3D Crystal Calorimeter for CEPC: R&D status

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on behalf of the CEPC Calorimetry Working Group

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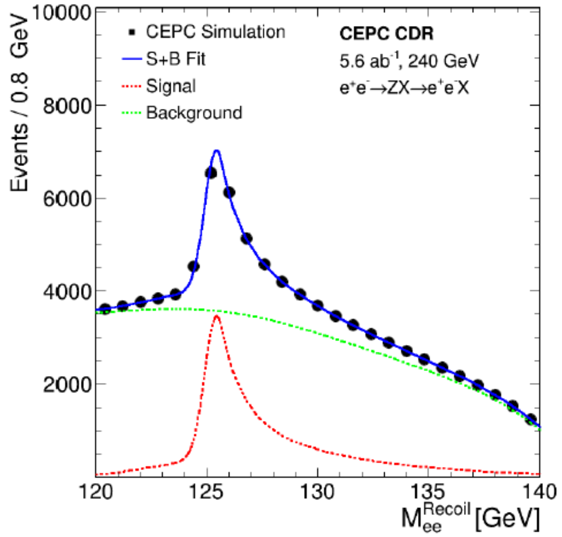
Motivations

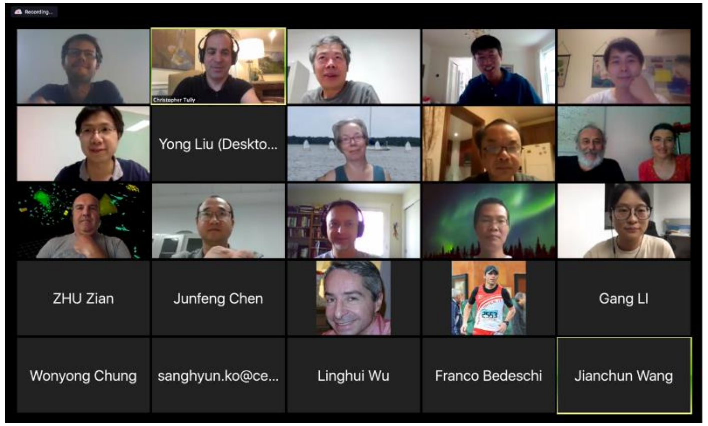


- Background: future lepton colliders (e.g. CEPC)
  - Precision measurements with Higgs and Z/W
- Why crystal calorimeter?
  - Homogeneous structure
    - Optimal intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$
  - Energy recovery of electrons: to improve Higgs recoil mass
    - Corrections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

3D crystal ECAL: past workshops

- Ideas firstly proposed: CEPC calorimetry workshop (March 2019)
- Follow-up workshop: Mini-workshop on a detector concept with a crystal ECAL
  - R&D efforts targeting key issues and technical challenges

Virtual mini-workshop on a detector concept with a crystal ECAL, July 22-23, 2020, https://indico.ihep.ac.cn/event/11938/

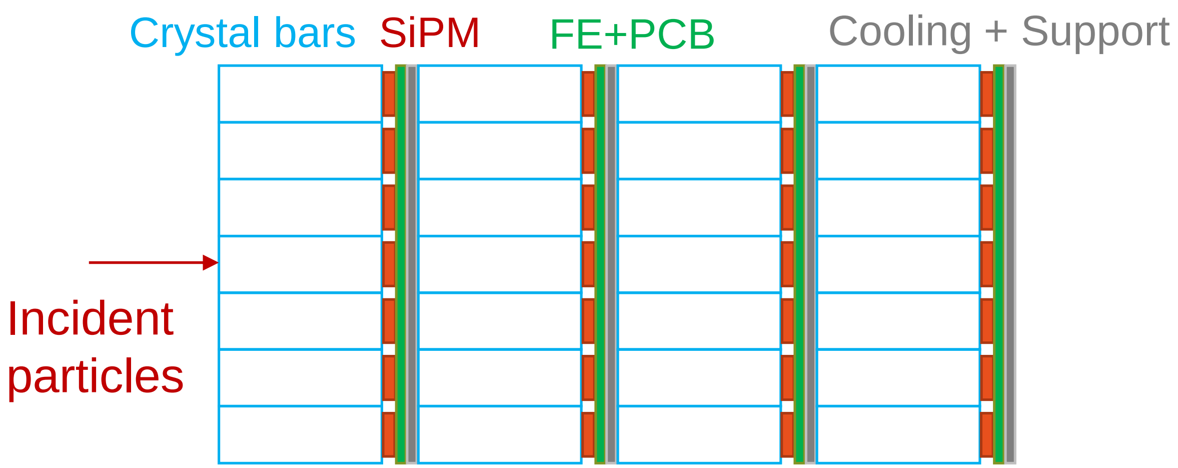


R&D efforts targeting key issues and technical challenges

- Key issues: performance studies and optimization
  - Segmentation: in longitudinal and lateral directions
  - Performance: single particles and jets with PFA -> separation, energy splitting
  - Impacts from dead materials: upstream tracker, services (cabling, cooling)
  - Fine timing: e.g. for positioning
  - Dual-gated or dual-readout techniques (to improve hadronic energy resolution)
- Critical technical questions/challenges
  - Detector unit: crystal options (BGO, PWO, etc.), SiPMs (HPK, NDL, etc.)
  - Front-end electronics: cornerstone for instrumentation of high-granularity calorimetry
    - Multi-channel ASIC: high signal-noise ratio, wide dynamic range, continuous working mode, minimal dead time, etc.
  - Cooling and supporting mechanics design
  - Calibration schemes and monitoring systems: SiPMs, crystals and ASICs
  - System integration: scalable detector design (modules), mass assembly, QA/QC

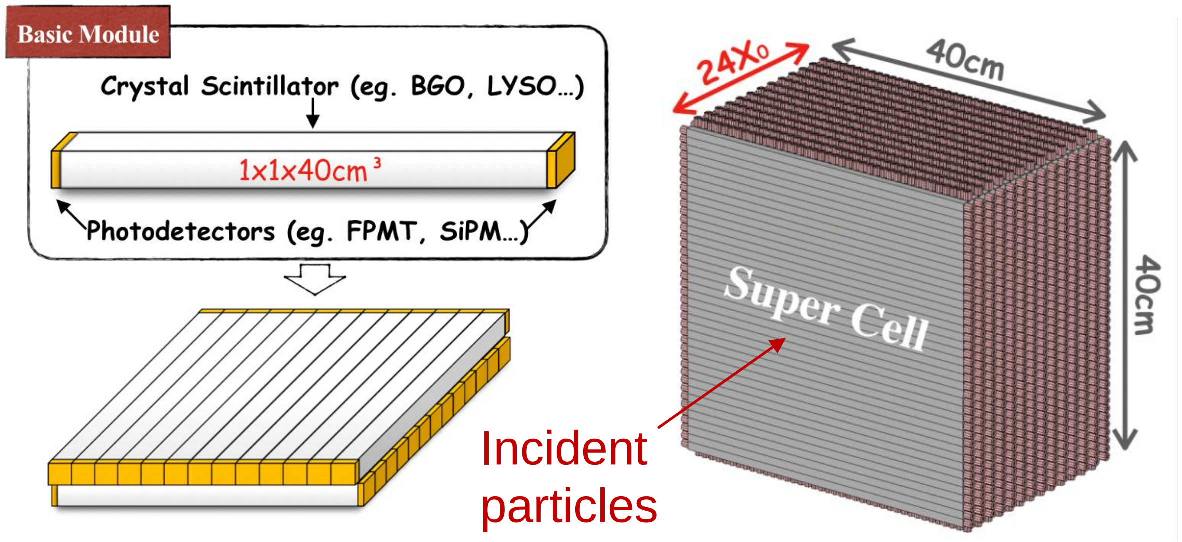
3D crystal ECAL: 2 major designs

Design 1



- Longitudinal segmentation
- Fine transverse segmentation
- Single-ended readout with SiPM
- PFA-oriented design
- High channel-count, impact from services

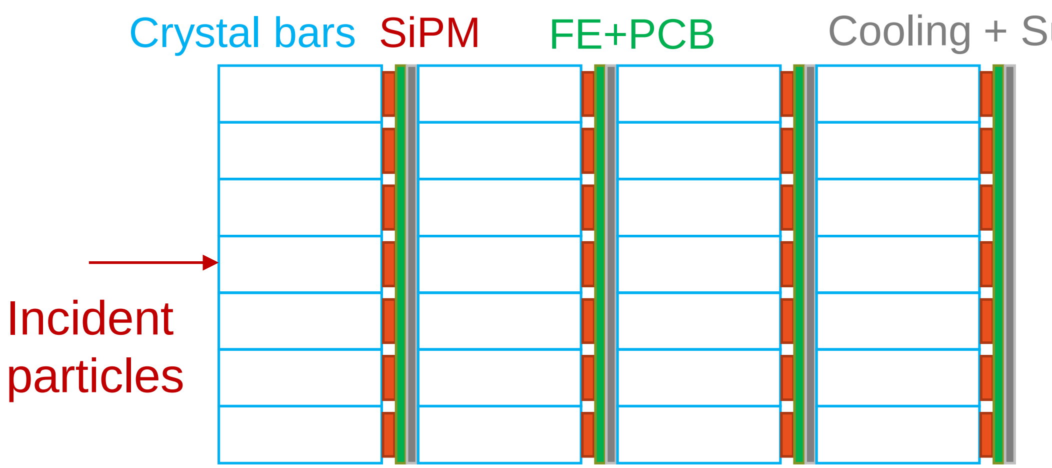
Design 2



- 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

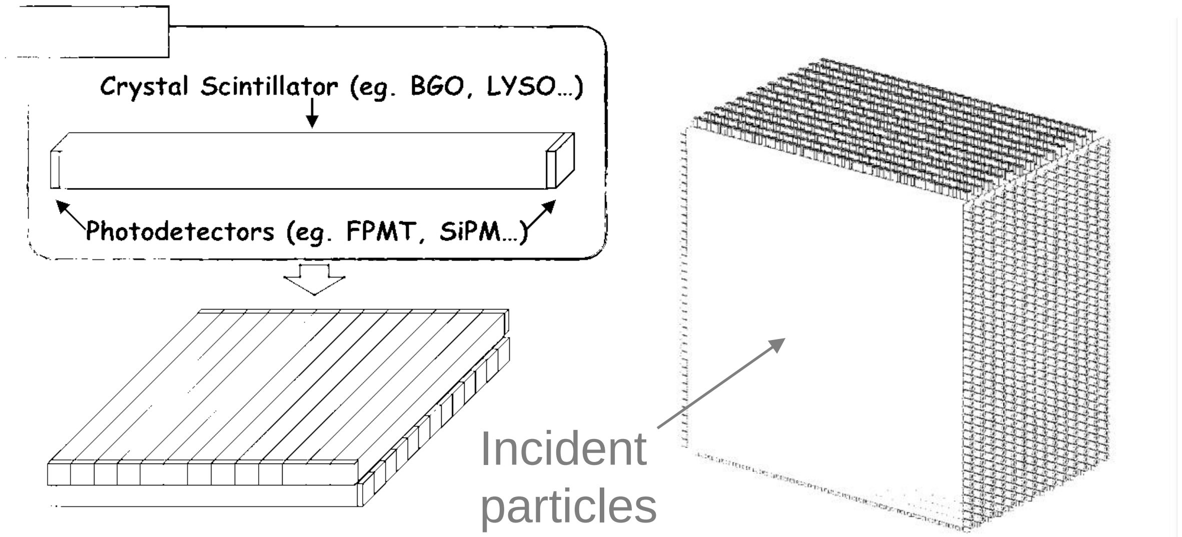
3D crystal ECAL: 2 major designs

Design 1



- Design optimisations
  - Transverse: separation power
  - Longitudinal: impact from dead material, leakage correction (backup)
- Neutral pion reconstruction (working)

Design 2

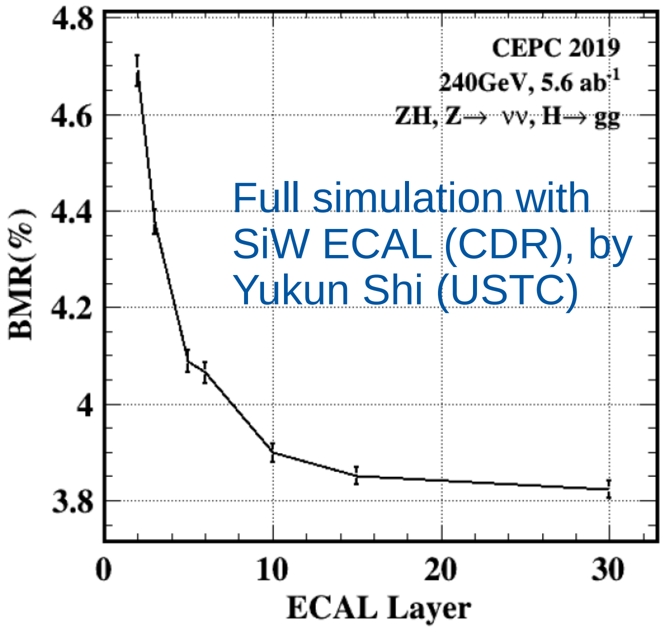


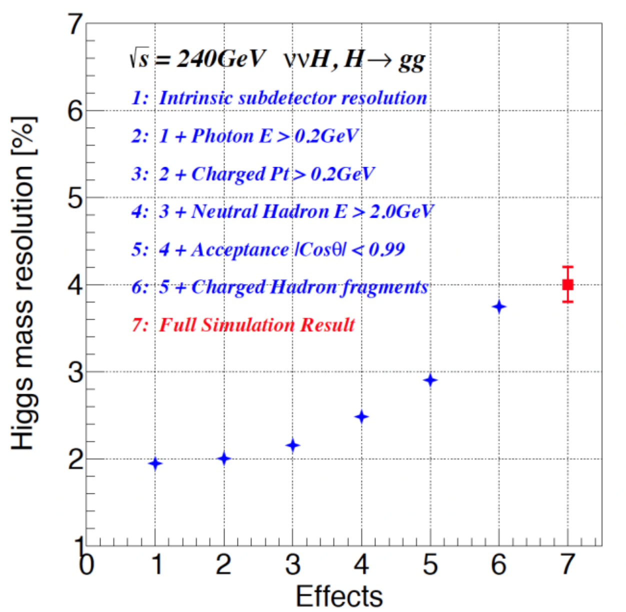
- Multiplicity of incident particles (jets)
  - Based on physics benchmarks (backup)
- Digitisation in each long bar: done
- Reconstruction algorithm under development
- Event display and (pattern) reconstruction

Longitudinal segmentation optimisation

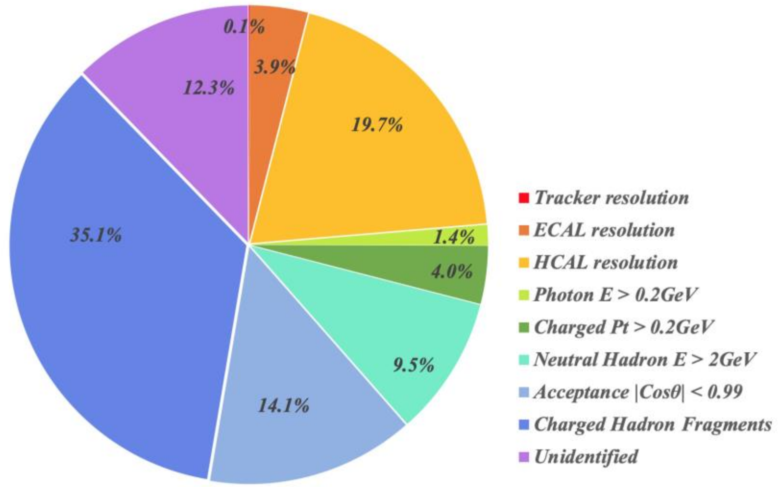
Boson Mass Resolution vs #Layer in ECAL

PFA Fast Simulation





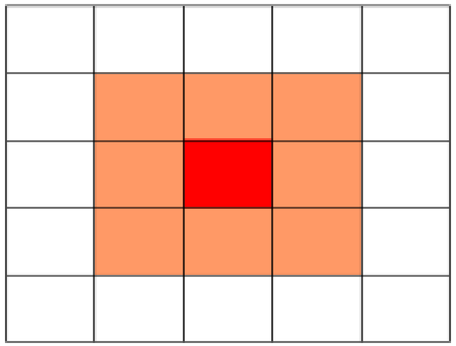
Yuexin Wang (IHEP)



- 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

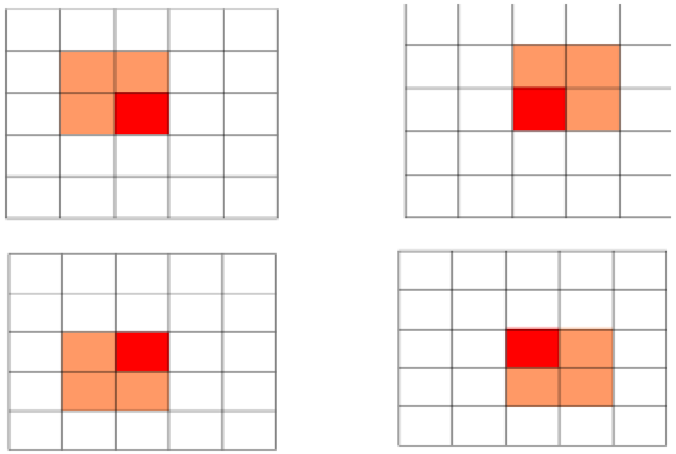
Crystal transverse size optimisation

- 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

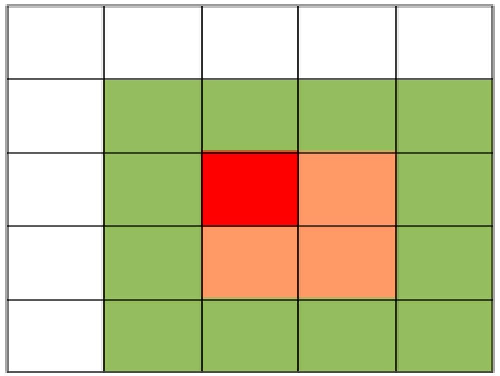


S_1, S_9, S_{25}: energy of seed, 3×3 and 5×5

$$F_9 = \frac{S_9 - S_1}{S_9}$$



S_4 chooses the energy maximum within the four 2×2 arrays



S_{16}

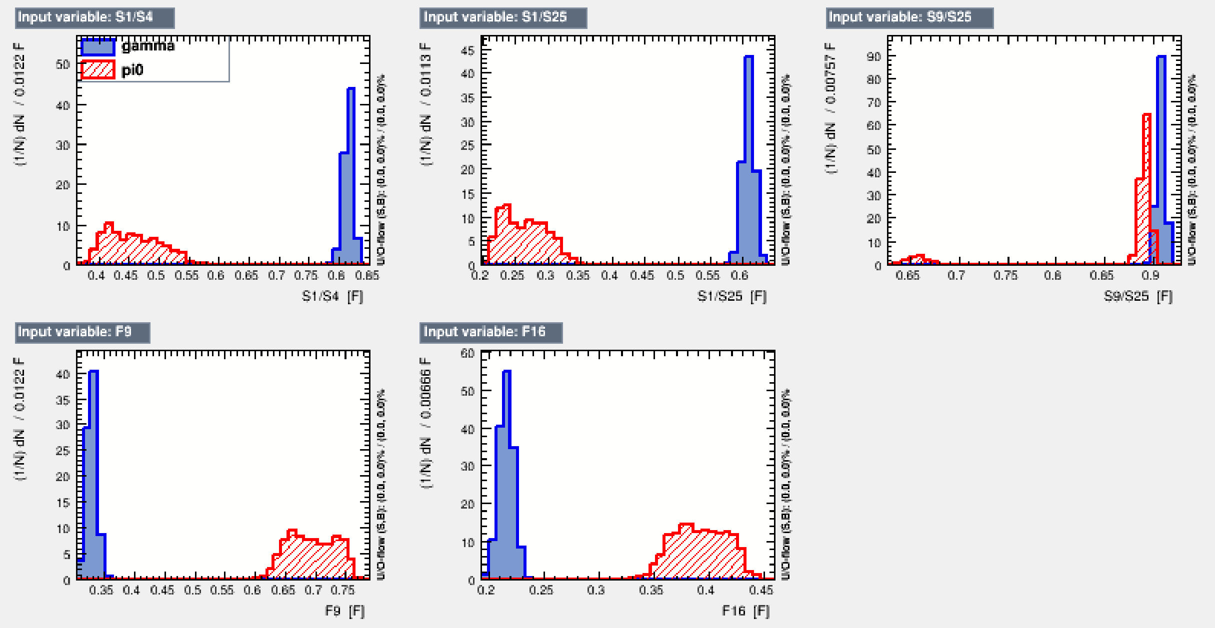
$$F_{16} = \frac{S_{16} - S_4}{S_{14}}$$

Crystal transverse size optimisation

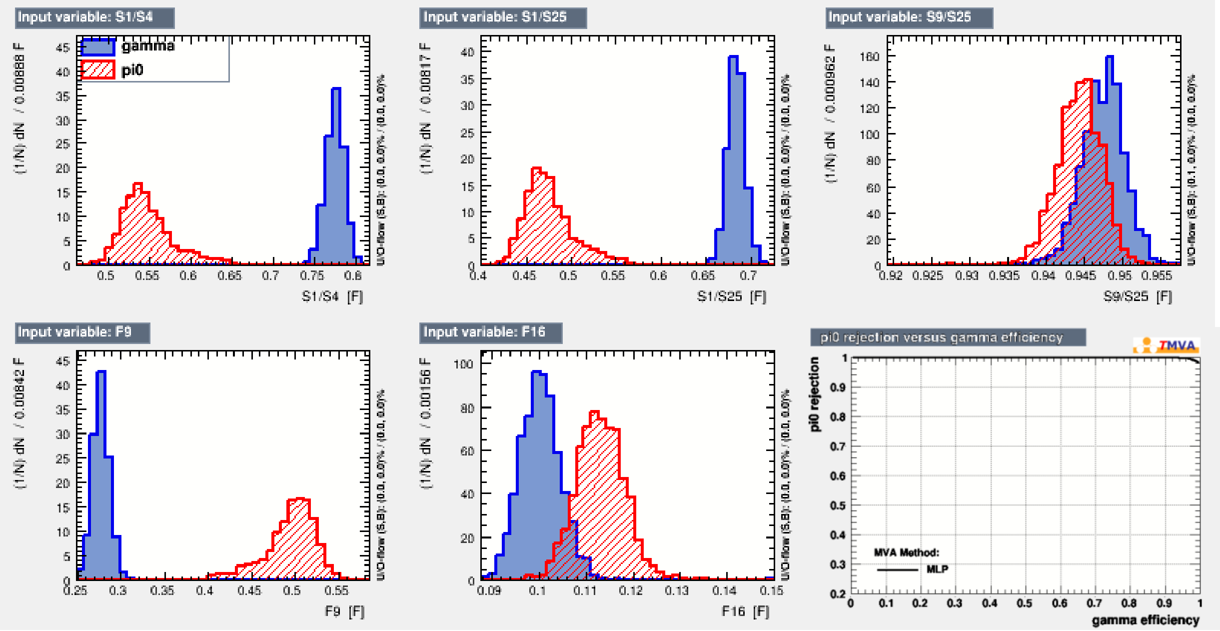
- Separation performance of the 40GeV γ and merged π^0

Crystal transverse size: 1x1 cm²

Crystal transverse size: 2x2 cm²



100% separation with most variables

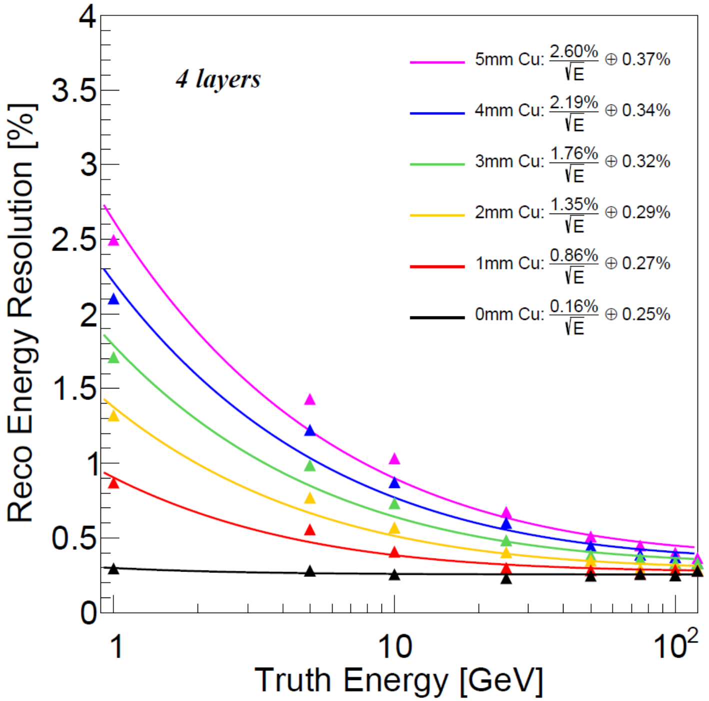


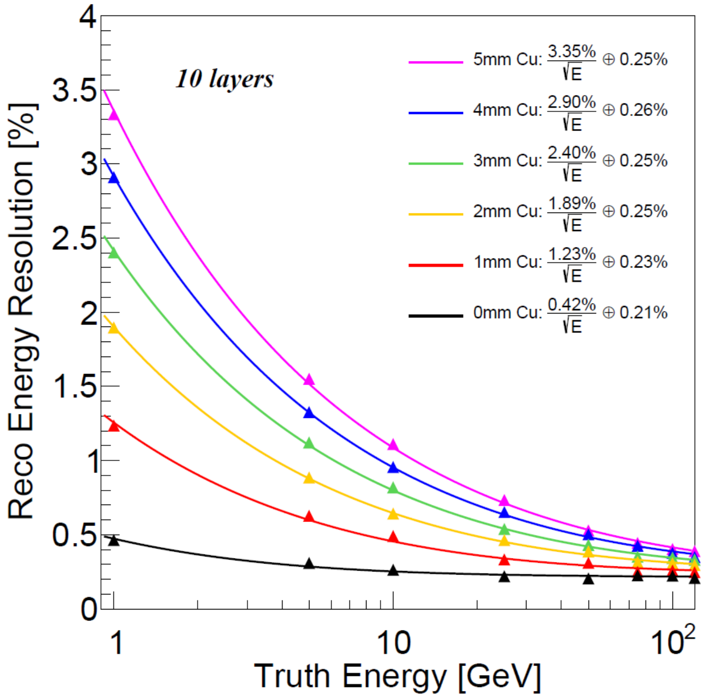
100% separation with variables like S1/S4, S1/S25 and F9

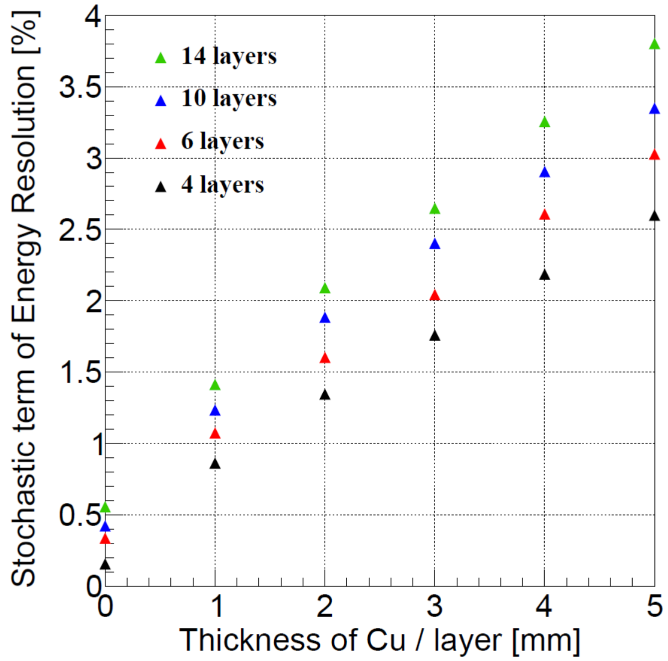
Preliminary studies show that 2x2 cm² transverse size can well separate γ/π^0 up to 40 GeV.
Next: what would be the performance of π^0 reconstruction (with different transverse sizes)?

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…





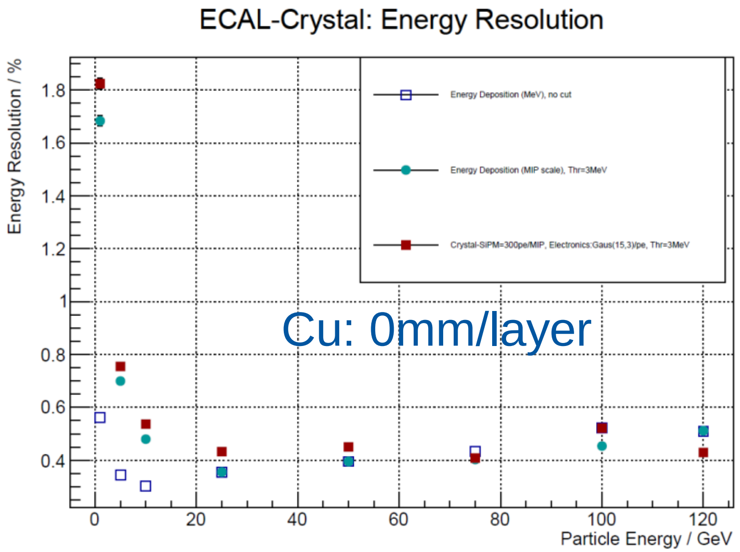


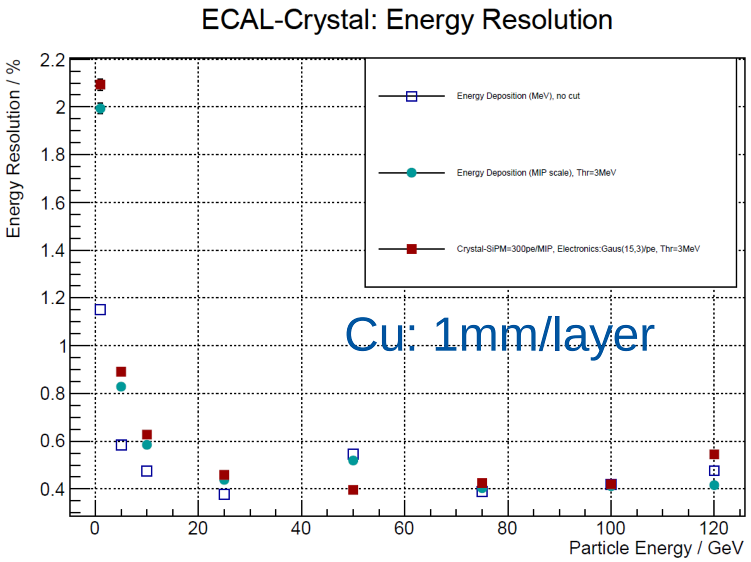
Note: energy fluctuations and leakages dominate; impacts of digitization in the next page

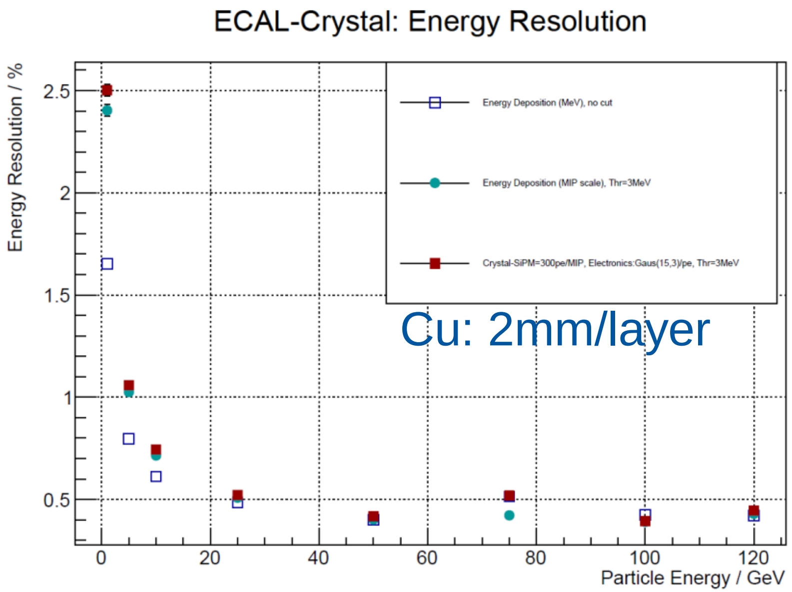
Longitudinal segmentation: with digitisation

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

6 longitudinal layers in depth: 4X0 crystal/layer







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

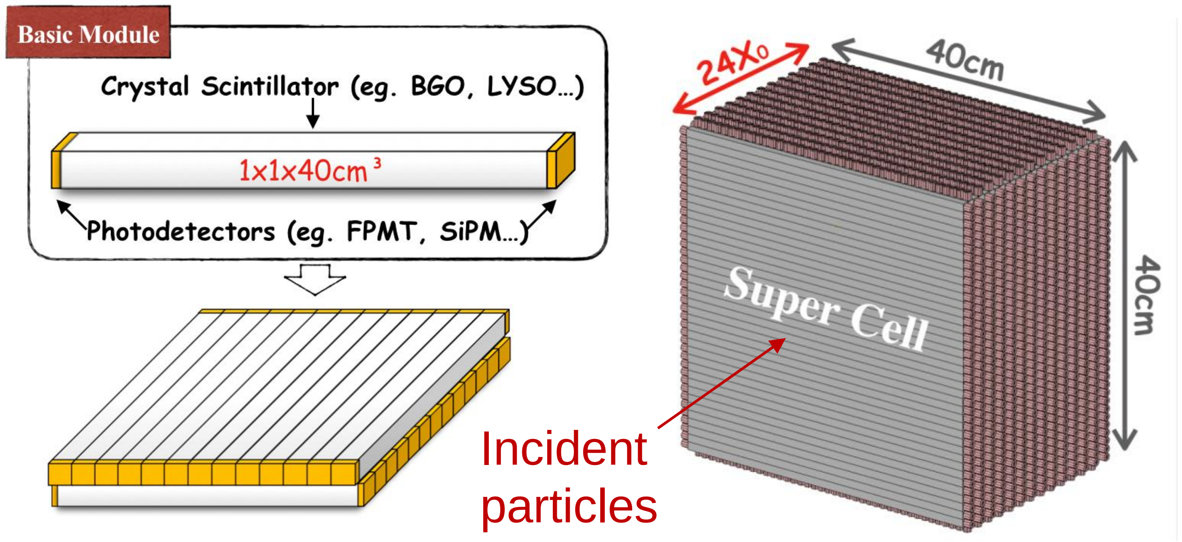
- 0.84X0 copper in total will degrade the stochastic term to ~2.5%

High-granularity crystal ECAL: 2 major designs

Design 1: short bars

- Design optimisations
- Transverse: separation power
- Longitudinal: impact from dead material, leakage correction (backup)
- Neutral pion reconstruction (working)

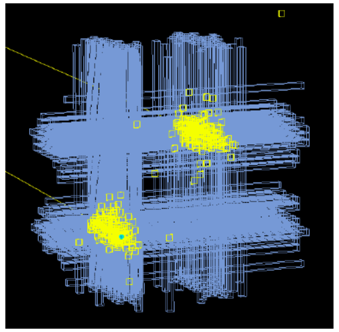
Design 2: long bars (current focus)



- **Advantages**
  - Longitudinal granularity: 24 layers, 1X0/layer
  - Save #channels, ~15 times less
  - De facto 3D calorimeter: timing for hit positions for transverse granularity
- **Key issues**
  - Ambiguity: multiple incident particles within one super cell
  - Separation of nearby showers
  - Impact on the Jet Energy Resolution (JER)

cReconstruction with 2 incident particles

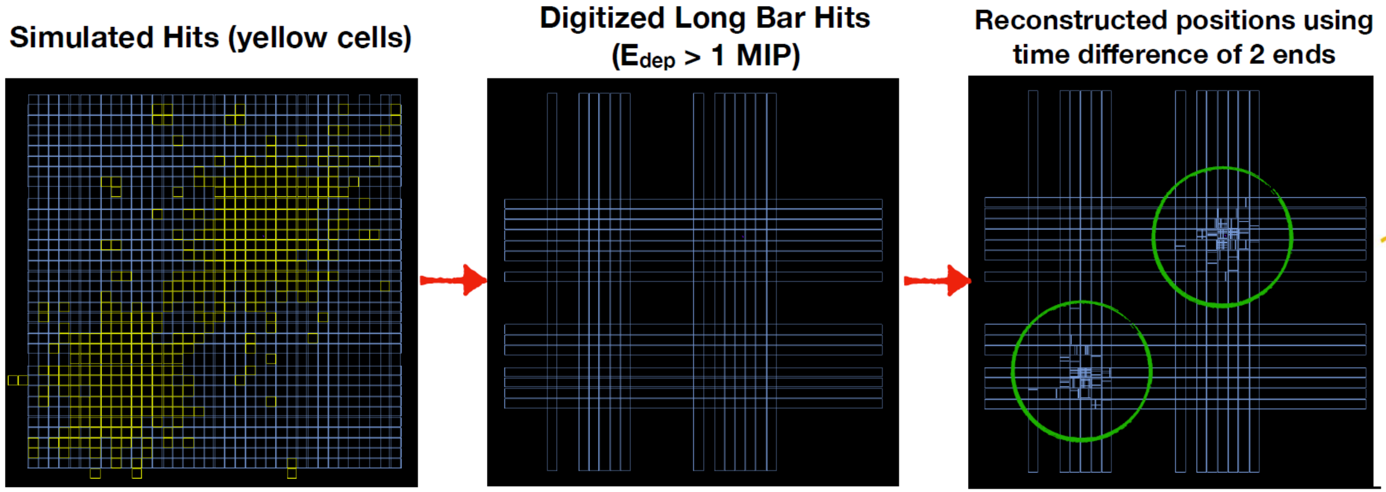
Patterns in event display: 2 photons

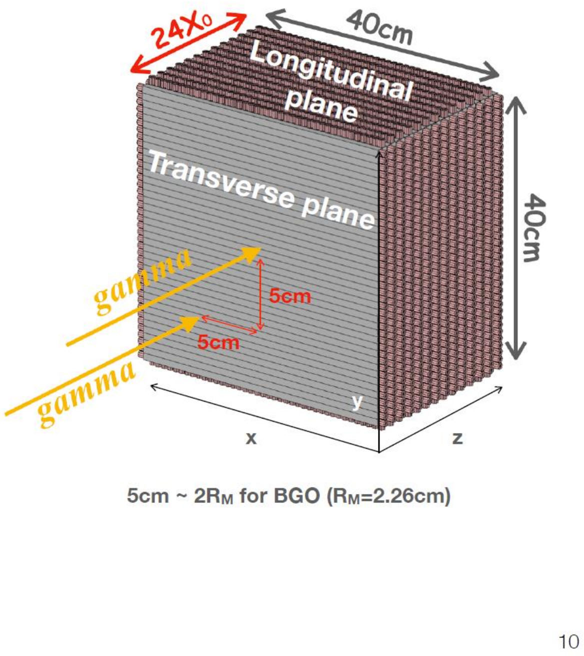


2 parallel 5GeV γ

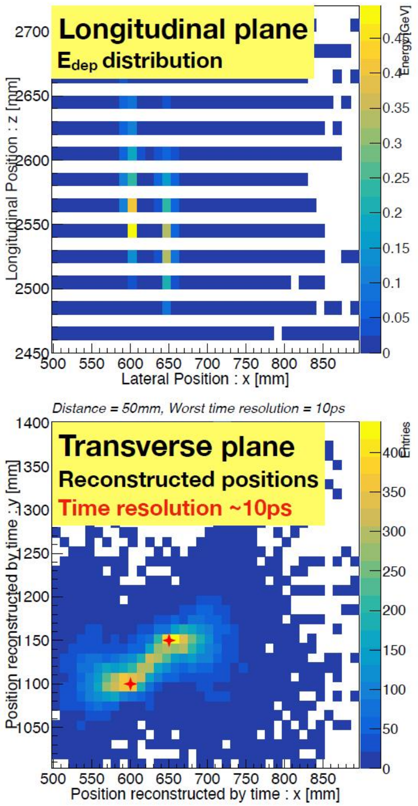
distance ~20cm along the diagonal

→ can be separated.



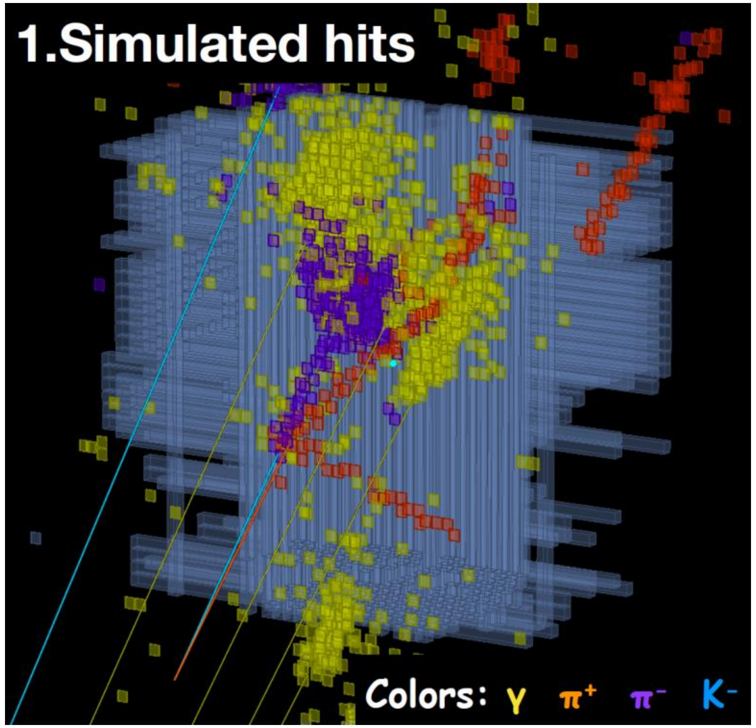


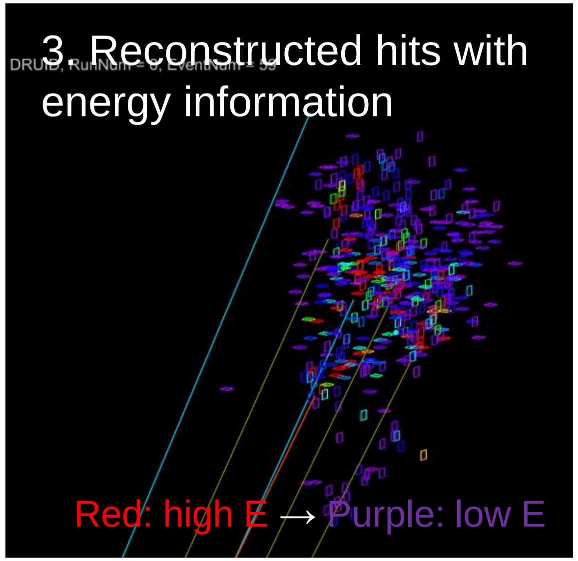
Shower profiles: 2 photons

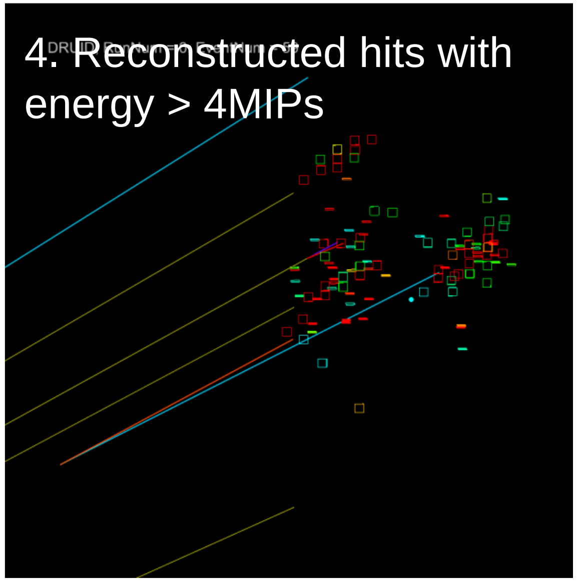


Patterns with jets in Event Display

- Patterns for first impression, but still complex…
- Need further studies on positioning and energy splitting

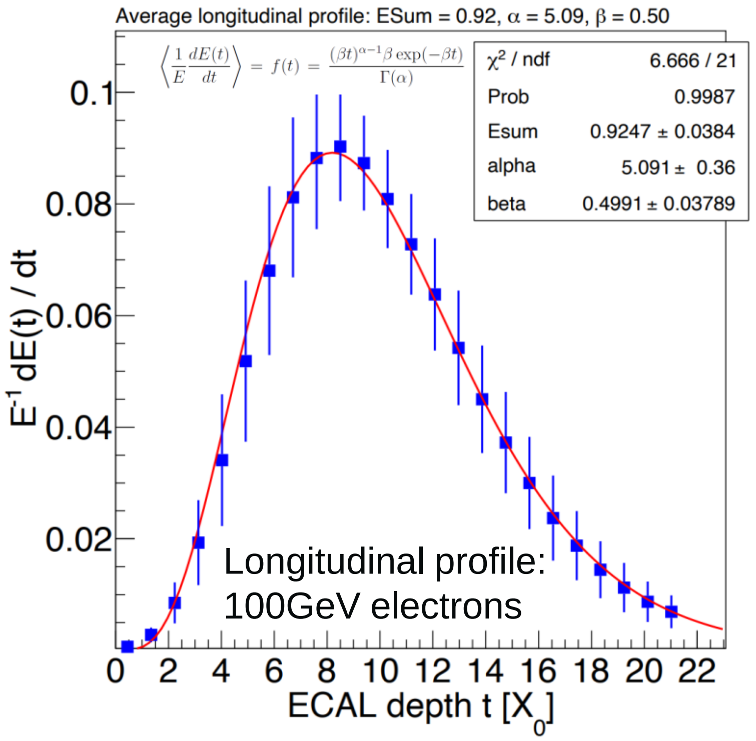




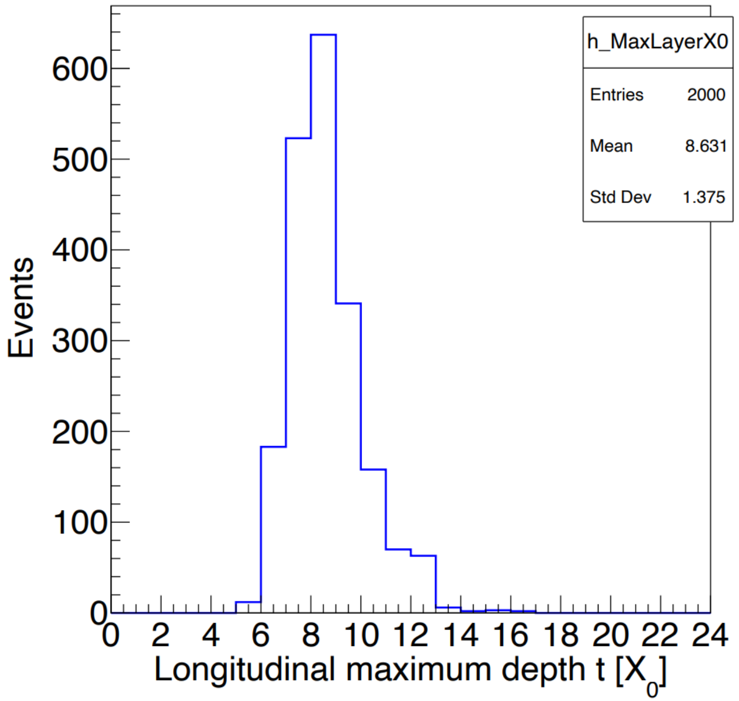


Shower profiles studies in simulation

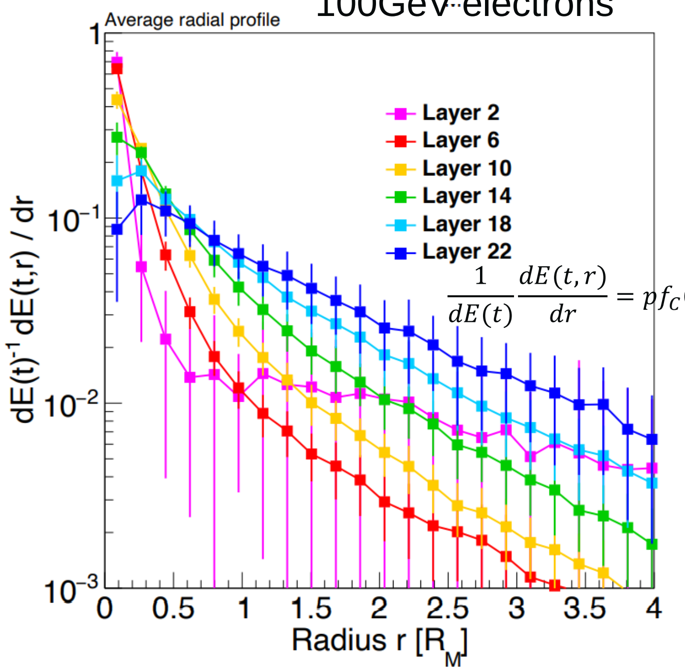
- How can we separate two close-by EM showers?
- EM shower profiles in 3D with highly granular cells: ongoing studies
  - Input to the weights for energy splitting



Longitudinal profile:
100GeV electrons



Lateral shower profile:
100GeV electrons

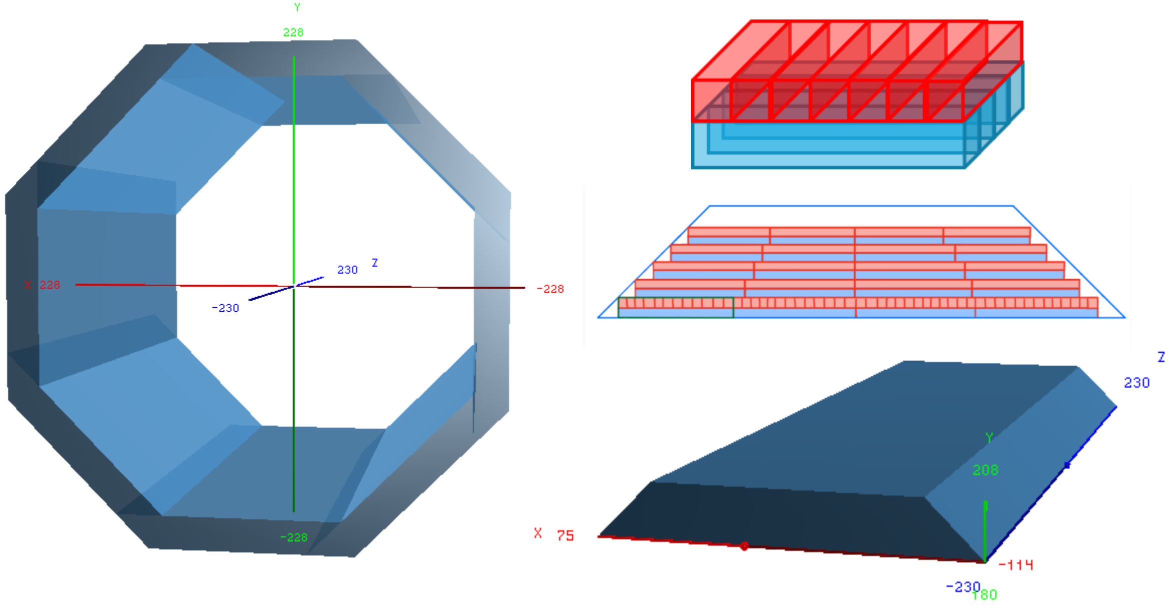


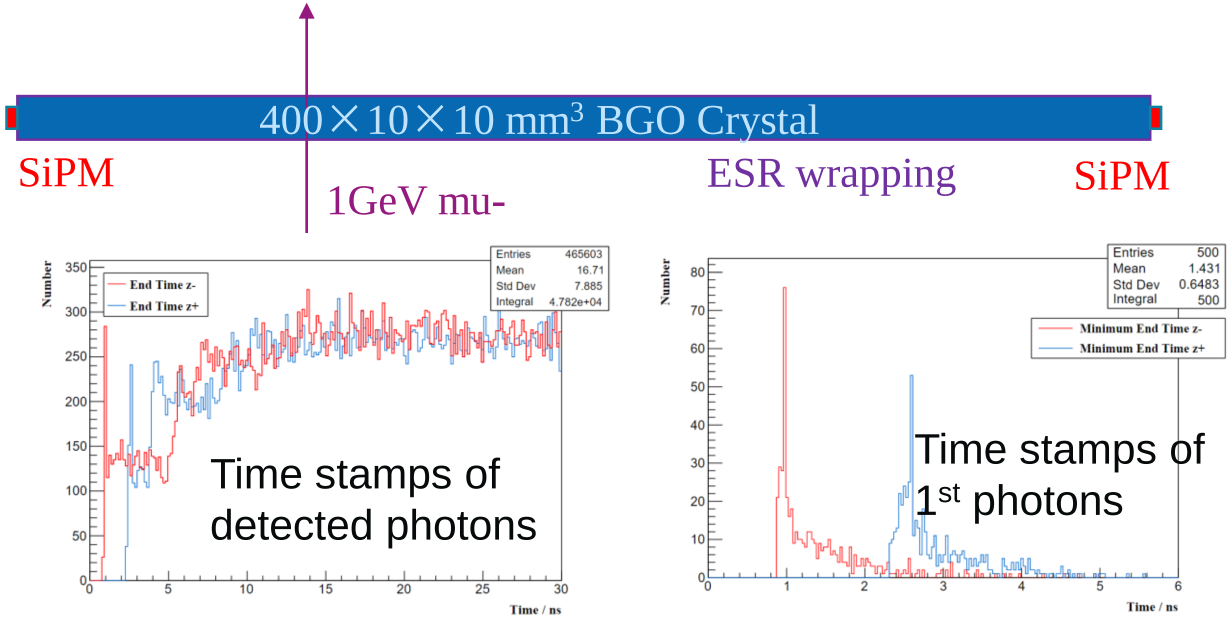
Distance along radial direction from shower axis (scaled in Moliere radius)

Latest progress in the new CEPC software

- Crystal calorimeter in CEPCSW (common framework)
  - Geometry of long crystal bars: implementation in DD4HEP (done)
  - Digitisation: based on the Geant4 full simulation of a single crystal bar (done)
  - Reconstruction with single particles and two close-by showers: ongoing

Crystal ECAL geometry (barrel) in CEPCSW





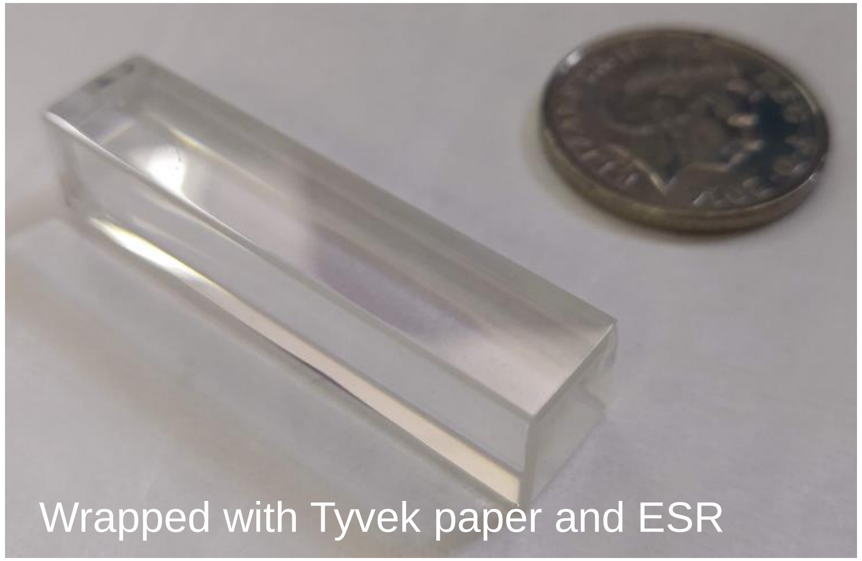
Geant4 full simulation established

Critical questions for 3D crystal ECAL: technical part

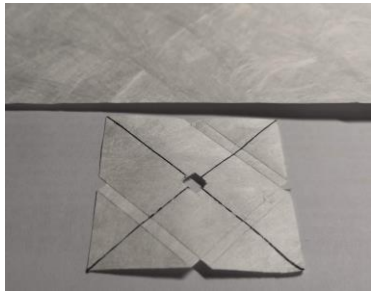
- Detector unit: crystal options (BGO, PWO, etc.), SiPMs (HPK, NDL, etc.)
- Front-end electronics
  - Cornerstone for successful instrumentation of high-granularity calorimetry: e.g. CALICE prototypes, CMS HGCAL project
  - Multi-channel ASIC: high signal-noise ratio, wide dynamic range, continuous working 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

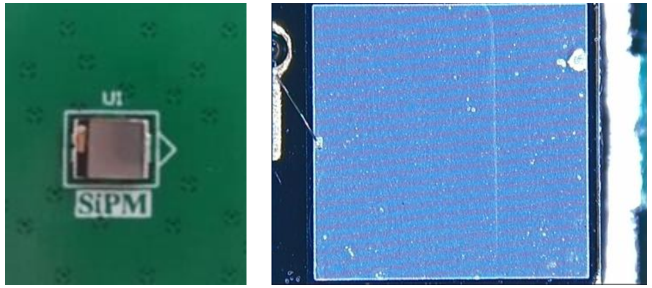
Studies with PWO crystal bar and NDL-SiPM

- Firsts tests with a PWO crystal using cosmics
  - Read out with a 3x3mm² SiPM, 90k pixels (not ideal sensor)
  - SiPM designed by Novel Device Lab (NDL) in Bejiing Normal University

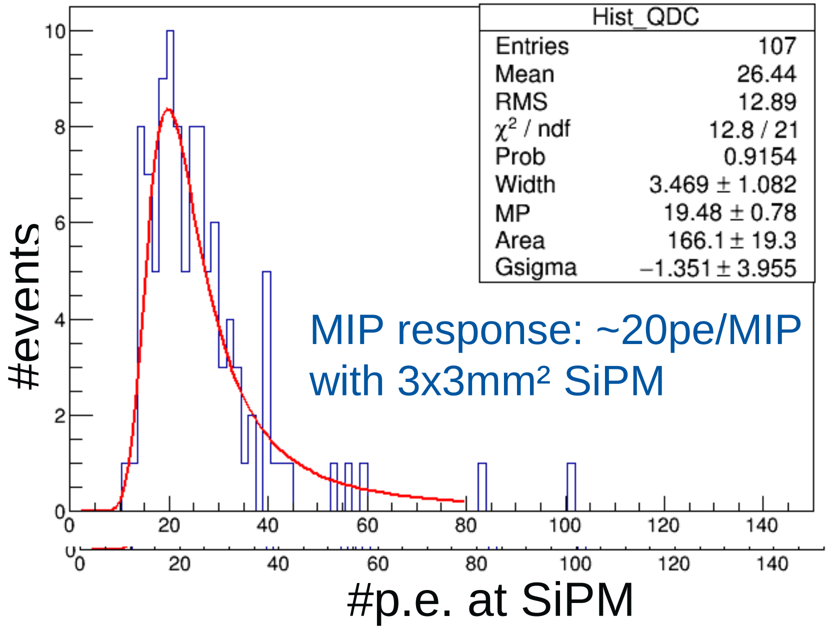


PbWO crystal (produced by SIC), 10x10x45 mm³


Example of pre-cut Tyvek paper

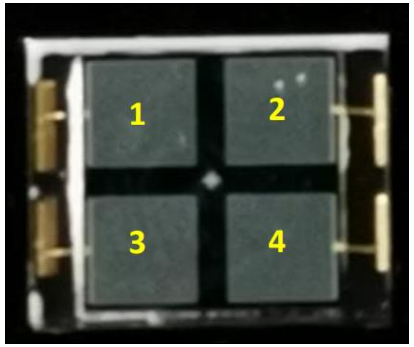


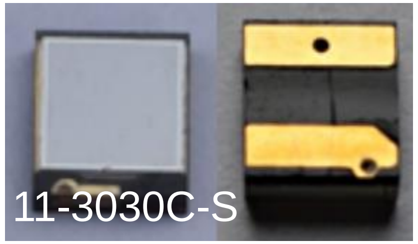
NDL-SiPM 3x3mm² with 10um pixels



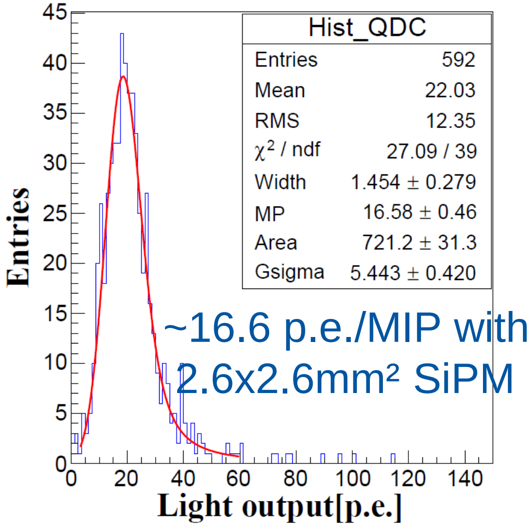
Note: a larger SiPM (e.g. 6x6mm² or larger) can be used for better light collection efficiency

First studies on new-generation of NDL-SiPM





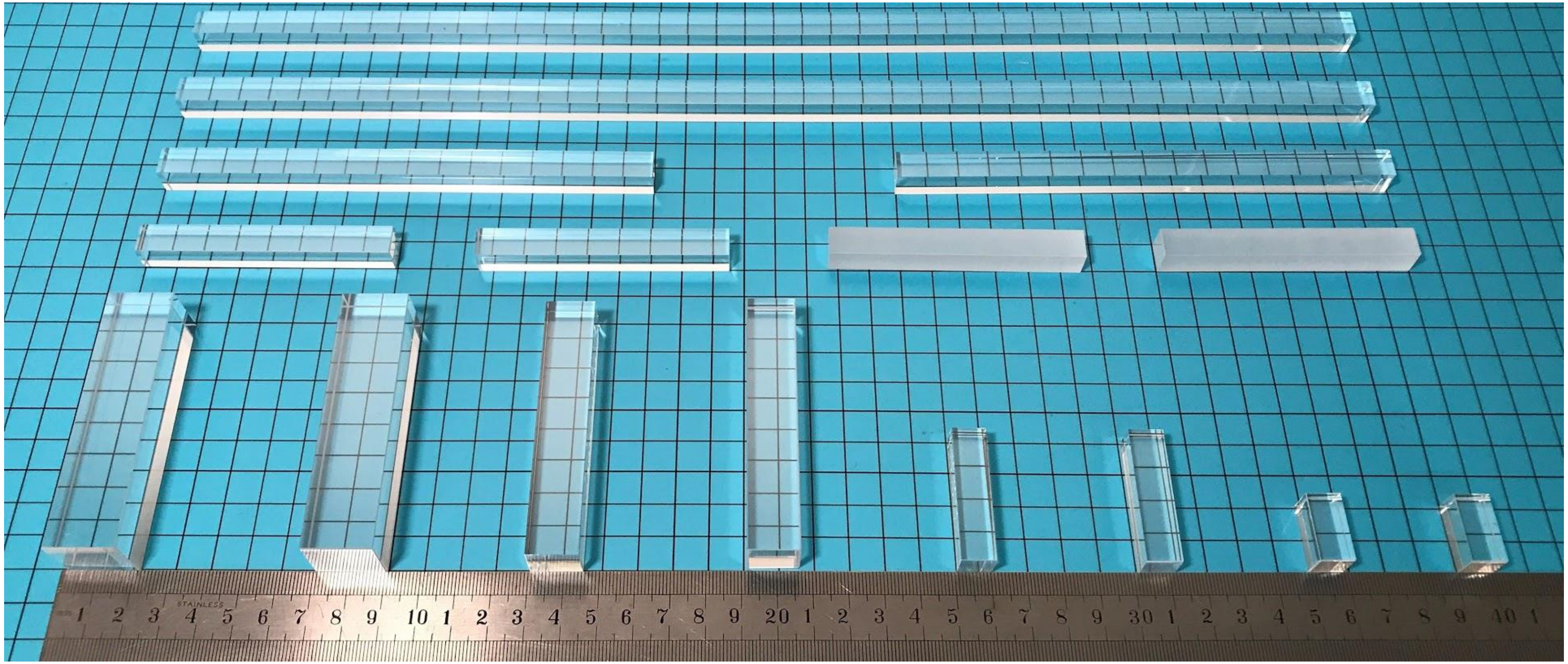
NDL-SiPMs Parameters	11-3030C-S	Latest prototype NDL 22-1313-15S
Breakdown Voltage	27.5 V	19 V
Pixel Pitch	10 µm	15 µm
Peak PDE	31% @420nm	45% @400nm
Pixels	90k	7.4k
Sensitive Area	3×3 mm²	2.6×2.6mm²
MIP response with 10x10x45 mm³ PWO bar	19.5 p.e./MIP	16.6 p.e./MIP



- Tests made for a NDL-SiPM prototype of the latest generation
  - Many improvements: lower dark-count noise, higher PDE,…
- Foresee further tests with new NDL-SiPMs (better candidates 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), under test

Crystal studies: near-future plans

- BGO and PWO crystal samples: varying dimensions, surface treatment
  - With a major focus on timing performance: e.g. Cherenkov photons



Two long BGO bars ready (1×1 ×40 cm³)

Short BGO bars with different dimensions and surface treatment

PWO crystals (SIC) also delivered to IHEP

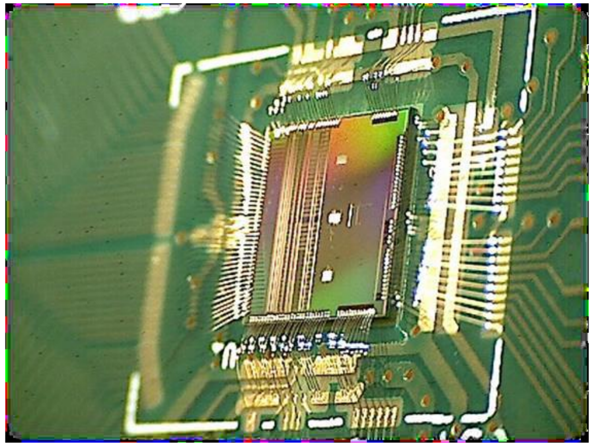
BGO crystal samples already delivered to IHEP (photo by courtesy of Junfeng Chen, SIC-CAS)

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

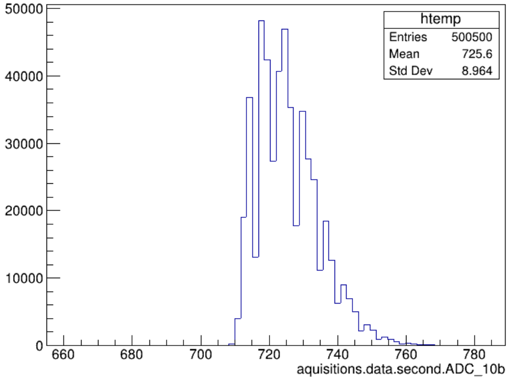
Wire-bonded Klaus5 chip



Klaus5 in BGA

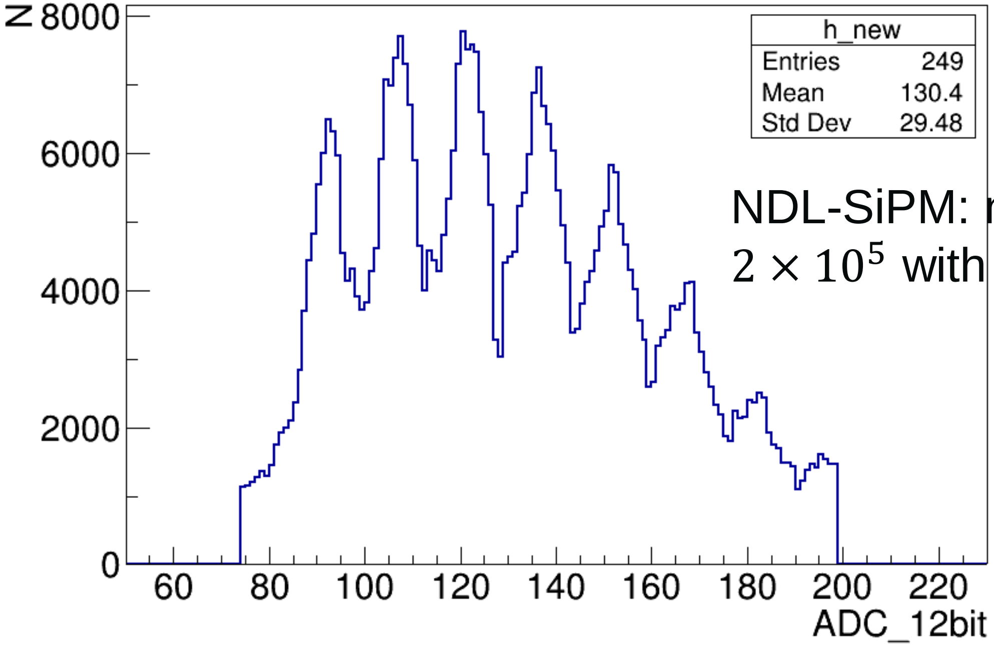
Klaus5 tests with NDL-SiPM

- 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

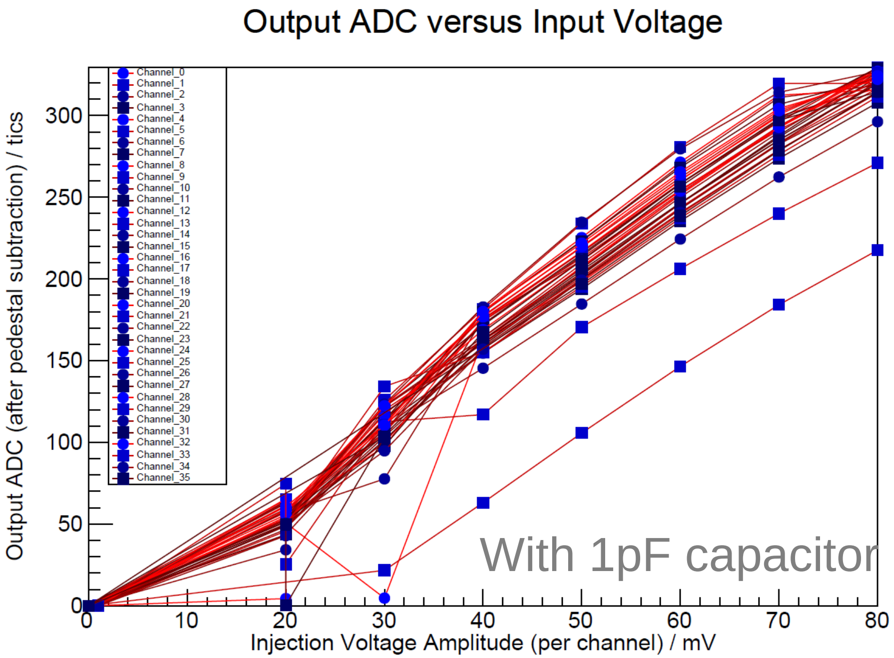


NDL-SiPM: nominal gain 2×10^5 with 10µm pixels

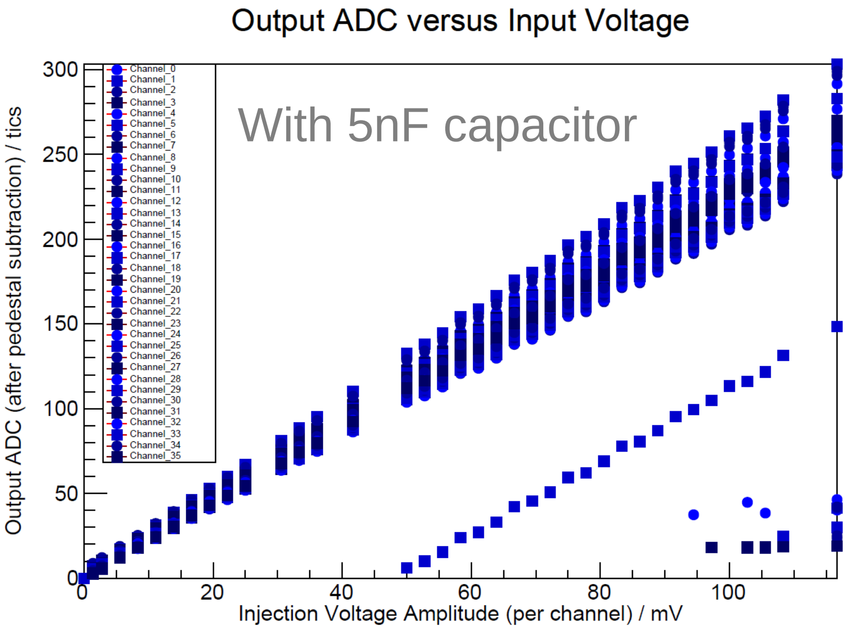
Klaus5 dynamic range: charge injection

- 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



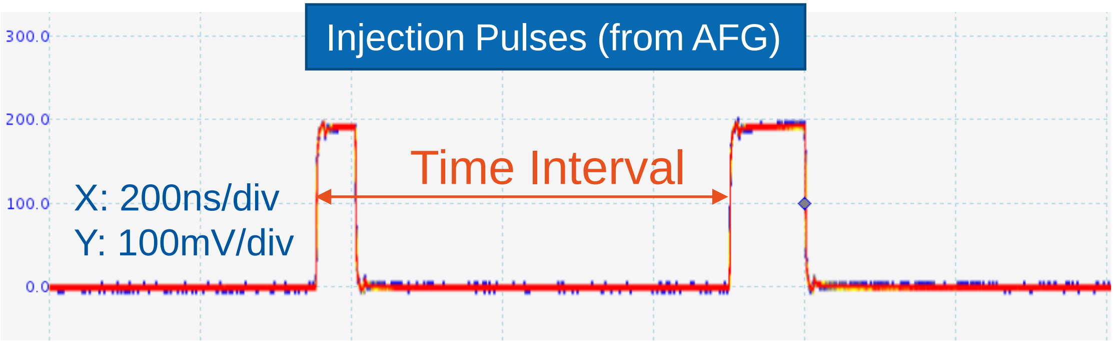
ADC after pedestal subtraction (mid High Gain mode)

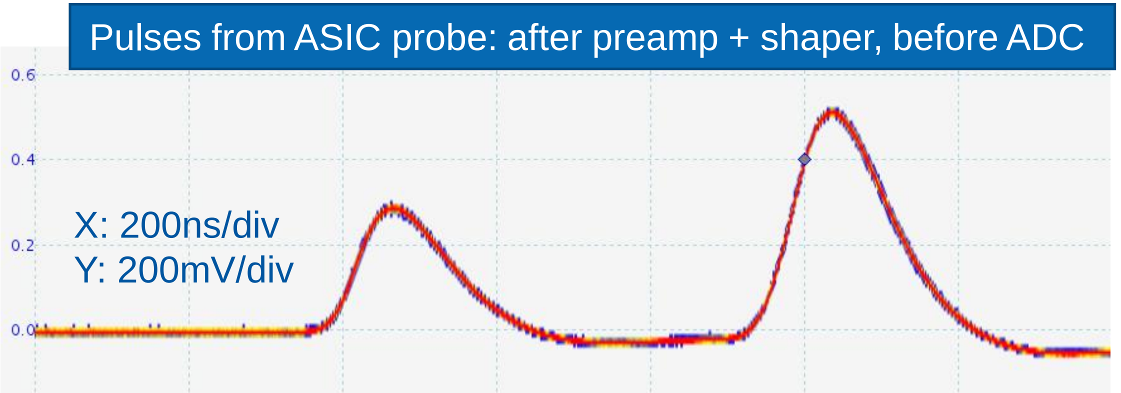


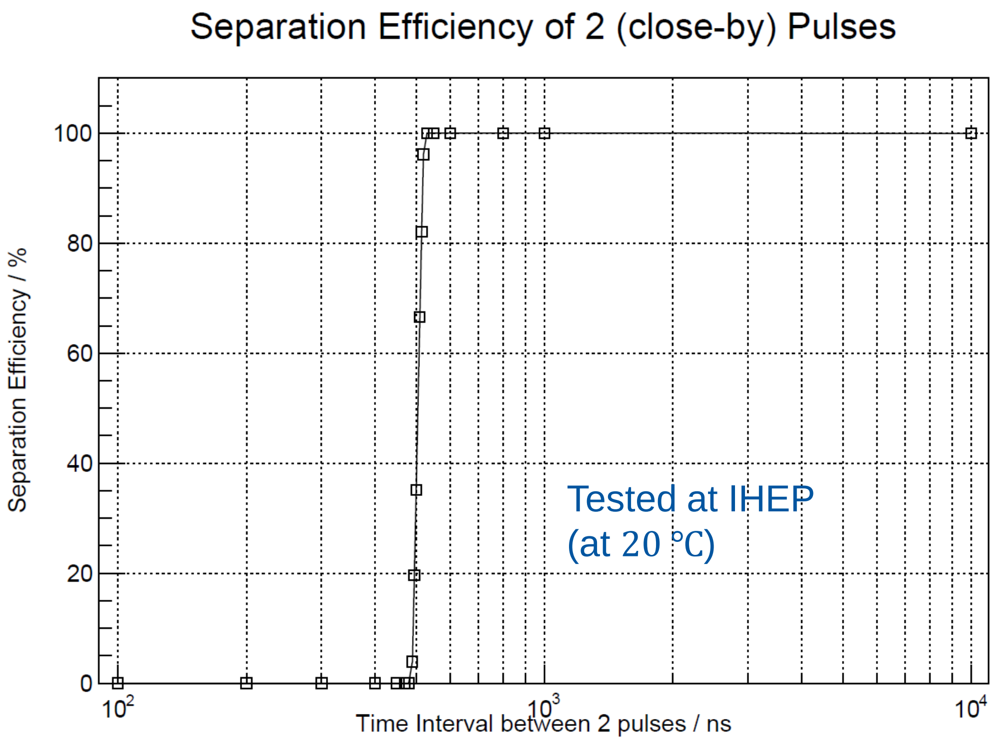
ADC after pedestal subtraction (ultra Low Gain mode)

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
  - To be noted: tests were made for a single channel
  - 36 channels: bottleneck of data transmission speed in DAQ (RaspberryPI-based)

Summary

- 3D crystal ECAL: high granularity
  - Aim to achieve optimal energy resolution and PFA capability
  - Key issues for optimization and technical challenges (partially) identified
    - Further studies, discussions and iterations
  - Steady R&D progress
    - Optimisation studies: longitudinal/transverse segmentation, depth
    - Simulation studies on the detector layout with long bars
    - Technical developments:
      - SiPMs and crystals
      - Characterisations of SiPM-dedicated low-power readout ASIC (KLauS)
      - Dynamic range: TOT technique (in backup)
- Welcome broader collaborations: synergies with FCC-ee
  - Early R&D stage, many open questions/issues
  - In the common software framework (Gaudi, Key4HEP, DD4HEP, …)

Backup slides

LOI for US Snowmass 21

- Letter of Intent on crystal calorimeter in the Instrumentation Frontier
  - https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF6_IF0_Yong_Liu-064.pdf

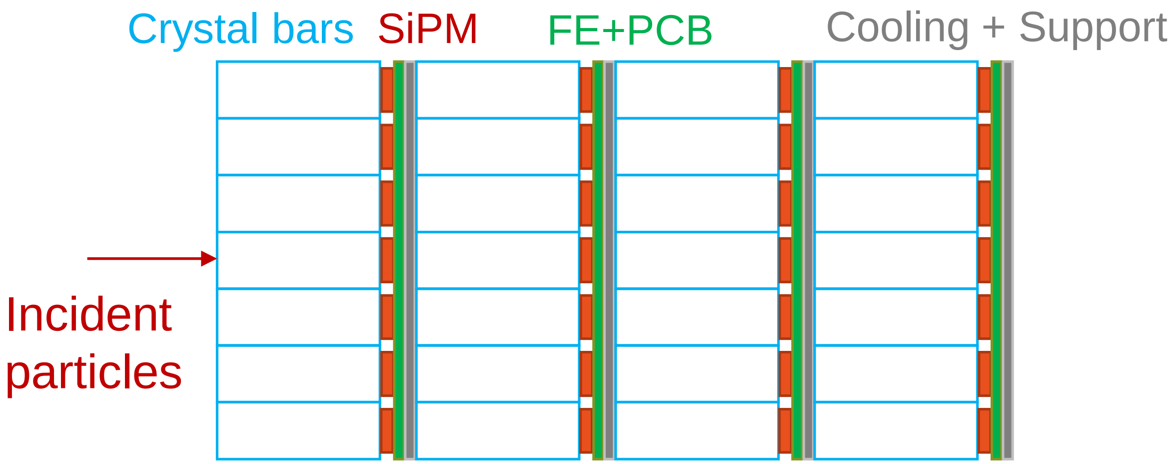
High-Granularity Crystal Calorimetry Letter of Intent – Snowmass 2021 *August 31, 2020*

High-Granularity Crystal Calorimetry Letter of Intent

Future lepton colliders provide a unique opportunity to probe the Standard Model and potentially uncover new physics beyond the Standard Model with Higgs, W, and Z bosons richly produced in the exceptionally clean environment. The recently released European Strategy Updates on the Particle Physics [1] elaborates this consensus that an electron-positron Higgs factory is the highest-priority next collider, including implementations such as the Circular Electron Positron Collider (CEPC) [2, 3], the Future Circular Collider (FCC-ee) [4], and International Linear Collider [5]. The precision physic programs set a stringent requirement on the jet energy resolution to separate and measure hadrons and jets. Detectors based on the Particle-Flow Approach (PFA) [6] provide an essential and feasible option to meet this goal and achieve an unprecedented jet energy resolution of around $30\%/\sqrt{E(\mathrm{GeV})}$), which further requires calorimetry to be finely segmented in 3 dimensions. Within the CALICE Collaboration [7], as proof-of-principles, various high-granularity calorimetry options have been extensively studied with prototyping and beam tests.

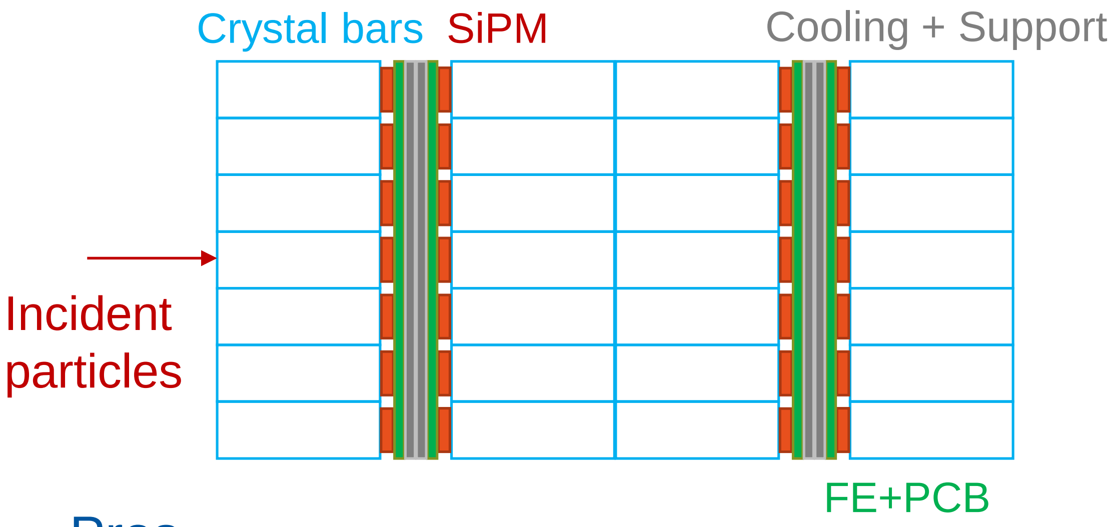
Considerations on detector layouts

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

Studies on physics requirements

Yuexin Wang (IHEP)

- Estimate the multiplicity level of jets: fast simulation
  - Mean ~4 particles within the hottest tower

Multi-jet events at generator level:

☞ *Calculate the impact point of visible final states on the inner surface of ECAL*

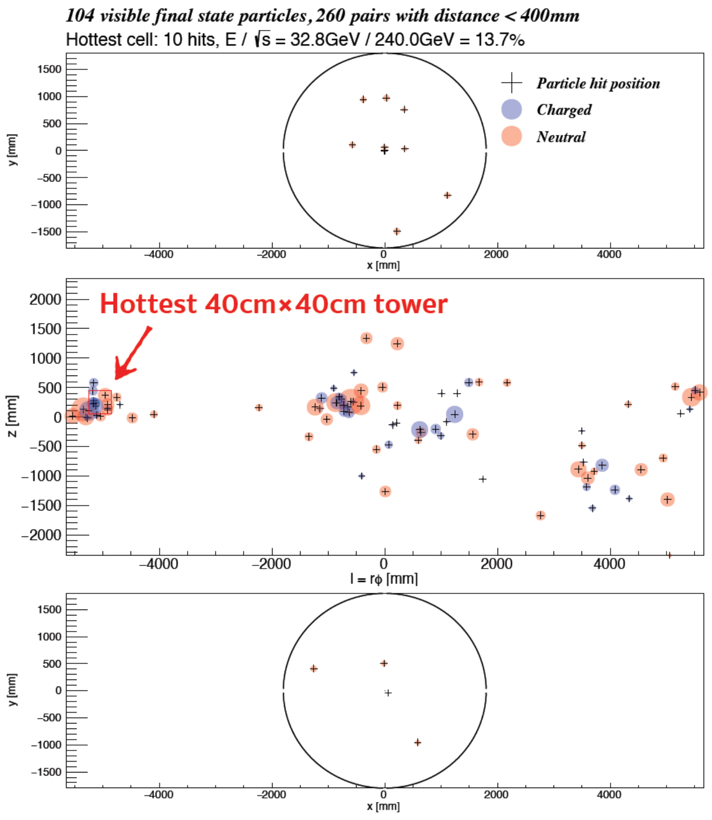
☞ *240GeV, ZH (Z→qq, H→gg) (4-jet event)* as an *example*

Parameters in calculation:

- *A simple cylinder ECAL*
- *Inner Radius, R=1800mm*
- *Barrel Length, L=4700mm*
- *Magnetic Field, B=3T*

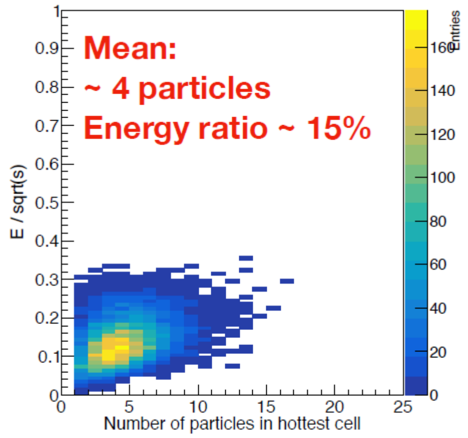
Analysis level:

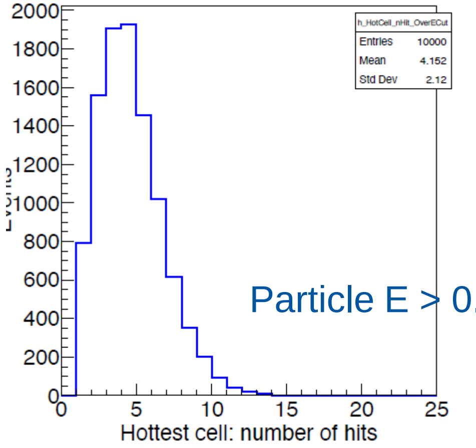
- *Hottest tower (with maximum energy)*
  - *multiplicity and energy ratio to √s*
- *Average proportion of towers with multi-particle*



Unfolded cylindrical ECAL

Hottest 40cm×40cm tower



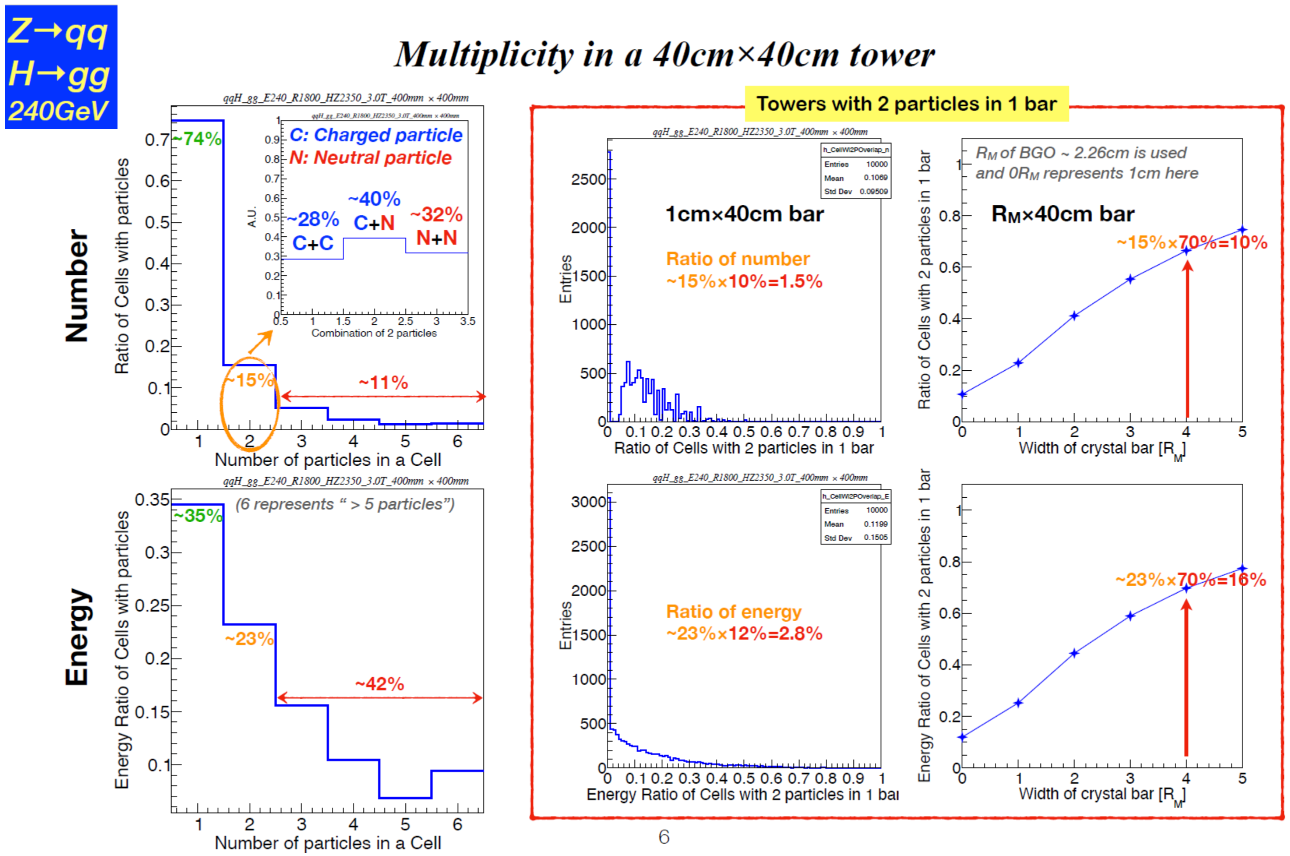


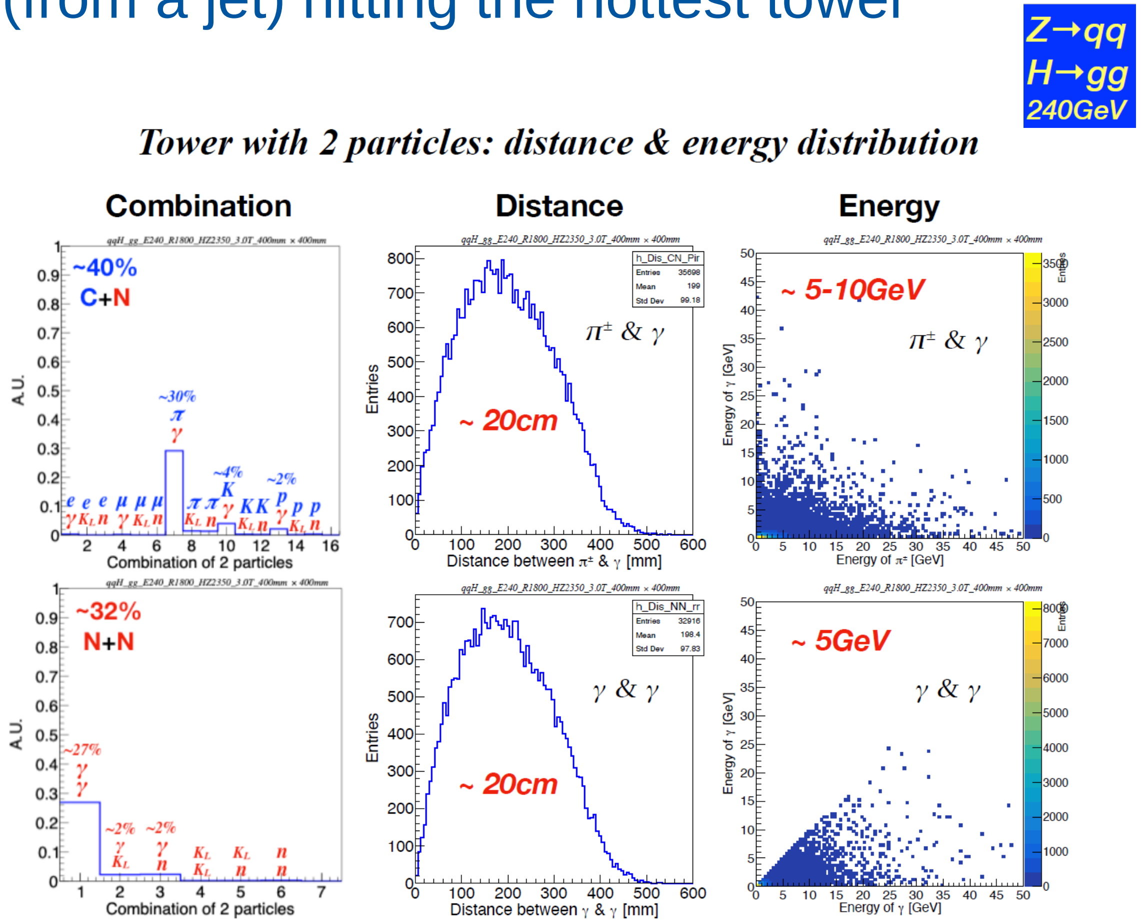
Particle E > 0.2GeV

Studies on physics requirements

Yuexin Wang (IHEP)

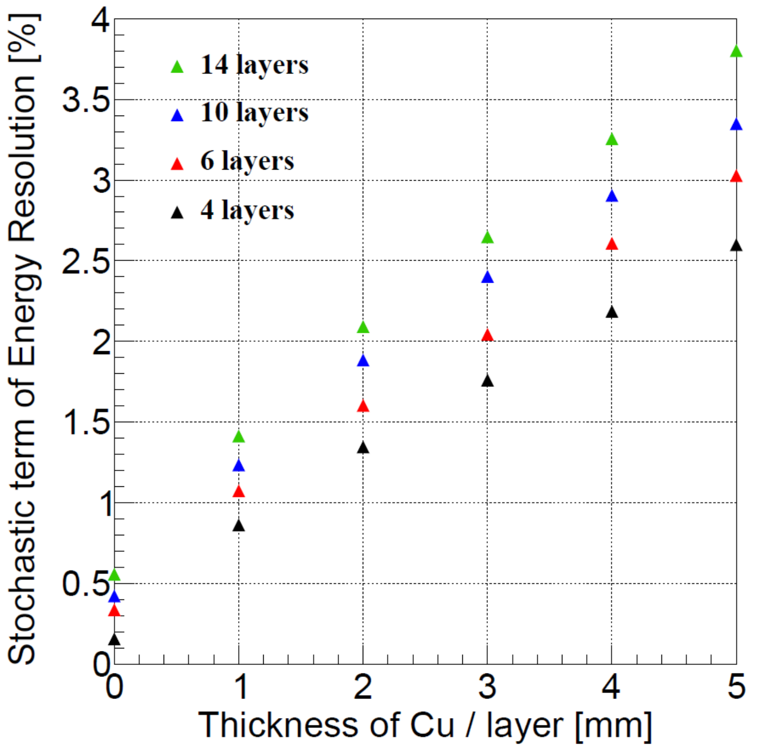
- Estimate the multiplicity level of jets: fast simulation
  - Detailed studies with 2 incident particles (from a jet) hitting the hottest tower

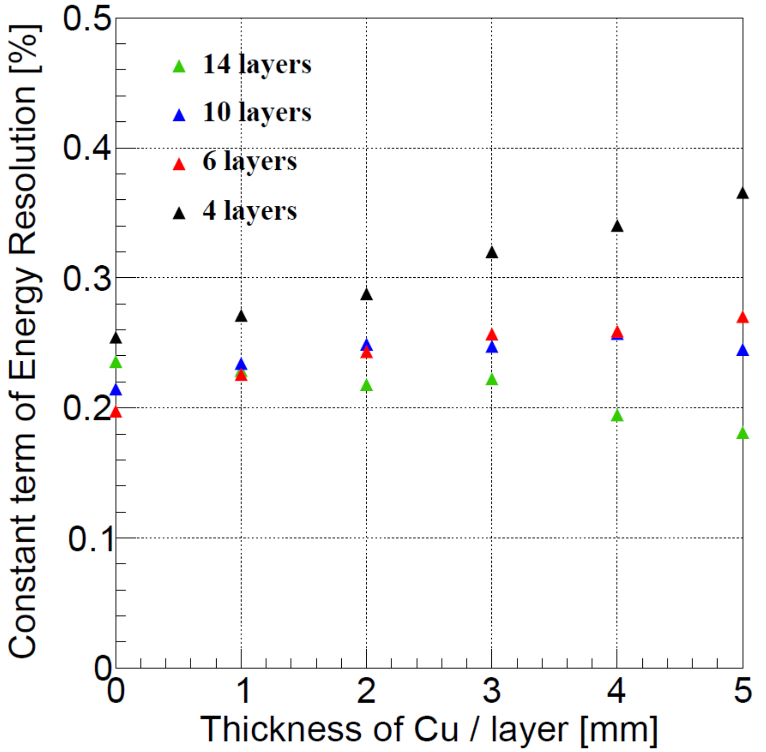




Longitudinal segmentation: impact from services

- 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)



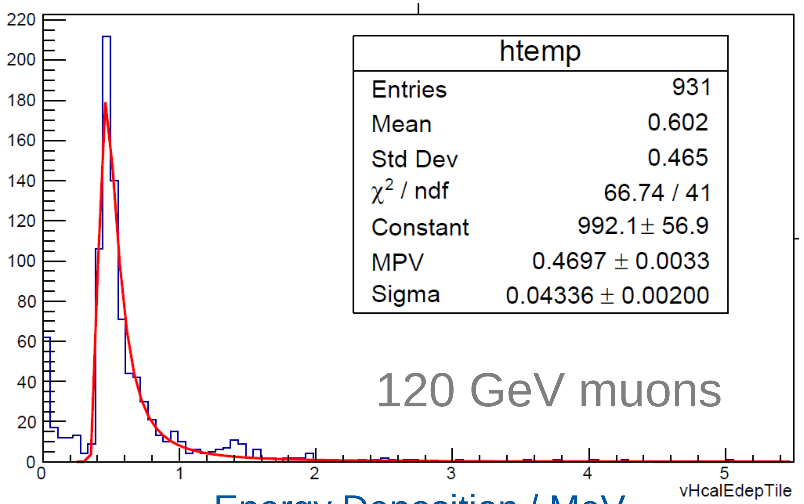


Note: digitization not implemented yet; so energy fluctuations (and leakages) dominate

Digitizer in simulation

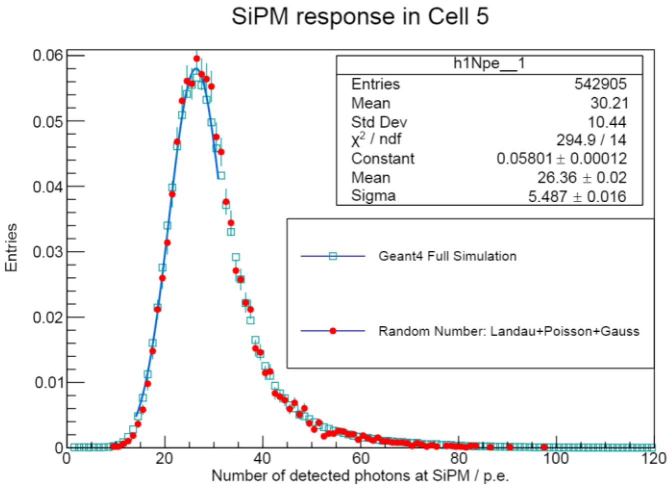
Geant4 version 10.5.0

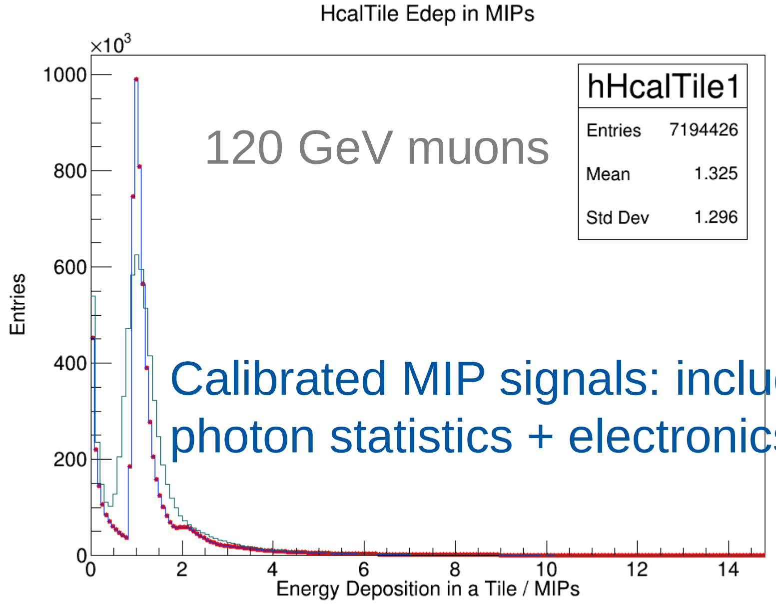
Energy Deposition in a scintillator tile



Energy Deposition / MeV

Digitizer can reproduce G4 full simulation with optical photons





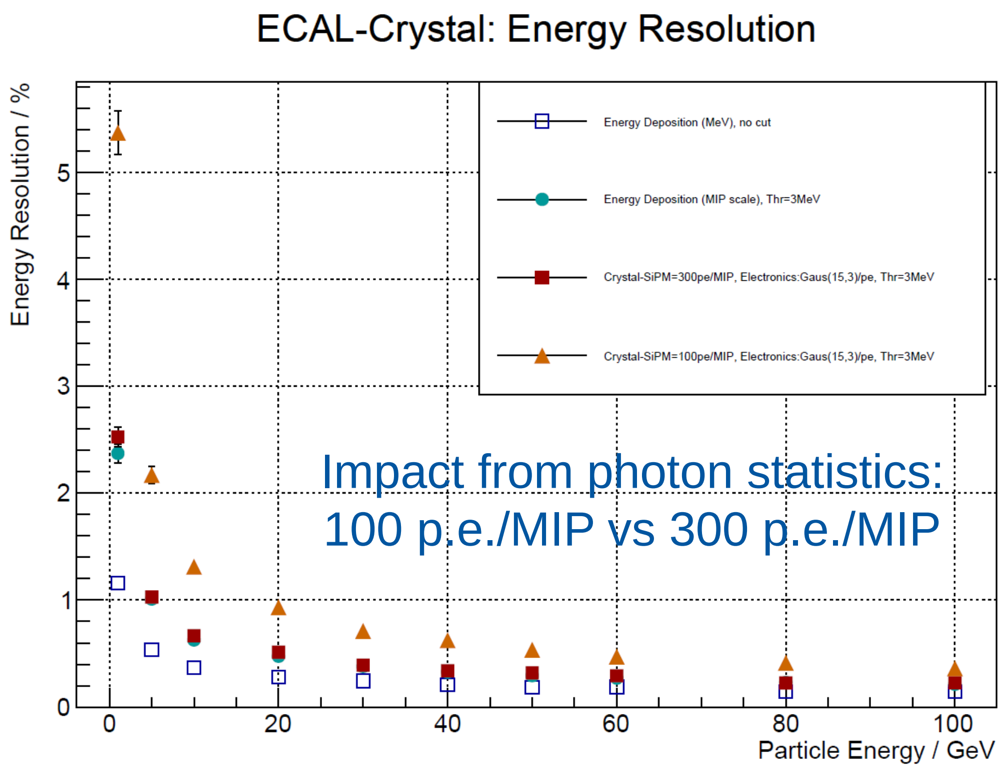
Calibrated MIP signals: including photon statistics + electronics

- 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.

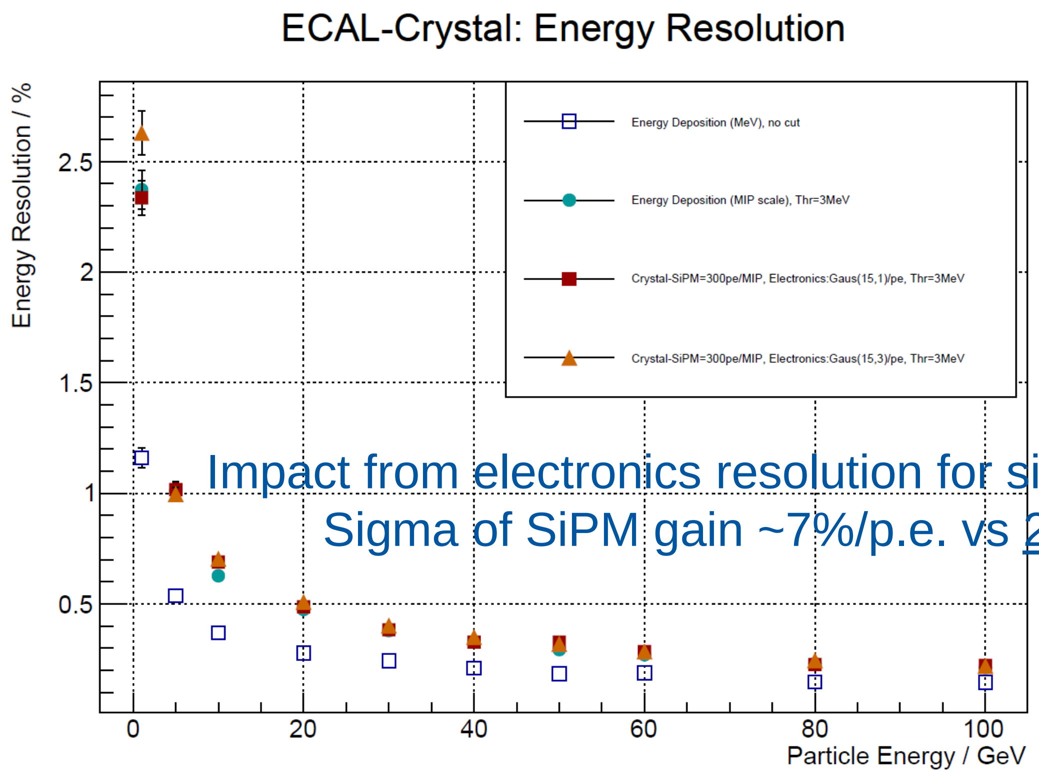
Digitizer in simulation for crystal ECAL

Geant4 version 10.5.0

MC samples: electrons



Impact from photon statistics:
100 p.e./MIP vs 300 p.e./MIP

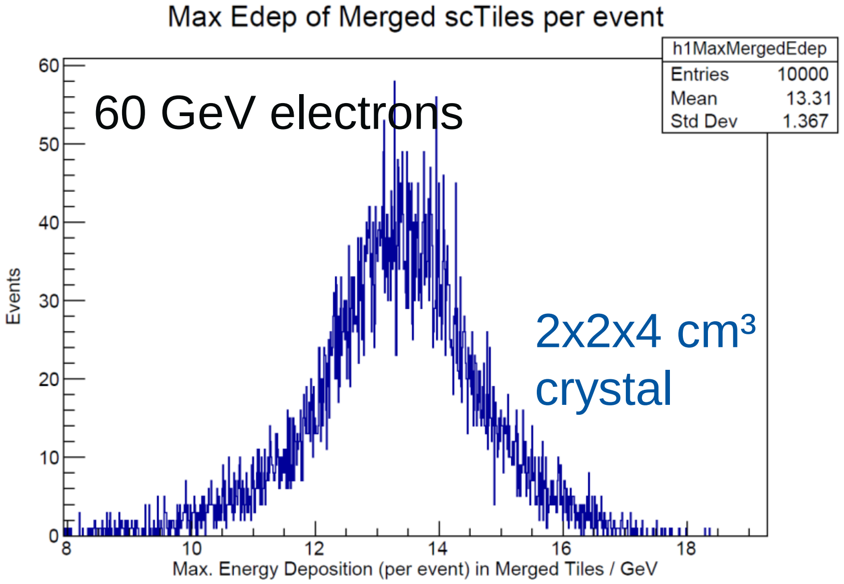


Impact from electronics resolution for single photons:
Sigma of SiPM gain ~7%/p.e. vs <u>20%/p.e.</u>

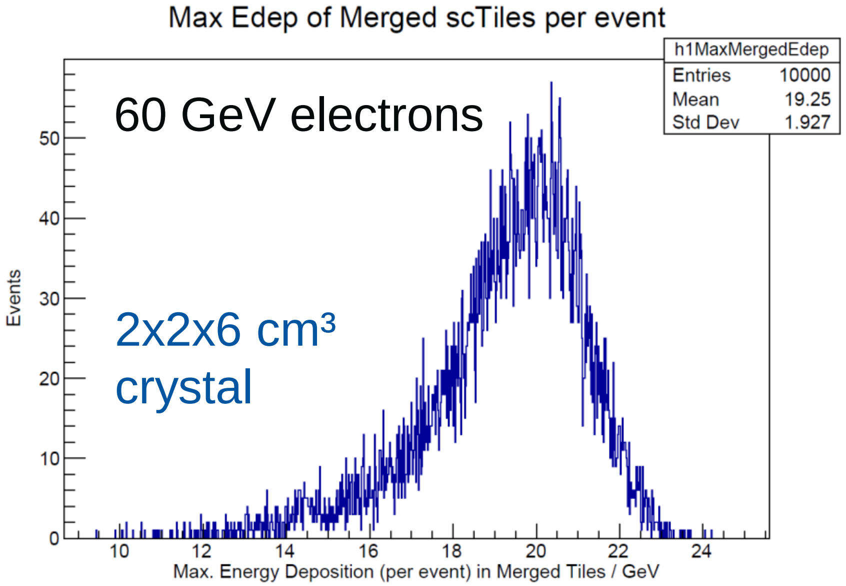
- Quantitative studies for the impacts of photostatistics and electronics
  - Stochastic terms: ~5% for lower light yield (e.g. PWO), ~2% for higher light yield (e.g. BGO)
  - Negligible impact from single photon resolution at energy regions > 5GeV

Dynamic range: simulation with high-energy electrons

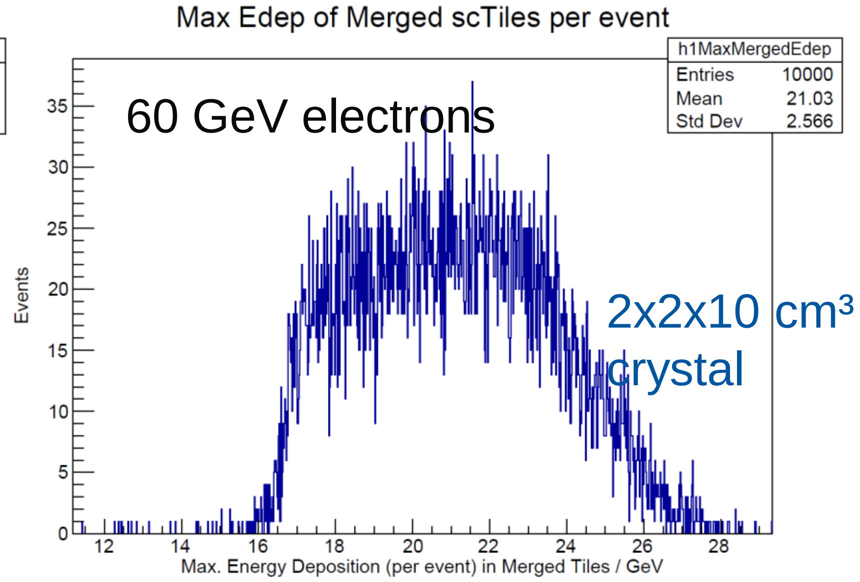
- Maximum energy deposition per cell
  - Depends on the crystal segmentation configurations
  - Provide inputs for the SiPM and its readout electronics



~13 GeV/cell



~19 GeV/cell

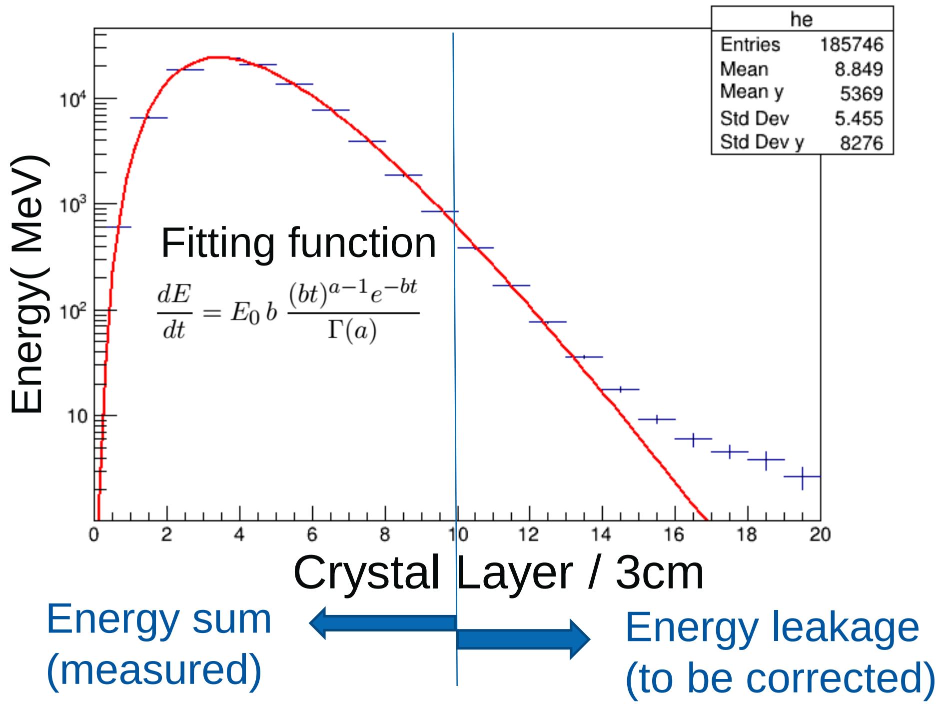


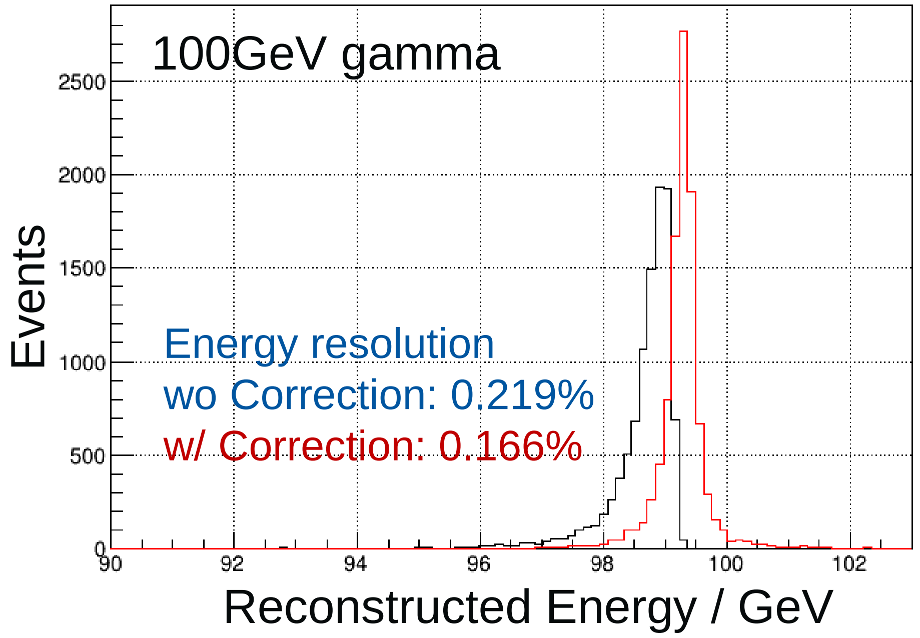
~21 GeV/cell

Crystal granularity optimisations

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)

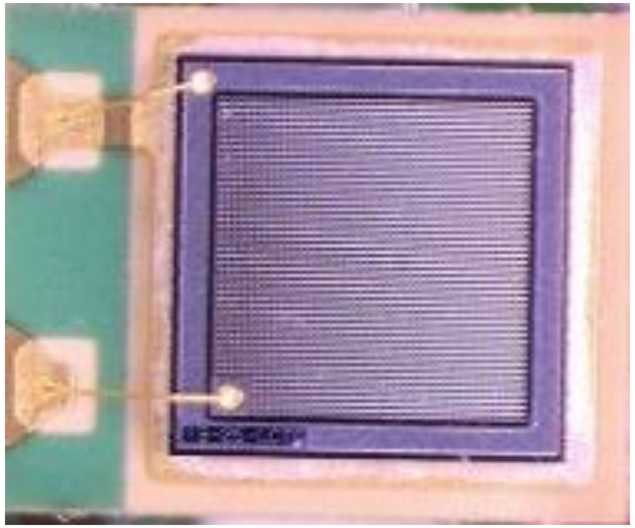


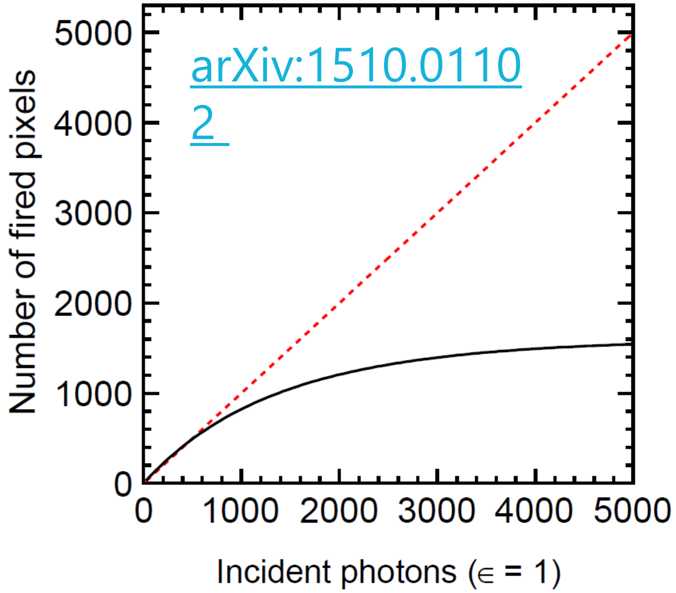


30cm long BGO (~27X0), 10 layers, 3cm per layer

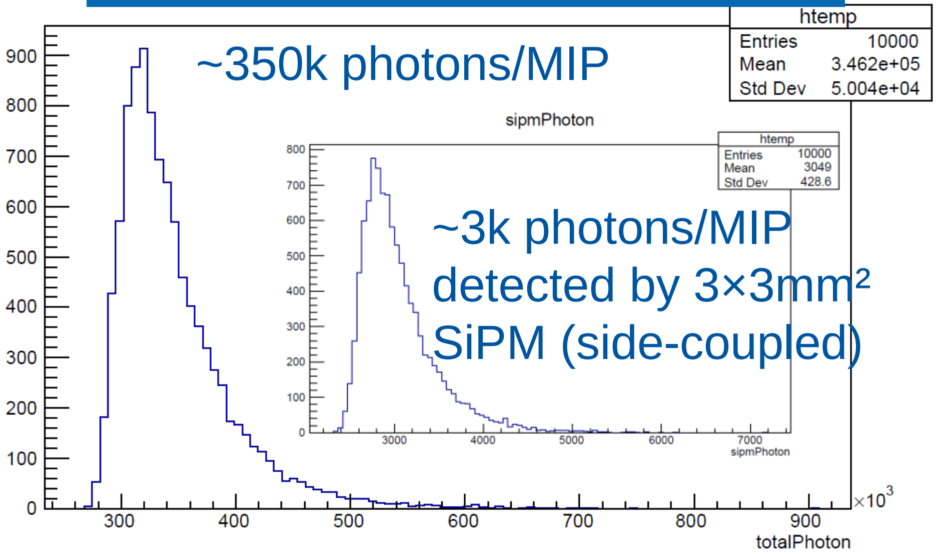
Crystal cells: dynamic range

- 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





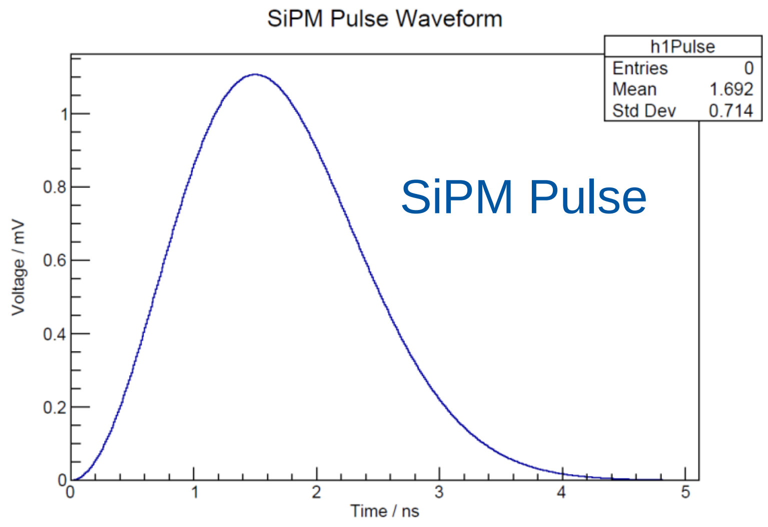
Geant4 simulation of BGO crystal



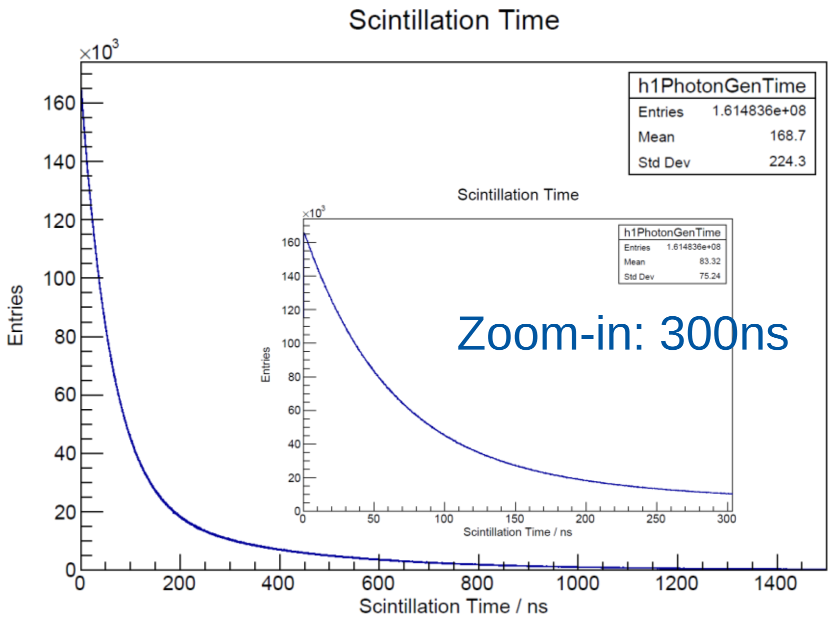
~40 MeV energy deposition for 1 GeV muons passing through a 45 mm crystal bar (BGO)

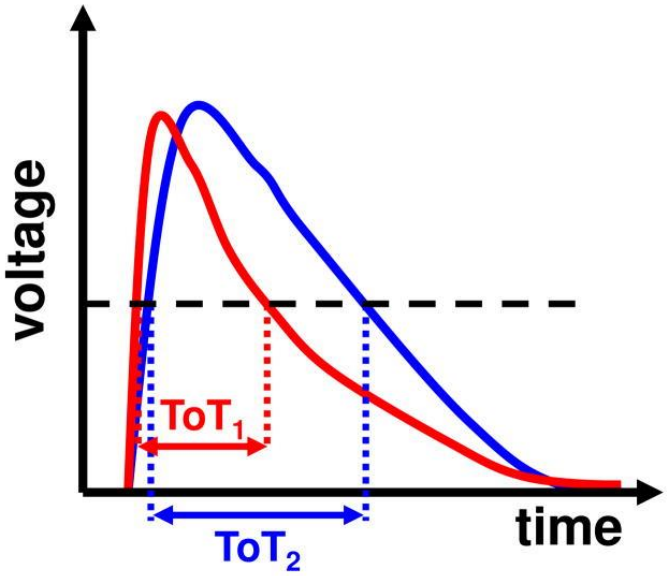
Crystal cells: dynamic range

- 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

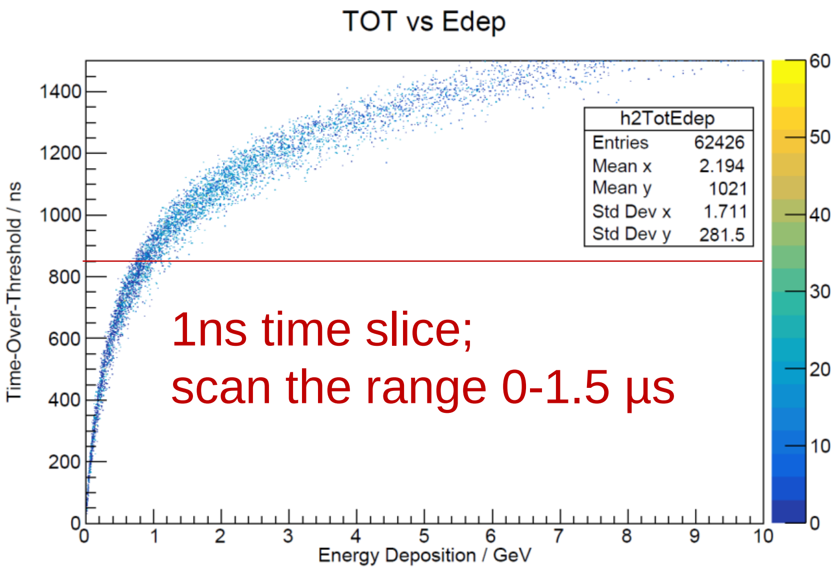


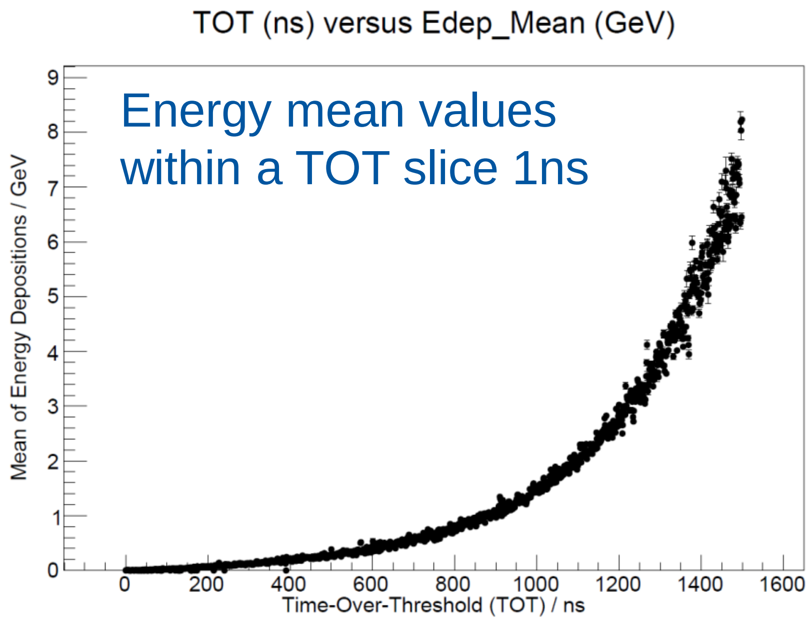


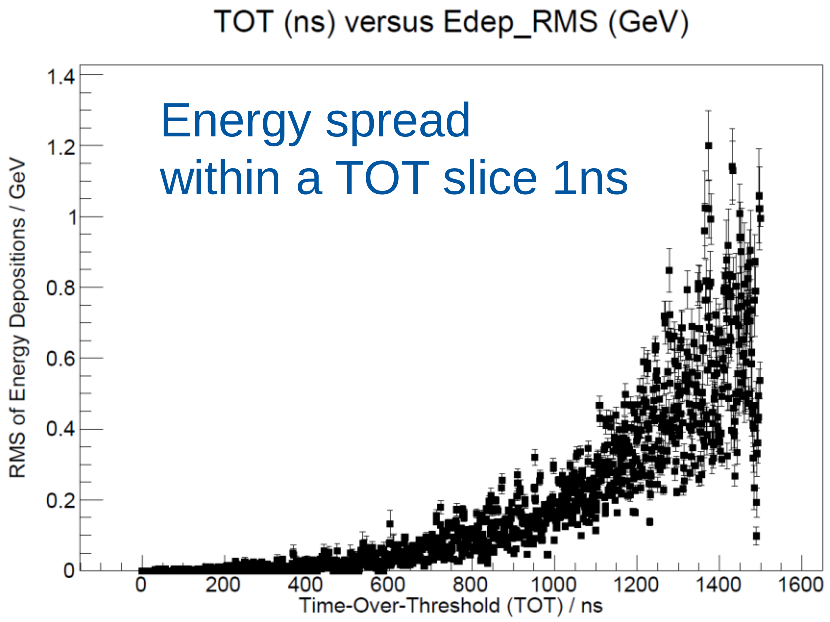
Computing intensive for the simulation (>1M photons); techniques developed to fasten the procedure

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



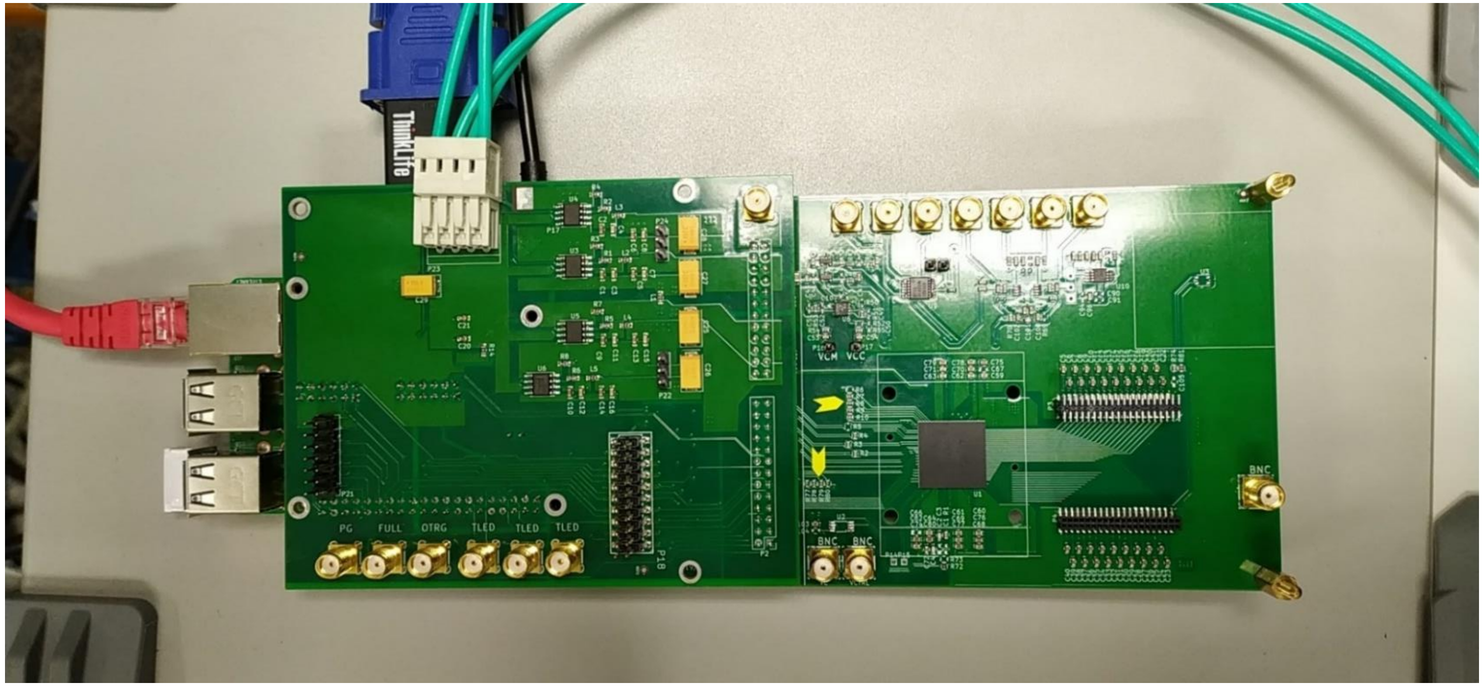


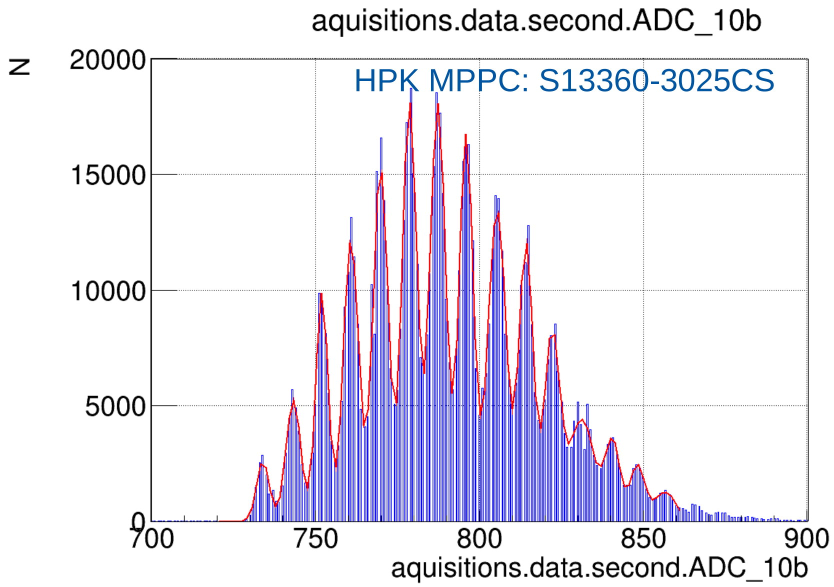


Front-end electronics for SiPM readout

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

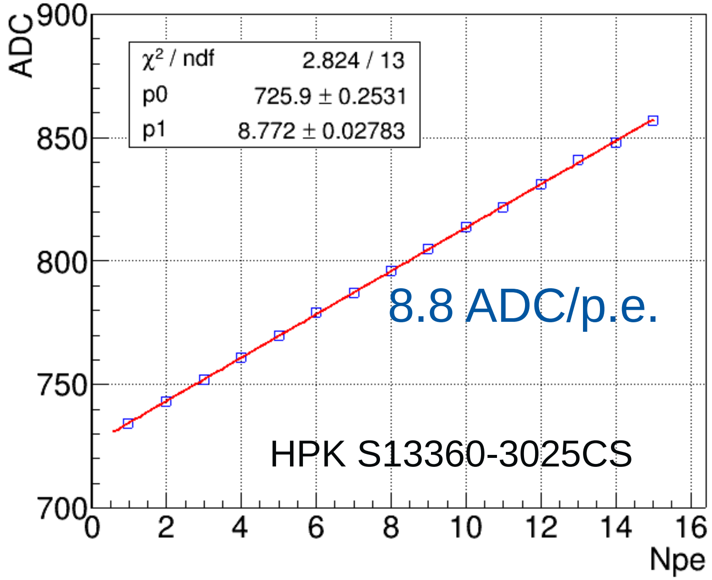




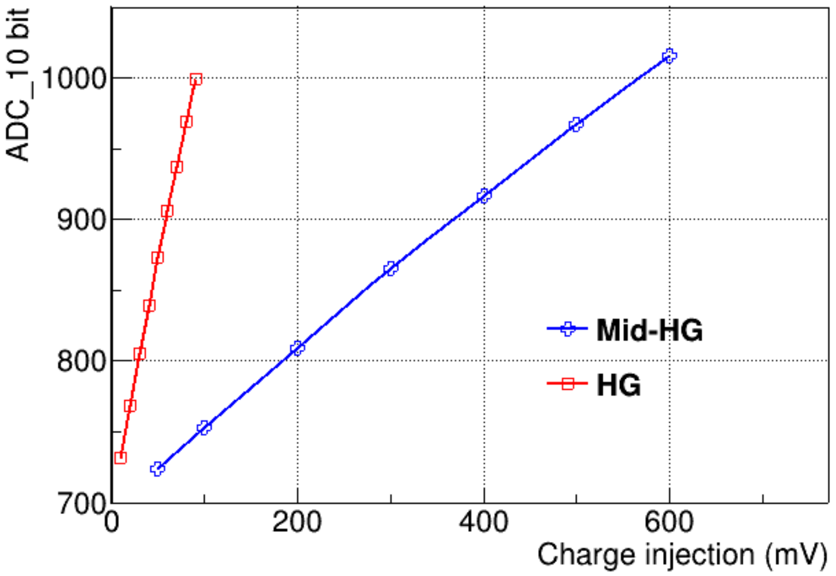
Klaus5: first tests with SiPM and light sources

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

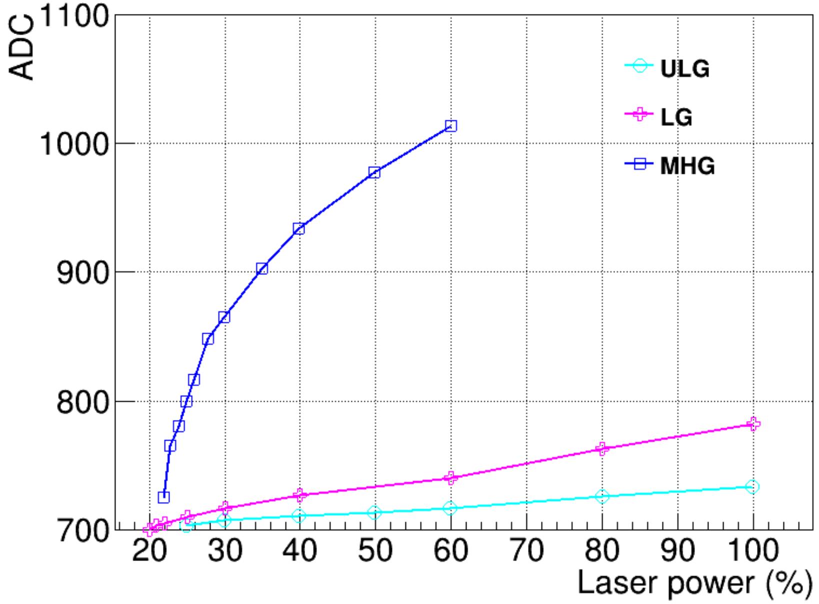
LED calibration in High Gain



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)

Crystal options

	BGO	$PbWO_4$
Density (g/cm³)	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 placed in the backup)