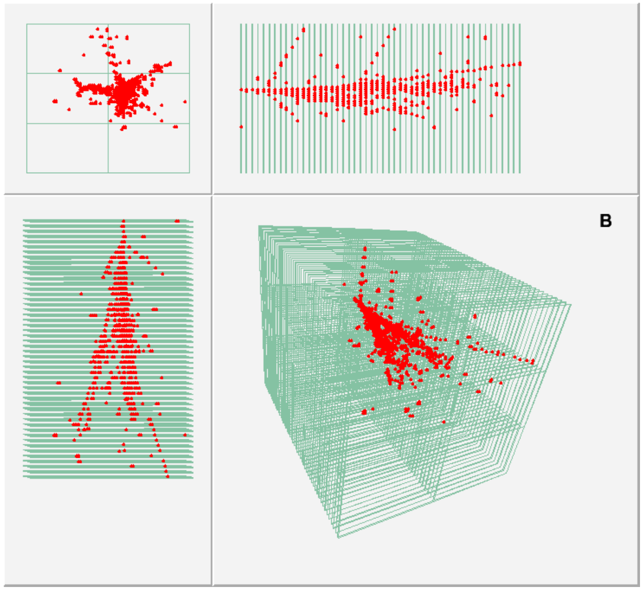
Review of the Status of the RPC-DHCAL



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Argonne National Laboratory

SiD Workshop
SLAC, Stanford, California
October 14 – 16, 2013

This talk will

Review the status of the RPC-DHCAL

→ Emphasis on what we have learned
→ Emphasis on open questions

Outline

DHCAL: Quick recap
Operational problems
Simulation of response
Calibration of RPC response
Response/resolution
Further R&D

DHCAL Construction

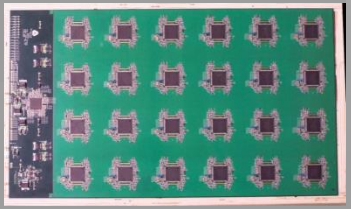
Fall 2008 – Spring 2011

Resistive Plate Chamber

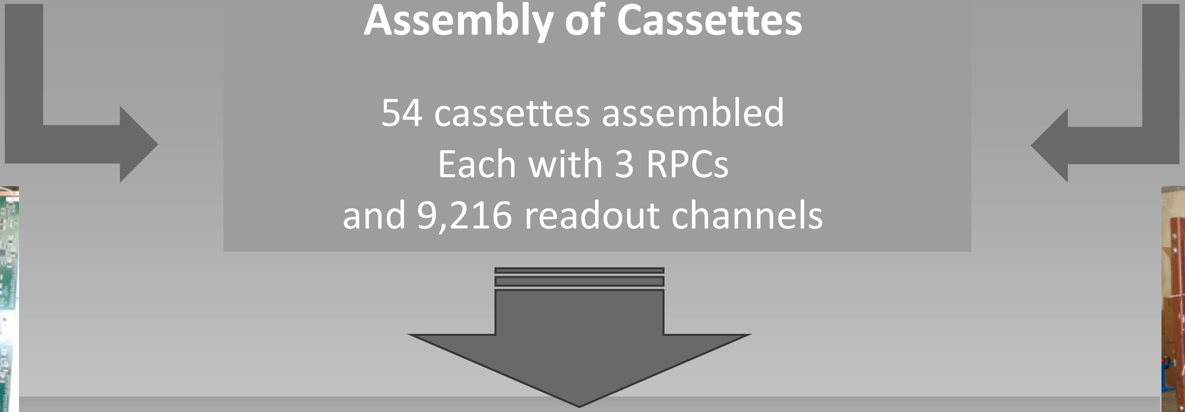
Sprayed 700 glass sheets
Over 200 RPCs assembled
→ Implemented gas and
HV connections

Electronic Readout System

10,000 ASICs produced (FNAL)
350 Front-end boards produced
→ glued to pad-boards
35 Data Collectors built
6 Timing and Trigger Modules built



Extensive testing at every step



Assembly of Cassettes

54 cassettes assembled
Each with 3 RPCs
and 9,216 readout channels

350,208 channel system in first test beam
Event displays 10 minutes after closing enclosure

Testing in Beams

Fermilab MT6

October 2010 – November 2011
1 – 120 GeV
Steel absorber (CALICE structure)

CERN PS

May 2012
1 – 10 GeV/c
Tungsten absorber
(structure provided by CERN)

CERN SPS

June, November 2012
10 – 300 GeV/c
Tungsten absorber

RPCs flown to Geneva
All survived transportation

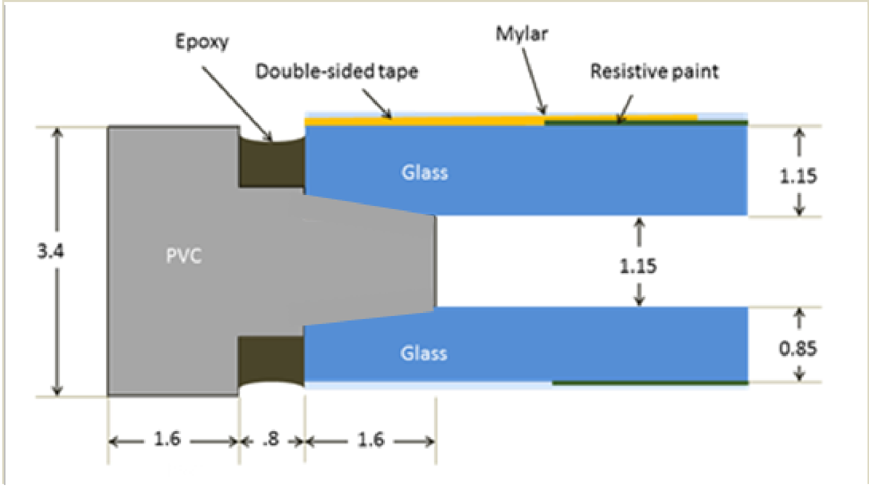
A unique data sample

Test Beam	Muon events	Secondary beam
Fermilab	9.4 M	14.3 M
CERN	4.9 M	22.1 M
TOTAL	**14.3 M**	**36.4 M**

Operational/design problems

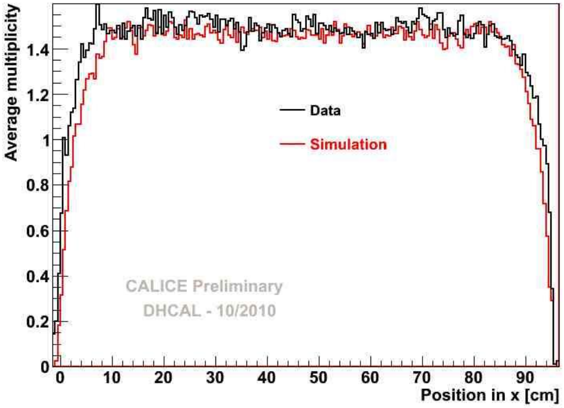
Loss of efficiency on edges of RPCs

Due to slight increase in gap size
Channels not perfectly molded
Simple solution for future RPCs



Loss of HV contact

Glass sprayed with resistive 'artist' paint
Surface resistivity 1 – 10 MΩ/☐
As time passed, order 20/150 RPCs lost HV
In part compensated by raising HV (6100 → 6800 V)
In future will use carbon film (was not available in 2008 – 10)



Simulation of the Muon Response

Simulation procedure

Take location of each energy deposit in gas gap from GEANT4
Eliminate close-by avalanches within $\mathbf{d_{cut}}$
Generate charge according to measured distribution, adjust using $\mathbf{Q_0}$
Spread charge on anode pads using various spread functions
Apply threshold **T**

RPC_sim_	Spread functions	Comment
3	$R\, e^{-ar} + (1-R)\, e^{-br}$	To help the tail
4	e^{-ar}	Based on measurement by STAR
5	$R\, e^{-(r/\sigma 1)^\wedge 2} + (1-R)\, e^{-(r/\sigma 2)^\wedge 2}$	Commonly used
6	$1/(a + r^2)^{3/2}$	Recently came across

Tuning of parameters

Choose ‘clean’ regions away from problems

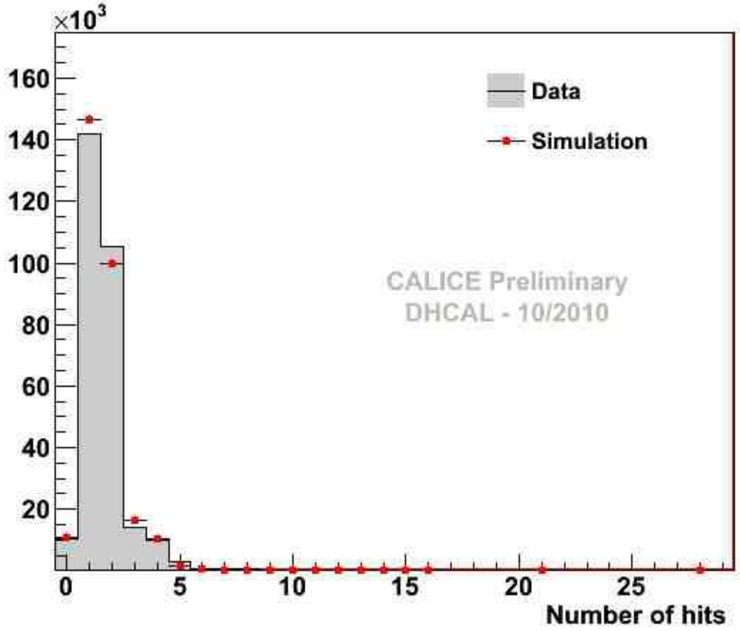
d_{cut} parameter to be tuned later with electrons

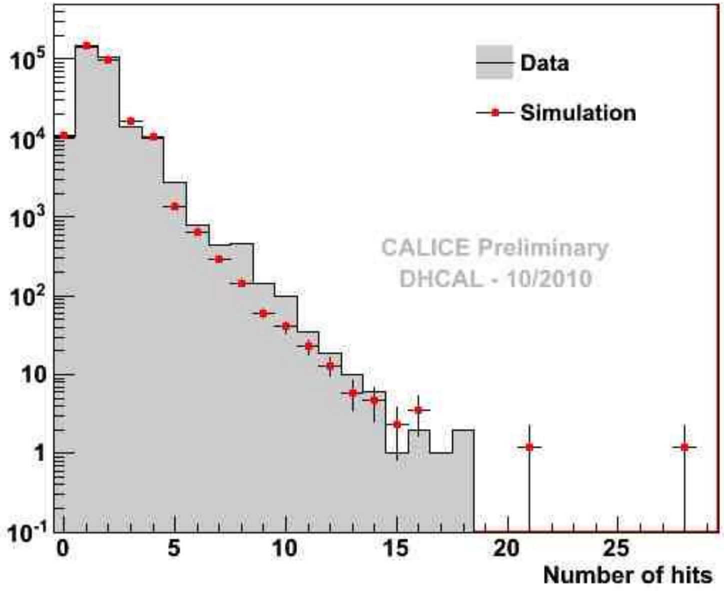
Difficult to tune simultaneously core and tail of distribution

RPC_sim_5 my personal favorite

But RPC_sim_3 only released for public consumption

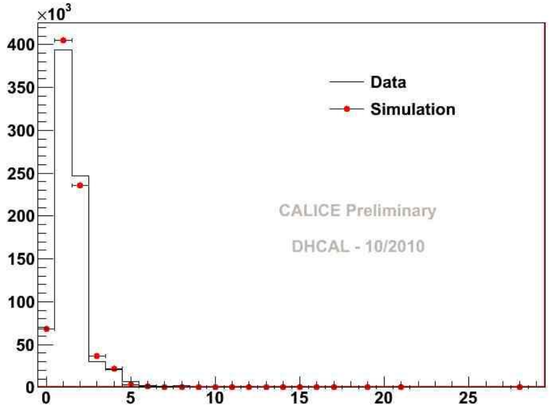
RPC_sim_3 (2 exponentials)

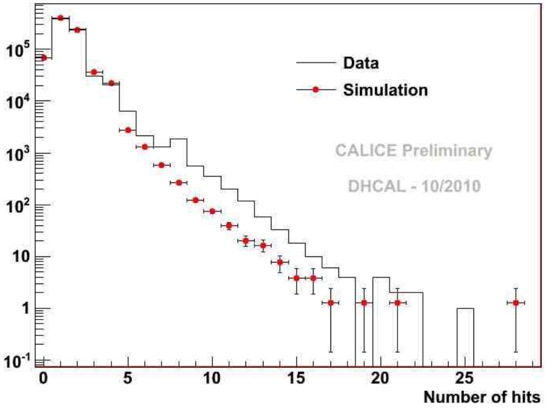




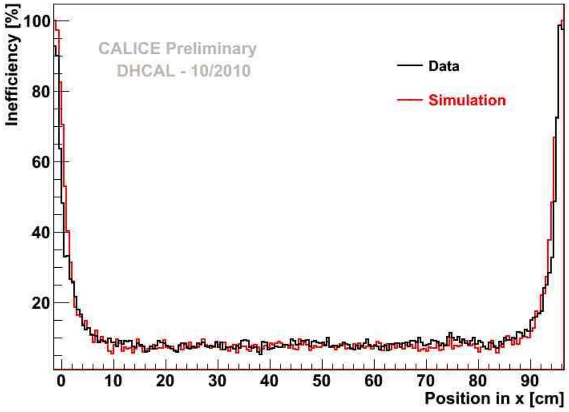
Response in entire plane

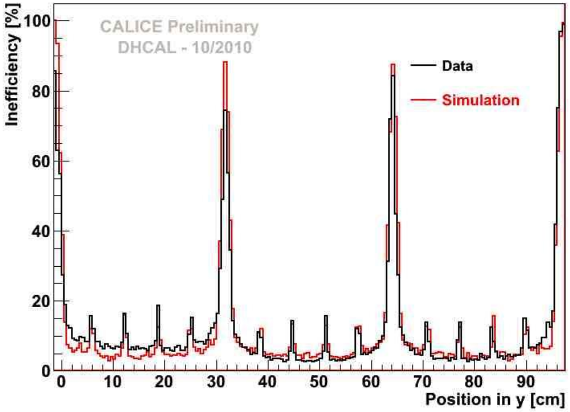
Fishing lines simulated by GEANT4
Loss of efficiency at edges simulated with decrease of Q





RPC_sim_3
(2 exponentials)





Simulation of electrons

In principle only d_{cut} parameter left to tune
Different RPC_sim programs result in widely different

Response
Shower shapes
Hit density distributions

→ The simulation of the tail in the muon spectra is important

Simulation of pions

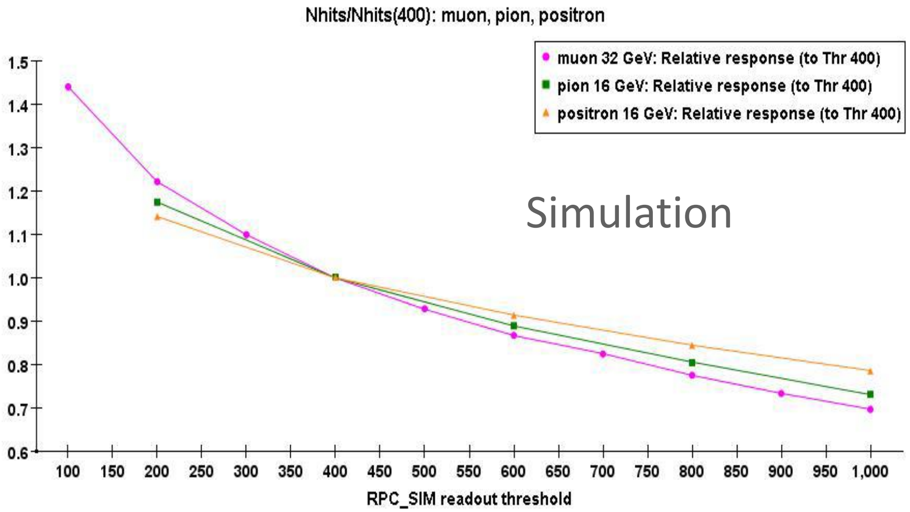
No additional parameters
'Absolute' prediction
Uncertainties in muon simulation packed into systematic error

Back to simulating muons

Attempt to take ionization of particles ($\beta\gamma$) into account
Attempt to take location of ionization in gas gap into account

Calibration of the DHCAL

Correction for differences in efficiency/multiplicities between RPCs



RPC performance

Efficiency to detect MIP ε ~ 95%
Average pad multiplicity μ~ 1.5
Calibration factors C = εμ

Equalize response to MIPS (muons)

$$H_{calibrated} = \sum_{i=RPC_0}^{RPC_n} \frac{\varepsilon_0 \mu_0}{\varepsilon_i \mu_i} H_i$$

Full calibration

Calibration for secondary beam

If more than 1 particle contributes to signal of a given pad
→ Pad will fire, even if efficiency is low
→ Full calibration will overcorrect

Density weighted calibration

Warning:
This is rather
COMPLICATED

Derived entirely based on Monte Carlo

Assumes correlation between

Density of hits ↔ Number of particles contributing to signal of a pad

Mimics different operating conditions with

Different thresholds

Utilizes fact that hits generated with the

Same GEANT4 file, but different operating conditions can be correlated

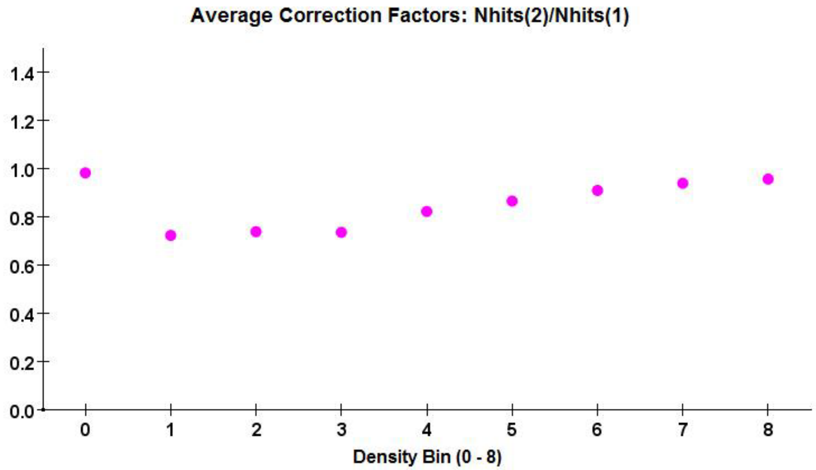
Defines density bin for each hit

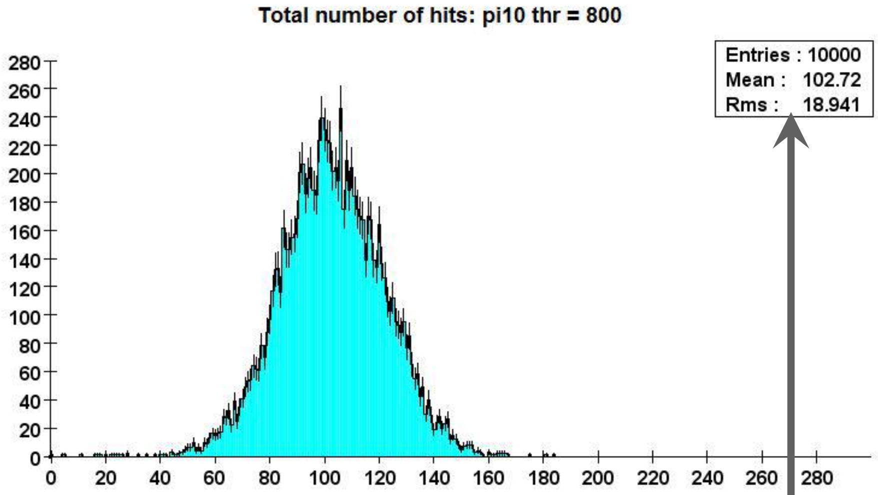
Bin 0 – 0 neighbors, bin 1 – 1 neighbor …. Bin 8 – 8 neighbors

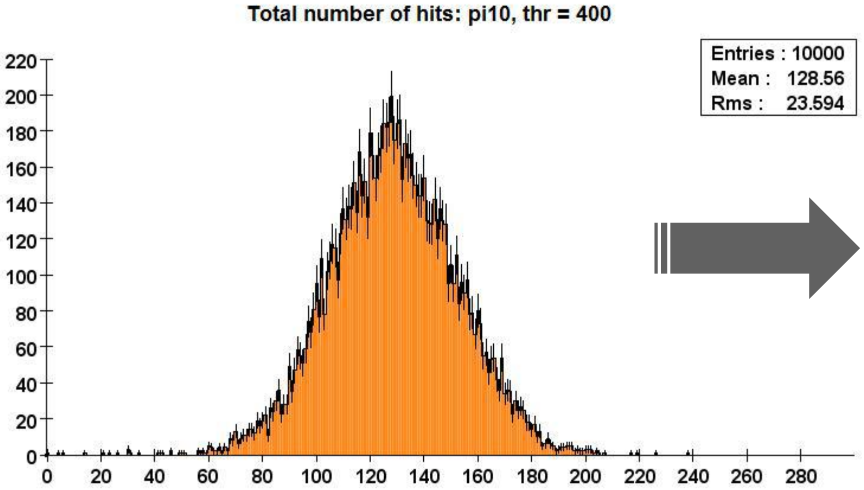
Weights each hit

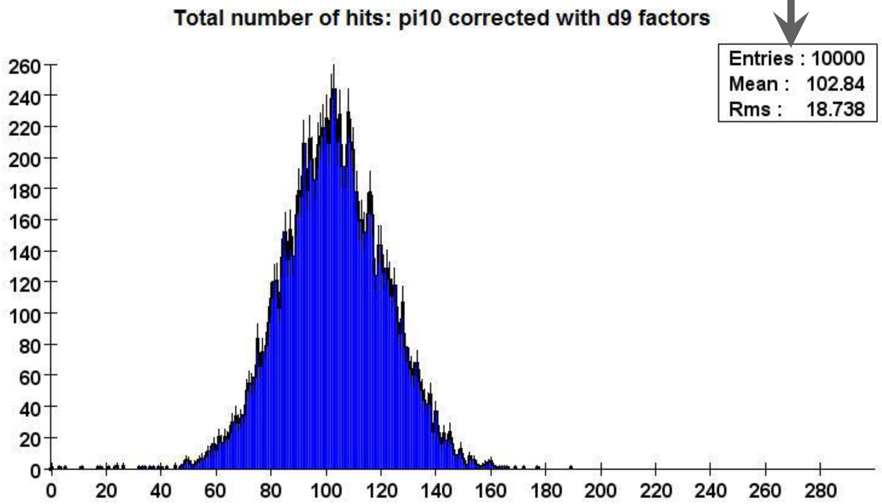
To restore desired density distribution of hits

Example: 10 GeV pions: Correction from T=400⟶ T=800


Average Correction Factors: Nhits(2)/Nhits(1)


Total number of hits: pi10 thr = 800


Total number of hits: pi10, thr = 400


Total number of hits: pi10 corrected with d9 factors

Expanding technique to large range of operating conditions

GEANT4 files

Positrons: 2, 4, 10, 16, 20, 25, 40, 80 GeV
Pions: 2, 4, 8, 9.9 19.9 25, 39.9 79.9 GeV

Digitization with RPC_sim

Thresholds 0f 0.2, 0.4, 0.6, 0.8, 1.0

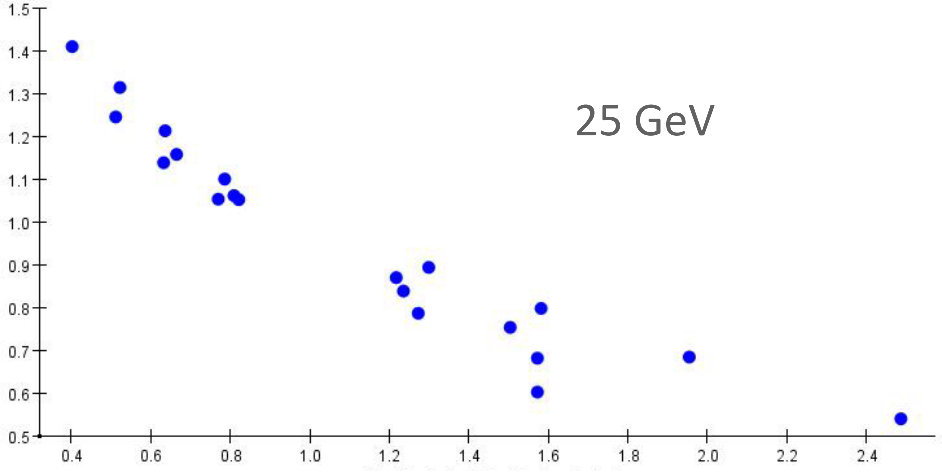
Calculate calibration factors

Use one sample as ‘data’
Correct to another sample used as ‘target’
Use all combinations of ‘data’ and ‘target’

Plot

For each density bin, plot C as function of R = $(\varepsilon_T\mu_T)/(\varepsilon_D\mu_D)$
→ Some scattering of the points

π: Density bin 3



25 GeV

R = $(\varepsilon_T\mu_T)/(\varepsilon_D\mu_D)$

Empirical function of ε_T, μ_T, ε_D, μ_D

Positrons

$$R_e = \frac{\varepsilon_T^{0.3}\mu_T^{2.0}}{\varepsilon_D^{0.3}\mu_D^{2.0}}$$

Pions

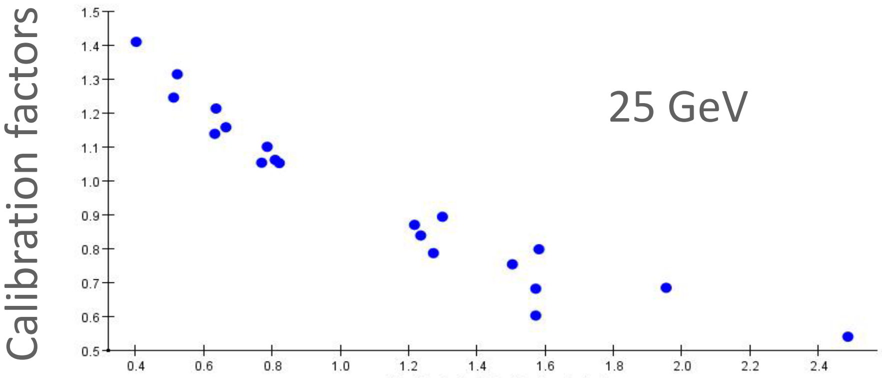
$$R_\pi = \frac{\varepsilon_T^{0.3}\mu_T^{1.5}}{\varepsilon_D^{0.3}\mu_D^{1.5}}$$

Different energies

Similar results

→ Assume CF energy independent

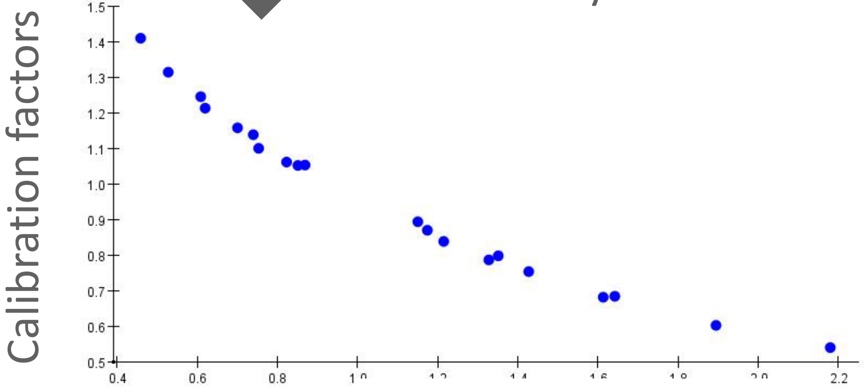
π: Density bin 3



25 GeV

$R = (\varepsilon_T\mu_T)/(\varepsilon_D\mu_D)$

π: Density bin 3



$R = (\varepsilon_T\mu_T)^{0.3}/(\varepsilon_D\mu_D)^{1.5}$

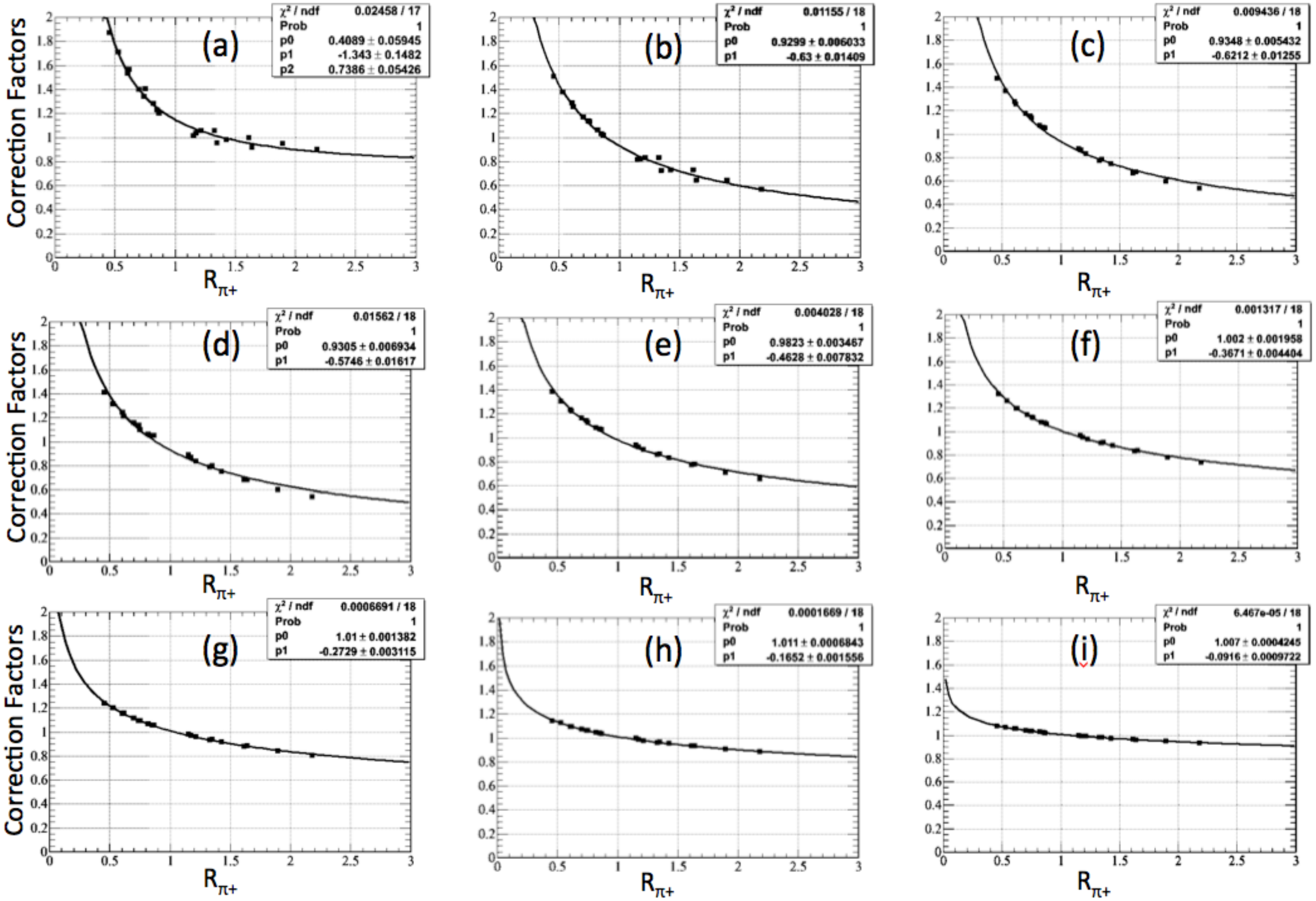
Fits of CFs as function of R

Power law $C = \alpha R_p^{\beta}$

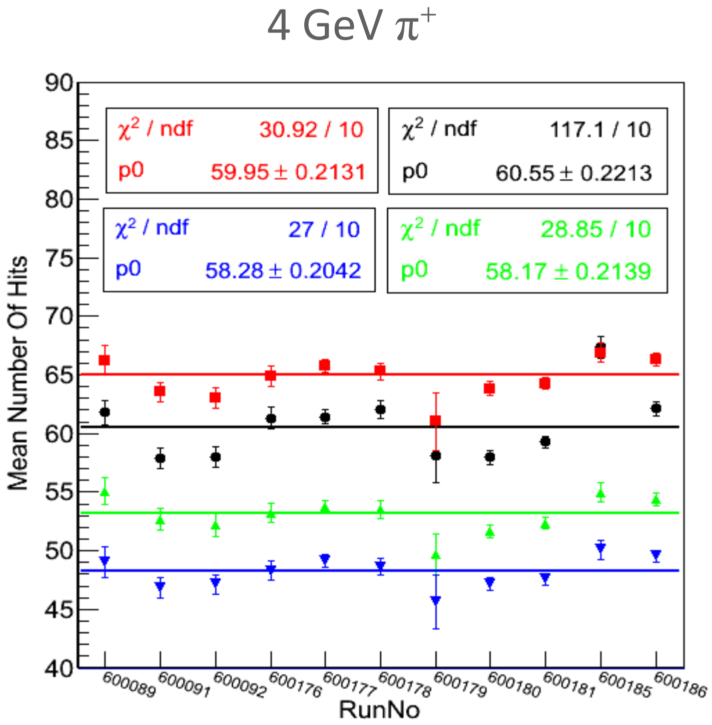
Pion fits

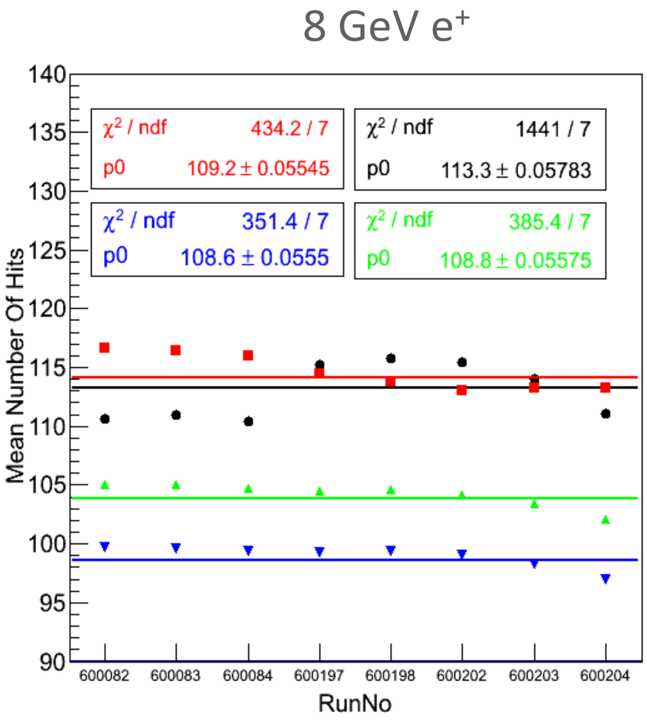
Positron fits

similar



Calibrating different runs at same energy





Uncalibrated response

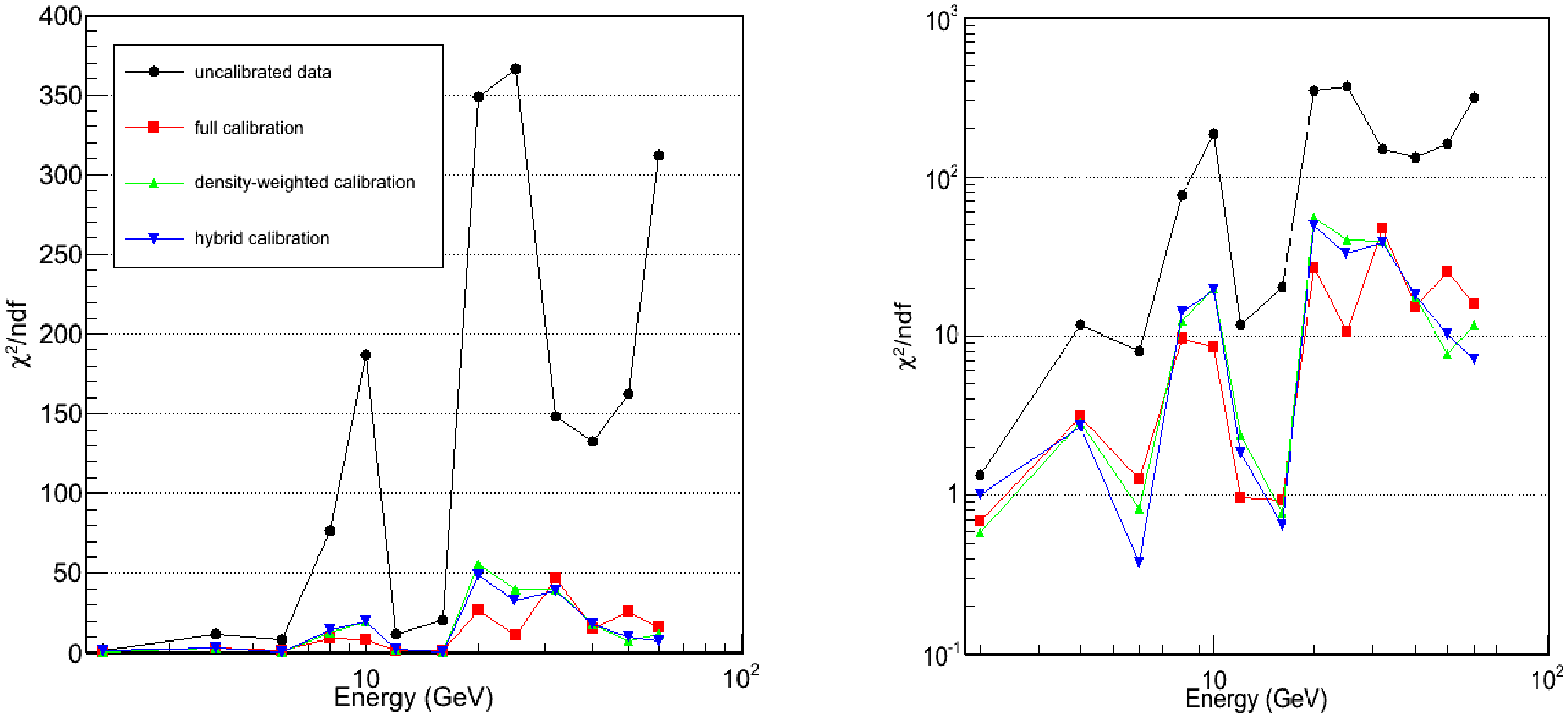
Full calibration

Density – weighted calibration

Hybrid calibration (density bins 0 and 1 receive full calibration)

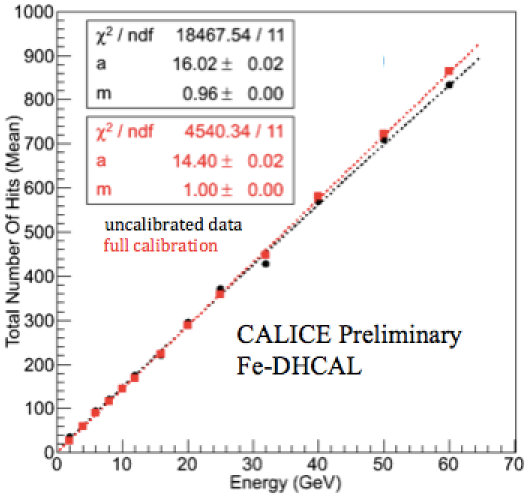
Comparison of different calibration schemes

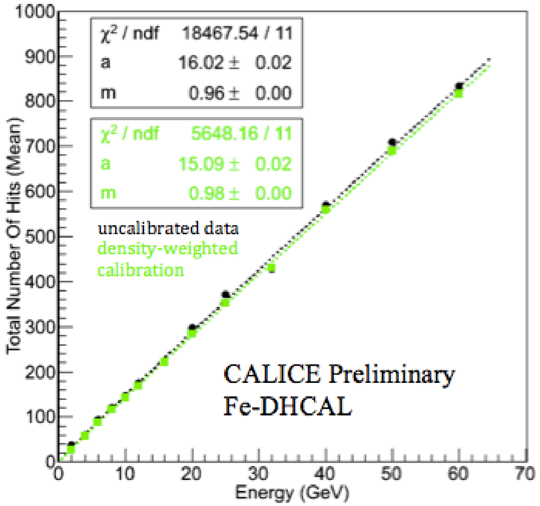
χ^2 of distribution of means for different runs at same energy

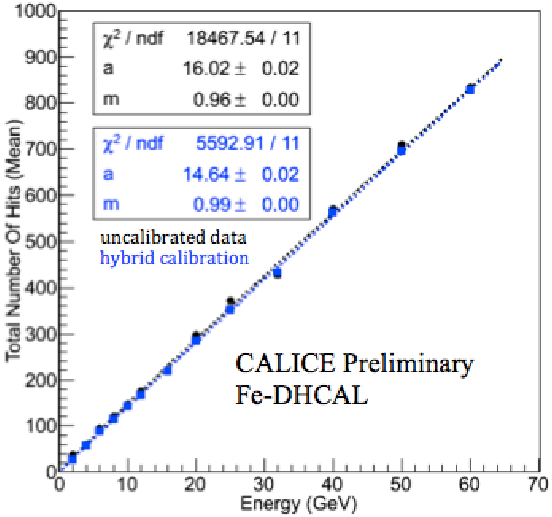


→ **All three schemes improve the spread**

Linearity of pion response: fit to aE^m







Uncalibrated response

4% saturation

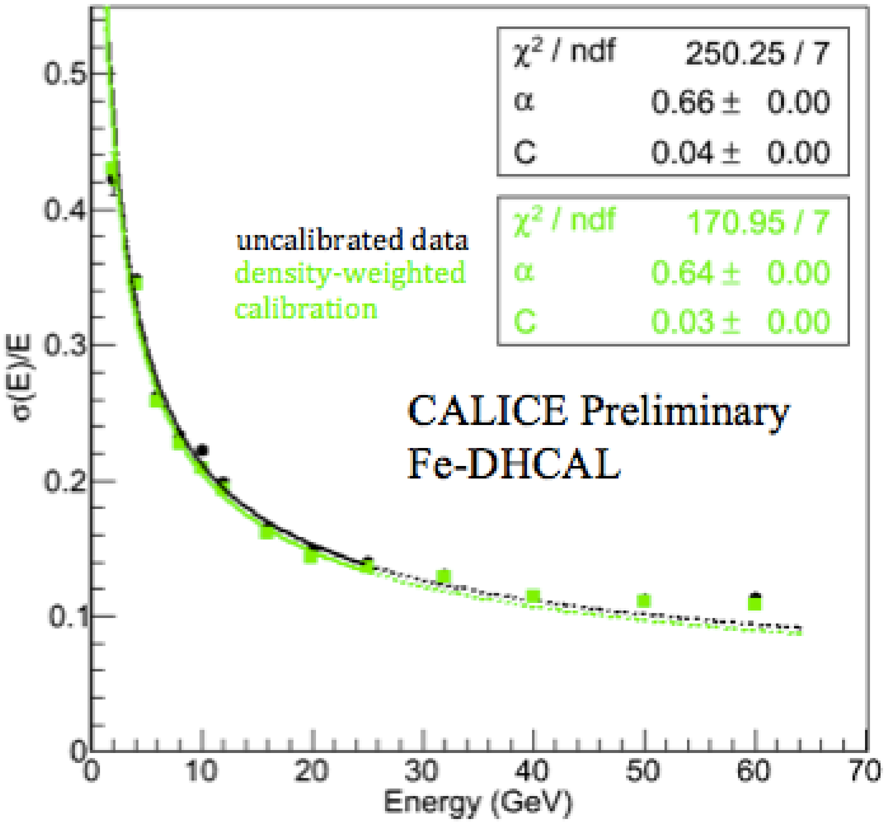
Full calibration

Perfectly linear up to 60 GeV (in contradiction to MC predictions)

Density- weighted calibration/Hybrid calibration

1 – 2% saturation (in agreement with predictions)

Resolution for pions



Calibration

Improves result somewhat

Monte Carlo prediction

Around 58%/√E
with negligible constant term

Saturation at higher energies

→ Leveling off of resolution

Software compensation

Typical calorimeter

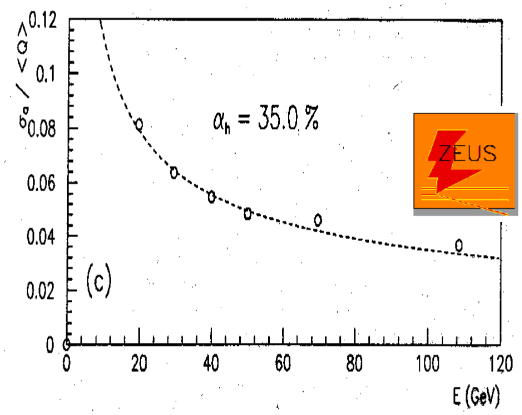
Unequal response to electrons and hadrons
Hadronic showers contain varying fraction of photons
→ Degraded resolution for hadrons

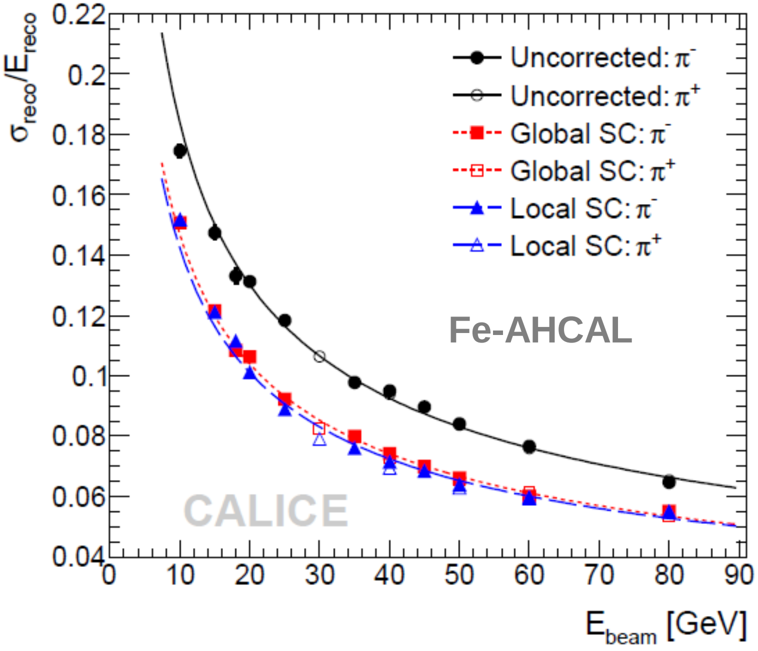
Hardware compensation

Equalization of the electron and hadron response
Careful tuning of scintillator and absorber thicknesses
ZEUS calorimeter best example

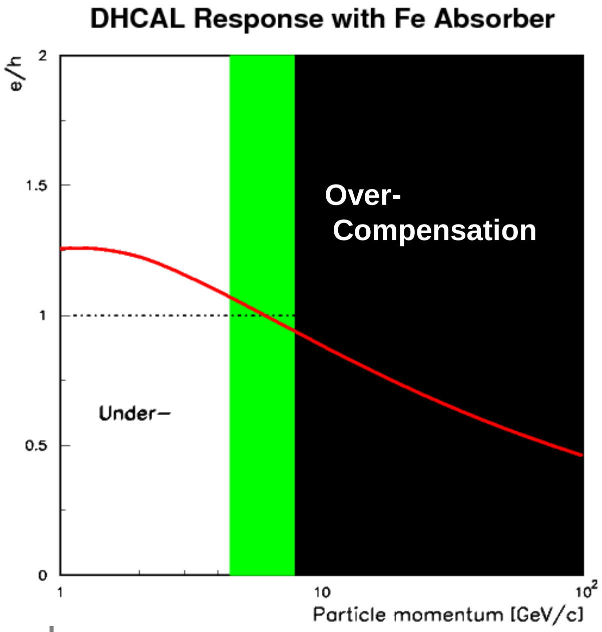
Software compensation

Identification of electromagnetic subshowers
Different weighting of em and hadronic shower deposi
Significant improvement of hadronic resolution





Compensating the DHCAL



Response of the DHCAL

Em response is highly non-linear (saturating)
Hadronic response is close to linear
Response compensating around 8 GeV

Definition of hit density

Defined for each hit
Hit density = number of close-neighbor hits in the same plane

Assumption

Hit density is related to local particle density

Studies limited to simulation

Linearize the em response

By weighting hits in each hit density bins

Check the hadronic response and resolution

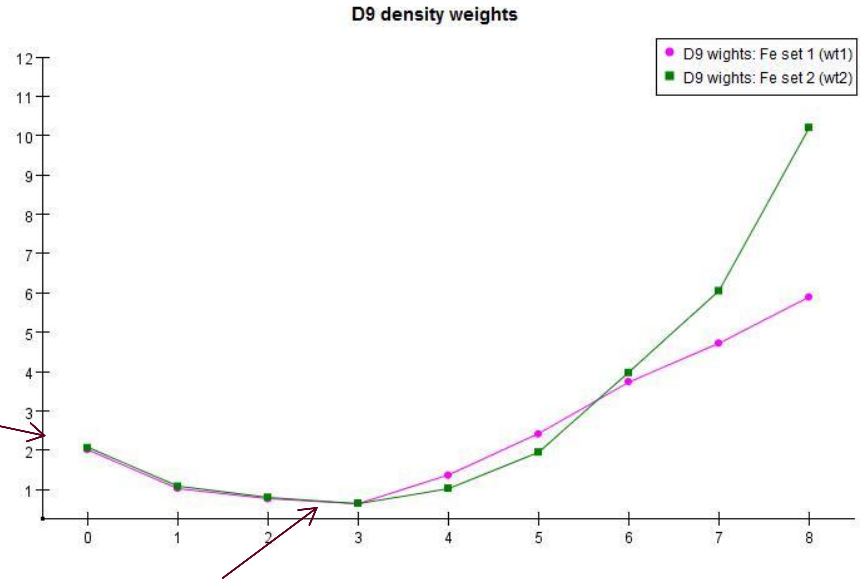
Linearizing the EM Response – Fe-DHCAL

Simulation of positron showers

Set 1: 2, 6, 10, 16, 25 GeV
Set 2: 2, 6, 16 , 32, 60 GeV

Target response

14.74 hits/GeV (arbitrary)
Weights calculated such that linearity is optimized

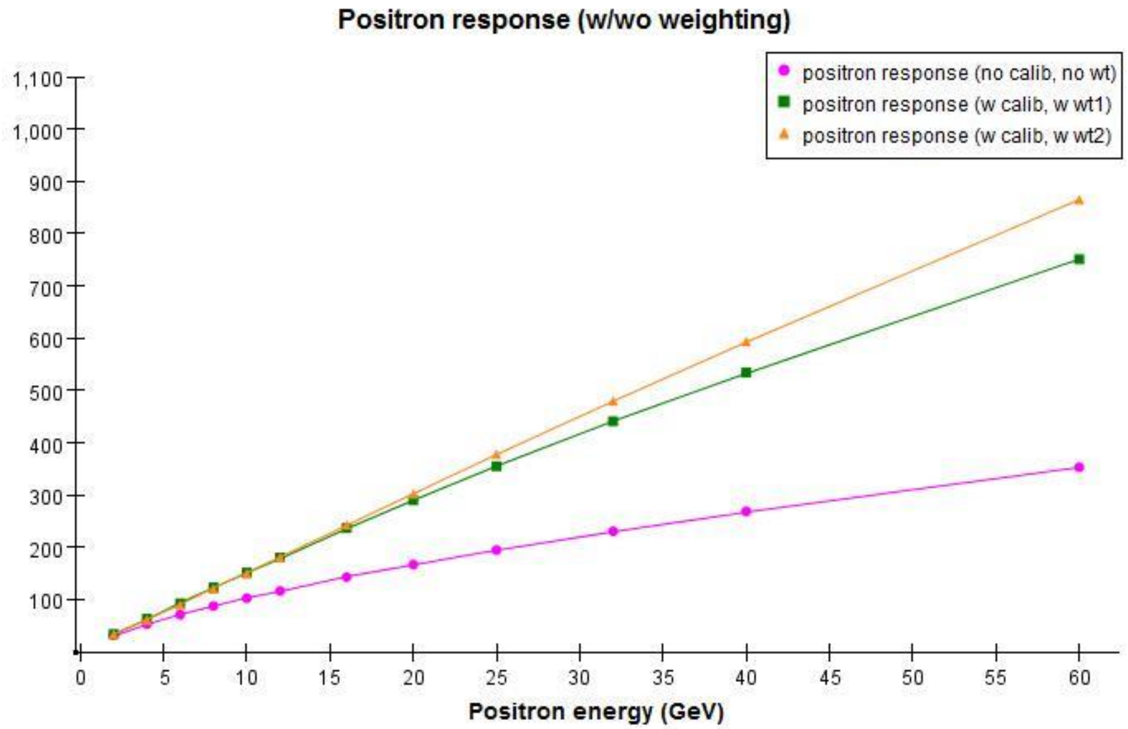


High weights for
isolated hits

Very high weight for
high density bins:
correction for saturation

Low weights for medium density: mostly due to hit multiplicity ~ 1.6

Positron Response after Weighting – Fe-DHCAL



$16.687 \times E^{0.966}$

(set 2 weights)

$20.240 \times E^{0.885}$

(set 1 weights)

$20.866 \times E^{0.692}$

(no weights)

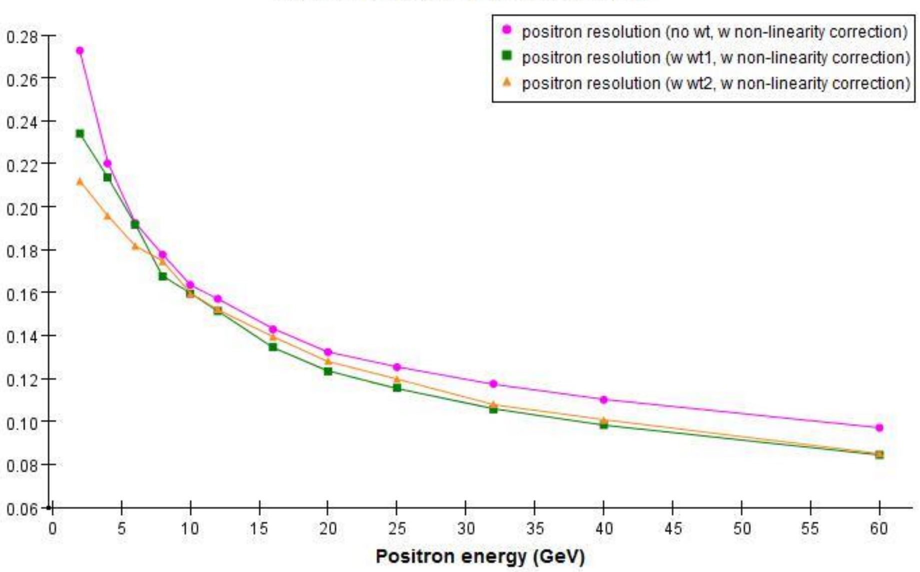
Fits to power law αE^{β}

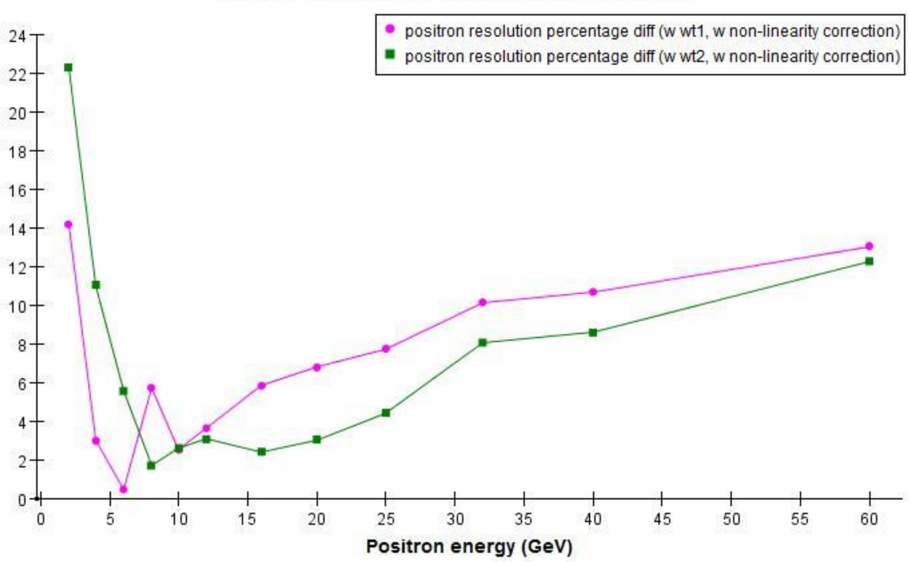
β=1 means **linear**

Results as expected

Linearity significantly improved
Set 2 weights provide better results

Positron Resolution after Weighting – Fe-DHCAL

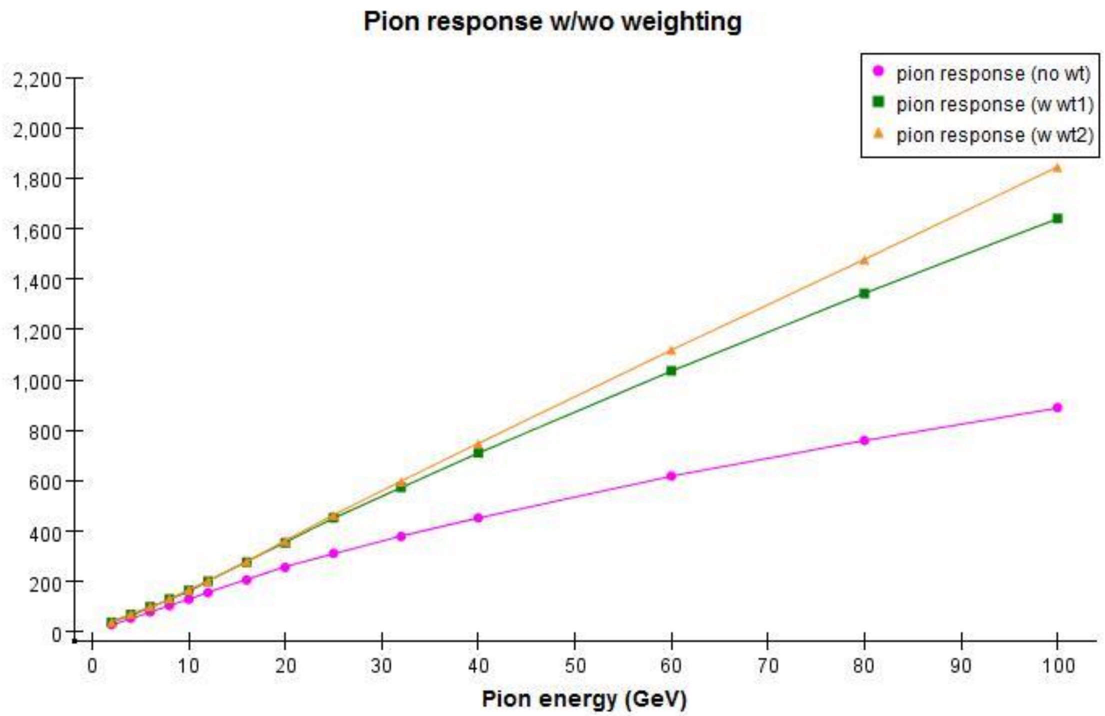

Positron resolution (w/wo weighting)


Percentage improvement of positron resolution

Results

Corrected for non-linearity effects (important!)
Resolution calculated from full-range Gaussian fits (not good at low energy)
Not much difference between set 1 and 2
Overall modest improvement (as expected)

Pion Response after Weighting – Fe-DHCAL



$17.690 \times E^{1.010}$

(set 2 weights)

$20.500 \times E^{0.954}$

(set 1 weights)

$22.918 \times E^{0.799}$

(no weights)

Fits to power law αE^{β}

β=1 means **linear**

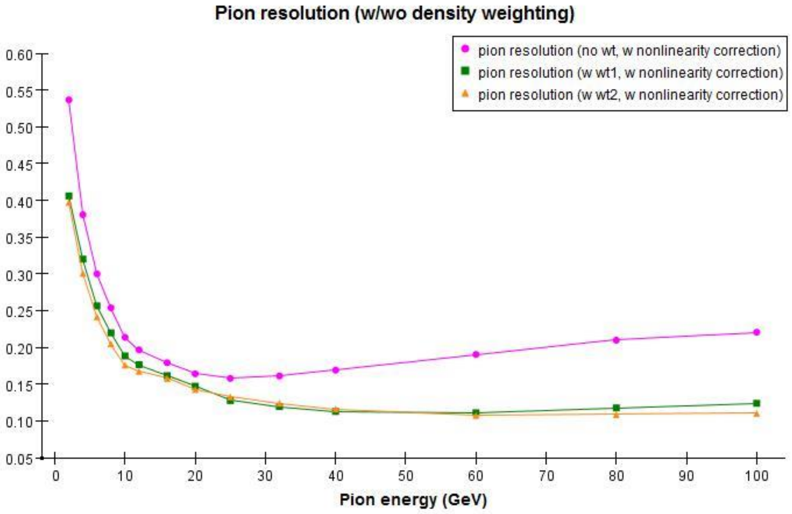
Results

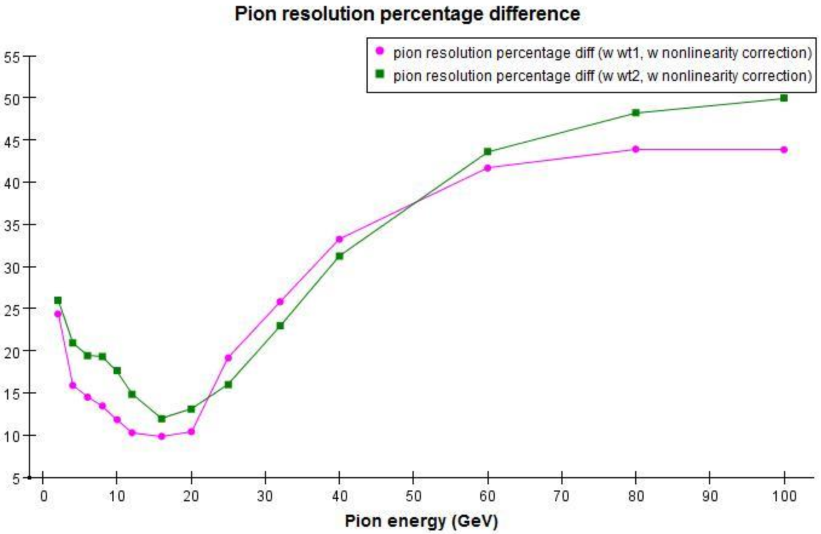
Un-weighted linearity much worse than in data

→ Due to differences in real and simulated avalanches in RPCs

Leakage cut applied: no more than 10 hits in tail catcher

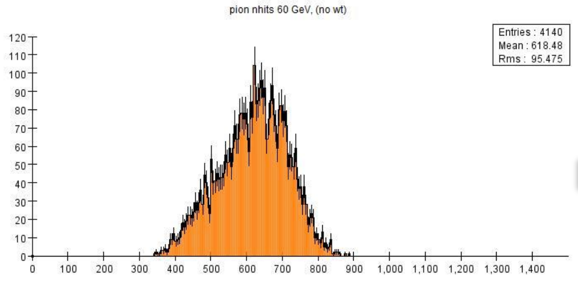
Pion Resolution after Weighting – Fe-DHCAL

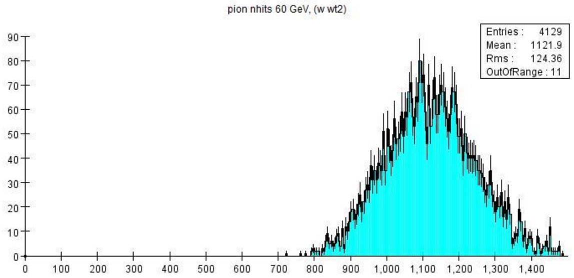




Results

Pion linearity and resolution significantly improved
At high energies, distributions become more symmetric
→ Example: 60 GeV pions





Software Compensation in Data – Fe-DHCAL

Results

Similar to simulation, but not quite as good
(e/h closer to unity in data)

A few issues to be sorted out, such as contamination in data sample

Not yet approved for public consumption

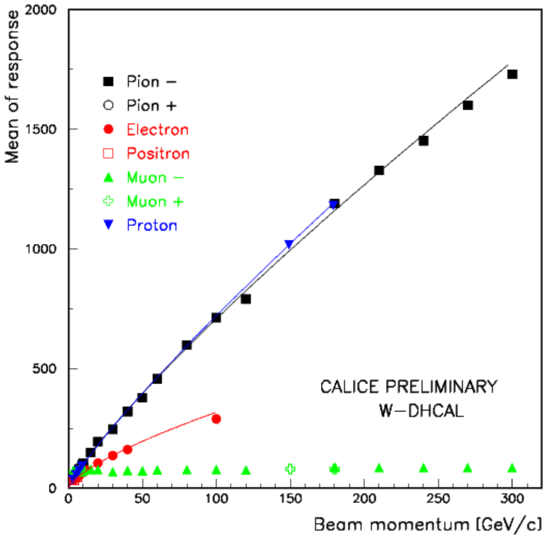
Software Compensation in Simulation – W-DHCAL

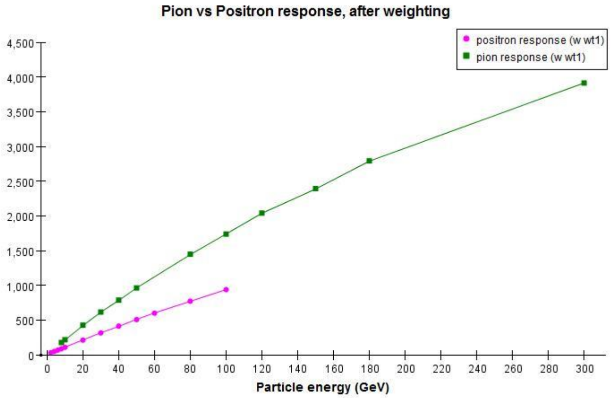
Comparison with the Fe-DHCAL

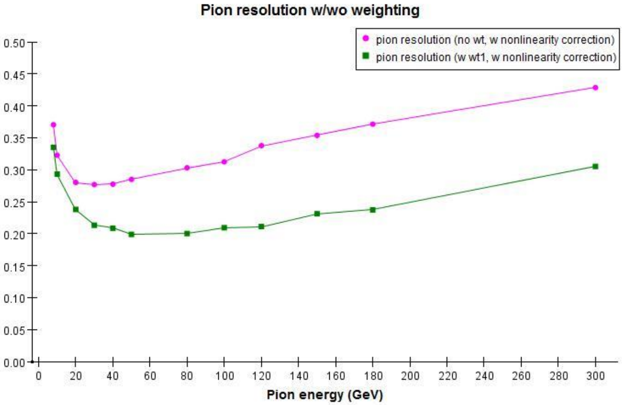
e/h much smaller than for Fe-DHCAL
→ Expect larger improvement

Pion results

Linearity improved, but e/h still far from unity
Resolution improved by 25 – 50%
Distributions improved, but tail remains

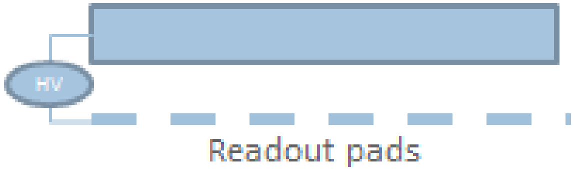






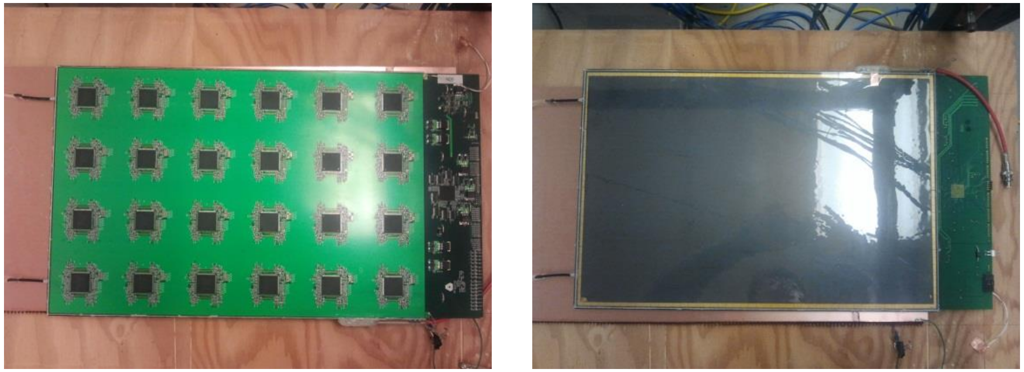
Further R&D

1-glass RPCs



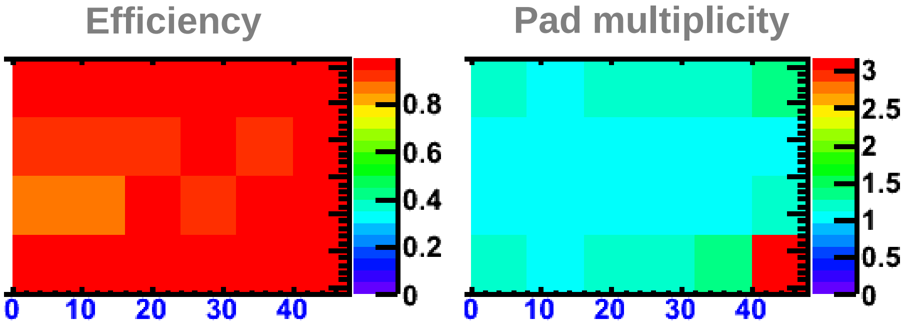
Offers many advantages

Pad multiplicity close to one
→ easier to calibrate
Better position resolution
→ if smaller pads are desired
Thinner
→ safes on cost
Higher rate capability
→ roughly a factor of 2



Status

Built several large chambers
Tests with cosmic rays very successful
→ chambers ran for months without problems
Both efficiency and pad multiplicity look good



Rate capability of RPCs

Measurement of efficiency

With 120 GeV protons
In Fermilab test beam

Rate limitation

NOT a dead time
But a loss of efficiency

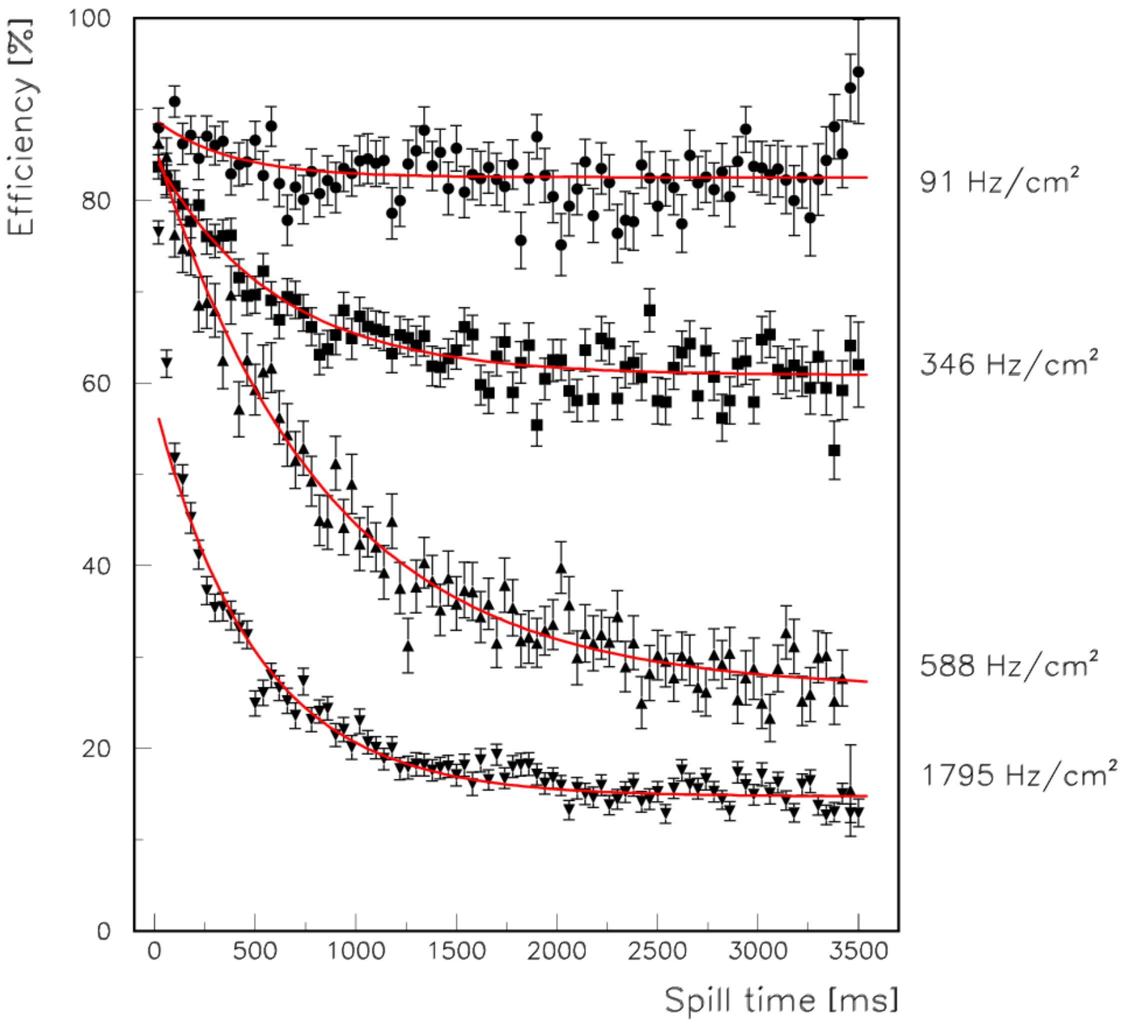
Theoretical curves

Excellent description of effect

Rate capability depends

Bulk resistivity R_{bulk} of resistive plate
(Resistivity of resistive coat)

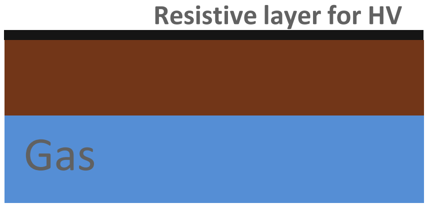
Not a problem for an HCAL at the ILC



B.Bilki et al., JINST 4 P06003(2009)

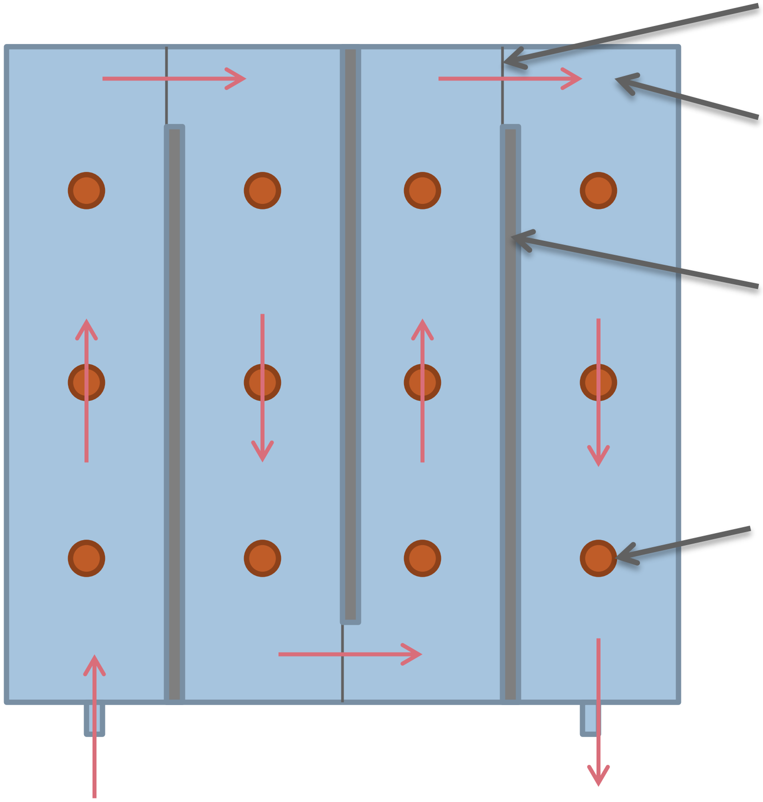
High-rate Bakelite RPCs

Bakelite does not break like glass,
is laminated
but changes R_{bulk} with depending on humidity
but needs to be coated with linseed oil



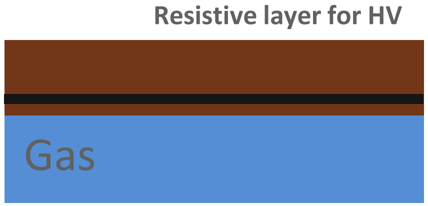
Use of low R_{bulk} Bakelite with $R_{bulk} \sim 10^8 - 10^{10}$ and/or Bakelite with resistive layer close to gas gap

Several chambers built at ANL



High-rate Bakelite RPCs

Bakelite does not break like glass,
is laminated
but changes R_{bulk} with depending on humidity
but needs to be coated with linseed oil



Use of low R_{bulk} Bakelite with
$R_{bulk} \sim 10^8 - 10^{10}$ and/or Bakelite
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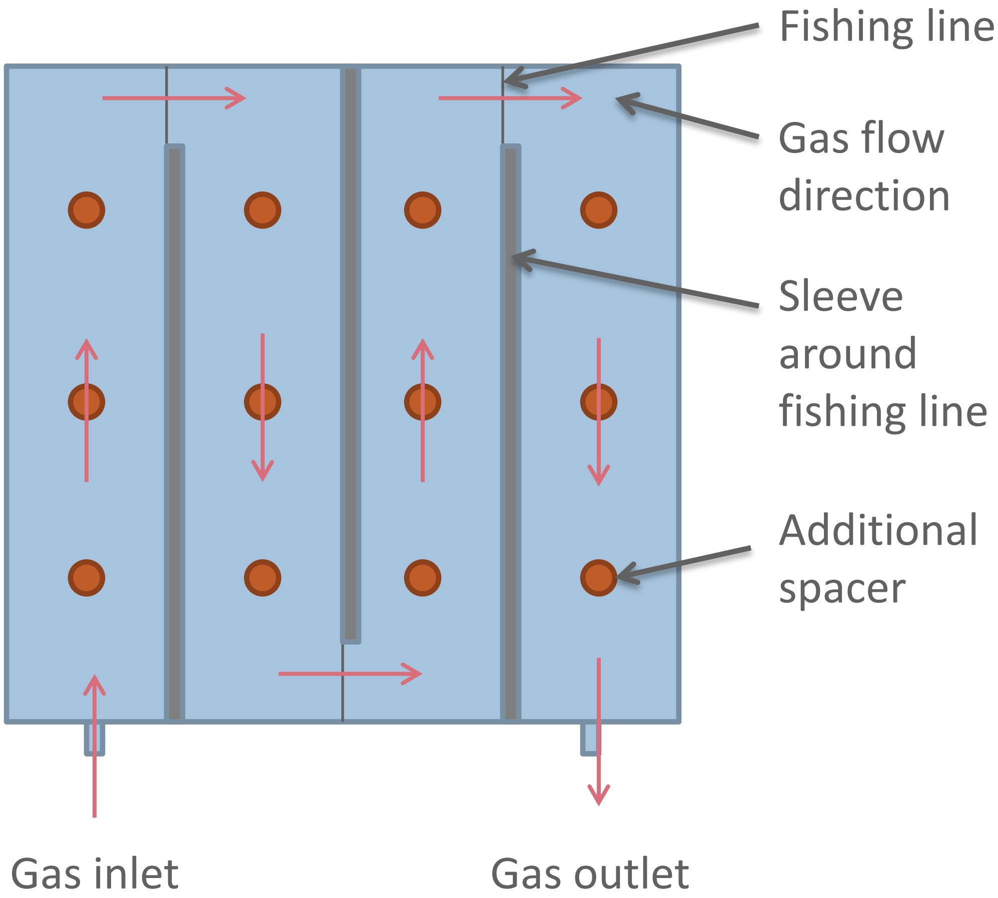
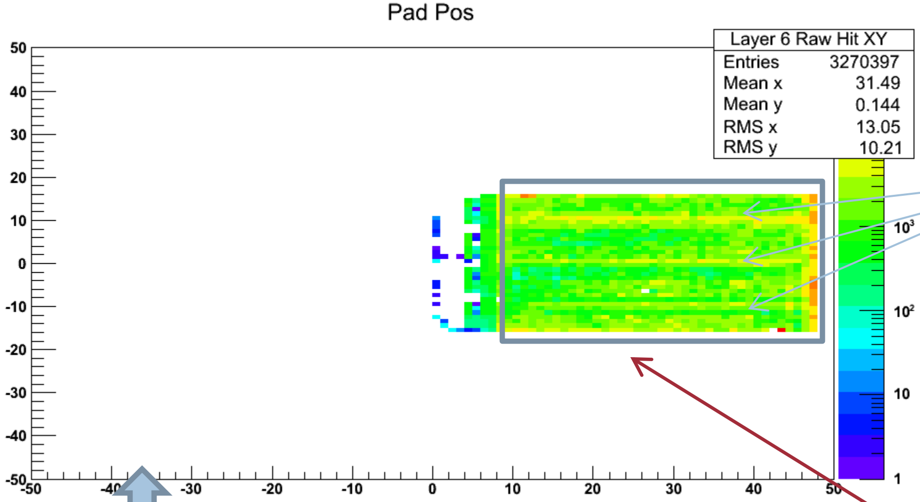
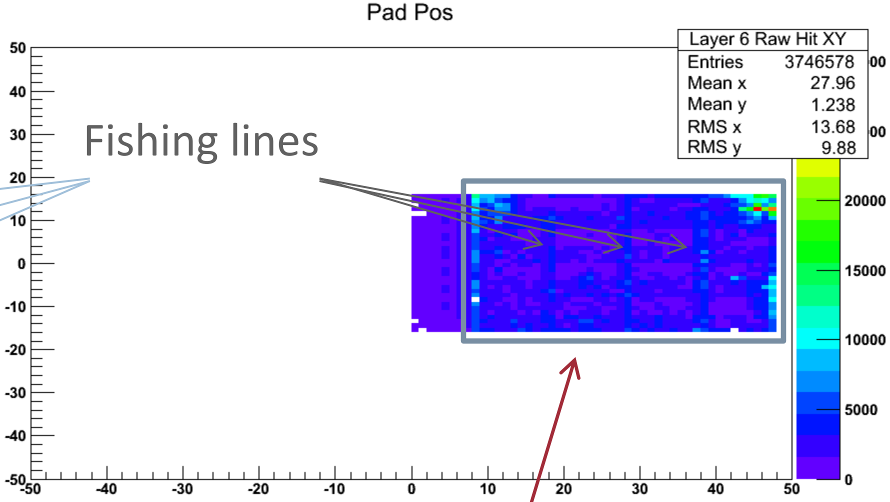


Noise measurement: B01

(incorporated resistive layers)

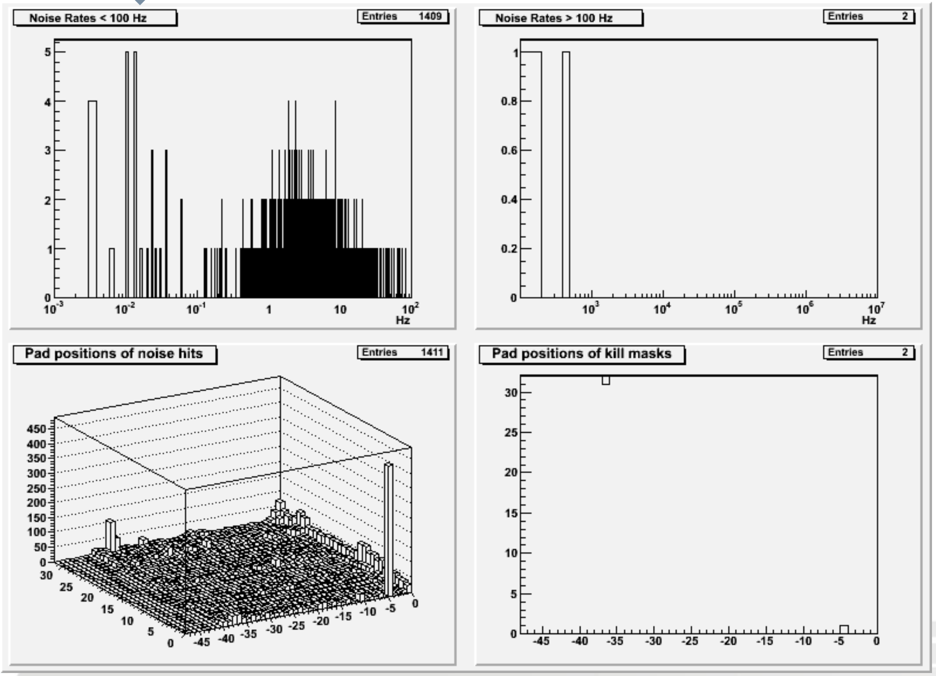




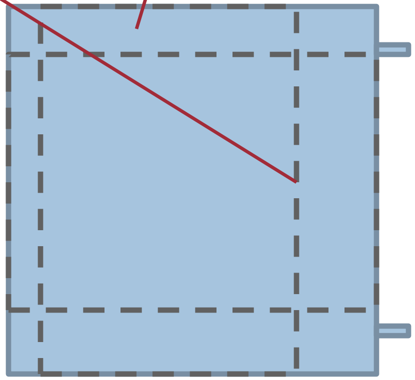
Fishing lines

1st run at 6.4 kV

Last run, also 6.4kV, RPC rotated 90⁰



Readout area



Noise measurements

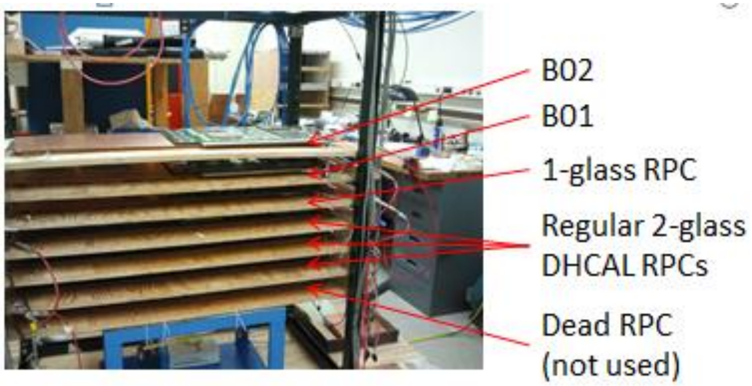
Applied additional insulation

Rate 1 – 10 Hz/cm^2 (acceptable)

Fishing lines clearly visible

Some hot channels (probably on readout board)

No hot regions

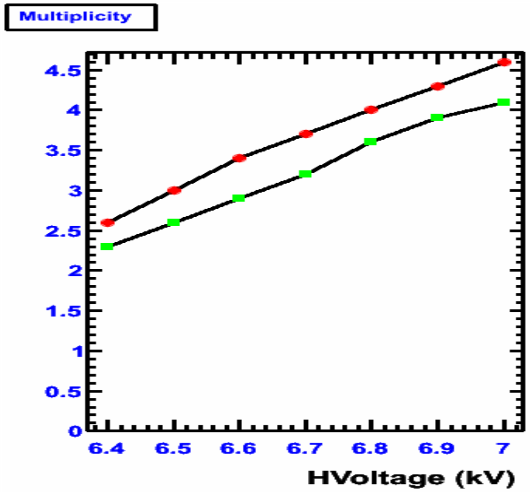


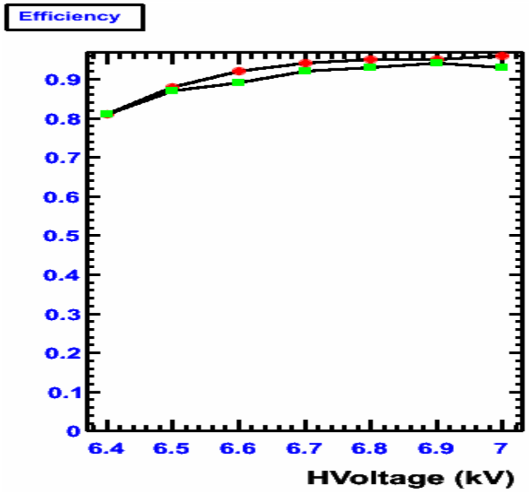
Cosmic ray tests

Stack including DHCAL chambers for tracking

Efficiency, multiplicity measured as function of HV

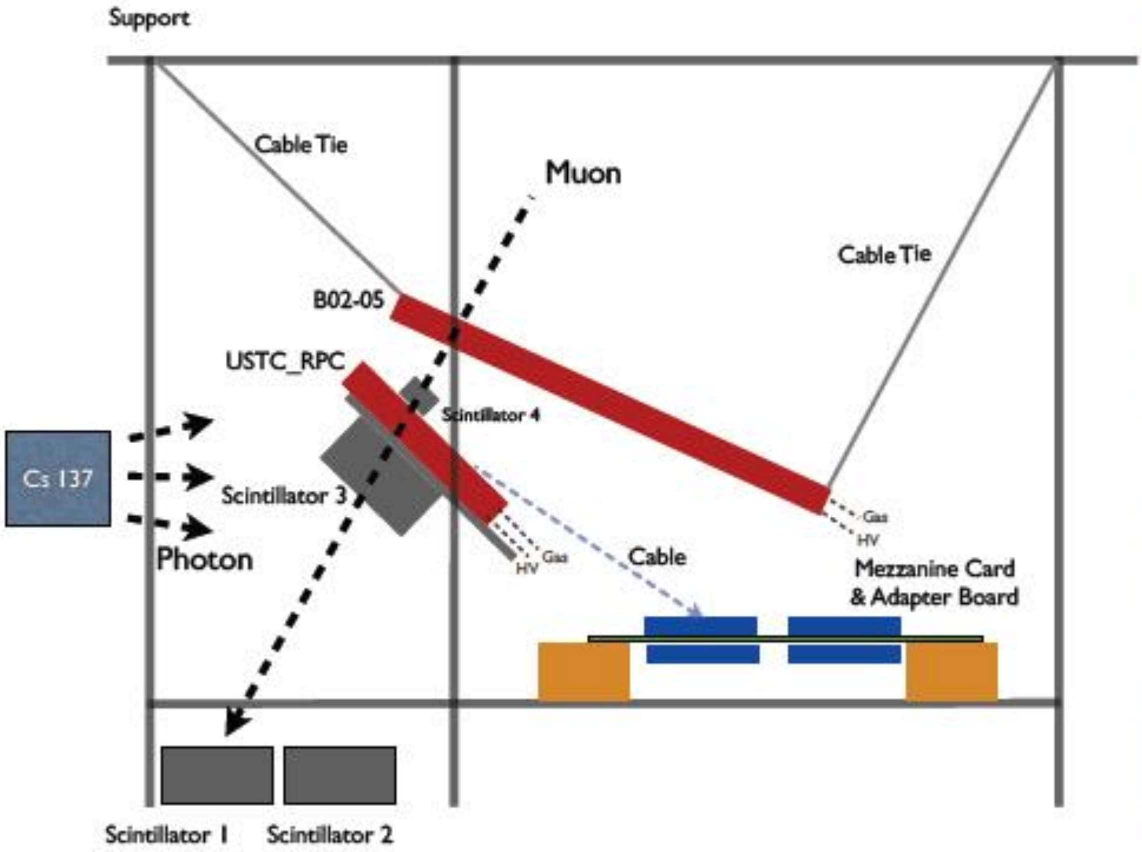
High multiplicity due to Bakelite thickness (2 mm)

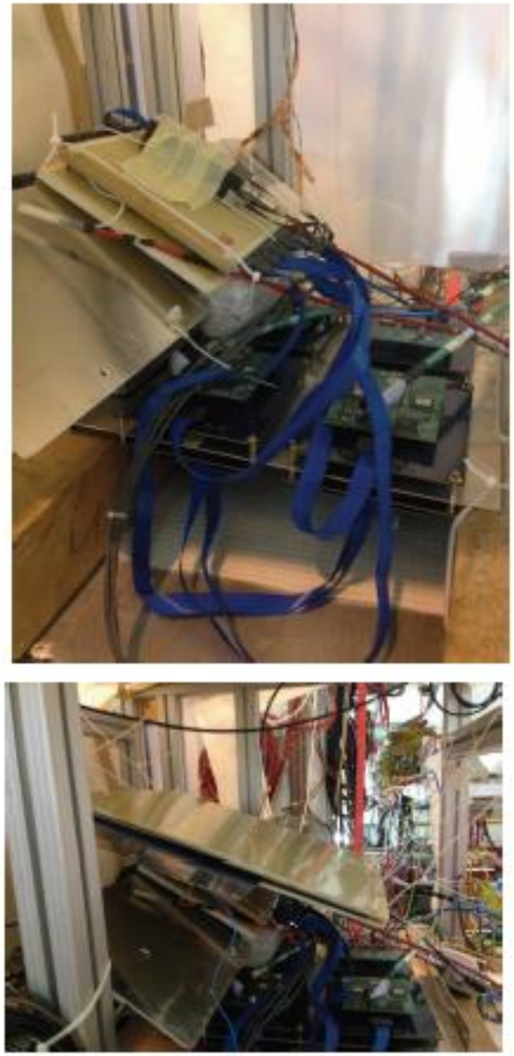




GIF Setup at CERN

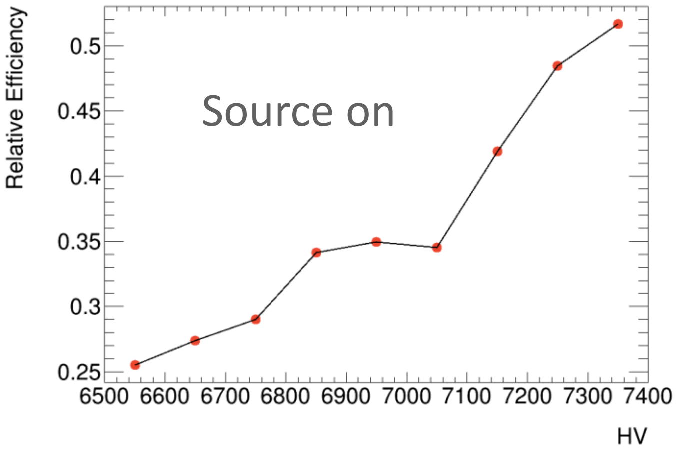
Trigger = (Sci1 or Sci2) and Sci3

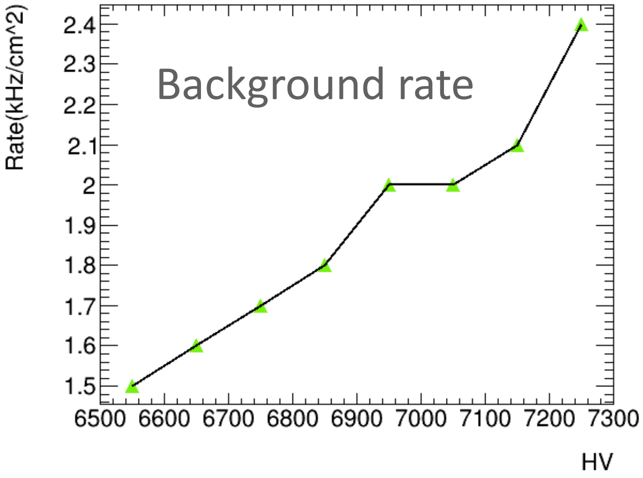


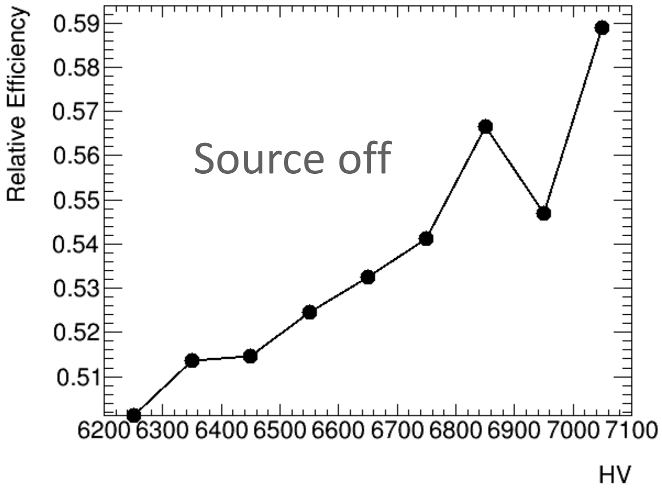


Tests carried out by University of Michigan, USTC, Academia Sinica

First results from GIF







Absolute efficiency not yet determined

Clear drop seen with source on

Background rates not corrected for efficiency drop

Irradiation levels still to be determined (calculated)

Development of semi-conductive glass

Co-operation with COE college (Iowa) and University of Iowa

⬇

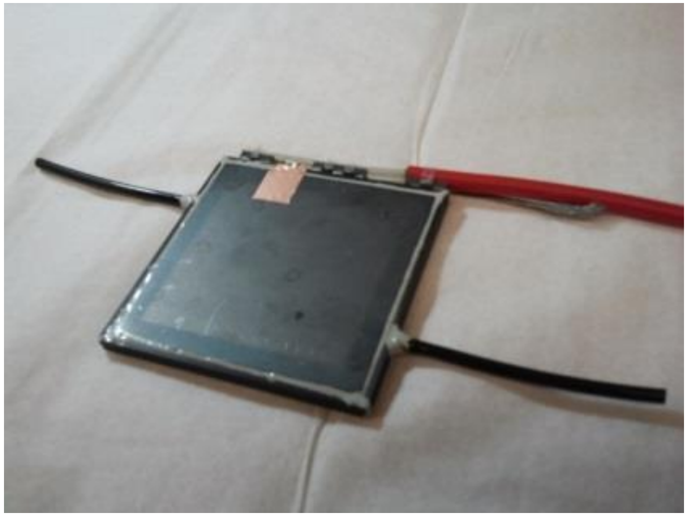
World leaders in glass studies and development

Development of Vanadium based glass (resistivity tunable)

First samples produced with very low resistivity R_{bulk} ~ 10^8 Ωcm

New glass plates with R_{bulk} ~ 10^{10} Ωcm in production

Glass to be manufactured industrially (not expensive)



High Voltage Distribution System

Generally

Any large scale imaging calorimeter will need to distribute power in a safe and cost-effective way

HV needs

RPCs need of the order of 6 – 7 kV

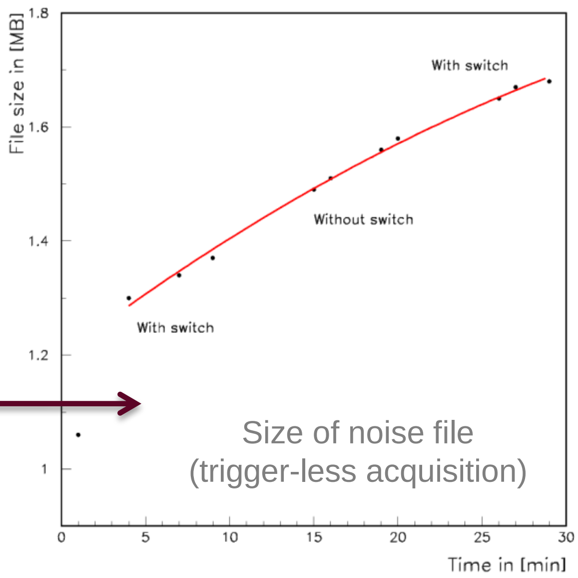
Specification of distribution system

Turn on/off individual channels
Tune HV value within restricted range (few 100 V)
Monitor voltage and current of each channel

Status

Iowa started development
First test with RPCs encouraging
Work stopped due to lack of funding

Threshold at 80



Size of noise file
(trigger-less acquisition)

Gas Recycling System

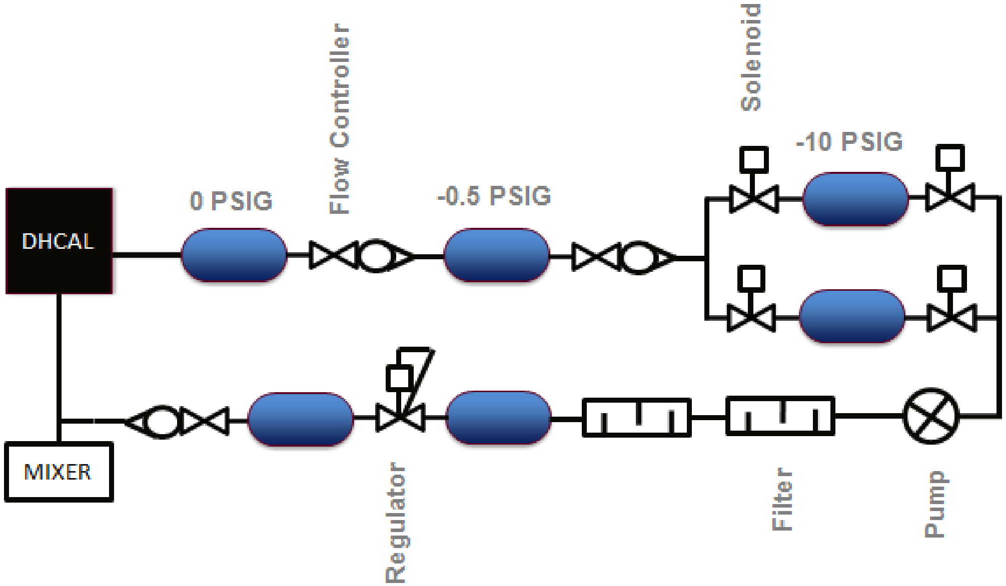
DHCAL's preferred gas

Gas	Fraction [%]	Global warming potential (100 years, $CO_2 = 1$)	Fraction * GWP
Freon R134a	94.5	**1430**	1351
Isobutan	5.0	3	0.15
SF_6	0.5	**22,800**	114

Recycling mandatory for larger RPC systems

Development of 'Zero Pressure Containment' System

Work done by University of Iowa/ANL



Status

First parts assembled…

Summary

The DHCAL

was successfully designed and built (2008 – 2010)
was successfully tested at FNAL with Fe-absorber plates (2010 – 2011)
was successfully tested at CERN with W- absorber plates (2012)

had few design/operational issues (HV contact, gas gap thickness)

taught us a lot about digital calorimetry (simulation, calibration, software compensation)

The RPC-DHCAL is a viable technology for imaging hadron calorimetry at the ILC

Open issues

optimization (chamber design, pad size ← requires tuning of PFAs)
mechanical integration
power distribution (common to all technologies)
gas recirculation
high-rate capability (ILC forward region)