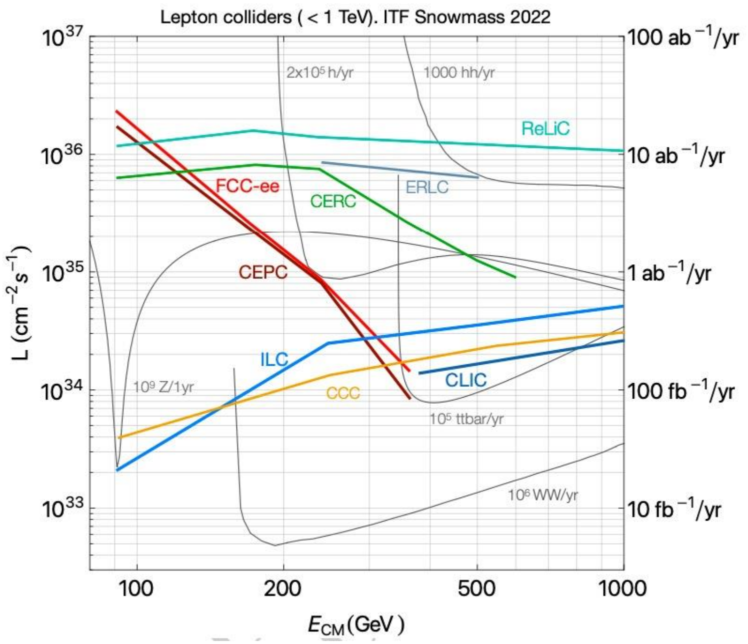
PFA-oriented Sampling and Crystal Calorimeters: Beamtest Studies and Plans

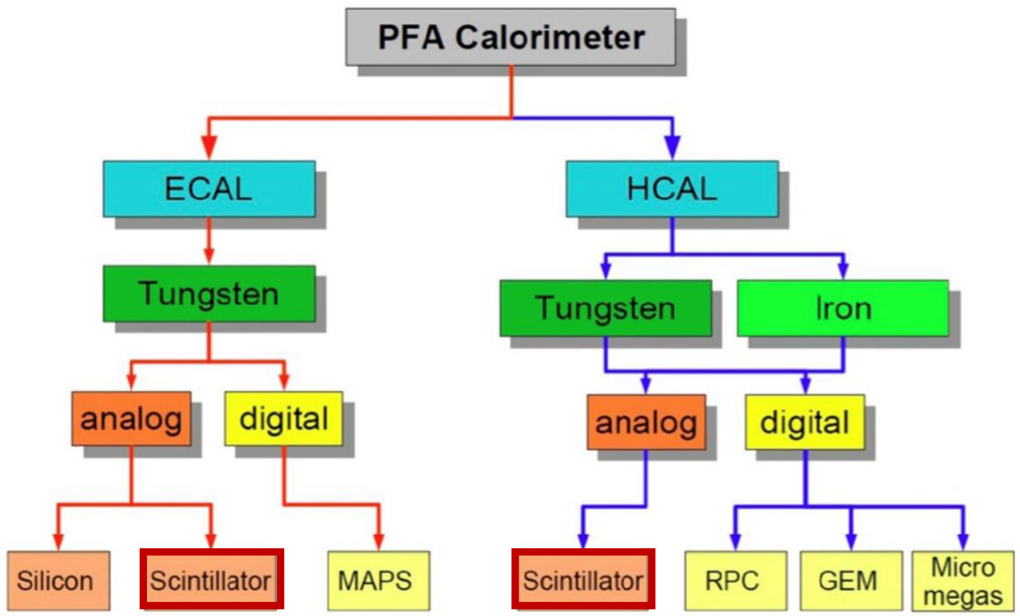
Yong Liu (IHEP),

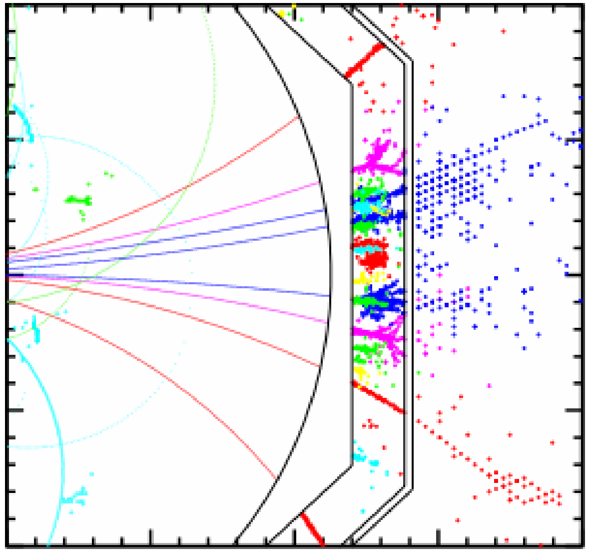
for CALICE and CEPC Calorimeter teams

CEPC Day, Dec. 27, 2023

High granularity calorimetry





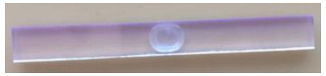


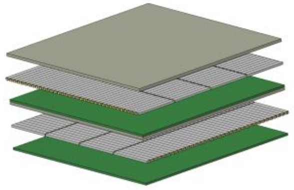
- Future Higgs/EW/top factories
  - Requires unprecedented energy resolution for jet measurements
  - A major calorimetry category: highly granular (imaging) + particle flow algorithms (PFA)
- PFA calorimetry: various options explored in the CALICE collaboration
- Focus in this talk: **scintillator-SiPM** prototypes and new concept on crystal ECAL

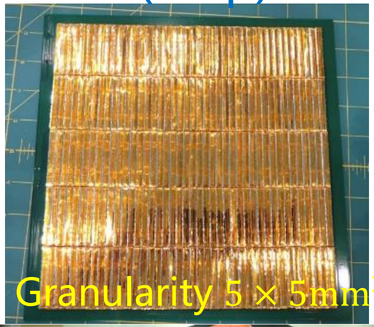
CALICE scintillator-calorimeter prototypes

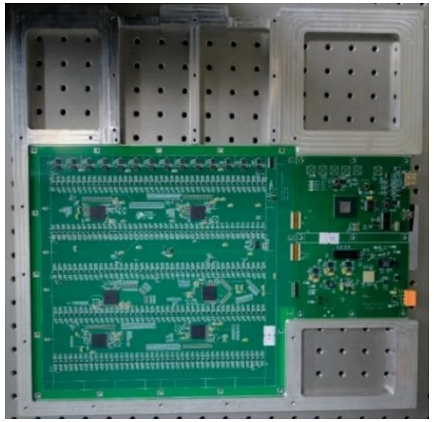
2016-2023

ECAL prototype: scintillator (strip)+SiPM/CuW

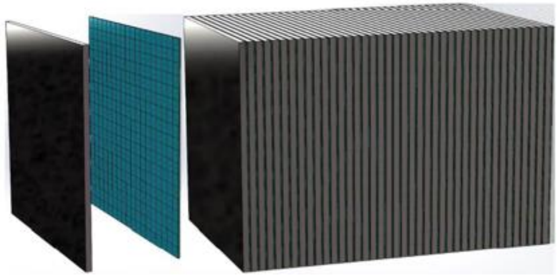


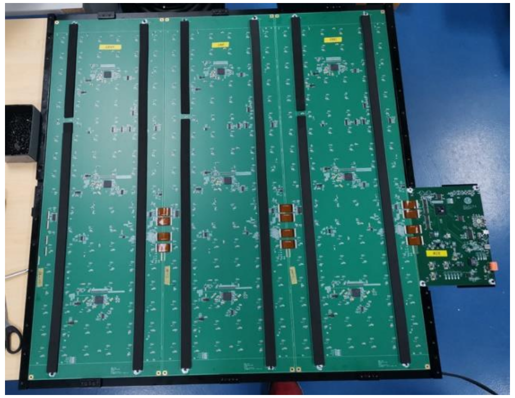






HCAL prototype: scintillator (tile)+SiPM/iron



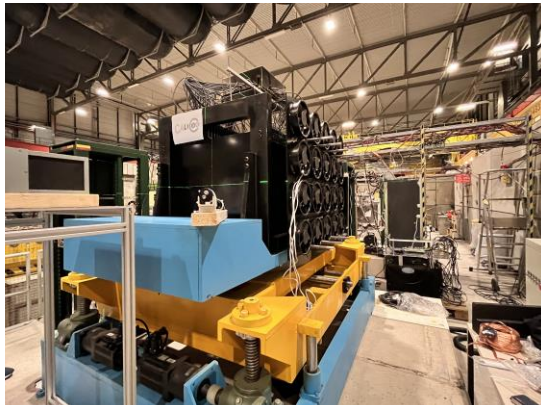


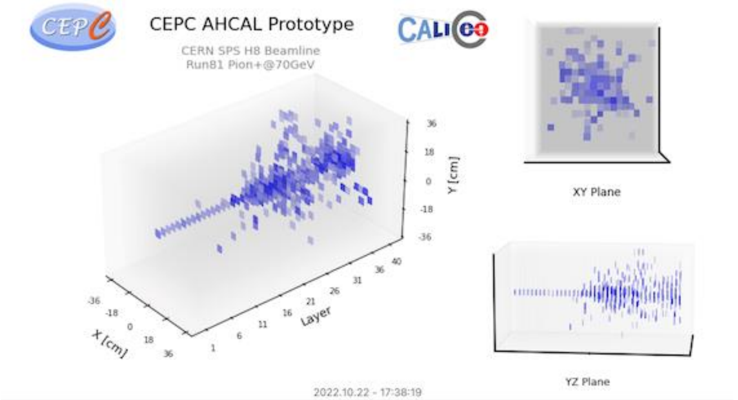
- ScW-ECAL prototype: transverse $\sim 20 \times 20\mathrm{cm}^2$, 32 sampling layers
  - 6,720 channels, ~350 kg, SPIROC2E (192 chips), developed in 2016-2020
- AHCAL prototype: transverse $72 \times 72\mathrm{cm}^2$, 40 sampling layers
  - 12,960 channels, ~5 tons, SPIROC2E (360 chips), developed in 2018-2022

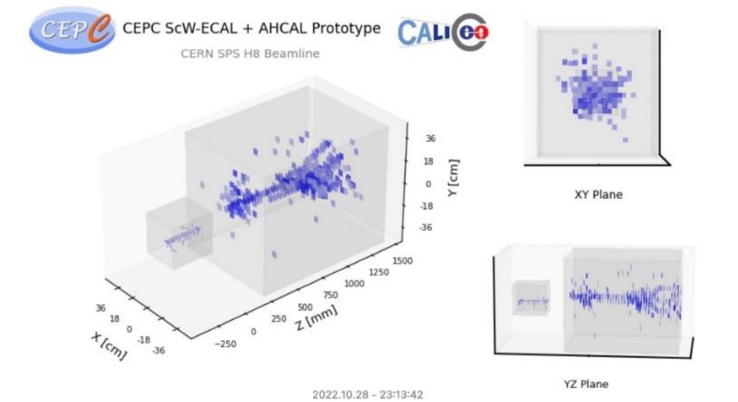
Prototypes developed within CALICE

- China: IHEP, SJTU, USTC
- Japan: U. Shinshu, U. Tokyo
- France: CNRS Omega
- Israel: Weizmann

CERN beamtest in 2022





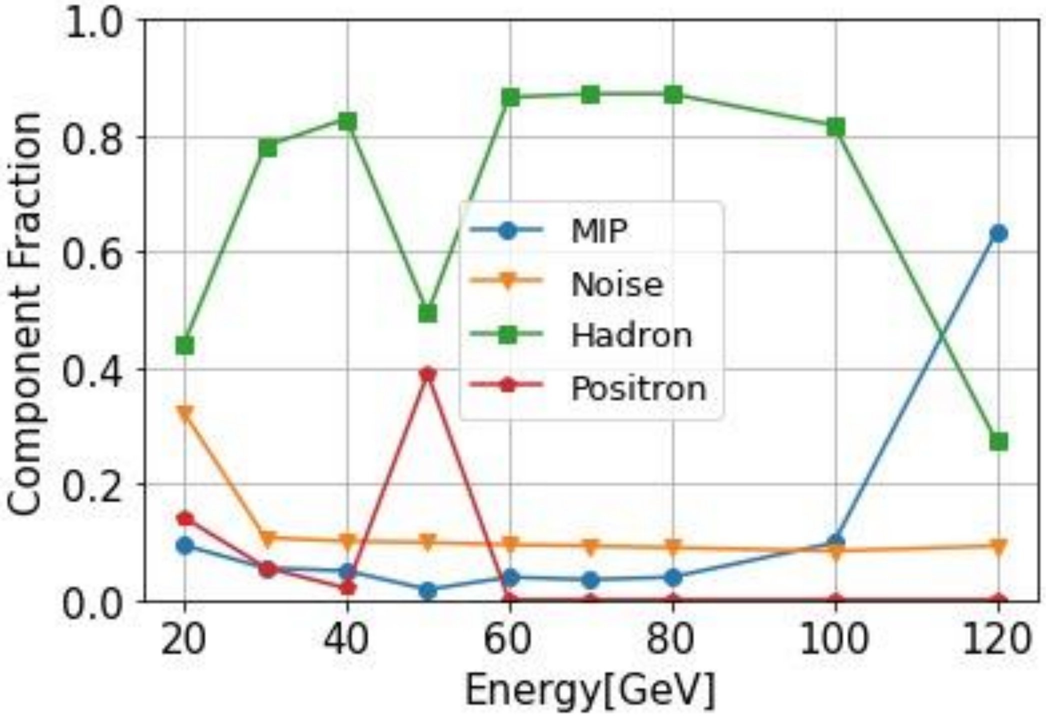

- First successful beamtest at CERN SPS H8: Oct-Nov, 2022
  - High energy particle beams: muons, positrons and hadrons (10 - 160 GeV)
  - Collected data sets for detector performance and detailed shower studies
  - **Beam purity issue** at H8: mixture of positrons and pions/protons

2022 SPS-H8 beam purity: preliminary results

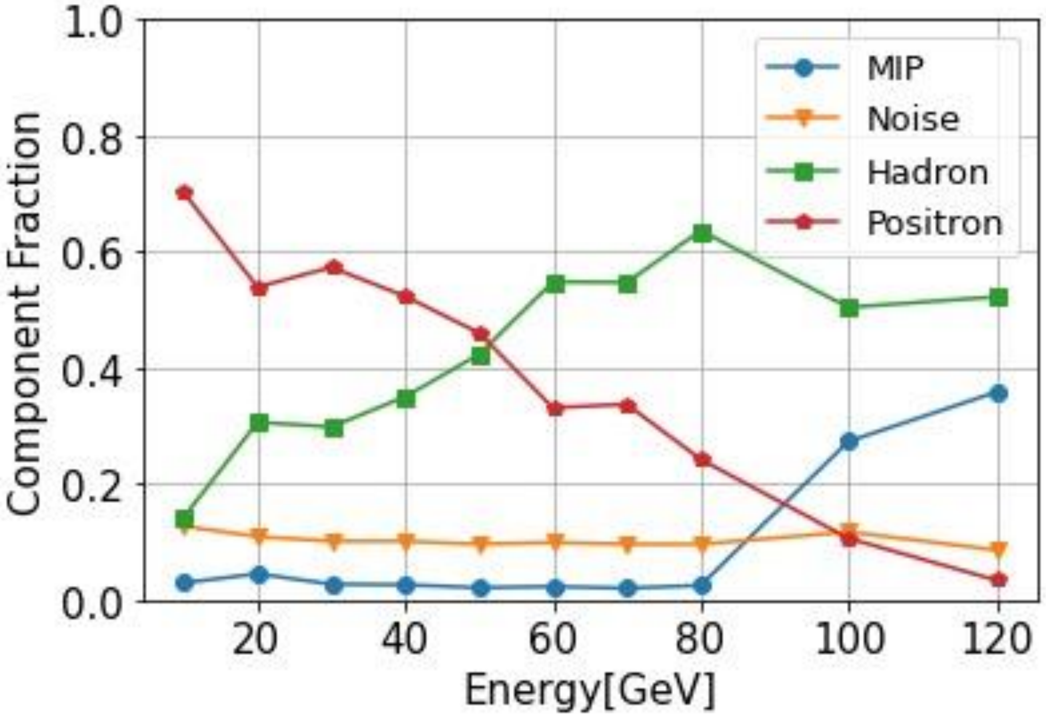
Yuzhi Che, Xin Xia (IHEP)

- Imaging calorimeter: characteristics of hit patterns with $\mu^+/e^+/\pi^+$
- Positron beam: largely dominated by hadrons, barely no positrons >60 GeV
- Hadron beam: a considerably large fraction of positrons (esp. with lower energy)

2022 SPS-H8 positron beam data



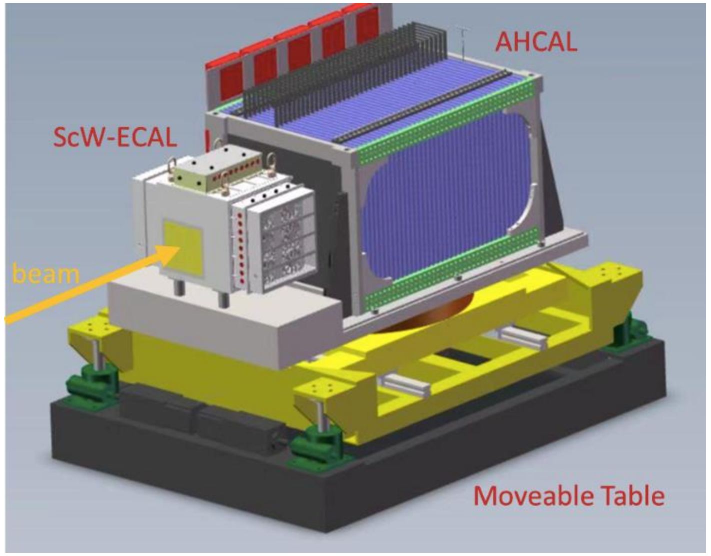
2022 SPS-H8 hadron beam data

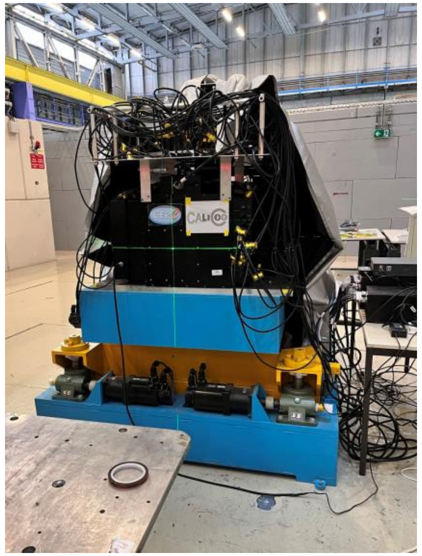


Prototypes: beamtests in 2023

- CERN SPS-H2
  - μ^- beam (100 GeV): MIP calibration
  - e^- beam (10 – 250 GeV): calibrations of SiPMs and ASICs, EM performance
  - π^- beam (10 – 350 GeV): hadronic performance, validation of hadronic shower simulation
- CERN PS-T09
  - 10 GeV μ^-, 1-5 GeV e^- and 1-15 GeV π^- beams

→Overlapped energy points (10-15 GeV) at PS and SPS

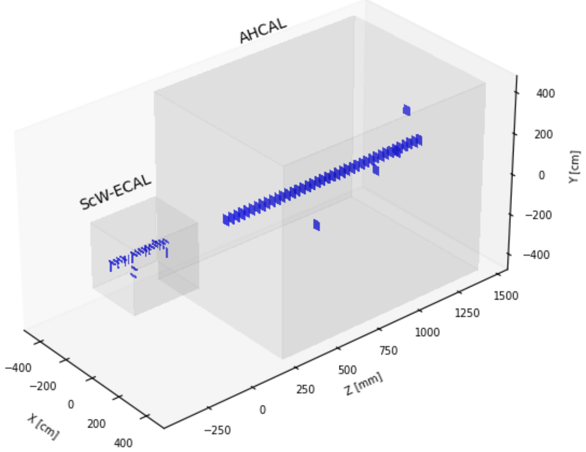


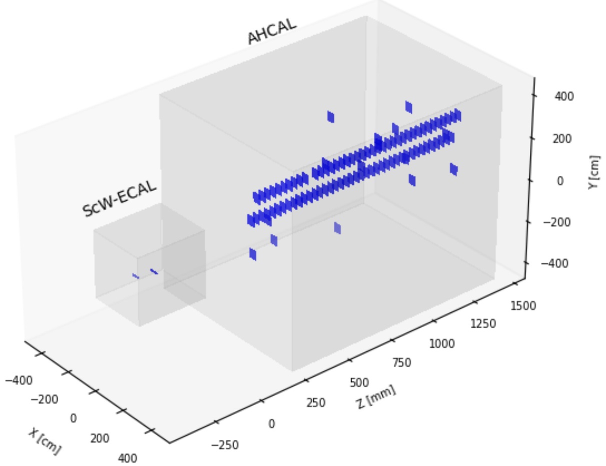


Event display with ScECAL+AHCAL

Siyuan Song (SJTU)

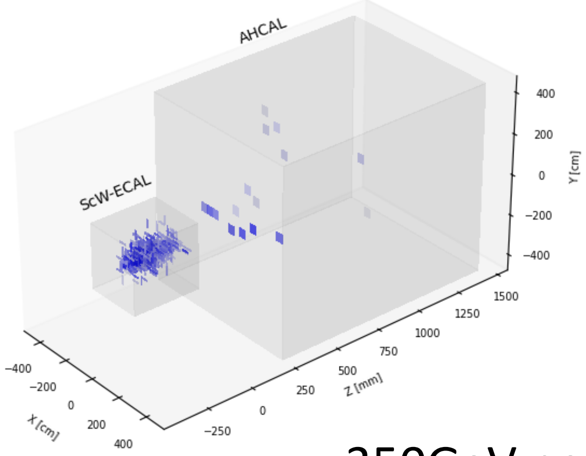
100 GeV mu-



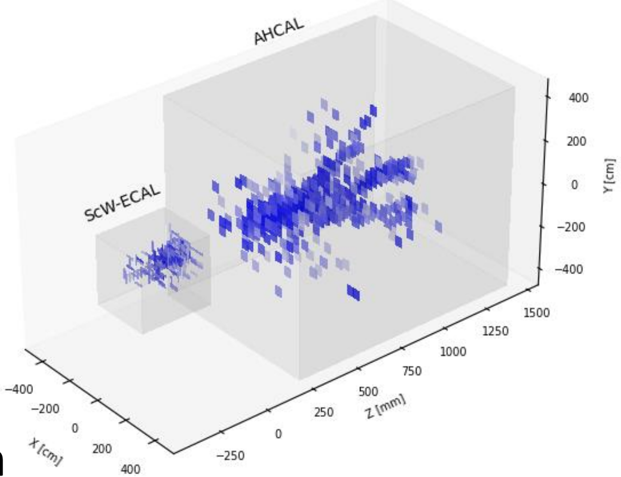


One run of different position scans: muon beam out of ScW-ECAL acceptance

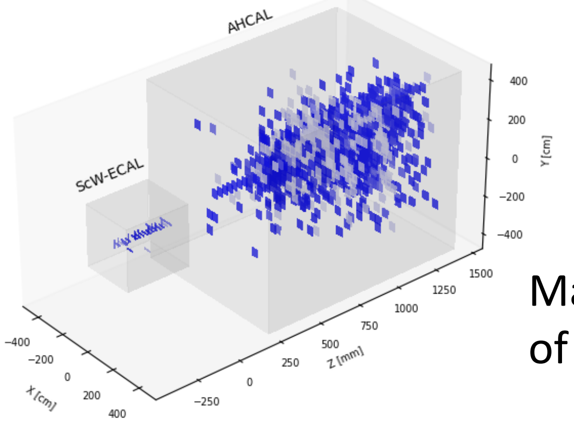
60GeV electron



60GeV negative pion



350GeV negative pion

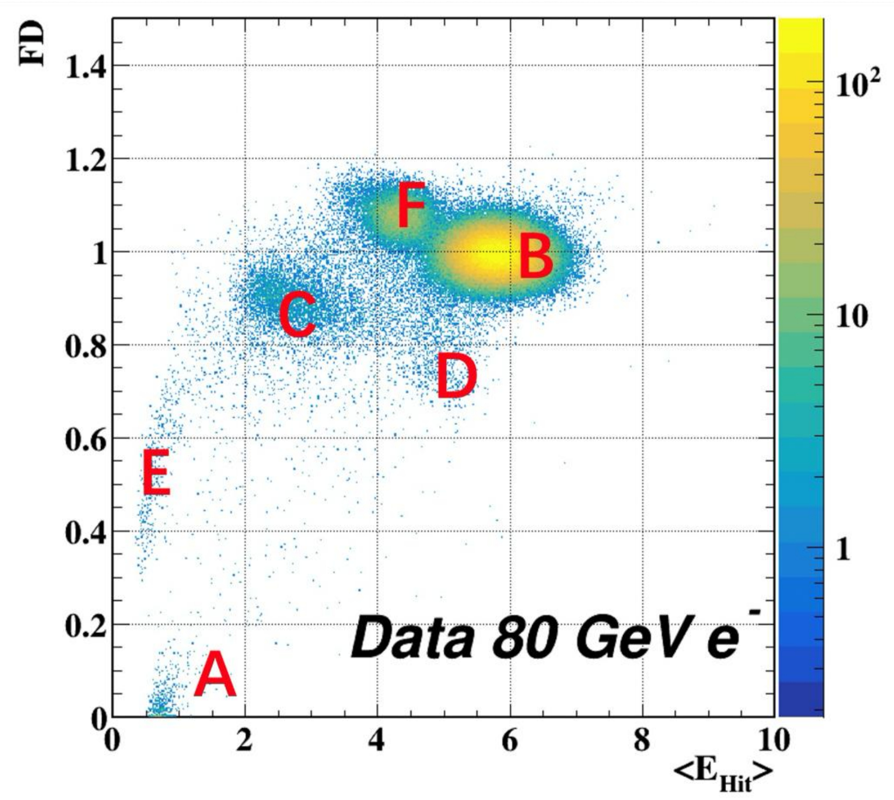


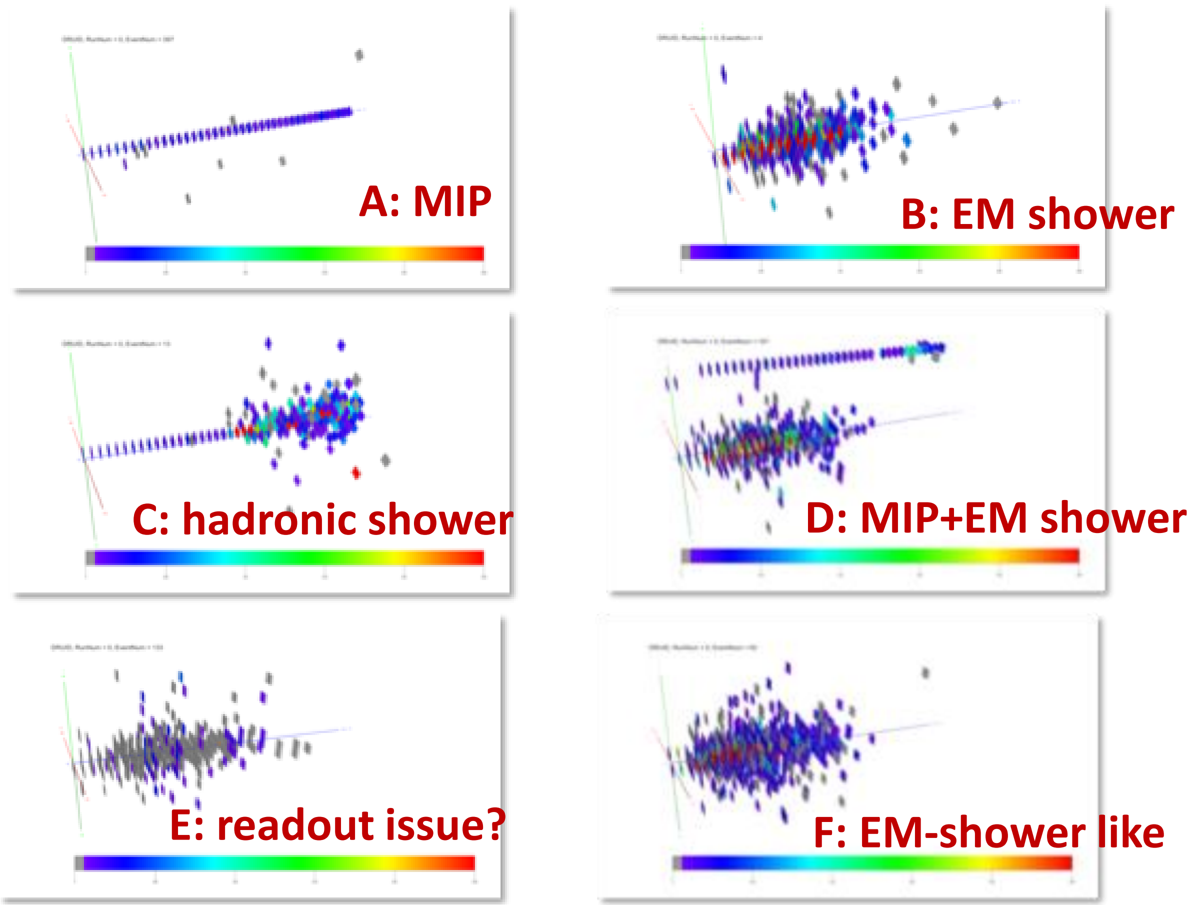
Maximum pion beam energy of existing testbeam facilities

Much better purity of electron and pion beams at H2 in 2023 than at H8 in 2022

Xin Xia (IHEP)

- Characteristics of <u>Fractal Dimension</u> (FD) with different beam particles
  - Only possible with imaging calorimeter (high granularity)





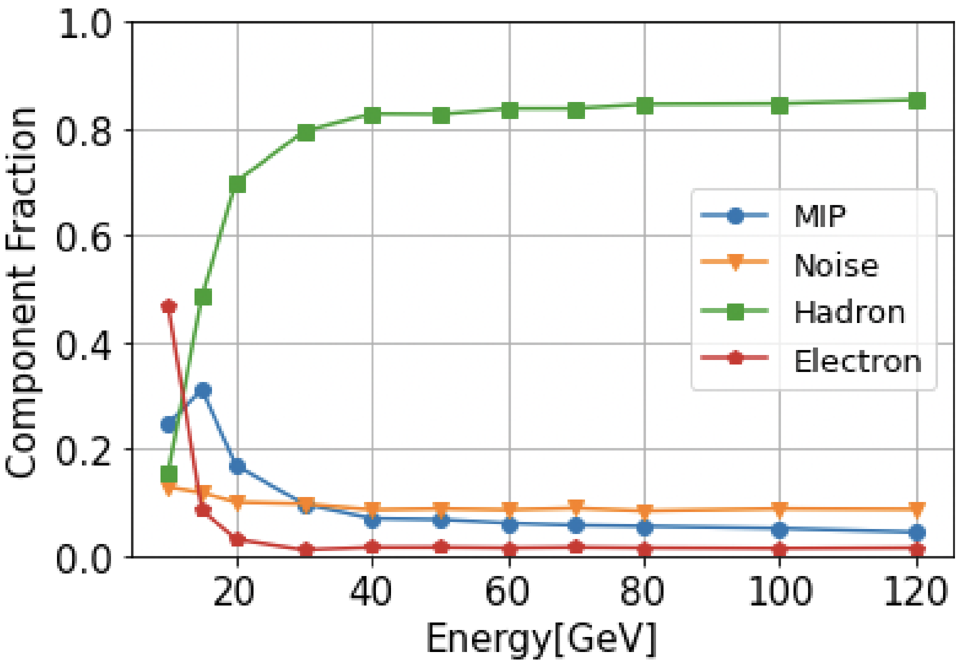
FD methodology based on
M. Ruan et al., Phys. Rev. Lett. **112**, 012001

PID studies with fractal dimension

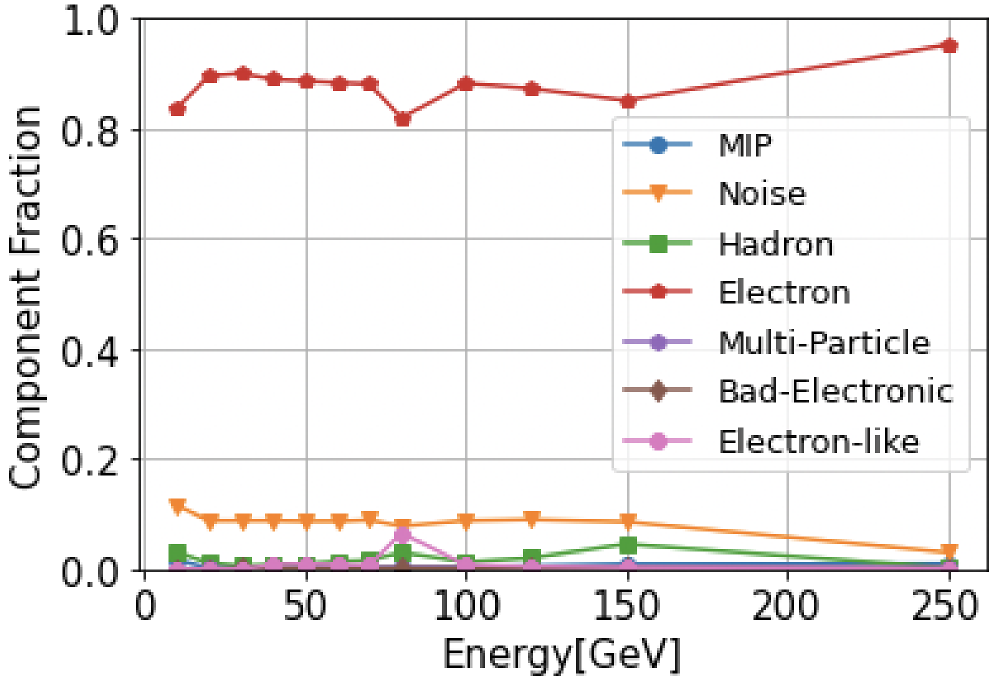
Xin Xia (IHEP)

- SPS-H2 beam purity >80% for electron and pion beams >30 GeV
- Significantly better beam purity at H2 than H8
- Noise events now become a dominating factor: ongoing studies

SPS-H2 Pion Beam

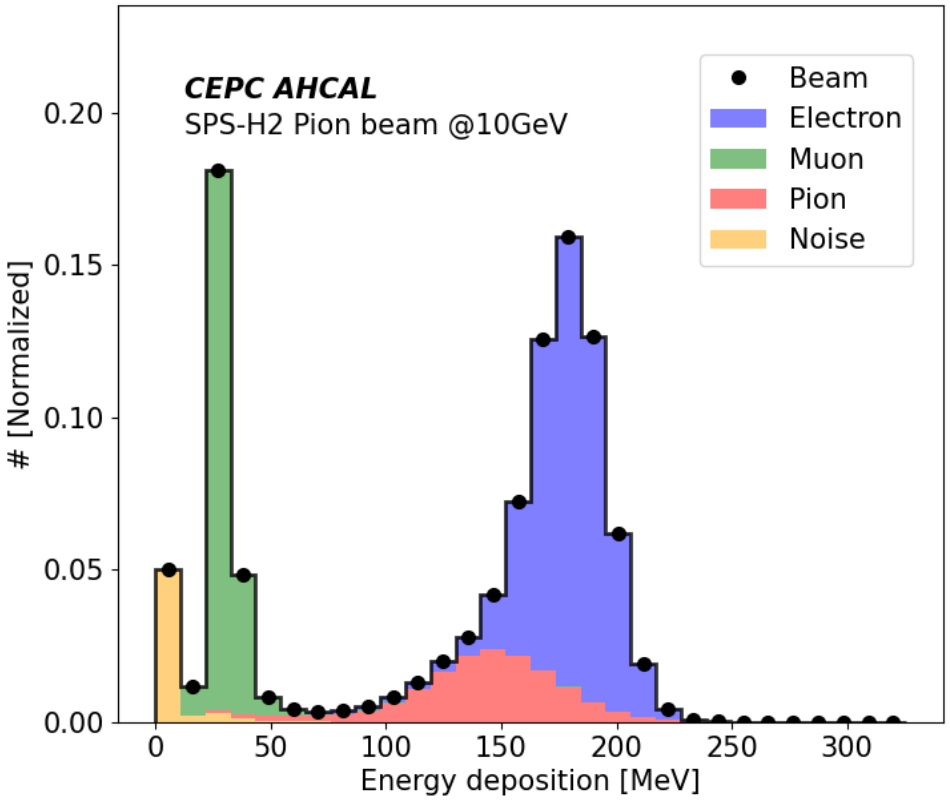


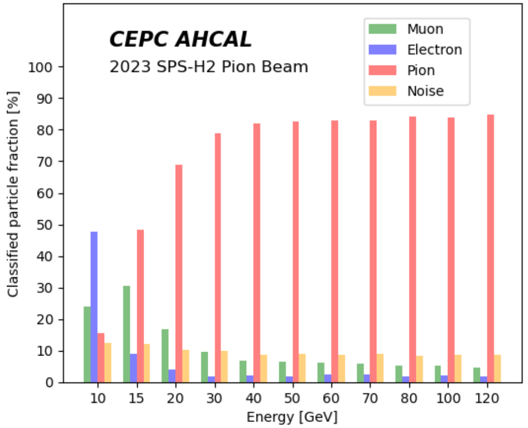
SPS-H2 Electron Beam

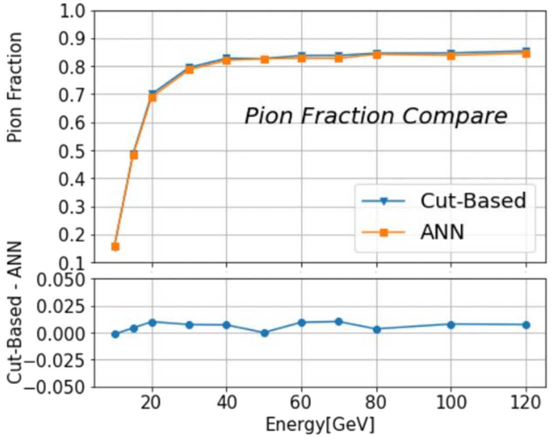


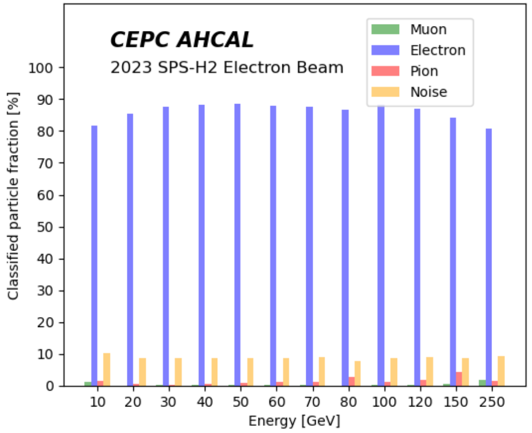
PID studies with ANN

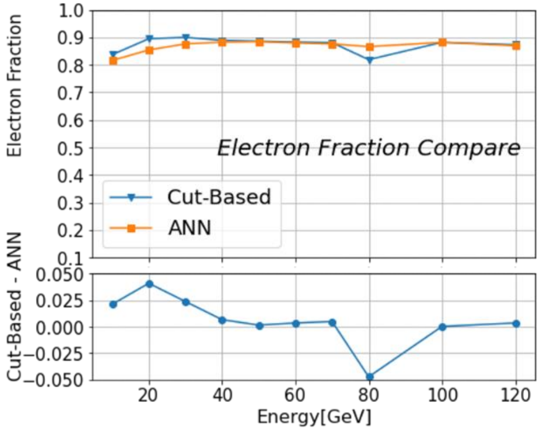
- **PID based on ANN (ResNet): input tensor of energy deposition per AHCAL tile**
- ANN results mostly consistent with Fractal Dimension (FD results)
  - Pion beam: difference within 1%; electron beam: within 5%







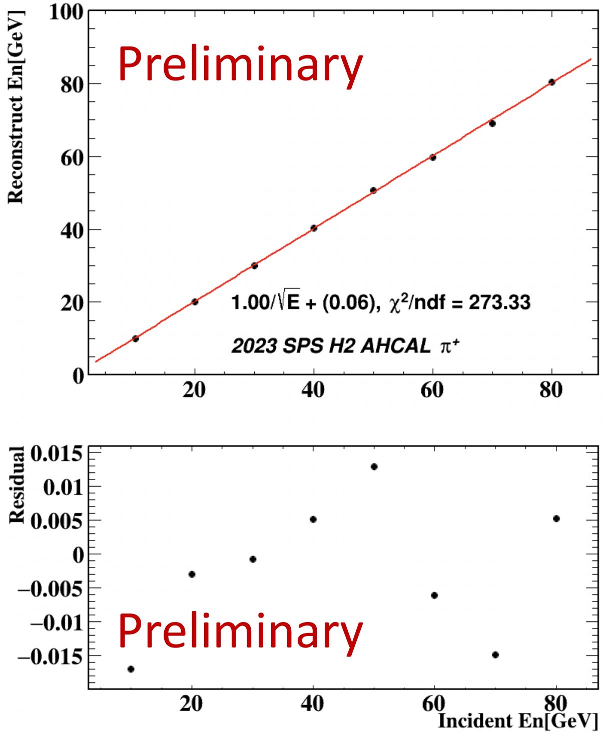


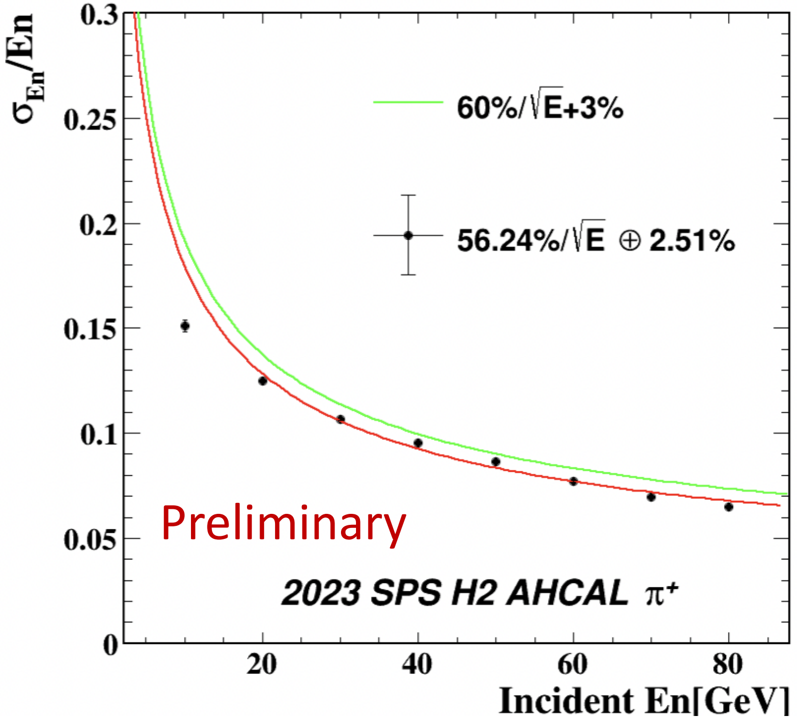


Key performance: first preliminary results

Xin Xia (IHEP)

- AHCAL prototype (alone) using data sets after PID selections
  - Energy linearity within $\pm 1.5\%$
  - Energy resolution $56.2\%/\sqrt{E(GeV)} \oplus 2.5\%$ (expected $60\%/\sqrt{E(GeV)} \oplus 3\%$)

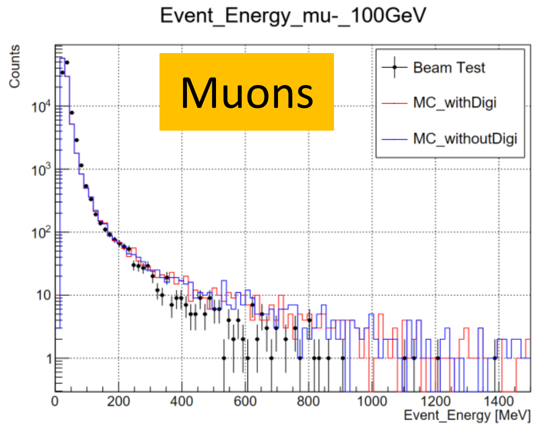


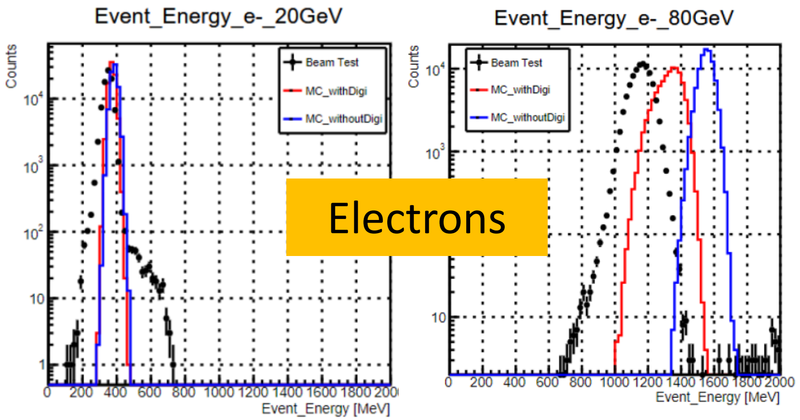


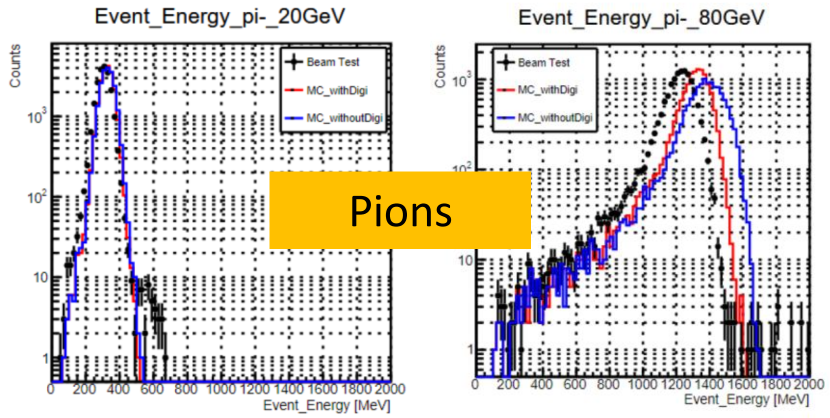
Critical issues (ongoing studies): non-linearity effects and corrections (SiPMs, ASICs), MC validation with data

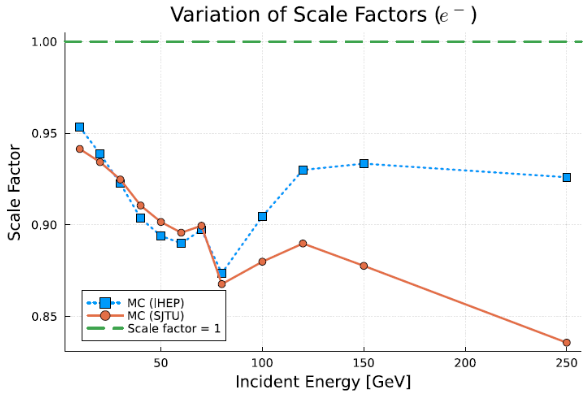
Beamtest data: ongoing studies

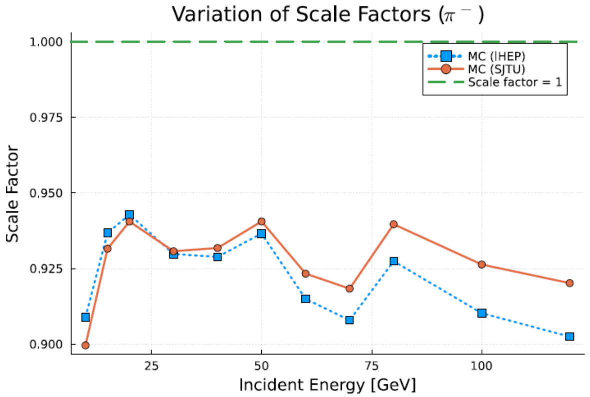
- Ongoing studies to address critical issues
  - Non-linearity effects and corrections: saturations in SiPM and ASIC with large signals
  - MC validation with electron and pion data: to improve MC/data consistency











MC: Geant4 simulation w/wo digitisation for scintillator-SiPM and ASIC

Plans: ScECAL and AHCAL prototypes

- Further plans: beamtest data analysis within CEPC-Calo team
  - Performance studies with combined ScW-ECAL and AHCAL
  - Validation of Geant4 hadron interaction models, especially in 1-10 GeV
  - PFA clustering studies
- ScECAL and AHCAL: further R&D proposals within DRD6
  - R&D more concentrated to address critical issues at circular colliders
    - Front-end ASICs: capable for continuous and high-rate readout
    - Active cooling: optimised for continuous readout

Table extracted from ECFA DRD6 proposal

Task/Subtask	Sensitive Material/ Absorber	DRDTs	Target Application	Current Status
Task 1.1: Highly pixelised electromagnetic section				
Subtask 1.1.4: Sc-Ecal	Scintillating plastic strips/ Tungsten	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed
Task 1.2: Hadronic section with optical tiles				
Subtask 1.2.1: AHCAL	Scintillating plastic tiles/ Steel	6.2	e^+e^- collider central detector	Prototype for finalising R&D for LC, Specification for CC and of timing for PFA needed

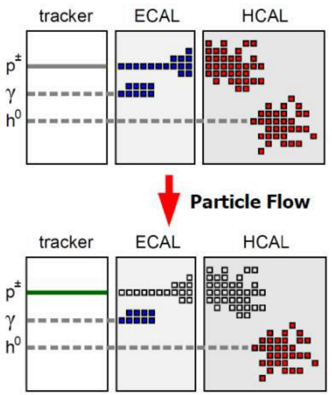
Side Remarks

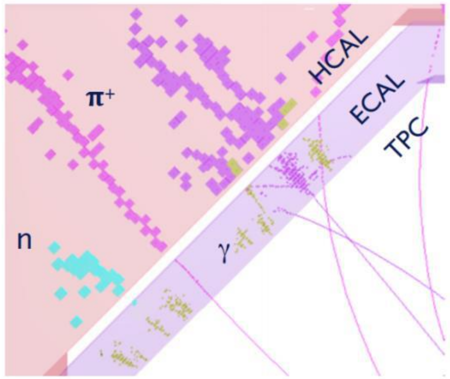
- *ALL current prototypes equipped with ASICs designed for linear colliders*
- *Passive cooling in current prototypes*

New concepts for CEPC calorimetry

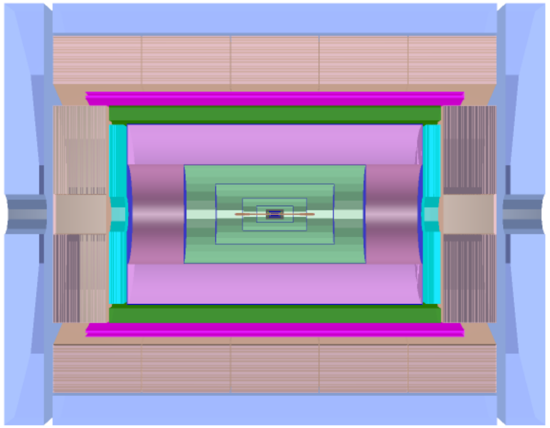
- High-granularity calorimetry with PFA
  - Requires Boson Mass Resolution <4%
- Electromagnetic calorimeter
  - Crystal option: 3D-positioning and timing
  - To improve EM energy resolution from $\sim 16\%/\sqrt{E}$ (CEPC-CDR) to $\sim 3\%/\sqrt{E}$
- Hadron calorimeter
  - Scintillating glass (dense and bright): in the form factor of tiles for high granularity (PFA-compatible)
  - To improve hadron energy resolution from $\sim 60\%/\sqrt{E}$ (CEPC-CDR) to $30\% \sim 40\%/\sqrt{E}$

PFA-oriented Calorimetry





CEPC: the 4th Conceptual Detector Design



Calorimeters: crystal ECAL and ScintGlass HCAL

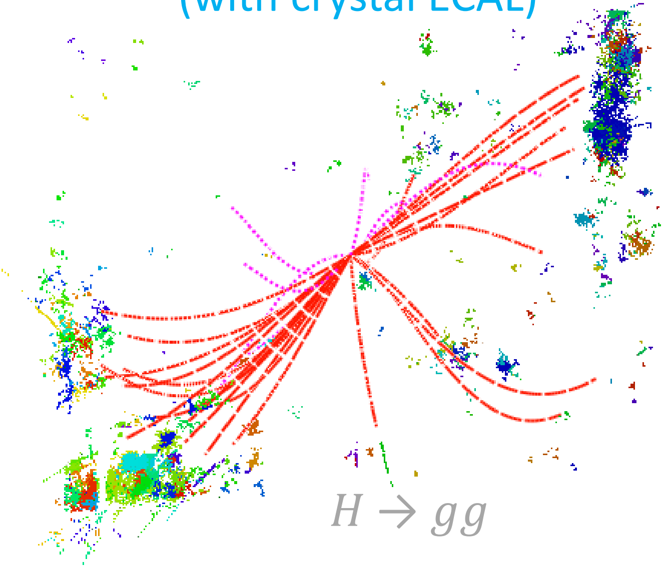
Jianchun Wang, "Status and Perspective of the CEPC" at CLHCP2023

Higgs physics benchmarks

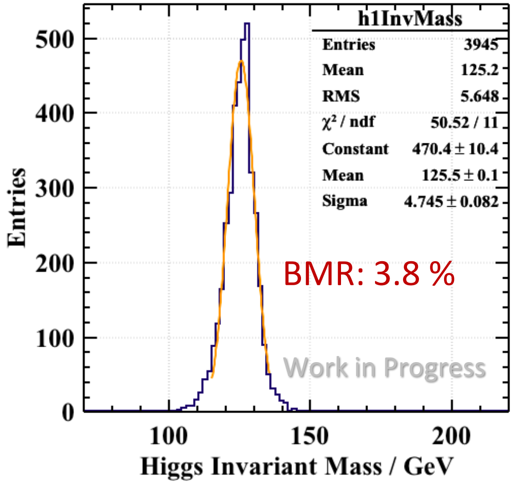
Baohua Qi, Dan Yu (IHEP); Zhiyu Zhao (SJTU)

- Physics potentials with crystals
  - Photons and jets
- Boson Mass Resolution (BMR)
  - Jets ($H \rightarrow gg$): 3.8 % → 3.6%
  - Photons ($H \rightarrow \gamma\gamma$): 2.1% → 1.2%

Higgs to 2 gluon jets
(with crystal ECAL)

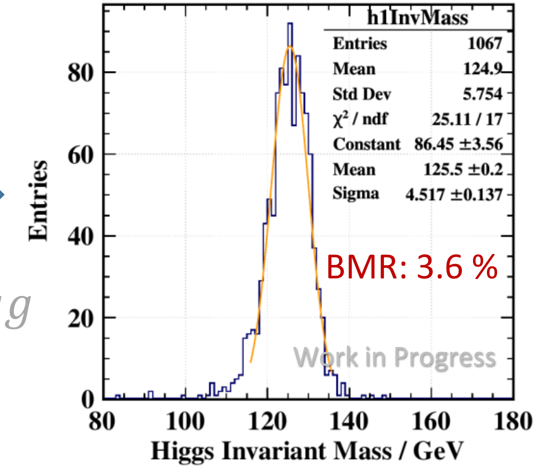


Detector with SiW-ECAL option

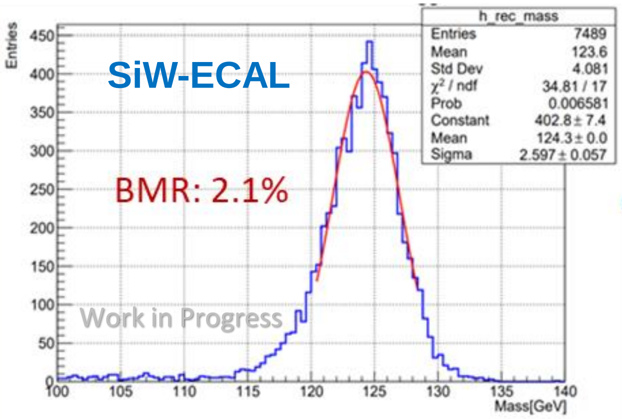


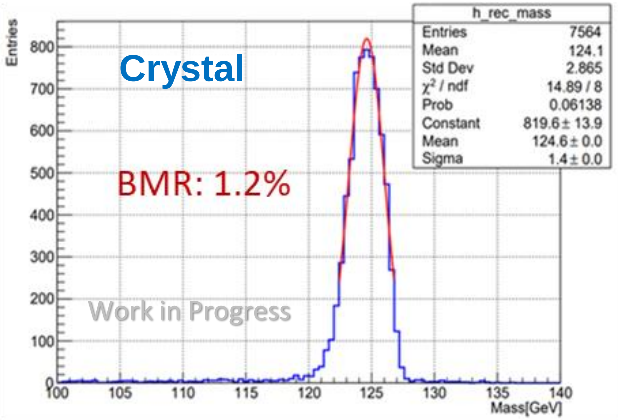
$H \rightarrow gg$

Detector with crystal ECAL option



BMR ($H \rightarrow \gamma\gamma$)





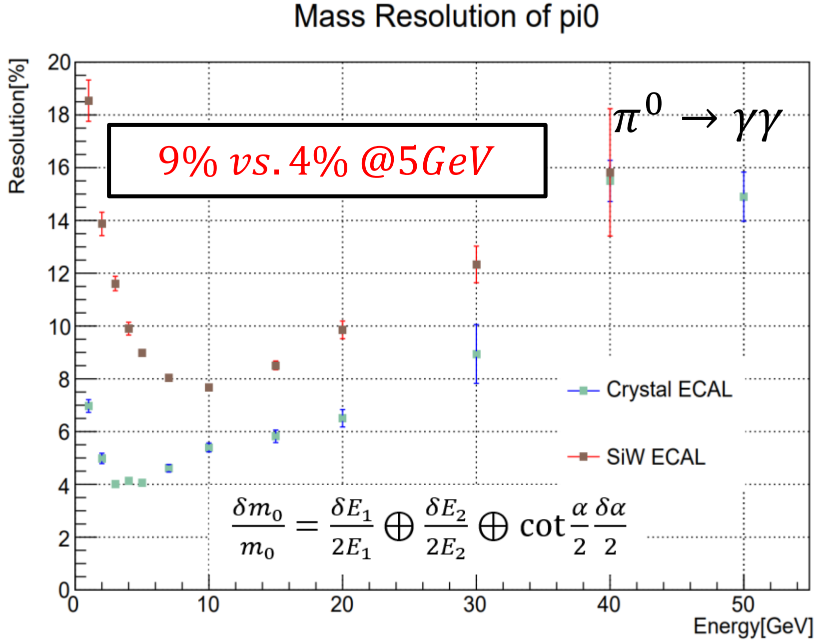
Flavor physics potentials

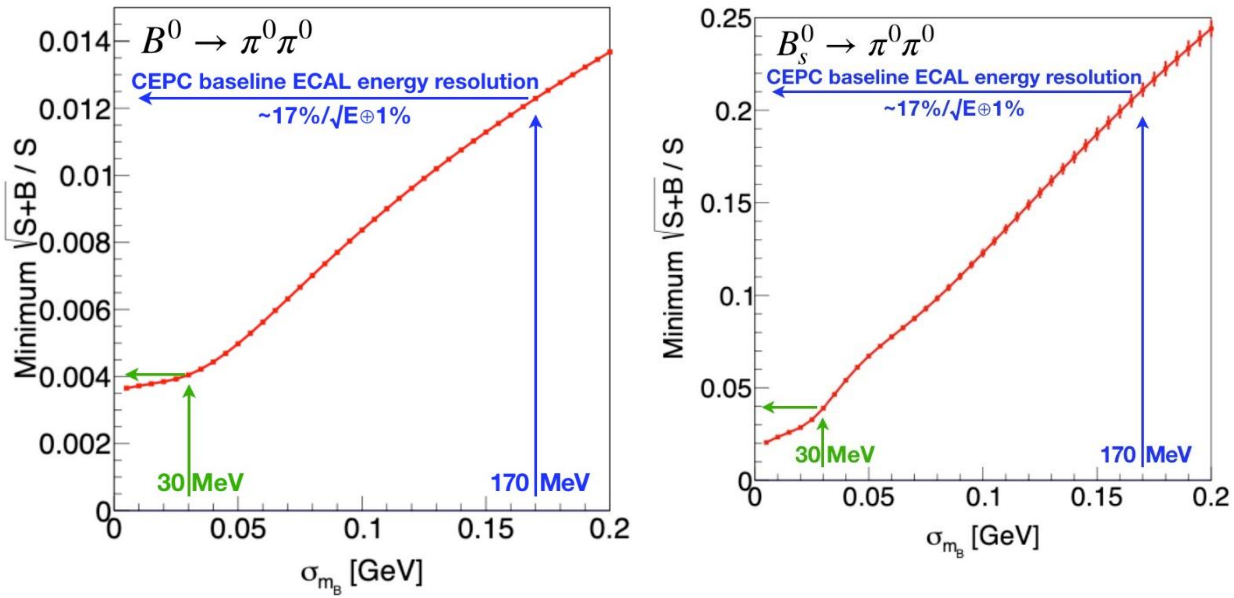
Zhiyu Zhao (SJTU), Yuexin Wang (IHEP)

- Crystal ECAL
  - Higher sensitivity to photons and much better EM resolution
- Potentials for π^0/γ in flavor physics

B0 to pipi @CEPC(CEPC Flavor Physics/New Physics/Detector Technology Workshop, Fudan, 2023), Yuexin Wang

ECAL Resolution	σ_{m_B} (MeV)	$B^0 \to \pi^0\pi^0$	$B_s^0 \to \pi^0\pi^0$
$17\%/\sqrt{E}\oplus1\%$	170	~ 1.2%	~ 21%
$3\%/\sqrt{E}\oplus0.3\%$	30	~ 0.4%	~ 4%





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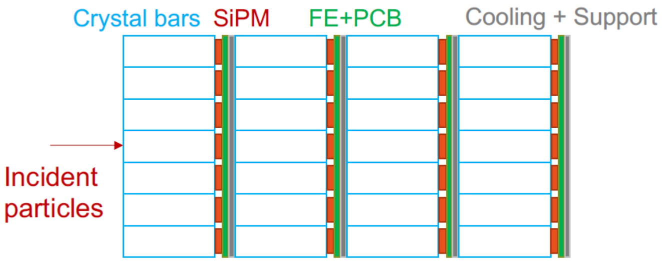
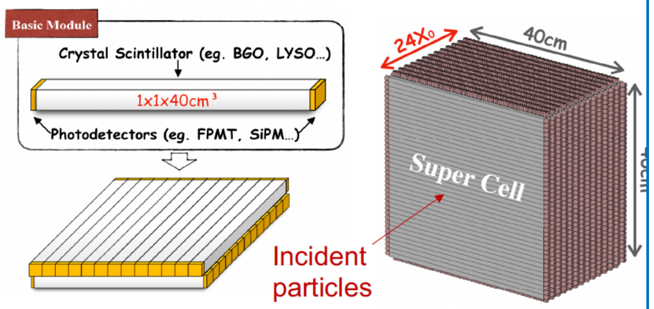
Crystal calorimeter: designs and specs

Design 1: short bars



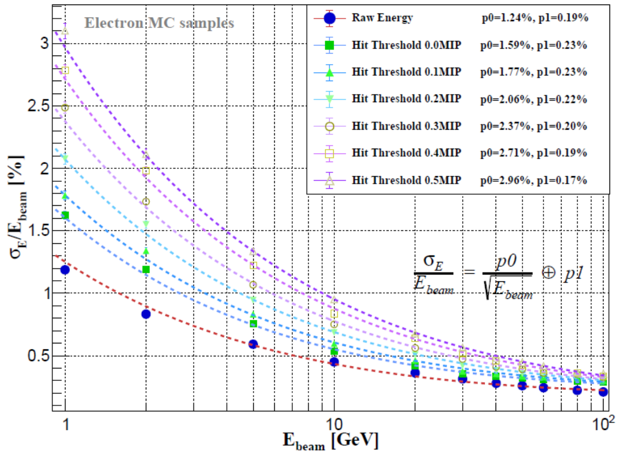
- A natural design compatible with PFA
  - Fine segmentation in Both longitudinal and transverse
  - Single-ended readout with SiPM

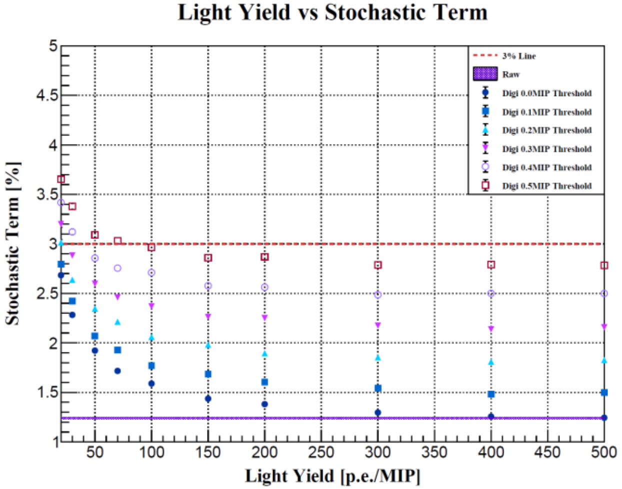
Design 2: long bars



- 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

Key Parameters	Value
MIP light yield	~200 p.e./MIP
Dynamic range	$1-10^5$ p.e.
Energy threshold	~0.1 MIP
Timing resolution	1ns (→100 ps?)
Response non-uniformity	<1%
Temperature stability	Stable at ~ 0.05 ℃
Gap tolerance	~100 µm

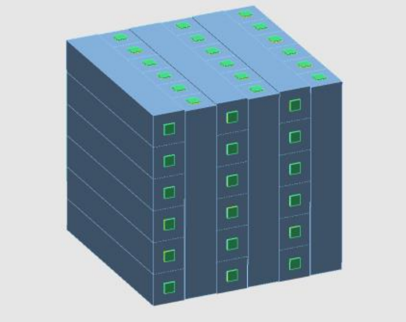


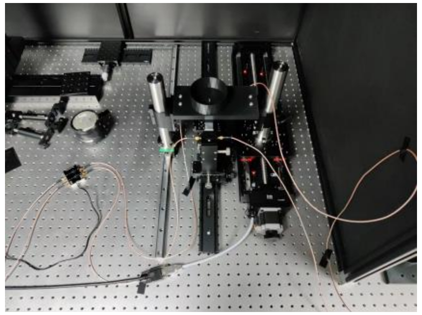


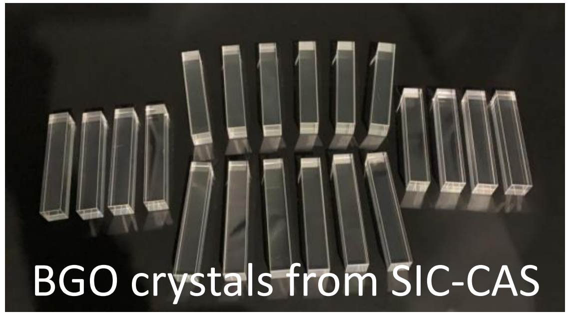
- Designs and specifications
  - Based on Geant4 simulation and digitisation for crystal-SiPM
  - Stringent requirement on dynamic range
  - Need further validation with data

Crystal calorimeter: the first module

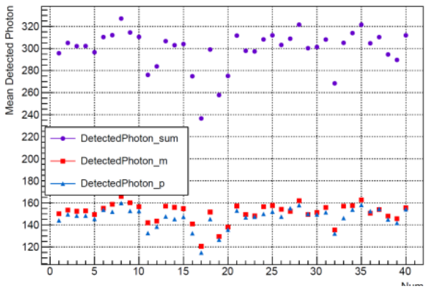
Baohua Qi (IHEP)



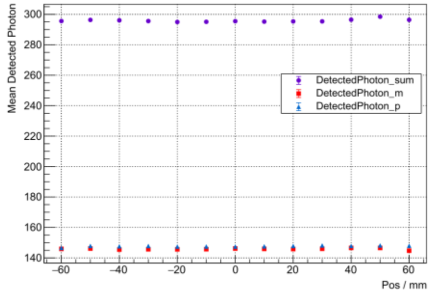


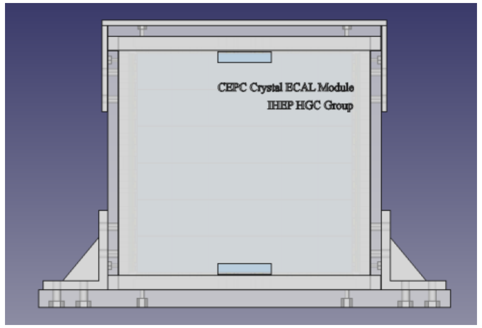


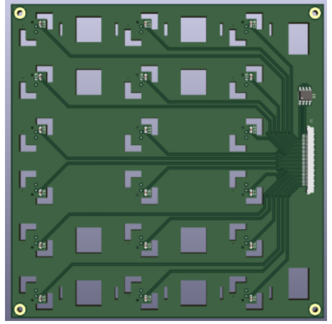
Uniformity of 40 crystal bars

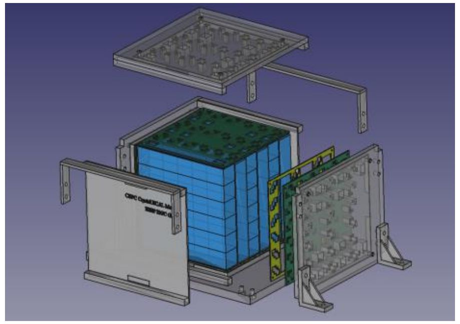


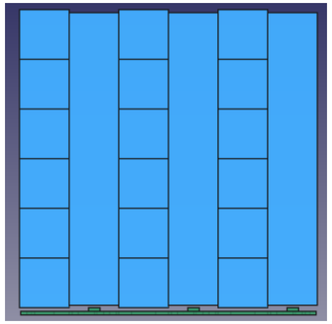
Uniformity along a crystal bar









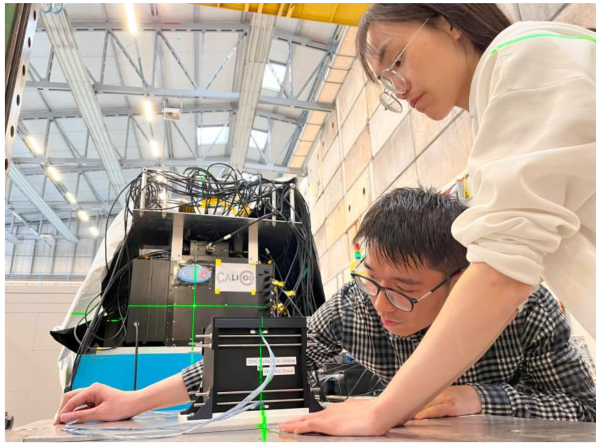


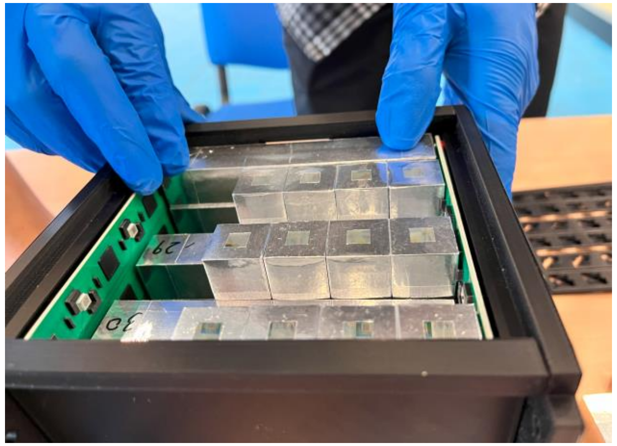
- First crystal module: successful development
  - To address key issues on system integration
  - Along with test stands for crystal uniformity studies
  - To evaluate EM performance with beam data

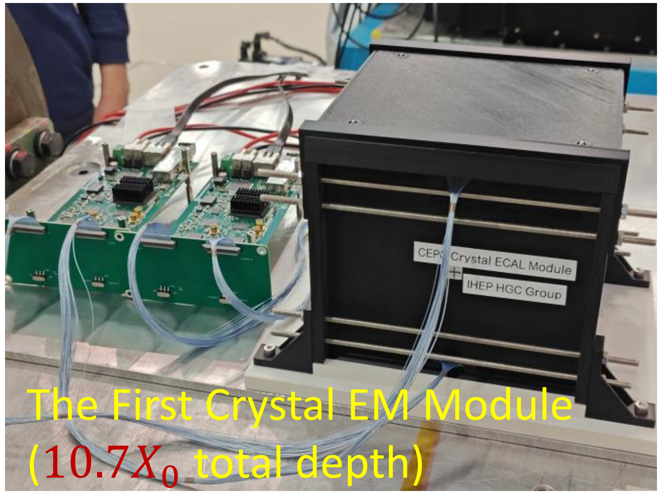
First crystal module: 2023 CERN beamtest

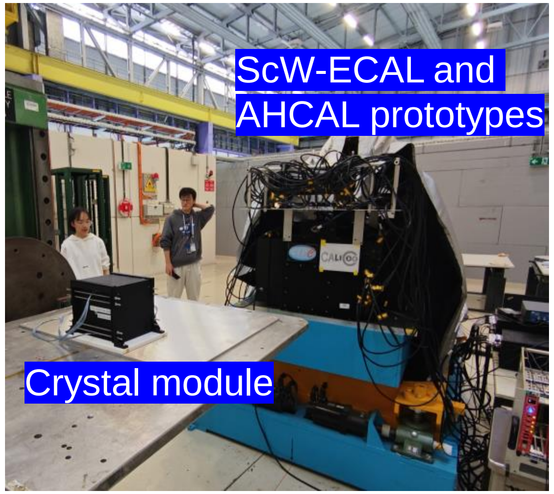
Baohua Qi (IHEP)

CERN beamtest: parasitic runs at PS-T09 (May 16-23, 2023)

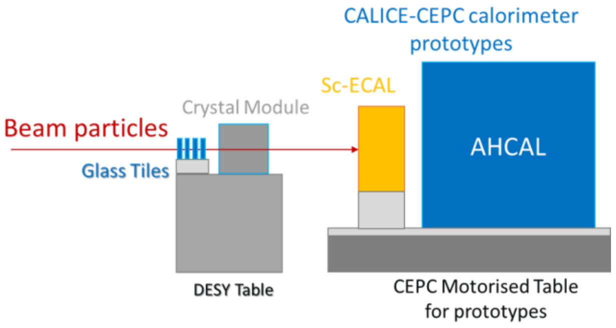




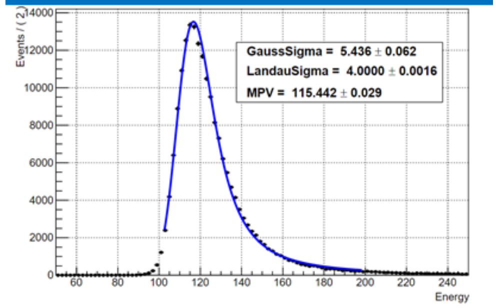




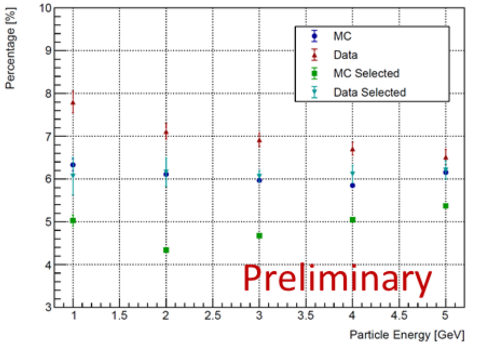
Combined beamtests with CEPC calorimeter prototypes



MIP calibration with muons



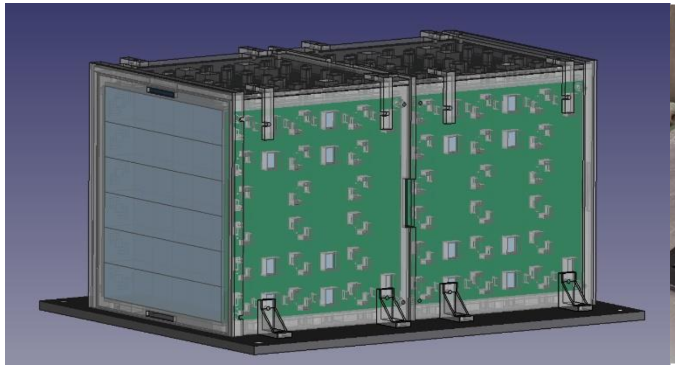
EM resolution: MC vs data

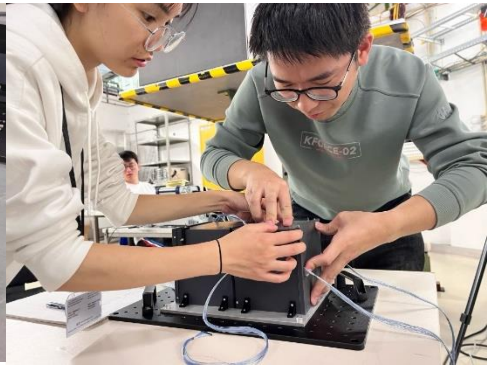


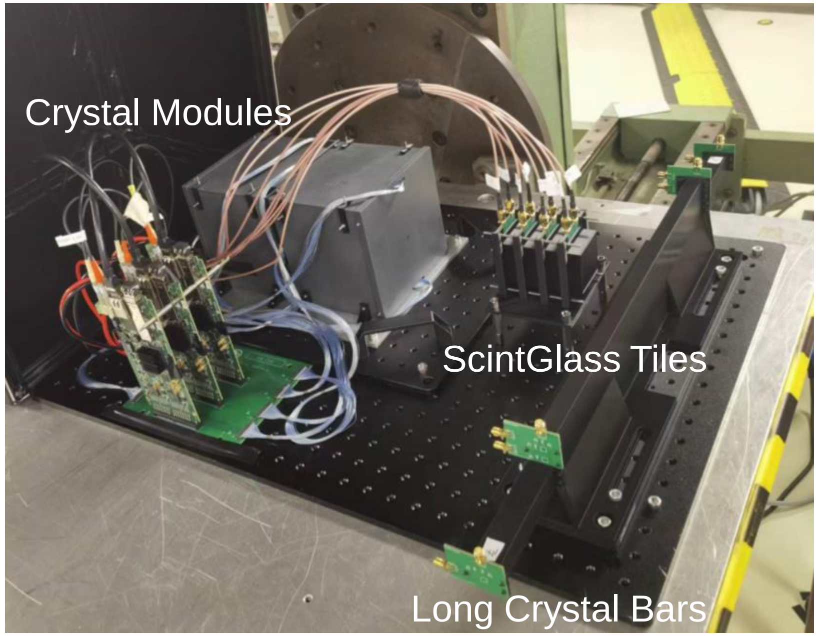
- Beamtest of the first crystal module
  - 15 GeV muons for MIP calibration
  - 1-5 GeV electrons for EM shower studies
  - Data sets for validation of simulation + digitisation

DESY beamtest in October 2023

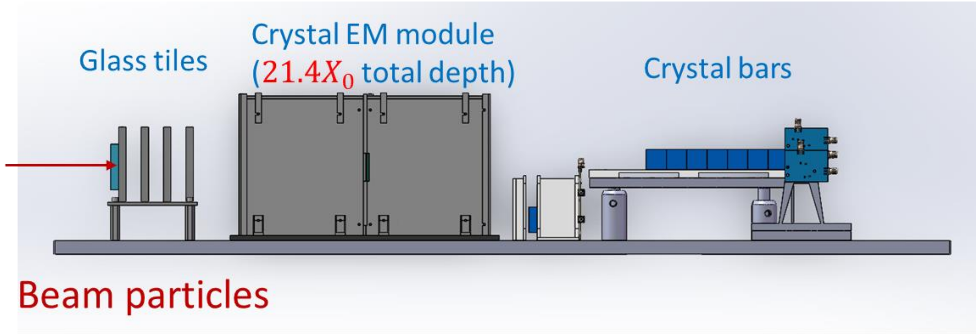
Fangyi Guo, Baohua Qi (IHEP)



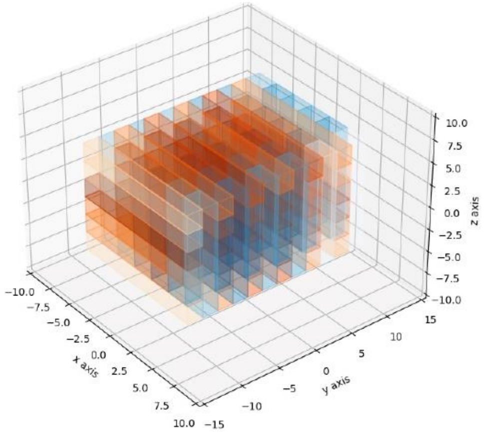




Beamtest at DESY TB22 (Oct. 2-15, 2023)



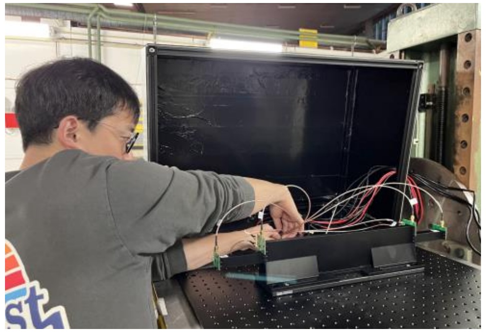
- DESY TB22 electron beam (1-6 GeV) to study new prototype and key components
  - Physics Prototype of Crystal Calorimeter ($21X_0$): system integration, EM performance
  - Long crystal bars (40/60cm): timing resolution
  - The 2nd batch of tiles from the “Glass Scintillator Collaboration” (4x4x1cm): MIP signals
  - A new SiPM-ASIC (32-ch): single photon spectrum, dynamic range

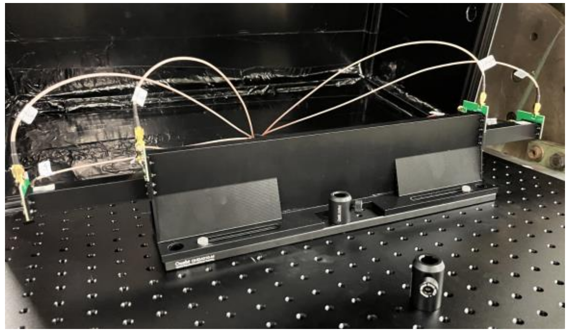


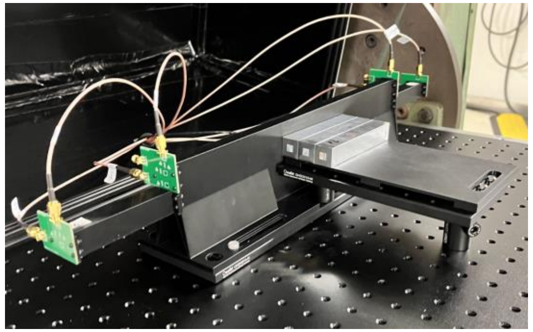
DESY beamtest: preliminary results

Zhiyu Zhao (SJTU)

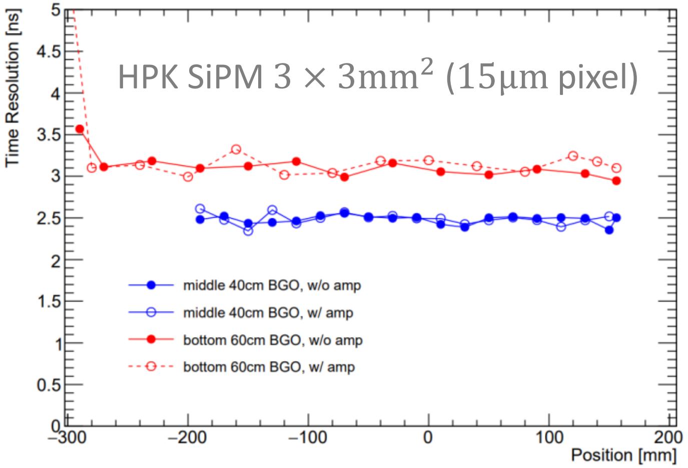
- Long crystal bars tested with 5GeV electrons
  - Timing resolution (MIP level) vs beam hit positions: ~1.8 ns (two ends) → ~1.3ns (single end)
  - Timing resolution vs signal amplitude (upstream crystals as pre-shower): ~0.7 ns (single end for large signals)



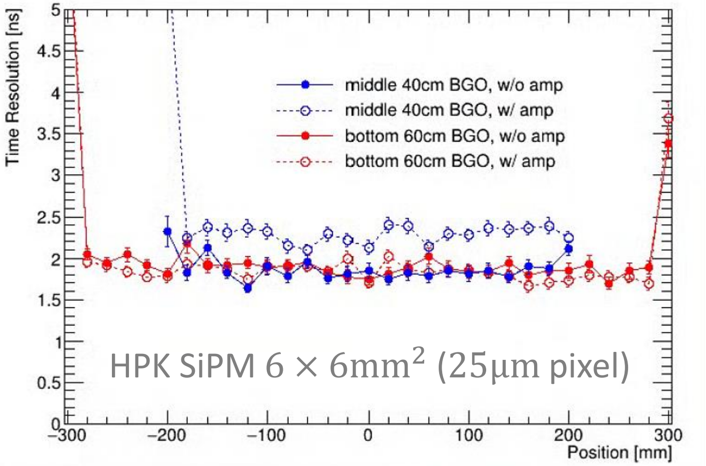




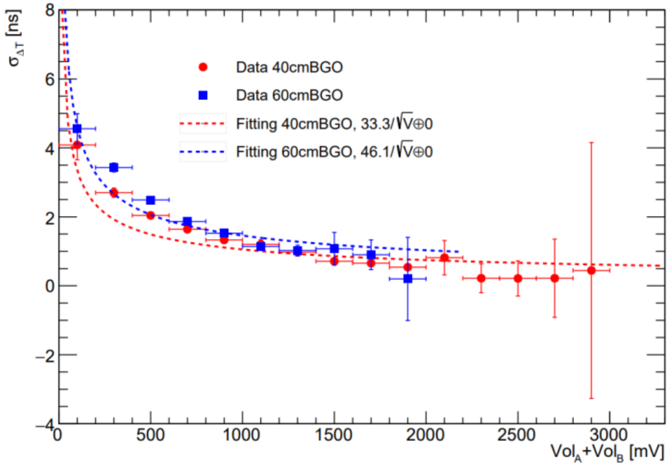
Resolution of time difference at two ends



Resolution of time difference at two ends



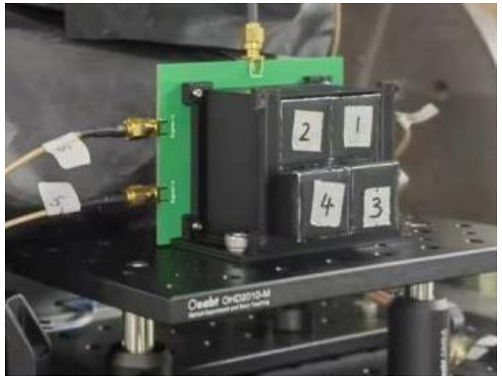
Time Resolution vs Signal Amplitude



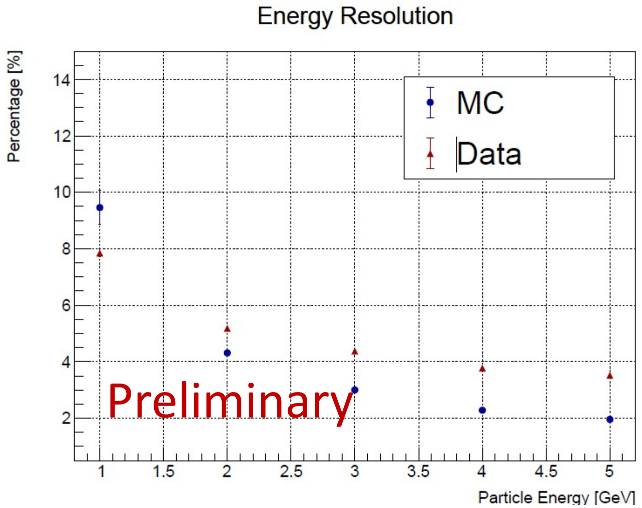
DESY beamtest: preliminary results

Fangyi Guo, Baohua Qi (IHEP);
Zhiyu Zhao (SJTU)

- Crystal ECAL prototype: EM performance in 1-5 GeV
  - Significant impacts from momentum uncertainty of electron beam
- Short crystal bars: validation of simulation + digitisation
  - Digitisation of SiPM-crystal: the dominant factor from SiPM saturation
  - MC can well reproduce SiPM-crystal response in data (a full range of 1-5 GeV)

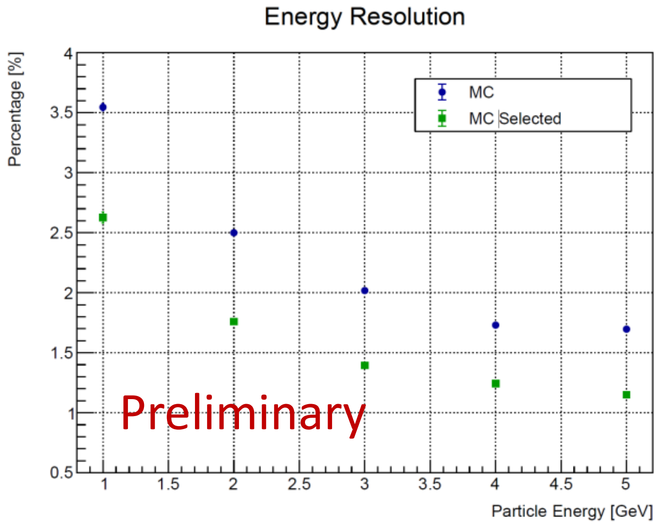


DESY TB22 beam: MC vs data

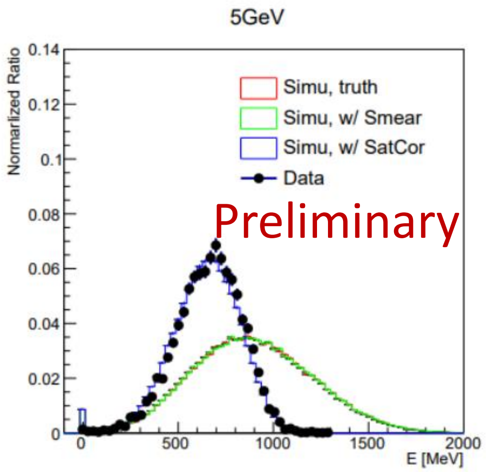


DESY-II TB21 beam spread ~16% at 1 GeV; no measurements for TB22 …

Expected performance at CERN PS-T9



Based on PS-T9 beamline document: 0.5% (FWHM) of beam spread (from Lattice)



Short crystal + SiPM

Downstream Beam Collimator (minimum-possible aperture)

Plans: crystal ECAL R&D in future

- MOST Phase-3 (MOST3) project: 5-year support (Dec. 2023 – Nov. 2028)
  - Task-3 in MOST3: "*Homogeneous electromagnetic calorimetry*"
  - To address key issues: PFA performance, optimal design, technological prototype, etc.
- ECFA DRD-on-Calorimetry (DRD6) proposal: Subtask 3.1.1 ("*High-Granularity Crystal Calorimeter*")

项目编号：2023YFA1606300　　密　级：公开

国家重点研发计划
项目任务书

项目名称：	高能量加速器关键技术研究
所属专项：	大科学装置前沿研究
指南方向(榜单任务)：	1.7 高能量加速器关键技术研究（共性关键技术）
创新分类：	基础研究
项目管理专业机构：	科学技术部高技术研究发展中心
推荐单位：	中国科学院
项目牵头承担单位：	中国科学院高能物理研究所（公章）
项目负责人：	王建春
执行期限：	2023 年 12 月 至 2028 年 11 月

中华人民共和国科学技术部制
2023 年 12 月 20 日

课题编号：2023YFA1606303　　密　级：公开

国家重点研发计划
课题任务书

课题名称：	全吸收型电磁量能器技术
所属项目：	高能量加速器关键技术研究
所属专项：	大科学装置前沿研究
项目牵头承担单位：	中国科学院高能物理研究所
课题承担单位：	上海交通大学
课题负责人：	杨海军
执行期限：	2023 年 12 月 至 2028 年 11 月

中华人民共和国科学技术部制
2023 年 12 月 18 日

- MOST3 leader: Prof. Jianchun Wang (IHEP)
- Task-3 leader: Prof. Haijun Yang (SJTU)
- 4 institutions involved
  - IHEP, SIC, SJTU, UTSC

Extracted from ECFA DRD6 proposal

Project	Calorimeter type	Scintillator/WLS	Photodetector	DRDTs	Target
Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters					
HGCCAL	EM / Homogeneous	BGO, LYSO	SiPMs	6.1, 6.2	e^+e^-
MAXICC	EM / Homogeneous	PWO, BGO, BSO	SiPMs	6.1, 6.2	e^+e^-
Crilin	EM / Quasi-Homog.	PbF_2, PWO-UF	SiPMs	6.2, 6.3	$\mu^+\mu^-$

5.2.1 Task 3.1: Homogeneous and quasi-homogeneous EM calorimeters

- Subtask 3.1.1: The *H*igh-*G*ranularity *C*rystal *Cal*orimeter (**HGCCAL**) [15] is a homogeneous calorimeter with high transverse and longitudinal segmentation based on $1 \times 1 \times 40$ cm^3 crystal bars arranged in a grid structure with double-ended SiPM readout. The calorimeter is optimised for event reconstruction based on particle flow algorithms (PFA) to achieve about a $3\%\sqrt{E}$ resolution for electromagnetic showers and a $30\%\sqrt{E}$ energy resolution for jets, crucial for the physics programs of future e^+e^- colliders.
  Key R&D required: Mechanical design and integration, development of an EM shower-scale prototype.

Acknowledgements

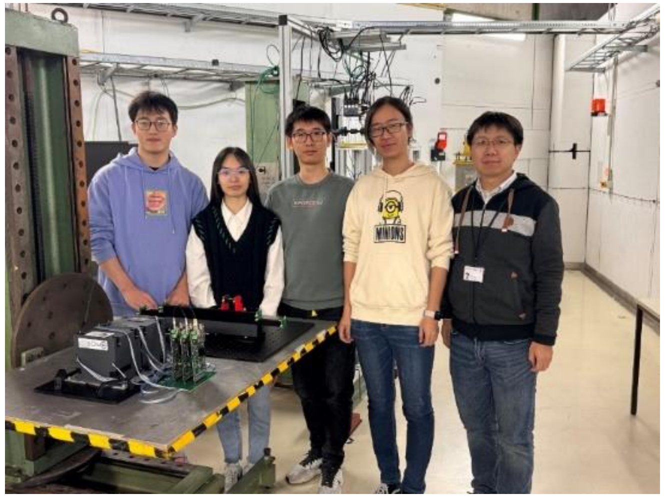
- Successful beam test campaigns with strong teamwork
- A big Thank You to CALICE and CEPC calorimeter teams
- Enormous and substantial support received from CERN, CALICE and DESY

CERN PS-T9, May 2023

CERN SPS-H2, May 2023

CALICE spokesperson's visit

DESY TB22, Oct. 2023



Summary and prospects

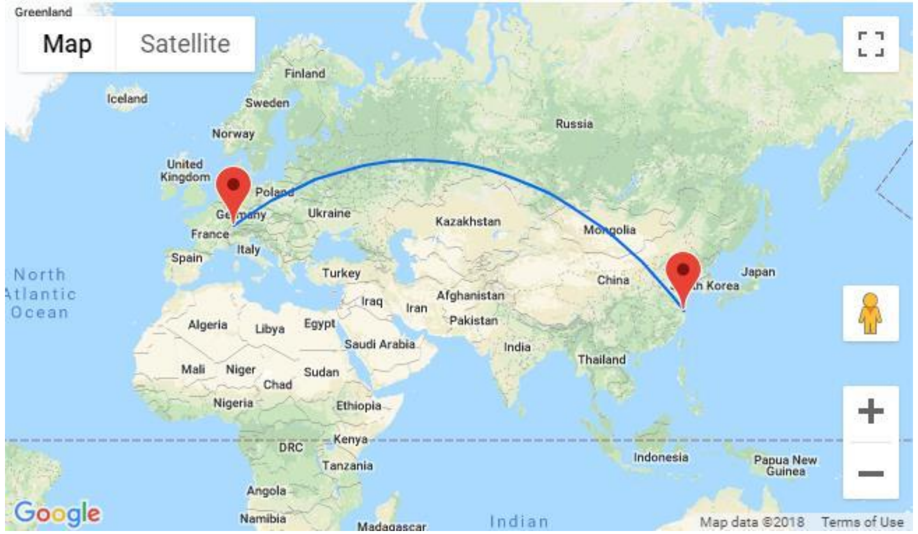
- CEPC scintillator-based calorimeter prototypes
  - Successful beam test campaigns at CERN (SPS-H2, H8 and PS-T9) during 2022-2023
  - Collected decent statistics of data samples in the wide energy range
  - Invaluable for detector performance evaluation and shower studies
- Preliminary results look promising, detailed studies under way
  - Key performance: energy linearity and resolution
  - PID and particle-flow studies
  - Validation of Geant4 hadronic models
- High-granularity crystal calorimeter: a new option for CEPC
  - Steady progress in several aspects: simulation, optimization and prototyping
  - Combined beamtests at CERN and dedicated beamtest at DESY in 2023
  - MOST3 support: more progress and results would be expected

Thank you!

Backup

CERN beamtests: logistics and preparations

Calorimeters in flight

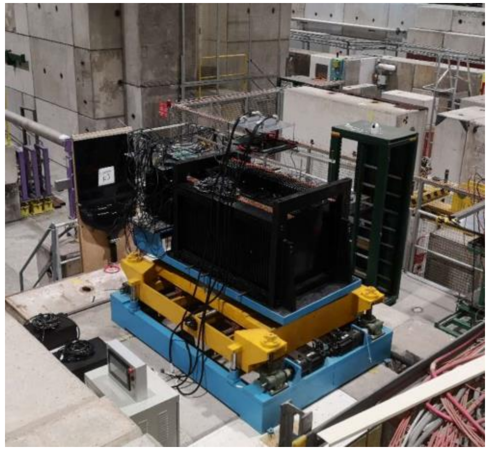


Flying calorimeter

Before cabling

- Successful transportation from China to CERN in Sep. 2022
- First transported to SPS beam area H8C (PPE168)
  - Two prototypes (ScW-ECAL and AHCAL) + motorised stage
  - Impressions: cubic meters and ~10 tons
- Stored at CERN for beamtests at SPS-H2 and PS-T09 in 2023

After cabling (parasitic runs)



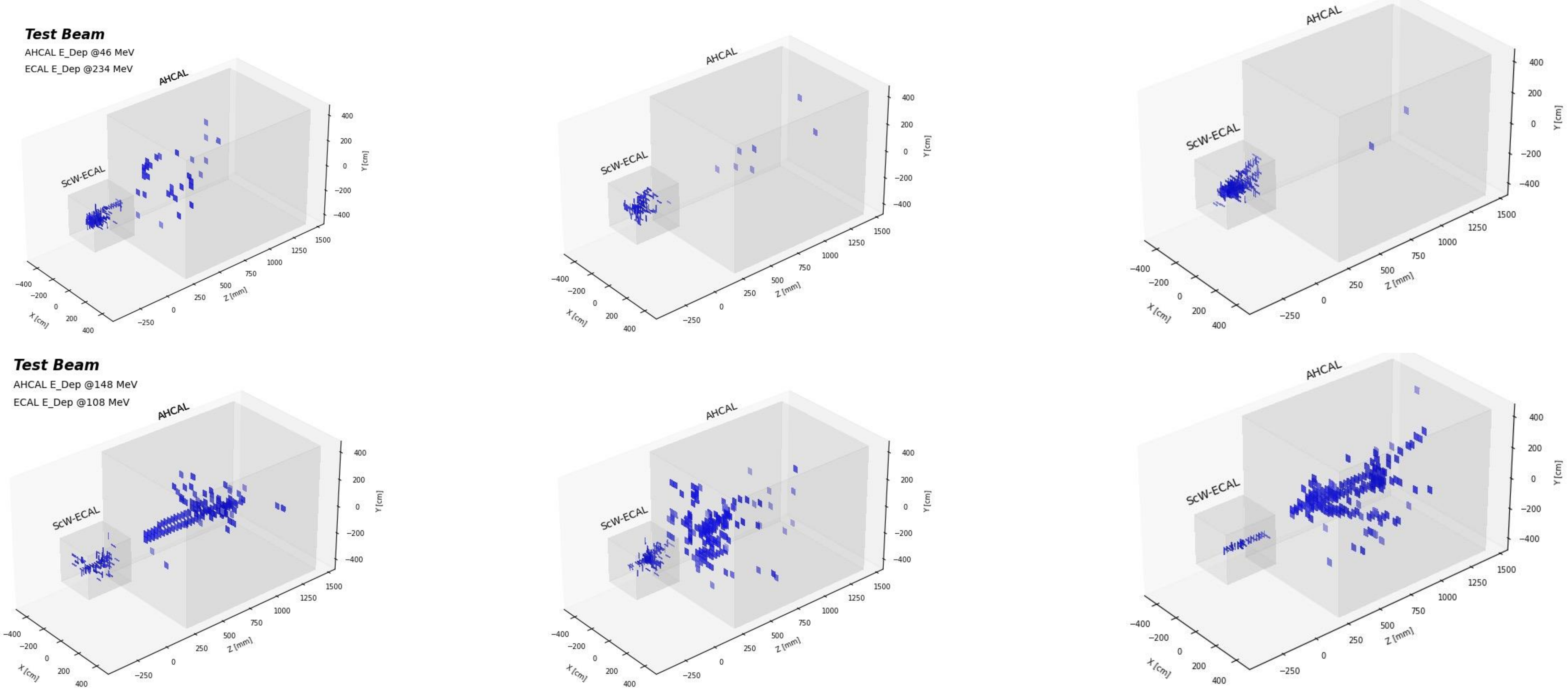
Final transportation back to China

- Loading at CERN on June 7, 2023
- Successfully transported back to China (Hefei) on June 17, 2023

Hadronic showers in ECAL+HCAL at PS

Siyuan Song (SJTU)

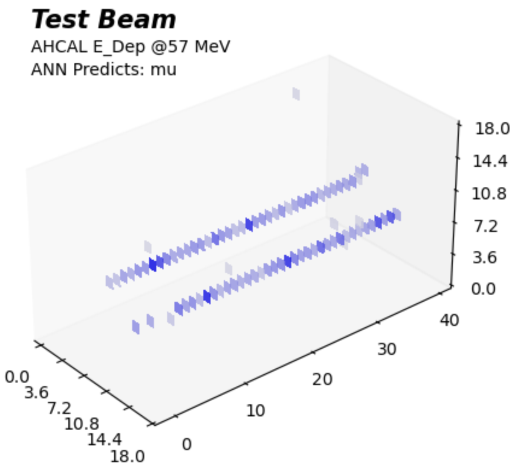
5 GeV π^- | 10 GeV π^- | 15 GeV π^-

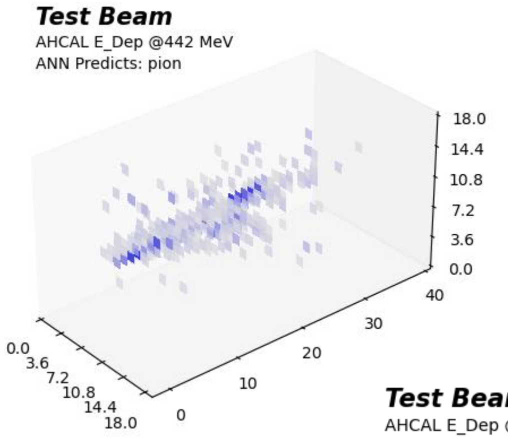


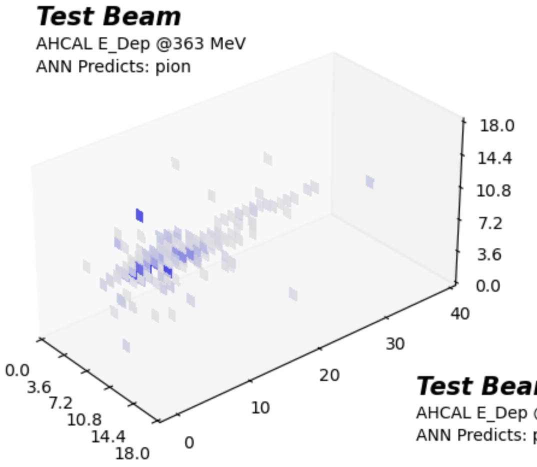
Event display with AHCAL alone at PS

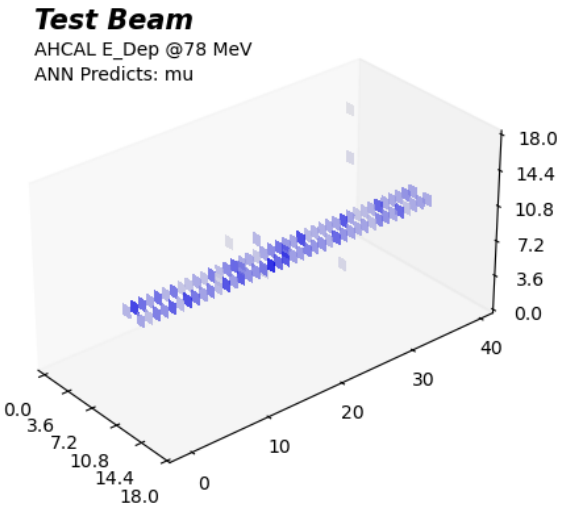
Siyuan Song (SJTU)

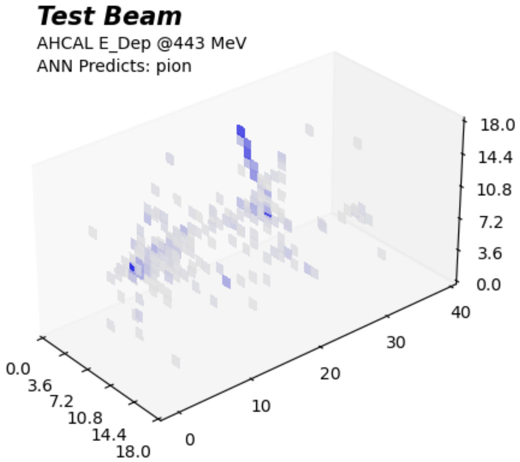
- Hadronic showers with 10 GeV pions
- Multiple MIP tracks from 10 GeV muons

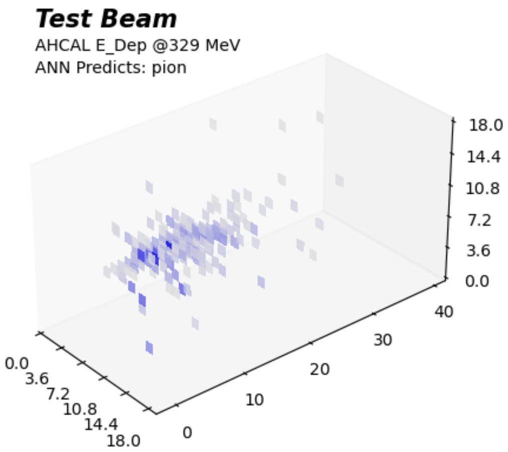








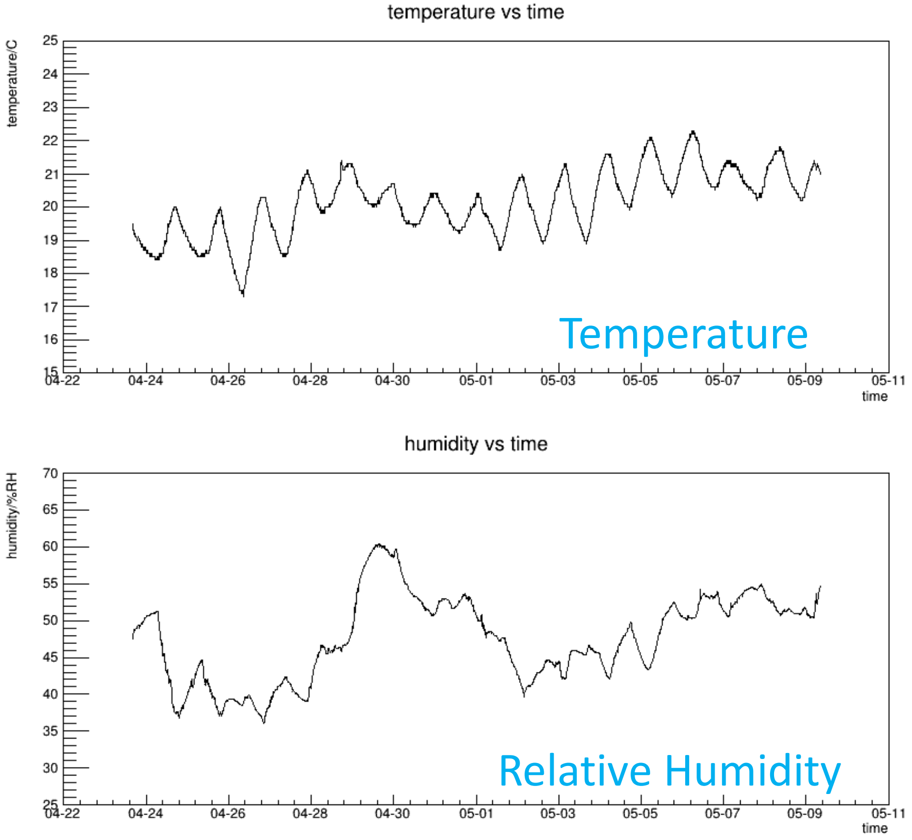




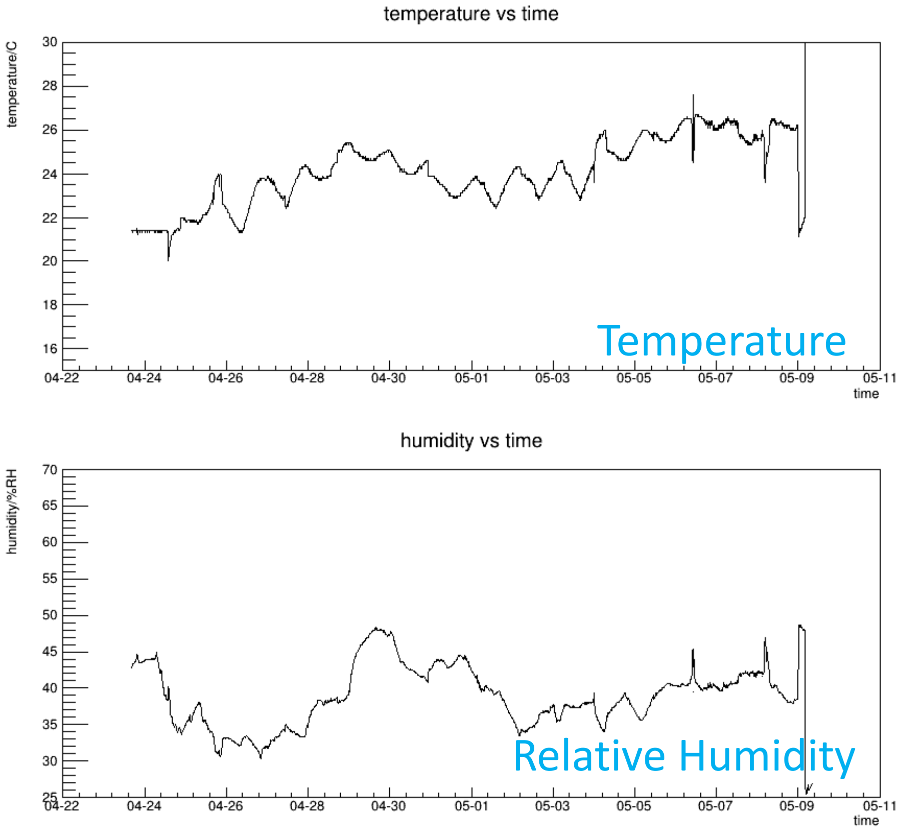
Environment monitoring

Yunlong Zhang (USTC), Siyuan Song (SJTU)

- Temperature and humidity at SPS-H2



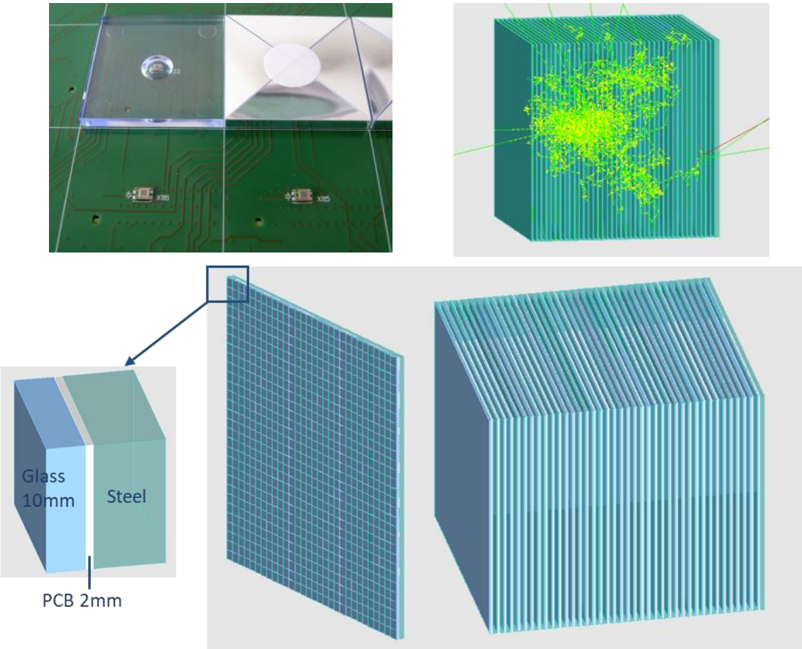
Experimental area

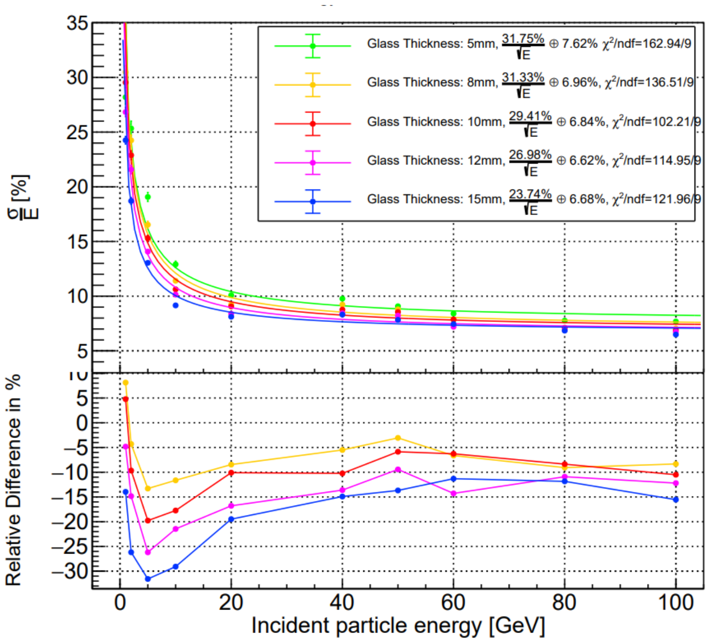


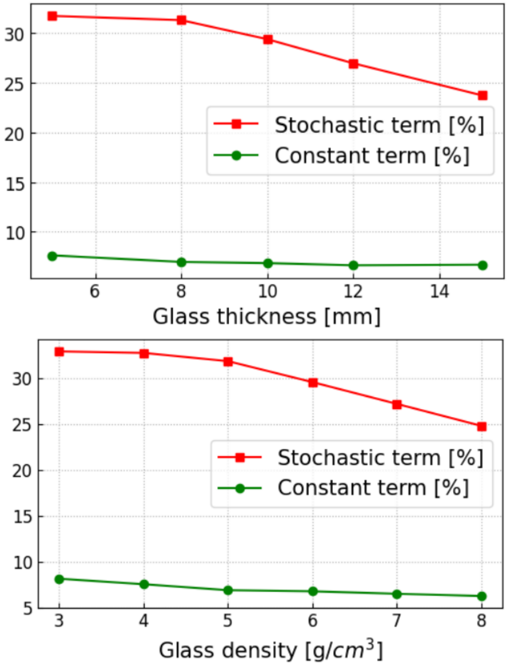
Within AHCAL sensitive layers

Scintillator glass calorimeter

Dejing Du (IHEP)

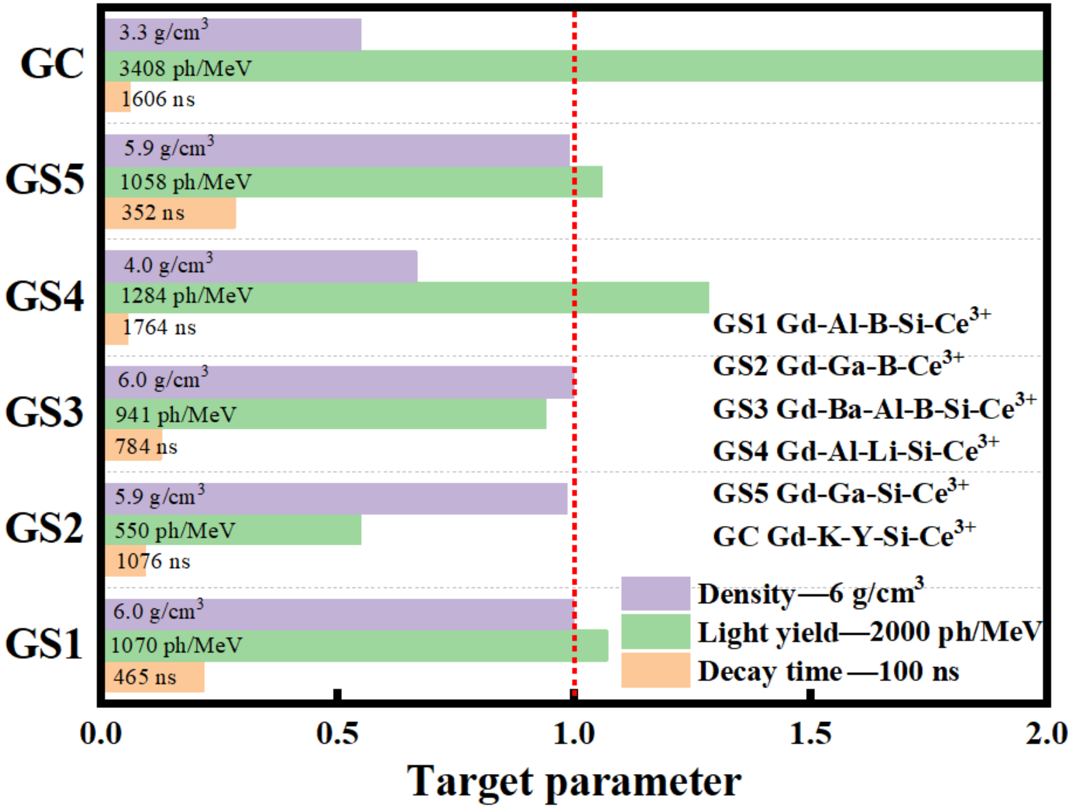






- Sampling scintillator-steel structure: a la CALICE-AHCAL
  - To replace plastic scintillator with glass
  - In the same form factor of tiles: fine segmentation for PFA compatibility
- Simulation studies: promising improvement in hadron energy resolution
  - Design specs: glass density, thickness; energy threshold, signal time window

Glass Scintillator R&D

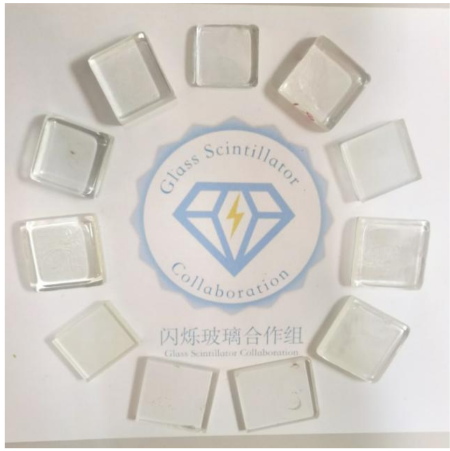


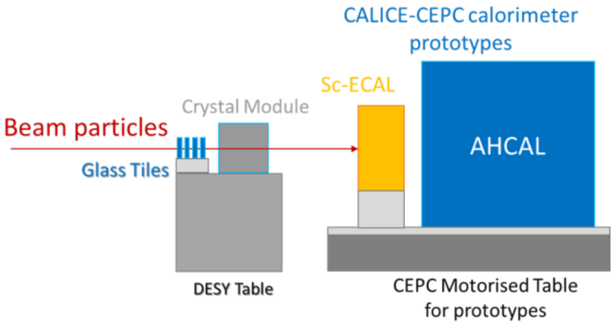
- R&D within the Glass Scintillator Collaboration
- Targets
  - 6 g/cm^3, 2000 ph/MeV, 100 ns
- Best glass sample in mm scale
  - 5.9 g/cm^3, 1058 ph/MeV, 352 ns
- Challenges
  - Increase density while keeping high light yield and transparency
  - Synthesizing large cm-scale glass tiles with good scintillation and optical properties

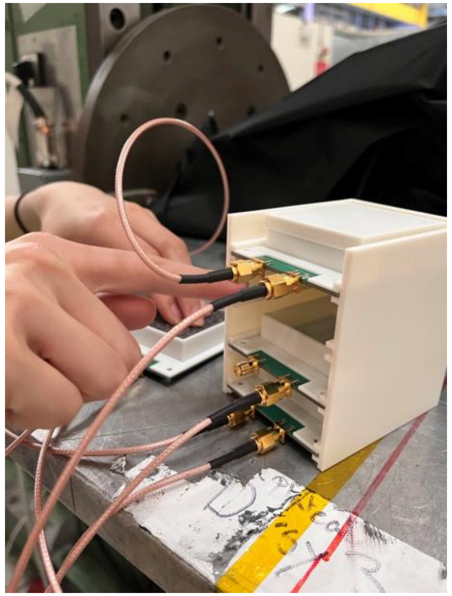
闪烁玻璃合作组
Glass Scintillator Collaboration

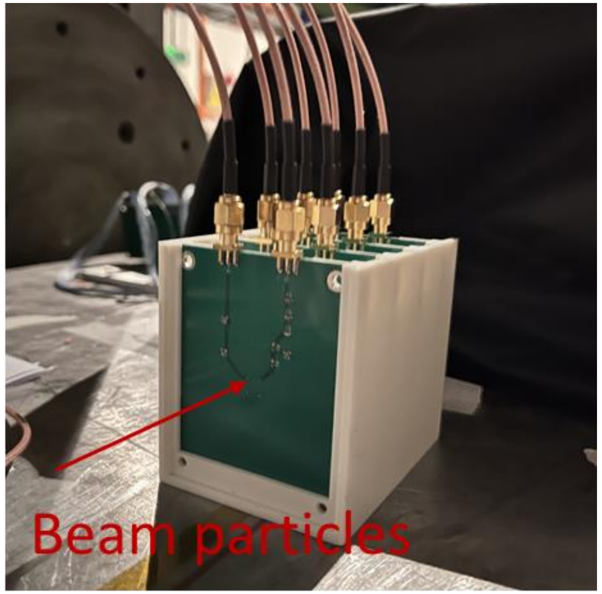
Scintillator glass tiles: CERN beamtest in 2023

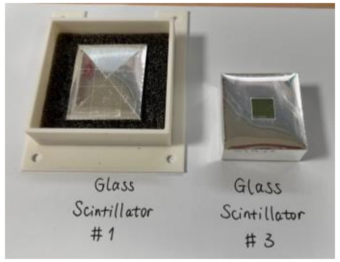
- Successful beamtest with scintillator glass tiles
  - Combined tests with CEPC calorimeter prototypes
  - 11 pieces of large-area glass tiles: the first batch produced by the "Glass Scintillator Collaboration"
  - Clear MIP signals in all 11 glass samples with 15 GeV muons
  - 3 glass tiles showed promising MIP response

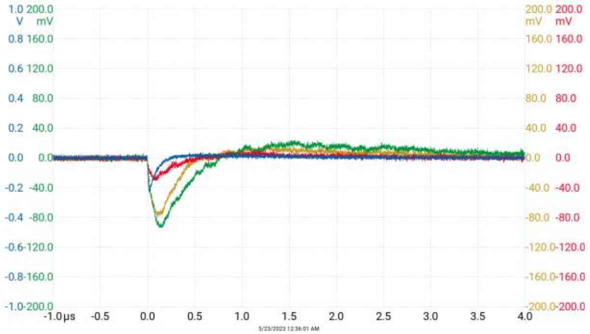


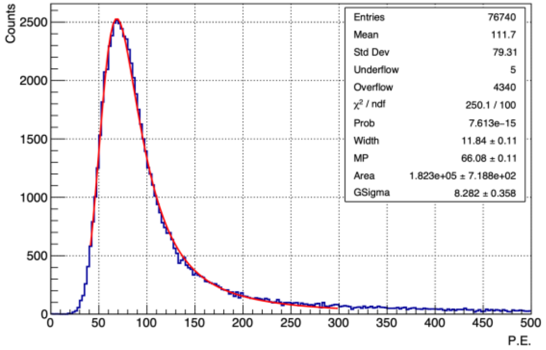










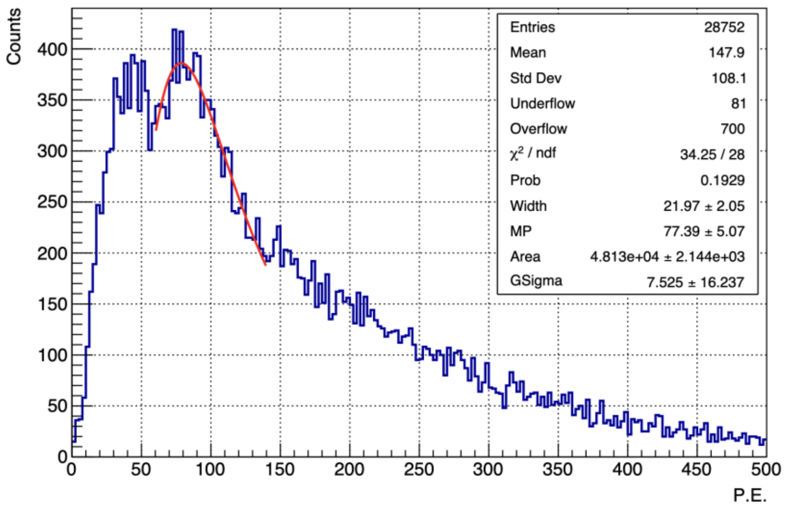


Glass scintillator (#3): 66 p.e./MIP
($29.8 \times 28.1 \times 10.2\ \mathrm{mm}^3$)

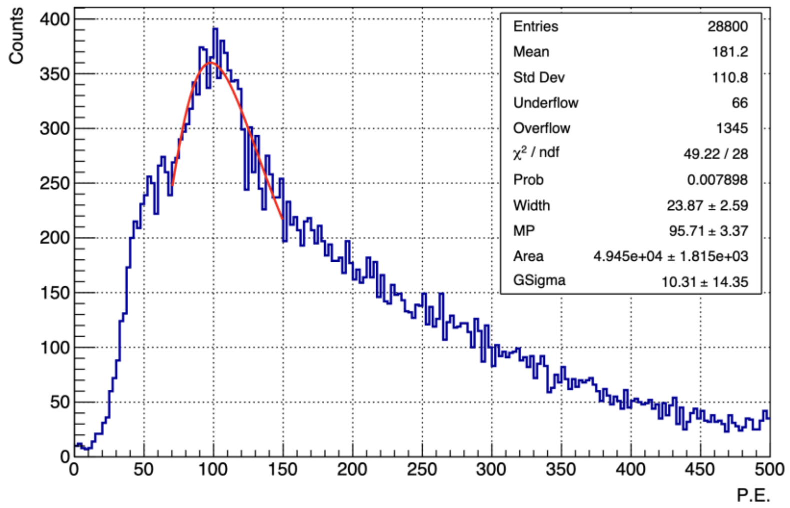
DESY beamtest results: MIP responses

- Observed clear (quasi-)MIP signals in all glass samples
  - Typical MIP response: 70 – 95 p.e./MIP
  - Showed generally relatively good uniformity
- Quasi-MIP energy spectrum (5GeV electrons)
  - Different shape from CERN muon beam; also observed some structures
  - Further studies with Geant4 full optical simulation

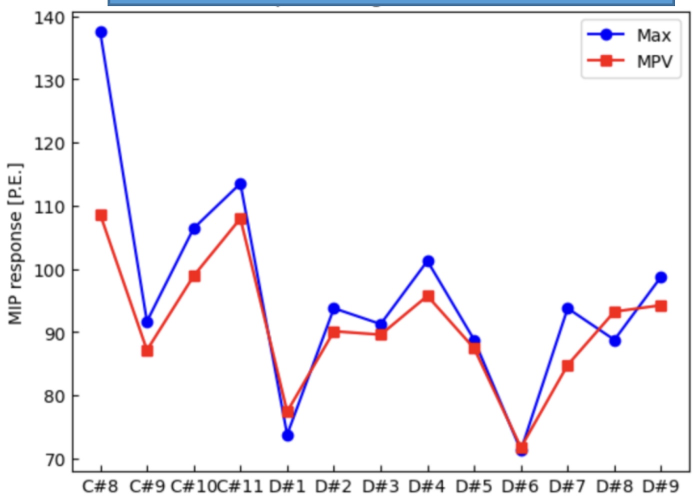
DESY#1: 77.4 p.e./MIP



DESY#4: 95.7 p.e./MIP



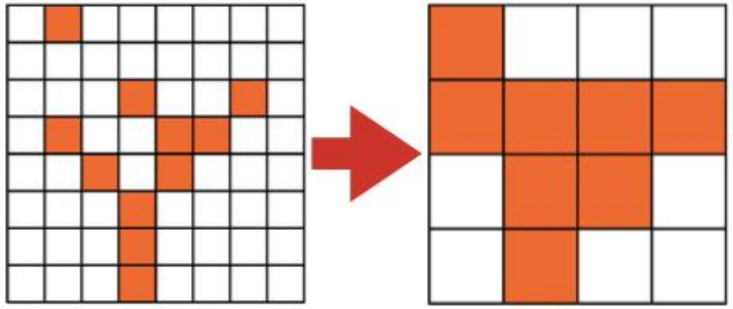
MIP response of each tile



Fractal Dimension

Particle Identification

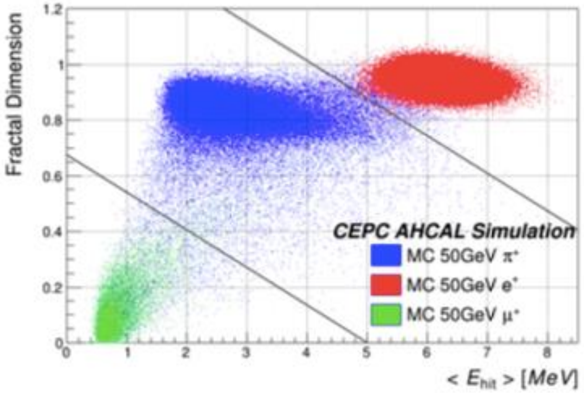
- **Cut-based PID:** FD vs $< E_{Hit} >$
  - $\mathrm{FD} = \left\langle \frac{\log(\mathrm{R}_{\alpha,1})}{\log(\alpha)} \right\rangle$, where $\mathrm{R}_{\alpha,1} = \mathrm{N}_1/\mathrm{N}_\alpha$
  - N_α: number of hits scaled by α
  - $< E_{Hit} > = E_{dep}/N_{hit}$



Take $\alpha = 2$ as an example

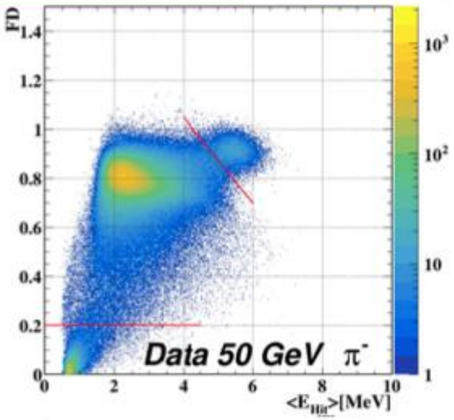
Efficiency @ 50 GeV MC

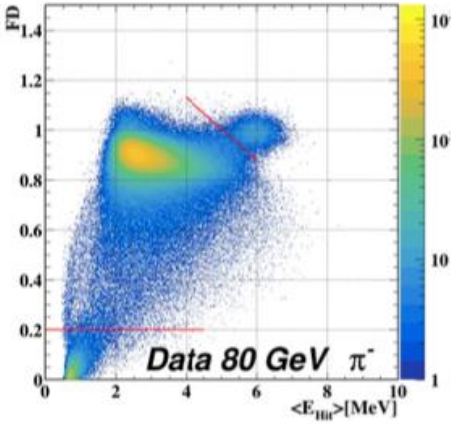
Truth \ ID	μ^+	π^+	e^+
μ^+	99.4%	0.6%	0
π^+	3.6%	94.1%	2.3%
e^+	0	0.3%	99.7%



Achieved Promising separation power on MC samples.

FD Ref: PhysRevLett.112.012001





Work on Pion Beam data

Self-similar pattern of particle showers in transverse direction

Oct 26, 2023 Siyuan Song (siyuansong@sjtu.edu.cn), SJTU. The 2023 International Workshop on CEPC 16