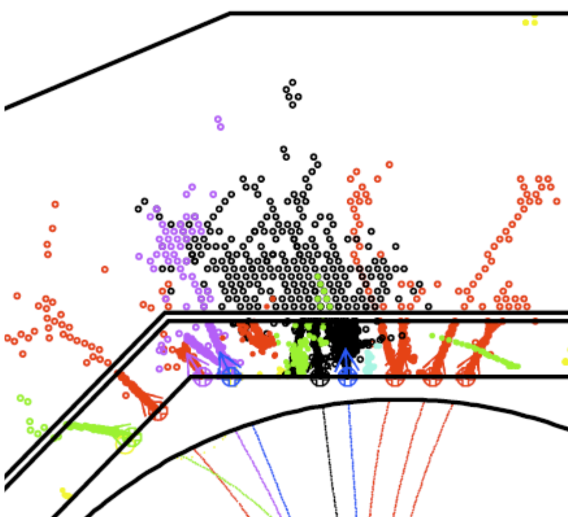
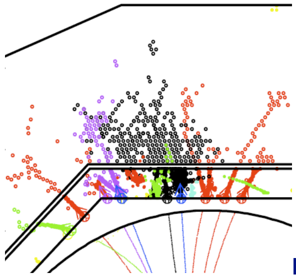
Calorimeters for CLIC - Technologies and Performance

Felix Sefkow



Review of the CLIC Physics and Detector CDR
Manchester, October 18-20, 2011

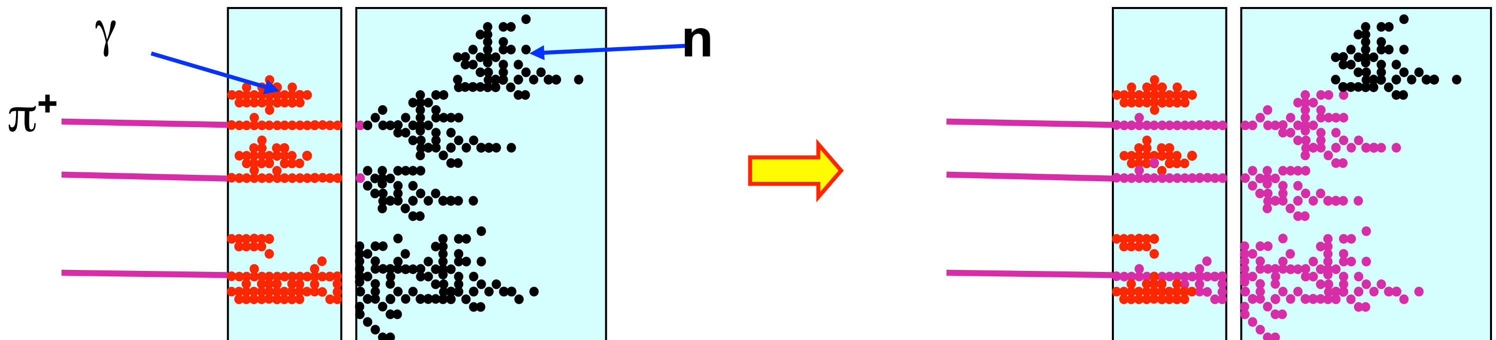


Outline

- The CLIC Physics and Detector CDR chapter on calorimetry was edited by Tohru Takeshita (Japan), Andy White (USA), and FS
- A particle flow calorimeter for CLIC
- ECAL and HCAL technologies and tests
- Performance at CLIC
- Calorimeter R&D for CLIC

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**



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

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

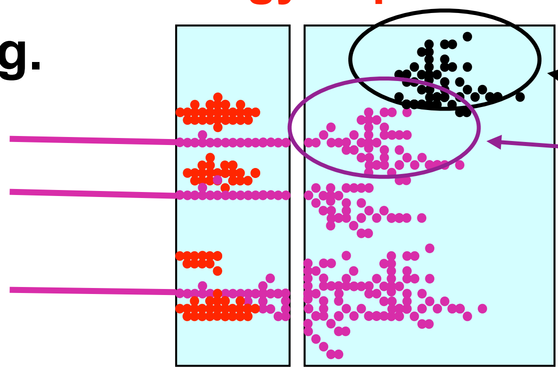
- **Particle Flow Calorimetry paradigm:**
  - **charged particles measured in tracker (essentially perfectly)**
  - **Photons in ECAL:** $\sigma_\mathrm{E}/\mathrm{E} < 20\,\%/\sqrt{\mathrm{E(GeV)}}$
  - **Neutral hadrons (ONLY) in HCAL**
  - **Only 10 % of jet energy from HCAL** ⇒ **much improved resolution**

Particle Flow Reconstruction

Reconstruction of a Particle Flow Calorimeter:

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

e.g.

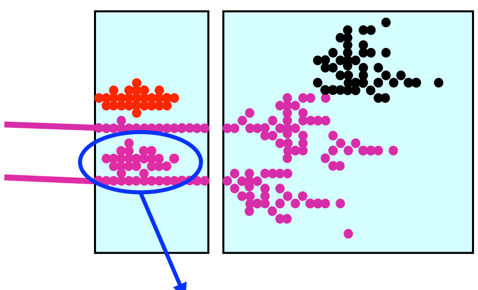


If these hits are clustered together with **these**, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

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

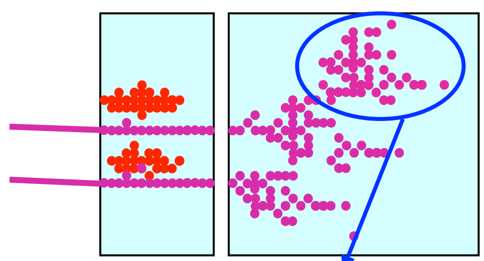
Three types of confusion:

i) Photons



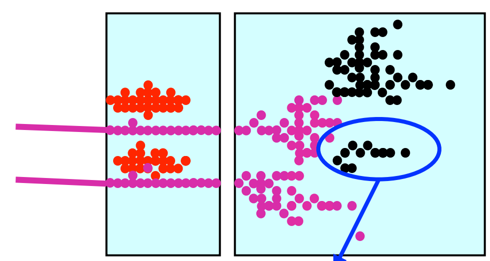
Failure to resolve photon

ii) Neutral Hadrons

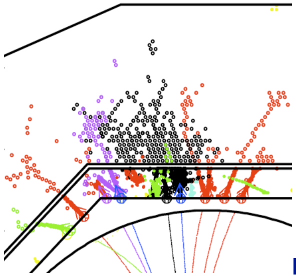


Failure to resolve neutral hadron

iii) Fragments

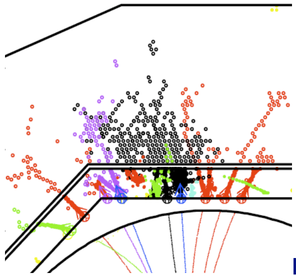


Reconstruct fragment as separate neutral hadron



Calorimeter concept

- large radius and length
  - to separate the particles
- large magnetic field
  - to sweep out charged tracks
- “no” material in front
  - stay inside coil
- small Moliere radius
  - to minimize shower overlap
- small granularity
  - to separate overlapping showers



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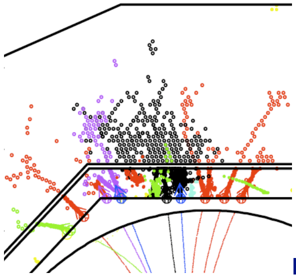
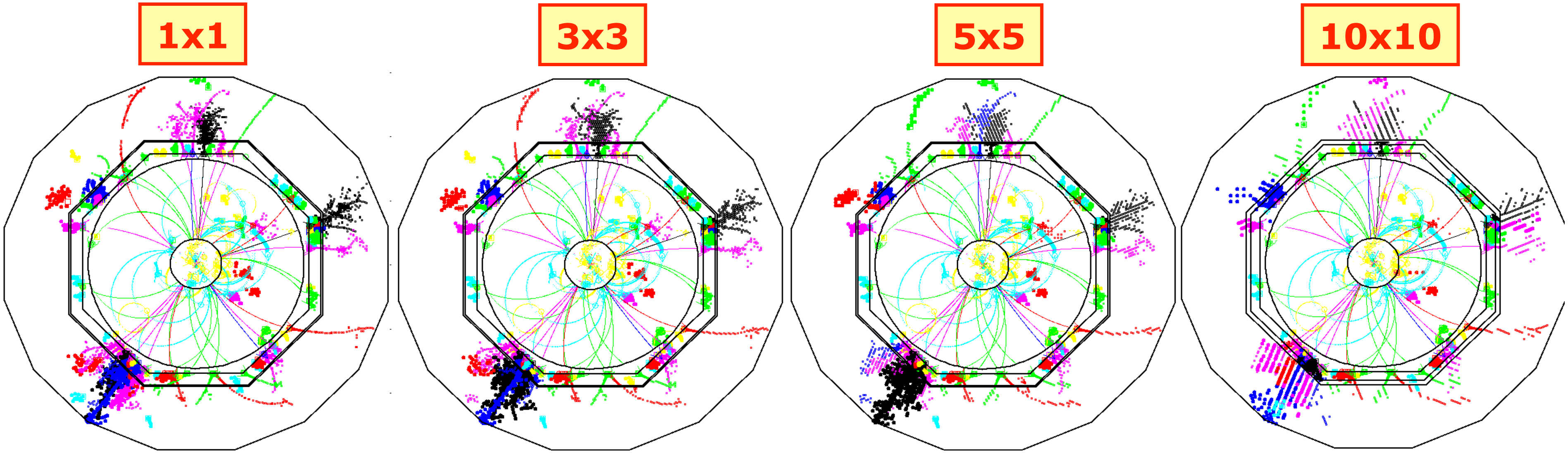
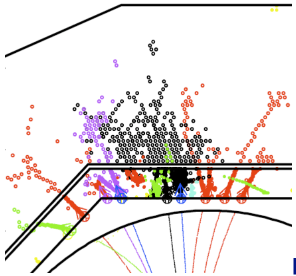


Granularity

- Studies for ILD with PandoraPFA, full simulation and reco



M.Thomson



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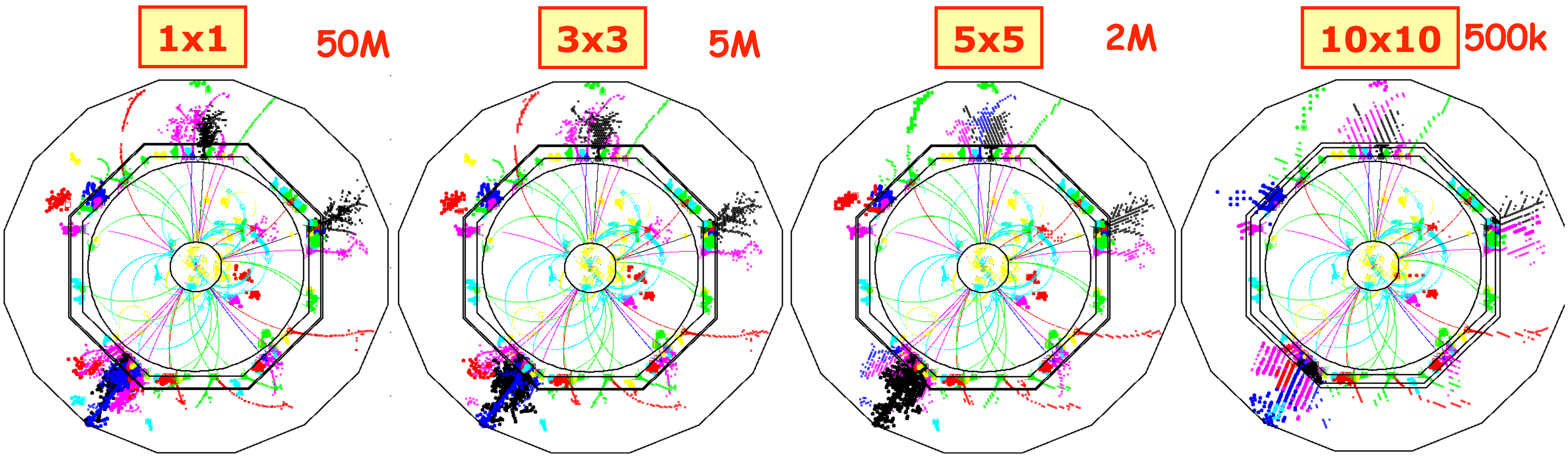

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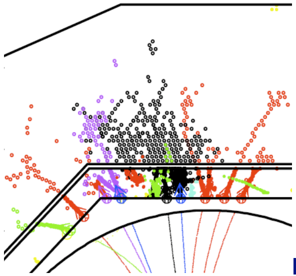

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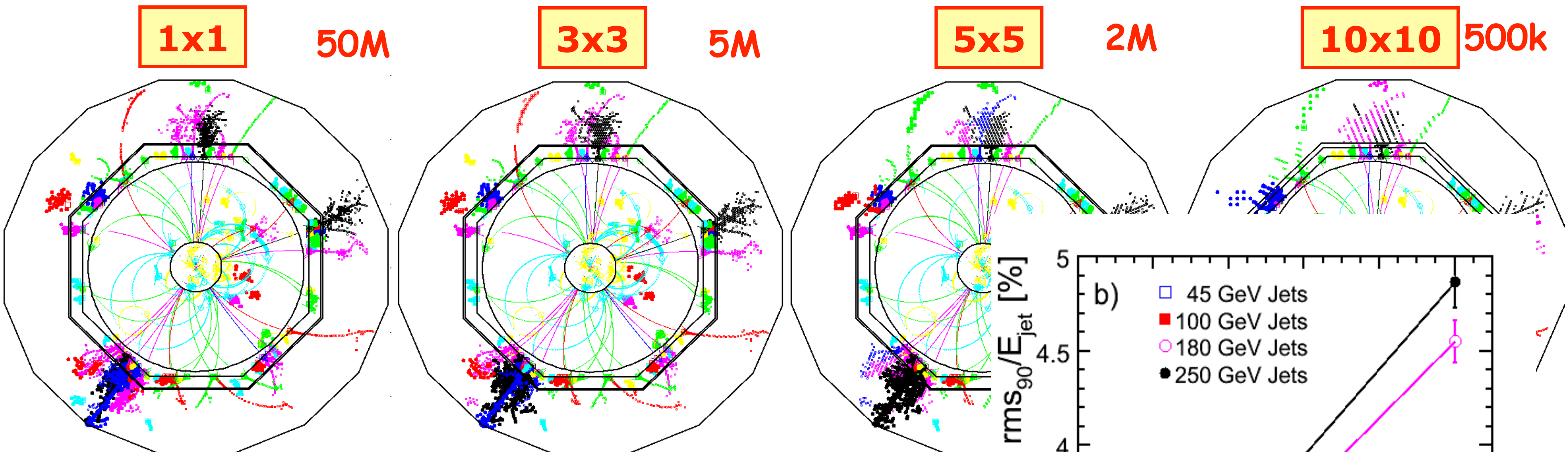
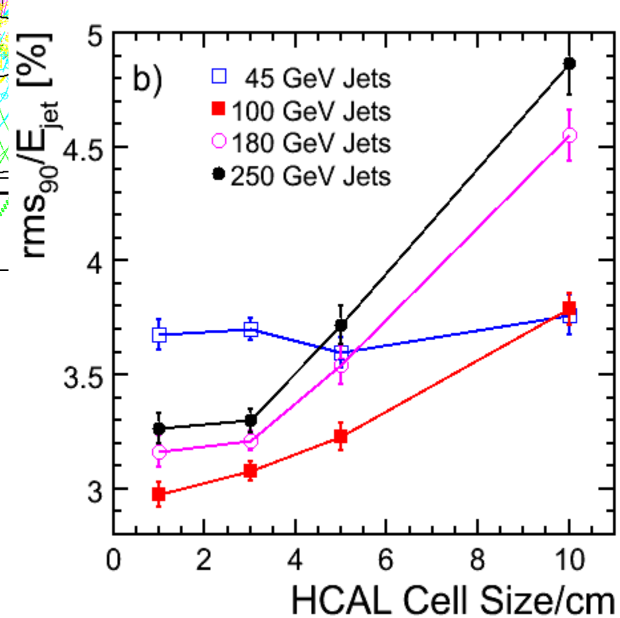
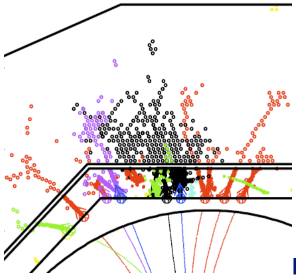




M.Thomson

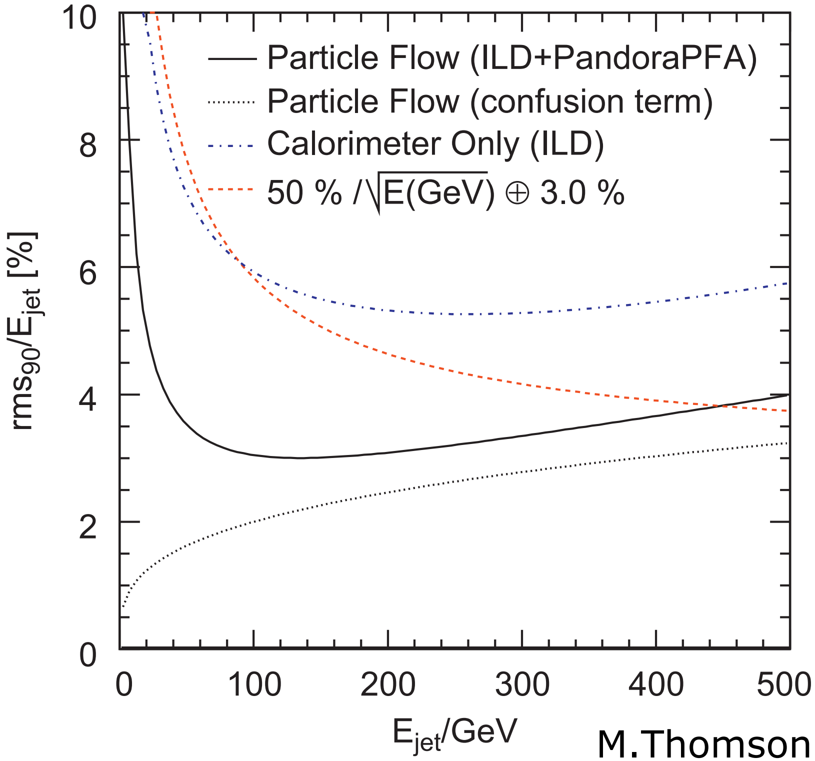
- Confirms earlier studies for test beam prototype with 2nd PFA
- 3x3 cm^2 nearly optimal for (scintillator) HCAL
- Similar study: 0.5-1cm for ECAL

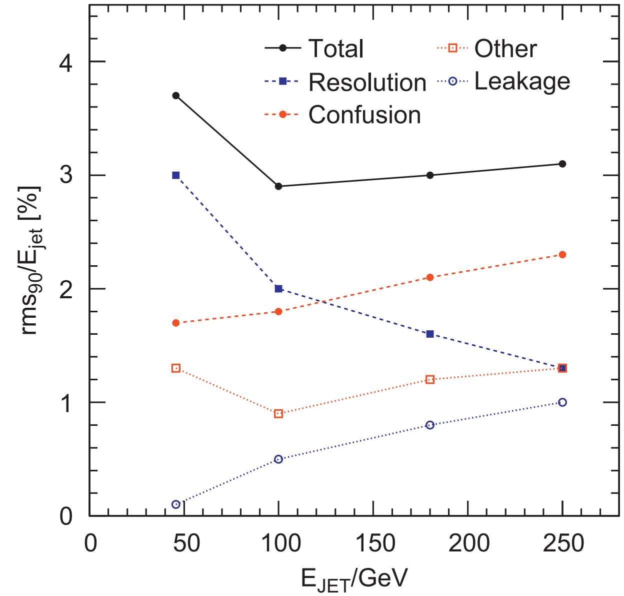


Understand particle flow performance

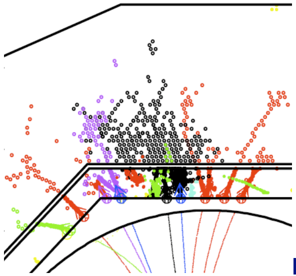
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution Tracking Leakage Confusion





- Particle flow performs always better than calo alone
  - even at high jet energies
- Leakage becomes important for CLIC energies
- Initial studies: need ~8λ



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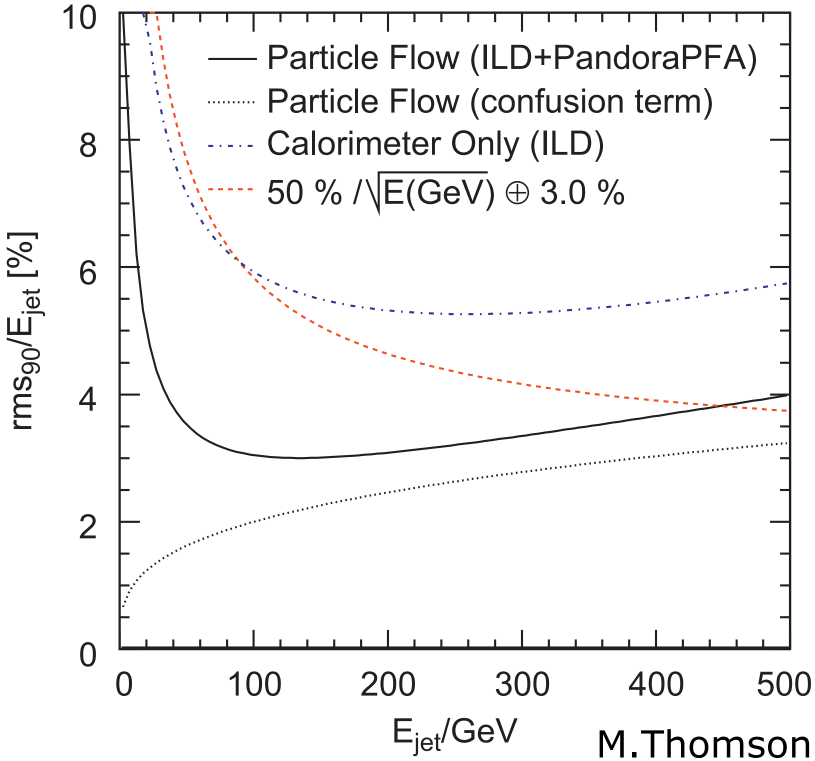
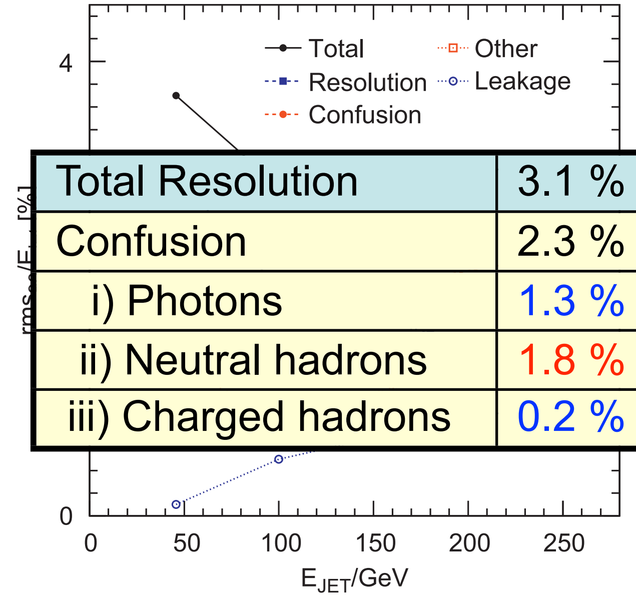
$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution | Tracking | Leakage | Confusion





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

- Particle flow performs always better than calo alone
  - even at high jet energies
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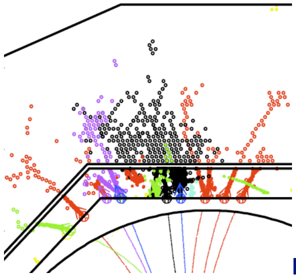
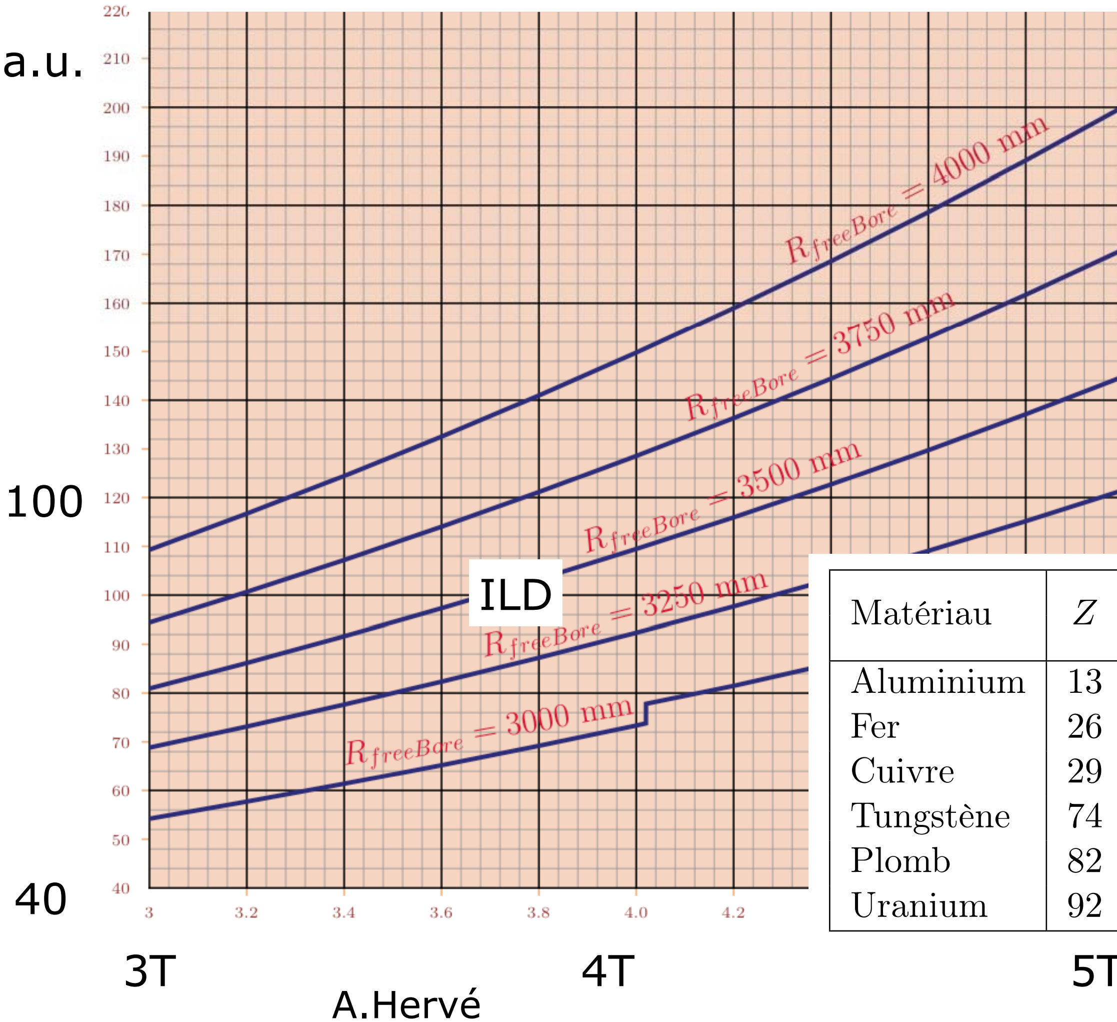
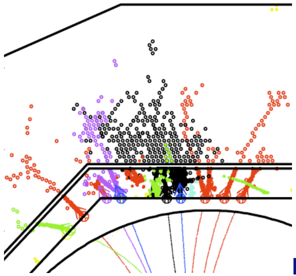


Larger or denser?



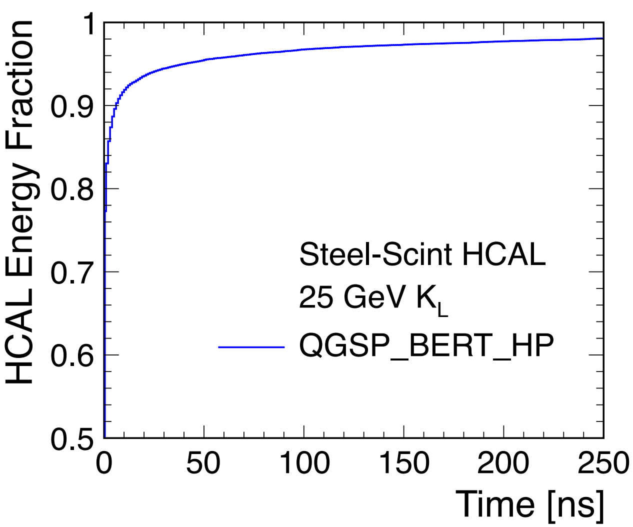
- ILD: "upper limit"
  - magnet, yoke, cost
- tungsten HCAL cost-competitive!
  - denser than U
  - no environmental issues

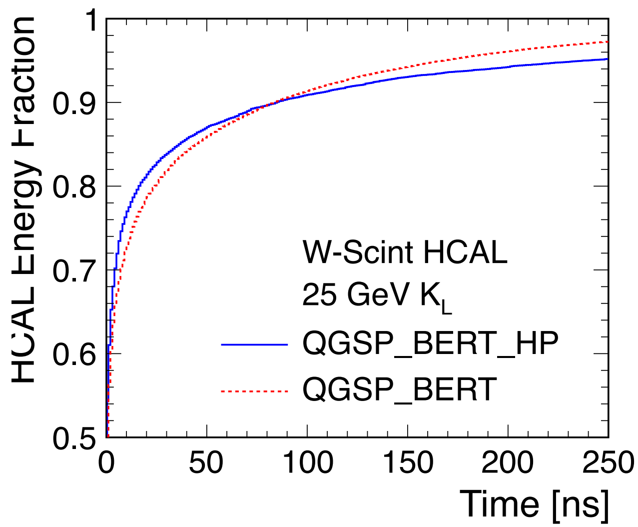
Matériau	Z	Densité [g.cm^{-3}]	X_0 [mm]	λ_I [mm] $\pi^{\pm}$	λ_I [mm] p,n	$(dE/dx)_{MIP}$ [MeV.cm^{-1}]
Aluminium	13	2.70	88.8	506	397	4.35
Fer	26	7.87	17.6	204	167	11.4
Cuivre	29	8.6	15.6	185	153	12.6
Tungstène	74	19.3	9.3	113	99	22.1
Plomb	82	11.3	16.	199	175	12.7
Uranium	92	18.95	10.1	124	110	20.5

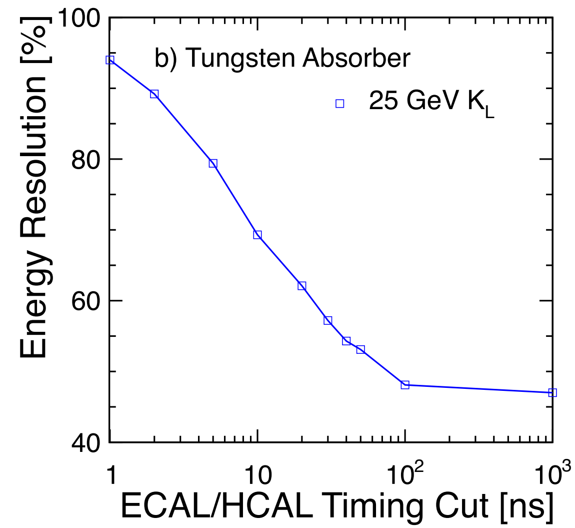


Tungsten response vs time

- W is neutron rich, not magic like Fe
- “slower” response due to de-excitation and slow neutrons
- limitations to time stamping, need longer integration time
- Geant 4 model uncertainties: need experimental validation
  - physics and detector aspects, scintillator and gas
- choice of steel as absorber for the end cap







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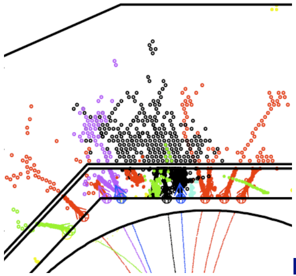
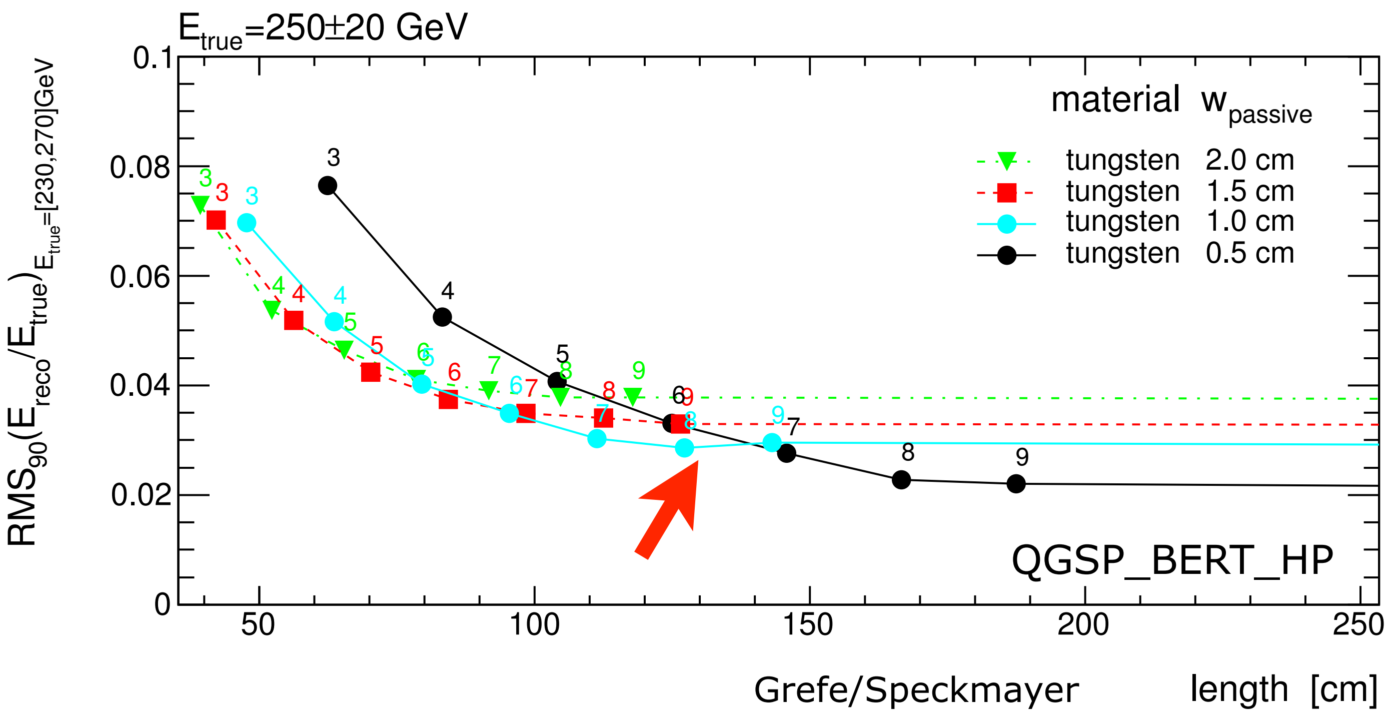
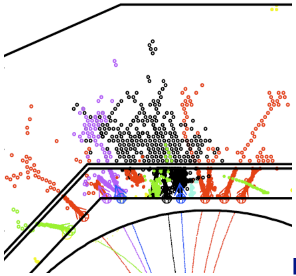


Optimization of sampling

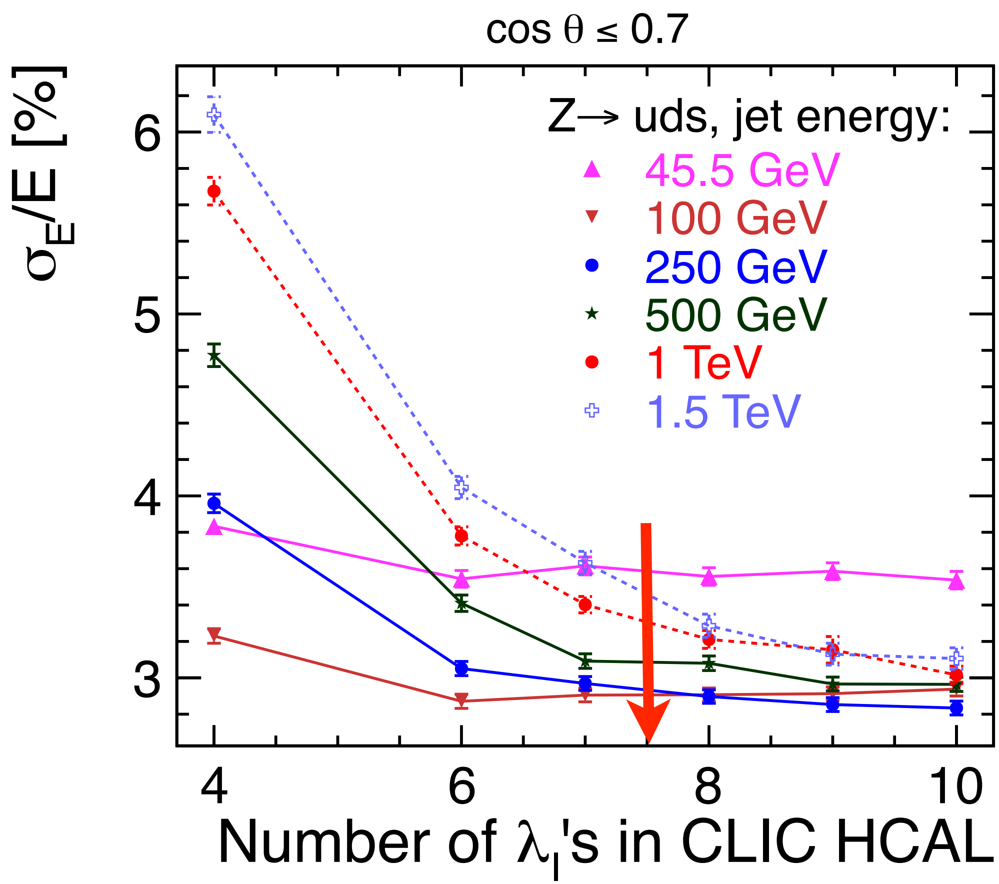
- In a PFLOW calorimeter every layer is read out individually
  - signal over noise, electronics: minimum active layer thickness
- Geant 4 study with single particles, vary plate d and n
- cf steel: need 50cm more to reach plateau





Optimization of depth

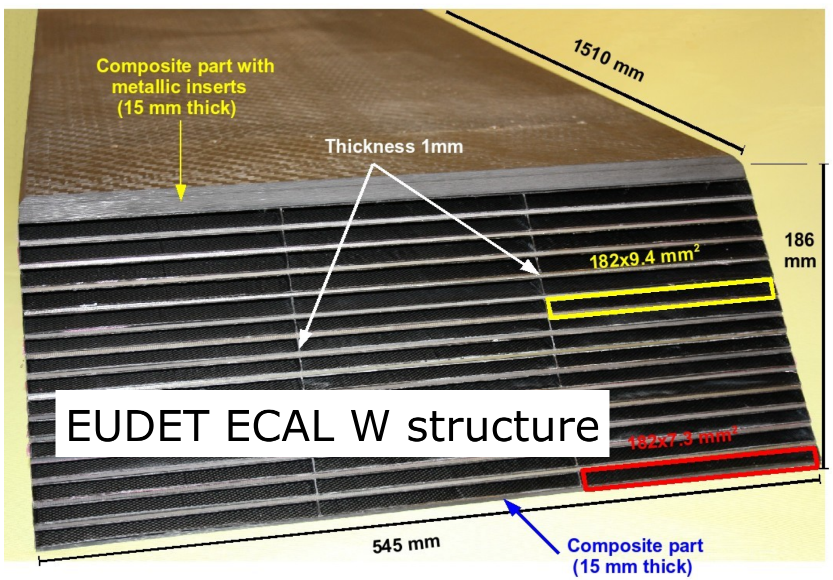
- overall effect depends on abundance of high energy singe particles
- jet study using PandoraPFA
- NB: no topological leakage estimation used yet



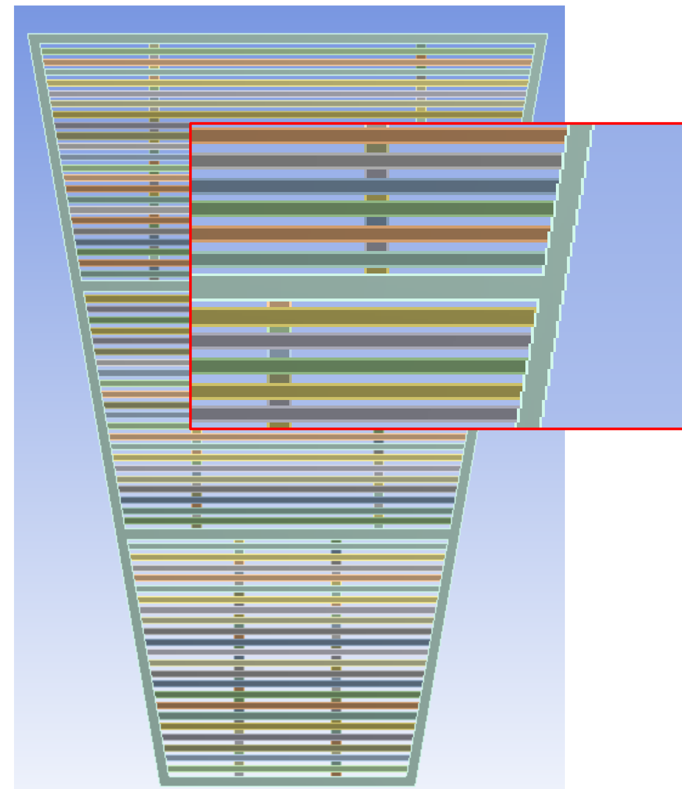
A.Lucaci

Tungsten engineering

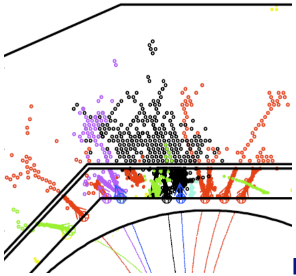
- market survey; use non-mag alloy with Ni, Cu, not as brittle as pure W
- engineering study (FEM)for HCAL absorber with steel support
  - minimal dead mazterial
  - no structural show stopper



EUDET ECAL W structure

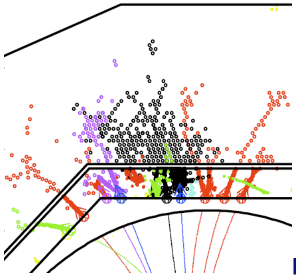


HCAL barrel sector

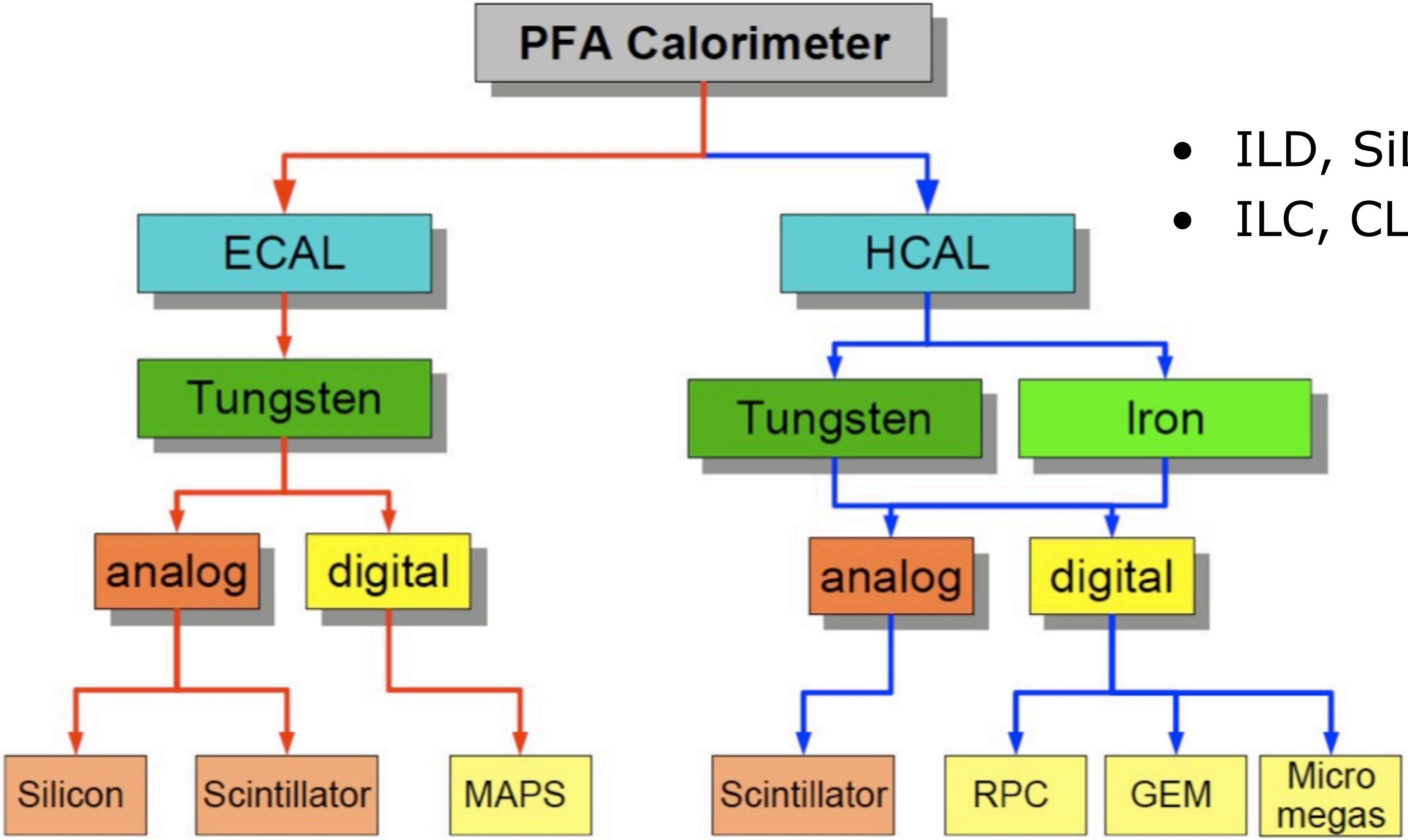


Summary concept

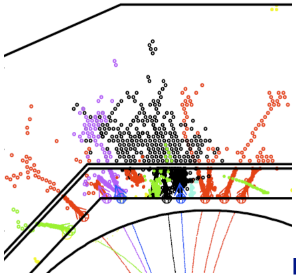
- The promising first results on particle flow at CLIC energies have boosted the development and understanding of Pandora
- Results confirm that physics performance can be achieved
- Coil is limited: the barrel HCAL absorber needs to be dense
- Engineering aspects have been explored
  - LHC and first own experience
- Calorimetric properties of tungsten need to be experimentally validated, including the time structure



Technology tree



- ILD, SiD
- ILC, CLIC



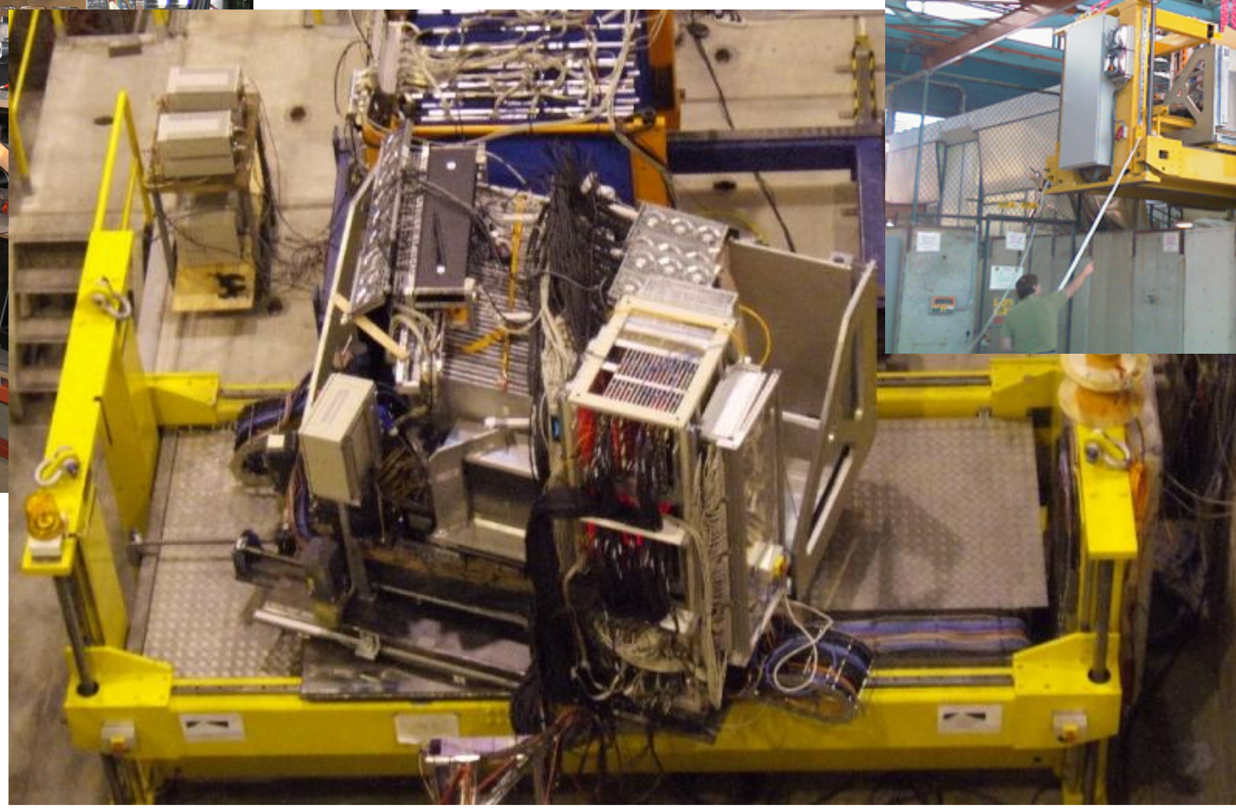
CALICE collaboration

- >300 physicists and engineers from 57 institutes in Africa, America, Europe and Asia
- Twofold approach:
  - Physics prototypes and test beam
    - Operational experience with new technologies, Test of shower simulation models,
    - Reconstruction algorithms with real data
  - Technical prototypes
    - Realistic, scalable design (and costing)

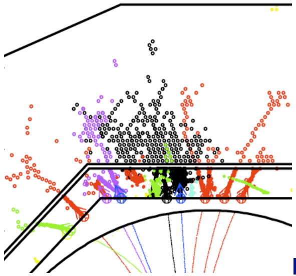
Test beam experiments

DESY 2005

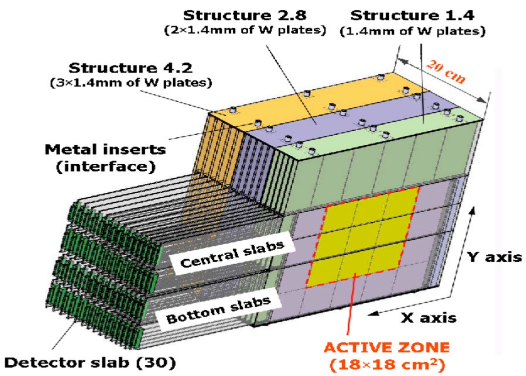
CERN 2006-2007

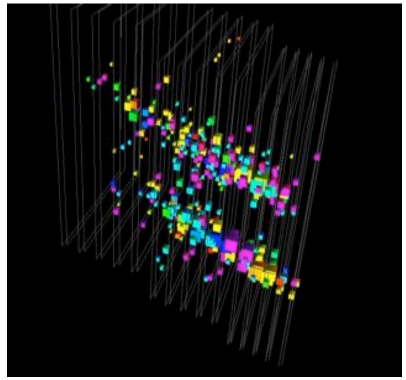


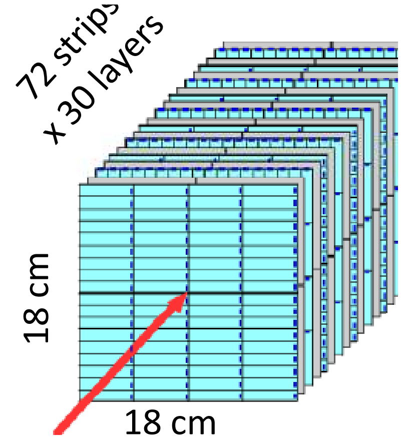
FNAL 2008..

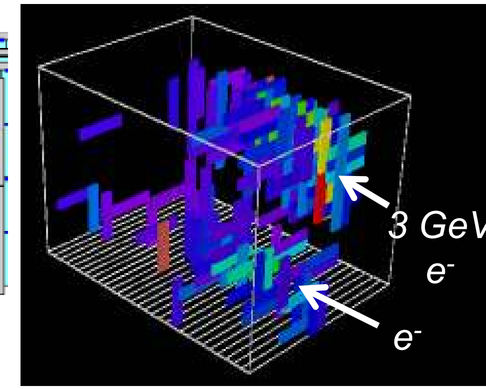


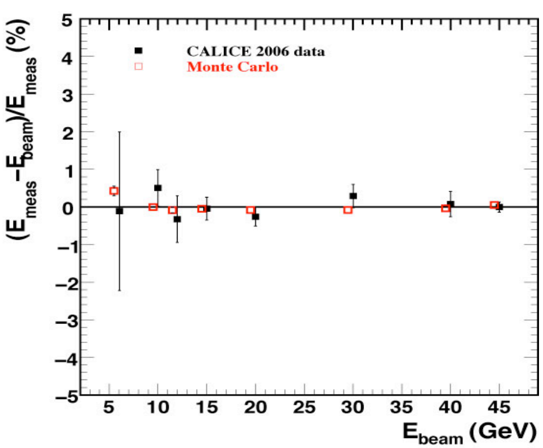
ECAL test beam results

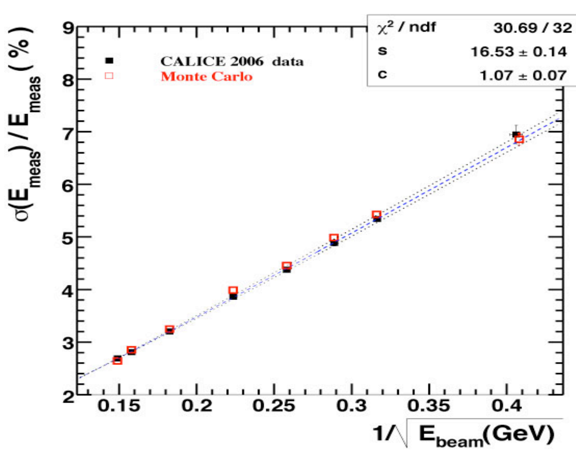


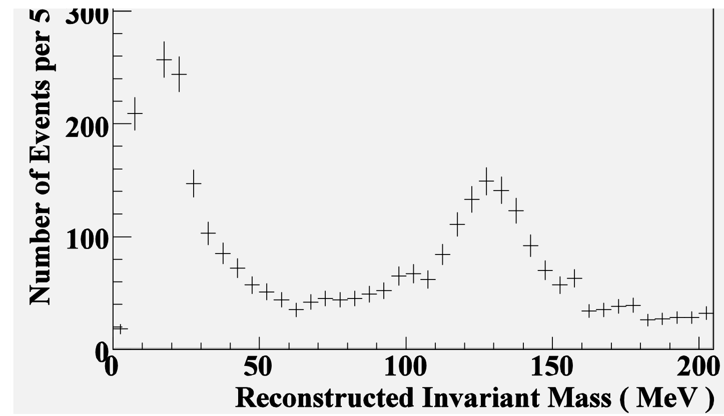




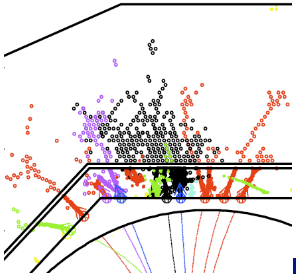






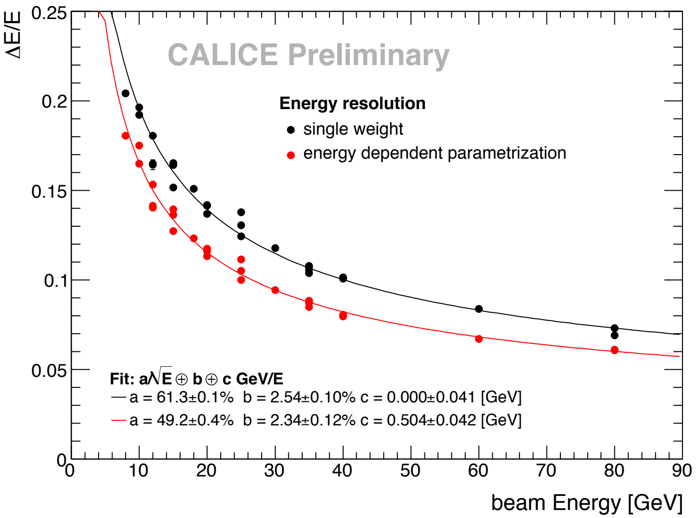


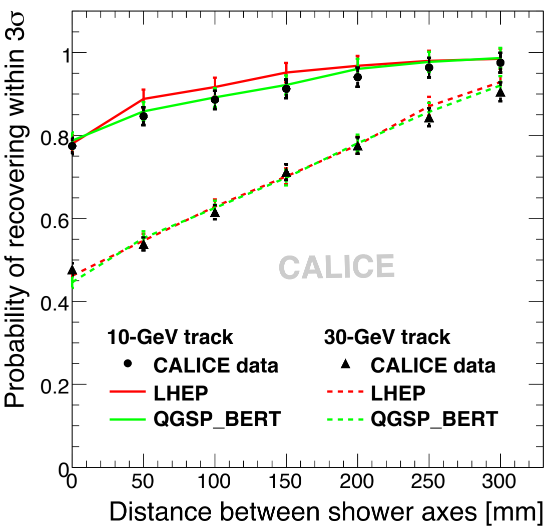
- W Si or Sci: common mechanics, similar electronics

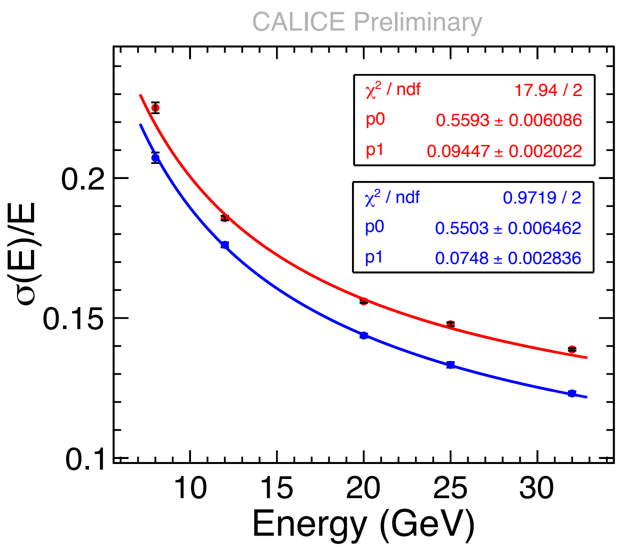


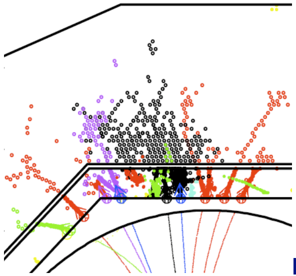
HCAL test beam results

- Energy resolution confirmed
- Weighting techniques established
- Particle flow performance validated
- First results with digital calorimetry

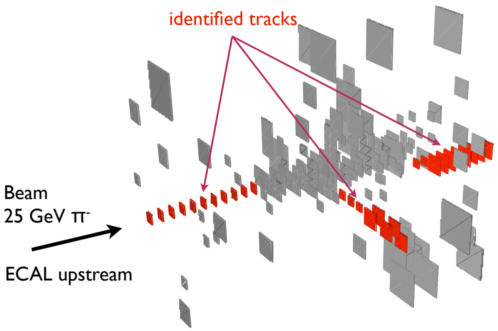


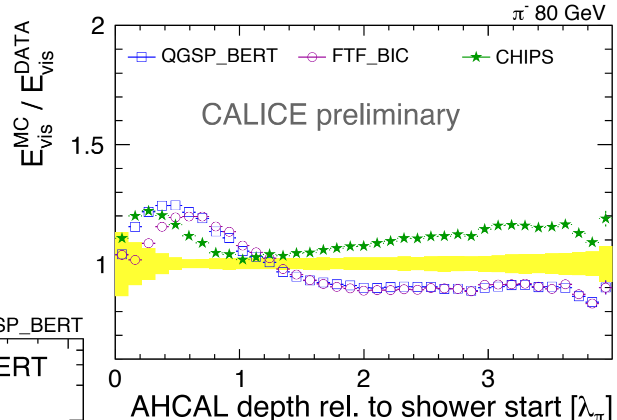


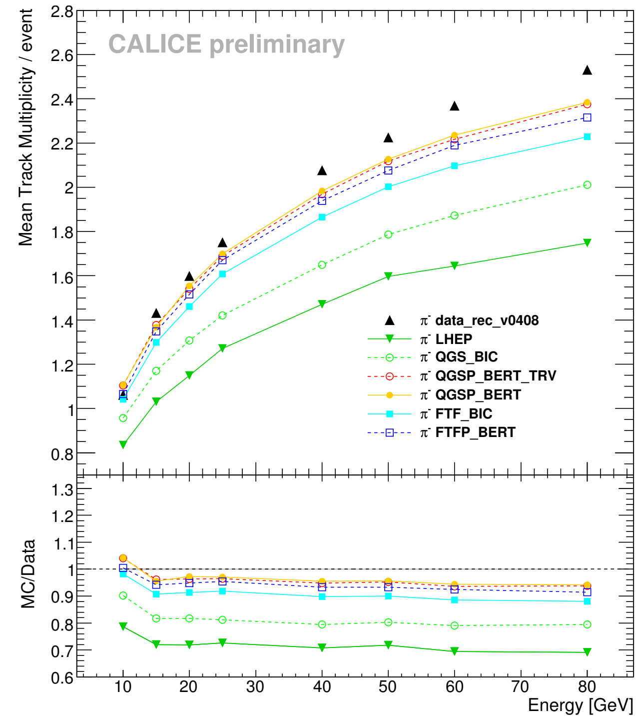


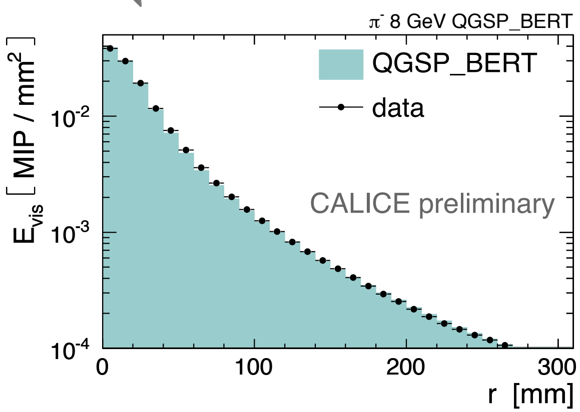


Geant 4 validation

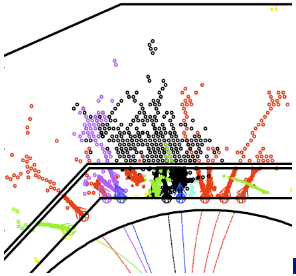








- Recent G4 versions still not perfect, but much better than in the past
- Particle flow performance rather robust



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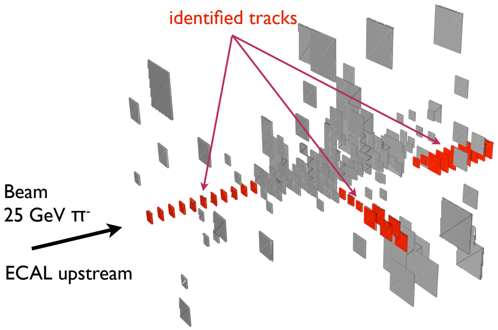
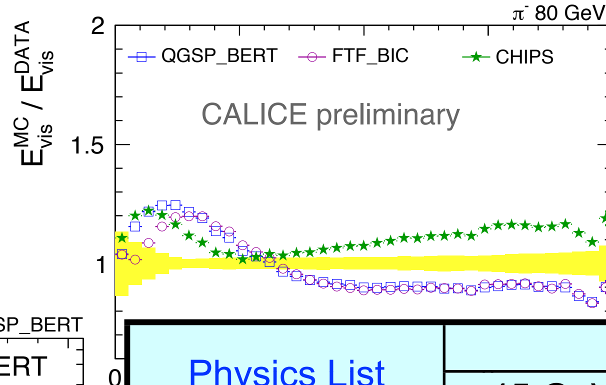
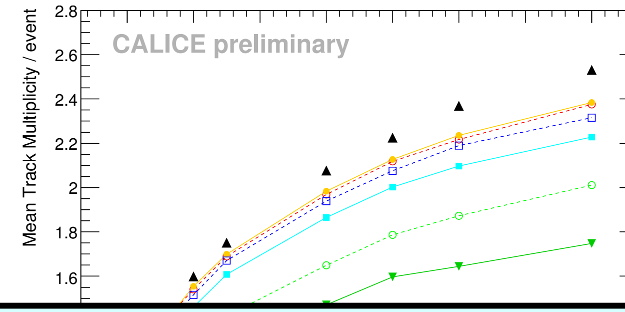
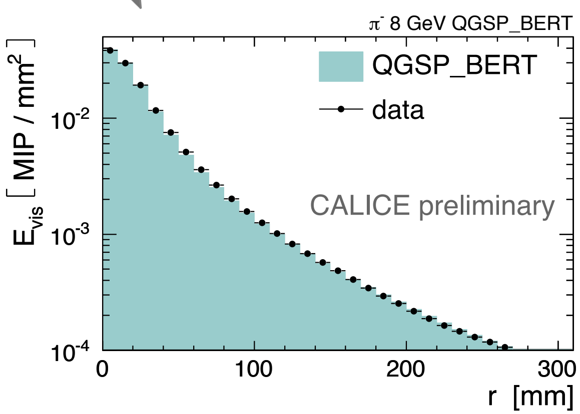


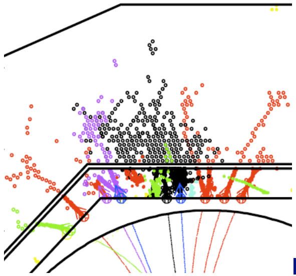






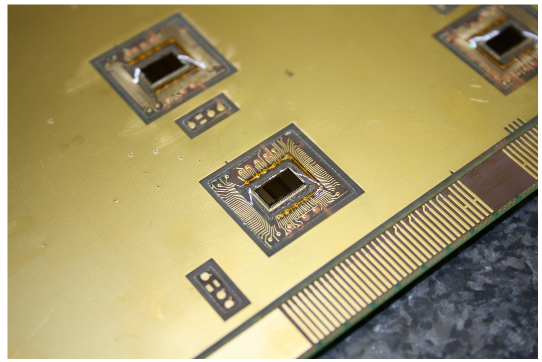
Physics List	Jet Energy Resolution			
	45 GeV	100 GeV	180 GeV	250 GeV
LCPhys	3.74 %	2.92 %	3.00 %	3.11 %
QGSP_BERT	3.52 %	2.95 %	2.98 %	3.25 %
QGS_BIC	3.51 %	2.89 %	3.12 %	3.20 %
FTFP_BERT	3.68 %	3.10 %	3.24 %	3.26 %
LHEP	3.87 %	3.15 %	3.16 %	3.08 %
χ^2	23.3 / 4	17.8 / 4	16.0 / 4	6.3 / 4
rms	4.2 %	3.9 %	3.5 %	2.5 %

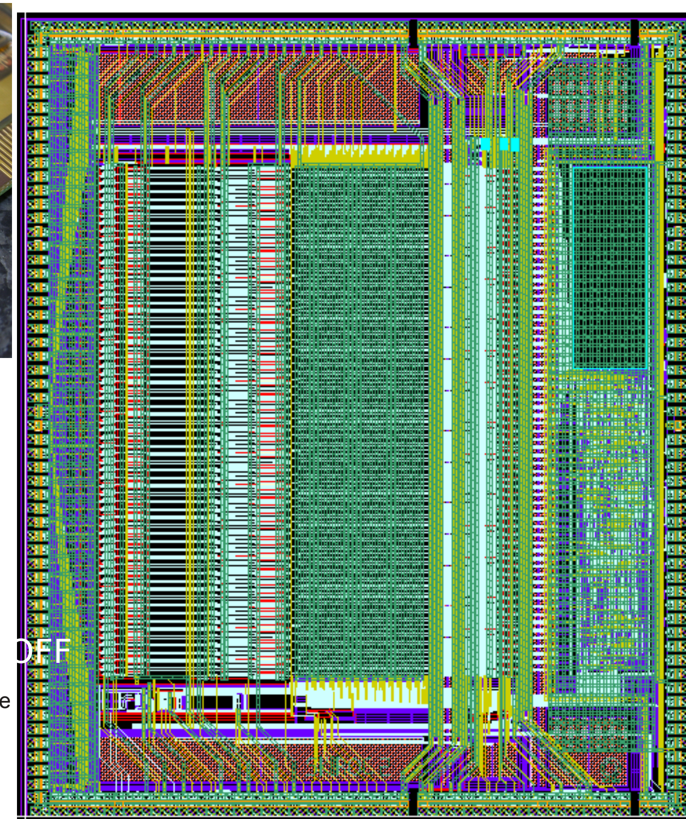
- Recent G4 versions still not perfect, but much better than in the past
- Particle flow performance rather robust



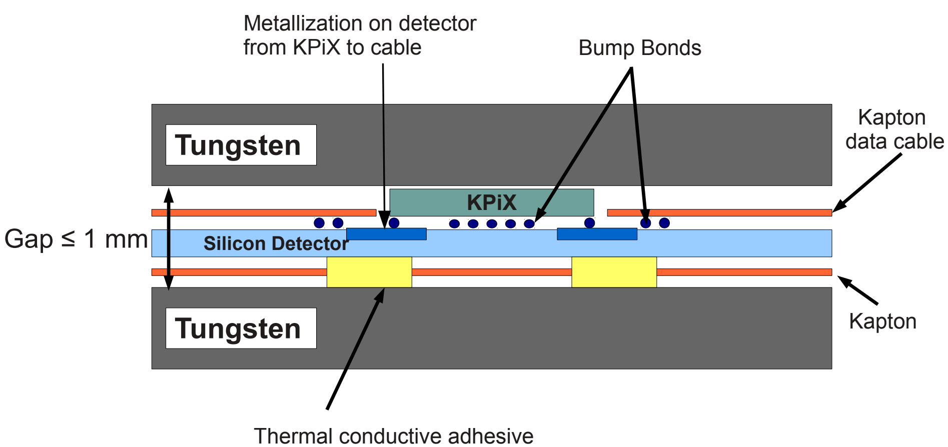
Technology: ECAL

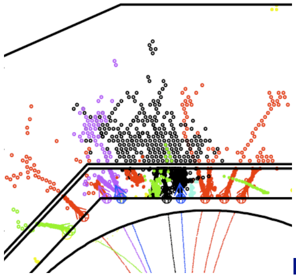
- Key issues:
- micro-electronics integration
- ultra-low power
- ILD: chip-on board





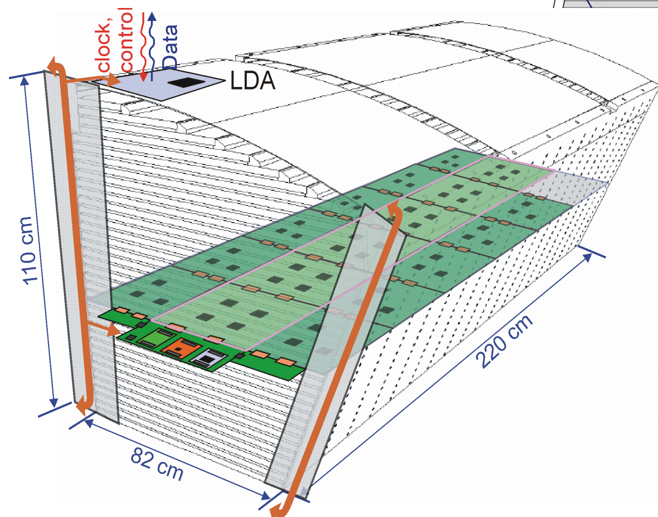
- SiD approach:

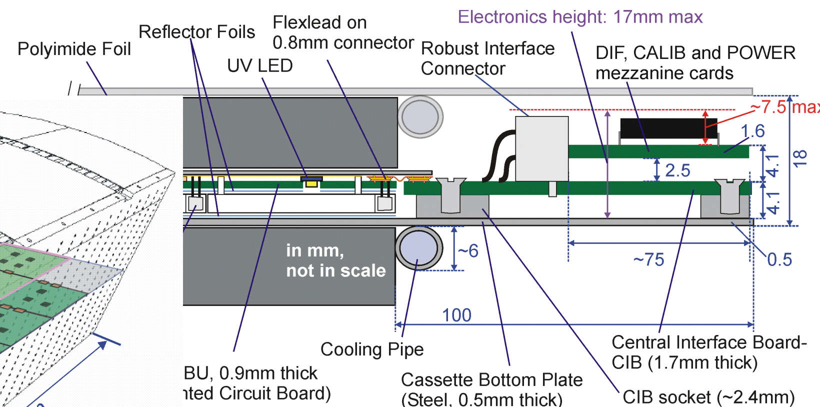


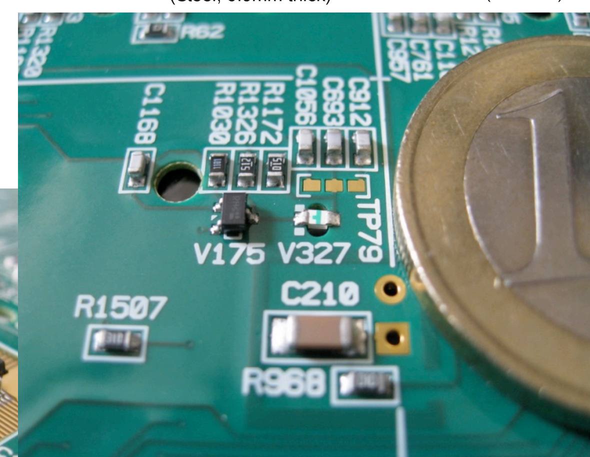


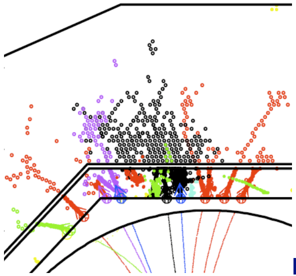
Technolgical prototypes: HCAL

- compact, embedded design



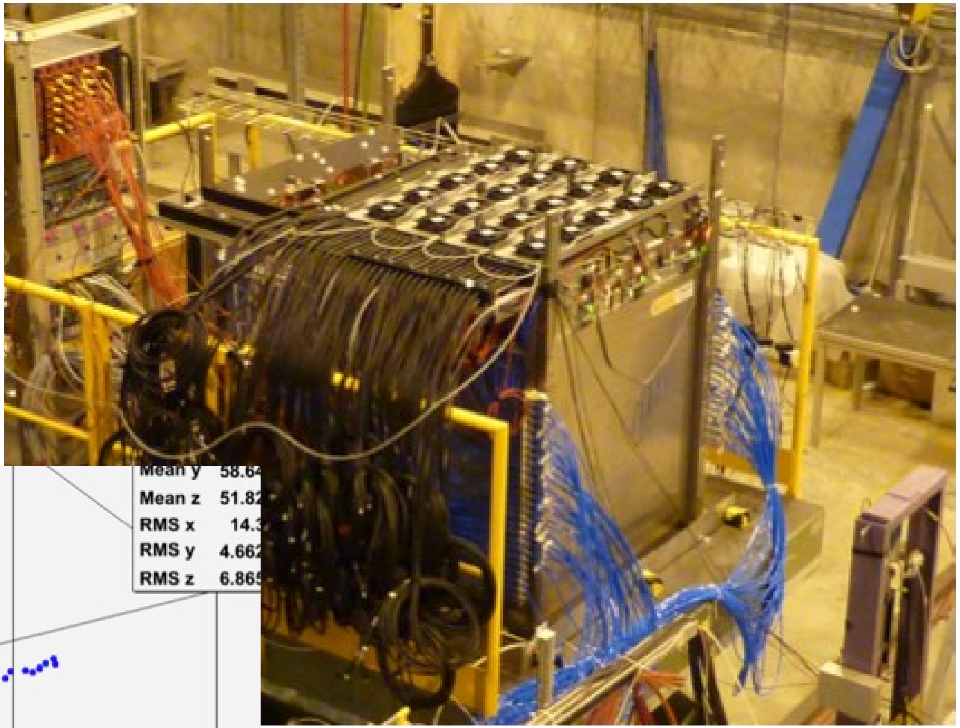


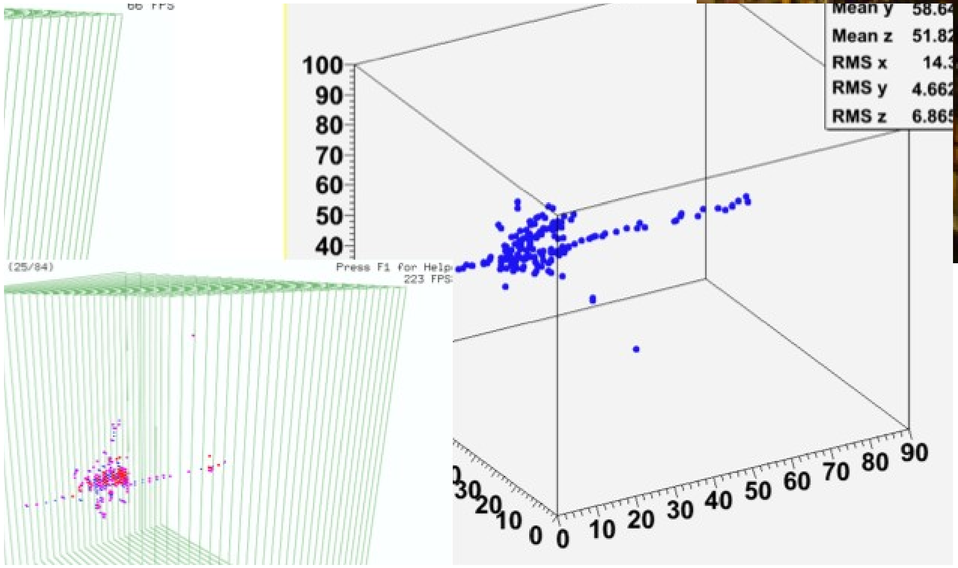


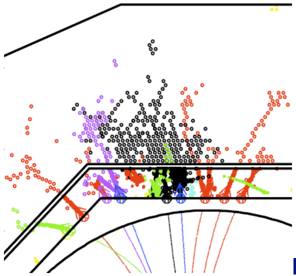


SDHCAL commissioning

- m3 prototype with 2nd generation electroncis
- DAQ still to be timed and run in
- First showers recorded

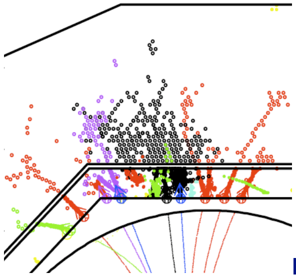






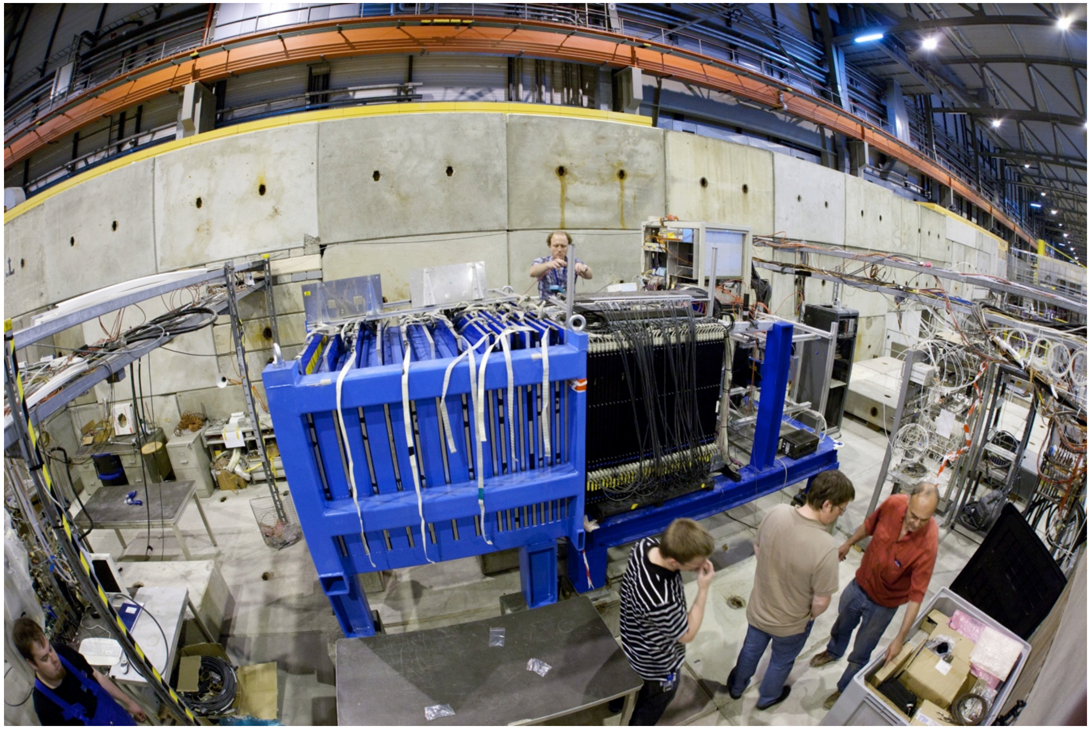
Summary technology

- There are formidable challenges associated with the tremendous channel count of PFLOW calorimeters
  - micro-electronics integration
  - power consumption and heat dissipation
  - connectivity
  - (equalization)
- Being addressed with technical prototypes
  - under construction
  - performance validation to come
- Will allow time-dependent shower analyis

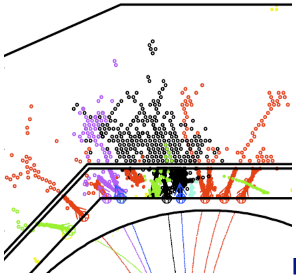


Tungsten test beam

- Test simulation of neutron-rich response and time structure
- start with existing scintillator r/o
- test bed for 2nd generation scintillator
- T3B: tiles with picosecond electronics: first results
- Next year: US RPCs

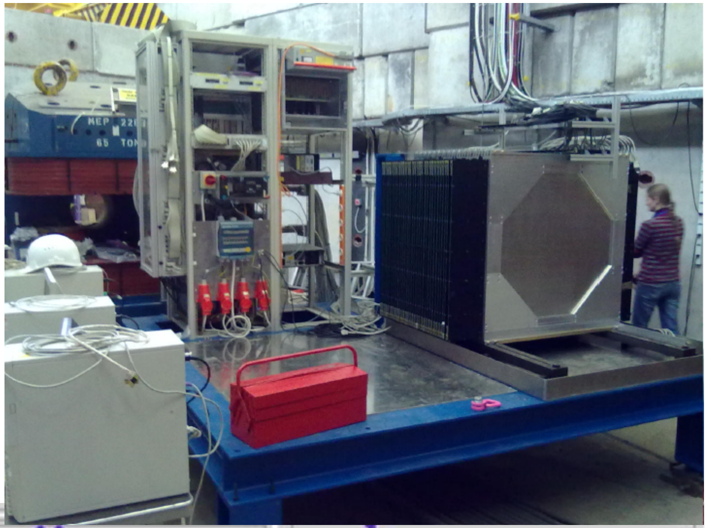


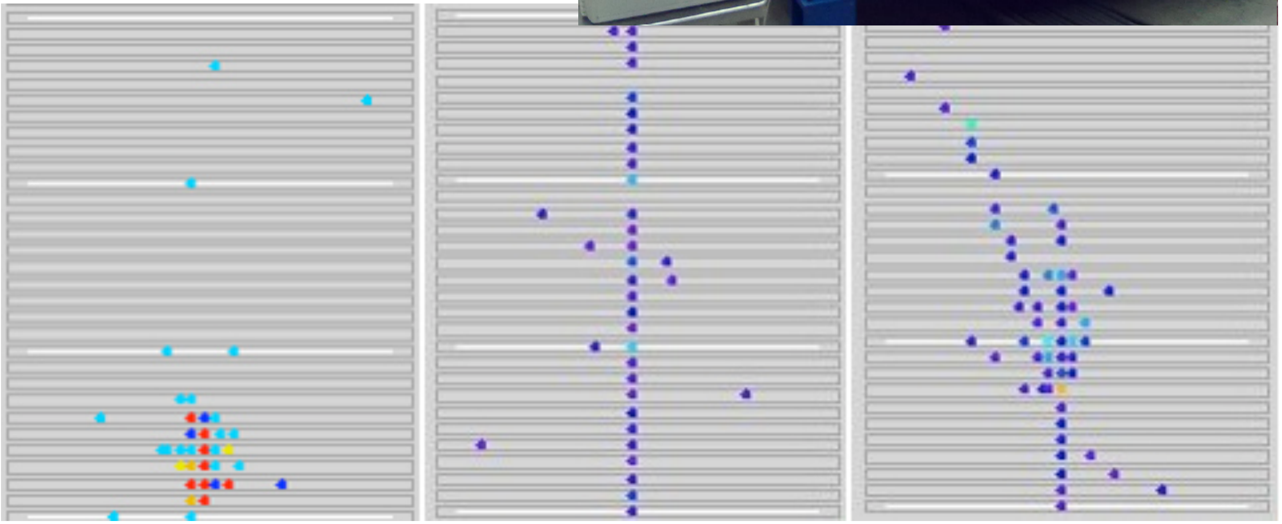
set-up at the SPS with tail catcher

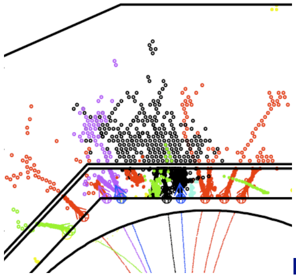


W HCAL tests

- First experience with tungsten mechanics
- large data samples 1-250 GeV
- T3B: first results
- timing of first hit: large model sensitivity
  - only isolated late hits







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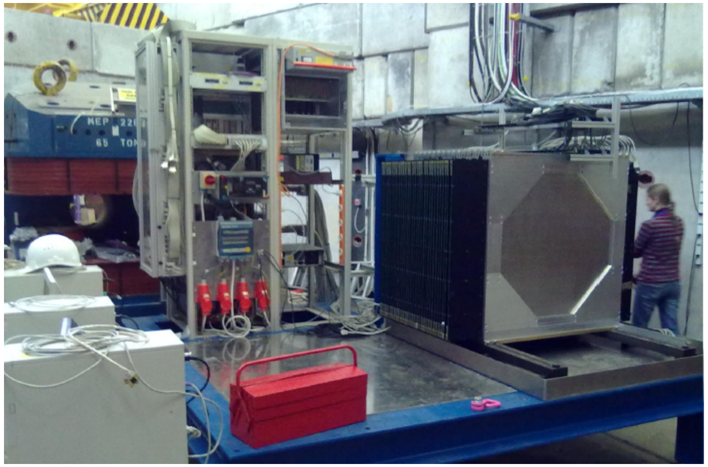

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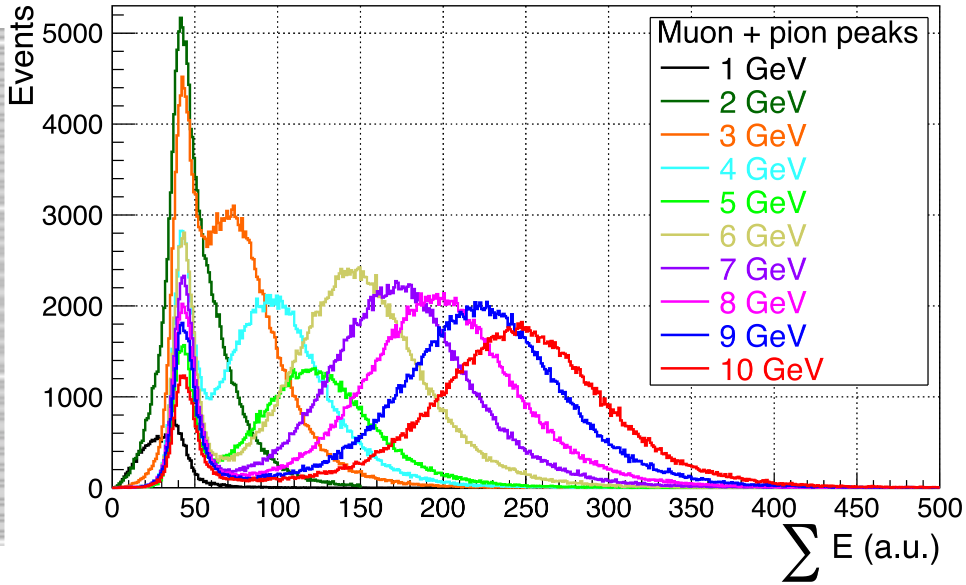

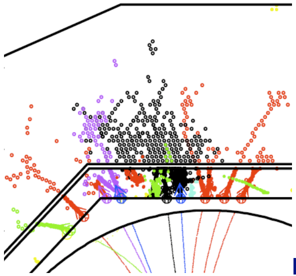

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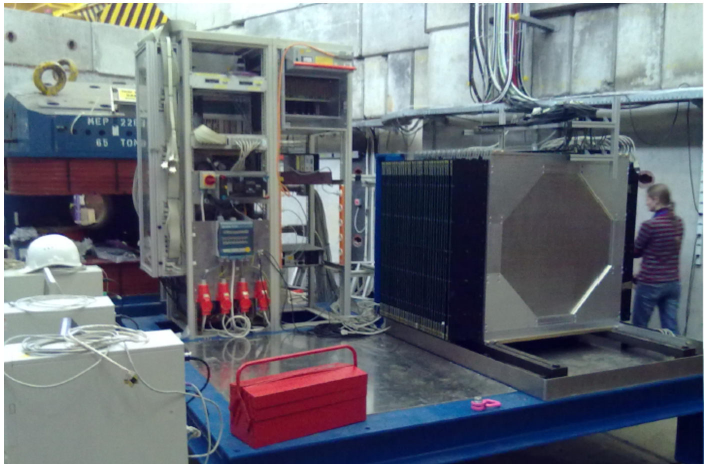

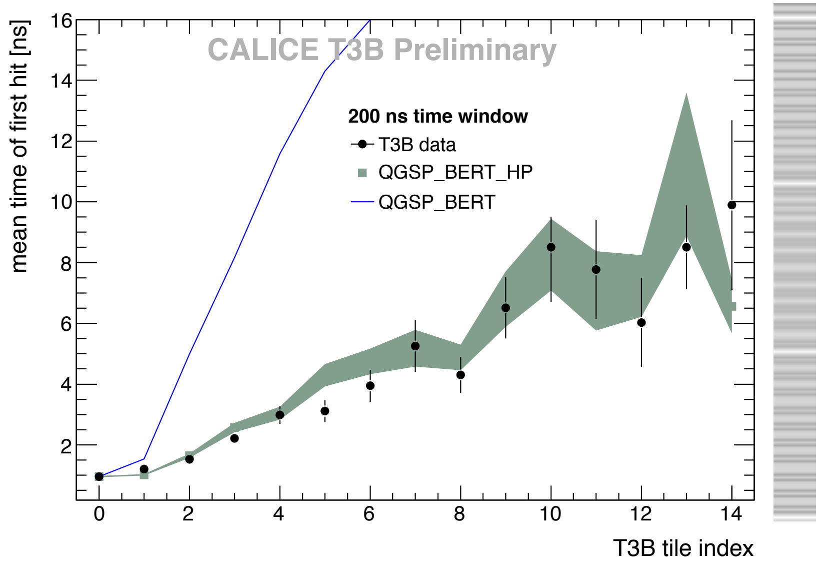

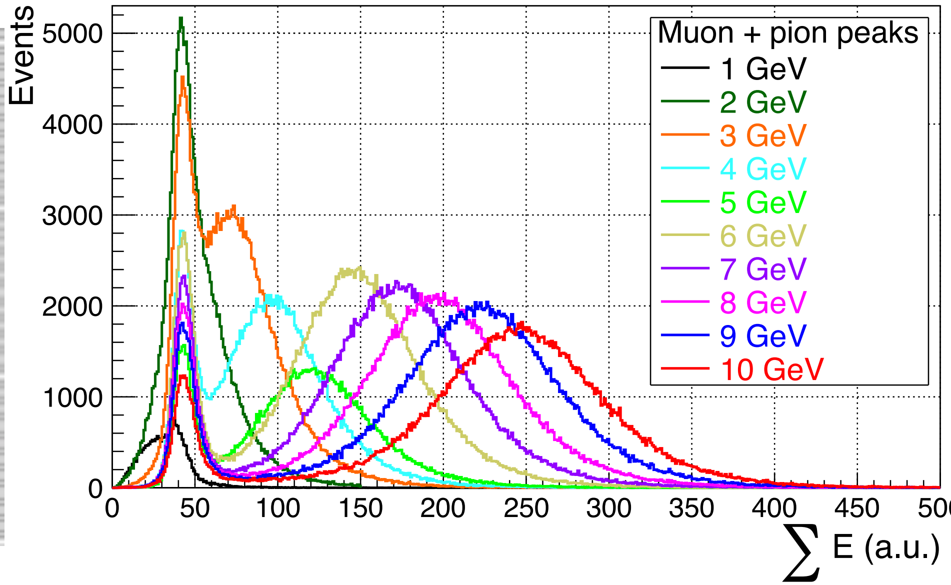

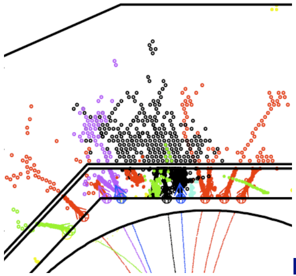

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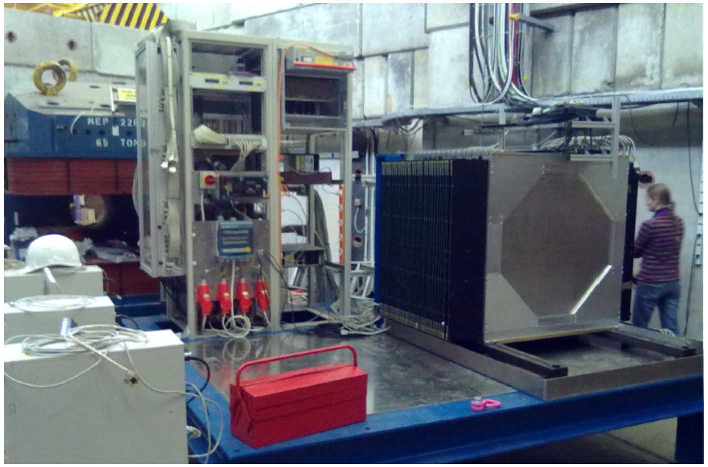
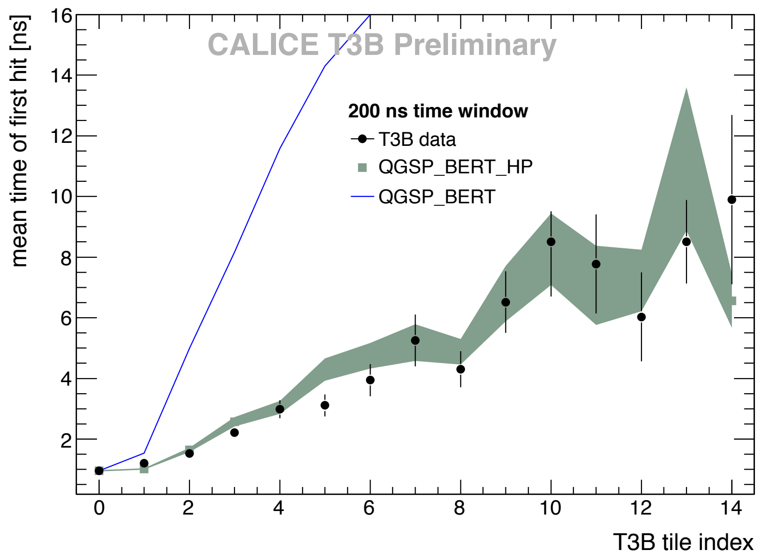
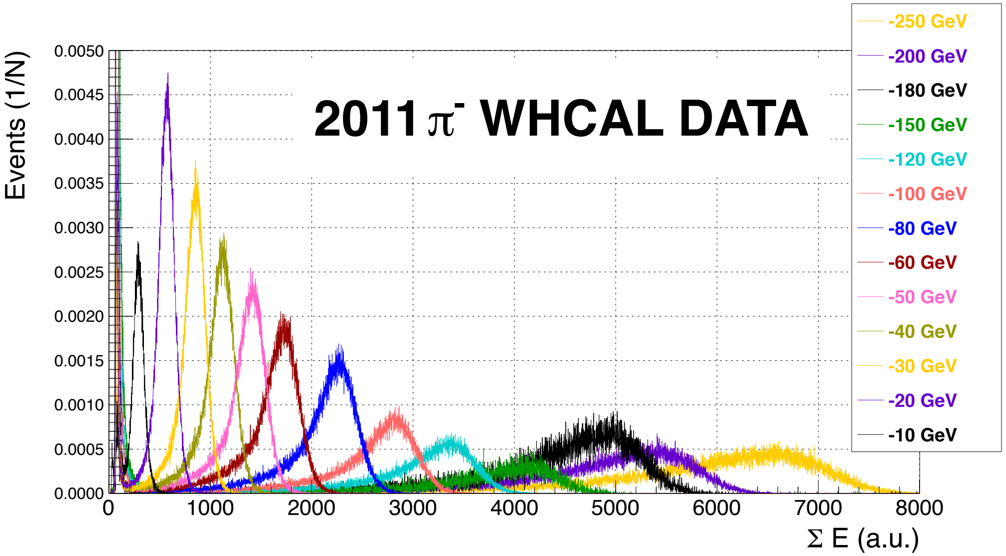
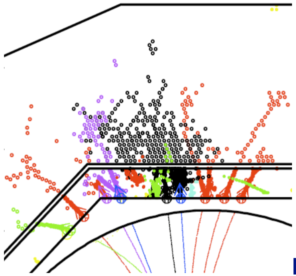


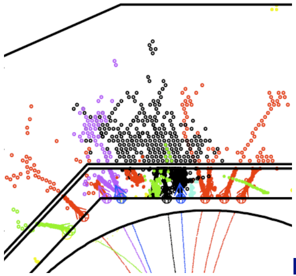






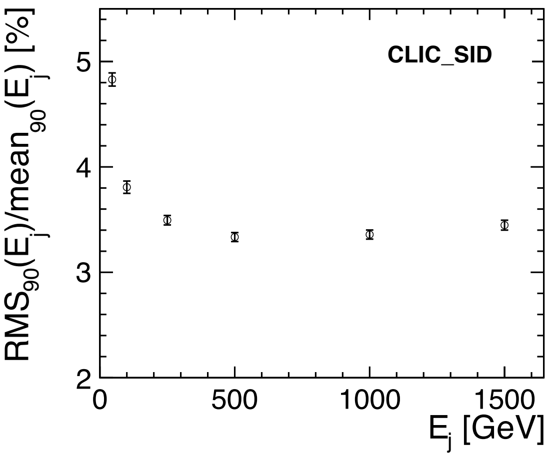
Timing performance

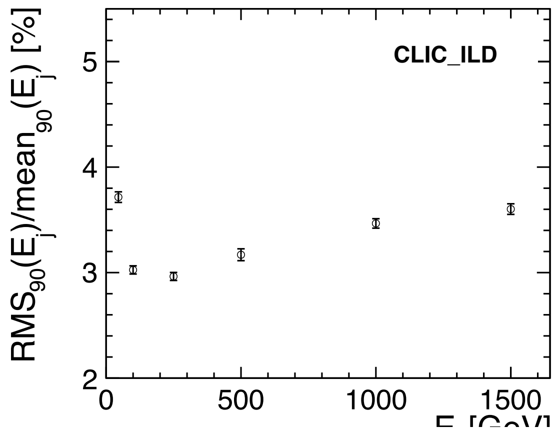
- Timing performance of a few ns at hit level gives sub-nanosecond precision at cluster level
- Hit timing ingredients:
  - shower development
  - signal generation
  - electronics chain
- Si sensors, SiPMs, RPCs are all fast
- present HCAL electronics already designed to nanosecond timing requirements
  - tungsten test beam studies
- Overall concept for fast CLIC electronics: see A. Kluge's talk

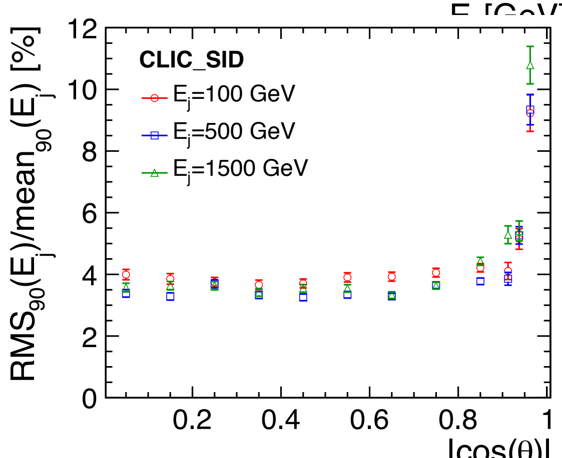


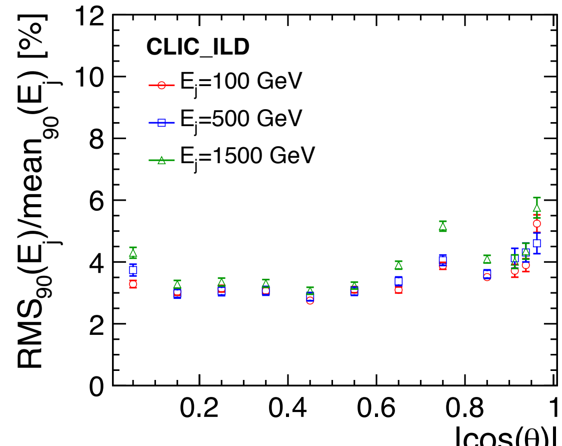
Jet energy performance

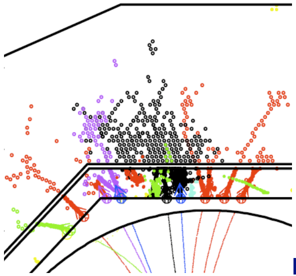
- Using Z→ uds events, reconstructed with PandoraPFA
- studies with timing cuts and background: see subsequent talks







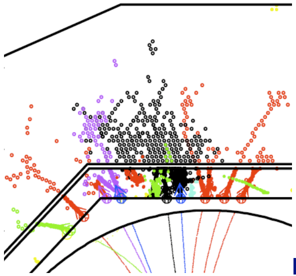




Future R&D

- Till end 2012:
- round up optimization
  - re-optimize mask design
  - revisit granularity, occupancies
  - study tungsten iron transition region
- refine electronics conceptual design
  - specs and R&D guidance

- Project implementation phase:
- tungsten test beam, also with gaseous readout
- power-aware fast electronics design
- active layer R&D: SiPMs, MPGDs,...
- engineering and integration issues



Summary

- Particle flow drives the calorimeter design at CLIC energies
- Builds on technologies established in ILC context
- Challenges: heavy absorber and timing
- Lively test beam program to validate performance