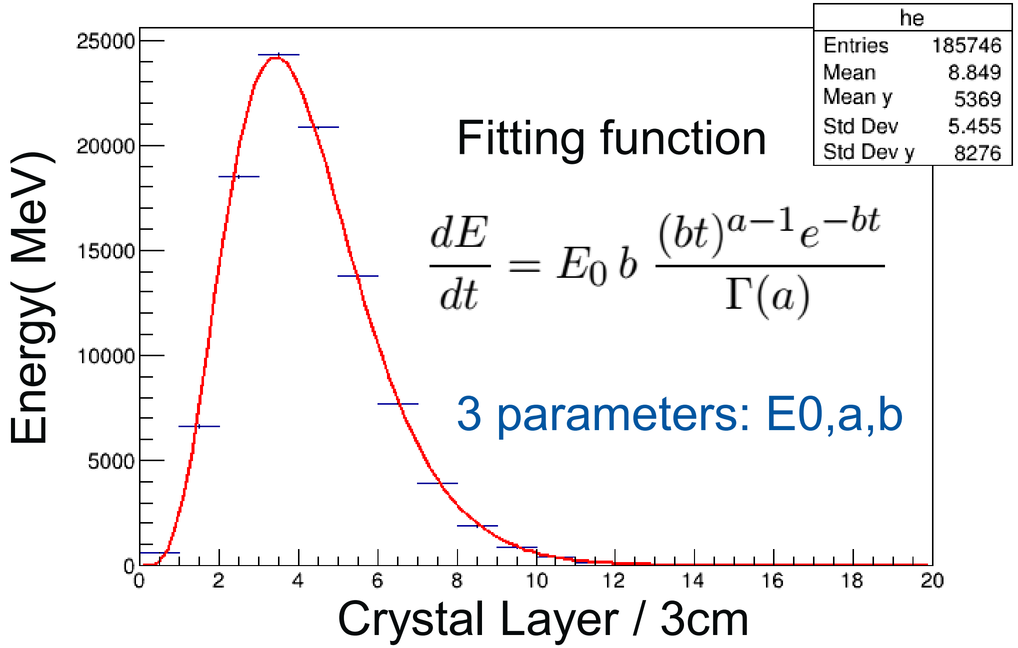
- Plenty of room for broad collaborations
  - New ideas proposed and discussed in a dedicated CEPC calorimetry workshop in March 2019
  - Need to identify key issues and technical challenges
- R&D activities: recent progress
  - Crystal granularity optimisation: longitudinal depth, lateral segmentation
  - Crystal readout scheme: simulation tools recently developed
  - Dynamic range studies
  - Readout electronics: tests with KLauS ASIC

Crystal cell optimisations

Chunxiu Liu (IHEP)

- Crystal longitudinal depth
  - Use shower profiles in segmented layers to correct for tails (energy leakage)
  - Aim for shorter crystal depth (cost), balance with performance (correction precision)
- Crystal transverse segmentation
  - Crystal transverse size: separation of neutral pions and photons

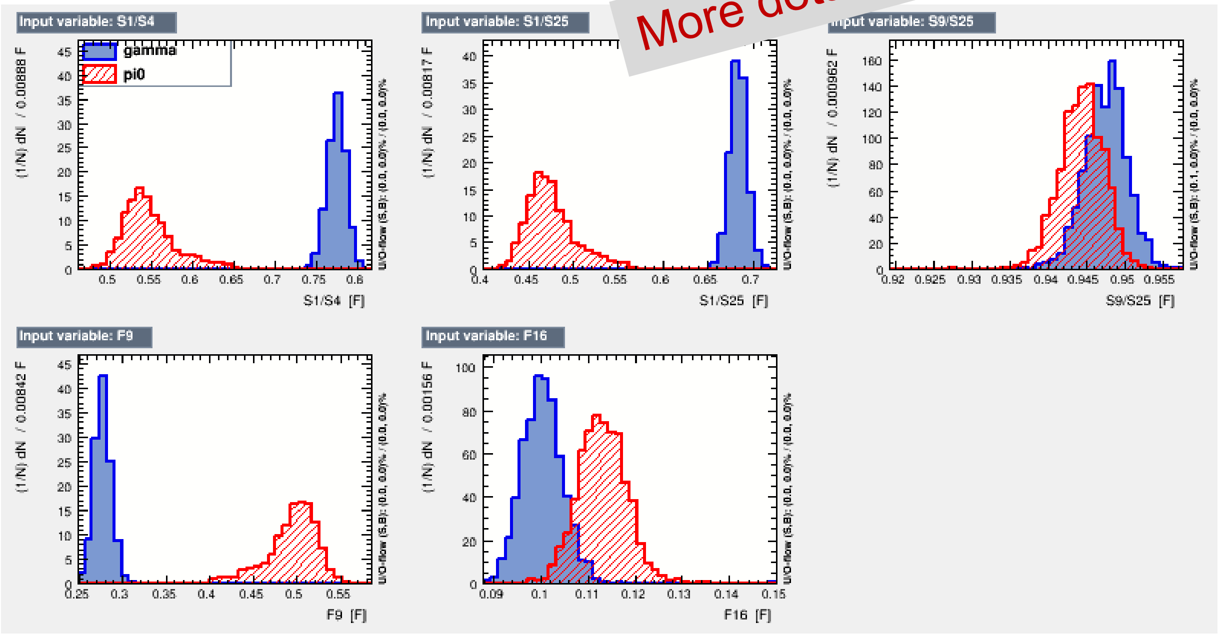
More details in the next talk



Fitting function

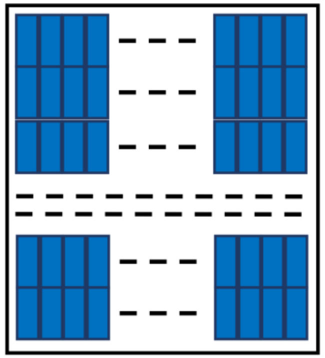
$$\frac{dE}{dt} = E_0\, b\, \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

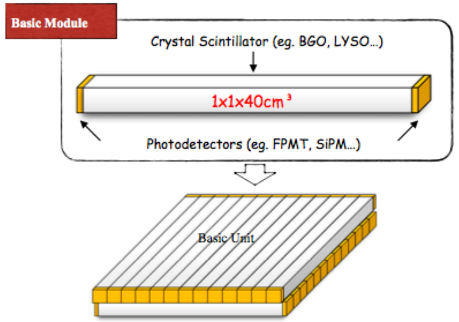
3 parameters: E0,a,b

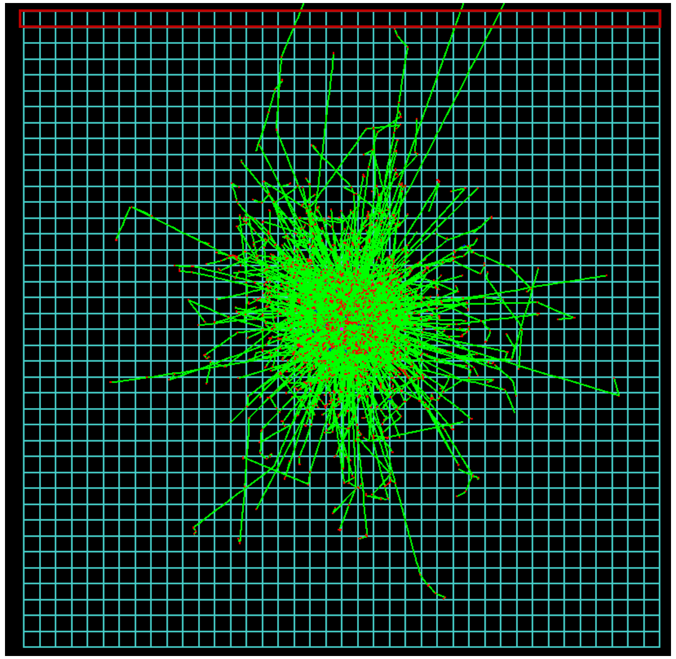


Crystal readout schemes

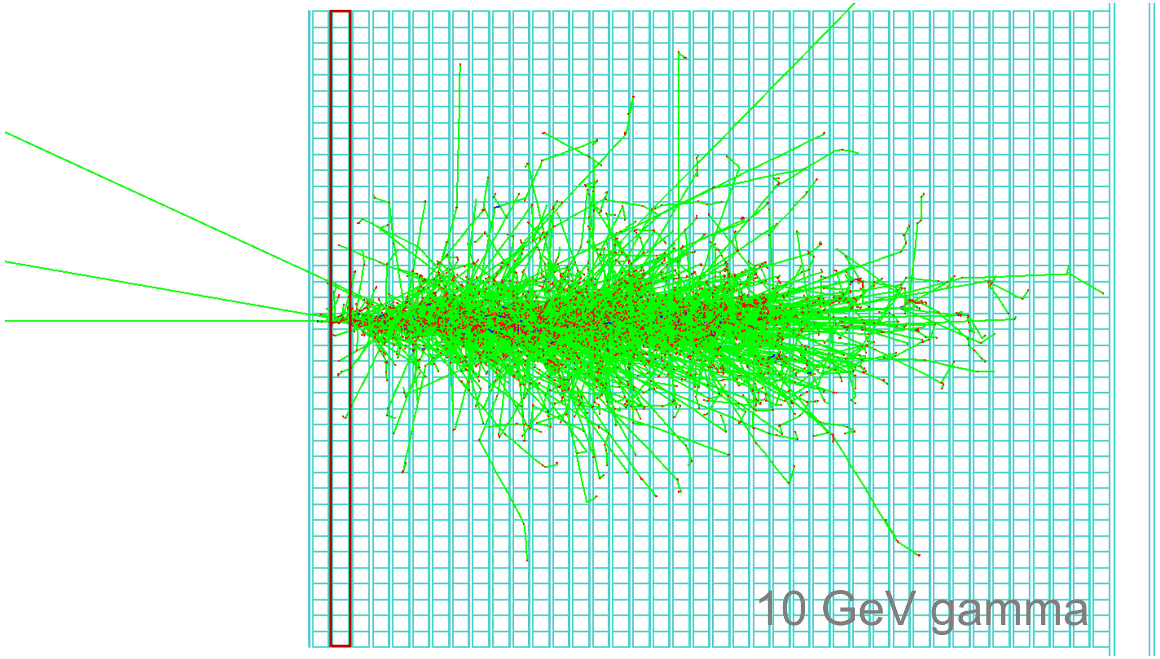
- Geant4 simulation: flexible for 2 readout schemes
  - Single-ended readout: in all previous studies
  - Double-ended readout: to use timing at 2 ends for position reconstruction
    - To study the feasibility to separated multiple incident particles







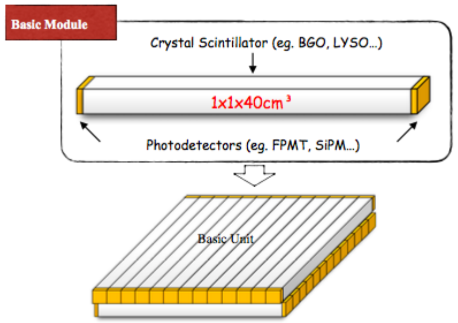
Front View

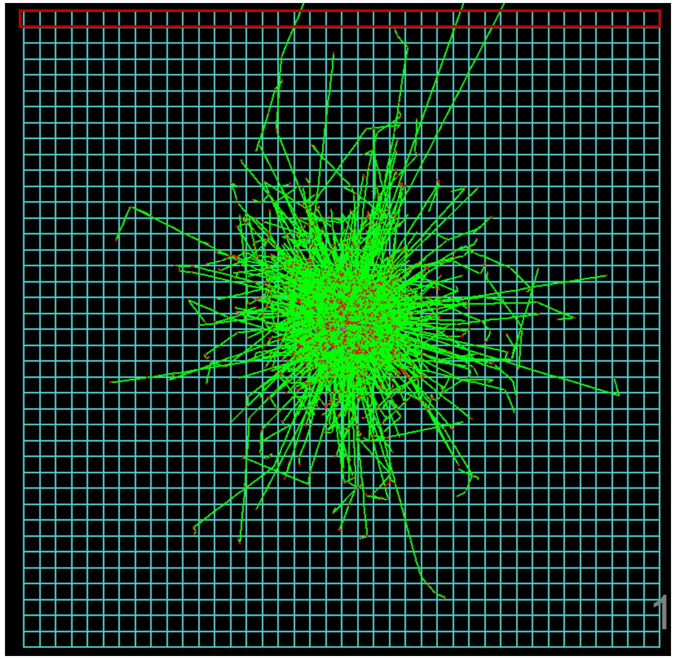


Side View

Crystal readout schemes

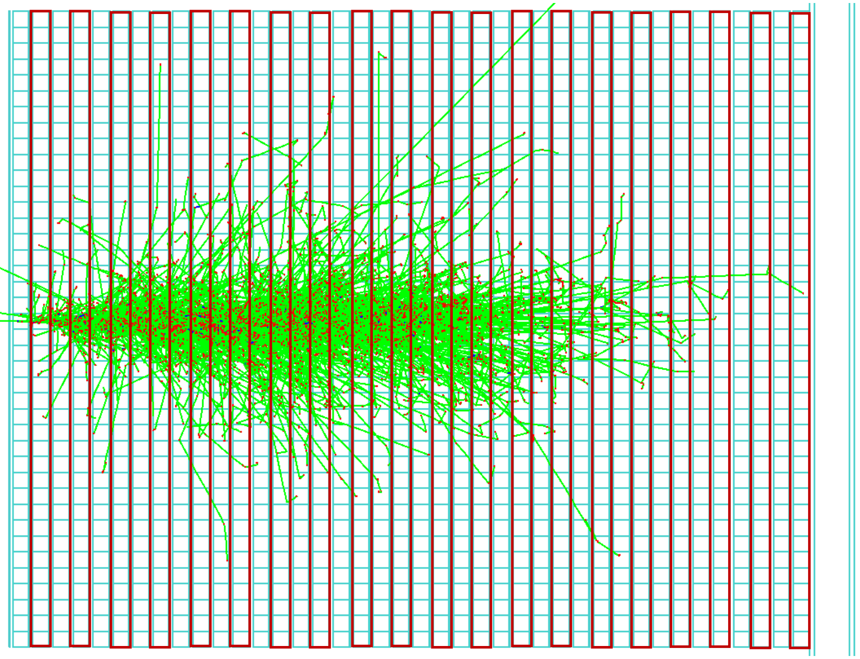
- Geant4 simulation: flexible for 2 readout schemes
  - 1cm³ crystal cube in the simulation: shower grids
  - Flexible to group cubes differently
    - E.g. group 40x1 cubes as for a long bar: <u>time stamps</u> and <u>detected photons</u> at 2 ends





Front View

10 GeV gamma

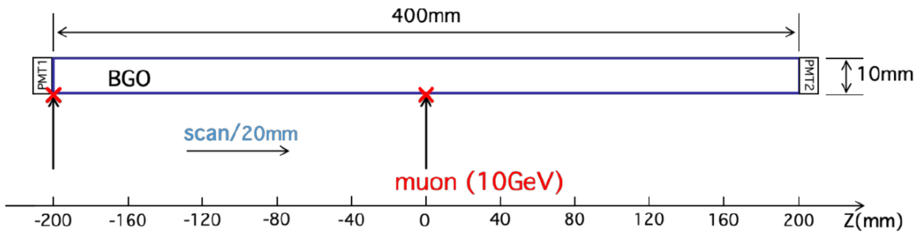


Side View

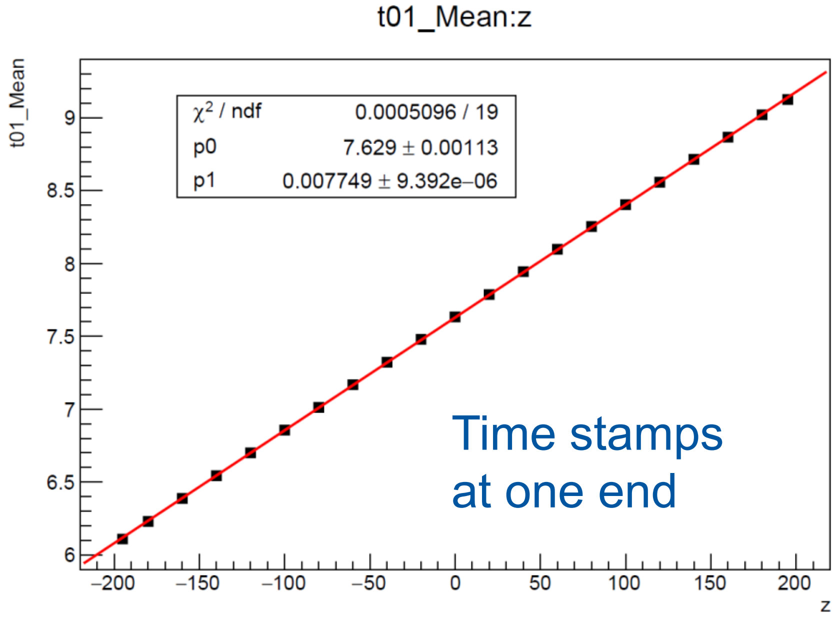
Crystal readout schemes: simulation tools

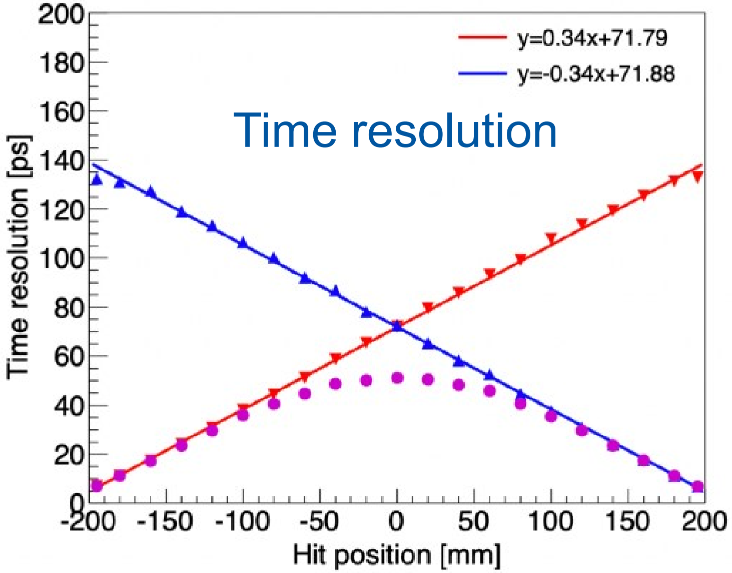
- Fully make use of the information from Geant4 full simulation
  - With optical photon processes for a single crystal bar

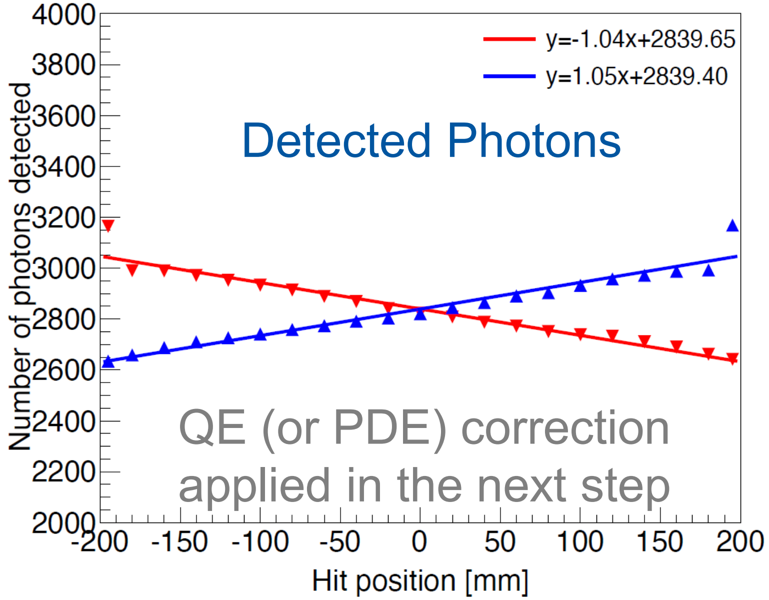
Based on the work of Yuexin Wang (IHEP)



Including scintillation, light propagation → realistic modeling of time stamps and #photons at each end



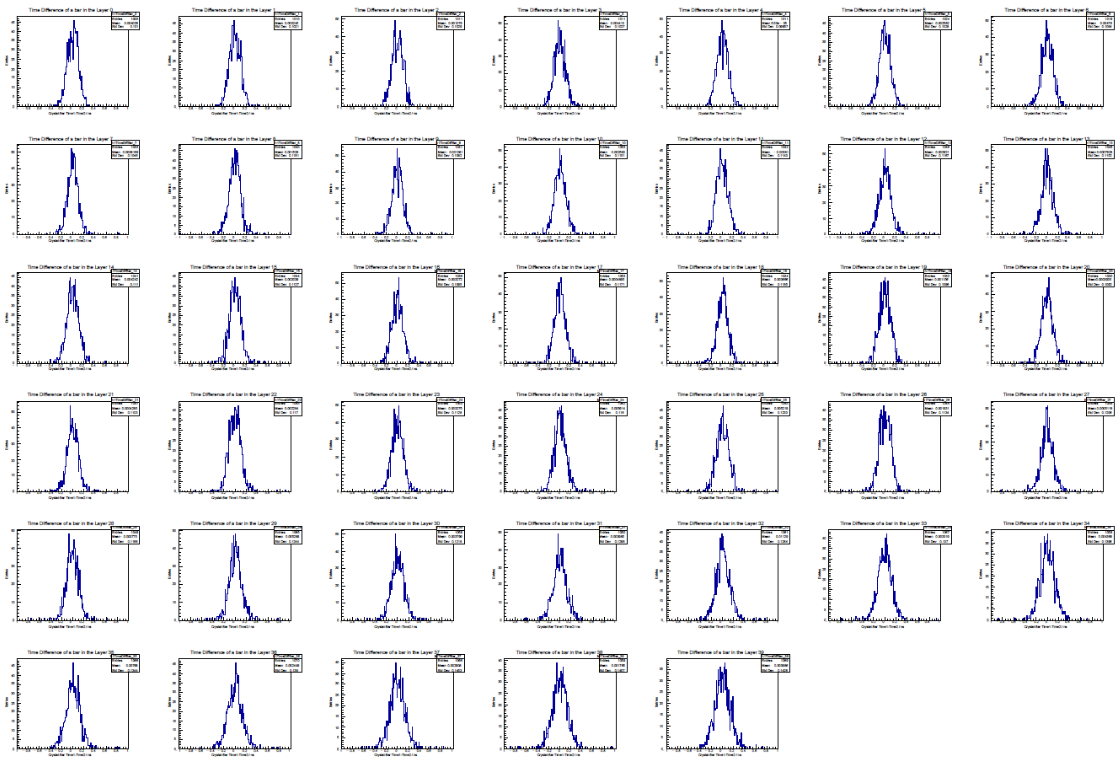




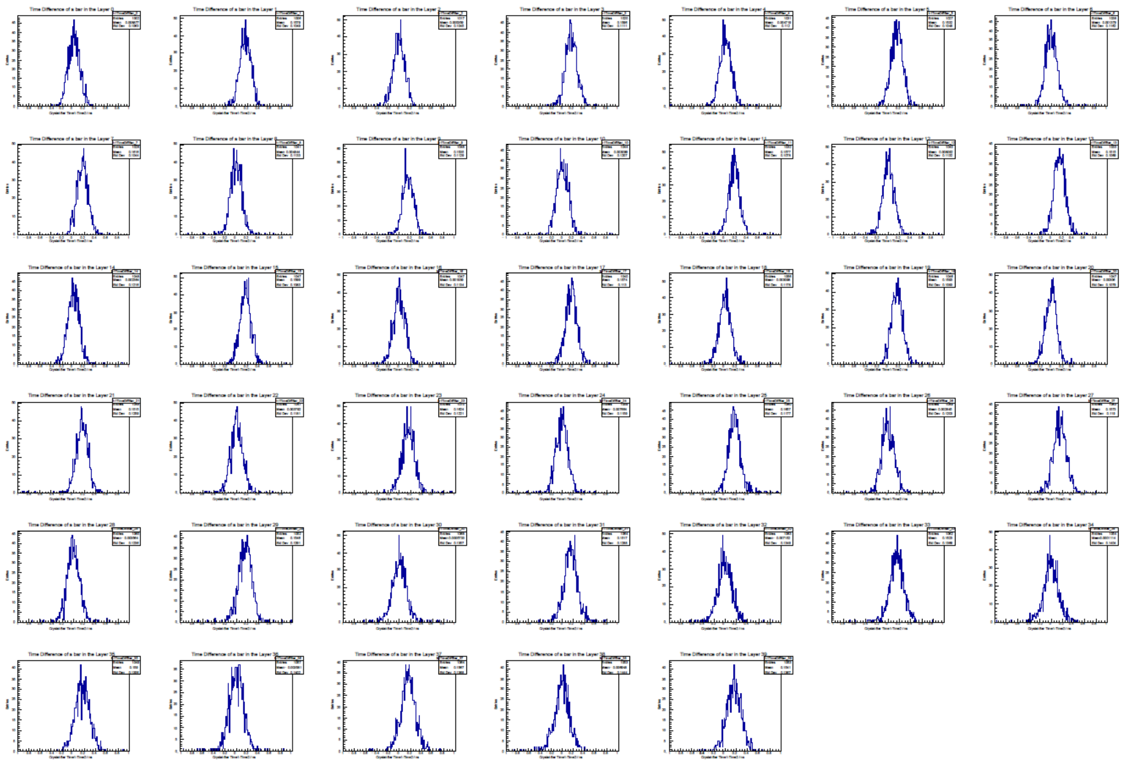
Crystal readout schemes: simulation tools

- First preliminary results
  - Two close-by muons, separated by 1cm, as for the first exercise

Time difference of a single long bar per layer (X=0cm)



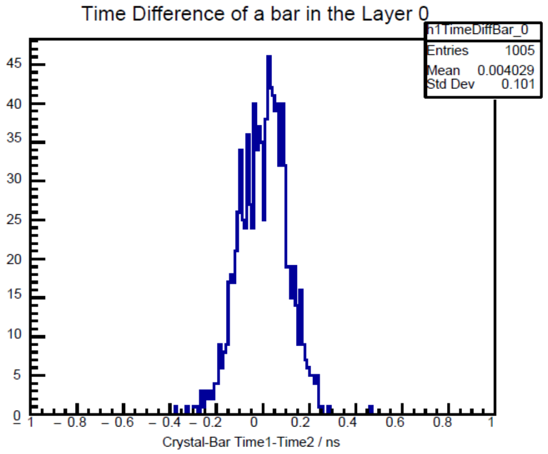
Time difference of a single long bar per layer (X=1cm)

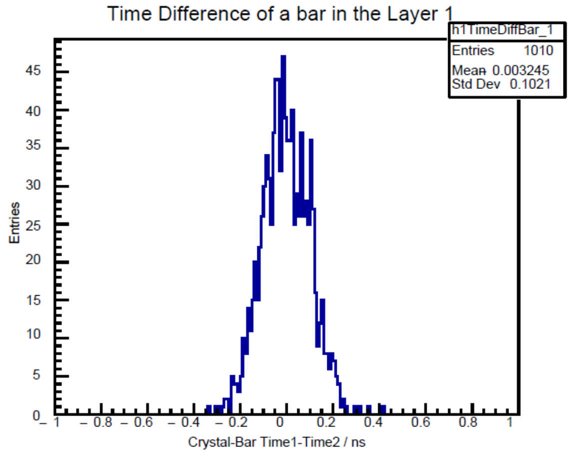


Crystal readout schemes: simulation tools

- First preliminary results
  - Two close-by muons, separated by 1cm, as for the first exercise

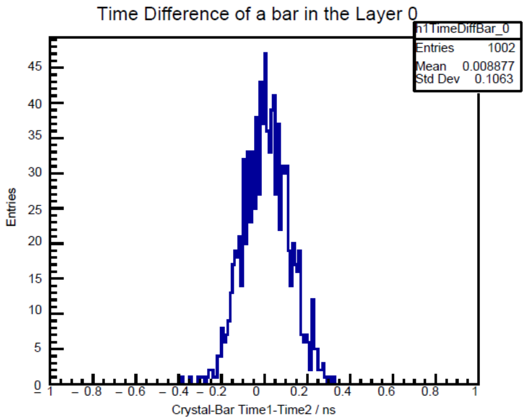
Time difference of a single long bar for 2 first layers (incident muons at X=0cm)

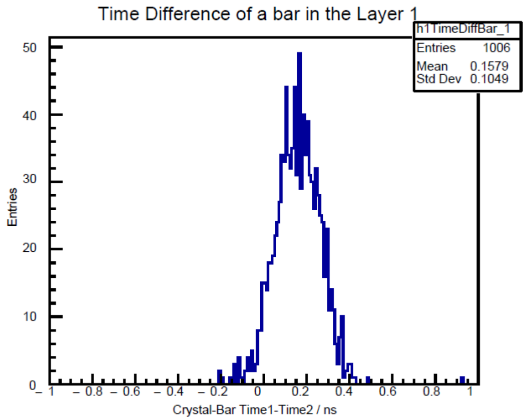




Time difference (mean) at around 0

Time difference of a single long bar for 2 first layers (incident muons at X=1cm)

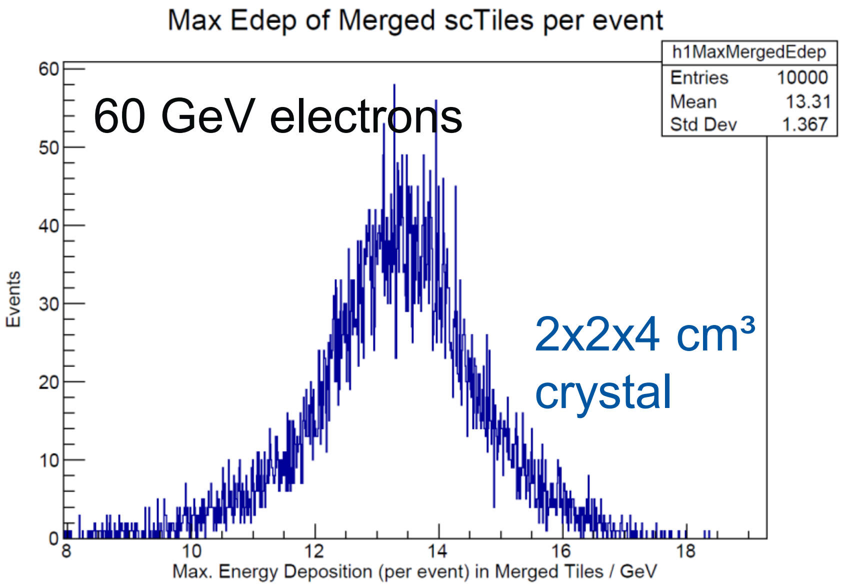


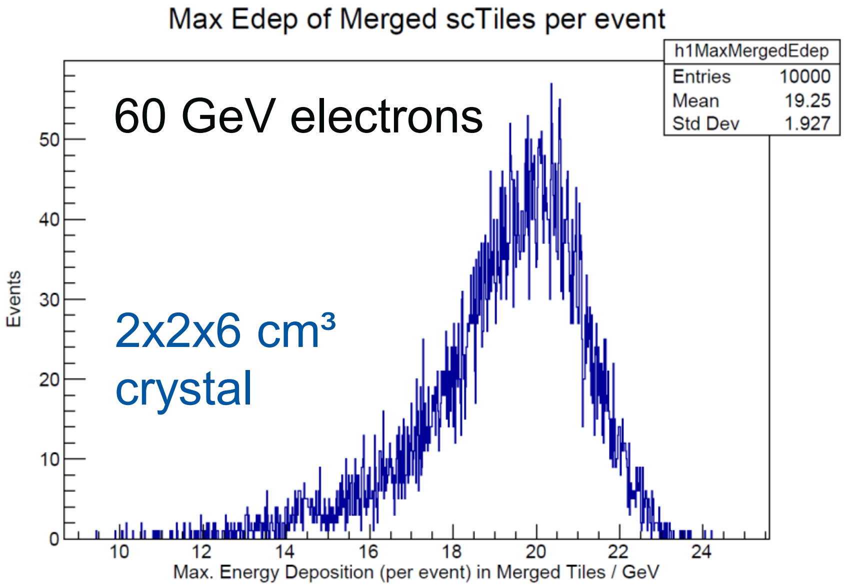


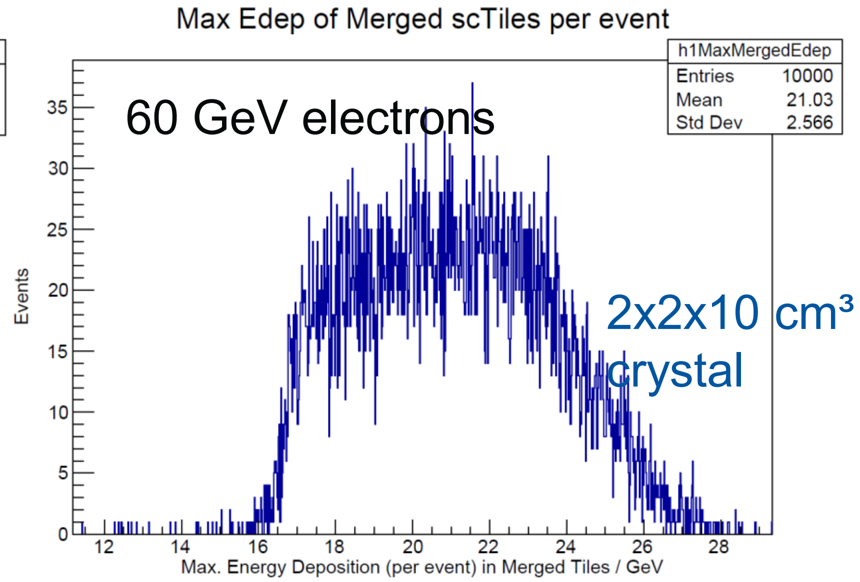
Time difference (mean) offset at around 150 ps

Dynamic range: simulation with high-energy electrons

- Use the simulation tool to group 1cm³ crystal cubes for readout
- Maximum energy deposition per cell
  - Depends on the crystal segmentation configurations
  - Provide inputs for the SiPM and its readout electronics

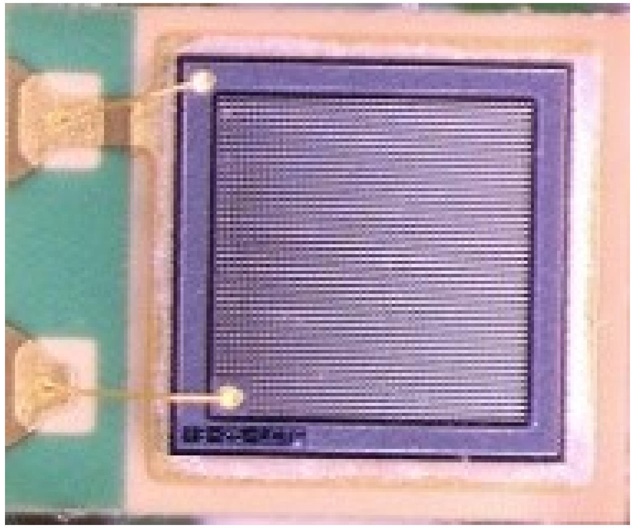


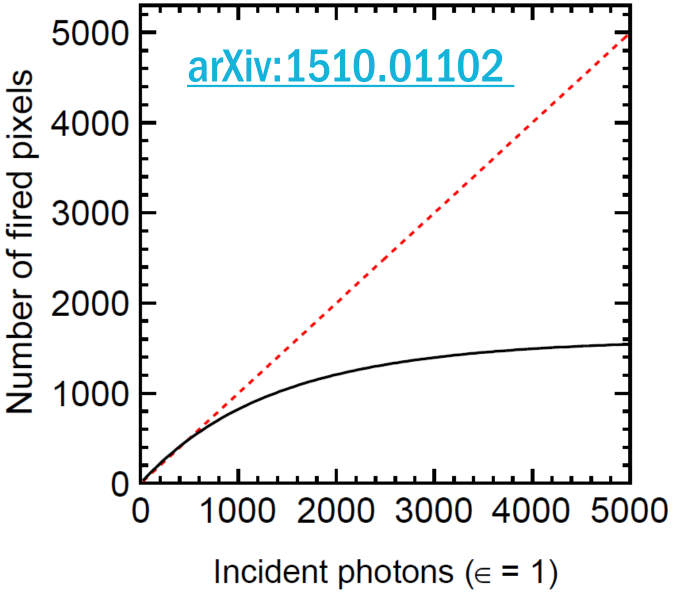




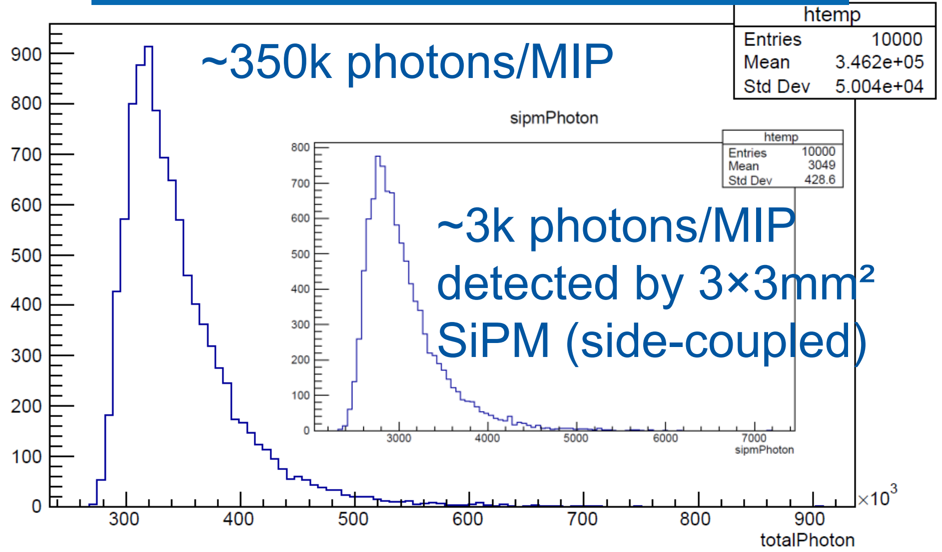
Crystal cells: dynamic range (reminder)

- Silicon Photomultiplier (SiPM)
  - 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





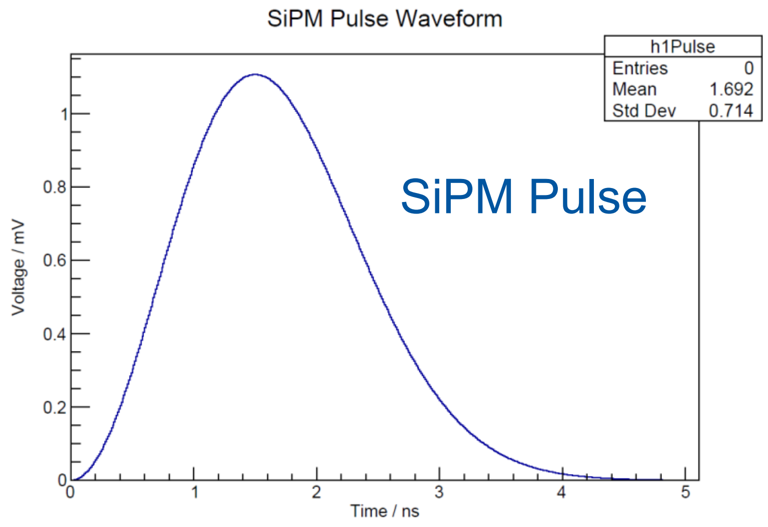
Geant4 simulation of BGO crystal



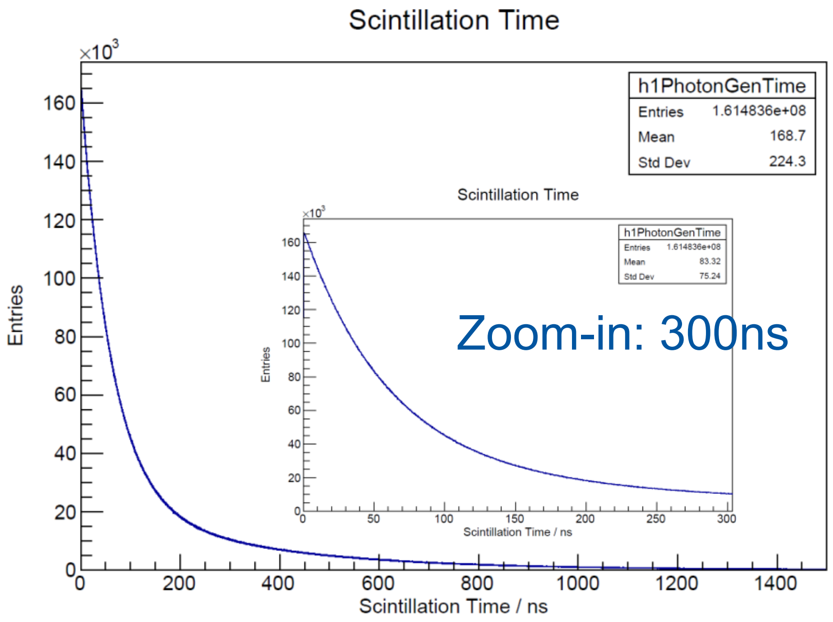
~40 MeV energy deposition for 1 GeV muons passing through a 45 mm crystal bar (BGO)

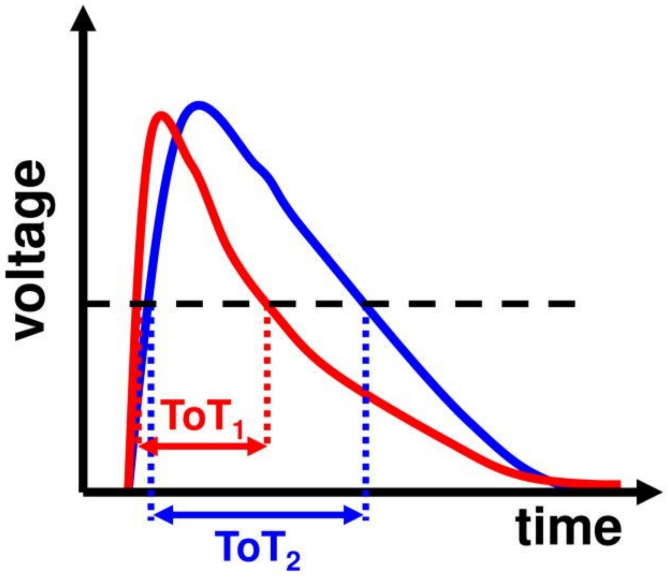
Crystal cells: dynamic range (reminder)

- Geant4 full simulation of TOT with BGO crystals
  - Realistic simulation of BGO scintillation: detailed properties
    - 8200 photons/MeV, time constants tau1=60ns, tau2=300ns
  - TOT: time duration of the rising and trailing edges at a fixed threshold



SiPM Single-Photon Pulse Waveform

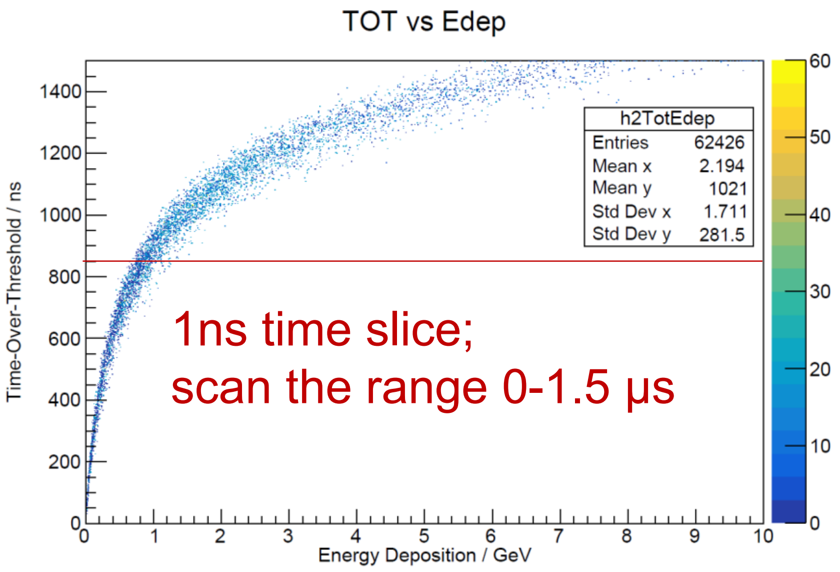


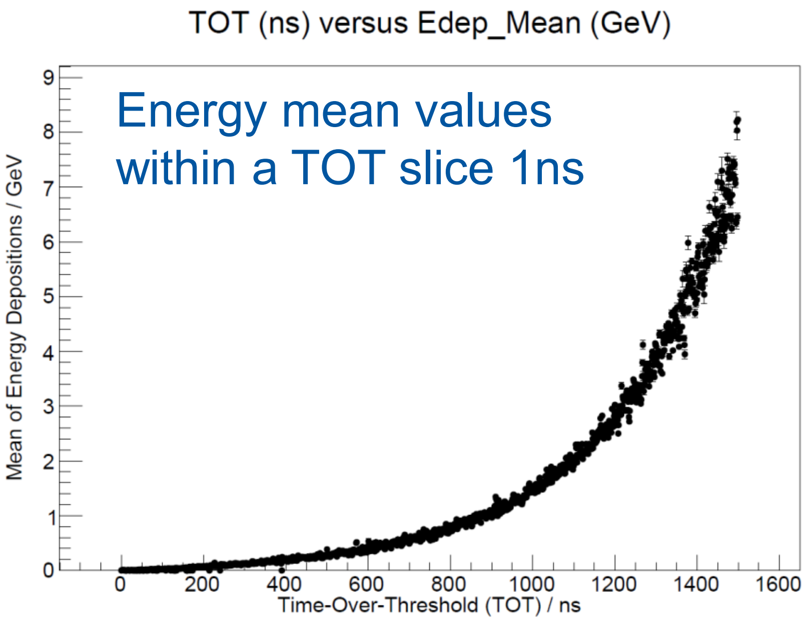


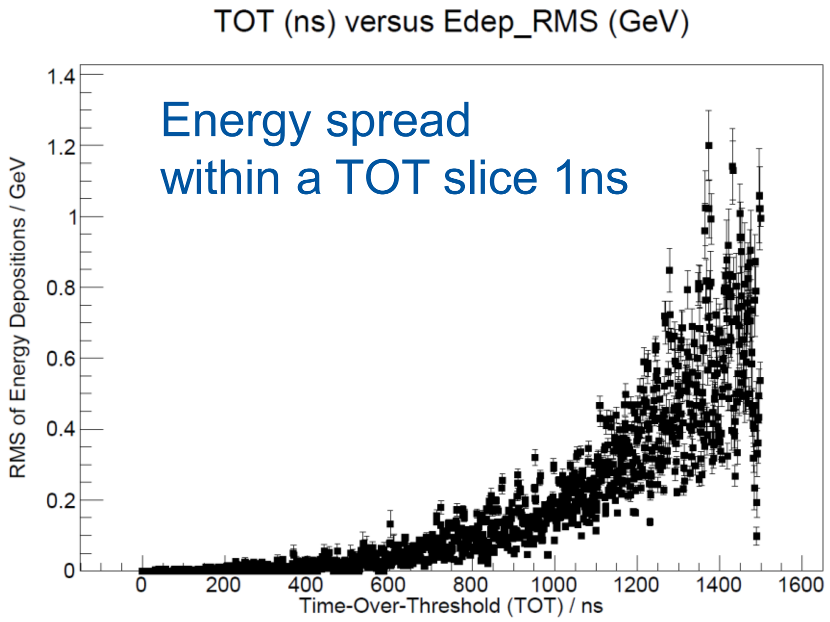
Computing intensive for the simulation; techniques used to fasten the procedure

Dynamic range: TOT simulations

- Energy depositions in a crystal cell: 10MeV – 8 GeV
  - TOT values will go beyond 1.5 μs for energy deposition larger than 8 GeV
  - Energy spread
    - Fluctuations due to BGO scintillation long slow slope

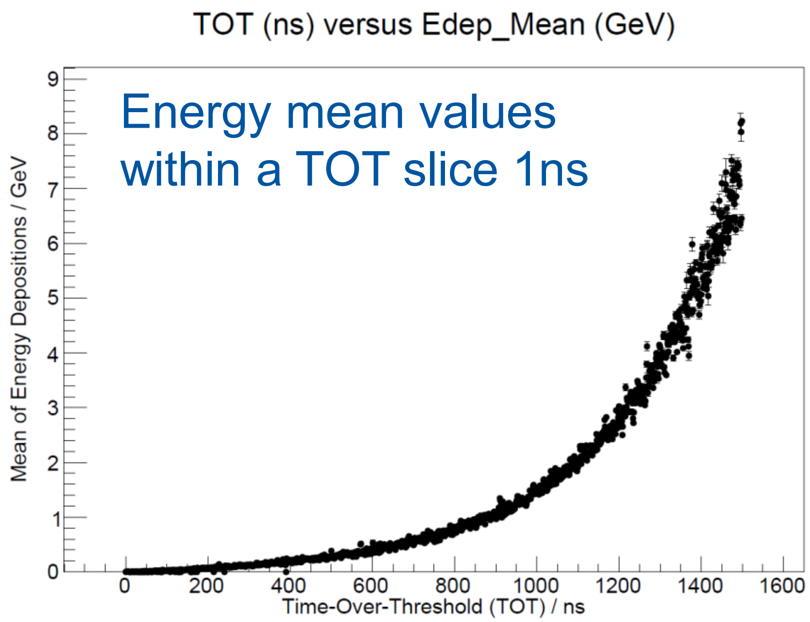


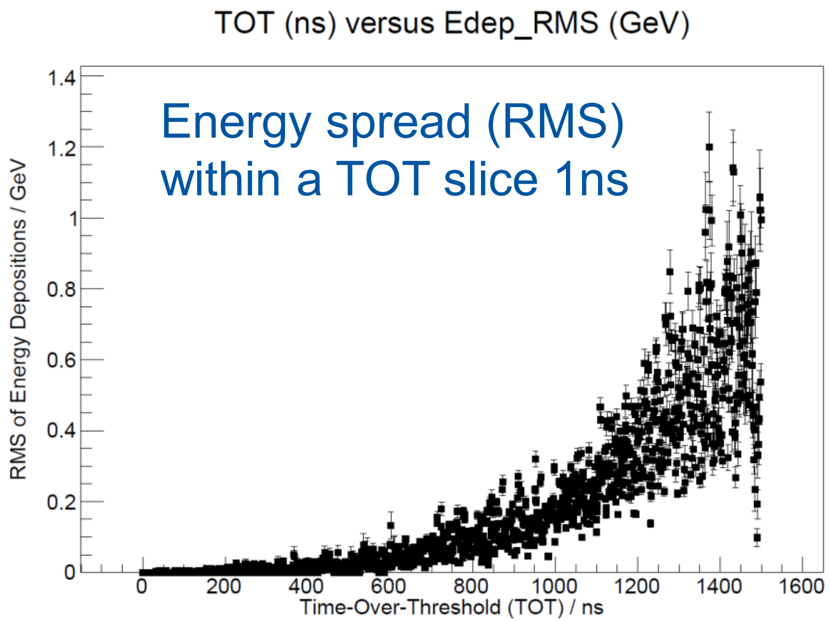


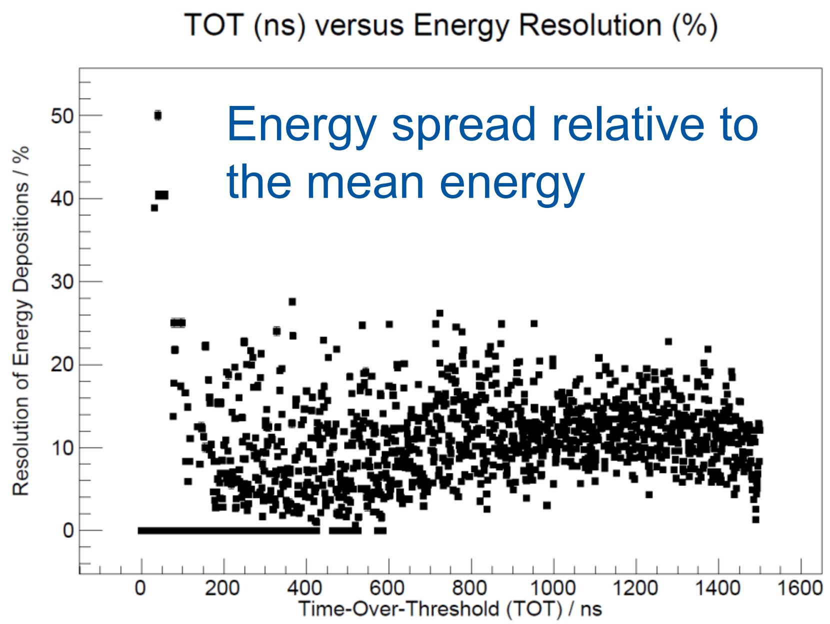


Dynamic range: TOT simulations

- Energy depositions in a crystal cell: 10 MeV – 8 GeV
  - TOT values will go beyond 1.5 μs for energy deposition larger than 8 GeV
  - Energy spread: 10~20 % of energy deposition
    - Fluctuations due to the long slow slope of BGO scintillation



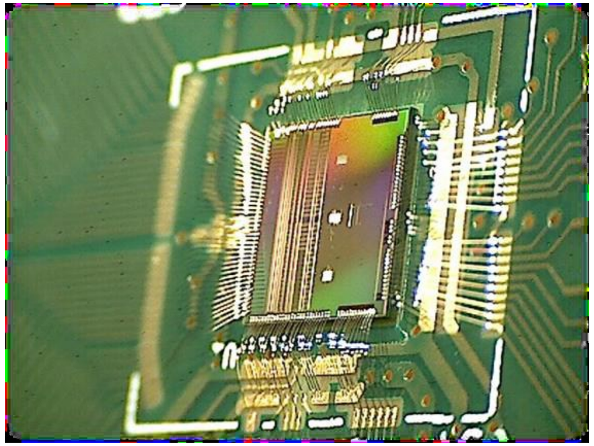




Front-end electronics for SiPM readout (reminder)

- ASIC “KLauS”, developed within CALICE
  - 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

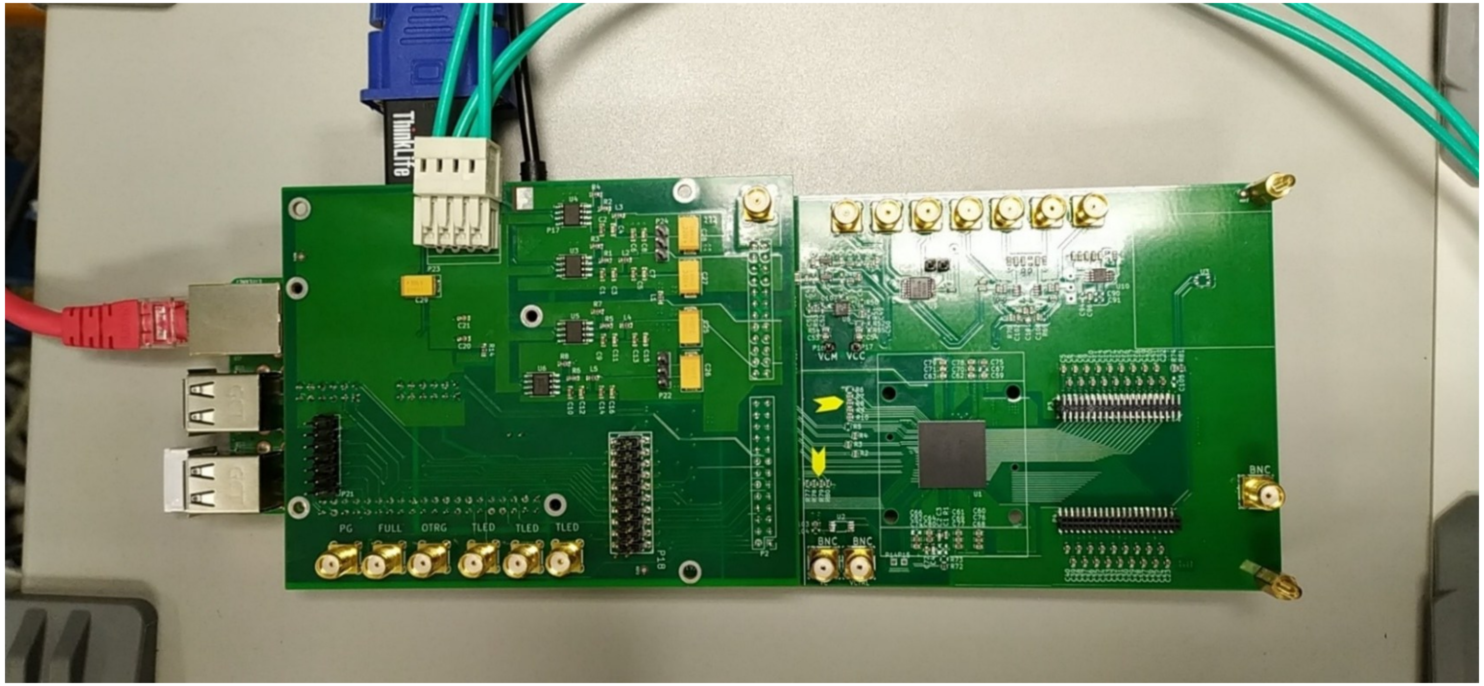


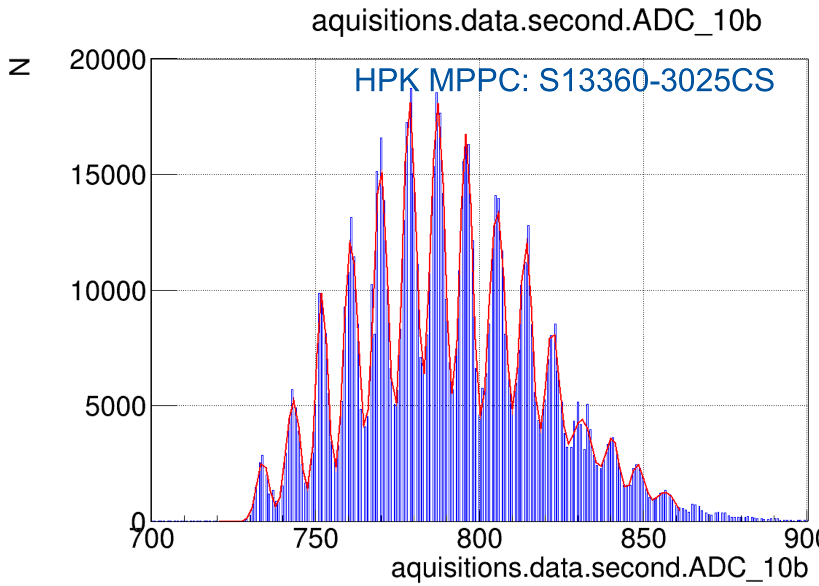
U. Heidelberg, IHEP

Front-end electronics for SiPM readout

U. Heidelberg, IHEP

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

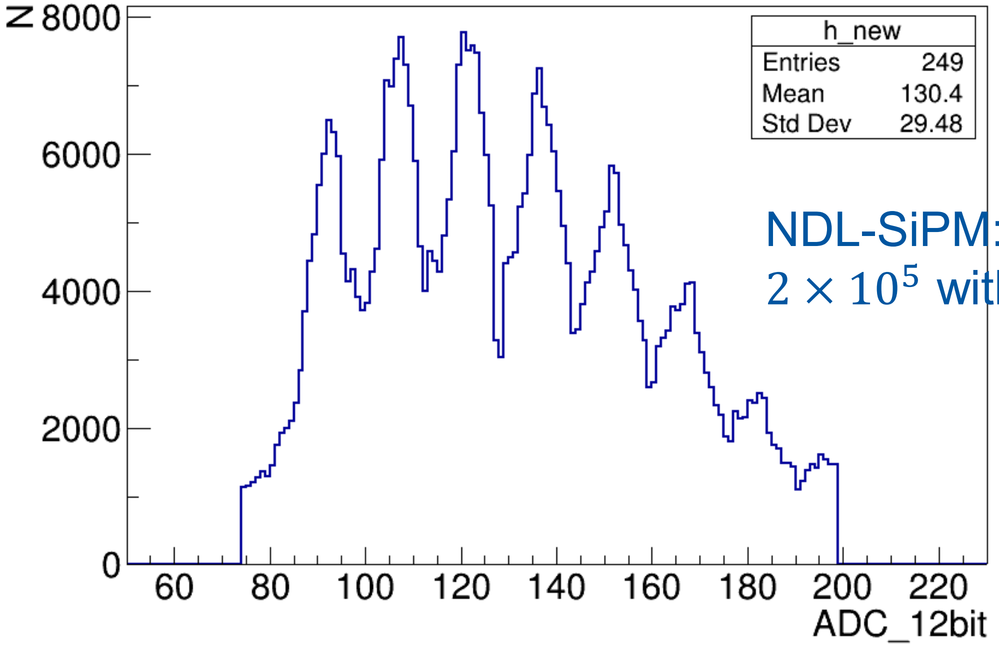




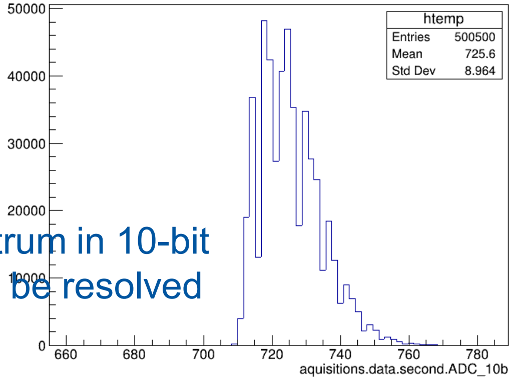
Klaus5: first tests with NDL-SiPM (reminder) U. Heidelberg, IHEP

- 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 12-bit ADC mode: after corrections



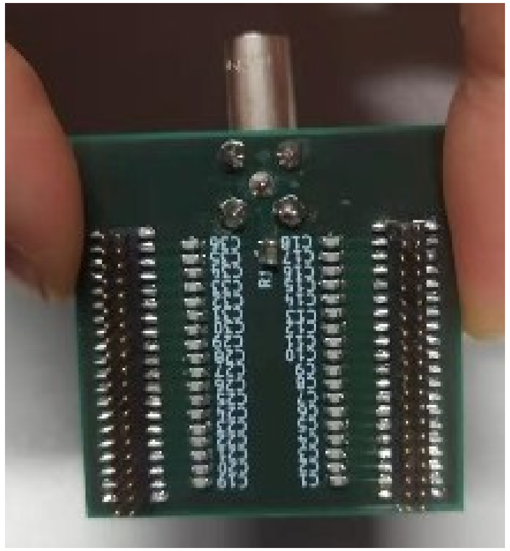
NDL-SiPM: nominal gain 2×10^5 with 10µm pixels



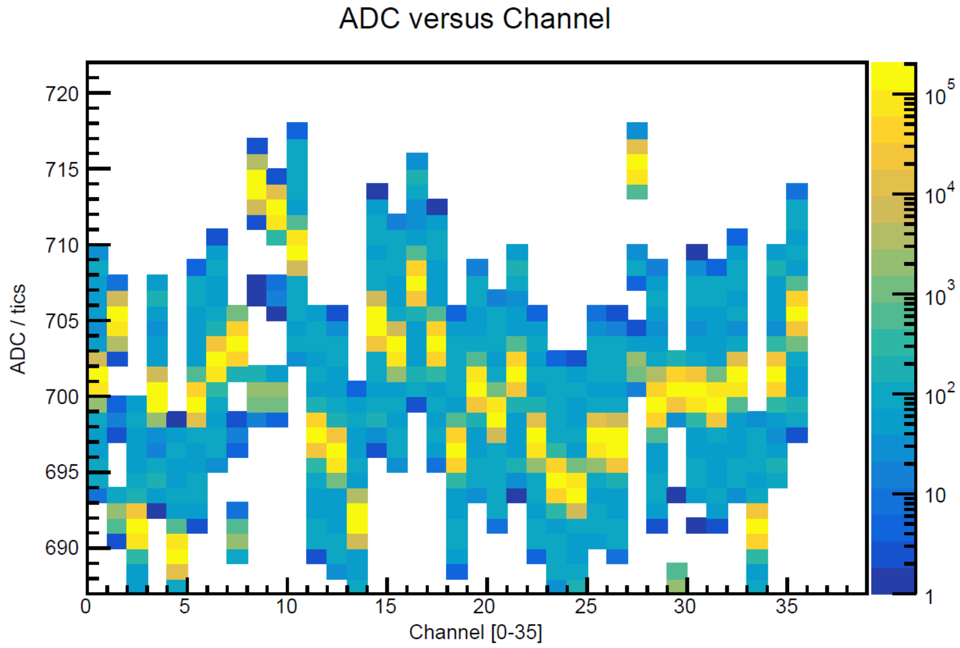
Single photon spectrum in 10-bit ADC mode: can not be resolved

Klaus5: tests with charge injection

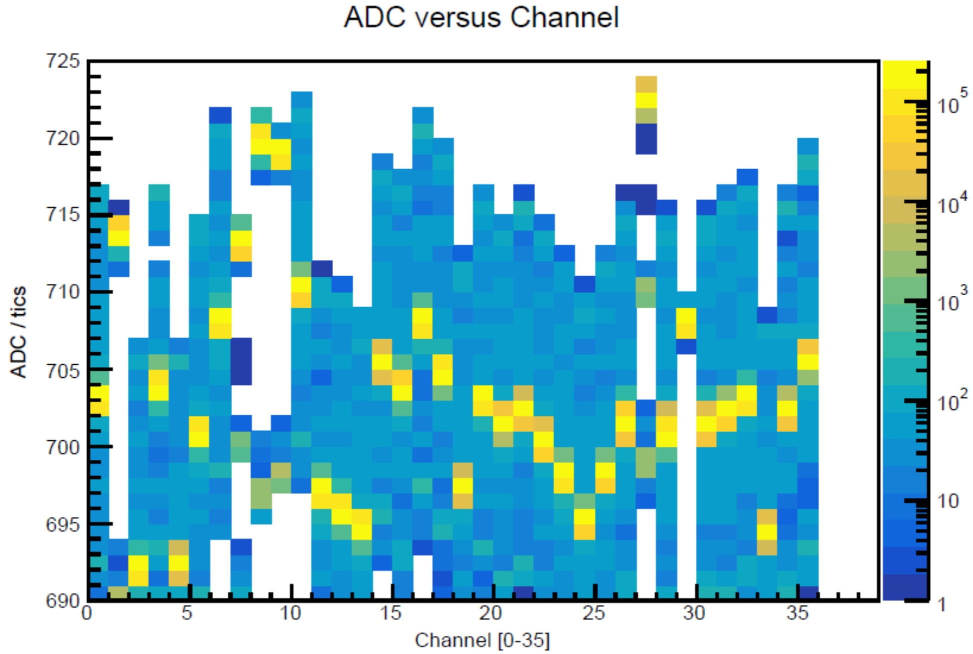
- Pulses injected to all 36 channels
  - Varying input capacitors on adapter PCBs
  - Varying pulse voltages from a pulse generator



Adapter PCB to inject charge pulses injection to 36 channels



Pedestals in (mid) High Gain mode

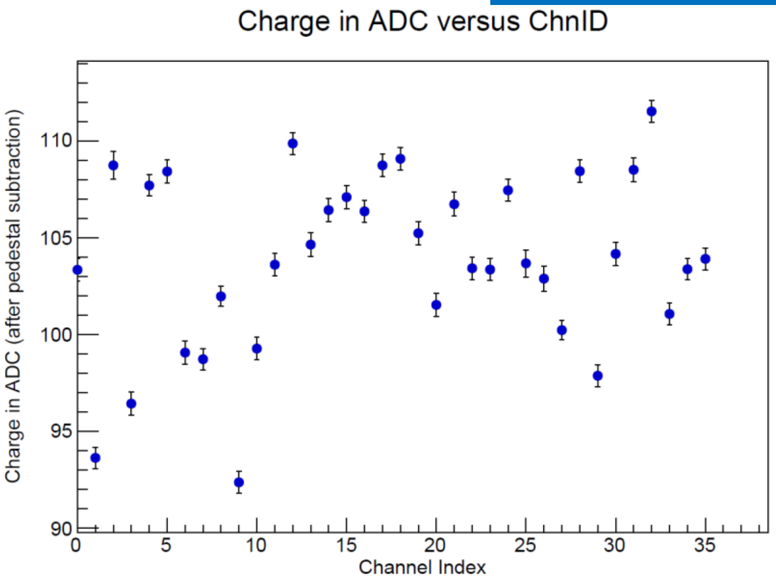


Pedestals in Low Gain mode

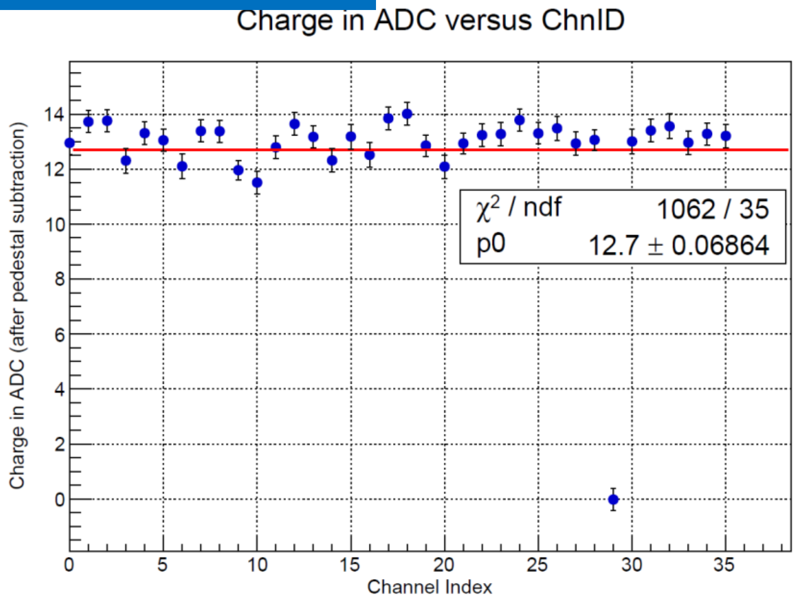
Klaus5: tests with charge injection

- Large amounts of data taken, to be analyzed to evaluate…
  - Dynamic range: different working modes of gains
  - Dead time when all channels are fed with data

Charge Injection to 36 channels

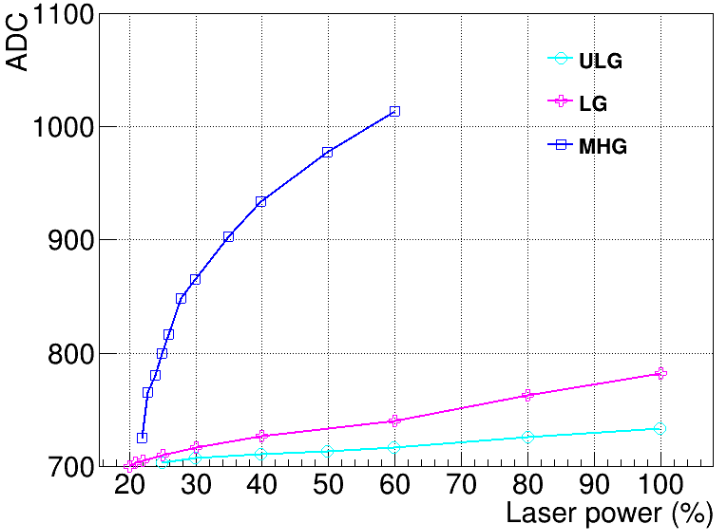


5V pulse input in (mid) High Gain mode



5V pulse input in Low Gain mode

Laser tests for a single channel



Summary

- High-granularity crystal ECAL: steady R&D progress
  - Crystal readout scheme: simulation tools recently developed
    - Single-end versus double-end
    - Flexible to merge crystal cubes for readout
  - Crystal granularity optimisation
    - Crystal depth, pi0/gamma separation power
  - Dynamic range: requirements and TOT technique studies
  - SiPM readout ASIC: characterisations with pulse injection

Thank you!