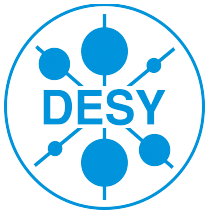
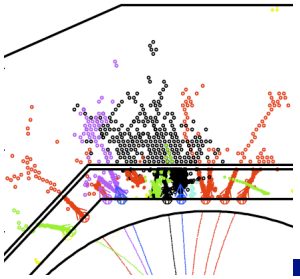
Highly segmented Calorimeters for Particle Flow

Felix Sefkow

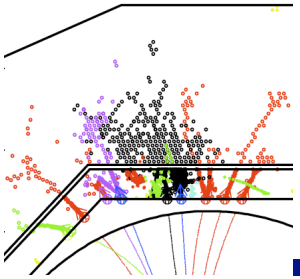


PHENIX Decadal R&D Workshop, December 14, 2010

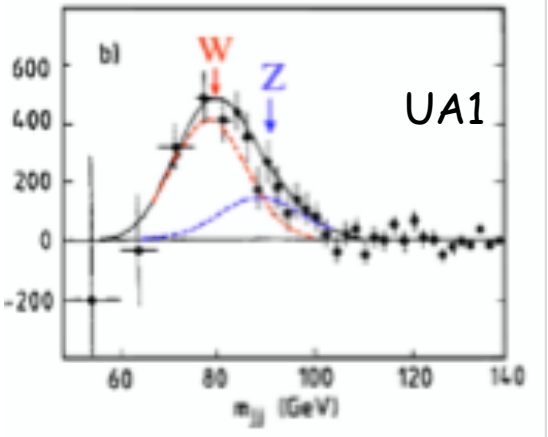


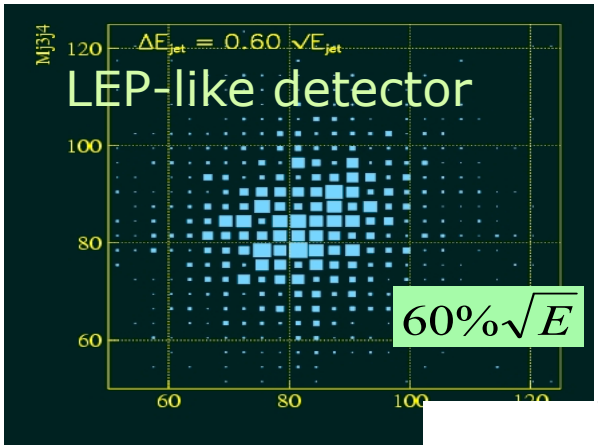
Outline

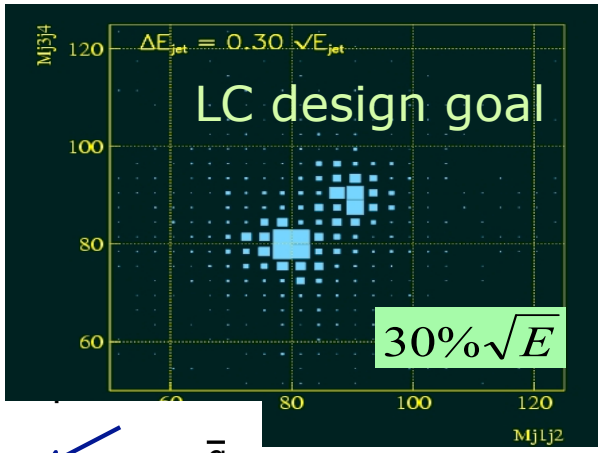
- Introduction:
  - calorimeter R&D for the linear collider
  - the Particle Flow concept
- Physics prototypes
  - Validate simulation
  - test the algorithms
  - test the new technologies
- Technology prototypes
  - tackle the integration challenge

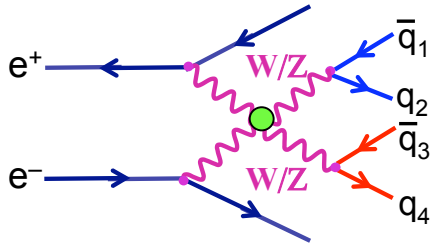


Challenge: W Z separation

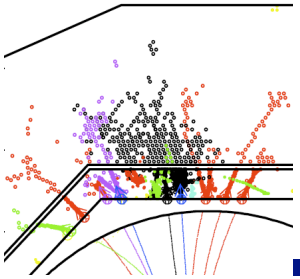








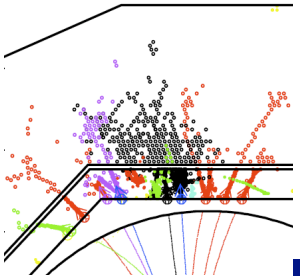
- At the Tera-scale, we need to do physics with W's and Z's as Belle and Babar do with D^+ and D_s
- Calorimeter performance for jets has to improve by a factor 2
- Rather young and dynamic development



Hadron and jet calorimetry:

- Hadron showers: large variety of physics processes
  - With different detector responses
  - In general non-linear
  - Inevitably invisible energy; ultimate limit
  - Large fluctuations
  - Large volume, small signals
  - Difficult to model

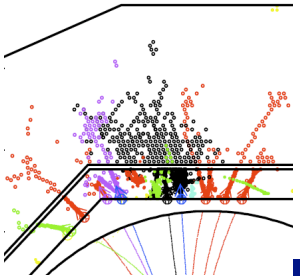
- Jet energy performance = hadron performance or worse



New concepts

- Hardware (and software): ultimate compensation by directly measuring the electromagnetic component in each event, in addition to the total energy, and correcting for it
- ➔ dual readout calorimeters (scint and Cerenkov light)

- Software (and hardware): measure each particle in a jet individually and limit the problems of hadron calorimetry to the 10% or so of K_L and n in the jet; needs imaging granularity
- ➔ particle flow approach

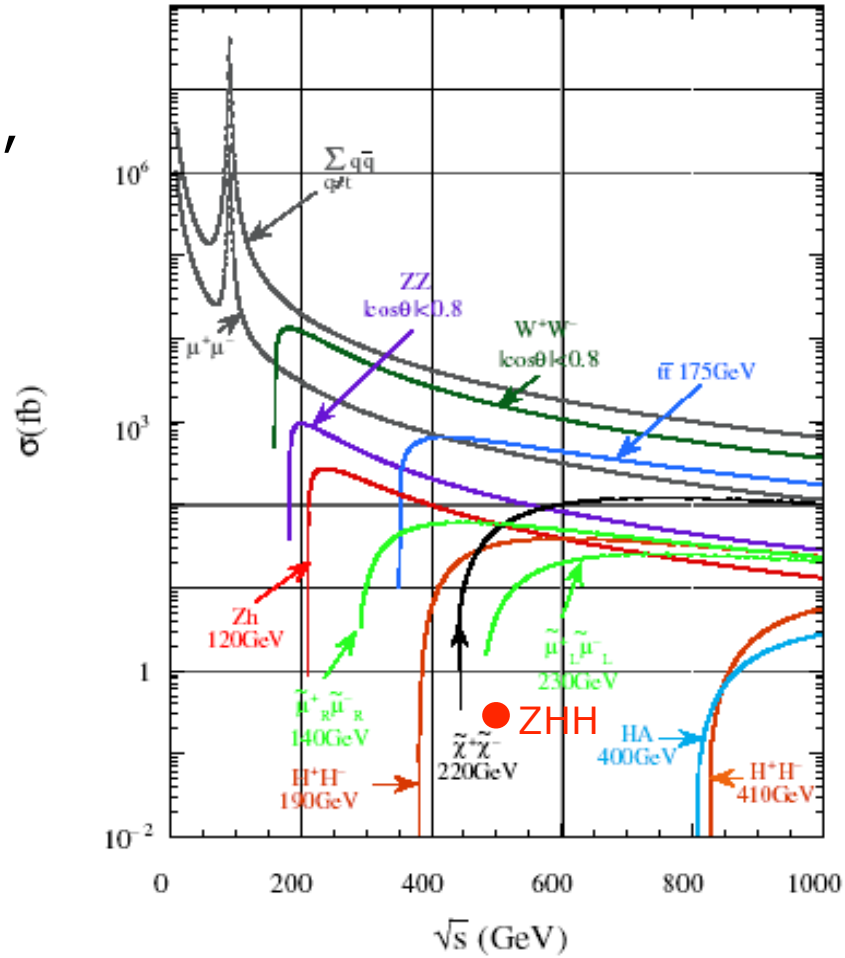


LC jet energies

- Q-Qbar events are boring
- $E_{jet} = \sqrt{s}/2$ is wrong
- Mostly 4-, 6-fermion final states, ee➔ ttH ➔ 8 -10 jets

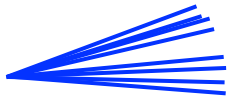
- At ILC 500: E_{jet} = 50…150 GeV
  - Mean pion energy 10 GeV
- At ILC 1 TeV: E_{jet} < ~ 300 GeV
- At CLIC (3 TeV) < ~ 500 GeV

- W reconstruction with
- $\sigma_m/m = 2.5/91$
  need $\sigma_E/E = 3.8\%$

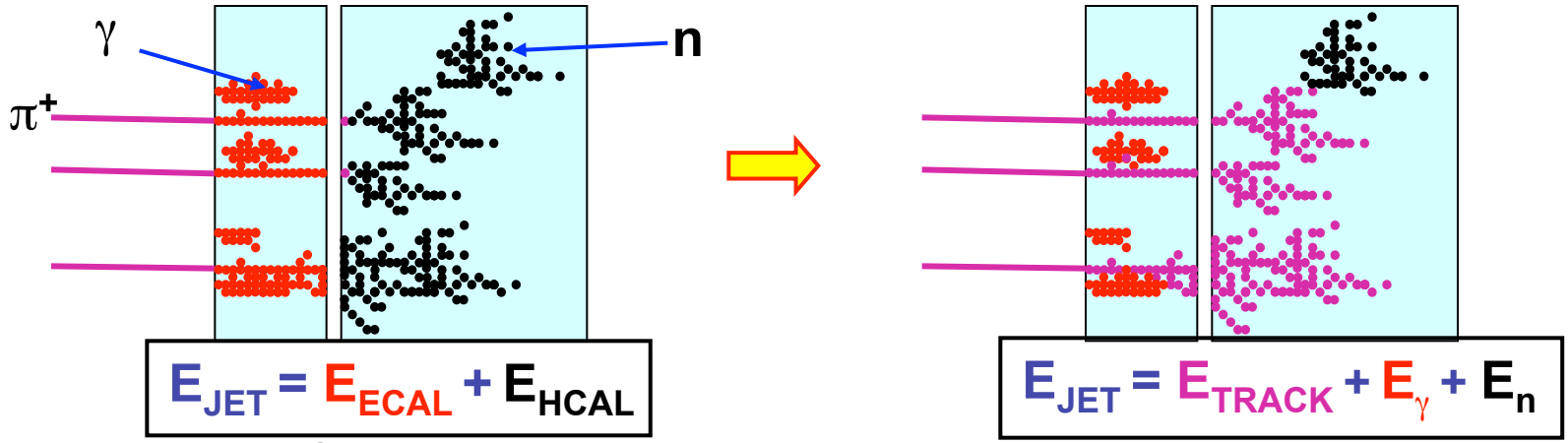


Particle Flow Calorimetry

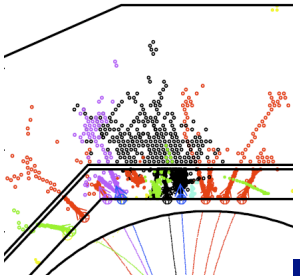
- **In a typical jet :**
  - **60 %** of jet energy in charged hadrons
  - **30 %** in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - **10 %** in neutral hadrons (mainly n and K_L)



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

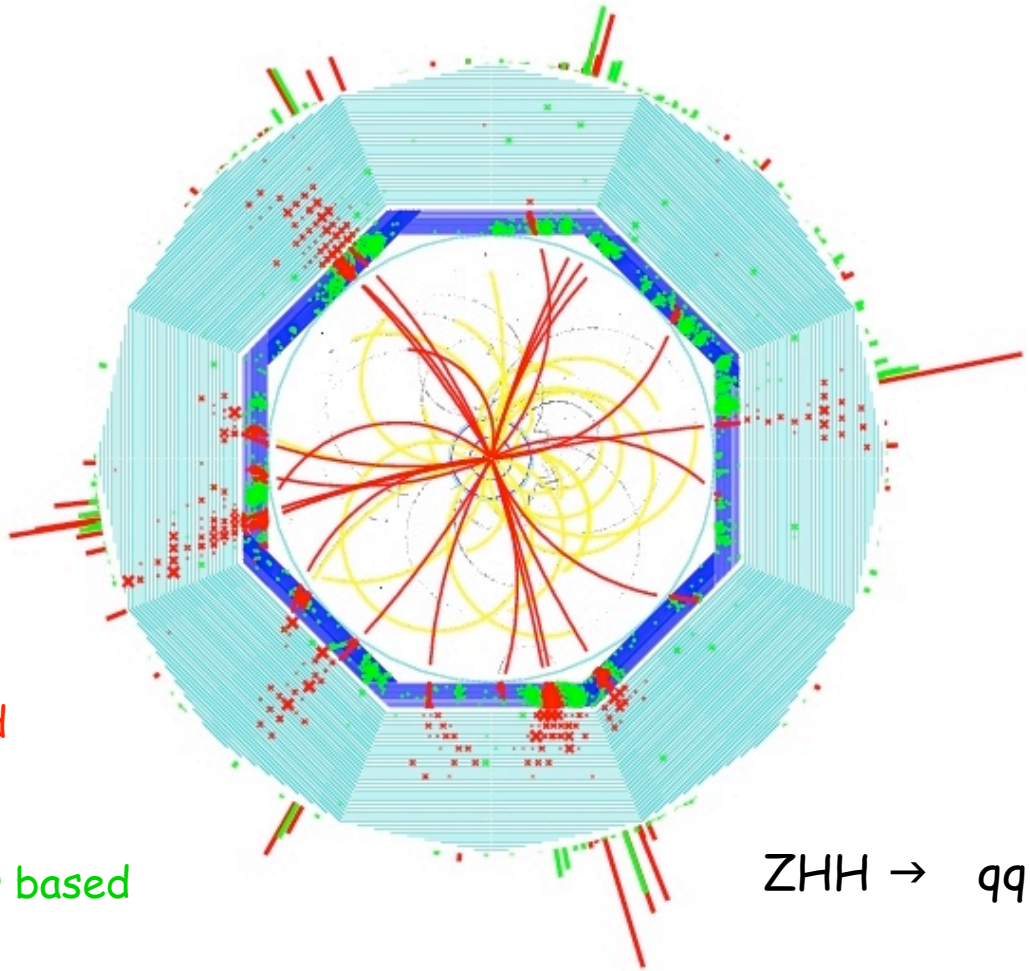


- **Particle Flow Calorimetry paradigm:**
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_E/E < 20\%/\sqrt{E(GeV)}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⇒ much improved resolution



Imaging calorimetry

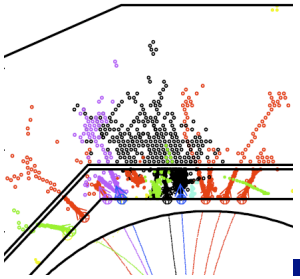
Reconstruct each particle individually



red:
track based

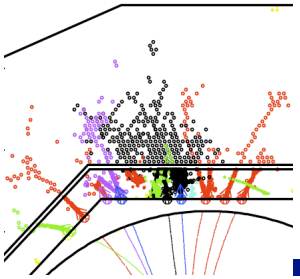
green:
calorimeter based

ZHH → qqbbbb



Calorimeter concept

- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- "no" material in front
  - stay inside coil
- small Moliere radius
  - to minimize shower overlap
- small granularity
  - to separate overlapping showers



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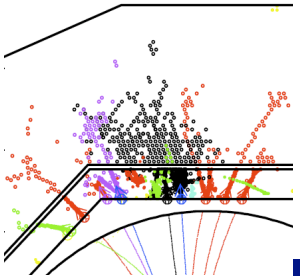
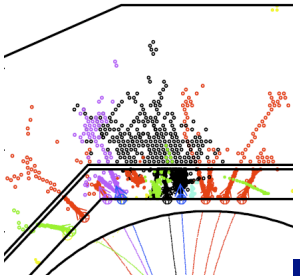


ILC detector concepts

- PFLOW involves entire detector, not just calorimetery

- ILD: TPC for highest pattern recognition efficiency
- B=3.5T
- ECAL and HCAL inside (CMS-like) solenoid
- Highly segmented and compact calorimeters

- 2nd PFLOW-based concept: SiD, higher B, smaller R, Si tracker, same calorimeter technologies



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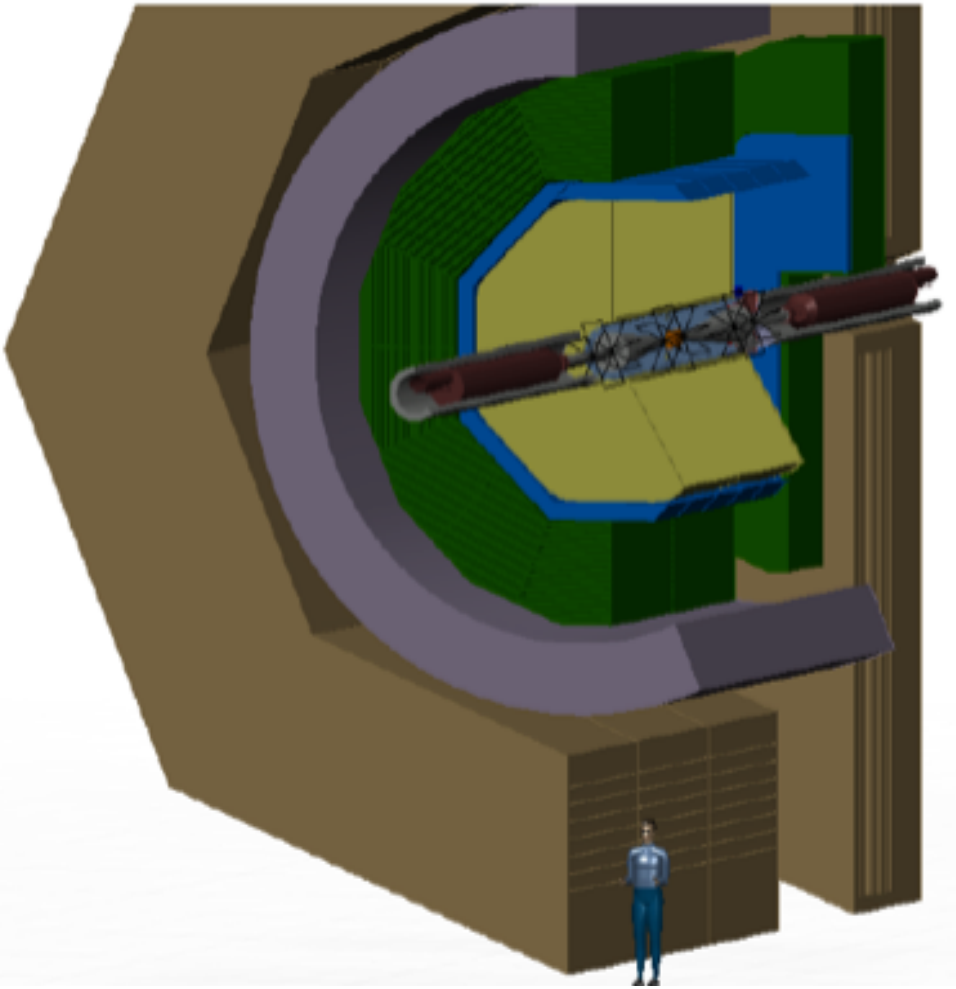
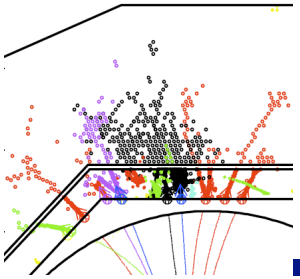
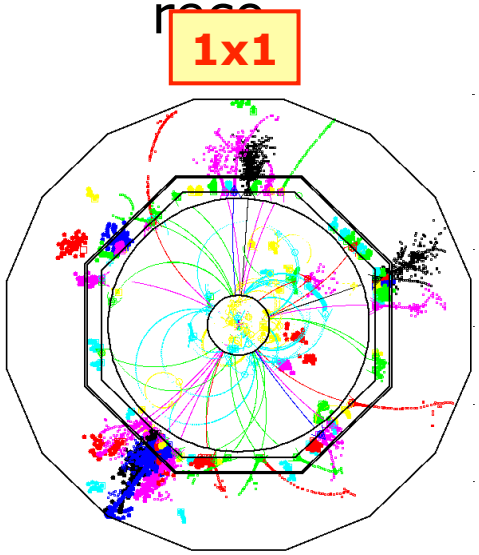
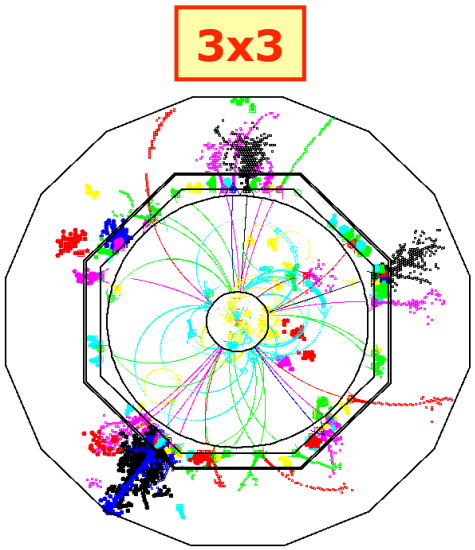


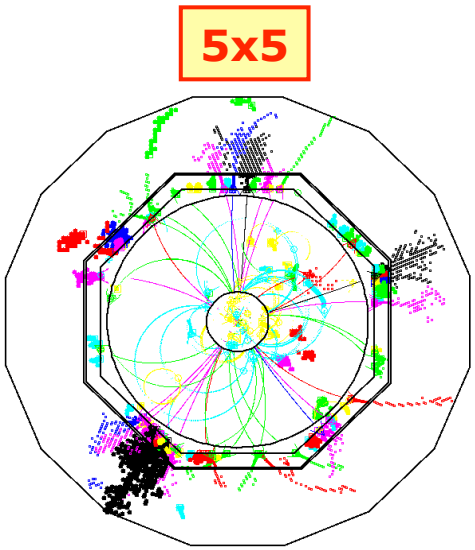


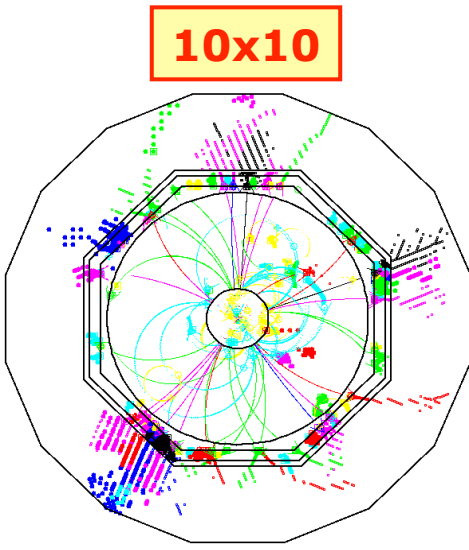
Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco

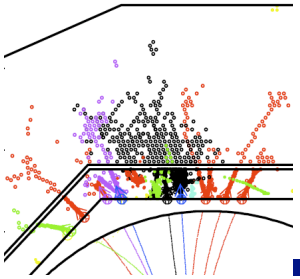








M.Thomson (Cambridge)



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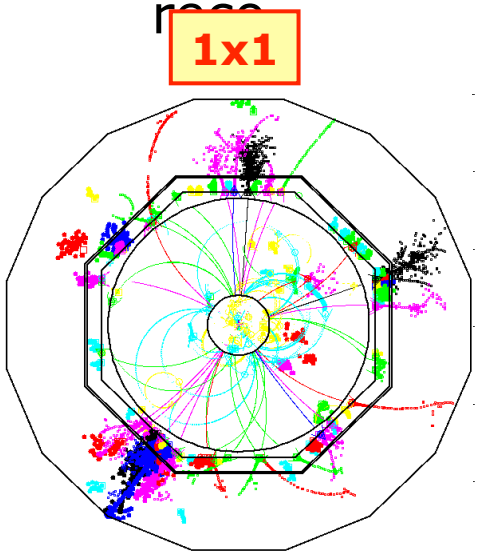

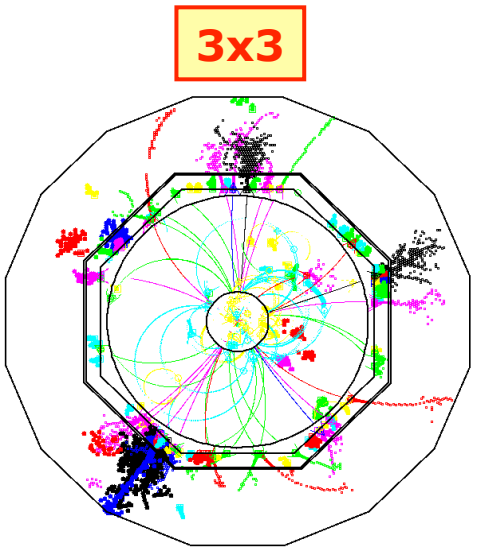

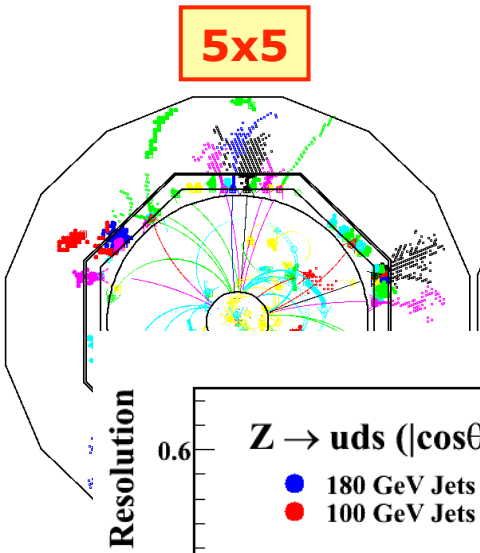

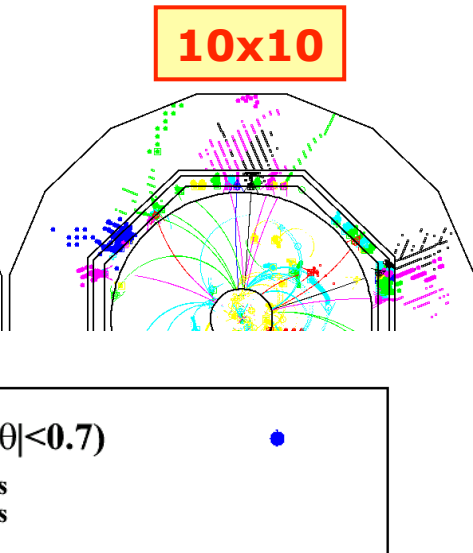

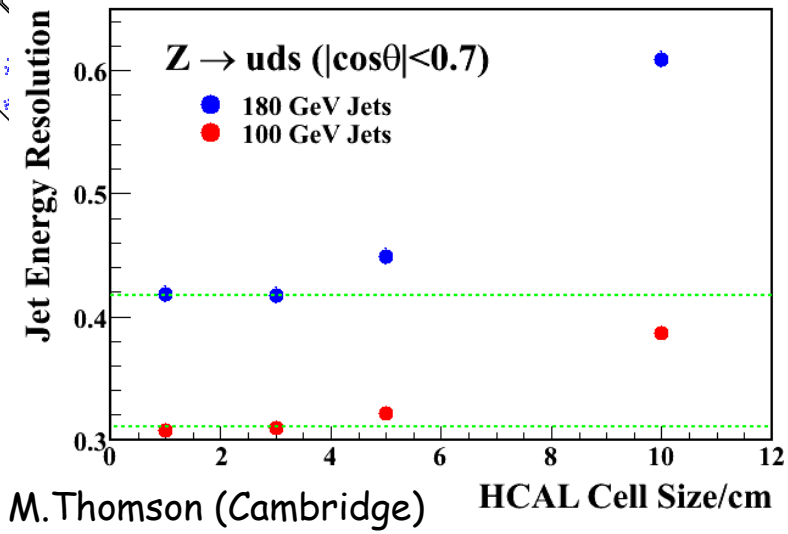

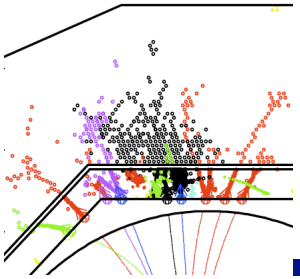

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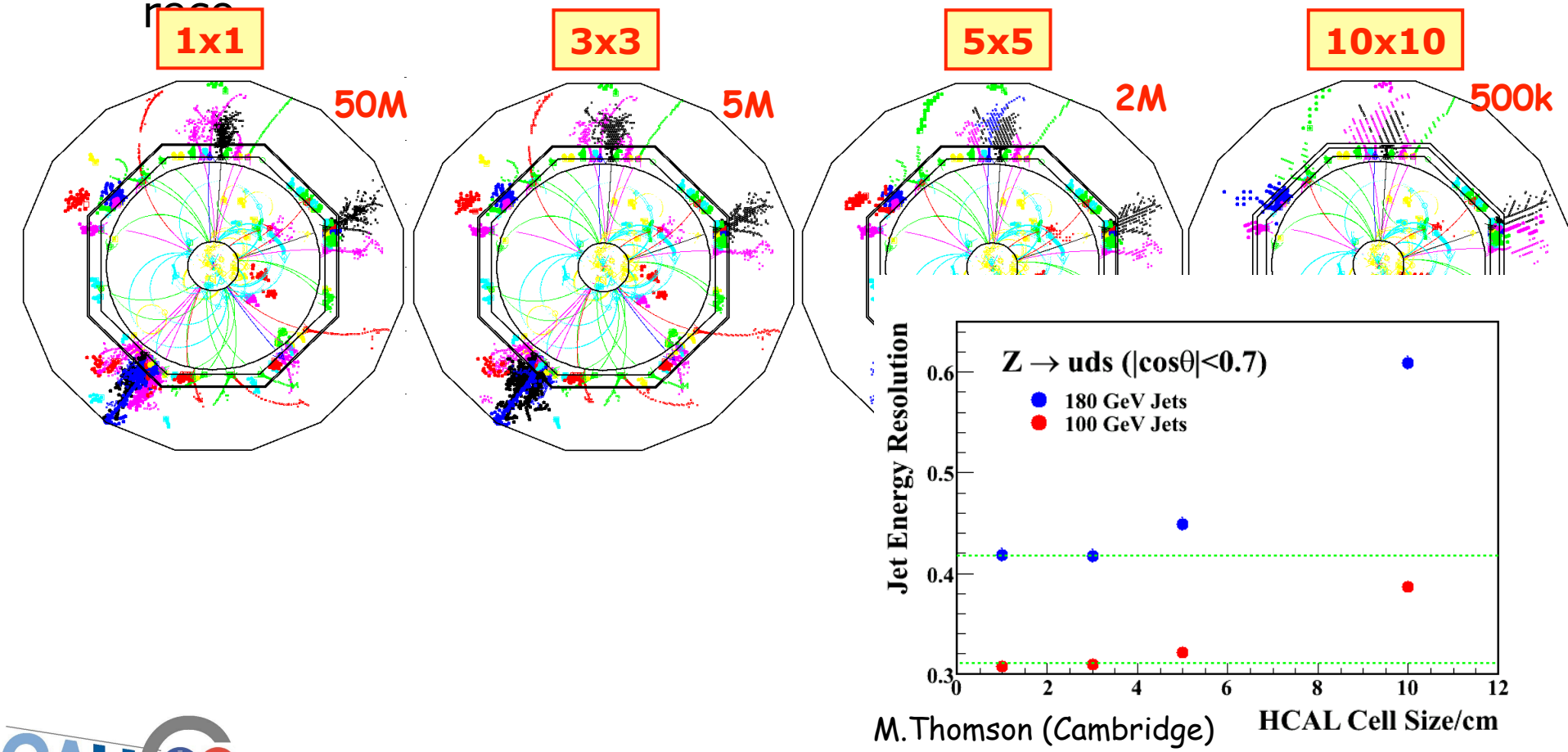
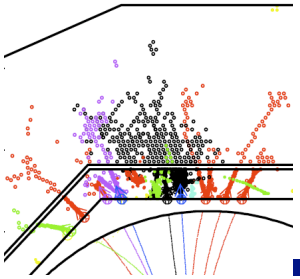
- Recent studies with PFLOW algorithm, full simulation and reco





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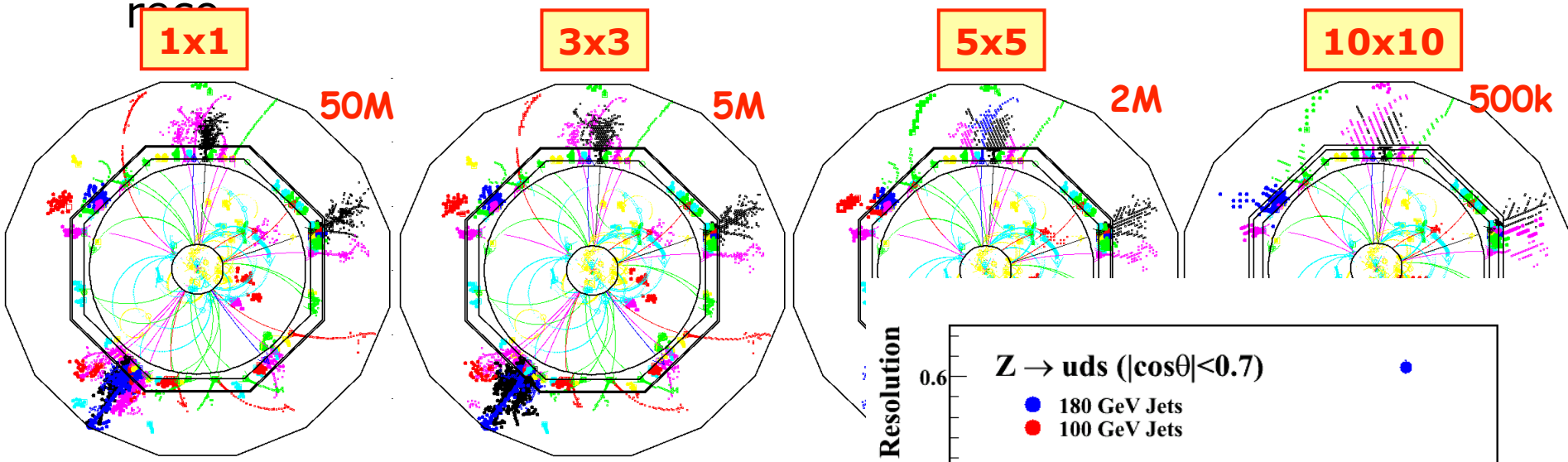
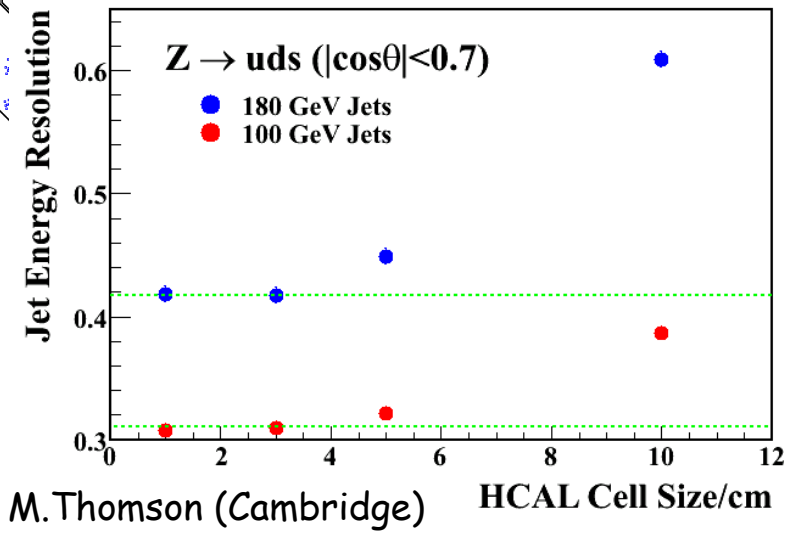
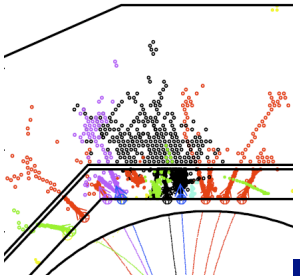




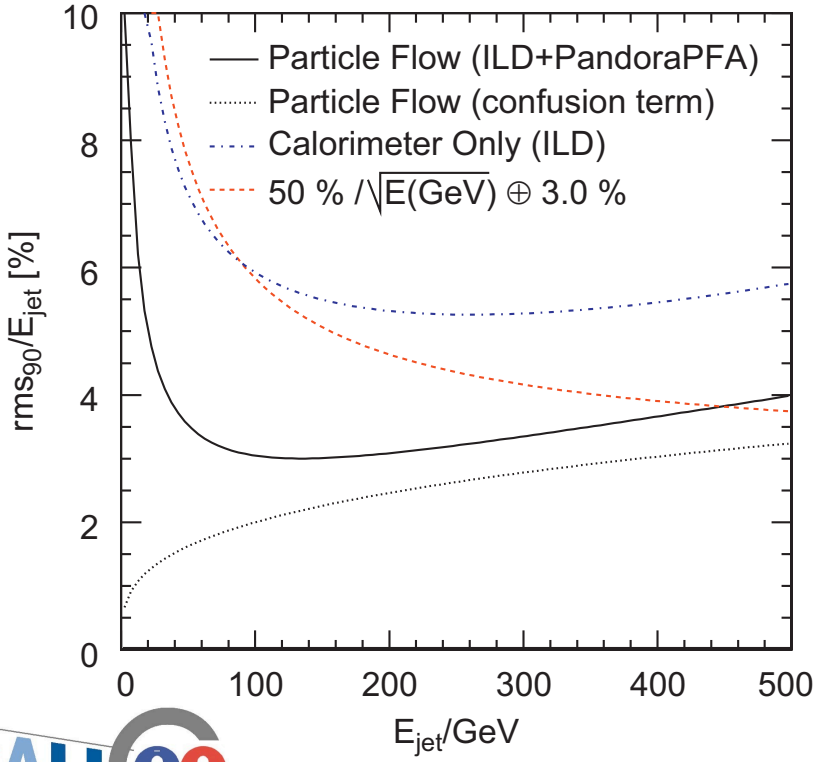
- Confirms earlier studies for test beam prototype
- 3x3 cm^2 nearly optimal

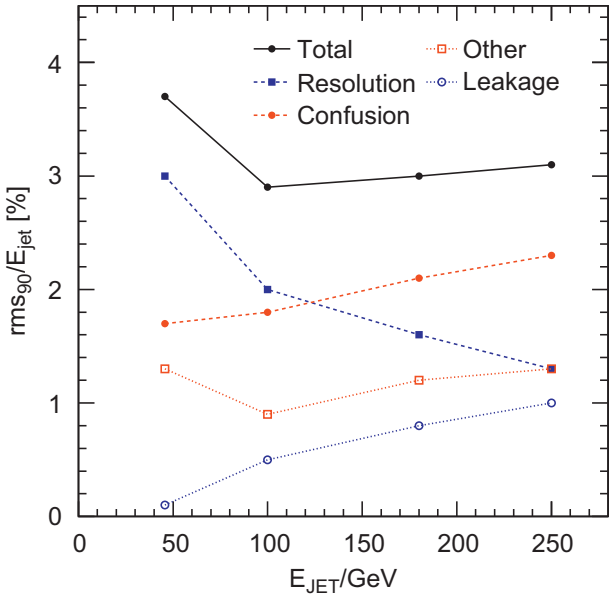


Understand particle flow performance

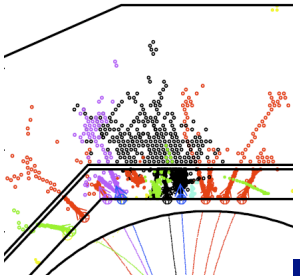
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution | Tracking | Leakage | Confusion



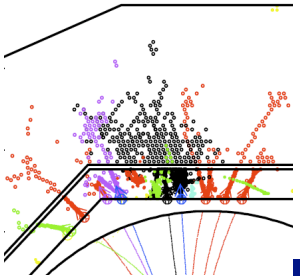


- Particle flow is always better
  - even at high jet energies
- HCAL resolution does matter
  - also for confusion term
- Leakage plays a role, too



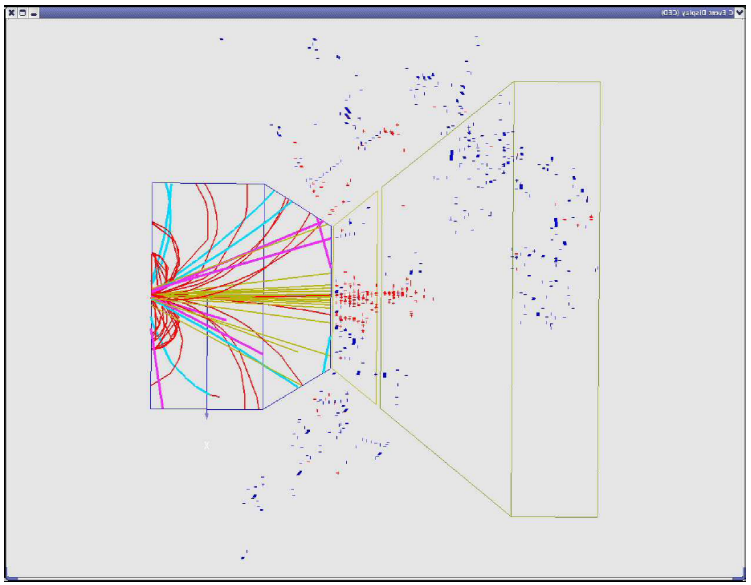
PFLOW detector concept

- Optimal use of all detector components: reconstruct each particle individually
- Interplay of highly granular detectors and sophisticated pattern recognition (clustering) algorithms
- Following detailed simulation and reconstruction studies, LC performance goals can be met
- Basic detector parameters thoroughly optimized
- A PFLOW detector is not cheap: do we believe in simulations?



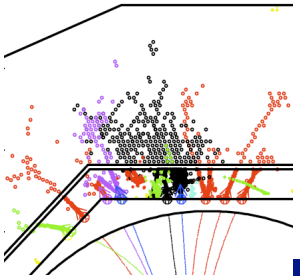
How to test it experimentally?

- "Jets" from thin targets?
  - Would require magnet spectroscopy and large acceptance ECAL + HCAL
    - Simulation study
  - Multi-million $ experiment
  - and still inconclusive
    - need to control target losses and acceptance losses at 1-2% level
    - model dependence



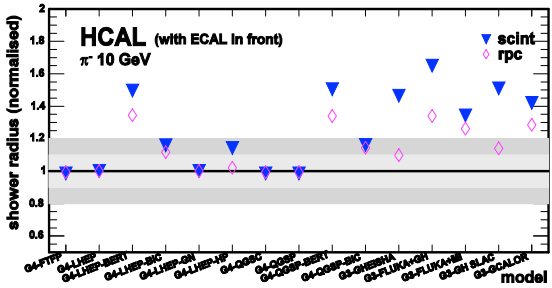
20 GeV pion, 0.8 T

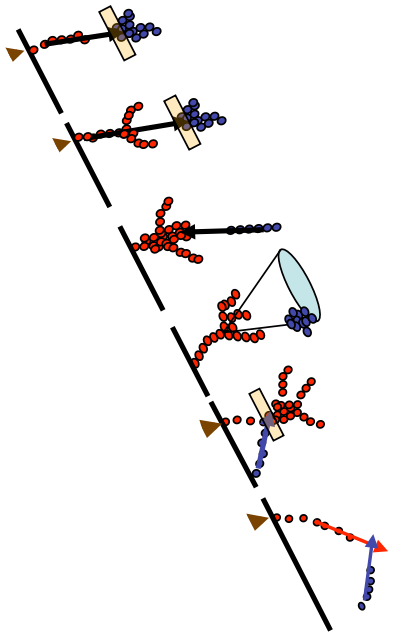
- Factorize the problem: check the ingredients
  - simulation
  - algorithms
  - technical performance

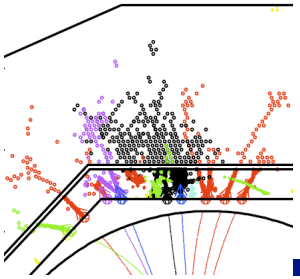


Critical questions

- Are the basic detector **performance** predictions confirmed?
- Are the **shower parameters** well enough simulated to predict PFLOW?
- Is the **substructure** actually there and well modeled
- Can one realize the potential of **software compensation** for gain and linearity?
- Can we verify the "**double track resolution**" of a tracking calorimeter?
- Are **detector effects** under control?
- Can we **calibrate** millions of cells and control stability?
- Can we build the detector without spoiling it by **dead material** everywhere?
- What are the relative merits of **different technologies** for PFLOW?

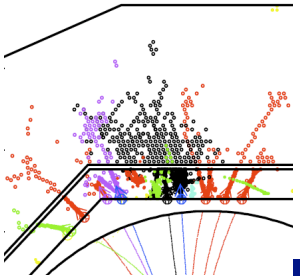




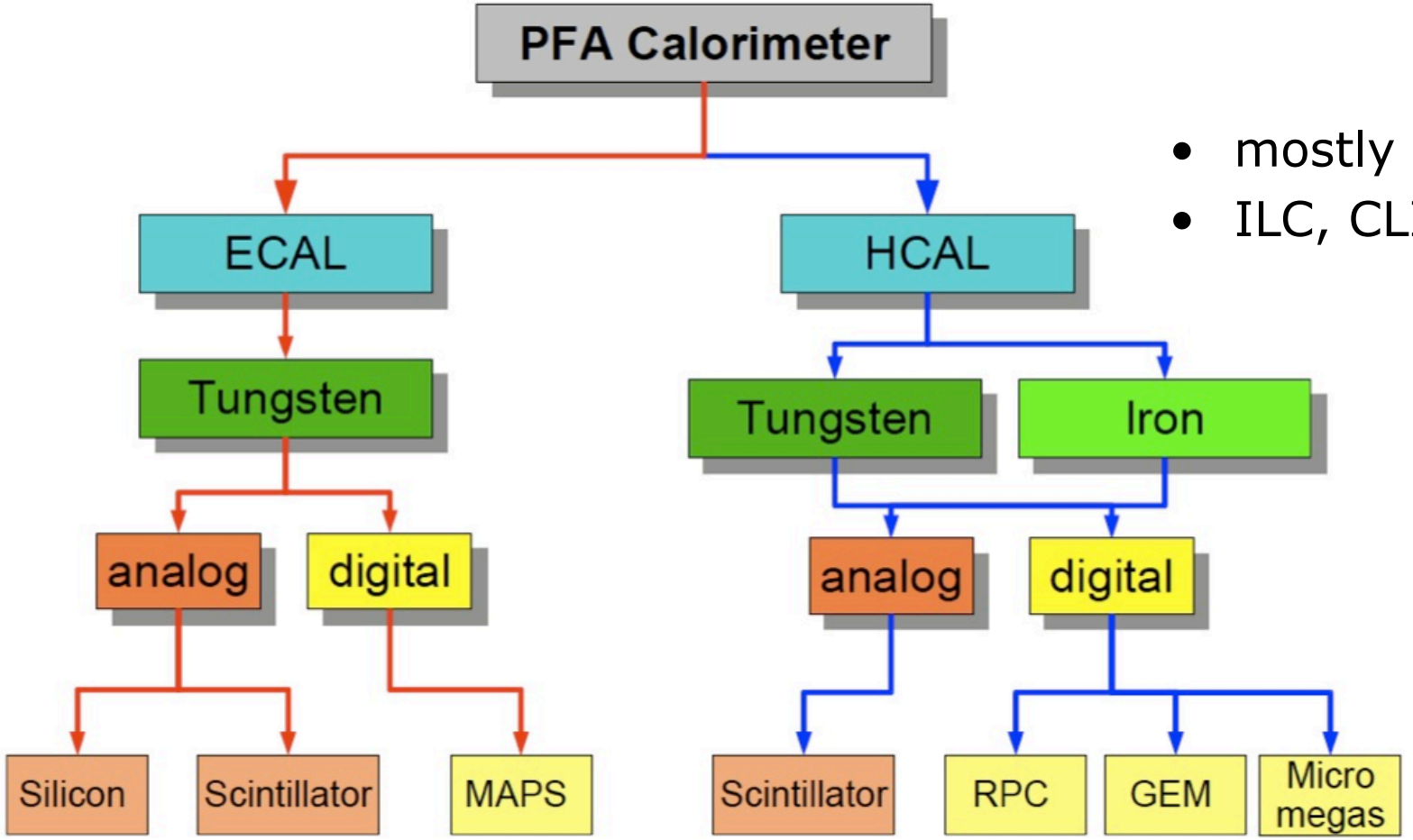


CALICE

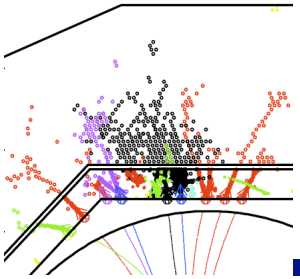
- We are more than 300 physicists and engineers from 57 institutes in Africa, America, Europe and Asia
- Our goal: develop highly granular calorimeter options based on the particle flow approach for an e+e- linear collider
- Twofold approach:
  - Physics prototypes and test beam
    - Operational experience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



Technology tree

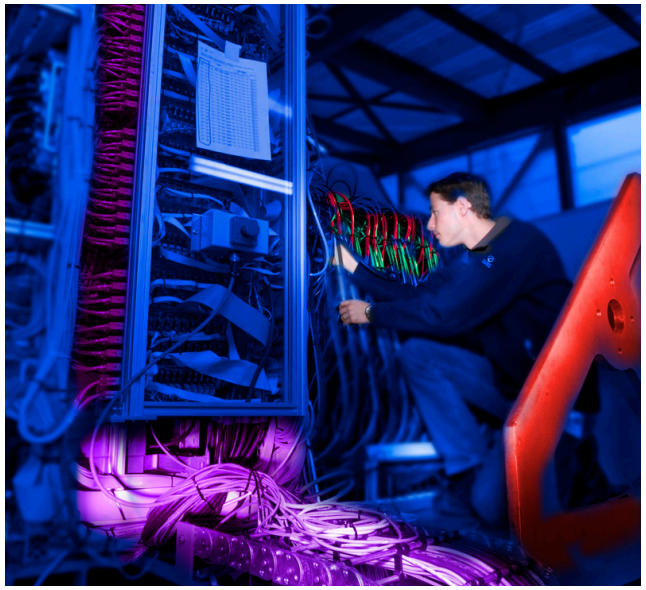


- mostly ILD, SiD
- ILC, CLIC

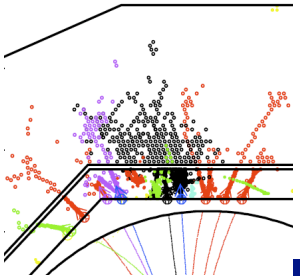


Overall status

- Major test beam campaigns at DESY, CERN and Fermilab
- 1st generation **"physics" prototypes**
- Mostly combined set-ups
  - ECAL-HCAL-TCMT
- Si W ECAL 2005-08
- Scint W ECAL 2007-09
- Scint Fe HCAL 2006-09
- W HCAL started Sept 2010
- RPC Fe HCAL started Oct 2010



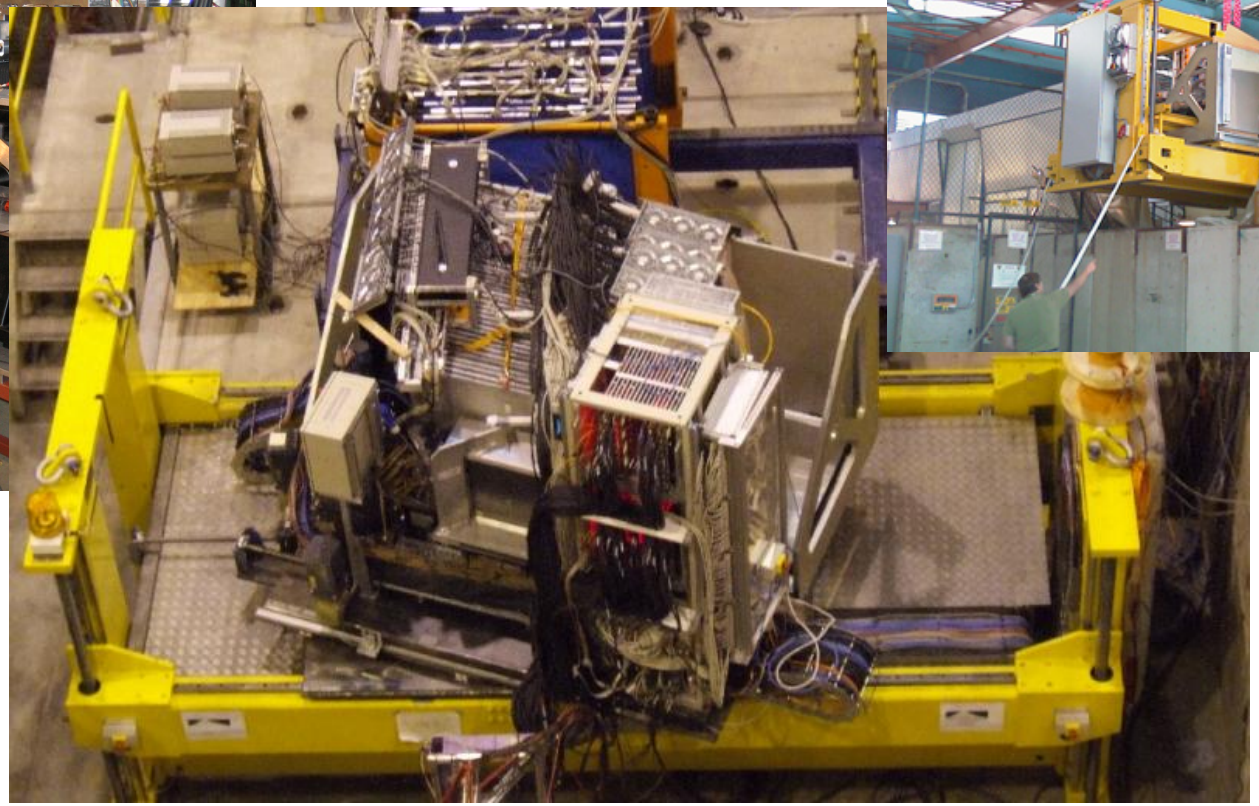
- 2nd generation **"technical" prototypes**: construction and commissioning ongoing, single or few layers available
  - Scint, RPCs, GEMs, MicroMEGAS
- Complete detectors to start with RPC-Fe HCAL June 2011
- ECAL, Scint Fe HCAL later



Test beam experiments

DESY 2005

CERN 2006-2007

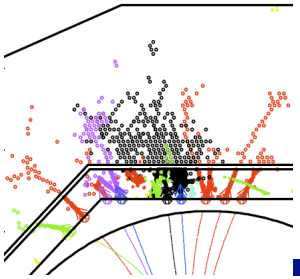


FNAL 2008..

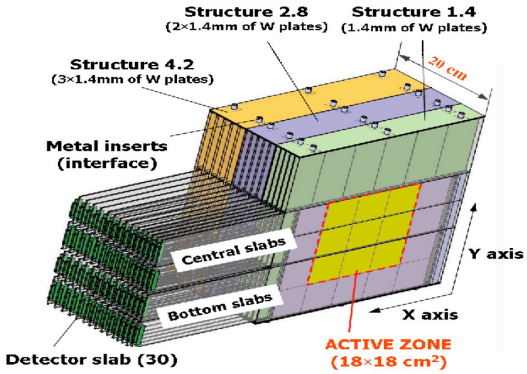
Validation of the simulations

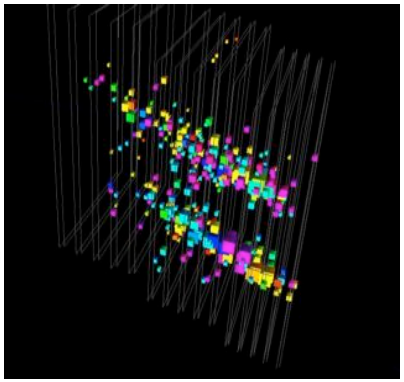
detector performance

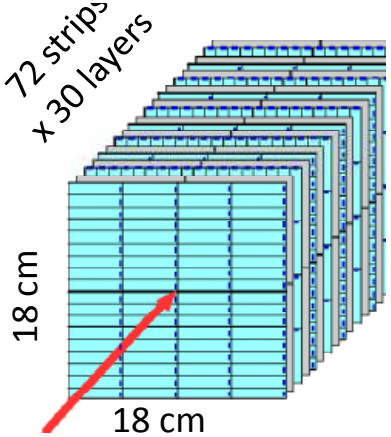
shower models

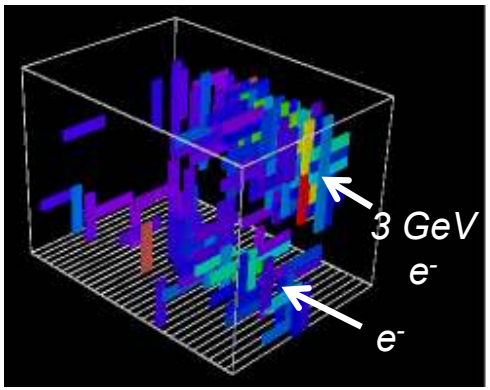


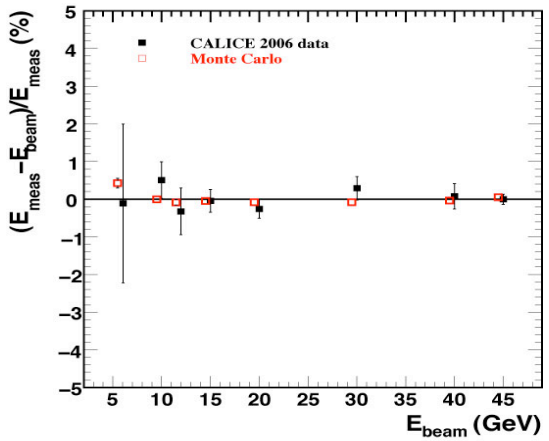
ECAL options

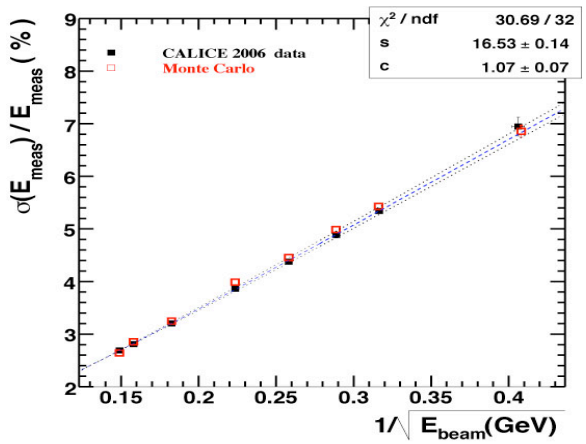


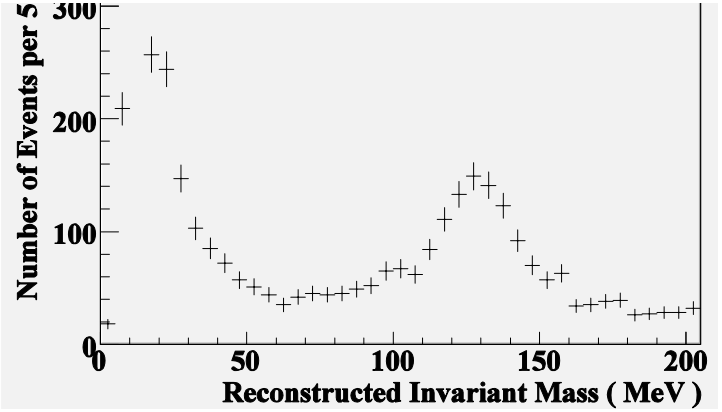




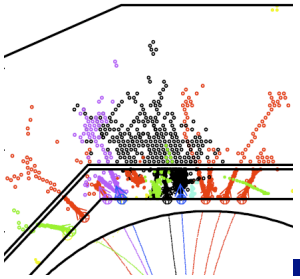






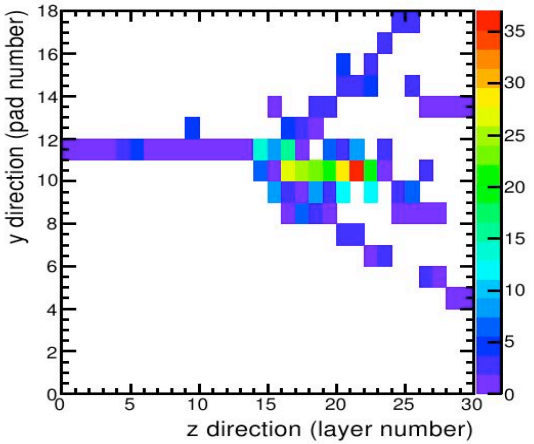


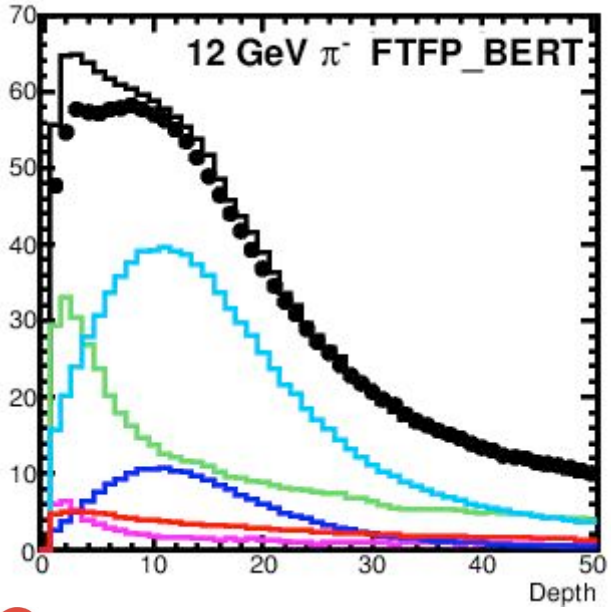
- W Si or Sci: common mechanics, similar electronics



Pions in the SiW ECAL

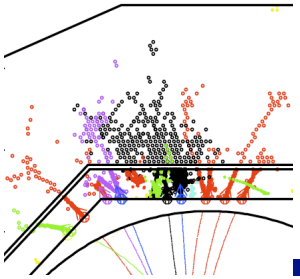
- test Geant 4 predictions with 1 cm^2 granularity
- sensitive to shower decomposition
- favor recent G4 physics lists
- certainly not perfect - certainly not bad either!



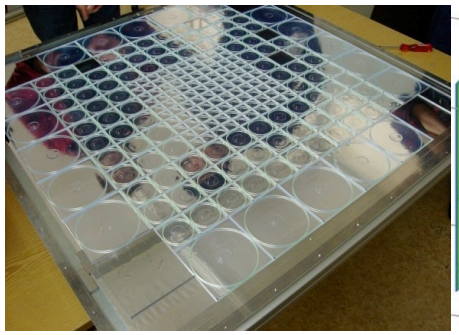


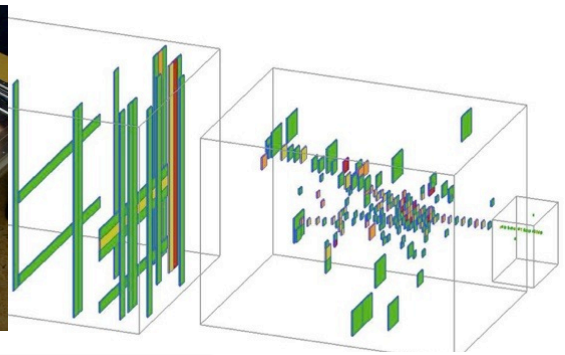
Shower Components:

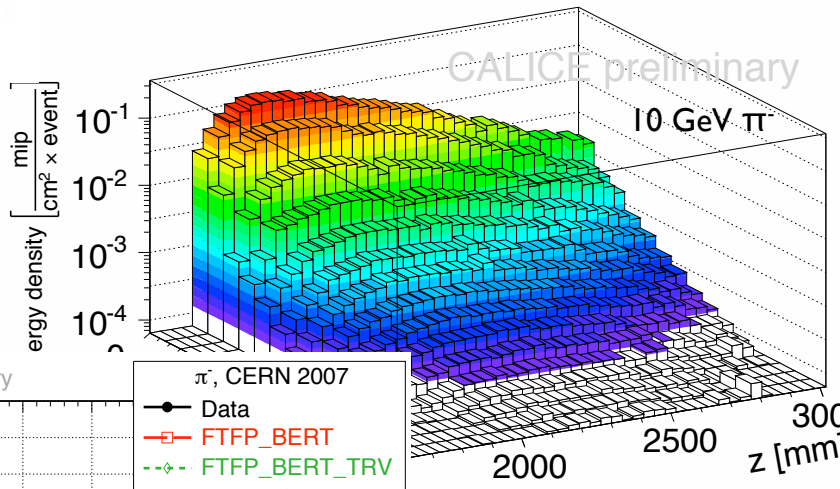
- electrons/positrons
  knock-on, ionisation, etc.
- protons
  from nuclear fragmentation
- mesons
- others
- sum

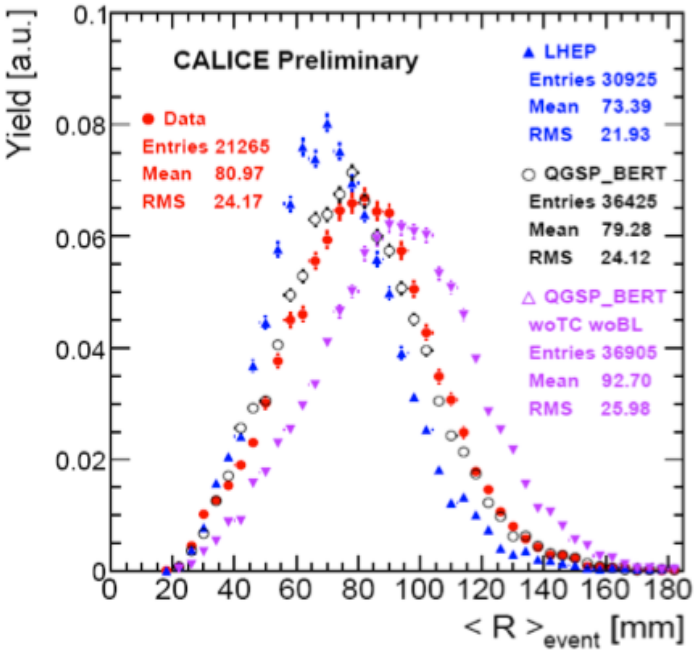


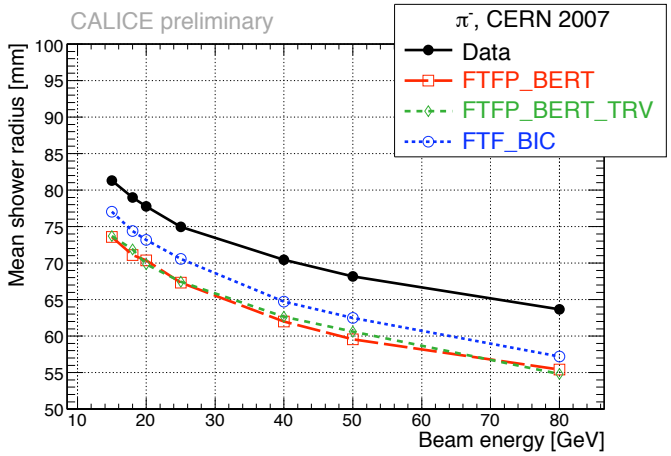
Fe Scint tile HCAL





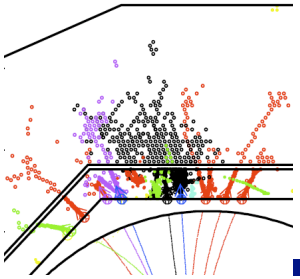




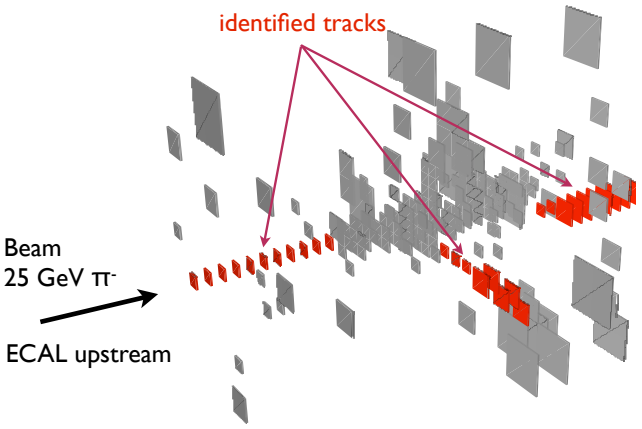


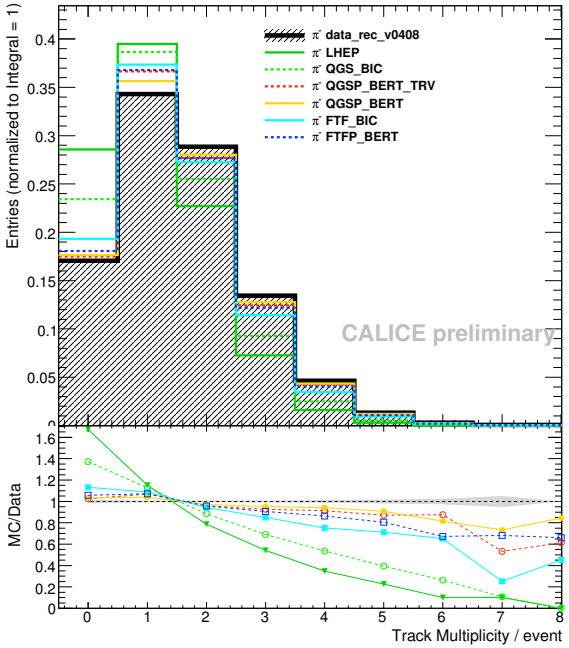
2D profile from starting point

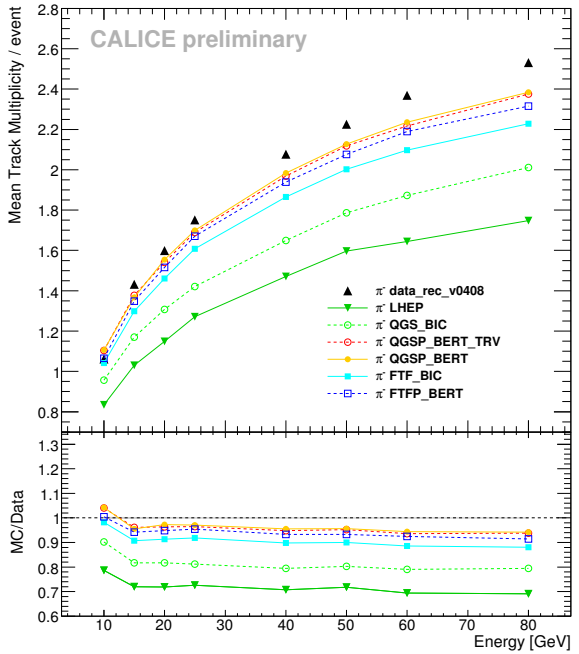
- Present-day simulation quality requires good detector understanding to discriminate
- Fluctuations also well reproduced



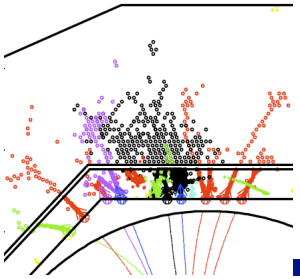
Shower fine structure







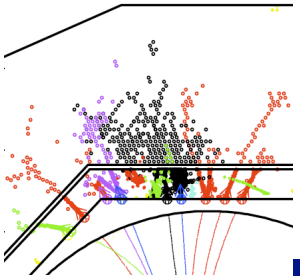
- Could have the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already



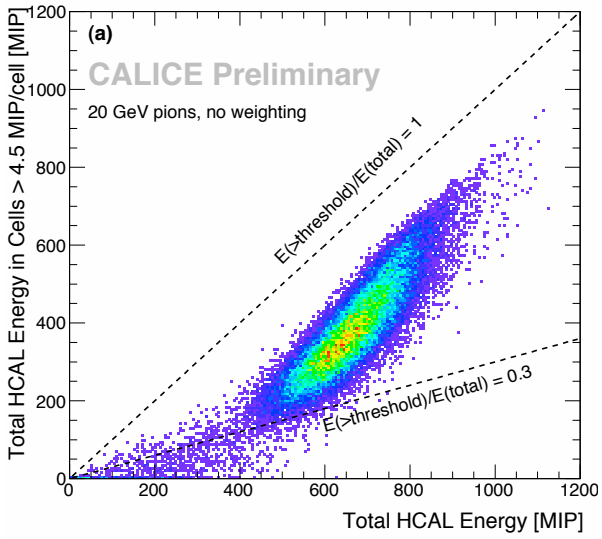
Summary on validation:

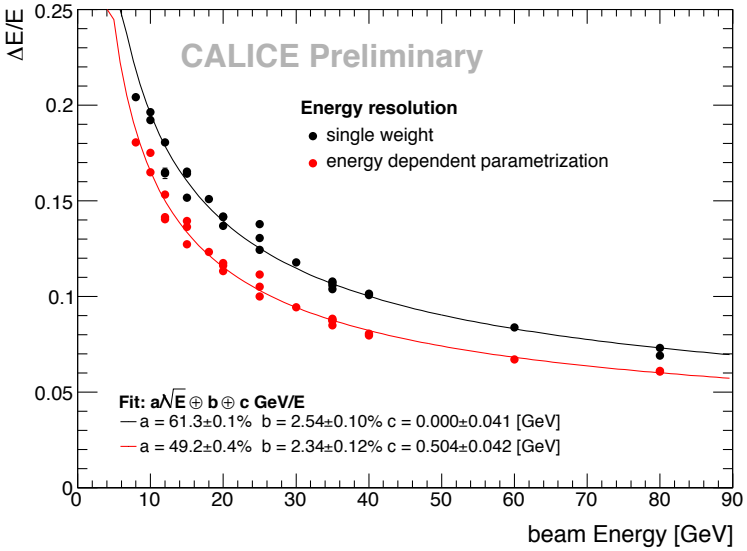
- The particle flow detectors perform as expected
  - support predictions for full-scale detector
- Geant 4 simulations not perfect, but also not as far off as feared a few years ago
  - fruitful close cooperation with model builders ongoing
- Predicted shower sub-structure is seen
  - detailed checks possible, benefits for all calorimeters

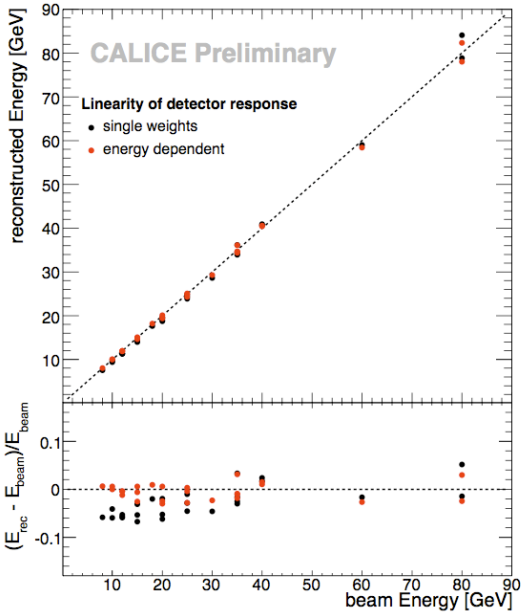
Test the algorithms with real data



Resolution, compensated

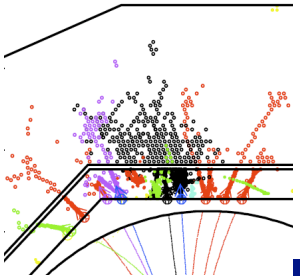




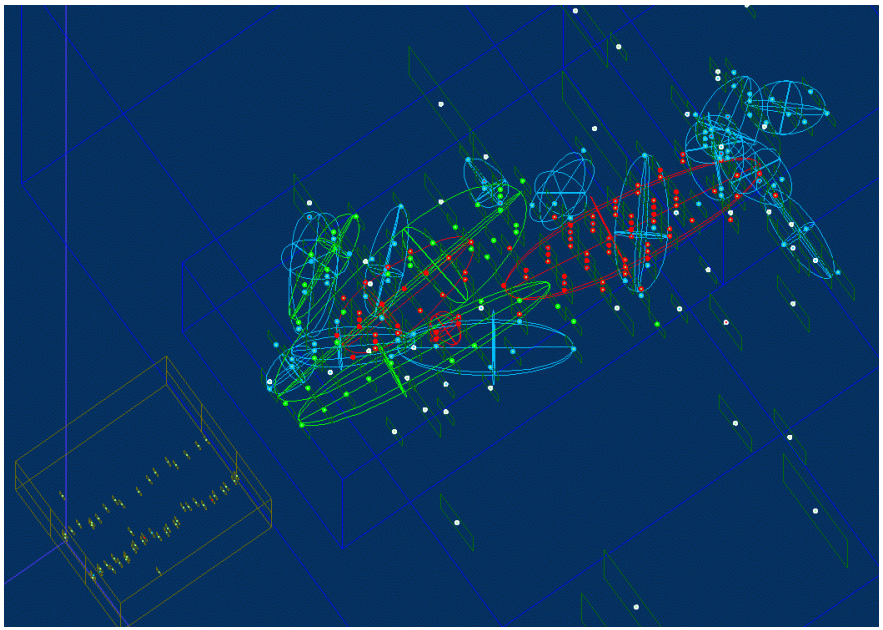


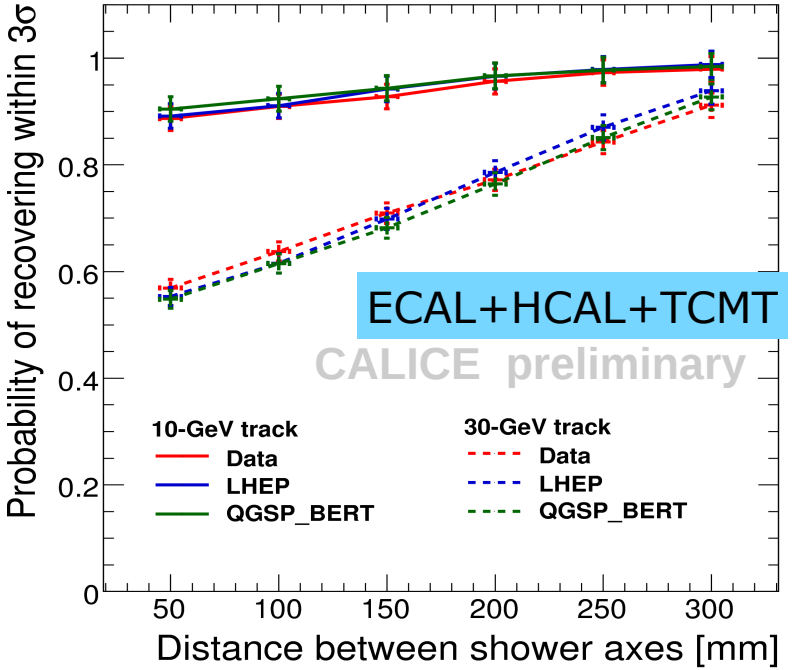
ECAL+HCAL+TCMT

- Poor man's dream: s/w compensation
- Significantly improved resolution AND linearity
- High granularity - many possibilities



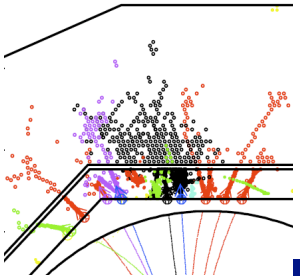
PFLOW: two-particle separation





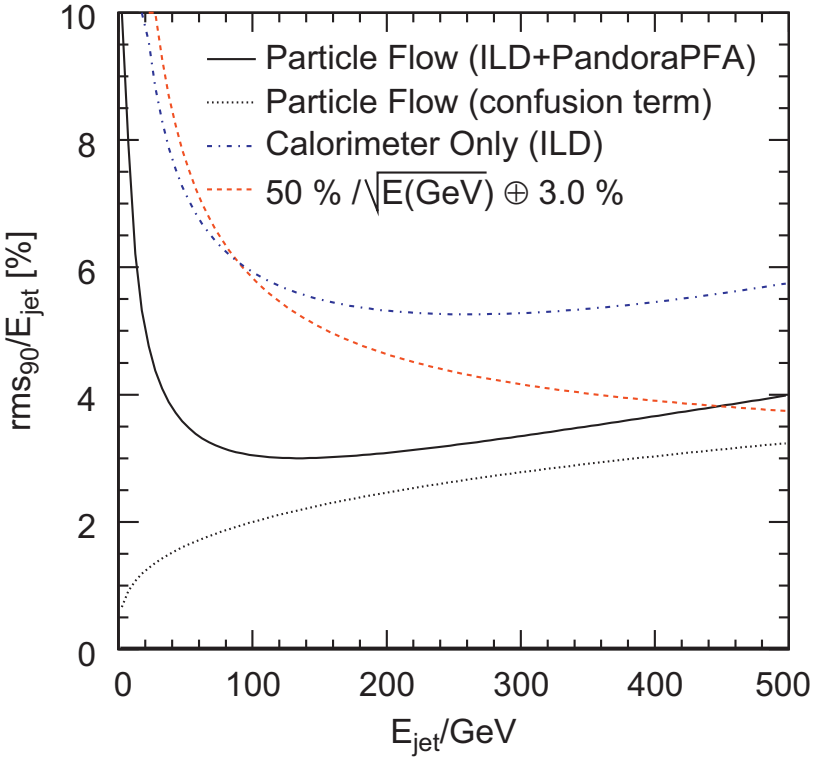
- The "double-track resolution" of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- Important: agreement data - simulation
  - sharing the same limitations

to be done with photons, too

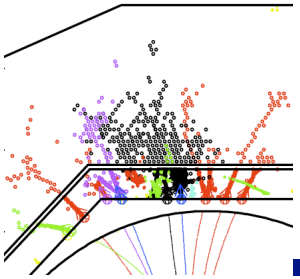


Summary on algorithms

- Granularity is extremely powerful
- Energy resolution and imaging capabilities verified with data at sub-structure level
  - the main drivers of PFLOW performance
- Leakage estimation and software compensation not yet implemented in present Pandora



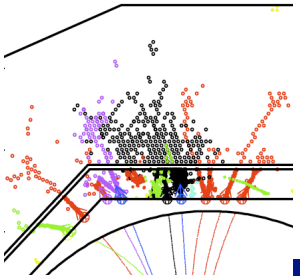
Test the technologies and establish feasibility



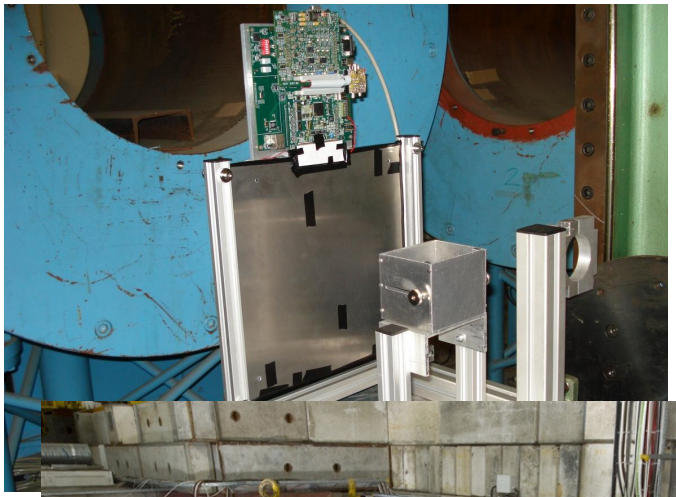
ILD, SiD: R&D Priority issues

- Physics:
- Gaseous hadron calorimeter
  - digital or semi-digital
  - operation, calibration, detector modeling, shower modeling, energy and topology resloution
- Scintillator: study timing for PFLOW
  - particularly interesting with tungsten HCAL absorber

- Technology:
- Integration: handle the high granularity
  - compactness, dead spaces
  - power pulsing, online zero suppression
- Cost



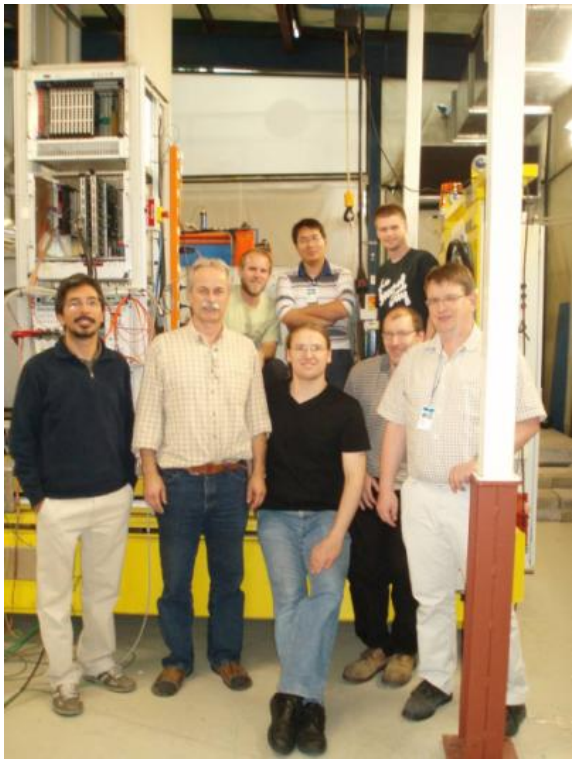
Test beam experiments 2010



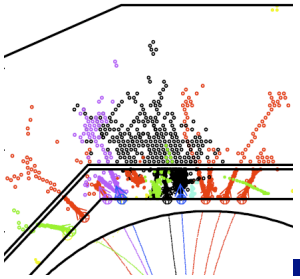
DESY

CERN

FNAL

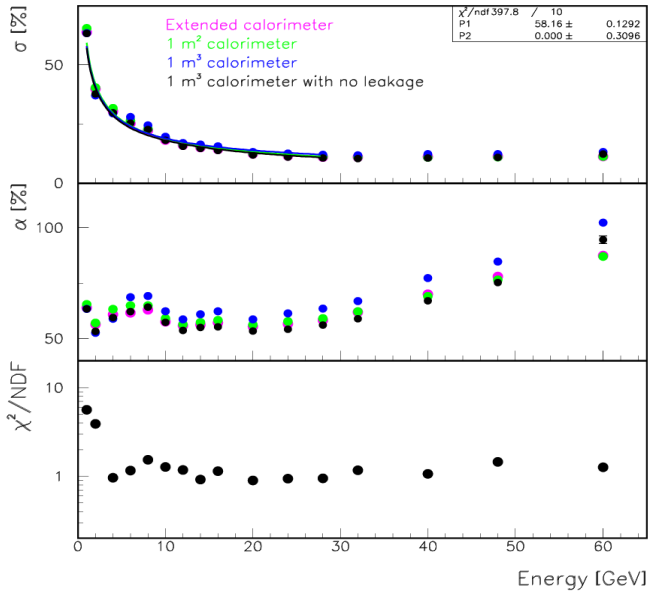


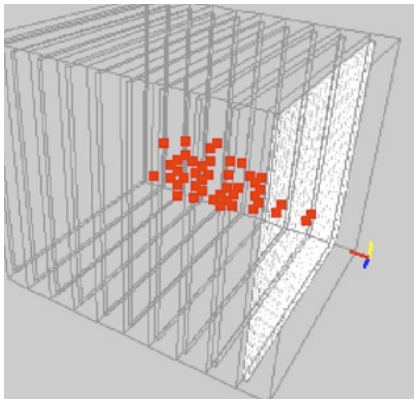
and more:
RPCs in B field, micromegas, GEMs

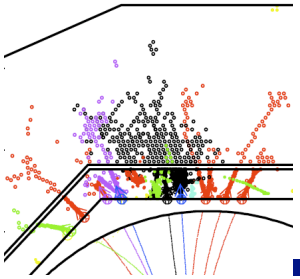


Digital calorimetry

- Digital and semi-digital hadron calorimeter
  - even higher granularity
  - suppress dE/dx fluct.
  - reduced n sensitivity
  - limited at high E?
- Small RPC proto successful
- Educated simulations
- Full-size RPC based prototypes under test and underway

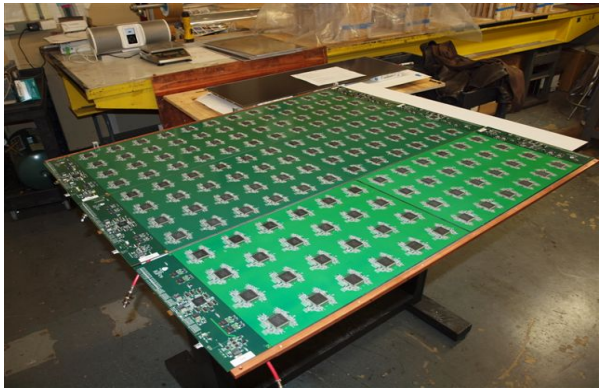




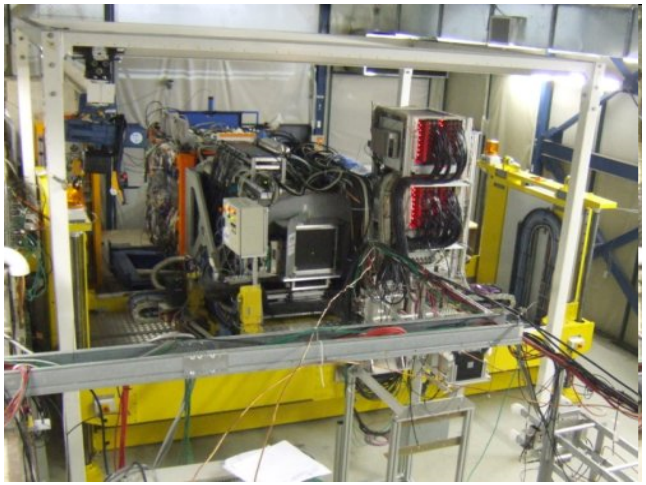


RPC DHCAL m3 at FNAL

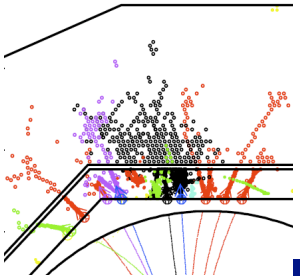
- started this week, hadrons later today
- common running with SiW ECAL
  - April 2011
  - should put DHCAL on equal footing



- TCMT instrumentation options
  - presently scintillator strips
  - will be exchanged against RPC



- Possible continuation at CERN
  - higher E, higher duty cycle, tungsten



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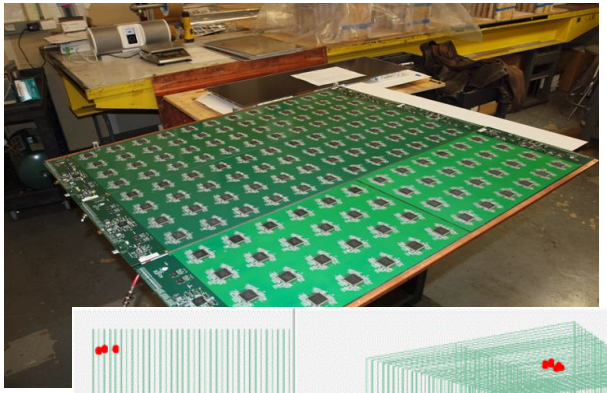

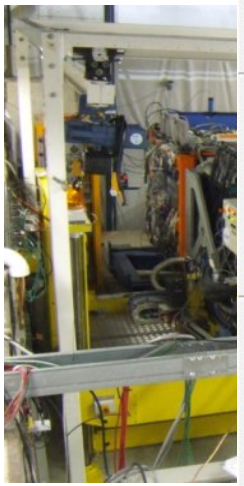

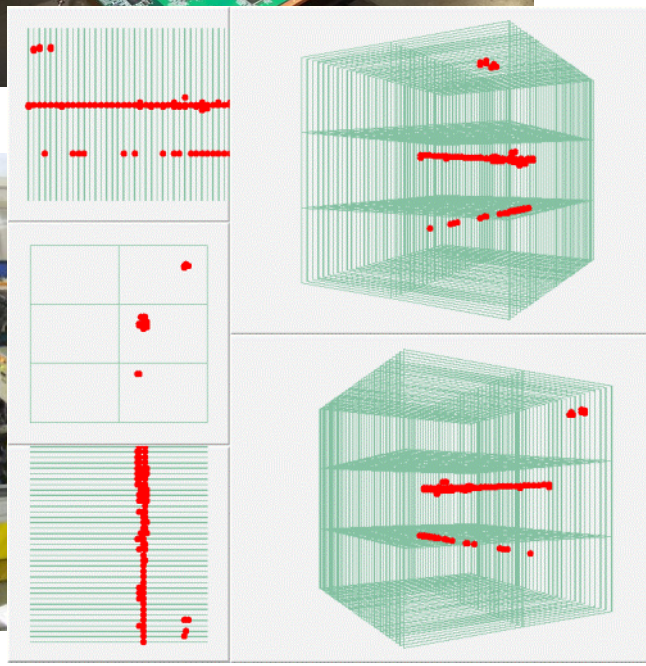

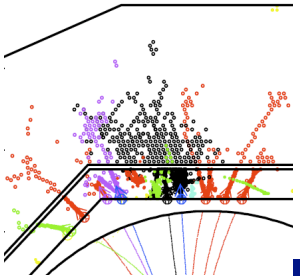

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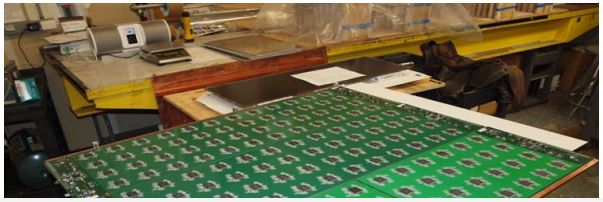
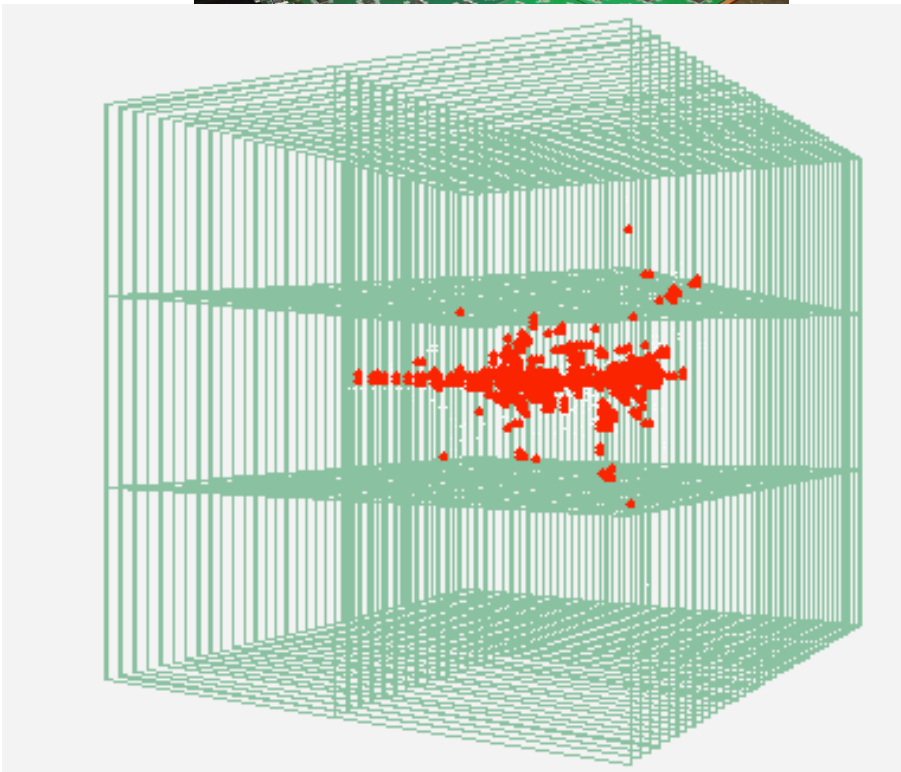
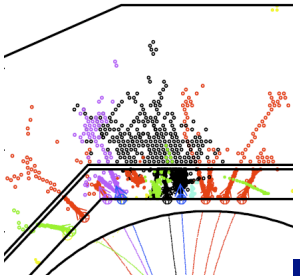
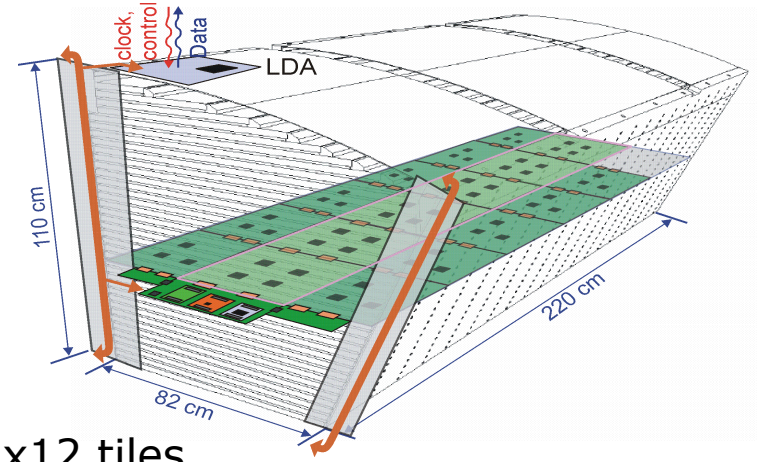




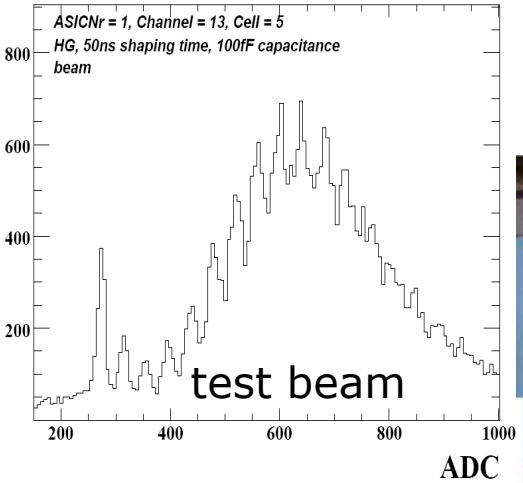


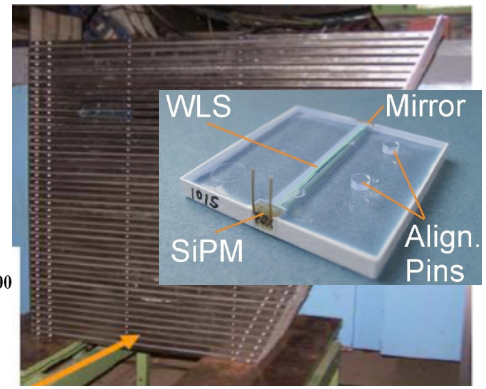
Scint HCAL: 2nd generation

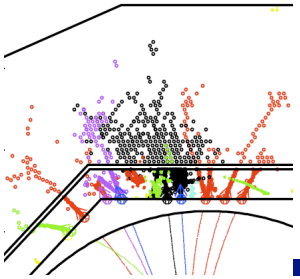
- integrate readout ASICs and LED system
  - include ADCs and **TDCs**
  - power pulsing, zero suppression
- Different options for photo-sensor
- Different options for coupling
  - via WLS fibre or direct
  - pins or SMD SiPMs (NIU)
- Interfaces to be done
  - cooperation with NIU/FNAL
- First layers: demonstrator
  - 2 m2 steel gap, start W
- Later: full tungsten HCAL
  - and steel wedge



12x12 tiles,
36x36 cm2

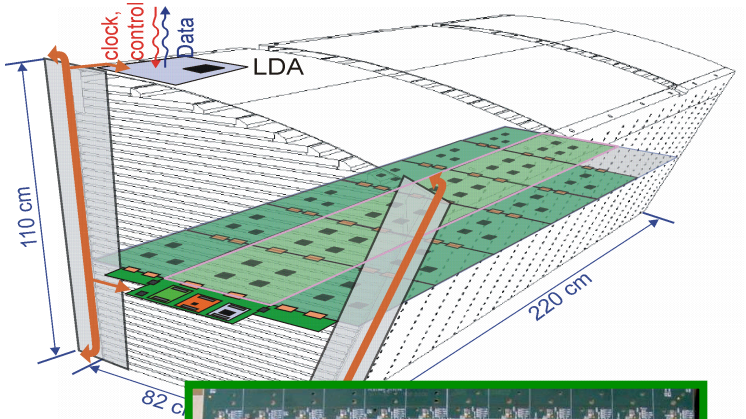




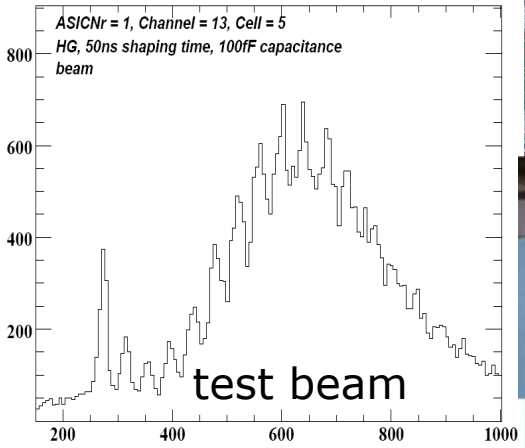


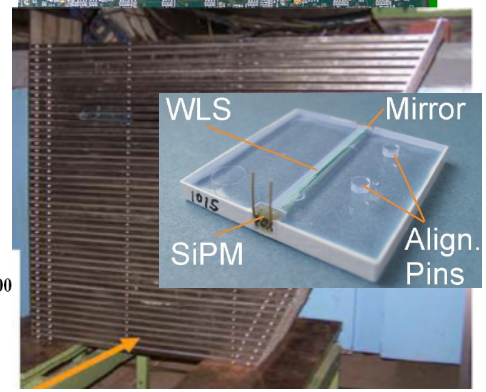
Scint HCAL: 2nd generation

- integrate readout ASICs and LED system
  - include ADCs and **TDCs**
  - power pulsing, zero suppression
- Different options for photo-sensor
- Different options for coupling
  - via WLS fibre or direct
  - pins or SMD SiPMs (NIU)
- Interfaces to be done
  - cooperation with NIU/FNAL
- First layers: demonstrator
  - 2 m2 steel gap, start W
- Later: full tungsten HCAL
  - and steel wedge

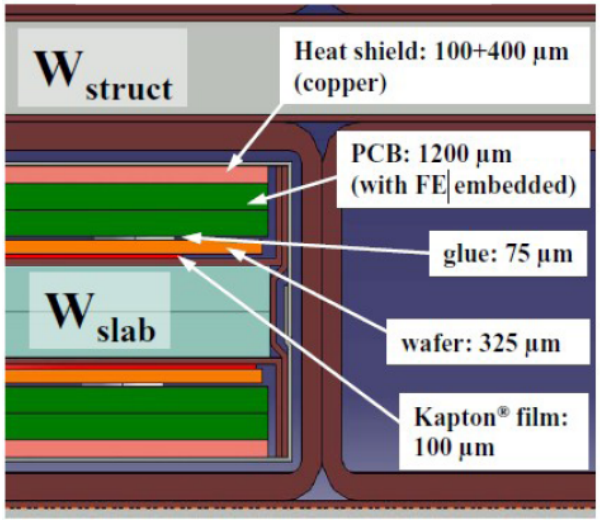


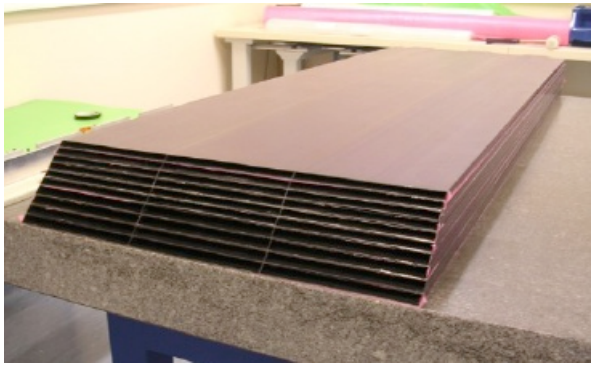
12x12 tiles,
36x36 cm2

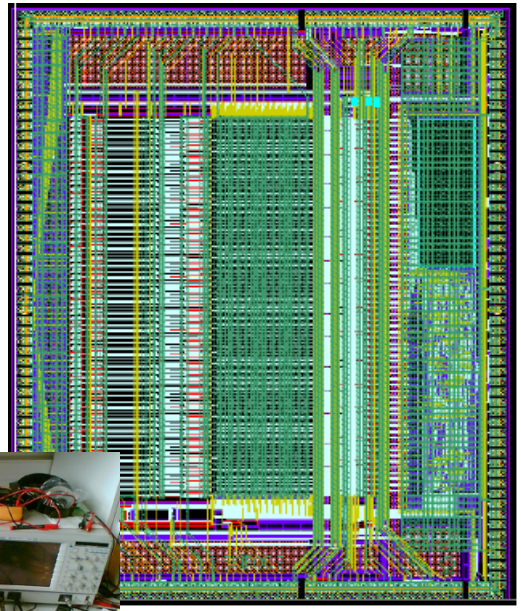


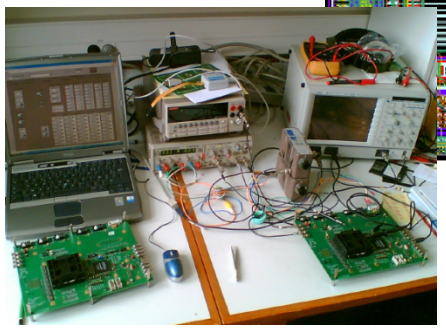


Status: Silicon – Tungsten ECAL → Technological Prototype









Mechanical structure

Undergoing various tests (heat, mechanical…)

SKIROC2 (Front-end chip)

Engineering run produced 1650 samples

64 channels per chip

Option of power – pulsing implemented

FEV8 (Front-end board)

Schematic almost complete

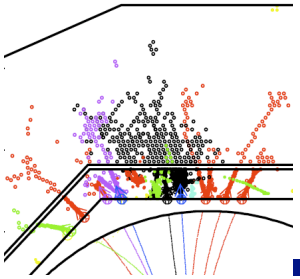
1024 channels on a 180 x 180 mm^2 board

Plans

Assembly of 1st short slab 2nd half of 2011

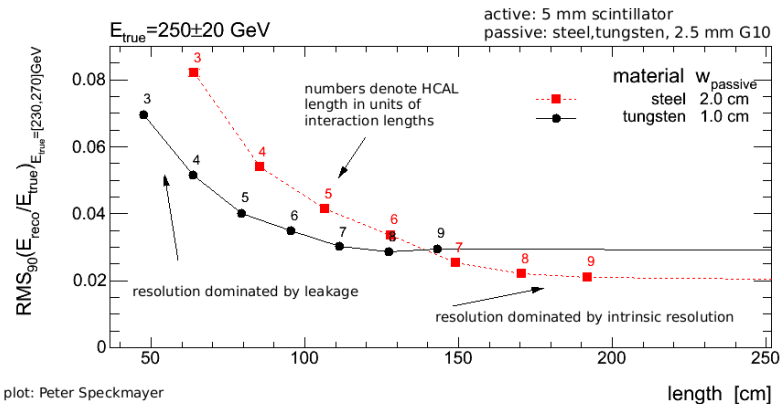
First tests end of 2011

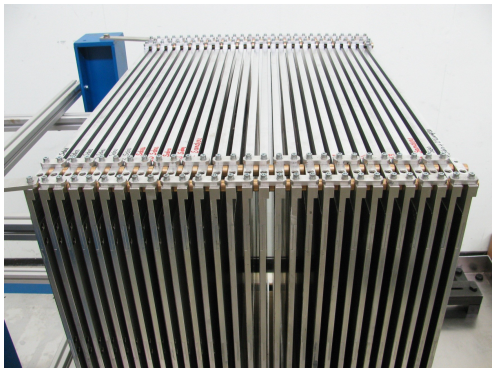
After that test of long detector slab and filling of module

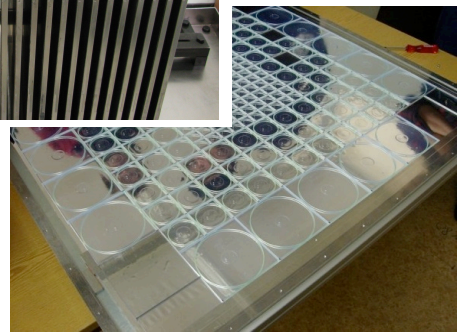


High energy

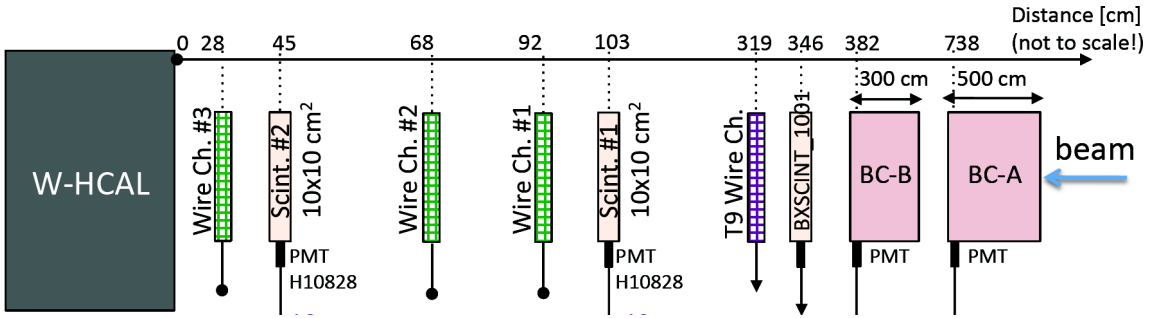
- Particle flow also a promising option for CLIC energies
- Leakage expected to limit PFLOW performance
  - need 1 λ ECAL + 7 λ HCAL
- Tungsten absorber cost-competitive with larger coil - and less risky
- Test beam validation with scintillator and gas detectors
- More neutrons:
  - different model systematics
  - timing measurements



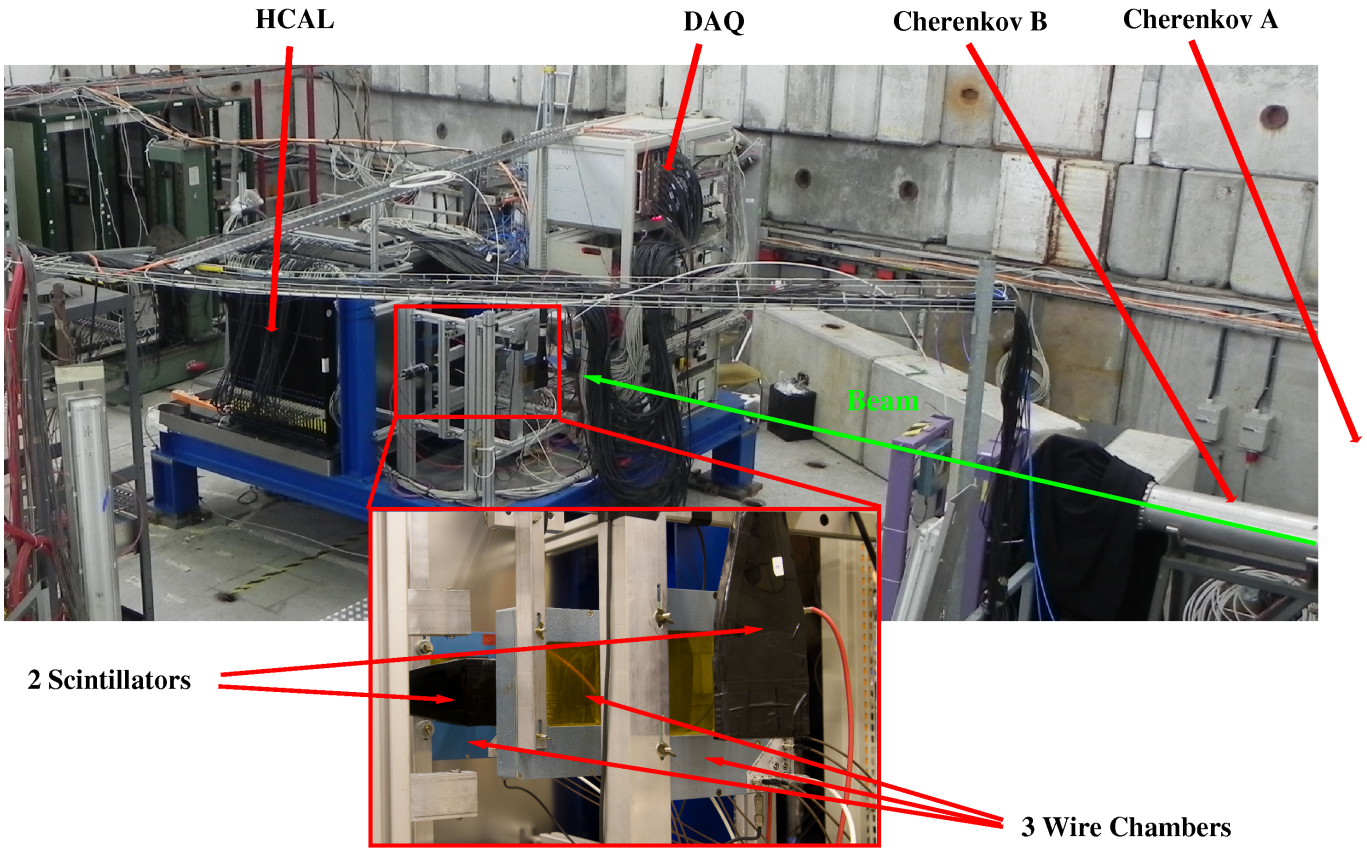




Test Beam Setup

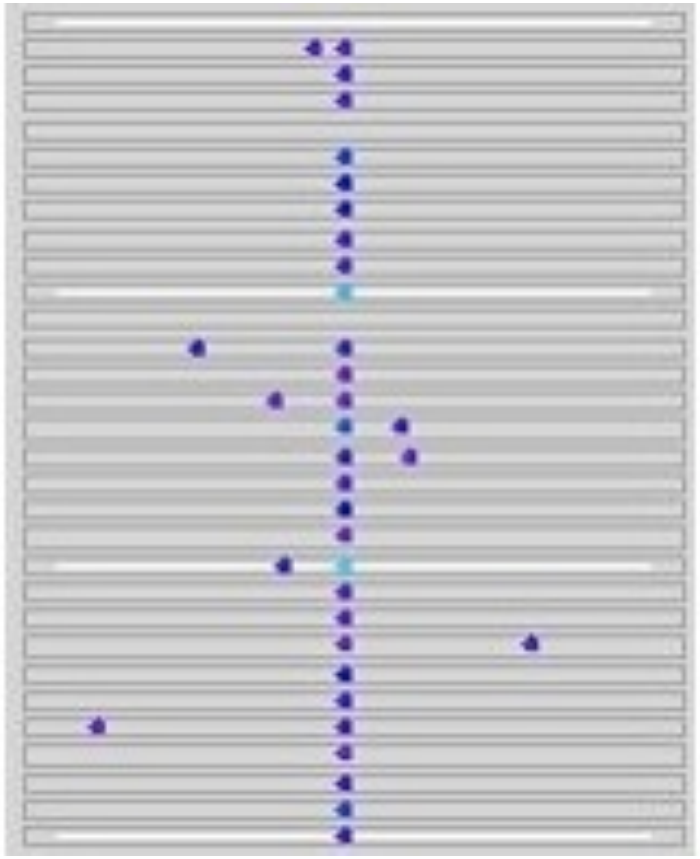


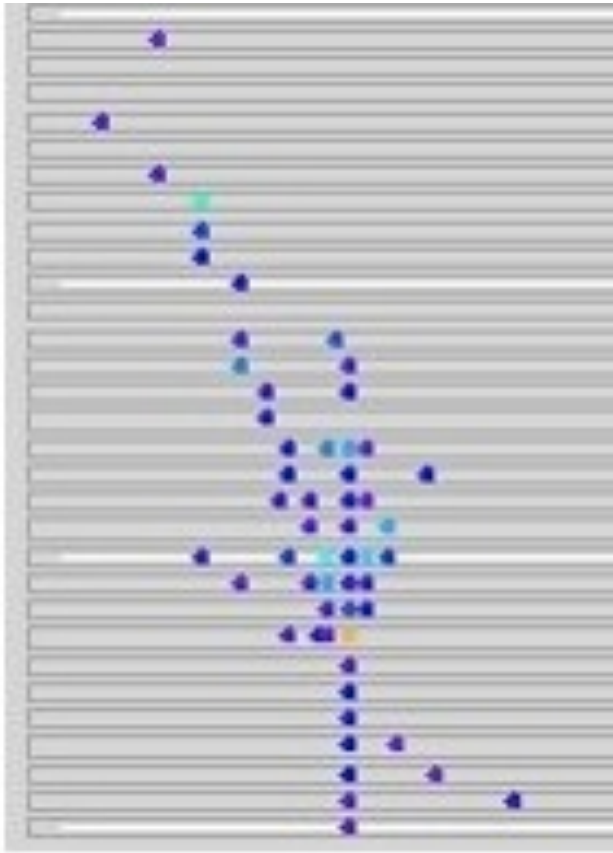
Trigger= coincidence of Scinti #1 and #2



First Results: Particle ID

ALL PLOTS VERY PRELIMINARY





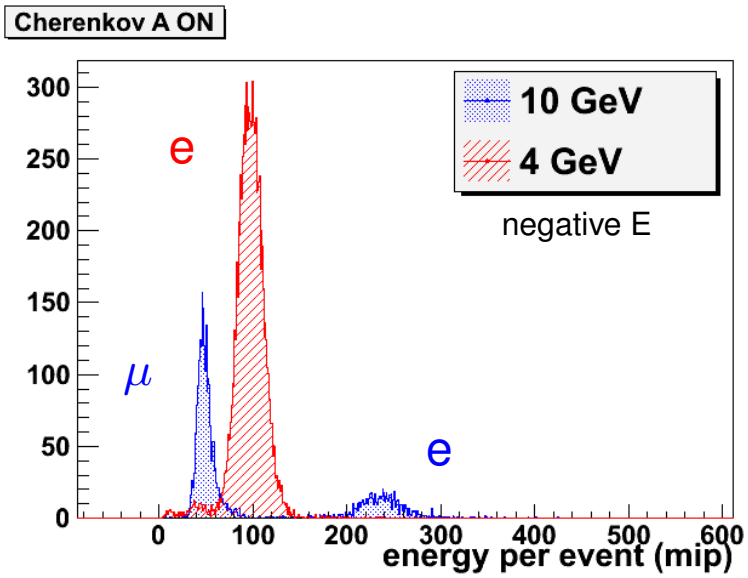
Electron

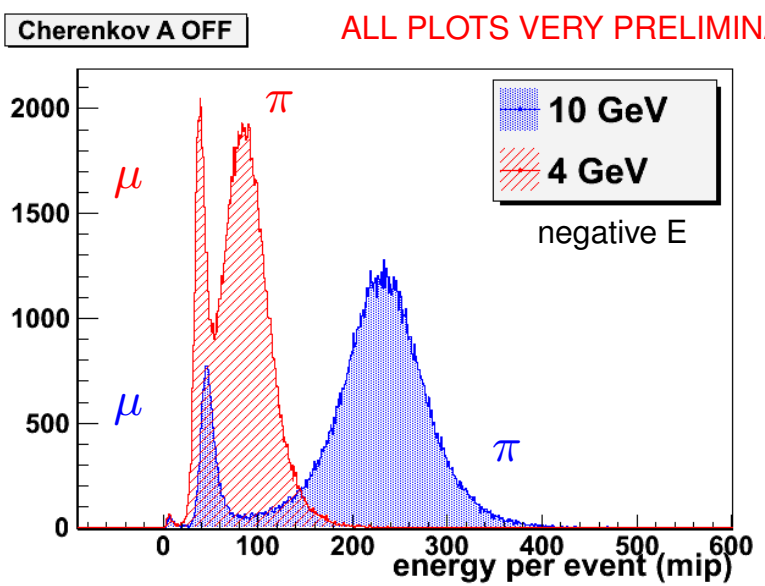
Muon

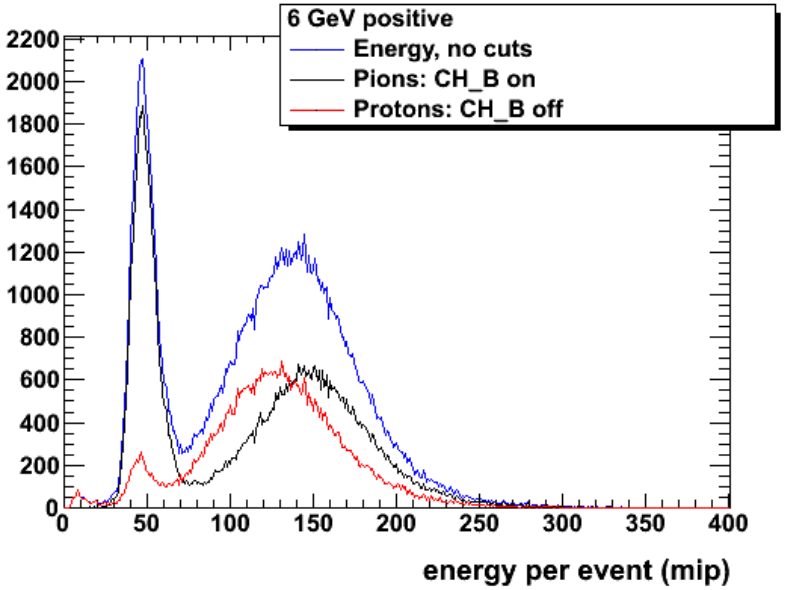
Pion [8 GeV]

Cherenkovs better

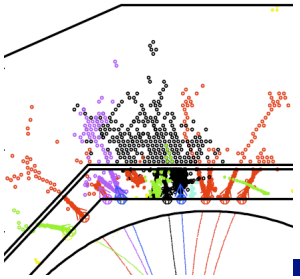
First Results: Particle ID





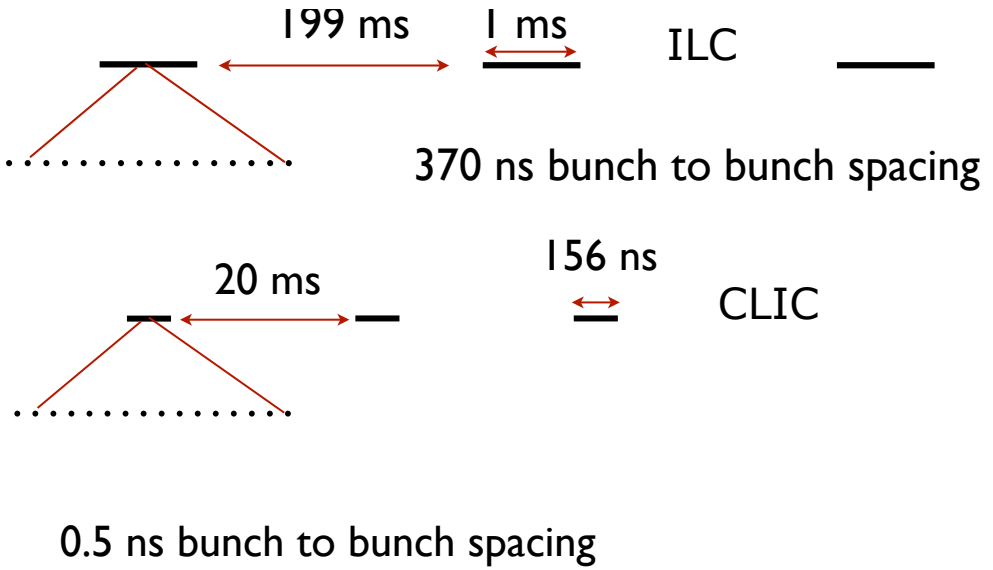


- Ch. A at low pressure (0.2 bar) to ID electrons
- Ch. B at higher pressure (3 bar) to distinguish between pions and protons
- Separation better at higher energy, also efficiency of Cherenkovs better



Timing, occupancies

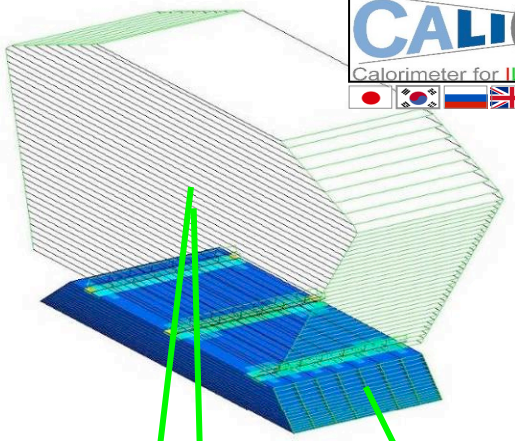
- Both ILC and CLIC have low duty cycle
  - power pulsing
  - trigger-less readout
- Occupancy in e+e- small
  - typically 10^{-4}
- Pile-up becomes an issues at CLIC
  - hadronic $\gamma\gamma$ events
  - peaks in endcaps
  - needs time-stamping
    - 10 ns accuracy



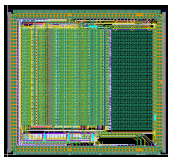
Second generation ASICs for EUDET

- Add auto-trigger, analog storage, digitization and token-ring readout !!!
- Include power pulsing : <1 % duty cycle
- Optimize commonalities within EUDET (readout, DAQ…)
- Dedicated run produced in march 2010
  - 25 wafers received in june (<1€/ch)
  - Plastic packaging in the US

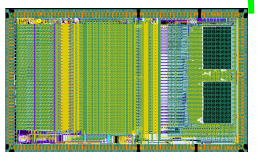
FLC_PHY3 (2003)



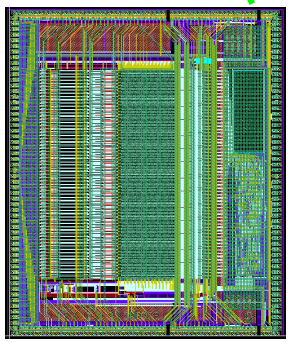
HARDROC2
SDHCAL RPC
64 ch 16 mm²



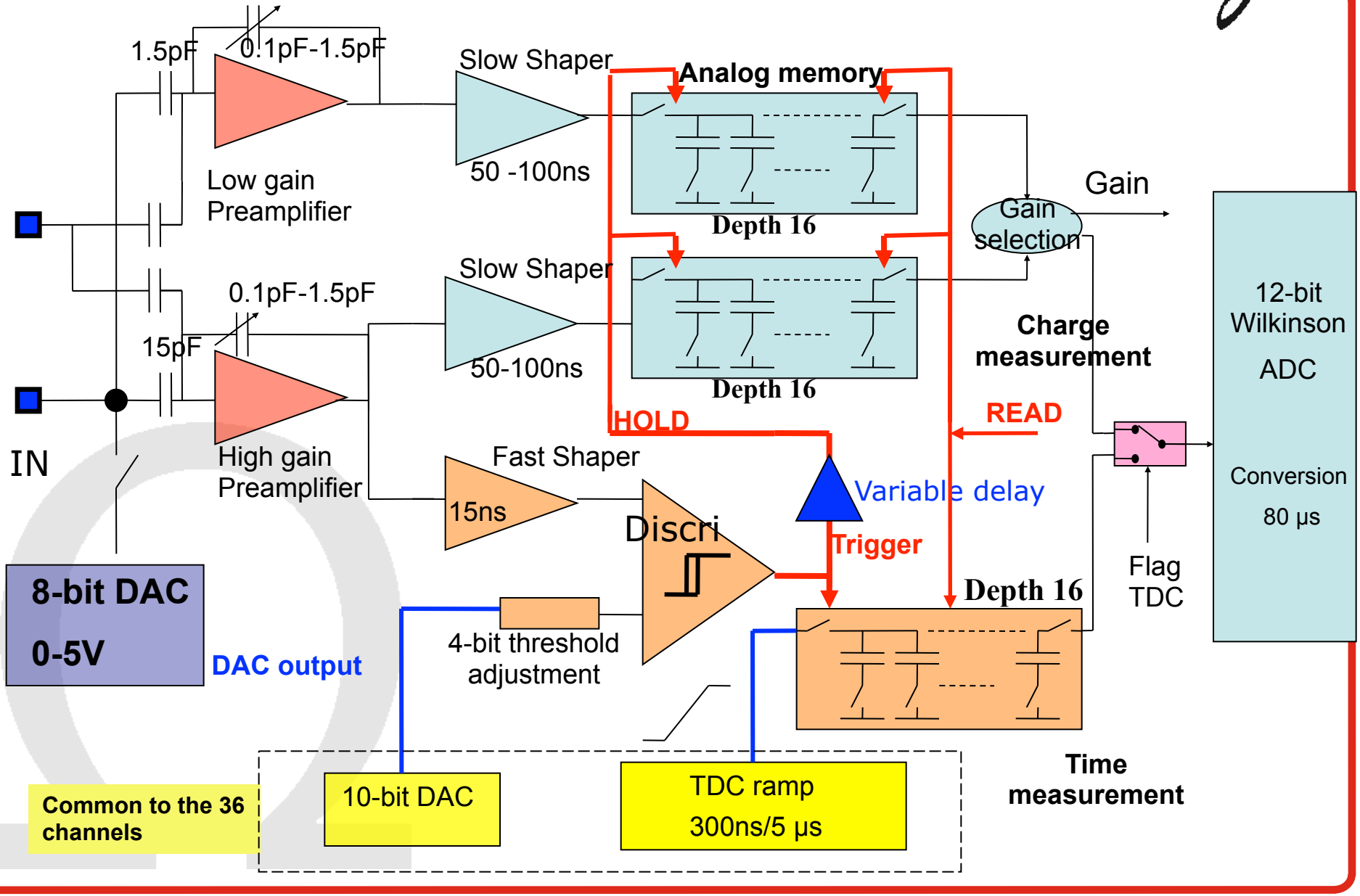
SPIROC2
AHCAL SiPM
36 ch 30 mm²

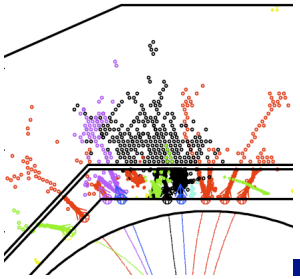


SKIROC2
ECAL Si
64 ch. 70 mm²



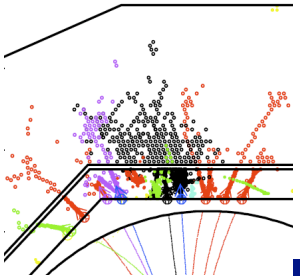
SPIROC : One channel schematic





Summary on technologies

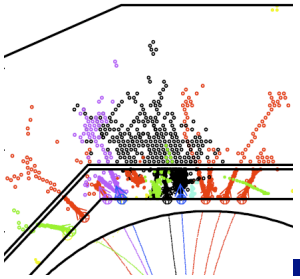
- a leap in several orders of magnitude in channel count
- new sensor technologies, new integration concepts
  - the latter is part of the feasibility demonstration
- progress towards realism:
  - realistic designs
  - realistic simulations
  - realistic cost
  - realistic proposal
- Digital calorimetry ready for exploration



Conclusion

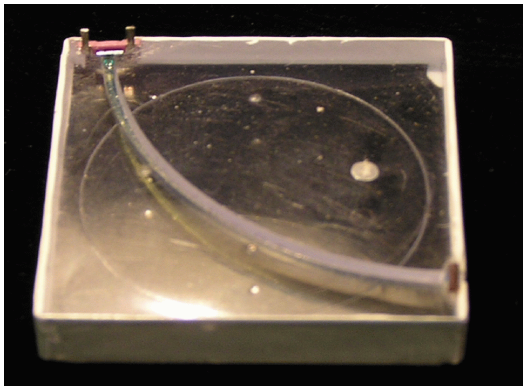
- Particle flow calorimetry does not solve the inherent problems of hadron calorimeters
- But it holds the promise of providing a highly performant work-around
- Focussed program: thrust is in
  - completing the large scale physics tests for all active and passive media
  - demonstration of integration feasibility
- Looking forward: Increased test beam activity 2011-12

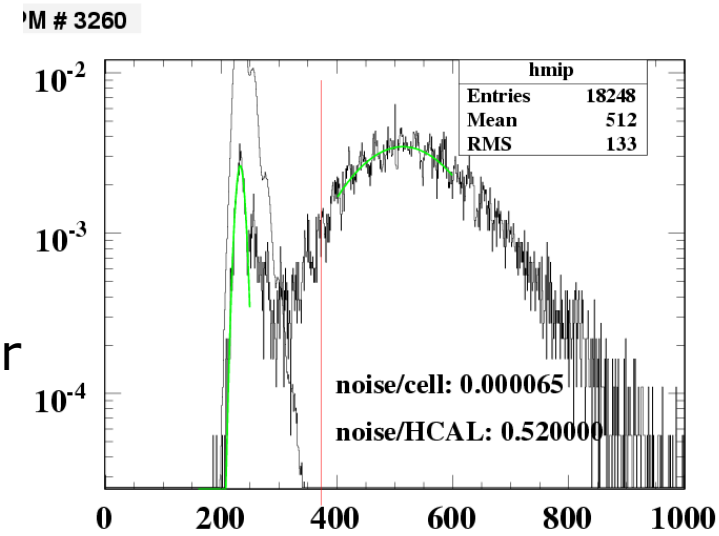
Back-up slides

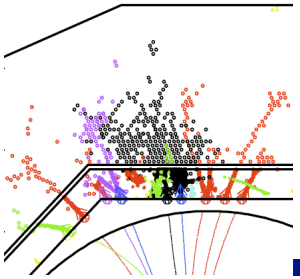


Present test beam system

- Tiles 3x3x0.5 cm^3, 1 mm Kuraray WLS fibre
- 7608 SiPMs from MEPhI/PULSAR
  - 1156 pixels, gain ~ 5e6, dark rate <3 MHz
  - light yield 15 px/MIP nominal ~13 in practice
- Critical parameter: Noise above threshold
  - 3kHz at ½ MIP
    - Depends on dark rate, Xtalk, effic.
  - Occupancy 1e-3, just OK
  - Requires careful bias setting
  - Want factor 10 less for ILC
  - And more operational safety
- Dynamic range: OK; the more the merrier
- Temperature sensitivity: G 2%, A 5%; should not increase

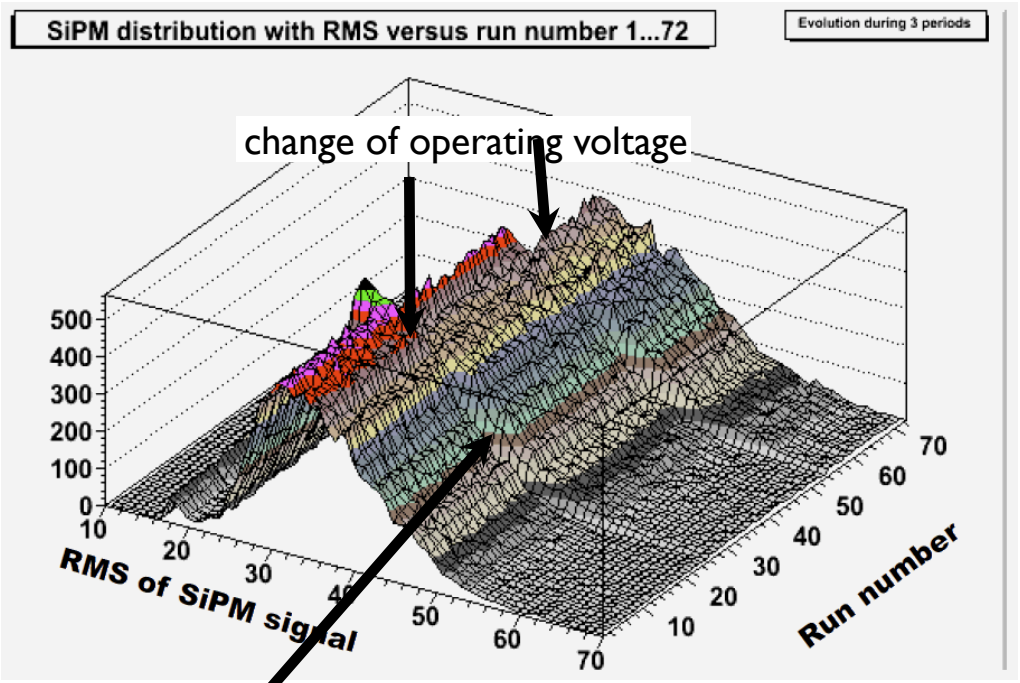






Long-Term Stability

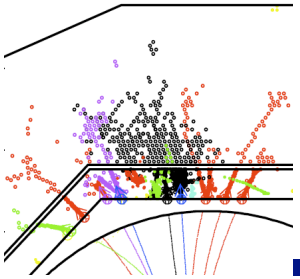
- Monitoring of pedestal distribution to detect changes in status and potential aging



intercontinental move: CERN to FNAL

stable performance over long period CERN – FNAL 2007-08

small increase of dead channels (total < 3 %, bad solder)



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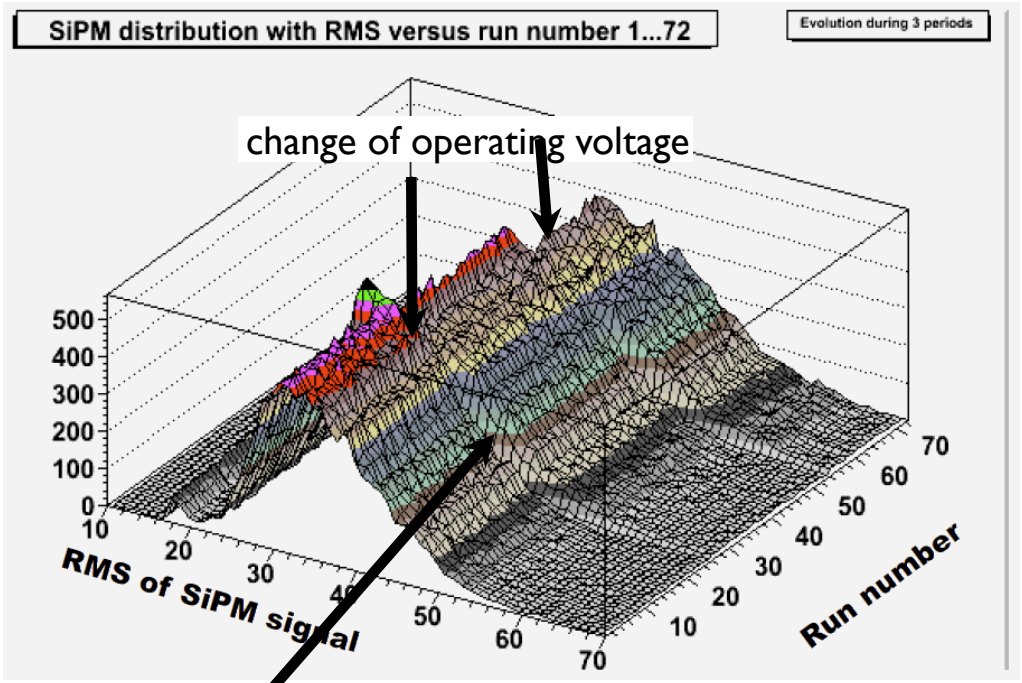

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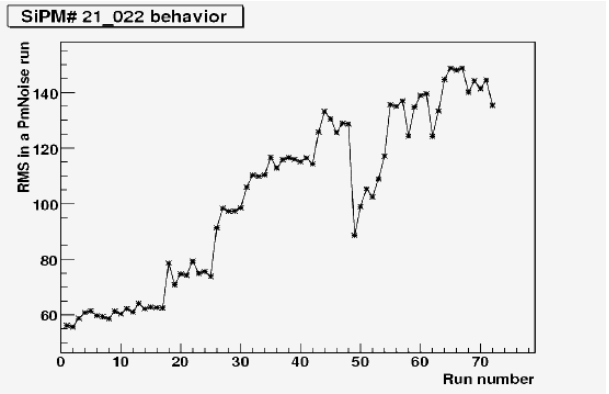
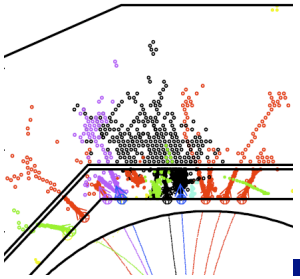


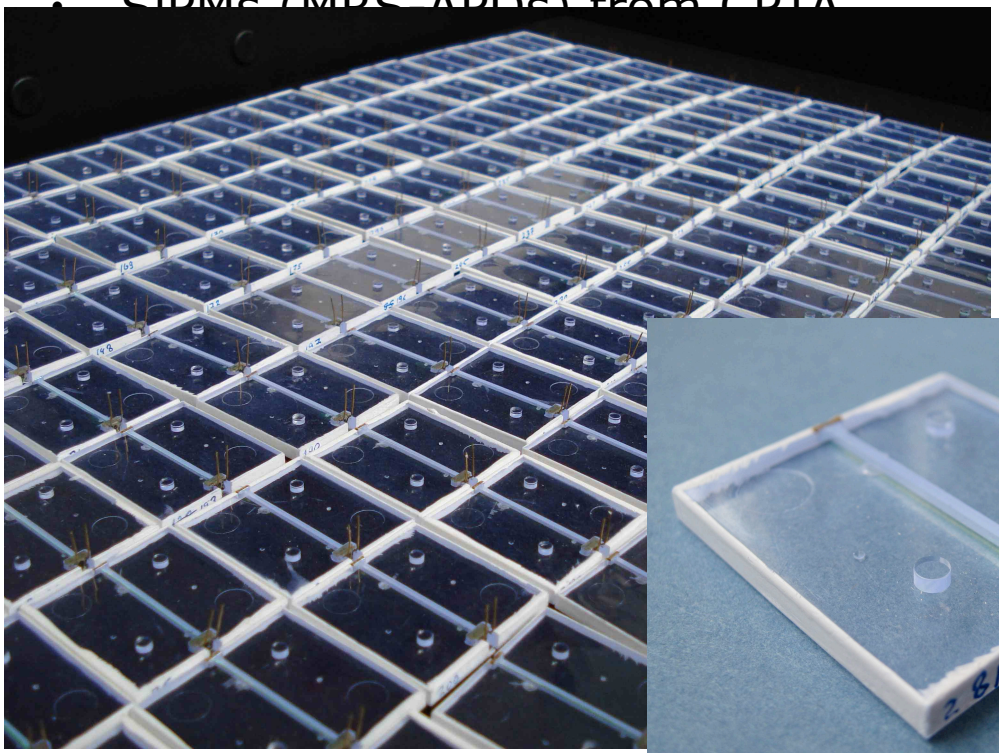
only 8 out of 7608 SiPMs show increasing noise levels with time

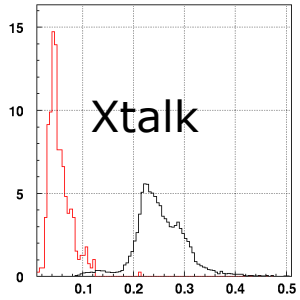


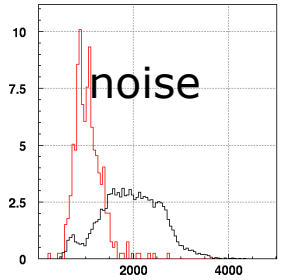
New tiles and SiPMs

- First 144 tiles from ITEP
  - Larger set underway for 2m layer
- SiPMs (MRS APDs) from CPTA

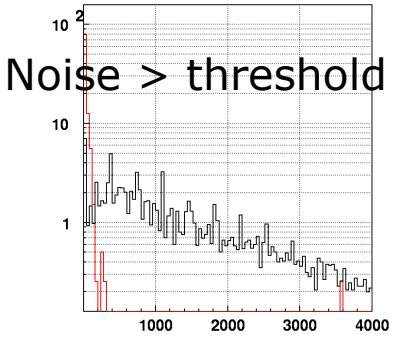
Improved properties w.r.t. PPT SiPMs

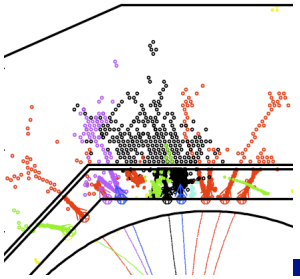






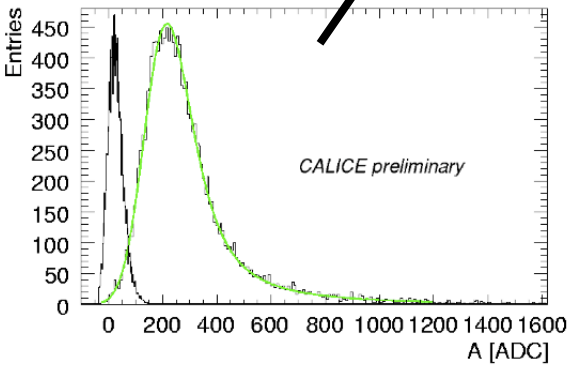
ITEP



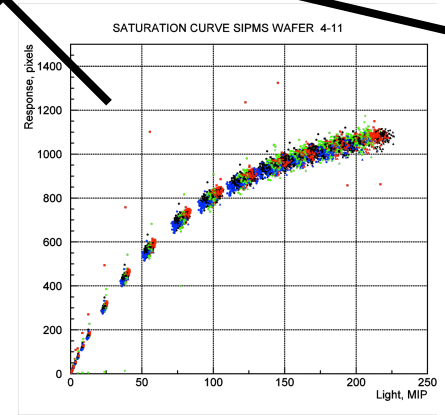


Calibration

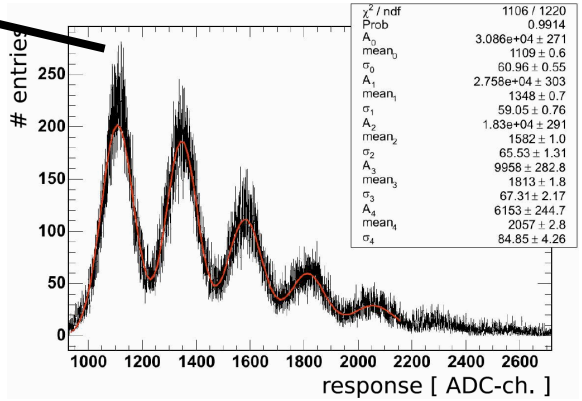
- $E(MIP) = A / A_{MIP} * f(A/A_{pixel})$ A = signal in ADC counts



MIP calibration:
1.5 days in test beam

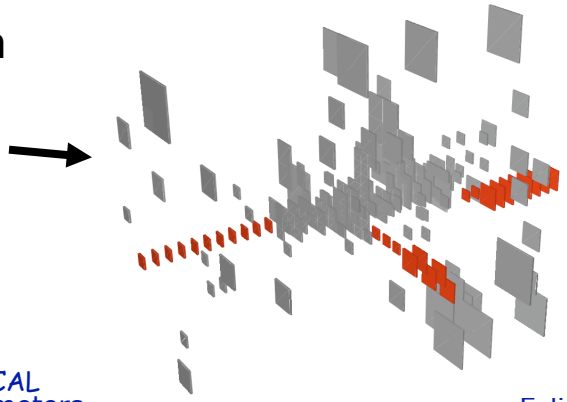


SiPM response function
From test bench

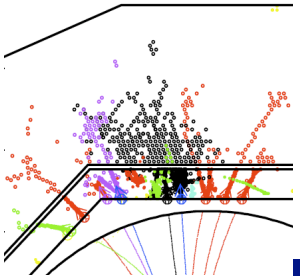


Gain auto-calibration:
Low intensity LED light
Single photo-electrons

At LC: use tracks in
hadron showers



Temperature monitoring:
Correct MIP and gain
Future: compensate by HV
adjustment

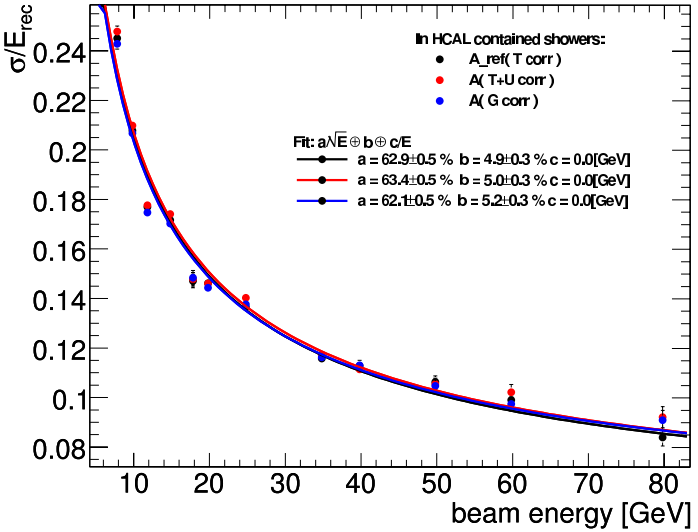


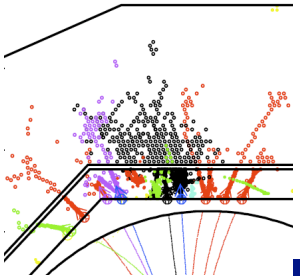
Calibration

- Study triggered by review of LC detector LOI
- Can you calibrate millions of channels and maintain stability?
  - not really a worry for Si, but could be an issue for scintillator

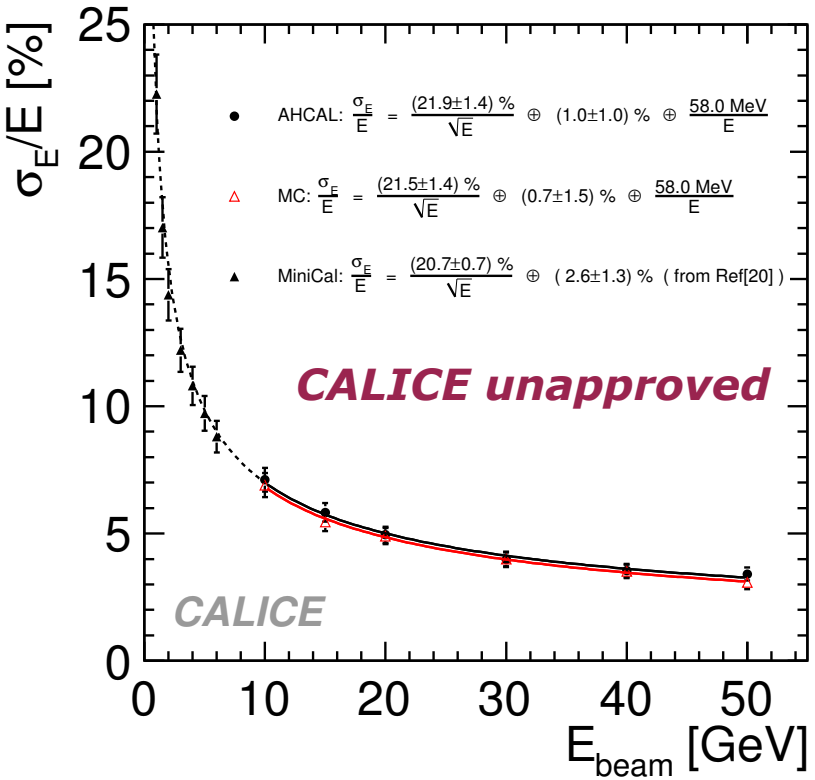
- 1. Simulate impact of statistic (uncorrelated) and systematic (correlated) calibration errors, find $\int L$ for in-situ calibration
  - PFLOW performance VERY robust w.r.t. channel-to-channel variations; coherent effects easy to control

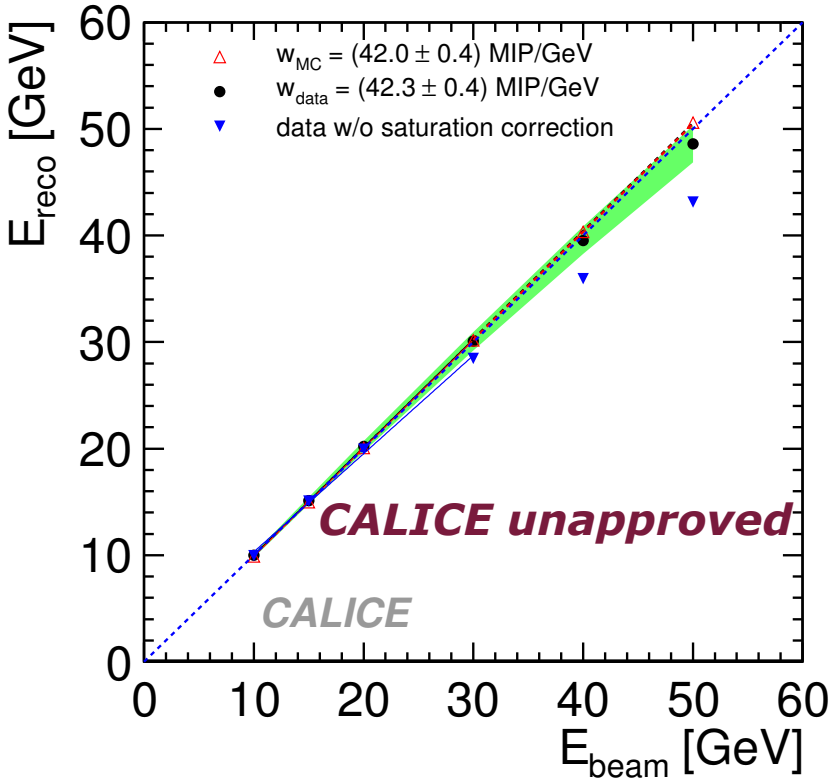
- 2. Exercise in-situ methods (SiPM auto-calib, track segments) with test beam data from CERN and FNAL
  - transport calibration across the ocean and restore performance



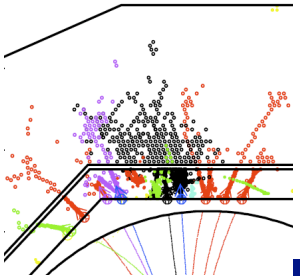


SiPM calo with electrons



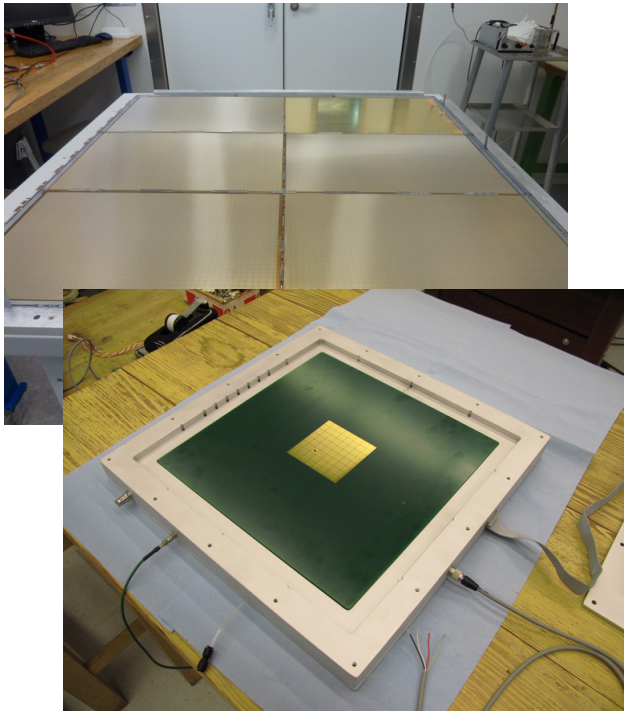


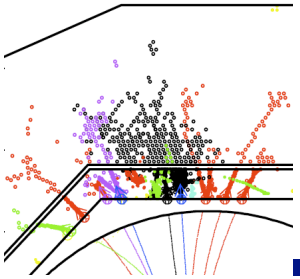
- validates detector understanding and linearity for hadrons



(S)DHCAL options

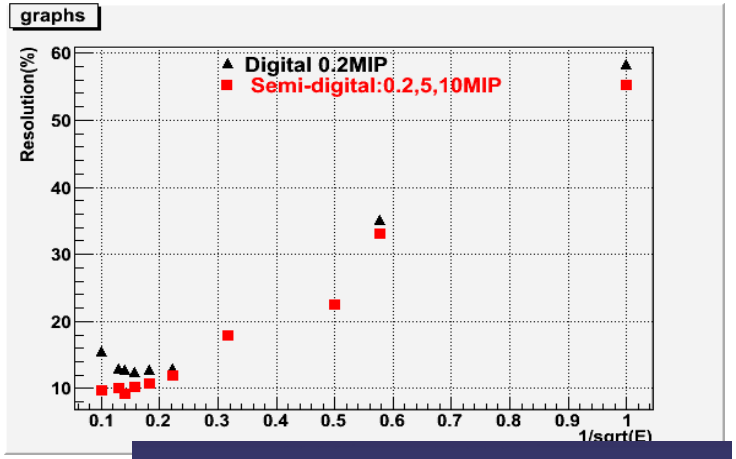
- Micromegas
  - 1m2 built
  - new ASIC MicroROC
  - parasitic test with W in 2010
- GEMs
  - moving to larger area modukes with KPix chips
  - beam tests 2010-11
- Most likely no full scale hadron tests, but addressing the critical integration issues





Semi-digital GRPC HCAL

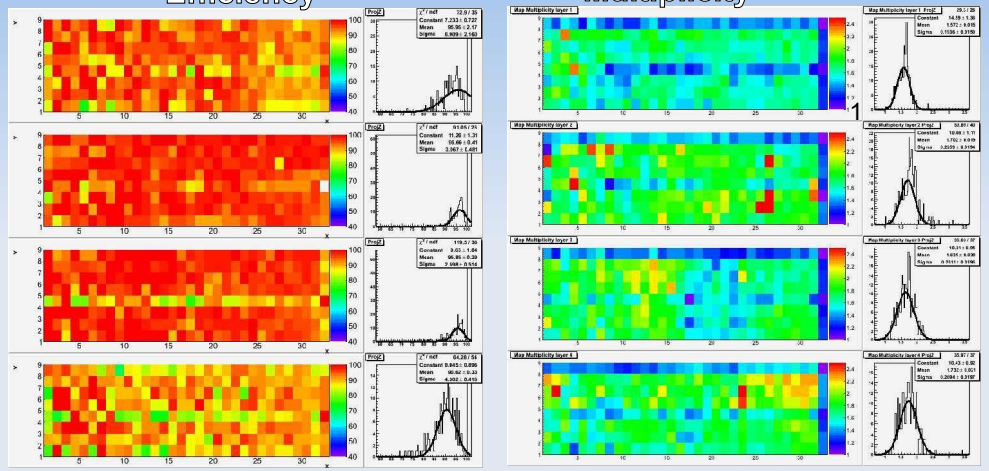
- idea: recover high energy resolution
- aim at cubic-metre ~ 2011
- will need stage at some point
- 3 layers built

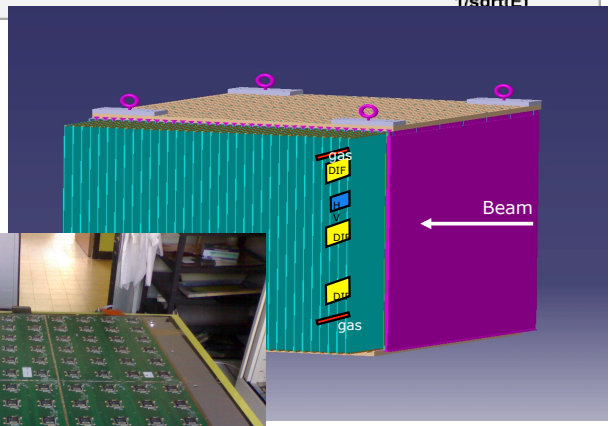


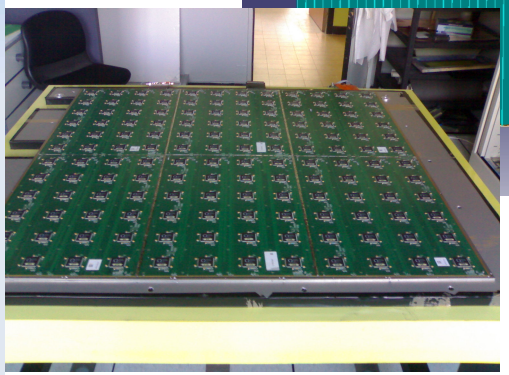
Uniformity of response

CALICE Calorimeter for ILC

Efficiency Multiplicity







- Full train reconstruction (→ ×10 in statistics)
- Global *efficiency* spread (⊃ statistics [25k evts] & defaults) ~ **3%**
- Multiplicity spread in a chamber ~0.2 (⊃ borders & fish line)
  - ≤3% between chambers