Particle Flow Calorimetry

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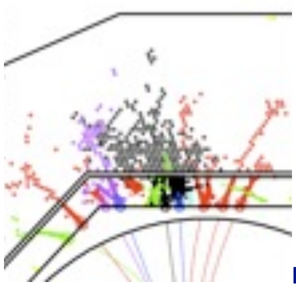
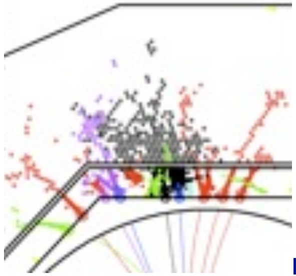
LINEAR COLLIDER COLLABORATION
Designing the world's next great particle accelerator

EDIT 2020

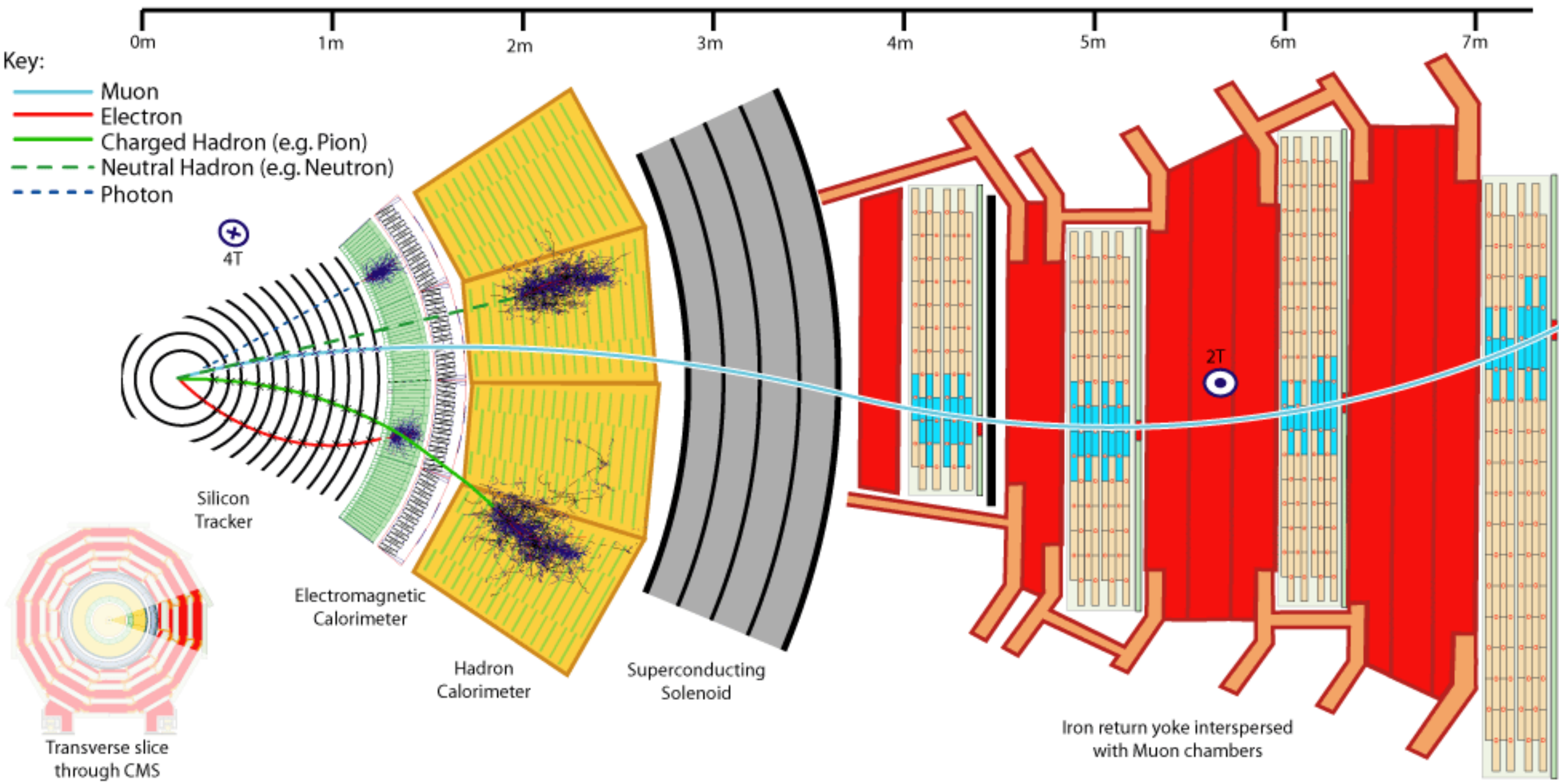


Outline

- Recall some calorimeter basics
- Particle flow calorimetry
- The exercise

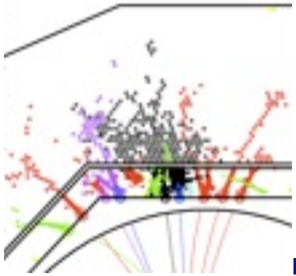


A generic collider detector



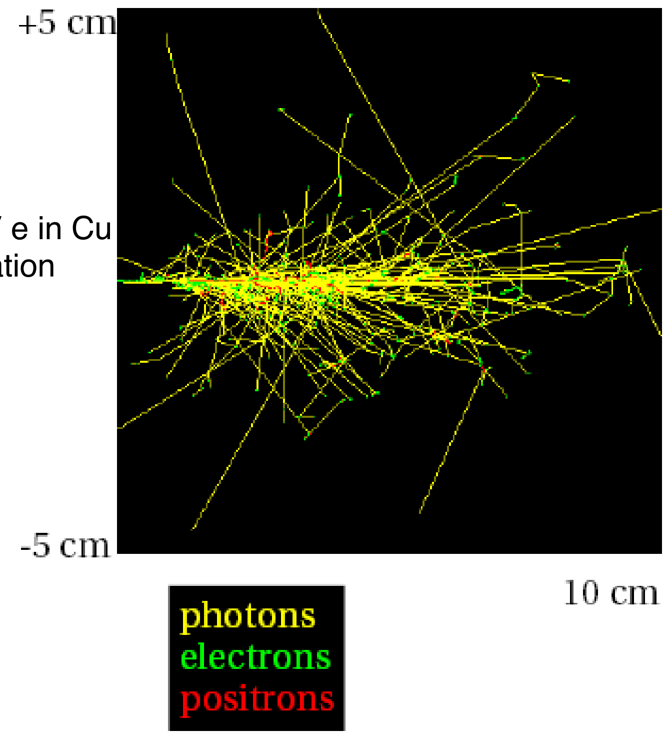
- Only charged particles produce signals

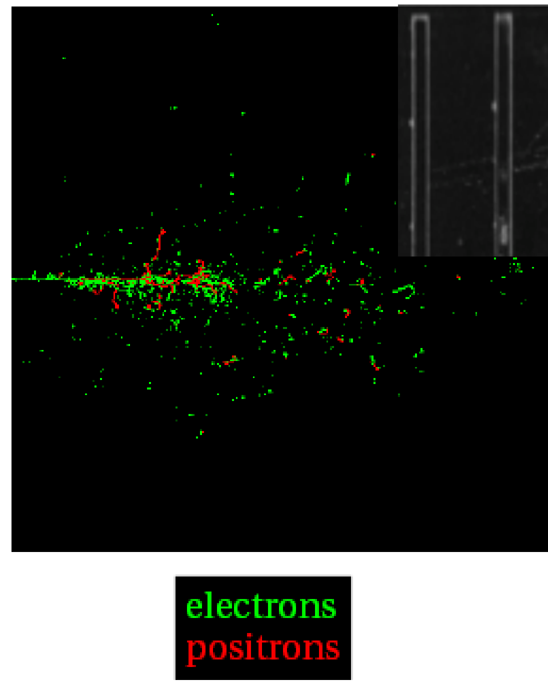
Recall some basics

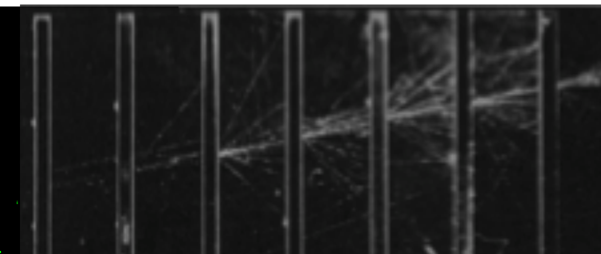


Electromagnetic showers

1 GeV e in Cu simulation

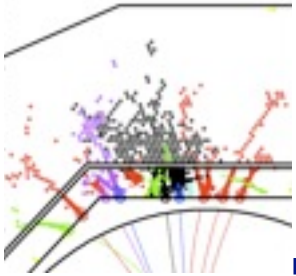






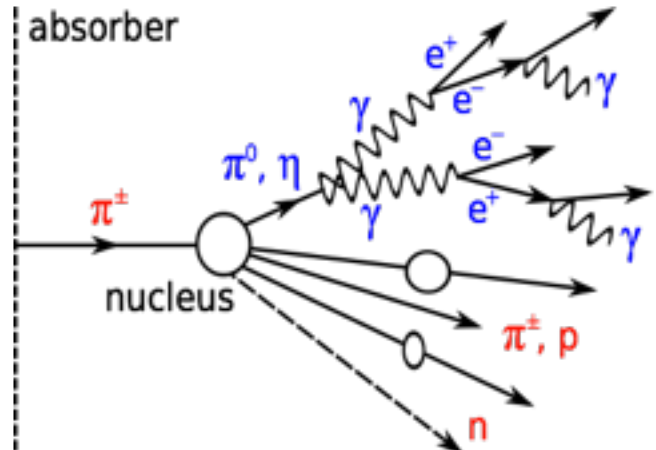
Lead absorbers in cloud chamber

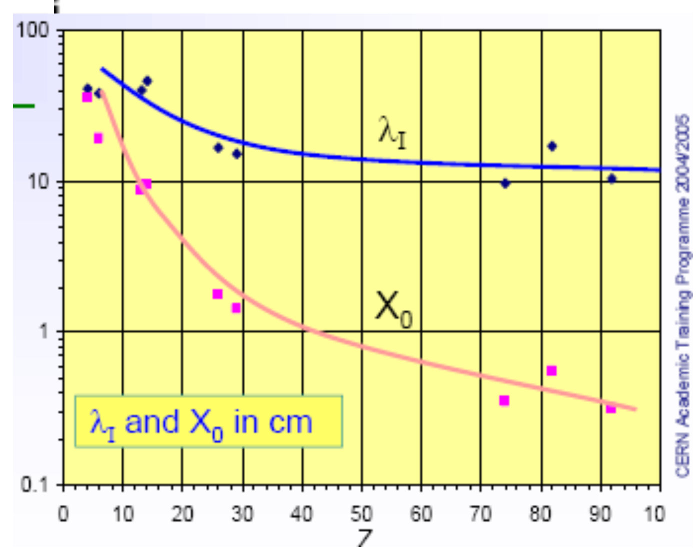
- Bremsstrahlung and pair creation until ionisation takes over
  - at $E_{crit} \sim 1/Z$, $N \sim E/E_{crit}$ particles: 1000s of e, millions of γ
- Radiation length X_0 (~ cm)
- Exponential growth: shower size and shape vary with *log* E

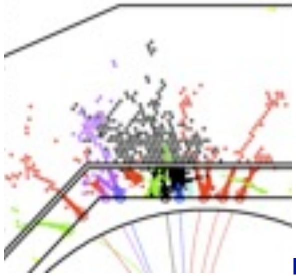


Hadron showers

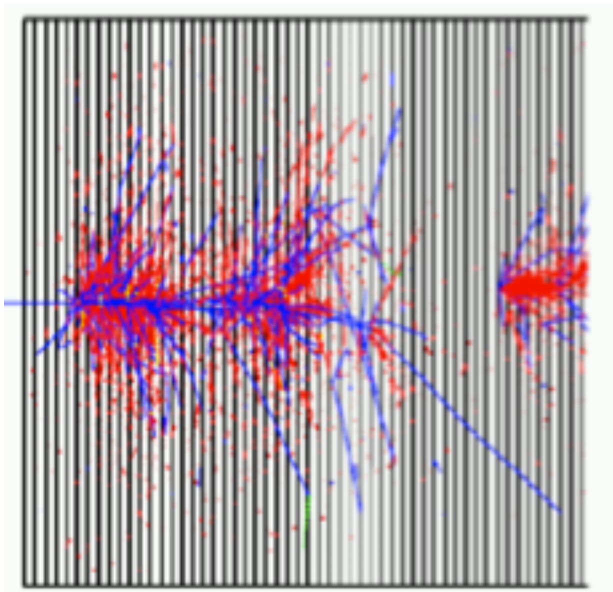
- Hadrons undergo strong interactions with detector material; nuclear collisions
- Secondary particles are produced
  - Partially undergo tertiary nuclear interactions ➔ formation of a hadronic cascade
  - Electromagnetically decaying particles initiate em showers, in general different response
  - Part of the energy is absorbed as nuclear binding energy or target recoil and remains invisible
  - Similar to em showers, but much more complex
- Numerical examples for copper
  - 10 GeV: f = 0.38; 9 charged h, 3 π^0
  - 100 GeV: f = 0.59; 58 charged h, 19 π^0
- Small numbers, large fluctuations
  - E.g. charge exchange $\pi^- p$ ➔ $\pi^0 n$ (prb 1%) gives f_{em} = 100%
- Different scale: hadronic interaction length λ
  - global shape λ, substructure X_0



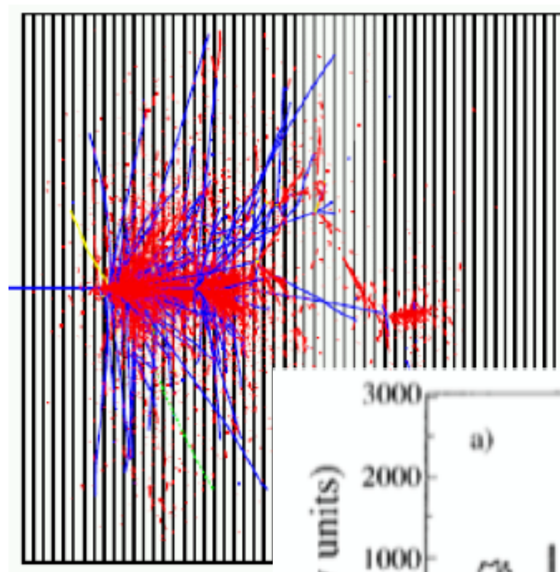




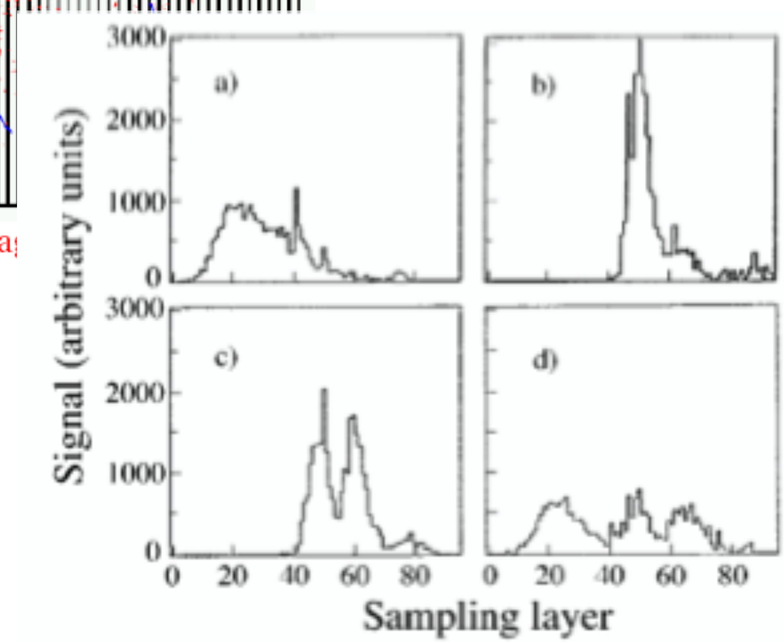
Fluctuations: sampling, leakage



blue = hadronic component



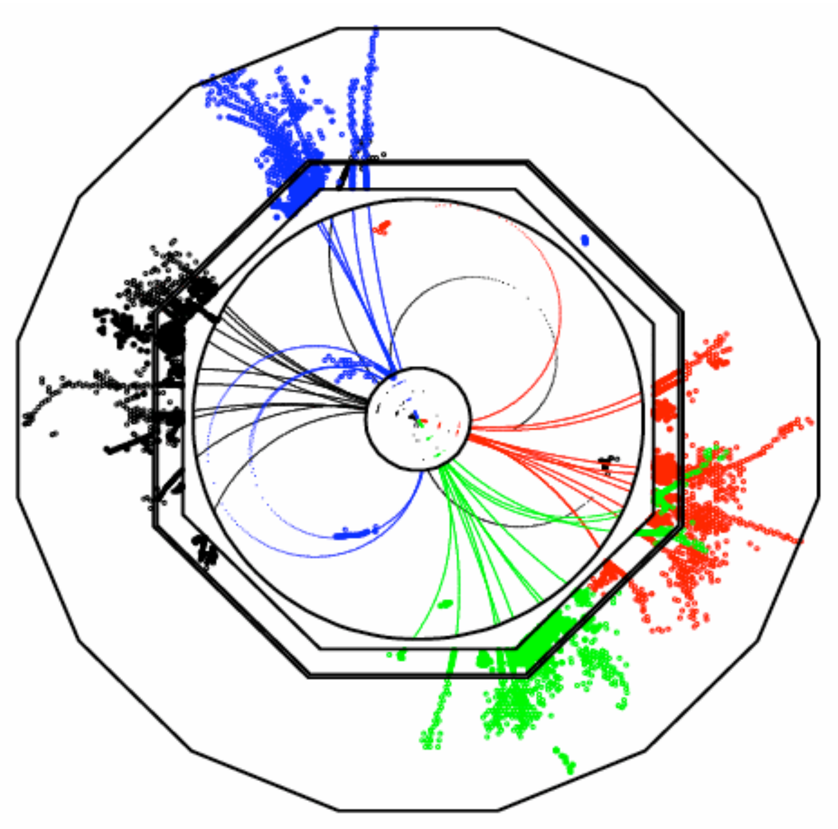
red = electroma



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

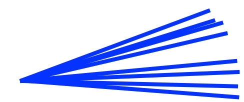
sampling fluctuations

Particle flow concept

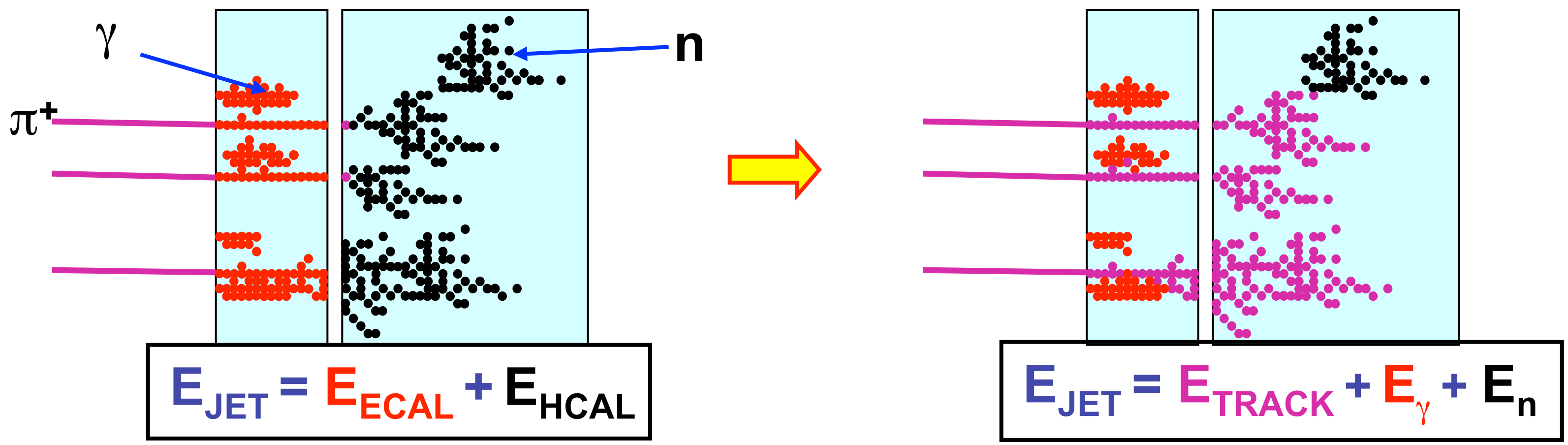


Particle Flow Calorimetry

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



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



- **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

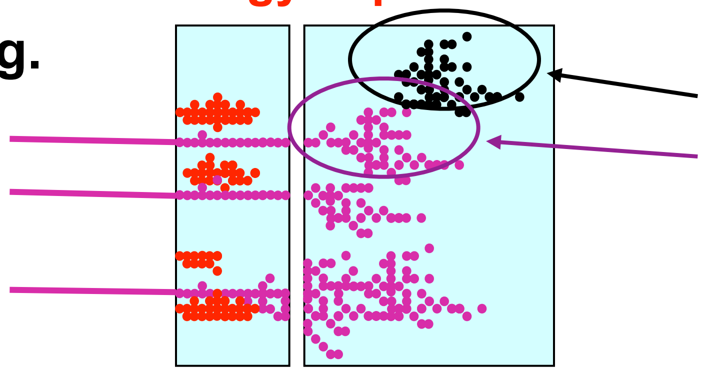
Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

★ Avoid double counting of energy from same particle

★ Separate energy deposits from different particles

e.g.

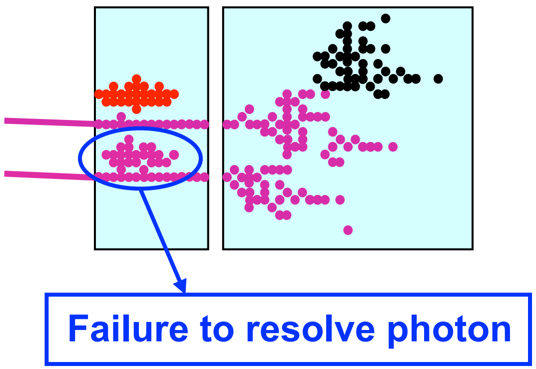


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

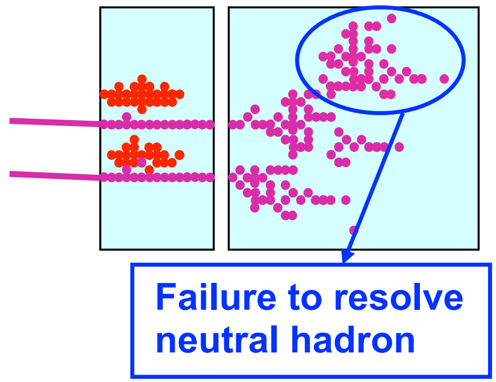
Level of mistakes, "confusion", determines jet energy resolution
not the intrinsic calorimetric performance of ECAL/HCAL

Three types of confusion:

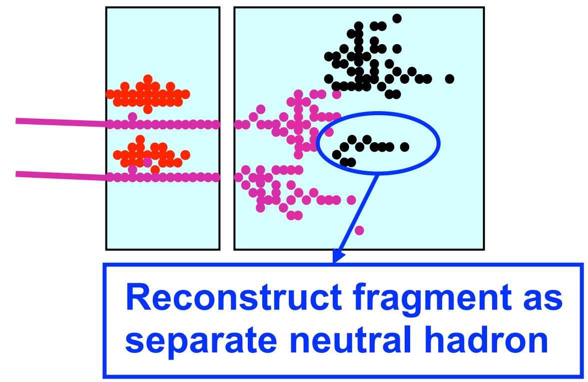
i) Photons

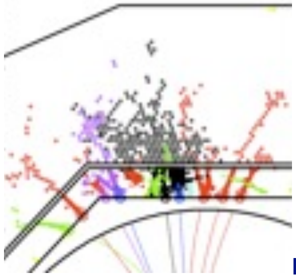


ii) Neutral Hadrons



iii) Fragments



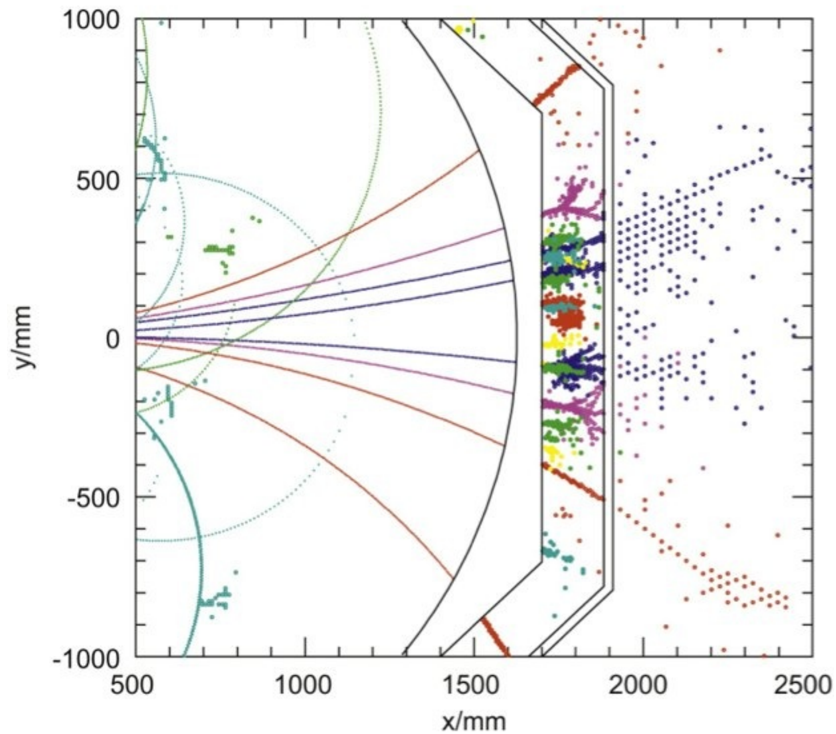


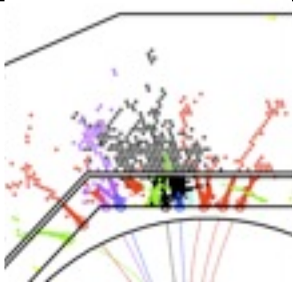
Particle flow detectors

- Large radius, high magnetic field, calorimeters inside coil
- Dense and compact design

- Very high granularity
  - order of Moliere radius
  - ECAL: 0.5 - 1 cm, 10^8 cells
  - HCAL: 1 - 3 cm, 10^7 -10^8 cells

- Cost is rather driven by instrumented area then by cell size

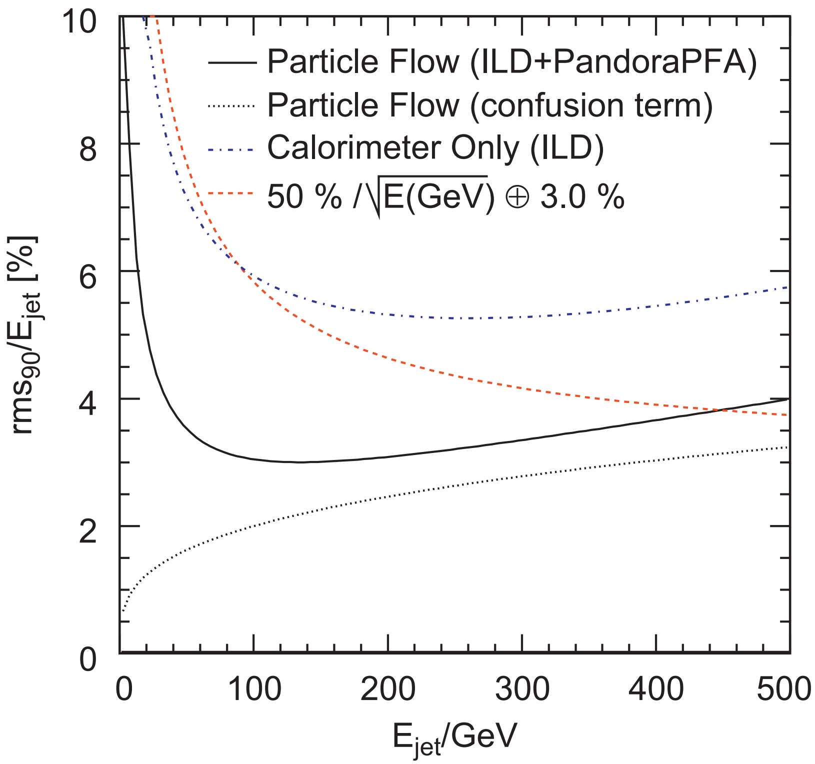


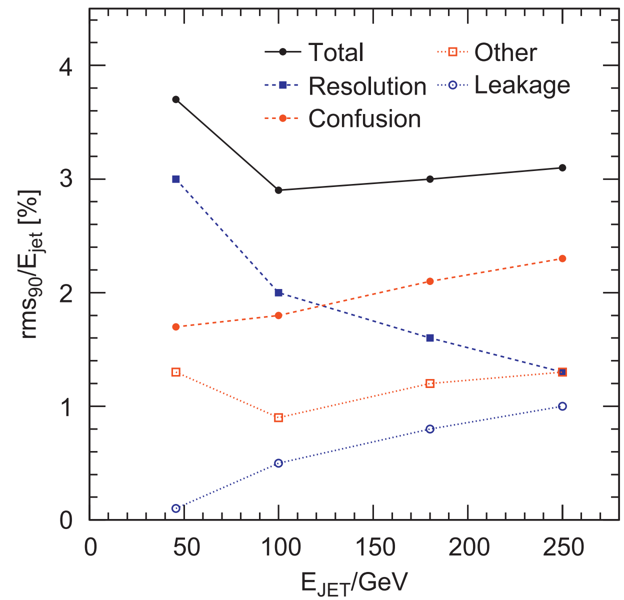


Understand particle flow performance

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

Resolution — Tracking — Leakage — Confusion

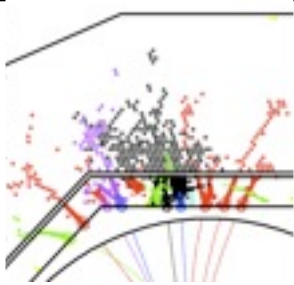




- Particle flow is always a gain
  - even at high jet energies
- Calorimeter resolution does matter
  - dominates up to ~ 100 GeV
  - contributes to resolve confusion
- Leakage plays a role, too
  - but less than in classic case

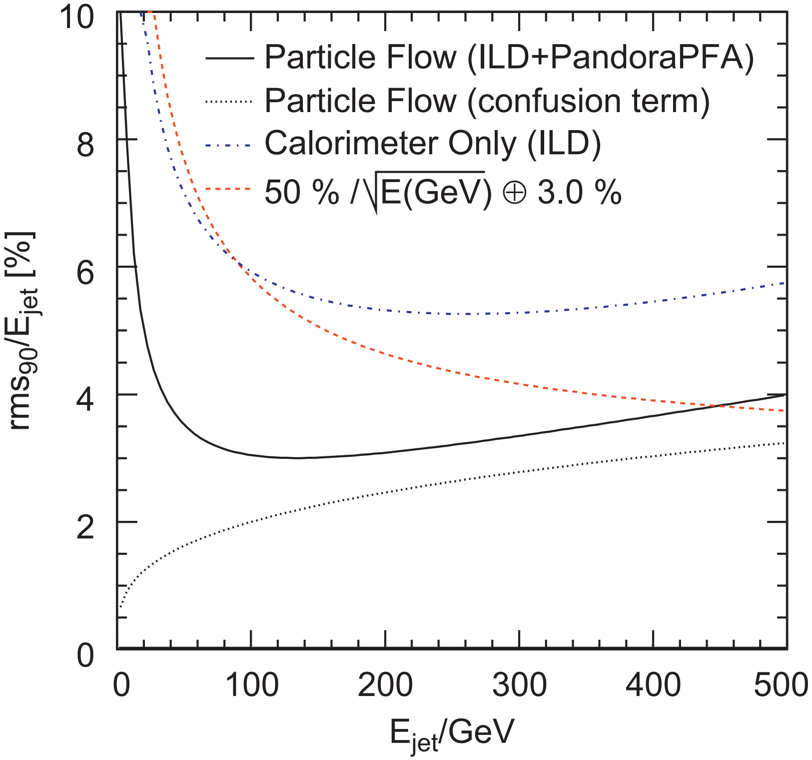
M.Thomson, Nucl.Instrum.Meth. A611 (2009) 25-40

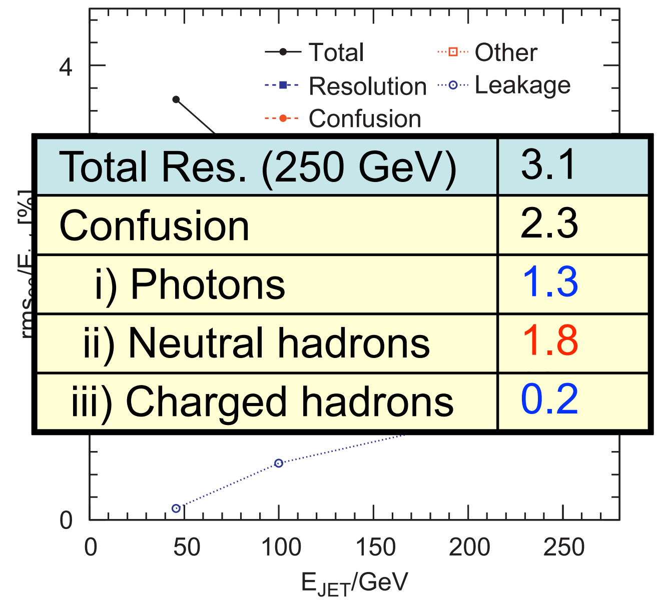
Understand particle flow performance



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

Resolution · Tracking · Leakage · Confusion





Total Res. (250 GeV)	3.1
Confusion	2.3
i) Photons	1.3
ii) Neutral hadrons	1.8
iii) Charged hadrons	0.2

- Particle flow is always a gain
  - even at high jet energies
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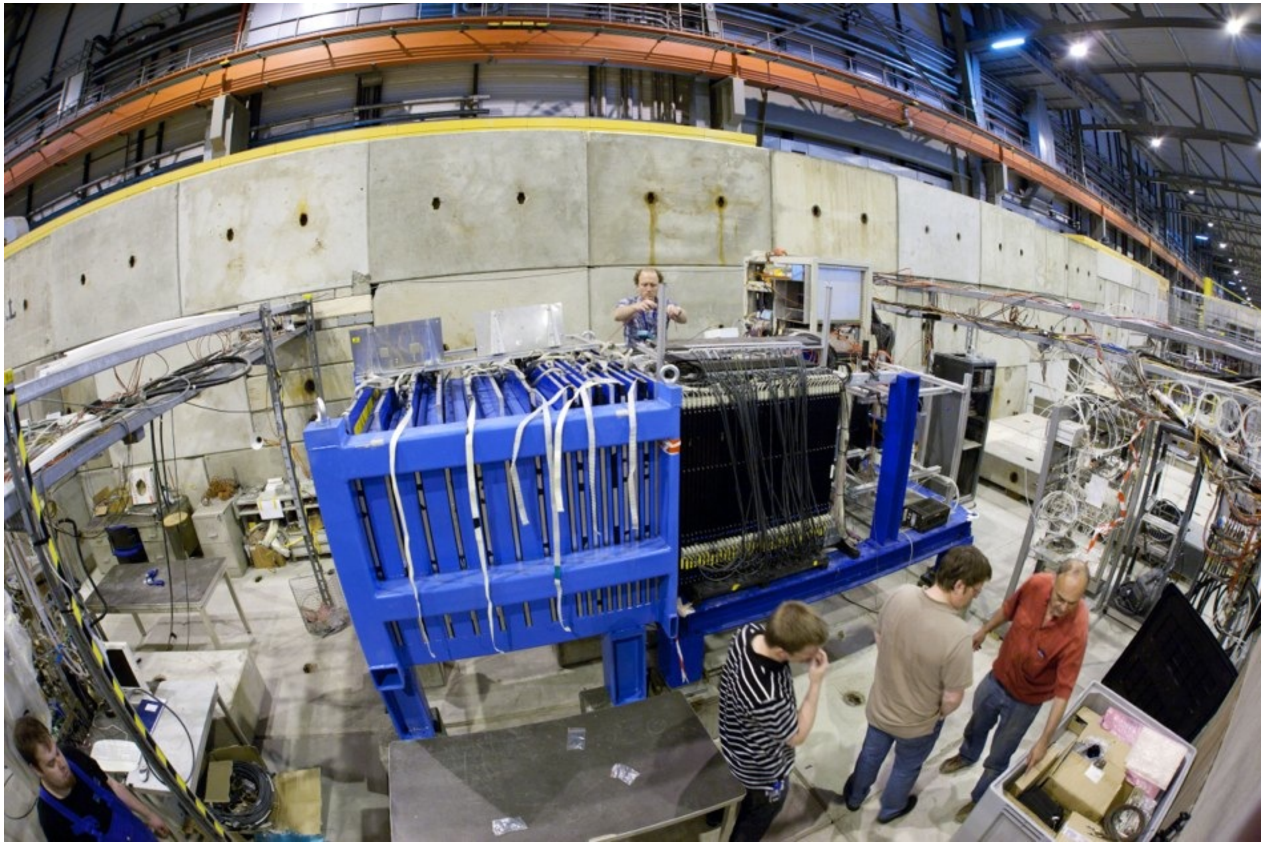
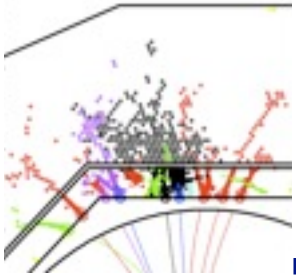
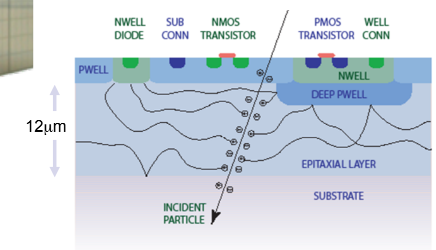
Technologies and test beam performance



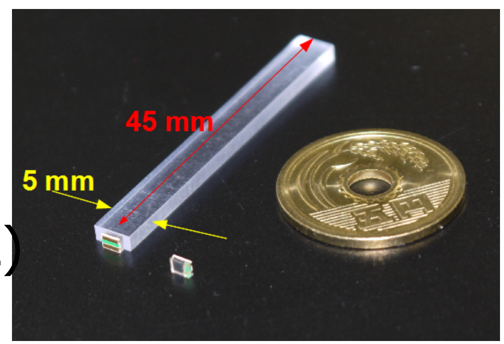


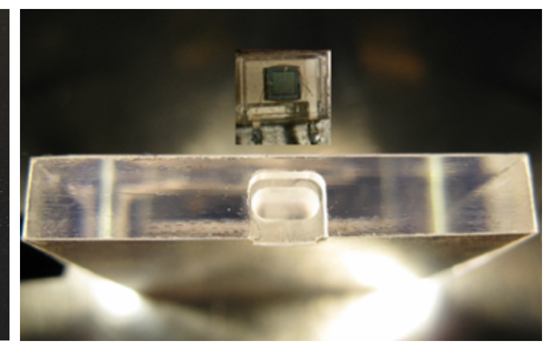
Particle flow technologies

- Silicon (ECAL)
  - most compact solution, stable calibration
  - 0.5 - 1 cm² cell size
  - MAPS pixels also studied

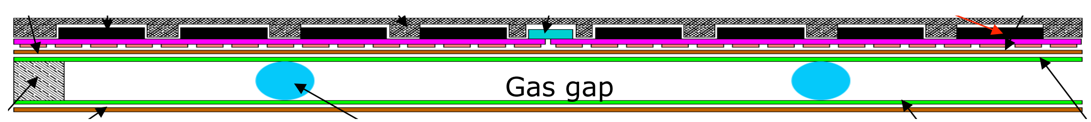


- Scintillator SiPM (ECAL, HCAL)
  - robust and reliable, SiPMs..
  - ECAL strips: 0.5 - 1 cm eff.
  - HCAL tiles: 3x3 cm²

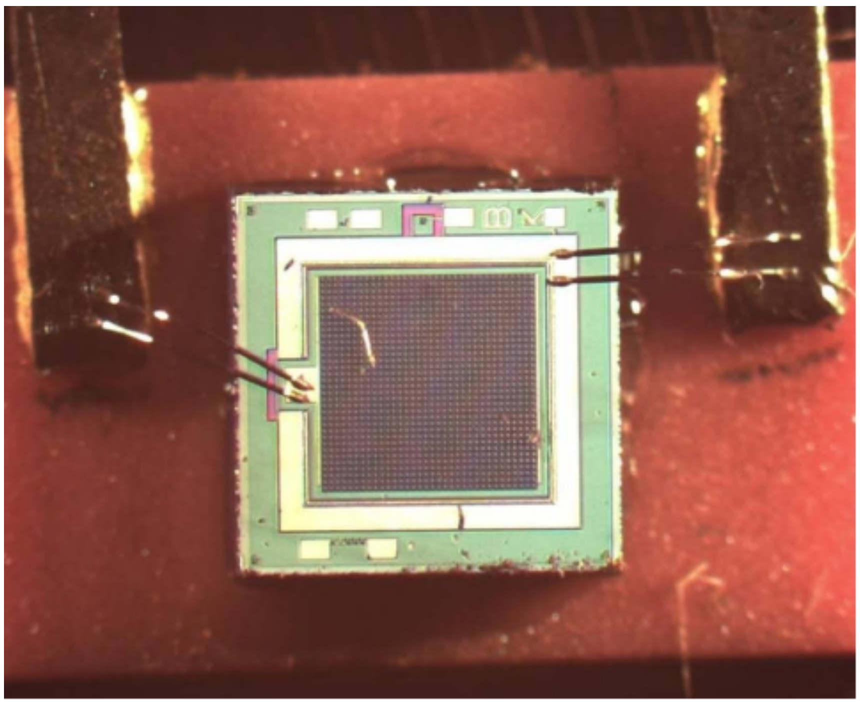




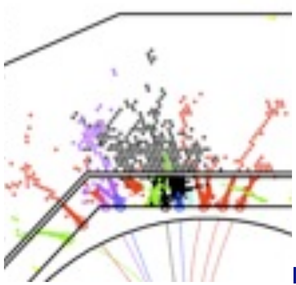
- Gaseous technologies (HCAL)
  - fine segmentation: 1 cm²
  - Glass RPCs: well known, safe
  - MPGDs: proportional, rate-capable
    - GEMs, Micromegas



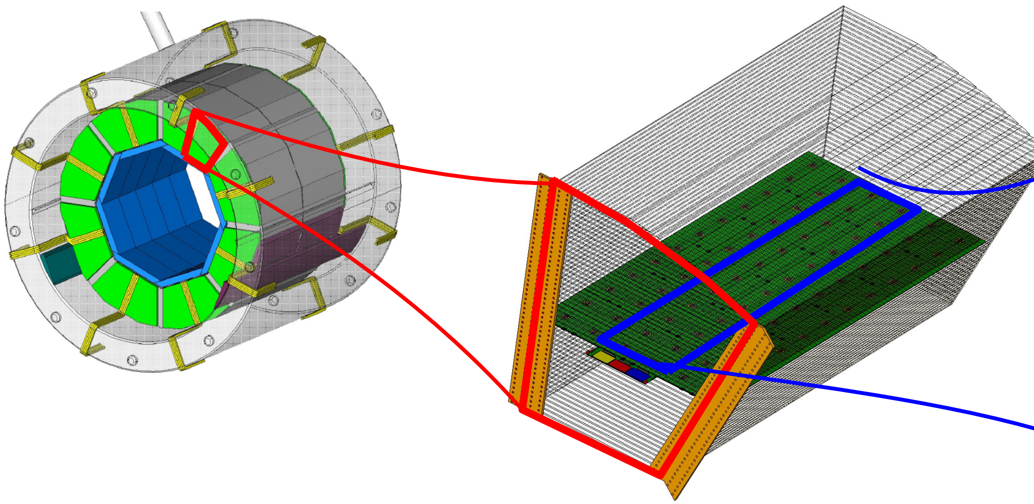
SiPMs

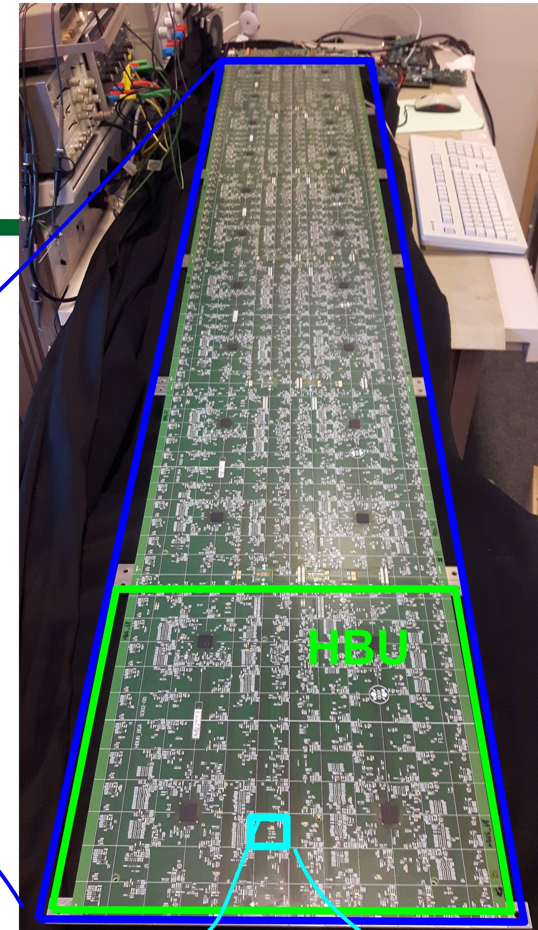


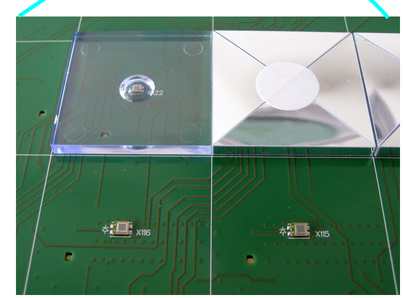
- pixelated
- avalanche photodiodes operated in Geiger mode
- sensitive to single photons
- gain of about 10^6
- insensitive to magnetic fields
- recently many developments in industry, e.g. reduced noise rates, more pixels, sensitivity to UV
- used e.g. in HCAL outer upgrade of CMS



The AHCAL







- hadron calorimeter concept for future electron-positron collider
- highly granular scintillator SiPM-on-tile calorimeter, 3*3 cm² scintillator tiles optimised for uniformity
- fully integrated electronics
- scalable to full detector (~8 million channels)
- **H**CAL **B**ase **U**nit: 36*36 cm^2, 144 tiles, 4 SPIROC2E ASICs

- Testbeam prototype: 7 layers of 1 HBU each

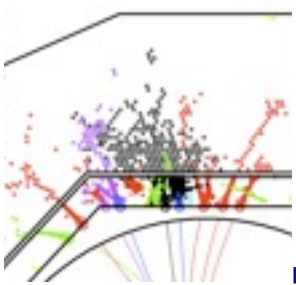
EDIT Exercises

SiPM Gain

- Goal: learn about single-photon sensitivity of SiPMs, Single Pixel Spectra as basis for calibration

- Measure Spectra for several light intensities, analyse them, determine gain
  - does it depend on light intensity? Do we need to know the intensity?

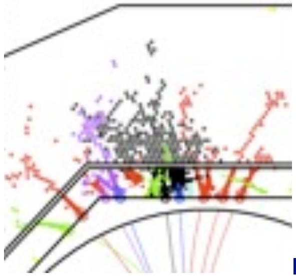
- If time allows: change SiPM bias voltage, does this influence the gain? Consequences for detector?



MIP Measurement

- Goal: learn about the energy deposition of minimal ionising particles (MIPs) as basic unit of hit energy measurement

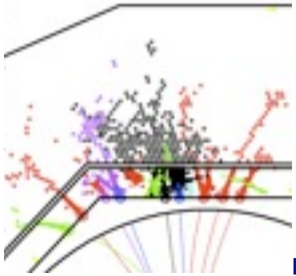
- Measure hit energies in a “naked" AHCAL layer (without absorber) in the DESY testbeam for several electron energies
- Analyse and fit the hit energy spectra
- With the gain determined in an earlier measurement, calculate the light yield



Shower Measurement

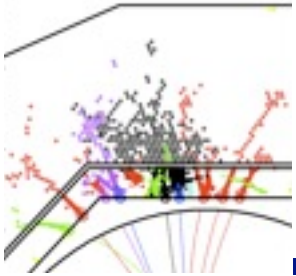
- Goal: learn how electromagnetic showers look like, how does the energy resolution depend on the particle energy

- Measure electron showers in the DESY testbeam for several energies
- Analyse the data
  - find cuts to clean the sample
  - look at reconstructed energy distribution (mean and width) as a function of particle energy



Calorimeter event analysis

- Goal: A hands-on experience with showers, their topologies and the fluctuations of energy and shape
  - Check event displays of prototype data (22000 channels!)
- Vary
  - Particle type: electrons and pions
  - Energy
- Some simple analysis on larger samples: Do you understand the results?
- Determine the interaction length of the calorimeter prototype by investigating the shower start distribution

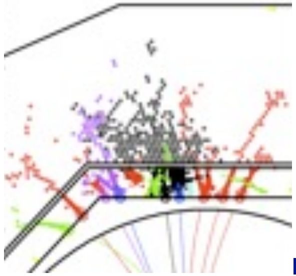


Running particle flow reconstruction

- Calorimeter+track standalone and full simulated e+e- collider events!
- Goal: Hands-on experience with power and limitations of high granularity and particle flow
- Run interactive particle flow reconstruction step by step
  - Associate tracks and calorimeter objects
- Vary the energy and look at simple and complicated scenarios
- Look at the results: What went right, what went wrong?
  - Both can be interesting!
  - Single particle level and “confusion matrix”: Reconstructed vs true energy

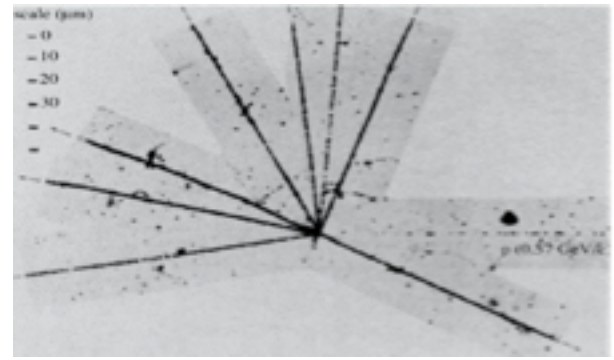
Enjoy!

Back-up slides

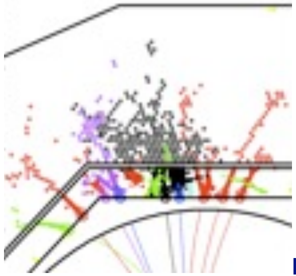


Hadronic interactions

- 1st stage: the hard collision
  - Multiplicity scales with E
  - ~ 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

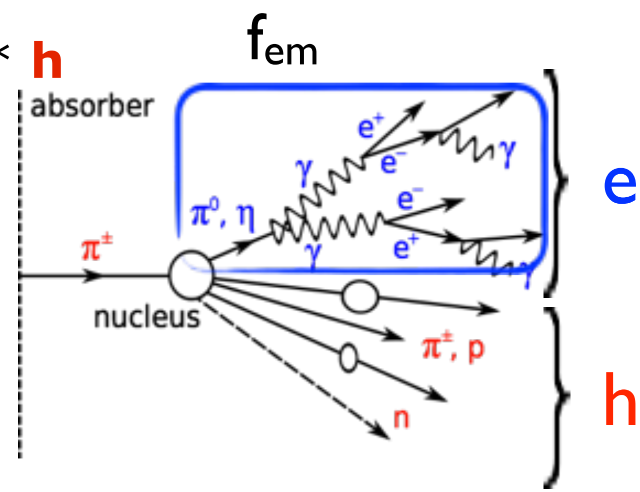


- The response to the hadronic part of a hadron-induced shower is usually smaller than that to the electromagnetic part: **h ≠ e**
  - Due to the invisible energy
  - Due to the short range of spallation nucleons
  - Due to saturation effects for slow, highly ionizing particles

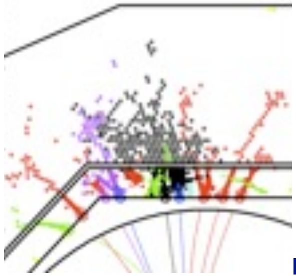


Electromagnetic fraction

- π⁰ production irreversible; "one way street"
  - π⁰ ➔ γγ produce em shower, no further hadronic interaction
  - Remaining hadrons undergo further interactions, more π⁰
  - Em fraction increases with energy, $f = 1 - E^{m-1}$
- Response non-linear: signal ~ f * **e** + (1-f) * **h**



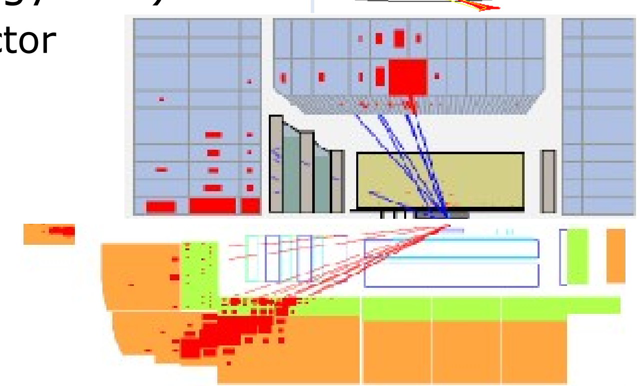
- Numerical example for copper
  - 10 GeV: f = 0.38; 9 charged h, 3 π⁰
  - 100 GeV: f = 0.59; 58 charged h, 19 π⁰
  - Cf em shower: 100's e⁺, 1000's e⁻, millions γ
- Large fluctuations
  - E.g. charge exchange π⁻ p ➔ π⁰ n (prb 1%) gives f_{em} = 100%



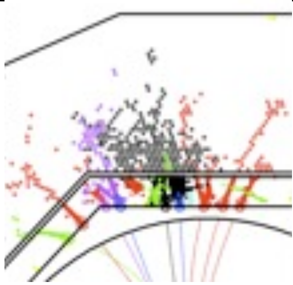
Compensation

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)
      - Tunable 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

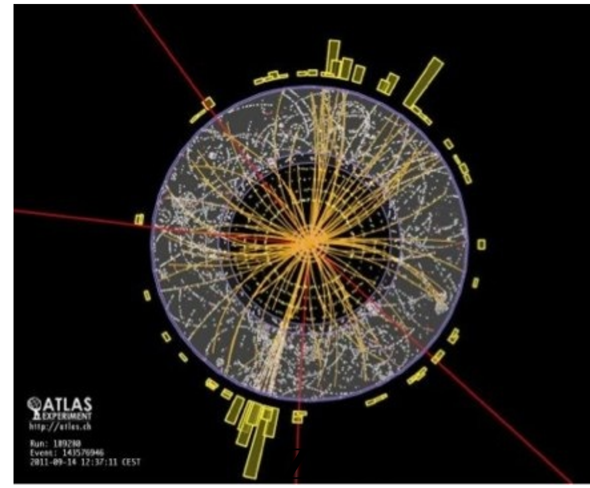


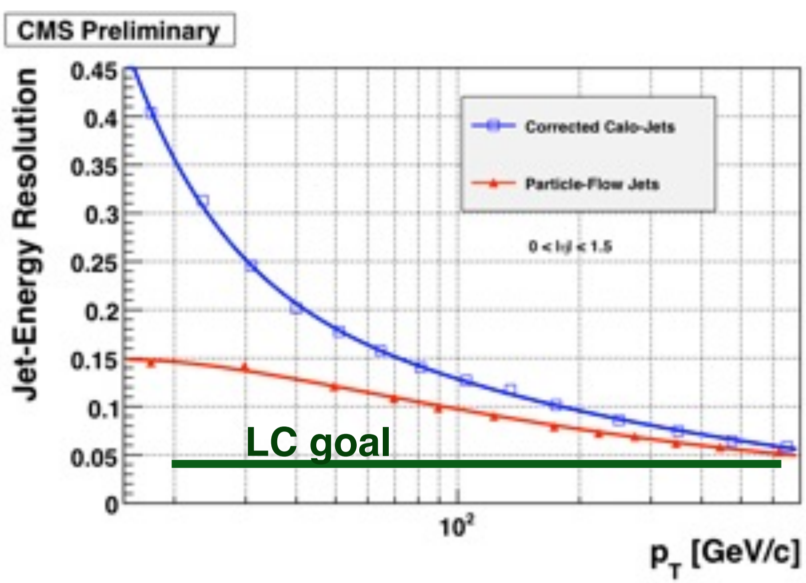
NB: Does not remove fluctuations in invisible energy



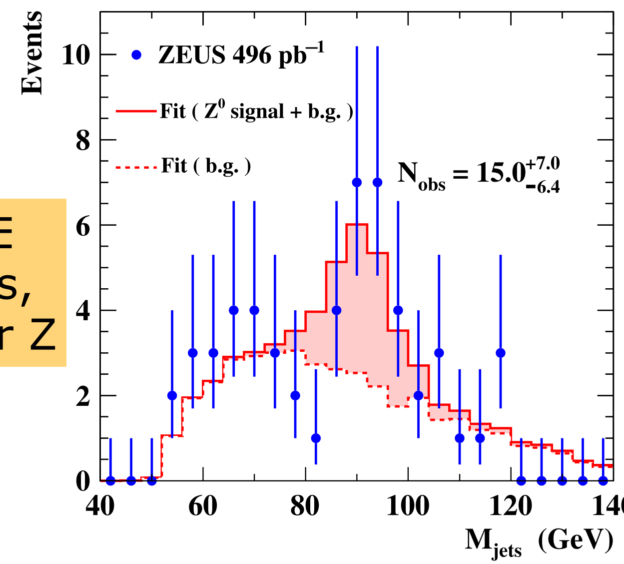
The jet energy challenge

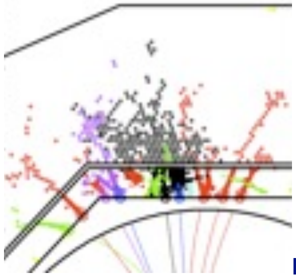
- Jet energy performance of existing detectors is not sufficient for separation of W and Z bosons
  - E.g. CMS: ~ 100%/√E, ATLAS ~ 70%/√E
- Calorimeter resolution for hadrons is intrinsically limited, e.g. nuclear binding energy losses
- Resolution for jets worse than for single hadrons
- It is not sufficient to have the world’s best calorimeter





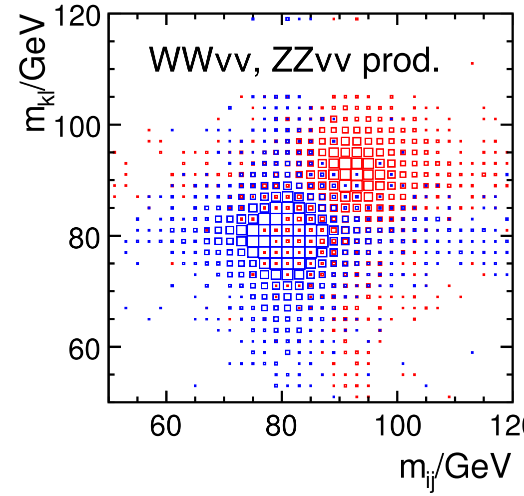
35%√E for pions, 6 GeV for Z

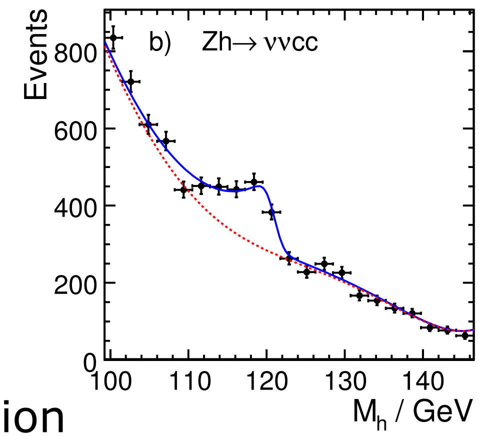


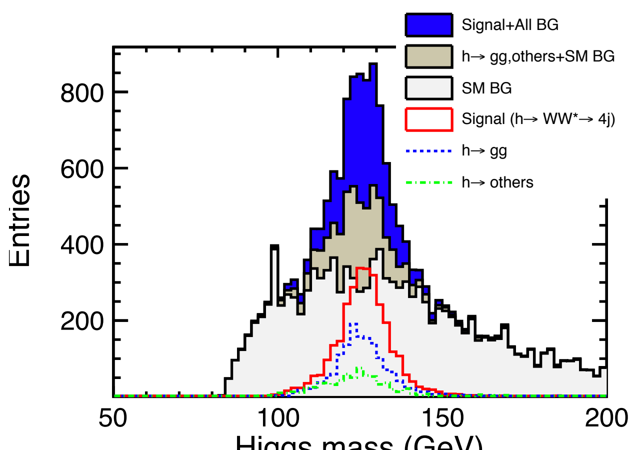


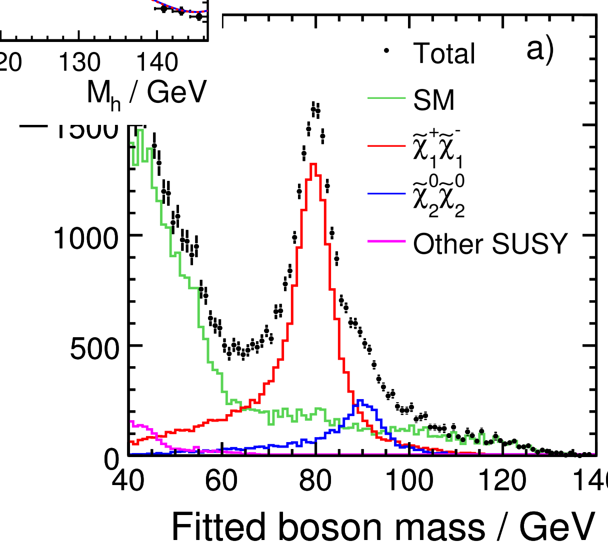
LC physics with jets: M_{inv}

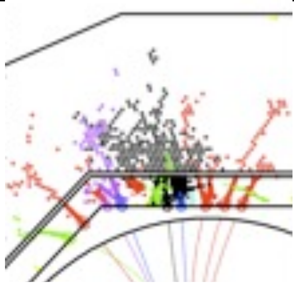
- W - Z separation
  - study strong e.w. symmetry breaking at 1 TeV
- Other di-jet mass examples
  - H → cc, Z → vv
  - Higgs recoil with Z → qq
  - invisible Higgs
  - WW fusion → H → WW
    - total width and g_{HWW}
- SUSY example:
  - Chargino neutralino separation







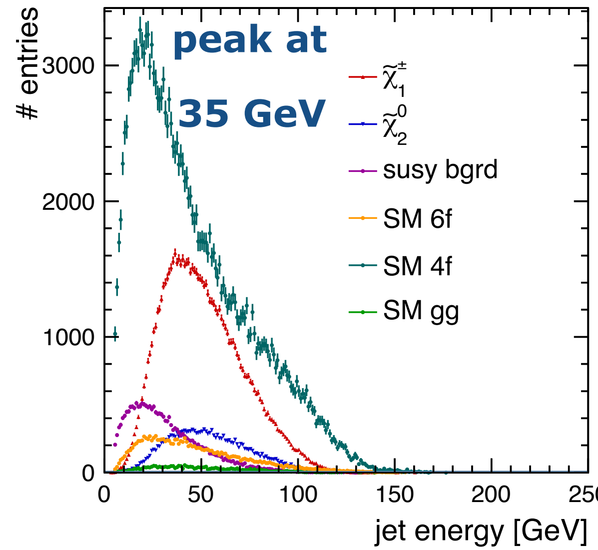


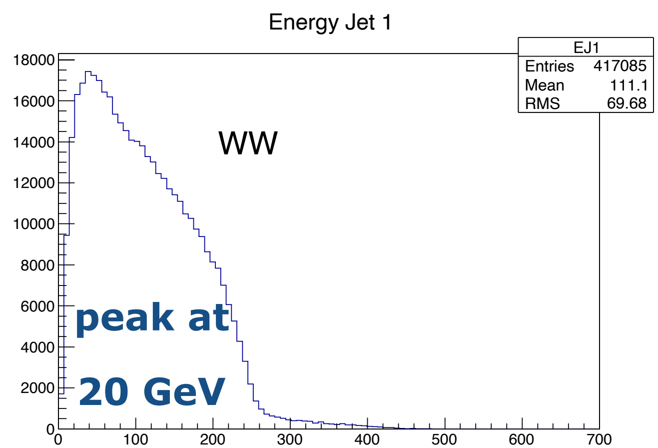


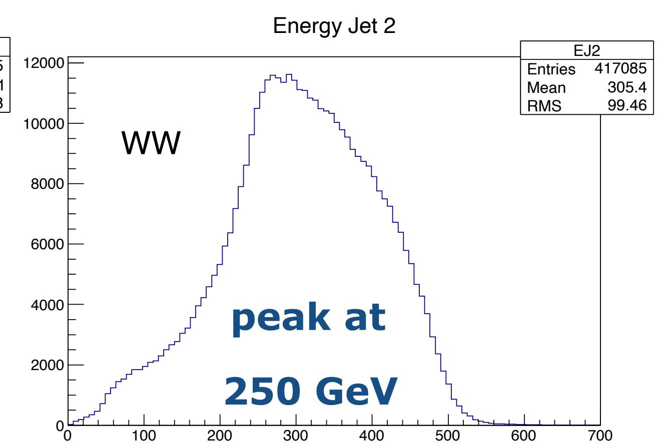
Jet energies

- $\sigma_m/m = 1/2 \sqrt{(\sigma_{E1}/E_1)^2+(\sigma_{E2}/E_2)^2}$
  - low energy jets important
  - high energy, too

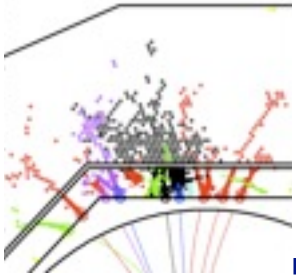
- At $\sqrt{s}$ = 500 GeV
- example chargino, neutralino → qq + invis.
- At $\sqrt{s}$ = 1 TeV
- example WW→H → WW → lνqq







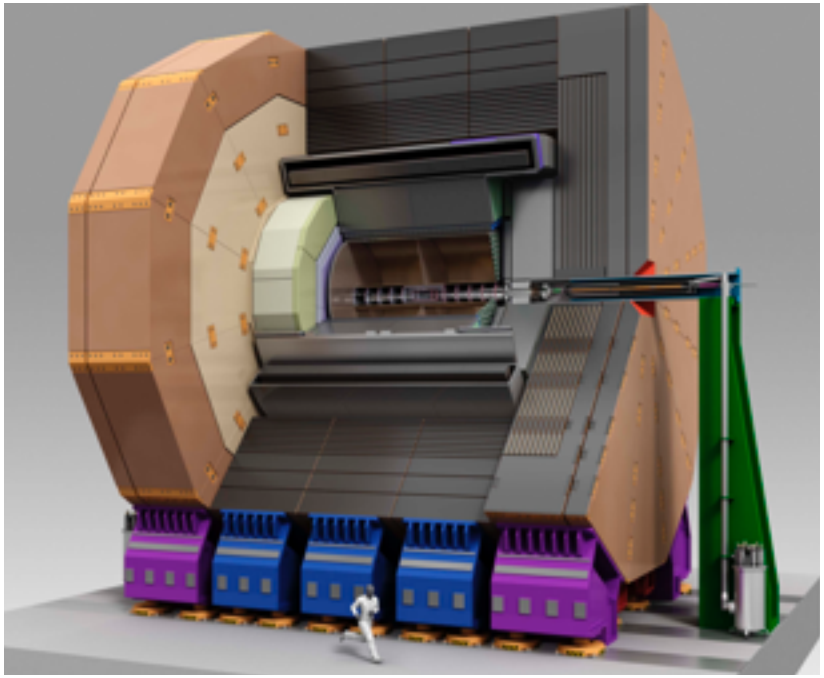
plots:
J.List, M.Chera, A.Rosca
DESY



Particle flow detectors

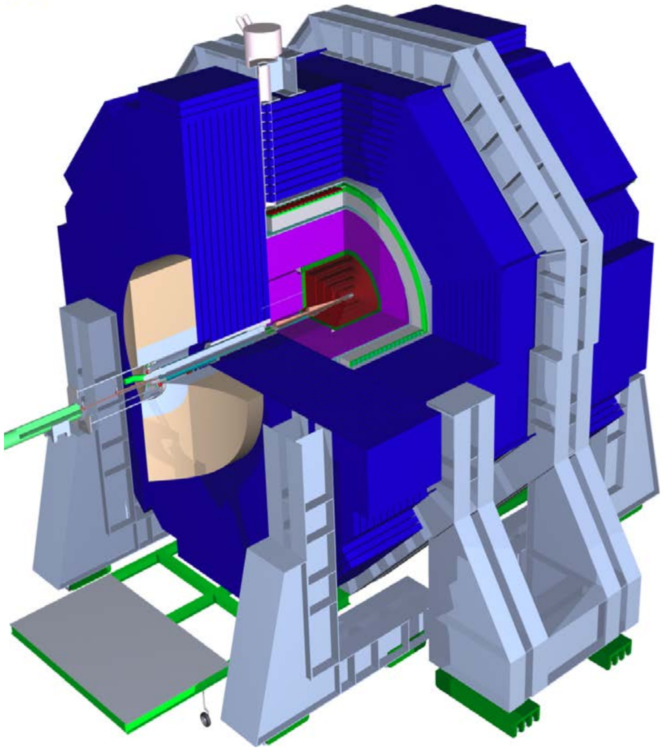
- large radius, large field, compact calorimeter, fine 3D granularity
  - Typ. 1X0 long., transv.: ECAL 0.5cm, HCAL 1cm (gas) - 3cm (scint.)
- optimised in full simulations and particle flow reconstruction

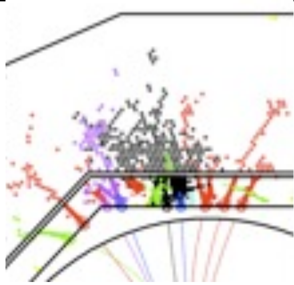
ILD: large TPC, B=3.5T, PFLOW calo



SiD:all-Si tracker, B=5T, PFLOW calo

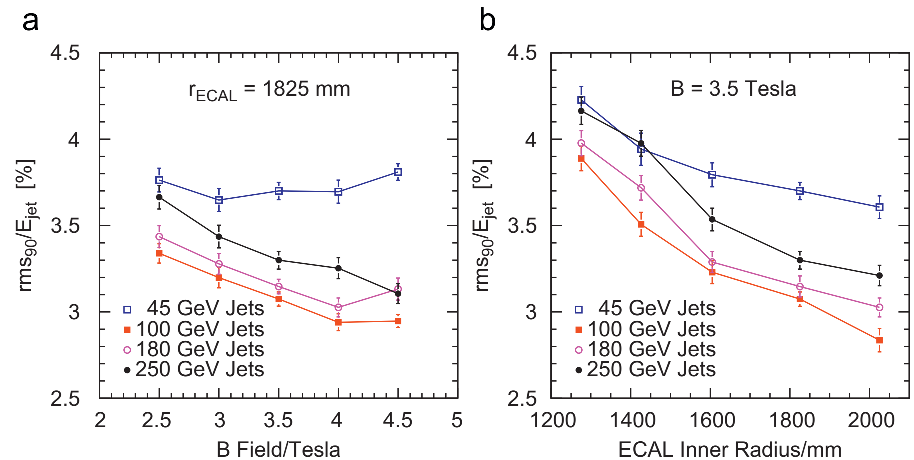
CLIC: tungsten barrel HCAL considered

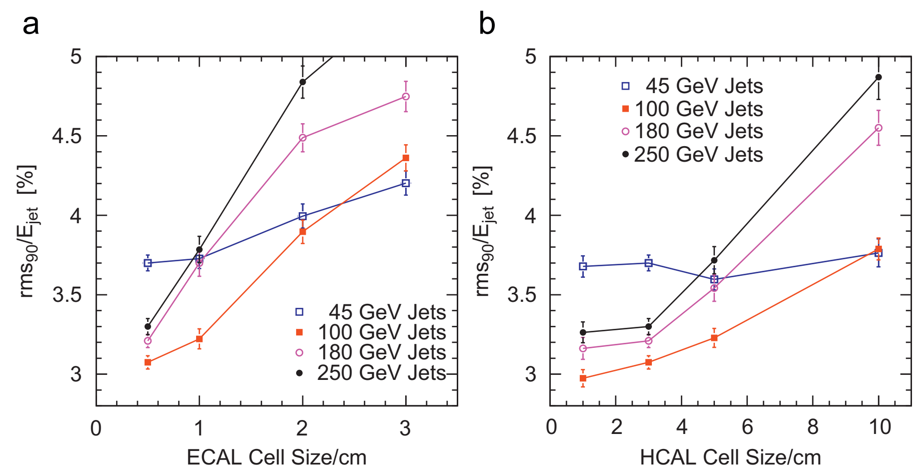


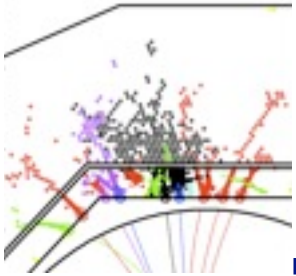


Granularity optimisation

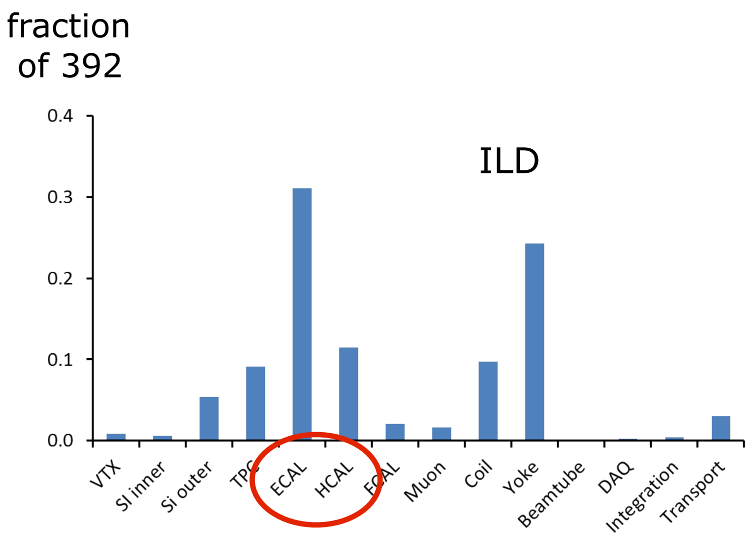
- Based of Pandora PFA
- Large radius and B field drive the cost
- Both ECAL and HCAL segmentation of the order of X_0
  - longitudinal: resolution
  - transverse: separation
- Cost optimisation to be done

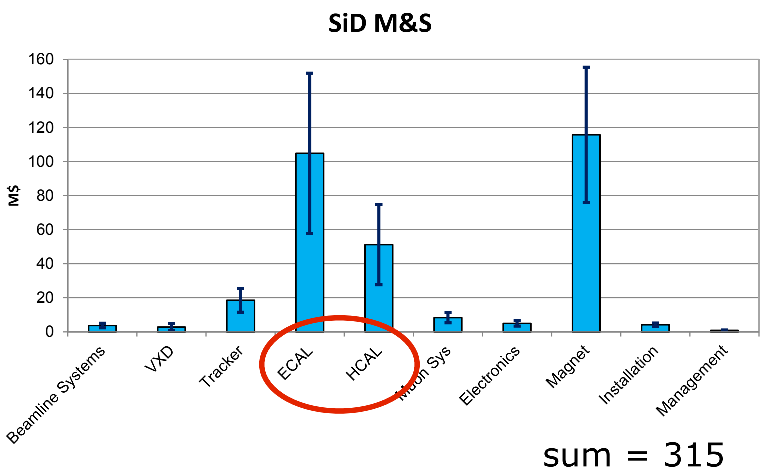




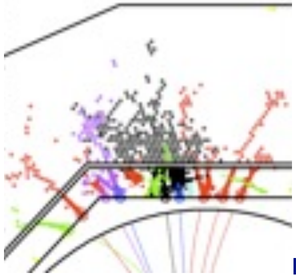


Calorimeter cost

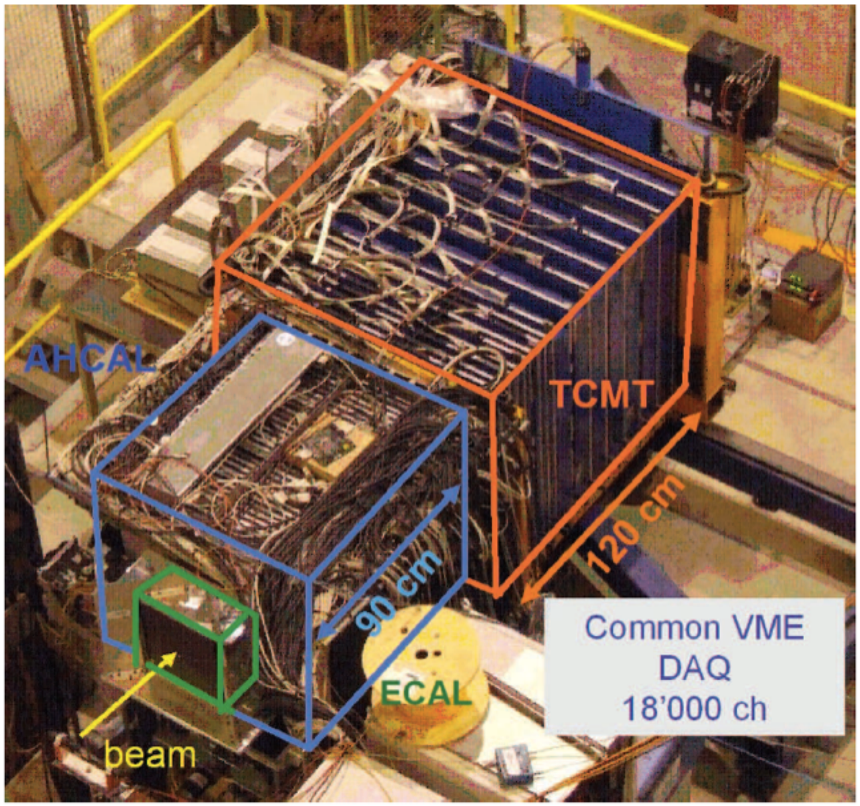


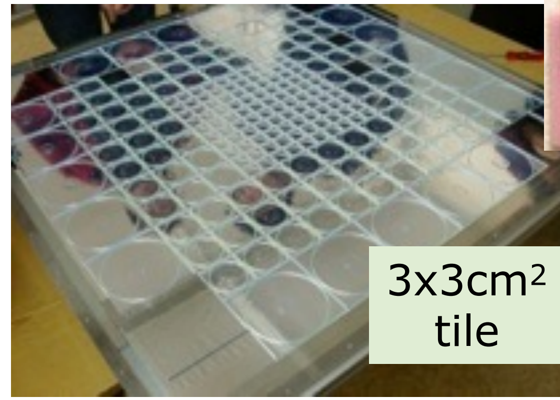


- Costing is at a very early stage
- Yet, many lessons learnt from 2nd generation prototypes
- Example HCAL:
- example ILD scint HCAL: 45M
  - 10M fix, rest ~ volume
  - 10M absorber, rest ~ area (n_{Layer})
  - 16M PCB, scint, rest ~ channels
  - 10 M SiPMs and ASICs
- ECAL:
- main cost driver: silicon area
- ILD 2500 m^2, SiD 1200 m^2
  - cf. CMS tracker 200 m^2
  - cf. CMS ECAL+HCAL endcap 600 m^2

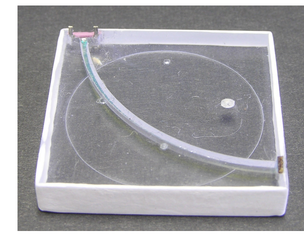


Test beam set-up

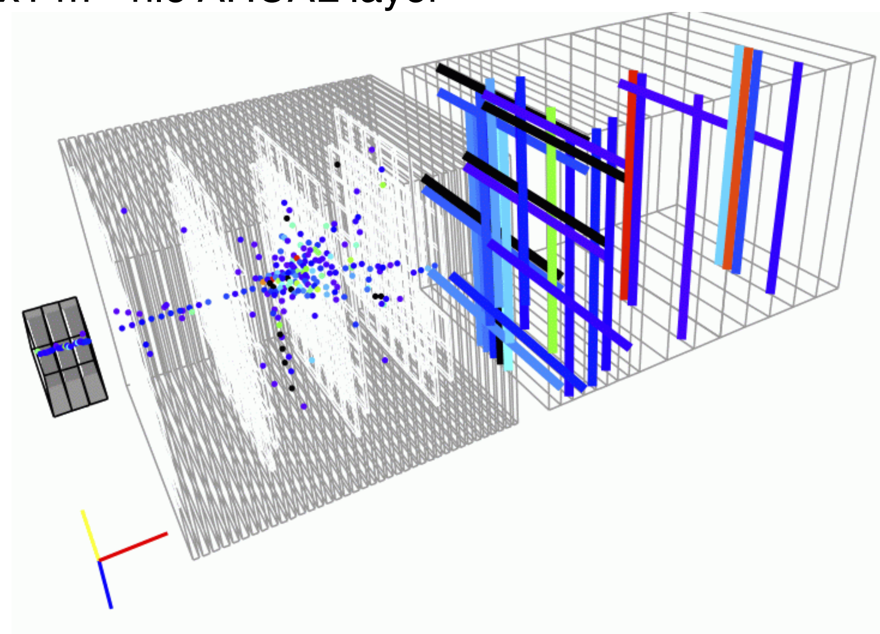




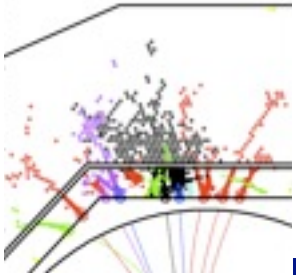
1mm^2
SiPM



1x1 m^2 rile AHCAL layer



- at CERN SPS

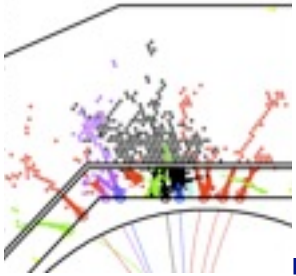


Steel and Tungsten

λ = 17 cm
X_0 = 1.9 cm
d = 2 cm
~ 0.1 λ, 1 X_0

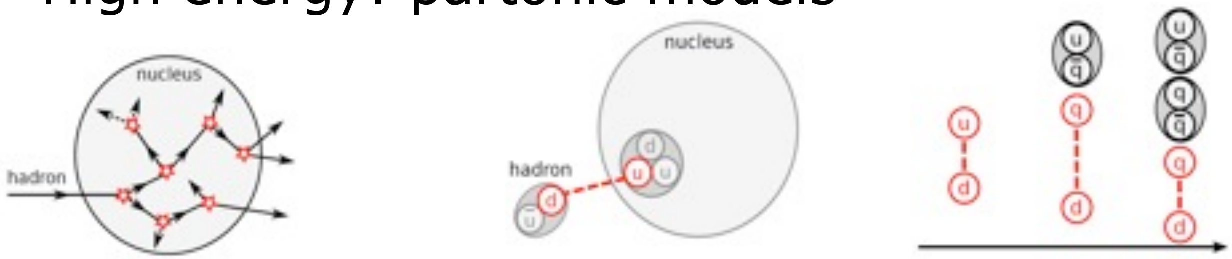
λ = 10 cm
X_0 = 0.4 cm
d = 1 cm
~ 0.1 λ, 2.5 X_0

- Same sampling for hadronic showers
- Different sampling for electromagnetic (sub) showers

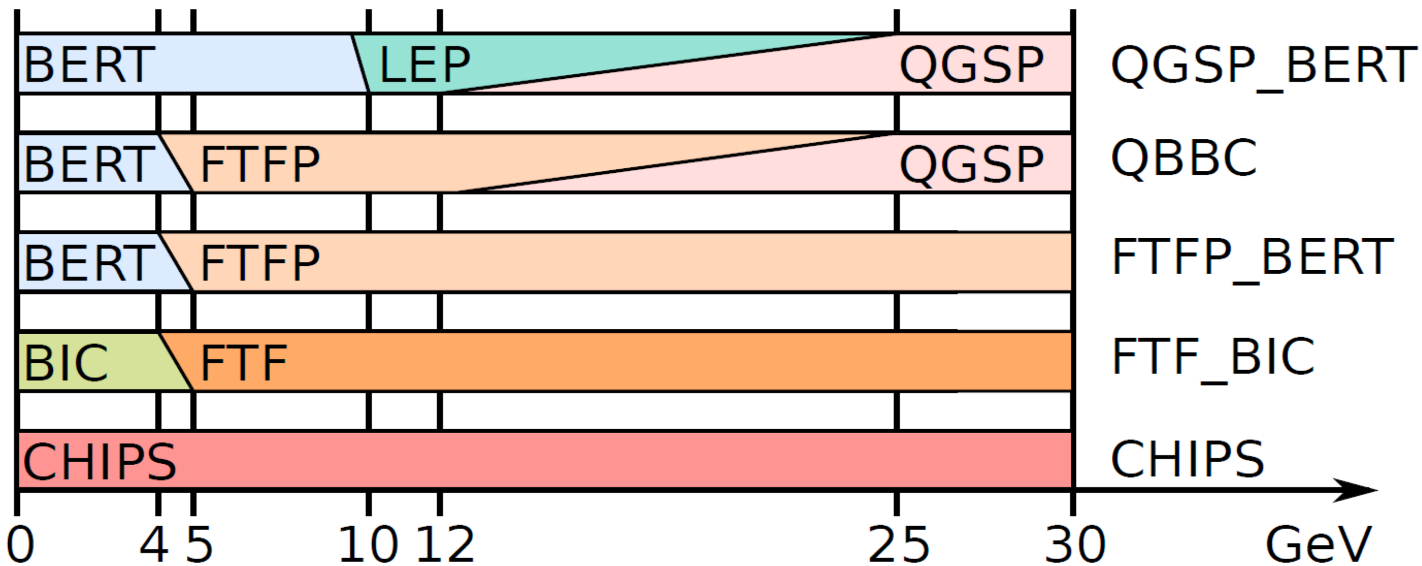


Shower simulation in Geant 4

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



minimize use of phenomenological parameterization



"legacy"

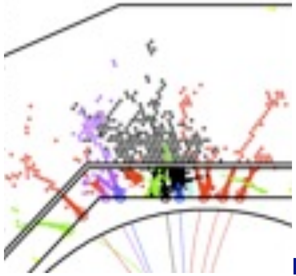
"linear combin."

"production"

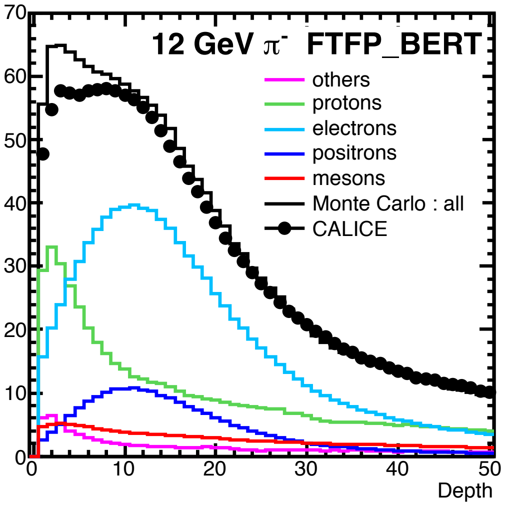
"systematics"

"experimental"

Validation of Geant 4 models

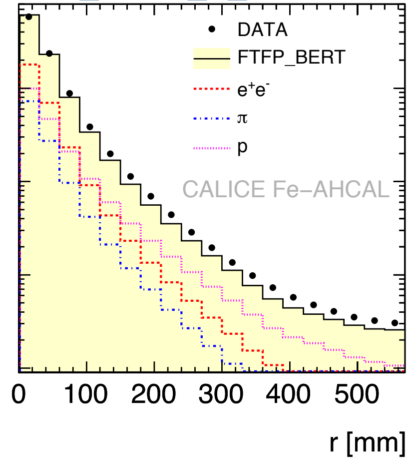


2010_JINST_5_P05007



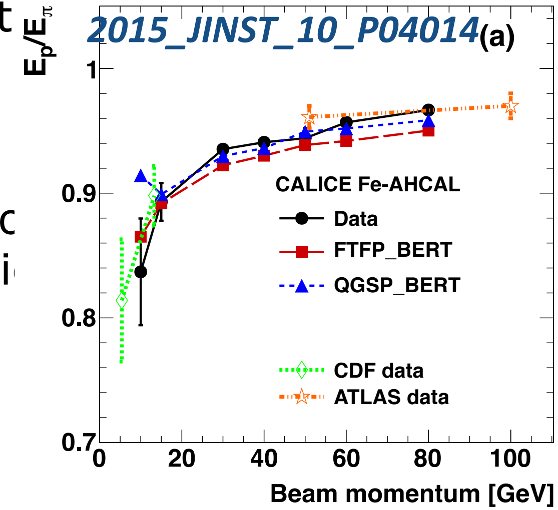
SiW ECAL longit. profile

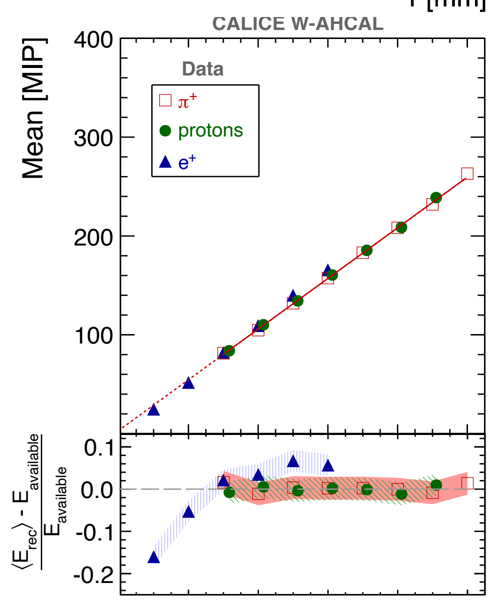
2013_JINST_8_P07005



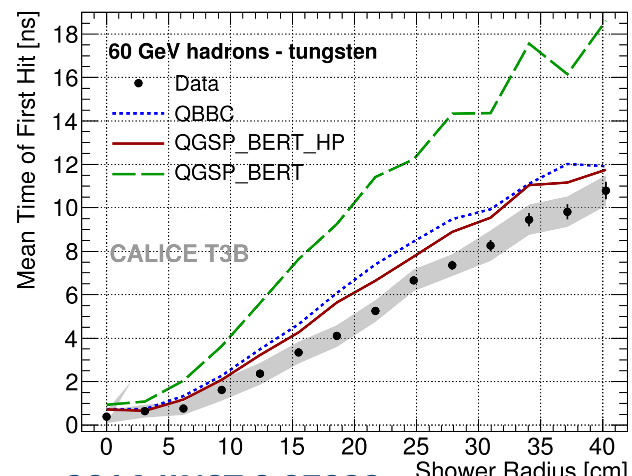
Fe Scint HCAL radial profile, roton pic esp. rati

2015_JINST_10_P04014





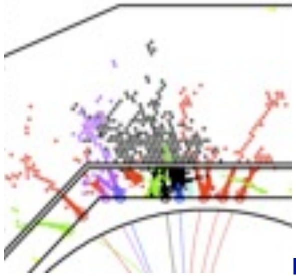
2014_JINST_9_P01004



2014 JINST 9 07022

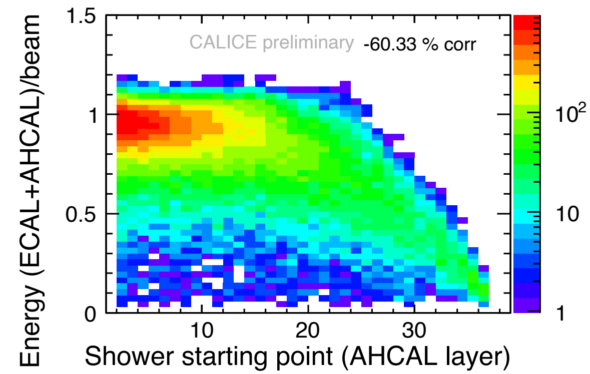
W Scint HCALresponse, timing

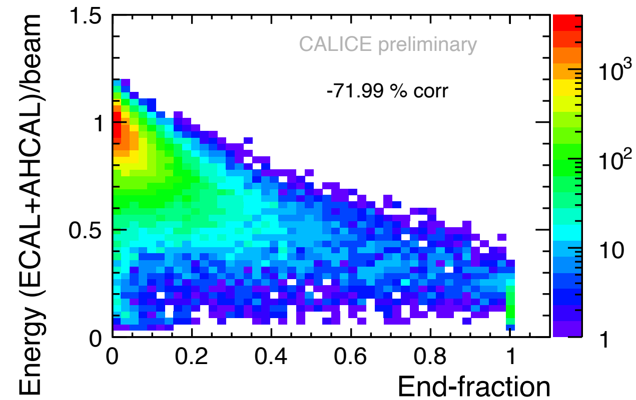
- just a few examples
- altogether at 5% or better

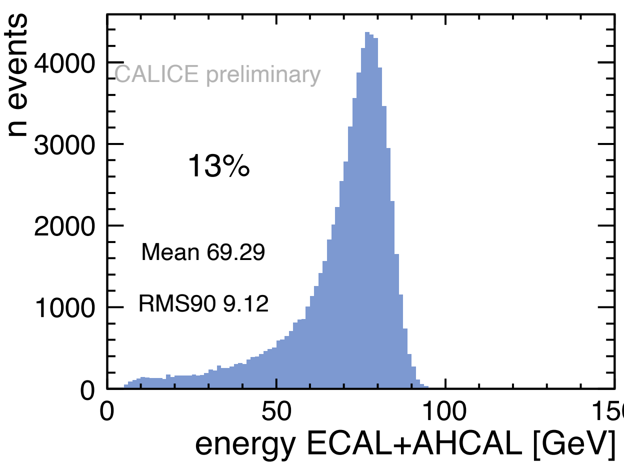


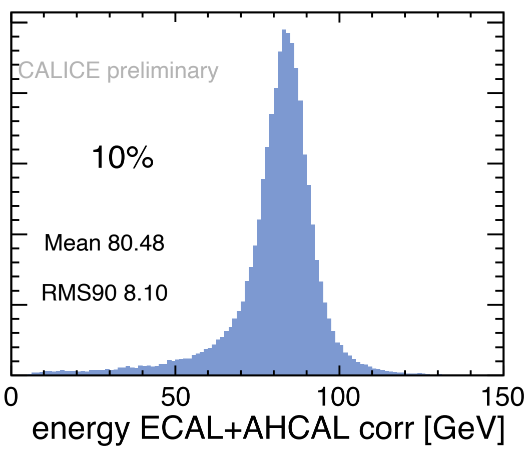
Leakage estimation

- Exploit the 3-D granularity
- ECAL 1λ, HCAL 4.5λ
- Observables
  - shower start
  - energy fraction in rear layers
  - measured energy

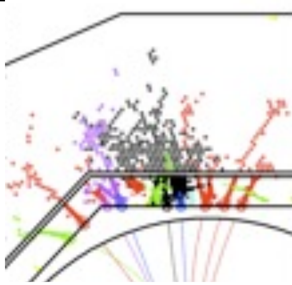






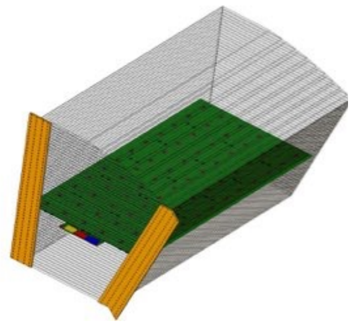


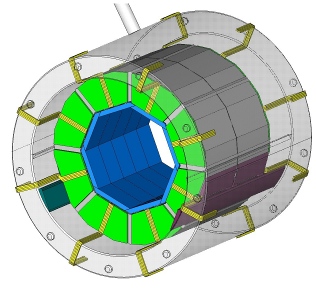
cf : with tail catcher, no coil: 5.4%

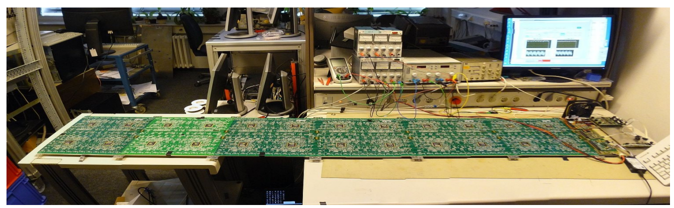


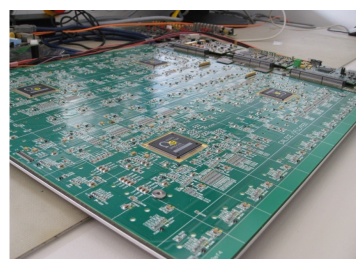
Industrialisation: Numbers!

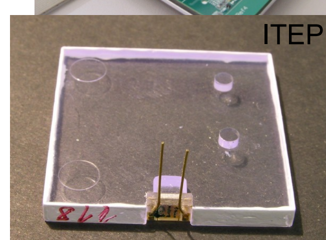
- The AHCAL
- 60 sub-modules
- 3000 layers
- 10,000 slabs
- 60,000 HBUs
- 200’000 ASICs
- 8,000,000 tiles and SiPMs



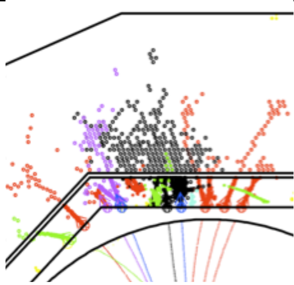






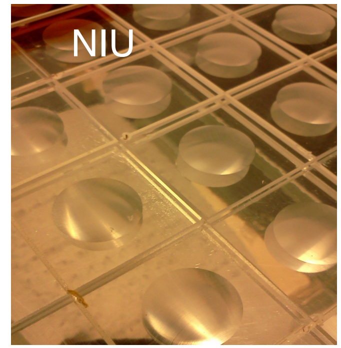


- One year
- 46 weeks
- 230 days
- 2000 hours
- 100,000 minutes
- 7,000,000 seconds

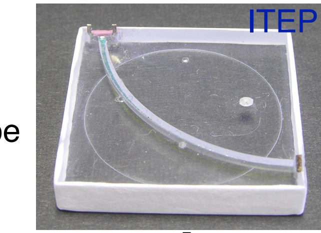


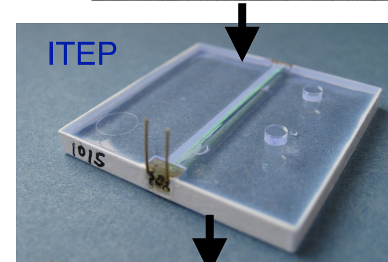
Directions in tile and SiPM R&D

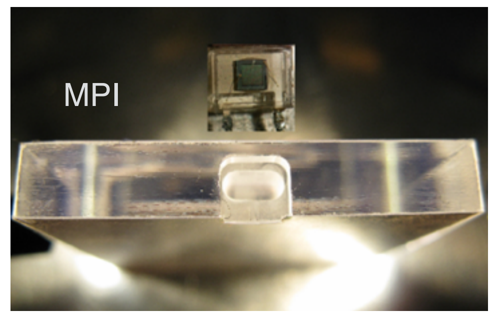
- Revise tile design in view of automatic pick & place procedures
- Consider SMD approach, originally proposed by NIU
- Light yield becomes an issue again
  - build on advances in SiPMs
- Very different assembly, QC and characterisation chain

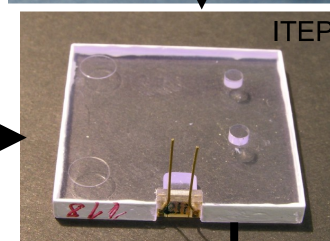


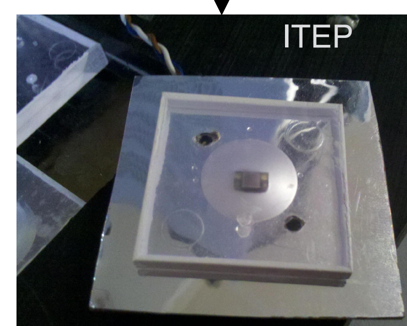
7608 ch
physics
prototype

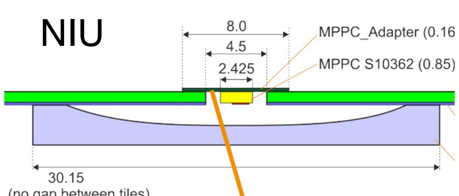












board coming to life

Mainz