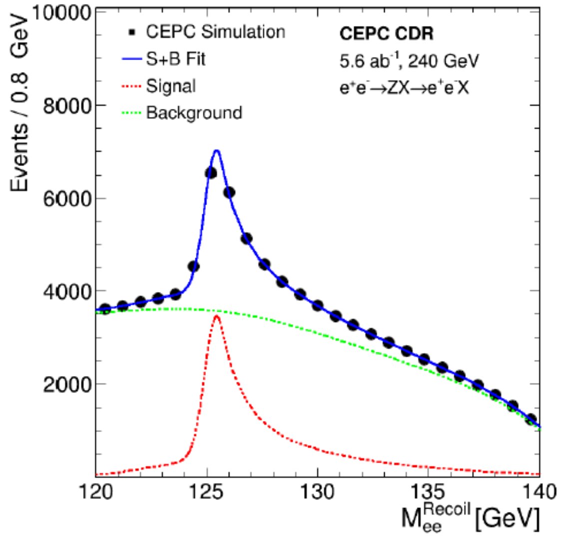
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

High-granularity Crystal Calorimeter: R&D status

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

Mini-workshop on a detector concept with a crystal calorimeter
July 22-23, 2020

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 single photons
    - Flavour physics at Z-pole
    - Potentials in search of new physics, …
- Fine segmentation
  - PFA capability for precision measurements of jets

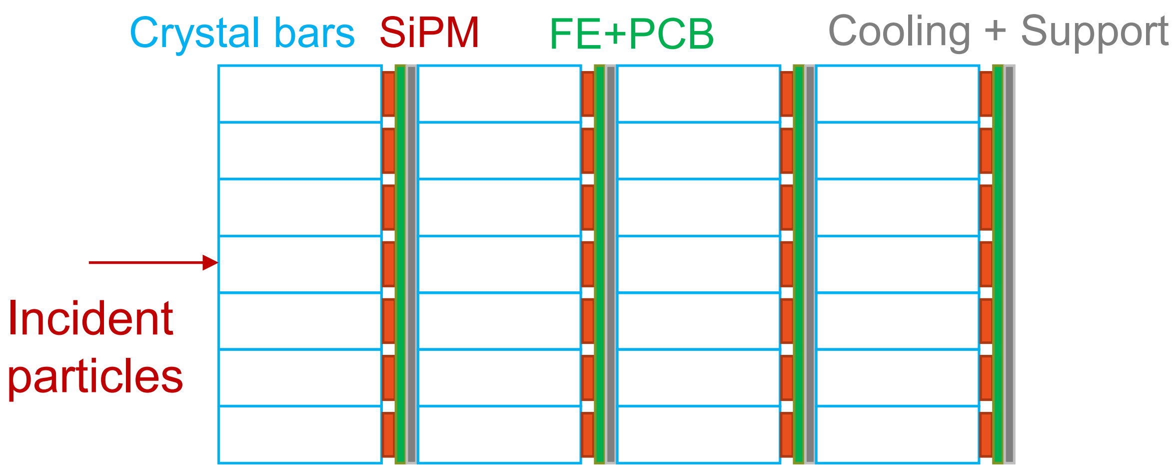
High-granularity crystal ECAL: key issues

- Plenty of room for broad collaborations
  - New ideas proposed and discussed in a dedicated CEPC calorimetry workshop in March 2019
  - Key issues and technical challenges: listed and needs further iterations

- Key issues: optimization part
  - Segmentation: in longitudinal and lateral directions
  - **Performance: single particles and jets with PFA**
  - Costing
  - Impacts from dead materials: upstream, services (cabling, cooling)
  - Fine timing information
  - Dual-gated readout techniques (hadronic energy resolution)
  - …

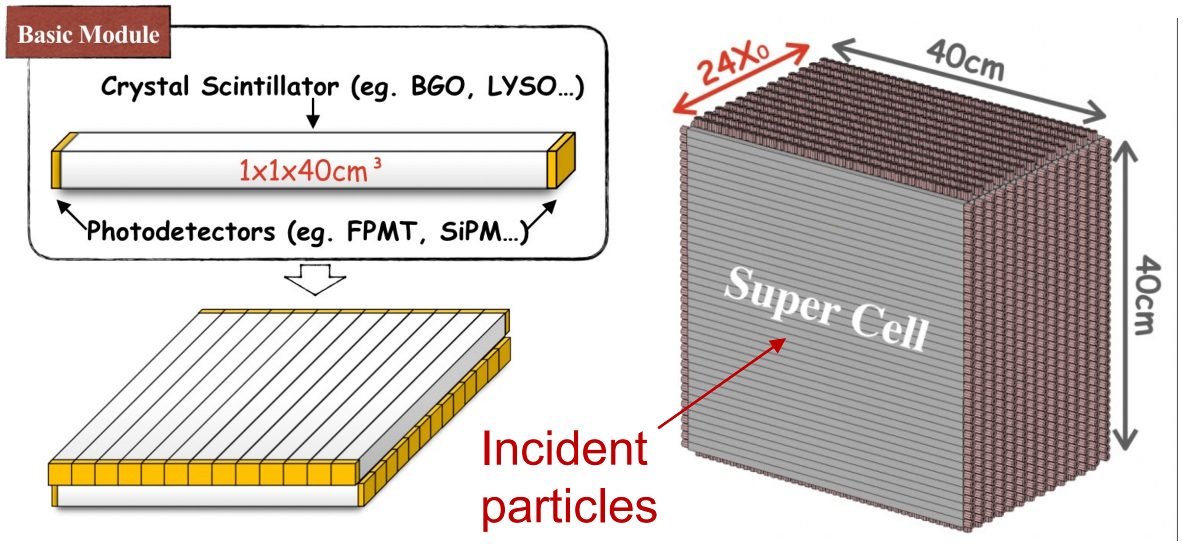
High-granularity crystal ECAL: 2 major designs in pursuit

Design 1



- Longitudinal segmentation
- Fine transverse segmentation
  - 1×1cm or 2×2cm cells
- Single-ended readout with SiPM
- Potentials with PFA

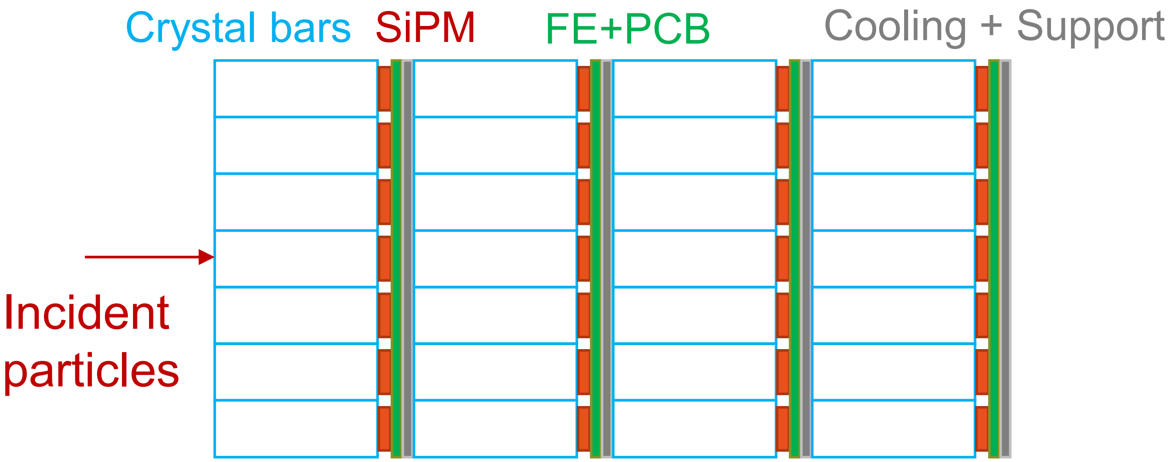
Design 2



- Long bars: 1×40cm, double-sided readout
  - Super cell: 40×40cm cube
- Crossed arrangement in adjacent layers
- Significant reduction of #channels
- Timing at two sides: positioning along bar

High-granularity crystal ECAL: 2 major designs in pursuit

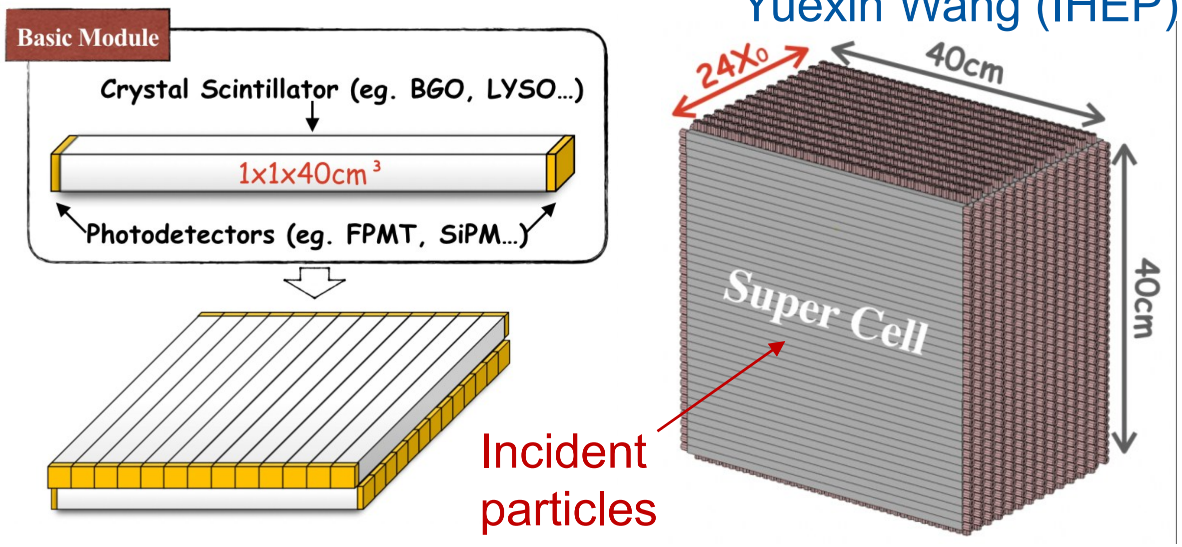
Design 1



- Design optimisations
  - Transverse: separation power
  - Longitudinal: leakage correction
- Neutral pion reconstruction (in plan)

Design 2

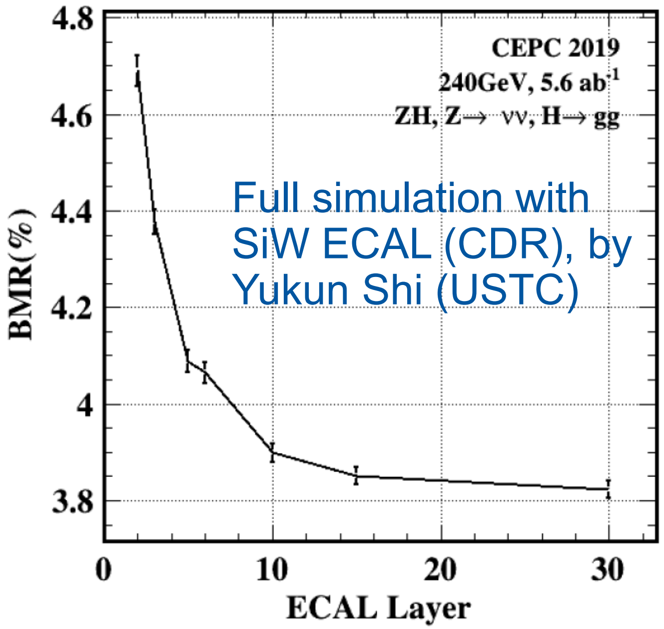
Details in the talk by Yuexin Wang (IHEP)



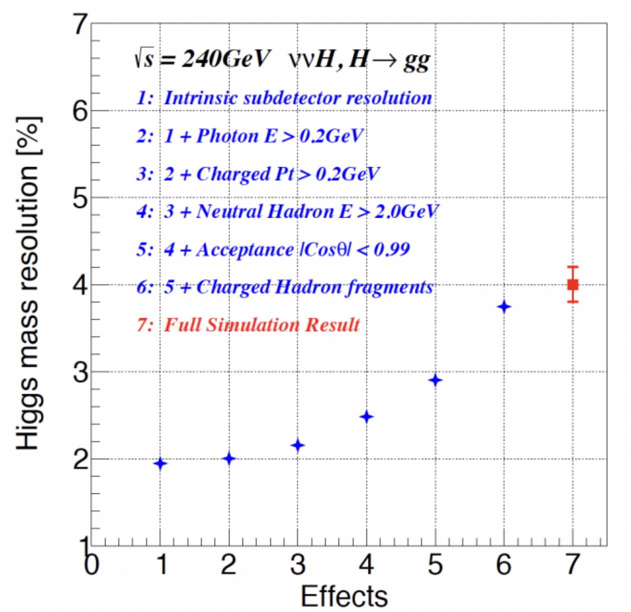
- Multiplicity of incident particles (jets)
  - Based on physics benchmarks
- Digitisation in each long bar
- Time stamps, #photons detected
- Event display and (pattern) reconstruction

Longitudinal segmentation optimisation

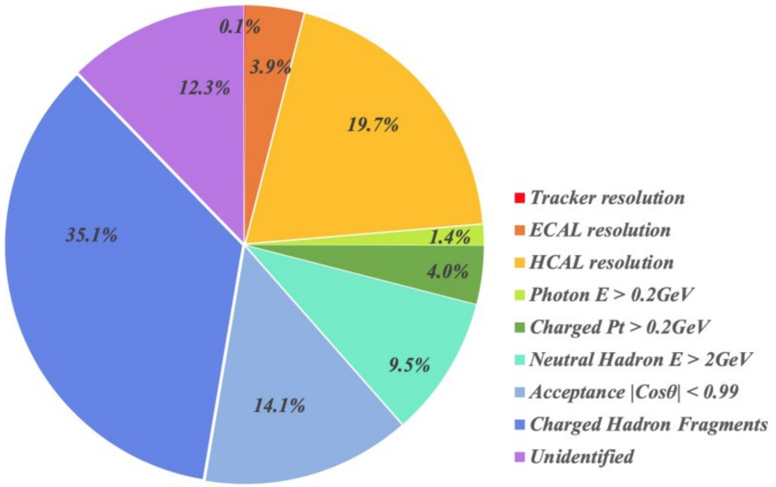
Boson Mass Resolution vs #Layer in ECAL



PFA Fast Simulation



Yuexin Wang (IHEP)

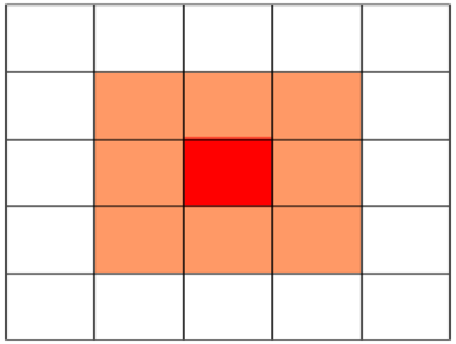


- Full simulation with SiW-ECAL via the benchmark Higgs to 2 gluons
  - 10 longitudinal layers or more in ECAL can help achieve better than 4% of BMR
  - Expect small impact from ECAL intrinsic energy resolution (PFA fast simulation)
- Guidance for the longitudinal segmentation
  - Will perform more benchmark studies for crystal ECAL in the CEPC detector simulation

Crystal transverse size optimisation

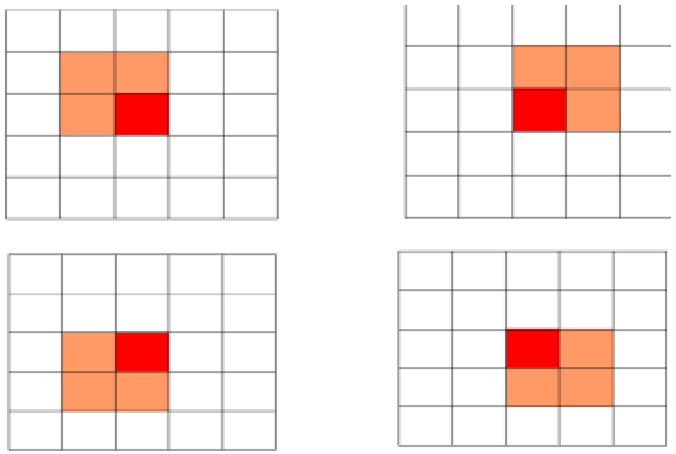
Details in the talk by
Chunxiu Liu (IHEP)

- Study of the separation performance of γ and merged π^0
  - Can not be distinguished in transverse shower profiles
- Energy-related variables defined for TMVA
  - S1/S4, S1/S9, S1/S25, S9/S25, S4/S9, F9, F16

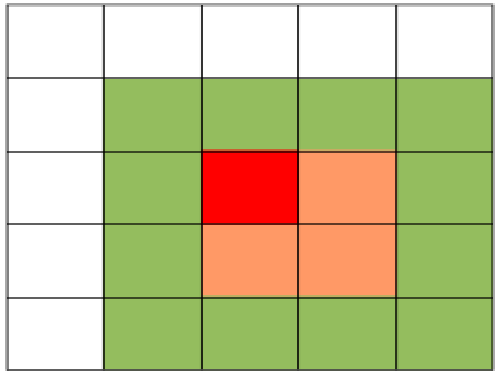


S1,S9,S25

$$F_9 = \frac{S9 - S1}{S9}$$



S4 the energy maximum
in the four 2x2 arrays



S16

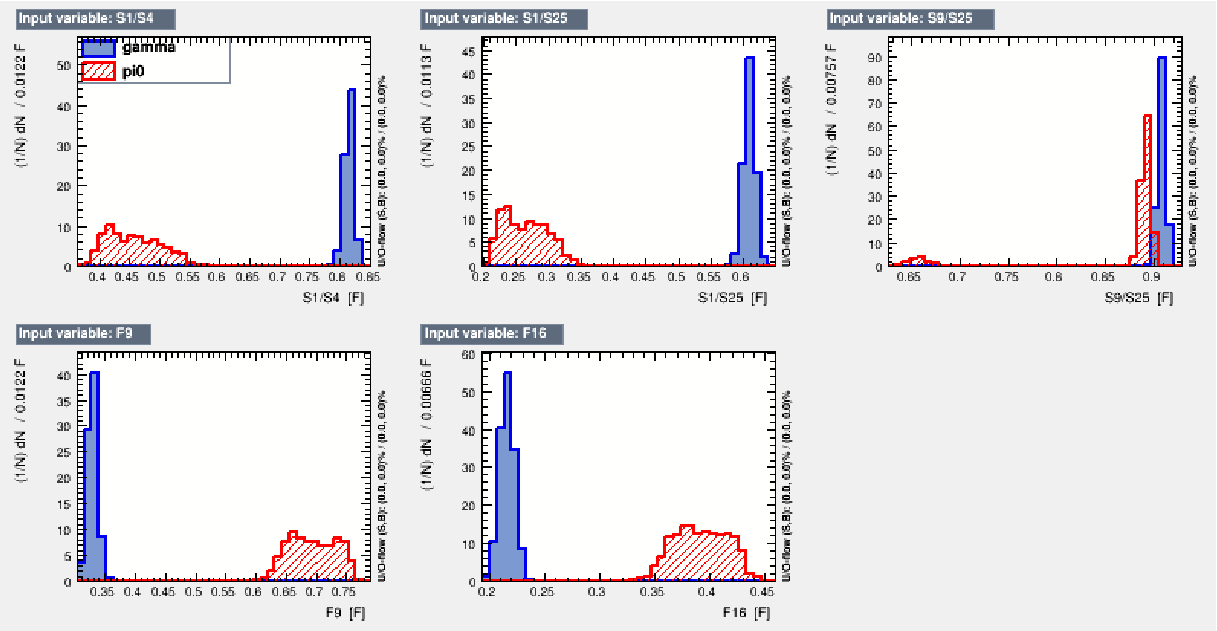
$$F_{16} = \frac{S16 - S4}{S16}$$

Crystal transverse size optimisation

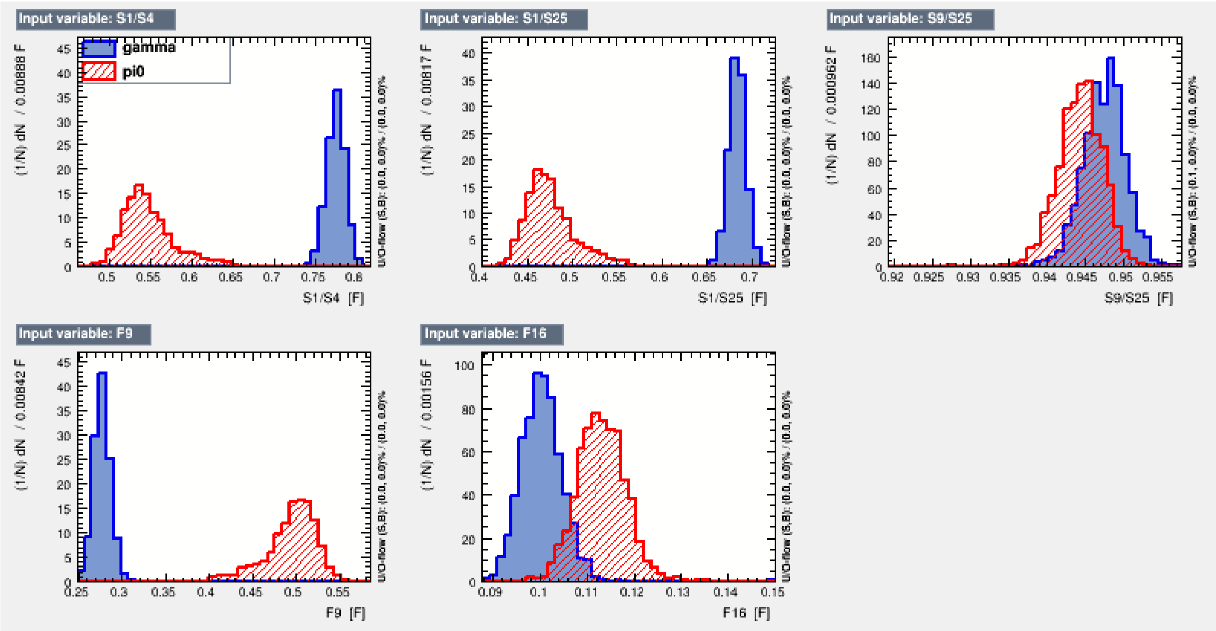
Details in the talk by
Chunxiu Liu (IHEP)

- Separation performance of the 40GeV γ and merged π^0

Transverse size 1x1cm2



Transverse size 2x2cm2



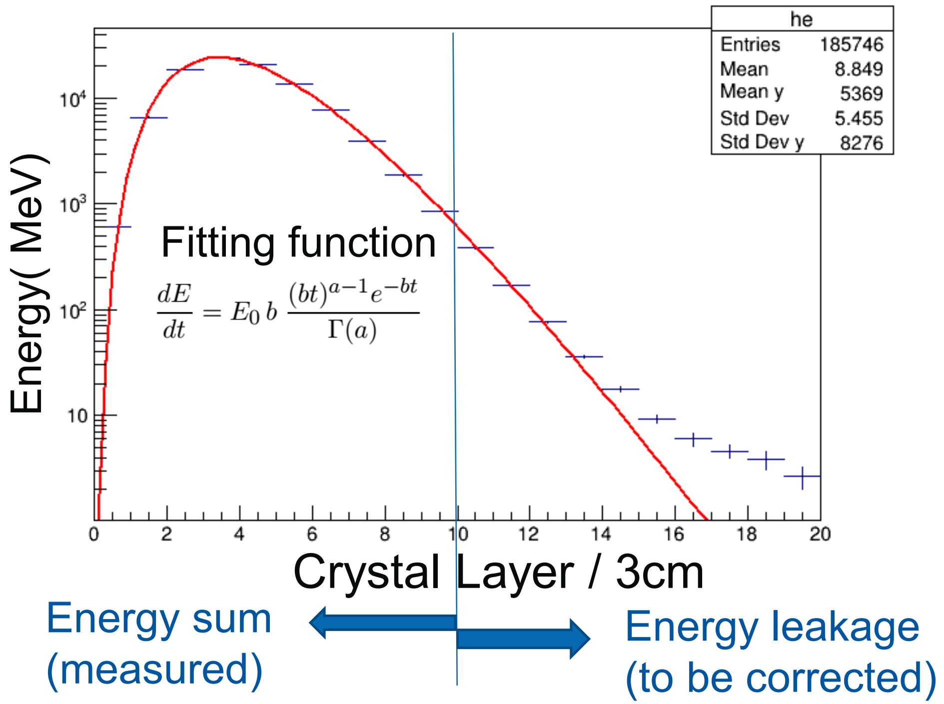
100% separation with most variables

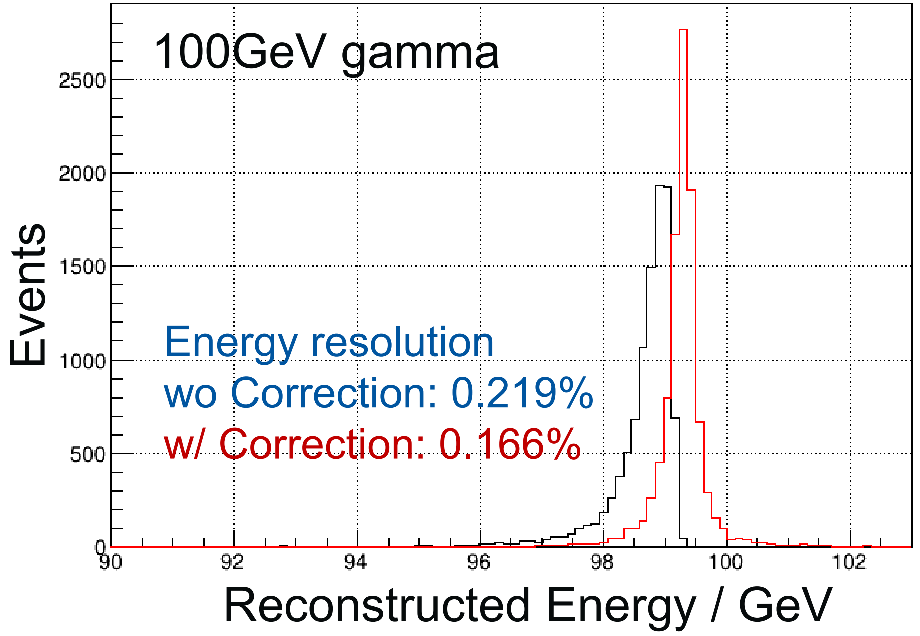
100% separation with variables like S1/S4, S1/S25 and F9

Crystal granularity optimisations

Details in the talk by Chunxiu Liu (IHEP)

- 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)
- Longitudinal segmentation: impact from inter-layer services (next pages)

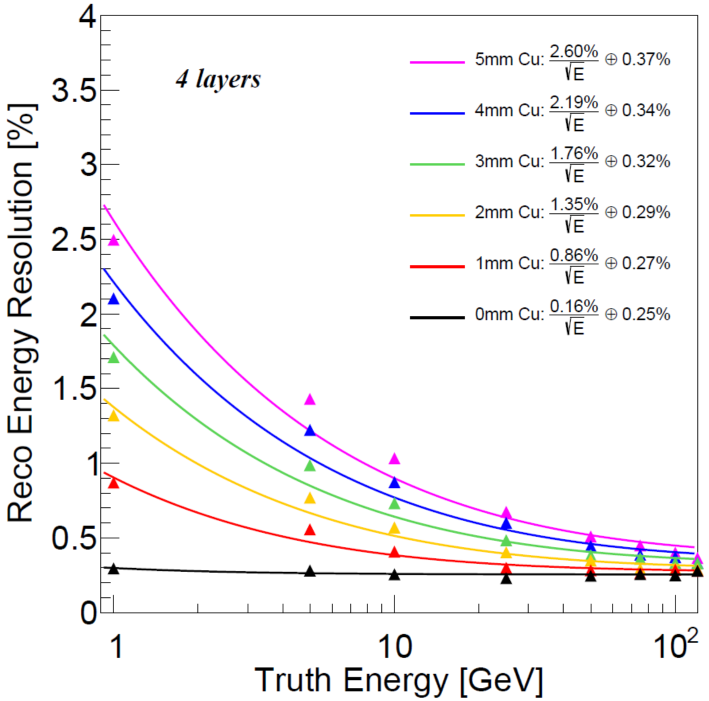


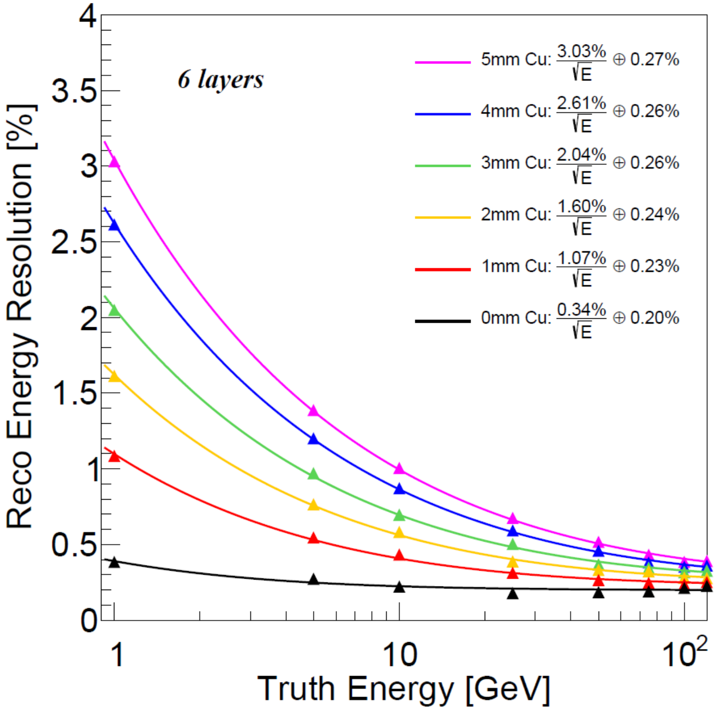


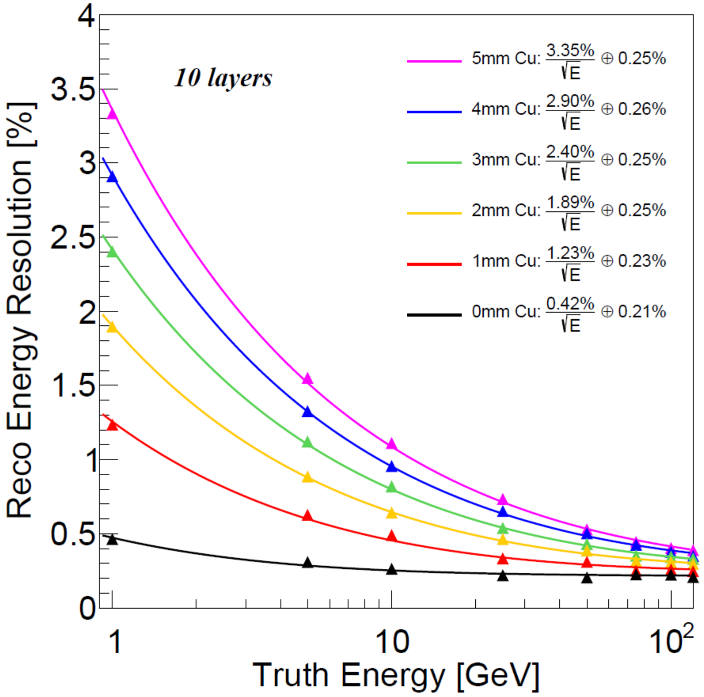
30cm long BGO (~27X0), 10 layers, 3cm per layer

Longitudinal segmentation: impact from services

- Energy resolution with different numbers of sampling layers
  - 24X0 total depth for crystals (fixed) in all scenarios
  - Used copper to model the inter-layer services (e.g. cooling)
    - Light materials will be considered for realistic cooling designs: Al, carbon-fibre…



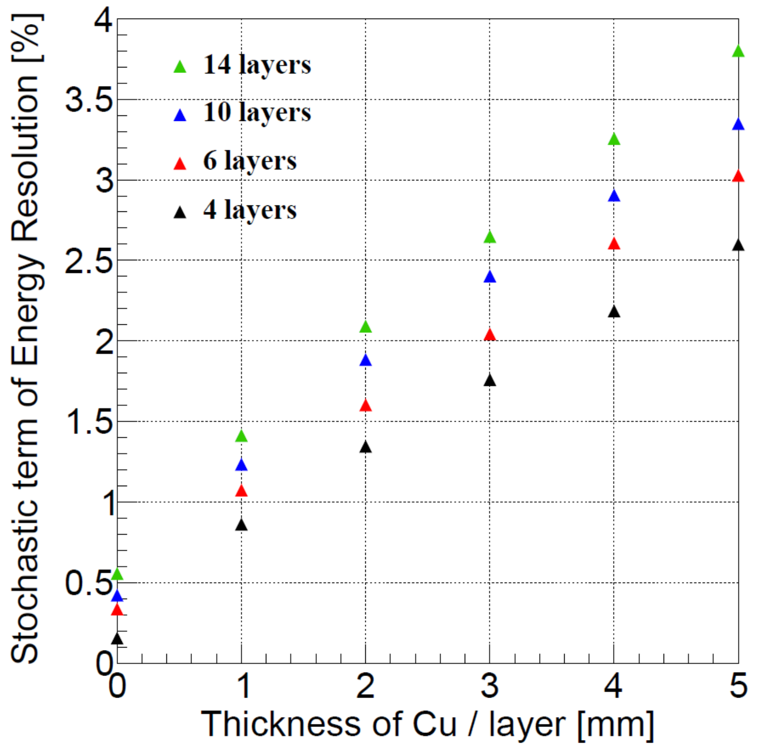


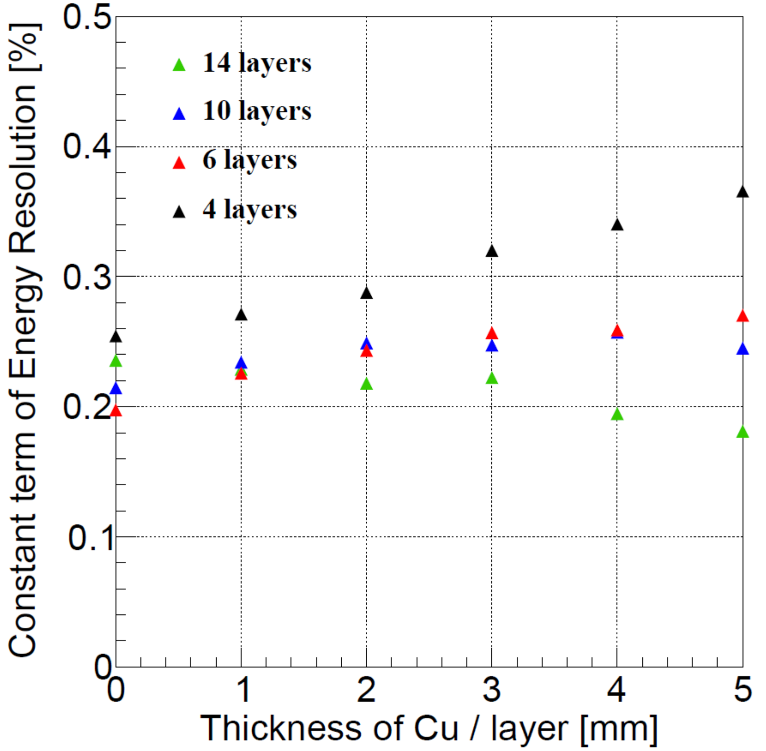


Note: digitization not implemented yet; so energy fluctuations and leakages dominate

Longitudinal segmentation: impact from services

- Stochastic and constant terms (extracted from the previous page)
  - Varying thickness of dead materials between layers (services as cooling, cabling, etc.)
  - Effects digitisation in the next page (photon statistics and electronics resolution)



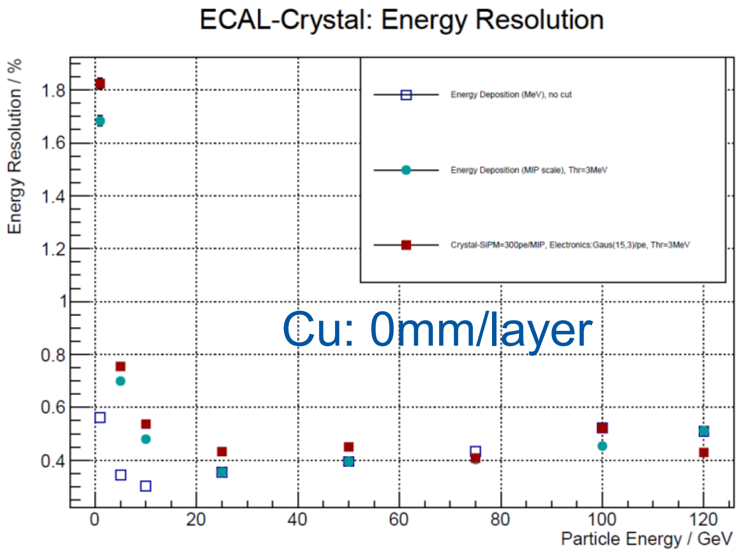


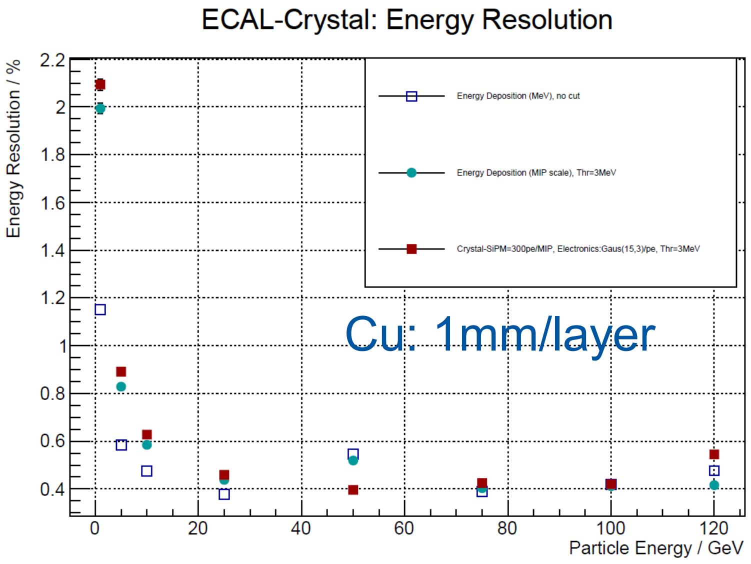
Note: digitization not implemented yet; so energy fluctuations (and leakages) dominate

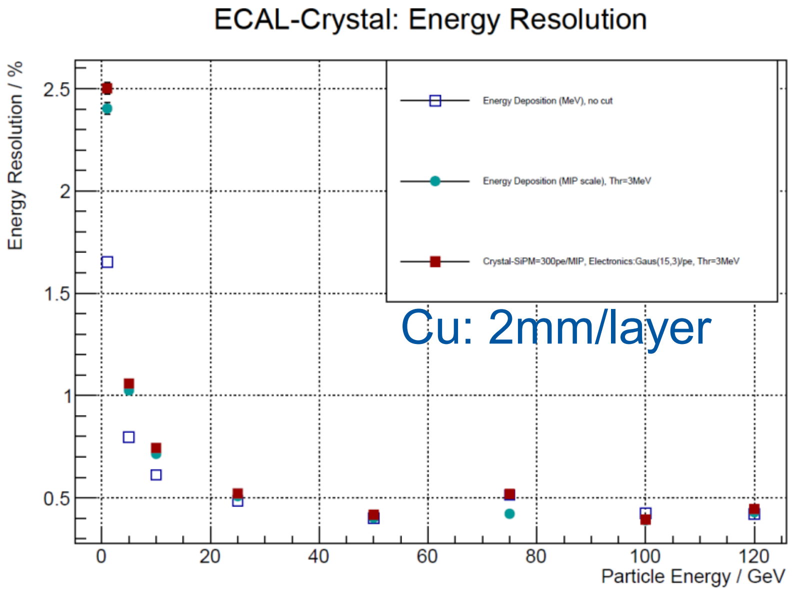
Longitudinal segmentation: with digitisation

- Digitisation tool
  - Photon statistics (crystal and SiPM): reasonably high light yield
  - Electronics resolution for single photons: taken from the existing ASIC

Total 6 Longitudinal Layers: 4X0 crystal/layer







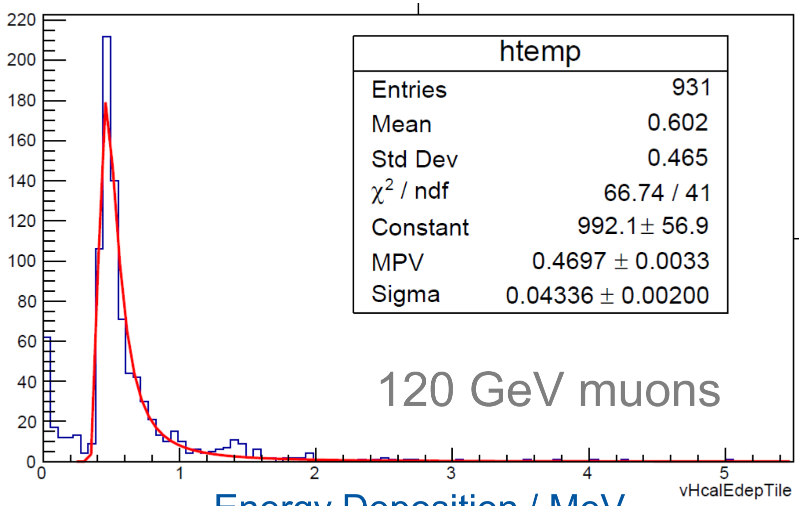
Note: for copper, X0=14.36mm, 1mm Cu = 0.07X0; for Aluminum, 0.07X0 = 6.2mm (X0=88.97mm)

- 0.84X0 copper in total will degrade the stochastic term to ~2.5%

Digitizer in simulation

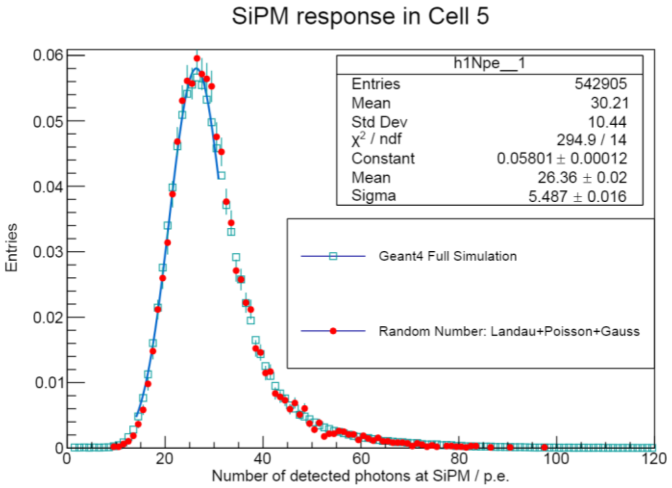
Geant4 version 10.5.0

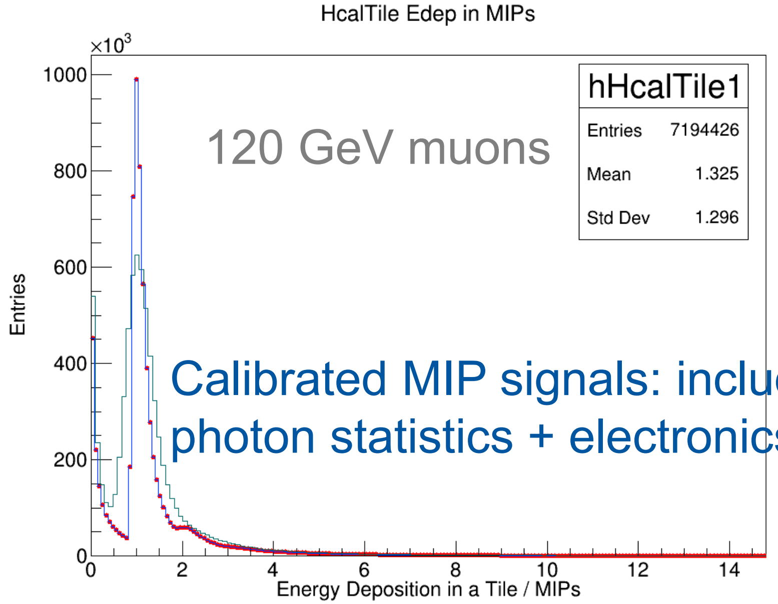
Energy Deposition in a scintillator tile



Energy Deposition / MeV

Digitizer can reproduce G4 full simulation with optical photons





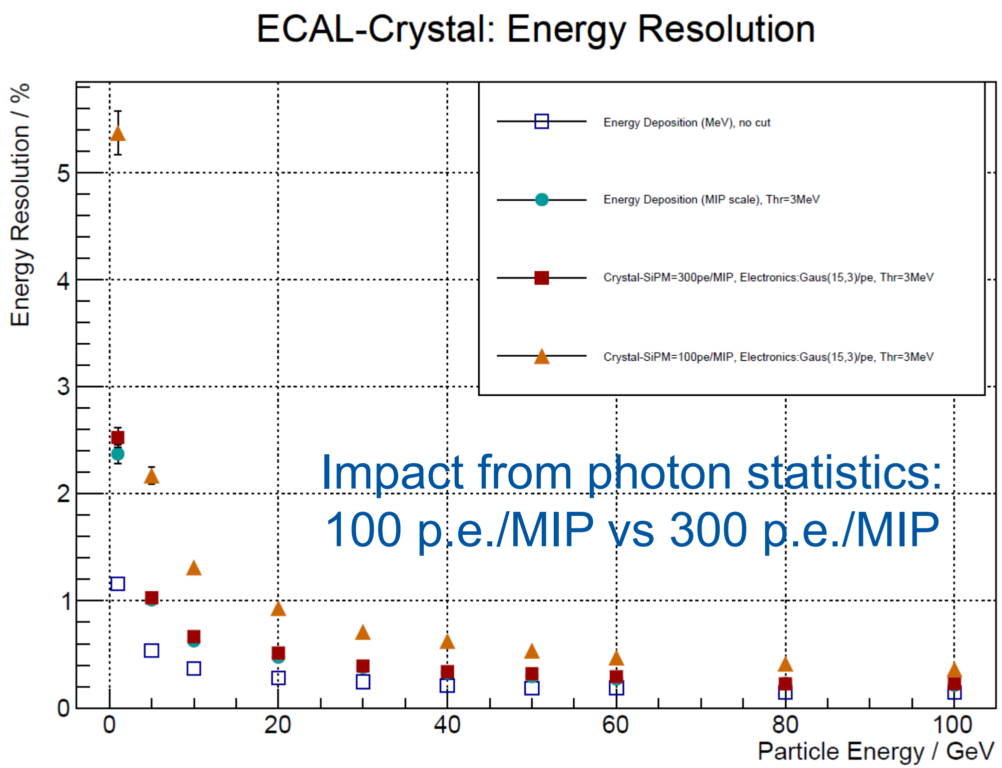
Calibrated MIP signals: including photon statistics + electronics

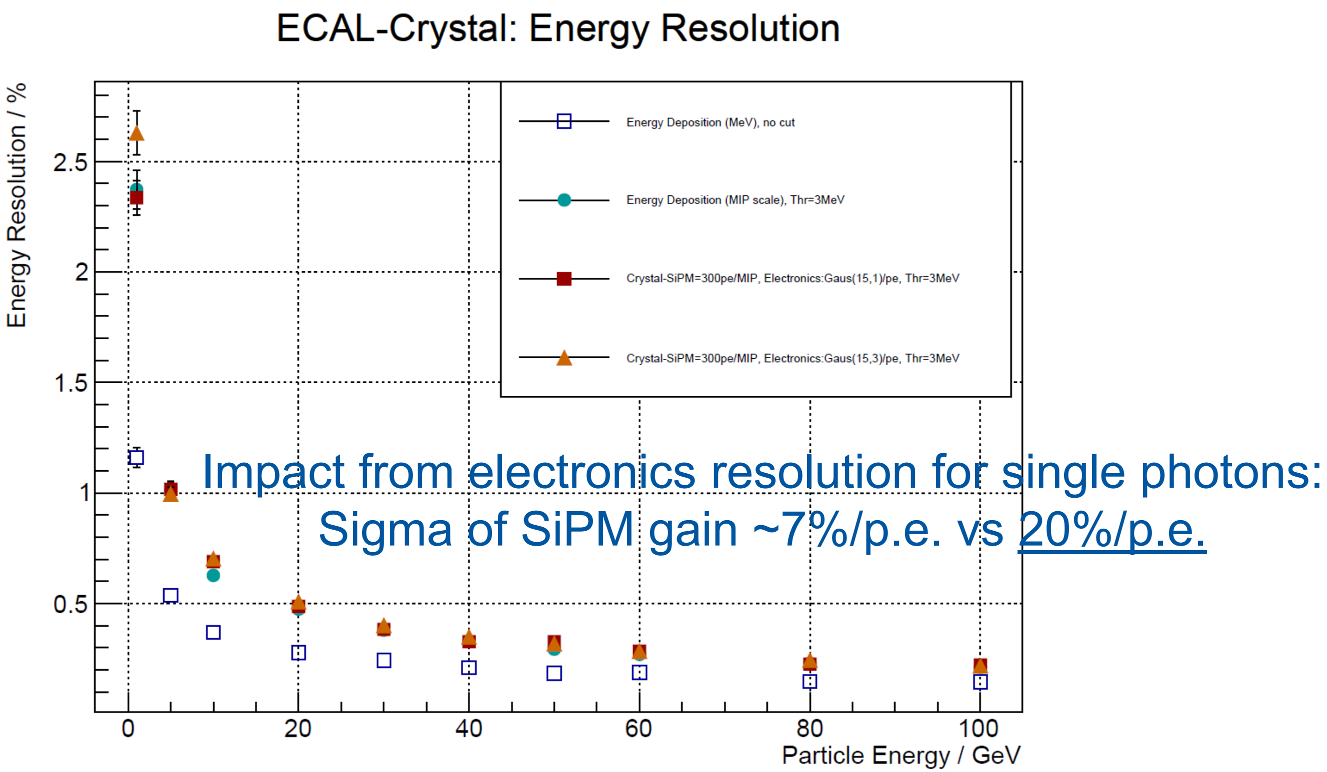
- Geant4 hit (energy deposition) → ADC signal in electronics (charge)
- Realistic factors that influence energy resolution
  - Photon statistics: #p.e./MIP, guided by Geant4 full simulation (optical photons)
  - Electronics resolution for single photons: #ADCs/p.e.

Digitizer in simulation for crystal ECAL

Geant4 version 10.5.0

MC samples: electrons





- Quantitative studies for the impacts of photostatistics and electronics
  - Stochastic terms: ~5% for lower light yield (e.g. PWO), ~2% for higher light yield (e.g. BGO)
  - Negligible impact from single photon resolution at energy regions > 5GeV

High-granularity crystal ECAL: technical part

- Detector unit: crystal options (BGO, PWO, etc.), SiPMs (HPK, NDL, etc.)
- Front-end electronics
  - Cornerstone for successful instrumentation of high-granularity calorimetry: e.g. 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 and supporting mechanics design
  - Power consumption (solid inputs from electronics)
  - Impacts of cooling structure to performance
- Calibration schemes and monitoring systems
  - For SiPMs, crystals and ASICs in the long term
- System integration: scalable detector design (modules), mass assembly, QA/QC

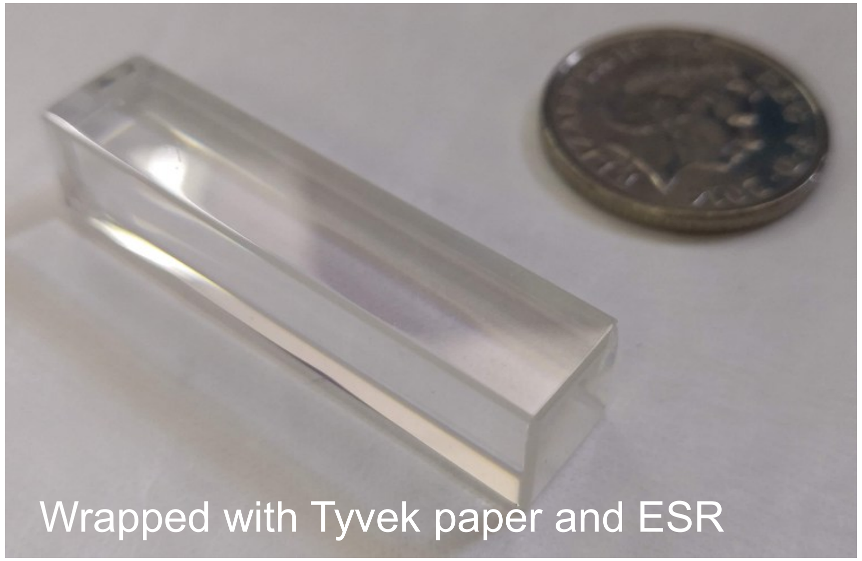
Crystal options

	BGO	$PbWO_4$
Density (g/cm^3)	7.13	8.3
Radiation Length X_0 (cm)	1.12	0.89
Moliere Radius R_M (cm)	2.259	1.959-2.19
Minimum ionization (MeV/cm)	8.918	10.2
Refractive Index	2.15	2.20
Decay Time (ns)	fast 60 slow 300	fast <10 slow 30
Light Yield (photons/MeV)	8000-12000	100-150

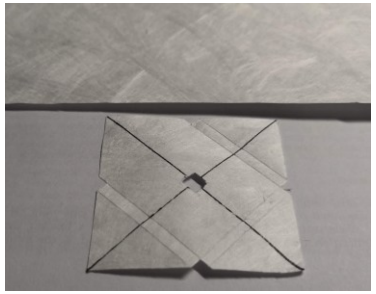
- PWO
  - Pros
    - Compact (smallest X0, cost saving), fast scintillation (timing)
    - Dynamic range suitable for the linear region of SiPM (high-density pixels)
  - Cons: low intrinsic light yield: ~100 photons/MeV
- BGO
  - Pros: high intrinsic light yield: 8k~12k photons/MeV, therefore high sensitivity to low energy particles
  - Cons
    - Less compact than PWO, larger volume for the same depth (e.g. 24X0)
    - Much slower scintillation → other techniques (e.g. TOT) considered to enlarge the dynamic range (studies in the following pages)

Studies with PWO crystal bar and NDL-SiPM

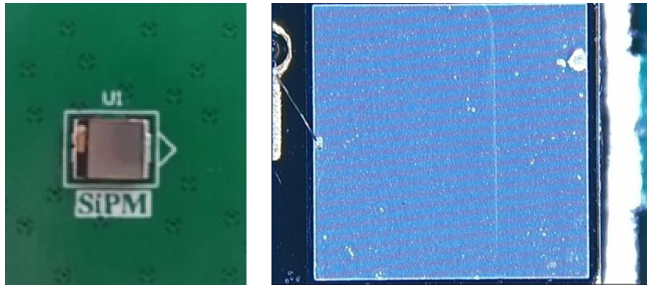
- Cosmic ray tests with a PWO crystal
  - Read out with a 3x3mm² SiPM (90k pixels)
  - SiPM designed by Novel Device Lab (NDL) in Bejiing Normal University



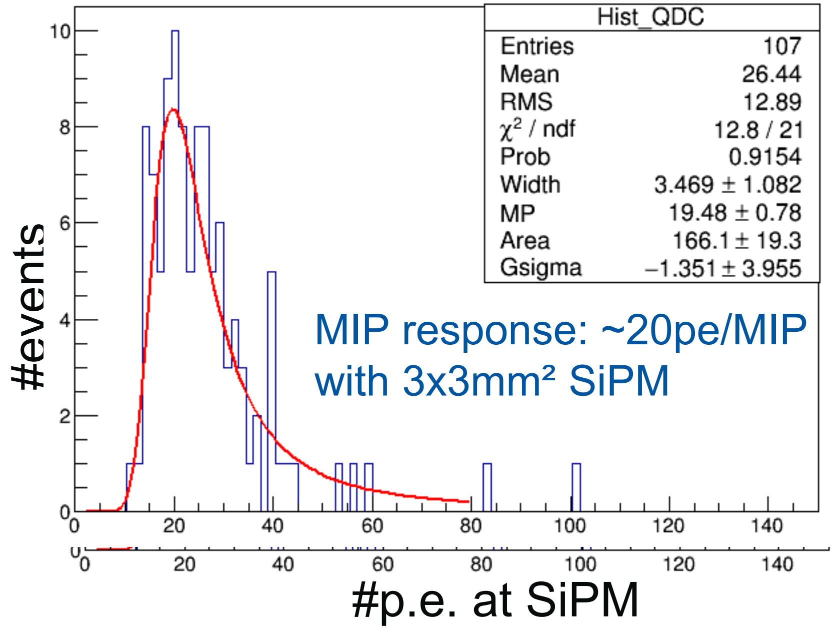
PbWO crystal (produced by SIC), 10x10x45 mm³



Example of pre-cut Tyvek paper

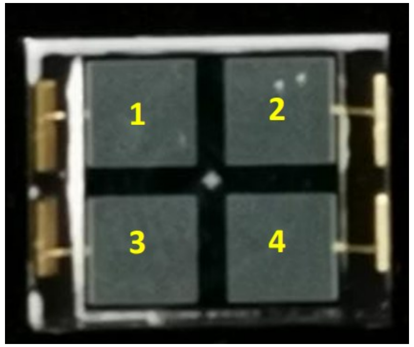


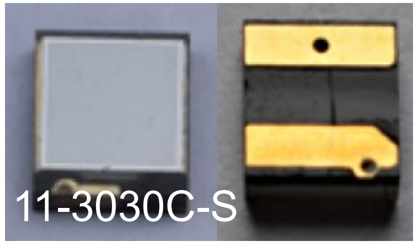
NDL-SiPM 3x3mm² with 10um pixels



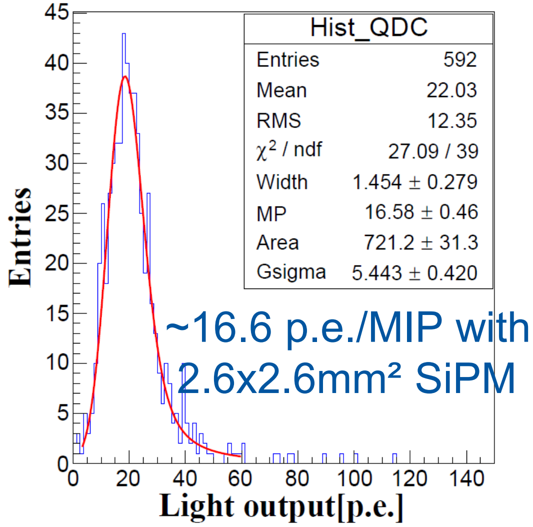
Note: a larger SiPM (e.g. 6x6mm²) can be used for better light collection efficiency

First studies on new-generation of NDL-SiPM





NDL-SiPMs Parameters	11-3030C-S	Latest prototype NDL 22-1313-15S
Breakdown Voltage	27.5 V	19 V
Pixel Pitch	10 μm	15 μm
Peak PDE	31% @420nm	45% @400nm
Pixels	90k	7.4k
Sensitive Area	3×3 mm²	2.6×2.6mm²
MIP response with 10x10x45 mm³ PWO bar	19.5 p.e./MIP	16.6 p.e./MIP



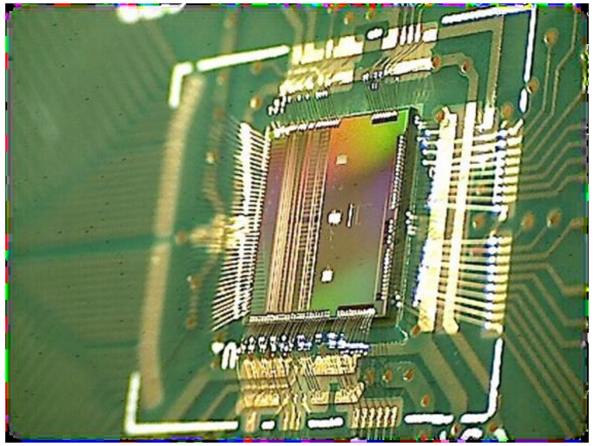
- Tests made for a NDL-SiPM prototype of the latest generation
  - Many improvements: lower dark count noise, higher PDE,… (highly desirable)
- Foresee further tests with NDL-SiPMs that are better suited for crystal readout
  - High density: 3×3 mm², 6μm, 245k pixels, PDE~30% (e.g. for BGO)
  - Large area: 6×6 mm², 15μm, 170k pixels, PDE~40% (e.g. for PWO)

Front-end electronics for SiPM readout

U. Heidelberg, IHEP

- ASIC "KLauS": developed within the CALICE collaboration
  - Designed by U. Heidelberg (KIP), originally for CALICE AHCAL (scintillator-SiPM)
  - Promising candidate: 36-channel, low-power
    - 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

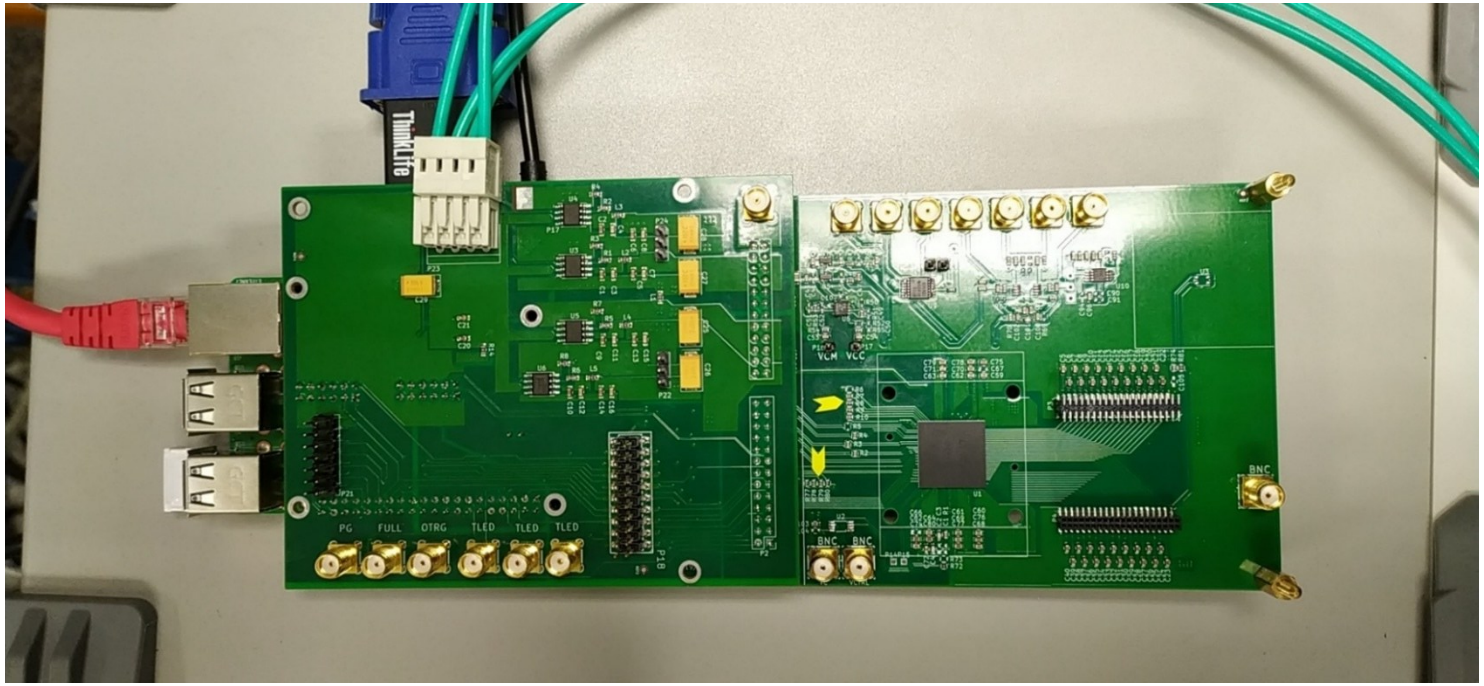


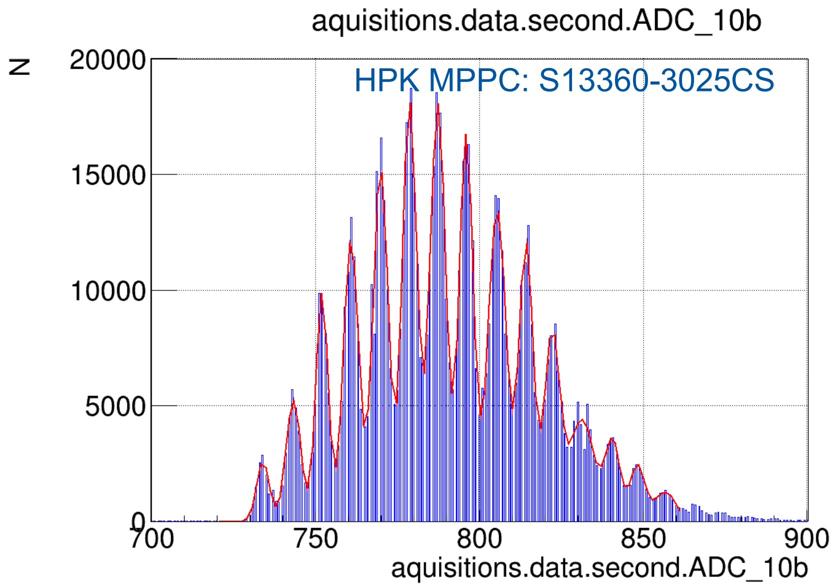
Klaus5 in BGA

Front-end electronics for SiPM readout

U. Heidelberg, IHEP

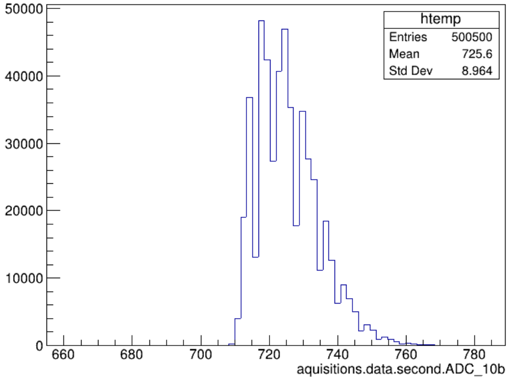
- Test boards for KLauS-5 in BGA
  - Boards produced after several iterations of designs/debugging
  - Boards tested first at Heidelberg and later at IHEP
  - Synergies with the JUNO-TAO team





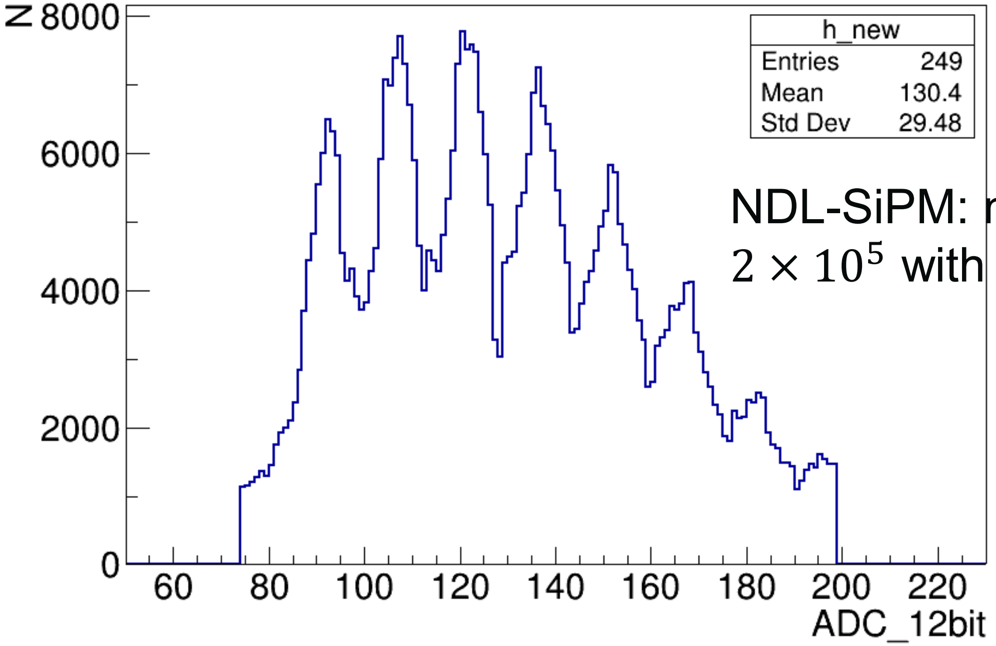
Klaus5 tests with NDL-SiPM

- NDL-SiPM features: small pixel pitch (10μm or smaller), high PDE
  - Requires high S/N ratio in electronics to resolve single photons (small gain)
- Klaus5 proved to be able to resolve the single photons (32fC/p.e.)
  - Benefits from its high S/N ratio and high resolution



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

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

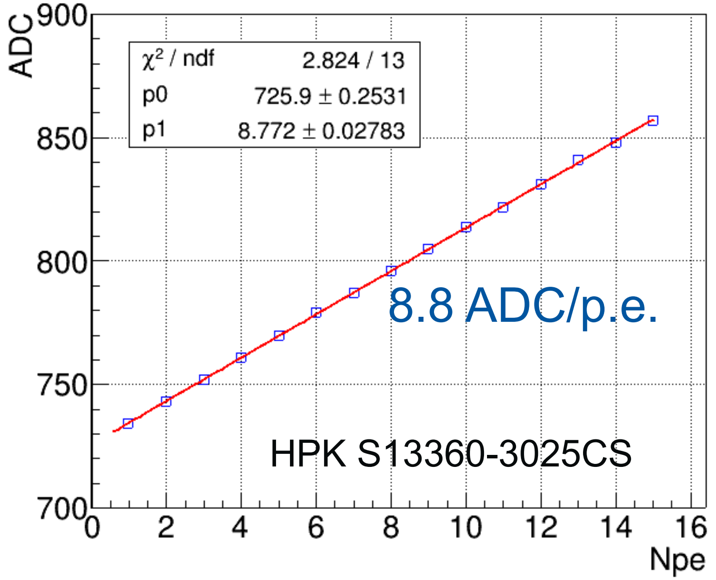


NDL-SiPM: nominal gain 2×10^5 with 10μm pixels

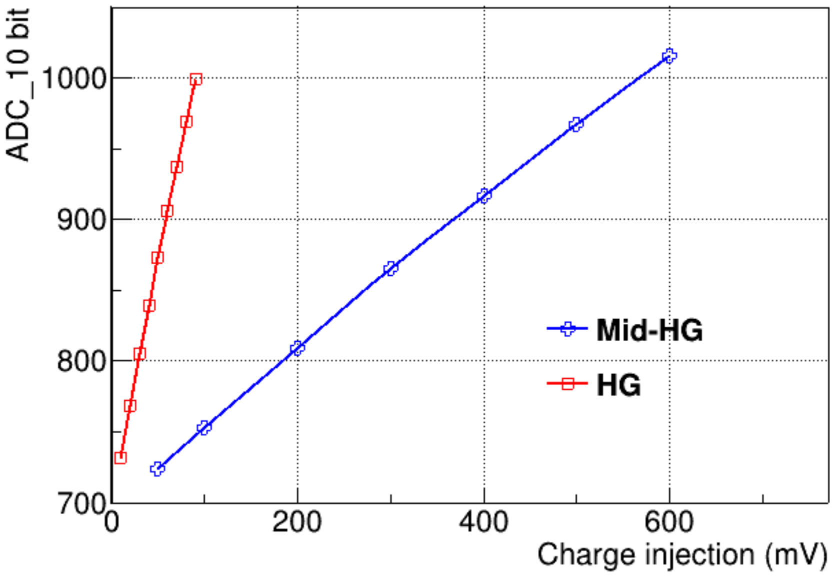
Klaus5: first tests with SiPM and light sources

- LED for SiPM gain calibration: done for various SiPMs
- Laser for the first test of dynamic range: qualitative results

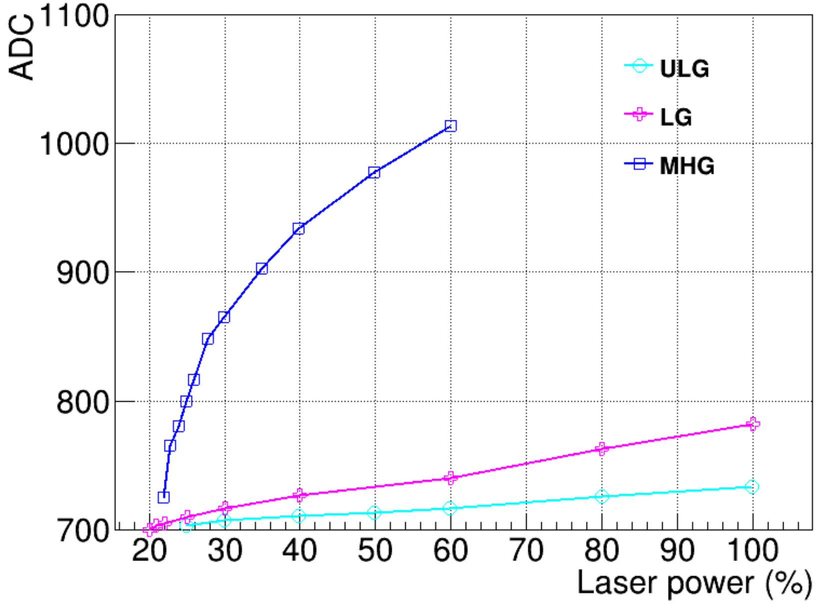
LED calibration in High Gain



Charge injection with HG and Mid-HG



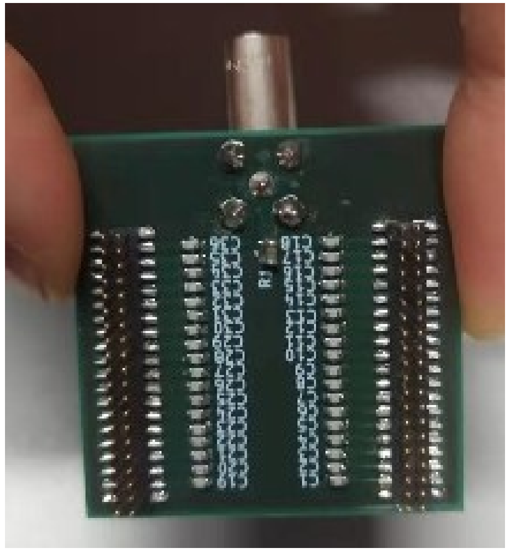
Laser tests in Low Gain modes



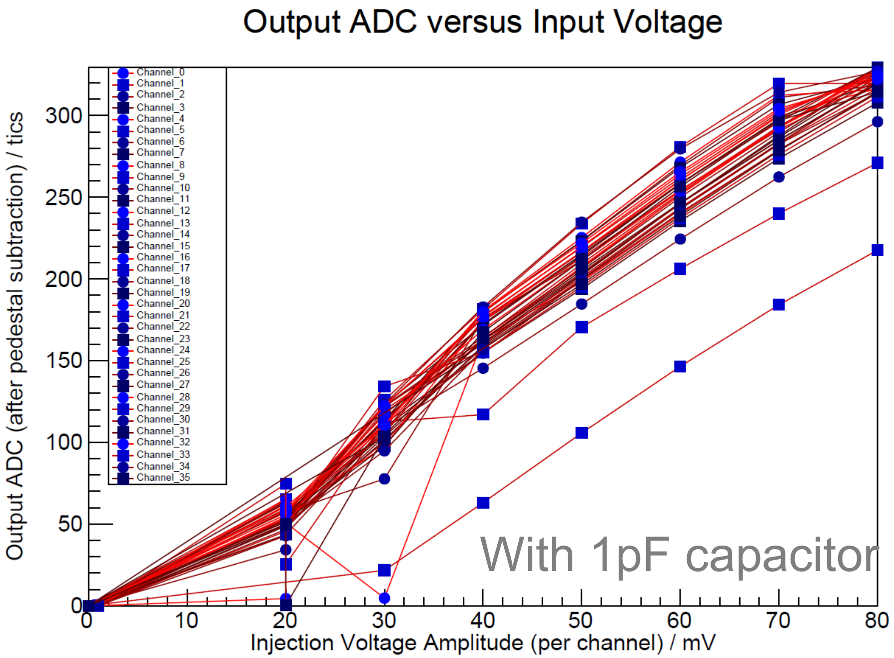
- High Gain modes: HG (1:1), Mid-HG (1:7)
- Low Gain modes: LG (1:40), Ultra-LG (1:100)

Klaus5 tests with charge injection

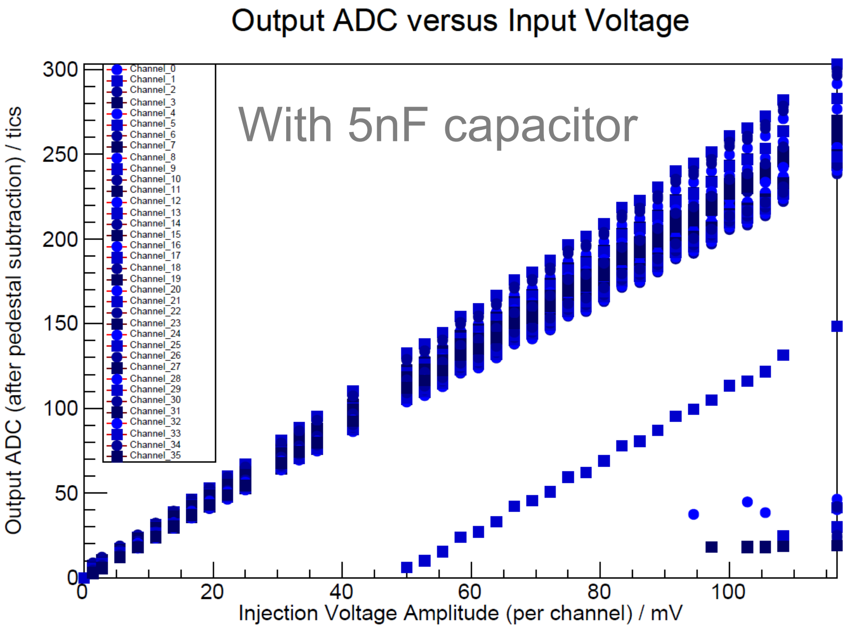
- Testing of all 36 channels
  - Different working modes (high gain and low gain)
  - Dynamic range: ~550pC as the maximum charge (preliminary results)



Adapter PCB to inject charge pulses injection to 36 channels



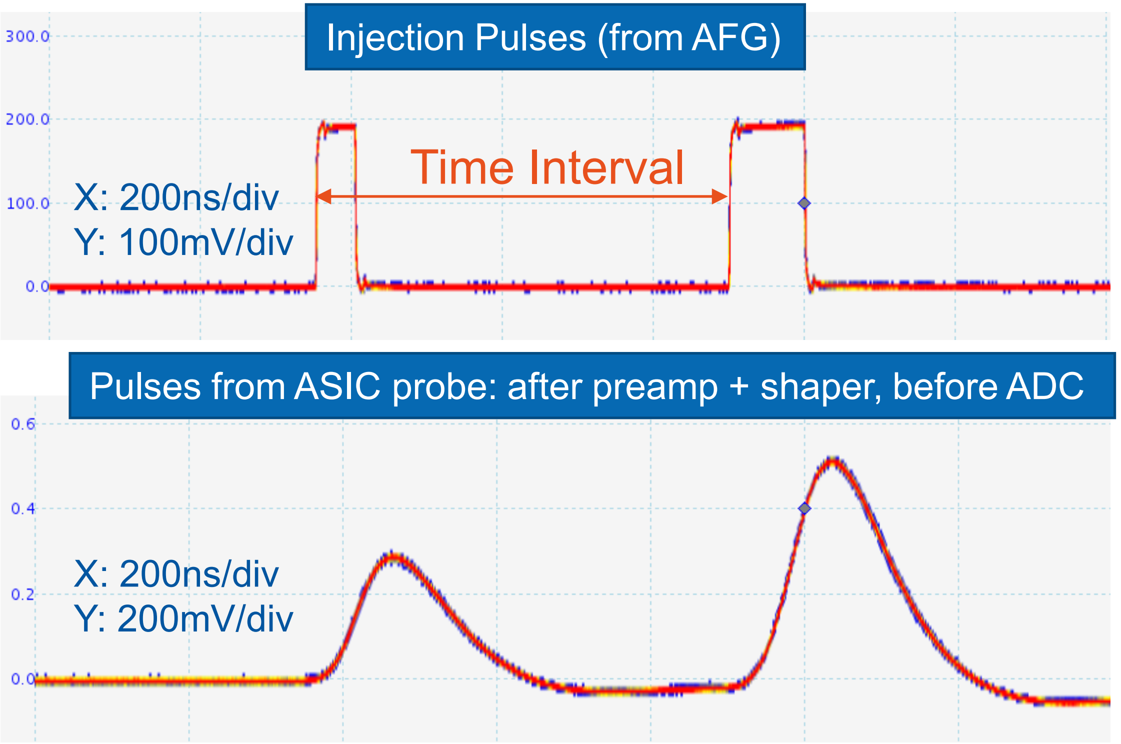
ADC after pedestal subtraction (mid High Gain mode)

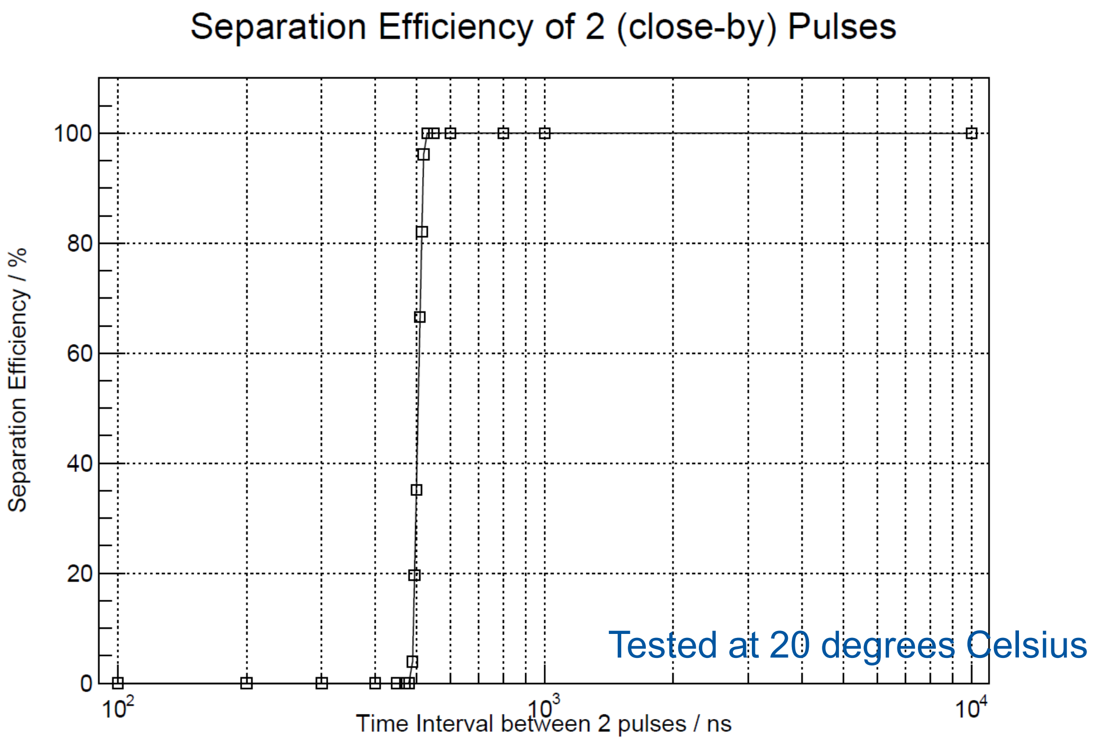


ADC after pedestal subtraction (ultra Low Gain mode)

Klaus5: dead time measurements

Similar results at arXiv:2005.08745

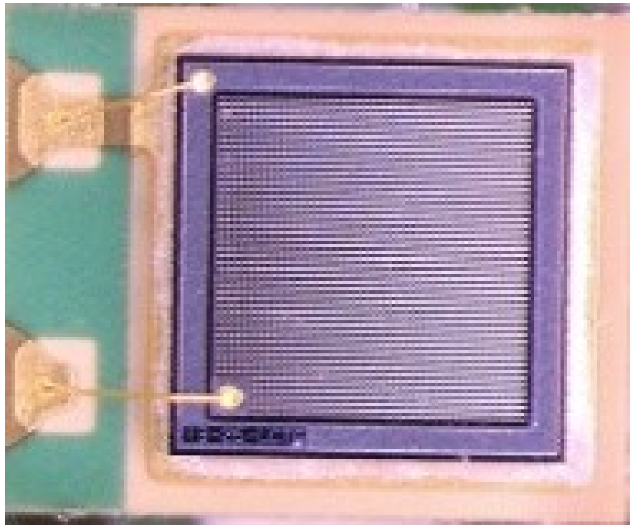


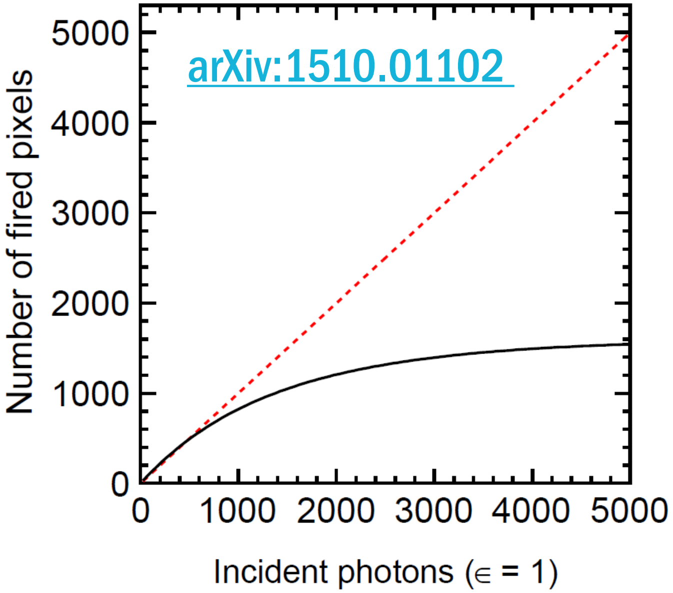


- Varying time interval between 2 injection pulses: 100ns - 10μs
- When time interval > 500ns, 100% efficiency of separating the two pulses
  - Promising feature for 100% duty cycle at circular colliders
  - Tests were made for a single channel
  - 36 channels: bottleneck of data transmission speed in DAQ; need to figure out a solution

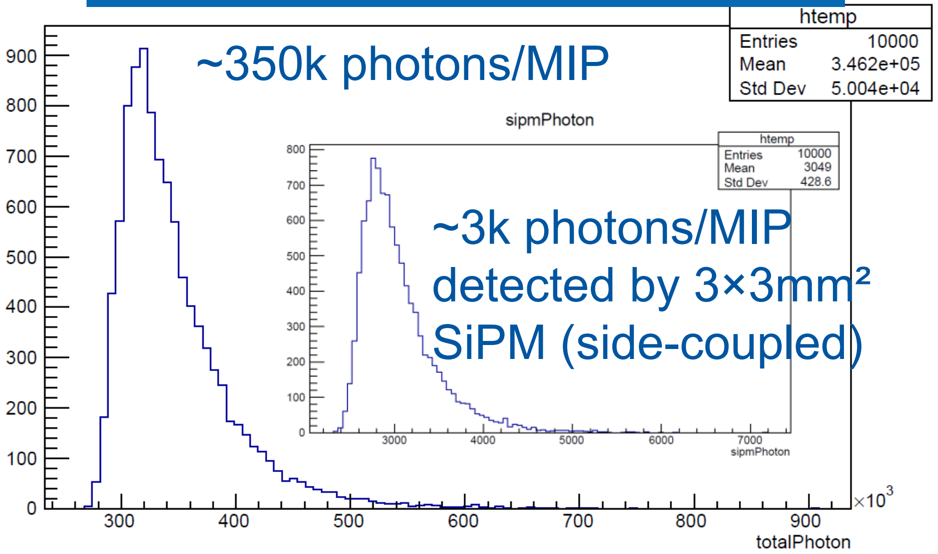
Crystal cells: dynamic range

- 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





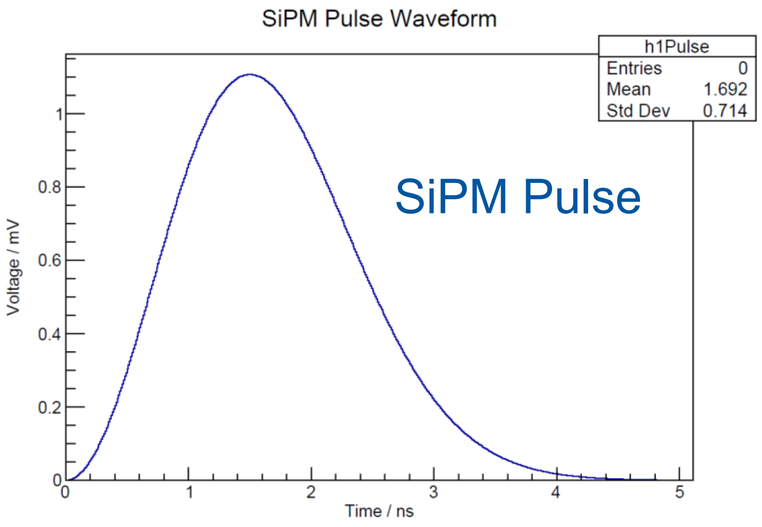
Geant4 simulation of BGO crystal



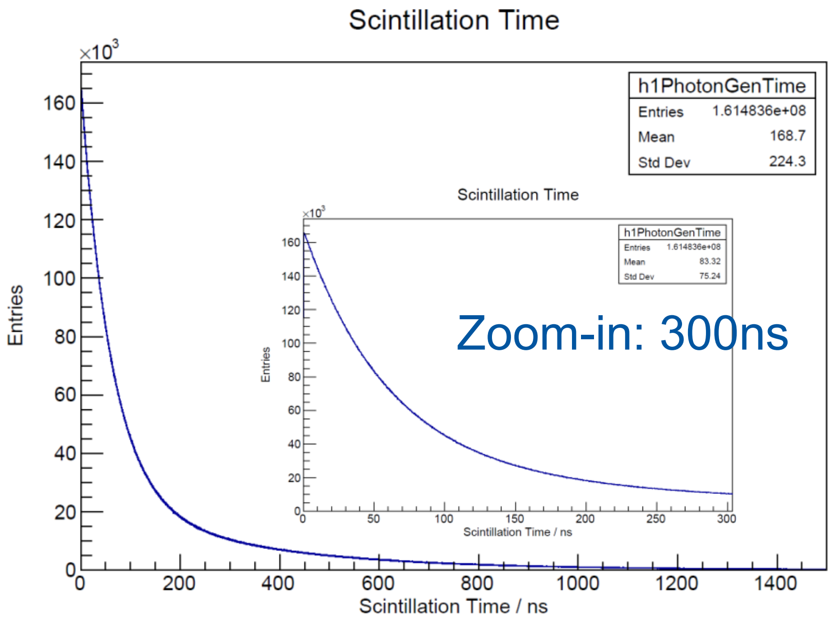
~40 MeV energy deposition for 1 GeV muons passing through a 45 mm crystal bar (BGO)

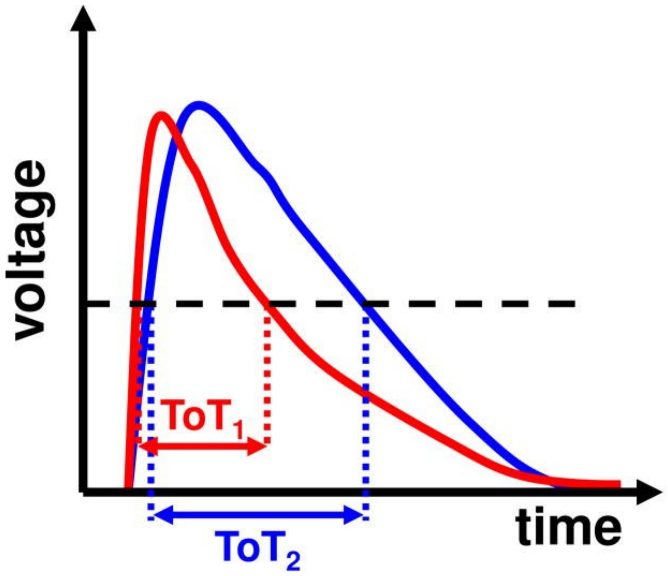
Crystal cells: dynamic range

- 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

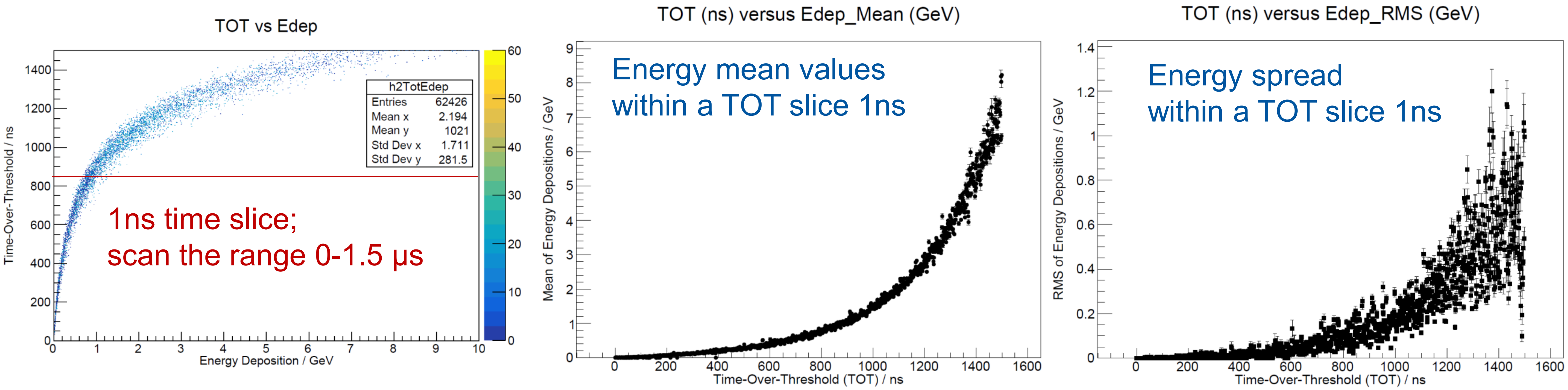




Computing intensive for the simulation (>1M photons); techniques developed to fasten the procedure

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
  - Future studies: impact from TOT threshold, design with multiple thresholds



Summary

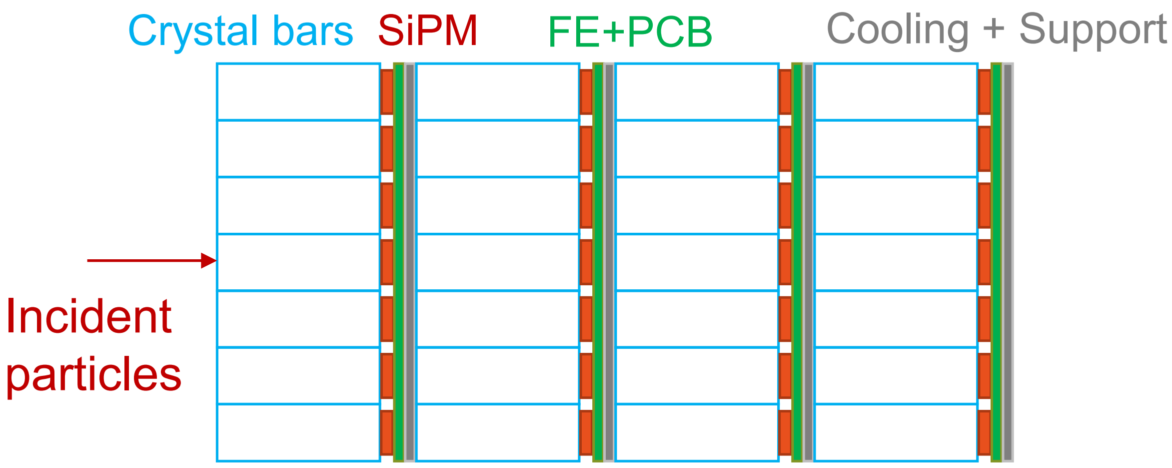
- High-granularity crystal ECAL
  - Aim to keep optimal energy resolution and PFA capability
  - Key issues for optimization and technical challenges (partially) identified
    - Needs further discussions and iterations
  - Steady R&D progress
    - Optimisation studies: longitudinal depth and segmentation, transverse
    - Technical developments:
      - SiPMs and crystals
      - Characterisations of SiPM-dedicated low-power readout ASIC (within CALICE)
      - Dynamic range: TOT technique
- Welcome broader collaborations
  - Early R&D stage, many open issues

Thank you!

Backup slides

Considerations on detector layouts

Layout 1: same module for each layer



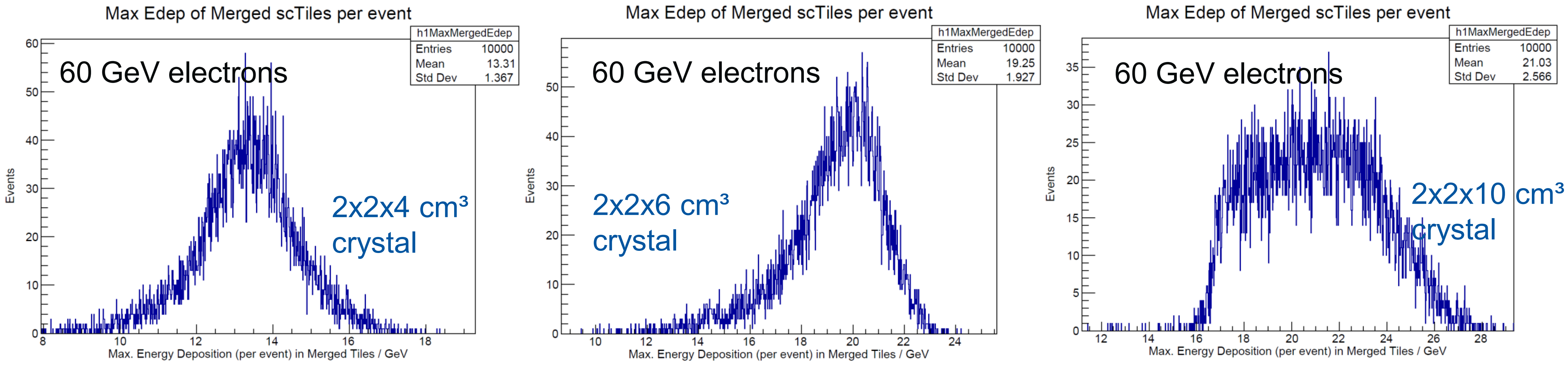
- Pros
  - Modular design
  - Uniform structure (easy calibration)
- Cons
  - Material budgets (cooling, mechanics)

Layout 2: every two layers share the same cooling service and mechanics

- Pros
  - Save material budget (e.g. a factor of two)
- Cons
  - Non-uniform sampling structure: will need specific considerations for calibration

Dynamic range: simulation with high-energy electrons

- Maximum energy deposition per cell
  - Depends on the crystal segmentation configurations
  - Provide inputs for the SiPM and its readout electronics

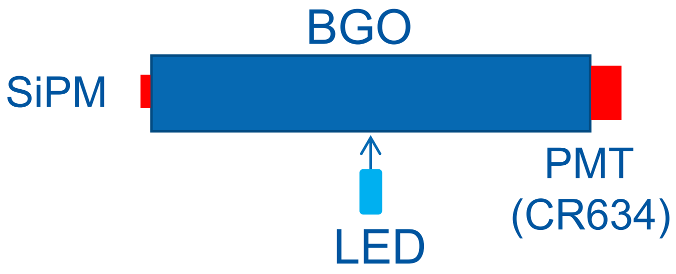


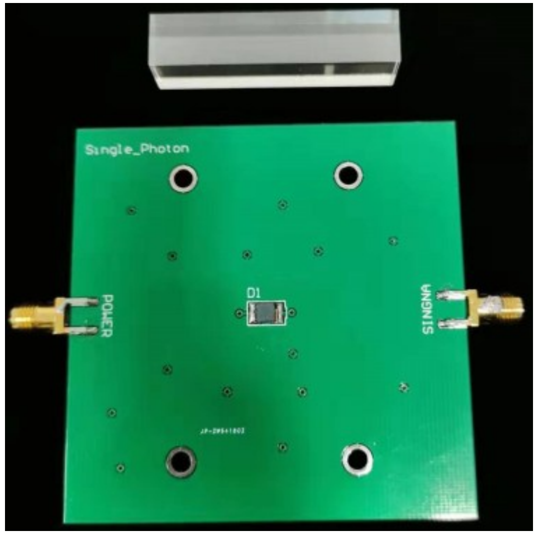
~13 GeV/cell ~19 GeV/cell ~21 GeV/cell

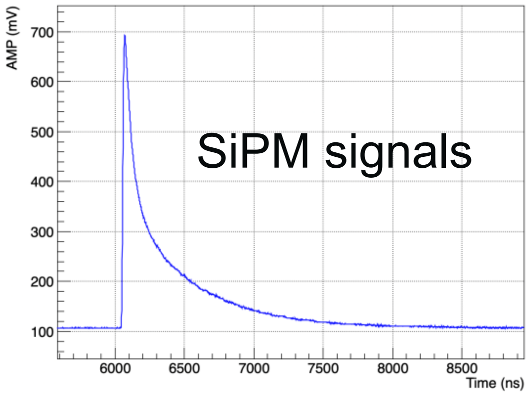
Dynamic range: TOT measurements

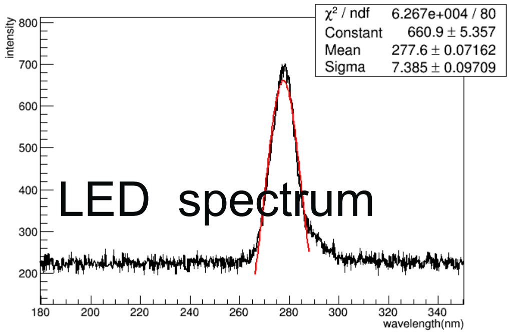
Zhigang Wang (IHEP)

- First TOT tests with UV-LED for BGO-SiPM readout
  - Preliminary: a few percent resolution achieved in the range 1-350 MIPs









Use UV light to excite BGO

Further detailed analysis and upgrade of the setup will be performed in the future.