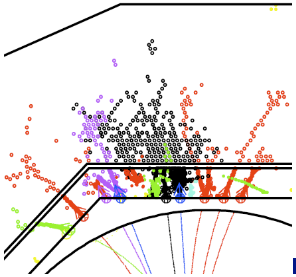
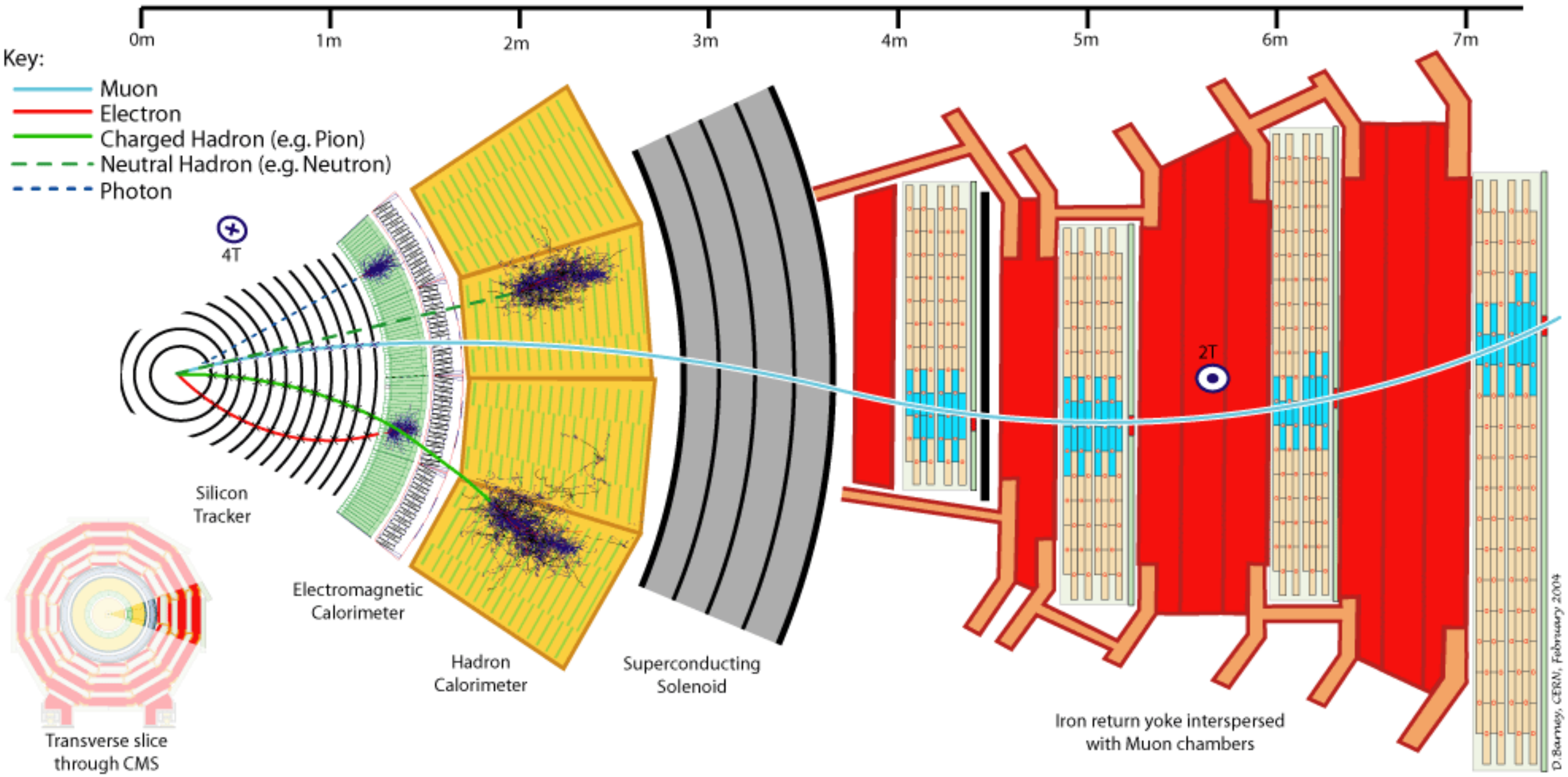
Recent trends in calorimetry: the new image of hadrons

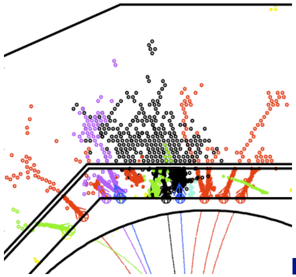
Felix Sefkow

DESY instrumentation seminar, April 29, 2011

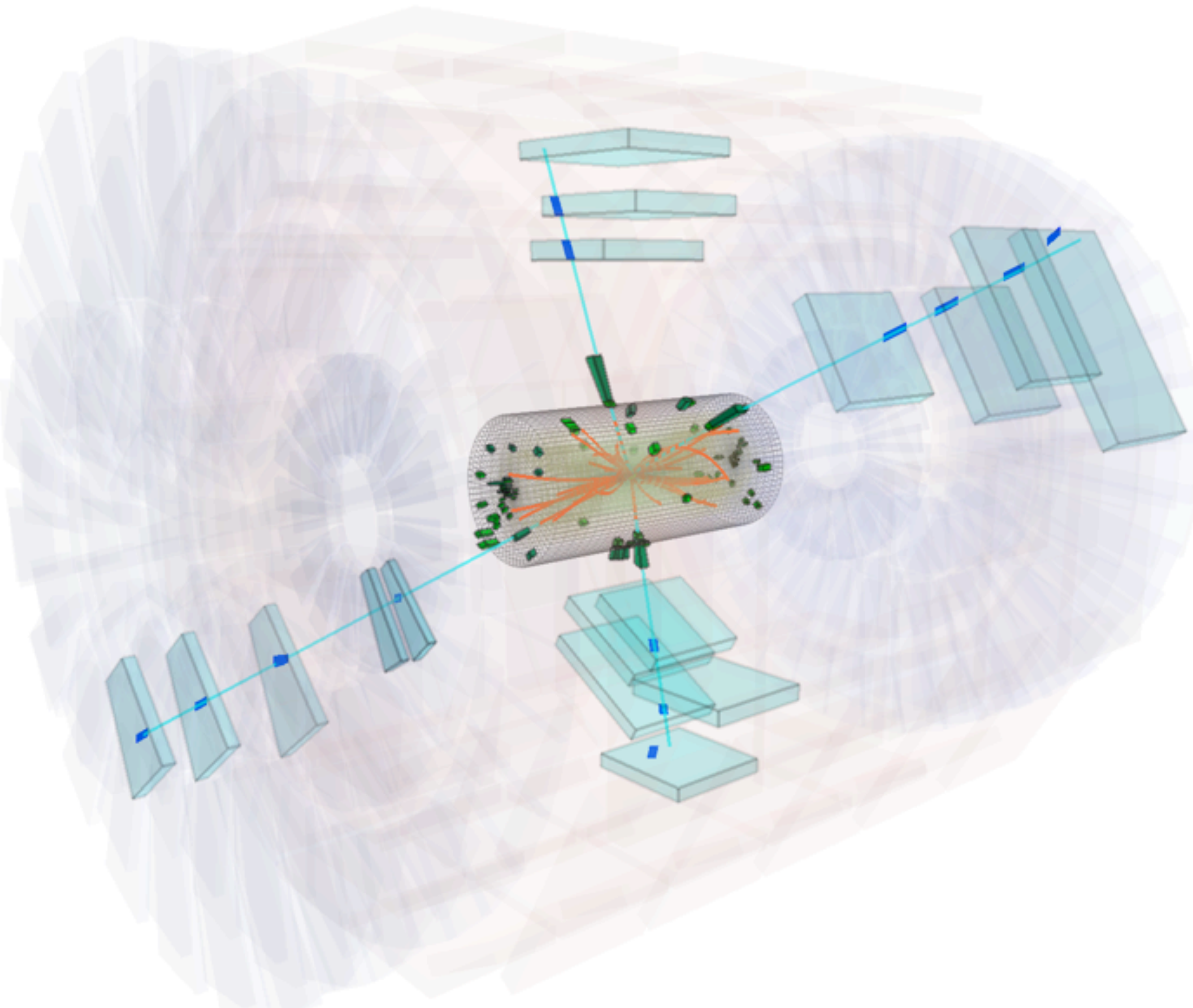


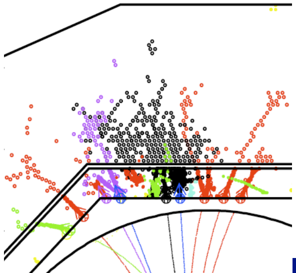
A generic collider detector





Today’s detectors





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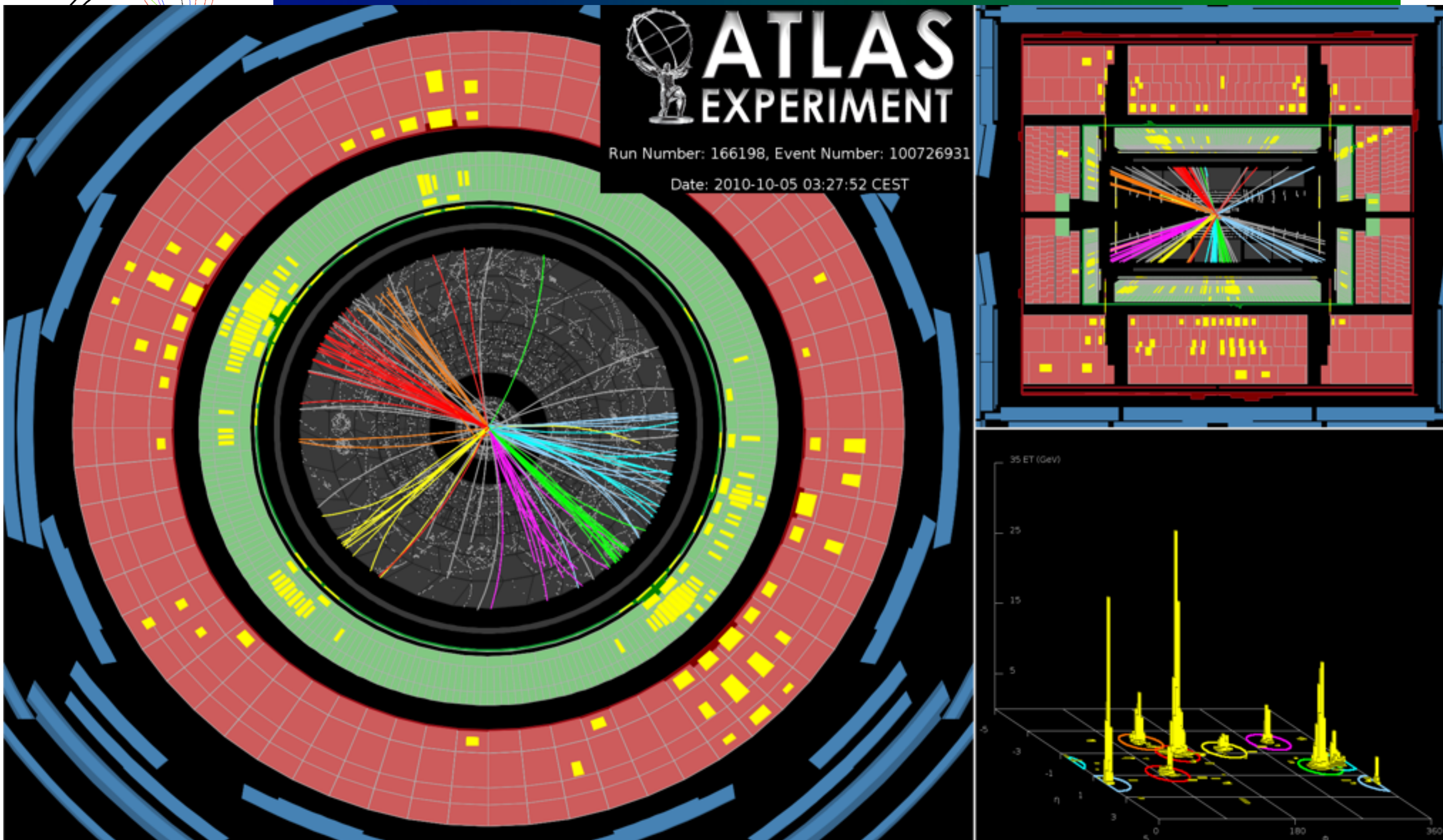
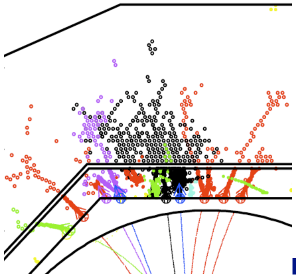
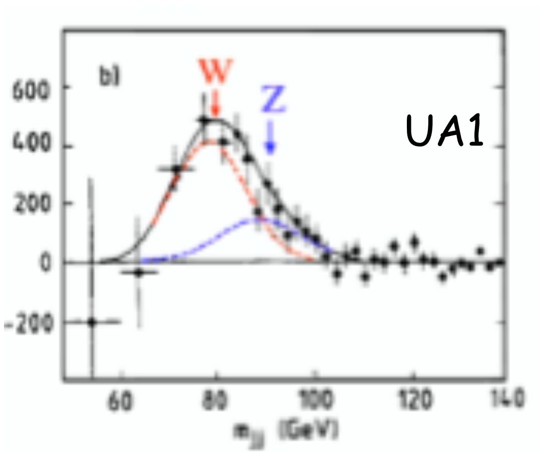
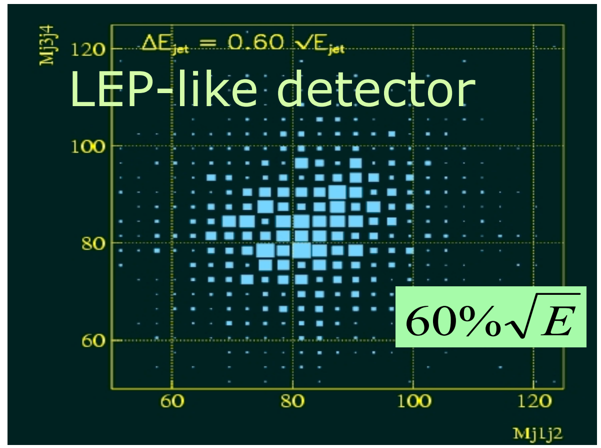
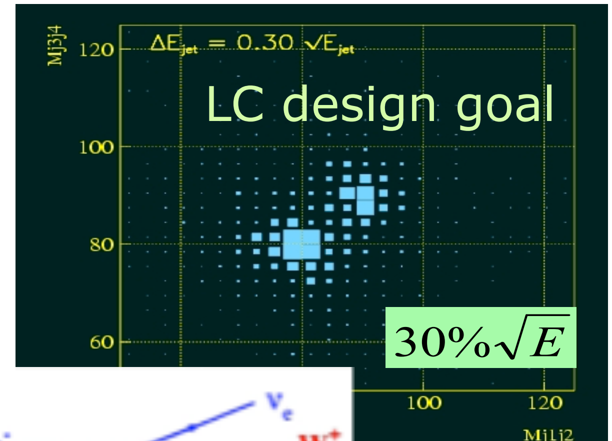


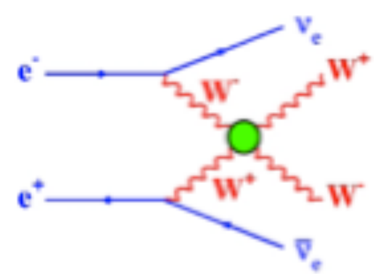


Challenge: W Z separation

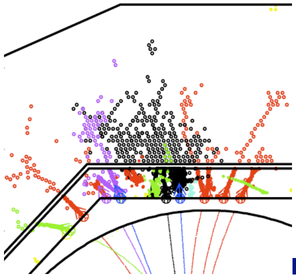








- At the Tera-scale, we need to do physics with W's and Z's as Belle and Babar do with D^+ and D_s
- Calorimeter performance for jets has to improve by a factor 2
- Rather young and dynamic development

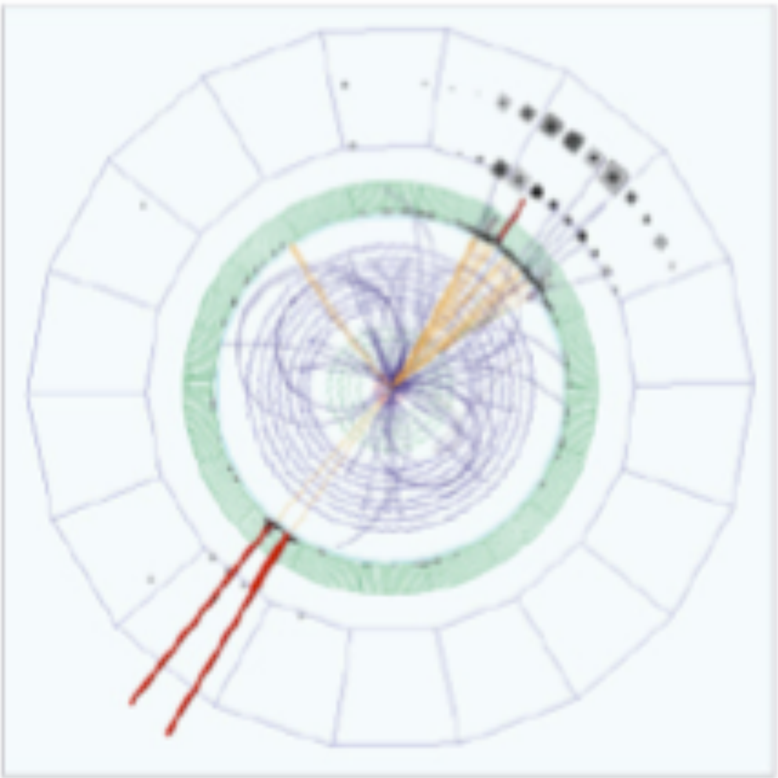


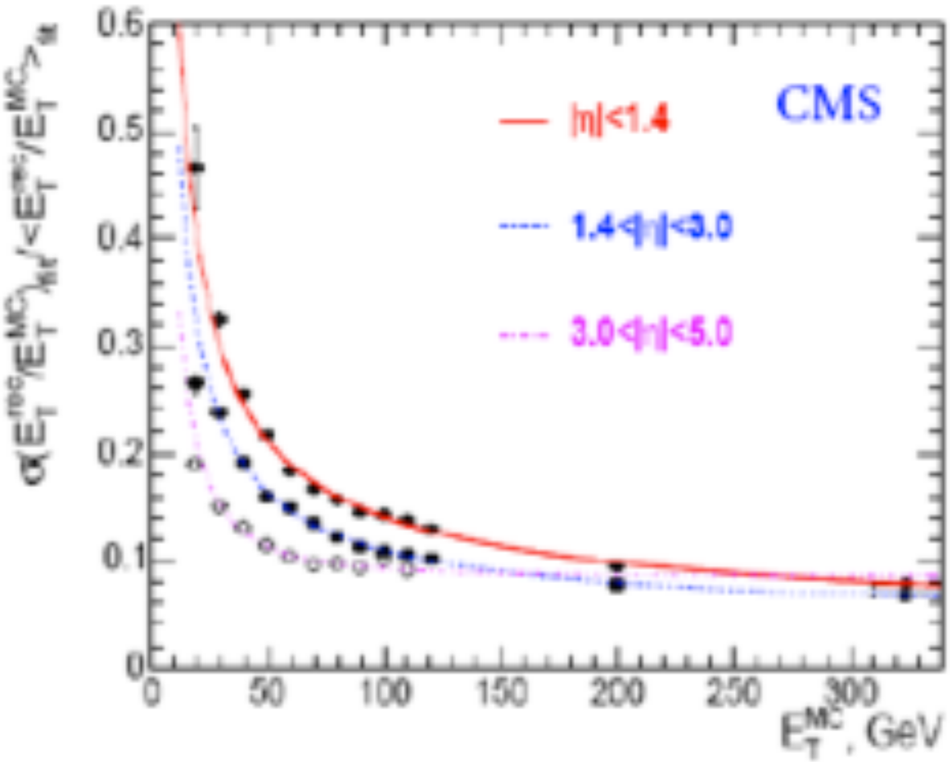
Outline

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

Recall some basics

Jet energy resolution





> 100 % / √E

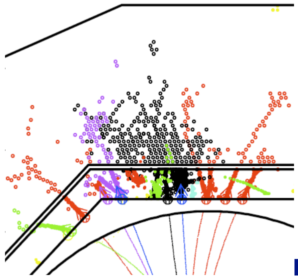
Electrons:

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

0.6% at 50 GeV.

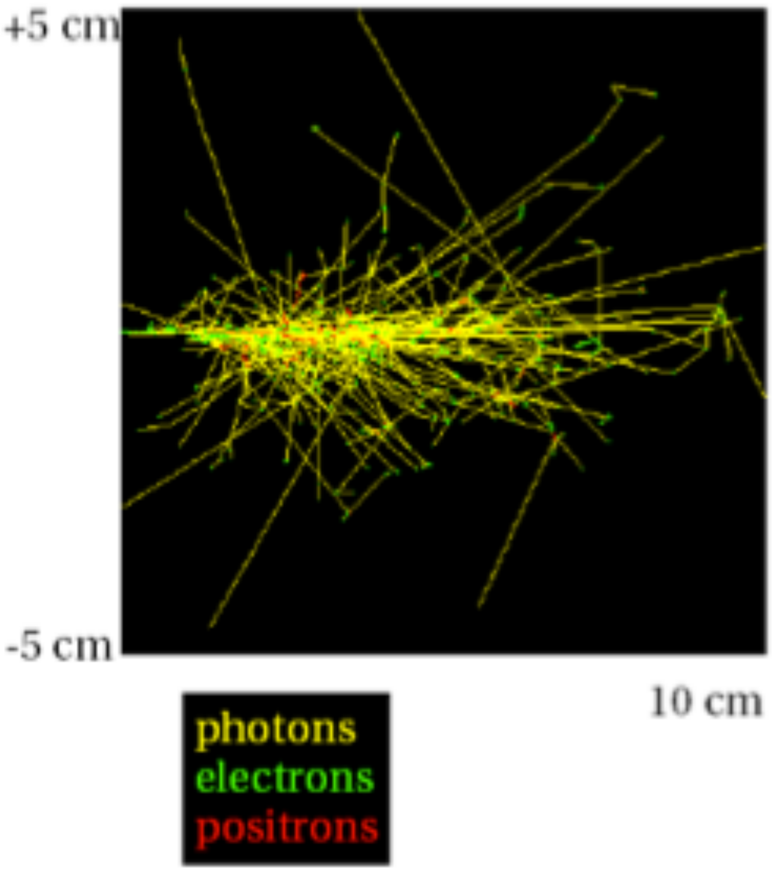
ECAL+HCAL energy resolution for pions:

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

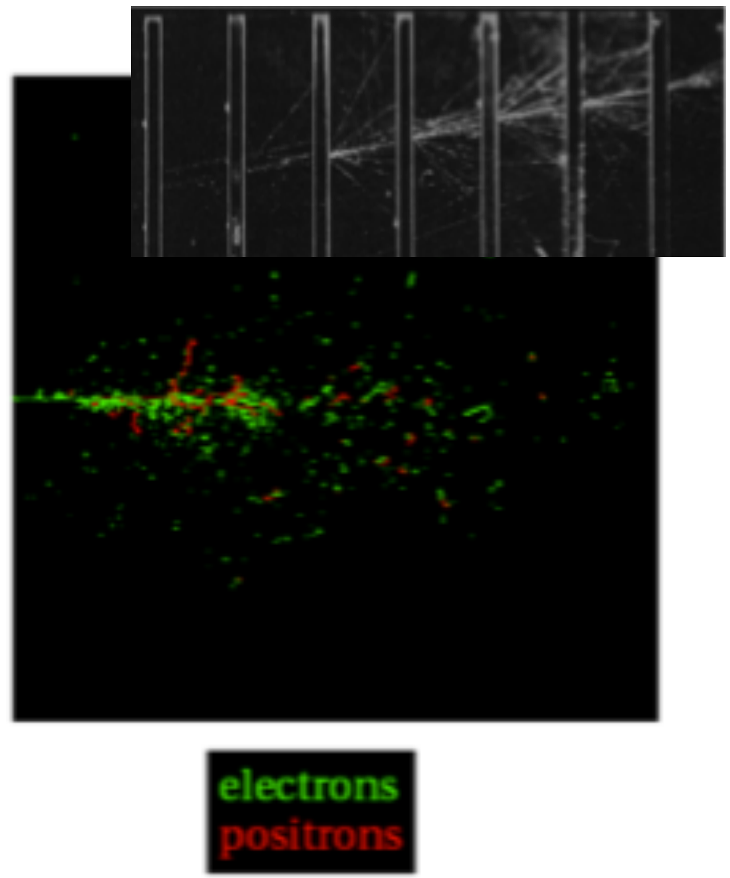


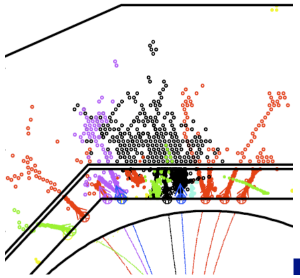
Electromagnetic showers

- Simulation: 1 GeV electron in lead



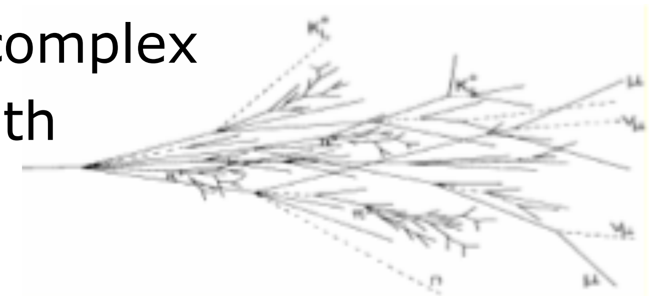
Lead absorbers in cloud chamber

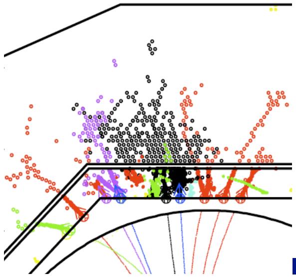




Hadron showers

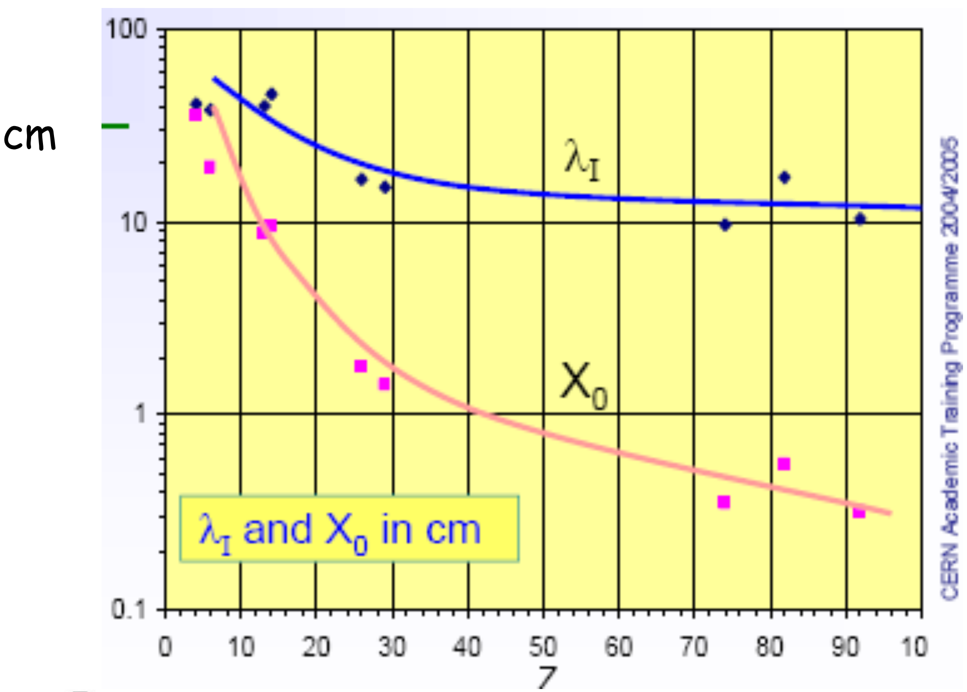
- Hadrons undergo strong interactions with detector (absorber) material
  - Charged hadrons: complementary to track measurement
  - Neutral hadrons: the only way to measure their energy
- In nuclear collisions numbers of secondary particles are produced
  - Partially undergo secondary, tertiary nuclear interactions ➔ formation of a 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

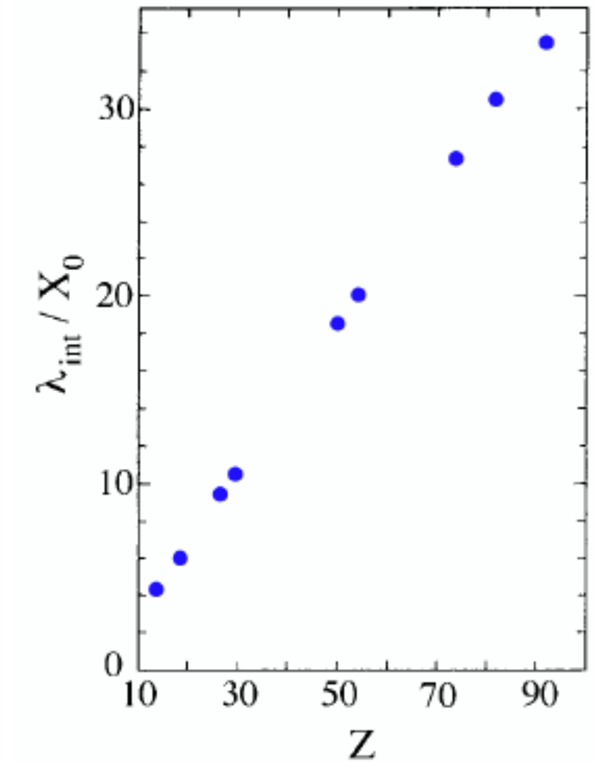




Hadronic interaction length

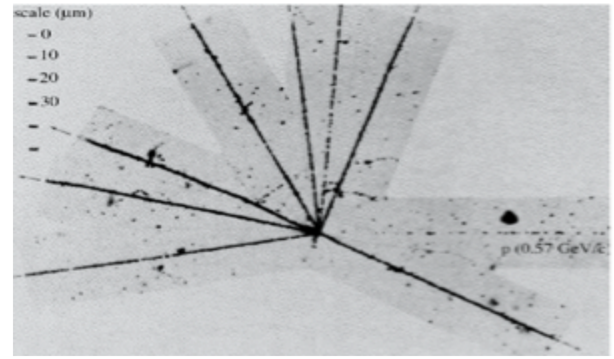
- λ_I: mean free path between nuclear collisions
- Hadron showers are much larger – how much, depends on Z
- Both scales present in every hadron shower



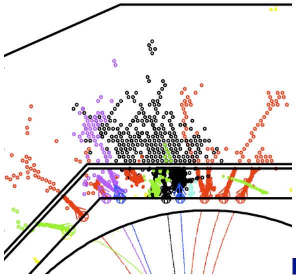


Hadronic interactions

- 1st stage: the hard collision
  - Multiplicity scales with E
  - ~ 1/3 π⁰ ➔ γγ
  - Leading particle effect: depends on incident hadron type,
    - e.g fewer π⁰ 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



- 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

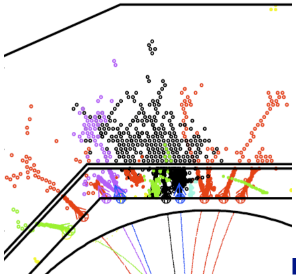


Electromagnetic fraction

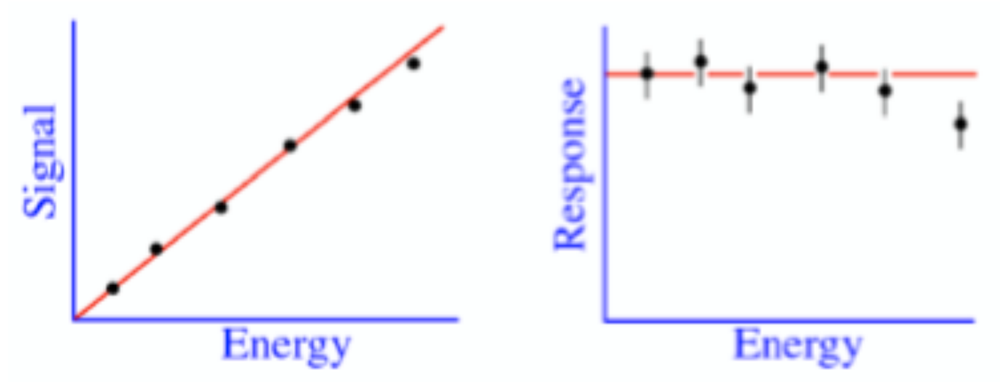
- In first collision, ~ 1/3 of produced particles are π^0
- $\pi^0 \rightarrow \gamma\gamma$ produce em shower, no further hadronic interaction
- Remaining hadrons undergo further interactions, more π^0

- 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

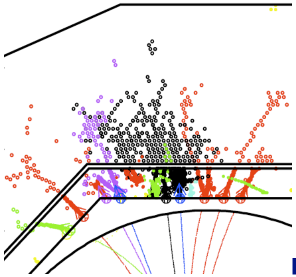
- Large fluctuations
  - E.g. charge exchange $\pi^- p \rightarrow \pi^0 n$ (prb 1%) gives f_{em} = 100%



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 principle for jets
  - 2 particles at 50 GeV not equal to 1 particle at 100 GeV
  - Non-linearity cannot simply be "calibrated away"

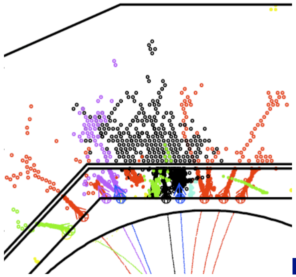


Compensation

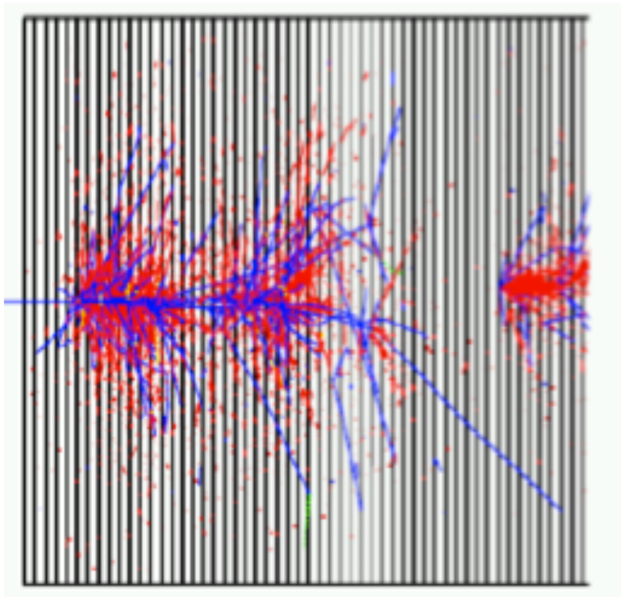
Different strategies, which can also be combined

- Hardware compensation
  - Reduce em response
    - High Z, soft photons
  - Increase had response
    - Neutron part (correlated with binding energy loss)
      - Tuneable via thickness of hydrogenous detector
  - Example ZEUS: uranium scintillator,
  - 35% /√E for hadrons, 45% /√E for jets
- Software compensation
  - Identify em hot spots and down-weight
    - Requires high 3D segmentation
  - Example H1, Pb/Fe LAr, ~ 50% /√E for hadrons

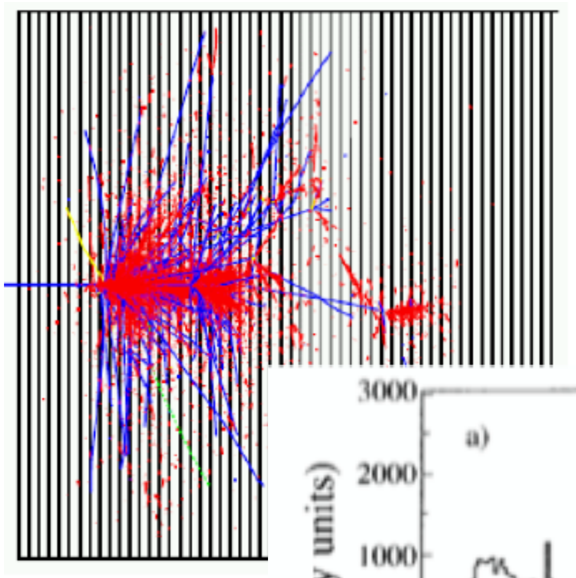
NB: Do not fully remove fluctuations in invisible energy



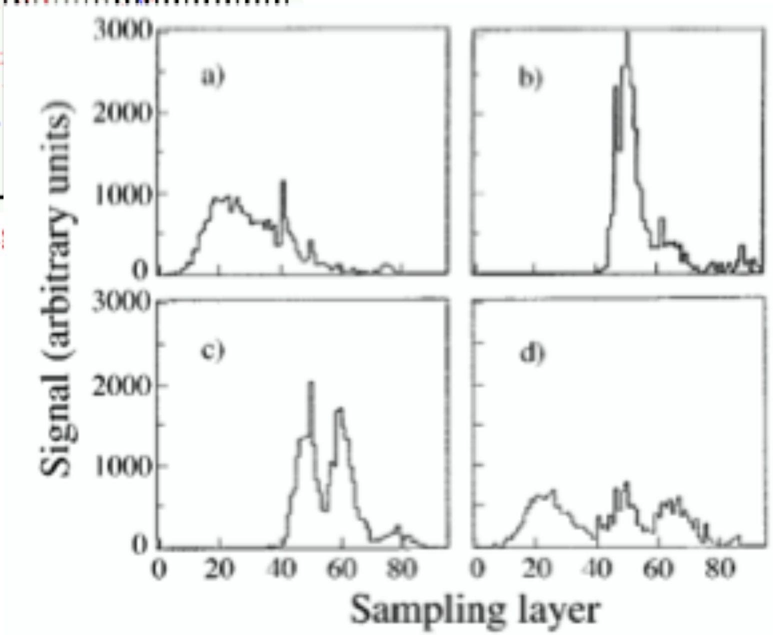
More fluctuations



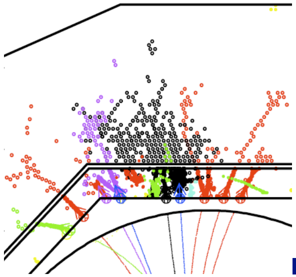
blue = hadronic component



red = electroma



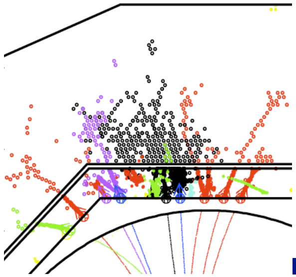
Leakage: in principle no problem
But: leakage fluctuations are!
(rule of thumb: $\sigma_{leak} \sim 4\ f_{leak}$)



Hadron and jet calorimetry:

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

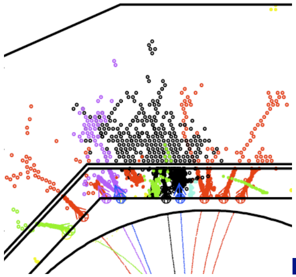
- Jet energy performance = hadron performance or worse



New concepts

- Hardware (and software): ultimate compensation by directly <u>measuring</u> the electromagnetic component in each event, in addition to the total energy, and correcting for it
- ➔ dual readout calorimeters
  - scintillator light to measure total energy
  - Cerenkov light to measure relativistic e/m part
  - 41% /√E for pions achieved

- 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

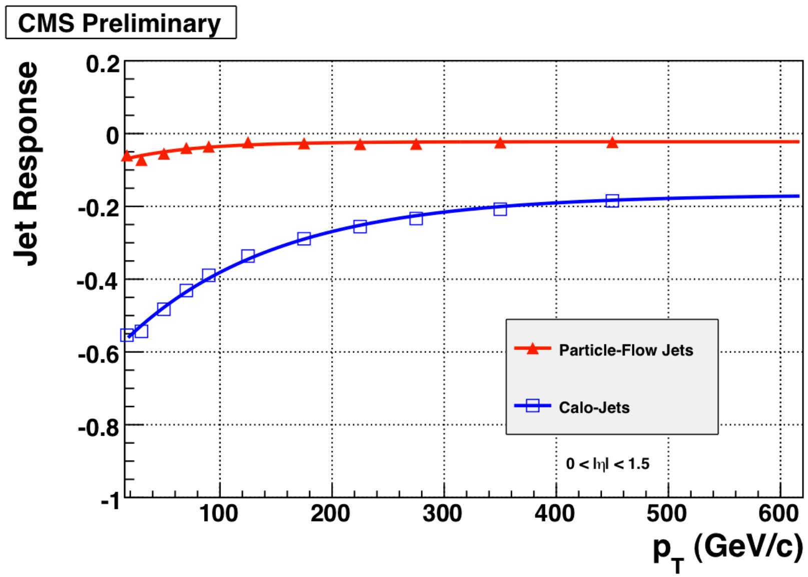


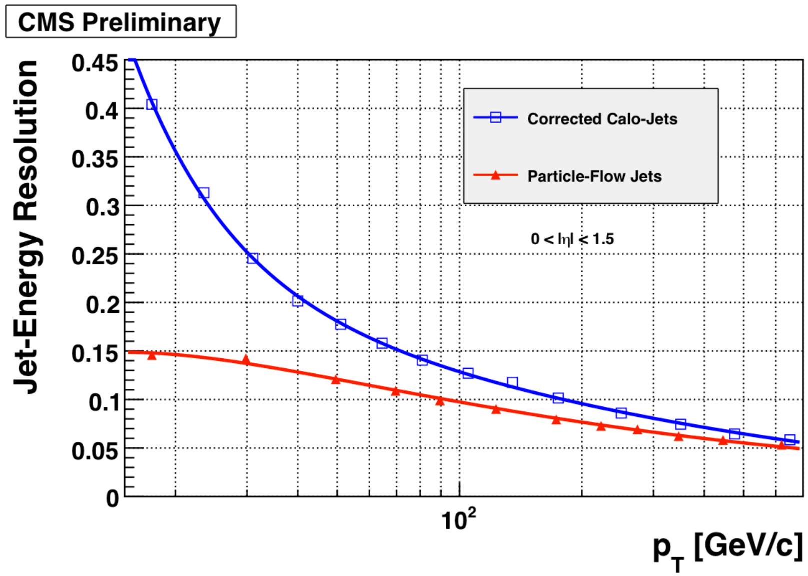
DREAM

DREAM

Jet pT Response and Resolution

Response   CMS   Resolution for *corrected* jets





Energy correction: $f(\eta, p_T)$ → brings response to 1

Adding a dependence on jet contents does not bring anything

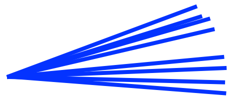
http://cdsweb.cern.ch/record/1194487?ln=en

Colin Bernet

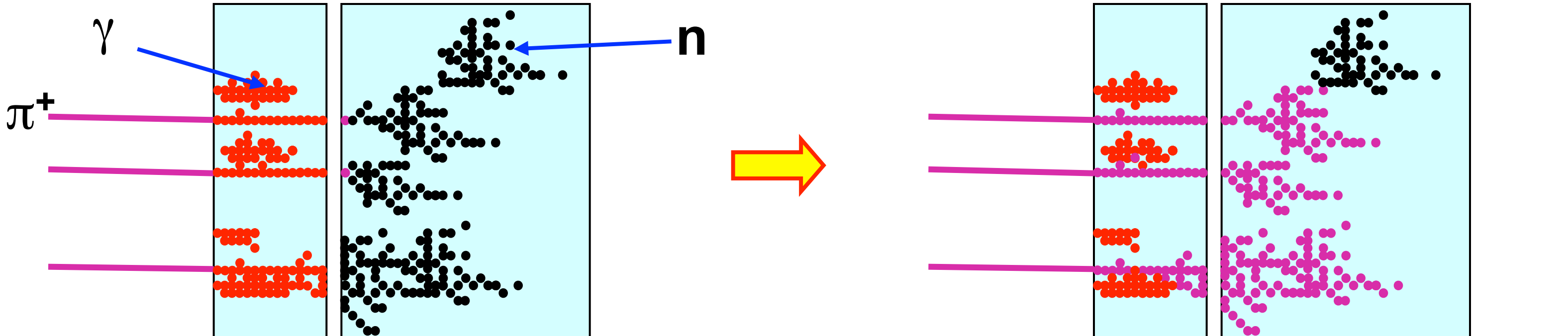
Particle flow concept and detectors

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: $\sigma_\mathrm{E}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Intrinsically "poor" HCAL resolution limits jet energy resolution



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

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

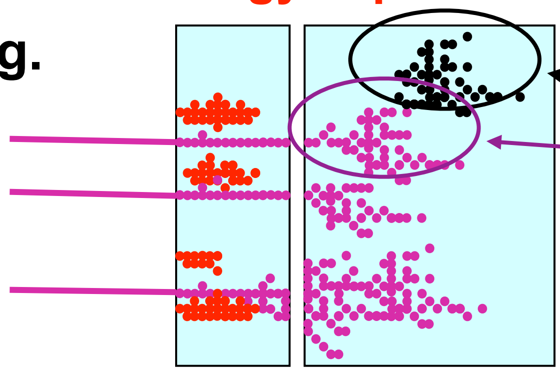
- **Particle Flow Calorimetry paradigm:**
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_\mathrm{E}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⇒ much improved resolution

Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

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

e.g.

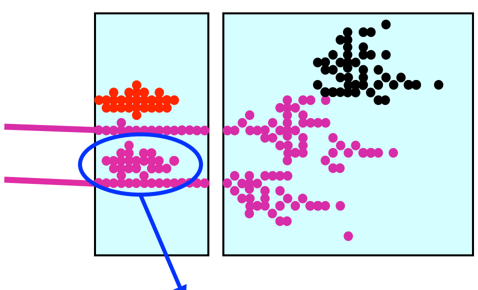


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

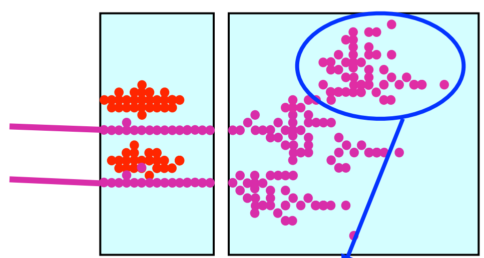
Three types of confusion:

i) Photons



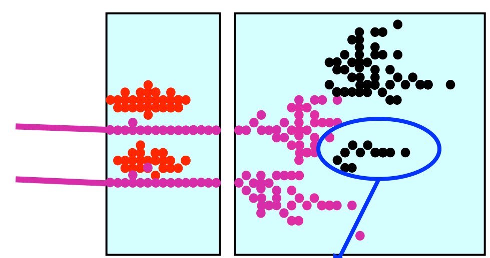
Failure to resolve photon

ii) Neutral Hadrons

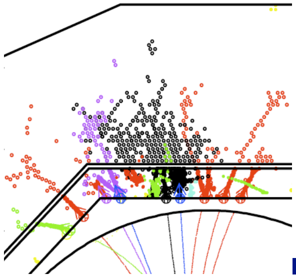


Failure to resolve neutral hadron

iii) Fragments

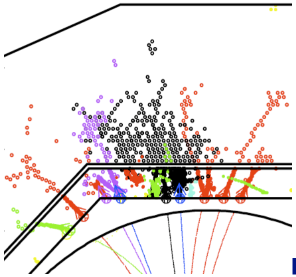


Reconstruct fragment as separate neutral hadron



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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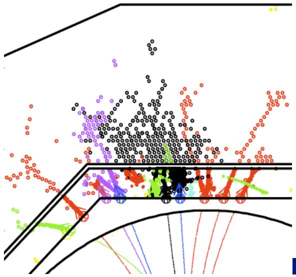
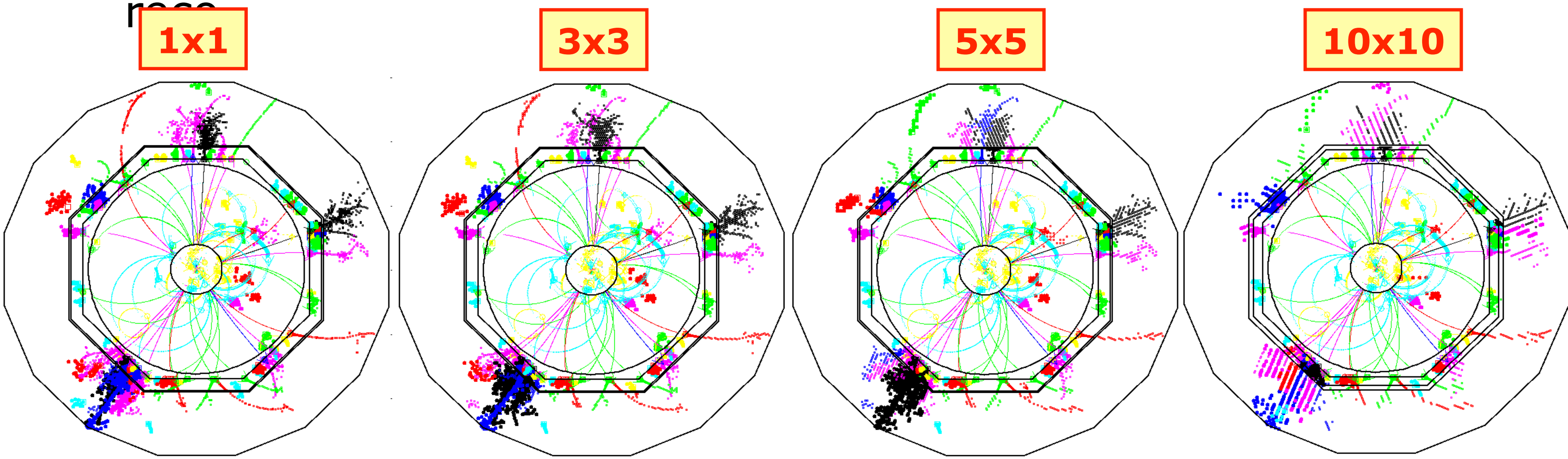
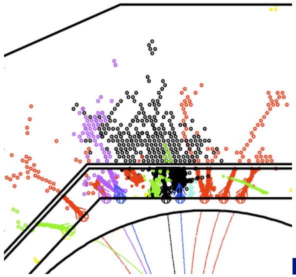


Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco



M.Thomson (Cambridge)



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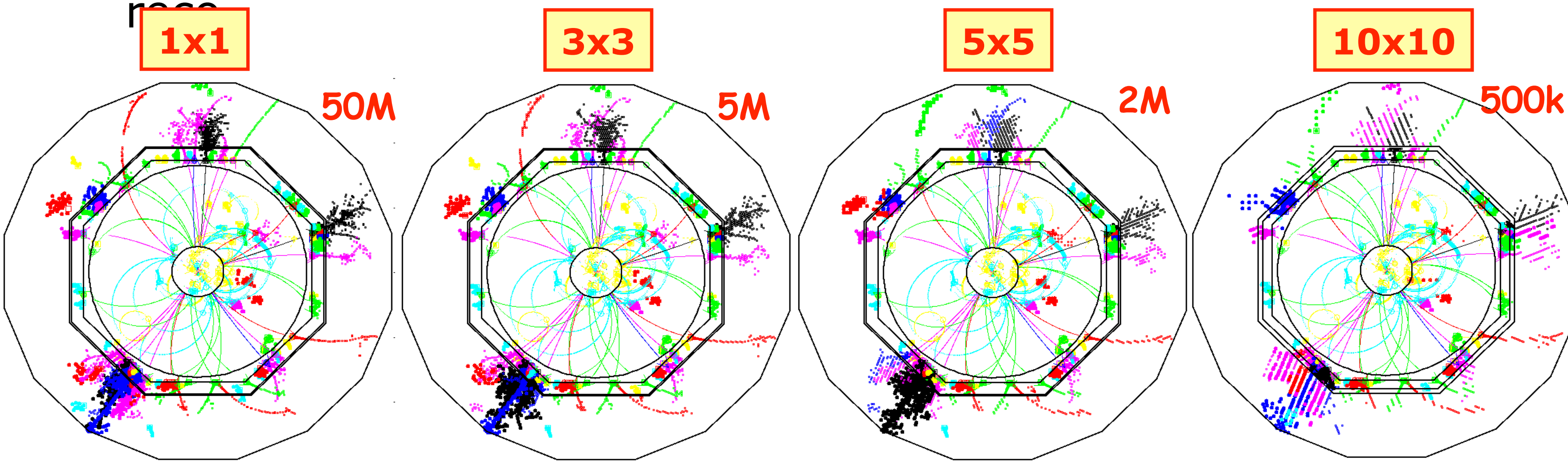

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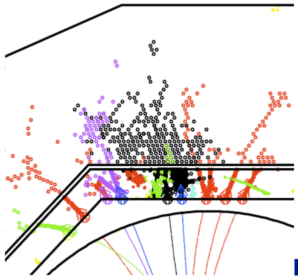

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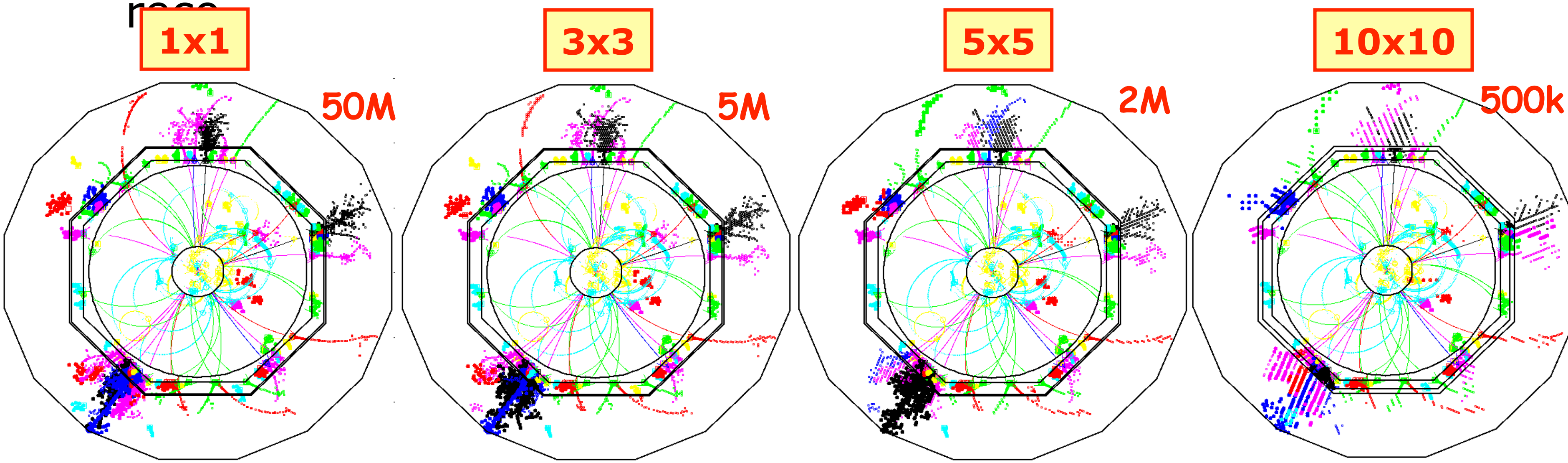

- Confirms earlier studies for test beam prototype
- 3x3 cm^2 nearly optimal

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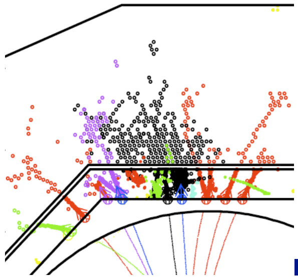

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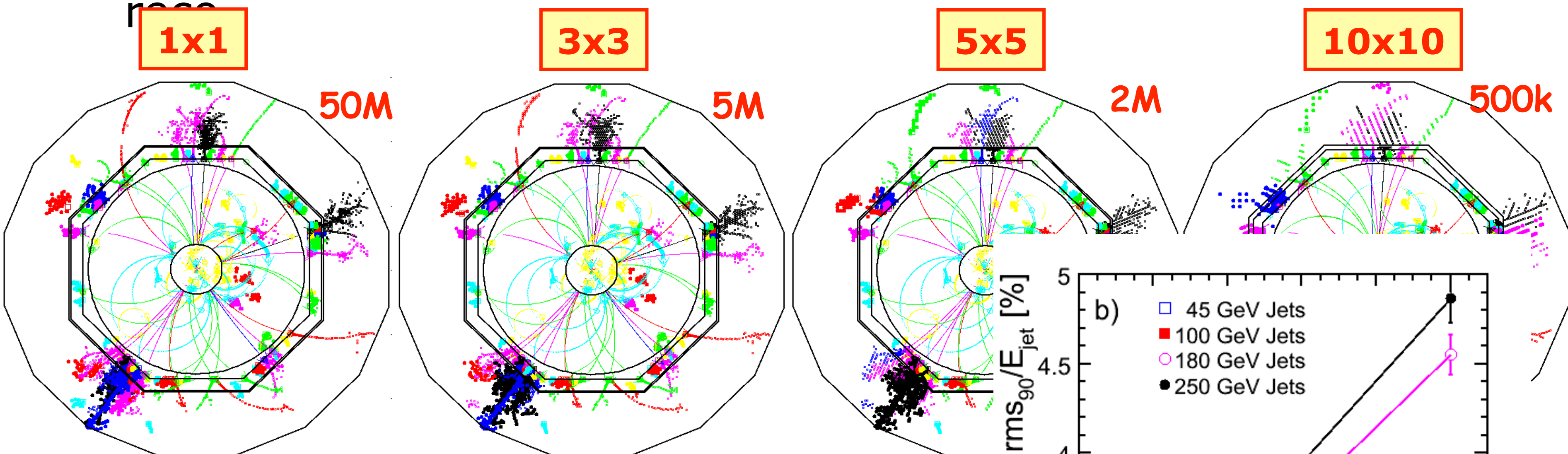

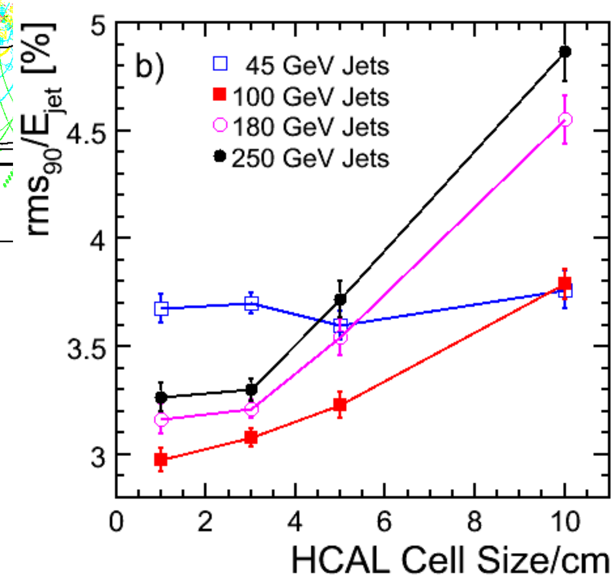

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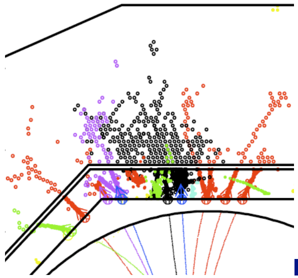
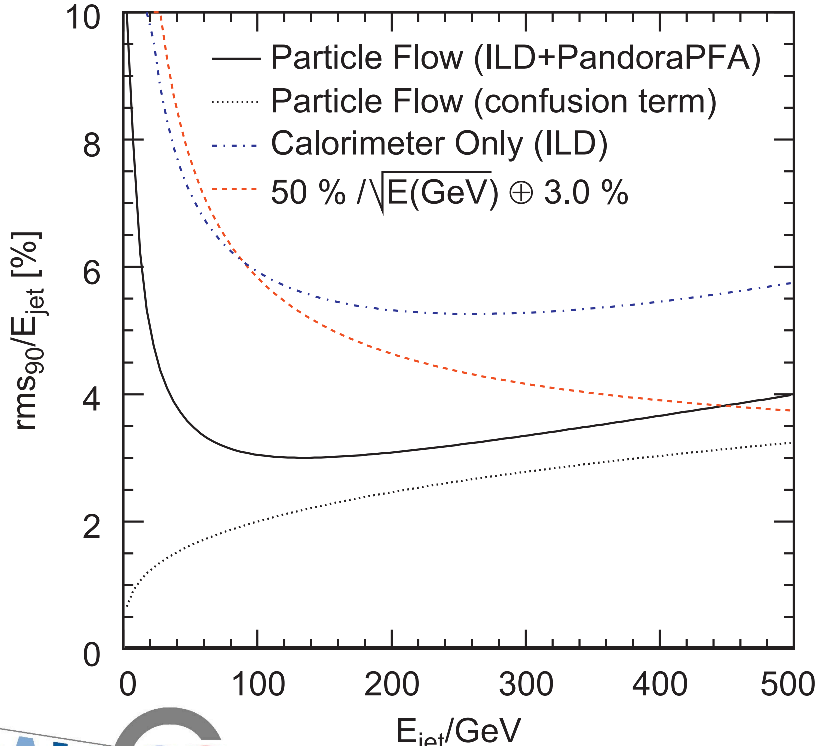
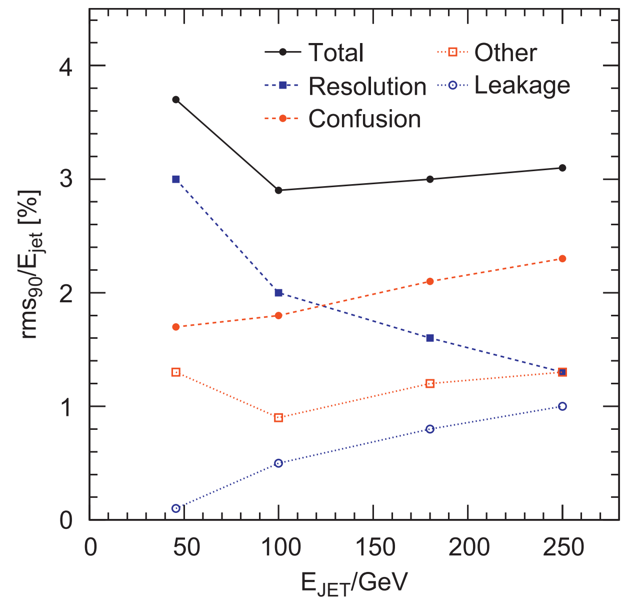


Understand particle flow performance

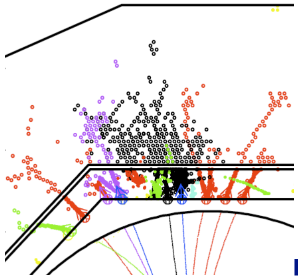
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution — Tracking — Leakage — Confusion





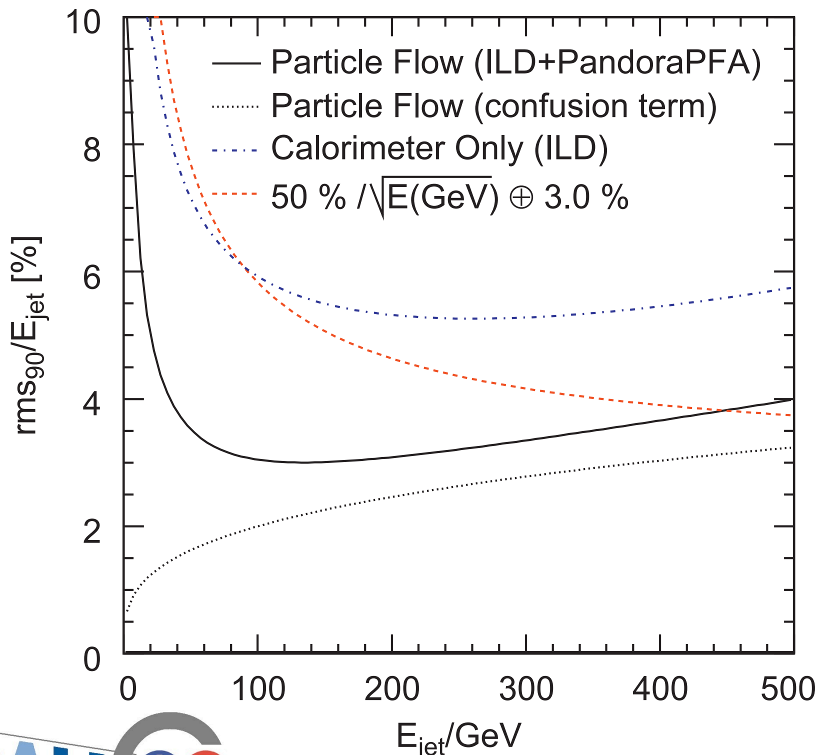
- Particle flow is always better
  - even at high jet energies
- HCAL resolution does matter
  - also for confusion term
- Leakage plays a role, too

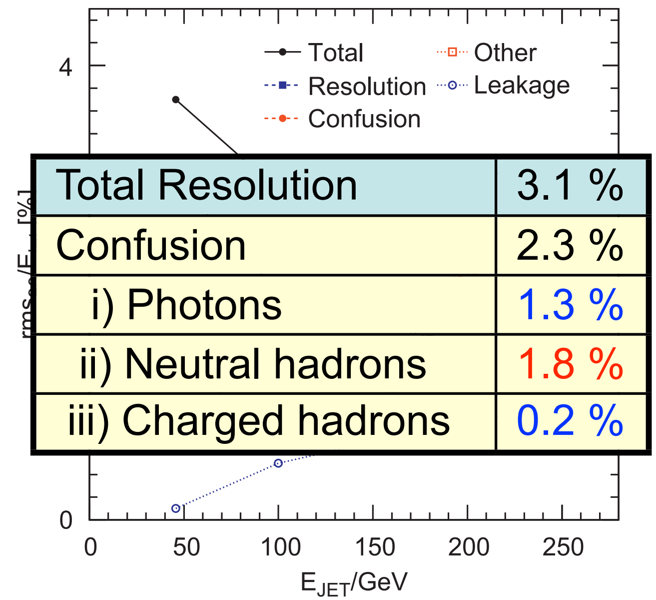


Understand particle flow performance

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

Resolution | Tracking | Leakage | Confusion





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

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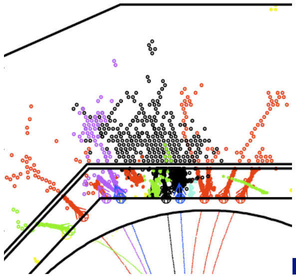


PFLOW detector concept

- 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

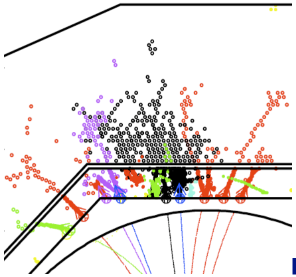
- Basic detector parameters thoroughly optimized

- A PFLOW detector is not cheap: do we believe in simulations?

Validation of the simulations

detector performance

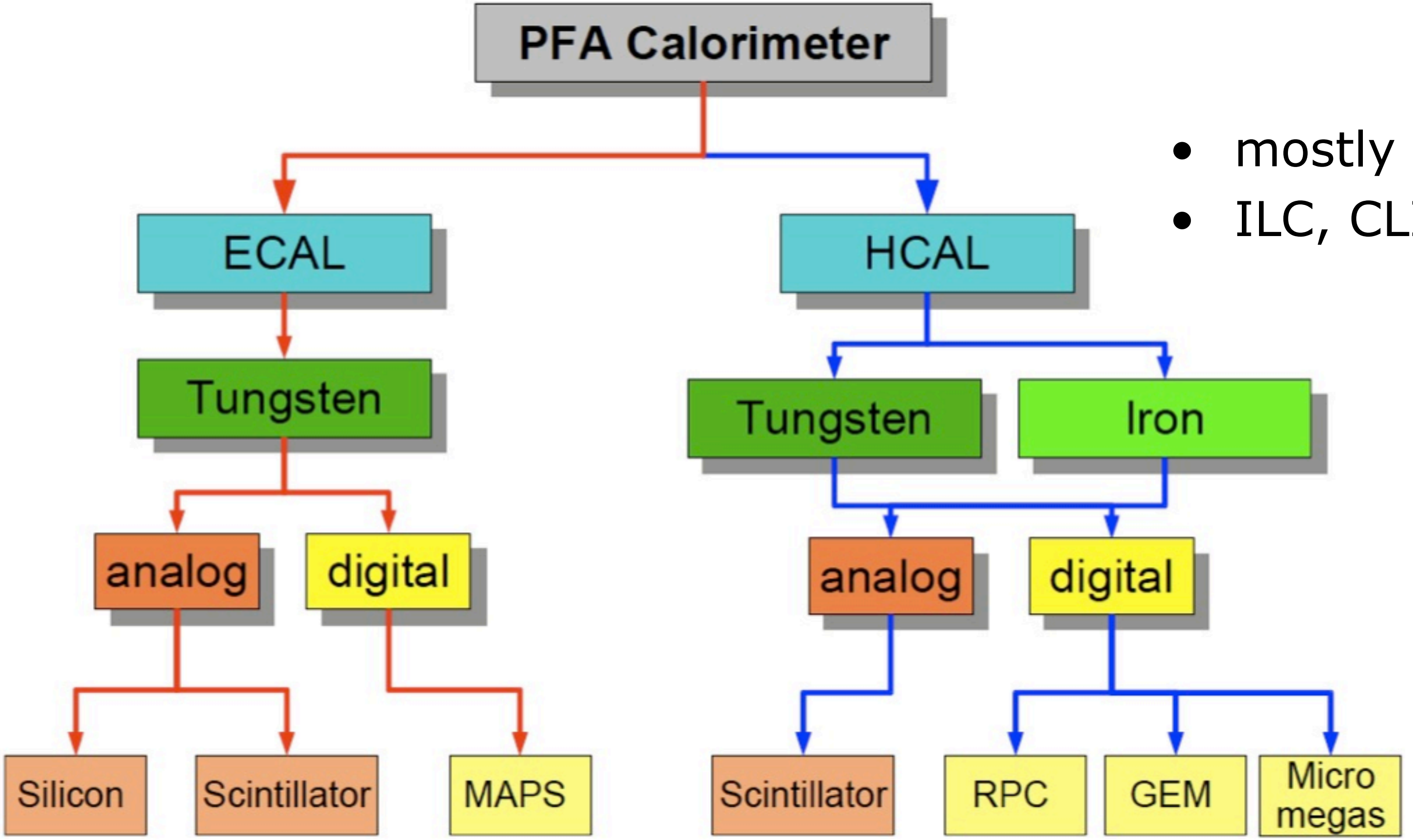
shower models



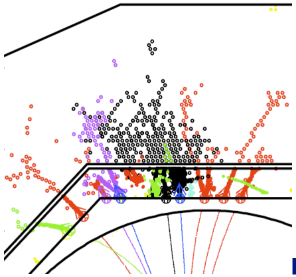
CALICE

- 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

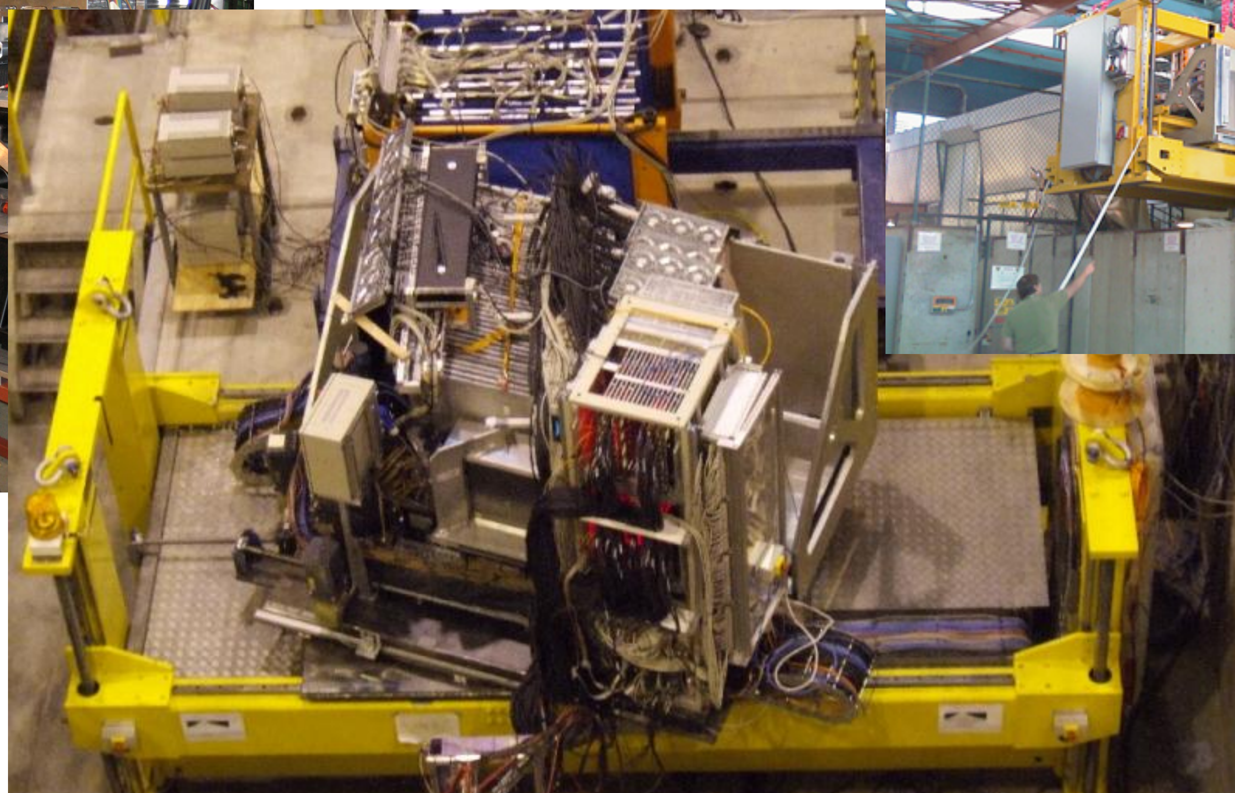
Technology tree



- mostly ILD, SiD
- ILC, CLIC



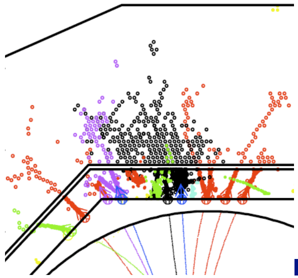
Test beam experiments



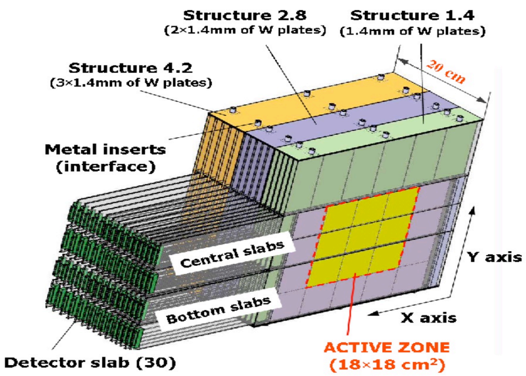
CERN 2006-2007

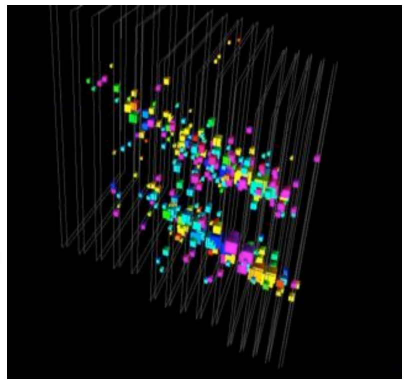
FNAL 2008..

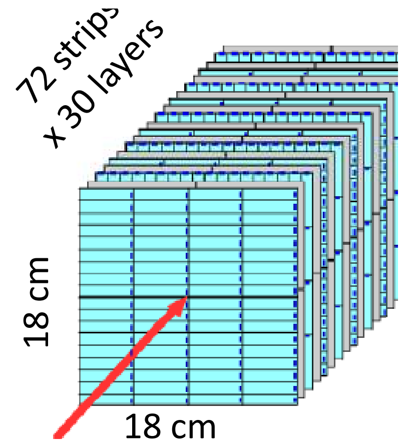
DESY 2005

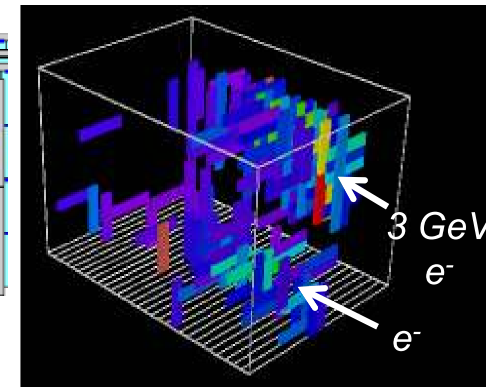


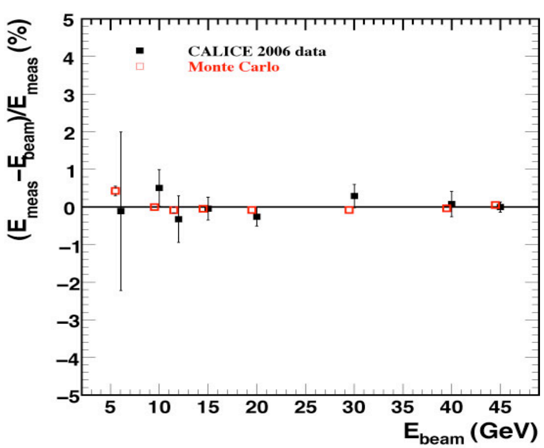
ECAL options

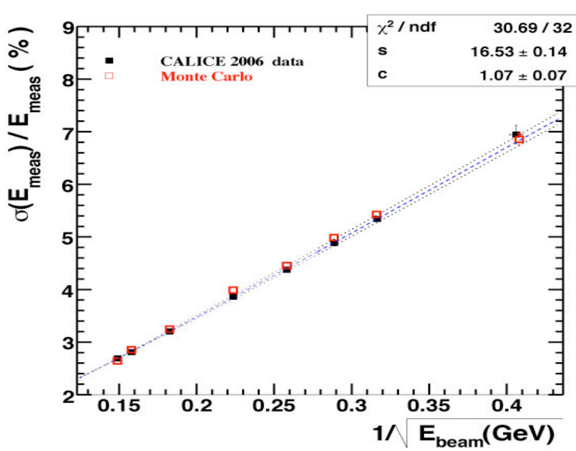


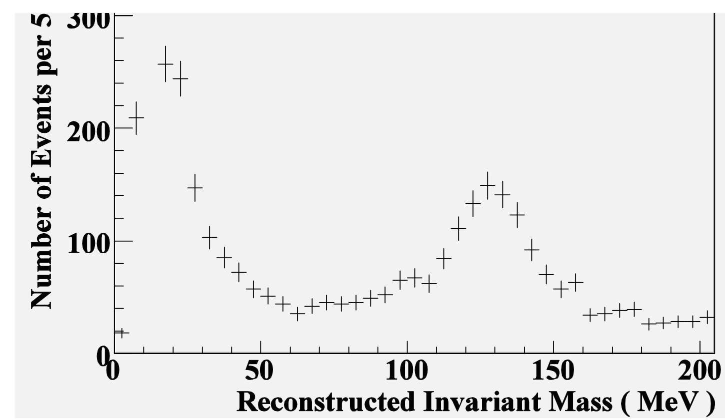




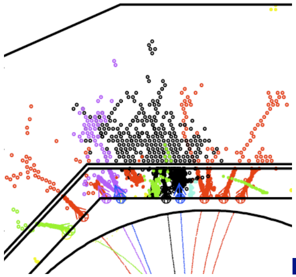






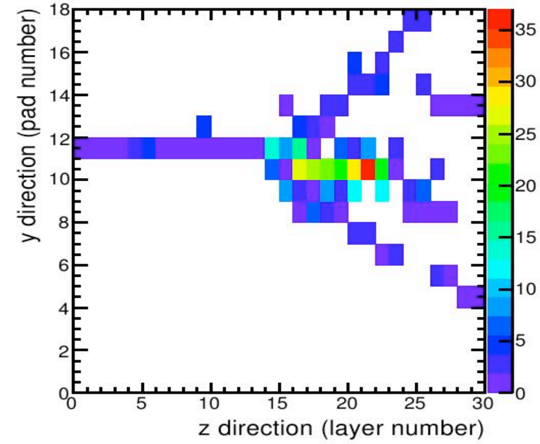


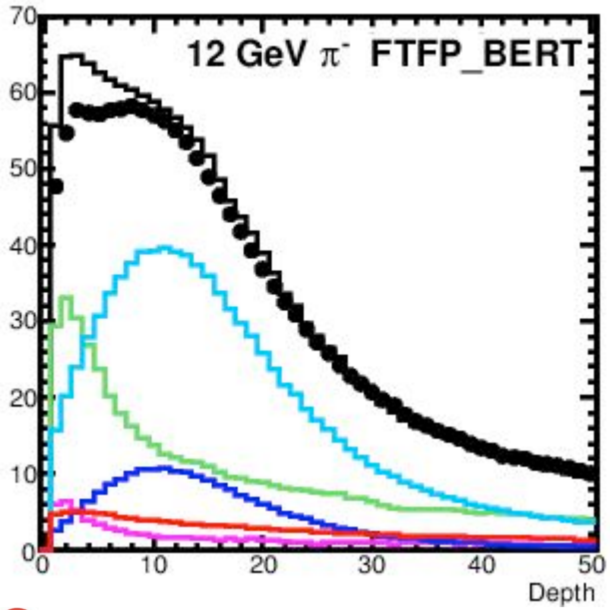
- W Si or Sci: common mechanics, similar electronics



Pions in the SiW ECAL

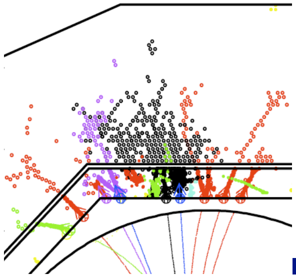
- test Geant 4 predictions with 1 cm^2 granularity
- sensitive to shower decomposition
- favor recent G4 physics lists
- certainly not perfect - certainly not bad either!





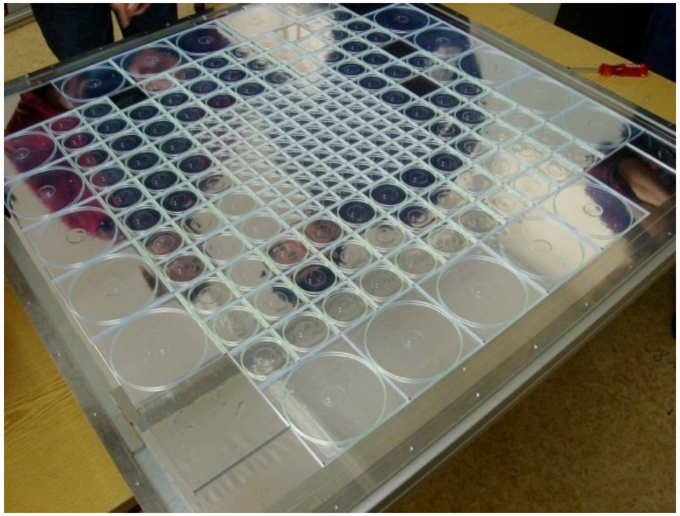
Shower Components:

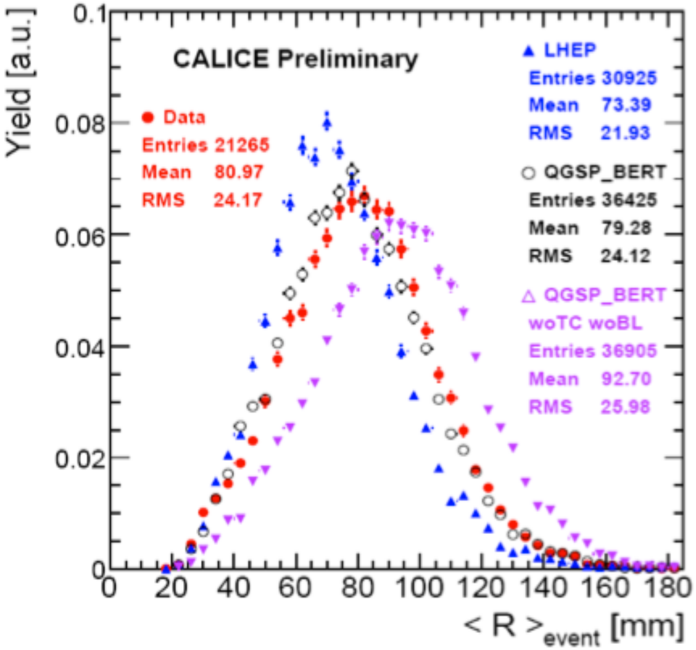
- electrons/positrons
  knock-on, ionisation, etc.
- protons
  from nuclear fragmentation
- mesons
- others
- sum



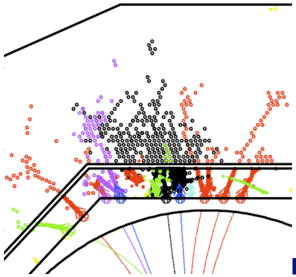
Fe Scint tile HCAL

- 38 layers steel sandwich
- 7600 tiles with SiPMs

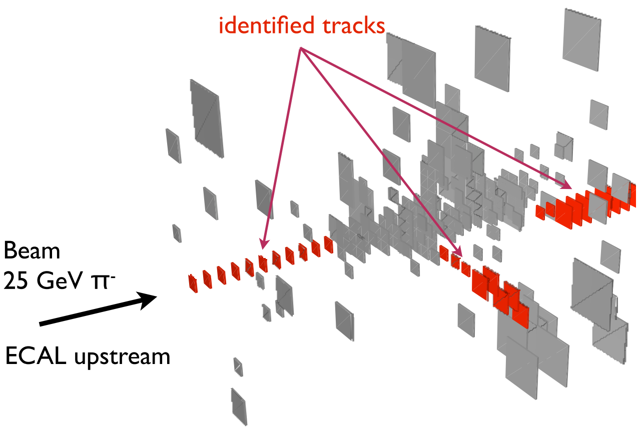


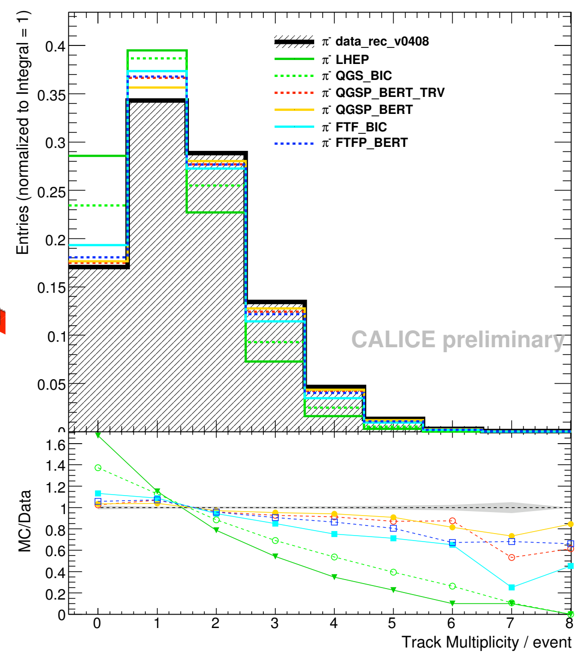


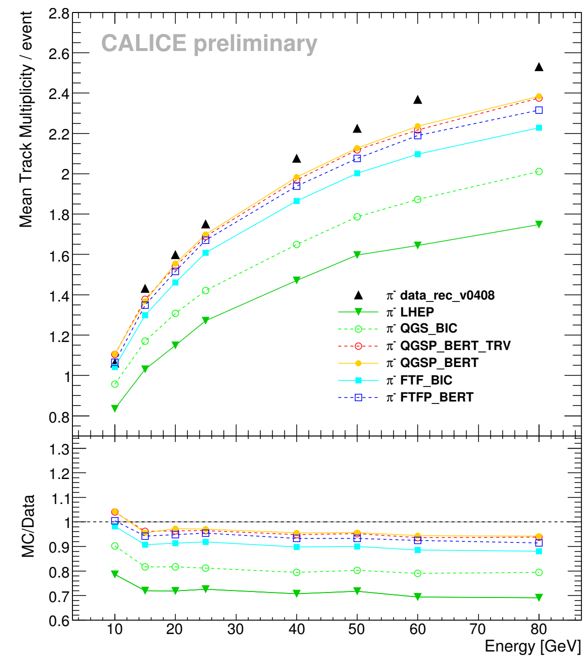
- Present-day simulation quality requires good detector understanding to discriminate
- Fluctuations also well reproduced



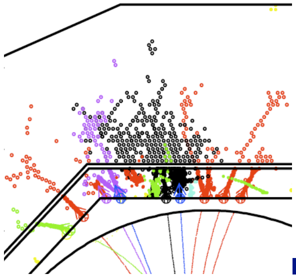
Shower fine structure







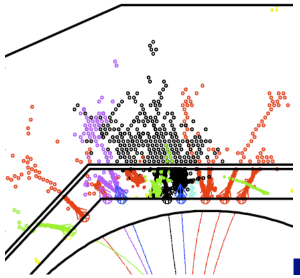
- Could have the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already - for more recent models



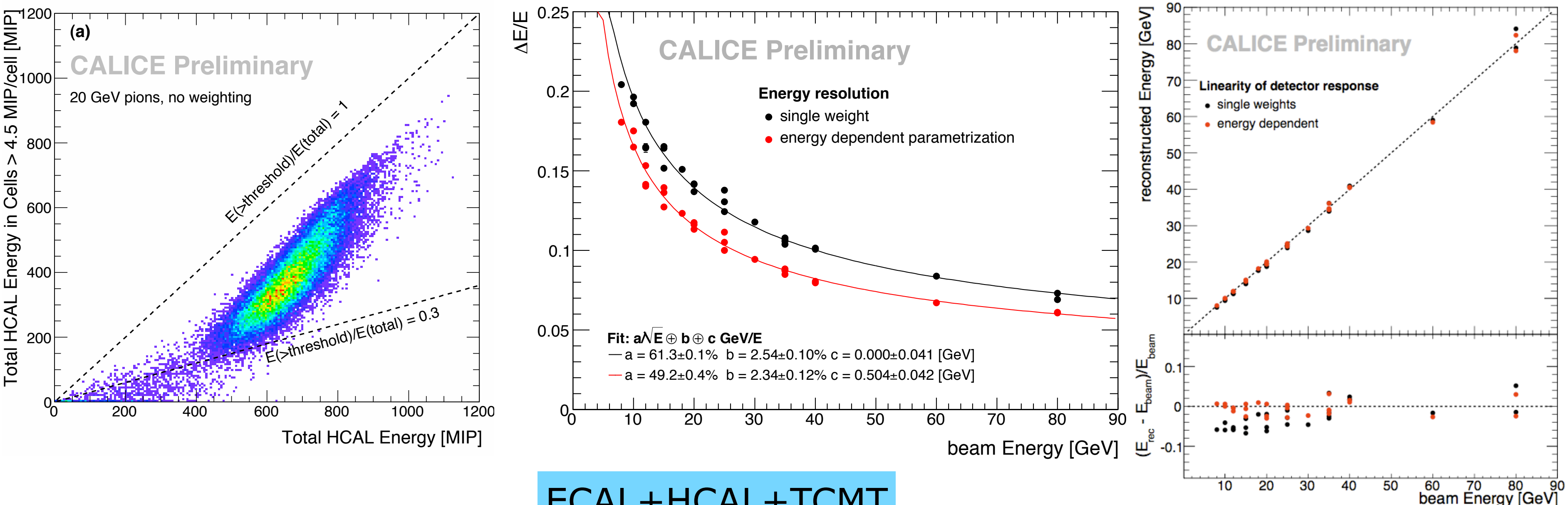
Summary on validation:

- 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

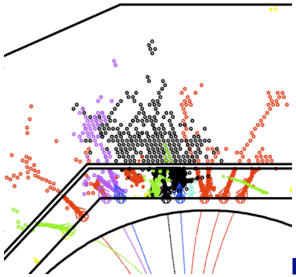


Resolution, compensated

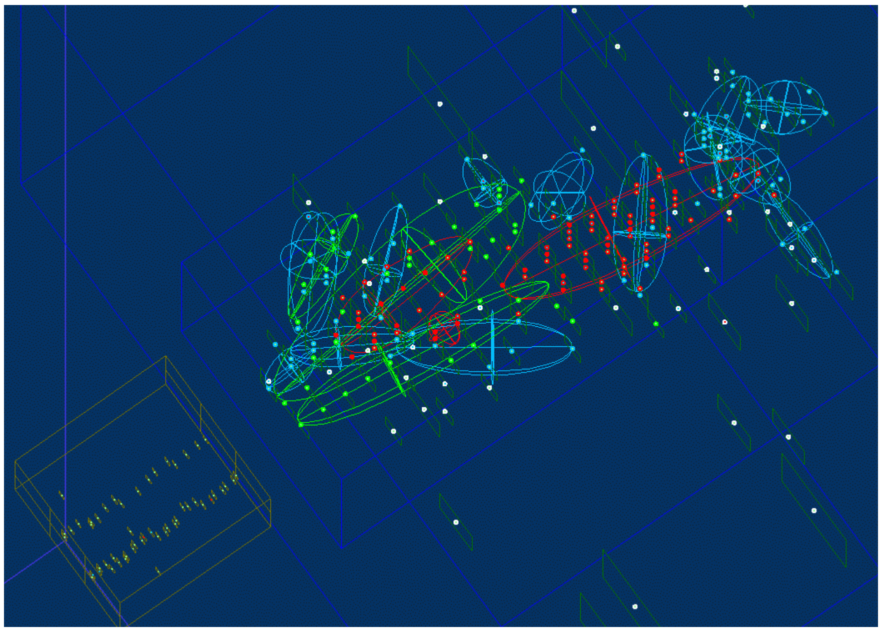


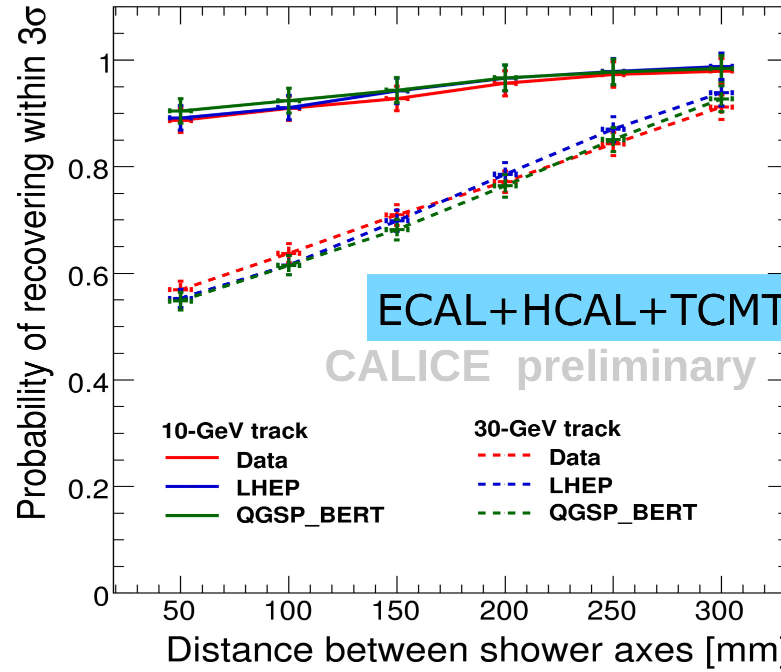
ECAL+HCAL+TCMT

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



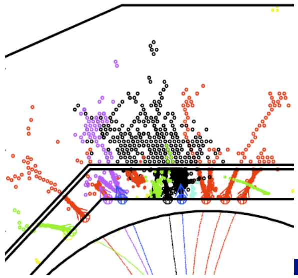
PFLOW: two-particle separation





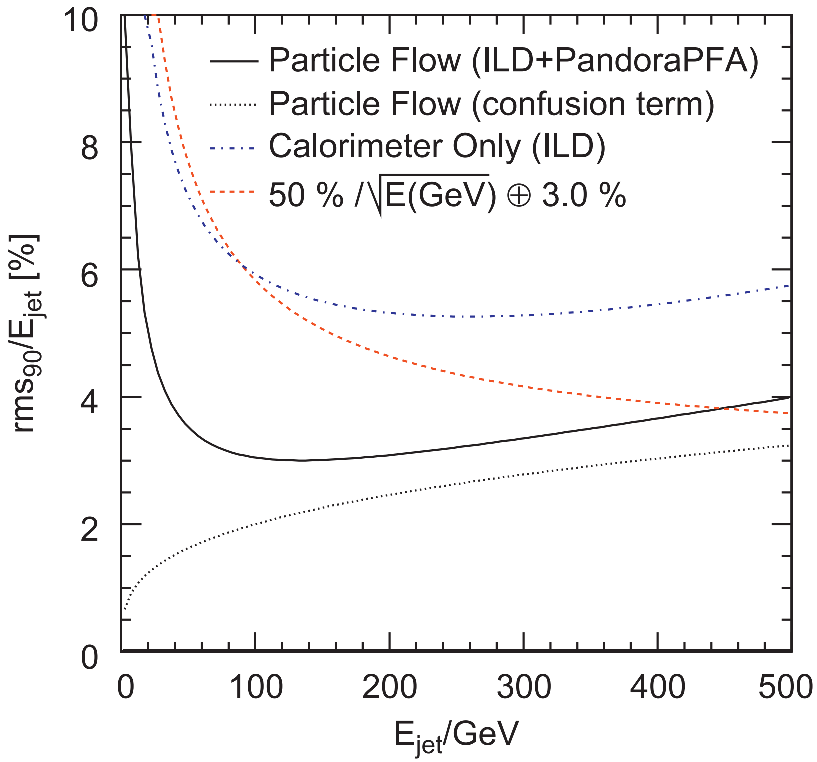
- The “double-track resolution” of an imaging calorimeter
- Small occupancy: use of event mixing technique possible
- Important: agreement data - simulation
  - sharing the same limitations

to be done with photons, too

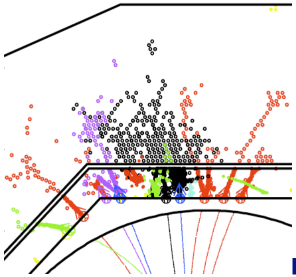


Summary on algorithms

- 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

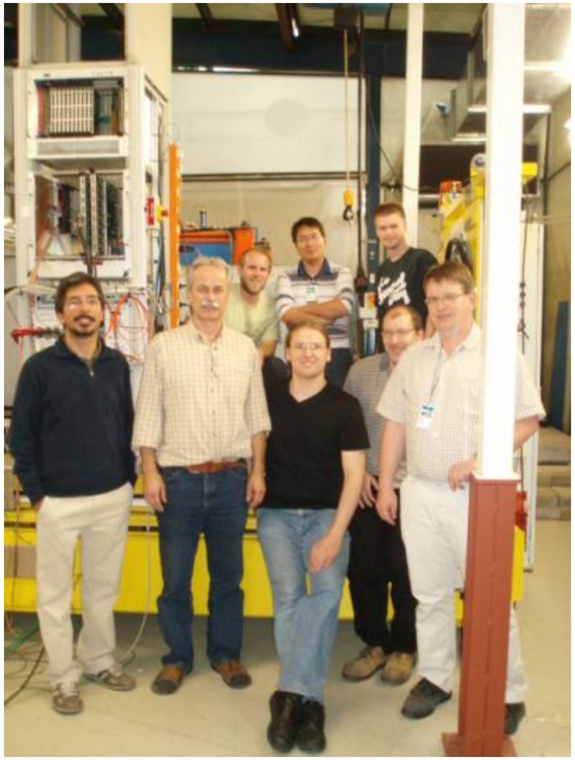


Test beam experiments 2010+

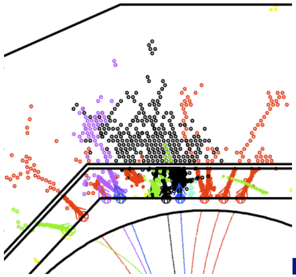
DESY

CERN

FNAL

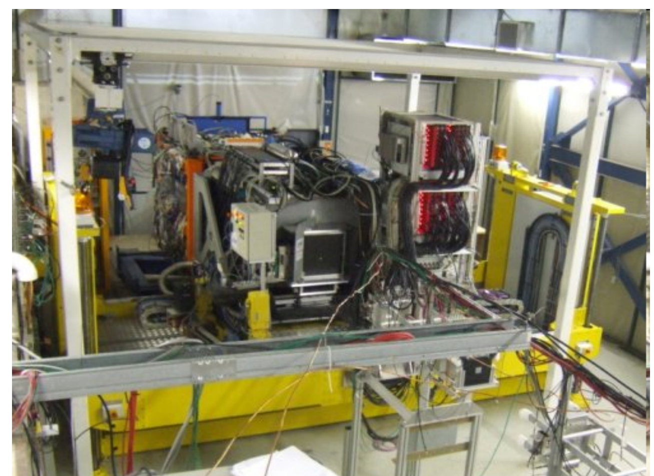


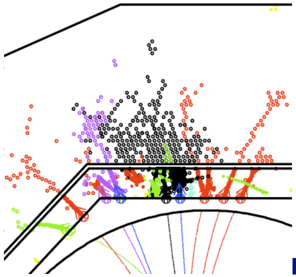
and more:
RPCs, power pulsing in B field, micromegas, GEMs



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





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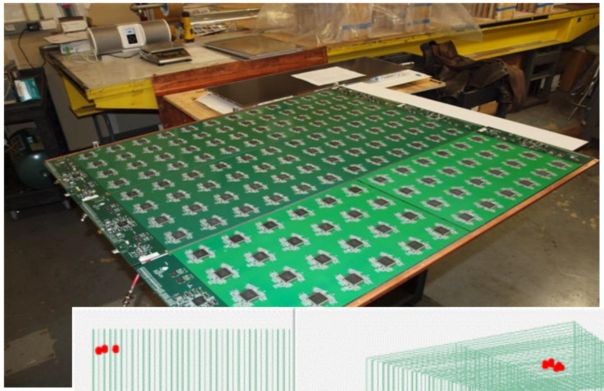
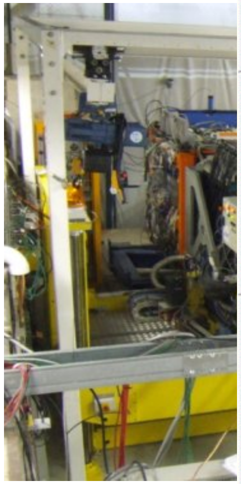
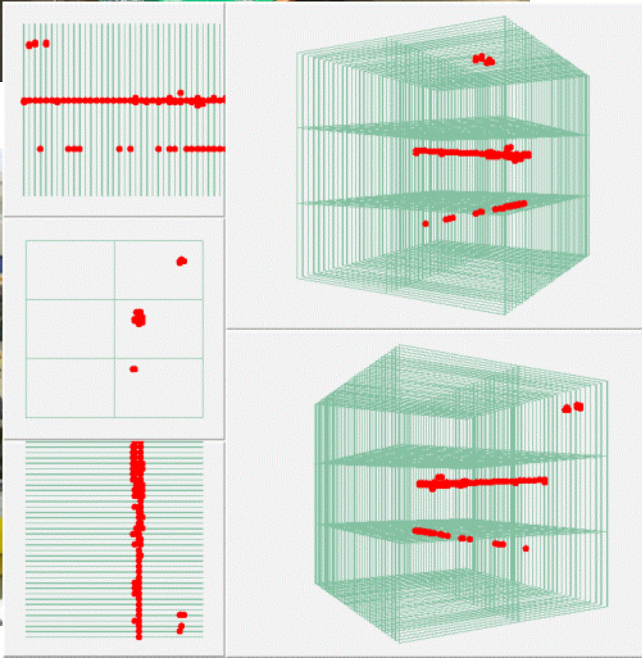
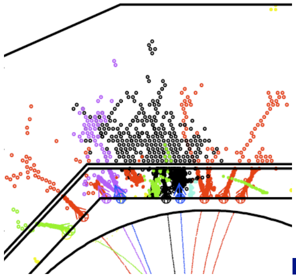






Calorimeter for ILC



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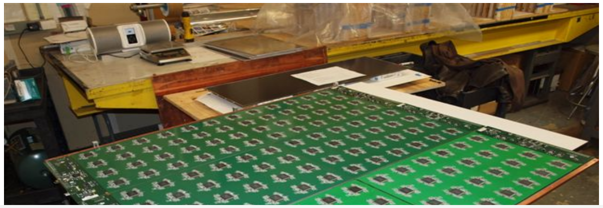
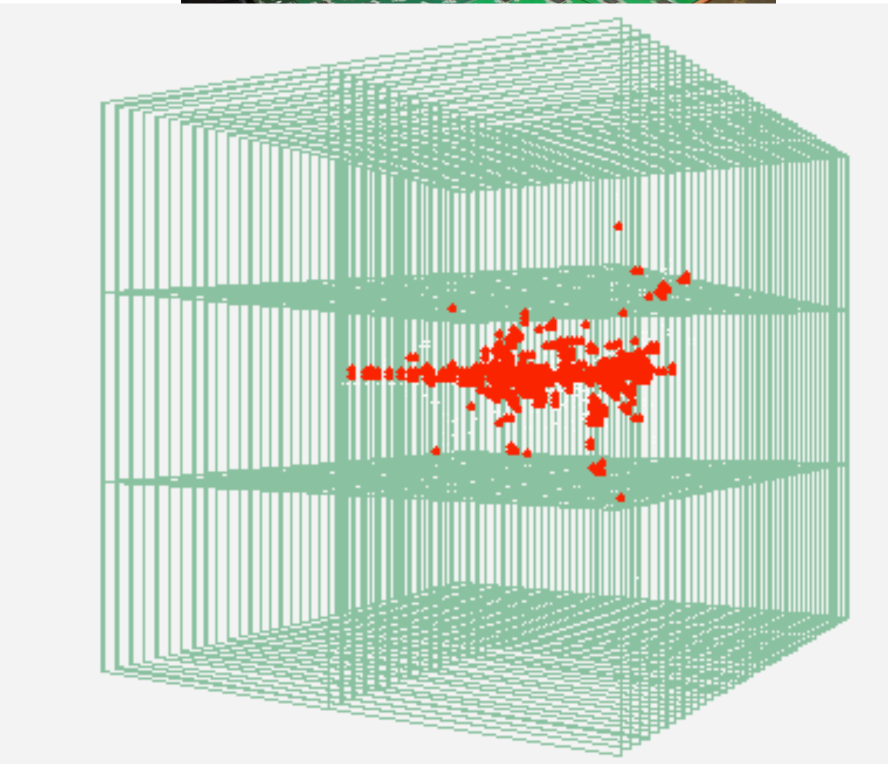
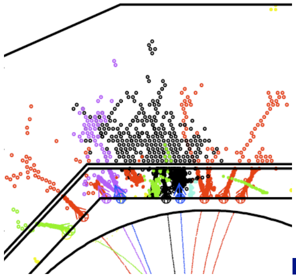
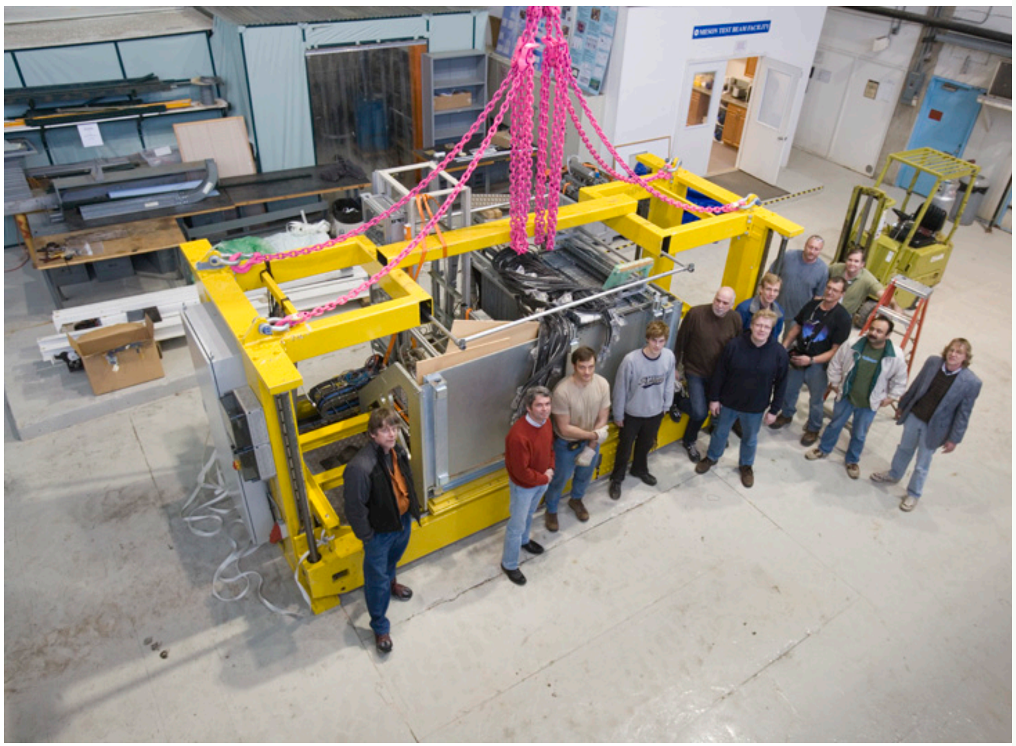


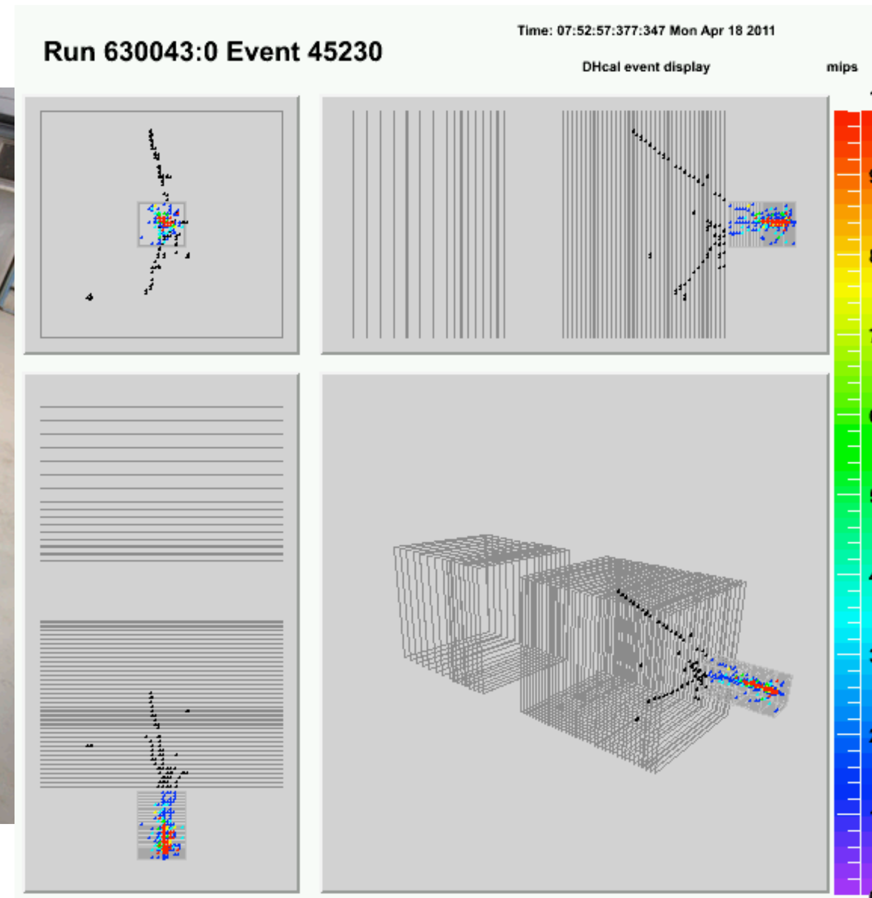


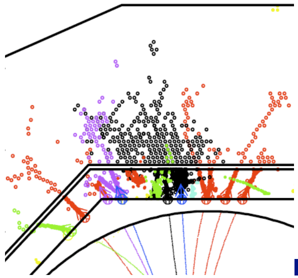


Thank you, DESY

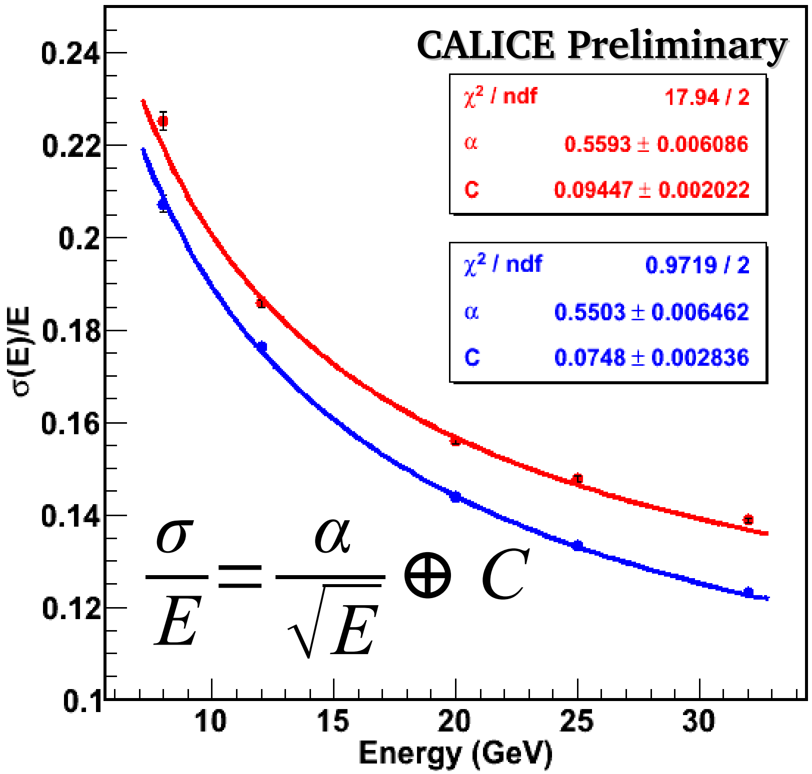
- The DHCAL test at Fermilab uses the AHCAL absorber and movable stage which were built at DESY with this in mind







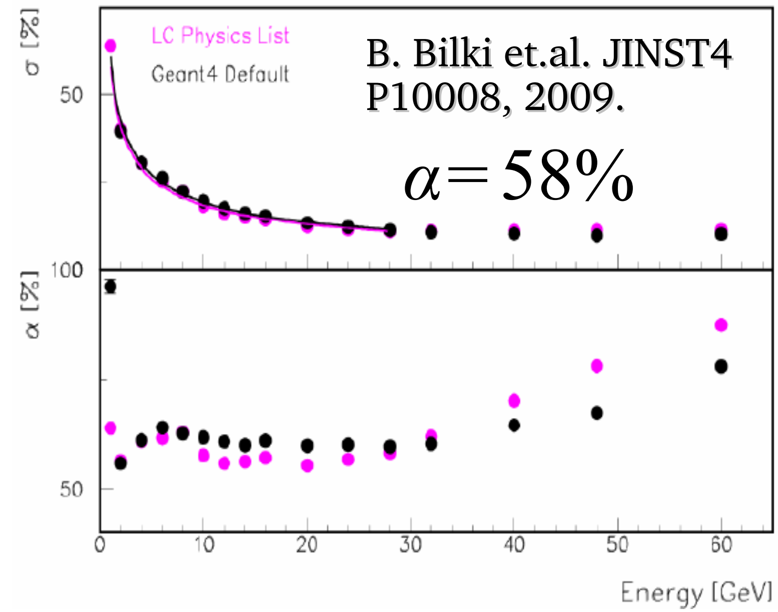
DHCAL results: pions



32 GeV data point is not included in the fit.

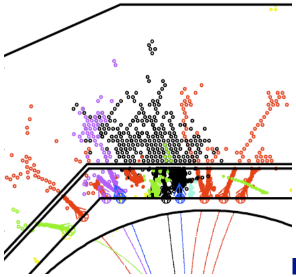
Standard pion selection

+ No hits in last two layers



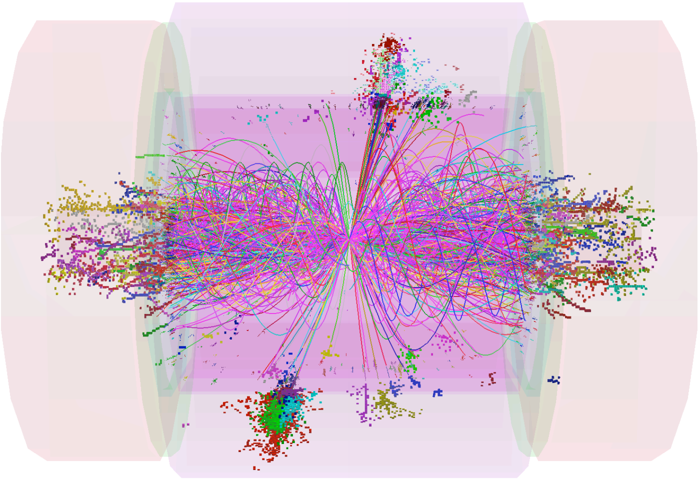
MC predictions for a large-size DHCAL based on the small-size prototype results.

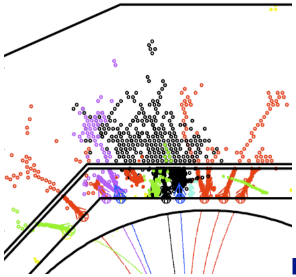
16



W HCAL tests

- CLIC study suggests W HCAL
- test simulation of neutron-rich response and time structure
- Test beam in 2010 with 30 W absorber and scint active layers
  - 2011: add 10 layers and tail catcher
- T3B: tiles with picosecond electronics: first results





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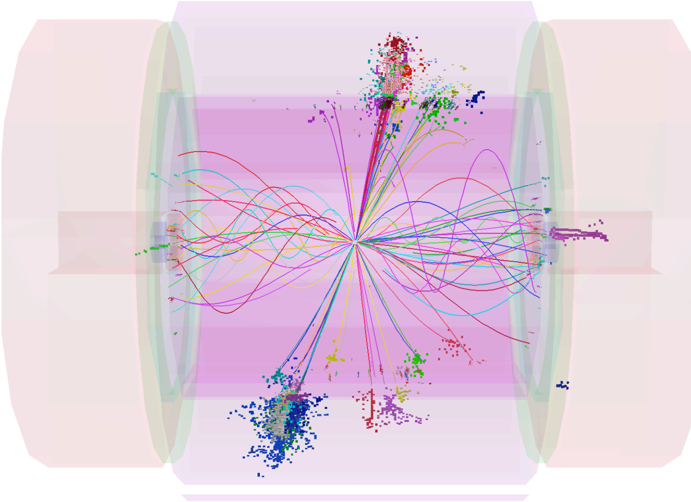

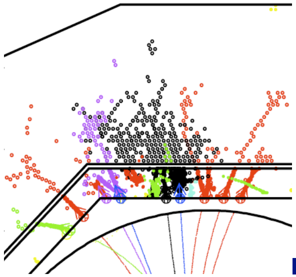

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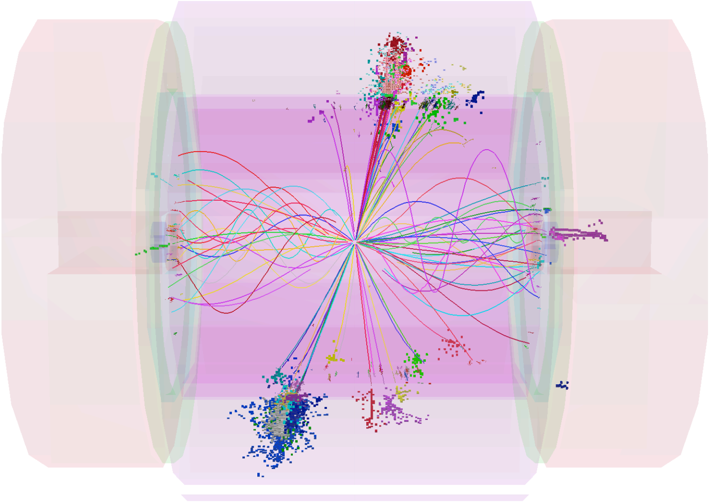

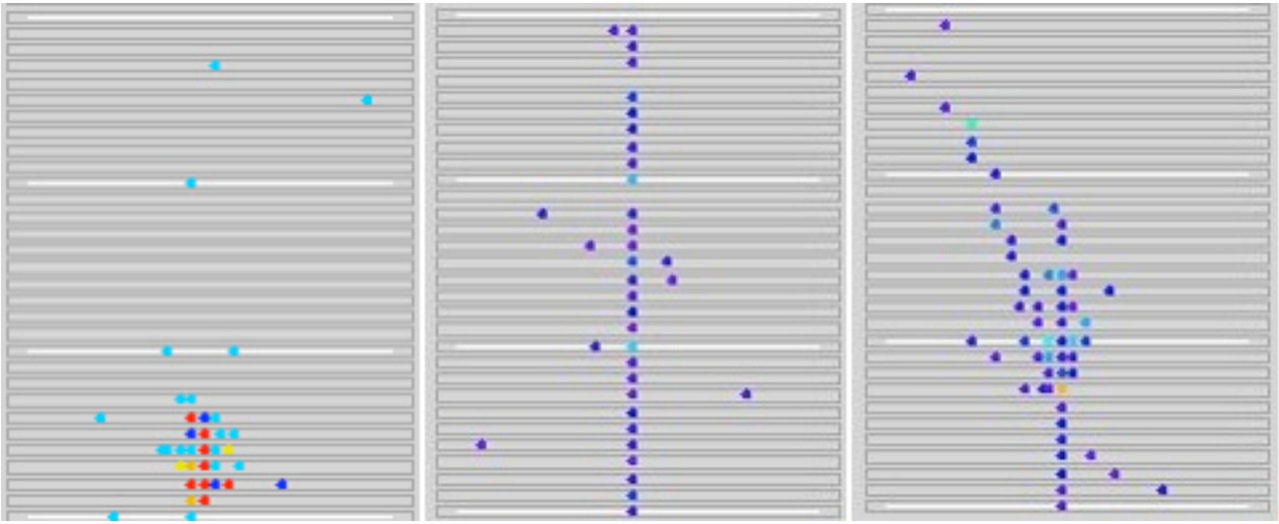

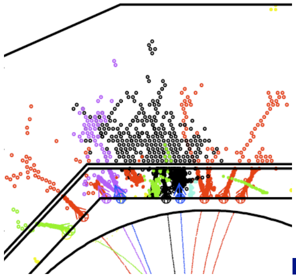

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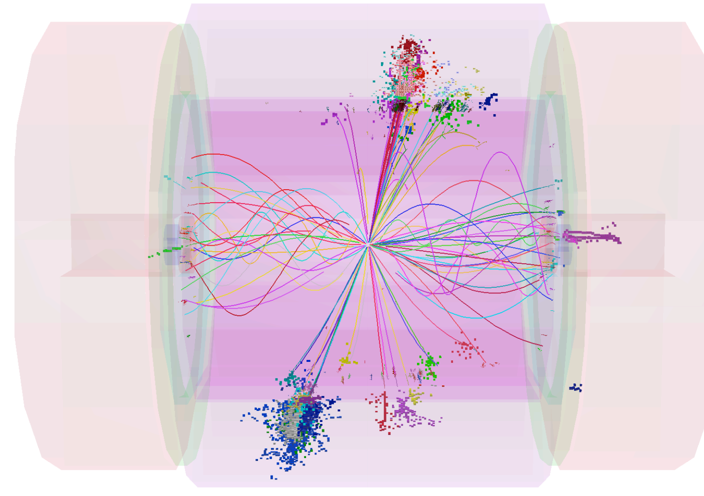
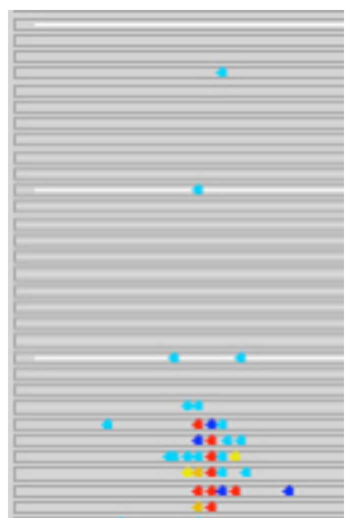
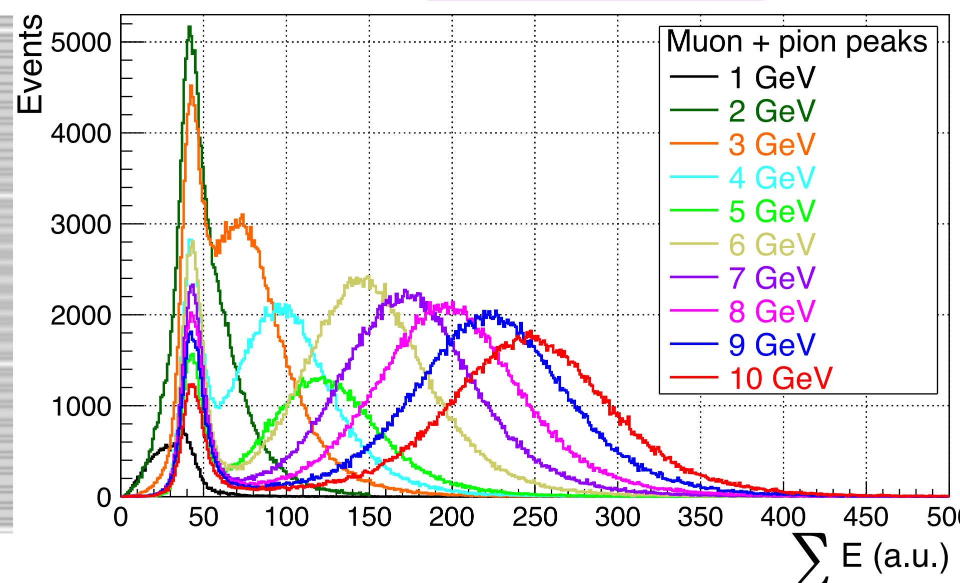
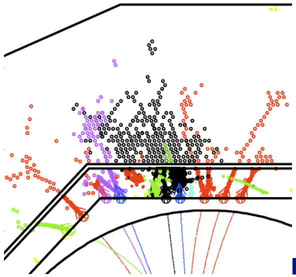


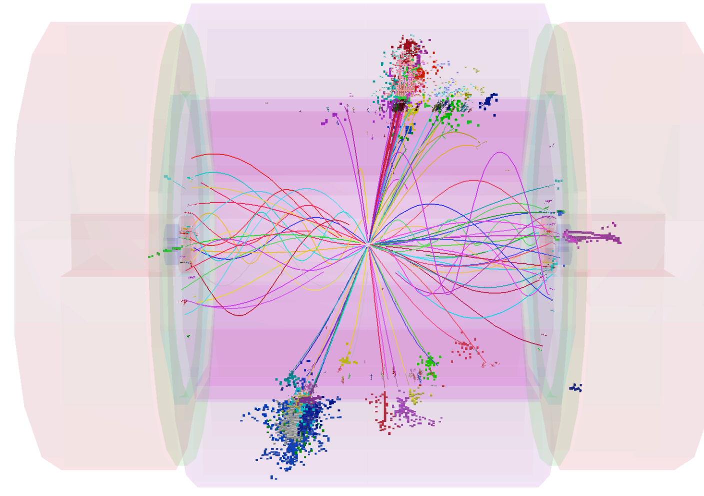


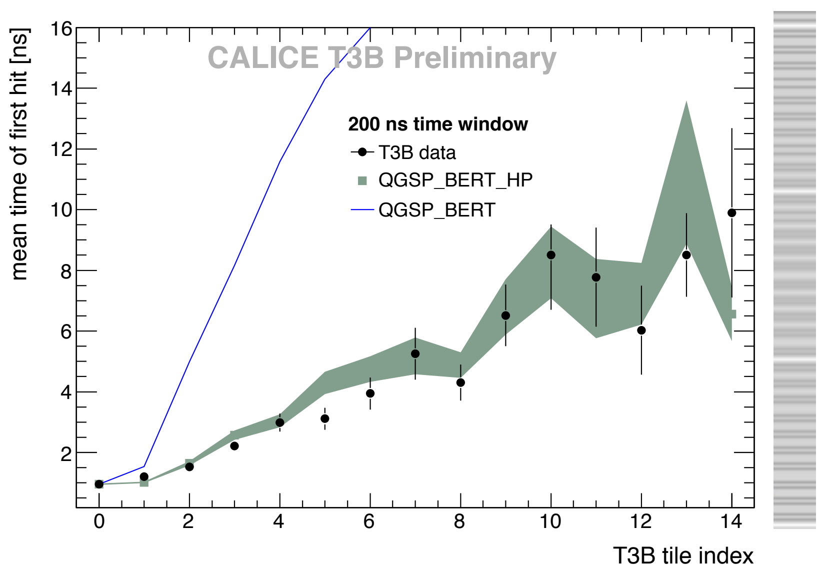


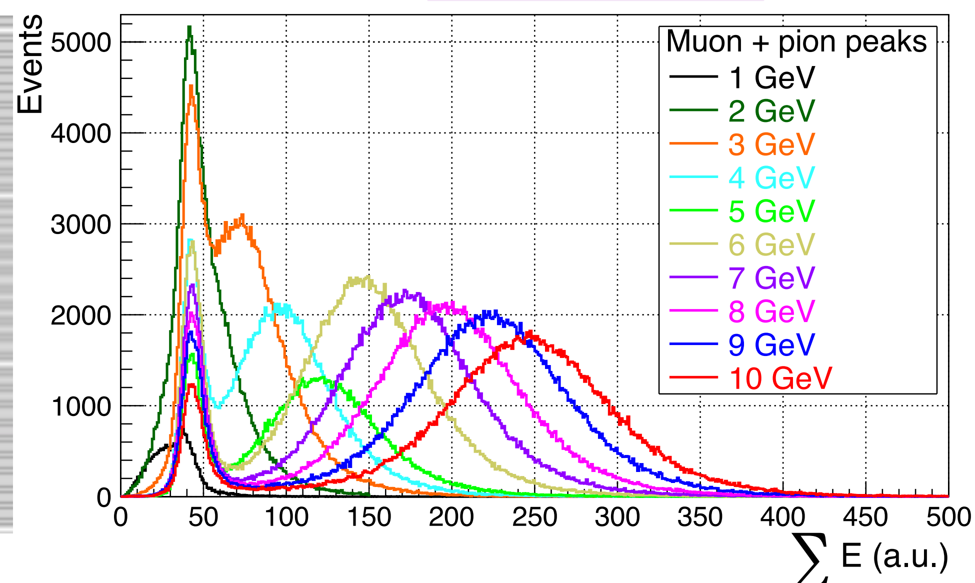


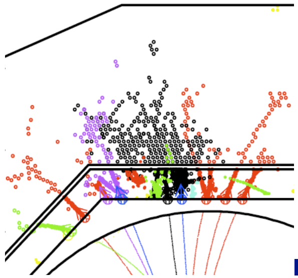
W HCAL tests

- CLIC study suggests W HCAL
- test simulation of neutron-rich response and time structure
- Test beam in 2010 with 30 W absorber and scint active layers
  - 2011: add 10 layers and tail catcher
- T3B: tiles with picosecond electronics: first results



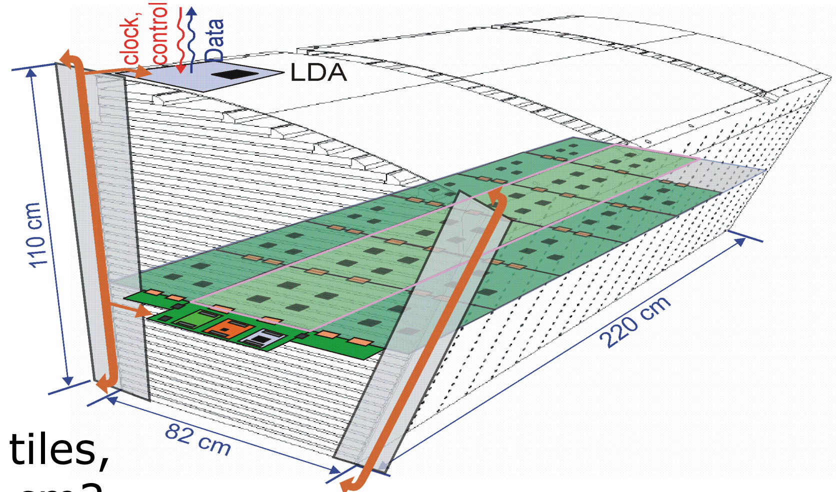




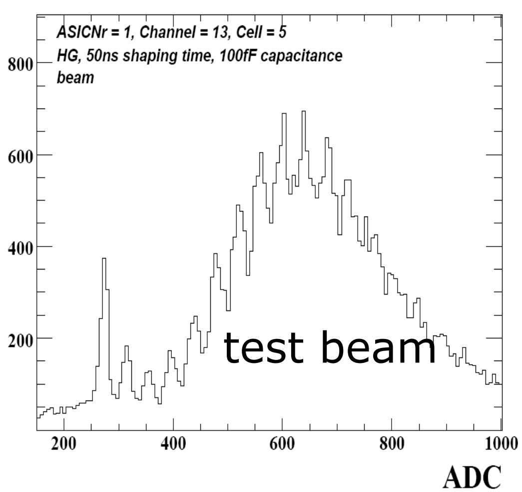


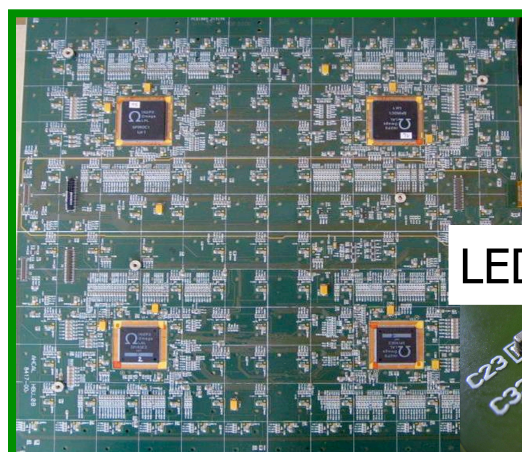
Scint HCAL: 2nd generation

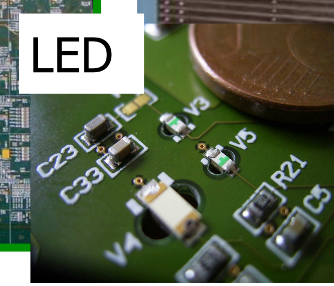
- integrate readout ASICs and LED system
  - include ADCs and **TDCs**
  - power pulsing, zero suppression
- First layers: tested
  - see module on display
- Later: full tungsten HCAL



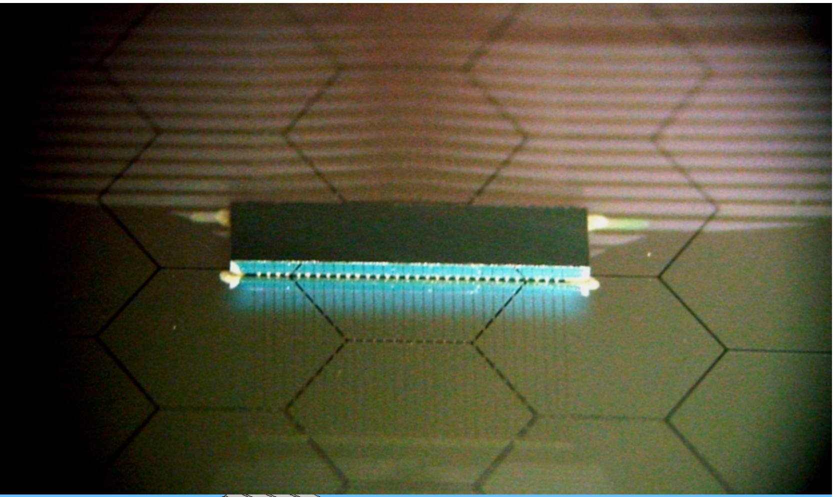
12x12 tiles,
36x36 cm2

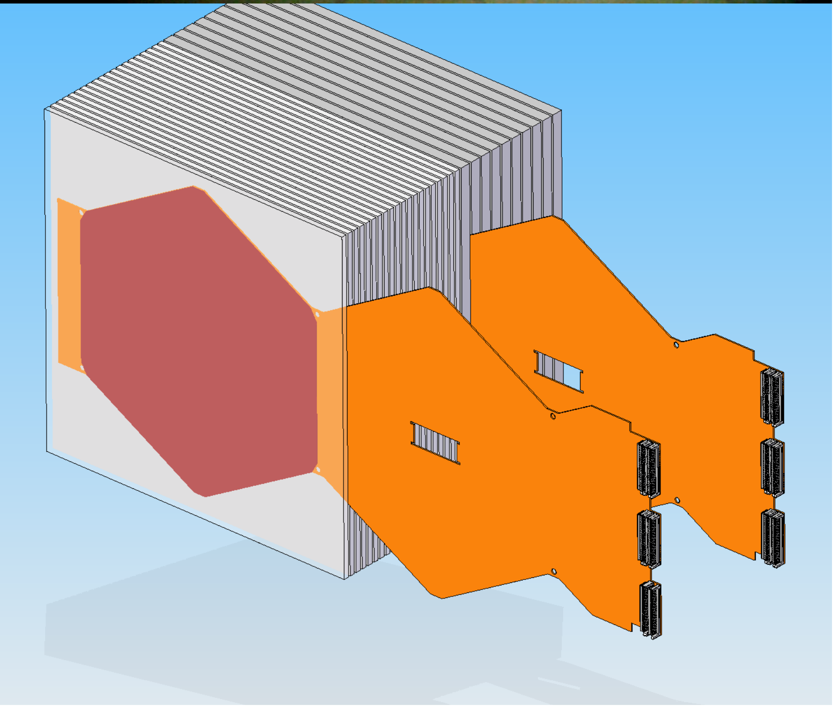






SiD Si W ECAL test beam module



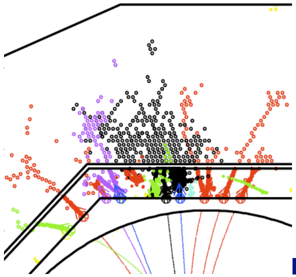


R&D project goal: Produce full-depth (30 layer) module which uses the technologies for a full LC ECal.

- 1024-channel KPiX chips (30)
  - in hand, testing
- 1024 pixel silicon sensors (30)
  - in hand
- KPiX bump-bonded to Si sensors
  - in progress
- Tungsten
  - in hand

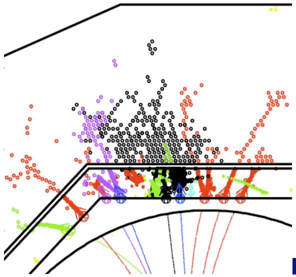
SLAC
Oregon
Davis

- The test module is 15cm x 15cm x 30 layers; 30 short readout cables carrying one digitized data stream
- Should be ready to characterize in a test beam ~ summer 2011



Summary on technologies

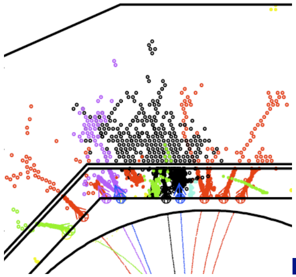
- a leap in several orders of magnitude in channel count
- new sensor technologies, new integration concepts
  - the latter is part of the feasibility demonstration
- progress towards realism:
  - realistic designs
  - realistic simulations
  - realistic cost
  - realistic proposal



Conclusion

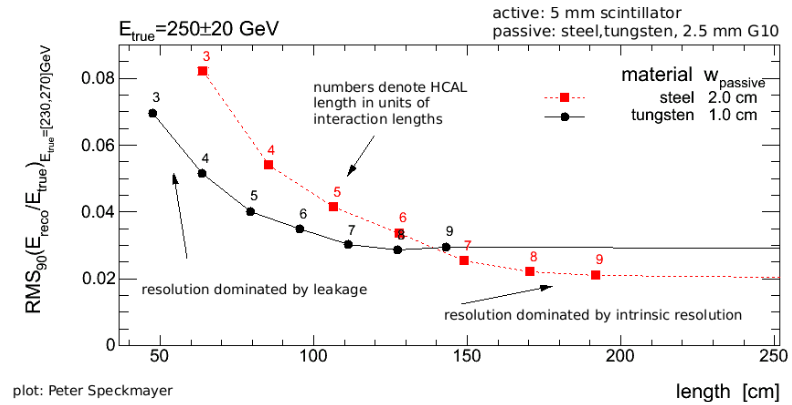
- Silicon has conquered calorimetry and triggered a little revolution
- Particle flow does not solve the inherent problems of hadron calorimeters
- But it holds the promise of providing a highly performant work-around
- Looking forward: Increased test beam activity 2011-12

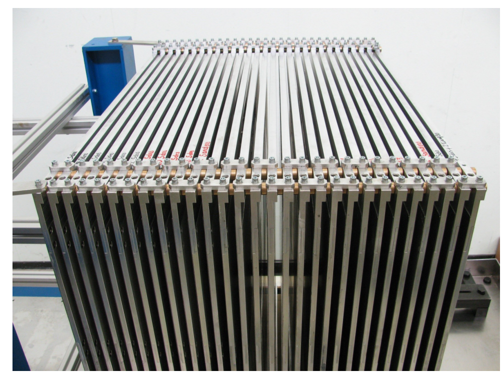
Back-up slides

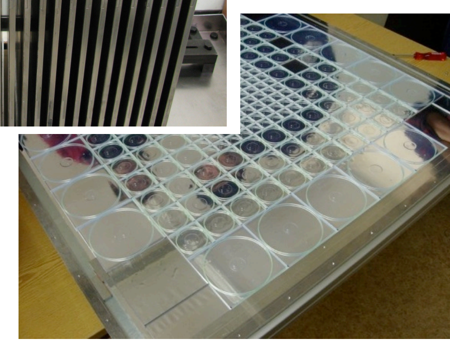


High energy

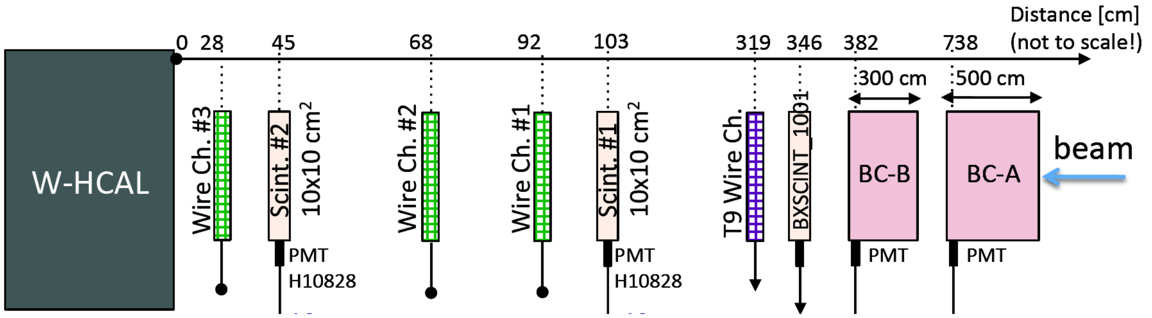
- Particle flow also a promising option for CLIC energies
- Leakage expected to limit PFLOW performance
  - need 1 λ ECAL + 7 λ HCAL
- Tungsten absorber cost-competitive with larger coil - and less risky
- Test beam validation with scintillator and gas detectors
- More neutrons:
  - different model systematics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



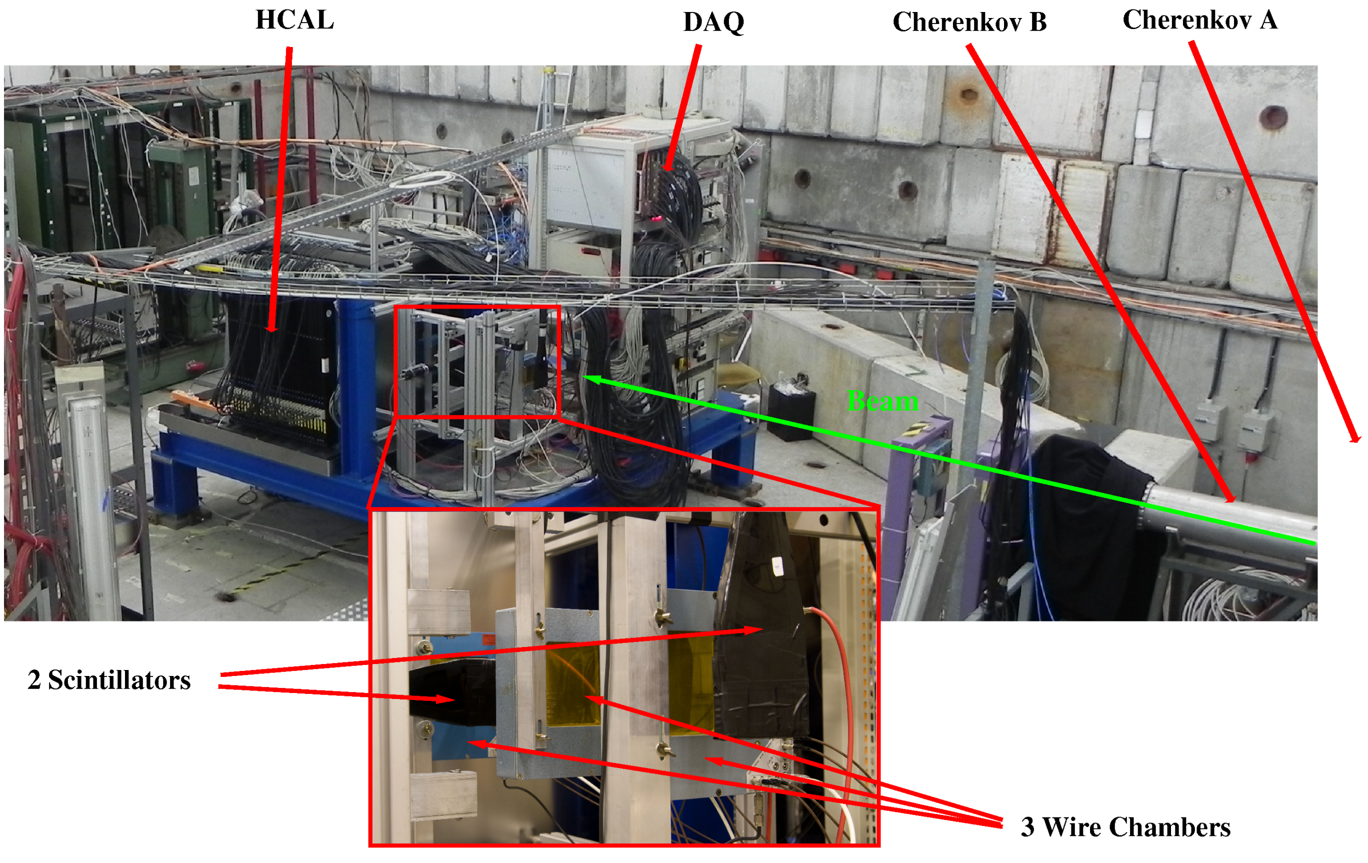




Test Beam Setup

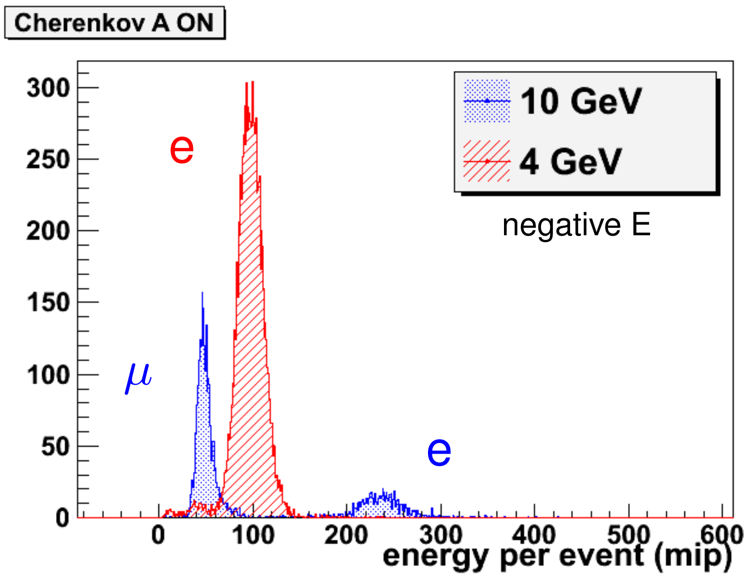


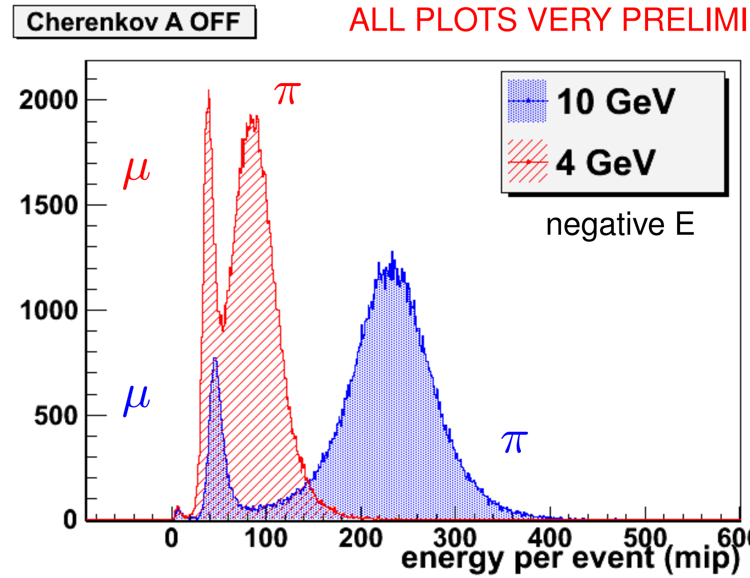
Trigger= coincidence of Scinti #1 and #2

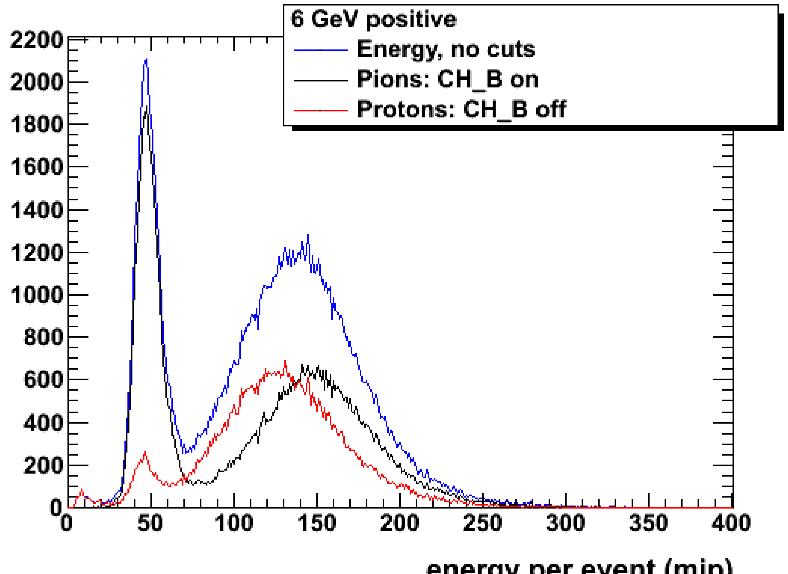


First Results: Particle ID

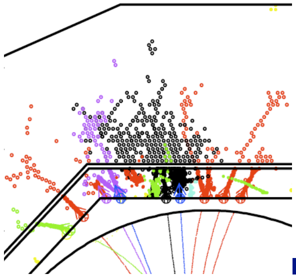
ALL PLOTS VERY PRELIMINARY







- 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

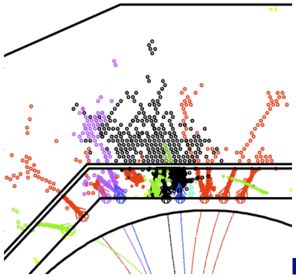


Em and hadronic response

- 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} ➔ non-linearity
- Approaches 1 for e/h -> 1 or for f_{em} -> 1 (high energy limit)

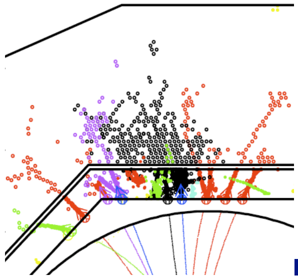


Compensation

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 % / √E
- Software compensation
  - Identify em hot spots and down-weight
    - Requires high 3D segmentation
  - Example H1, Pb/Fe LAr, ~ 50% / √E

NB: Do not remove fluctuations in invisible energy

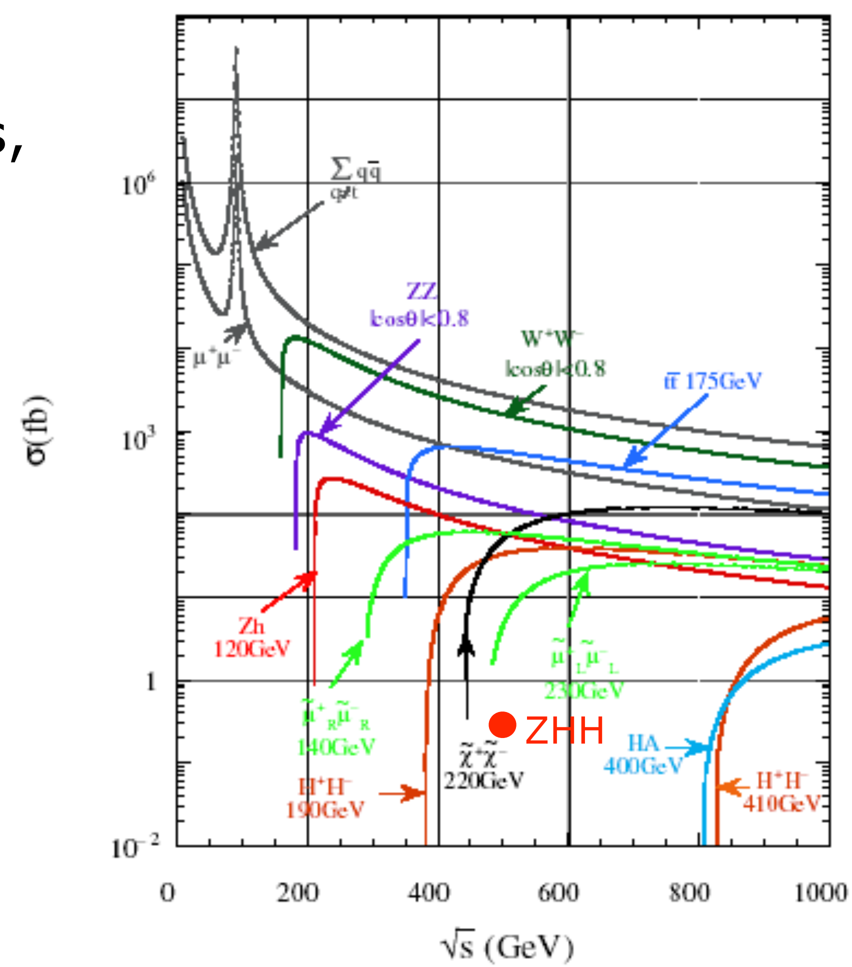


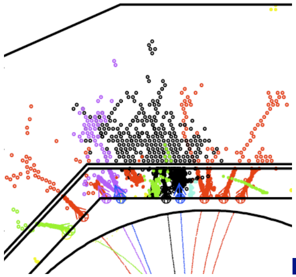
LC jet energies

- Q-Qbar events are boring
- E_{jet} = √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

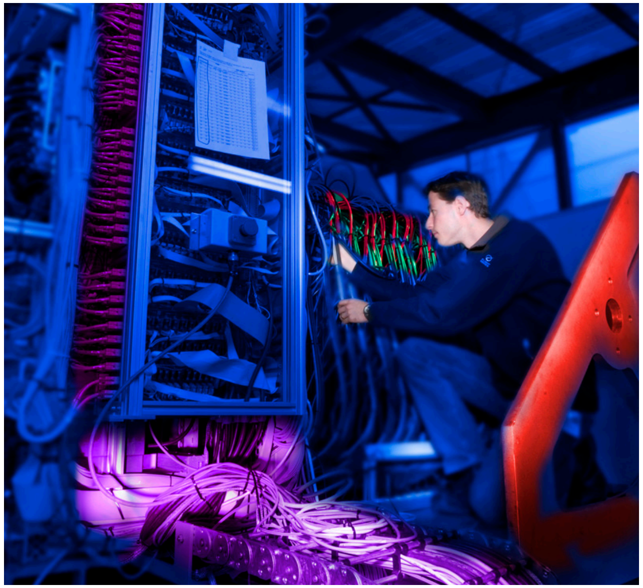
- W reconstruction with
- $\sigma_m/m = 2.5/91$
  need σ_E/E = 3.8%



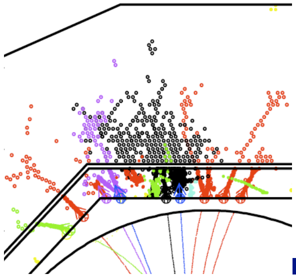


Overall status

- 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

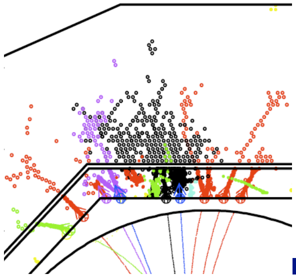


ILC detector concepts

- 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 nologies



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