Calorimeter R&D

for the International Linear Collider

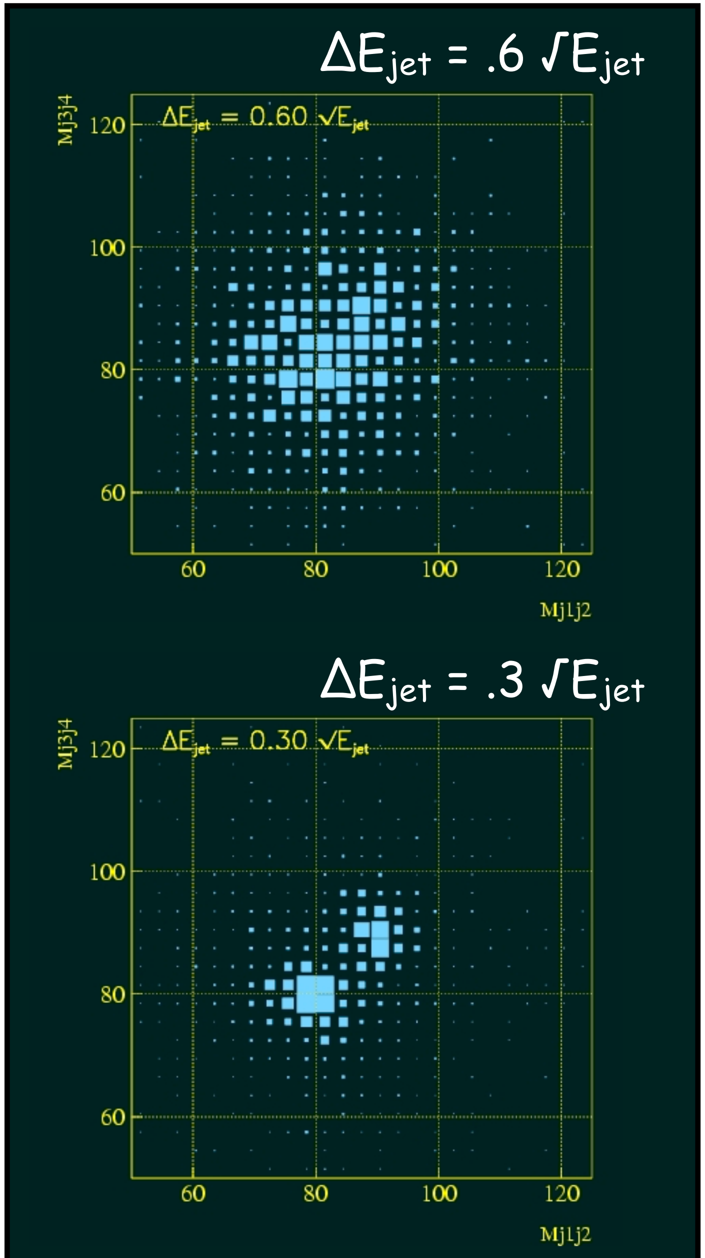
Hans-Christian Schultz-Coulon

Kirchhoff-Institut für Physik
Universität Heidelberg

Helmholtz Alliance Detector Workshop, Karlsruhe, April 2008

ILC Physics and Calorimetry

M_{j3j4}



M_{j1j2}

Separation of WW & ZZ final states

Precision measurements

- Higgs Properties
- SUSY Particle Properties
- Rare SM Processes

Physics categorized by

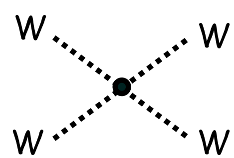
- Multi-Jet Final States
- Small Cross Sections

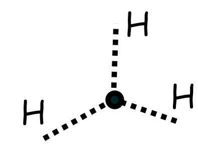
e.g.: $e^+e^- \rightarrow ZHH$

$e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu qqqq$

$e^+e^- \rightarrow eeZZ \rightarrow \nu\nu qqqq$

WW Scattering

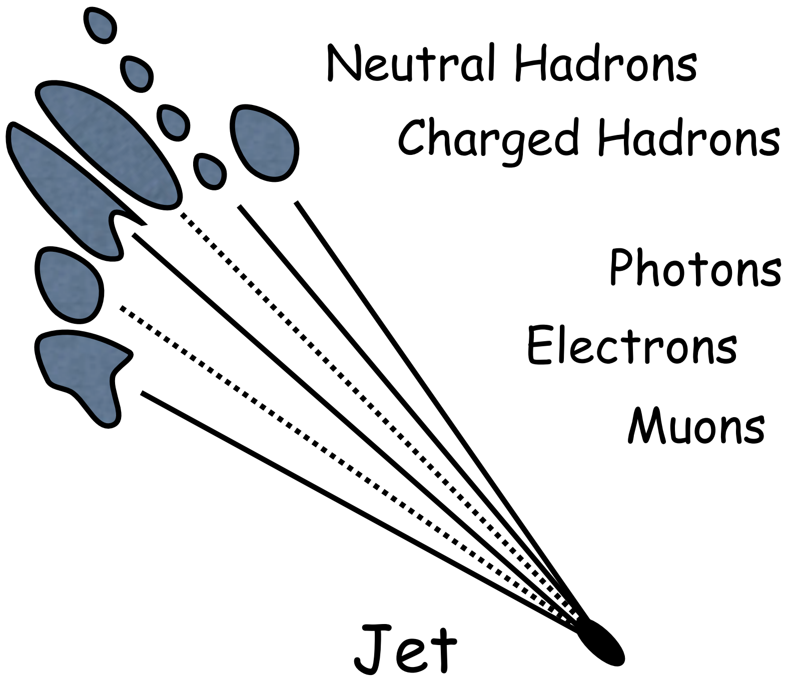




Higgs Self-Coupling

Jet Energy Resolution directly impacts Physics

Jet Energy Measurement



Problems:

Non-Compensation
[hadr. vs. electrom. energy]

Missing energy
[e.g. muon tracks]

Double counting
[when using track momenta]

A

Particle
Flow Calorimetry

Reduce role of 'hadron' calorimetry to measurement of n, K^0

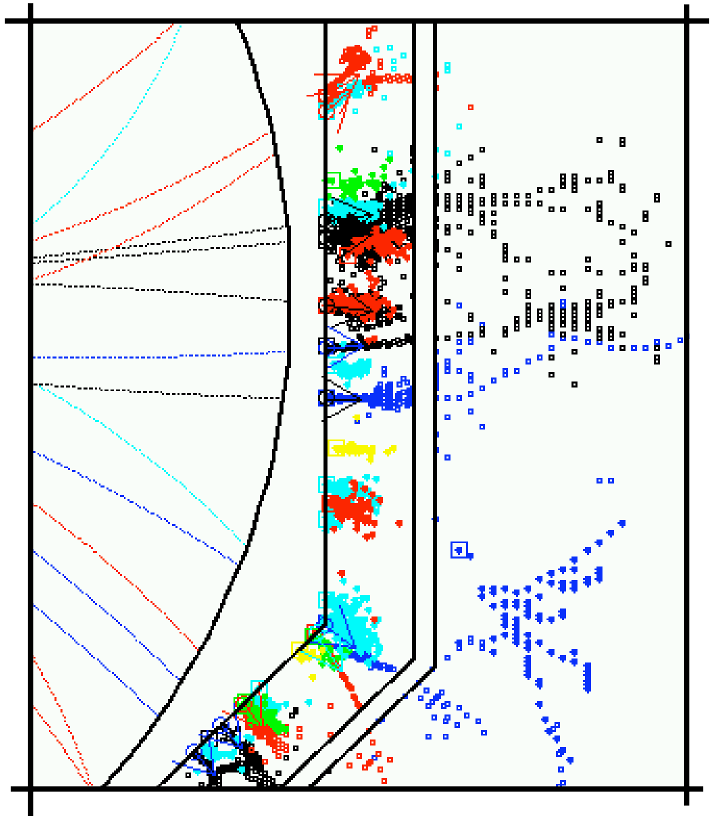
B

Compensating
Calorimetry

Correcting hadronic energy for nuclear-binding energy loss.

No. 1 Approach: "Imaging Calorimetry"

Component	Detector	Fraction	Part. Resol.	Jet Energy Res.
Charged ($X^{\pm}$)	Tracker	60%	$10^{-4}\ E_x$	negligible
Photons (γ)	ECAL	30%	$0.1/\sqrt{E_\gamma}$	$.06/\sqrt{E_{jet}}$
Neutral Hadrons (h)	E/HCAL	10%	$0.5/\sqrt{E_{had}}$	$.16/\sqrt{E_{jet}}$



Particle Flow (PFA):

Choose detector best suited for particular particle type ...

i.e.: use tracks and distinguish 'charged' from 'neutral' energy to avoide double counting

distinguish electromagnetic and hadronic energy deposits for software compensation

No. 1 Approach: "Imaging Calorimetry"

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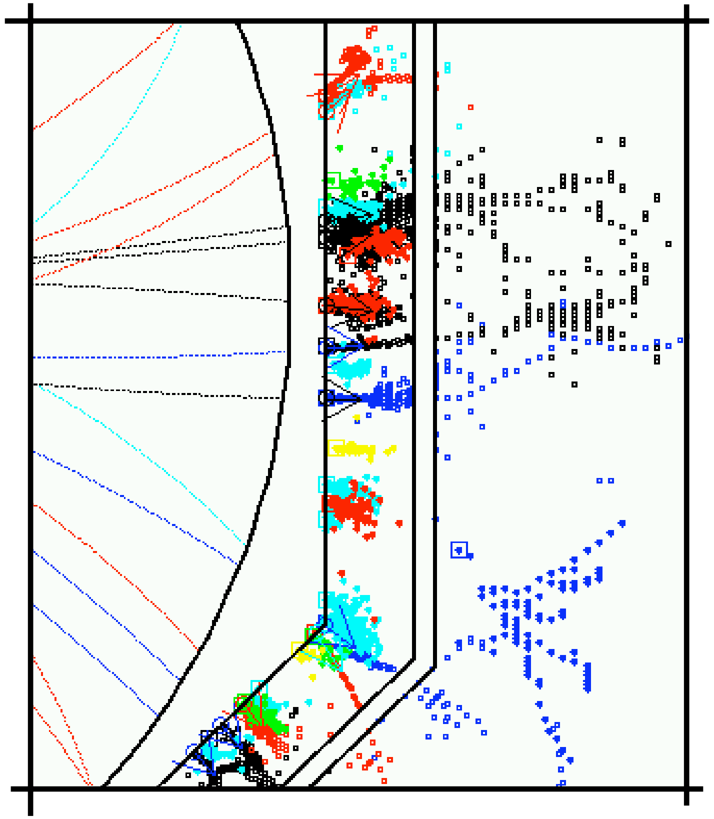

PFA – Energy Resolution:

$$\sigma_{jet}^2 = \sigma_X^2 + \sigma_\gamma^2 + \sigma_{had}^2$$

$.17/\sqrt{E}$

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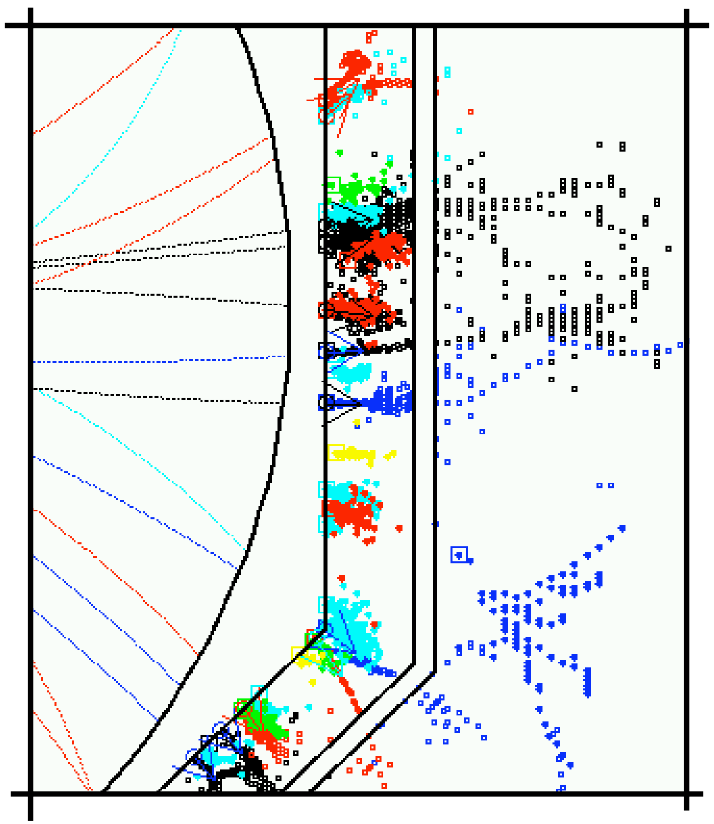

PFA - Energy Resolution:

$$\sigma_{jet}^2 = \sigma_X^2 + \sigma_\gamma^2 + \sigma_{had}^2 \qquad .17/\sqrt{E}$$

$$+\ \sigma_{confusion}^2 + \ldots \qquad < .25/\sqrt{E}\ ?$$

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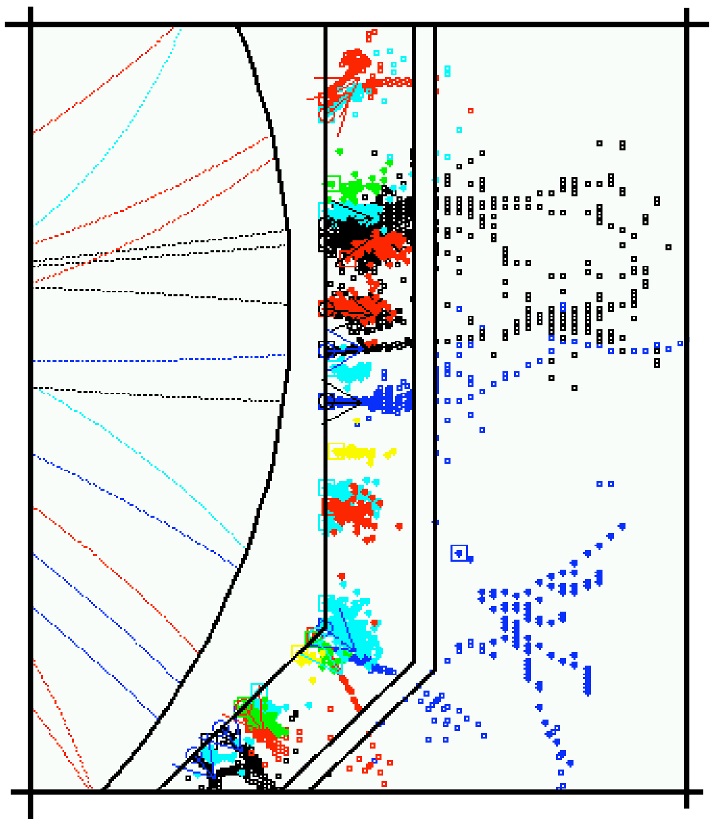


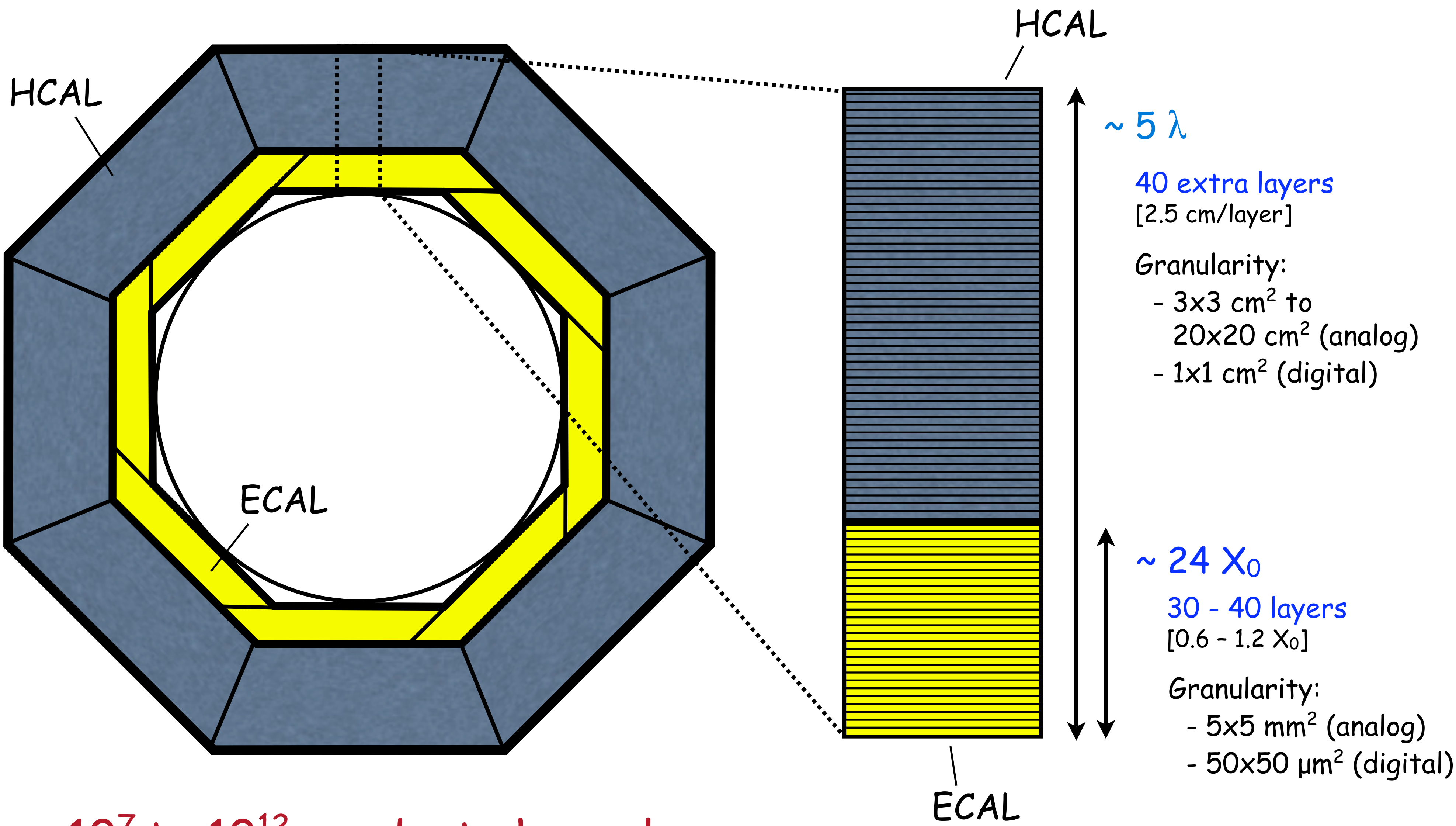
PFA – Energy Resolution:

$$\sigma^2_{jet} = \sigma^2_X + \sigma^2_\gamma + \sigma^2_{had} \qquad .17/\sqrt{E}$$

$$+ \sigma^2_{confusion} + \ldots \qquad < .25/\sqrt{E}\ ?$$

Granularity more important than energy resolution !?

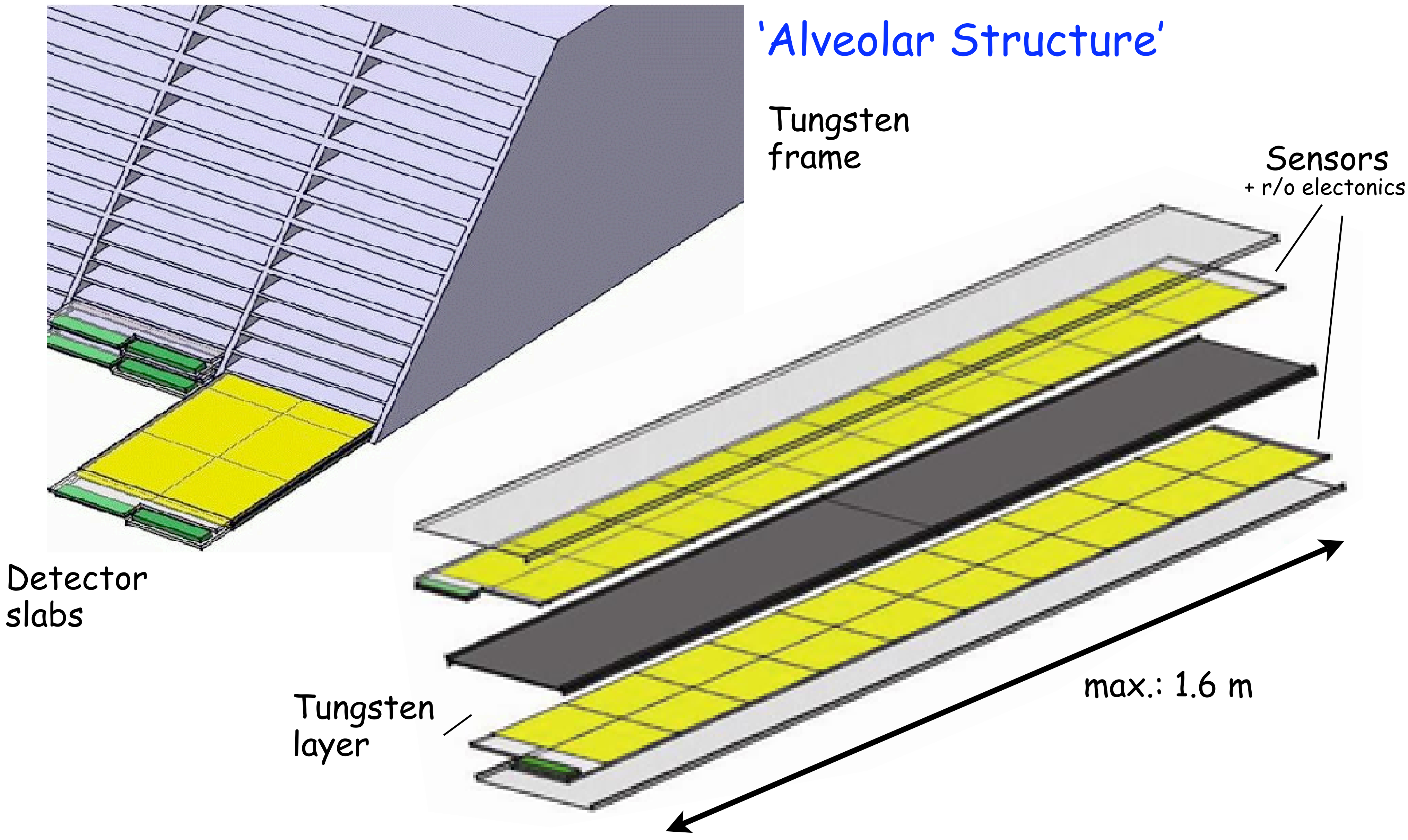
Overall Calorimeter Design



10^7 to 10^{12} readout channels

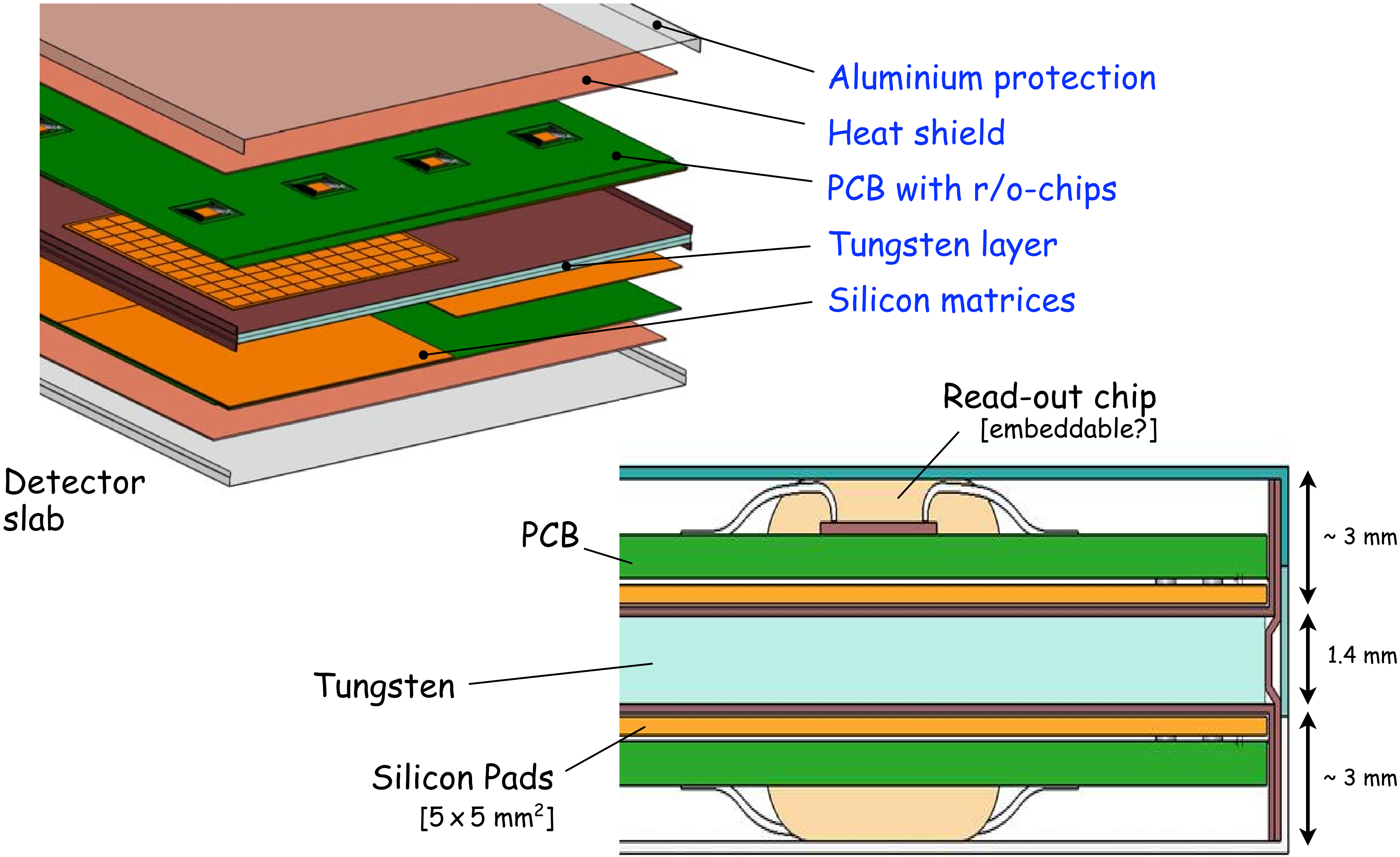
[high-level of integration, low power consumption]

Silicon Tungsten Calorimeter



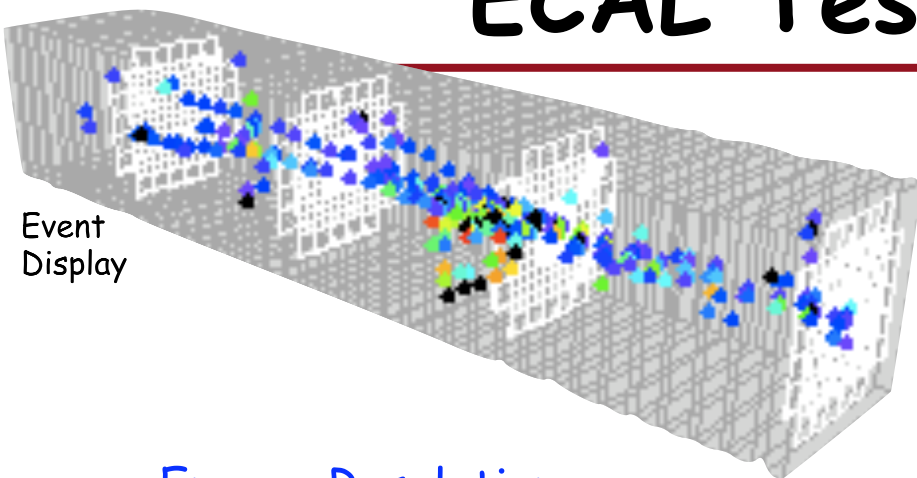
[... similar approach: US SiD-Design]

Basic CALICE ECAL Design

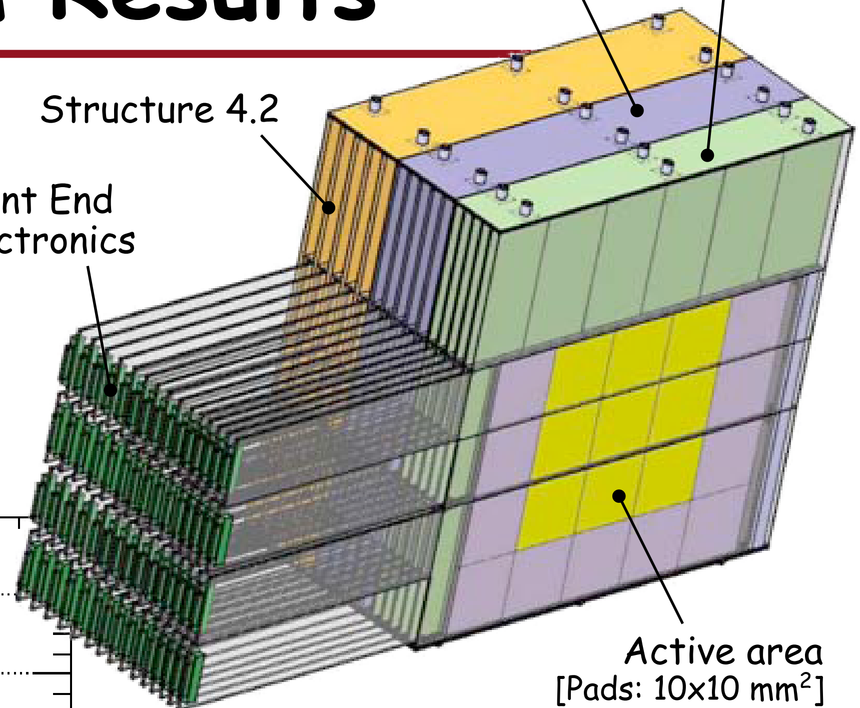


CALICE

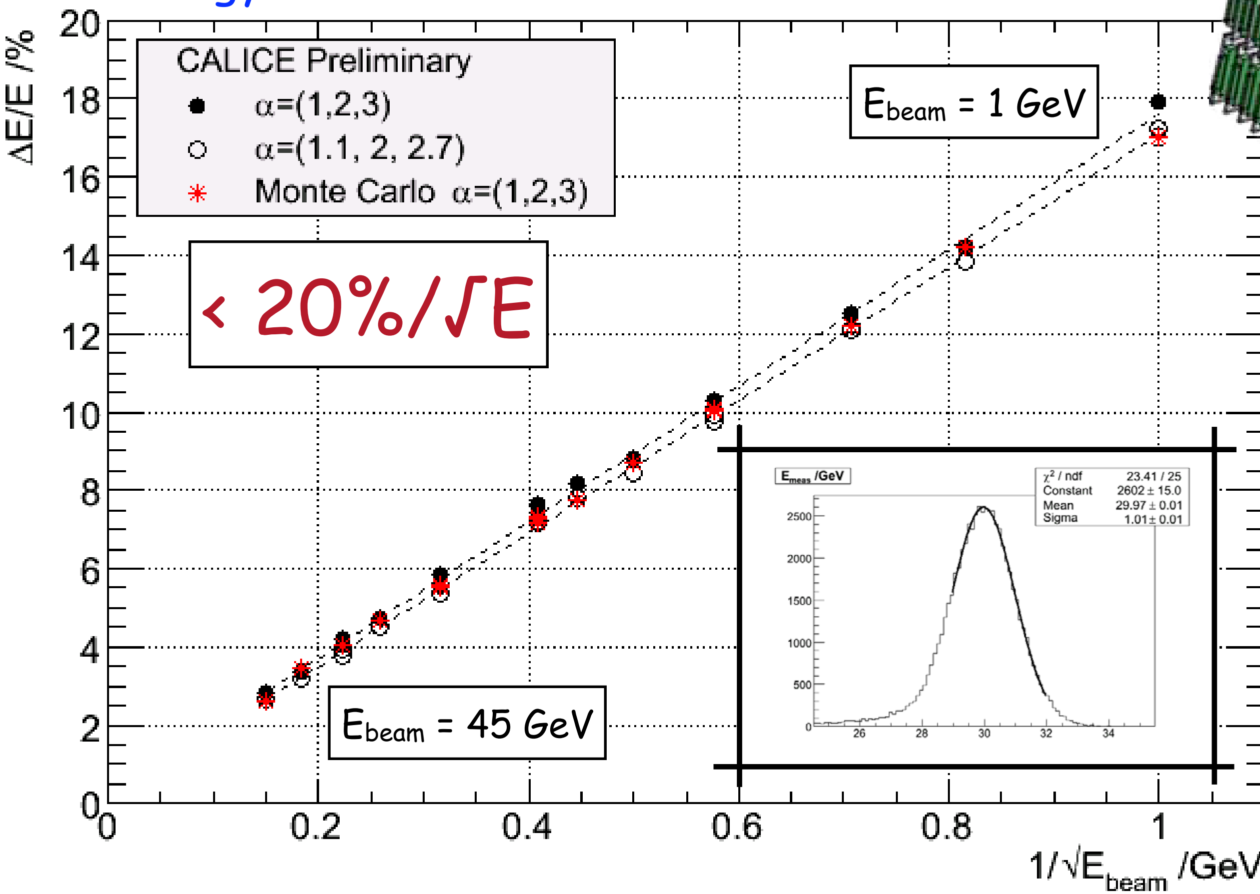
ECAL Test Beam Results

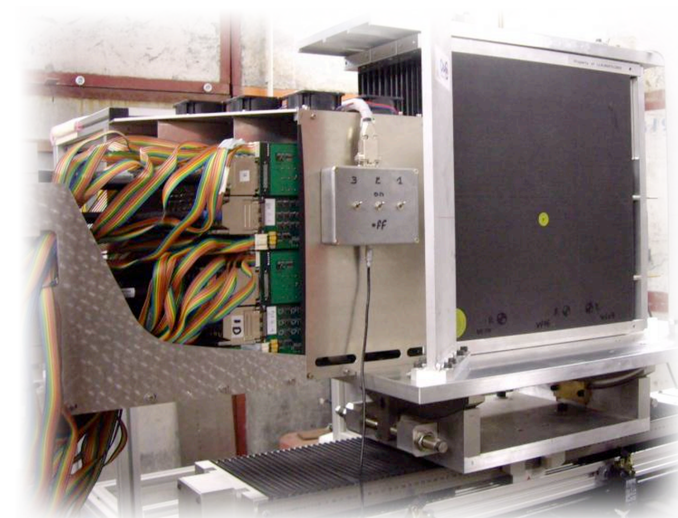


Event Display



Energy Resolution





ECAL 'Physics' Prototype [CALICE]

Monolithic Active Pixel Digital ECAL

MAPS:

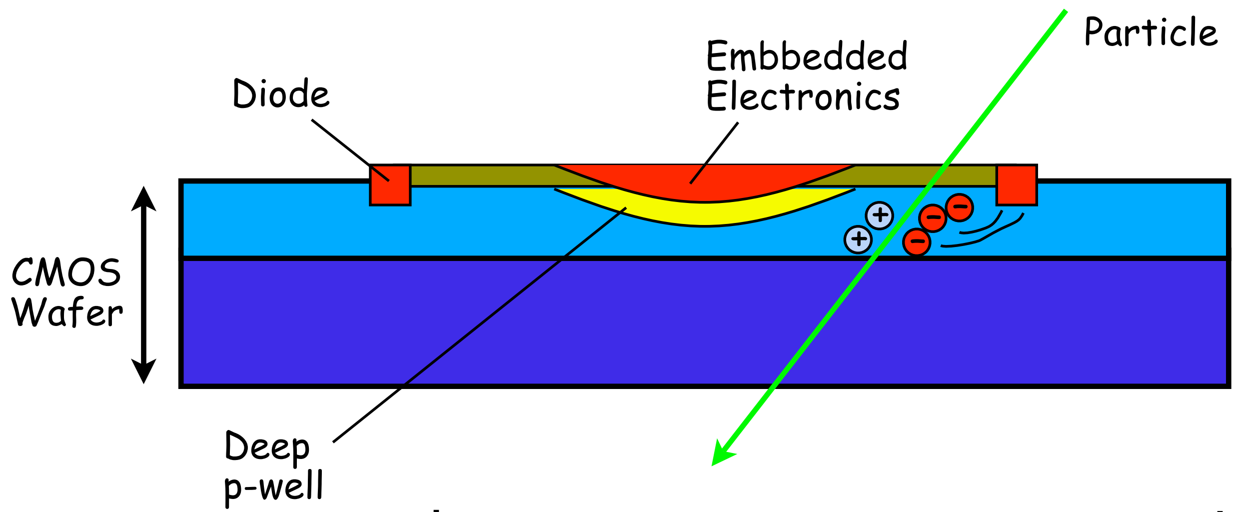
Monotlithic
Active Pixel Sensor

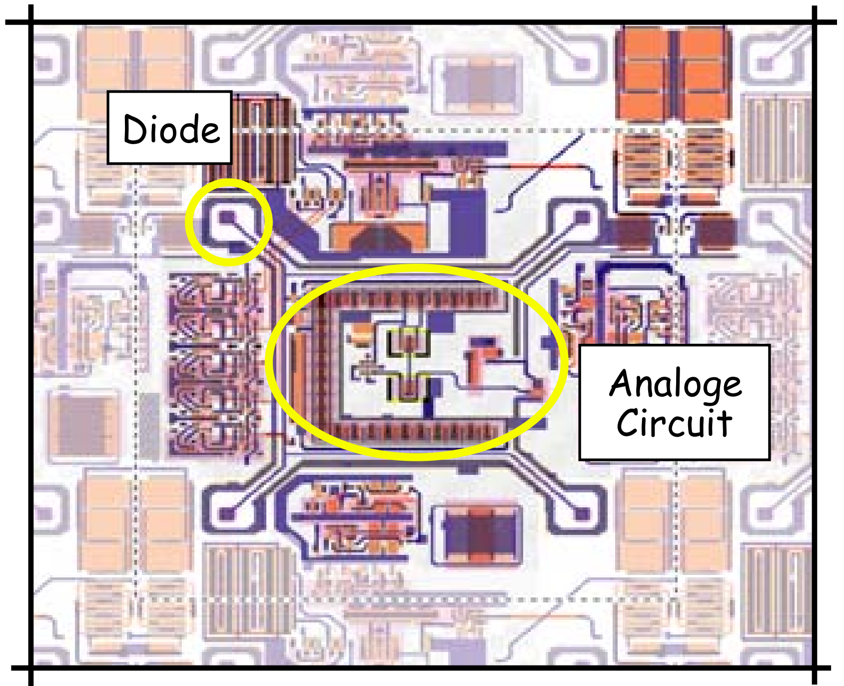
Pixel size: 40x40 μm^2
Channel number: 8x10^{11}
Absorber: Tungsten
Binary readout

Integration of
sensor and readout electronics

Manfactured in
standard CMOS process

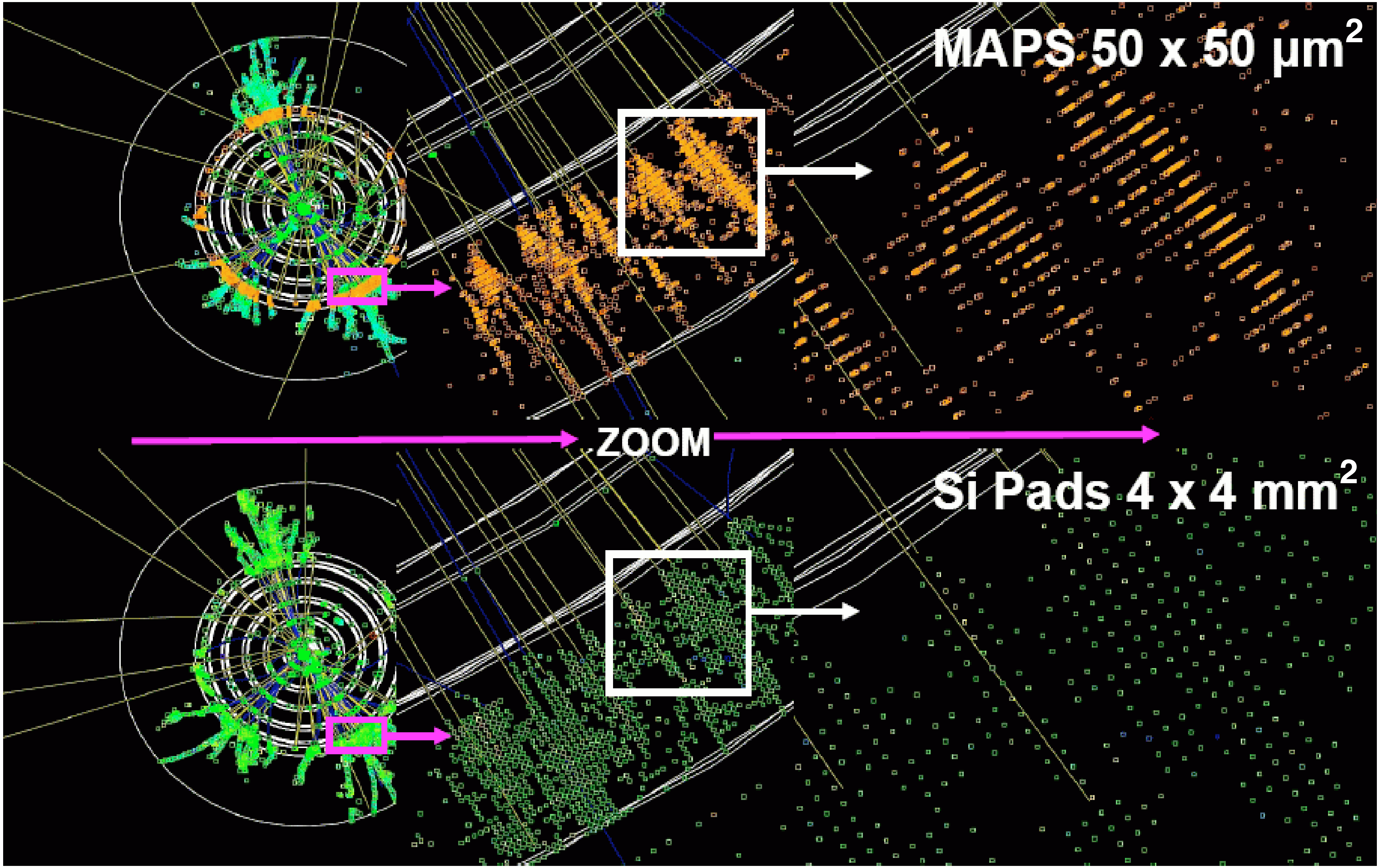
Concerns:
Power consumption: 40 μW/mm^2
DAQ needs 400 Gbit/s





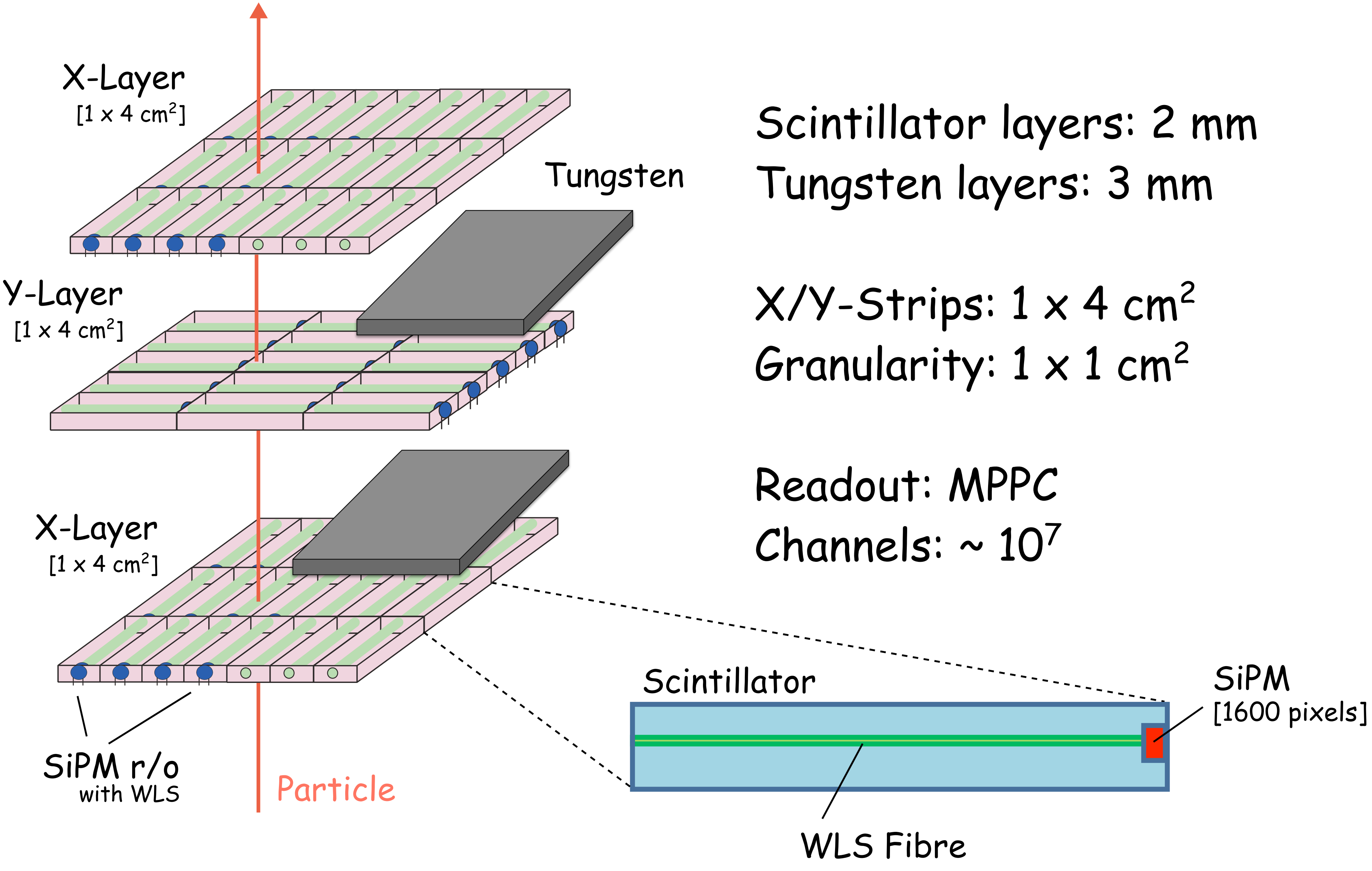
Sensor Layout (RAL)
[0.18 Micron]

Digital ECAL: Shower Imaging



Simulation

Scintillator-Tungsten ECAL (Asia)

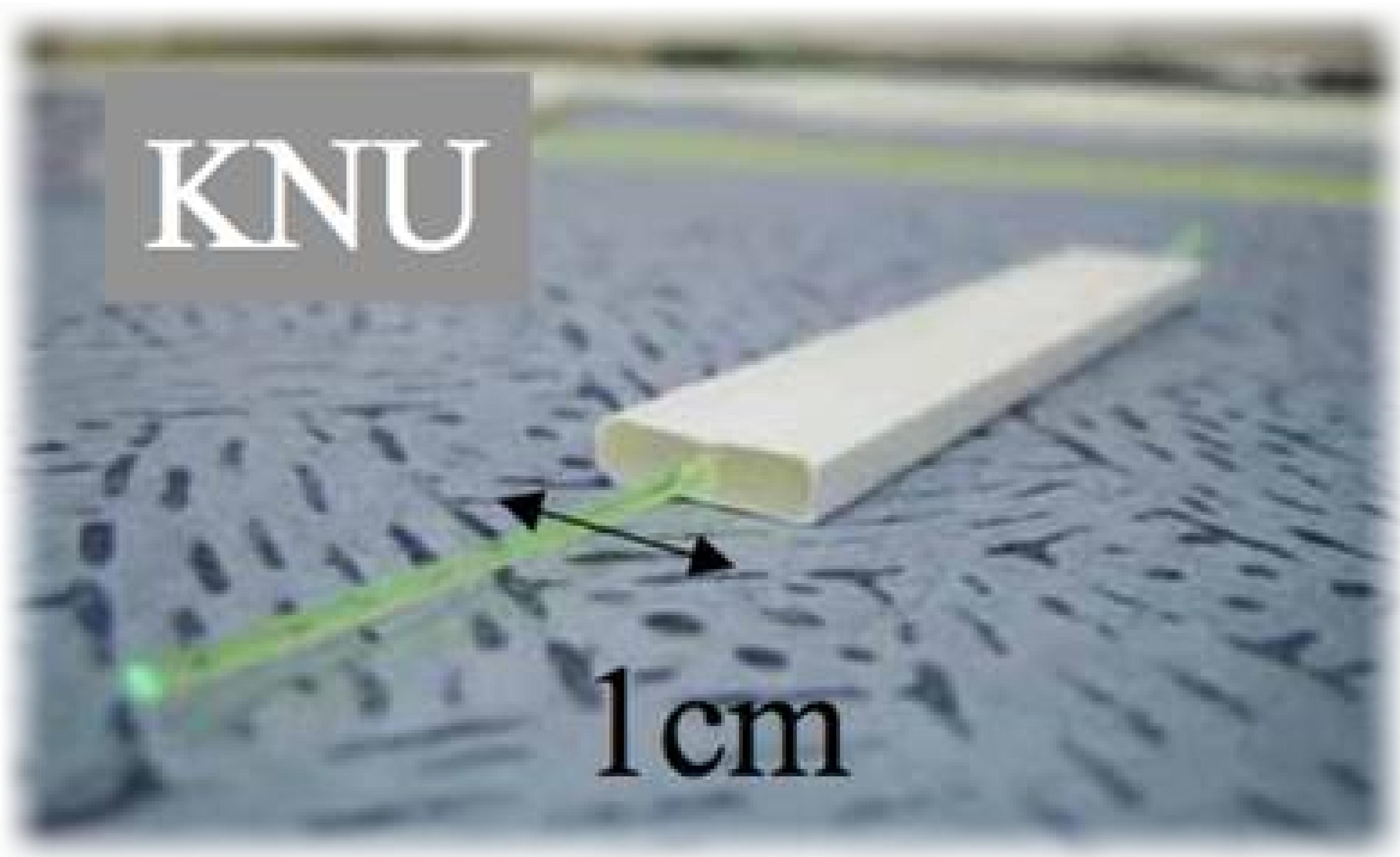


Scintillator layers: 2 mm
Tungsten layers: 3 mm

X/Y-Strips: 1 x 4 cm^2
Granularity: 1 x 1 cm^2

Readout: MPPC
Channels: ~ 10^7

Scintillator-Tungsten ECAL (Asia)



Silicon Photomultipliers (SiPM)

SiPMs:

Pixelated APDs
operated in limited Geiger mode

Signal = sum of fired pixels

MEPhi/Pulsar	:	SiPMs
Hamamatsu	:	MPPCs
SENSL	:	SPMs
Photonique	:	SSPMs
Voxtel	:	MAPDs

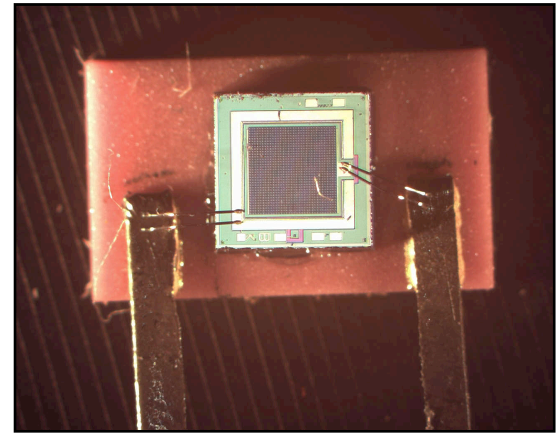
Pros: small size, cheap,
work in magnetic field

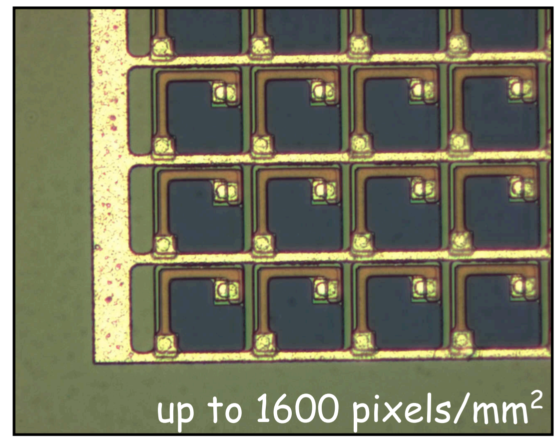
Cons: temperature & voltage dep.,
non-linearity, ...

Research in progress ...

SiPM
[MEPhi/Pulsar]

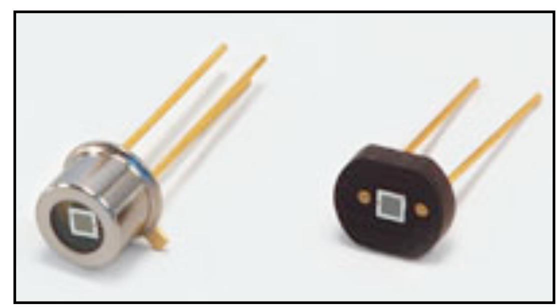
used for
analog HCAL





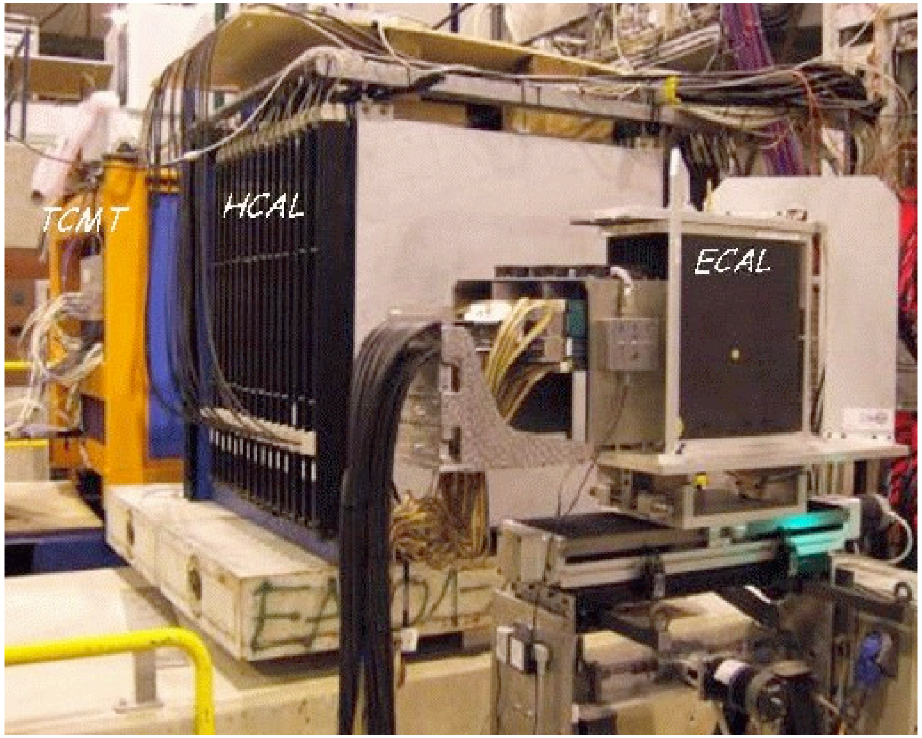
MPPC
[Hamamatsu]

used for
analog ECAL



CALICE – Analog HCAL

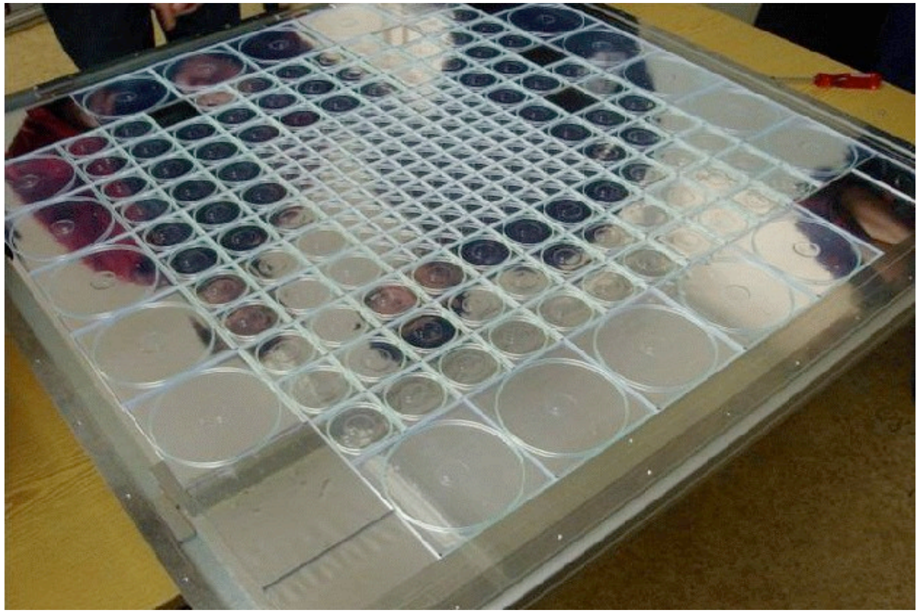
1m^3-Prototype
38 layers



2006/2007 CERN Testbeam
[2008 → Fermilab]

Sandwich structure:

- Scintillator Tiles+WLS+SiPMs (.5 cm)
- Stainless steel absorber (1.6 cm)



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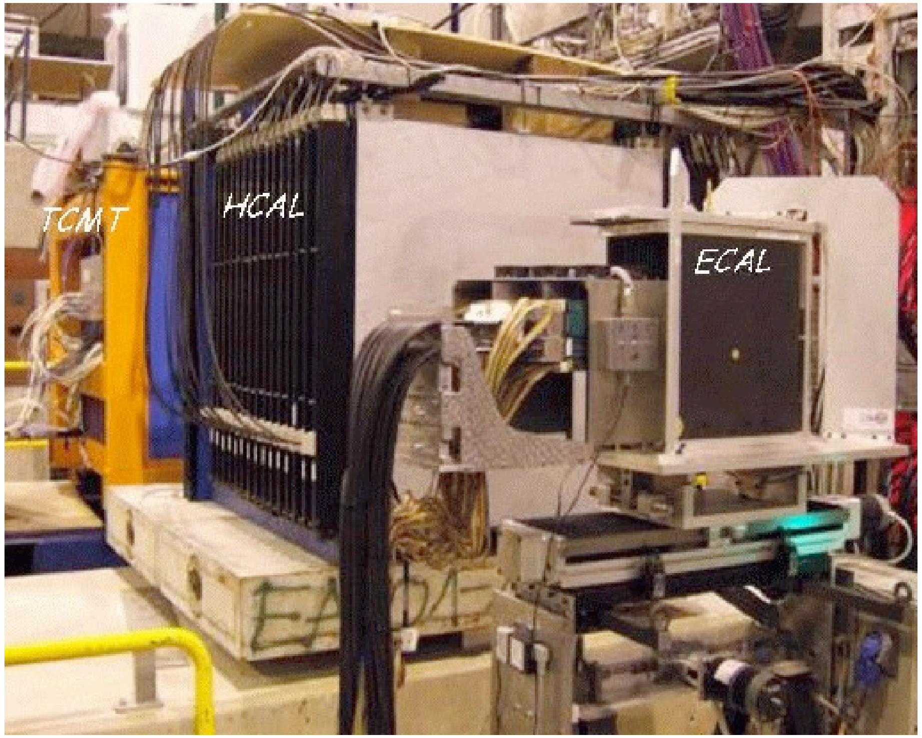

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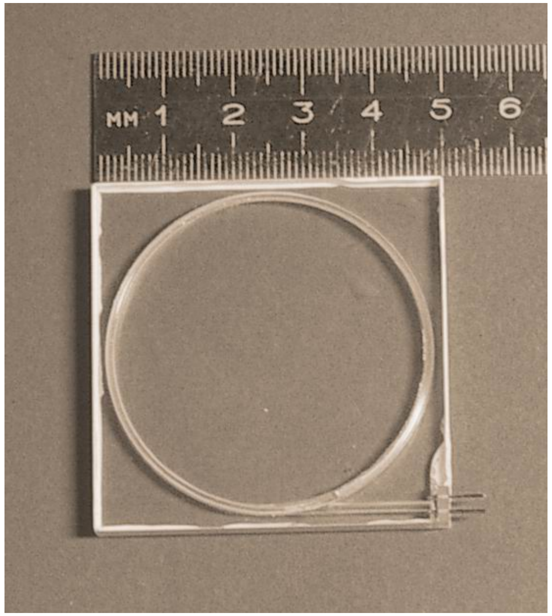

3x3 cm^2 Tile

CALICE – Analog HCAL

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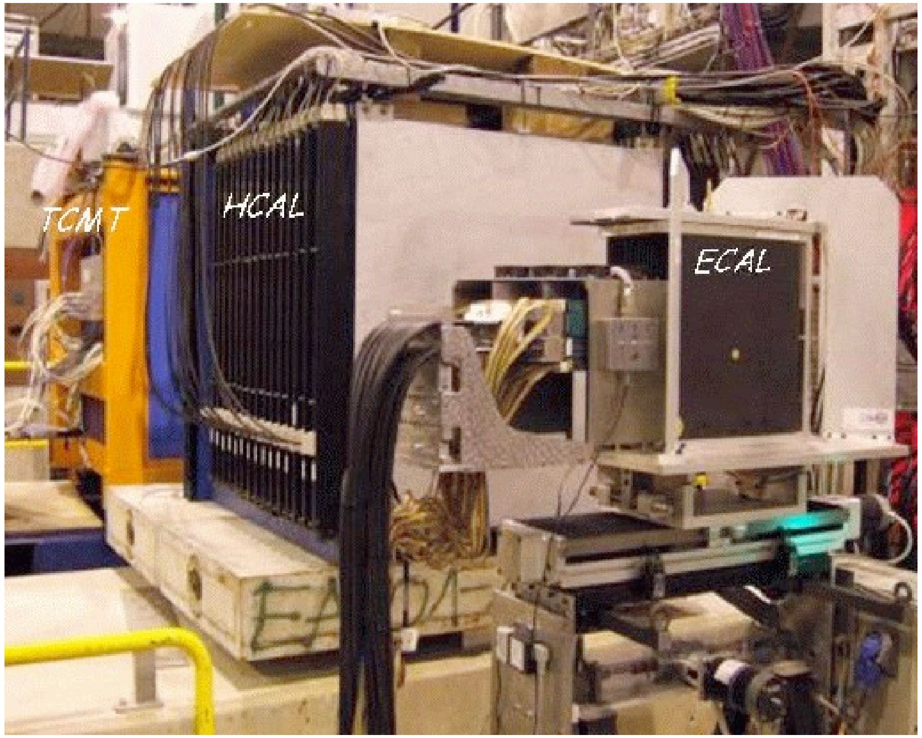

2006/2007 CERN Testbeam
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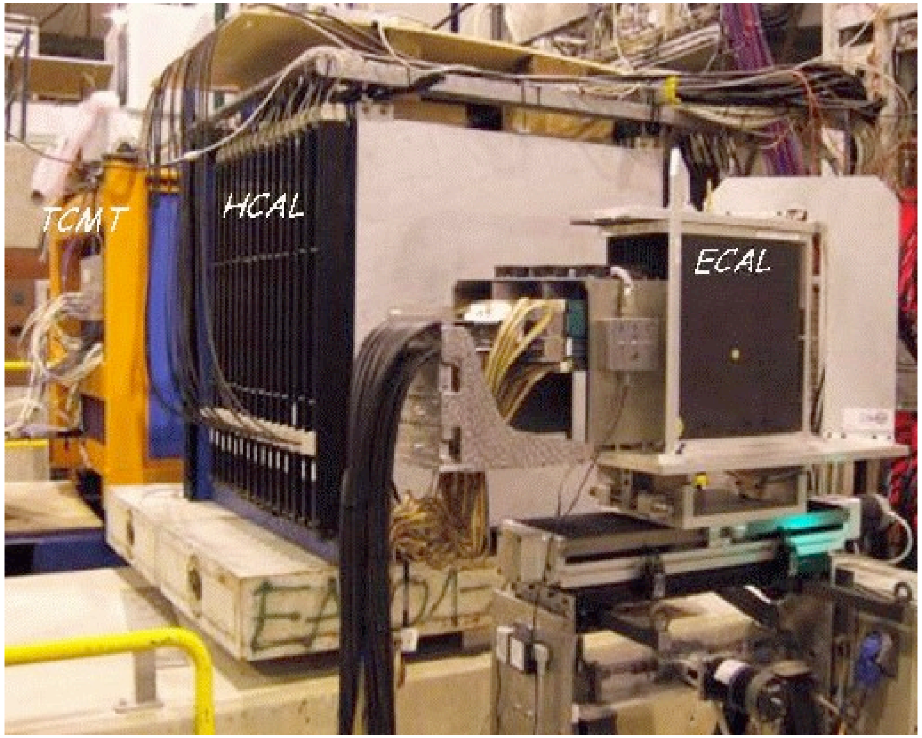
Mounted SiPM

CALICE – Analog HCAL



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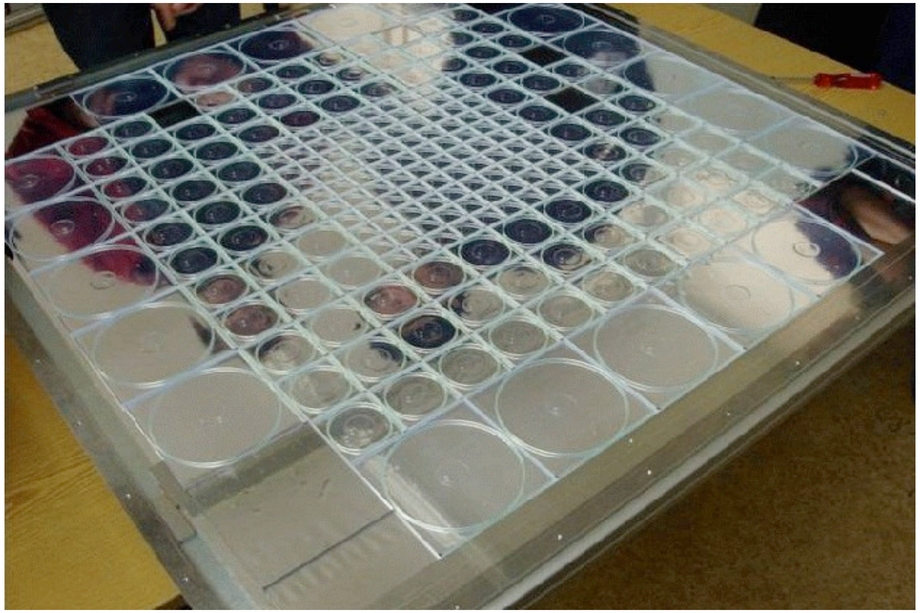

2006/2007 CERN Testbeam
[2008 → Fermilab]

Combined
Test Beam Data:

- 100 Million Events collected
- Analysis ongoing

CALICE – Analog HCAL

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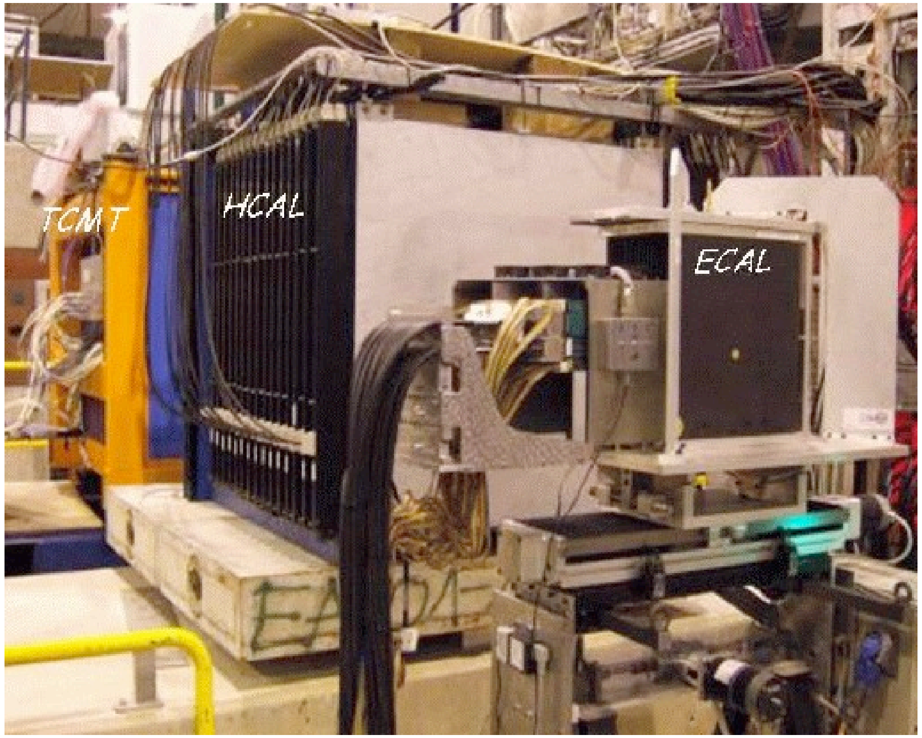
38 layers



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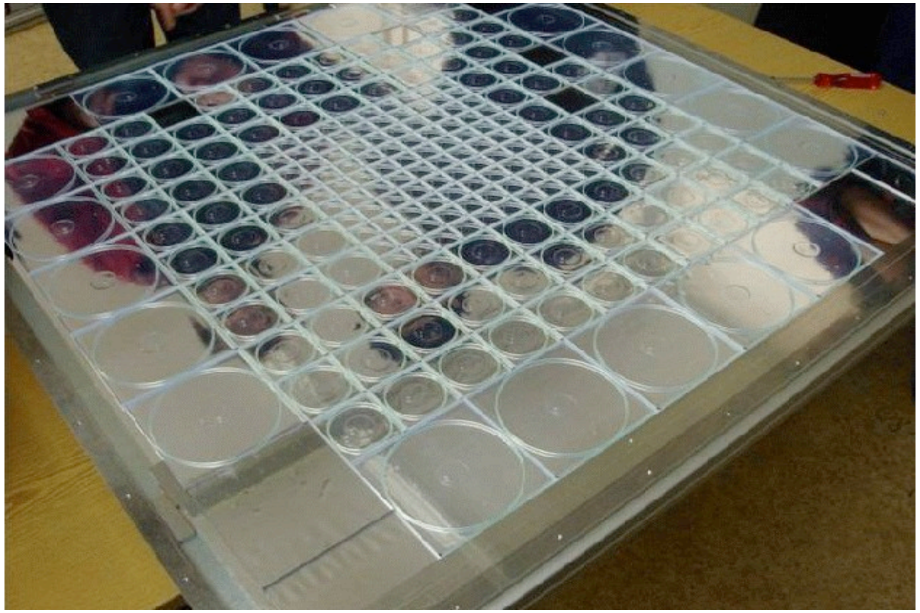

2006/2007 CERN Testbeam
[2008 → Fermilab]

Combined
Test Beam Data:

- 100 Million Events collected
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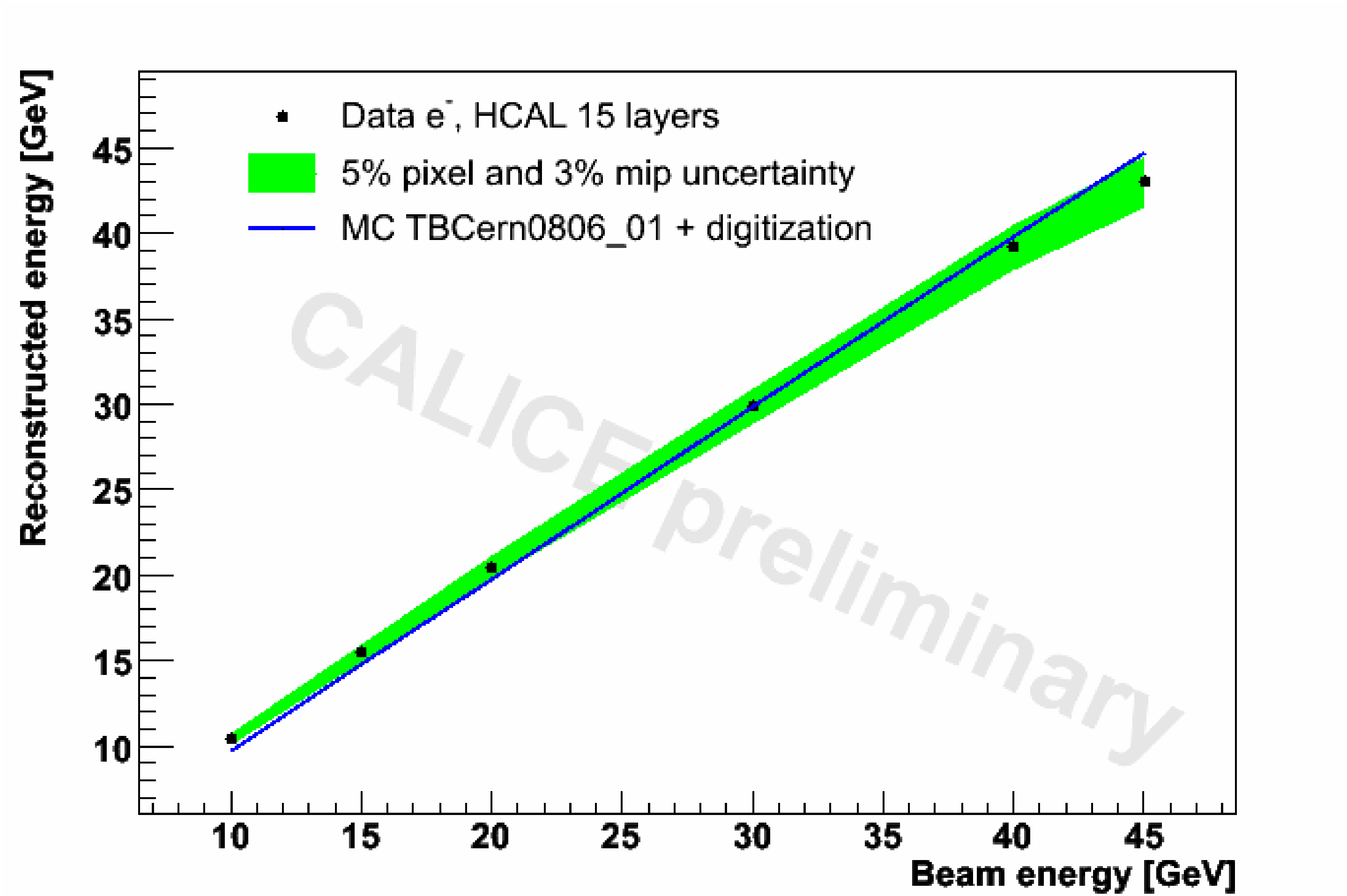
... next big step: technical prototype !

Analog HCAL – Test Beam Result



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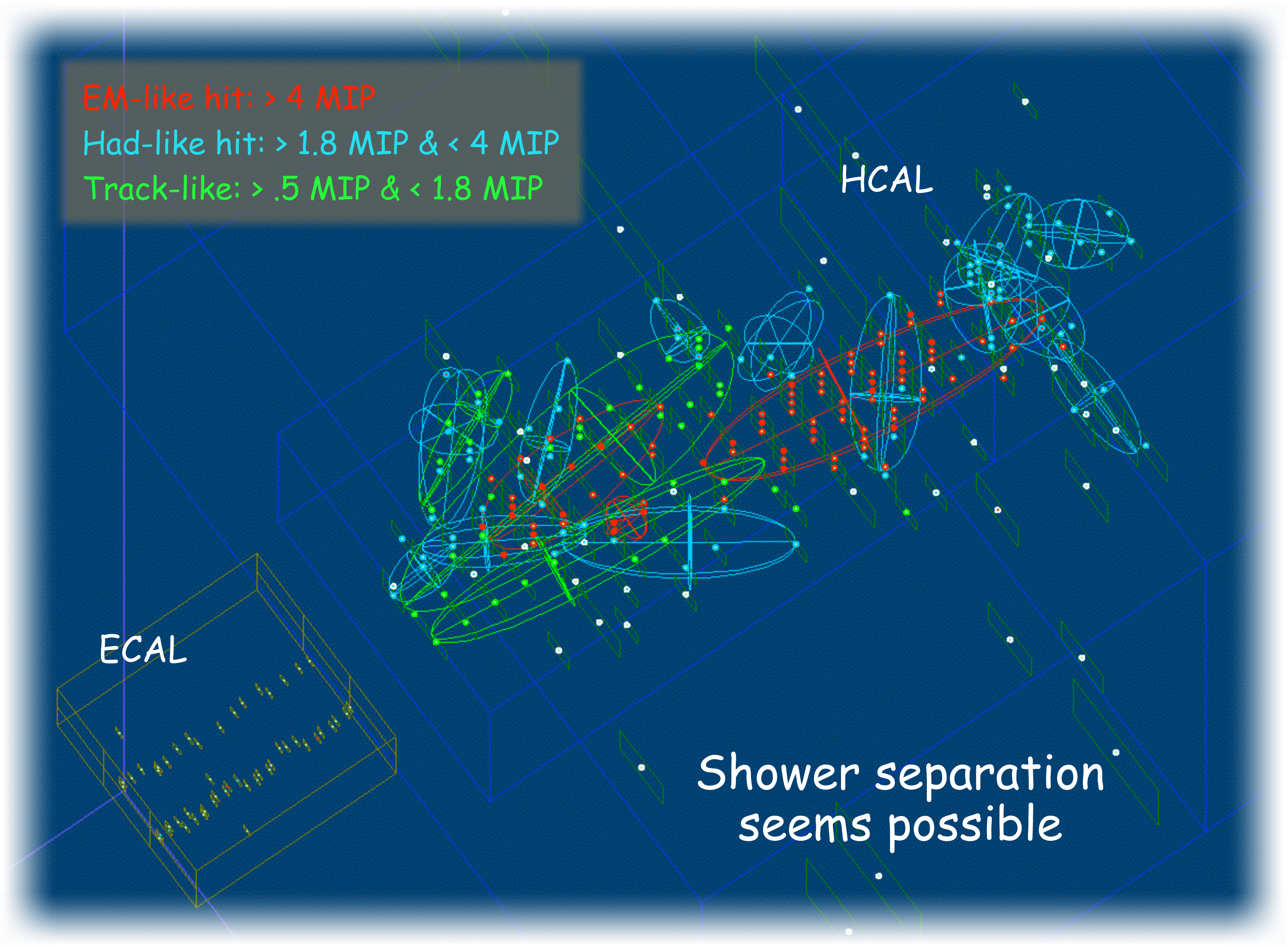


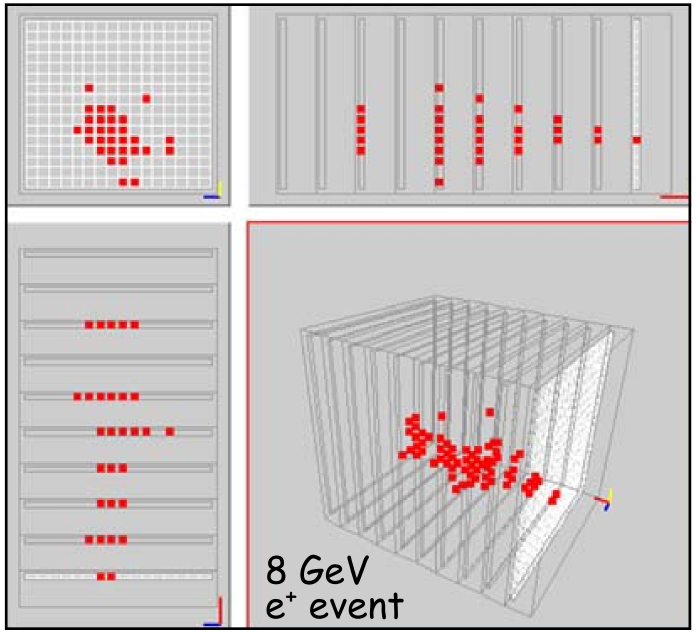
HCAL – The Digital Approach

Why digital ?

- better PFA performance
- cheap, robust detectors ...
- small total thickness ...

Used Technologies:

- GEMs
- µMegas
- RPCs



Example RPCs:

Pad Size: 1 x 1 cm^2
Total thickness: < 6 mm possible

Vertical Slize Test with
9 small chambers successful

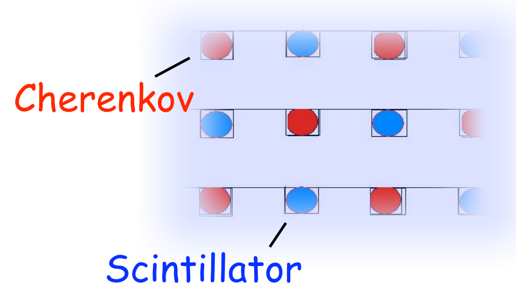
Large Prototype to be built

Dual-Readout Calorimetry (4th)

Concept:

Cherenkov-assisted
Hadron Calorimetry

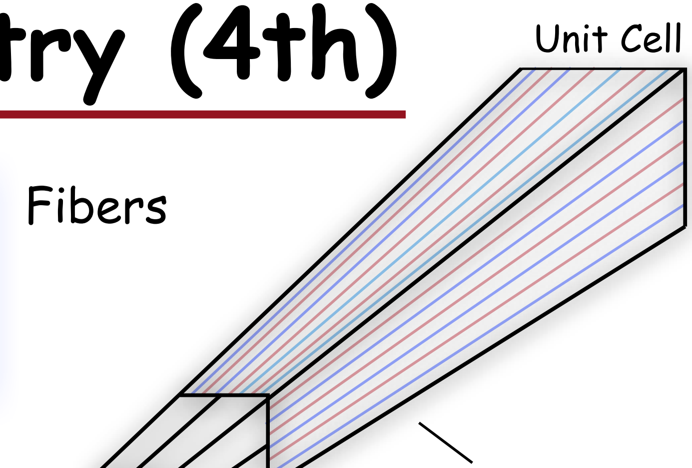
$$\frac{E_{\mathrm{em}}}{E_{\mathrm{tot}}} \sim \frac{E_{\mathrm{Cherenkov}}}{E_{\mathrm{Ionization}}}$$

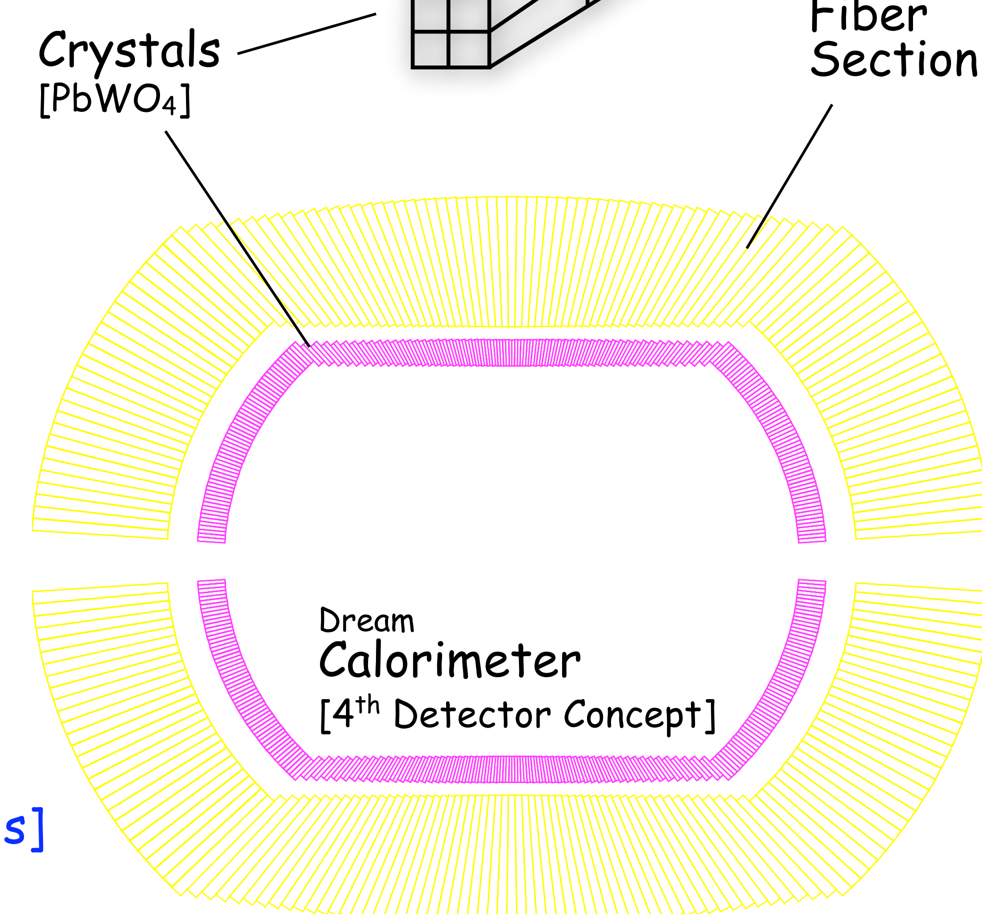


"DREAM 1&2"

EM: clear fibers, Č-light [$E_{\mathrm{Cherenkov}}$]
Charged: scintillation fibers [$E_{\mathrm{Ionization}}$]
Neutrons: time history measurement

"DREAM 3"



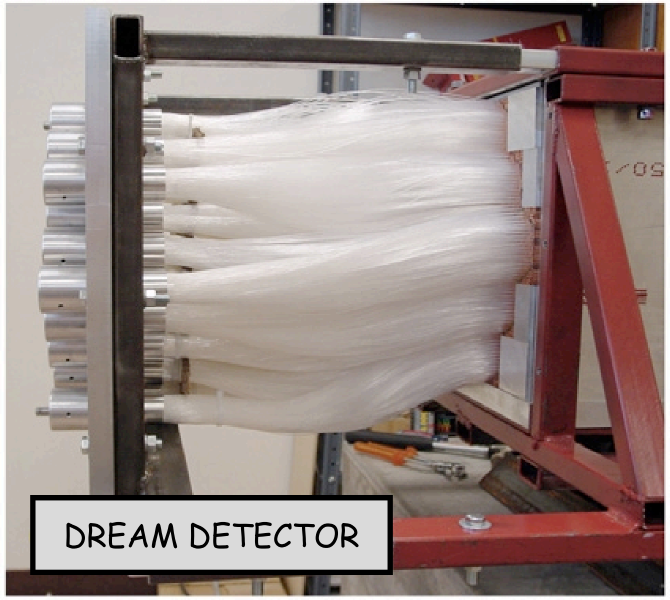


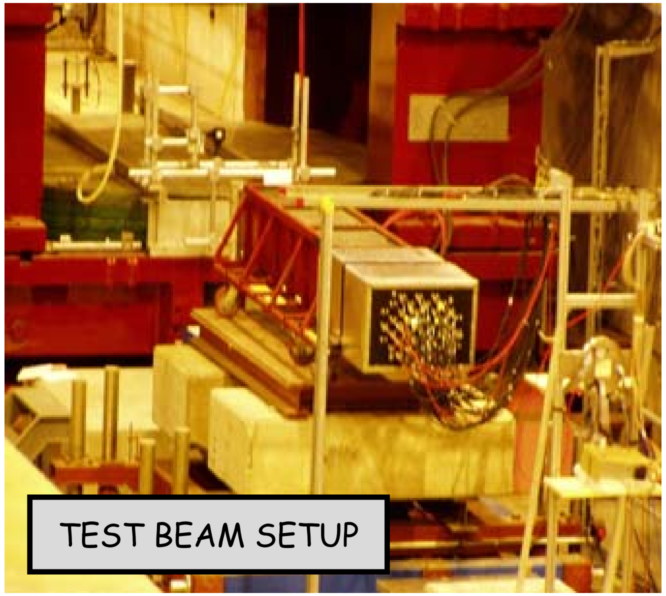
Plans:

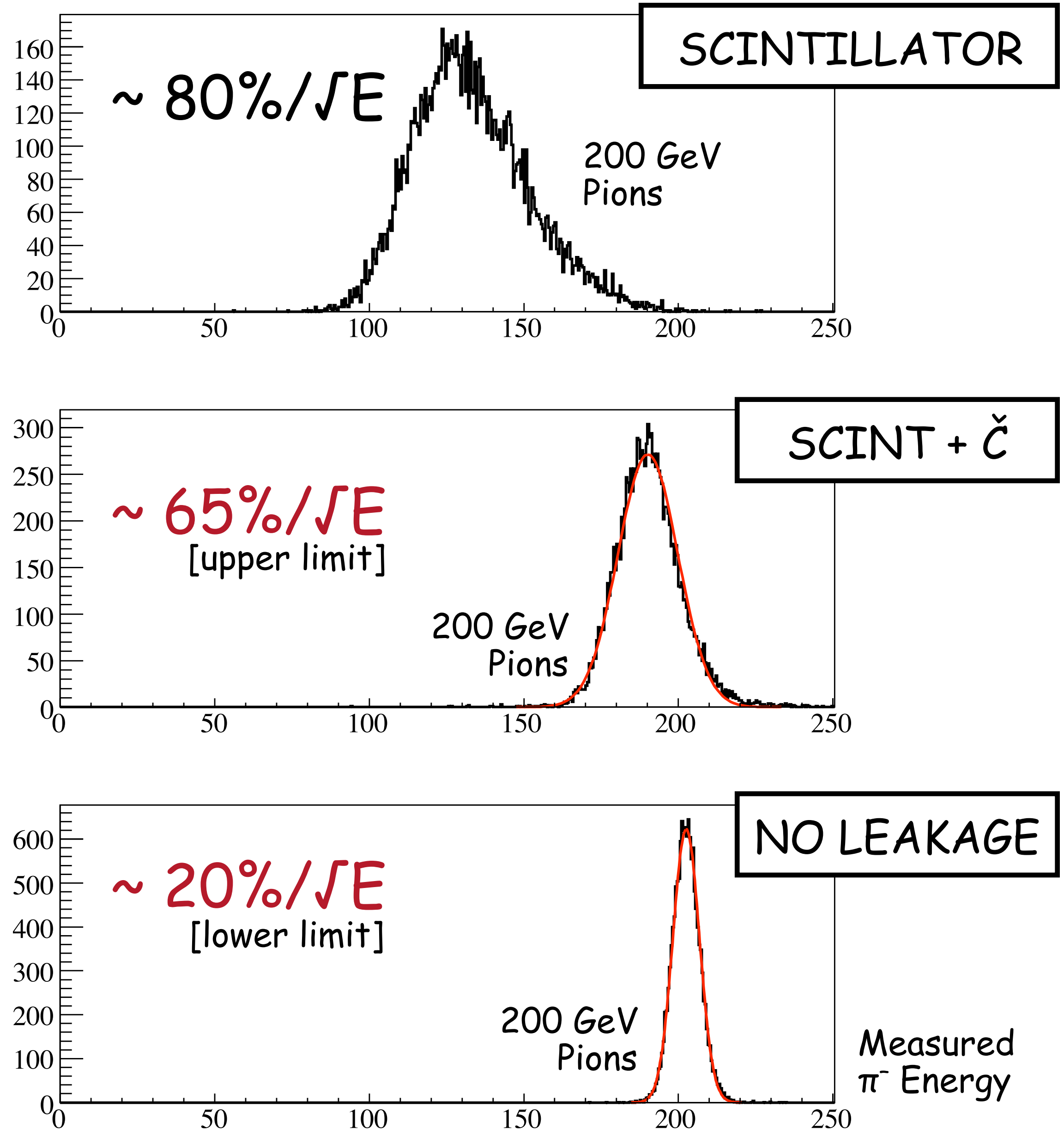
Scaleable module (unit cell)

Fiber Section: W absorber, MPPC for r/o
EM Section: Dual-readout [$PbWO_4$-Crystals]

Dual-Readout Calorimetry (4th)







Summary

Gaol: unprecedented jet energy resolution

ILC: precision physics, Multi-Jet final states, low cross sections

Many interesting research projects

High granular HCAL & ECAL (analog & digital), dual-readout calorimetry

Main approach: Particle Flow Algorithm (PFA)

Granularity more important than energy resolution

Alternative: Cherenkov-assisted Hadron Calorimetry

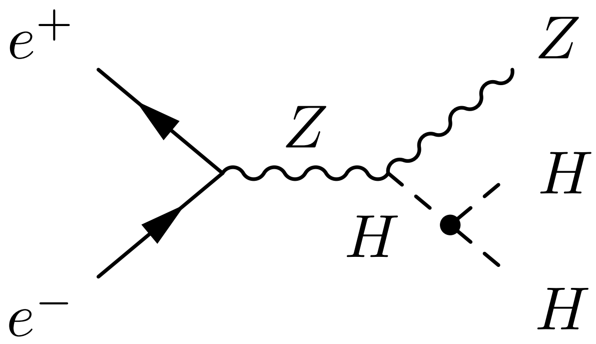
Dual read-out of cherenkov and scintillation light

Germany: Analog HCAL [incl. SiPMs & Electronics]

DESY, Hamburg, Heidelberg, München, Wuppertal

Backups

Example: Higgs Self-Coupling



$\sigma_{ZHH} \sim g^2_{hhh}$

Improvement of

Jet Energy Resolution

60%/√E → 30%/√E

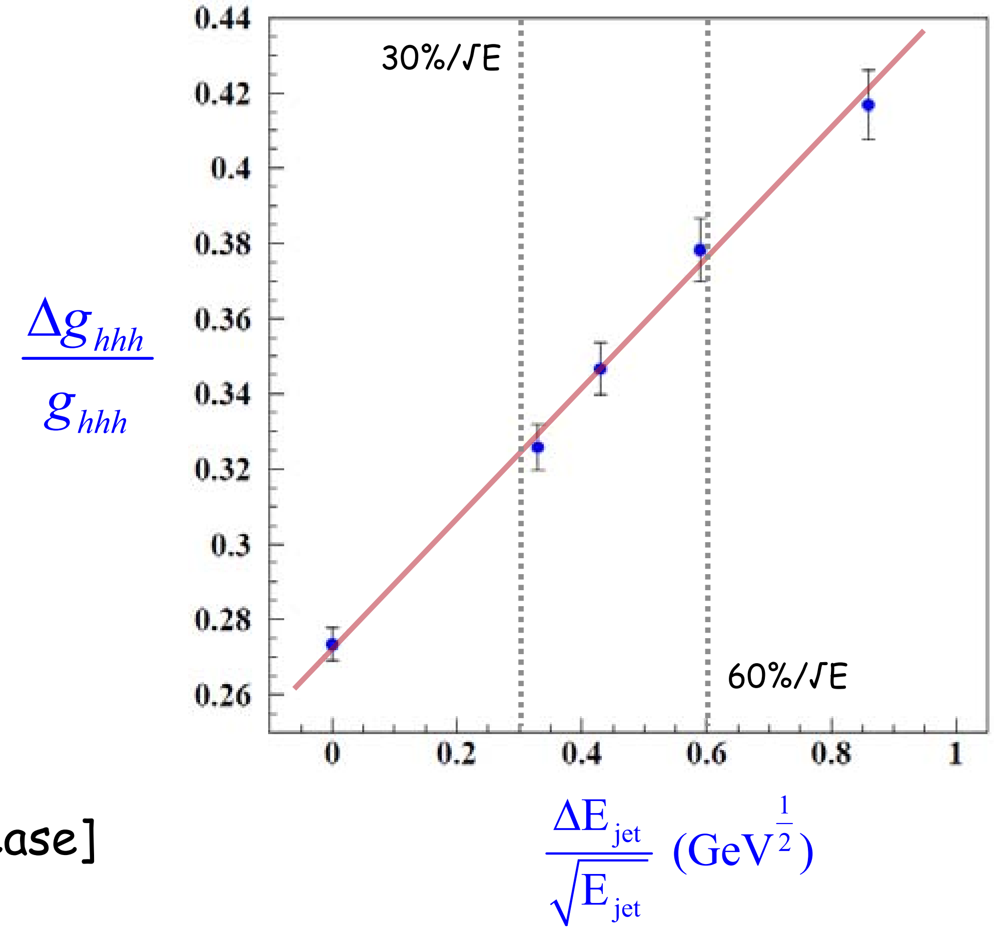
→ 20% smaller uncertainty

[equivalent of 40% luminosity increase]

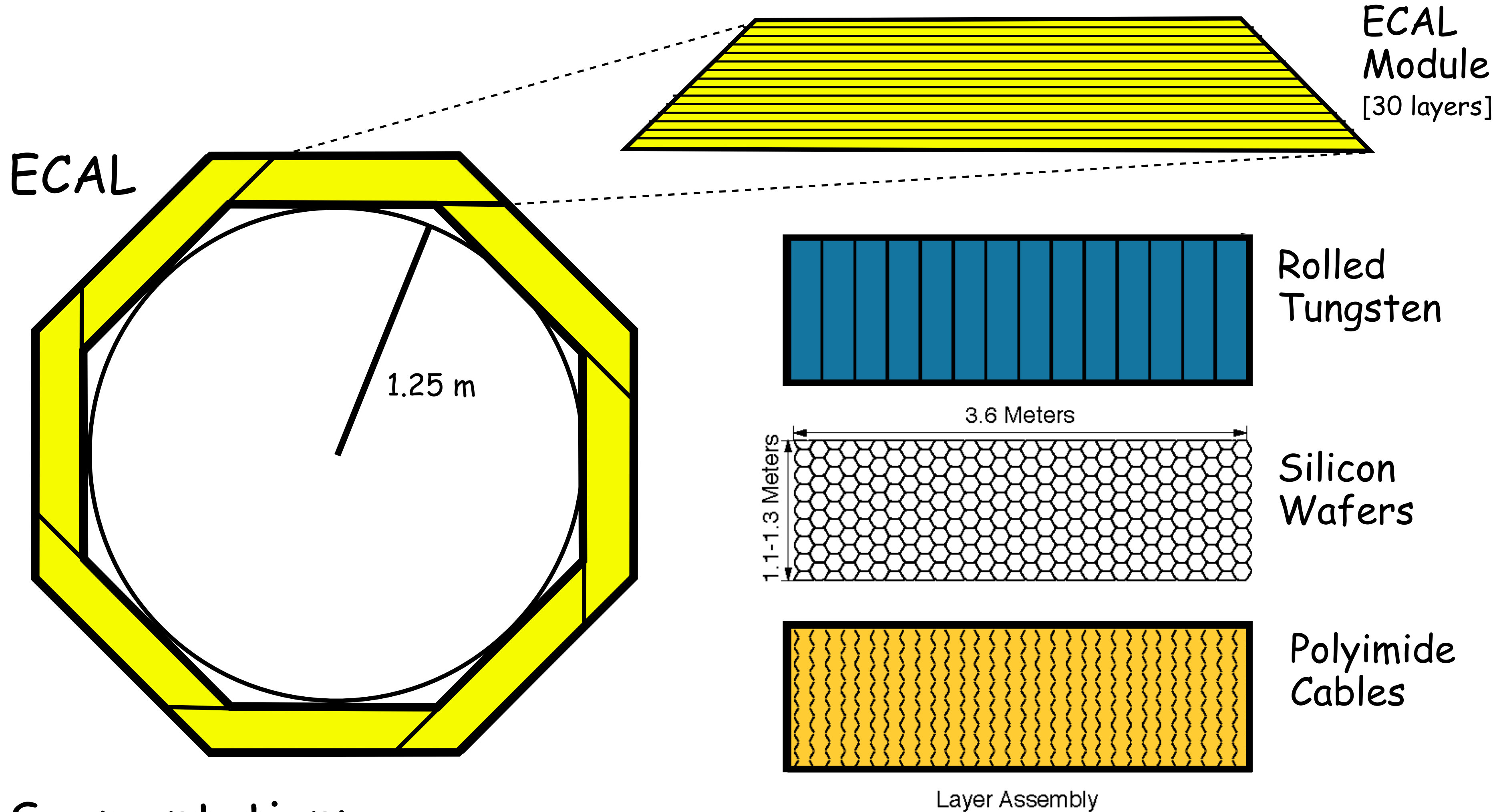
Typical !

L = 2000 fb^{-1}

$\sqrt{s}$ = 500 GeV



US ECAL Design (SiD)

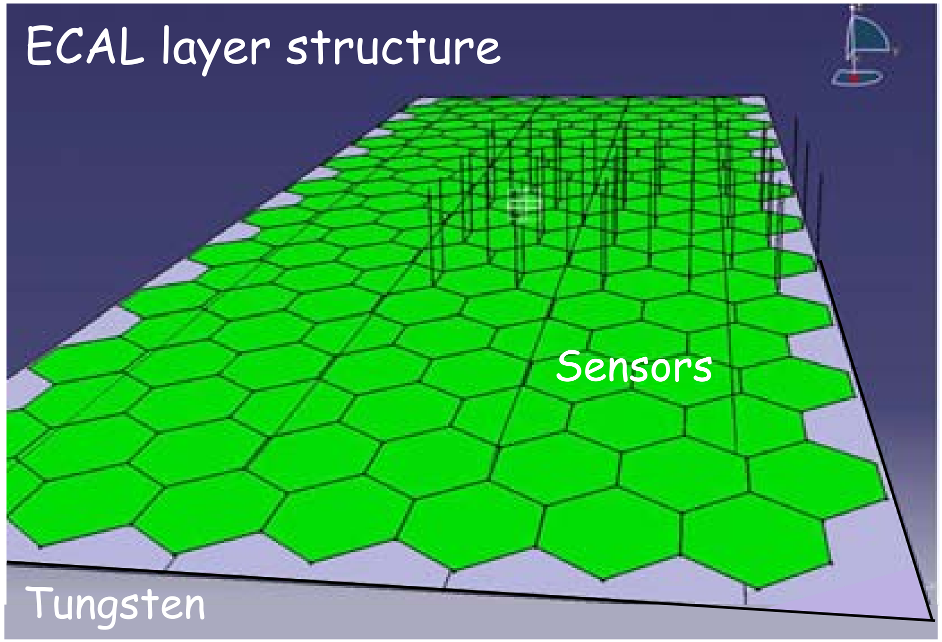


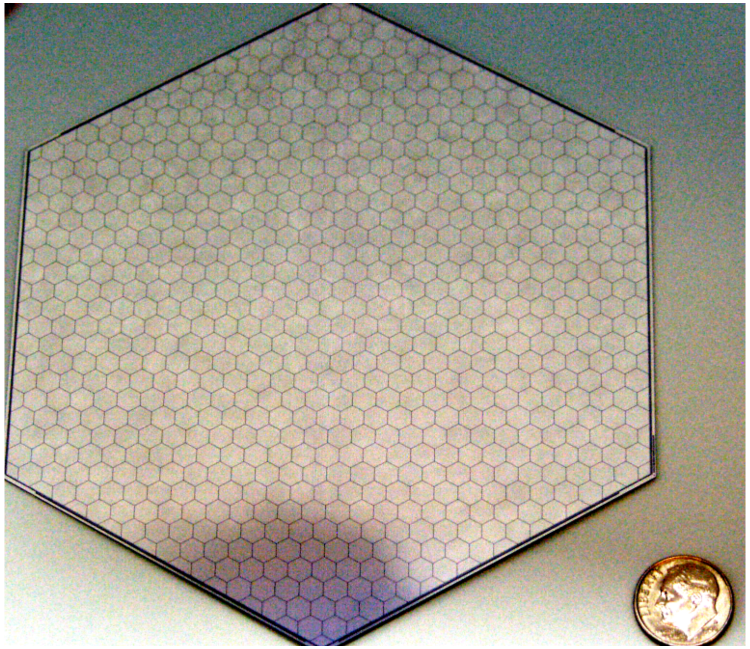
Segmentation:

Transverse: 12 mm^2
Longitudinal: 30 layers
[0.7 - 1.4 X_0]

Energy resolution: ~ 17%/√E

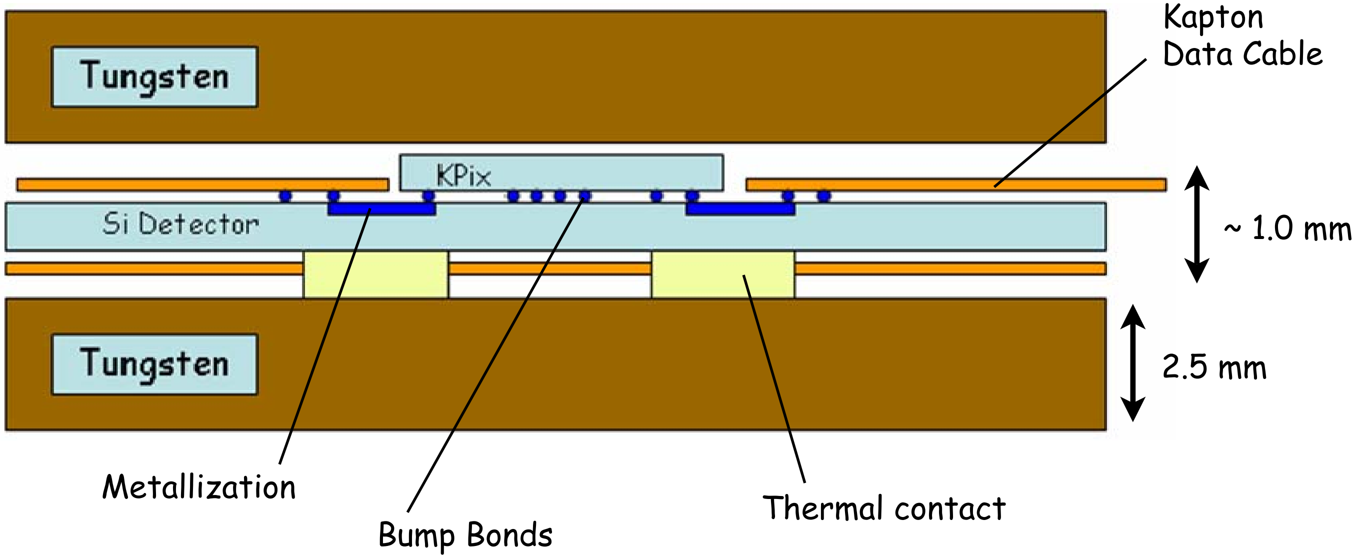
US ECAL Design (SiD)





1024 hex-diodes [12 mm^2]

6-inch wafers



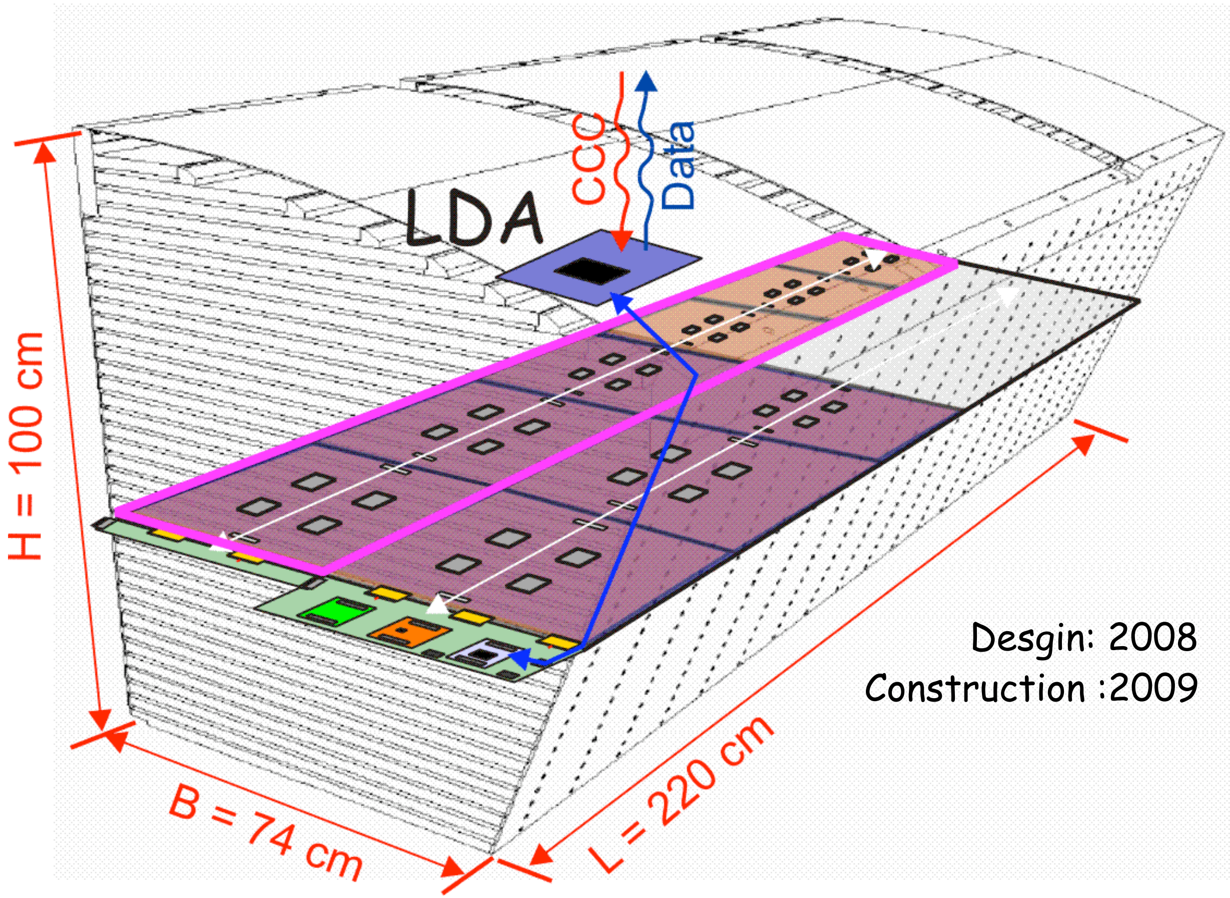
ECAL
Cross Section

Analog HCAL – Technical Prototype

Goal: Compact & realistic design, i.e. scaleable with embedded electronics

Integration issues:

- readout architecture
- ultra-low power ASICs
- calibration system
- tile and SiPM integration
- absorber mechanics with minimal cracks



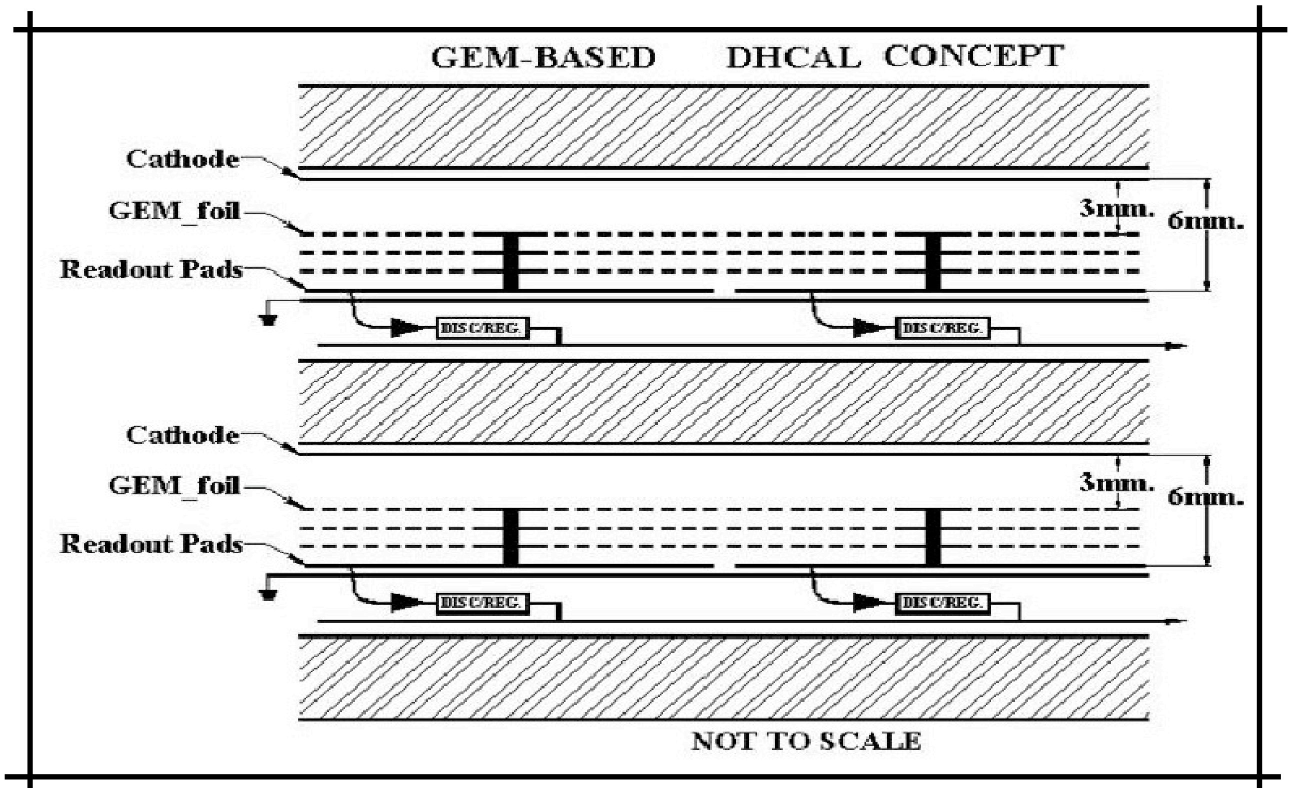
Feedback from test beam essential

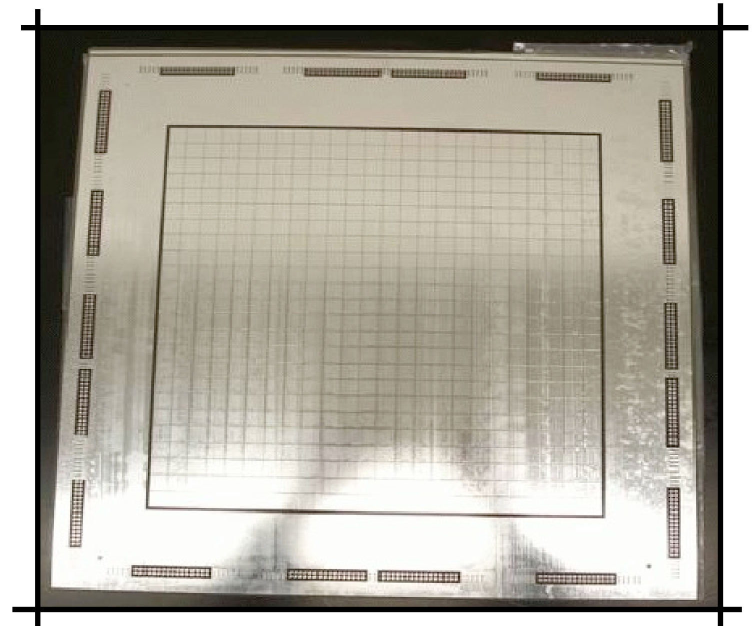
[e.g. calibration concept, overall detector optimization]

Digital HCAL: GEM

Why digital ?

- better PFA performance
- cheap, robust detectors ...
- small total thickness ...





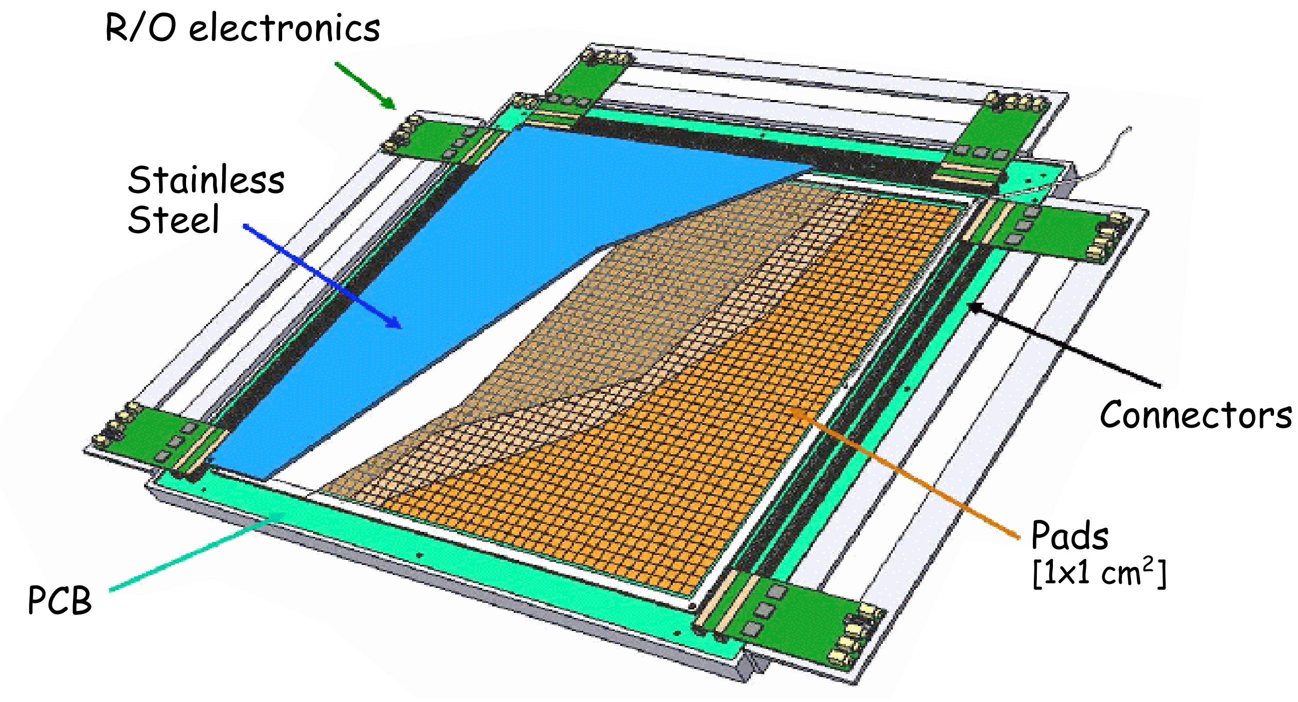
[30 x 30 cm^2 GEM chamber]

A first
Test chamber works

- 80% Ar & 20 % CO_2
- Pad Size: ~ 1x1 cm^2

Full size
test beam module: 2008
[equipped with 100 x 30 cm2 chambers]

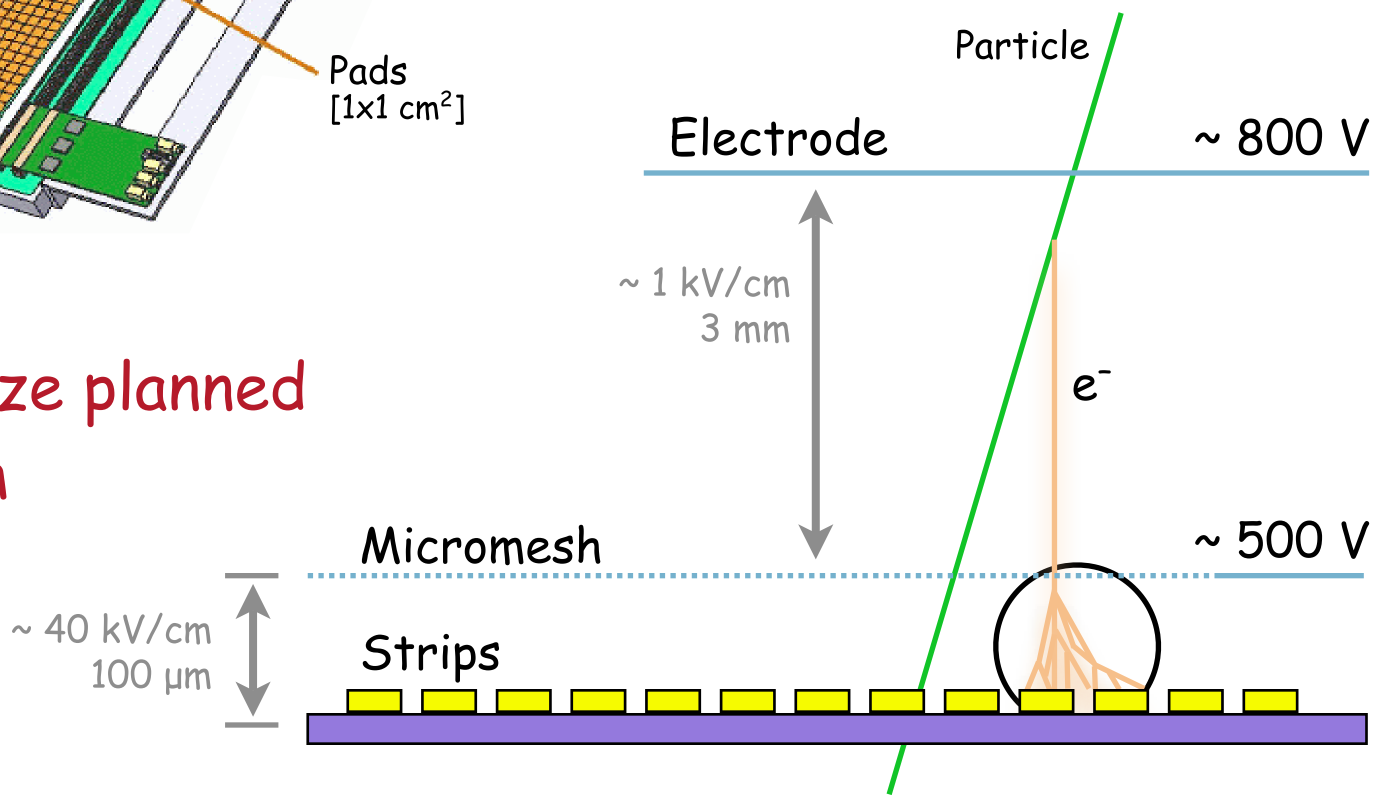
Digital HCAL: µMEGAS



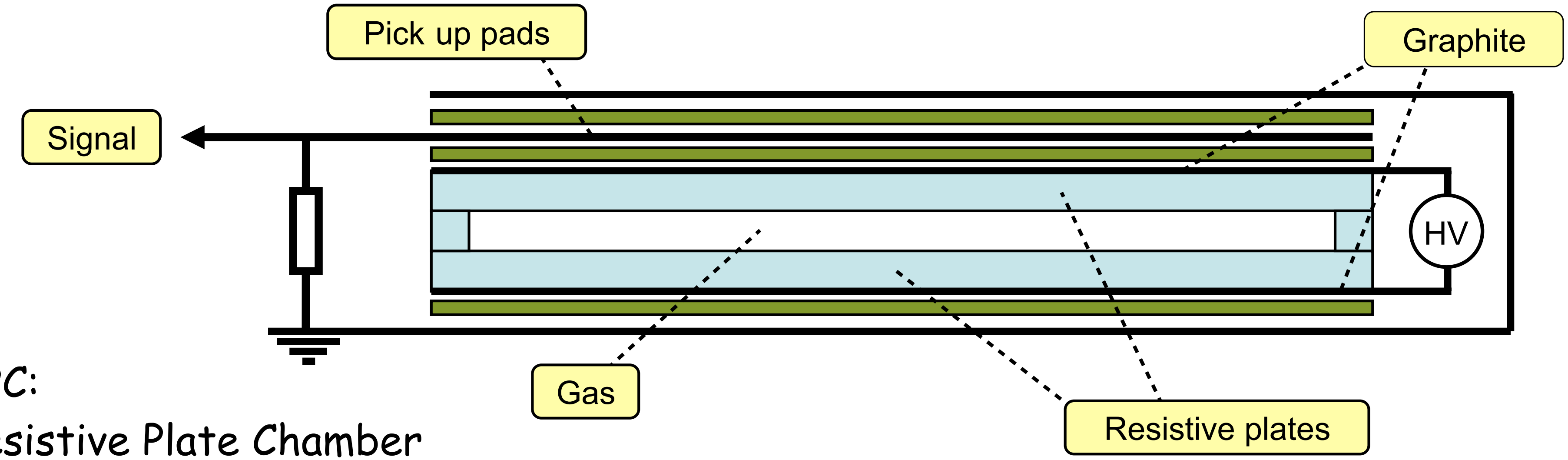
Status:

Cosmics with
6 x 16 cm^2 Protoype

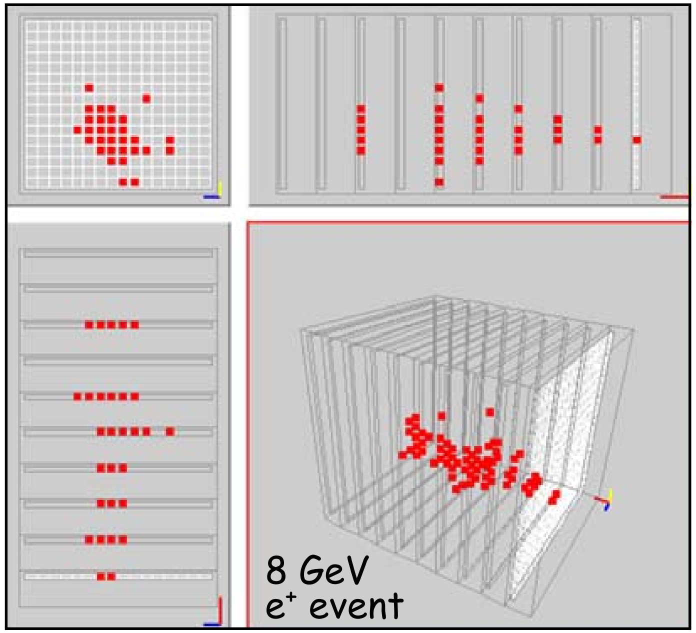
Plane with 1x1 m^2 size planned for 2008 test beam



Digital HCAL: RPCs



RPC:
Resistive Plate Chamber



Pad Size: 1 x 1 cm^2
Total thickness: < 6 mm possible

Vertical Slize Test with
9 small chambers successful

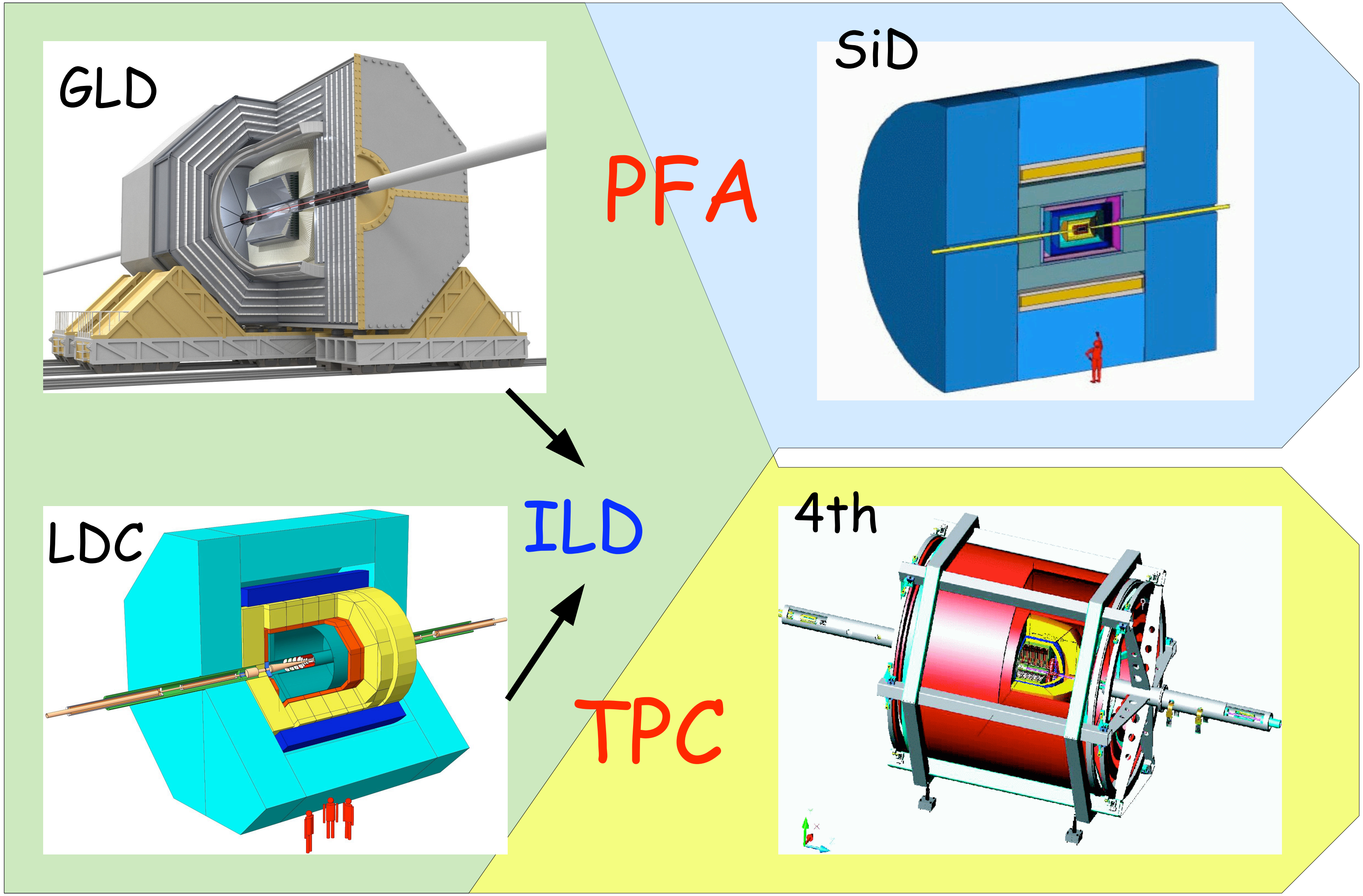
Large Prototype to be built

ILC Calorimeter R&D — Overview

ILC CALORIMETRY R&D	
ECALs	Silicon – Tungsten
	MAPS – Tungsten
	Scintillator – Tungsten
HCALs	Scintillator – Steel
	RPCs – Steel
	GEMs – Steel
	μMegas – Steel
Dual-Readout	Scintillator – Steel
TCMT	Scintillator – Steel

Detector Concept	Optimized for PFA	Compensating Calorimetry
SiD	Yes	No
LDC	Yes	No
GLD	Yes	Yes
4th Concept	No	Yes

Detector concepts



from
S.Schuwalov

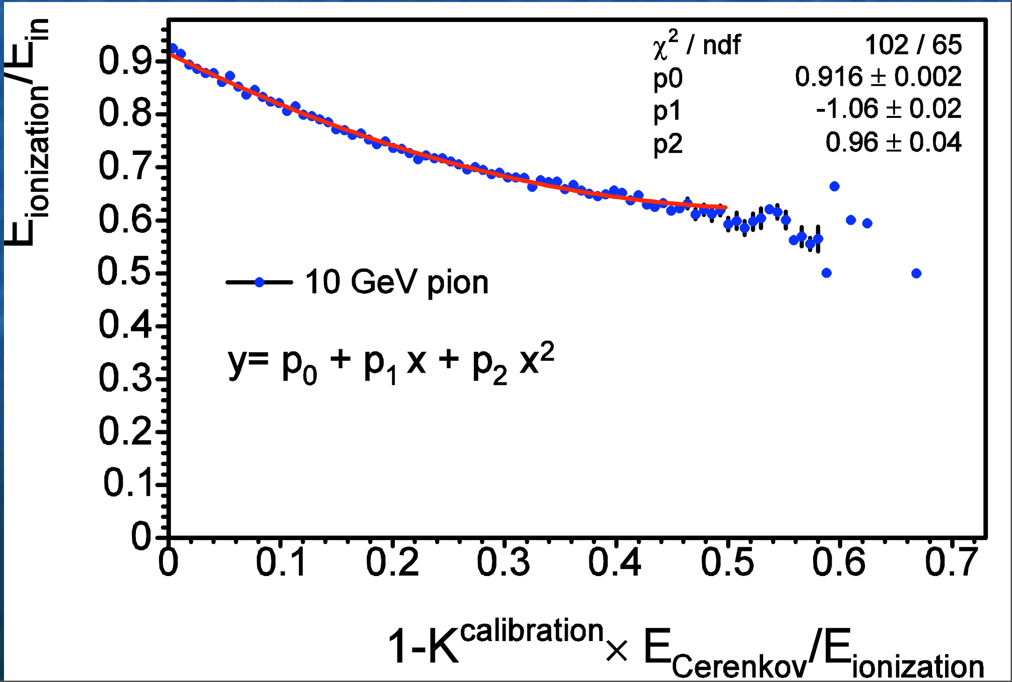
from Zaho et al.

Path to High Precision Hadron Calorimetry: Compensate for the Nuclear Energy Losses

- Compensation principle: $E = E_{obs} + k*N_{nucl}$
- Two possible estimators of N_{nucl}:
  - $N_{nucl} \sim N_{slow\ neutrons}$
  - $N_{nucl} \sim (1-E_{em}/E_{tot})$

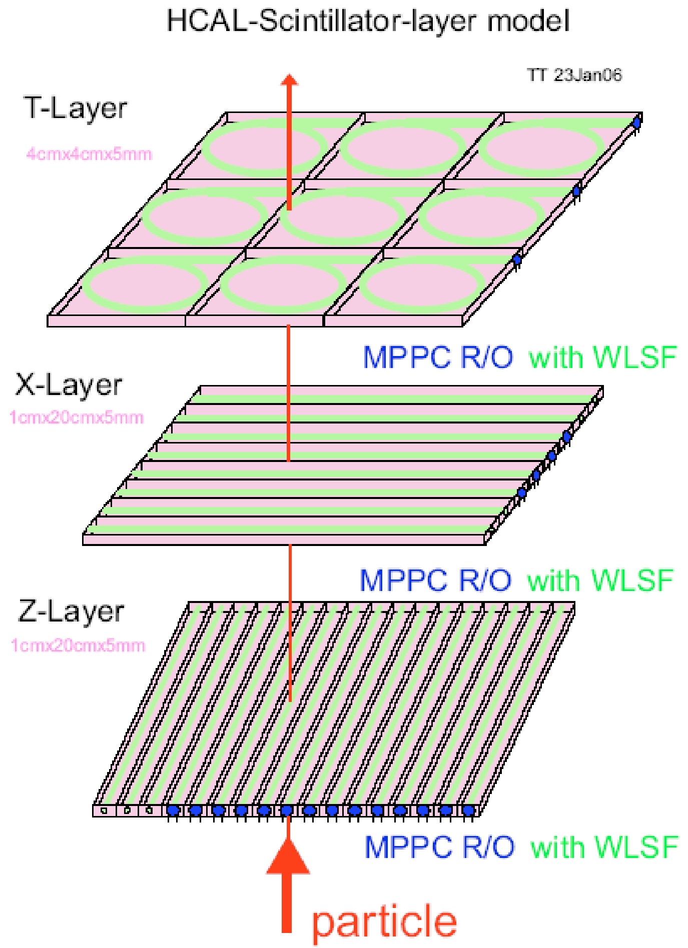
Cherenkov-assisted hadron calorimetry: $E_{em}/E_{tot} \sim E_{Cherenkov}/E_{ionization}$

- 'EM' shower: relativistic electrons, relatively large amount of Cherenkov light
- 'hadronic' shower – most of the particles below the Cherenkov threshold



Pb-Sci AHCAL

- Hardware compensation
  - Pb:Sc = 9.1:2
  - Strip/tile sizes are to be optimized
- Strips
  - Better position resolution for same channel count
  - Potential degradation of pattern recognition due to ghost hits



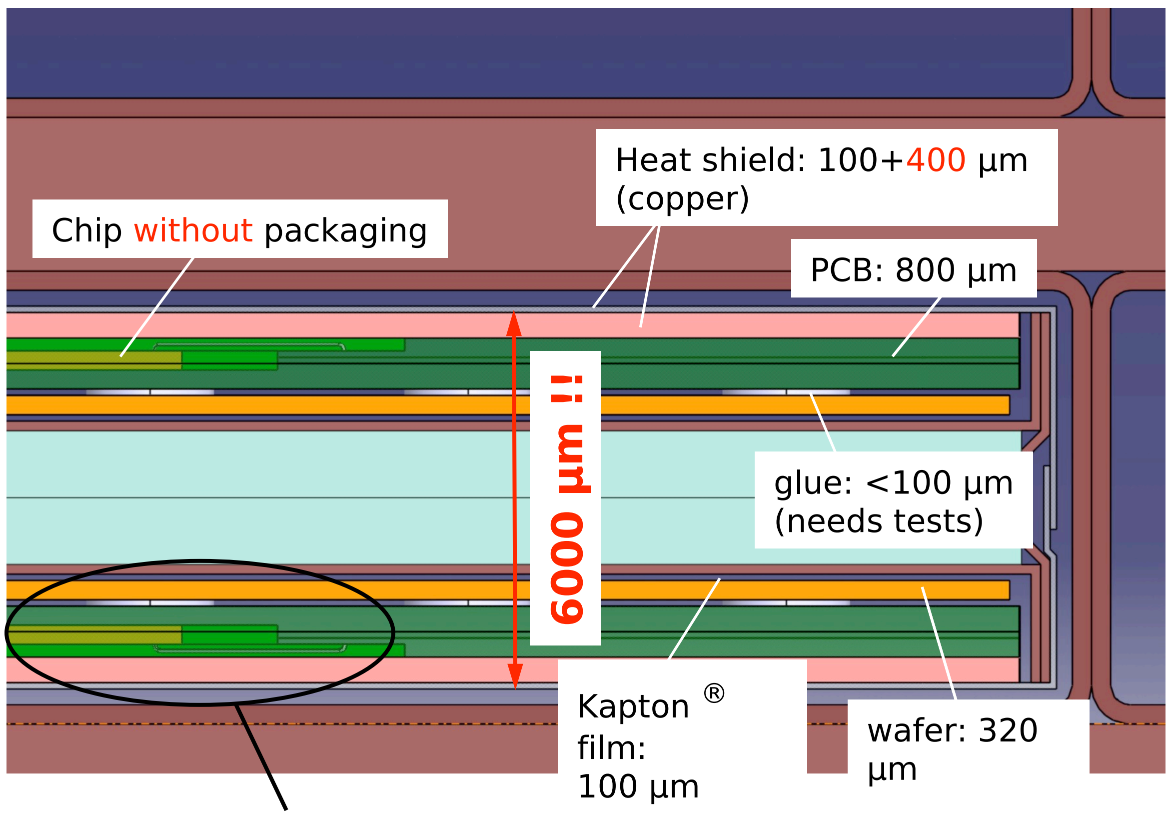
from

S.Schuwalov

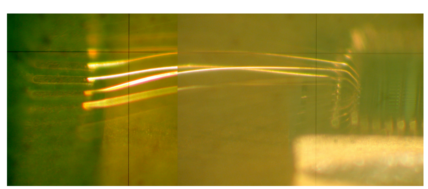
Design of Slab – Cross Section

The expected alveolar thickness is 6.5 mm **if** :

Design EUDET Slab



Chips and bonded wires inside the PCB

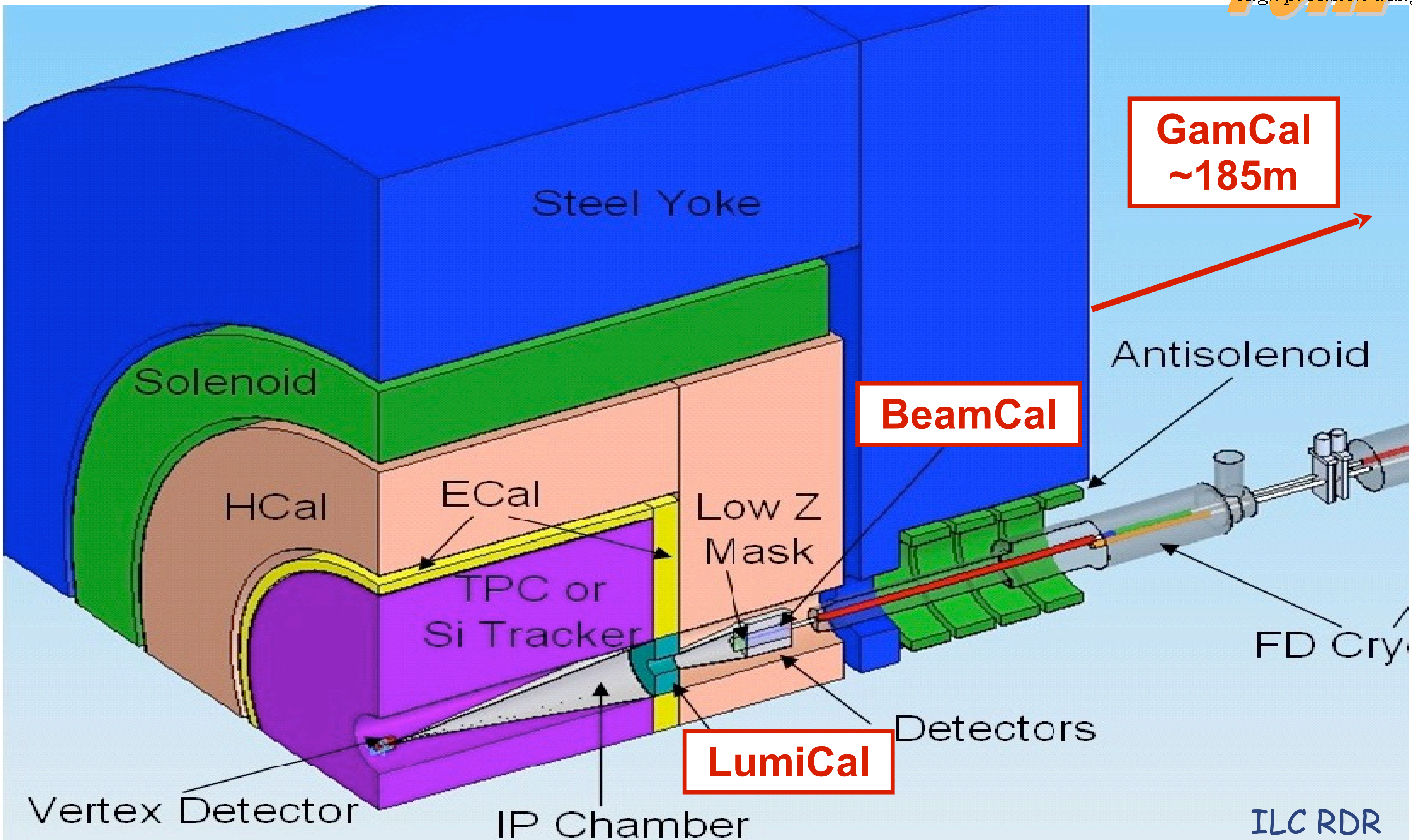


- ⇨ Gaps (slab integration) : 500 μm ?
- ⇨ Heat shield : 400 μm ?
  but real thermal dissipation ?
  (active cooling ?)
- ⇨ PCB : 800 μm (tolerances : ± ?)
  but chips embedded in PCB ?
- ⇨ Thickness of glue : < 100 μm ?
  study of the size of dots
- ⇨ Thickness of wafer : 320 μm – (± ?)
  30 matrix ordered (90×90 mm²)
- ⇨ Kapton® film HV feeding :
  100 μm - OK *(DC coupling)*
- ⇨ Thickness of W : 2100 μm (± 80 μm)

Several technological issues have to be studied and validated

from R.Pöschl

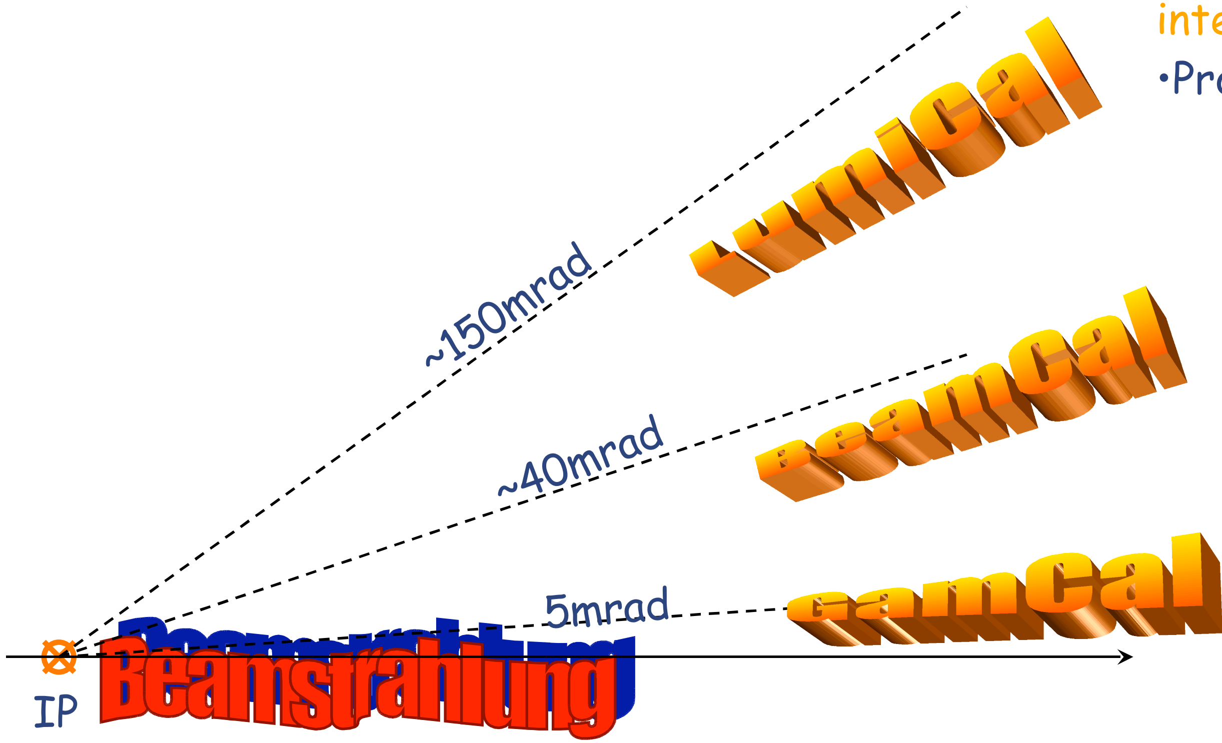
Design of the Forward Region



from
S.Schuwalov

Tasks of the Forward Region

ECal and Very Forward Tracker acceptance region.



- Precise measurement of the integrated luminosity ($\Delta L/L \sim 10^{-4}$)
- Provide 2-photon veto

- Provide 2-photon veto
- Serve the beamdiagnostics using beamstrahlung pairs

- Serve the beamdiagnostics using beamstrahlung photons

Challenges:

High precision, high occupancy, high radiation dose, fast read-out!

from
S.Schuwalov

Impact of gaps on PFA

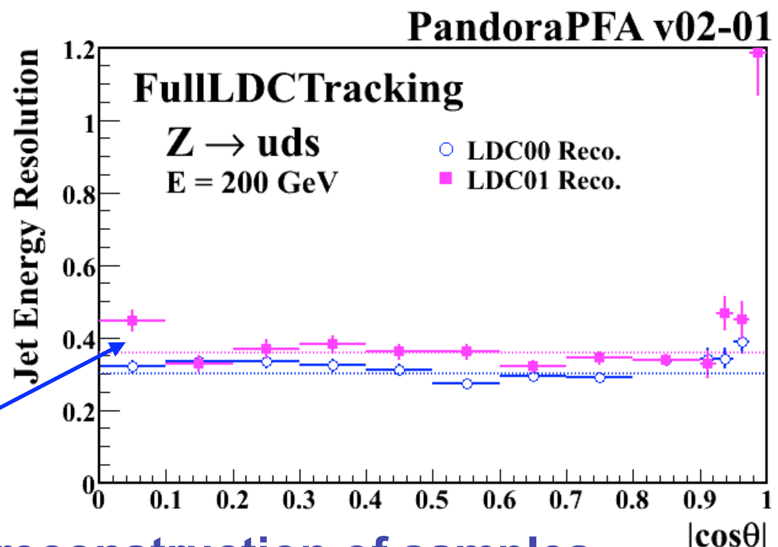
- Assuming 60% charged particles, 30 % photons, 10 % neutral hadrons, can *estimate* contributions to PFA performance

45 GeV jets: $\sigma_E = \alpha\sqrt{E}$

α	ECAL	HCAL	Confusion	Other	Total
LDC00Sc	0.07	0.17	0.11	0.09	0.235
LDC01_05Sc	0.14	0.17	0.12	0.09	0.267

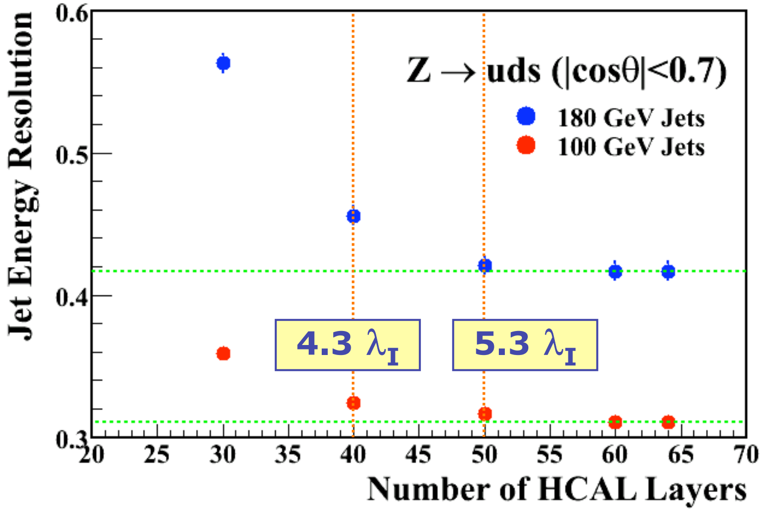
- For **LDC01_05Sc** ECAL energy resolution is a significant contribution to jet energy resolution !
- Expect impact of gaps to increase with energy – there is some evidence for this for 200 GeV **Z→uds** events

at small cosθ (where gaps are Most important) degraded performance



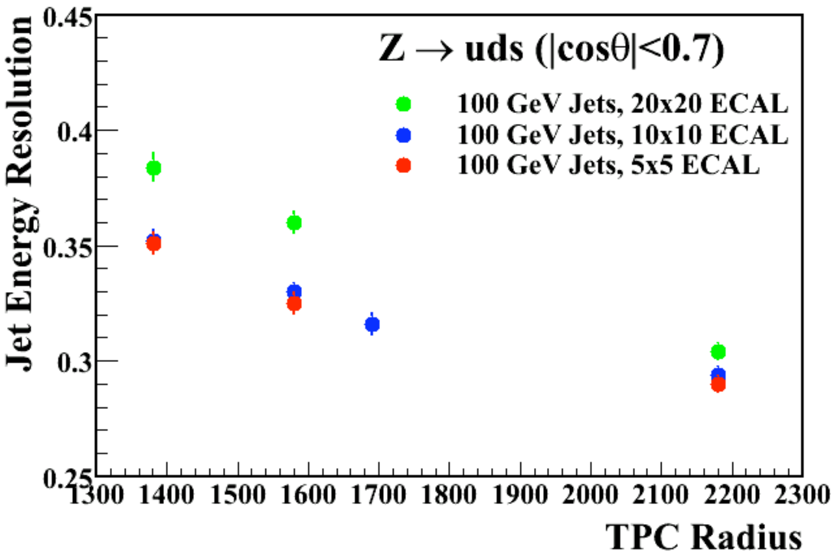
- Ideally address this issue before mass reconstruction of samples.

Some preliminary answers to some PFA questions, e.g.



HCAL depth

ECAL transverse granularity



e.g. for PFA, what are the main detector questions ?

(at Snowmass LDC/GLD/SiD came up with list of questions)

★ Have "answers" to some of these questions (marked in green)

The A-List (in some order of priority)

1) B-field : why 4 T ? Does B help jet energy resolution
2) ECAL inner radius/TPC outer radius
3) TPC length/Aspect ratio
4) Tracking efficiency – forward region
5) How much HCAL – how many interactions lengths 4, 5, 6…
6) Impact of dead material – see my talk on Wednesday
7) Longitudinal segmentation – pattern recognition vs sampling frequency for calorimetric performance
8) Transverse segmentation ECAL/HCAL
   ECAL : does high/very high granularity help ?
9) Compactness/gap size
10) HCAL absorber : Steel vs. W, Pb, U…
11) Circular vs. Octagonal TPC (are the gaps important)
12) HCAL outside coil…
13) TPC endplate thickness and distance to ECAL
14) Material in VTX – how does this impact PFA

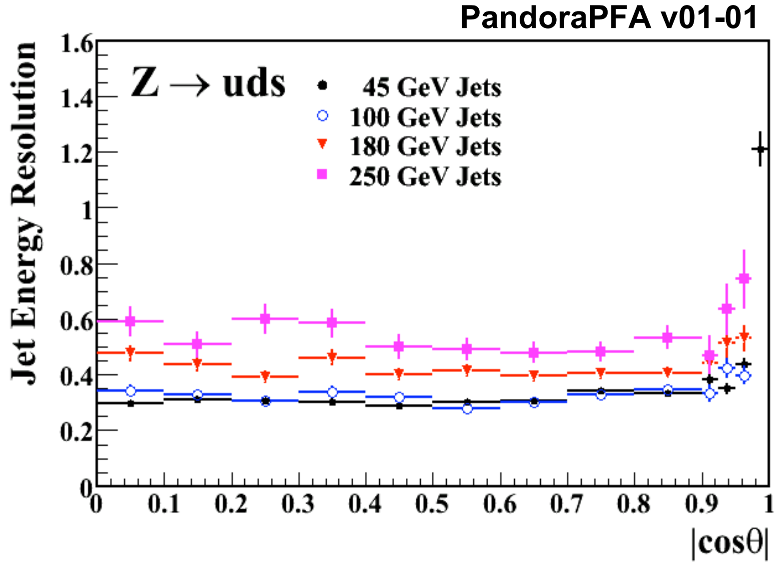
★ How about a similar list for Vertex and Tracking ?

❷ Status at LCWS07

★ Full simulation studies using the LDC ILC detector concept with the PandoraPFA algorithm. Use $Z \rightarrow u\bar{u}, d\bar{d}, s\bar{s}$ decays at rest to benchmark performance

rms90* PandoraPFA v01-01

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ $\lvert\cos\theta\rvert<0.7$	σ_E/E_j
45 GeV	0.295	4.4 %
100 GeV	0.305	3.0 %
180 GeV	0.418	3.1 %
250 GeV	0.534	3.3 %



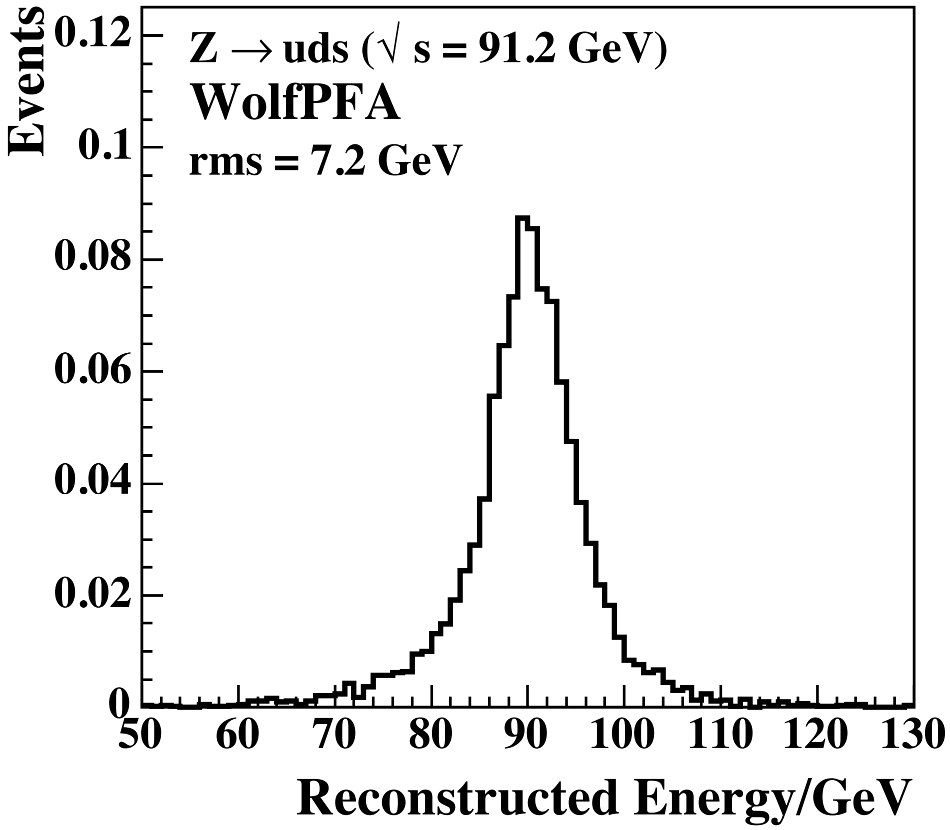
★ For jet energies below 100 GeV achieve $\sigma_E/E < 0.30/\sqrt{E_{jj}(\mathrm{GeV})}$

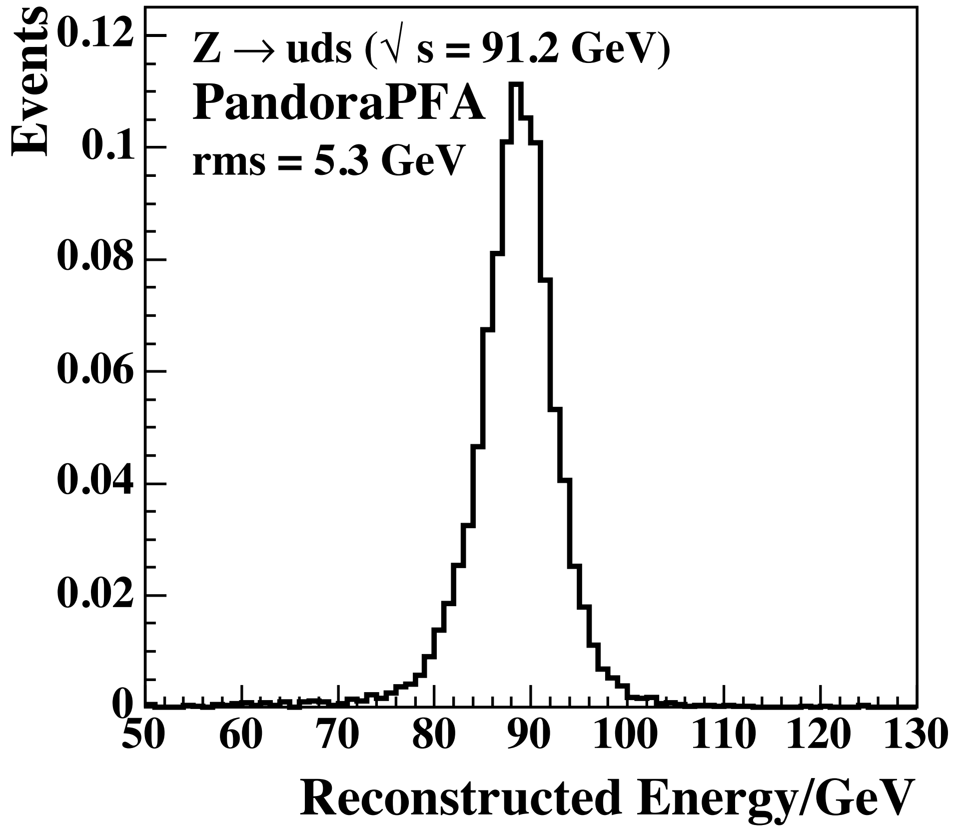
★ Perhaps more importantly, for jet energies above ~75 GeV achieved

$$\sigma_{E_j}/E_j < 3.8\%$$

★ Post-LCWS emphasis shifted to improving low energy performance, important in likely initial phase of ILC at $\sqrt{s}$ ~ 200-500 GeV

Particle Flow Performance

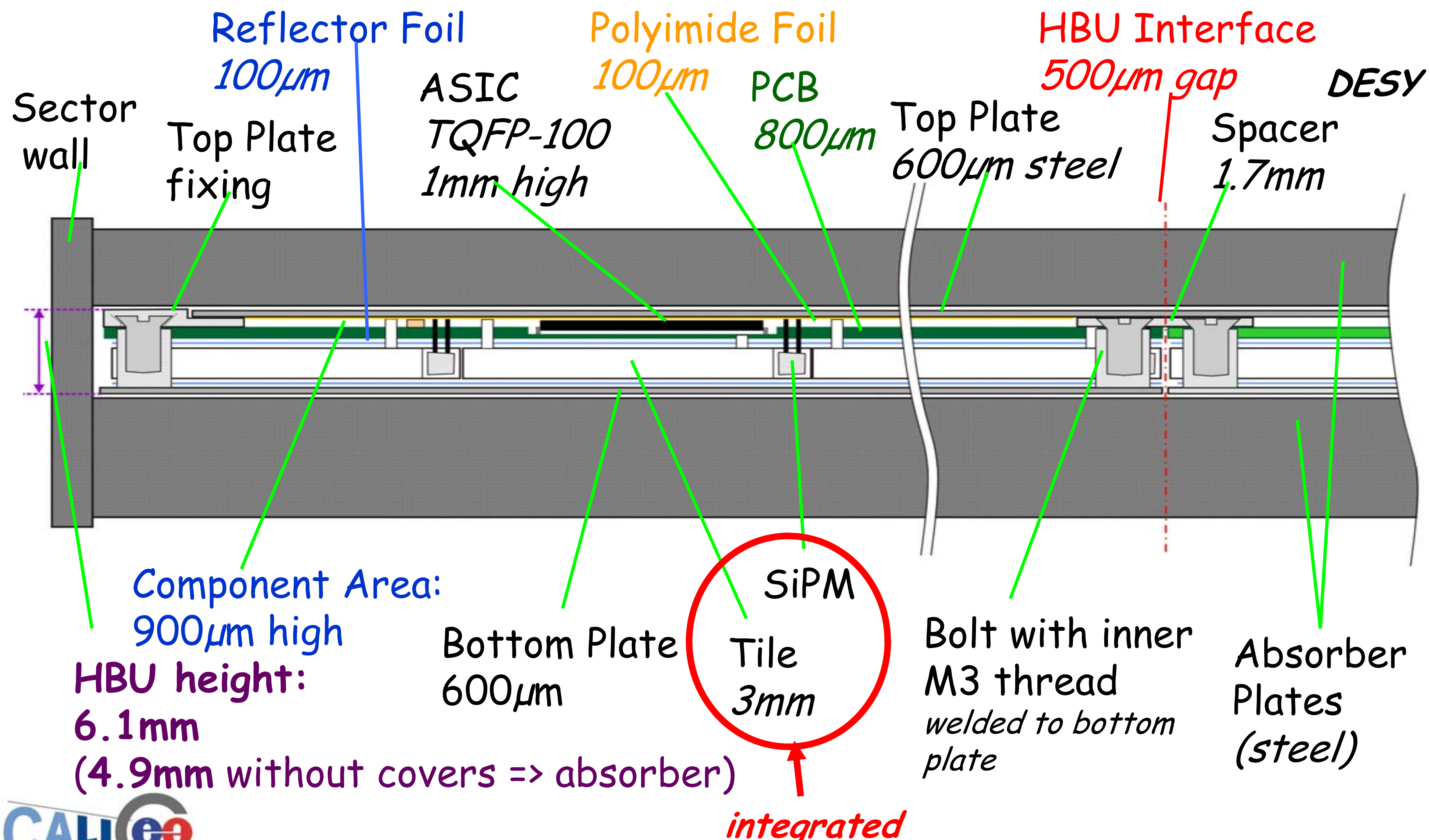




~ 50%/√E

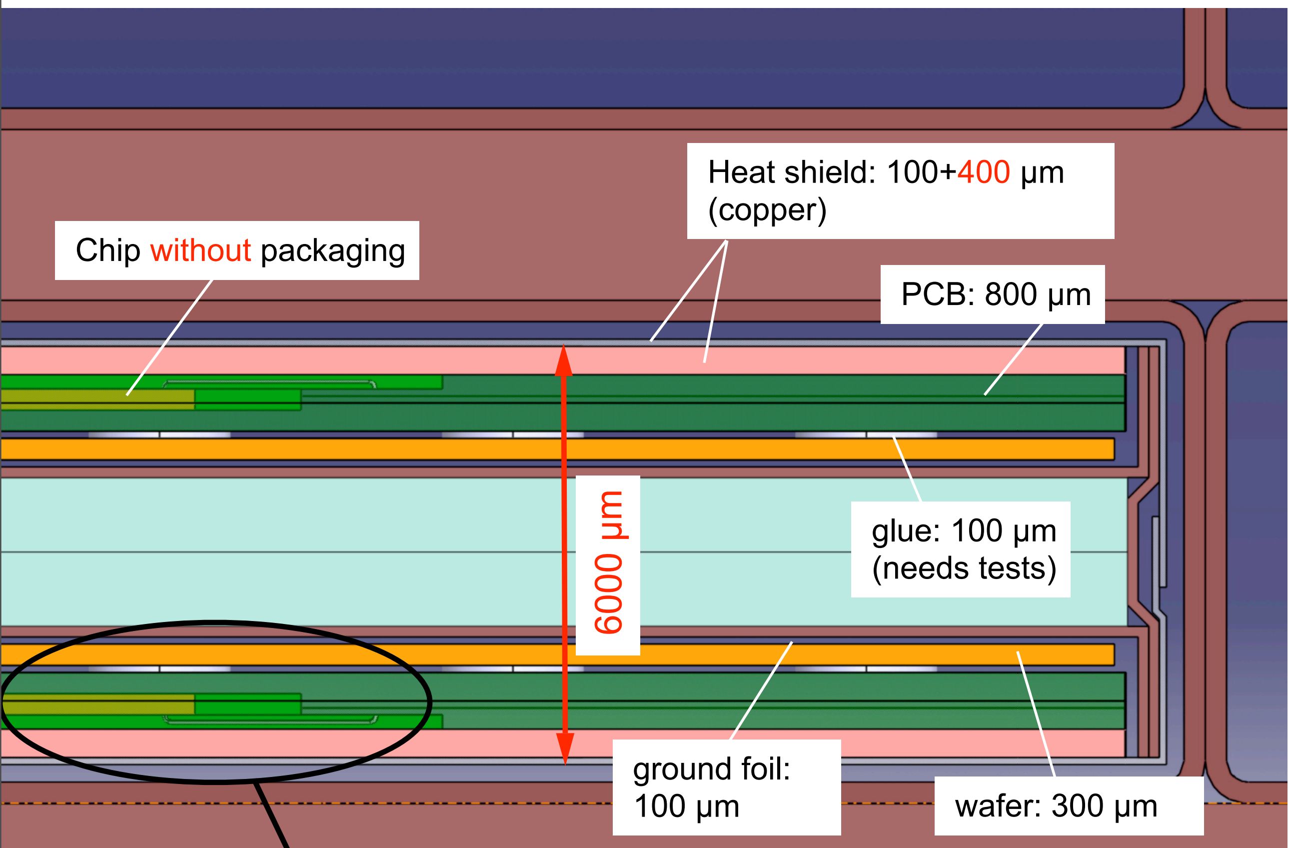
~ 30%/√E

Integrated layer design



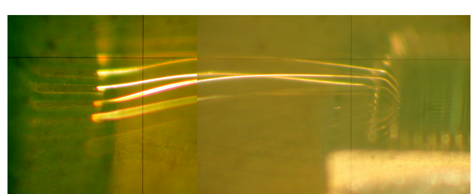
Design of the module…

… based on the definition of the detector slab :



Design EUDET Slab

Chips and bonded wires inside the PCB



The expected alveolar thickness is 6.5 mm **if** :

- ⇨ Gaps (slab integration) : 500 µm - OK
- ⇨ Heat shield : 400 µm ?
  but real thermal dissipation ?
  (active cooling ?)
- ⇨ PCB : 800 µm
  but chips embedded in PCB ?
- ⇨ Thickness of glue : 100 µm ?
  study of the size of dots ?
- ⇨ Thickness of wafer : 300 µm ?
- ⇨ Ground or isolate foil : 100 µm ?
  AC vs DC ?
- ⇨ Thickness of W : 2100 µm - OK

Several technological issues have to be studied and validated

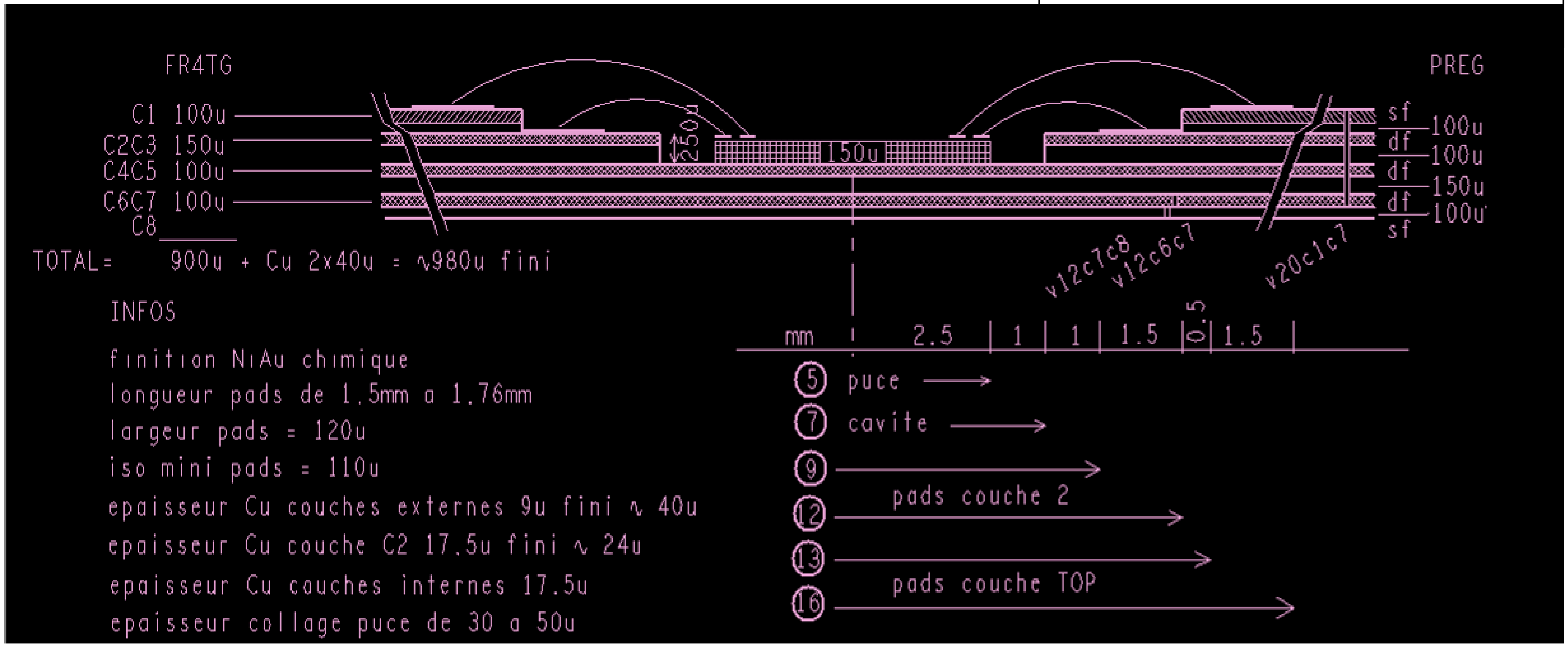
From M. Anduze

Chip Integration in PCB

ECAL

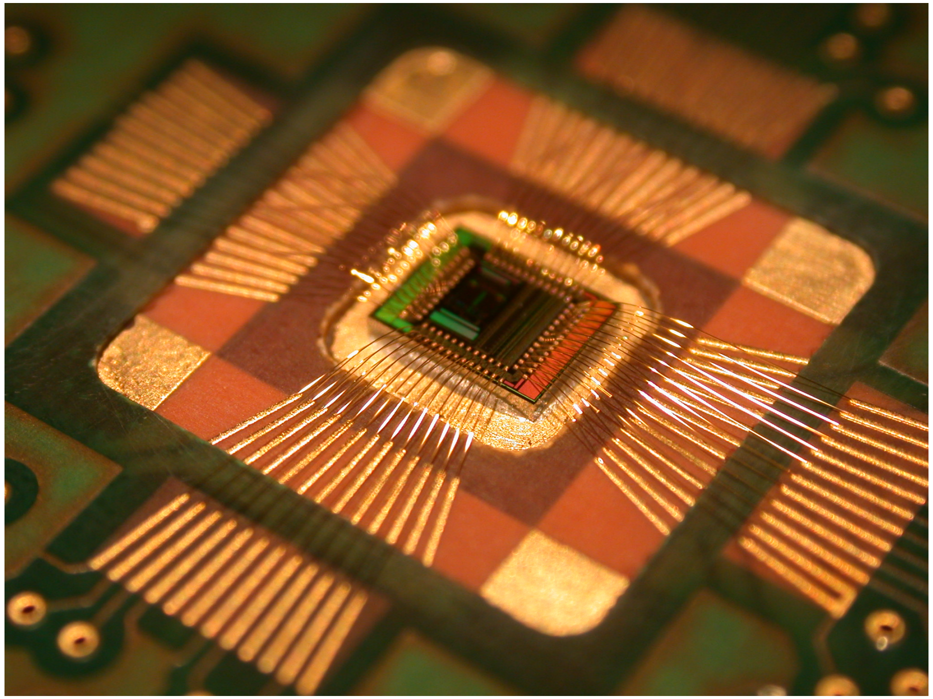
Pile-up	
TOP	GND+routing
C2	AVDD+routing
C3	AVDD+DVDD
C4	GND + horizontal routing
C5	AVDD+ vertical routing
C6	GND+pads routing
C7	GND (pads shielding)
BOT	PADS

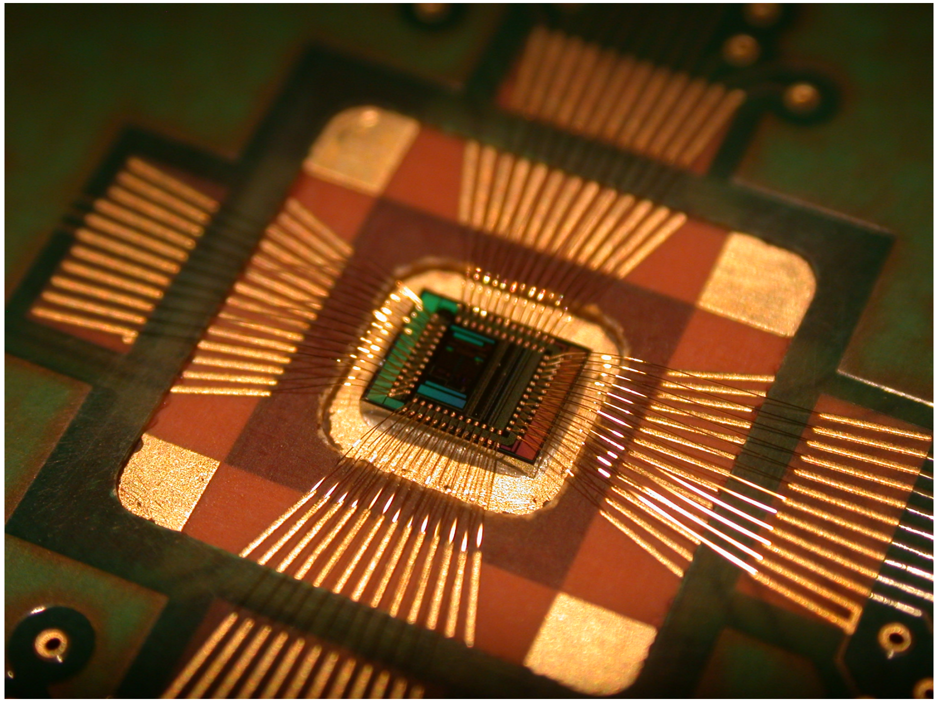
3 drilling sequences :
- Laser C7-C8 120µ filled
- Laser C6-C7 120µ
- Mechanical C1-C7

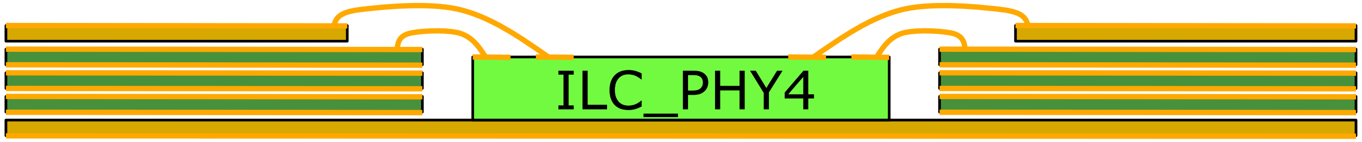


- Bonding wires from Chip to PCB challenging due to large number of channels
- Has to fit into overall mechanical tolerances (see above)

Chip on board design







Last prototype

EUDET prototype