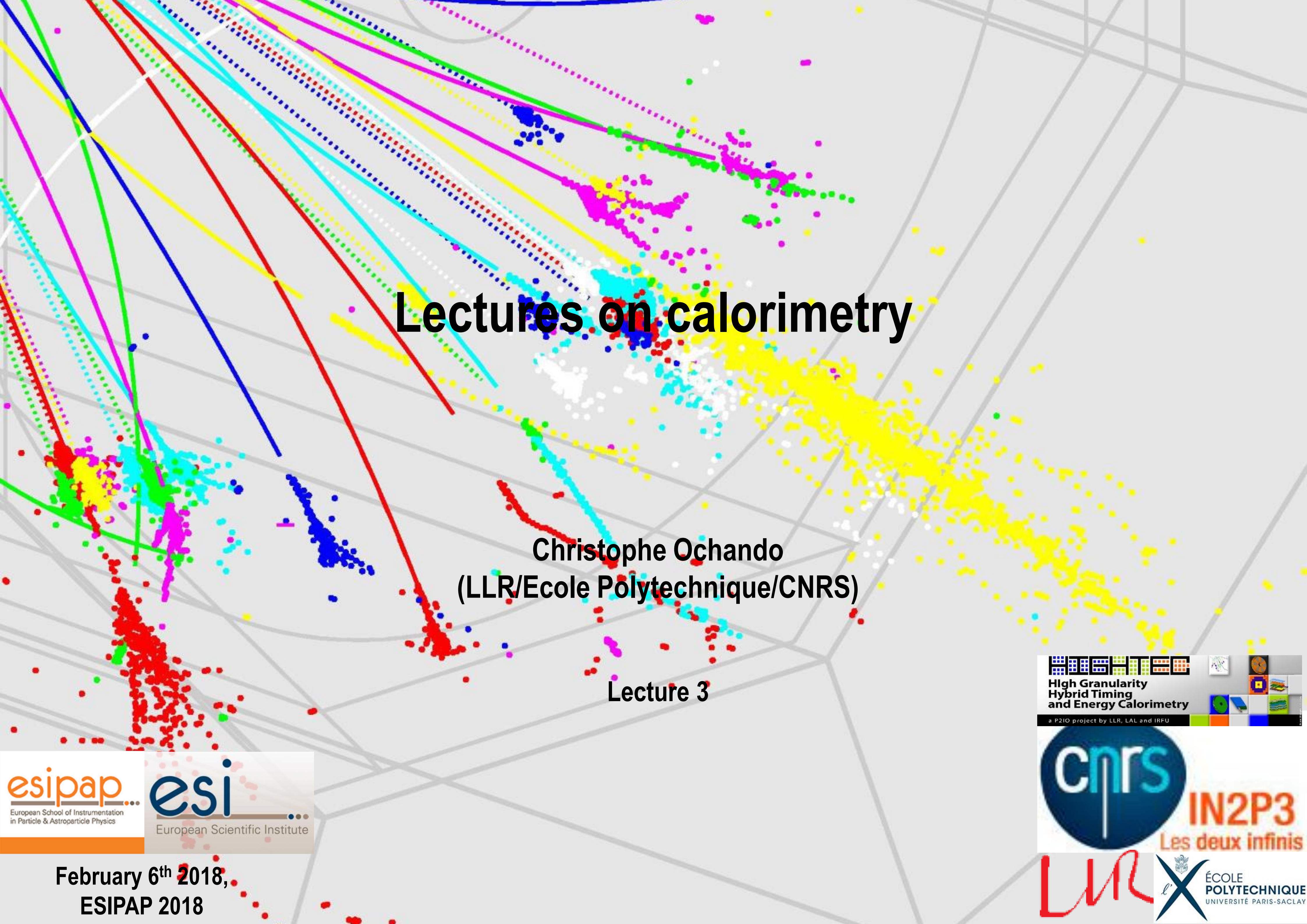


Lectures on calorimetry

Christophe Ochando
(LLR/Ecole Polytechnique/CNRS)

Lecture 3

HIGHTEC
HIgh Granularity Hybrid Timing and Energy Calorimetry
a P2IO project by LLR, LAL and IRFU

esipap
European School of Instrumentation in Particle & Astroparticle Physics

esi
European Scientific Institute

CNRS IN2P3 Les deux infinis

LLR

ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY

February 6th 2018,
ESIPAP 2018

Plan of lectures

Lecture 1

Why/what calorimeters ?

Physics of EM & HAD showers

Calorimeter Energy Resolution

Lecture 2

ATLAS & CMS calorimeters

Calorimeter Objects

Triggering

Lecture 3

Example of calorimeters (suite)

Future of calorimetry

Lecture 4

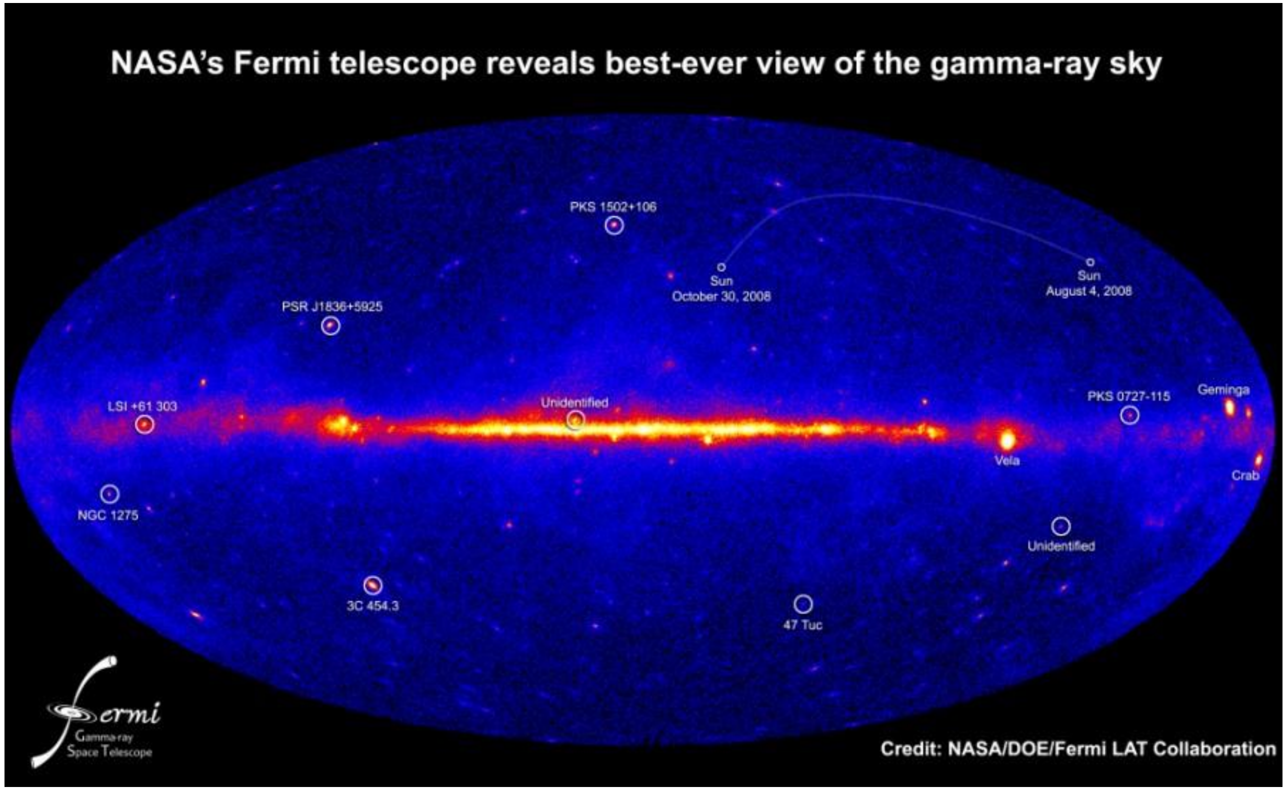
Tutorial
Exercises

Calorimeters: (more) examples

NA48 liquid Kr calorimeter

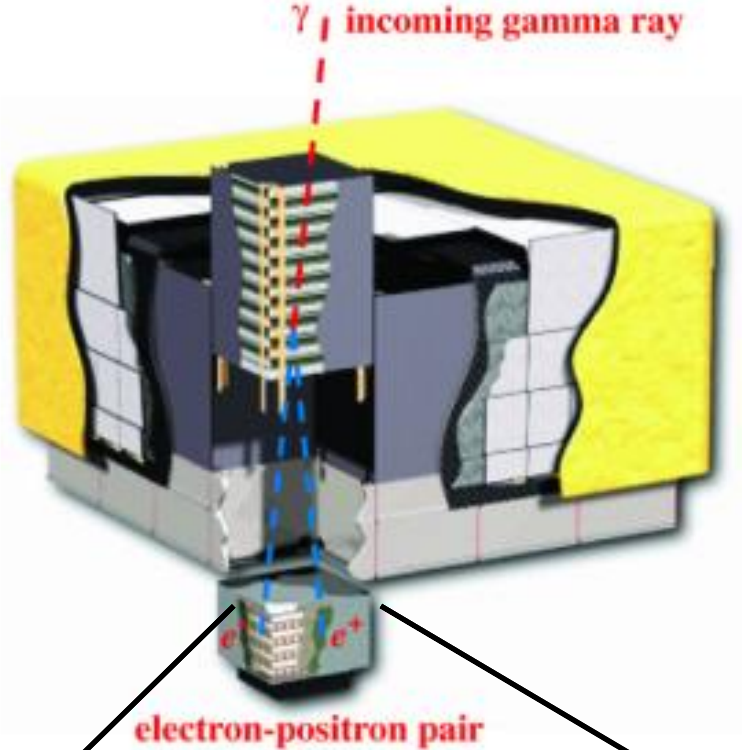
Calorimeters in space: FERMI/LAT

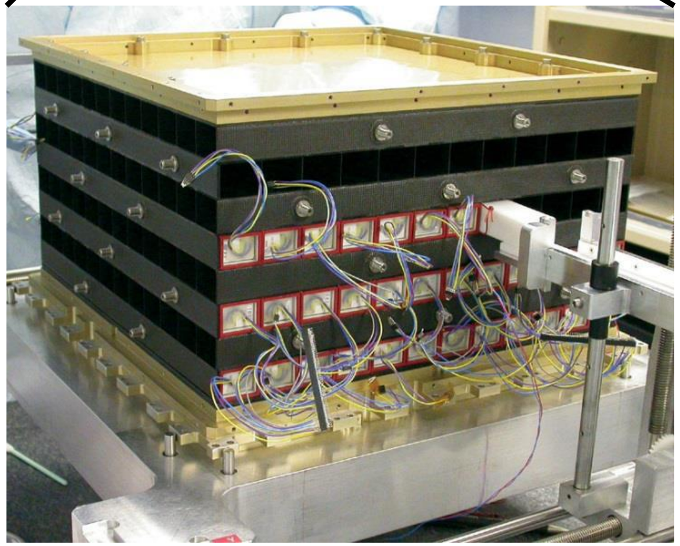
- **Fermi Satellite with Large Area Telescope (LAT) instrument.**
- **Gamma-Ray Telescope**
  - (200 MeV < γ < 300 GeV)
- Launched June 11 2008
- Consists of:
  - Tracker: Pb foils + Si strips
  - Calorimeter (**see next slide**)
  - Anticoincidence Detector : plastic scintillator tiles



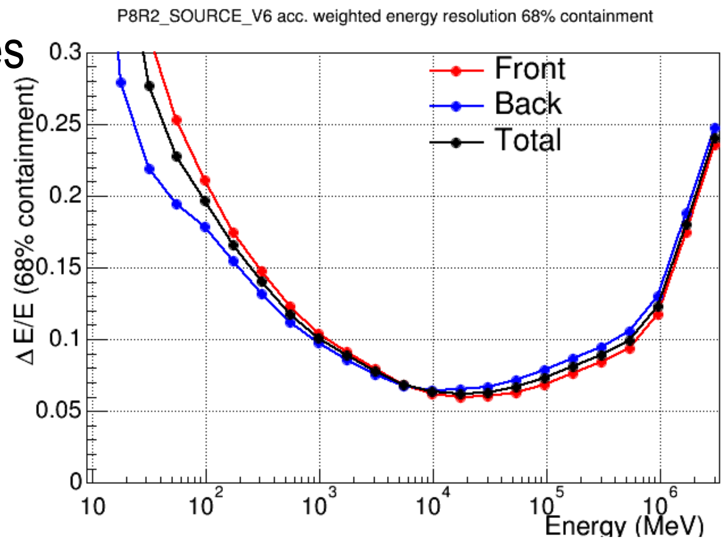
Calorimeters in space: FERMI ECAL

Homogenous calorimeter made from 1728 CsI(Tl) scintillating crystals





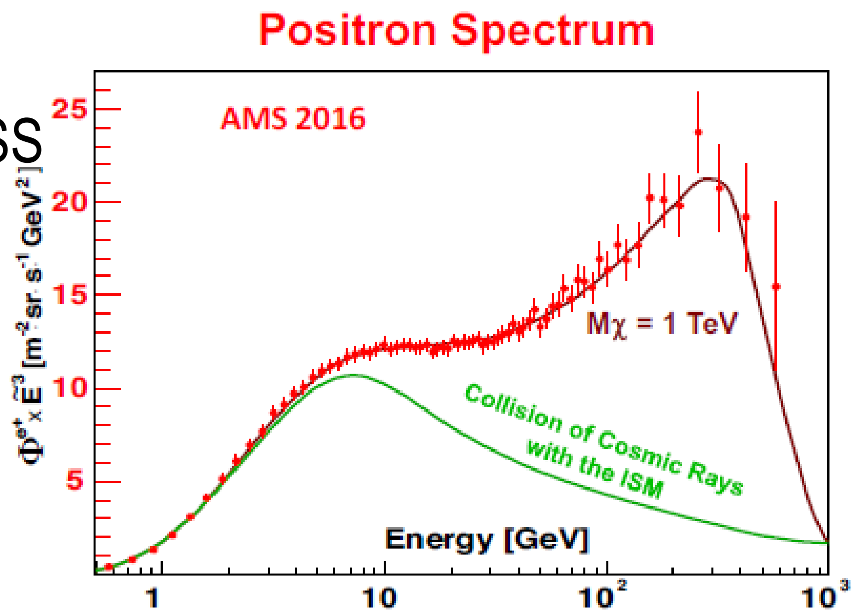
- 18 modules (400mmx400mmx250mm) ~100 kg each
- 1 module:
  - carbon-fiber alveolar structure +
  - **96 CsI(Tl) crystals (2.7 cm x 2.0 cm x 32.6 cm)**
  - arranged in 8 layers of 12 crystals each
- Each module aligned 90° wrt its neighbors, forming x,y (hodoscopic) array
- **Depth**: 8.6 X_O (10.1 including tracker)
  $\Rightarrow$ **Need shower leakage correction**
- Light read by 2 photo-diodes

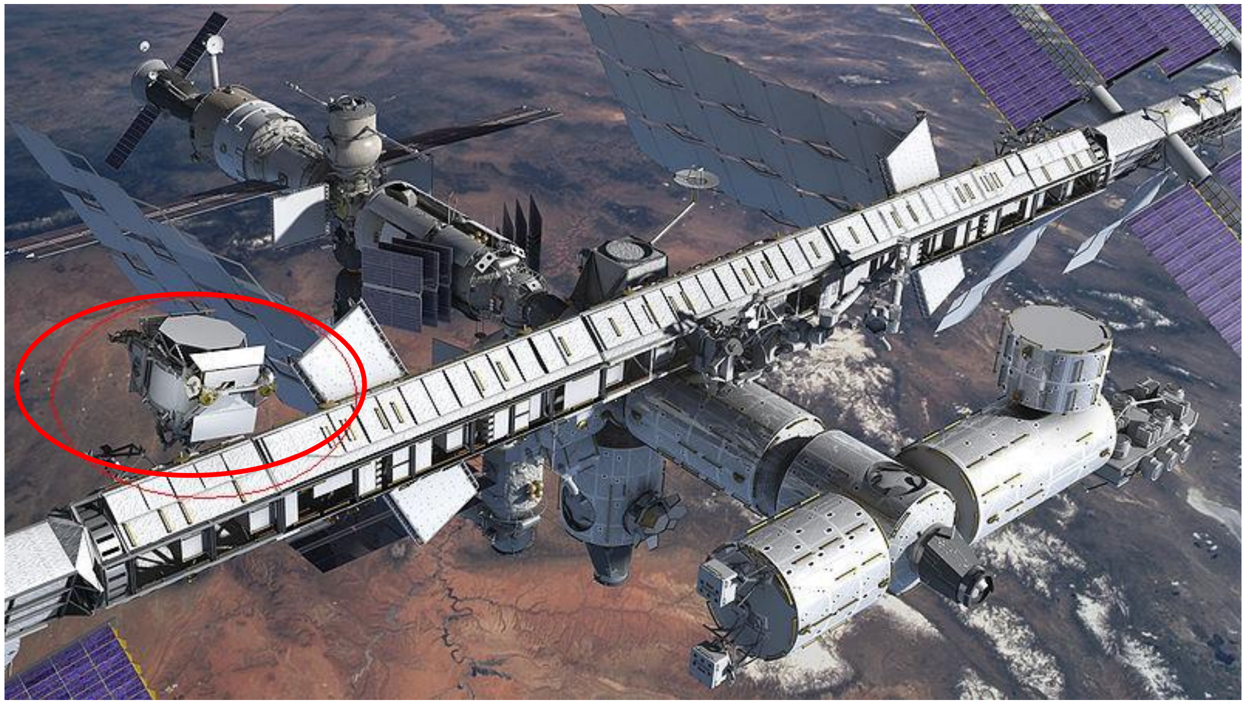


Calorimeters in space: AMS-02

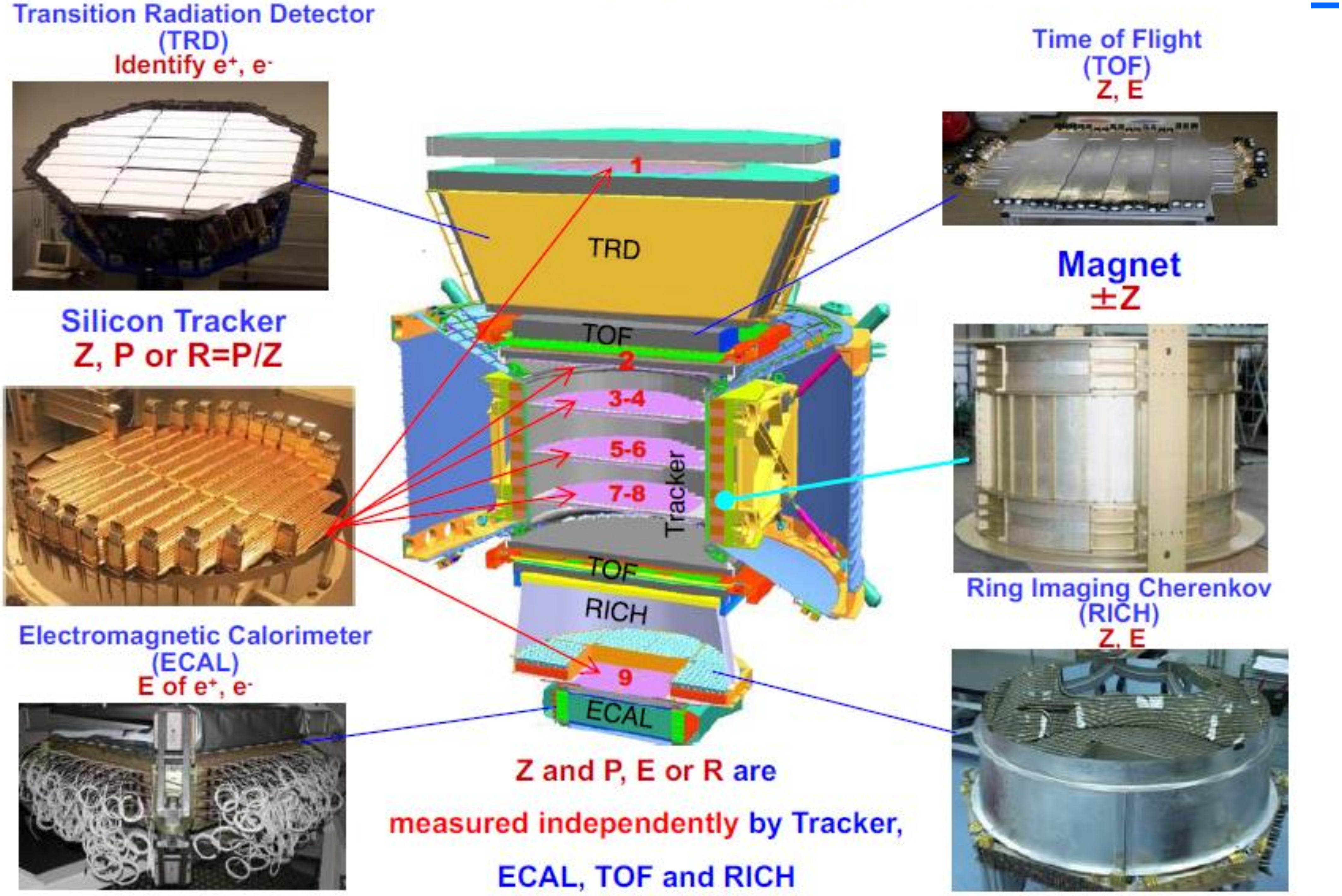
- **Alpha Magnetic Spectrometer (AMS):**
  - HEP-like detector operating as external module on ISS
  - Launched in 2011

- Search for Dark Matter, anti-matter, precise study of high energy cosmic ray (flux, composition), gamma rays.





AMS: A TeV precision, multipurpose, magnetic spectrometer

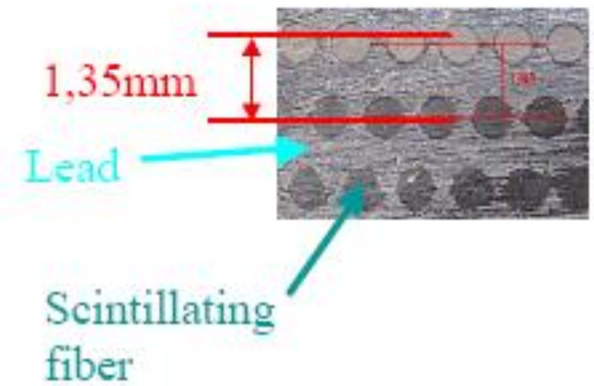


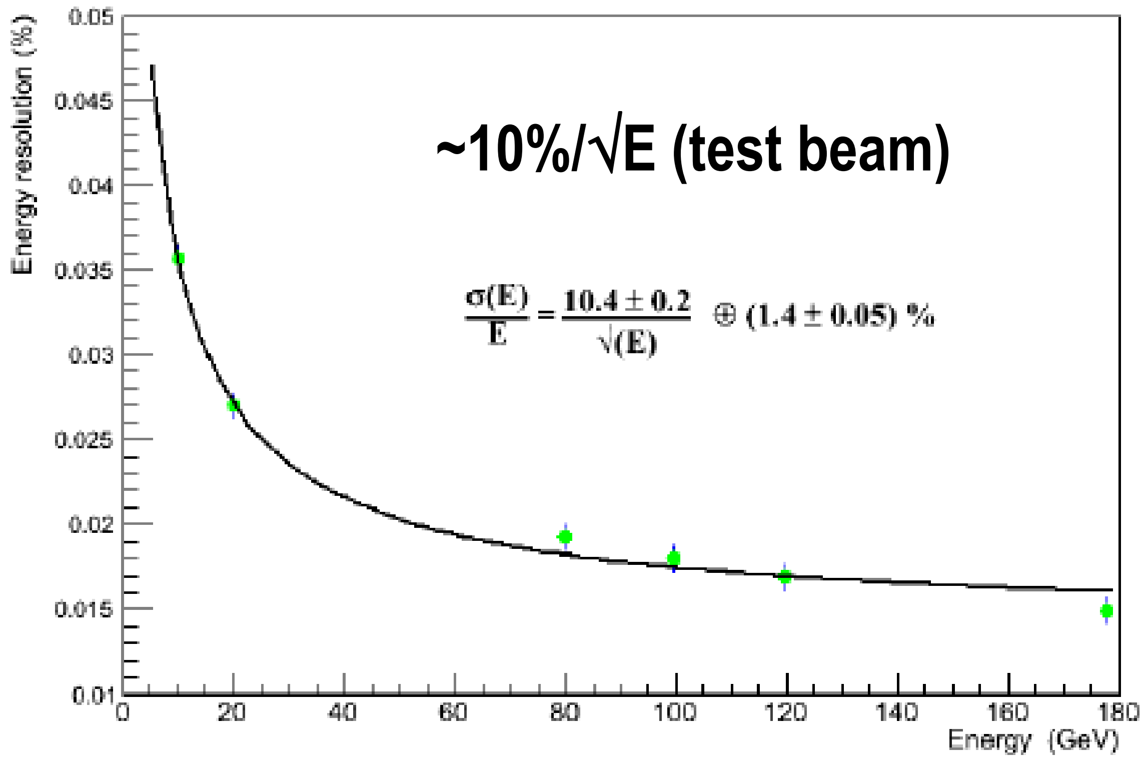
The AMS-02 ECAL

Sampling calorimeter made from Lead + Scintillating fibers

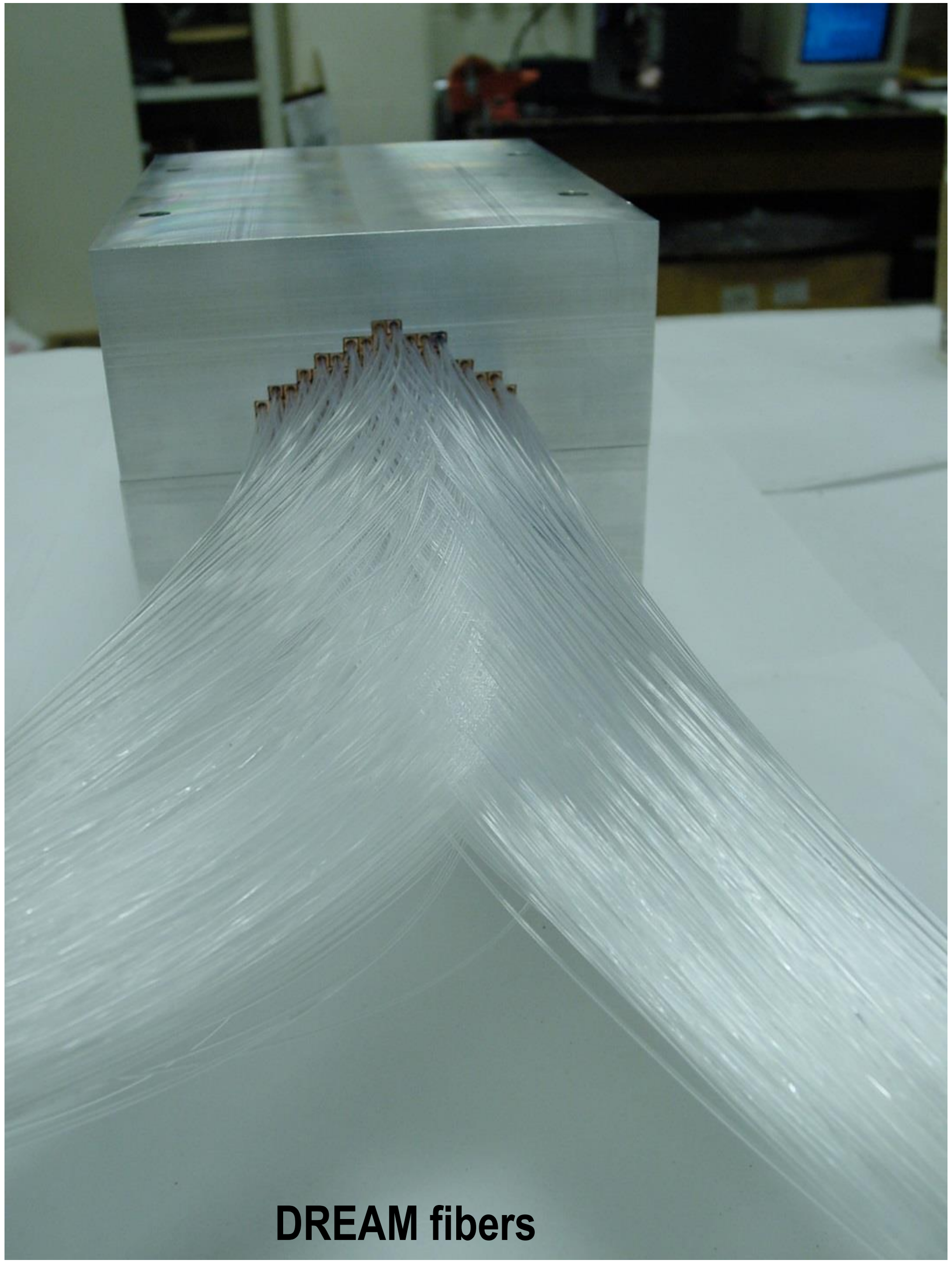
- **3-D imaging of shower development**
  - 9 Super-Layers (SL) alternatively oriented along X and Y axis (5 SL along X, 4 long Y)
- 1 Super-Layer (~18.5mm):
  - 11 grooved, Pb foils (1mm thick) interleaved with 10 layers of scintillating fibers (Ø~1mm) glued by epoxy-resin
- **Depth:** ~17 X0
- Fibers read by PMT

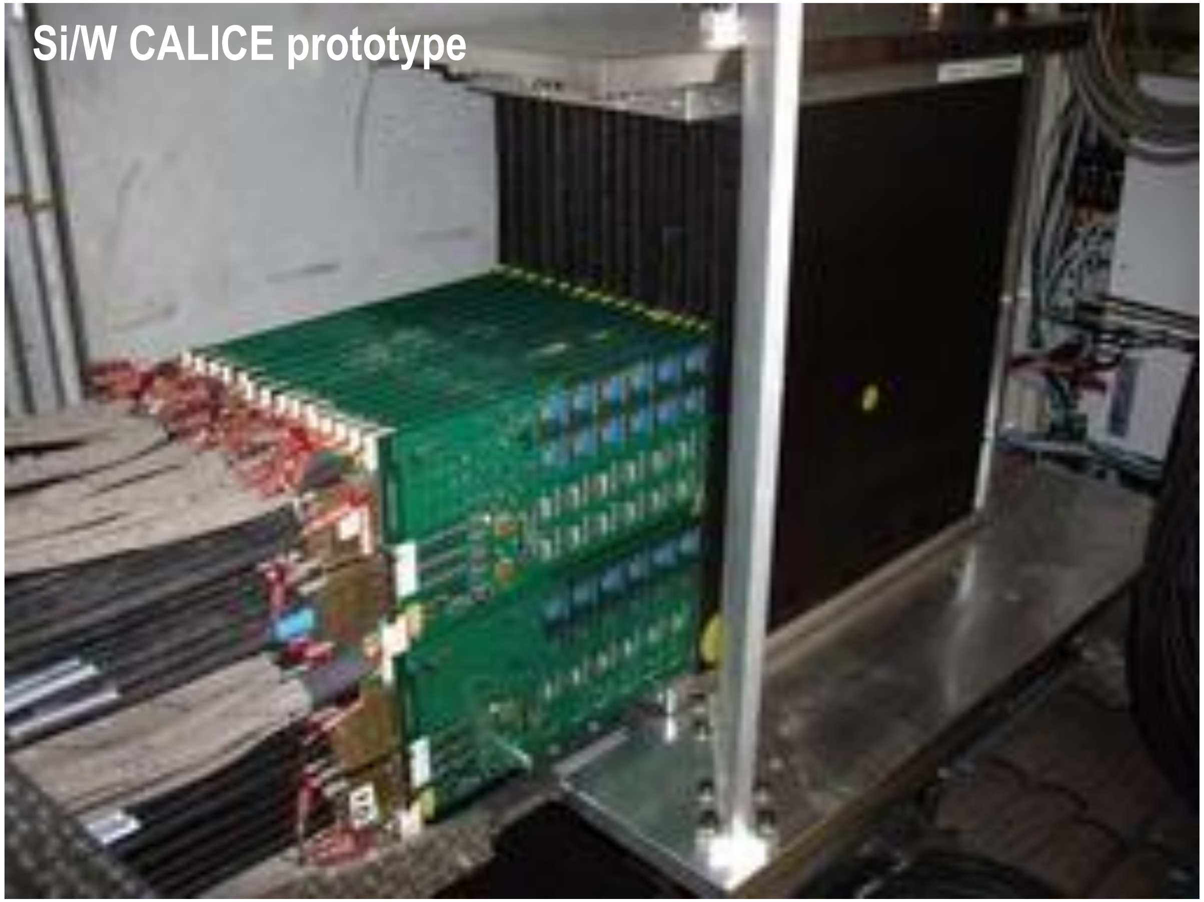
ECAL support structure



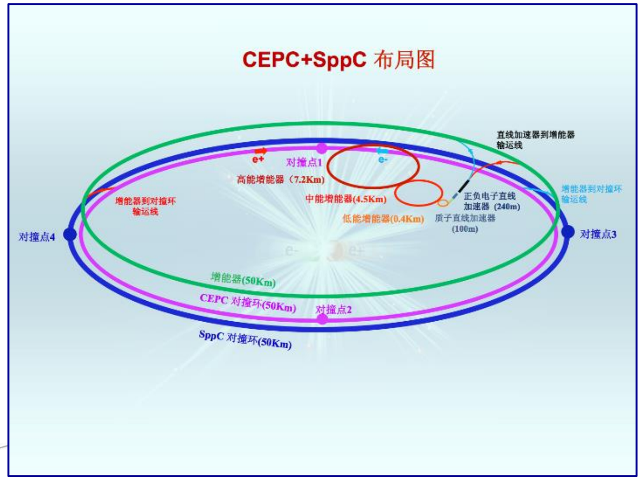


“Future” of calorimetry



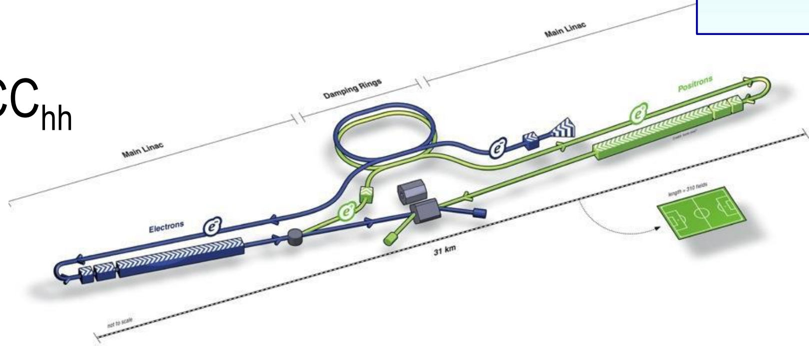


(selected) Future of HEP at colliders.



- **“Short” term:** HL-LHC (2025-2035)
  - Upgrade of ATLAS, CMS… (**see later**)

- **Longer term** (30-50 years)
  - Lots of on-going discussions on what will be the “best” machine
  - Possible new e+e- colliders
    - Linear (ILC, CLIC)
    - Circular (FCC_{ee}, CEPC,…)
  - Possible new hadron colliders: FCC_{hh}
  - μ-colliders, …



- **Physics Goals:**
  - **Higgs**
    - high precision measurement on couplings to fundamental fields,
    - Tri- and quadri-linear couplings (HH, HHH production)
  - Search / Study of **new physics**
    - SUSY, extra-dimensions, …
      - => High mass resonances (d-ijet, $\gamma\gamma$, ee,…), jets+MET, multi-leptons, …

Require **high precision for calorimetry**, in particular for jets !
+ timing capabilities
+ radiation hardness…

Jet Resolution

- Worst than (or at most as good as) single hadron resolution
  - **How to improve on jet resolution ?**
    - ie, how to get rid / mitigate the inherent fluctuations (in particular on fEM) ??

- **Two approaches:**
  - Minimize influence of calorimeter: use combination of all detectors
    =>"particle flow" (software and hardware)

  - Measure the shower components in each event: access the source of the fluctuations
    => Dual readout (mostly hardware + software)

Hadronic/Jet Resolution

- **Hadron Calorimeter Resolution limited by fluctuations** (sampling, f_{EM}, quantum, leakage, …)
  - Non-compensation degrades resolution.

- Excellent hadron resolution already achieved by several experiment (~30%/√E):
  - Absorber/scintillating fibers compensated calorimeters: ZEUS (Ur), SpaCAL (Pb)
    - Resolution ultimately limited by sampling fluctuations

- **How to improve resolution**, ie:
  - Reduce contribution from sampling fluctuations
  - Elimate/Reduce effect of fluctuations in fEM
  - Elimate/Reduce effect of fluctuation in invisible energy

… **WITHOUT the inherent problems** of "standard" compensation ?
(time integration, volume, sampling fraction)

⇨ **Dual readout calorimeter !**
(one possible solution)

Dual REAdout Method (DREAM): concept

- **Estimate f_{EM} event-by-event [1]:**
  - "hardware" identification
  - comparing light from Cerenkov light and light from scintillation (dE/dx)

- Note: ideally, one wants to measure also f_n (proportional to binding energy) to remove fluctuations in invisible energy
  - Using time structure of showers

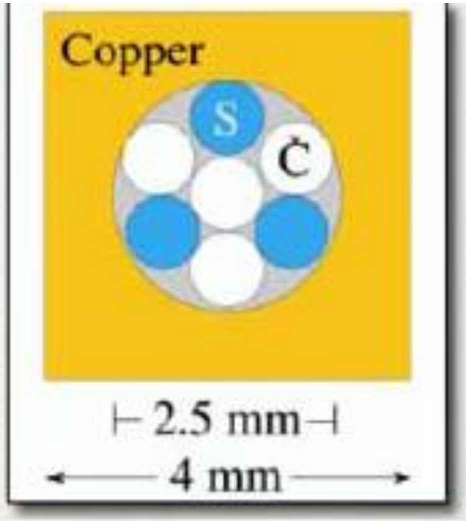
- **Why Cerenkov light ?**
  - almost exclusively produced by EM component
  - 80% of non-em energy deposited by non-relativistic particles
    (mainly spallation protons with E~few hundred of MeV => no Cerenkov light)

- Same medium read by 2 different fibers
  - **2 e/h for the same event**

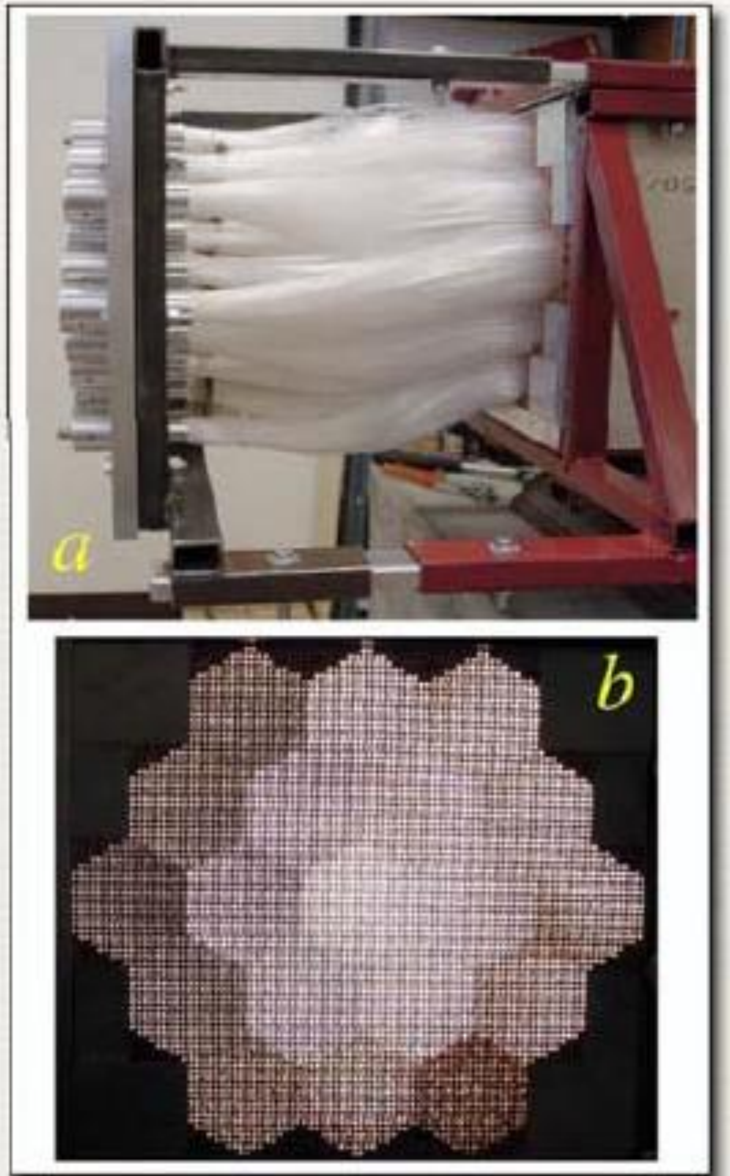
[1]. "old" idea; although not initially with 2 types of fibers. P. Mockett, "A review of the physics and technology of high-energy calorimeter devices," Proc. 11th SLAC Summer Inst. Part. Phy., July 1983, SLAC Report No. 267 (July 1983), p. 42

DREAM Prototype

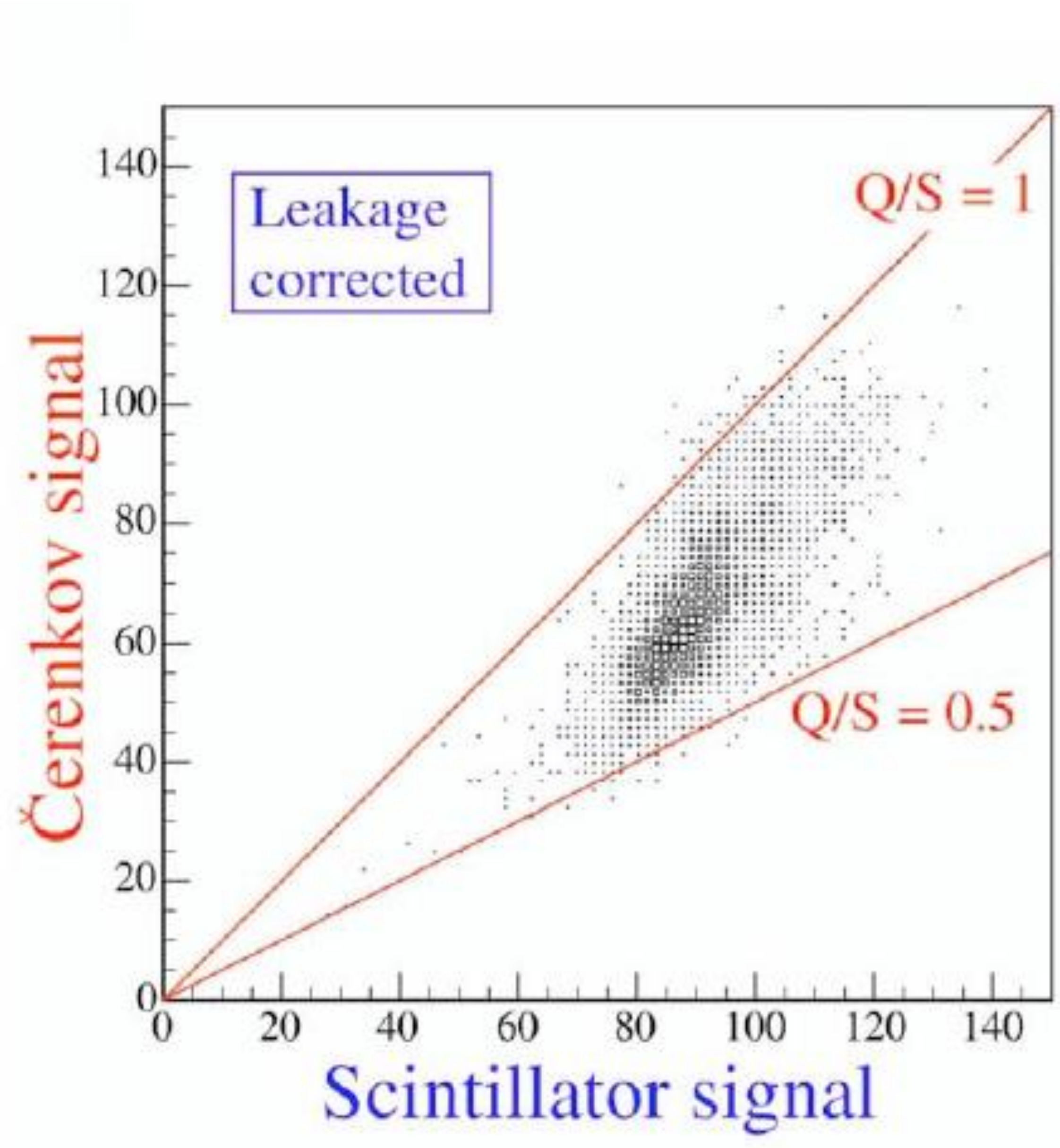
Basic structure:
4x4 mm^2 Cu rods
2.5 mm radius hole
7 fibers
3 scintillating
4 Čerenkov



DREAM prototype:
5580 rods, 35910 fibers, 2 m long (10 λ_{int})
16.2 cm effective radius (0.81 λ_{int}, 8.0 ρ_M)
1030 Kg
X_0 = 20.10 mm, ρ_M =20.35 mm
19 towers, 270 rods each
hexagonal shape, 80 mm apex to apex
Tower radius 37.10 mm (1.82 ρ_M)
Each tower read-out by 2 PMs (1 for Q and 1 for S fibers)
1 central tower + two rings



How to determine E and f_{EM} ?



$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

$$Q = E\left[f_{em} + \frac{1}{(e/h)_Q}(1 - f_{em})\right]$$

e.g. If $e/h = 1.3$ (S), 4.7 (Q)

$$\frac{Q}{S} = \frac{f_{em} + 0.21\,(1 - f_{em})}{f_{em} + 0.77\,(1 - f_{em})}$$

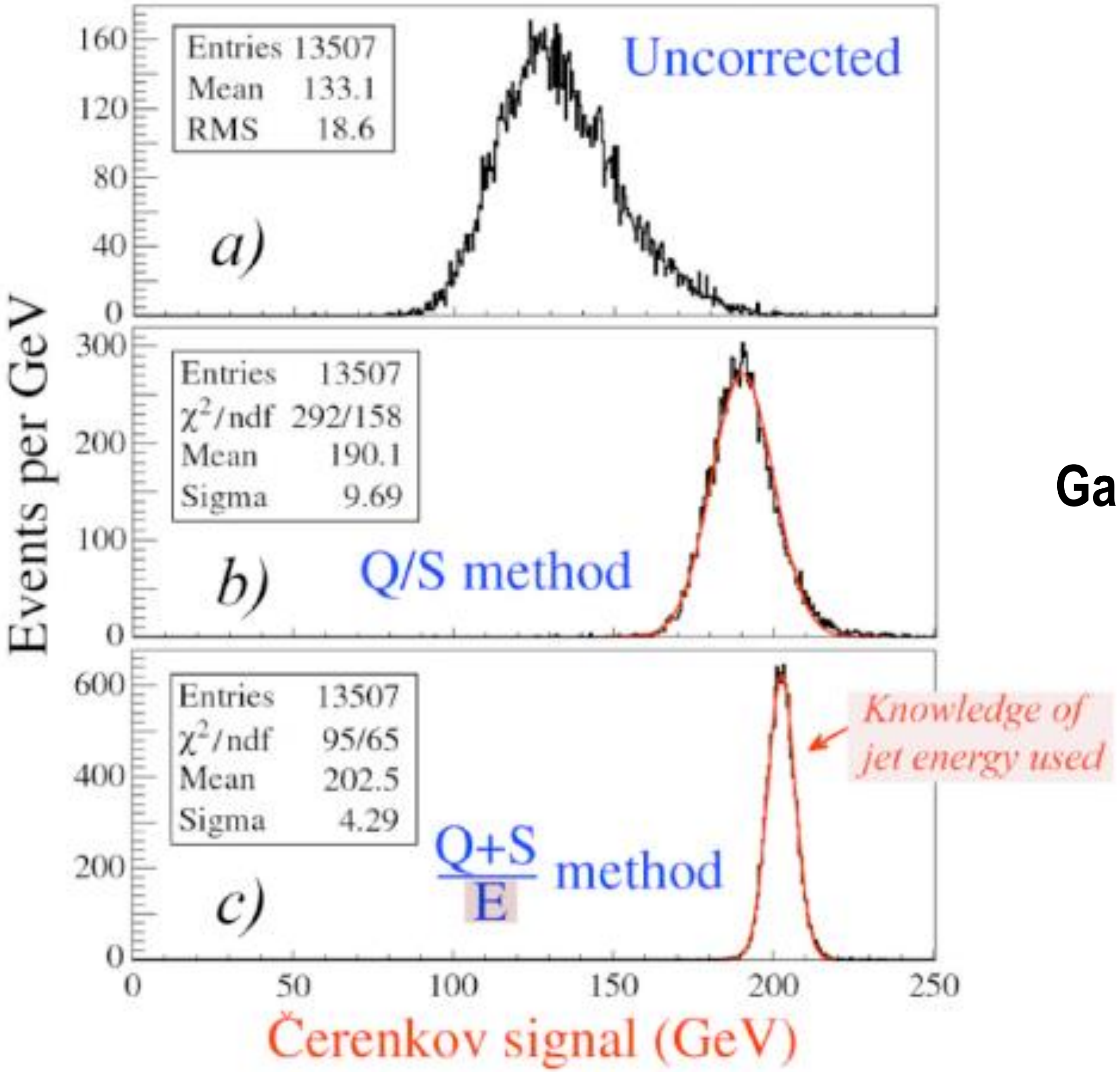
$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$

Q: Cerenkov

S: Scintillation

DREAM prototype results (1)

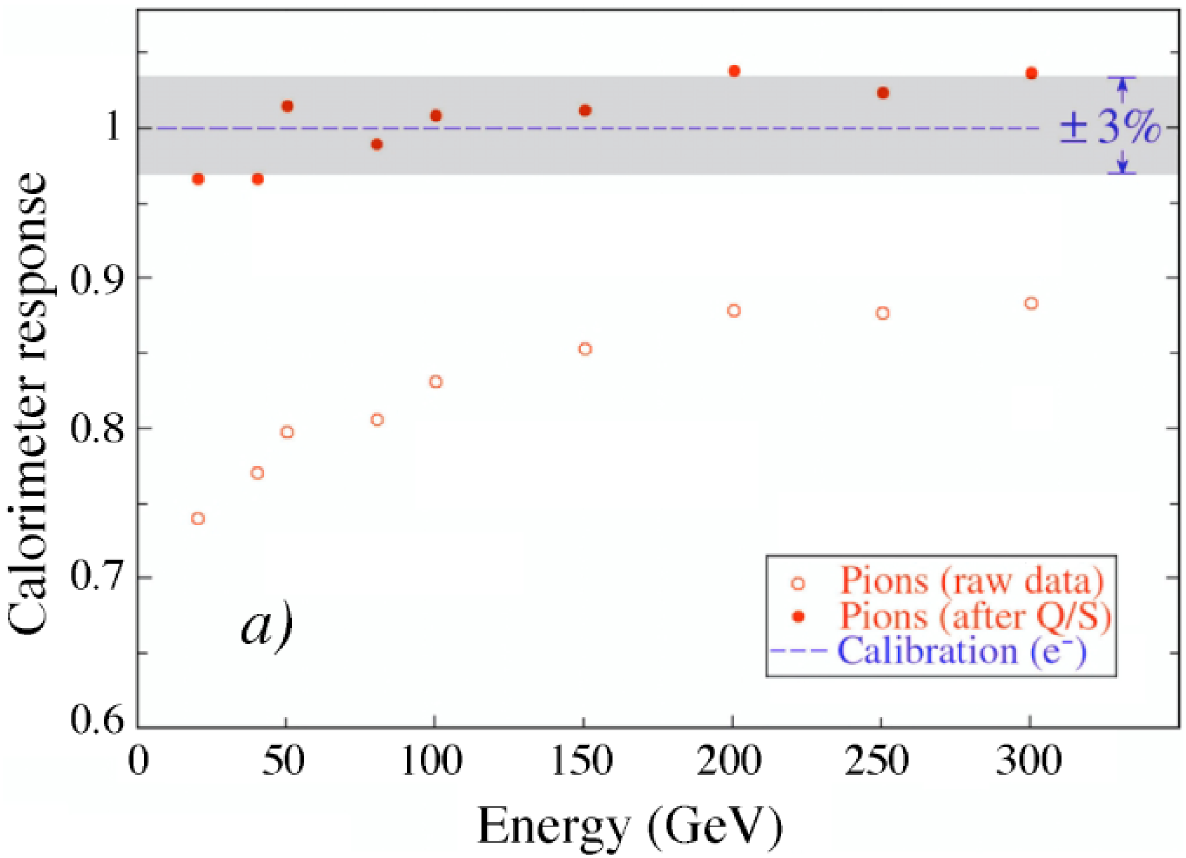


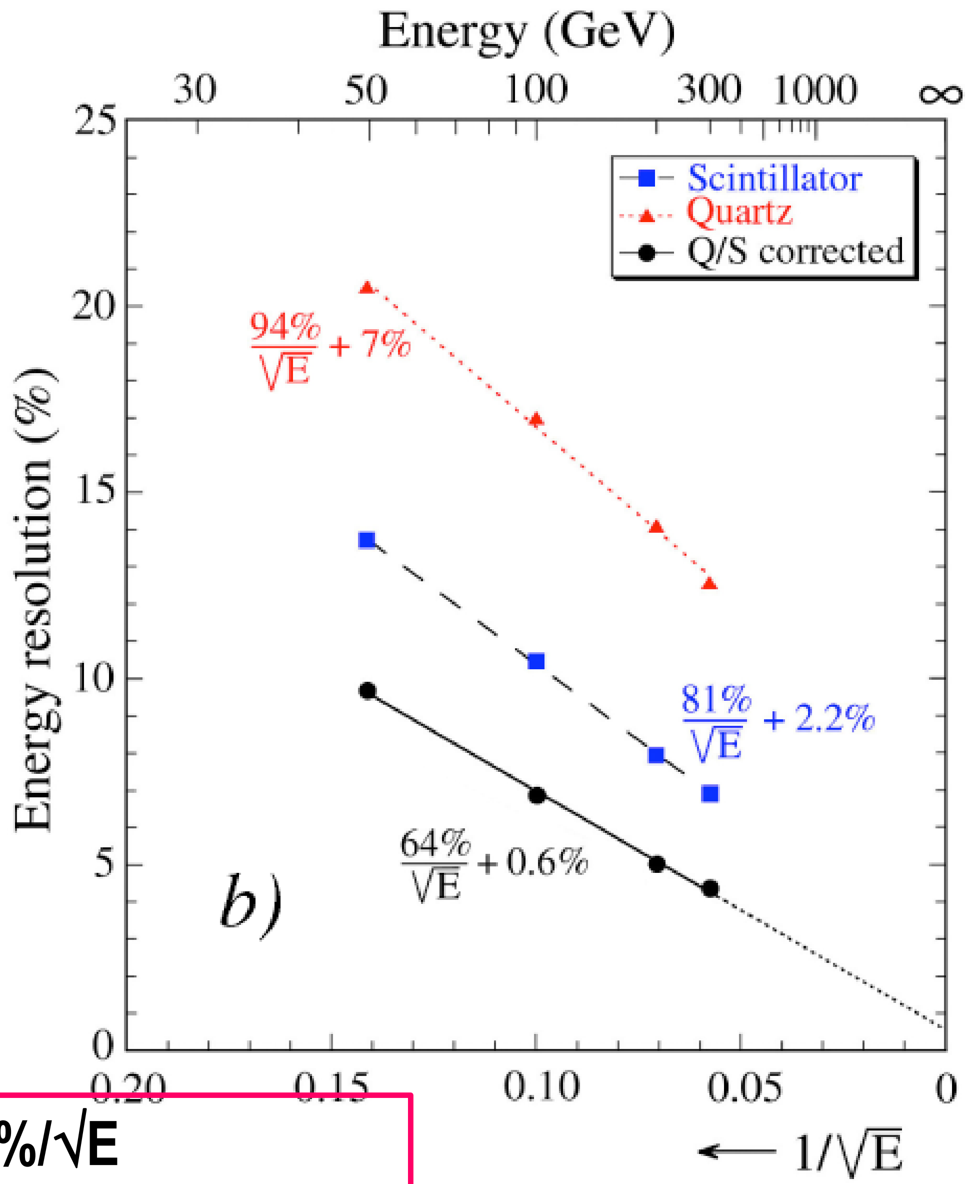
Gaussian response

Figure 2: Čerenkov signal distributions for 200 GeV multi-particle events. Shown are the raw data (*a*), and the signal distributions obtained after application of the corrections based on the measured em shower content, with (*c*) or without (*b*) using knowledge about the total "jet" energy [5].

DREAM prototype results (2)

Linearity of response !





Ultimately expect ~20%/√E
Prototype Resolution Limited by (lateral) leakage

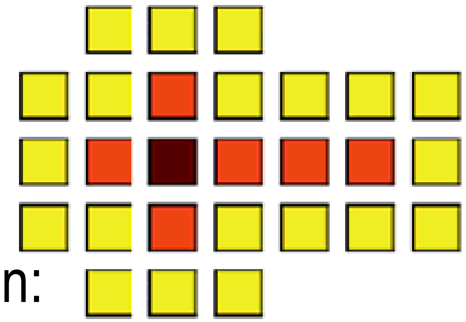
- Many other tests done (with Pb instead of Cu, with crystals, …)
- **Would need to see what it gives in a real experiment…**

Jet Resolution improvement: another path

Energy Flow, Particle Flow (1)

- **Two ways to deal with fluctuations:**
  - Adjust the hardware to response to equalize the e & h (**“hardware” compensation**)
  - Identify the various components (EM, non-EM) and weight them adequately (**“software” compensation**)

- **Software weighting** was deployed at H1 detector (LAr, SpaCal calorimeters) in the 90’s.



  - Reconstruct 3D-cluster (group of “connected” cells of calorimeter)
  - Energy of every cells is corrected by a weighting factor, depending on:
    - energy density of cell (E_{cell} / V_{cell})
      - dense EM deposits vs mip from hadronic
    - total energy of the cell cluster

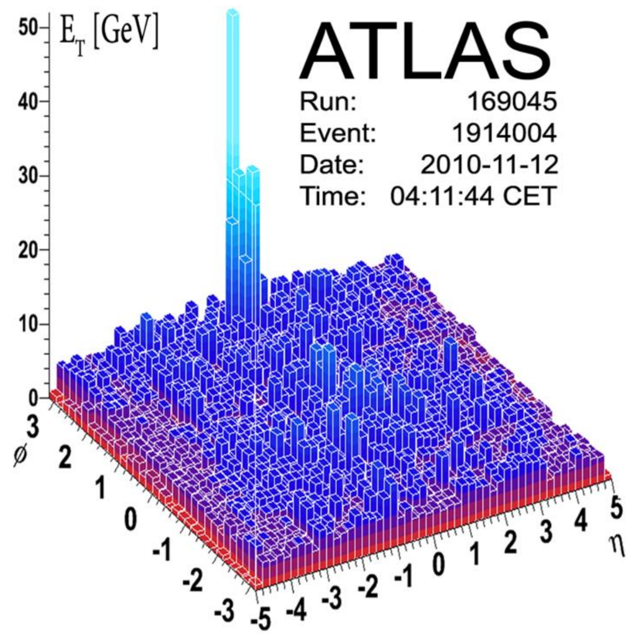
=> less tail in energy distribution, more Gaussian shape, and **15% improved resolution**

Energy Flow, Particle Flow (2)

Going a step forward…

- Typically, the jet energy fraction can be split **on average:**
  - ~65% charged hadrons
  - ~25% photons
  - ~10% neutral hadrons

- **"Default" way to reconstruct/identify particles.**
  - Neutrinos: via missing energy
  - e/γ: mainly ECAL (+tracker)
  - Charged hadrons: calorimeters (but tracking system can be used as well)
  - Important to understand if prompt or non-prompt (decay of V^0's,…)
  - Neutral hadrons: calorimeters (mainly HCAL)
  - Muons: muon station + tracker

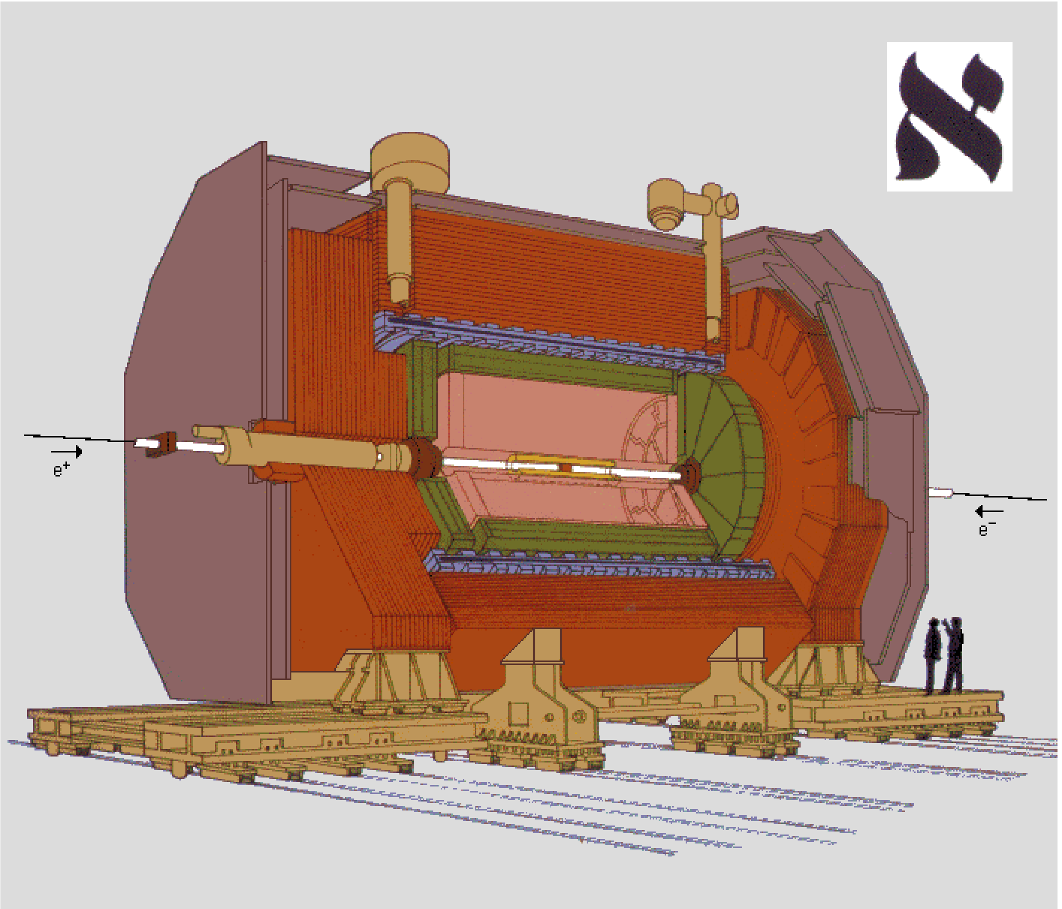


- But **no attempt to reconstruct individual particles and/or avoid double counting (tracker/calo)**
  - Jets are "clusters" of calorimeter deposits/towers/…

Can we combine measurement of tracker and calorimeter ?

Energy Flow, Particle Flow (3)

Pioneered in ALEPH at LEP (90's)



The ALEPH Detector

- Vertex Detector
- Inner Tracking Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil **1.5 T**
- Hadron Calorimeter
- Muon Chambers
- Luminosity Monitors

Tracking:

- Large number of hits O(20),
- redundancy of measurements
- Very High precision

ECAL (Pb/wire chambers):

- 3x3cm transverse segmentation
- 3 longitudinal compartments
- Multiple readout
- $\sigma \sim 20\%/\sqrt{E}$

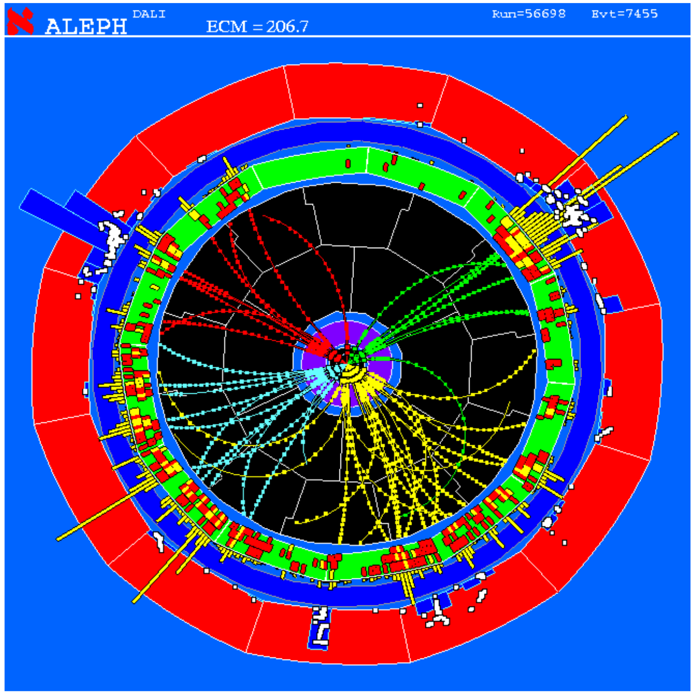
HCAL (Fe/readout tubes):

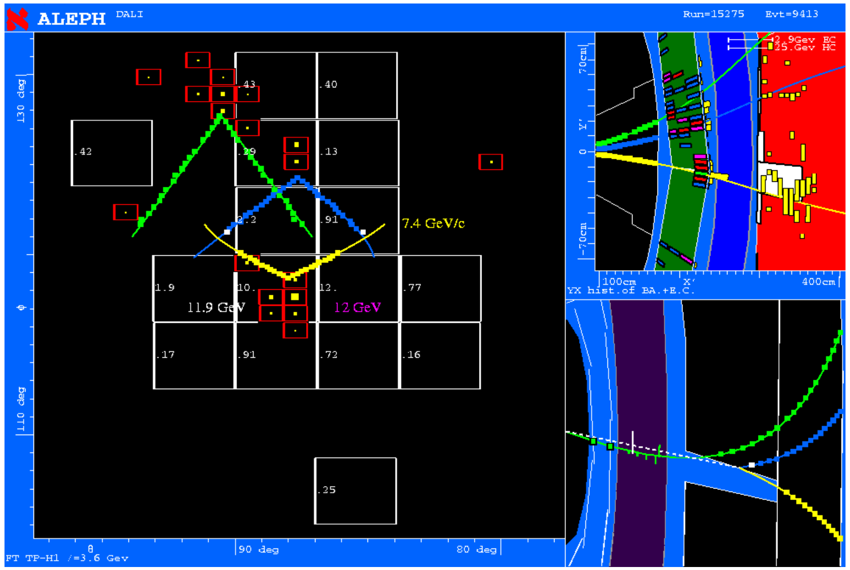
- Coarse granularity
- $\sigma \sim 100\%/\sqrt{E}$
- **AFTER the coil…**

"simple design" !

Energy Flow @ ALEPH: description

WW→qqqq





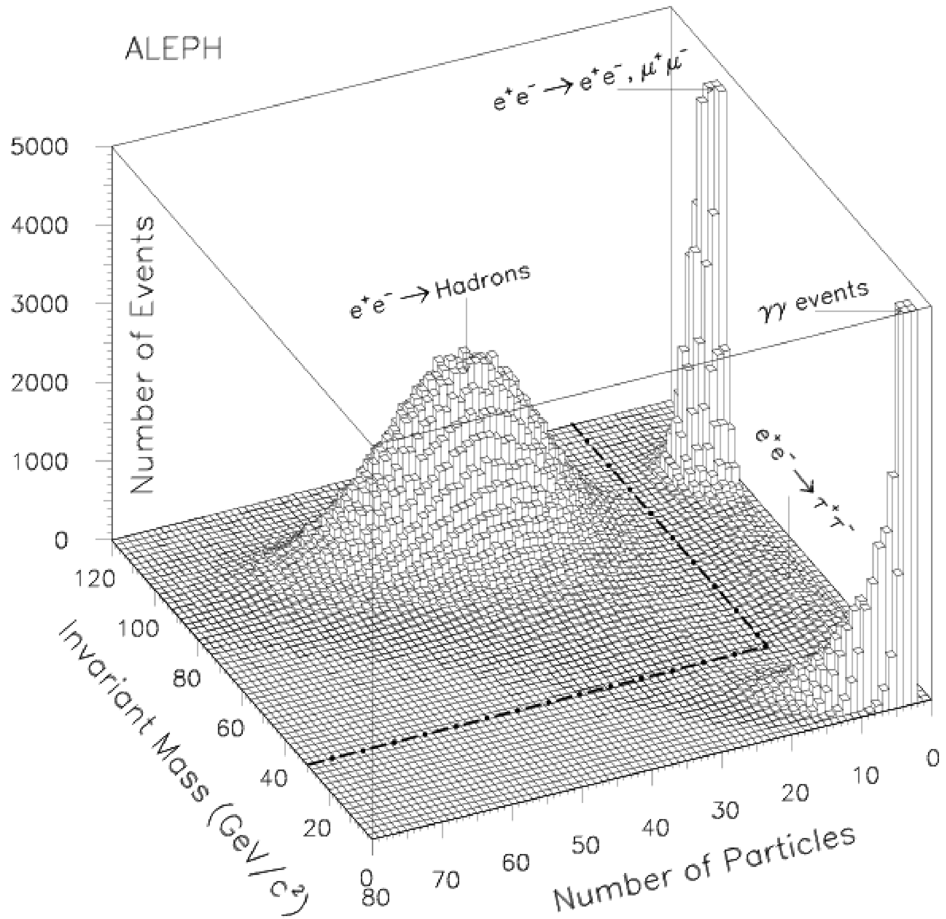
(simplified) Overview of the algorithm

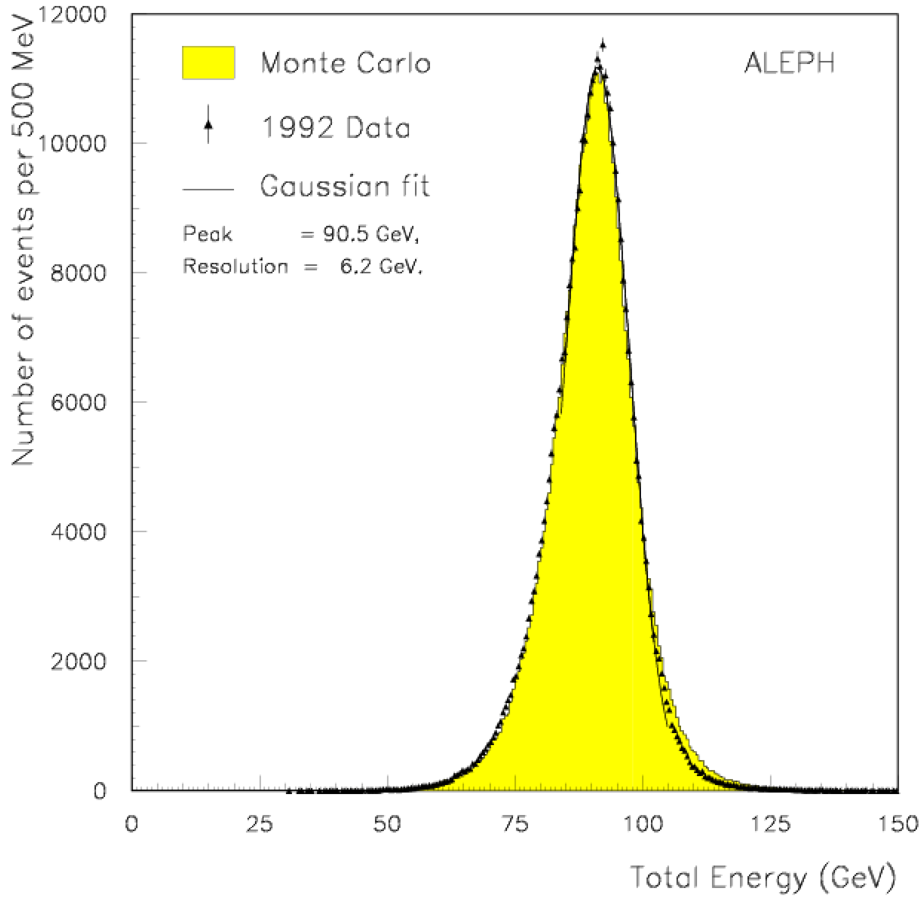
- Reconstruct charged tracks and clusters in calorimeters
  - Including cleaning (noisy channels, …)
- Extrapolate tracks to calorimeters and form “calo objects”

- For each calo object:
  - for identified electrons, muons, γ, $\pi 0$, remove energy from calorimeters
  - Only charged hadrons (mostly pions) and neutral hadrons should remain
  - Neutral are built as clusters not linked to tracks or with incompatible E/p

"Energy Flow" in ALEPH: (some) results

e+e- → Z→qq





6 GeV resolution
vs 13 GeV for calorimeter only

- Also: better angular resolution, b-tagger improved by a factor 2…
- **BUT**: ultimately limited by HCAL resolution… and loss of information due to interaction in the coil before reaching the HCAL.

Beyond Calorimetry: The Particle Flow paradigm

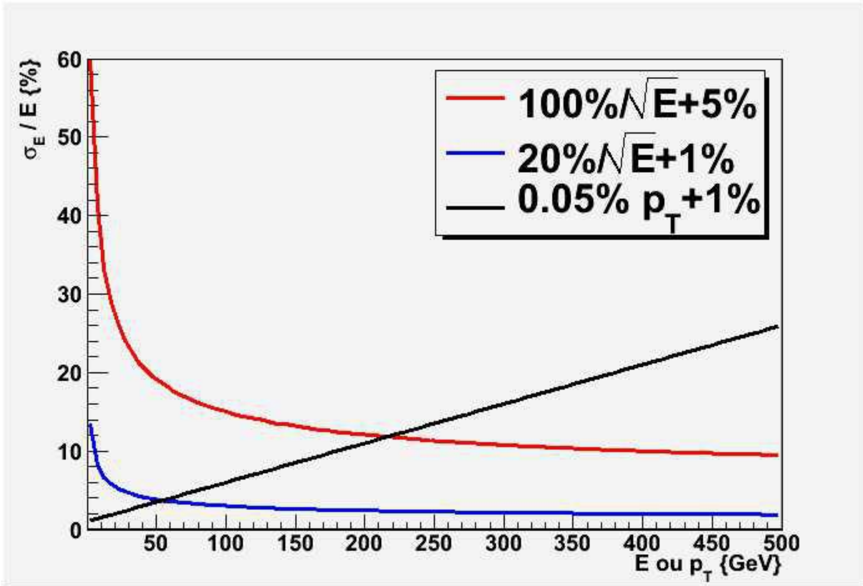
Particle Flow:

- Reconstruct and identify every stable particle in the event
  - Combining Optimally all information from all sub-detectors

- Charged particles measured by tracker (~perfect)
- Photons by ECAL ($\sigma E/E$ ~10-20%)
- Neutral hadrons (ONLY) by HCAL ($\sigma E/E$ ~50-100%)

  ⇒ **Much improved resolution on jets wrt calorimeter measurement only**

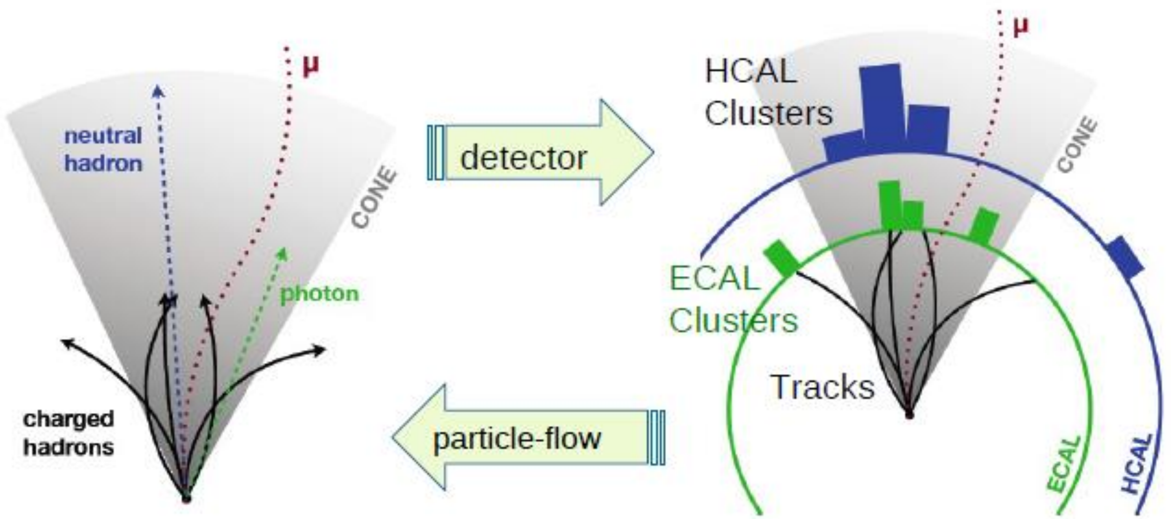
  (vs ~70% of particles measured with HCAL in traditional approach)



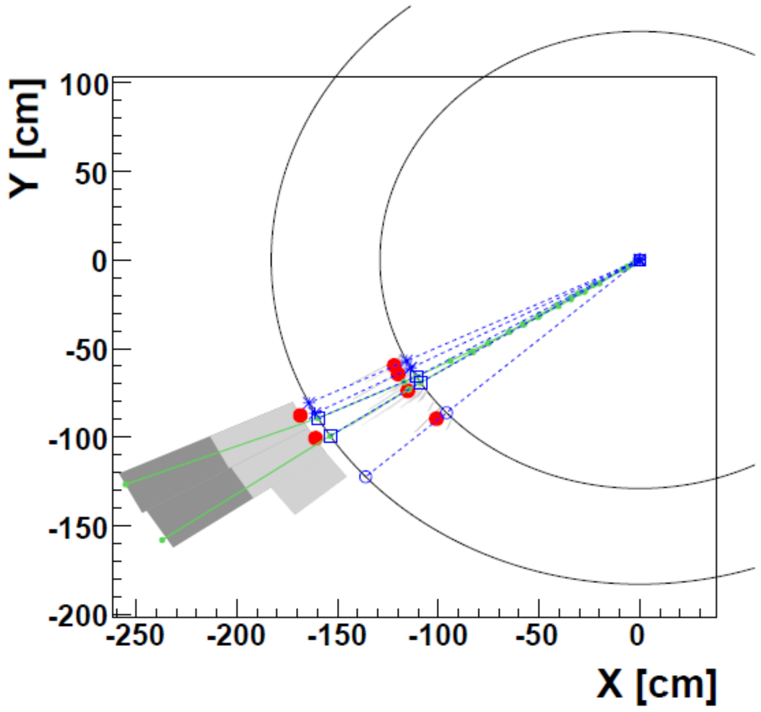
- **Not only:**
  - Aim at having a "Global Event Description"
  - Use adapted calibration for each object
  - Natural mitigation of pile-up (at hadron colliders)
  - Improved angular resolution
  - Access to sub-structure of shower
  - etc….

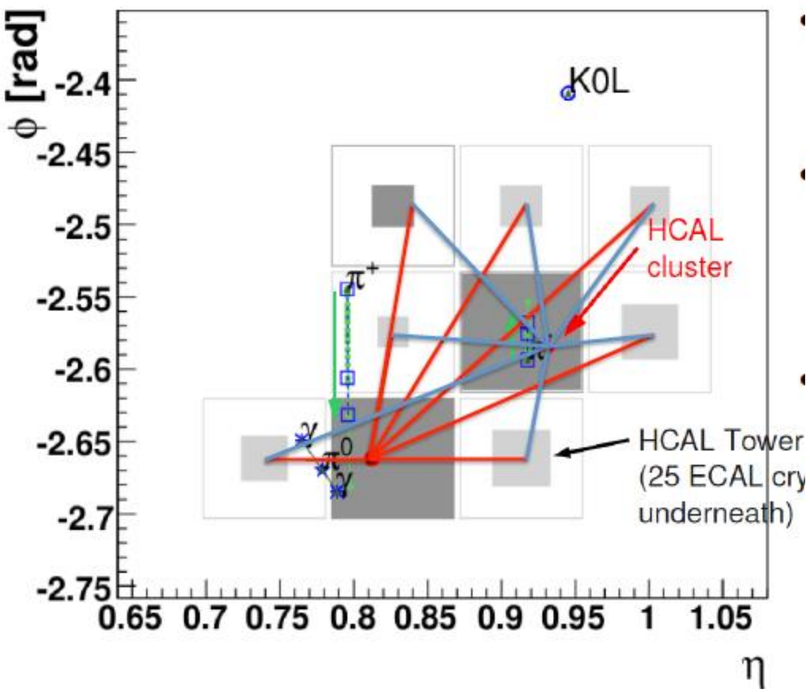
Needed ingredients for a good Particle Flow

- **Good separation of charged and neutrals**
  - high field integral (BxR), "effective granularity"
  - Small granularity (to minimize overlapping showers)
- **"No" material before the calorimeters**
  - "light" tracker, calorimeters inside the coil
- **Small Moliere Radius**
  - to minimize shower overlap
- **Efficient Tracking**



Particle Flow @ LHC (CMS)



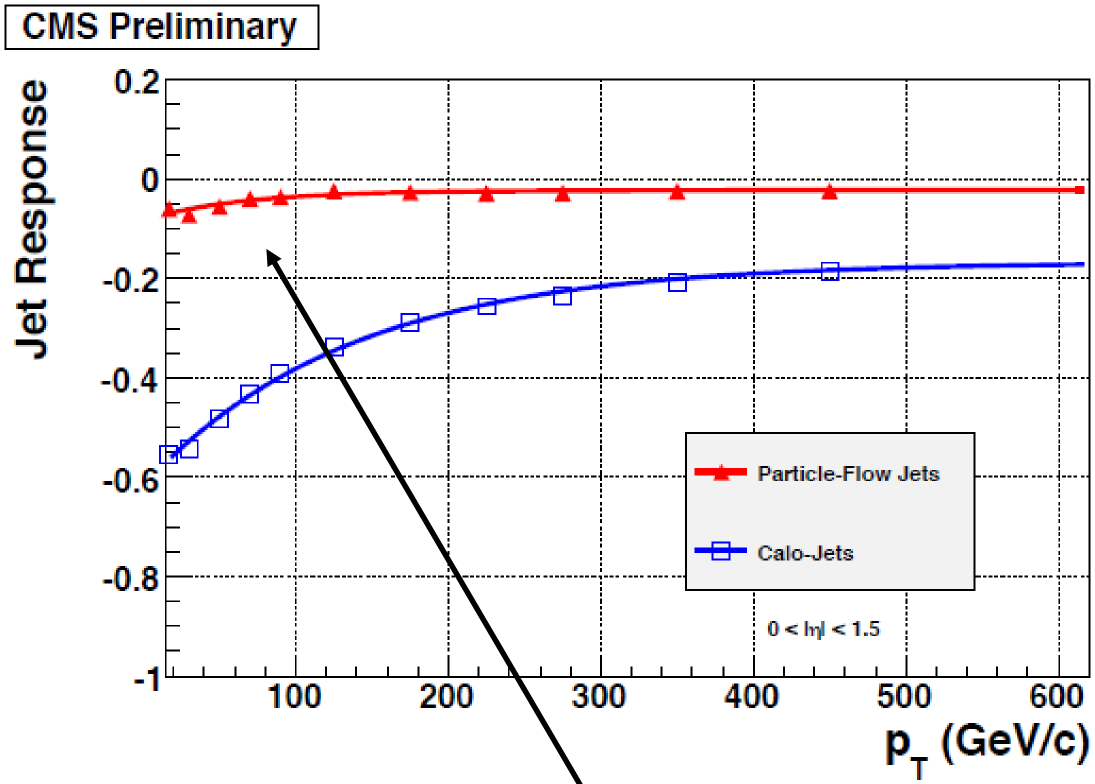


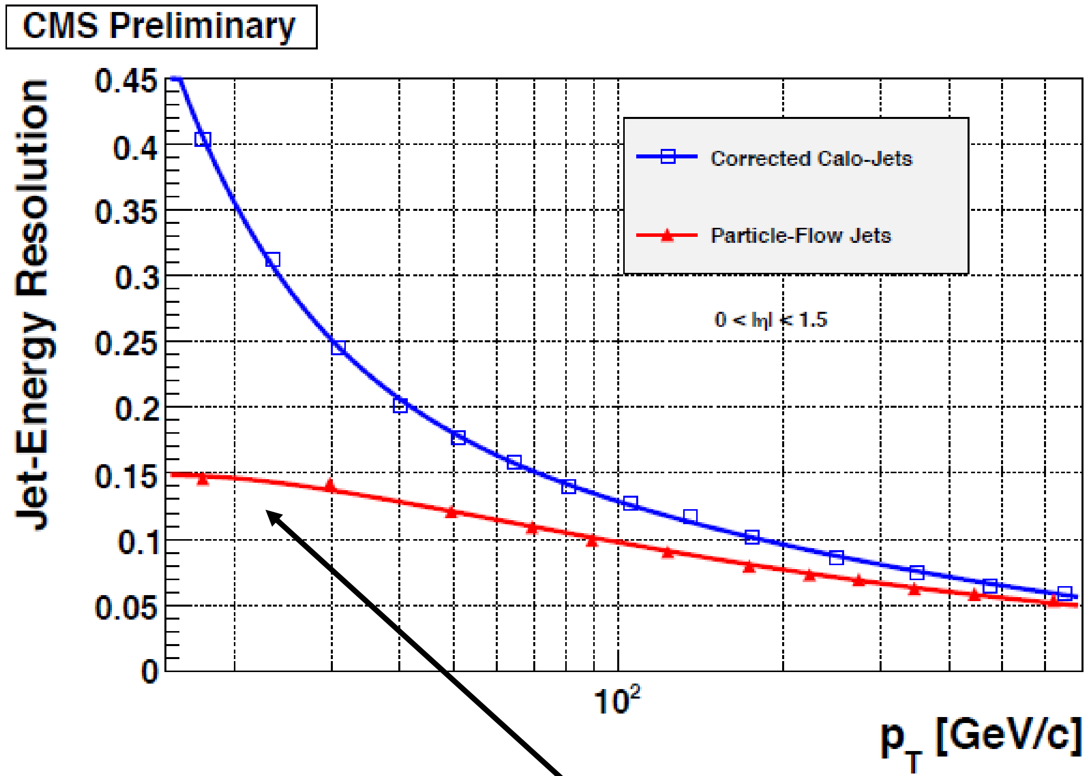
- **CMS design meets several of the criteria for a good PF**
  - **Large Field Integral:** BxR = 4.9 T.m
    - CMS: B=3.8 T, Ecal Radius R = 1.29m
    - ALEPH: 1.5 x 1.8 = 2.7 T.m
  - **ECAL** with excellent resolution (σ_E/E ~10-3%), granularity and small R_M (2.2 cm).
    - poor HCAL resolution (as ALEPH)
  - **Excellent tracking** (high granularity, σ_{pT}/pT~1% pT)

- **BUT, considerable challenges!**
  - Up to 2 X0 of tracker material in front of ECAL
    - Nuclear & EM interactions in the tracker…
  - pp collisions, pile-up and (very) high density of particles

First studies started in ~2004

PFLow @ CMS: Results

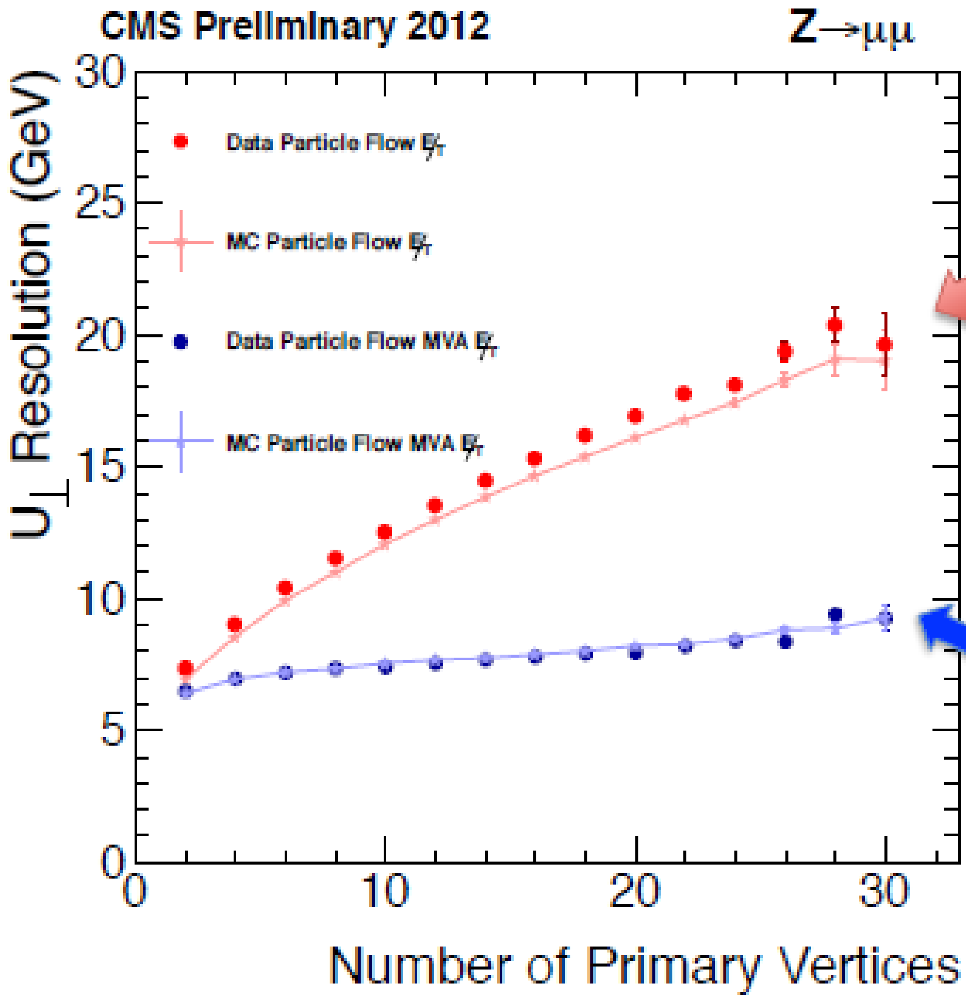




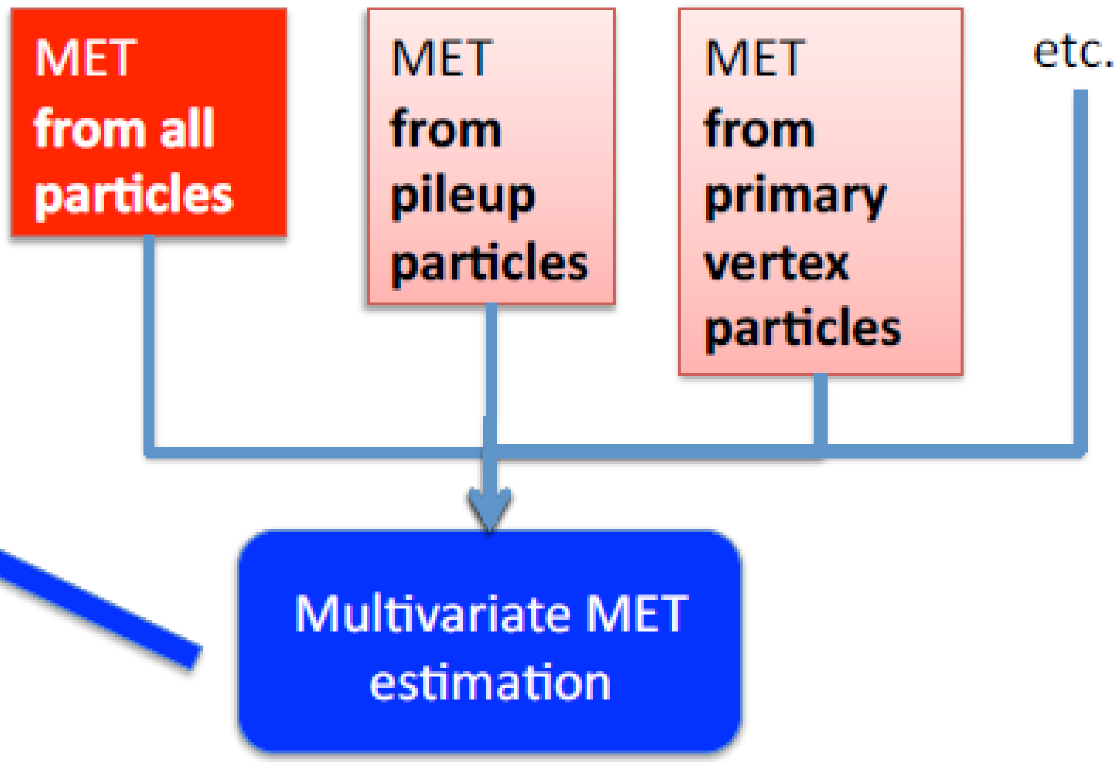
Jet Response close to 1
BEFORE any jet correction
(use of calibrated particles!)

Large improvement in Jet
Resolution, especially at low pT

PFLow @ CMS: Results



several kinds of particle-flow MET:



Almost insensitive to pile-up

PFLow @ CMS: Results

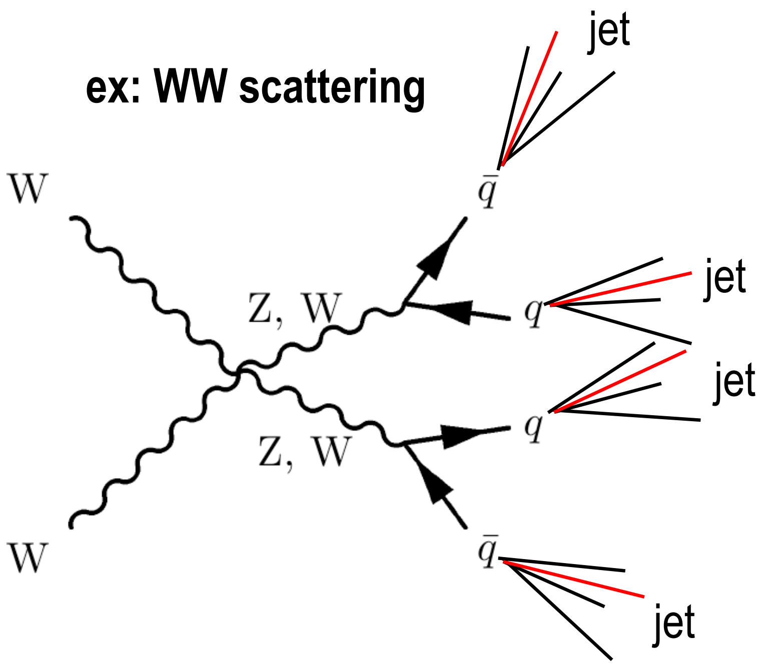
Not only for jets…

- **Jets**
  - energy resolution / 2
  - angular resolution / 3
  - Flavour dependence of response / 3
  - Systematic error on JES / 2
  - « electron in jet » b tagging
  - quark-gluon jet tagging
- **MET:**
  - resolution / 3
  - smallest tails
- **τ**
  - jet fake rate / 3 @ same eff.
  - energy resolution / 4
- **Electrons**
  - down to pT = 3 GeV
  - in jets
- **μ**
  - 4% more efficient ID @ same bgd rate
  - better momentum assignment at high pT
- **e, μ, τ, γ isolation**
  - pile-up control
- **Physics analyses**
  - Better trigger for jets, MET, taus (PF@HLT)
  - e.g:
    - FSR photon recovery in H→ZZ
    - embedding in H→ττ
    - jet substructure

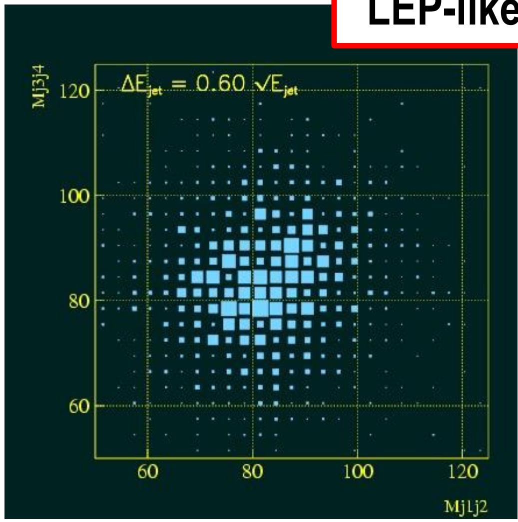
The ILC case

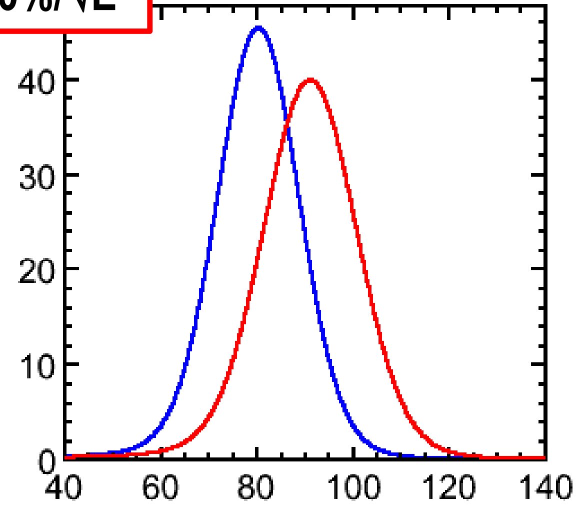
- **Study Higgs, Unitarity, top at e+e- linear colliders** (ILC, CLIC, …)
  - Heavily involves W, Z and H in hadronic modes (high BR)

ex: WW scattering



LEP-like, 60%/√E

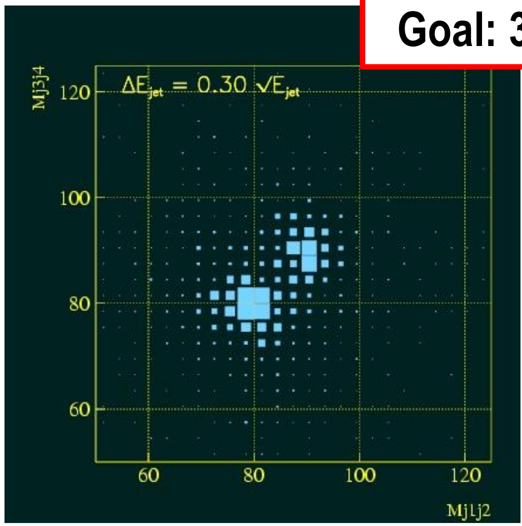


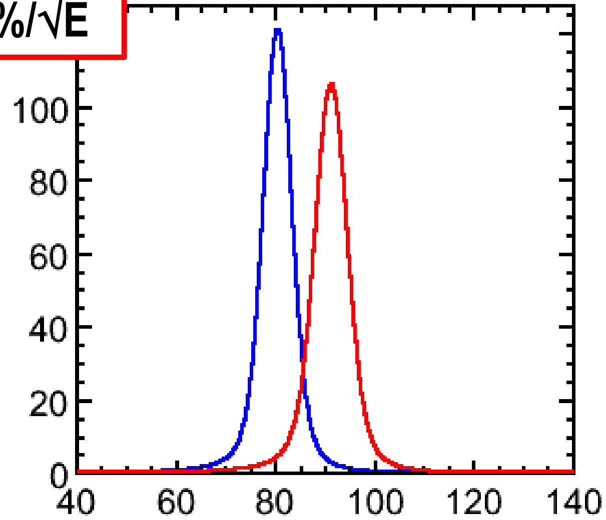


- **Challenge: W/Z separation**
  - Hadronic decay of W/Z
  - Need to separate W&Z
    ie, measure the mass of di-jet pairs:

ΔM(W,Z)~10 GeV

Goal: 30%/√E





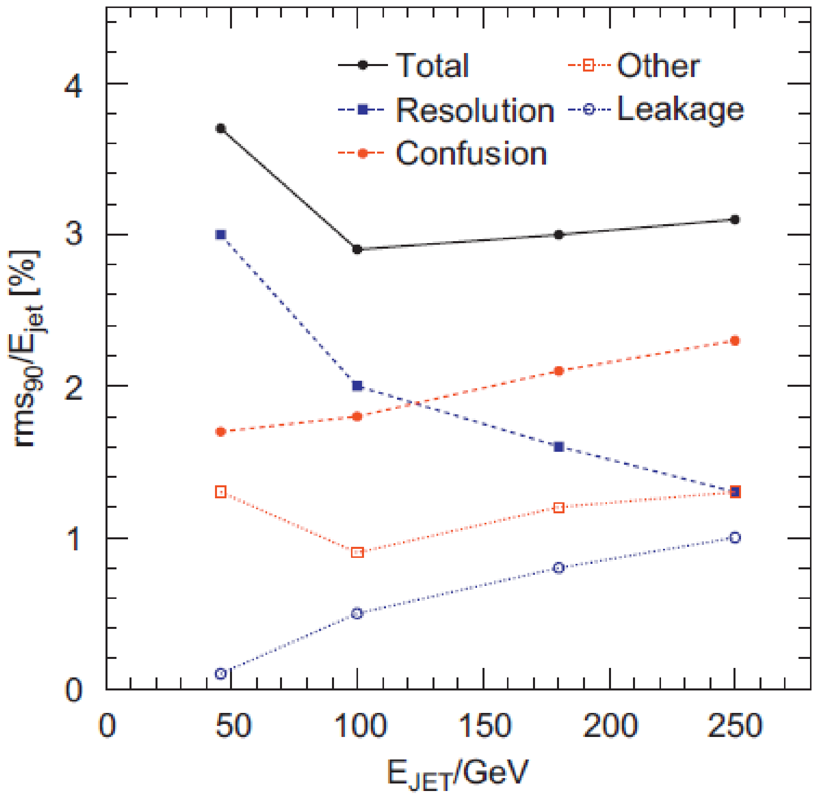
=> σE/E~3%

A word on resolution…

➢ Forgetting the correlations, the jet resolution can be written as:

$$\sigma^2_{jet} = \sigma^2_{h\pm} + \sigma^2_{\gamma} + \sigma^2_{h\circ} + \sigma^2_{confusion} + \sigma^2_{threshold} + \sigma^2_{losses}$$

$\sigma_{confusion}$: mixing between neutral and hadron deposited energy
$\sigma_{threshold}$: threshold for each species (integrate fluctuations at low energy of jet fragmentation)
σ_{losses}: losses due to imperfect reconstruction



➢ Studies show the **confusion term play a major role** !

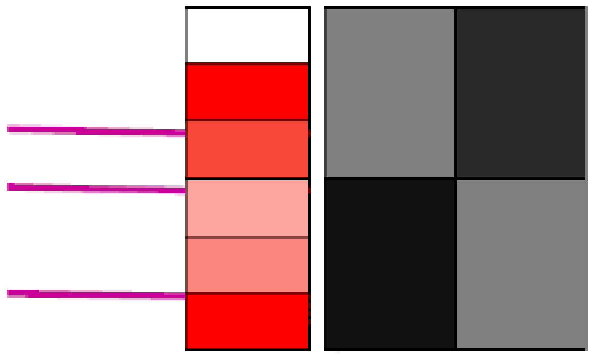
➢ Towards ultimate Pflow performance:
- **focus more on separating showers (ie, granularity)** than single particle resolution

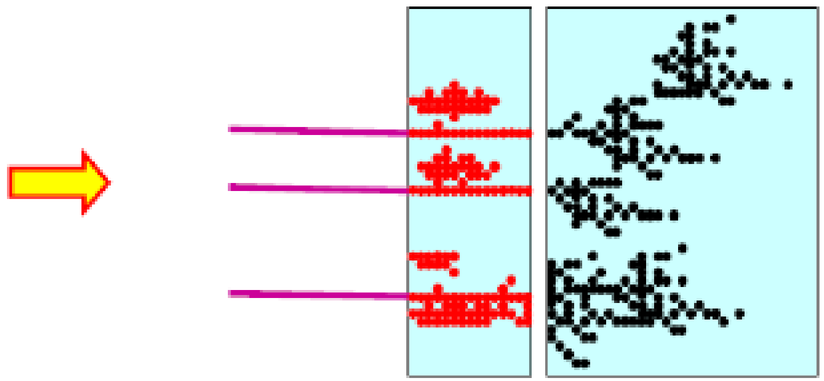
"Particle Flow Calorimeters"

Another step beyond: Design the detector for PFLOW

Hardware:

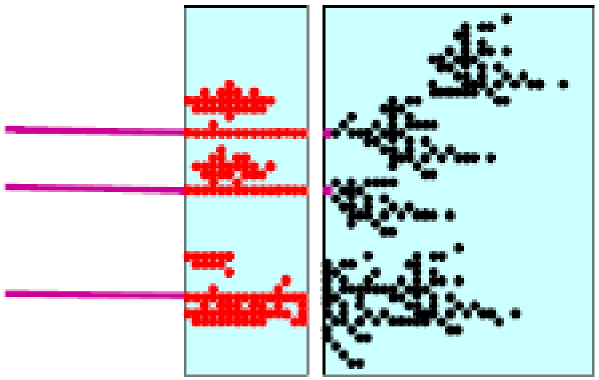
- ★ Need to be able to resolve energy deposits from different particles
  ➡ Highly granular detectors (as studied in CALICE)

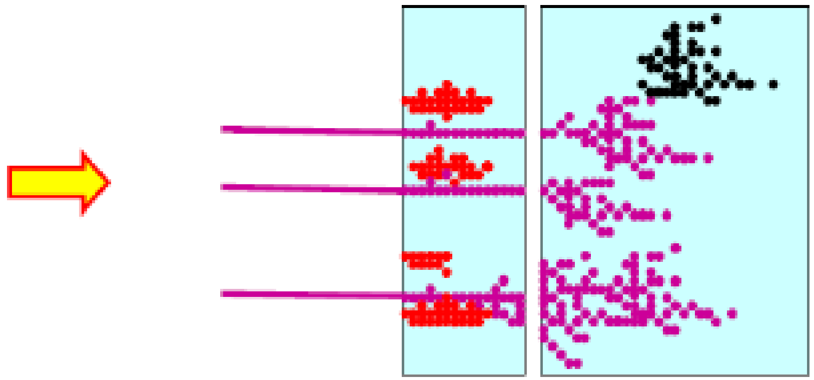




Software:

- ★ Need to be able to identify energy deposits from each individual particle !
  ➡ Sophisticated reconstruction software



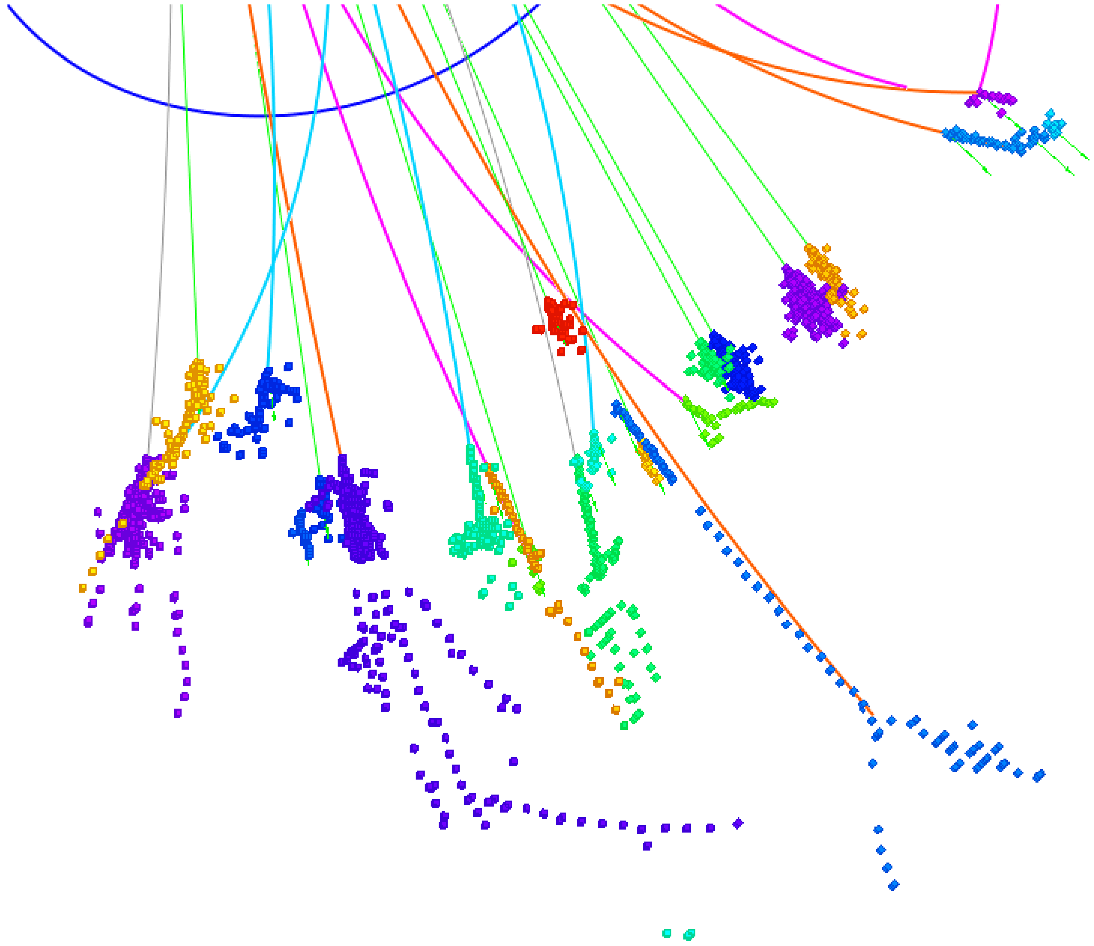


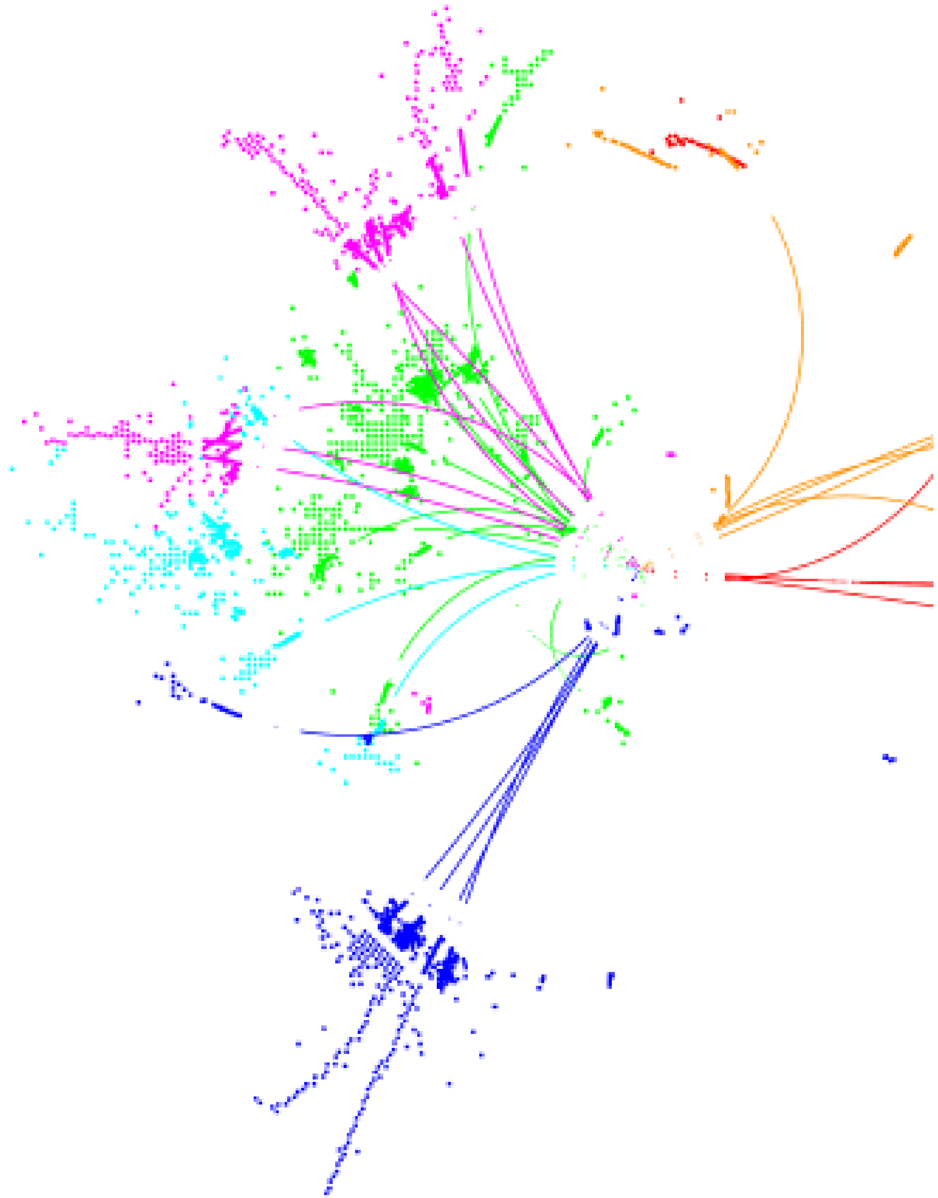
★ Particle Flow Calorimetry = HARDWARE + SOFTWARE

Initially thought for TESLA in 2000's, then ILC.

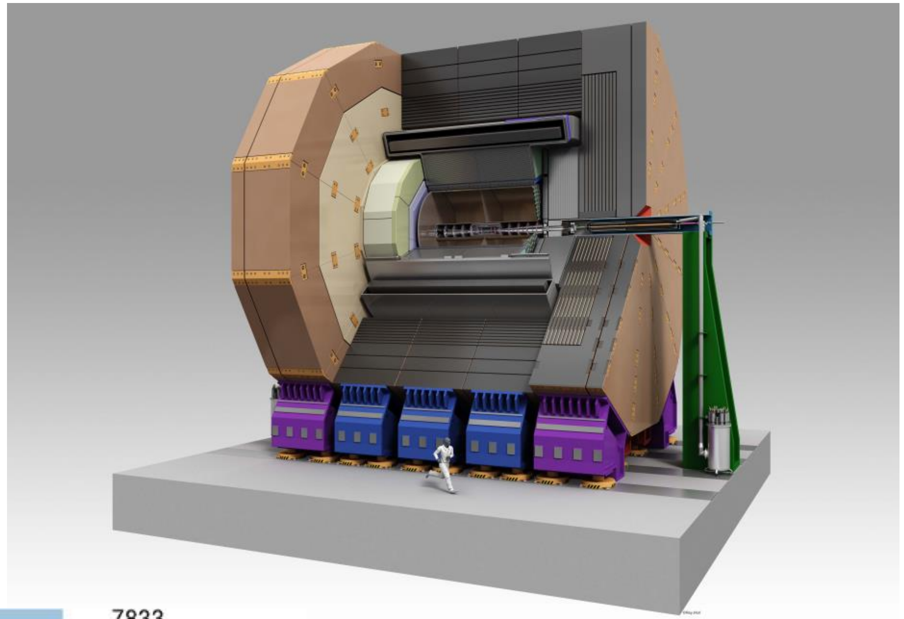
"Particle Flow Calorimeters"… or "Imaging Calorimeters" !

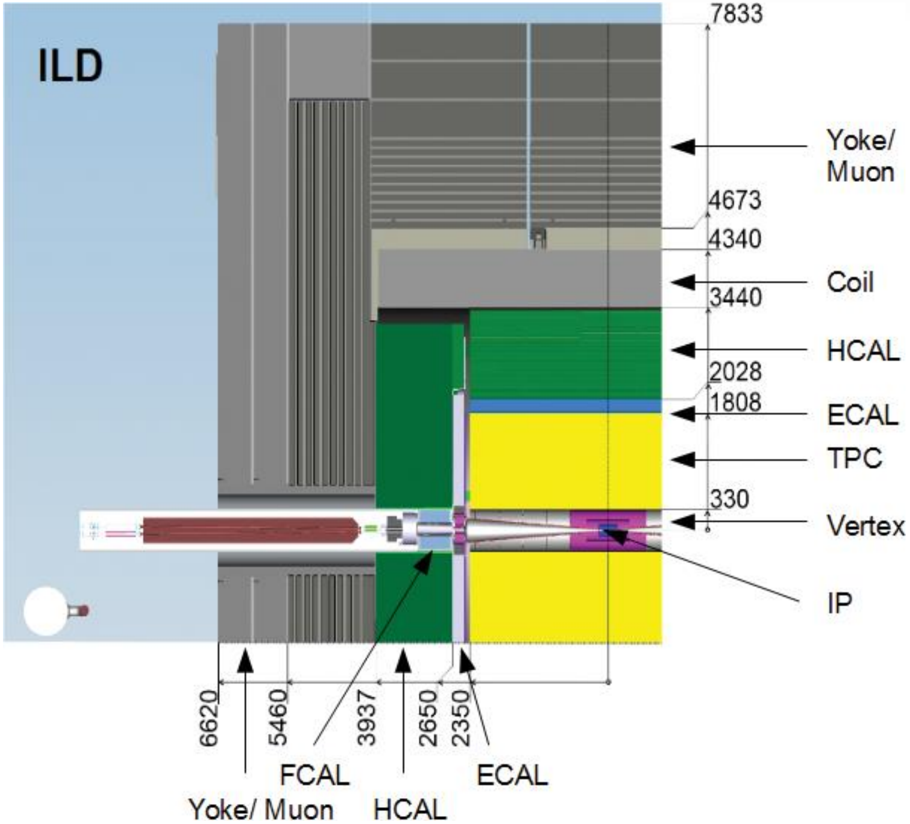
Another step beyond: Design the detector for PFLOW





Detectors for ILC

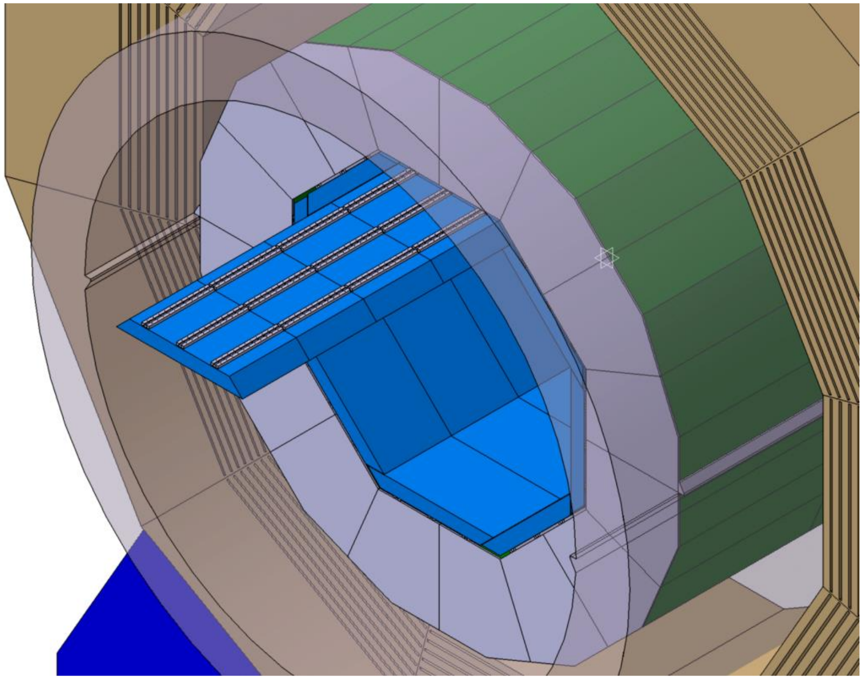


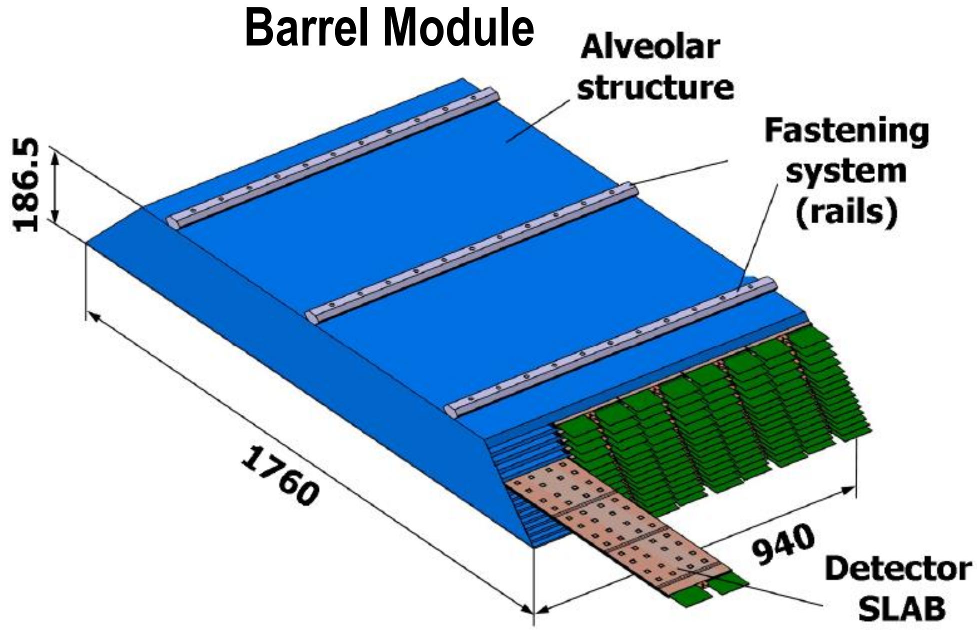


- **Lots of R&D since 15 years. TDR in 2013.**
- Lots of possible options. Ex:
  - 3D-tracking:
    - High Precision vertex (Si) detector + TPC
  - High Granular Calorimeters
    - ECAL with 30 longitudinal samples
    - HCAL (48 long. Samples)
  - B-field: 3.5 T
  - Iron yoke instrumented with Muons detection system (Gas or scintillators)

Si / W high-granularity ECAL (1)

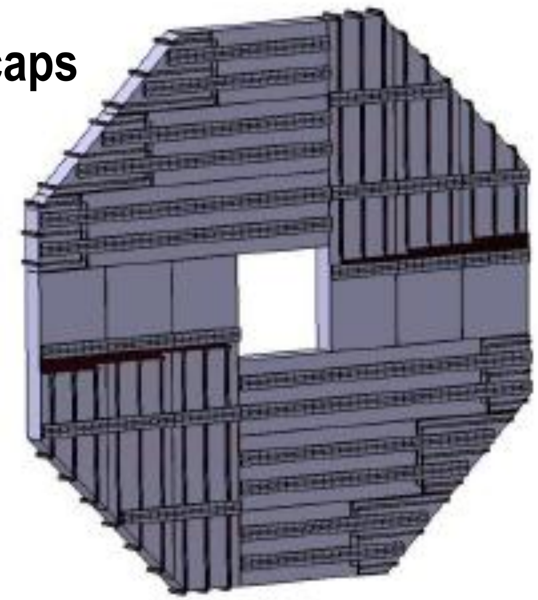
- One possible option studied inside the CALICE collaboration: Si/W sampling calorimeter



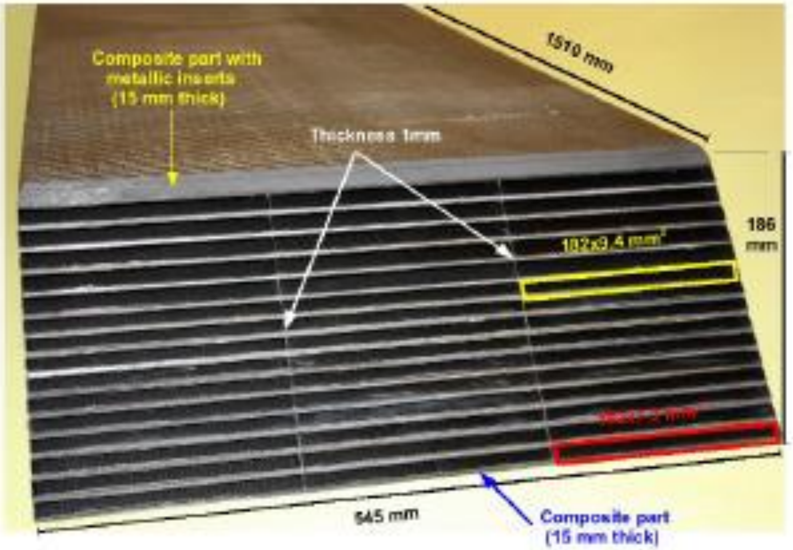


- R~1.8m
- **W absorber**
  - Ensure compactness (~20 cm thickness),
  - small RM
- **Si as active medium**
  - for 30 layers: ~2600 m² of Si,
  - Large S/N
- **Extreme high granularity**
  - 10^8 channels (vs 10^5 at LHC !!!)

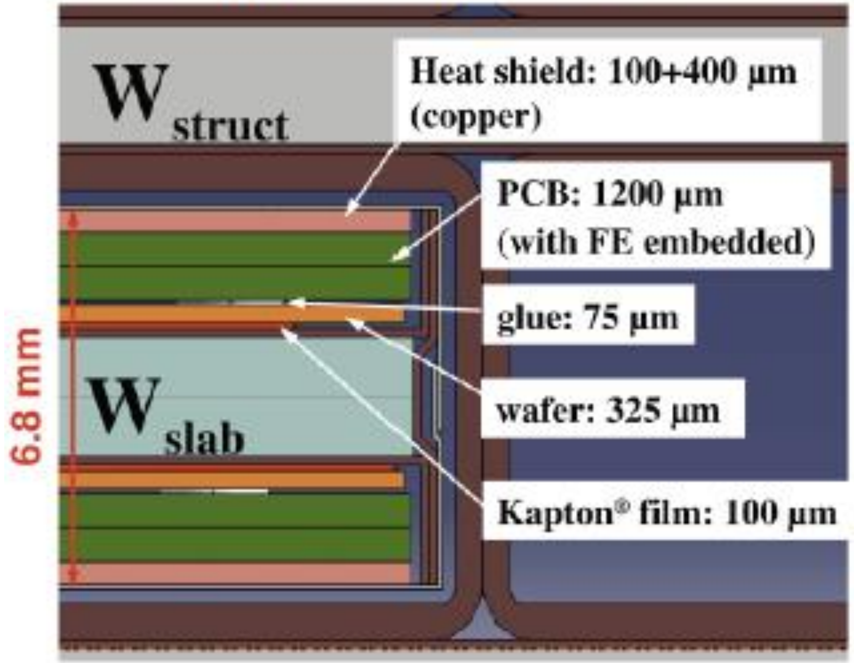
Endcaps



Si / W high-granularity ECAL (2)



Prototype: 3/5 of one module.

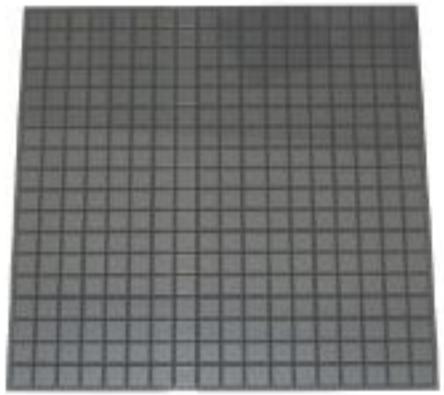


Carbon-fibre support contains every second W plate.

2 PCBs of embedded front end electronics with glued 16x16 sensors are on both sides of other W plates.

1 barrel module = 5 x 15 slabs
1 slab = 8. . . 13 x Active Sensor Units,
1 ASU = 4 x Si sensors = 1024 chan.

HV, LV, signal cables, water cooling run in 3 cm ECAL - HCAL gap, exit between barrel - endcap.



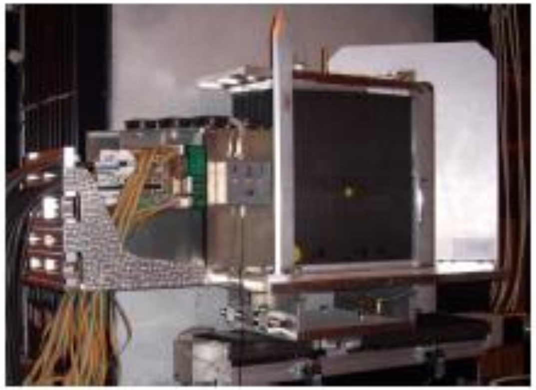
Hamamatsu Si sensor

Si/W prototypes

Physics Prototype

Proof of principle

2003 - 2011



JINST 3, 2008

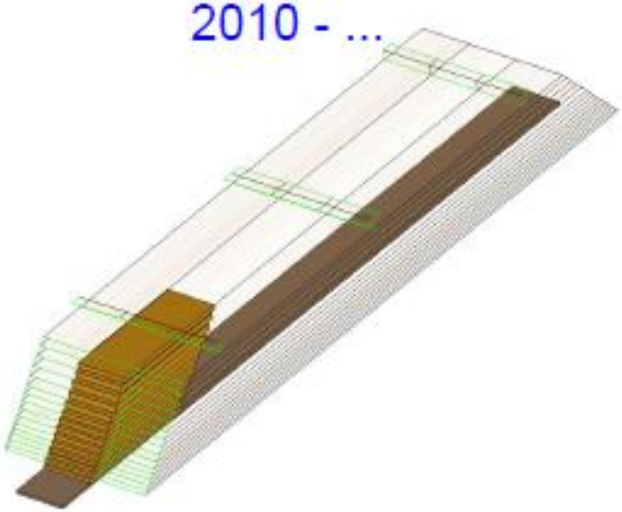
Number of channels : 9720

Weight : ~ 200 Kg

Technological Prototype

Engineering challenges

2010 - ...

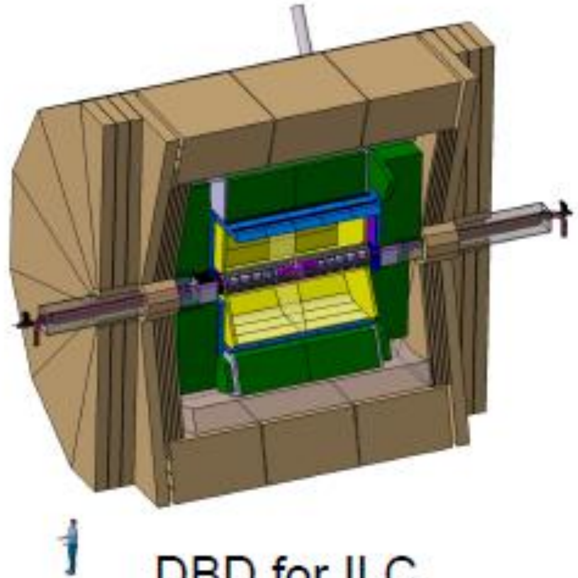


TDR EUDET-Report-2009-01

Number of channels : 45360

Weight : ~ 700 Kg

LC detector



DBD for ILC
CDR for CLIC

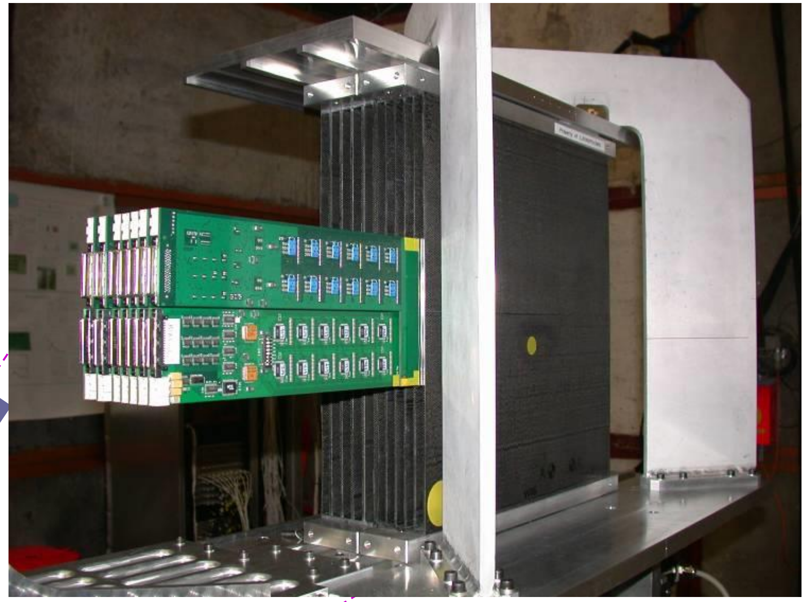
ECAL :

Channels : ~ 100 10^6

Total Weight : ~ 130 t

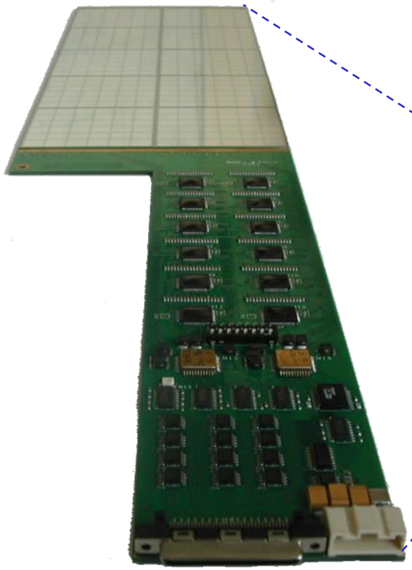
Si/W: physics prototype

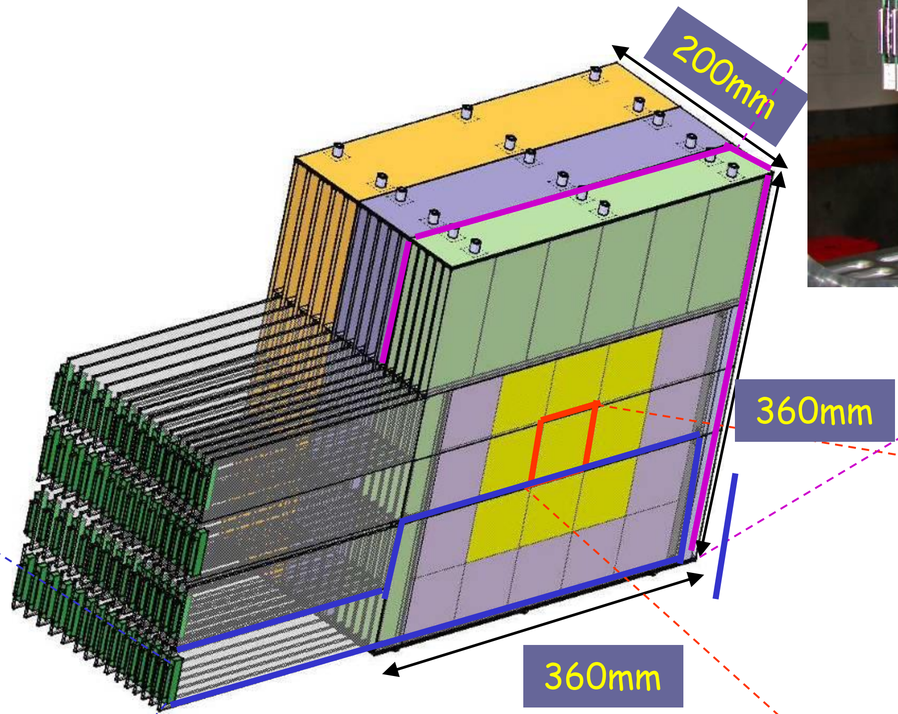
- 30 layers of variable thickness Tungsten
- Active silicon layers interleaved
- Front end chip and readout on PCB board
- Analog signals sent to DAQ
- 10,000 channels

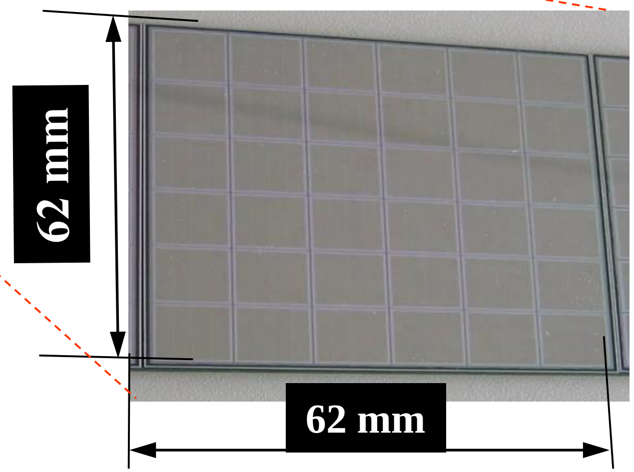


© M. Anduze

- PCB contains VFE electronics
- 14 layers, 2.1mm thick
- Analogue signals sent to DAQ



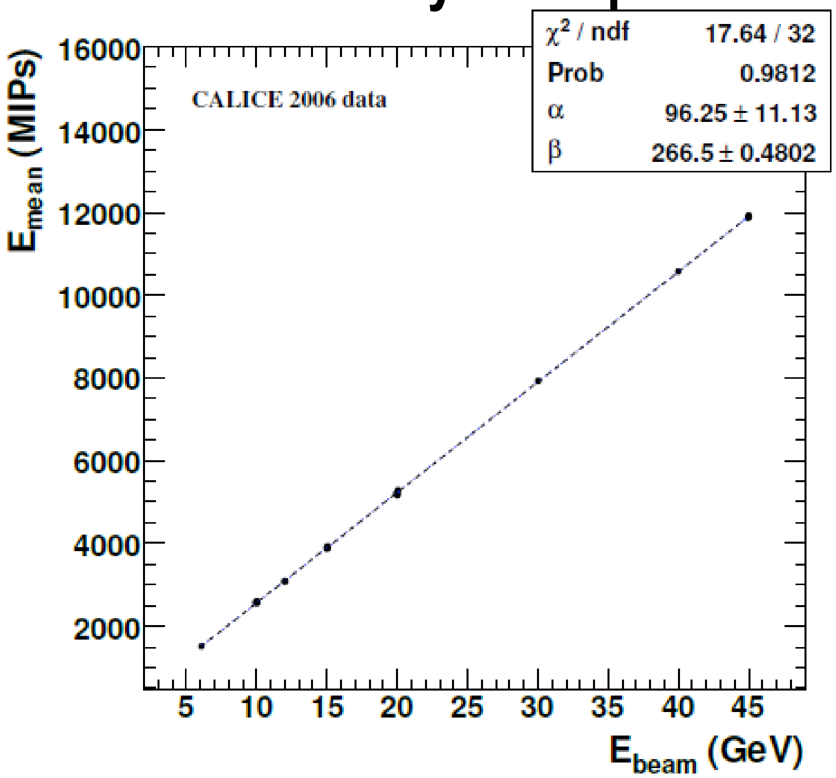




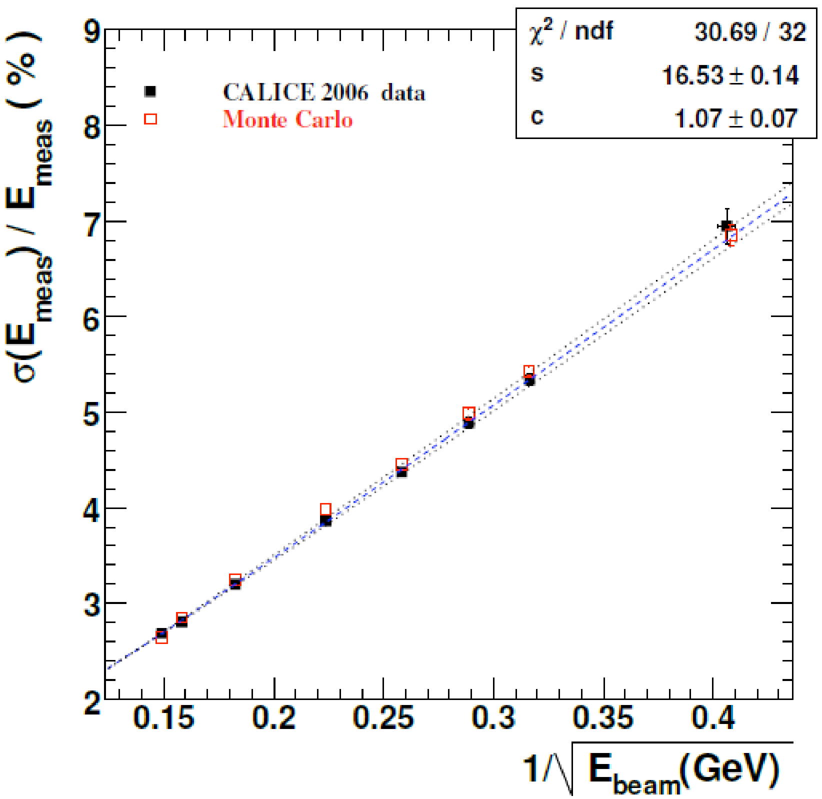
- 6x6 $1x1cm^2$ silicon pads
- Connected to PCB with conductive glue

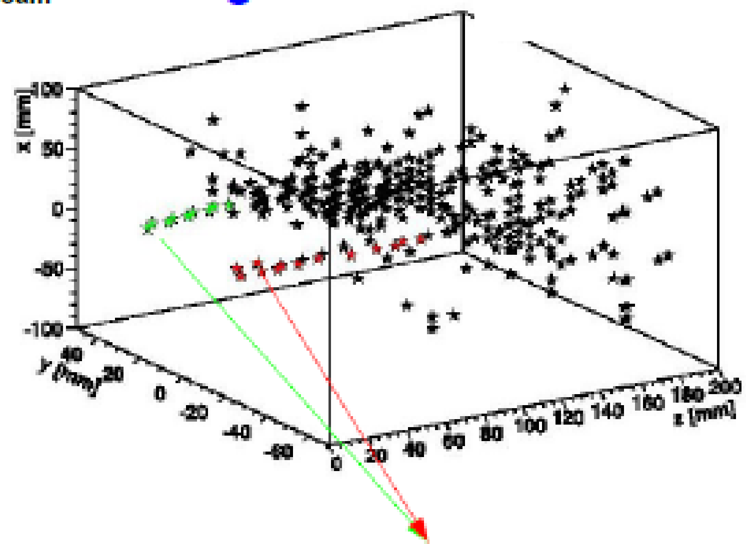
Si/W: physics prototype test beam results

Linearity of response



Resolution, ~16%/√E



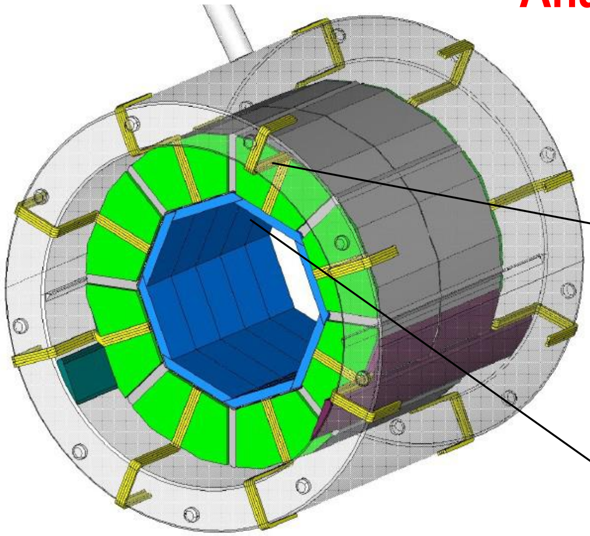


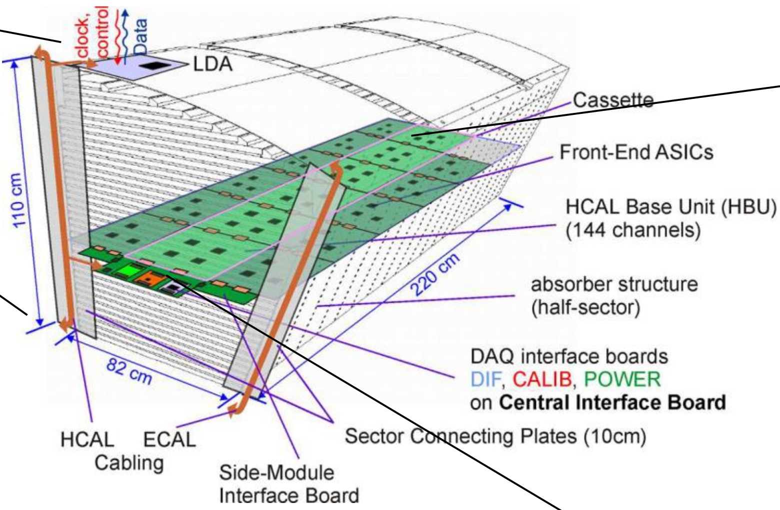
Two pions entering the SiW Ecal

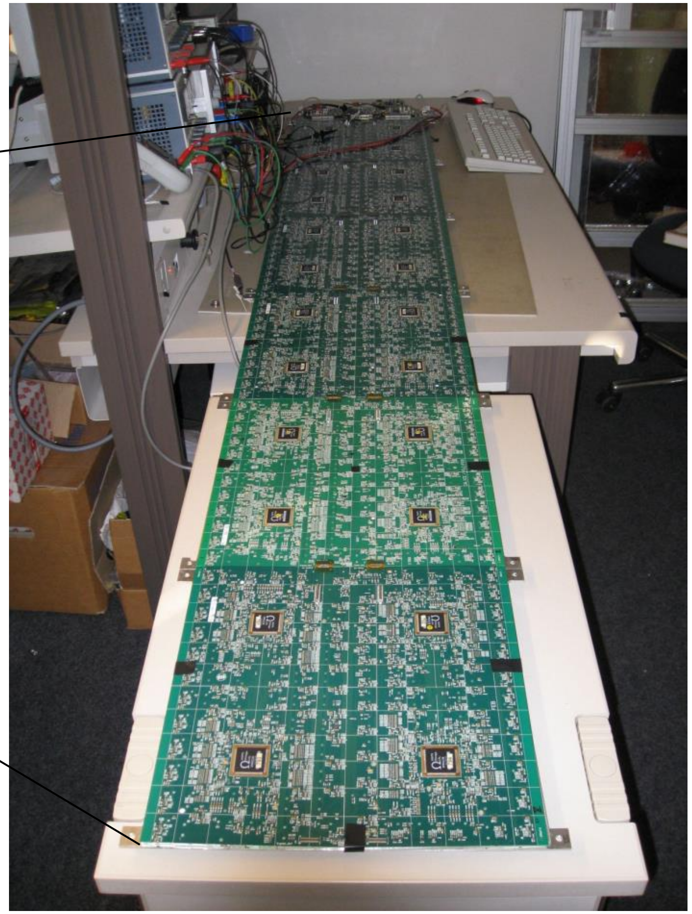
HCAL for ILC: AHCAL (1)

- One possible option studied inside the CALICE collaboration:

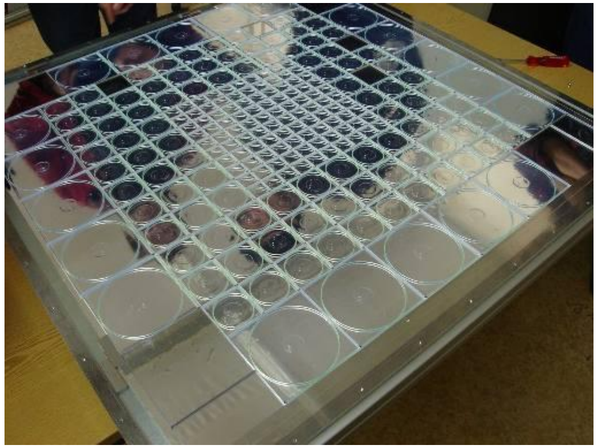
Analogue HCAL Stainless Steel / Scintillators sampling calorimeter



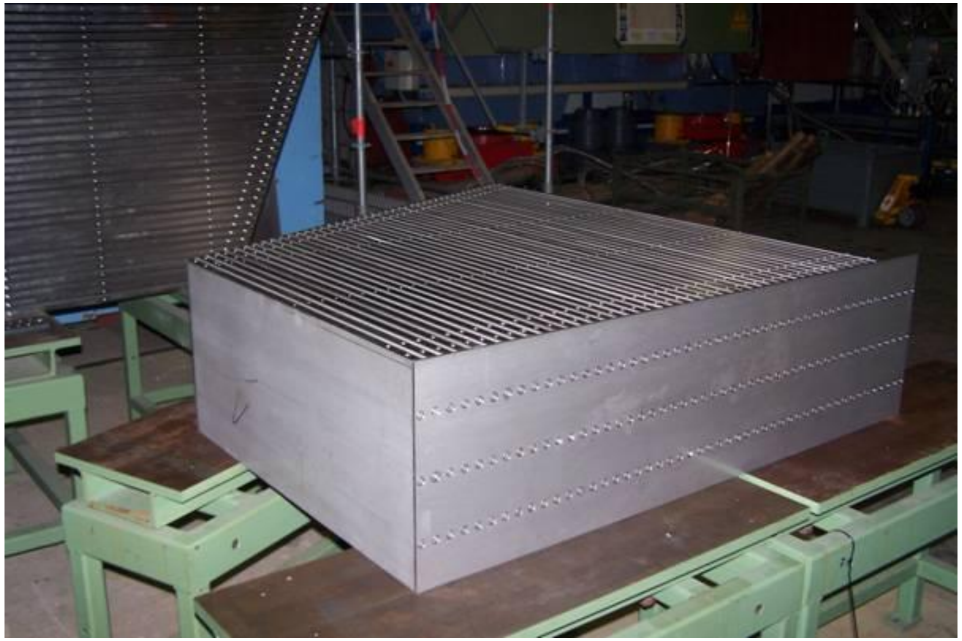


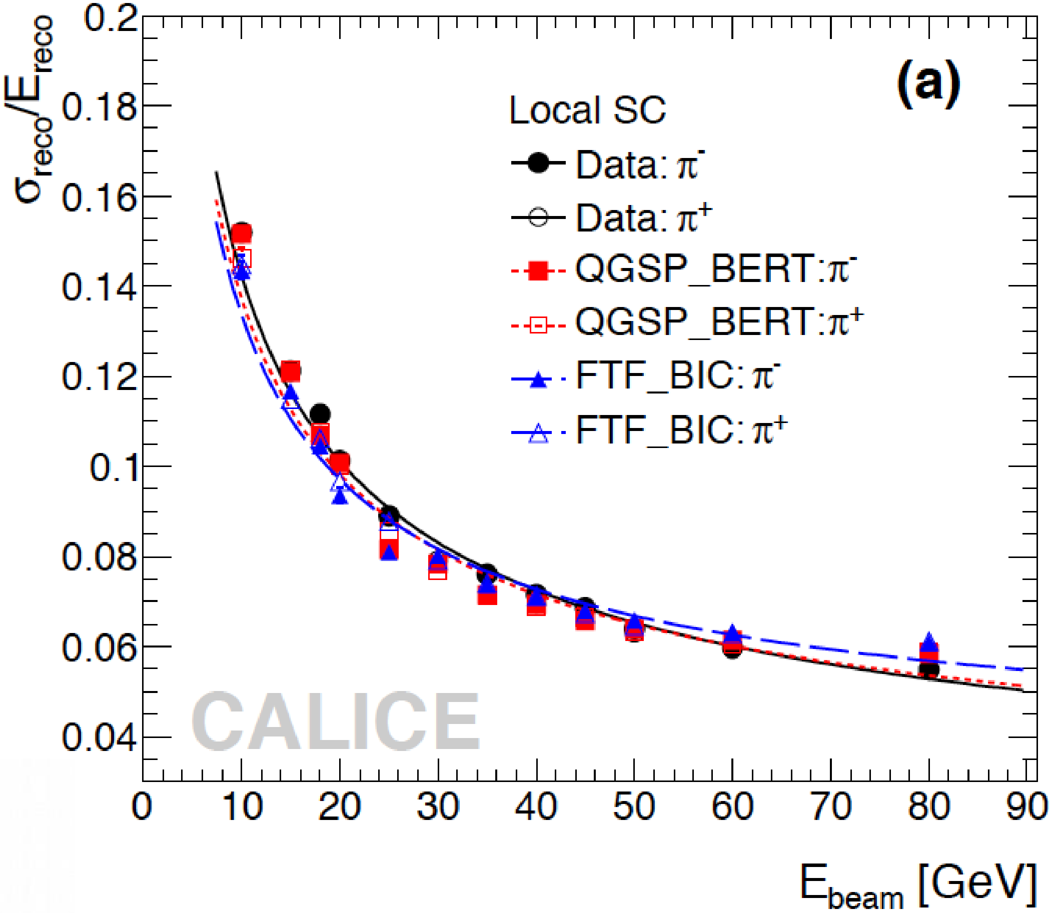


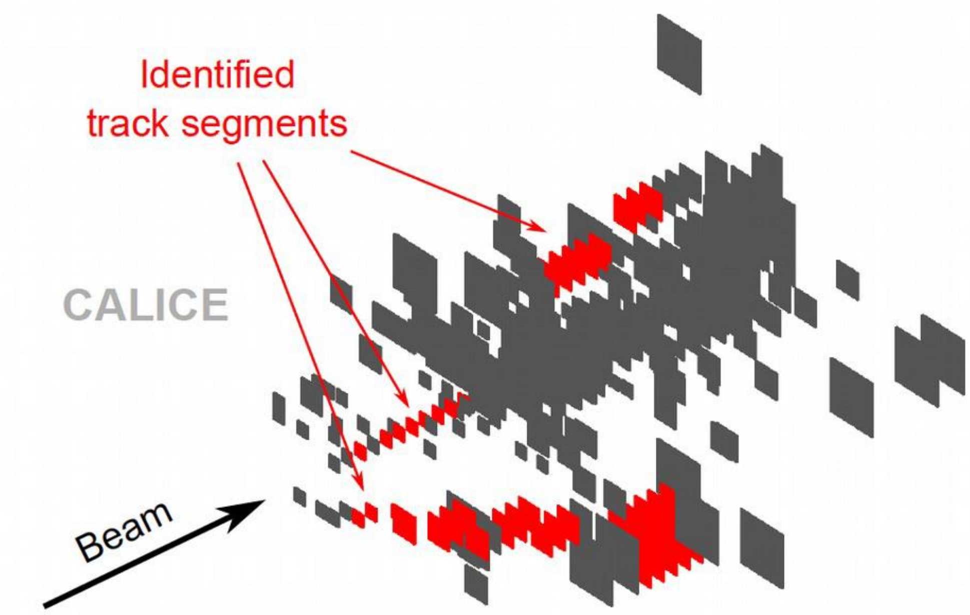
- 3x3 cm² scintillator tiles
- 8.10^6 channels
  vs O(10k) for ATLAS/CMS !



HCAL for ILC: AHCAL (2)



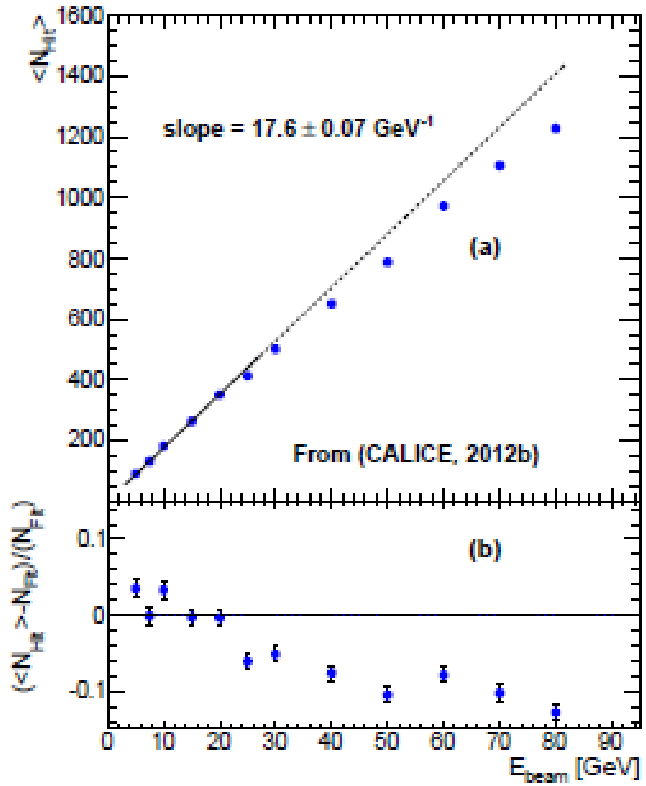


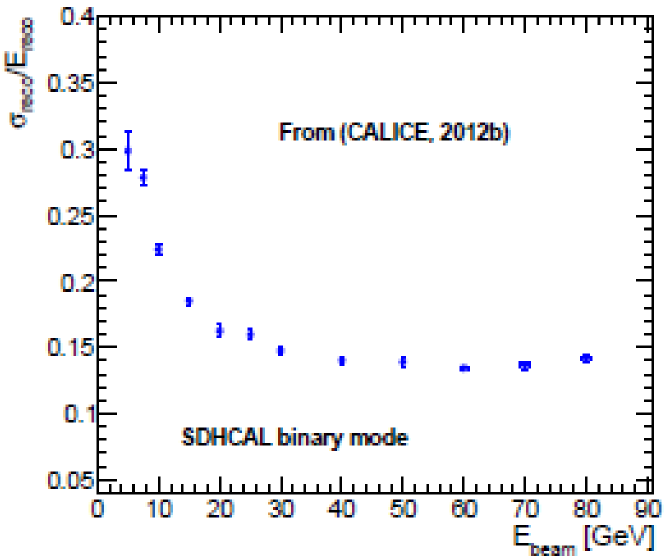


~50%/√E obtained in test beams (after software compensation)

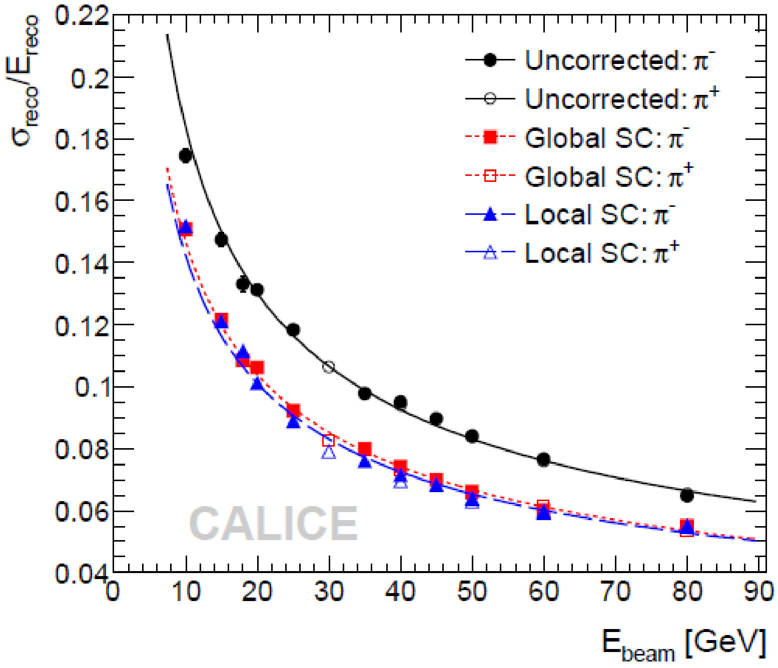
Some other results

Linearity & Resolution of Semi-Digital HCAL

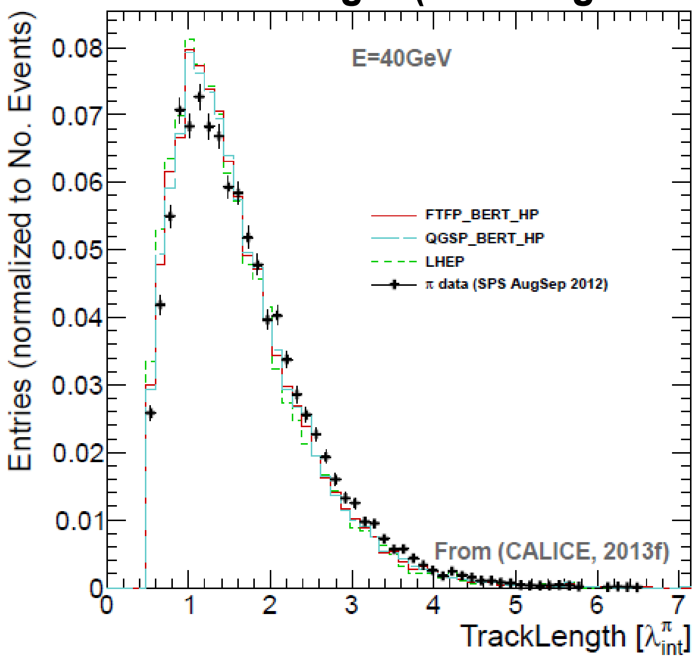




Resolution of A-HCAL with/without software compensation



Data/MC Track Length (Semi-Digital HCAL)

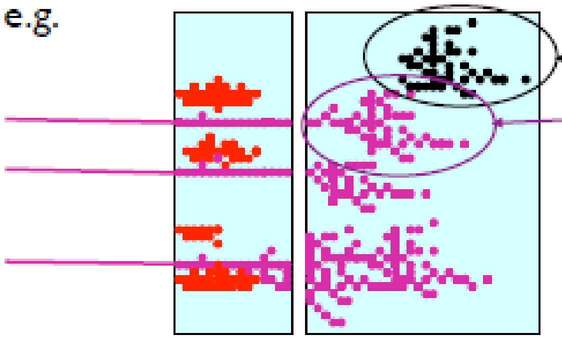


Particle Flow Algorithms for High Granular Calorimeters

High Granular / Imaging Calorimeters need
powerful and innovative reconstruction algorithms to be fully exploited

- Lots of R&D in parallel to detector developments.
- **Challenges:**
  - Avoid double counting of energy from same particles
  - Separate energy deposits from different particles

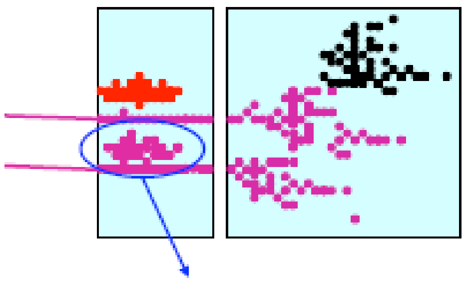
e.g.



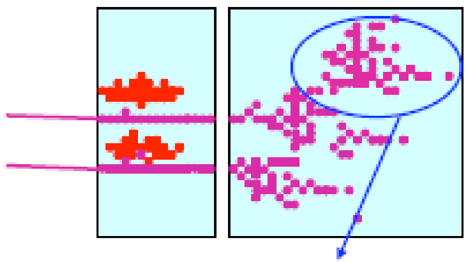
If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

Level of mistakes, "confusion", determines jet energy resolution, not intrinsic calorimetric performance

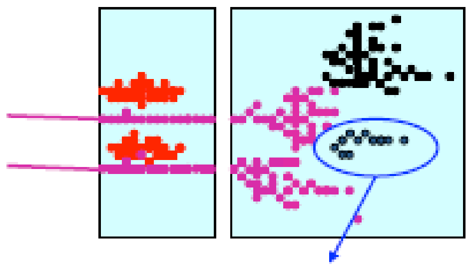
Three basic types of confusion:



Failure to resolve photons

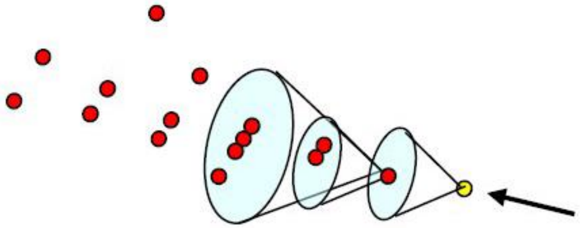


Failure to resolve neutral hadrons



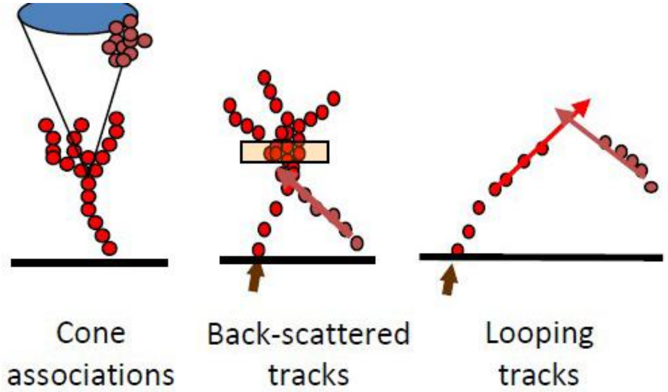
Reconstruct fragments as separate neutral hadrons

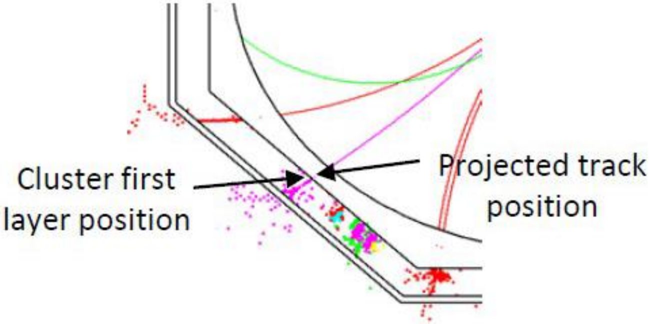
PANDORA Particle Flow Algorithms (PFA)



ConeClustering Algorithm

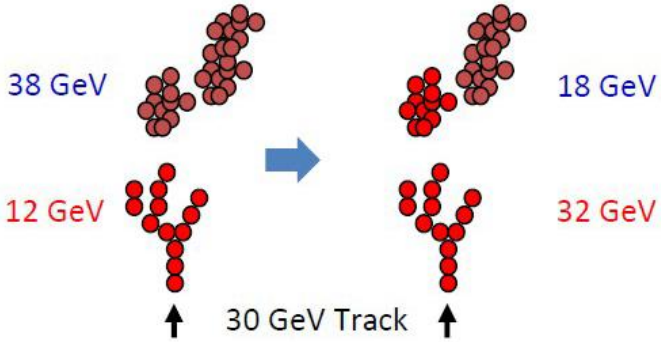
Topological Association Algorithms

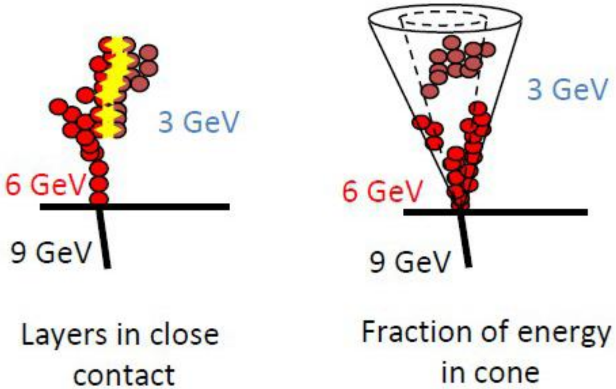




Track-Cluster Association Algorithms

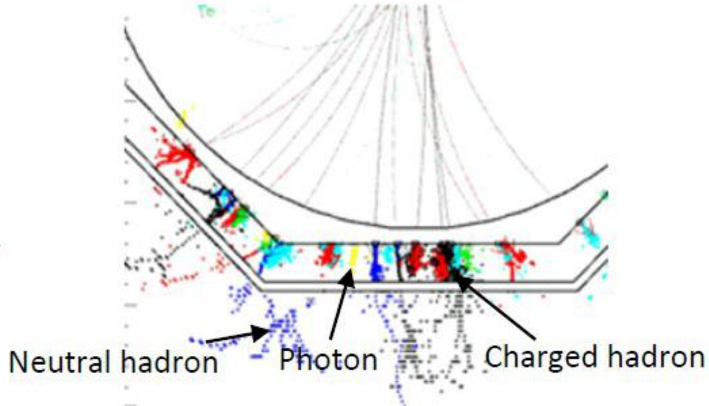
Reclustering Algorithms





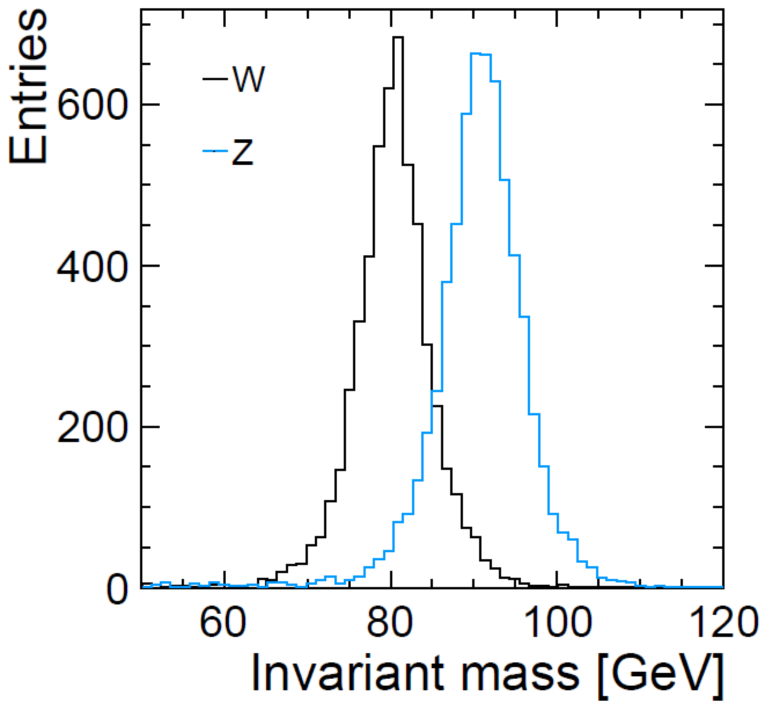
Fragment Removal Algorithms

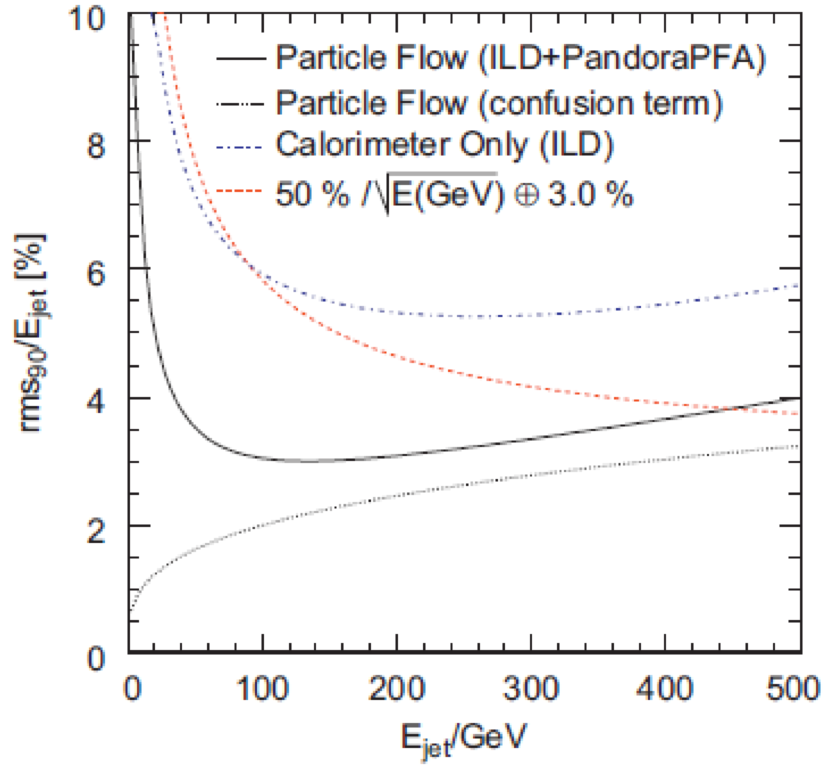
PFO Construction Algorithms



PFA Results (examples)

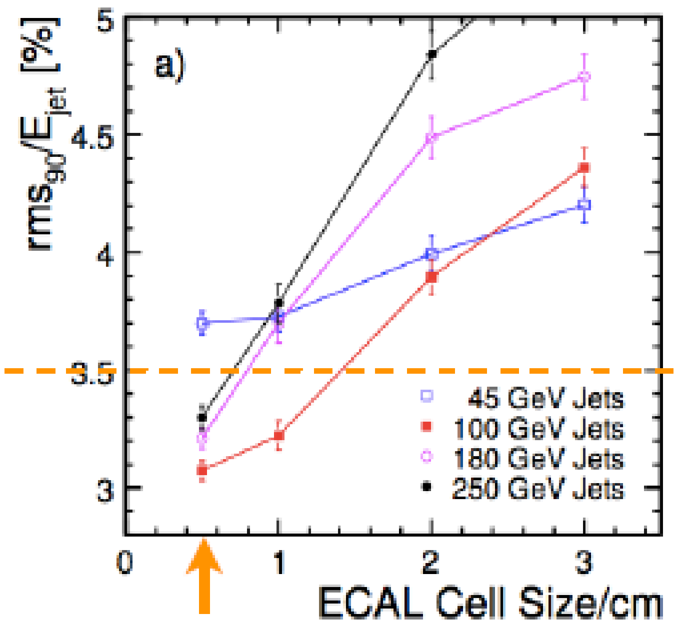
W/Z separation (2-3 sigmas)

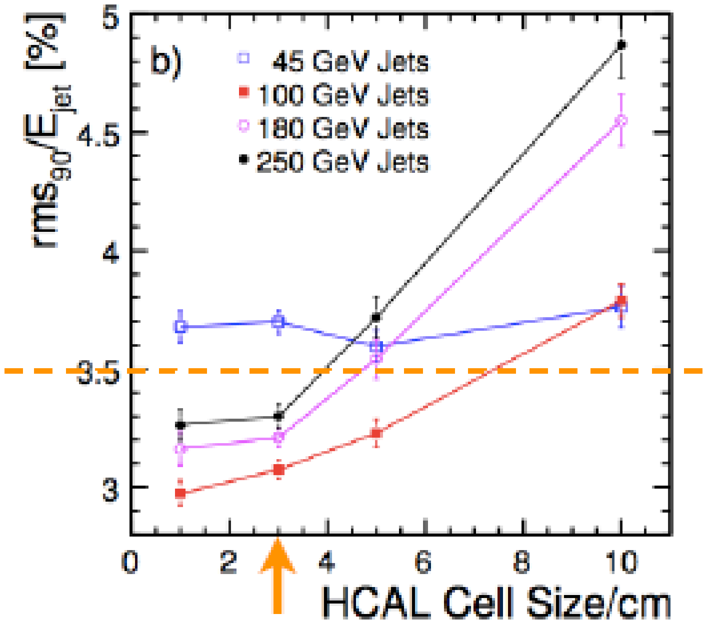




PFLow always “wins” against standard calorimetry

Optimization studies

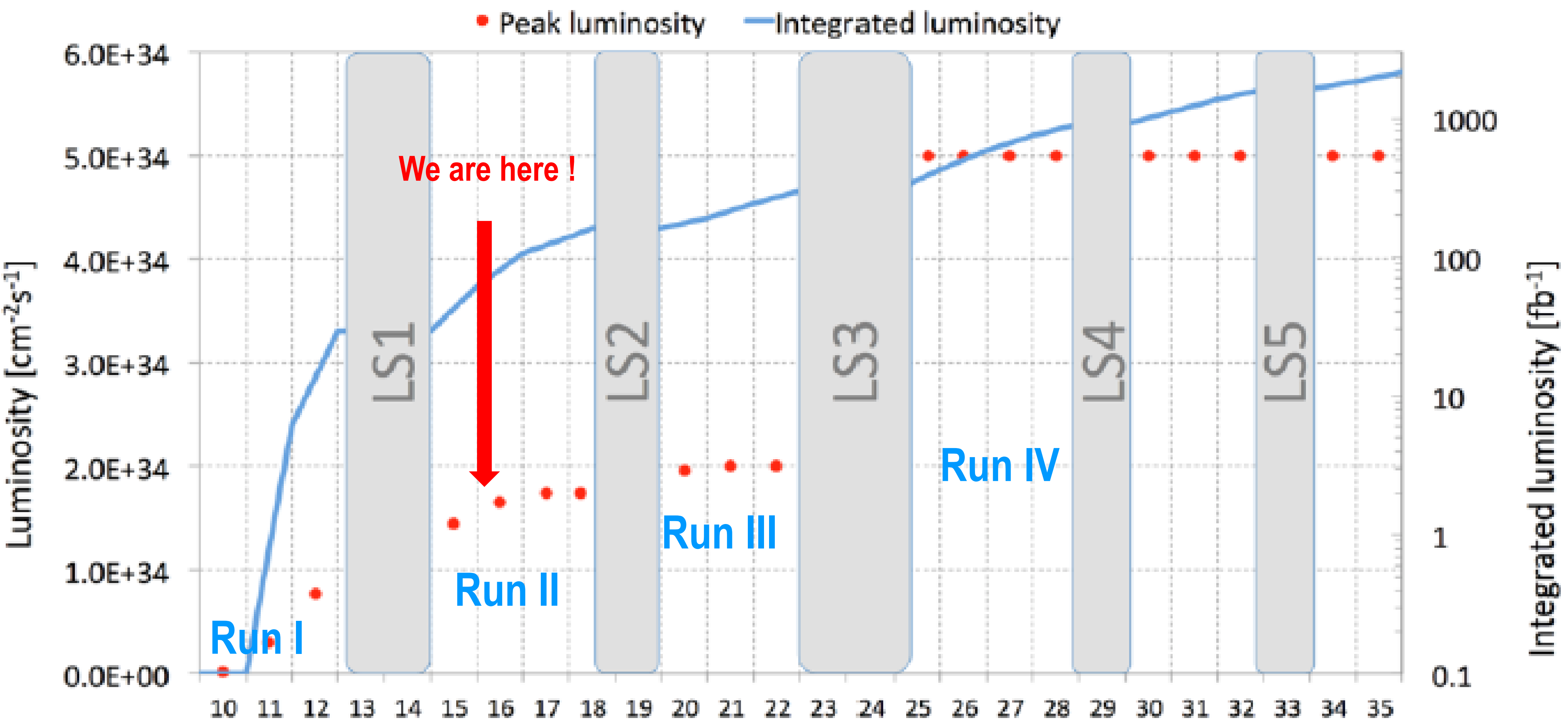




(near) Future at LHC

High
Luminosity
LHC

LHC: from Run I to HL-LHC



"Phase 0",

Phase I

Phase II (HL-LHC, >2025)

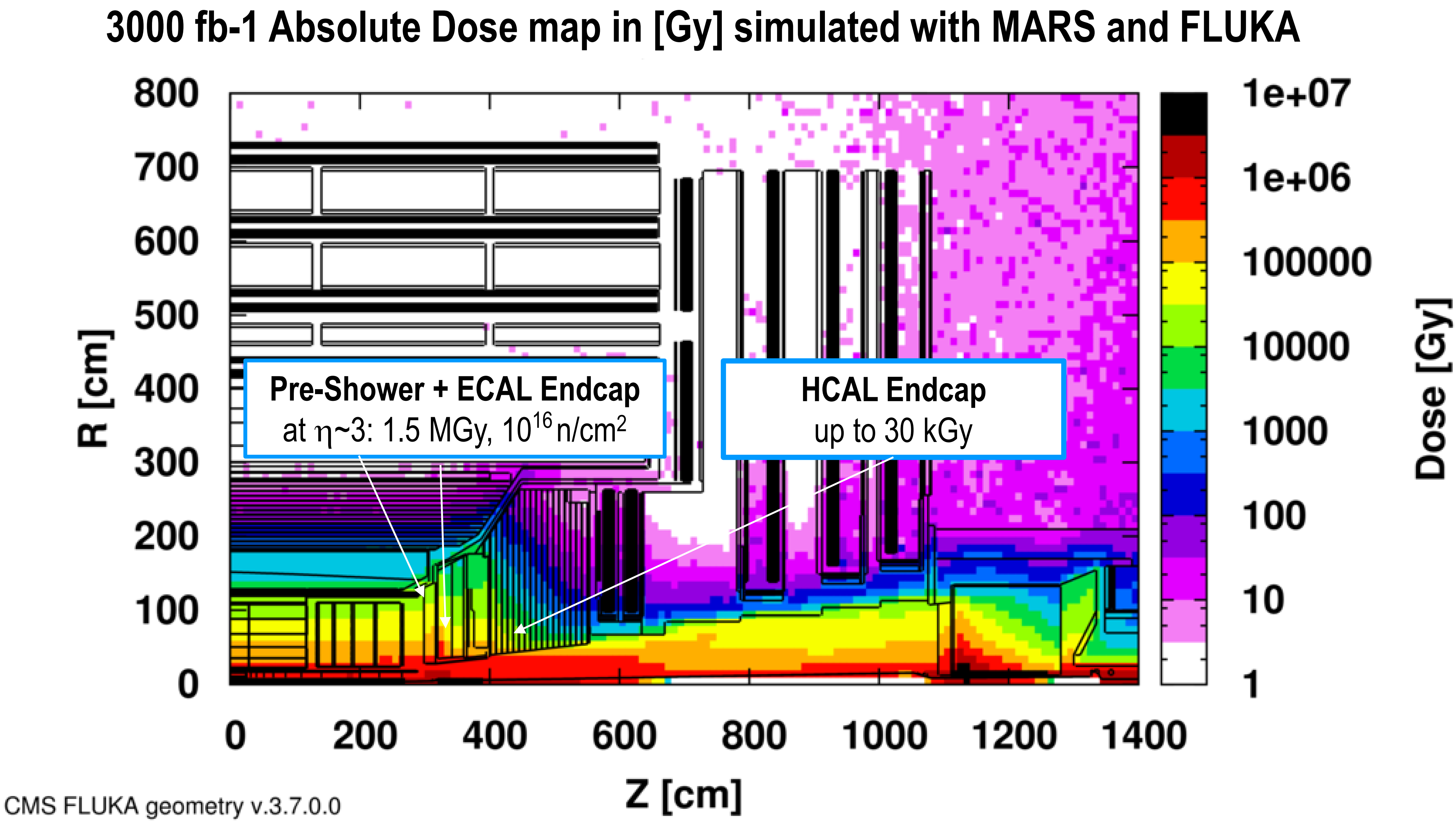
$\sqrt{s}$ = 7-8 TeV
∫ L dt = 25 fb^{-1}
Higgs boson discovery !

$\sqrt{s}$ = 13 TeV
Lumi inst. : up to 2.5×10^{34} $cm^{-2}s^{-1}$,
∫ L dt = 300-500 fb^{-1}
<PU> : from ~25 to 60
X(750) ? SUSY ? ☺

$\sqrt{s}$ = 13-14 TeV
Lumi inst. : >= 5×10^{34} $cm^{-2}s^{-1}$,
∫ L dt : 3000 fb^{-1}
<PU> : ~140-200

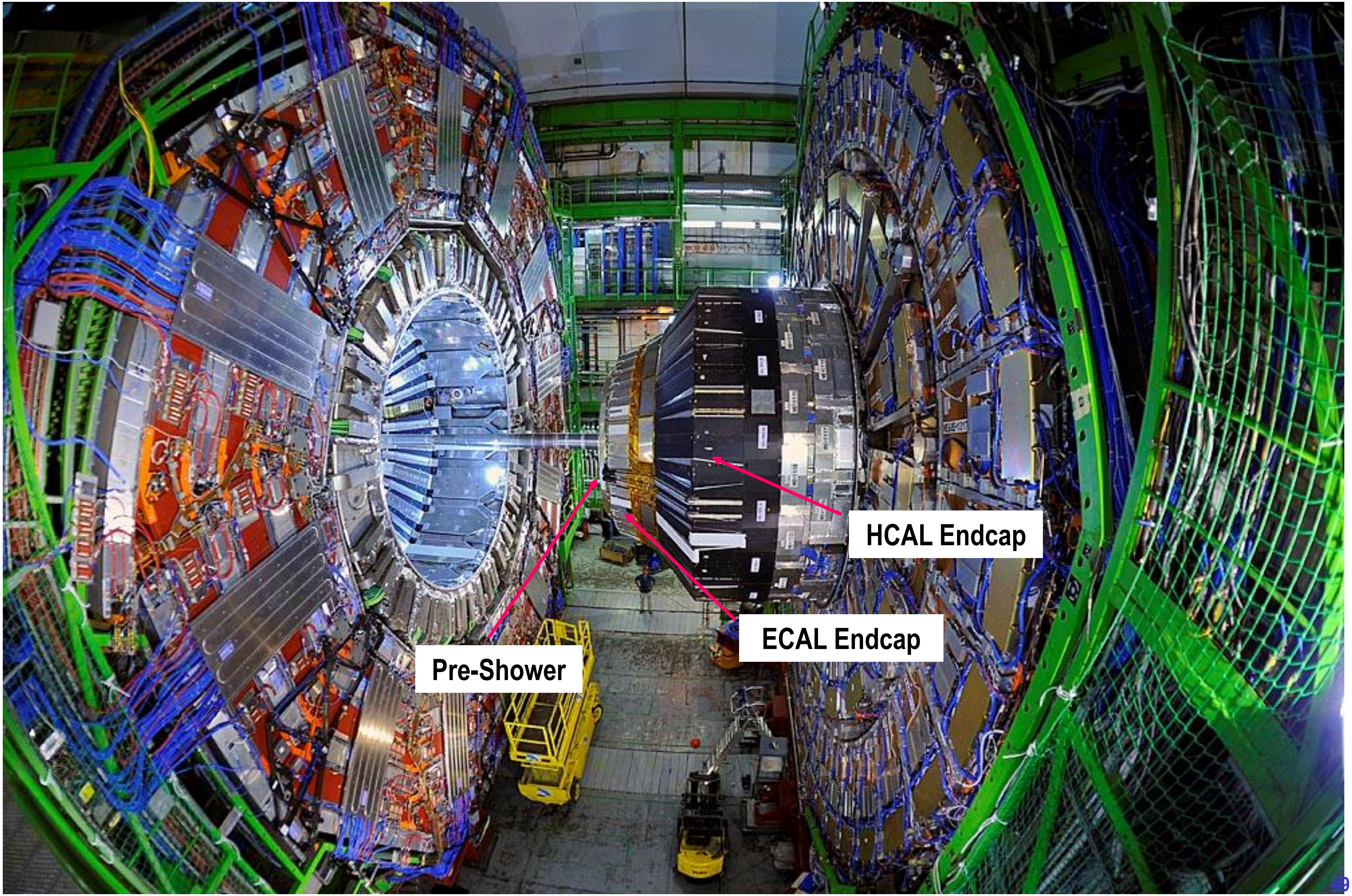
Well beyond design !

Challenges: Radiation damage



Aging studies shows that **Endcap Calorimetry (+Tracker) has to be replaced.**

CMS Endcap



Challenges: Pile-Up (PU)

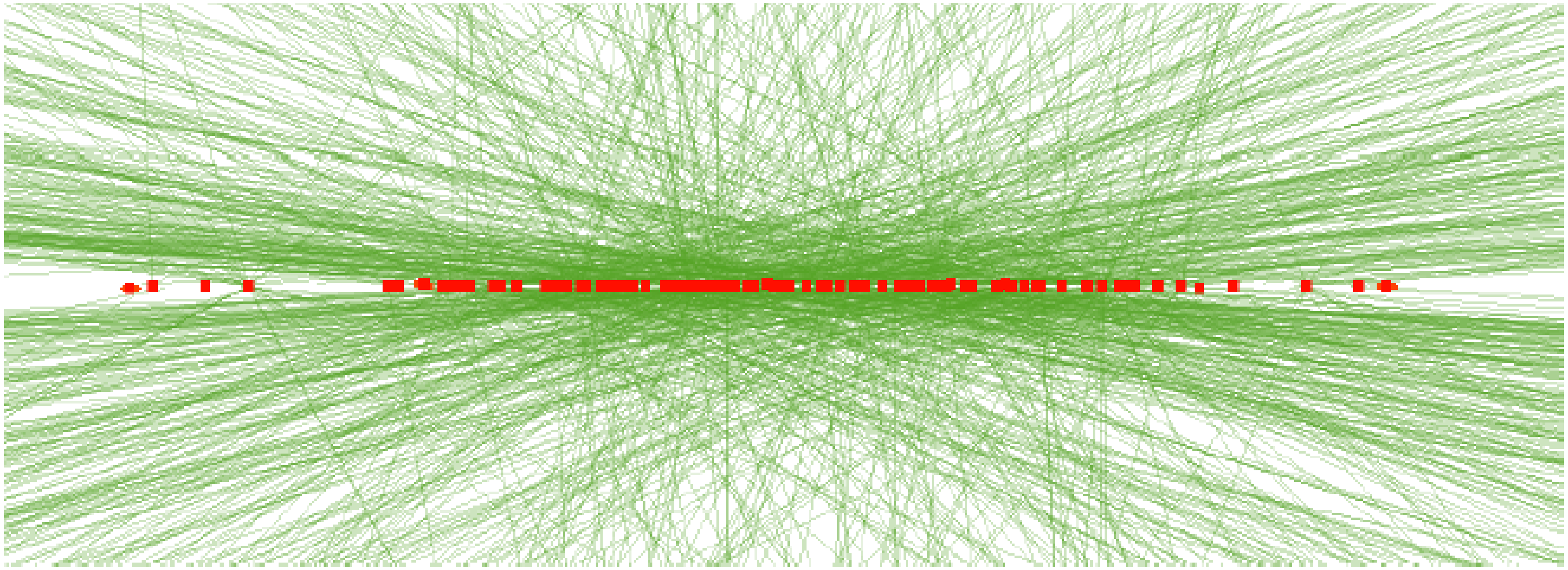


Figure 9.1: An event display showing reconstructed tracks and vertices of a simulated top-pair event with additional 140 interactions overlaid for the Phase-II detector.

- HL-LHC Nominal Parameters:
  - 140 additional interactions per bunch crossing (every 25 ns) + out-of-time PU
    - Could go up to 200
  - Instantaneous Peak Luminosity: 5×10^{34} $cm^{-2}s^{-1}$,

- **Challenges for Triggers (especially Level 1 !) & offline reco + computing (30xLHC)**

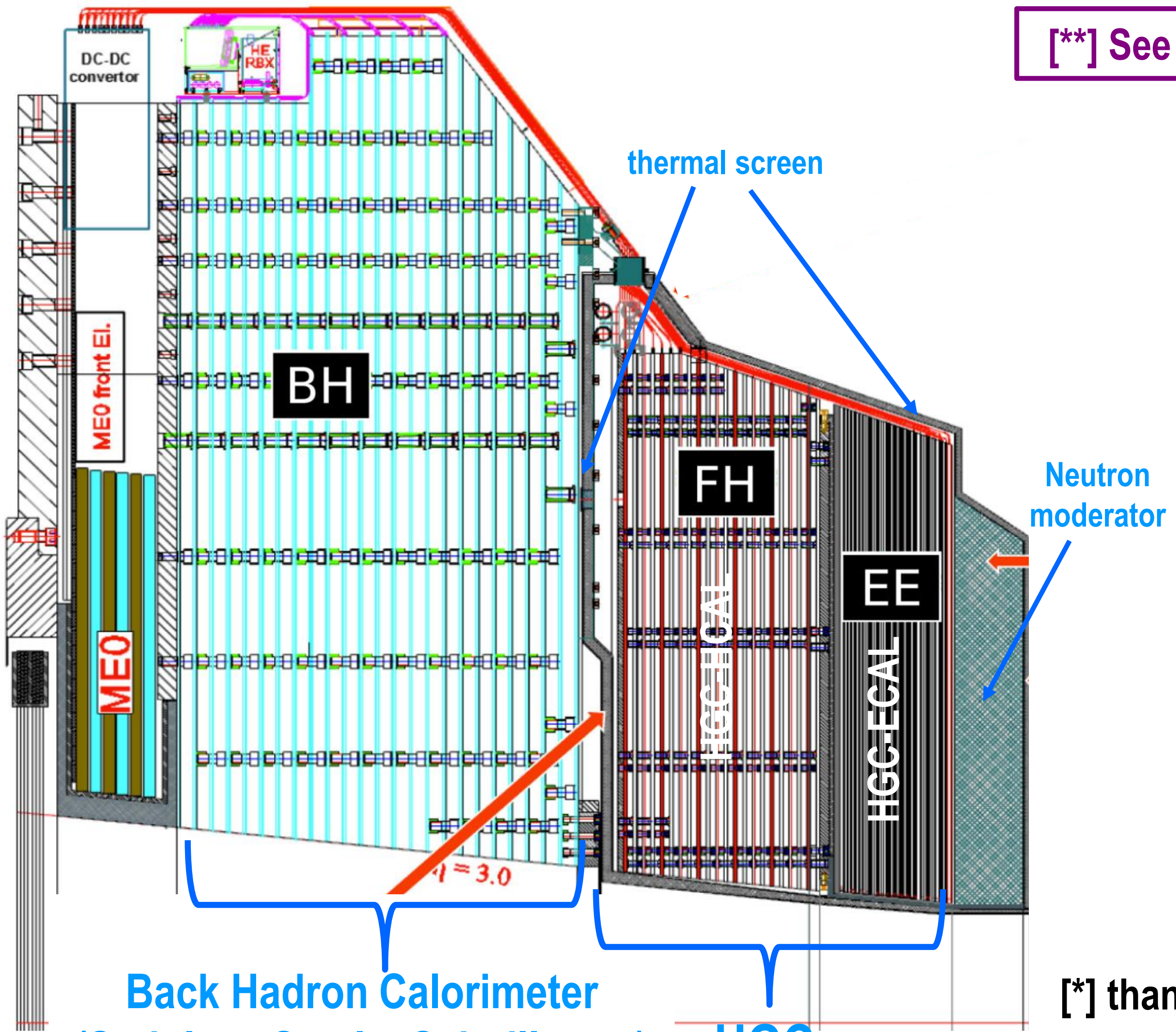
Need to preserve "low" energy physics (125 GeV Higgs) and explore TeV scale (e.g. SUSY) in a very harsh environment !

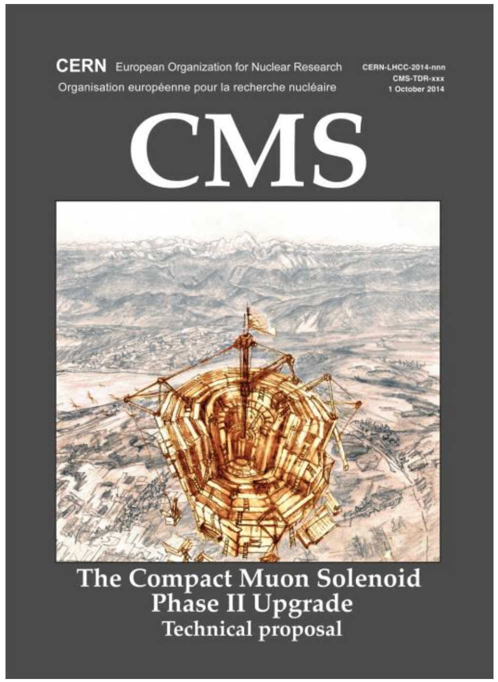
HGCAL: General Layout

CMS choice: **High Granular Sampling Si-based Calorimeter [*]**
with 4D measurement of showers (energy, position)
(possibly 5D with timing) [**]

[**] See talk by N. Akchurin

HGC+BH: covers η range up to 3

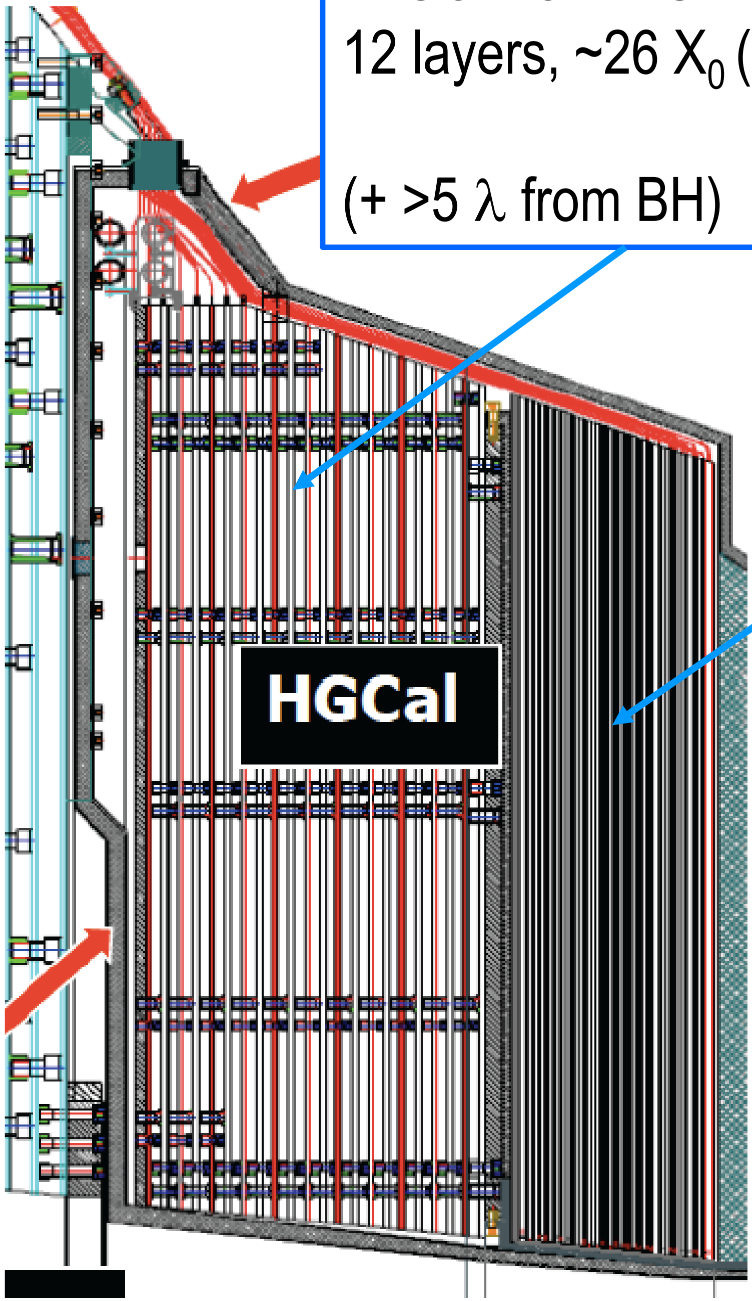




Technical Proposal
CERN-LHCC-2015-010

[*] thanks to CALICE developments, progress on Si & data transmission

HGC Parameters



HGC-HCAL: Si+Brass or Steal
12 layers, ~26 X_0 (>3.5 λ)

(+ >5 λ from BH)

HGC-ECAL: Si+W/Cu
28 layers, ~26 X_0 (1.5 λ)
10 x 0.65 X_0 +
10 x 0.88 X_0 +
8 x 1.26 X_0

Operation at -30°C via CO_2 Cooling
(to mitigate Si leakage current)

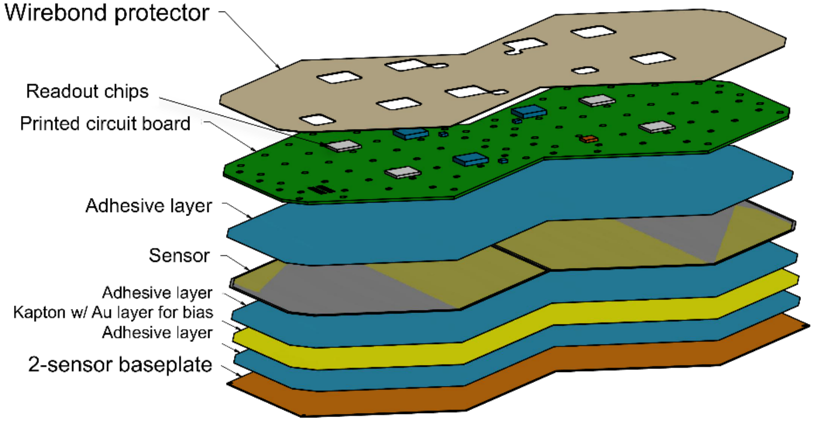
Table 3.2: Parameters of the EE and FH.

	EE	FH	Total
Area of silicon (m^2)	380	209	589(*)
Channels	4.3M	1.8M	6.1M
Detector modules	13.9k	7.6k	21.5k
Weight (one endcap) (tonnes)	16.2	36.5	52.7(**)
Number of Si planes	28	12	40

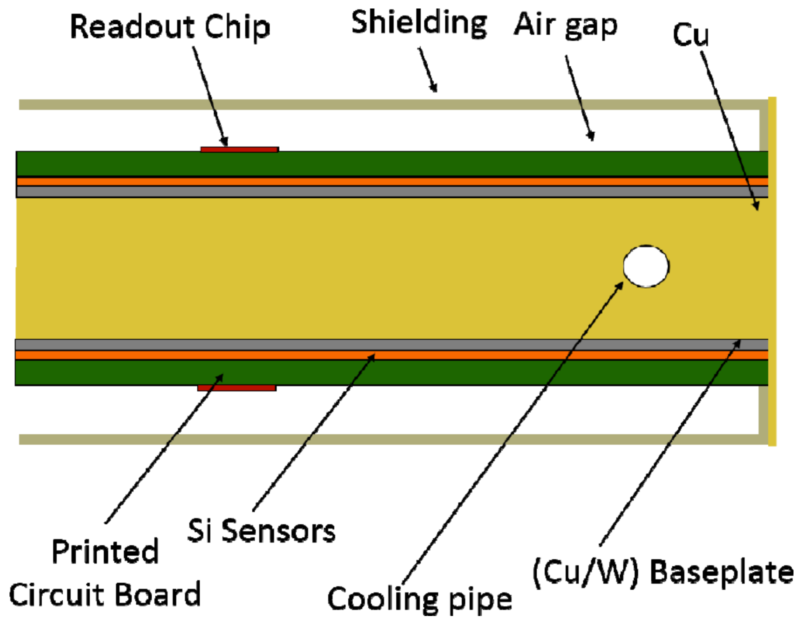
(*) 3x CMS tracker !　　(**) one HGC+BH endcap: ~230 tonnes

Modules, Cassettes & Mechanics (Technical Proposal)

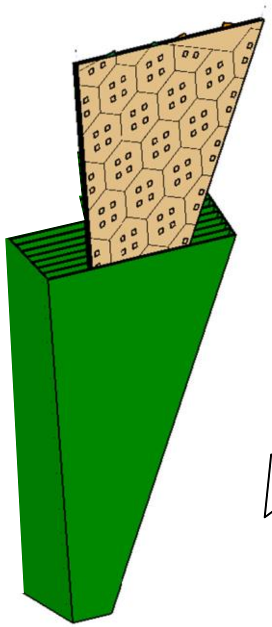
Modules
with 2x6 or 8” Hexagonal Si sensors,
PCB, FE chip, on W/Cu baseplate



Modules mounted on
Cu Cooling plate with embedded pipes
== **Cassettes**



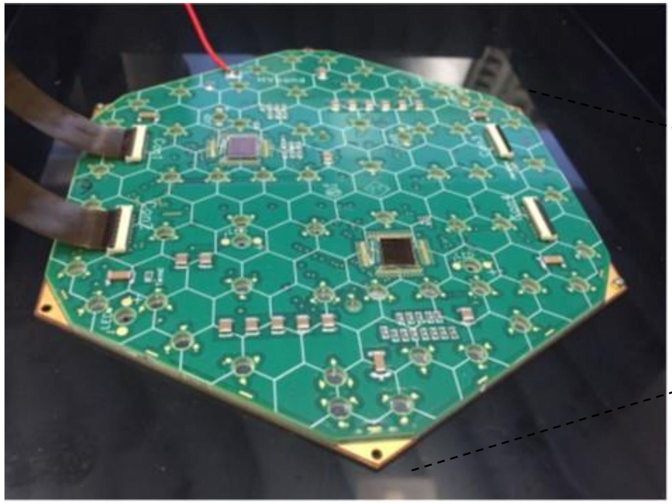
Cassettes
inserted in **mechanical structure**
(containing absorber)

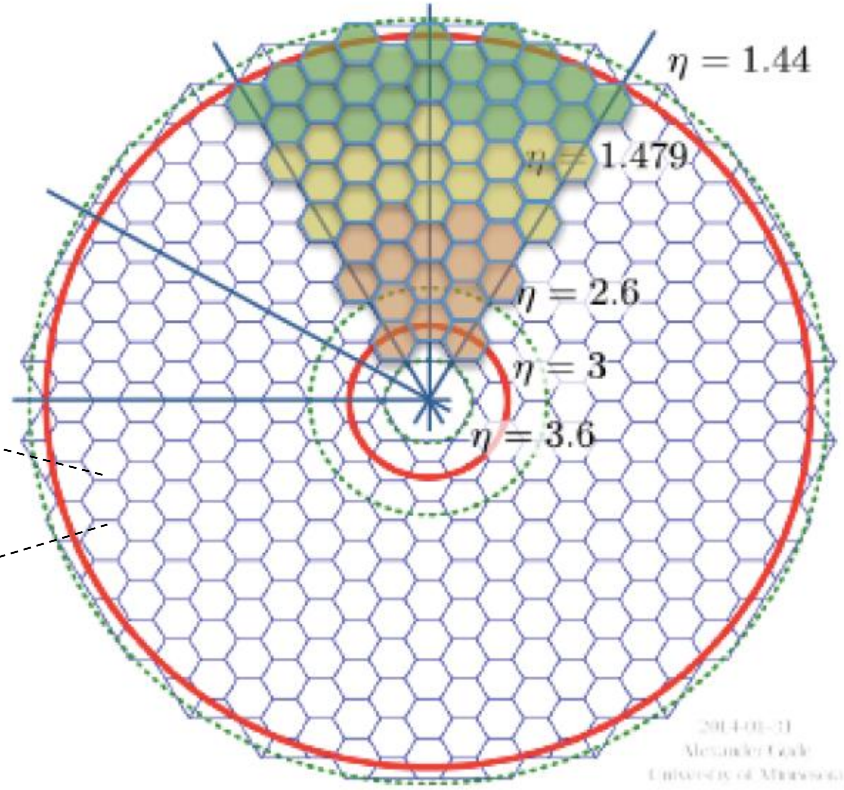


W/C-fiber EE alveolar structure

Modules, Cassettes & Mechanics (Si & modules)

Modules
with 2x6 or 8" Hexagonal Si sensors, PCB, FE chip, on W/Cu baseplate





To cope the irradiation / PU:

- η-dependent depletion of Si
- η-dependent cell size

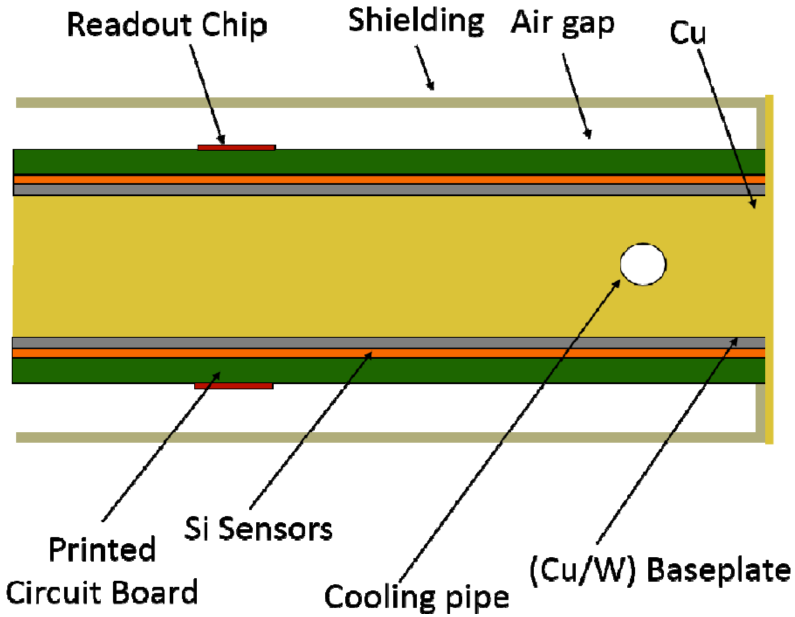
Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after 3000 fb^{-1}	6.5	2.7	1.7

Modules, Cassettes & Mechanics (Cassettes)

“dummy” cassette for thermal tests

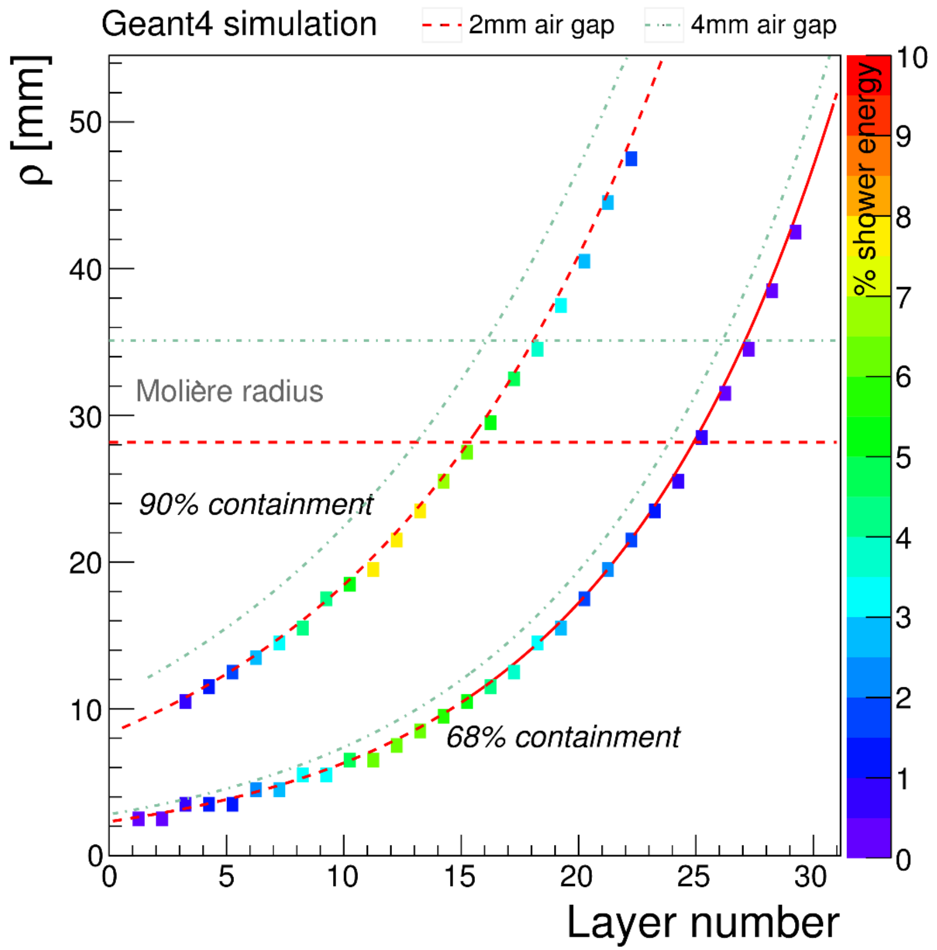
CO_2 cooling plant at FNAL

Modules mounted on
Cu Cooling plate with embedded pipes
== **Cassettes**

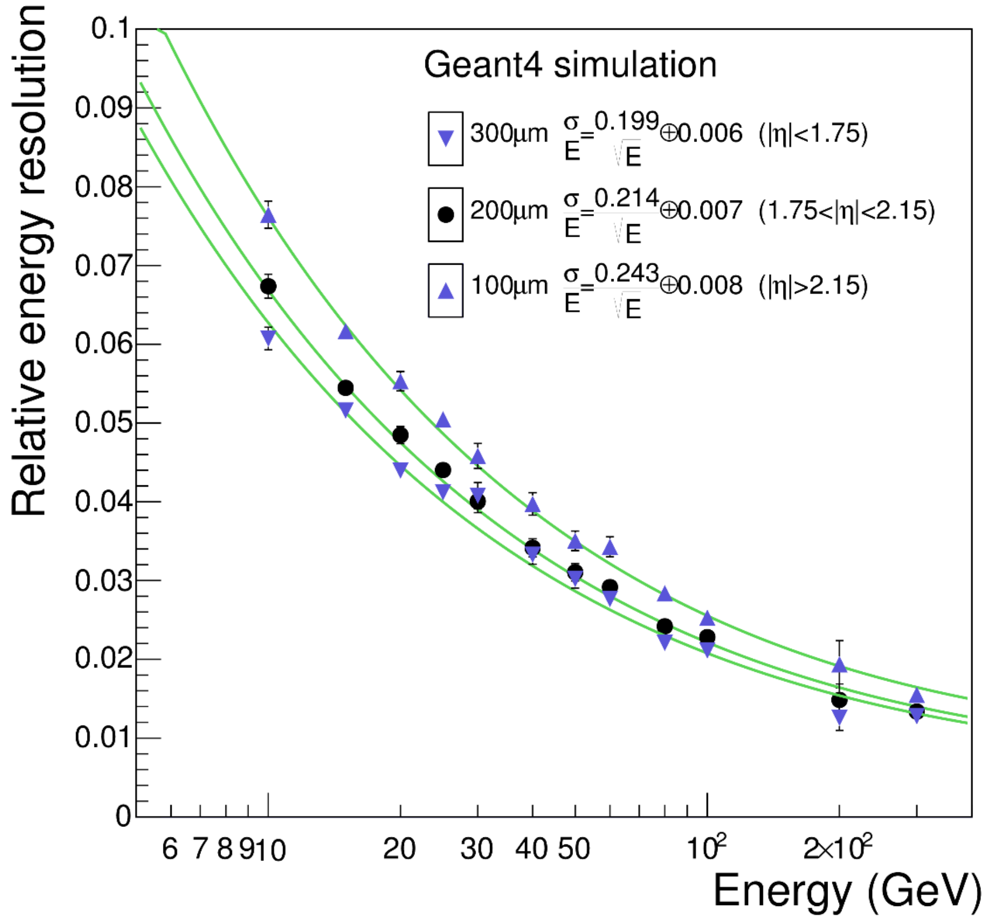


HGC Performance (1)

EM shower energy containment



Electron energy resolution vs Si thickness



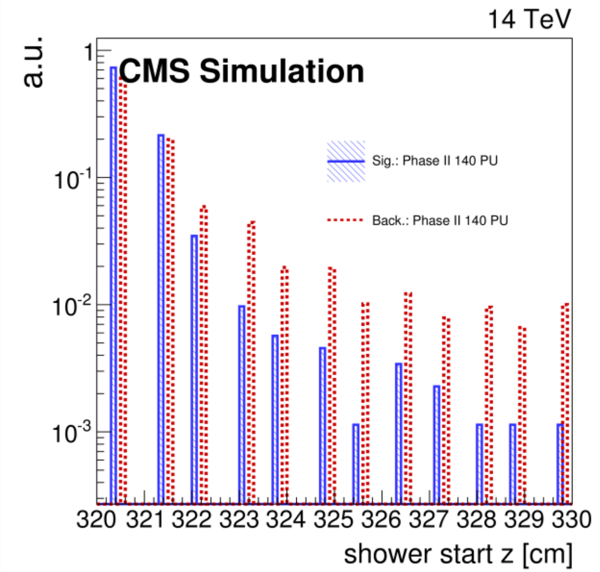
Shower radius quite small in first layers.
Can use longitudinal segmentation for PU rejection, …

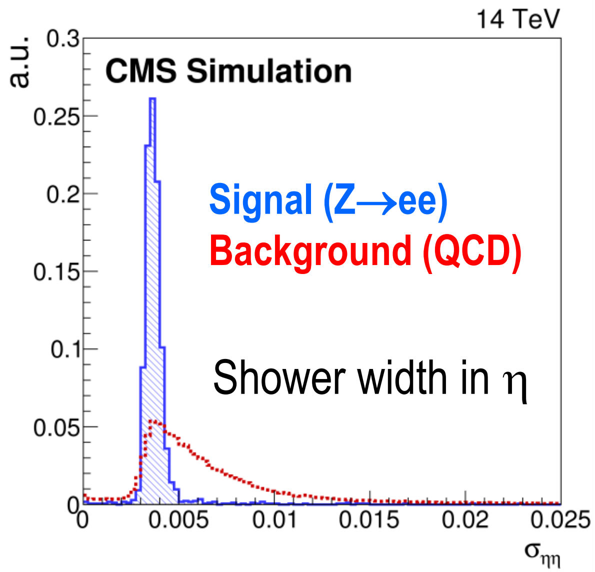
Stochastic term: ~20%
but **low constant term** (target: 1%)

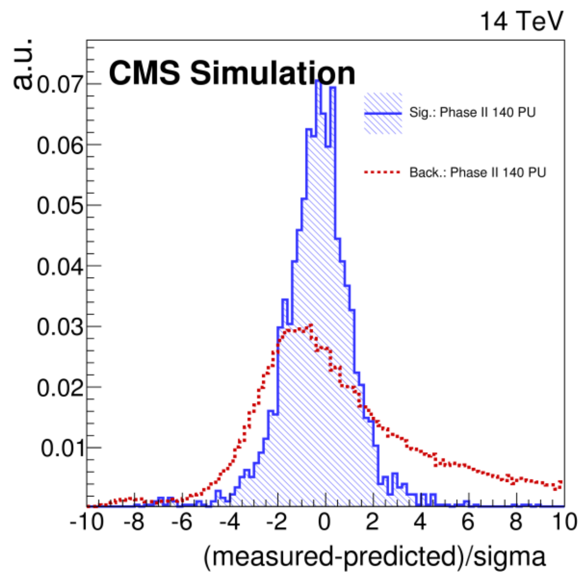
Obtained with standalone G4 simulation. Benchmarked againt CALICE test-beam results

HGC Performance (2)

- **High Granularity + longitudinal segmentation gives additional powerful handles for particle ID:**
  - shower start, shower length compatibility, restoration of projectivity, 3D shower profile fits, layer-by-layer PU subtraction, etc…

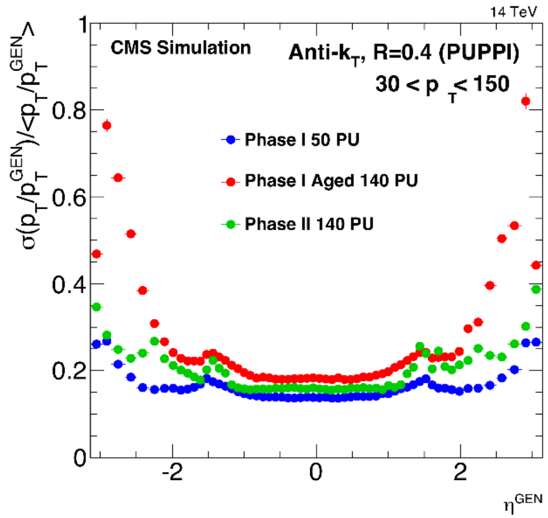




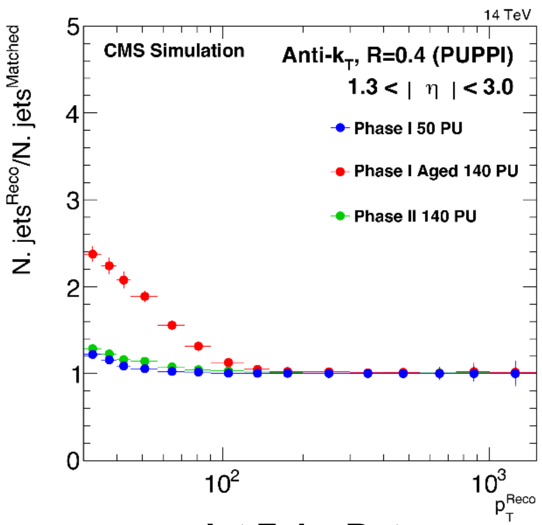


With 1x1 cm^2 squared cells

- Combination of HGC and Tracker (with far from optimal PFlow algo)



Jet Energy Resolution vs η



Jet Fake Rate

- **~Recover Phase I 50 PU performance !**

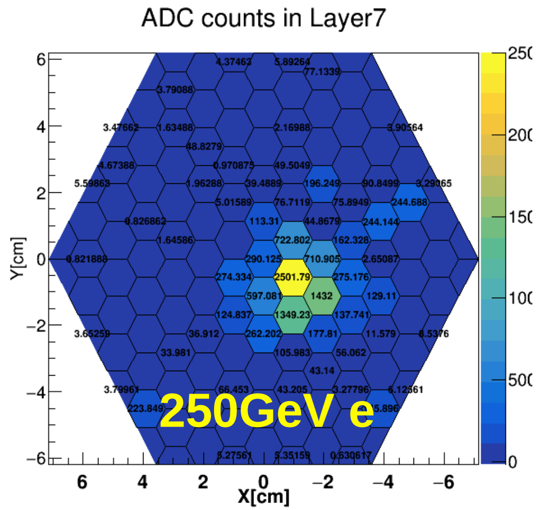
HGC: Test beams

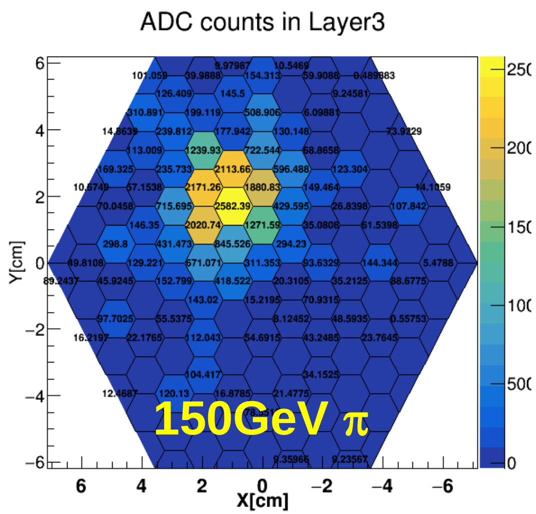
- **Goals:**
  - Performance studies: S/N, timing, energy and positions resolutions
  - Comparison with simulation

- **Several test beams campaign** (FNAL, CERN)
  - FNAL: 120 GeV protons, 4-32 GeV electrons/pions
  - CERN: 125 GeV pions, 20-250 GeV electrons

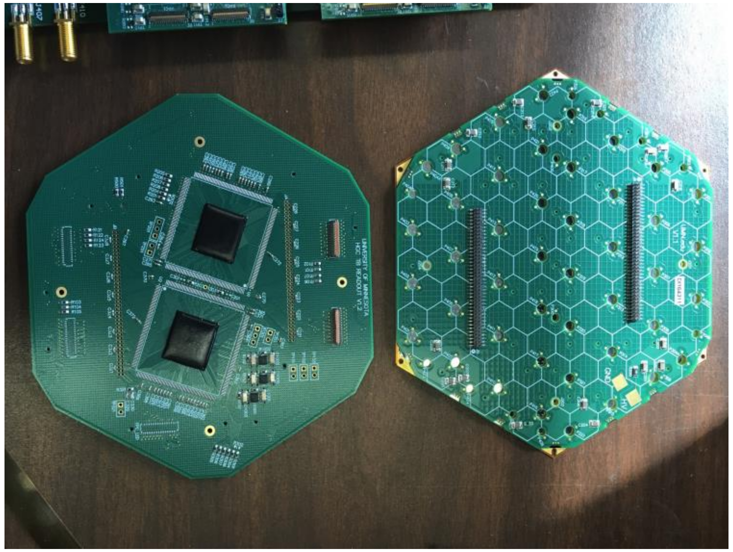
Laboratory	Layers	X_0	Date
FNAL	1	6	March 2016
FNAL	4	12	May 2016
FNAL	16	15	July 2016
CERN	8	27	Aug 2016

+ various timing tests
(next in November at CERN?)



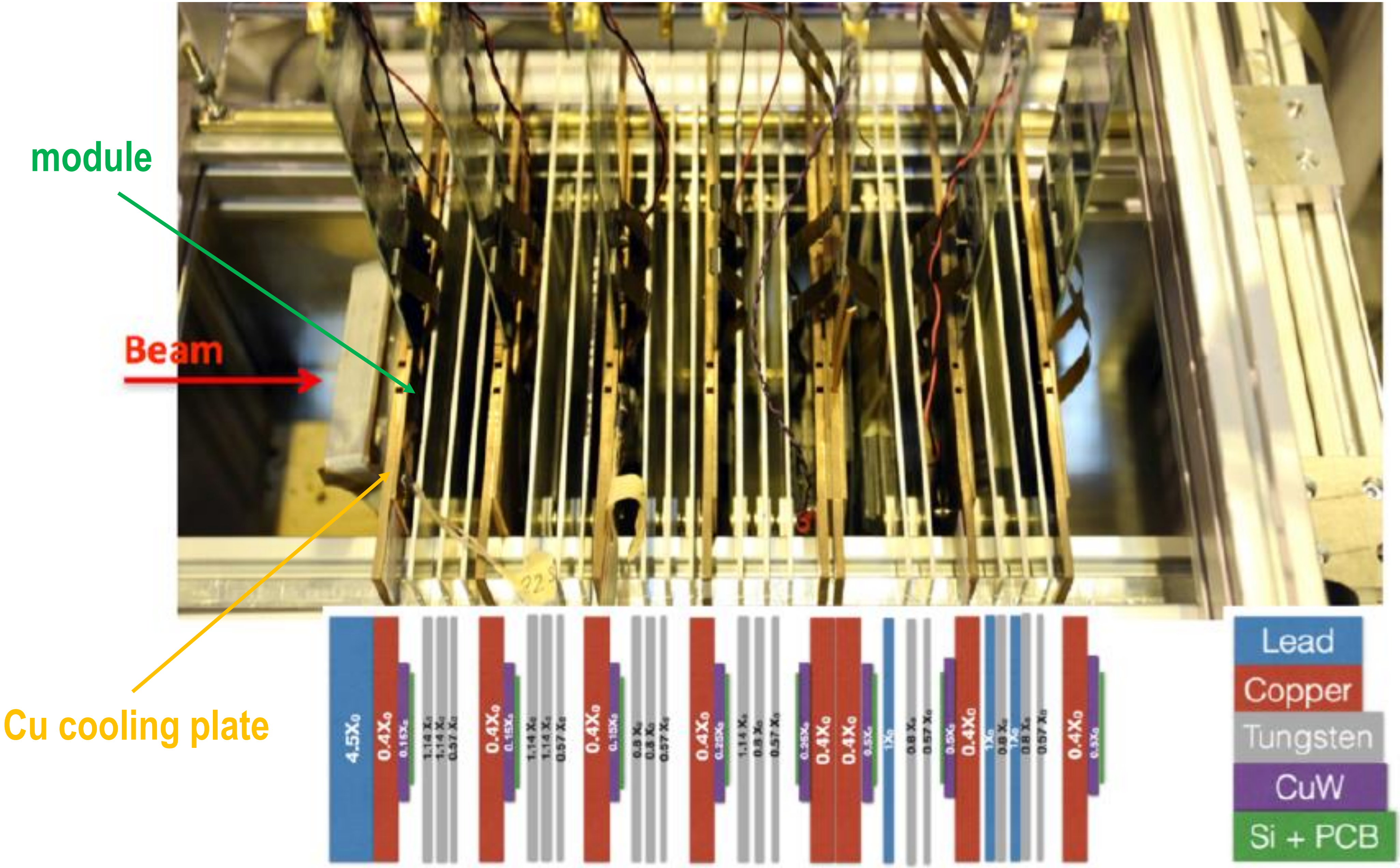


- **Common DAQ, Modules:**
  - 6” Si wafers, 200um, p-on-n,
  - 1.1 cm² cells,
  - 2-layers PCB, SKIROC2 chip
  (single PCB version still at work…)



Test Beams: set up

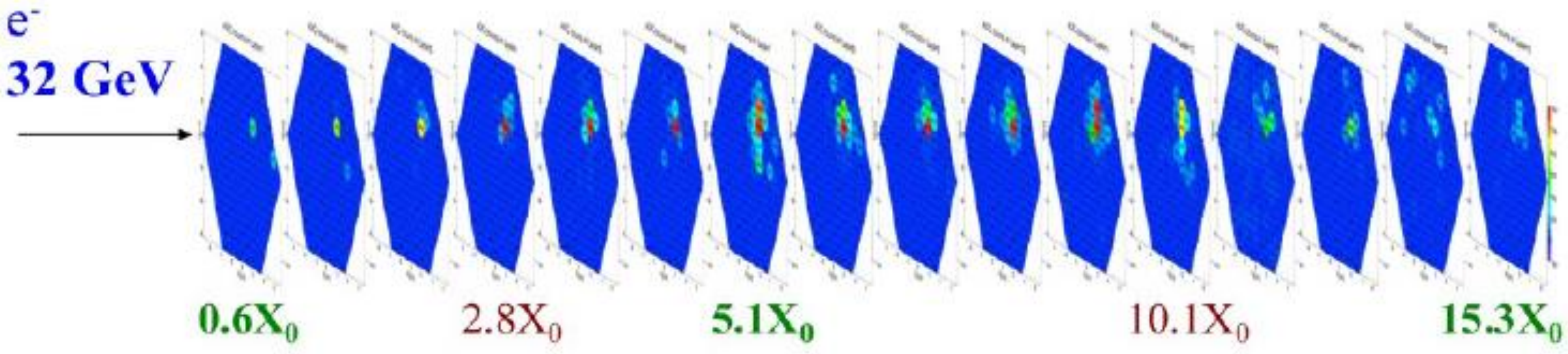
CERN (Similar at FNAL)



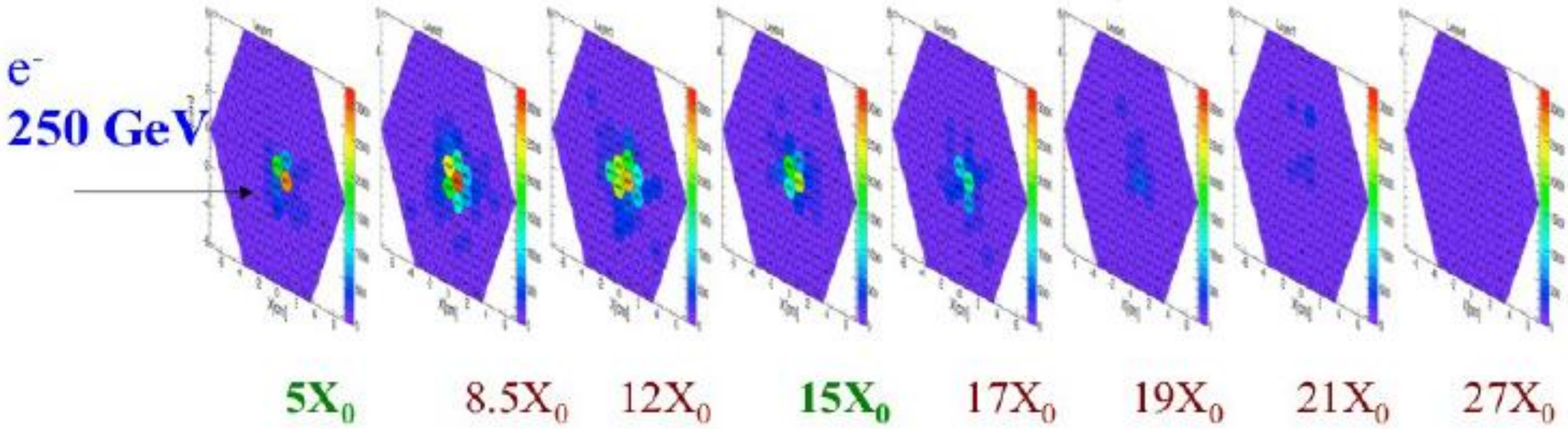
Mechanical design allows flexible insertion of modules and absorbers plates

HGC Test beams: (some) results

- FNAL: 32 GeV electron passing through 16 layers (15 X0)

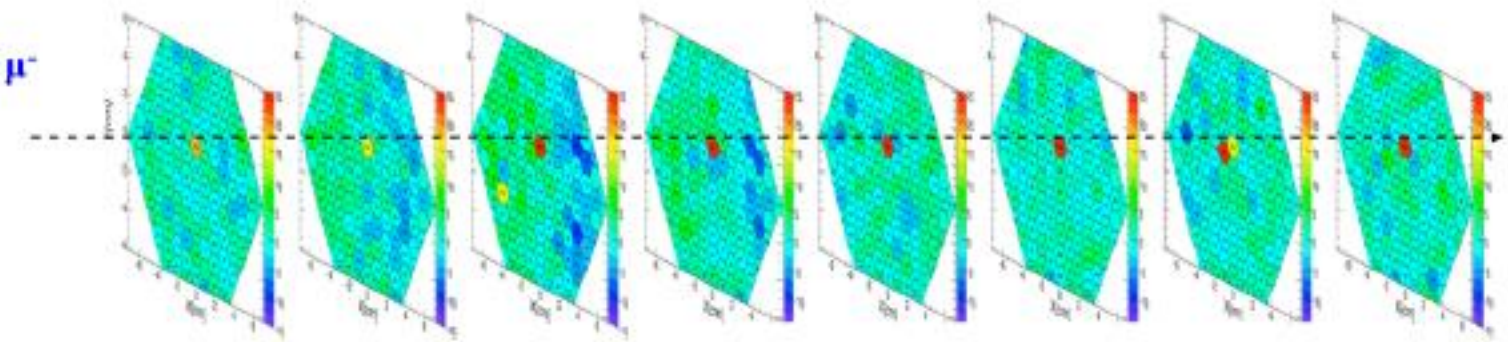


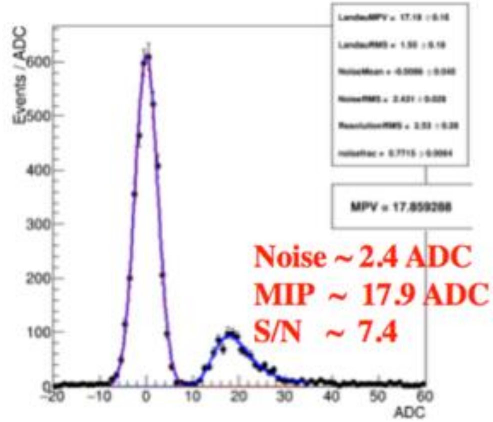
- CERN: 250 GeV electron passing through 8 layers (27 X0)



Test Beams: (some) results

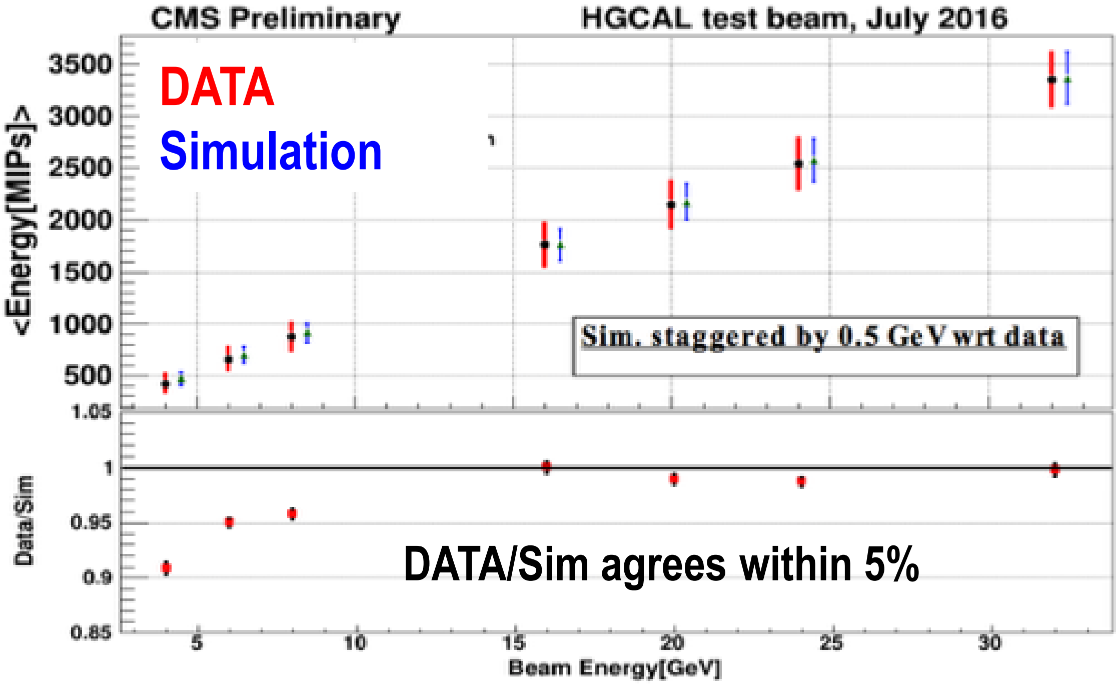
- CERN





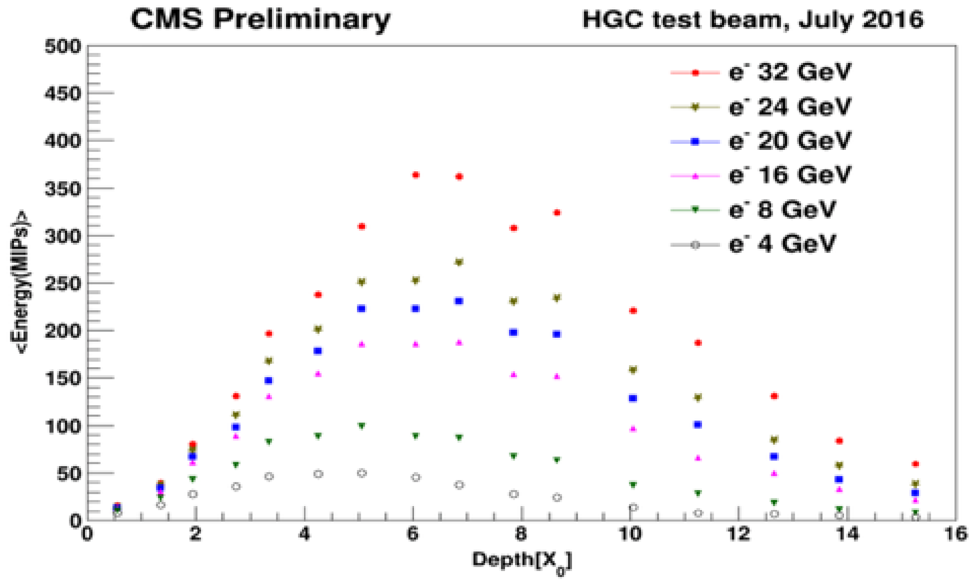
- FNAL

Total energy deposited in all layers vs e- beam energy

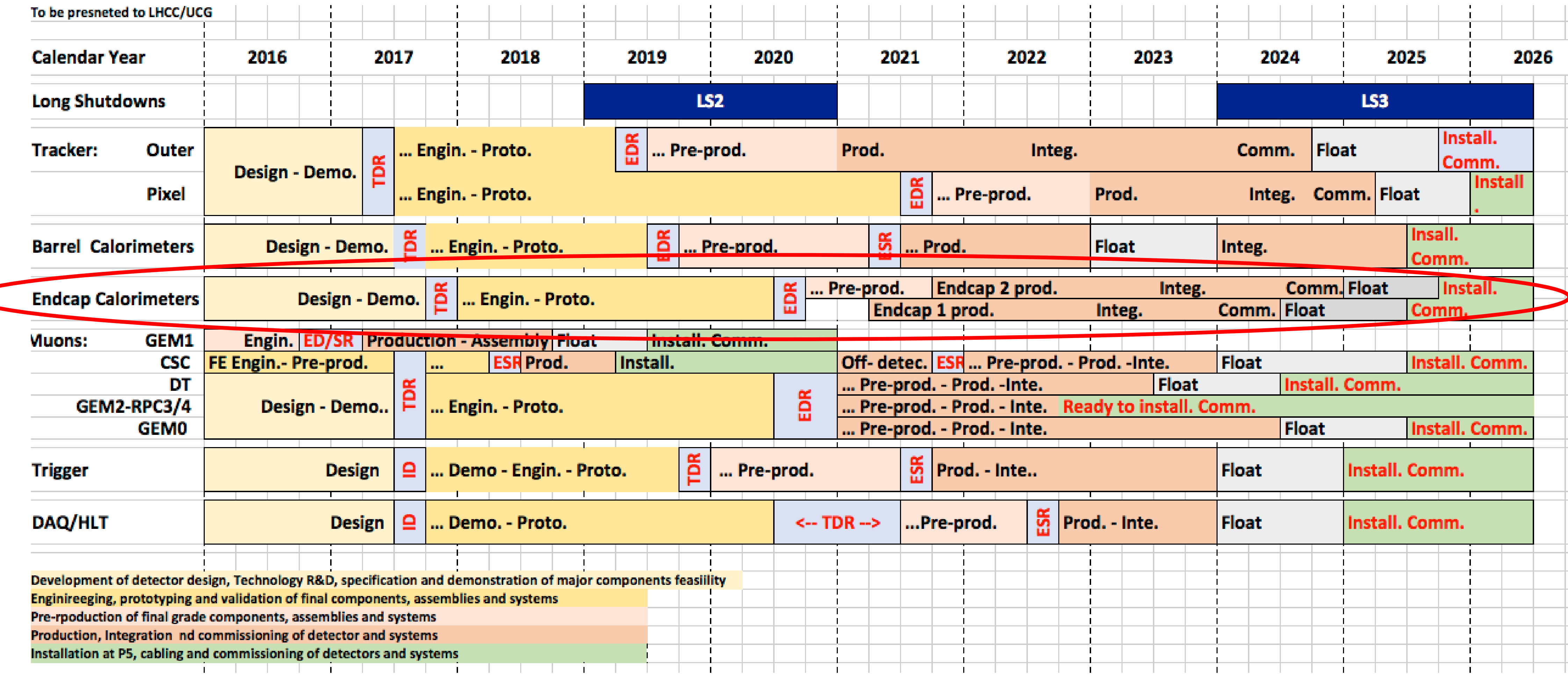


Energy deposited in each layer

Shower max moves to higher depth as expected



HGCAL Timeline



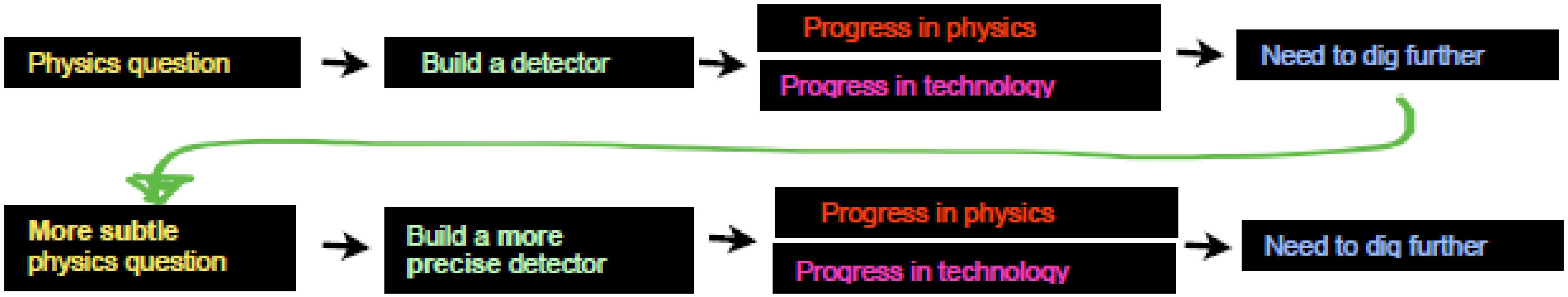
HGCAL Schedule:

- -> 2020 : Prototyping
- 2020 – 2014 : Pre-production et Production
- 2024 – 2026 : Installation

First time a high-granularity 5D (x,y,z,E, t) calorimeter will be installed in an experiment taking data !

Summary / Conclusion (1)

PHYSICS DRIVES the DETECTOR DESIGN



INSTRUMENTATION, DEVELOPMENTS PERMIT ADVANCE in PHYSICS

DETECTOR PERFORMANCE, IN HOSTILE ENVIRONMENT as LHC, REQUIRES THOROUGH DATA ANALYSIS

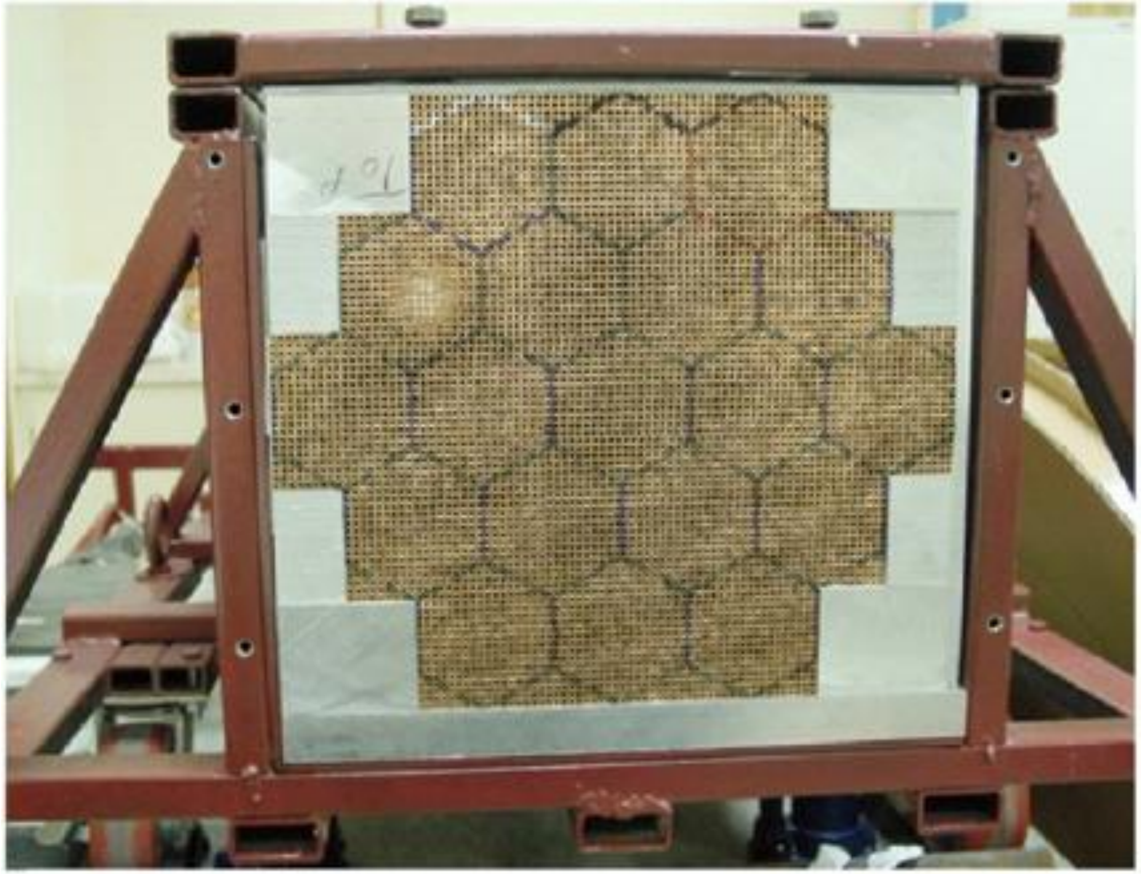
THESE LECTURES HAVE ONLY TOUCHED THE SURFACE of WHAT ALREADY EXISTS.

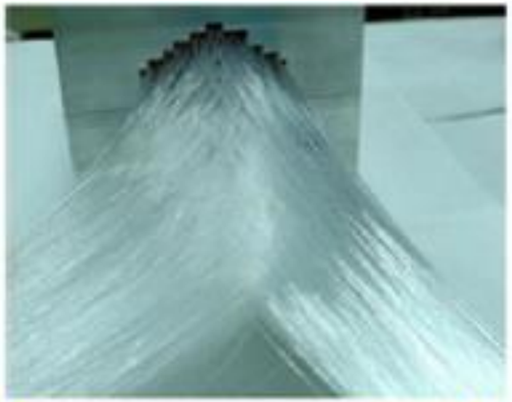
Summary / Conclusion (2)

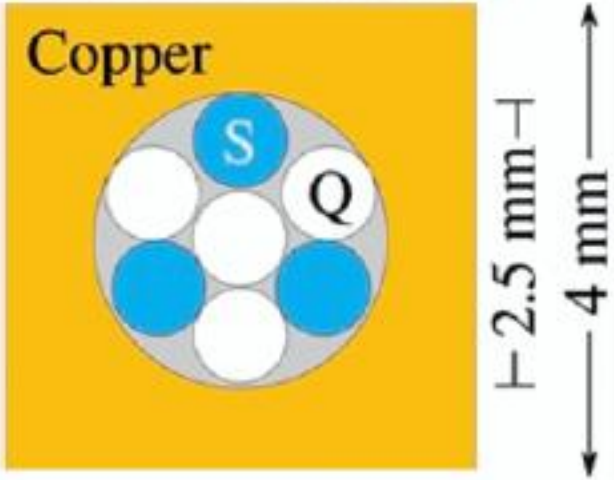
- Calorimetry has been (and is still!) studied for decades
- **Calorimeters plays a unique role in HEP experiments.**
  - Their usage have lead to major discovery in physics (W/Z bosons, top quark, Higgs boson,…)
- **Calorimetry has evolved** from early energy measurement techniques, addressing the problem of the compensation of the intrinsic response to electromagnetic and hadronic showers, **to arrive ultimately at "particle flow" (PFlow) techniques** where the individual contributions of the particles are disentangled.
  - This improves the measurement of jets and allows for a complete and coherent reconstruction of collision events.
- Still, these developments will not kill other types of calorimeters
  - "hardware" compensation is pursued (ex: dual readout calorimeters).
  - "standard" calorimeters (crystals, Pb/scintillating fibers, …) will still be used (and their performance improved), depending on physics case/cost/…
    - Can PFLOW calorimeters play a role at 100 TeV pp colliders ?

BACK UP SLIDES

DREAM prototypes



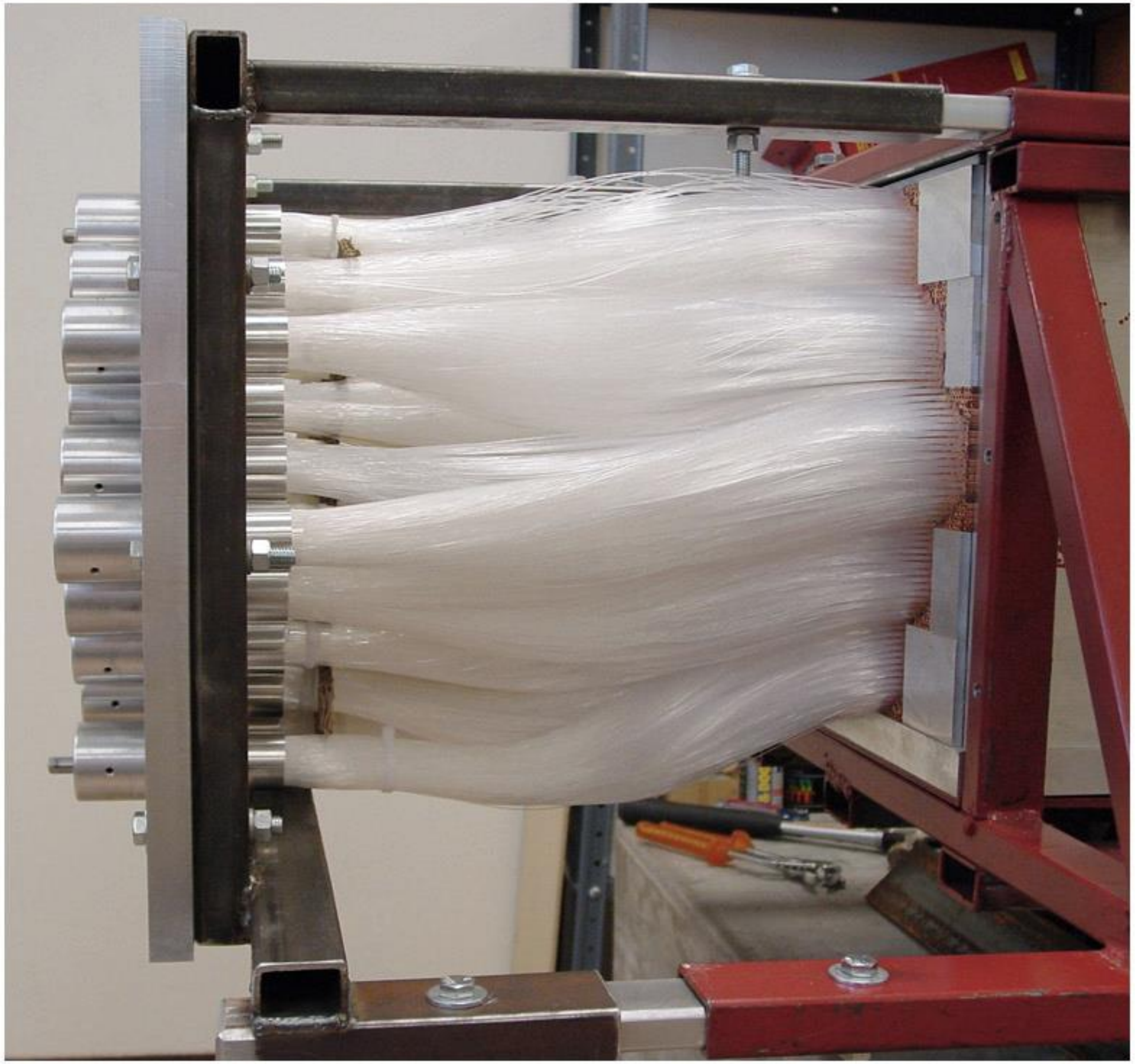




- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length $\approx$ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

DREAM prototype

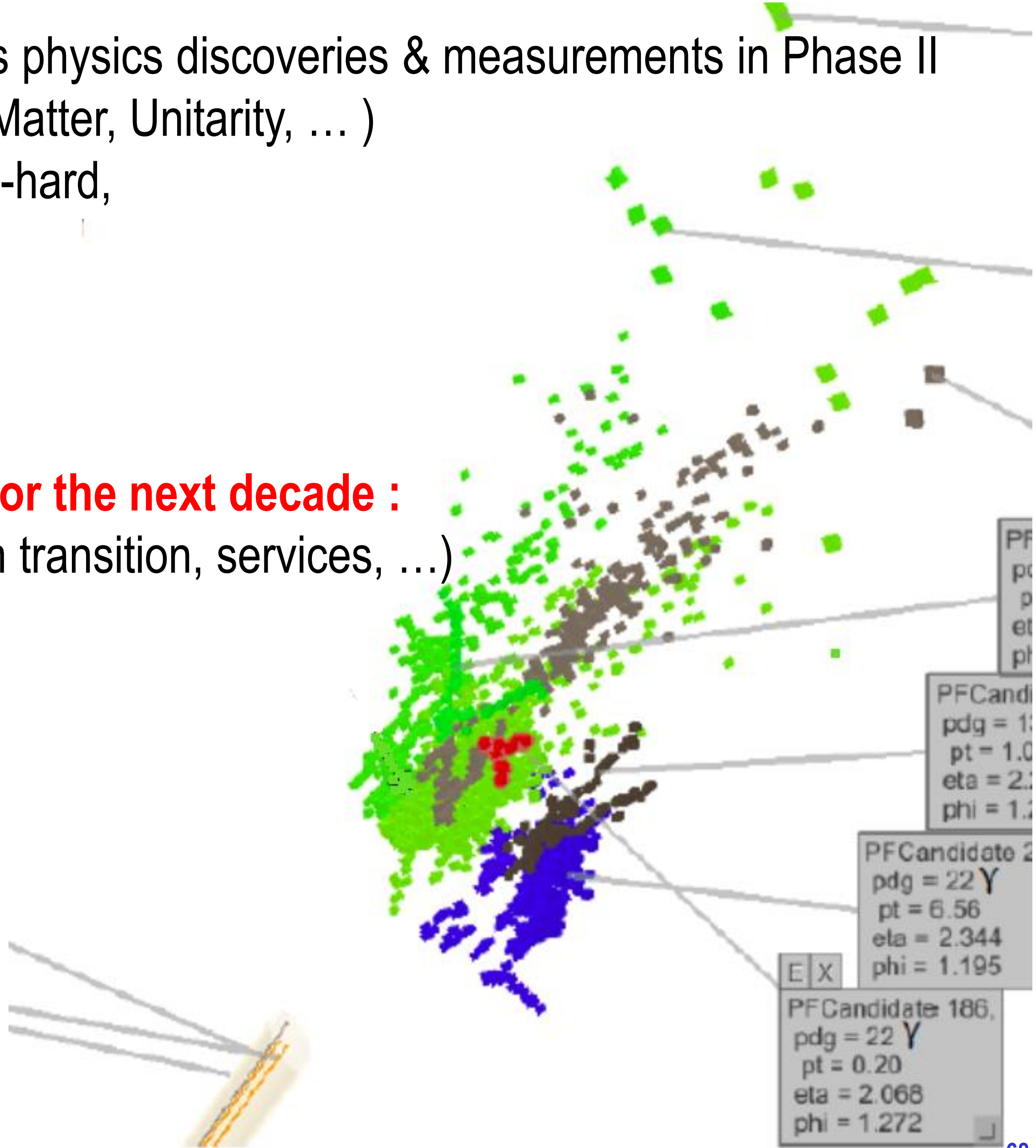
DREAM readout



Conclusion & Perspectives (1)

➢ HGCAL is on the critical path towards physics discoveries & measurements in Phase II (HH, VBF jets for Higgs/SUSY/Dark Matter, Unitarity, …)
and has all ingredients for being rad-hard,
mitigate PU,
deal with high rates,…

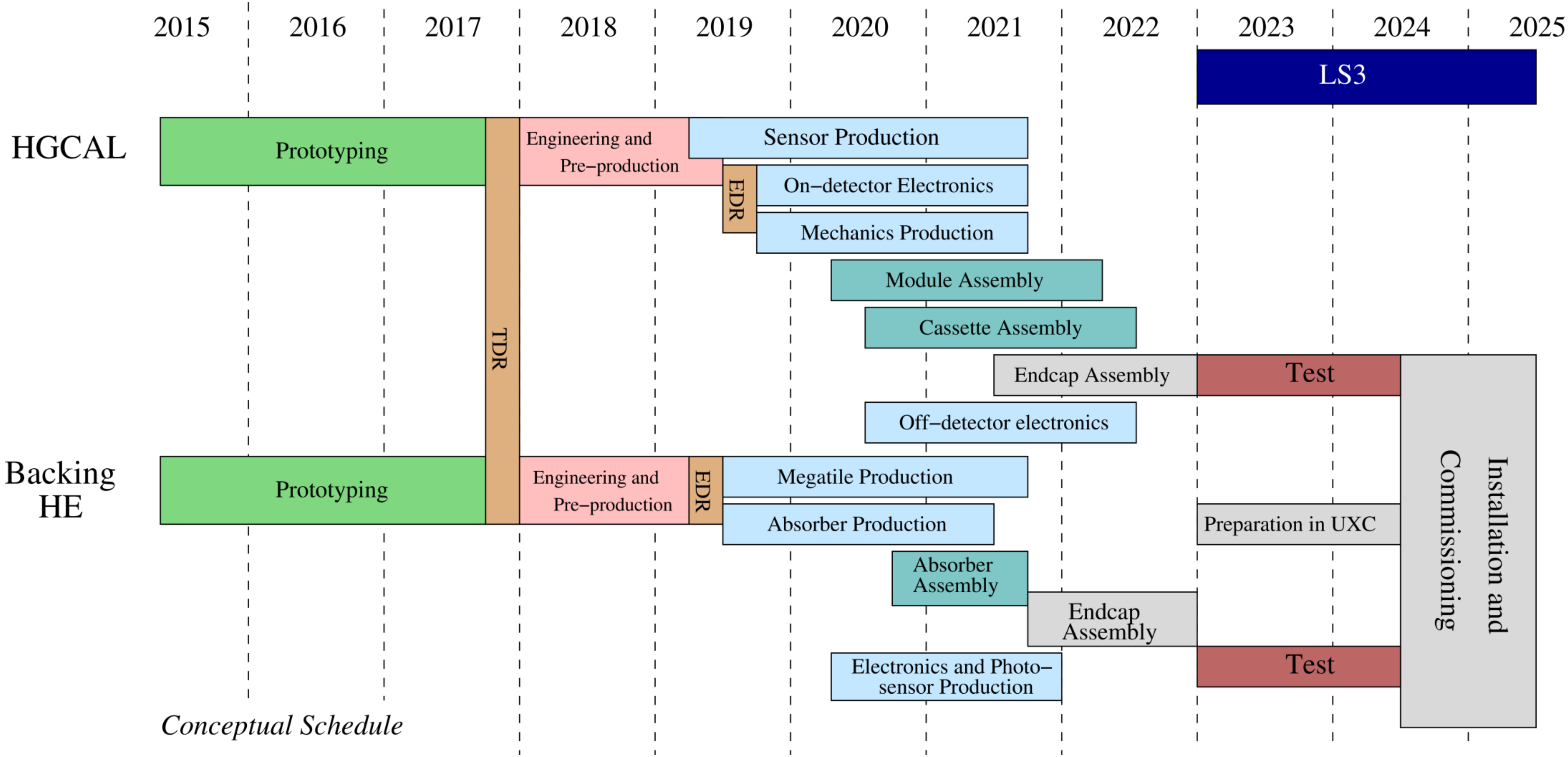
➢ **Many major & excited challenges for the next decade :**
- Engineering (includes cold/warm transition, services, …)
- FE electronics & L1 Trigger
- Software, computing
- …



Conclusion & Perspectives (2)

- **Now in R&D phase**
  - Fast progress since Technical Proposal (mechanics, sensors & modules, FE, …)
  - Several **test beams session scheduled this year** (FNAL, CERN)
  - **TDR expected end of 2017**, including key technical choices
  - Construction starts in ~2019

See talk by Z. Gecse (test beam)



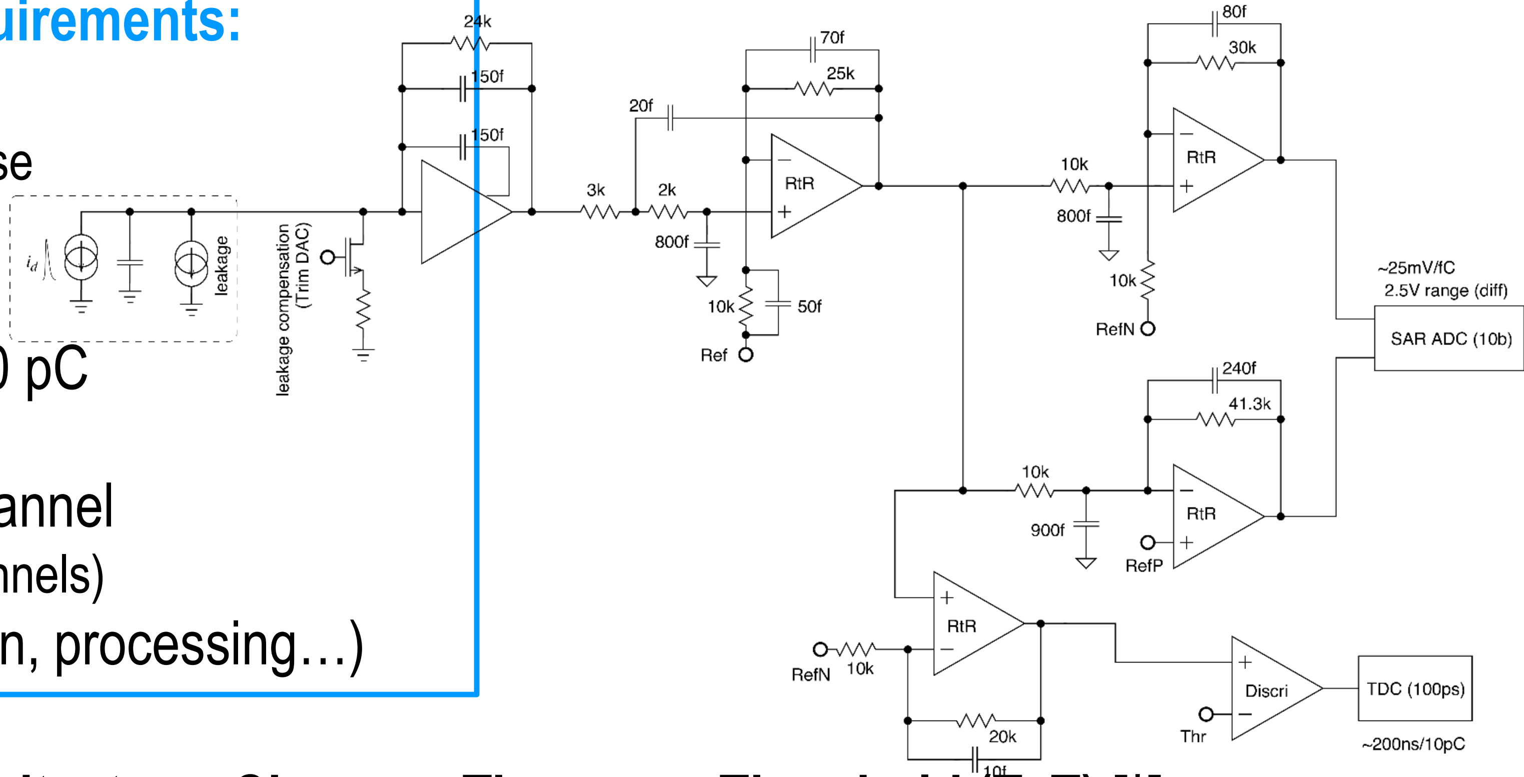
Front-End Electronics (1)

One of the most challenging aspect of the project !

Need to have large dynamic range @ low power + low noise

➢ (stringent) Requirements:

- **Low Noise**: ~ 2000 e-
  - including sensor I_{leak} noise
- Shaping Time: 10-20 ns
  - Pulse Shape is 1-2 ns
- Dynamic Range: up to ~10 pC
  - ~3000 MIP in 300μm Si
- **Low Power**: ~10 mW / channel
  - (Σ = 100 kW for 6M channels)
- System on chip (digitization, processing…)



➢ Baseline architecture: Charge + Time-over-Threshold (ToT) [*]

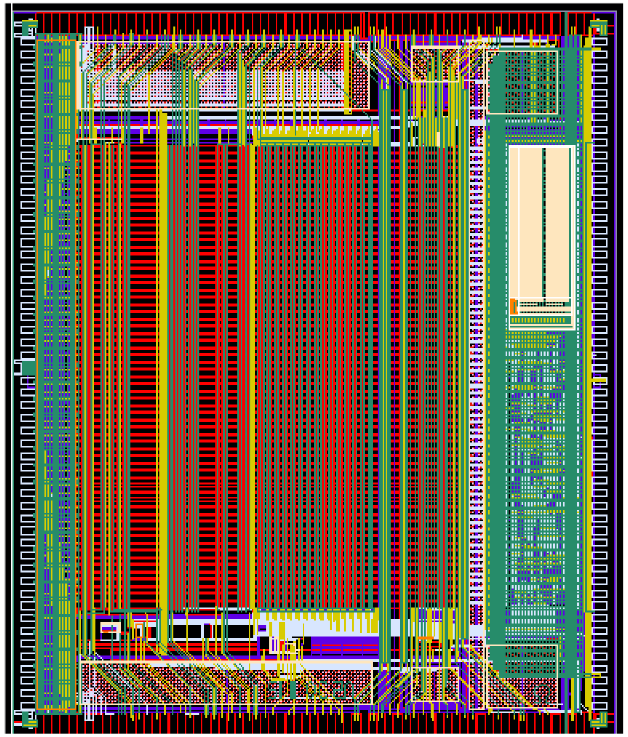
- Switch from charged readout to ToT at ~100 fC
- ADC (10 bits) and TDC (12 bits) with existing designs
- Potential for 50 ps timing per cell

[*] alternative: more classical readout (bi-gain) or switched feedback

Front-End Electronics (2)

One of the most challenging aspect of the project !

Need to have large dynamic range @ low power + low noise



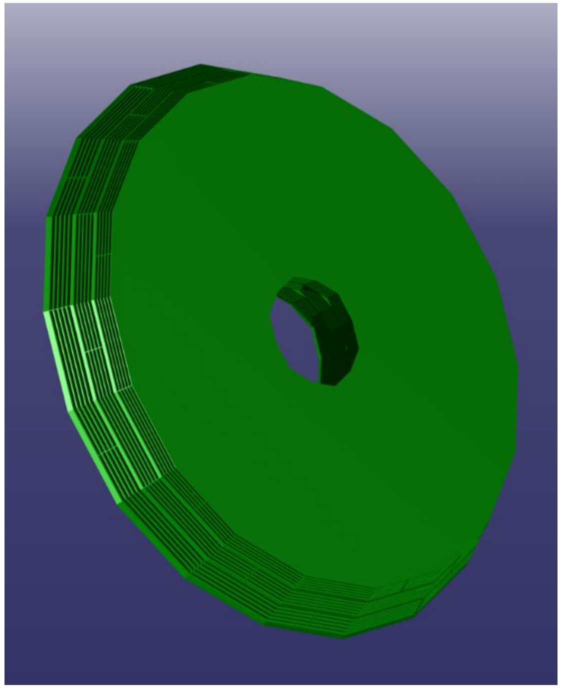
➢ **SKIROC2_CMS** (not the final chip)**:**

- Includes some of the HGC features:
  - ~20ns shaping time and 40MHz sampling
  - ADC + TOA (~50ps) + TOT
  - P-on-N and N-on-P read-out options
- **Production launched in January, Available in ~June**
- Plan to use it for CERN test beams (Fall)
  - after tests on board (noise, stability, linearity, crosstalk, …)

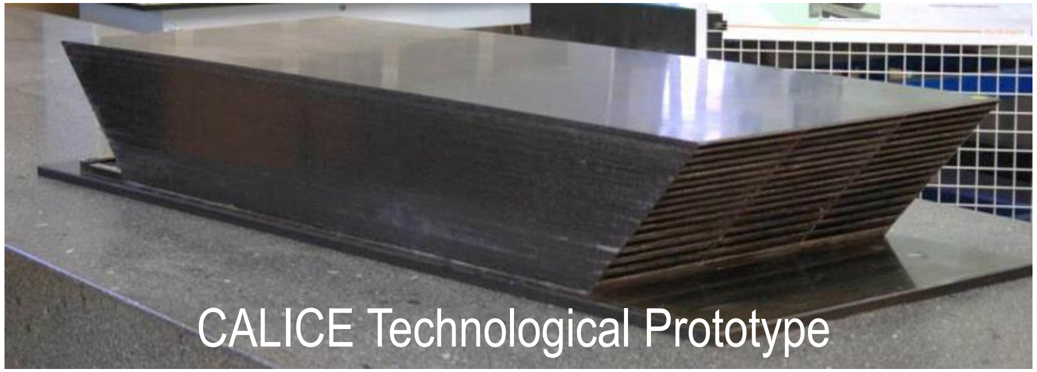
- Also: test vehicles on blocks launched (TSMC 130nm)
- **First iteration of full chip expected by Spring 2017.**
  - with feedback from test vehicles & SKIROC2_CMS

Modules, Cassettes & Mechanics (Structures)

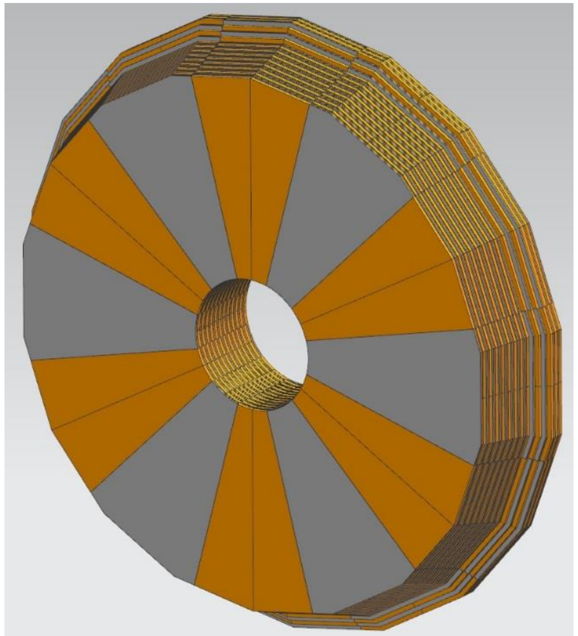
HGC-EE: C-fiber Alveolar structure with embedded W plates



Inspired from CALICE Si/W

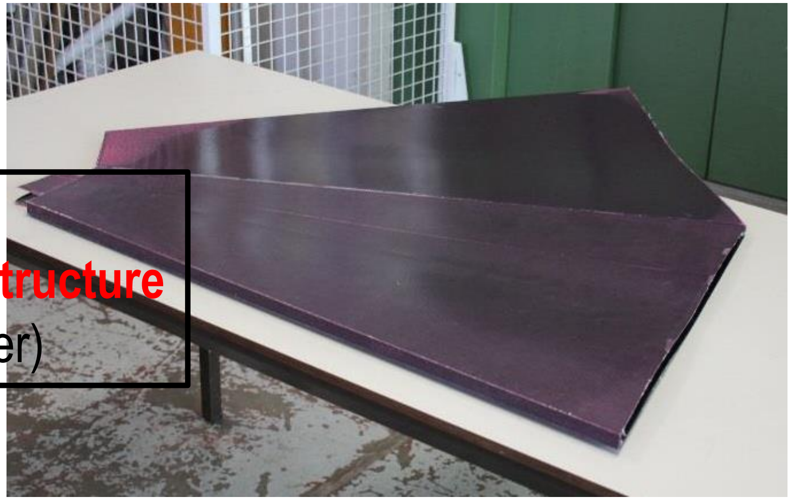


HGC-HCAL Structure (similar to current HE)



Will evolve if absorber=steel to minimize machining

Cassettes inserted in **mechanical structure** (containing absorber)



C-fiber "petal" alveolar prototypes