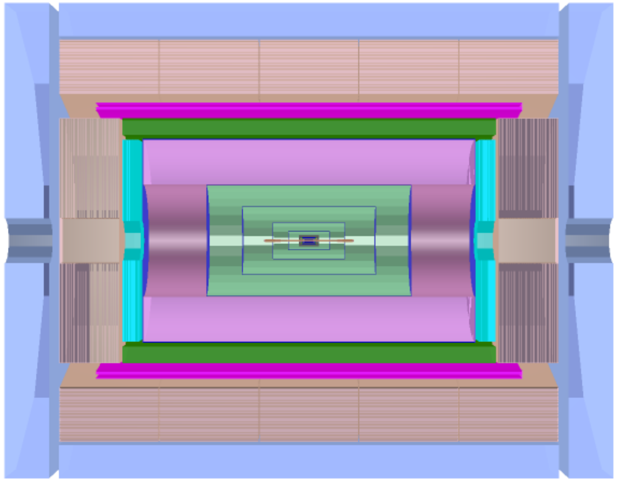
Hadronic performance with a homogeneous calorimeter

Yong Liu (IHEP)

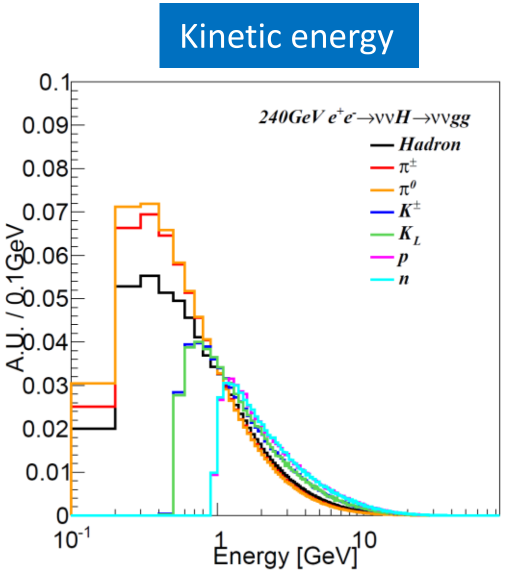
Apr. 20, 2022

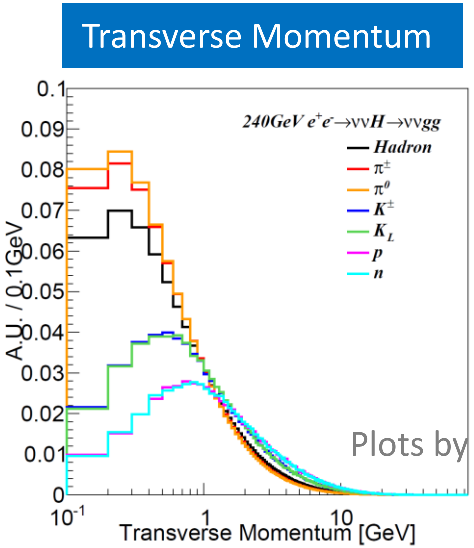
Motivations

- 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: **esp. the hadronic resolution**



Calorimeters: crystal ECAL and Scintillating Glass HCAL





Plots by Yuexin Wang (IHEP)

Motivations

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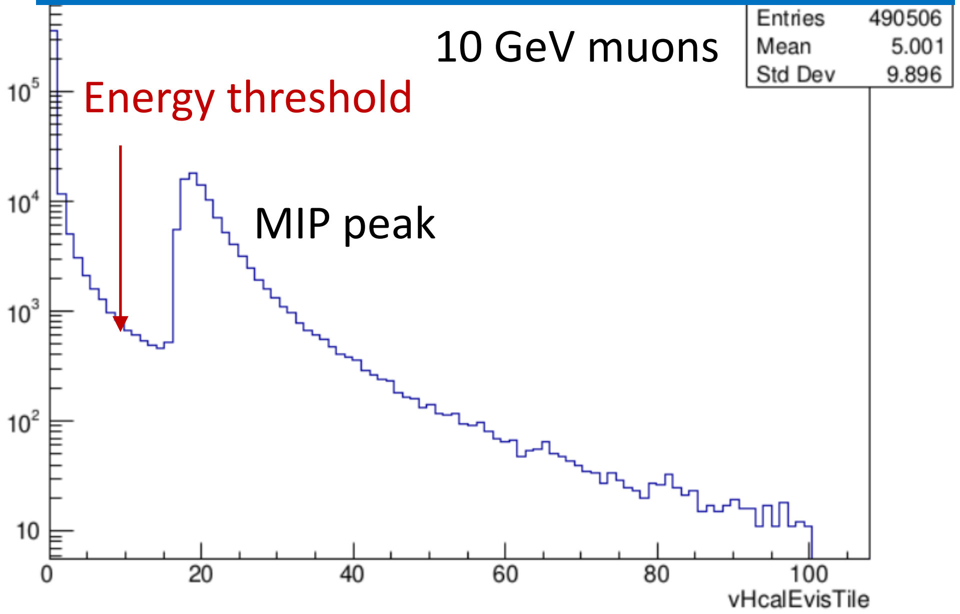
  - Hadronic decays of Higgs/Z/W bosons: abundant hadrons (<10 GeV) within jets
- Crucial: hadrons in scintillator-based calorimeters
  - Within the CEPC 4^{th} concept detector: crystal ECAL + scintillating glass HCAL
    - A leap in terms of sampling fractions
    - Aim to improve the energy resolution: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

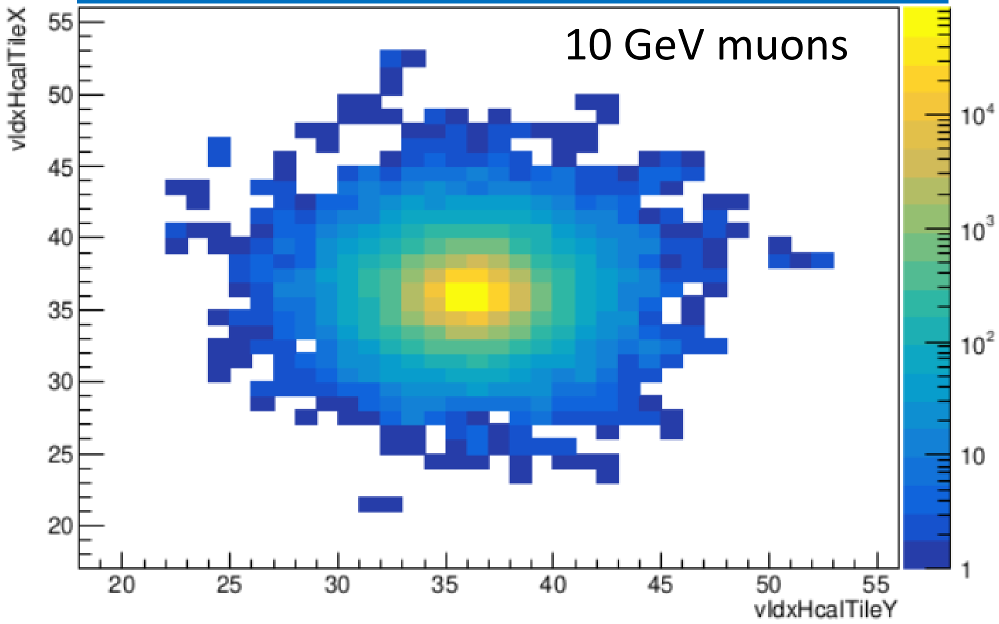
MIP calibration with muons

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

Energy deposition (in MeV) per tile (all tiles)



Hit Map in the transverse plane (all layers)



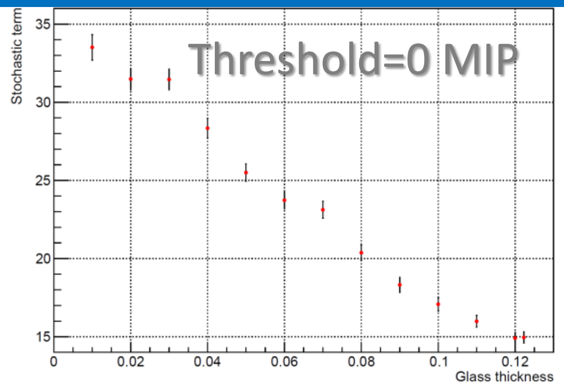
- Energy threshold: finally to be determined by several factors
  - FE electronics (pedestals, occupancy), SiPM noises, beam-related backgrounds, etc.
- CALICE prototypes: 0.3 – 0.5 MIP thresholds (depending on technical options)

Hadronic energy resolution: reminder

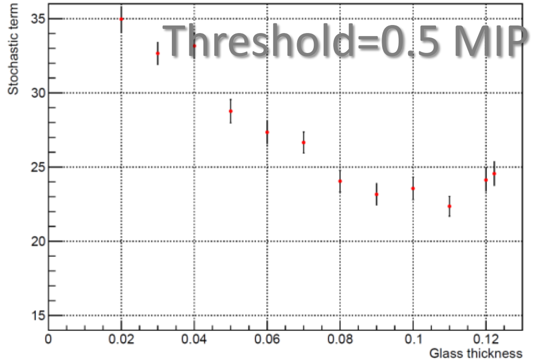
Plots by Dejing Du (IHEP)

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

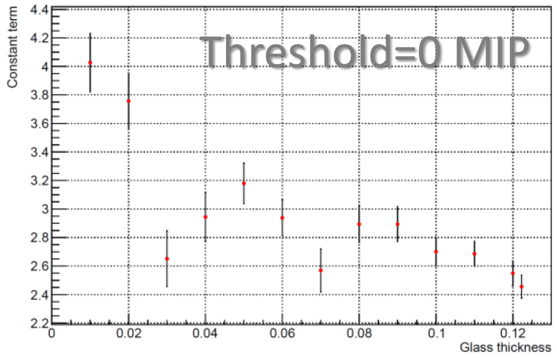
Stochastic term vs. glass thickness (λ_I)



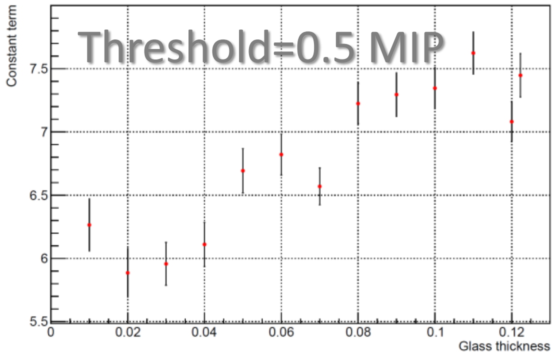
Stochastic term vs. glass thickness (λ_I)



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: hadronic responses

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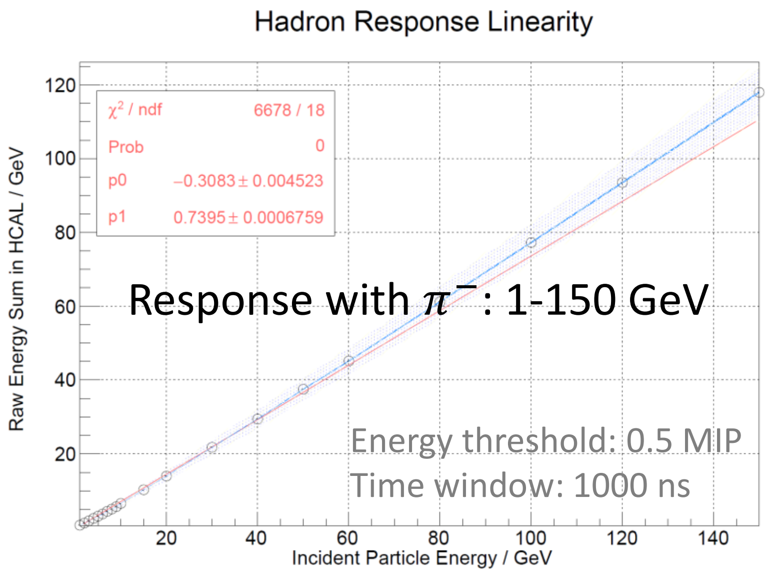
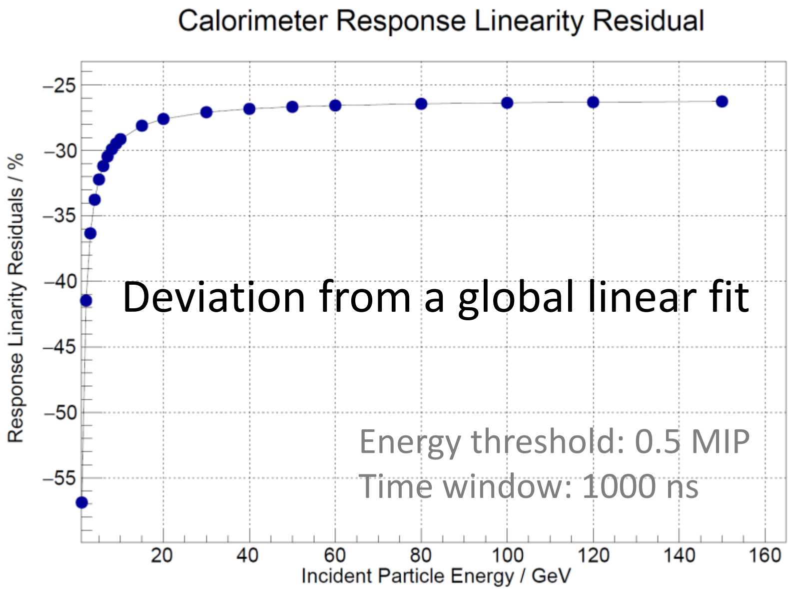
- Starting from this page: **homogeneous calorimeter** with scintillating glass tiles
  - 23 mm thick tiles; large and deep layers for minimum leakage
  - Synergies between crystal ECAL and scintillating glass HCAL





- 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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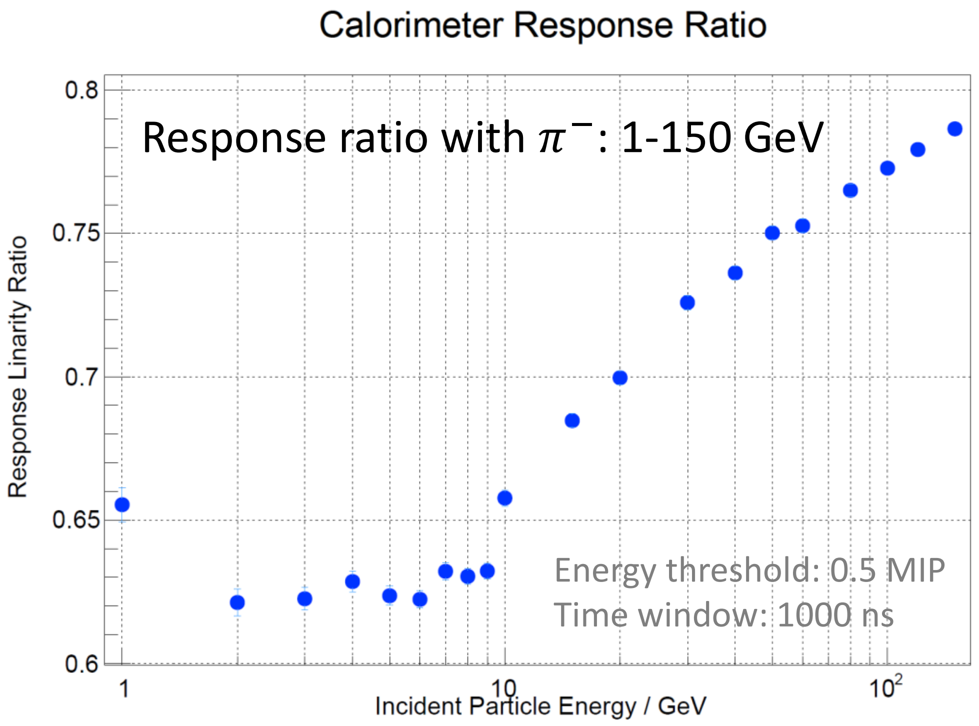
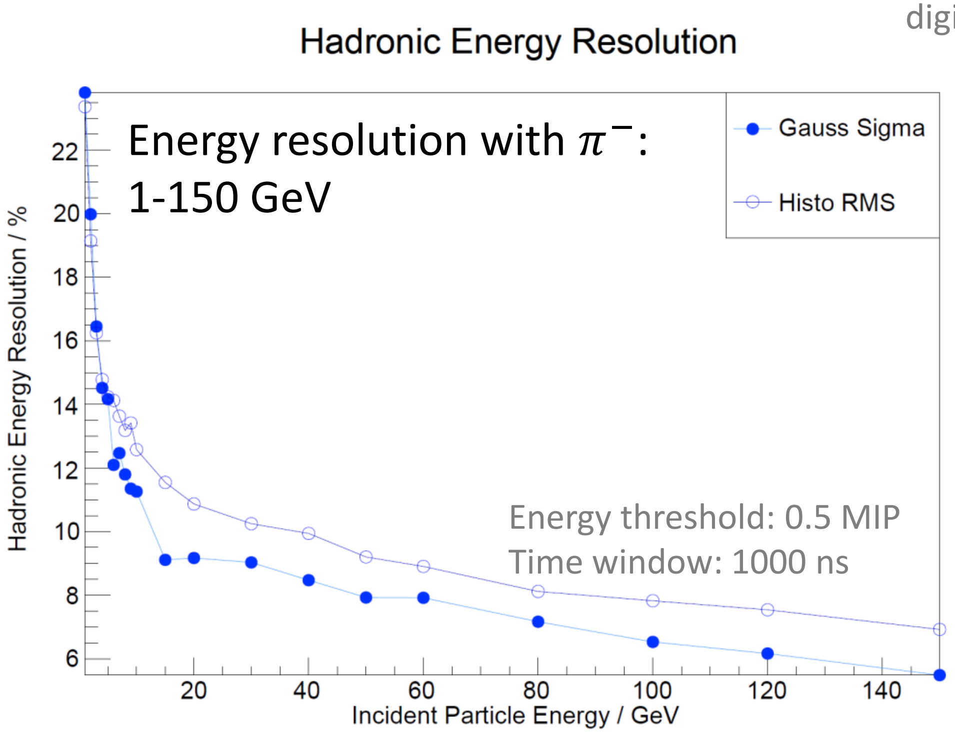
- Hadronic response ratio and energy resolution

Energy deposition only: digitisation not included





- Significantly lower response in 1-10 GeV region
- Note: scintillator quenching effects (Birks law) not yet included in the plots (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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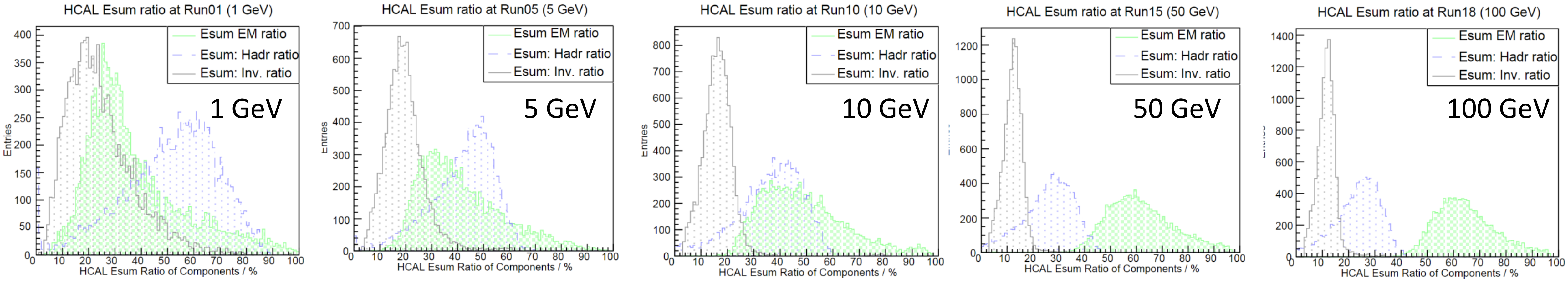
- Categorize energy depositions of hadronic showers
  - Components within hadronic showers: EM, hadronic, invisible
    - EM component primarily from π^0's produced in the hadronic cascade
    - EM energy deposition usually detected with higher efficiency

Component Energy Ratio

MC samples with π^-



- EM component fraction: incident energy dependent
- EM/hadronic energy depositions: non-Gaussian fluctuations

Homogeneous calorimeter: hadronic showers

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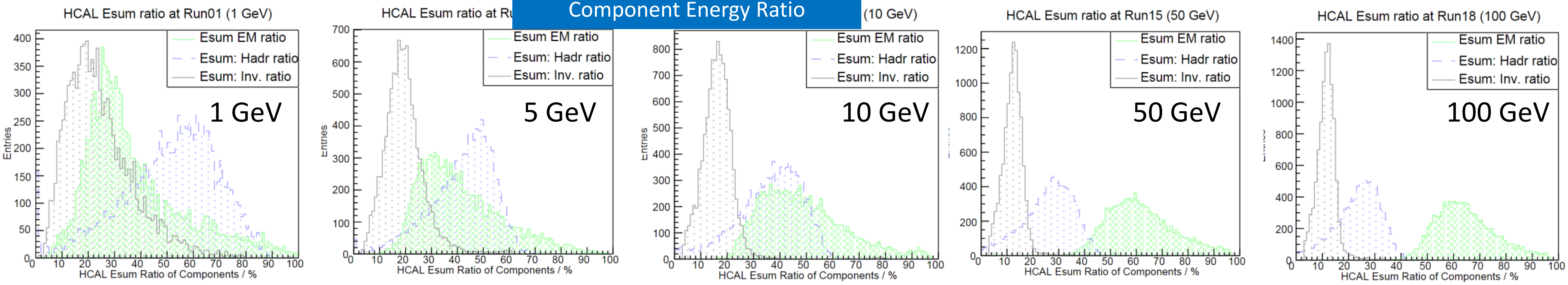
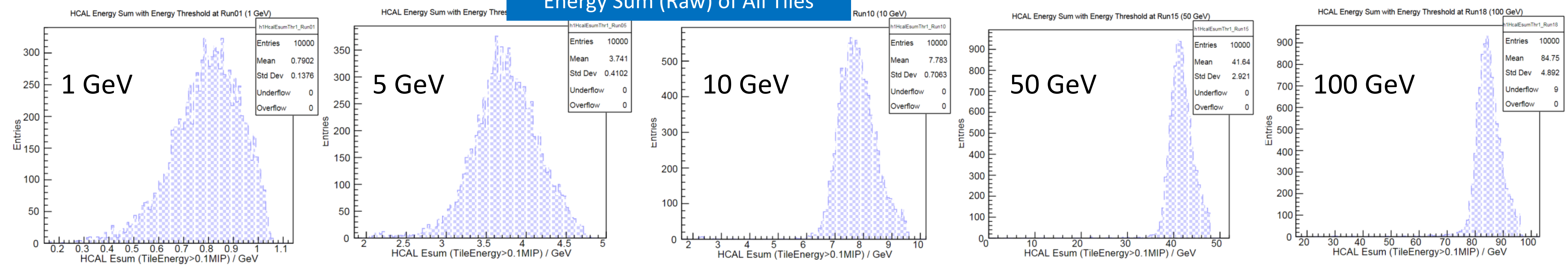
- Categorize energy depositions of hadronic showers
  - Total energy deposition: distribution

MC samples with π^-

Component Energy Ratio



Energy Sum (Raw) of All Tiles



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

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- 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

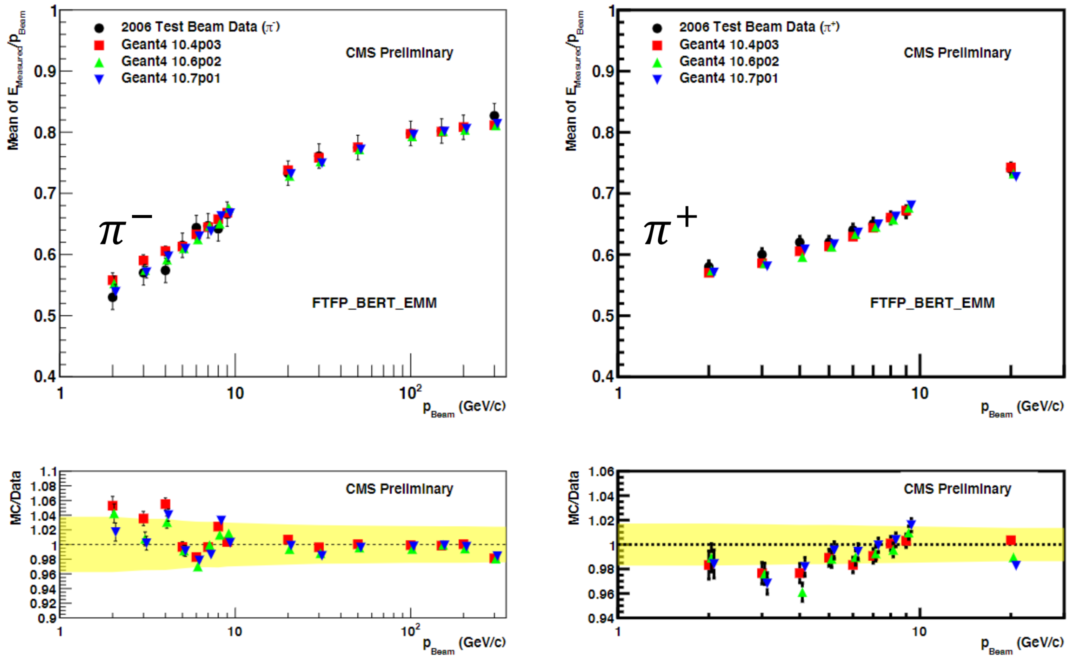
Validation studies: CMS calorimeters

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

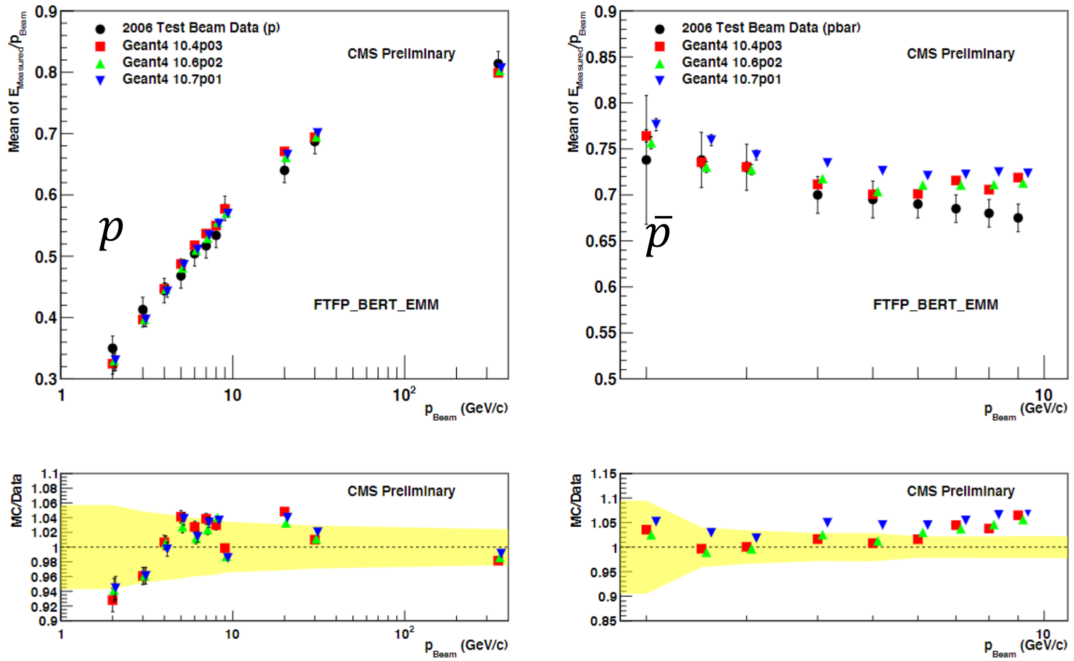
Sunanda Banerjee and Vladimir Ivanchenko, Validation of Physics Models of Geant4 Versions 10.4.p03, 10.6.p02 and 10.7.p01 using Data from the CMS Experiment

CMS combined EB+HB: selected results

Energy response (average) of charged pions



Energy response (average) of protons/anti-protons

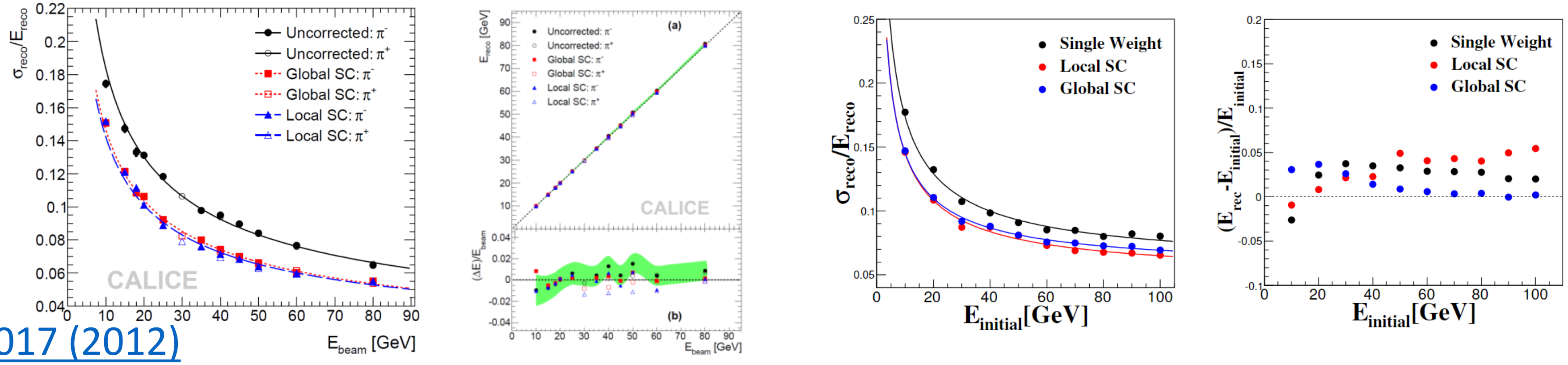


- Geant4 simulation can well reproduce hadronic responses
  - Impressive consistency: MC/data discrepancy within a few percent
  - Note: only “simple” digitization for EB+HB (Gaussian smearing for hit energy)

→ 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: energy deposition density, timing (new progress)
  - Established for AHCAL option and validated with prototype beamtest data
  - We can further try to explore potentials for crystal/scintillating glass options



JINST 7 P09017 (2012)

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

Hadronic energy resolution

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  - Established for AHCAL option and validated with prototype beamtest data
  - We can 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
  - Some detailed potential studies in the next pages

Dual readout technique: reminder

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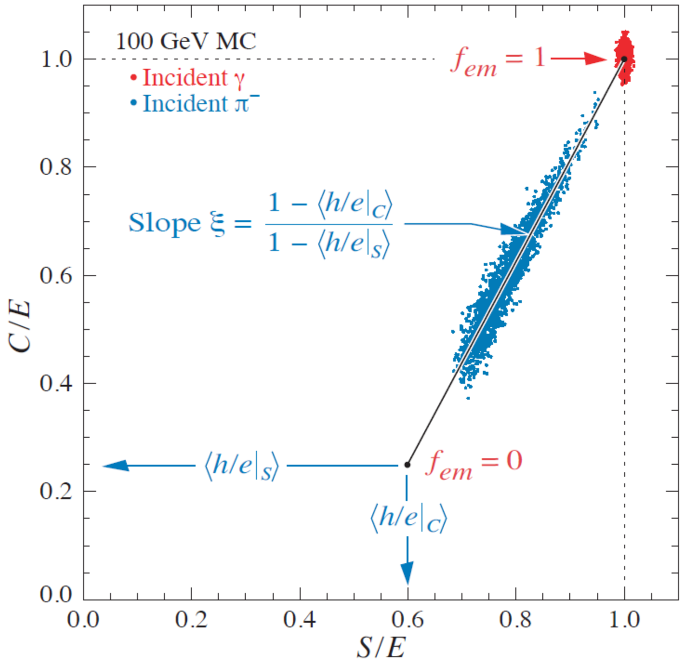
- Energy estimators: scintillation and Chereknov light
  - **Crystal/scintillating glass: possible to produce and detect scintillation photons (S) and Cherenkov photons (C) at the same time**
  - Implemented in the Geant4 full simulation for homogeneous calorimetry



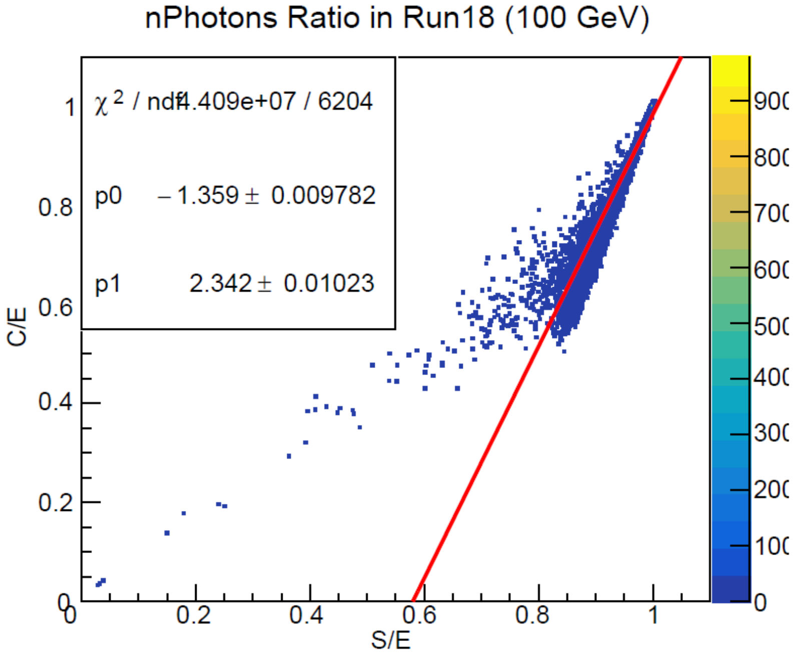
Reference: D. E. Groom, HCAL in PDG (2020)

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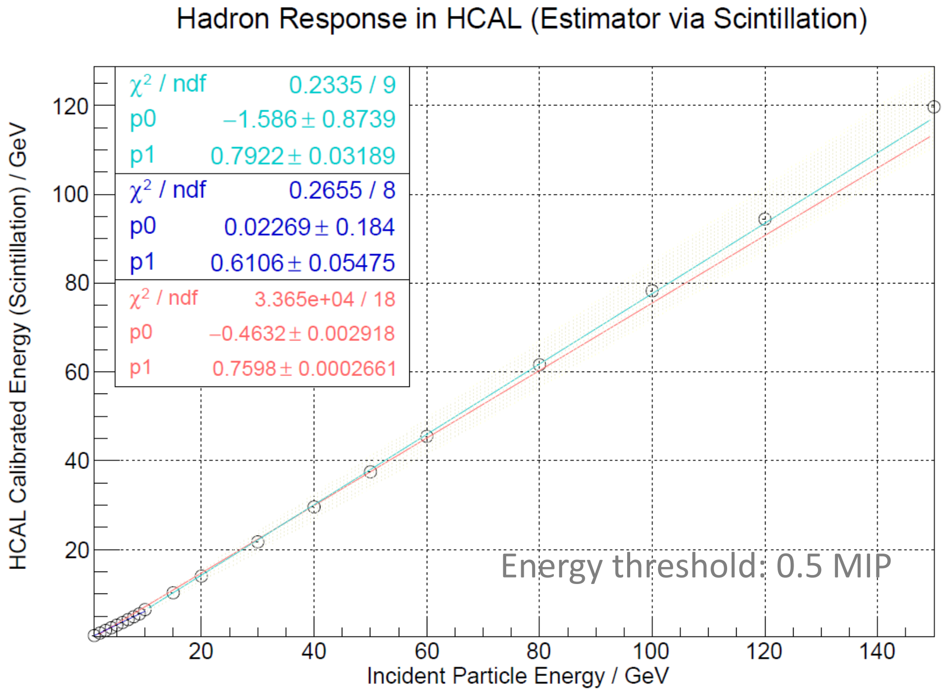
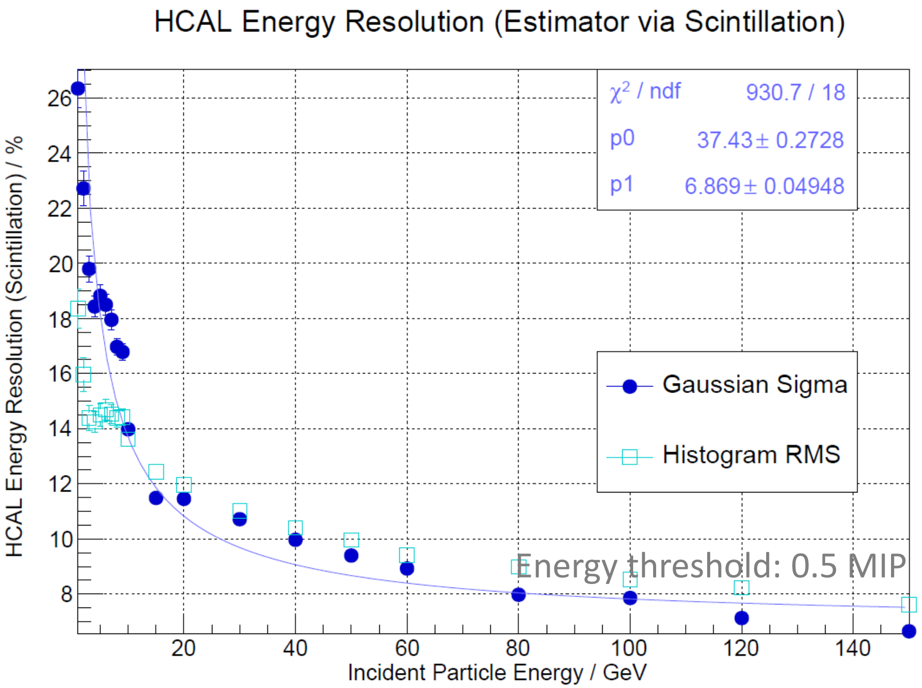
- "Conventional" readout scheme
  - Use only scintillation light as energy estimator

Energy deposition + scintillation process: "partial" digitisation included





- A global linear curve <u>can not</u> well calibrate the hadronic response
- Separate energy calibrations for low and high energy regions
  - Still 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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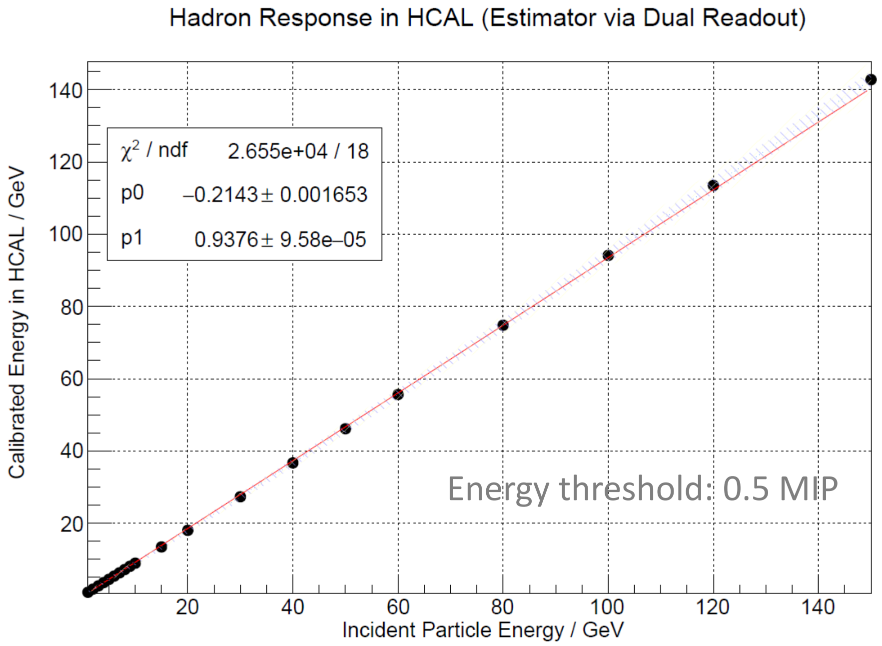
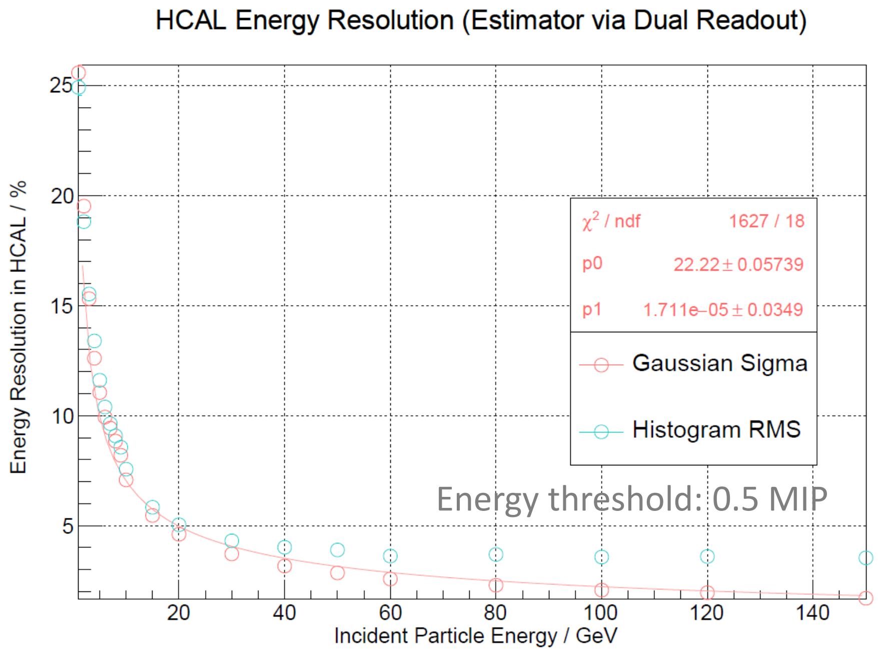
- Dual-readout readout scheme
  - Use both scintillation + Cherenkov light as energy estimator





- Good linear response resumed with the dual-readout scheme
- 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

Dual-readout simulation: further information

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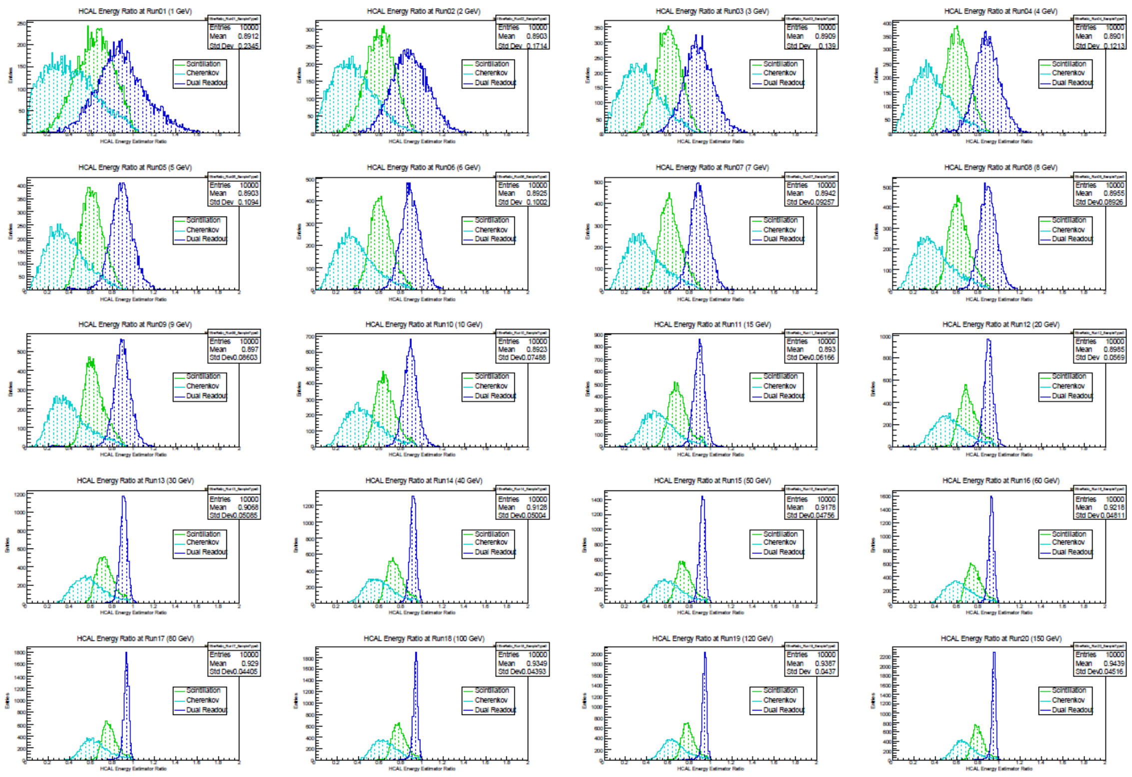
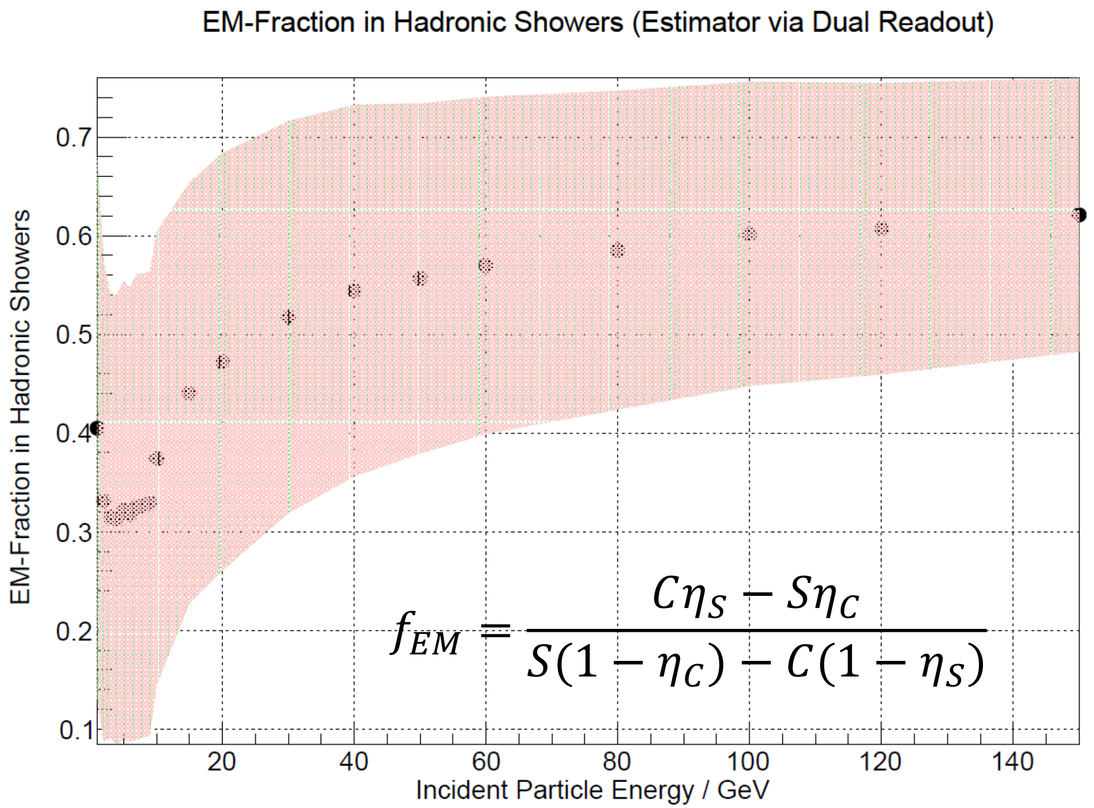
- Comparison of energy estimators: Cherenkov, scintillation and dual-readout
  - Minimum width for scintillation at low energy; dual-readout work mainly for high energy





- EM fraction vs. incident energy: estimator by dual-readout

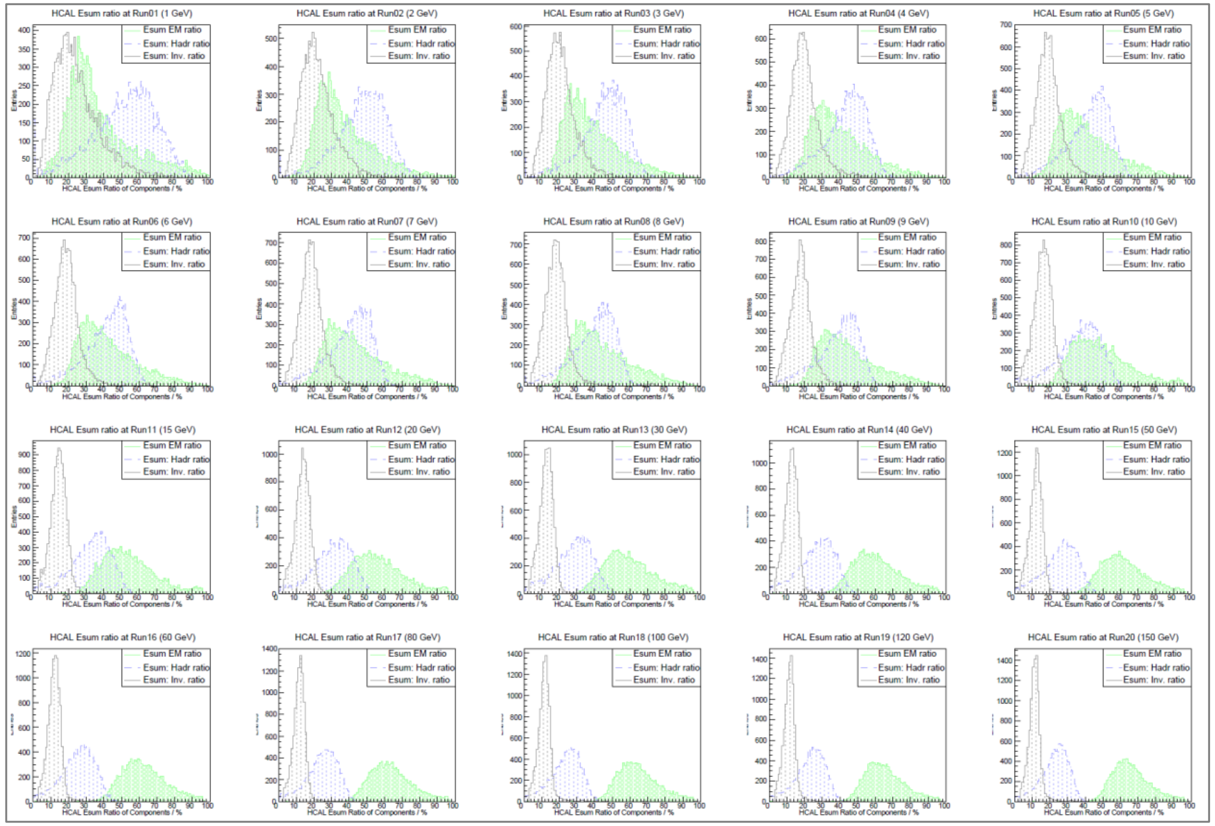
Summary

- Hadronic performance studies in simulation
  - Complicated hadronic shower behaviors: non-Gaussian fluctuations
  - Synergies for new concepts: PFA-oriented crystal and scintillating glass calorimeters
  - Geant4 validation studies with CMS calorimeter data for hadronic responses
- Studies on hadronic performance with a homogeneous calorimeter
  - Homogeneous calorimeter alone does not naturally guarantee good hadronic performance
    - In contrast to the EM performance
  - Studies on the potentials of dual readout technique: good response linearity and resolution
    - Hadronic energy resolution can achieve $\sim 20\%/\sqrt{E(GeV)}$
  - Lower energy threshold is (always) favored for better performance
- Discussions and plans
  - Would be interesting to evaluate the "software compensation" potentials for crystal/scintillating glass
    - Comparison with dual readout performance
  - To establish the link among energy threshold, tile design and properties of scintillating glass
  - "Dual-readout" technique would require good UV transmission of crystal/glass

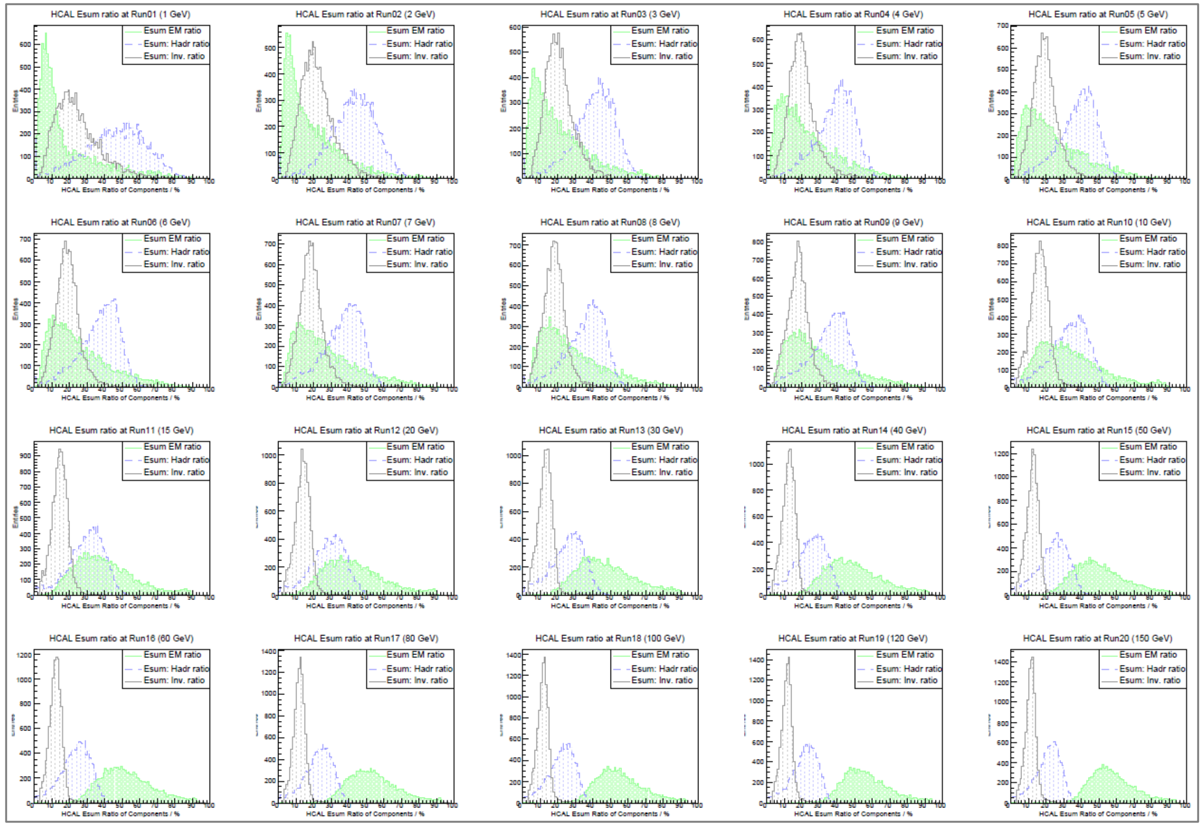
Backup

- Categorize energy depositions: EM, hadronic, invisible

Energy threshold: 0

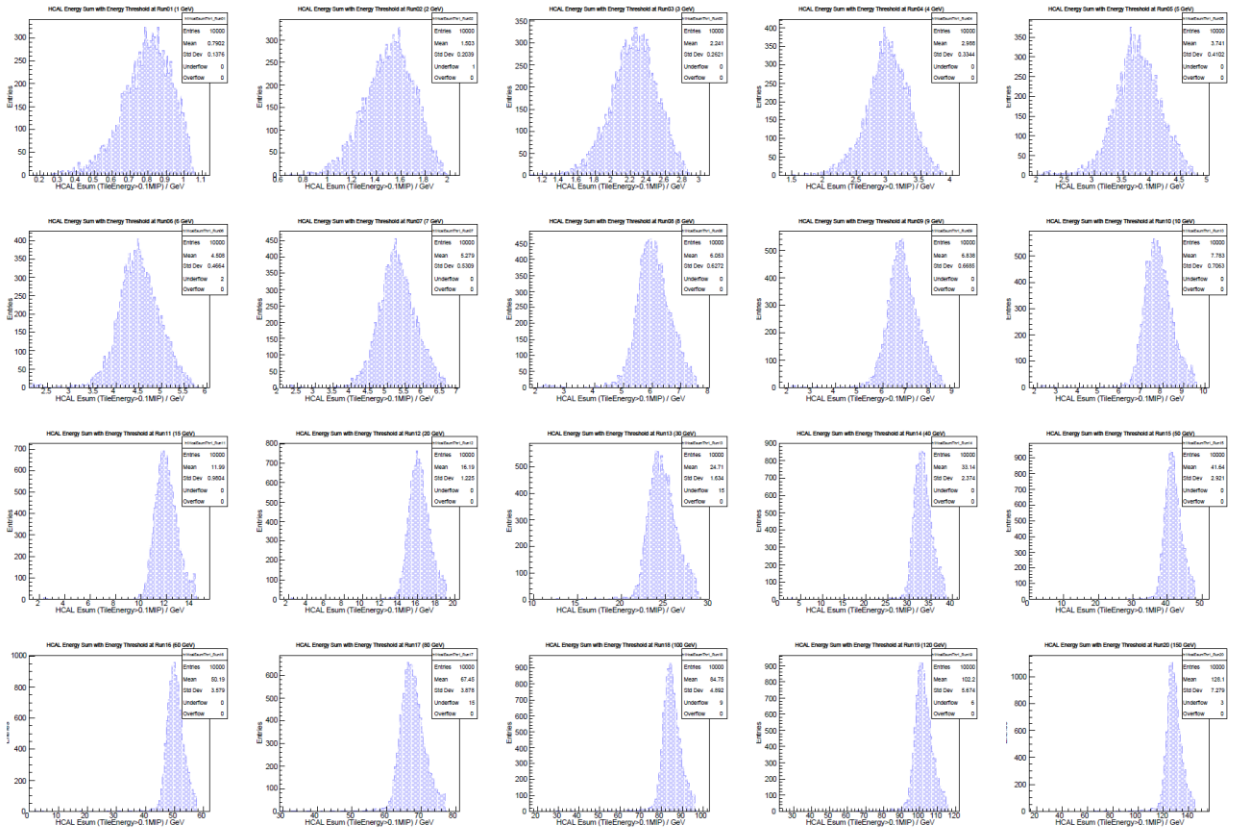


Energy threshold: 0.5 MIP



Scintillating Glass HCAL: energy depositions with π^-

Energy sum



e/h ratio: event level