Frontiers and Trends in Particle Flow Calorimetry

Felix Sefkow

DESY

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

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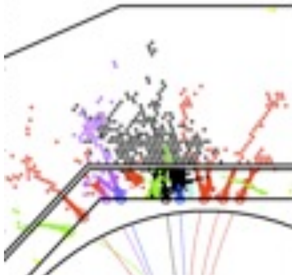
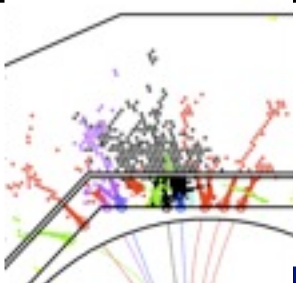
Thank you so much for the invitation to Trieste !

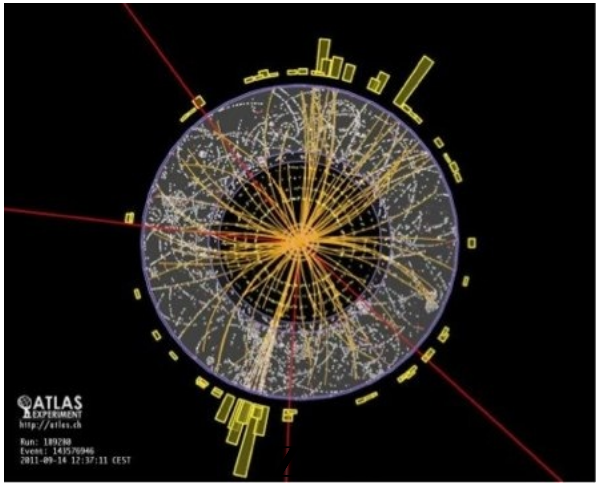


Outline

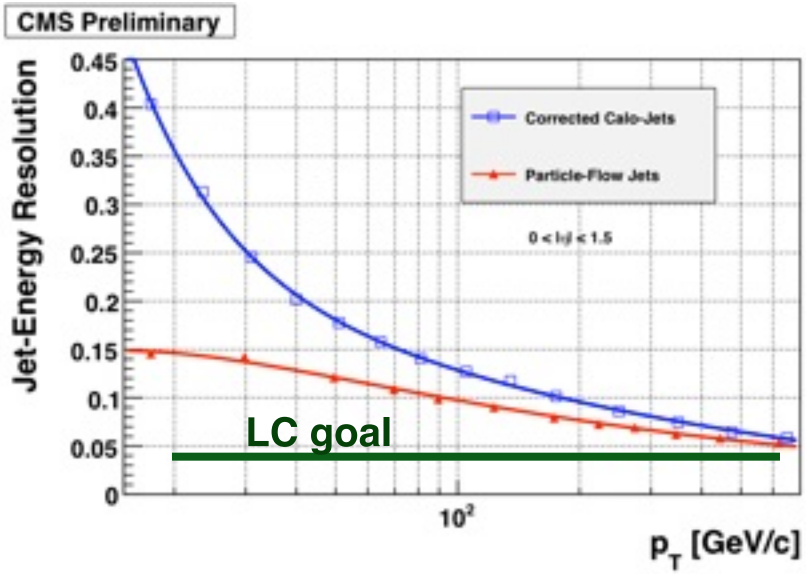
- Particle flow calorimetry
- Technologies for high granularity
- Test beam validation
- Frontiers and trends



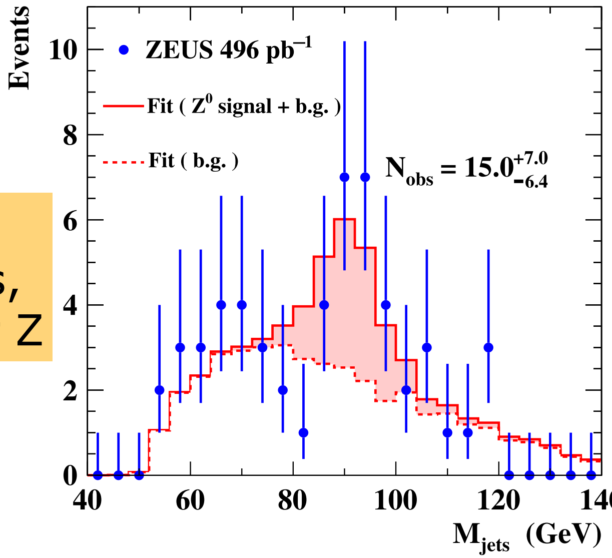
The jet energy challenge



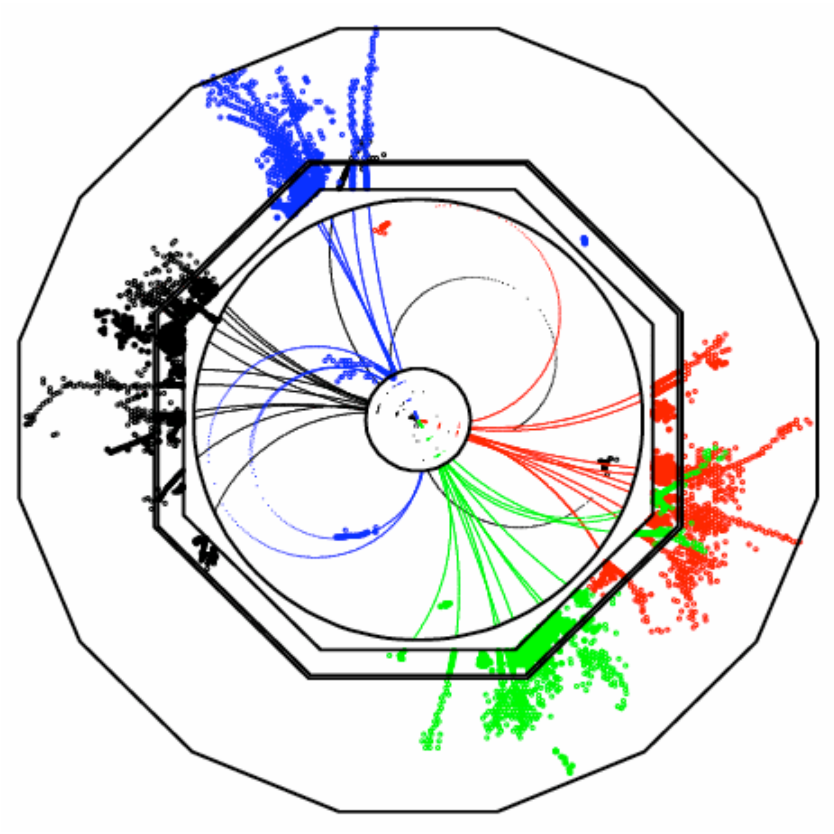
- Jet energy performance of existing detectors is not sufficient for separation of W and Z bosons
  - E.g. CMS: ~ 100%/√E, ATLAS ~ 70%/√E
- Calorimeter resolution for hadrons is intrinsically limited, e.g. nuclear binding energy losses
- Resolution for jets worse than for single hadrons
- It is not sufficient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



35%√E for pions, 6 GeV for Z

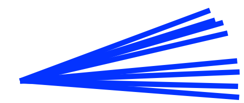


Particle flow concept

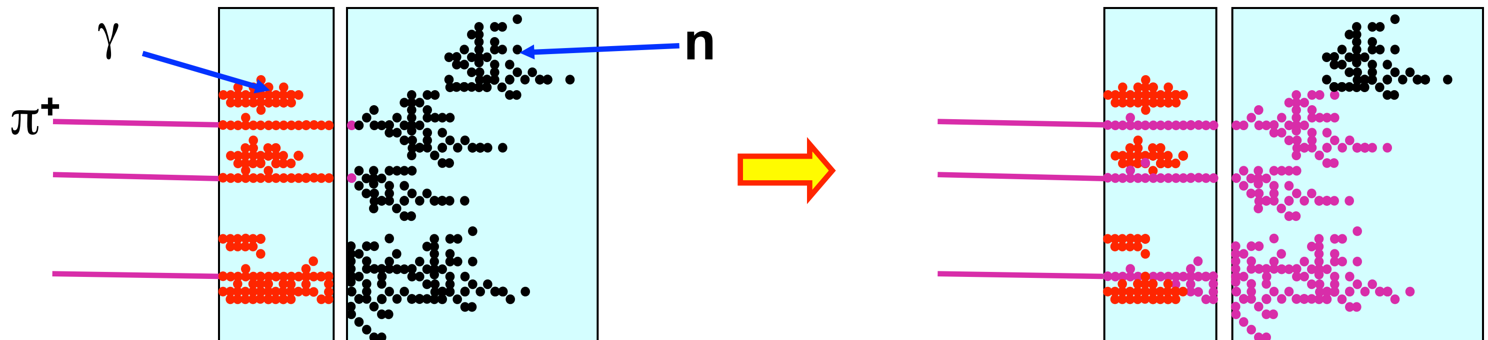


Particle Flow Calorimetry

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



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



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

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

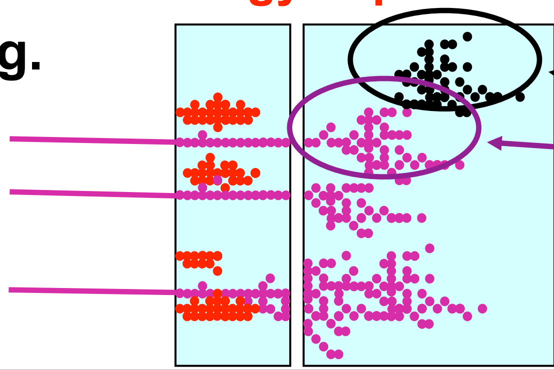
- **Particle Flow Calorimetry paradigm:**
  - charged particles measured in tracker (essentially perfectly)
  - Photons in ECAL: $\sigma_E/E < 20\%/\sqrt{E(\mathrm{GeV})}$
  - Neutral hadrons (ONLY) in HCAL
  - Only 10 % of jet energy from HCAL ⇒ much improved resolution

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.

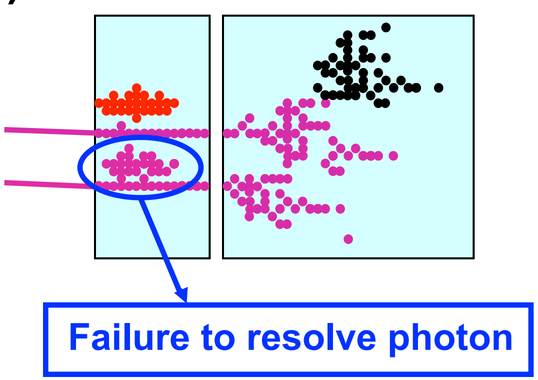


If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

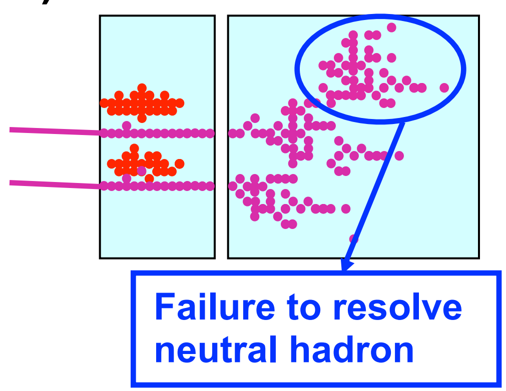
Level of mistakes, "confusion", determines jet energy resolution
not the intrinsic calorimetric performance of ECAL/HCAL

Three types of confusion:

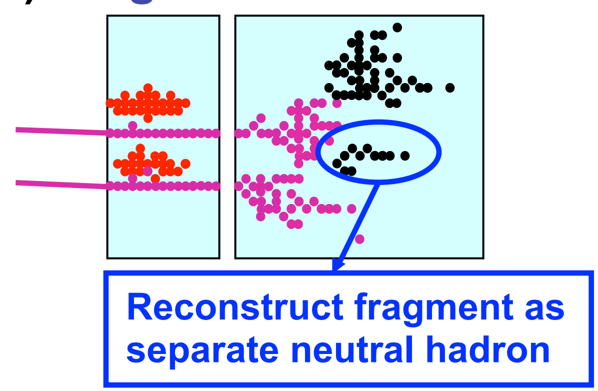
i) Photons

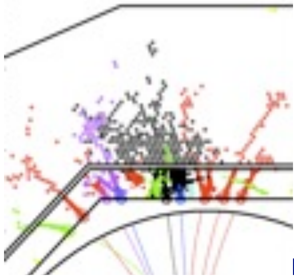


ii) Neutral Hadrons



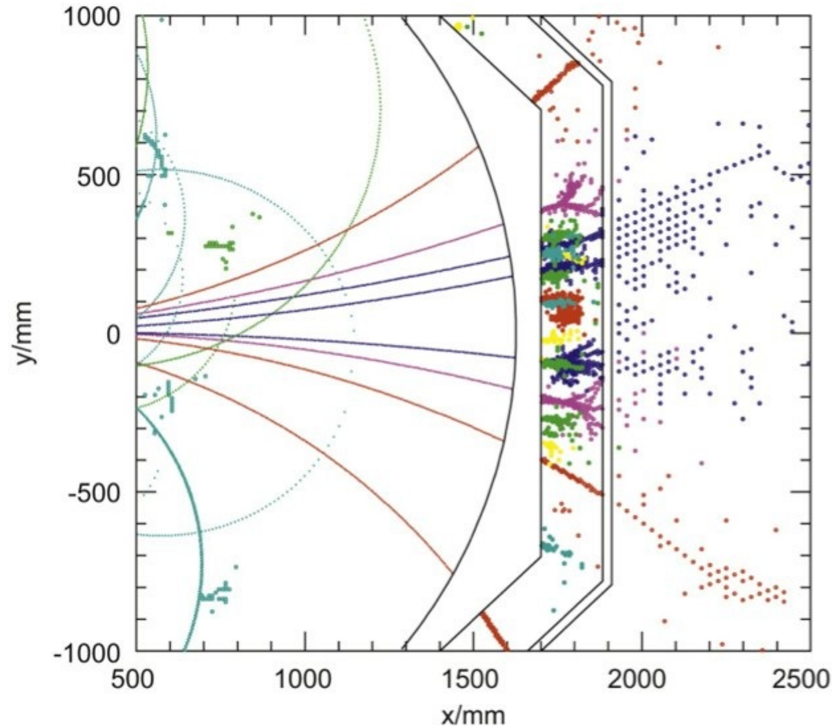
iii) Fragments

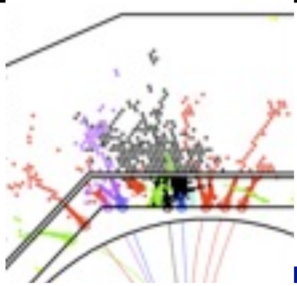




Particle flow detectors

- 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

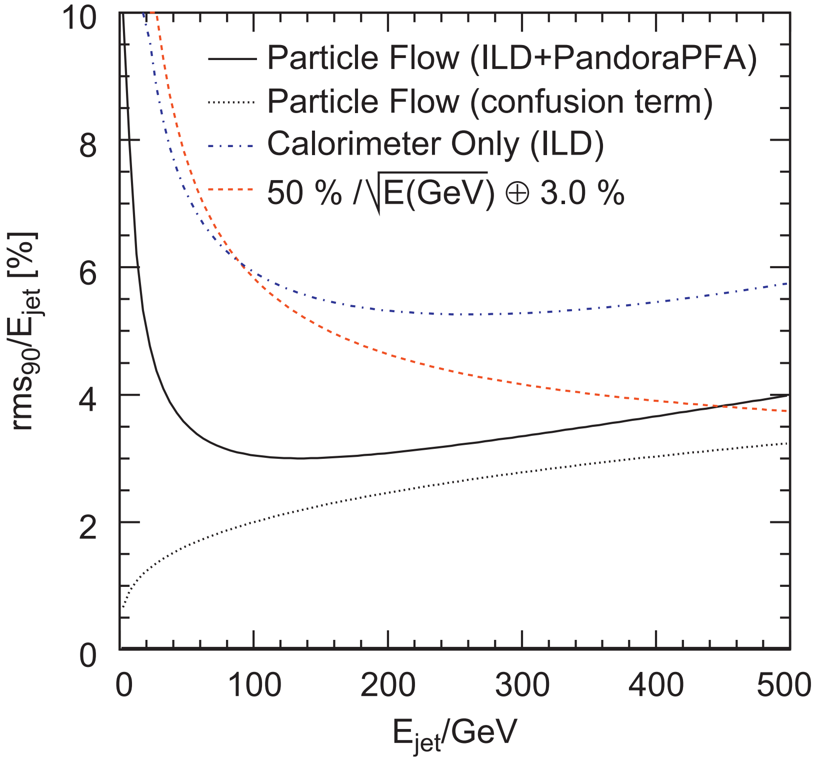


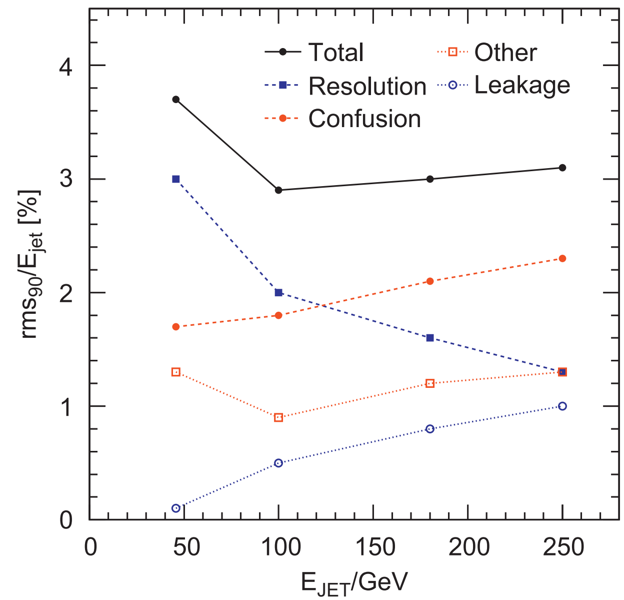


Understand particle flow performance

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

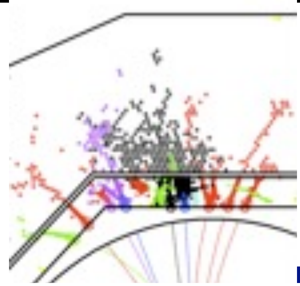
Resolution | Tracking | Leakage | Confusion





- 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



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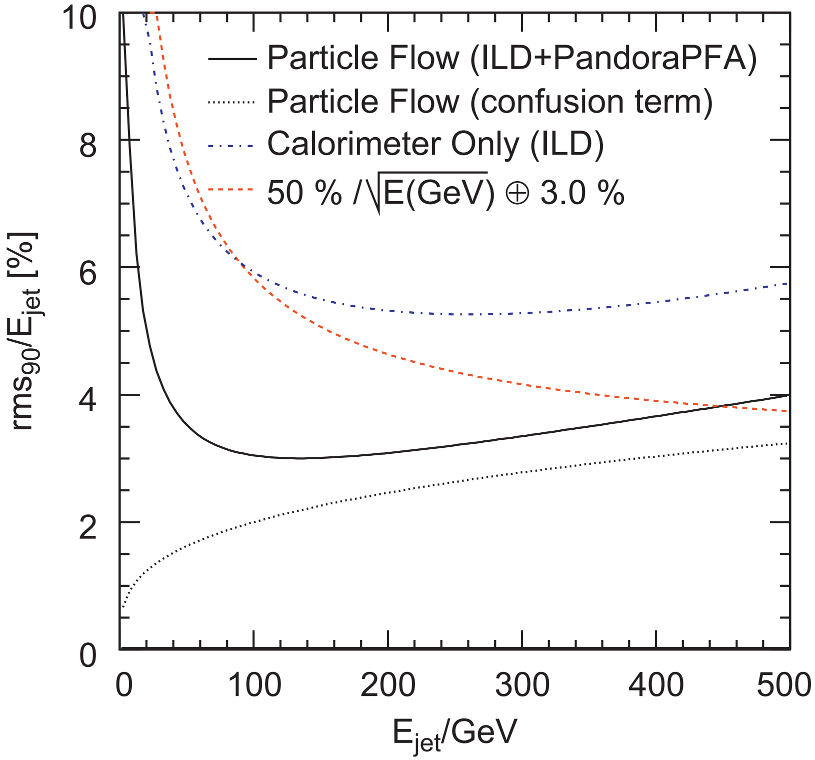
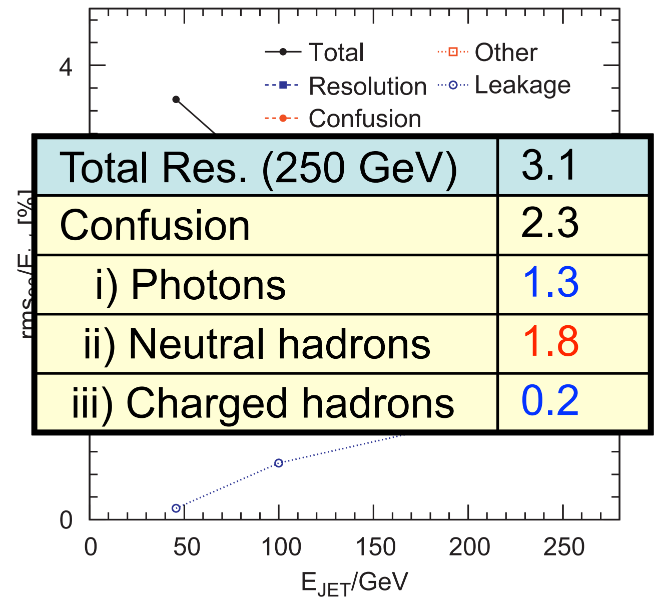
Resolution — Tracking — Leakage — Confusion





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

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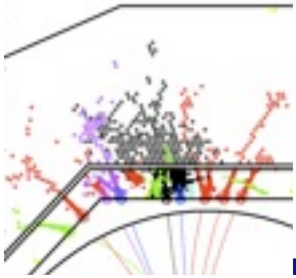
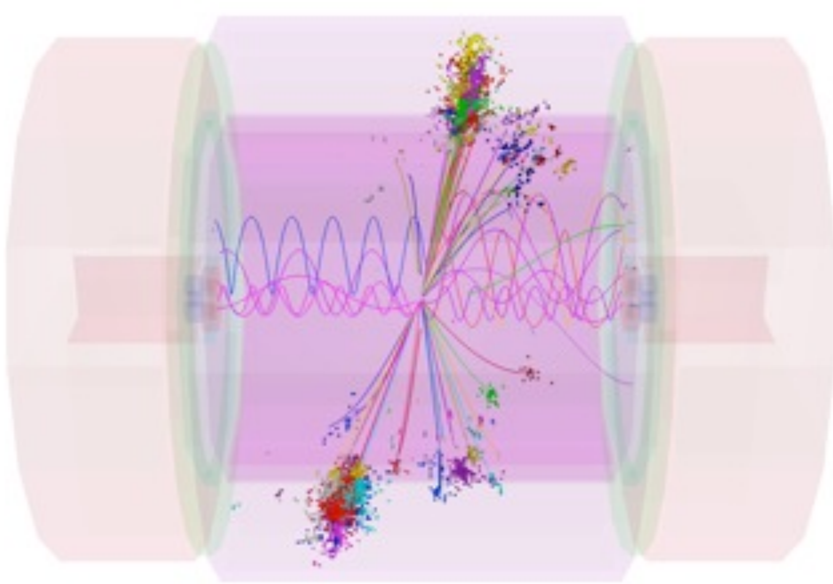
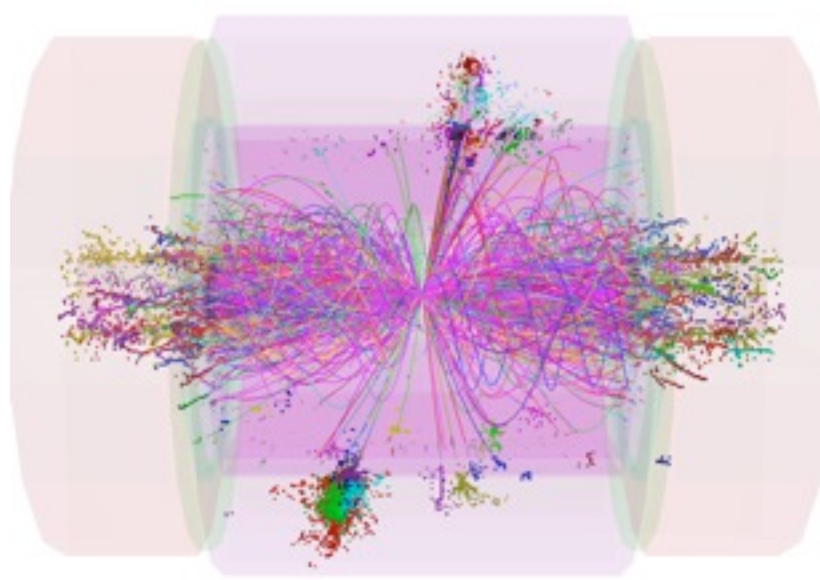


Particle flow and pile-up

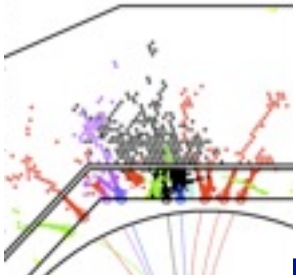
- Studied intensively for CLIC: harsh backgrounds and short BX 0.5 ns
- Overlay γγ events from 60 BX, take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- Apply combination of topological, pt and timing cuts on cluster level (sub-ns accuracy)



Z @ 1 TeV



+ 1.4 TeV BG (reconstructed particles)



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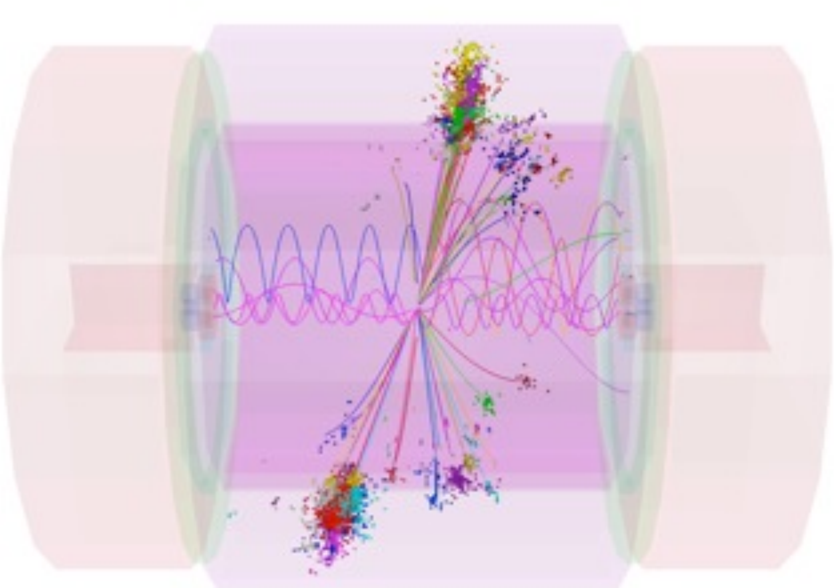

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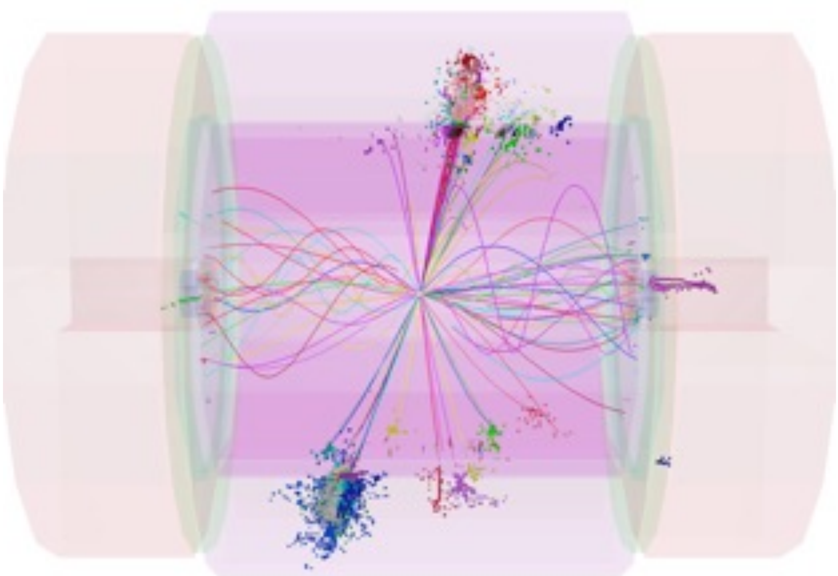

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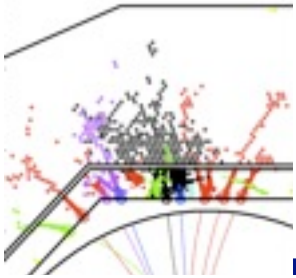

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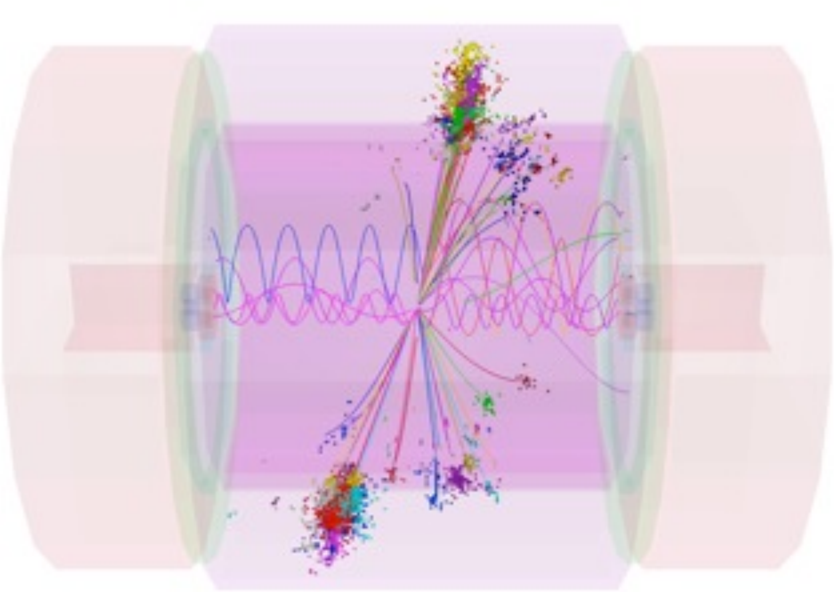
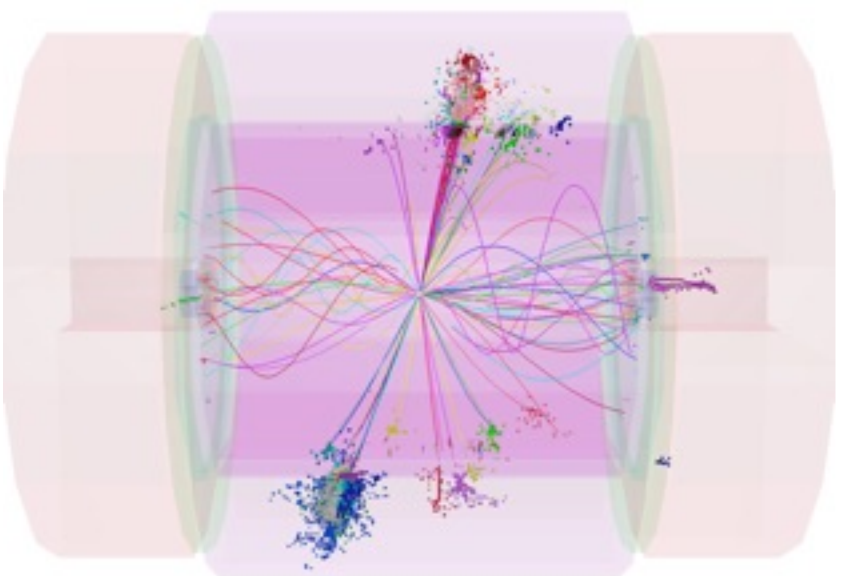


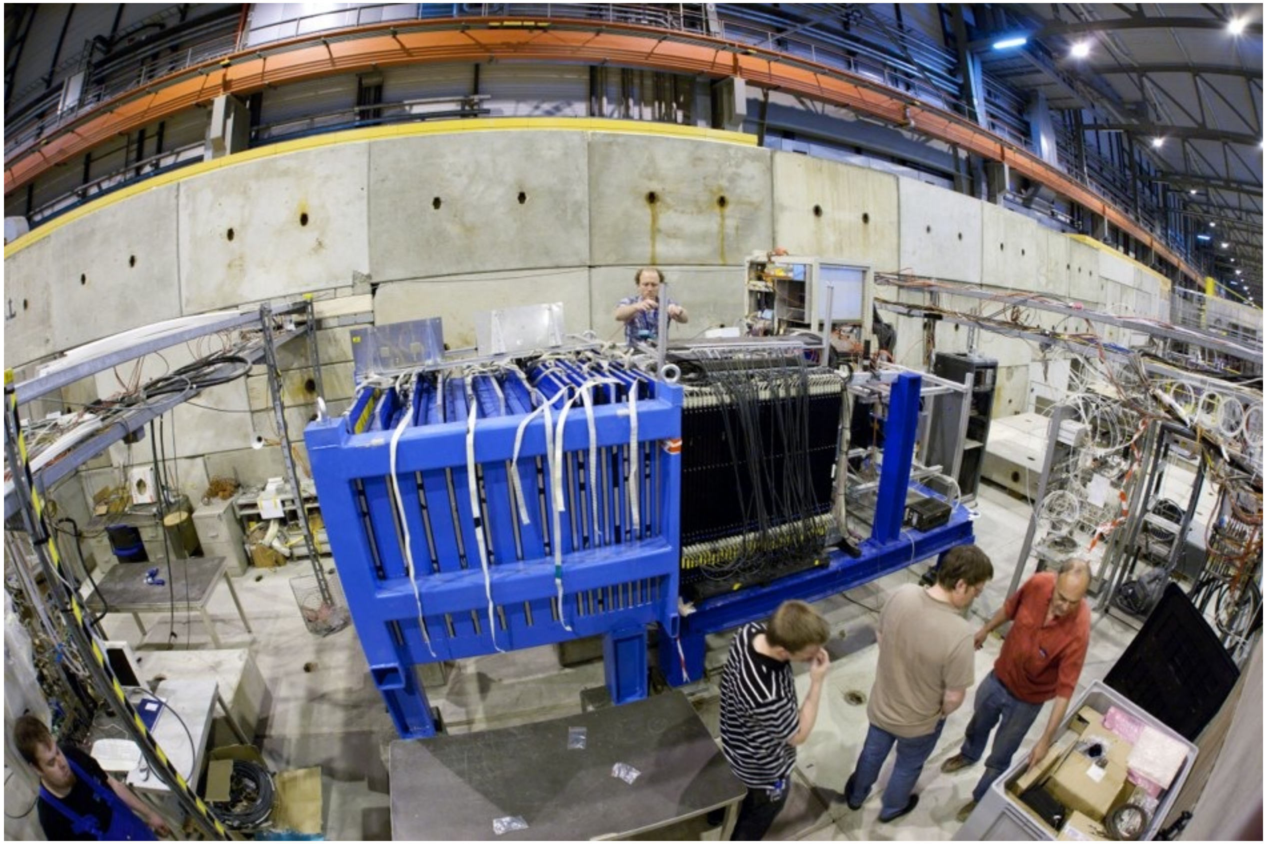


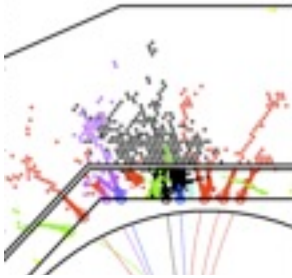
Z @ 1 TeV

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
  - even in harsh back/ground condition and with pile-up
- Particle flow calorimeters feature good energy resolution **and** high granularity, 10 to 100 million channels
- Detector cost driven by instrumented area rather than cell size

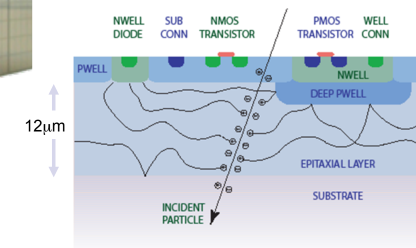
Technologies and test beam performance

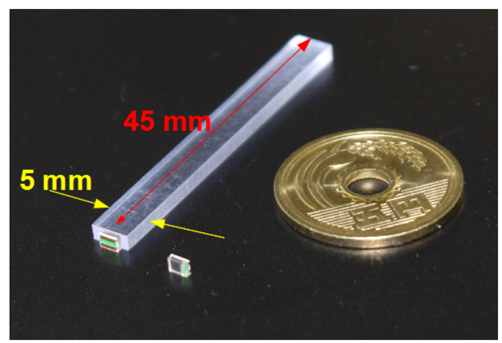


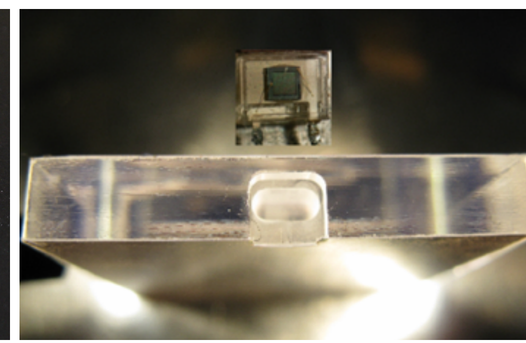


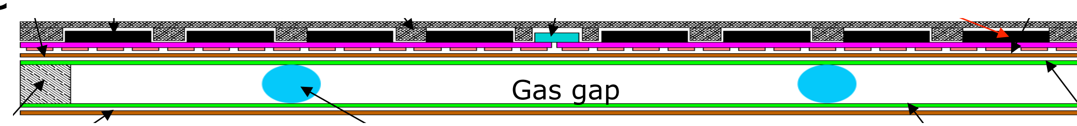
Particle flow technologies

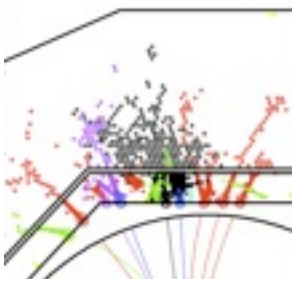
- Silicon (ECAL)
  - most compact solution, stable calibration
  - 0.5 - 1 cm^2 cell size
  - MAPS pixels also studied
- Scintillator SiPM (ECAL, HCAL)
  - robust and reliable, SiPMs..
  - ECAL strips: 0.5 - 1 cm eff.
  - HCAL tiles: 3x3 cm^2
- Gaseous technologies
  - fine segmentation: 1 cm^2
  - Glass RPCs: well known, safe
  - MPGDs: proportional, rate-capable
    - GEMs, Micromegas







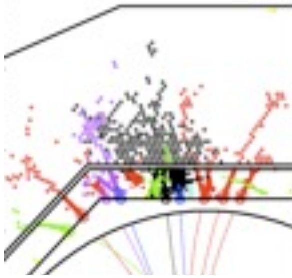




MPGDs for calorimetry

- Gaseous HCAL with **analogue** readout would have poor resolution
  - small sampling, large Landau fluctuations
- **Digital** calorimeter idea: count particles, ignore fluctuations
  - 1cm^2 cells: saturate above 30 GeV
- **Semi-digital** idea: mitigate saturation using several thresholds and weights
  - assumes signal prop. to E deposition

M.Chefdeville



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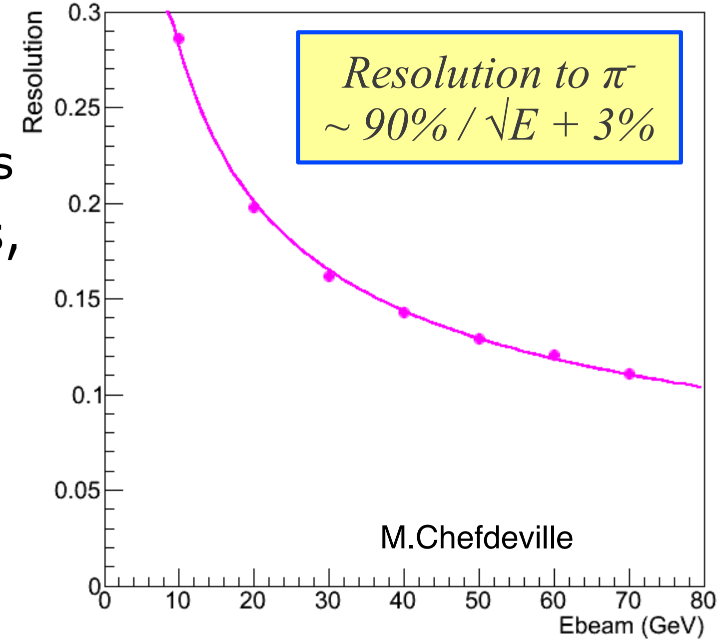

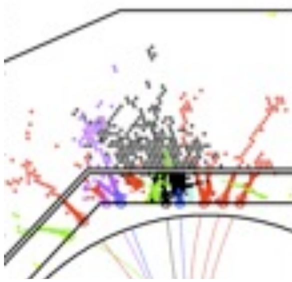

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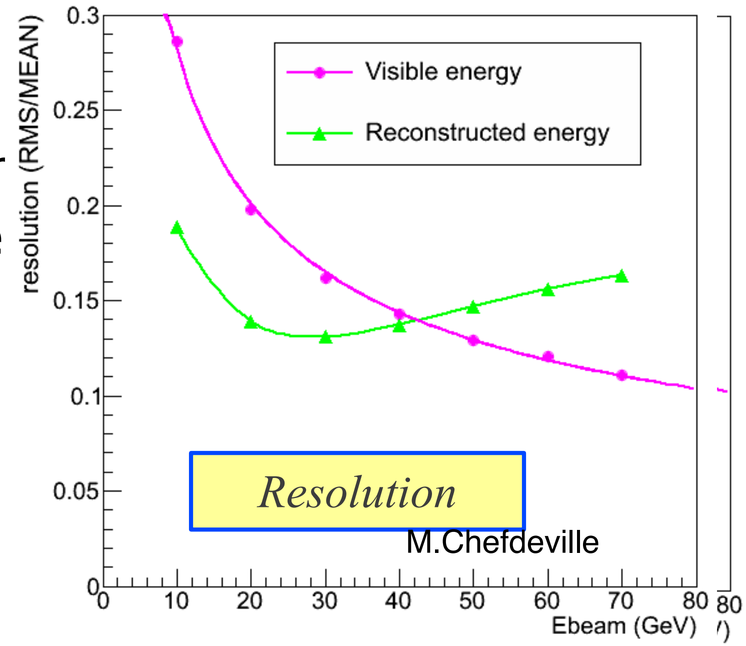

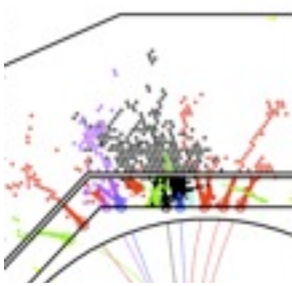

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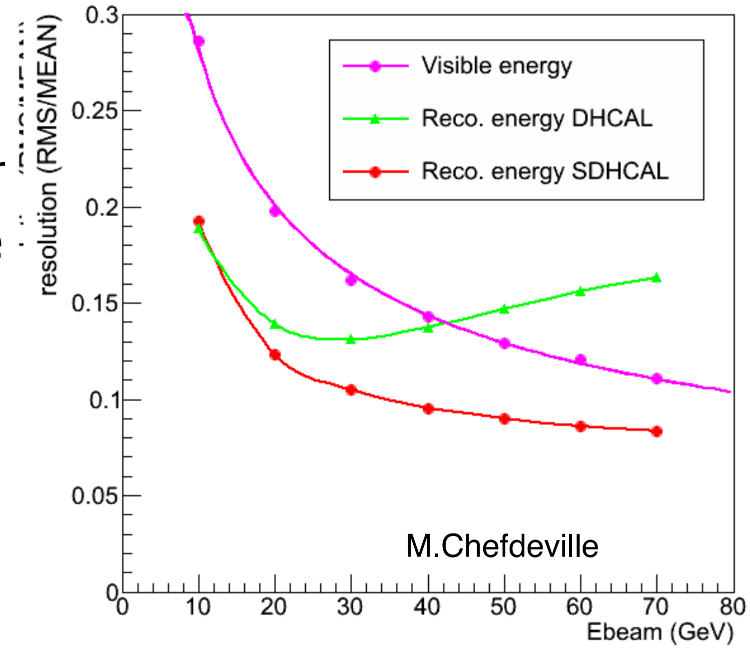

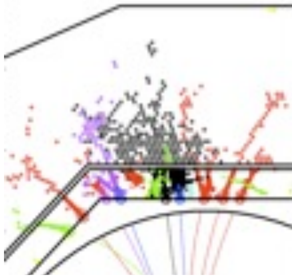

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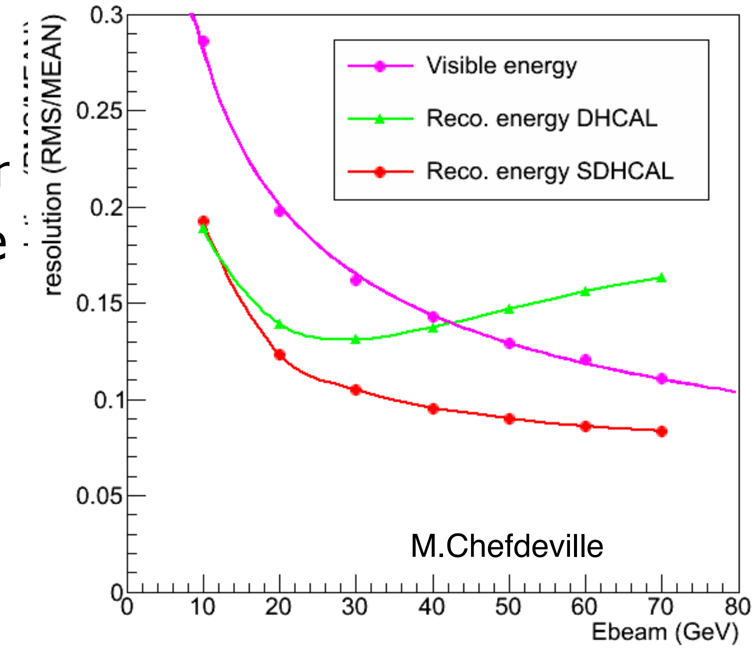
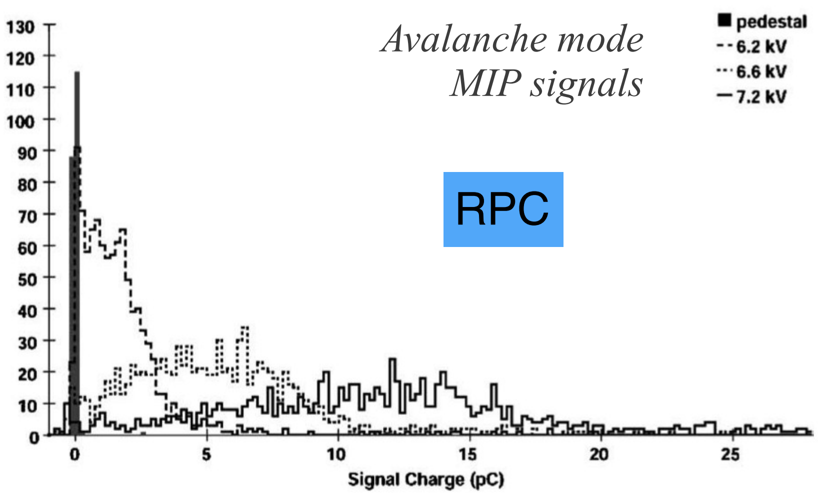
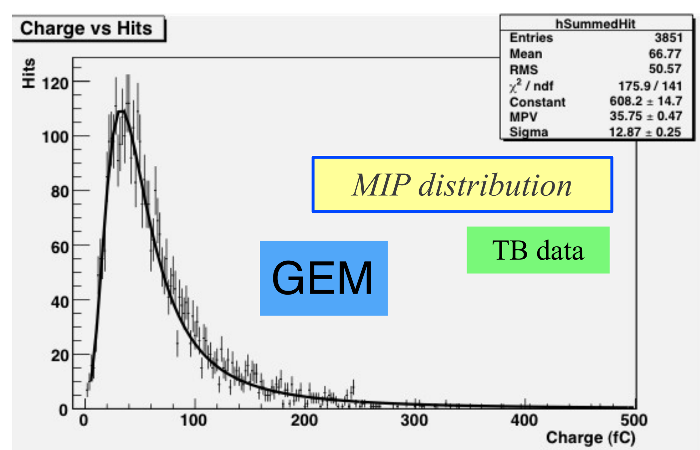
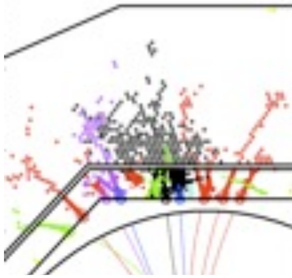
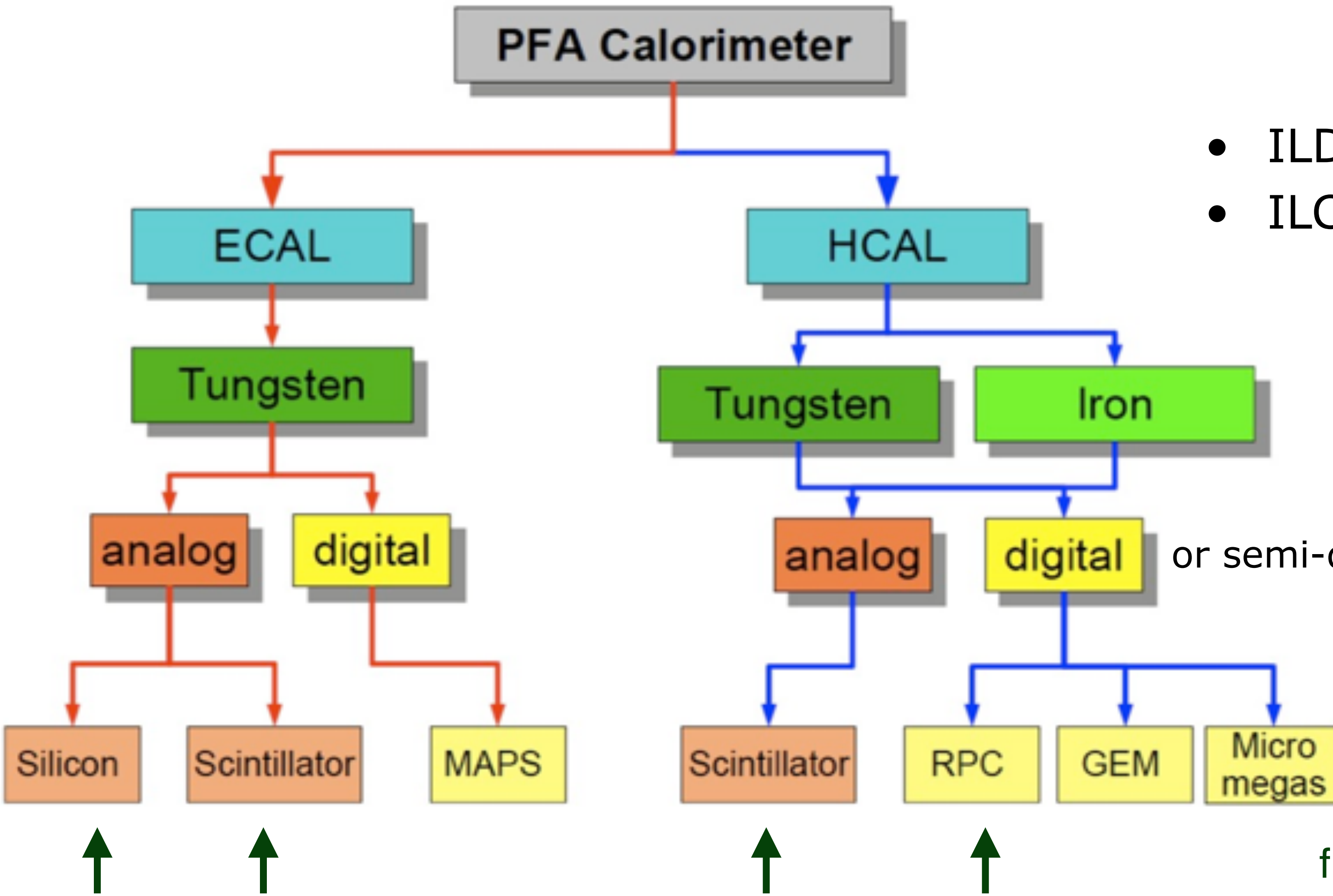








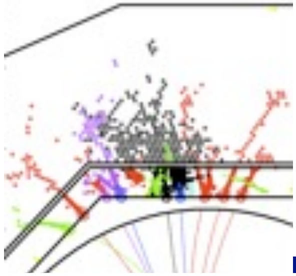
Calorimeter technologies



or semi-digital

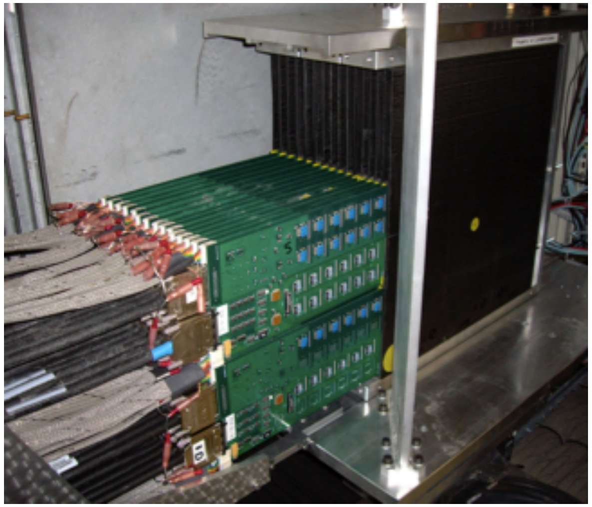
- ILD, SiD
- ILC, CLIC

full prototypes

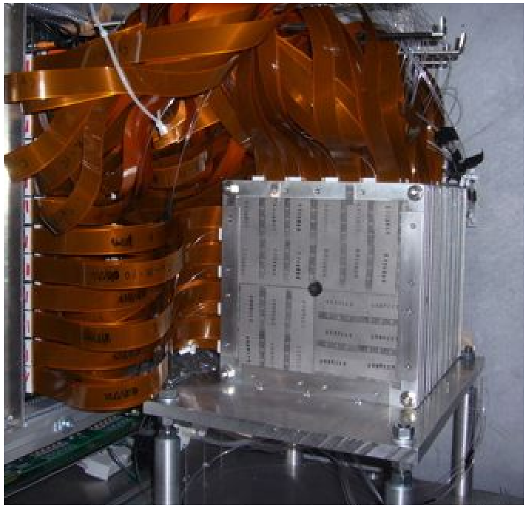


Test beam prototypes

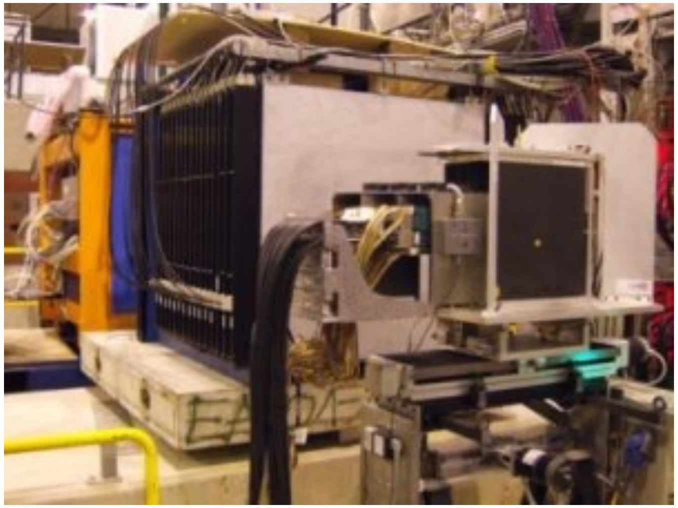
SiW ECAL



ScintW ECAL

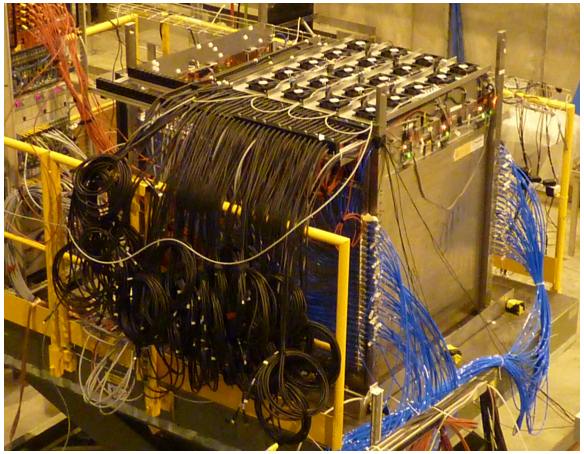


Scint AHCAL, Fe & W



RPC DHCAL, Fe & W

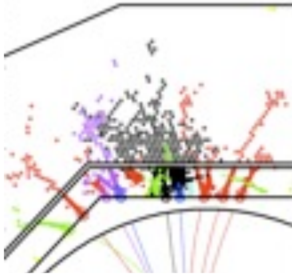
RPC SDHCAL, Fe



plus tests with small numbers of layers:

- ECAL, AHCAL with integrated electronics

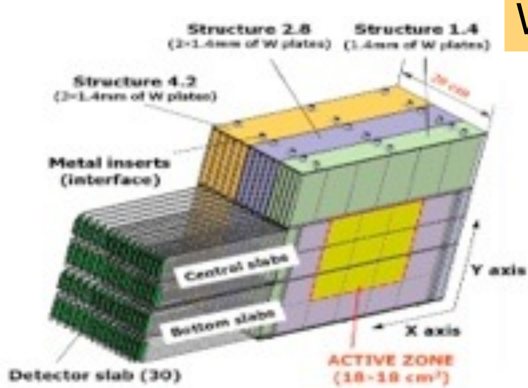
- Micromegas and GEMs

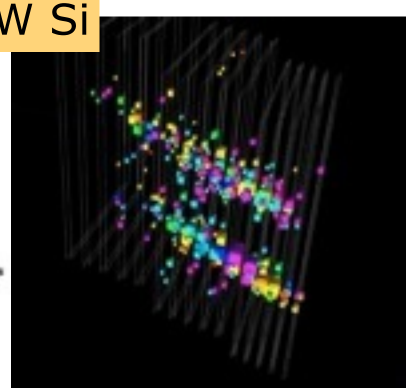


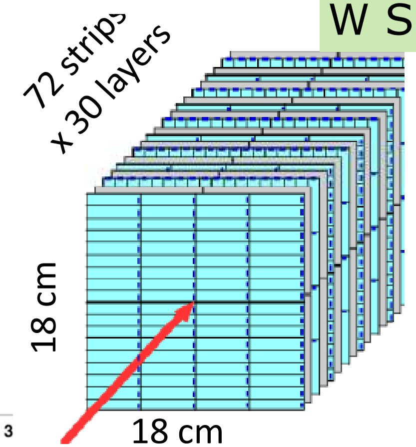
CALICE ECALs performance

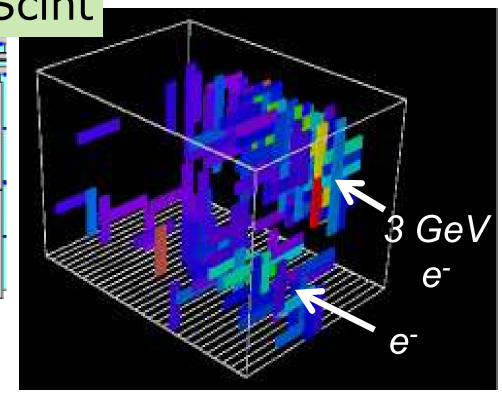
W Si

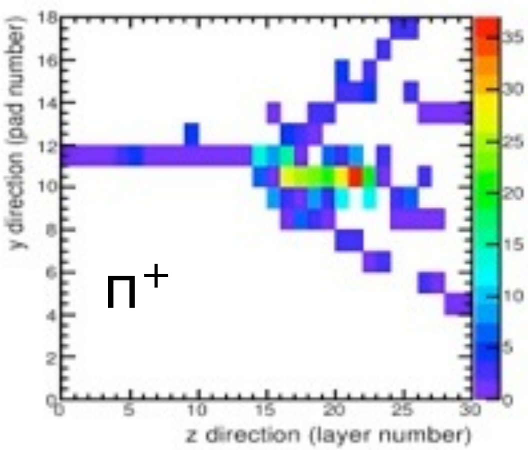
W Scint

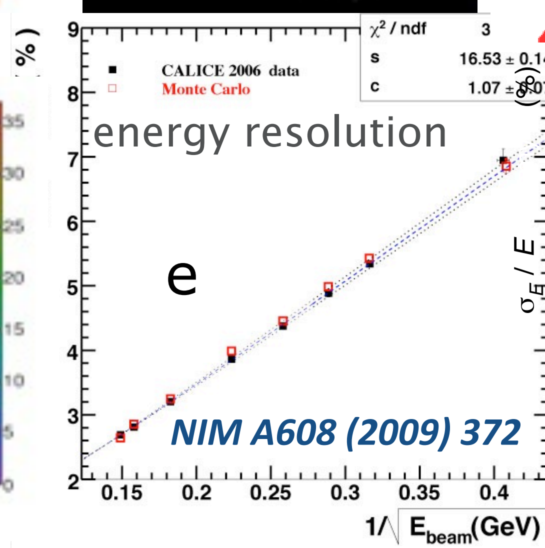


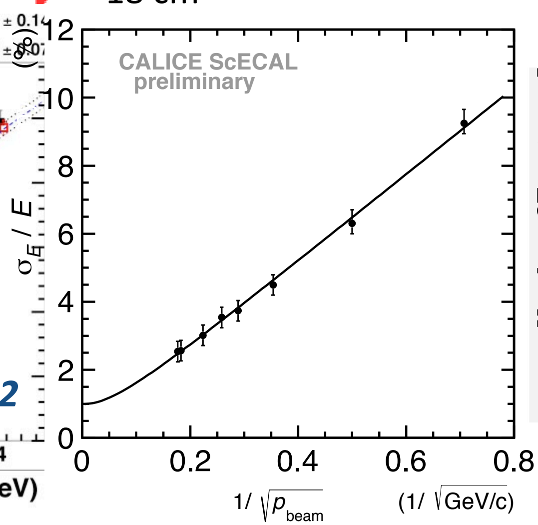


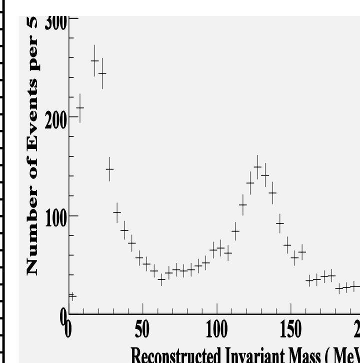




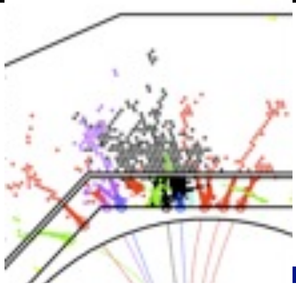






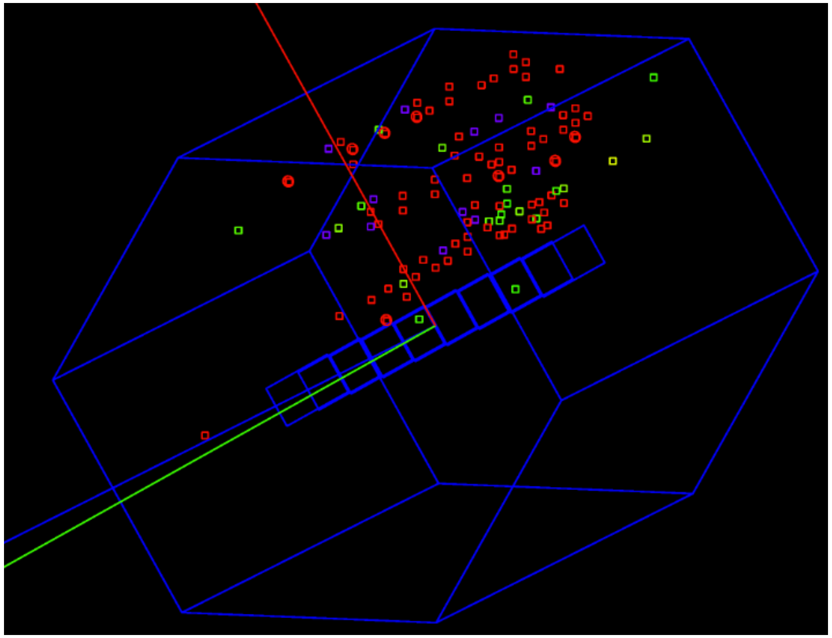


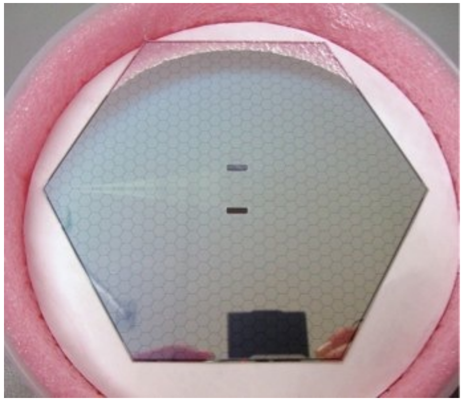
- data and sim agree

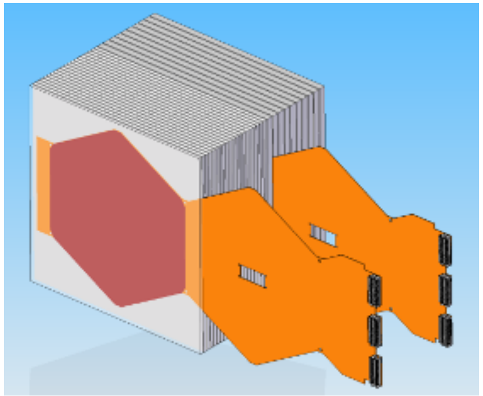


SiD ECAL

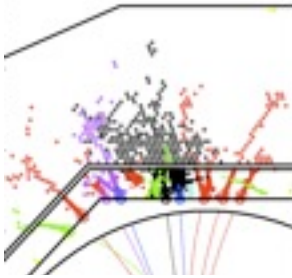
- SiD made some ambitious design choices
  - most compact ECAL
    - smallest $R_{Moliere}$
  - most light-weight Silicon tracker
  - both based on KPiX chip (1024 ch)
  - directly bonded to wafer
- ECAL: no PCB
  - 1.1 mm thin active gap



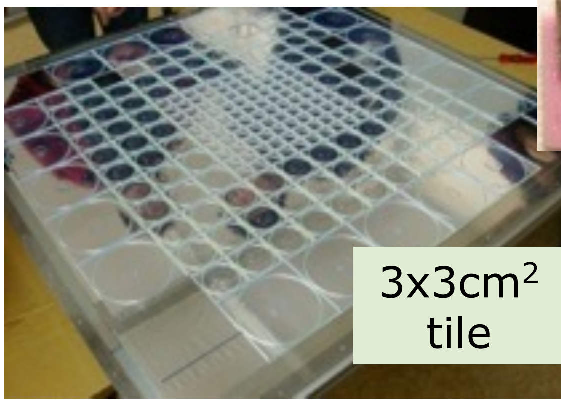




July 2013
9 layers in the beam
at SLAC End Station A

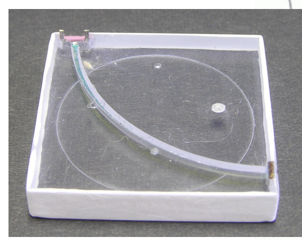


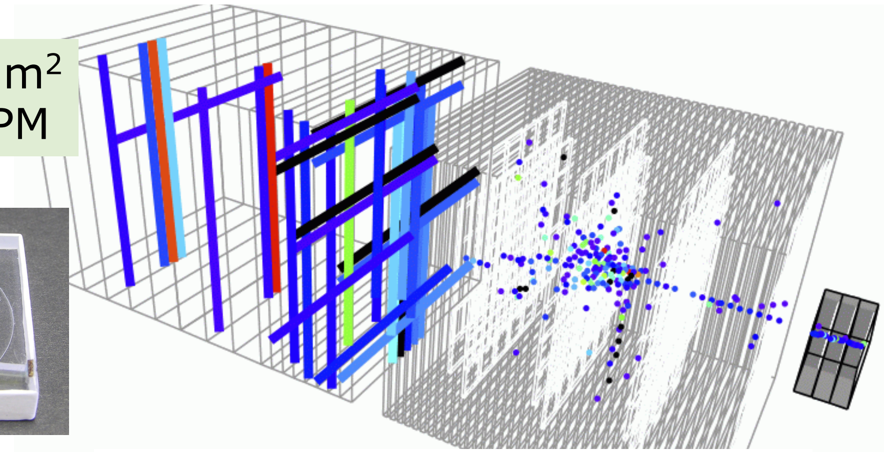
Scintillator HCAL performance



3x3cm^2 tile

1mm^2 SiPM

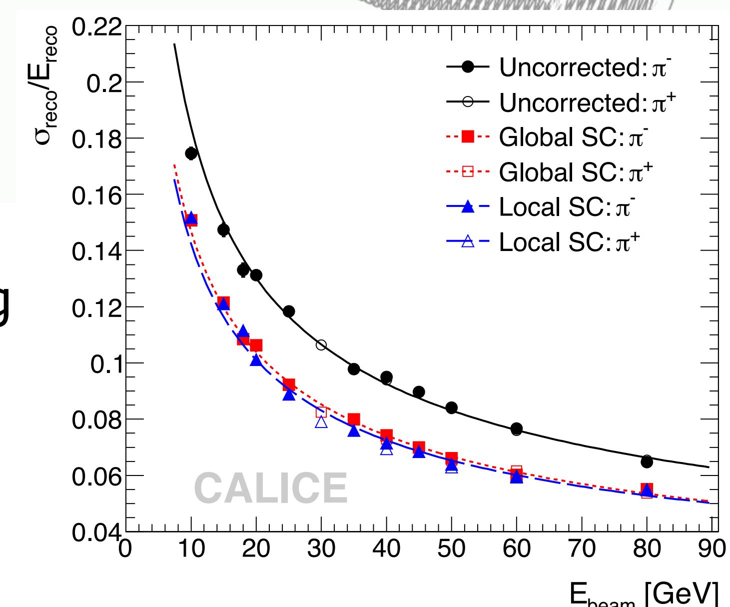




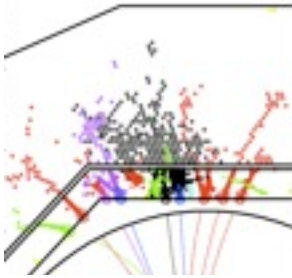
- 38 layer steel and tungsten
- 7608 channels: first large scale SiPM application
- very robust: 6 years of data taking at DESY, CERN, Fermilab
- a very good calorimeter, too

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

software compensation

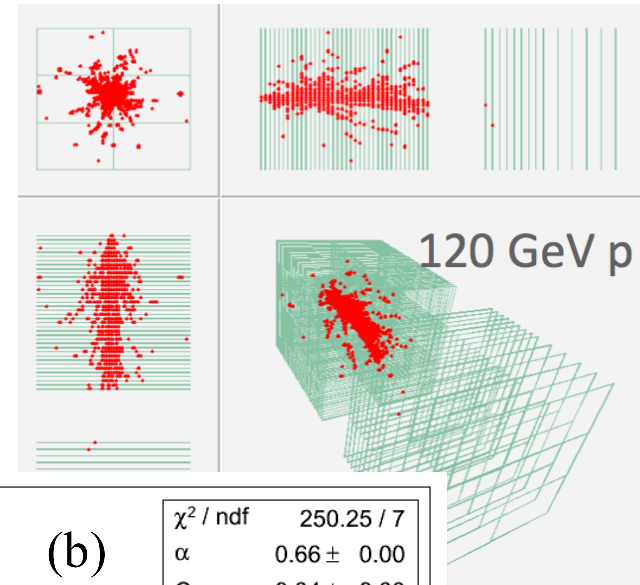


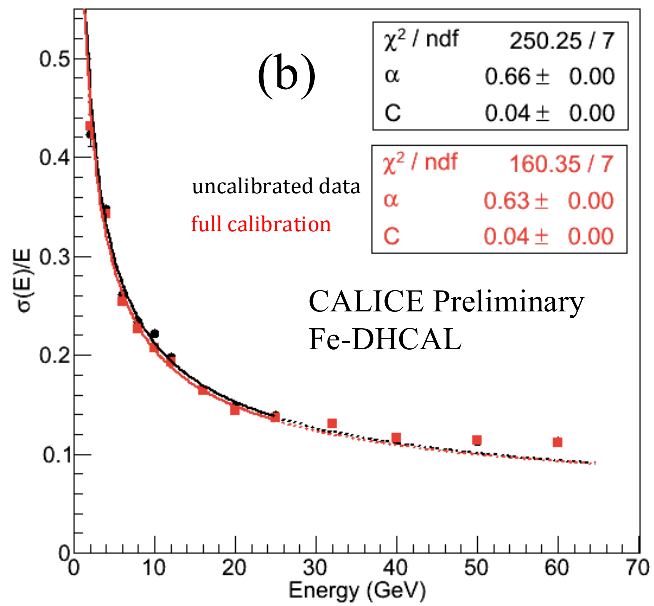
JINST 7, P00917 (2012)

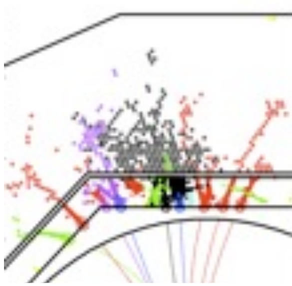


Digital RPC HCAL

- 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

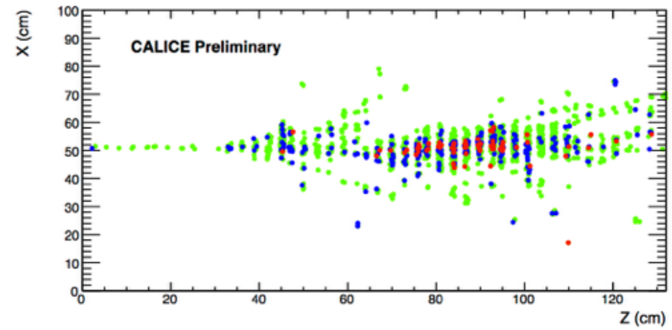


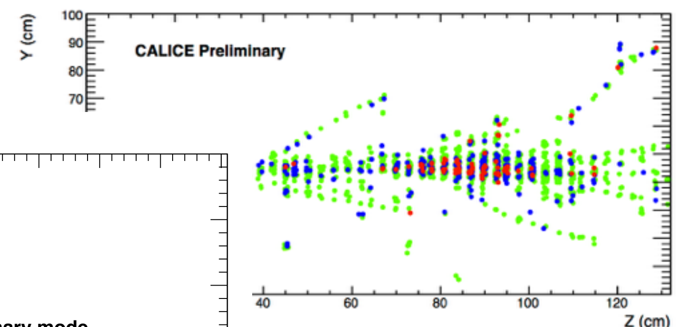


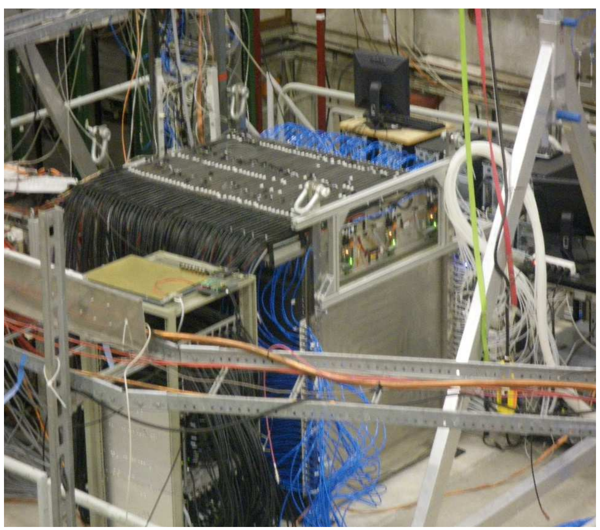


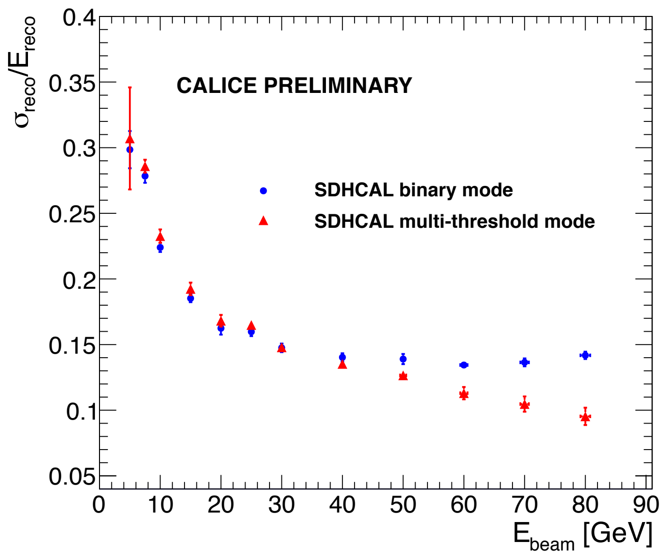
Semi-digital RPC HCAL

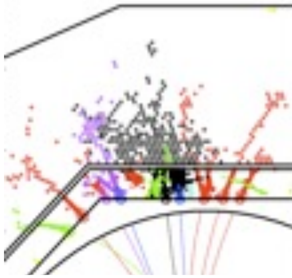
- 48 RPC layers, 1cm^2 pads
- embedded electronics
  - power-cycled
- 2 bit, 3 threshold read-out
  - mitigate resolution degradation at high energy











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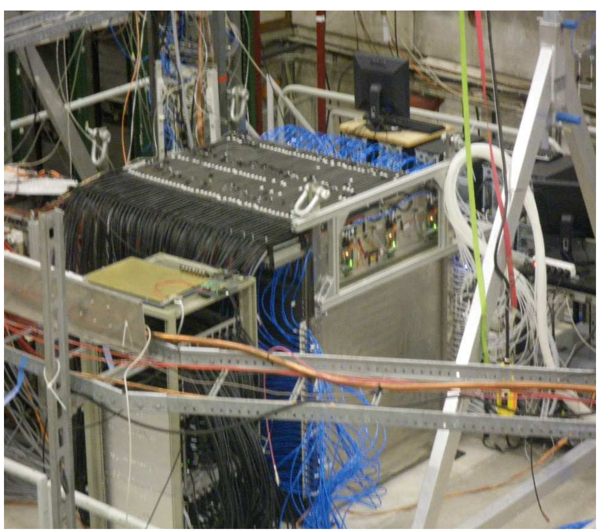
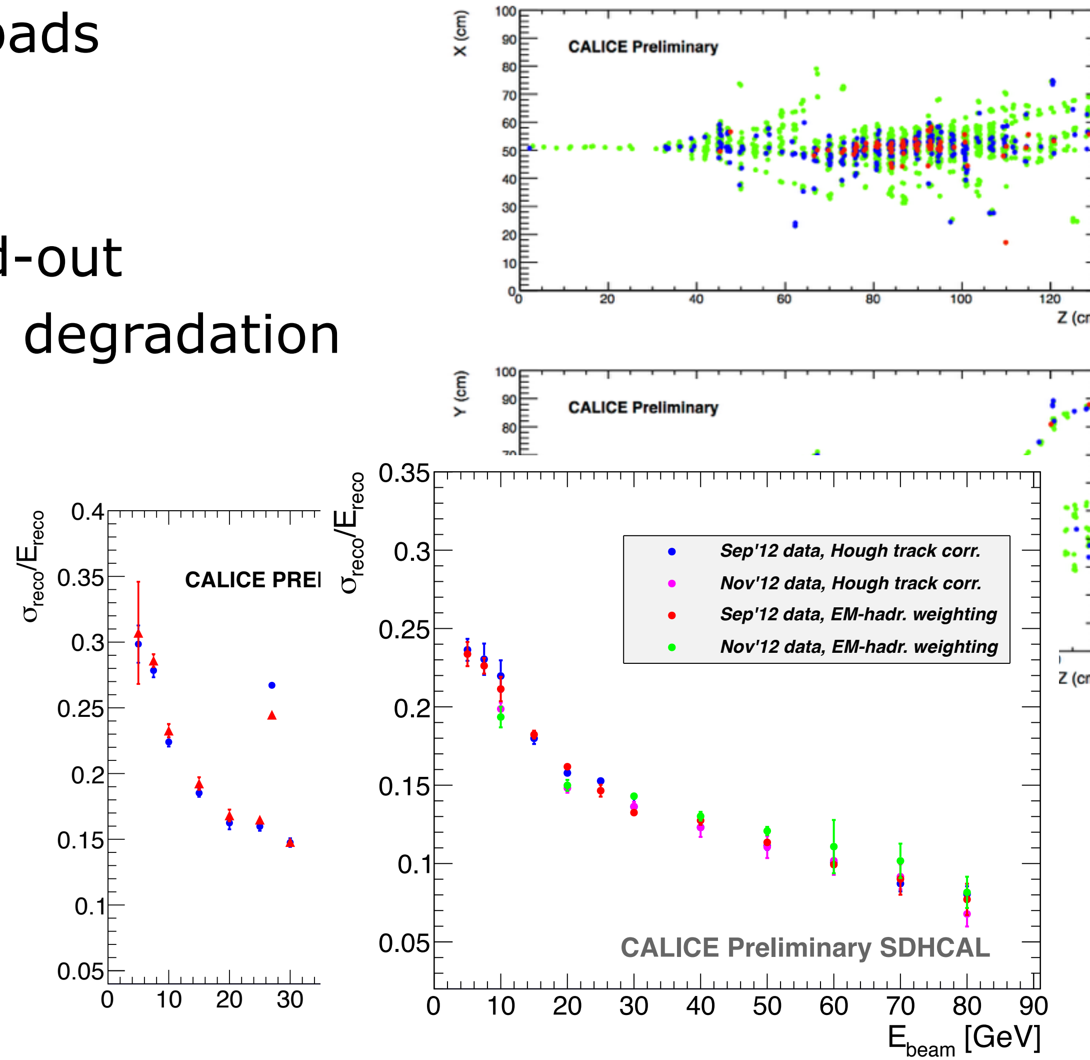
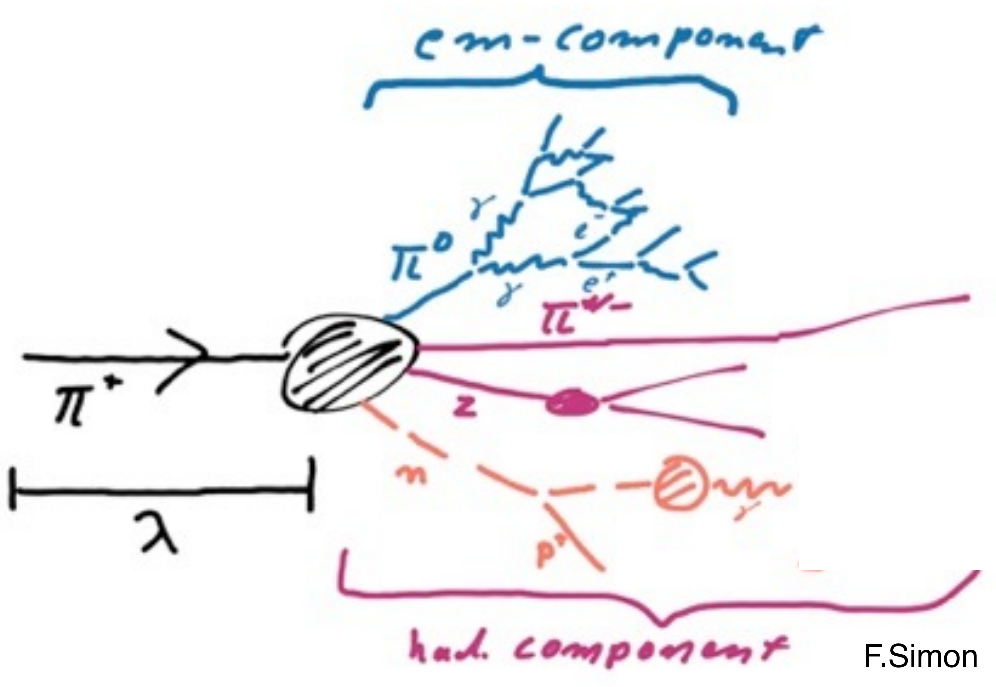
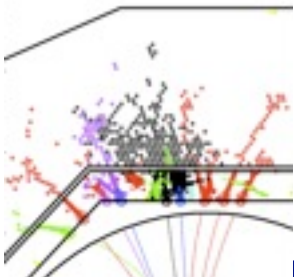




Validation of Geant 4 shower models

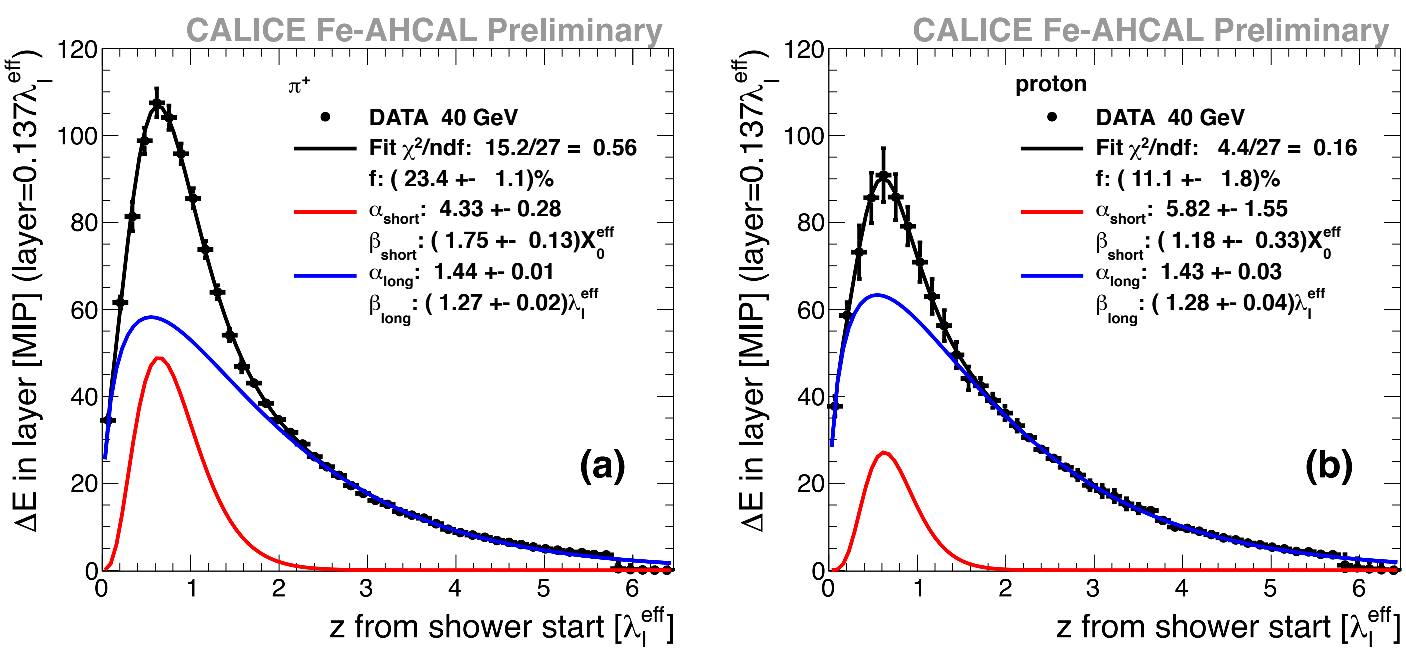


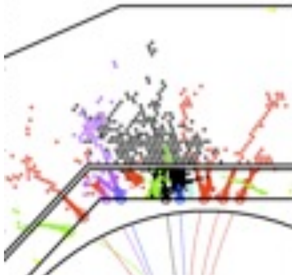
F.Simon



Longitudinal shower profiles

- Measure hadronic shower profiles from the reconstructed point of the first hard interaction
- Parameterise in terms of
  - a short component related to electromagn. component
  - a long component related to the hadronic part
  - similar decomposition works for radial profiles





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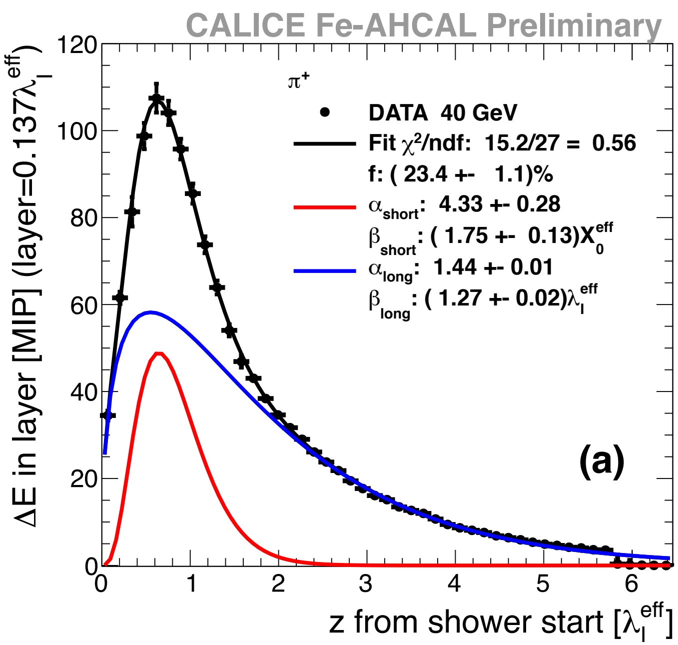
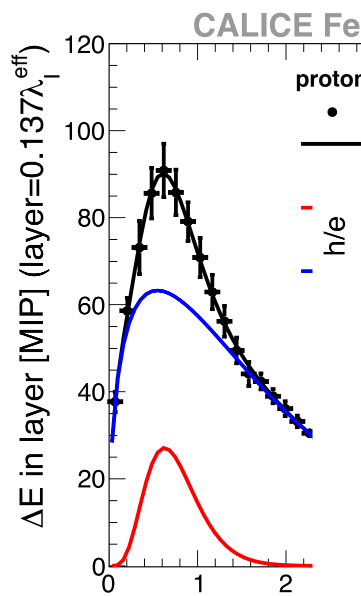
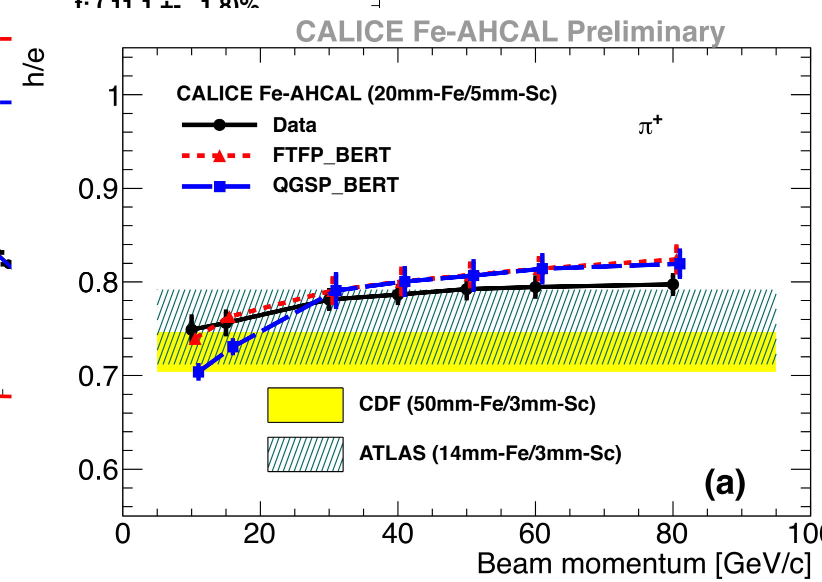
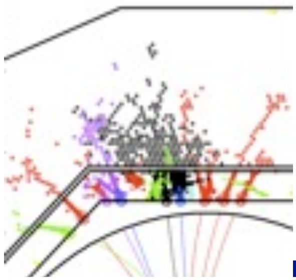
- Determine h / e ratio without assumption on energy dependence

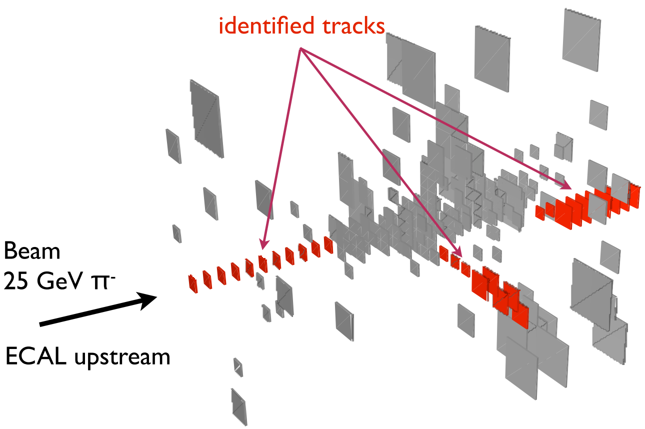


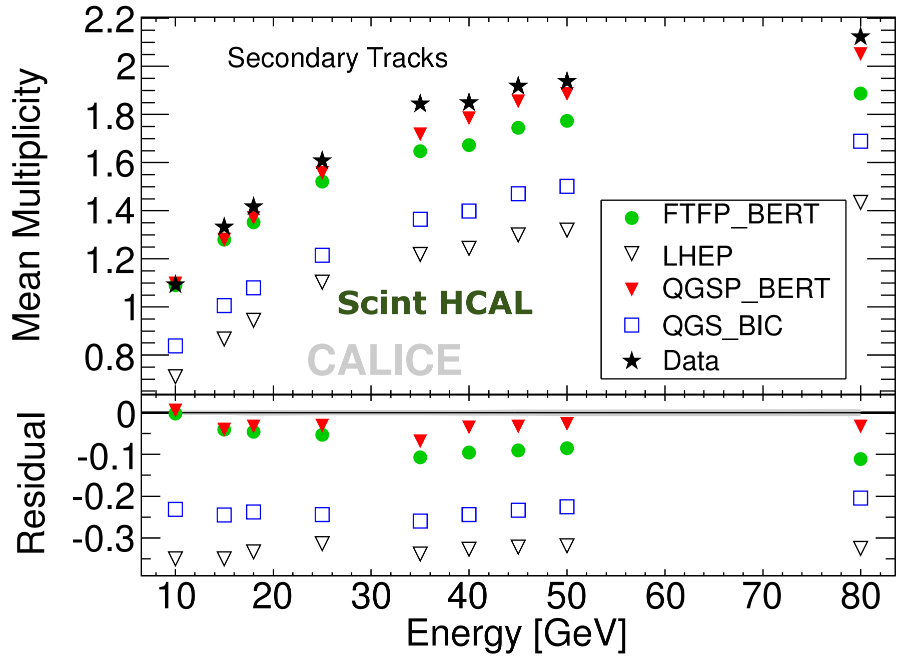




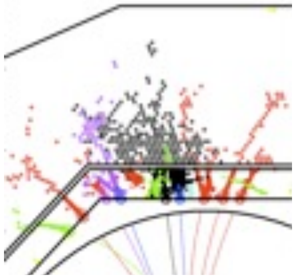


Shower fine structure





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



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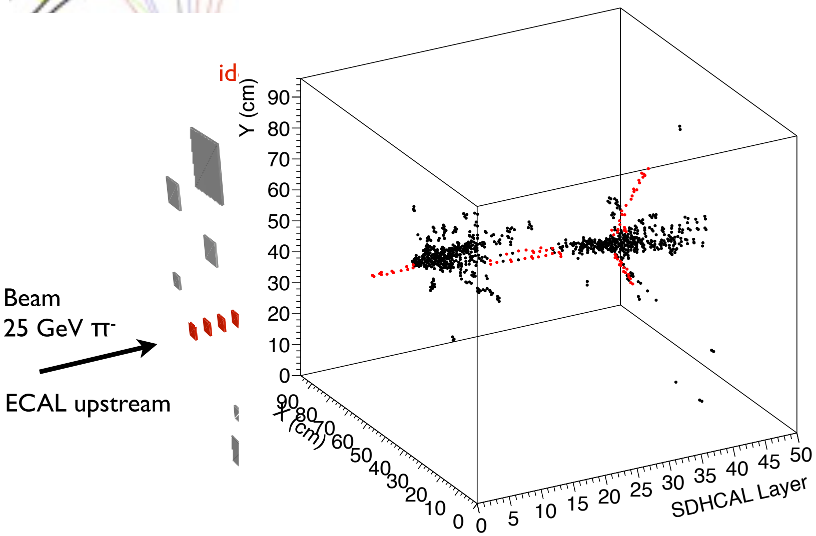

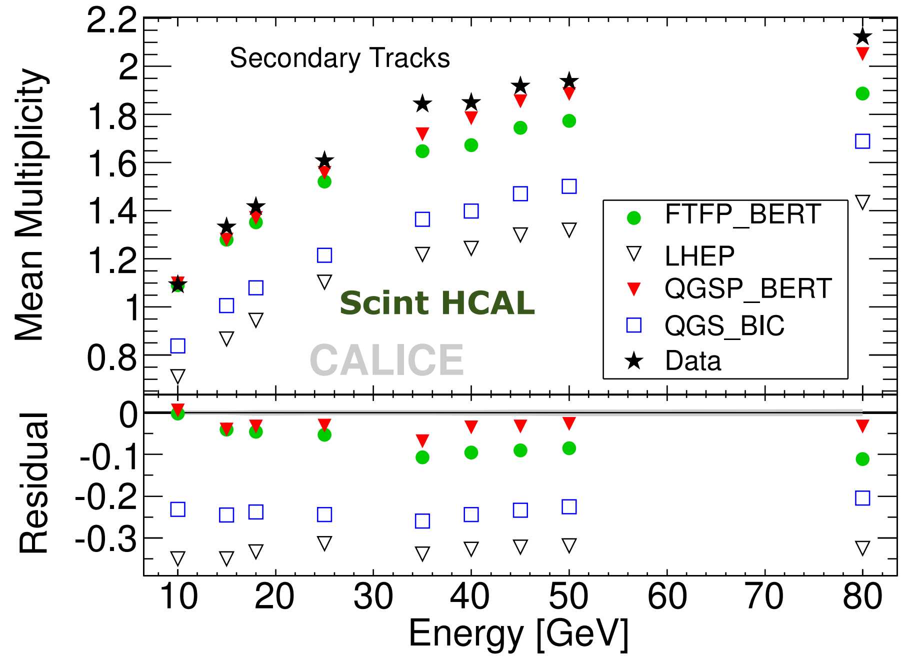

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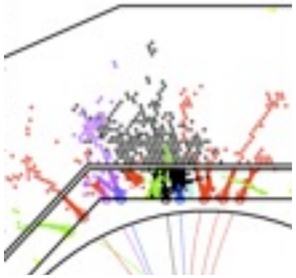

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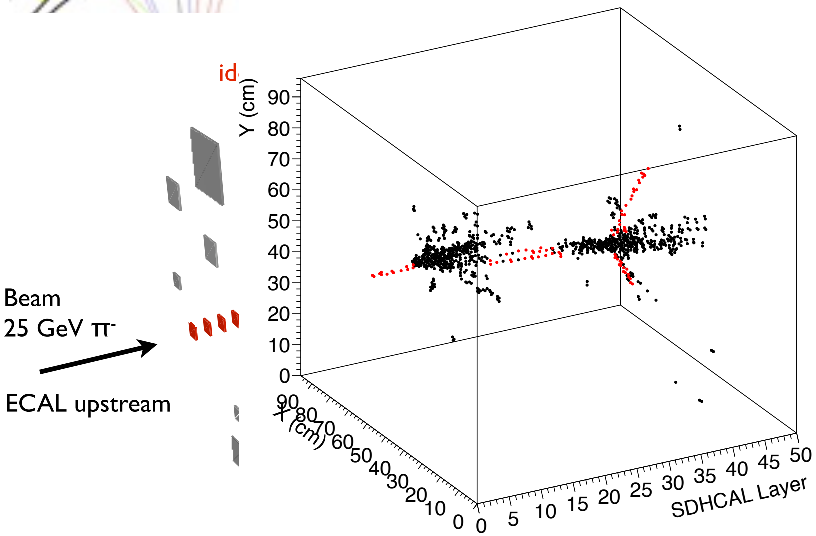

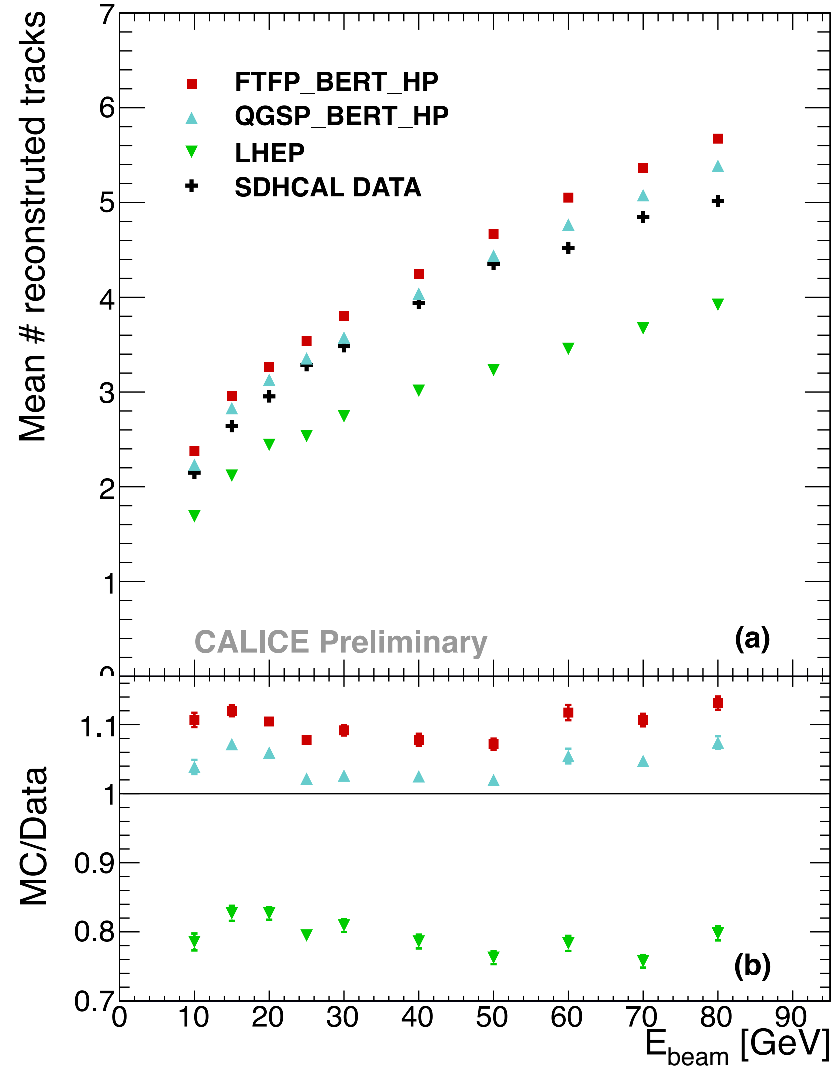

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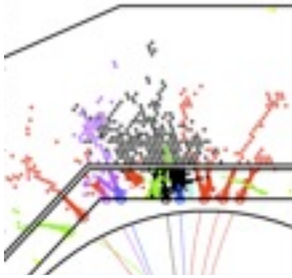
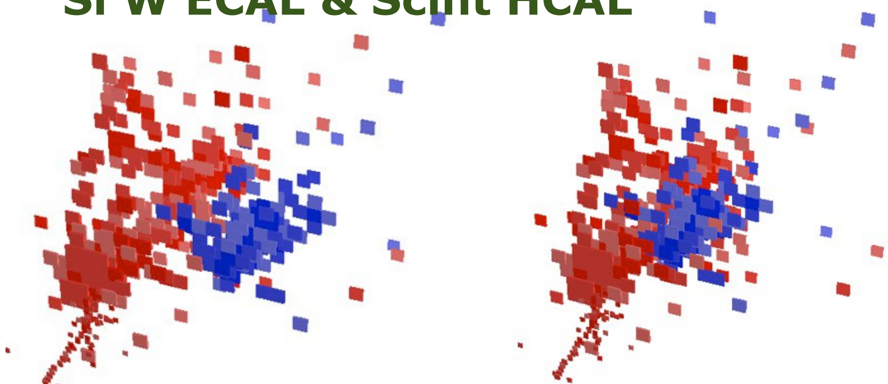


PFLOW with test beam data

Si W ECAL & Scint HCAL

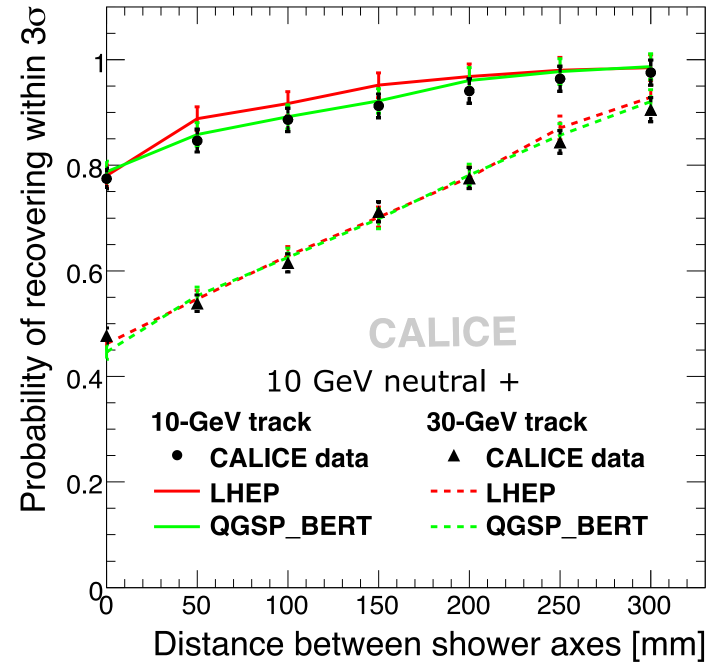


~18 cm separation of shower

~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
- Study degradation if second particle comes closer
- Important: agreement data - simulation

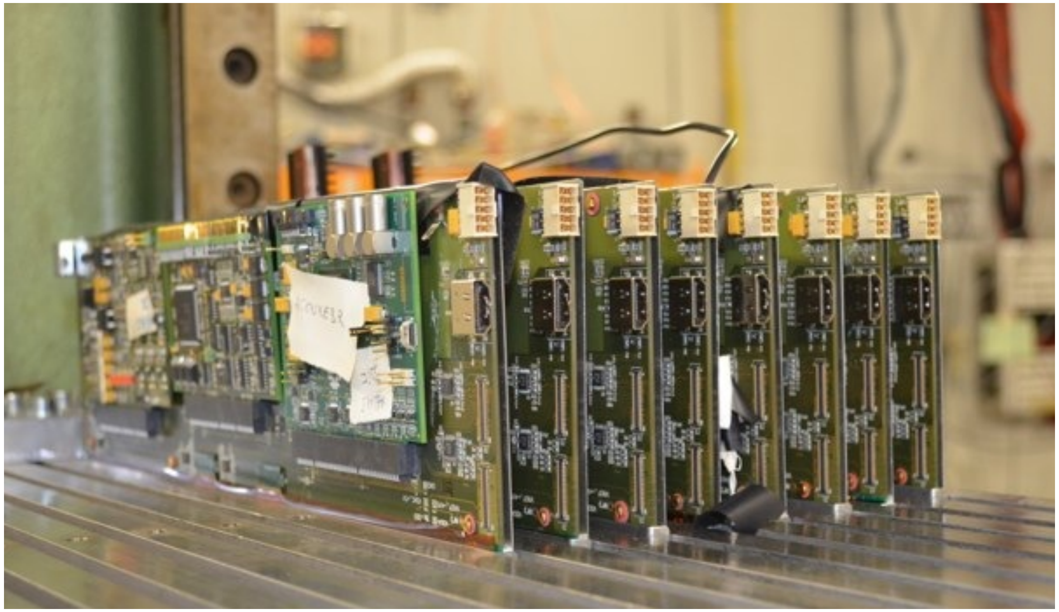
JINST 6 (2011) P07005

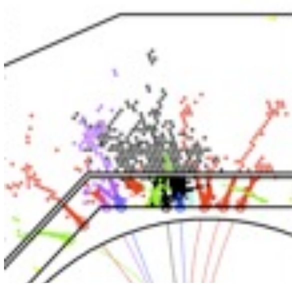
What we learnt

- 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.
  - No time to show plethora or results, e.g. on time structure, or W
- Shower substructure can be resolved and is also reproduced by shower simulations.
- Particle flow algorithms are validated with test beam data.

Frontiers & trends

(a personal view)

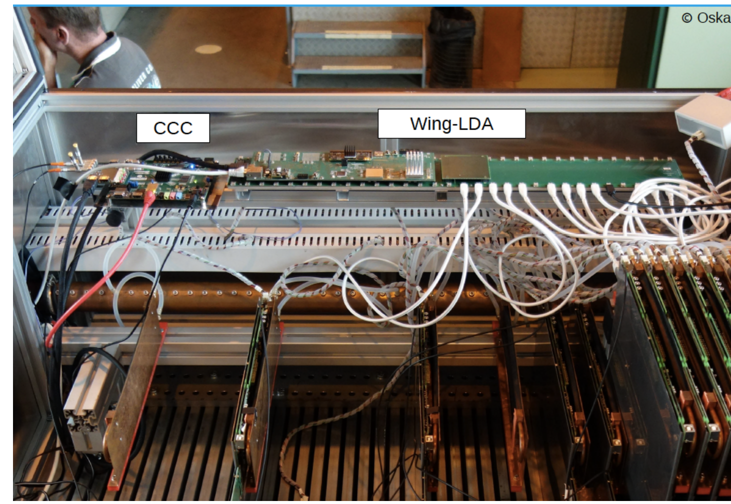




Frontiers

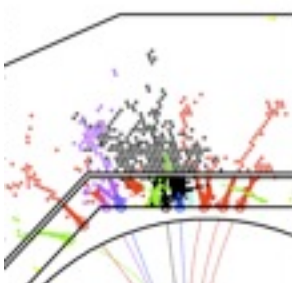
- Technology frontier
  - 10 years progress in SiMs
  - 1 glass RPCs, THGEMs, resistive μMs
- Integration frontier
  - electronics integration, low power
  - scalable solutions for DAQ and services →
- Industrialisation frontier
  - design simplifications
  - mass production and QA schemes
- Calibration frontier
  - monitoring and correction procedures
- Simulation frontier
  - model μ, e, π showers in gaseous HCAL: low and high density
- Reconstruction frontier
  - threshold weights, software compensation
- Algorithm frontier
  - understand relative importance of active medium, granularity and r/o scheme
  - develop second, independent algorithm
- Hadron collider frontier
  - ...

This conference



will read 2 segments. 96 layers, 250k channels

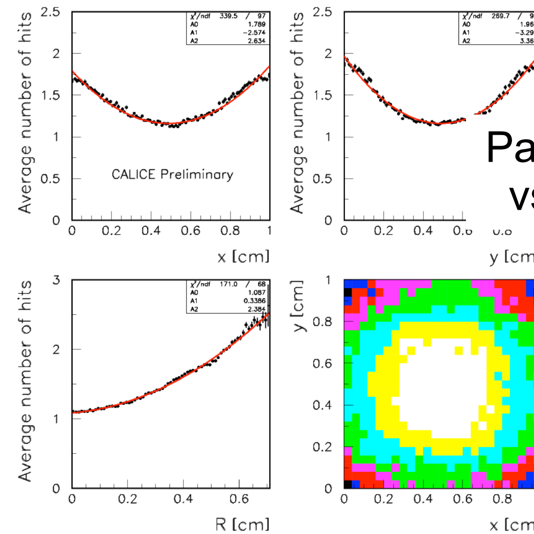
Calorimetric issues



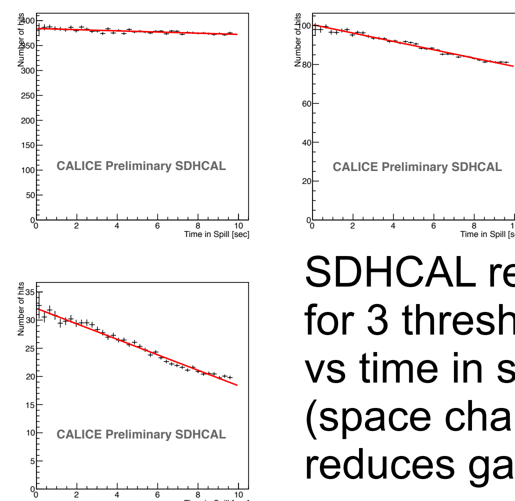
Calibration frontier

- Main difficulty is that the DHCAL is not digital
- Response in number of hits depends on gas gain and thus on many factors
  - T, p, thickness, purity, rate, local occupancy
  - calibration & monitoring not simple
- May be mitigated for other technologies with <m> ~ 1.0
  - μM, GEM, 1-glass RPC
  - to be seen
- Semi-digital readout helps
  - but environmental dependence aggravated for higher thresholds
- For the use of analoge information the (semi-) digital read-out lacks redundancy for calibration & monitoring
  - concepts to be developed

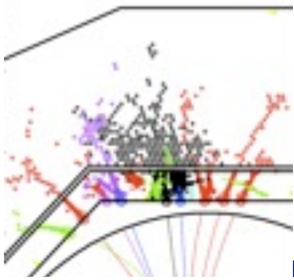
Data



Pad multiplicity vs μ position

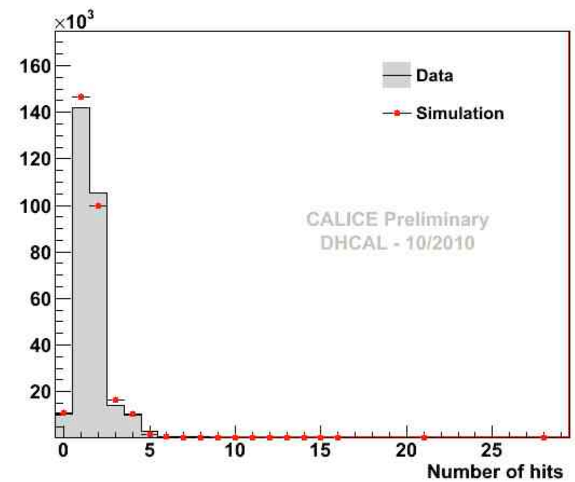


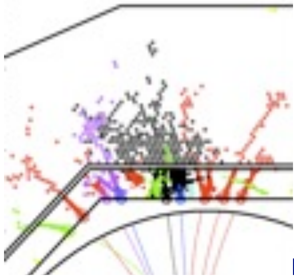
SDHCAL response for 3 thresholds vs time in spill (space charge reduces gain)



Simulation frontier

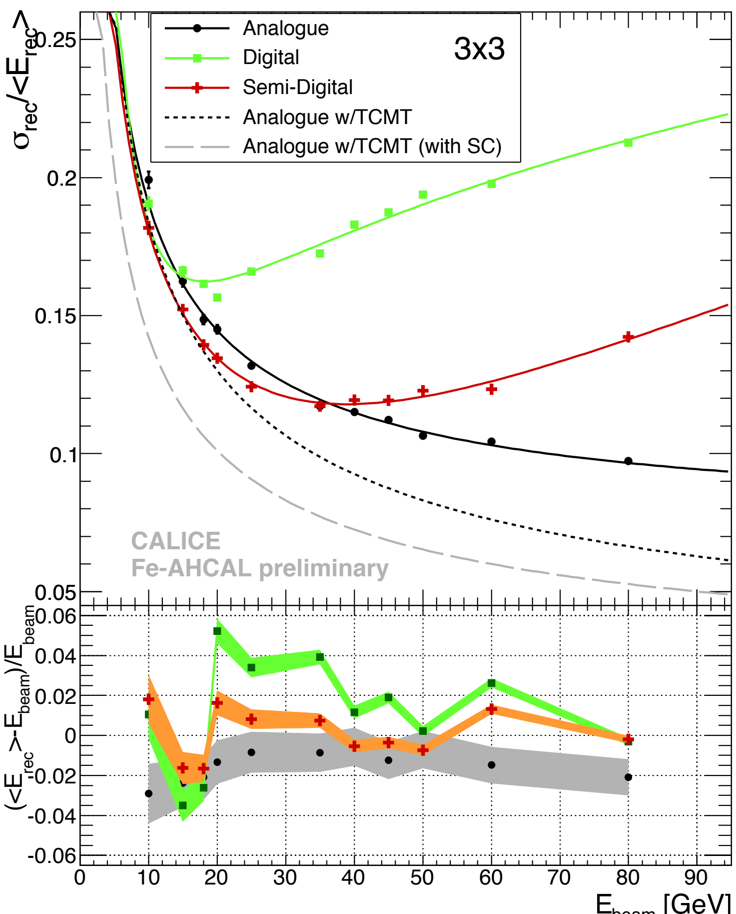
- For silicon and scintillator, simulation parameters are obtained from MIP response (amplitude and width)
  - gives absolute prediction for showers
  - electrons to validate detector model, hadrons to validate shower physics model
- For gaseous detectors: the same in case of isolated particles
  - response $N_{hit} = \Sigma_i$ (efficiency · multiplicity)$_i$
- Additional effects at high particle density need to be accounted for
  - e.g. RPC blind for 2nd particle in avalanche of 1st
  - use cut-off parameter, tune with electrons
  - difficult, few experimental constraints
- Results for simulations of electron and hadron showers still to come
  - on the way, stay tuned

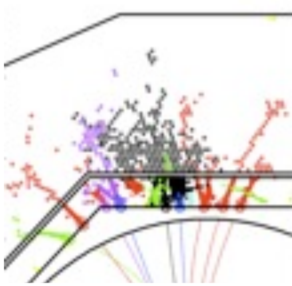




Reconstruction frontier

- Saint and gas prototypes differ also in cell size and read-out scheme
- All of them affect single hadron and jet energy resolution
- Disentangle with validated simulations, and optimise, incl. s/w comp





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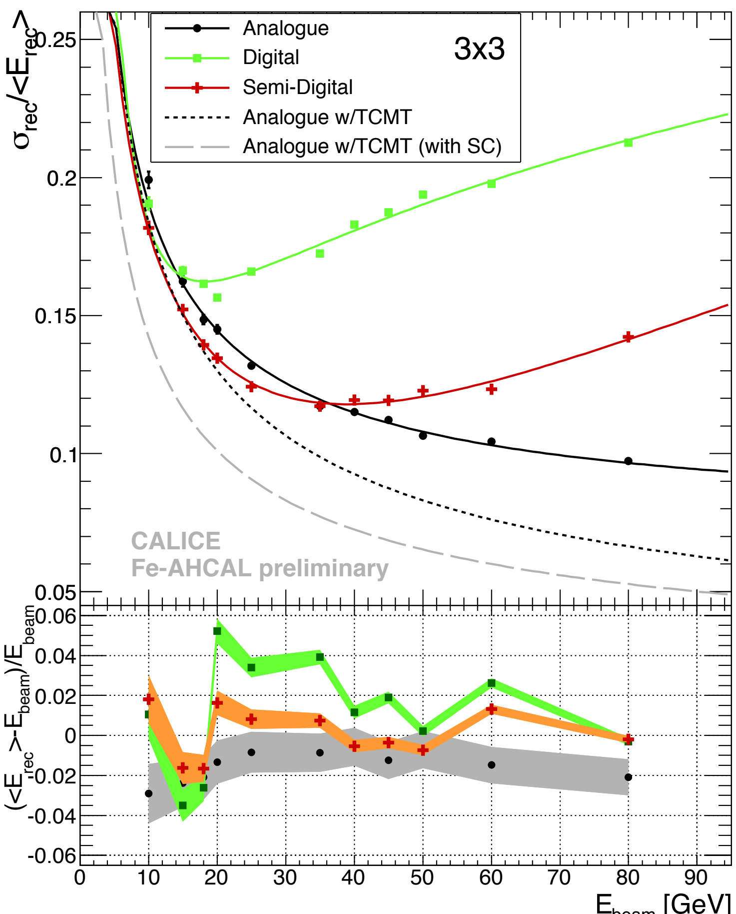

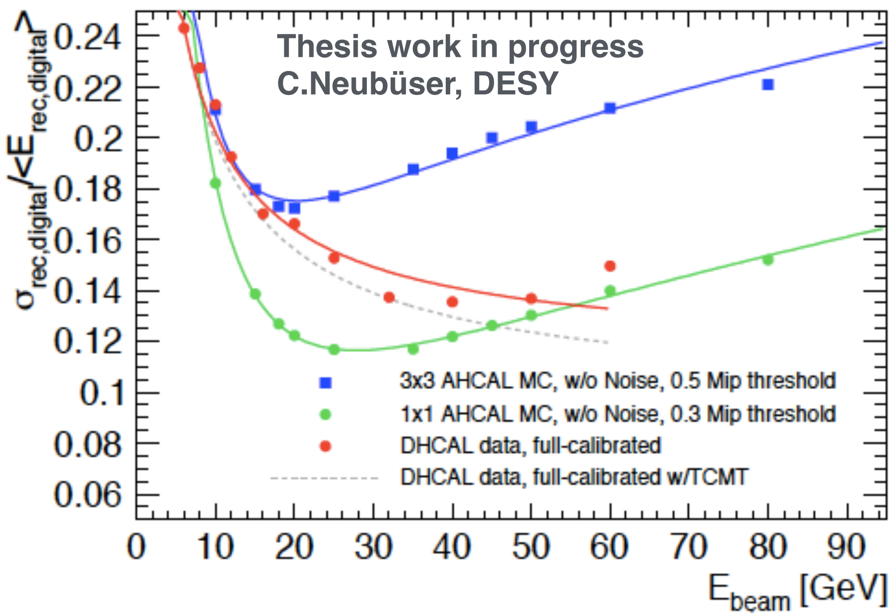

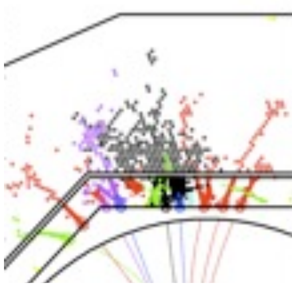

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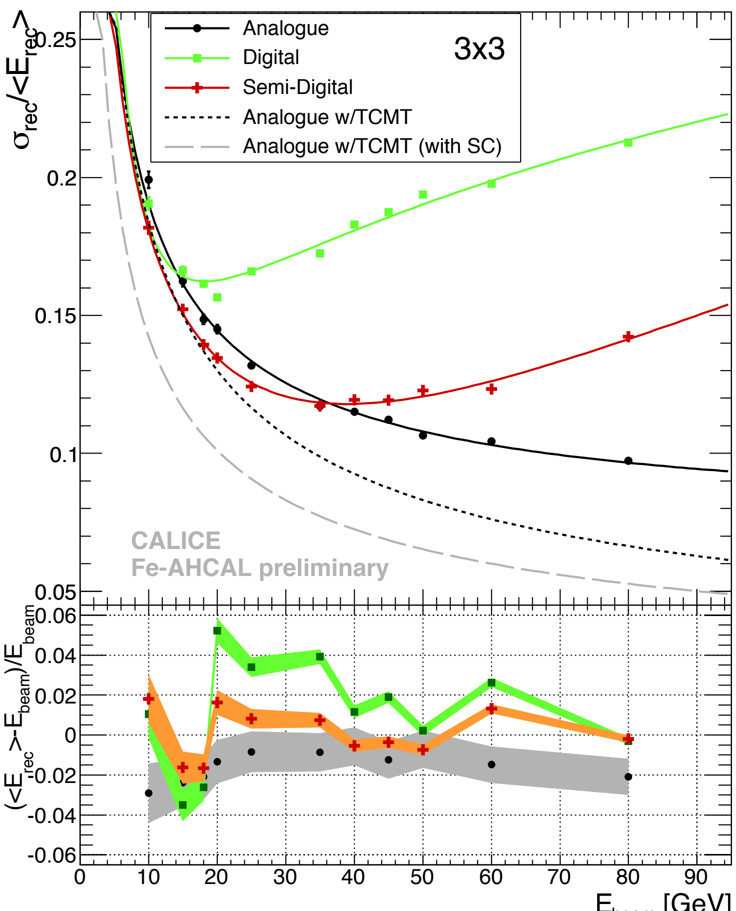
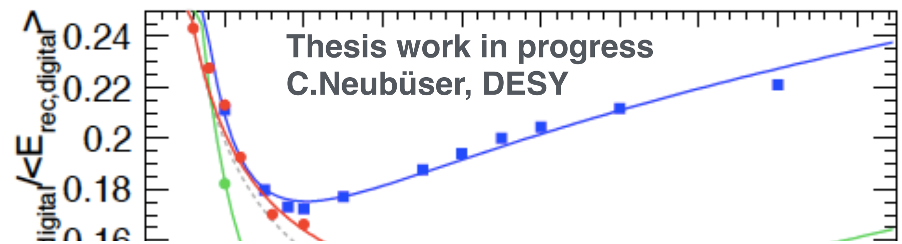
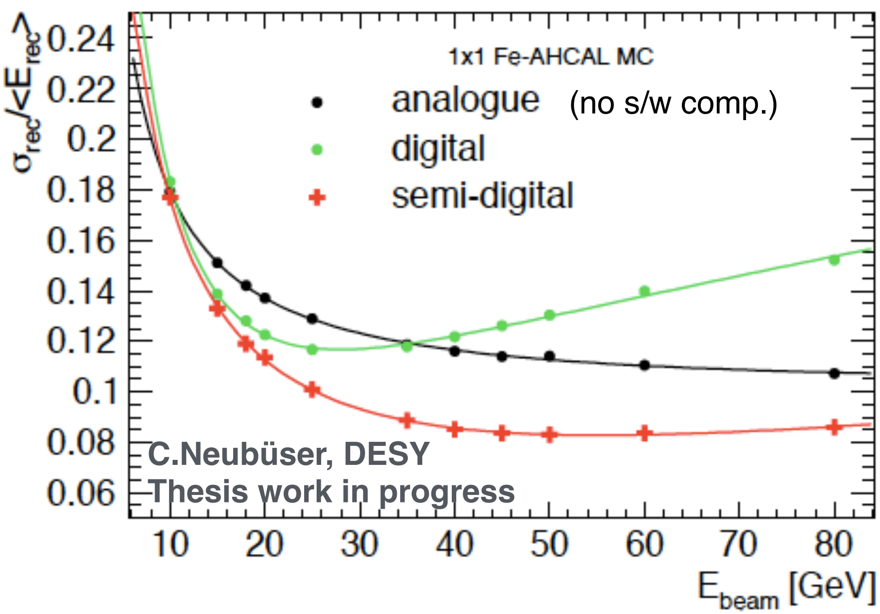
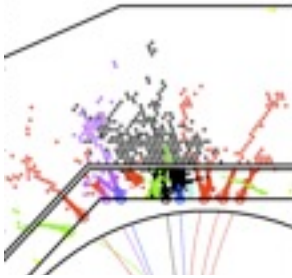


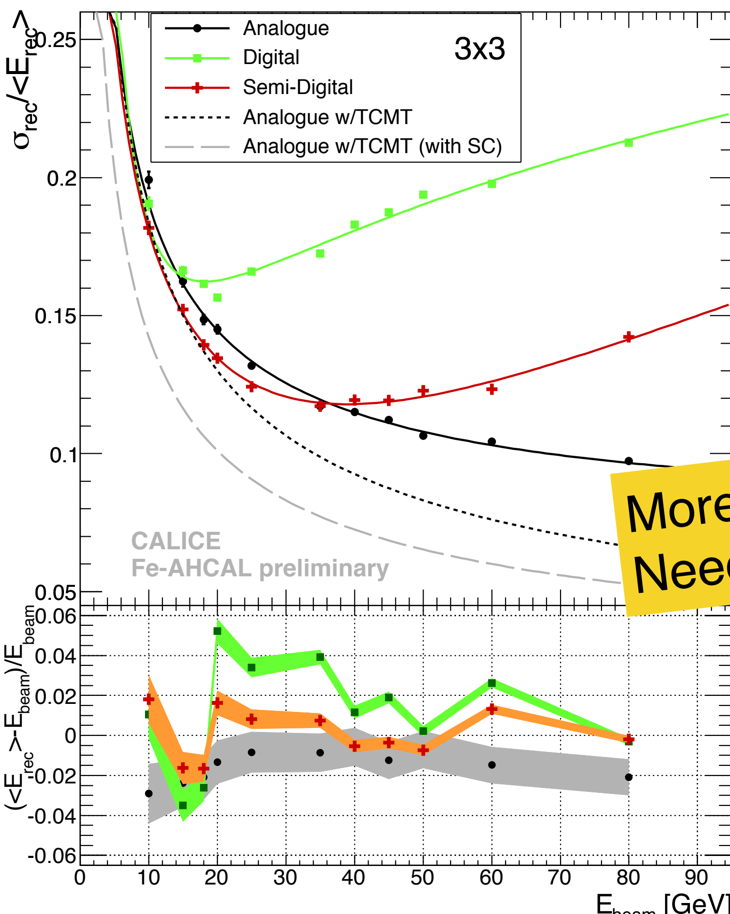


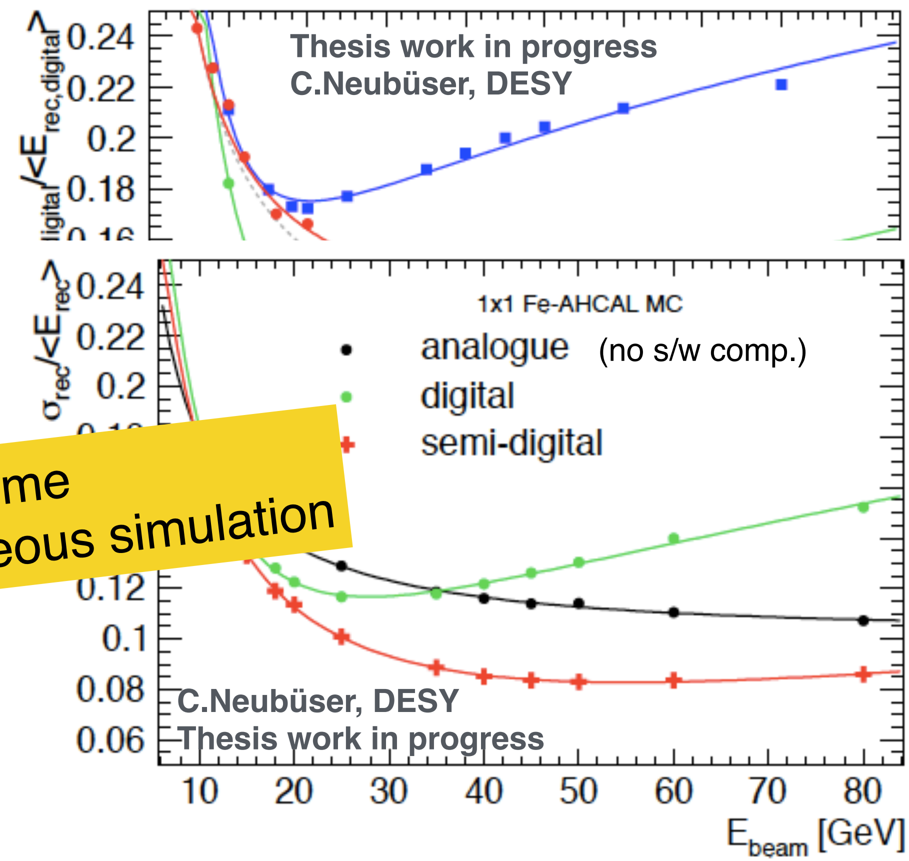




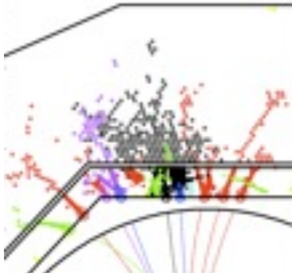
Reconstruction frontier

- Saint and gas prototypes differ also in cell size and read-out scheme
- All of them affect single hadron and jet energy resolution
- Disentangle with validated simulations, and optimise, incl. s/w comp



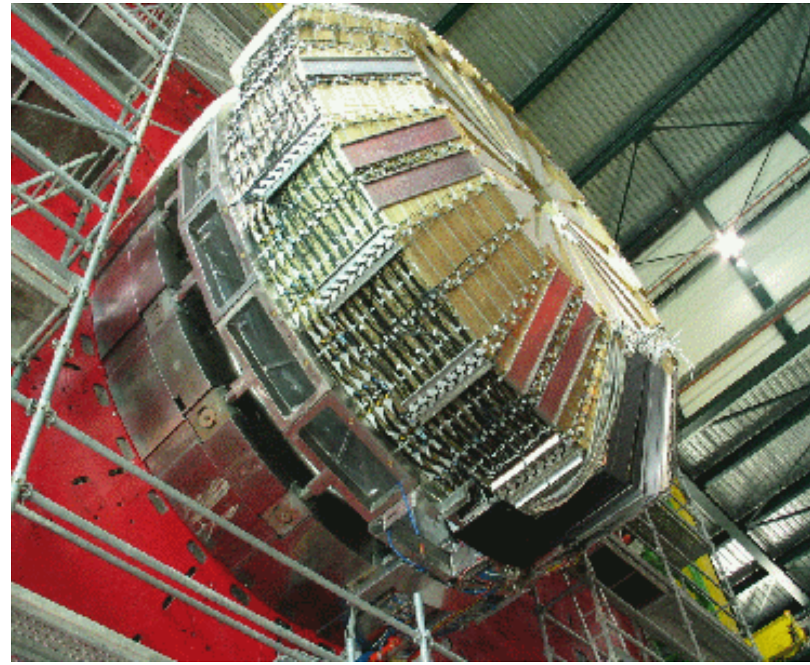


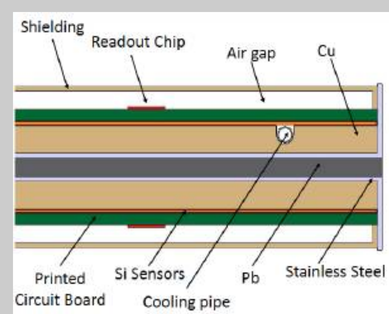
More to come
Need gaseous simulation

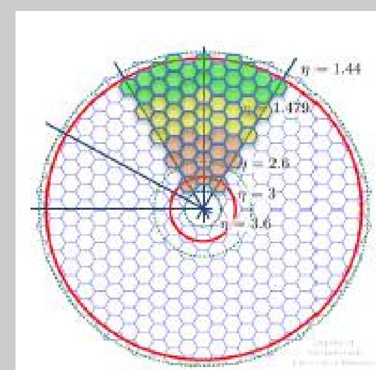


Hadron collider frontier

- 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
  - 600 m^2 of Si, 0.5 - 1 cm^2
  - Backing: 5 λ brass, scint or gas
- particle ID, pile-up subtraction, …, particle flow
- Much more challenging than e+e-
  - radiation hardness
  - cooling of sensors
  - rate capability of electronics
  - no power pulsing







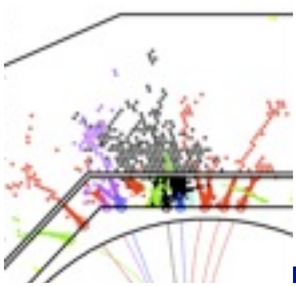
Conclusion

- Calorimetry has changed - particle flow concept established experimentally
- Bearing fruit beyond LC community
- Now fully in second phase: make it realistic
- There are many open issues = room for new ideas
- MPGDs are (at) the frontier

Thank you for your attention!

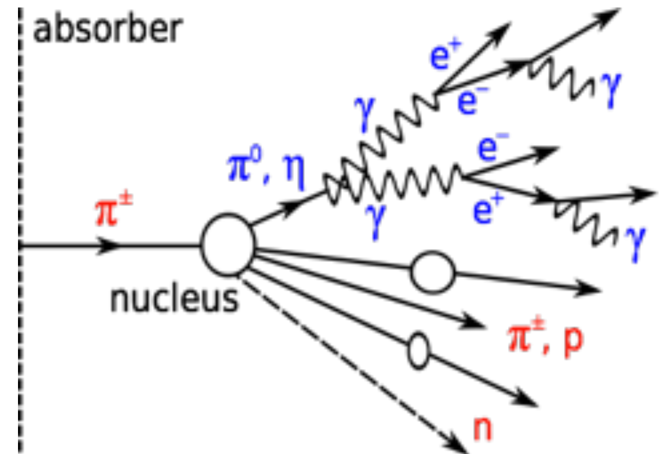
Back-up slides

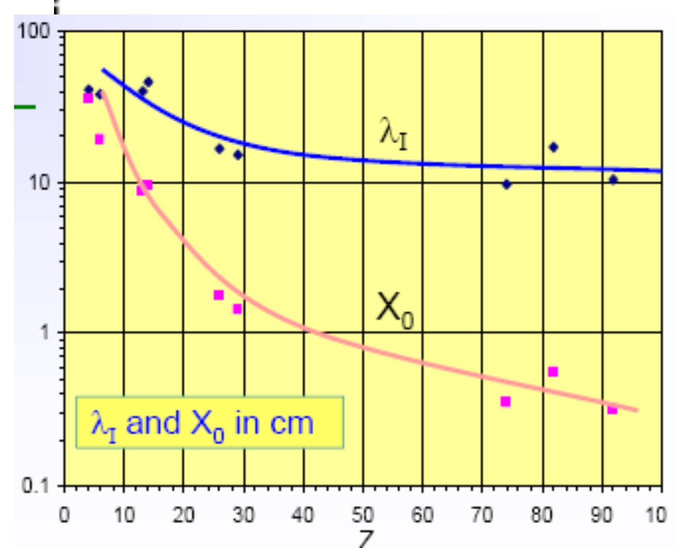
Recall some basics

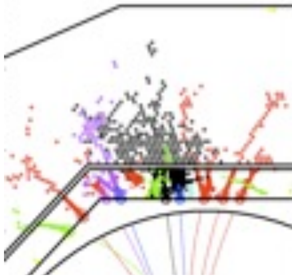


Hadron showers

- 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

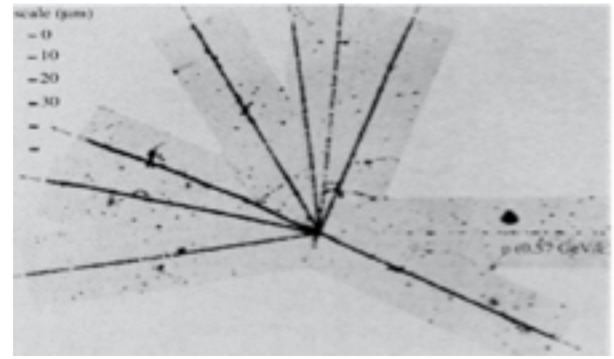




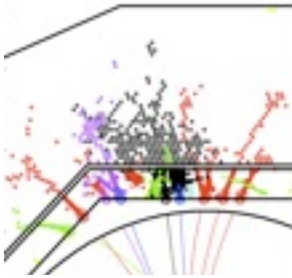


Hadronic interactions

- 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

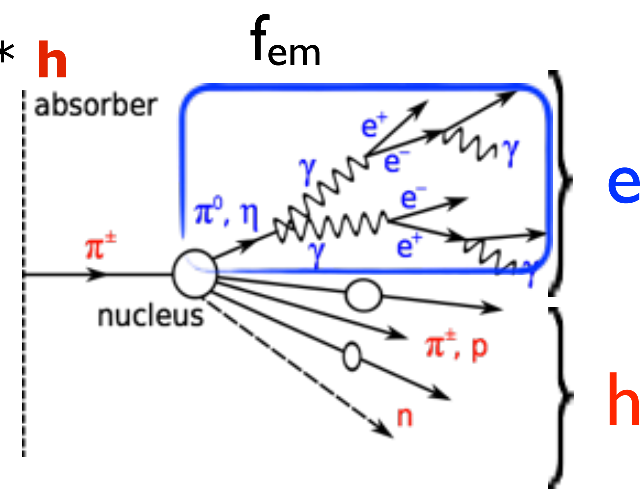


- The response to the hadronic part of a hadron-induced shower is usually smaller than that to the electromagnetic part: **h ≠ e**
  - Due to the invisible energy
  - Due to the short range of spallation nucleons
  - Due to saturation effects for slow, highly ionizing particles

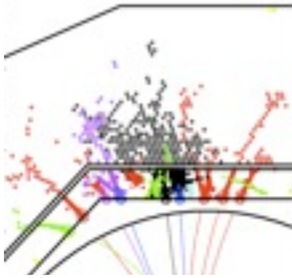


Electromagnetic fraction

- 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**



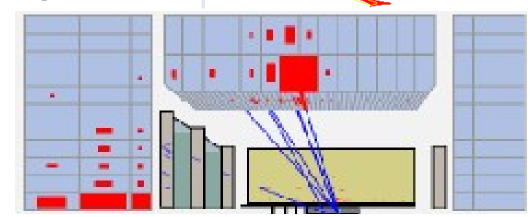
- Numerical example for copper
  - 10 GeV: f = 0.38; 9 charged h, 3 π^0
  - 100 GeV: f = 0.59; 58 charged h, 19 π^0
  - Cf em shower: 100's e^+, 1000's e^-, millions γ
- Large fluctuations
  - E.g. charge exchange $\pi^- p \rightarrow \pi^0 n$ (prb 1%) gives f_{em} = 100%

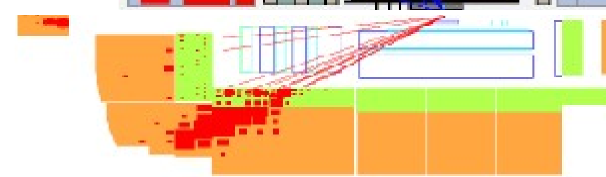


Compensation

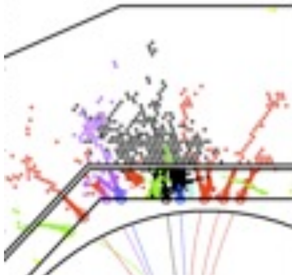
Different strategies, which can also be combined

- 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

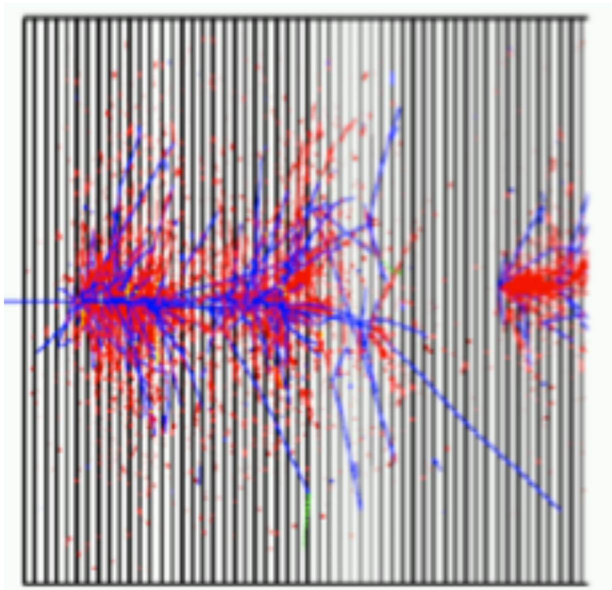




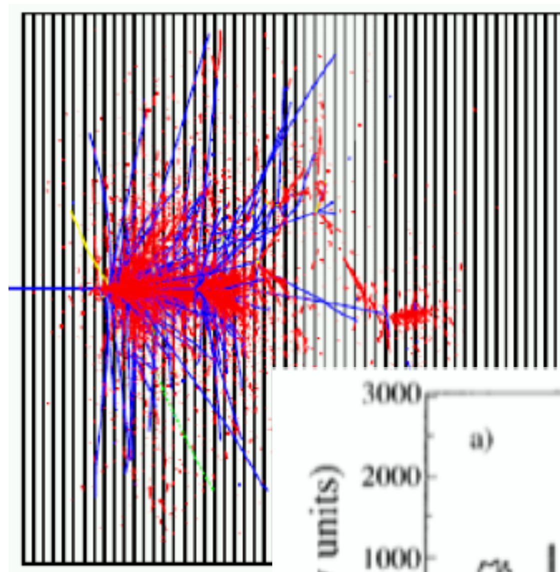
NB: Does not remove fluctuations in invisible energy



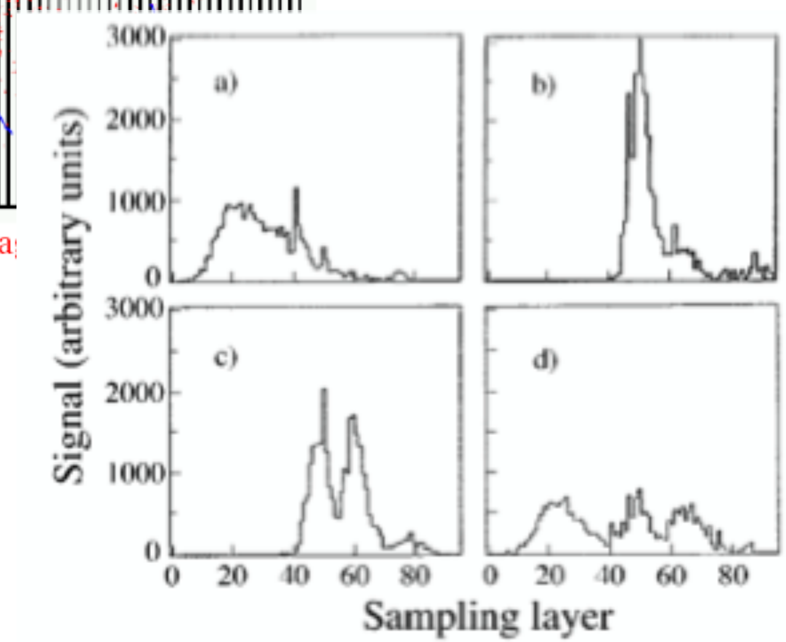
More fluctuations: leakage



blue = hadronic component

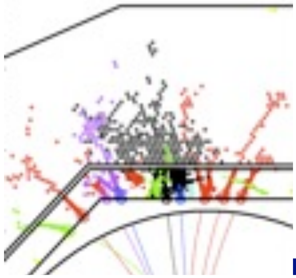


red = electroma



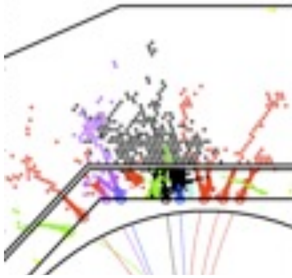
Leakage: in principle no problem
But: leakage fluctuations are!
(rule of thumb: $\sigma_{leak} \sim 4\ f_{leak}$)

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



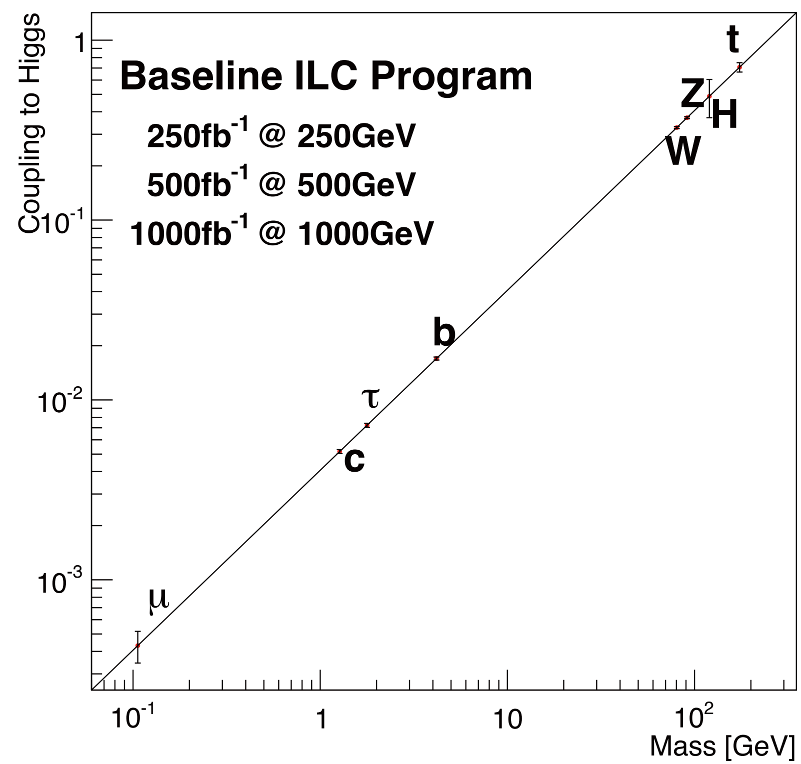
Higgs physics drives the field

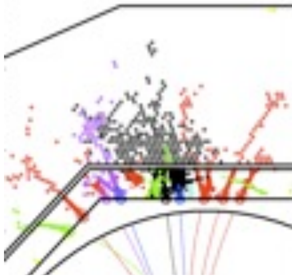
"Driver" = a compelling line of inquiry that shows great promise for major progress over the next 10-20 years. Each has the potential to be transformative. Expect surprises.

- Use the Higgs as a new tool for discovery.

S.Ritz, Report on P5

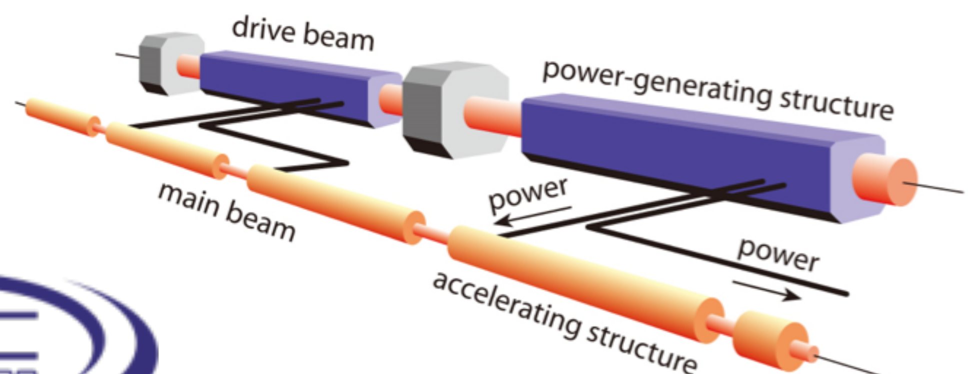
- The main question today:
- establish the Higgs profile
  - mass, spin, parity
  - above all: couplings
- Is the Higgs(125) *the* Higgs and does it fulfil its role in the Standard Model?
- Or does it hold the key to New Physics?





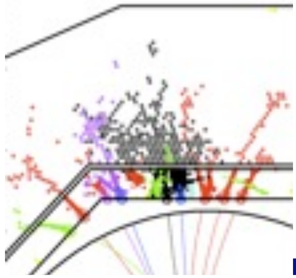
Future e^+e^- colliders

- 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

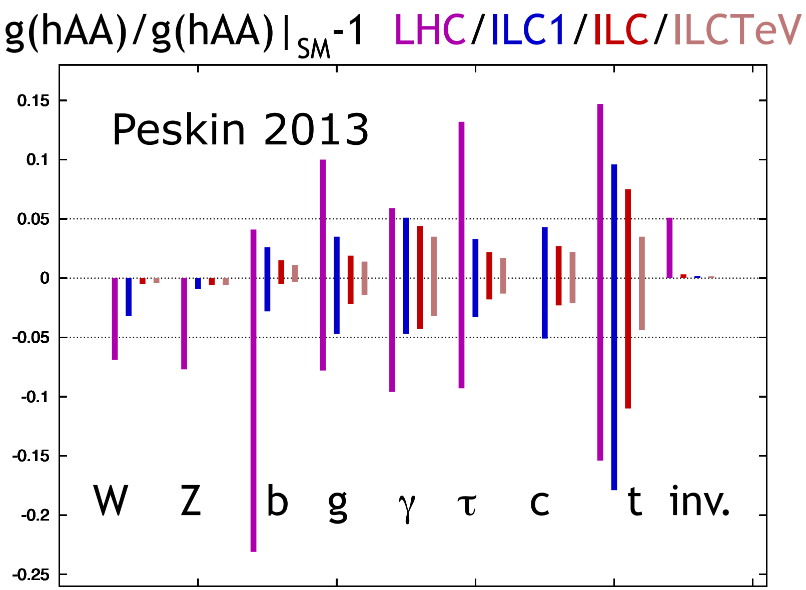


CEPC

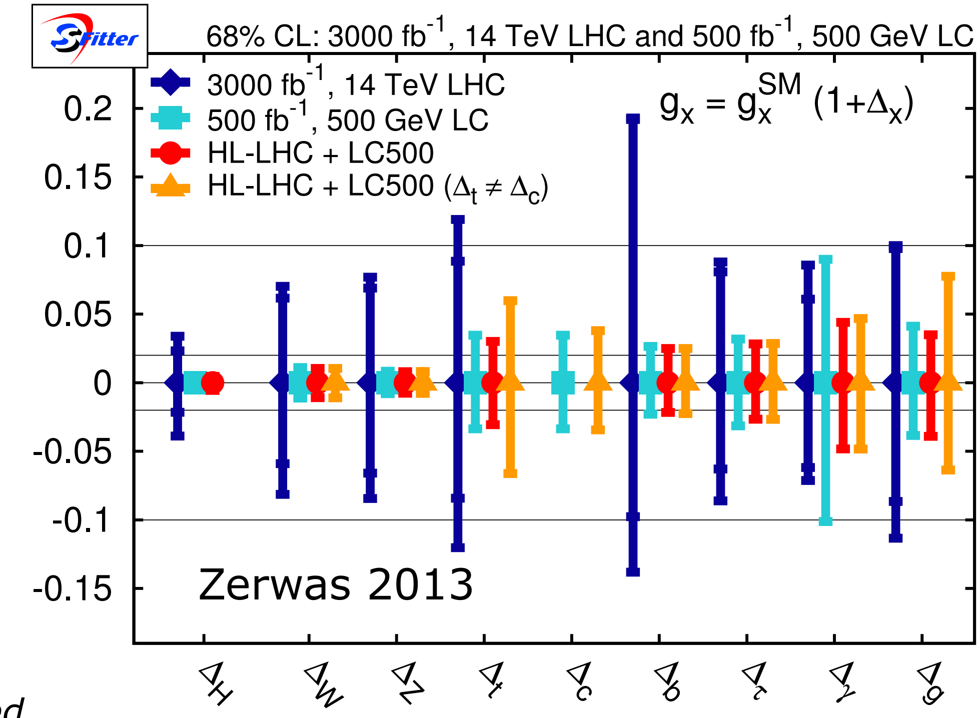
FCC hh ee he



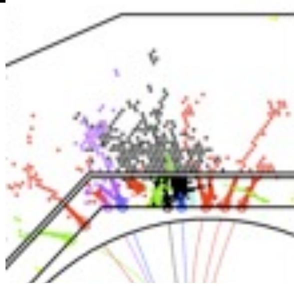
ILC and LHC



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*

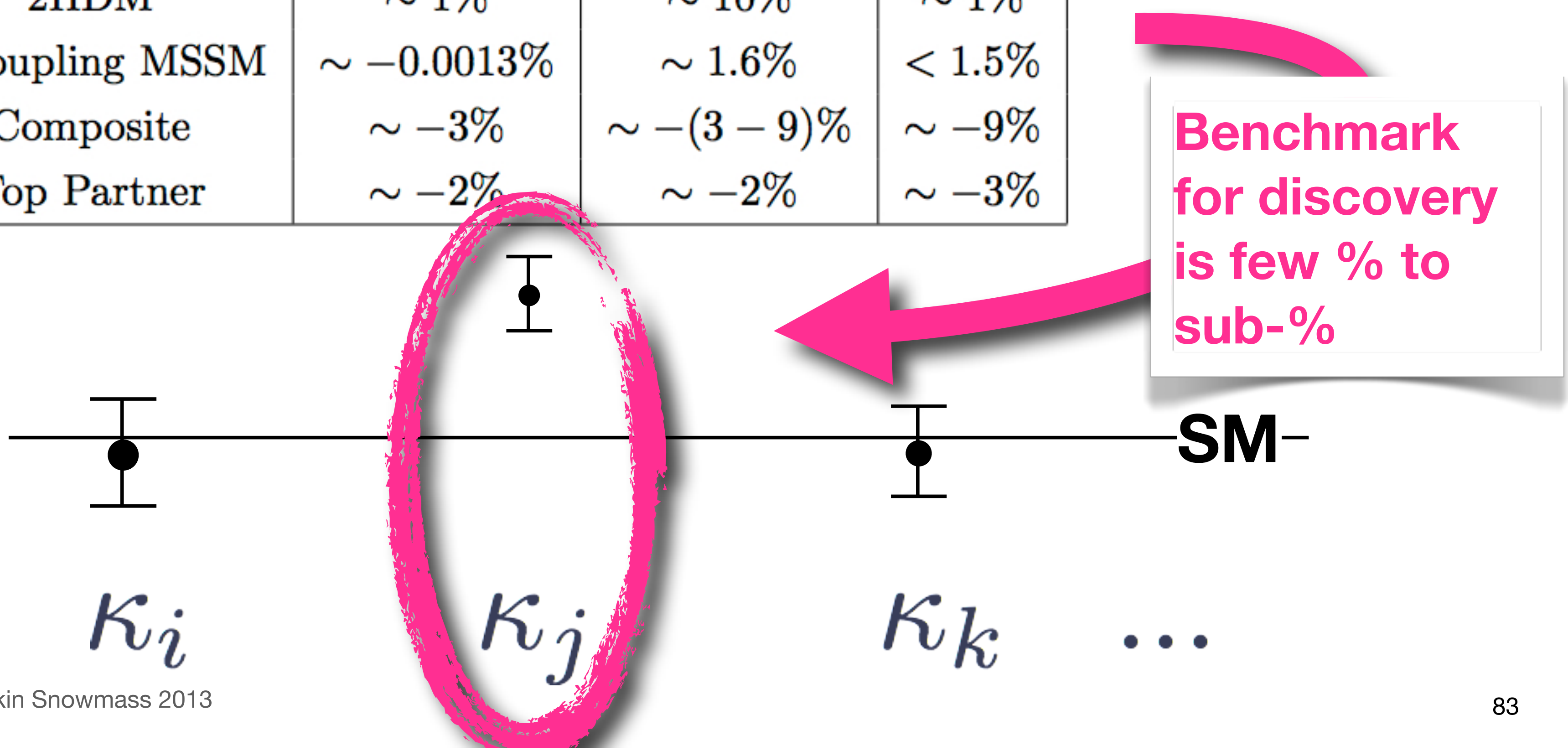


- Only with e+e- collisions one can reach the percent level precision to probe new physics
- also true w.r.t. high lumi LHC



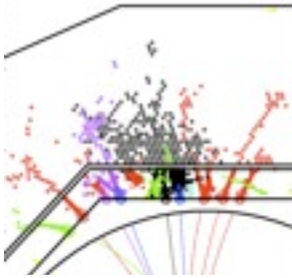
Precision for discovery

	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	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



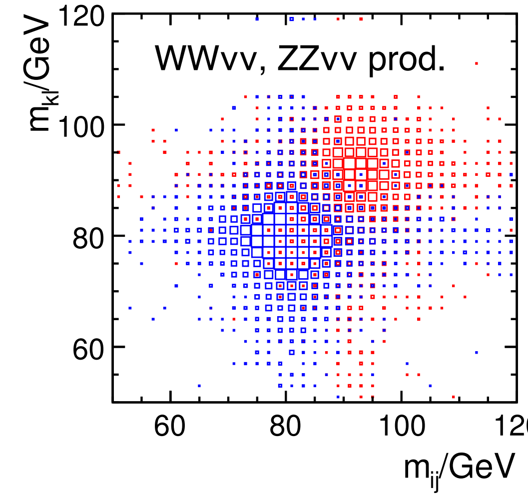
Brock/Peskin Snowmass 2013

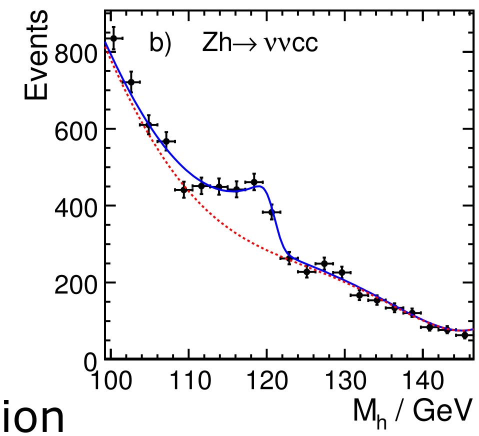
83

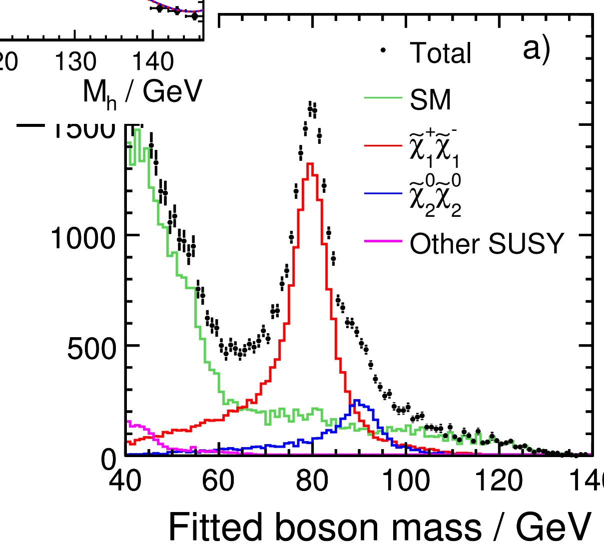


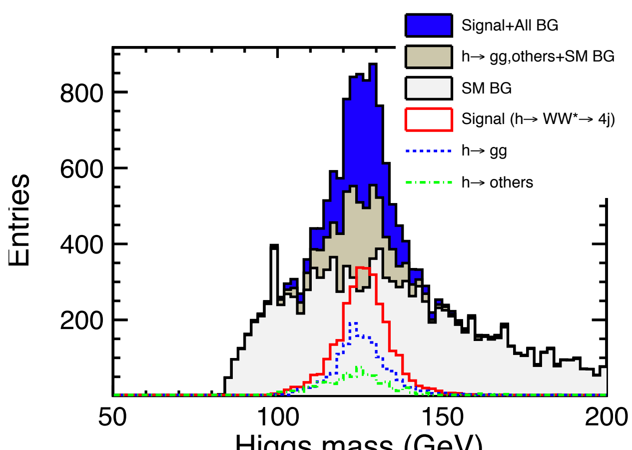
LC physics with jets: M_{inv}

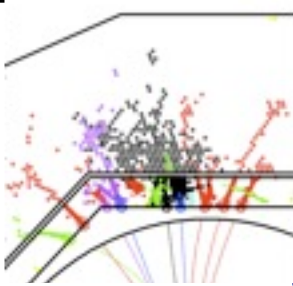
- W - Z separation
  - study strong e.w. symmetry breaking at 1 TeV
- Other di-jet mass examples
  - H → cc, Z → νν
  - Higgs recoil with Z → qq
  - invisible Higgs
  - WW fusion → H → WW
    - total width and g_{HWW}
- SUSY example:
  - Chargino neutralino separation





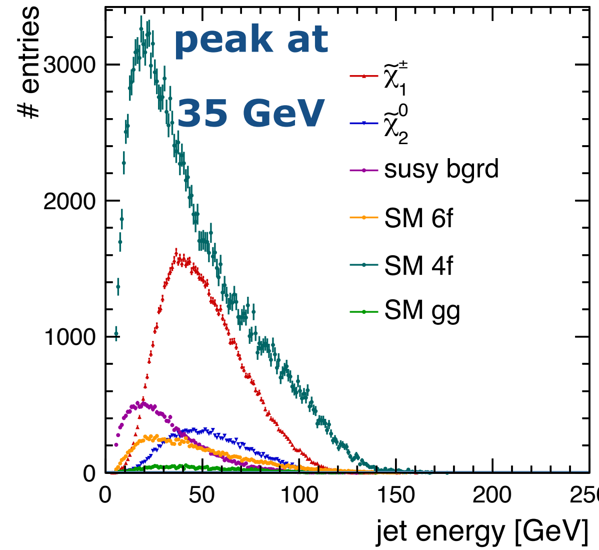




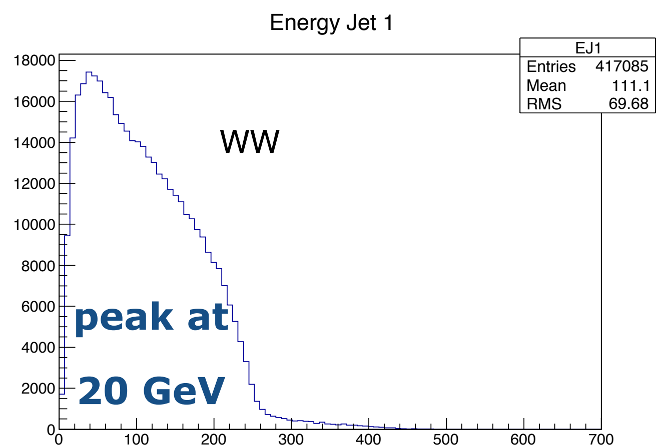


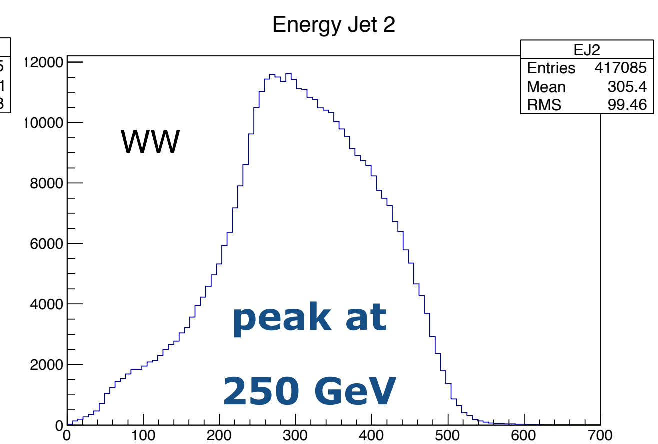
Jet energies

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

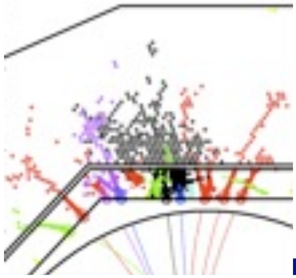


- At $\sqrt{s}$ = 500 GeV
- example chargino, neutralino → qq + invis.
- At $\sqrt{s}$ = 1 TeV
- example WW→H → WW → lνqq





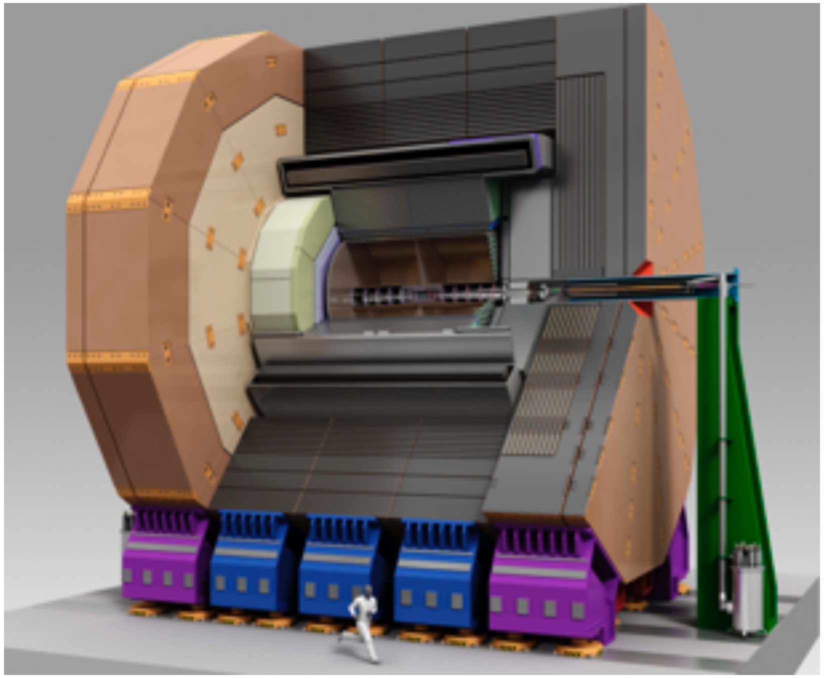
plots:
J.List, M.Chera, A.Rosca
DESY



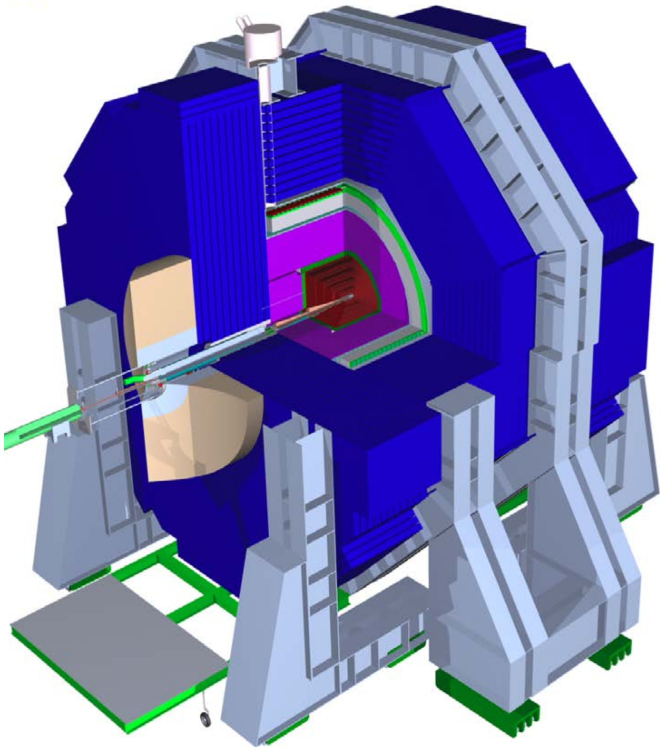
Particle flow detectors

- 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

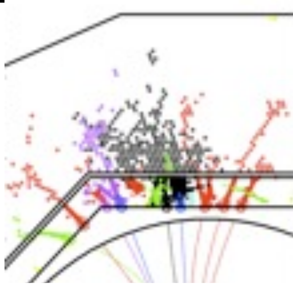
ILD: large TPC, B=3.5T, PFLOW calo



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

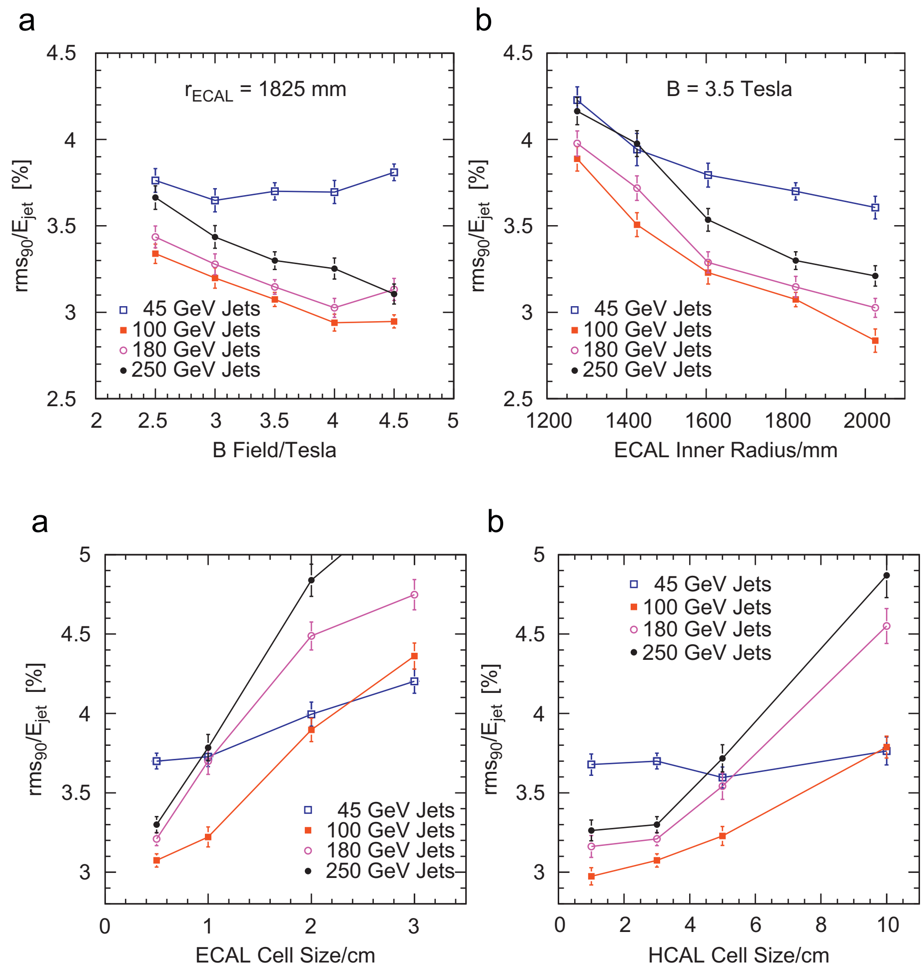


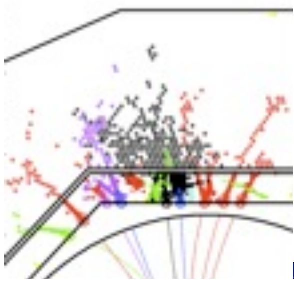
CLIC:
tungsten
barrel HCAL
considered



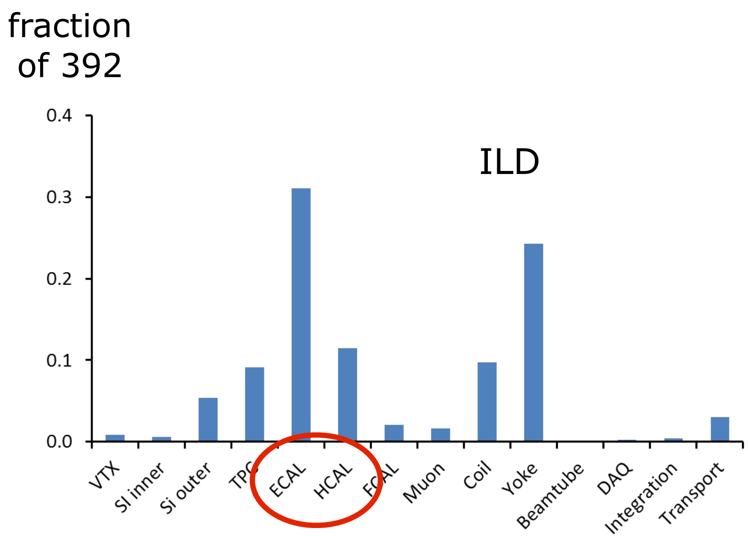
Granularity optimisation

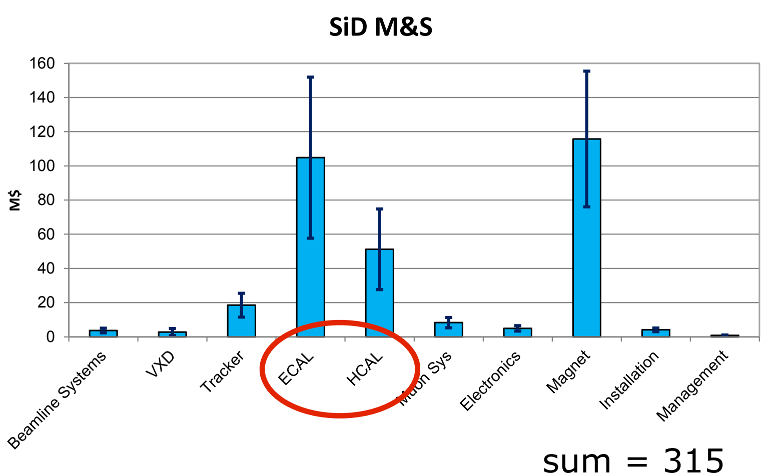
- Based of Pandora PFA
- Large radius and B field drive the cost
- Both ECAL and HCAL segmentation of the order of X_0
  - longitudinal: resolution
  - transverse: separation
- Cost optimisation to be done



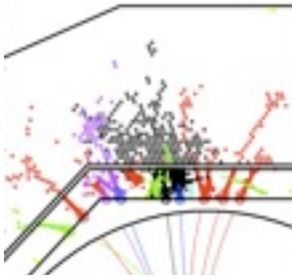


Calorimeter cost



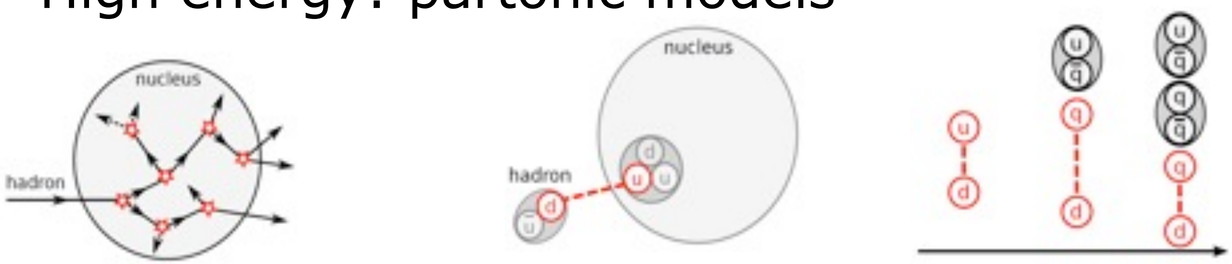


- Costing is at a very early stage
- Yet, many lessons learnt from 2nd generation prototypes
- Example HCAL:
- example ILD scint HCAL: 45M
  - 10M fix, rest ~ volume
  - 10M absorber, rest ~ area (n_{Layer})
  - 16M PCB, scint, rest ~ channels
  - 10 M SiPMs and ASICs
- ECAL:
- main cost driver: silicon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

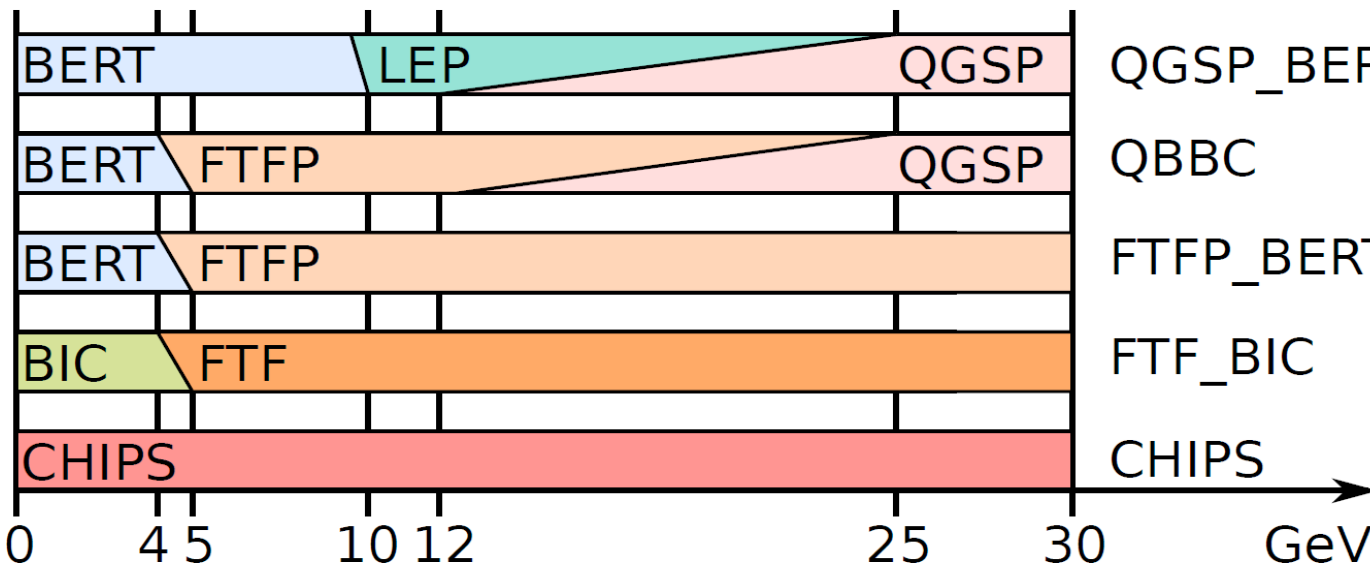


Shower simulation in Geant 4

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



minimize use of phenomenological parameterization



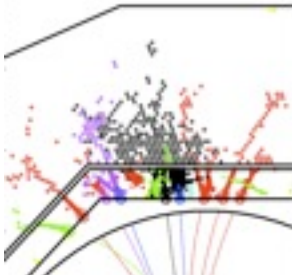
"legacy"

"linear combin."

"production"

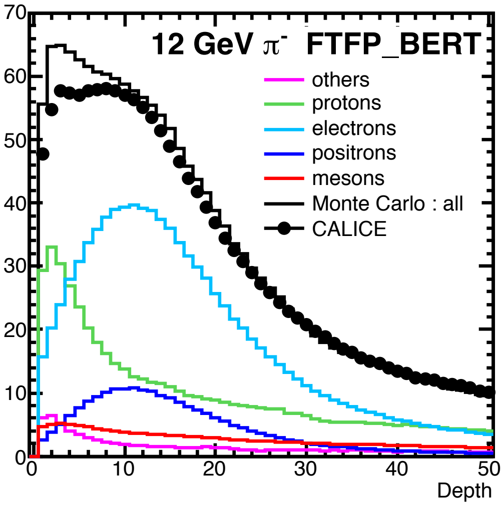
"systematics"

"experimental"



Validation of Geant 4 models

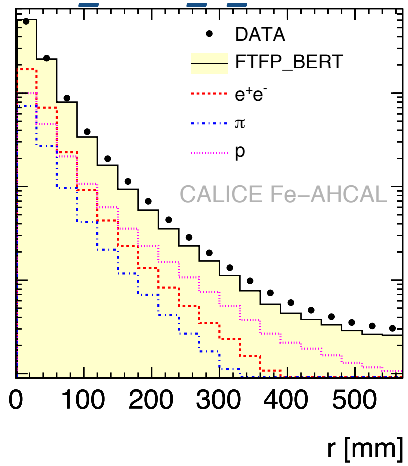
2010_JINST_5_P05007



SiW ECAL longit. profile

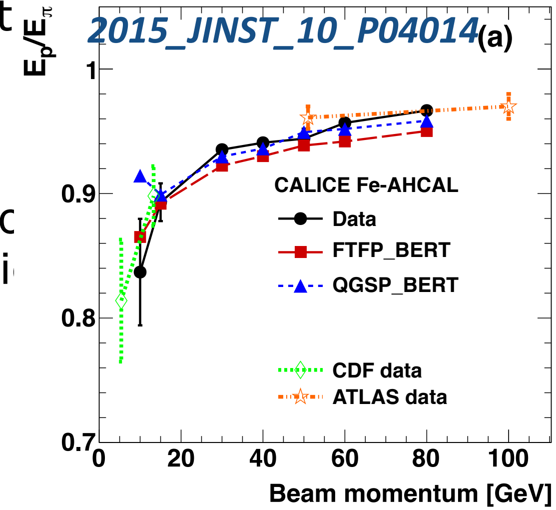
- just a few examples
- altogether at 5% or better

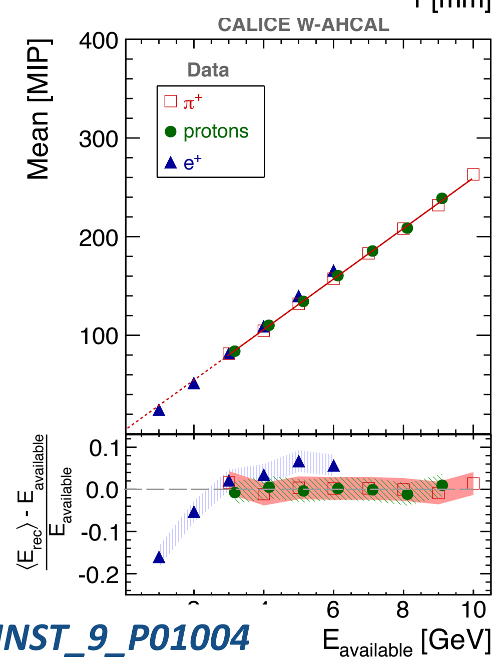
2013_JINST_8_P07005



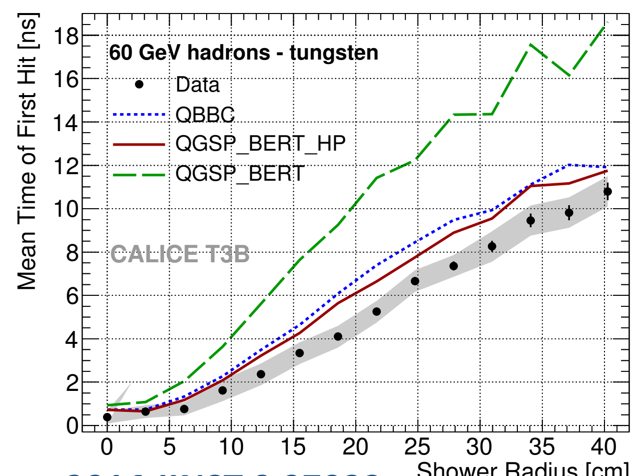
Fe Scint HCAL radial profile, roton pic 'esp. rati

2015_JINST_10_P04014





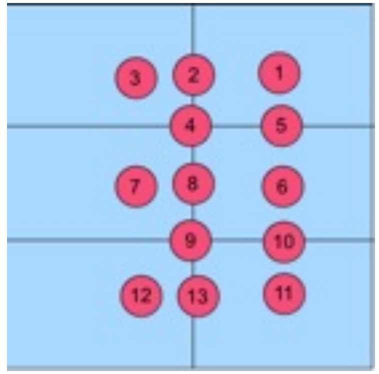
2014_JINST_9_P01004



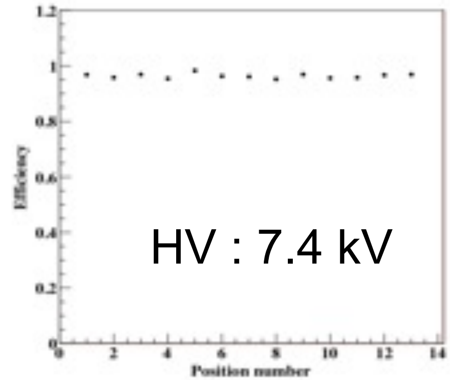
2014 JINST 9 07022

W Scint HCALresponse, timing

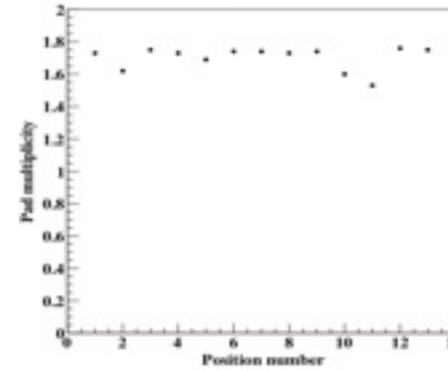
The homogeneity of the detector and its readout electronics were studied



Beam spot position



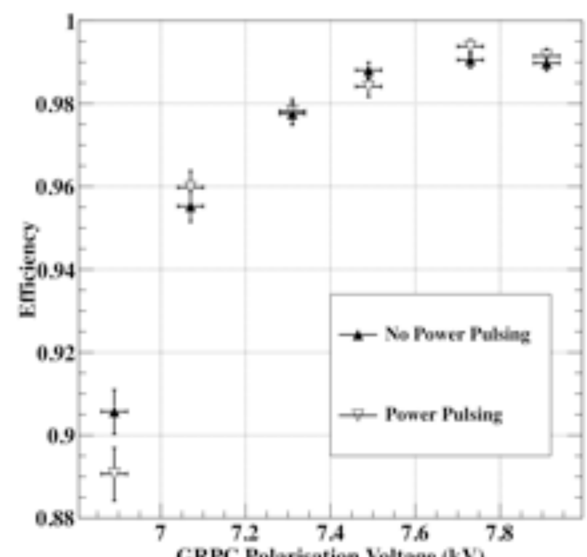
Efficiency



Multiplicity

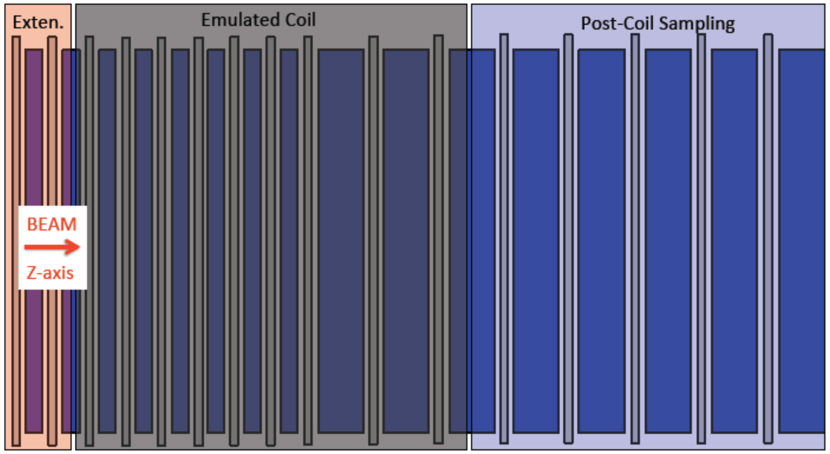
Power-Pulsing mode was tested in a magnetic field of 3 Tesla

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



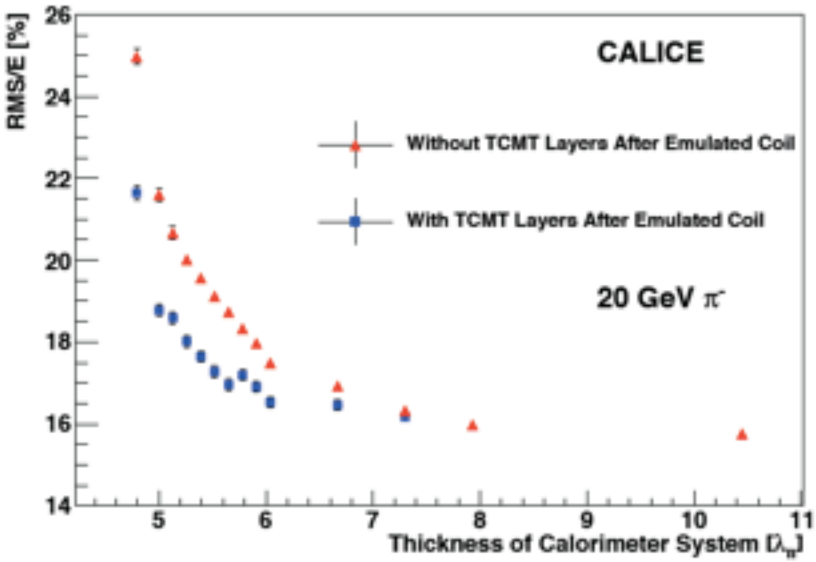
Containment – use of Tail Catcher

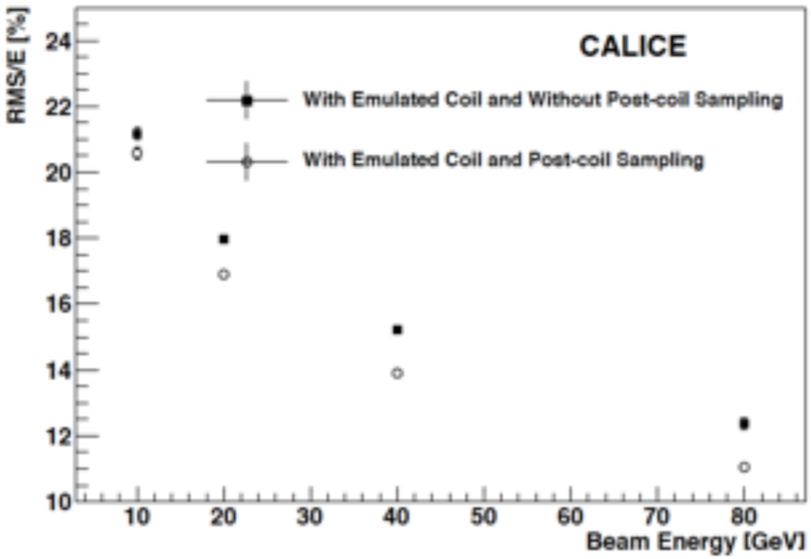
- Tail catcher gives us information about tails of hadronic showers.
- Use ECAL+HCAL+TCMT to emulate the effect of coil by omitting layers in software, assuming shower after coil can be sampled.
- Significant improvement in resolution, especially at higher energies.

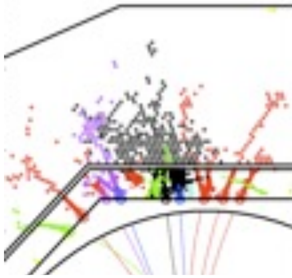


2012_JINST_7_P04015

arxiv:1201.1653 (accepted by JINST)

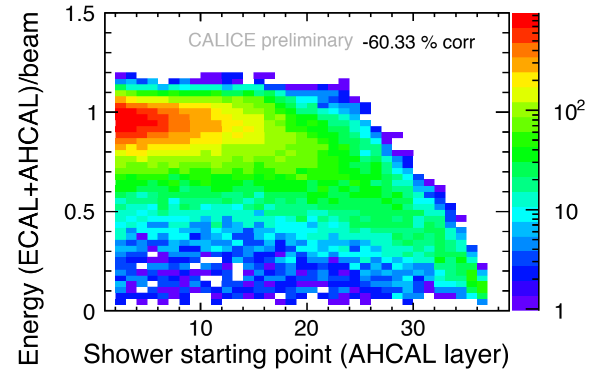


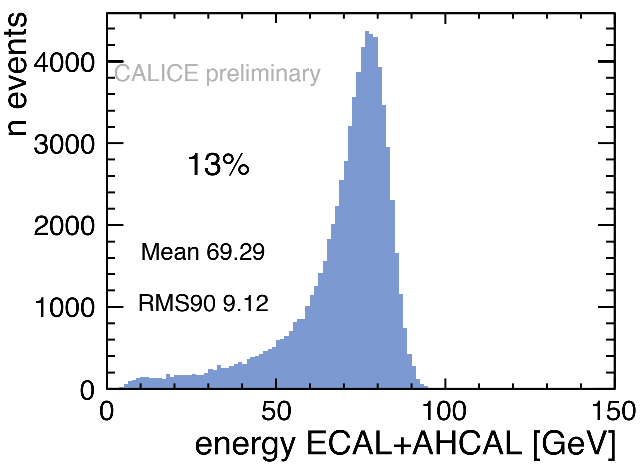


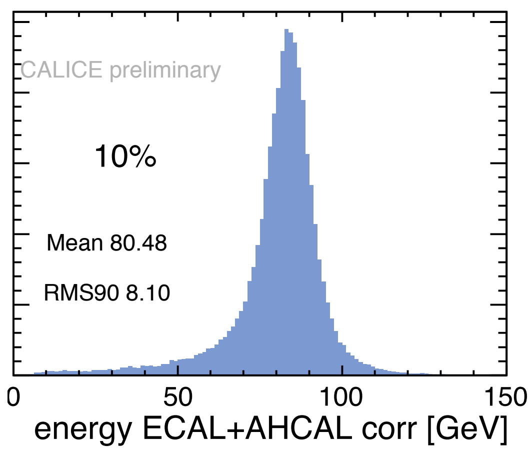


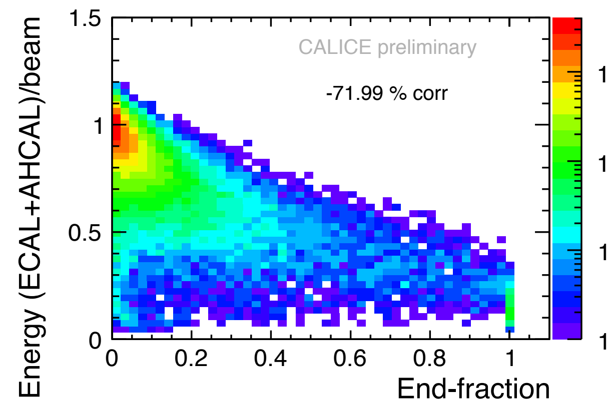
Leakage estimation

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

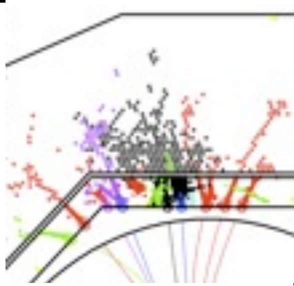








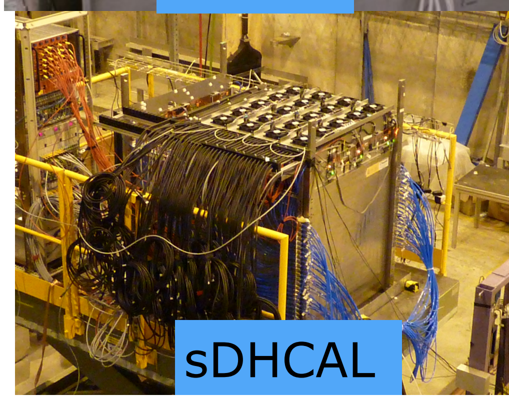
cf : with tail catcher, no coil: 5.4%



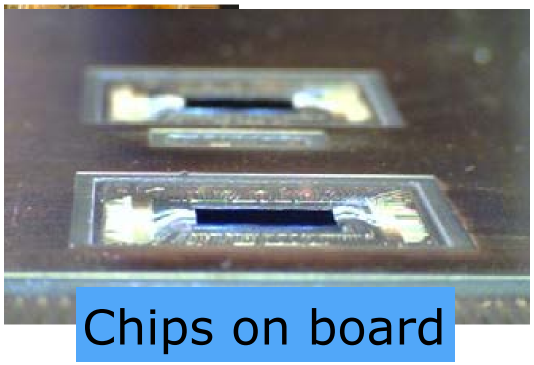
Technological prototypes

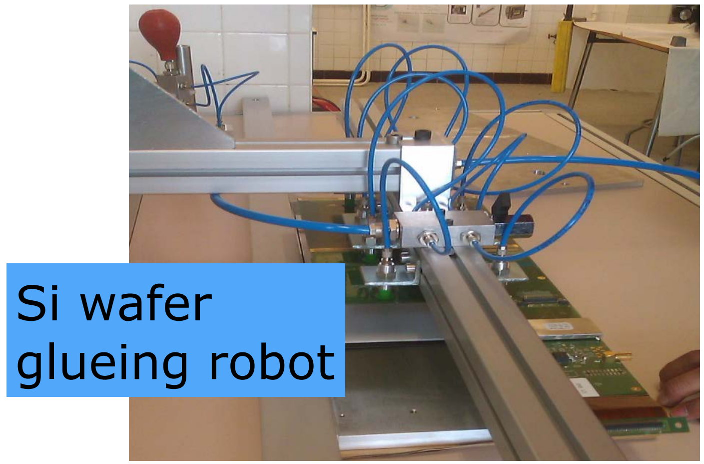
- Electronics integration, power pulsing
- Compact design: absorbers and PCBs
- Scalability

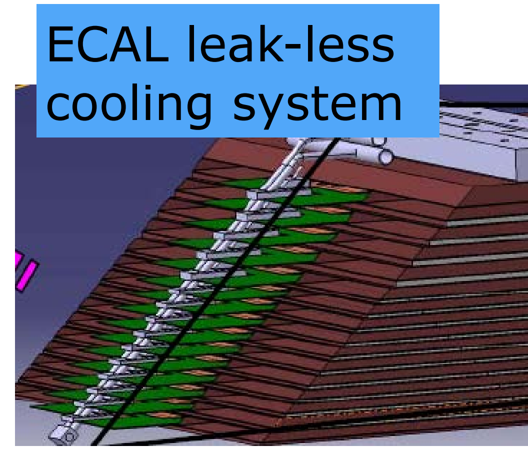
- Integration solutions exist
- Components were prototyped
- Si ECAL, scintillator HCAL: small set-ups tested, <10 small layers
- Gas HCAL: the only large 2nd gen prototype
- None addresses all integration issues yet
- Funding limited

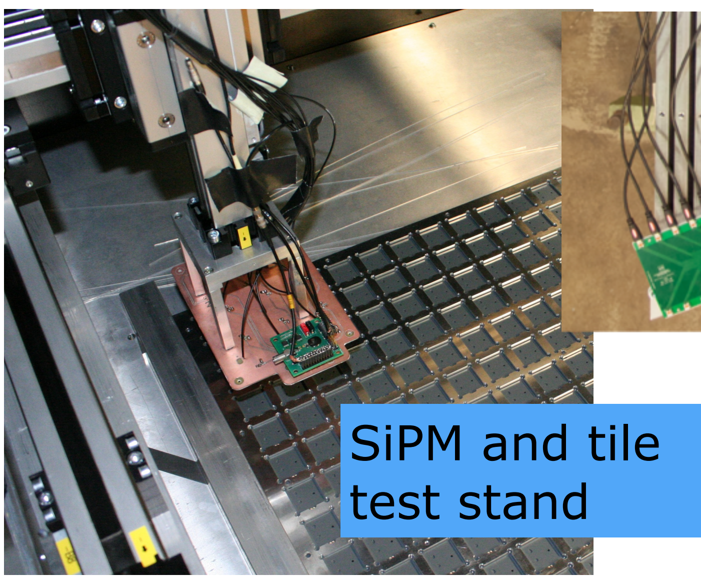


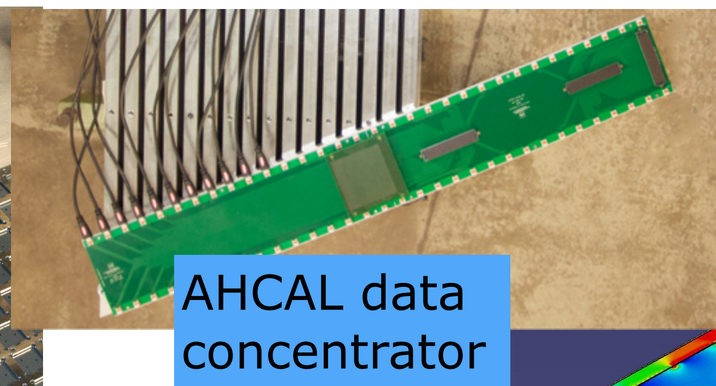
System integration & Tooling

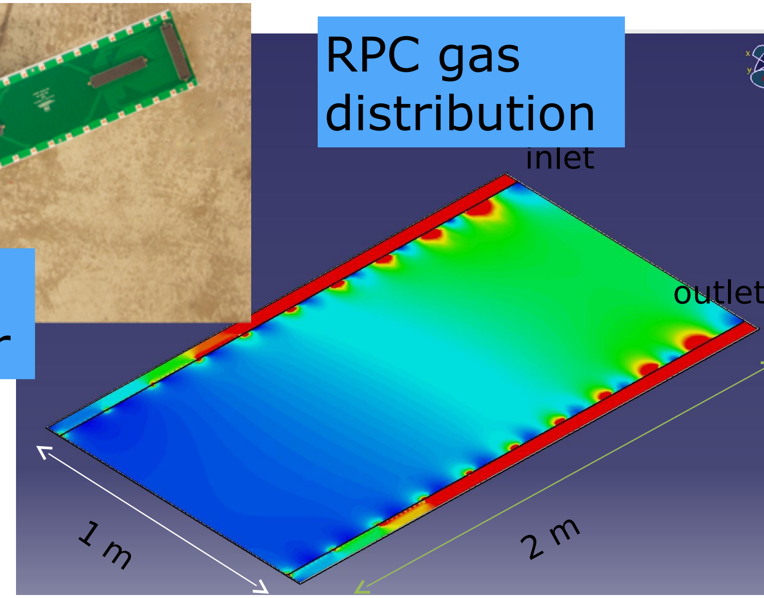


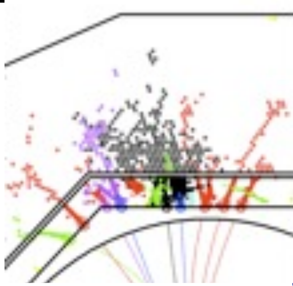






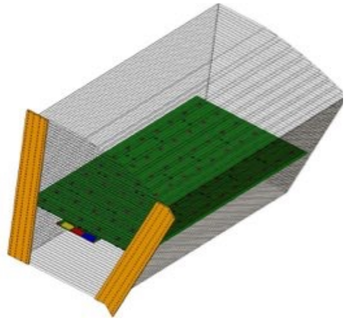


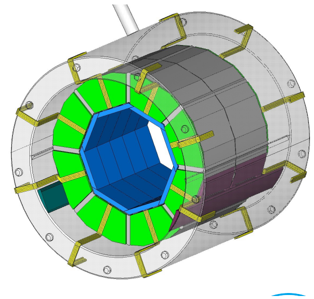


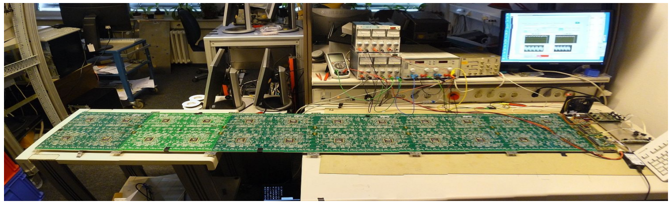


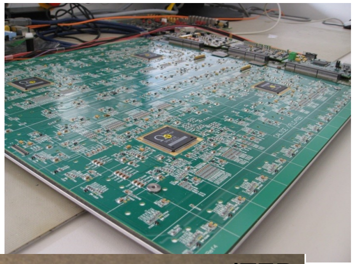
Industrialisation: Numbers!

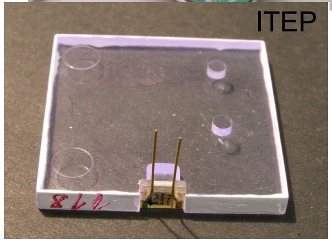
- The AHCAL
- 60 sub-modules
- 3000 layers
- 10,000 slabs
- 60,000 HBUs
- 200’000 ASICs
- 8,000,000 tiles and SiPMs



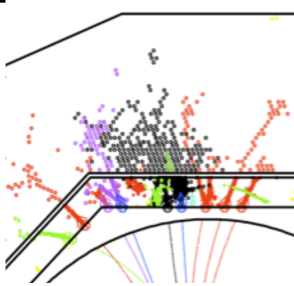






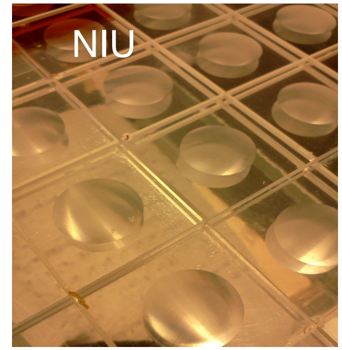


- One year
- 46 weeks
- 230 days
- 2000 hours
- 100,000 minutes
- 7,000,000 seconds

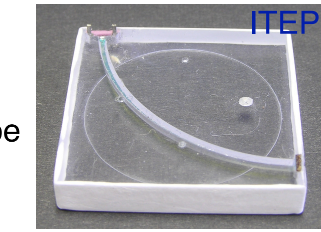


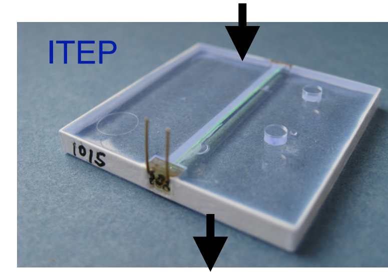
Directions in tile and SiPM R&D

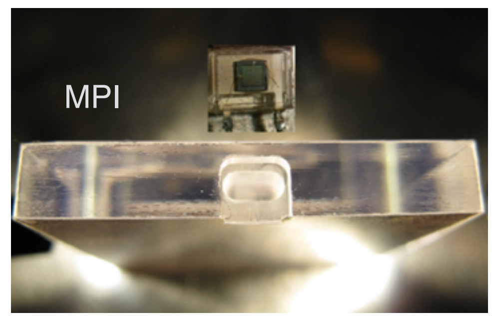
- Revise tile design in view of automatic pick & place procedures
- Consider SMD approach, originally proposed by NIU
- Light yield becomes an issue again
  - build on advances in SiPMs
- Very different assembly, QC and characterisation chain

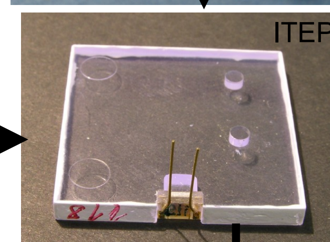


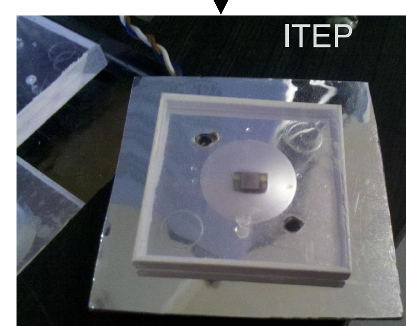
7608 ch physics prototype



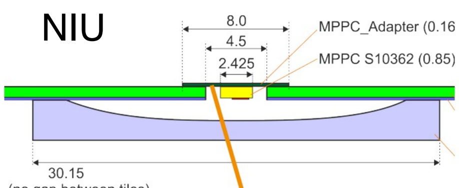








NIU



board coming to life

Mainz