A novel concept of 4D crystal calorimetry for future lepton colliders: R&D highlights

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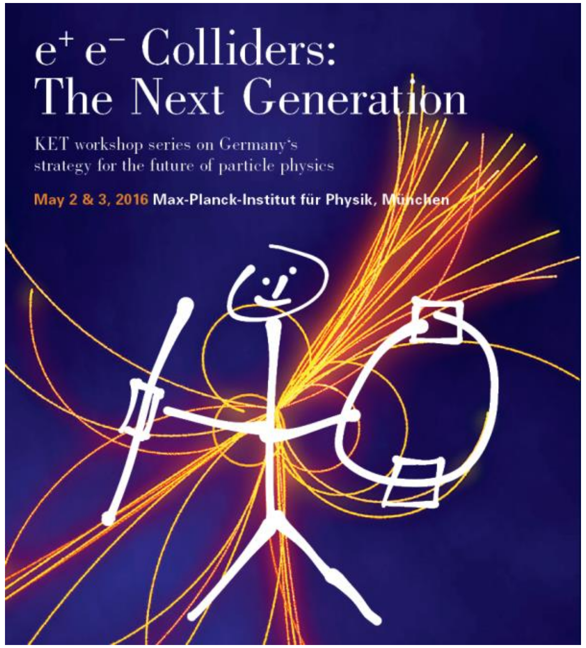
Chinese Physics Society HEP Branch: Annual Meeting 2021

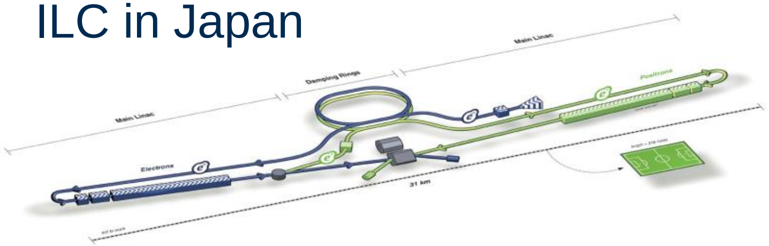
August 16-19, 2021

Next-generation colliders: a brief overview

- Higgs factory: consensus in strategies of global HEP community
  - A next-generation collider will most likely be an electron-positron collider
  - Precision measurements of the Higgs boson; use Higgs as a probe for new physics
- Challenge: requires unprecedented jet energy resolution (calorimetry as a key)

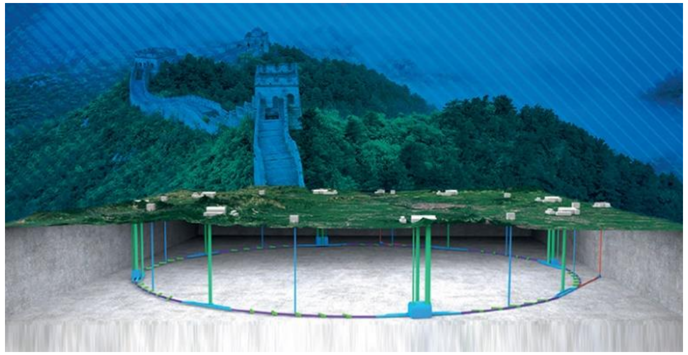


ILC in Japan

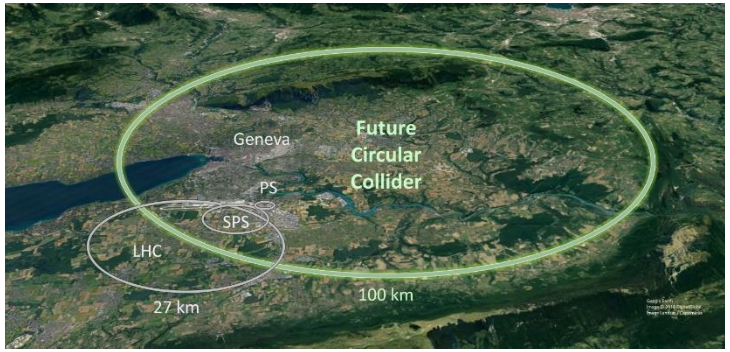


CLIC at CERN

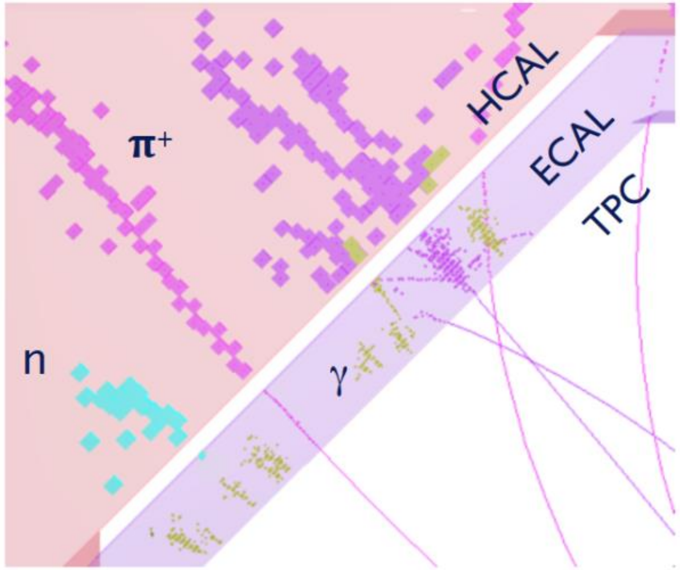
CEPC in China

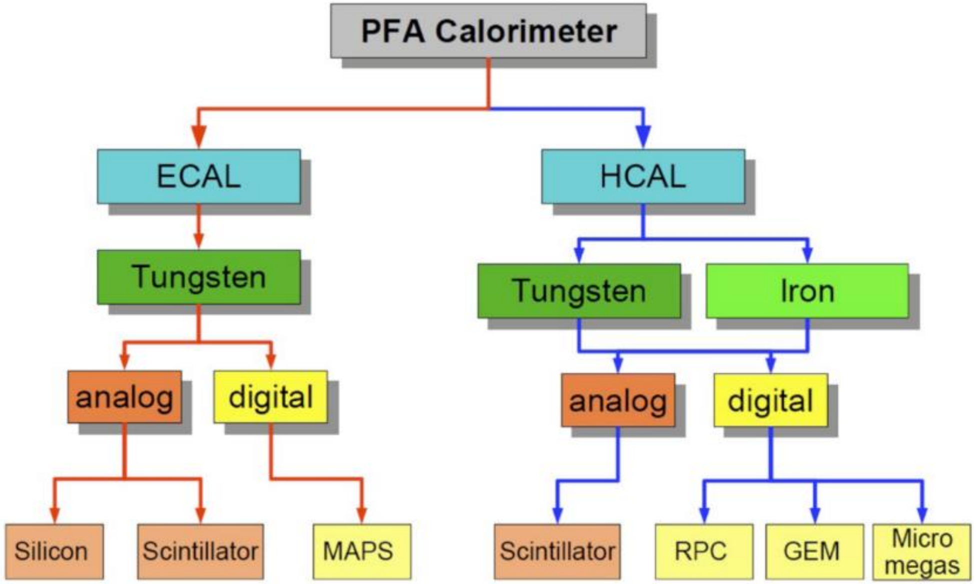


FCC at CERN



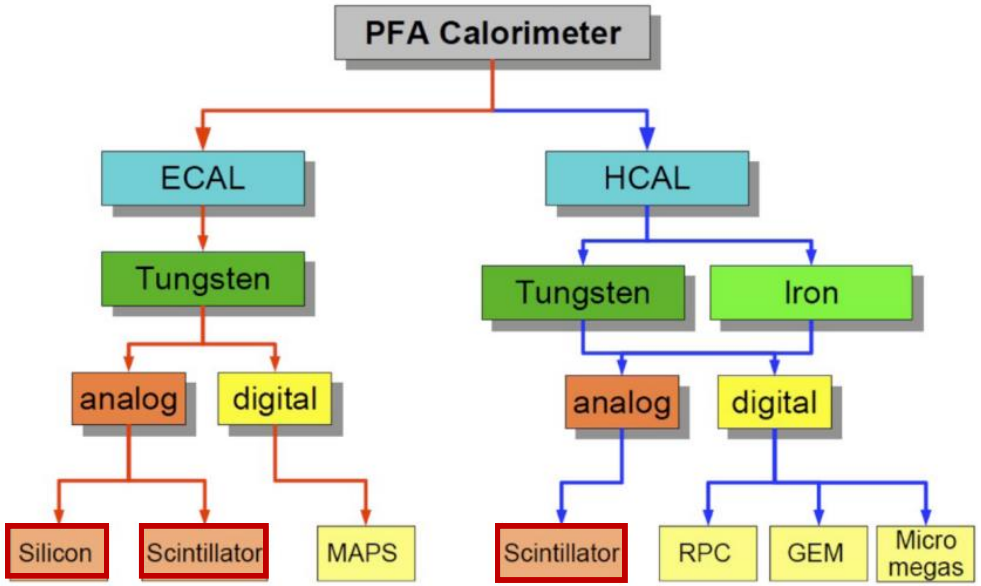
High-granularity calorimeters





- Particle Flow Algorithm (PFA)
  - Choose sub-detector best suited for each particle type
  - Separate showers of close-by particles in the calorimeters
- High-granularity (imaging) calorimeters: R&D within the CALICE collaboration
  - Hardware: explosion of readout channels (on the order of 1~10 million)
  - Compact (all inside magnet), hermetic (minimum gaps), limited space for instrumentation

High-granularity calorimeters



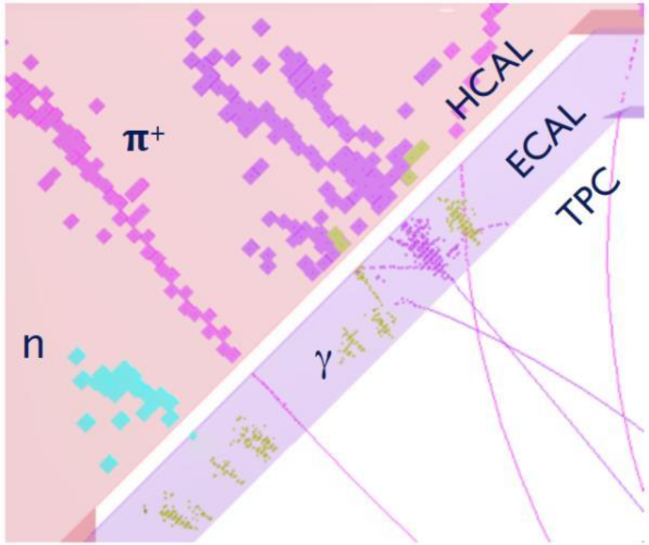
Other talks on PFA calorimeters in this conference:

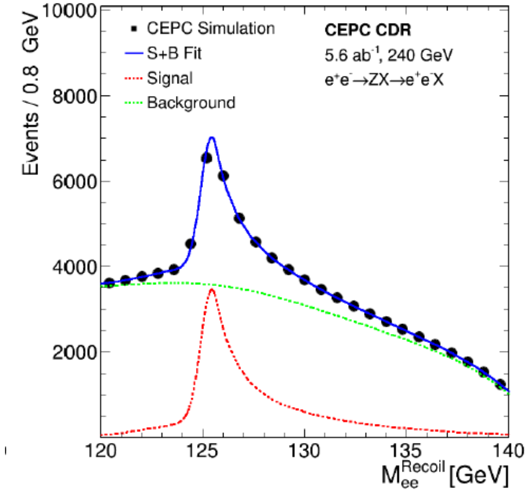
- Silicon-Tungsten ECAL in the CMS-HGCAL project
  - H.Q. Zhang: Development of the CMS-HGCAL silicon module center in Beijing
- Scintillator-Tungsten ECAL
  - Y.Z. Niu: Development of a highly granular electromagnetic calorimeter prototype for the CEPC
- Scintillator-Steel HCAL
  - Y.K. Shi: R&D activities of highly granular hadron calorimeters for the CEPC

- High-granularity (imaging) calorimeters: R&D efforts within the CALICE collaboration
  - Excellent spatial resolutions (good separation capability) and timing resolution for (pile-up rejection, etc.)
- Existing designs: sampling structures (sensitive layers + absorber plates)
- A novel design proposed with finely segmented crystals: homogeneous calorimeter for PFA

Major motivations

- Background: future lepton colliders
  - 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: precision γ/π^0 reconstruction
    - Potentials in search of BSM physics
  - Fast timing capability
- 4D calorimeter with finely segmented crystals: spatial + timing
  - PFA capability for precision measurements of jets
  - Jet energy resolution aims for 3~4%

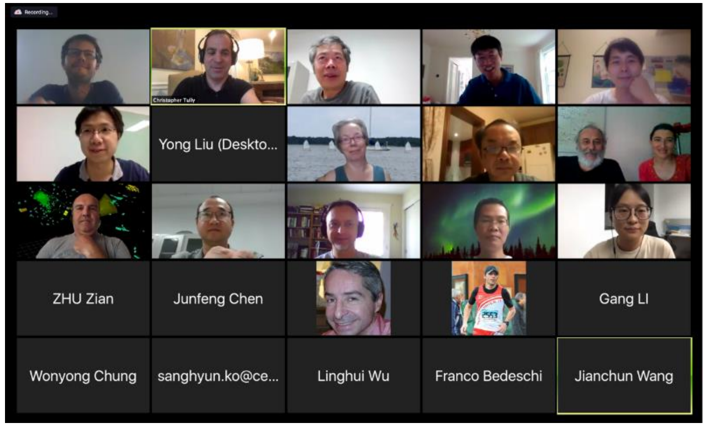




High-granularity Crystal Calorimeter: past events

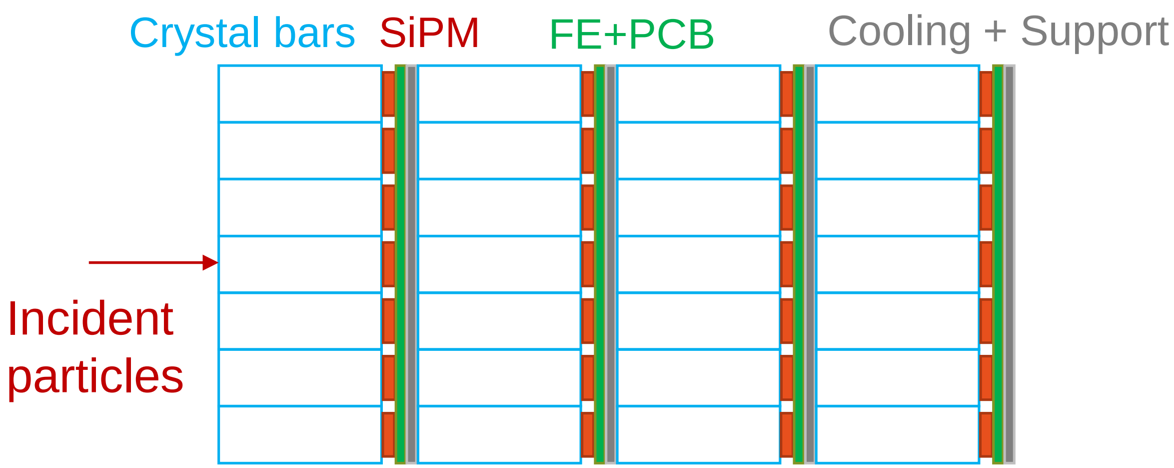
- Firstly proposed in CEPC calorimetry workshop (March 2019)
- Follow-up workshop: Mini-workshop on a detector concept with a crystal ECAL
- R&D efforts targeting key issues and technical challenges

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



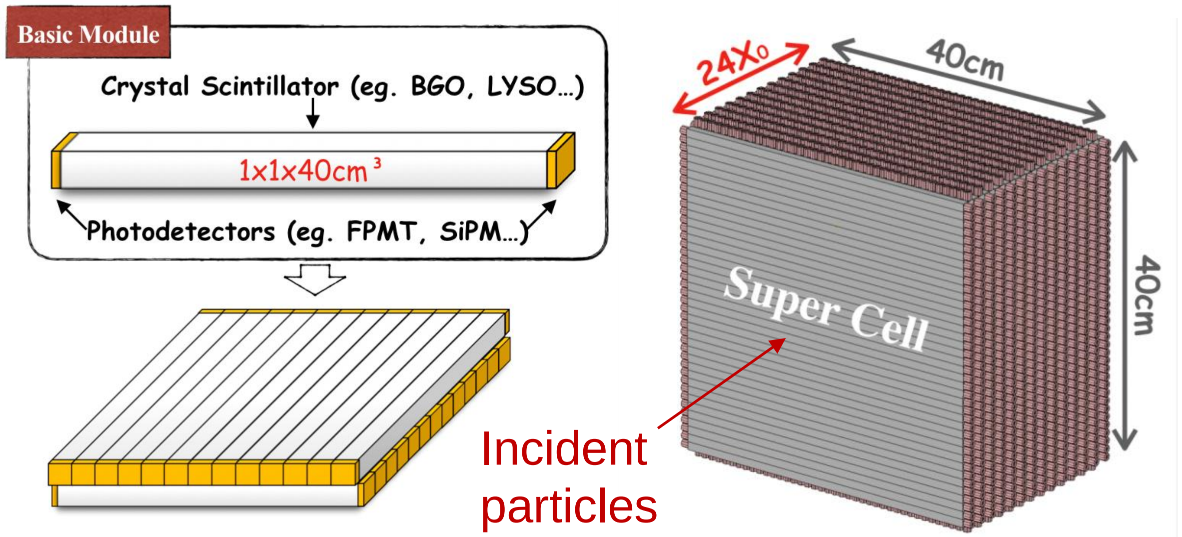
High-granularity crystal ECAL: 2 major designs

Design 1: short bars



- A natural design compatible with PFA
  - Fine segmentation in both longitudinal and transverse
  - Single-ended readout

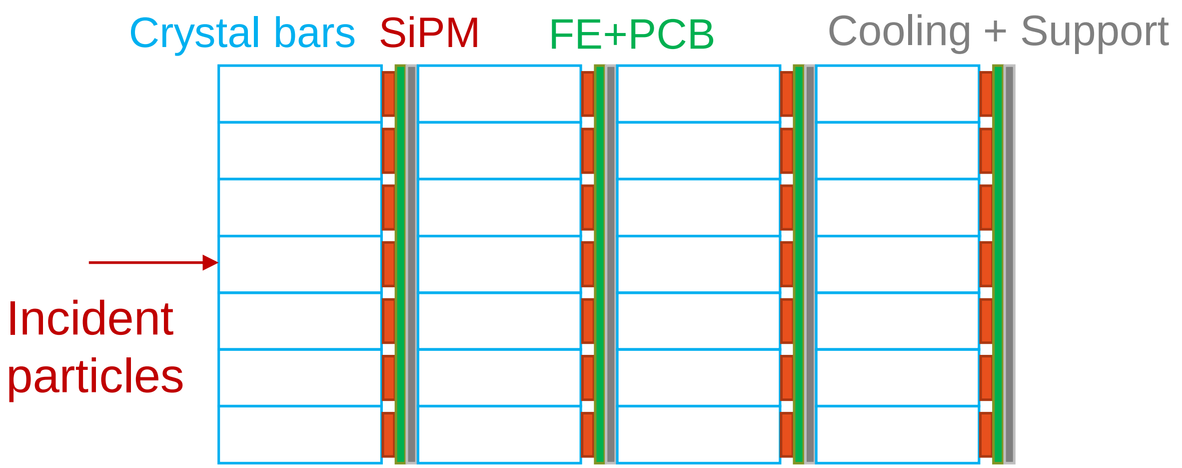
Design 2: long bars



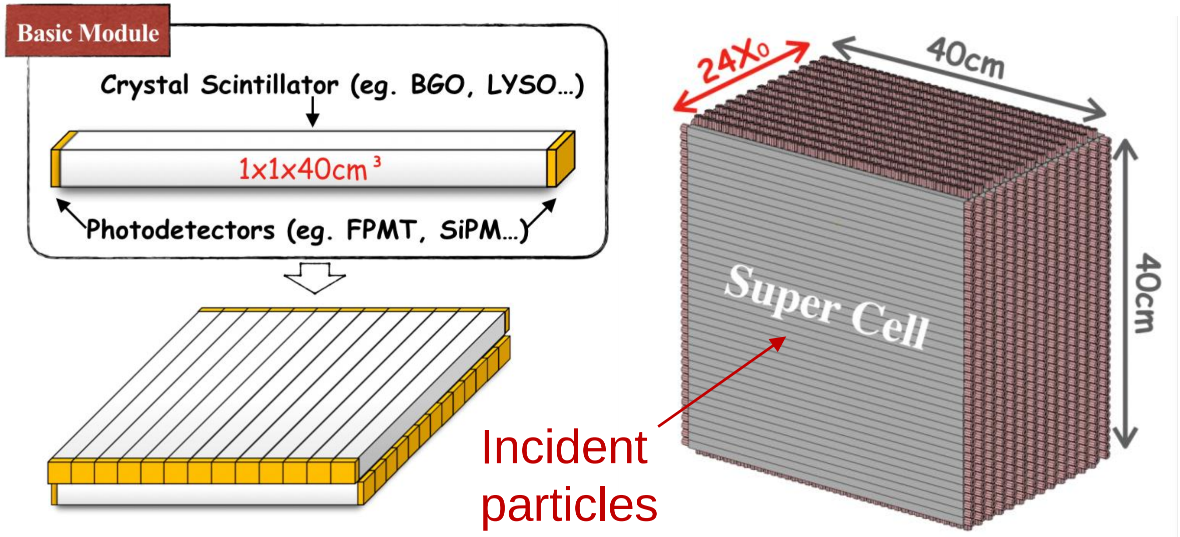
- Long bars: 1×40cm, double-sided readout
  - Super cell module: 40×40cm
  - Crossed arrangement in adjacent layers
  - Fine longitudinal granularity
- Save #channels and minimize dead materials
- Timing at two sides: positioning along bar

High-granularity crystal ECAL: 2 major designs

Design 1: short bars



Design 2: long bars (major focus)



- **Focus on PFA performance studies**
- Crystal cubes (ideal granularity) for physics benchmarks
- Inputs for optimization of the existing PFA for crystals

- **Focus on reconstruction algorithm development**
- **Key issues**
  - Separation capability of multiple incident particles (of jets)
  - PFA performance

R&D efforts targeting key issues and technical challenges

- Key issues: performance studies and optimization
  - Detector layout design
  - Reconstruction algorithms
  - Performance: single/multiple particles, physics benchmarks
  - Impacts from dead materials: upstream tracker, services (cabling, cooling)
  - Potentials: dual-gated or dual-readout for better hadronic energy resolution
- Critical technical questions/challenges
  - Detector unit design: 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.
  - Light-weight cooling and supporting mechanics
  - Calibration schemes and monitoring systems: SiPMs, crystals and ASICs
  - System integration: scalable detector design (modules), mass assembly, QA/QC

Crystal calorimeter: R&D highlights

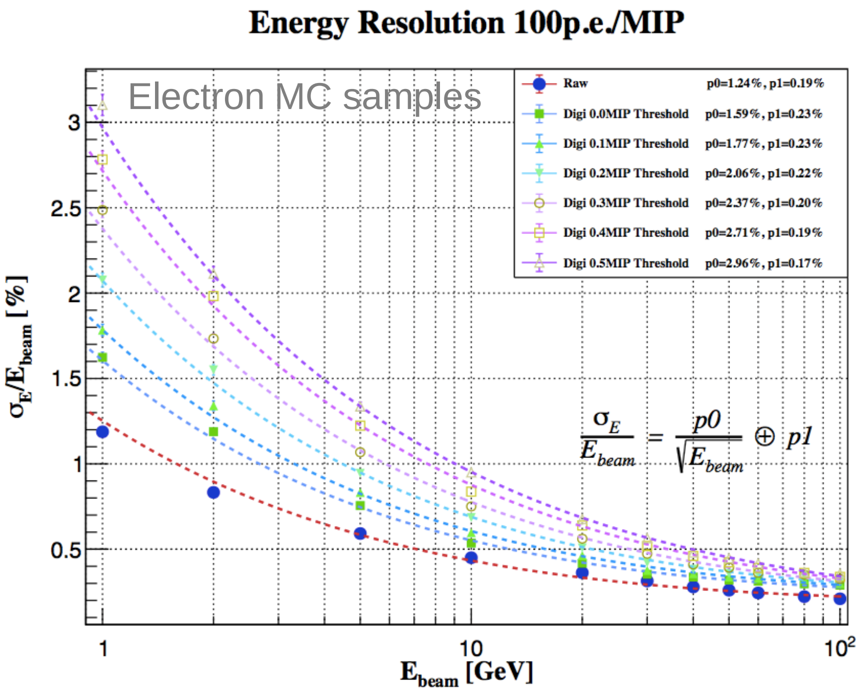
- Performance studies
  - EM energy resolution
  - Higgs benchmark $ZH(Z \to \nu\nu, H \to \gamma\gamma)$: BMR
  - Neutral pions: invariant mass resolution

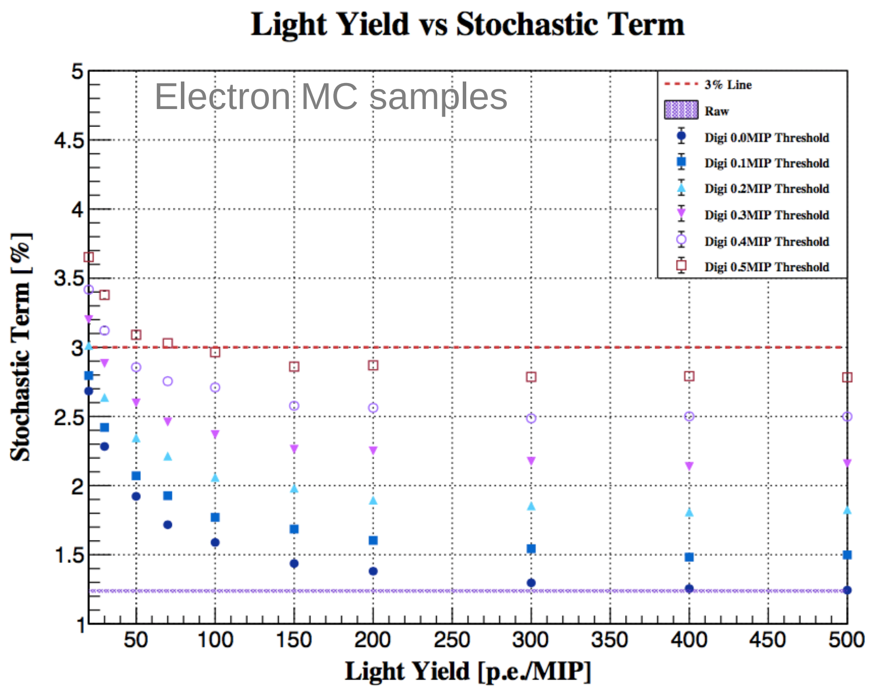
- Reconstruction for the design with long bars
  - Fast simulation studies
  - Algorithm development and performance studies

- Technical developments: crystals-SiPM and electronics
  - Geant4 full simulation with optical physics processes
  - Energy resolution and response uniformity: measurements with radioactive sources
  - SiPM-readout ASIC tests

Crystal calorimeter: Geant4 simulation studies

- EM energy resolution: impacts from different aspects
  - MIP response ("light yield" in plots) and energy threshold
  - Digitisation: photon statistics (crystal+SiPM), electronics resolution



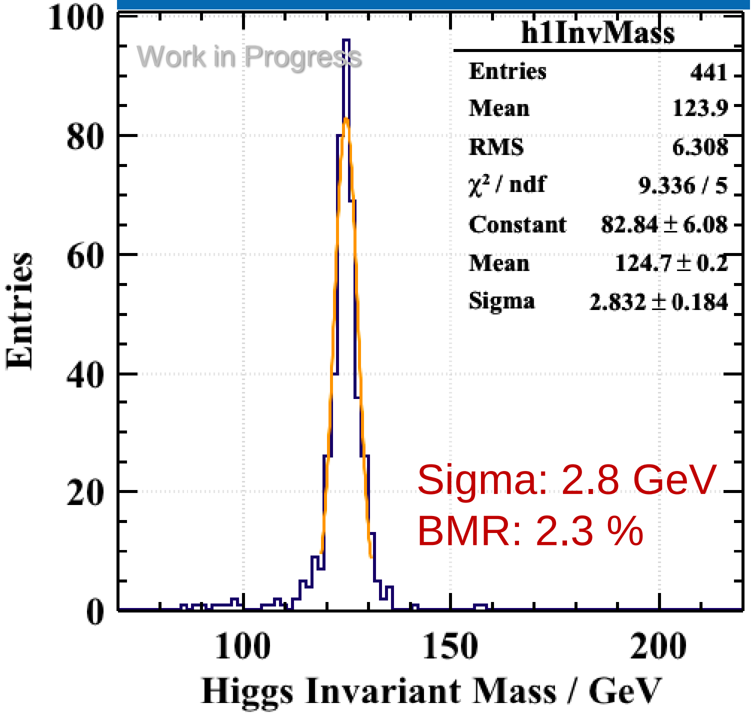


- Moderately high light yield and low threshold required for better than 3% stochastic term

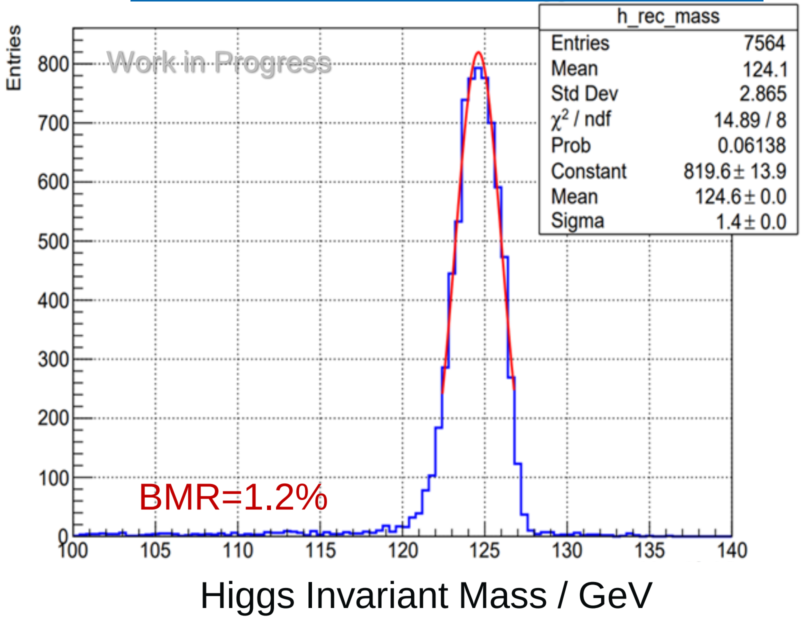
Physics benchmark with two photons in final states

- Full simulation studies with $ZH(Z \to \nu\nu, H \to \gamma\gamma)$ at 240 GeV
  - Compared with the SiW ECAL option (stochastic term ~17%) in CEPC CDR
  - Crystal ECAL improves Boson Mass Resolution (BMR) by a factor of ~2

Detector with SiW ECAL option



Detector with SiW ECAL option

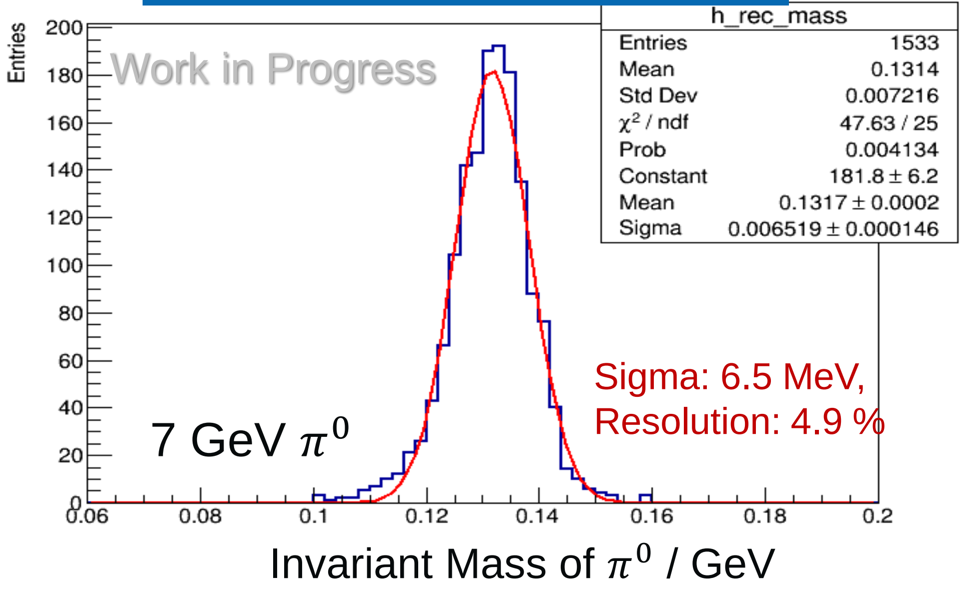


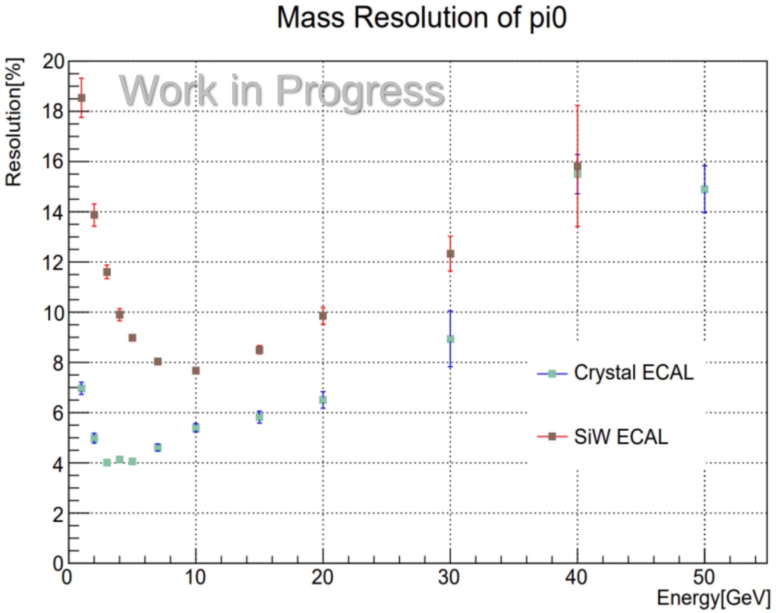
Constant term in energy resolution not included; to be further studied

Performance studies: neutral pions with Arbor-PFA

- Reconstruction of π^0 in ECAL: invariant mass and its resolution
  - Single π^0's generated by the particle gun
  - Significant resolution improvement with crystals compared with SiW ECAL
  - Further studies on photon positioning/angular resolution: ongoing

Detector with Crystal ECAL



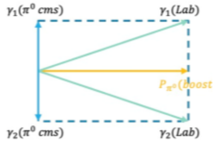


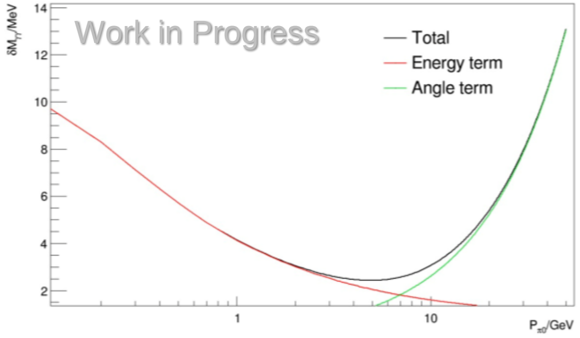
Mass width with P_{π^0}

Totally from calculation: $\frac{\delta m}{m} = \frac{\delta E_1}{2E_1} \oplus \frac{\delta E_2}{2E_2} \oplus \cot\frac{\theta}{2}\frac{\delta\theta}{2}$.

For two photons: $E_1 = E_2$, $\theta = \theta_{min}$.

Resolution: $\frac{\delta E}{E} = a \oplus \frac{b}{\sqrt{E}}$, a=1%, b=3%. $\delta\theta = 0.03°$





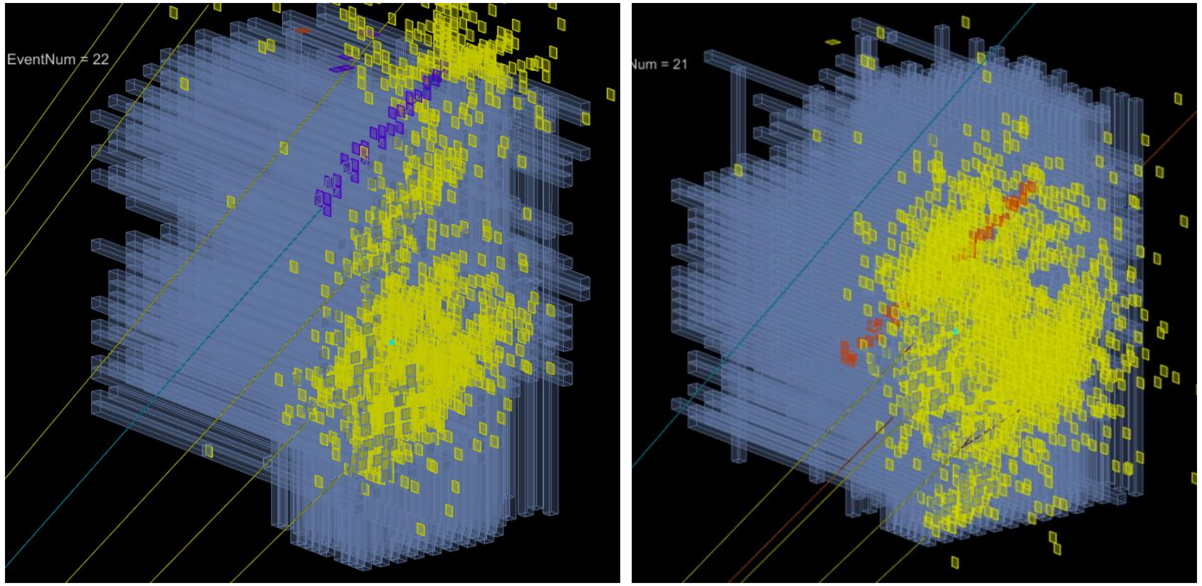
Crystal calorimeter: R&D highlights

- Performance studies
  - Higgs benchmark $ZH(Z \to \nu\nu, H \to \gamma\gamma)$: BMR
  - Neutral pions: invariant mass resolution
- Reconstruction for the design with long bars
  - Fast simulation studies
  - Algorithm development and performance studies
- Technical developments: crystals-SiPM and electronics
  - Geant4 full simulation with optical physics processes
  - Energy resolution and response uniformity: measurements with radioactive sources
  - SiPM-readout ASIC tests

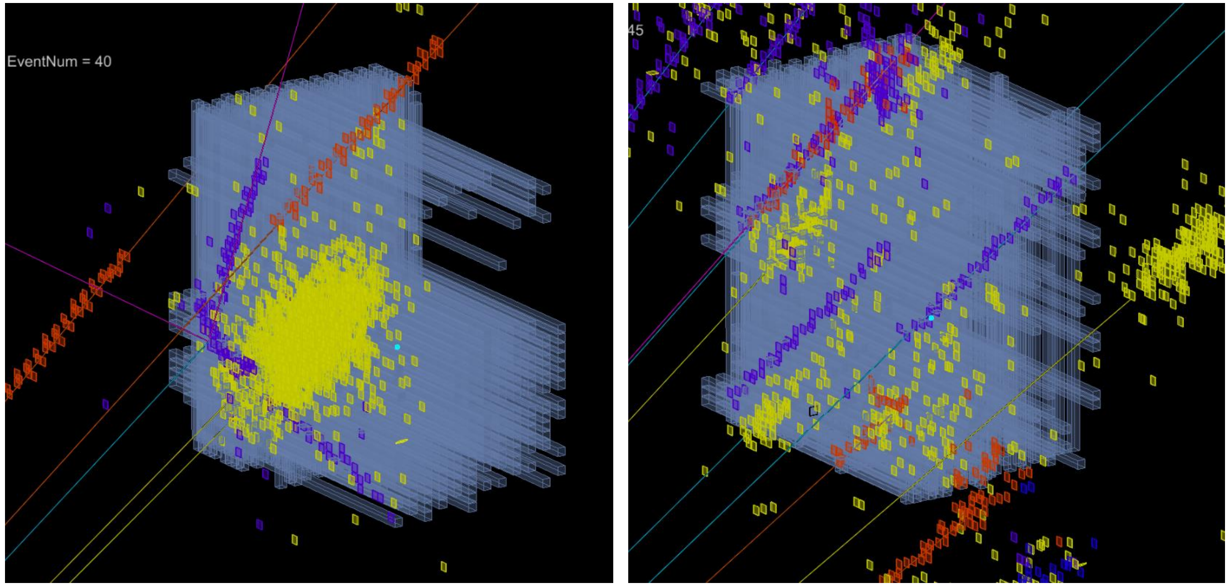
Jets in crystal calorimeter: event display

- Impressions of topology of EM/hadron showers within jets
- Intuitive guidance for the reconstruction development
- Strategy
    - First studies with (close-by) EM showers and MIP-like particles
    - Then hadron showers: due to intrinsic complexity

Di-jet events from $Z \rightarrow qq$



Multiple gammas and a charged pion



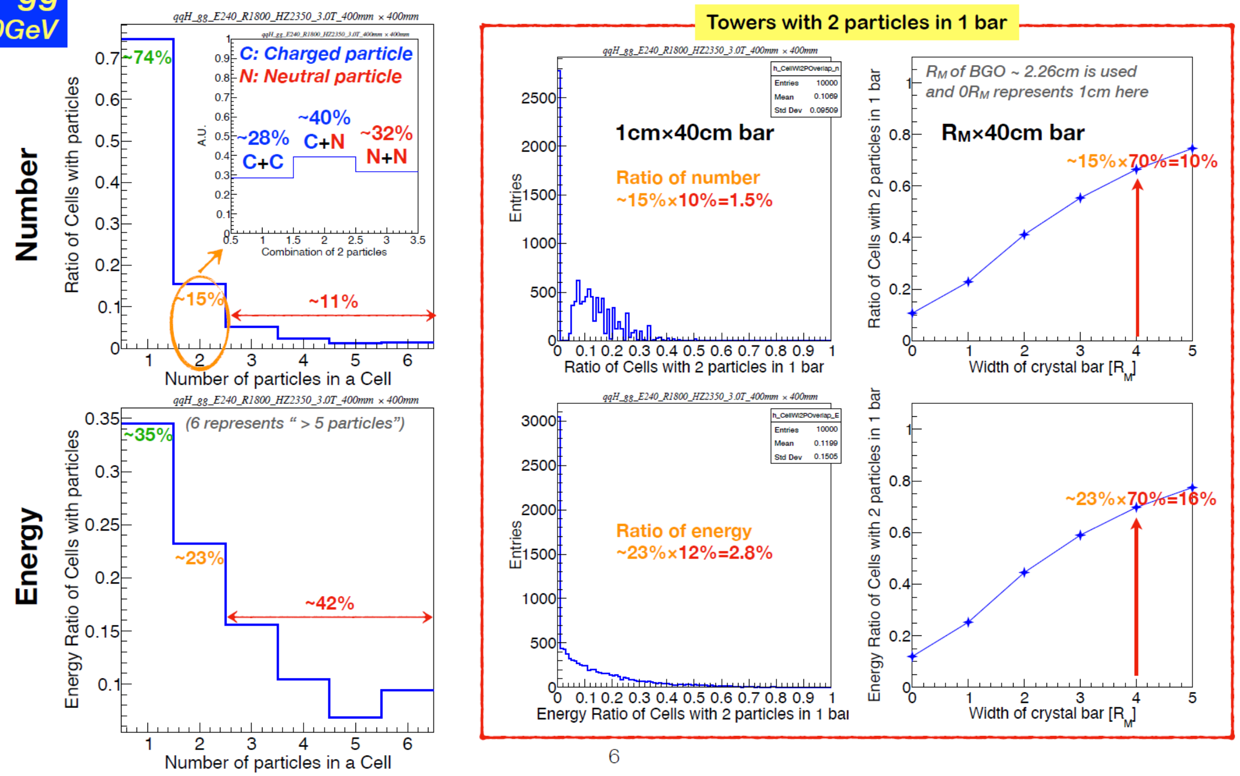
Multiple gammas and hadrons

Studies on physics requirements: fast simulation

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

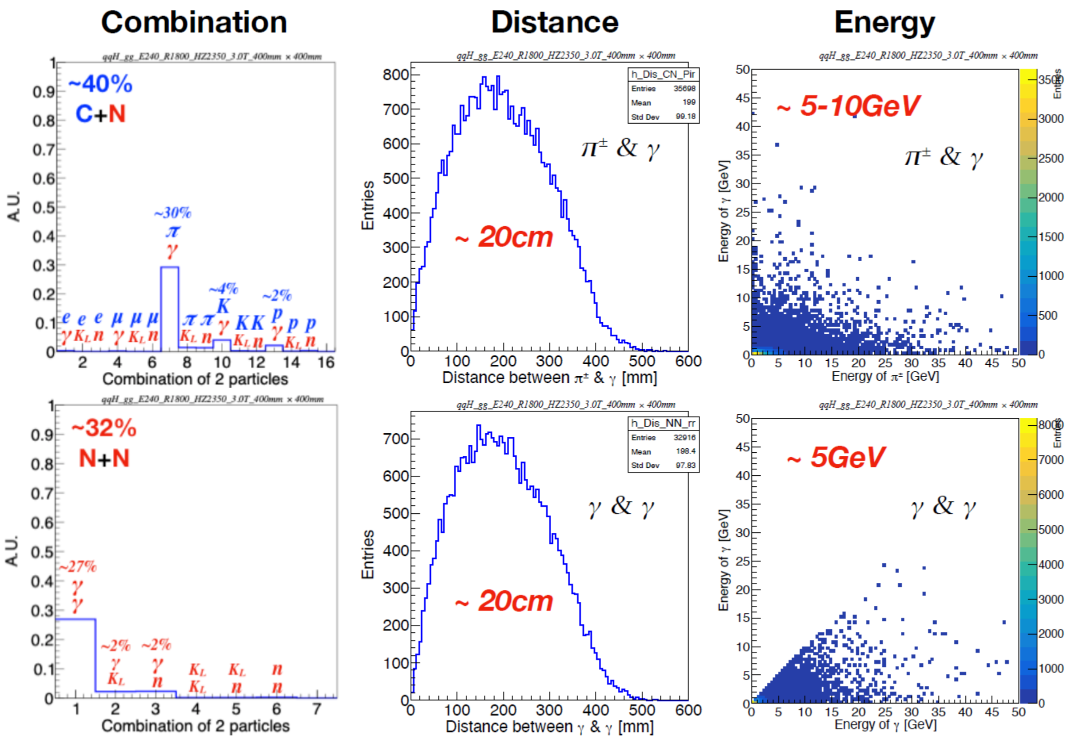
$Z \to qq$
$H \to gg$
240GeV

Multiplicity in a 40cm×40cm tower



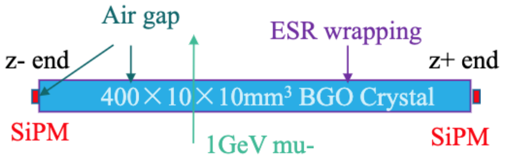
Tower with 2 particles: distance & energy distribution

$Z \to qq$
$H \to gg$
240GeV

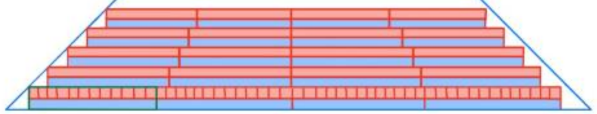


Layout with long crystal bars: simulation and reconstruction

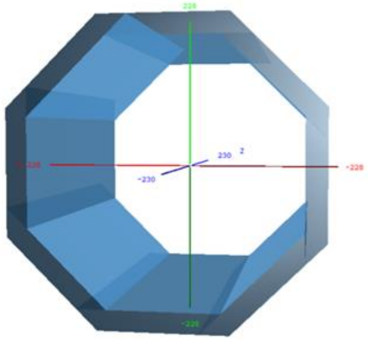
- Simulation
  - Established a full barrel geometry with DD4HEP
  - Digitisation: energy threshold and timing resolution

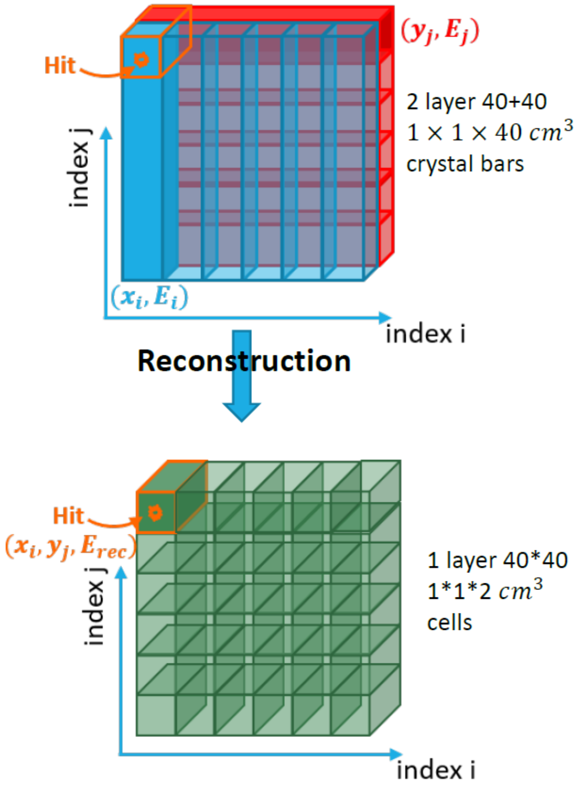


An octave in the barrel ECAL with long crystal bars



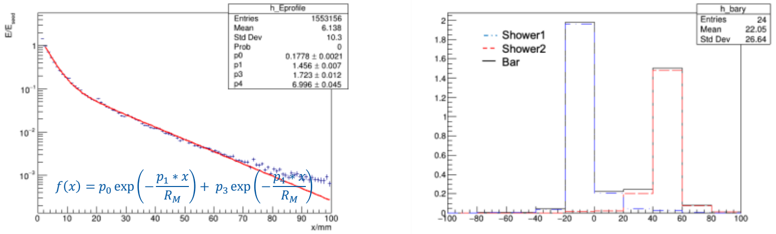
Barrel ECAL



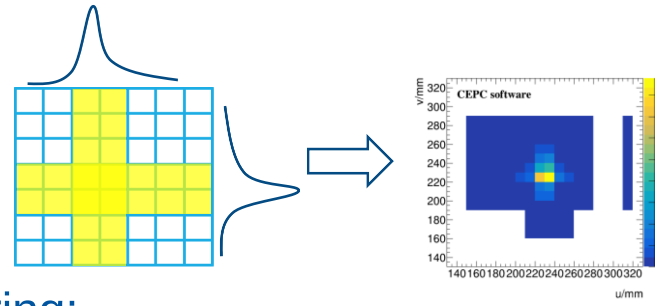


Reconstruction

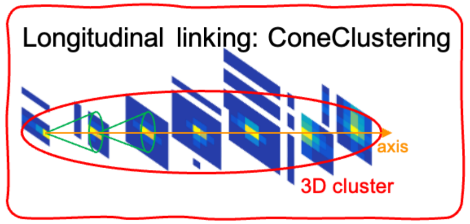
- 1D clustering & cluster splitting:
  - "Seed" in 1D cluster: local maximum && E>5MeV (~0.5MIP).
  - If ≥ 2 seeds in one cluster: split with transverse profile.



- 2D matching: match X-Y bars to showers in plane:

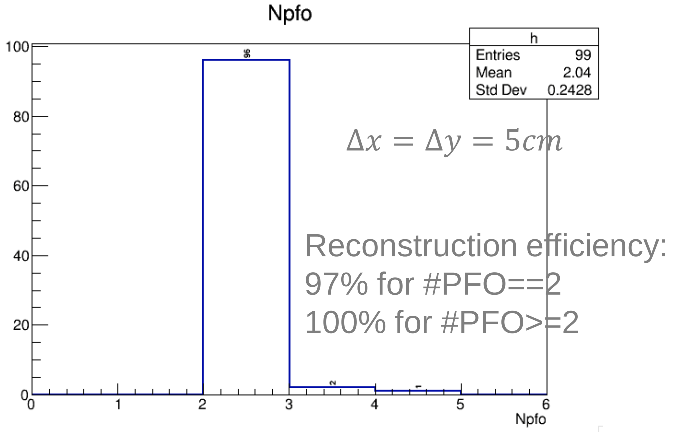


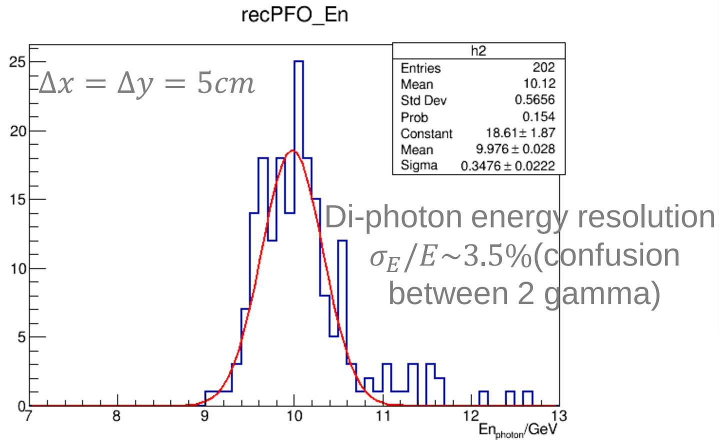
- 3D clustering:



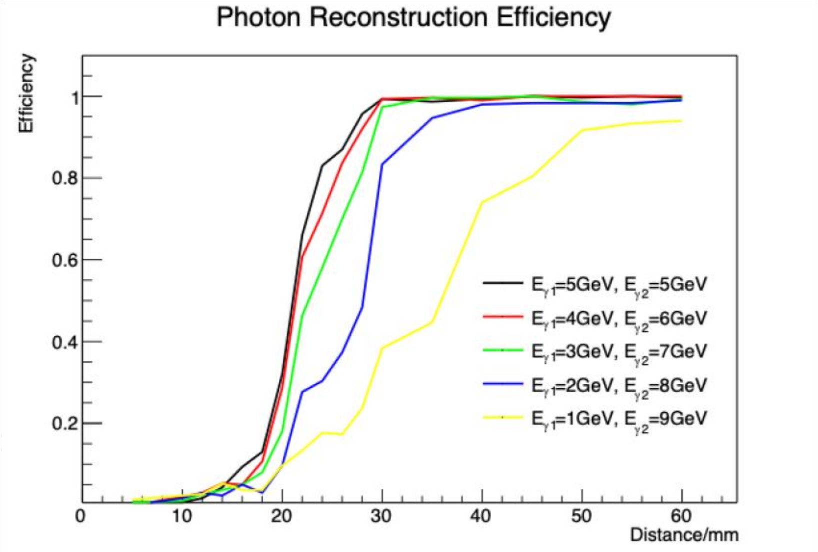
Layout with long crystal bars: reconstruction development

- New algorithm can handle ambiguities of 2 photons: good separation efficiency
- Now working on the reconstruction of hadron showers: to address several challenges

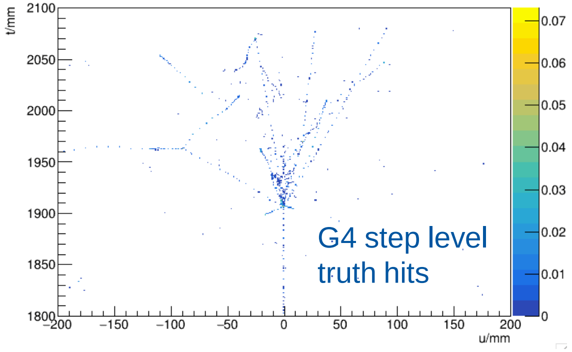


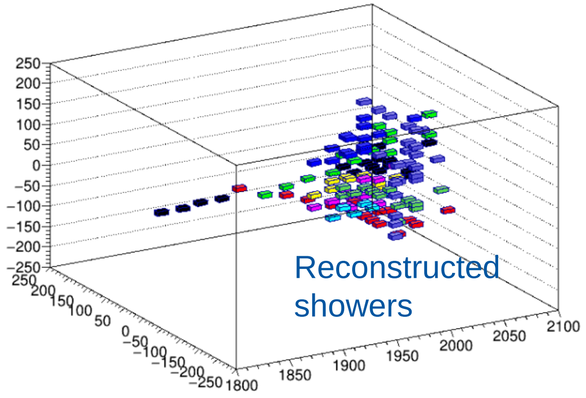


Separation efficiency curve with two photons and with varying distances



Hadron showers: ongoing studies





Crystal calorimeter: R&D highlights

- Performance studies
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  - Neutral pions: invariant mass resolution
- Reconstruction for the design with long bars
  - Fast simulation studies
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- Technical developments: crystals-SiPM and electronics
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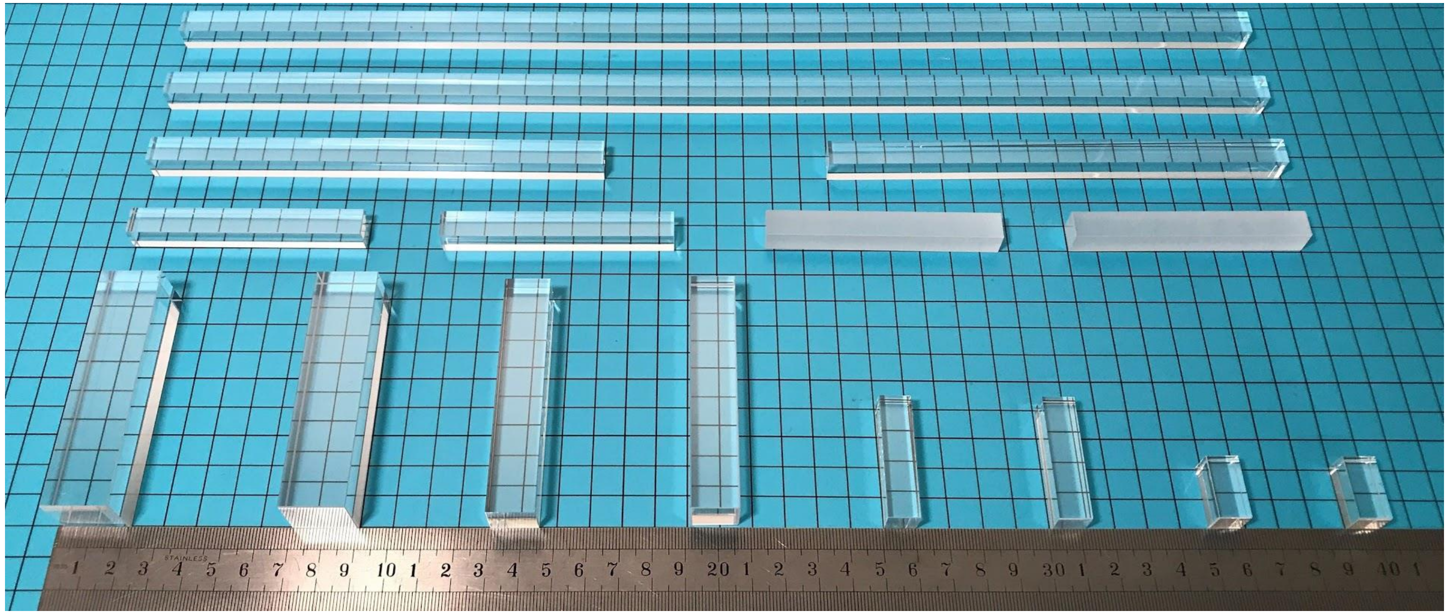
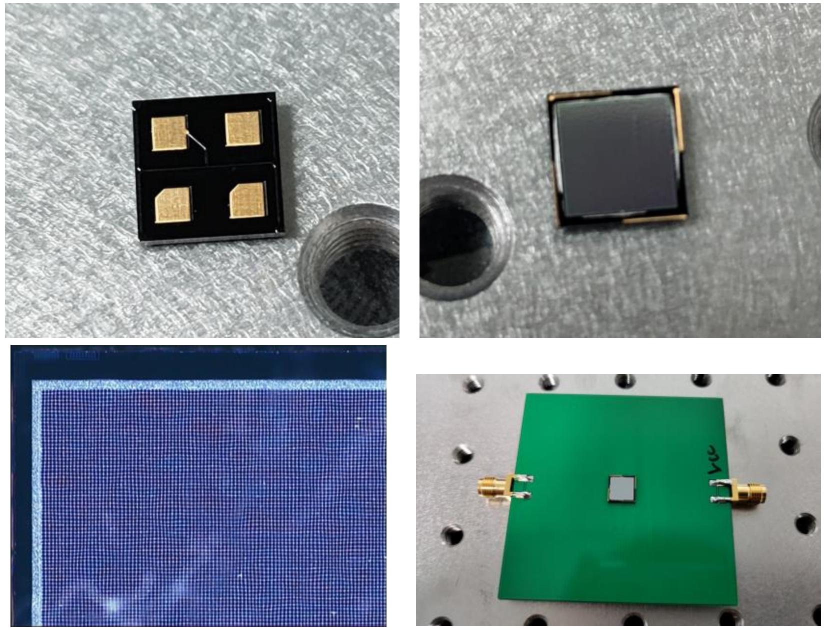
Crystal-SiPM studies

- To address key questions
  - Performance of crystal bars and SiPMs
  - Validation of Geant4 full simulation, which will be used for digitization
- Infrastructure established: mechanics for crystals, SiPM readout electronics
  - To test with SiPMs (different types, vendors) and wrapping foils



BGO crystals (photo courtesy: Dr. Junfeng Chen, SIC-CAS)



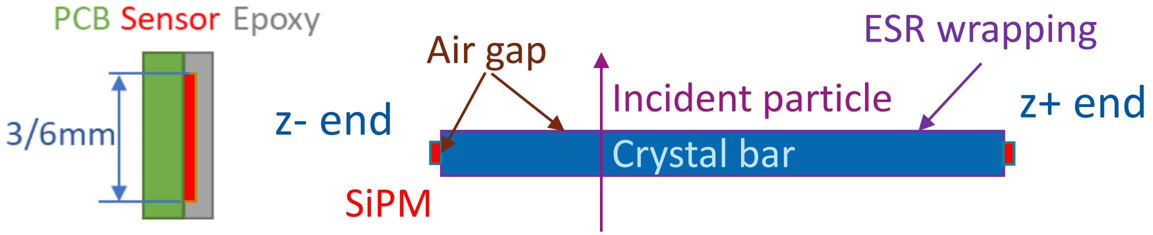
Geant4 full simulation: a single crystal bar

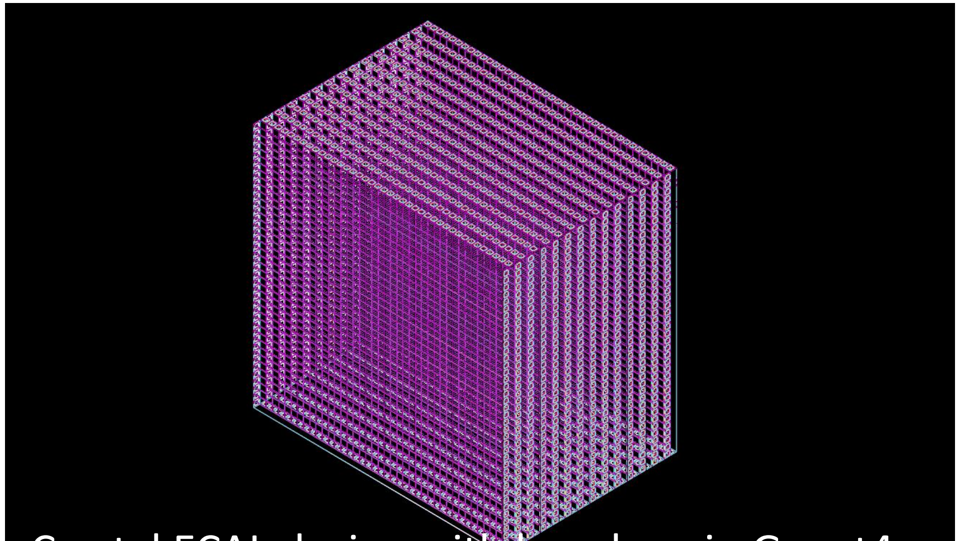
Simulation model

- A single crystal bar wrapped with reflective foil
- Physics processes
  - Scintillation and Cherenkov
  - Boundary processes and absorption
  - SiPM modelling: realistic geometry, surfaces and response to photons (PDE)

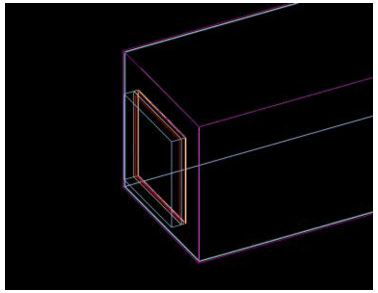
Key questions to be addressed

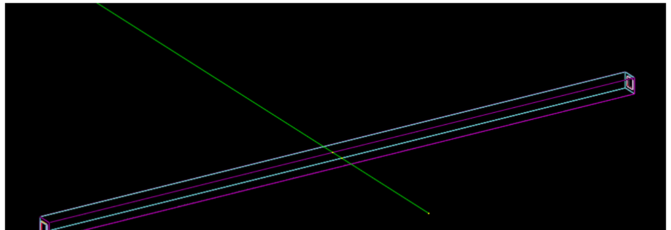
- Comparison with measurements of crystals in the lab
- Comparison of models of optical processes in Geant4





Crystal ECAL design with long bars in Geant4





A single crystal bar

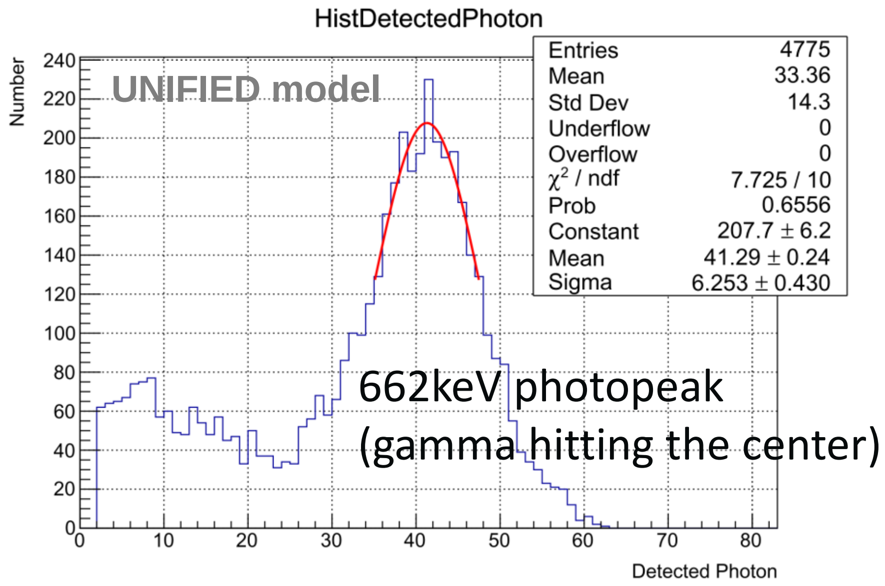
Key quantities

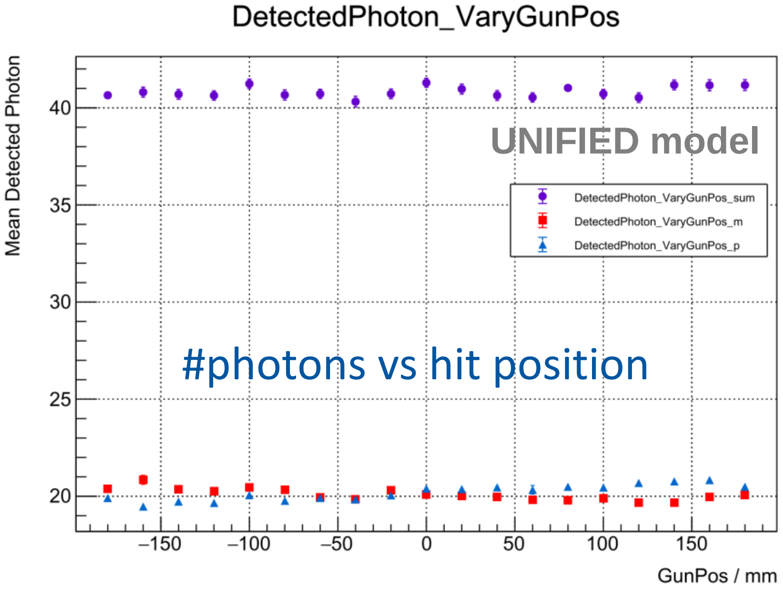
- Number of photons detected by 2 SiPMs
- Time stamps of each detected photons

Uniformity scan in Geant4 simulation

Geant4 10.7

- BGO response uniformity scan:
  - 662keV gamma from Cs-137
  - 400mm BGO crystal bar, transverse $1cm^2$
  - Varying Cs-137 positions
  - Fit the 662keV photopeak to get #photons

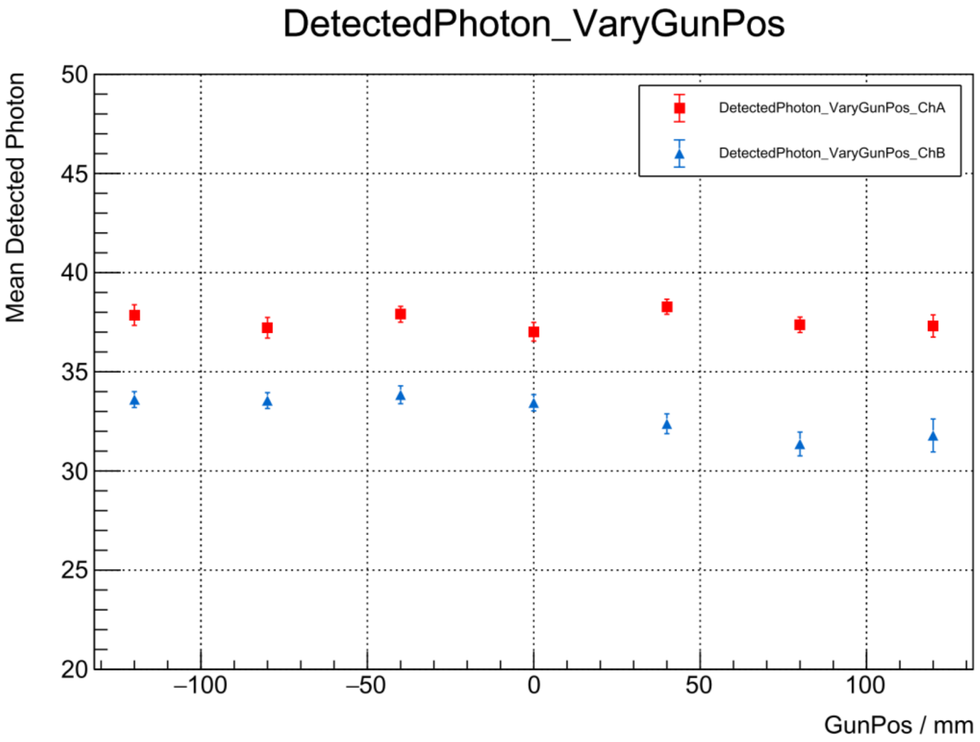


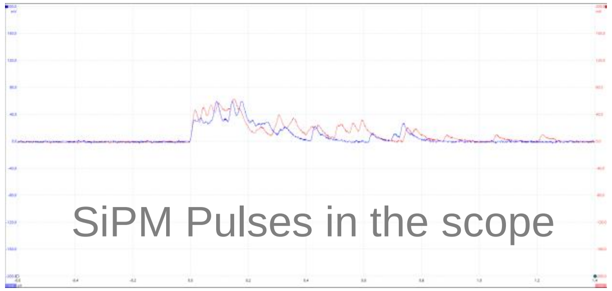


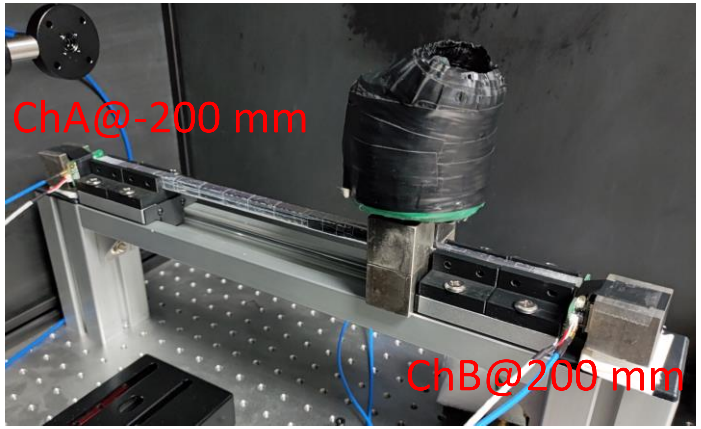
- Generally good response uniformity expected in G4 simulation

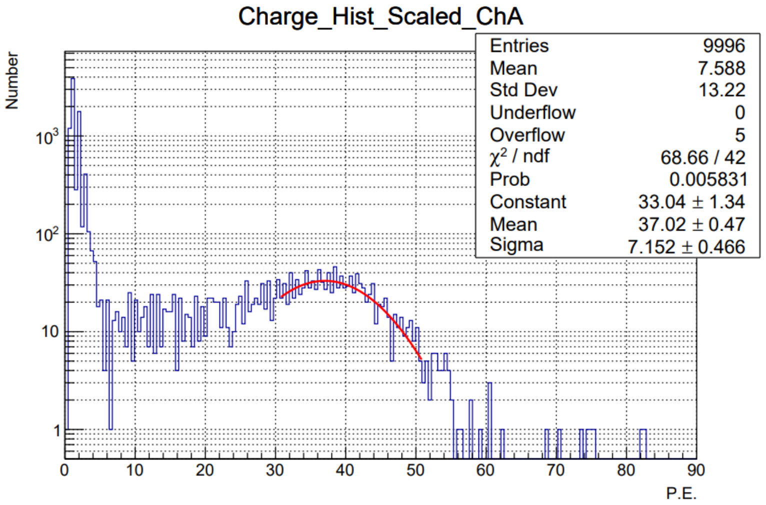
First measurements for the uniformity scan

- Setup: 400mm long BGO crystal (with ESR foil) and ^{137}Cs source
- The same configuration as the simulation







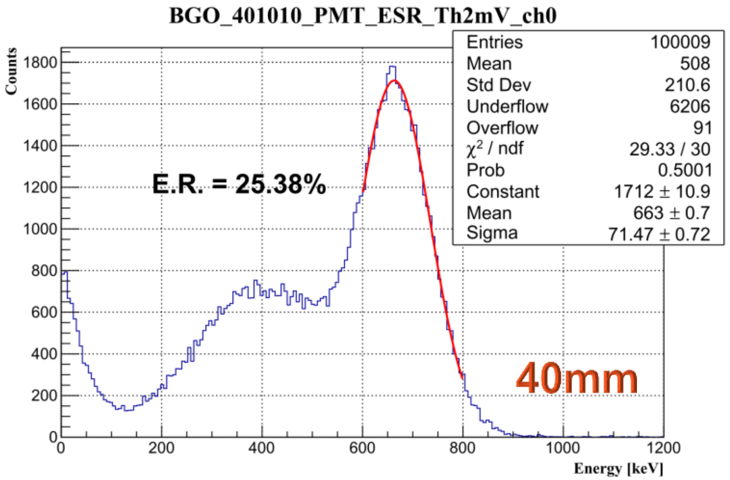


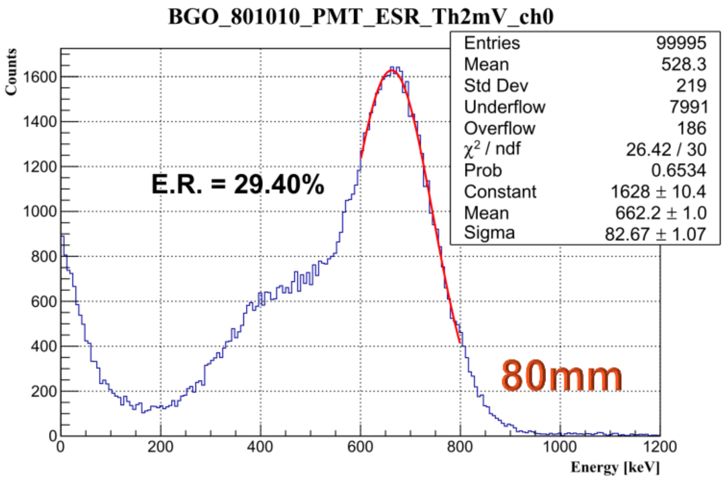
- Trends are not significant enough due to the systematic difference between 2 SiPMs
- Refractive indices of materials
  - Air: 1.00
  - Epoxy: 1.52
  - BGO: 2.15

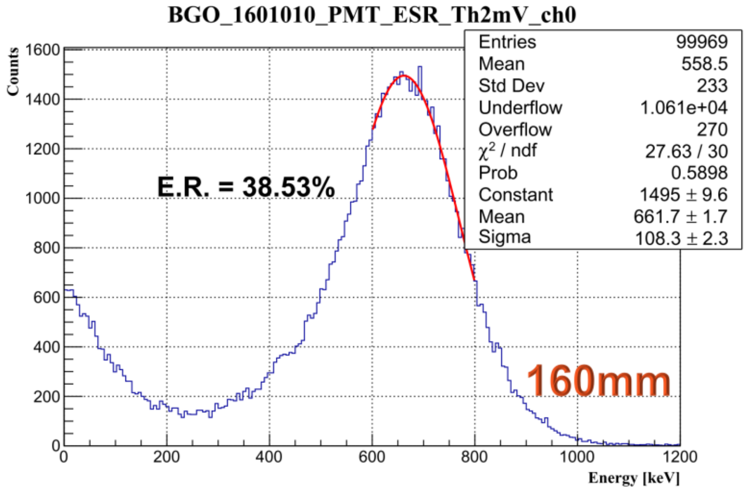
- Work plan: to use optical grease to improve the crystal-SiPM coupling and reproducibility

Response and energy resolution: impacts of crystal length

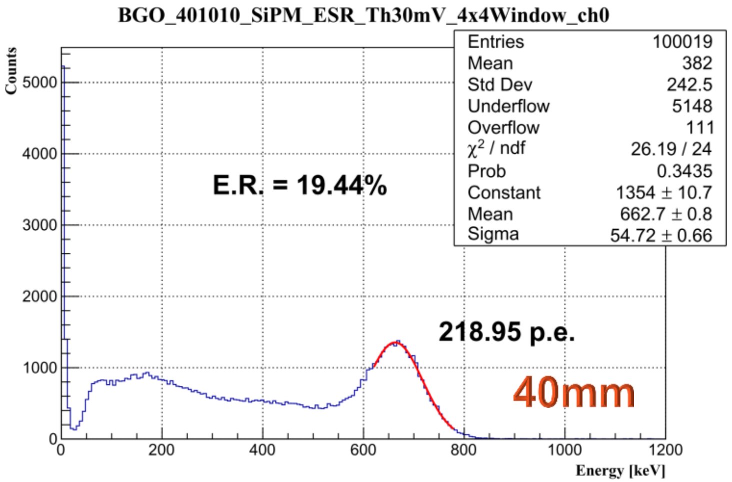
PMT

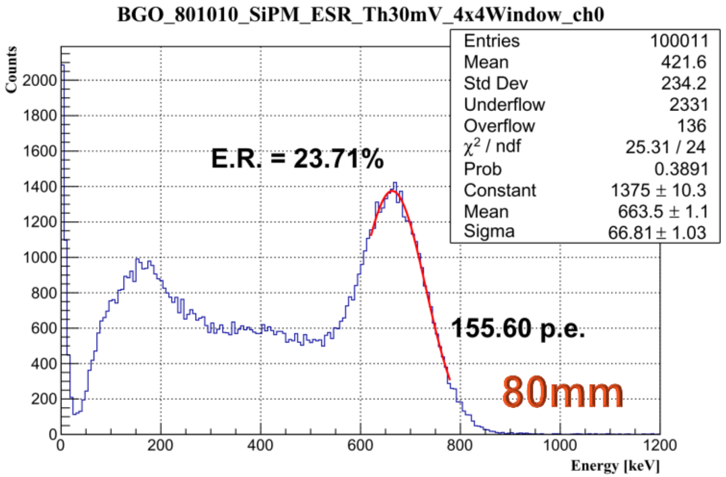


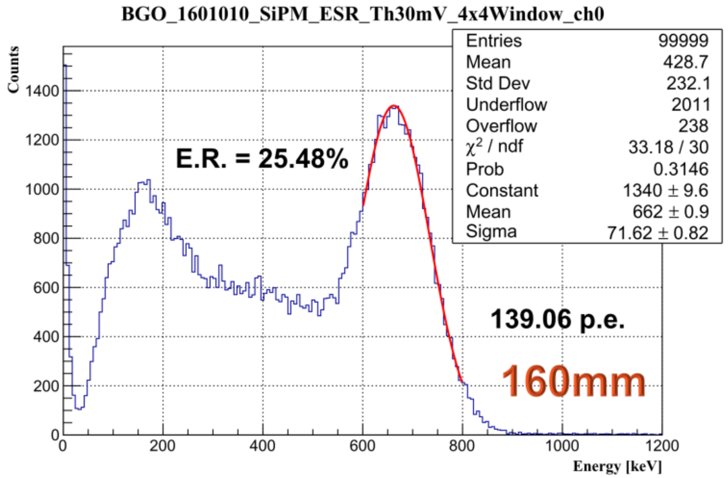




SiPM





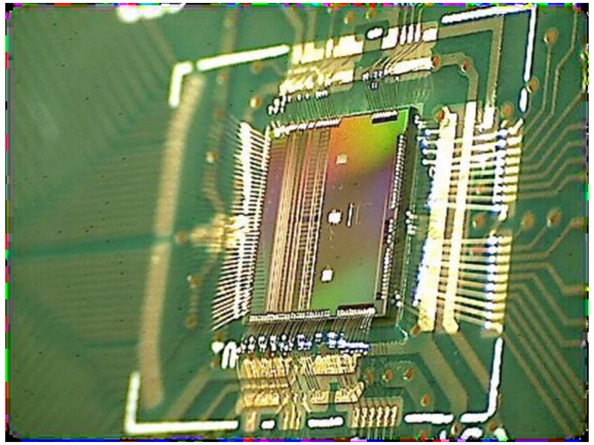


- PMT has better acceptance (full coverage of crystal transverse area) than SiPM; to be updated with larger SiPMs
- Further comparisons will be done with simulation

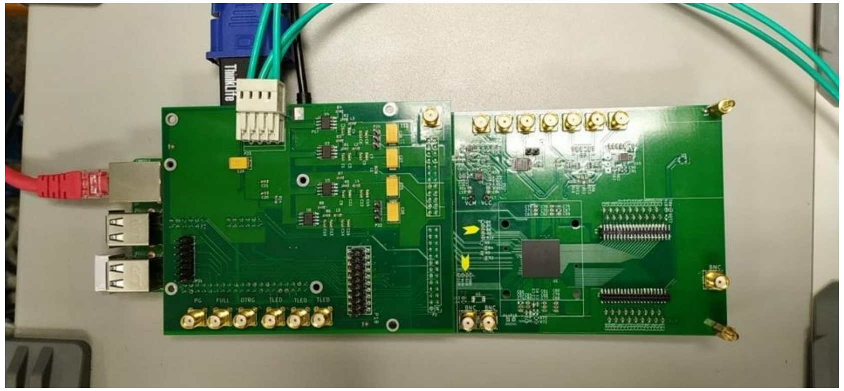
Front-end electronics for SiPM readout

- ASIC "KLauS": developed within the CALICE collaboration
  - Designed by U. Heidelberg (KIP), originally for CALICE AHCAL
  - Promising candidate for SiPM readout: 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 study performance: with evaluation boards

Wire-bonded Klaus5 chip



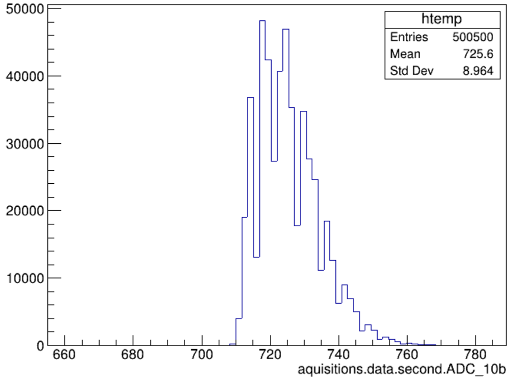
Klaus5 in BGA



Joint efforts with JUNO-TAO team

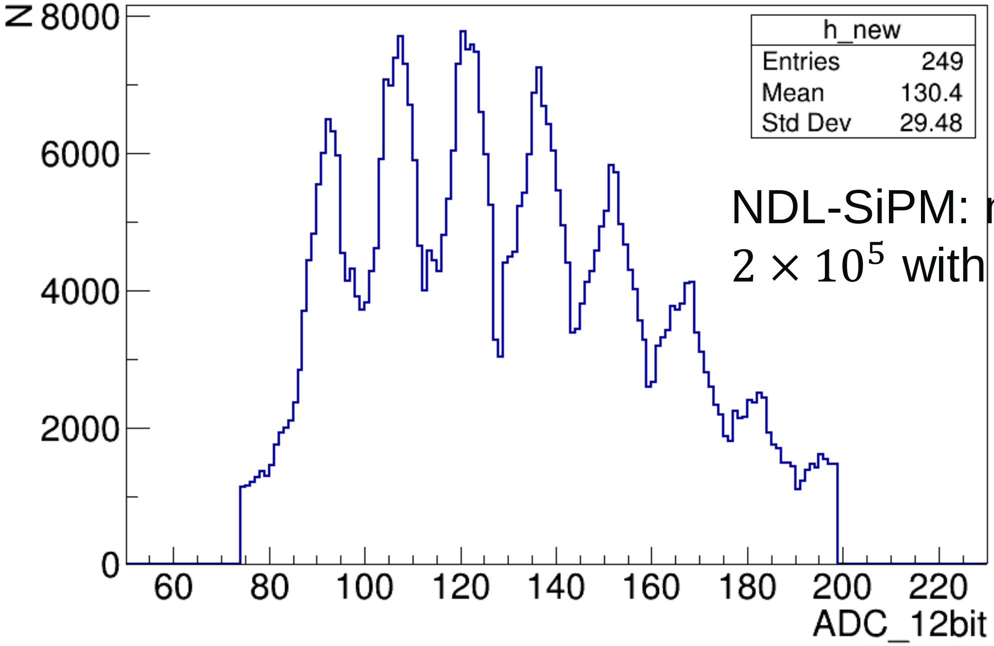
Klaus5 tests with NDL-SiPM

- NDL-SiPM features: high pixel density (>10k pixels/mm²) and high PDE
  - Requires high S/N ratio in electronics to resolve single photons, due to the low intrinsic gain of small pixel pitches
- Klaus5 tested and 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

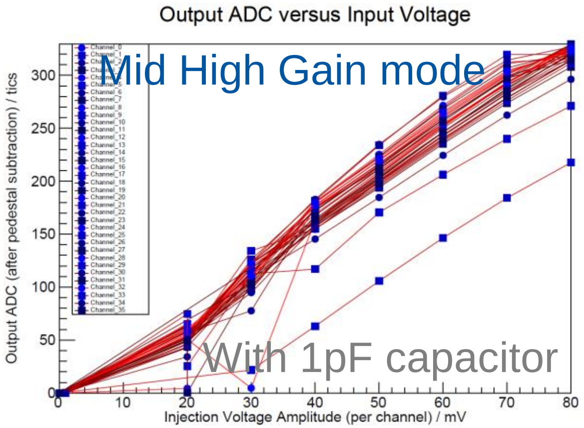


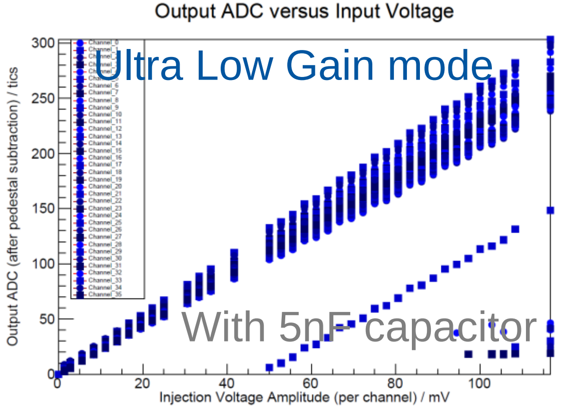
NDL-SiPM: nominal gain 2×10^5 with 10μm pixels

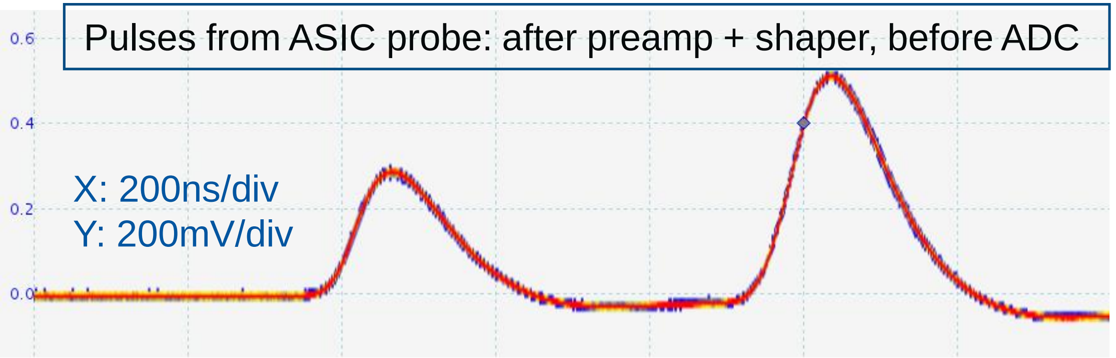
Klaus5: dynamic range and dead time

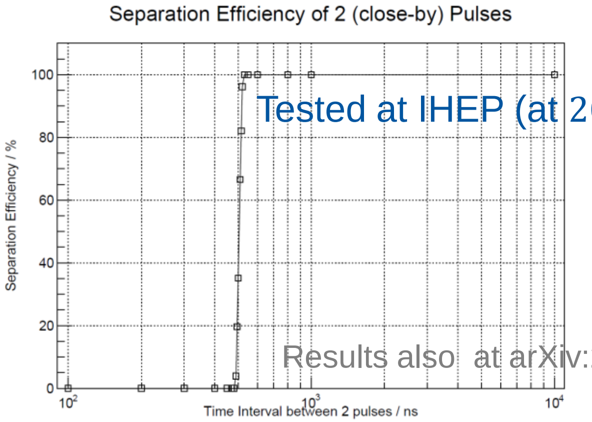
- Charge injection tests
  - Dynamic range: ~550pC as the maximum charge (preliminary results)
  - When time interval > 500ns, 100% efficiency of separating the two pulses

Adapter PCB to inject charge pulses injection to 36 channels









Summary and prospects

- 4D high-granularity crystal calorimeter
  - Aim to achieve optimal EM energy resolution and PFA capability
  - Steady R&D progress targeting key issues
- Performance studies with crystals using Arbor-PFA
  - Performance studies with neutral pions and Higgs benchmark
- Reconstruction algorithm development for the design of long bars
  - Fast simulation and performance studies
- Technical developments
  - SiPM and crystal studies: measurements and Geant4 simulation studies
  - SiPM-readout ASIC characterisations

- Welcome broader collaborations

Thank you!

Backup slides

Legendary crystal calorimeters at colliders

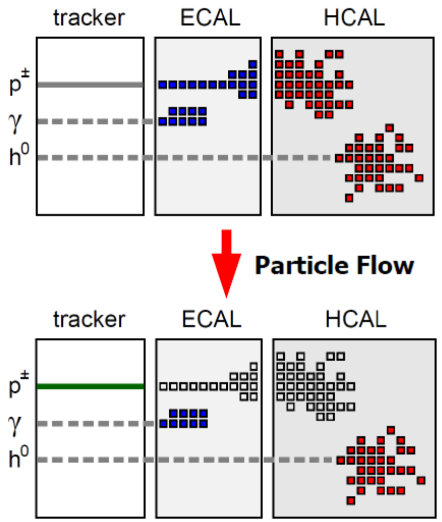
Table 35.8: Resolution of typical electromagnetic calorimeters. E is in GeV.

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16–18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
CsI(Tl) (BES III)	$15X_0$	2.5% for $E_\gamma = 1$ GeV	2010
$PbWO_4$ (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
$PbWO_4$ (ALICE)	$19X_0$	$3.6\%/\sqrt{E} \oplus 1.2\%$	2008
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990

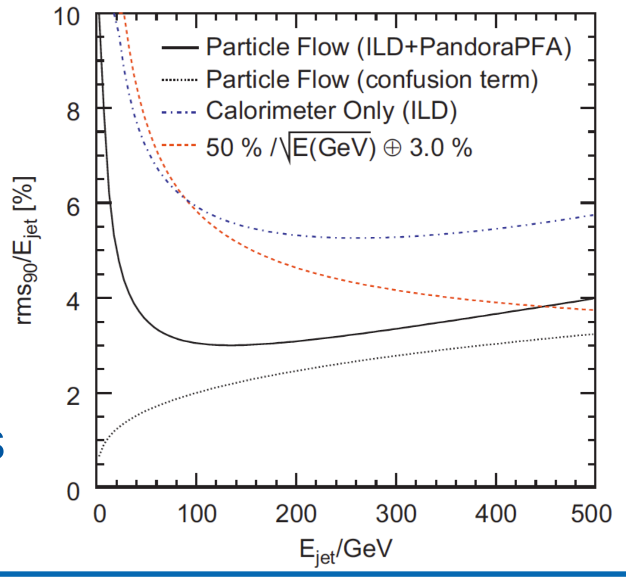
Reference: Review of Particle Detectors at Accelerators in 2020 (https://pdg.lbl.gov/)

Particle-flow algorithm

Components in jets	Sub-Detectors	Energy fraction (average) within a jet	Detector Resolution
charged particles ($X^{\pm}$)	Tracker	$60\%\ E_j$	$10^{-4}E^2{}_X$
photons (γ)	ECAL	$30\%\ E_j$	$0.15\sqrt{E_\gamma}$
neutral hadrons (h)	ECAL+HCAL	$10\%\ E_j$	$0.55\sqrt{E_h}$



- Reminder: multiple particles in a jet
- Particle Flow Algorithm (PFA)
  - Choose a sub-detector best suited for each particle type
  - Charged particles measured in tracker
  - Photons in ECAL
  - Neutral hadrons in HCAL: reduce the role of hadron calorimetry
- Separation of energy depositions of close-by particles in the calorimeters
  - Crucial for the track-calorimeter matching



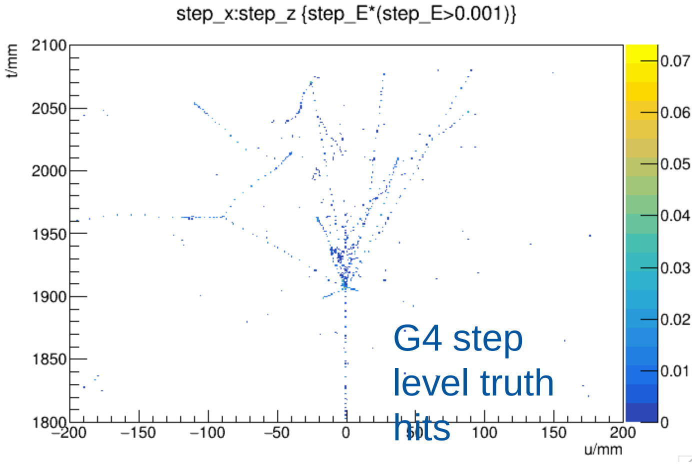
Reconstruction development: strategies and status

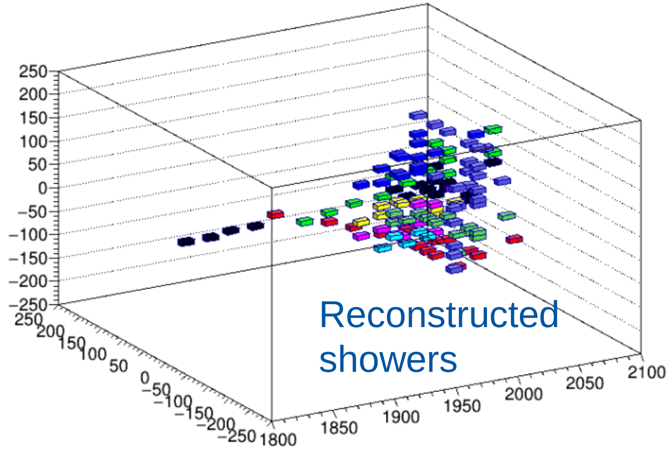
- Reconstruction algorithm of long bars: start from simple and evolve to complex
  - Level 1: single EM particle (γ) and single MIP (finished)
    - Model the EM showers; identify the MIP track and match it with tracker
  - Level 2: separation of two simple particles ($\gamma + \gamma$, $\gamma + \mu$) (finished)
    - Energy splitting between two EM showers; reduce ghost hits
  - Level 3: single hadrons (work ongoing)
    - Model the hadronic showers
  - Level 4: multi-particles (to be done)
    - Shower confusion, neutral particle identification, etc.
  - Level 5: Jets (to be done)

- Performance in physics benchmarks like $ZH \rightarrow \nu\nu gg, qqgg$.

Hadronic showers in ECAL: ongoing work

- Challenges in hadronic shower reconstruction
  - Multiple secondary particles in the shower.
  - Nearly no longitudinal or track information to use.
  - A large amount of ghost hits.
- Ideas and possible solutions
  - Use Arbor's ideas to connect hits
  - Reduce the iteration times
  - New χ^2 algorithm for ghost hits: match with minimum χ^2 and reduce hit conditions.
  - (Ongoing) Merge clusters with specific topology
  - (Ongoing) Identify and tag photons and MIPs first

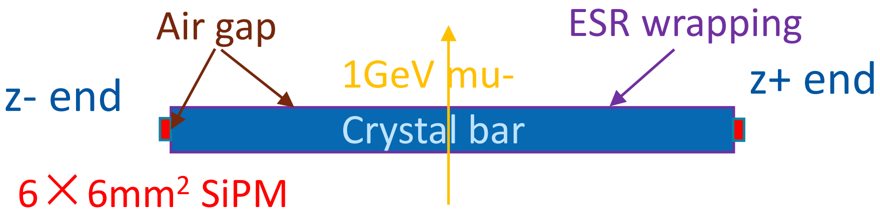


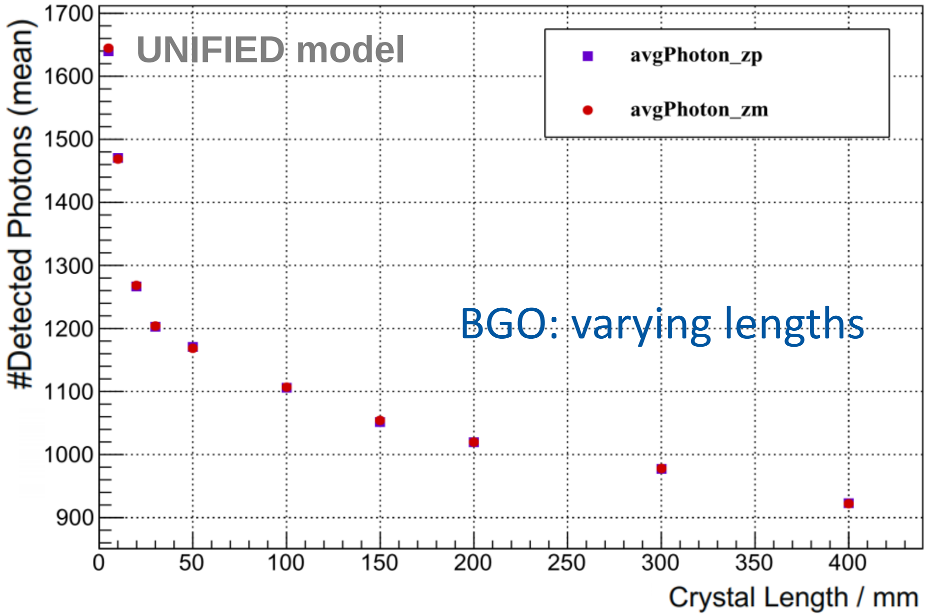


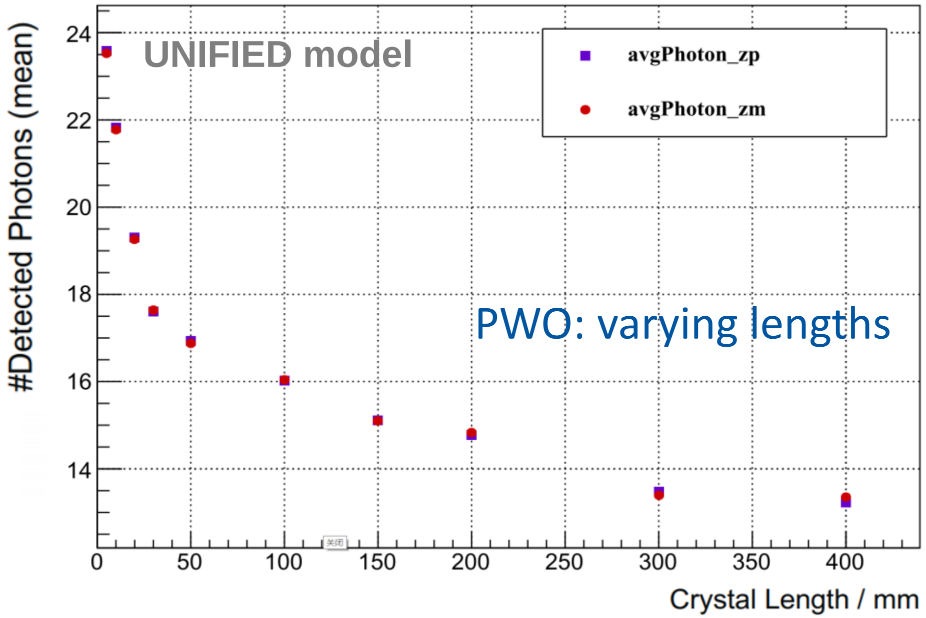
MIP response with various crystal lengths

Geant4 10.7

- MIP response: number of detected photons
  - Muon shooting the crystal bar center
  - Crystal length varies from 5mm to 400mm
  - Crystal transverse size: 1cm^2







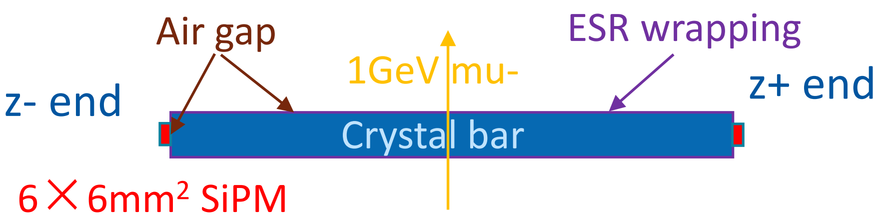
- MIP response significantly depends on crystal length
- Sufficiently high MIP response of 40cm long BGO

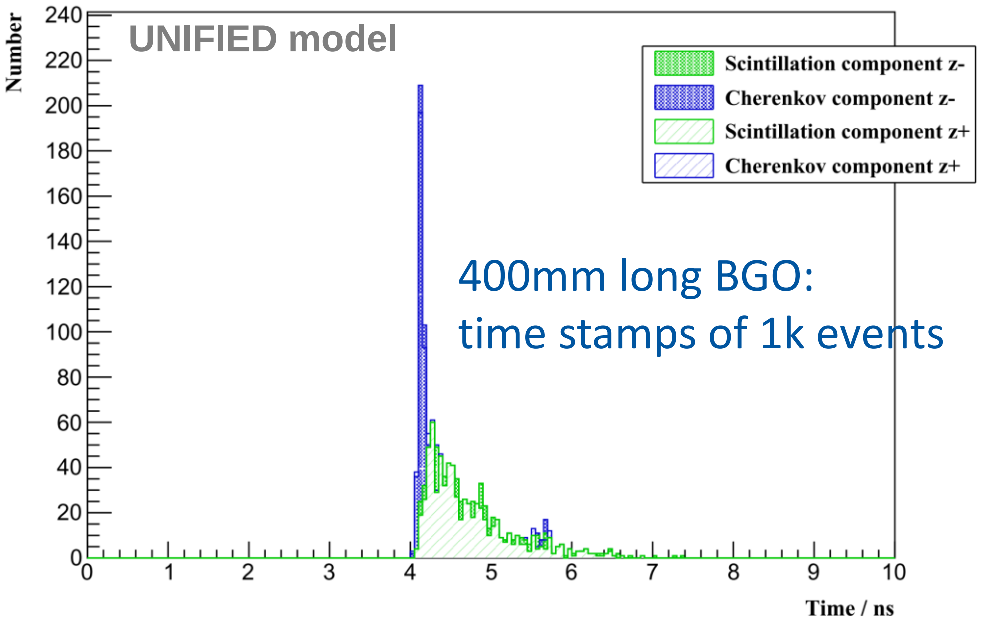
Light yield: 8200/MeV for BGO, 120/MeV for PWO
MIP energy deposition: ~ 9MeV (MPV)

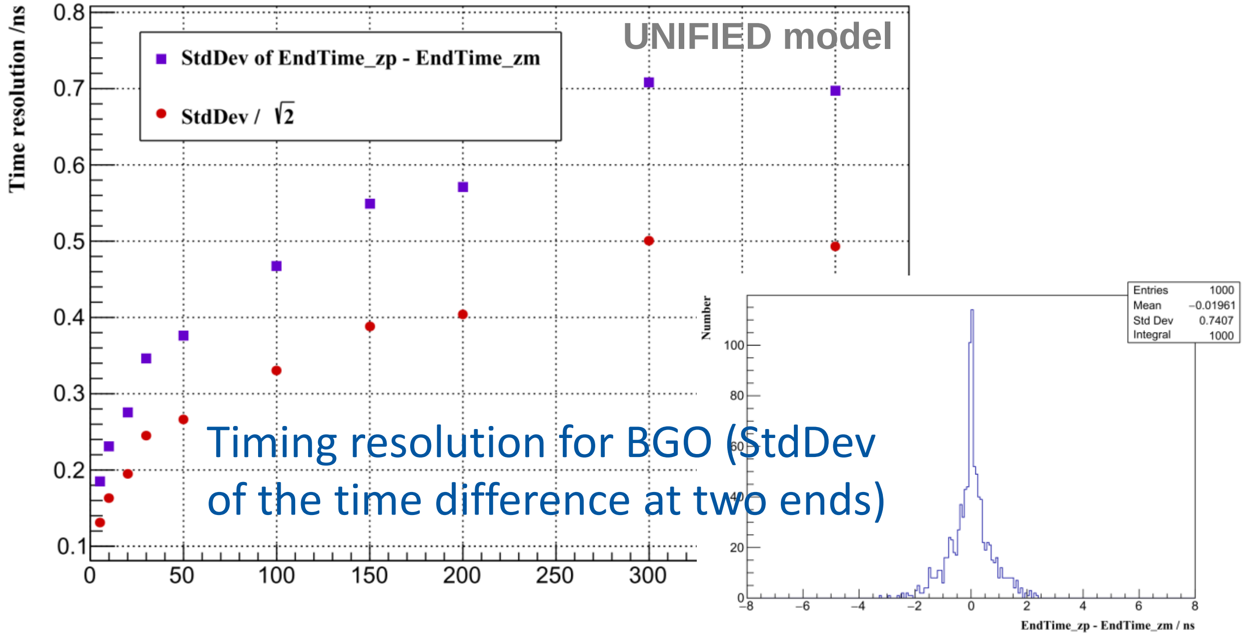
Timing resolution with various crystal lengths

Geant4 10.7

- Timing: time stamps of the first detected photons
  - Muon shooting the crystal bar center
  - Crystal length varies from 5mm to 400mm
  - Crystal transverse size: $1cm^2$





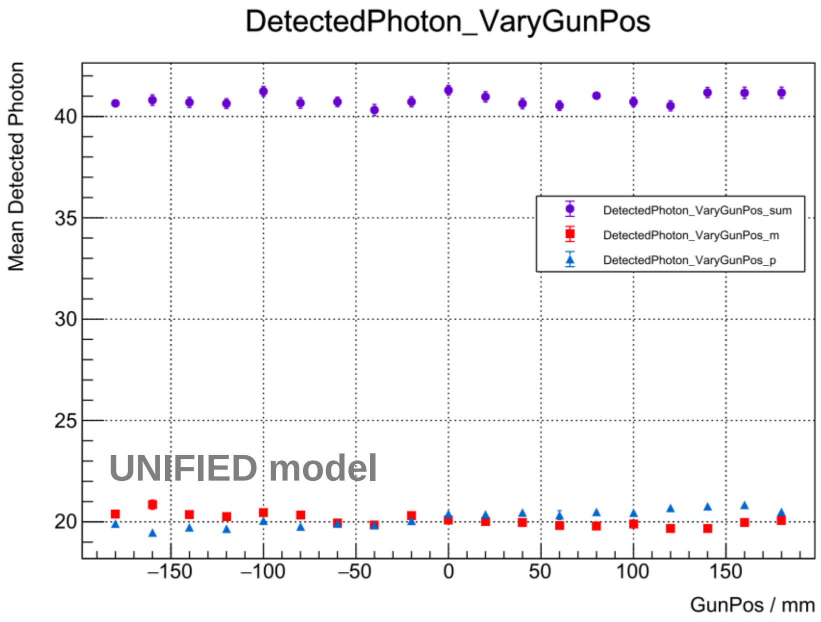


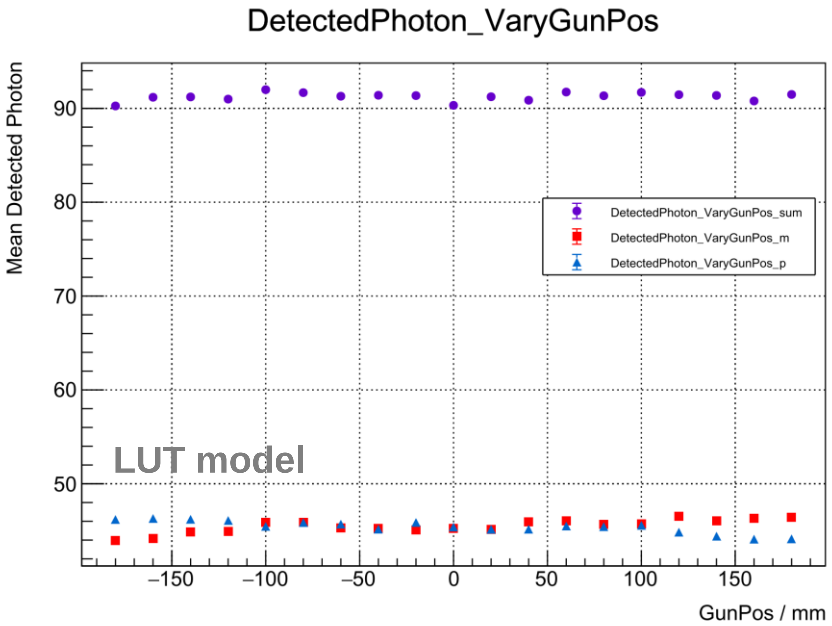
- 0.5~0.7 ns time resolution expected for 40cm long BGO
- Fast and slow components in time spectrum

Light yield: 8200/MeV for BGO, 120/MeV for PWO
MIP energy deposition: ~ 9MeV (MPV)

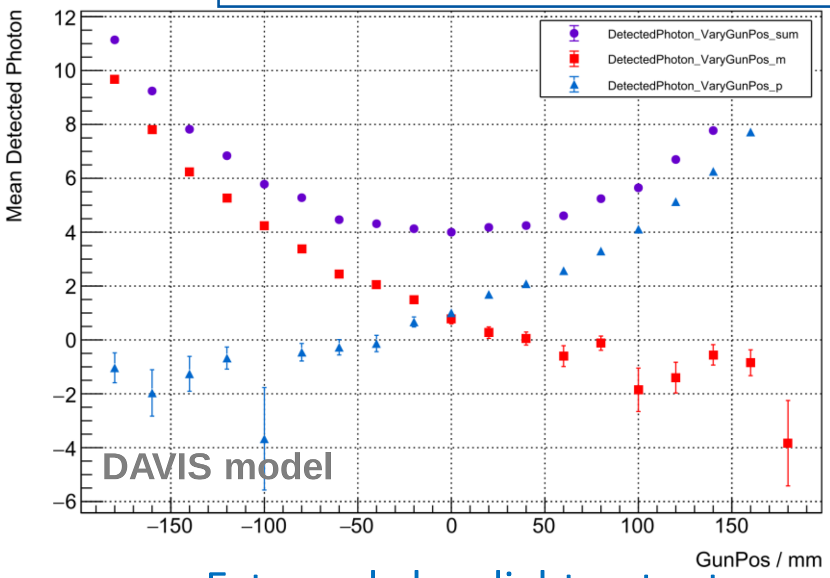
Comparison of optical models in Geant4

- Comparison of 3 models for optical processes in Geant4
  - UNIFIED (analytical calculation, fast and relatively accurate)
  - LUT (BGO measurements), LUT_DAVIS (LYSO measurements)
- Simulation was set up for further comparisons with measurements





Negative values due to the Gaussian fit;
Poisson fit should be used instead, will be updated



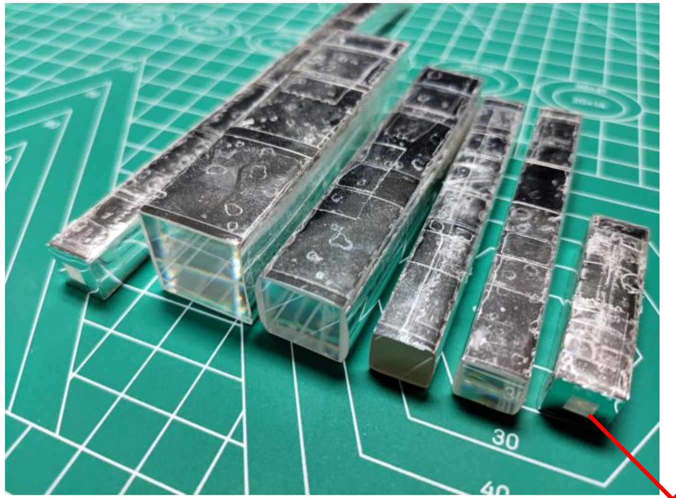
3 models present different uniformity curves and response levels

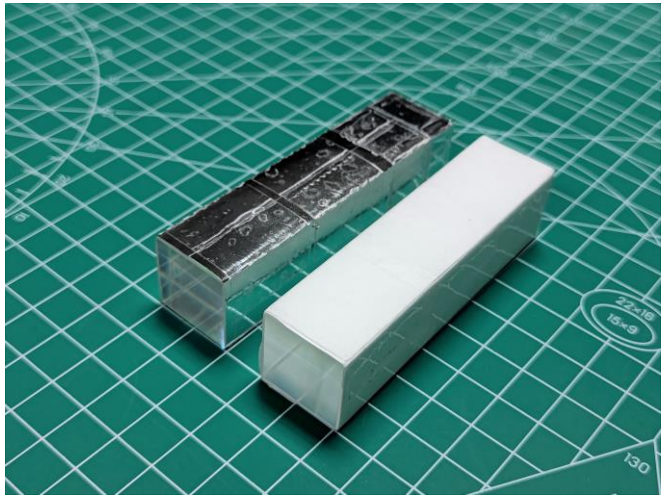
Extremely low light output

Measurements of the BGO energy resolution: setup

BGO Crystal:

- Lengths: 40/80/160mm
- Widths: 20/15/10mm
- Surfaces: polished/ground
- Tyvek / ESR wrapping





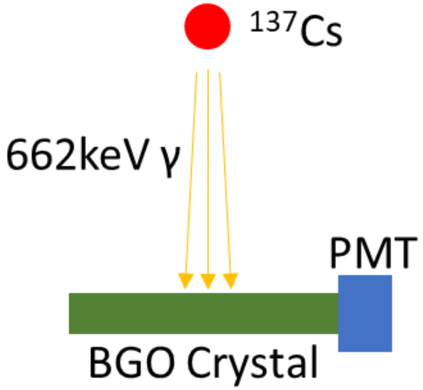
$4\times4mm^2$ window for SiPM readoout

Photosensitive Device:

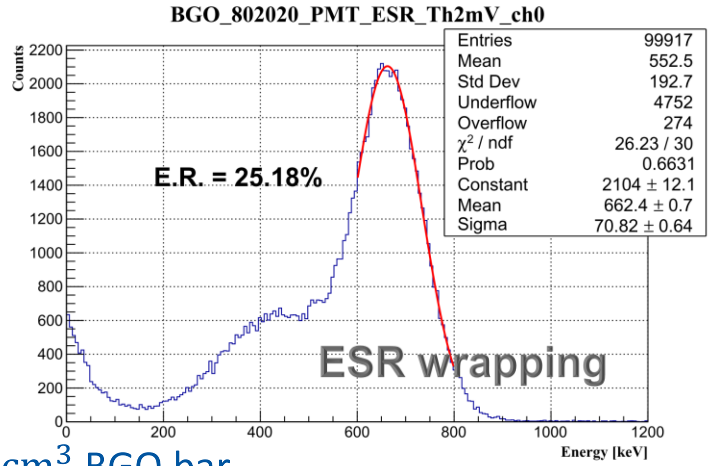
- SiPM & PMT
- SiPM: S13360-3050CS
  - 50µm pitch, $3\times3mm^2$, 3600 pixels
- PMT: R11065
  - 76mm (3”), gain: 5×10^6

Crystal measurements: impacts of wrapping and surfaces

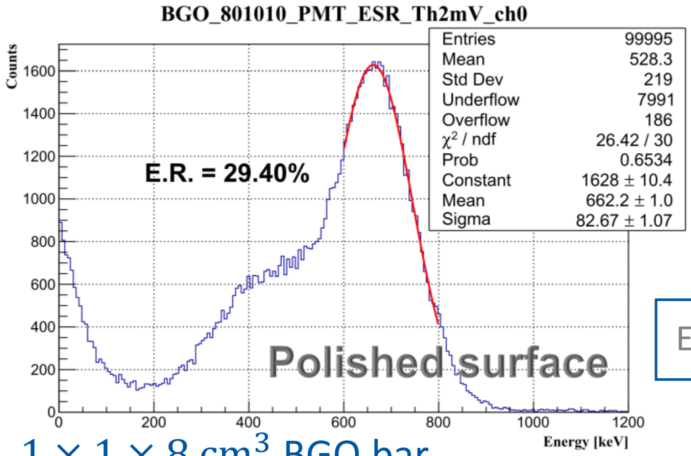
- ESR foil wrapping and polished surface show better energy resolution



Energy Resolution (E.R.) = $2.355 \times \frac{\sigma}{mean}$, defined as FWHM



$2 \times 2 \times 8\ \mathrm{cm}^3$ BGO bar



$1 \times 1 \times 8\ \mathrm{cm}^3$ BGO bar