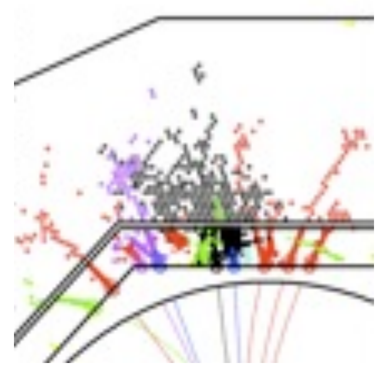
Imaging Calorimeters for Particle Flow reconstruction

Felix Sefkow

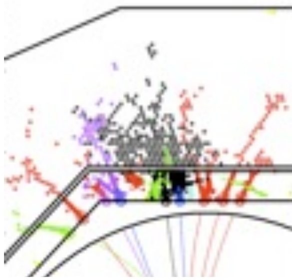
CALICE
Calorimeter for ILC

DESY



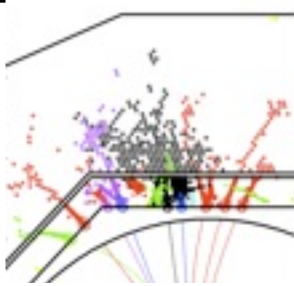
Particle Physics Seminar
Université de Genève, May 27, 2015

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



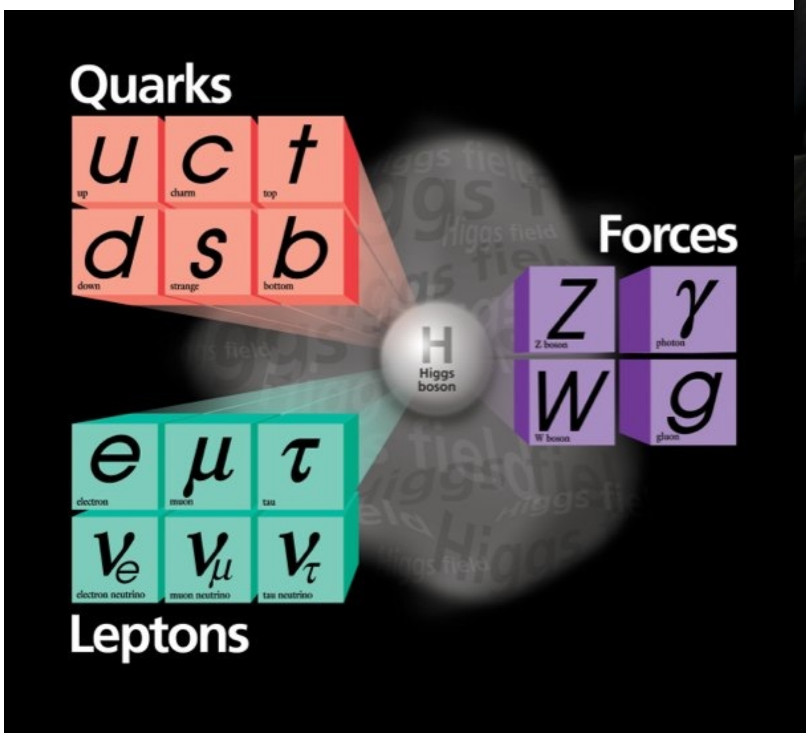
Outline

- LC physics with jets
- Particle flow calorimetry
- Test beam validation
- ECAL and HCAL developments

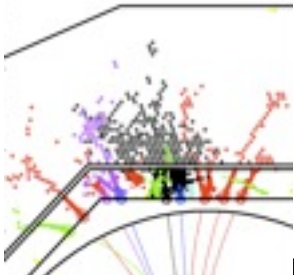


Higgs discovery

2013 Nobel prize in physics



- A turning point:
- after 50 years the last building block falls into place
- and opens the door to something completely new

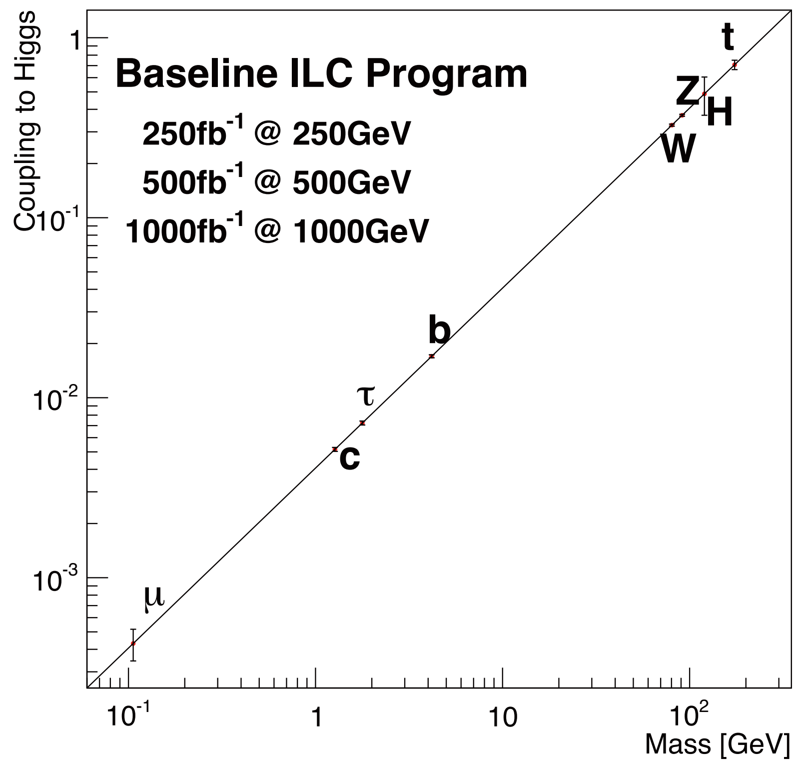


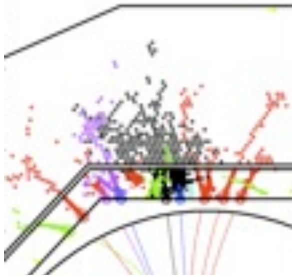
Higgs physics drives the field

"Driver" = a compelling line of inquiry that shows great promise for major progress over the next 10-20 years. Each has the potential to be transformative. Expect surprises.

- Use the Higgs as a new tool for discovery. *S.Ritz, Report on P5*

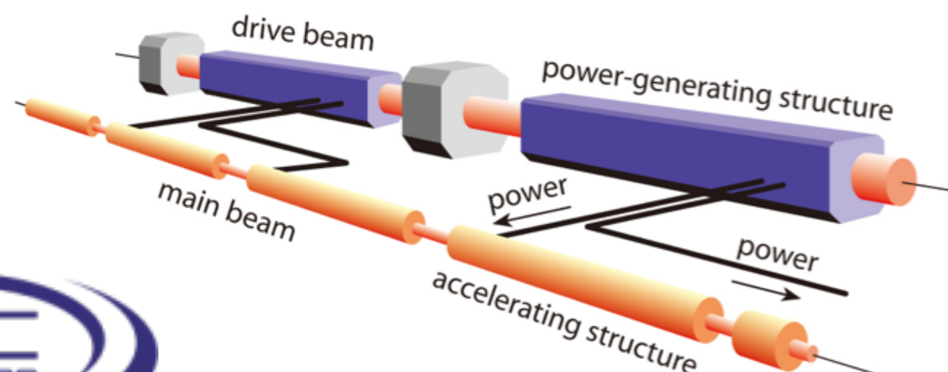
- The main question today:
- establish the Higgs profile
  - mass, spin, parity
  - above all: couplings
- Is the Higgs(125) *the* Higgs and does it fulfil its role in the Standard Model?
- Or does it hold the key to New Physics?

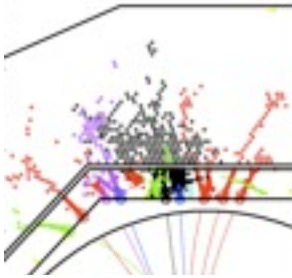




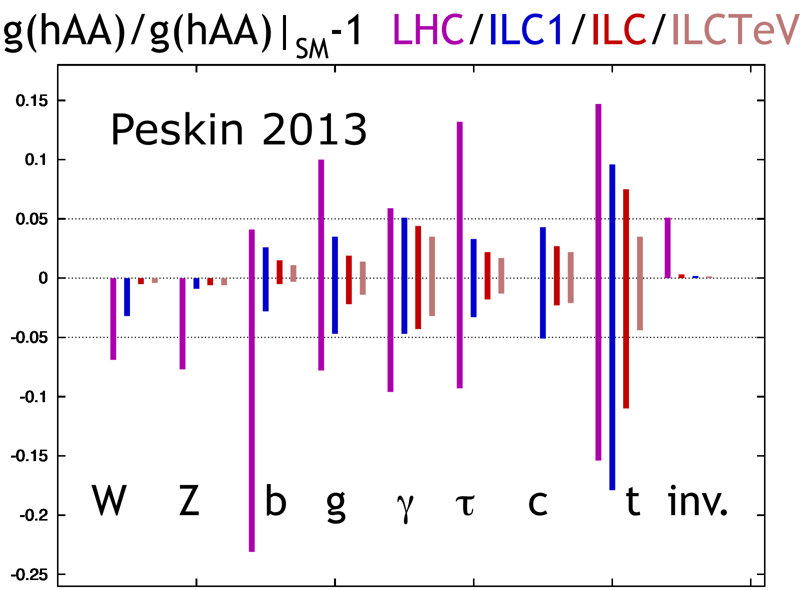
Future e^+e^- colliders

- International Linear Collider
  - 250-1000 GeV
  - TDR 2012
  - studied at government level in Japan
- Compact Linear Collider at CERN
  - 350-3000 GeV
  - CDR 2012
- Circular collider studies
  - CEPC in China
  - FCCee at CERN

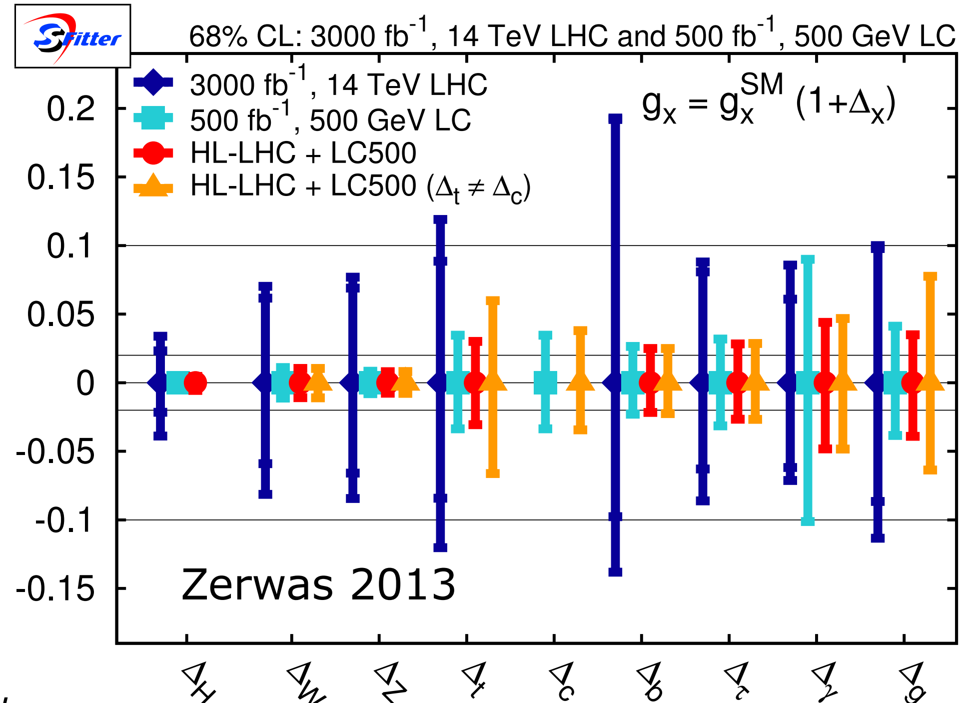




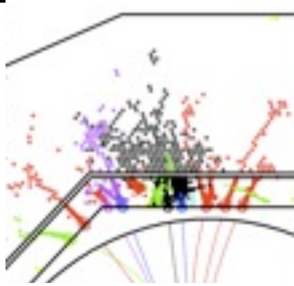
ILC and LHC



LHC 300 fb^{-1} @ 14 TeV
ILC1 250 fb^{-1} @ 250 GeV
ILC 500 fb^{-1} @ 500 GeV
ILC1T 1000 fb^{-1} @ 1 TeV *successively included*

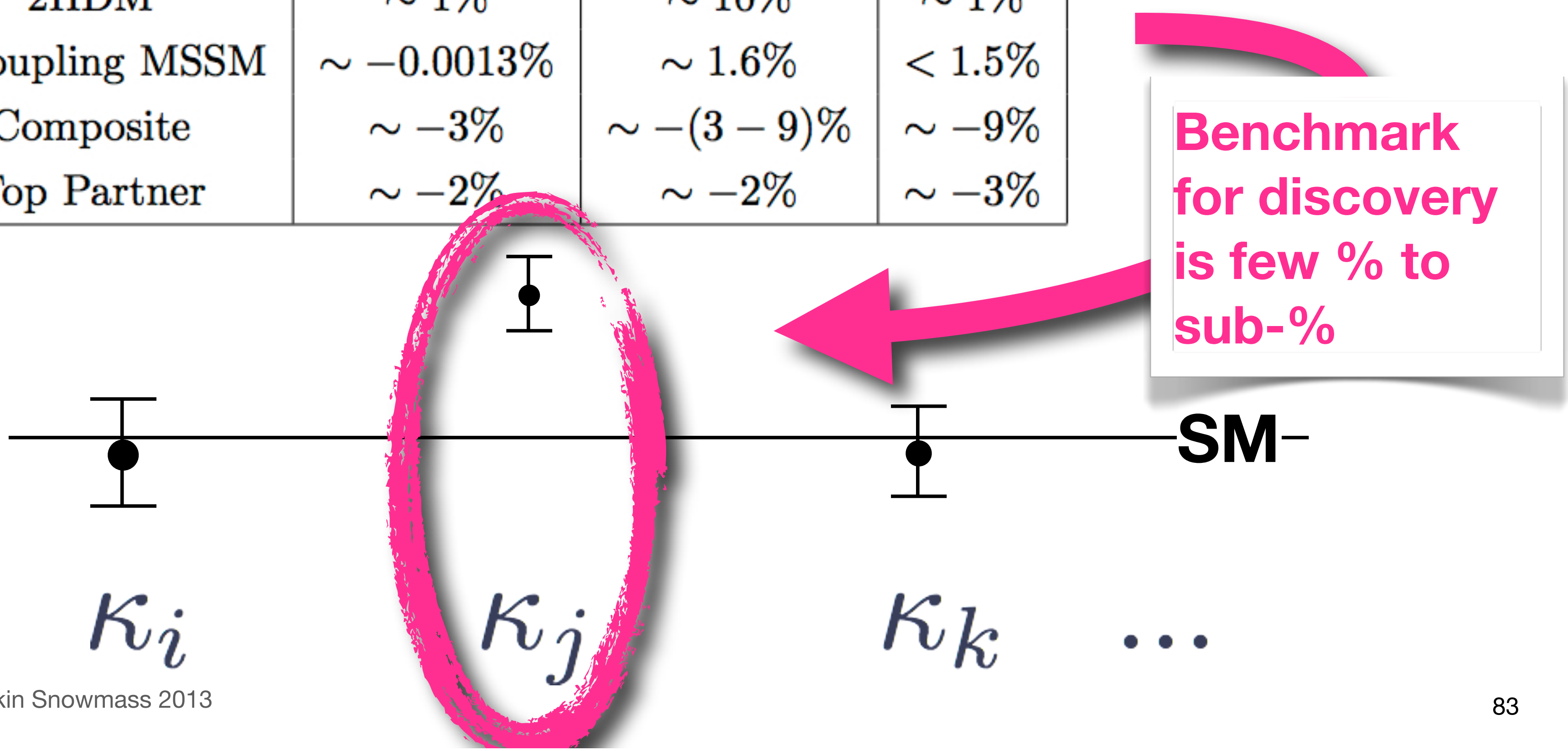


- Only with e+e- collisions one can reach the percent level precision to probe new physics
- also true w.r.t. high lumi LHC



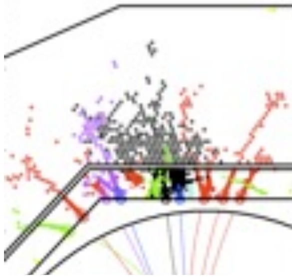
Precision for discovery

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



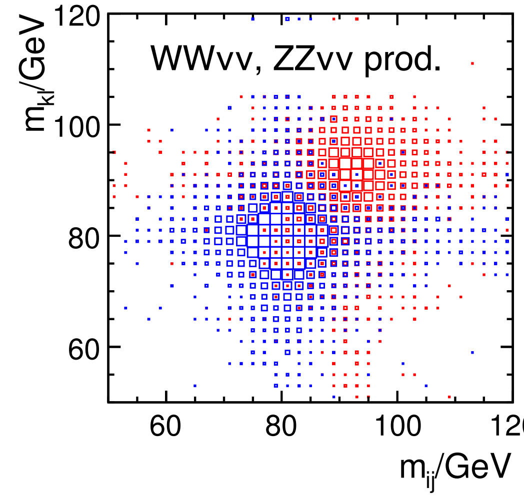
Brock/Peskin Snowmass 2013

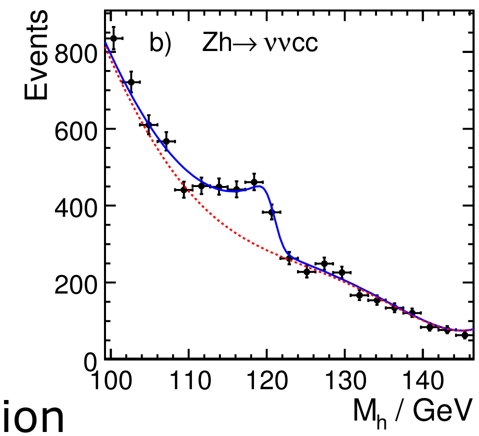
83

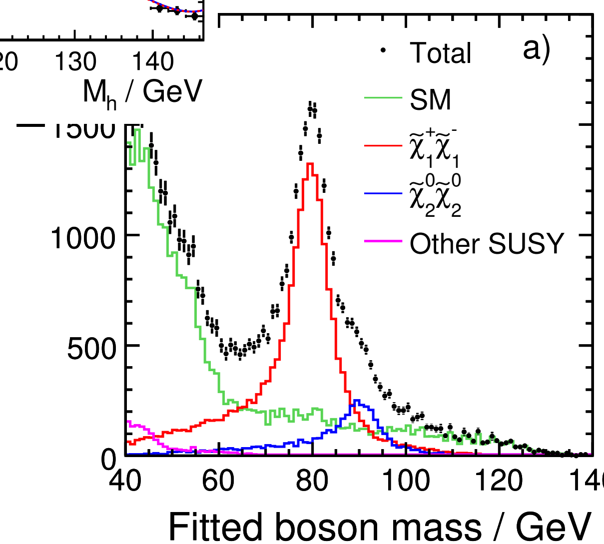


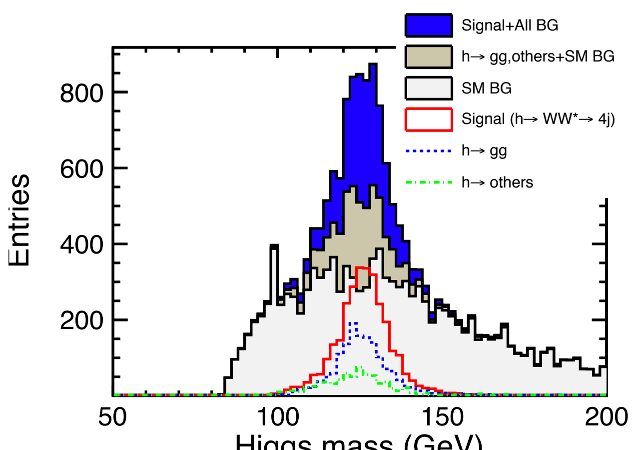
LC physics with jets: M_{inv}

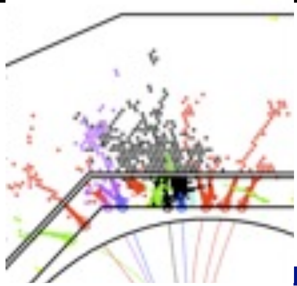
- W - Z separation
  - study strong e.w. symmetry breaking at 1 TeV
- Other di-jet mass examples
  - H → cc, Z → νν
  - Higgs recoil with Z → qq
  - invisible Higgs
  - WW fusion → H → WW
    - total width and g_{HWW}
- SUSY example:
  - Chargino neutralino separation





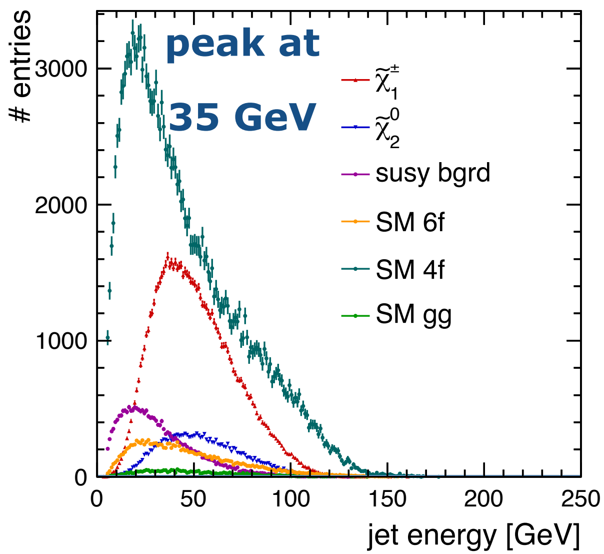




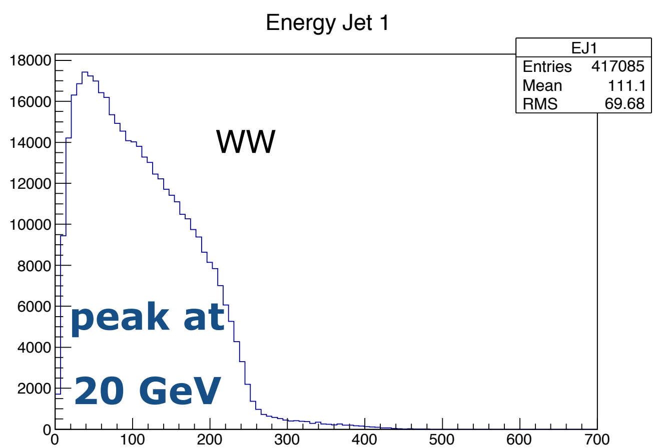


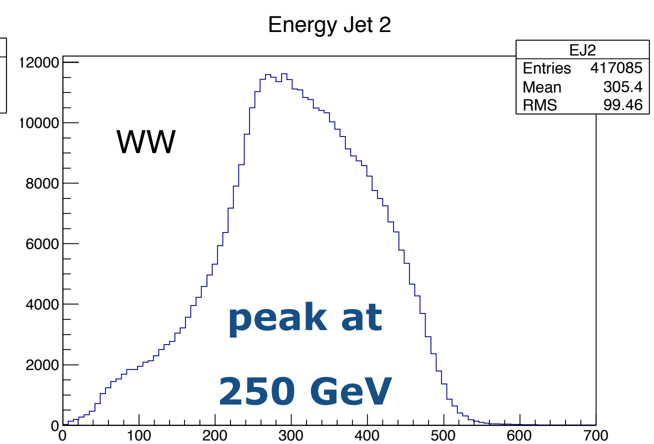
Jet energies

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



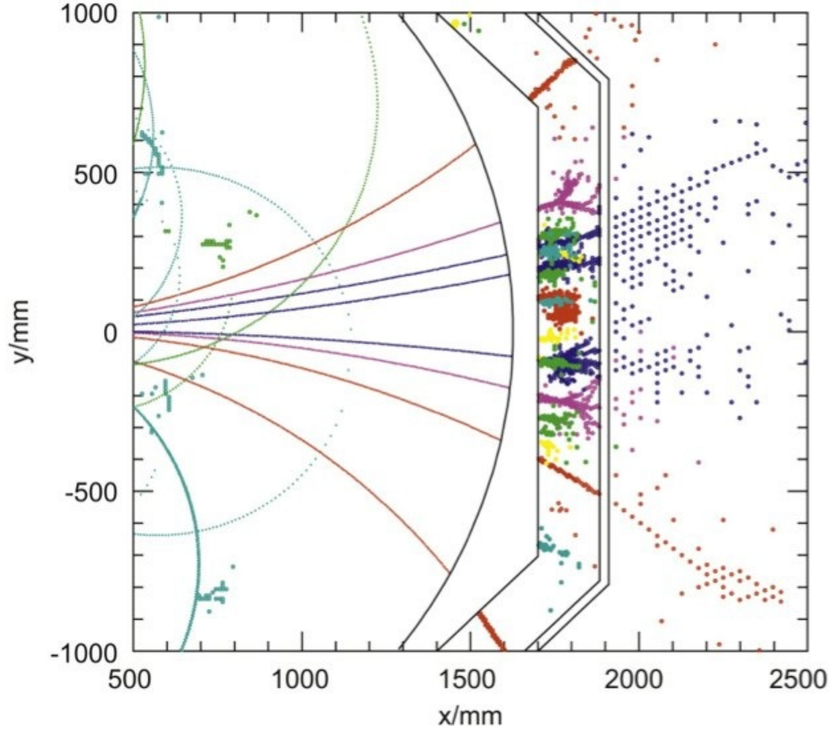
- At $\sqrt{s}$ = 500 GeV
- example chargino, neutralino → qq + invis.
- At $\sqrt{s}$ = 1 TeV
- example WW→H → WW → lνqq

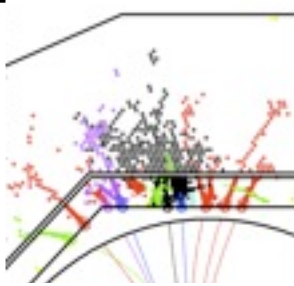




plots:
J.List, M.Chera, A.Rosca
DESY

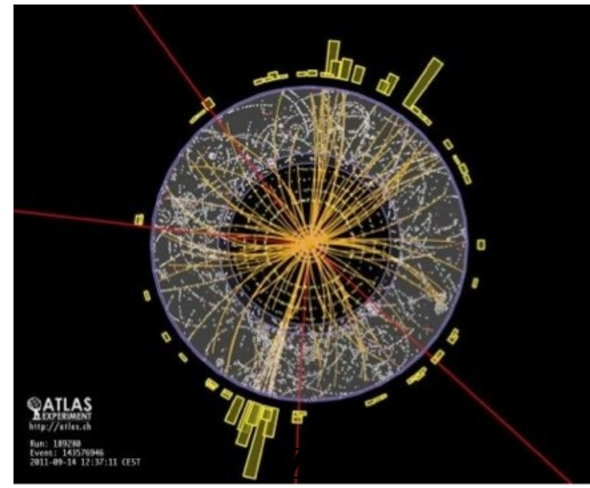
Particle flow concept and detectors

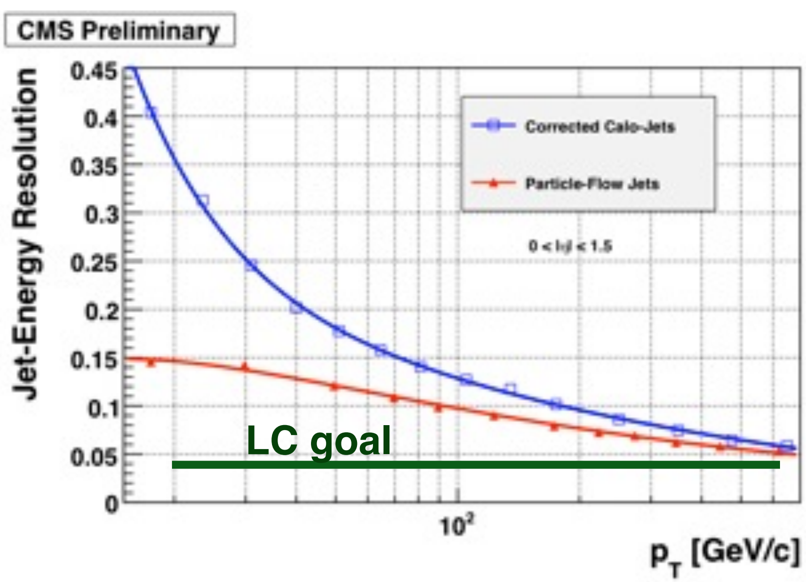




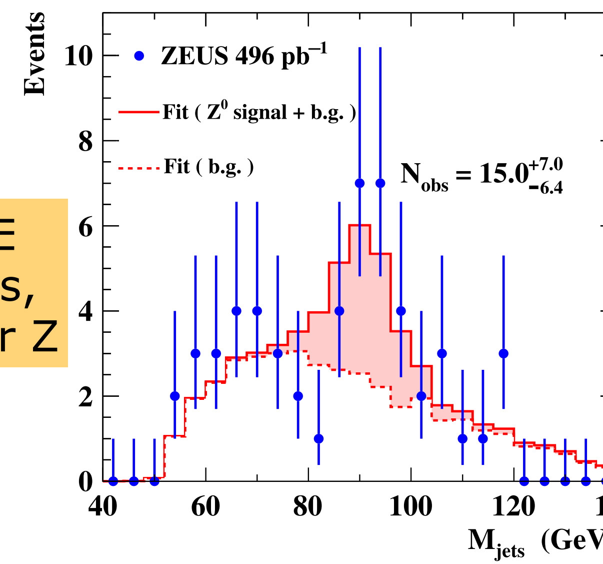
The jet energy challenge

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

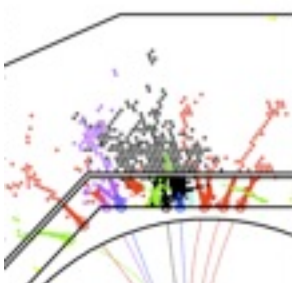




35%√E
for pions,
6 GeV for Z

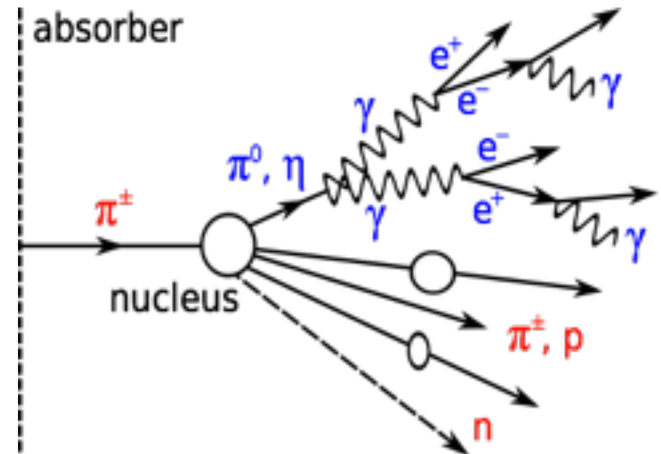


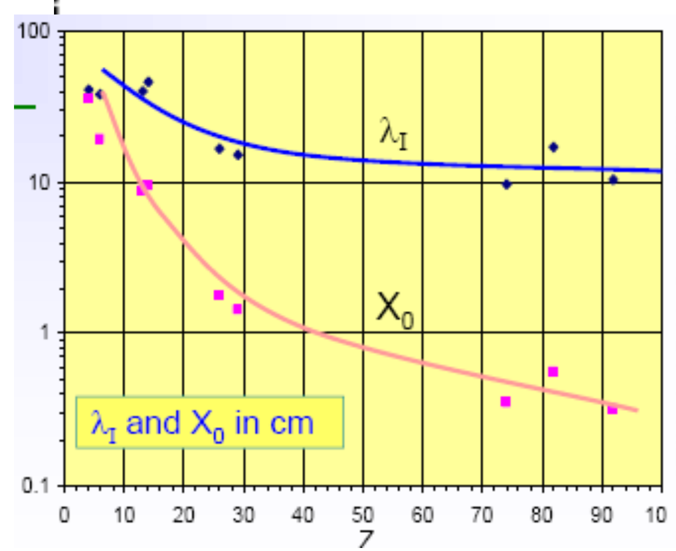
Recall some basics

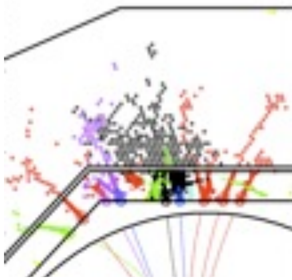


Hadron showers

- 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 remains invisible
- Similar to em showers, but much more complex
- Different scale: hadronic interaction length
  - both scales present

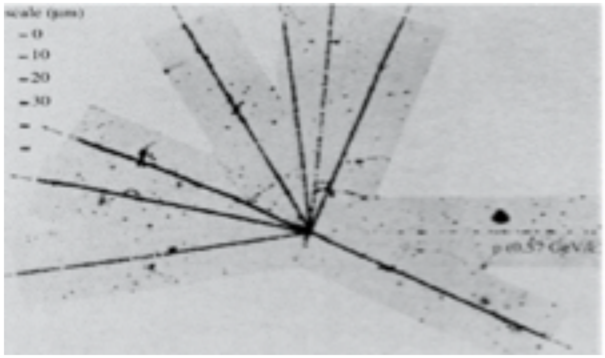




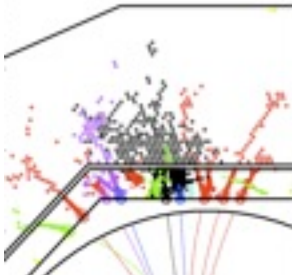


Hadronic interactions

- 1^{st} 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
- 2^{nd} stage: spallation
  - Intra-nuclear cascade
    - Fast nucleons and other hadrons
  - Nuclear de-excitation
    - Evaporation of soft nucleons and α particles
    - Fission + evaporation

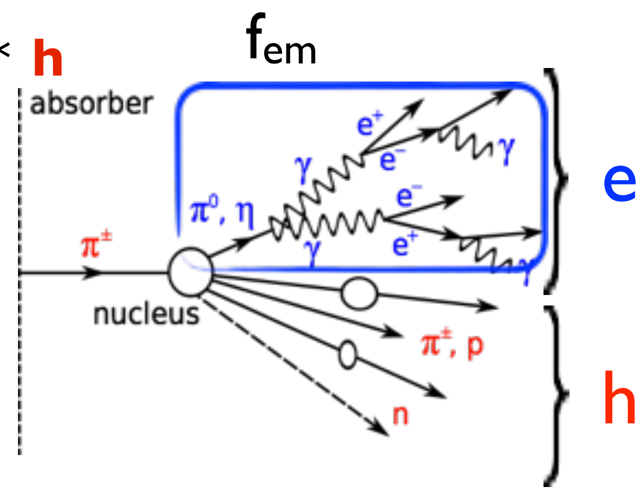


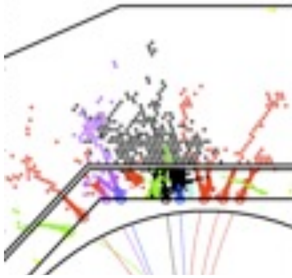
- The response to the hadronic part of a hadron-induced shower is usually smaller than that to the electromagnetic part: **h ≠ e**
  - Due to the invisible energy
  - Due to the short range of spallation nucleons
  - Due to saturation effects for slow, highly ionizing particles



Electromagnetic fraction

- π^0 production irreversible; "one way street"
  - $\pi^0 \rightarrow \gamma\gamma$ produce em shower, no further hadronic interaction
  - Remaining hadrons undergo further interactions, more π^0
  - 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 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%



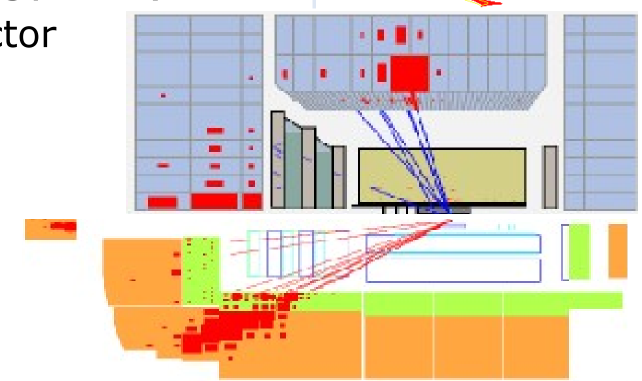


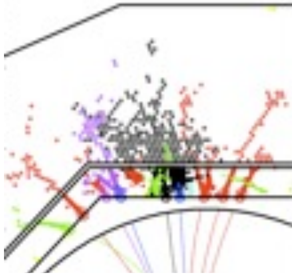
Compensation

Different strategies, which can also be combined

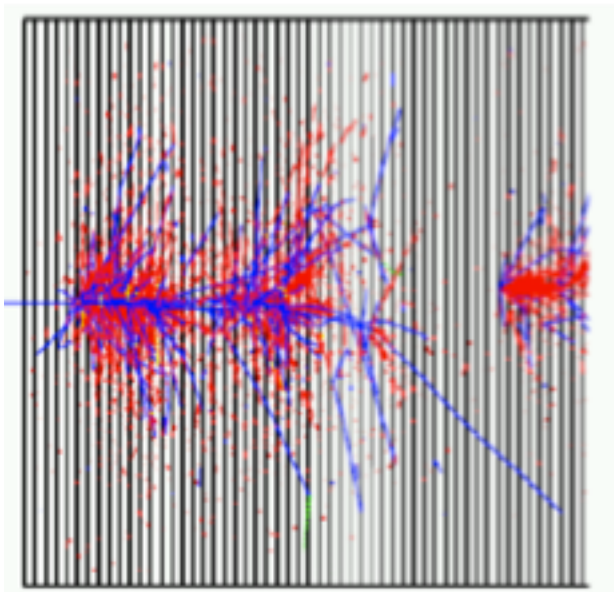
- Hardware compensation
  - Reduce em response
    - High Z, soft photons
  - Increase had response
    - Neutron part (correlated with binding energy loss)
      - Tunable via thickness of hydrogenous detector
  - Example ZEUS: uranium scintillator,
  - 35% /√E for hadrons, 45% /√E for jets
- Software 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

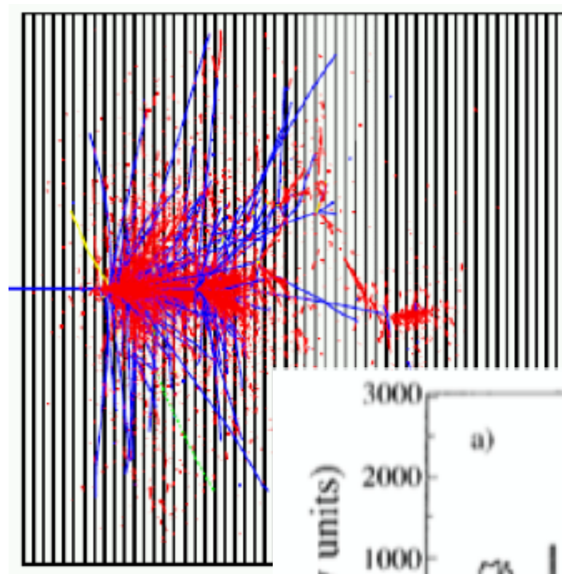




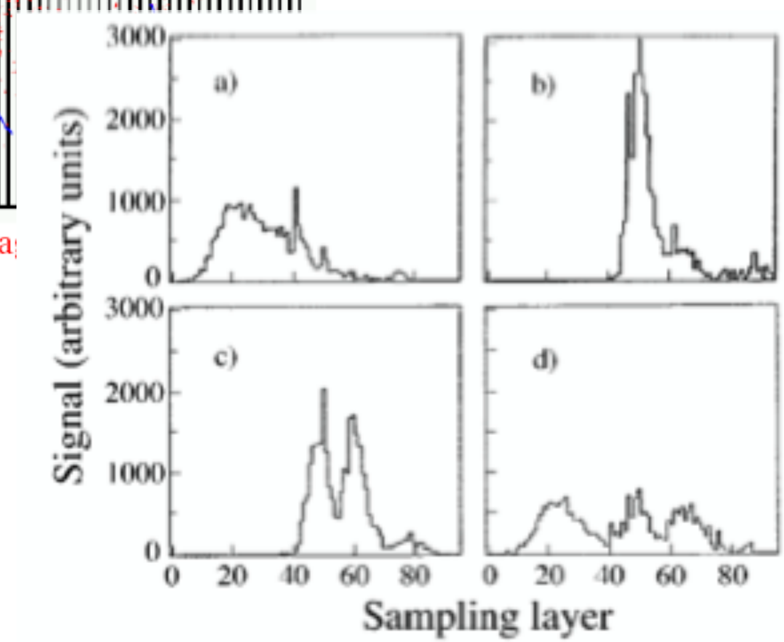
More fluctuations: leakage



blue = hadronic component

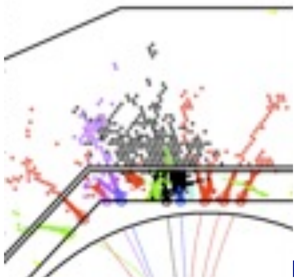


red = electroma



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

sampling fluctuations



Hadron and jet calorimetry:

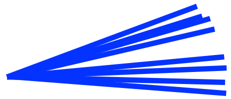
- Hadron showers:
  - Large variety of physics processes
  - With different detector responses e, h
  - In general non-linear
  - Inevitably invisible energy; ultimate limit for resolution
  - Small numbers, large fluctuations
  - Large volume, small signals
  - Difficult to model

- Jet energy performance = hadron performance or worse

Particle Flow Calorimetry

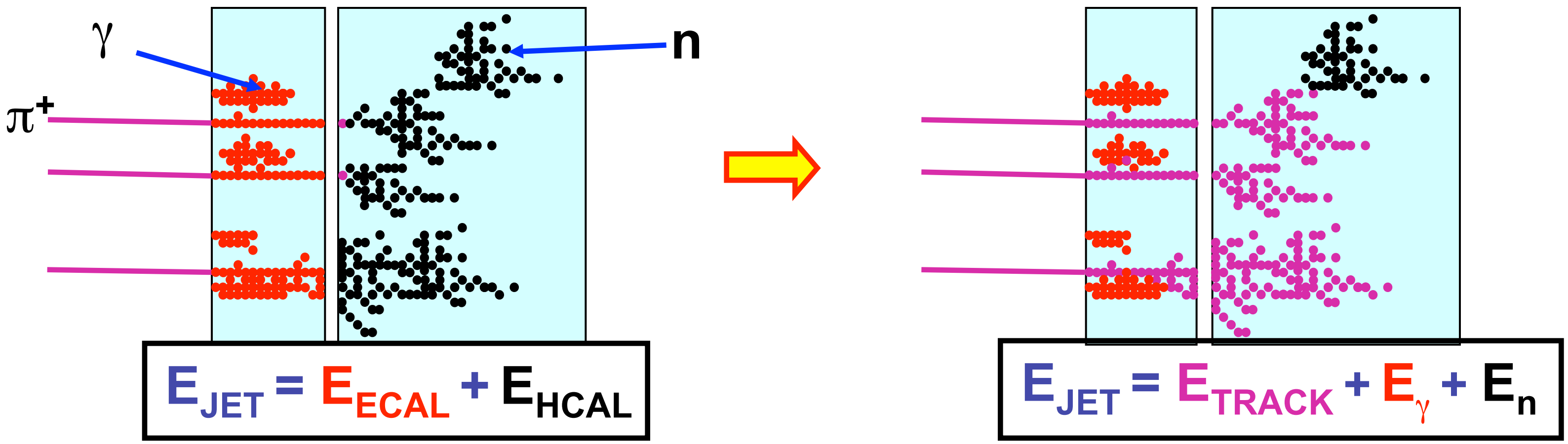
★ **In a typical jet :**

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



★ **Particle Flow Calorimetry paradigm:**

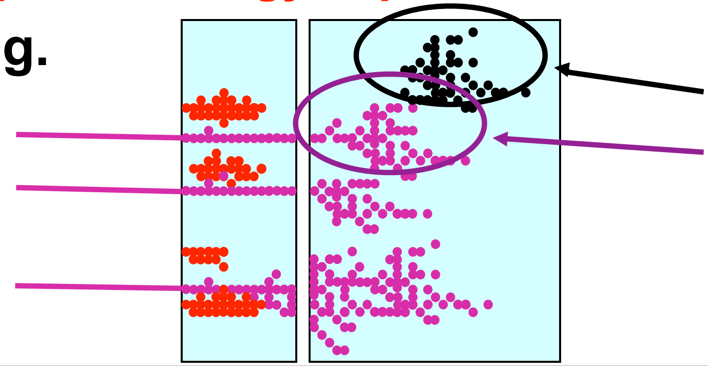
- charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_E/E < 20\,\%/\sqrt{E(\mathrm{GeV})}$
- Neutral hadrons (ONLY) in HCAL
- Only 10 % of jet energy from HCAL ⇒ much improved resolution

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.

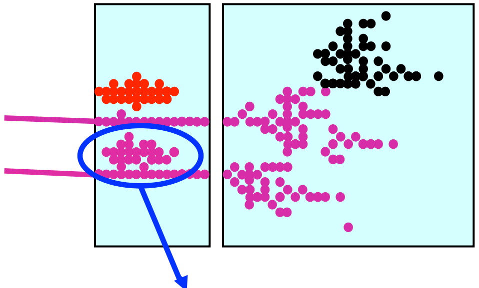


If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

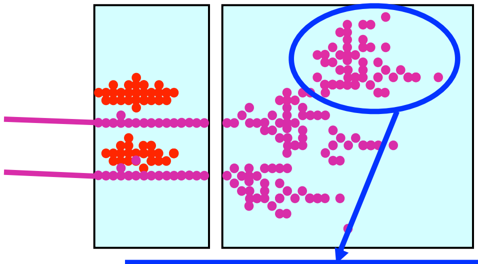
Three types of confusion:

i) Photons



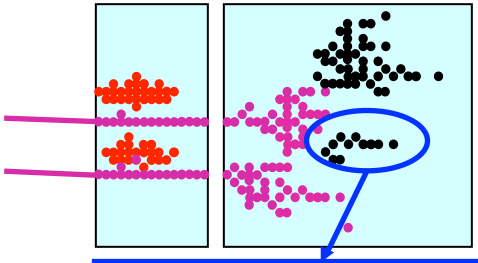
Failure to resolve photon

ii) Neutral Hadrons

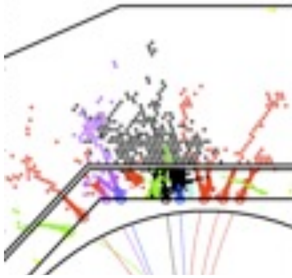


Failure to resolve neutral hadron

iii) Fragments



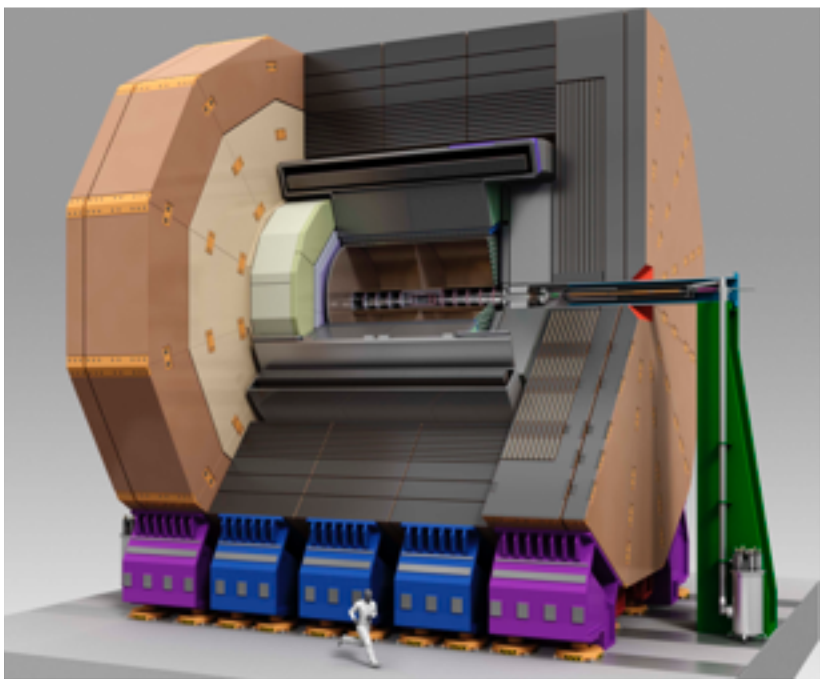
Reconstruct fragment as separate neutral hadron



Particle flow detectors

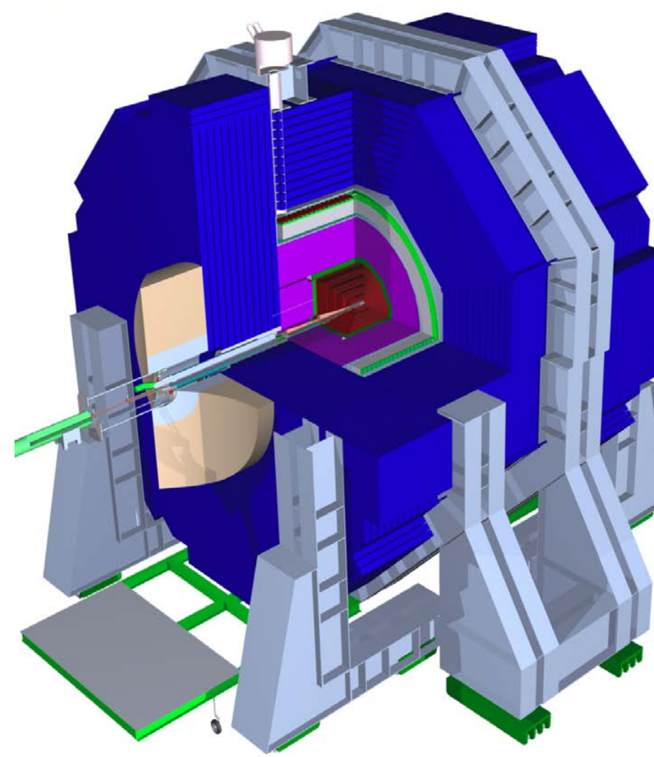
- large radius, large field, compact calorimeter, fine 3D granularity
  - Typ. 1X0 long., transv.: ECAL 0.5cm, HCAL 1cm (gas) - 3cm (scint.)
- optimised in full simulations and particle flow reconstruction

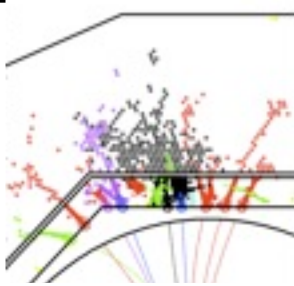
ILD: large TPC, B=3.5T, PFLOW calo



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

CLIC:
tungsten
barrel HCAL
considered

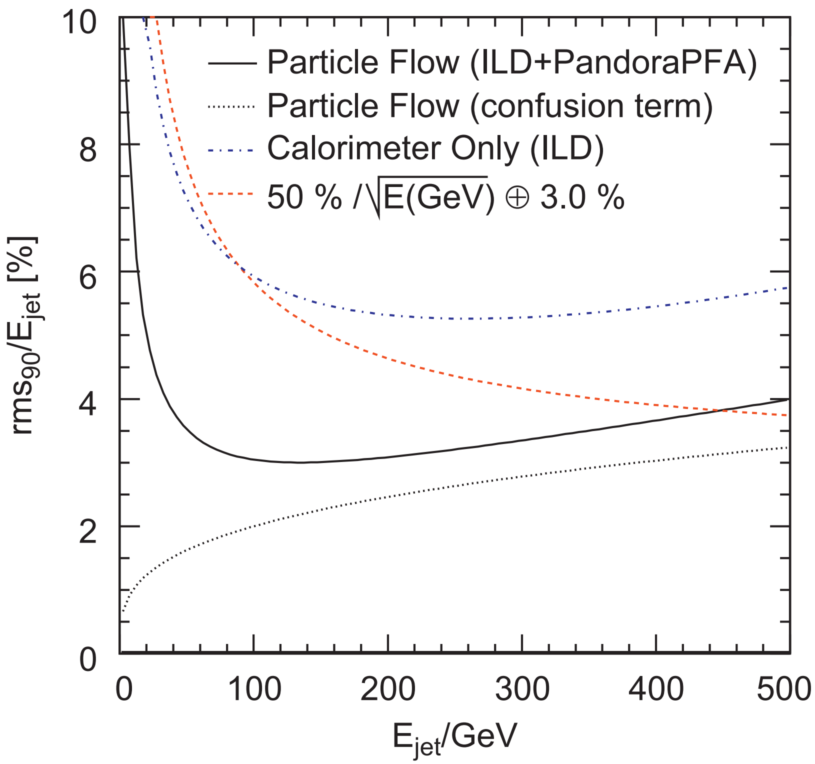


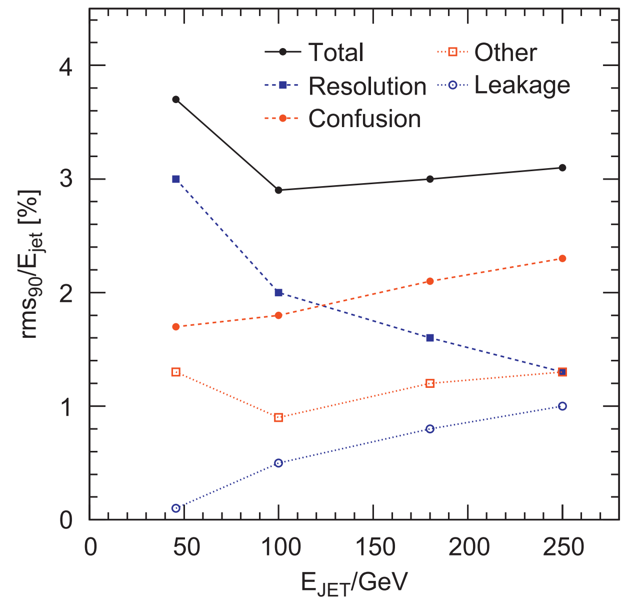


Understand particle flow performance

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

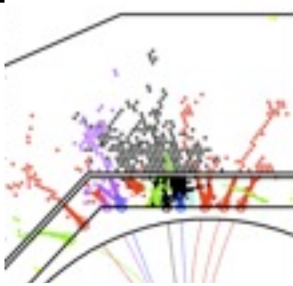
Resolution | Tracking | Leakage | Confusion





- Particle flow is always a gain
  - even at high jet energies
- HCAL resolution does matter
  - dominates up to ~ 100 GeV
- Leakage plays a role, too
  - but less than for the calo alone

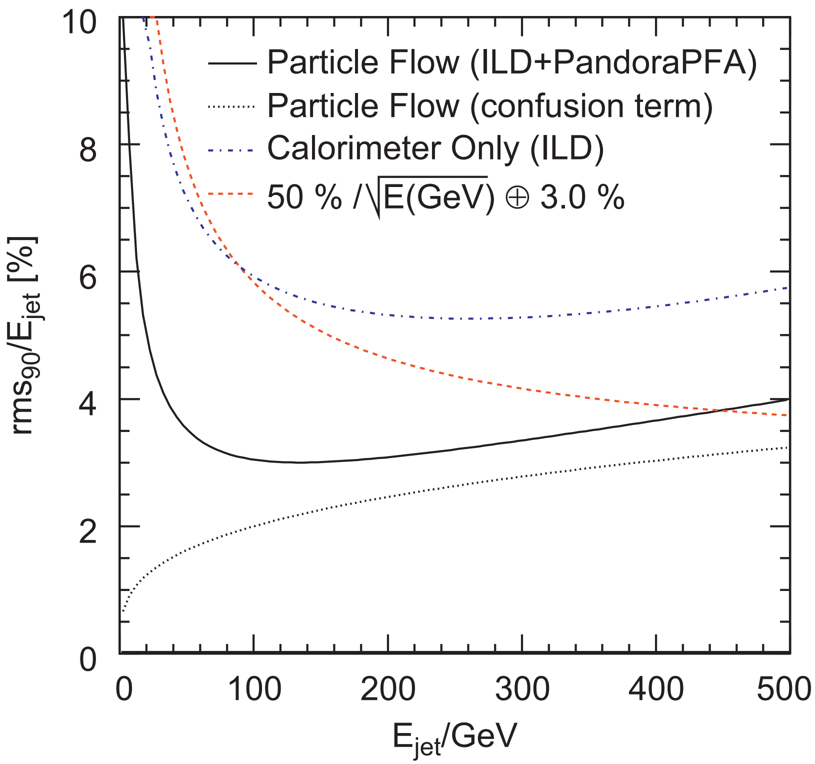
M.Thomson, Nucl.Instrum.Meth. A611 (2009) 25-40

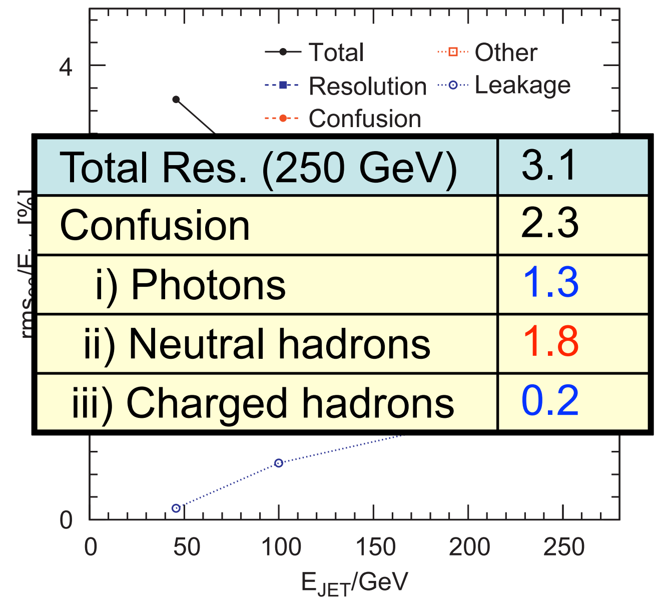


Understand particle flow performance

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

Resolution — Tracking — Leakage — Confusion

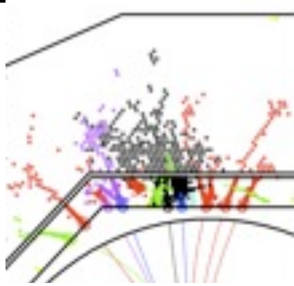




Total Res. (250 GeV)	3.1
Confusion	2.3
i) Photons	1.3
ii) Neutral hadrons	1.8
iii) Charged hadrons	0.2

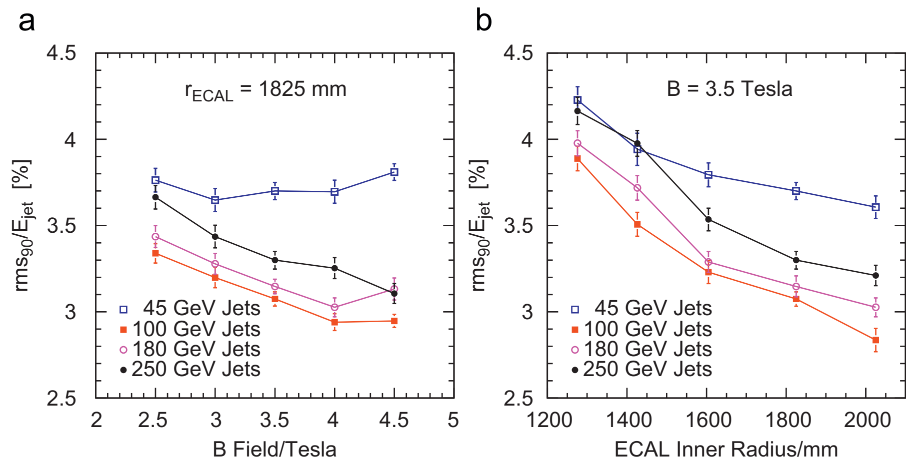
- Particle flow is always a gain
  - even at high jet energies
- HCAL resolution does matter
  - dominates up to ~ 100 GeV
- Leakage plays a role, too
  - but less than for the calo alone

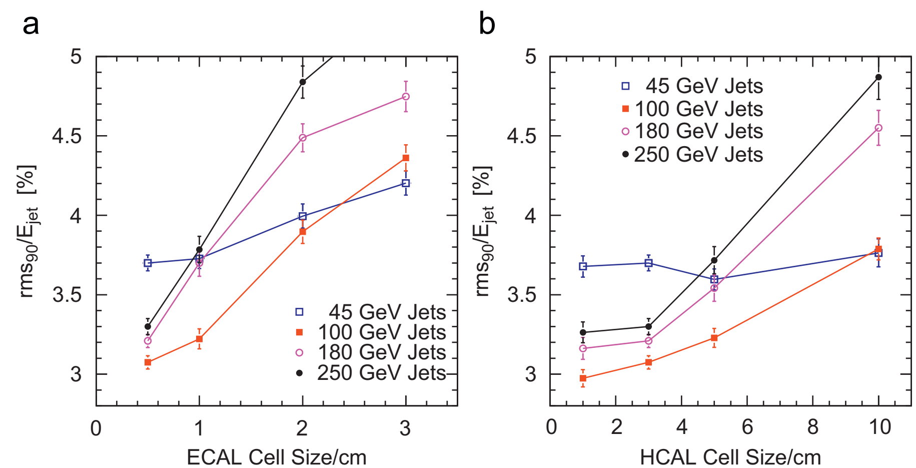
M.Thomson, Nucl.Instrum.Meth. A611 (2009) 25-40



Granularity optimisation

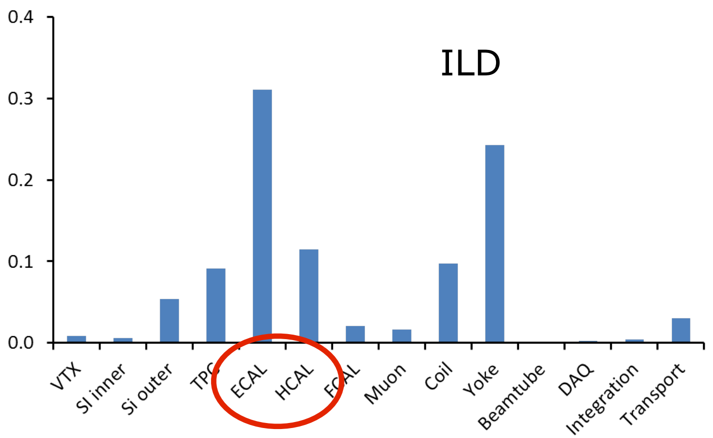
- Based of Pandora PFA
- Large radius and B field drive the cost
- Both ECAL and HCAL segmentation of the order of X_0
  - longitudinal: resolution
  - transverse: separation
- Cost optimisation to be done

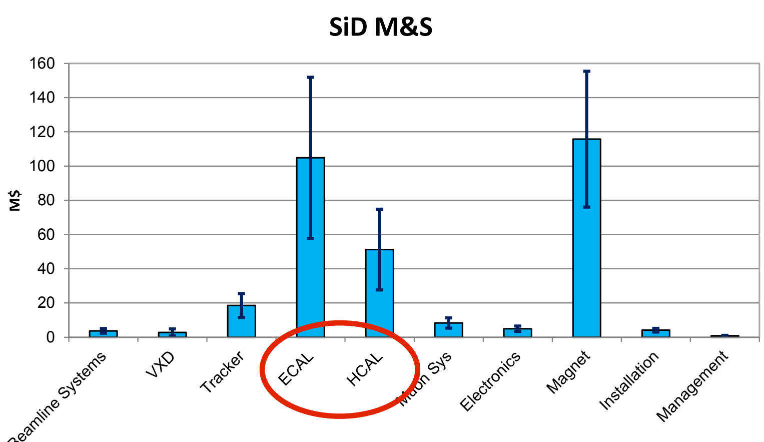




Calorimeter cost

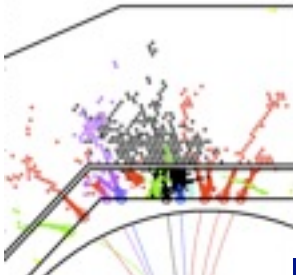
fraction
of 392





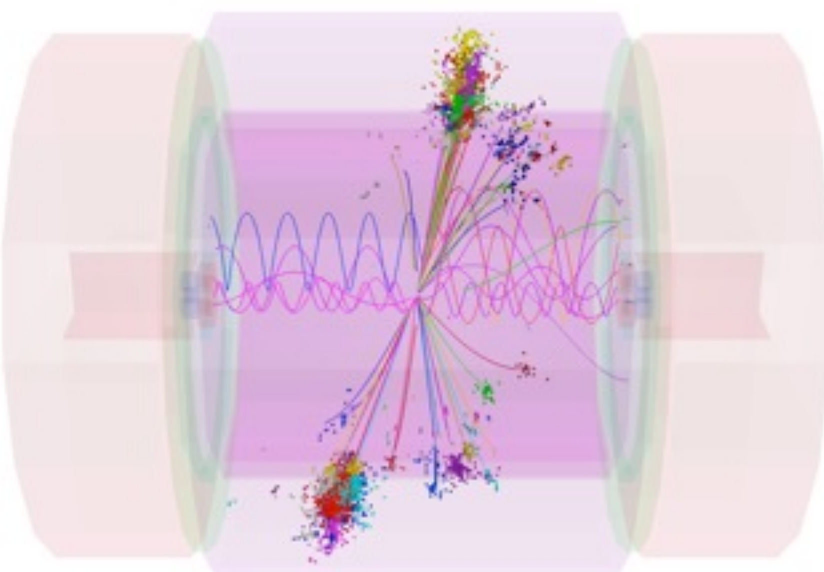
sum = 315

- 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

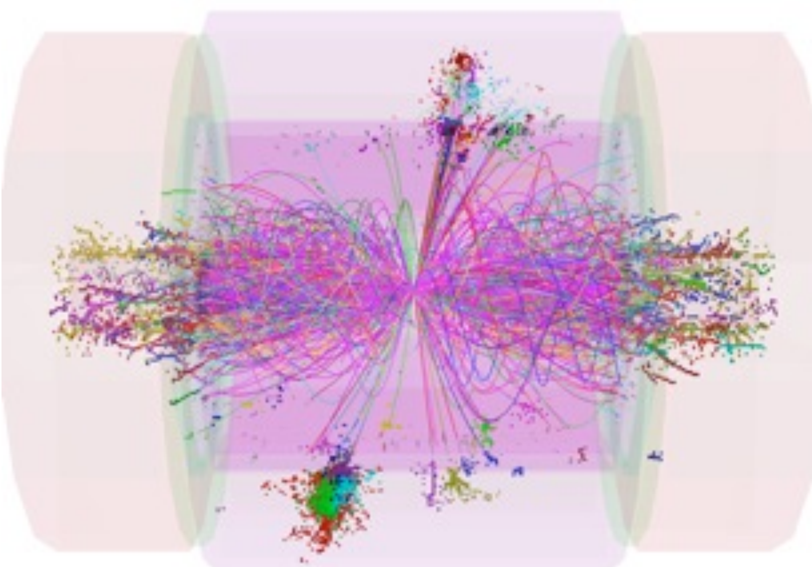


PFLOW under CLIC conditions

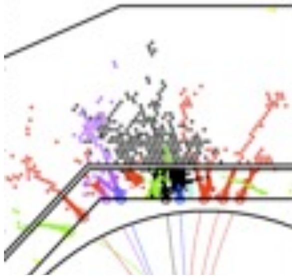
- Overlay γγ events from 60 BX (every 0.5 ns)
- take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- apply pt and timing cuts on cluster level (sub-ns accuracy)



Z @ 1 TeV



+ 1.4 TeV BG (reconstructed particles)



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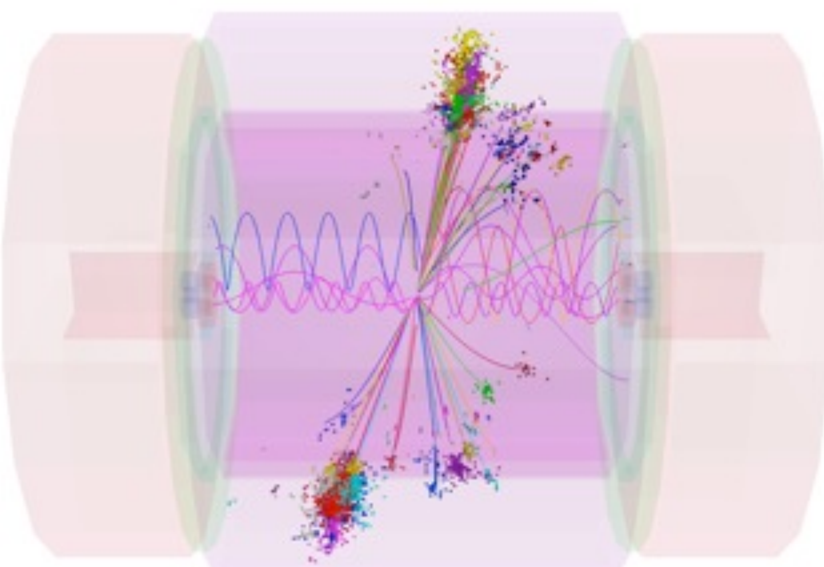
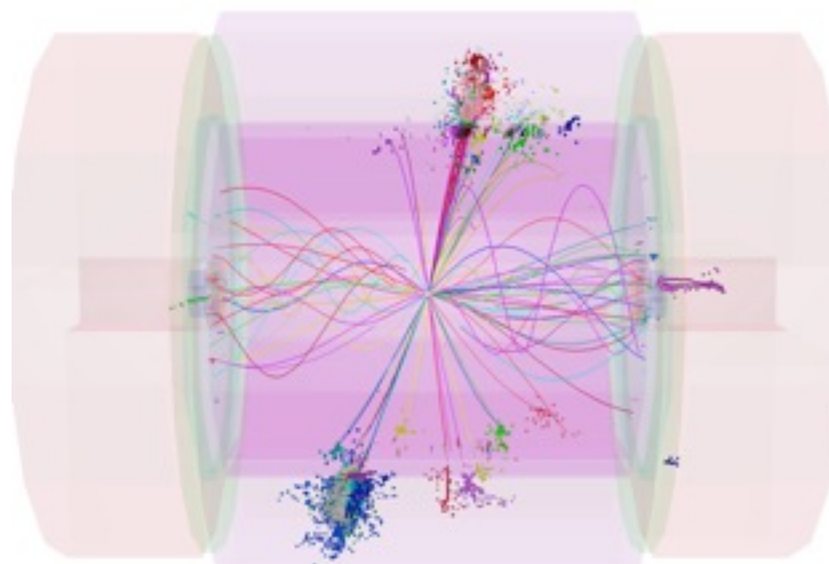


Z @ 1 TeV



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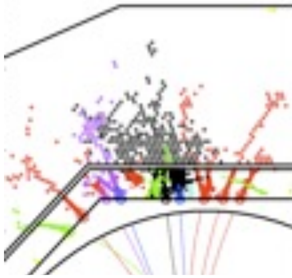

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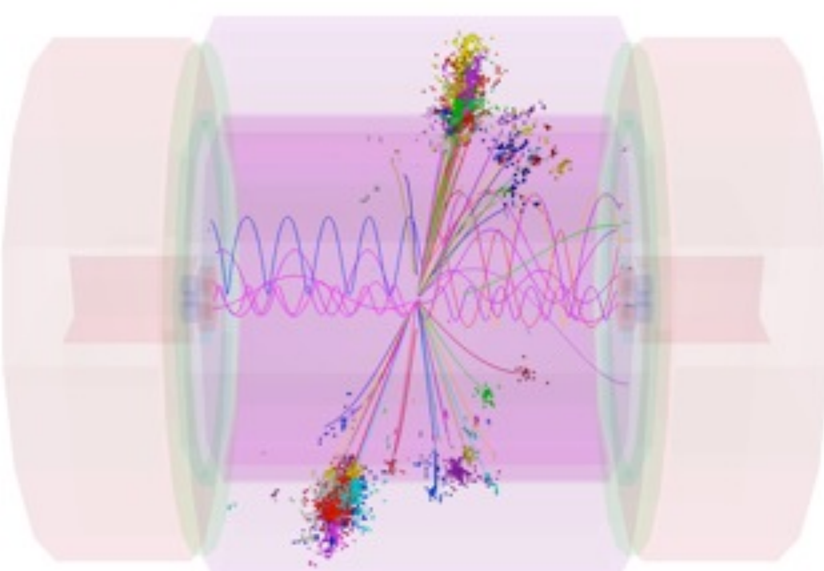
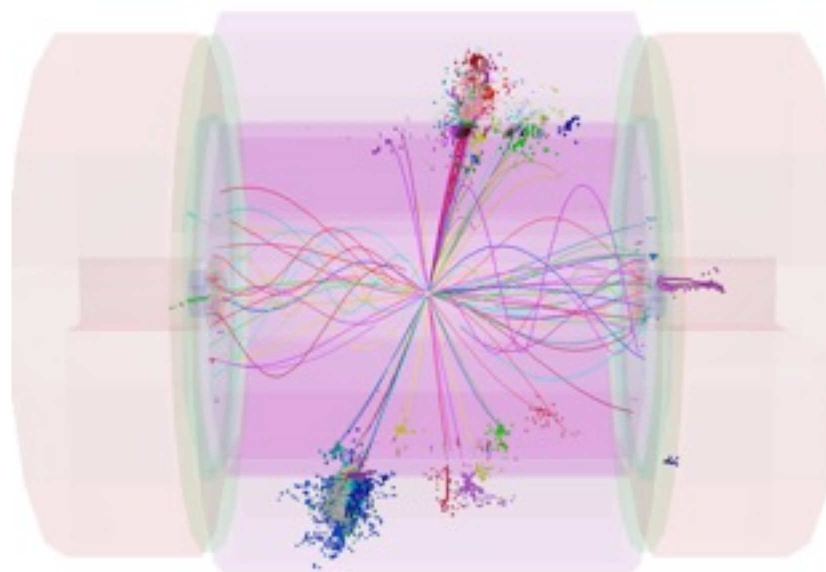
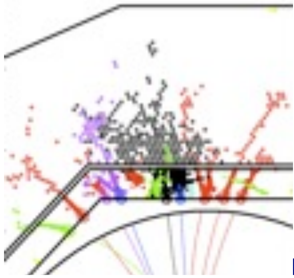




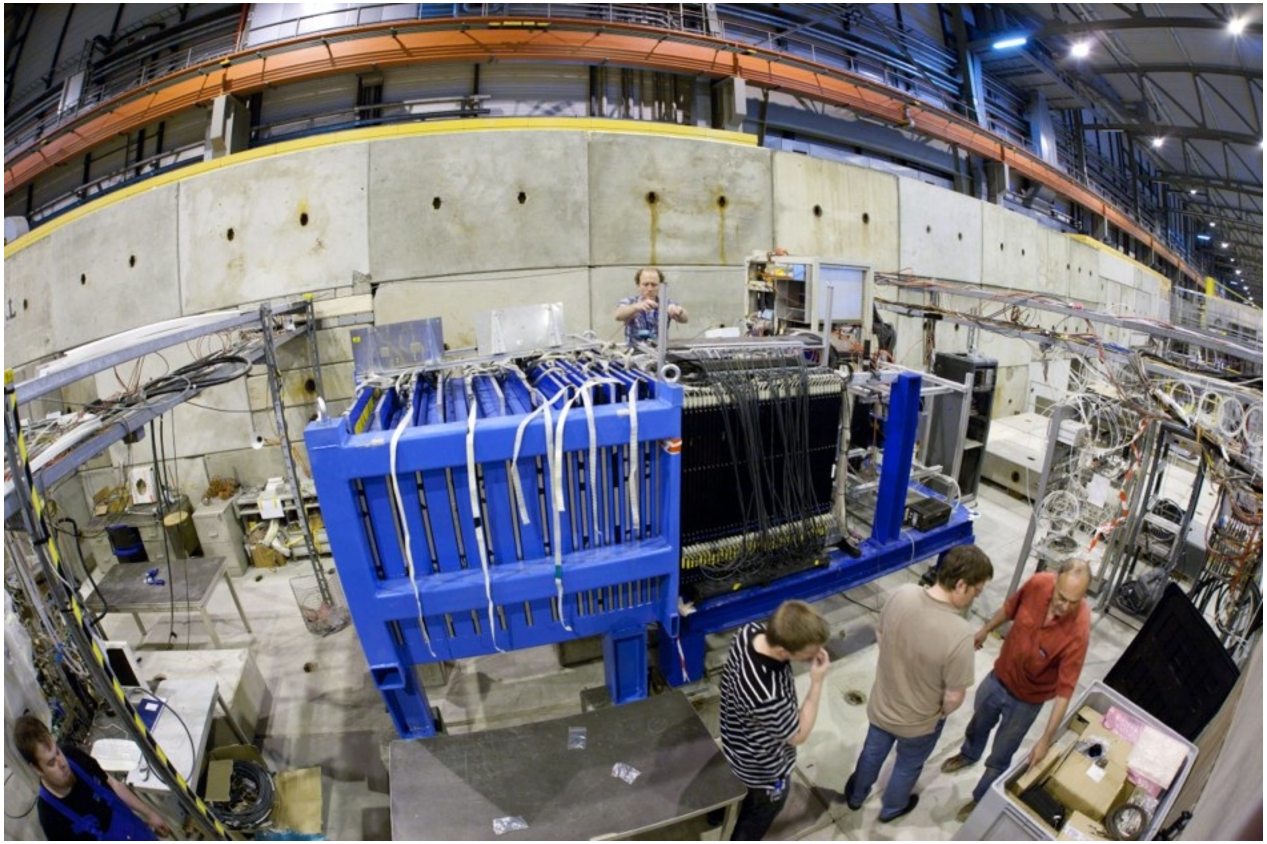
Z @ 1 TeV

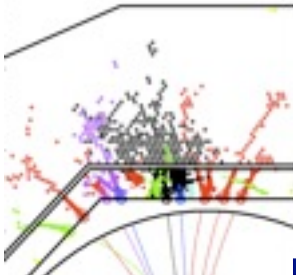


Main ideas:

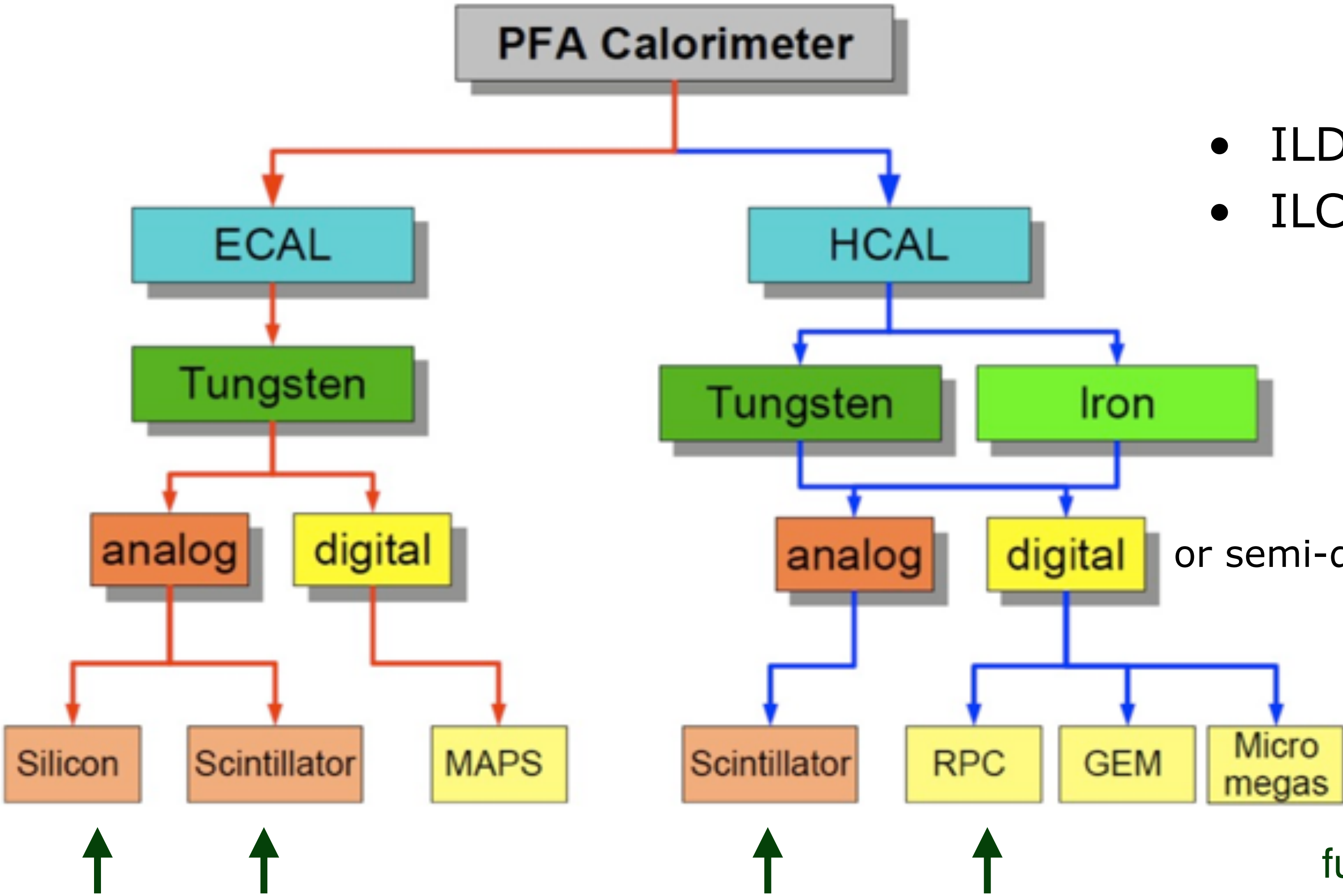
- Linear collider physics demands 3-4% jet energy resolution, which cannot be achieved with classical calorimetry
- Particle flow detectors achieve this precision over a wide energy range for ILC and CLIC
  - and under CLIC background and pile-up conditions
- Particle flow calorimeters feature good energy resolution **and** high granularity
- Detector cost is driven by instrumented area rather than channel count

Test beam validation





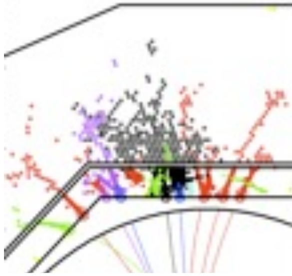
Calorimeter technologies



- ILD, SiD
- ILC, CLIC

or semi-digital

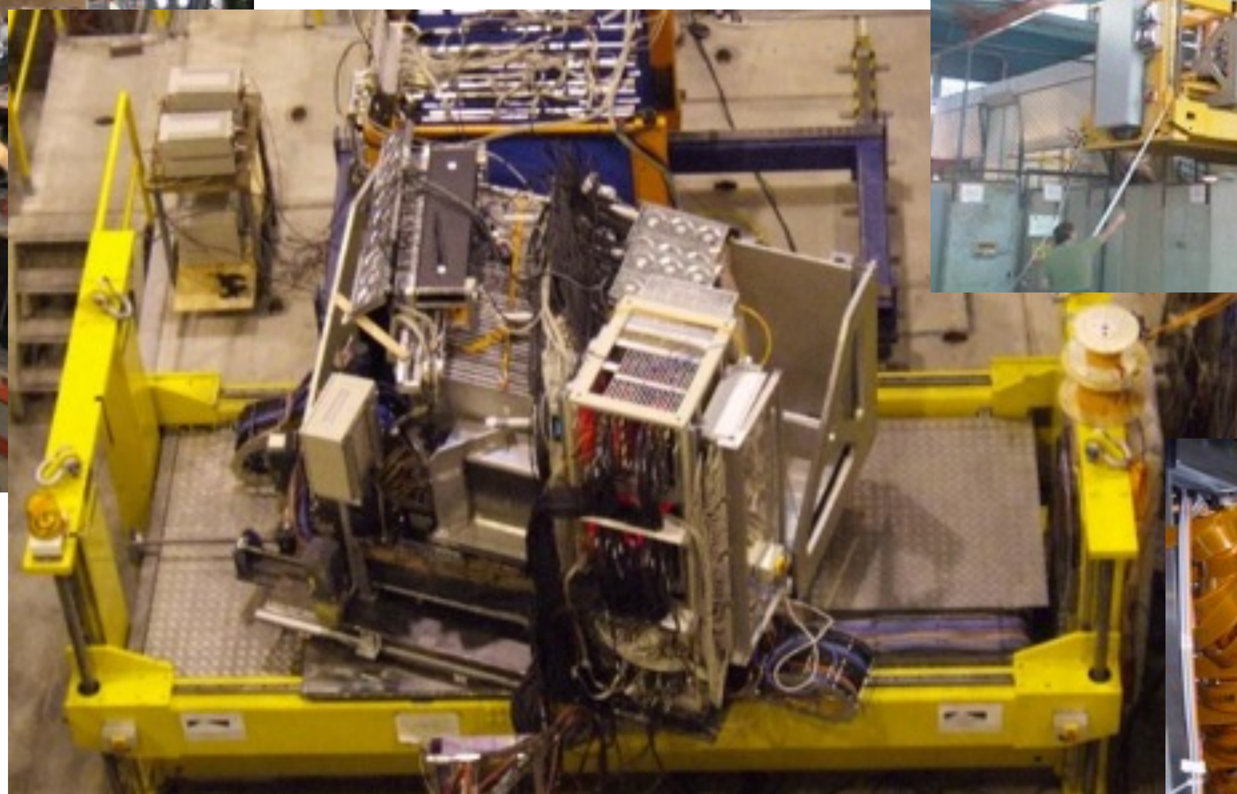
full prototypes



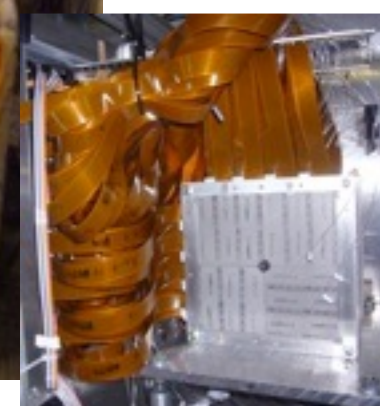
Test beam experiments

DESY 2005
SiECAL

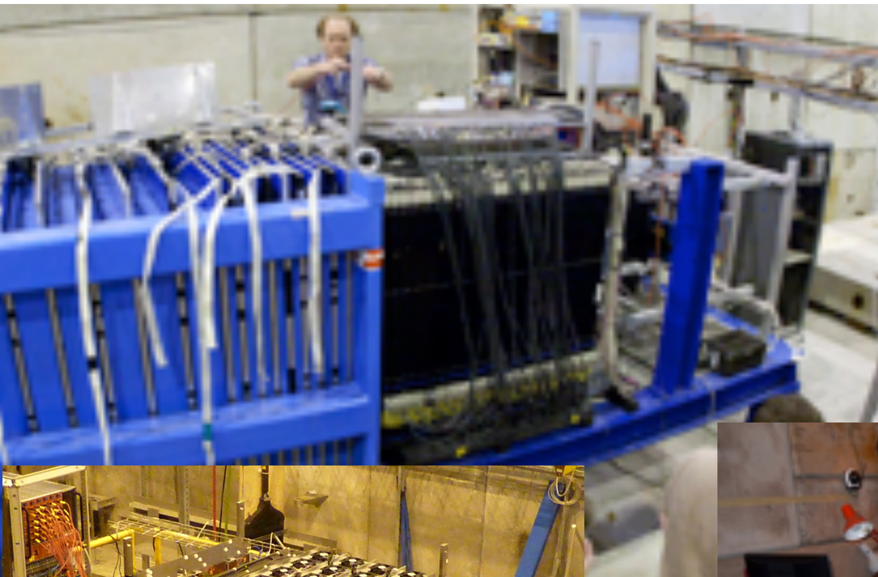
CERN 2006-2007
add Scint HCAL



FNAL 2008-09
Si -> Sci ECAL

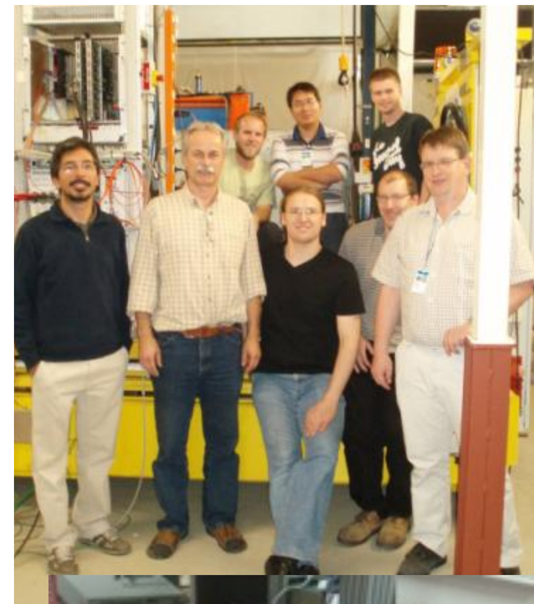


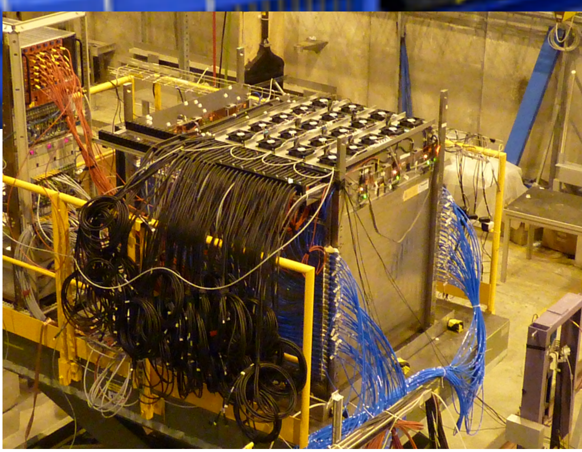
+ Test beam experiments

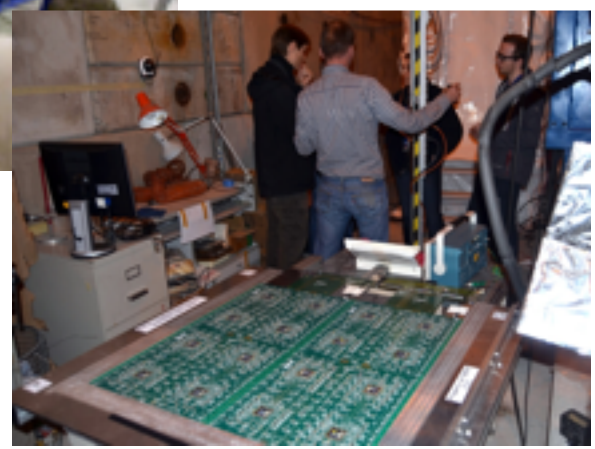


CERN
2010-11
Tungsten
AHCAL
2012:
DHCAL

FNAL2010-11:
m^3 Fe DHCAL



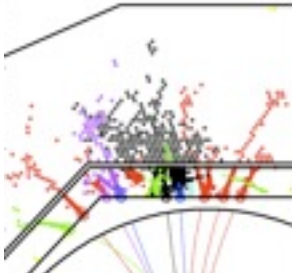




CERN 2012:
m^3 SDHCAL

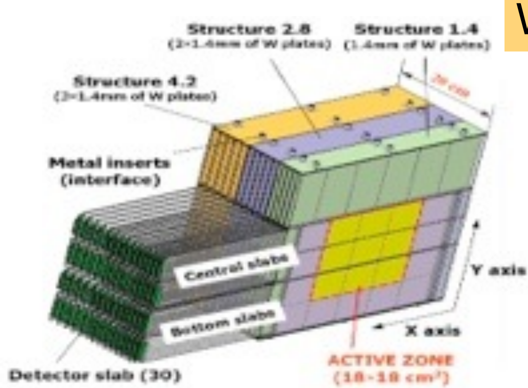
CERN 2012
2nd generation
scint HCAL

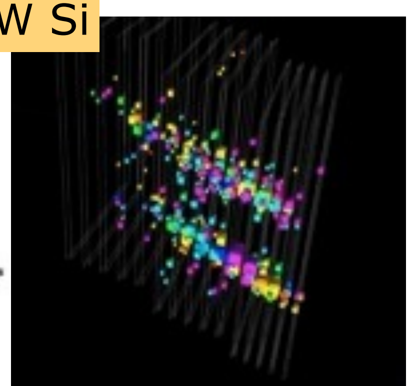
DESY 2012
2nd generation
SiW ECAL

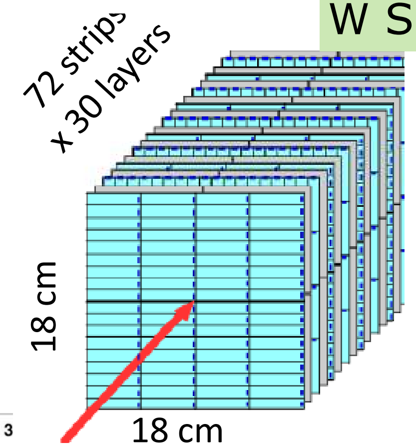


CALICE ECAL performance

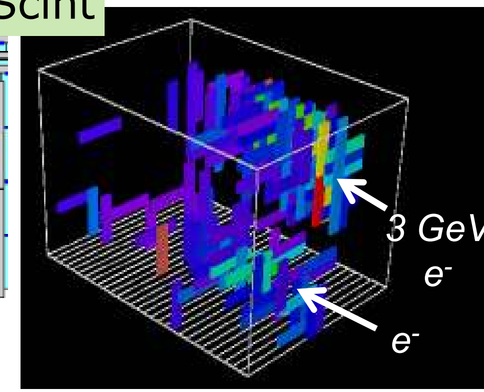
W Si

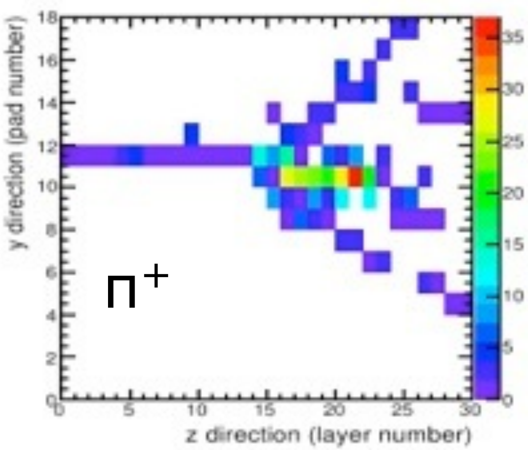


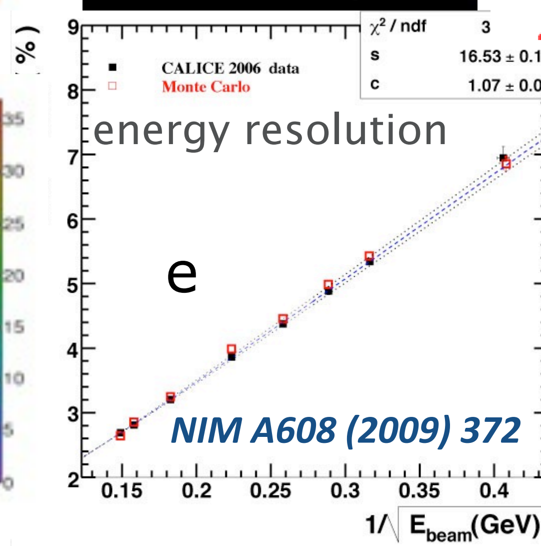




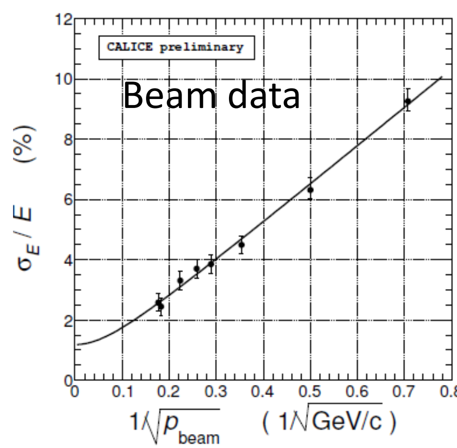
W Scint

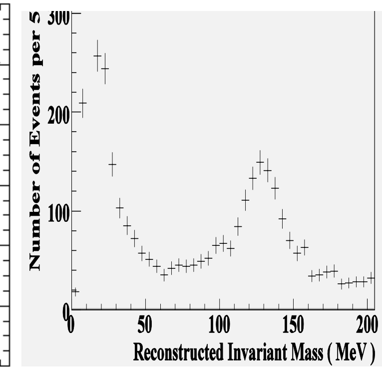






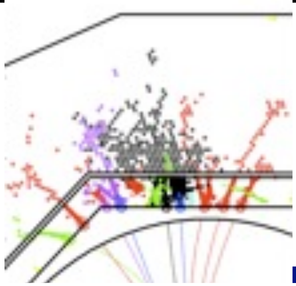
- data and sim agree





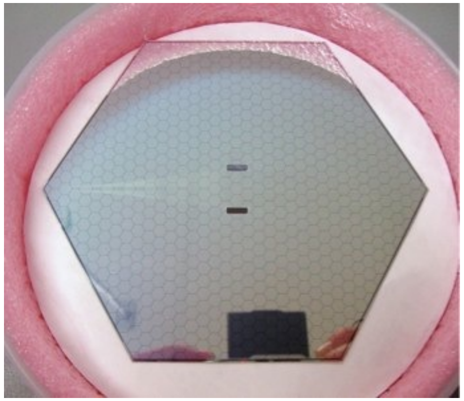
12.9 $\pm$ 0.1(stat.) $\pm$ 0.4 (syst.)%

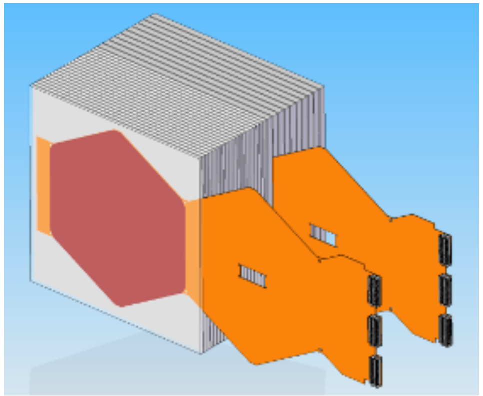
1.2$\pm$ 0.1(stat.) $^{+0.4}_{-1.2}$ (syst.)%

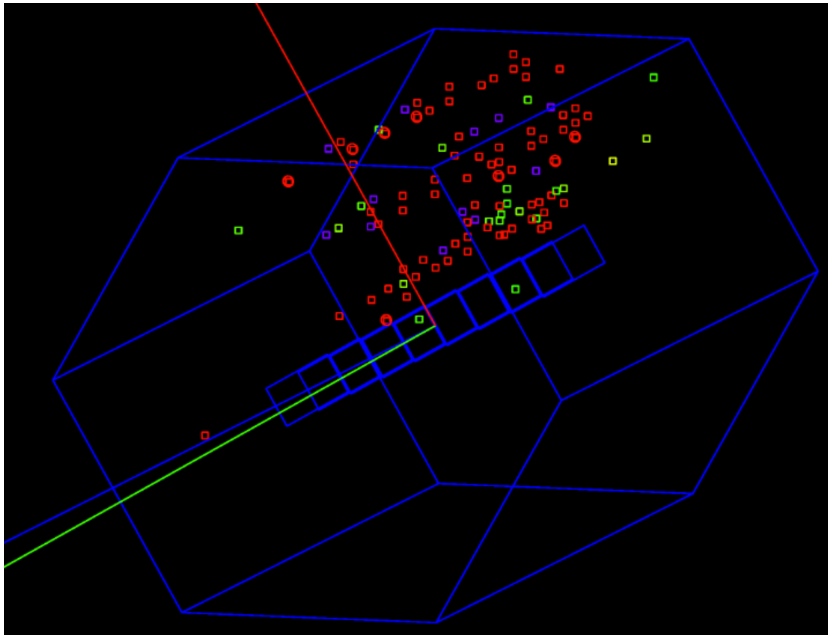


SiD ECAL

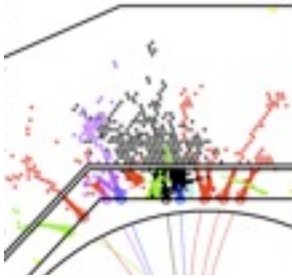
- SiD made some ambitious design choices
  - most compact ECAL
    - smallest $R_{Moliere}$
  - most light-weight Silicon tracker
  - both based on KPiX chip (1024 ch)
  - directly bonded to wafer
- ECAL: no PCB
  - 1.1 mm thin active gap



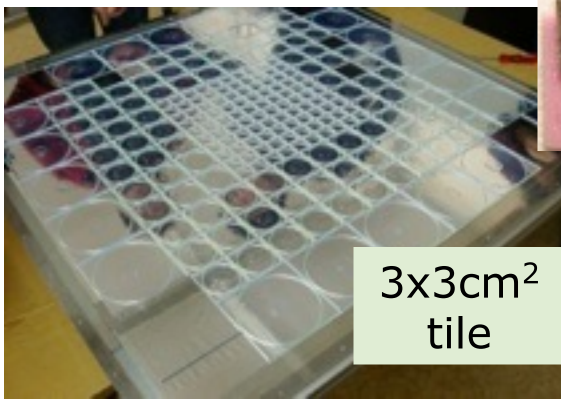




July 2013
9 layers in the beam
at SLAC End Station A

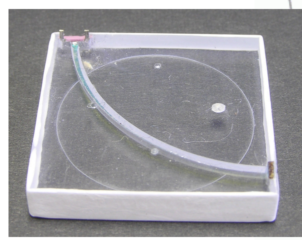


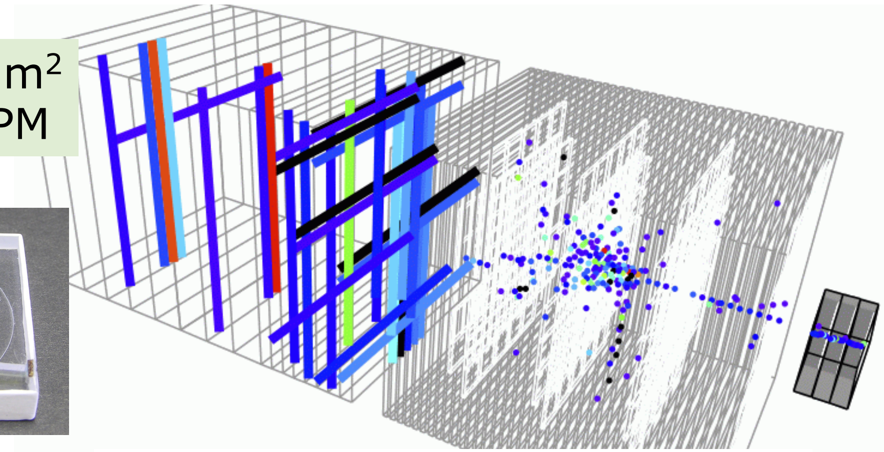
Scintillator HCAL performance



3x3cm² tile

1mm² SiPM

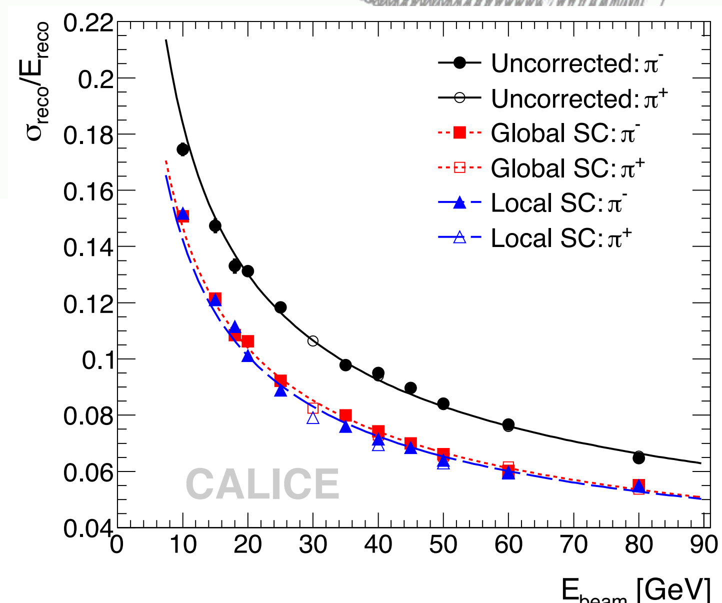




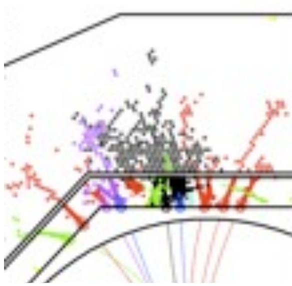
- 38 layer steel and tungsten
- 7608 channels: first large scale SiPM application
- very robust: 6 years of data taking at DESY, CERN, Fermilab
- a very good calorimeter, too

$\sigma/E = 45.1\%/\sqrt{E} \oplus 1.7\% \oplus 0.18/E$

software compensation

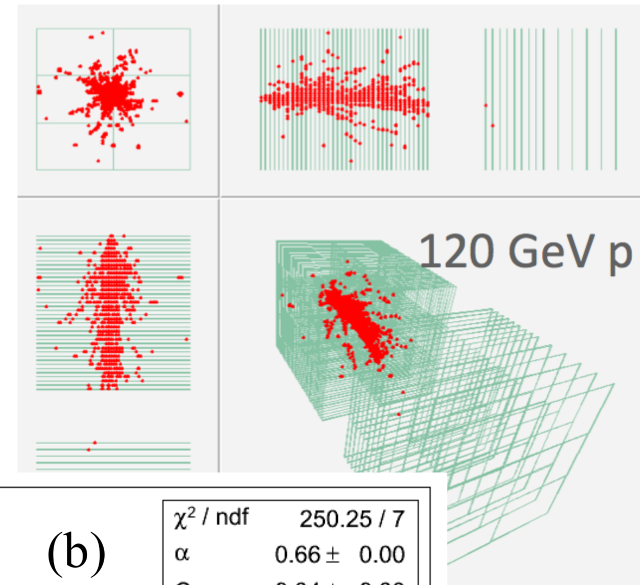


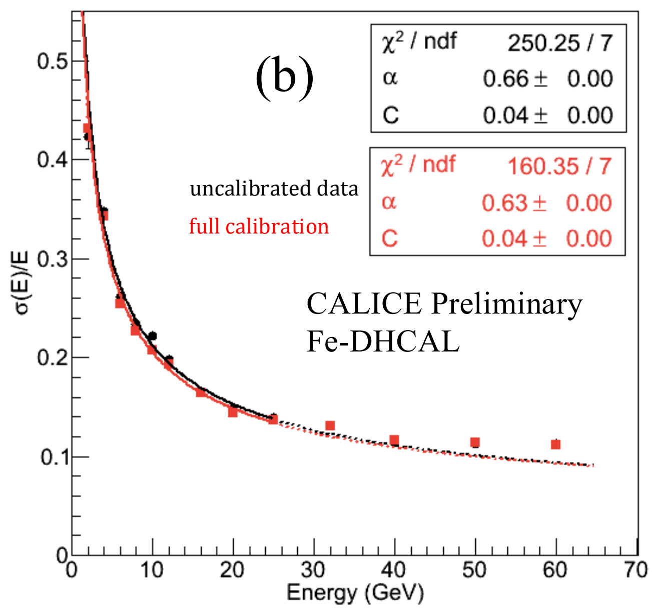
JINST 7, P00917 (2012)

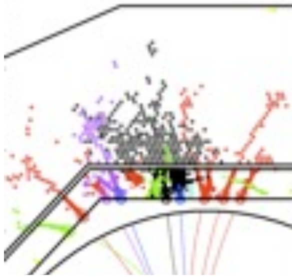


Digital RPC HCAL

- Resistive plate chambers
- 1x1cm^2 pads, 1 bit read-out
- 500’000 channels
- digitisation electronics embedded
- tested with steel and tungsten
- digital calorimetry does work

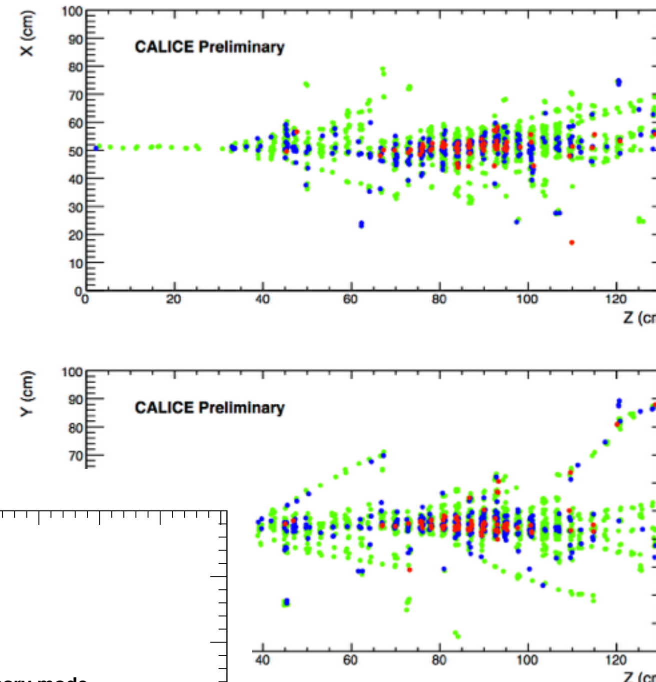


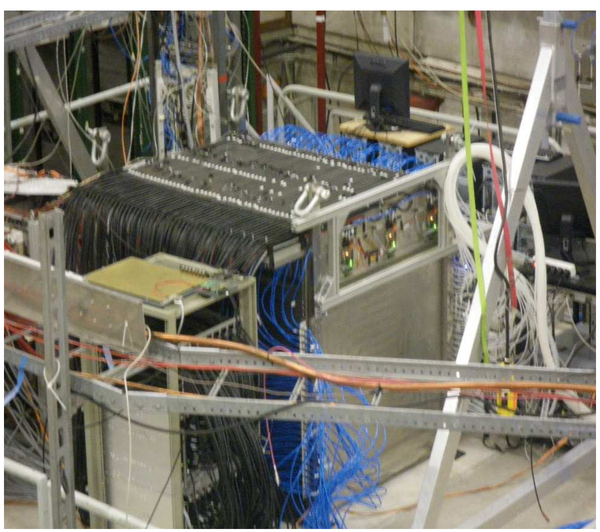


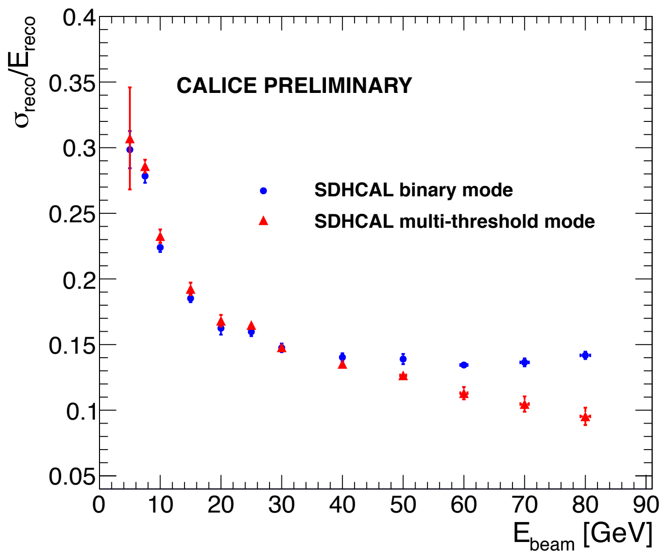


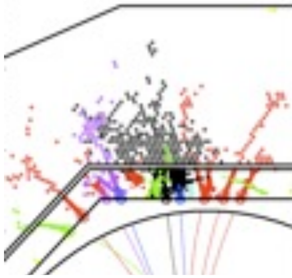
Semi-digital RPC HCAL

- 48 RPC layers, 1cm^2 pads
- embedded electronics
  - power-cycled
- 2 bit, 3 threshold read-out
  - mitigate resolution degradation at high energy









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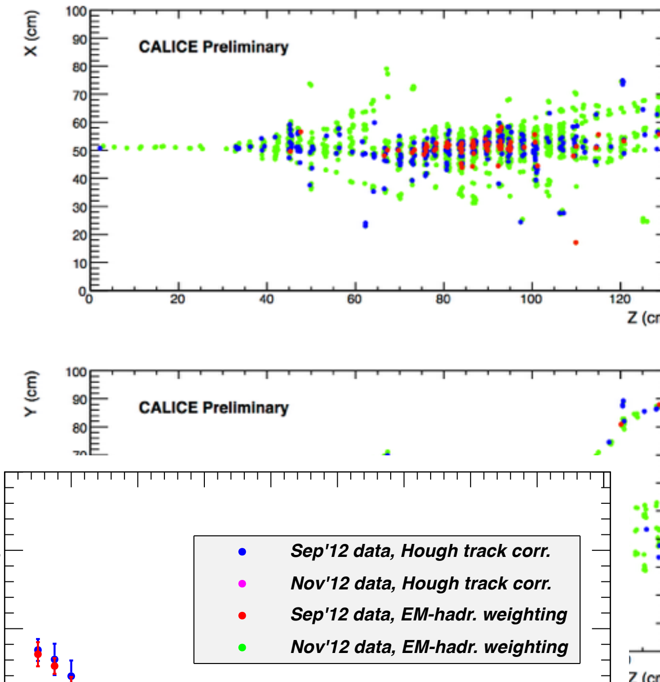
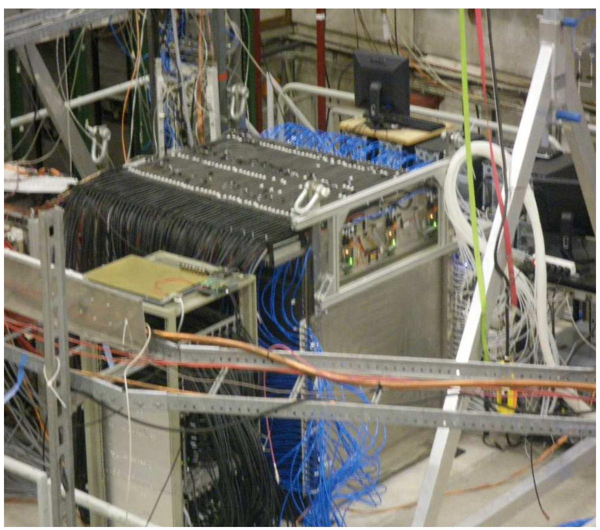
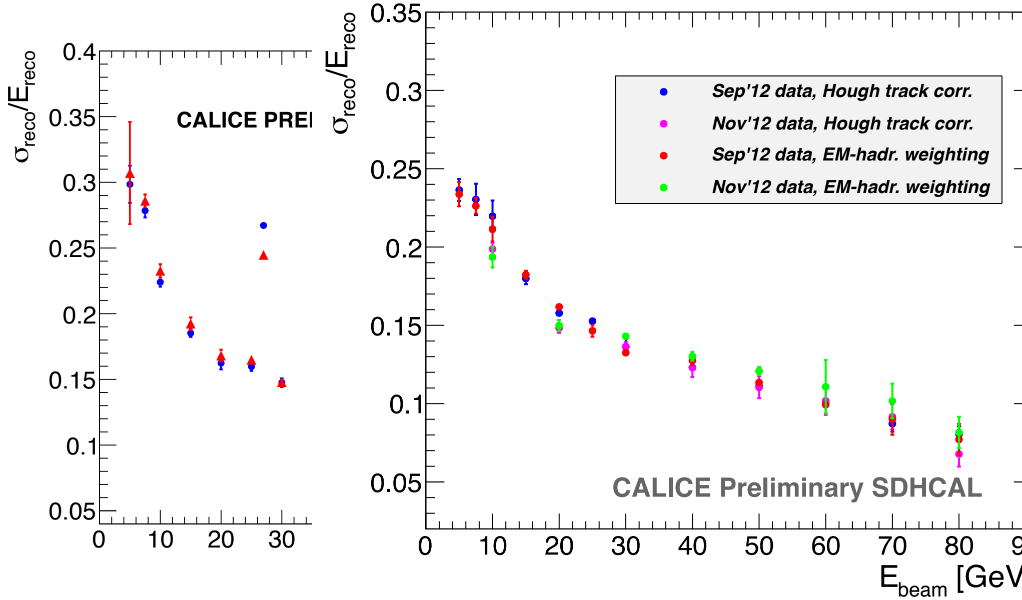
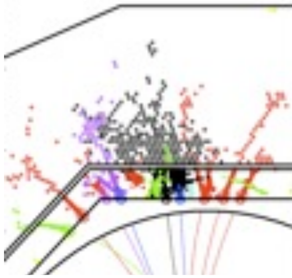


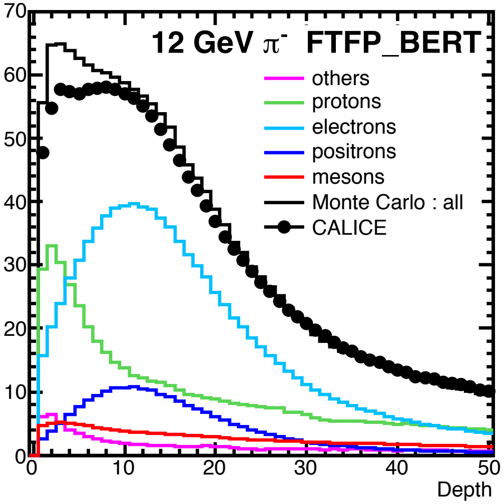






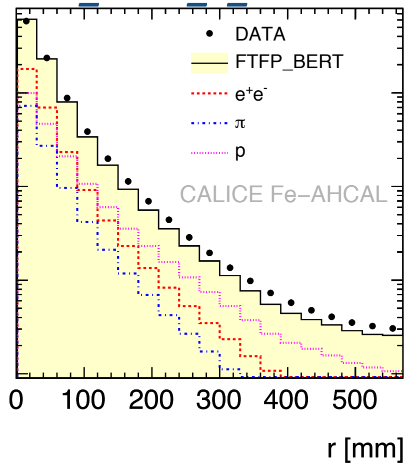
Validation of Geant 4 models

2010_JINST_5_P05007



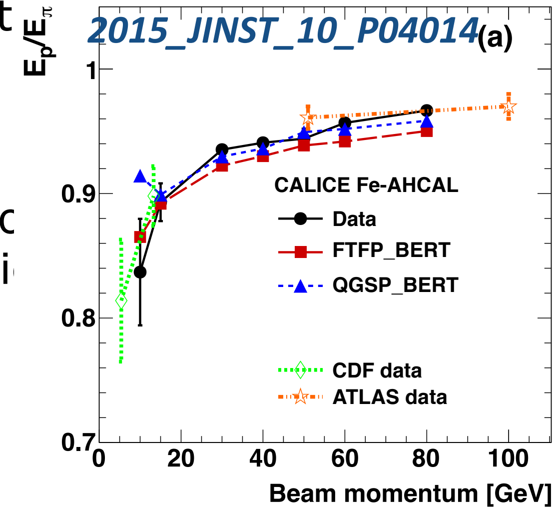
SiW ECAL
longit. profile

2013_JINST_8_P07005

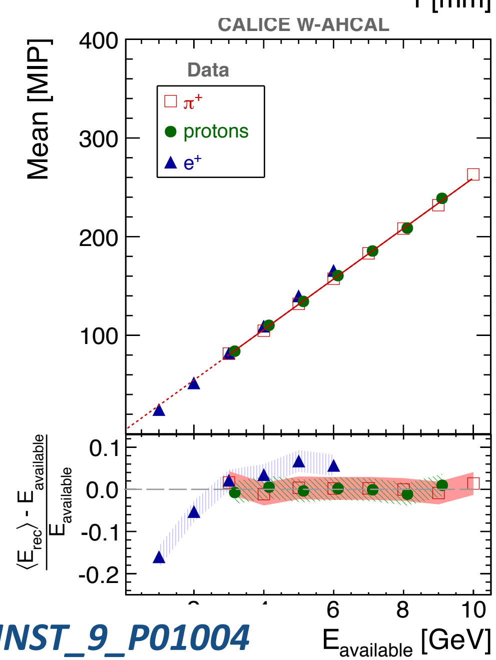


Fe Scint
HCAL
radial
profile,
roton pic
esp. rati

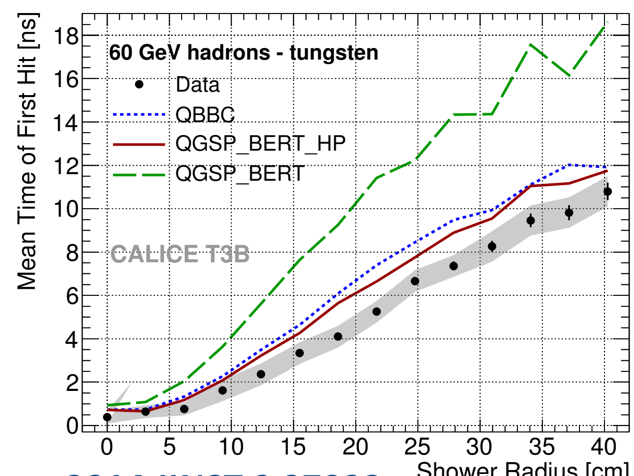
2015_JINST_10_P04014



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

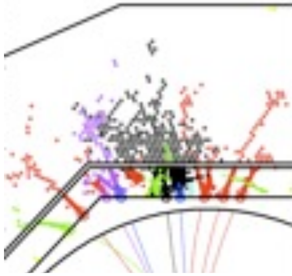


2014_JINST_9_P01004



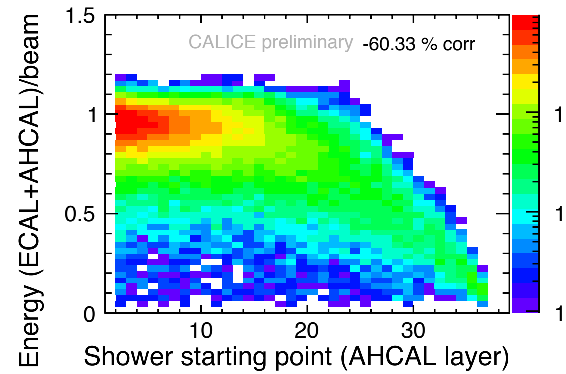
2014 JINST 9 07022

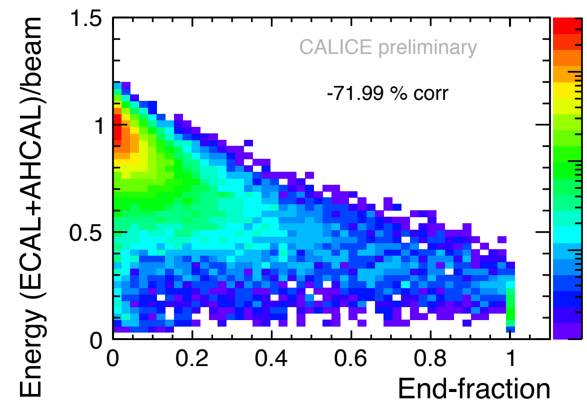
W Scint HCALresponse, timing

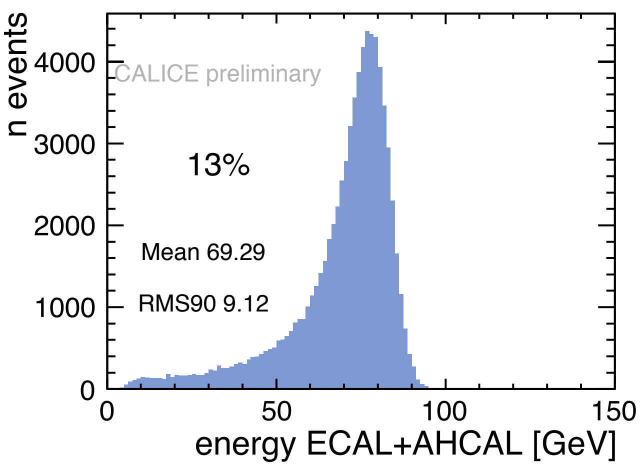


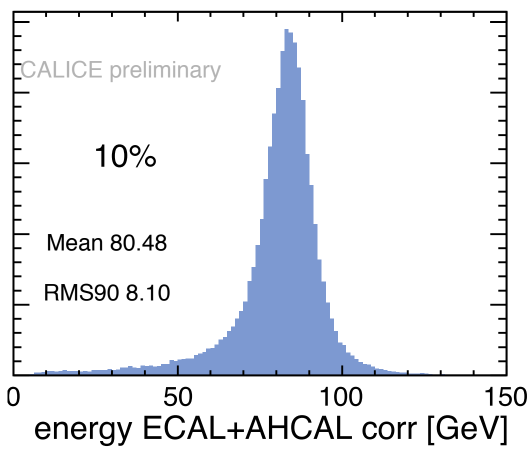
Leakage estimation

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

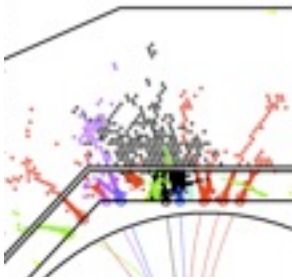




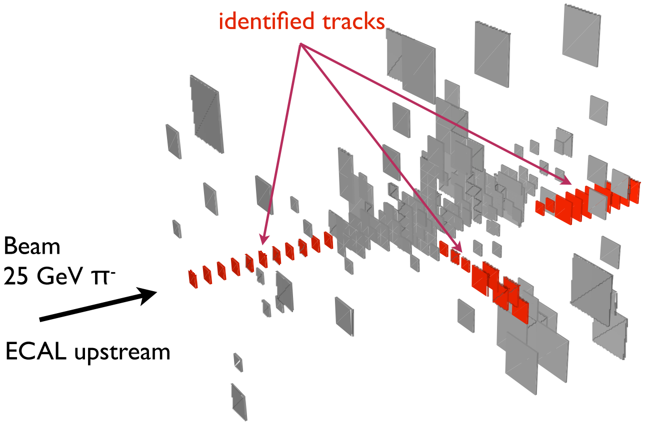


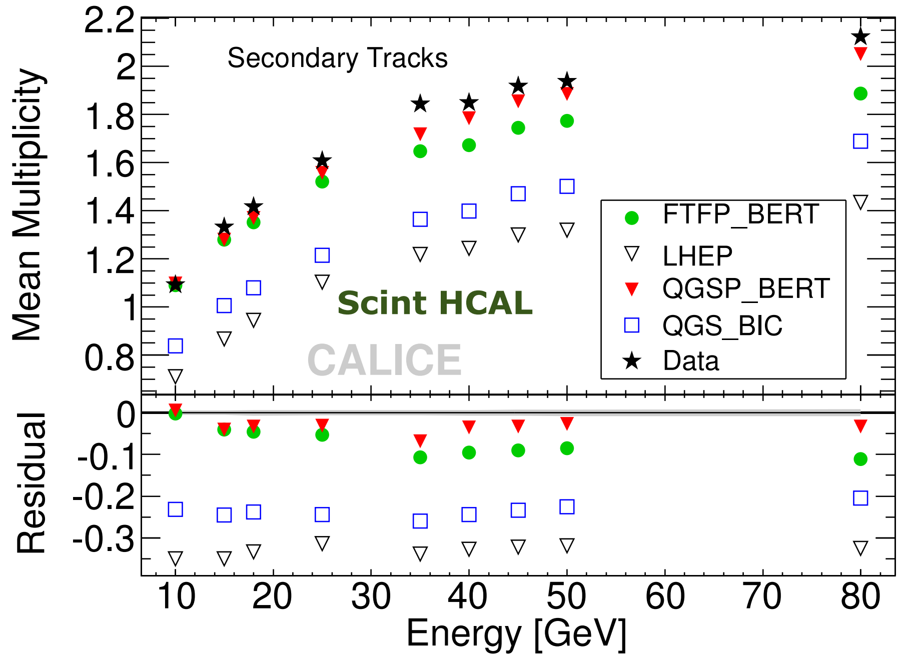


cf : with tail catcher, no coil: 5.4%

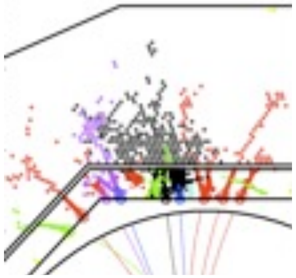


Shower fine structure

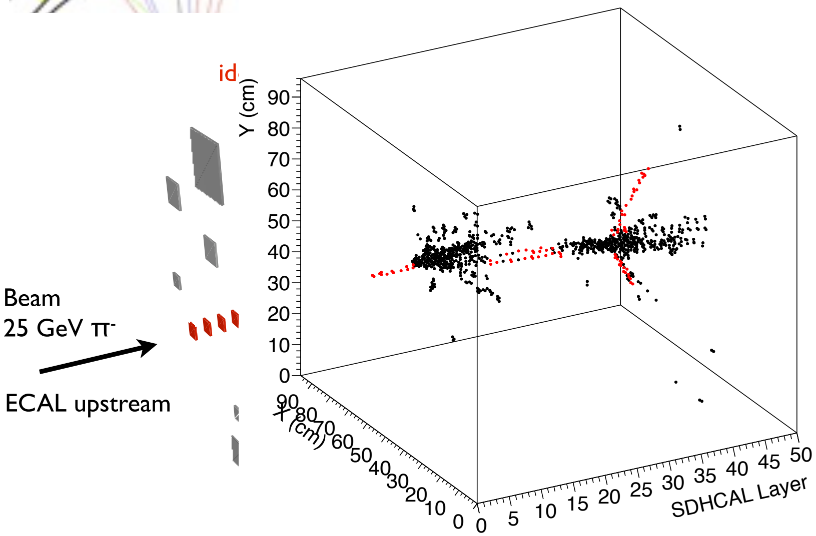


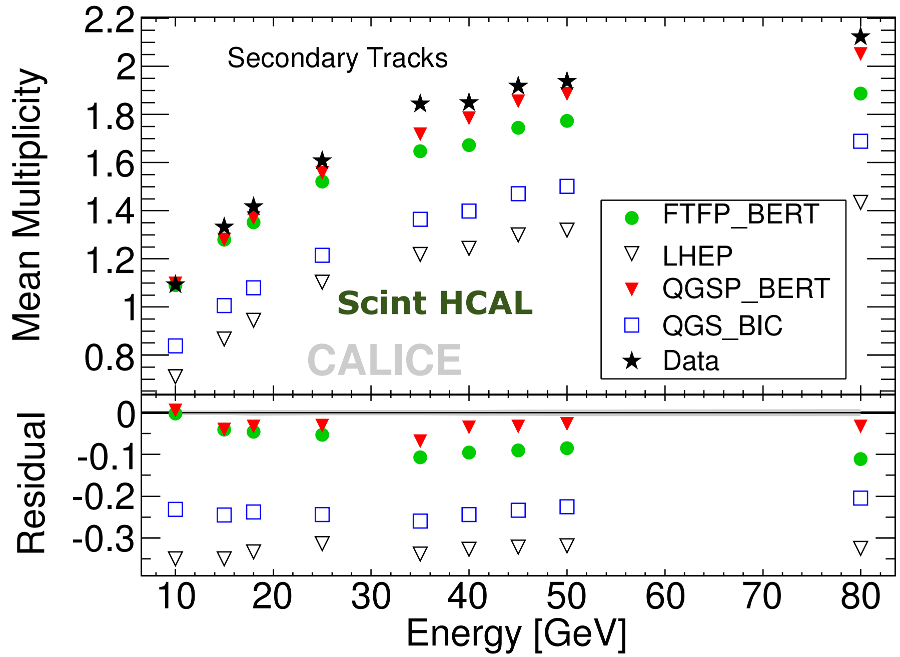


- Could have had the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already - for more recent models



Shower fine structure





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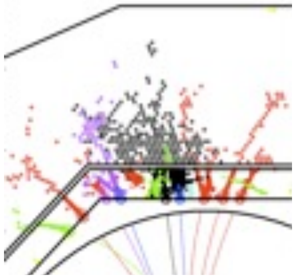
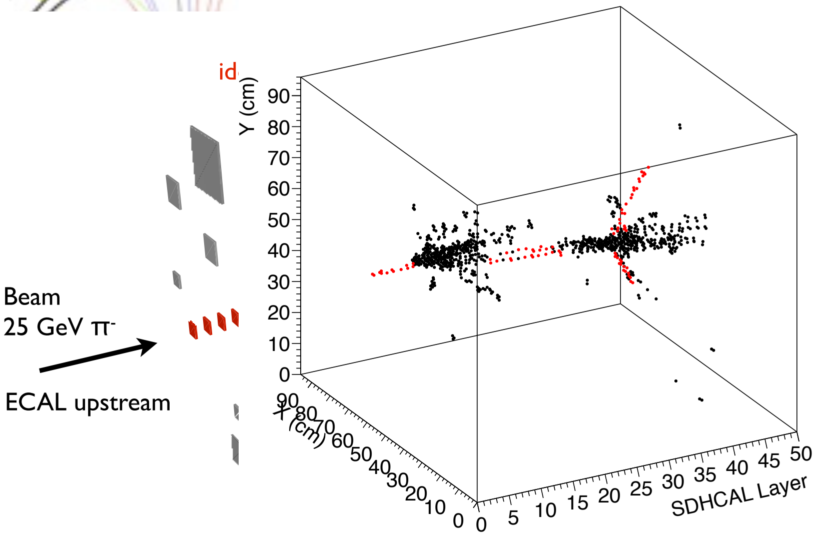
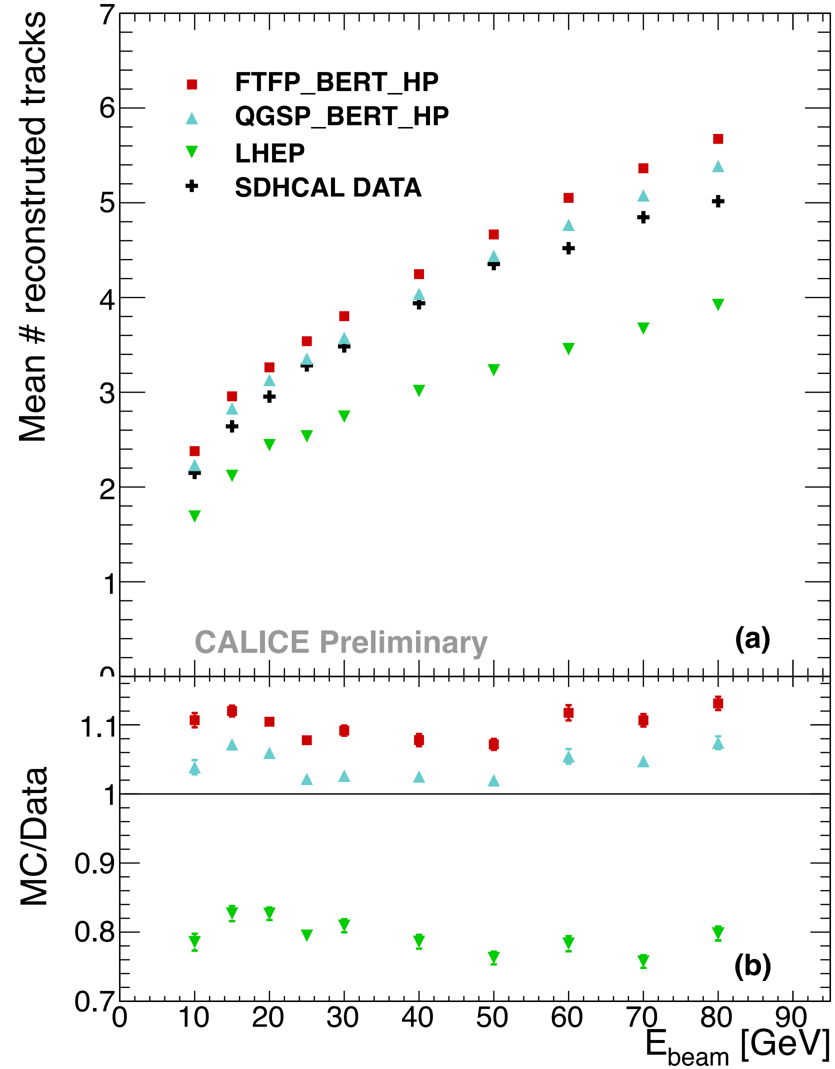


Shower fine structure





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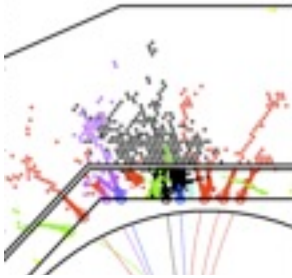
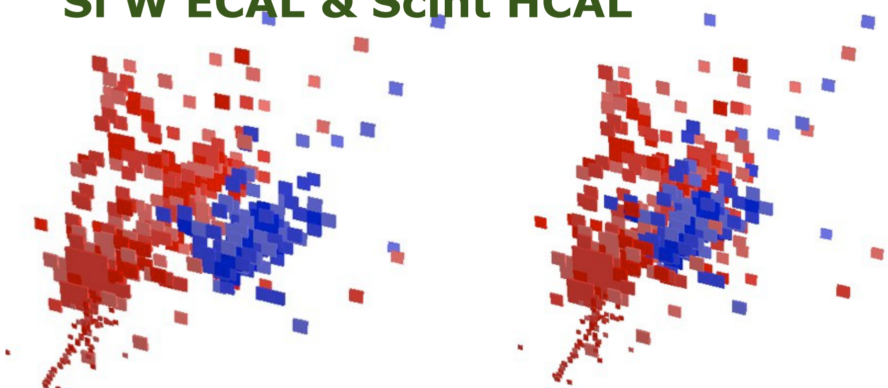


PFLOW with test beam data

Si W ECAL & Scint HCAL

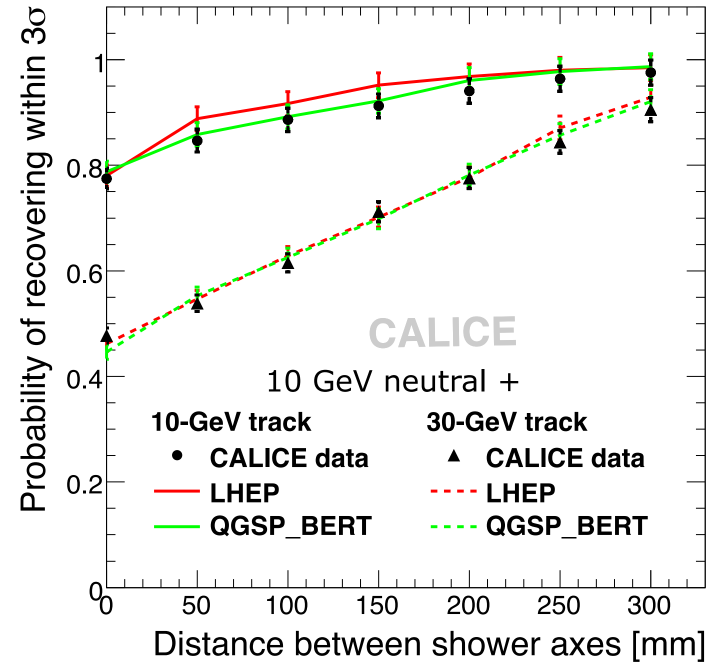


~18 cm separation of shower

~7 cm separation of shower

30 GeV charged hadron

10 GeV 'neutral' hadron



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

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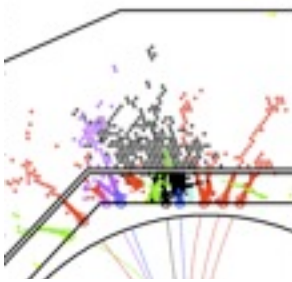
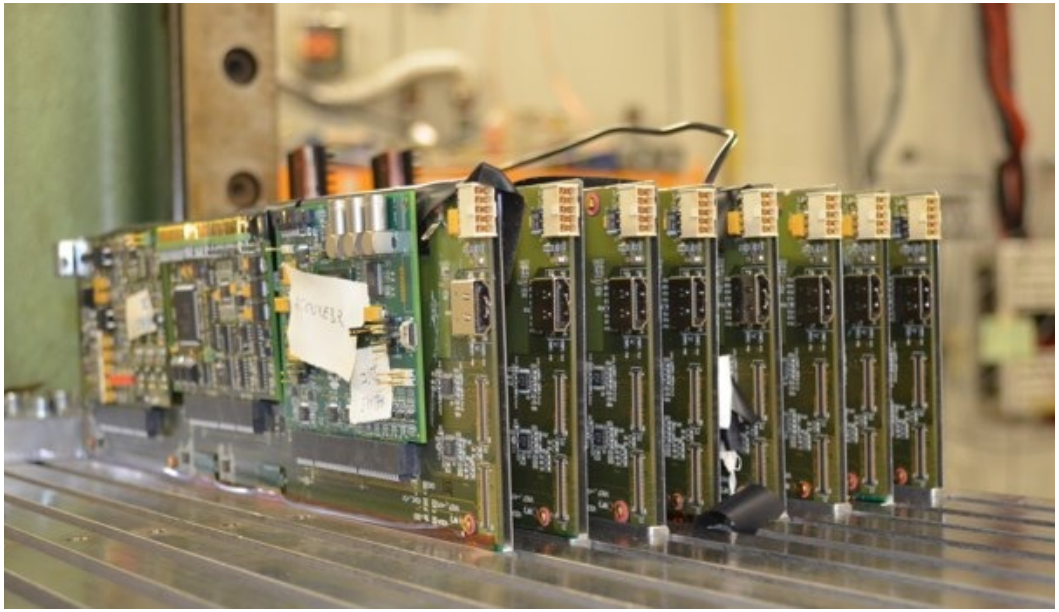
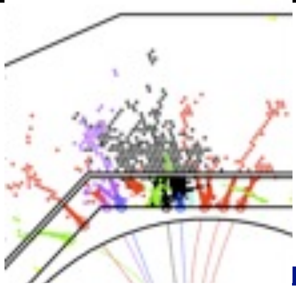


What we learnt

- The novel ECAL and HCAL technologies work as expected
  - Si W ECAL and Sci Fe AHCAL analysis nearly complete
  - Analysis of the more recent tests has just begun, but all results so far are encouraging - still a huge potential
- The detector simulations are verified with electromagnetic data.
- The hadronic performance is as expected, including software compensation.
- The Geant 4 shower models reproduce the data with few % accuracy.
  - Time structure is reproduced by HP simulations.
- Shower substructure can be resolved and is also reproduced by shower simulations.
- Particle flow algorithms are validated with test beam data.

Current trends

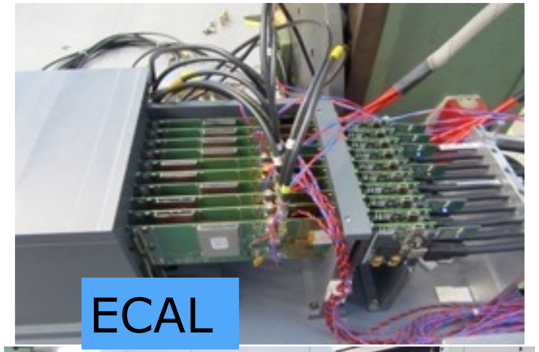


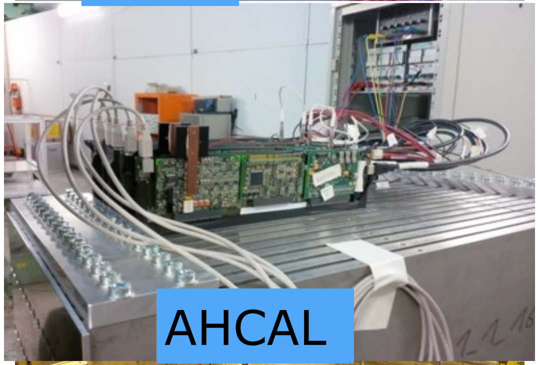


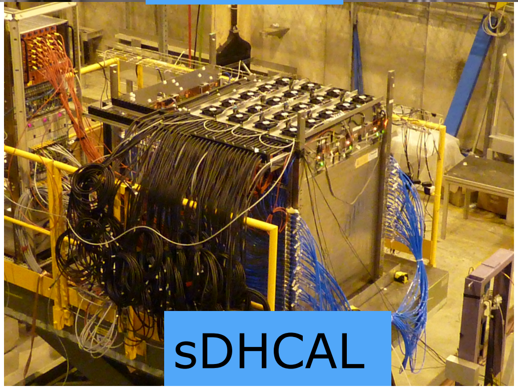
Technological prototypes

- Electronics integration, power pulsing
- Compact design: absorbers and PCBs
- Scalability

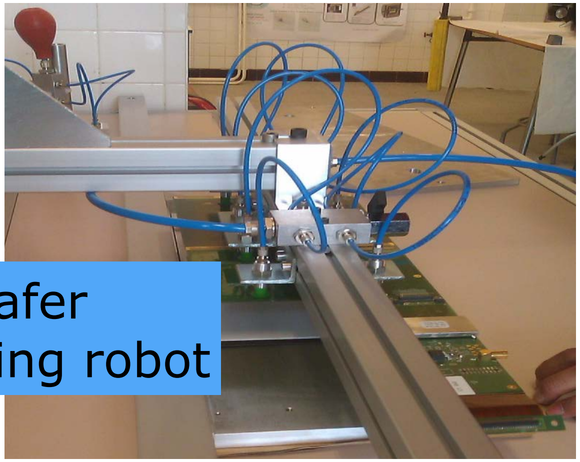
- Integration solutions exist
- Components were prototyped
- Si ECAL, scintillator HCAL: small set-ups tested, <10 small layers
- Gas HCAL: the only large 2nd gen prototype
- None addresses all integration issues yet
- Funding limited

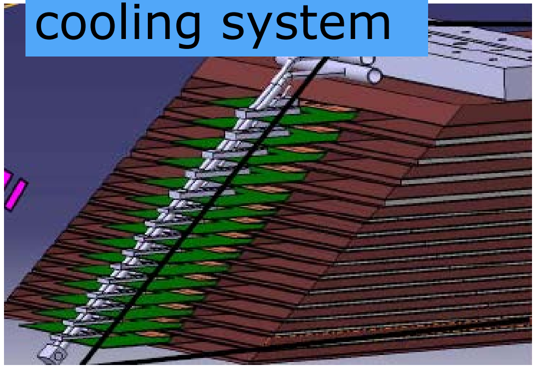


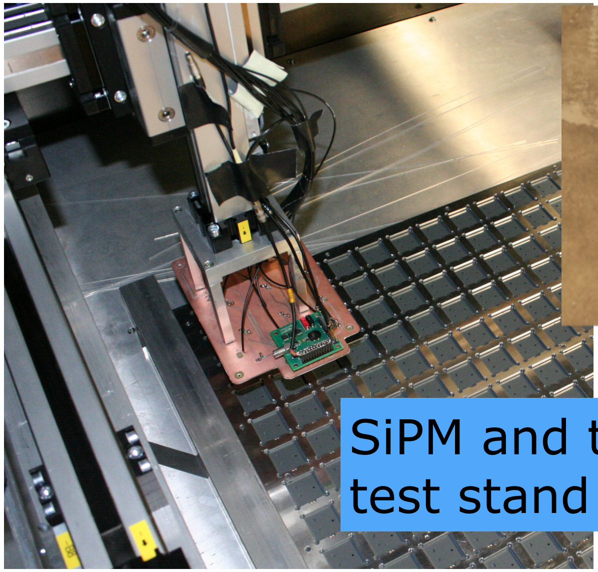


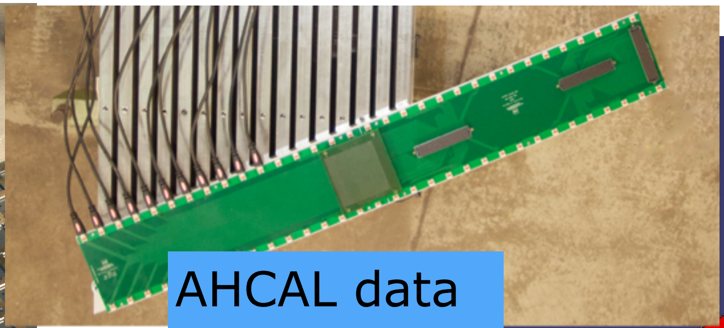


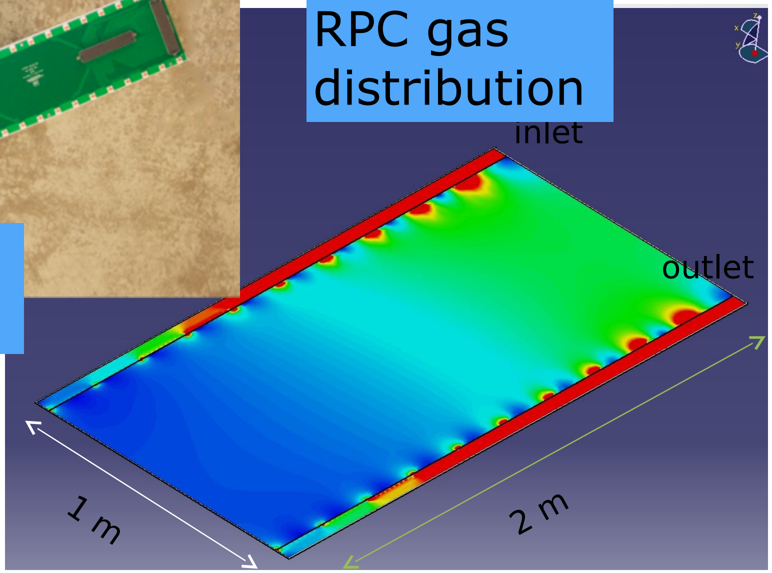
System integration & Tooling

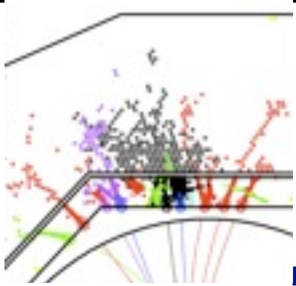




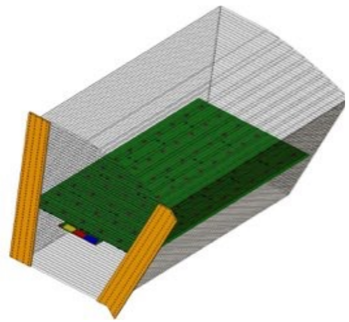


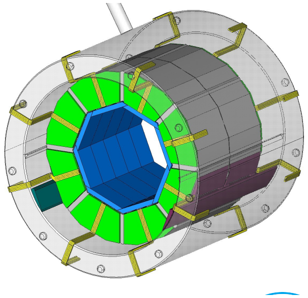


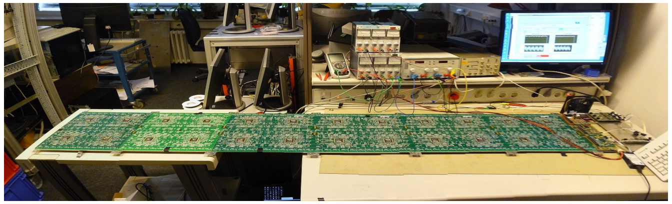


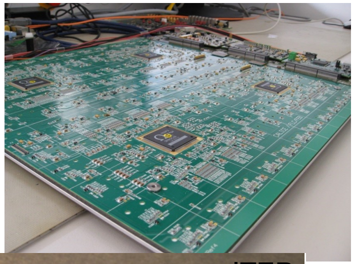


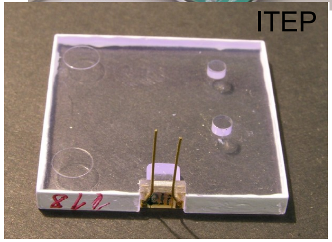
Industrialisation: Numbers!





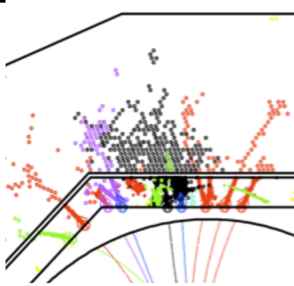






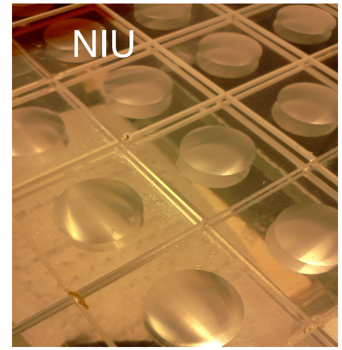
- The AHCAL
- 60 sub-modules
- 3000 layers
- 10,000 slabs
- 60,000 HBUs
- 200’000 ASICs
- 8,000,000 tiles and SiPMs

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

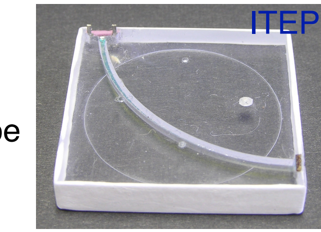


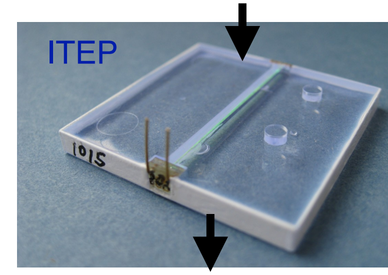
Directions in tile and SiPM R&D

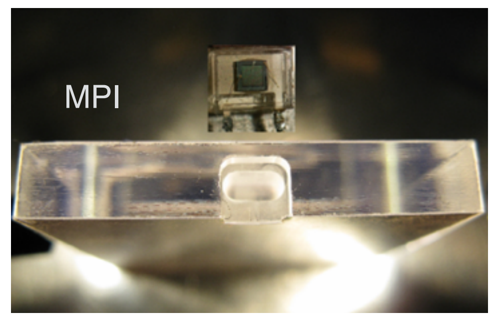
- Revise tile design in view of automatic pick & place procedures
- Consider SMD approach, originally proposed by NIU
- Light yield becomes an issue again
  - build on advances in SiPMs
- Very different assembly, QC and characterisation chain

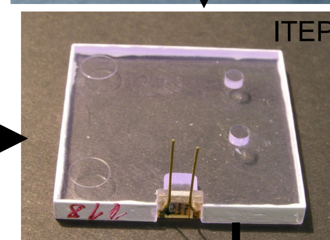


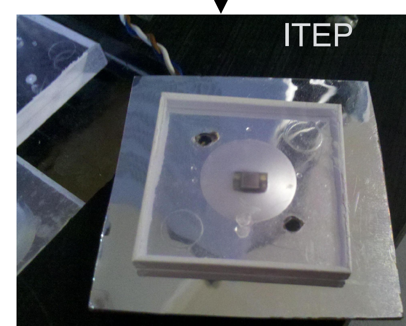
7608 ch physics prototype

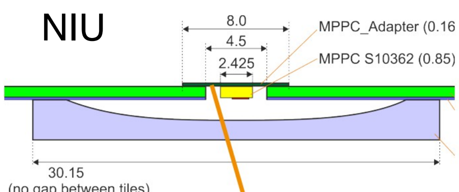






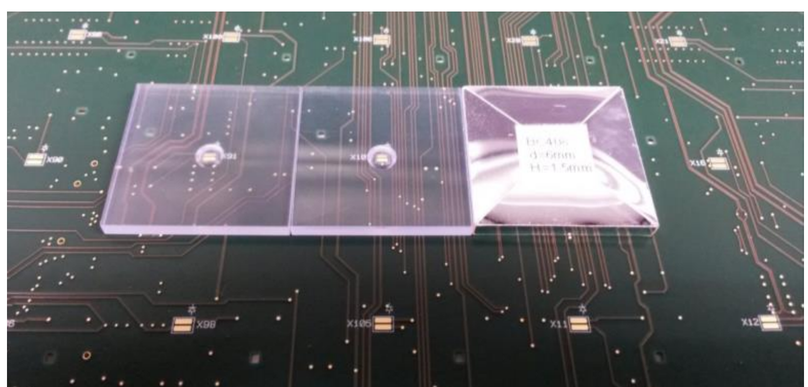


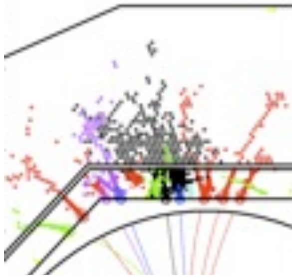




board coming to life

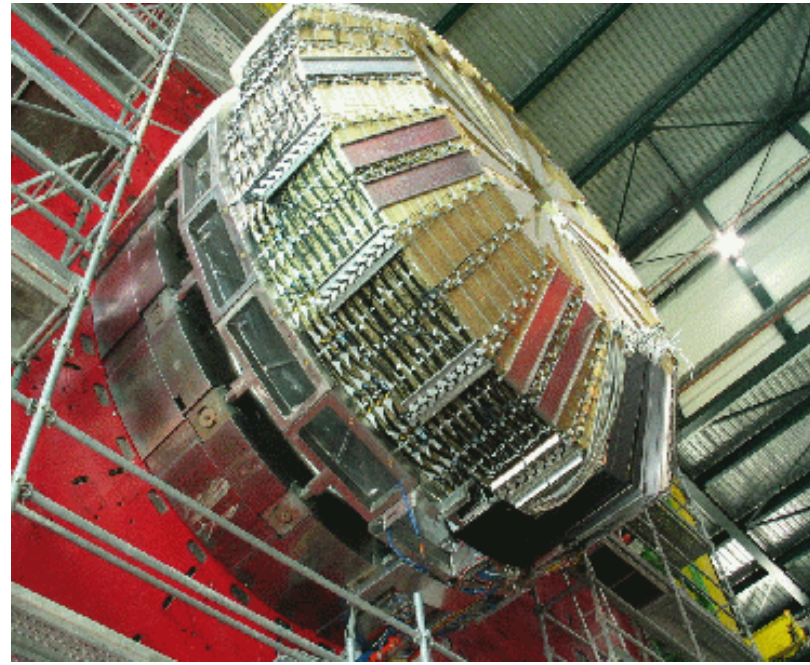
Mainz

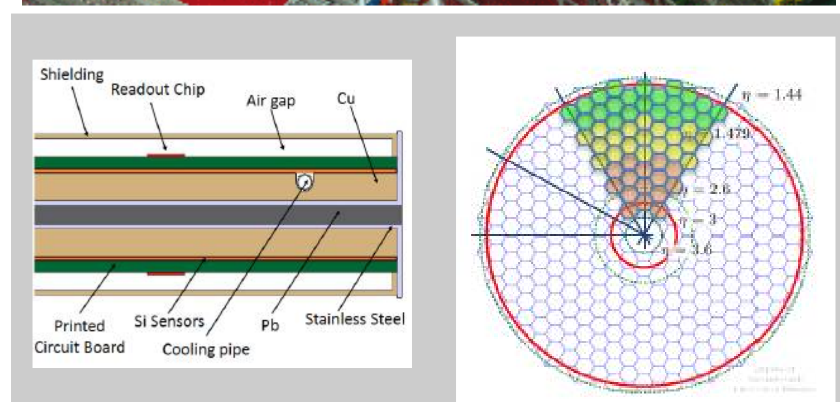


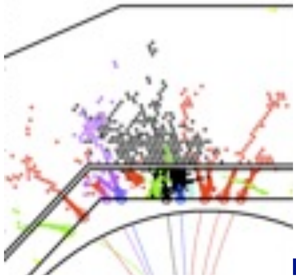


High Granularity for CMS

- CMS decided for a high granularity option of their endcap calorimeter upgrade
  - EM: Si Pb/Cu
    - 35 layers, 25 X0
  - HAD: Si brass
    - 12 layers, 5 λ
  - Backing: scint brass, 5 λ
  - 600 m^2 of Si
  - 0.5 - 1 cm^2
- particle ID, pile-up subtraction, …, particle flow
- radiation hardness, rate capabilities and cooling much more challenging than in e+e-



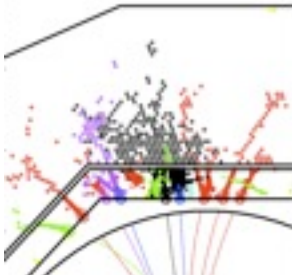




Conclusion

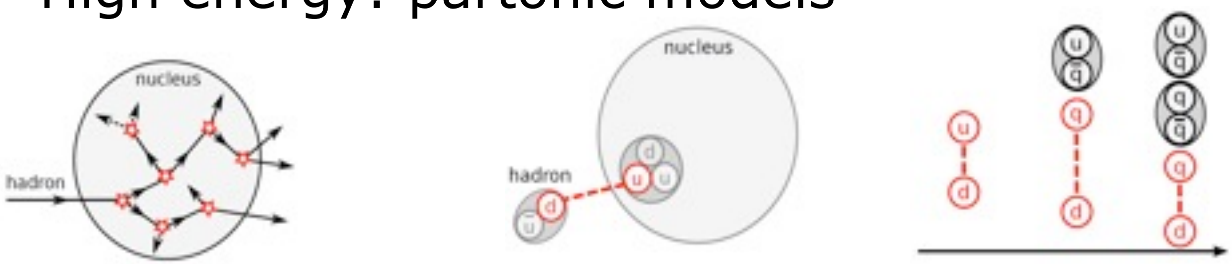
- Calorimetry has changed - particle flow concept established experimentally
- Now fully in second phase: make it realistic
- There are many open issues = room for new ideas

Back-up slides

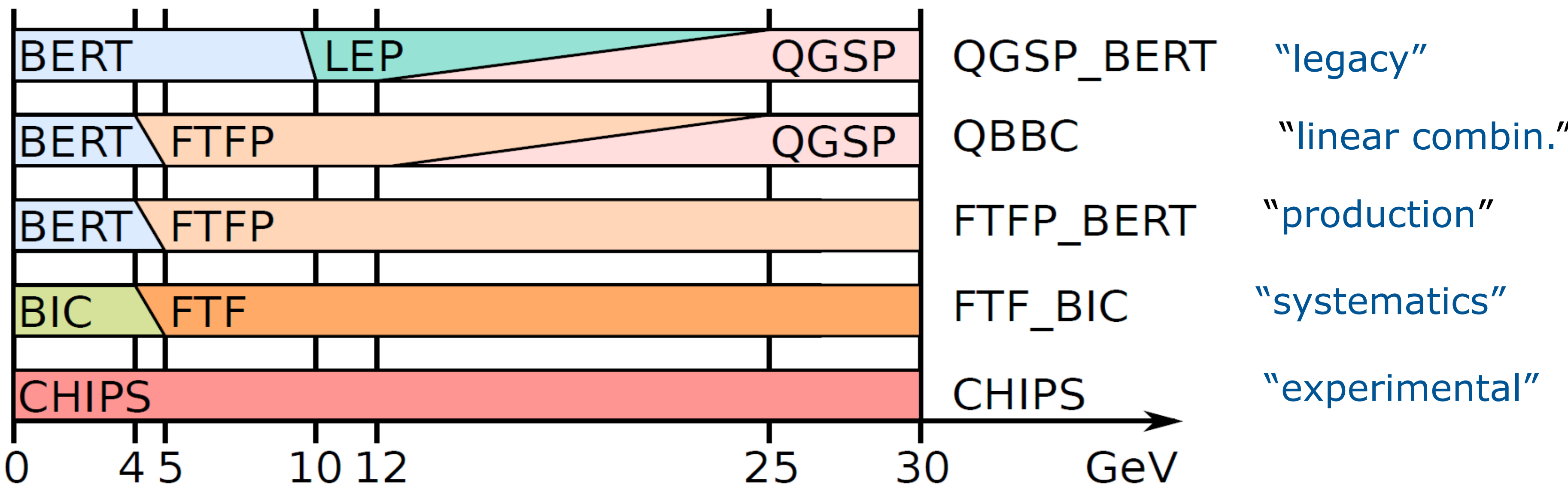


Shower simulation in Geant 4

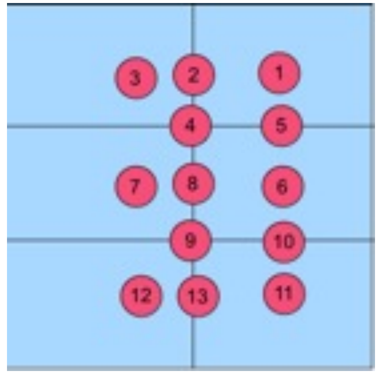
- Low energy: cascade models
- High energy: partonic models



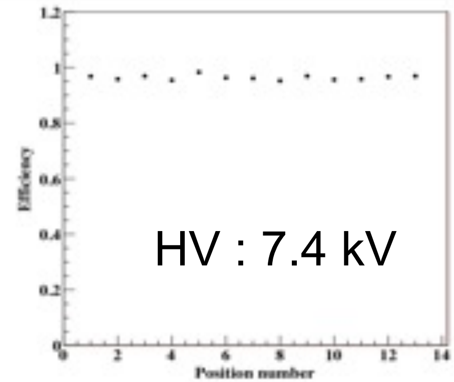
minimize use of phenomenological parameterization



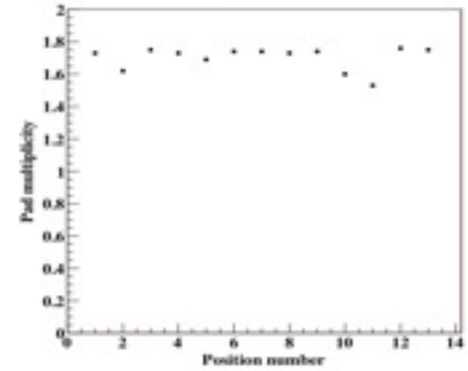
The homogeneity of the detector and its readout electronics were studied



Beam spot position



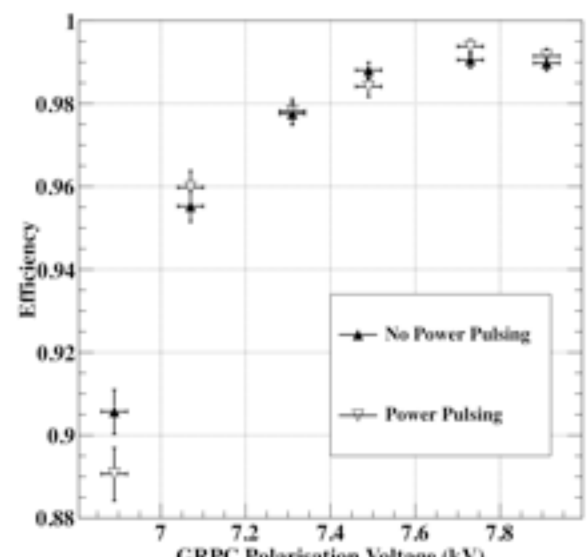
Efficiency



Multiplicity

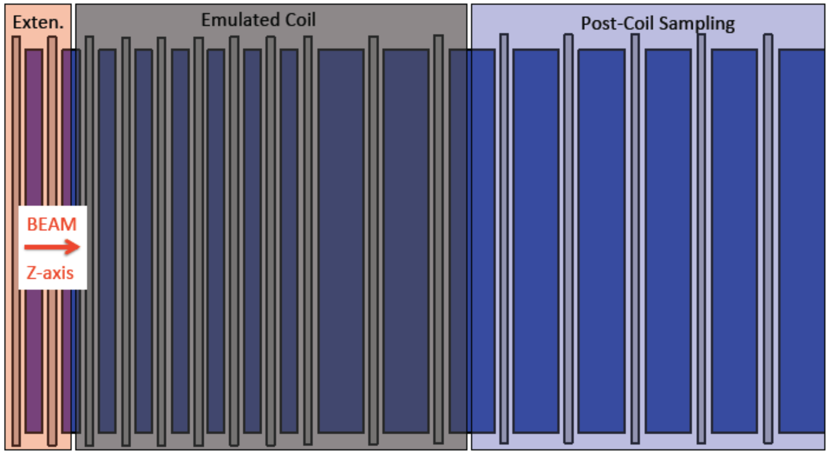
Power-Pulsing mode was tested in a magnetic field of 3 Tesla

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



Containment – use of Tail Catcher

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



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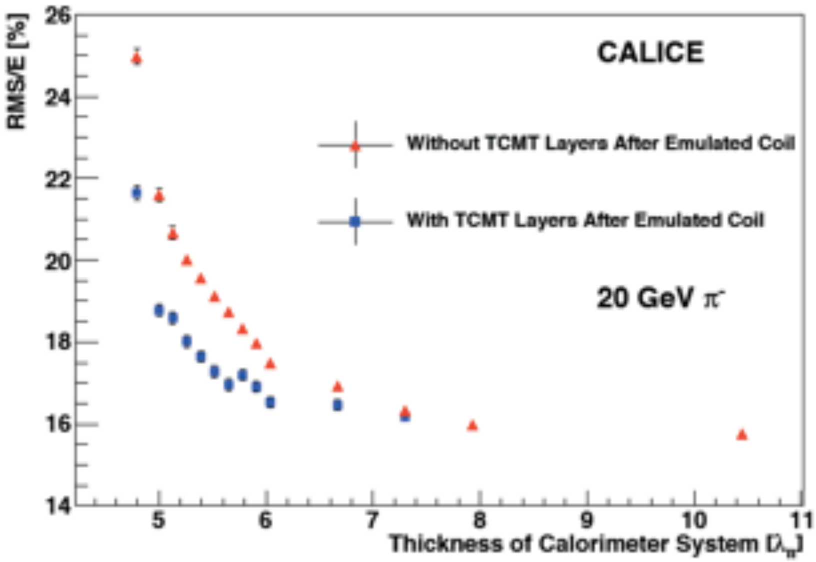
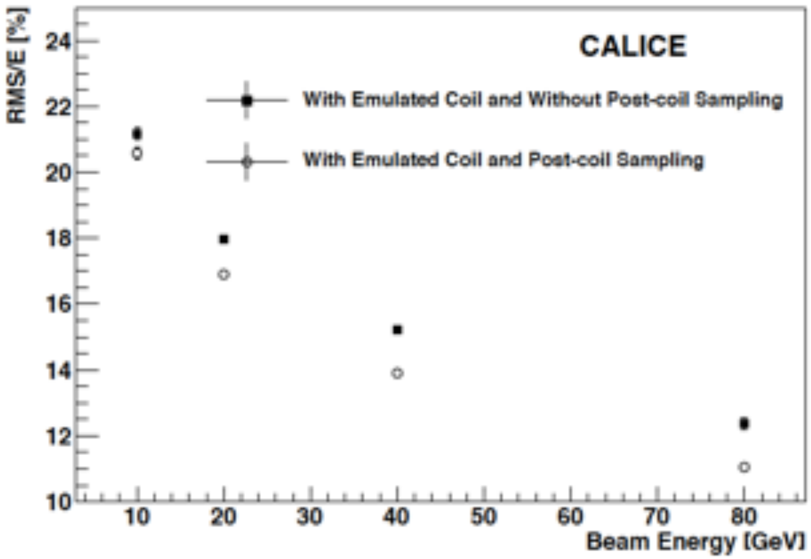
arxiv:1201.1653 (accepted by JINST)





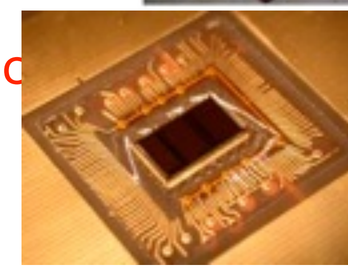
Common developments

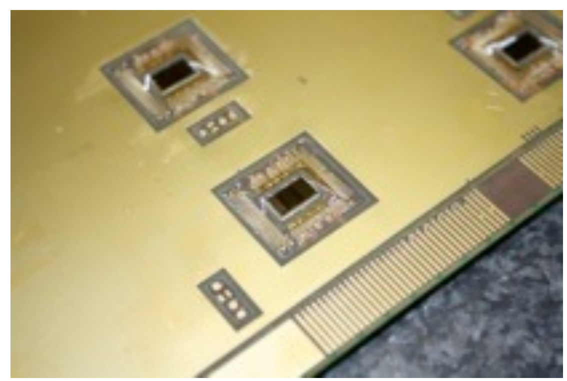
Front end electronics

not reported here: test beam infrastructure, DAQ, software and computing

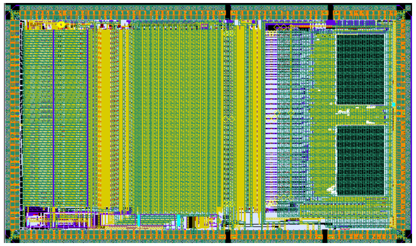
ILC Challenges for electronics

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

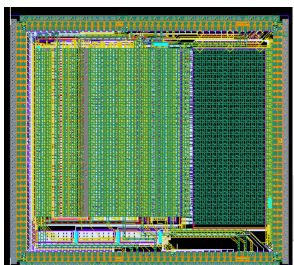




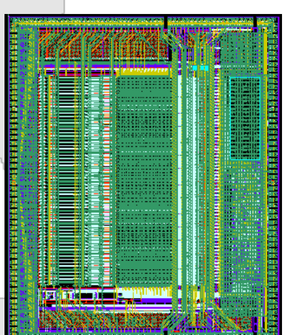
ASICs for ILC prototypes



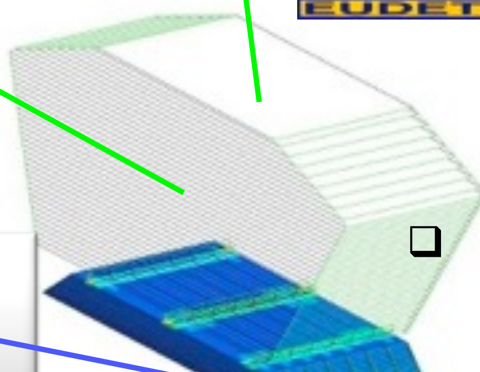
SPIROC2
Analog HCAL (AHCAL)
(SiPM)
36 ch. 32mm²
June 07, June 08, March 10



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



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



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