Advanced Calorimetry

R&D Trends on calorimetry for existing and future collider facilities

- Calorimeter systems @ LHC and their evolutions:
    - Overview existing detector technologies
    - Longevity challenges of the systems and upgrade plans for HL-LHC
- Dual Readout Detectors
    - DREAM/RD52
    - Inorganic scintillator R&D @ CERN (P. Lecoq)
- Calorimeter R&D for ILC/CLIC
    - Particle Flow Algorithm
    - SiW ECAL
    - HCAL R&D

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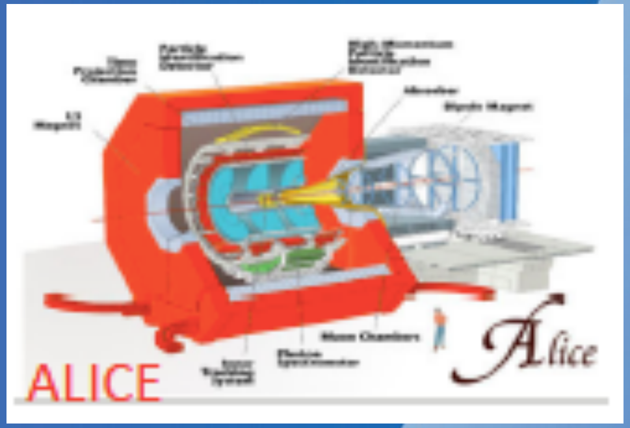
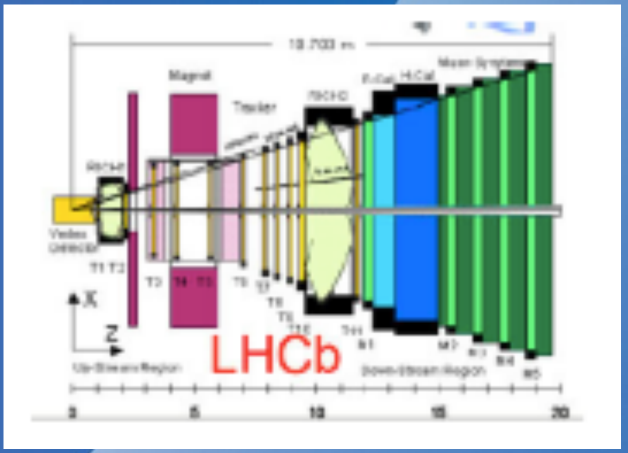
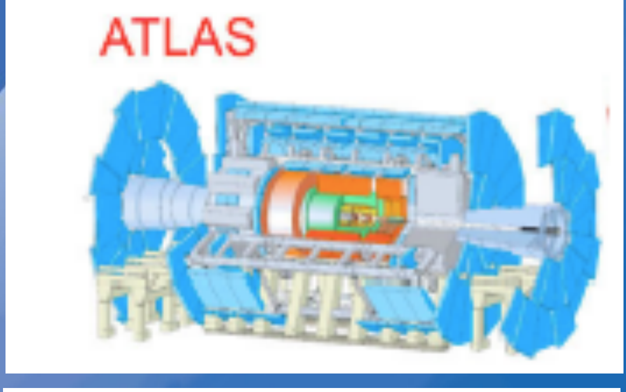
Brookhaven National Laboratory

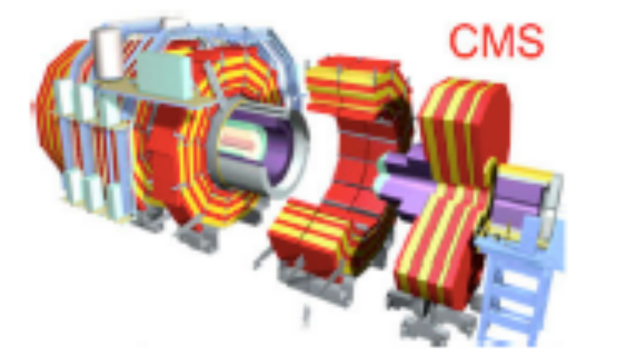
Technologies used in the LHC calorimeters

- $PbWO_4$ homogeneous calorimeter:
  - CMS ECAL, ALICE PHOS
- LAr sampling calorimeter:
  - ATLAS EM Barrel and Endcap, Hadronic Endcap, Forward calorimeters
- Scintillator/WLS fiber sampling calorimeters:
  - CMS HCAL Barrel and Endcap, ATLAS TileCal (barrel HCAL), LHCb HCAL
- Shashlik Pb/Scint sampling calorimeters:
  - ALICE EMCal/DCal, LHCb ECAL
- Quartz Fiber/Steel sampling calorimeter:
  - CMS HCAL Forward









Upgrade Roadmap in the next two decades

2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	...	2030
	LS1					LS2					LS3		

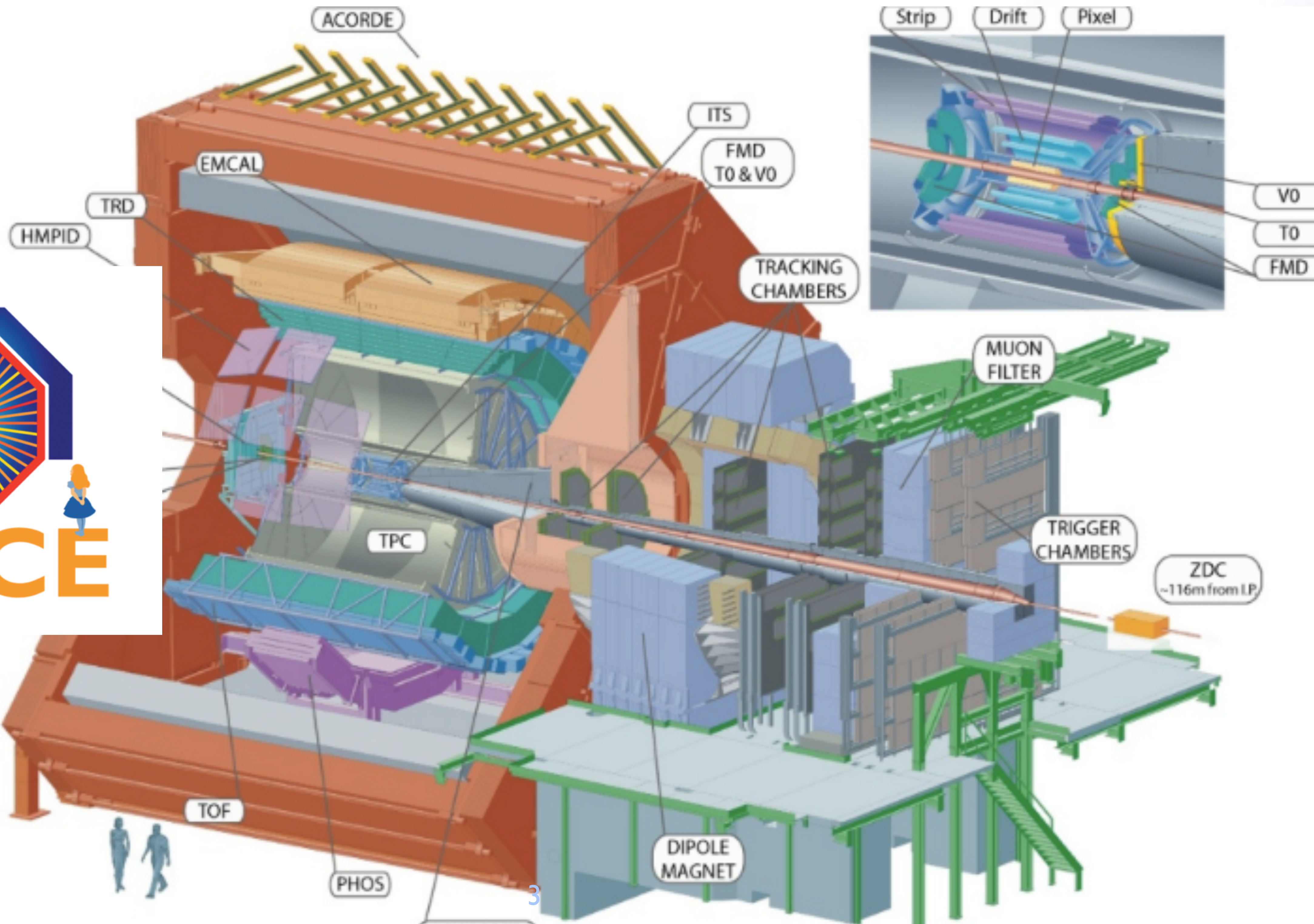
Detector Consolidation

Phase-I Upgrades

Phase-II Upgrades

Detectors

Electronics and Trigger



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Detector Consolidation

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Phase-II Upgrades

EMCal extension (DCal):

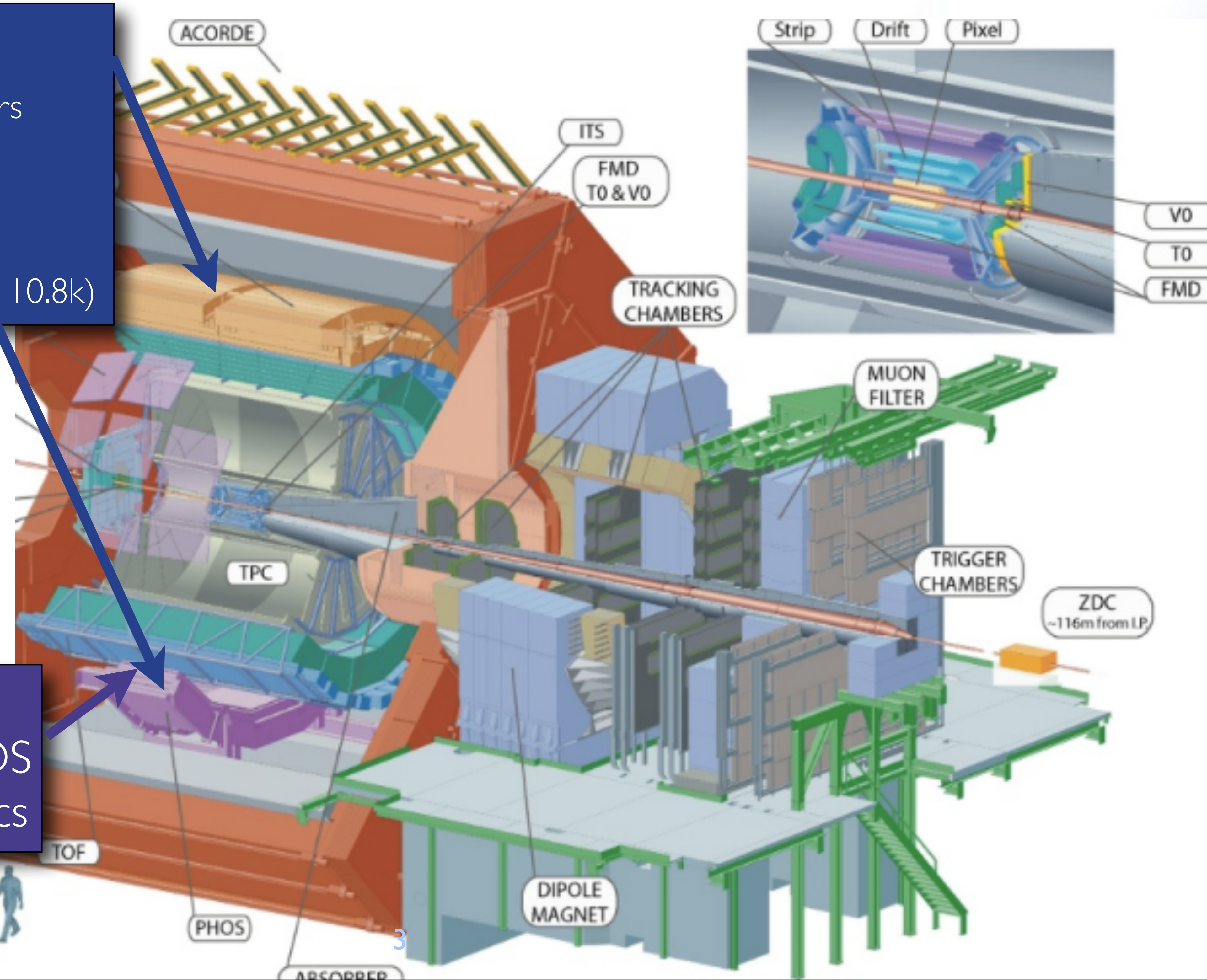
- 17.7k Pb/Scint Shashlik towers (from 12.3k)

PHOS 4th module installation:

- 14.3k $PbWO_4$ crystals (from 10.8k)

D

Electronics and Trigger



Upgrade of the EMCAL and PHOS readout electronics

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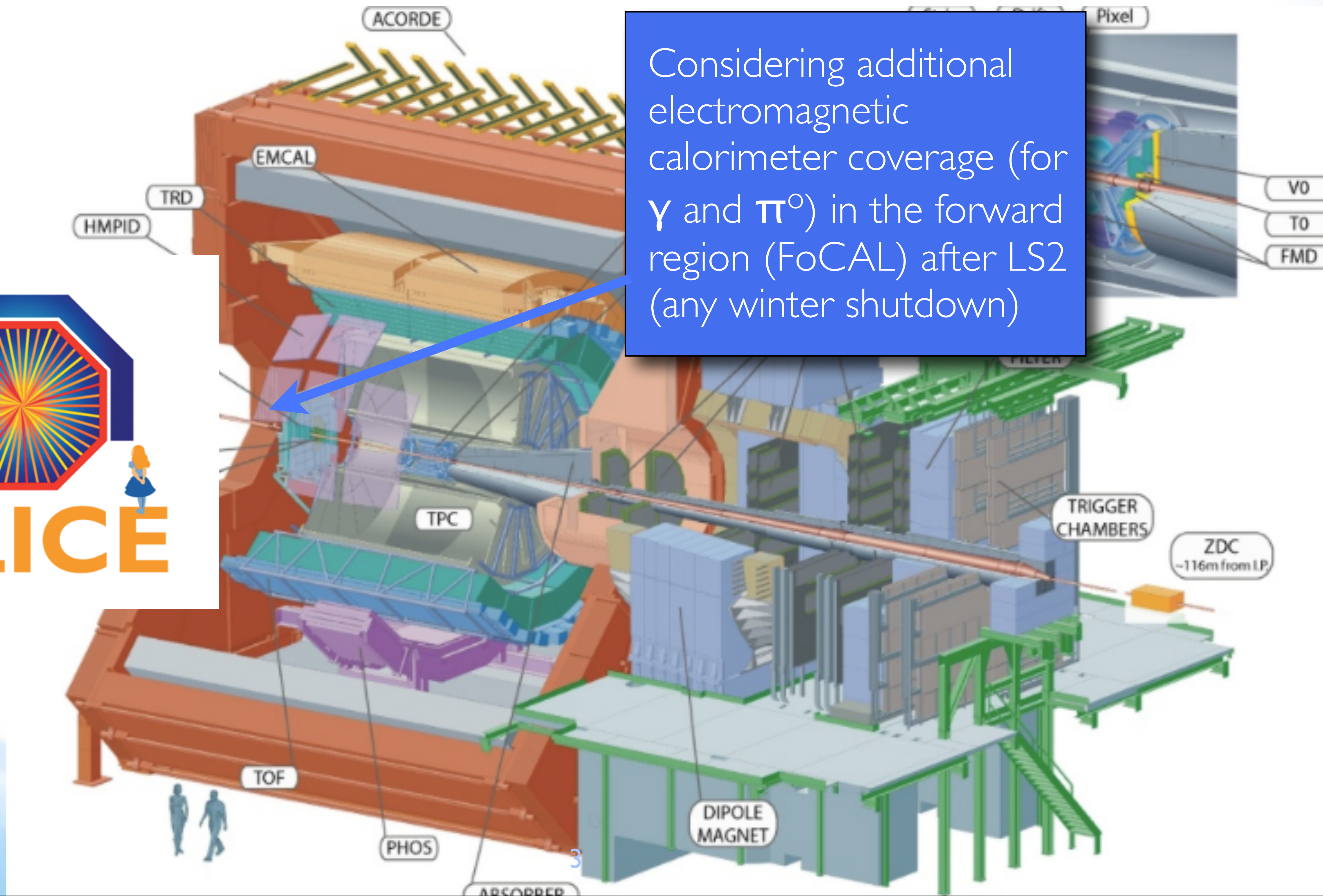
Detector Consolidation | Phase-I Upgrades | Phase-II Upgrades

Detectors

Electronics and Trigger

Considering additional electromagnetic calorimeter coverage (for γ and π^0) in the forward region (FoCAL) after LS2 (any winter shutdown)



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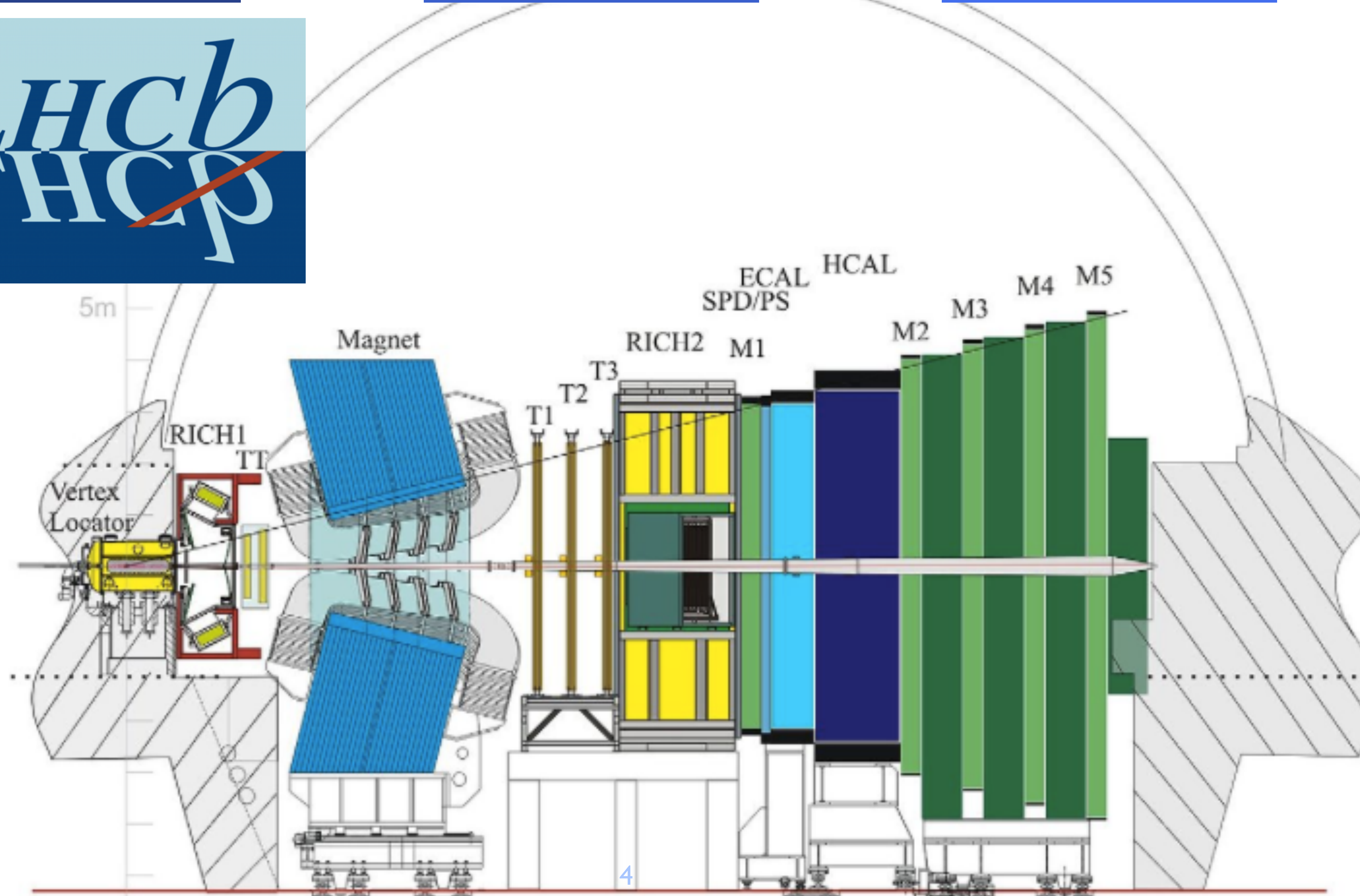

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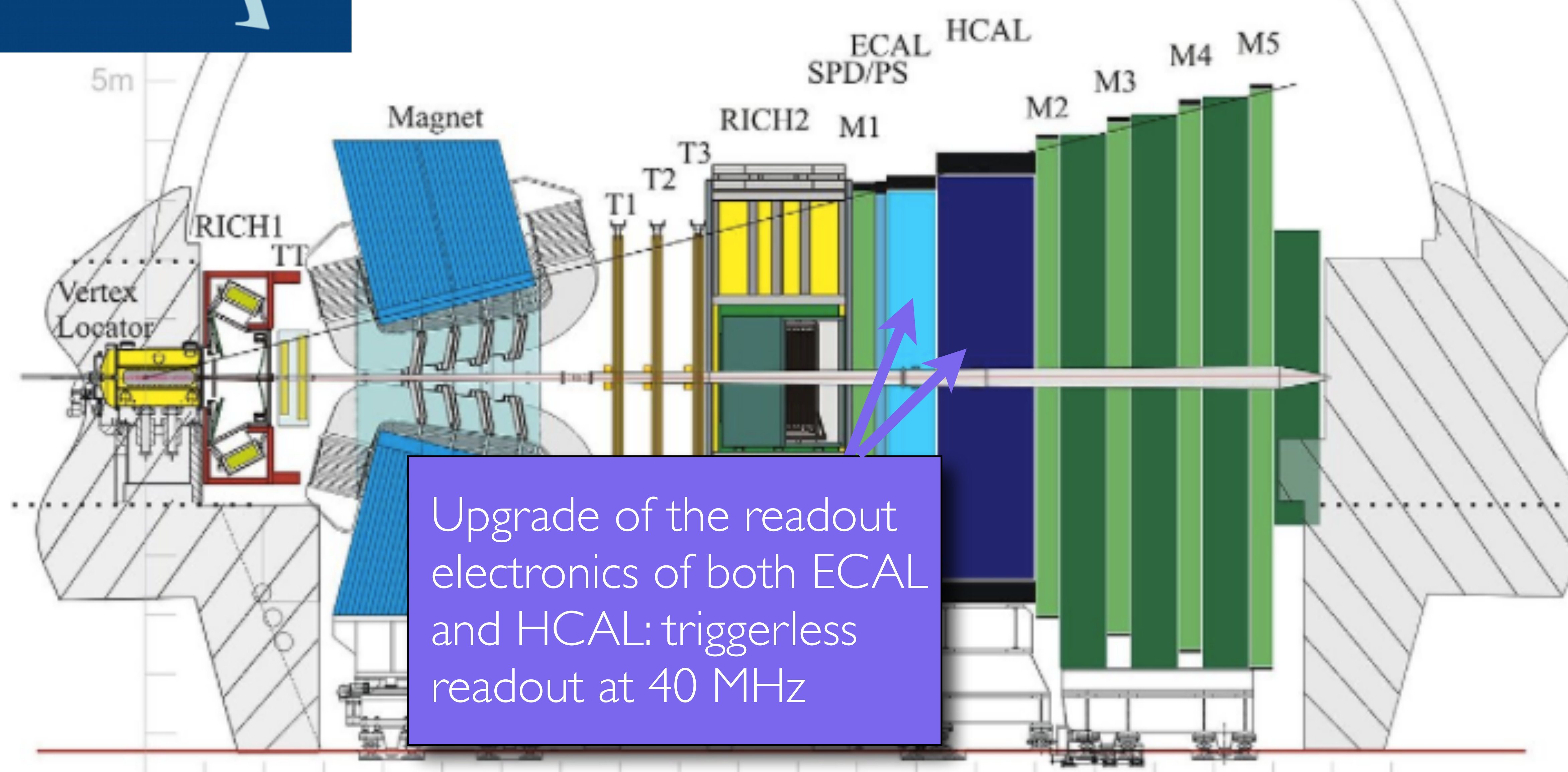

Upgrade of the readout electronics of both ECAL and HCAL: triggerless readout at 40 MHz

Upgrade Roadmap in the next two decades

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Detector Consolidation

Phase-I Upgrades

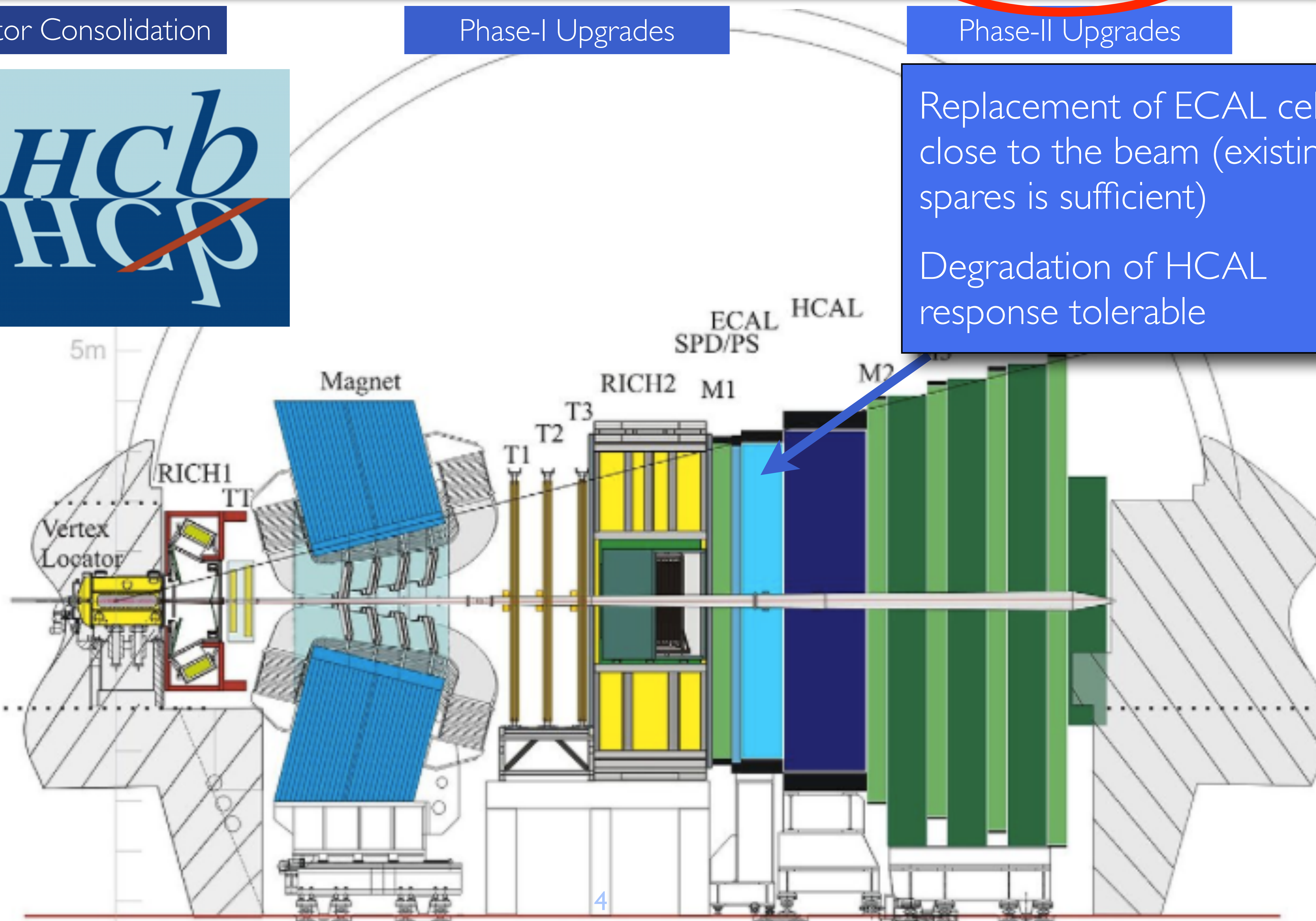
Phase-II Upgrades

Detectors

Electronics and Trigger

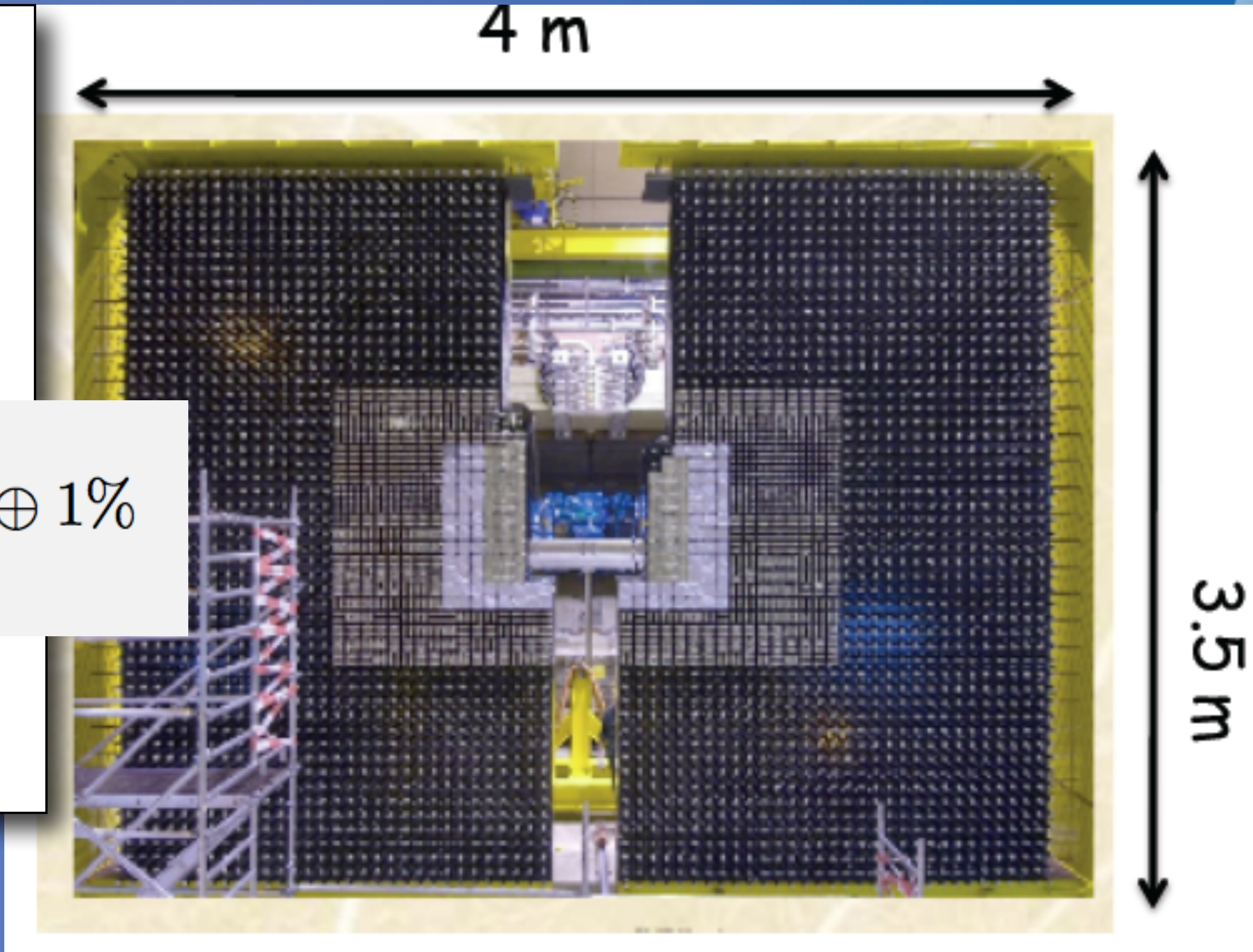
Replacement of ECAL cells close to the beam (existing spares is sufficient)

Degradation of HCAL response tolerable



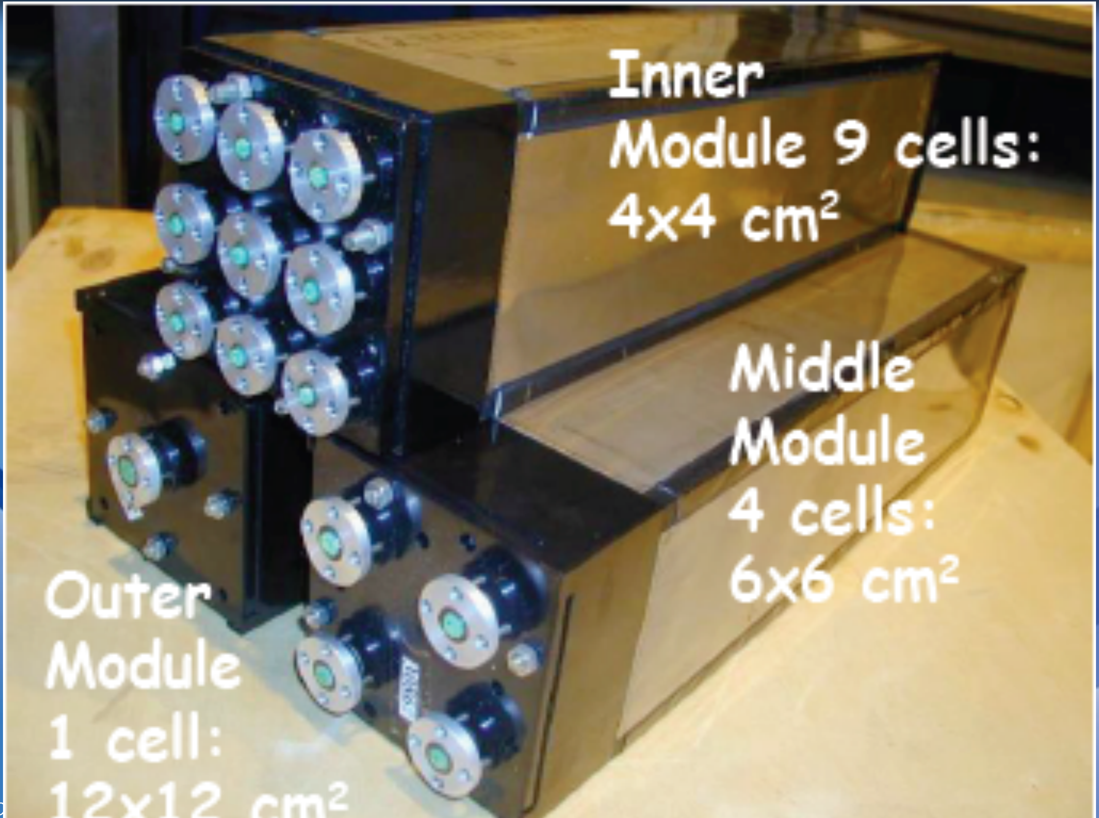
LHCb ECAL

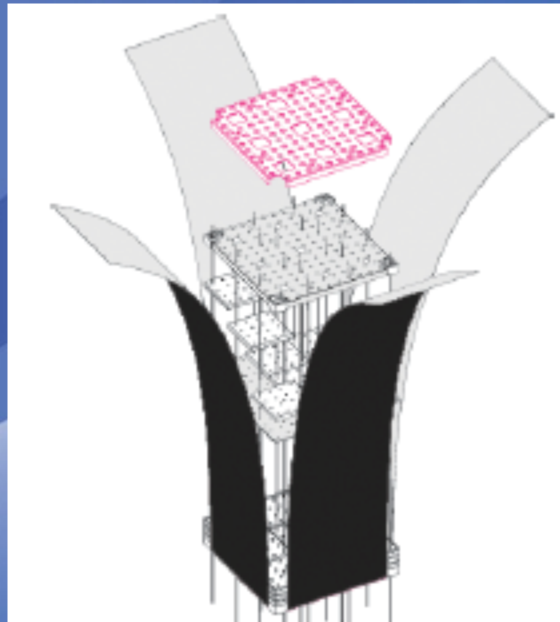
- Shashlik technology
  - 66 layers alternating scintillator (4mm)/Pb (2mm) → 25 Xo
  - Light collection by WLS fibers
  - Readout by multi-anode PMT



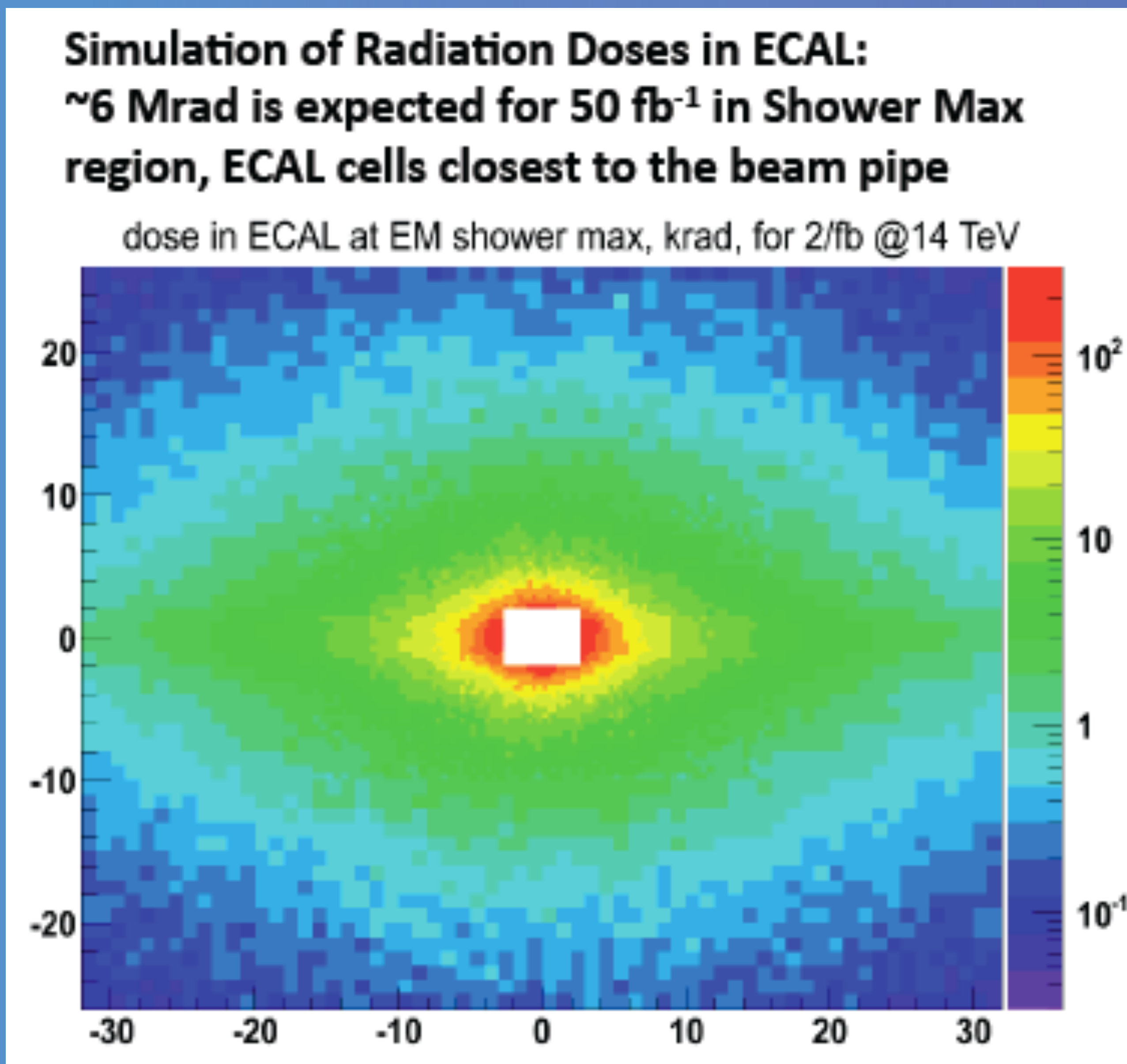
- Requirements:
  - Energy Resolution:
  - Fast response ~25ns
  - Stable operation under high radiation rate
  - Small lateral segmentation

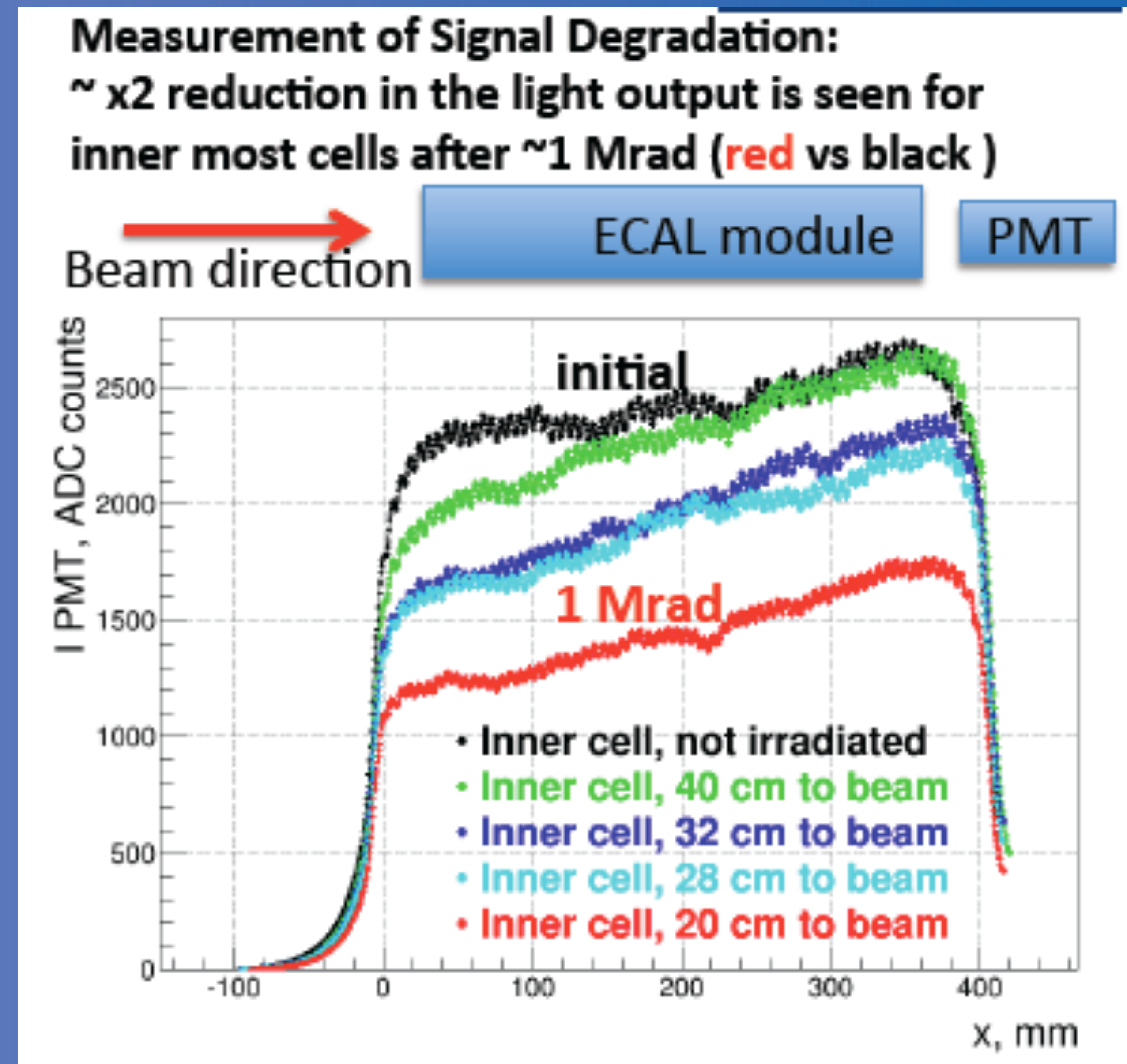
$$\frac{\sigma}{E} = \frac{10.0\%}{\sqrt{E}} \oplus 1\%$$





LHCb ECAL Longevity





- Reduction by x5 is acceptable from resolution point of view. Satisfactory till LS3
- LHCb plans replacement of ECAL central modules (48 out of 6000) with spare ones during LS3

Upgrade Roadmap in the next two decades

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Phase-I Upgrades

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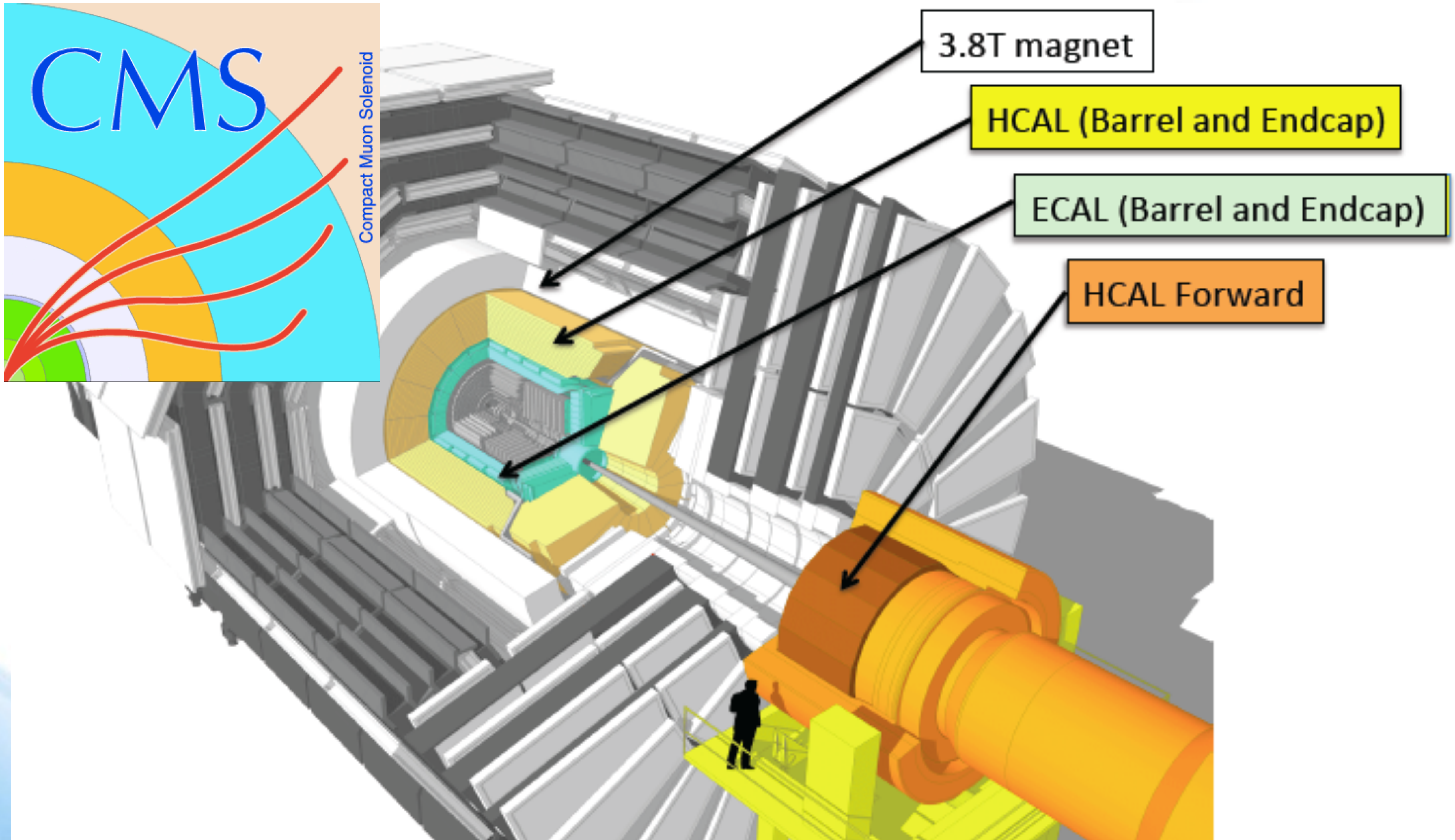
Electronics and Trigger



Upgrade Roadmap in the next two decades

CERN · ALICE · ATLAS EXPERIMENT http://atlas.ch · CMS · LHCb

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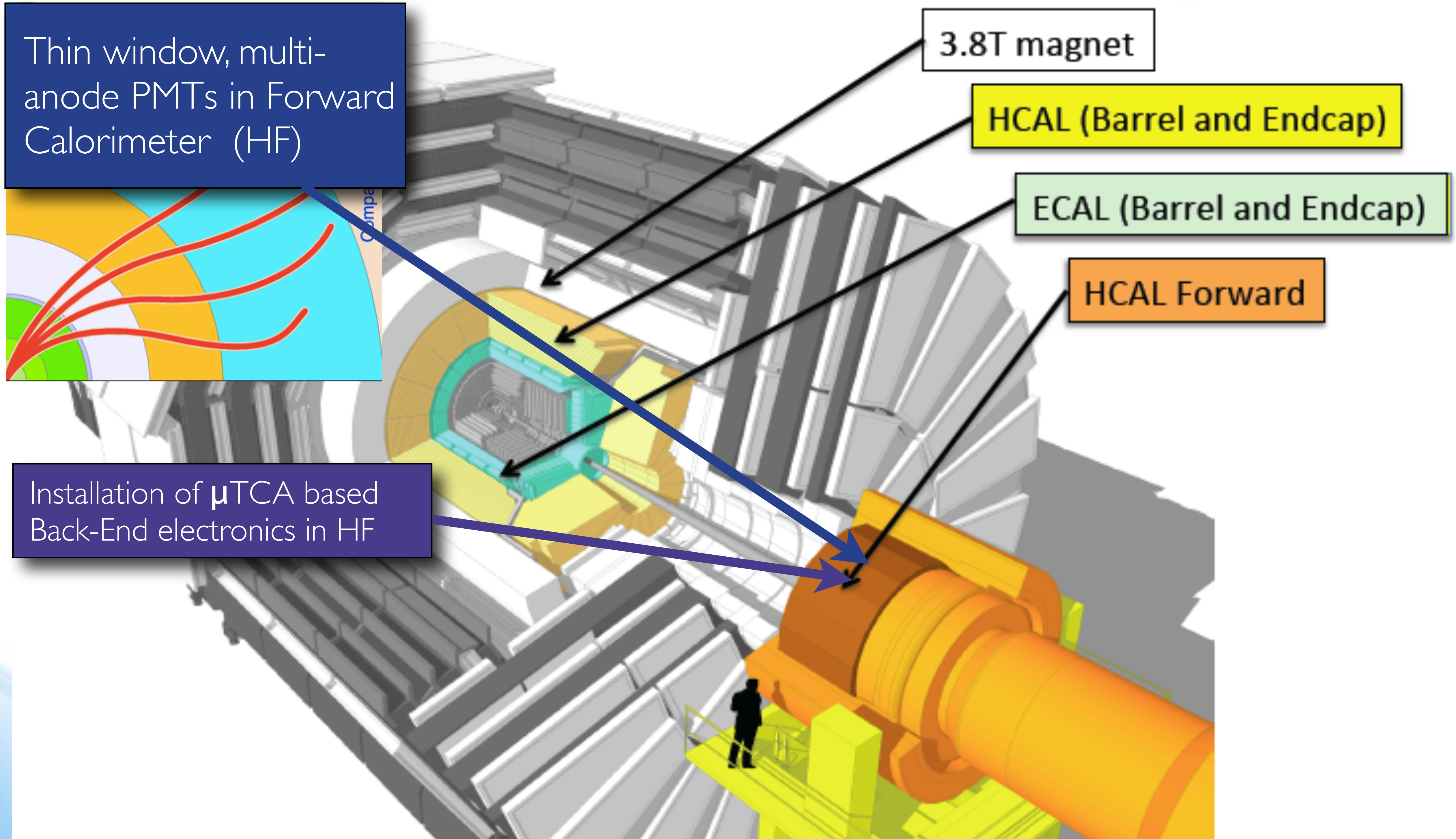

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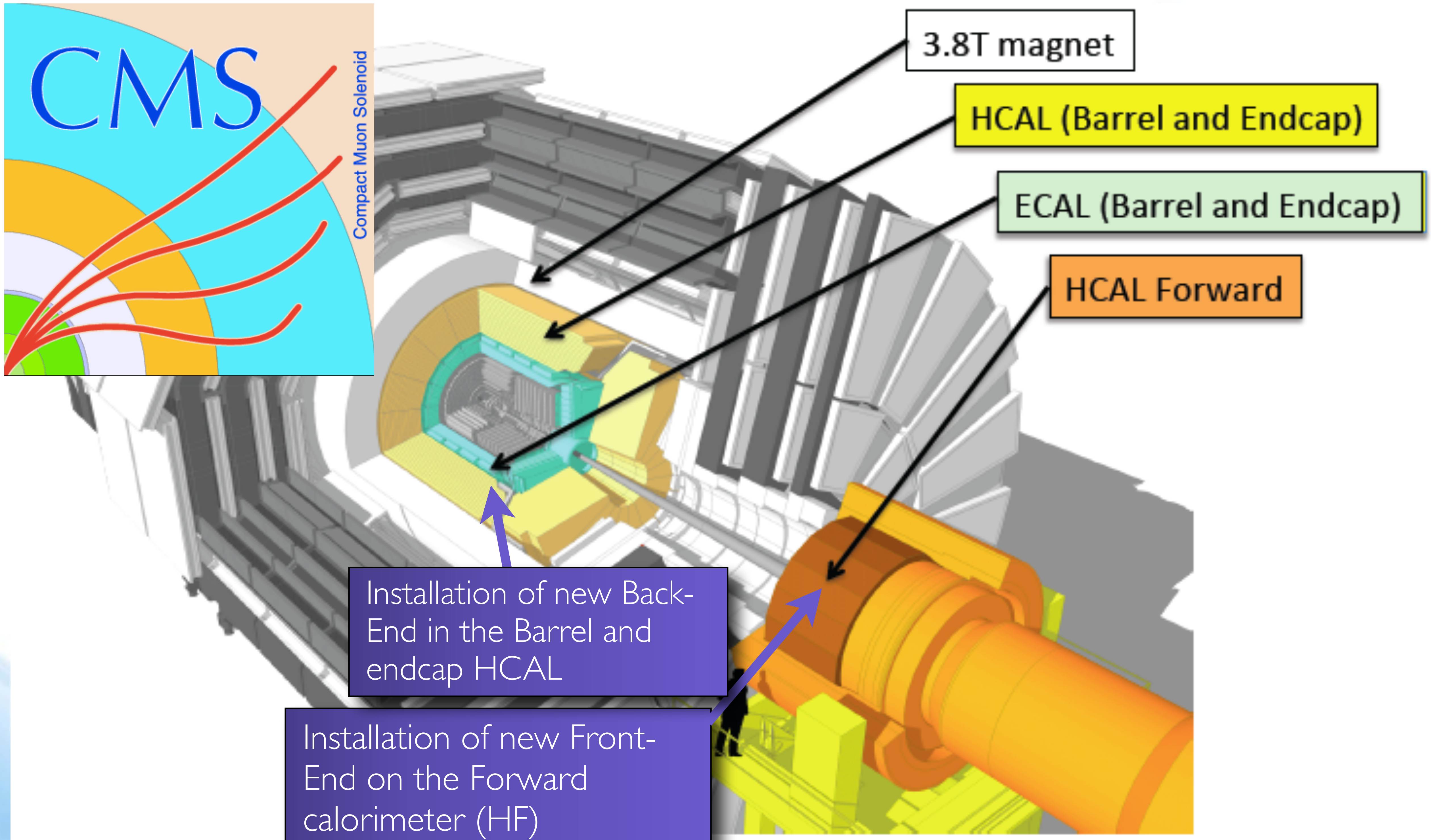

Electronics and Trigger

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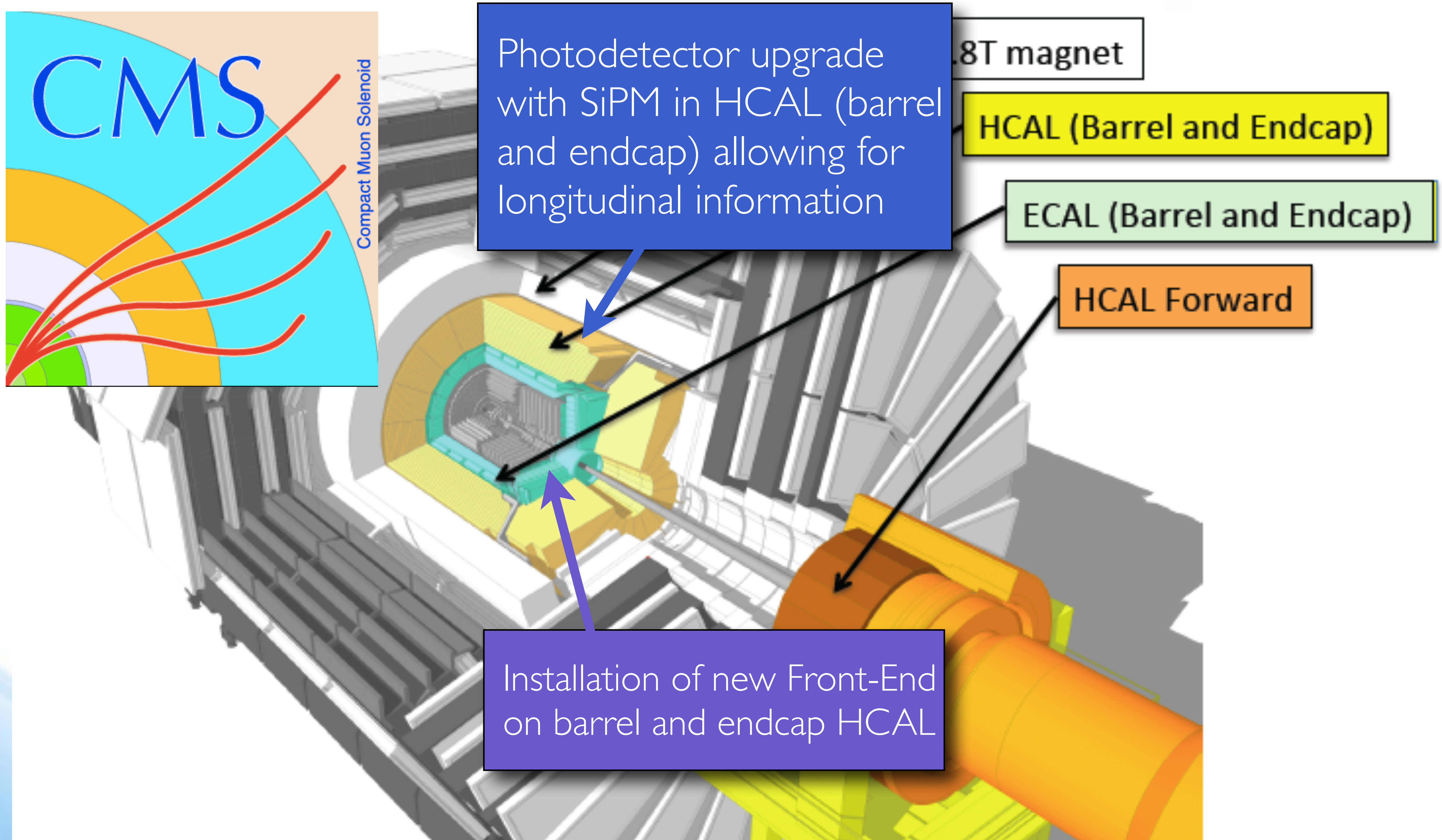
Detectors

Electronics and Trigger



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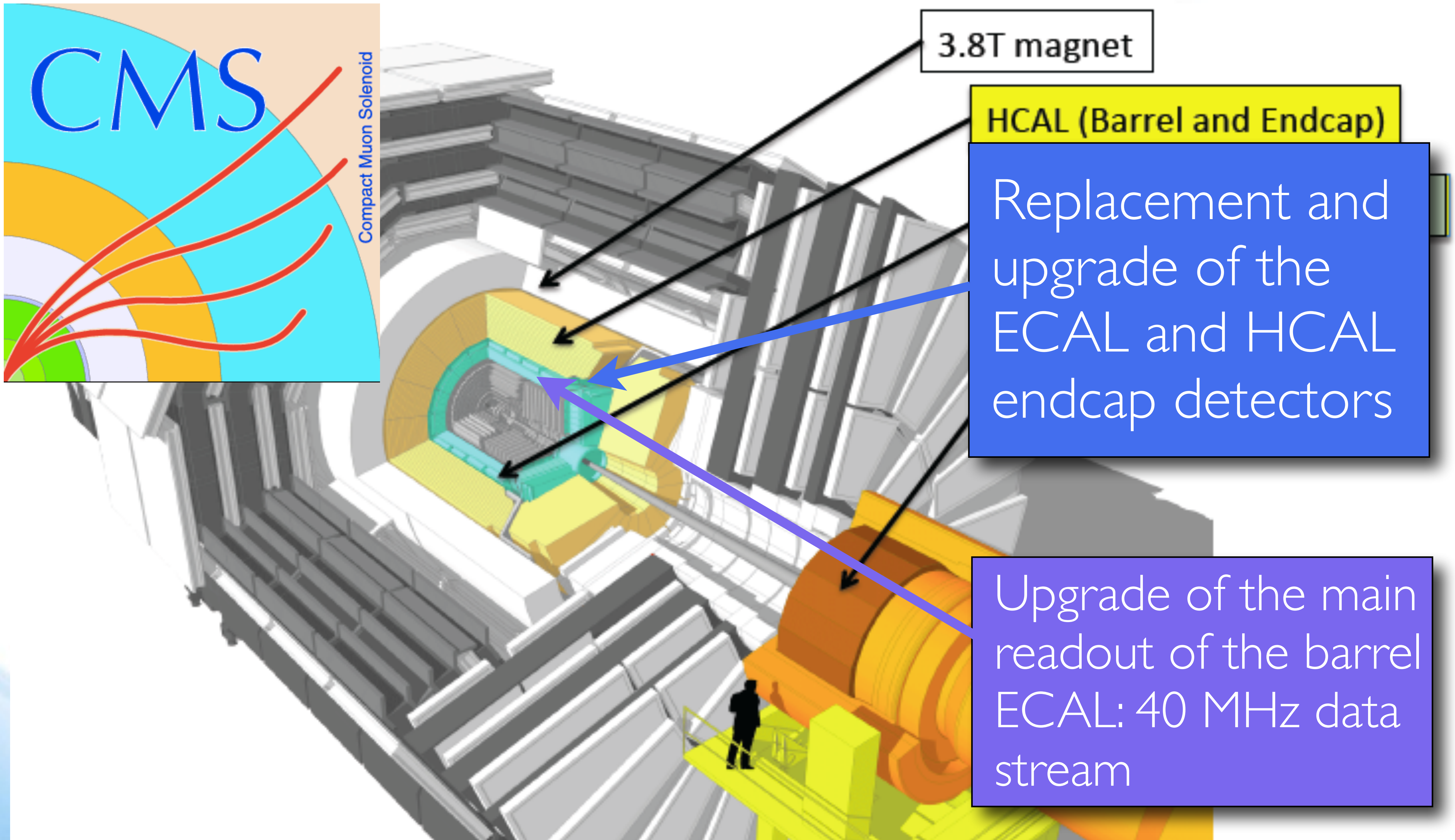
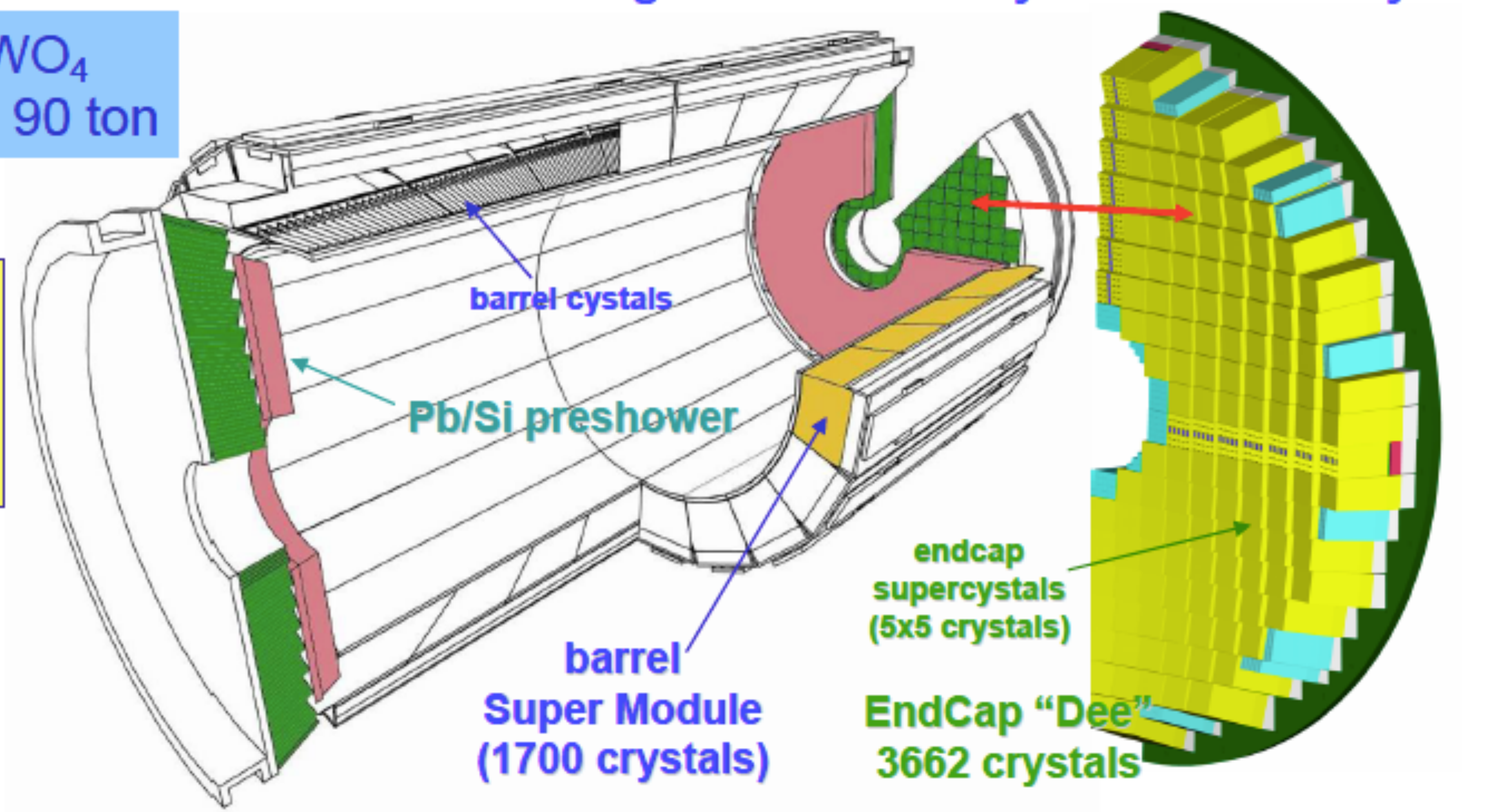


CMS ECAL

Precision electromagnetic calorimetry: 75848 PWO crystals

PWO: $PbWO_4$
about 10 m³, 90 ton

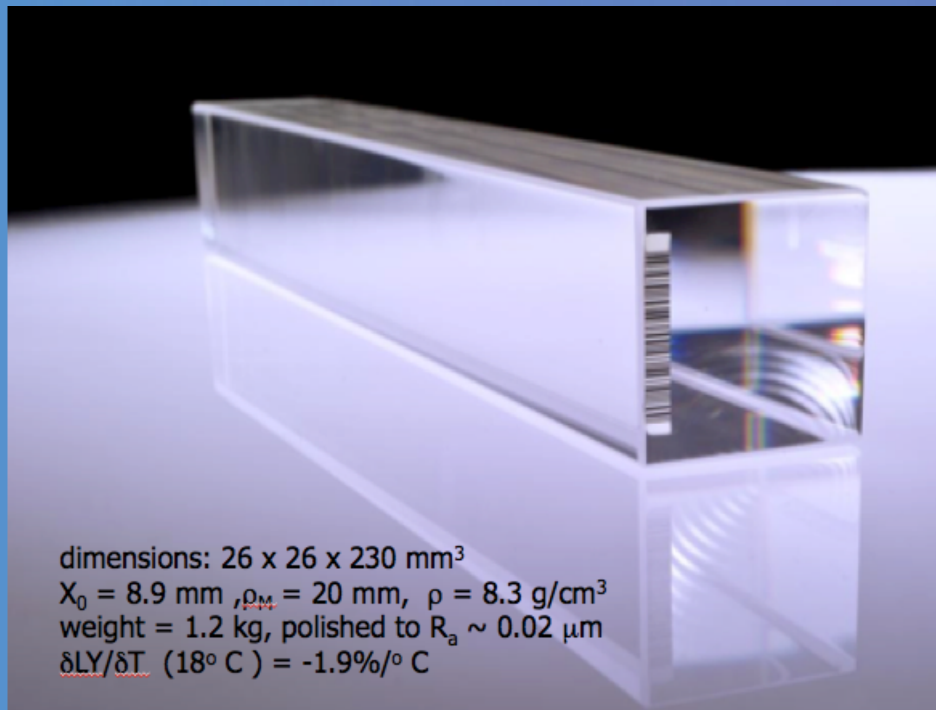
Previous Crystal calorimeters: max 1m³

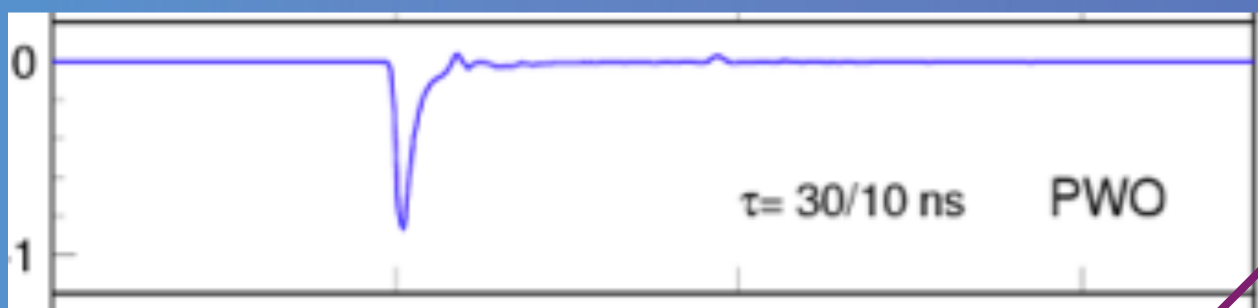


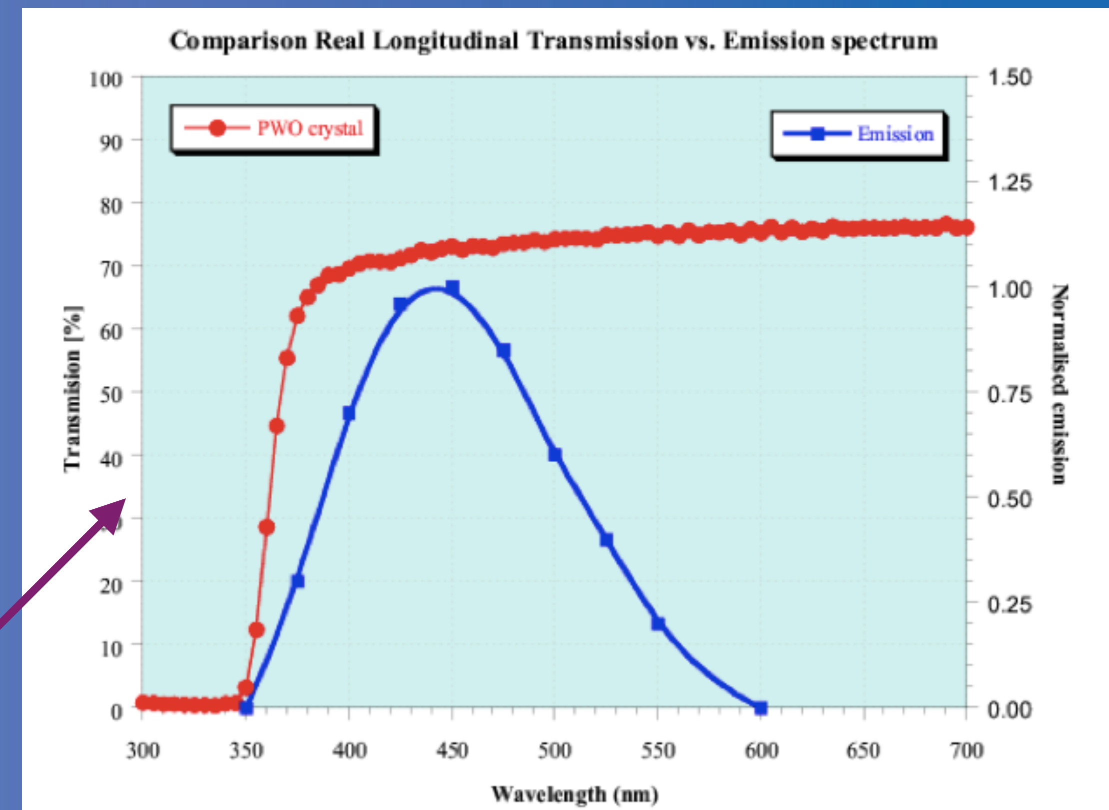
Barrel: $|\eta| < 1.48$
36 Super Modules
61200 crystals (2x2x23cm³)

EndCaps: $1.48 < |\eta| < 3.0$
4 Dees
14648 crystals (3x3x22cm³)

CMS ECAL



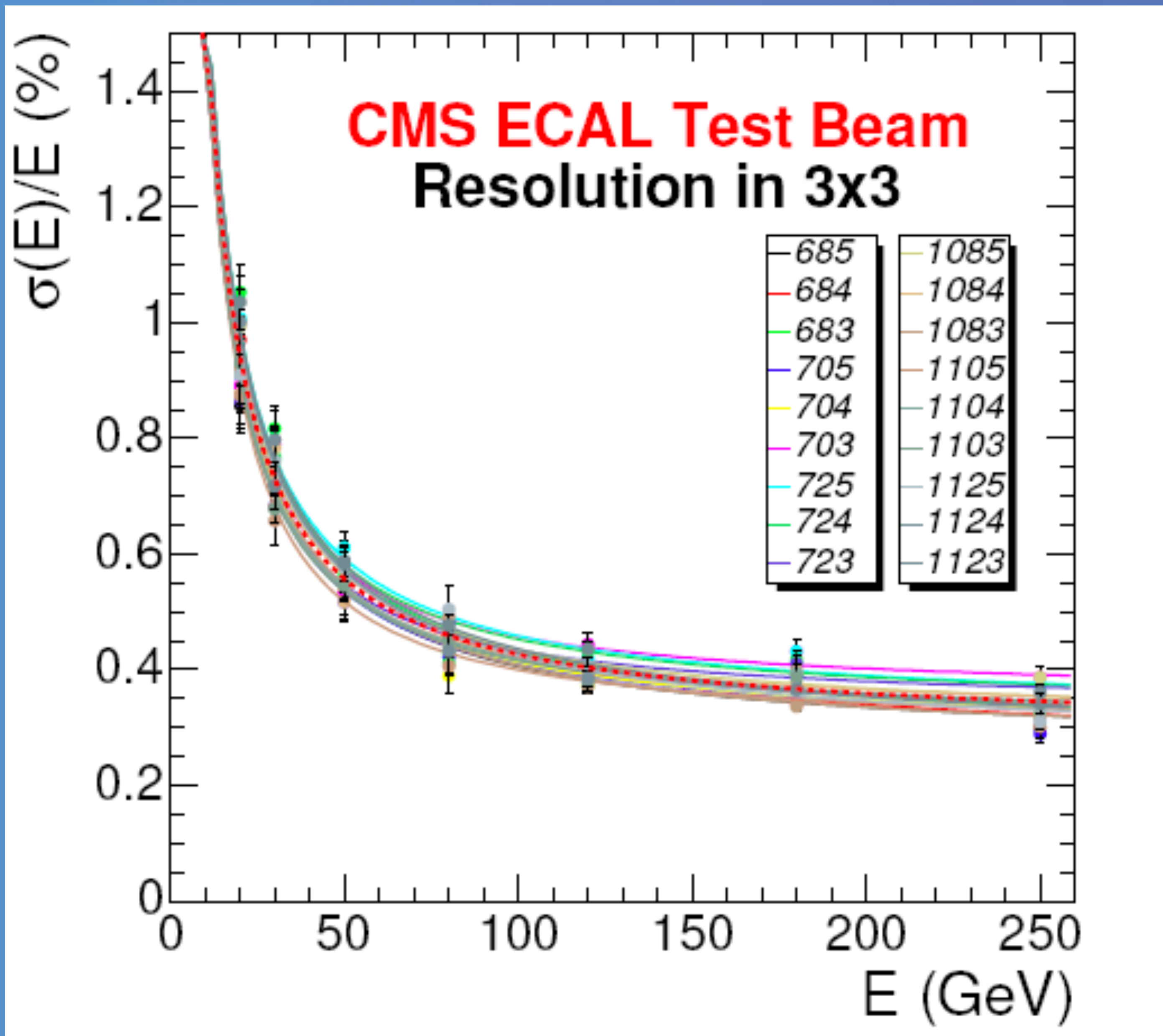


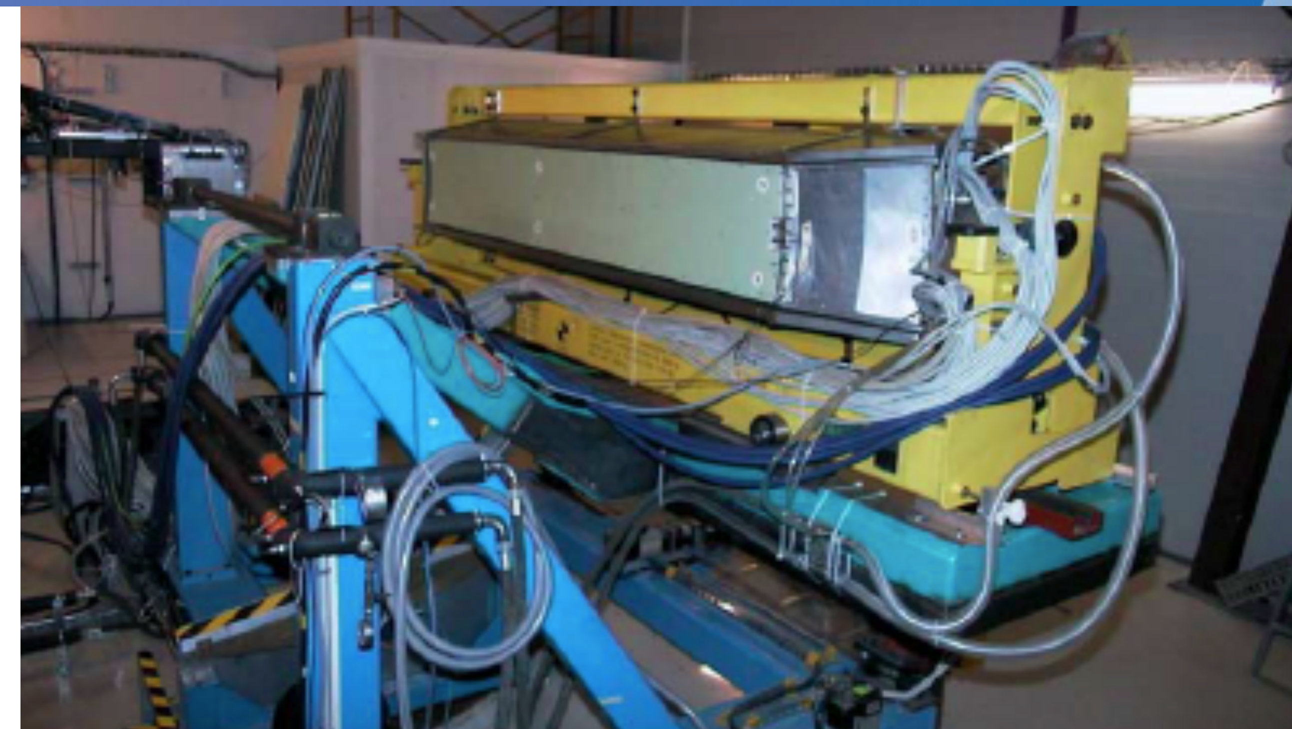


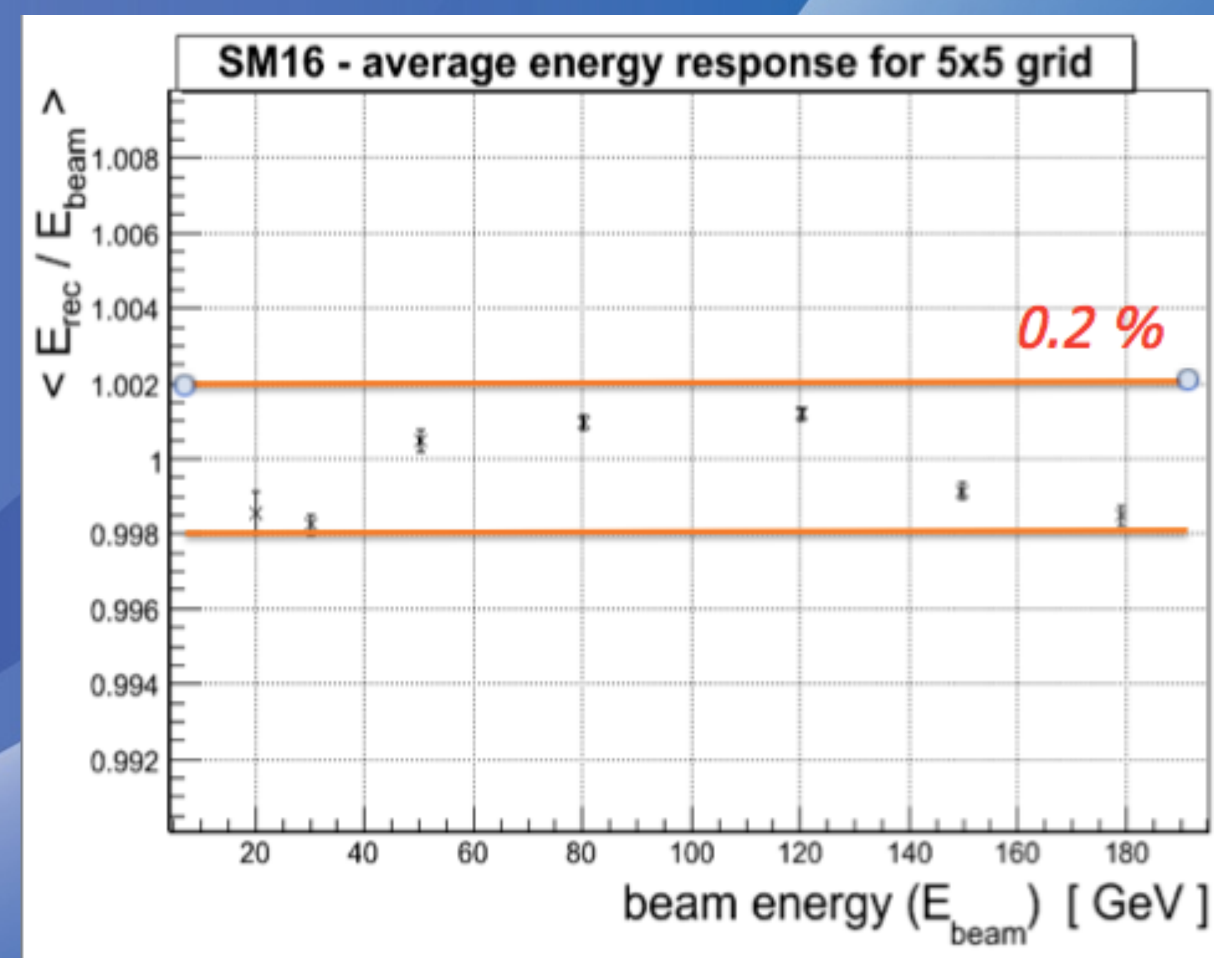
- PbWO4 crystals developed for CMS
- Advantages:
  - Very effective in shower containment (23cm)
  - Transparent to its emission
  - Fast
- Disadvantages:
  - Low light output
  - Hard light extraction

Parameter	Value
Radiation Length [cm]	0.89
Moliere Radius [cm]	2.2
Refractive Index	2.3
Peak Emission [nm]	440
% of light in 25 ns	80%
Light yield (23 cm) [ph/	100

CMS ECAL: Testbeam performance

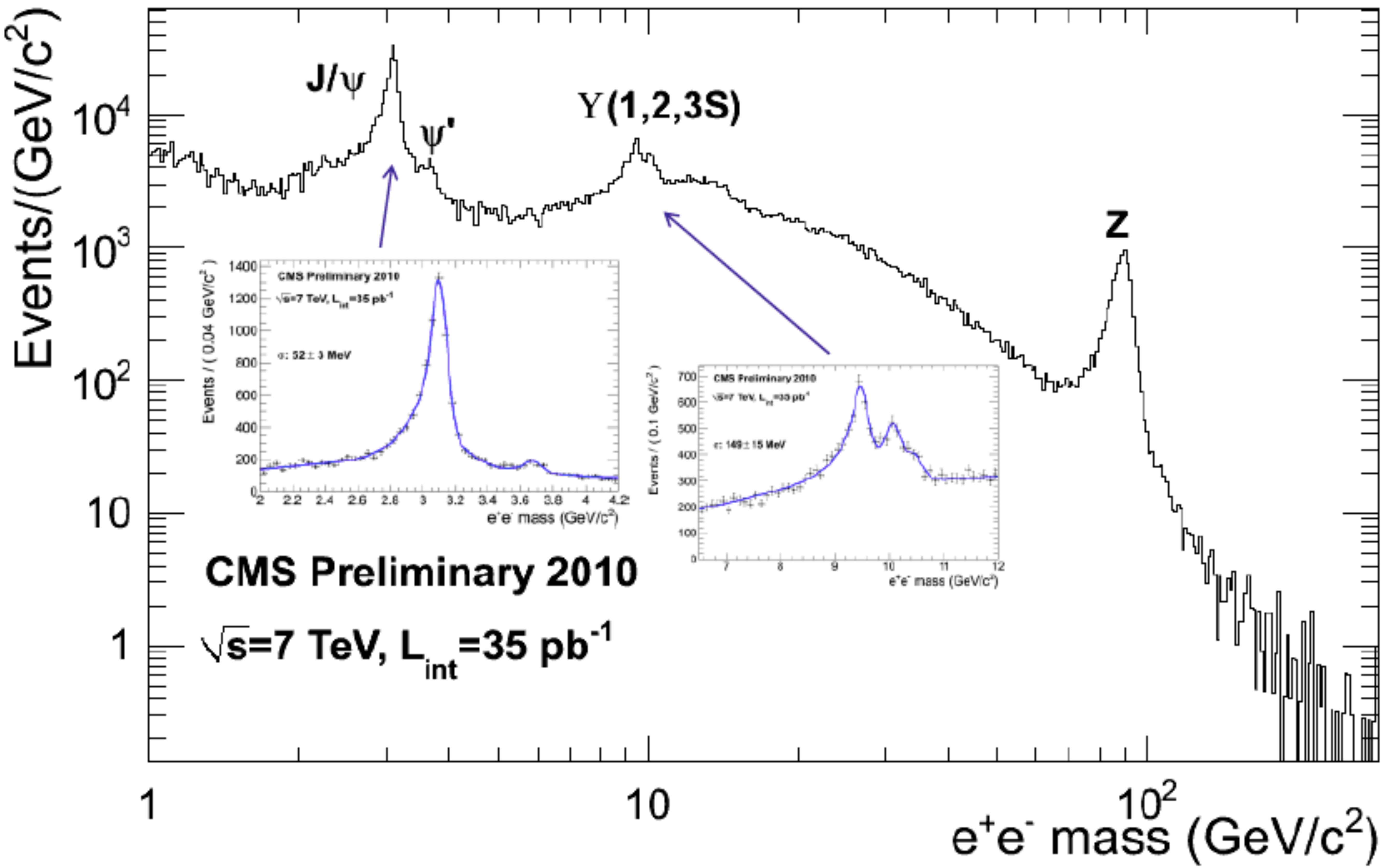






$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\mathrm{GeV})}} \oplus \frac{125}{E(\mathrm{MeV})} \oplus 0.3\%$$

CMS ECAL: in-situ performance

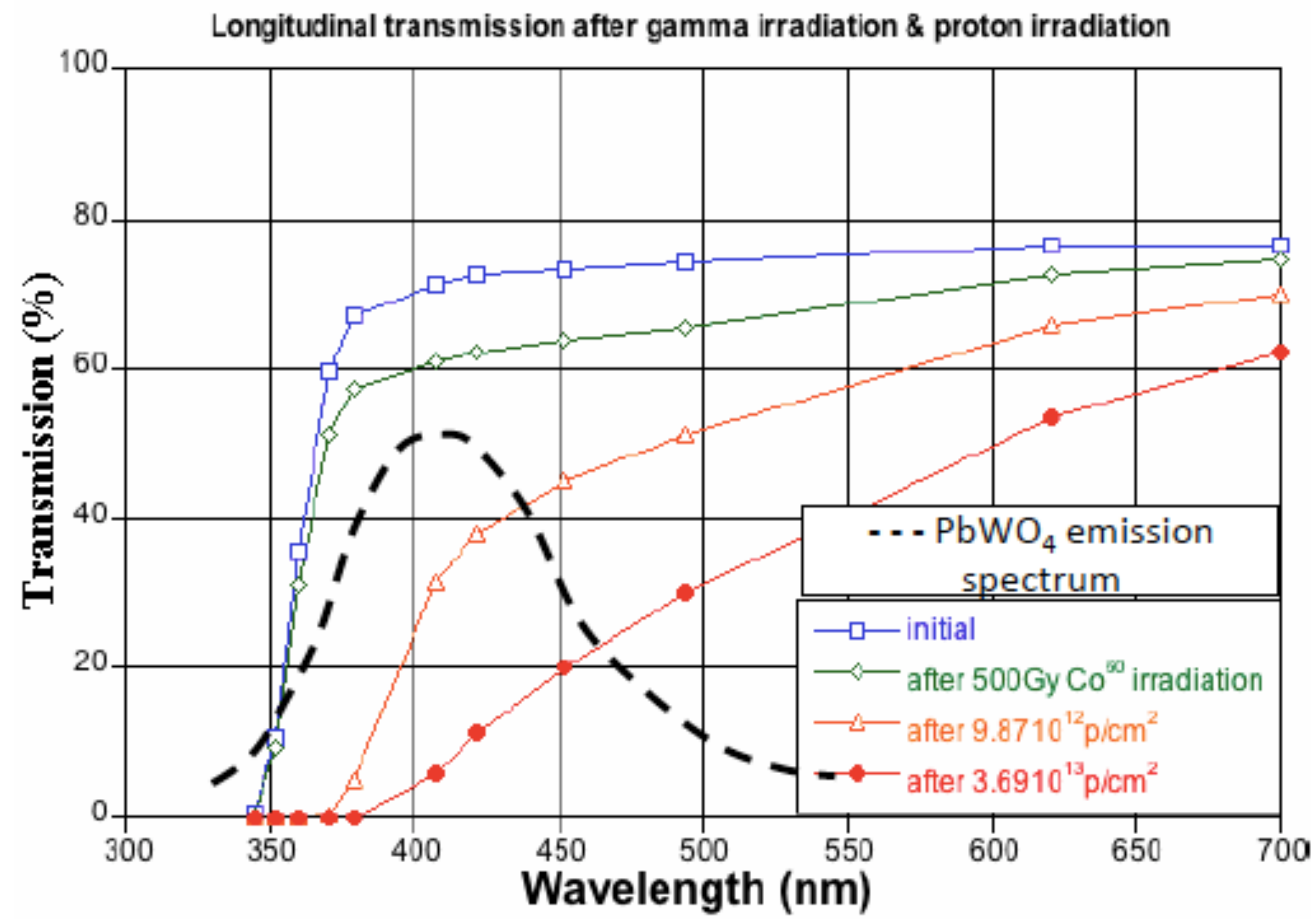


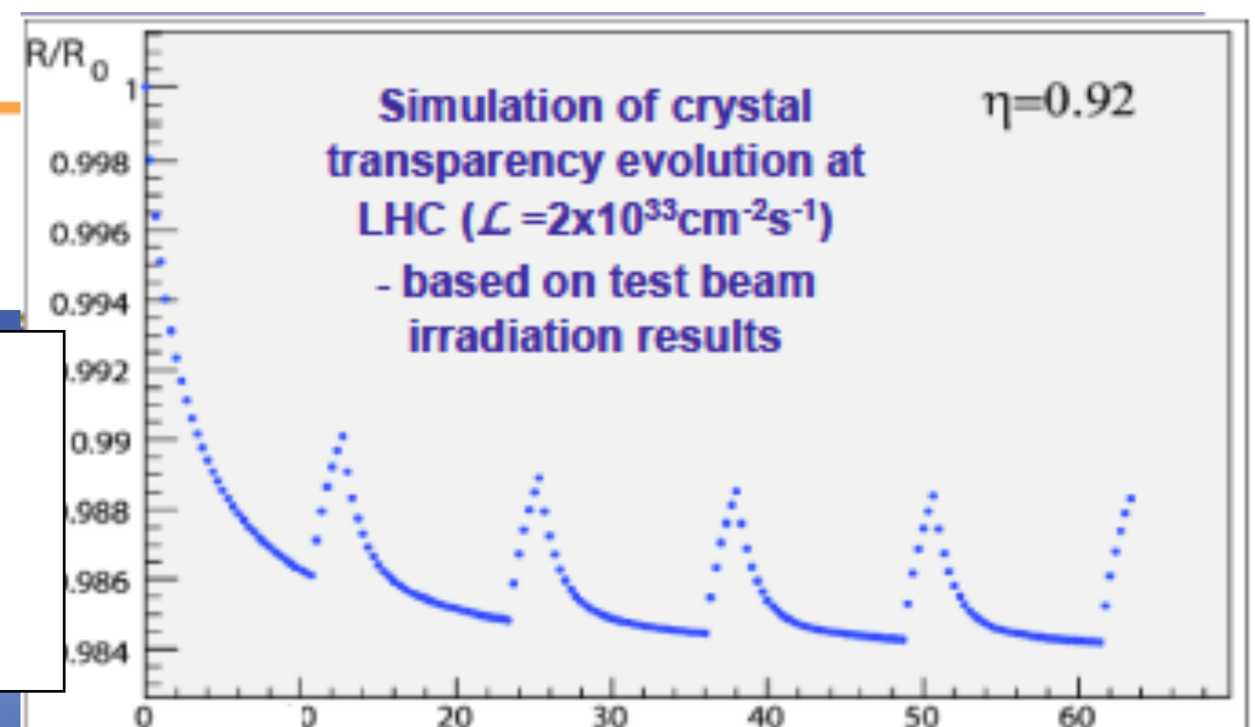
CMS ECAL: Radiation Damage

Crystals are subject to two types of irradiation:

1. Gamma irradiation causes damage which is **spontaneously recovered** at room temperature.
* Recovery has been observed in 2011 and 2012 during long shutdowns, technical stops etc.
* Loss of transmission caused by γ irradiation for few fb^{-1} (at η = 2.6): green line vs. blue line

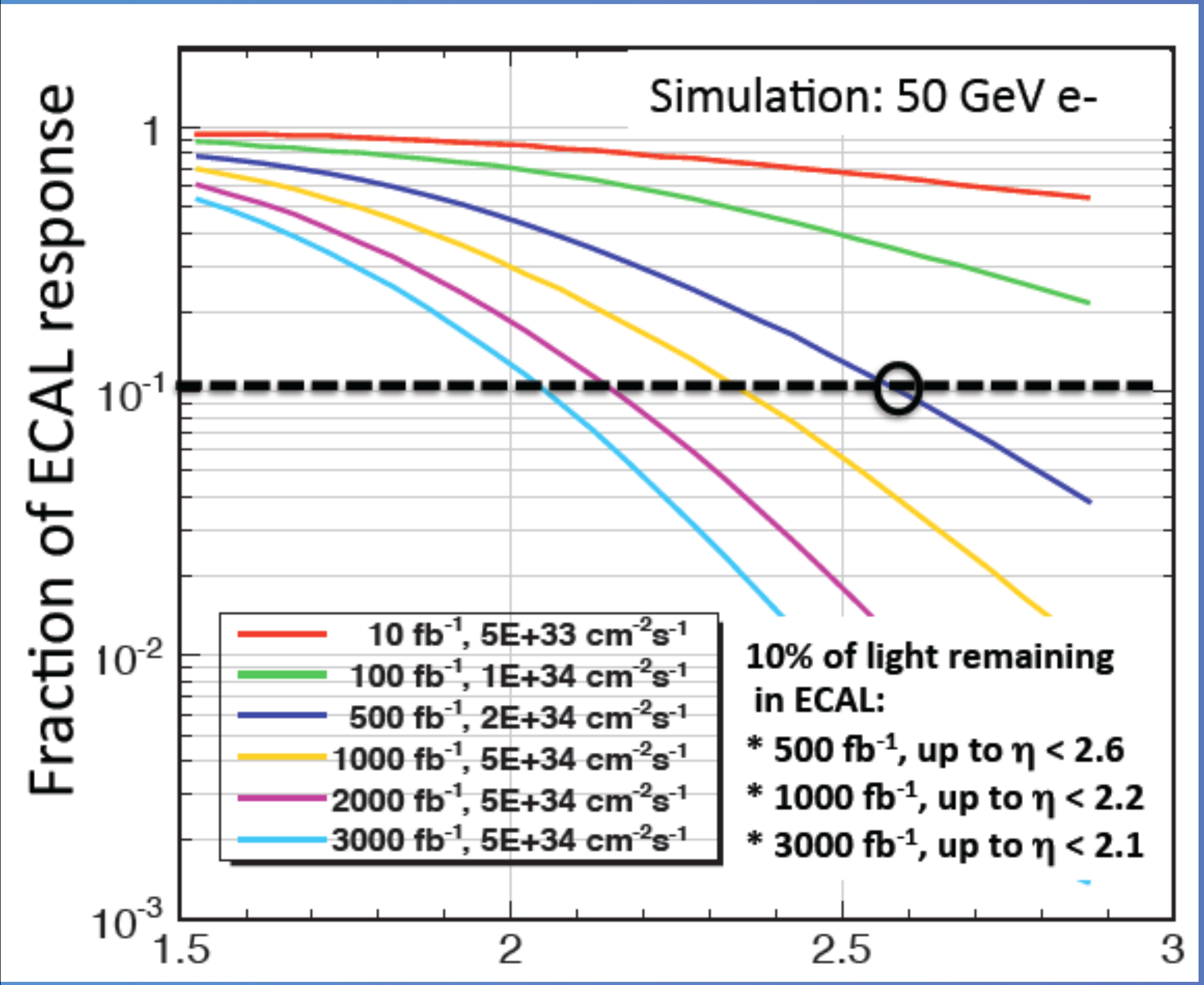
2. Hadron damage creates defects which cause light transmission loss. The damage is **permanent and cumulative** at room temperature.
* Loss of caused by proton irradiation:
  -> 150 fb^{-1} (at η = 2.6): orange line vs. blue line
  -> 600 fb^{-1} (at η = 2.6): red line vs. blue line
* Hadron damage **causes band-end shift** at low wave lengths of the $PbWO_4$ emission spectrum.

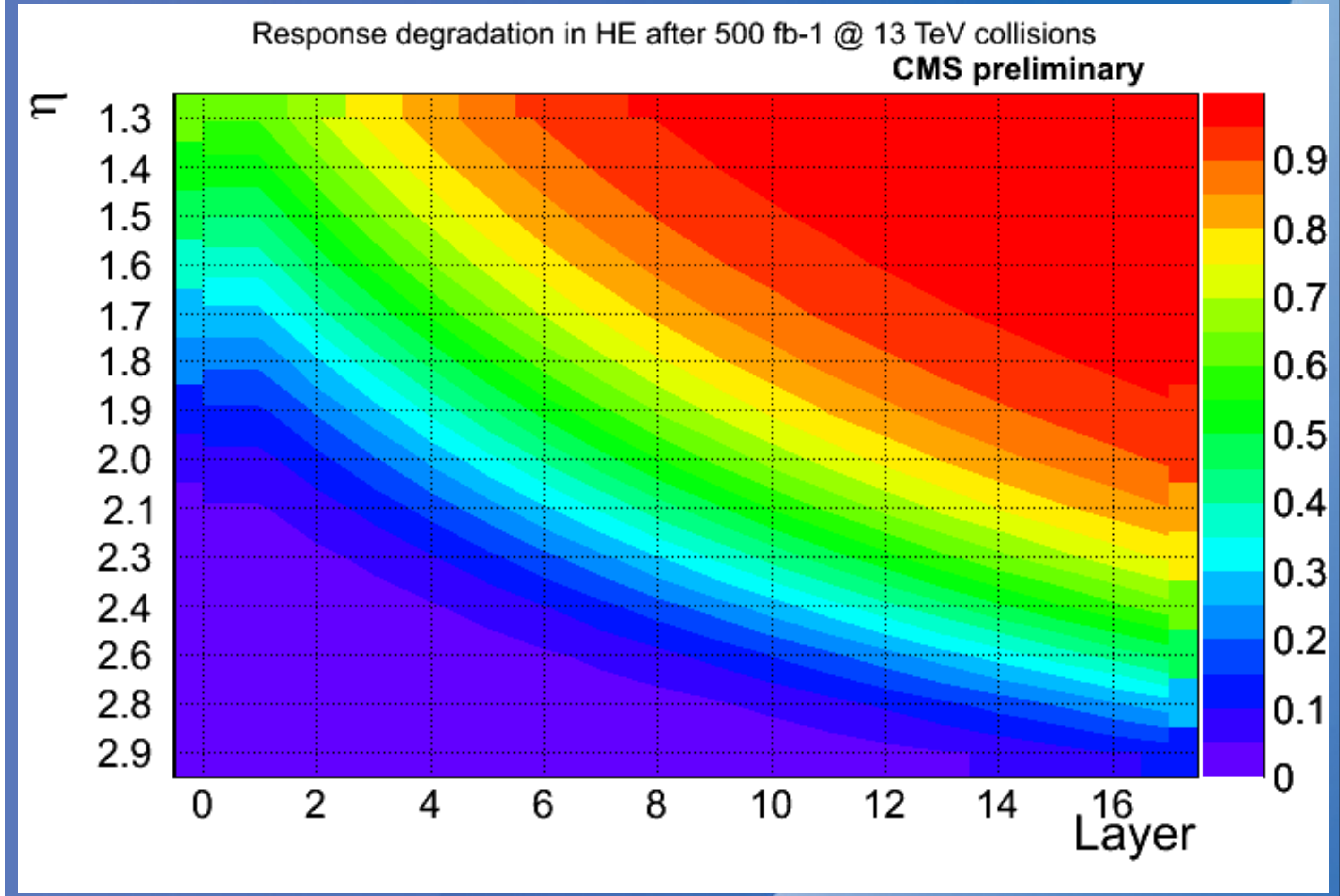




Effects that requires correction given the precision required in the central ECAL

CMS ECAL+HCAL: Radiation Damage



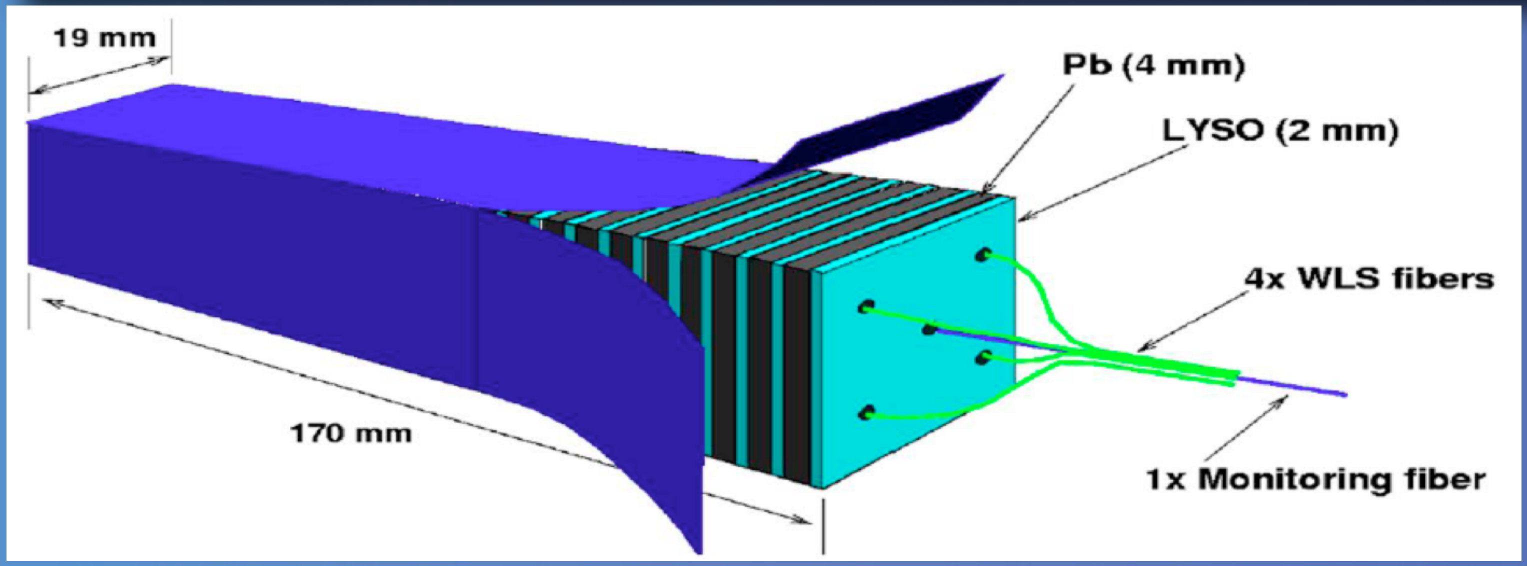


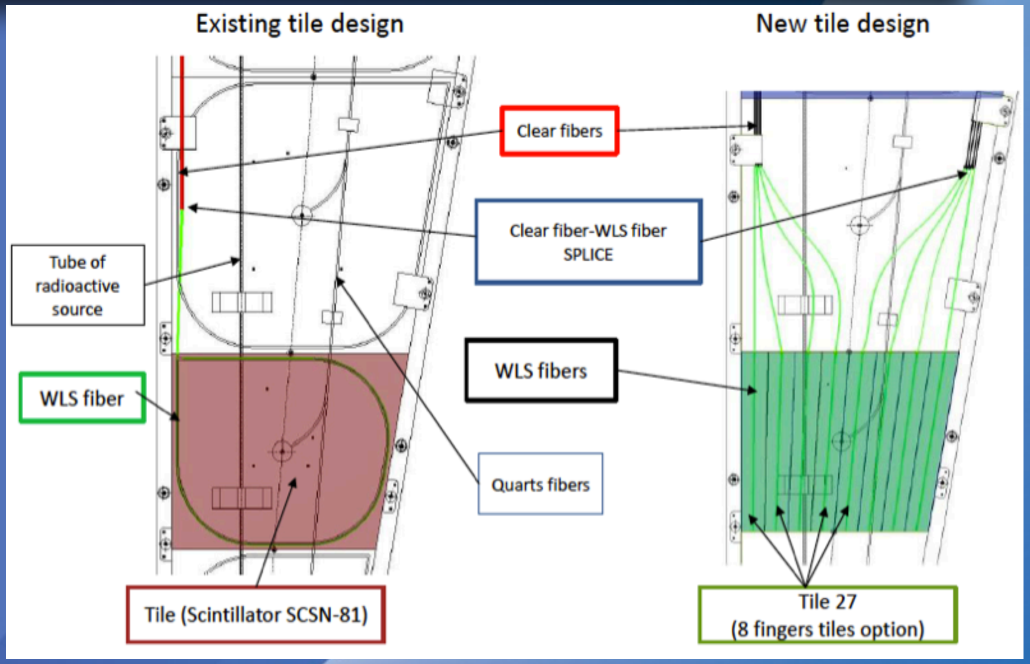
In the endcap radiation damage is very severe. It will require upgrade of the endcap ECAL+HCAL detector before HL-LHC

CMS Endcap Upgrade Options

Two approaches

1. Maintain traditional geometry:
   - ECAL w. Shashlik-like design with rad. hard scintillators, e.g. LYSO, CeF3
   - HCAL w. rad. hard scintillators and more readout fibers





2. Alternative geometry/concepts with potential improved performance at high pileup
   - Dual Readout following DREAM/RD52
   - Particle Flow Calorimeter w. high granularity detector following work of CALICE

Considering an integrated approach with an endcap detector covering up to $\eta \simeq 4$

Upgrade Roadmap in the next two decades

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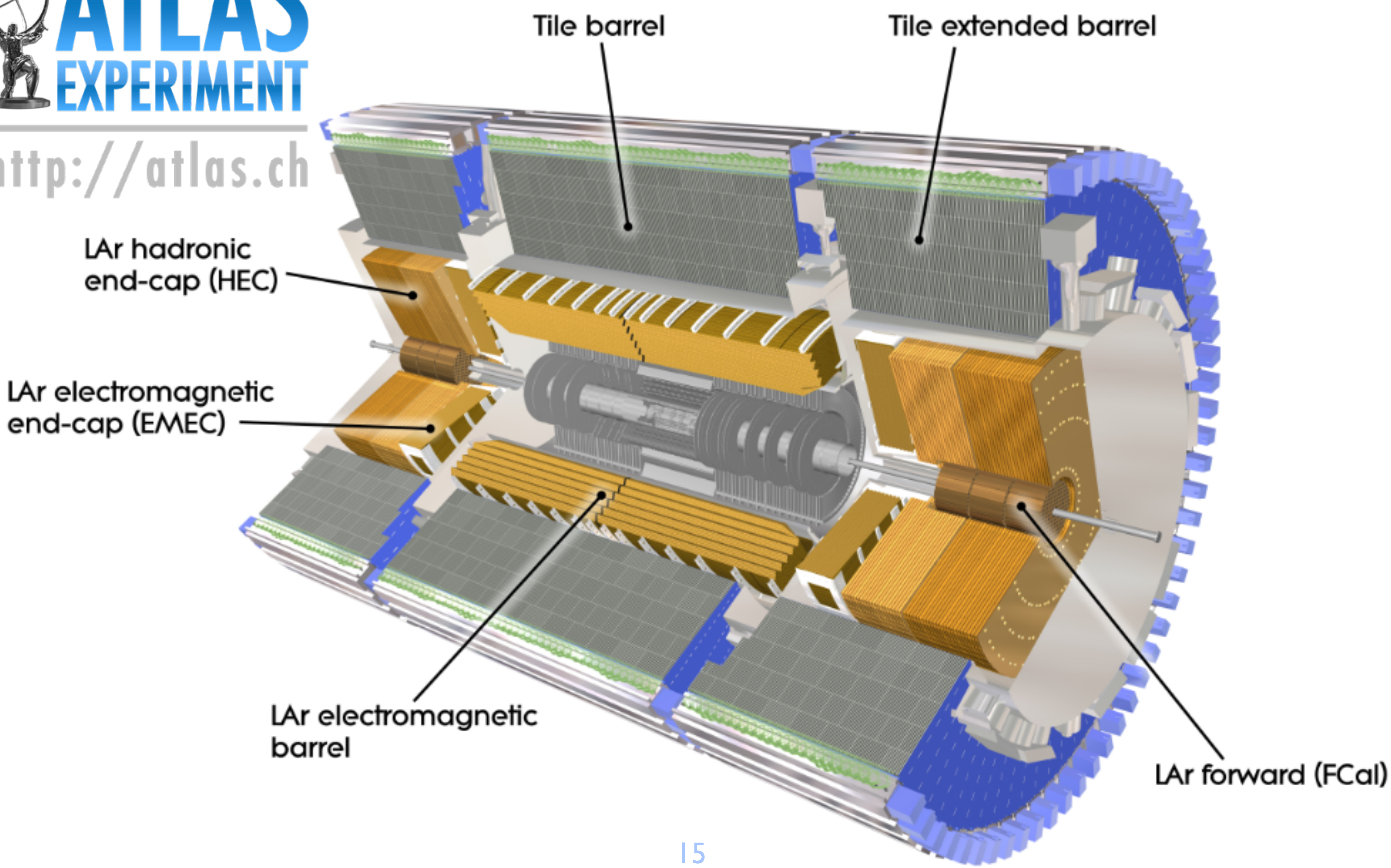
Detector Consolidation

Phase-I Upgrades

Phase-II Upgrades

Detectors

Electronics and Trigger



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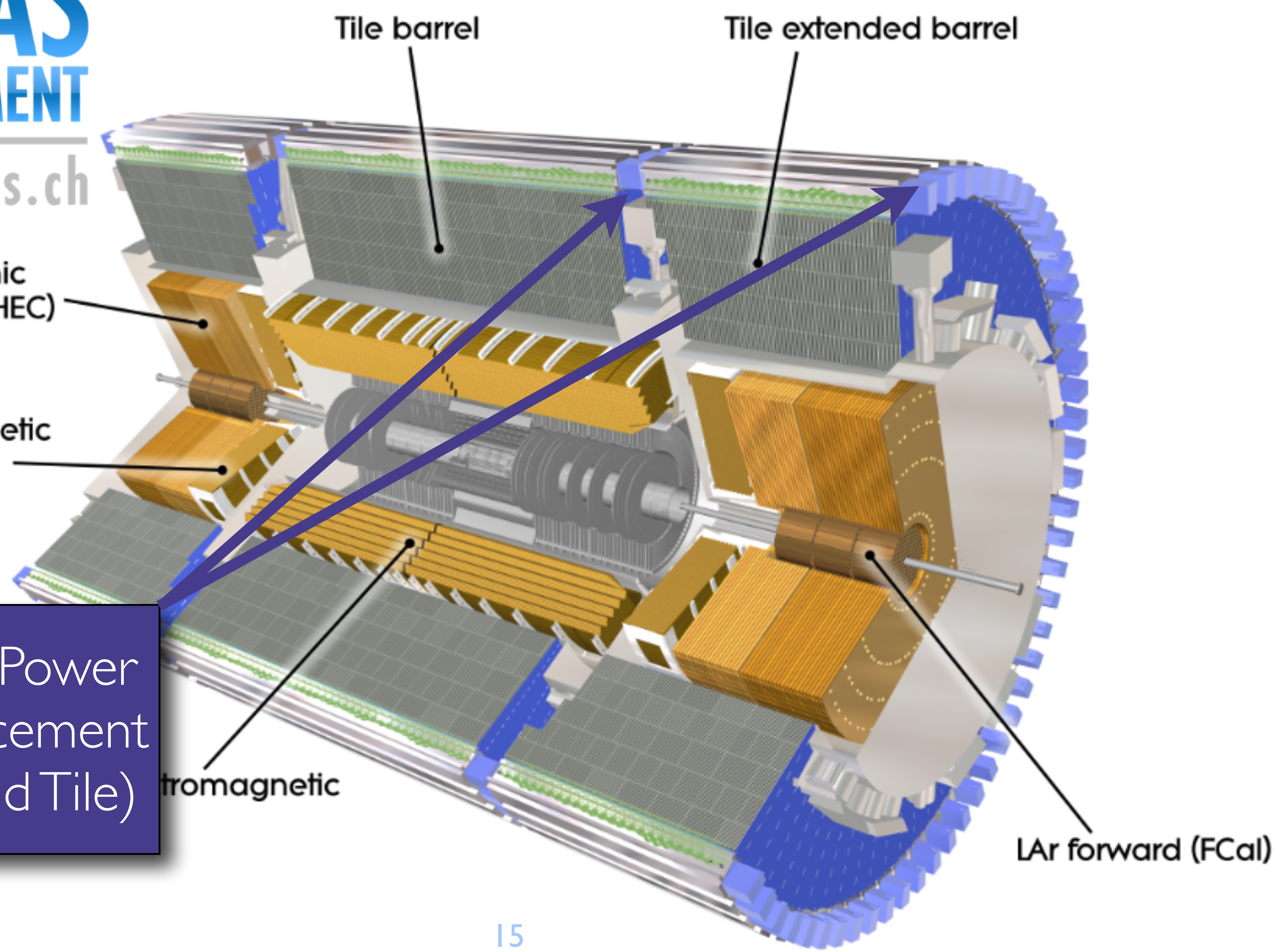

Low Voltage Power Supply replacement (both LAr and Tile)

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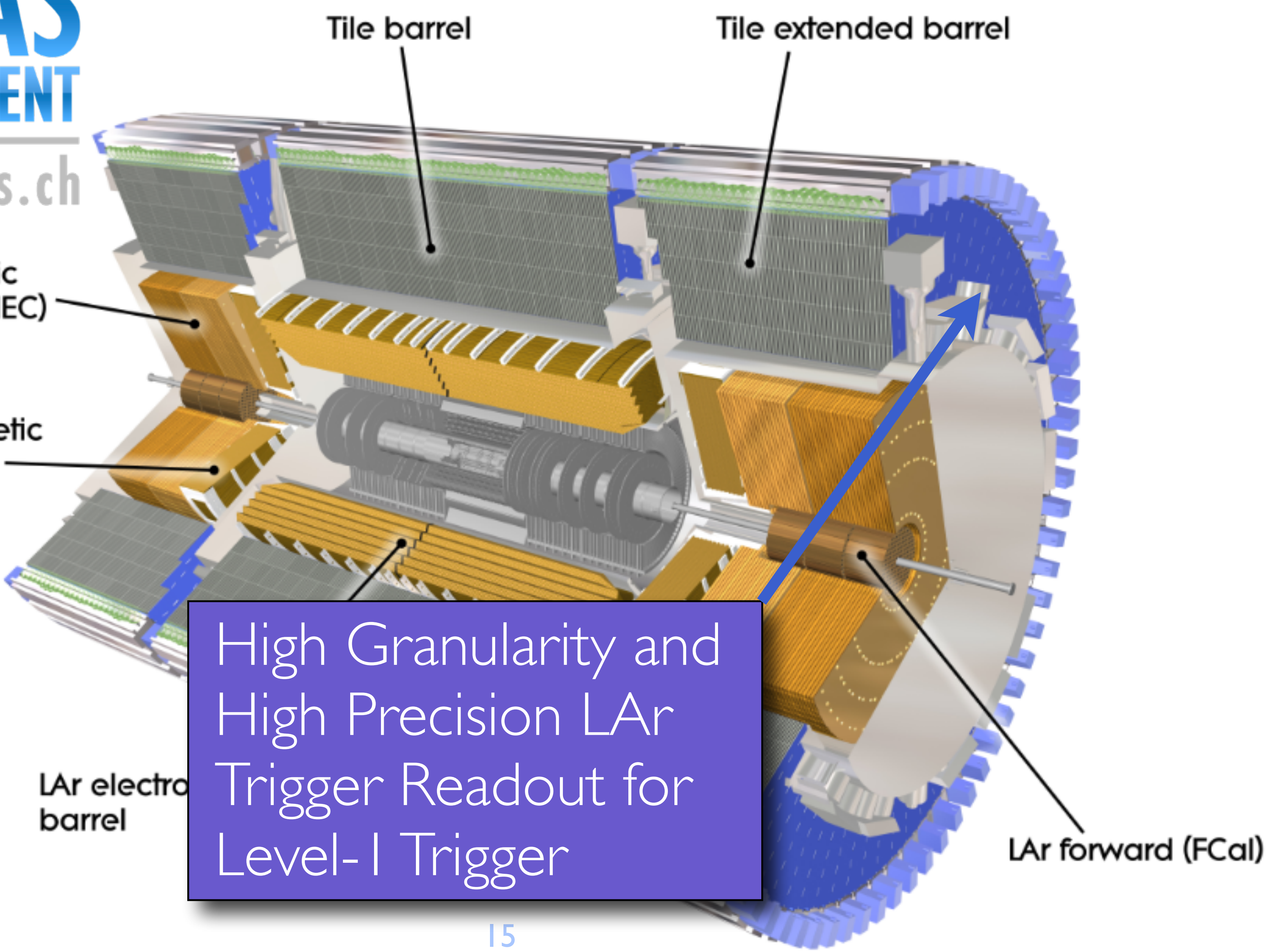

High Granularity and High Precision LAr Trigger Readout for Level-1 Trigger

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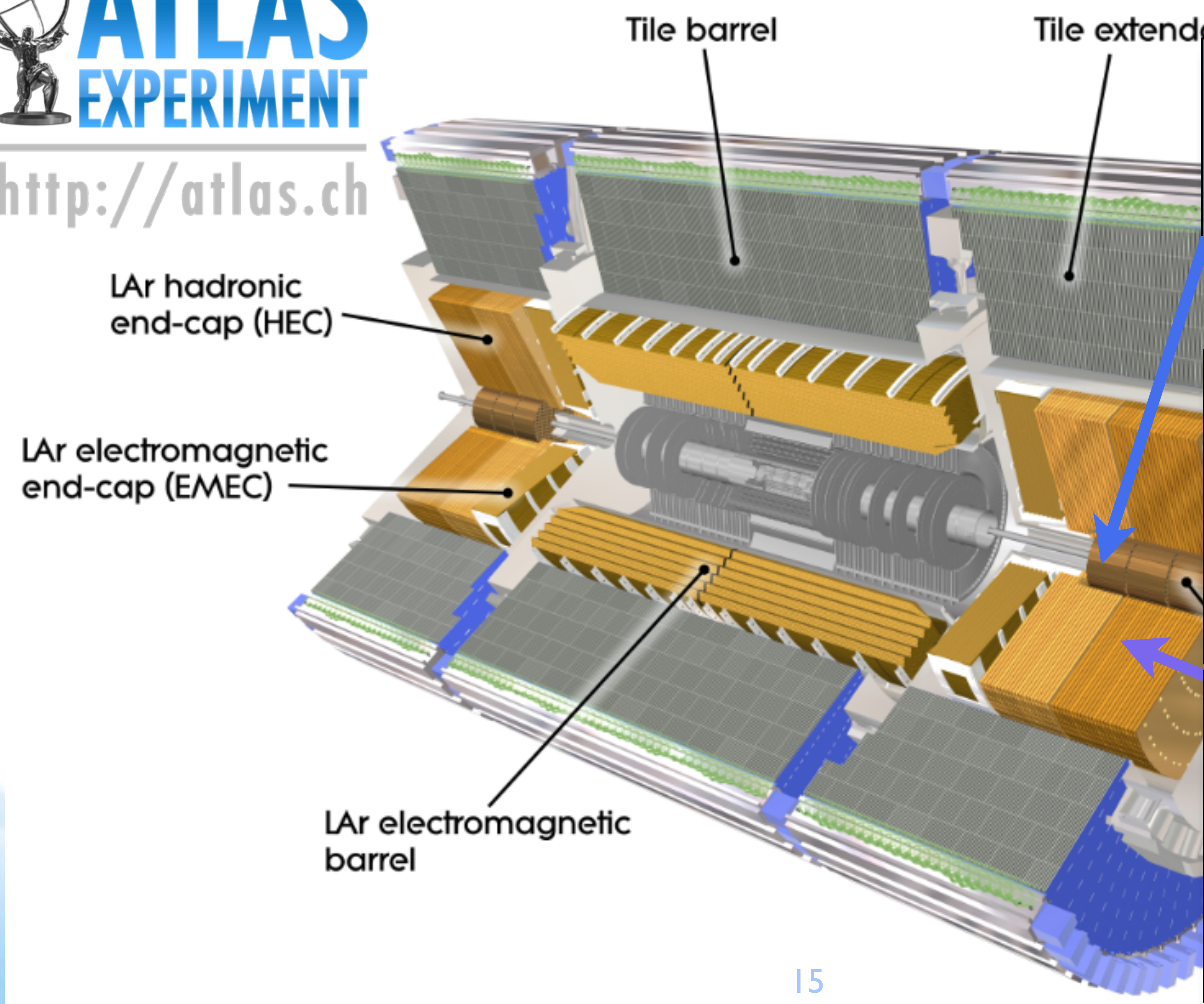
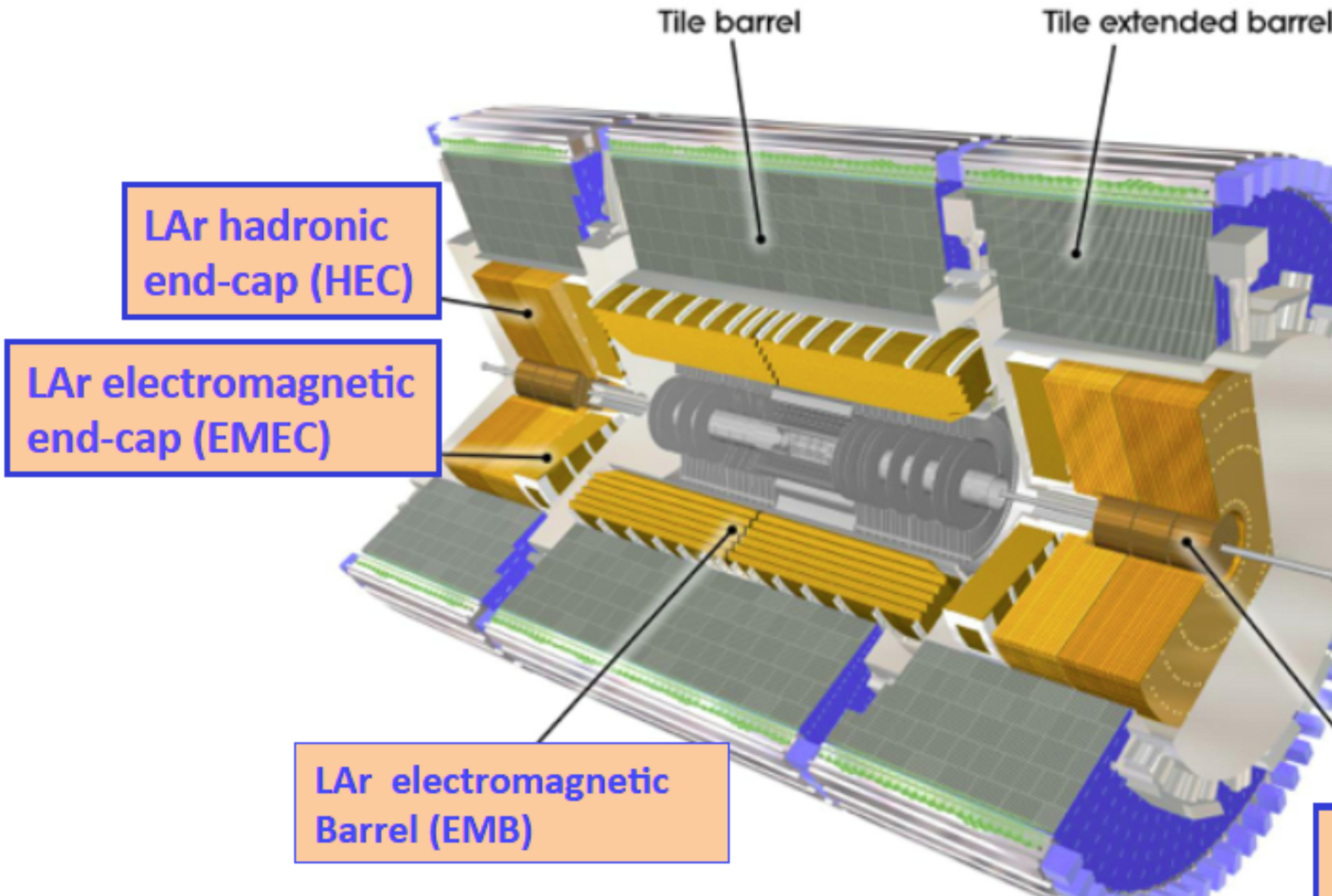


Possible upgrade of the Forward Calorimeter (FCAL)

Upgrade of the main readout (both Tile and LAr): 40 MHz data stream

Possible upgrade of the cryogenic analog front-end of the LAr hadronic endcap (HEC)

ATLAS Calorimetry



Liquid Argon:

EM barrel and end-cap
* Lead absorber
* Accordion geometry
* Barrel: $|\eta| < 1.475$
* End-cap: $1.375 < |\eta| < 3.2$

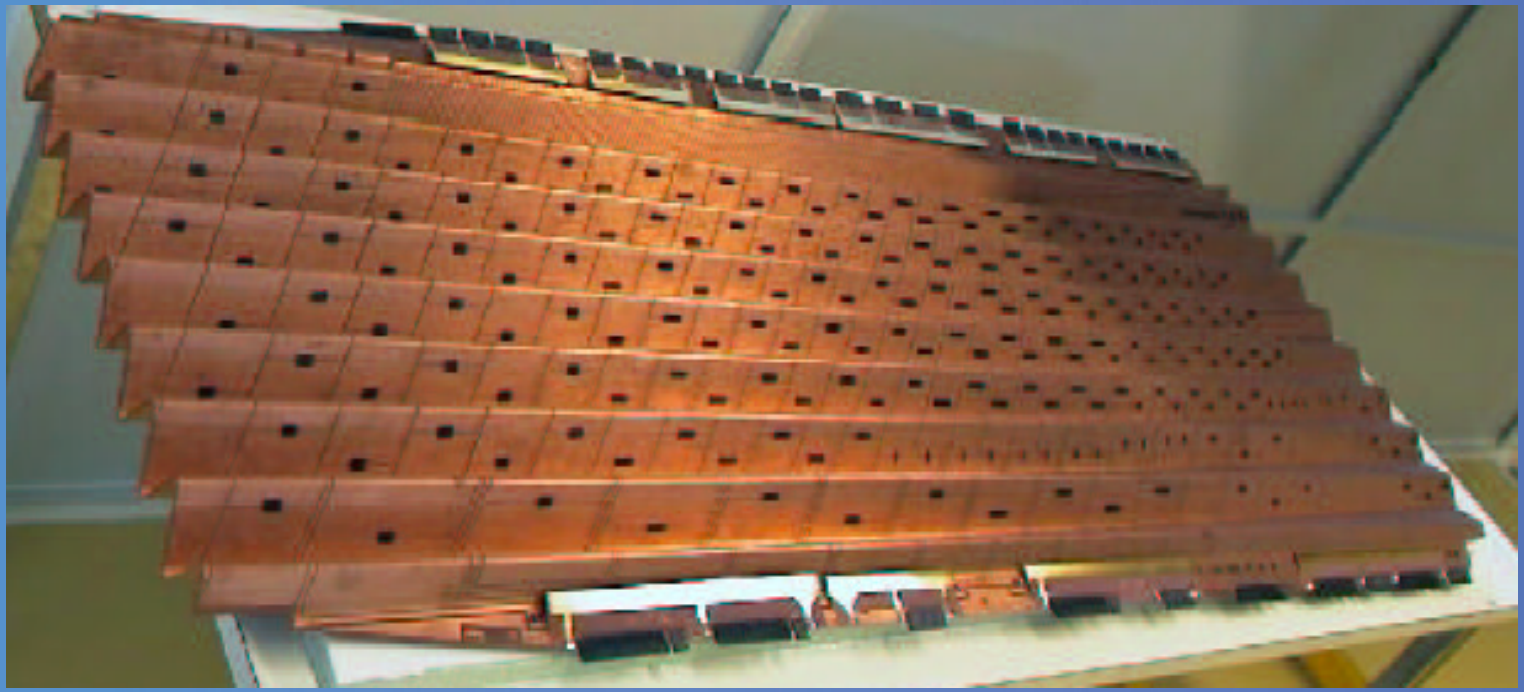
Hadronic end-cap
* Copper absorber
* Parallel plate electrodes
* Coverage: $1.5 < |\eta| < 3.2$

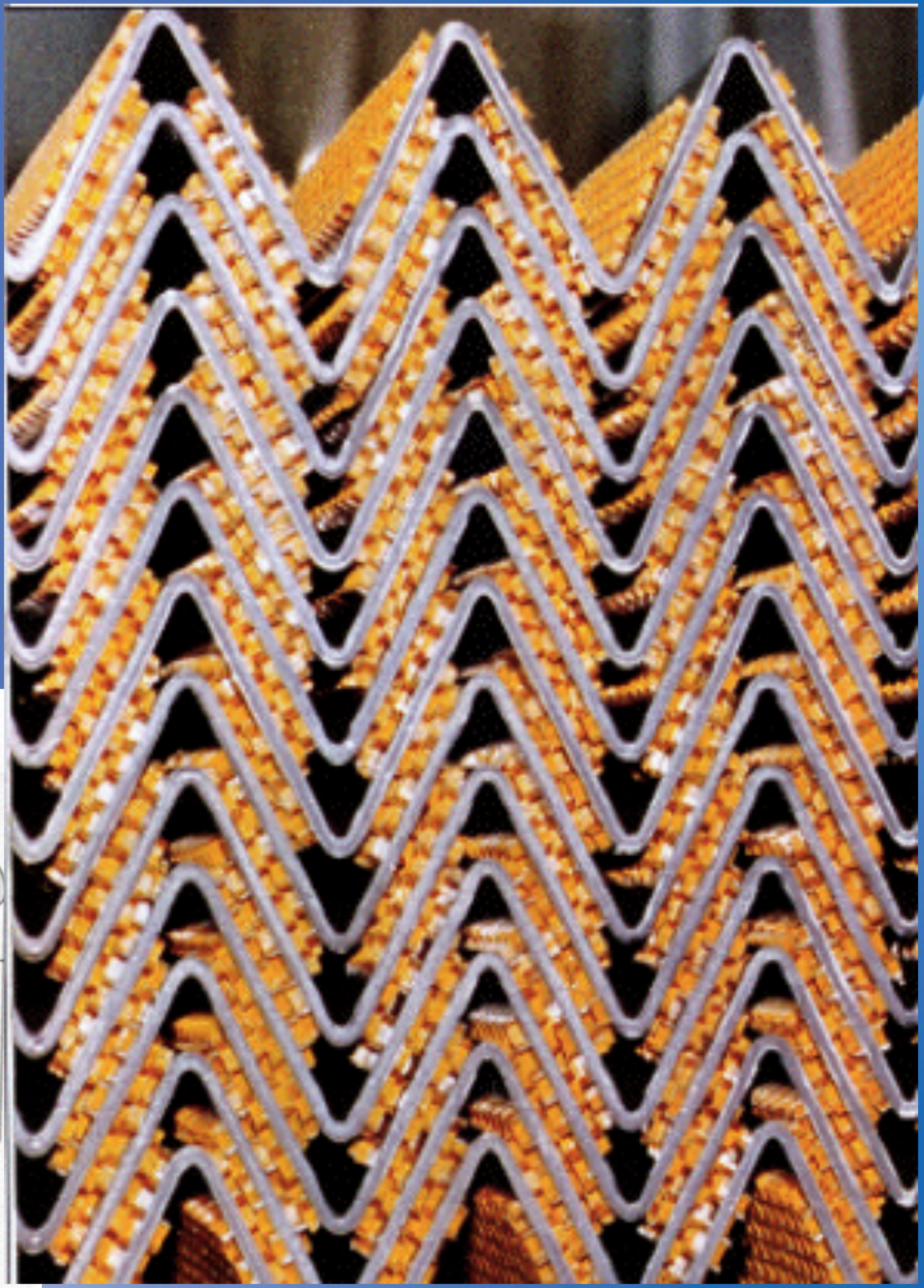
Forward Calorimeter
* tubes and rods in copper or tungsten matrix
* Coverage: $3.1 < |\eta| < 4.9$

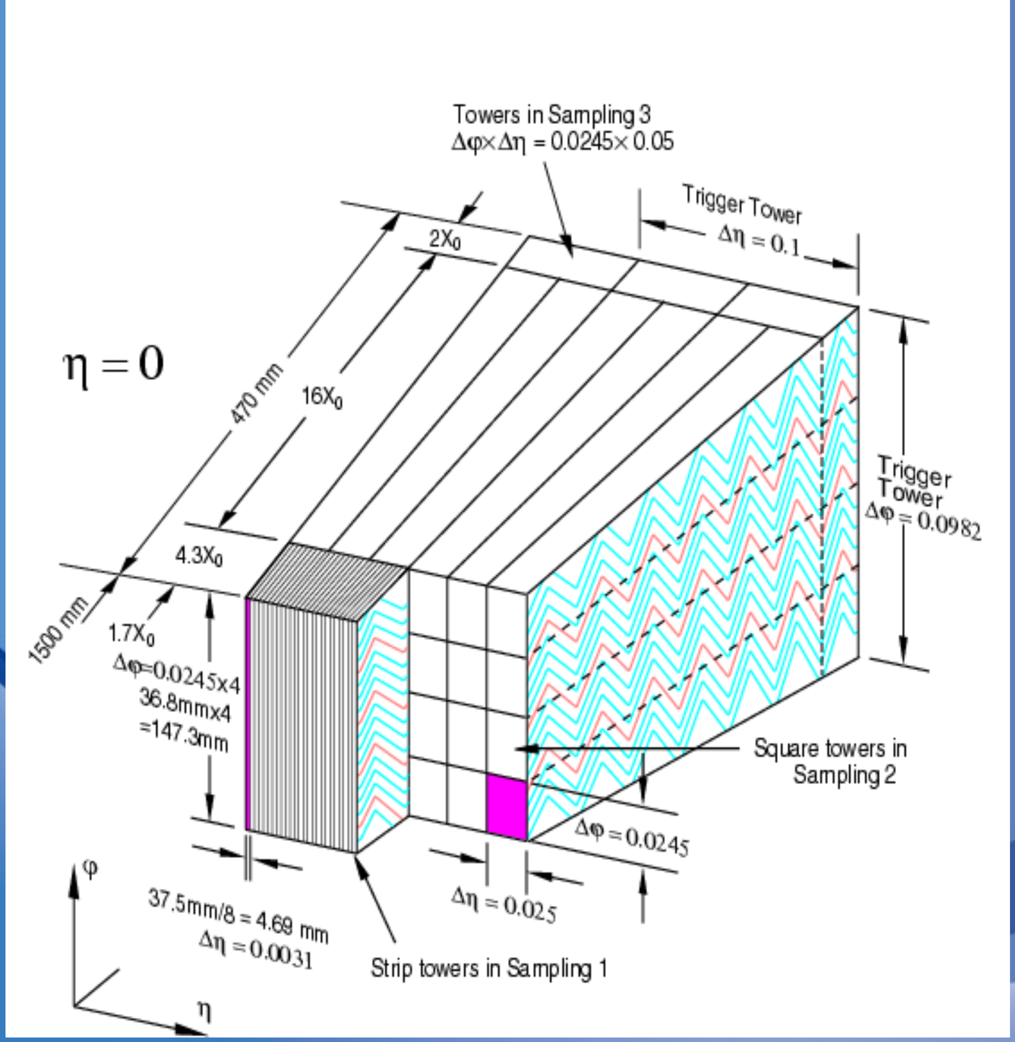
Longevity of ATLAS LAr

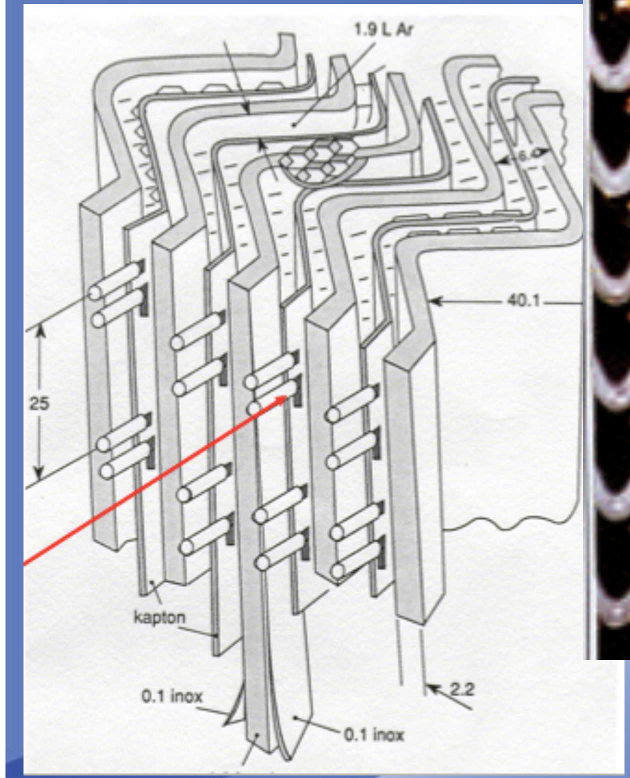
- Liquid Argon calorimeters are intrinsically radiation tolerant.
- Integrated dose in LAr expected during Phase2 will not pose operational problems.

ATLAS LAr Calorimeters

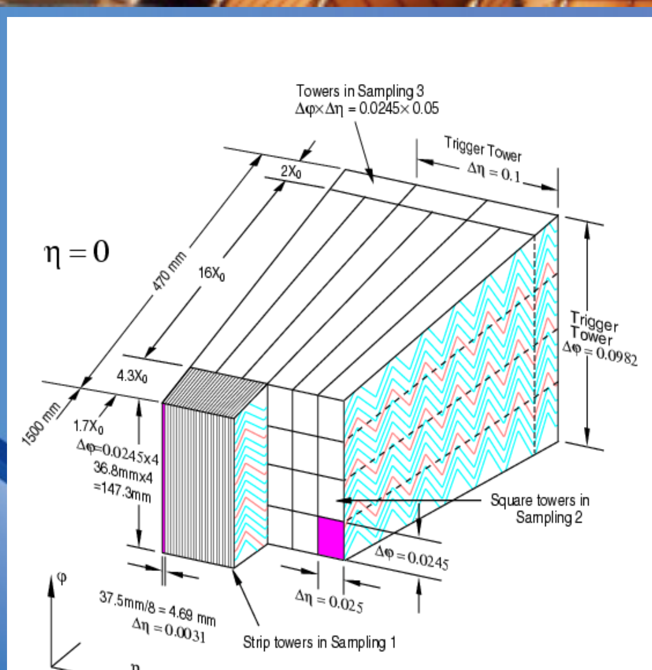


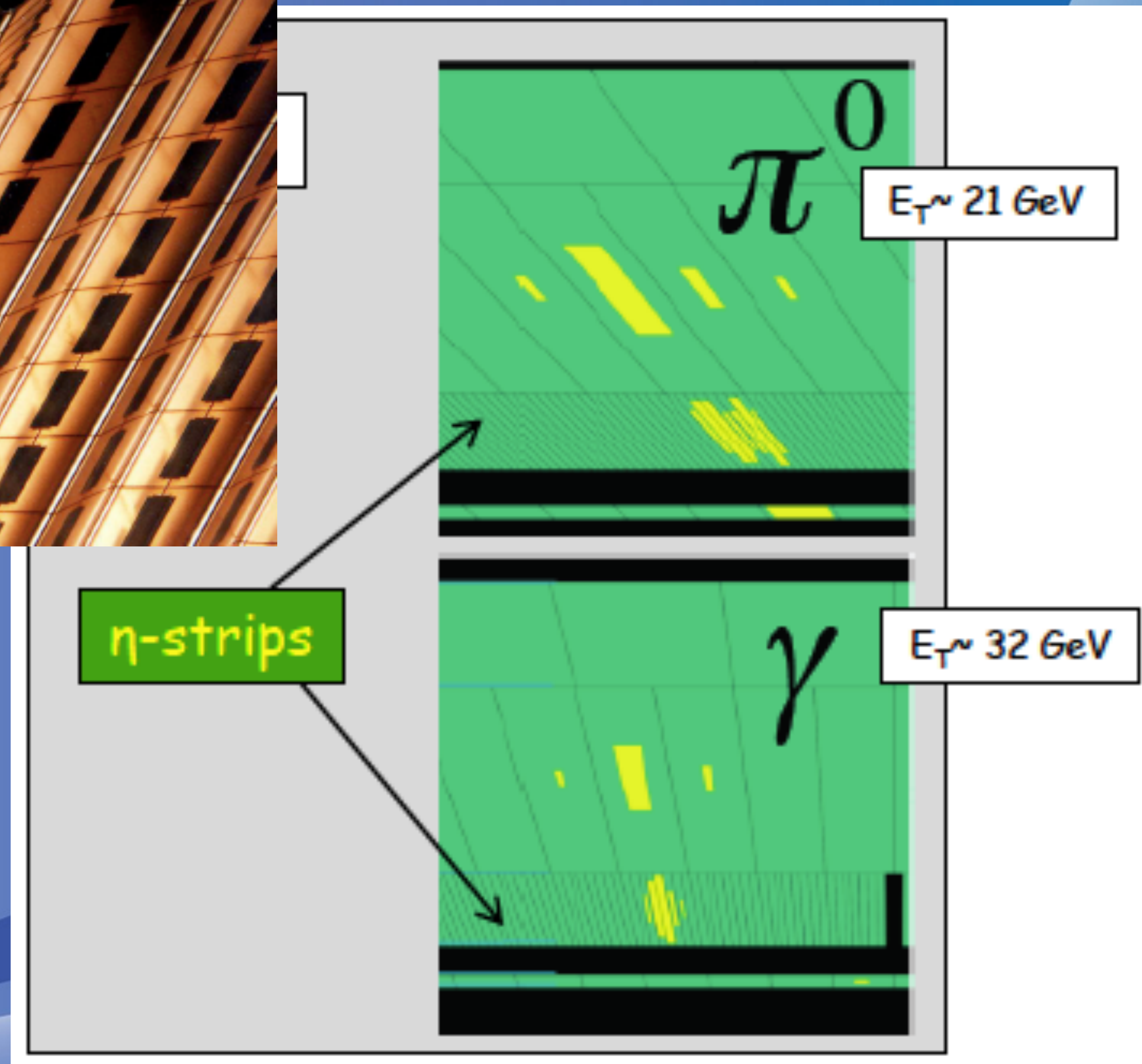




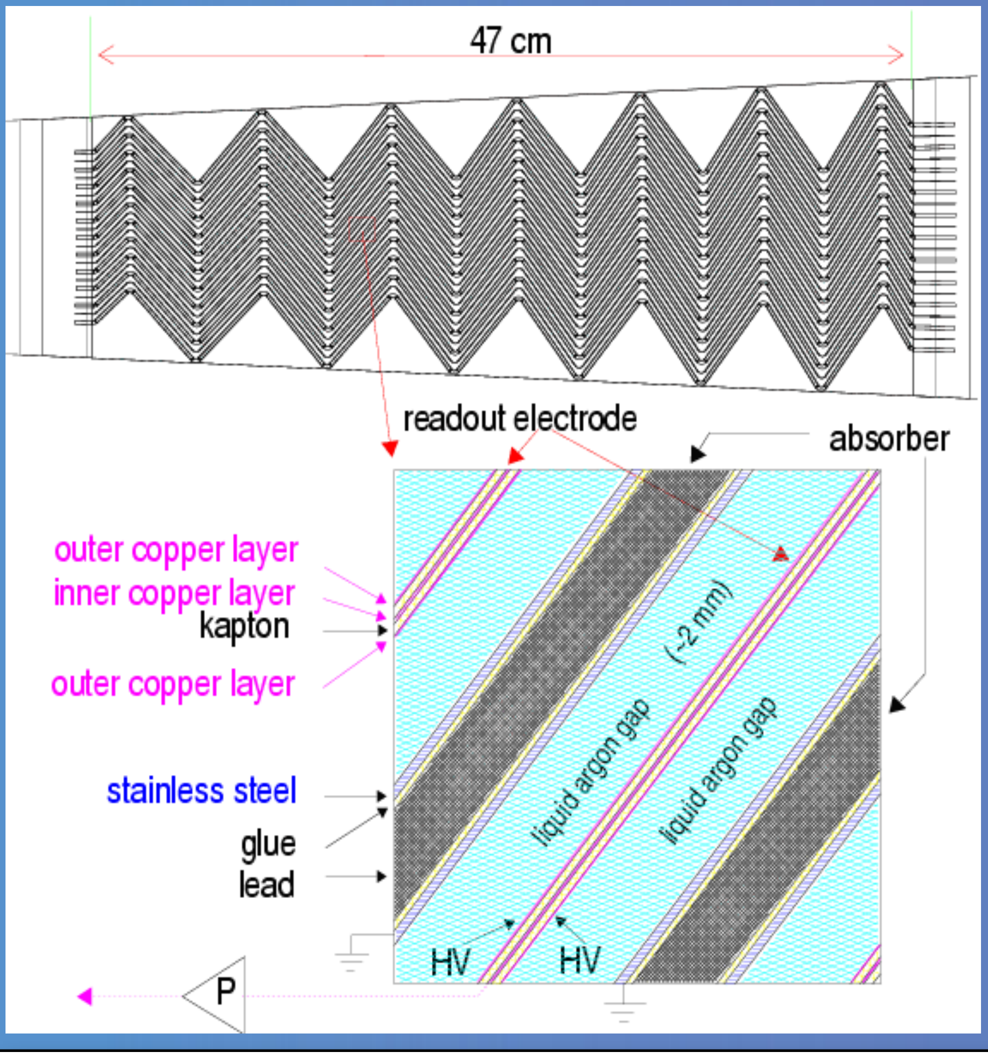


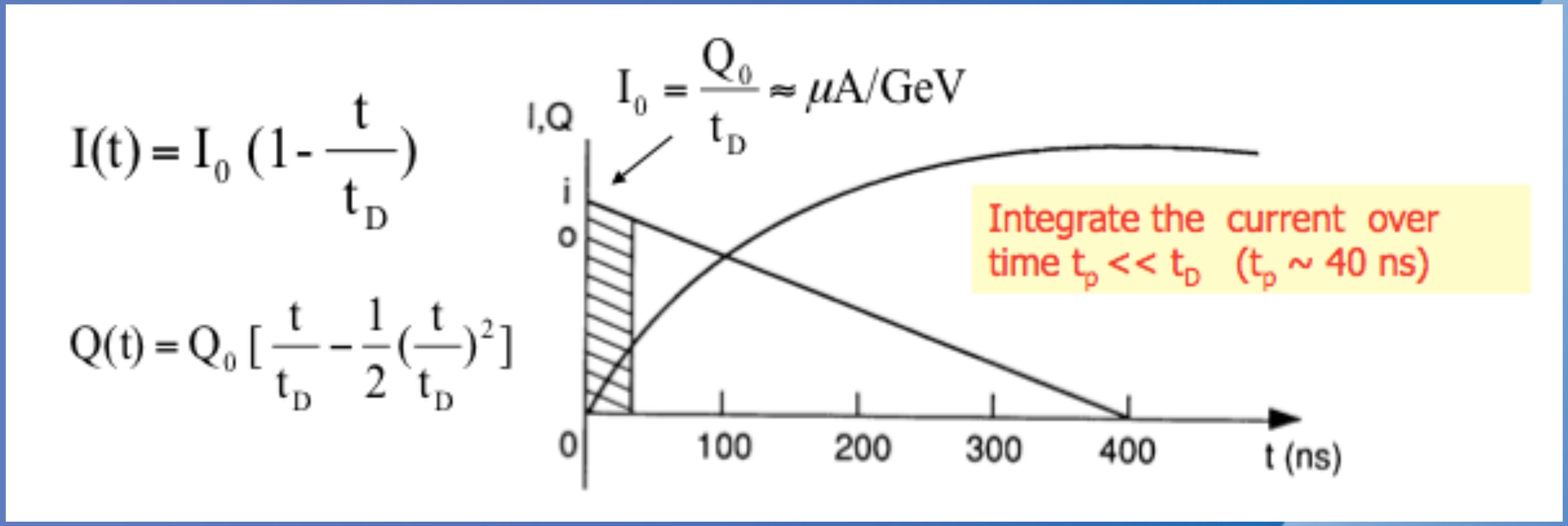
ATLAS LAr Calorimeters

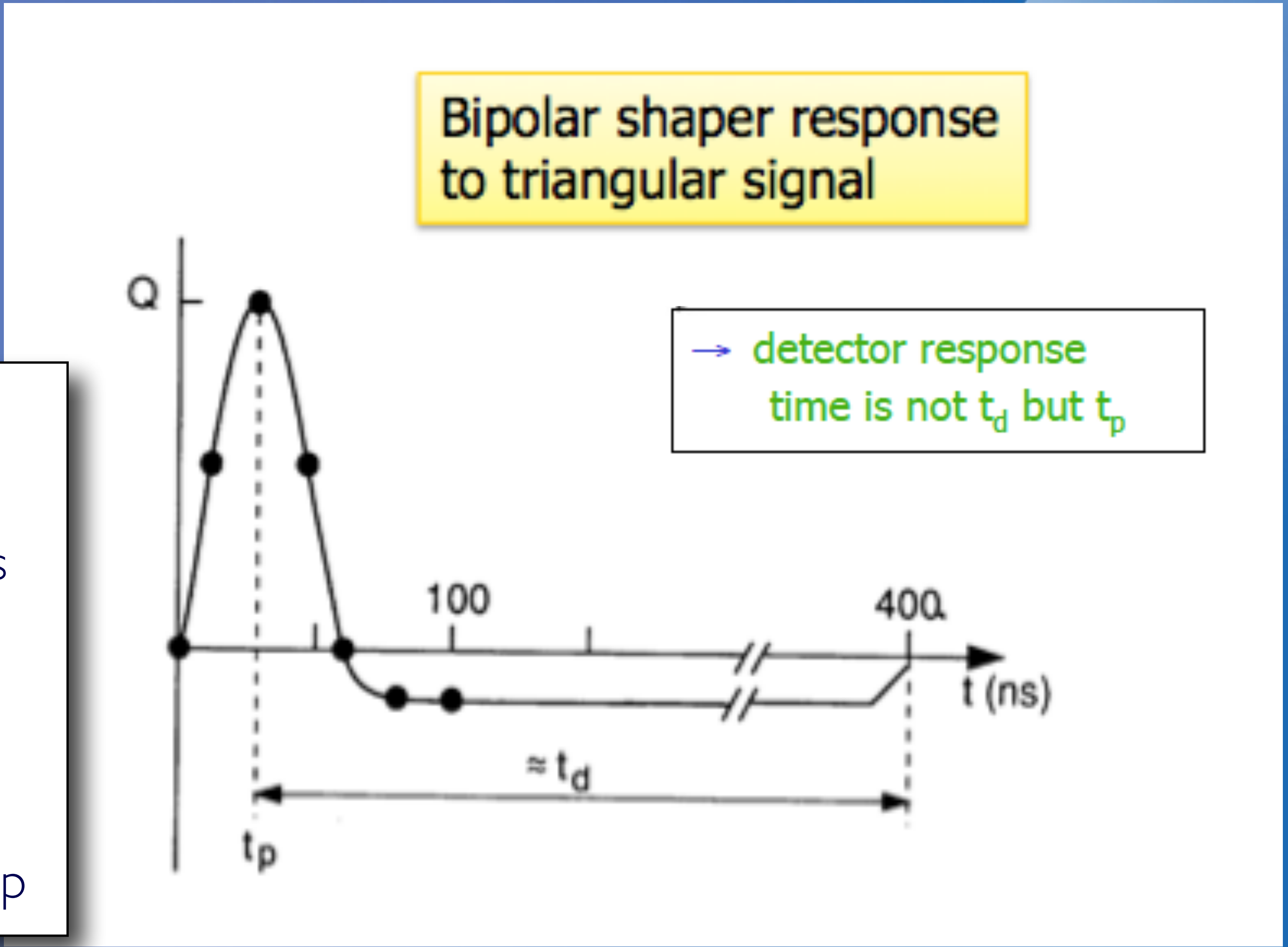




ATLAS LAr Calorimeters



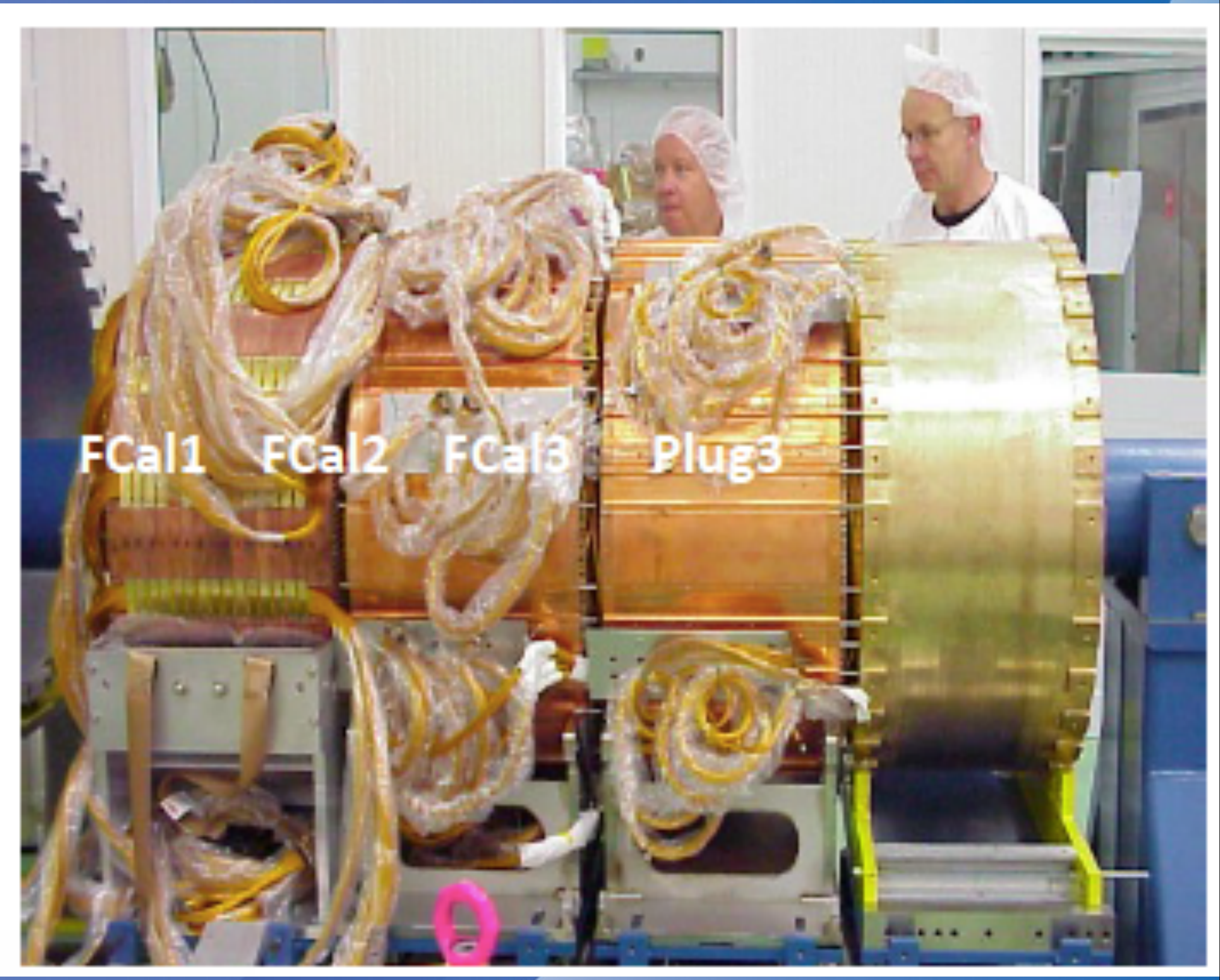


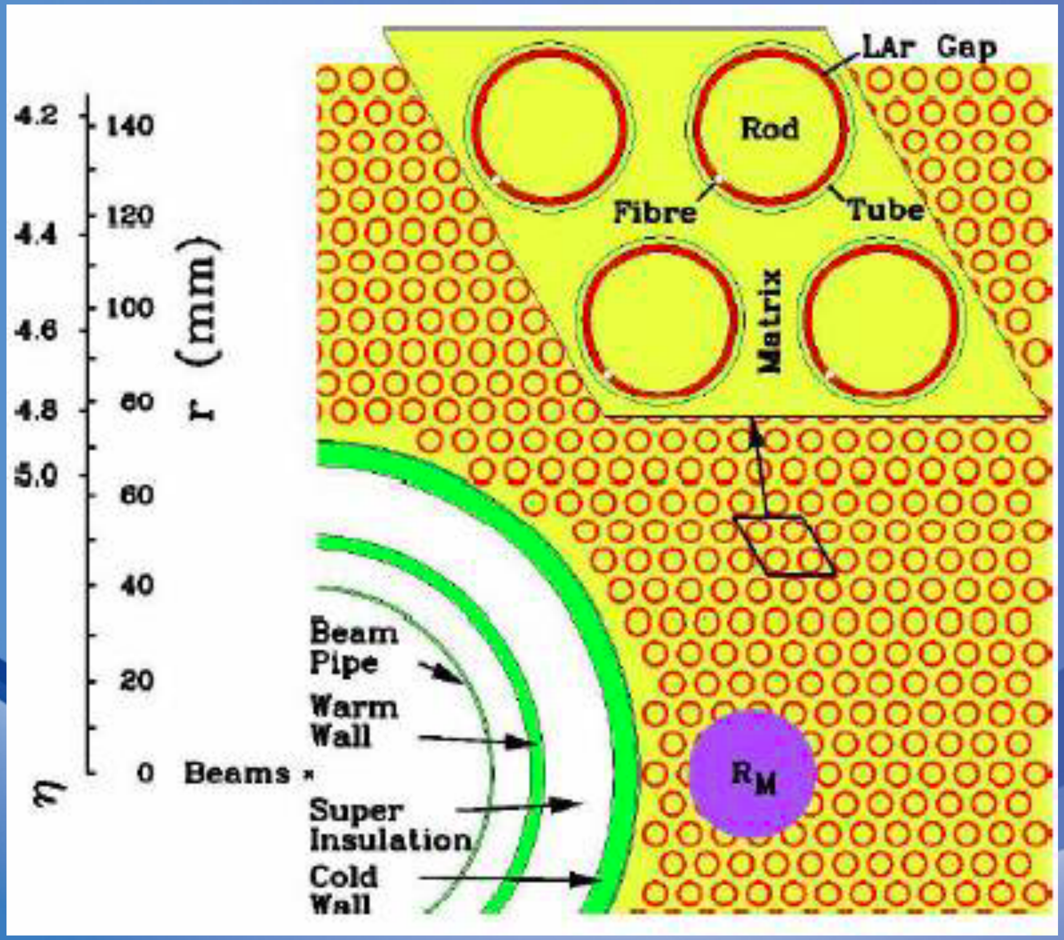


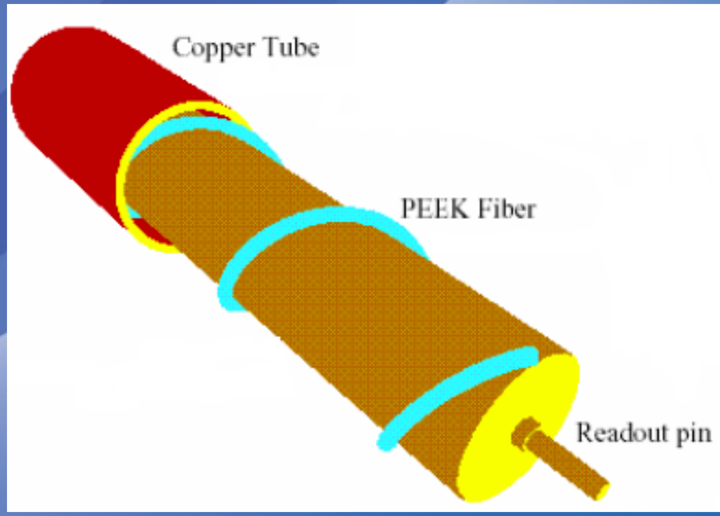
- Shower development and creation of ionization is instantaneous
- Drift across the 2mm LAr gap takes ~450ns
- To speed the response integrate 'effectively' the charge to about 10% of the drift time
- by shaping the preamplifier output signal
- bipolar shaping to reduce sensitivity to pileup

ATLAS LAr Forward Calorimeter

- 3 modules in each endcap covering 3.1<|η|<4.9
- FCAL1: LAr+Cu, 28 Xo e.m. module
- FCAL2,3: LAr+W, 2x3.7λ hadronic modules
- LAr gaps: 0.25, 0.375, 0.5mm
- To speed the response integrate 'effectively' the charge to about 10% of the drift time
- by shaping the preamplifier output signal
- bipolar shaping to reduce sensitivity to pileup



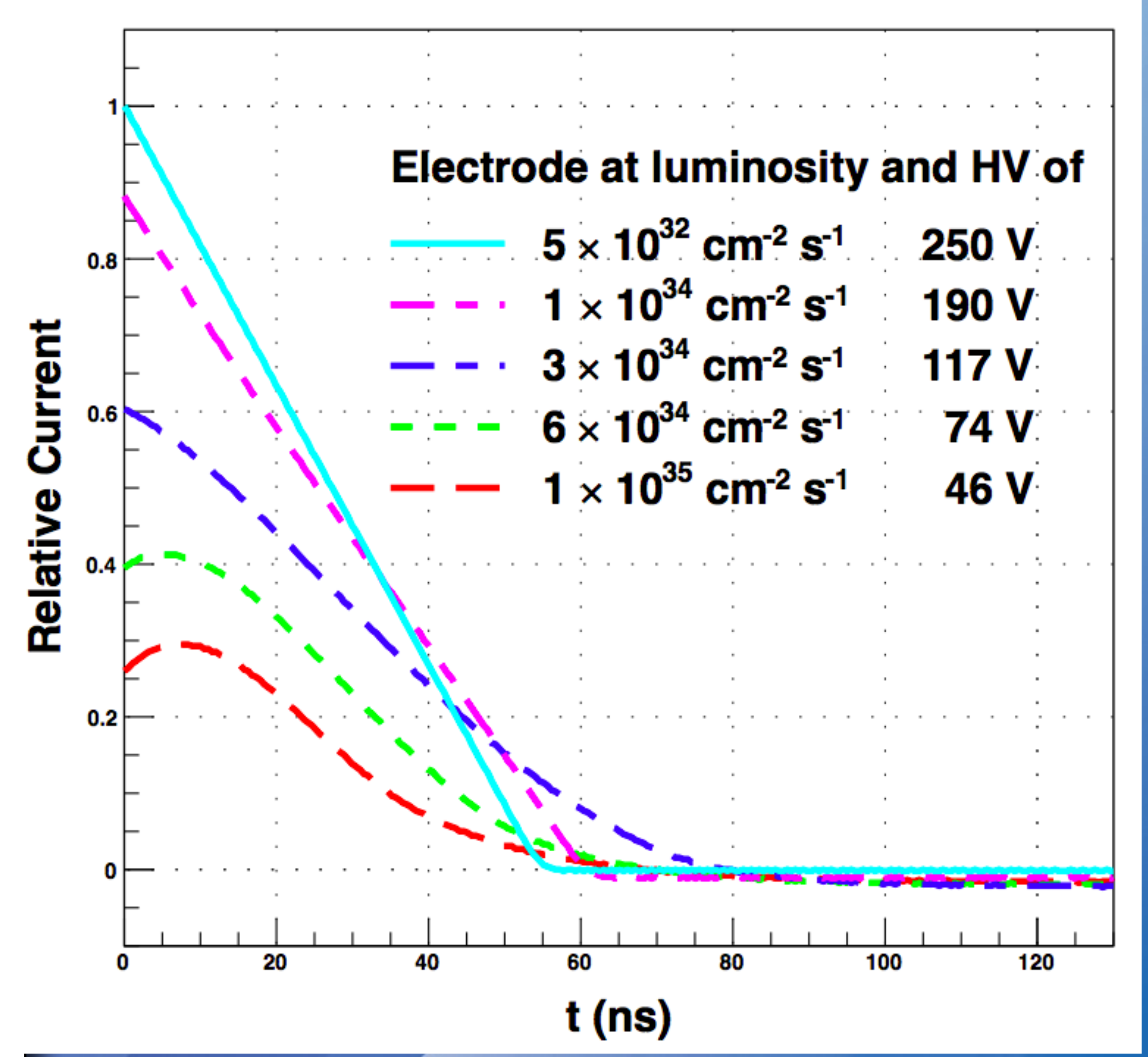




ATLAS LAr Forward Calorimeter

3 mechanisms could lead to performance degradation at high instantaneous luminosities:

- Space Charge Effects: build up of Ar+ ions lead to drift field distortion and consequently signal degradation
- Large currents drawn through protection resistors lowers significantly the HV in the LAr gap enhancing the signal degradation
- Bubble formation in LAr due to the excessive heat produced by energy deposition
- FCAL1 response could be degraded in the high |η| region



Performance implications on:

- Missing E_T resolution and tails
- Forward jet tagging

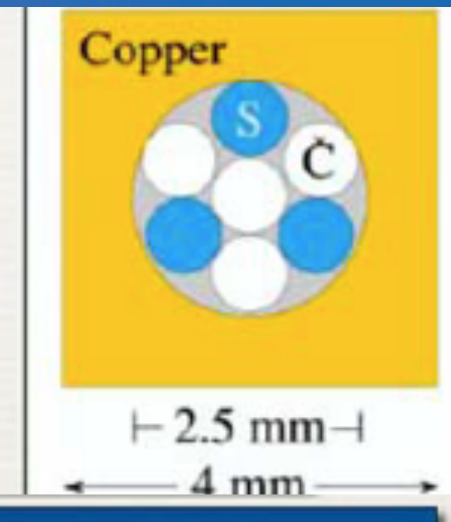
Quantitative evaluation on-going. Several options for upgrade considered

Dual Readout Calorimetry

DREAM and RD52

- **DREAM = Dual Readout Method**
  - Compensating calorimeter based on both readout of scintillation light and Cerenkov radiation
  - Quartz fibers (Cerenkov) are only sensitive to EM components in a hadronic shower development
  - Regular scintillation readout measures visible energy
- Combining the two methods allow for a measurement of f_{em} in a hadronic shower
  - eliminating largest source of fluctuations
- First test-beam results with the DREAM prototype in ~2005
- RD52 testbeam end of 2012 and reported to CERN SPC

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

DREAM and RD52

- **DREAM = Dual Readout Method**
  - Compensating calorimeter based on both readout of scintillation light and Cerenkov radiation
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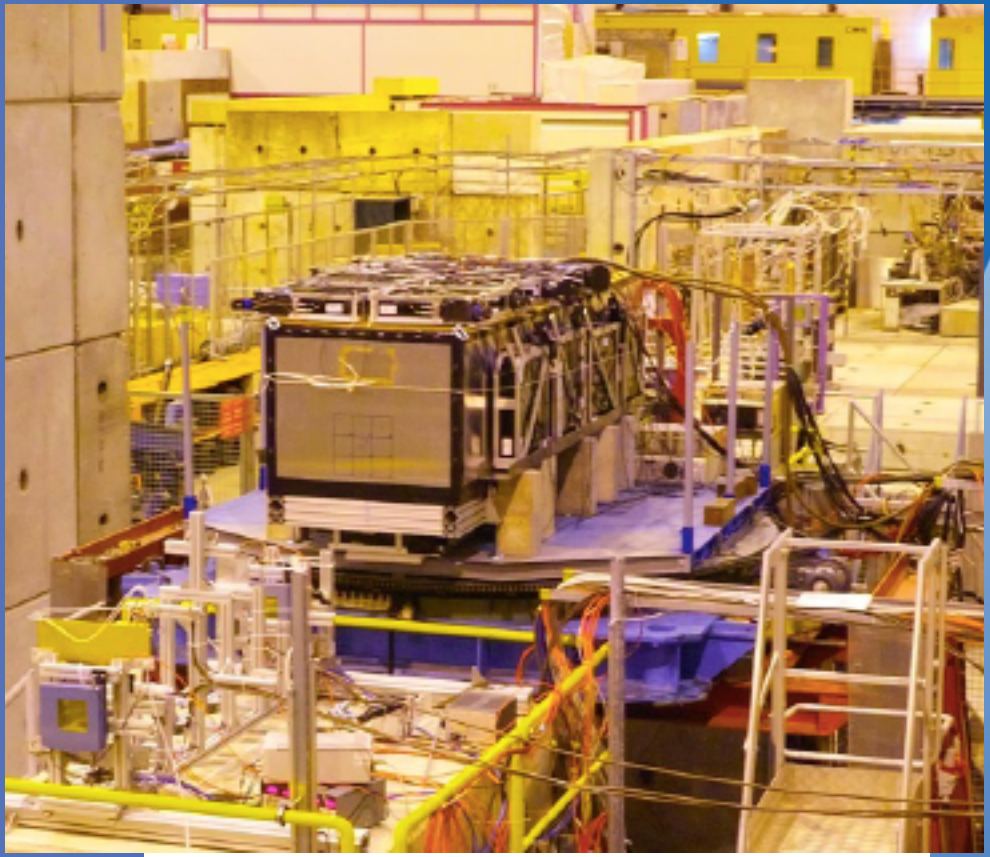
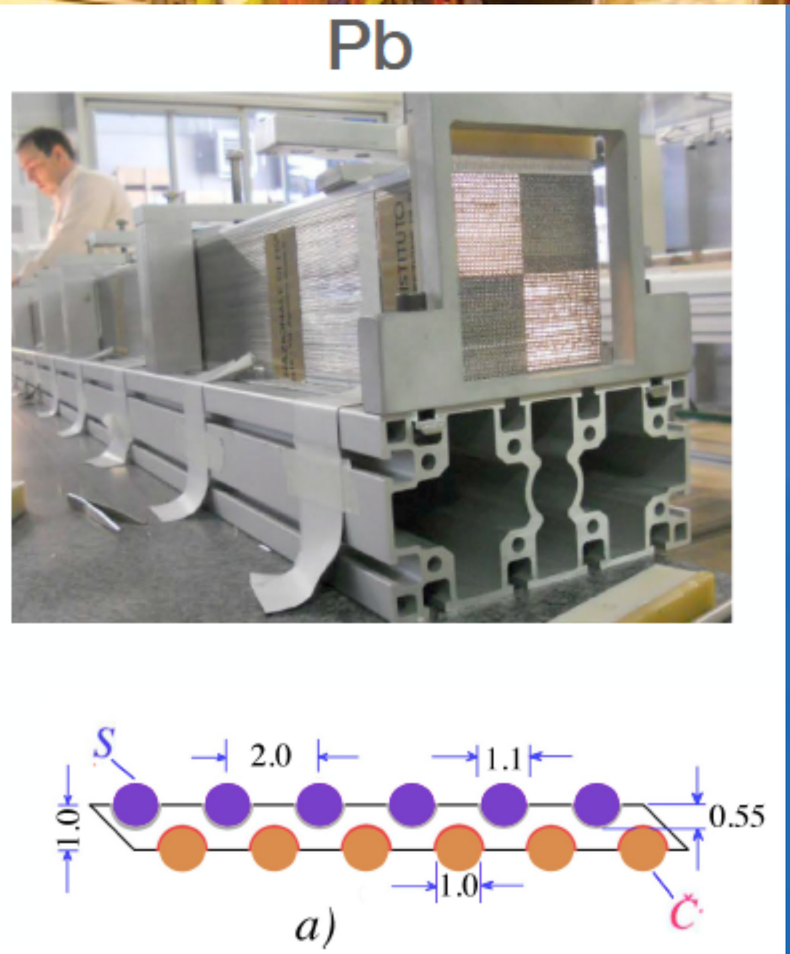
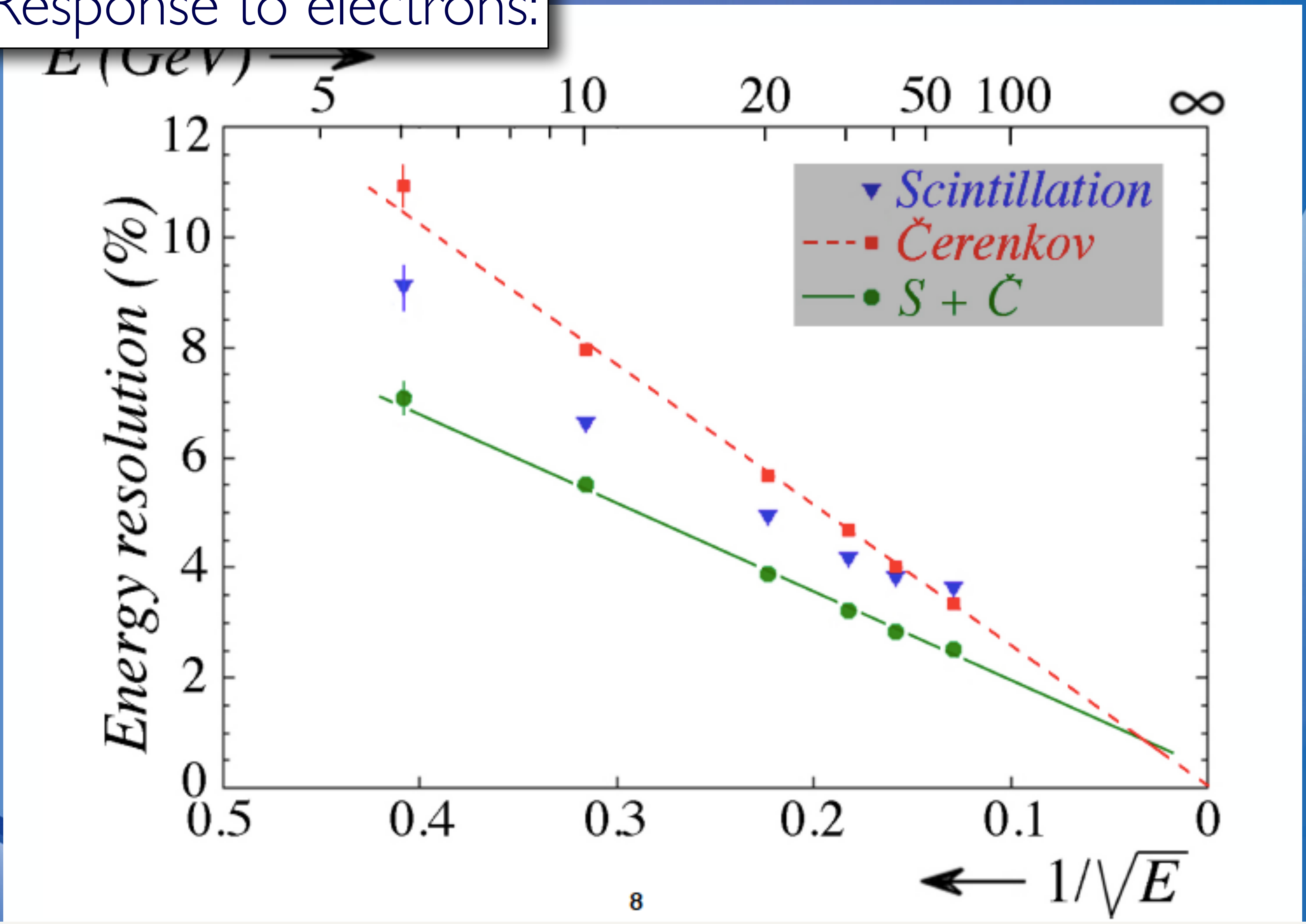




RD52: Testbeam Results

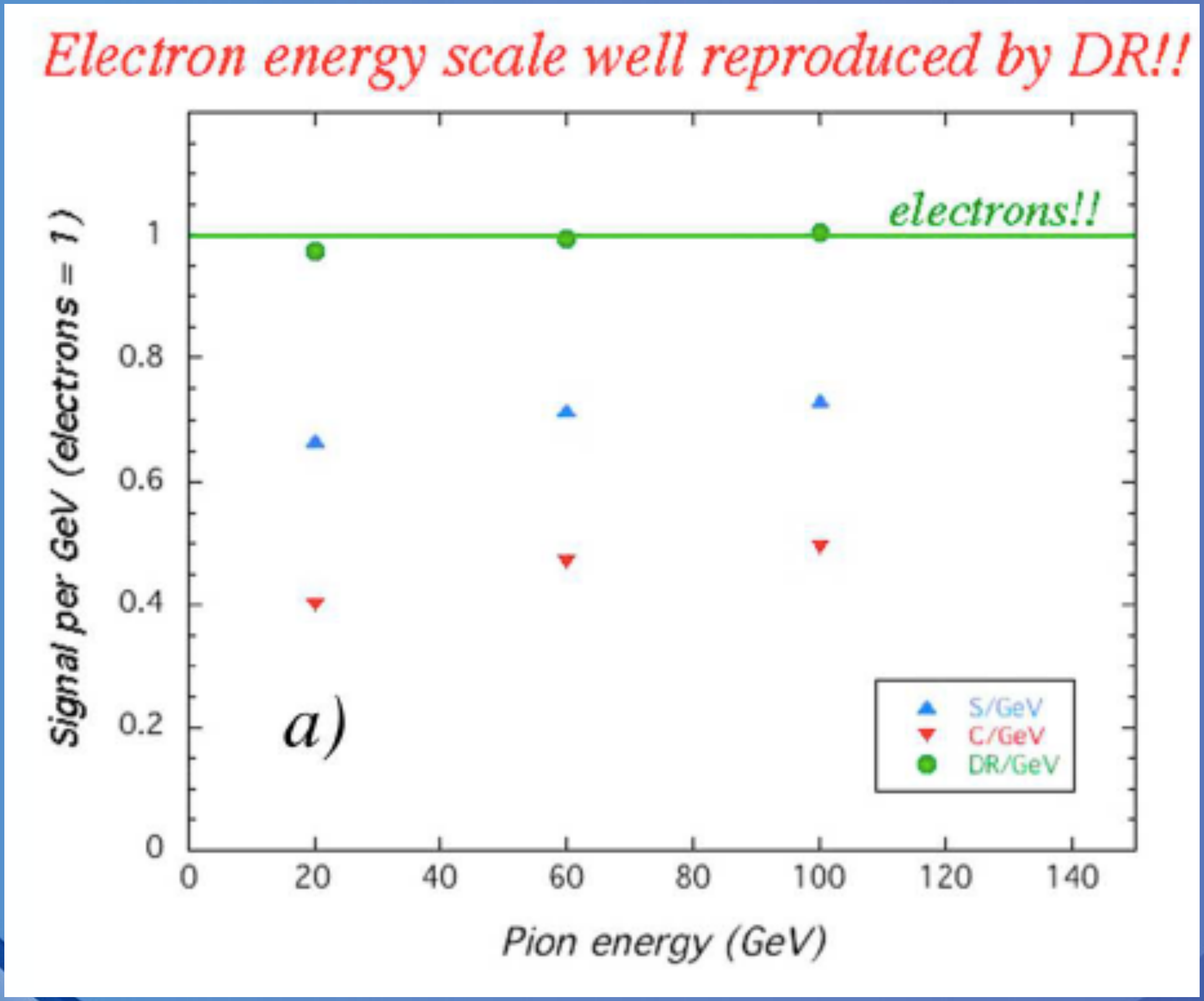
- Response to electrons:

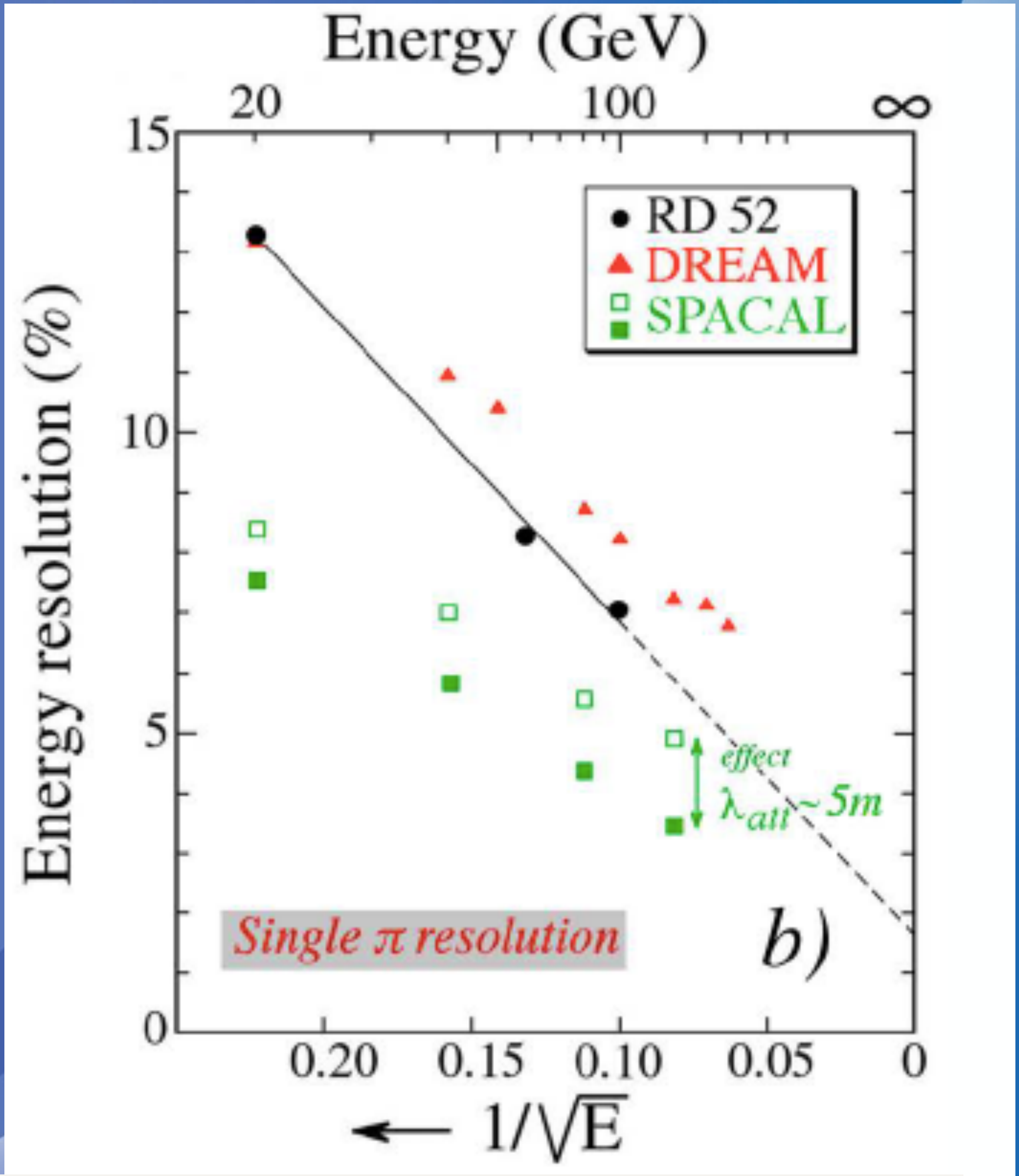


Sehwook Lee (Texas Tech University, USA), *Precision Energy Measurements with the RD52 Fiber Calorimeter,* 2013 IEEE, Seoul, South Korea, Oct. 29, 2013

RD52: Testbeam Results

- Response to pions:





Sehwook Lee (Texas Tech University, USA), *Precision Energy Measurements with the RD52 Fiber Calorimeter,* 2013 IEEE, Seoul, South Korea, Oct. 29, 2013

Dual Readout R&D @ CERN

- Based on the concept of **meta-cable structures**:
  - A heavy non-intrinsic scintillating material with high-bandgap for low UV absorption
  - The undoped host acts as efficient Cerenkov emitter: heavy material, high refraction index, high UV transmission
  - Cerium or Praesodinum doping will make the fiber act as efficient and fast scintillator:
    - ~40ns for Ce doping
    - ~20ns for Pr doping
  - Excitation and emission spectra separated
- Bulk material approach
  - L(Y)SO, LuAG, GdScAG
  - Heavy fluoride glasses (HFG) [radiation damage is an issue]

Dual Readout R&D @ CERN

Lutetium Aluminum Garnet LuAG ($Lu_3Al_5O_{12}$)

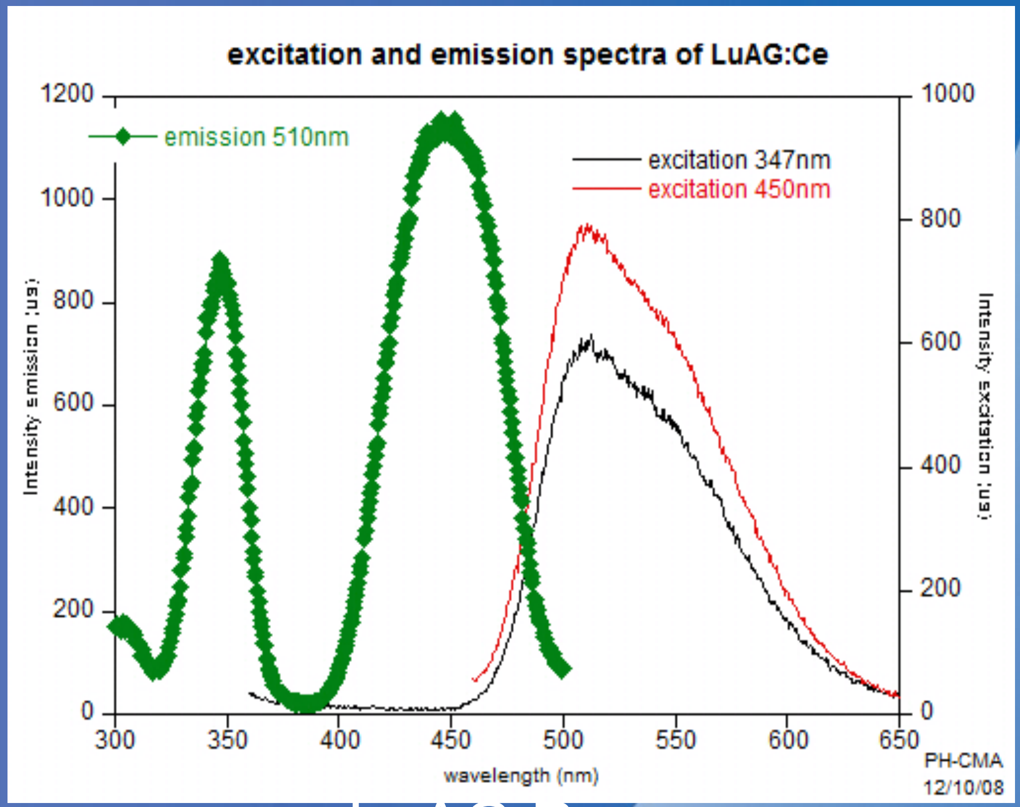
Physico-chemical properties

Structure / Space group	Cubic / Ia3d
Density (g/cm³)	6.73
Zeff	62.9
Radiation length X_0 (cm)	1.41
Interaction length (cm)	23.3 *LuAP: 19.8* *Fe: 17*
Hardness (Mohs)	7.5 *PWO: 3* *BGO, glass: 5*
Fracture toughness (Mpa.m$^{1/2}$)	1.1
Cleavage plane / H_2O solubility	No / No
Melting point (°C)	2260
Thermal expansion @ RT (°K^{-1})	8.8 10^{-6}
Thermal conductivity @ RT (W/m°K)	31

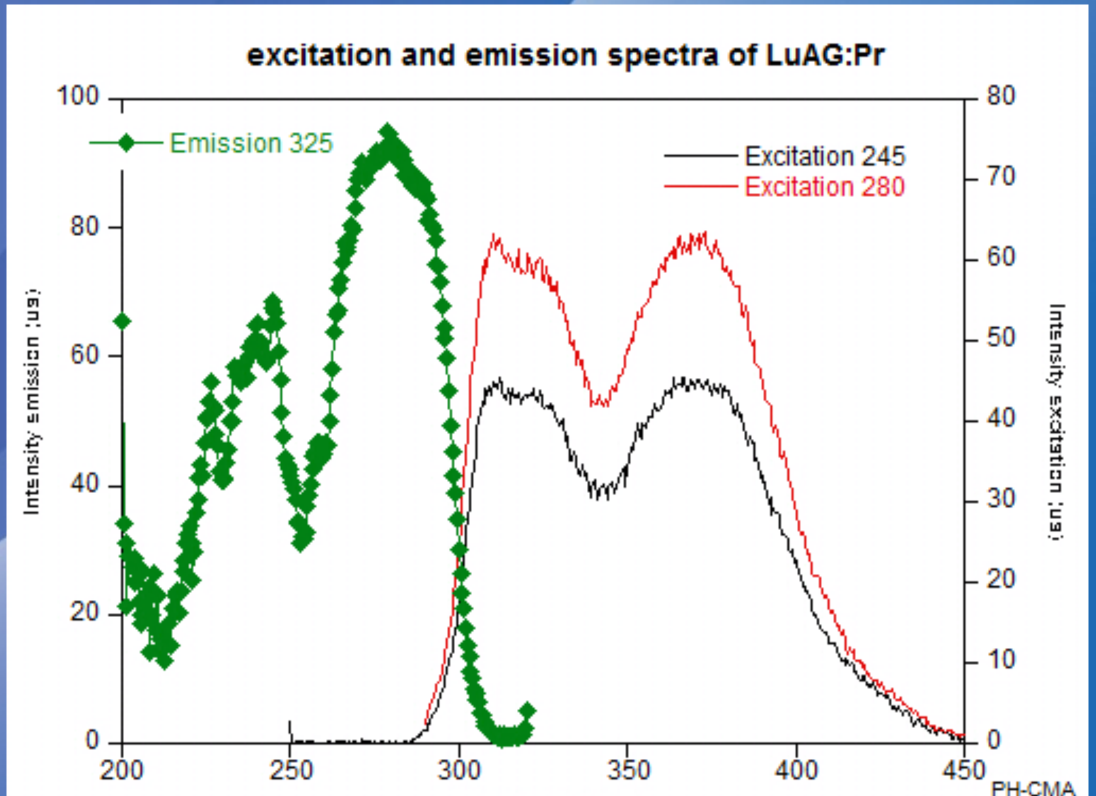
Optical properties

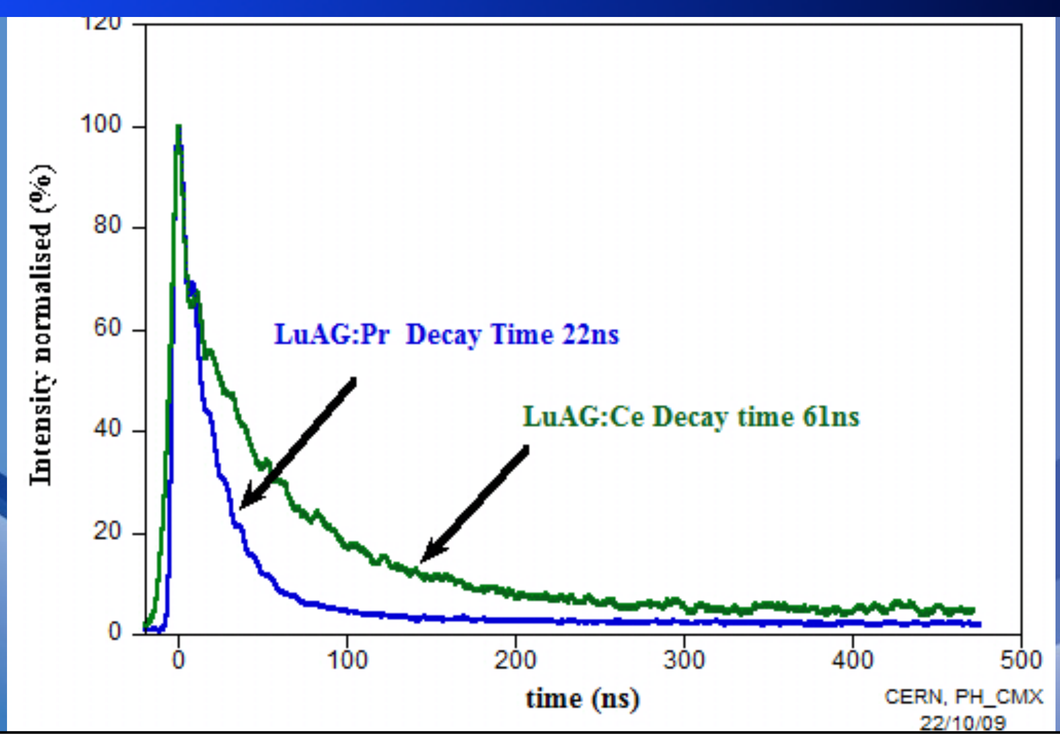
Light yield: Ce or Pr doped (ph/MeV)	20' 000 *1/2 NaI(Tl)*
d(LY)/dT	0.8%/°C
Emission wavelength (nm): Ce doped / Pr doped	535 / 290, 350
Decay time (ns): Ce doped / Pr doped	70 / 20
Refractive index @ 633nm (isotropic) n^2= 3.3275151 - 0.0149248 λ^2	1.842 *Quartz: 1.55*
Fundamental absorption undoped (nm)	250
Max. Cerenkov 1/2 angle	57°
Total reflexion 1/2 angle	33°
Cerenkov threshold e energy (KeV)	97

LuAG:Ce



LuAG:Pr

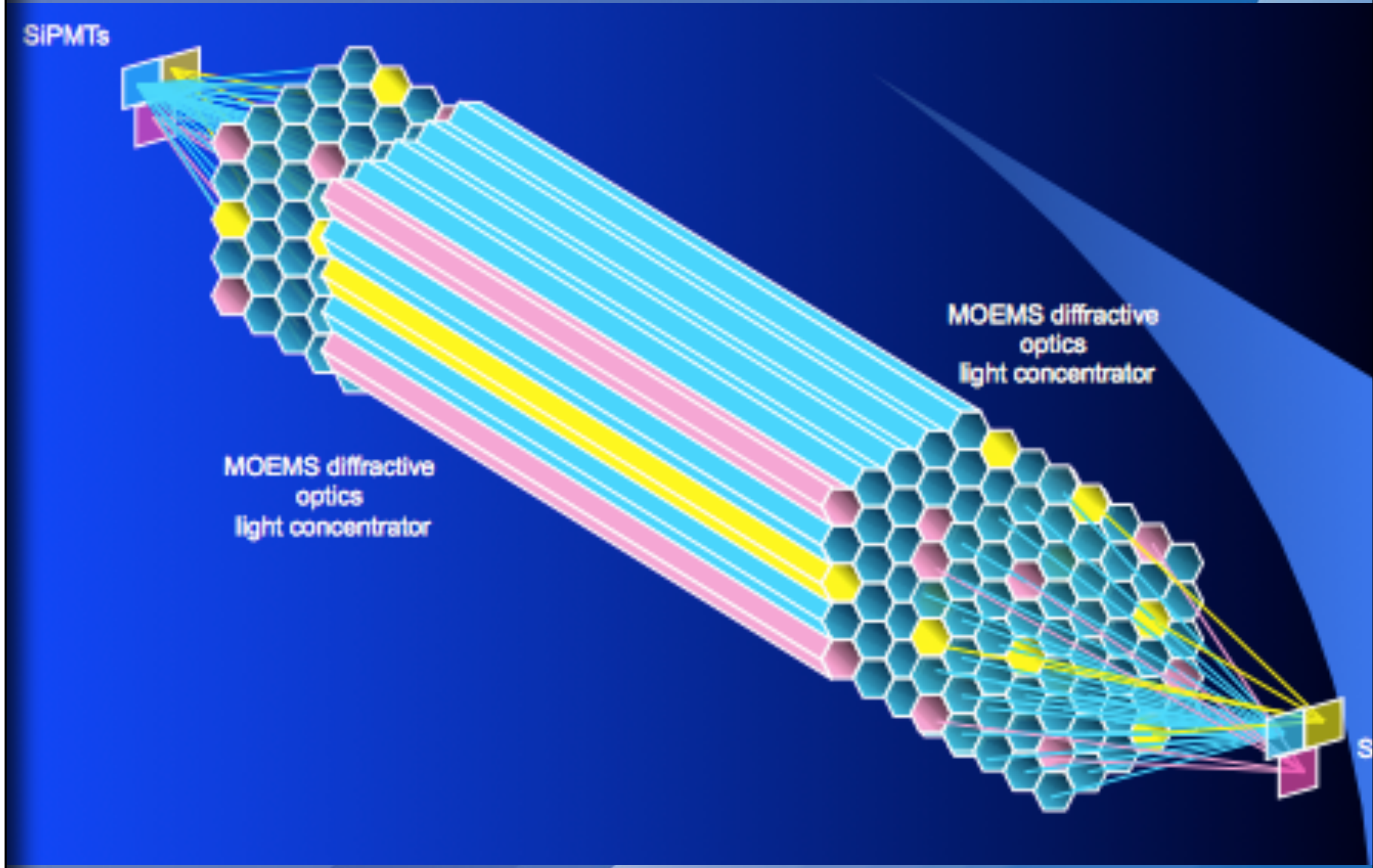




P. Lecoq, *Organic and Inorganic Scintillators*, XII ICFA School on Instrumentation in Elementary Particle Physics, Bogota' Columbia, December 2013

Dual Readout R&D @ CERN

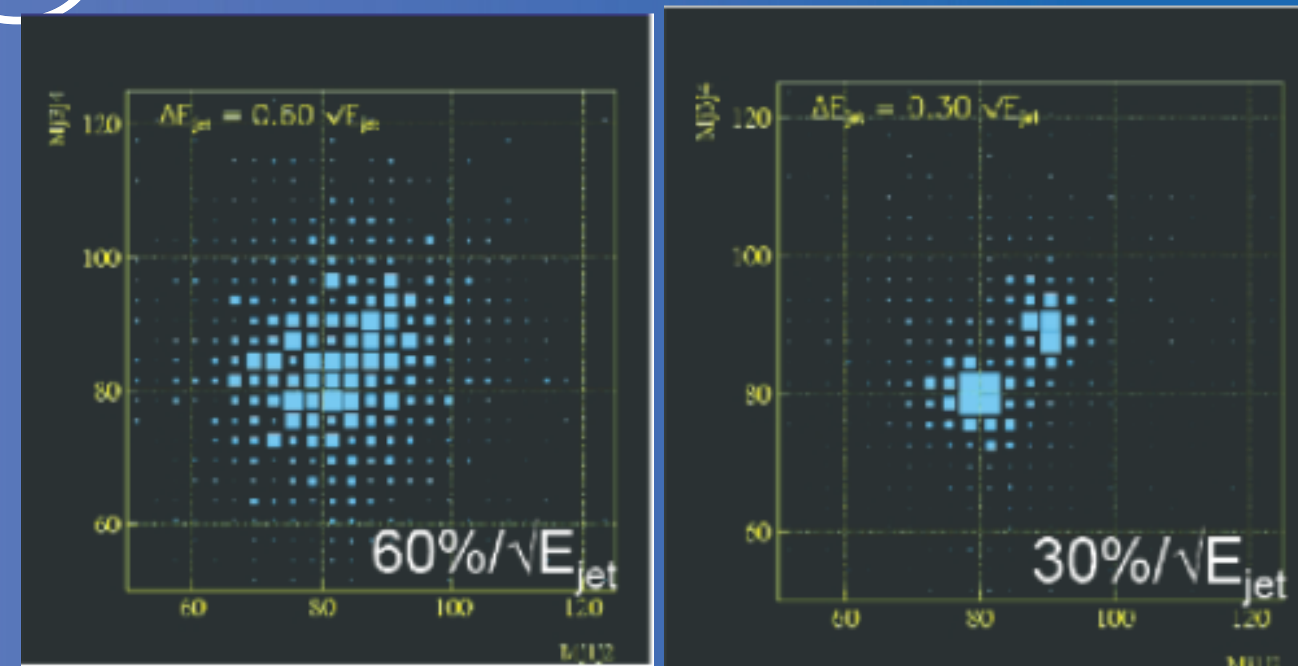
- quasi-homogeneous calorimeter
  - scintillating and Cerenkov fibers of the same heavy material eliminating sampling fluctuations
- **very flexible fiber arrangement for any lateral or longitudinal segmentation**
- **Possibility of combining PFA (high segmentation) and Dual Readout Technique**
- Diffractive optic light concentrator to a photo-detector (SiPM). Readout at both ends



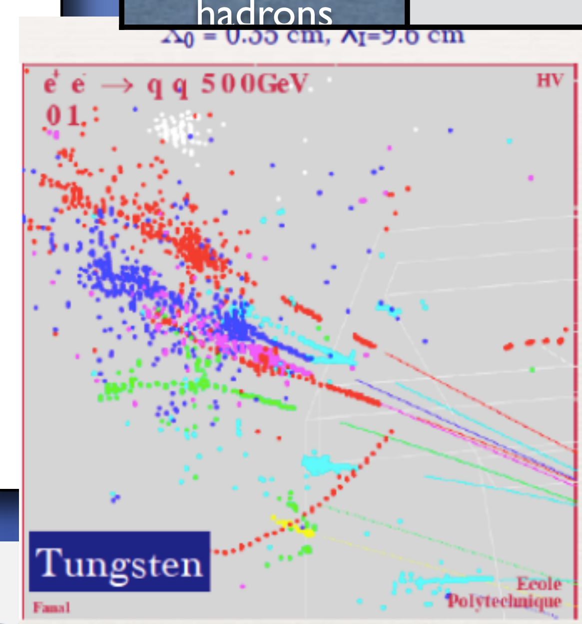
Calorimetry R&D @ ILC

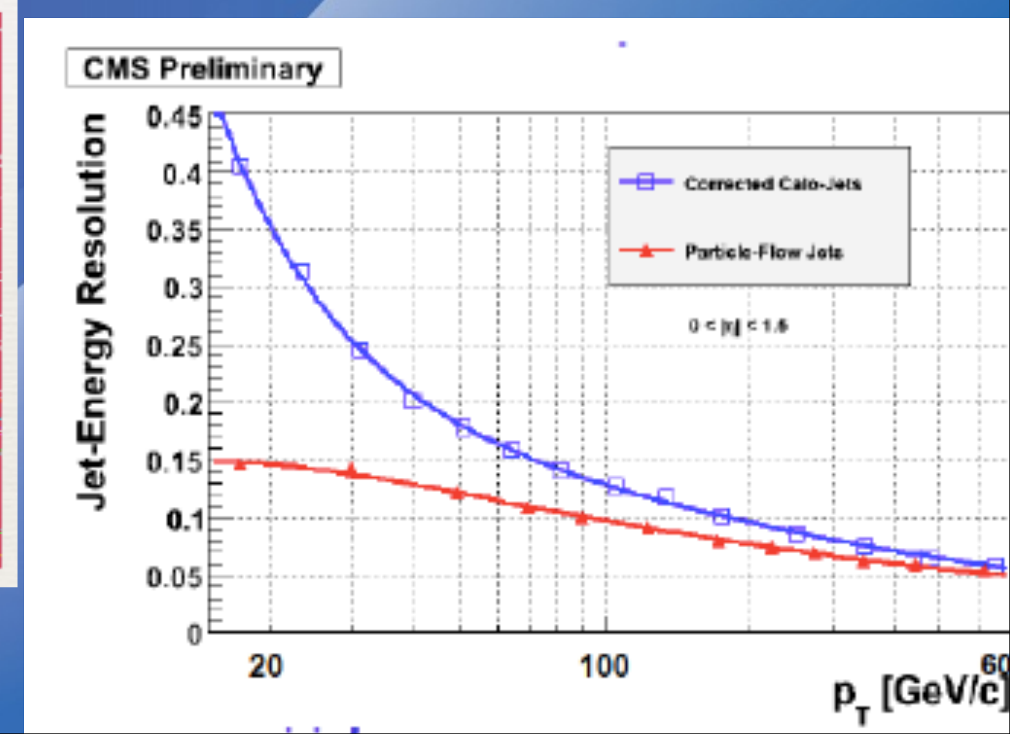
Calorimetry @ ILC/CLIC

- Goal: distinguish W,Z hadronic decays
  - WW/ZZ → 4 jets
- Requirement: jet energy resolution ~3-4% @ ~50 GeV
  - 30%\√E stochastic term
- High granularity detectors
- Particle Flow Algorithm:
  - measure charged particles with trackers
  - photons with ECAL
  - neutral hadrons with ECAL+HCAL
  - Combine tracker and calo information to separate clusters originated by charged from those by neutral
  - Minimization of shower overlaps to avoid ambiguity and double counting



Particles in jet	fraction of energy in jet	detector	single particle resolution	jet energy resolution
charged particles	60%	tracker	~0.01% · p_T	negligible
photons	30%	ECAL	~15%/√E	~5%/√E
neutral hadrons	10%	ECAL+HCAL	~45%/√E	~15%/√E

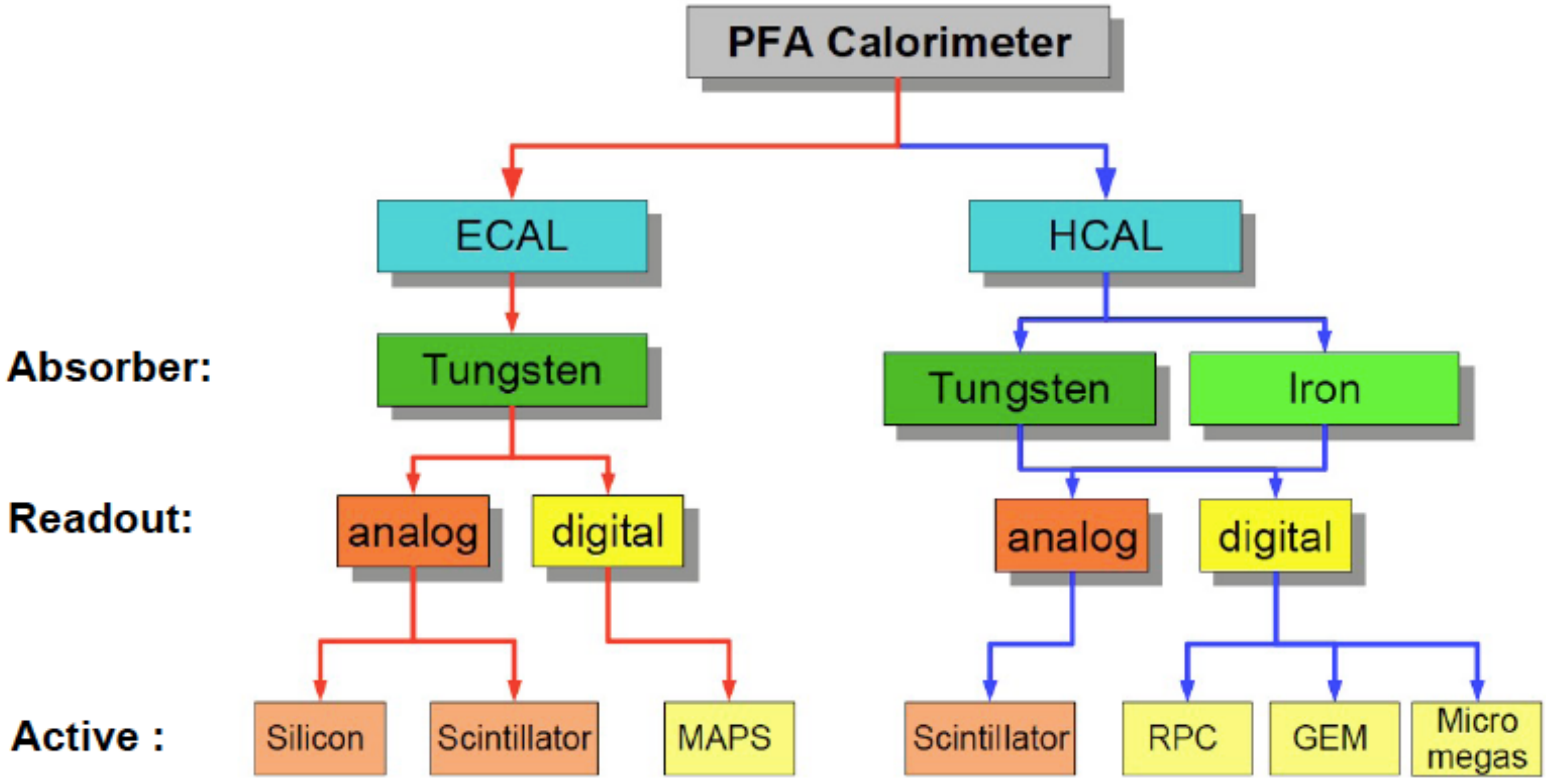




$$\sigma = \sigma_{charged} \oplus \sigma_{\gamma} \oplus \sigma_{neutral} \oplus \sigma_{confusion}$$

Calorimetry @ ILC/CLIC

★Various options for high granularity sampling calorimeters…

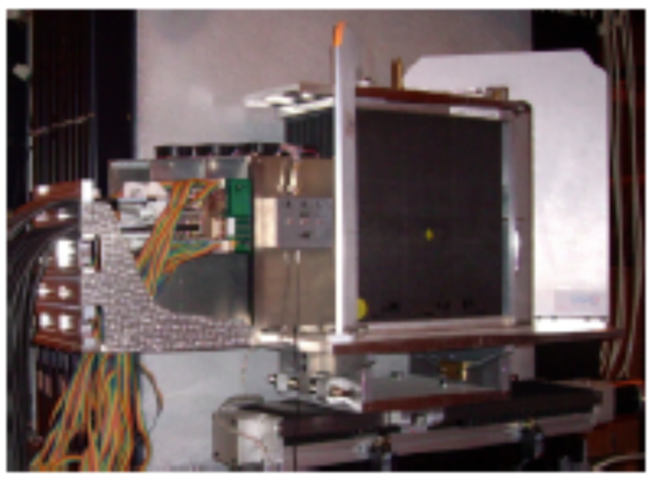


Calorimetry @ ILC: SiW ECAL

Physics Prototype

Proof of principle

2003 - 2011



JINST 3, 2008

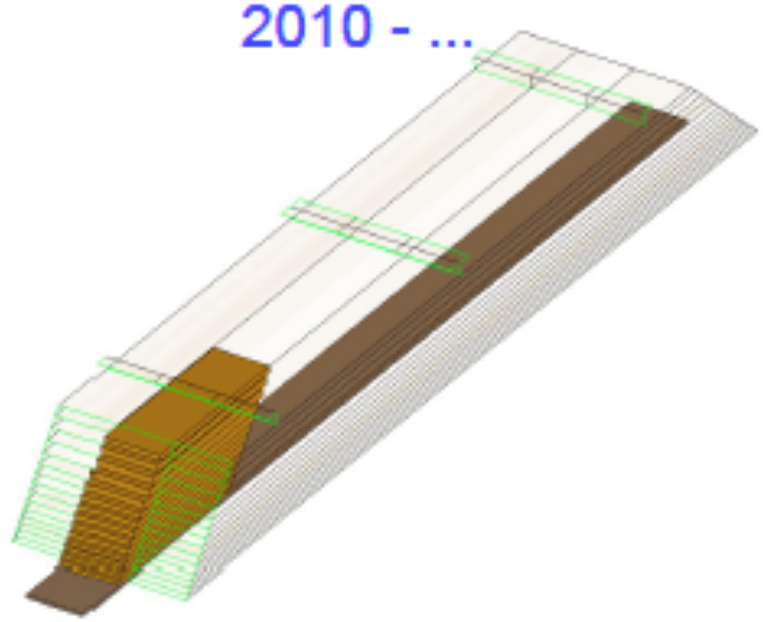
Number of channels : 9720

Weight : ~ 200 Kg

Technological Prototype

Engineering challenges

2010 - ...

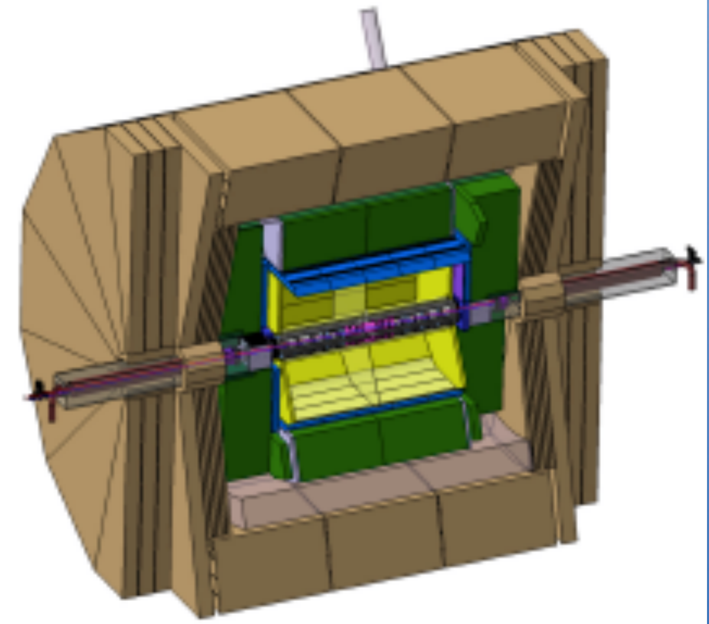


TDR EUDET-Report-2009-01

Number of channels : 45360

Weight : ~ 700 Kg

LC detector



DBD for ILC
CDR for CLIC

ECAL :

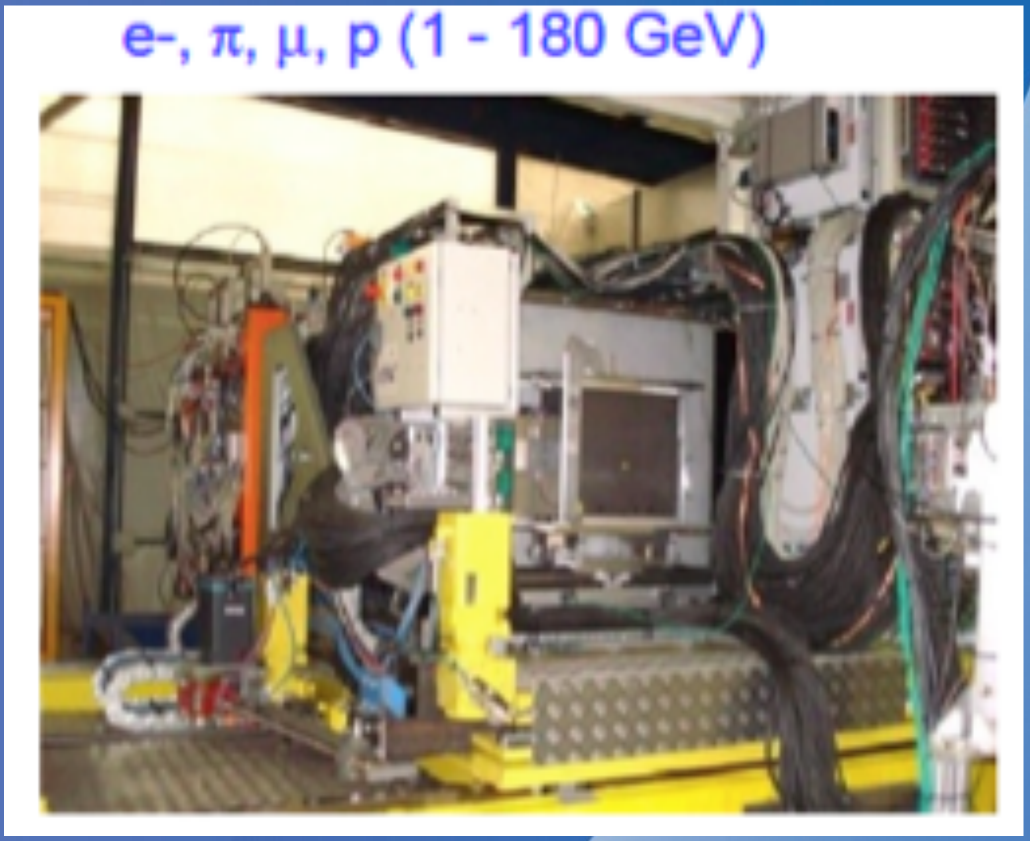
Channels : ~ 100 10^6

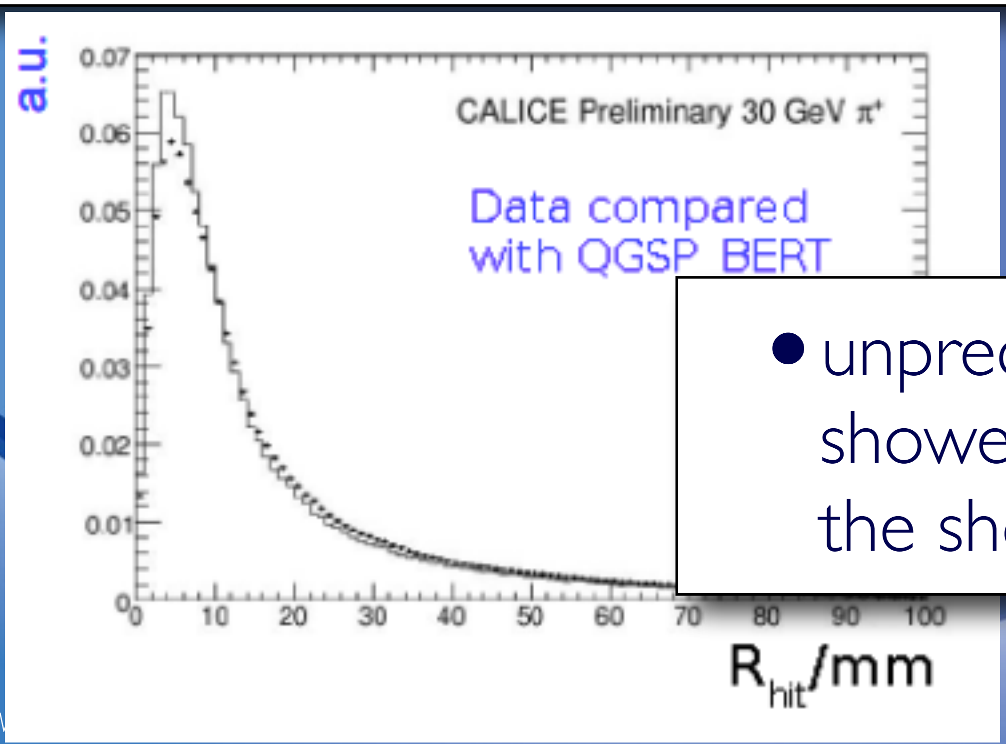
Total Weight : ~ 130 t

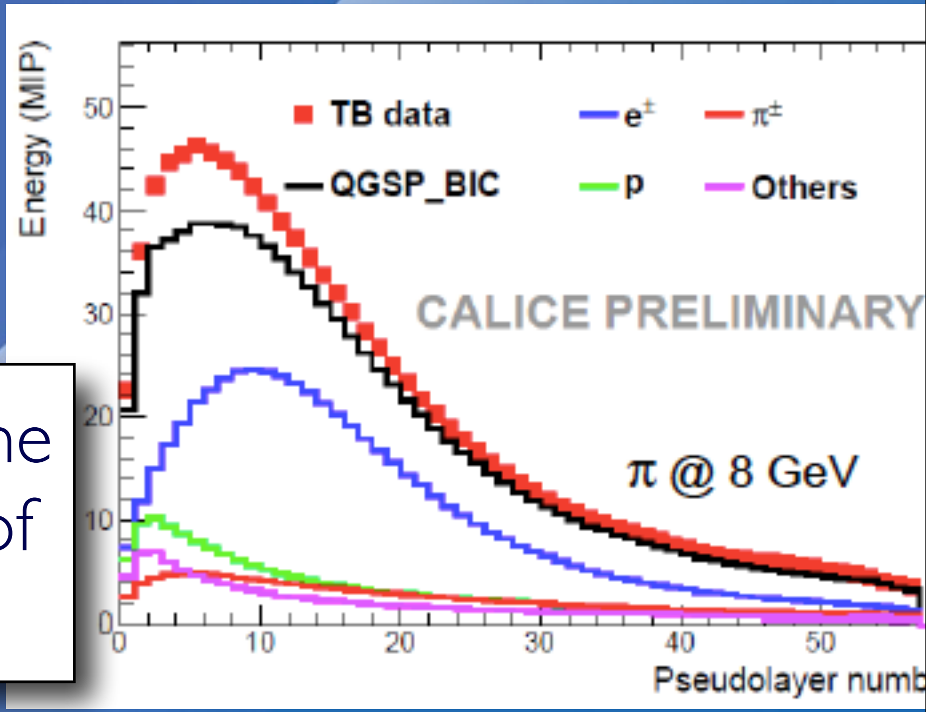
Calorimetry @ ILC: SiW ECAL

- Beam tests 2006-2011 with the first prototype (DESY, CERN, FNAL)

- Proof of principle. Improve understanding of the detector technology and of methods
  - Unprecedented granularity: shower development and detailed comparison with Geant4 simulations
  - Better understanding of hadronic non-em components
  - Noise, calibration, performances
  - Development and testing algorithms







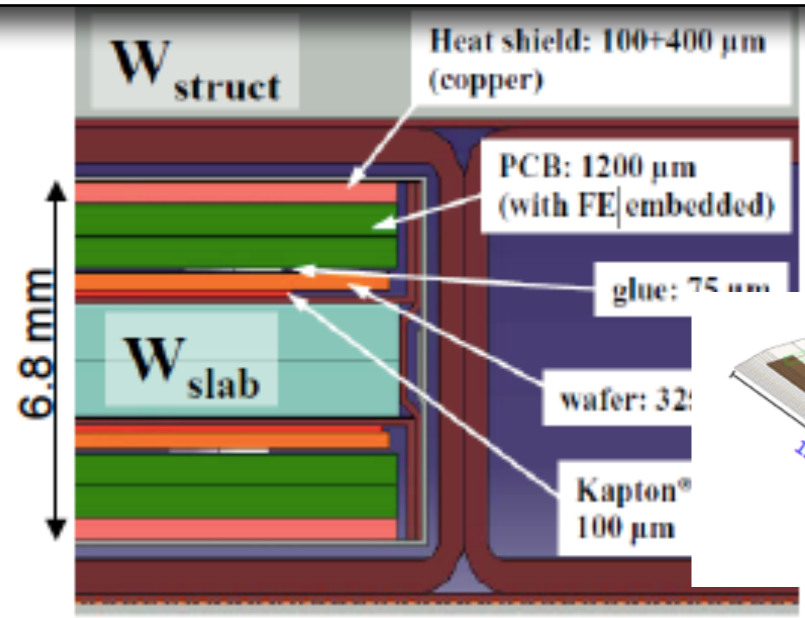
- unprecedented details of the shower development and of the shower components

Calorimetry @ ILC: SiW ECAL

Technological prototype (started 2010): realistic dimensions, integration and power pulsed electronics

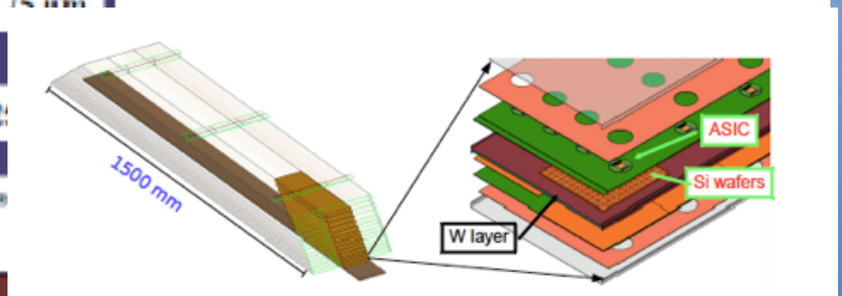
1 Active Sensor Units (ASU)

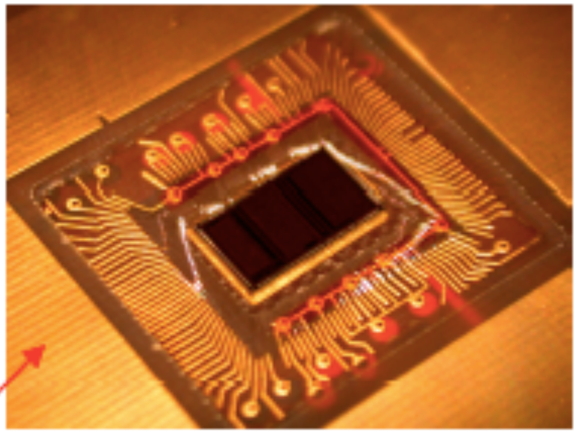
- 1 kapton (HV for PIN diodes)
- 1 layer PIN diodes
- 1 PCB with microchips embeded
- 1 thermal drain (copper)



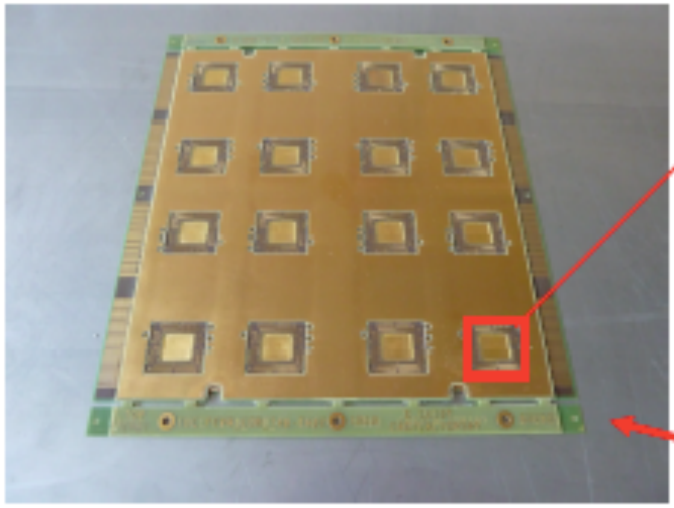
W thickness:

- 2.1 mm (20 layers)
- 4.2 mm (9 layers)

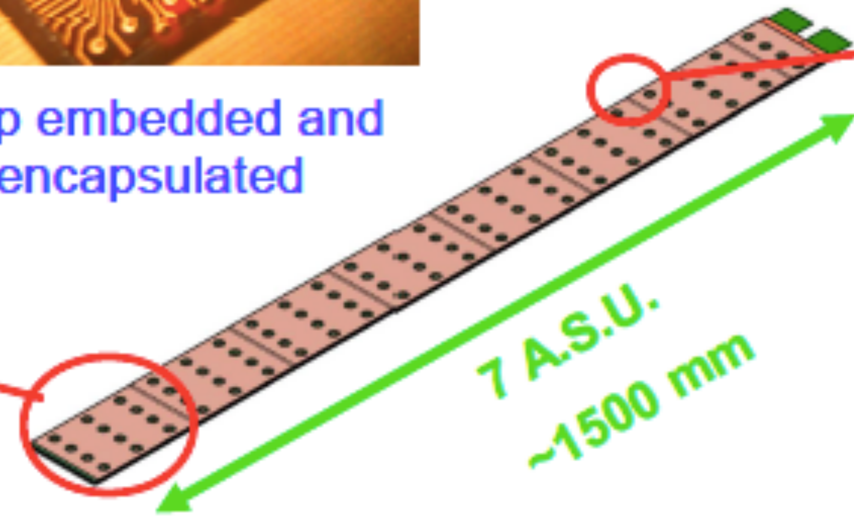




Chip embedded and encapsulated



PCB prototype



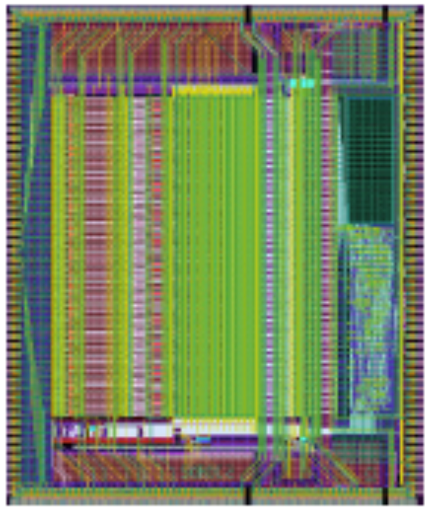
Interconnection studies

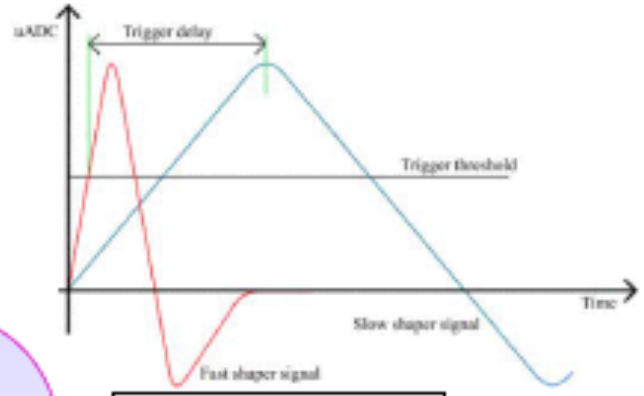
Calorimetry @ ILC: SiW ECAL

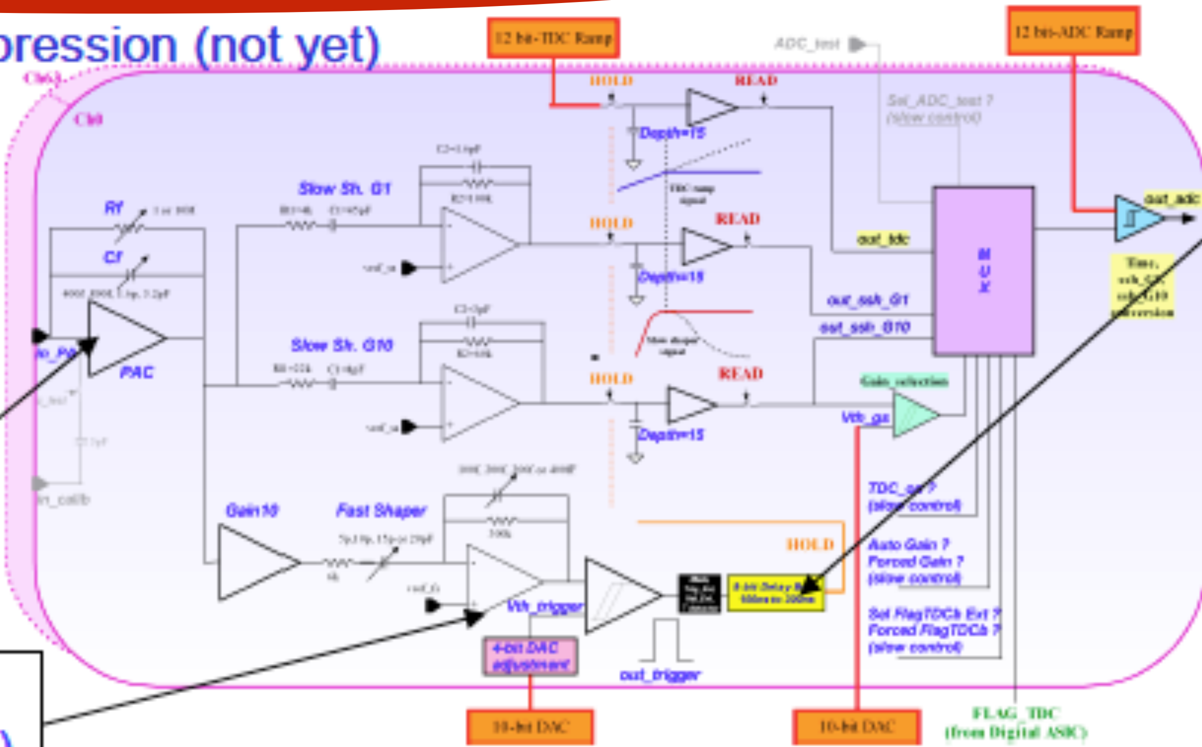
Front end electronics: SKIROC

SKIROC (Silicon Kalorimeter Integrated Read Out Chip)

- SiGe 0.35µm AMS
- 7.5 mm x 8.7 mm
- High integration level (variable gain charge amp, 12-bit ADC, digital logic)
- 64 channels
- Large dynamic range (~2500 MIPS), low noise (0.4 fC – 10 pC)
- Auto-trigger at ½ MIP
- Low Power: 25µW/ch (power pulsing)
- On chip zero suppression (not yet)







Trigger delay

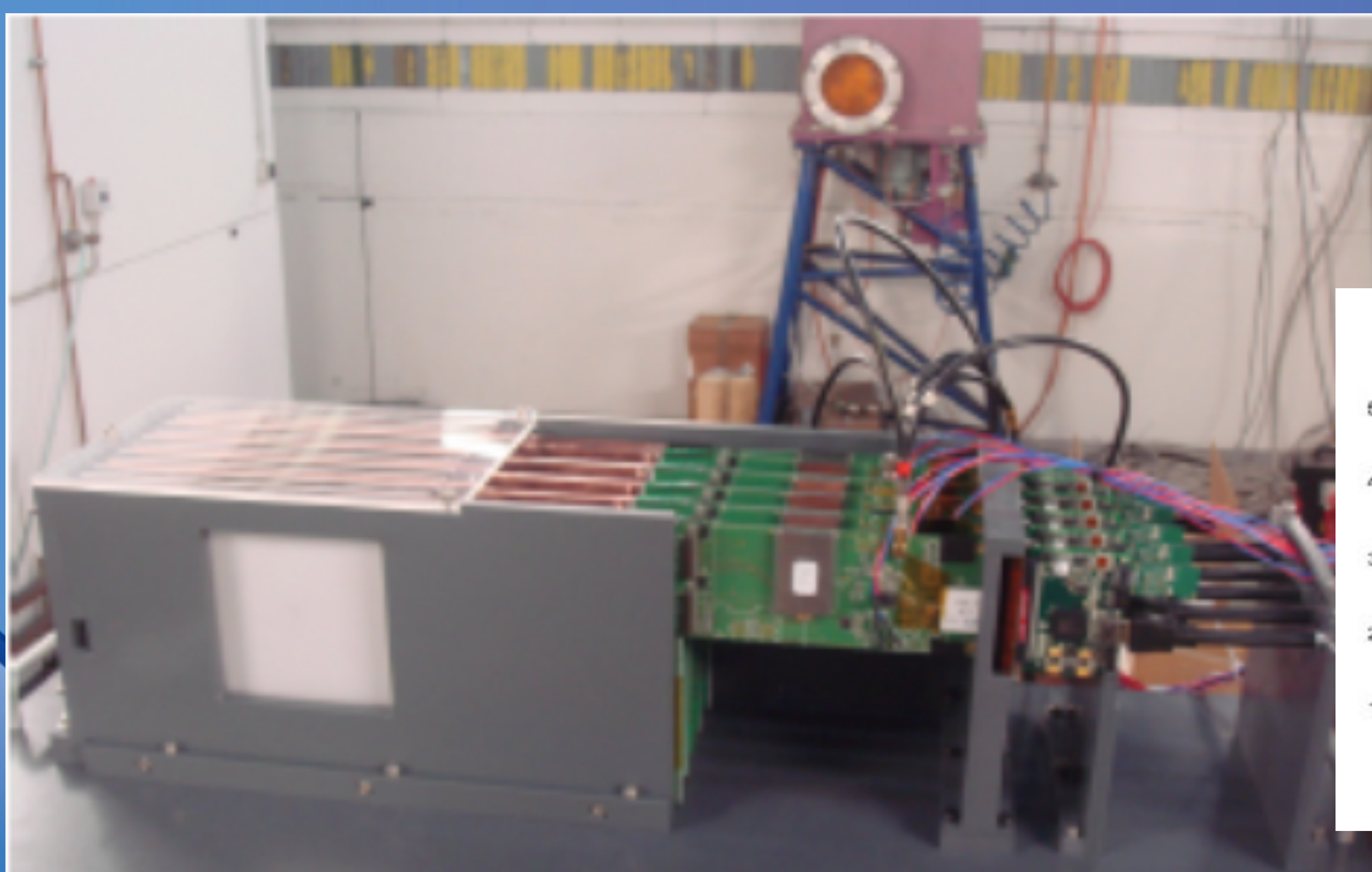
Preamplifier (adjustable gain)

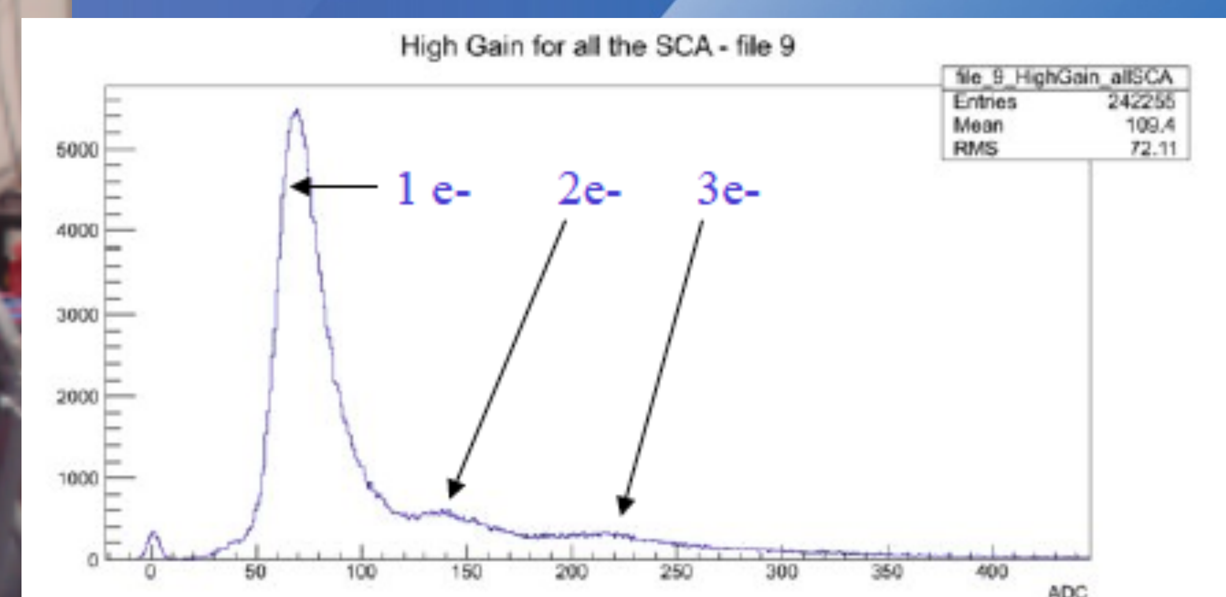
Internal trigger (self-triggering capability)

Calorimetry @ ILC: SiW ECAL

- Beam tests @ DESY (low energy electrons)
  - 6 layers July 2012 (1536 channels)
  - 8 layers Feb 2013 (2048 channels)
    - 4 layers in power pulsing mode

- Understanding of the electronics
- Establishment of calibration procedure
- Homogeneity of response through x,y scans

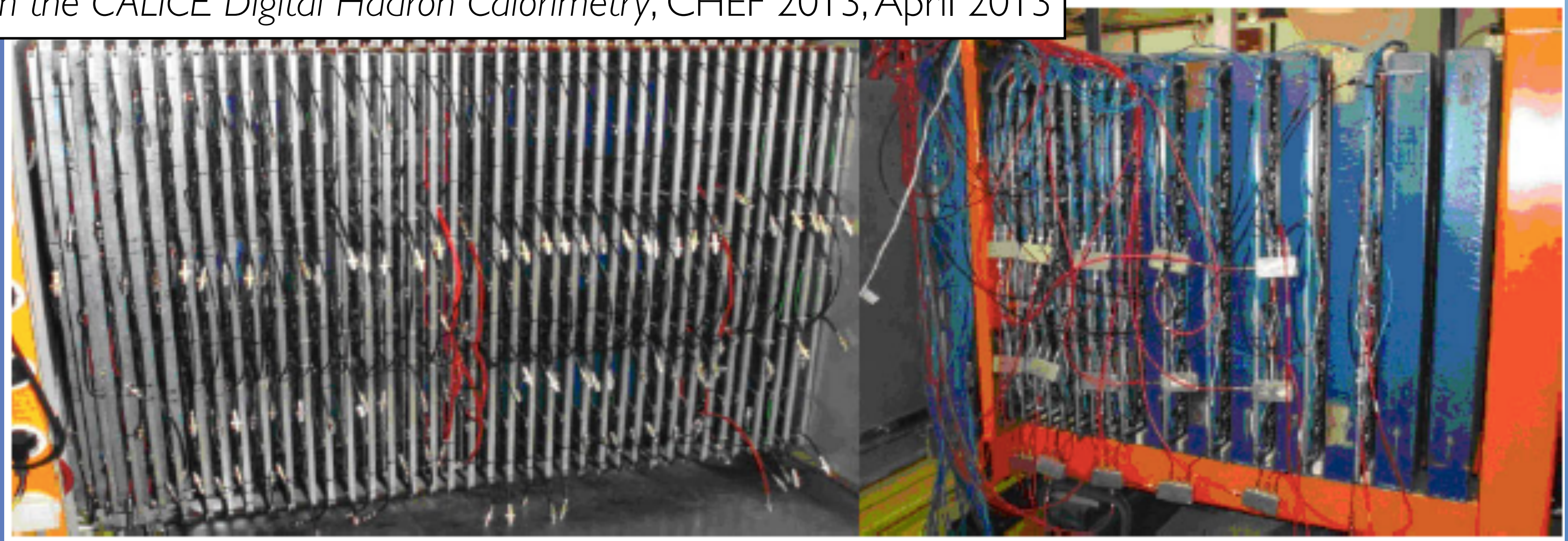


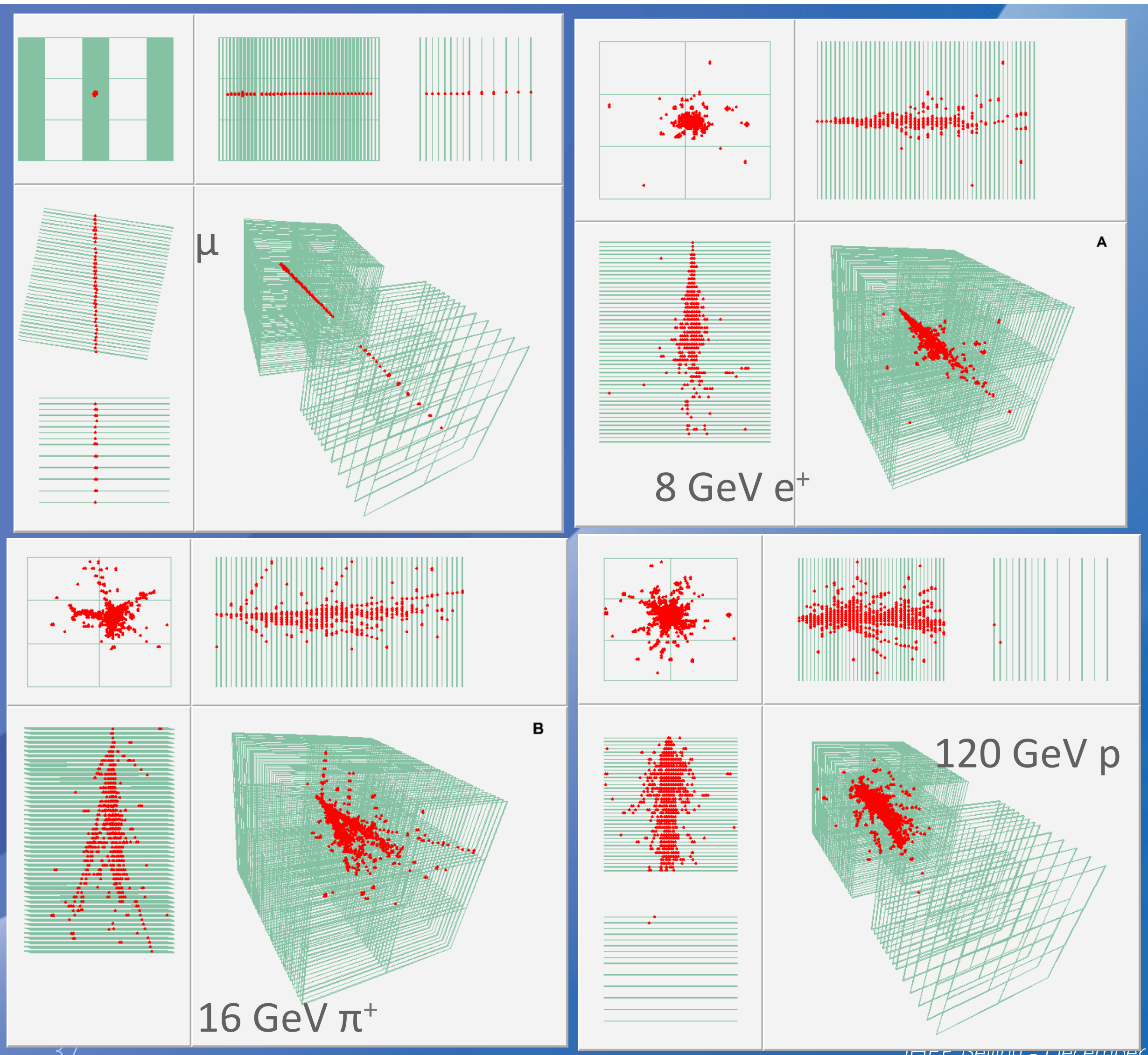


Calorimetry @ ILC: DHCAL

J. Repond, *First Results from the CALICE Digital Hadron Calorimetry*, CHEF 2013, April 2013

- DHCAL prototype:
  - RPC + Fe (or W) absorbers
  - Main stack (38-layers 17.5mm steel)
  - Tail catcher (14-layer 25 mm steel + 6x10mm)
  - Each layer (1m2 area) consists of 3 RPCs (1cm2 pads) for approximately ~9000 channels/layer
- Exposed on testbeam at FNAL first and then to CERN on PS and SPS beams

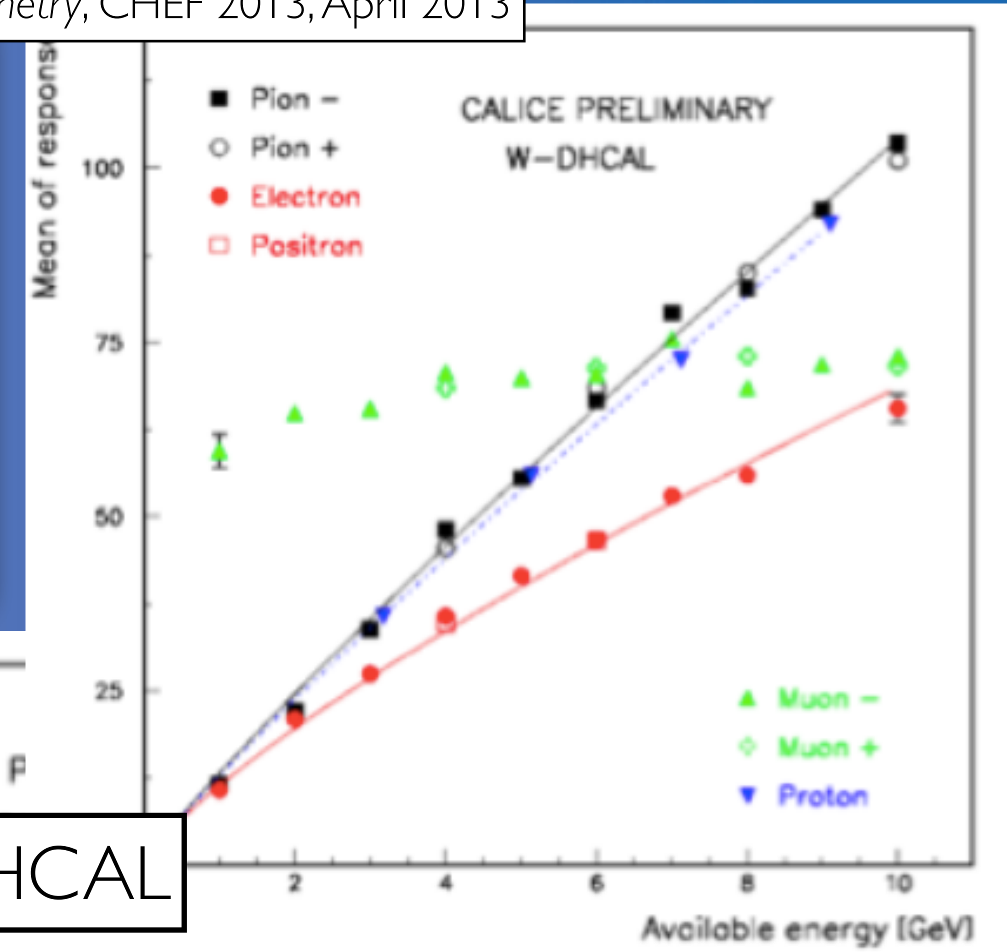


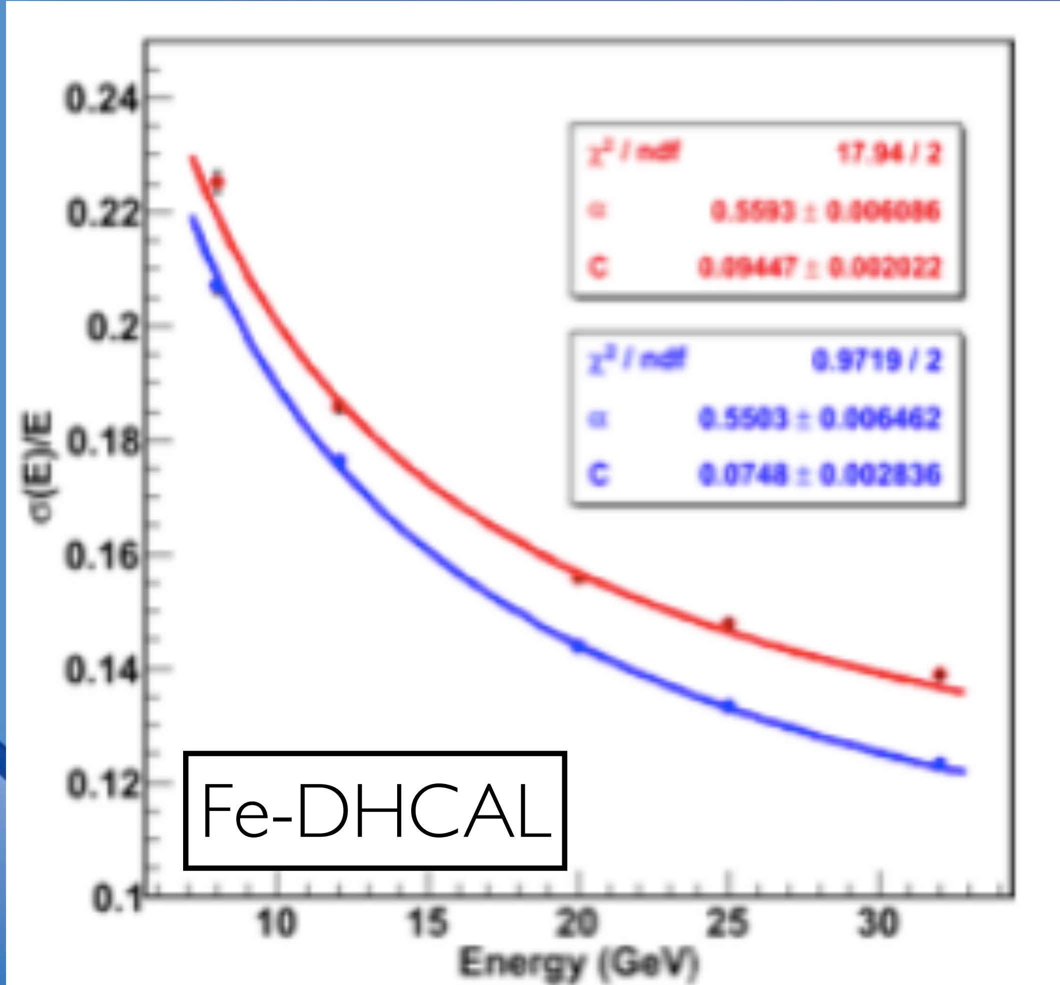


Calorimetry @ ILC: DHCAL

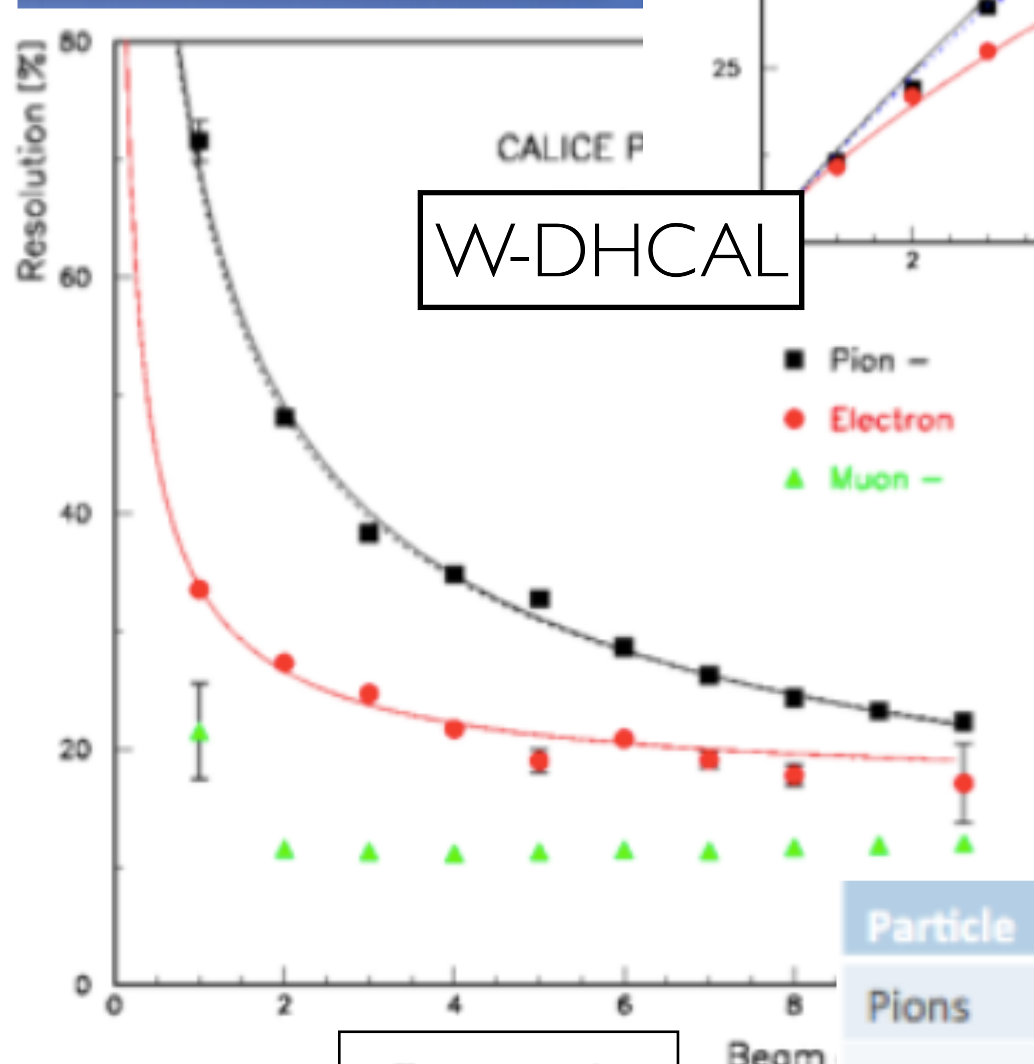
J. Repond, *First Results from the CALICE Digital Hadron Calorimetry*, CHEF 2013, April 2013

- Prototype tested with Fe and W absorbers
  - Non-linearity: data empirically fit by a power low αE^{β} (β=0.9 for hadrons, 0.78 for electrons)





Standard pion selection
+ No hits in last two layers
(longitudinal containment)



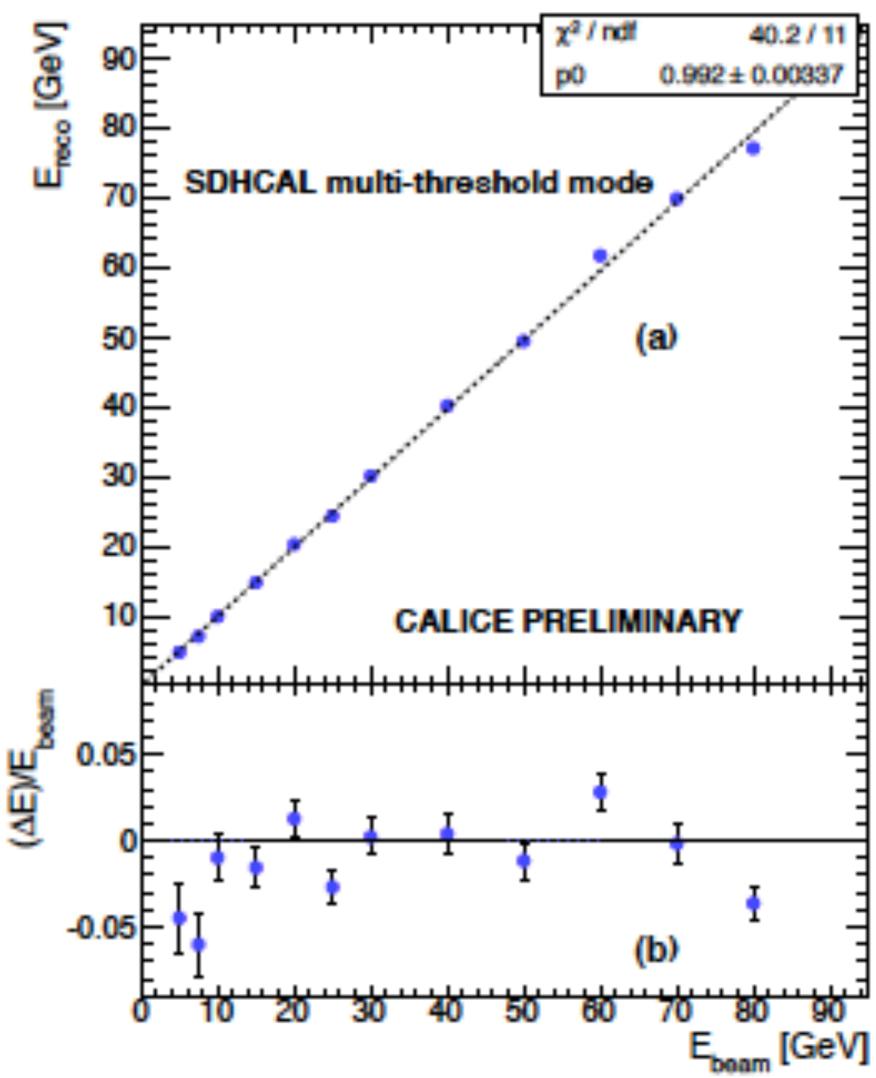
$$\frac{\sigma}{E} = c \oplus \frac{\alpha}{\sqrt{E}}$$

Particle	α	c
Pions	(68.0±0.4%	(5.4±0.7)%
Electrons	(29.4±0.3)%	16.6±0.3)%

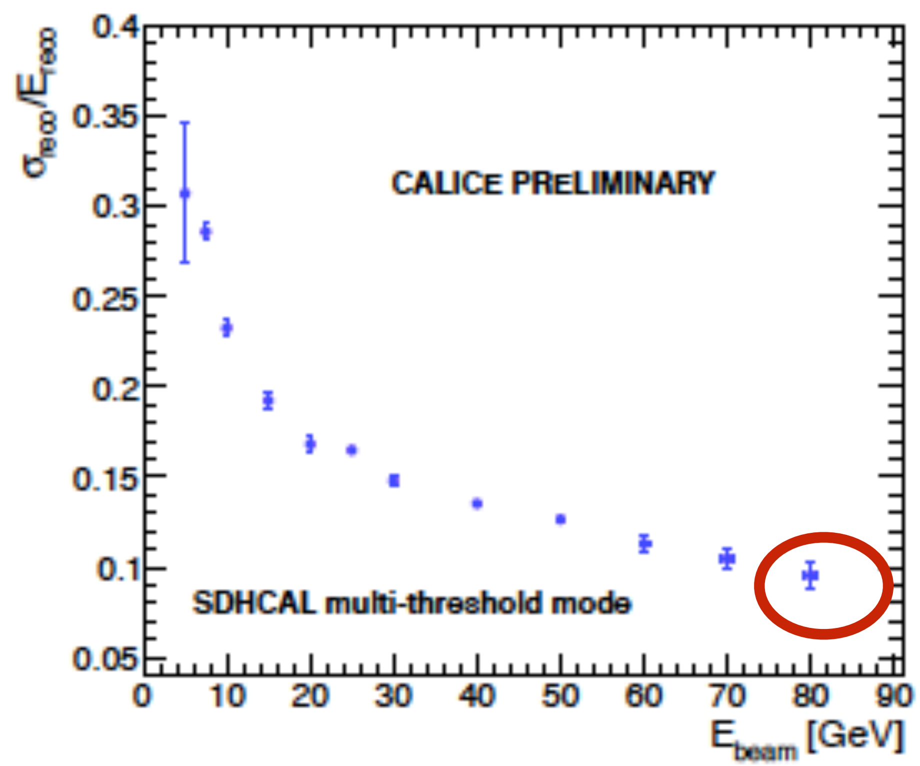
Calorimetry @ ILC: SDHCAL

Linearity recover (INL<5%) with semi-digital readout with multiple (Nthr=3) thresholds

Multi-threshold mode : linearity & resolution



- Linearity $\lesssim 5\%$ over full range
- Significant impact on the energy resolution



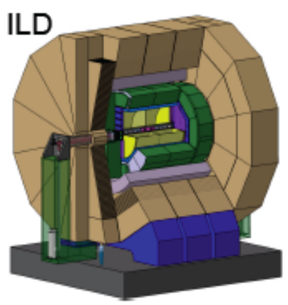
σ(E)/E<10% @ 80GeV

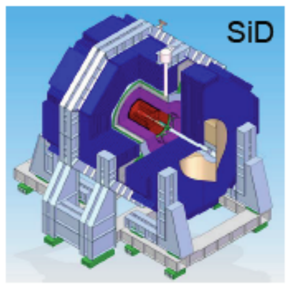
What calorimeters at future facilities?

- P. Janot @TLEP workshop October 2013: "What detector for…?"
- Questions obviously apply to calorimetry as well

What detector for TLEP ? (1)

- First approach (ILC/CLIC)
  - Push detector design towards highest achievable performance



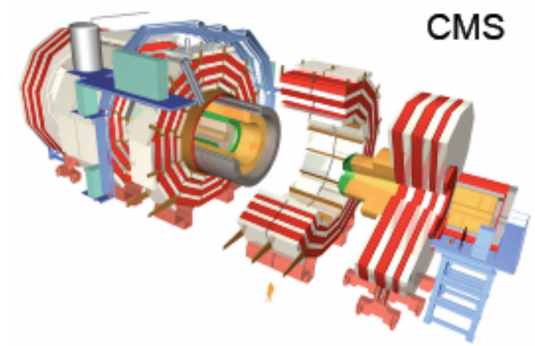


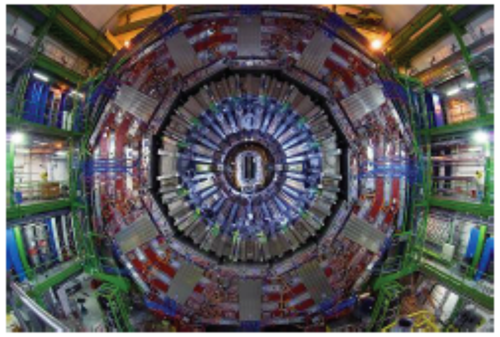
Mark Thomson
"A detector for TLEP: Synergies with ILC/CLIC"

- +++ Clearly suitable to cover the full TLEP physics programme
- – Might be over-designed ?
- – – Power pulsing is not a option at TLEP
  - ➨ Either more cooling (material) or less channels (granularity)
- – – – Cost !
  - ➨ 0.5 to 1 B$ each – and TLEP may want to have 4 of them

- Second approach (LHC)
  - Use existing LHC detectors

PJ et al. (arXiV:1208.1662, 1308.6176)
"First look at the physics case of TLEP

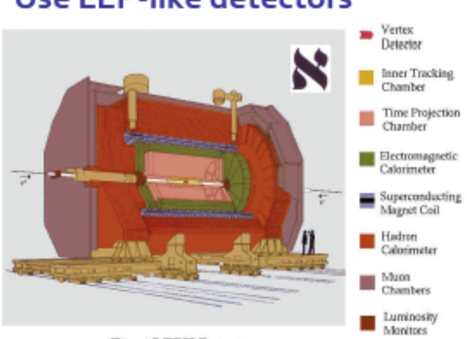




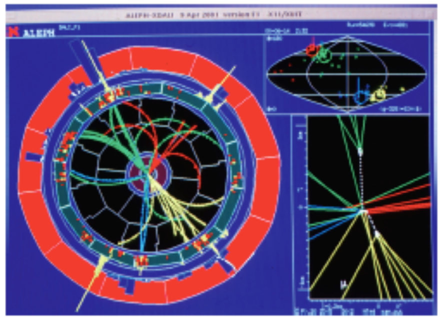
- +++ Realistic, most conservative
  - ➨ sub-optimal hadron calorimetry, lots of material, $\Delta p_T/p_T$
- ++ can cope with TLEP-Z event rate
- – not thought for e^+e^- collisions
- – – cost !
  - ➨ Almost 0.5 BCHF / detector

- Third approach (LEP)
  - Use LEP-like detectors

Tried back in the mid 1990's
For the studies of "NLC"



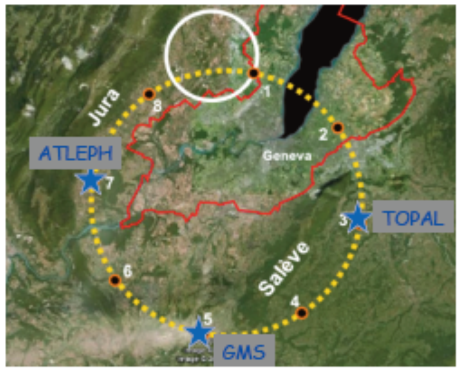
The ALEPH Detector

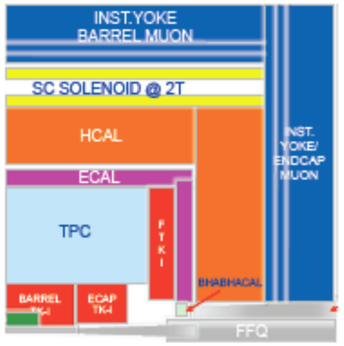


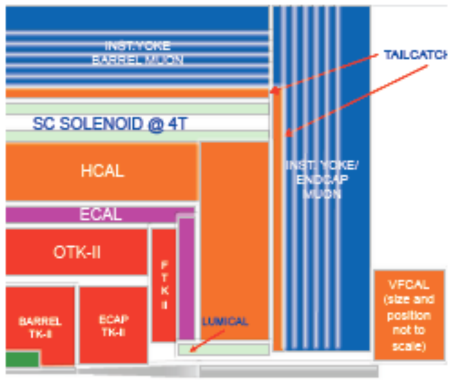
- +++ Cost !
  - ➨ 100 MCHF / detector – Could easily afford four of them.
- ++ Realistic, conservative enough, globally suitable
- – TLEP-Z event rate ?
- – – Outdated/not challenging technology ?

- Fourth approach (FCC)
  - A detector common to TLEP and VHE-LHC ?

Emilio Meschi
Talks at TLEP Workshops







- Pros and cons need to be worked out
  - ➨ Can a detector and its electronics survive half a century ?

Is it actually desirable ?