Calorimeters for ILC detectors

LHC Terascale @ Nagoya

2013-5-24

Daniel Jeans
Department of Physics
The University of Tokyo

東京大学
THE UNIVERSITY OF TOKYO

Linear Collider

Detectors for LC

Biased towards ILD

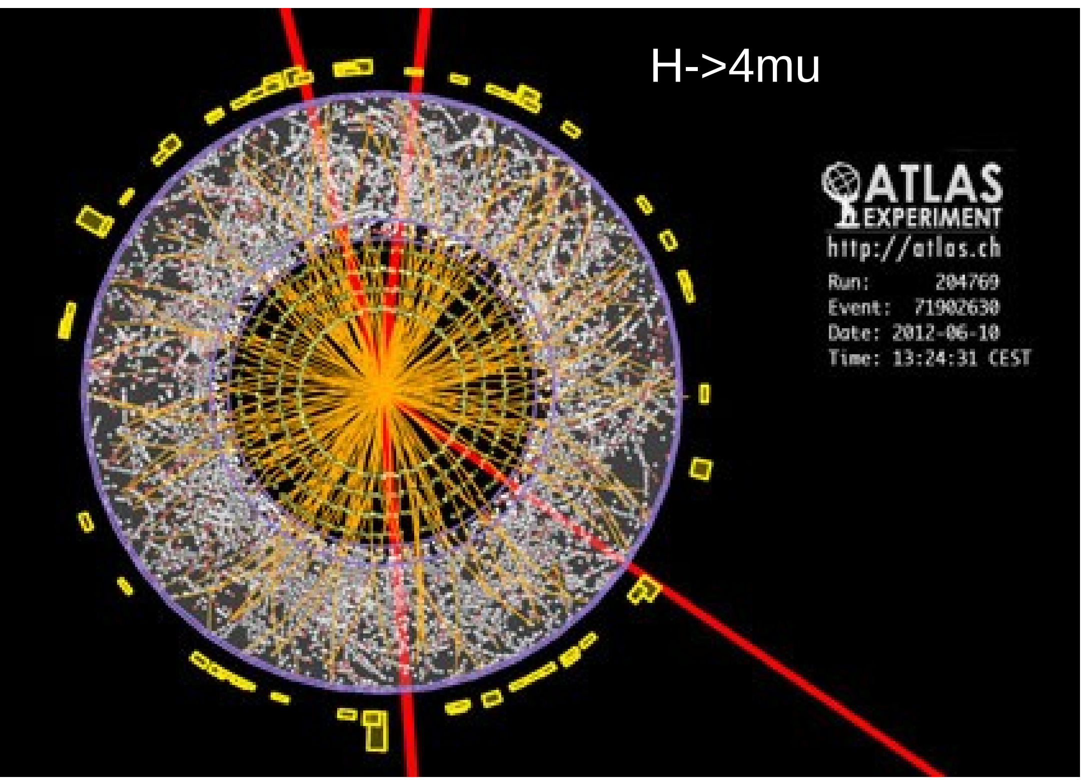
Calorimetry for LC

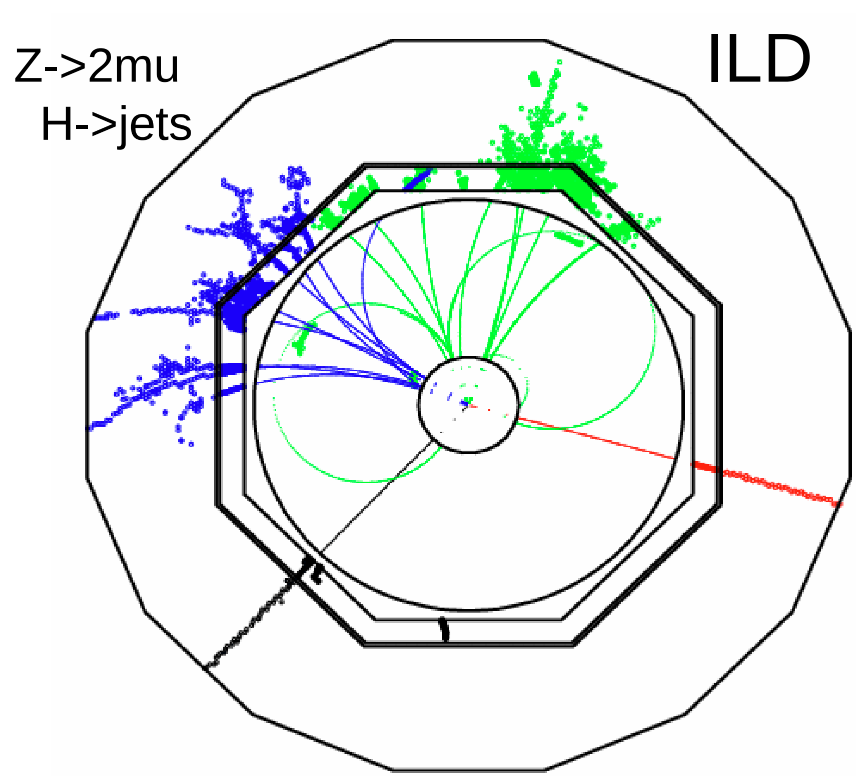
Why a lepton collider?

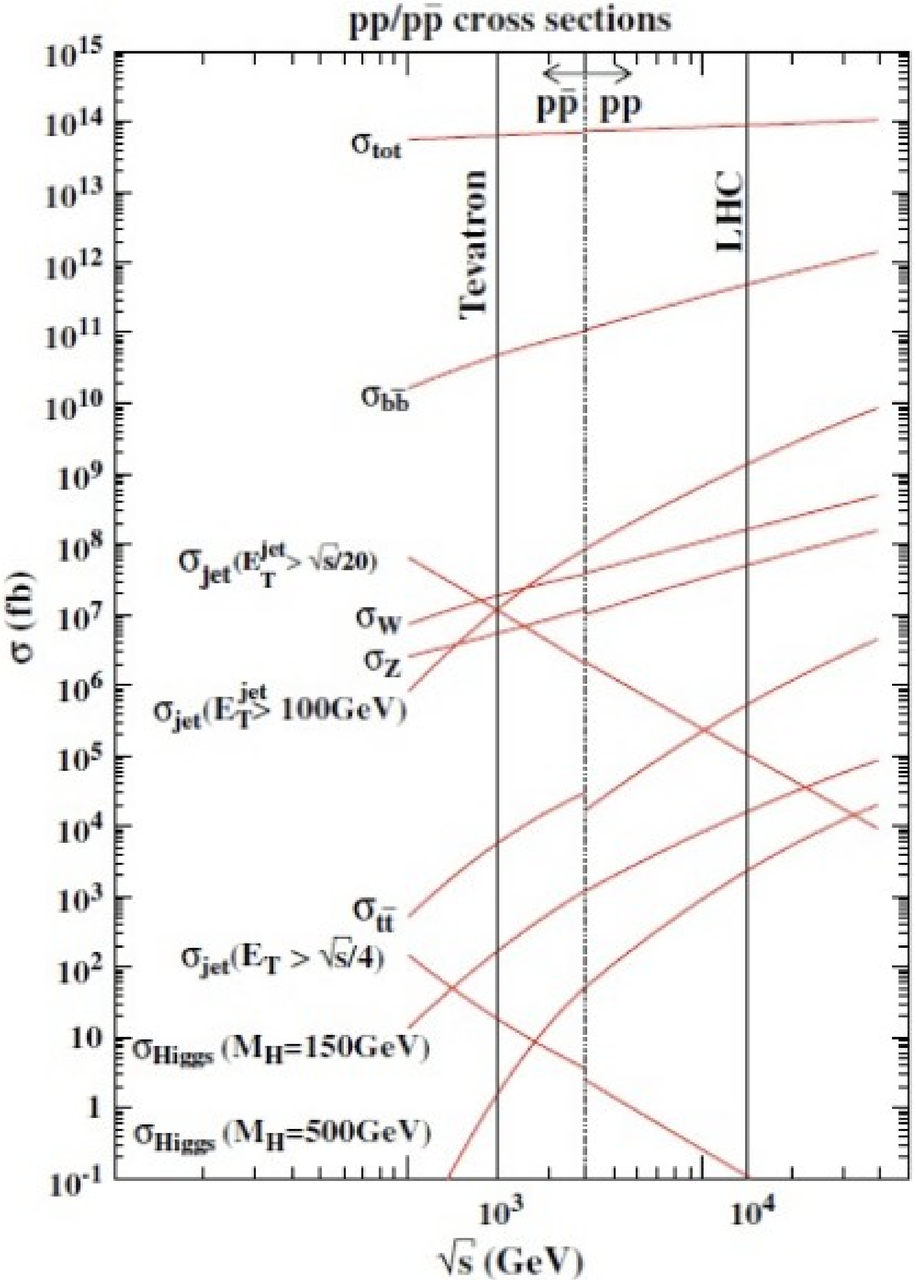
elementary initial particles
    no underlying event from spectators

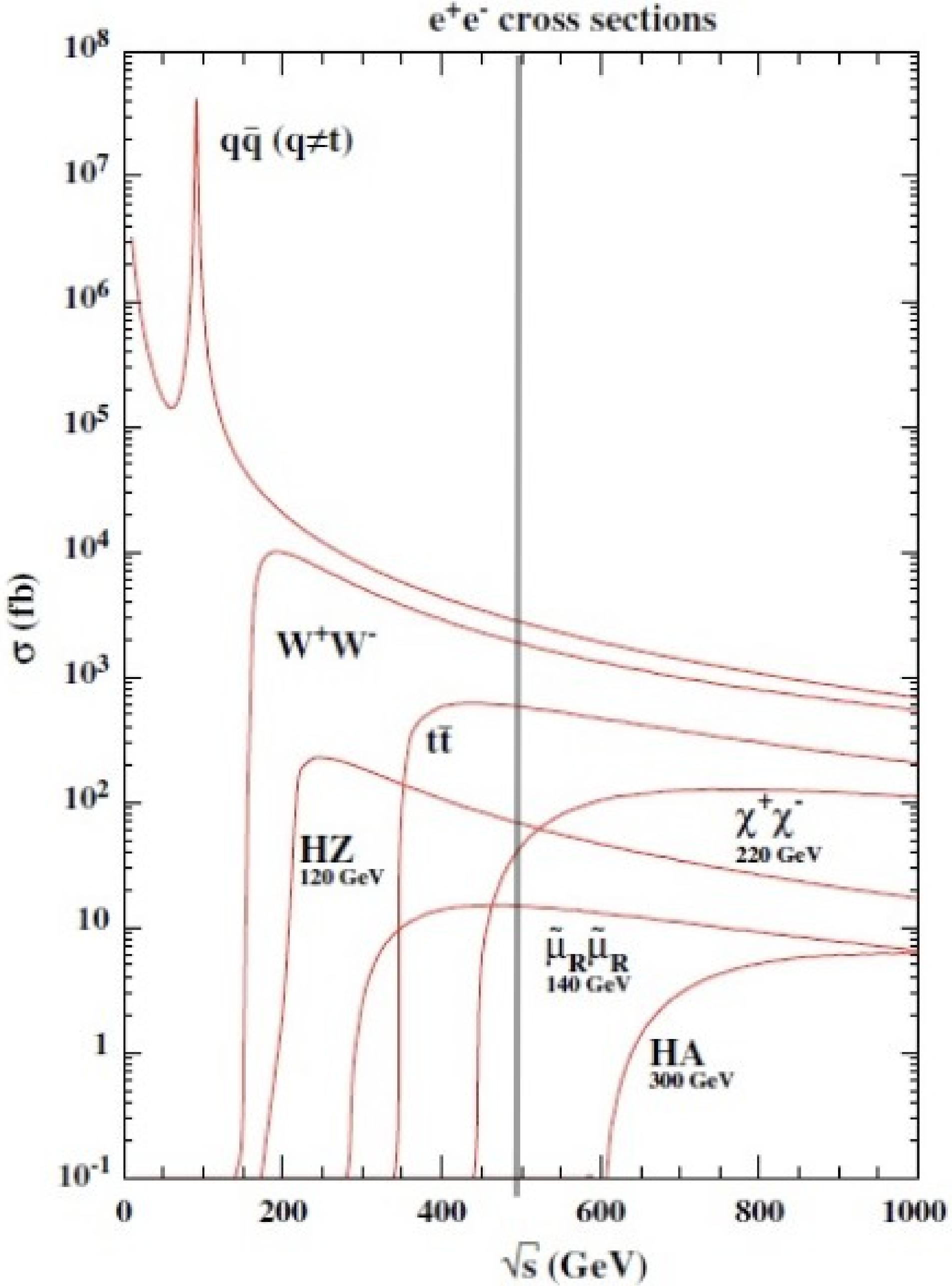
well defined initial state
    energy, momentum
    polarisation (ILC: ~80% for electrons, ~30% for positrons)

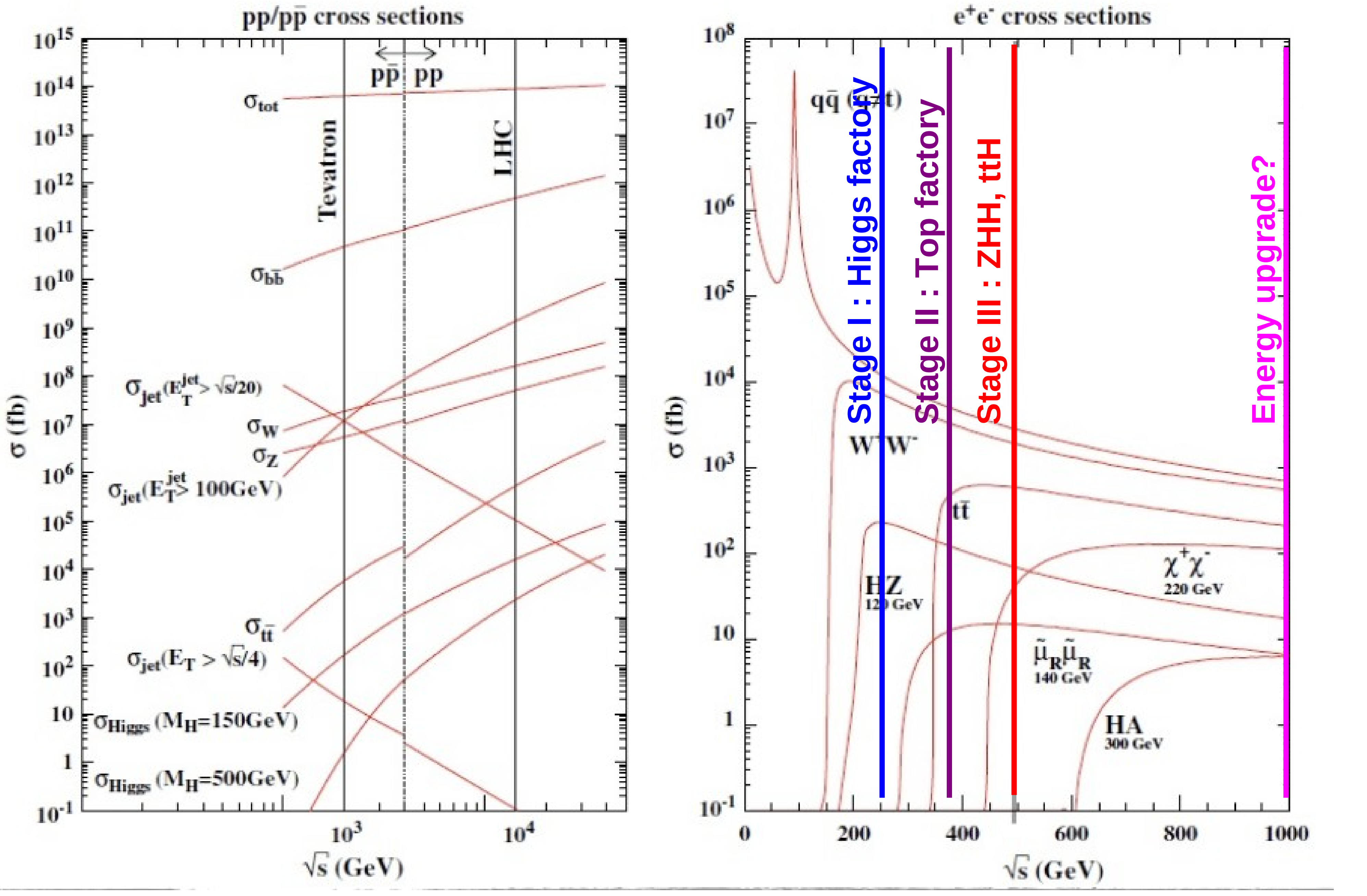
no huge xsec QCD background processes
    pile-up






pp/pp̄ cross sections
pp̄ pp
Tevatron
LHC
σ (fb)
√s (GeV)
σtot
σbb̄
σjet(ETjet > √s/20)
σW
σZ
σjet(ETjet > 100GeV)
σtt̄
σjet(ET > √s/4)
σHiggs (MH=150GeV)
σHiggs (MH=500GeV)


e+e- cross sections
σ (fb)
√s (GeV)
qq̄ (q≠t)
W+W-
tt̄
HZ
120 GeV
χ+χ-
220 GeV
μ̃Rμ̃R
140 GeV
HA
300 GeV



Can scan cross-section thresholds

Major physics aims

Staged approach:

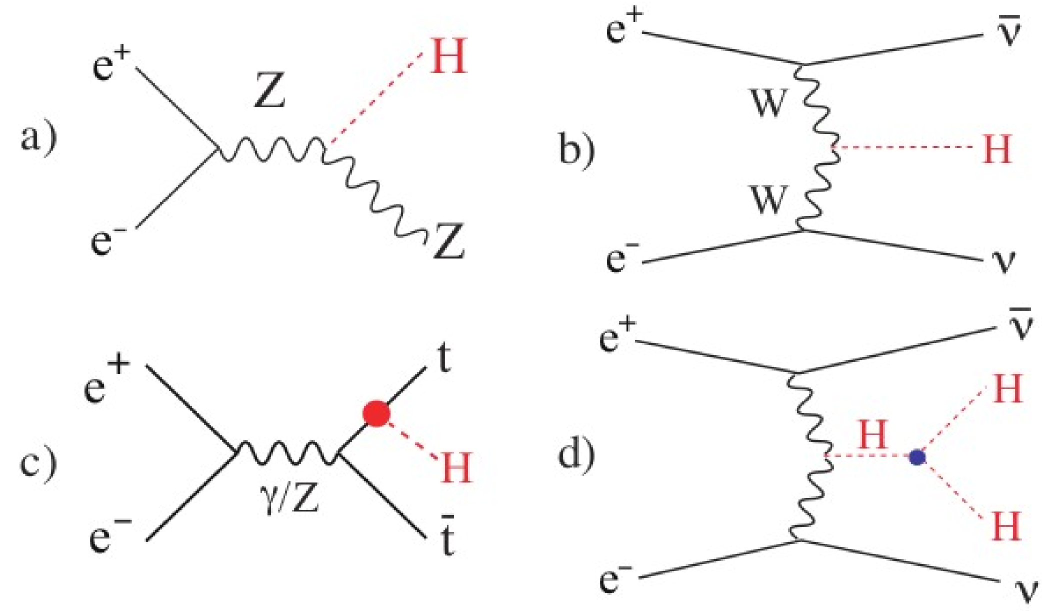
250 GeV: HZ production

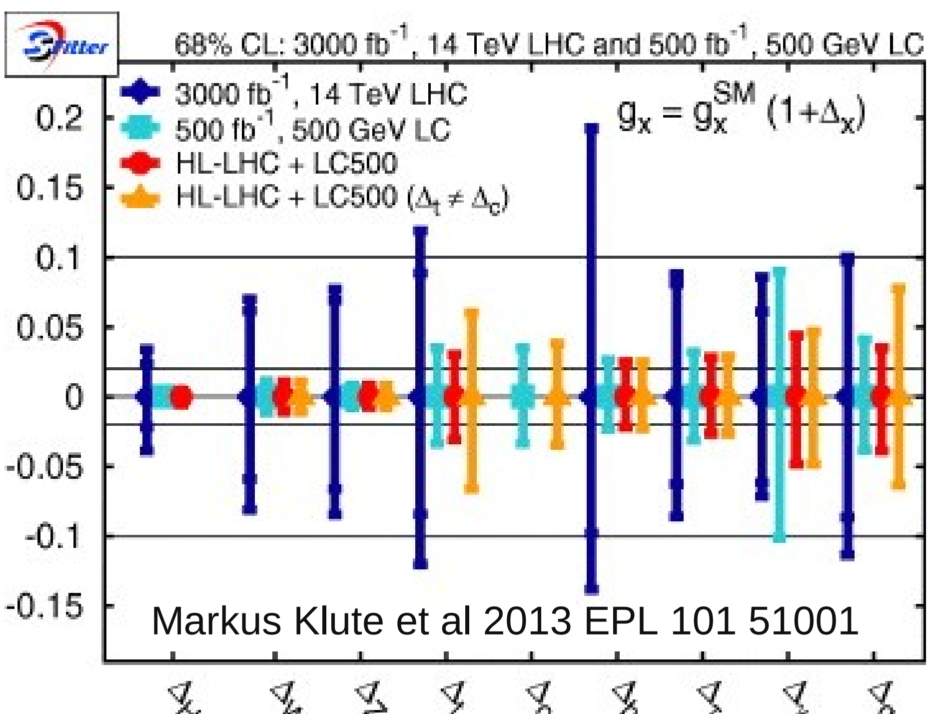
350 GeV: t-tbar, HZ

500 GeV: ttH, ZHH (H self-coupling)

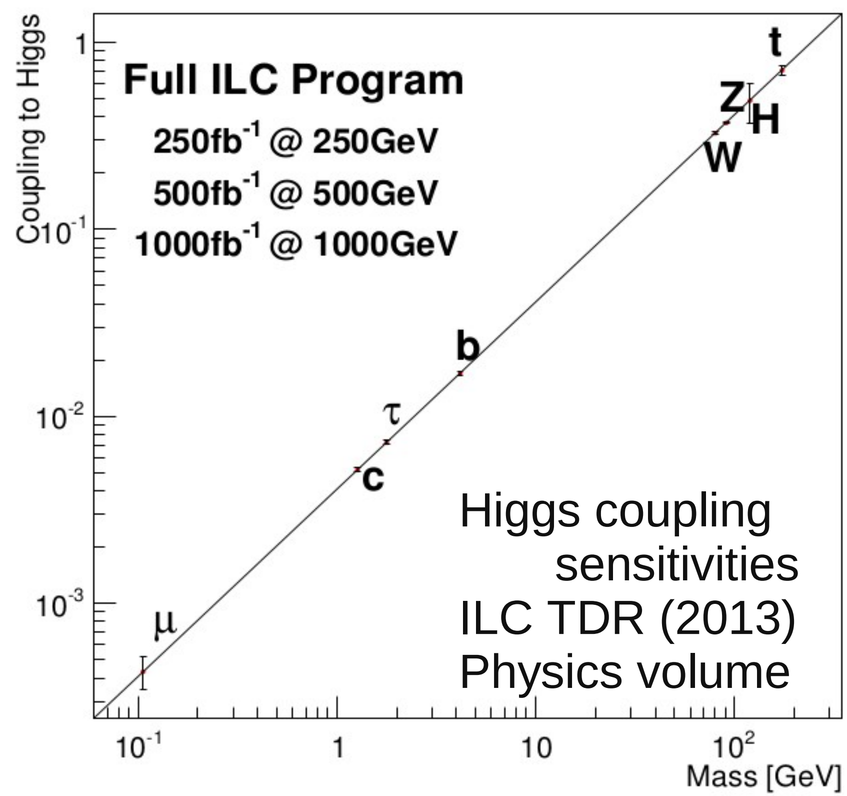
Precision EW measurements
sensitivity to high scales via loops

(Plus any new particles discovered by LHC,
if in energy range)





Markus Klute et al 2013 EPL 101 51001



Higgs coupling sensitivities
ILC TDR (2013)
Physics volume

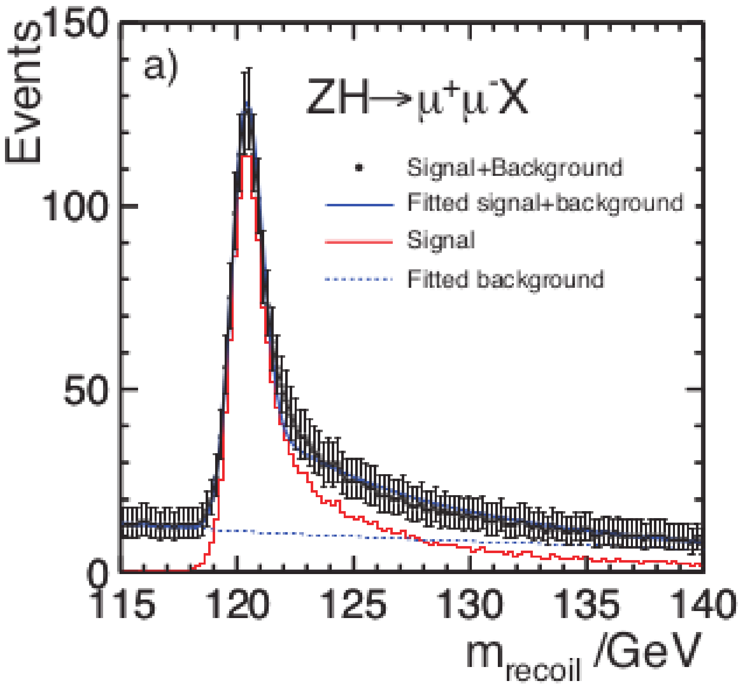
Detector requirements

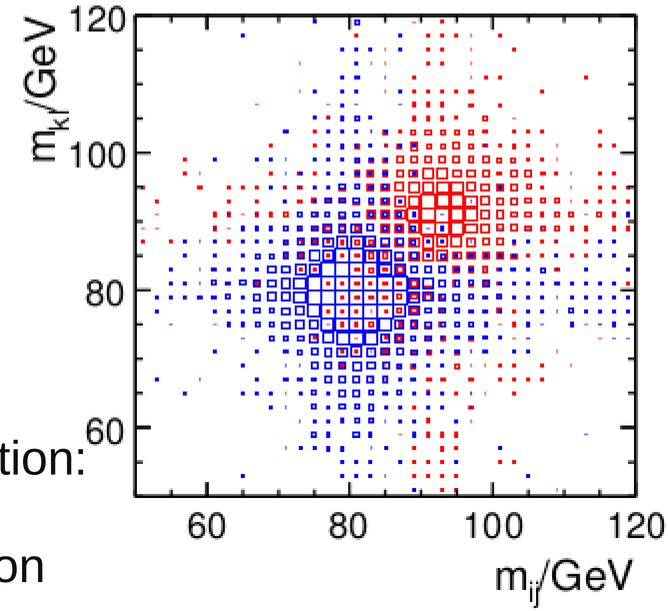
excellent momentum resolution
    recoil mass measurement for ZH

Vertex detector: b, c tagging
    Low backgrounds -> can get to ~1.5cm of beam

Jet energy resolution
    Make full use of (often dominant) hadronic decay channels
        (n.b. no large QCD background)
    Most demanding request -> separate hadronic W and Z decays

Highly hermetic, close to 4π coverage
    Tagging of invisible particles





Jet energy resolution:

WW, **ZZ** separation

Particle Flow (PF) for jet energy measurement

Basic idea:

Individually measure each particle's momentum/energy
in the most appropriate (precise) sub-detectors

Average ~65%: Charged particles -> magnetic spectrometer
~25%: Photons-> ECAL
~10%: Neutral hadrons -> ECAL+HCAL

Such approaches used in past and present experiments
using detectors not optimised for this approach

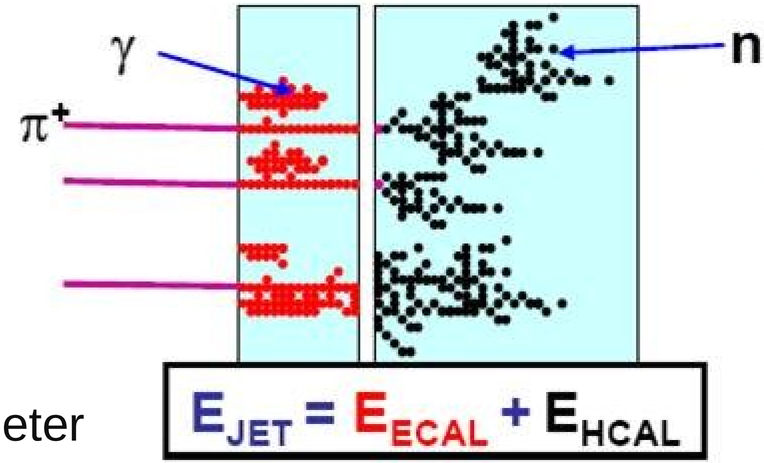
LC detectors are being designed with PF
as major design requirement

Requires:

Highly segmented calorimeter readout to distinguish
single particle deposits

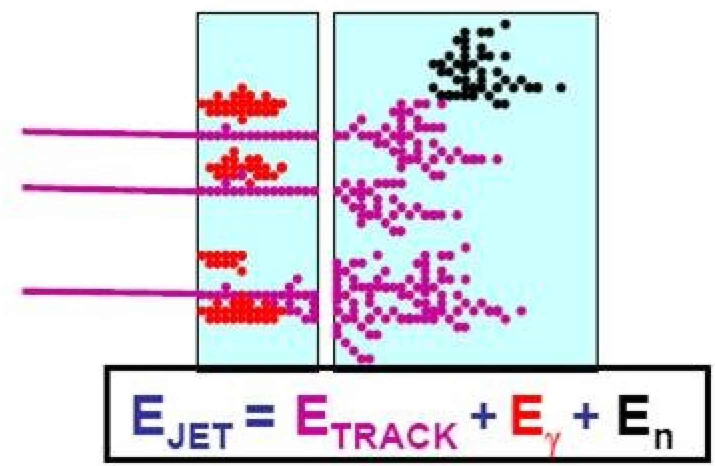
Minimum material before calorimeters
hadronic interactions in detector leads to confusion

"Confusion": misidentification of charged and neutral energy deposits
Major contribution to JER at higher jet energies



Traditional calorimetry

Particle Flow



ILD and SiD detector concepts

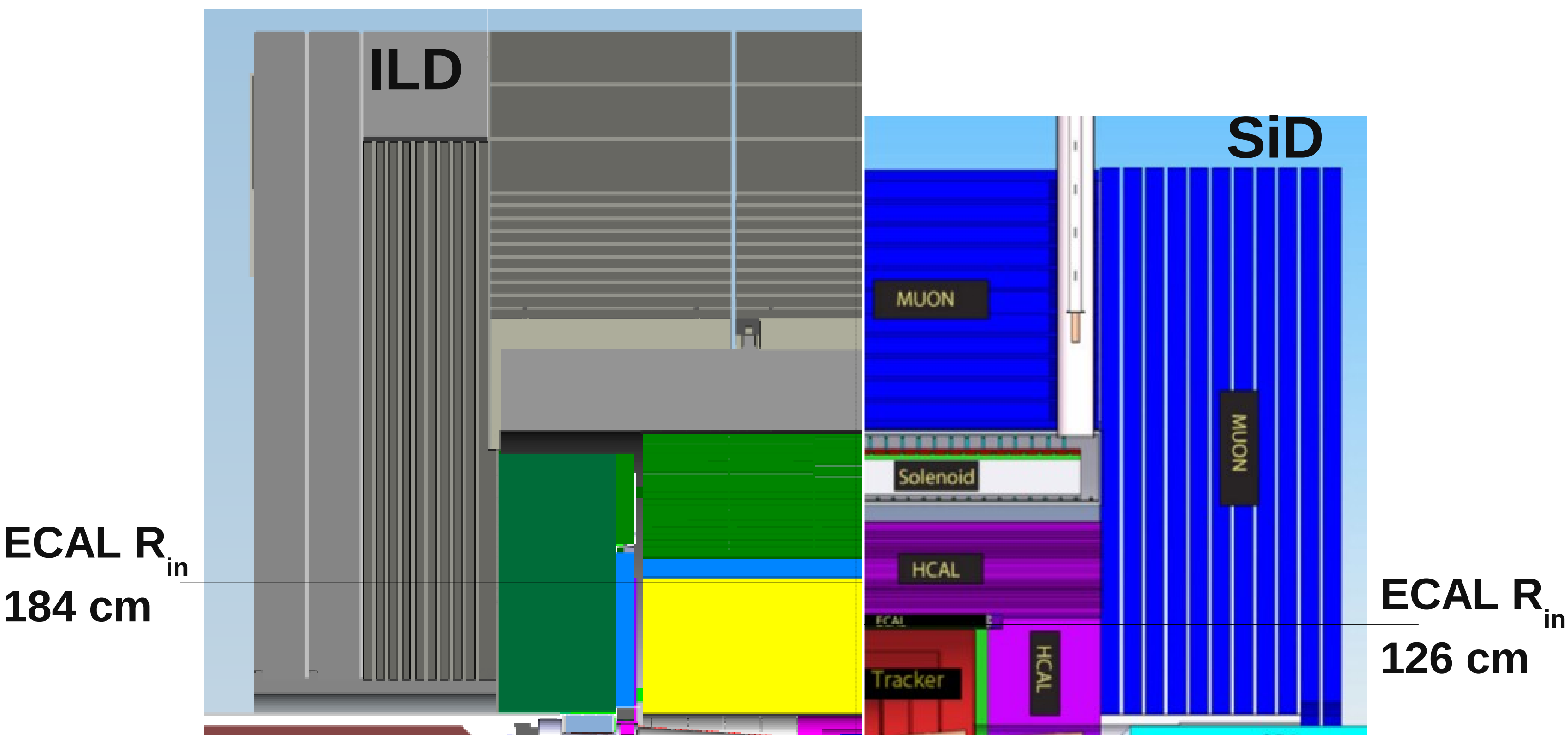
single ILC interaction region designed to allow 2 detectors

"push-pull" configuration: alternate detectors in beam position

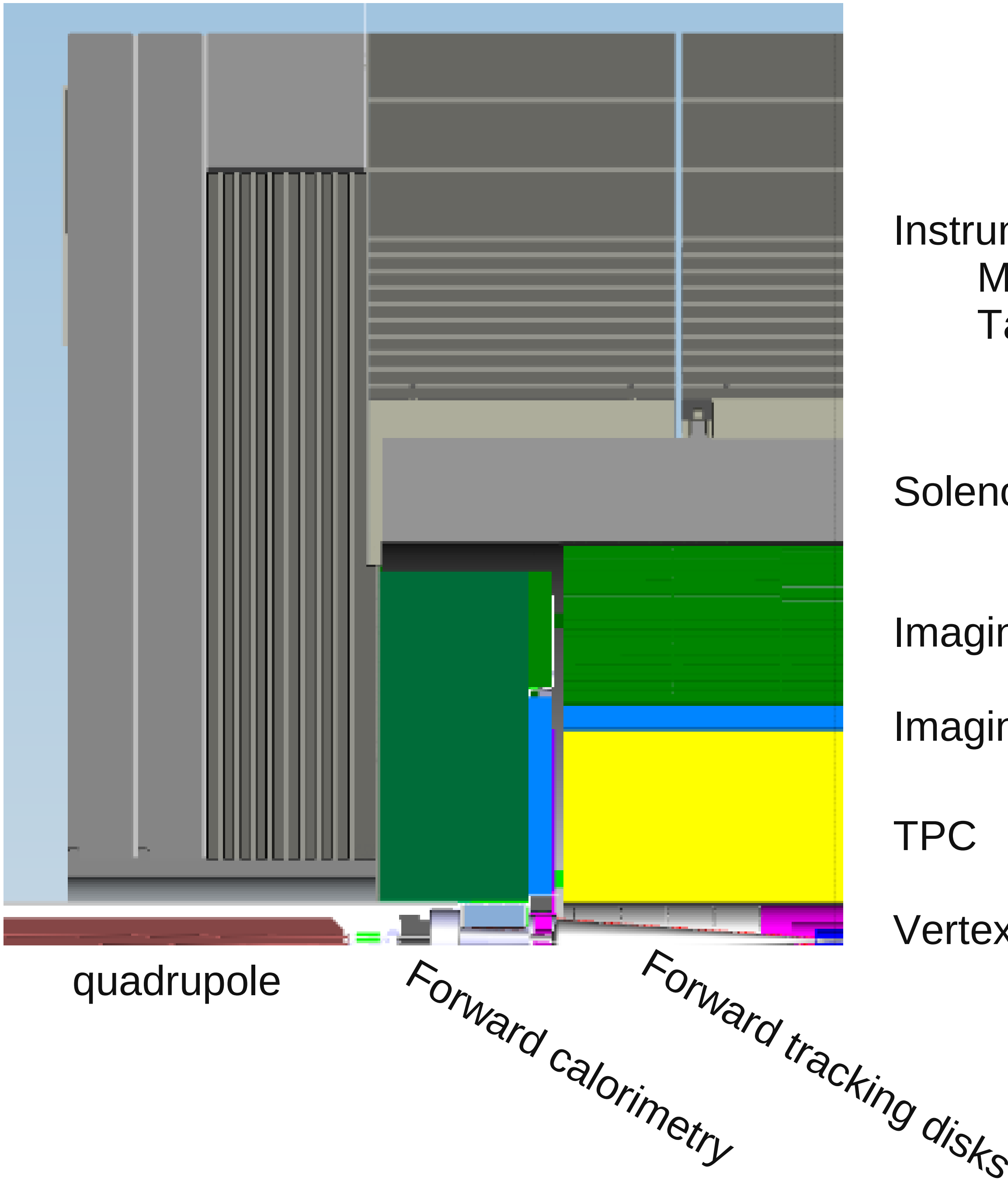
ILD	**SiD**
Time projection chamber	Silicon-only tracker
Larger radius	Smaller radius
Smaller B field (3.5T)	Larger B field (5T)

Particle Flow calorimetry

High precision vertex detector



ILD subdetectors

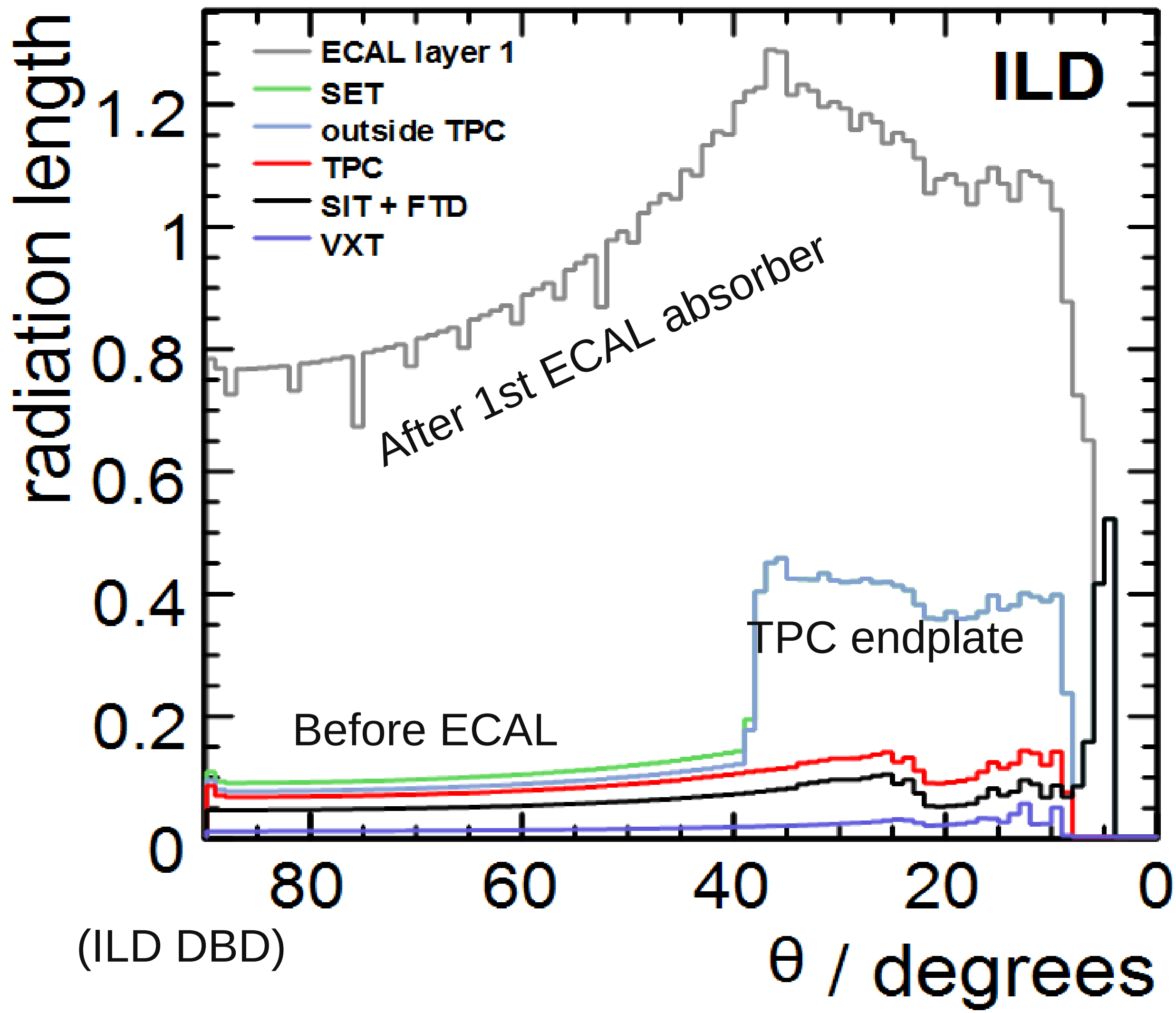


Tracker material budget

Conscious effort to minimise
tracker material

Interactions well before ECAL
particularly damaging for PFA

Hadronic interactions worst:
Impossible to tell if neutrals from
primary or material interactions



(ILD DBD)

Calorimeters

<u>Requirements from Particle Flow</u>

Identify single particle deposits in dense environment
  “tracking calorimetry”
Measure energy of these deposits reasonably well

-> Highly segmented readout
  ~ radiation length (longitudinal),
  ~ Molière radius (transverse)
-> Reasonable (not excellent is OK) single particle energy resolution

Sampling calorimeters
  with highly segmented readout
    can satisfy these requirements
  High density
    small particle showers
      (reduce shower overlaps->limit confusion)

<u>Physical constraints</u>

calorimeters inside solenoid
  to minimise hadronic interactions before
as thin as possible

Sampling calorimeters with thin highly segmented active layers

Large number of channels (~10^8) imposes
very low power front end electronics
embedded inside the calorimeter
extract only digitised zero-suppressed signals
(average per-event occupancy rather low)

Minimise space needed for cables, cooling systems

ILC beam structure
1ms trains of ~3000 bunches
5Hz repetition (-> 0.5% duty cycle)

Many sub-detectors plan to “power pulse” front end electronics
to lower average consumption

During 99.5% of time with no beam between trains
Read out detectors (typically 1%)
Power off (typically 98%)

In calorimeter VFE, typical average power 25 µW per channel

Calorimeter optimisation

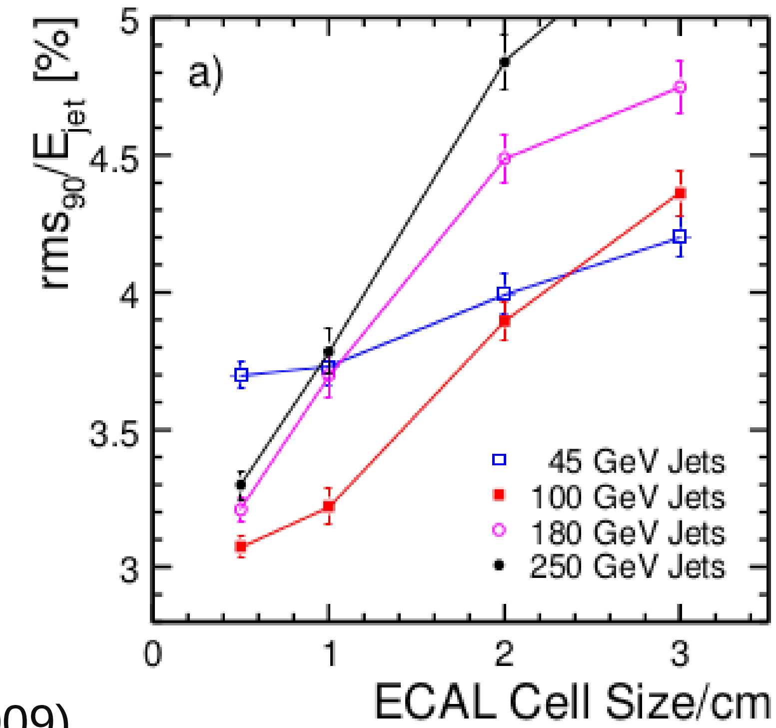
Cell size

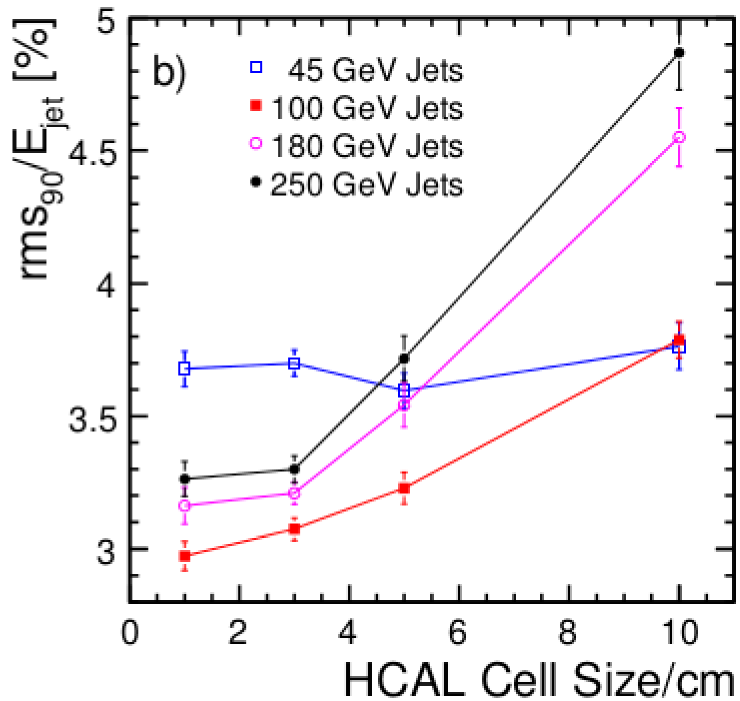
Number of layers

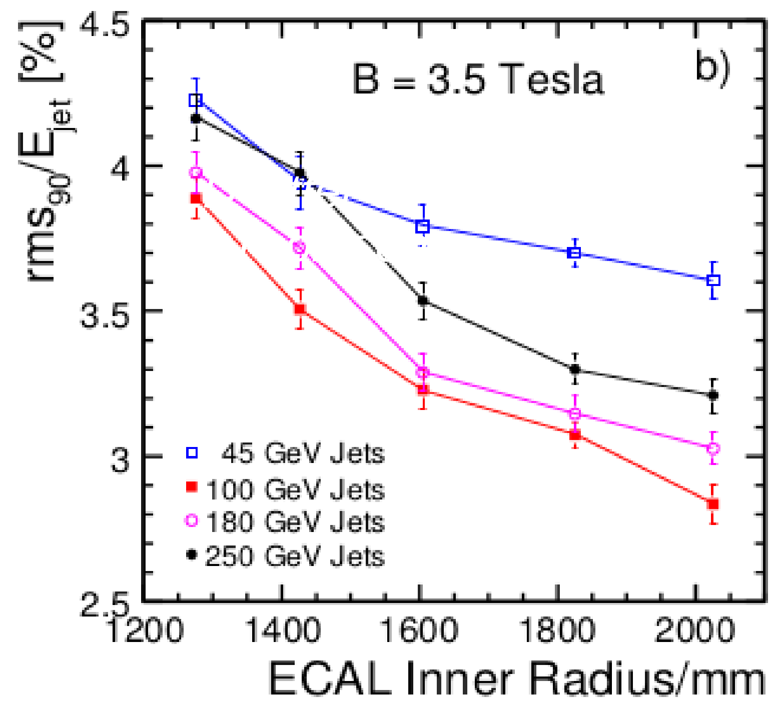
Inner radius

Thickness

Example plots from
ILD Letter of Intent (2009)







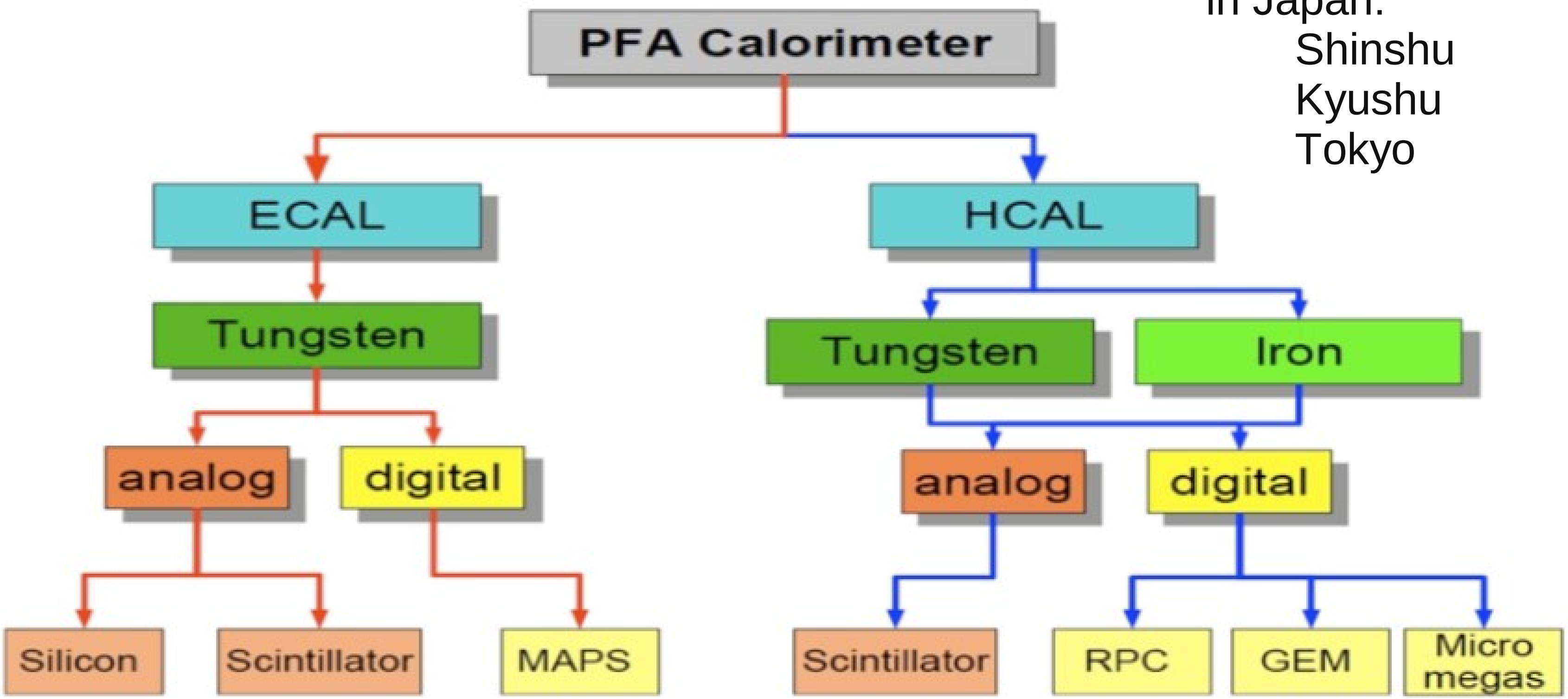
Technical realisation

of high granularity calorimetry
(for linear colliders)

Carried out largely by CALICE collaboration
(except ECAL of SiD)

Calorimeter for ILC

>350 people, >17 countries
in Japan:
Shinshu
Kyushu
Tokyo



Development and testing of these technologies has been active over the last ~10 years
Principles of operation and performance well understood

Over last few years, emphasis has been on “technological prototypes”
Preparing for real collider detector design and construction

CALICE combined testbeams

common DAQ, data format...

tested at same beamlines

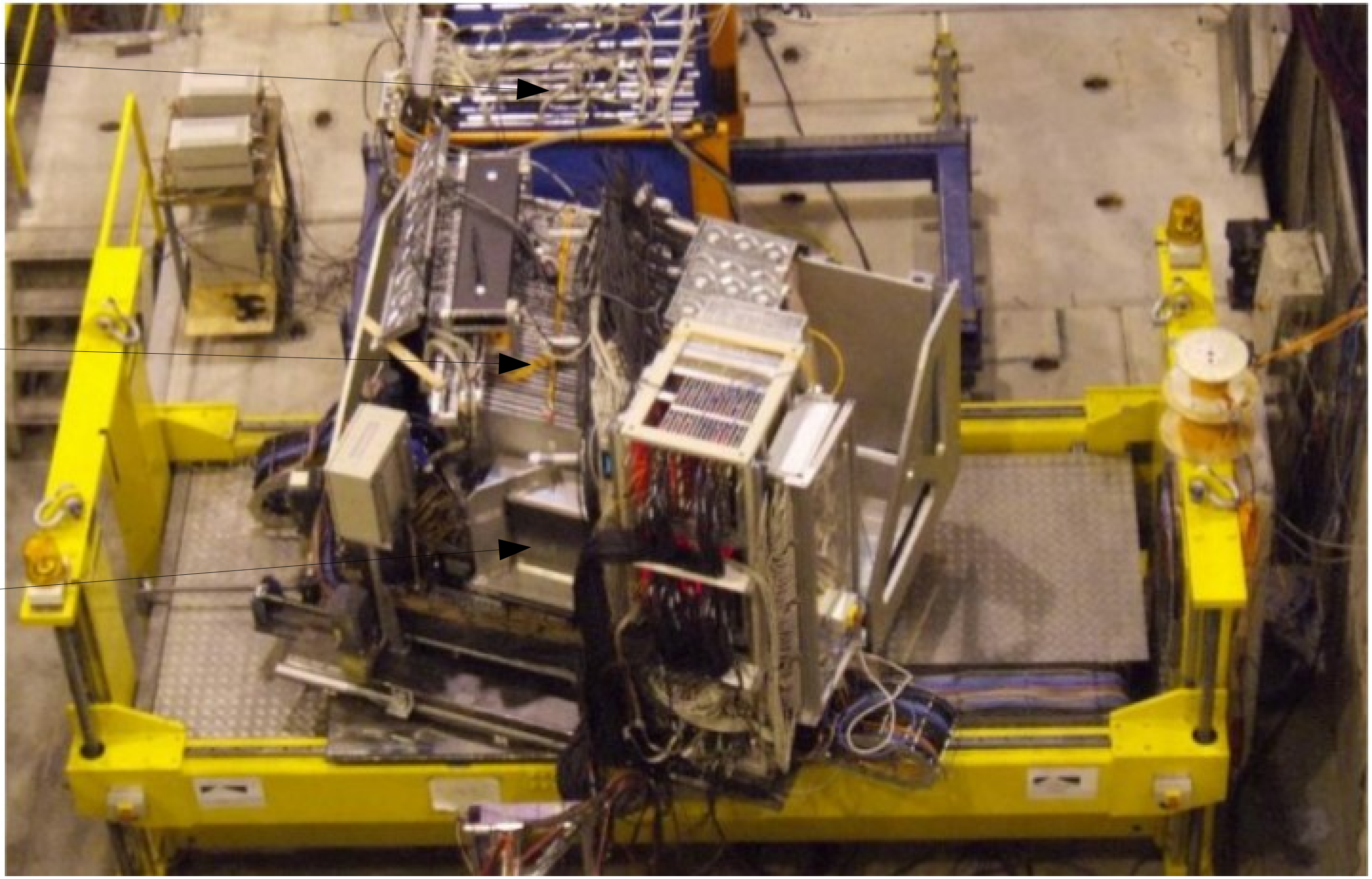
allows "direct" comparison of technologies

Tail catcher

Scintillator HCAL

Silicon ECAL

(all 1st generation)



ECAL

Tungsten absorber is close to ideal:

- Small X0 (~3.5mm)
- Small Moliere radius (~10mm)
- Relatively large λ_I (~10cm)
- Mechanical properties OK

~27X_0 thickness

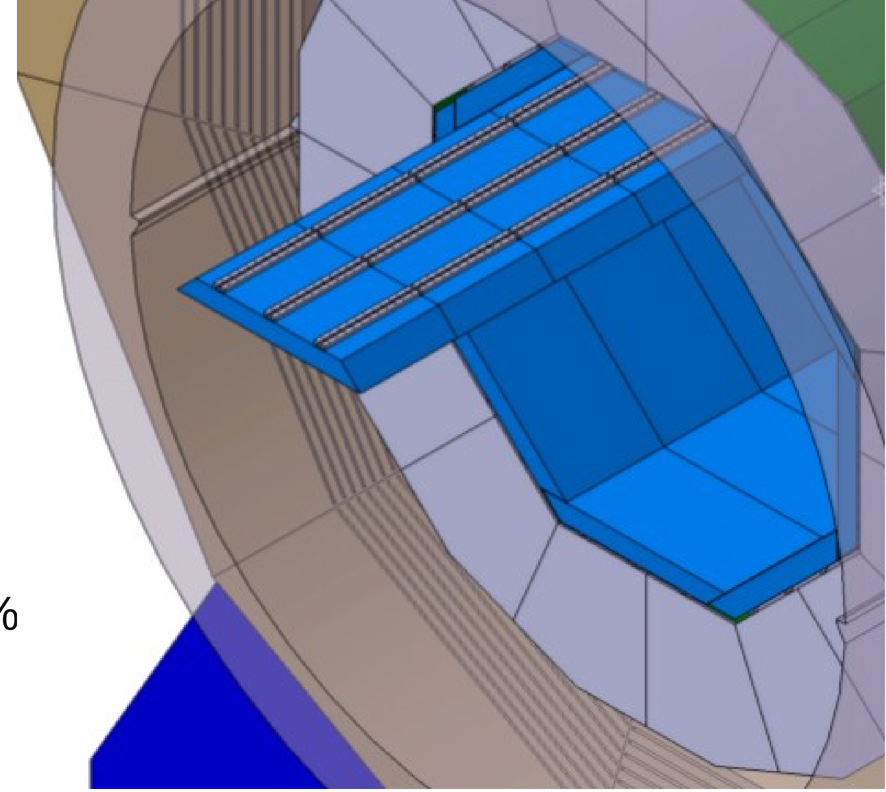
~30 samplings gives sufficient energy resolution ~17%

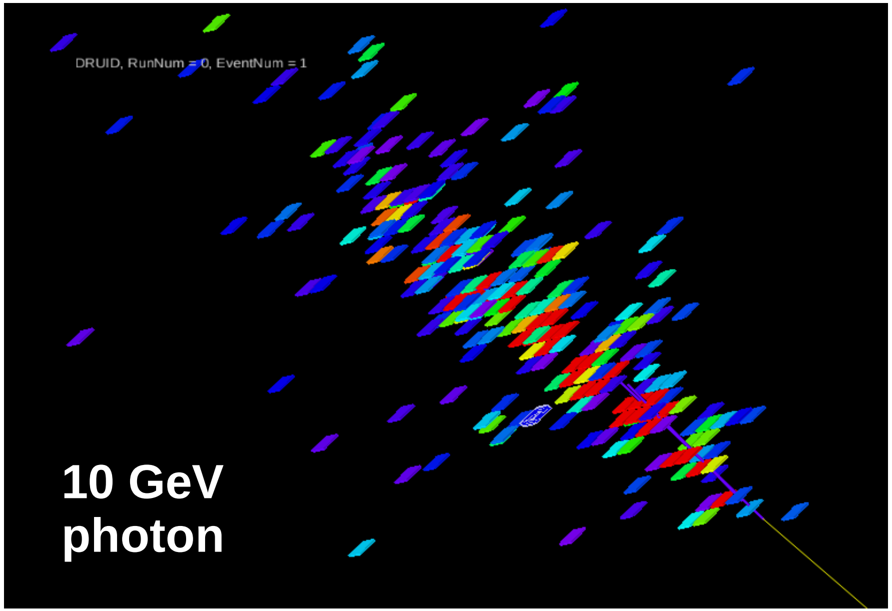
e.g. 20 W layers @ 0.6 X_0, 9 layers @ 1.2X_0

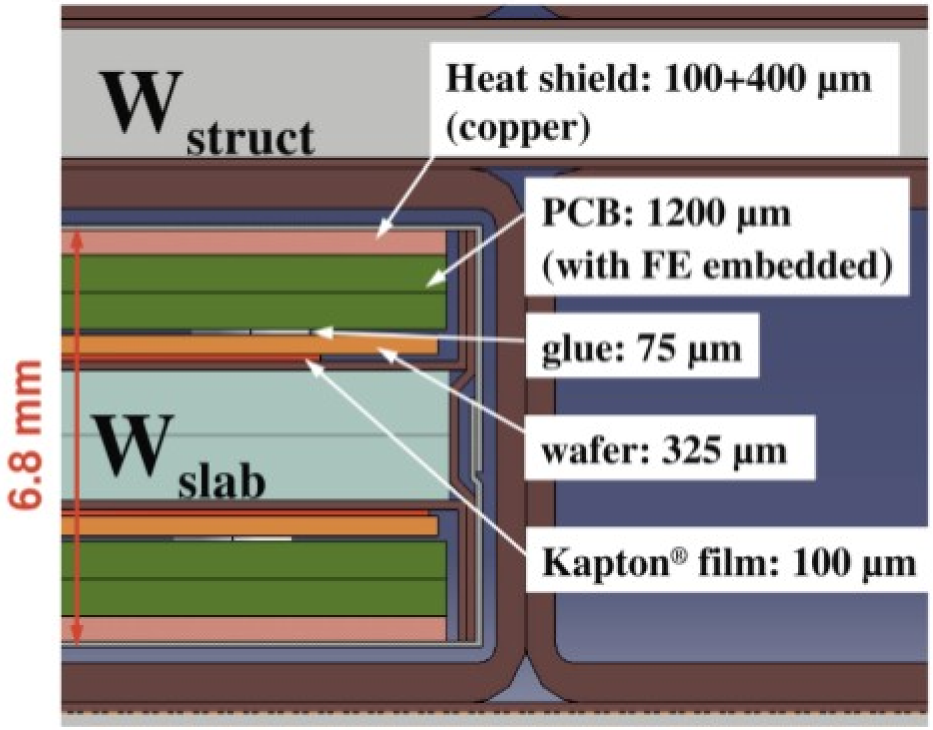
Readout granularity ~ 5mm

~ 2500 m^2 sensitive area

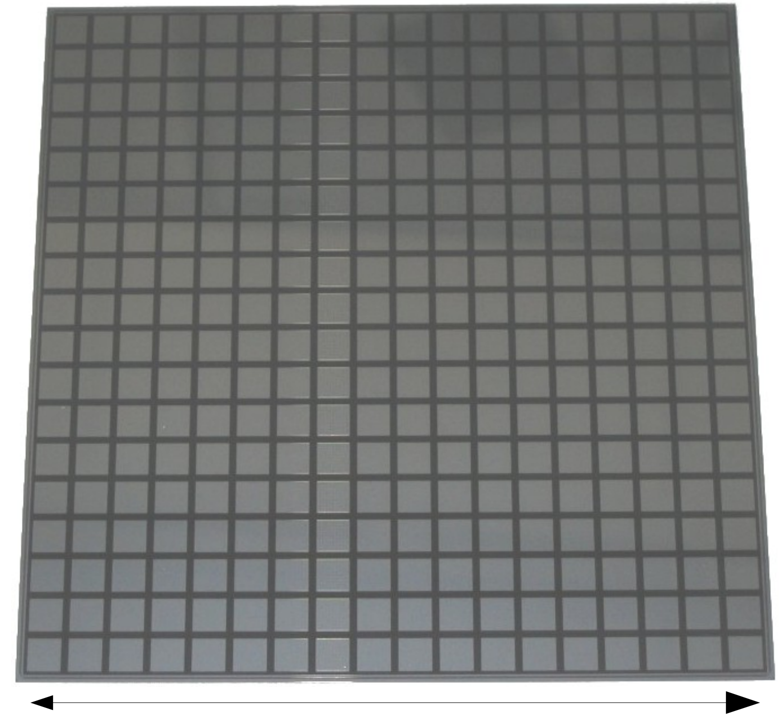
~ 10^7 -> 10^8 readout channels







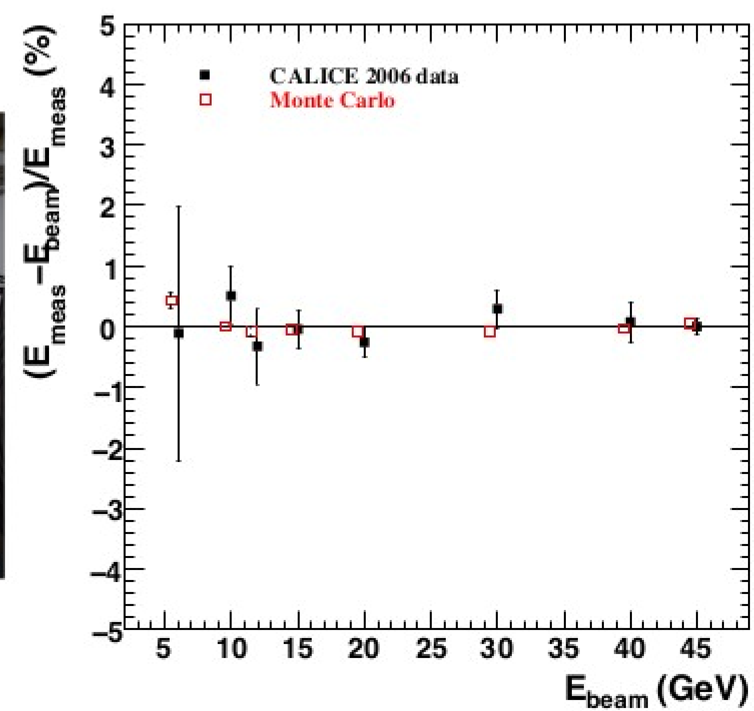
ECAL sensitive layers



Silicon

PIN diode matrices: (3~5 kΩ cm)
- Stable behaviour, easy to operate
- Excellent S/N
- Thin ~320 μm
- ~any geometry/segmentation possible
  - now using 5.5 x 5.5 mm^2

Expensive ~ few 100 yen / cm^2
- Total area ~ 2.5 x 10^7 cm^2



First, “physics” prototype
(in use 2005-2011)

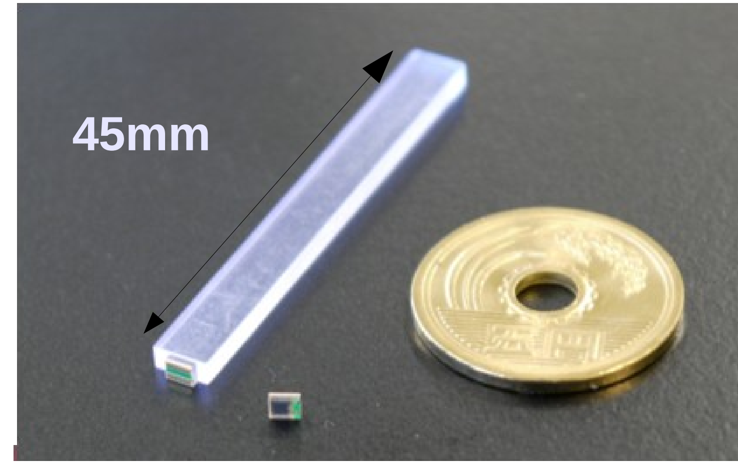
ECAL sensitive layers

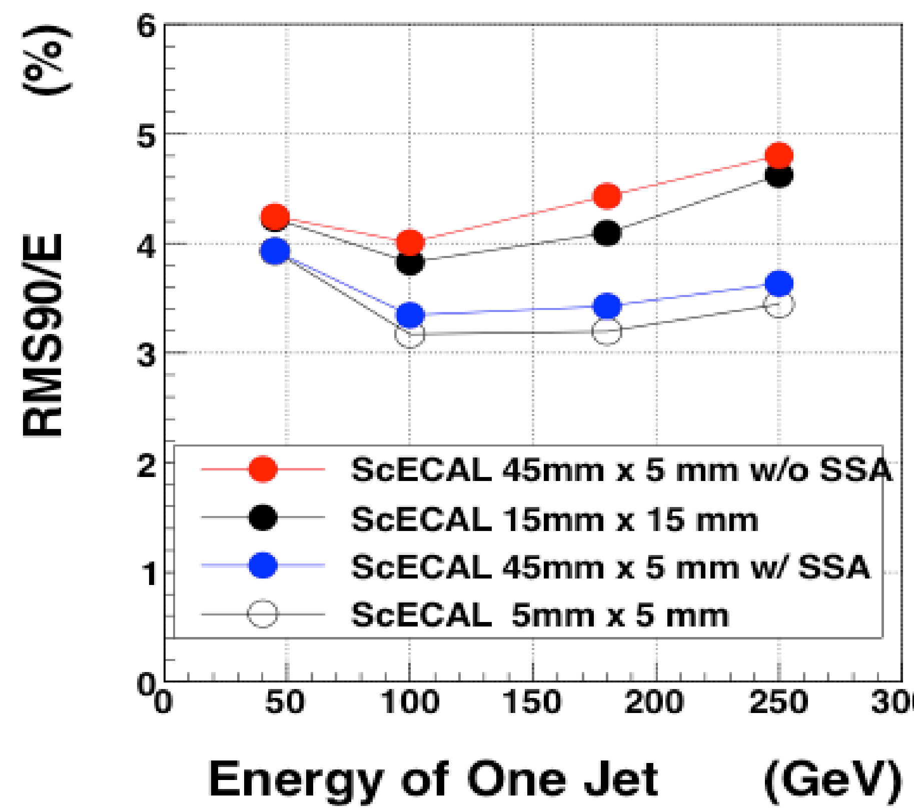
Scintillator

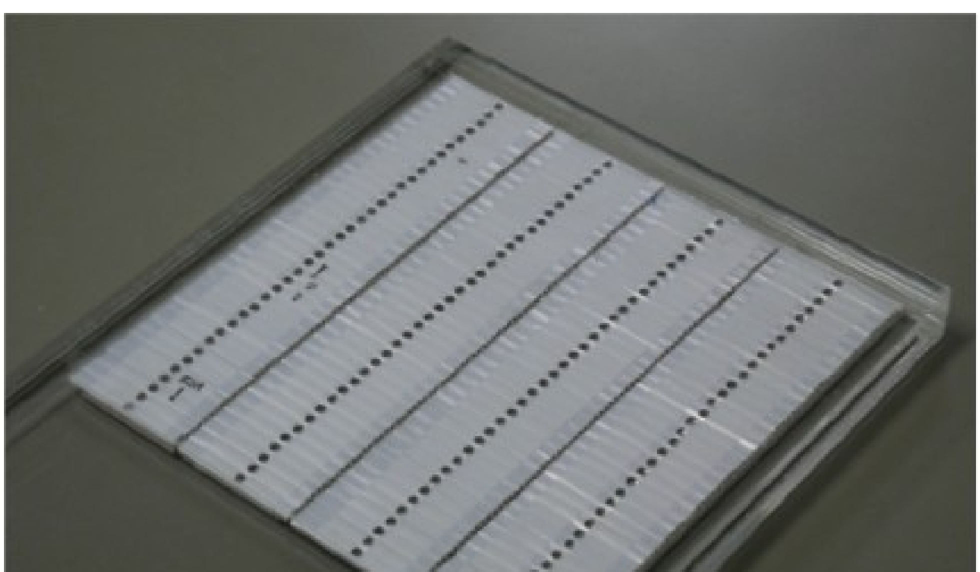
Scintillator strips 5 x 45 x (1->2) mm3
MPPC readout
Orthogonal strips ->
close to 5x5mm2 effective segmentation
using dedicated reconstruction (SSA)

Significantly less expensive

Response varies with temperature
In a well understood way
Smaller dynamic range
(but improved MPPC models arriving)







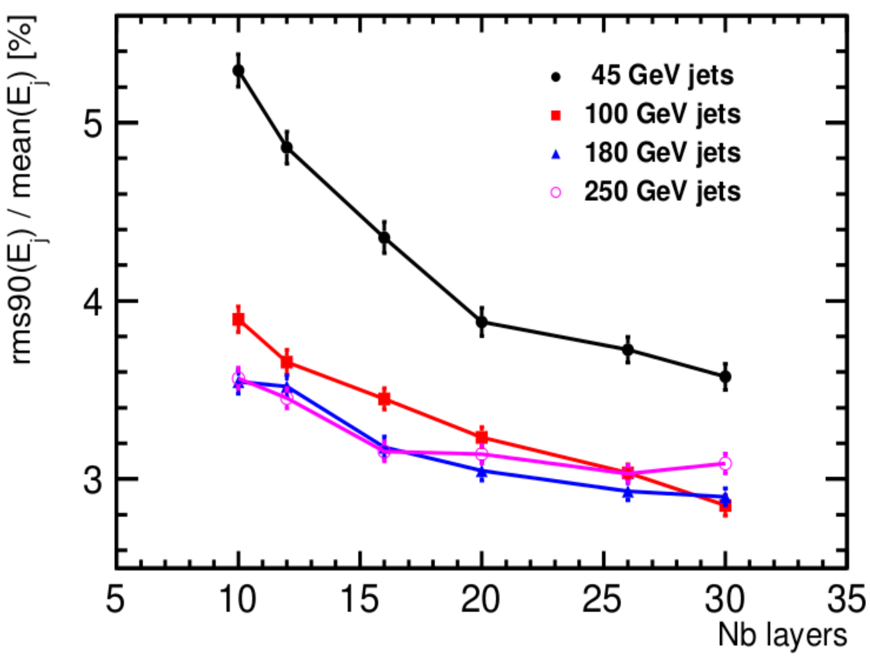
ECAL – cost optimisation

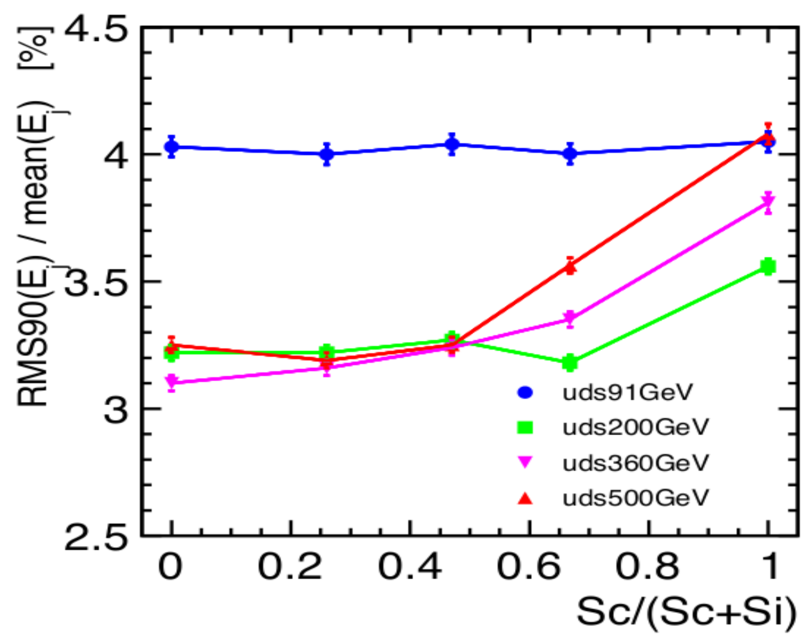
ECAL represents major cost driver of ILD
particularly with silicon readout (cost driven by silicon sensor area)

A number of studies are underway investigate cost reduction strategies

- smaller number of sampling layers
  cost decreases faster than performance

- hybrid silicon and scintillator designs
  Interleaved silicon layers can significantly improve reconstruction
  50% silicon, 50% scintillator seems to have
  rather small performance penalty





HCAL

Inside solenoid coil -> compact

- Stainless steel absorber structure
  - ~48 layers, 2cm (1 X_0) thick
- Sensitive layers a few mm thick

pattern recognition capabilities

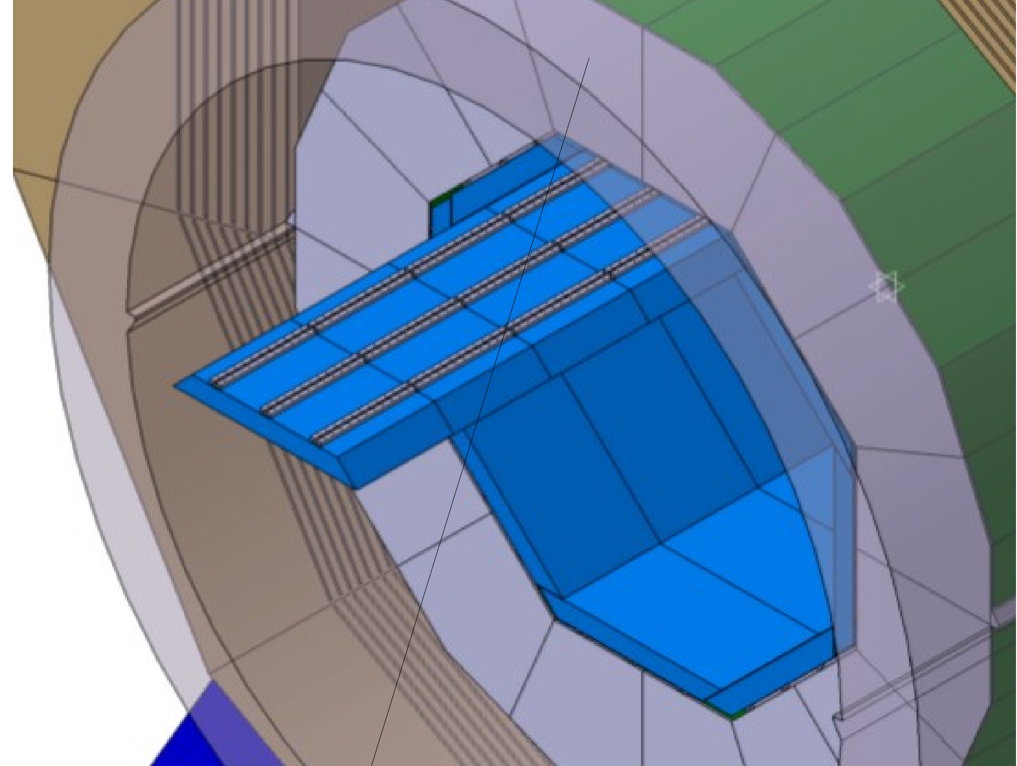
- -> highly segmented readout
  - 1x1 -> 3x3 cm^2

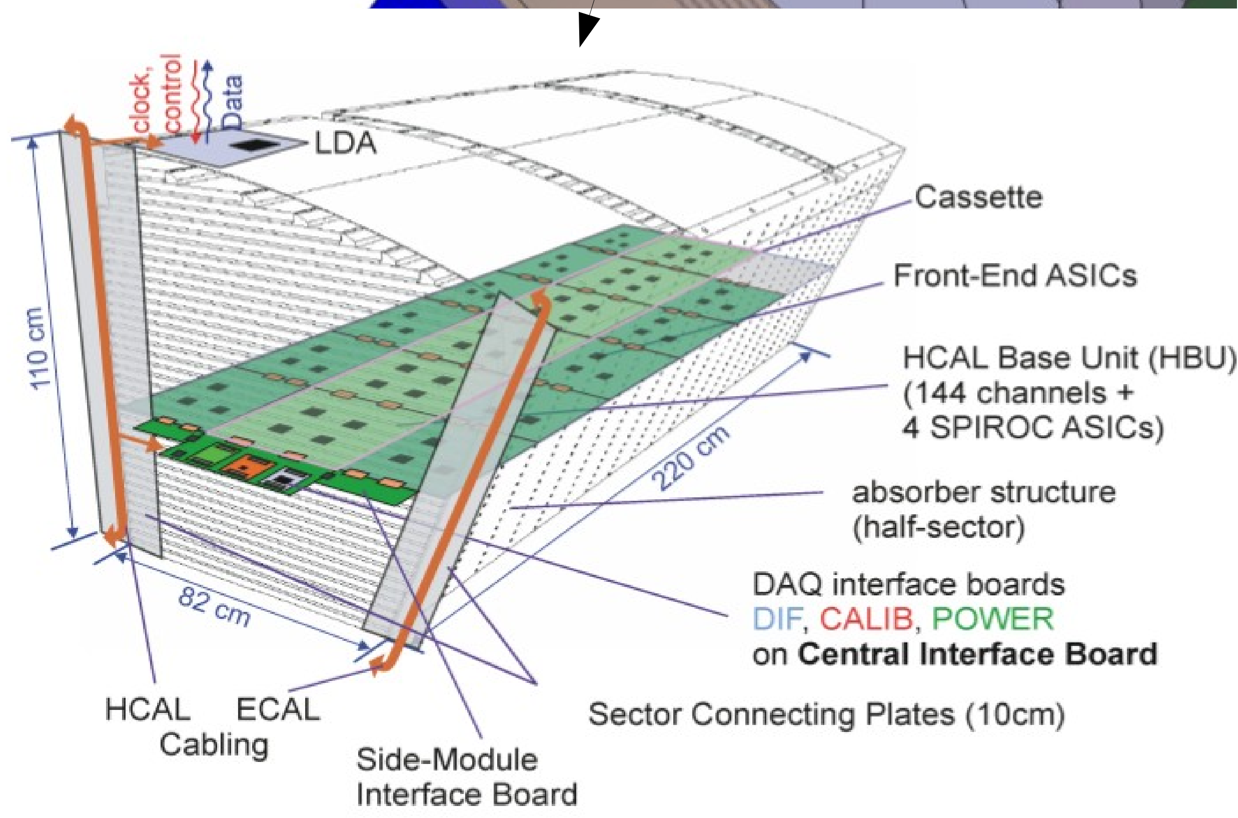
Integrated low power FE electronics

- Reduce dead volumes
  - from cables and cooling

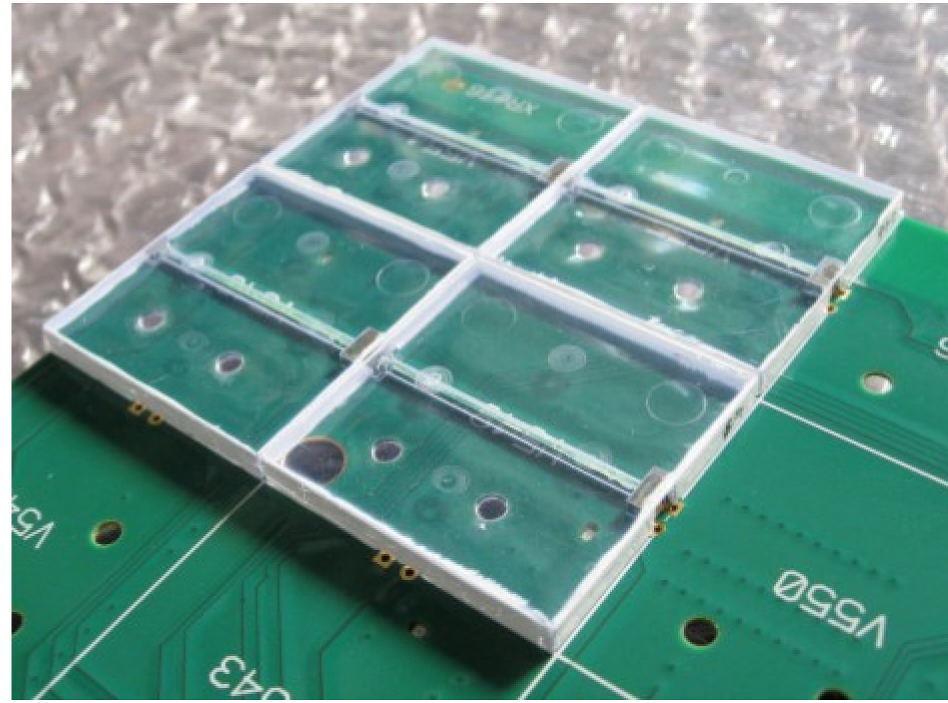
Several technologies being conside

- Scintillator tile or strip
  - SiPM readout
- Gaseous detectors
  - RPC, GEM, MicroMegas





Scintillator + SiPM

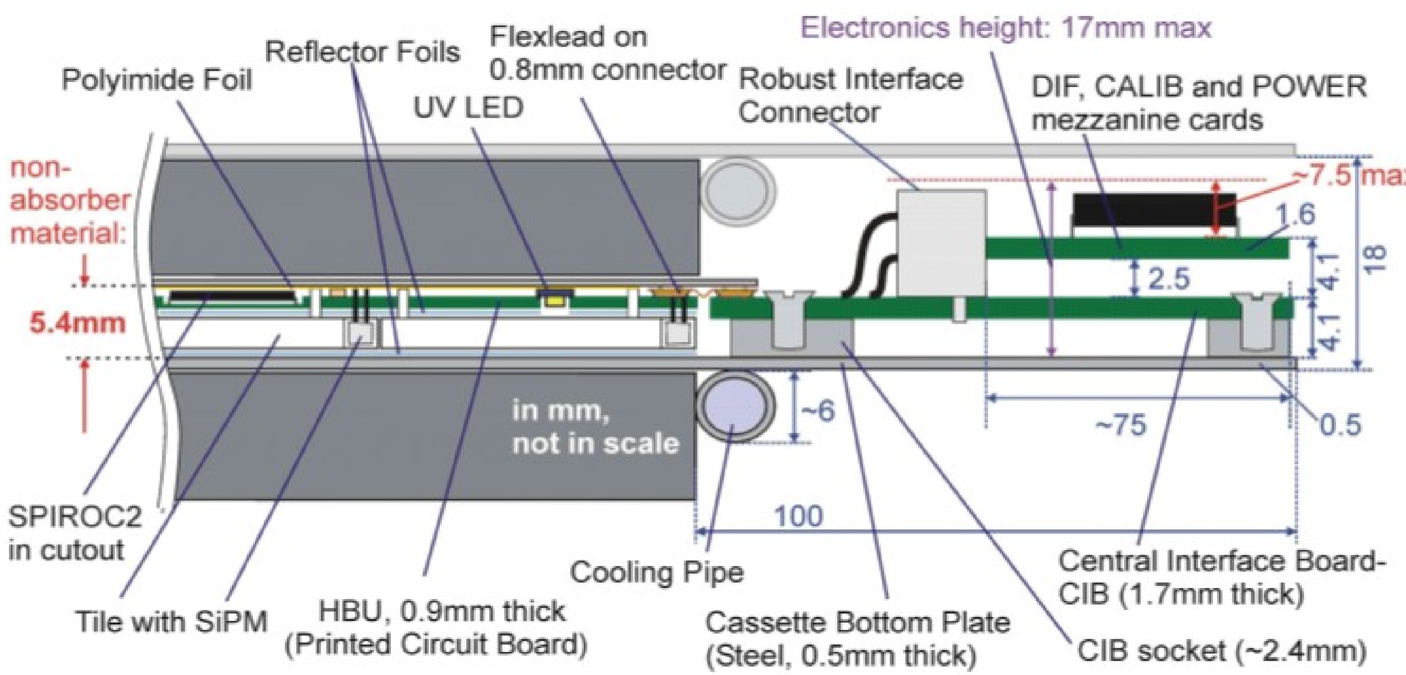


3 x 3 x 0.3 cm^3 scintillator tiles

WLSF – SiPM readout
Analogue (12-bit) readout

Integrated LED calibration system

Results from 1st prototype used to
select GEANT4 models



Gaseous detectors

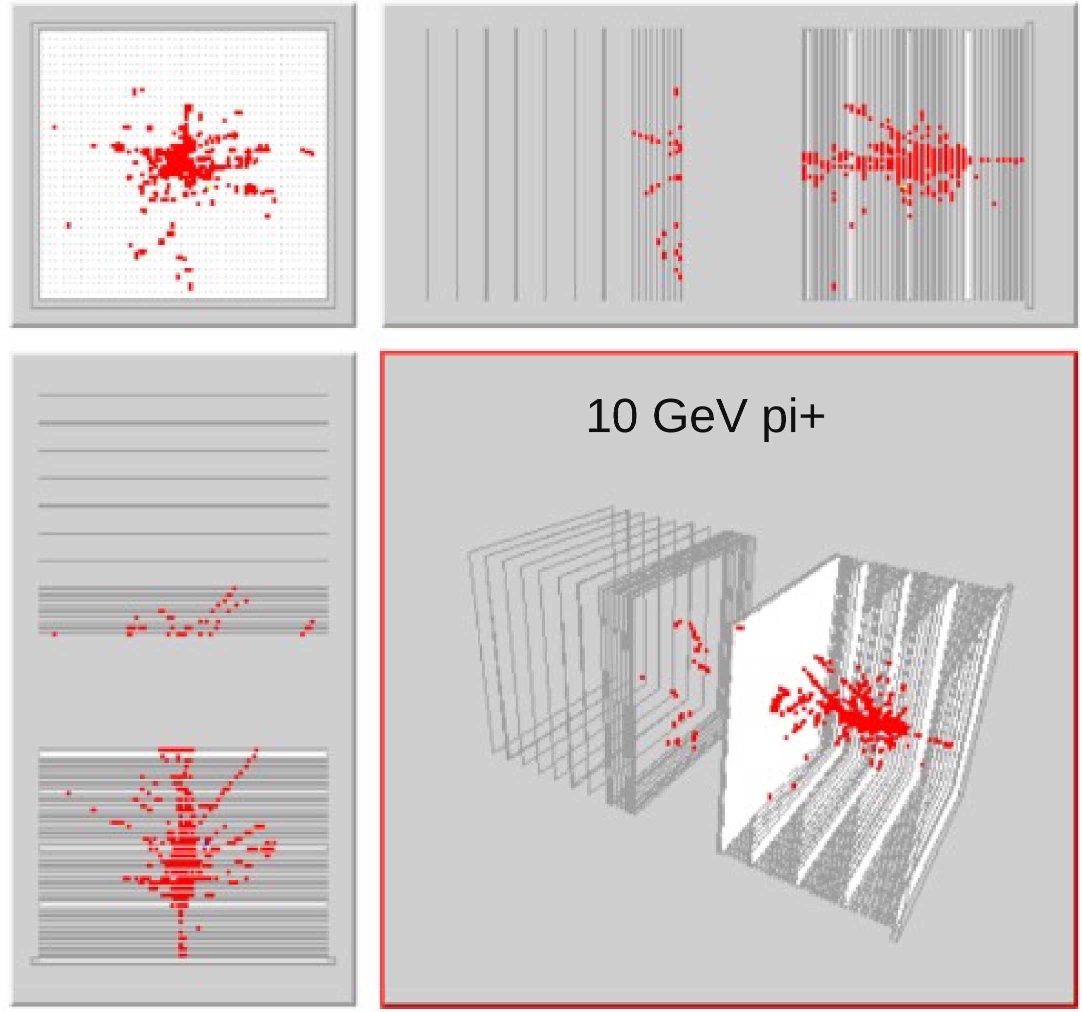
Resistive Plate Chambers

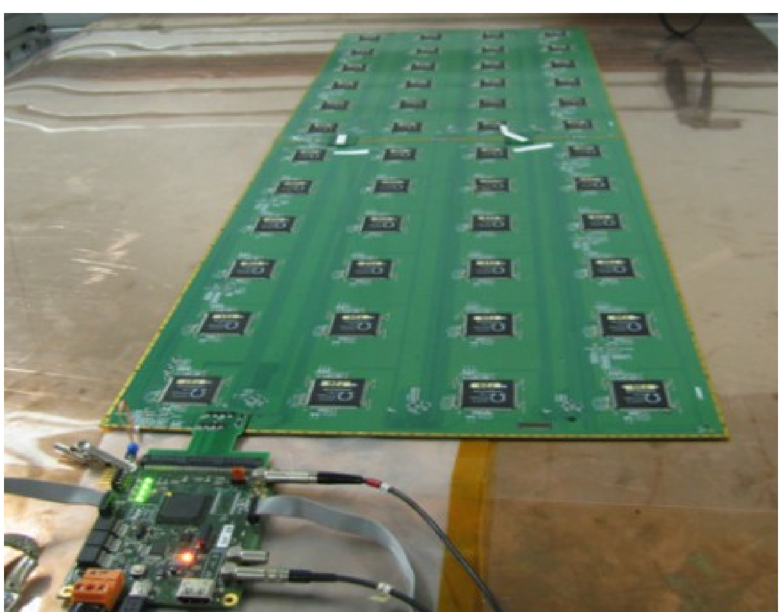
GEM

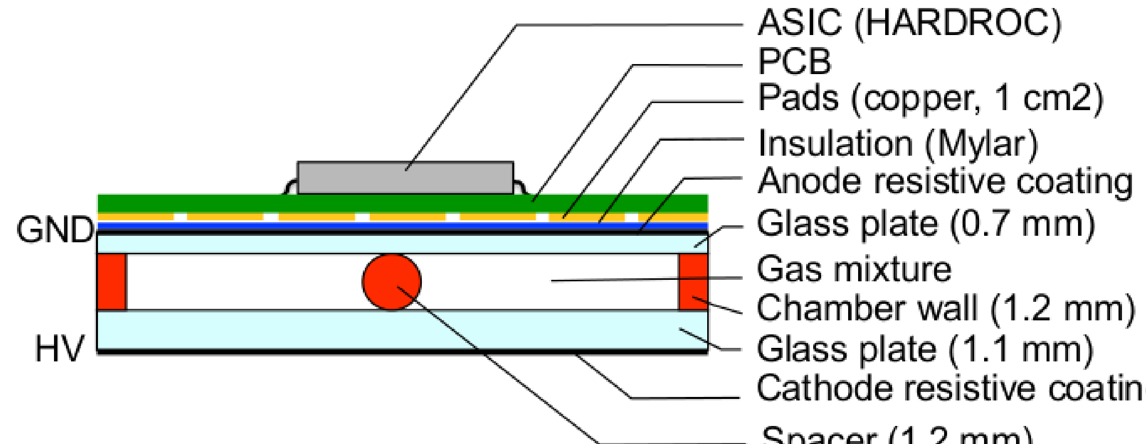
Micromegas

Typically

- digital readout (1 or 2 bits)
- 1X1cm^2 readout granularity







Software compensation in HCAL

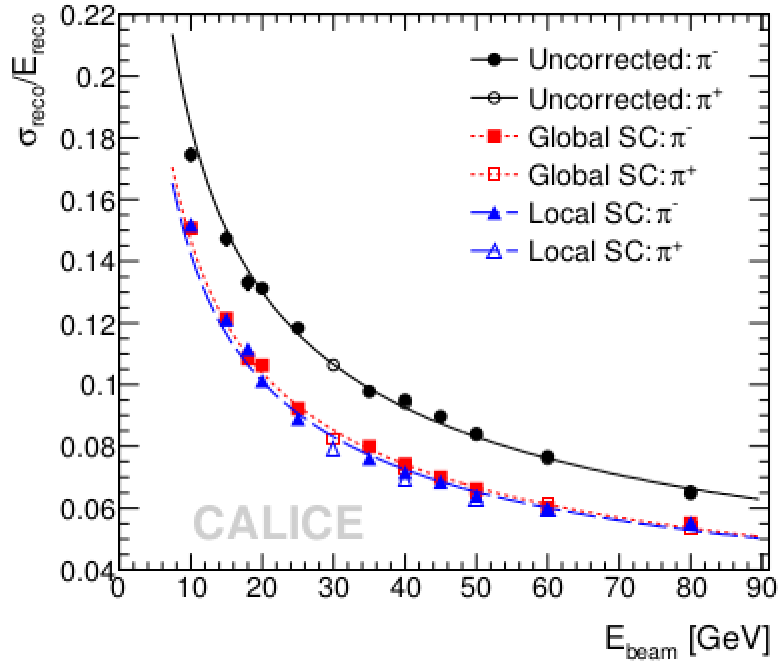
Calorimeters not intrinsically compensating
- Different response to hadronic and
  - electromagnetic energy

Thanks to granularity,
- software compensation is possible

Can identify EM sub-showers (π^0...) within
- hadronic showers (shower shape, energy density)

Can weight individual cells or showers
- according to measured EM fraction to
  - achieve better compensation
    - and improve energy resolution

Significant improvements in energy resolution
- demonstrated in testbeam data



fit results		
	stochastic	constant
initial	57.6%	1.6%
global SC	45.8%	1.6%
local SC	44.3%	1.8%

Scintillator HCAL

Summary

Particle Flow reconstruction can give excellent (hadronic, tau) jet reconstruction
- particularly important at lepton colliders
  - but also applicable in other environments

R&D for "Particle Flow" calorimetry has been active for ~10 years
- well understood technique (e.g. well described in simulation)
  - ready for implementation

Several technological approaches are proposed
- each with advantages and disadvantages
  - technology decisions will be based on
    - performance
    - reliability
    - cost & finance

Many more details available, *e.g.* in:
- ILC TDR – to be published in June
- https://twiki.cern.ch/twiki/bin/view/CALICE/
- arXiv:1212.5127

Backup slides

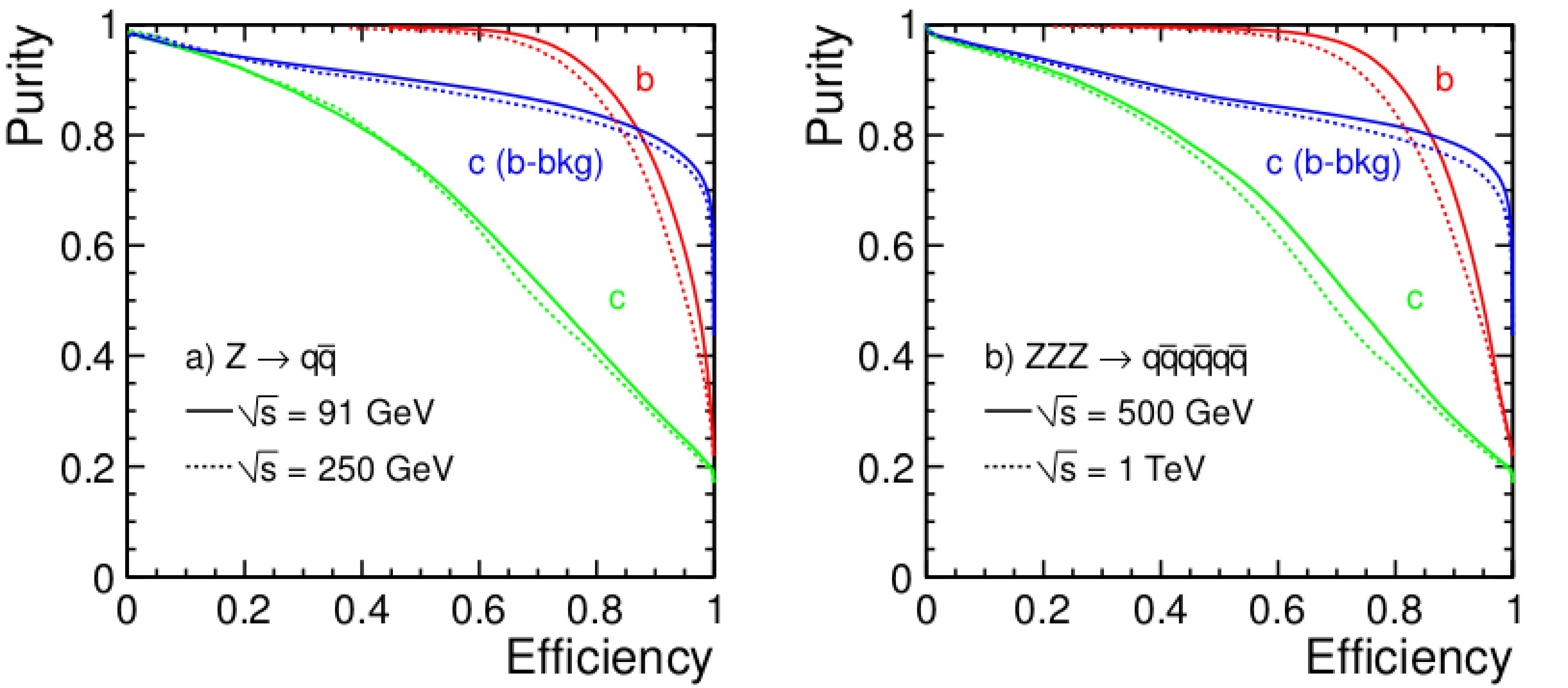


Figure 4.1.5: Flavour tagging performance plots for (a) Z $\rightarrow q\bar{q}$ samples at $\sqrt{s} = 91\,\mathrm{GeV}$ and $250\,\mathrm{GeV}$, and (b) ZZZ $\rightarrow q\bar{q}q\bar{q}q\bar{q}$ samples at $\sqrt{s} = 500\,\mathrm{GeV}$ and $1\,\mathrm{TeV}$.

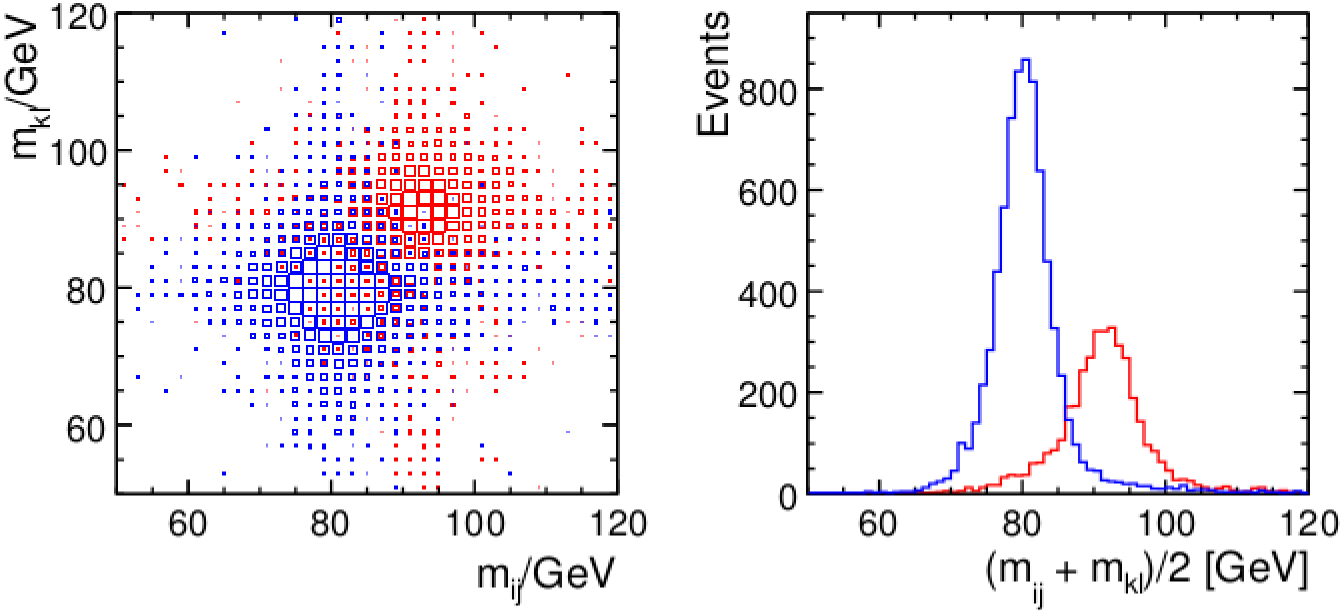
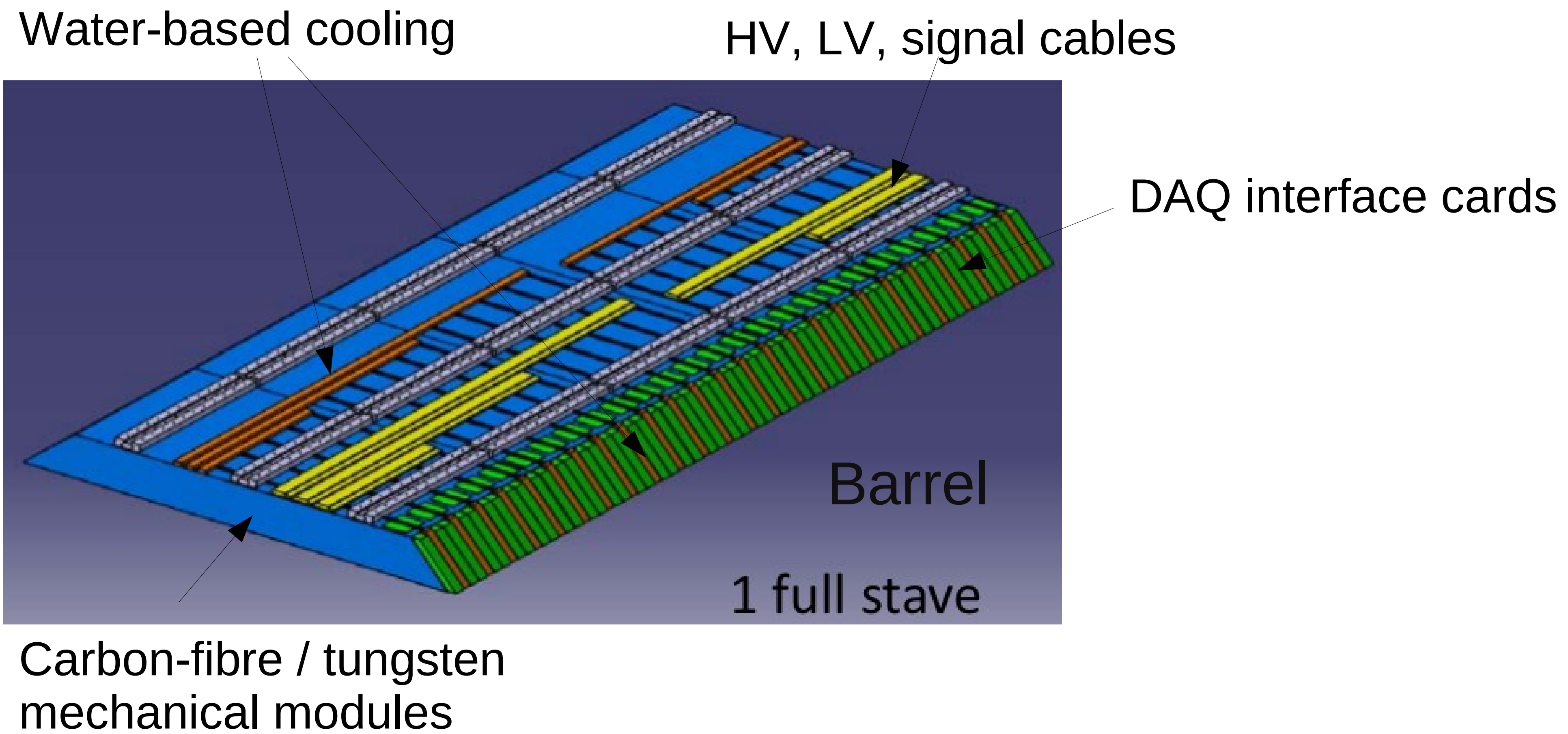
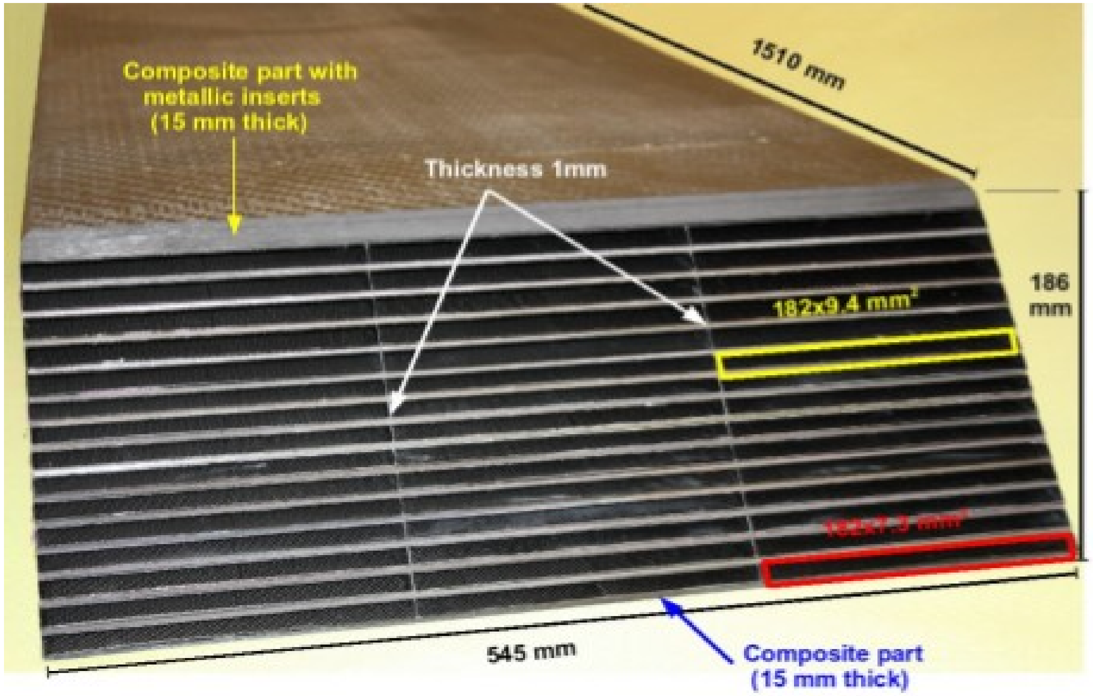


Figure 4.2.3: a) The reconstructed di-jet mass distributions for the best jet-pairing in selected $\nu_e\bar{\nu}_e$WW (blue) and $\nu_e\bar{\nu}_e$ZZ (red) events at $\sqrt{s} = 1\,TeV$. b) Distributions of the average reconstructed di-jet mass, $(m_{ij} + m_{kl}^B)/2.0$, for the best jet-pairing for $\nu_e\bar{\nu}_e$WW (blue) and $\nu_e\bar{\nu}_e$ZZ (red) events.

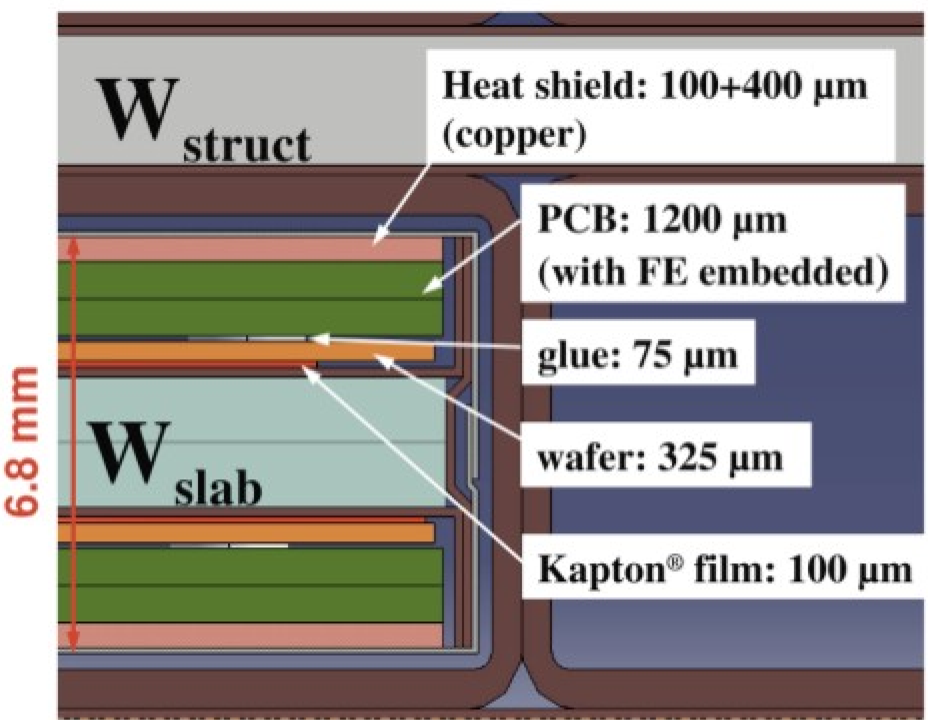

Water-based cooling
HV, LV, signal cables
DAQ interface cards
Barrel
1 full stave
Carbon-fibre / tungsten mechanical modules

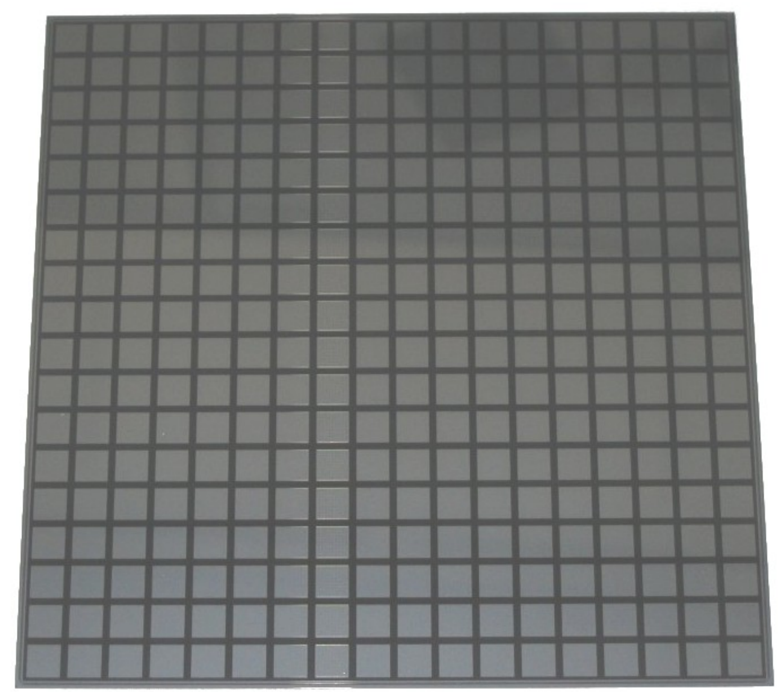


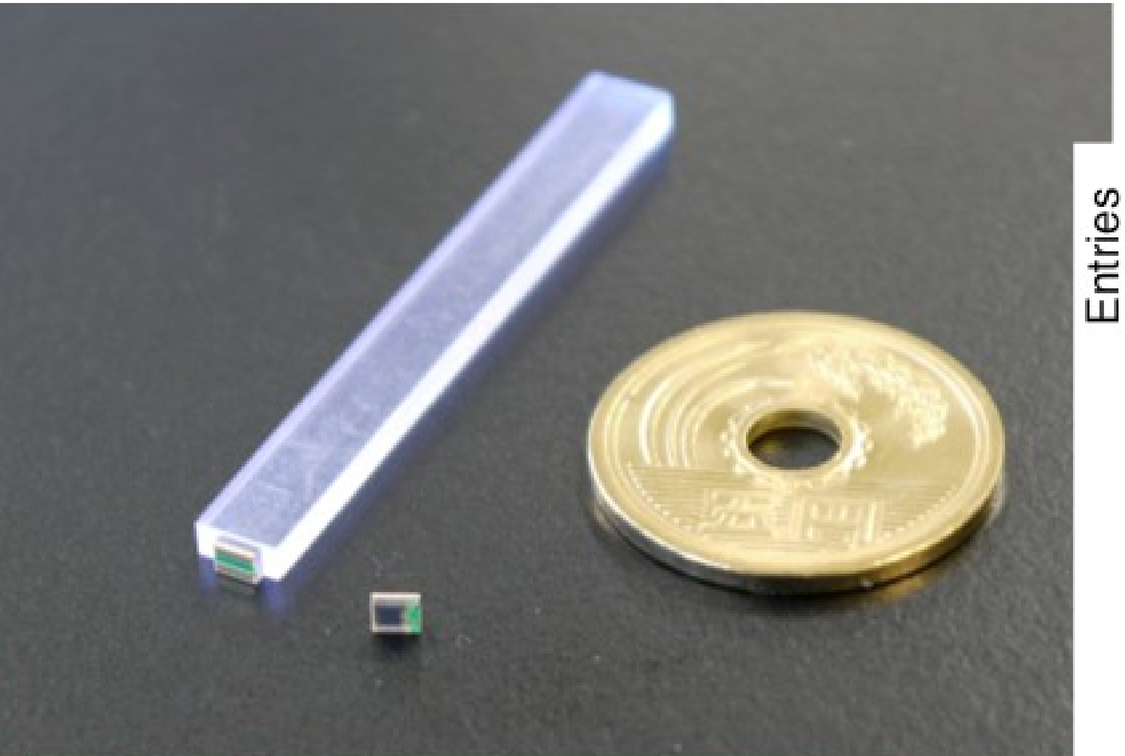
Carbon-fibre/tungsten mechanical structure

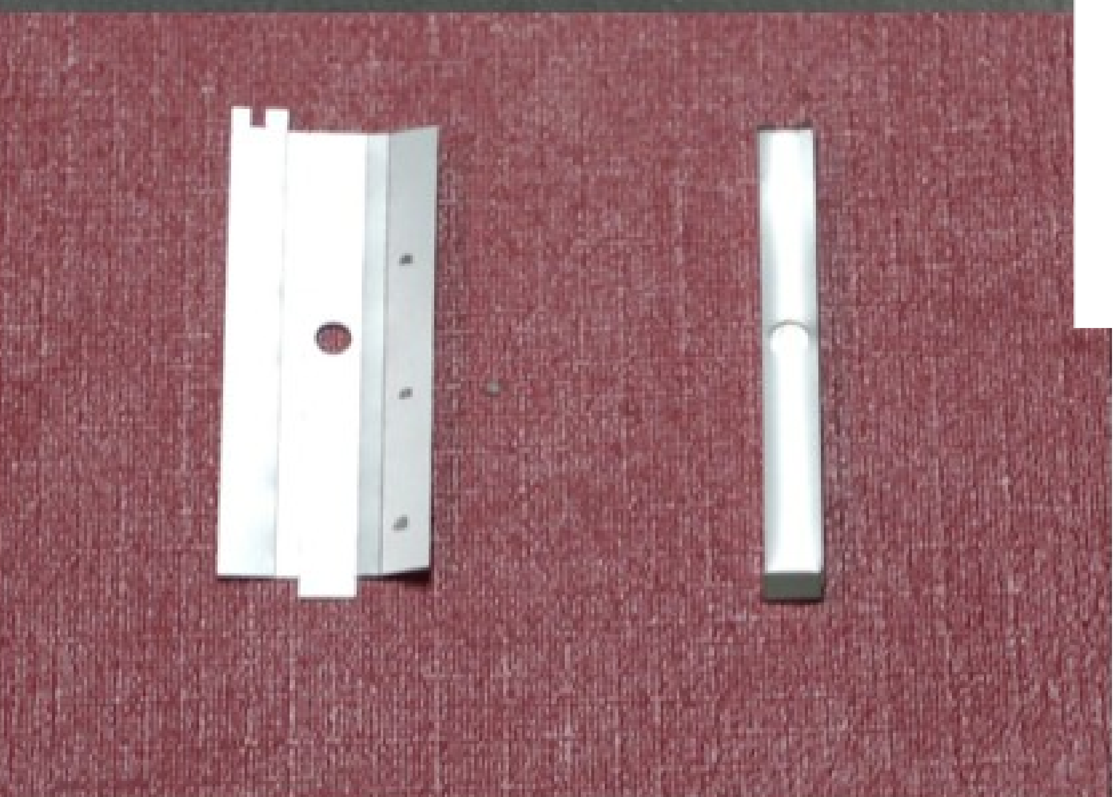
Active Sensor Unit (1024 readout channels)
- 18×18 cm^2 PCB
- 16 readout ASICs
- 4 silicon sensors
  - (each with 256 5×5 mm^2 pads)

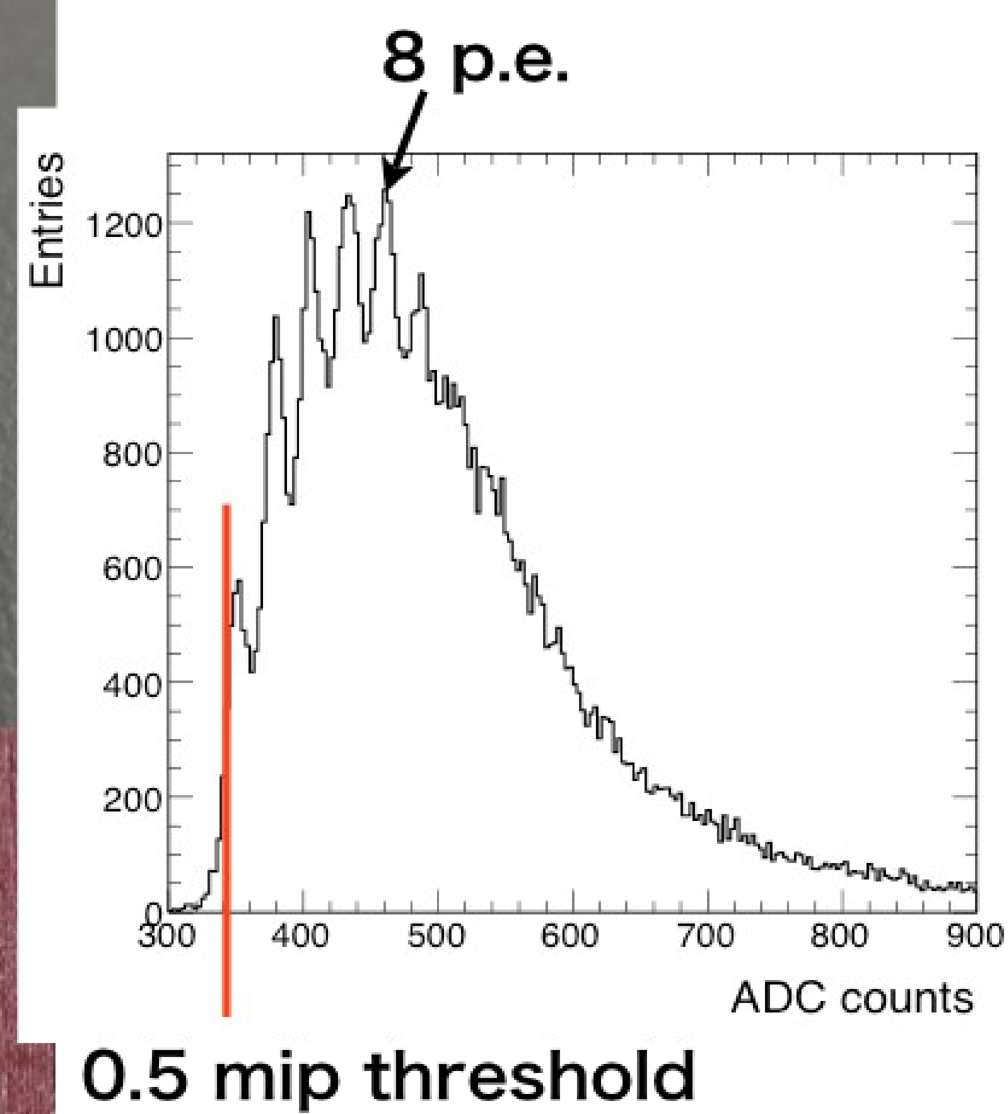
Dynamic range: single MIP to
EM shower core @ 100s GeV

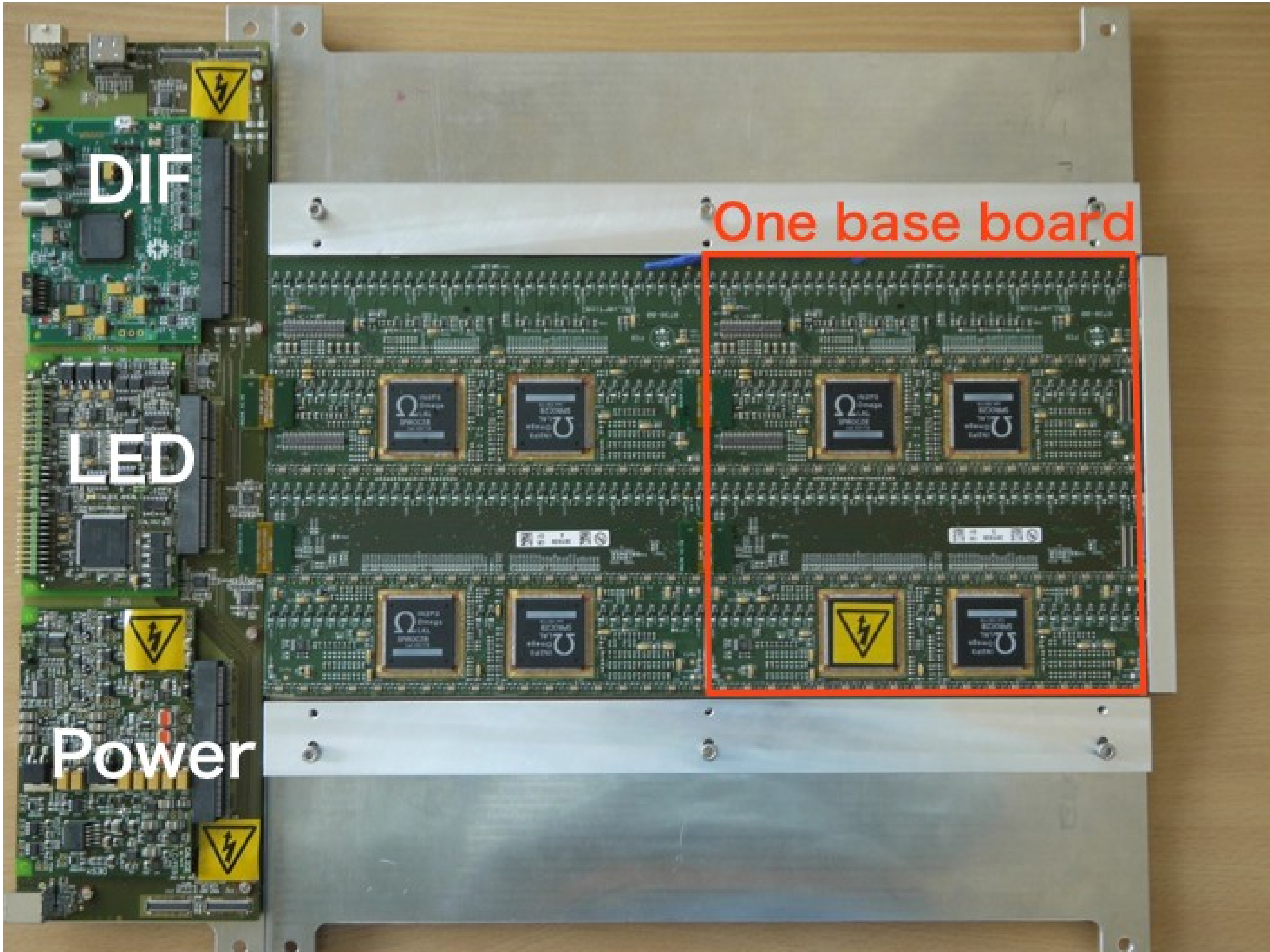


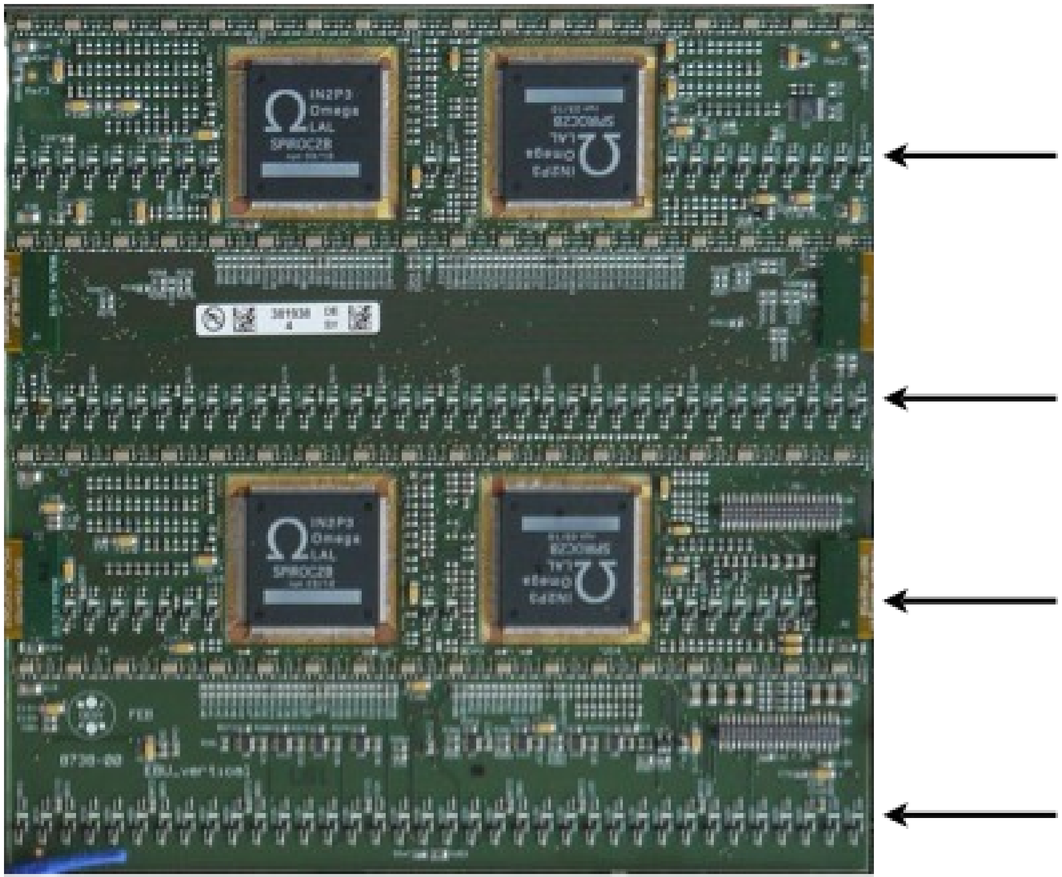


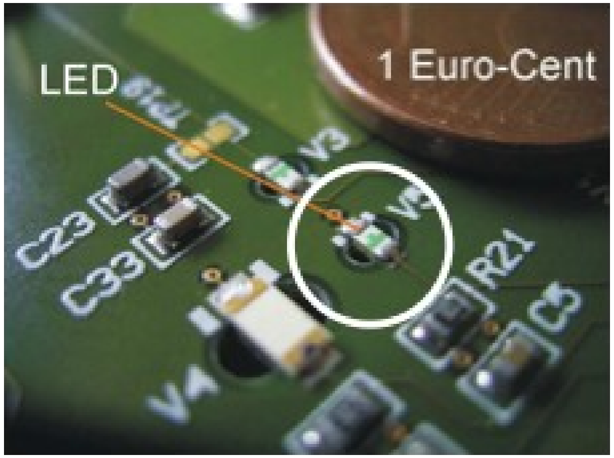




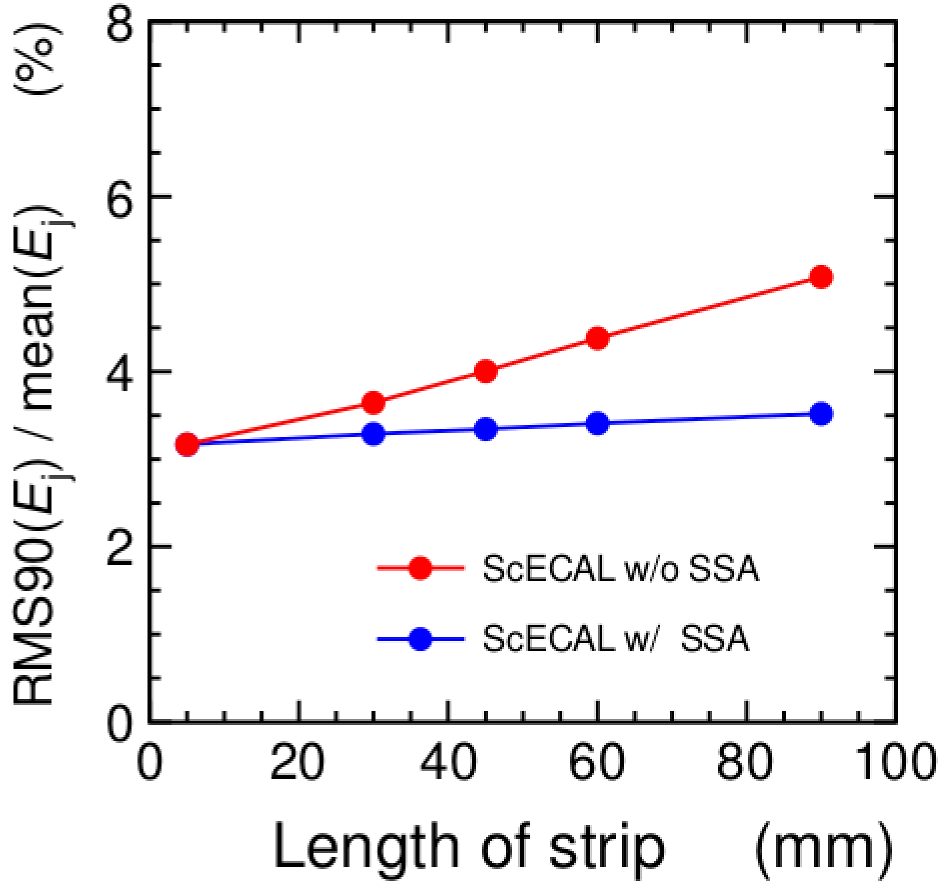

8 p.e.
Entries
1200
1000
800
600
400
200
0
300
400
500
600
700
800
900
ADC counts
0.5 mip threshold

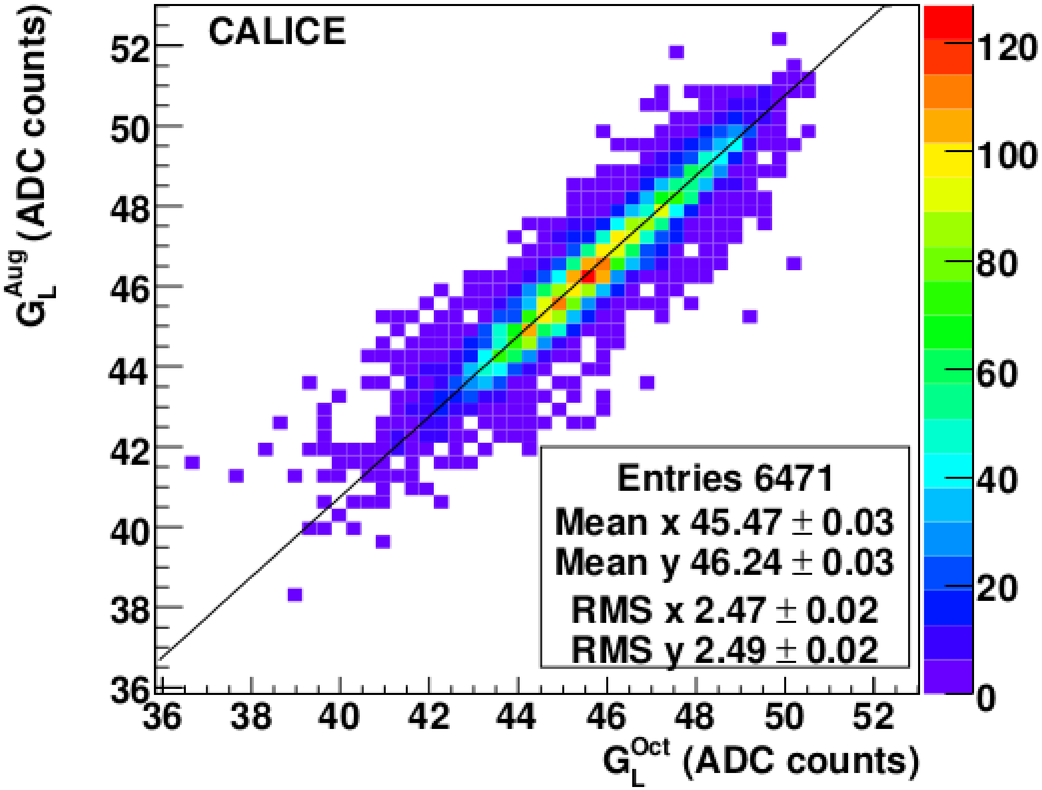

DIF
LED
Power
One base board



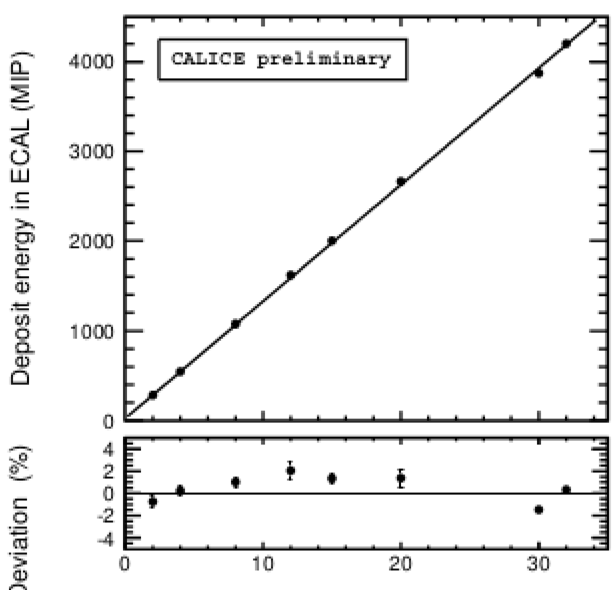


EBU has LEDs for each channel

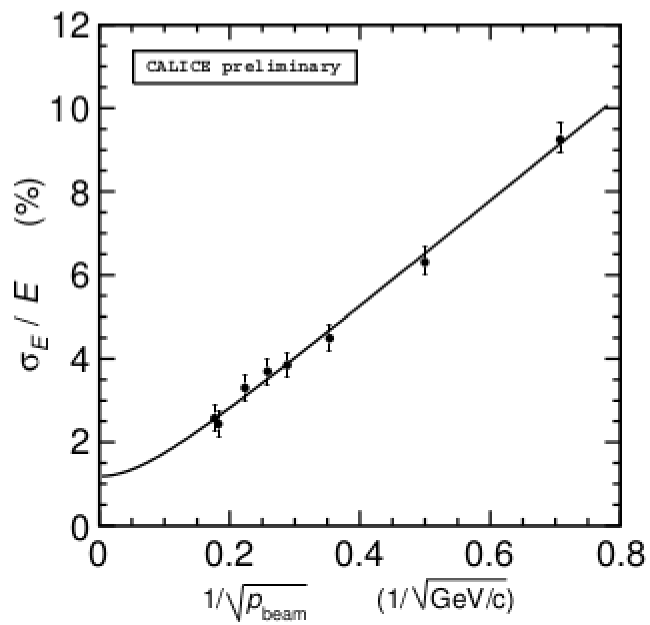

RMS90(E_j) / mean(E_j) (%)
0
2
4
6
8
0
20
40
60
80
100
Length of strip (mm)
ScECAL w/o SSA
ScECAL w/ SSA



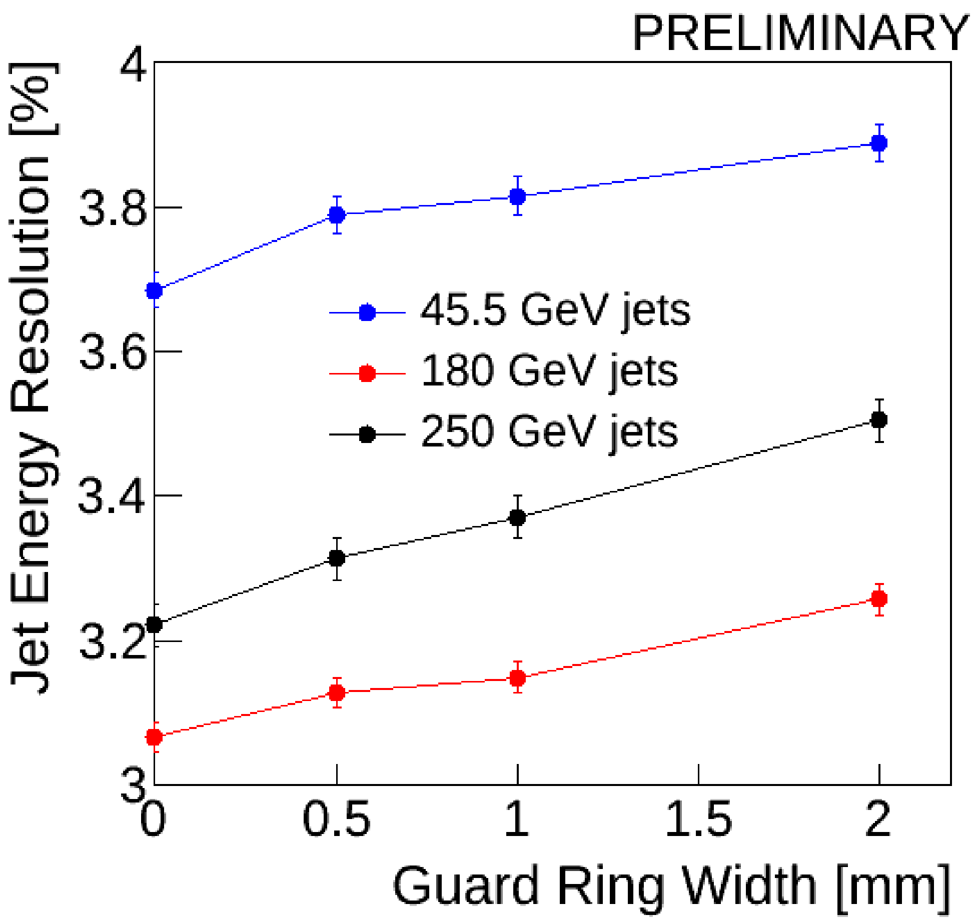
CALICE
G_L^{Aug} (ADC counts)
G_L^{Oct} (ADC counts)
Entries 6471
Mean x 45.47 ± 0.03
Mean y 46.24 ± 0.03
RMS x 2.47 ± 0.02
RMS y 2.49 ± 0.02

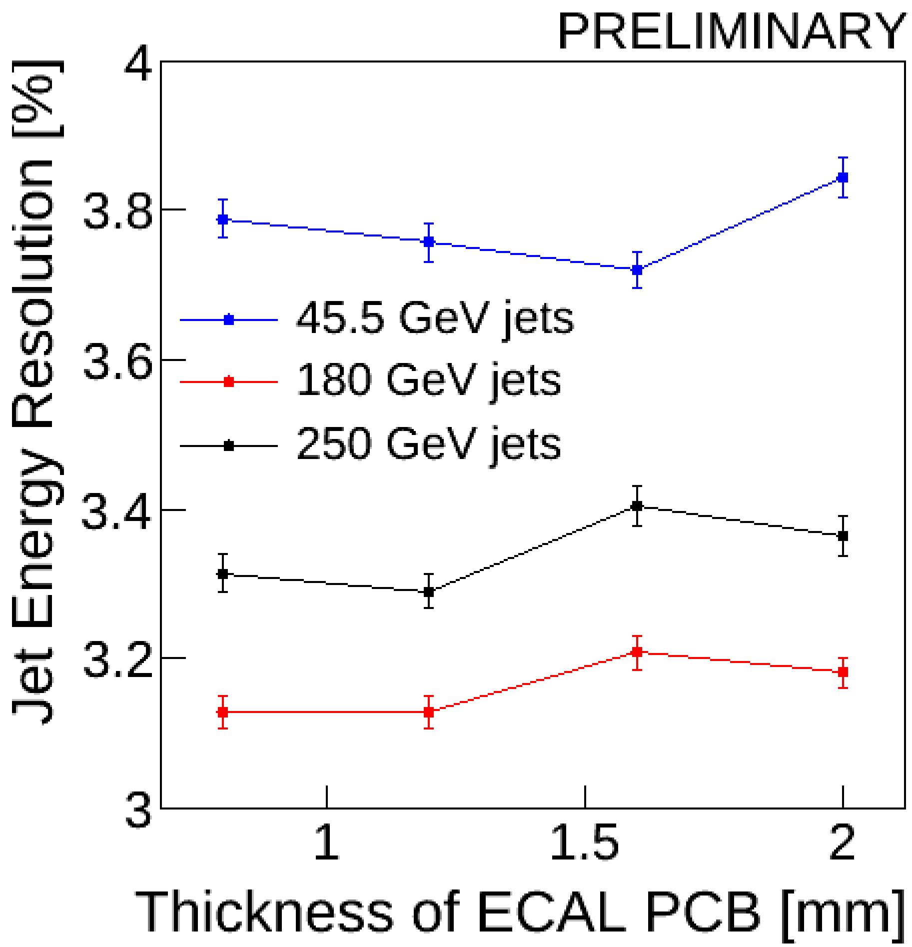


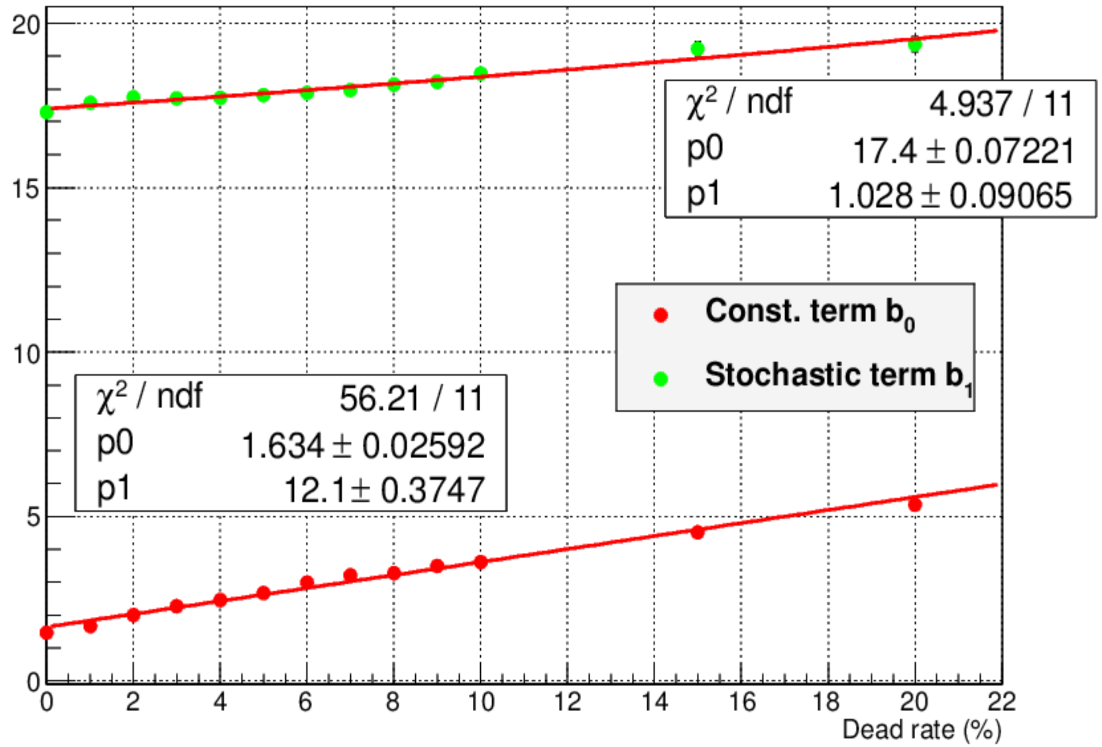
CALICE preliminary
Deposit energy in ECAL (MIP)
Deviation (%)
Beam momentum (GeV/c)



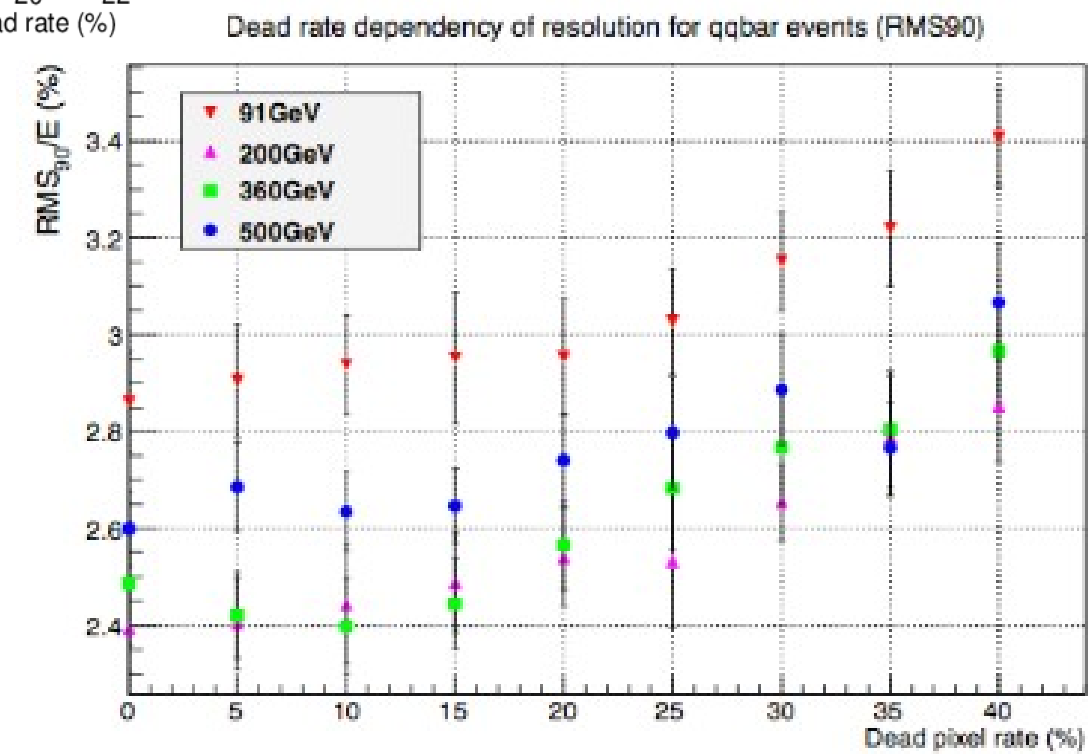
CALICE preliminary
σ_E / E (%)
$1/\sqrt{p_{beam}}$ $(1/\sqrt{GeV/c})$


PRELIMINARY
Jet Energy Resolution [%]
4
3.8
3.6
3.4
3.2
3
0
0.5
1
1.5
2
Guard Ring Width [mm]
45.5 GeV jets
180 GeV jets
250 GeV jets


PRELIMINARY
Jet Energy Resolution [%]
4
3.8
3.6
3.4
3.2
3
1
1.5
2
Thickness of ECAL PCB [mm]
45.5 GeV jets
180 GeV jets
250 GeV jets



χ² / ndf 4.937 / 11
p0 17.4 ± 0.07221
p1 1.028 ± 0.09065
Const. term b0
Stochastic term b1
χ² / ndf 56.21 / 11
p0 1.634 ± 0.02592
p1 12.1 ± 0.3747
Dead rate (%)



Dead rate dependency of resolution for qqbar events (RMS90)
RMS90/E (%)
91GeV
200GeV
360GeV
500GeV
Dead pixel rate (%)

Calibration

How can you hope to calibrate 10^8 detector channels?

Each shower measured by many ~(10s->100s) detector cells
- Shower calibration accuracy ~ cell calibration accuracy / sqrt(N)

PIN diode response expected to be very stable
- seen in test beams over ~5 year period

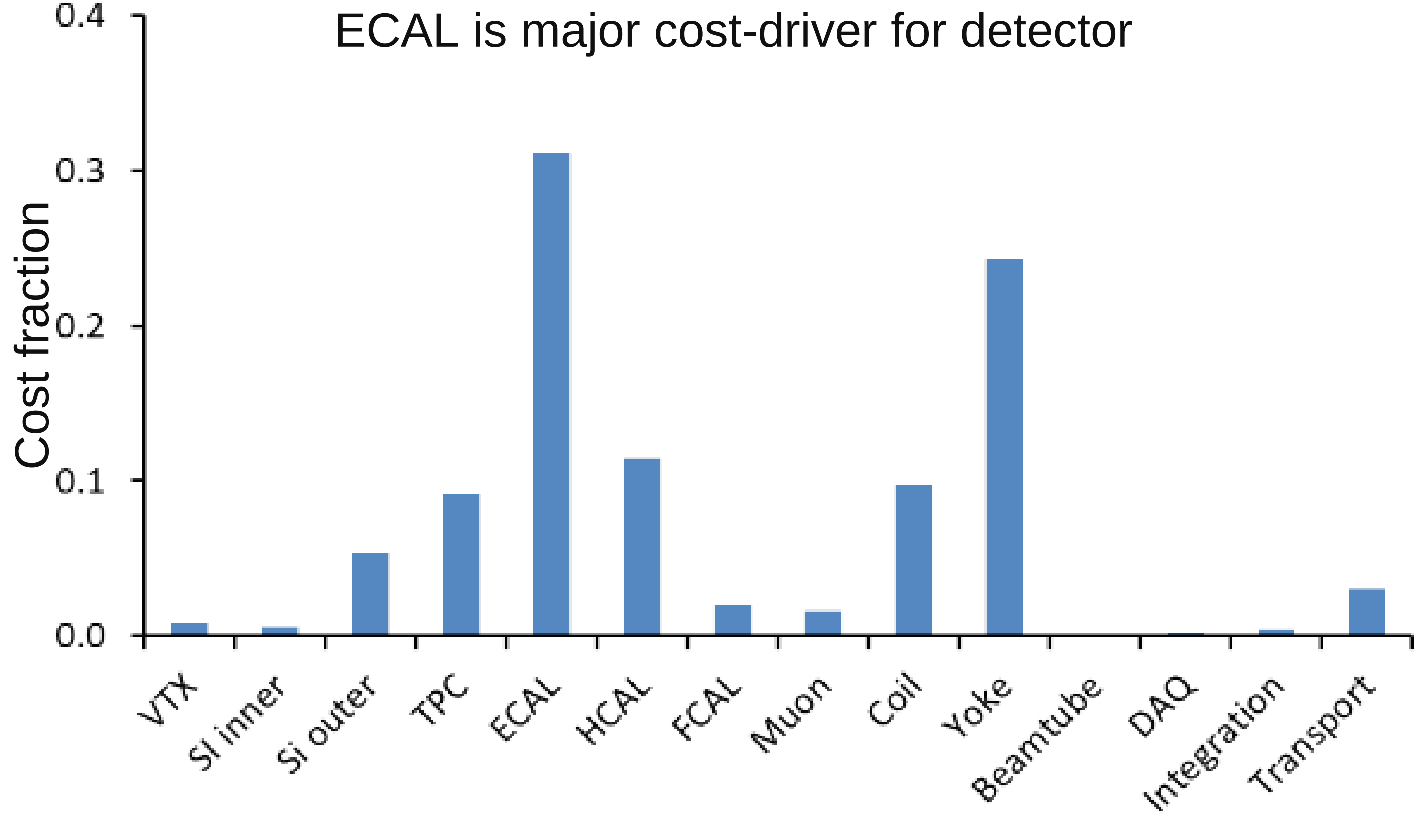
Electrical characterisation of PIN diodes
- width of depletion layer

SiPM/MPPC allows gain calibration: observe individual photon peaks
- LED-based calibration system.
  - Well understood gain-temperature dependence

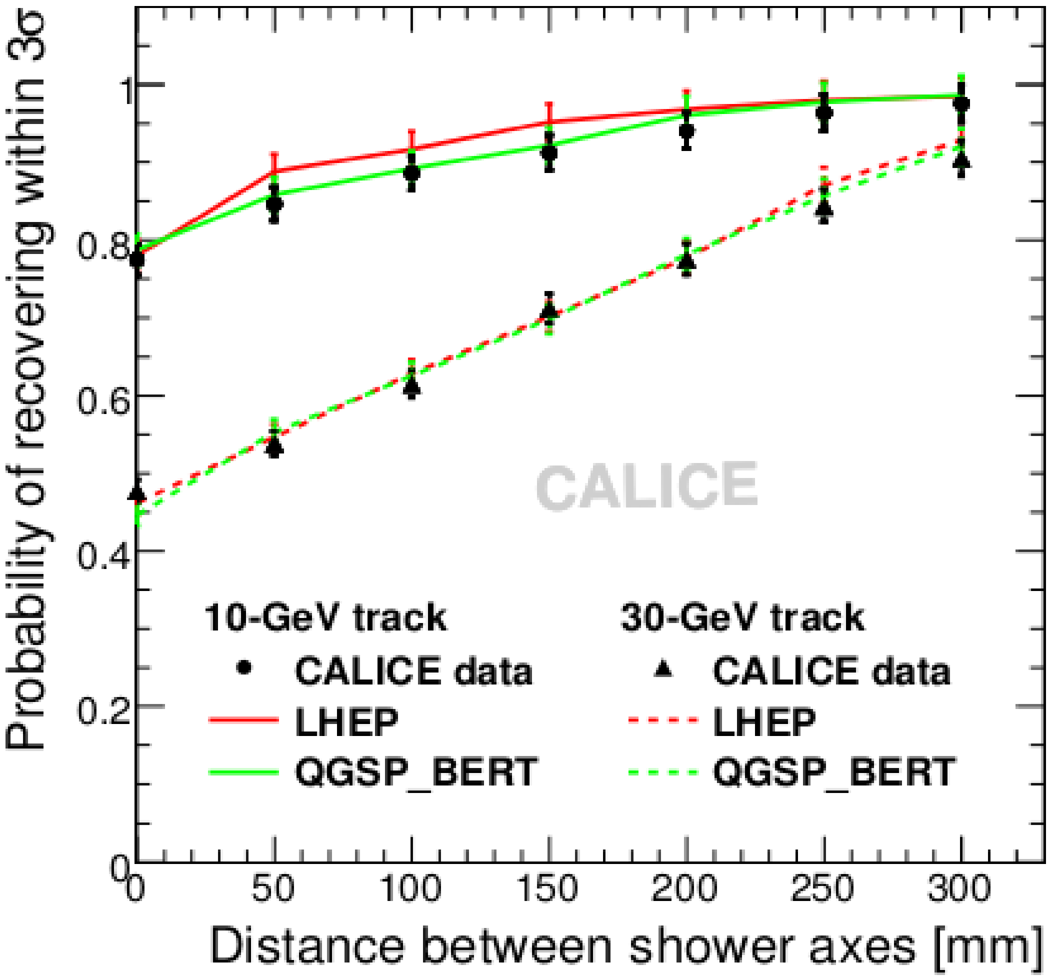
Calibrate all ASUs before final assembly
- Sensor + front end ASIC
- Muon beam and/or cosmics
- Relative channel-to-channel calibration

Absolute energy scale
- Completed module(s) in test beam

In-situ monitoring
- MIP-like tracks in jets (hadrons, muons), Bhabha, Z->e+e-, E/p



ECAL is major cost-driver for detector
Cost fraction
0.4
0.3
0.2
0.1
0.0
VTX
SI inner
Si outer
TPC
ECAL
HCAL
FCAL
Muon
Coil
Yoke
Beamtube
DAQ
Integration
Transport



PFA tests overlaying testbeam events

10 GeV “neutral” + 10 or 30 GeV charged hadrons