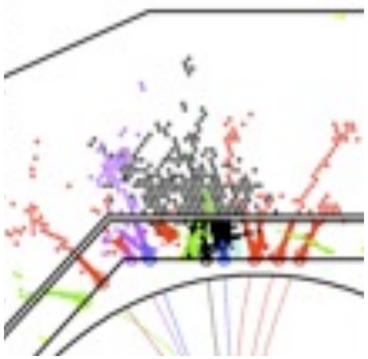
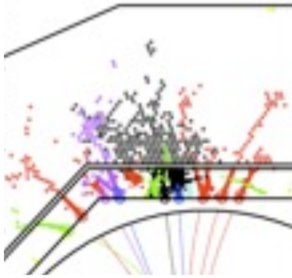
Particle Flow Calorimetry for Linear Collider Experiments

Felix Sefkow

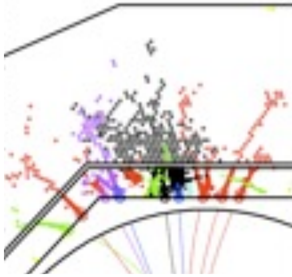


Instrumentation for Colliding beam Physics
Novosibirsk, February 27, 2014



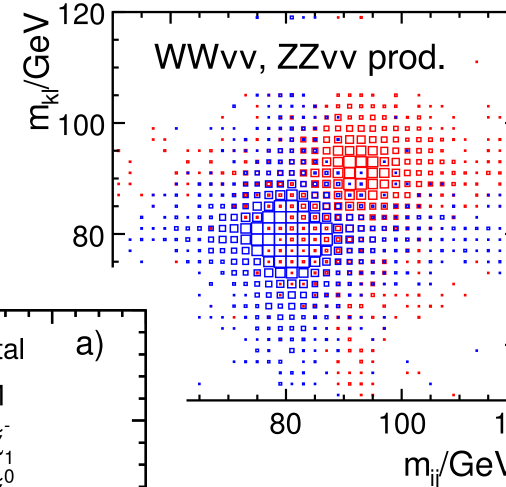
Outline

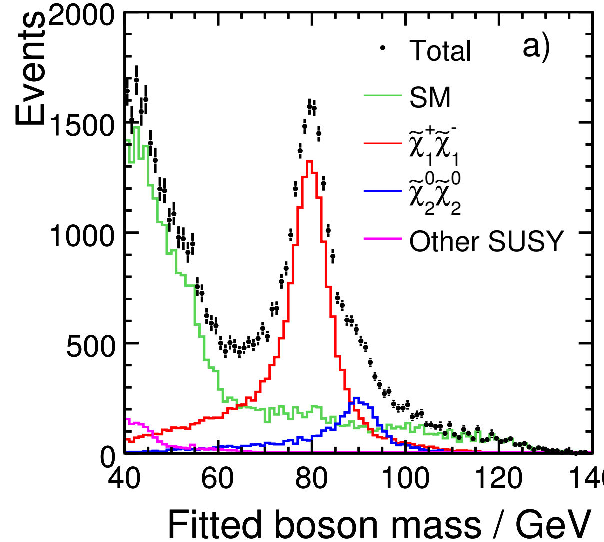
- Particle flow calorimetry
- Test beam validation
- ECAL and HCAL technologies
  - status and open issues

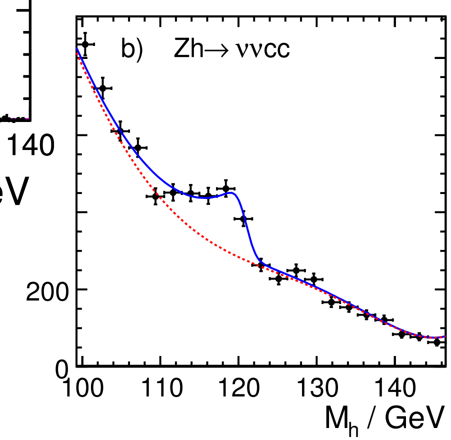


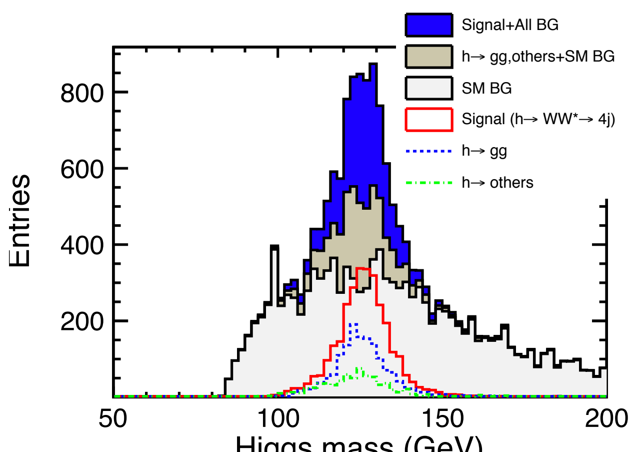
LC physics with jets

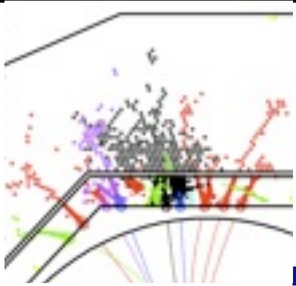
- W - Z separation
  - study strong e.w. symmetry breaking at 1 TeV
- Other W-Z examples
  - Chargino neutralino separation
- Other di-jet mass examples
  - H → cc, Z → νν
  - Higgs recoil with Z → qq
  - invisible Higgs
  - WW fusion → H → WW
    - total width and g_{HWW}





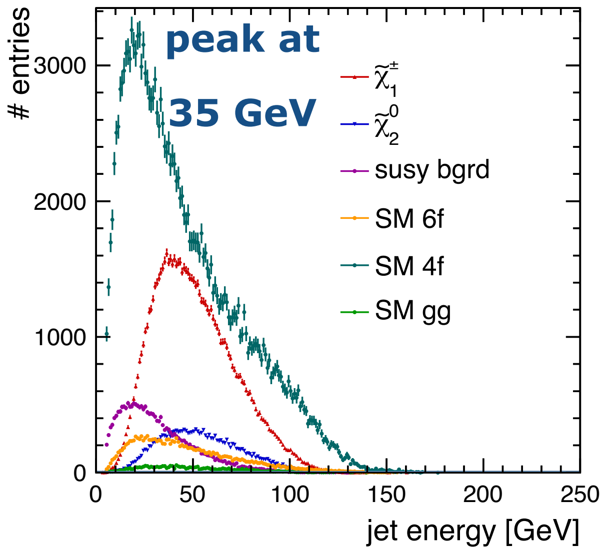




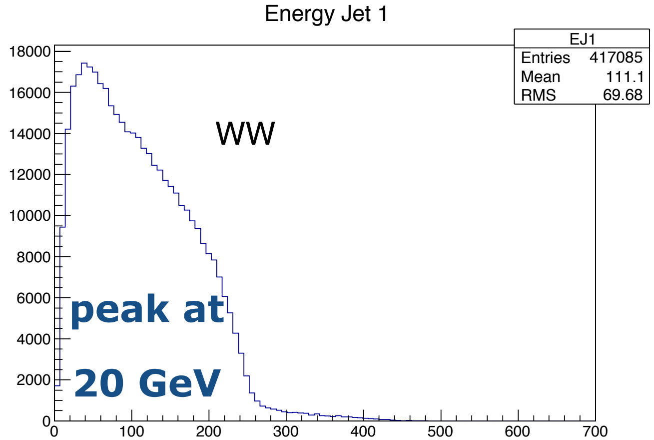


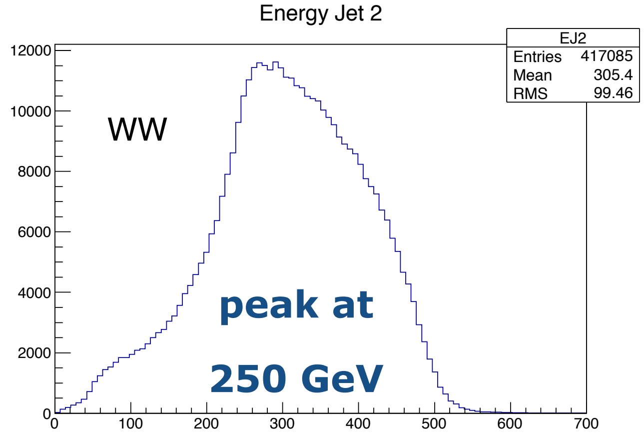
Jet energies

- $\sigma_m/m = 1/2 \sqrt{(\sigma_{E1}/E_1)^2+(\sigma_{E2}/E_2)^2}$
  - lowest E dominates



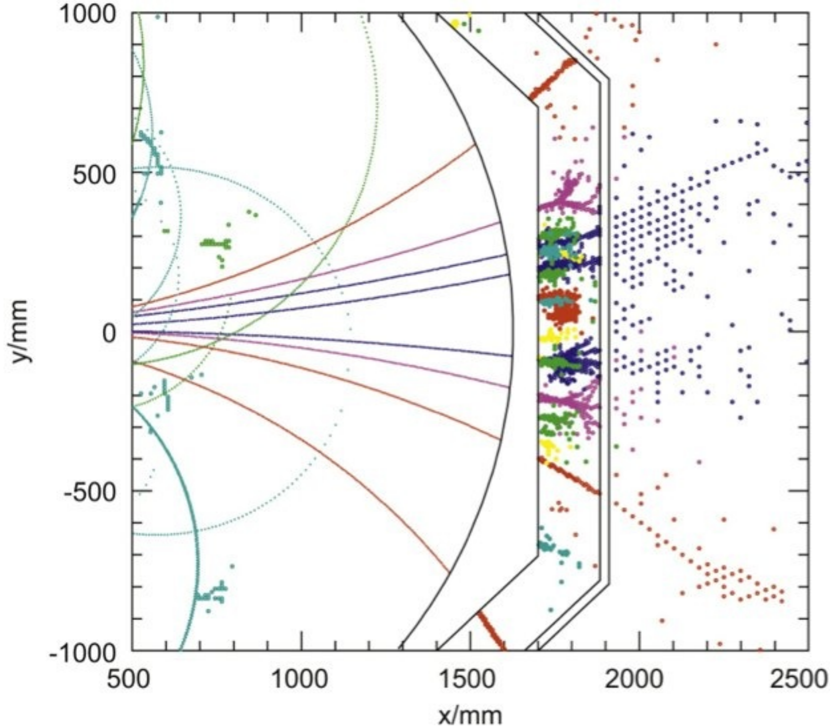
- At $\sqrt{s}$ = 500 GeV
- example chargino, neutralino → qq + invis.
- At $\sqrt{s}$ = 1 TeV
- example WW→H → WW → lvqq

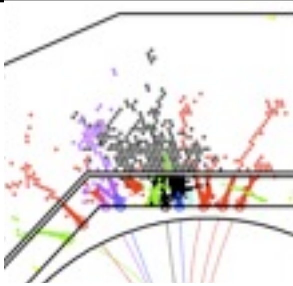




plots:
J.List, M.Chera, A.Rosca
DESY

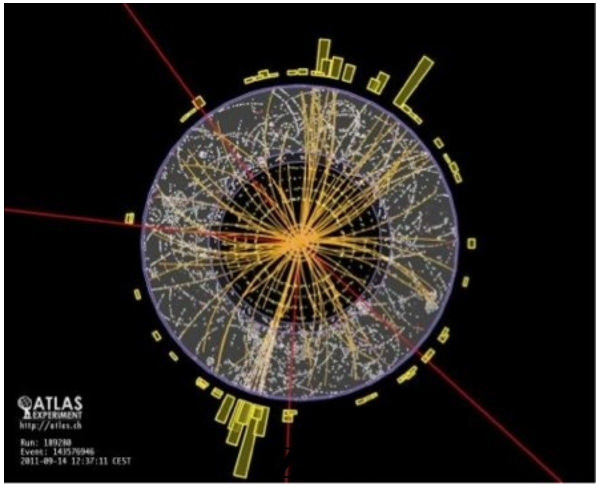
Particle flow concept and detectors

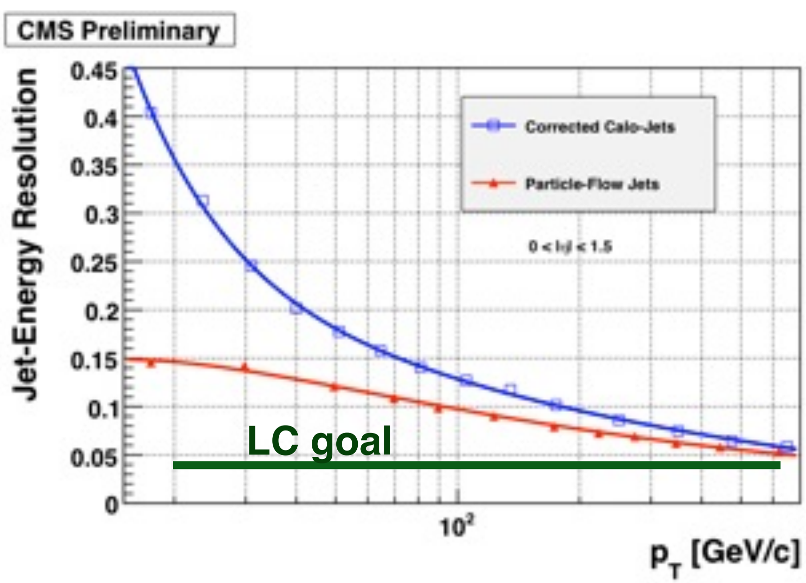




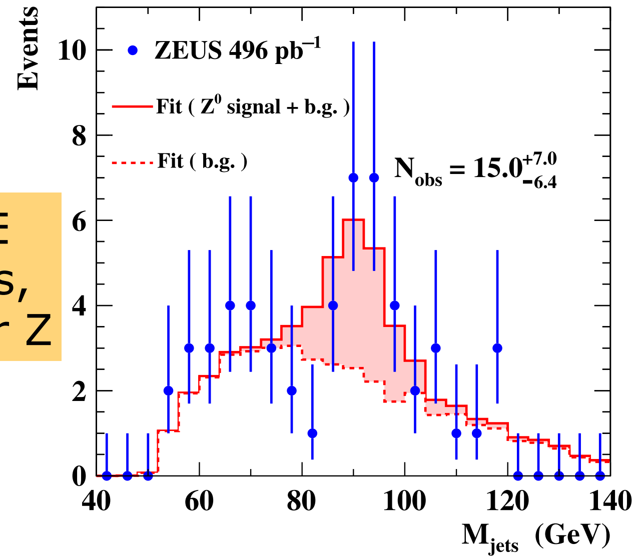
The jet energy challenge

- 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



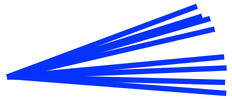


35%√E
for pions,
6 GeV for Z

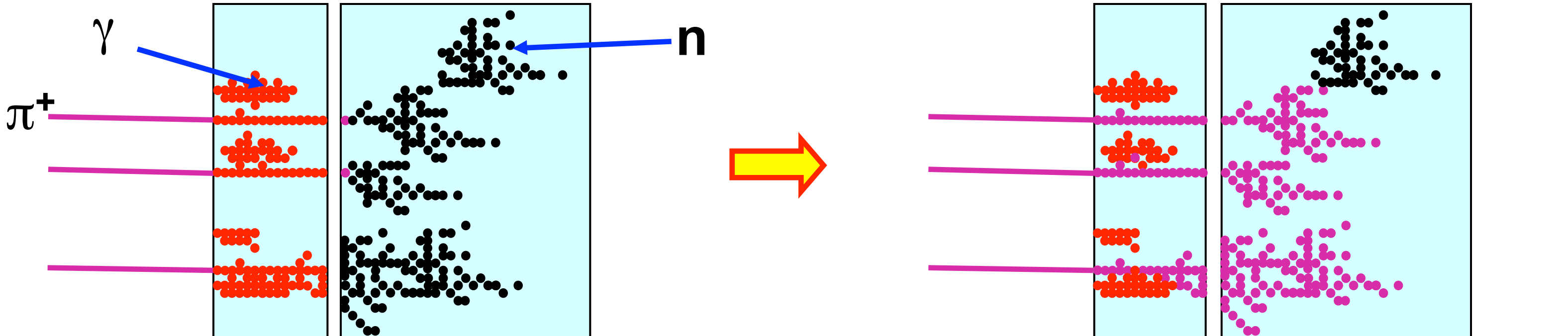


Particle Flow Calorimetry

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



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



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

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

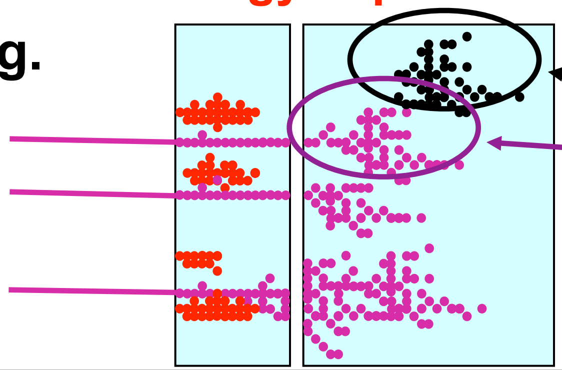
★ **Particle Flow Calorimetry paradigm:**
- charged particles measured in tracker (essentially perfectly)
- Photons in ECAL: $\sigma_\mathrm{E}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
- Neutral hadrons (ONLY) in HCAL
- Only 10 % of jet energy from HCAL ⇨ much improved resolution

Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

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

e.g.

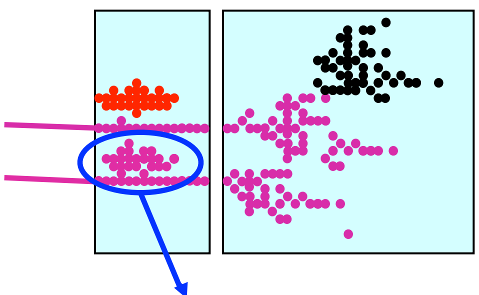


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

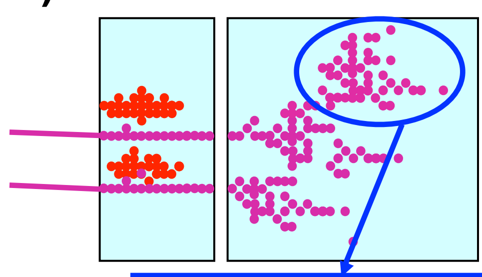
Three types of confusion:

i) Photons



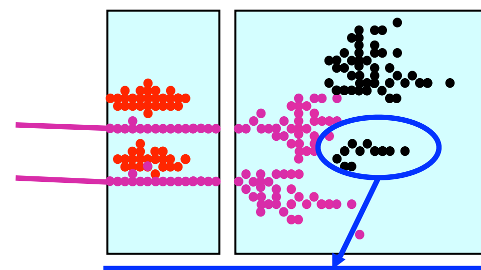
Failure to resolve photon

ii) Neutral Hadrons

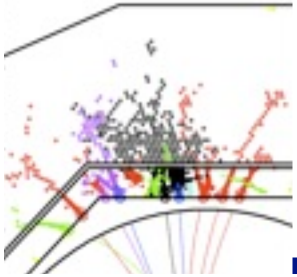


Failure to resolve neutral hadron

iii) Fragments



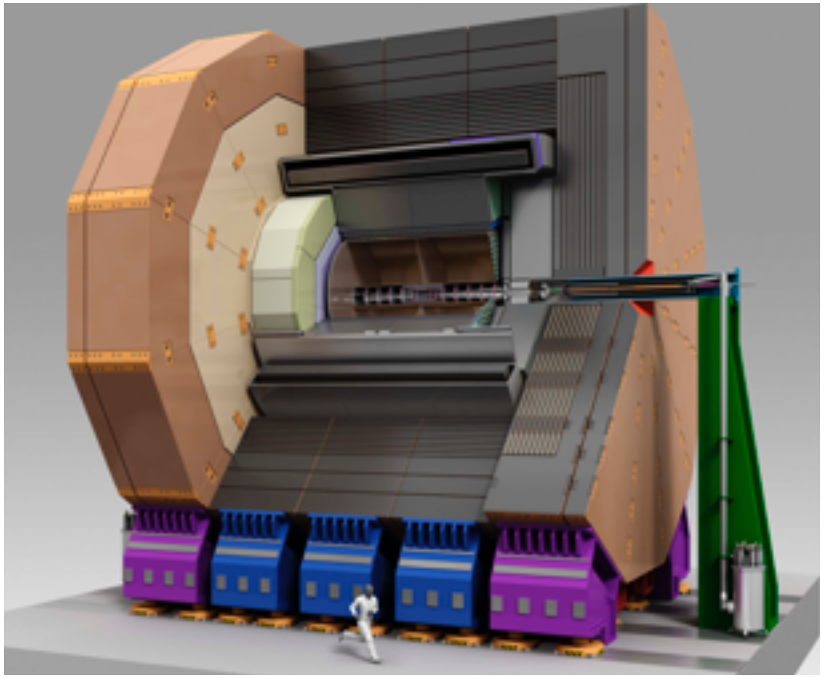
Reconstruct fragment as separate neutral hadron



Particle flow detectors

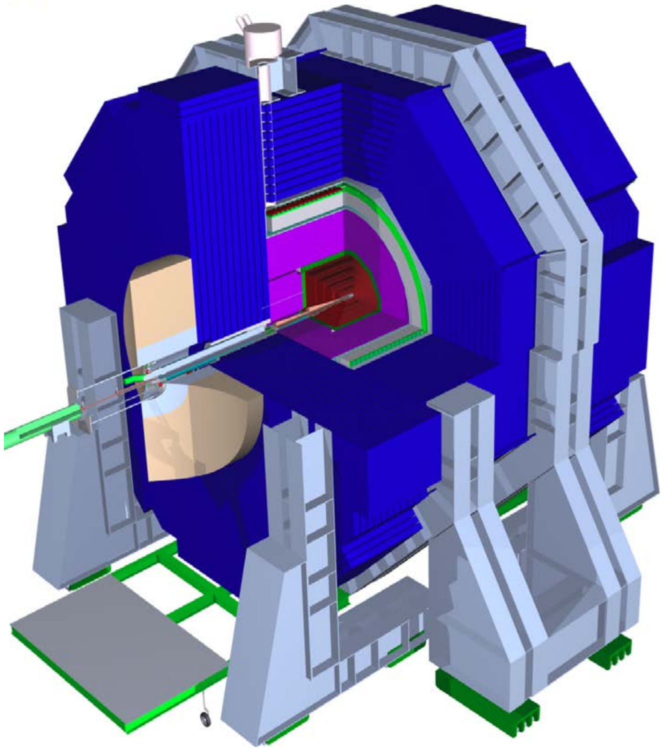
- large radius, large field, compact calorimeter, fine 3D granularity
  - Typ. 1X0 long., transv.: ECAL 0.5cm, HCAL 1cm (gas) - 3cm (scint.)
- optimised in full simulations and particle flow reconstruction

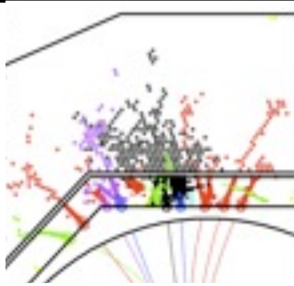
ILD: large TPC, B=3.5T, PFLOW calo



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

CLIC:
tungsten
barrel HCAL

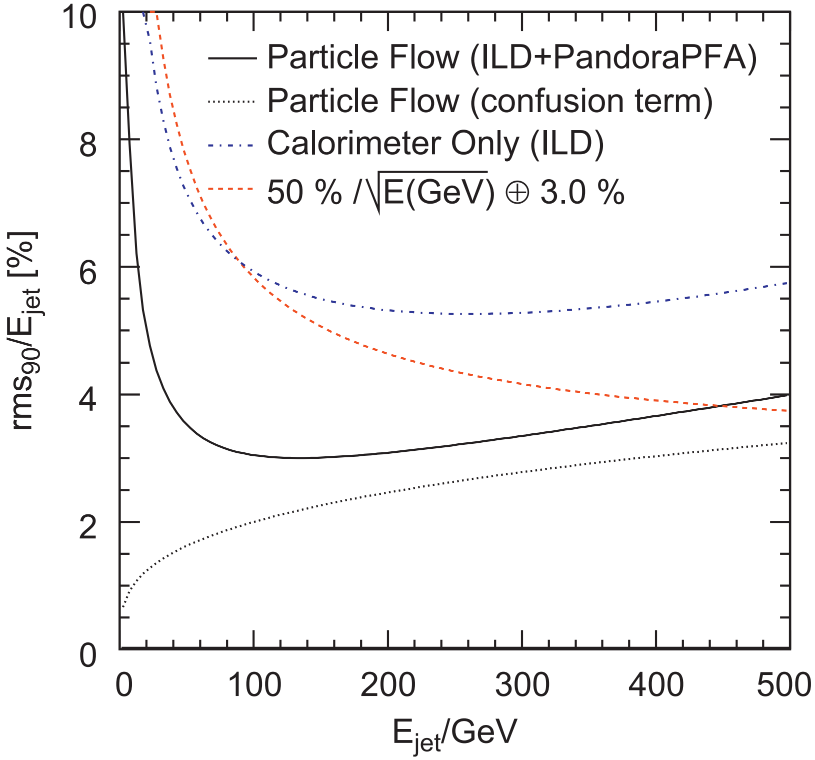


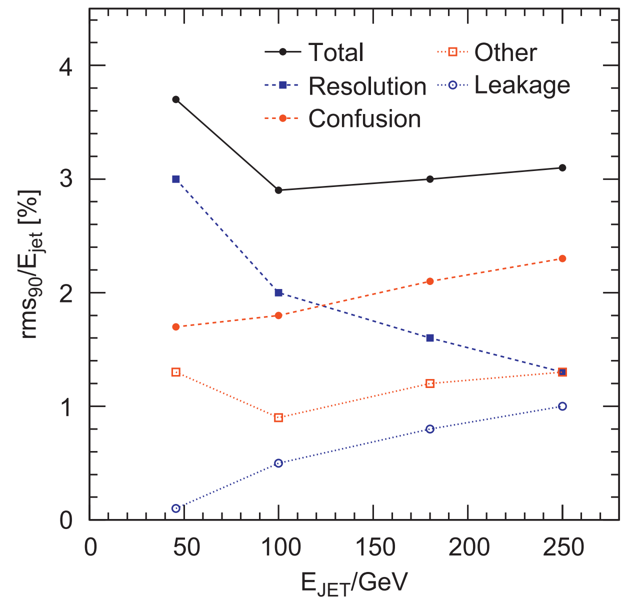


Understand particle flow performance

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

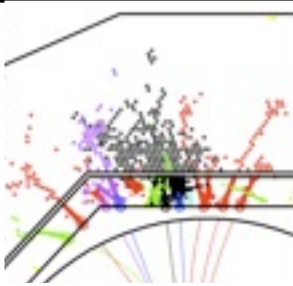
Resolution — Tracking — Leakage — Confusion





- 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



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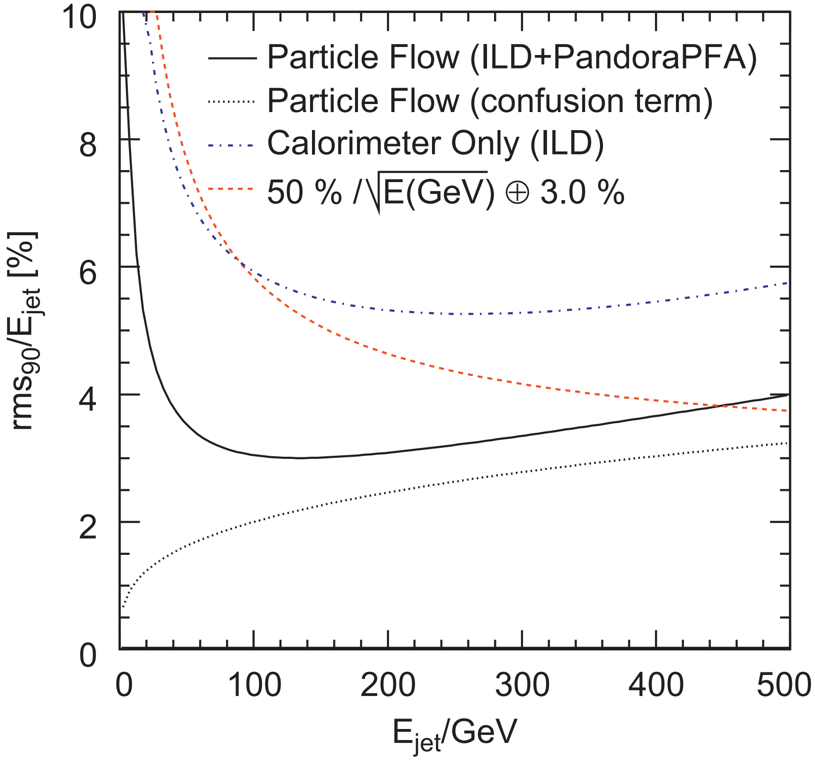

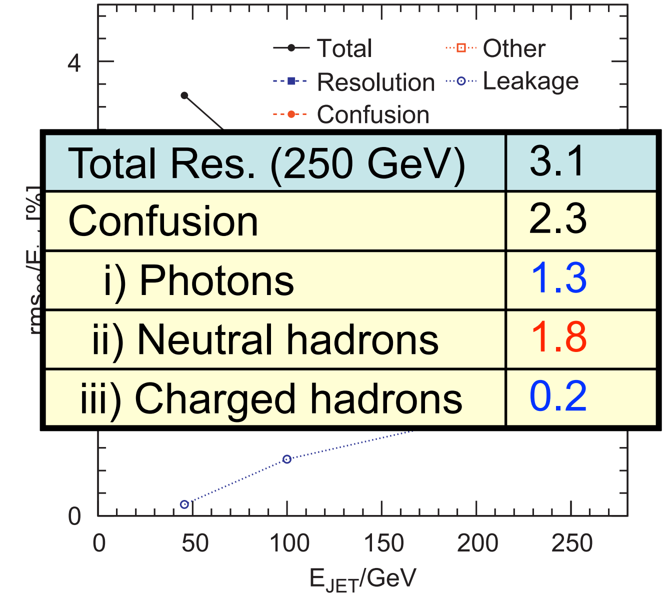

Total Res. (250 GeV)	3.1
Confusion	2.3
i) Photons	1.3
ii) Neutral hadrons	1.8
iii) Charged hadrons	0.2

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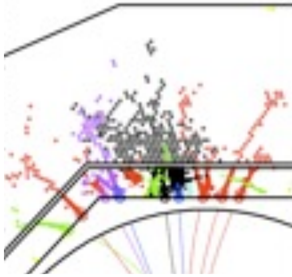
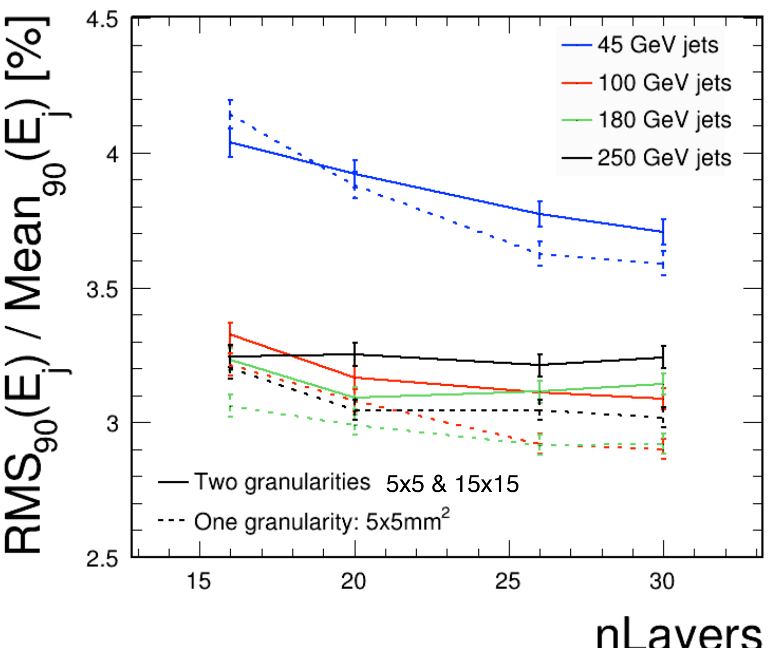
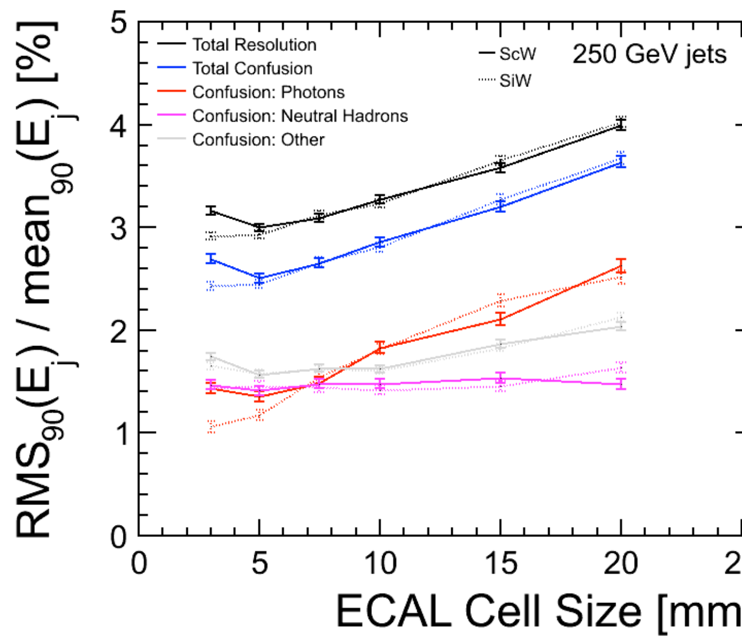
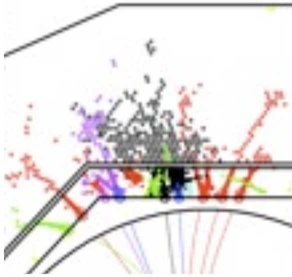


Optimisation

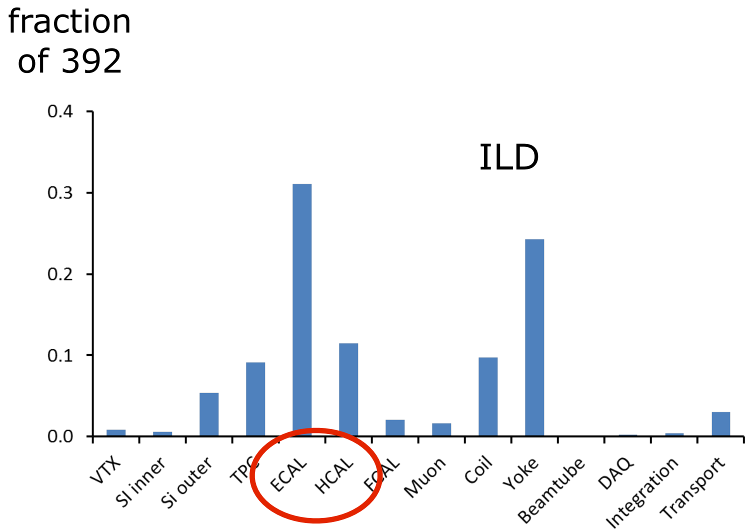
- Example ECAL
- longitudinal segmentation drives resolution
  - impact at low energy
- transverse segmentation drives photon hadron separation
  - impact at high energy
  - little impact on hadron hadron separation → HCAL
- technology choice driven by operational issues and cost

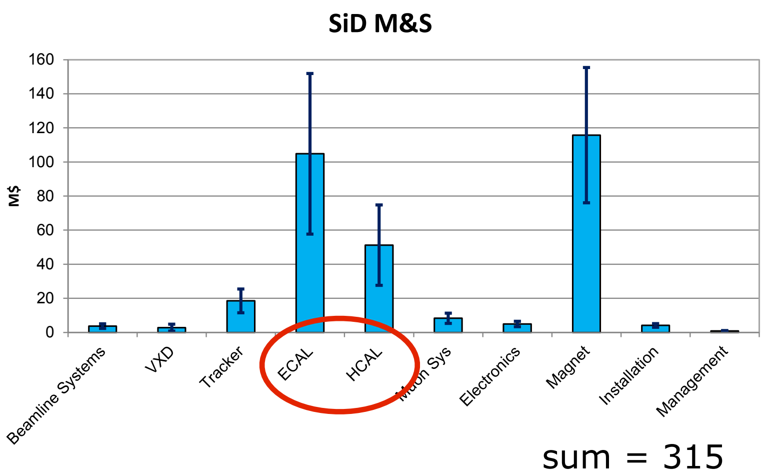




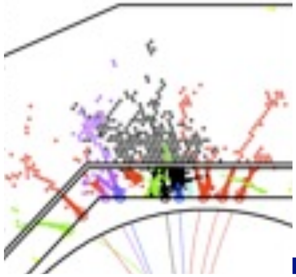


Calorimeter cost





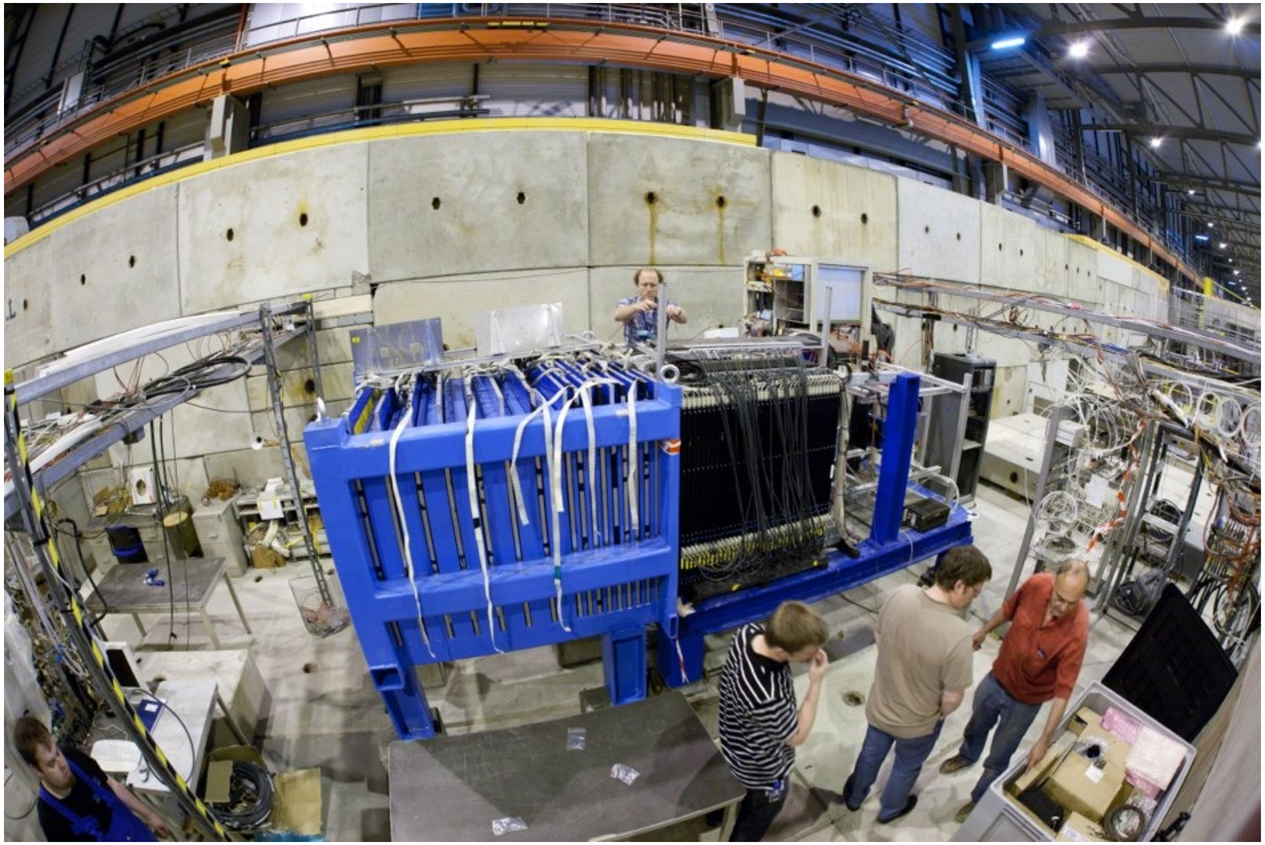
- Costing is at a very early stage
- Yet, many lessons learnt from 2nd generation prototypes
- HCAL:
- example ILD scint HCAL: 45M
  - 10M fix, rest ~ volume
  - 10M absorber, rest ~ area (n_{Layer})
  - 16M PCB, scint, rest ~ channels
  - 10 M SiPMs and ASICs
- ECAL:
- main cost driver: silicon area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

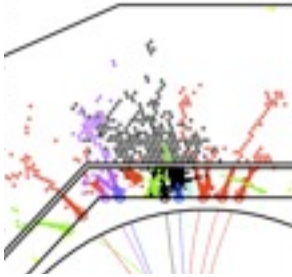


Main ideas:

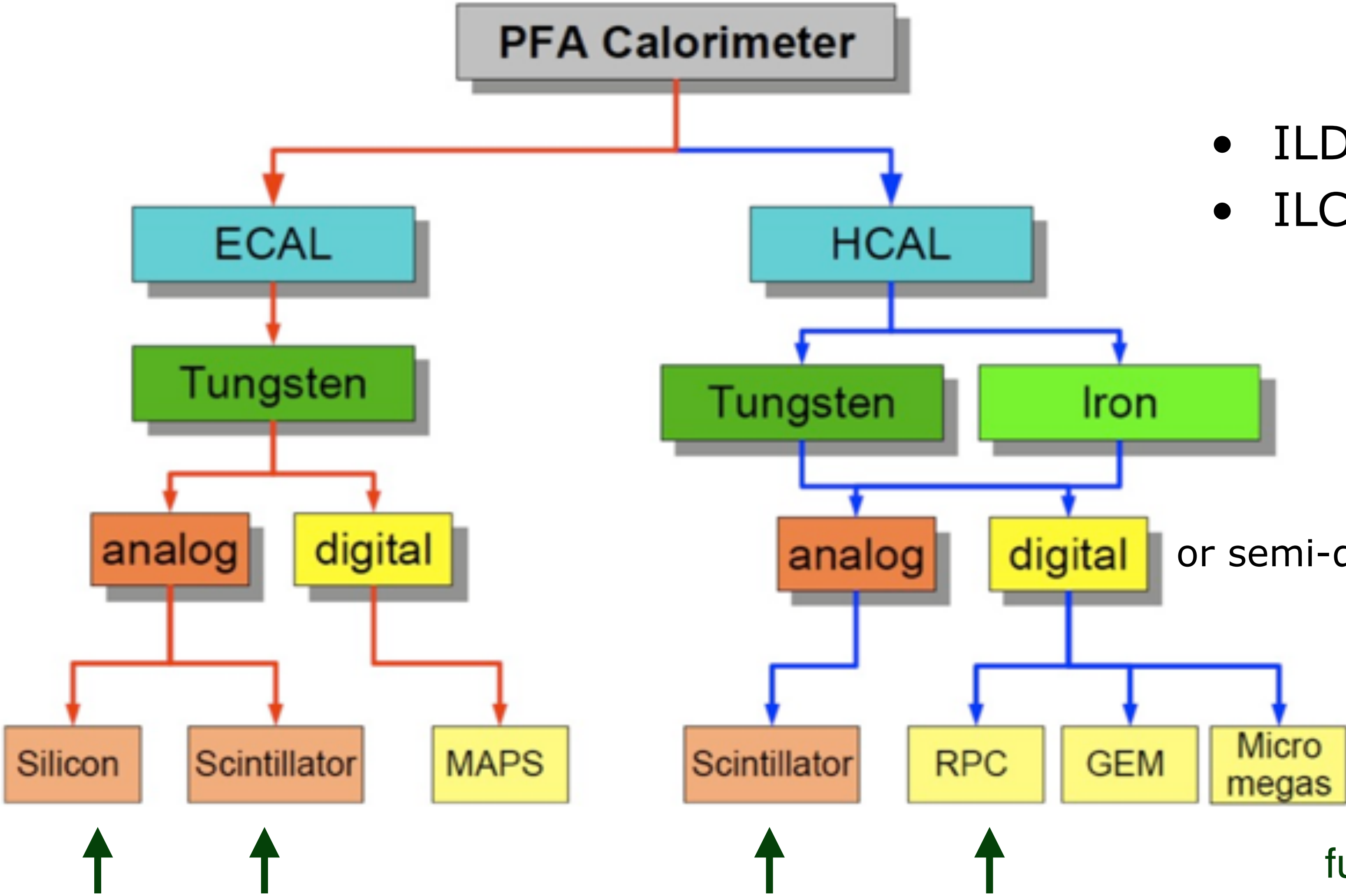
- Linear collider physics demands 3-4% jet energy resolution, which cannot be achieved with classical calorimetry
- Particle flow detectors achieve this precision over a wide energy range for ILC and CLIC
  - and under CLIC background and pile-up conditions
- Particle flow calorimeters feature good energy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

Test beam validation





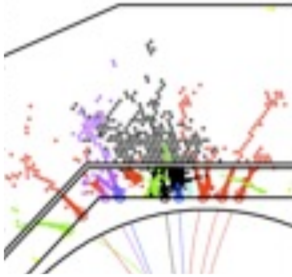
Calorimeter technologies



- ILD, SiD
- ILC, CLIC

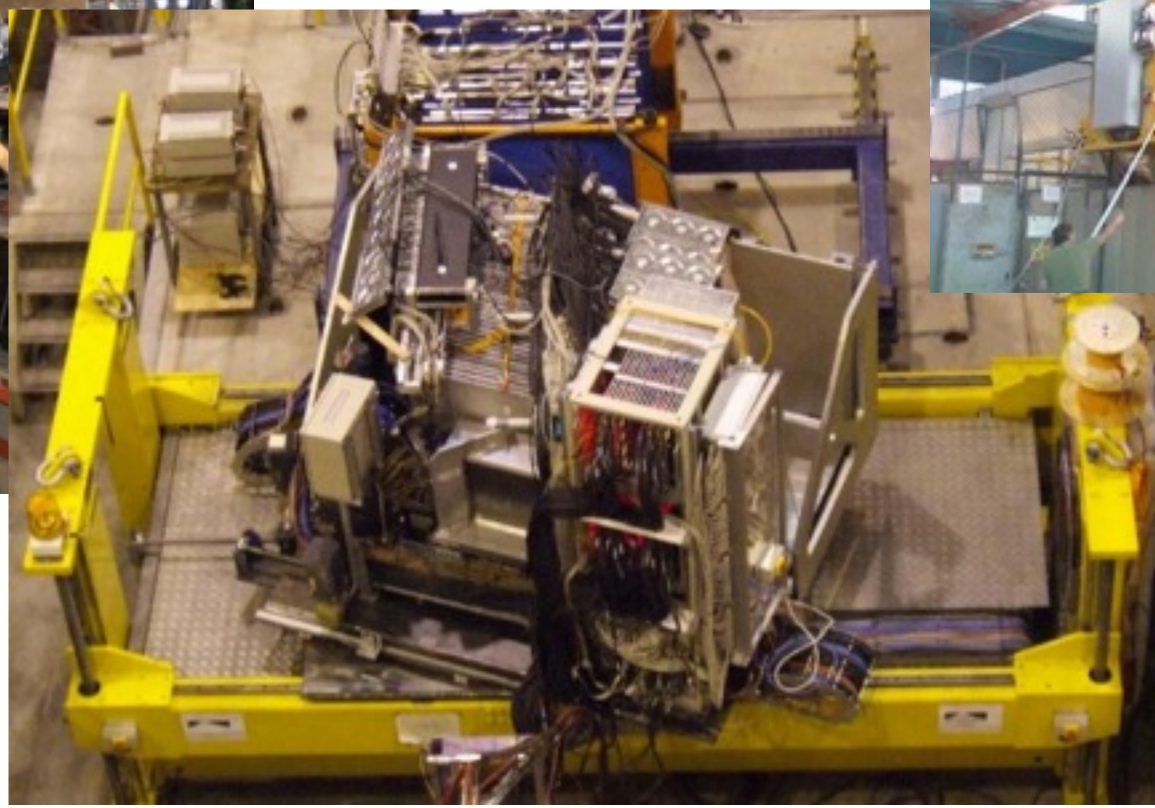
or semi-digital

full prototypes



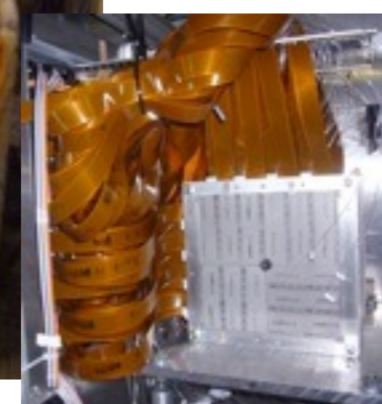
Test beam experiments

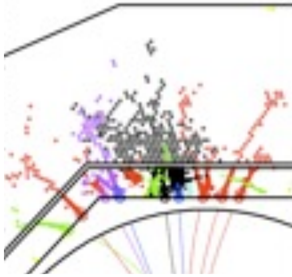
DESY 2005
SiECAL



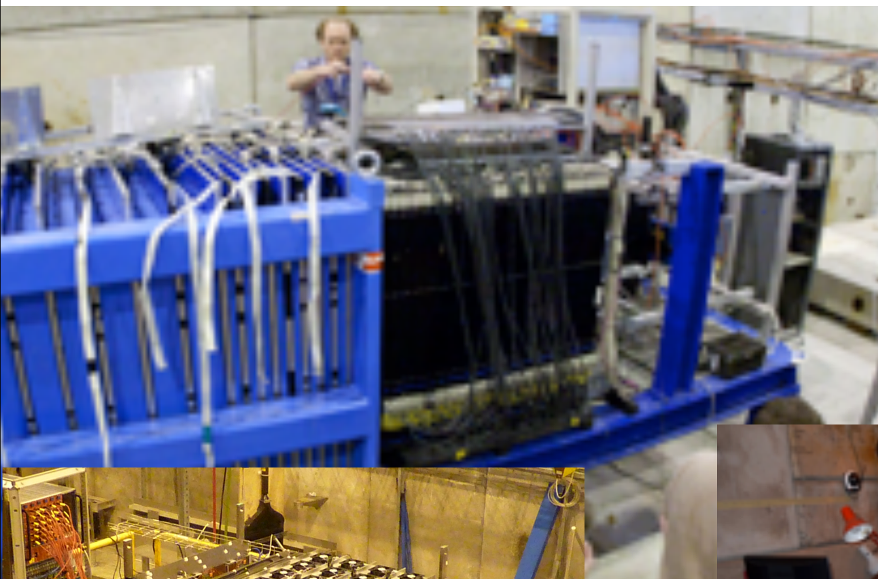
CERN 2006-2007
add Scint HCAL

FNAL 2008-09
Si -> Sci ECAL



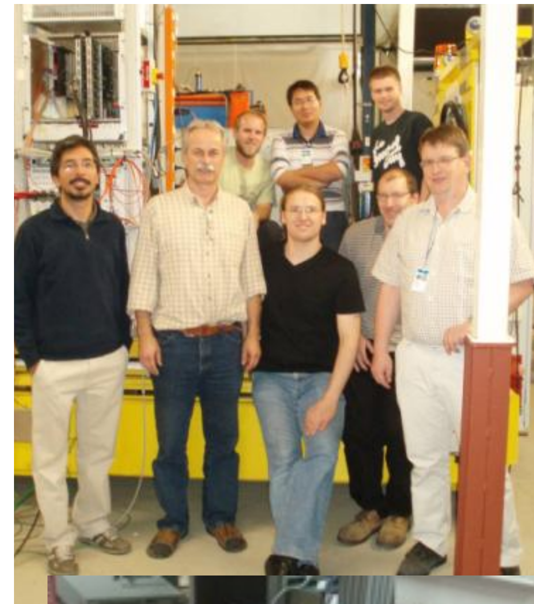


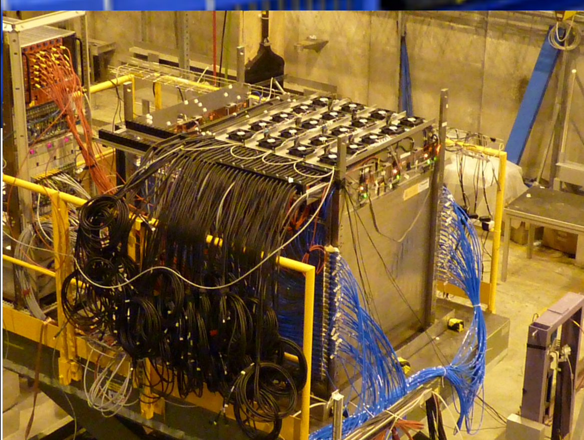
+ Test beam experiments



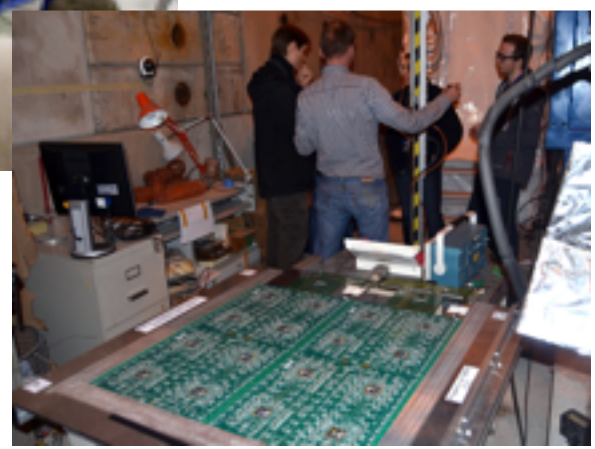
CERN
2010-11
Tungesten
AHCAL
2012:
DHCAL

FNAL2010-11:
m^3 Fe DHCAL



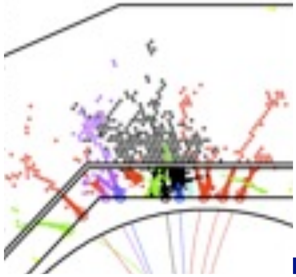


CERN 2012:
m^3 SDHCAL



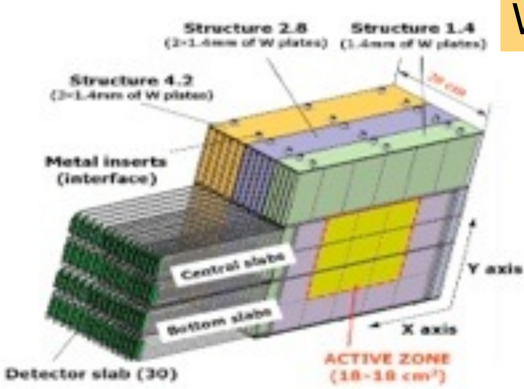
CERN 2012
2nd generation
scint HCAL

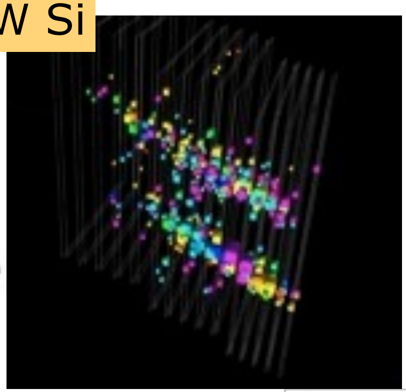
DESY 2012
2nd generation
SiW ECAL



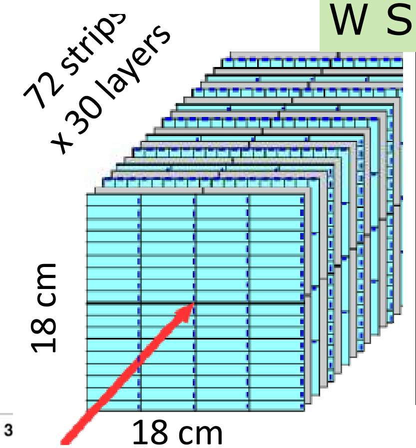
ECAL performance

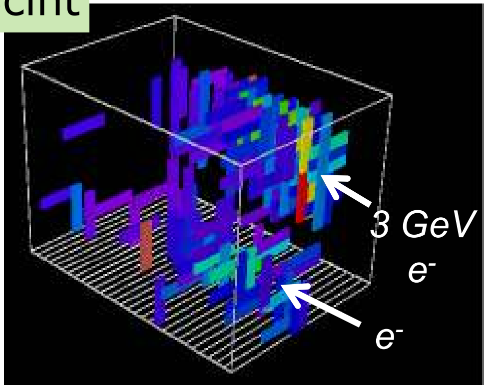
W Si

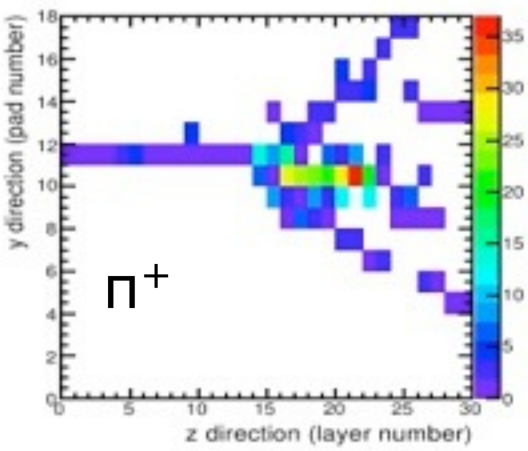


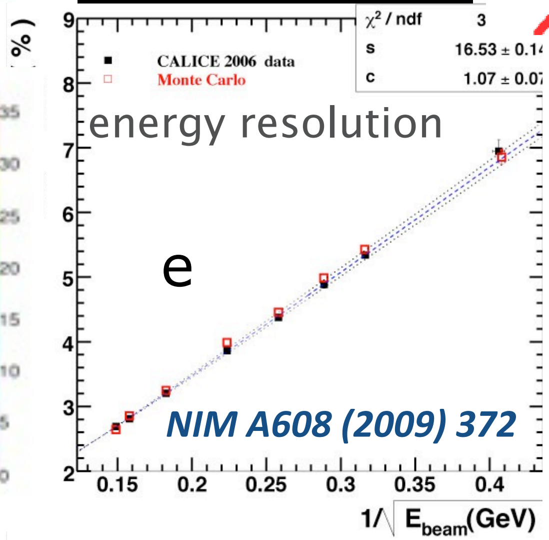


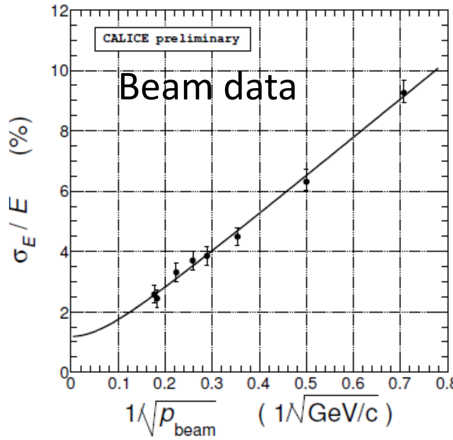
W Scint

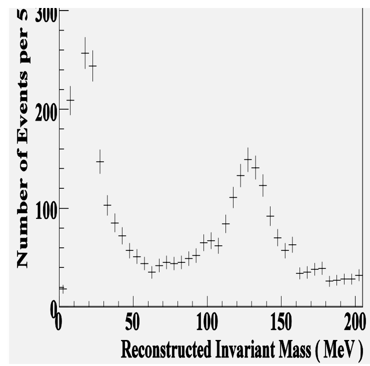








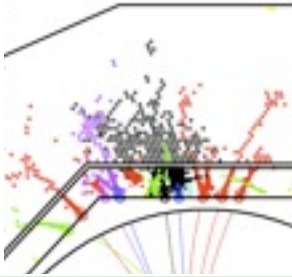




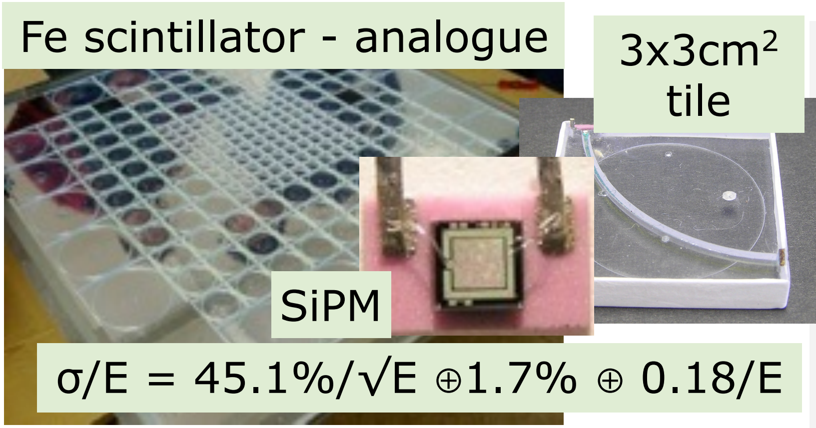
- data and sim agree

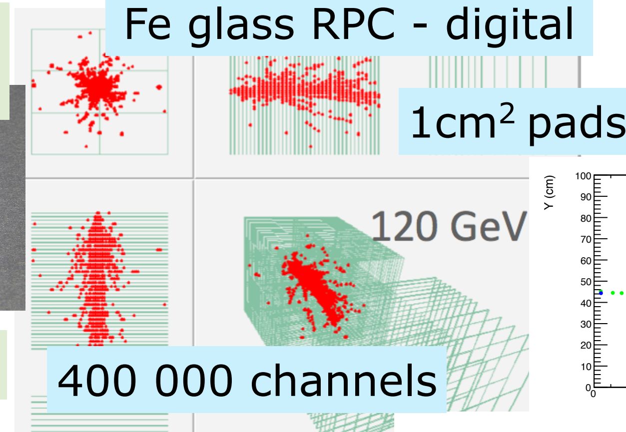
$12.9 \pm 0.1(\text{stat.}) \pm 0.4\ (\text{syst.})\%$

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

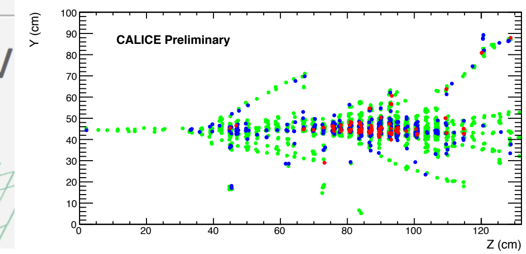


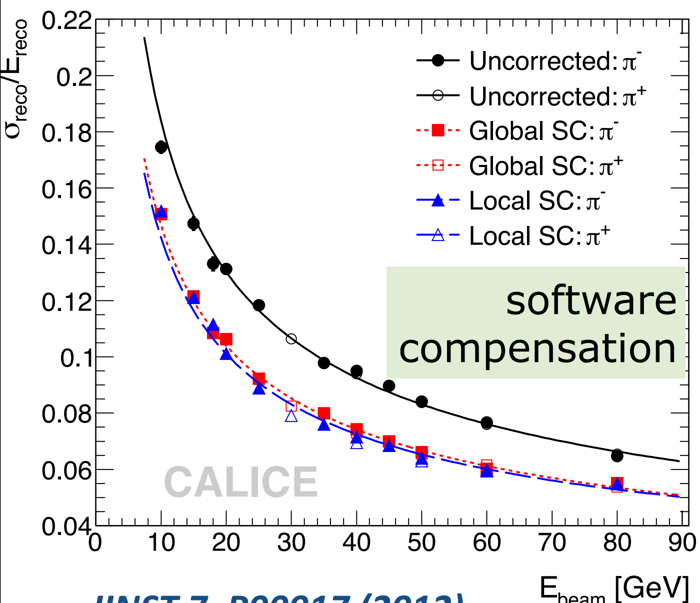
HCAL performance



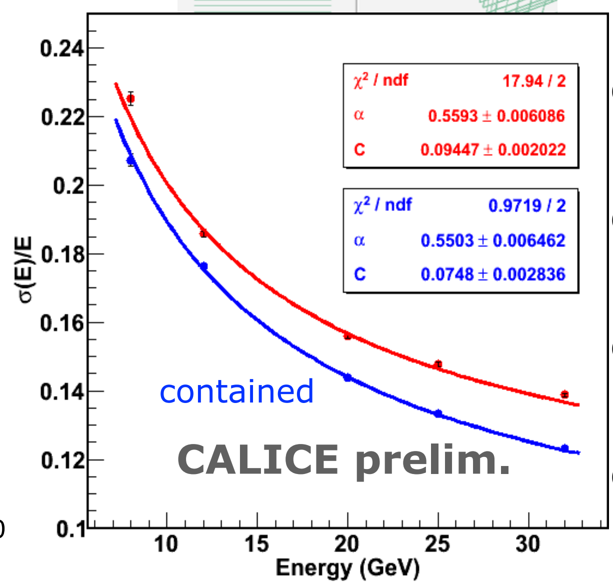


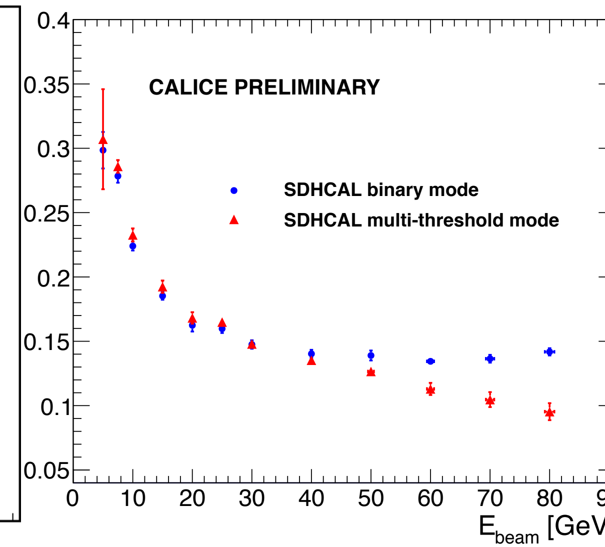
Fe glass RPC semi-digital 2-bit

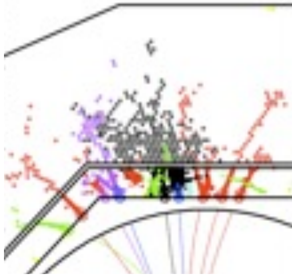




JINST 7, P00917 (2012)

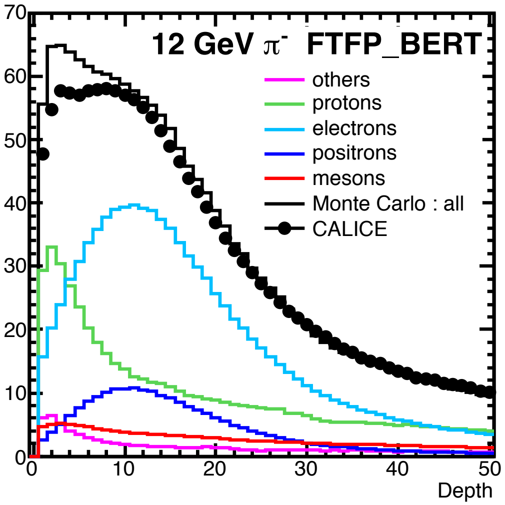






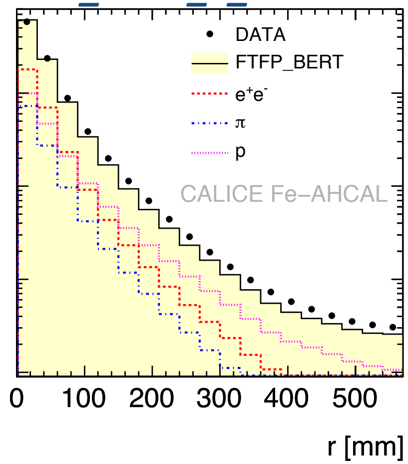
Validation of Geant 4 models

; 2010_JINST_5_P05007

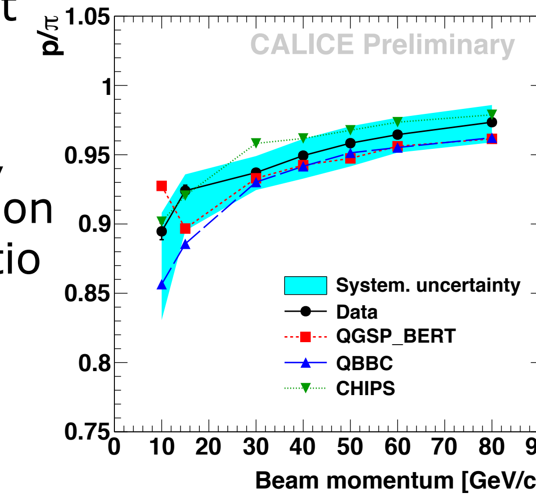


SiW ECAL
longit. profile

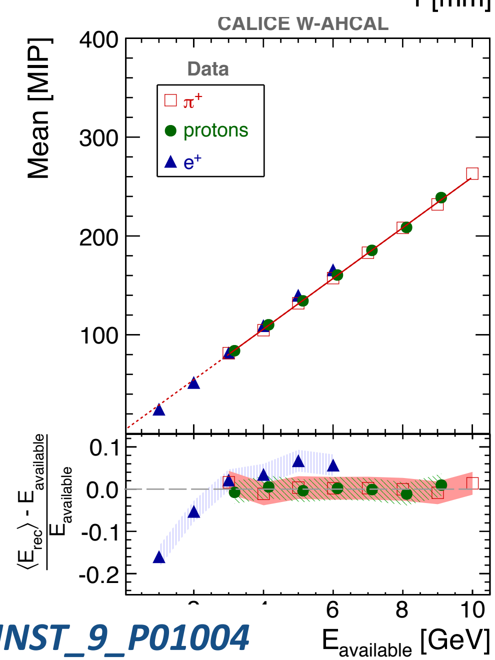
2013_JINST_8_P07005

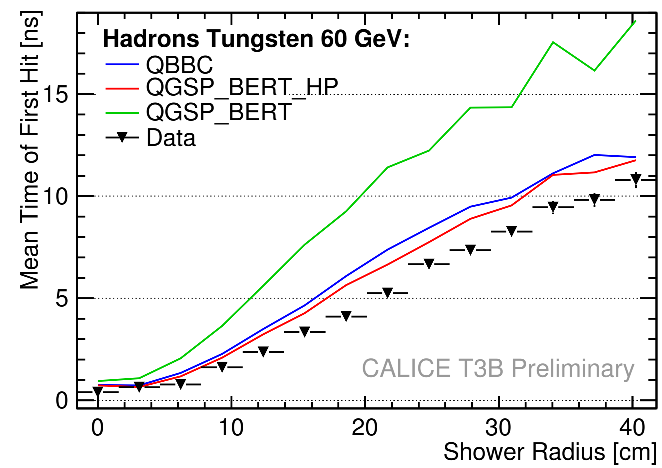


Fe Scint
HCAL
radial
profile,
roton pion
'esp. ratio



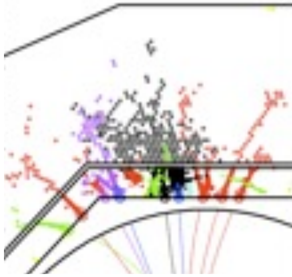
- just a few examples
- altogether at 5% or better



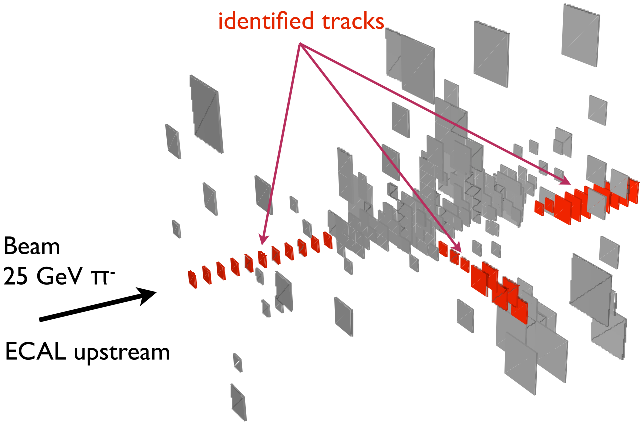


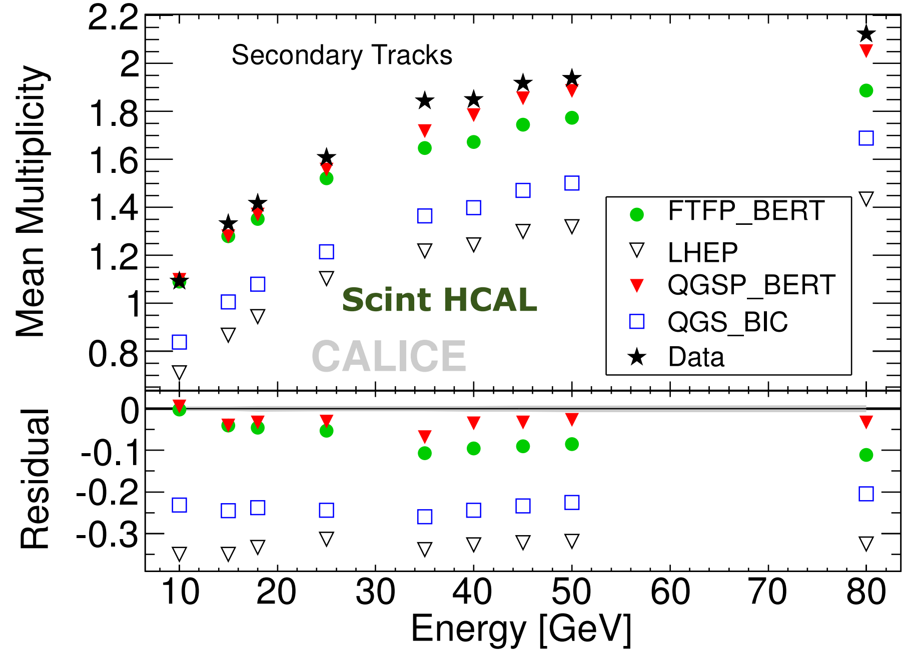
W Scint HCALresponse, timing

2014_JINST_9_P01004

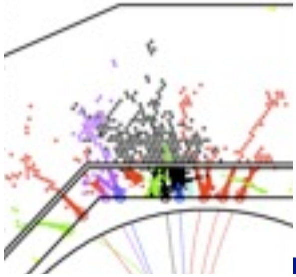


Shower fine structure

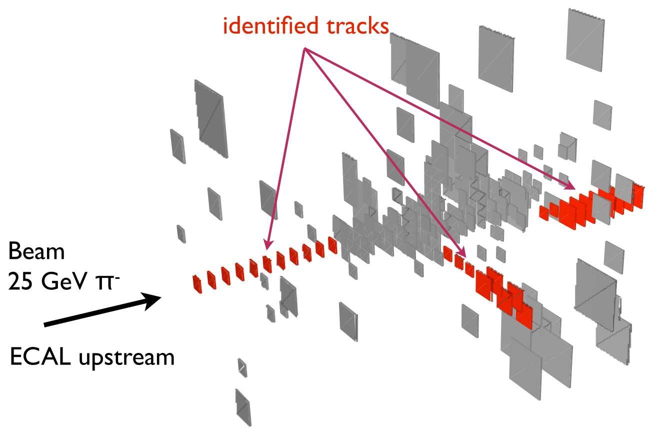


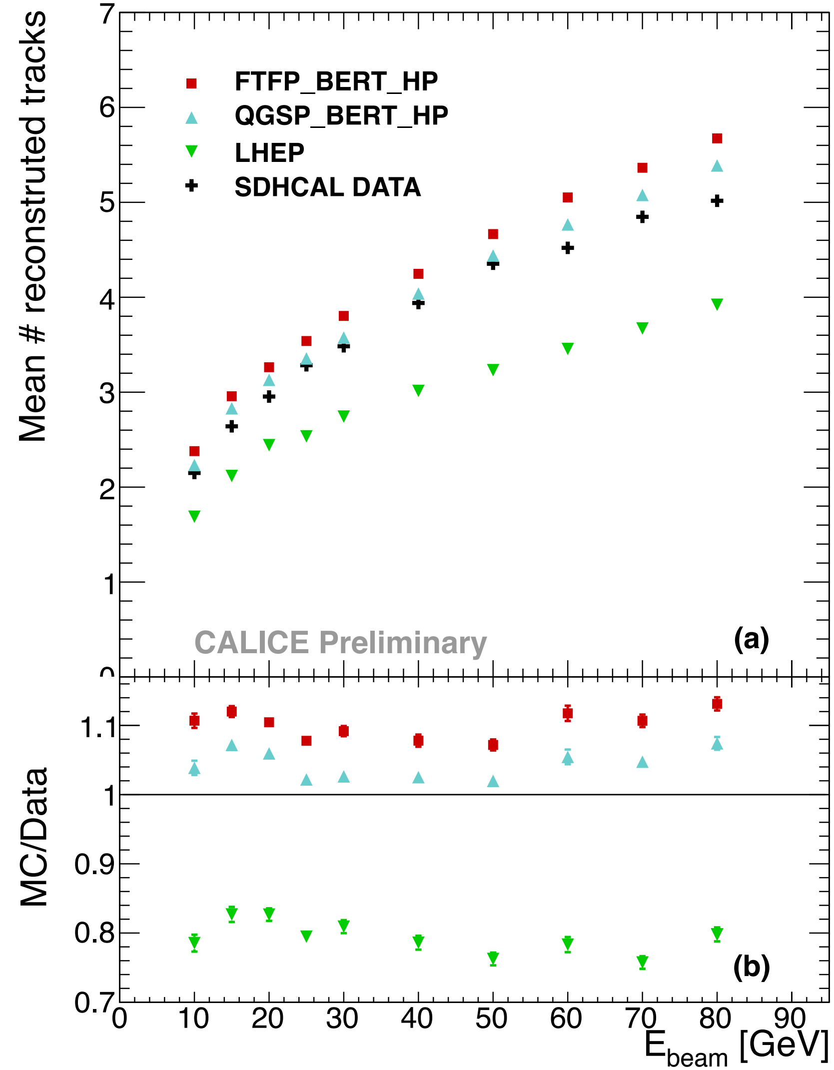


- Could have had the same global parameters with “clouds” or “trees”
- Powerful tool to check models
- Surprisingly good agreement already - for more recent models



Shower fine structure





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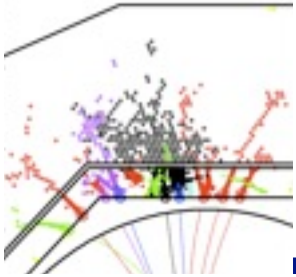
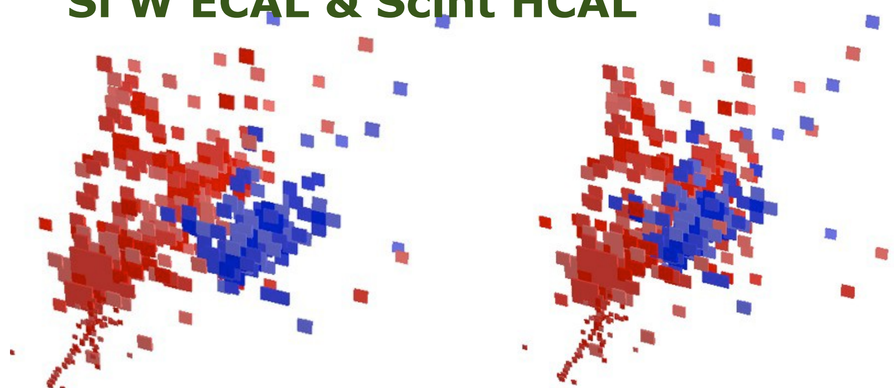


PFLOW with test beam data

Si W ECAL & Scint HCAL

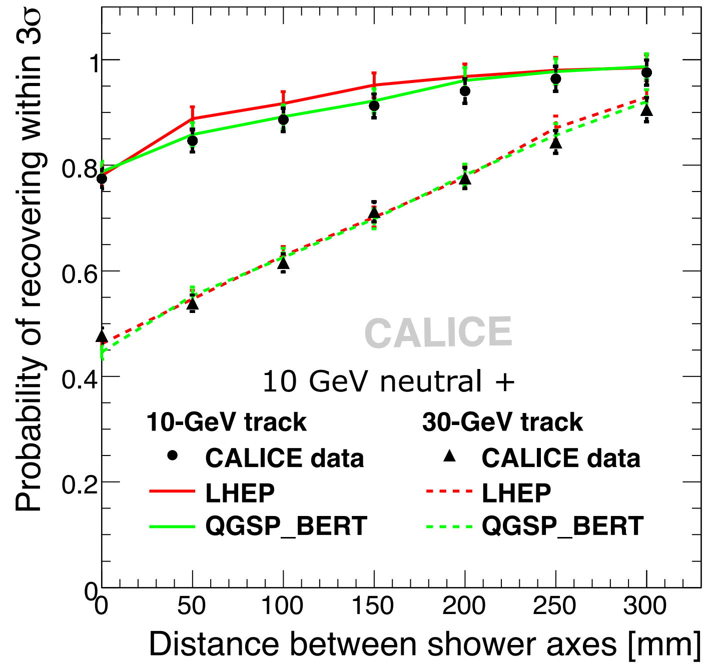


~18 cm separation of shower

~7 cm separation of shower

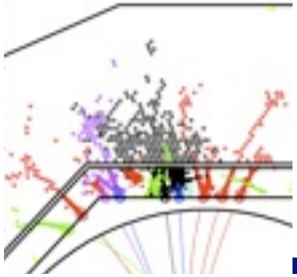
30 GeV charged hadron

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

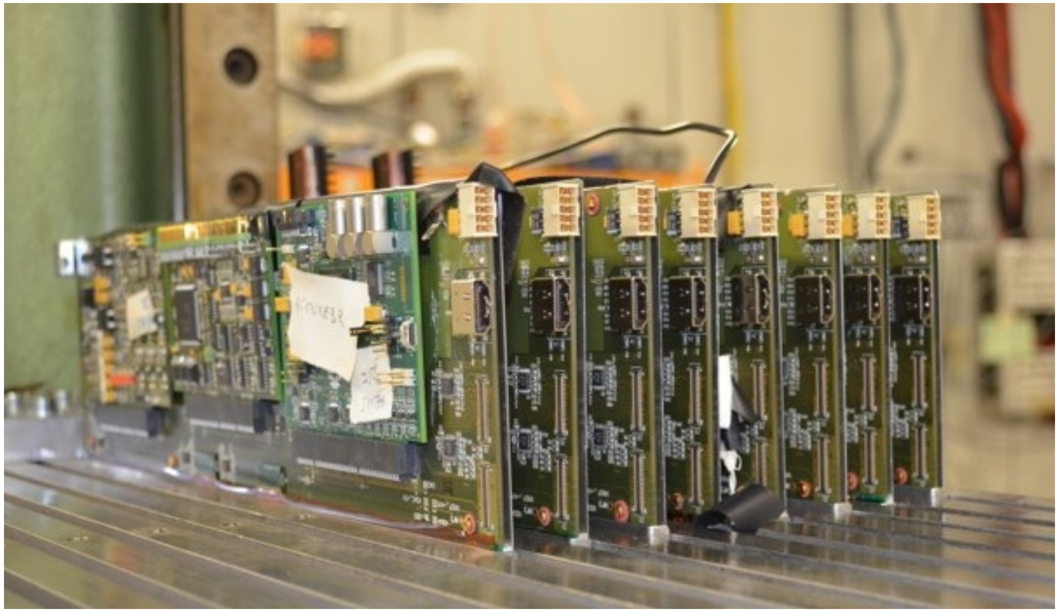
JINST 6 (2011) P07005

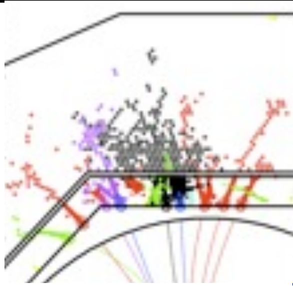


What we learnt

- 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.
  - 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

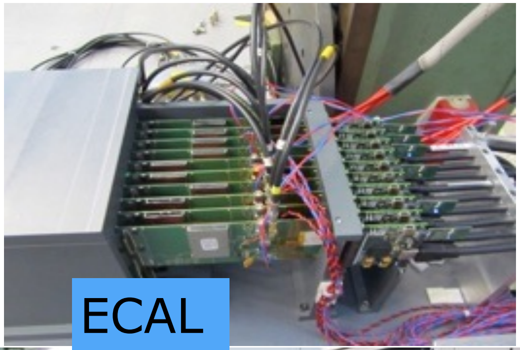


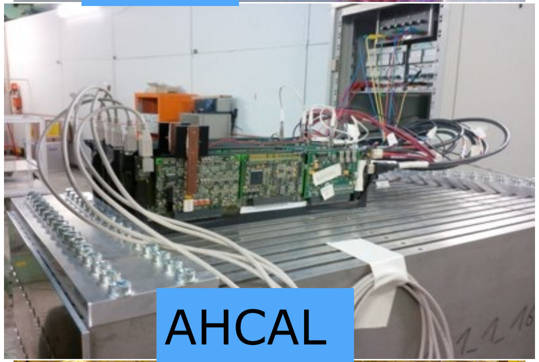


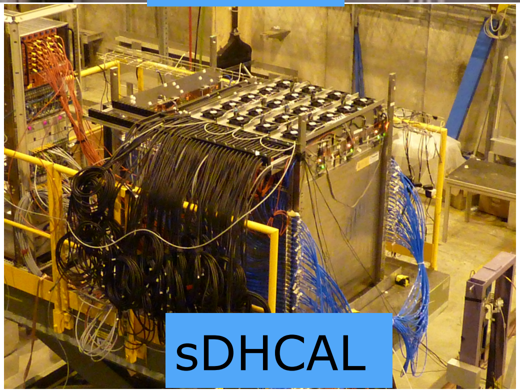
Technological prototypes

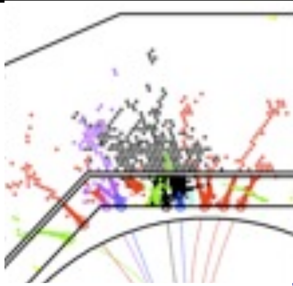
- Electronics integration, power pulsing
- Compact design: absorbers and PCBs
- Scalability

- 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



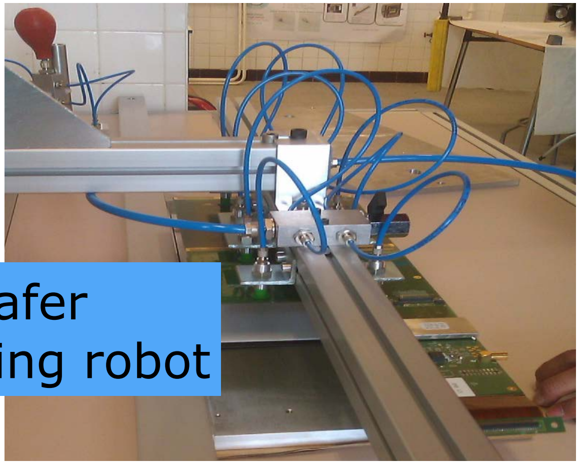




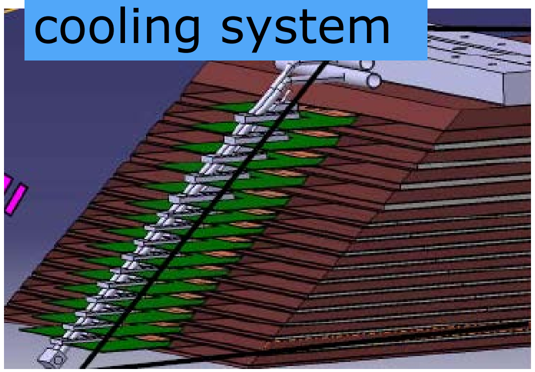


System integration & Tooling

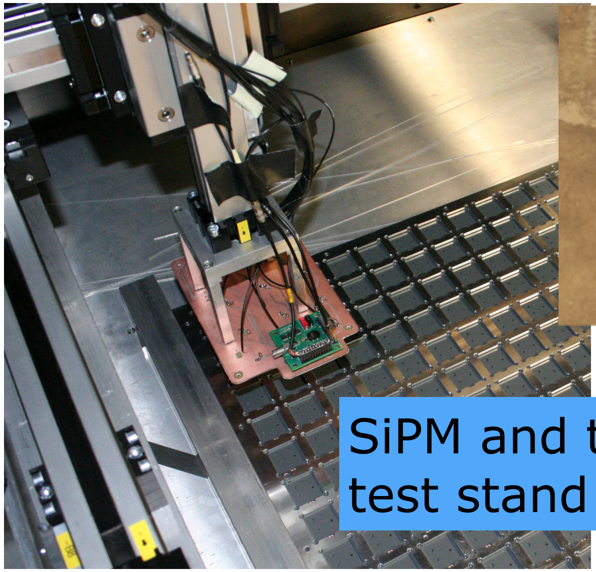
Chips on board



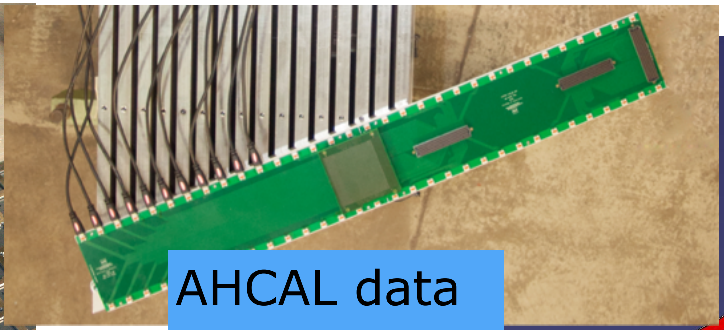
Si wafer glueing robot



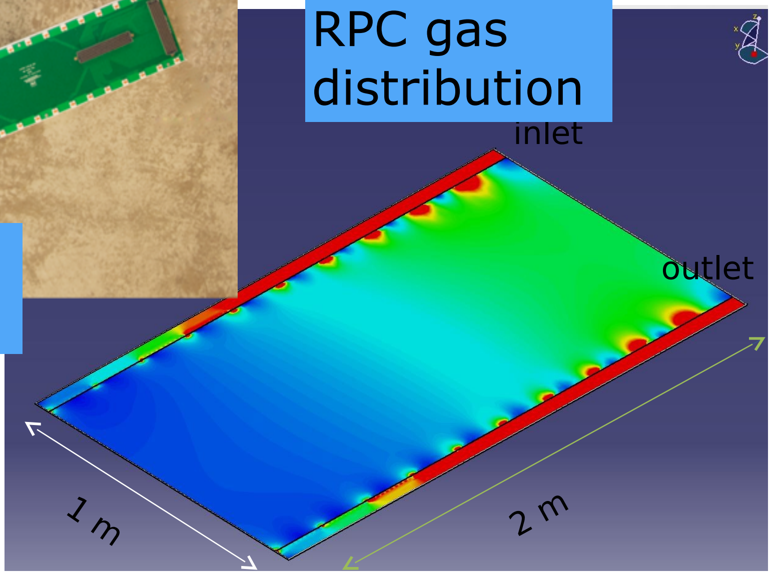
ECAL leak-less cooling system



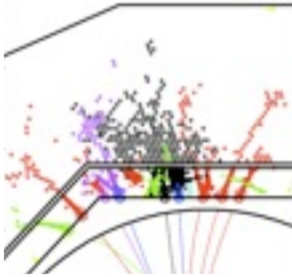
SiPM and tile test stand



AHCAL data concentrator

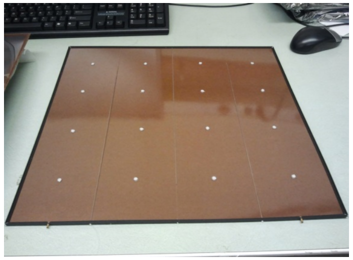


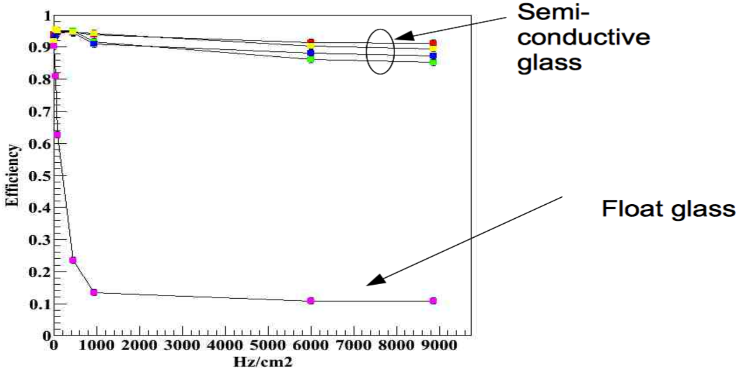
RPC gas distribution

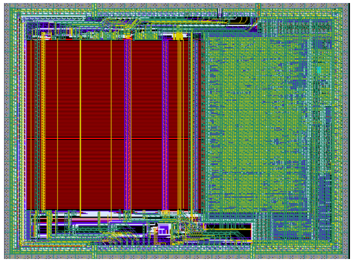


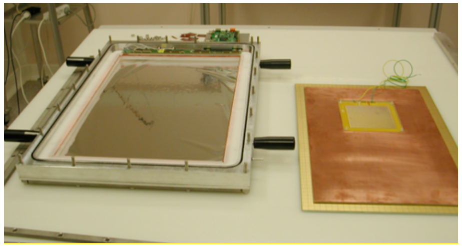
Gaseous HCAL

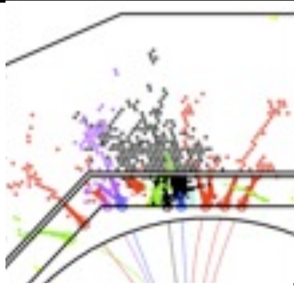
- Analysis: huge potential
  - modelling response for low and high density
  - optimise energy measurement, weighting
- RPC DHCAL, sDHCAL:
  - Large area ($2m^2$) chambers
  - HV and gas distribution
  - overcome rate limitations
    - 1-glass chambers
    - semi-conductive glass
    - bakelite
  - electronics and DAQ
- Micromegas:
  - resistive detectors; limit discharges
    - reduce active components
  - single mesh large size chambers
- GEMs, TGEMs:
  - large areas
  - optimise chambers
  - integrate uM ASIC





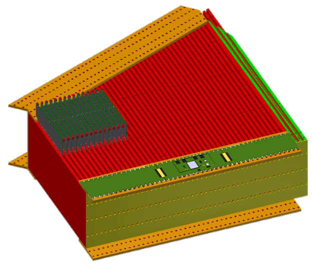


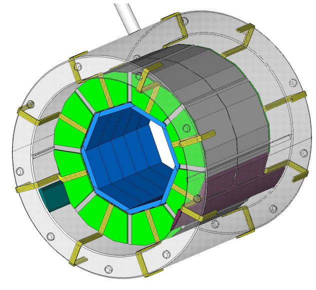


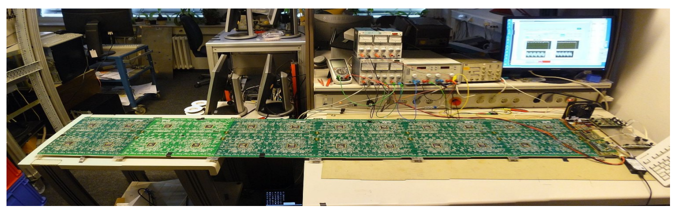


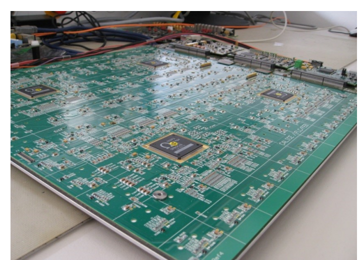
Industrialisation: Numbers!

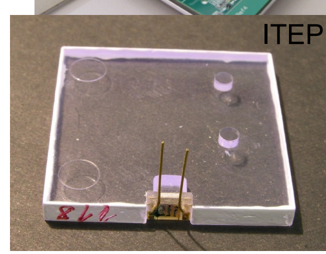
- The AHCAL
- 60 sub-modules
- 3000 layers
- 10,000 slabs
- 60,000 HBUs
- 200’000 ASICs
- 8,000,000 tiles and SiPMs



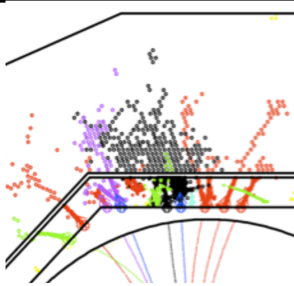






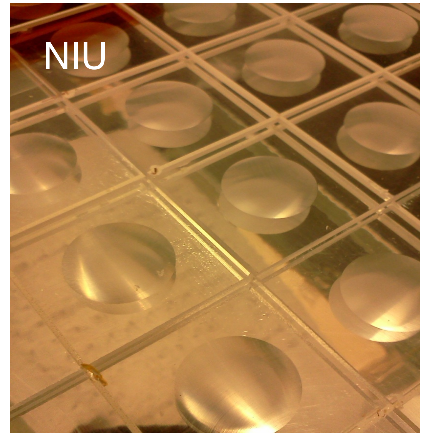


- One year
- 46 weeks
- 230 days
- 2000 hours
- 100,000 minutes
- 7,000,000 seconds

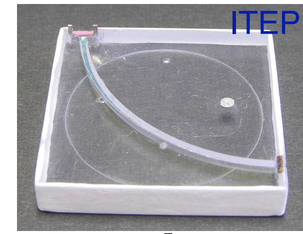


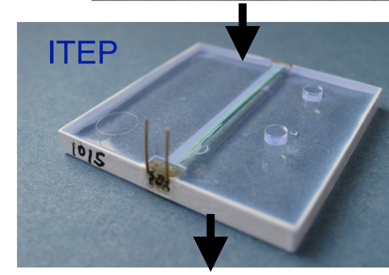
Directions in tile and SiPM R&D

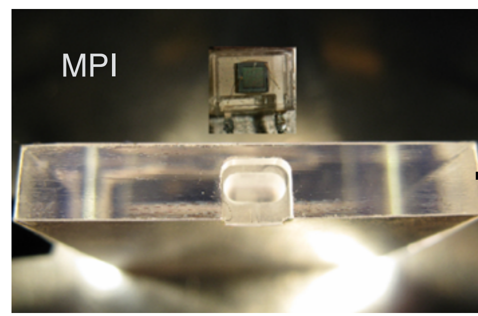
- Revise tile design in view of automatic pick & place procedures
- Consider SMD approach, originally proposed by NIU
- Light yield becomes an issue again
  - build on advances in SiPMs
    - see Yu.Musienko's talk
- Very different assembly, QC and characterisation chain

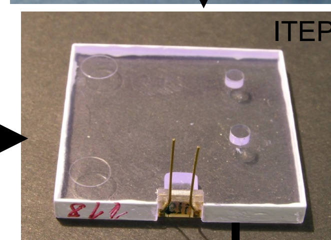


7608 ch physics prototype

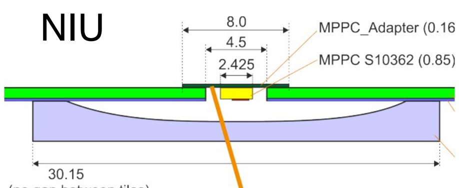








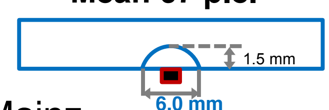
NIU



board coming to life

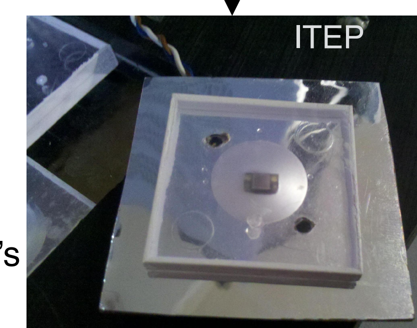
$1.2 \times 1.2\ mm$ SiPM

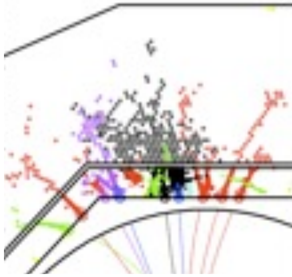
Mean 67 p.e.



Mainz

see D.Mironov's talk

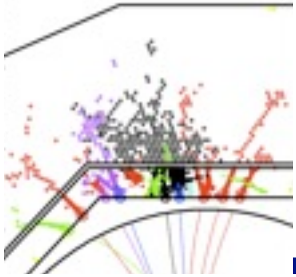




Conclusion

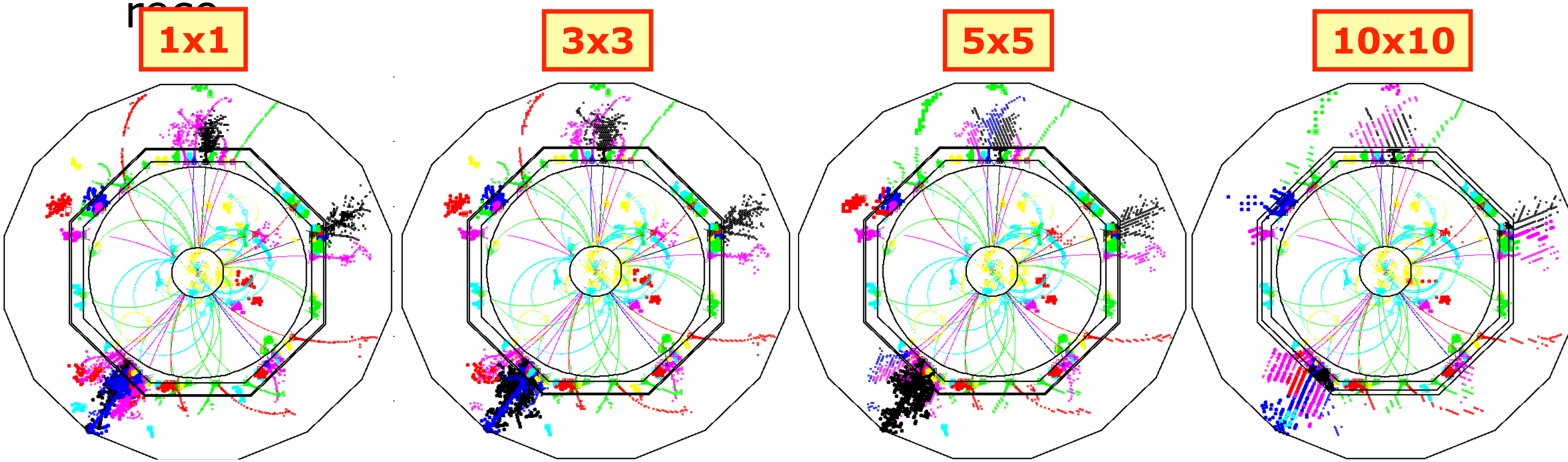
- Calorimetry has changed - particle flow concept established experimentally
- Now fully in second phase: make it realistic
- There are many open issues = room for new ideas

Back-up slides

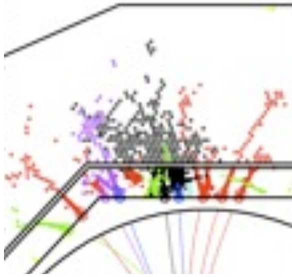


Tile granularity

- Recent studies with PFLOW algorithm, full simulation and reco



M.Thomson (Cambridge)



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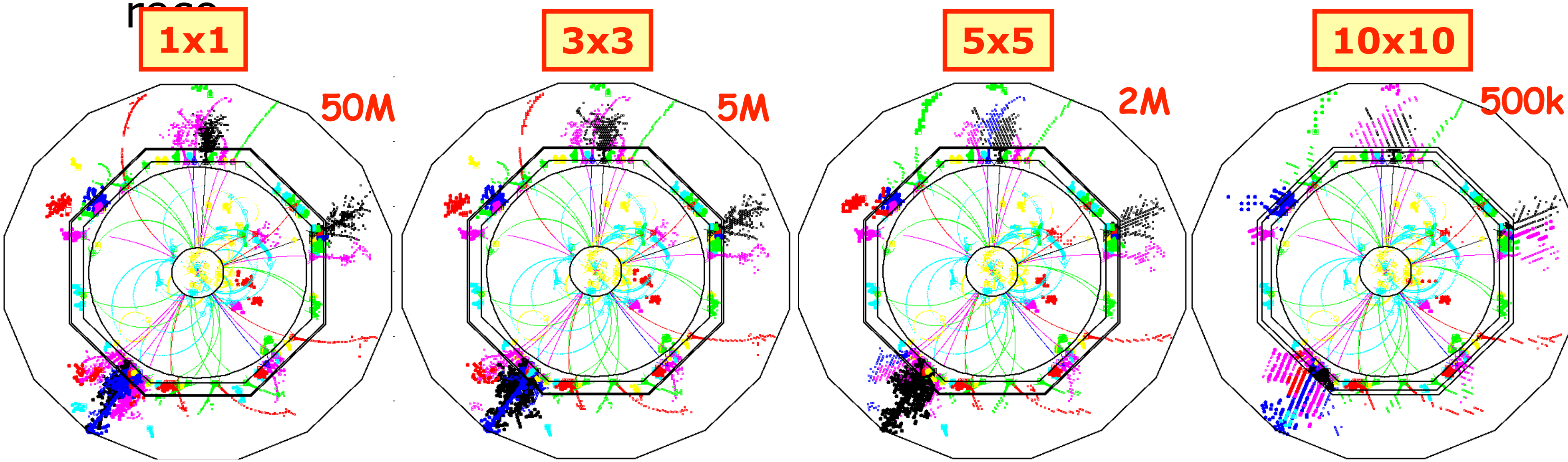

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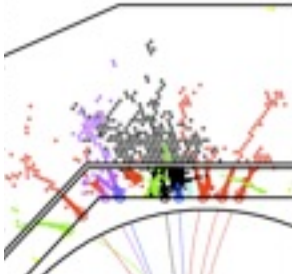

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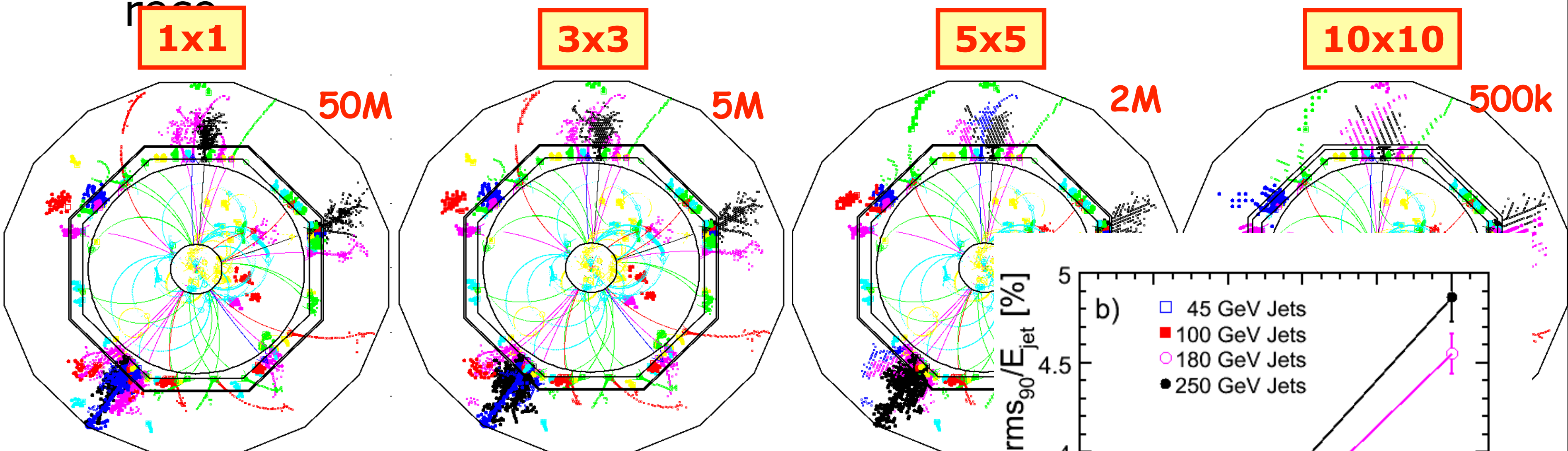
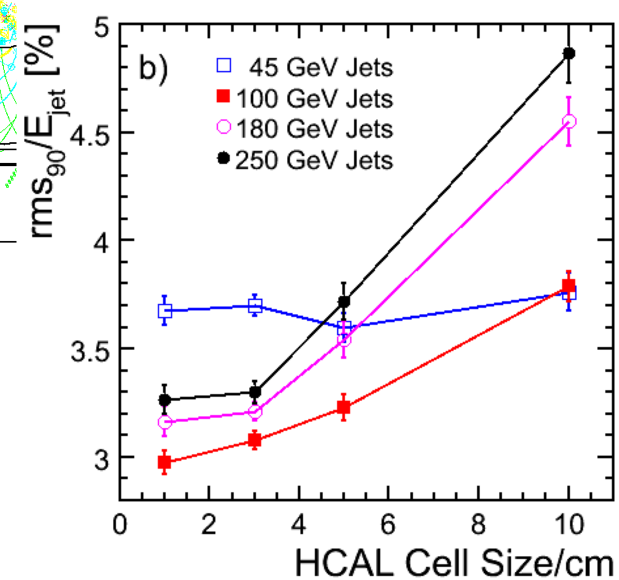
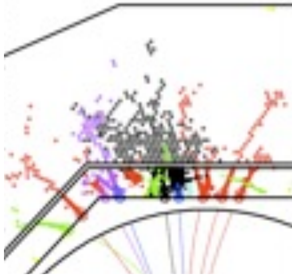




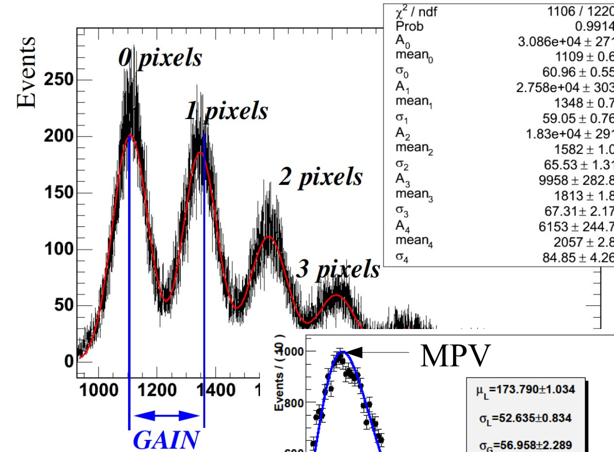
- Confirms earlier studies for test beam prototype
- 3x3 cm^2 nearly optimal

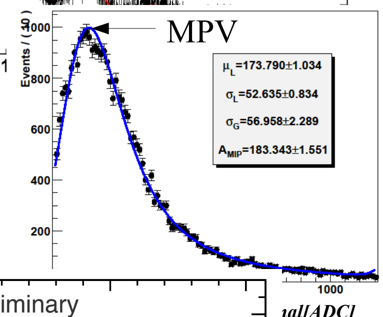
M.Thomson (Cambridge)

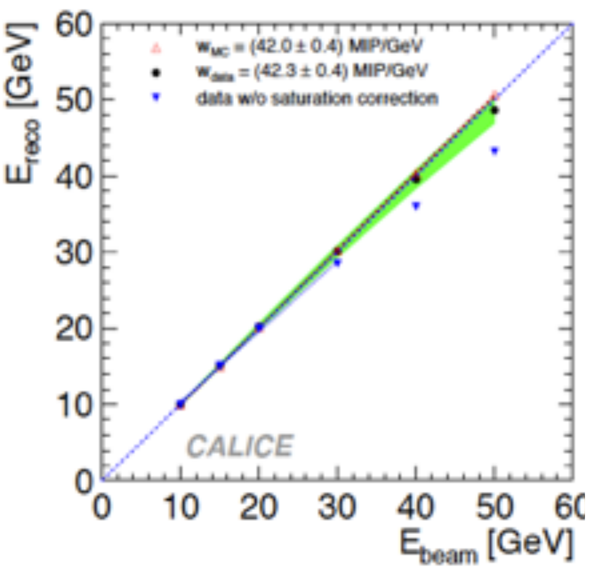


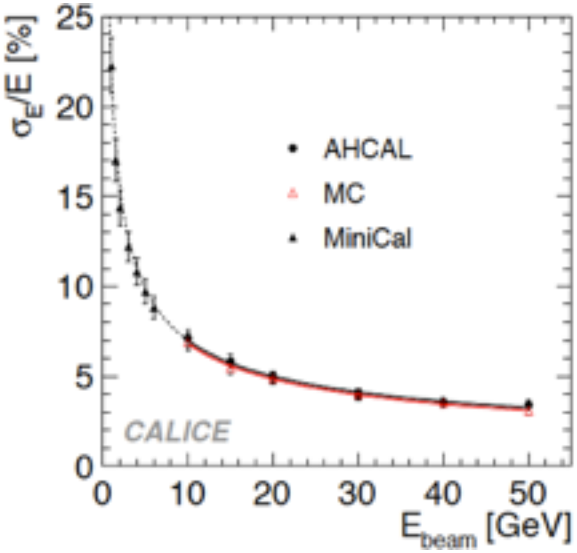
Scint AHCAL calibration and electromagnetic performance

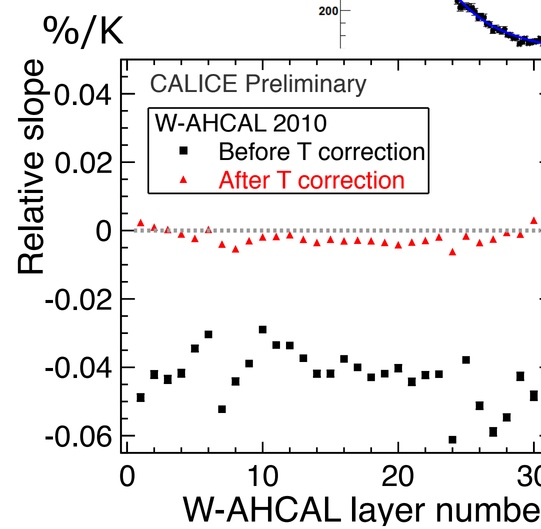
- SiPM gain monitoring: self-calibrating
- Cell equalization: MIPs
- Temperature correction: ~4%/K
- Validation of calibration and simulation with electrons



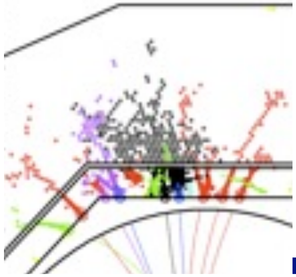






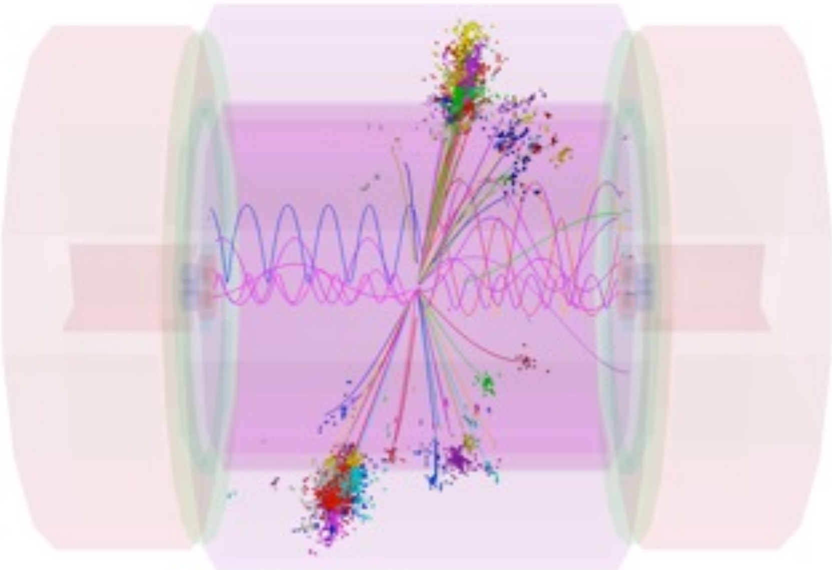


Published in JINST 6, P04003 (2011)

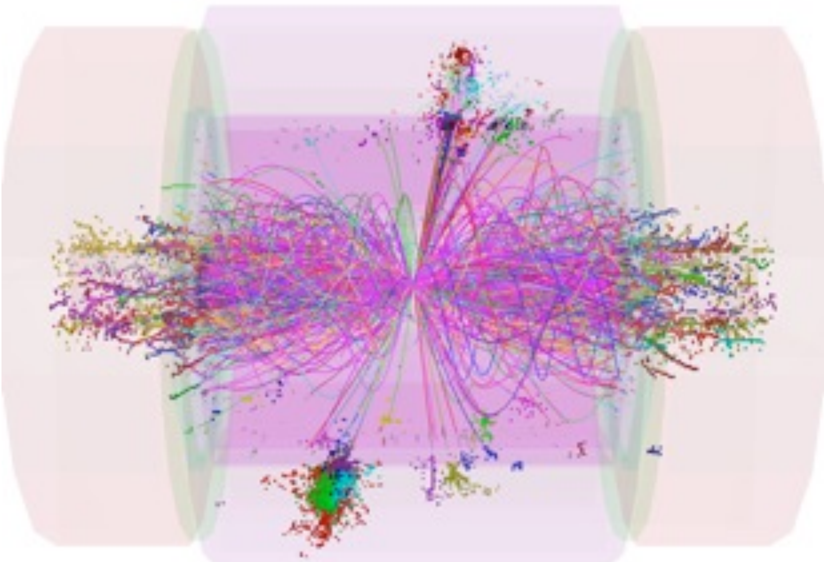


PFLOW under CLIC conditions

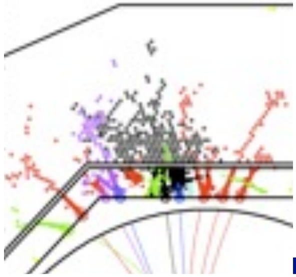
- Overlay γγ events from 60 BX (every 0.5 ns)
- take sub-detector specific integration times, multi-hit capability and time-stamping accuracy into account
- apply pt and timing cuts on cluster level (sub-ns accuracy)



Z @ 1 TeV



+ 1.4 TeV BG (reconstructed particles)



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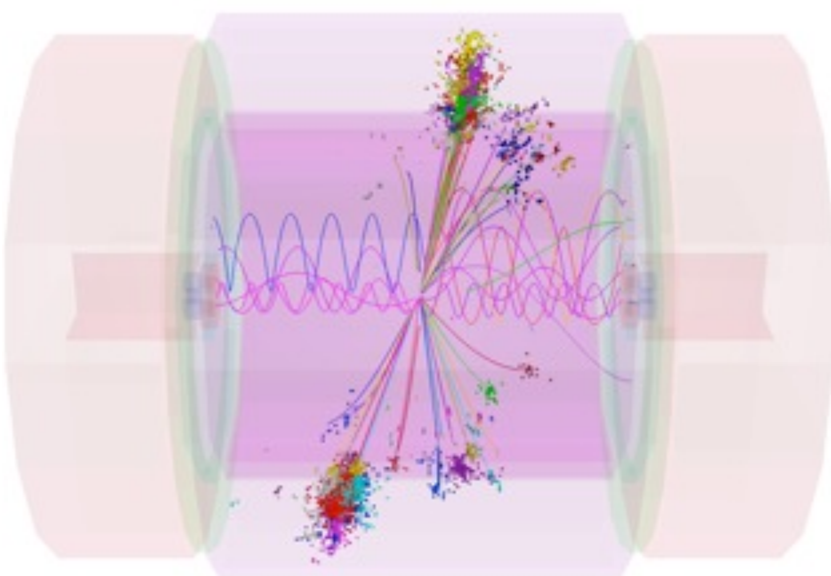
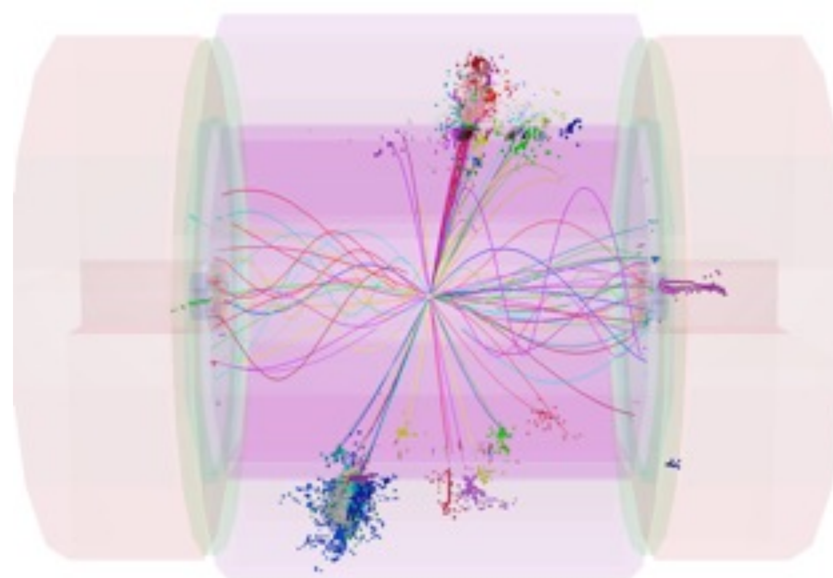


Z @ 1 TeV



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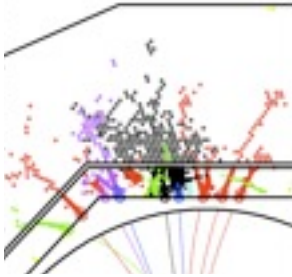

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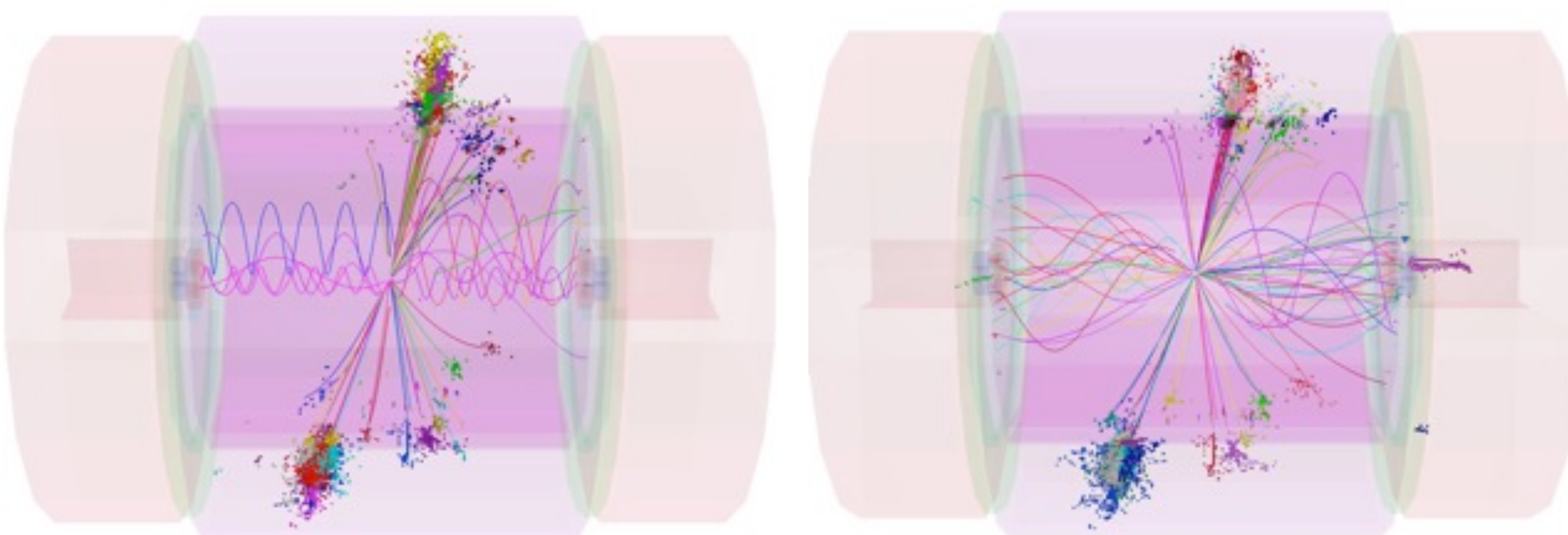

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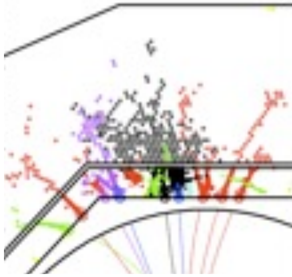
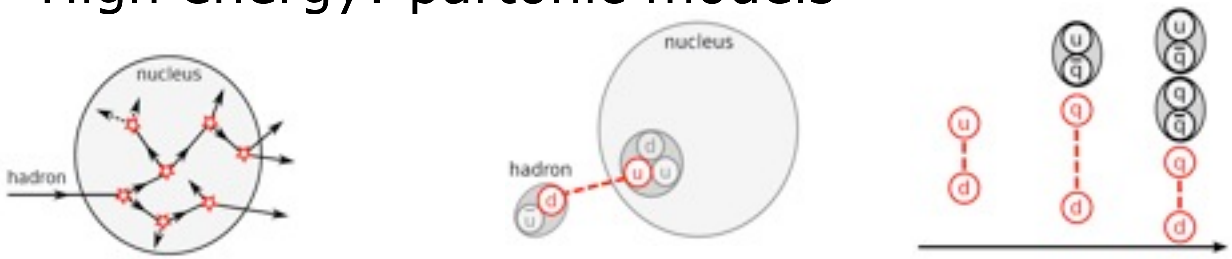
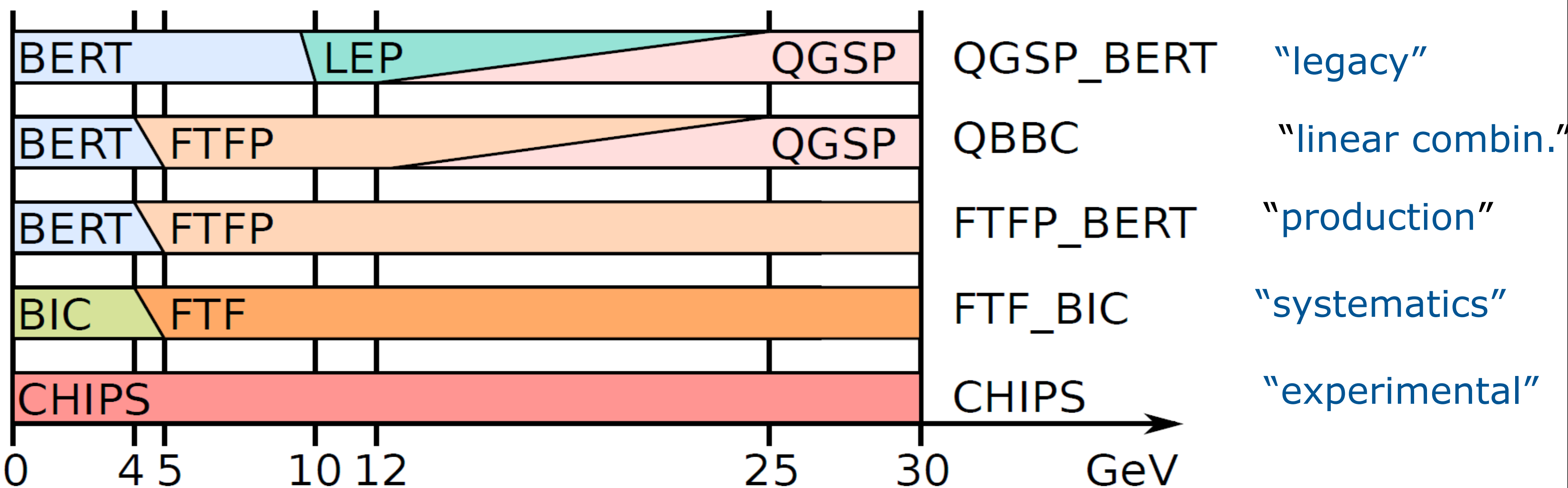


Shower simulation in Geant 4

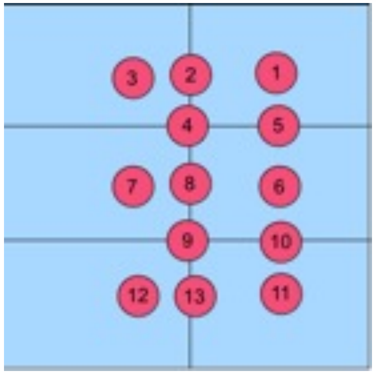
- Low energy: cascade models
- High energy: partonic models



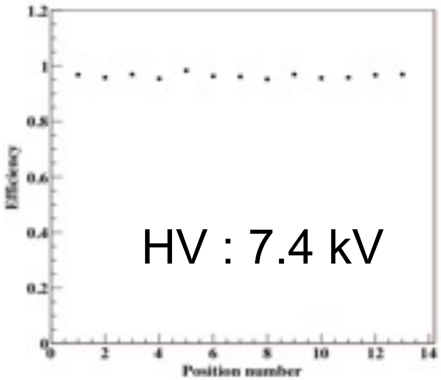
minimize use of phenomenological parameterization



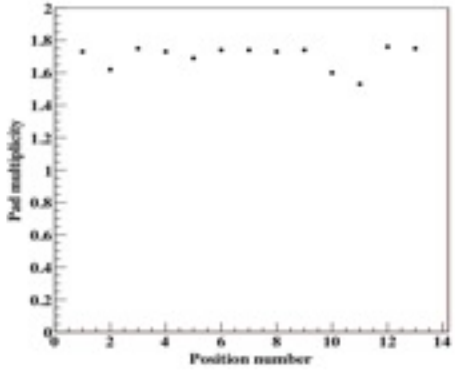
The homogeneity of the detector and its readout electronics were studied



Beam spot position



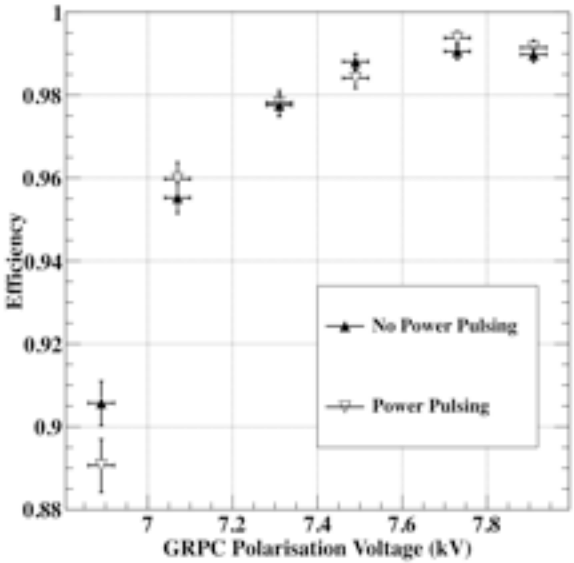
Efficiency



Multiplicity

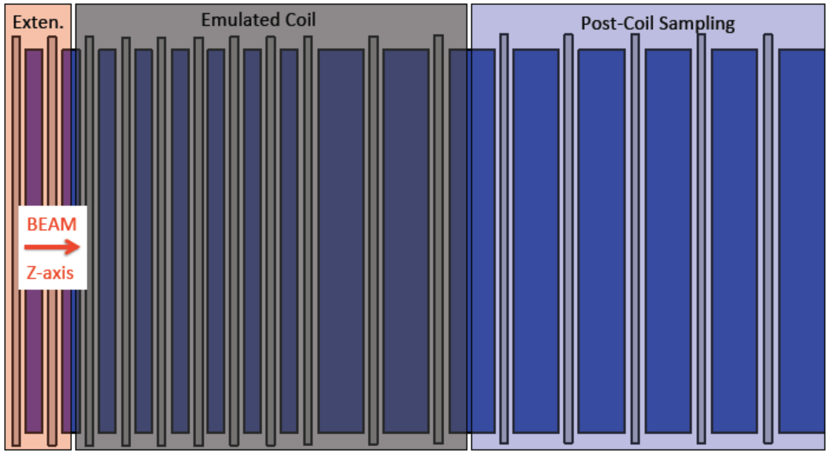
Power-Pulsing mode was tested in a magnetic field of 3 Tesla

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



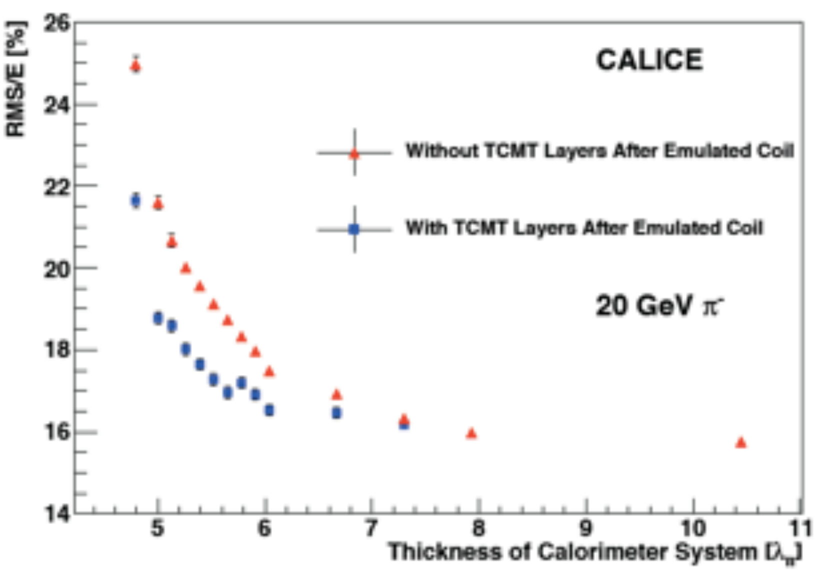
Containment – use of Tail Catcher

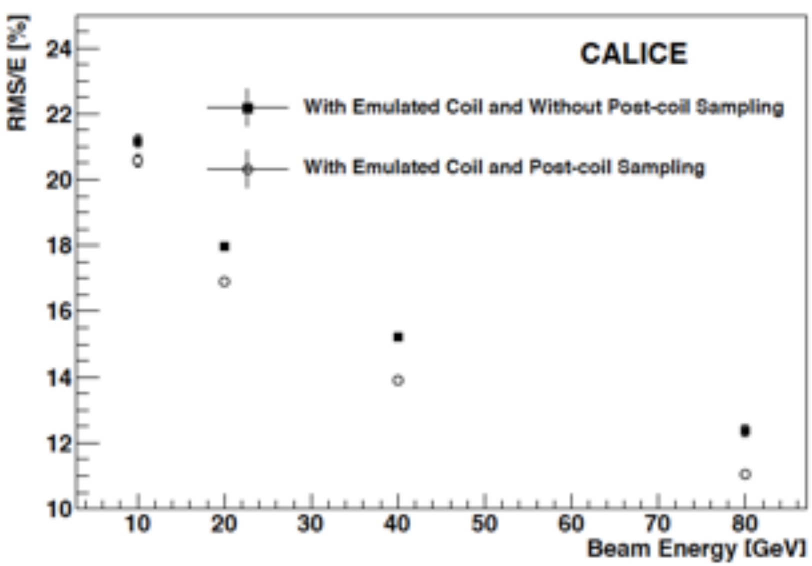
- Tail catcher gives us information about tails of hadronic showers.
- Use ECAL+HCAL+TCMT to emulate the effect of coil by omitting layers in software, assuming shower after coil can be sampled.
- Significant improvement in resolution, especially at higher energies.



2012_JINST_7_P04015

arxiv:1201.1653 (accepted by JINST)





Common developments

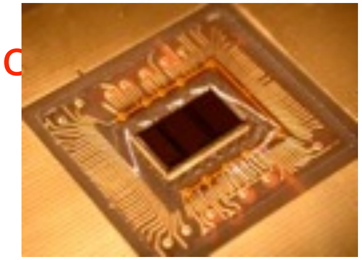
Front end electronics

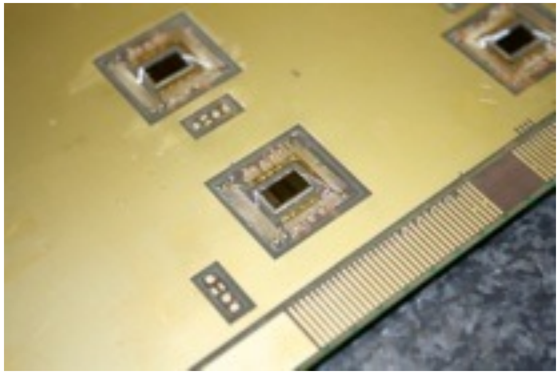
not reported here: test beam infrastructure, DAQ, software and computing

ILC Challenges for electronics

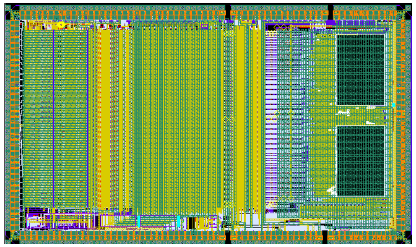
- Requirements for electronics
  - Large dynamic range (15 bits)
  - Auto-trigger on ½ MIP
  - On chip zero suppress
  - Front-end embedded in detector
  - 10^8 channels
  - **Ultra-low power : (25µW/ch)**
  - Compactness
- « Tracker electronics with calorimetric performance »

it's gonna heat !
=>Power pulse

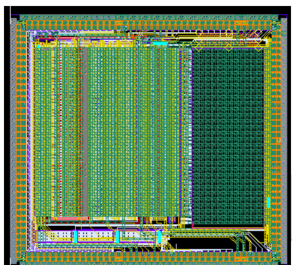




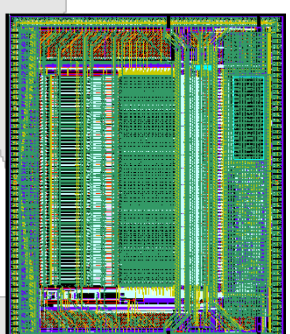
ASICs for ILC prototypes



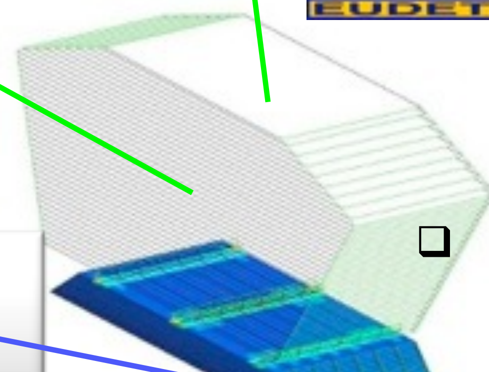
SPIROC2
Analog HCAL (AHCAL)
(SiPM)
36 ch. 32mm²
June 07, June 08, March 10



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 Zer suppress**