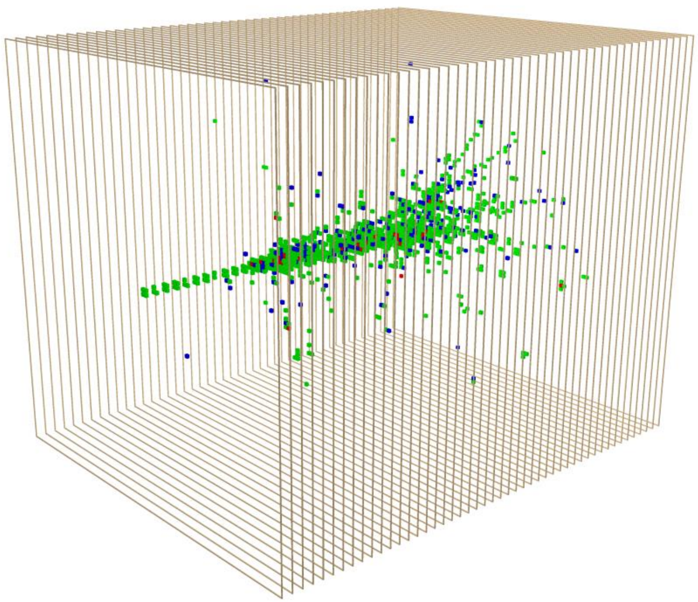
Calorimetry for the Future



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Argonne National Laboratory

LHeC Workshop
CERN
September 11-13, 2017

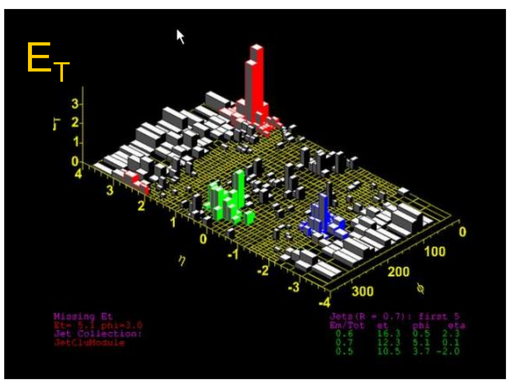
Trend in Calorimetry

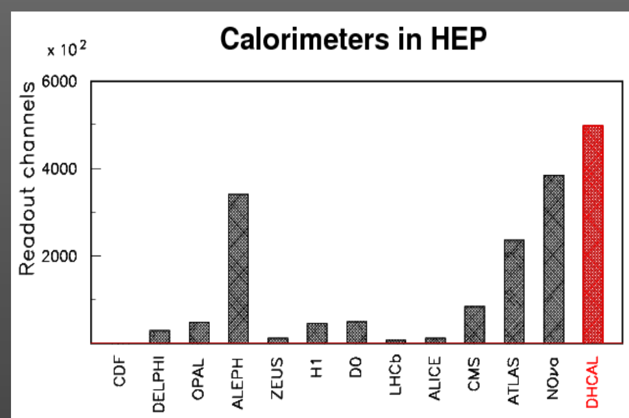
Tower geometry

Energy is integrated over large calorimeter volumes into single channels

Readout typically with high resolution (> 10 bits/channel)

Individual particles in a hadronic jet not resolved



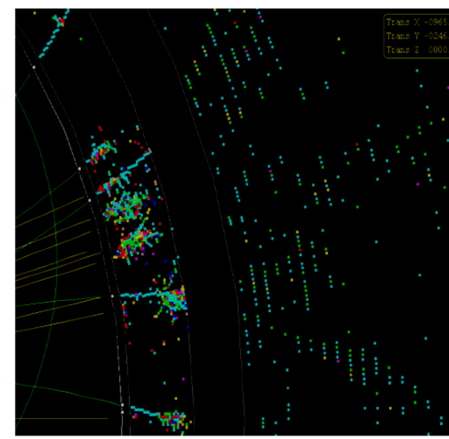


Imaging calorimetry

Large number of calorimeter readout channels (~10^7)

Option to minimize resolution on individual channels (1, 2… bits/channel)

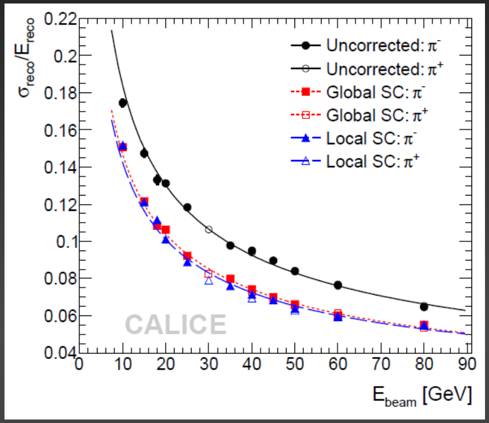
Particles in a jet are measured individually

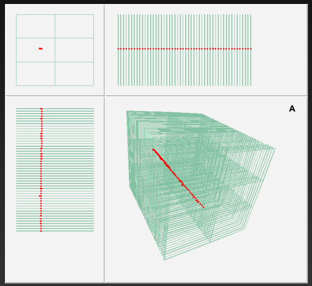


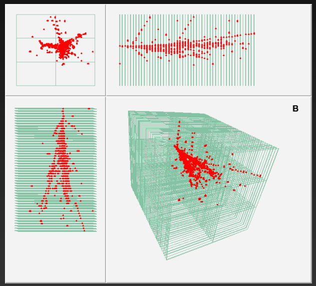
Advantages of Imaging Calorimetry

Particle ID

Electrons, muons, hadrons ⟶ (almost) trivial







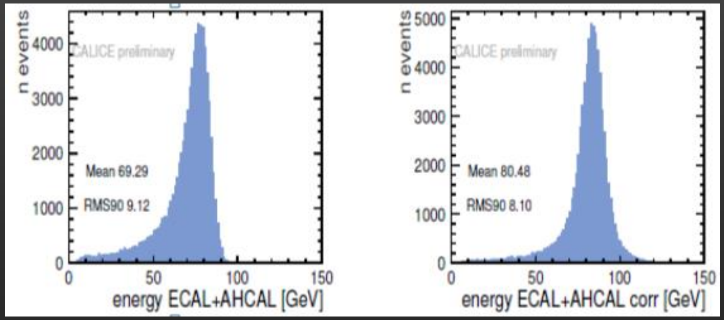
Software compensation

Typical calorimeters have e/h ≠ 1

Weighting of individual sub-showers possible

⟶ significant improvement in σ_E^{had}

Leakage corrections



Use longitudinal shower information to compensate for leakage

⟶ significant improvement in σ_E^{had}

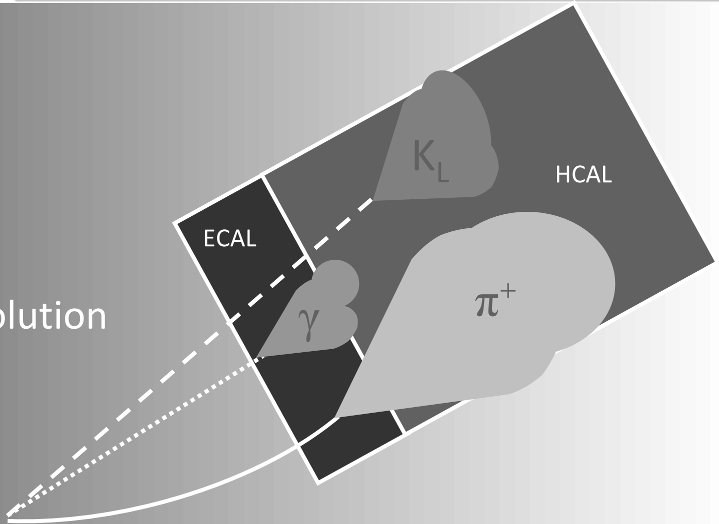
Measure momentum of charged particles exiting calorimeter

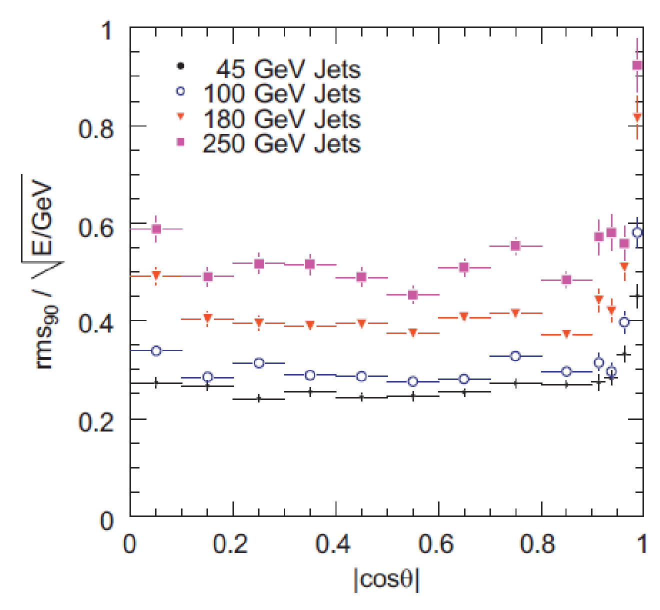
Application of Particle Flow Algorithms (PFAs)

Use PFAs to reconstruct the energy of hadronic jets

Particle Flow Algorithms

Attempt to measure the energy/momentum of each particle in a hadronic jet with the detector subsystem providing the best resolution





Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion	If goal is to achieve a resolution of 30%/√E →		**$\leq 0.24^2\ E_{jet}$**

PANDORA PFA based on ILD detector concept

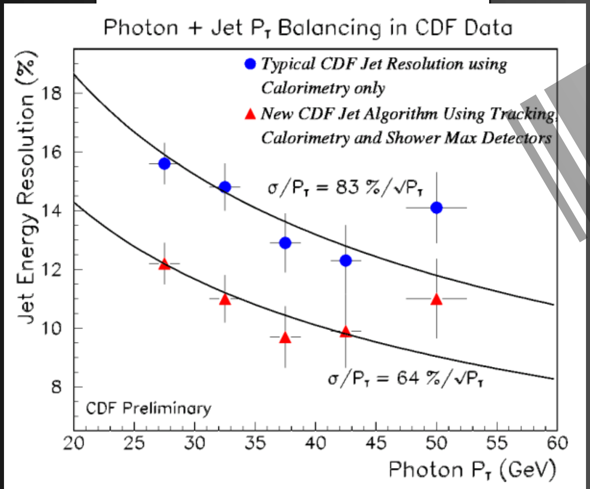
Factor ~2 better jet energy resolution than previously achieved

Application of PFAs

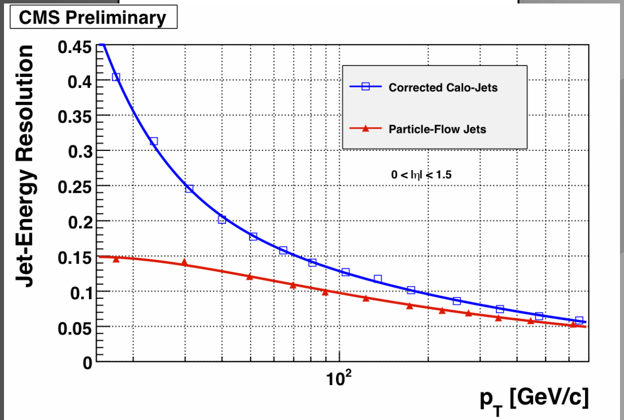
Past

Pioneered by
ALEPH

Used by
ZEUS, CDF…



Present



CMS

Future

ILC/CLIC detectors
CMS endcaps
ALICE forward
Any new colliding beam detector
LHeC, EIC…

Detectors optimized for PFAs

PFA Implications for Calorimetry

- Calorimeter needs to be optimized for photons: separation into **ECAL + HCAL**
- Calorimeters need to be placed **inside the coil** (to preserve resolution)
- To minimize the lateral size of showers, the $\mathbf{R_{moli\grave{e}re}}$ of the ECAL needs to minimized
- The **segmentation of the readout** needs to be maximized
- The **active layer or the depth of the E+HCAL** needs to be minimized (cost)
- The **front-end readout electronics** needs to be embedded into the calorimeter

The role of the HCAL reduced to measure the part of showers from neutral hadrons leaking from the ECAL

Two performance measures of a calorimeter optimized for PFAs

Energy resolution for single neutral particles ⟷ **Identification of energy deposits (minimize confusion)**

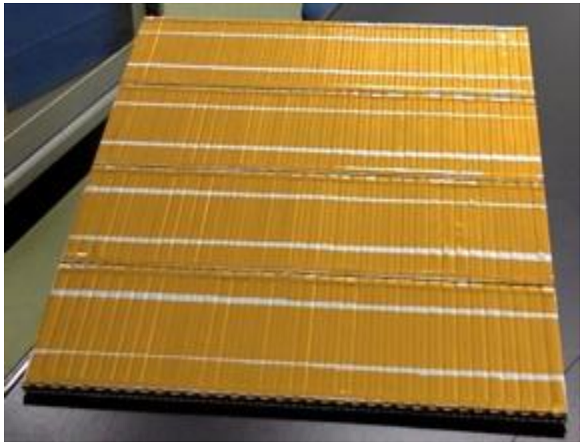
Electromagnetic Calorimeters

Role

Precision measurement (position, energy) of photons

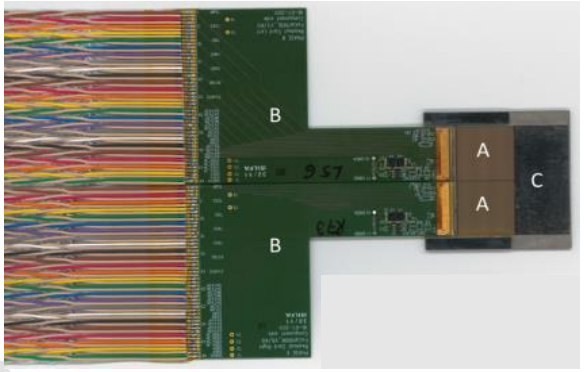
Absorber

Tungsten (alloy) -> small Moliere radius = 3.5 mm
Other possible absorbers not considered
Depth about 20 X_0, to minimize leakage into HCAL



Active media

Silicon pads (1 x 1 cm^2 -> 0.25 x 0.25 cm^2, 0.13 cm^2)
Scintillator strips with SiPM readout (45 x 10 mm^2)
MAPS (30 x 30 μm^2 + digital readout) -> DECAL



Prototypes constructed and tested

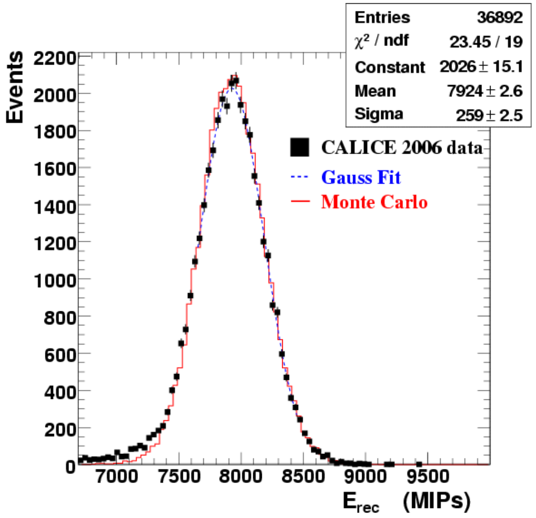
CALICE Si-W ECAL (10k channels)
SiD Si-W ECAL (10k channels)
CALICE Scintillator-W (2k channels)
ALICE FoCAL (39M channels)

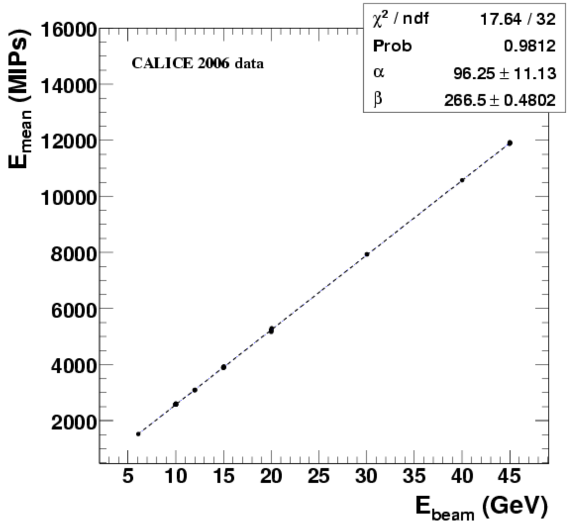
CALICE Silicon-Tungsten ECAL

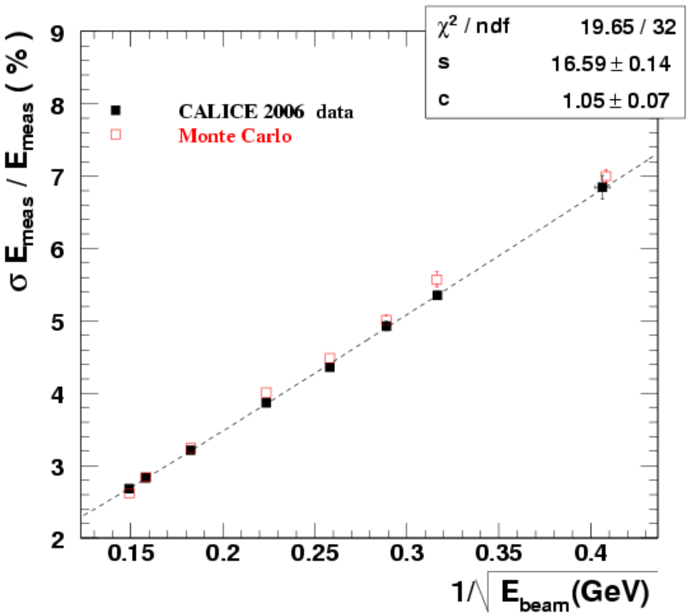
Linear within ±1% up to 45 GeV
Resolution adequate

$$\frac{\sigma_E}{E} = \left(\frac{16.6 \pm 0.1}{\sqrt{E(GeV)}} \oplus (1.1 \pm 0.1)\right)\%$$

-> Negligible contribution to $\sigma(E_{jet})$
Excellent agreement with GEANT4 simulation







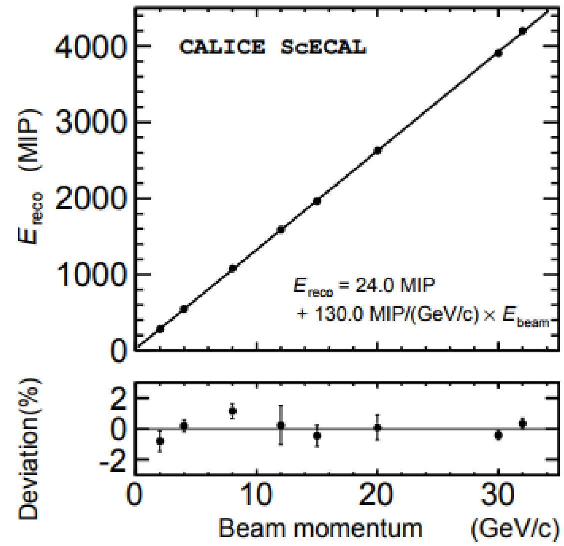
Both concept and technical implementation validated

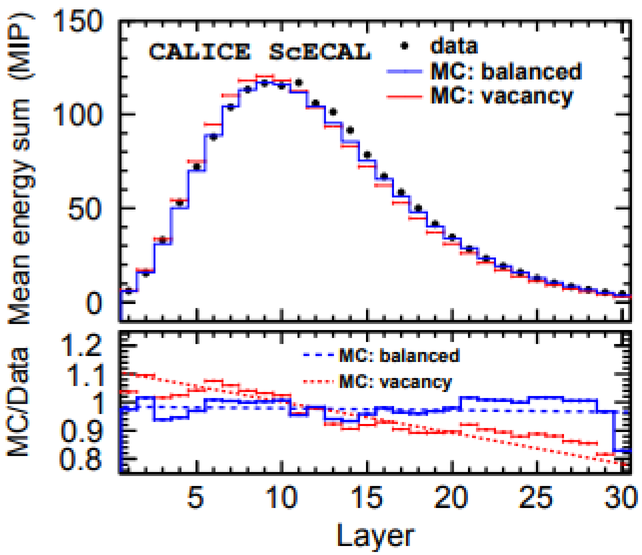
CALICE Scintillator-Tungsten ECAL

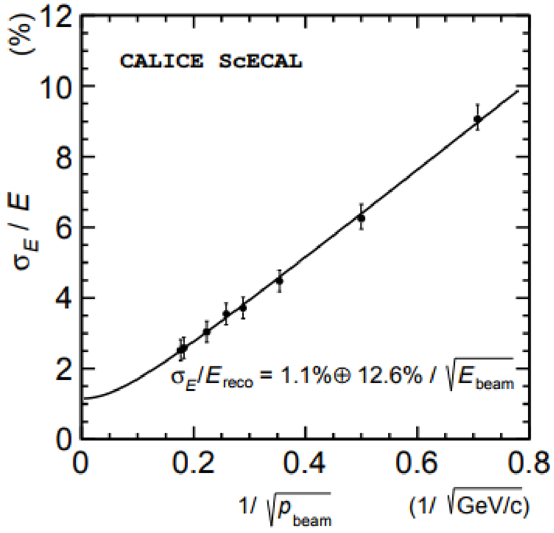
Linear within ±1% up to 32 GeV
Resolution quite good

$$\frac{\sigma_E}{E} = \left(\frac{12.6 \pm 0.4}{\sqrt{E(GeV)}} \oplus \left(1.1^{+0.6}_{-0.7}\right) \right)\%$$

-> Negligible contribution to $\sigma(E_{jet})$
Excellent agreement with simulation



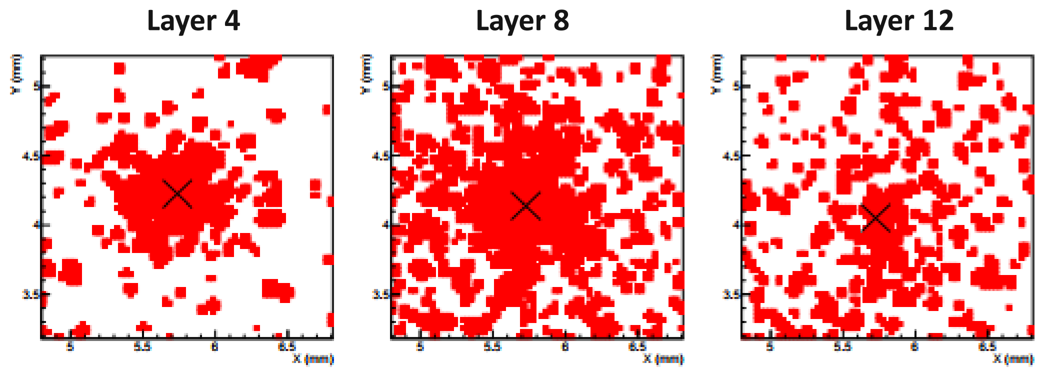




Both concept and technical implementation validated

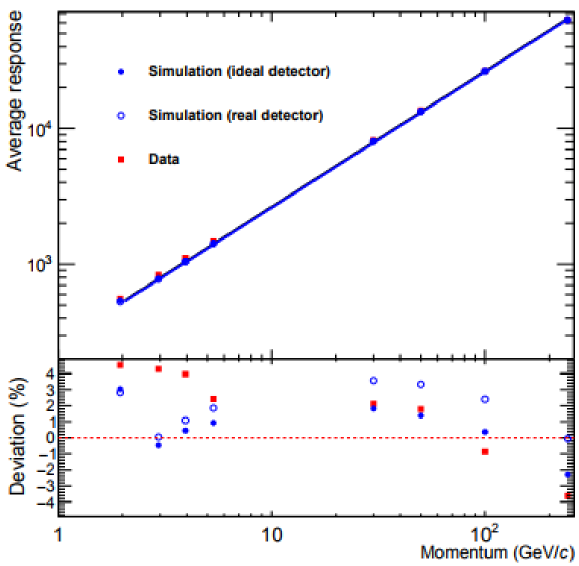
ALICE Forward Calorimeter Upgrade

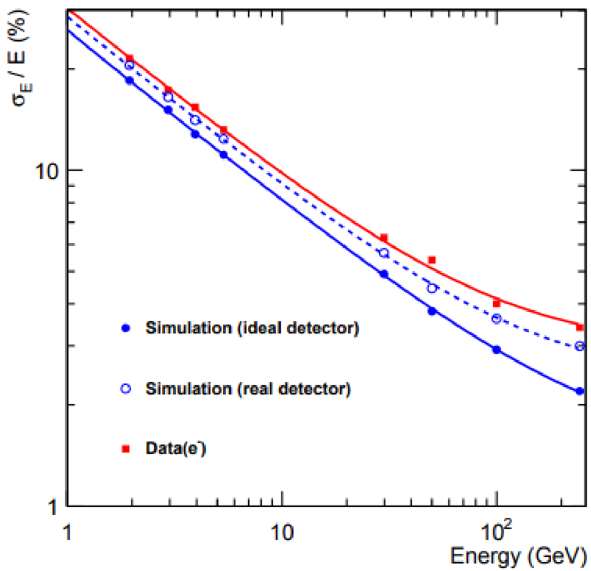
244 GeV electron



The ultimate digital calorimeter

Pixels of 30 x 30 μm^2 area
Total of 39 million channels
1-bit readout -> digital
Energy reconstructed as function of number of hits





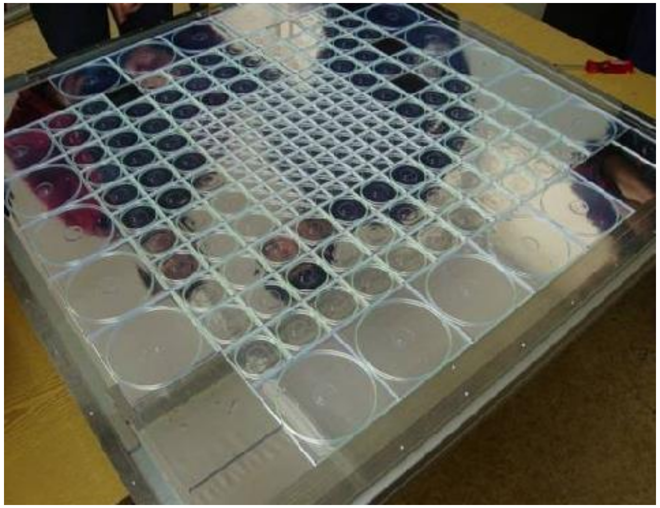
Response surprisingly linear up to 244 GeV

Resolution not overwhelming

$$\frac{\sigma_E}{E} = \left(\frac{6}{E(GeV)} \oplus \frac{30 \pm 4}{\sqrt{E(GeV)}} \oplus (3 \pm 2) \right) \%$$

Granularity particularly important in forward direction

Hadronic Calorimeters



Role

Measurement of neutral hadrons (n, K_L^0)

Absorber

Steel preferred
Tungsten was also explored
- More compact calorimeter (reduces cost)
- Degraded resolution (absorption of em component)

Active media

Scintillator pads (3 x 3 cm^2)
Resistive Plate Chambers (1 x 1 cm^2)
GEMs, Micromegas (1 x 1 cm^2)

Readout

Scintillator -> 14-bit = analog
Gaseous -> 1-bit = digital

Large prototypes constructed and tested

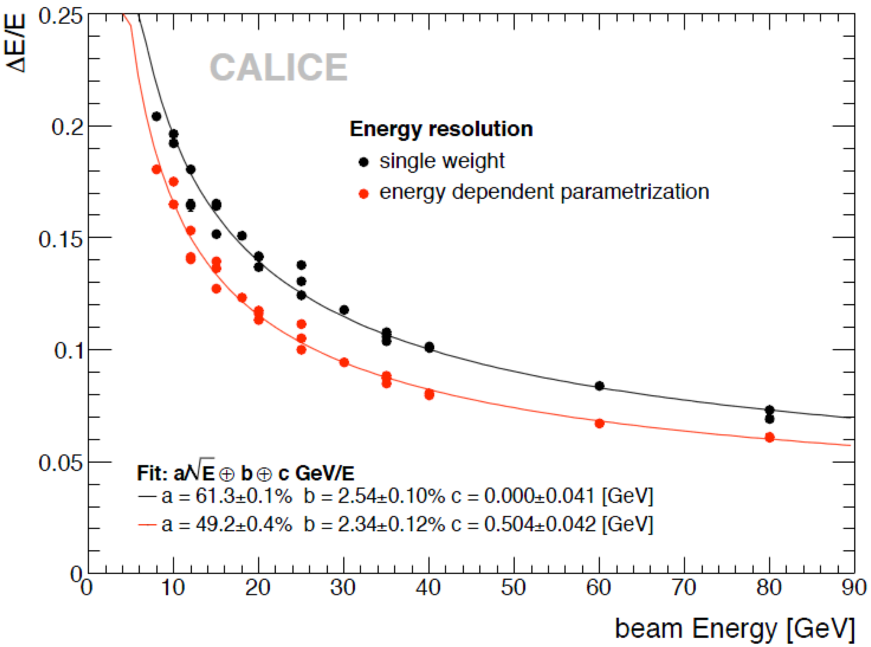
CALICE AHCAL(8k channels)
CALICE DHCAL (500k channels)
CALICE SDHCAL (400k channels)

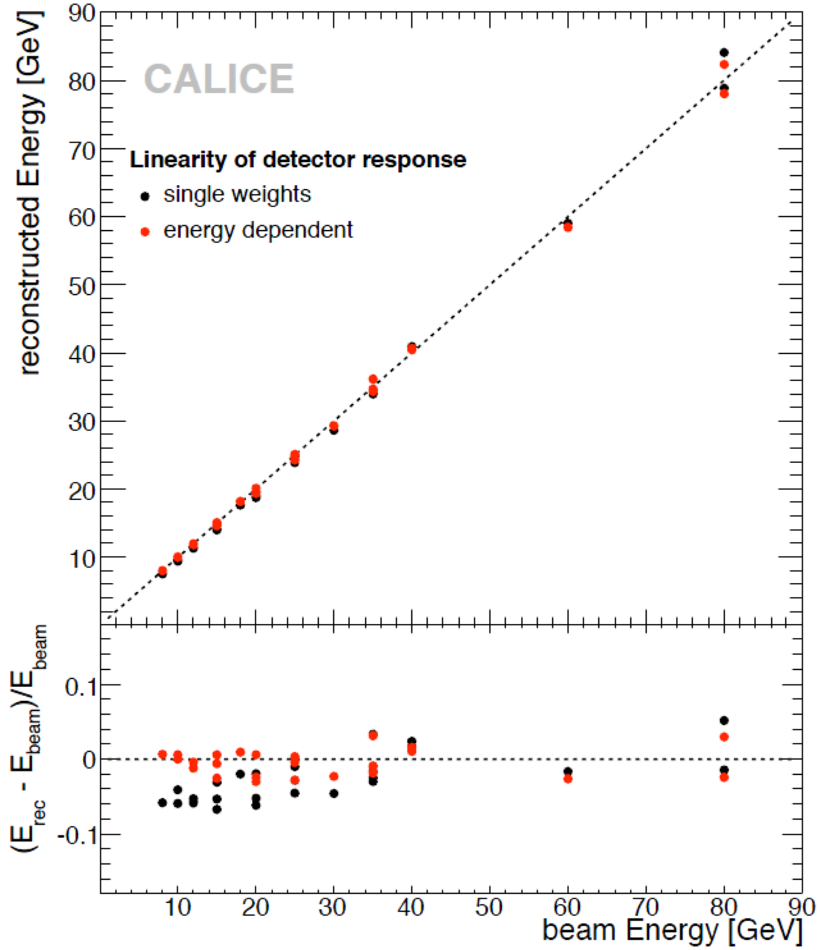
CALICE Scintillator-Steel HCAL

Pions between 8 and 80 GeV/c

Software compensation

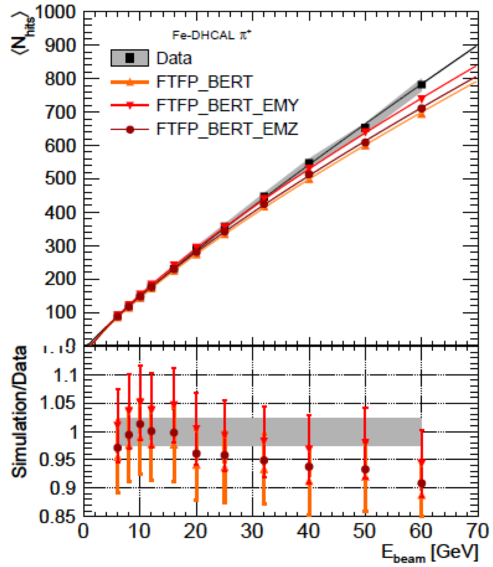
- Based on energy density weights
- Improves both linearity and resolution





Both concept and technical implementation validated

CALICE RPC-Steel HCAL – the DHCAL



Energy reconstruction

To first order E proportional N_{hit}

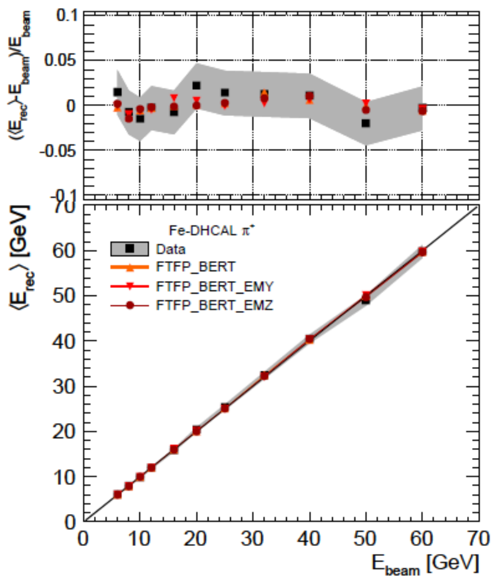
Response saturates (due to finite pad size)

Response fitted to a power law $N_{hit} = aE^b + c$

Energy reconstructed as

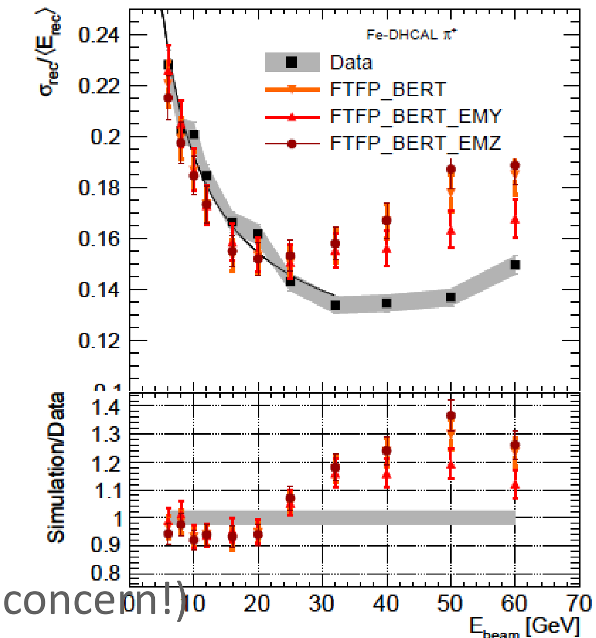
$$E_{rec} = \sqrt[b]{\frac{N_{hit} - c}{a}}$$

-> Linear response within ±2%



Energy resolution

$$\frac{\sigma_E}{E} = \left(\frac{51.4 \pm 0.1}{\sqrt{E(GeV)}} \oplus (10.3 \pm 0.1)\right)\%$$



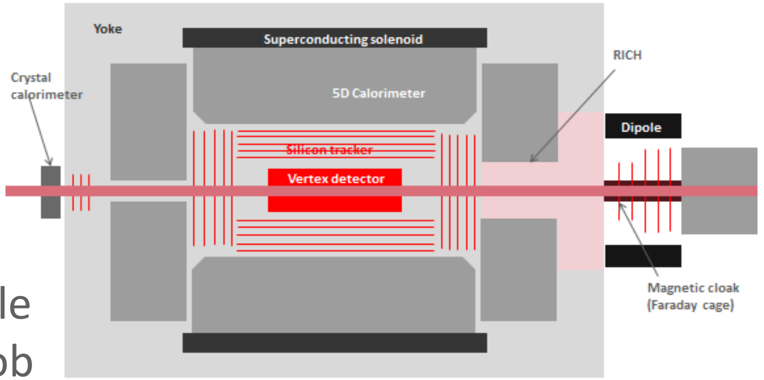
Not as good as the AHCAL

Levels out at high energies (not a concern!)

Can be improved with software compensation techniques

Both concept and technical implementation validated

The 5D Concept

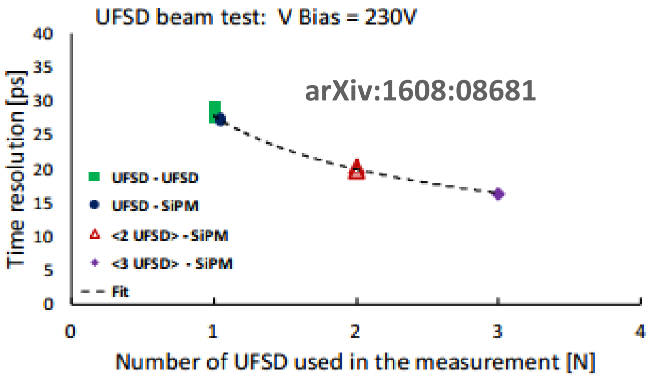


Particle identification (π – K – proton separation)

Important at the Electron-Ion Collider (EIC)
Particle momenta < 10 GeV/c for most of the solid angle
Time – of – flight with 10 ps resolution would do the job

The 5D concept

Measure (E,x,y,z,t) for every hit in tracker + calorimeter
Requires ultra-fast silicon sensors
Eliminates the need for additional PID detectors for most of the solid angle



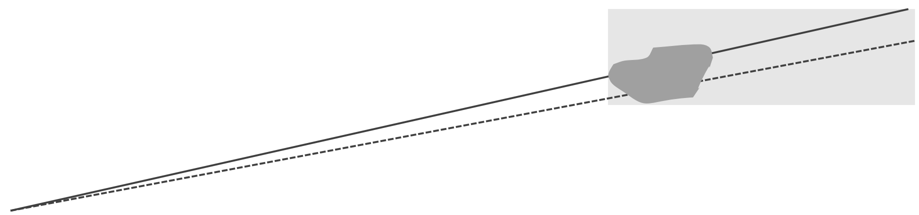
Ultra-fast Silicon Sensors

Currently being developed based on the LGAD technology
Best timing resolution about 27 ps
Further improvements ongoing
Interest in developing ultra-fast CMOS sensors (addition of amplification layer)

General Remarks about the Forward Region

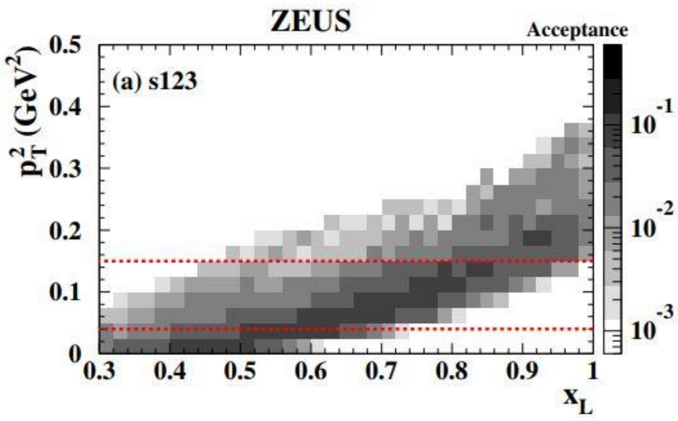
Forward jet production

Important for studies of BFKL dynamics
Longitudinal segmentation of forward calorimeter mandatory (for angle reconstruction)
(projective geometry not recommended as it creates leaks/non-uniformities)
Lateral segmentation obviously important



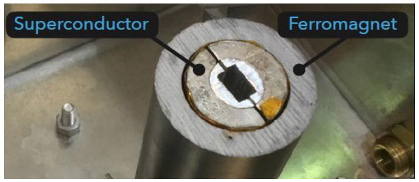
Diffractively scattered proton

Measurement requires Roman pots
Roman pots used at HERA, but with limited acceptance
Additional stations will be needed



Momentum measurement in the forward direction

EIC considers dipole magnet
Requires magnetic cloak (to shield electron beam)



Conclusions

Imaging calorimetry provides clear advantages

Particle ID
Particle Flow reconstruction
Software compensation
Might eliminate need of separate muon system

Technologies for imaging calorimeters

Have been developed by CALICE, SiD
Have been validated through testing of (large) prototypes
Further developments ongoing

5D detector concept

Attempt to provide all information: E,x,y,z,t