中国科学院高能物理研究所
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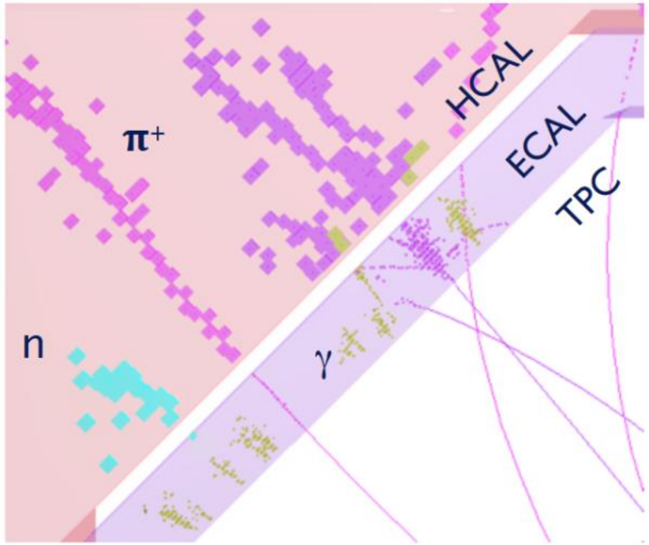
High-granularity Crystal Calorimeter: R&D status

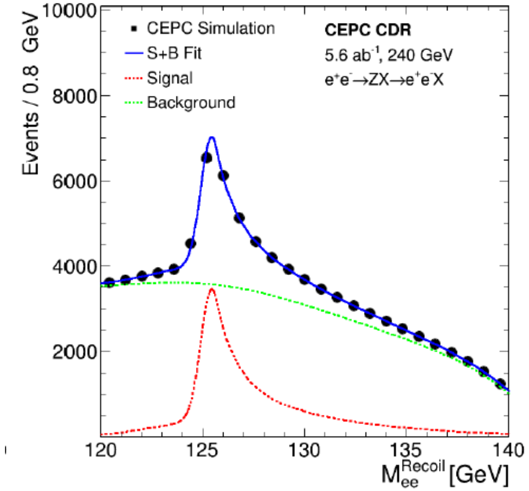
Yong Liu (Institute of High Energy Physics, CAS),
on behalf of the CEPC Calorimetry Working Group

Joint Workshop of the CEPC Physics, Software and New Detector Concept
April 14-17, 2021

Motivations

- Background: future lepton colliders (e.g. CEPC, ILC, etc.)
  - 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
- Finely segmented crystals
  - PFA capability for precision measurements of jets
  - Jet energy resolution aims for 3~4%

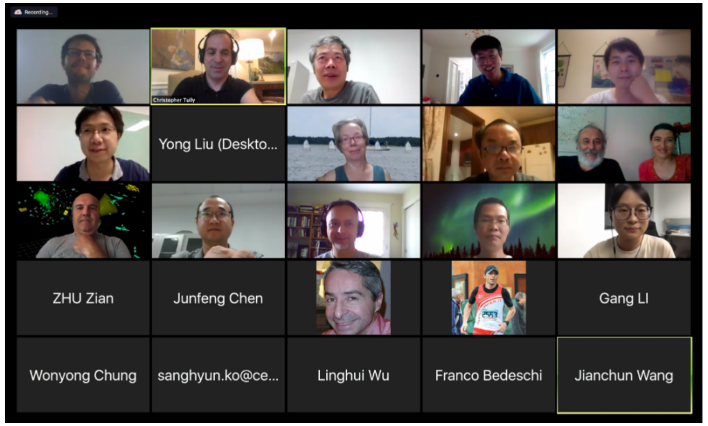


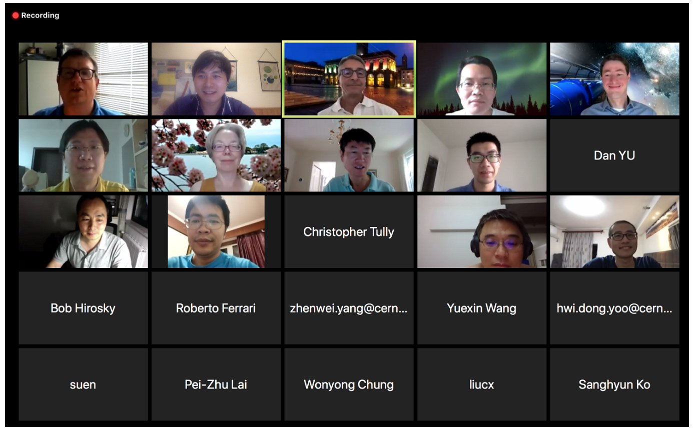


High-granularity Crystal Calorimeter: past events

- 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/



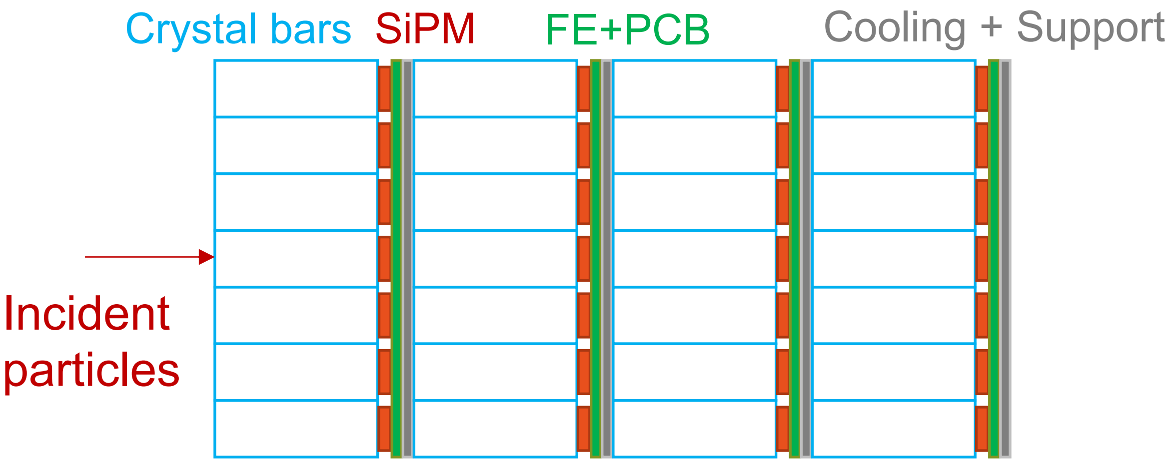


R&D efforts targeting key issues and technical challenges (reminder)

- Key issues: performance studies and optimization
  - Detector layout: crystal segmentation in longitudinal and lateral dimensions
  - Performance: single particles and jets with PFA
  - Fast timing
  - 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

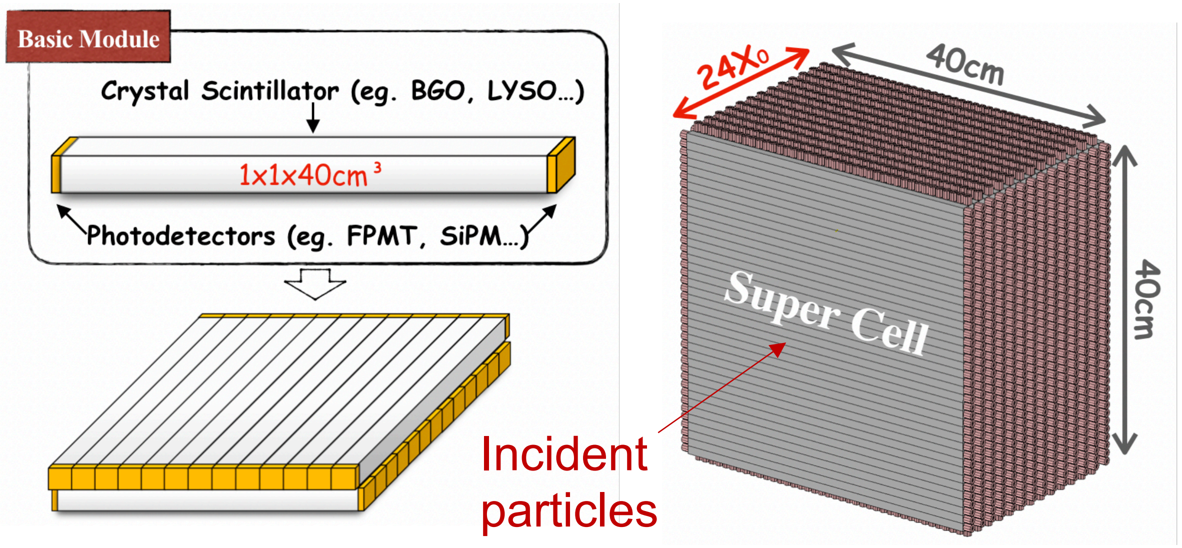
High-granularity crystal ECAL: 2 major designs

Design 1: short bars



- Fine segmentation
  - Both longitudinal and transverse
  - Single-ended readout with SiPM
- A natural design compatible with PFA

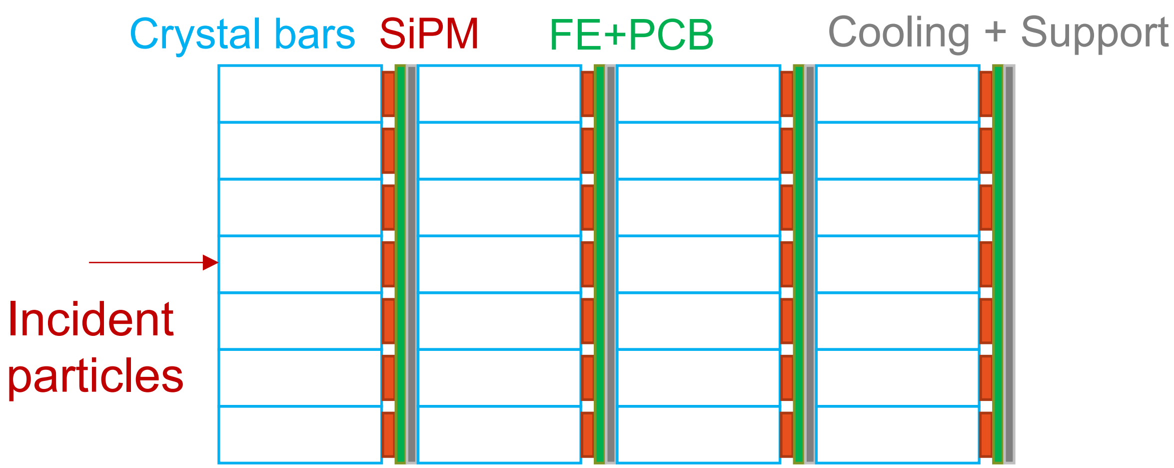
Design 2: long bars



- 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

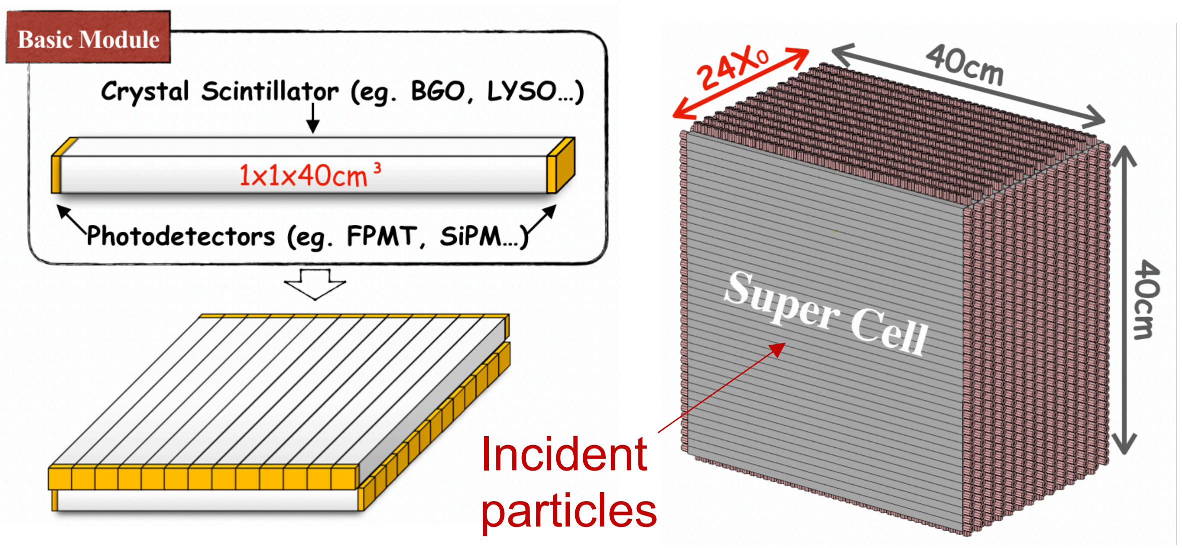
High-granularity crystal ECAL: 2 major designs

Design 1: short bars



- PFA performance studies
  - With crystal cubes (ideal granularity) for physics benchmarks
  - Inputs for optimization of PFA for crystals

Design 2: long bars (current focus)



- **Advantages**
  - Longitudinal granularity
  - Save #channels and minimize dead materials (between crystals)
- **Key issues:** impact on PFA performance
  - Reconstruction algorithm development
  - Ambiguity of multiple incident particles and separation capability

Recent progress on crystal calorimeter

- Key issues: performance studies and optimization
  - PFA performance with jets with PFA
  - Software development in the new framework CEPCSW
    - Layout of long crystal bars
    - Simulation and digitisation tools
    - Reconstruction: clustering and splitting
    - Performance validation

Talk on “Reconstruction Algorithm for Crystal ECAL” by S. Sun (same session)

- Critical technical questions/challenges
  - Detector unit (crystal + SiPM): simulation and tests
  - Front-end electronics: multi-channel ASIC testing

Recent progress on crystal calorimeter

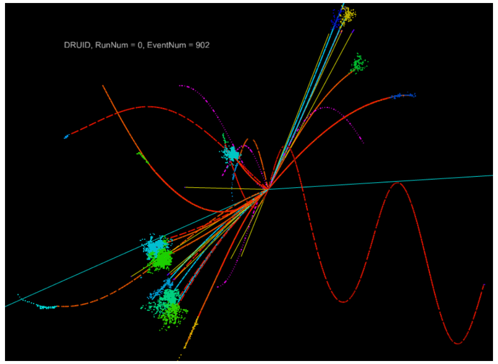
- Key issues: performance studies and optimization
  - Performance with ArborPFA: preliminary studies with crystal cubes
    - Studies with physics benchmarks
      - $ZH(Z \to \nu\nu, H \to gg)$
      - $ZH(Z \to \nu\nu, H \to \gamma\gamma)$
  - Performance studies: reconstruction of neutral pions
  - Separation capability of crystals with Arbor

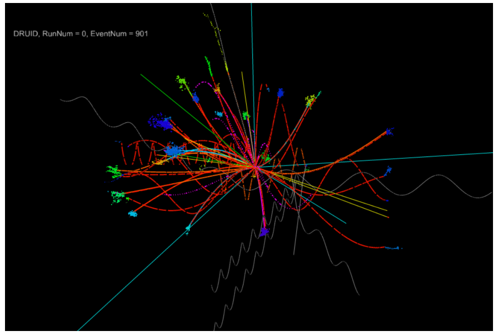
- Critical technical questions/challenges
  - Detector unit (crystal + SiPM): simulation and tests
  - Front-end electronics: multi-channel ASIC testing

PFA performance studies with crystal calorimeter

- Strategy/ideas
  - First start with an ideal finely segmented crystal calorimeter
  - BMR quantitative studies with physics benchmarks: e.g. 2 jets $(H \rightarrow gg)$ and 2 photons $(H \rightarrow \gamma\gamma)$
  - Change the crystal granularity → impacts → requirements on segmentation (e.g. BMR<4%)

    → **to compare with performance of the design of long crystal bars**
- Detector geometry CEPC_v4 (CDR), and replace SiW ECAL with crystal ECAL
  - Crystal ECAL geometry: first start with cubes (1 cm^3)
- Ongoing studies and plans
  - BMR with “default” ArborPFA parameters (tuned for SiW)
  - ArborPFA optimisation for crystals: e.g. clustering, separation power
    - Significantly wider shower profiles than in SiW, and more “isolated” hits
  - Calibration of crystal calorimeter to hadronic showers





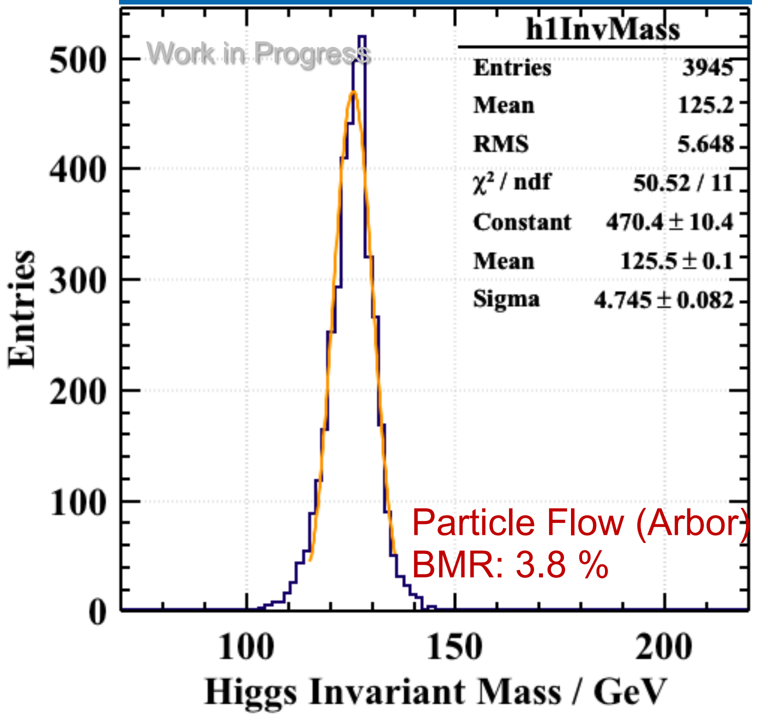
2 gluon-jets in $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$: event display

PFA performance: first studies with crystals

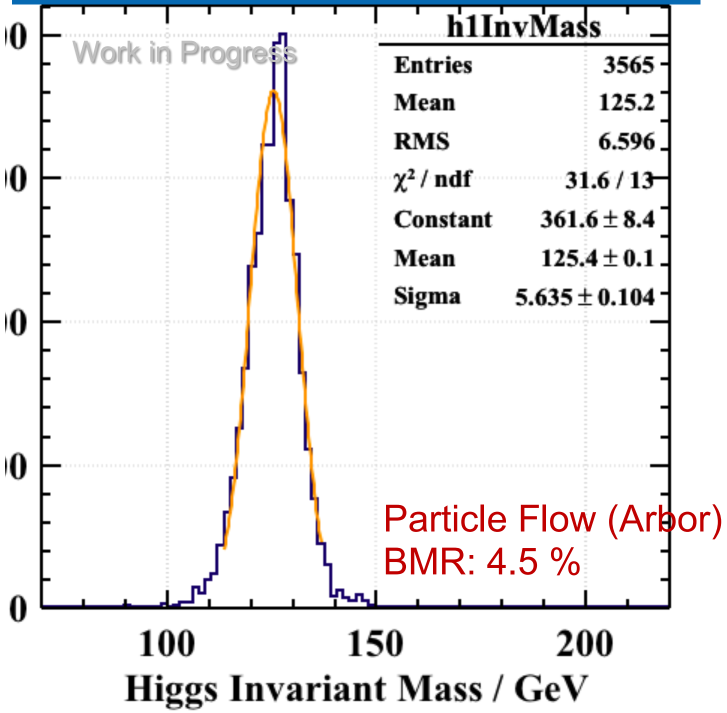
Dan Yu, YL (IHEP)

- 2-jet benchmark events in $ZH(Z \to \nu\nu, H \to gg)$ at 240 GeV
- Plenty of room to improve PFA performance with crystals
  - Essential: reconstruction algorithm, PFA parameters tuning for crystals

Detector with SiW ECAL option



Detector with Crystal ECAL option



Crystal ECAL: cubes (1cm^3)
SiW ECAL: silicon pads (1cm^2)

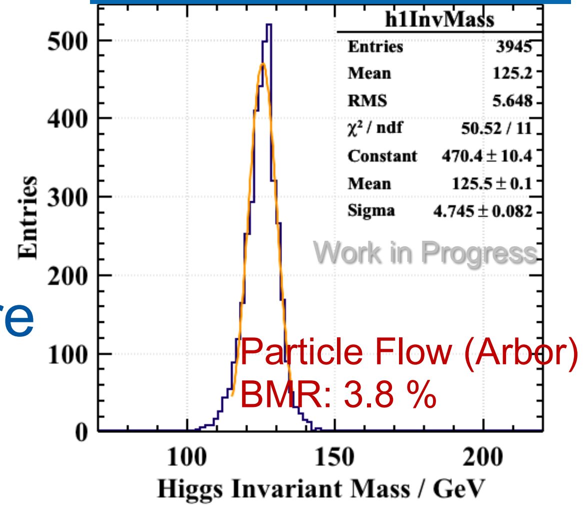
Same transverse granularity: $1{\times}1\ \text{cm}^2$

Note the Arbor PFA parameters not yet optimised for crystals: more overlaps in crystals expected (larger X_0, R_M than tungsten)

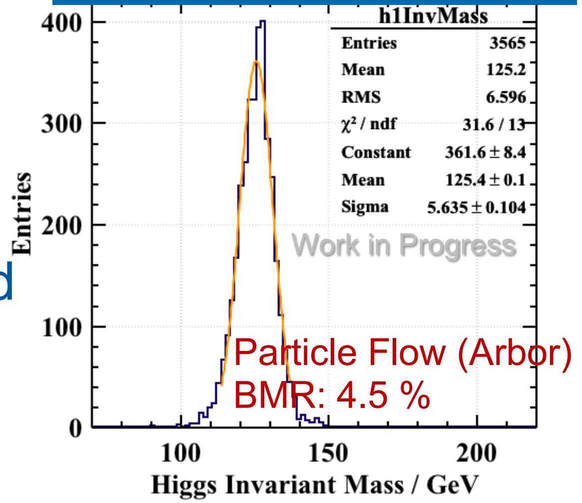
PFA performance: first studies with crystals

- 2-jet benchmark events in $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV
- Plenty of room to improve PFA performance with crystals
  - Essential: reconstruction algorithm, PFA optimsation for crystals
- A few points for further discussions (from my side): welcome more
  - Current PFA focuses on pattern recognition
    - Less stringent requirement on energy resolution
  - Crystal calorimeter: pros and cons
    - Precision energy information
      - But not yet used in PFA: new ideas highly desired
    - Challenges of good separation of multiple particles in jets
      - Intrinsically, shower profiles less compact and more isolated hits in crystals, compared with the SiW option
      - Overlapping of showers of close-by particles
      - How much room for improvement with fine energy info?

Detector with SiW ECAL option



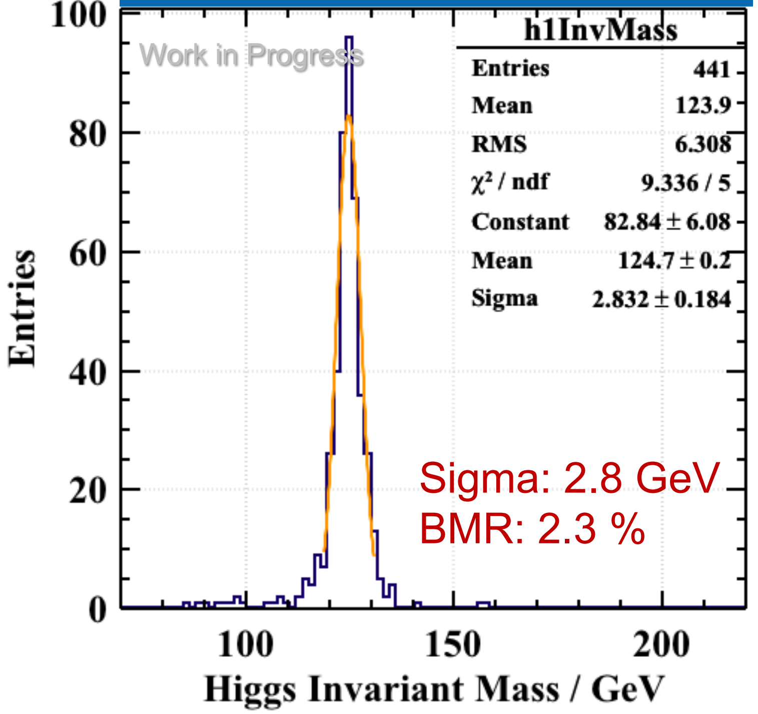
Detector with Crystal ECAL option



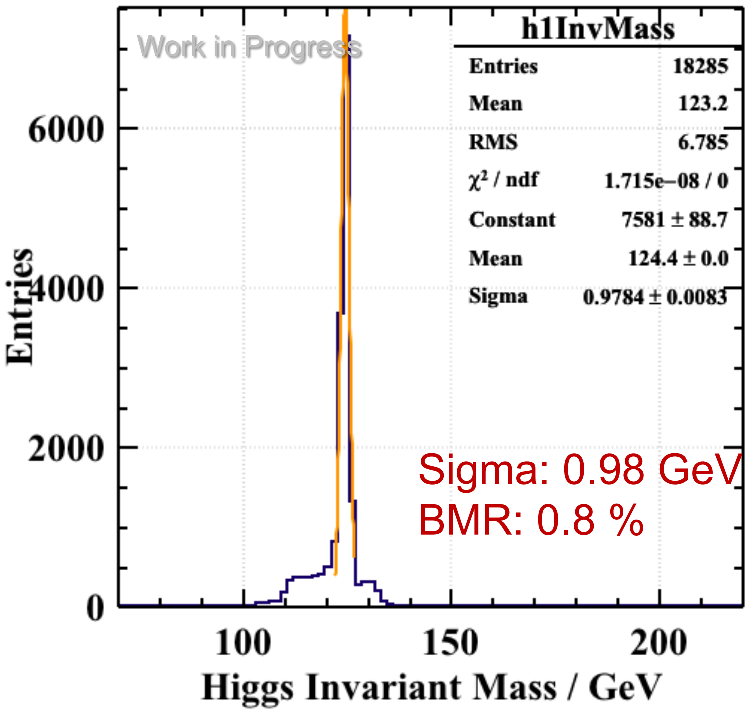
Physics benchmark with photons in final states

- Full simulation studies with $ZH(Z \to \nu\nu, H \to \gamma\gamma)$ at 240 GeV
  - Invariant of mass of $H \to \gamma\gamma$: a factor of 2~3 better resolution with crystals
  - Other structures in the InvMass spectrum: investigation efforts ongoing

Detector with SiW ECAL option



Detector with Crystal ECAL option



Crystal ECAL: cubes (1cm^3)
SiW ECAL: silicon pads (1cm^2)

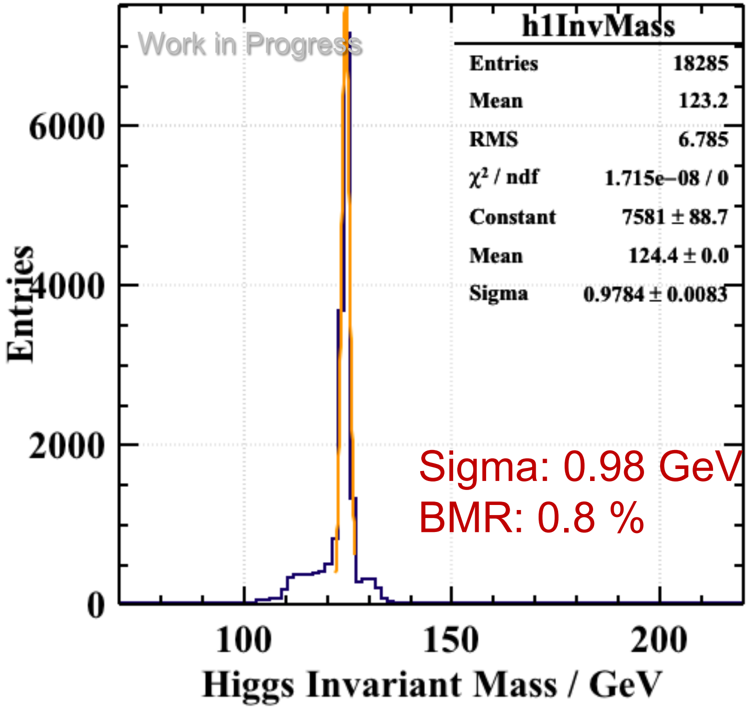
Same transverse granularity: $1 \times 1\ \text{cm}^2$

Physics benchmark with photons in final states

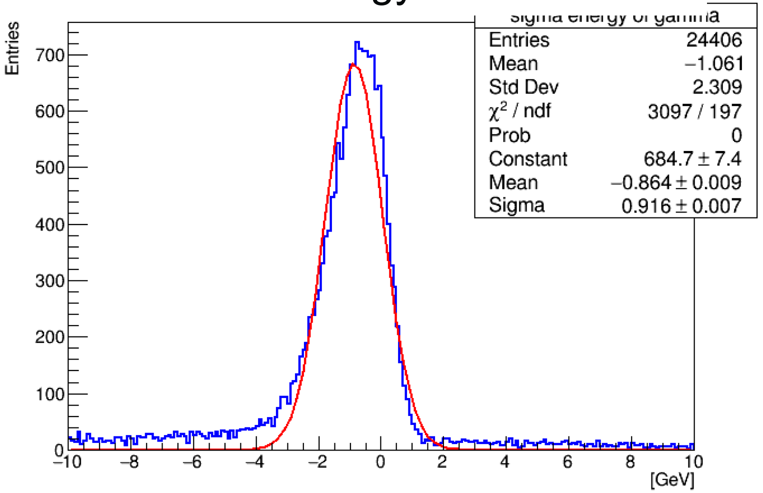
Zhiyu Zhao (IHEP/SJTU)

- Full simulation studies with $ZH(Z \rightarrow \nu\nu, H \rightarrow \gamma\gamma)$ at 240 GeV
  - Structures in the spectrum: investigating efforts ongoing

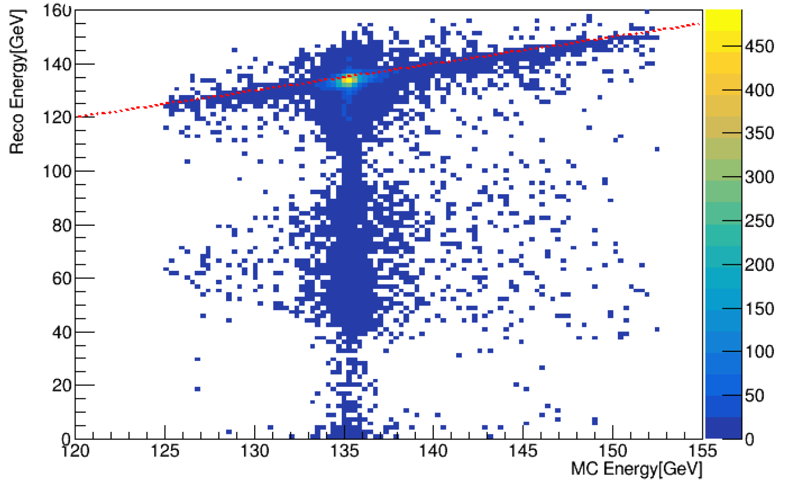
Detector with Crystal ECAL option



Photon Energy: Rec-MCtruth



Energy Linearity: Rec vs. MCtruth



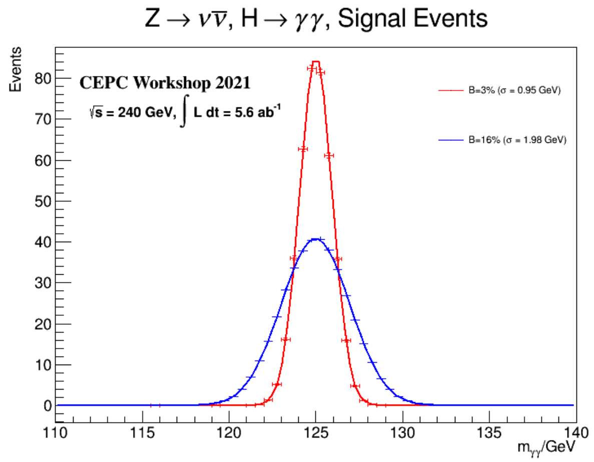
- A possible reason: energy calibration of crystal calorimeter
  - Energy dependency (seems more prominent than SiW)
- SiW ECAL with calibration constants at a fixed energy point

Physics benchmark with photons in final states

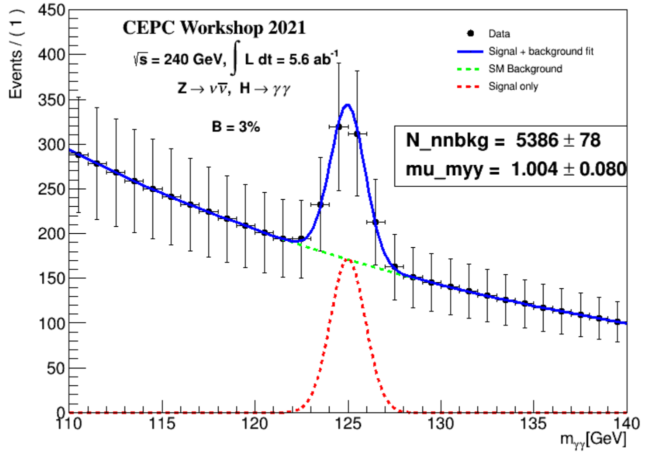
Fangyi Guo (IHEP),
Danyi Zhang (UCAS)

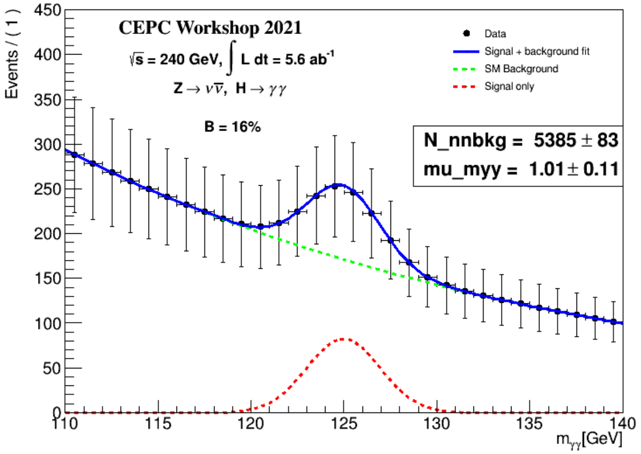
- MC simulation
  - $\sqrt{s} = 240GeV, \mathcal{L} = 5.6ab^{-1}$, Wizard 1.95+MoccaC
  - Signal: $e^+e^- \to ZH \to \nu\nu\gamma\gamma/\mu\mu\gamma\gamma$.
  - Background: 2 fermion diphoton continuum background.
- Fast detector simulation
  - Smear the MC truth photon energy with stochastic term B
  - 3% for the stochastic term in crystal calorimeter
  - 16% for the stochastic term in SiW calorimeter

  Constant term is fixed to 1% for both cases.



- Cut-based analysis in the combination of $\nu\nu\gamma\gamma$ and $\mu\mu\gamma\gamma$ channel, fit $m_{\gamma\gamma}$ shape to get $\delta(\sigma(ZH)\times Br(H \to \gamma\gamma))$





EM Resolution	$\delta(\sigma \times Br)$
$3\%/\sqrt{E} \oplus 1\%$	8.0%
$16\%/\sqrt{E} \oplus 1\%$	11%

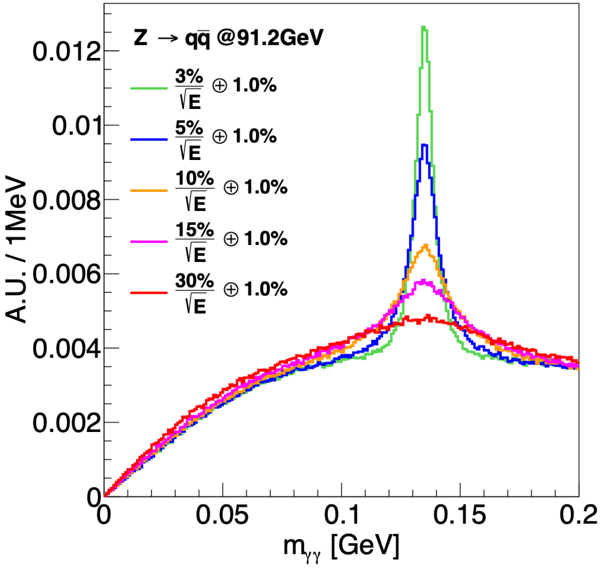
Details in the talk by Danyi Zhang at the Young Scientist Forum (Friday)

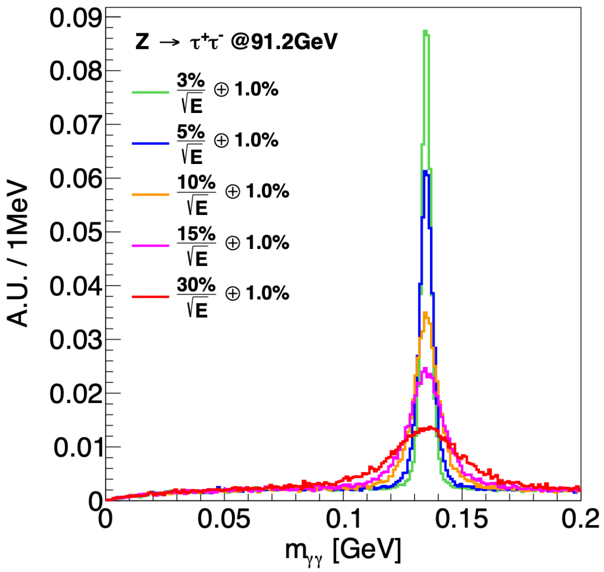
Physics benchmark with photons in final states

Yuexin Wang (IHEP)

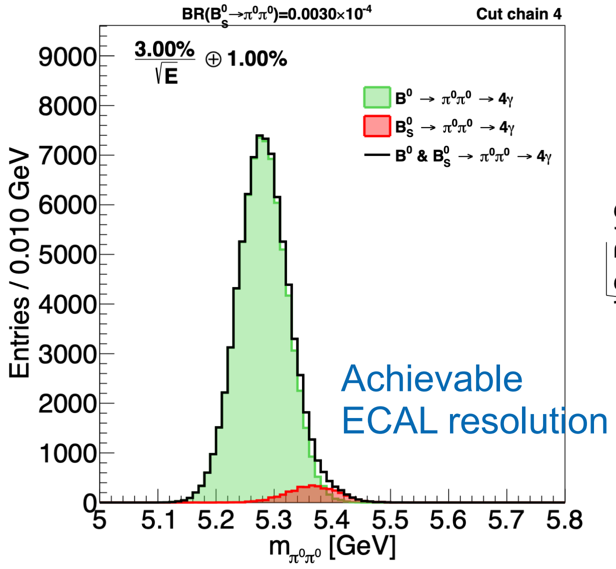
- $B^0/B_s^0 \to \pi^0\pi^0$ at CEPC: fast simulation studies
  - Physics requirements

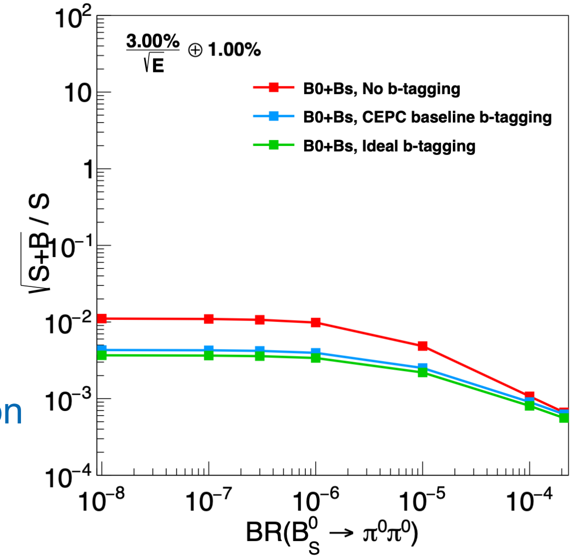
Reconstruction of π^0





Measurements of $B^0/B_s^0 \to \pi^0\pi^0$ with achievable ECAL resolution and baseline b-tagging





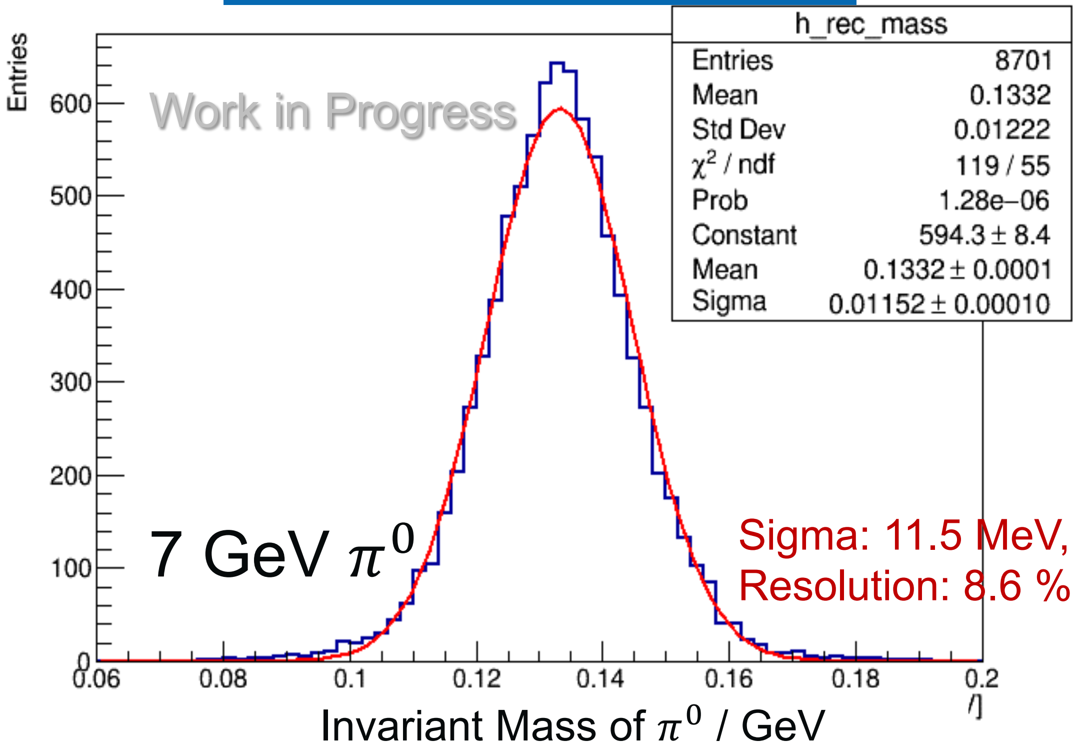
Details in the talk by Yuexin Wang in the Flavor Physics Session (April 15)

Performance studies with neutral pions

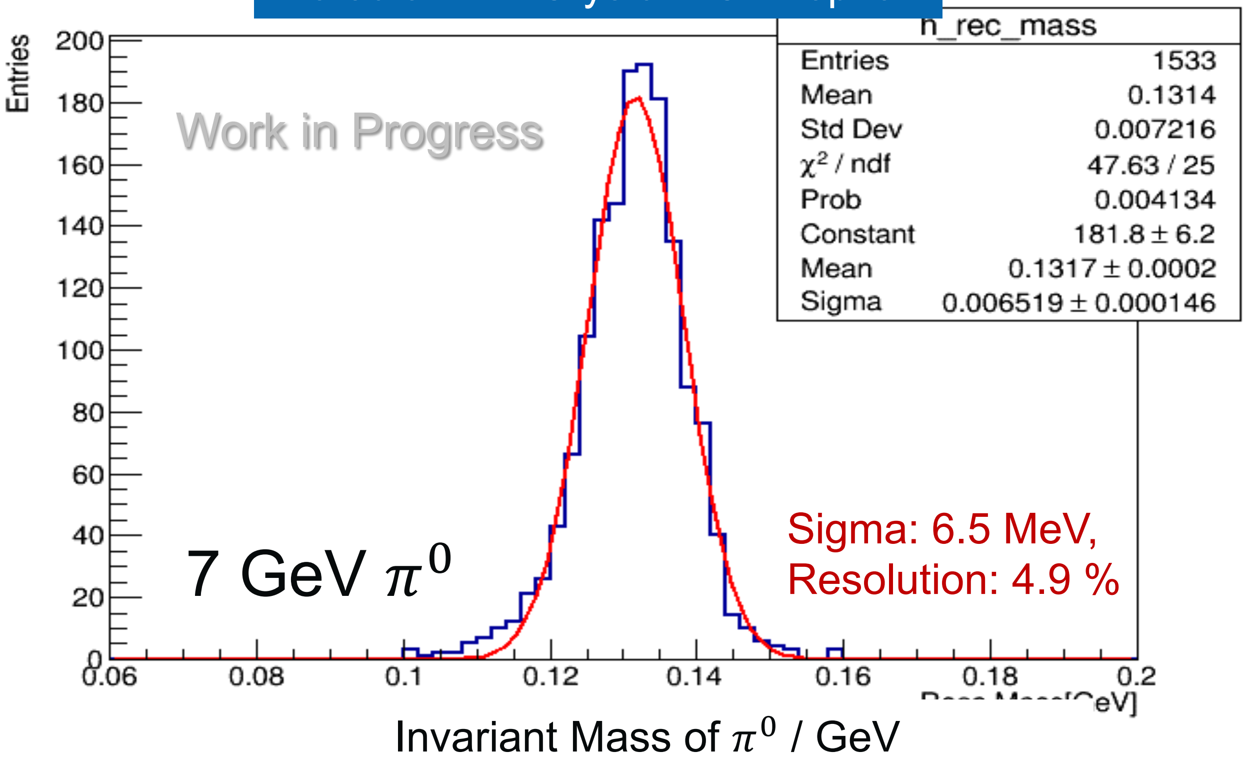
Zhiyu Zhao (IHEP/SJTU),
Fangyi Guo (IHEP)

- Invariant mass of π^0 : crystal ECAL vs. SiW ECAL
  - Single π^0's generated by the particle gun
- First full simulation studies: a factor of 2 (slightly less) in mass resolution

Detector with SiW ECAL option



Detector with Crystal ECAL option

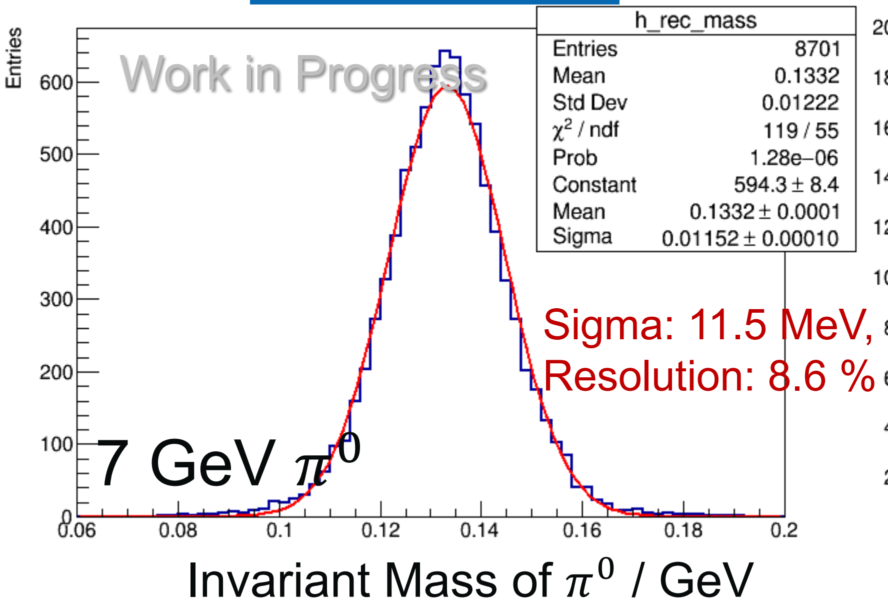


Performance studies with neutral pions

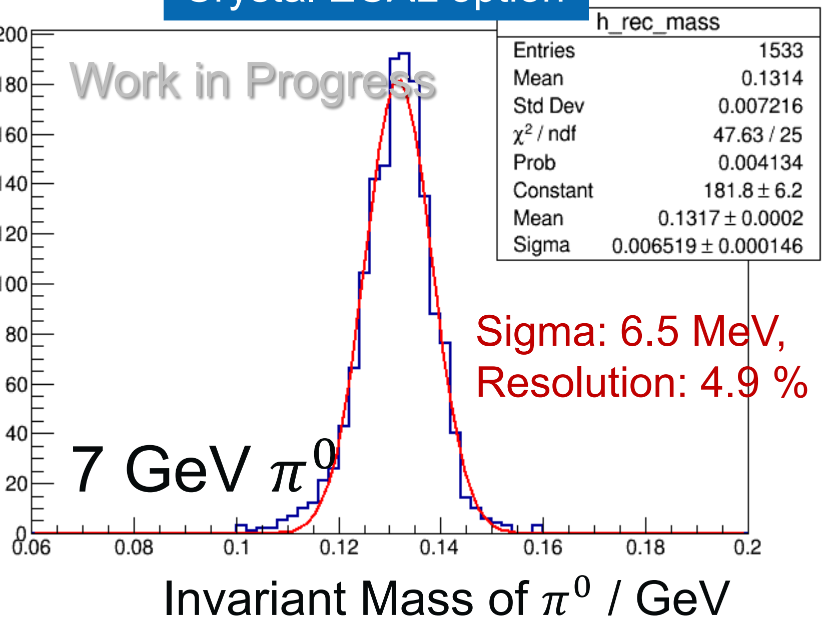
Zhiyu Zhao (DLUT), Fangyi Guo (IHEP)

- Invariant mass of π^0 : crystal ECAL vs. SiW ECAL
- First full simulation studies: a factor of 2 (slightly less) in mass resolution (7 GeV π^0)
    - Expected resolution ~3% for 7 GeV π^0 (energy and angular resolutions)
    - Some discrepancy exists, to be investigated

SiW ECAL option



Crystal ECAL option

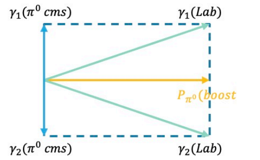


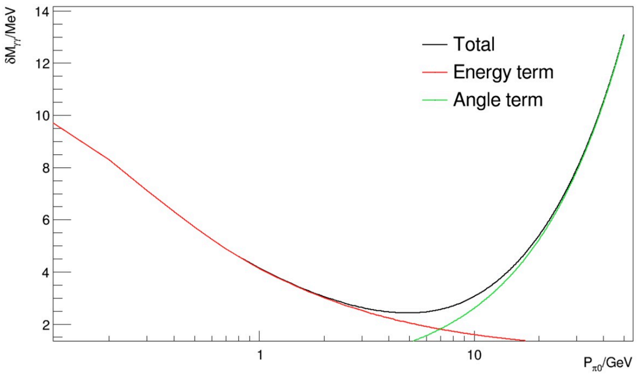
Mass width with P_{π^0}

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

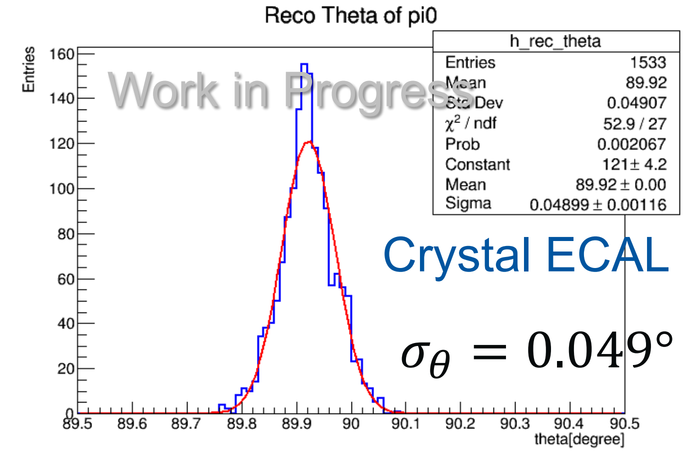
Resolution: $\frac{\delta E}{E} = a \oplus \frac{b}{\sqrt{E}}$, a=1%, b=3%. $\delta\theta = 0.03°$

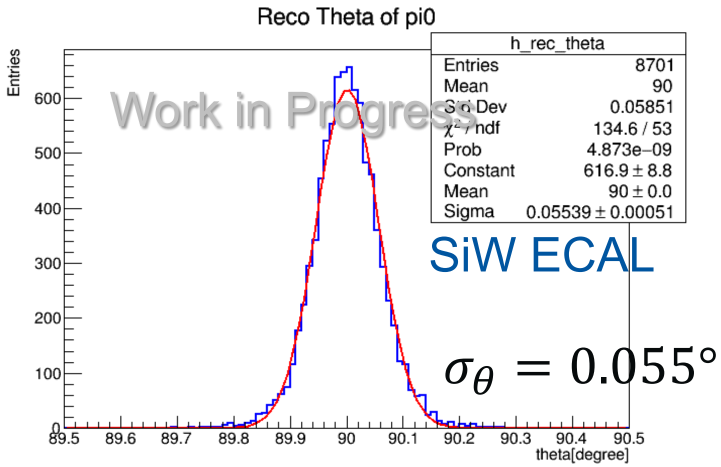


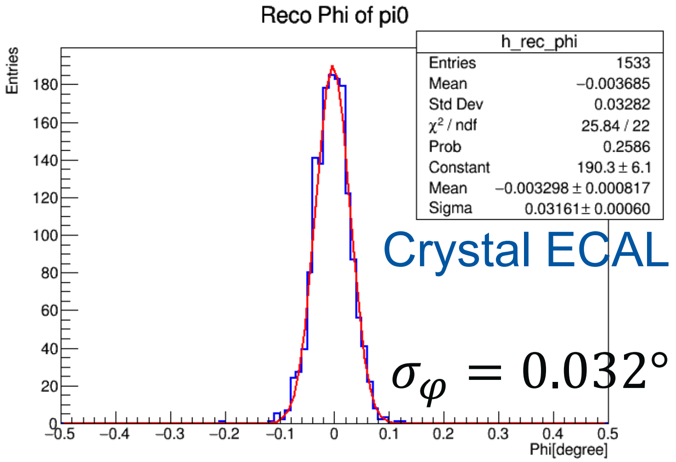


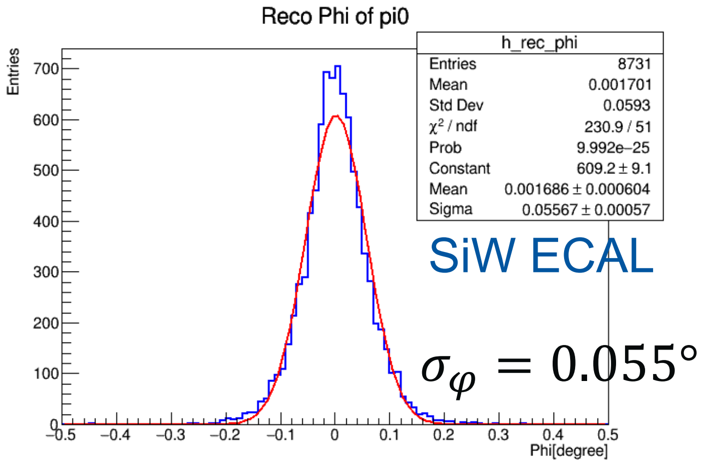
Performance studies with neutral pions

- Angular resolution of π^0 reconstruction: crystal ECAL vs. SiW ECAL







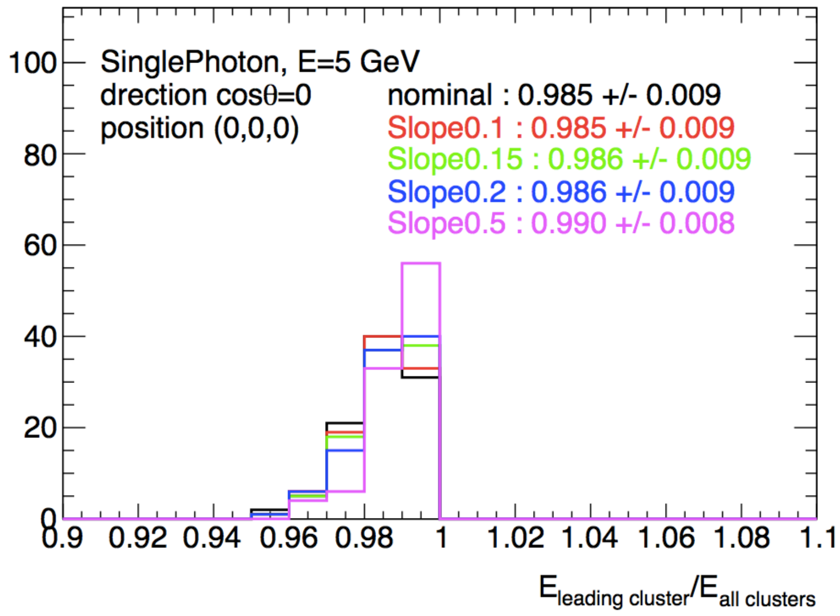


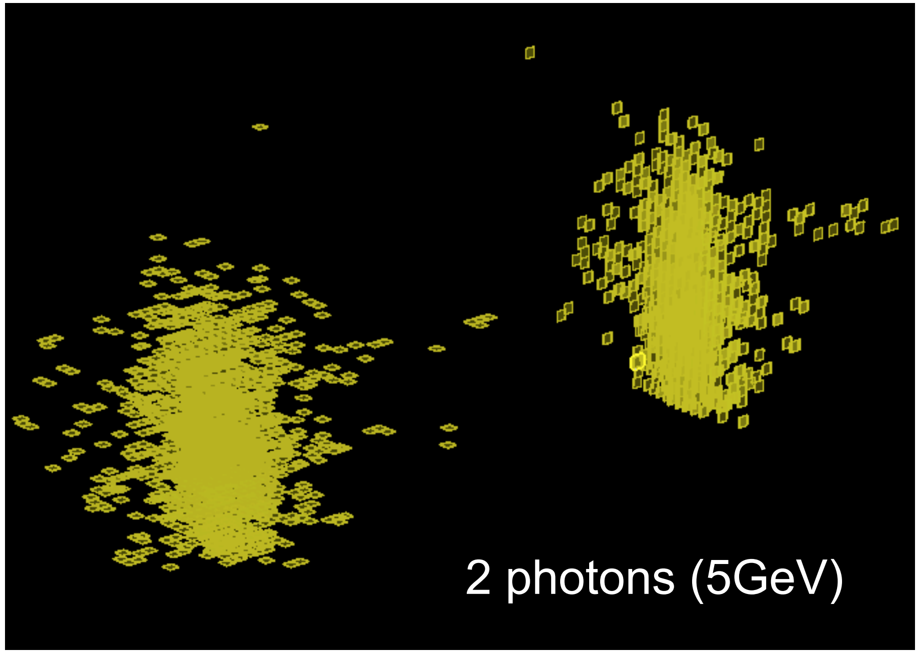
Similar performance with two ECAL options in general; crystal option slightly better

Photon separation studies with Arbor

Hideki Okawa,
Yu Zhang (Fudan U.)

- Clustering efficiency with a single photon
  - Energy ratio of the leading cluster and all clusters: 98~99%
- First separation studies with two photons
  - Perpendicular incidence to ECAL
  - In parallel, separated by a certain distance (not from the IP)

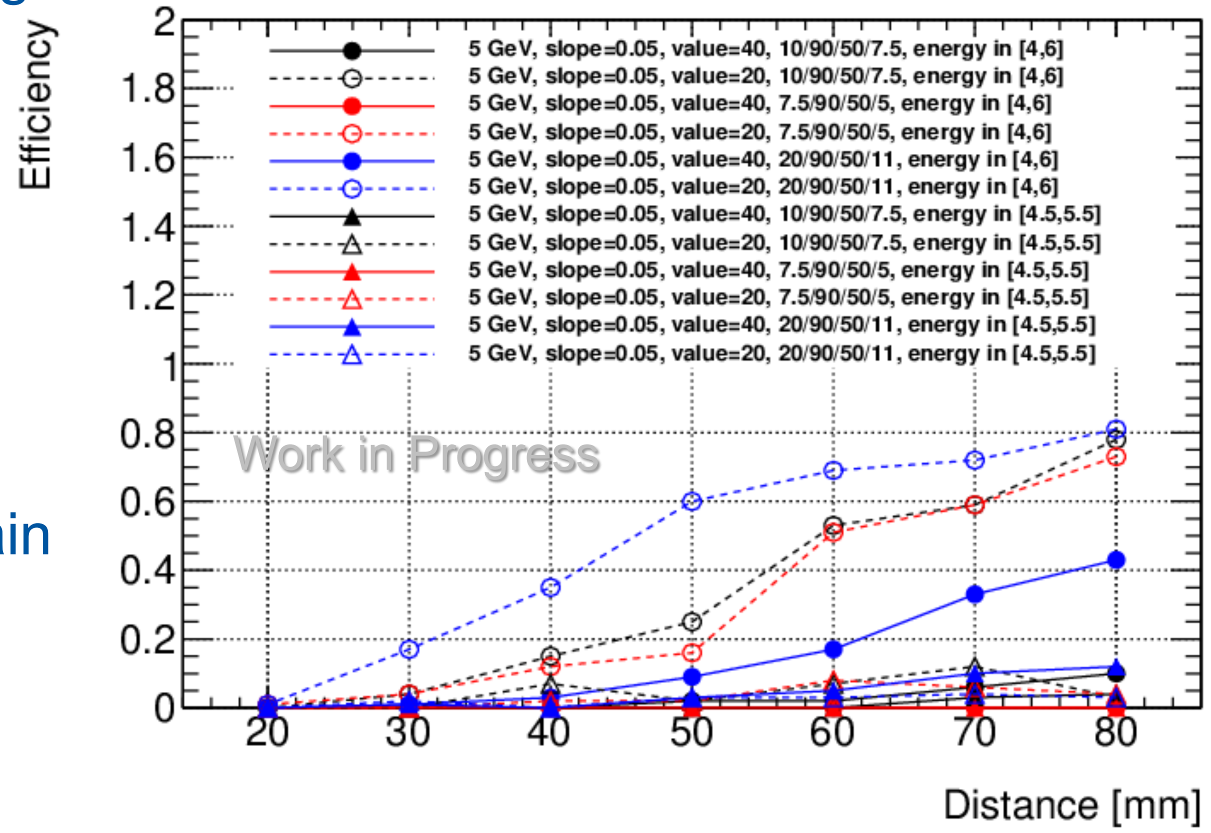




Photon separation studies with Arbor

Hideki Okawa,
Yu Zhang (Fudan U.)

- Separation studies with two photons
  - "Overlay" of two single-photon events
- 3 major parameter sets for tuning
  - Build connections (in Arbor)
  - Bush-Connect (in Arbor)
  - Energy region for reconstructed photons (efficiency definition)
- Preliminary (fresh) results
  - Training to go through the whole chain
  - <u>Only a start, not final numbers!</u>
  - Need further understanding and investigation or debugging



Recent progress on crystal calorimeter

- Key issues: performance studies and optimization
  - PFA performance with jets with ArborPFA: preliminary studies with crystal cubes
    - Studies with benchmarks $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ and $ZH(Z \rightarrow \nu\nu, H \rightarrow \gamma\gamma)$
  - Performance studies: reconstruction of neutral pions
  - Separation capability of crystals with ArborPFA

- Critical technical questions/challenges
  - Detector unit (crystal + SiPM) design
  - Front-end electronics: multi-channel ASIC testing

Detector unit: general considerations

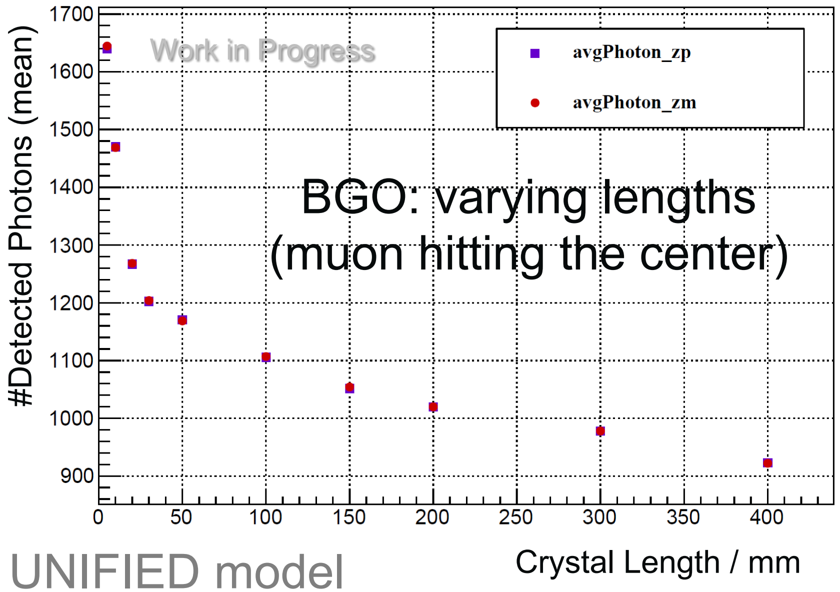
- Key parameters
  - MIP response (#p.e./MIP)
    - Photon statistics: significant impact to the stochastic term ($\leq 3\%$)
    - Energy threshold: sensitivity to low-energy photons
  - Dynamic range
    - Orders of magnitude: o(1MeV ~ 30 GeV) per crystal cell
      - Dependent on crystal dimensions
    - Impact from non-linearity effects of photosensors and electronics
      - SiPM: e.g. limited amount of pixels on a given sensitive area
      - Electronics: e.g. Time-over-Threshold technique
  - Fast timing
    - To explore potentials of <100ps and understand possible limitations

Crystal bar: length impacts and uniformity scan

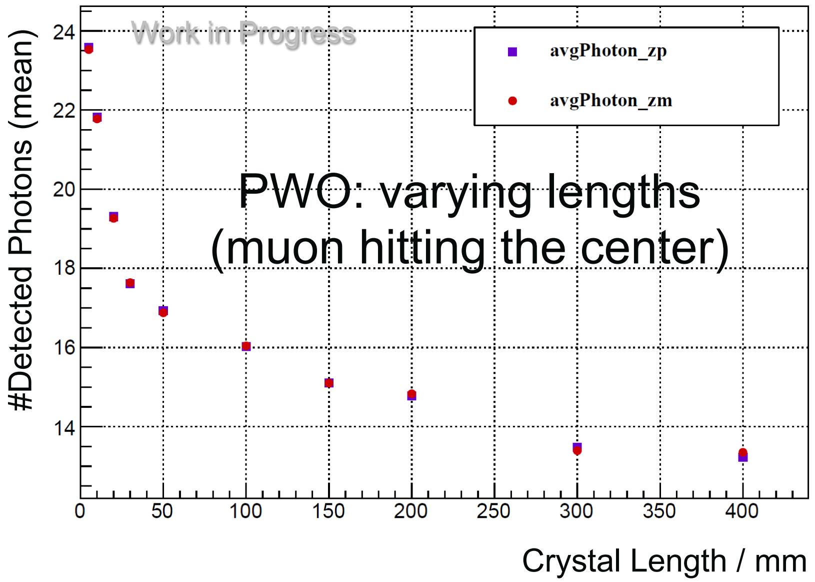
Baohua Qi (IHEP)

- G4 full simulation of MIP response
  - BGO and PWO crystals (varying lengths): photons detected at each SiPM
  - Also scanned different hit positions: response uniformity
- Measurements (cosmics) ongoing to validate the simulation

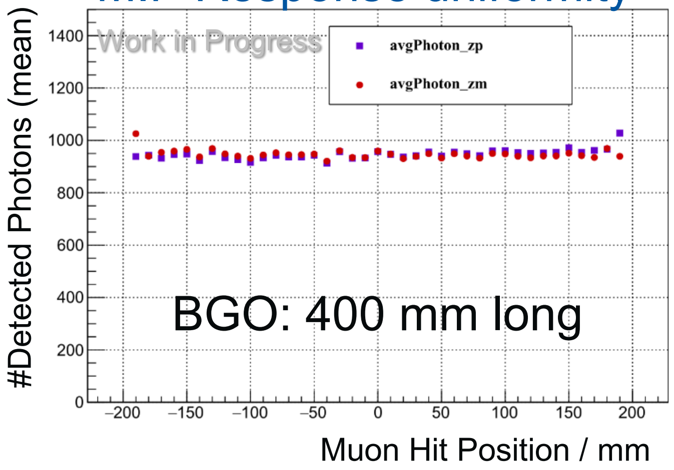
Geant4 10.5.0



UNIFIED model



MIP Response uniformity

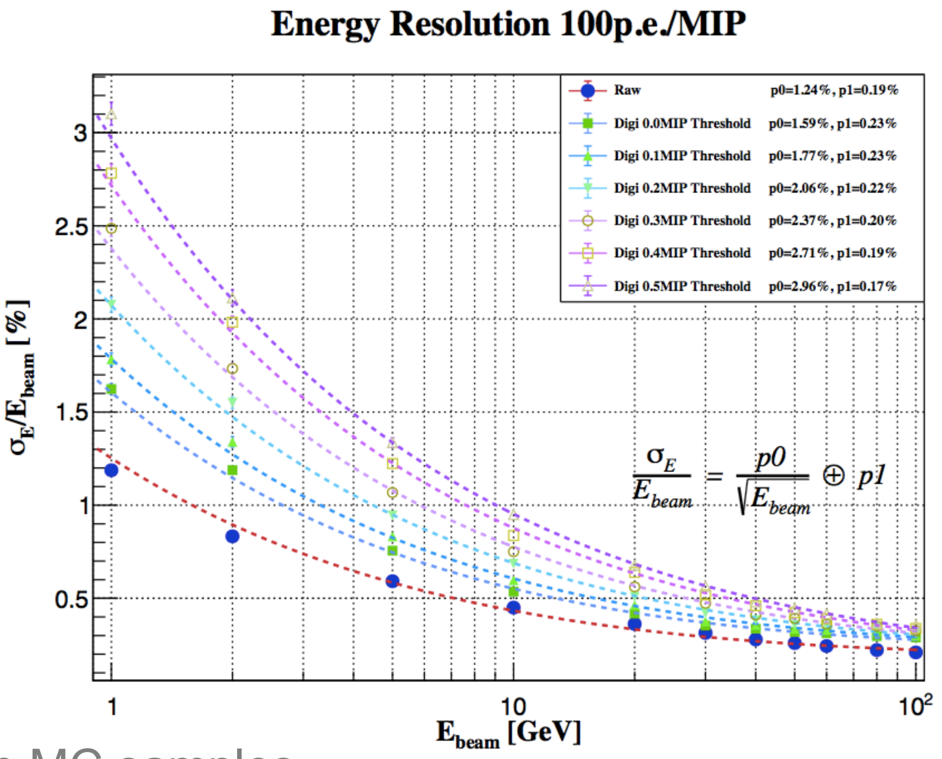


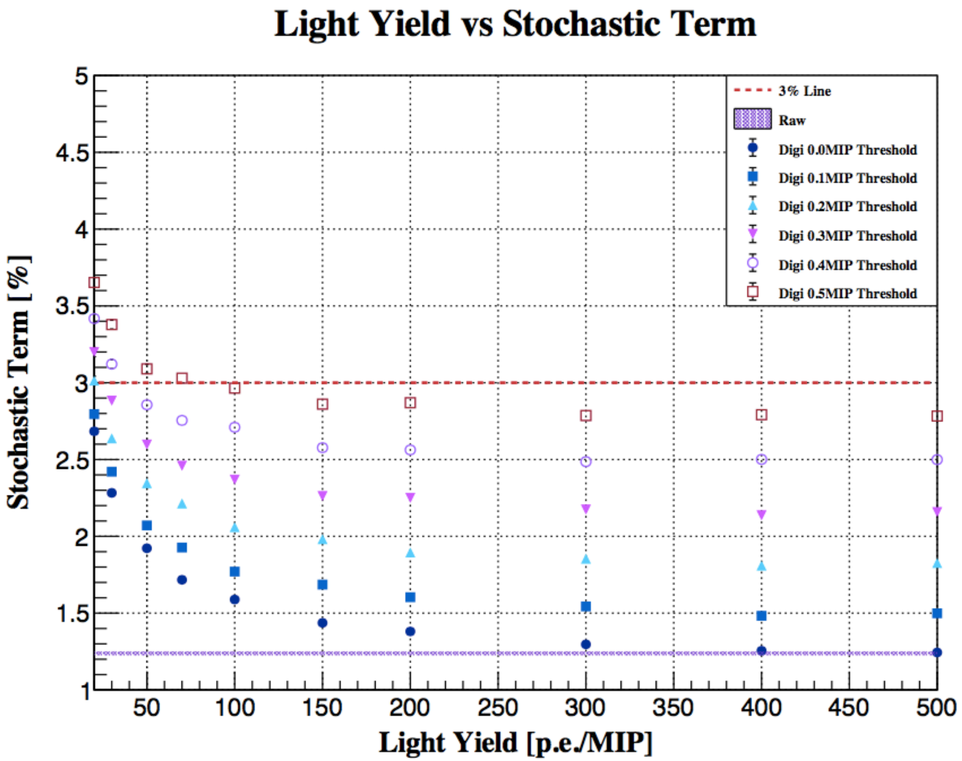
Crystal detector unit: simulation studies

Baohua Qi (IHEP)

- EM energy resolution
  - MIP response (“light yield” in plots) and energy threshold
  - Using digitisation tools: photon statistics (crystal+SiPM), electronics resolution

Geant4 10.5.0



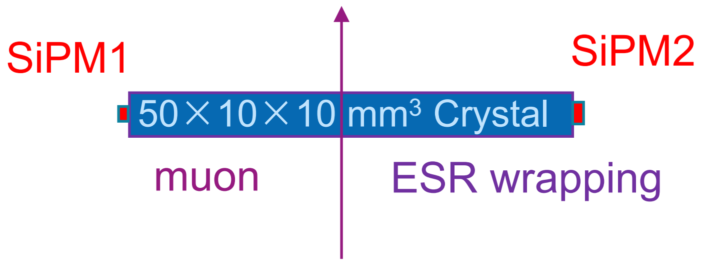


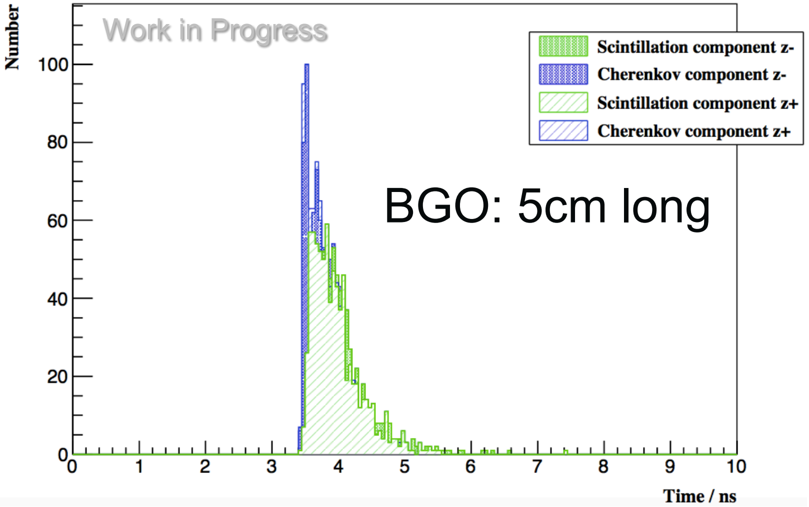
Electron MC samples

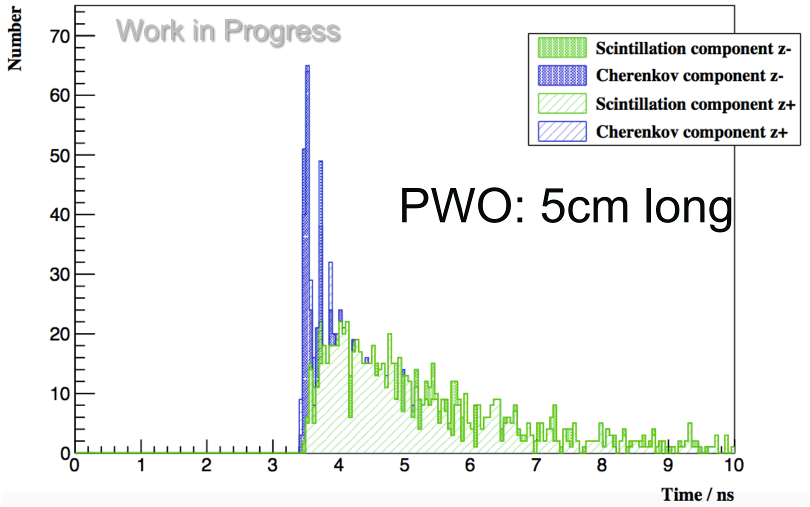
Crystal bar: timing studies

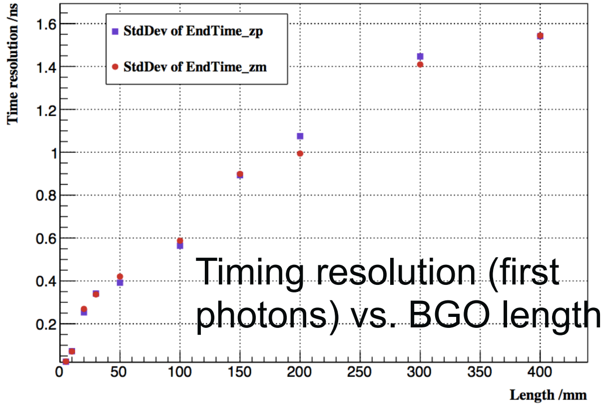
Baohua Qi (IHEP)

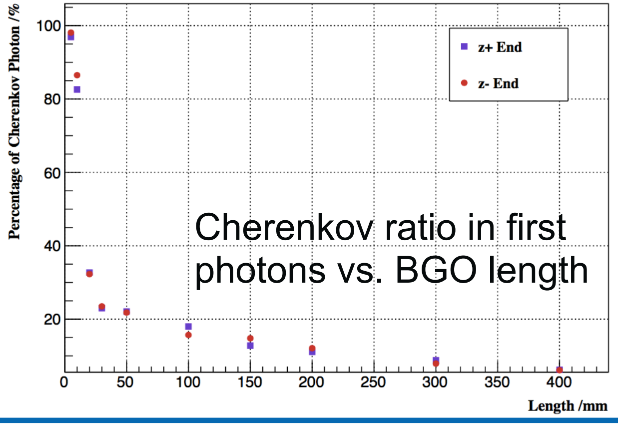
- Timing performance to MIPs in G4 full simulation: ongoing
  - BGO and PWO crystals (varying lengths): better time resolution with shorter crystal length
    - Time stamp of the first photon detected at each SiPM
  - Use Cherenkov light in the slow scintillator such as BGO?
  - Will look at other crystals and new materials for fast timing









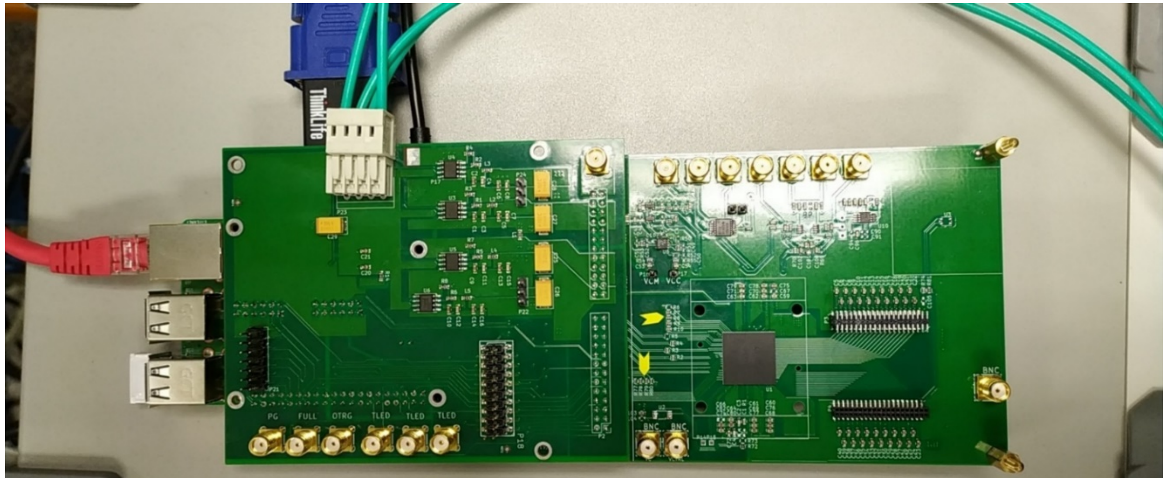


LUT_DAVIS model

Front-end electronics for SiPM readout

- Designed by KIP, U. Heidelberg
  - 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

Klaus5 in BGA



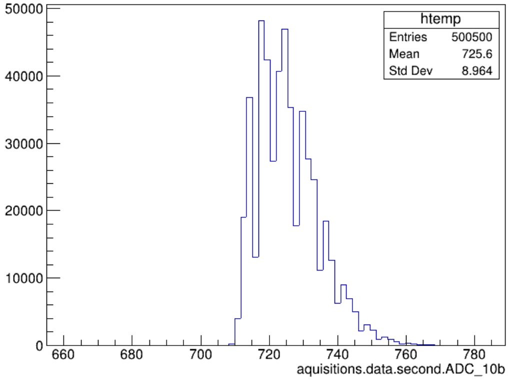
Test board for KLauS-5 in BGA package

Joint efforts with the JUNO-TAO team

Klaus5 tests with NDL-SiPM (reminder)

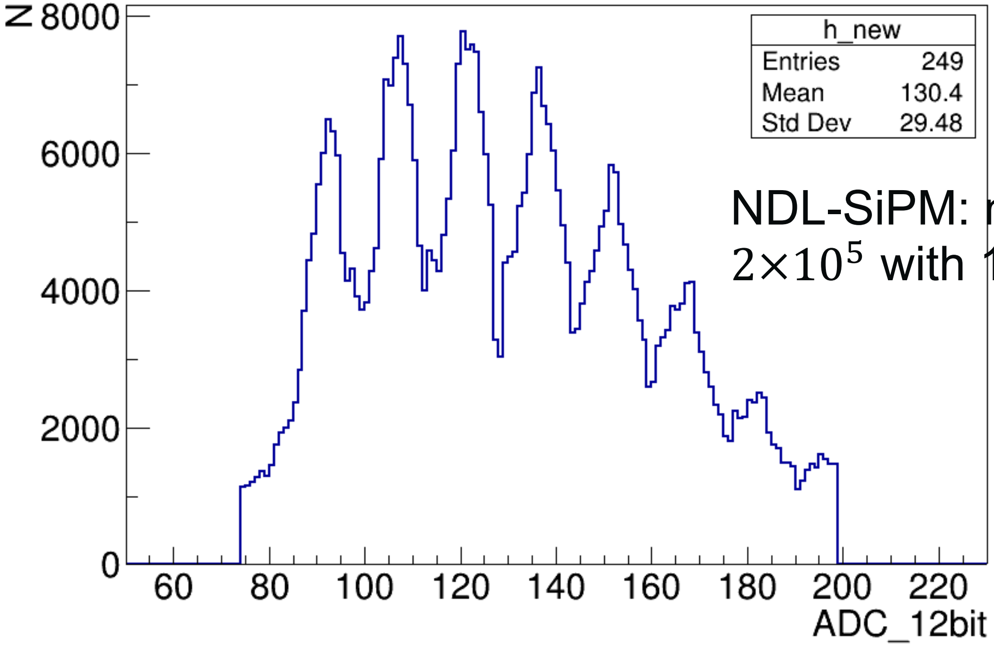
Single photon calibration

- 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

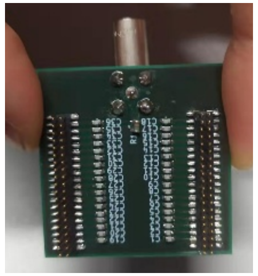


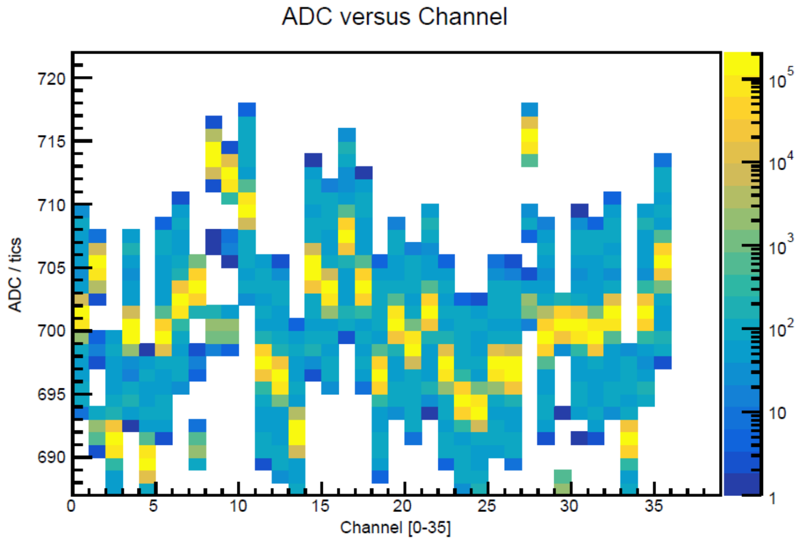
NDL-SiPM: nominal gain 2×10^5 with 10μm pixels

Klaus5 tests with charge injection

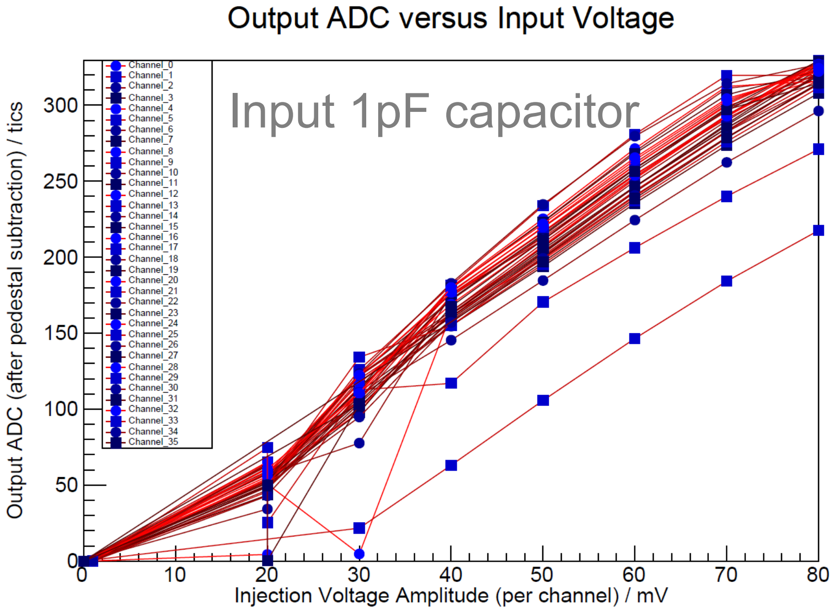
Dynamic Range

- Testing of all 36 channels
  - Good linearity in different working modes (high gain and low gain)
  - Small equivalent noise charge (ENC) ~4.5fC
  - Dynamic range: ~550pC as the maximum charge (preliminary)

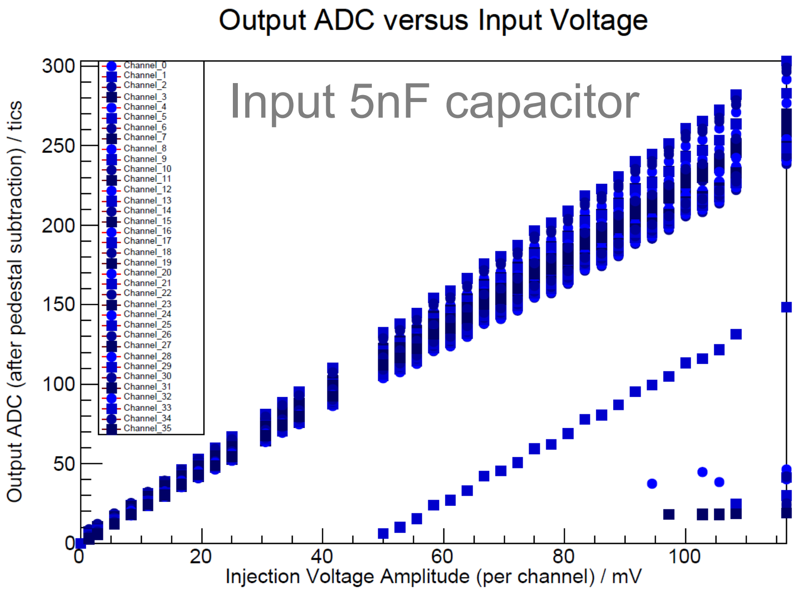




Pedestals in mid High Gain mode



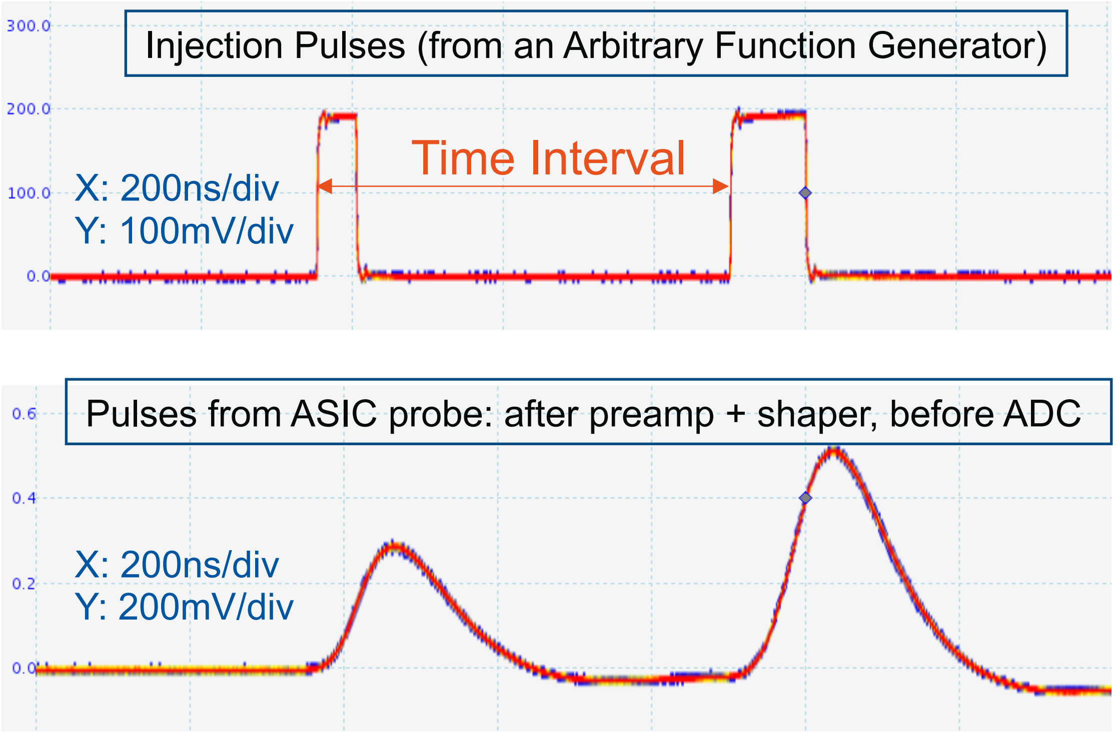
ADC in mid High Gain mode (after pedestal subtraction)

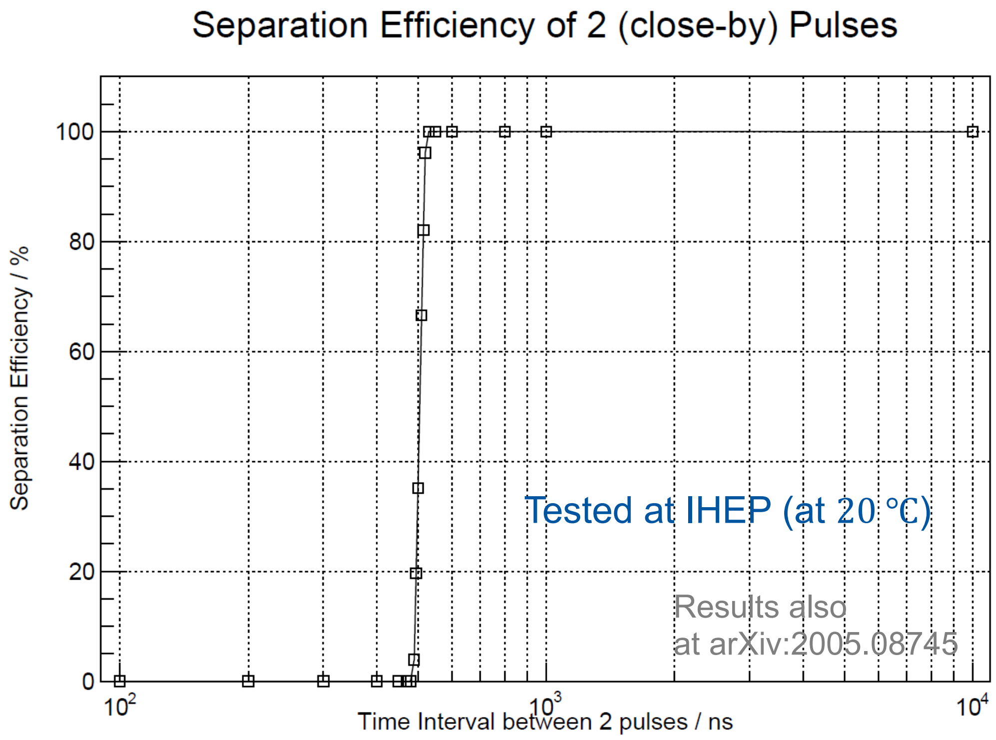


ADC in Ultra Low Gain mode (after pedestal subtraction)

Klaus5 dead time measurements (reminder)

Potential for continuous mode

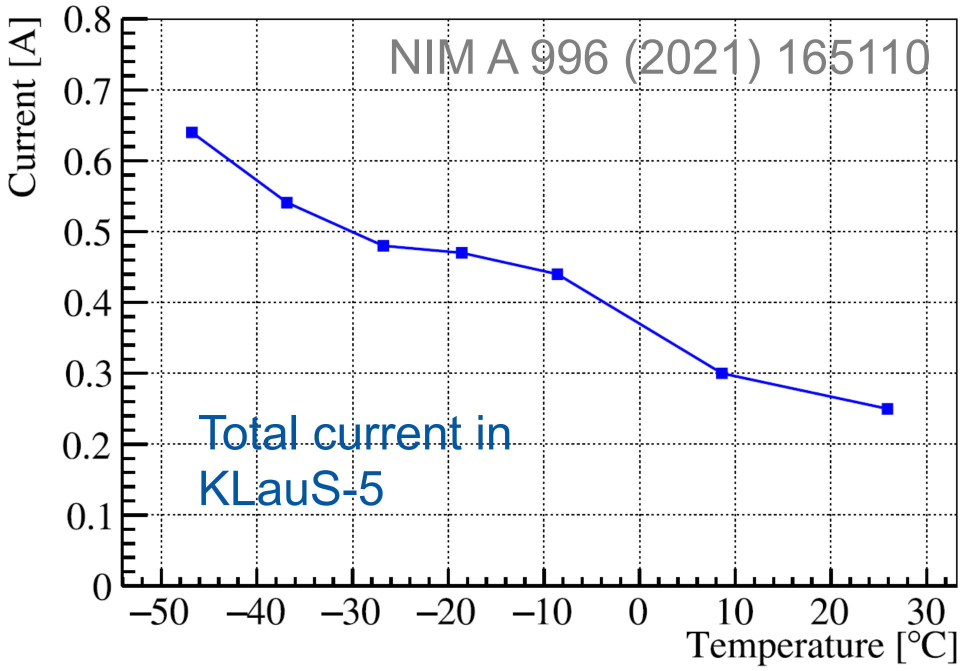


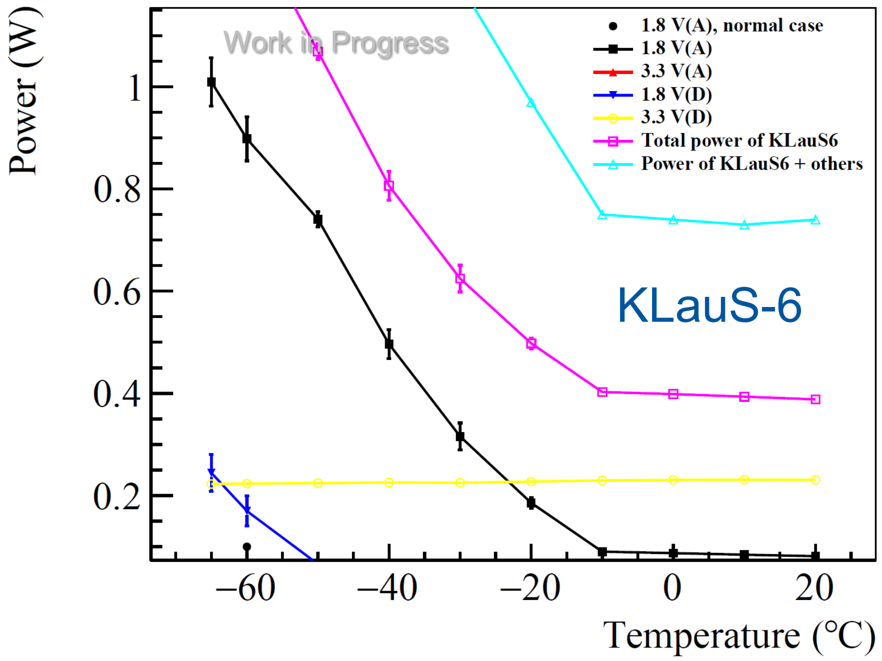


- Varying time interval between 2 injection pulses: 100ns - 10μs
- When time interval > 500ns, 100% efficiency of separating the two pulses
  - Promising feature for 100% duty cycle (required by circular colliders)

KLauS: power consumption

- Power consumption measurements with varying temperatures
  - KLauS chips (version 5, 6) and peripherals
  - KLauS6: ~0.4W/chip measured around room temperature
    - At threshold=0 (high trigger rate expected ~2MHz)



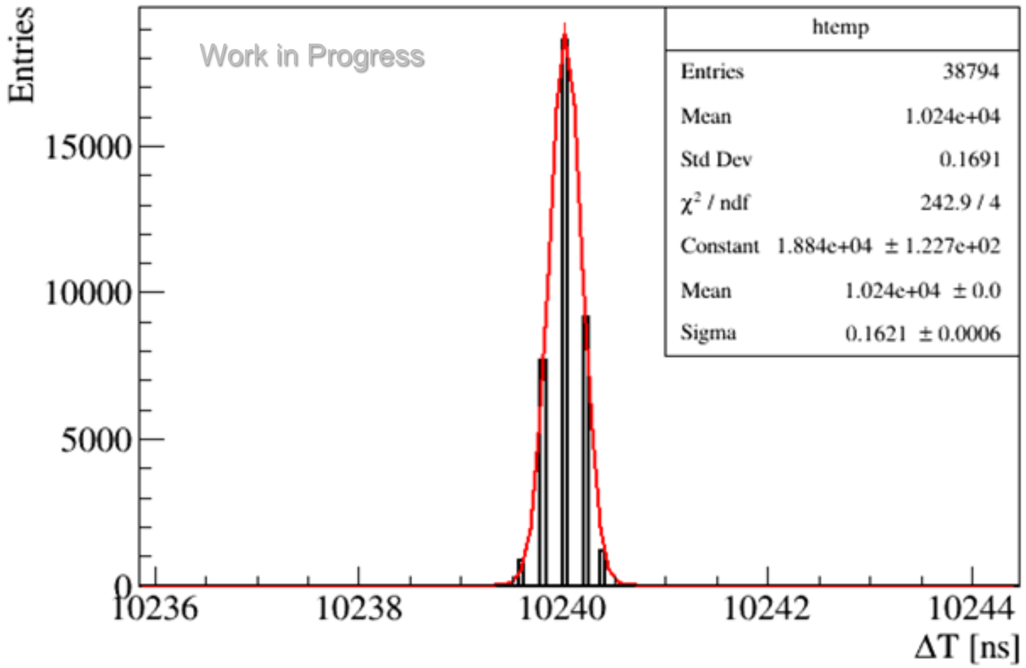


Typical 3.3mW/ch for Klaus5

With JUNO-TAO team

KLauS6: timing performance

- KLauS6: tested with a pulse generator
  - KLauS6 TDC bin 200 ps: theoretical resolution ~58 ps
  - Time intervals between 2 pulses
  - Timing resolution measured ~160ps
    - Still quite some room for improvement



Pulse generator settings
- 100kHz repetition rate
- 40mV pulse height
- 3ns rising edge
- 3ns rising falling edge

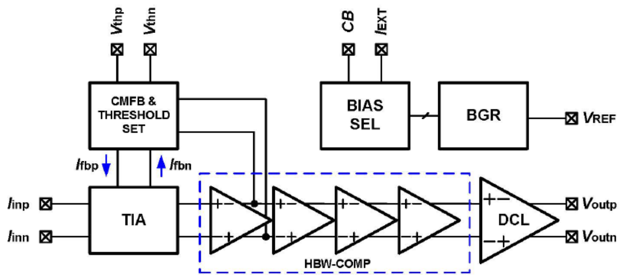
With JUNO-TAO team

Electronics: ongoing R&D

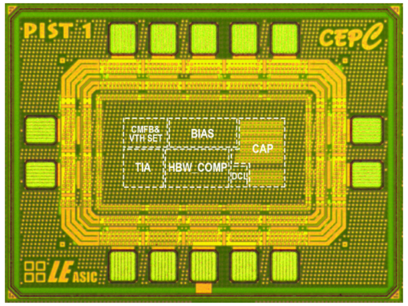
Bo Lu (IHEP), et al.

- PIST ASIC prototype for SiPM readout: fast timing and TOT

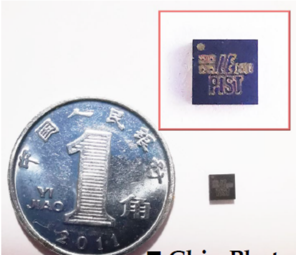
A Glance at the PIST ASIC



■ ASIC System Architecture



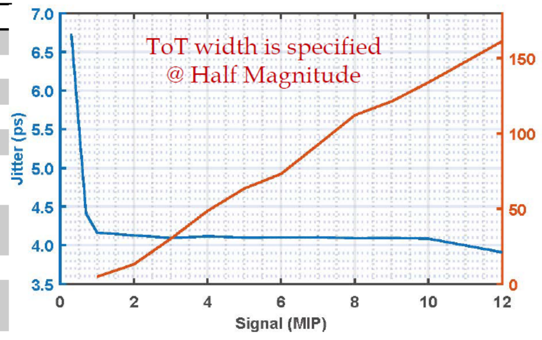
■ Micrograph



■ Chip Photo

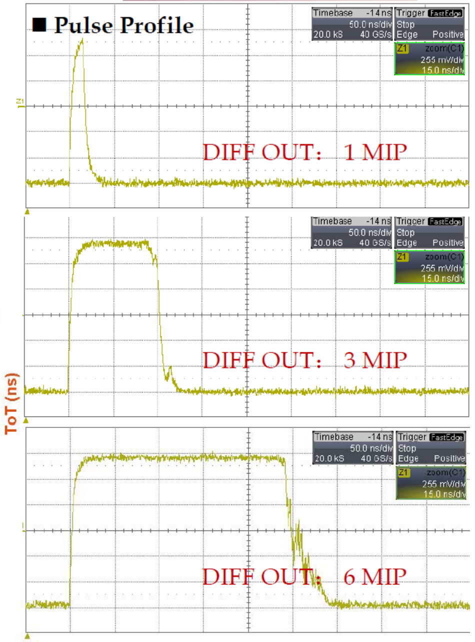
■ PIST v.s. NINO

Param.	Value	
ASIC	PIST	NINO
Technology	SMIC 55 nm CMOS	IBM 0.25 μm CMOS
Power Supply	1.2 V	2.5 V
Area	~ 220×125 μm²	~ 460×210 μm²
Signal Range	1~12 MIP	0.1 ~ 2 pC
Detector Capacitance (C_{DET})	55 pF	10 pF
Leading Edge Jitter	4 ps @ 1 MIP	> 20 ps ~70 ps @ 100 fC
ToT Linearity	-2.70 %/3.95 %	NA
Differential Input Impedance	30 ~ 60 Ω	40 ~ 75 Ω
Power Dissipation	18 mW/Channel	30 mW/Channel
Output Interface	DCL	DCL



■ Jitter and ToT performances

■ Pulse Profile



Summary

- High-granularity crystal caorimeter
  - Aim to achieve optimal EM energy resolution and PFA capability
  - Steady R&D progress targeting key issues
    - PFA performance: preliminary studies with crystals
    - Software developments in CEPCSW (a separate talk by Dr. S. Sun)
    - Performance studies with two photons
    - Technical progress
      - SiPM and crystal: design and timing potentials
      - SiPM-readout ASIC: characterisations and new developments
- Welcome broader collaborations
- Synergies expected: common software framework (Gaudi, Key4HEP, DD4HEP, …)

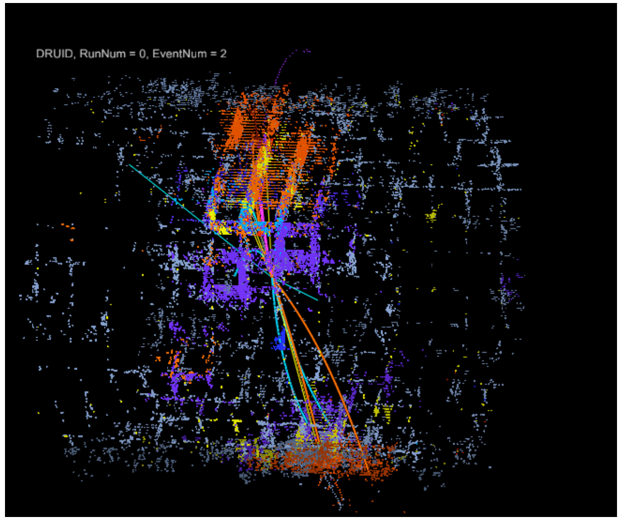
Thank you!

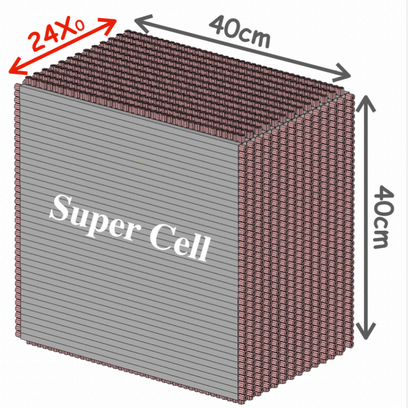
Backup slides

PFA performance: a first glance with crystals

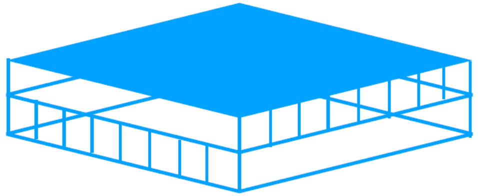
Dan Yu (IHEP)

- 2-jet benchmark events in $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV
- Simulation setup: a temporary layout for first studies
  - Crystal calorimeter with silicon layers
    - Use positioning info from silicon pads, energy from crystal bars
    - Reconstruction algorithm for crystals not ready yet
  - RPC-based semi-digital hadron calorimeter (SDHCAL)
  - Other subdetectors: CEPC CDR baseline





ECAL: 14 super-layers (24X0)



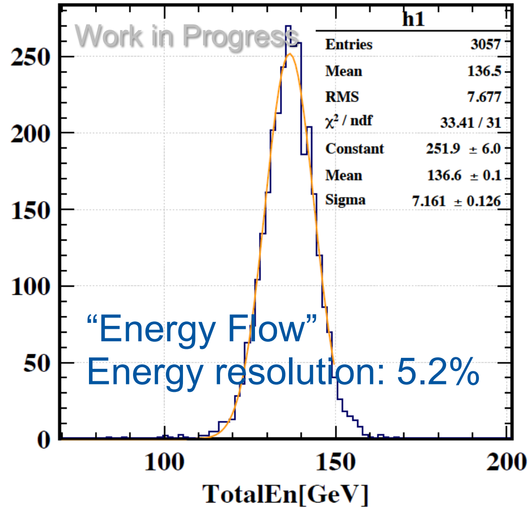
1 super-layer:
2 crystal layers (energy)
1 thin silicon layers (position)

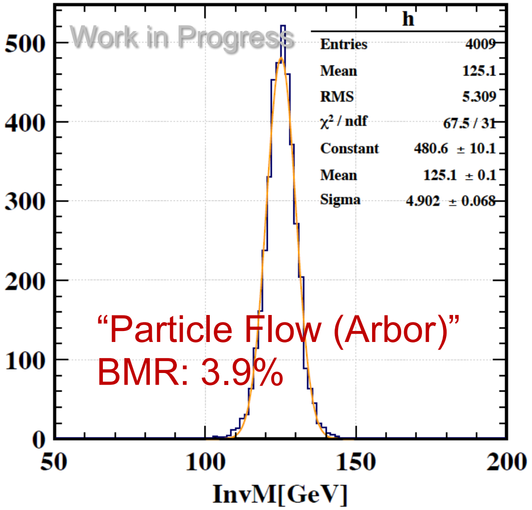
PFA performance with CDR baseline detector

Dan Yu (IHEP)

- 2-jet benchmark events in $ZH(Z \rightarrow \nu\nu, H \rightarrow gg)$ at 240 GeV
  - Energy flow: combination of hits in calorimeters only
  - Boson mass resolution (BMR)
- PFA improves the resolution from 5.2% to 3.9%

ECAL: 28 SiW layers (24X0)





CEPC CDR baseline detector:
BMR improved to 3.9% with PFA

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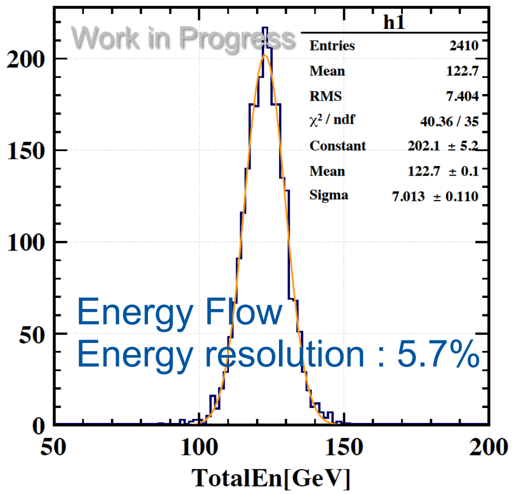
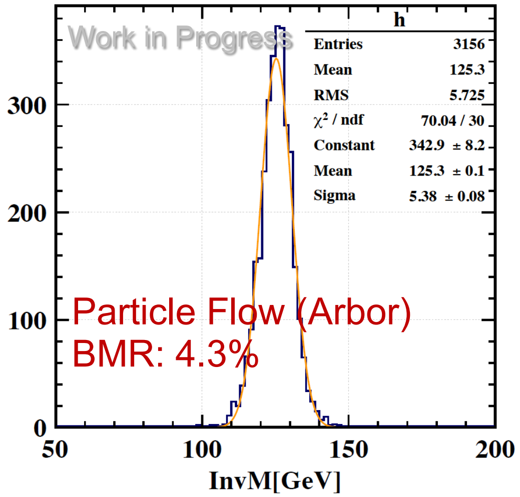


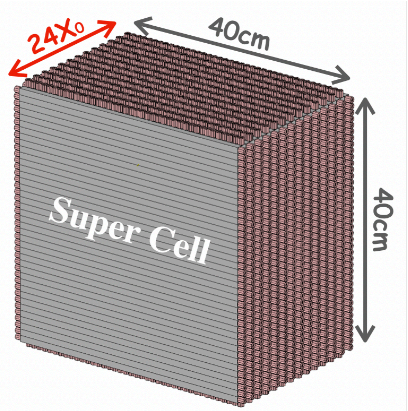


SiW ECAL with a factor of two lower sampling frequency:
to compare with crystals (next page)

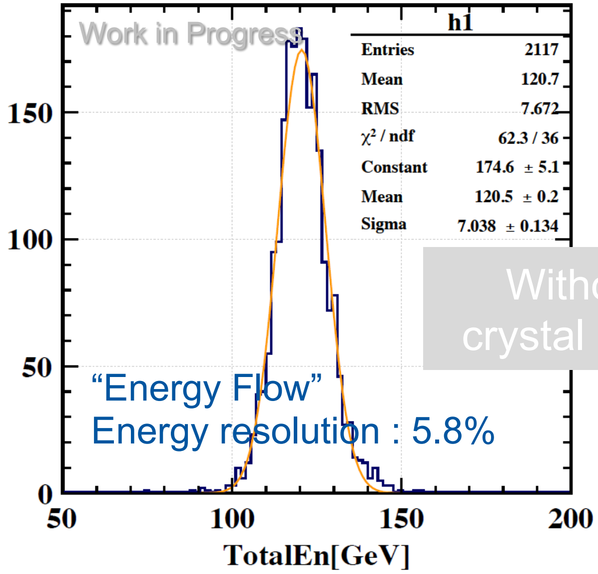
PFA performance: a first glance with crystals

Dan Yu (IHEP)

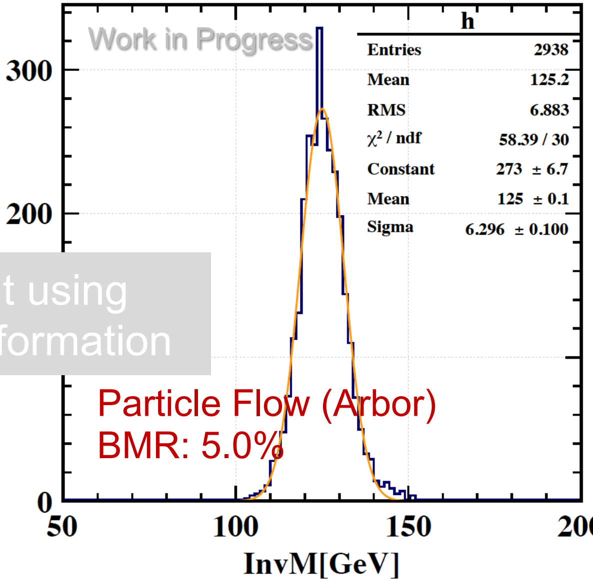
- 2-jet benchmark events in $ZH(Z \to \nu\nu, H \to gg)$ at 240 GeV
- **14 layers** of crystal and silicon: use silicon for positioning
  - Without crystal information: PFA improves resolution to 5.0% from 5.8%
  - With crystal energy information only: energy resolution ~4.8%
- Plenty of room to improve PFA performance with crystals
  - Essential: reconstruction algorithm, PFA optimisation for crystals

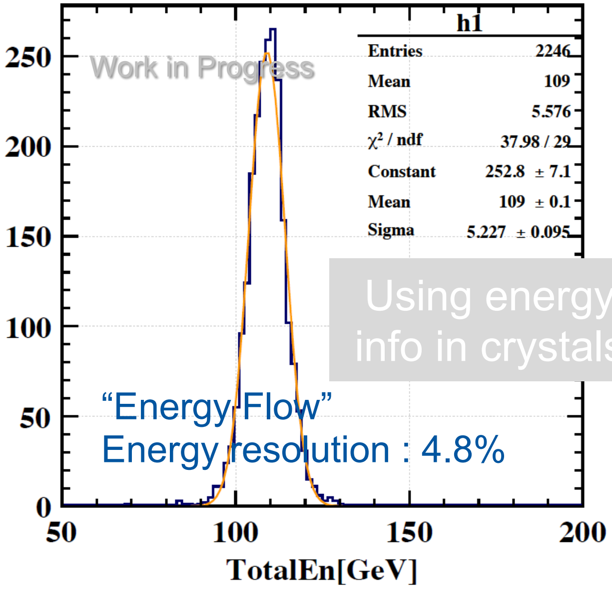


ECAL: 14 super-layers (24X0)

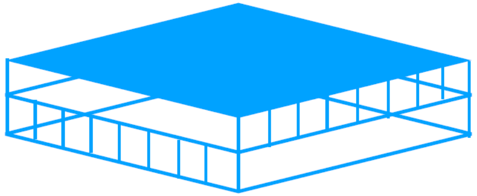


Without using crystal information





Using energy info in crystals

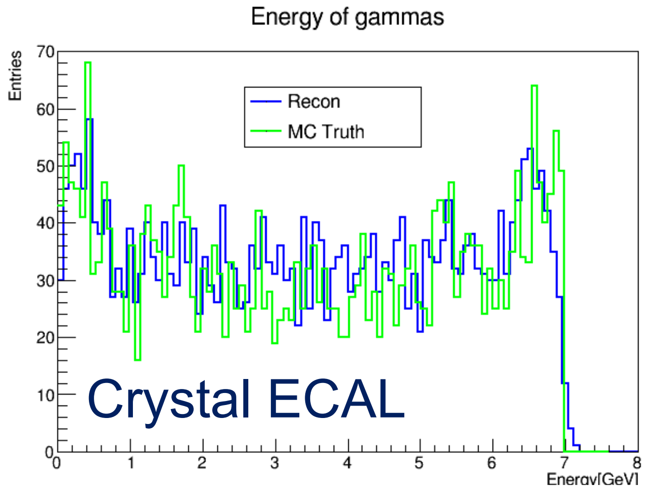


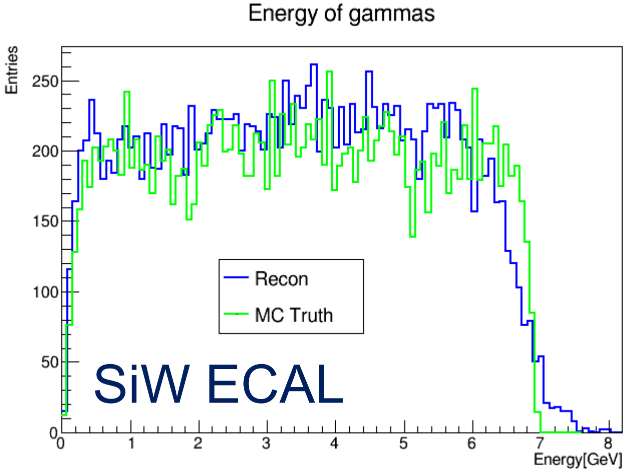
1 super-layer:
2 crystal layers (energy);
1 thin silicon layers (position)

Note the Arbor PFA parameters not yet optimised for crystals: more overlaps in crystals expected (larger X_0, R_M than tungsten)

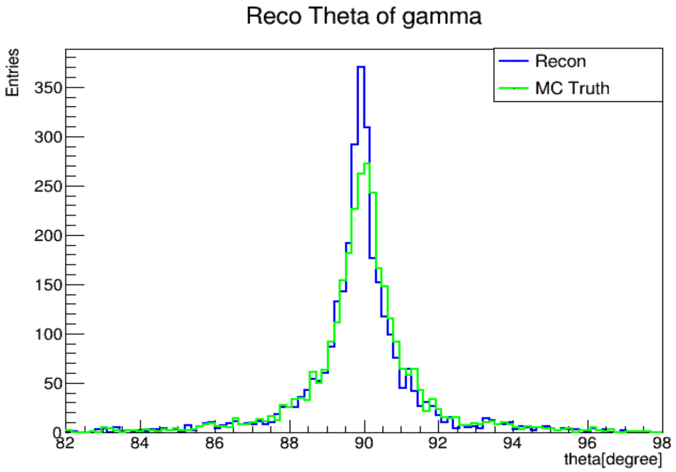
Neutral pion reconstruction: crosscheck with MC truth

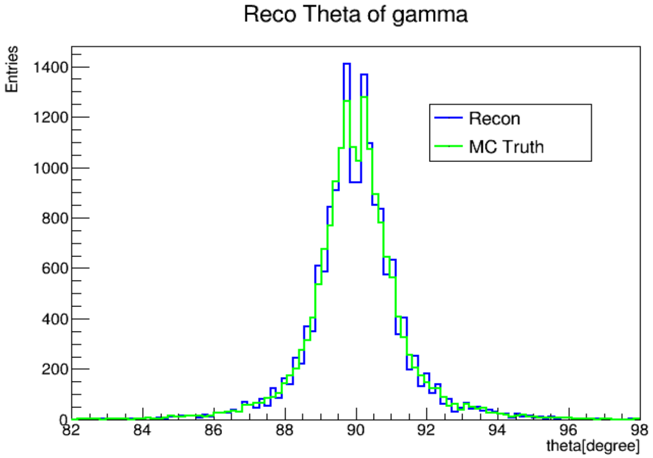
Photon Energy



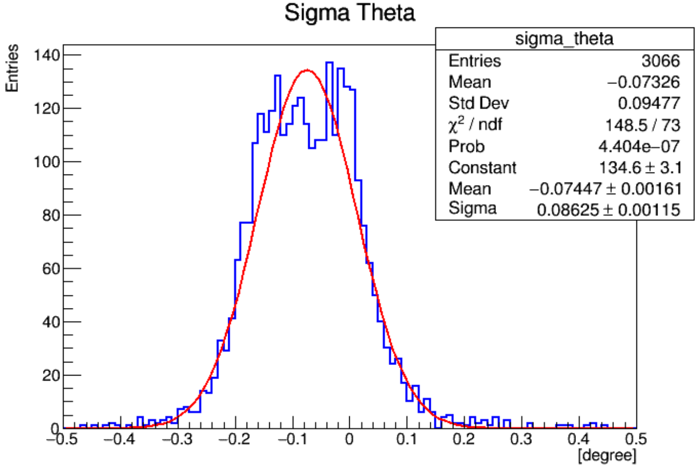


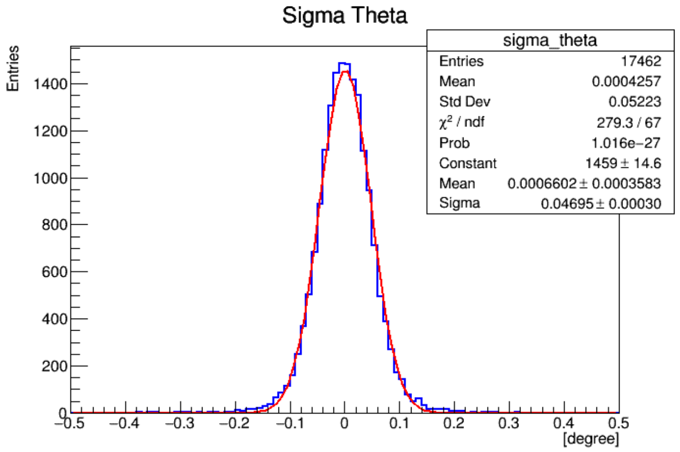
Photon Anle in Theta





Photon Theta: Reco– MC



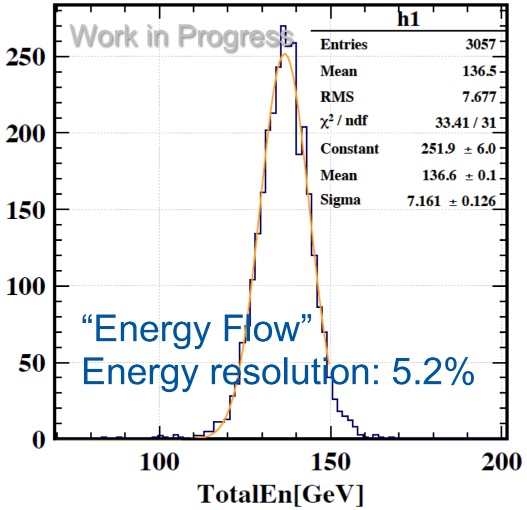


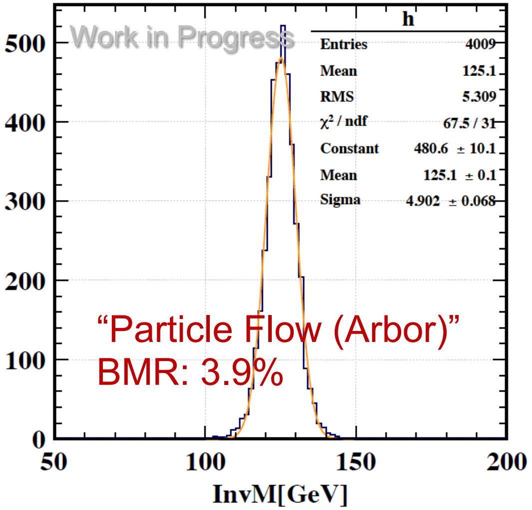
PFA performance with CDR baseline detector

Dan Yu (IHEP)

- 2-jet benchmark events in $ZH(Z \to \nu\nu, H \to gg)$ at 240 GeV
  - Energy flow: combination of hits in calorimeters only
  - Boson mass resolution (BMR)
- PFA improves the resolution from 5.2% to 3.9%

ECAL: 28 SiW layers (24X0)





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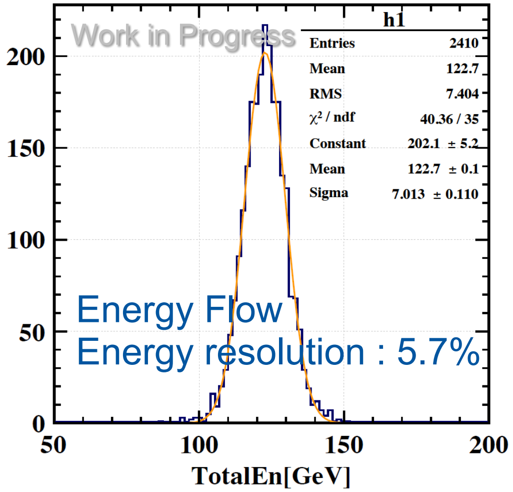
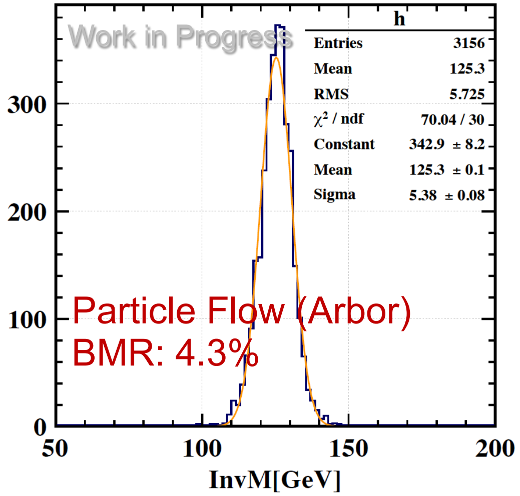


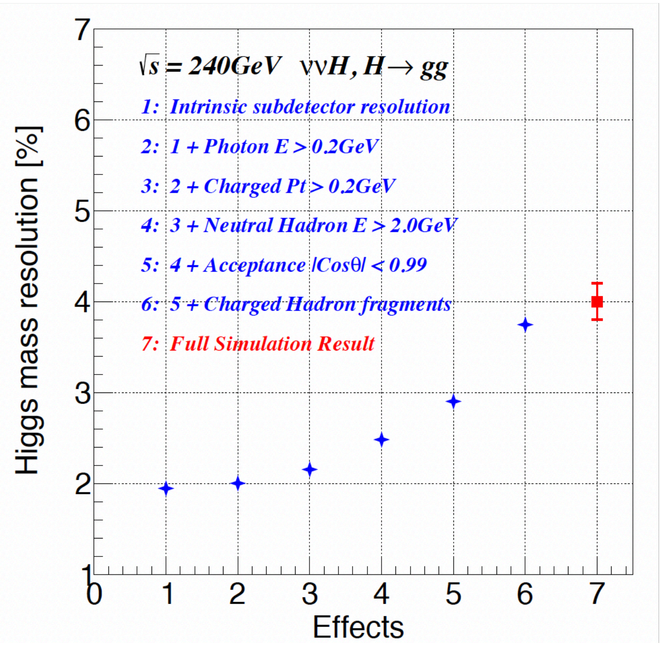


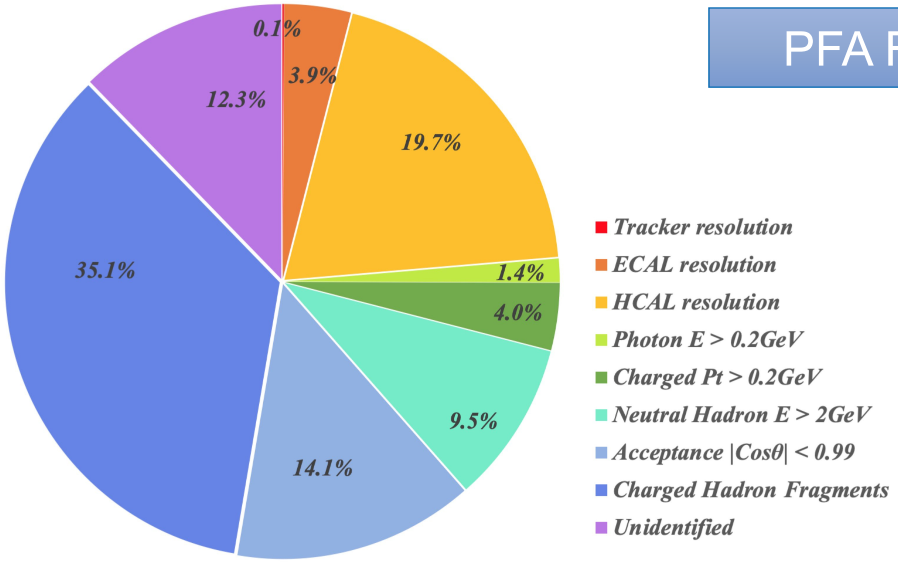
CEPC CDR baseline detector:
BMR improved to 3.9% with PFA

SiW ECAL with a factor of two lower sampling frequency:
to compare with crystals (next page)

Impacts to Higgs mass resolution: reminder

Yuexin Wang (IHEP)





PFA Fast Simulation

- 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 and SiW options

Crystal ECAL: BGO

- Optimal energy resolution $\frac{\sim 3\%}{\sqrt{E}} \oplus \sim 1\%$
  — Better jet energy resolution $0.17\sqrt{E_J}$
- Larger R_M ➔ larger lateral width of a shower
  — Increase probability of showers' overlap
- Larger λ_I / X_0 ➔ longitudinal development is determined by λ_I
  — Increase probability of hadronic shower in ECAL

$$\sigma_{Jet} = \sqrt{\sigma_{Track}^2 + \sigma_{Had}^2 + \sigma_{em}^2 + \sigma_{Confusion}^2}$$

Confusion is the limiting factor in PFA.

- Avoid double counting of same particle
- Separate energy from different particles

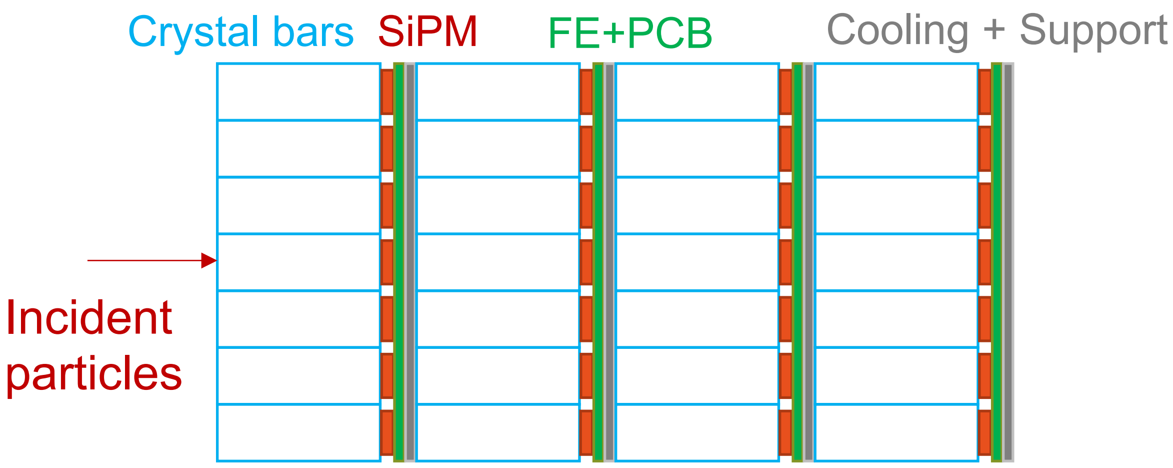
Material	X_0 /cm	R_M /cm	λ_I /cm	λ_I / X_0
W	0.35	0.93	9.6	27.4
BGO	1.12	2.23	22.8	20.3
Ratio	3.2	2.4	2.4	0.74

Component	Detector	Energy Fraction	Energy Resolution	Jet Energy Resolution
Charged Particles ($X^{\pm}$)	Tracker	$\sim 0.6\ E_J$	—	—
Photons (γ)	ECAL	$\sim 0.3\ E_J$	$0.15\sqrt{E_\gamma}$	$0.08\sqrt{E_J}$
			$0.03\sqrt{E_\gamma}$	$0.016\sqrt{E_J}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1\ E_J$	$0.55\sqrt{E_{h^0}}$	$0.17\sqrt{E_J}$

3

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

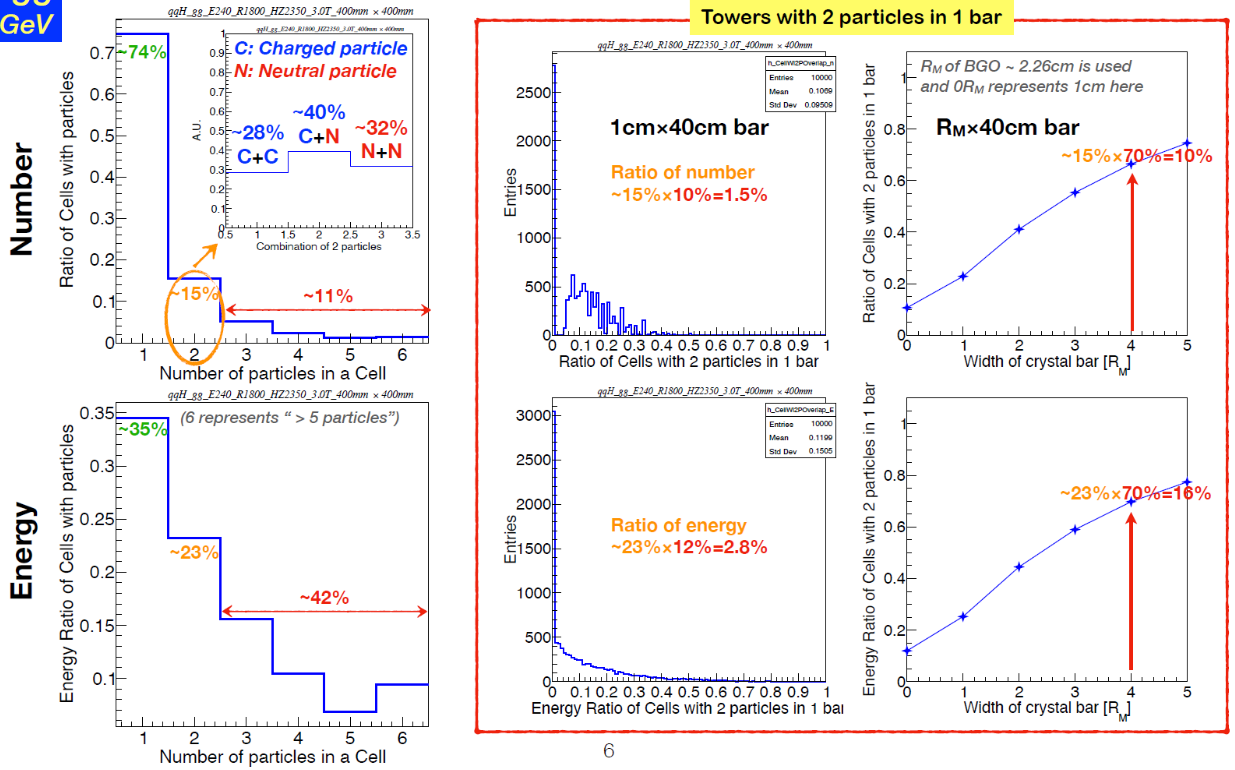
Studies on physics requirements

Yuexin Wang (IHEP)

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

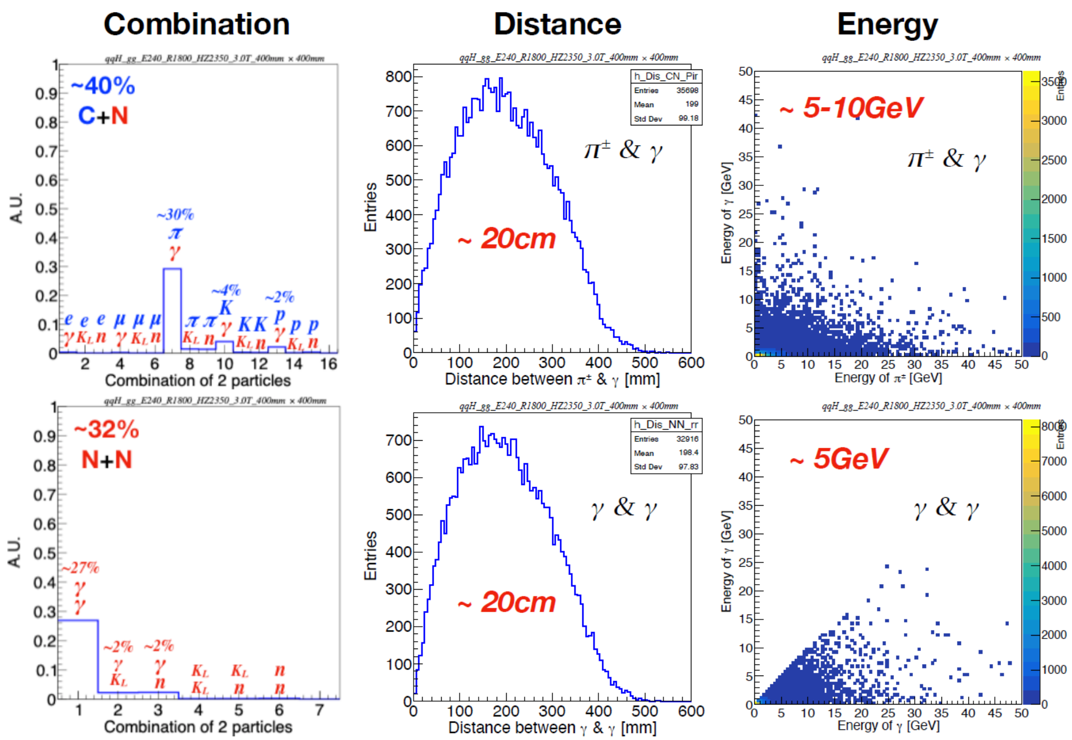
$Z \to qq$
$H \to gg$
240GeV

Multiplicity in a 40cm×40cm tower



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

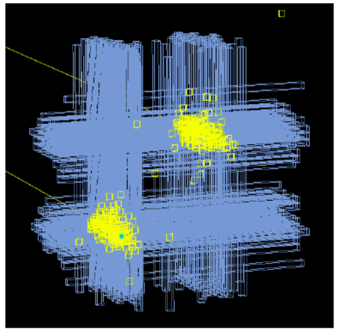
Tower with 2 particles: distance & energy distribution



Reconstruction: ongoing studies

Yuexin Wang (IHEP)

Patterns in event display: 2 photons

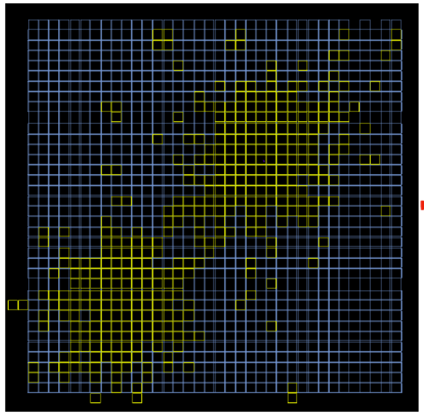


2 parallel 5GeV γ

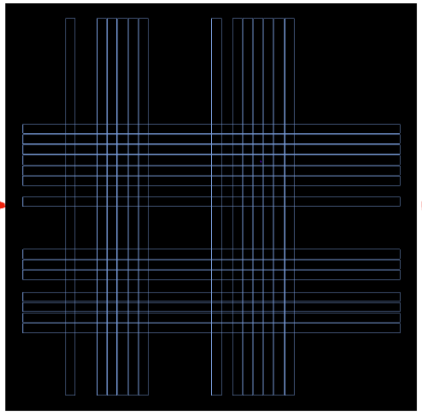
distance ~20cm along the diagonal

→ can be separated.

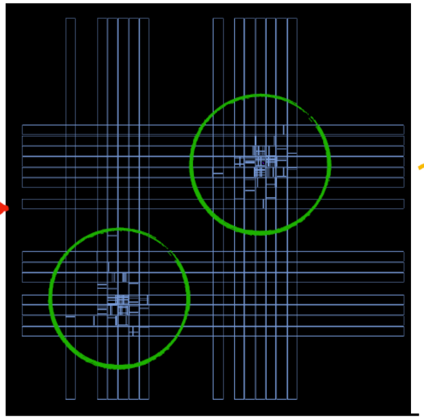
Simulated Hits (yellow cells)



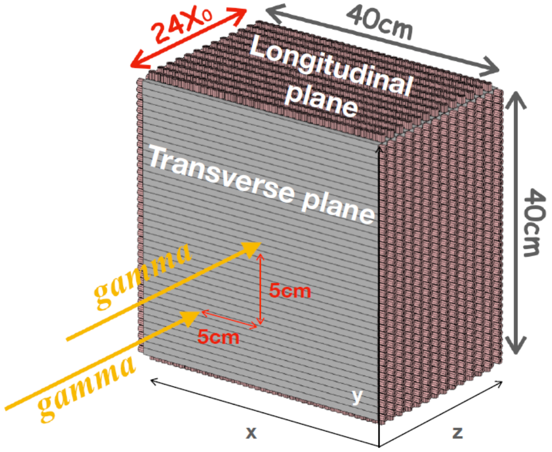
Digitized Long Bar Hits (E_{dep} > 1 MIP)



Reconstructed positions using time difference of 2 ends

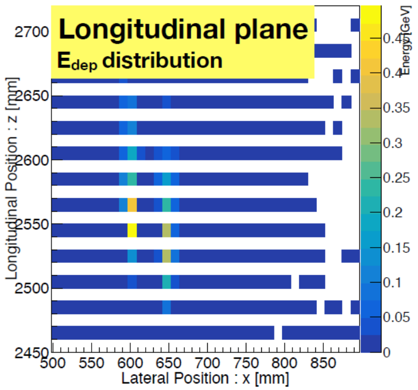


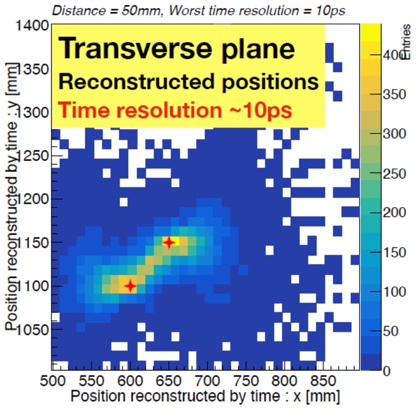
Shower profiles: 2 photons



5cm ~ 2R_M for BGO (R_M=2.26cm)

10





Pattern studies using Event Display

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