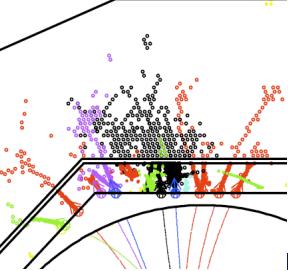


Particle Flow: A Calorimeter Reconstruction Exercise

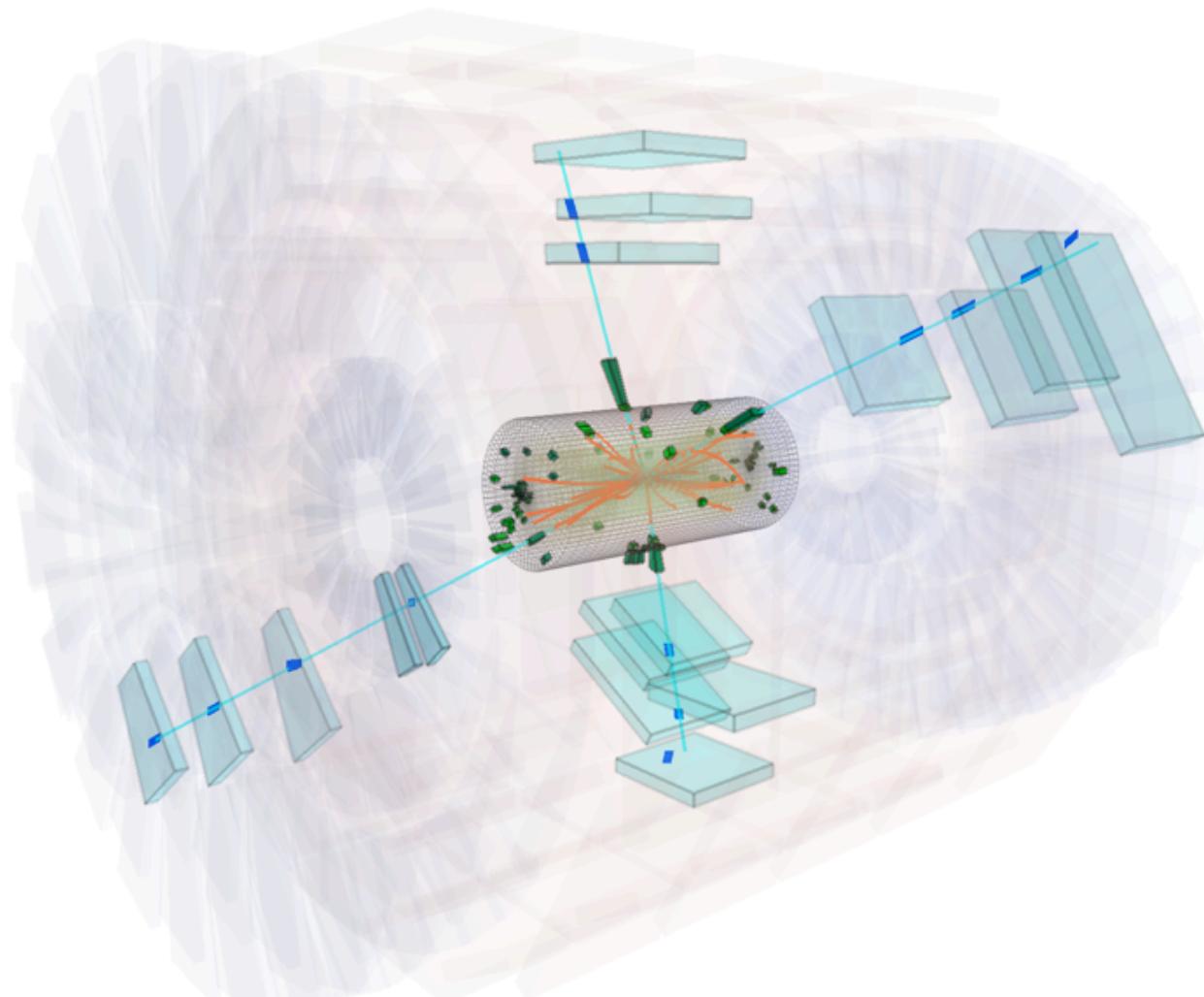
Felix Sefkow



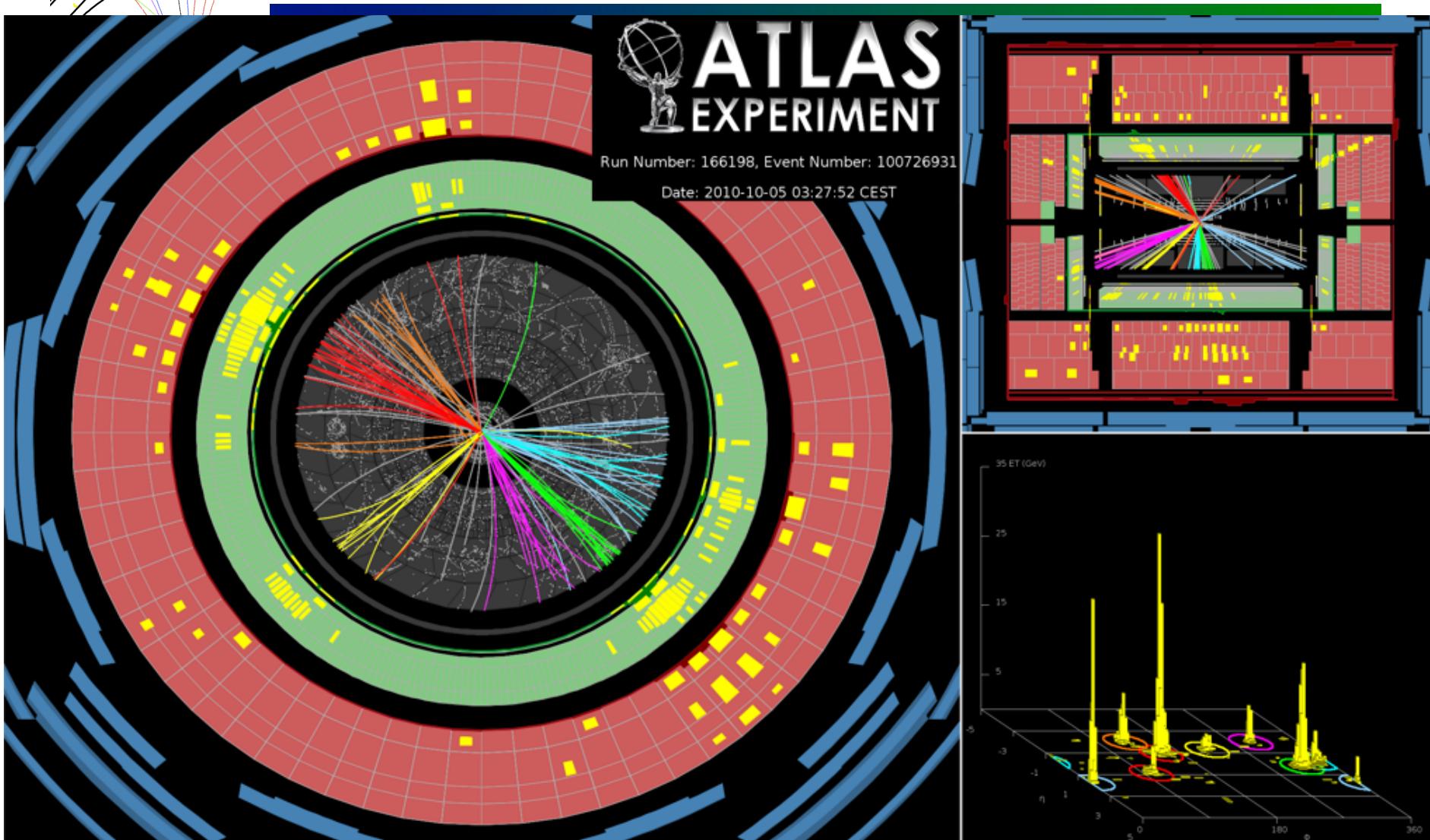
EDIT2010, CERN, Jan 31 - Feb 10, 2011

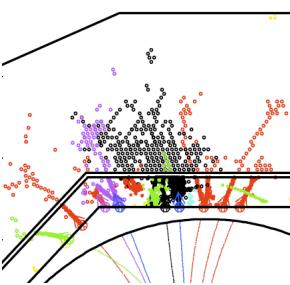


Celebrate detectors

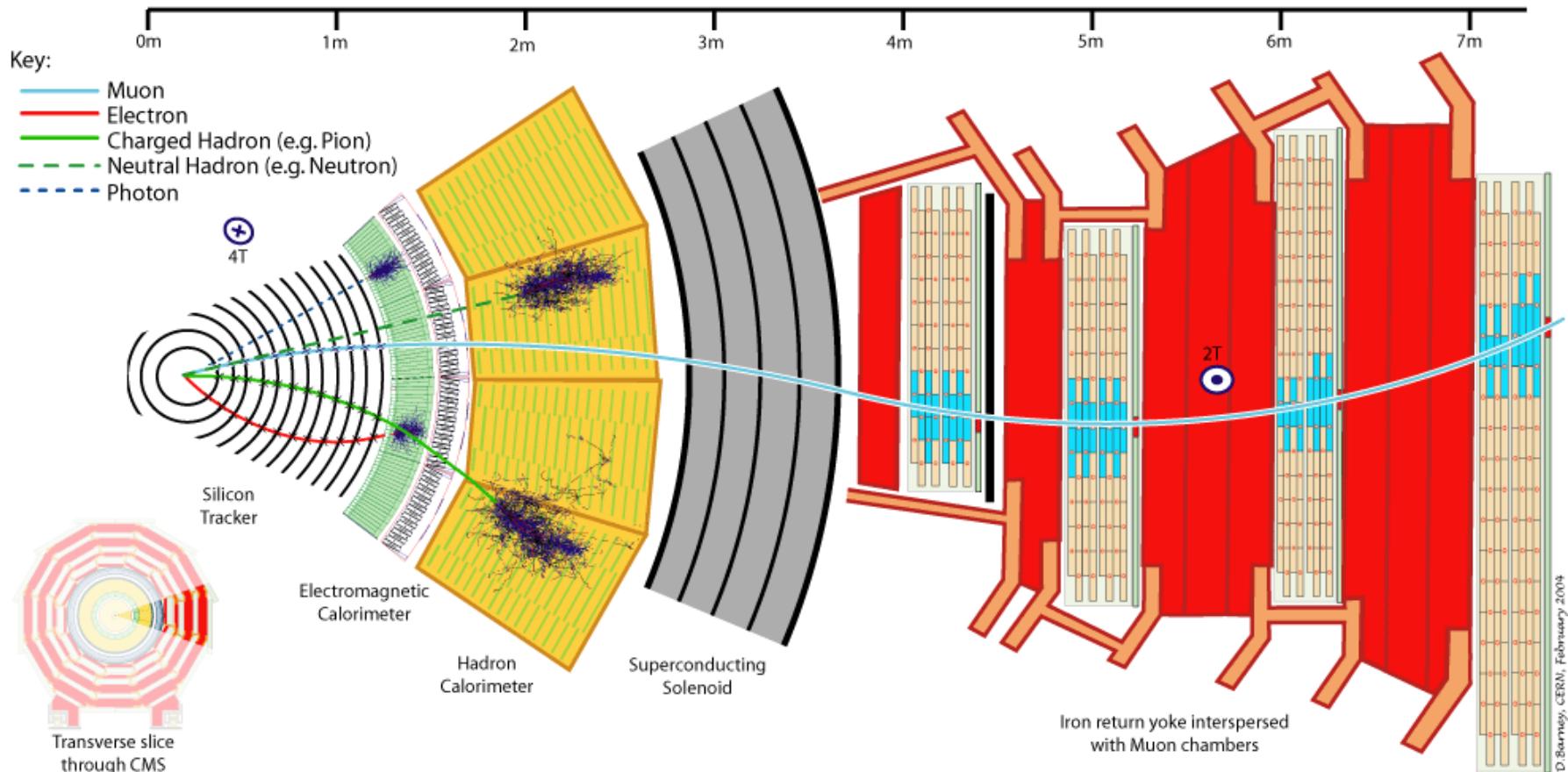


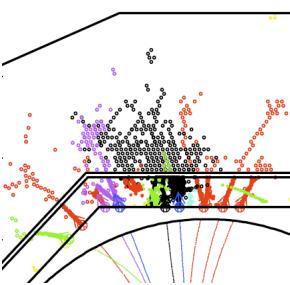
Celebrate detectors



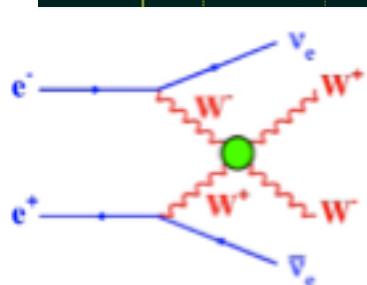
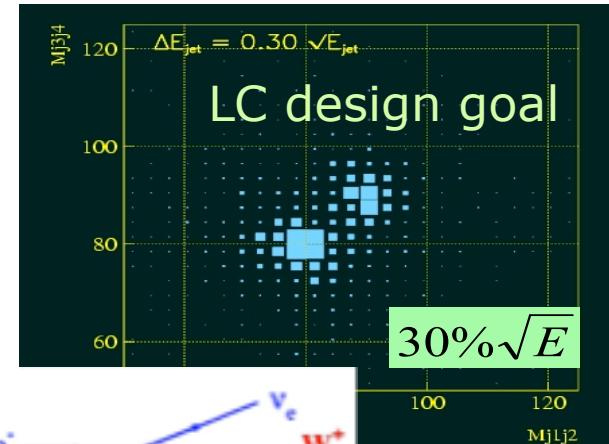
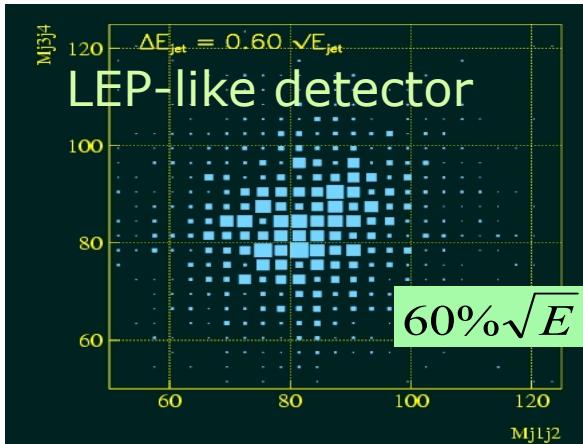
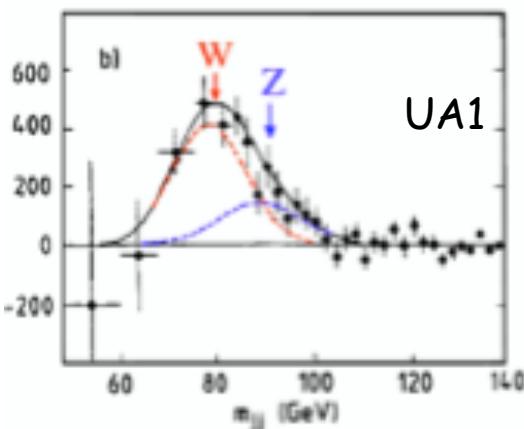


A generic collider detector

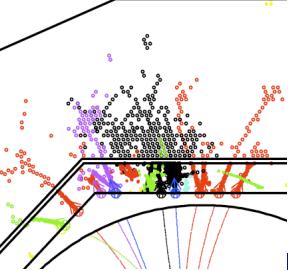




Challenge: W Z separation



- 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

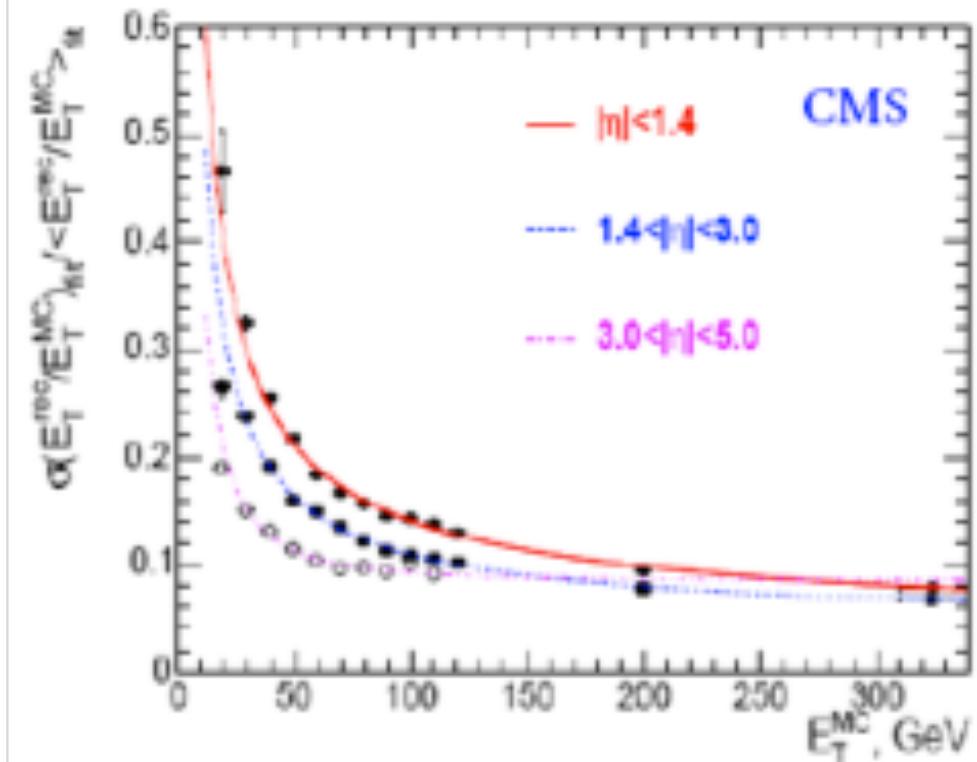
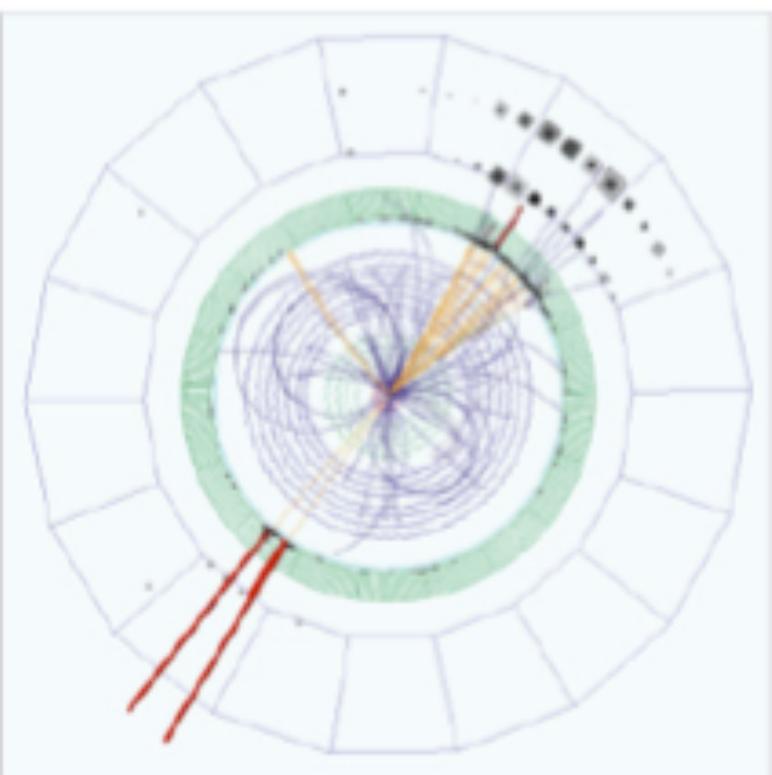


Outline

- Introduction:
 - intrinsic difficulties with hadron calorimetry
- The Particle Flow concept
- Calorimeters for particle flow
- The EDIT exercise

Recall some basics
see Richards lecture

Jet energy resolution



> 100 % / \sqrt{E}

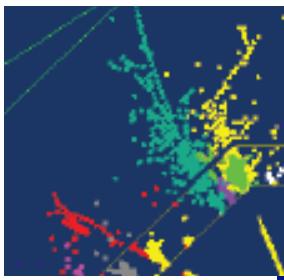
Electrons:

$$\frac{\sigma(E)}{E} = \frac{2.4\%}{\sqrt{E}} \oplus \frac{142 \text{ MeV}}{E} \oplus 0.44\%$$

0.6% at 50 GeV.

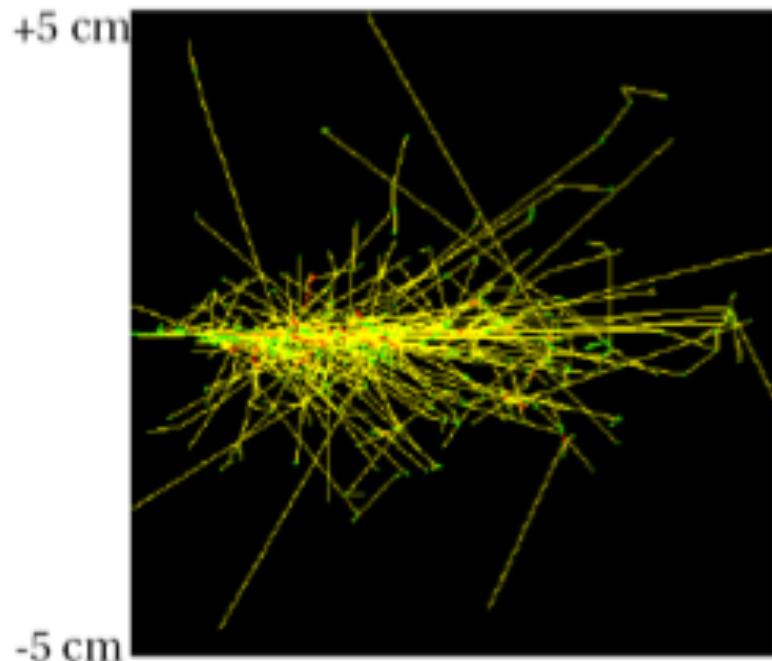
ECAL+HCAL energy resolution for pions:

$$\frac{\sigma(E)}{E} = \frac{127\%}{\sqrt{E}} \oplus 6.5\%$$



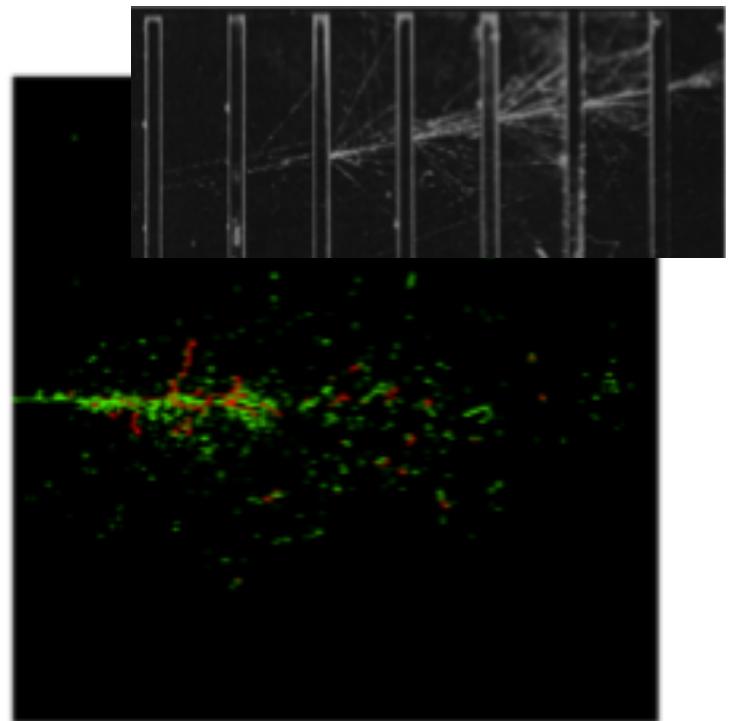
Electromagnetic showers

- Simulation: 1 GeV electron in lead

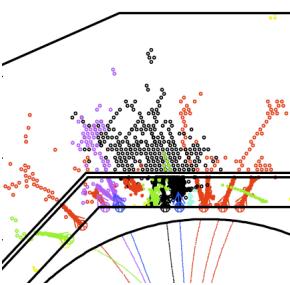


photons
electrons
positrons

Lead absorbers in cloud chamber

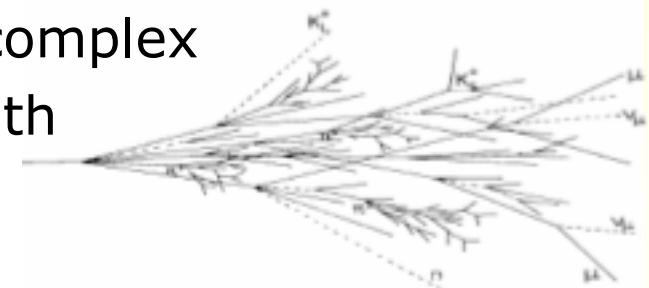


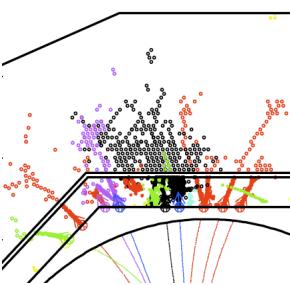
electrons
positrons



Hadron showers

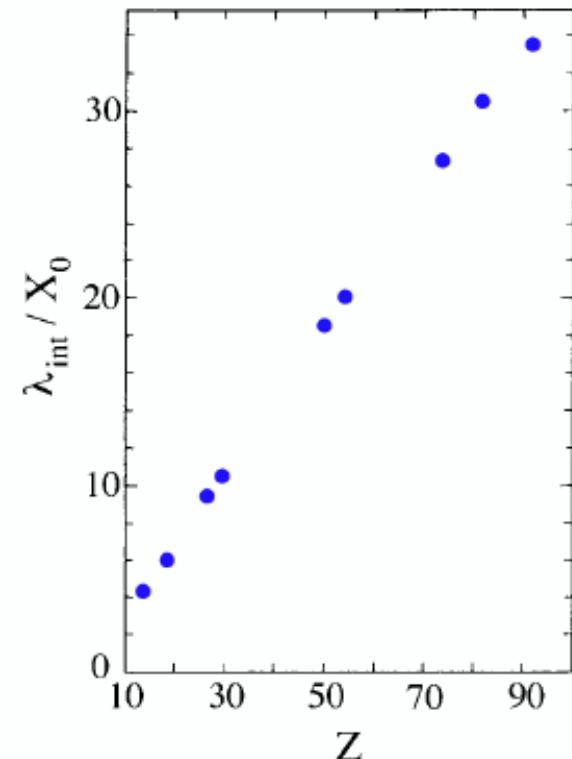
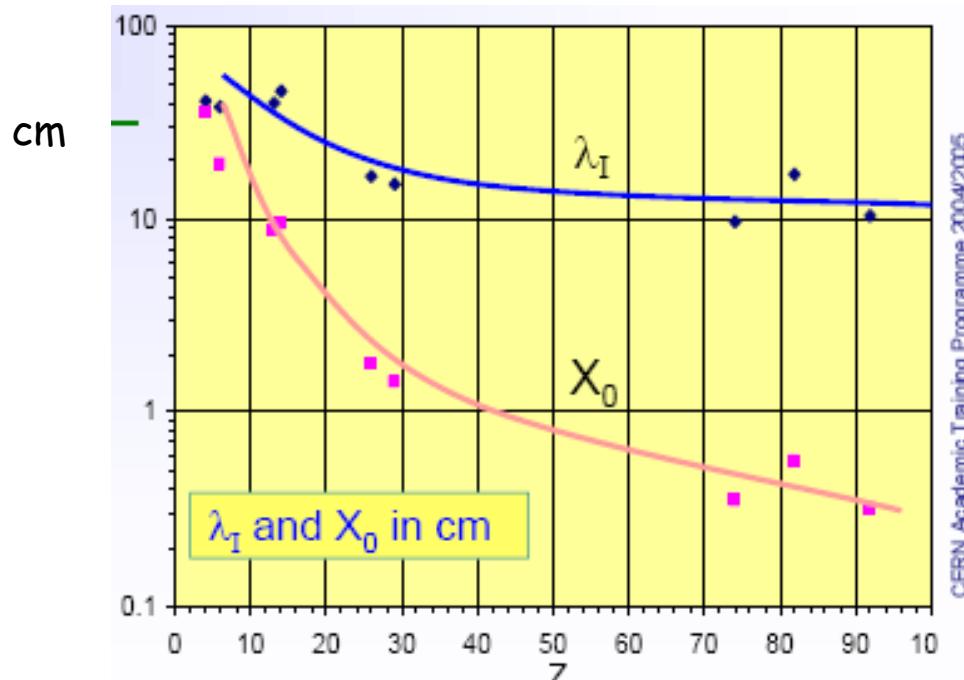
- Hadrons undergo strong interactions with detector (absorber) material
 - Charged hadrons: complementary to track measurement
 - Neutral hadrons: the only way to measure their energy
- In nuclear collisions numbers of secondary particles are produced
 - Partially undergo secondary, tertiary nuclear interactions → formation of hadronic cascade
 - Electromagnetically decaying particles initiate em showers
 - Part of the energy is absorbed as nuclear binding energy or target recoil and invisible
- Similar to em showers, but much more complex
- Different scale: hadronic interaction length

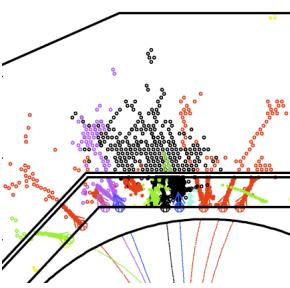




Hadronic interaction length

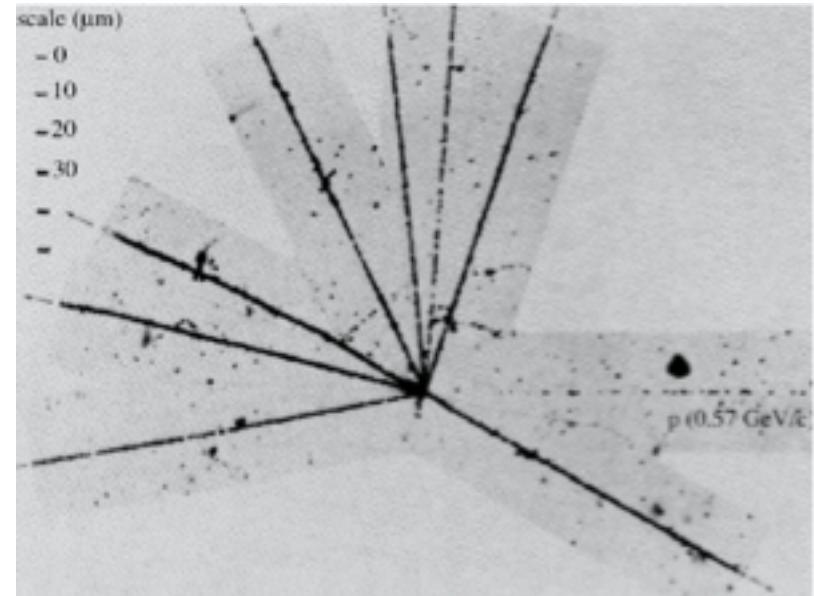
- λ_I : mean free path between nuclear collisions
- Hadron showers are much larger – how much, depends on Z
- Both scales present in every hadron shower

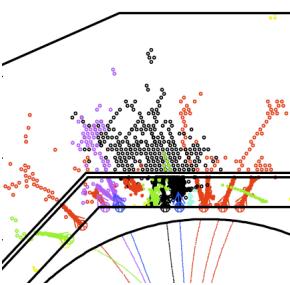




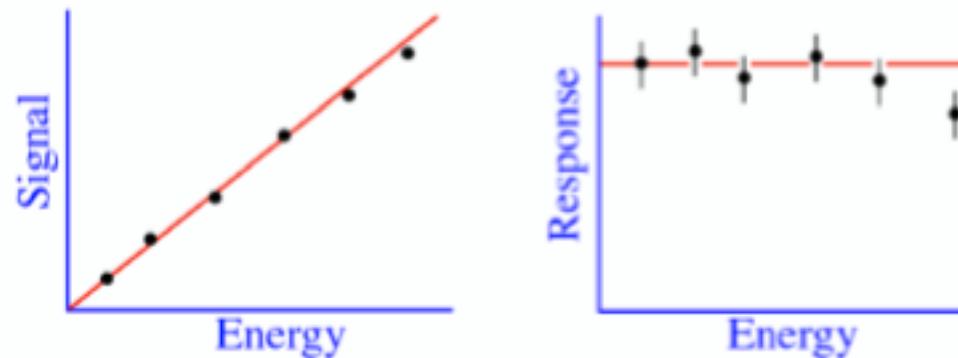
Hadronic interactions

- 1st stage: the hard collision
 - Multiplicity scales with E
 - $\sim 1/3 \pi^0 \rightarrow \gamma\gamma$
 - Leading particle effect: depends on incident hadron type,
 - e.g fewer π^0 from protons
- 2nd stage: spallation
 - Intra-nuclear cascade
 - Fast nucleons and other hadrons
 - Nuclear de-excitation
 - Evaporation of soft nucleons and α particles
 - Fission + evaporation

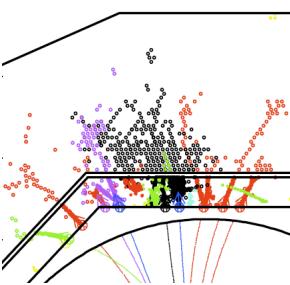




Response and linearity

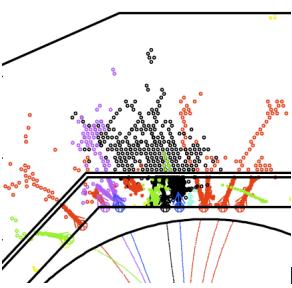


- A linear calorimeter has a constant response
- In general
 - Electromagnetic calorimeters are linear
 - Hadronic calorimeters are not:
 - Response depends on something which varies with energy
 - Em fraction, depth of interaction, leakage,
- No linearity – no superposition
 - 2 particles at 50 GeV not equal to 1 particle at 100 GeV
 - Non-linearity cannot simply be “calibrated away”



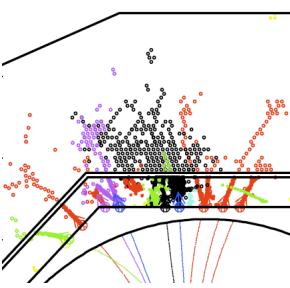
Electromagnetic fraction

- In first collision, $\sim 1/3$ of produced particles are π^0
- $\pi^0 \rightarrow \gamma\gamma$ produce em shower, no further hadronic interaction
- Remaining hadrons undergo further interactions, more π^0
- π^0 production irreversible; “one way street”
 - Em fraction increases with energy
- Numerical example for copper
 - 10 GeV: $f = 0.38$; 9 charged h, 3 π^0
 - 100 GeV: $f = 0.59$; 58 charged h, 19 π^0
- Cf em shower: 100's e^+ , 1000's e^- , millions γ
- Large fluctuations
 - E.g. charge exchange $\pi^+ p \rightarrow \pi^0 n$ (prb 1%) gives $f_{em} = 100\%$



Em and hadronic response

- The response to the hadronic part of a hadron-induced shower is usually smaller than that to the electromagnetic part
 - Due to the invisible energy
 - Due to short range of spallation nucleons
 - Due to saturation effects for slow, highly ionizing particles
- e : em response, h : hadronic response
- e/π : ratio of response to electron vs pion induced shower
- $$e/\pi = e / [f_{em} e + (1 - f_{em}) h] = e/h / [1 + f_{em} (e/h - 1)]$$
- Depends on E via f_{em} \rightarrow non-linearity
- Approaches 1 for $e/h \rightarrow 1$ or for $f_{em} \rightarrow 1$ (high energy limit)



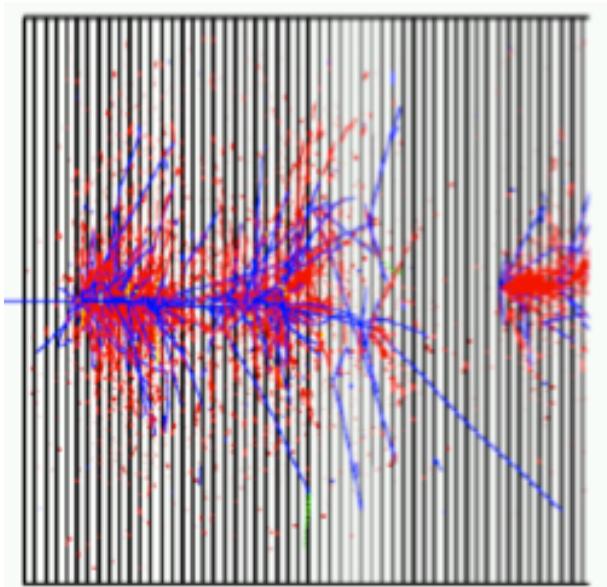
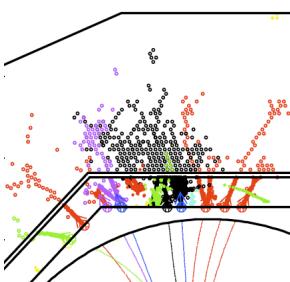
Compensation

Different strategies, can be combined

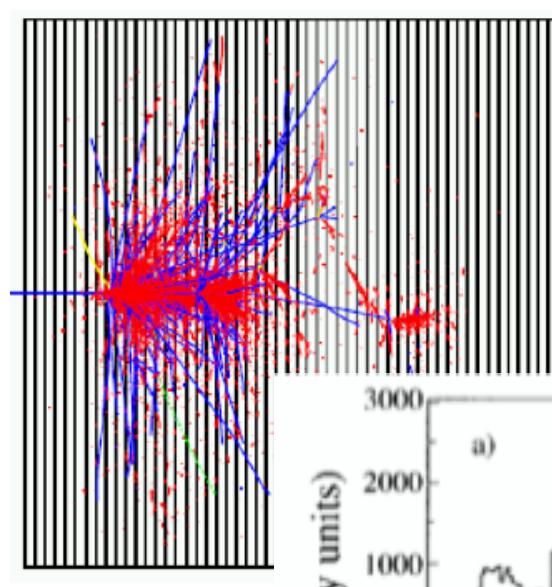
- Hardware compensation
 - Reduce em response
 - High Z, soft photons
 - Increase had response
 - Ionization part
 - Neutron part (correlated with binding energy loss)
 - Tuneable via thickness of hydrogenous detector
 - Example ZEUS: uranium scintillator, 45 % / \sqrt{E}
- Software compensation
 - Identify em hot spots and down-weight
 - Requires high 3D segmentation
 - Example H1, Pb/Fe LAr, $\sim 50\% / \sqrt{E}$

NB: Do not remove fluctuations in invisible energy

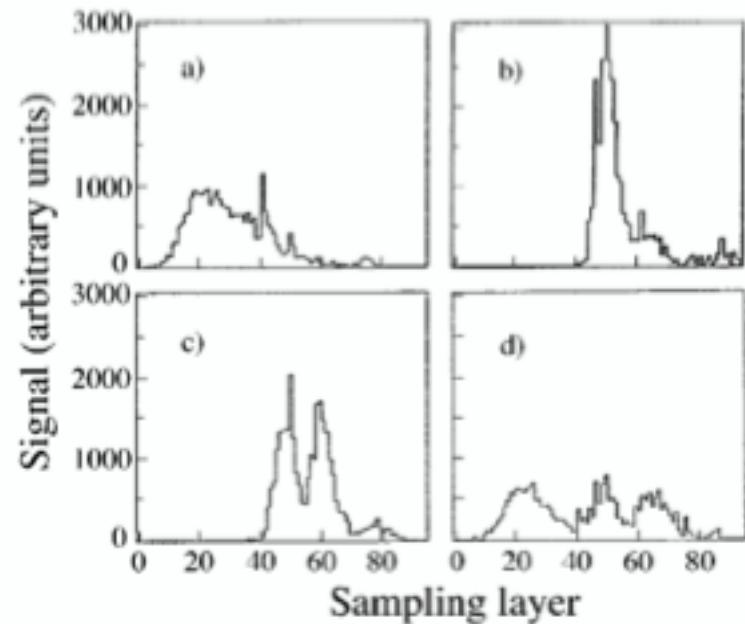
More fluctuations



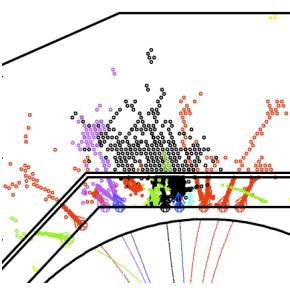
blue = hadronic component



red = electromagnetic component

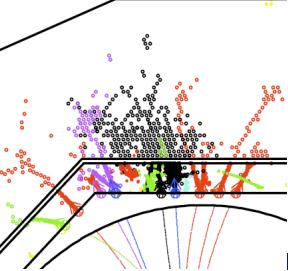


Leakage: in principle no problem
But: leakage fluctuations are!
(rule of thumb: $\sigma_{\text{leak}} \sim 4 f_{\text{leak}}$)



Hadron and jet calorimetry:

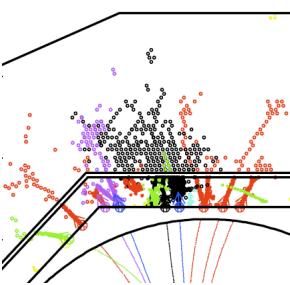
- Hadron showers: large variety of physics processes
 - With different detector responses
 - In general non-linear
 - Inevitably invisible energy; ultimate limit
 - Large fluctuations
 - Large volume, small signals
 - Difficult to model
- Jet energy performance = hadron performance or worse



New concepts

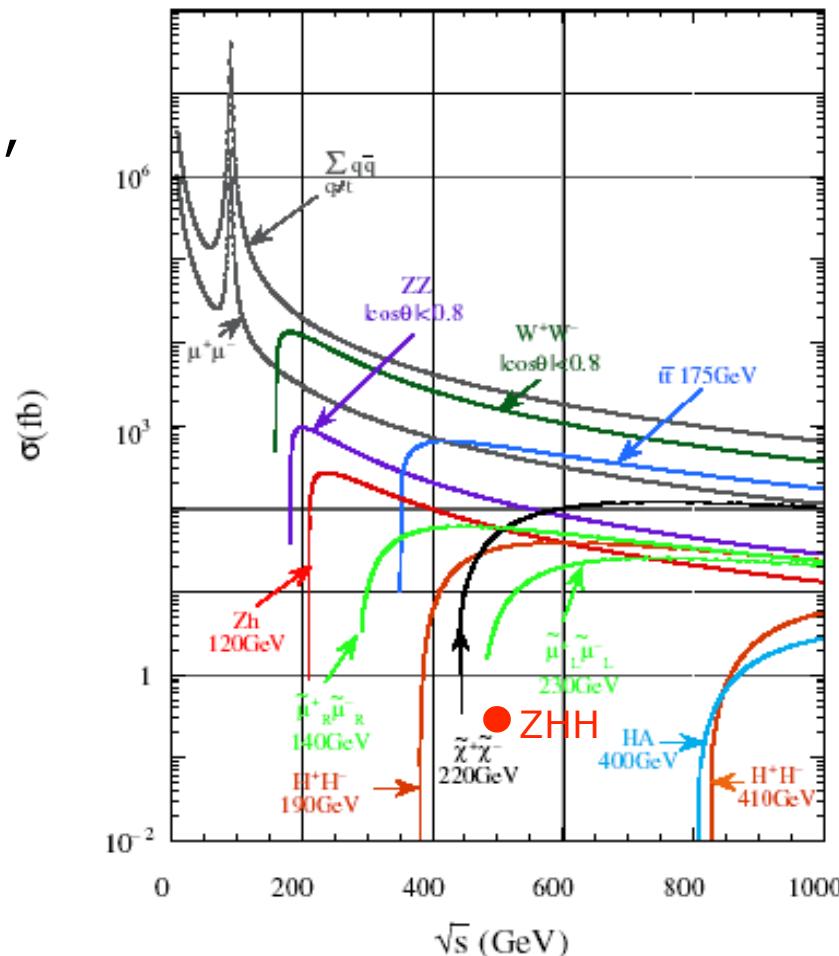
- Hardware (and software): ultimate compensation by directly measuring the electromagnetic component in each event, in addition to the total energy, and correcting for it
 - → dual readout calorimeters (scint and Cerenkov light)
- Software (and hardware): measure each particle in a jet individually and 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

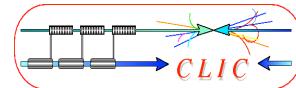
Particle flow concept and detectors



LC jet energies

- Q-Qbar events are boring
- $E_{jet} = \sqrt{s}/2$ is wrong
- Mostly 4-, 6-fermion final states,
 $ee \rightarrow ttH \rightarrow 8 - 10$ jets
- At ILC 500: $E_{jet} = 50...150$ GeV
 - Mean pion energy 10 GeV
- At ILC 1 TeV: $E_{jet} < \sim 300$ GeV
- At CLIC (3 TeV) $< \sim 500$ GeV
- W reconstruction with
- $\sigma_m/m = 2.5/91$
need $\sigma_E/E = 3.8\%$





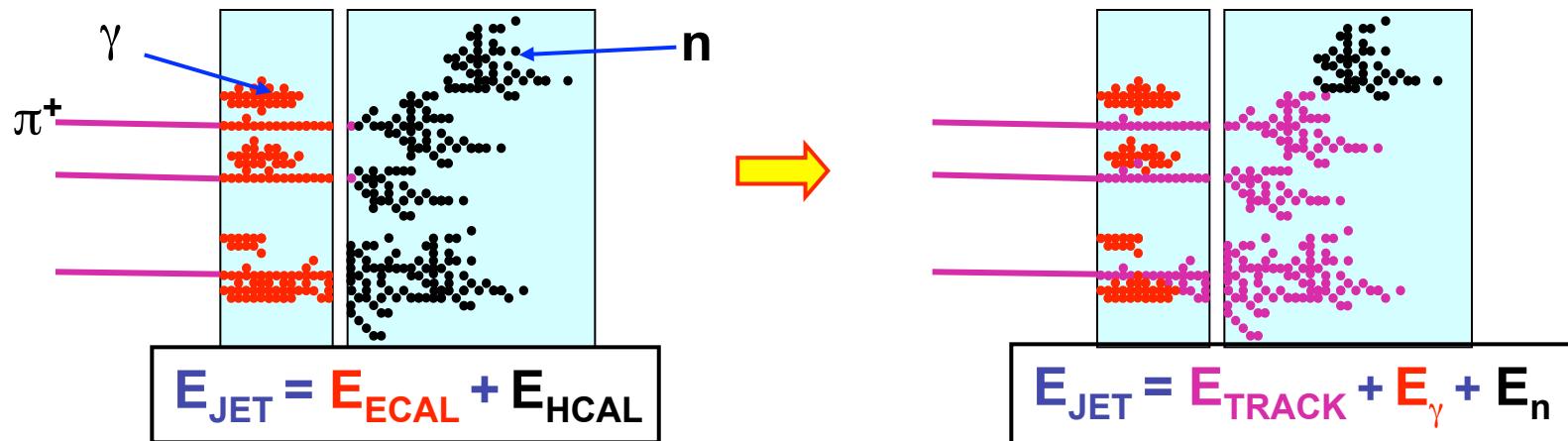
★ In a typical jet :

- ♦ 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)



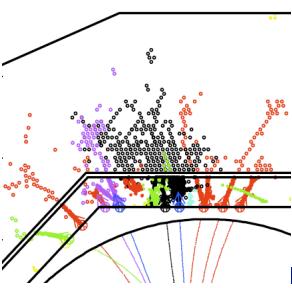
★ Traditional calorimetric approach:

- ♦ Measure all components of jet energy in ECAL/HCAL !
- ♦ ~70 % of energy measured in HCAL: $\sigma_E/E \approx 60\%/\sqrt{E(\text{GeV})}$
- ♦ Intrinsically “poor” HCAL resolution limits jet energy resolution



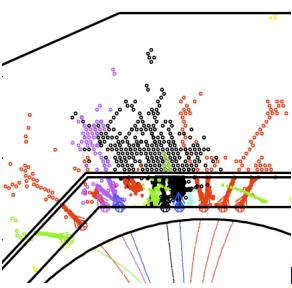
★ Particle Flow Calorimetry paradigm:

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



Calorimeter concept

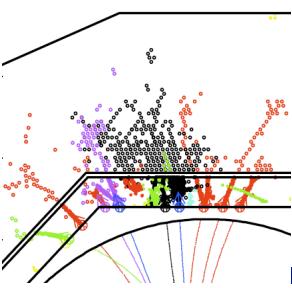
- large radius and length
 - to separate the particles
- large magnetic field
 - to sweep out charged tracks
- “no” material in front
 - stay inside coil
- small Moliere radius
 - to minimize shower overlap
- small granularity
 - to separate overlapping showers



Calorimeter concept

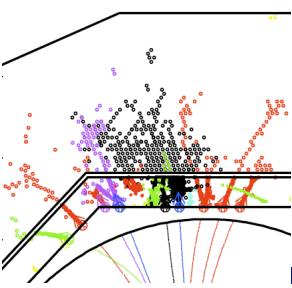
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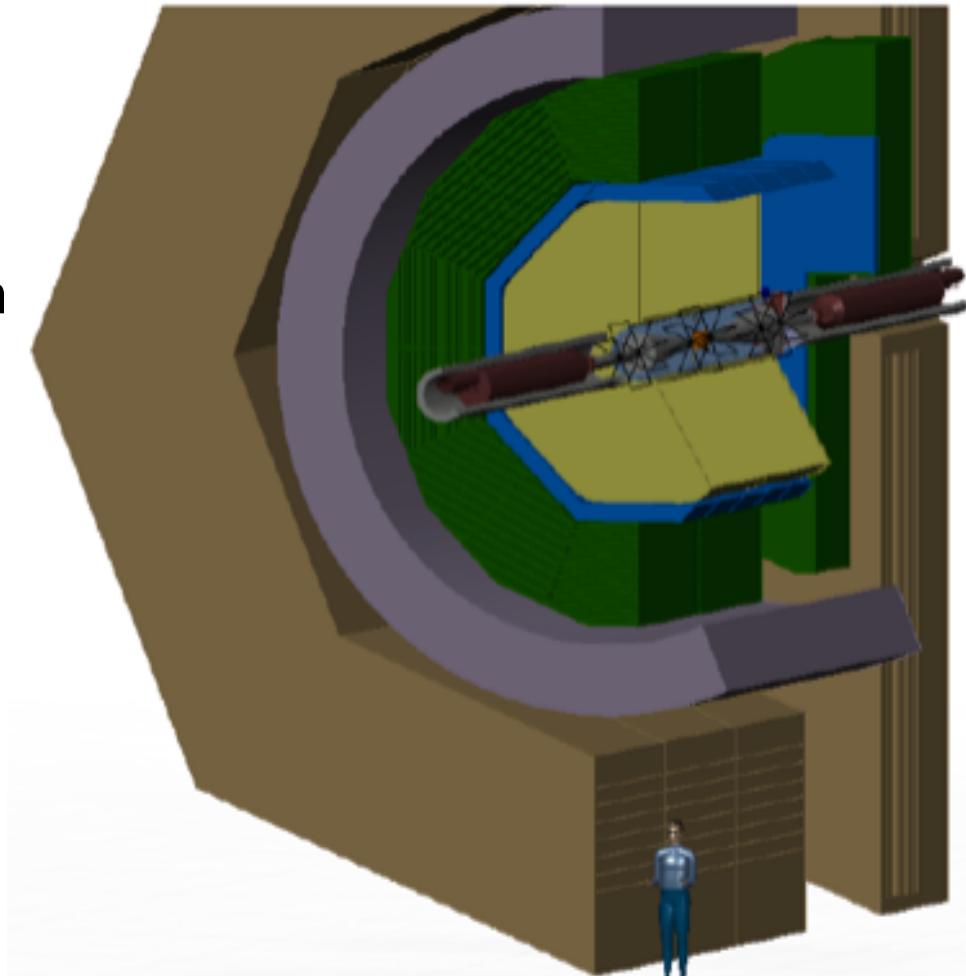
ILC detector concepts

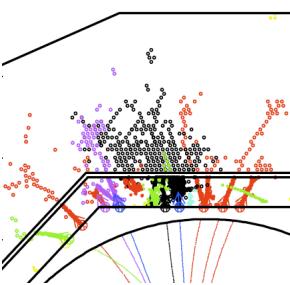
- PFLOW involves entire detector, not just calorimetry
- ILD: TPC for highest pattern recognition efficiency
- $B=3.5T$
- ECAL and HCAL inside (CMS-like) solenoid
- Highly segmented and compact calorimeters
- 2nd PFLOW-based concept: SiD, higher B , smaller R , Si tracker, same calorimeter



ILC detector concepts

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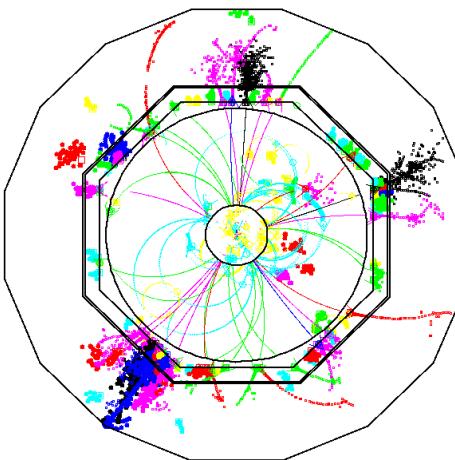




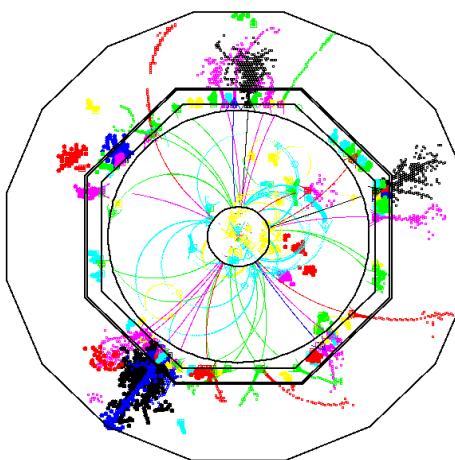
Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reconstruction

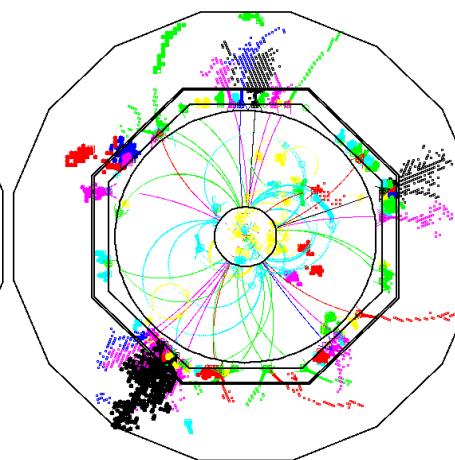
1x1



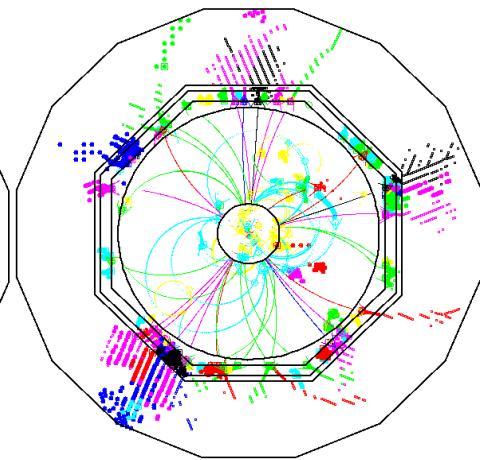
3x3

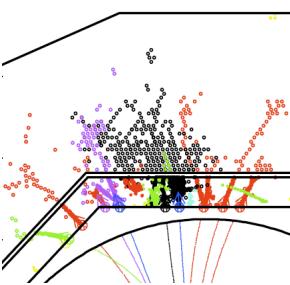


5x5



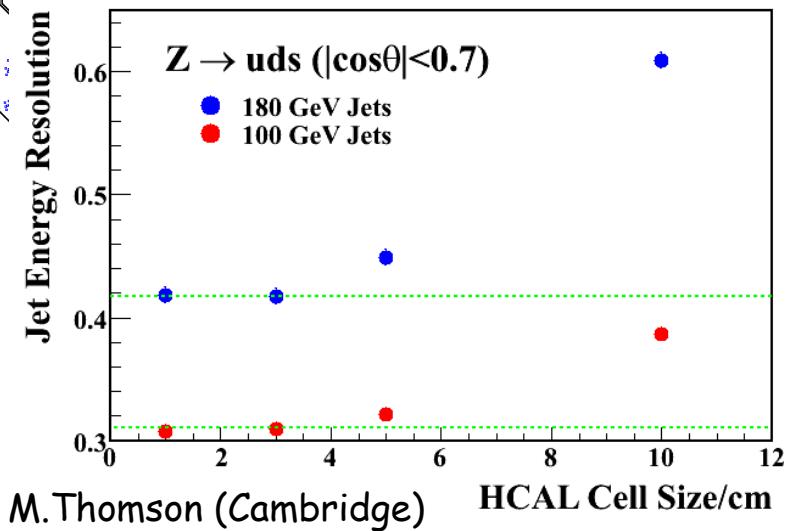
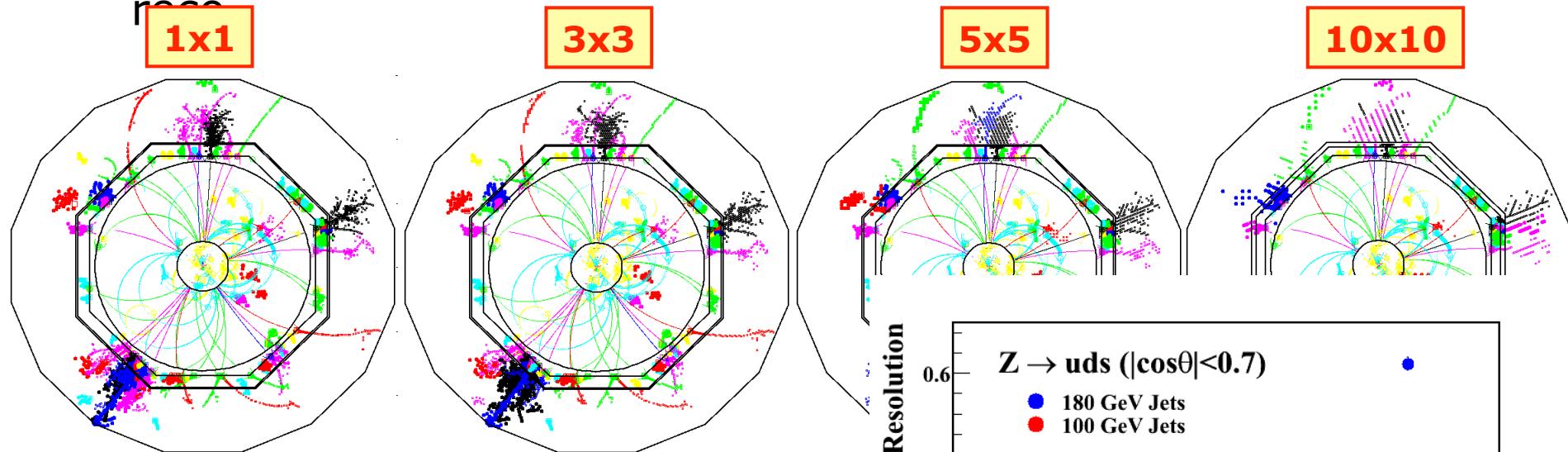
10x10

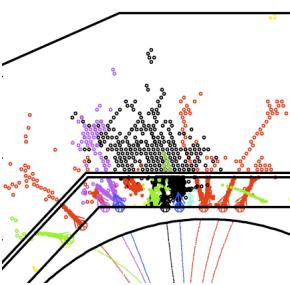




Tile granularity

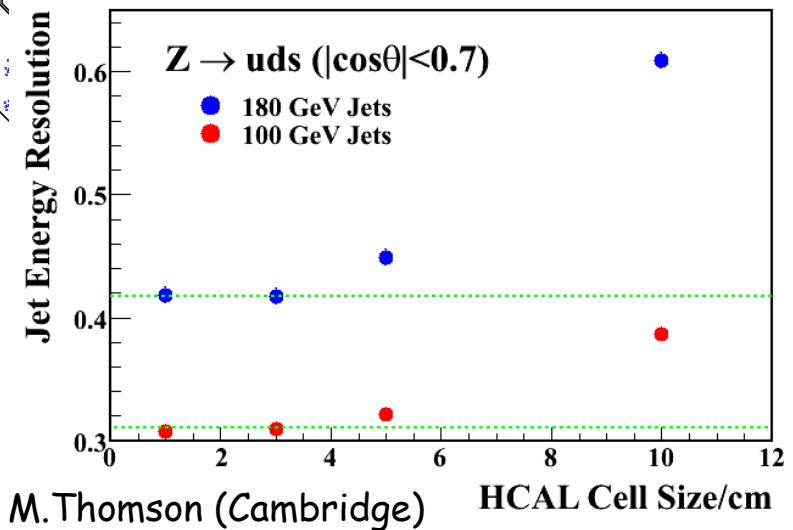
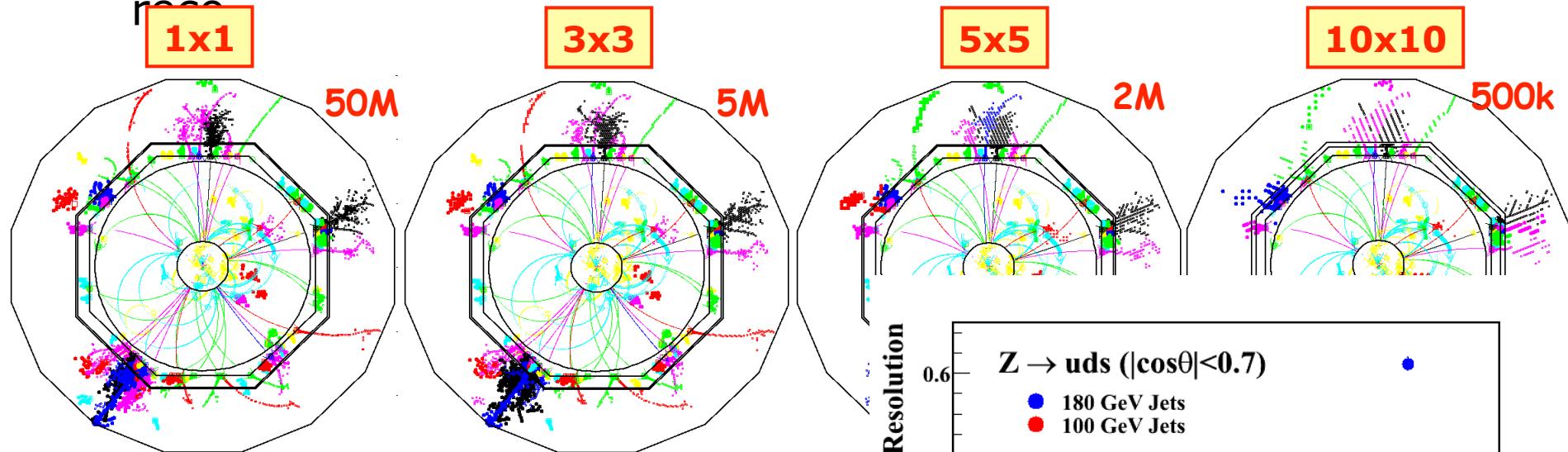
- Recent studies with PFLOW algorithm, full simulation and mcs

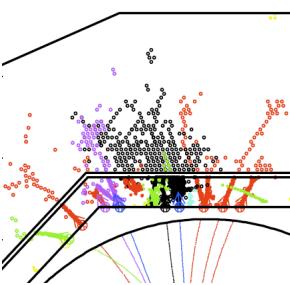




Tile granularity

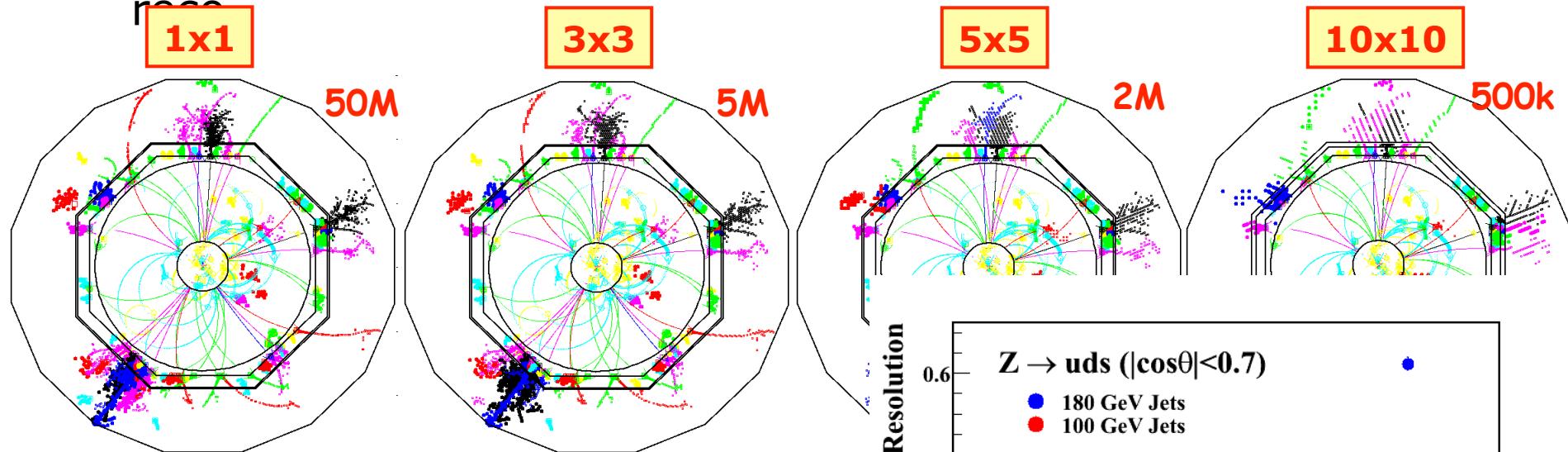
- Recent studies with PFLOW algorithm, full simulation and mso



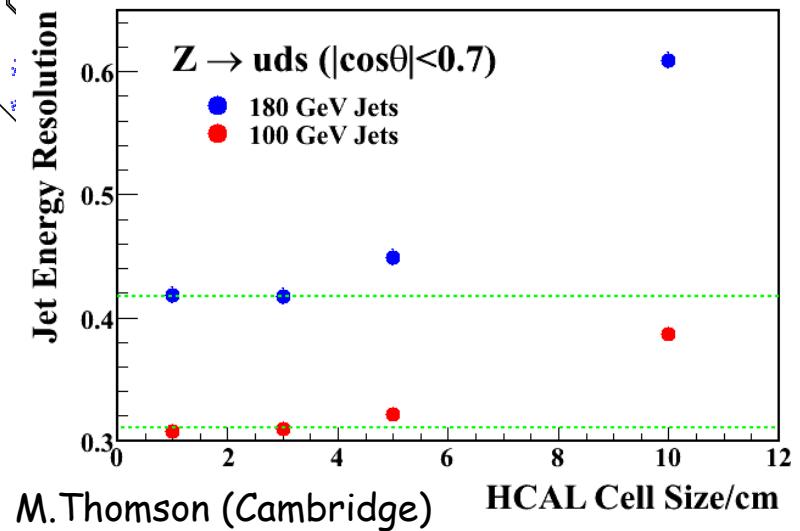


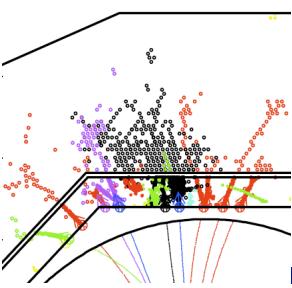
Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reconstruction



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

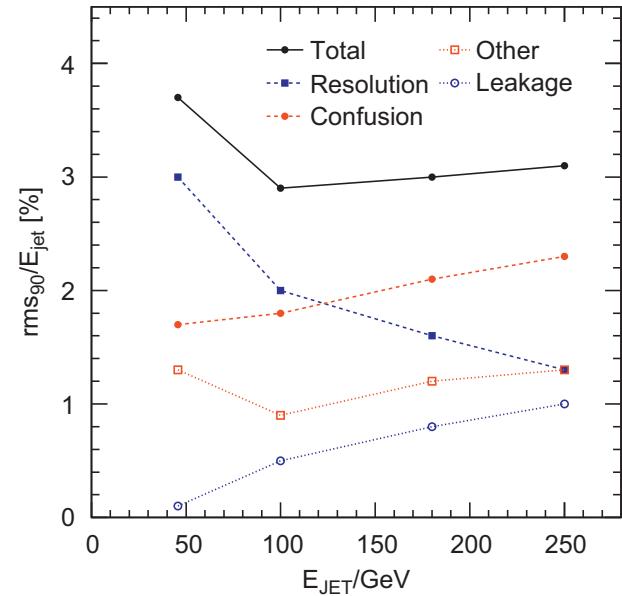
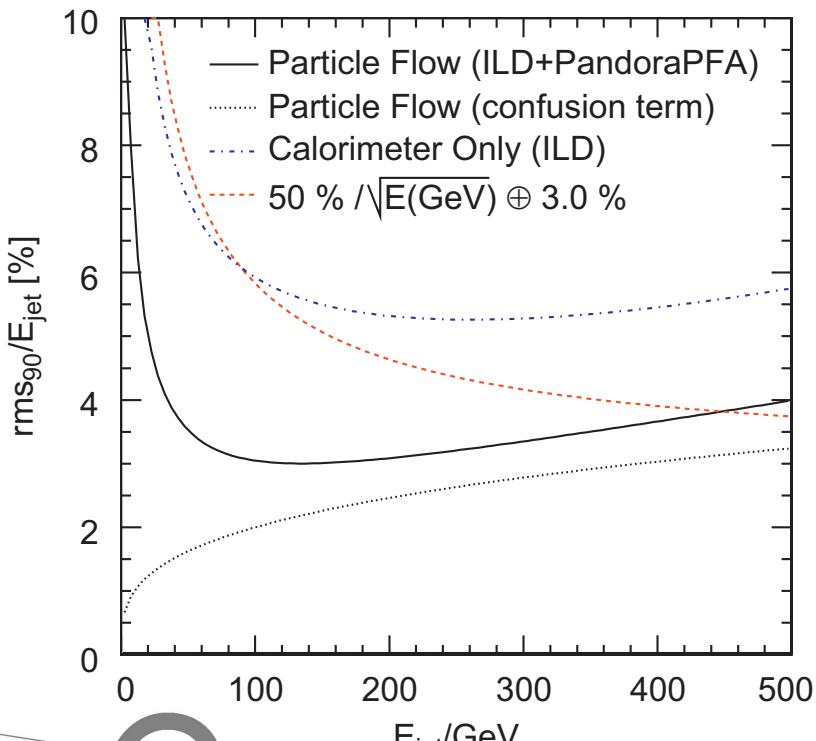




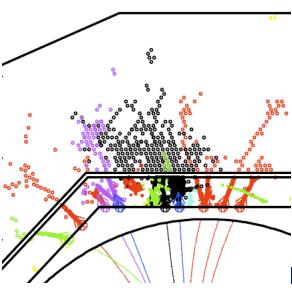
Understand particle flow performance

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

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

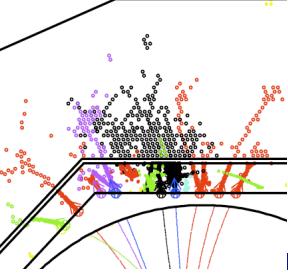


PFLOW detector concept

- 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?

Validation of the simulations

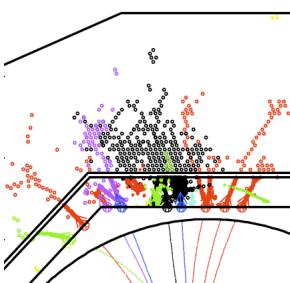
detector performance shower models



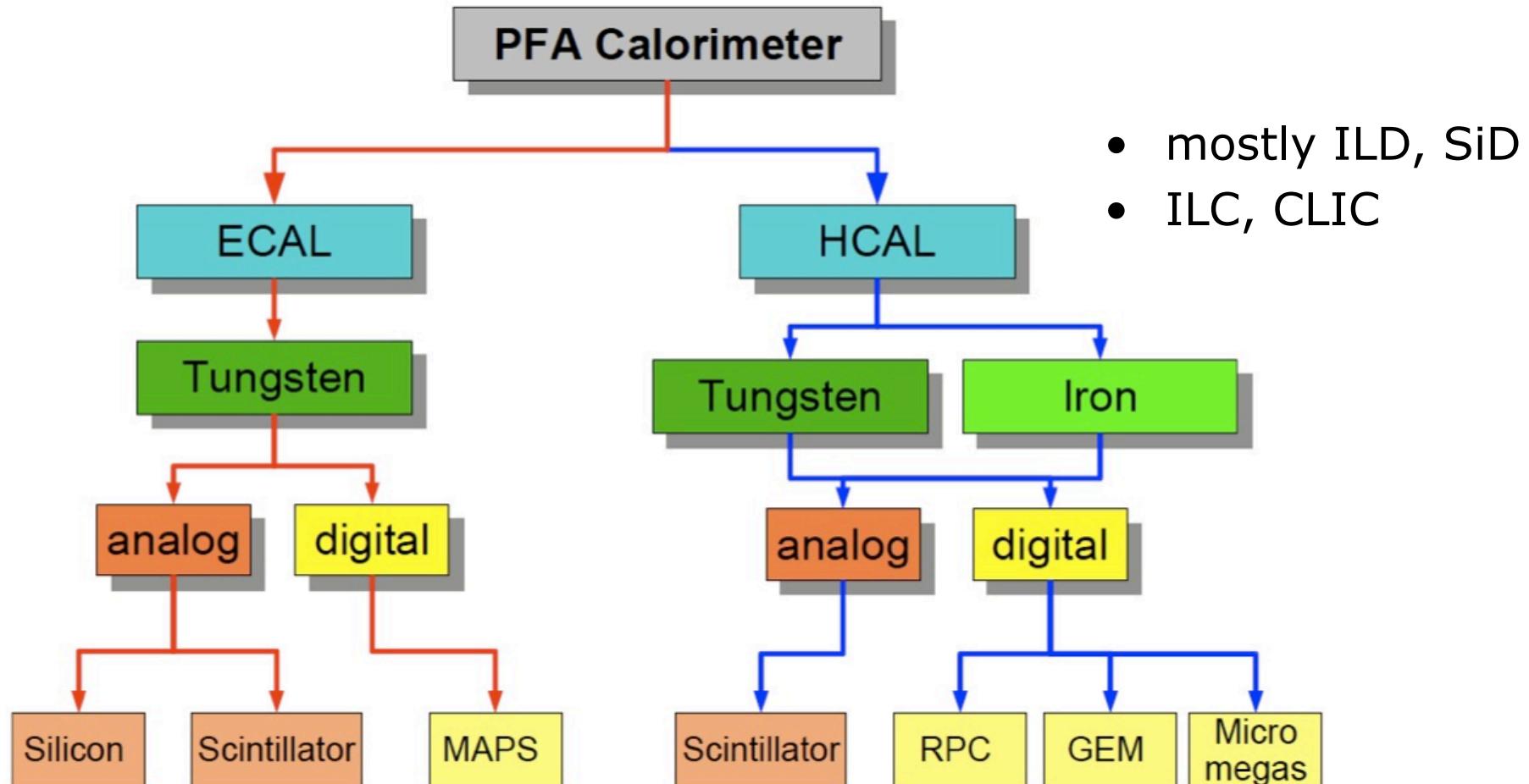
CALICE

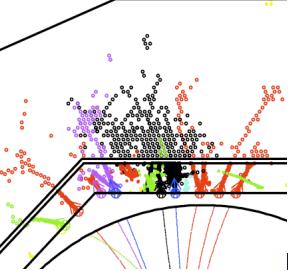


- We are more than 300 physicists and engineers from 57 institutes in Africa, America, Europe and Asia
- Our goal: develop highly granular calorimeter options based on the particle flow approach for an e+e- linear collider
- Twofold approach:
 - Physics prototypes and test beam
 - Operational experience 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



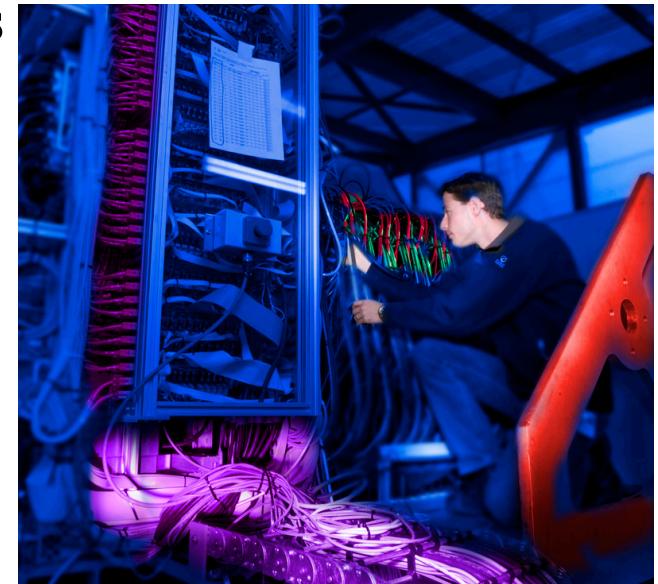
Technology tree

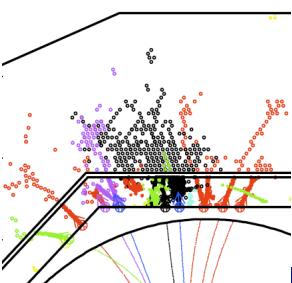




Overall status

- 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

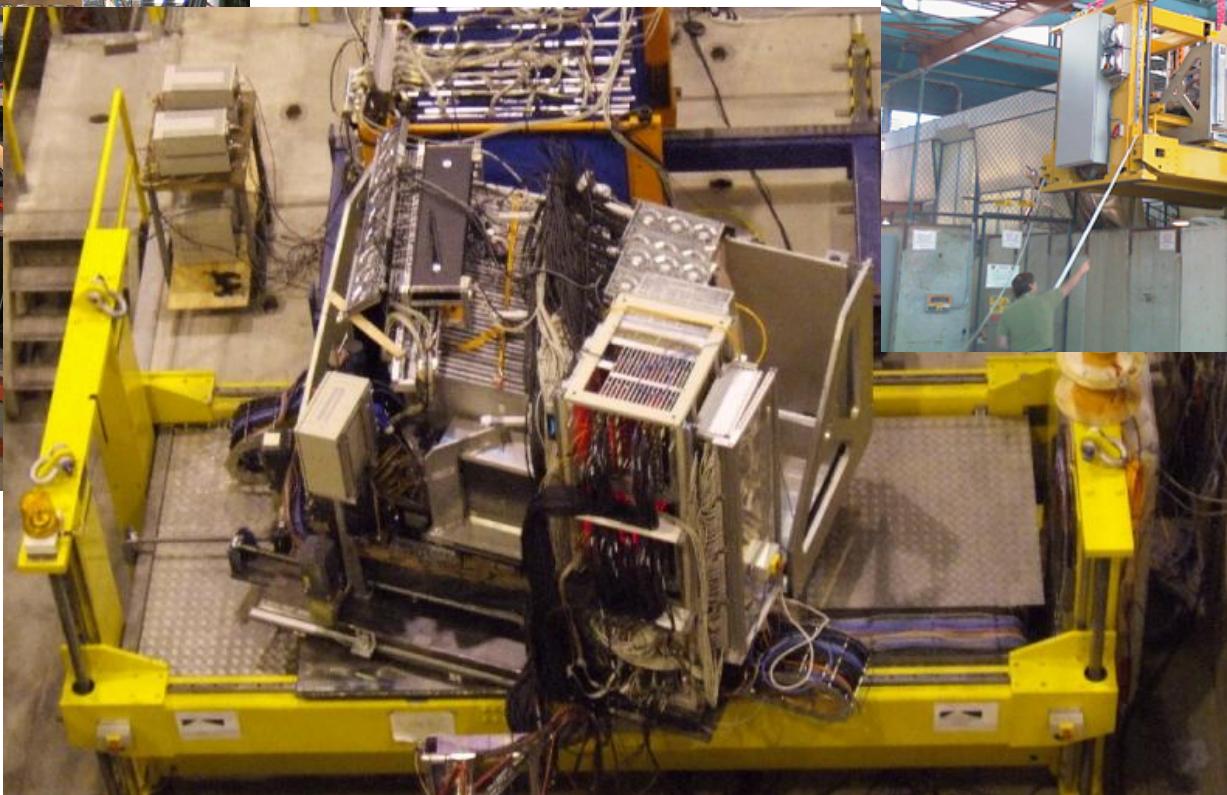




Test beam experiments



DESY 2005

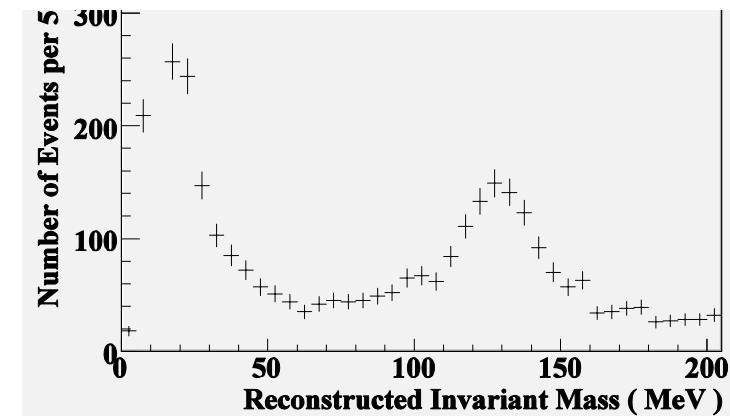
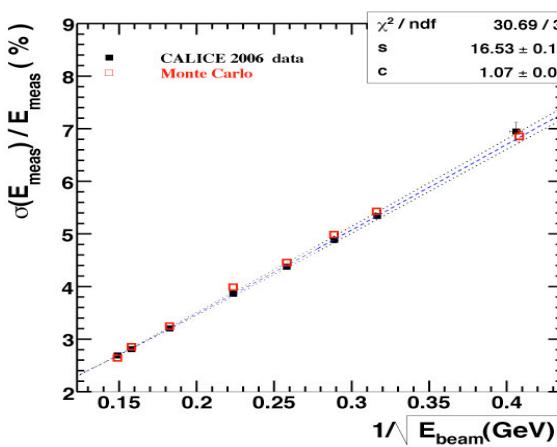
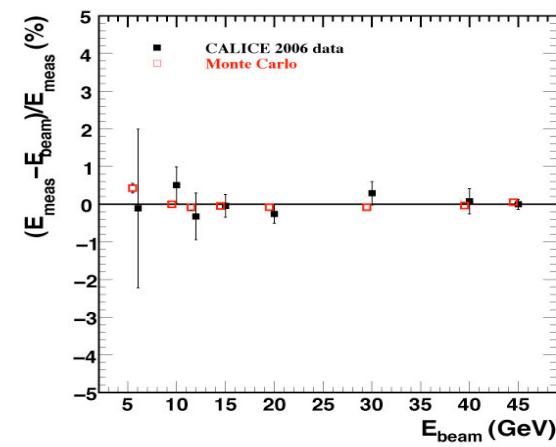
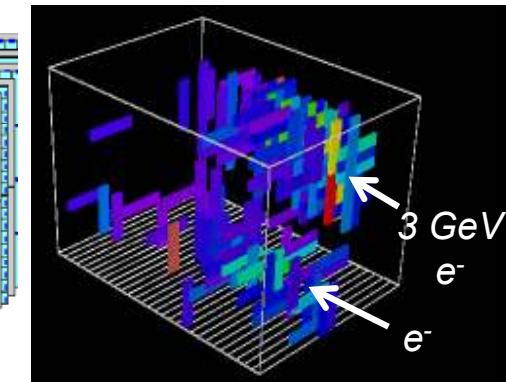
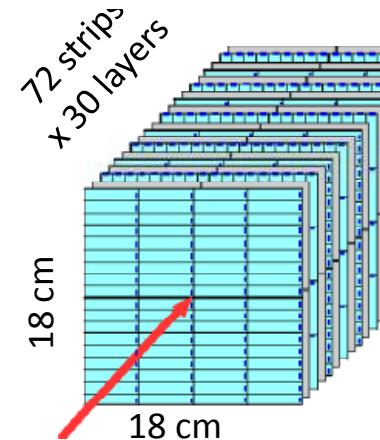
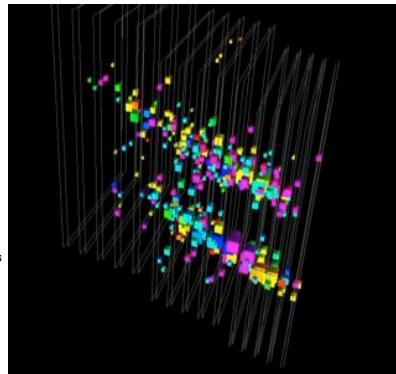
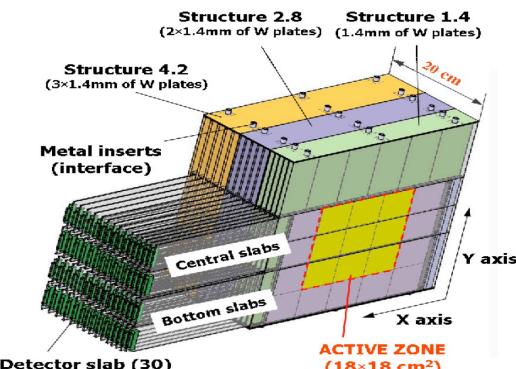
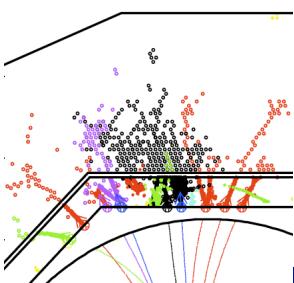


CERN 2006-2007

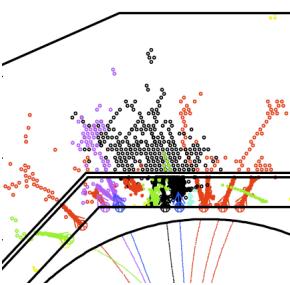


FNAL 2008..

ECAL options

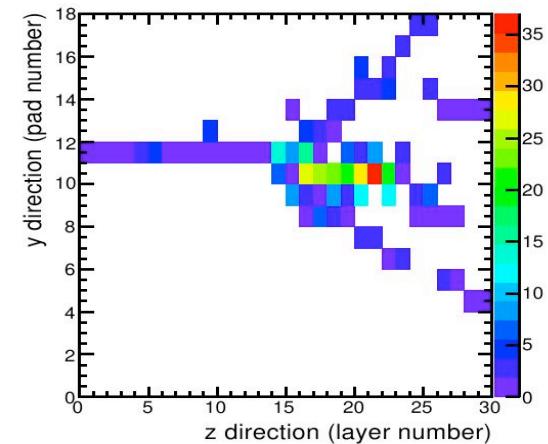
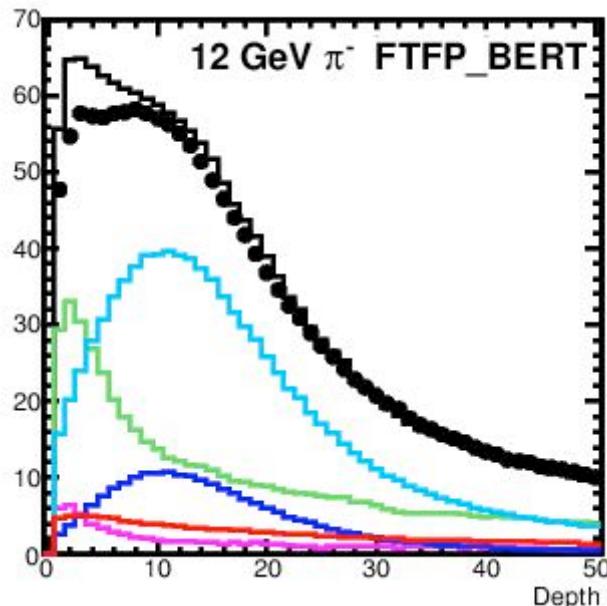


- W Si or Sci: common mechanics, similar electronics



Pions in the SiW ECAL

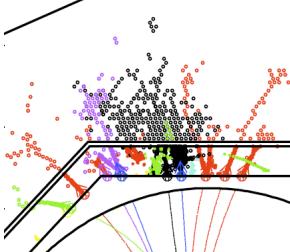
- test Geant 4 predictions with 1 cm² granularity
- sensitive to shower decomposition
- favor recent G4 physics lists
- certainly not perfect - certainly not bad either!



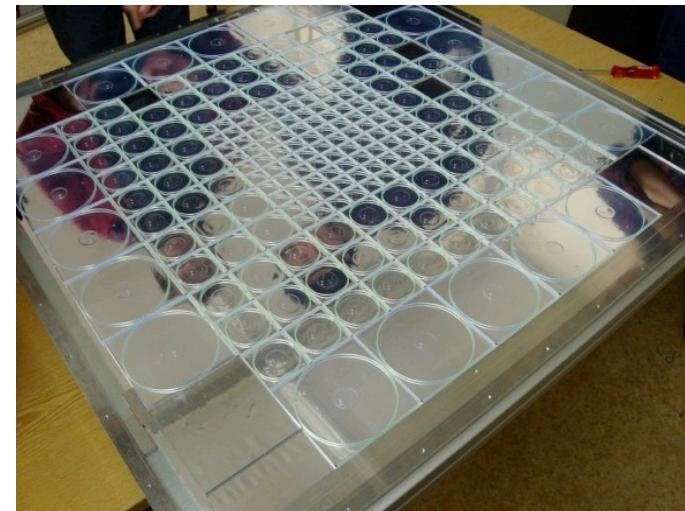
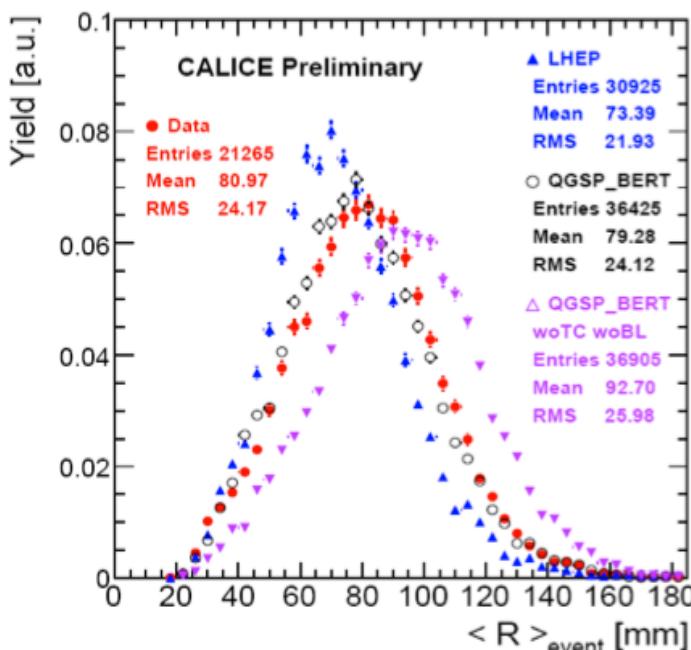
Shower Components:

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

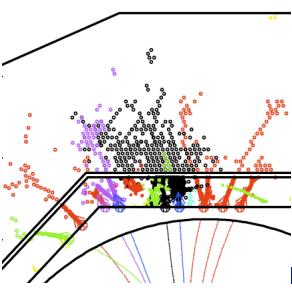
Fe Scint tile HCAL



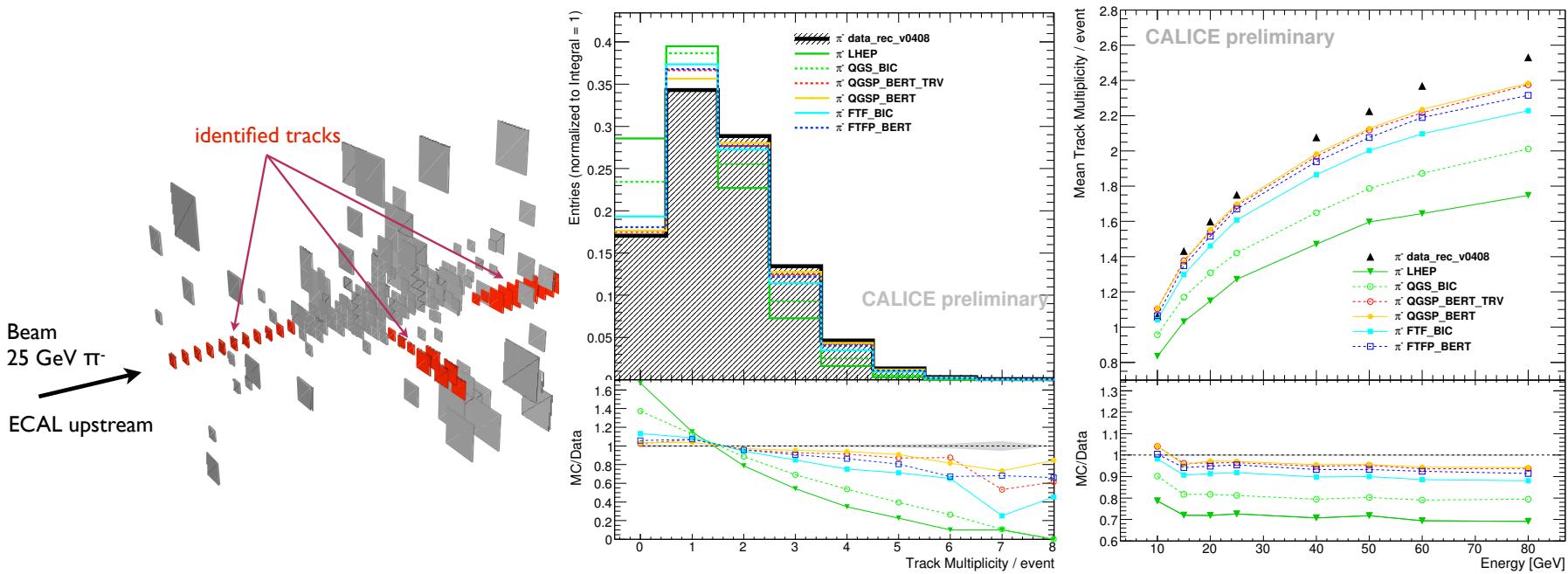
- 38 layers steel sandwich
- 7600 tiles with SiPMs



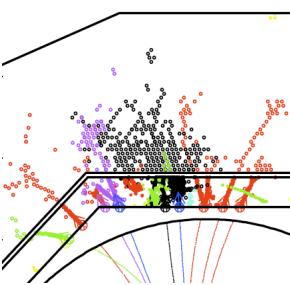
- Present-day simulation quality requires good detector understanding to discriminate
- Fluctuations also well reproduced



Shower fine structure



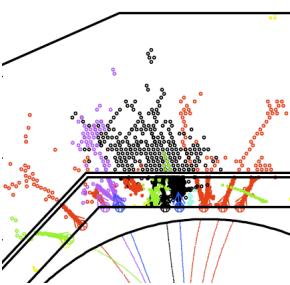
- Could have the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already



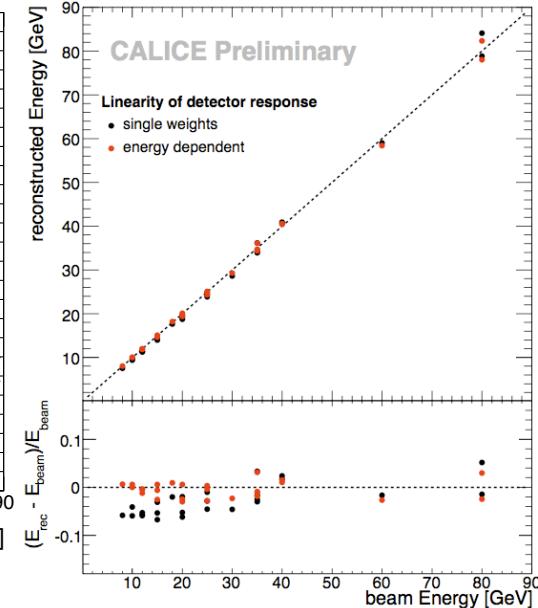
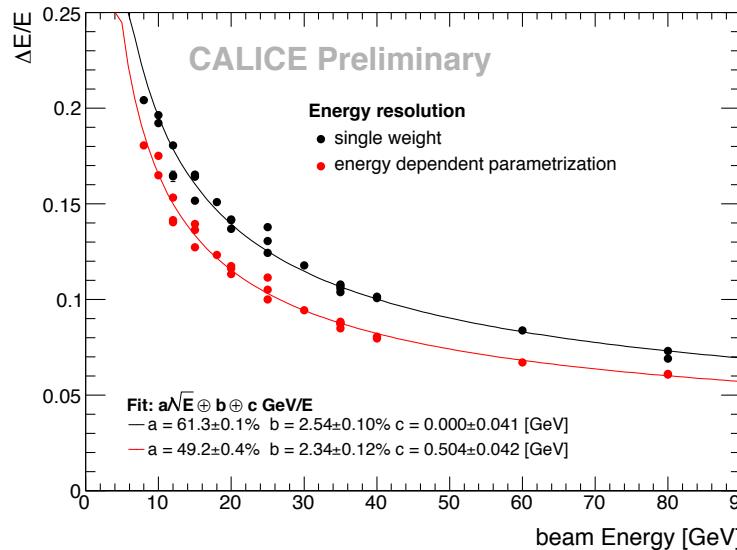
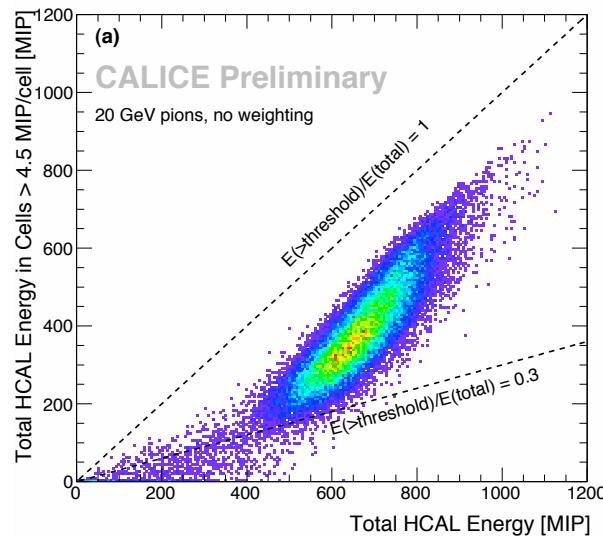
Summary on validation:

- 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

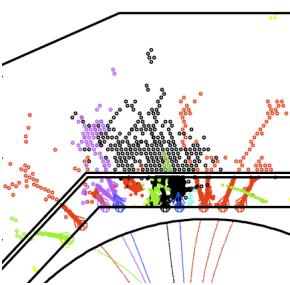


Resolution, compensated

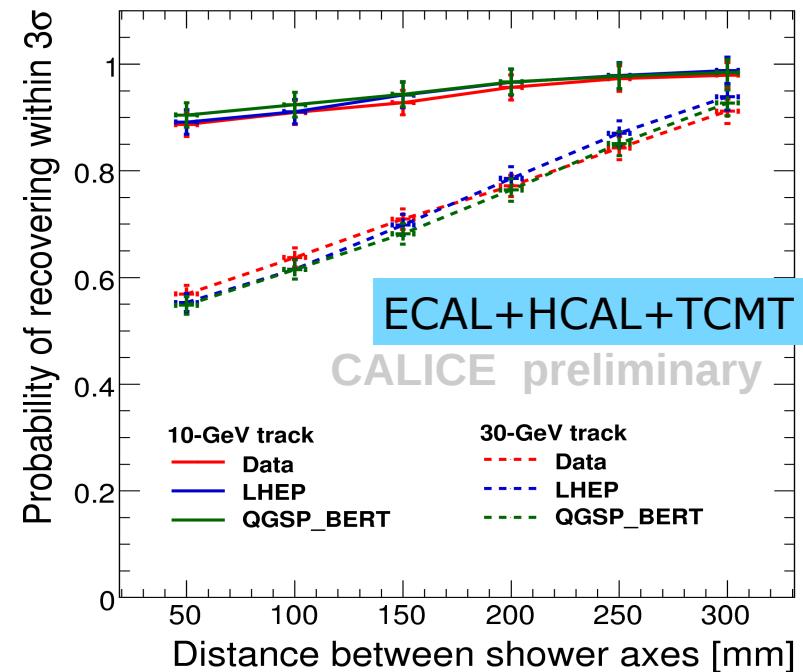
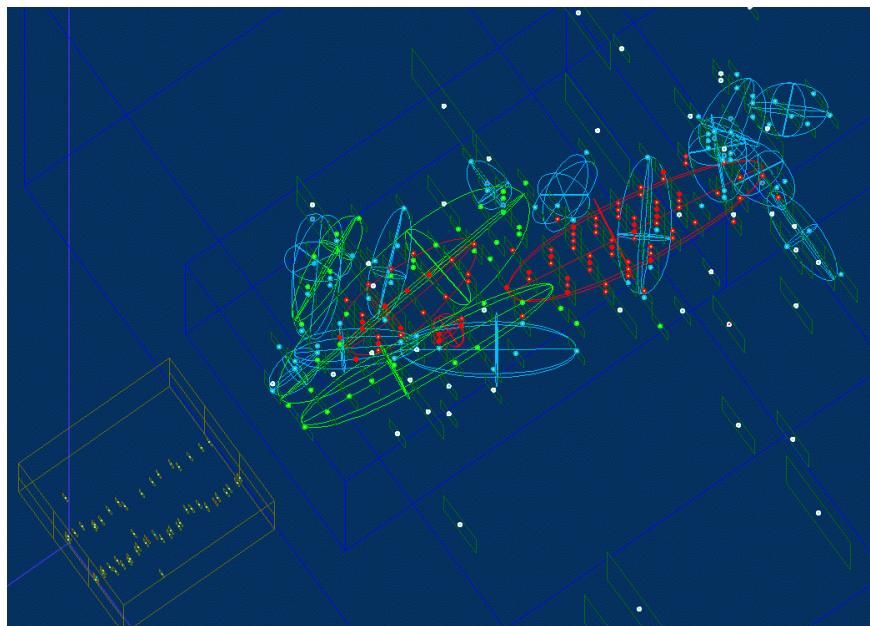


ECAL+HCAL+TCMT

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

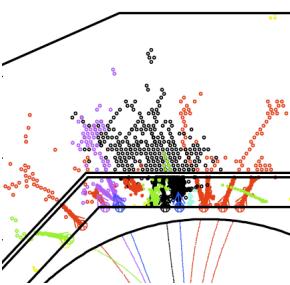


PFLow: two-particle separation



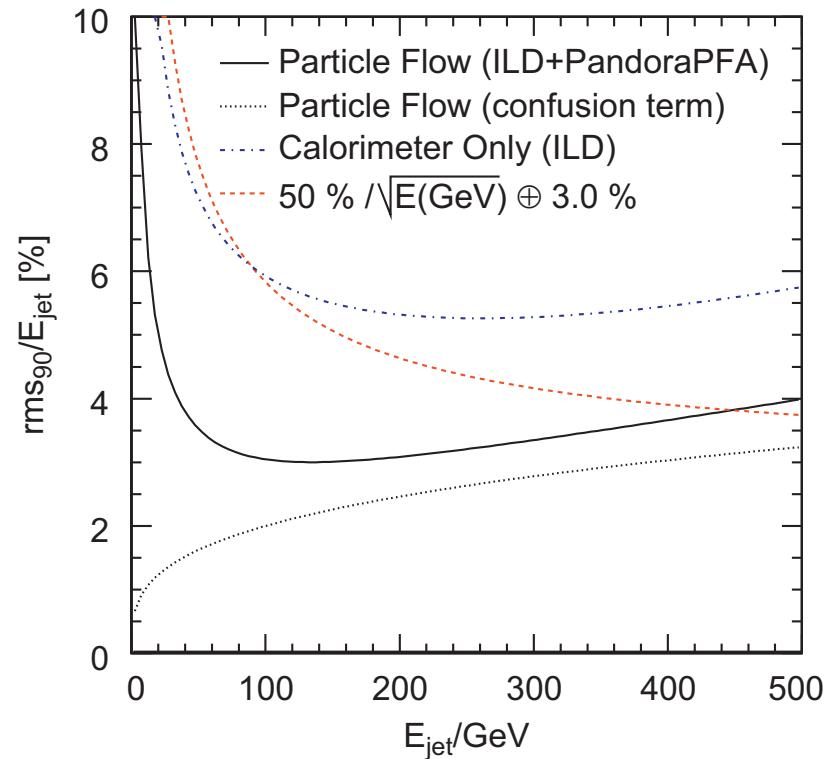
- The “double-track resolution” of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- Important: agreement data - simulation
 - sharing the same limitations

to be done with photons, too

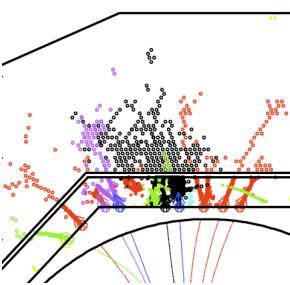


Summary on algorithms

- 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



Test beam experiments 2010

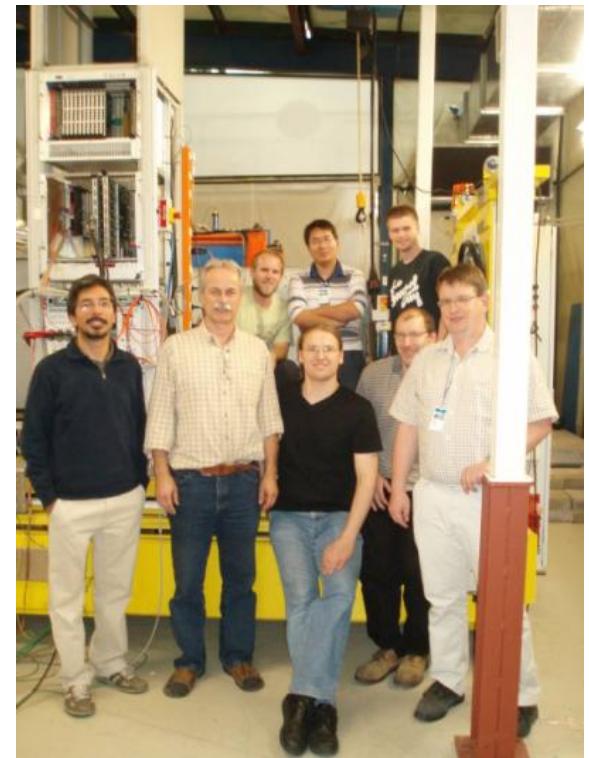


DESY

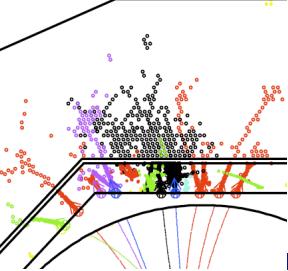


CERN

FNAL

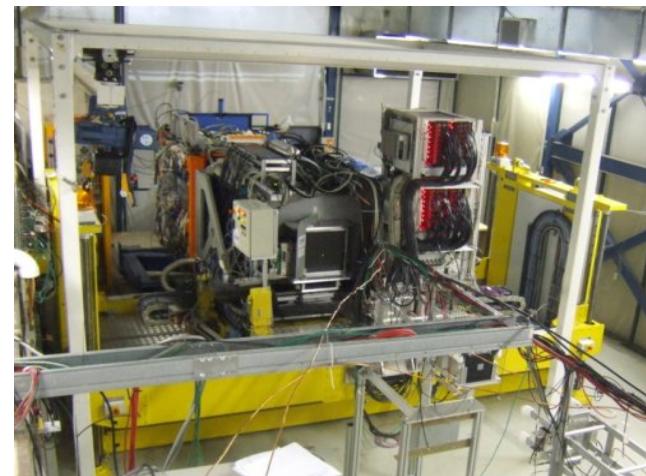


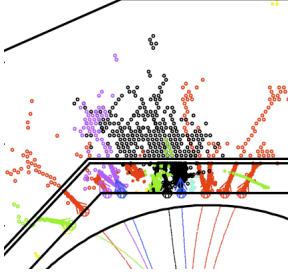
and more:
RPCs in B field, micromegas, GEMs



Digital calorimetry

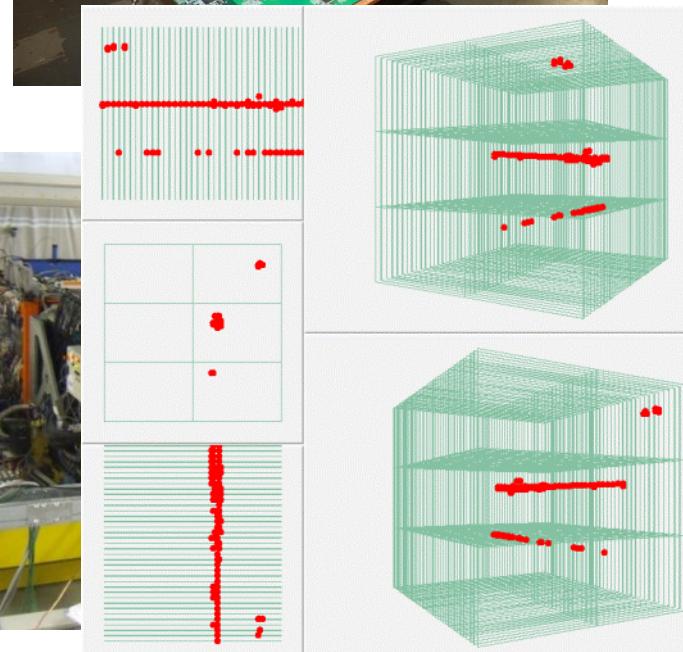
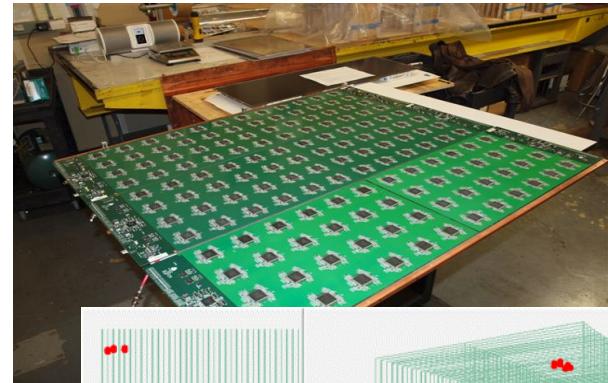
- Digital and semi-digital hadron calorimeter
 - even higher granularity
 - suppress dE/dx fluct.
 - reduced n sensitivity
 - limited at high E?
- test beam started in November at FNAL, running today
- Possible continuation at CERN
 - higher E, tungsten absorber
- Semi-digital prototype with ultra-low power electronics under construction for 2011

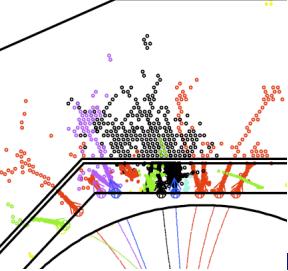




Digital calorimetry

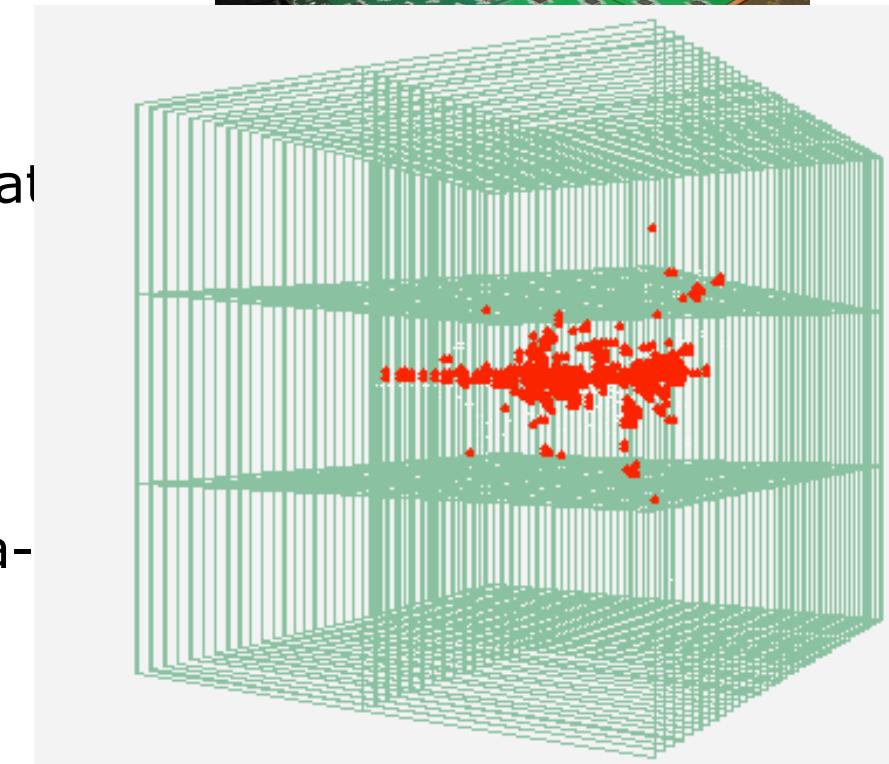
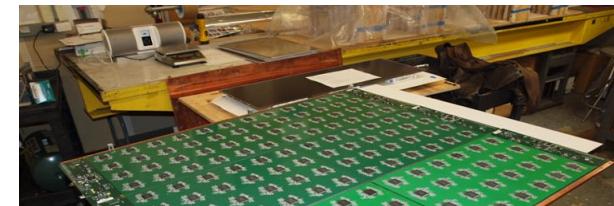
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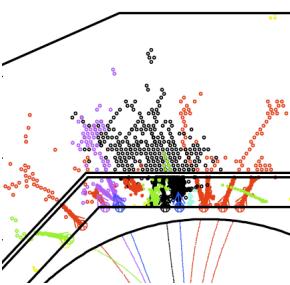




Digital calorimetry

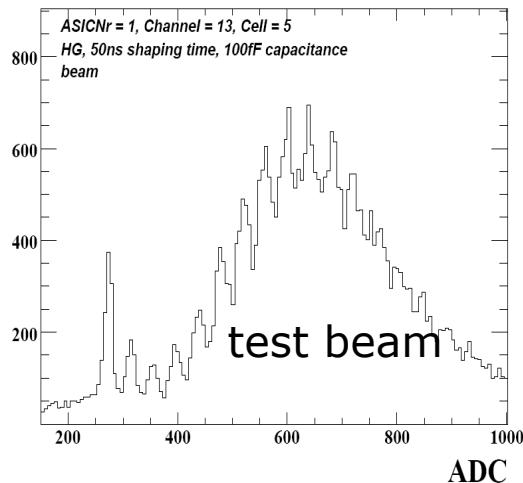
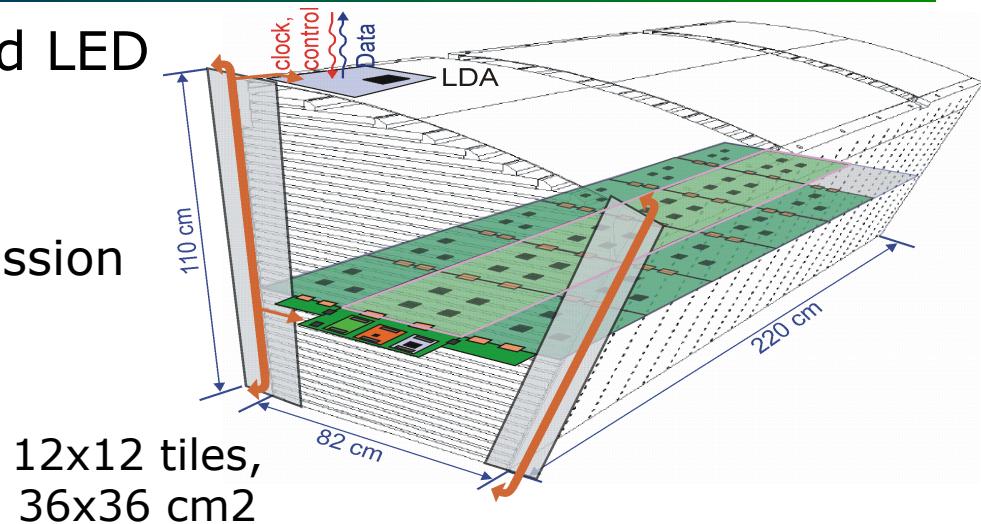
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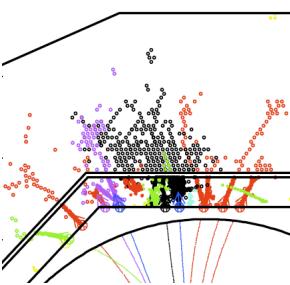




Scint HCAL: 2nd generation

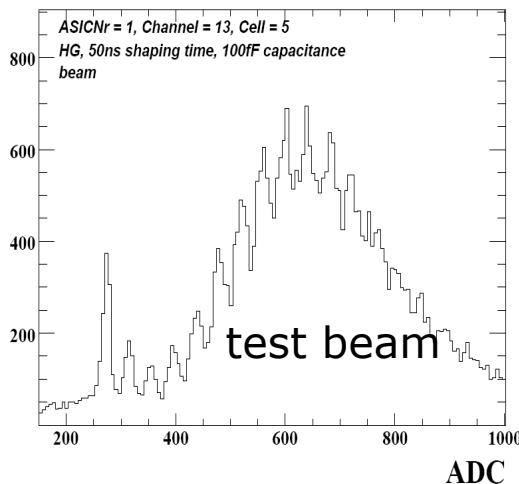
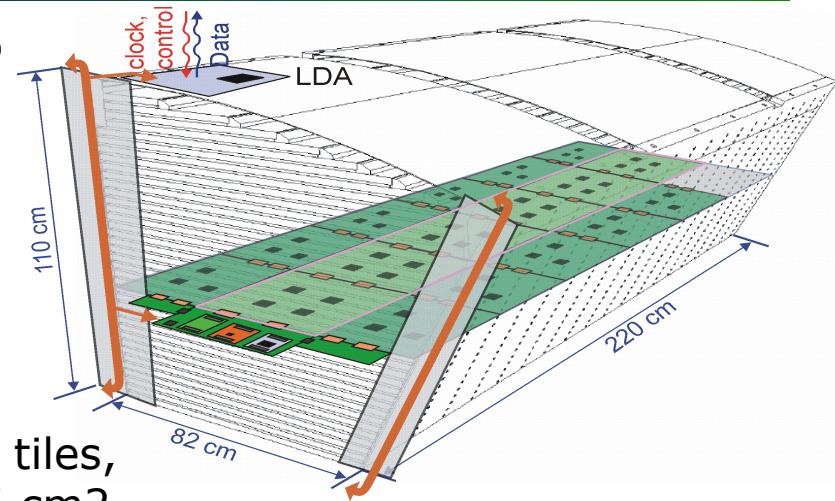
- integrate readout ASICs and LED system
 - include ADCs and **TDCs**
 - power pulsing, zero suppression
- First layers: tested
 - see module on display
- Later: full tungsten HCAL

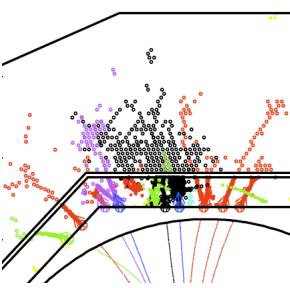




Scint HCAL: 2nd generation

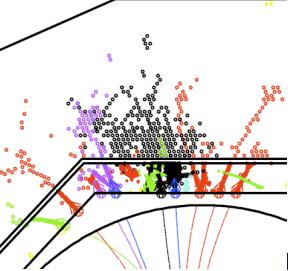
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Summary on technologies

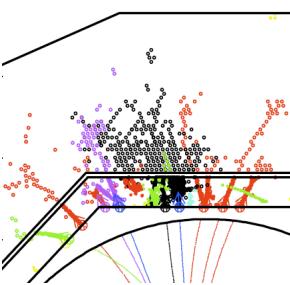
- a leap in several orders of magnitude in channel count
- new sensor technologies, new integration concepts
 - the latter is part of the feasibility demonstration
- progress towards realism:
 - realistic designs
 - realistic simulations
 - realistic cost
 - realistic proposal



Conclusion

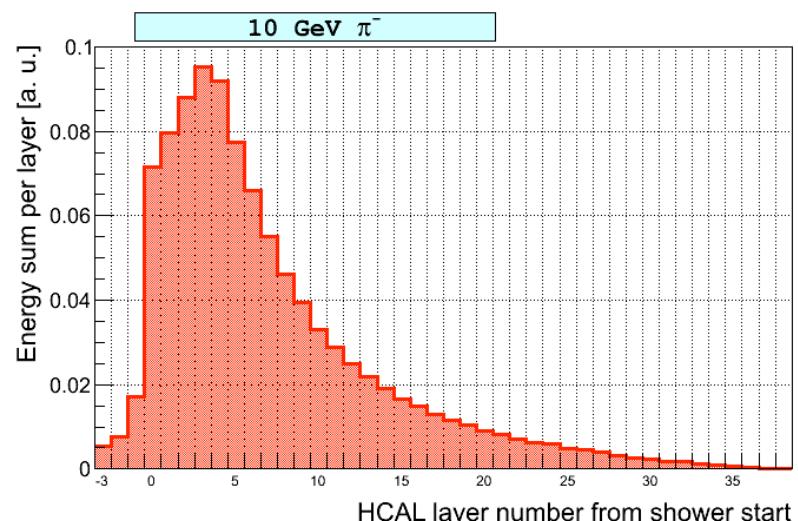
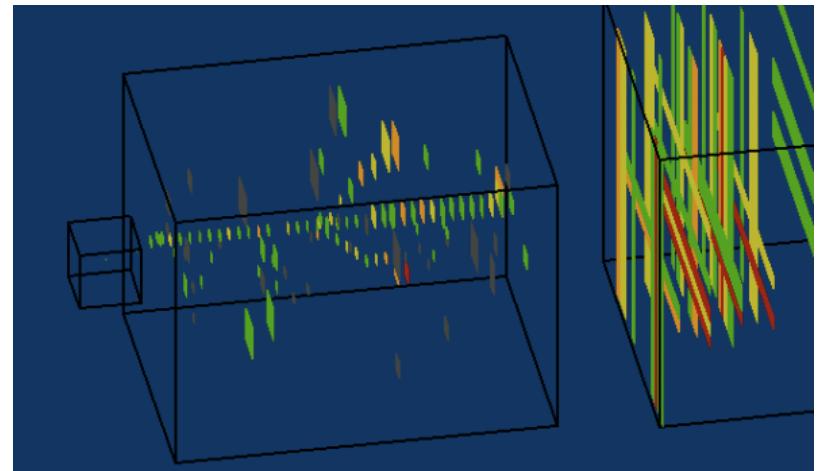
- Particle flow calorimetry does not solve the inherent problems of hadron calorimeters
- But it holds the promise of providing a highly performant work-around
- Looking forward: Increased test beam activity 2011-12

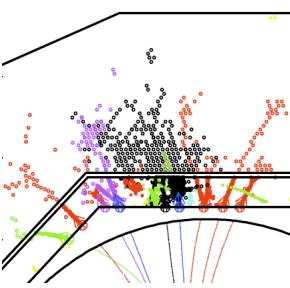
Hands-on



The EDIT exercises

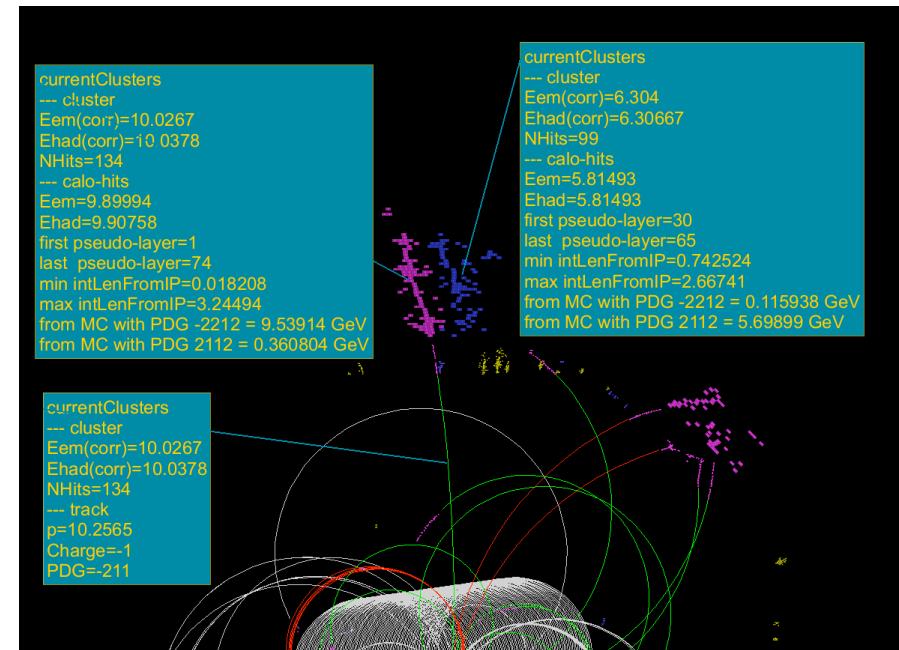
- Part A - with real data
 - Scan CALICE test beam events
 - appreciate the diversity
 - analyze shower properties
- Goal: get a feeling for dimensions and fluctuations

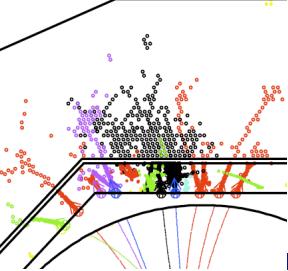




The EDIT exercises

- Part B - inevitably based on simulations
 - Scan ILC events with jets
 - see how the detector responds
 - see how the reconstruction copes with it
 - understand where it fails
- Goal: don't be afraid of confusion!



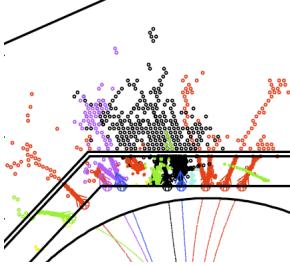


Disclaimer and plea

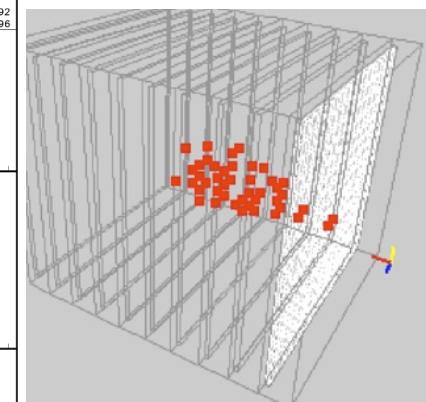
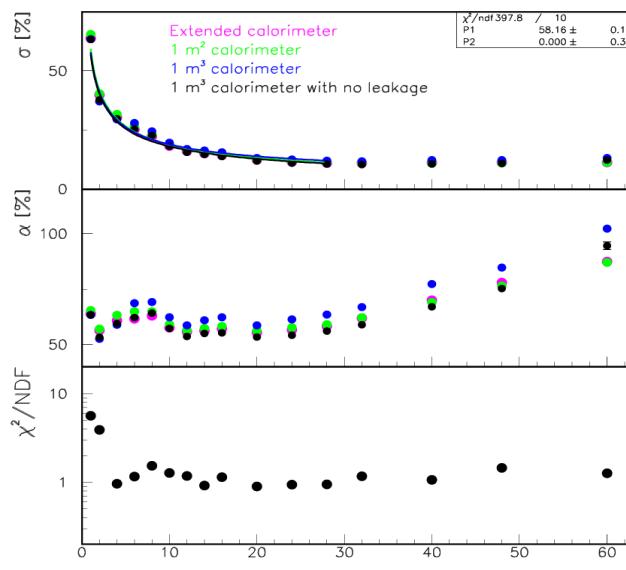
- This exercise has not been tried before, so you are the guinea-pigs in some sense
- Be graceful and help us with your feedback

Back-up slides

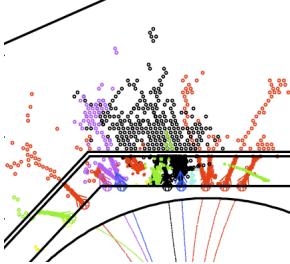
Digital calorimetry



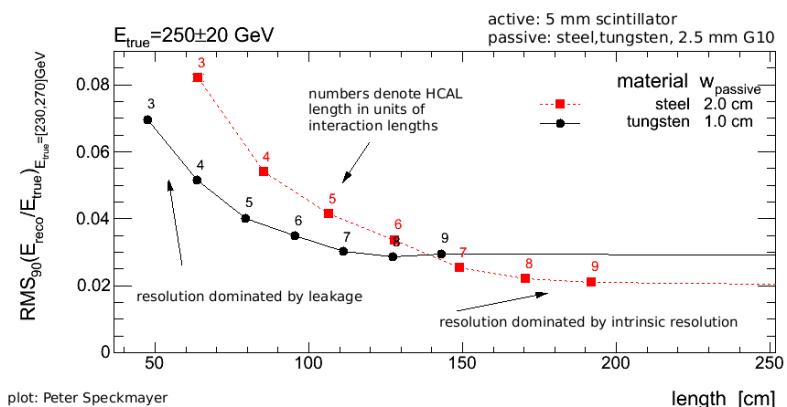
- Digital and semi-digital hadron calorimeter
 - even higher granularity
 - suppress dE/dx fluct.
 - reduced n sensitivity
 - limited at high E?
- Small RPC proto successful
- Educated simulations
- Full-size RPC based prototypes under test and underway



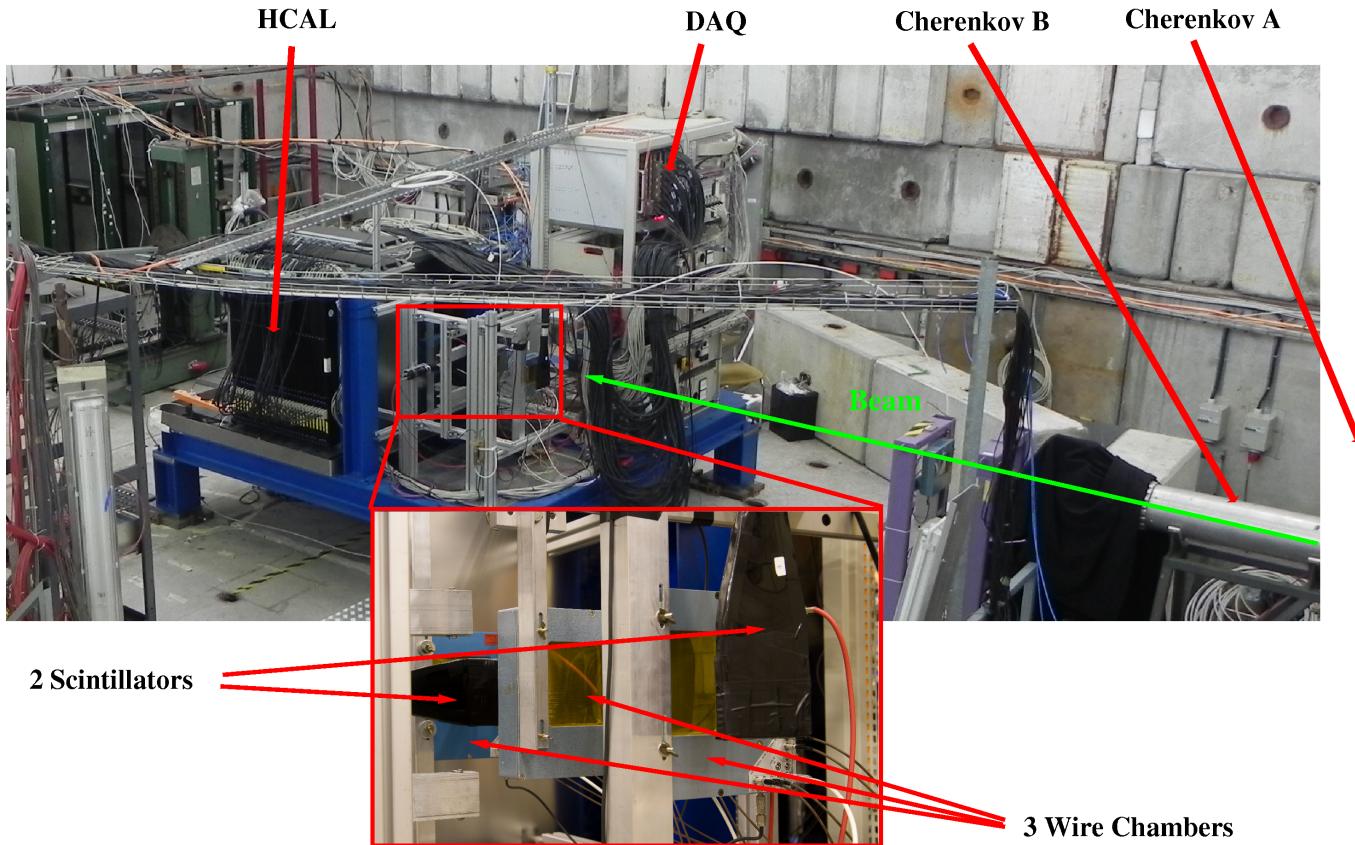
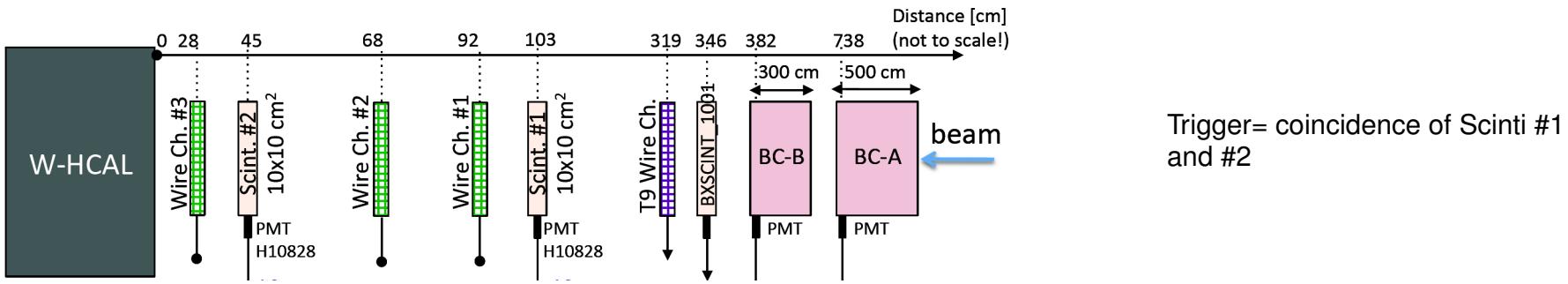
High energy



- Particle flow also a promising option for CLIC energies
- Leakage expected to limit PFLOW performance
 - need 1λ ECAL + 7λ 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

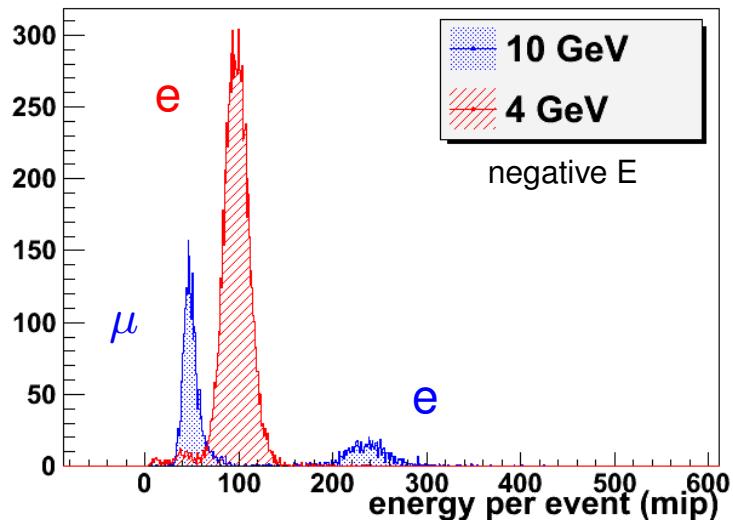


Test Beam Setup

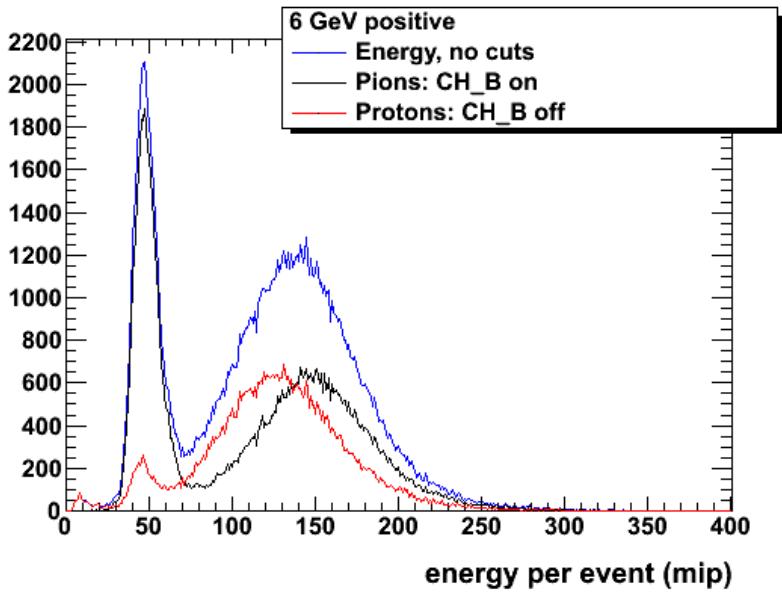
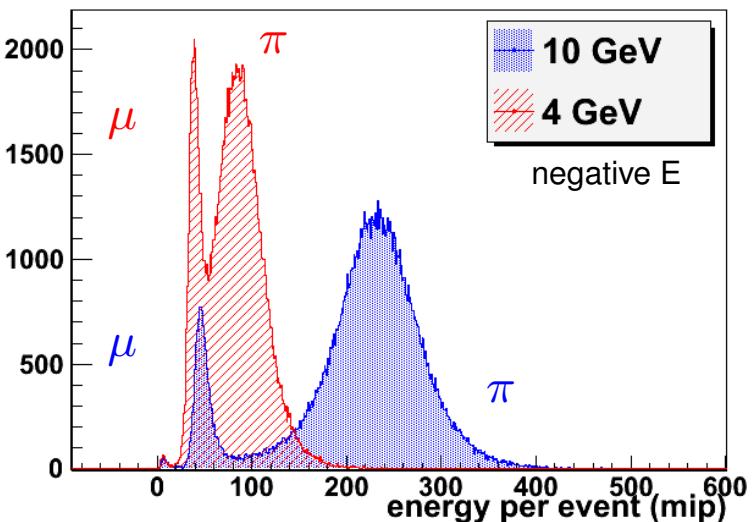


First Results: Particle ID

Cherenkov A ON



Cherenkov A OFF



- 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