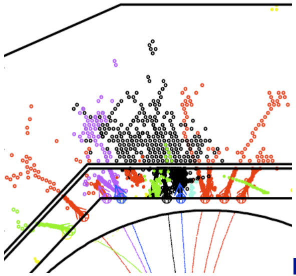
Calorimeter for ILC

Status Report

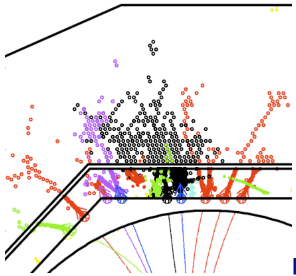
Felix Sefkow

Kick-off Meeting of the ECFA Detector Panel
DESY, Hamburg, May 2, 2012



Outline

- Introduction: Particle Flow and CALICE
- Detector technology projects
- Physics results
- Future plans

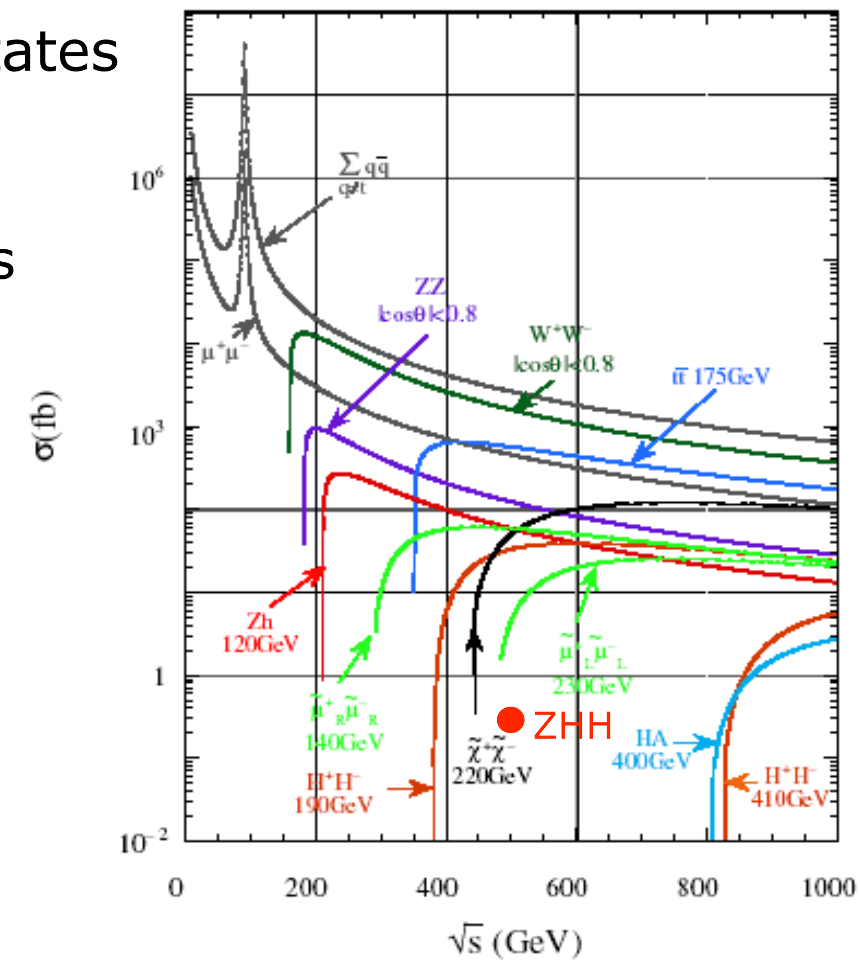


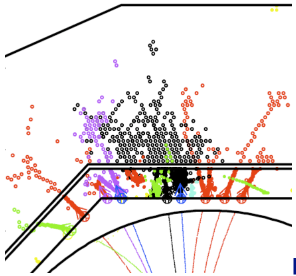
LC jet energies

- e^+e^- physics: exclusive final states
  - Q-Qbar events are boring
  - $E_{jet} = \sqrt{s}/2$ is rare
- Mostly 4-, 6-fermion final states
  - e.g. $e^+e^- \rightarrow ttH \rightarrow$ 8 -10 jets

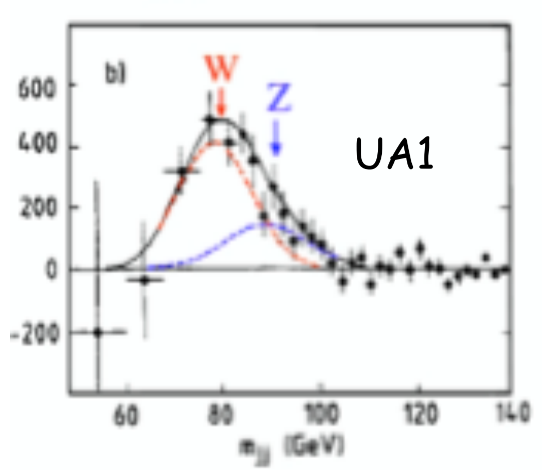
- At ILC 500: E_{jet} = 50…150 GeV
  - Mean pion energy 10 GeV
- At ILC 1 TeV: E_{jet} < ~ 300 GeV
- At CLIC (3 TeV) < ~ 600 GeV

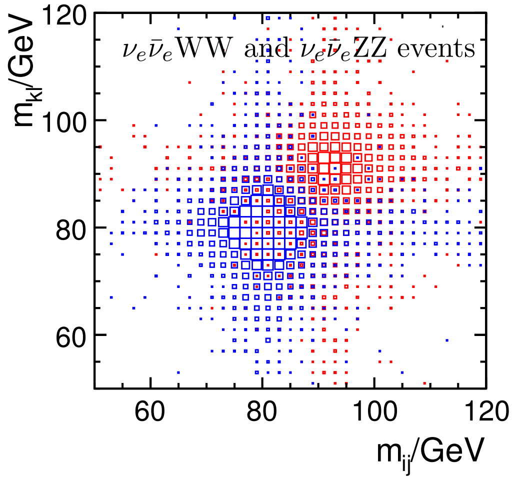
- Resolution matters!

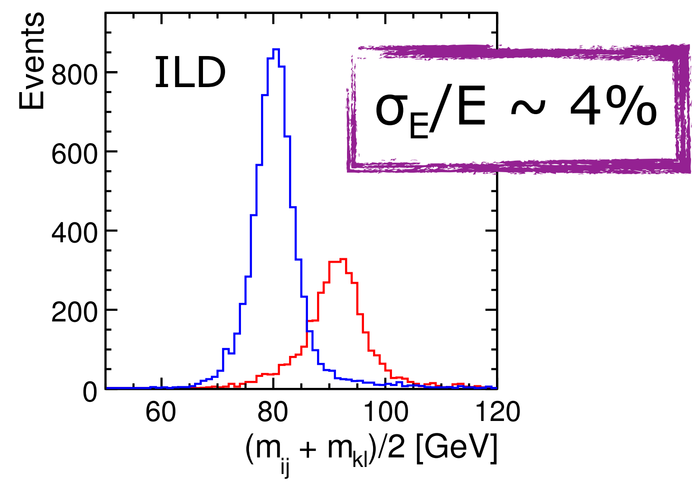


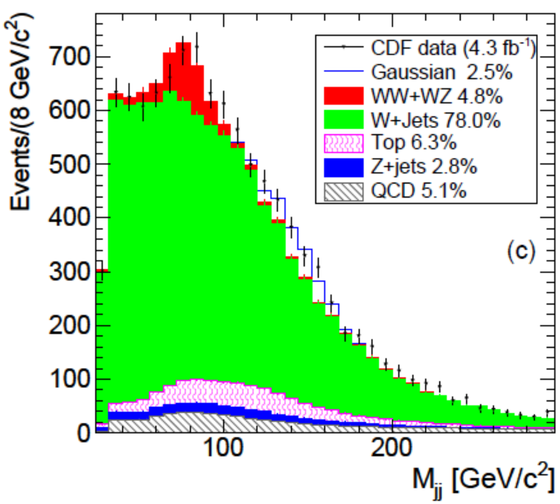


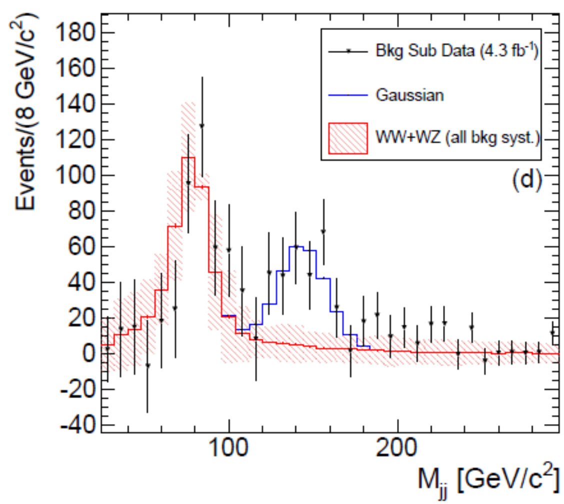
Challenge: W Z separation







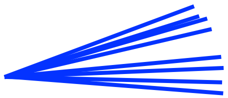




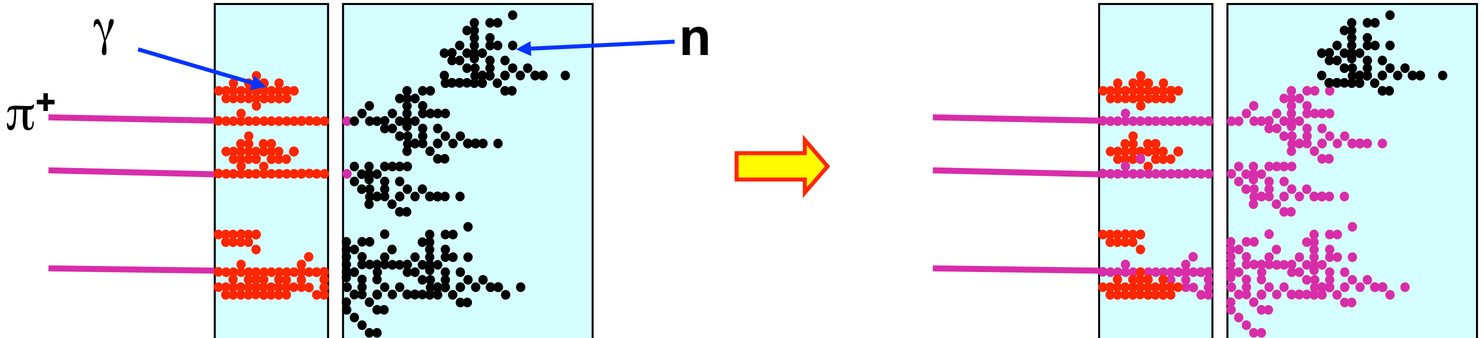
- Future precision physics with W and Z signals as Belle and LHCb do with D^+ and D_s
- **Jet energy resolution** has to improve by factor 2
- Radiation hardness and rate capabilities at LC not critical w.r.t. LHC

Particle Flow Calorimetry

- **In a typical jet :**
  - **60 % of jet energy in charged hadrons**
  - **30 % in photons (mainly from $\pi^0 \to \gamma\gamma$)**
  - **10 % in neutral hadrons (mainly n and K_L)**



- **Traditional calorimetric approach:**
  - **Measure all components of jet energy in ECAL/HCAL !**
  - **~70 % of energy measured in HCAL: $\sigma_\mathrm{E}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$**
  - **Intrinsically "poor" HCAL resolution limits jet energy resolution**



$E_{JET} = E_{ECAL} + E_{HCAL}$

$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

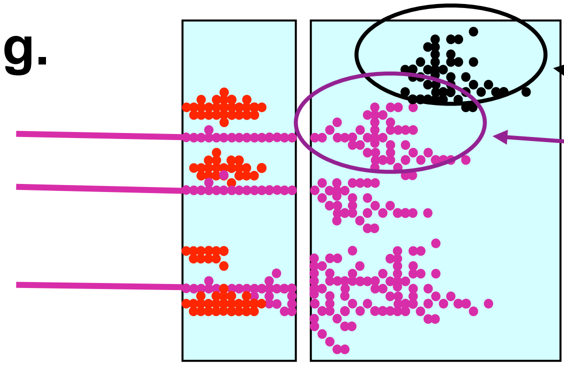
- **Particle Flow Calorimetry paradigm:**
  - **charged particles measured in tracker (essentially perfectly)**
  - **Photons in ECAL: $\sigma_\mathrm{E}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$**
  - **Neutral hadrons (ONLY) in HCAL**
  - **Only 10 % of jet energy from HCAL ⇨ much improved resolution**

Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

- ★ Avoid double counting of energy from same particle
- ★ Separate energy deposits from different particles

e.g.

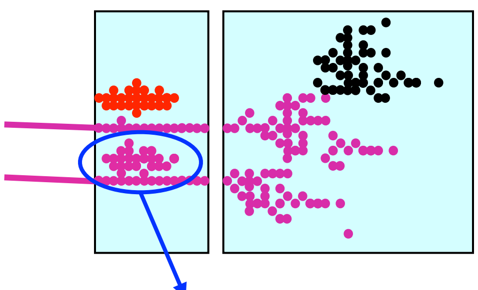


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

> Level of mistakes, "confusion", determines jet energy resolution **not** the intrinsic calorimetric performance of ECAL/HCAL

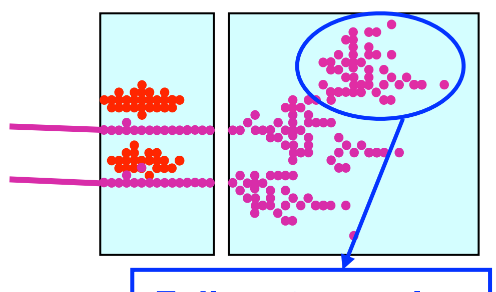
Three types of confusion:

i) Photons



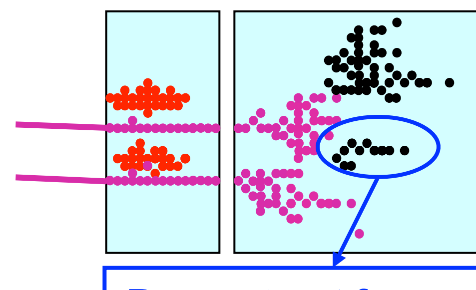
Failure to resolve photon

ii) Neutral Hadrons

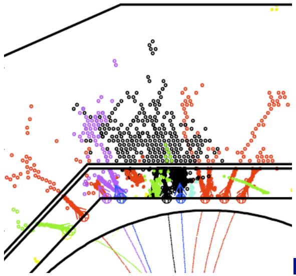


Failure to resolve neutral hadron

iii) Fragments



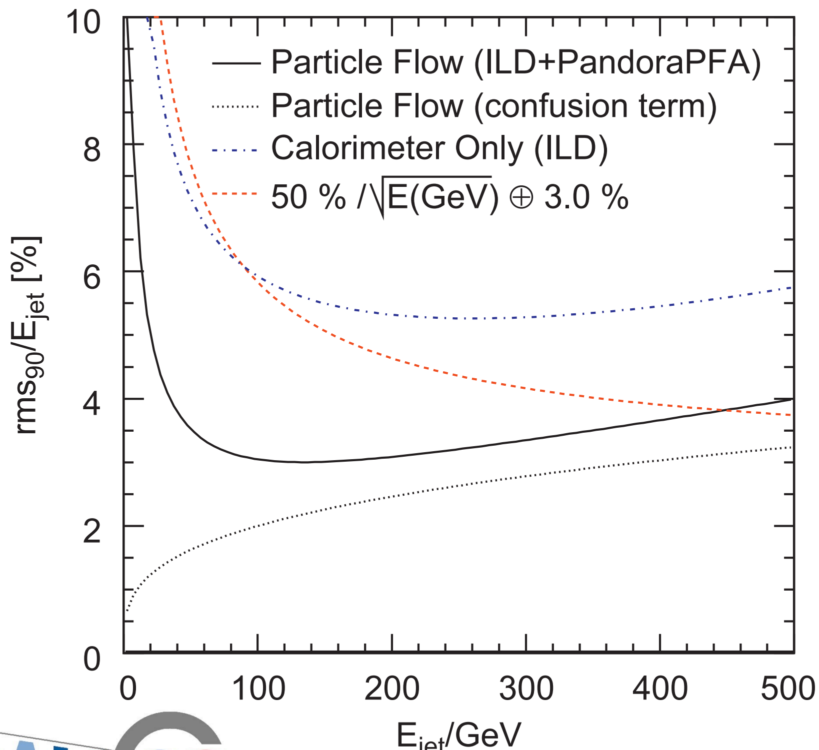
Reconstruct fragment as separate neutral hadron

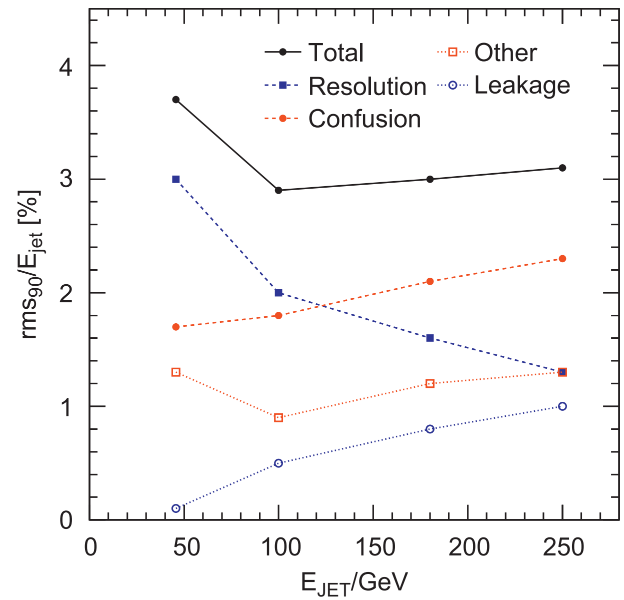


Understand particle flow performance

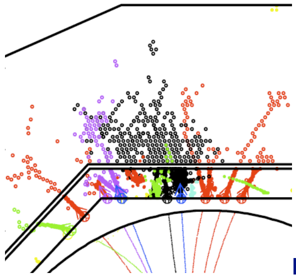
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution Tracking Leakage Confusion





- Particle flow is always better
  - even at high jet energies
- HCAL resolution does matter
  - also for confusion term
- Leakage plays a role, too



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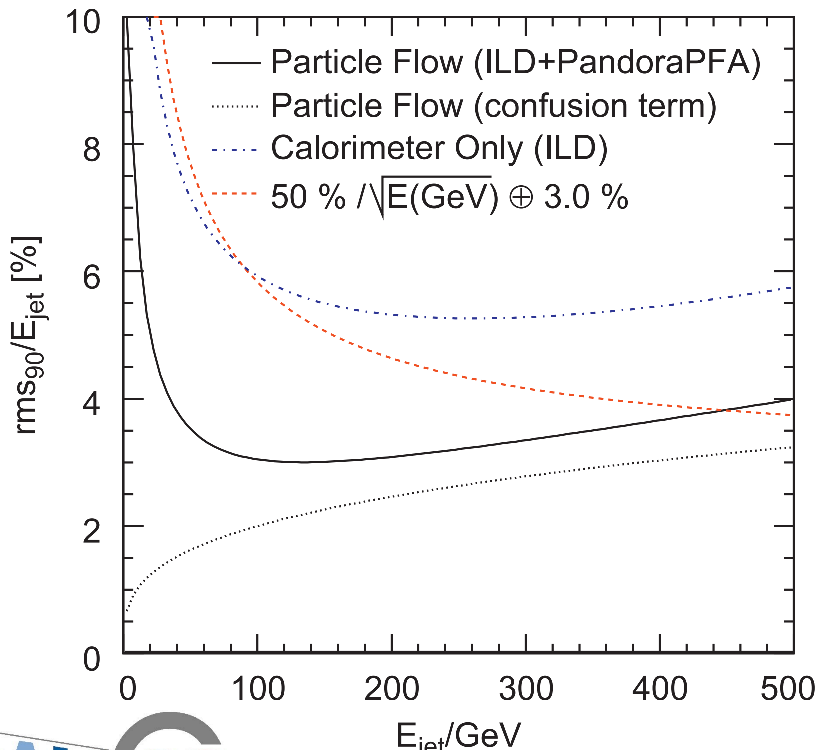

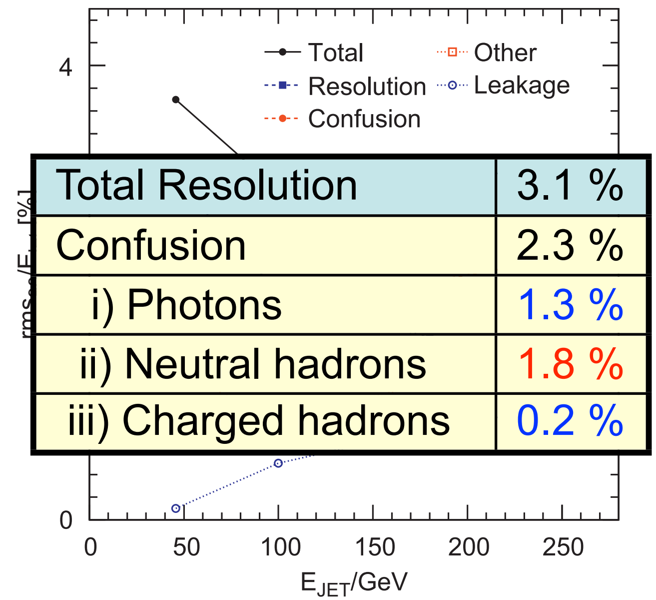

Total Resolution	3.1 %
Confusion	2.3 %
i) Photons	1.3 %
ii) Neutral hadrons	1.8 %
iii) Charged hadrons	0.2 %

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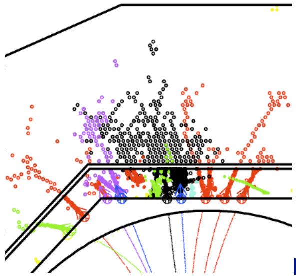

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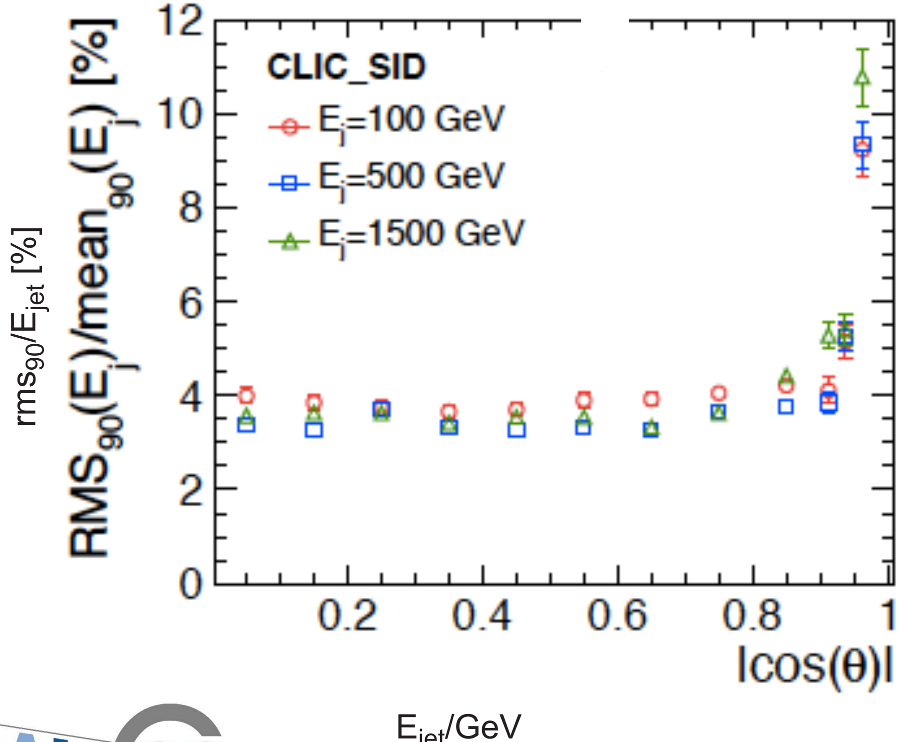
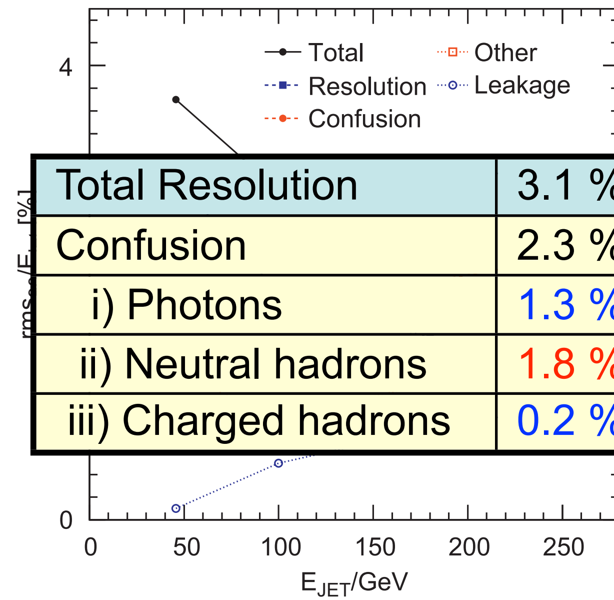
Resolution | Tracking | Leakage | Confusion





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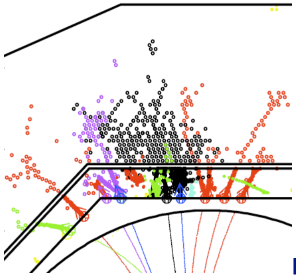
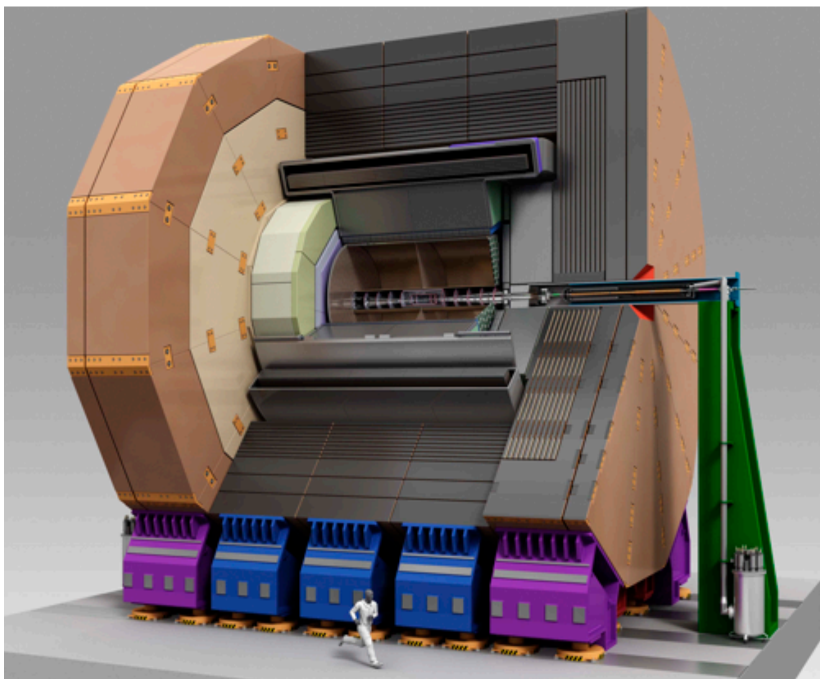


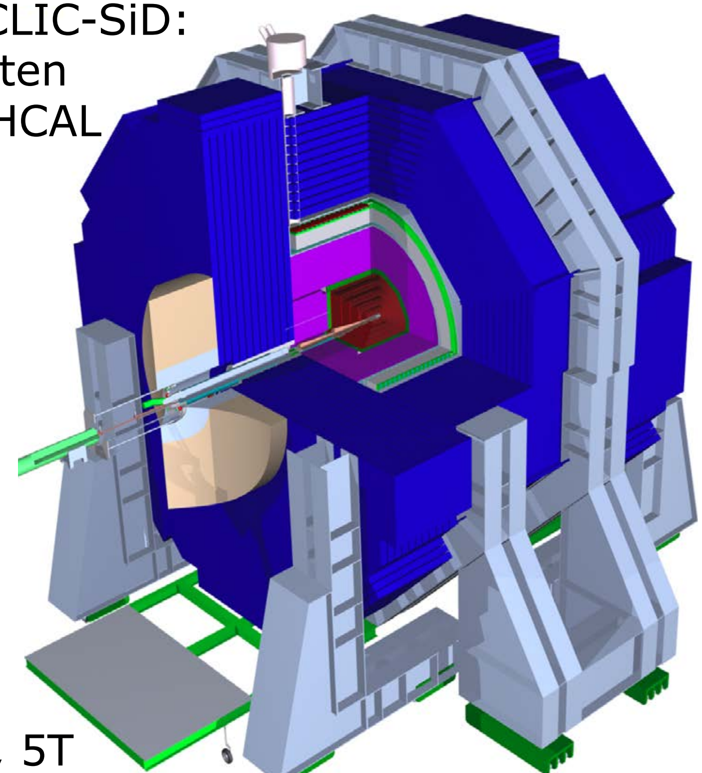
Particle flow detectors

- large radius, large field, fine 3D calorimeter granularity, compact
  - Typ 1X0 long, transv: 0.5cm ECAL, 1cm gas HCAL, 3cm scint.
- optimized in full simulations and particle flow reconstruction

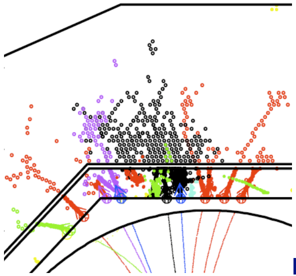


ILD: large TPC, B=3.5T

CLIC-ILD, CLIC-SiD:
tungsten
barrel HCAL

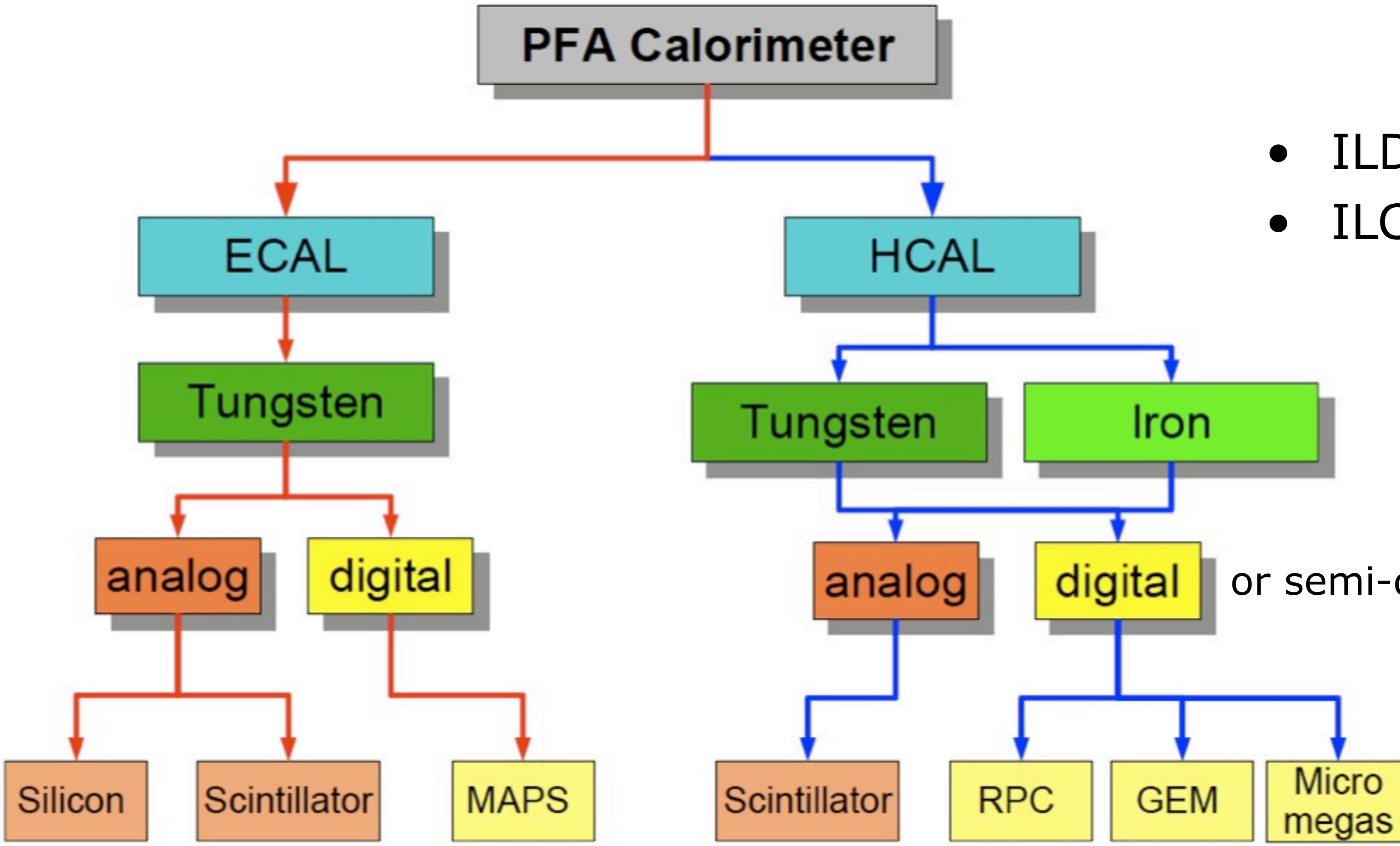


SiD:all-Si tracker, 5T

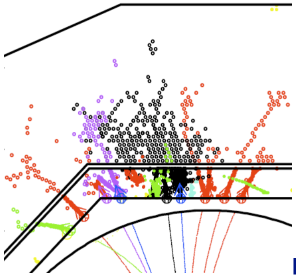


Calorimeter technology tree

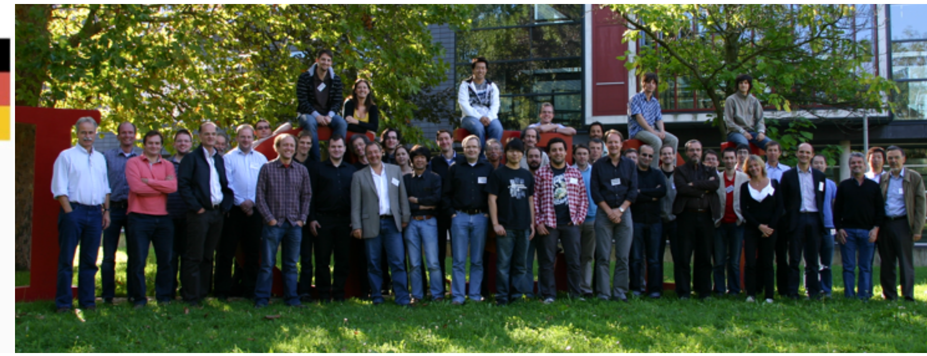
- ILD, SiD
- ILC, CLIC



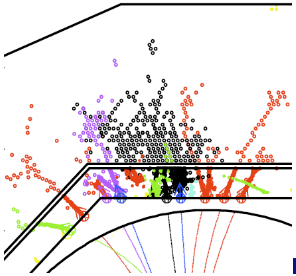
or semi-digital



CALICE



- We are more than 300 physicists and engineers from 57 institutes in Africa, America, Europe and Asia
- Our goal: develop highly granular calorimeter options based on the particle flow approach for an e+e- linear collider
- Twofold approach:
  - Physics prototypes and test beam
    - Proof of principle, test of shower simulation models, development of reconstruction algorithms with real data
  - Technical prototypes
    - Realistic, scalable design (and costing)



Particle flow calorimeters:

- Particle Flow concept proven in detailed simulations: provides required resolution up to CLIC jet energies

- Extremely fine calorimeter segmentation - 100M read-out cells - demands novel read-out technologies and poses new system integration challenges
  - remain compact: Moliere radius, stay inside coil
  - embed electronics, minimize power

- CALICE: collaborative R&D and test beam effort to
  - develop the technologies
  - establish the performance
  - validate the physics models
  - test the algorithms
  - demonstrate the scalability

Technologies for High Granularity

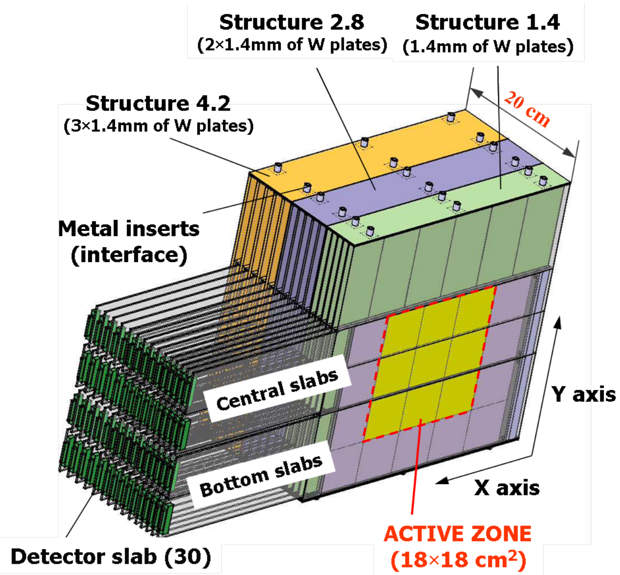
Si W ECAL

Sci W ECAL

not reported this time:

MAPS DECAL

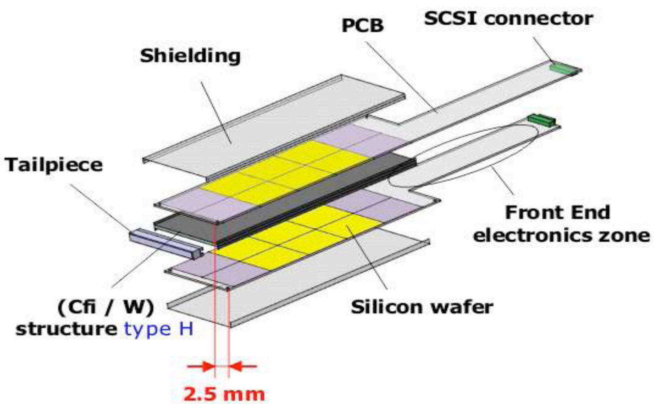
Physics prototype 2005-2011: demonstrate SiW ECAL technique

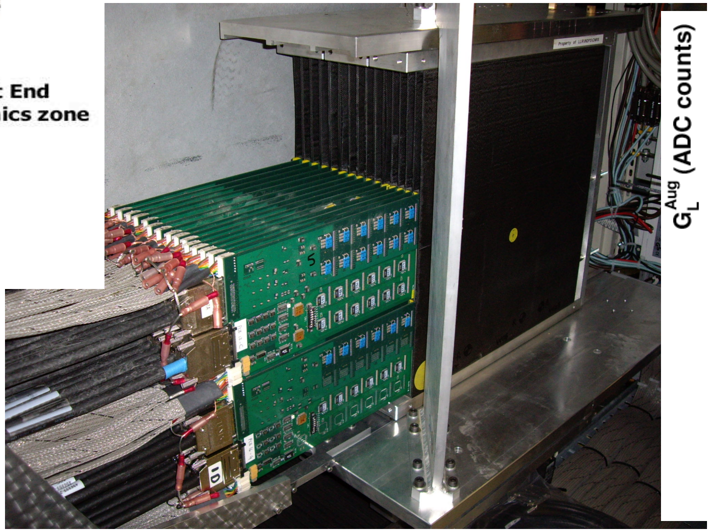


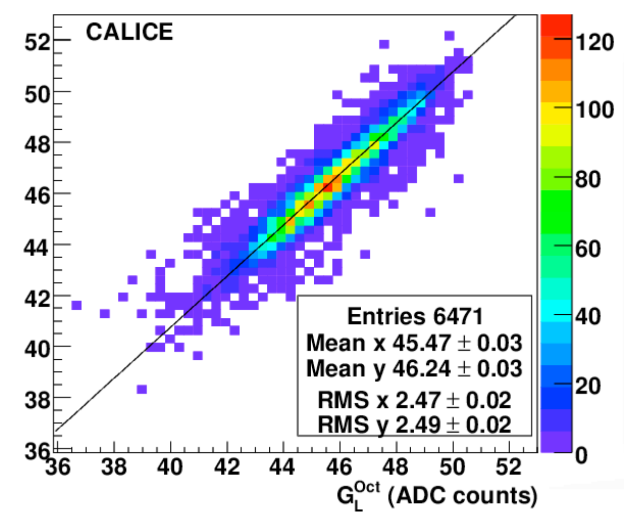
$18x18cm^2$ active area, 30 layers
$1x1cm^2$ segmentation
~10000 readout channels

5-year test beam campaign
muons, electrons, hadrons

detector calibration, EM response
validation of simulation, hadronisation models







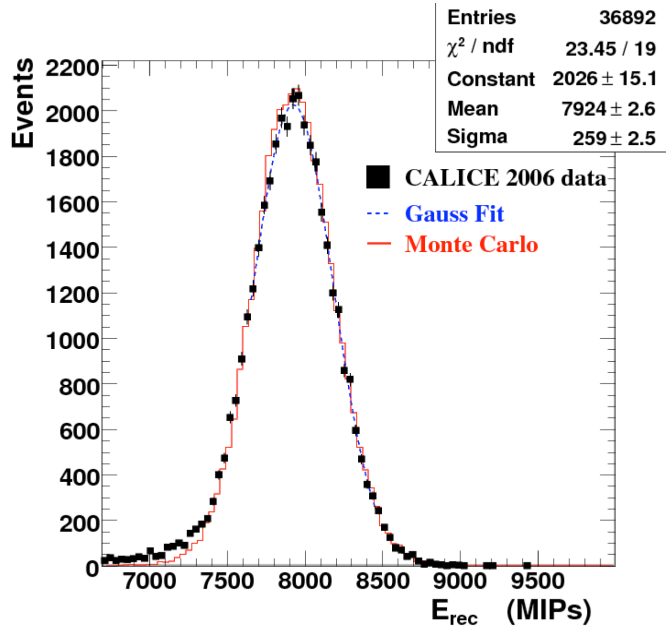
Physics prototype results

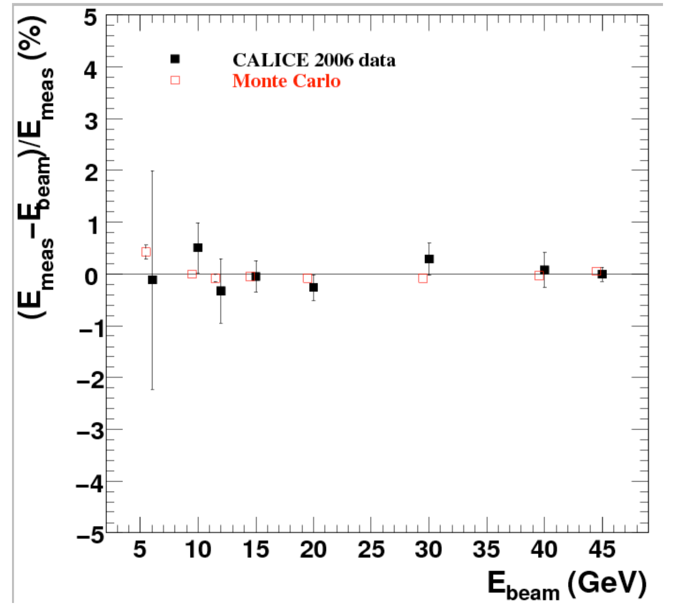
Response to electrons

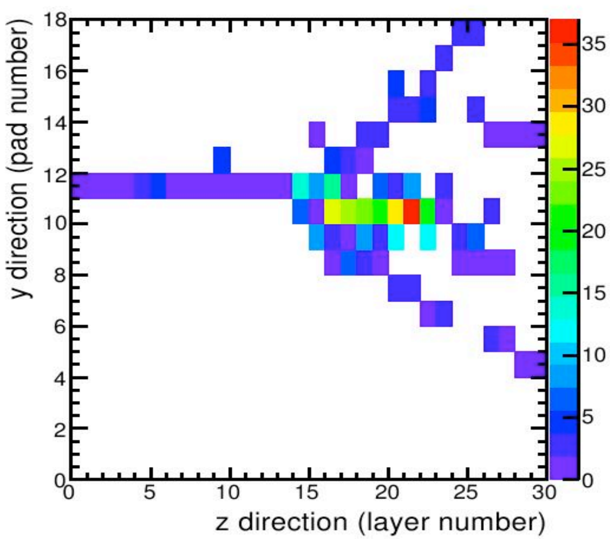
Linear energy response to ~1%

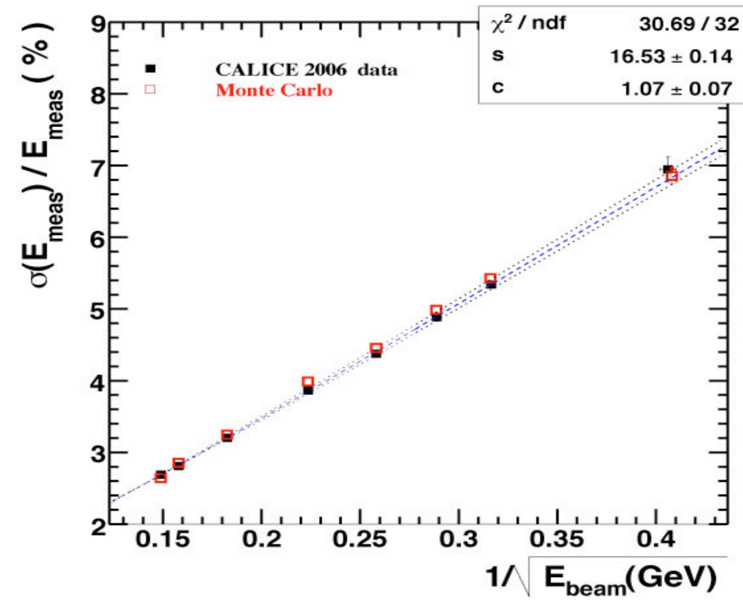
Good description by simulation

Excellent imaging







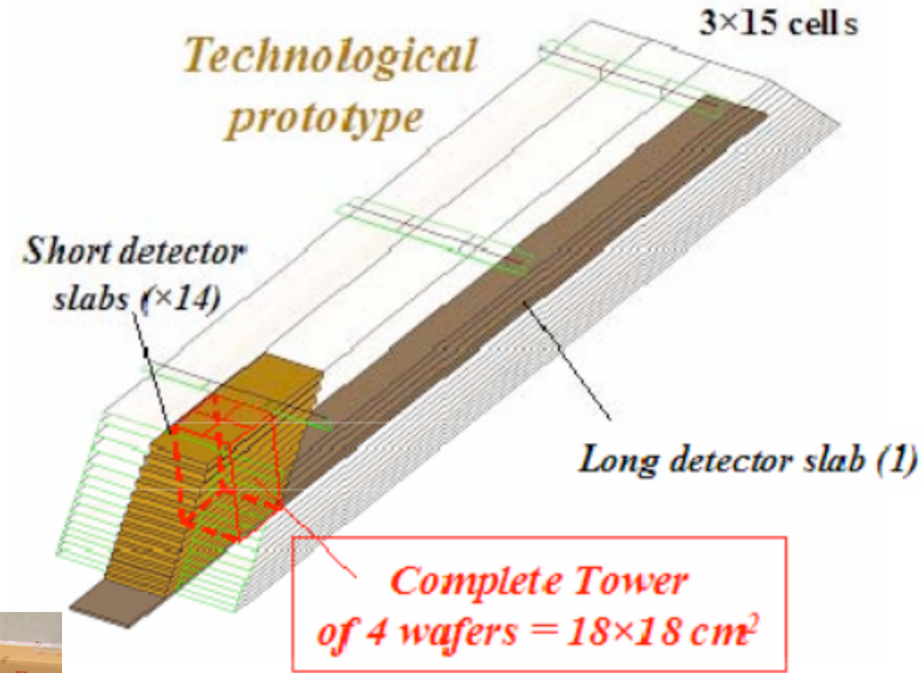


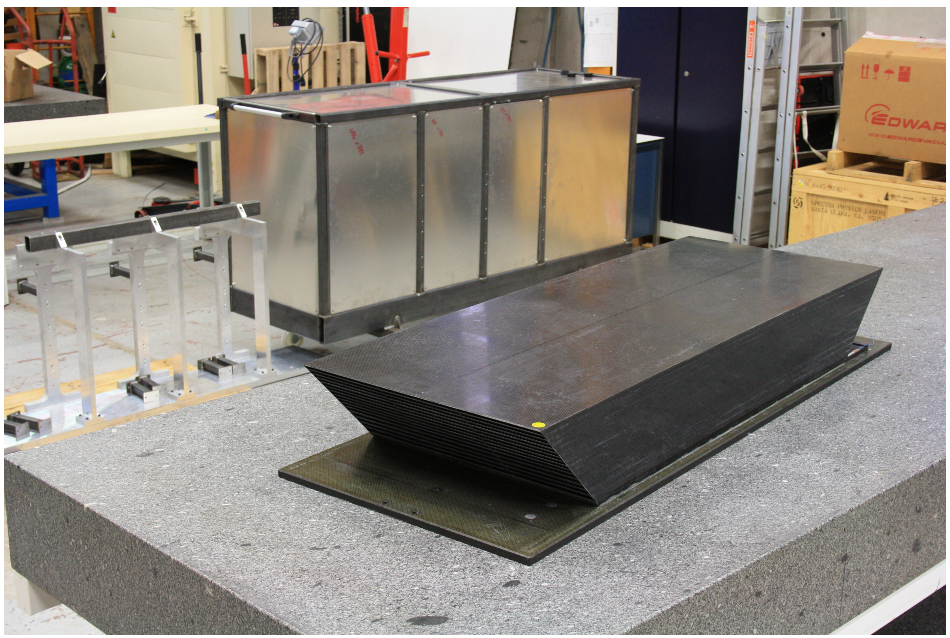
Technical prototype
under development

Higher readout granularity

Embedded low power FE electronics

Move towards industrial techniques
modular construction





~2/3 scale mechanical module
carbon fibre, tungsten
completed

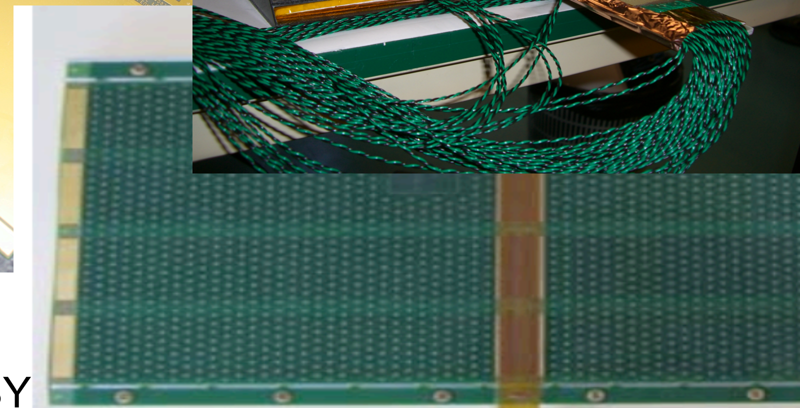
Will be partially instrumented
over next years, testing different
technological solutions

Some examples

PCB with embedded ASICs

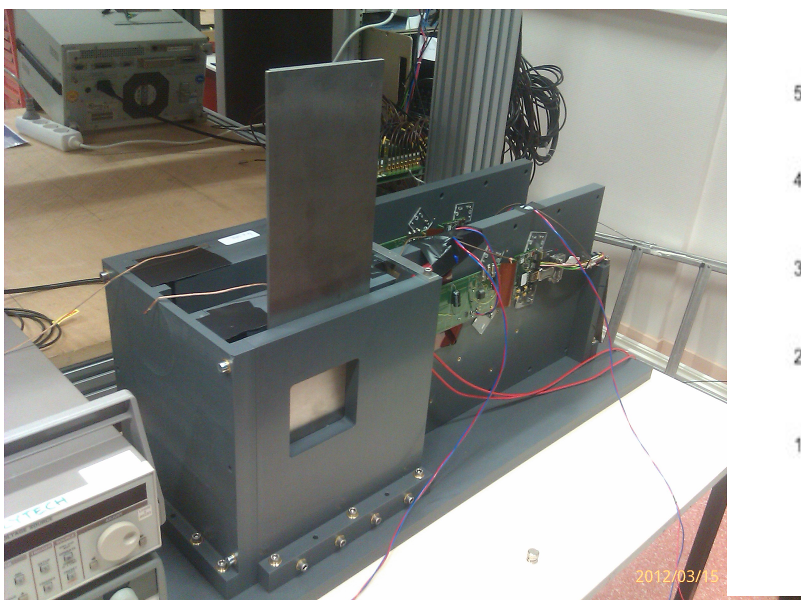
Low-volume interconnections

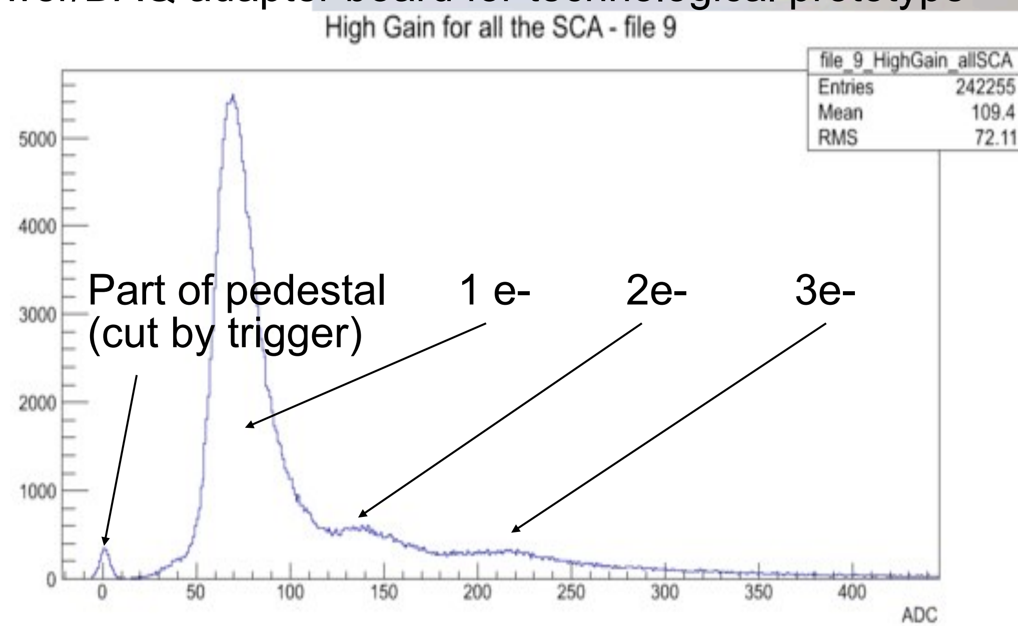
Water-based leakless cooling



Recent beam test of “technological” detector slab at DESY

Test of new ASIC, DAQ system, power/DAQ adapter board for technological prototype

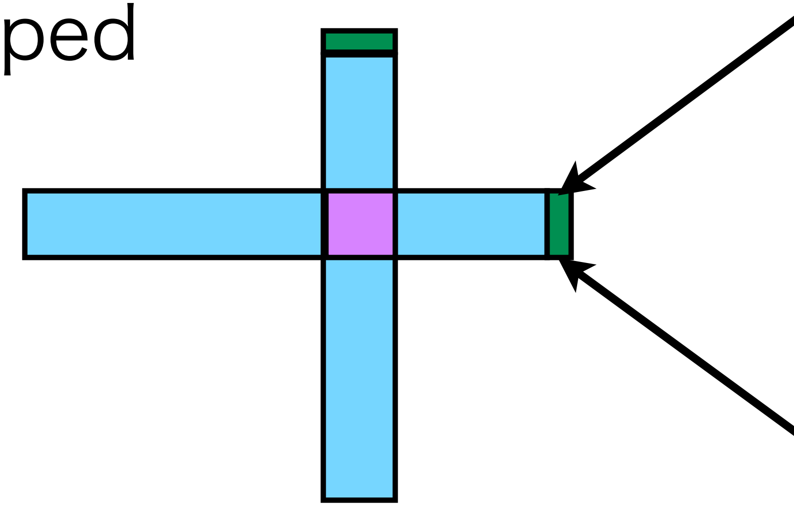


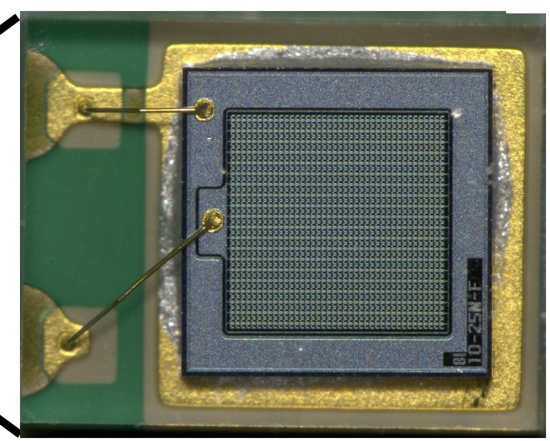


Second round of beam tests planned for summer: larger scale with ~10 layers

Scintillator ECAL overview and perspectives

- PFA requires highly granular ECAL
- to accommodate within reasonable cost
- scintillator strip ECAL with orthogonal directions to achieve fine segmentation
- very thin and novel photon sensor is developed

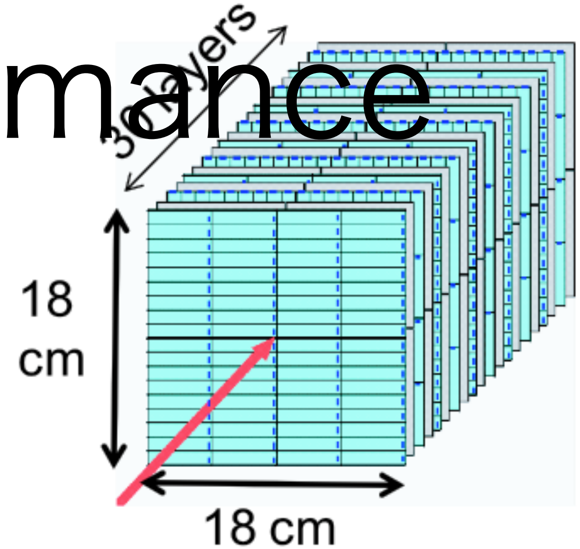


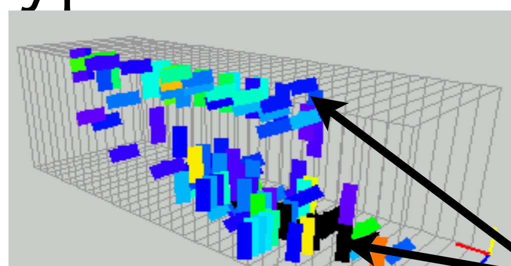


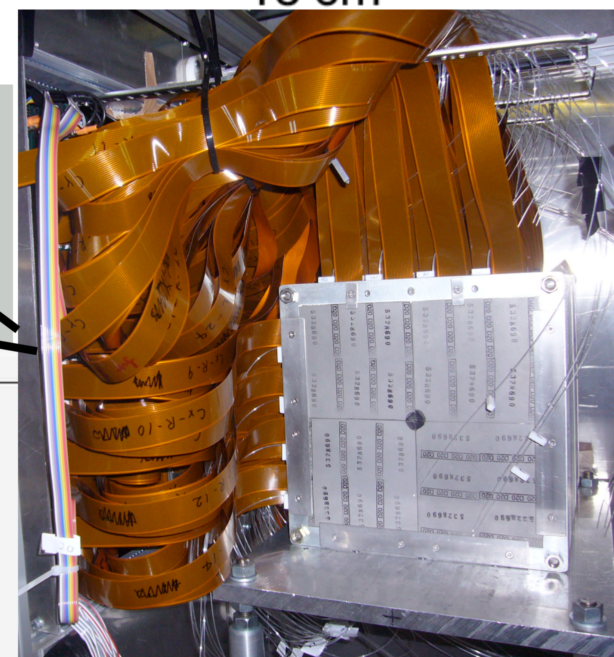
1.9mmx2.4mm

prototype & performance

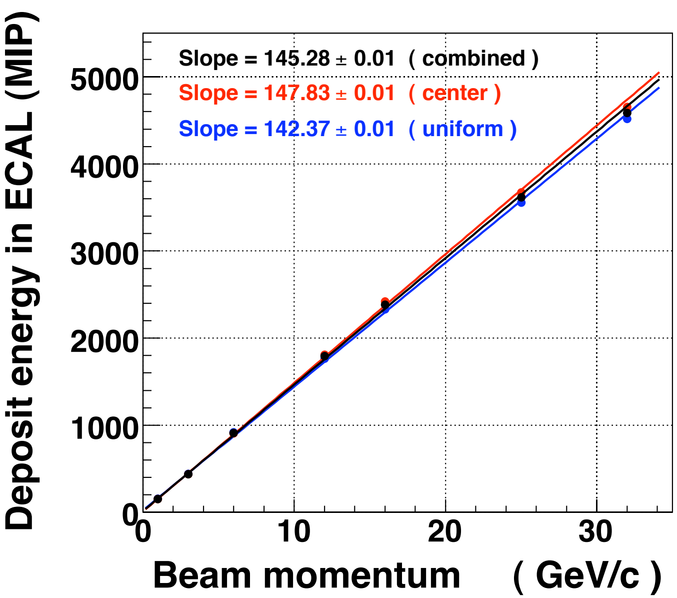
- 45mmx10mm strips
- 72 strips/layer
- 30 layer prototype

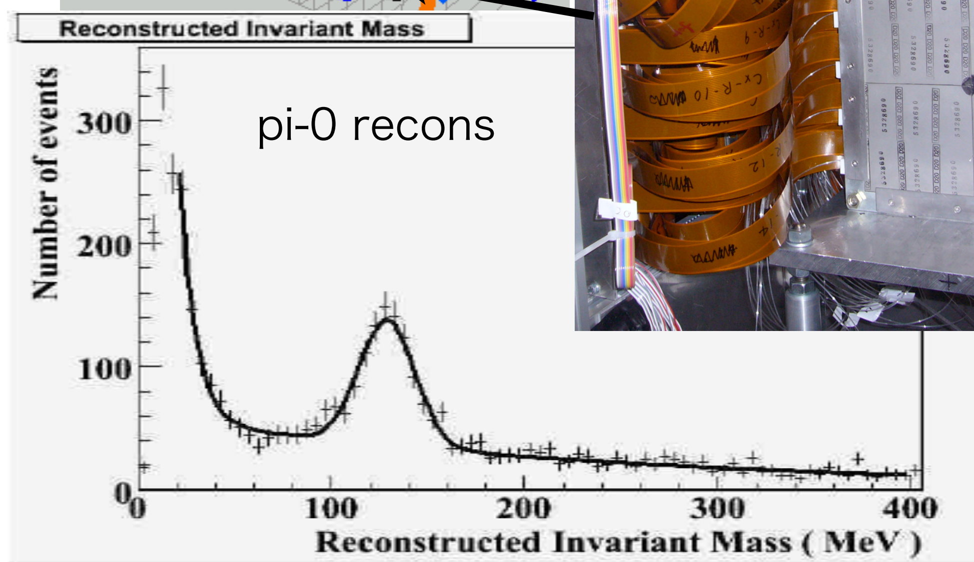






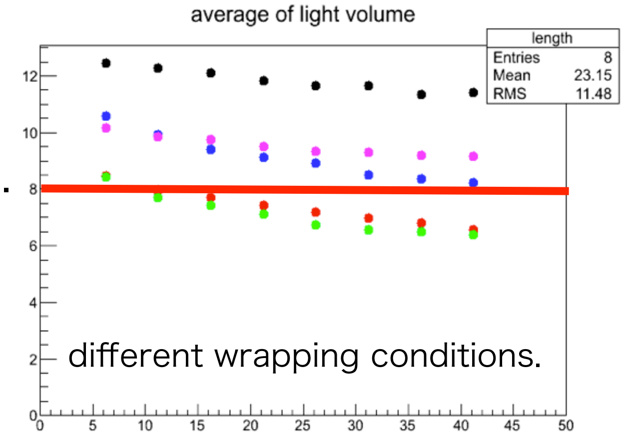
good linearity

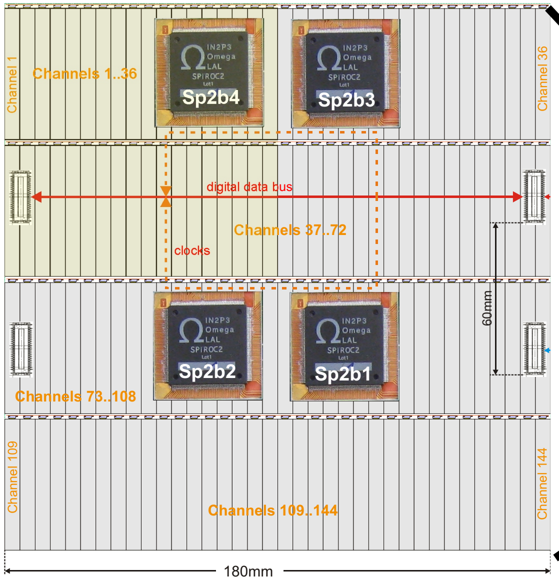




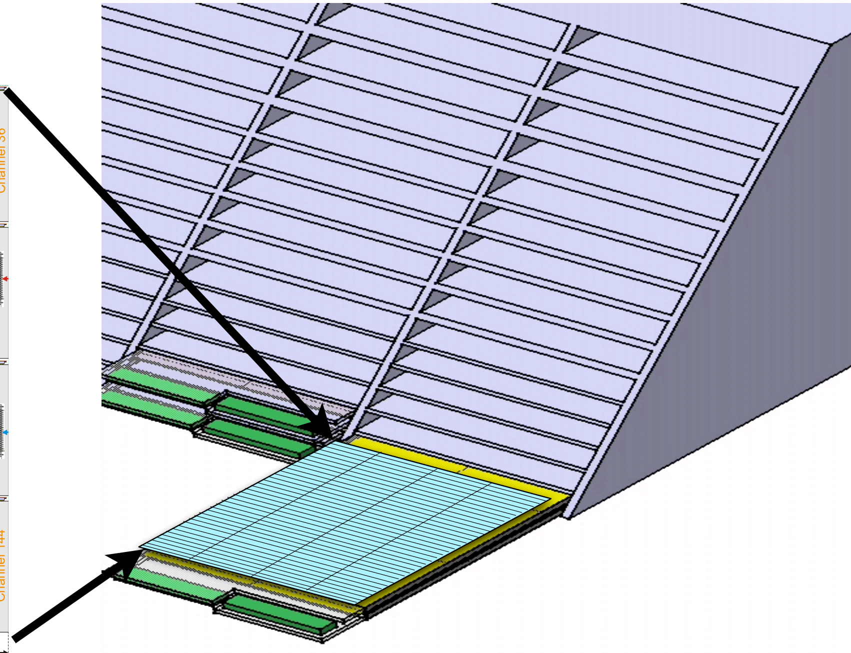
current development

- finer granularity up to 5mm
  more than 8 p.e. & uniform +-5%
- electronics integration
- Beam test 2012 fall
- with Silicon W ECAL





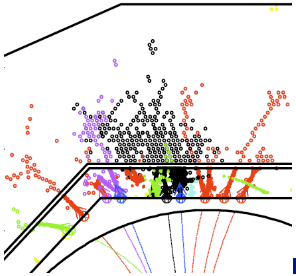
small-area version
of scint HCAL
read-out



Technologies for High Granularity

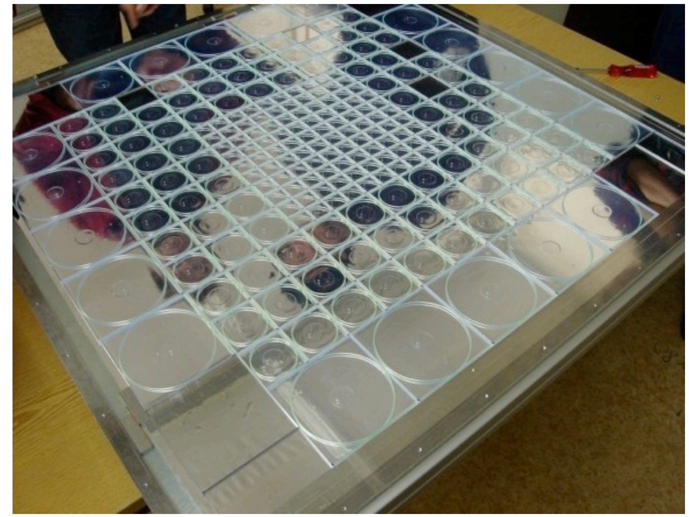
Sci Fe HCAL

Sci W HCAL

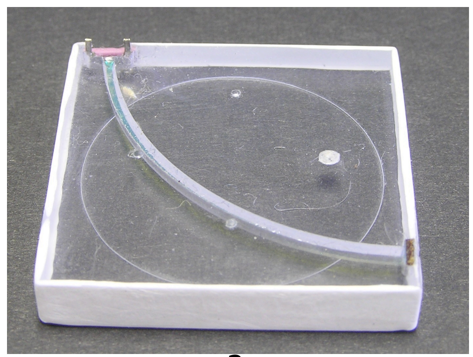


Fe Scint tile AHCAL

- 38 layers steel sandwich
- World's first large device with SiPMs: 7600 tiles / sensors
- Now used in CMS, T2K, medical imaging ,...

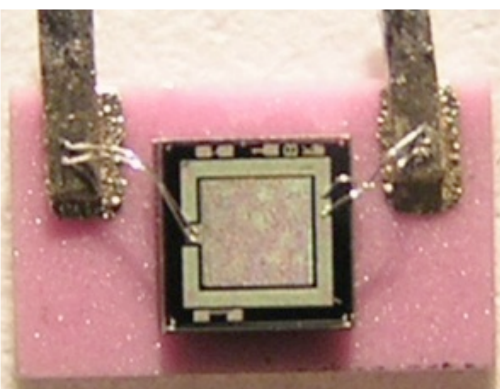


1x1 m^2 220 tiles



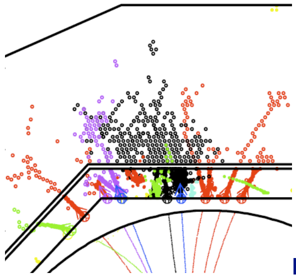
3x3 cm^2 x 5mm

SiPM: MEPHI /PULSAR



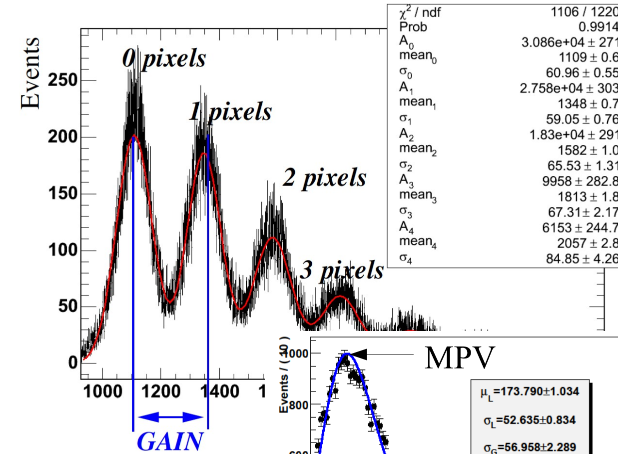
1x1 mm^2 1156 pixels

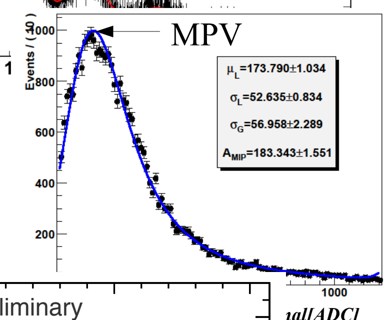
- Extremely robust: 6 years of data taking without problems
- Many trips with dis-and re-assembly of the HCAL
  - DESY CERN DESY FNAL DESY CERN-PS CERN-SPS

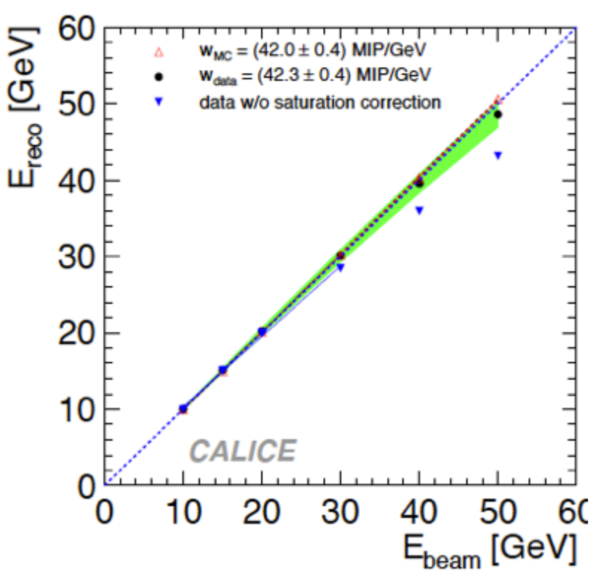


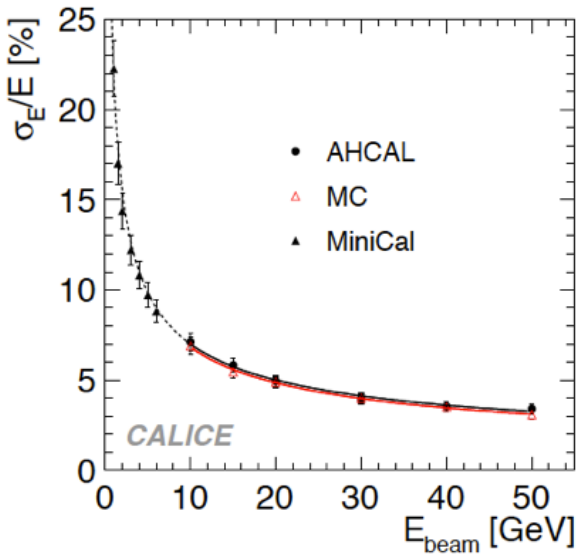
Scint AHCAL calibration and electromagnetic performance

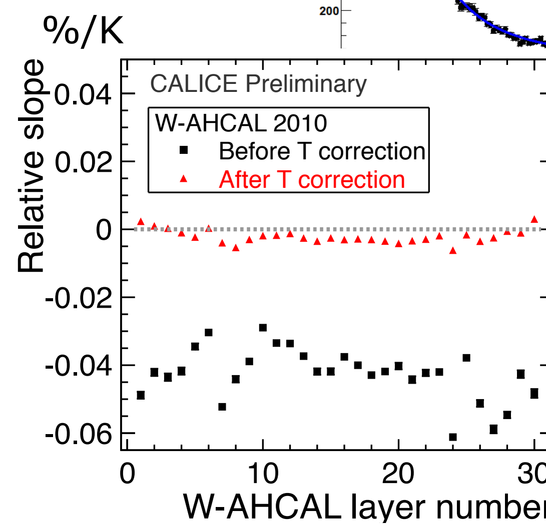
- SiPM gain monitoring: self-calibrating
- Cell equalization: MIPs
- Temperature correction: ~4%/K
- Validation of calibration and simulation with electrons



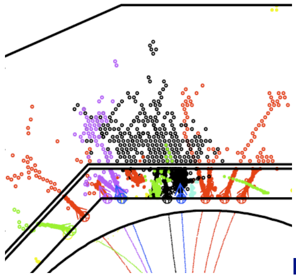




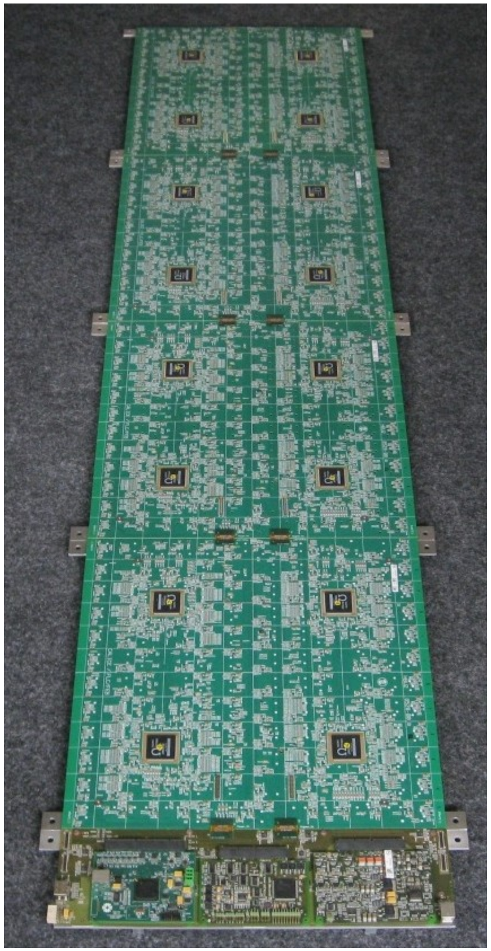




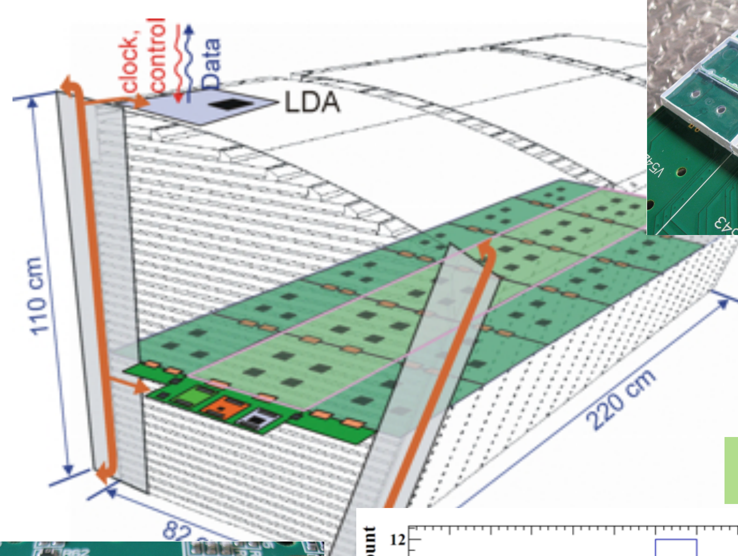
Published in JINST 6, P04003 (2011)

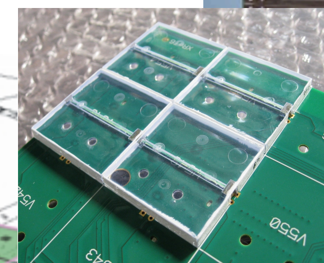


AHCAL technological prototype

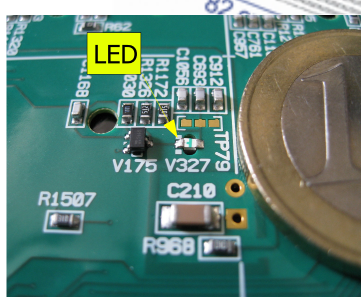


- integrated readout (ADC & TDC), auto-trigger and LED system
- 12x12 tiles / board

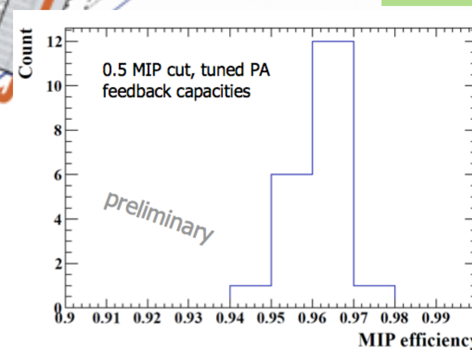


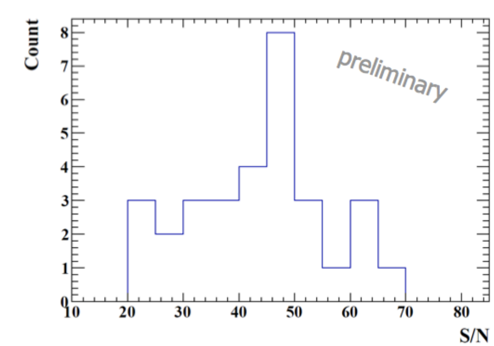


Mechanics:
1mm flatness over
2m w/o machining



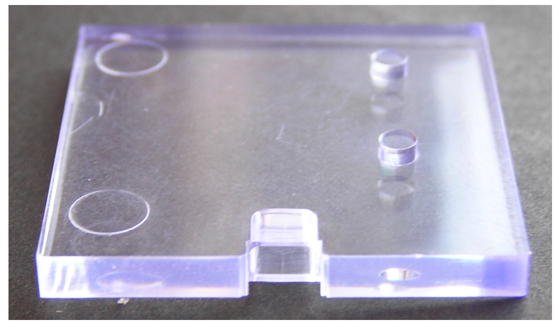
First test beam results

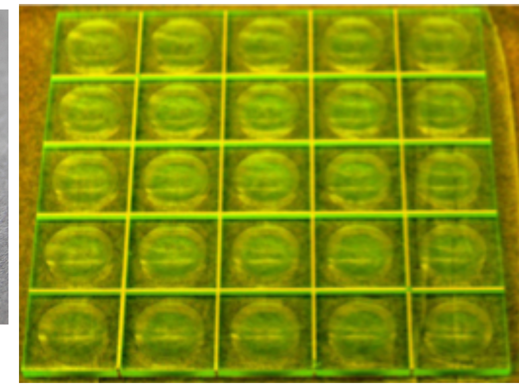




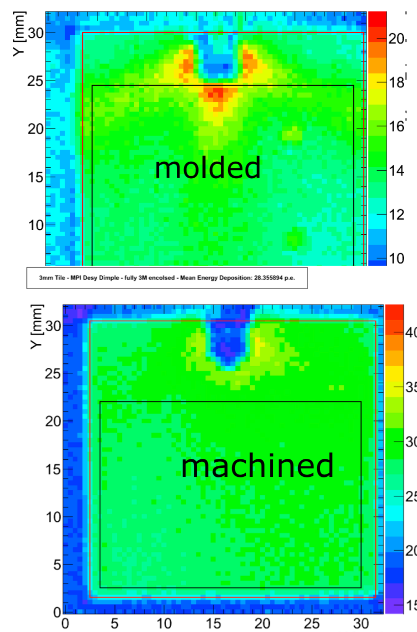
SiPMs and tiles

- Options for direct - fibre-less - coupling
- uniformity problems solved
- industrialized injection molding process
  - first tests

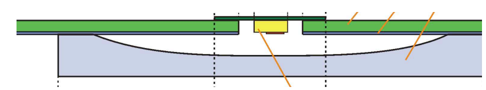




MPI / ITEP

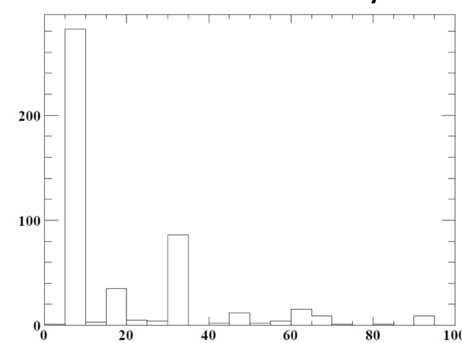


NIU



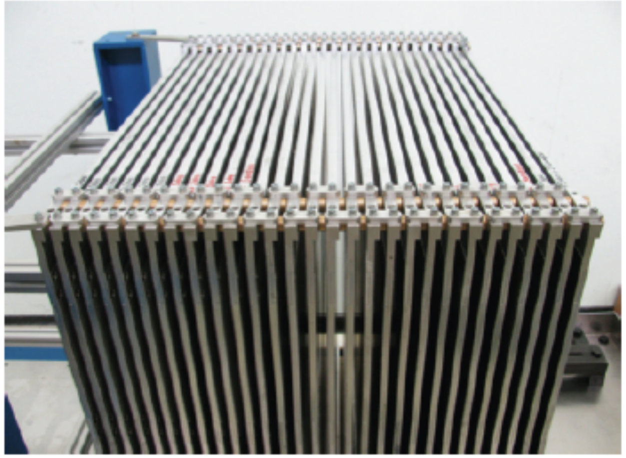
- several types of blue-sensitive SiPMs available
- much reduced noise and occupancy

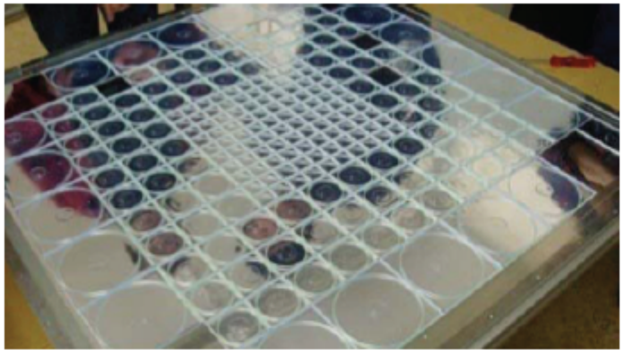
MRS APDs ITEP/CPTA



Tungsten AHCAL prototype

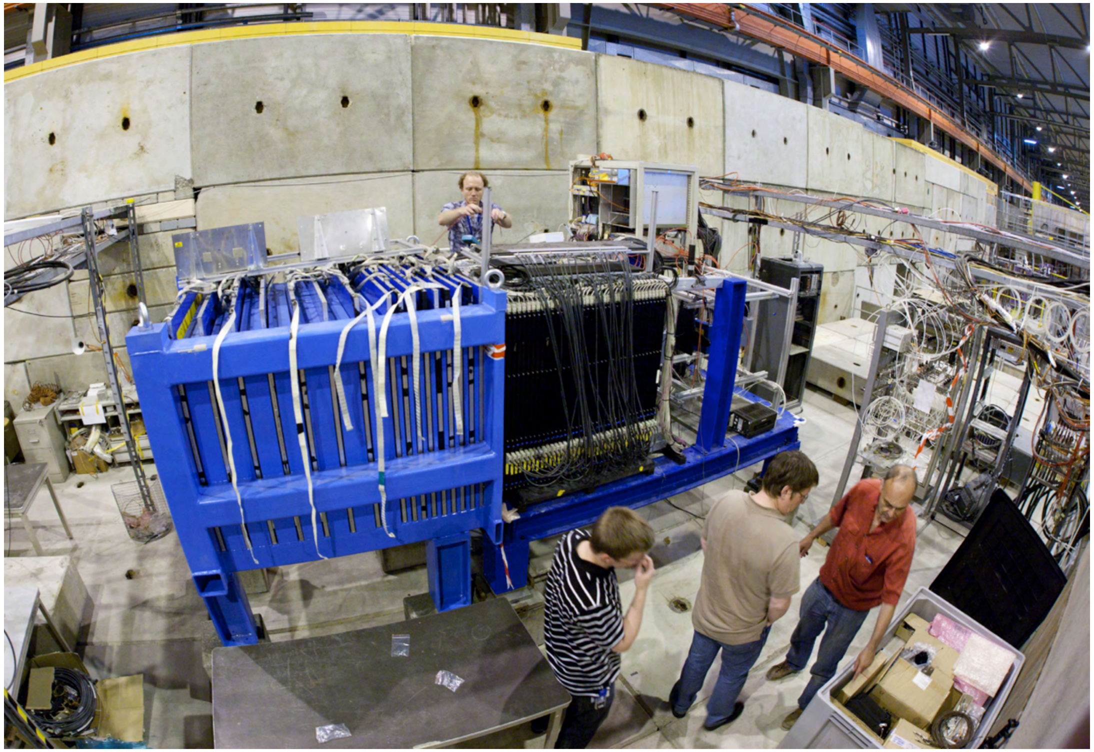
Main purpose: Validation of Geant4 simulation for hadronic showers in tungsten





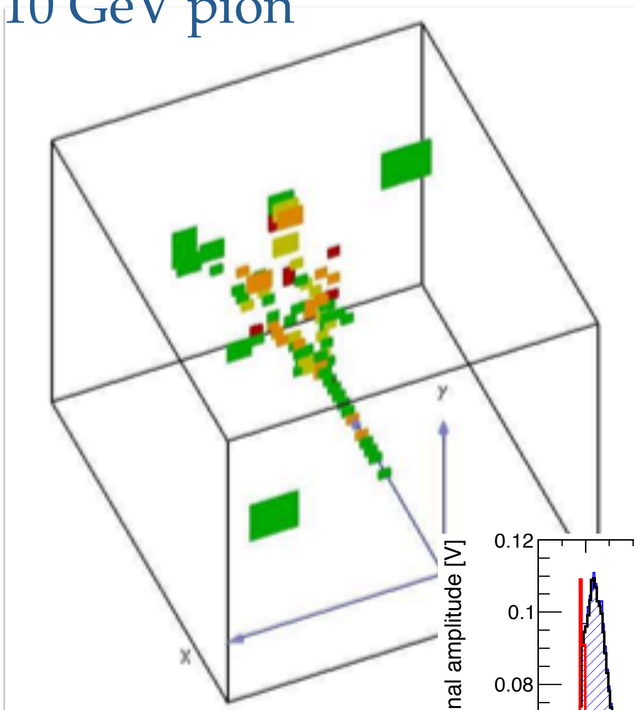
Scintillator tiles 3x3 cm² (in centre)
Read out by SiPM

Data taken 2010/11 at CERN-PS/SPS, mixed beams 1 – 300 GeV

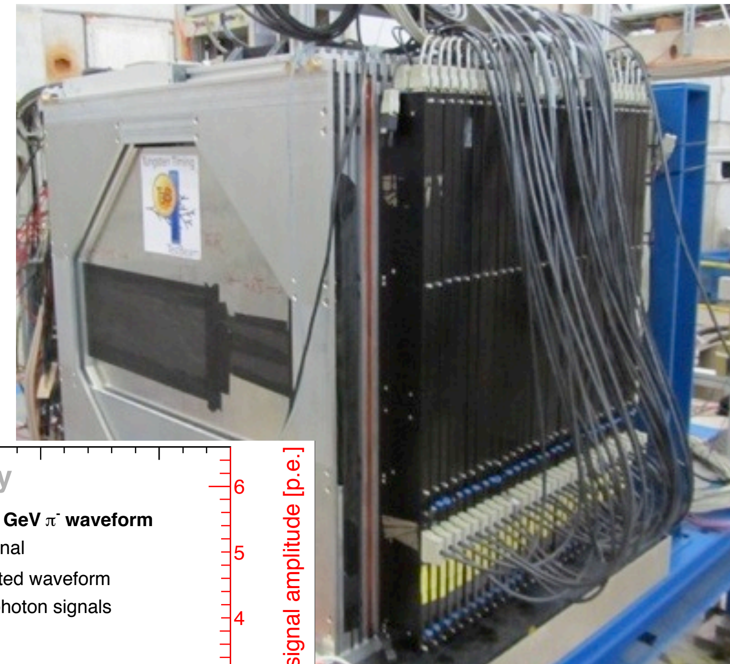


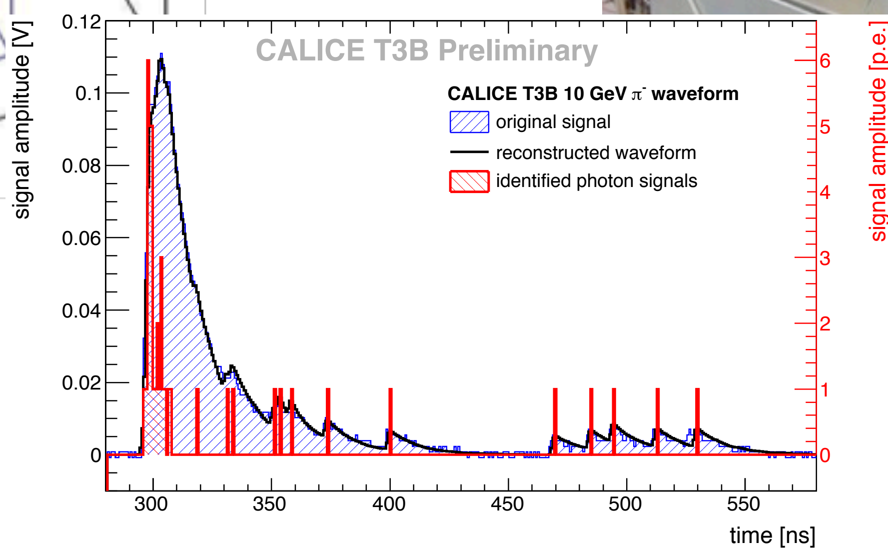
SiPM analog HCAL testbeam

10 GeV pion



T3B: Time structure of shower:
one row of 15 tiles with pico-scope read-out

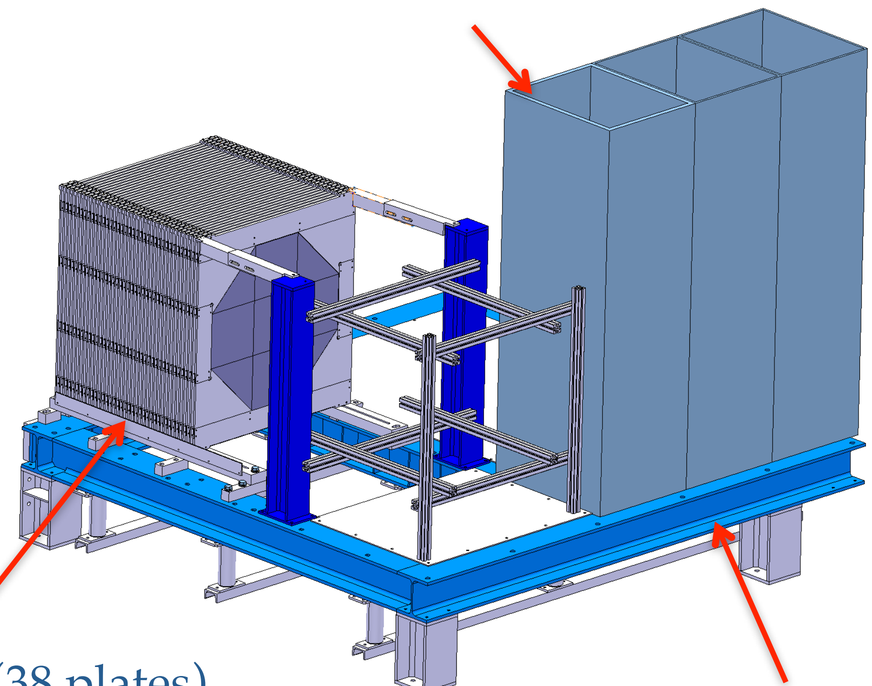




Digital glass RPC tungsten HCAL

- 2012: test tungsten HCAL with gaseous readout.
  - Due to slow neutrons from W, energy resolution of a W-HCAL with gas detectors might not be the same as with scintillators. This needs testing.
  - Have two independent data sets to validate tungsten Geant4 simulations.
- Infrastructure has been adjusted to accommodate the new equipment →

RPC version of T3B in preparation, too

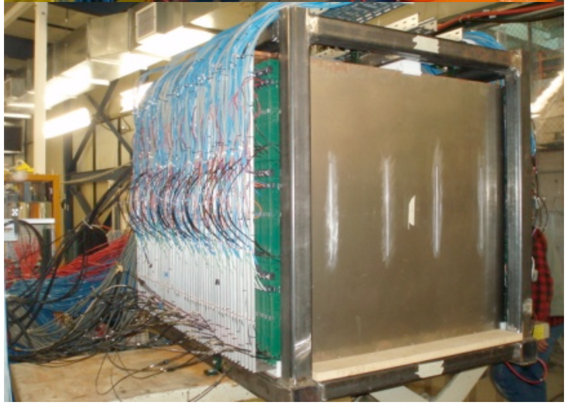


Technologies for
High Granularity

(Semi-) Digital HCAL
RPC, GEM, Micromegas

The Digital Hadron Calorimeter - DHCAL





RPC – based imaging calorimeter

DHCAL = First large scale calorimeter prototype with

Embedded front-end electronics
Digital (= 1 – bit) readout
Pad readout of RPCs (RPCs usually read out with strips)
Extremely fine segmentation with 1 x 1 cm^2 pads

DHCAL = World record channel count for calorimetry
World record channel count for RPC-based systems

479,232 readout channels

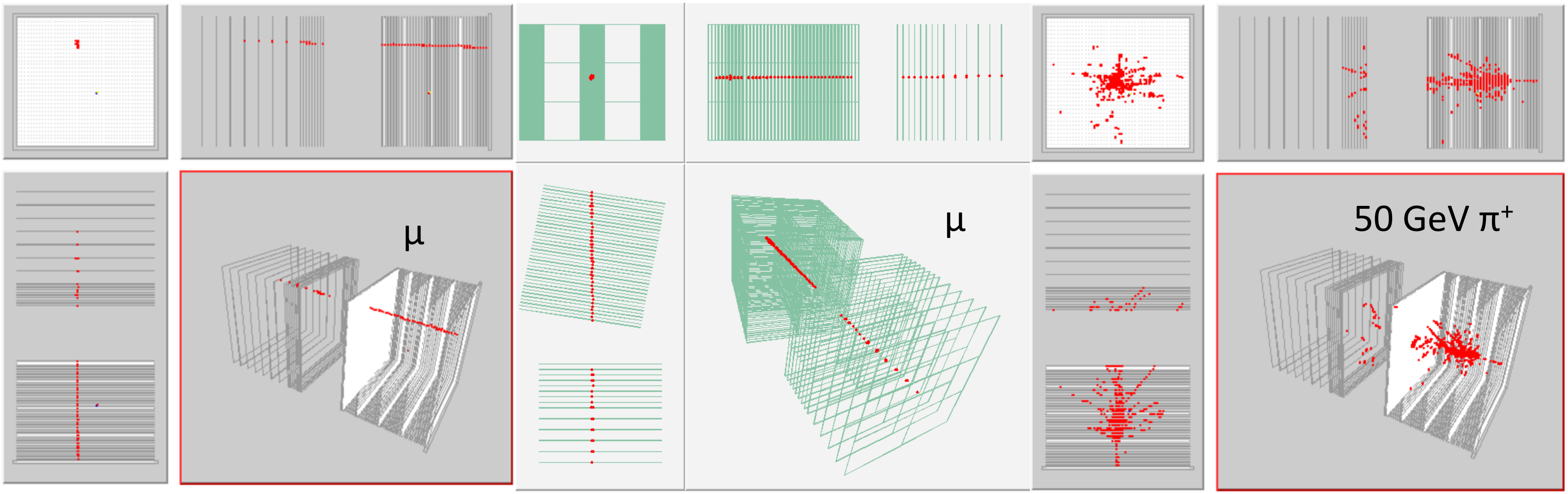
DHCAL construction

Started in fall 2008
Completed in winter 2011

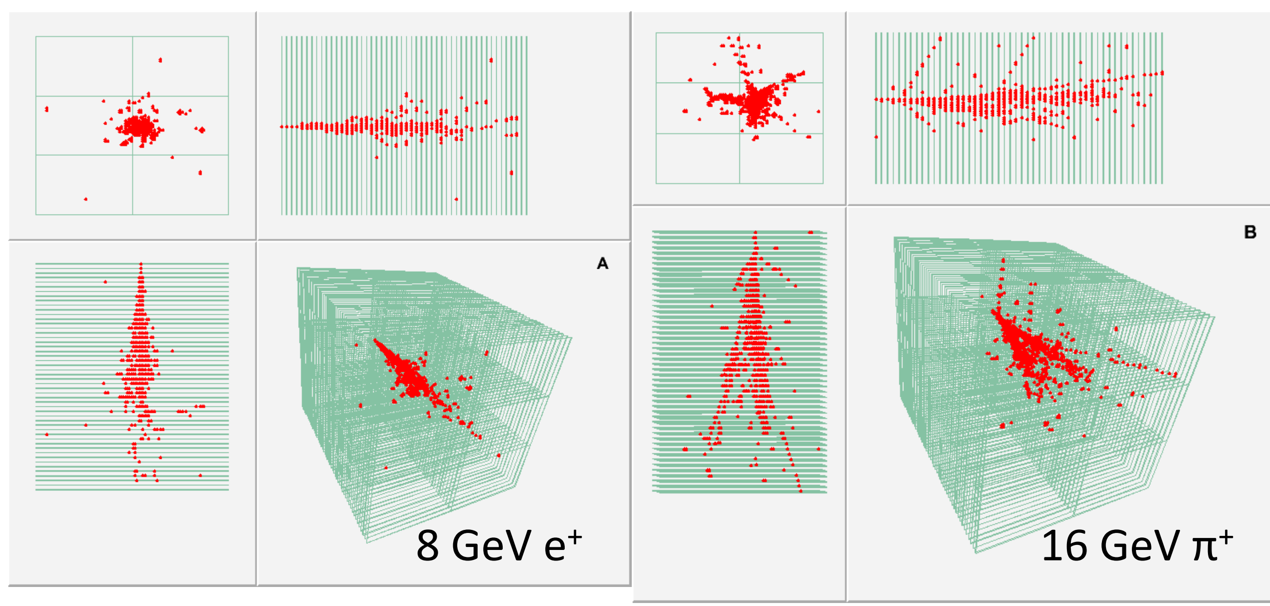
Test beam activities

10 Million muon events
25 Million secondary beam events
Collected in 5 periods at FNAL
Tests with Tungsten absorber ← starting now at CERN

Some nice DHCAL events



Configuration with minimal absorber



Muons in the DHCAL

Broadband muons

Obtained from +32 GeV beam with beam blocker

Reconstruct

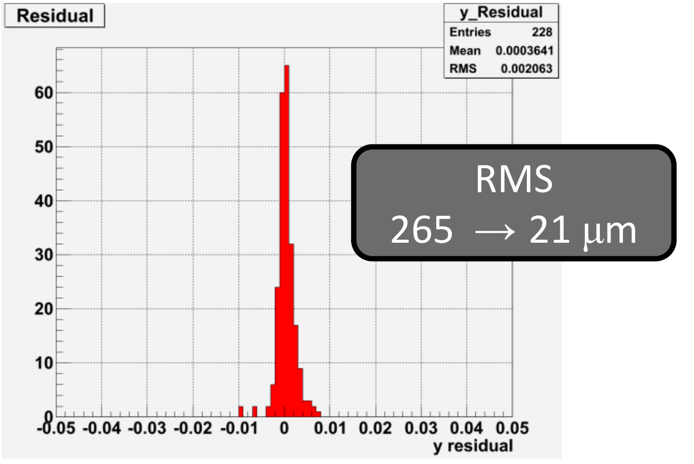
Tracks in the DHCAL → Software alignment of layers

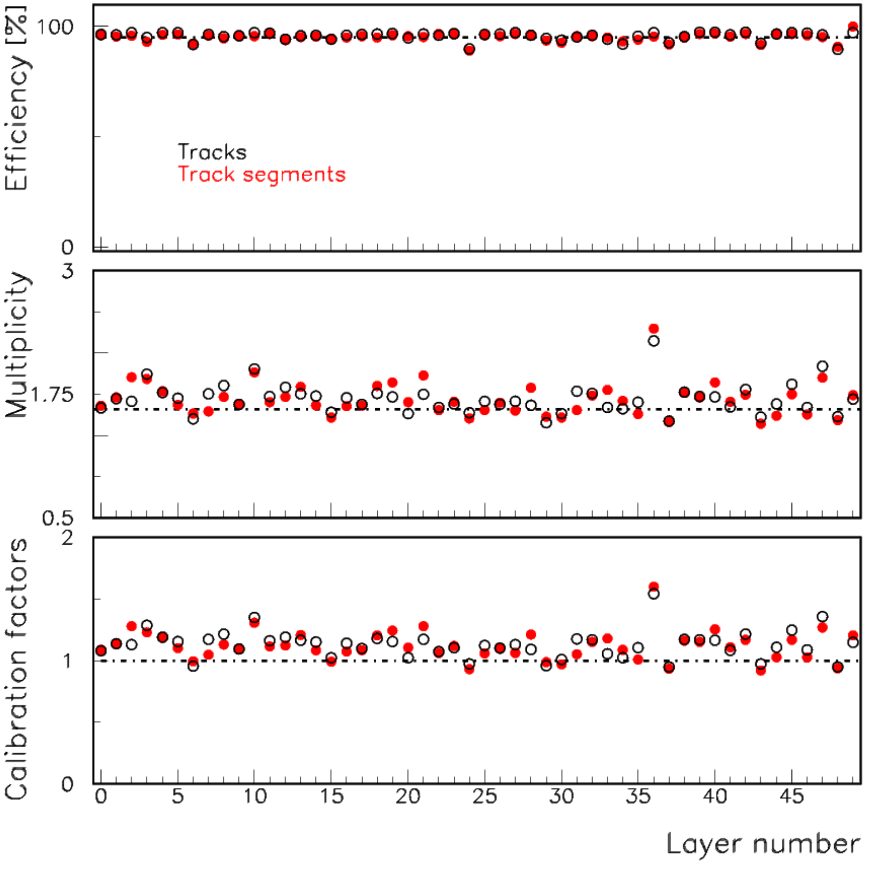
Measure

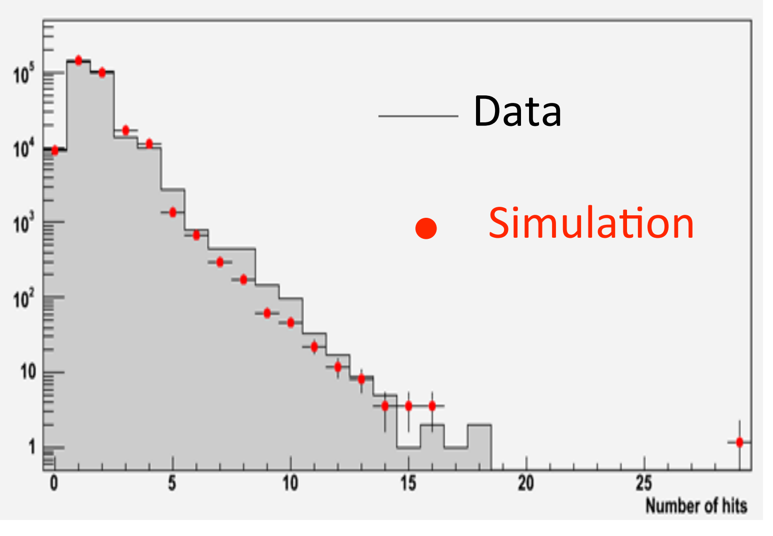
Efficiency, average pad multiplicity…

Tune

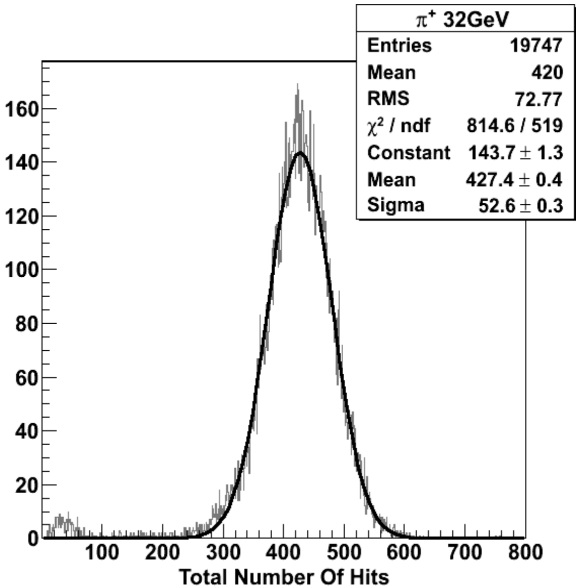
Monte Carlo simulation



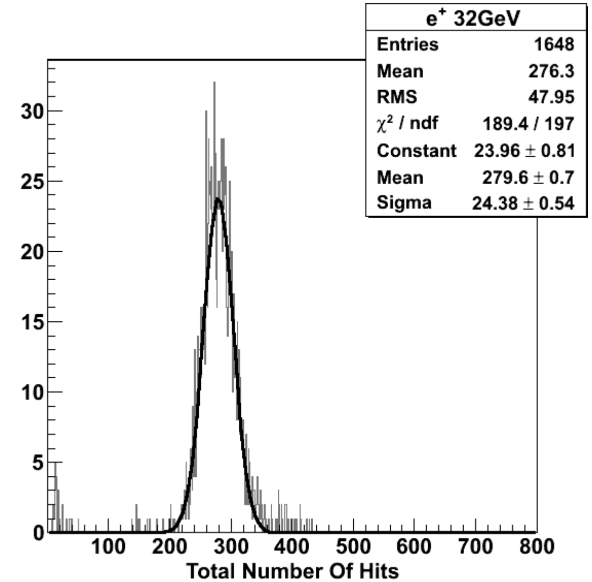




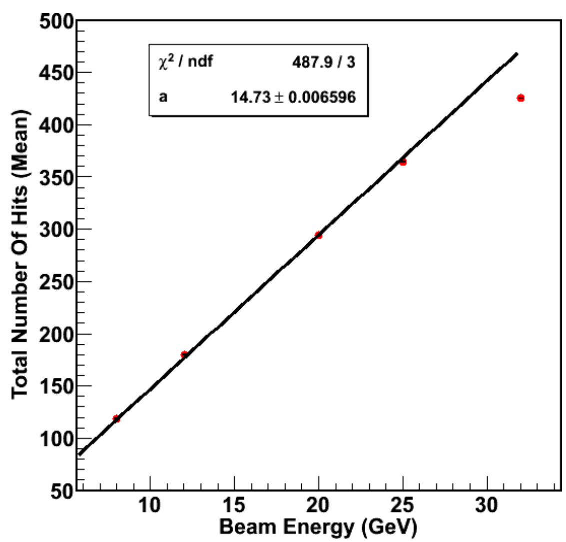
Secondary beam in the DHCAL



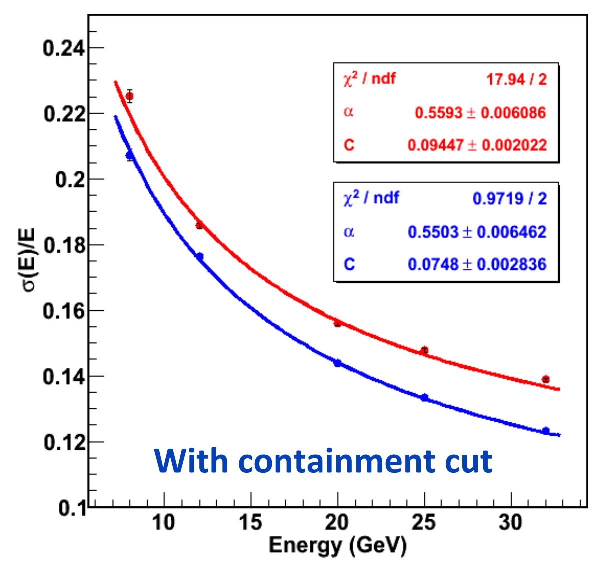
Results so far
- similar to expectations based on GEANT4 simulation



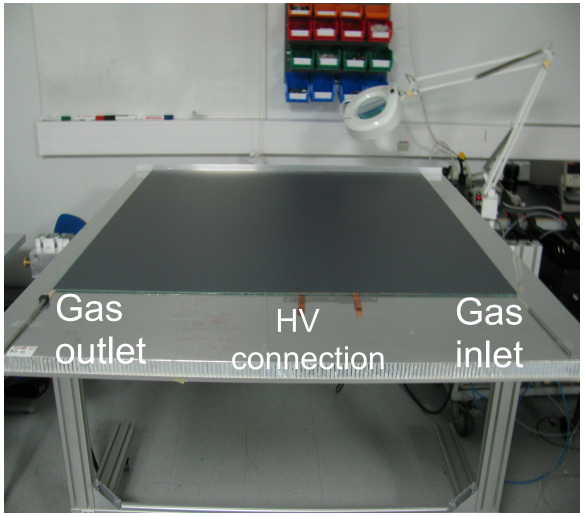
Hadron response (before calibration)

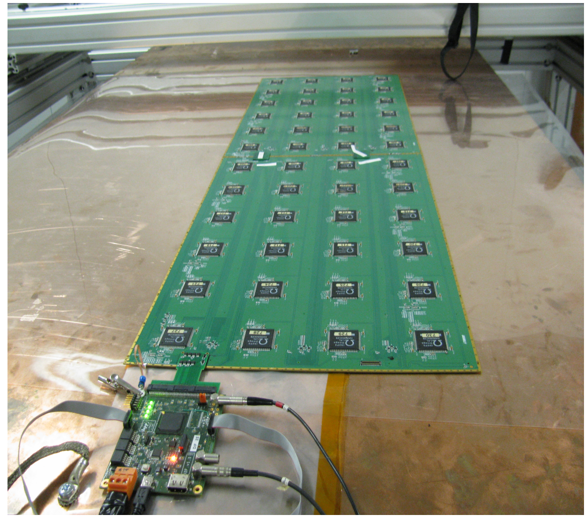


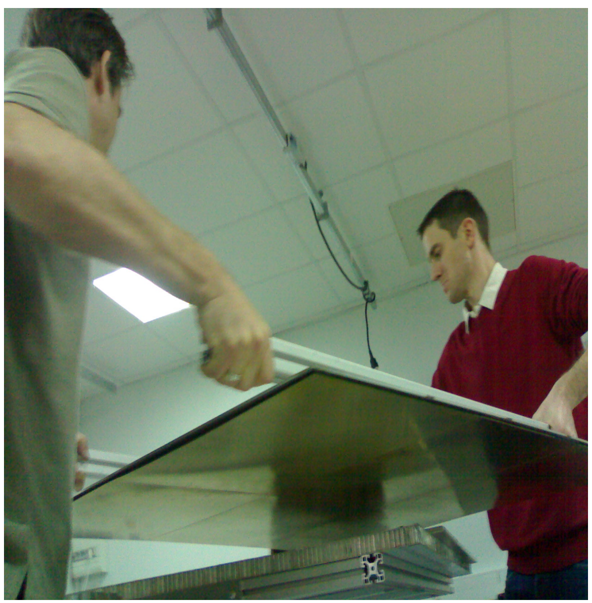
Hadron resolution $\frac{\sigma}{E} = \frac{\alpha}{\sqrt{E}} \oplus C$

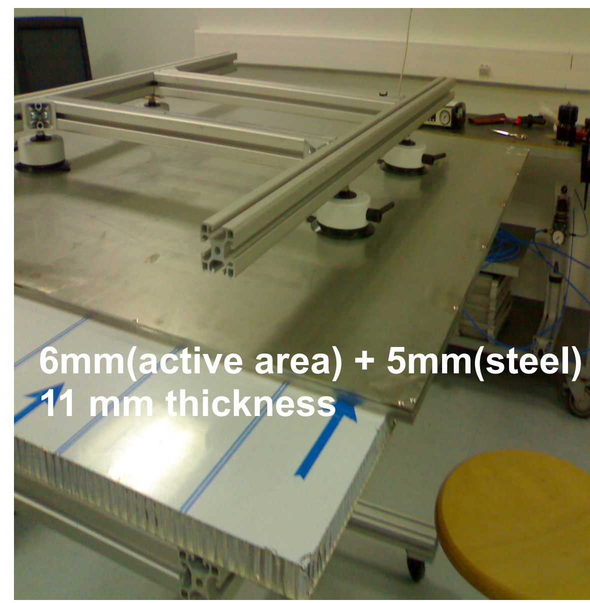


Construction of one unit of the SDHCAL prototype: 2-bit 3-threshold r/o

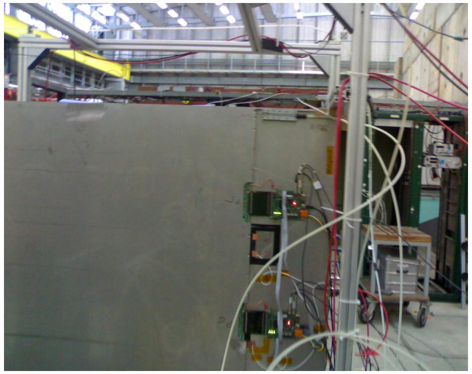


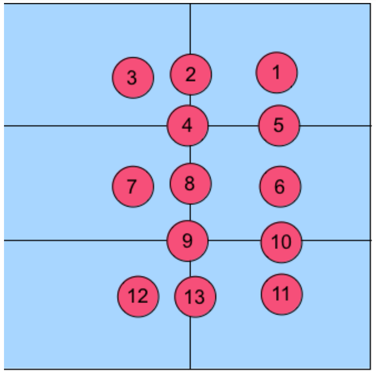




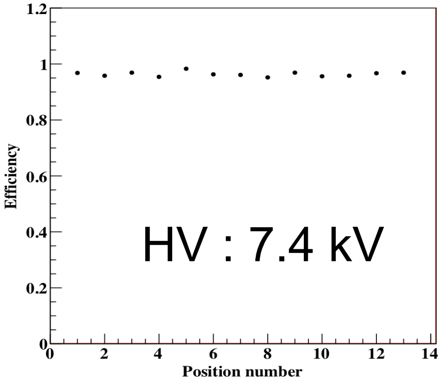


The homogeneity of the detector and its readout electronics were studied

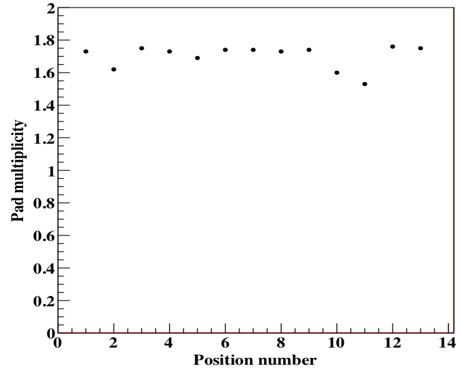




Beam spot position

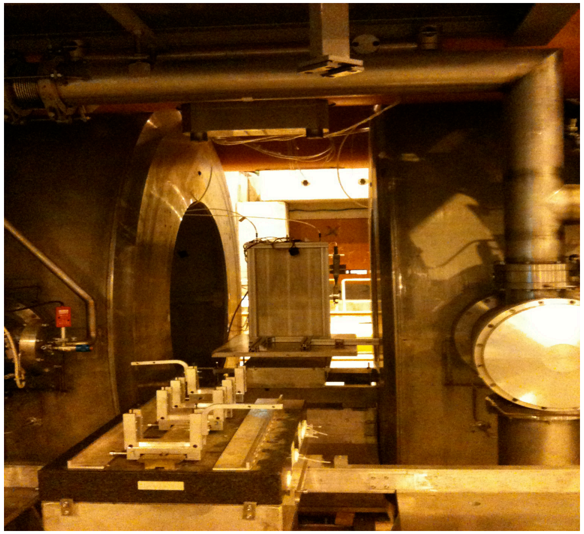


Efficiency

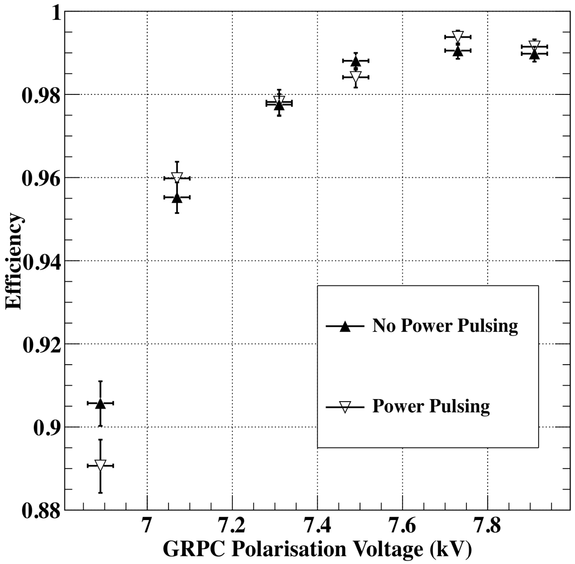


Multiplicity

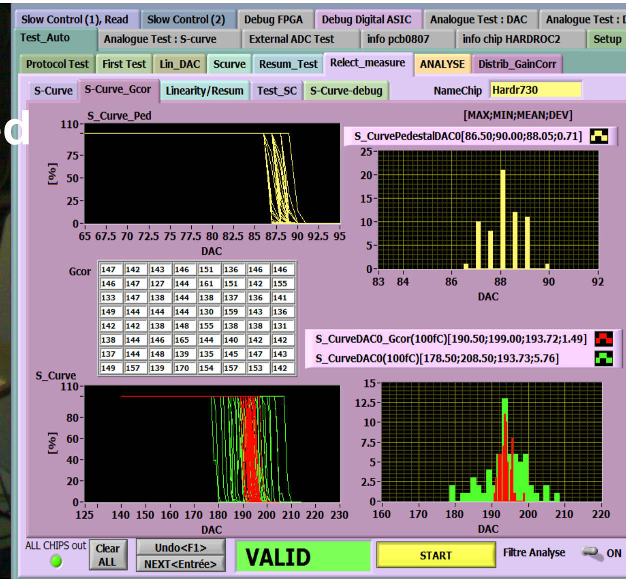
Power-Pulsing mode was tested in a magnetic field of 3 Tesla



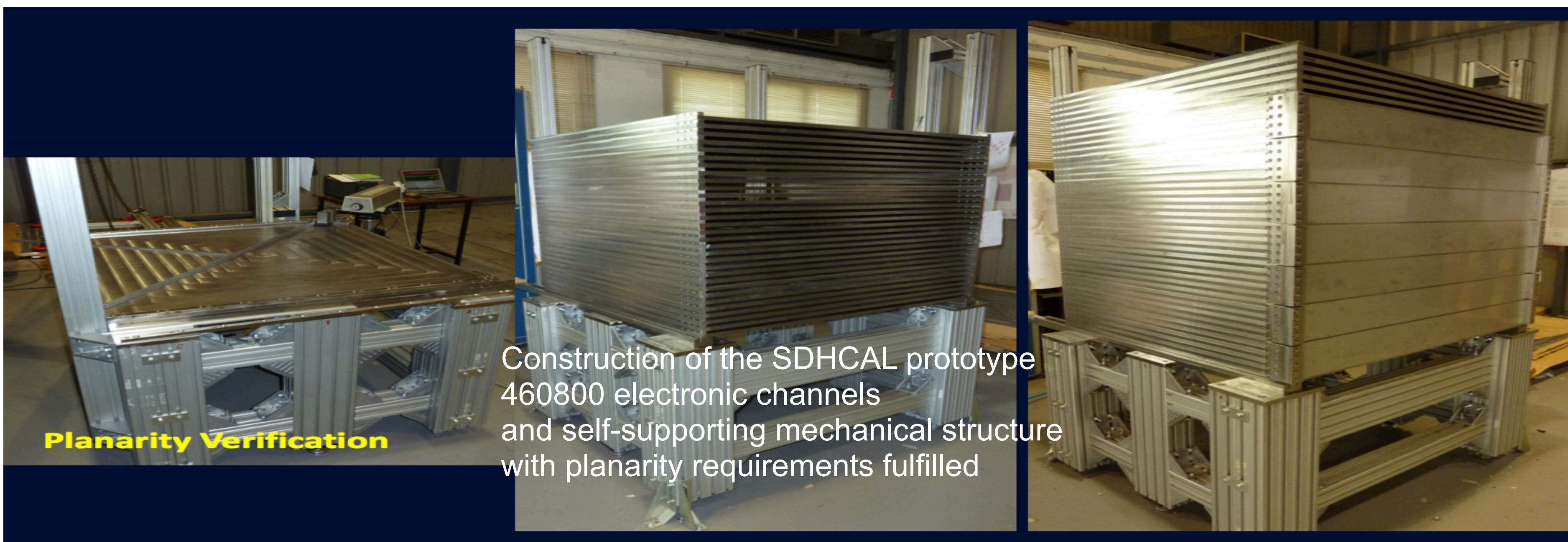
The Power-Pulsing mode was applied on a GRPC in a 3 Tesla field at H2-CERN
(2ms every 10ms)
No effect on the detector performance

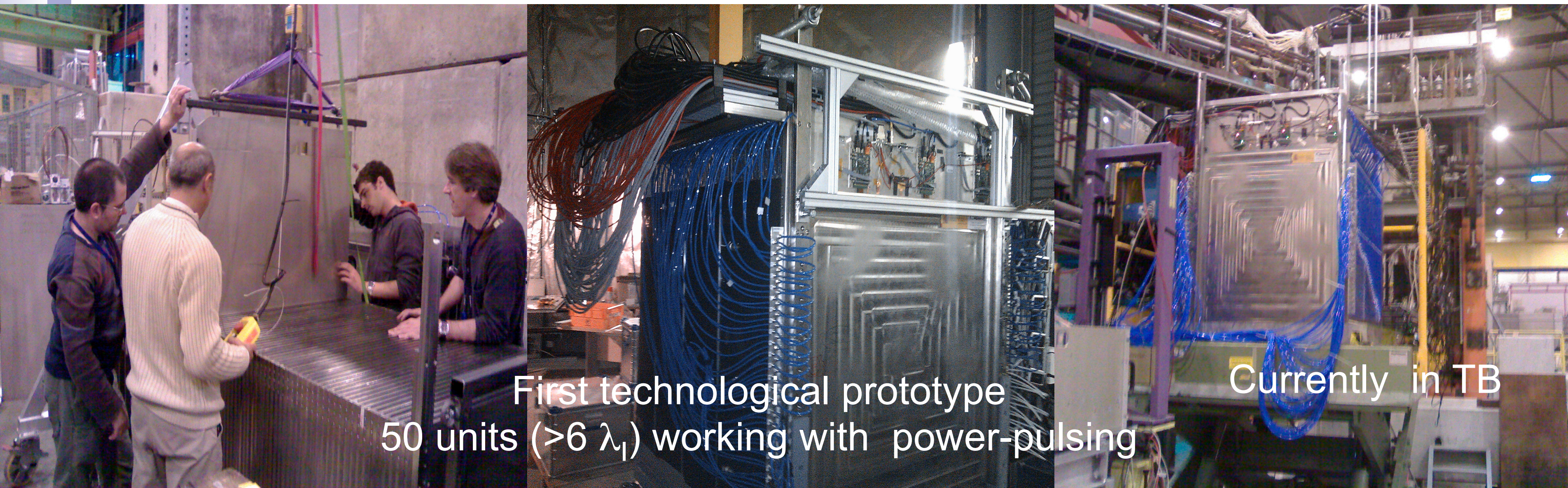


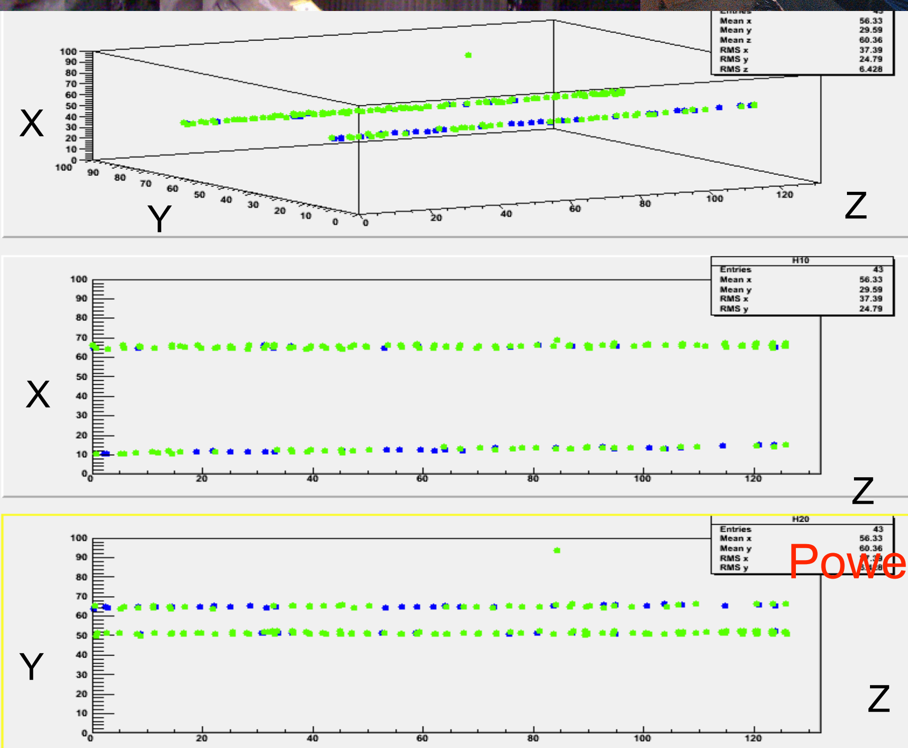

10500 ASIC
Were tested and calibrated

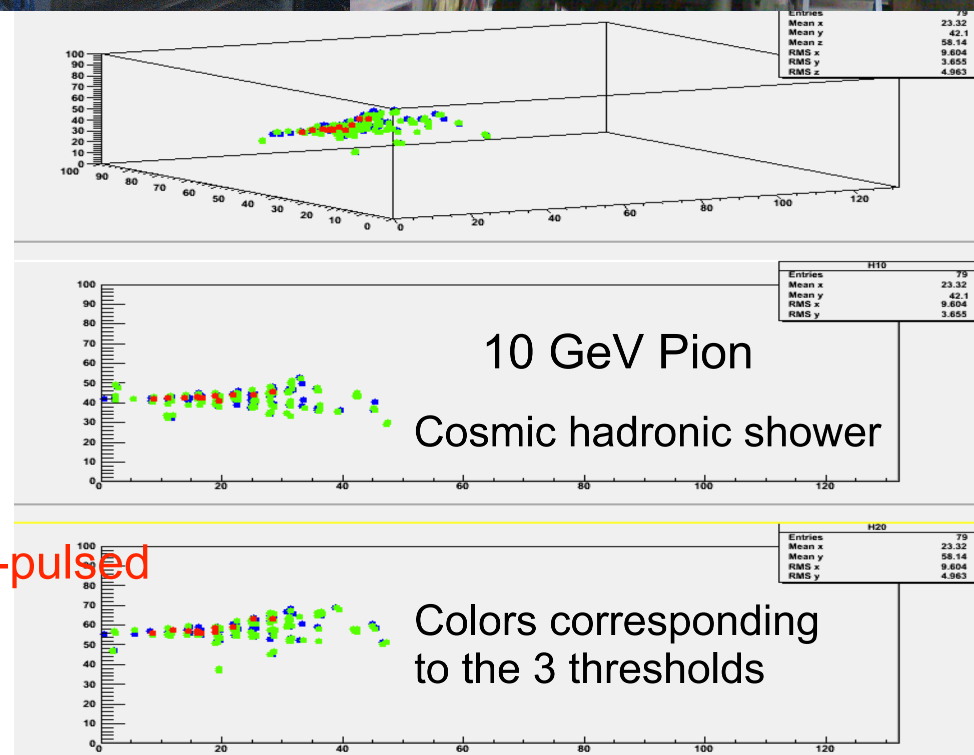

Slow Control (1), Read
Slow Control (2)
Debug FPGA
Debug Digital ASIC
Analogue Test : DAC
Test_Auto
Analogue Test : S-curve
External ADC Test
info pcb0807
info chip HARDROC2
Setup
Protocol Test
First Test
Lin_DAC
Scurve
Resum_Test
Relect_measure
ANALYSE
Distrib_GainCorr
S-Curve
S-Curve_Gcor
Linearity/Resum
Test_SC
S-Curve-debug
NameChip
Hardr730
S_Curve_Ped
[MAX;MIN;MEAN;DEV]
S_CurvePedestalDAC0[86.50;90.00;88.05;0.71]
[%]
DAC
Gcor
147 142 143 146 151 136 146 146
146 147 127 144 161 151 142 155
133 147 138 144 138 137 136 141
149 144 144 144 130 159 143 136
142 142 138 148 155 138 138 131
138 144 146 165 144 140 142 142
137 144 148 139 135 145 147 143
149 157 139 170 154 157 153 142
S_CurveDAC0_Gcor(100fC)[190.50;199.00;193.72;1.49]
S_CurveDAC0(100fC)[178.50;208.50;193.73;5.76]
S_Curve
ALL CHIPS out
Clear ALL
Undo<F1>
NEXT<Entrée>
VALID
START
Filtre Analyse
ON


52 units produced

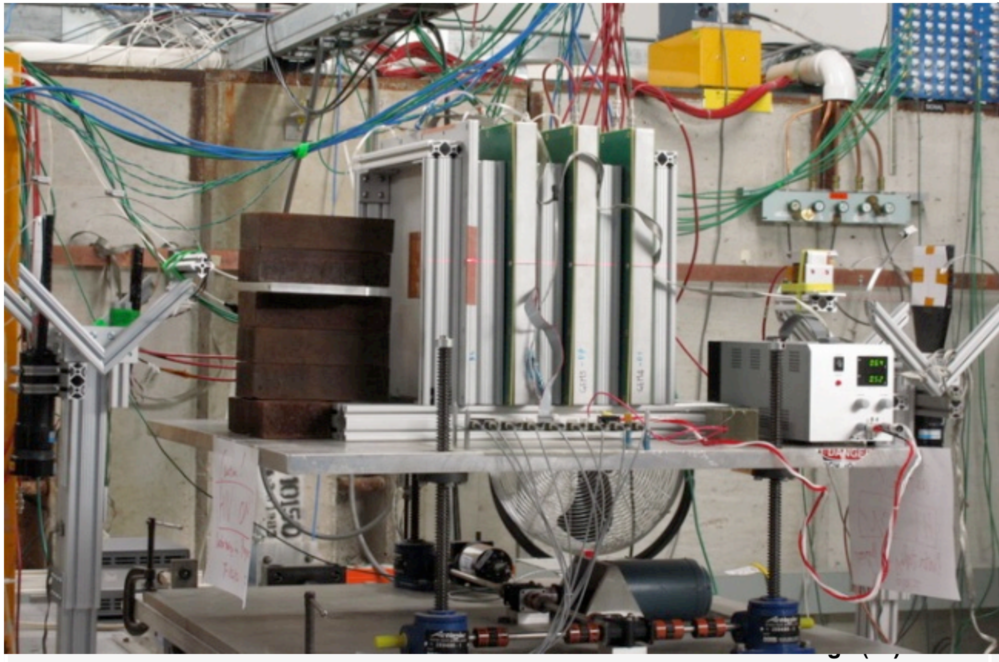

Planarity Verification
Construction of the SDHCAL prototype
460800 electronic channels
and self-supporting mechanical structure
with planarity requirements fulfilled

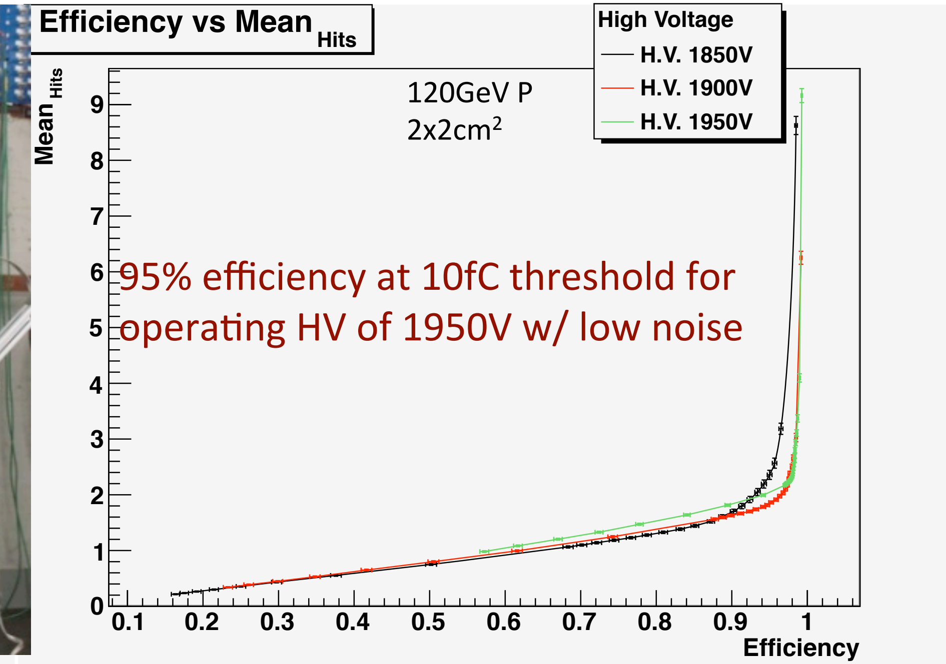

First technological prototype
50 units (>6 λI) working with power-pulsing
Currently in TB

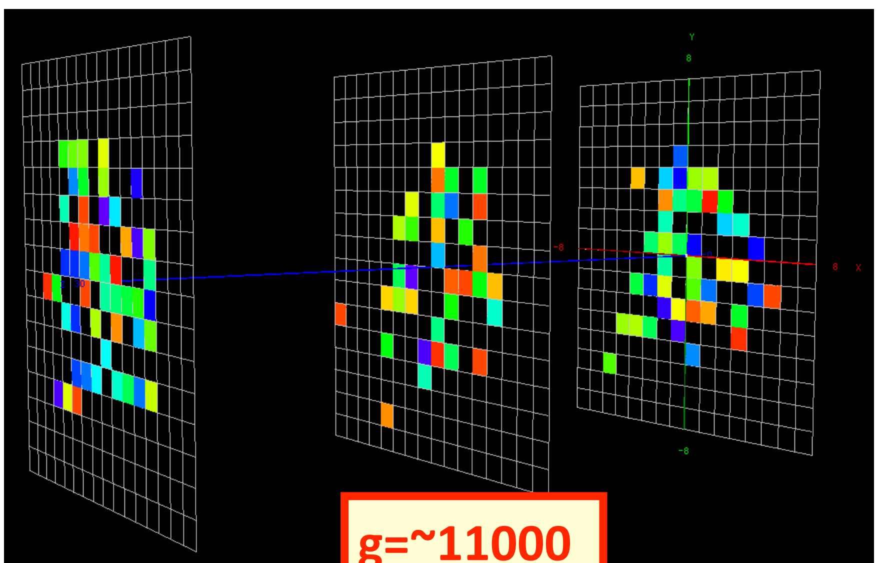

X
Y
Z
H10
H20
Power-pulsed


H10
H20
10 GeV Pion
Cosmic hadronic shower
Colors corresponding
to the 3 thresholds

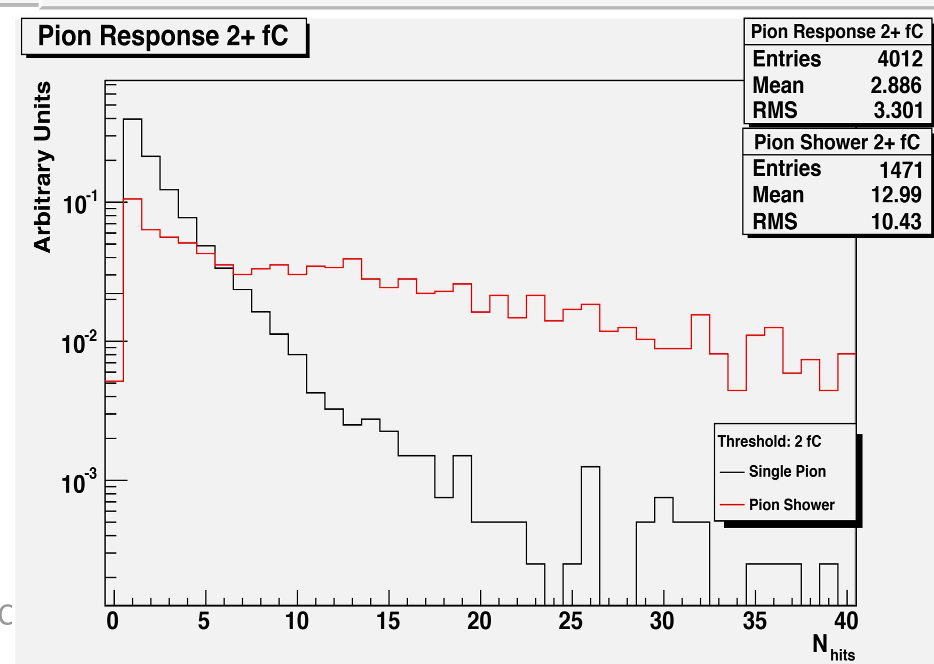
GEM Test Beam with KPiX: Efficiencies, Hit multiplicities



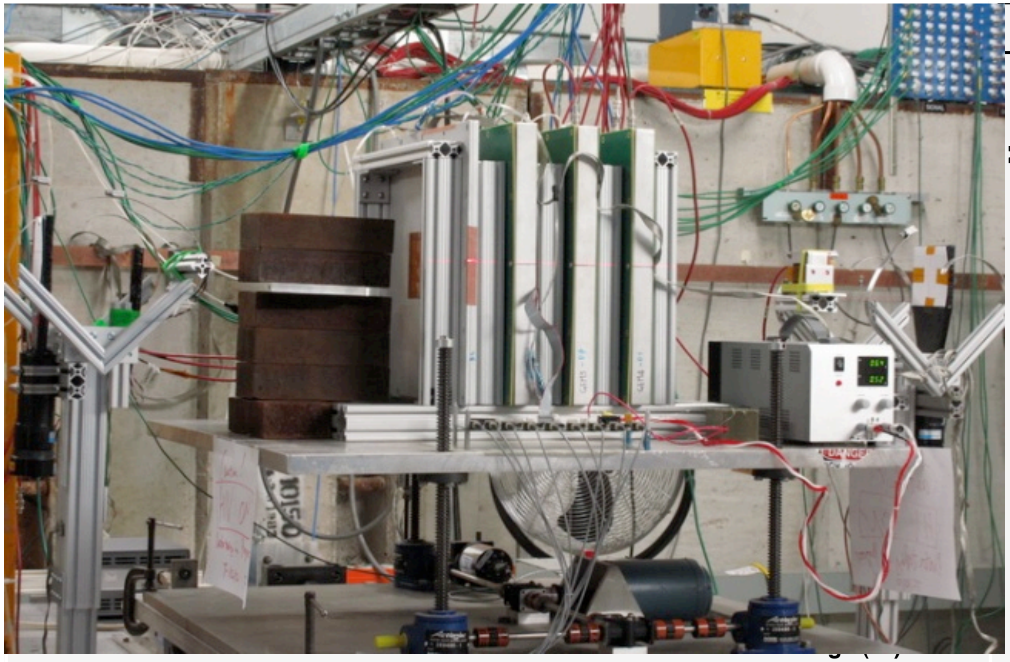


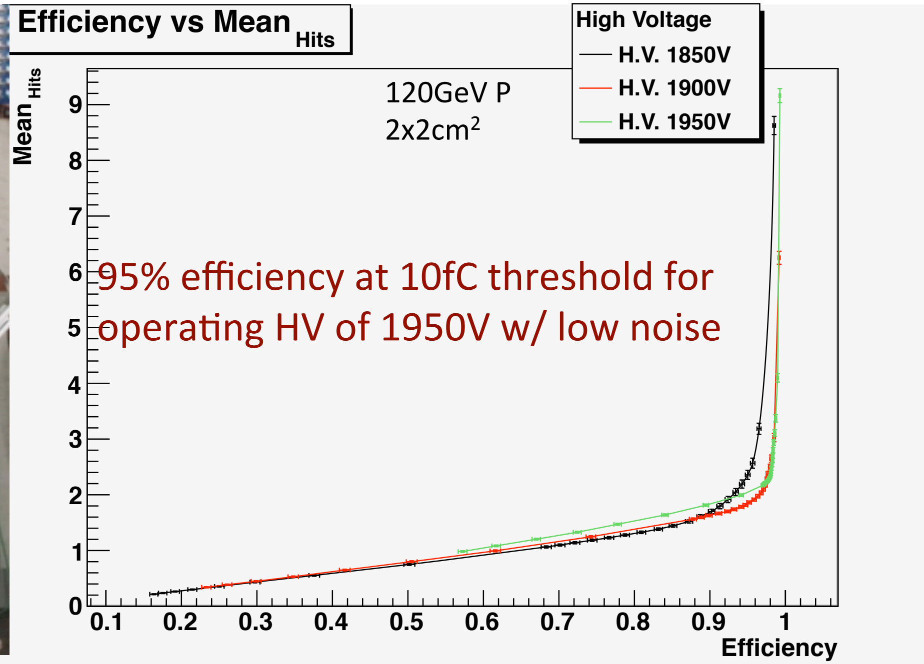


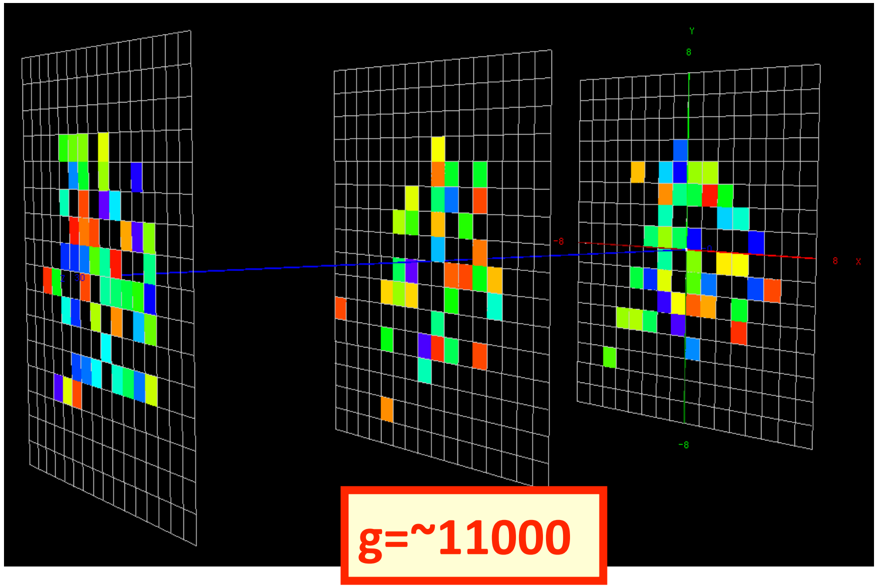
g=~11000

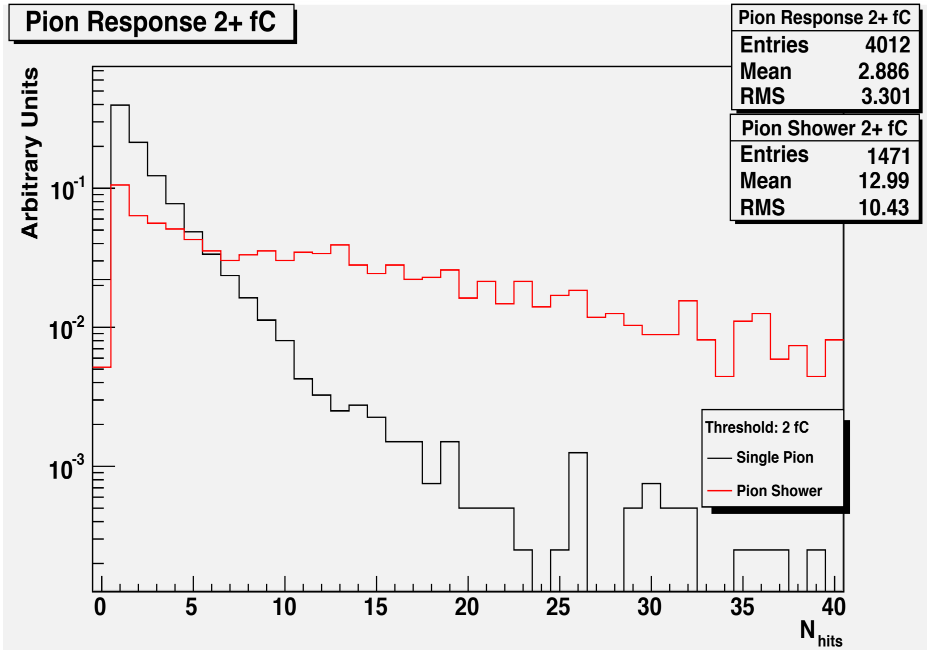


GEM Test Beam with KPiX: Efficiencies, Hit multiplicities

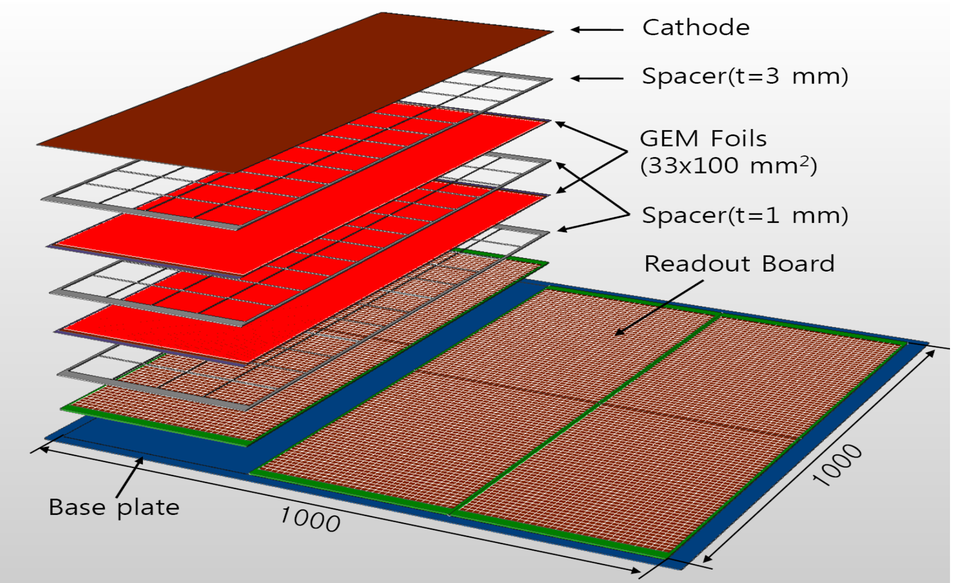








Toward 100cmx100cm GEM Planes!!



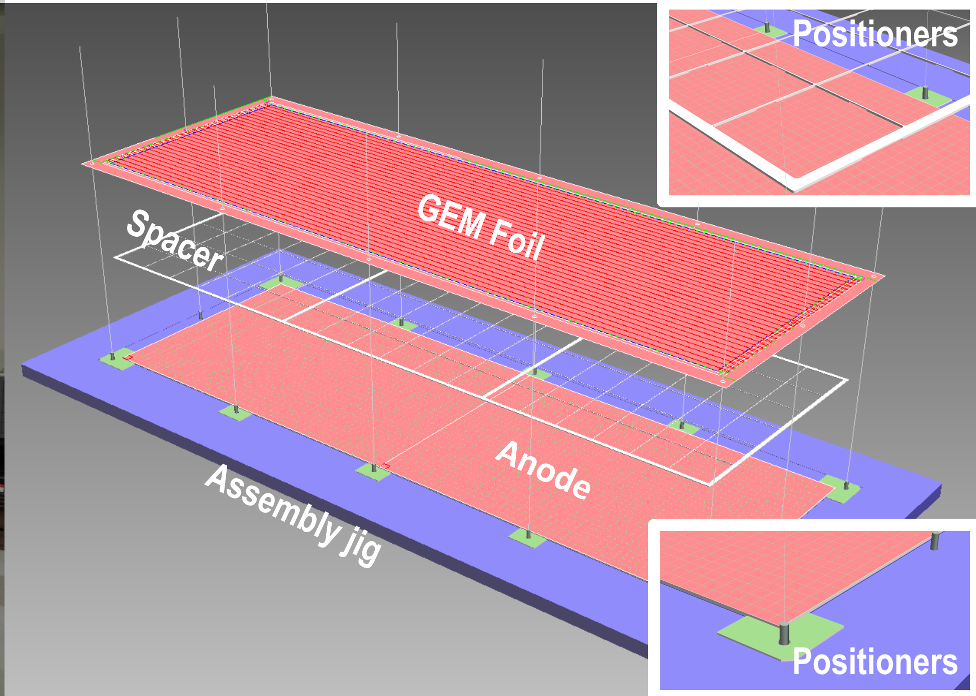
Each of the GEM 100cmx100cm planes will consist of three 33cmx100cm unit chambers

Qualification of five 33cmx100cm GEM foils completed!!

Two 33cmx100cm chamber parts delivered

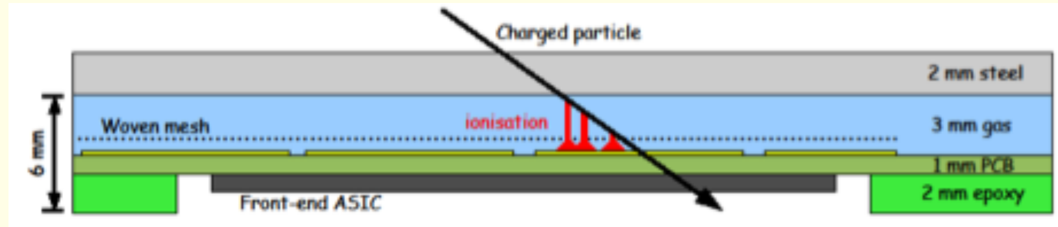
Class 10,000 clean room (12'x8') construction completed

Jig for 33cmx100cm chamber being procured



MICROMEGAS for a SDHCAL

- Characteristics:
  - Proportional mode
  - Bulk-MICROMEGAS
  - 1cm^2 pad readout
  - embedded readout electronics (3 thresholds)
  - Operating at low voltage < 500 V
  - High detection rate
  - Robust, cheap (industrial process)
  - Thickness: down to 6 mm
- Prototype basic performances
  - MIP most probable value : ~20fC
  - At 1.5 fC threshold :
    - Efficiency > 97%, channel disparity < 1%
    - Multiplicity < 1.1
  - Excellent behaviour in electromagnetic and hadronic showers



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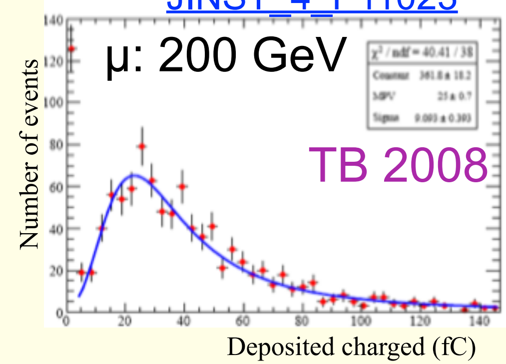
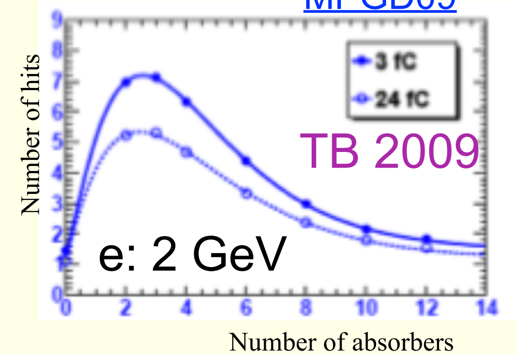


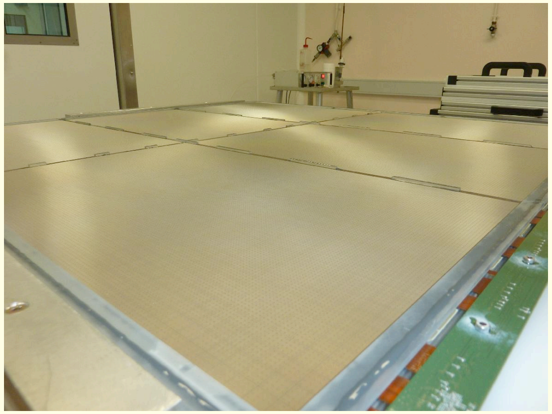
MPGD09



EN-ICE-DEM
PH-LCD

MICROMEGAS for a SDHCAL

- $1m^2$ MICROMEGAS layer:
  - 9216 pads of 1 cm^2 (2% dead areas)
  - 6 independent bulks
  - 7 mm total thickness
    + 2 mm stainless steel (SS)
  - fits in SS and W CALICE structures.
  - Prototype with MICROROC chip
    - Non-flammable mixture Ar/CF4/iC4H10 95/3/2
    - 2 weeks operation in August 2011 (SPS)
      with less than 10 HV trips, no dead channels
      (~ 6 millions of recorded triggers: 150 GeV μ and π)
    - 10 days in GRPC-DHCAL in October 2011 (SPS)
      (~ 1 millions of recorded hadron triggers: 60 to 180 GeV)
    - Efficiency = 98 %, hit multiplicity = 1.15 ,
      Noise = 0.1 Hz for the complete $1m^2$
    - Response in hadronic showers, triggerless mode
  - 4 MICROMEGAS layers expected for 2012 beam tests
    in GRPC-HCAL with common DAQ!



EN-ICE-DEM
PH-LCD

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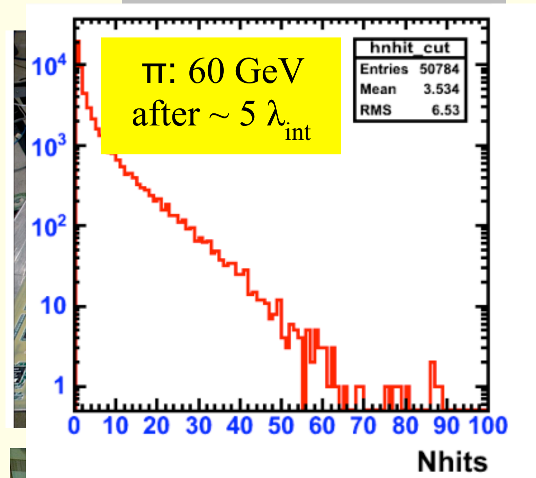
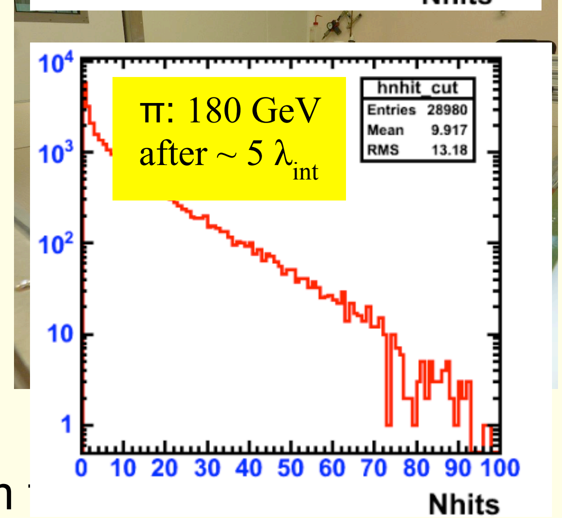




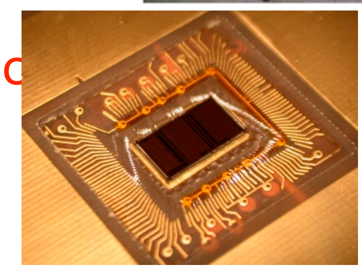
Common developments

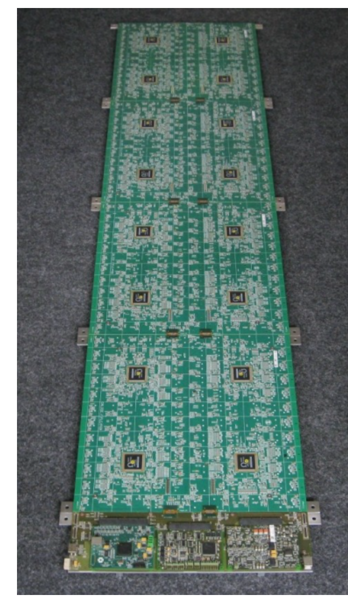
Front end electronics
DAQ

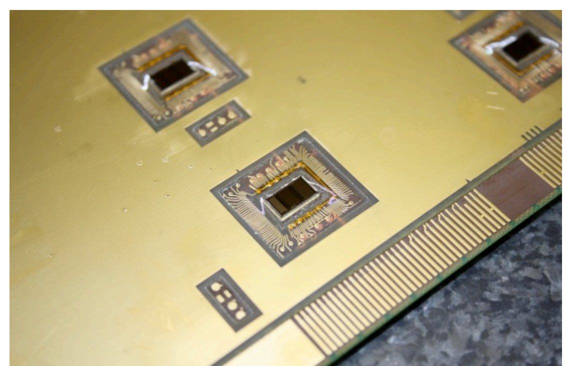
not reported here: test beam infrastructure, software and computing

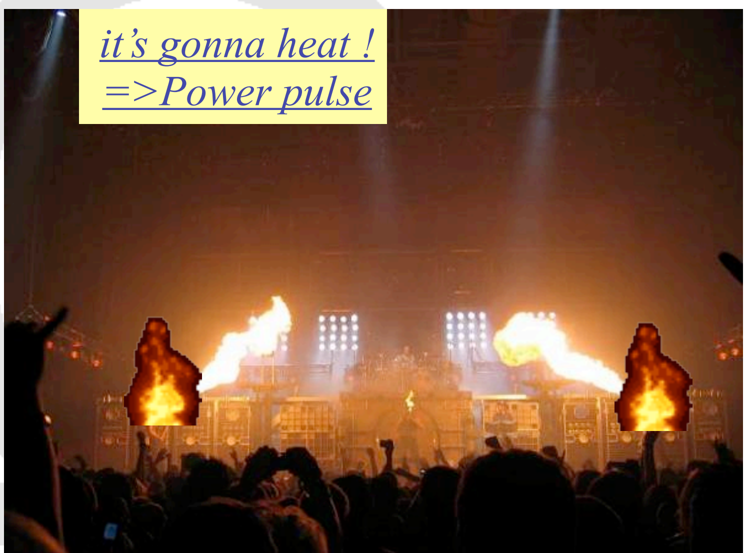
ILC Challenges for electronics

- Requirements for electronics
  - Large dynamic range (15 bits)
  - Auto-trigger on ½ MIP
  - On chip zero suppress
  - Front-end embedded in detector
  - 10^8 channels
  - **Ultra-low power : (25µW/ch)**
  - Compactness
- « Tracker electronics with calorimetric performance »



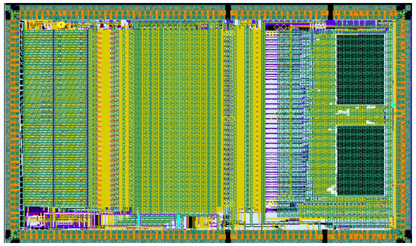




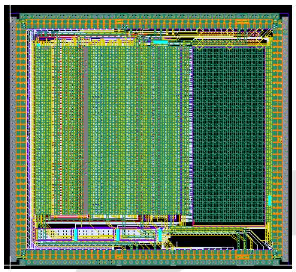


ASICs for ILC prototypes

Ωmega

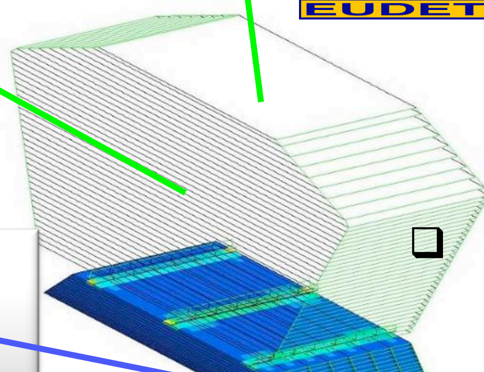


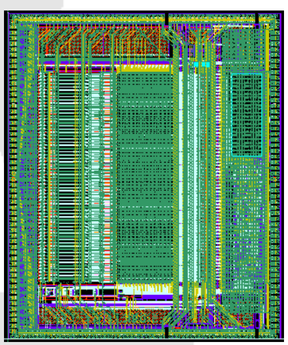
SPIROC2
Analog HCAL (AHCAL)
(SiPM)
36 ch. 32mm²
June 07, June 08, March 10



HARDROC2 and MICROROC
Digital HCAL (DHCAL)
(RPC, µmegas or GEMs)
64 ch. 16mm²
Sept 06, June 08, March 10

EUDET





SKIROC2
ECAL
(Si PIN diode)
64 ch. 70mm²
March 10

CALICE
Calorimeter for ILC

- ❑ 1st generation ASICs: FLC-PHY3 and FLC_SiPM (2003) for **physics prototypes**
- ❑ 2nd generation ASICs: ROC chips for **technological prototypes**
  - ✓ Address integration issues
  - ✓ Auto-trigger, analog storage, internal digitization and token-ring readout
  - ✓ Include power pulsing : <1 % duty cycle
  - ✓ Optimize commonalities within CALICE (readout, DAQ...)
- ❑ 3rd generation ASICs (AIDA funded):
  - ✓ **Independent channels to perform Zer suppress**

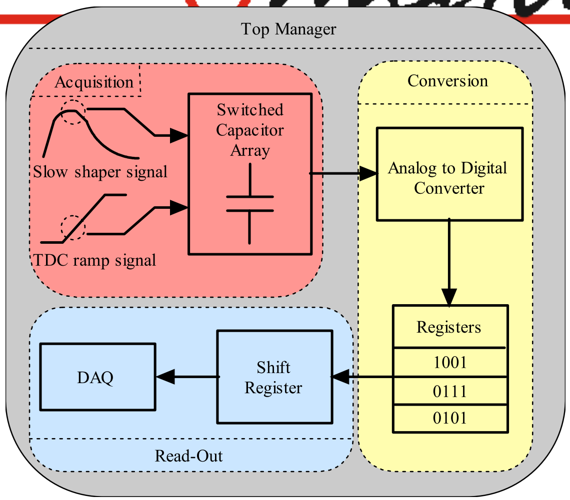
AIDA

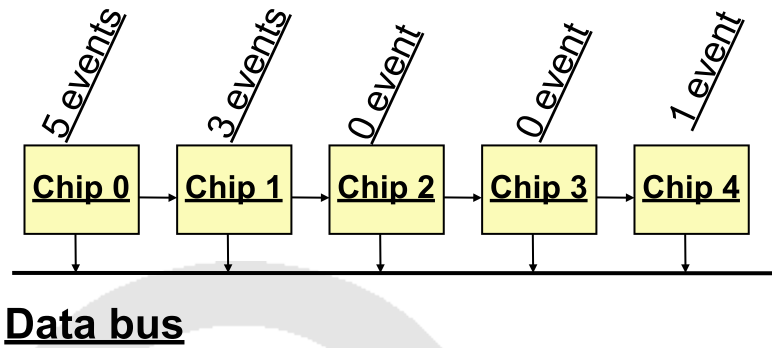
COMMON READOUT: TOKEN RING Mode

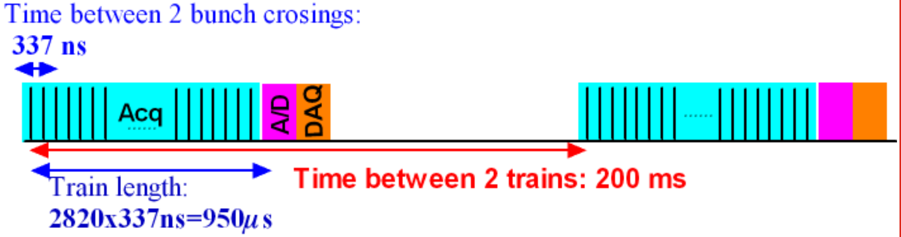
Readout architecture **common to all calorimeters** and **minimization of data lines & power**

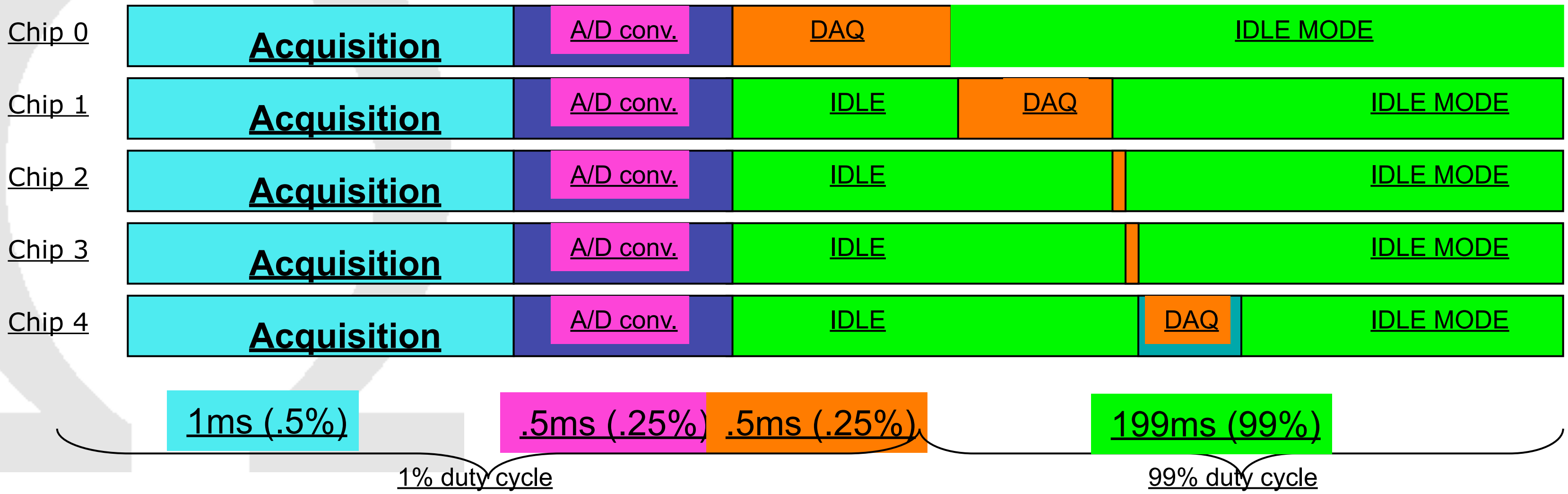
- **Daisy chain** using token ring mode
- Open collector, low voltage signals
- Low capacitance lines

SCA
in SK2 and Spiroc



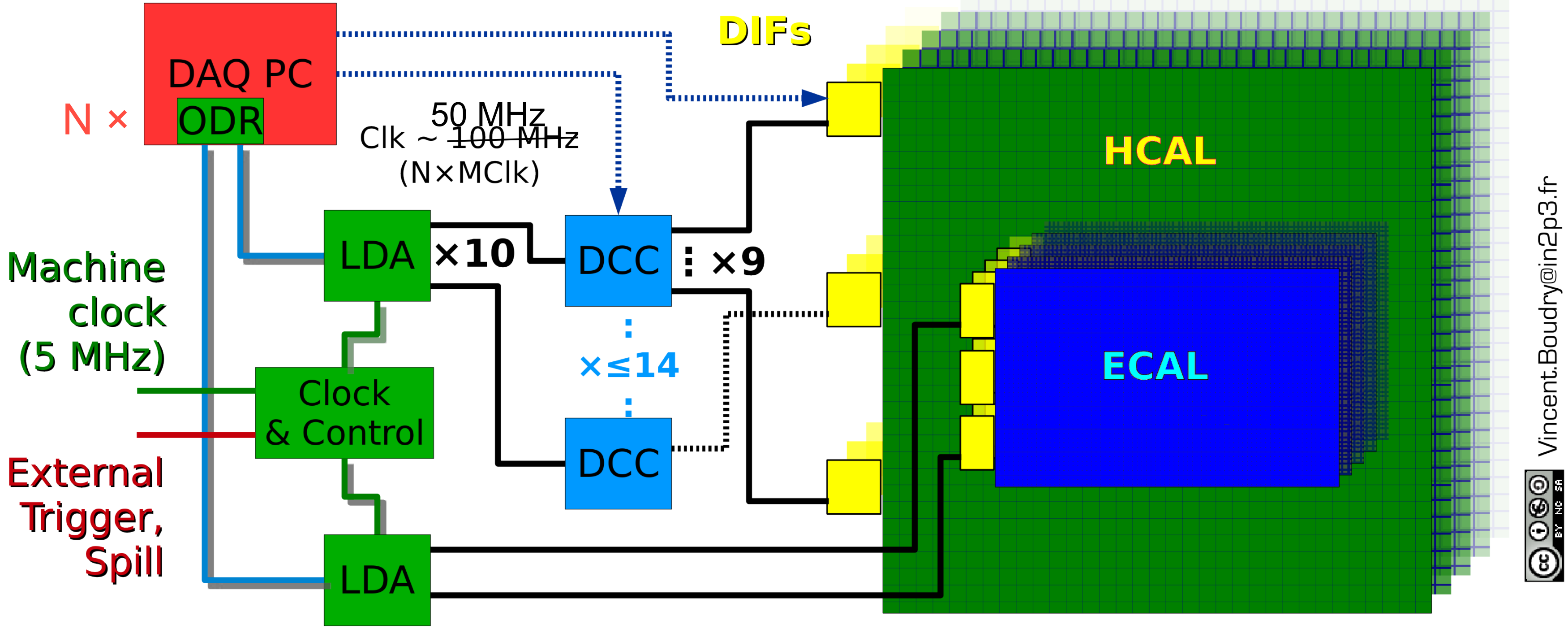






CALICE DAQ2 scheme

Original ideas and R&D from CALICE-UK (UCL, Cambridge U., Manchester U., RHUL)



LDA-DIF on HDMI (Config, Control, Data, Clock, Trig, Busy, Sync)

Clock, Trig, Busy & Sync on HDMI (compatible LDA-DIF)

Optique (alt. Cable) GigE

Debug USB

External Trigger

ODR = Off Detector Receiver
LDA = Link Data Agregator

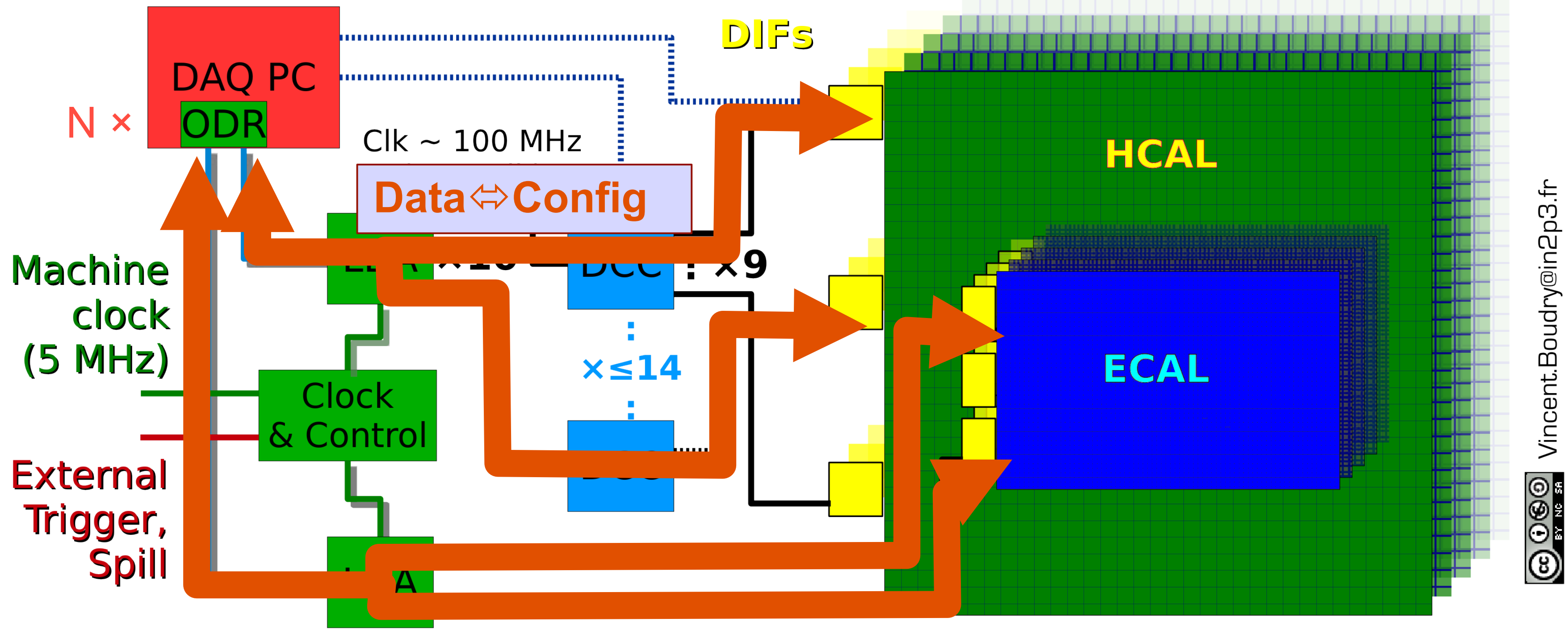
DCC = Data Concentrator Card
DIF = Detetcor InterFace

CCC = Clock & Control Card

Vincent.Boudry@in2p3.f

CALICE DAQ2 scheme

Implementation & debug made by CALICE-France:
LLR, IPNL, LAPP



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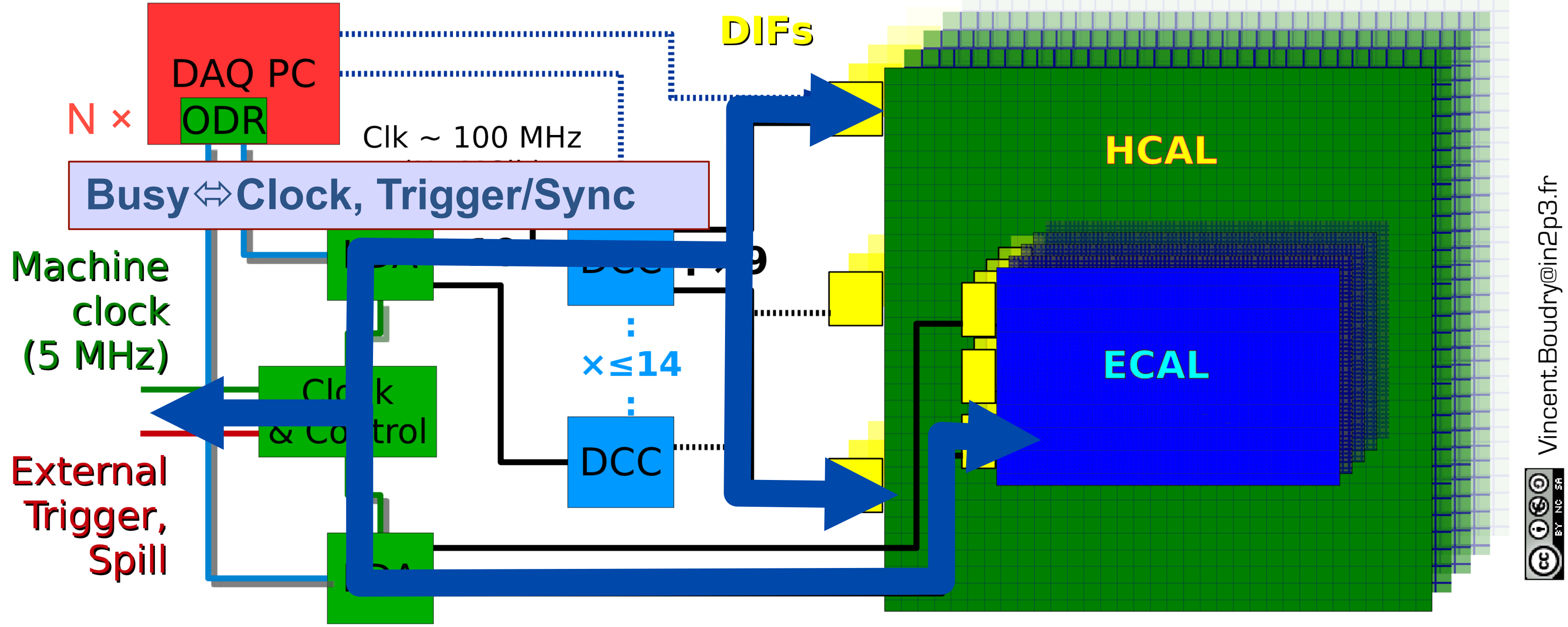

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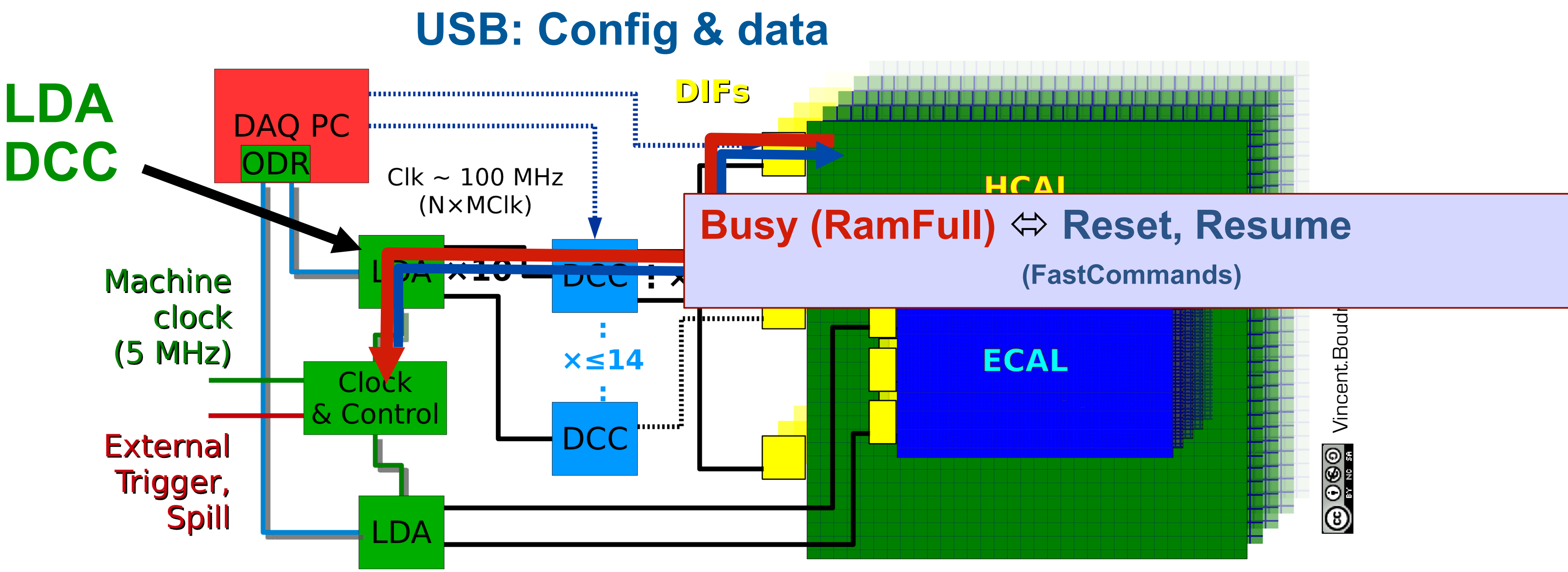
USB readout for SDHCAL



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Clock, Trig, Busy & Sync on HDMI (compatible LDA-DIF)

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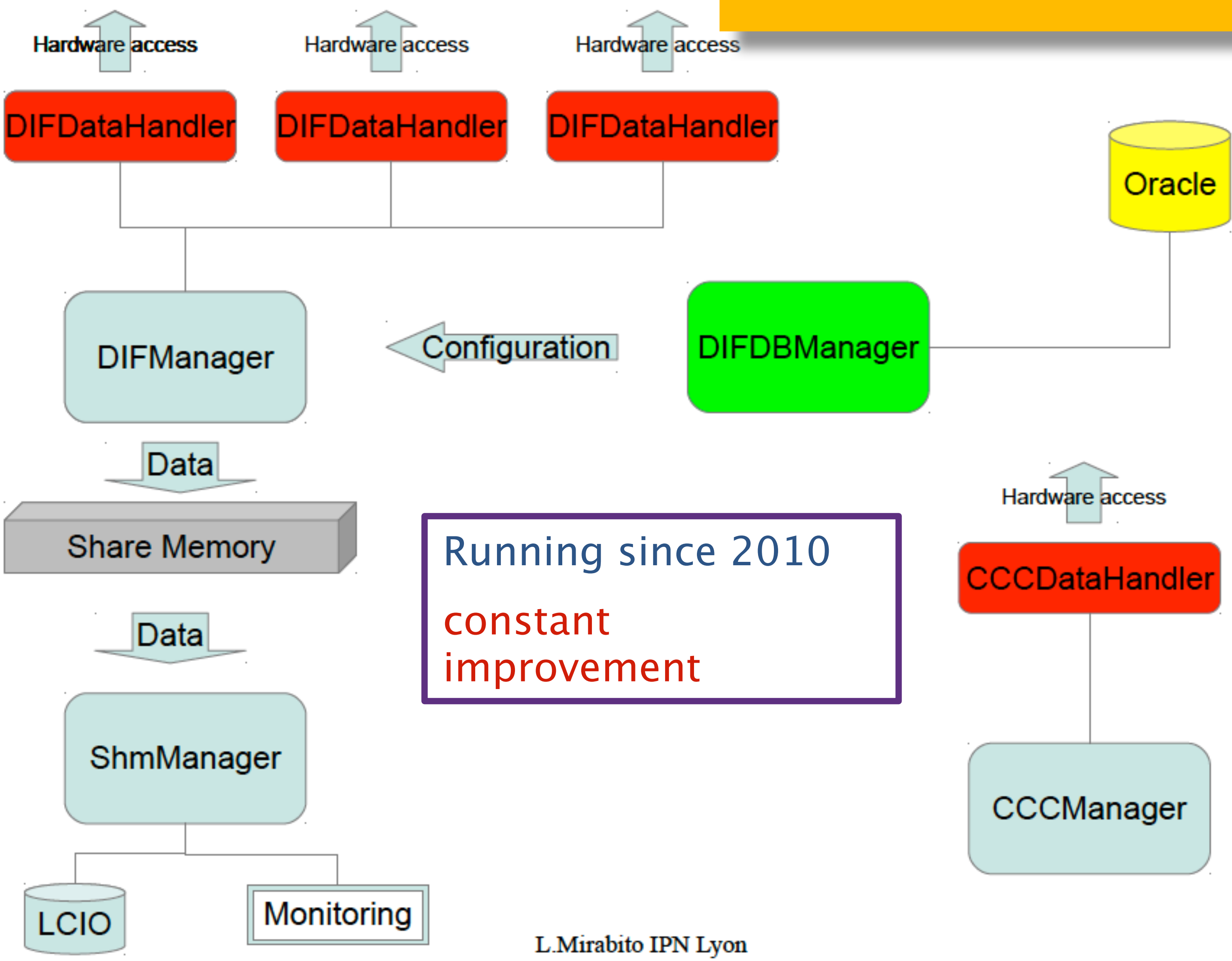
CCC = Clock & Control Card

Vincent.Boudry@in2p3.f

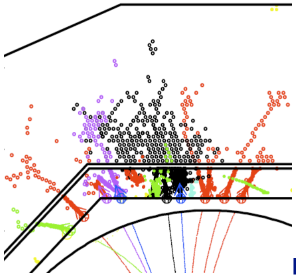
SW framework

XDAQ framework
+ Oracle DB for config.
+ LCIO for Data Output
USB or **HDMI** readout



Running since 2010

constant improvement



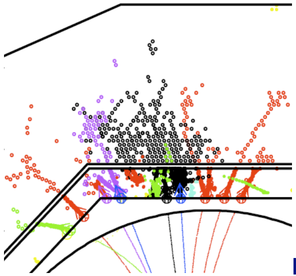
Technologies

- High granularity needs spur the use of novel detection techniques in calorimetry
  - Si pads at large scale, SiPMs, pad RPCs, MPGDs
  - ultra-low power mixed-circuit ASICs are key

- All major technologies have undergone or are undergoing extensive full-scale beam tests
- Si W ECAL and Sci Fe AHCAL analysis nearly complete
- Analysis of the more recent tests has just begun, but all results so far are encouraging and confirm the expectation

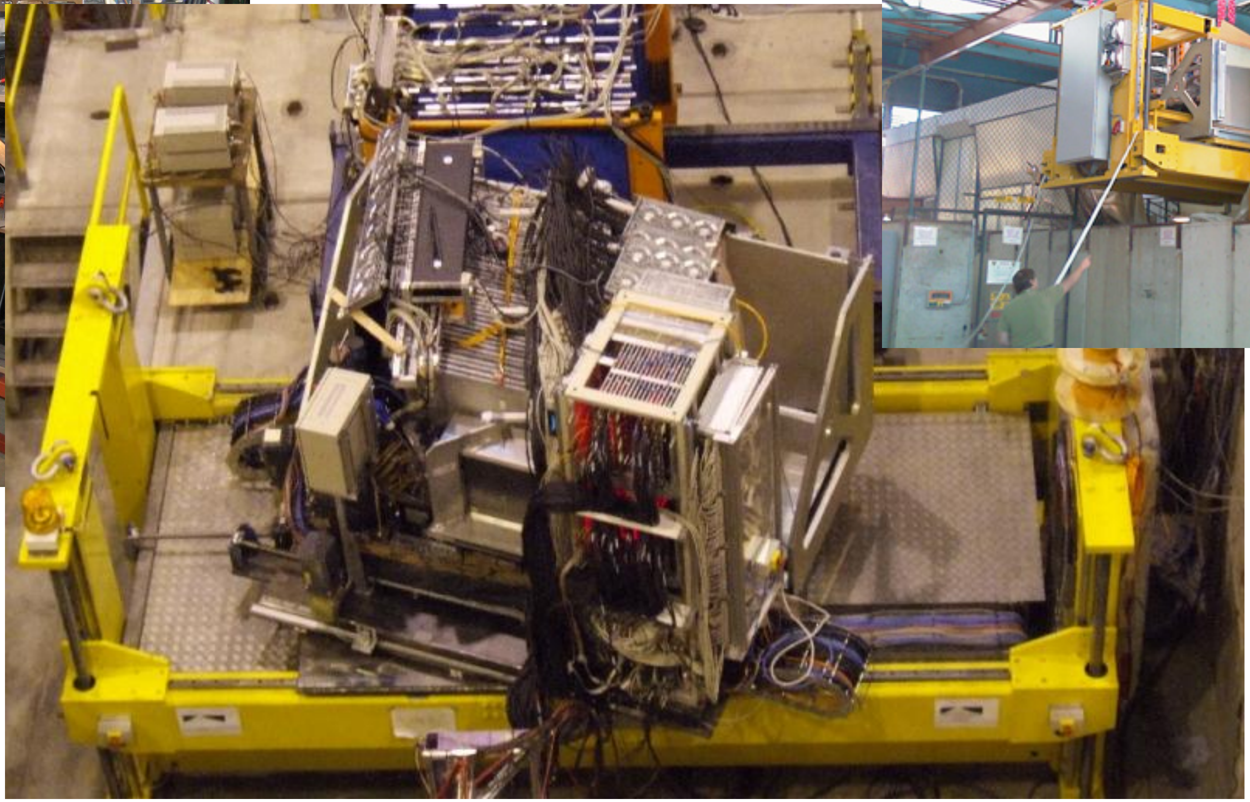
- Technological demonstrators of scalable systems start to provide first results
- No show stoppers seen, but more tests are necessary

Test beam experiments



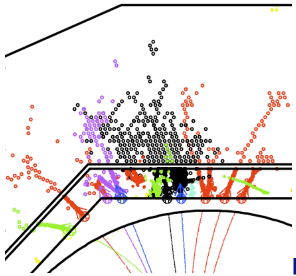
Test beam experiments

DESY 2005
SiECAL



CERN 2006-2007
add Scint HCAL

FNAL 2008-09
Si -> Sci ECAL

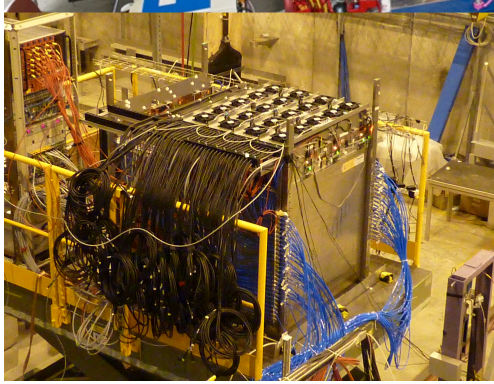


Test beam experiments 2010+

CERN
2010-11
W abs.
AHCAL

2012:
DHCAL

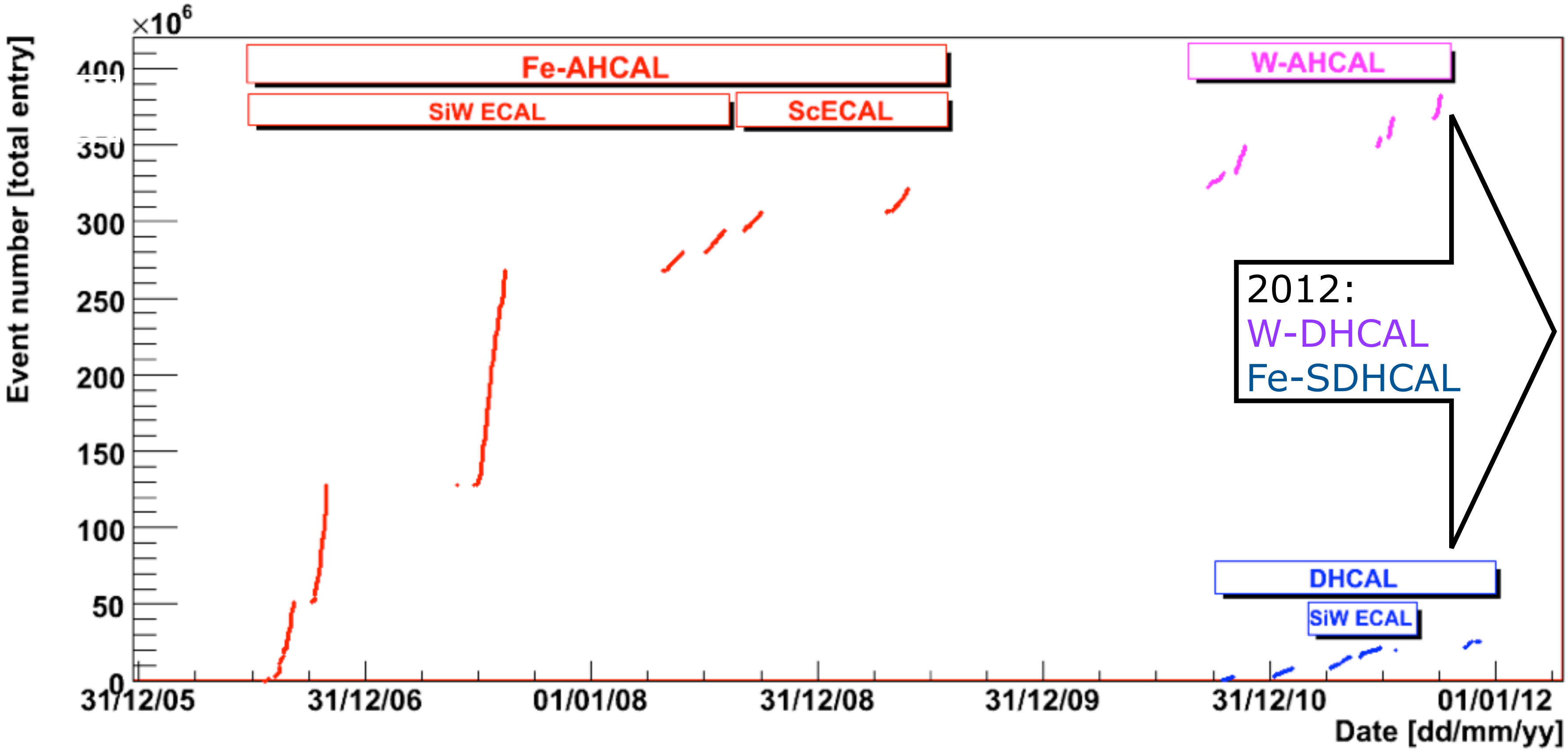
FNAL2010-11:
Scint AHCAL → RPC DHCAL



2012: m^3 SDHCAL

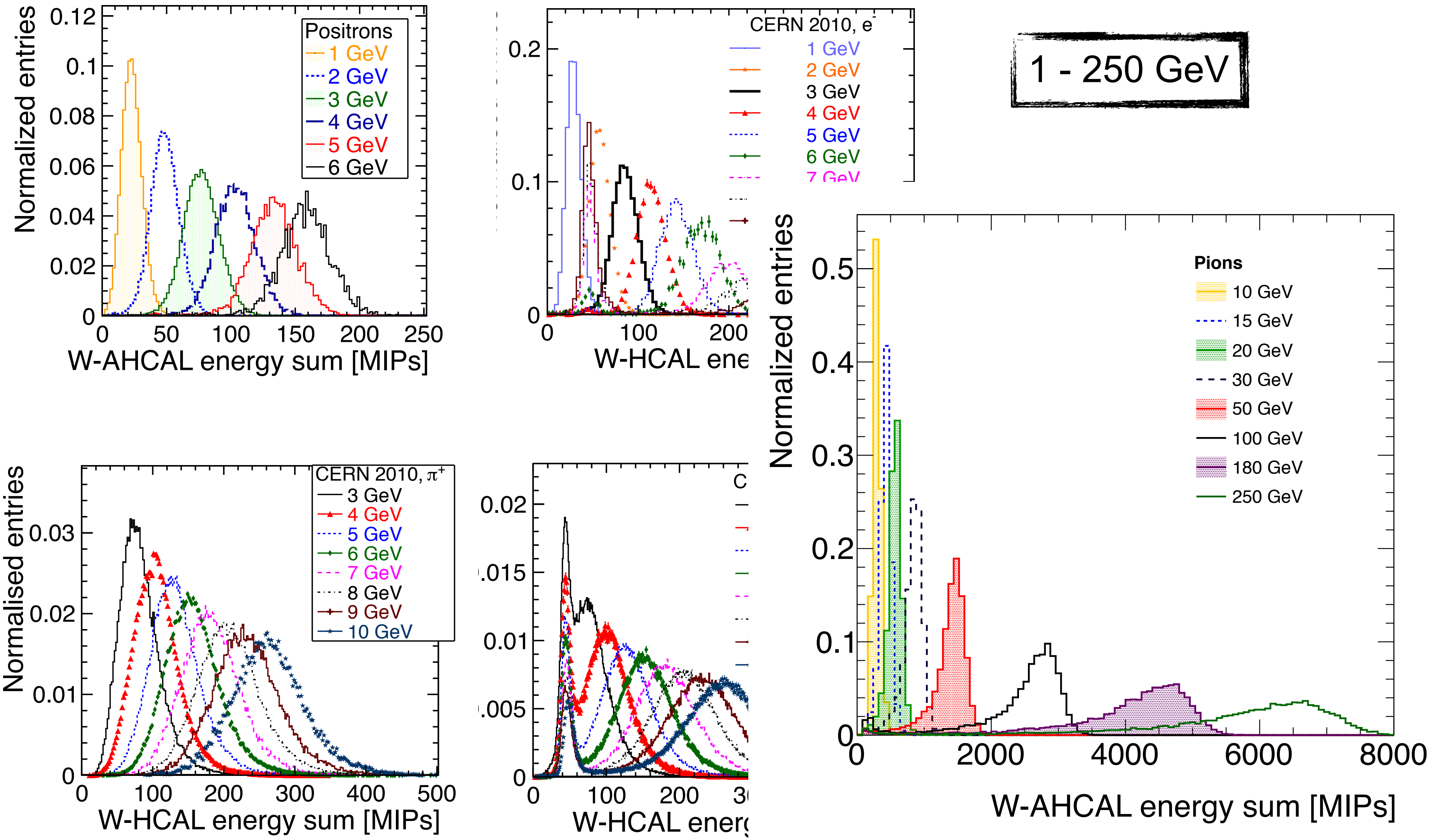
DESY
2nd generation
scint HCAL

Summary of data taken



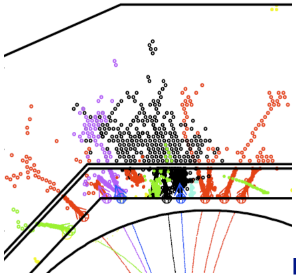
- Muon, LED and noise runs not included
- event size ~ 50kB -> 20 TB of physics data on the GRID

W-AHCAL Data taken at PS and SPS



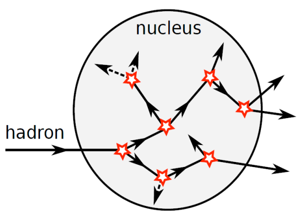
Physics results

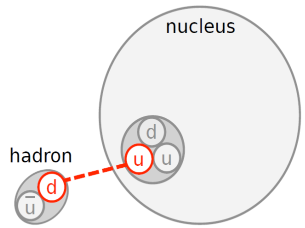
Validation of Geant 4 simulations,
Tests of particle flow algorithm

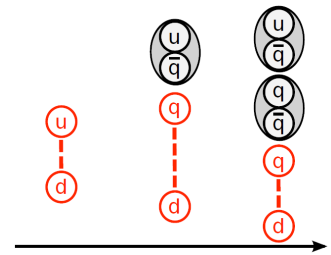


Shower simulation in Geant 4

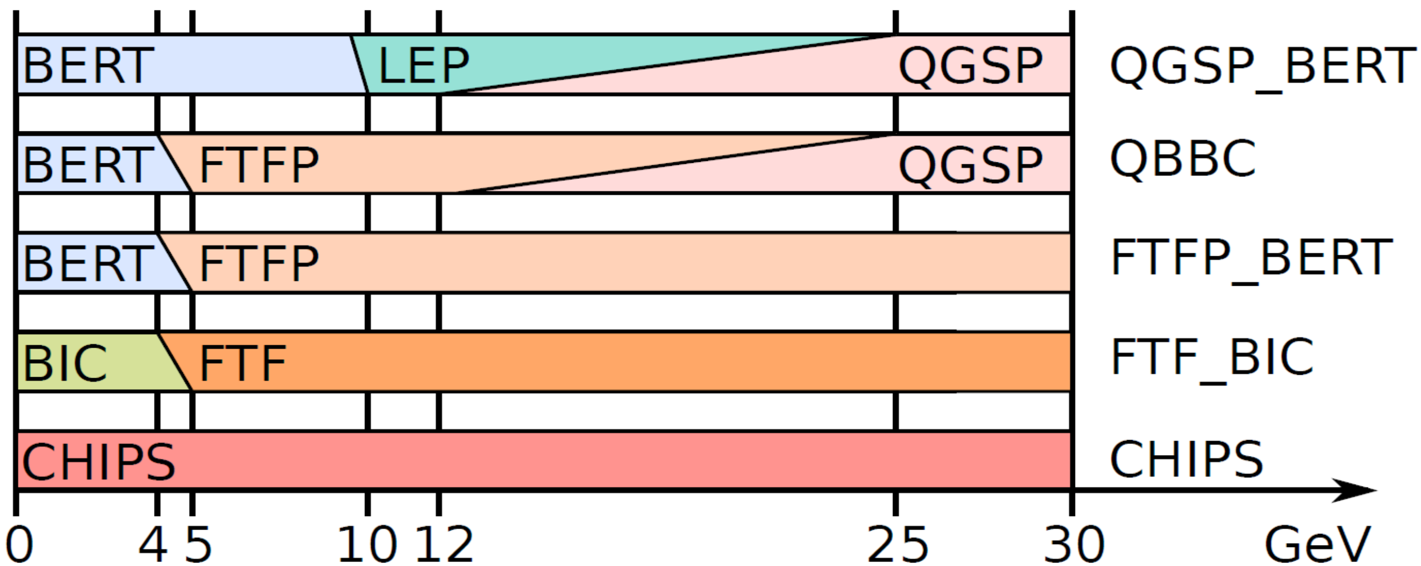
- Low energy: cascade models
- High energy: partonic models







minimize use of phenomenological parameterization



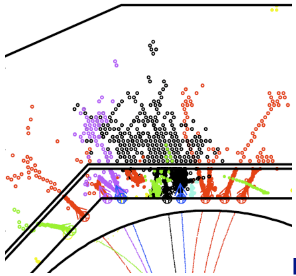
"legacy"

"linear combin."

"production"

"systematics"

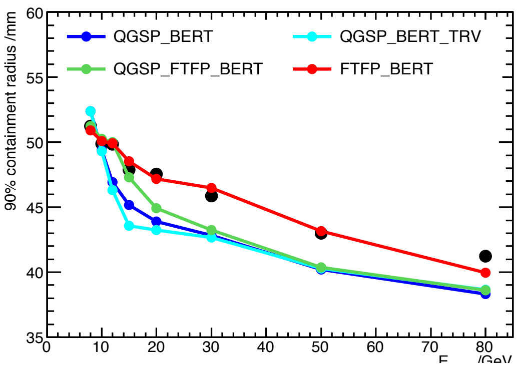
"experimental"

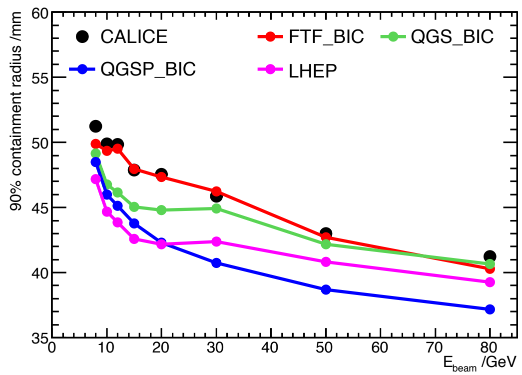


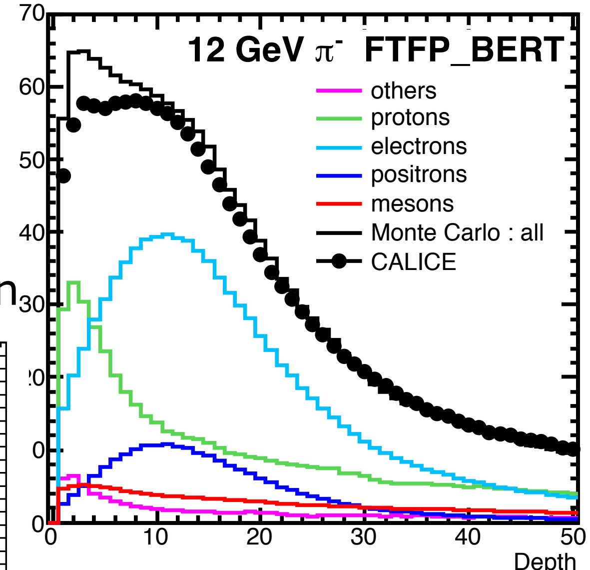
SiW ECAL data

- Very precise information thanks to high granularity
- Shower decomposition very instructive

note zero suppression

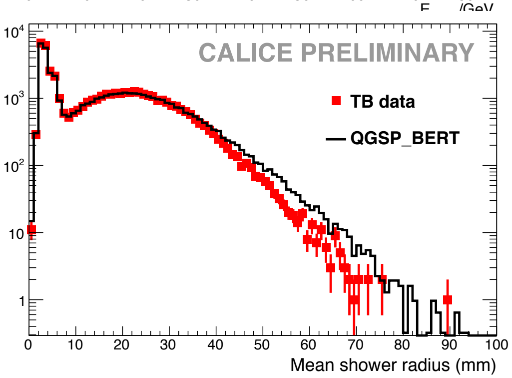




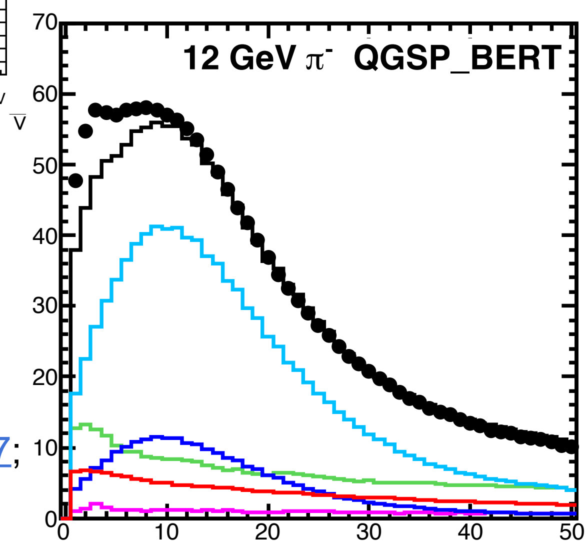


20 X0

0.8 λ



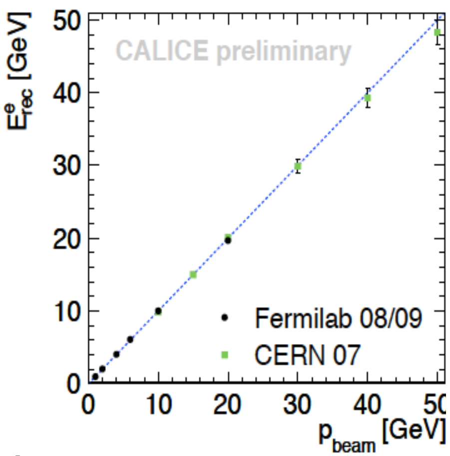
showers wider in data than most lists,
but FTFP_BERT does well
at low energy reversed



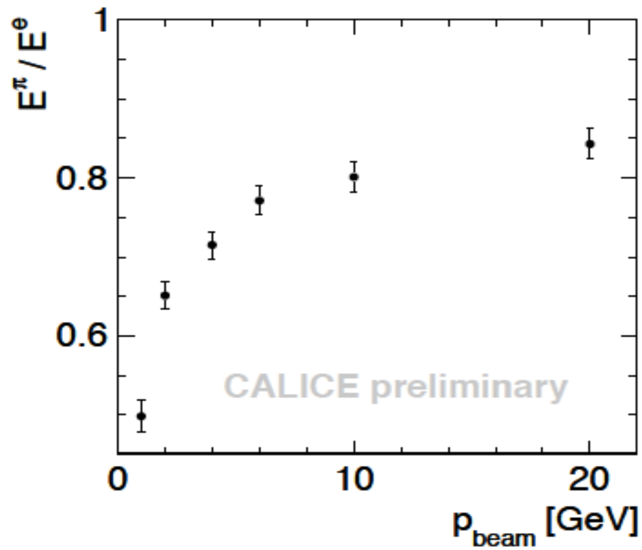
2010_JINST_5_P05007;

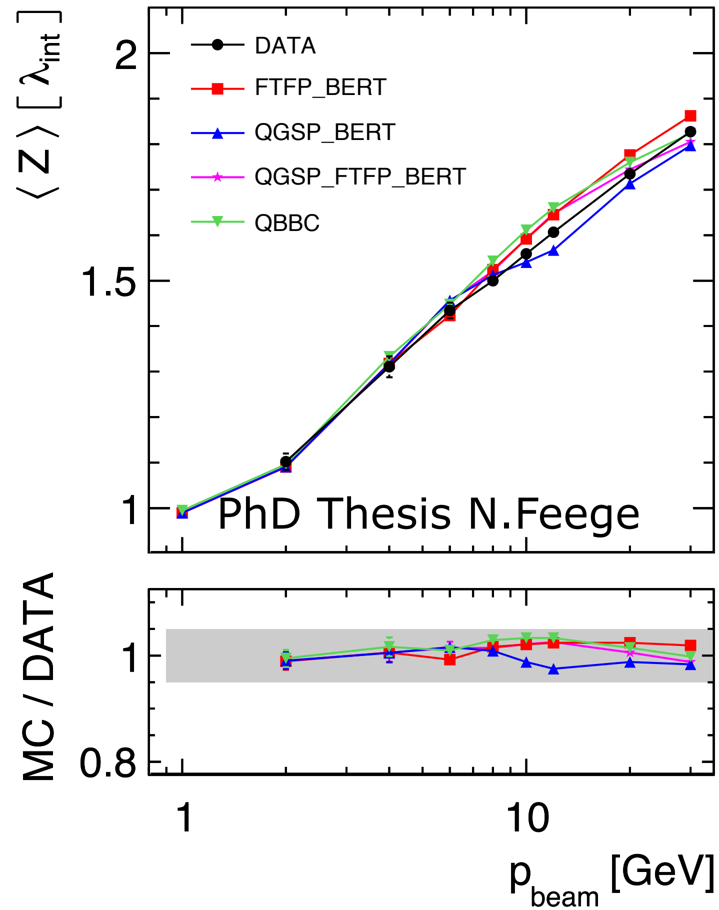
CERN and FNAL Fe AHCAL data

- Test beam at FNAL used to explore lower energies
- Important new tests of GEANT4
- Many low energy particles in jets, even at high energy.
- Good agreement with CERN data



AN-034





Publication draft

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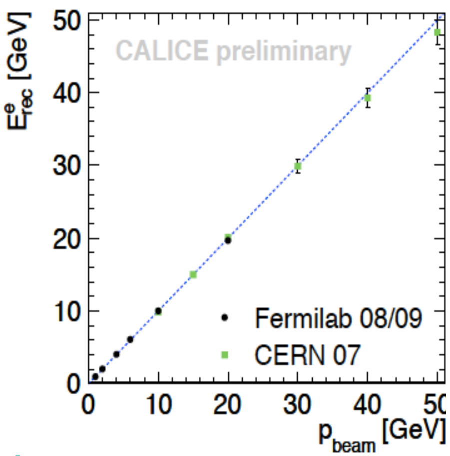
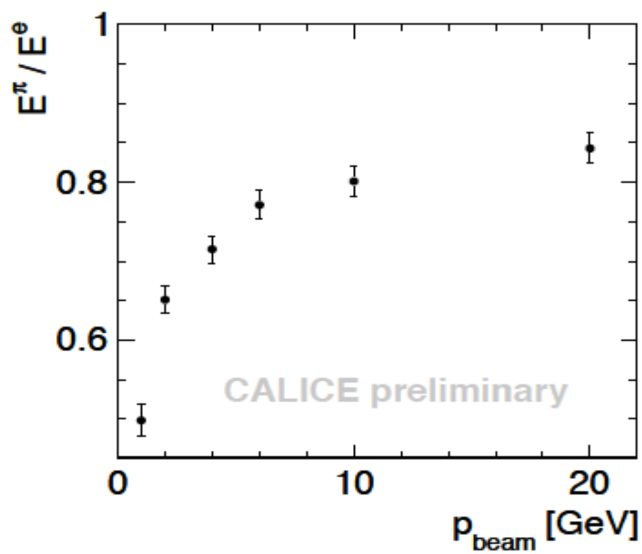
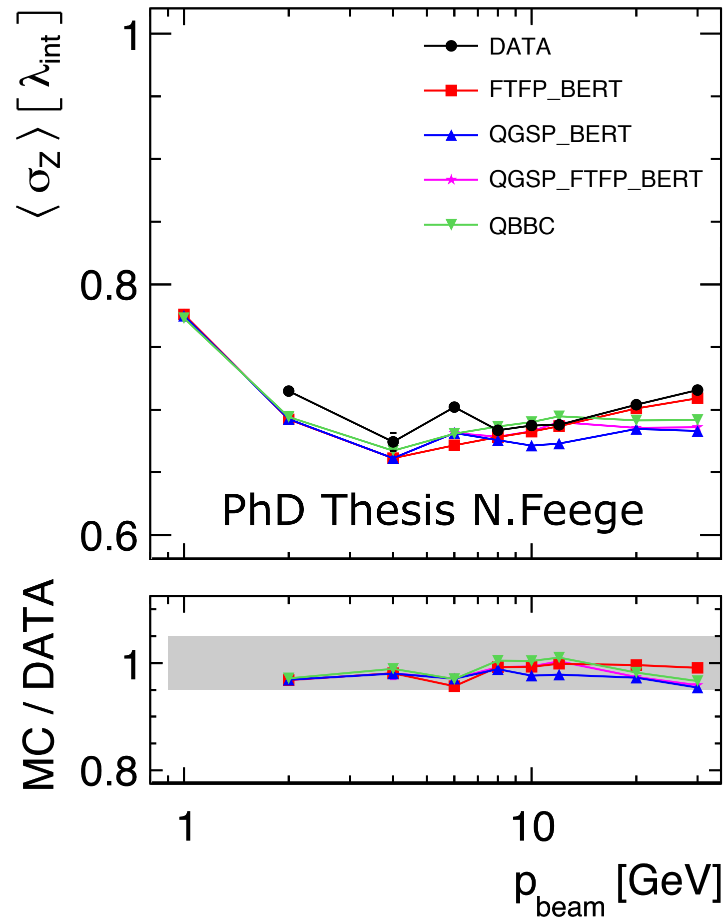


AN-034

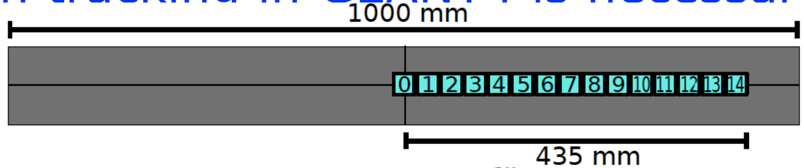


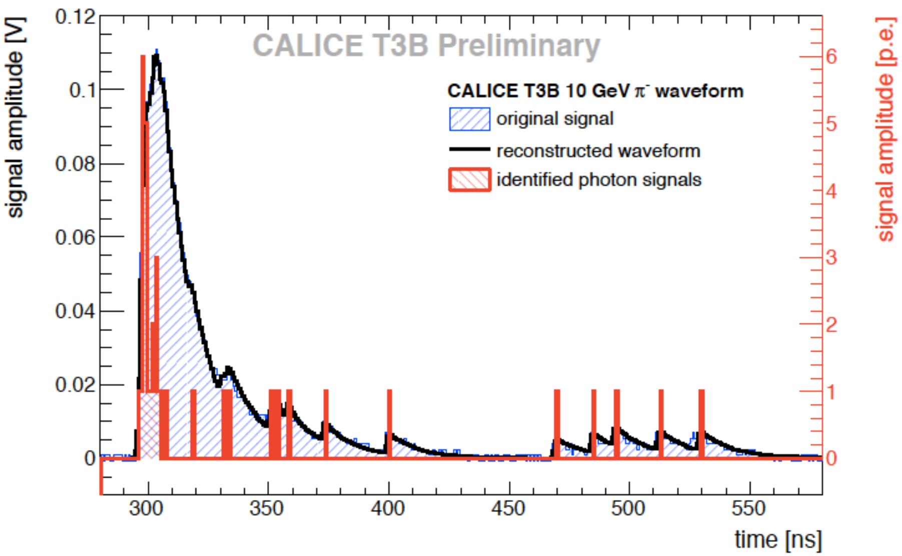


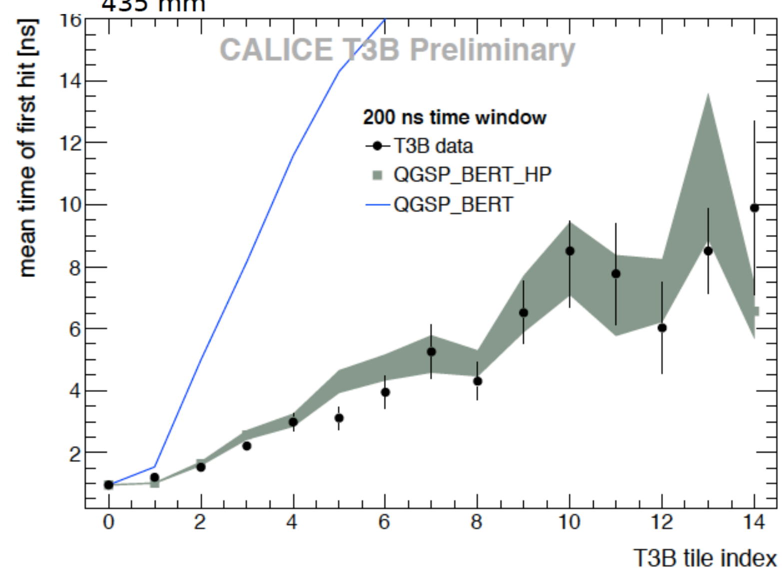
Publication draft

Timing in Tungsten HCAL

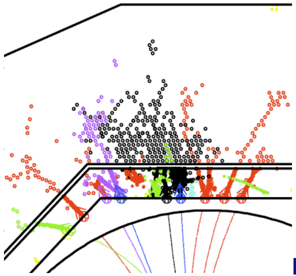
- For CLIC energies, containment becomes a major issue.
- Addressed using Tungsten HCAL – same scintillators with W absorber instead of Fe.
- Timing is also an issue at CLIC.
- Timing tests carried out using dedicated layer in the CALICE W-HCAL.
- (Overlapping) pulses can be resolved; examine time of first hit.
- Find detailed neutron tracking in GEANT4 is necessary to fit the observations.





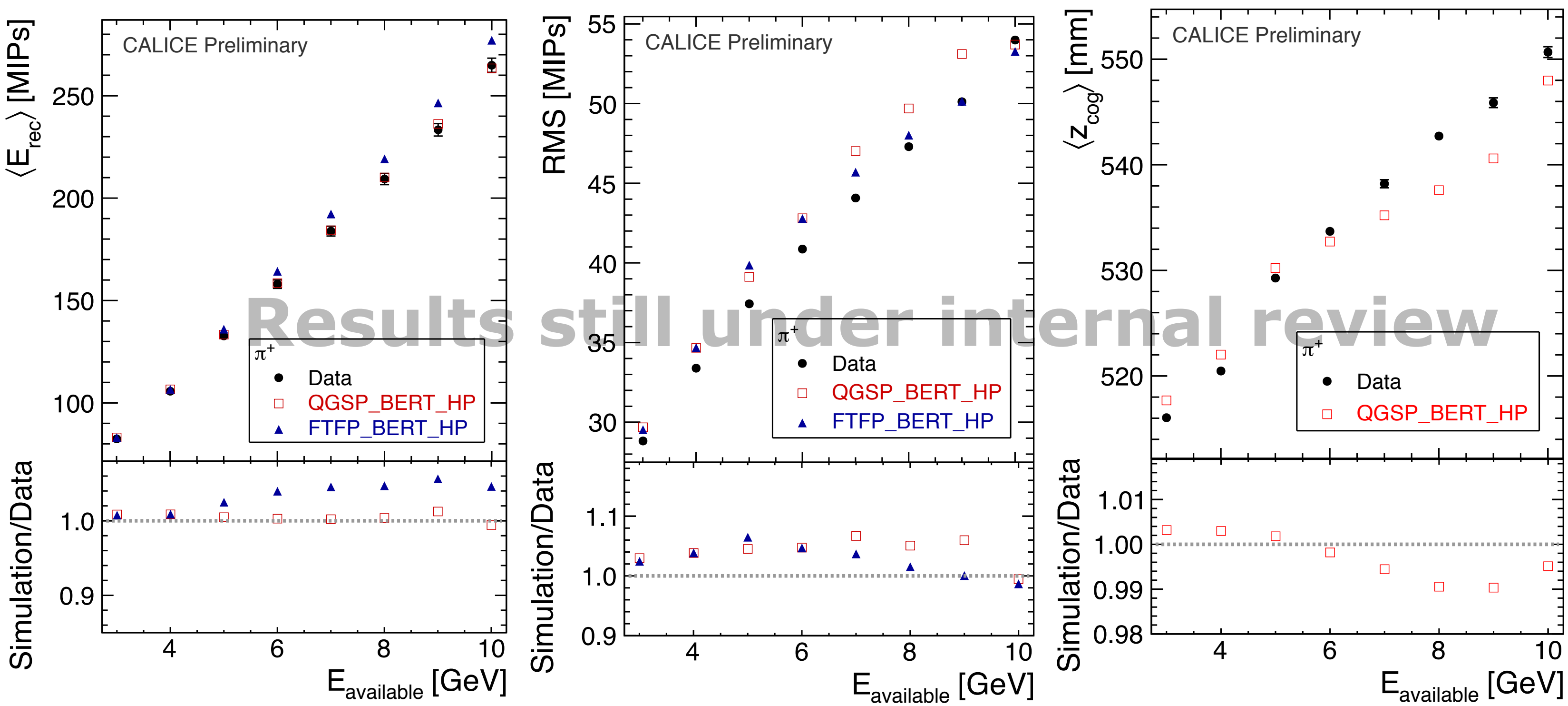


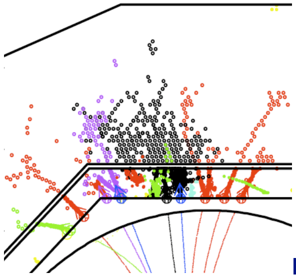
CAN-033



Validate Geant4 with tungsten

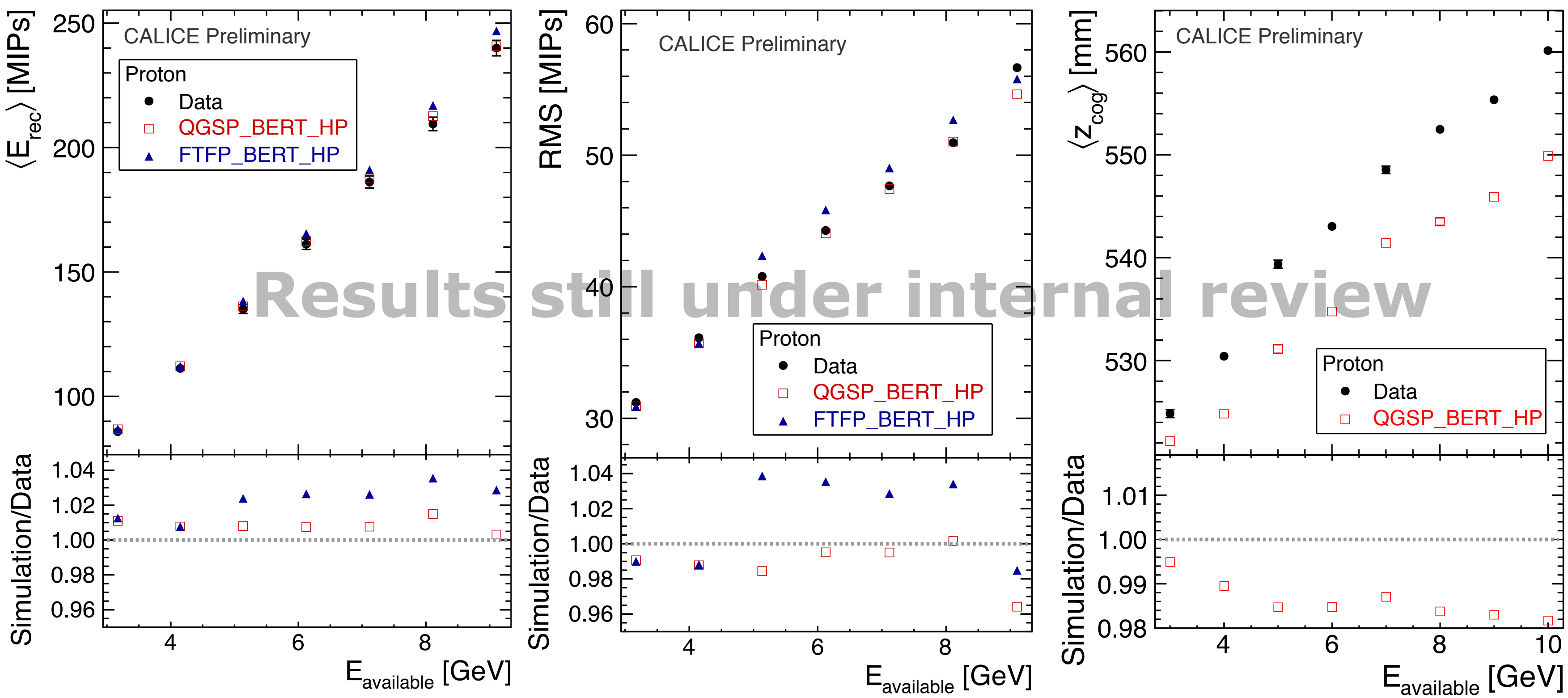
- Neutron-rich absorber - independent tests
  - not many data available anyway
- Amazing agreement for a difficult material in a difficult range

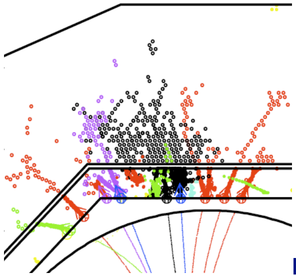




Validate Geant4 with tungsten

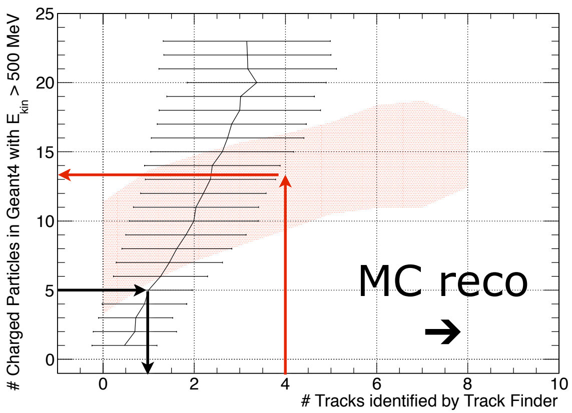
- Neutron-rich absorber - independent tests
  - not many data available anyway
- Amazing agreement for a difficult material in a difficult range

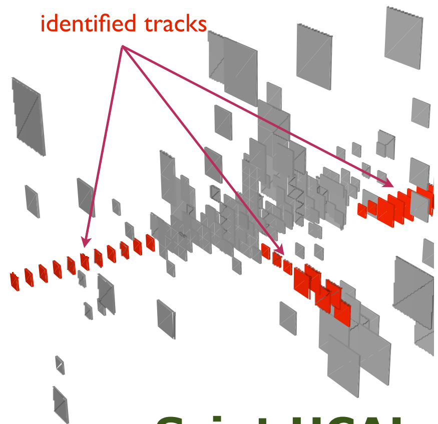




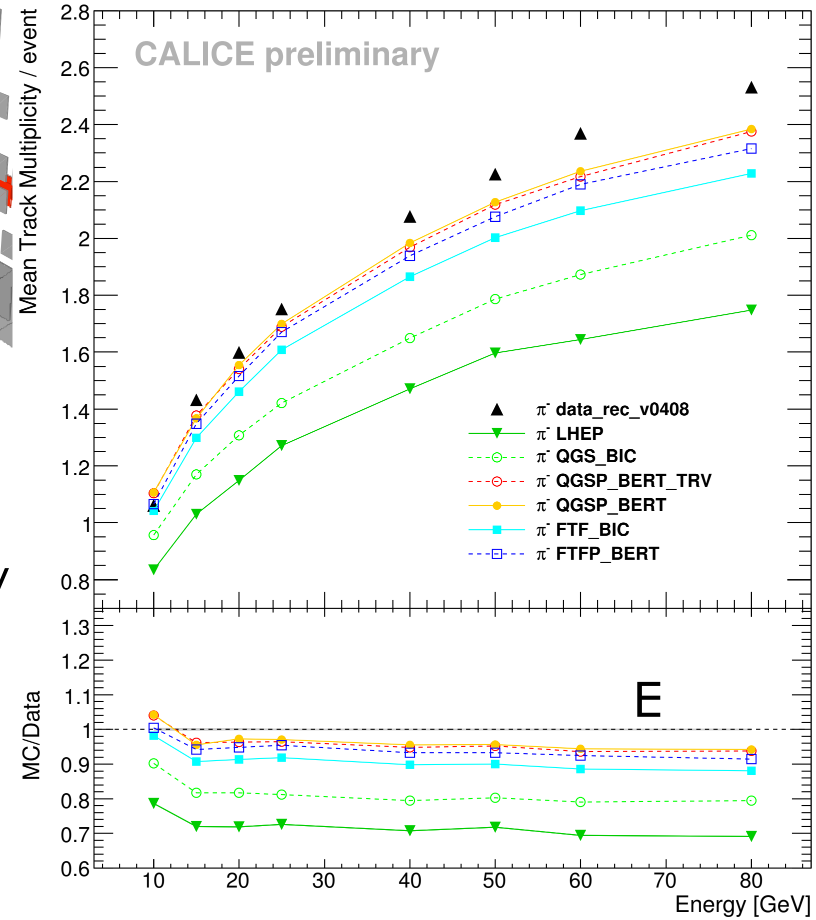
Shower fine structure

↑ MC truth





track multiplicity

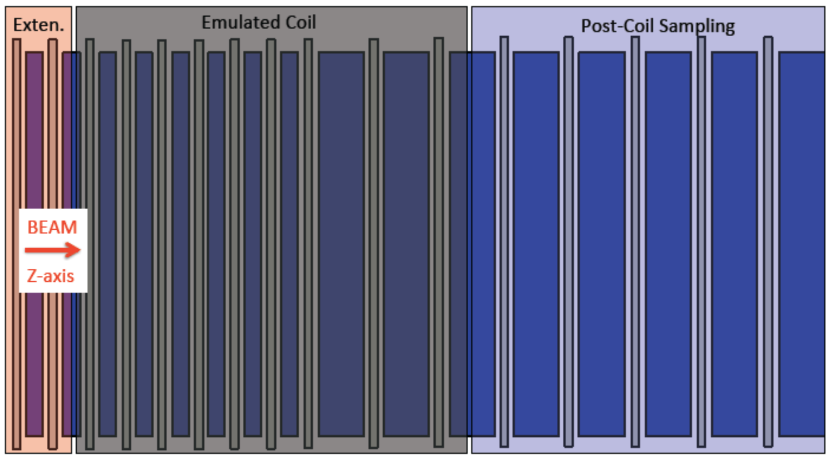


- Could have had the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already - for more recent models

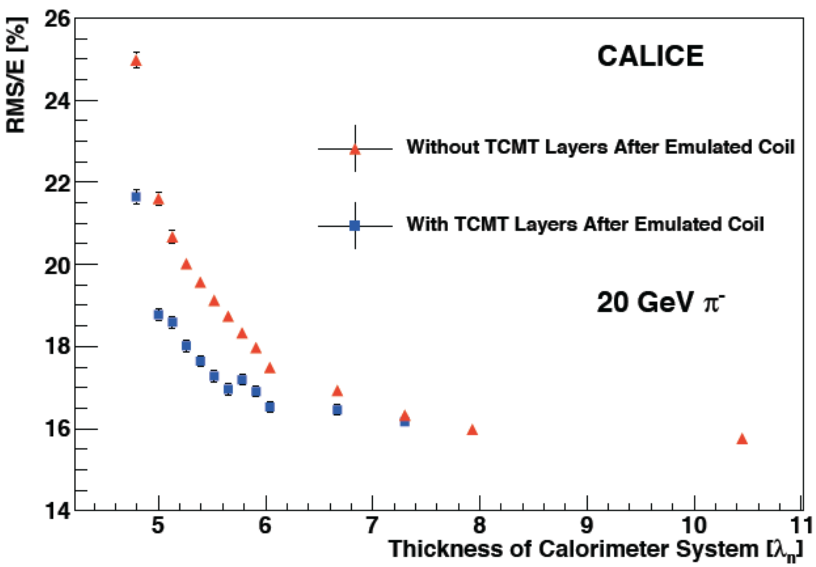
publication draft

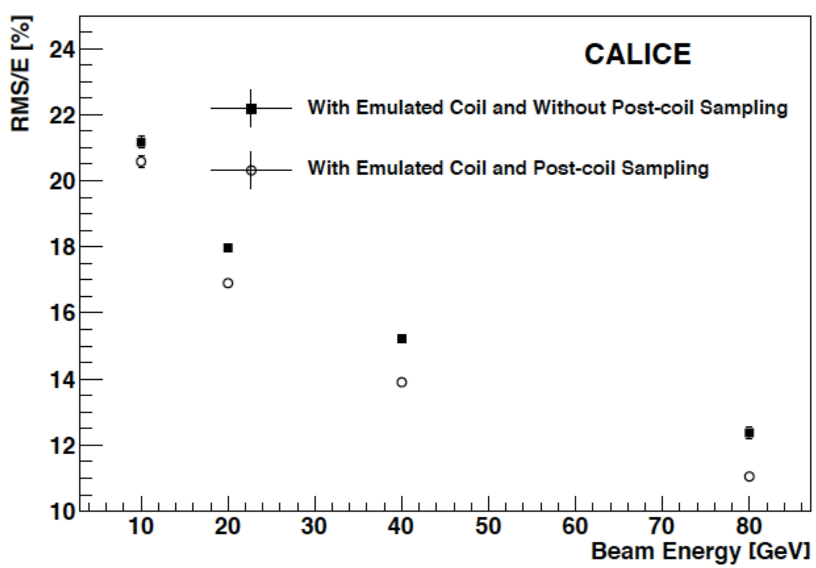
Containment – use of Tail Catcher

- Tail catcher gives us information about tails of hadronic showers.
- Use ECAL+HCAL+TCMT to emulate the effect of coil by omitting layers in software, assuming shower after coil can be sampled.
- Significant improvement in resolution, especially at higher energies.

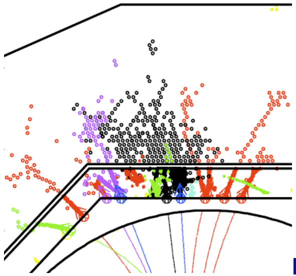


2012_JINST_7_P04015



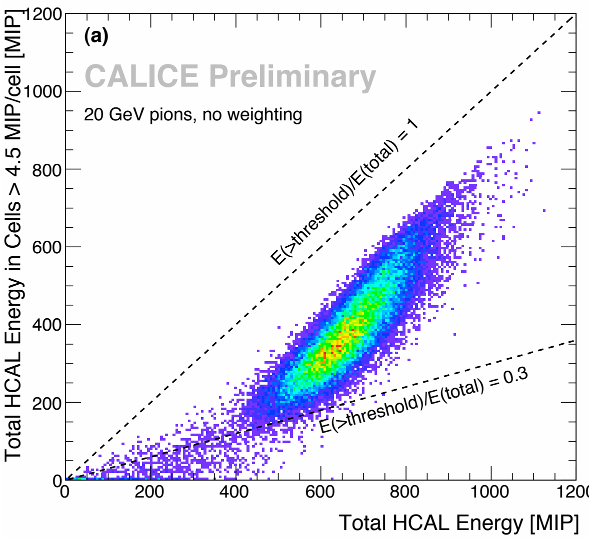


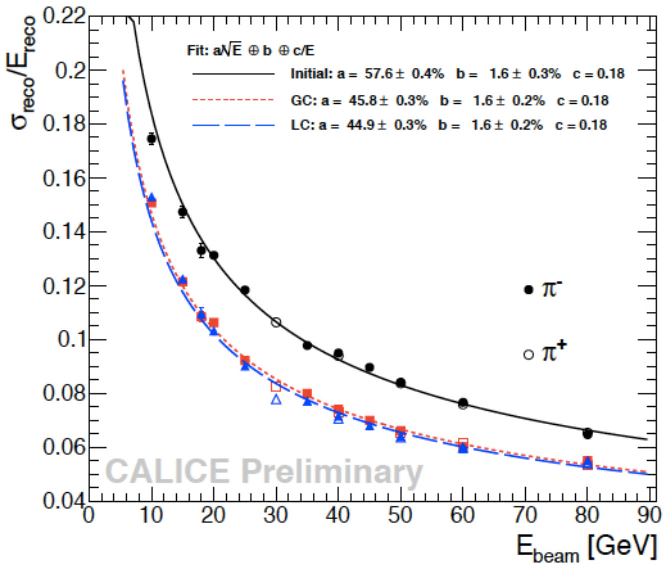
arxiv:1201.1653 (accepted by JINST)

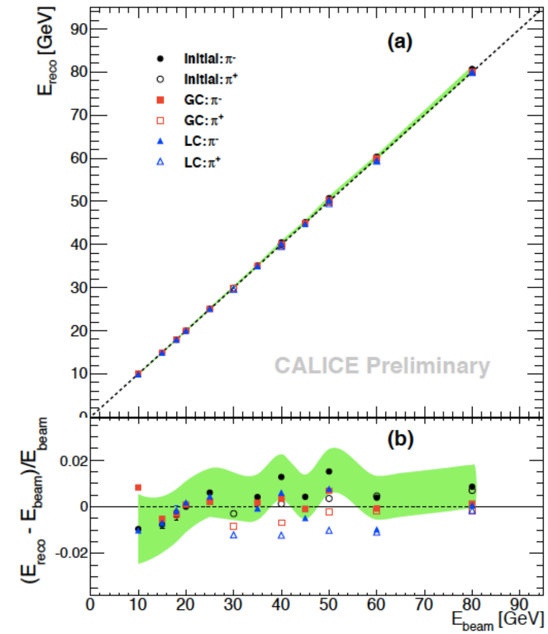


Software compensation

Scint HCAL

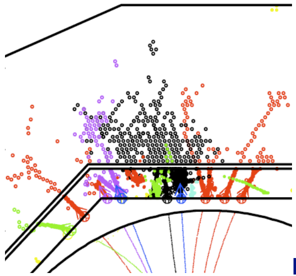






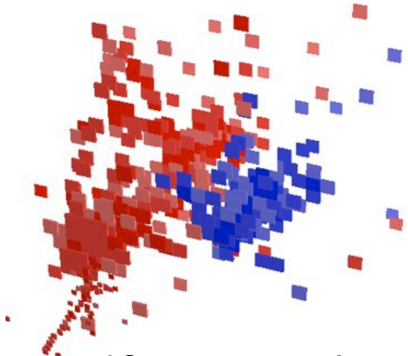
- Dream: s/w compensation with fine segmentation
- Significantly improved resolution AND linearity
- High granularity - many possibilities, local and global

publication draft



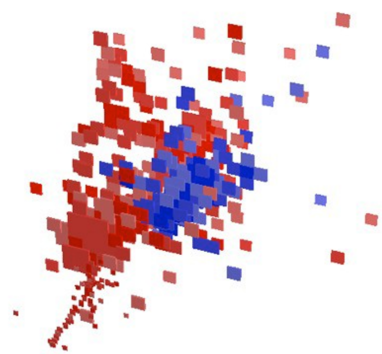
PFLOW with test beam data

Si W ECAL & Scint HCAL



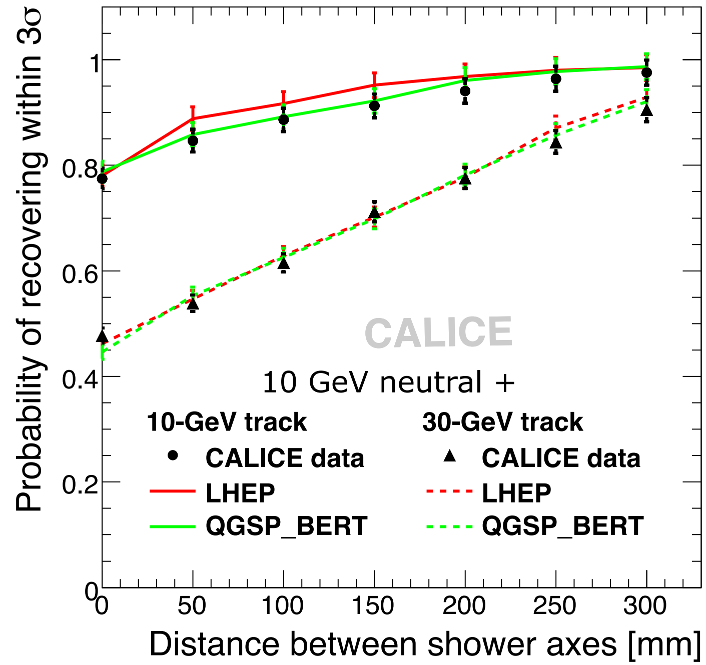
~18 cm separation of shower

30 GeV charged hadron



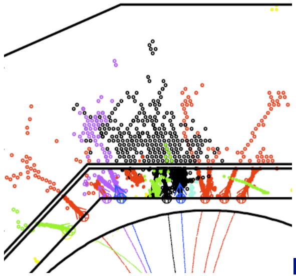
~7 cm separation of shower

10 GeV 'neutral' hadron

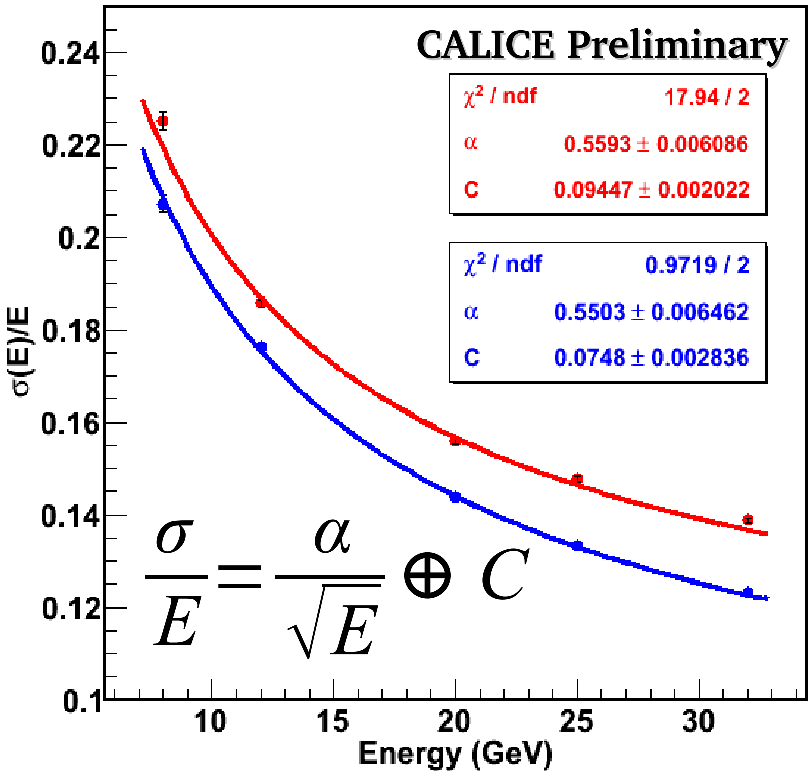


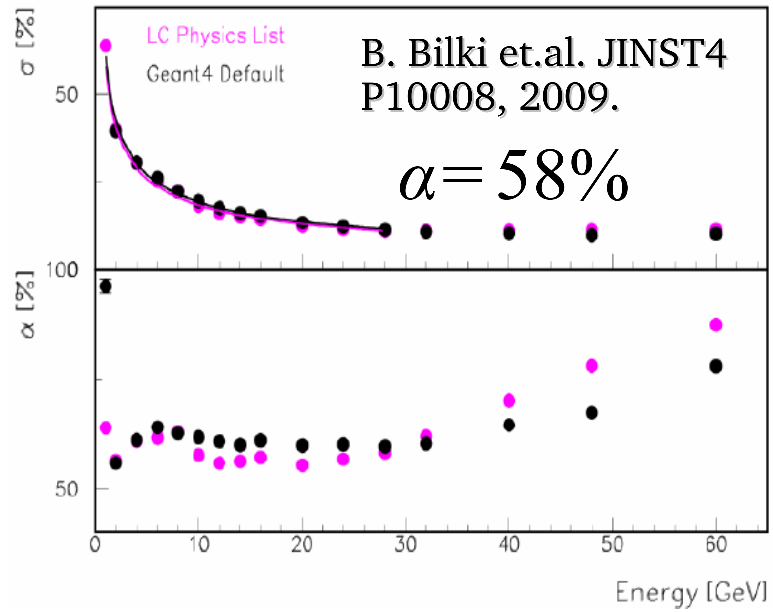
- The “double-track resolution” of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- test resolution degradation if second particle comes closer
- Important: agreement data - simulation

JINST 6 (2011) P07005



DHCAL first results: pions





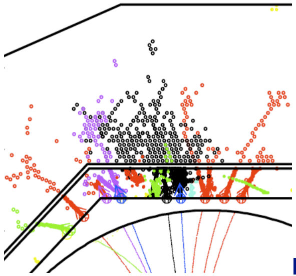
32 GeV data point is not included in the fit.

MC predictions for a large-size DHCAL based on the small-size prototype results.

Standard pion selection

+ No hits in last two layers

16



Summary on analysis

- The high granularity and the wide energy range covered allow unprecedented tests of the Geant 4 physics lists
- Altogether, the state of the art models yield a precise description up to a level of a few percent - of response, resolution and topology
- New observables like track multiplicity or timing give novel input to model builders

- The particle flow performance has been validated with test beam data

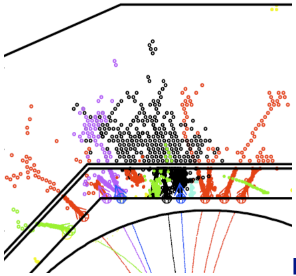
- There is still a huge potential on tape or in-coming, in particular with gaseous digital read-out, with Fe and with W

Future plans

- We must fully exploit the existing prototypes
  - more data taking after LS1
- We must fully exploit the existing data
  - physics analysis is involved, but rewarding

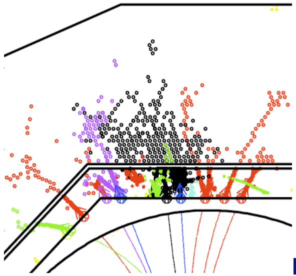
- We must proceed from single or few layer demonstrators to full-scale tests of the integration concepts
- New physics possibilities: 4x finer ECAL, timing in AHCAL

- There is lots to do on system level - powering, cooling, data concentration - before we can proceed to pre-production prototypes (module 0)



Conclusion

- Calorimetry is in revolutionary change - modern imaging calorimeters give insight
  - granularity - redundancy - modeling
- Particle flow detectors achieve W / Z separation, are experimentally validated in beams, and maturing in design
- Proof-of-principle test beam campaign to be completed for all technologies
  - Analysis partially completed, ongoing or just started
- Ready for the next phase
- Wealth of shower physics for the HEP community



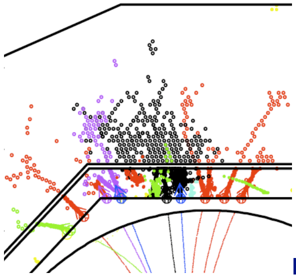
Acknowledgments

- Thanks for providing me with material for this talk:
  - Catherine Adloff, Vincent Boudry, Daniel Jeans, Erik van der Kraaij, Imad Laktineh, Shaojun Lu, Angela Lucaci-Timoce, Jose Repond, Nathalie Seguin-Moreau, Frank Simon, Tohru Takeshita, Mark Terwort, David Ward, Jae Yu

- Thanks to all my CALICE colleagues for continuous support

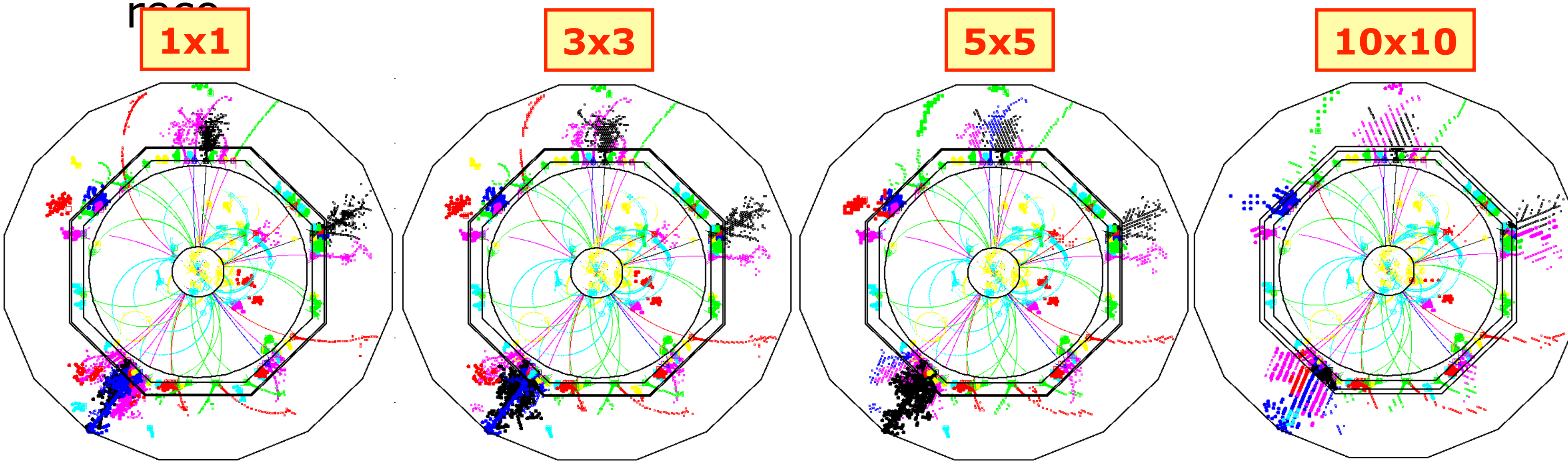
- Thank **you** for your attention!

Back-up
slides

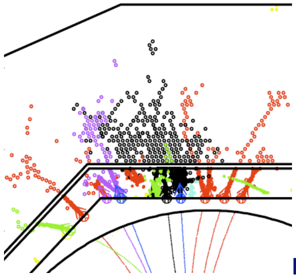


Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco



M.Thomson (Cambridge)



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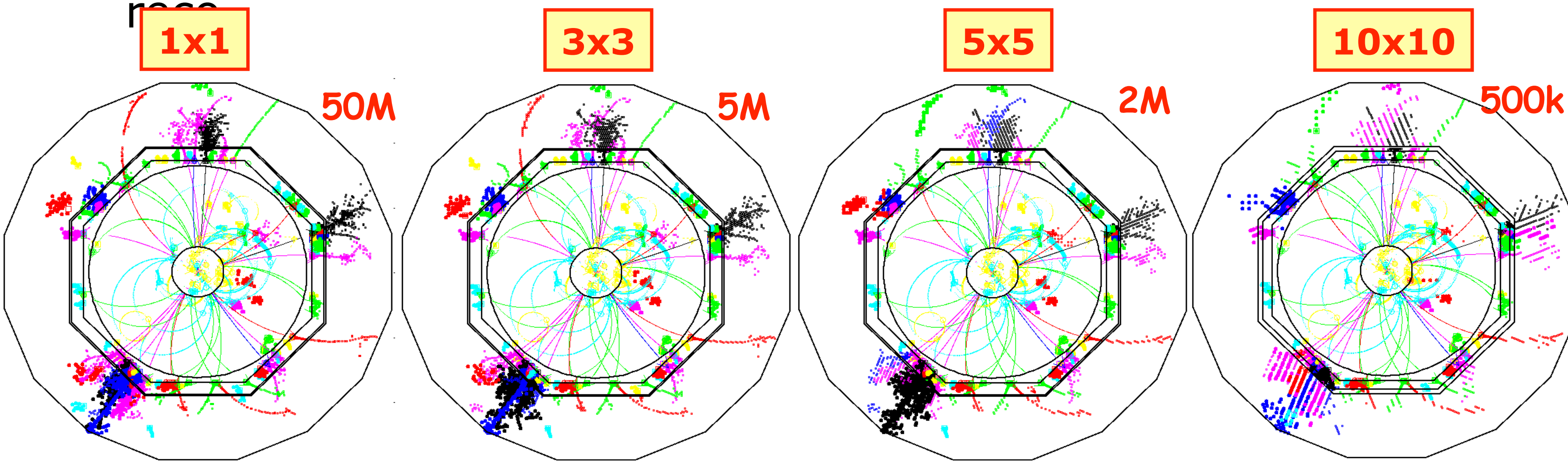

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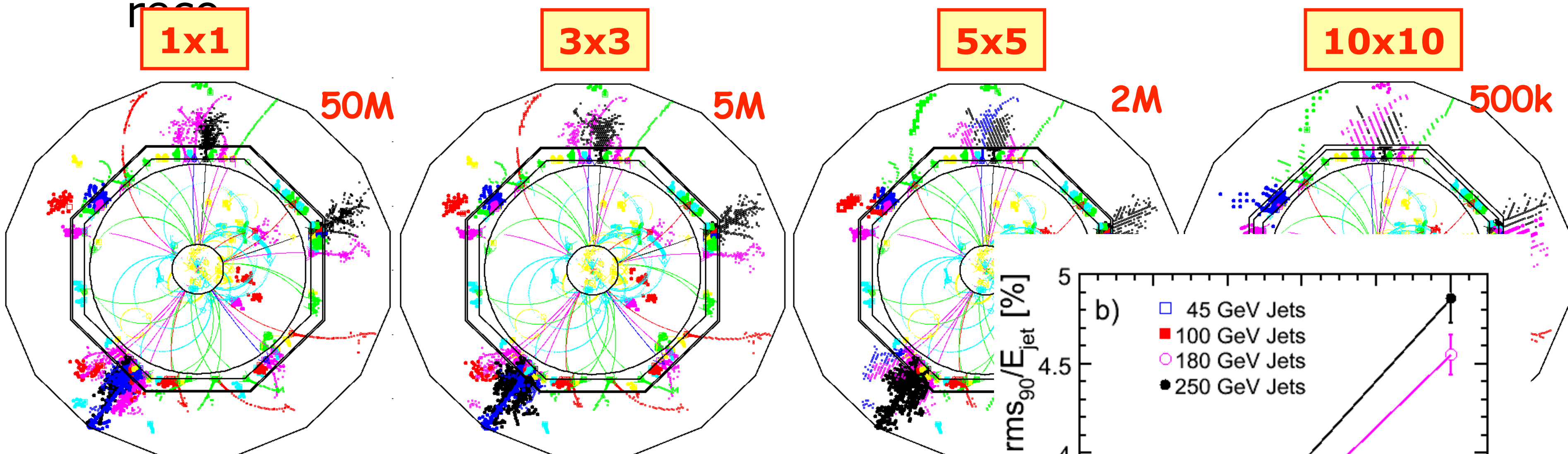
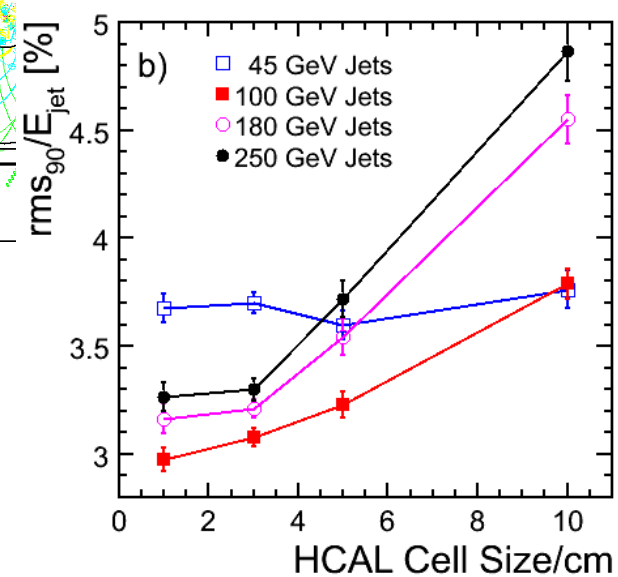
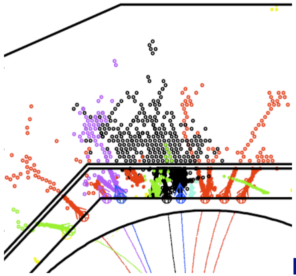




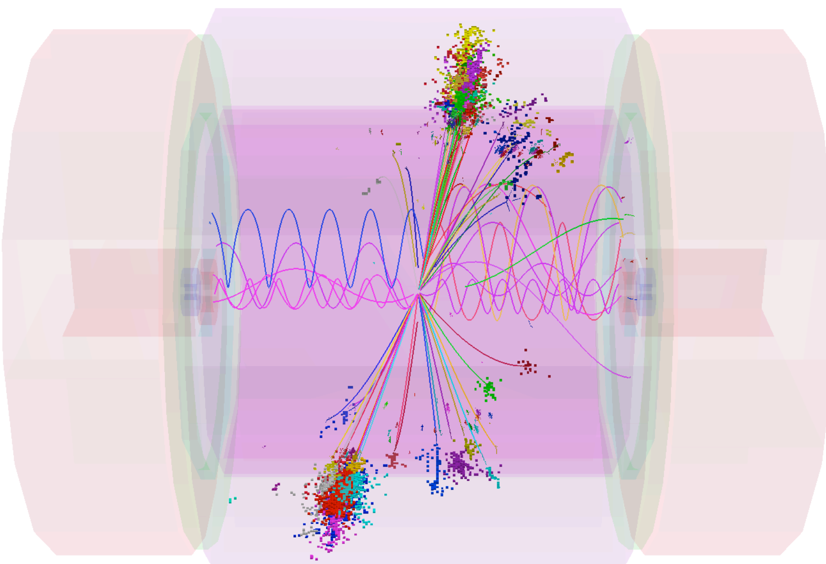
- Confirms earlier studies for test beam prototype
- 3x3 cm² nearly optimal

M.Thomson (Cambridge)

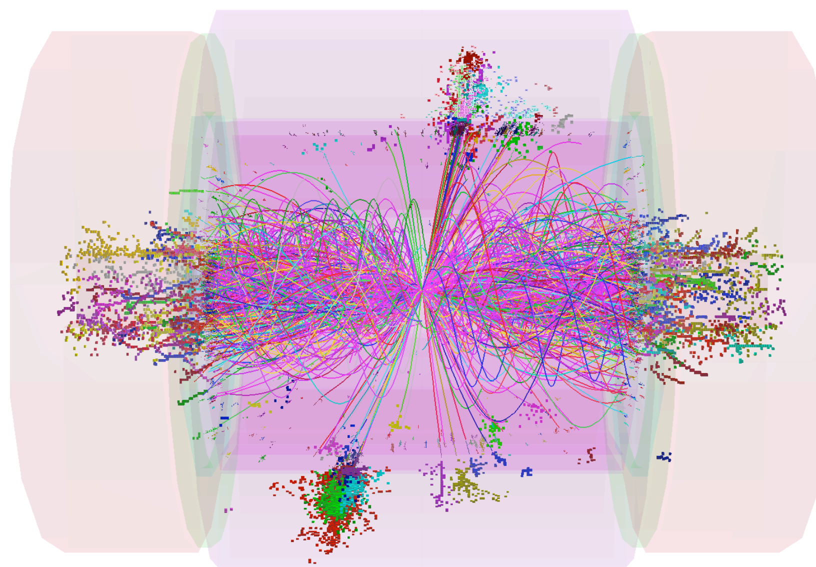


PFLOW under CLIC conditions

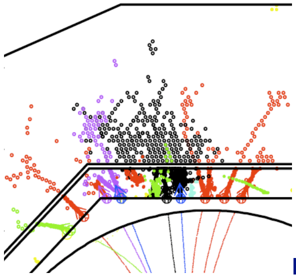
- Overlay γγ events from 60 BX (every 0.5 ns)
- take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- apply pt and timing cuts on cluster level (sub-ns accuracy)



Z @ 1 TeV



+ 1.4 TeV BG (reconstructed particles)



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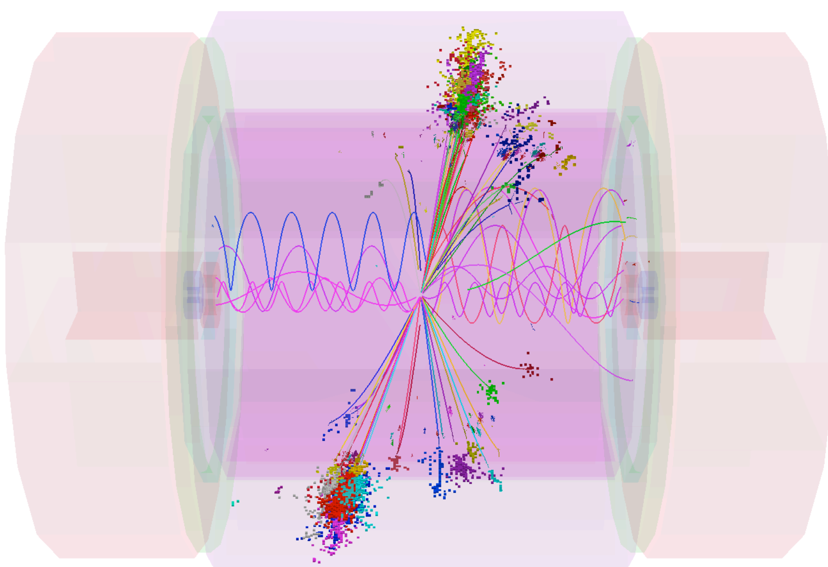

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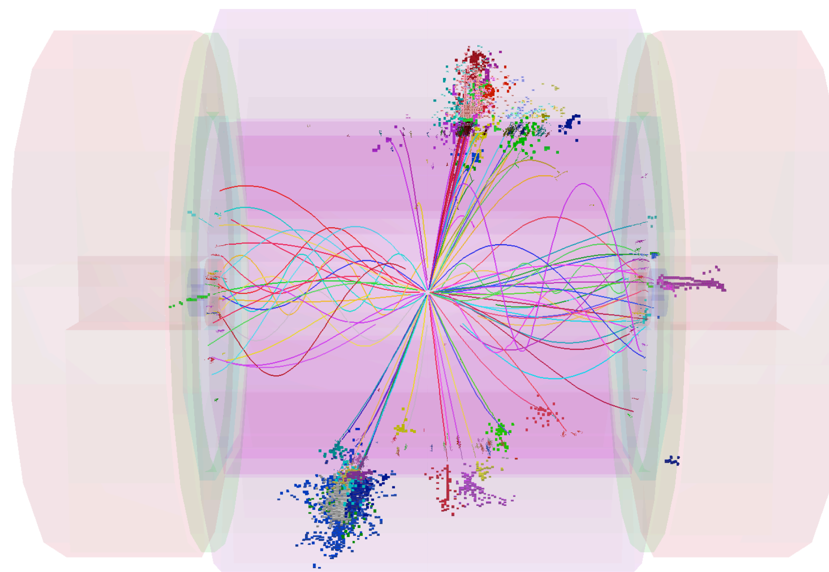

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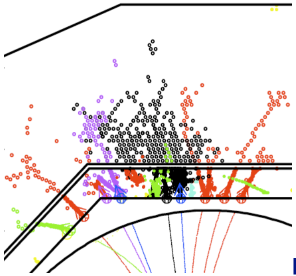

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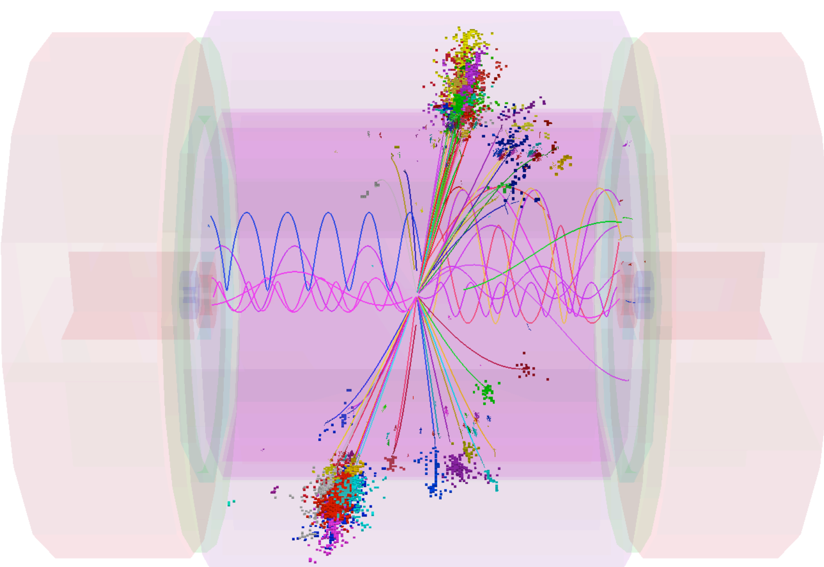

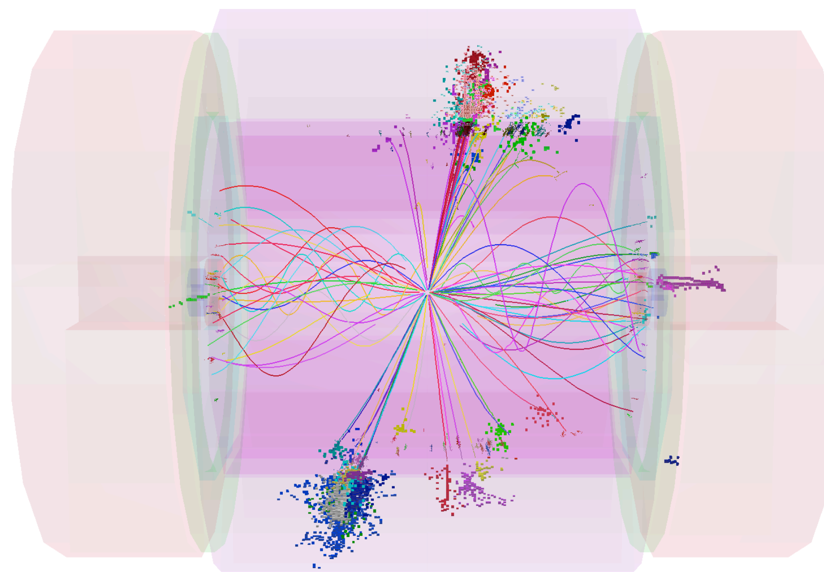

Z @ 1 TeV

Data taken

		# events	
π :	16 energy points in range from 10 to 300 GeV including ~400k Kaons at 60 and at 80 GeV	25.8 M	SPS H8
e :	6 energy points in range from 10 to 40 GeV	2.3 M	
μ :	for calibration over full surface	4.7 M	
π/e :	10 energy points in range from 1 to 10 GeV	17.5 M	PS T7 & T9
μ :	for calibration, mostly inner region	10 M	

T3B: A dedicated experiment to study shower time development. Took the same events in sync with AHCAL, plus standalone events.

GEM DHCAL Plans

GEM DHCAL Plans

- ✓ Phase I (Through late 2011) ➔ Completion of 30cm x 30cm characterization and DCAL chip integration
  - Performed beam tests @ FTBF with 30cm x 30cm double GEM chambers, one with KPiX9 and 3 with DCAL
  - Completion of 33cmx100cm large foil evaluation

GEM DHCAL Plans

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  - Completion of 33cmx100cm large foil evaluation
- Phase II (late 2011 – early 2013): 33cm x 100cm unit chamber development and characterization
  - Begin construction of 2 unit 100cmx33cm chambers, one with kPiX and one with DCAL
  - Bench test with sources and cosmic rays and beam tests
  - Construction of 100cmx100cm plane

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- Phase III (Early 2013 – mid 2014): 100cmx100cm plane construction
  - Construct 6 unit chambers with DCAL for two 100cmx100cm planes
  - Characterize 100cmx100cm planes with cosmic rays and beams

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  - Construct 6 unit chambers with DCAL for two 100cmx100cm planes
  - Characterize 100cmx100cm planes with cosmic rays and beams
- Phase IV (Mid 2014 – late 2015): 100cm x 100cm plane GEM DHCAL performances in the CALICE stack
  - Complete construction of five 100cm x 100cm planes inserted into existing CALICE calorimeter stack and run with either Si/W or Sci/W ECALs, and RPC or other technology planes in the remaining HCAL

a DAQ for all technological prototypes

Requirements

- «Generic» DAQ **extensible** for large detectors usable
  - in **Test Beams** for CALICE т protos
  - as **prototype** for ILC calorimeters
- Features (more on next slide)
  - Common interface for all protos: **Detector InterFace** (DIF) cards
  - 1 or 2 **concentrator** cards
  - all signals on 1 cable with secure communication protocol (8b/10b)

- 3 CALICE prototypes en route:
  - SDHCAL : ~400.000 ch; Digital (2b/ch)
  - ECAL : ~ 22.000 ch; Energy (12b)
  - AHCAL : ~ 52.000 ch: Energy & time (2×12 b)

- Acquisitions modes
  - Standard mode (ext[al] trigger) : not used
  - Triggered mode
    - ROC in auto-trigger; readout on external trigger (typical TB mode)
  - «ILC like»:
    - bunch acquisition without trigger
      (opt[lly] power pulsing): during a spill;
      readout on ROC full.
  - Calibration

Key elements:

- **Noise taming;**
- huge configurations;
- Stability

Vincent.Boudry@in2p3.f

History & Status

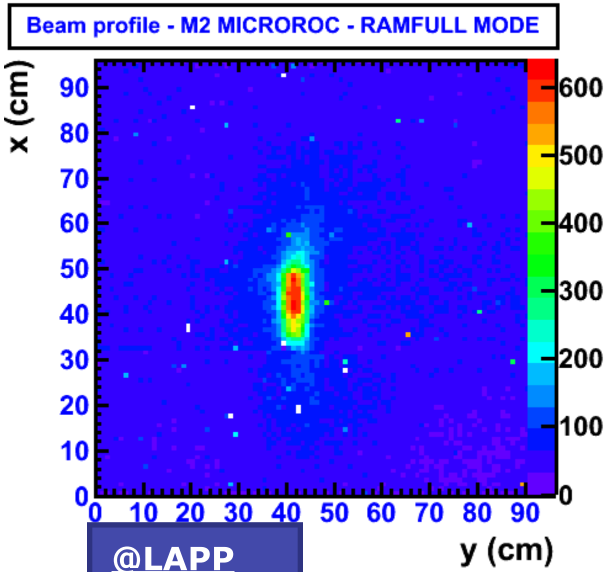
- Genesis
  - Most HW and FW blocks have been developed in UK; support vanished in 2011
    - Integration taken over @ LLR in 2010 → debug and dev^t (with DCC card)
- Implementation
  - First set-up on SDHCAL (LAPP) & ECAL (LLR); AHCAL just started (DESY)
  - SW started from scratch in 2010 @ IPNL on XDAQ (for SDHCAL) + Oracle
- Test beams:
  - SDHCAL with HDMI in 2011: too many instabilities... (mix of HW, FW, SW).
    - 2012: running 400 kCh / 50 planes / 150 DIFs on USB (⊖ perfs but now very stable...)
  - ECAL with full system (3 DIFs) in April
- Work in progress:
  - Deployment of SW for ECAL & AHCAL; later deployment of HDMI for SDHCAL
  - Replacement of HW: LDA → GigaDCC (LLR) and CCC → CCC2 (Mainz)...
  - Integration with AIDA DAQ (aka EUDAQ + beam interface)

- **HARDROC2 (DHCAL, RPC):**
  - semi digital readout with 3 thresholds
  - Auto trigger on 10fC up to 20 pC
  - Scalable readout scheme successfully tested
  - **power pulsing in magnetic field successfully tested in 2010**
  - SDHCAL technological proto with 40 layers (5760 HR2 chips) built in 2010-2011.

@IPNL Lyon

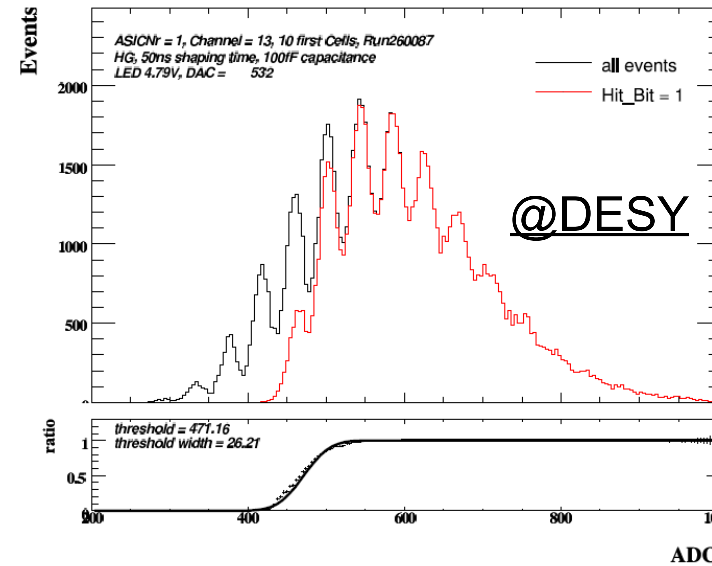
1 m³ RPC detector, 40 layers
Hardroc2: 37 000 channels

- **MICROROC: (DHCAL, µMEGAS)**
  - Similar to HARDROC (semi digital readout) with charge preamp input (smaller signals)
  - Noise: 0.2fC (Cd=80 pF). Auto trigger on 1fC up to 500fC
  - Very good performance of the electronics and detector (Threshold set to 1fC on 1 m2 in TB)

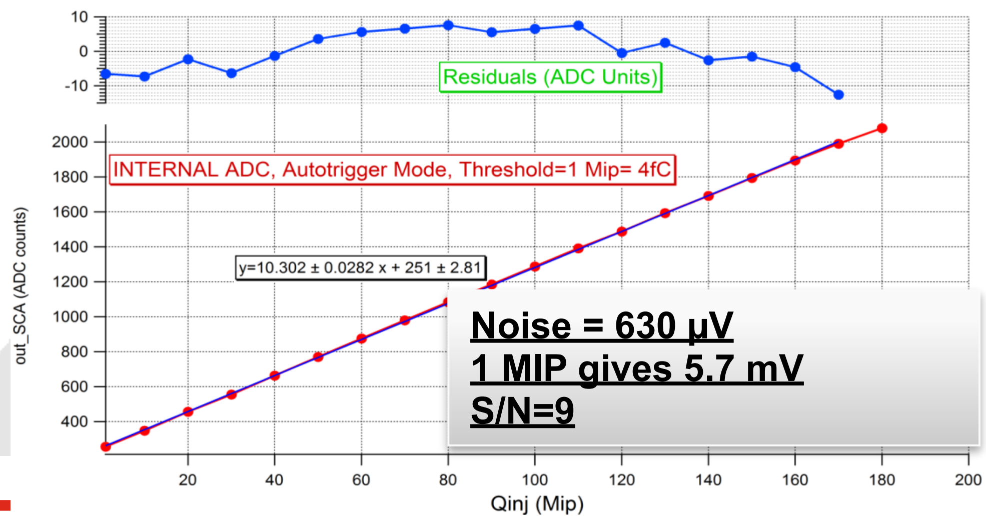


@LAPP

- **SPIROC2 (AHCAL, SiPM):**
  - Autotrigger on 1 spe (150 fC)
  - Charge measurement (up to 300 pC)
  - Time measurement (~ 1 ns)
  - 16 deep analog memory
  - Internal 12 bits ADC



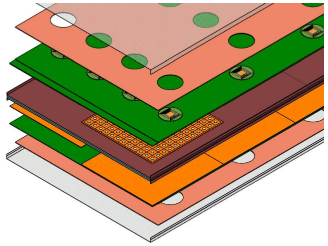
- **SKIROC2 (AHCAL, SiPM):**
  - Similar to SPIROC2 but with Charge preamp input (1 MIP= 4fC)
  - Very good performance on testbench
  - First measurements performed in Test beam: very promising

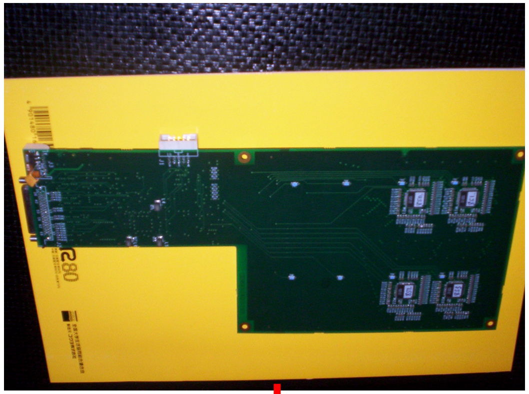


Noise = 630 µV
1 MIP gives 5.7 mV
S/N=9

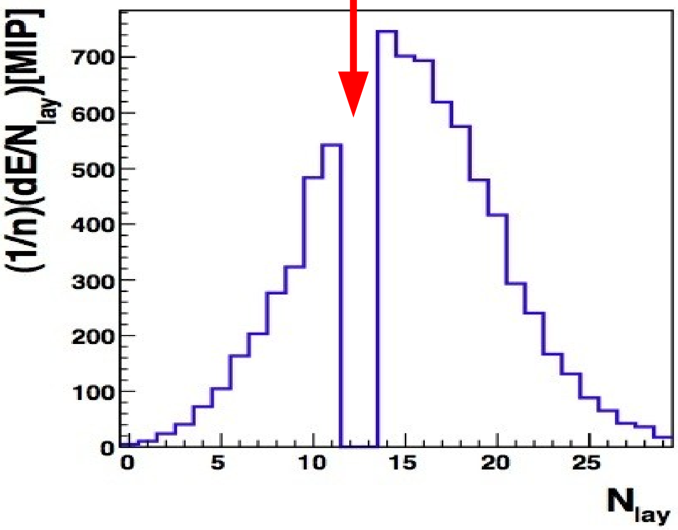
Embedded electronics - Parasitic effects?

Exposure of front end electronics to electromagnetic showers



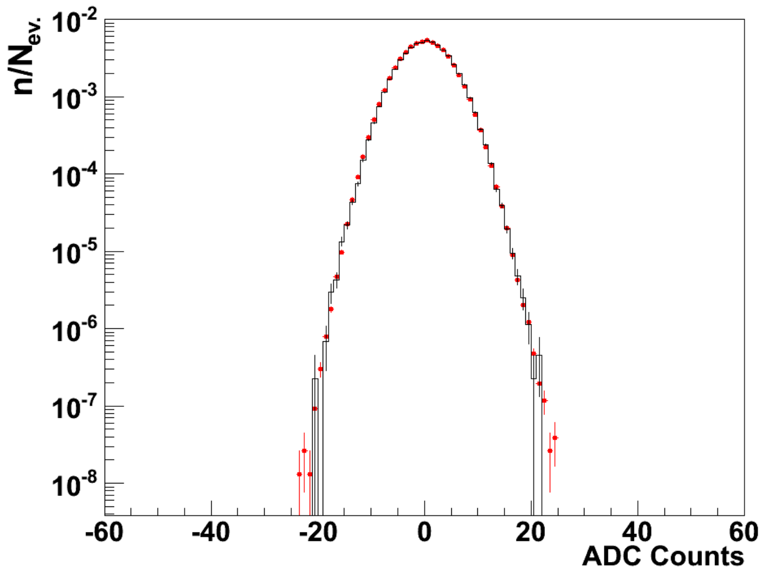


Chips placed in shower maximum
of 70-90 GeV elm. showers



Possible Effects: Transient effects
Single event upsets

Comparison: Beam events
(Interleaved) Pedestal events



- No sizable influence on noise spectra by beam exposure

  ΔMean < 0.01% of MIP ΔRMS < 0.01% of MIP
- No hit above 1 MIP observed

  => Upper Limit on rate of faked MIPs: ~7×10^{-7}

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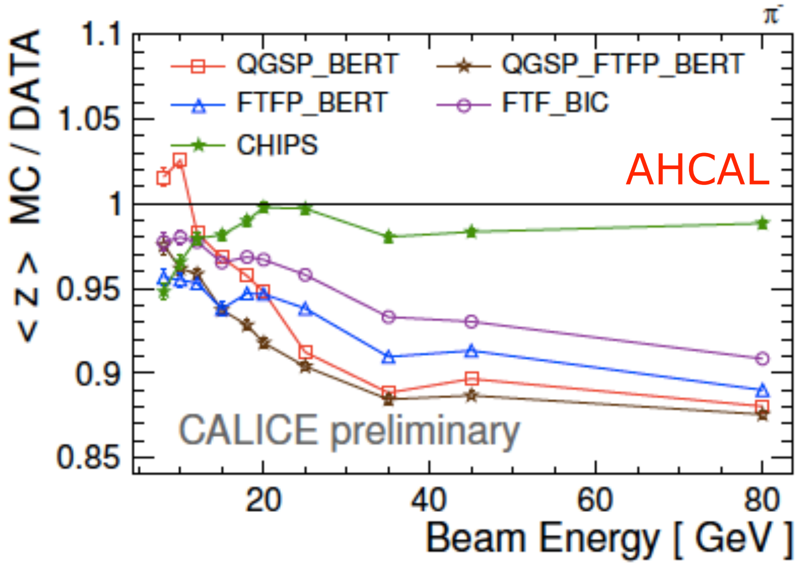
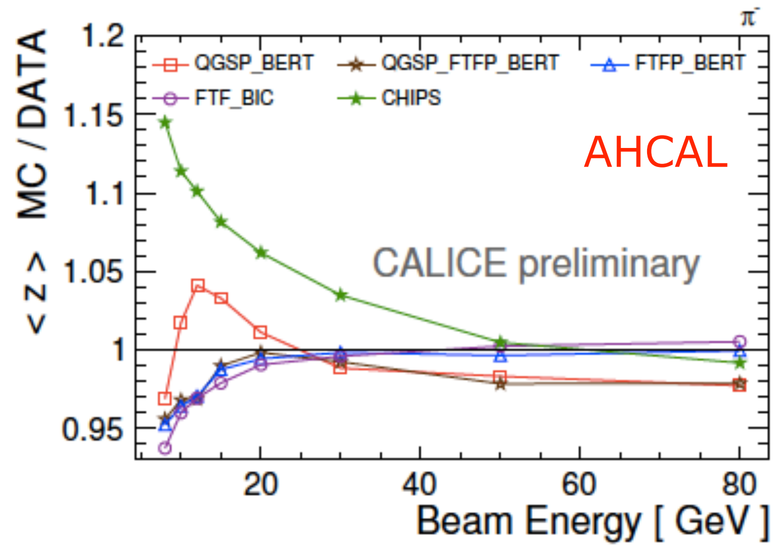
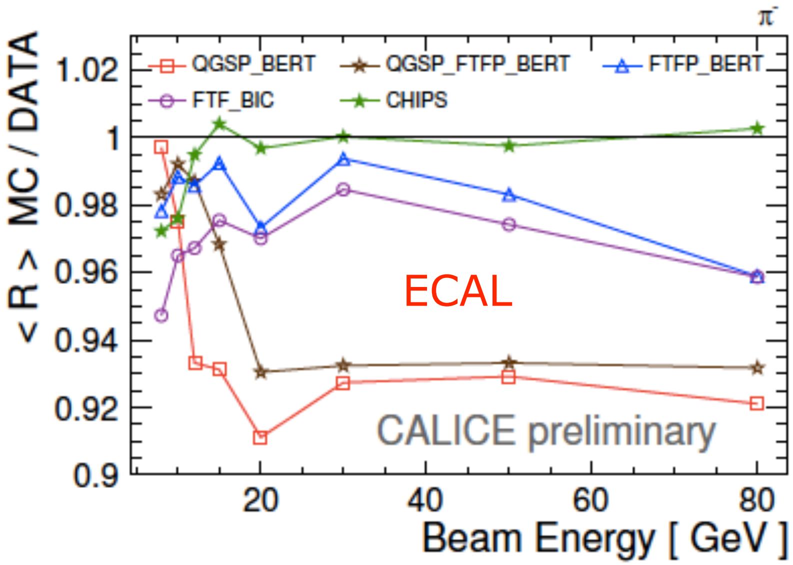
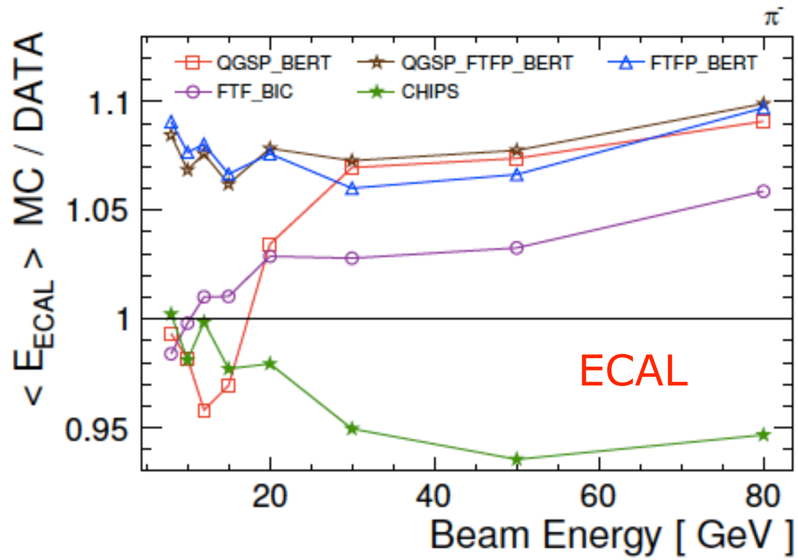
Tests of GEANT4 physics lists





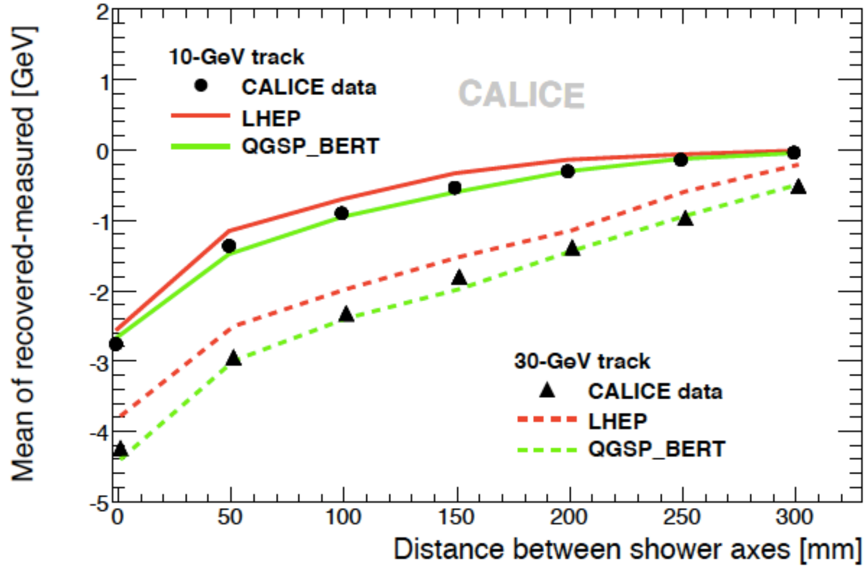


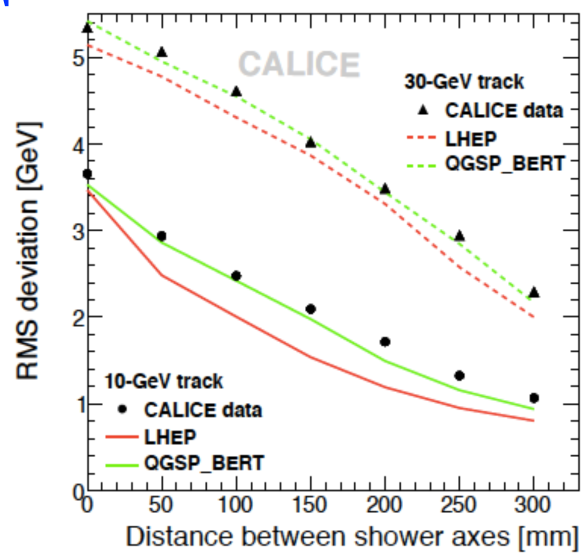


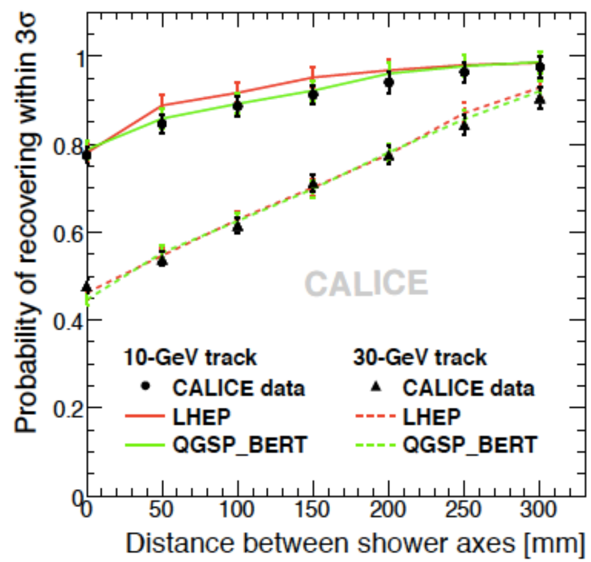
EUDET-Memo-2010-15

Tests of Particle Flow

- Ultimate aim is to design calorimeter optimised for particle flow.
- Test by overlaying charged and (fake-)neutral showers from data and reconstructing using PandoraPFA.
- Check simulation of performance as a function of separation between showers







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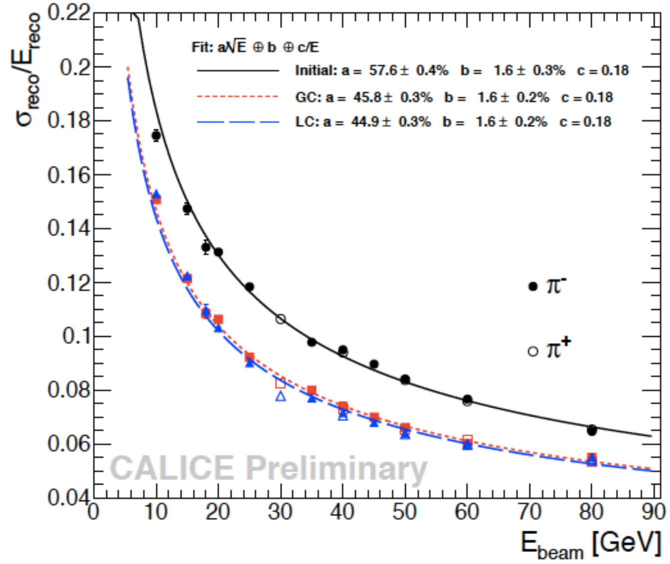
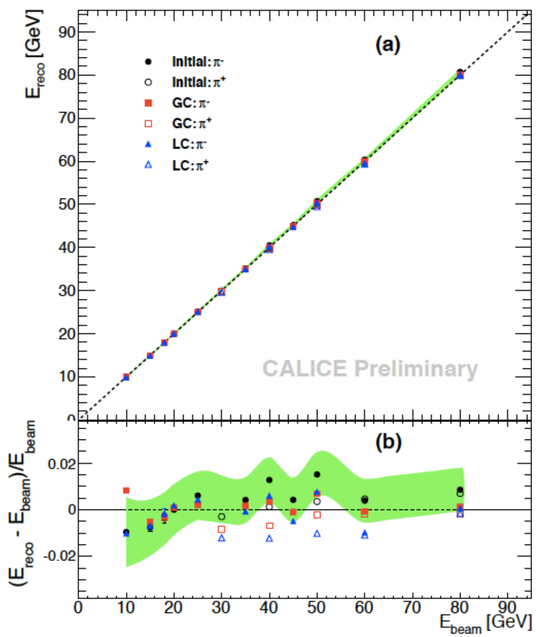
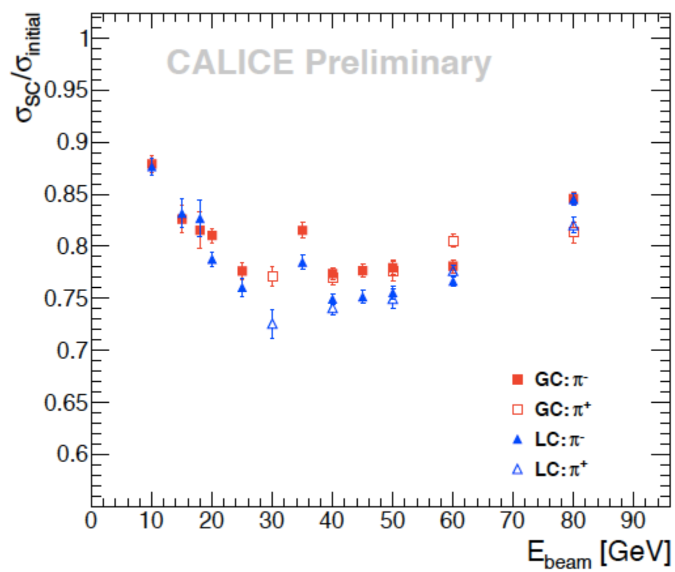
Software Compensation

- CALICE calorimeters not compensating.
- But can use granularity to distinguish electromagnetic and hadronic energy deposits, and weight accordingly.
- Various techniques give similar results.
- Improve resolution by ~20% across wide energy range; also slightly improve linearity of response.



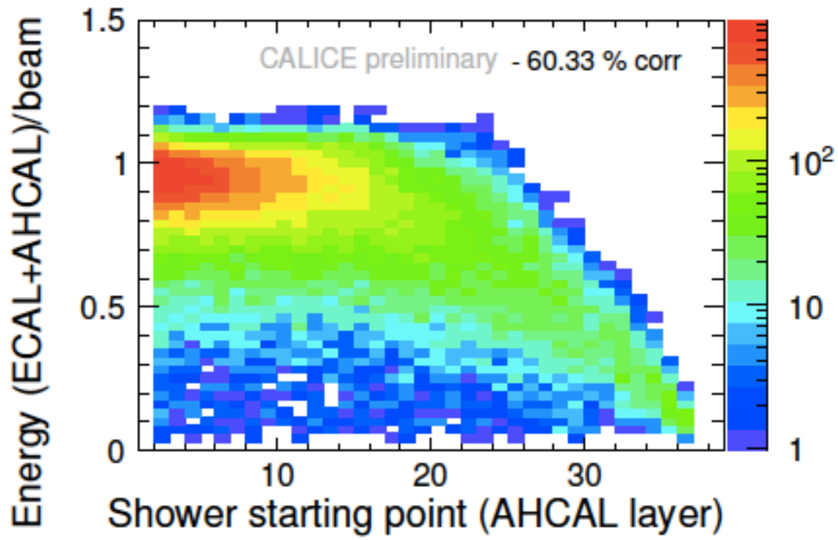




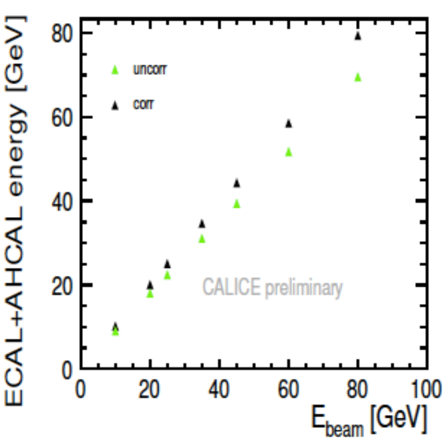
CAN-035

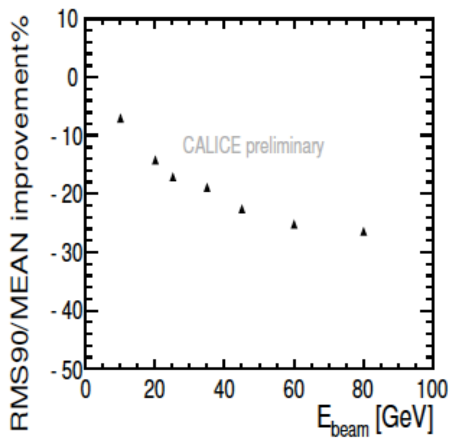
Correction of leakage using AHCAL alone?

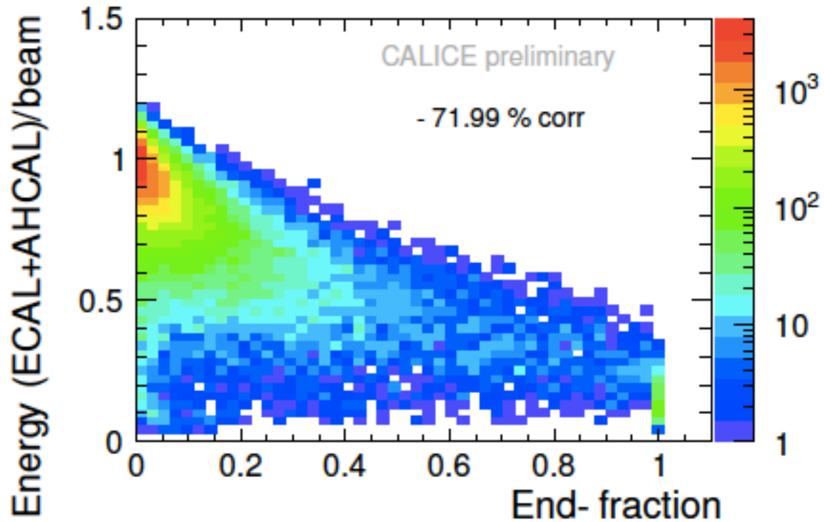
- How well can we do using HCAL alone?
- Correction based on observables sensitive to leakage:
  - Shower start point
  - Fraction in last 5 layers
- Can achieve improvement in both linearity and resolution.



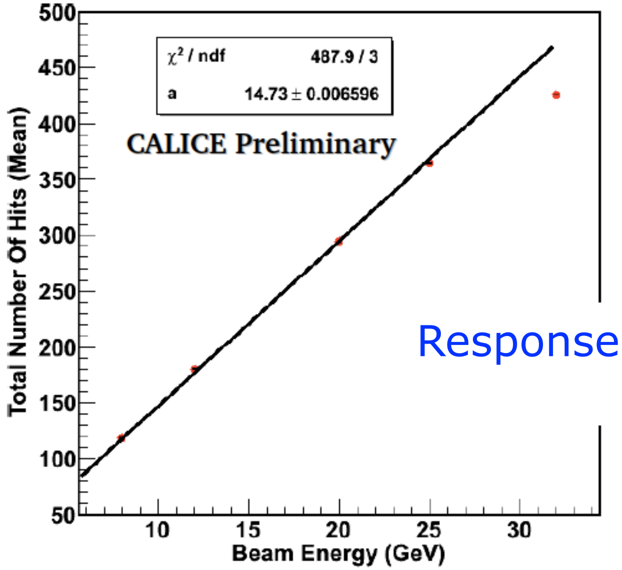
CAN-029





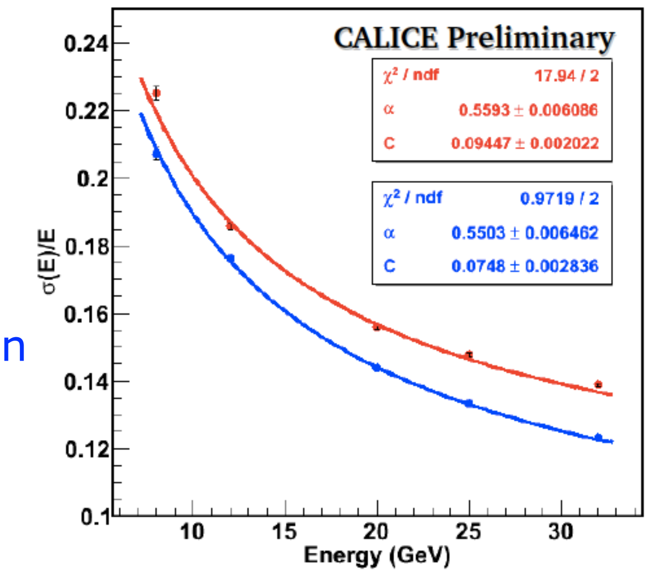


Digital HCAL

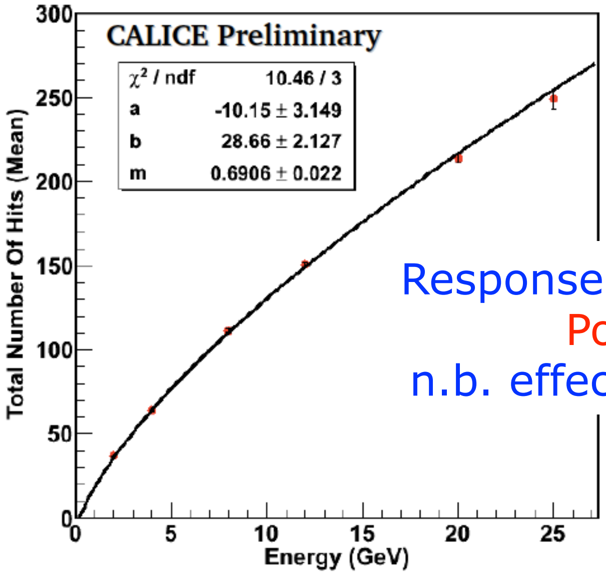


Response and resolution

Pions



CAN-032



Response and resolution

Positrons

n.b. effect of saturation