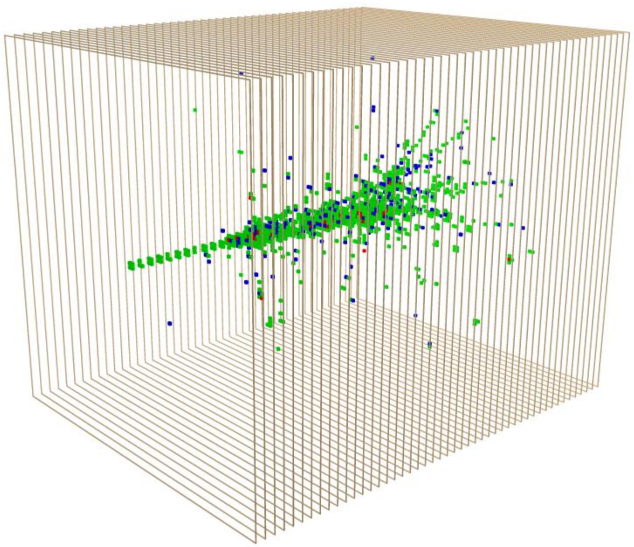
Development of Imaging Hadron Calorimetry



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EIC Detector R&D Meeting
Argonne National Laboratory
July 6 – 7, 2016

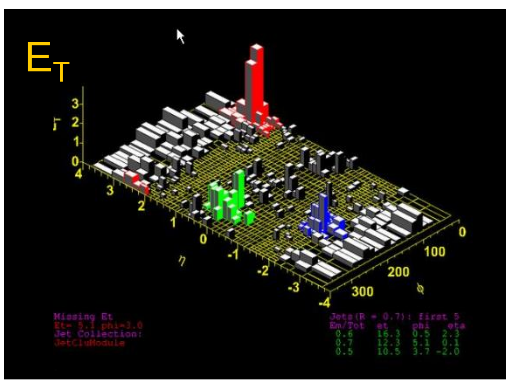
Trend in Calorimetry

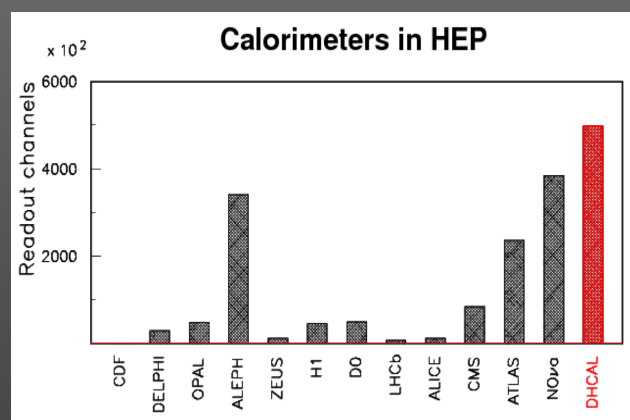
Tower geometry

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



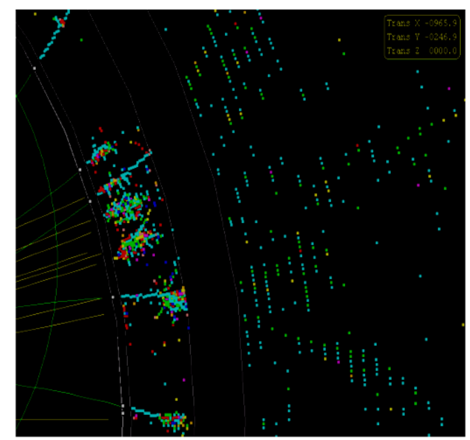


Imaging calorimetry

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

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

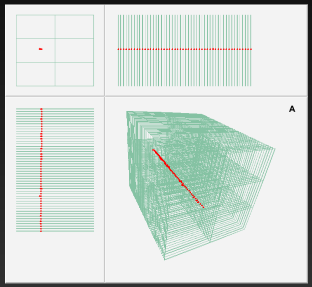
Particles in a jet are measured individually

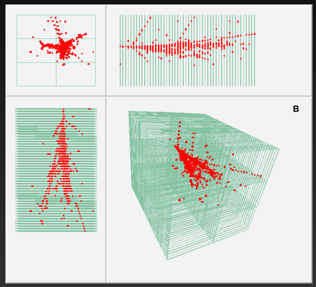


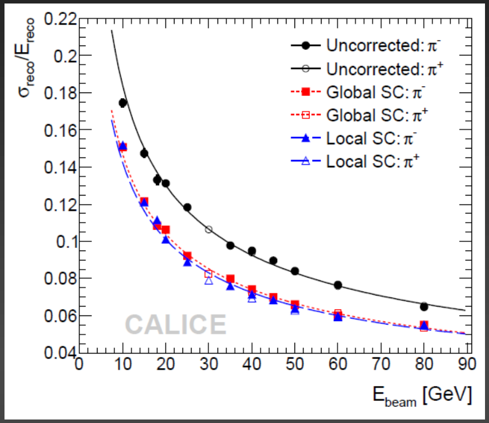
Advantages of Imaging Calorimetry

Particle ID

Electrons, muons, hadrons → (almost) trivial





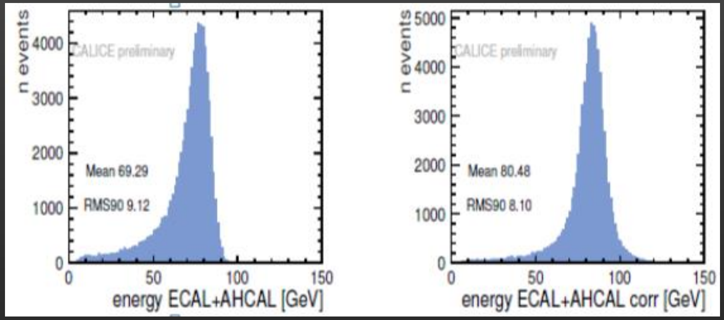


Software compensation

Typical calorimeters have $e/h \neq 1$
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

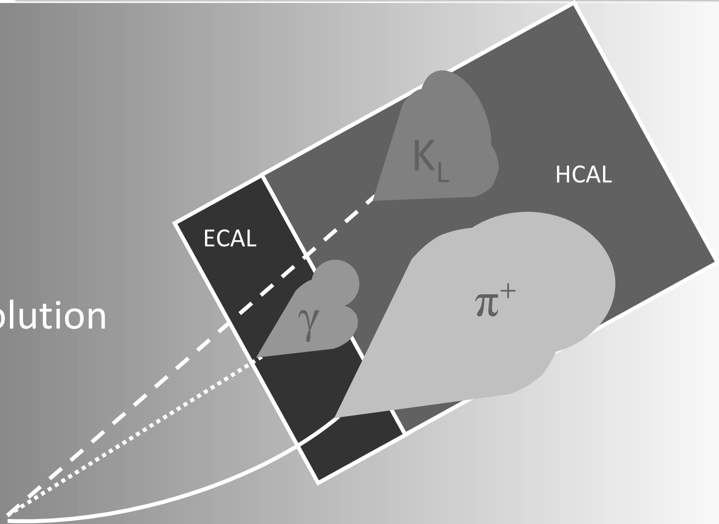


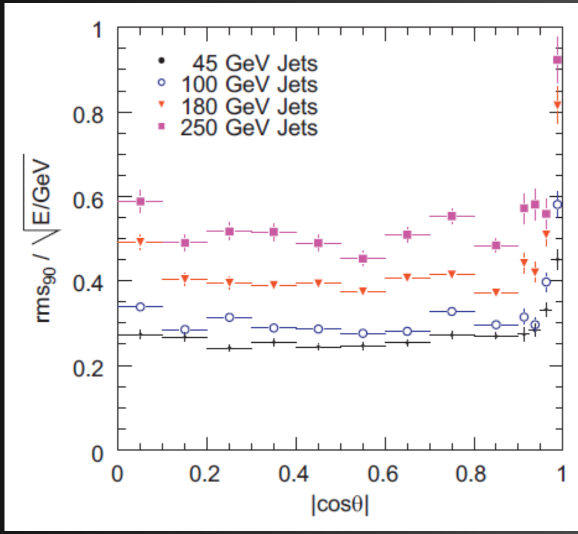
Application of Particle Flow Algorithms (PFAs)

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/E_{jet}]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07/\sqrt{E_{jet}}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16/\sqrt{E_{jet}}$
Confusion	If goal is to achieve a resolution of 30%/√E →		**$\leq 0.24/\sqrt{E_{jet}}$**

} 18%/√E

PANDORA PFA based on ILD detector concept

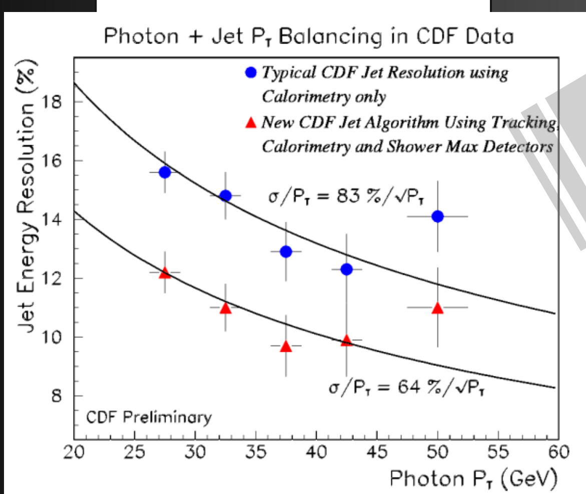
Factor ~2 better jet energy resolution than previously achieved

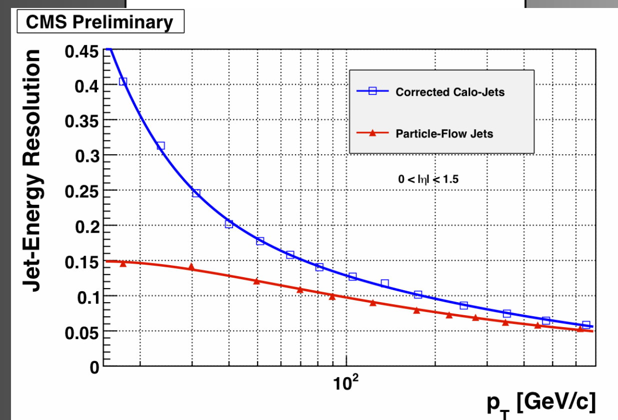
Application of PFAs

Past

Pioneered by
ALEPH

Used by
ZEUS, CDF…





Present

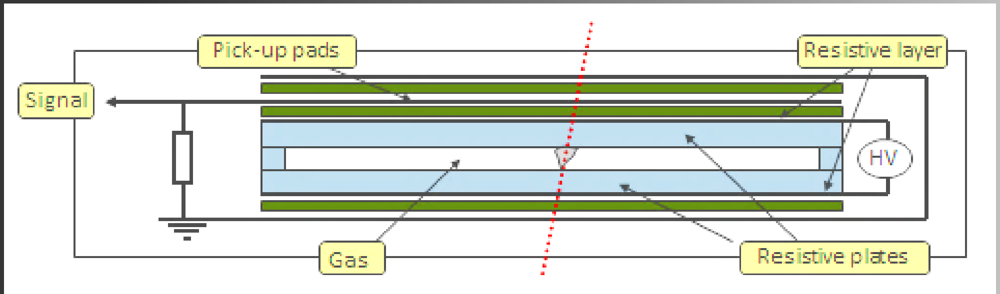
CMS

Future

ILC/CLIC detectors
CMS endcaps
ALICE forward
Any new colliding beam detector

Detectors optimized for PFAs

Resistive Plate Chambers (RPCs)



Invented/developed

In the 1980s

Many applications in HEP

Mostly as large area Muon Detectors, TOF counters

Used in

ATLAS, CMS, ALICE, BaBar, Belle, ARGO, CMB…

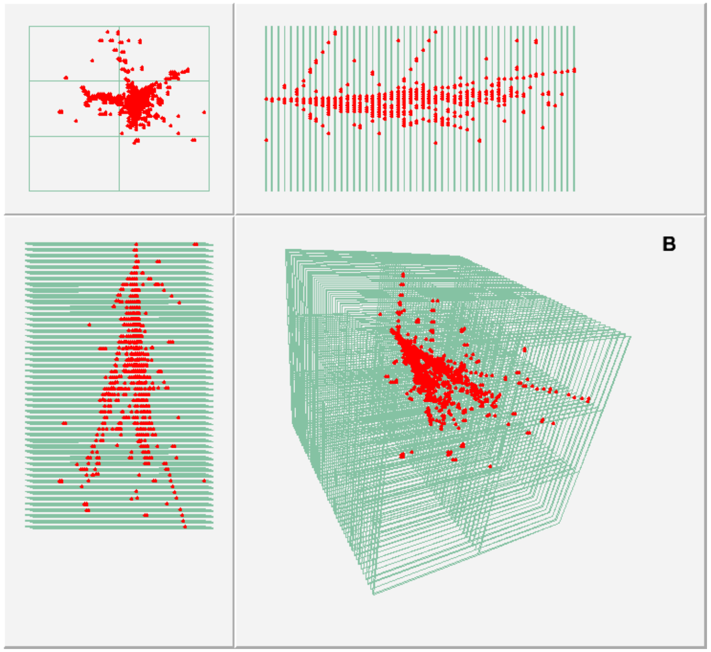
In general

Reliable, cheap, relatively thin, readout can be segmented which ever way…

Resistive plates

Here only glass being considered
Bakelite also widely used

The DHCAL



Description

54 active layers
Resistive Plate Chambers with 1 x 1 cm^2 pads
→ ~500,000 readout channels
Main stack and tail catcher (TCMT)

1st time in calorimetry →

Electronic readout

1 – bit (digital)
<u>Digitization embedded into calorimeter</u>

Tests at FNAL

with Iron absorber in 2010 – 2011
without absorber plates 2011

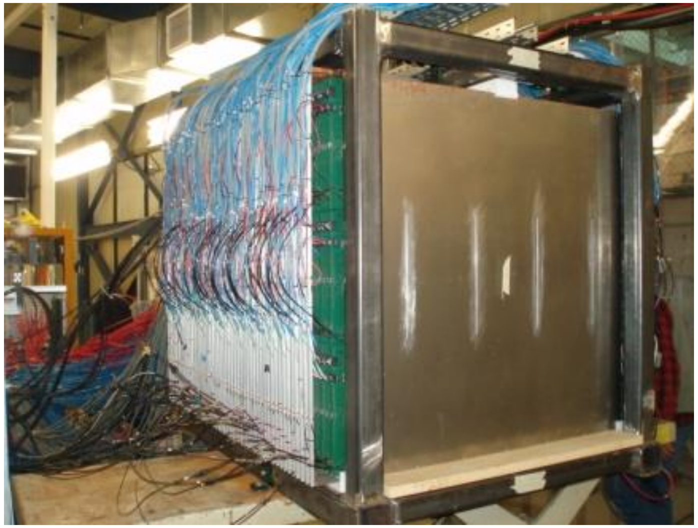
Tests at CERN

with Tungsten absorber 2012

Some recent results

To give you a flavor of what this is about…

The Min-DHCAL



Special tests

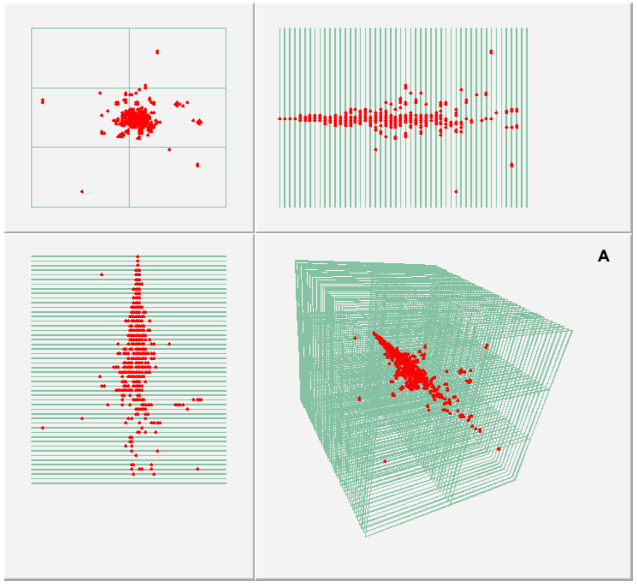
- Use of DHCAL layers (0.29 X_0)
- No absorber plates between layers
- 50 layers in total

Fermilab test beam

- Mixture of e^+, μ^+, π^+
- Momentum range of 1 – 10 GeV
- Data with extremely fine spatial segmentation

Analysis

- Positron data published
- Pion data being analyzed



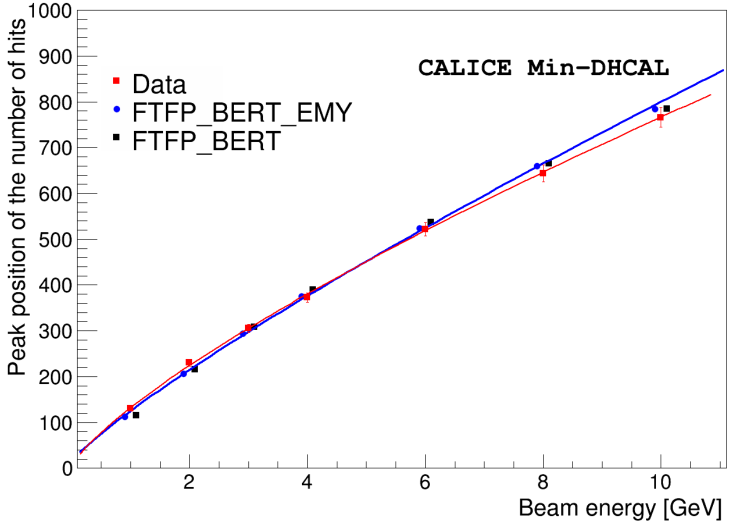
8 GeV e^+ shower in the Min-DHCAL

Min-DHCAL Positron Results I

Published in JINST (2016) 11 P05008

Main messages from paper

Default simulation of electromagnetic interaction not adequate
Need detailed simulation of electromagnetic interactions (Option 3 or _EMY)
High precision data ⟶ Well reproduced by simulation



Response in number of hits

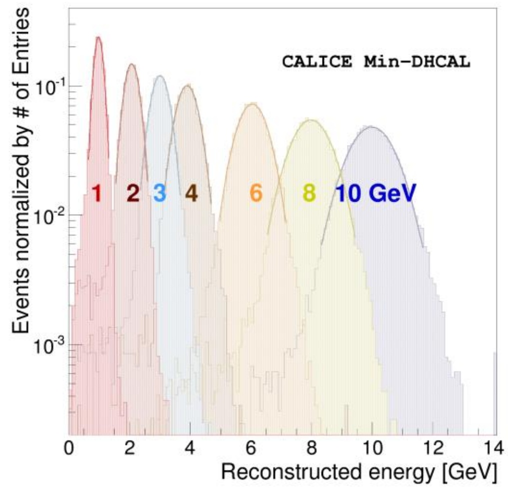
Non-linear (saturation)
Fit to power law

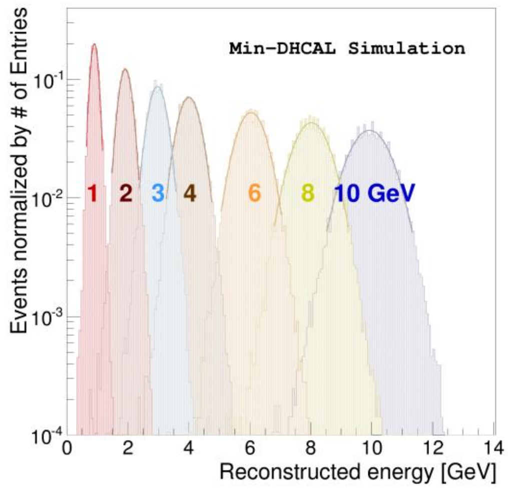
$$N_{hit} = a_0 (E_{beam} / GeV)^m$$

m = 0.76 ± 0.02 (m = 1 would be perfectly linear)
Invert power law to reconstruct energies

$$\frac{E_{rec}}{GeV} = \left(\frac{N_{hit}}{a_0} \right)^{1/m}$$

Min-DHCAL Positron Results II





Energy spectra

Fit to Gaussian within ± 2σ

No evidence of contamination from muons/pions

Response

Linear by construction

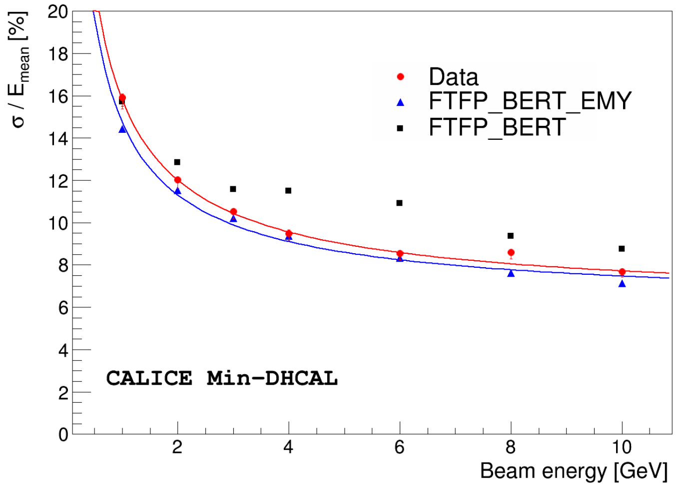
Resolution

Well reproduced by _EMY

Significantly worse with default simulation

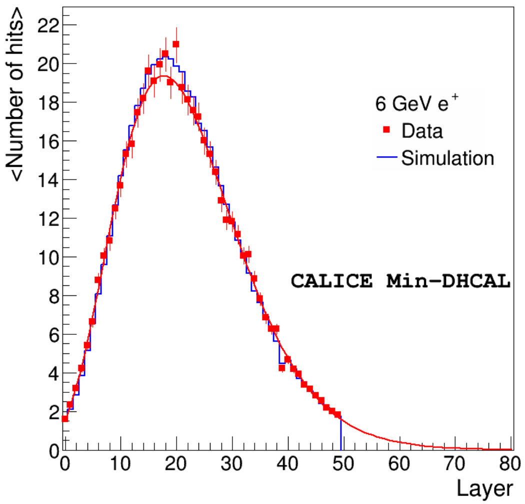
Fit to standard formula

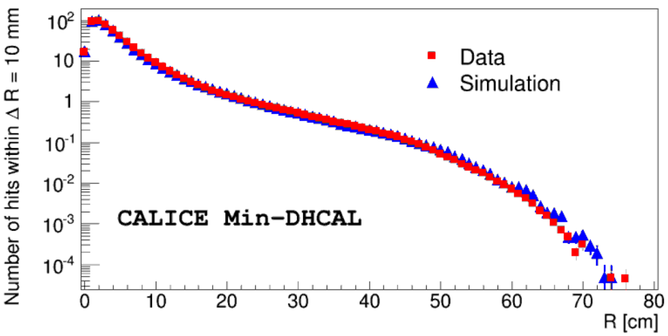
$$\frac{\sigma_E}{E} = c \oplus \frac{\alpha}{\sqrt{E/GeV}}$$

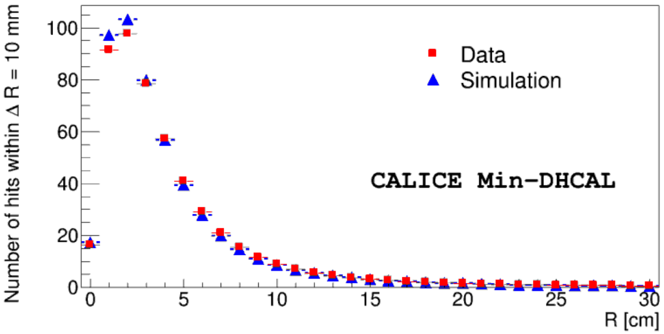


	c [%]	α[%]
Data	6.3±0.2	14.3±0.4
FTFP_BERT_EMY	6.2±0.1	13.2±0.2

Min-DHCAL Positron Results III





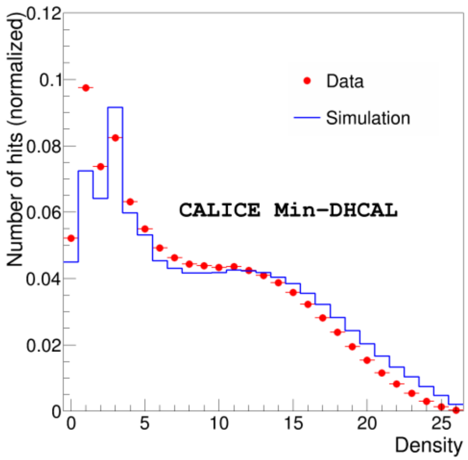


Precision shower shapes

<u>Longitudinal shape</u>

Fit to Gamma distribution

Small leakage observed



<u>Radial shower shape</u>

Covering 6 orders of magnitude in hit density

<u>Hit density</u>

Distribution of number of neighbors to a given hit

Some differences between data and simulation

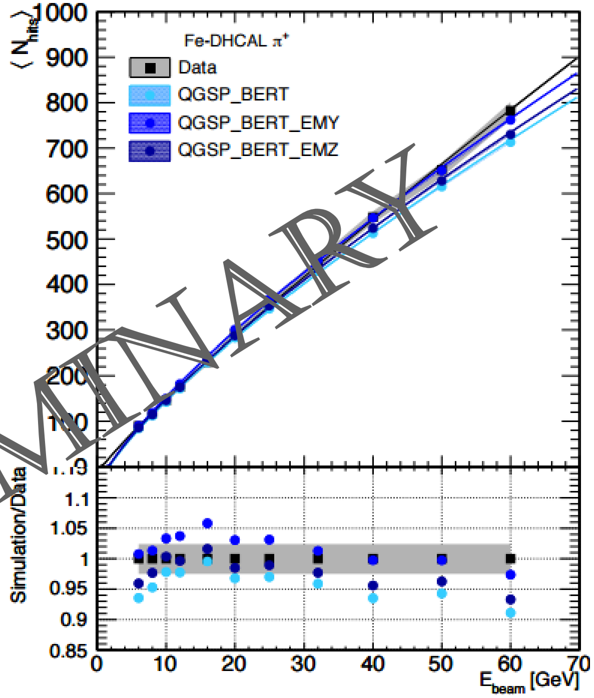
Fe-DHCAL Pion Results

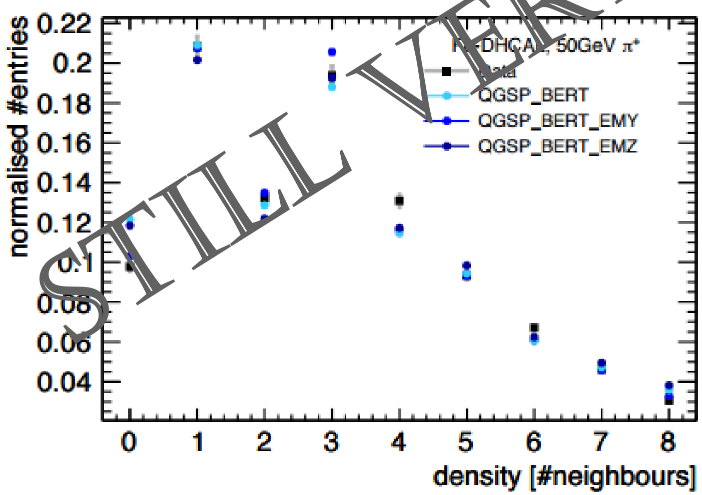
Sampling

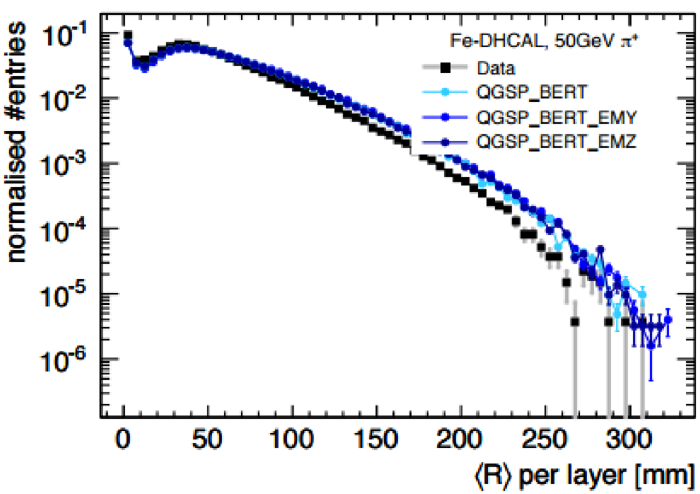
Absorber: Fe-plates each 1.2 X_0
In total 38 layers

Results

Very close to expectation







DHCAL Concept and Technology

Validated

From both the physics and technological point of view

DHCAL

First prototype ever of a digital hadron calorimeter
Many important features learned

Further R&D needed

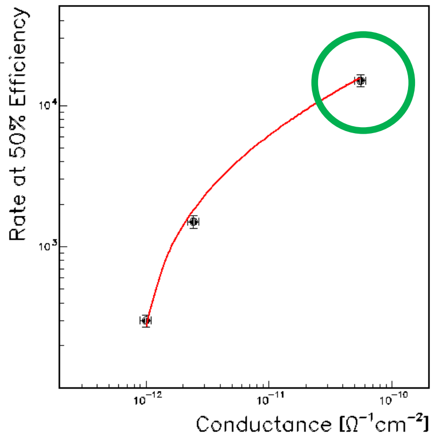
In specific areas
To turn the DHCAL concept into a mature technology

Proposed studies for the EIC I

1. **Long-term tests of 1-glass RPCs**

Novel RPC design: readout pads in gas volume
Advantages: thinner, pad multiplicity constant and around 1 (easy to calibrate!), higher rate capability
Design validated: **JINST 10 (2015) P05003**
Chemical stability of anode plane in gas volume?

Long-term tests with cosmic rays needed



2. **Long-tem tests of fast RPCs**

Use of semi-conductive glass as resistive plates
Rate capability improved by 2 orders of magnitude: **JINST 10 (2015) P10037**
Chemical stability of glass plates over time, with prolonged periods of HV?

Long-term tests with cosmic rays needed

Proposed studies for the EIC II

3. Development of a gas recycling system

Typical RPC avalanche gas harmful for the environment (green house gas)
Challenge: capture gas without changing the gas pressure in the chambers
Designed system which captures exhaust gas: ‘Zero Pressure Containment’ system
Assembled system and tested successfully

Implementation of filtering system and test with RPCs

4. Development of a High Voltage distribution system

An RPC based HCAL needs approximately 3,000 chambers with individual HV
Requires a HV distribution system
Each channel: option to turn on/off, monitor current and voltage,
adjust voltage to within ±100 V
First prototype designed, built (by University of Iowa) and tested successfully
1 channel, no monitoring, no voltage adjustment yet

Implement all features and test

Requests

1 Postdoc

$165K/year

M&S funds

$10k/year

Conclusions

Goal: Measure all properties about every particle produced with the best possible resolution

Imaging calorimetry is the way to go!

The DHCAL – prototype of an imaging hadron calorimeter

The DHCAL validated the concept (both physics and technology wise)

Many lessons learned by testing the DHCAL in particle beams

Proposal to turn this technology into a mature option for the EIC

- Long-term tests of fast-RPCs
- Long-term tests of 1-glass RPCs
- Development of a gas recycling system
- Development of a HV distributions system

} **Most important remaining issues**