PFA Crystal Calorimeter: hadronic performance studies and development status

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for the CEPC Calorimeter Working Group

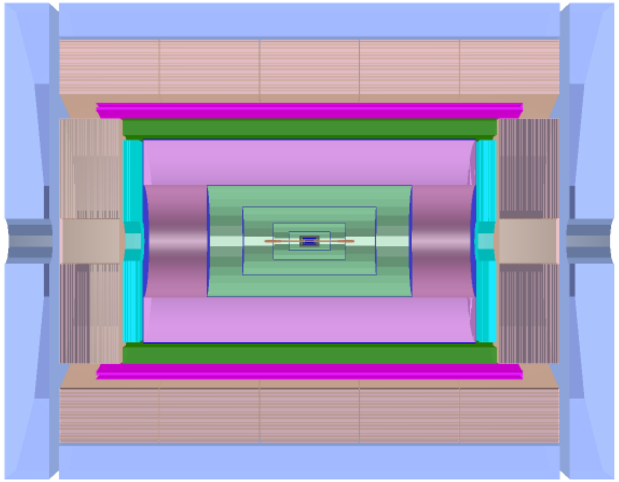
Apr. 22, 2022

Outline

- Hadronic performance with a homogeneous calorimeter
  - Motivation: abundant hadrons in jets → hadronic performance is a key
  - Method: single hadron studies with Geant4 full simulation
  - Key performance: response linearity and energy resolution
- PFA crystal calorimeter: development status
  - With a major focus on the hardware development

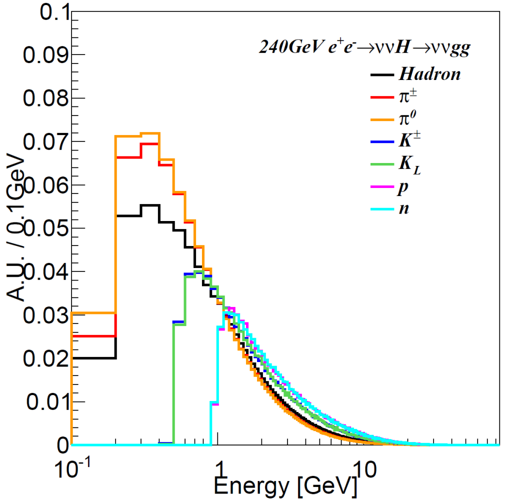
Motivations

- CEPC physics programs
  - Hadronic decays of Higgs/Z/W bosons: abundant hadrons (<10 GeV) within jets
- Crucial: hadrons in scintillator-based calorimeters
  - Within the CEPC 4th concept detector: crystal ECAL + scintillating glass HCAL
    - A leap in terms of sampling fractions
    - Aim to improve the energy resolution: **EM + hadronic energy resolution**

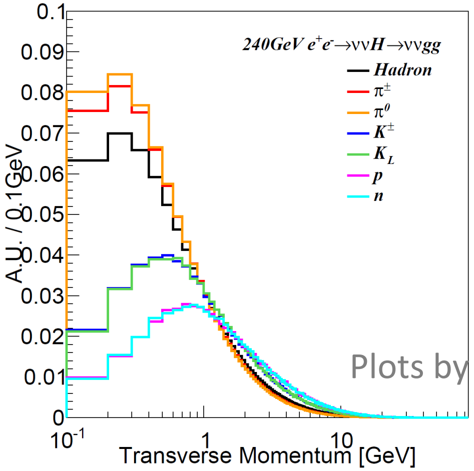


Calorimeters: crystal ECAL and Scintillating Glass HCAL

Kinetic energy



Transverse Momentum



Plots by Yuexin Wang (IHEP)

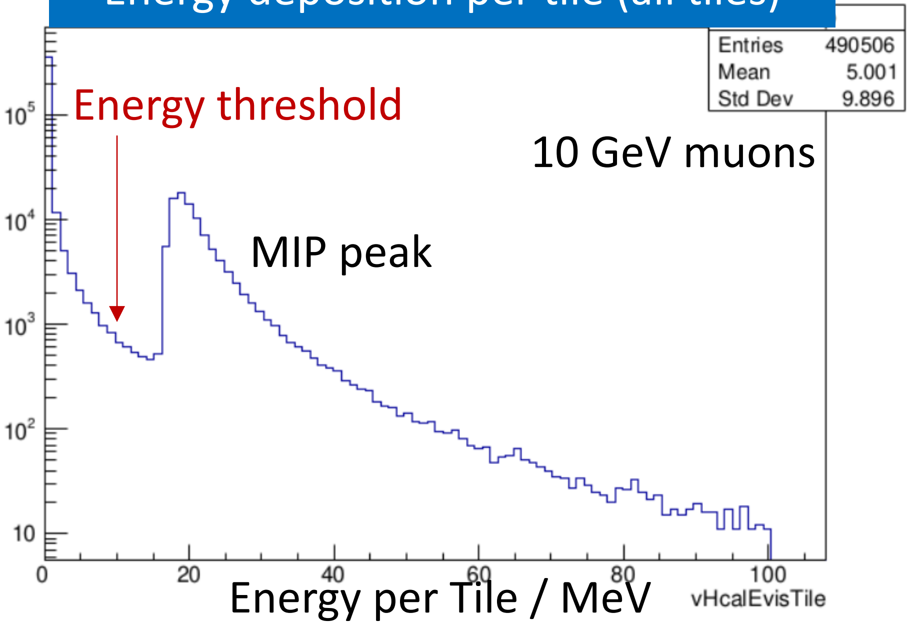
Motivations

- CEPC physics programs
  - Hadronic decays of Higgs/Z/W bosons: abundant hadrons (<10 GeV) within jets
- Crucial: hadrons in scintillator-based calorimeters
  - Within the CEPC 4^{th} concept detector: crystal ECAL + scintillating glass HCAL
    - A leap in terms of sampling fractions
    - Aim to improve the energy resolution: **esp. the hadronic resolution**
  - A large fraction of hadronic showers initiated in the crystal ECAL
  - Hadronic showers mostly contained in the scintillating glass HCAL
  - Synergies between crystal and glass calorimeters: **intrinsic hadronic performance**
- Hadronic responses: key aspects to be studied
  - Calorimeter responses and performance (linearity and resolution) in Geant4
  - Geant4 validation studies: profit from existing beam test data sets

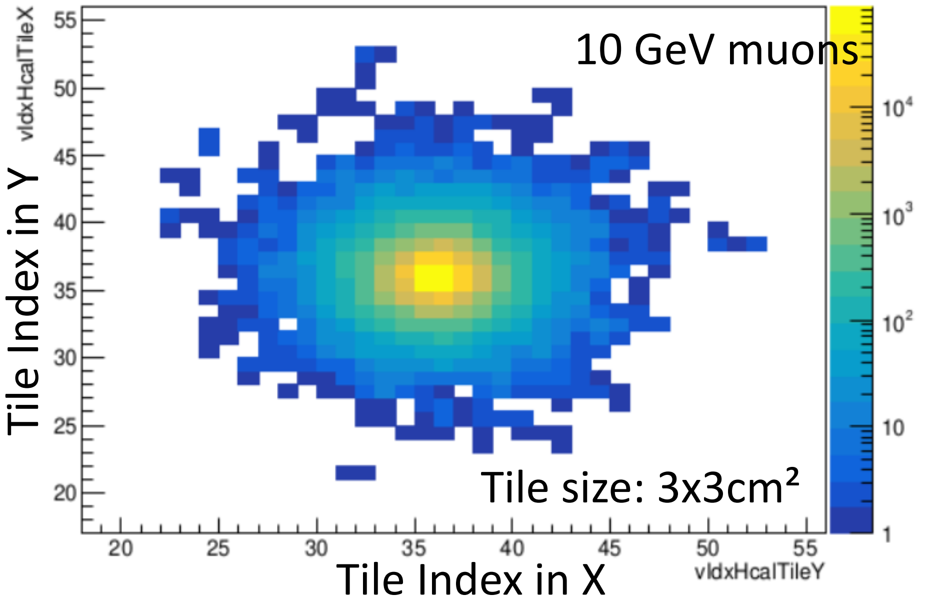
MIP calibration with muons

- MIP calibration: energy scale for reconstruction
  - Varying the energy threshold in simulation: 0 – 0.5 MIP

Energy deposition per tile (all tiles)



Hit Map in the transverse plane (all layers)



For crystal calorimetry, plenty of room to lower energy threshold per cell due to its high MIP light yield

- Energy threshold: finally to be determined by several factors
  - FE electronics (pedestals, occupancy), SiPM noises, beam-related backgrounds, etc.
- CALICE prototypes: 0.3 – 0.5 MIP thresholds (depending on technical options)

Hadronic responses

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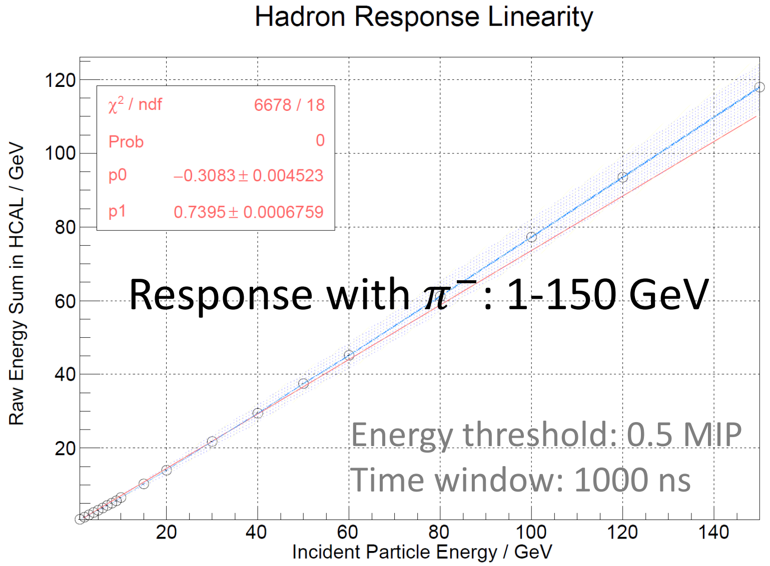
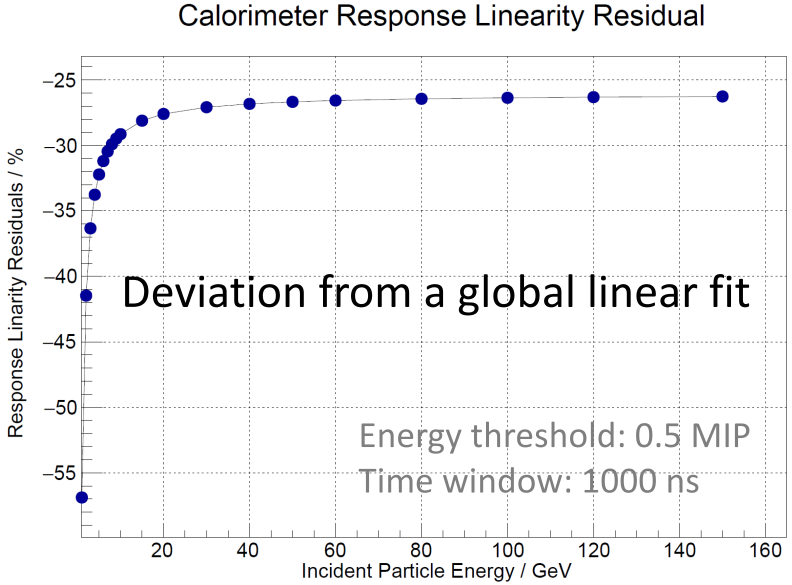
- Focus on the **homogeneous calorimeter**
  - Large and deep layers for minimum leakage effects
  - Synergies between crystal ECAL and scintillating glass HCAL

Remark: in real PFA-calos, longitudinal leakage can be mitigated and corrected: benefit from the high granularity by determining shower start point





- A global linear curve <u>can not</u> well calibrate the hadronic response
  - Noticeable deviations, especially in the lower energy region
  - Separate energy calibrations for low and high energy regions?

Homogeneous calorimeter: hadronic responses

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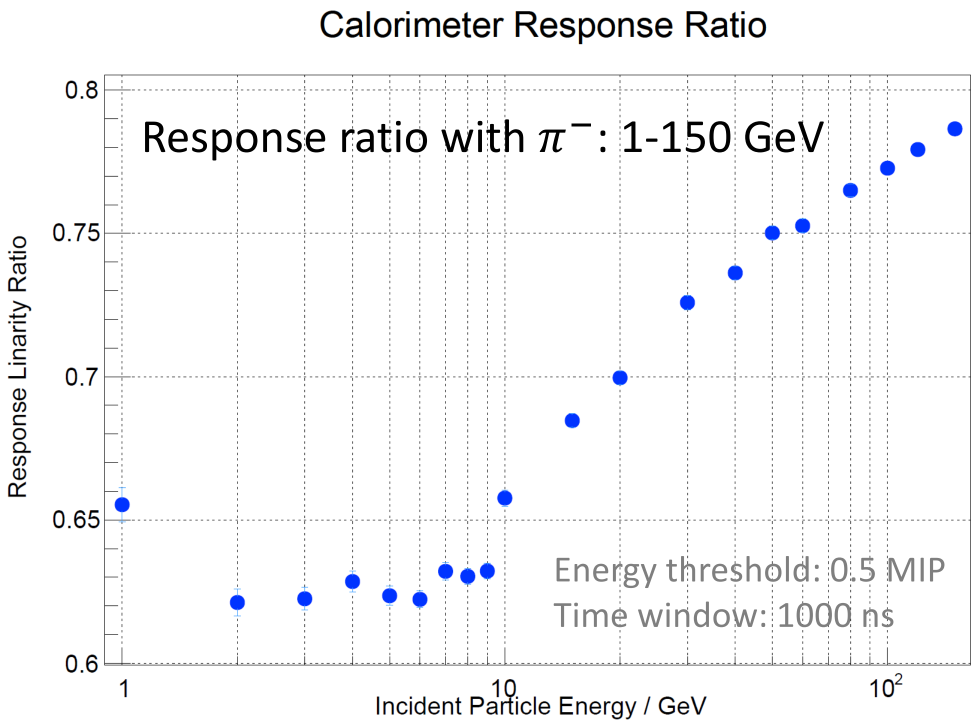
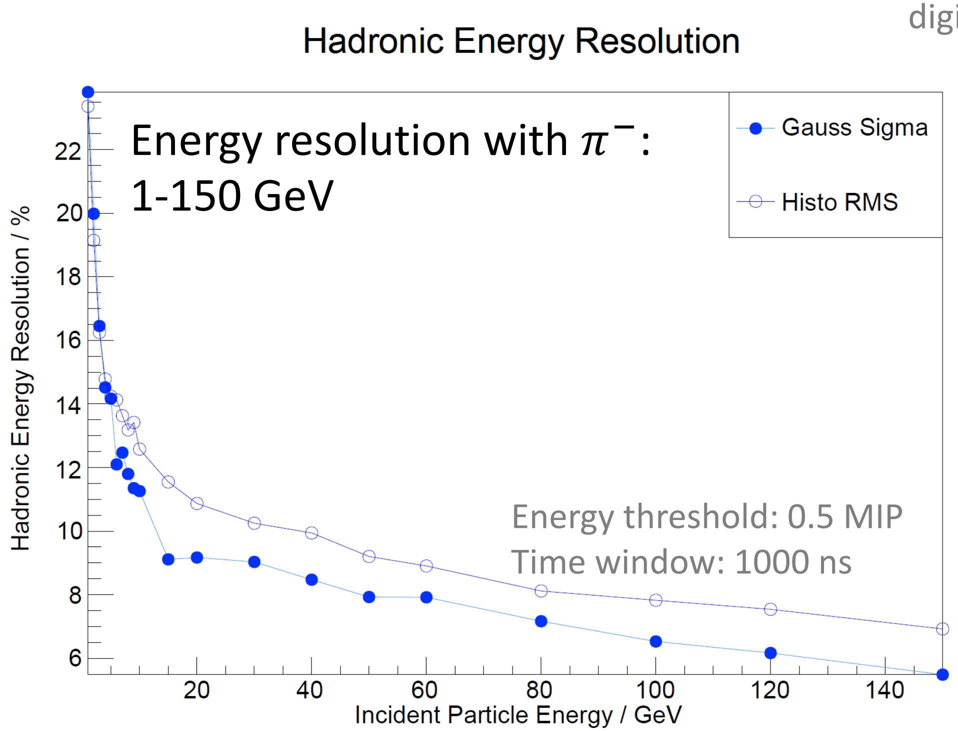
- Hadronic response ratio and energy resolution

Energy deposition only: digitisation not included





- Significantly lower response in 1-10 GeV region
- Note: scintillator quenching effects not yet included in the studies (ongoing studies)

- Energy resolution: non-Gaussian distributions
  - Significant difference between RMS and sigma
  - Not exactly follow $1/\sqrt{E(GeV)}$ curve
  - Large constant term: >5%

Homogeneous calorimeter: hadronic showers

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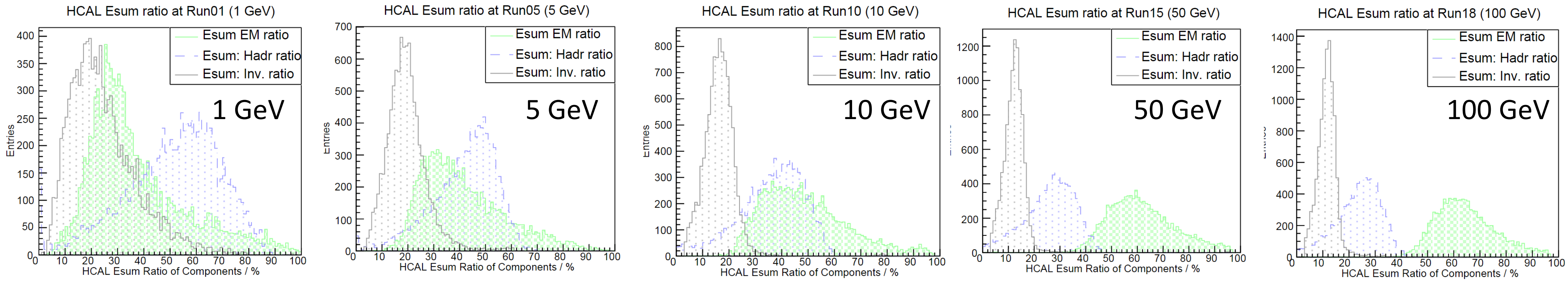
- Categorize energy depositions of hadronic showers
  - Components within hadronic showers: EM, hadronic, invisible
    - EM component primarily from π^0's produced in the hadronic cascade
    - EM energy deposition usually detected with higher efficiency

Component Energy Ratio

MC samples with π^-



- EM component fraction: incident energy dependent
- EM/hadronic energy depositions: significant **non-Gaussian fluctuations**
  - Determined by the **intrinsic behavior** of hadronic showers

Homogeneous calorimeter: hadronic showers

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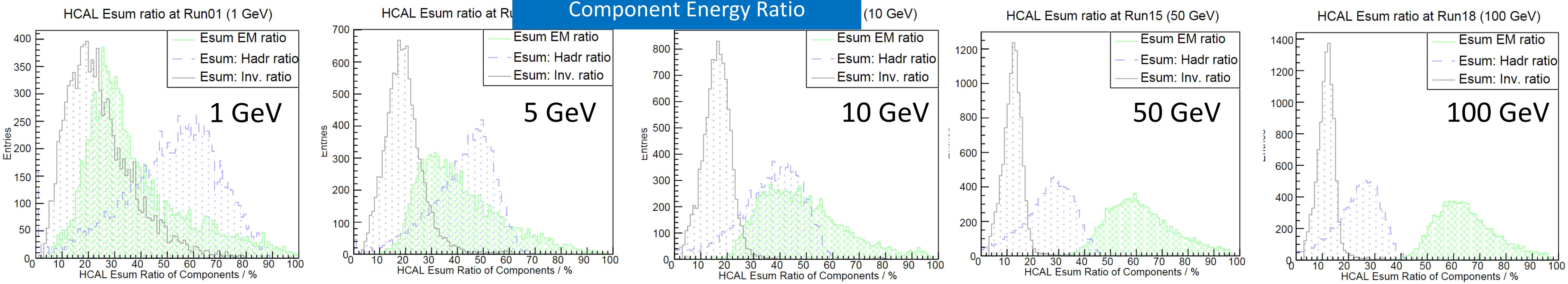
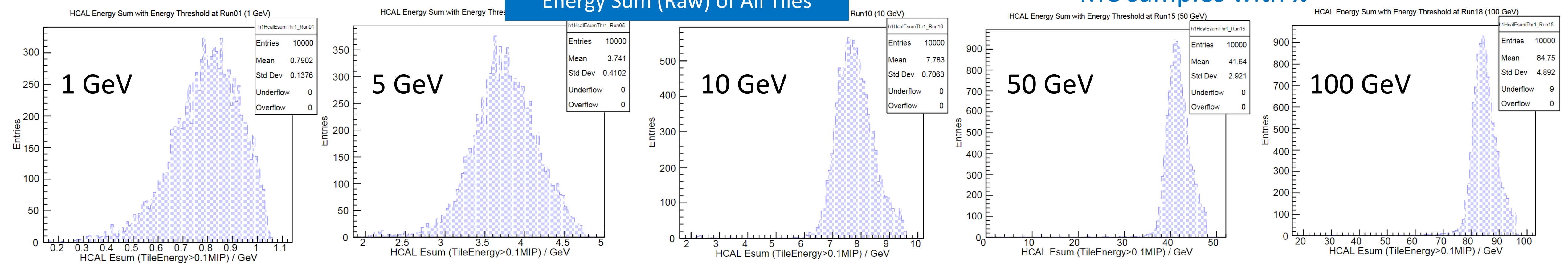
- Categorize energy depositions of hadronic showers
  - Total energy deposition: non-Gaussian distributions → Dominate the large constant term (>5%)

Component Energy Ratio



Energy Sum (Raw) of All Tiles

MC samples with π^-



How should we trust Geant4 simulation?

- Geant4 simulation for homogenous calorimetry
  - Can we trust the hadronic response in Geant4?

- Limited data sets of hadron beam tests for homogenous calorimeters
  - Existing calorimeters: homogenous ≈ crystals/lead glass
  - For crystal calorimeters: typical beam tests with electrons/gammas

How should we trust Geant4 simulation?

- Geant4 simulation for homogenous calorimetry
  - Can we trust the hadronic response in Geant4?

- Limited data sets of hadron beam tests for homogenous calorimeters
  - Existing calorimeters: homogenous ≈ crystals/lead glass, primarily as ECAL
  - For crystal calorimeters: typical beam tests with electrons/gammas

- Extensive studies with CMS calorimeters

Eur. Phys. J. C (2009) 60: 359–373

  - Combined beam tests of CMS ECAL barrel (EB) and HCAL barrel (HB) prototypes
    - Note: CMS **ECAL with PbWO4 crystal bars**; HCAL with plastic scintillator and brass as absorber
  - Valuable data sets with various species of hadrons ($\pi^{\pm}, K^{\pm},\ p/\bar{p}$) in 2-350 GeV
    - Especially in the energy range of 2-10 GeV
  - Geant4 validation studies with both beam tests and collision data

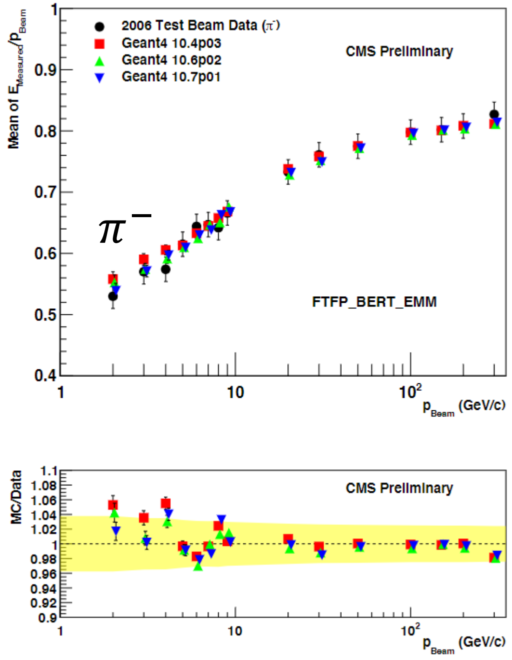
Validation studies: CMS calorimeters

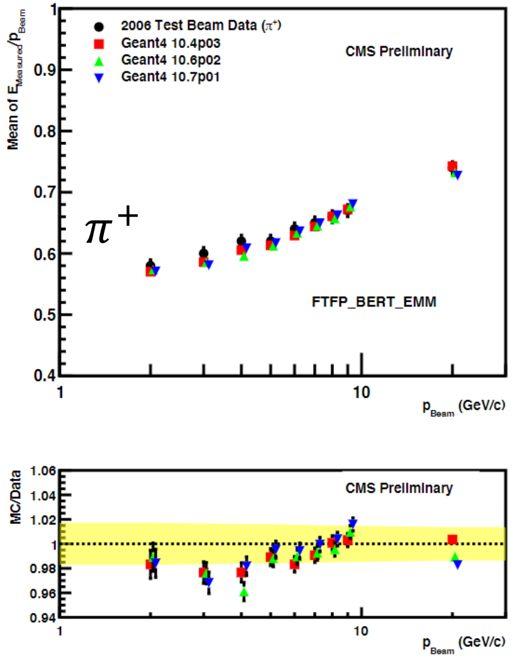
[EPJ Web of Conferences 251, 03010 (2021)](#)

Sunanda Banerjee and Vladimir Ivanchenko, Validation of Physics Models of Geant4 Versions 10.4.p03, 10.6.p02 and 10.7.p01 using Data from the CMS Experiment

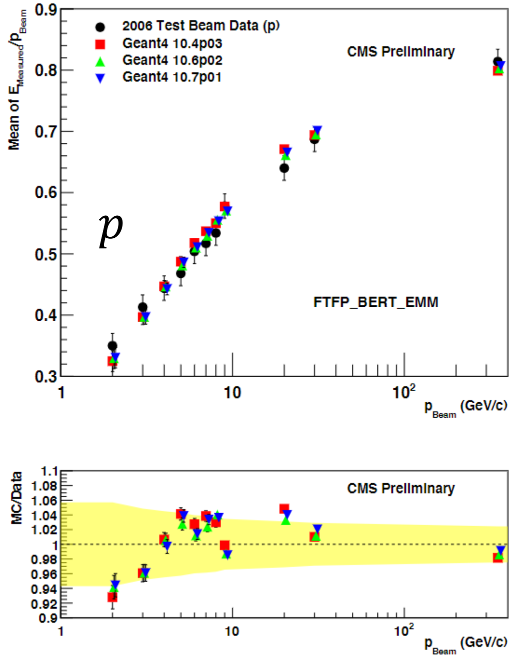
CMS combined EB+HB: selected results

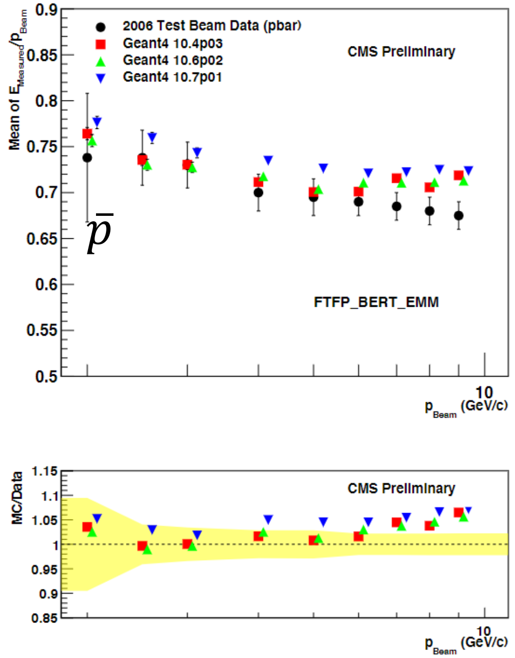
Energy response (average) of charged pions





Energy response (average) of protons/anti-protons



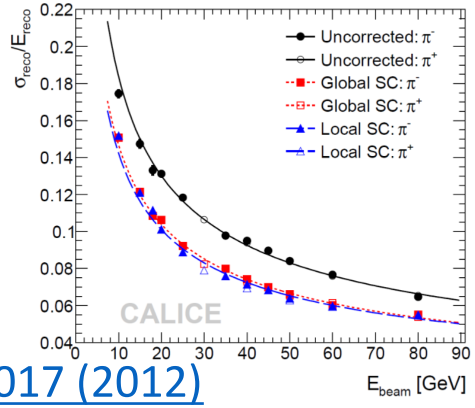


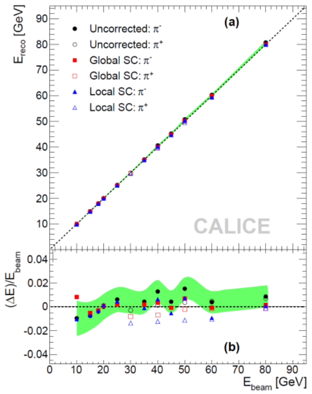
- Geant4 simulation can well reproduce hadronic responses
  - Impressive consistency: MC/data discrepancy within a few percent
  - Note: only “simple” digitization for EB+HB (Gaussian smearing for hit energy)

→ Need a “bridge” between CMS calorimeter simulation and our simulation

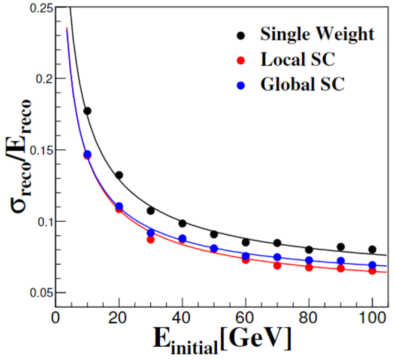
Hadronic energy resolution

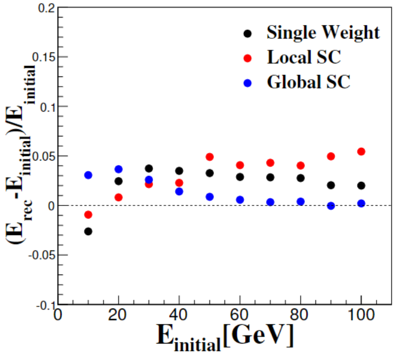
- How to further improve the energy resolution?
  - Distinguish EM/hadronic components
    - Event-by-event fluctuations + incident energy dependent
  - Perform event-level corrections
- Option 1: “Software compensation” technique
  - **Estimators: (1) energy deposition density, (2) timing (new)**
  - Established for the CALICE-AHCAL and validated with prototype beamtest data
  - We plan to further explore potentials for crystal/scintillating glass options





[JINST 7 P09017 (2012)]()





J. Jiang, UCAS Ph.D Thesis on AHCAL (2021)

Hadronic energy resolution

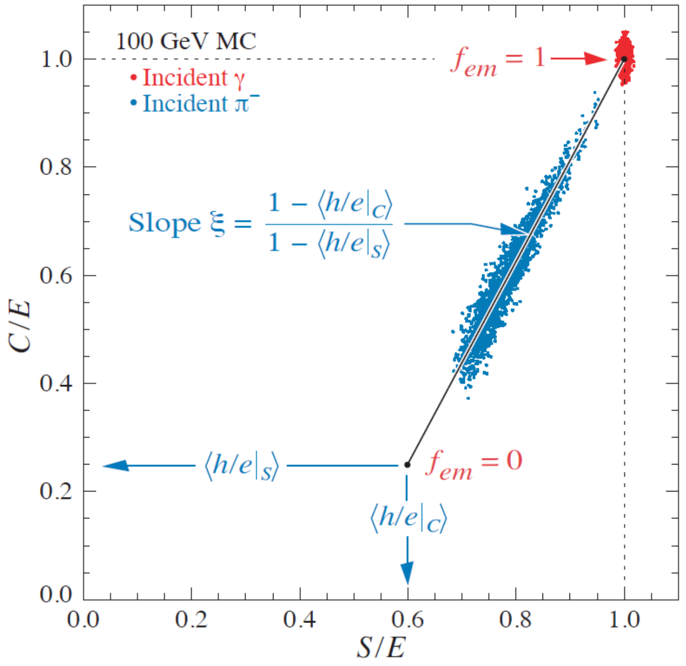
- Hadronic cascades by nature lead to non-Gaussian fluctuations
  - Undesired: prominent degrade in response linearity and resolution
- How to improve the hadronic energy linearity and resolution?
  - Distinguish EM/hadronic components
    - Event-by-event fluctuations + incident energy dependent
  - Perform event-level corrections
- Option 1: “Software compensation” technique
  - Estimators: energy deposition density, timing (new progress)
  - Established for AHCAL option and validated with prototype beamtest data
  - We plan to further explore potentials for crystal/scintillating glass options
- Option 2: “Dual-readout “ technique
  - Estimators: scintillation and Chereknov light
    - EM+Had components: scintillation photons
    - EM component: mostly with Cherenkov photons

Highlights of potential studies in the next pages

Dual readout technique: reminder

Geant4 10.05.p01

- Energy estimators: scintillation and Cherenkov light
  - Crystal/scintillating glass: capable to produce and detect scintillation photons (S) and Cherenkov photons (C) at the same time
  - Implemented them **Geant4 full simulation** for homogeneous calorimetry



Reference: D. E. Groom, HCAL in PDG (2020)

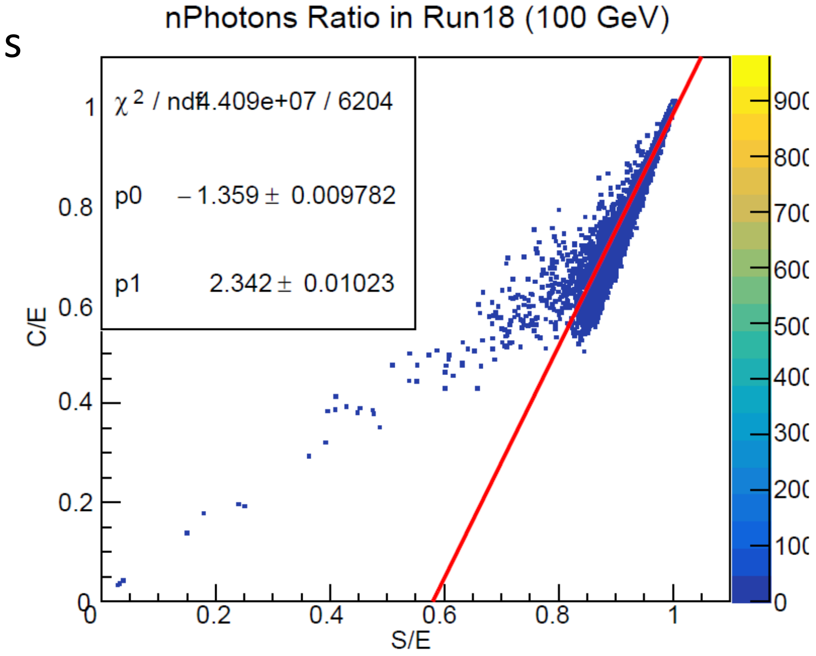
S and C signals normalized to electrons

$$C = E[f_{EM} + \langle h/e\rangle_C(1 - f_{EM})]$$

$$S = E[f_{EM} + \langle h/e\rangle_S(1 - f_{EM})]$$

$$\xi = \frac{1 - \langle h/e\rangle_C}{1 - \langle h/e\rangle_S} \equiv \frac{1 - \eta_C}{1 - \eta_S}$$

$$E = \frac{\xi S - C}{\xi - 1} = \frac{S(1 - \eta_C) - C(1 - \eta_S)}{\eta_S - \eta_C}$$



Full simulation with homogeneous scintillating glass tiles + S/C photons

Energy estimator with scintillation only

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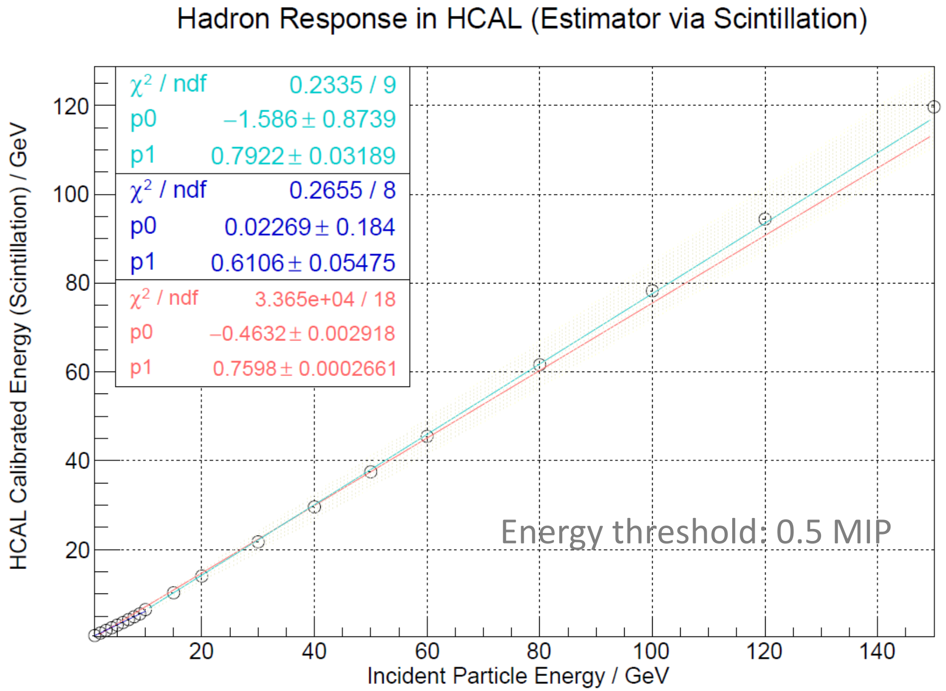
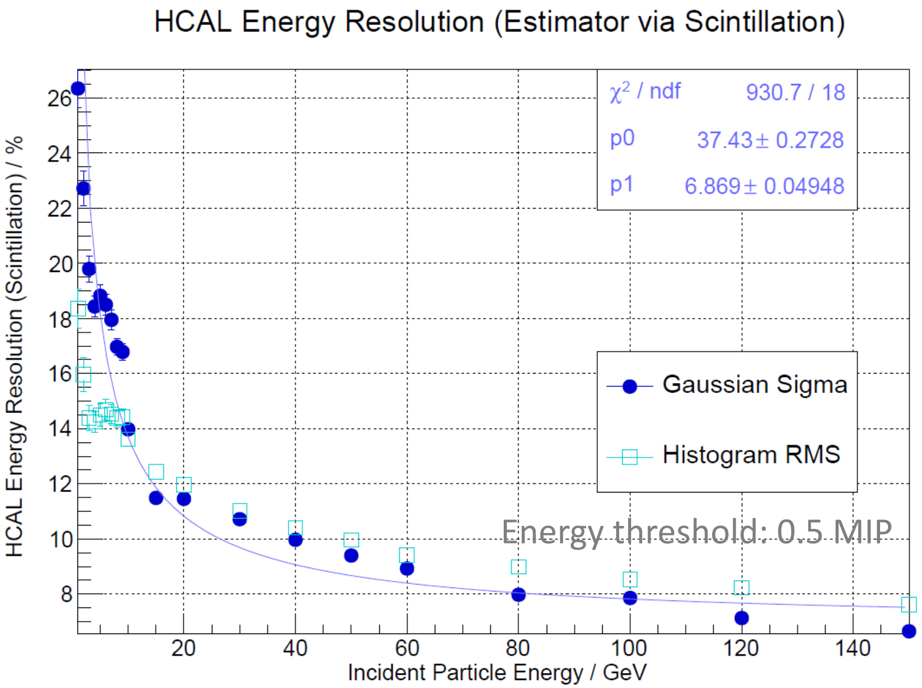
- "Conventional" readout scheme
  - Use only scintillation light as energy estimator

Energy deposition + scintillation process:
"partial" digitisation included





- A global linear curve can not well calibrate the hadronic response
- Separate energy calibrations for low and high energy regions
  - Not good: >20% difference for linear slopes at low/high regions

- Energy deposition: non-Gaussian distributions
  - Significant difference between RMS and sigma
- Energy resolution: not exactly follow $1/\sqrt{E(GeV)}$ curve
- Large constant term: >5%

Energy estimator with scintillation and Cherenkov

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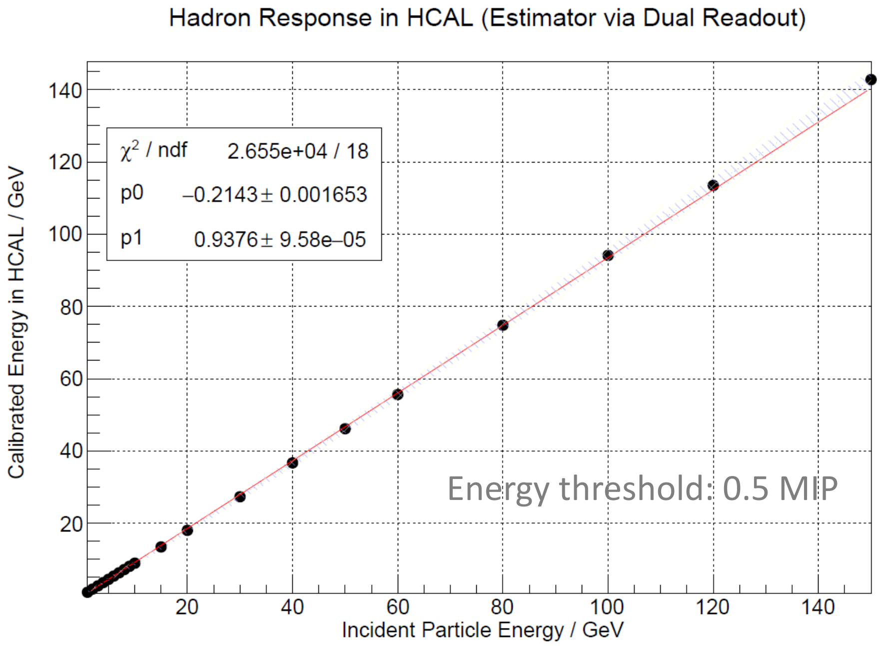
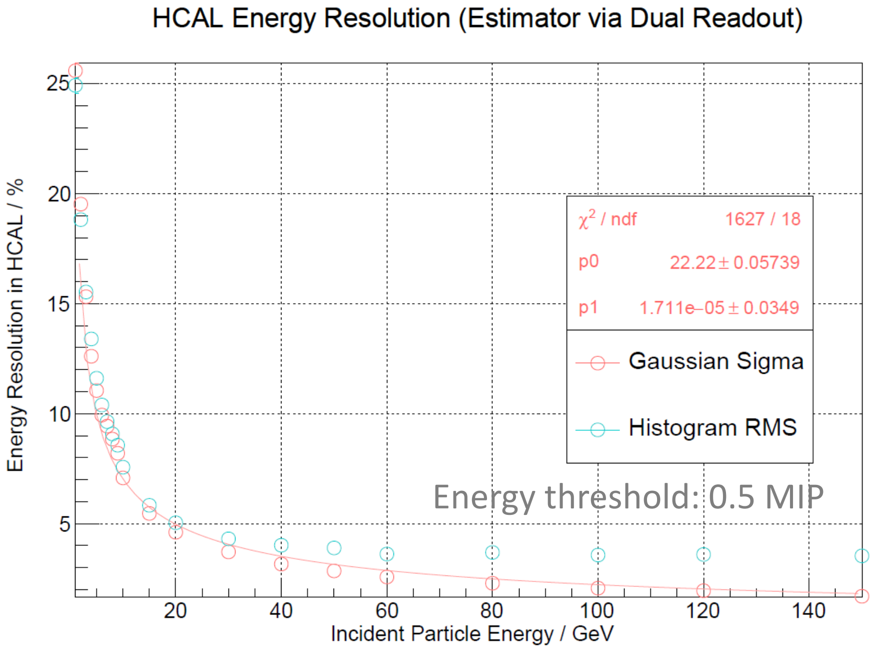
- Use both scintillation + Cherenkov light as energy estimator
  - Significantly improve response linearity and energy resolution





- Good linear response resumed with event-level corrections
- Deviations from the linear curve: to be evaluated

- Energy deposition: close to Gaussian distributions
- Energy resolution: follows $1/\sqrt{E(GeV)}$ curve
- Reasonable constant term

Simulation: further information

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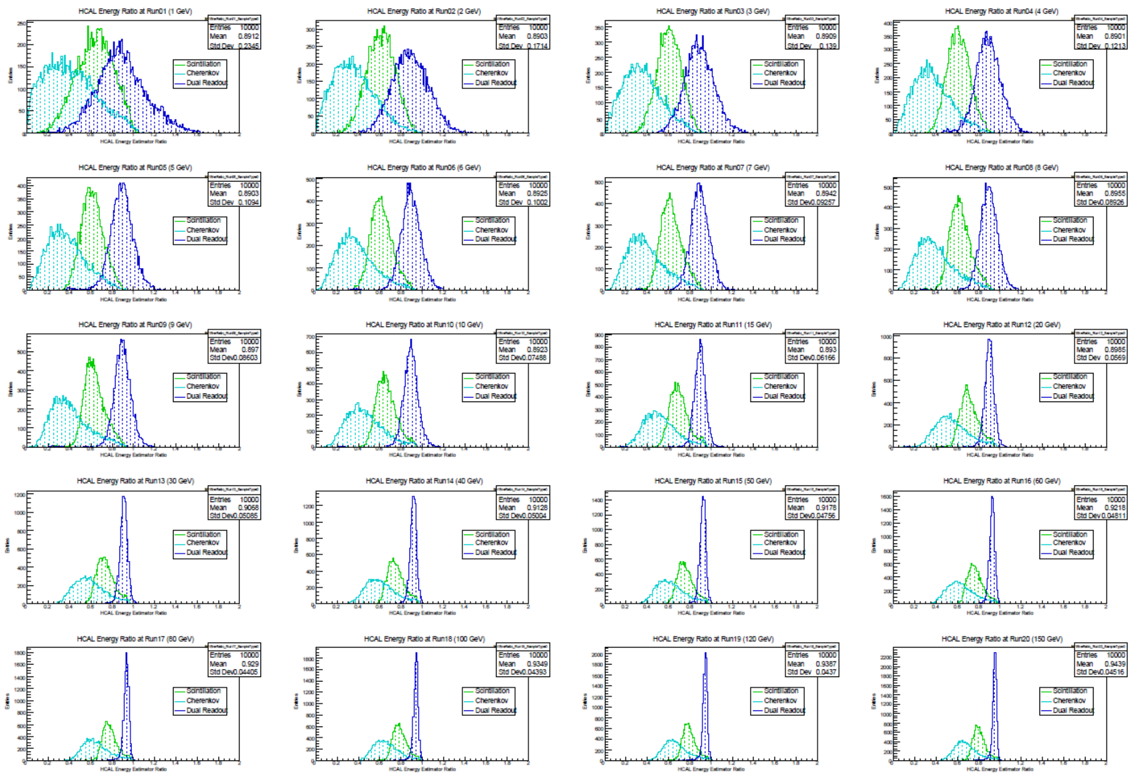
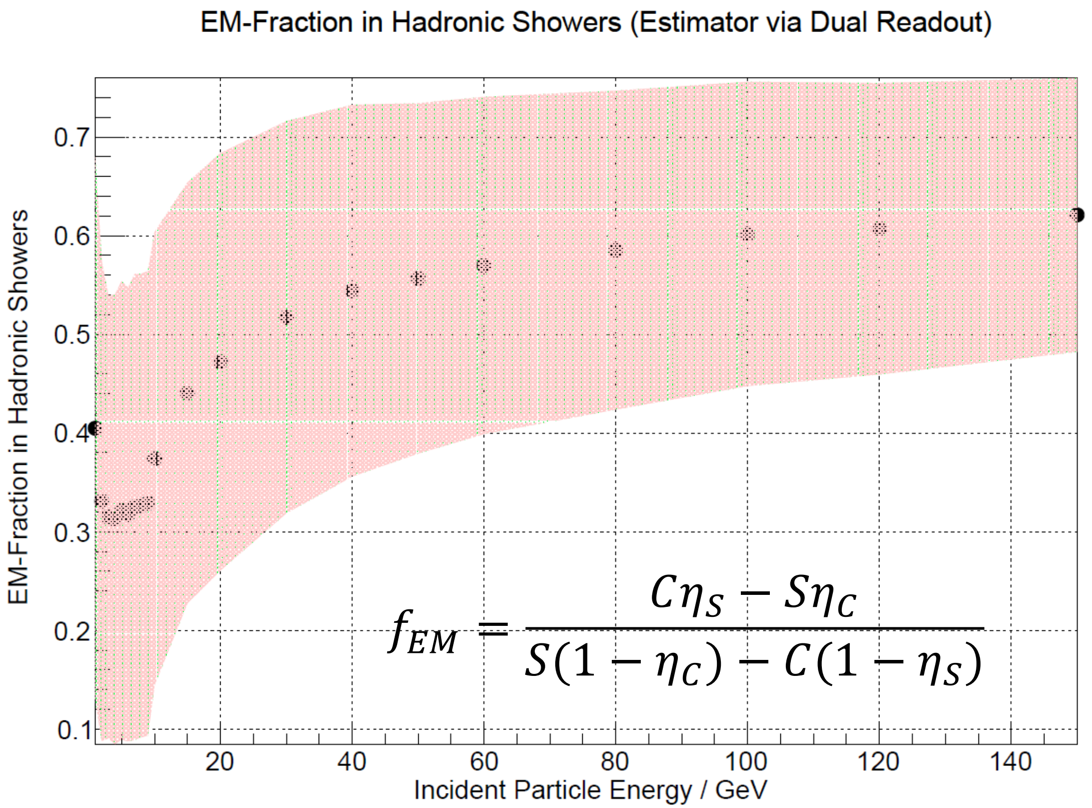
- Comparison of energy estimators
  - Cherenkov, scintillation and combined (S+C)



- Low energy: scintillation as the best energy estimator
- High energy: scintillation + Cherenkov combined the best



$$f_{EM} = \frac{C\eta_S - S\eta_C}{S(1-\eta_C) - C(1-\eta_S)}$$

- EM fraction vs. incident energy: measured by Scintillation/Cherenkov light

Summary for hadronic performance studies

- Hadronic performance studies with Geant4
  - Synergies for new concepts: PFA-oriented crystal and scintillating glass calorimeters
  - Due to intrinsic hadronic shower behaviors: non-Gaussian fluctuations
  - Homogeneous calorimeter alone does not naturally guarantee good hadronic performance
    - In contrast to the EM shower performance
    - Energy sampling fraction is a major aspect to improve hadronic performance, but not the only one
  - Studies on the potentials of “dual readout” technique with homogeneous structure
    - Hadronic energy resolution can achieve good linearity and resolution $(\sim 20\%/\sqrt{E(GeV)})$
  - Lower energy threshold is (always) favored for better performance
    - Plenty of room to keep threshold low, given relatively high light yield per crystal/glass cell
- Discussions and plans
  - Plan to evaluate the “software compensation” potentials for crystal/scintillating glass
  - To establish the link among energy threshold, tile design and properties of crystal and glass

Outline

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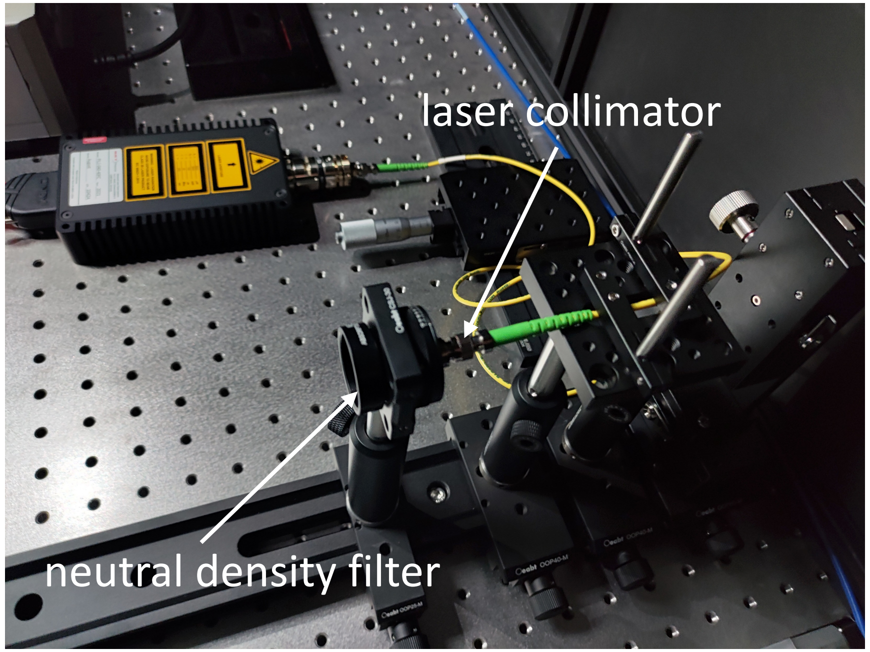
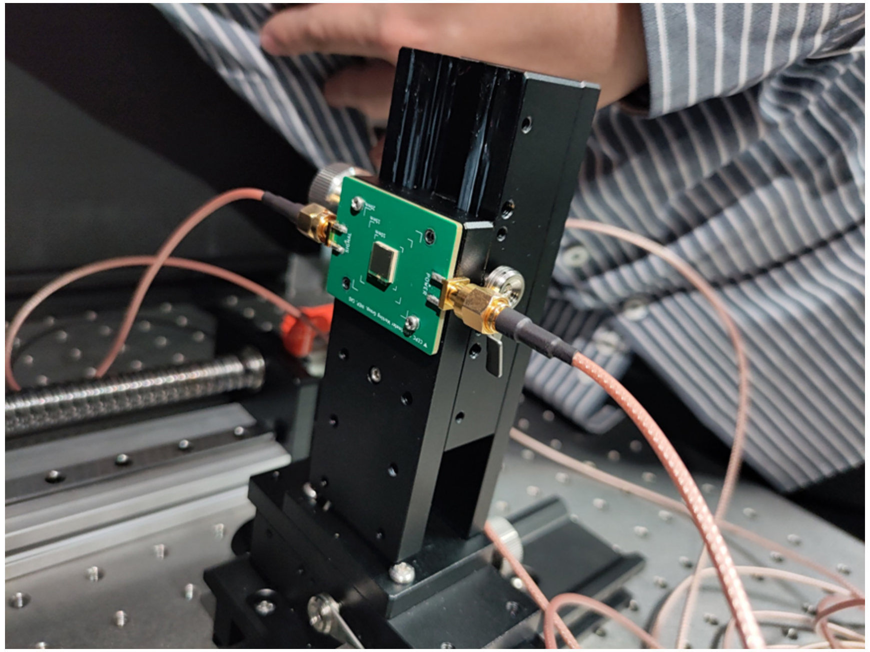
  - Motivation: abundant hadrons in jets → hadronic performance is a key
  - Method: single hadron studies with Geant4 full simulation
  - Key performance: response linearity and energy resolution
- PFA crystal calorimeter: development status
  - With a major focus on the hardware development
  - SiPM characterisation
  - SiPM-crystal unit: performance
  - Small-scale crystal prototype

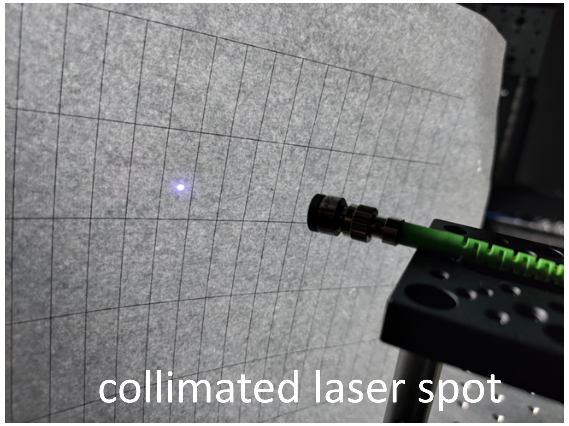
Characterizations of SiPMs with laser

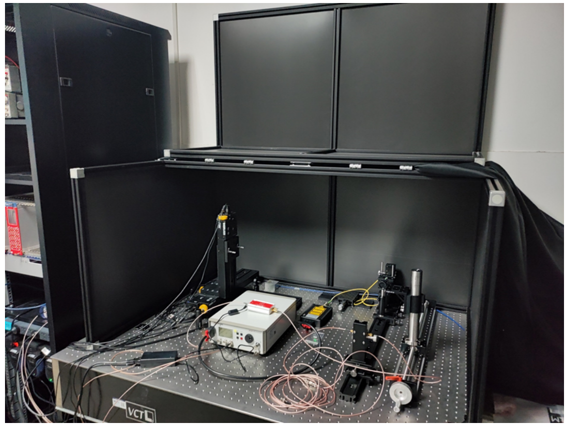
Baohua Qi (IHEP)

- Motivation: SiPM with a large dynamic range
  - SiPMs with large size and high pixel density → the thermal noise is significant
  - Pico-second laser for single photon spectrum
- Laser test stand setup
  - 405nm picosecond laser, collimator
  - Neutral density filter (0.1% transmittance) to reduce laser intensity





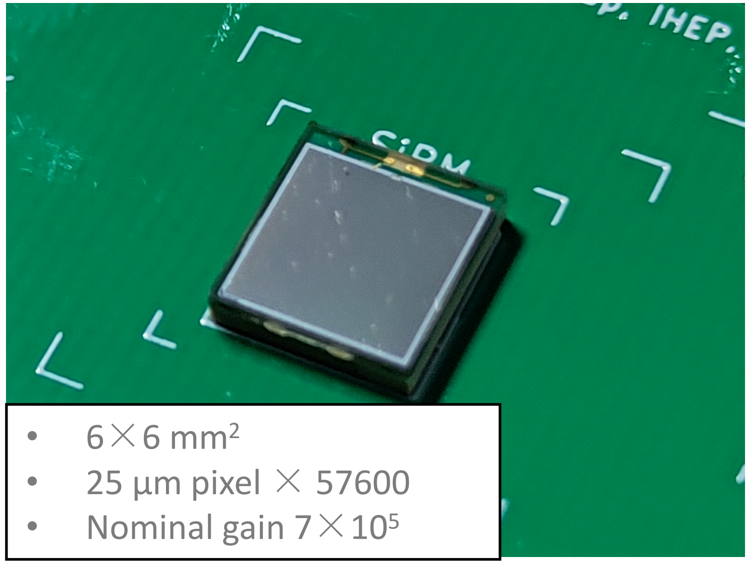




SiPM option: HPK and NDL

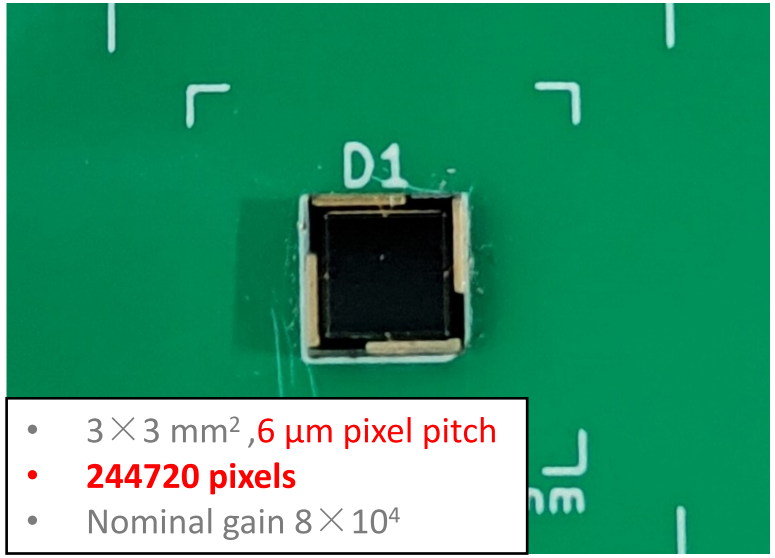
- NDL SiPM: high pixel density (small pixel pitch) is a promising candidate for large dynamic range

HPK S13360-6025PE



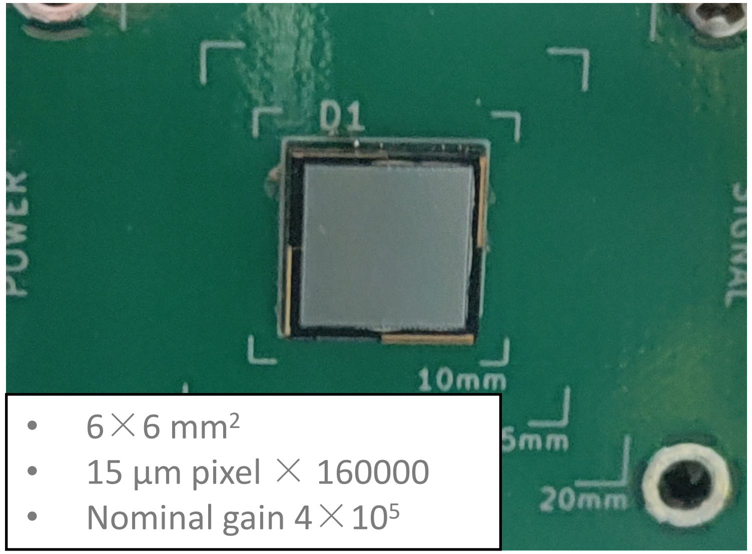
- 6×6 mm^2
- 25 μm pixel × 57600
- Nominal gain 7×10^5

NDL EQR06 11-3030D-S

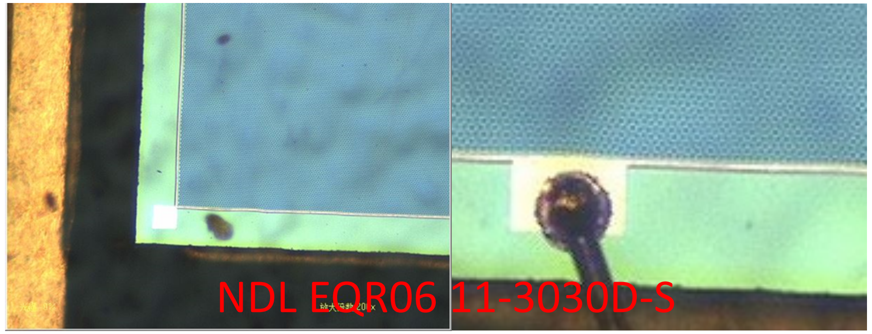


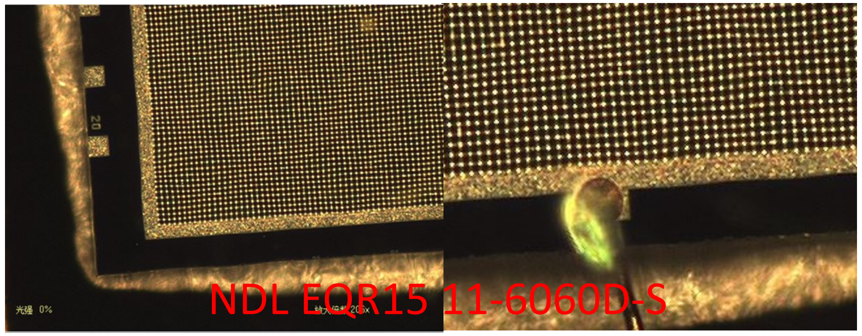
- 3×3 mm^2 ,6 μm pixel pitch
- **244720 pixels**
- Nominal gain 8×10^4

NDL EQR15 11-6060D-S



- 6×6 mm^2
- 15 μm pixel × 160000
- Nominal gain 4×10^5



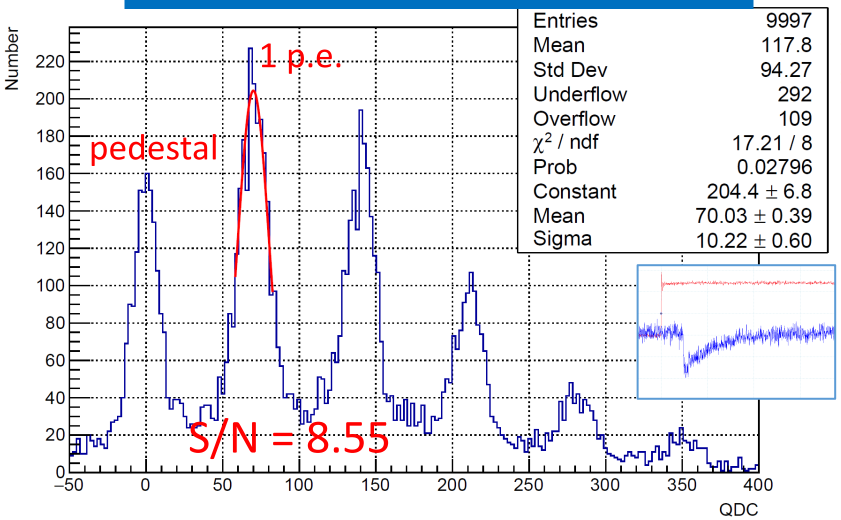


SiPMs: single photon spectrum

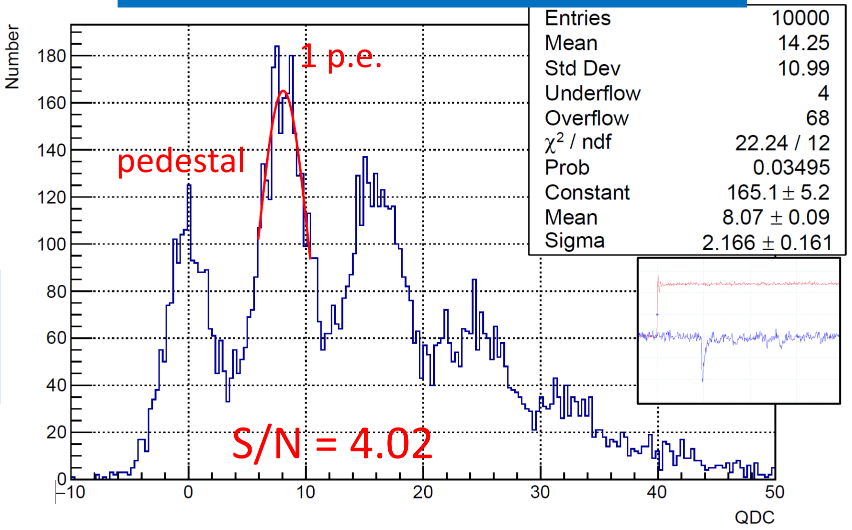
- Single photon spectrum of DUTs

$$S/N = \frac{\mathrm{Mean}_{1p.e.}}{\mathrm{Sigma}_{pedestal}}$$

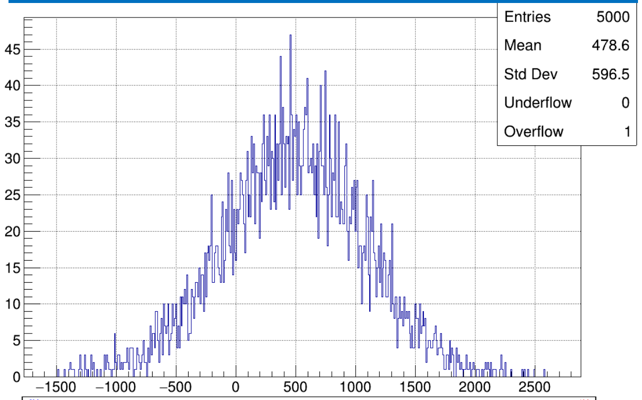
HPK S13360-6025PE

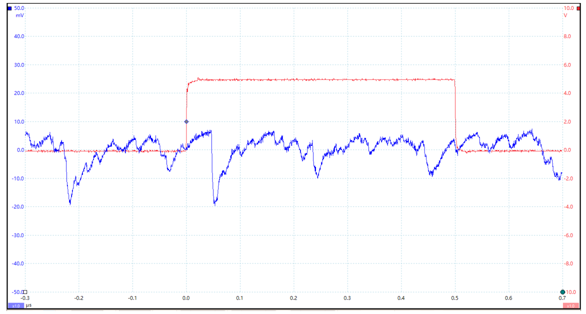


NDL EQR06 11-3030D-S



NDL EQR15 11-6060D-S





- Criteria for SiPMs: pixel size, gain, price, capability of single photon detection…
- NDL EQR06 series with 6 μm pixel and 3×3 mm² active area
  - ×4 more pixels than 25μm HPK one
  - Narrower pulse shape (~10 ns)
  - Half signal to noise ratio

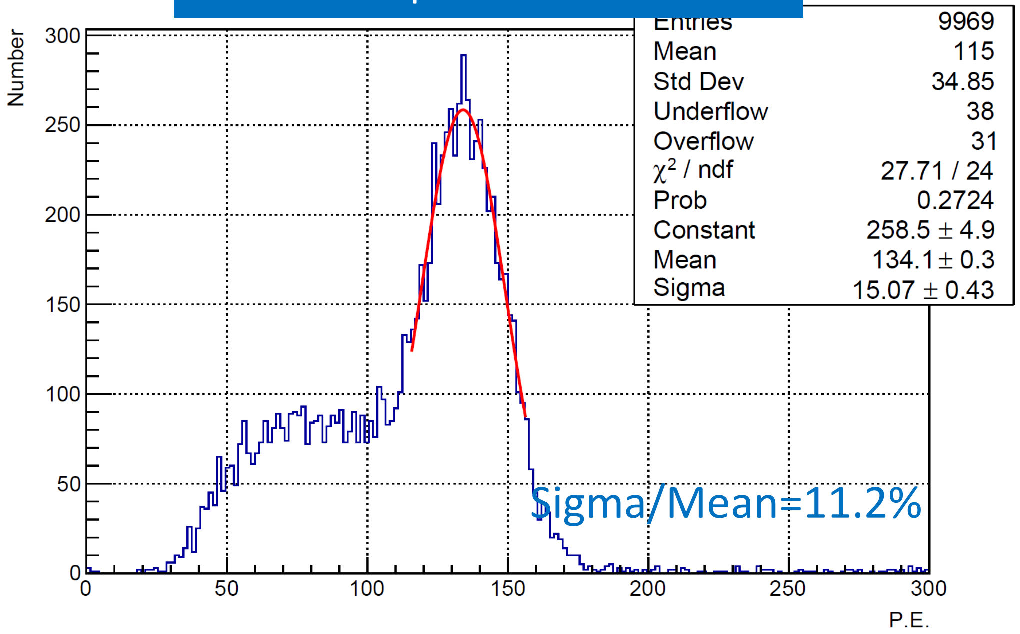
Gain crosscheck:
- $7\times10^5 / 8\times10^4 \approx 70.03 / 8.07$

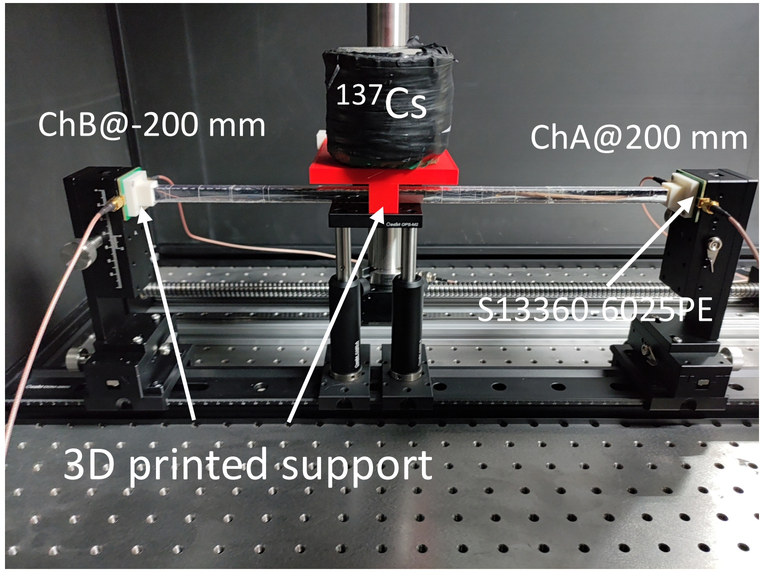
- Too many thermal noise signals
- Unstable baseline
- Single photon calibration failed
- To be discussed with BNU/NDL

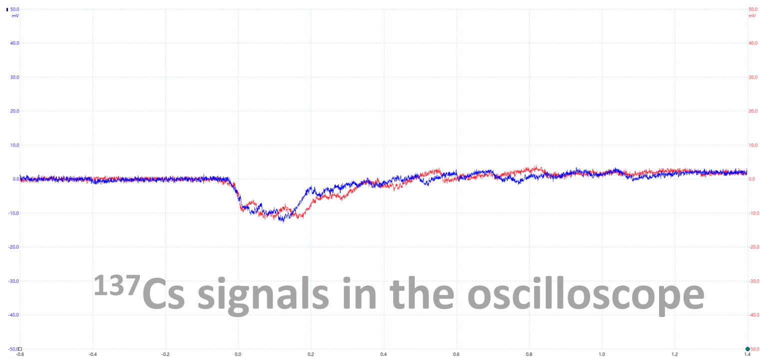
BGO crystal bar: energy resolution

- Experiment setup was upgraded recently
  - 662 keV gamma form ^{137}Cs, 1D moveable stage
  - ~5 mm spread of gamma source
  - $400 \times 10 \times 10$ mm^3 BGO crystal bar, ESR wrapping
  - 3×3 mm^2 SiPMs with 25 μm pixel, air coupling, double-sided readout

Detected photon: ChA + ChB







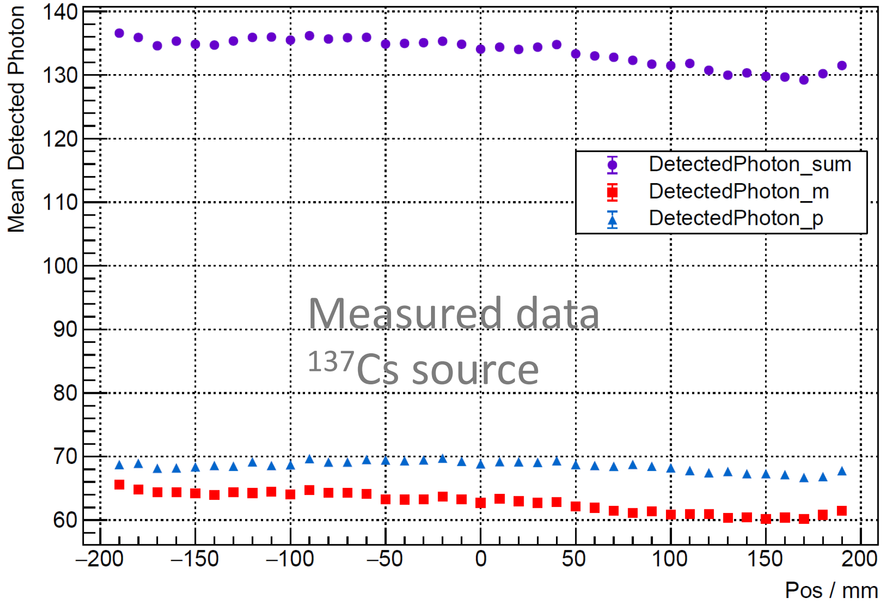
^{137}Cs signals in the oscilloscope

- Energy resolution for 662 keV gamma: ~11.2%

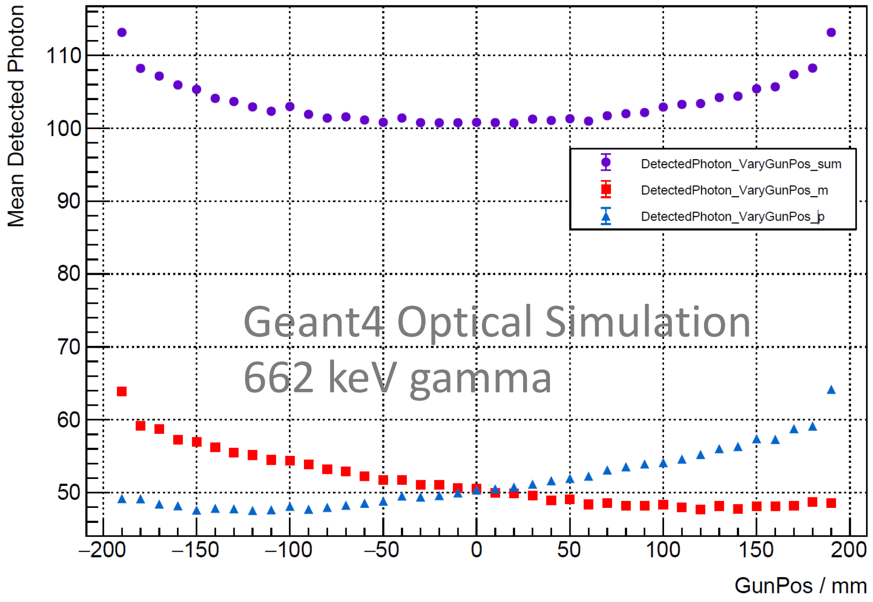
Radioactive source test of BGO crystal: response uniformity

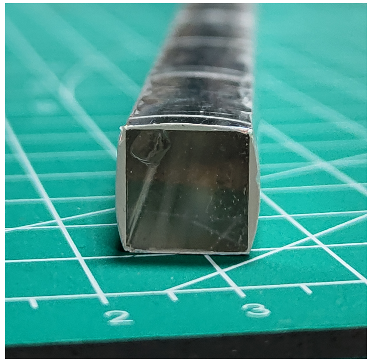
- 1D uniformity fine scan: 662 keV gamma for ^{137}Cs

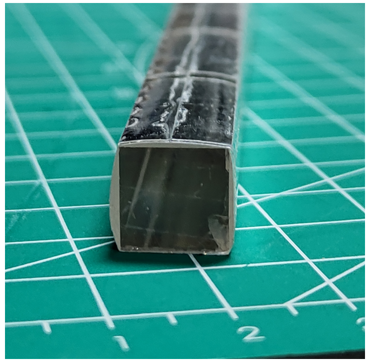
Experiment: detected photon



Simulation: detected photon



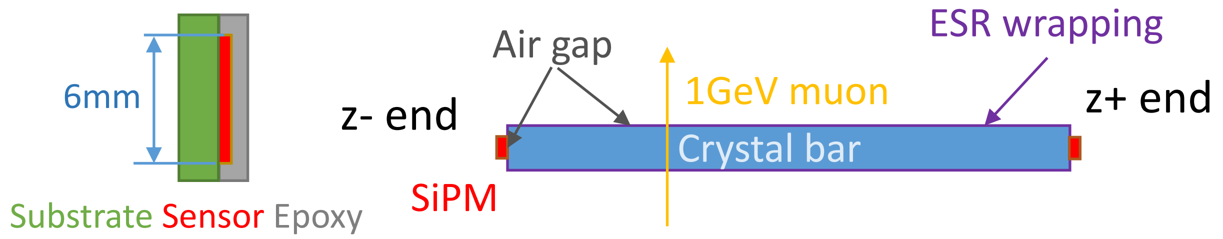




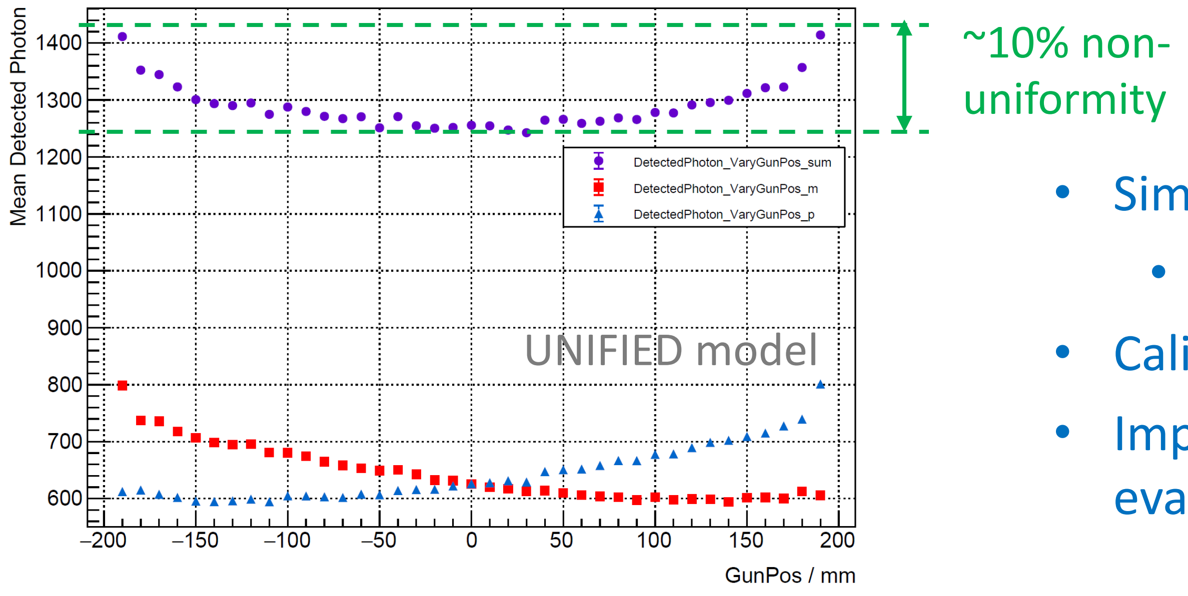
- Some discrepancy observed between measurement and simulation
  - Asymmetric pattern: relatively low response near one side
- Further repeatable measurements
  - SiPM-crystal coupling, radioactive source collimator, crystal side surface…

Simulation of 1D uniformity: reminder

- Geant4 optical simulation
  - A single BGO crystal bar wrapped with ESR reflector
- Physics processes
  - Scintillating & Cherenkov
  - Boundary processes and absorption
  - SiPM modelling: geometry and response (PDE)



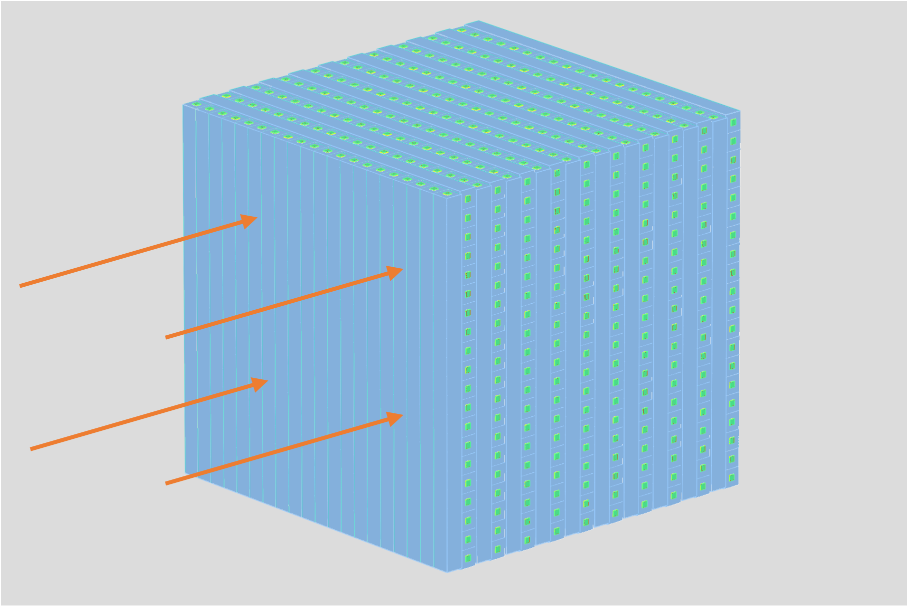
MIP response vs hit position

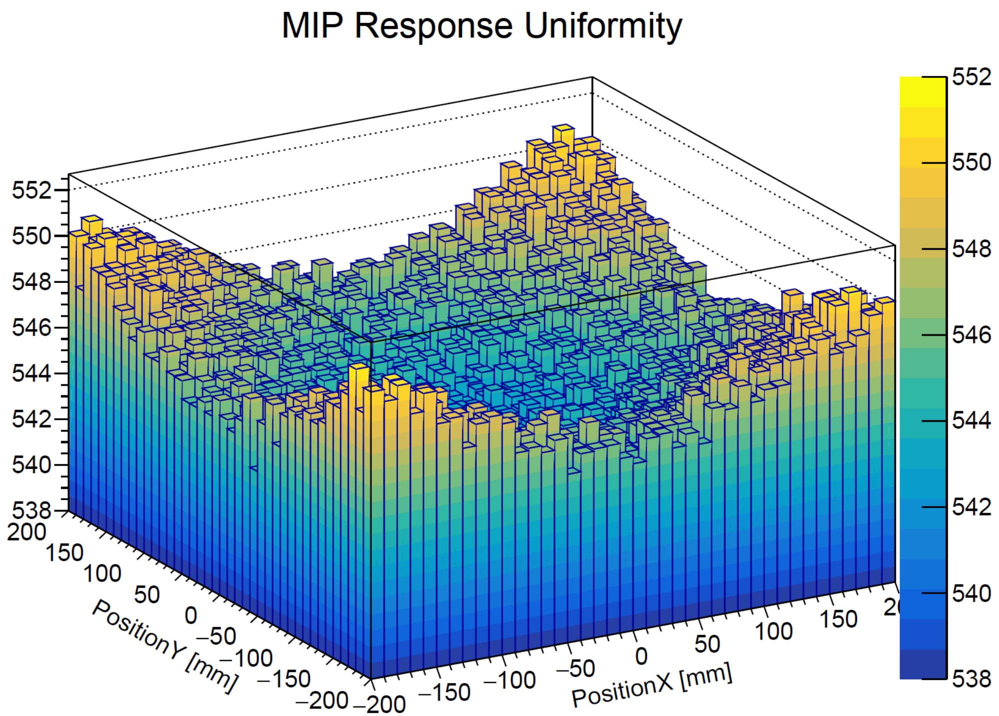


- Simulation predicts ~10% non-uniformity
  - >1000 photons detected per MIP
- Calibration scheme can correct this non-uniformity
- Implement this 1D uniformity curve in the simulation to evaluate the impacts to performance

Response uniformity of crystal ECAL module

- Simulation setup
  - 10×10×400 mm^3 BGO crystal Bar
  - Crossed bar, 40×40×60 module
  - 1 GeV muon, 2D uniformity scan
  - Response has been parameterized (simulated without optical process)

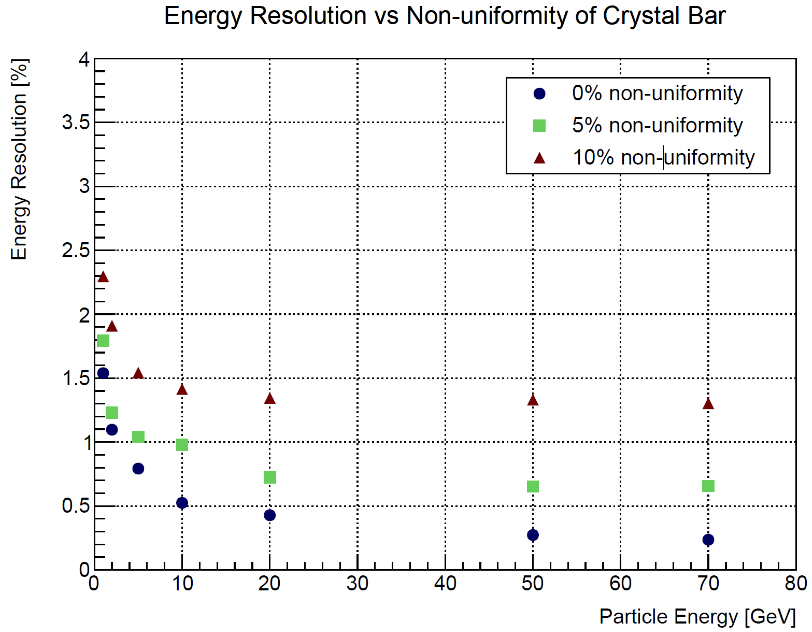


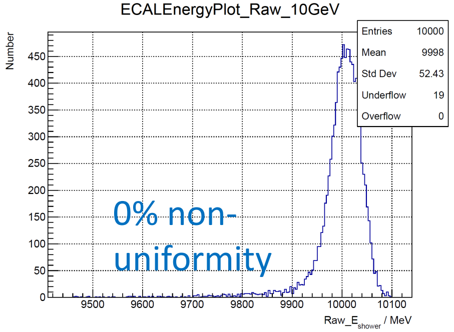


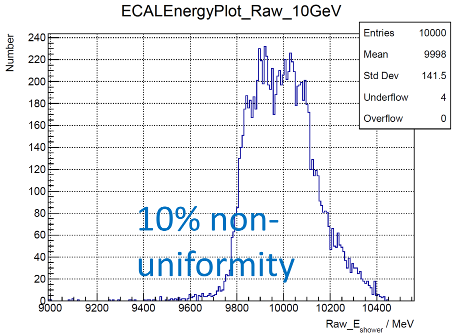
- MIP Response of four corners is higher
- 2D non-uniformity lower than 10%
- Calibration constants depend on hit positions
  - Good reconstruction algorithm is required to get precise position resolution

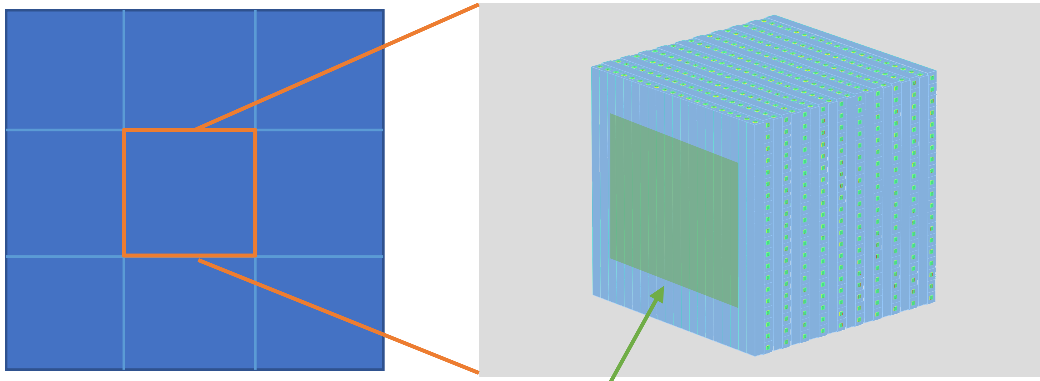
Simulation: impacts of response uniformity

- Impact on energy resolution
  - 1-100 GeV electron
  - 3×3 modules are used to prevent energy leakage
  - Digitization and energy calibration are implemented
  - Energy resolution = Mean/StdDeV





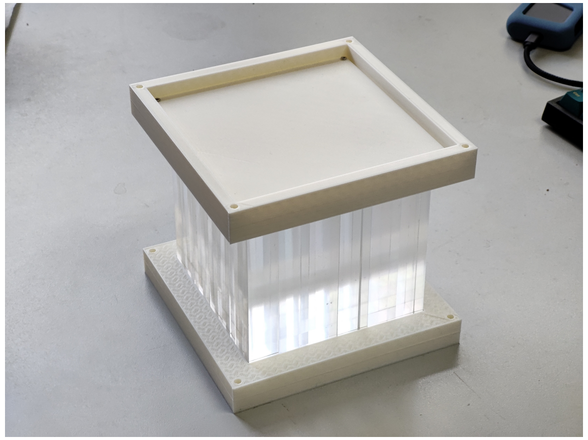




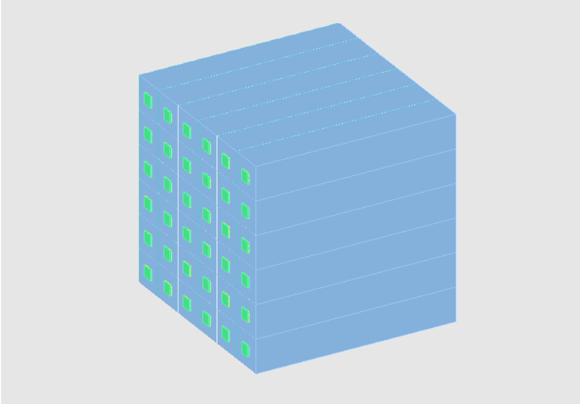
- Non-uniformity at ~10% level → significant energy loss in reconstruction
- Severe distortion of energy resolution
  - Major contribution to constant term
- Response non-uniformity requires calibration
  - Set requirements on calibration precision and good reconstructed positioning precision

Small-scale module design: ongoing efforts

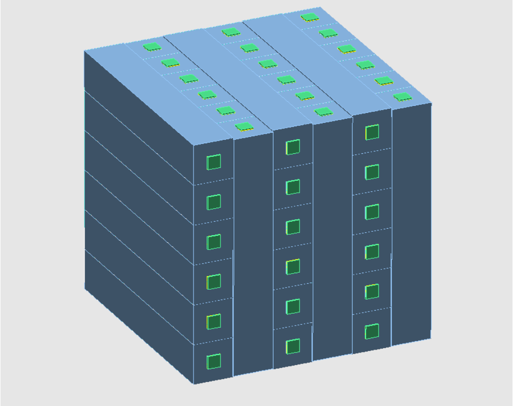
- Motivations: crystal module development
  - EM shower profiles are intrinsically compact
    - e.g. R_M = 2.26 cm for BGO
  - Small-scale modules is sufficient for EM showers
  - Crucial to have beam tests for system-level studies
  - Identify critical questions/issues for the large-scale detector design
  - Evaluate performance with data and to validate simulation
- Module design: crystal module ($12 \times 12 \times 12$ cm^3)
- Ongoing studies for future beam tests



A dummy crystal matrix with 3D printed structure;: quite useful for mechanics design



6×6 crystal matrix

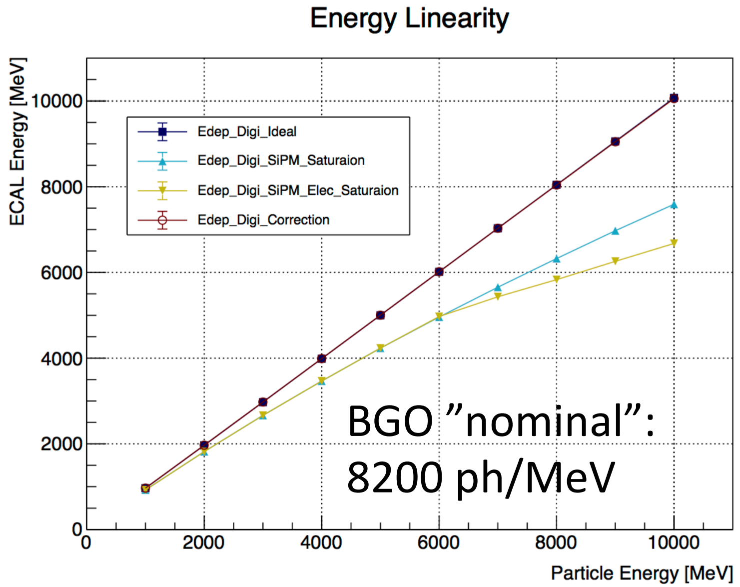


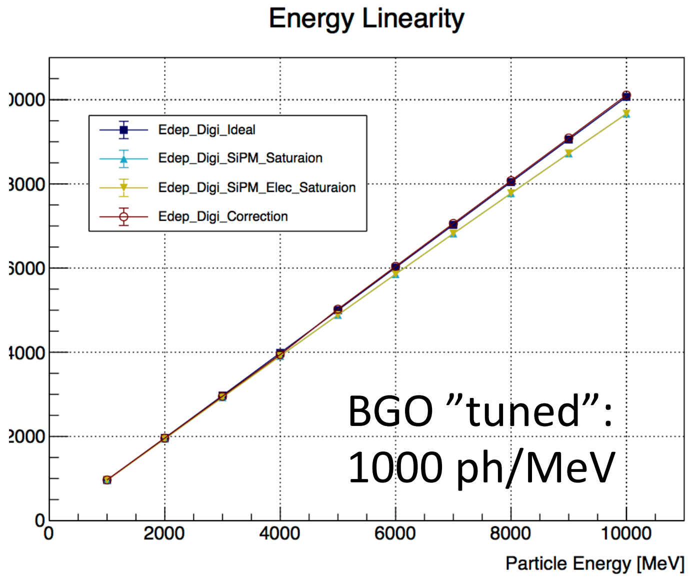
6×6 crossed crystal bar

- Beam test setup: plan to use two modules for sufficient longitudinal depth (21.4 X_0)

Small-scale crystal module: hardware and performance

- Energy region in the simulation: 1-10 GeV
  - DESY: 1-6 GeV electrons; CERN PS: 1-15 GeV electrons
  - For higher energy region >10 GeV: combined tests with an HCAL prototype
- A critical issue: a large dynamic range for crystal+SiPM unit
  - BGO light yield is one key parameter
  - Had meetings with SIC-CAS: possible to “tune” BGO light yield; plan for further R&D





Geant4 full simulation:
“Tuning” BGO light yield would largely improve the EM response linearity

Summary for PFA crystal ECAL development

- Detector design and performance
  - SiPM characterization: laser calibration
  - ^{137}Cs tests on long crystal bar: energy resolution & response uniformity
  - Simulation studies: single bar → crystal module
  - Small-scale detector module design efforts

- Prospects for other topics: ongoing efforts
  - Optimizing ArborPFA for crystal calorimeter
  - Reconstruction software dedicated to long crystal bars
  - Addressing key issues on the crystal module design

Current and future conferences

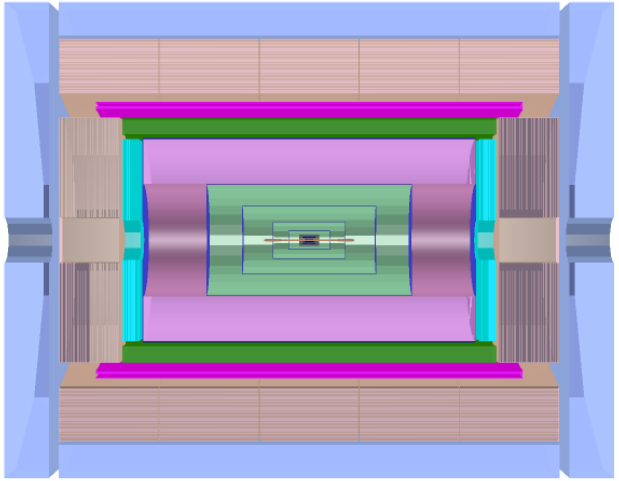
- Contributions on crystal ECAL + scintillating glass HCAL
- CALICE collaboration meeting in Valencia in April 20-22
  - Well presented and had fruitful discussions
  - Along with talks on ScECAL + AHCAL prototypes
- CALOR2022 in Sussex in May 16-20
  - Abstract approvals received
  - Along with other abstracts on ScECAL + AHCAL prototypes
- ICHEP2022 in Bologna in July 6-13
  - Two abstracts submitted

Thank you!

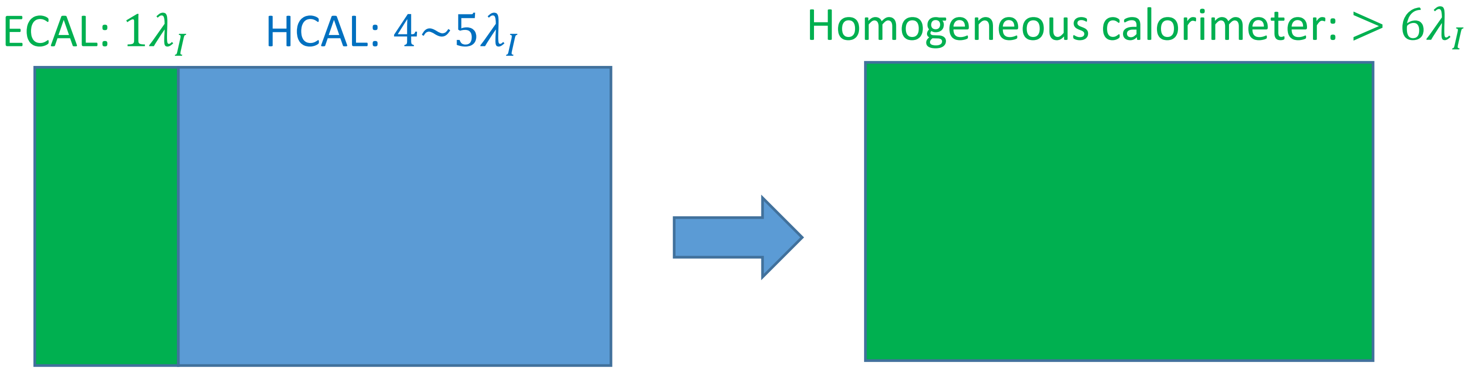
Backup

A few more words on methodology

- Crucial: hadrons in scintillator-based calorimeters
  - Within the CEPC 4th concept detector: crystal ECAL + scintillating glass HCAL
- In this simulation study
  - Focus on intrinsic performance
  - Not consider shower leakage effects at this stage
    - Reality: longitudinal (limited depth), transverse (e.g. crystal gaps, dead materials)



Calorimeters: crystal ECAL and Scintillating Glass HCAL



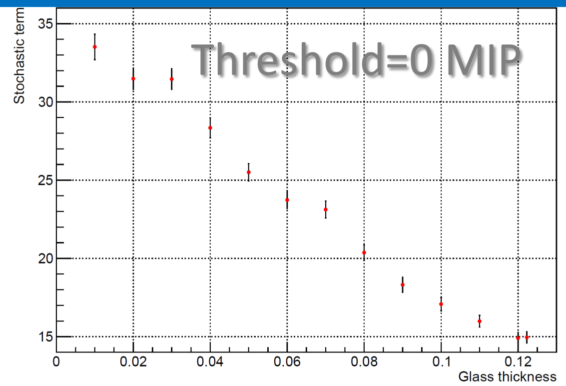
Extend crystal ECAL to contain hadronic showers;
Leakage effects can be studied in a later stage

Hadronic energy resolution: reminder

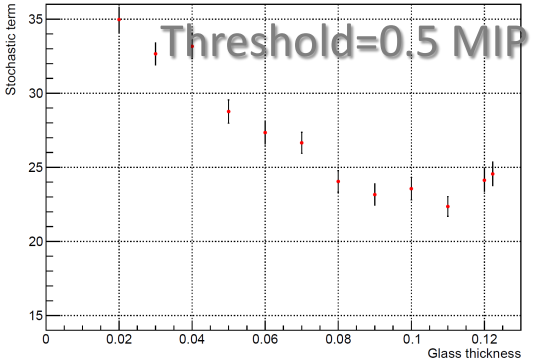
Plots by Dejing Du (IHEP)

- Scenarios: varying thickness of scintillating glass tiles and steel plates
  - Extraction of stochastic and constant terms
  - Sampling calorimeter → Homogeneous calorimeter (rightmost points)

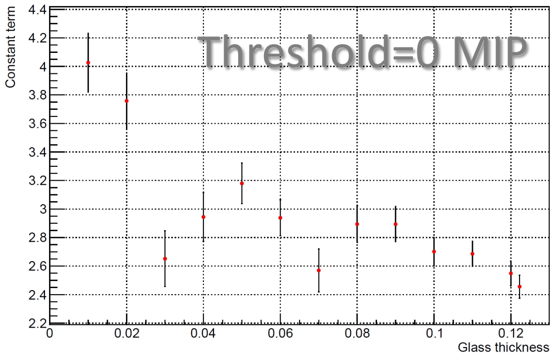
Stochastic term vs. glass thickness (λ_I)



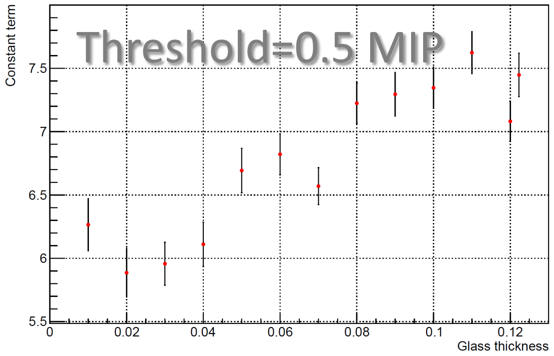
Stochastic term vs. glass thickness (λ_I)



Constant term vs. glass thickness (λ_I)



Constant term vs. glass thickness (λ_I)



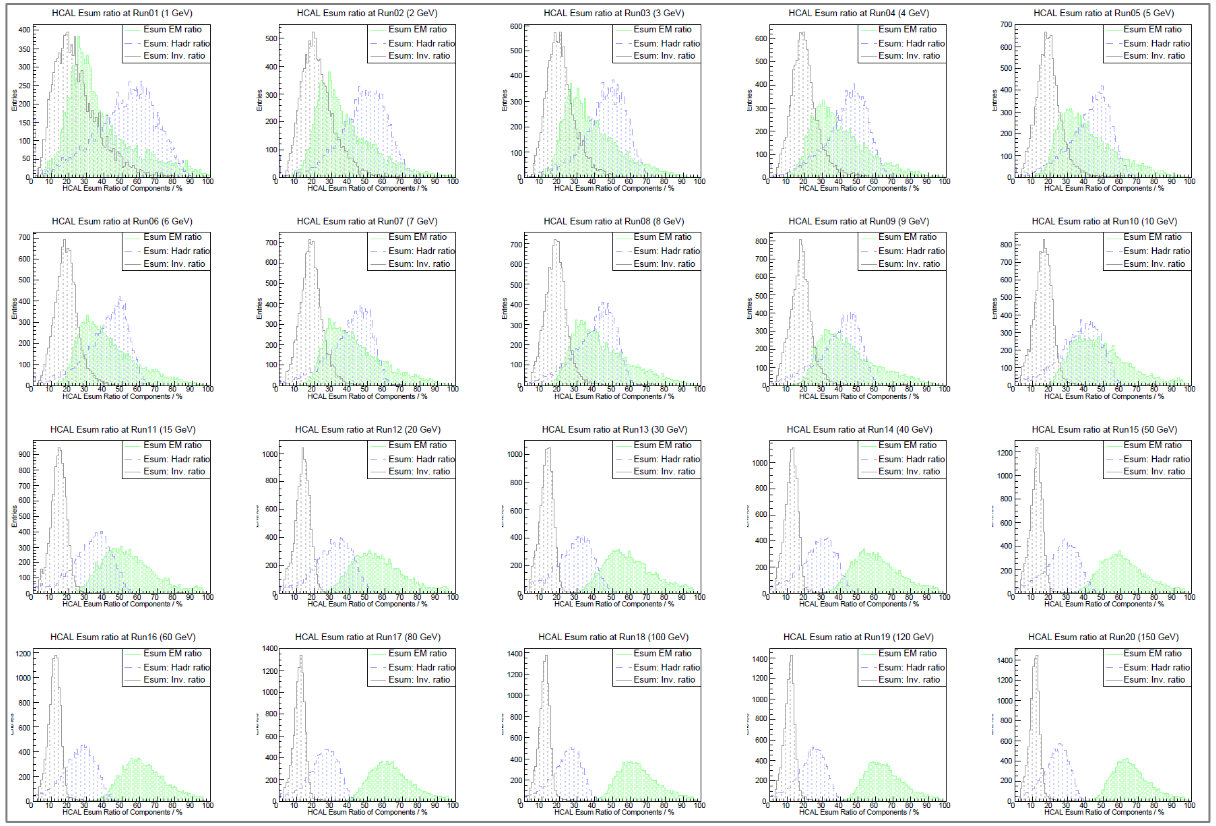
- Energy threshold has a significant impact on the energy resolution
- With the 0.5 MIP threshold, resolution will not be improved when glass thicker than $\sim 0.08\lambda_I$
- Higher threshold also significantly degrades the constant term
- Lower threshold would always be desirable for better resolution

MC samples with K_L^0

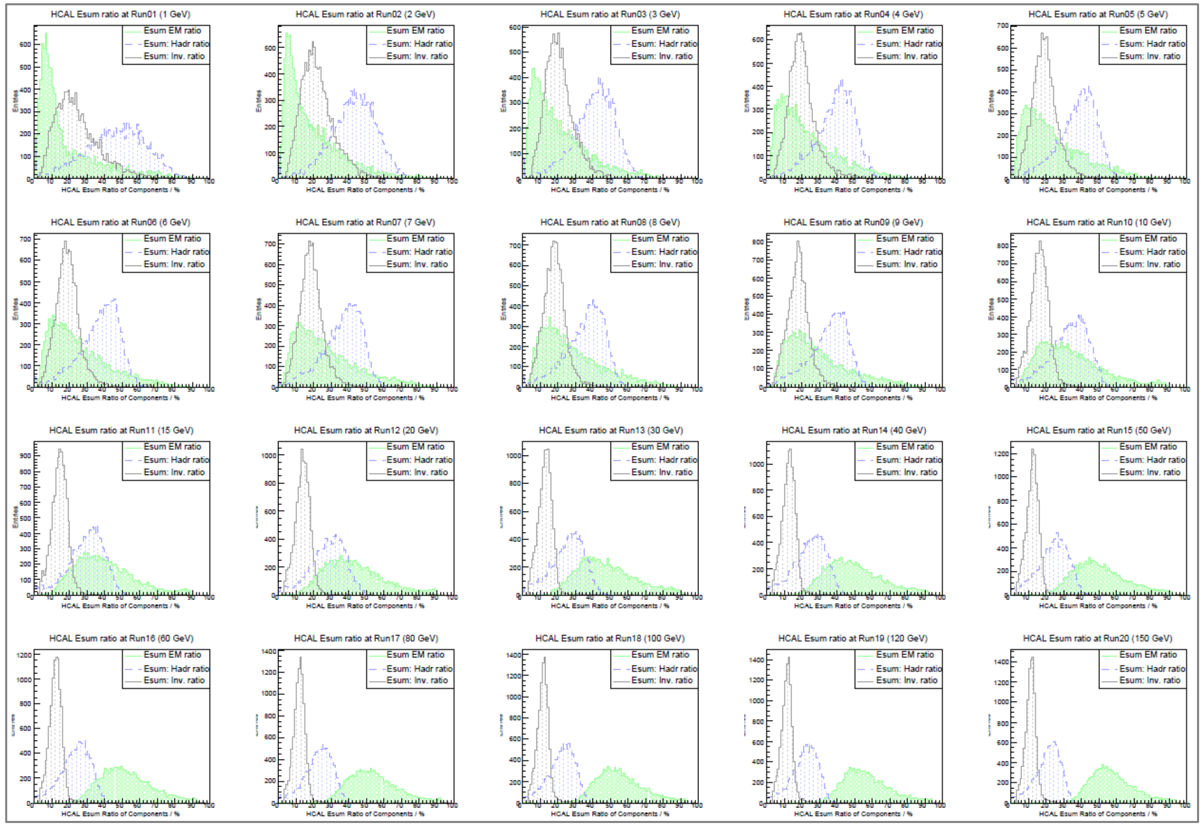
Homogeneous calorimeter: energy depositions with π^-

- Categorize energy depositions: EM, hadronic, invisible

Energy threshold: 0

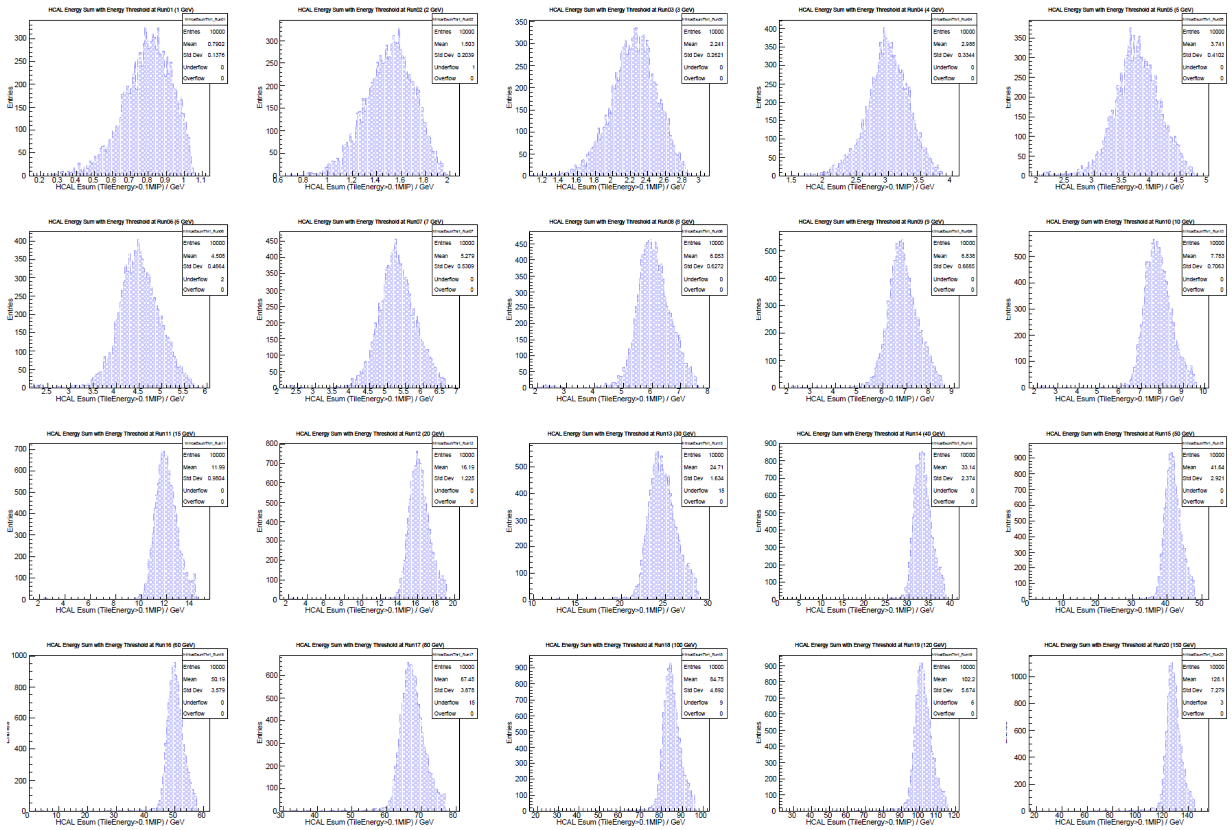


Energy threshold: 0.5 MIP



Scintillating Glass HCAL: energy depositions with π^-

Energy sum



e/h ratio: event level