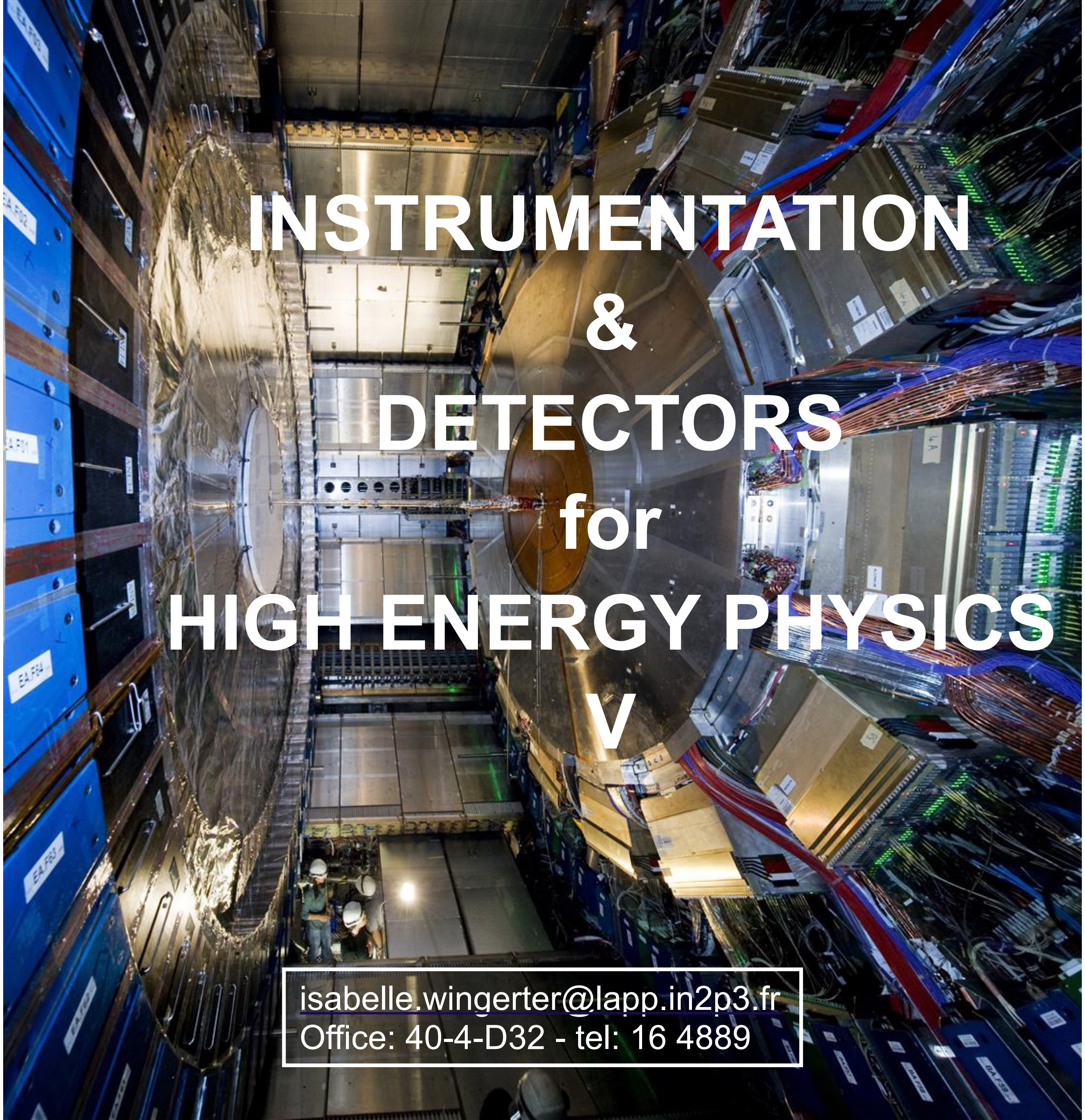

INSTRUMENTATION & DETECTORS for HIGH ENERGY PHYSICS V

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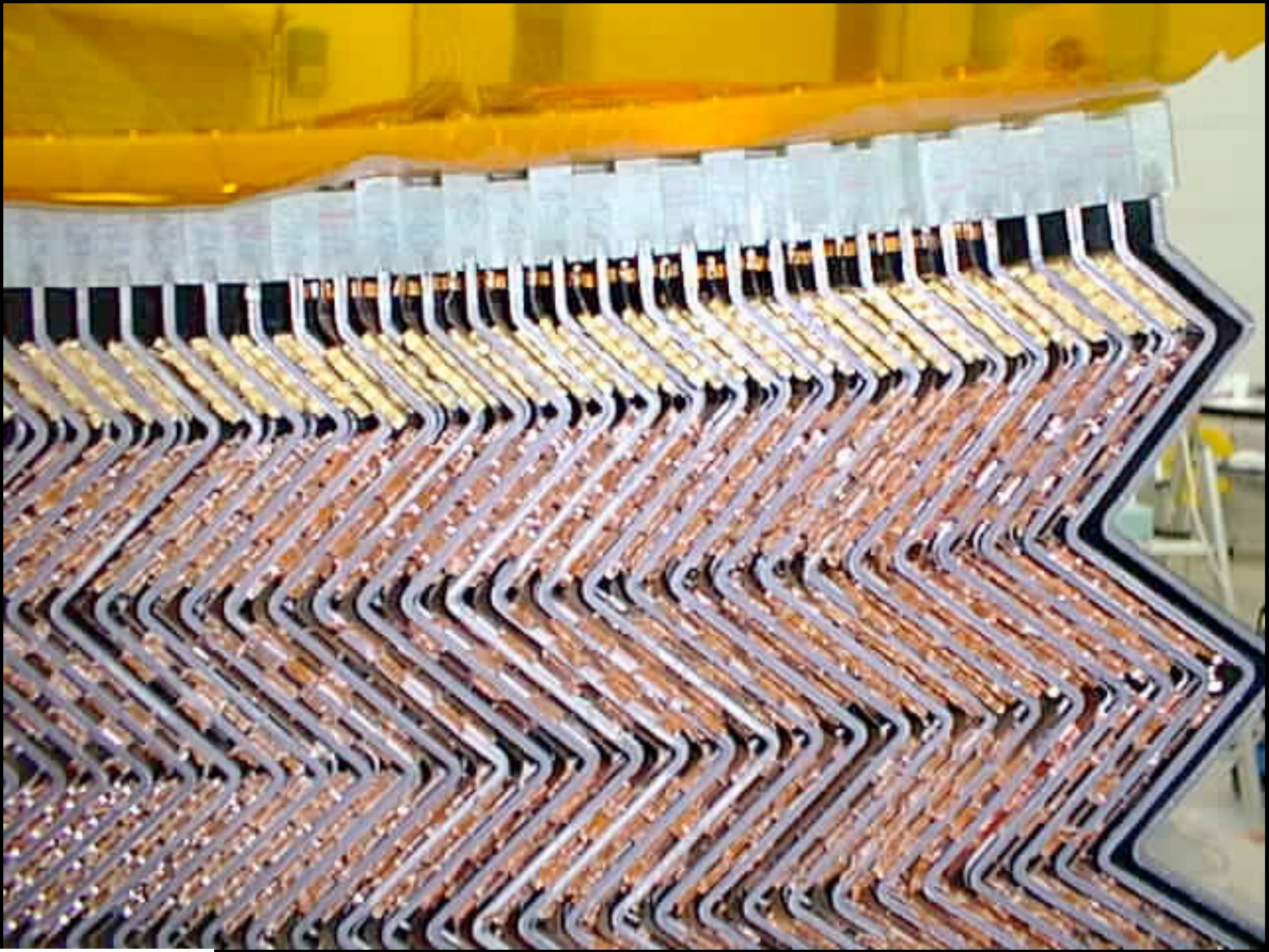


2000 - 2003

2004

TODAY

CALORIMETRY-2
&
A FEW EXAMPLES

HADRONIC SHOWERS

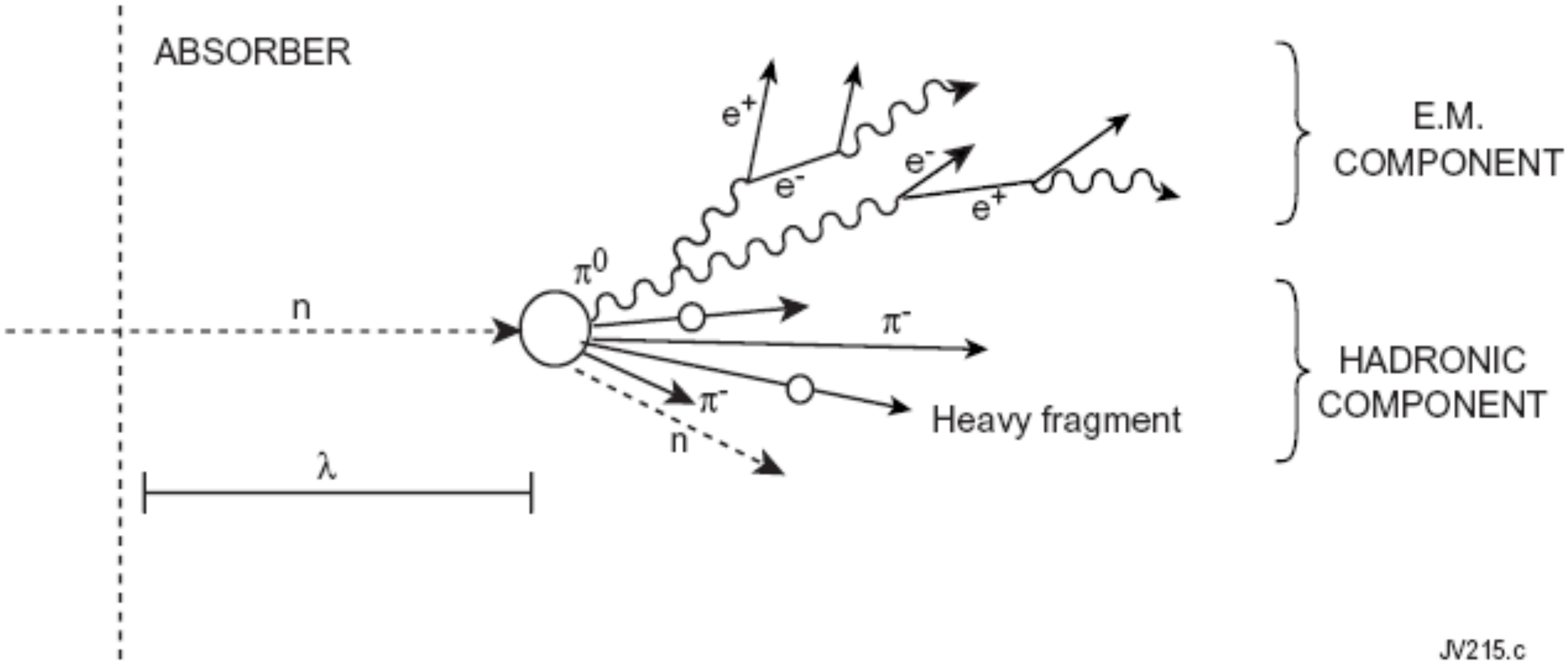
Hadronic cascades develop in an analogous way to e.m. showers

- Strong interaction controls overall development
- High energy hadron interacts with material, leading to multi-particle production of more hadrons
- These in turn interact with further nuclei
- Nuclear breakup and spallation neutrons
- Multiplication continues down to the pion production threshold
  - $E \sim 2m_\pi = 0.28$ GeV/c^2
- Neutral pions result in an electromagnetic component (immediate decay: $\pi^0 \rightarrow \gamma\gamma$) (also: $\eta \rightarrow \gamma\gamma$)

Energy deposited by:

- Electromagnetic component (i.e. as for e.m. showers)
- Charged pions or protons
- Low energy neutrons
- Energy lost in breaking nuclei (nuclear binding energy)

HADRONIC CASCADE



As compared to electromagnetic showers, hadron showers are:

- Larger/more penetrating
- Subject to larger fluctuations – more erratic and varied

HADRONIC SHOWERS: WHERE DOES THE ENERGY GO ?

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

HADRONIC INTERACTION

Simple model of interaction on a disk of radius R: $\sigma_{int} = \pi R^2 \propto A^{2/3}$

$\sigma_{inel} \approx \sigma_0 A^{0.7}$, $\sigma_0 = 35$ mb

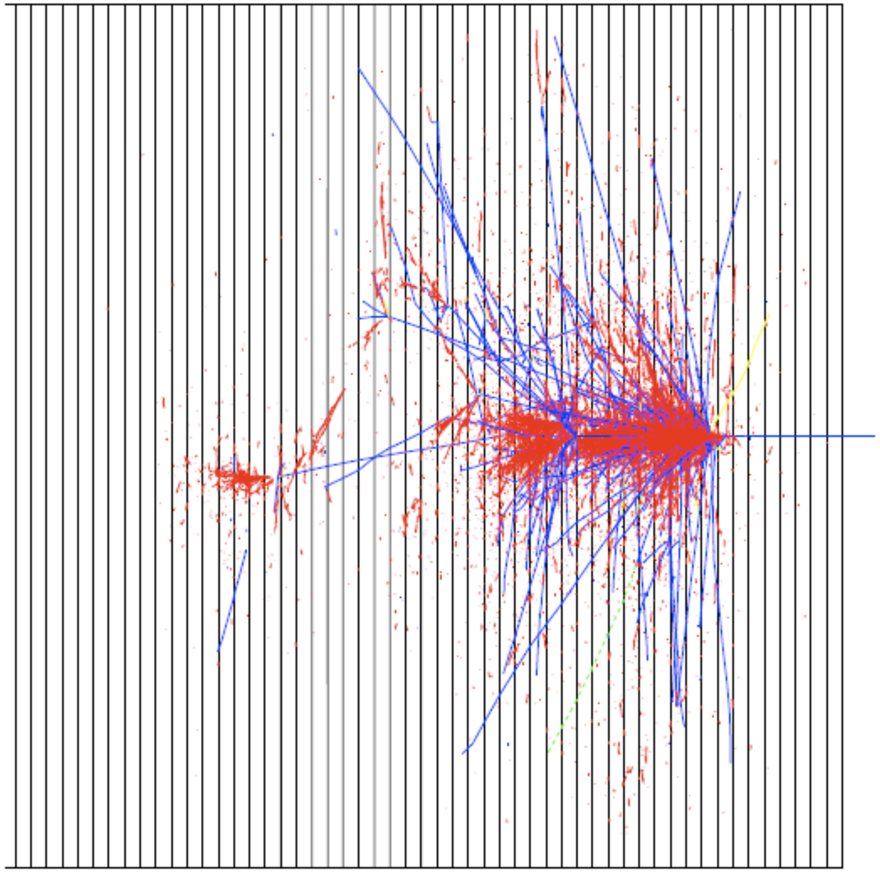
Nuclear interaction length: mean free path before inelastic interaction

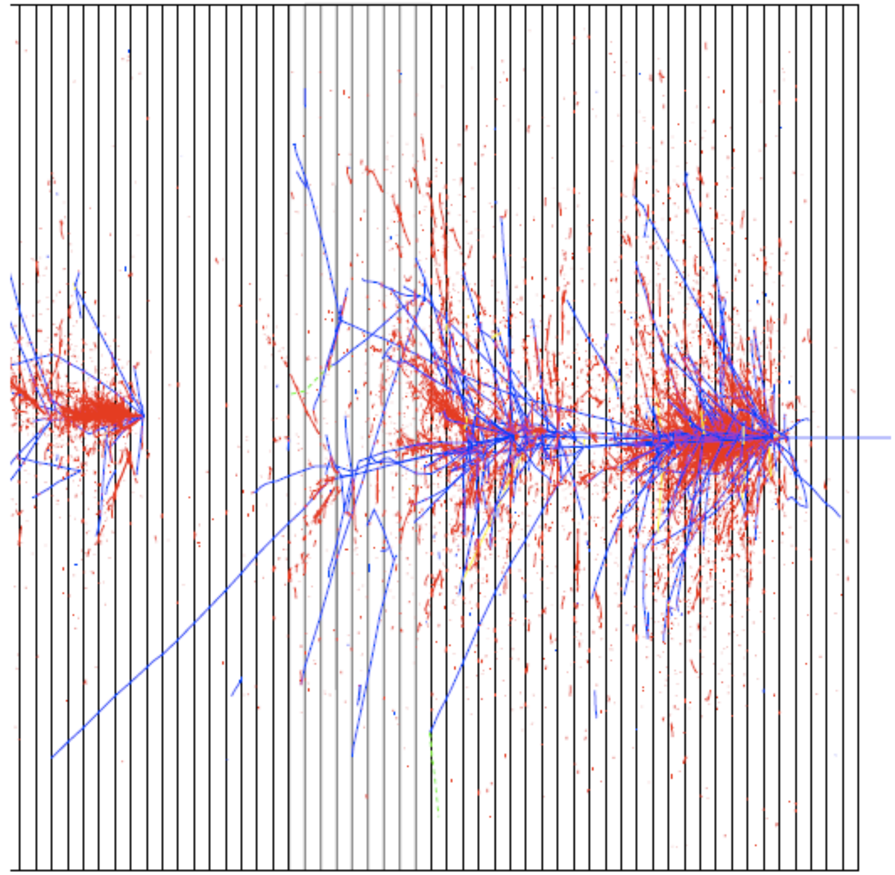
$$\lambda_{int} \approx \frac{A}{N_A \sigma_{int}} \approx 35 A^{1/3} g \times cm^{-2}$$

	Z	ρ (g.cm^{-3})	E_c (MeV)	X_0 (cm)	λ_{int} (cm)
Air				30 420	~70 000
Water				36	84
$PbWO_4$		8.28		0.89	22.4
C	6	2.3	103	18.8	38.1
Al	13	2.7	47	8.9	39.4
L Ar	18	1.4		14	84
Fe	26	7.9	24	1.76	16.8
Cu	29	9	20	1.43	15.1
W	74	19.3	8.1	0.35	9.6
Pb	82	11.3	6.9	0.56	17.1
U	92	19	6.2	0.32	10.5

HADRONIC SHOWERS

1. Individual hadron showers are quite dissimilar **2.**





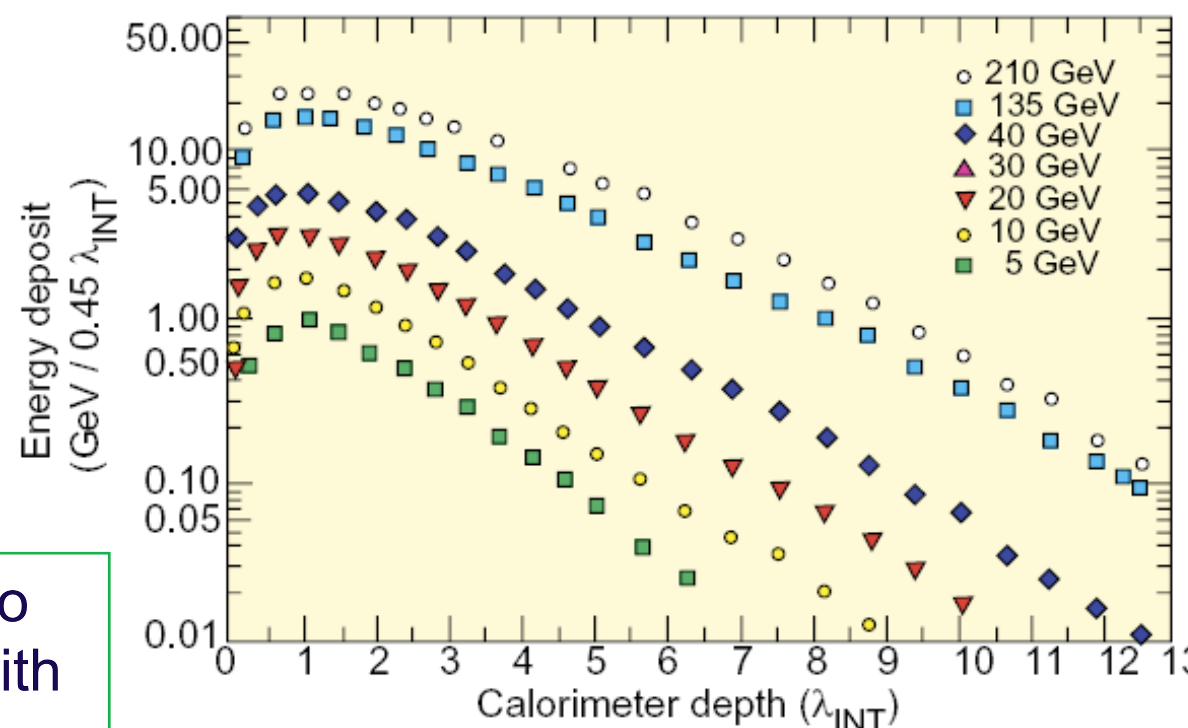
red - e.m. component
blue - charged hadrons

HADRONIC SHOWER LONGITUDINAL DEVELOPMENT

Longitudinal profile

- Initial peak from π^0s produced in the first interaction length
- Gradual falloff characterised by the nuclear interaction length, λ_{int}

WA78 : 5.4λ of 10mm U / 5mm Scint + 8λ of 25mm Fe / 5mm Scint



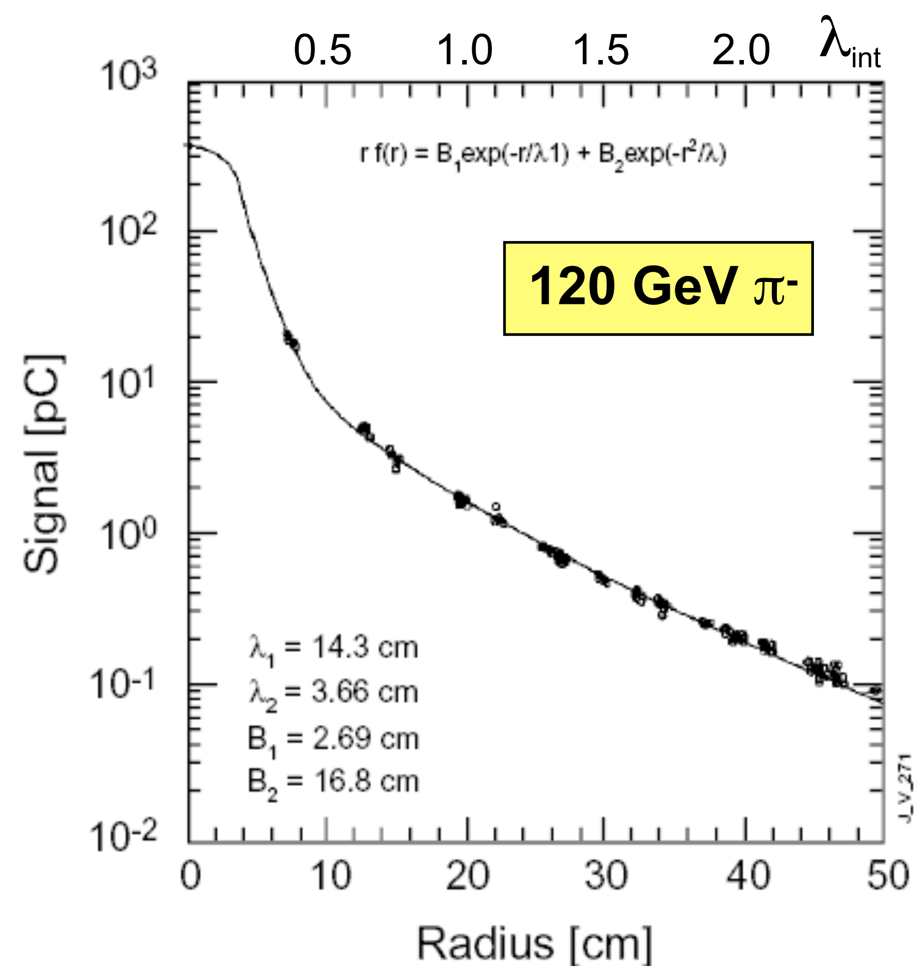
As with e.m. showers: depth to contain a shower increases with log(E)

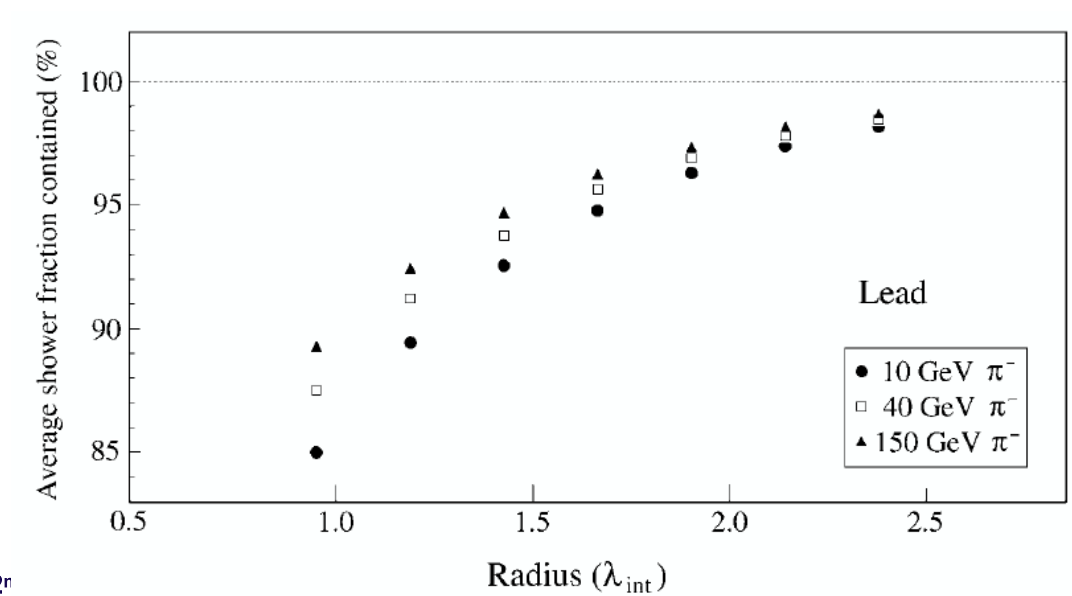
HADRONIC SHOWERS TRANSVERSE PROFILE

Mean transverse momentum from interactions, $\langle p_T \rangle \sim 300$ MeV, is about the same magnitude as the energy lost traversing 1λ for many materials

So radial extent of the cascade is well characterized by λ

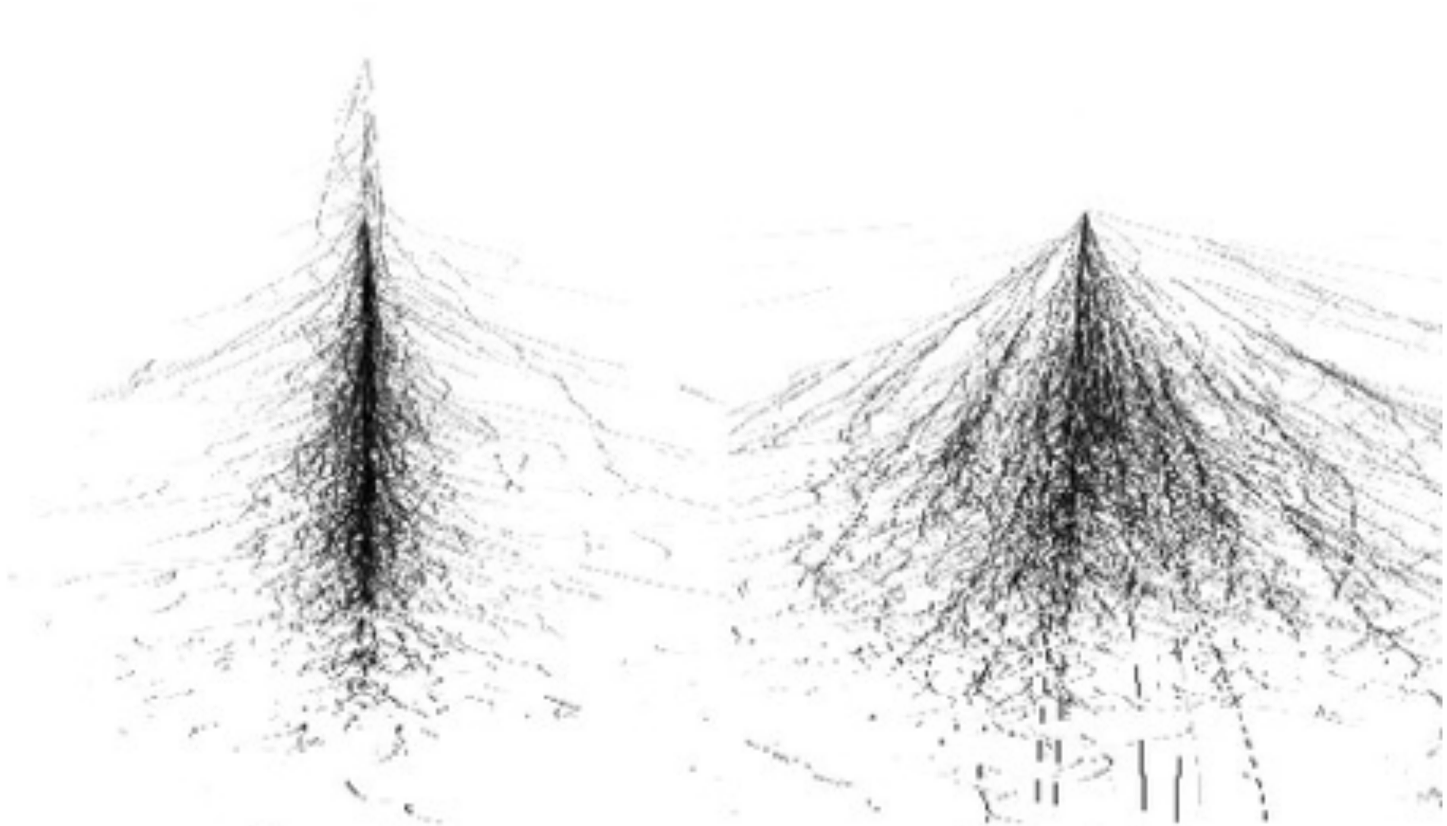
The π^0 component of the cascade results in an electromagnetic core





Lateral containment increases with energy

ELECTROMAGNETIC vs HADRONIC SHOWERS



Gamma shower

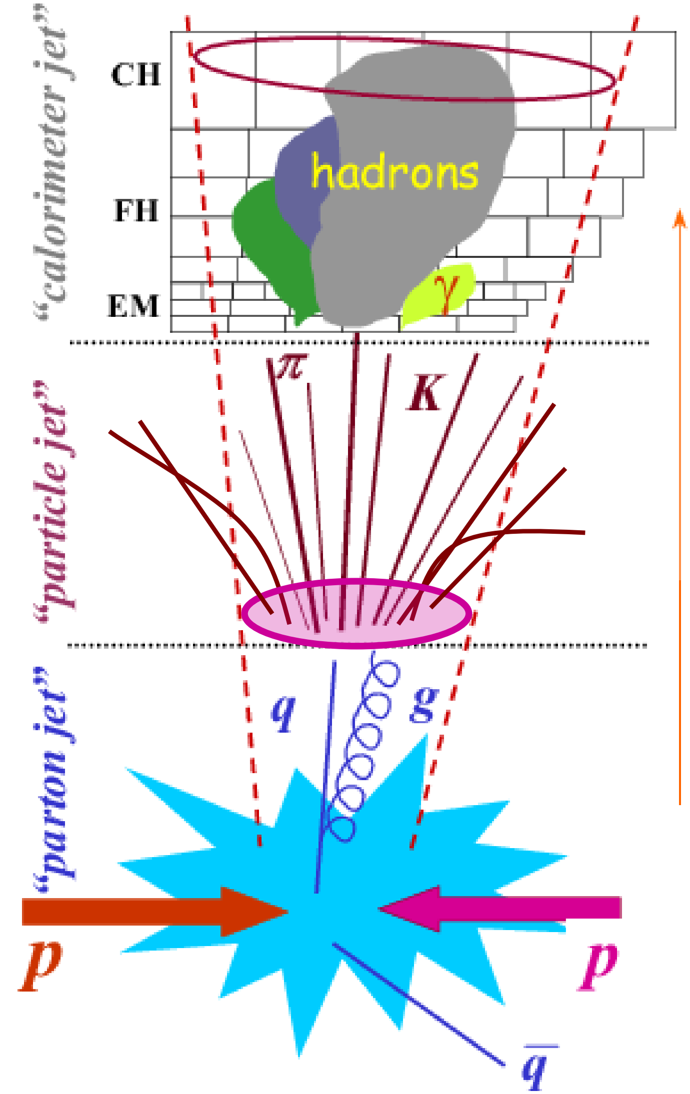
Hadronic shower

JETS at HIGH ENERGY COLLIDERS

At Hadronic Colliders, quarks & gluons produced, evolves (parton shower, hadronisation) to become jets

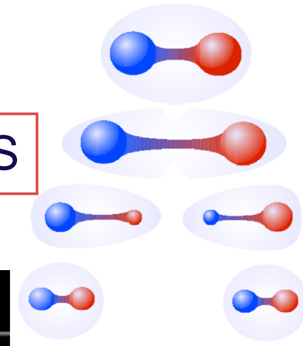
- In a cone around the initial parton: high density of hadrons
- LHC calorimeters cannot separate all the incoming hadrons
  - Use dedicated calibration schemes (based on simulation in ATLAS)
  - Use tracking system to identify charged hadrons (Particle Flow in CMS)

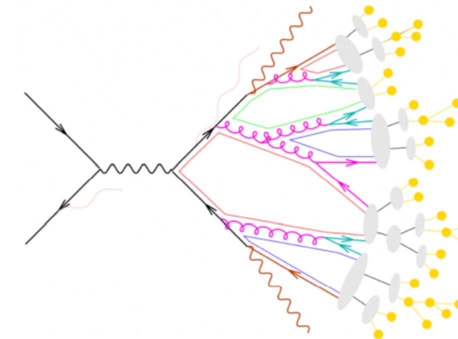
  - In the future, very highly segmented calorimeters

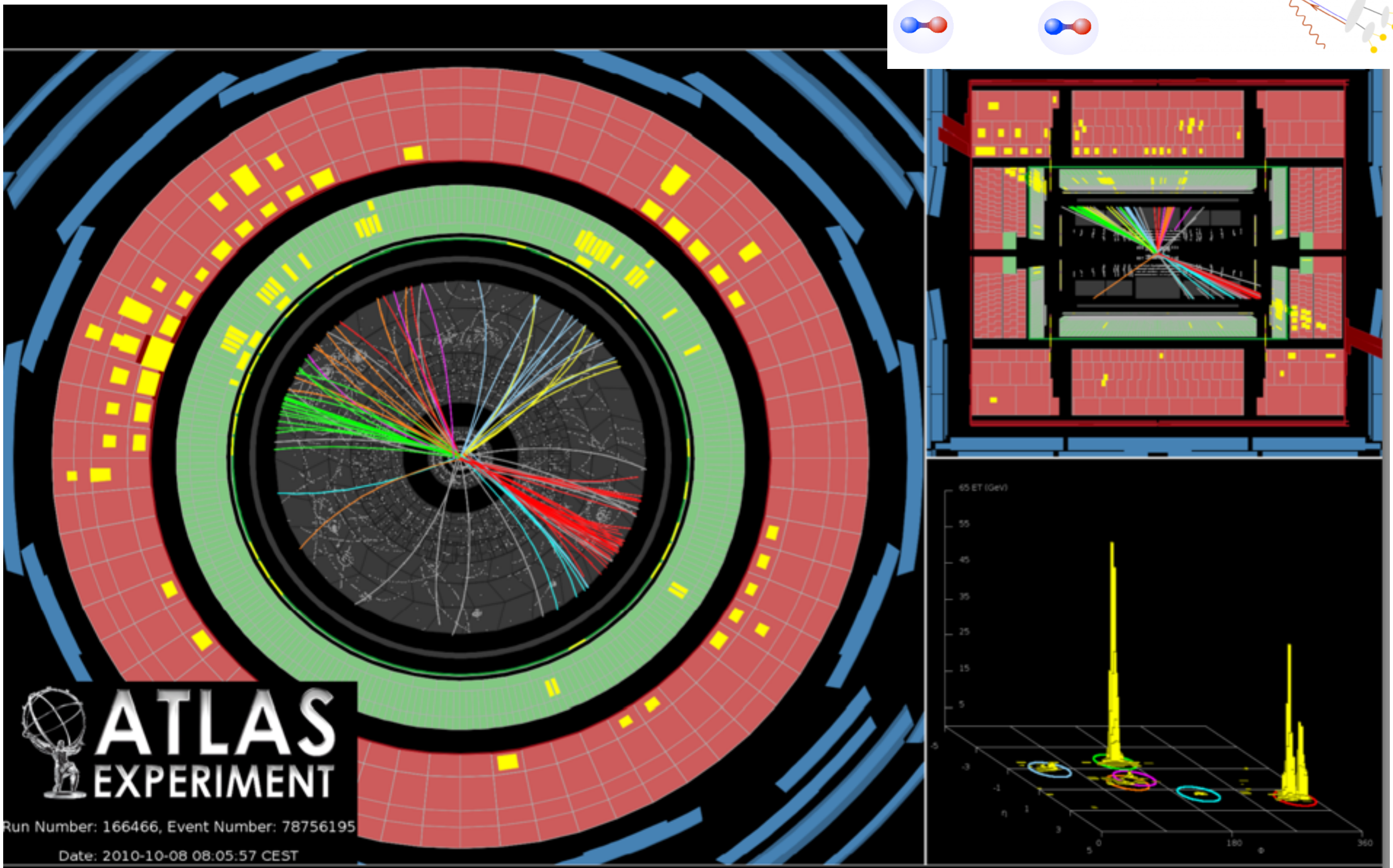


JETS

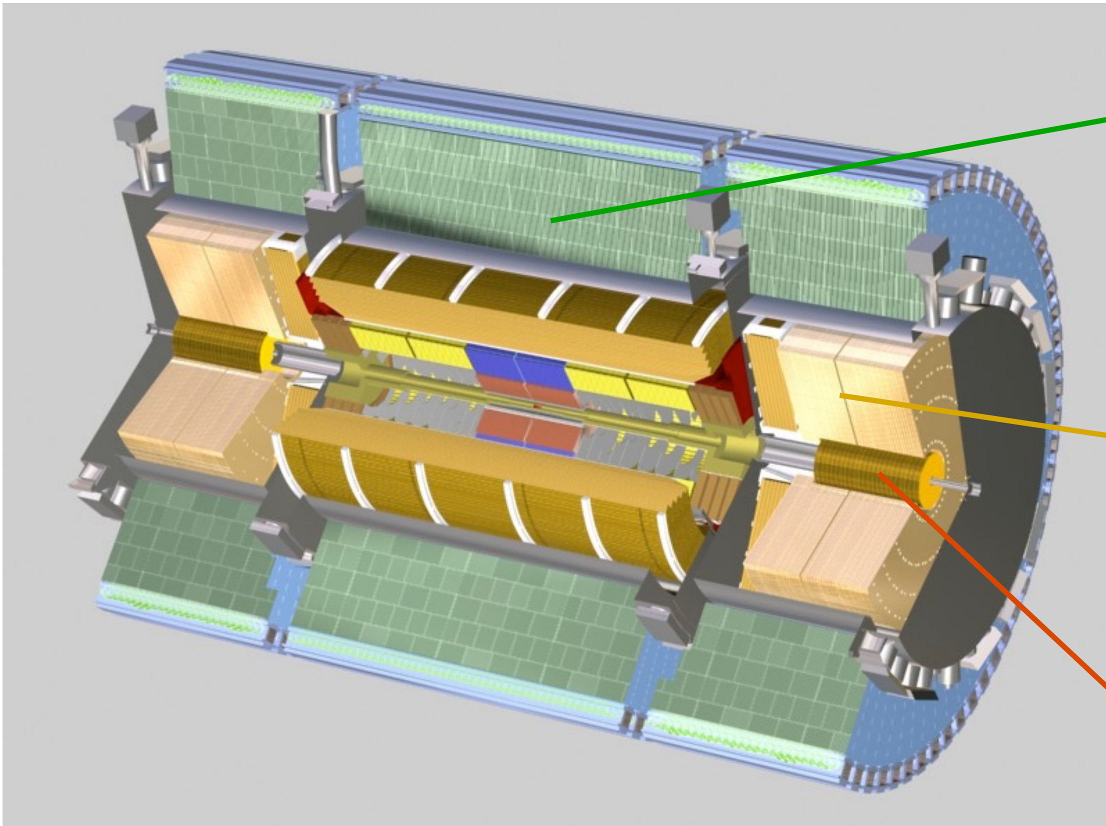
NEED a REFINED CALIBRATION PROCEDURE FOR JETS







ATLAS HADRON CALORIMETER



Tiles Calorimeter |η| < 1.7
Fe / Scintillator
3 layers in depth

LAr/Cu 1.7 <|η| < 3.2
4 layers in depth

Forward: 1 layer EM, 2 HAD
LAr/Cu or W 3.2 <|η| < 4.9

Total thickness: ~ 8 -10 λ
Use of different technics: cope with radiations in forward region

Scintillator tile calorimeter

	Barrel	Extended barrel
$\|\eta\|$ coverage	$\|\eta\| < 1.0$	$0.8 < \|\eta\| < 1.7$
Number of layers	3	3
Granularity $\Delta\eta \times \Delta\phi$	0.1×0.1	0.1×0.1
Last layer	0.2×0.1	0.2×0.1
Readout channels	5760	4092 (both sides)

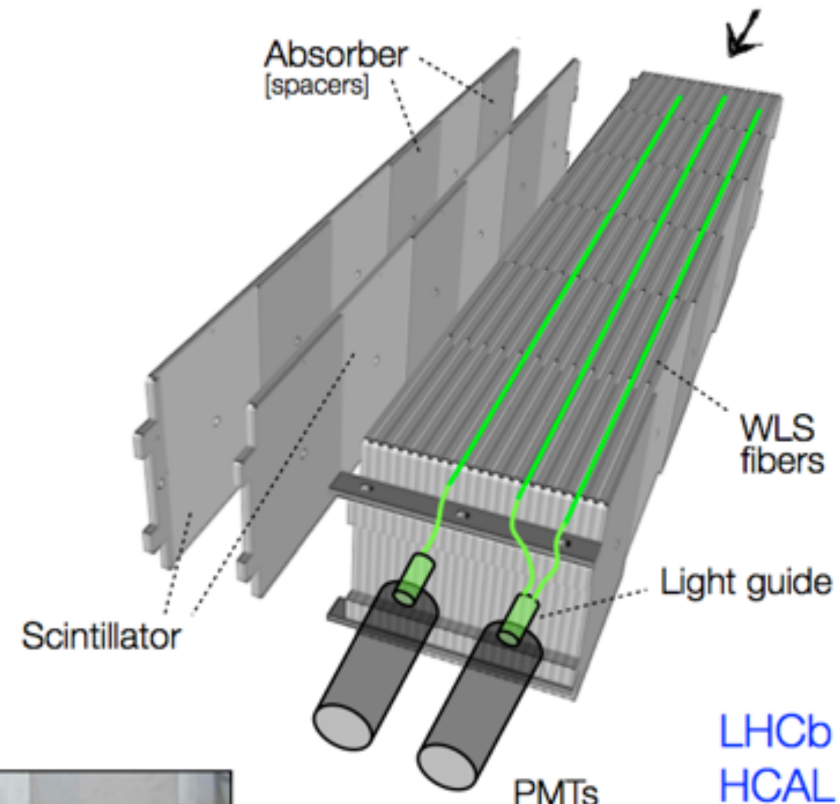
HADRONIC CALORIMETER

Most common realization: Sampling Calorimeter

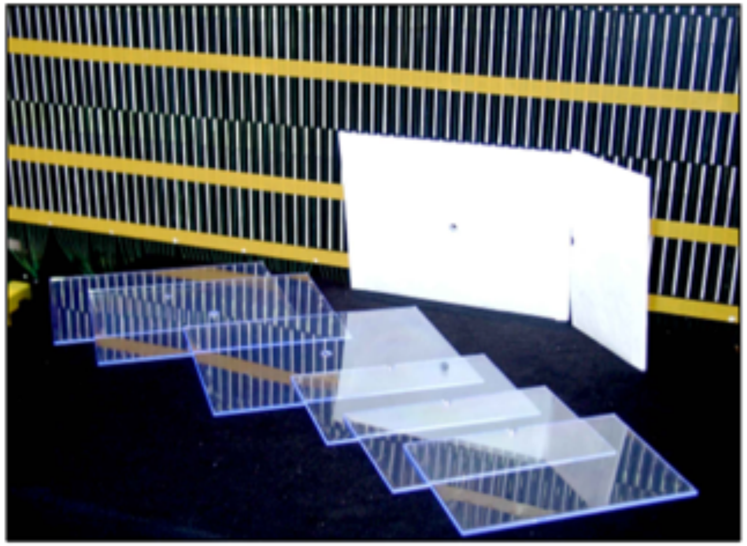
Utilization of homogenous calorimeters unnecessary (and thus too expensive) due to fluctuations of invisible shower components ...

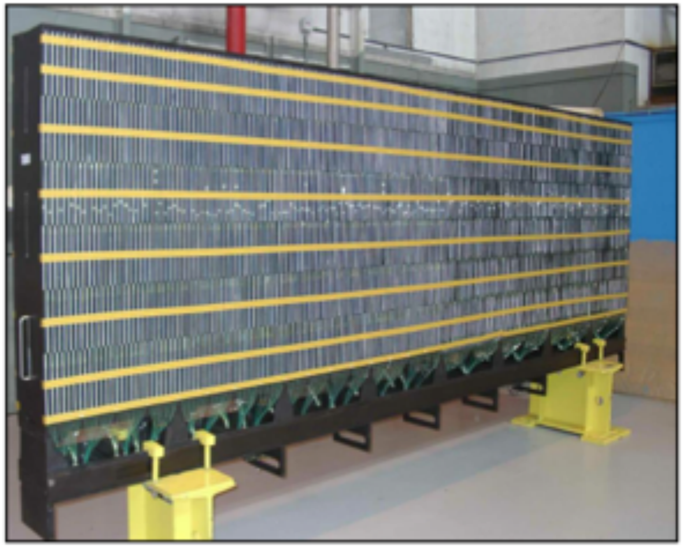
Typical absorbers : Fe, Pb, U ...
Sampling elements : Scintillators, LAr, MWPCs ...

Typical setup:
Alternating layers of active and passive material
[also: 'spaghetti' or 'shashlik' calorimeter]



LHCb HCAL

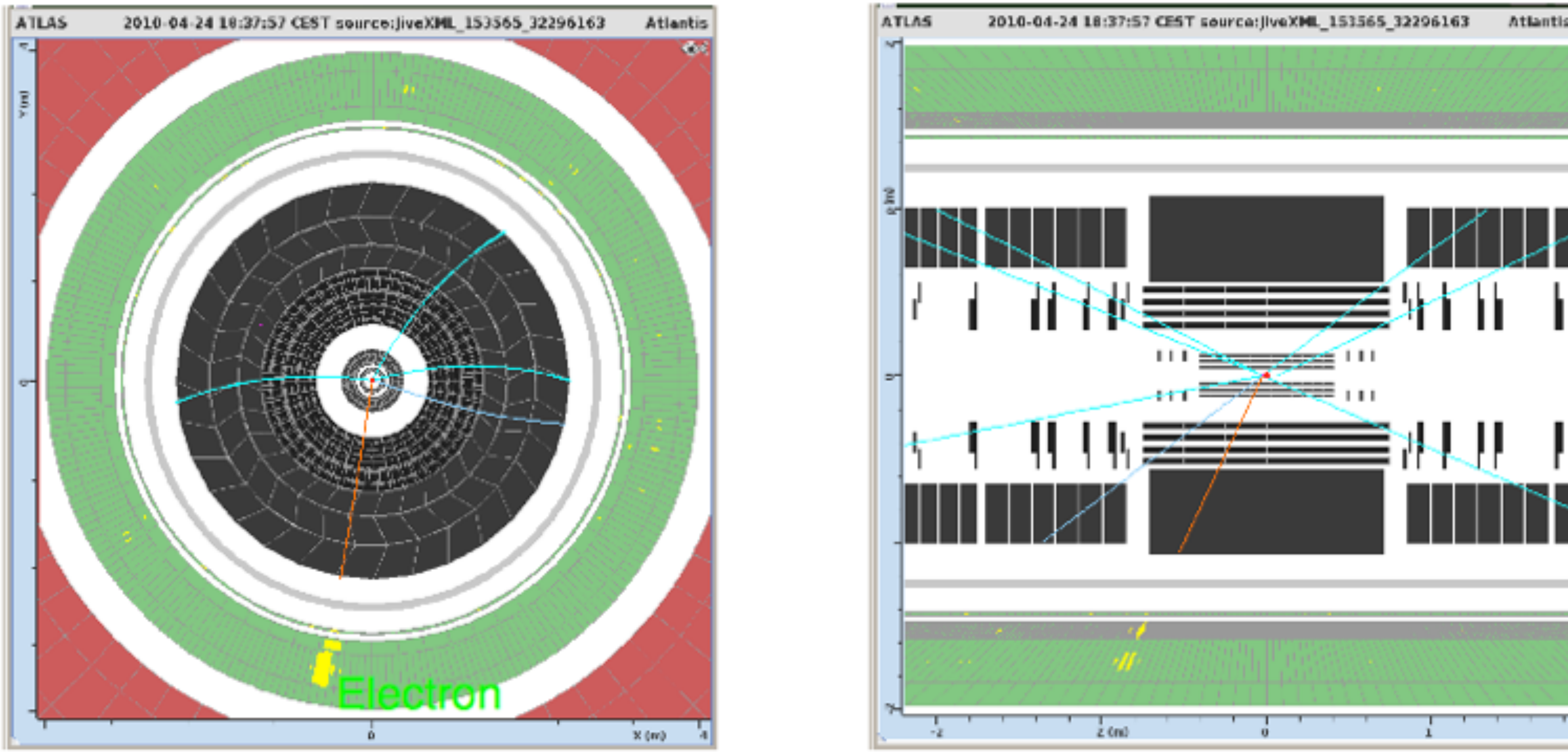




Example:
LHCb Hadron Calorimeter

MISSING TRANSVERSE ENERGY

Missing transverse energy : $W \rightarrow e\,\nu$ candidate



For a pp collision, for instance, and in the absence of escaping particles (neutrinos, neutralinos, DM,..) the transverse energy is ~balanced.

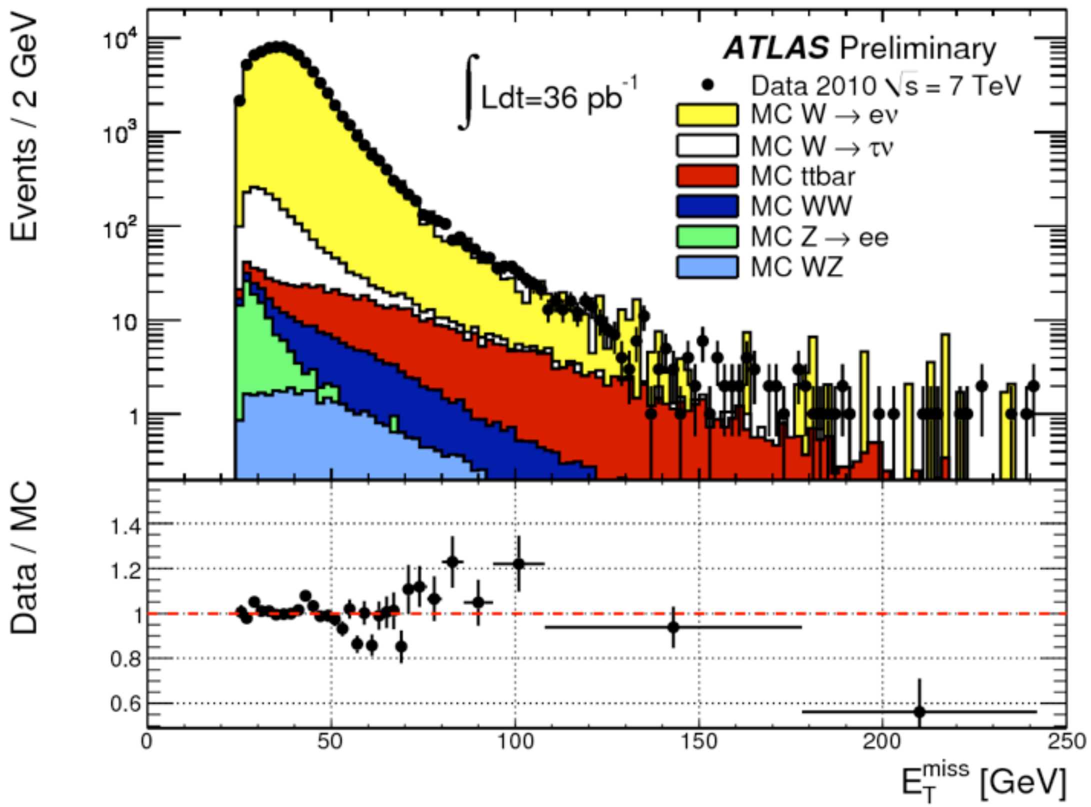
Missing transverse energy is interpreted as the presence of a neutrino.

$$\vec{E}_T^{miss} = -\sum_i^{cells} \vec{E}_T$$

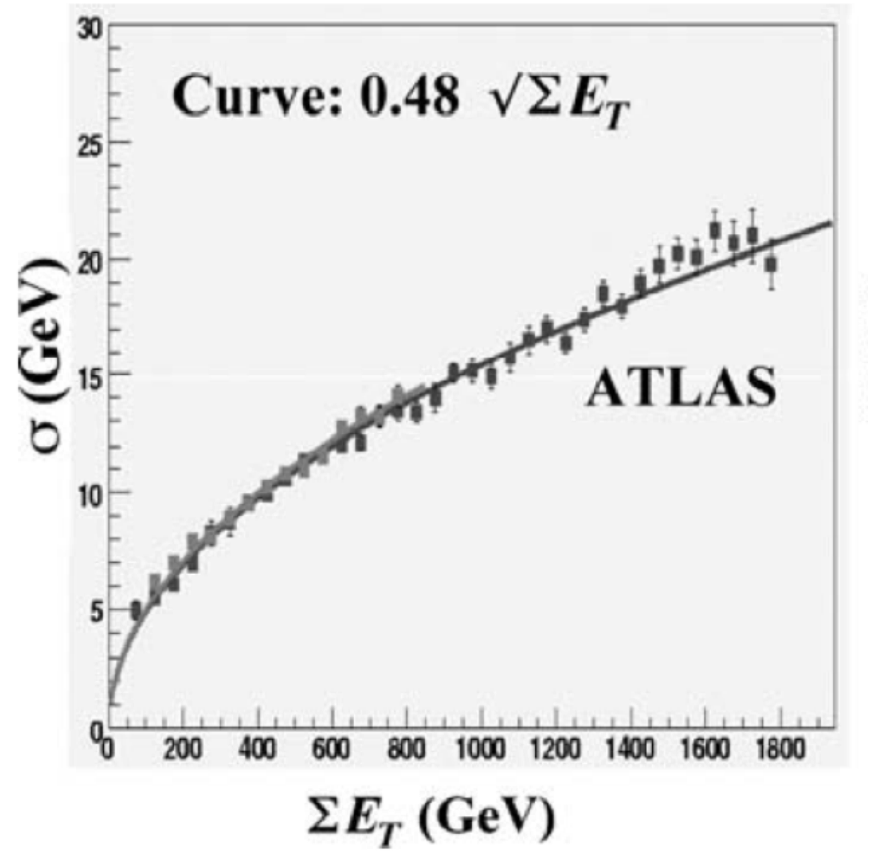
E_T^{miss} is the modulus of the vectorial sum of energy deposited in each calorimeter cell

MISSING TRANSVERSE ENERGY: CALIBRATION

Missing transverse energy in ATLAS for W→eν events



Missing transverse energy expected resolution in ATLAS



A FEW SUMMARY WORDS on CALORIMETERS

Calorimeters are attractive in our field for various reasons:

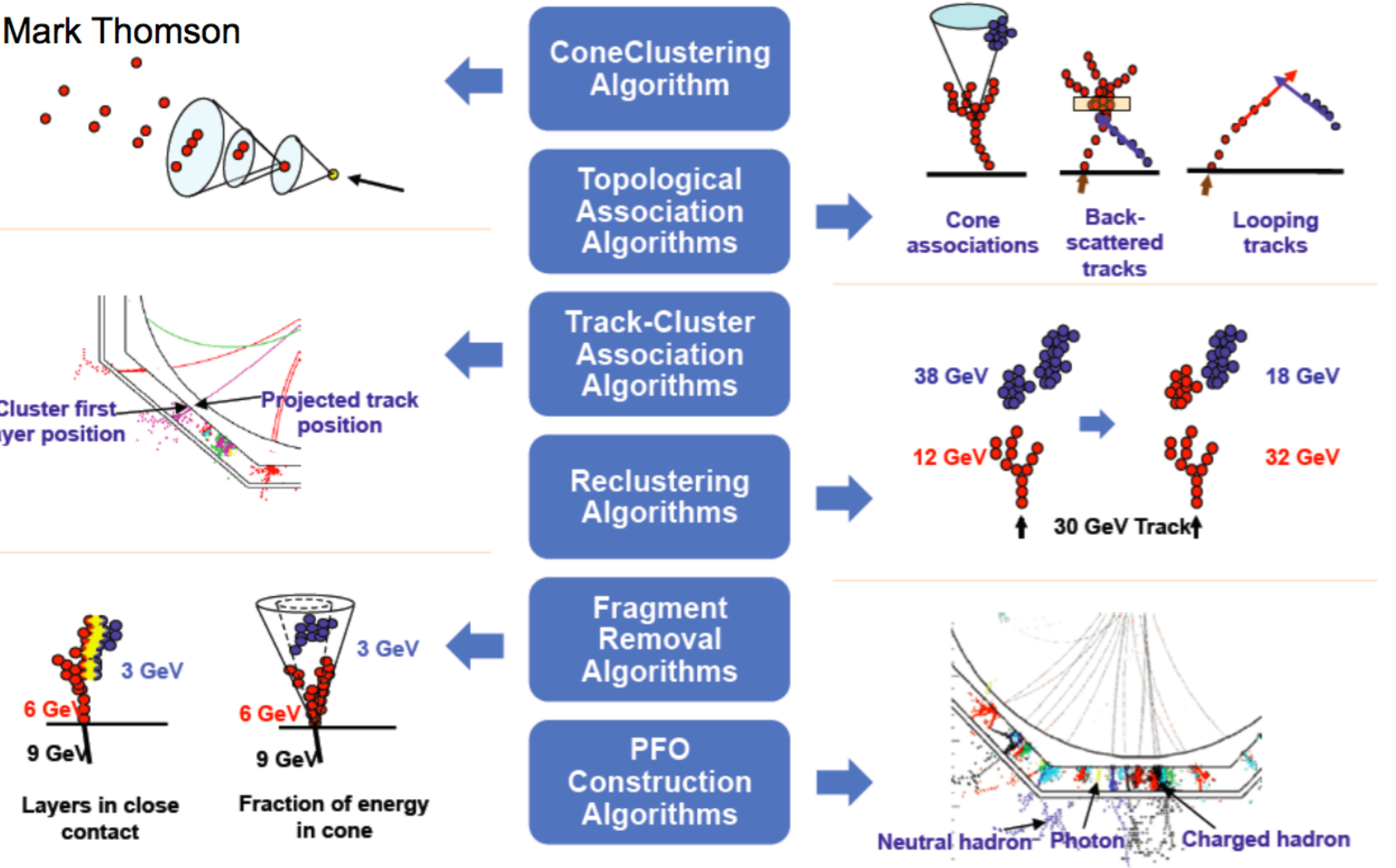
In contrast with magnet spectrometers, in which the momentum resolution deteriorates linearly with the particle momentum, on most cases the calorimeter energy resolution improves as 1/Sqrt(E), where E is the energy of the incident particle. Therefore calorimeters are very well suited for high-energy physics experiments.

In contrast to magnet spectrometers, calorimeters are sensitive to all types of particles, charged and neutral. They can even provide indirect detection of neutrinos and their energy through a measurement of the event missing energy.

Calorimeters are commonly used for trigger purposes since they can provide fast signals that are easy to process and interpret.

They are space and therefore cost effective. Because the shower length increases only logarithmically with energy, the detector thickness needs to increase only logarithmically with the energy of the particles. In contrast for a fixed momentum resolution, the bending power BL^2 of a magnetic spectrometer must increase linearly with the particle momentum.

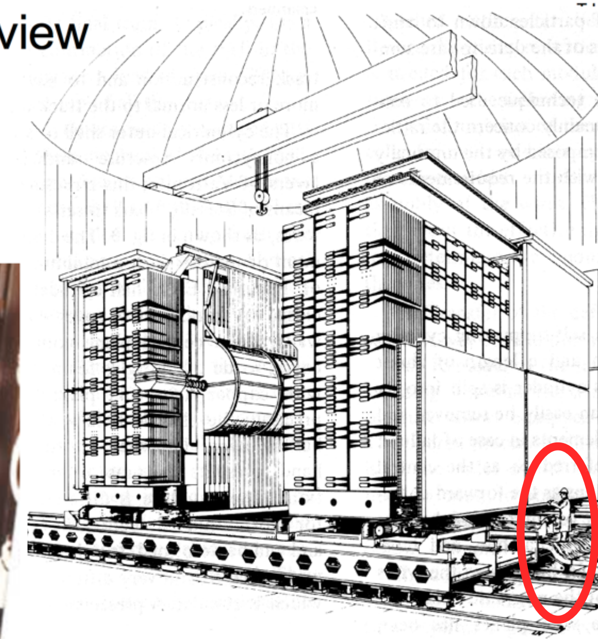
PARTICLE FLOW



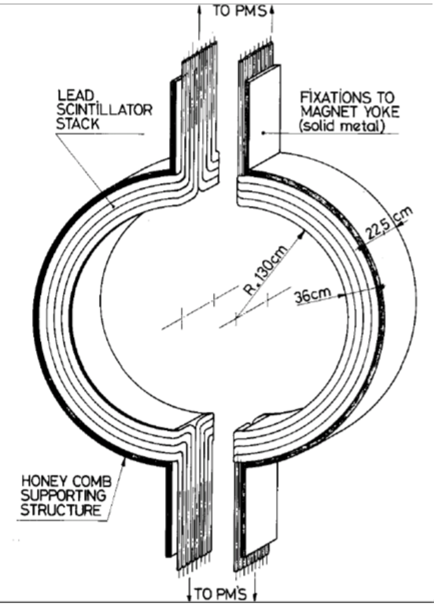
UA1 @ ppbar collider (1981): W/Z discovery

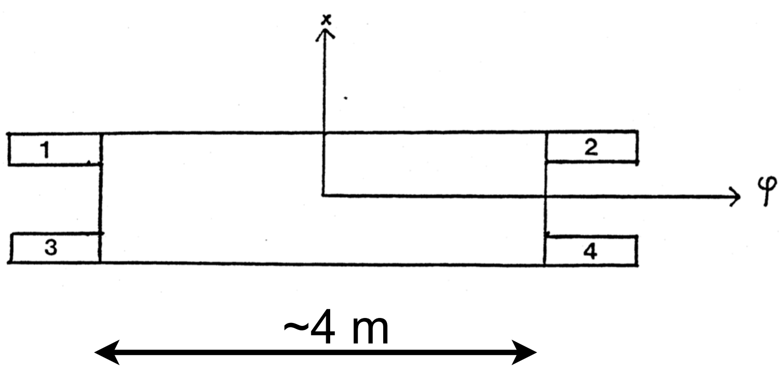
Design 1978-1980 - Built 1980-1982
Operation 1982-1990

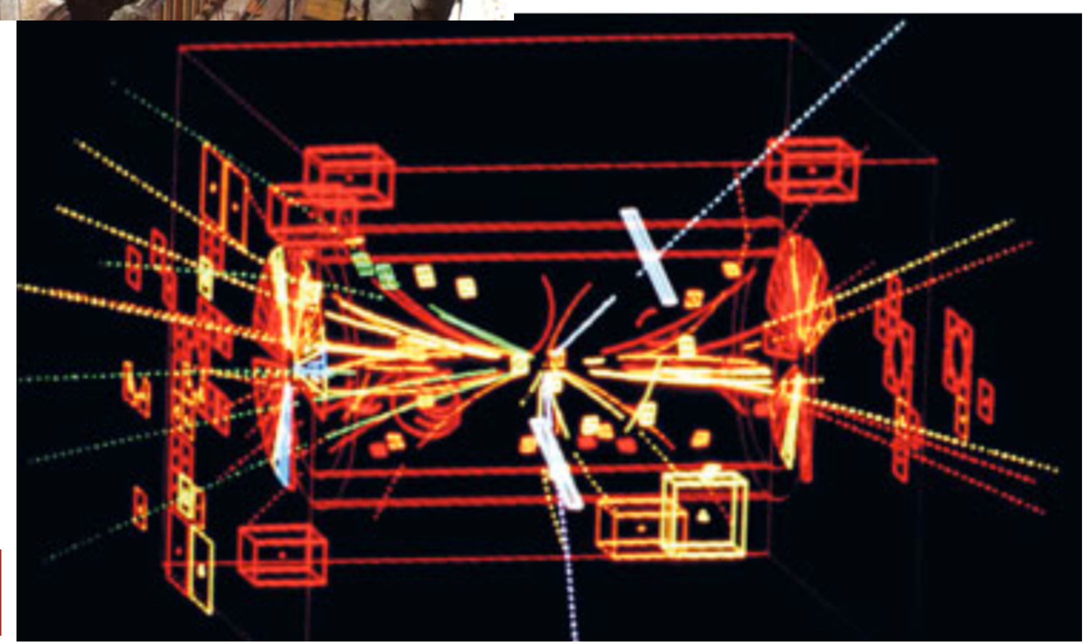
overview



electromagnetic calorimeter: gondola







20x400 cm² - σ/E~0.15/√E

ALEPH CALORIMETER: Z & WW studies

Design 1980-1982 - Built 1983-1988
Operation 1989-2000

1 The Electromagnetic Calorimeter (ECAL)

Description: A sampling calorimeter, consisting of lead sheets and wire chambers, situated inside the solenoid. The barrel and two end-caps each comprise 12 modules and the longitudinal shower development is sampled in 45 layers grouped in three stacks of 10, 23 and 12 layers. The wire chambers are Al extrusion covered with graphite coated mylar. Signals are taken from cathode pads as well as from the anode wires. In each stack the pads form towers pointing to the interaction vertex. Gas: $XeCO_2$ (80% : 20%).

Dimensions:

Thickness of lead plates	2 mm (stack 1+2), 4 mm (stack 3)
Diameter of tungsten wire	25 μ
Wire spacing	5 mm
Radiation length/stack	Barrel: $3.83X_0$, $8.80X_0$, $8.85X_0$
	Endcaps: $3.46X_0$, $8.86X_0$, $8.91X_0$
$8.91X_0$	
Interaction length	1.0 - 1.3 λ_{int} for 5GeV pions

Barrel:

Radius:	$R_{outer} = 225$ cm	$R_{inner} = 185$ cm
overall length	477 cm	
Weight per module	11 t (12 modules)	
Pad size at inner radius	3 cm ×3 cm	
Granularity	$\Delta\theta \times \Delta\phi sin\theta$	
	17 mrad ×17 mrad at 90^0	
	12 mrad ×12 mrad at 45^0	

Endcaps:

Radius:	$R_{outer} = 235.0$ cm	$R_{inner} = 54.0$ cm
Radius (active layers)	$R_{outer} = 227.5$ cm	$R_{inner} = 56.8$ cm
Distance from I.P.	250.5 cm	active layer: 255.0 cm
Overall length (each)	56.25 cm	active layers: 41.10 cm
Weight per module	2.6 t (2 × 12 modules)	
Granularity	$\Delta\theta \times \Delta\phi sin\theta$	
	12 mrad ×14 mrad	for $11^0 < \theta < 16^0$
	11 mrad ×12 mrad	for $16^0 < \theta < 27^0$
	10 mrad ×11 mrad	for $27^0 < \theta < 36^0$
	10 mrad ×10 mrad	for $36^0 < \theta < 42^0$

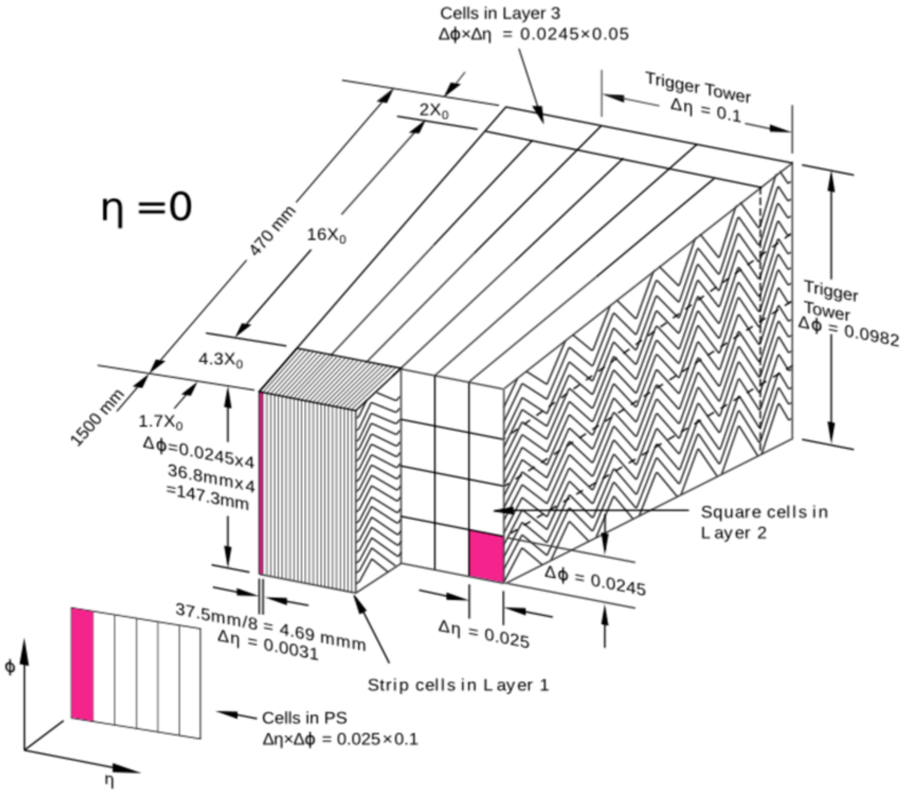
Readout: Channels:
Tower storeys = 12×3×4,096 (barrel) + 2×12×3×1,024 (endcap) = 221,184 (total)

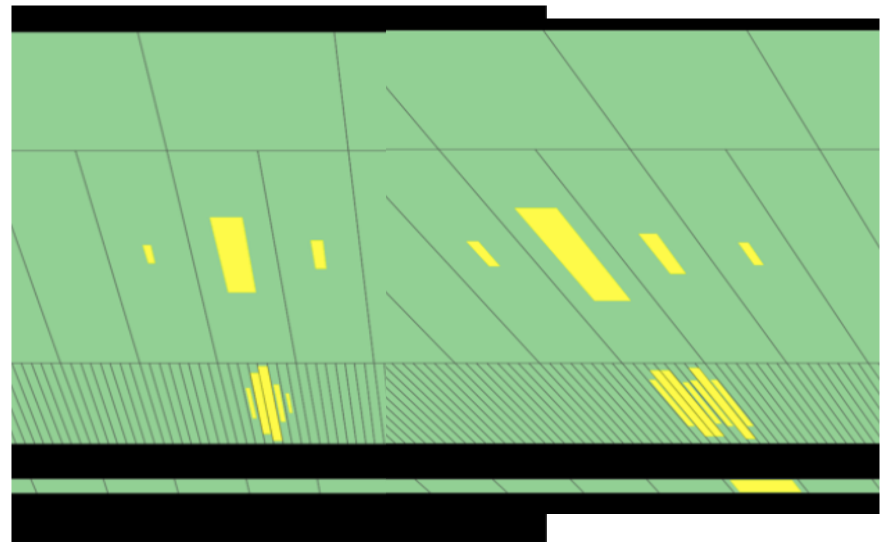
Performance: Energy resolution $\sigma/E = 0.01 + 0.18/\sqrt{E(GeV)}$
Angular resolution $\sigma_\phi = \sigma_\theta/\sin\theta = .32 + 2.7/\sqrt{E(GeV)}$ mrad

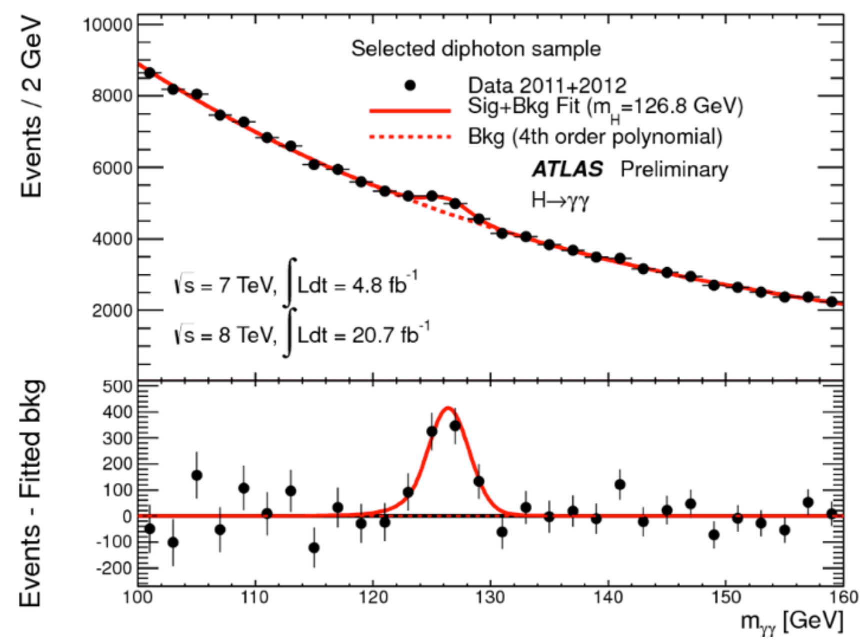
3x3 cm^2 - $\sigma/E \sim 0.18/\sqrt{E}$

ATLAS CALORIMETER: HIGGS BOSON DISCOVERY

Design 1997-2000 - Built 2001-2004
Operation 2007-2035 ?







LAr 182428 channels |η| < 4.9 (θ>0.6°)

EM ΔηxΔφ = 0.025x0.1 / 0.003x0.1 / 0.025x0.025 / 0.05x0.025

HAD ΔηxΔφ = 0.1x0.1 / 0.2x0.2

FCal ΔxxΔy ≃ 2x2 cm²

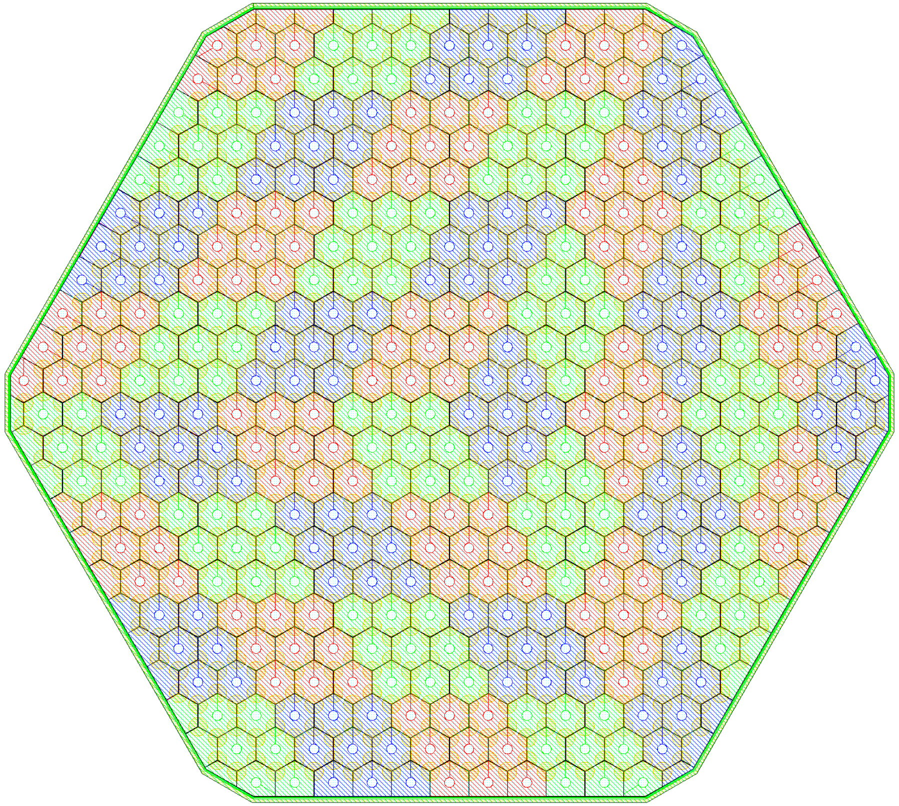
Tiles 9836 channels |η| < 1.7

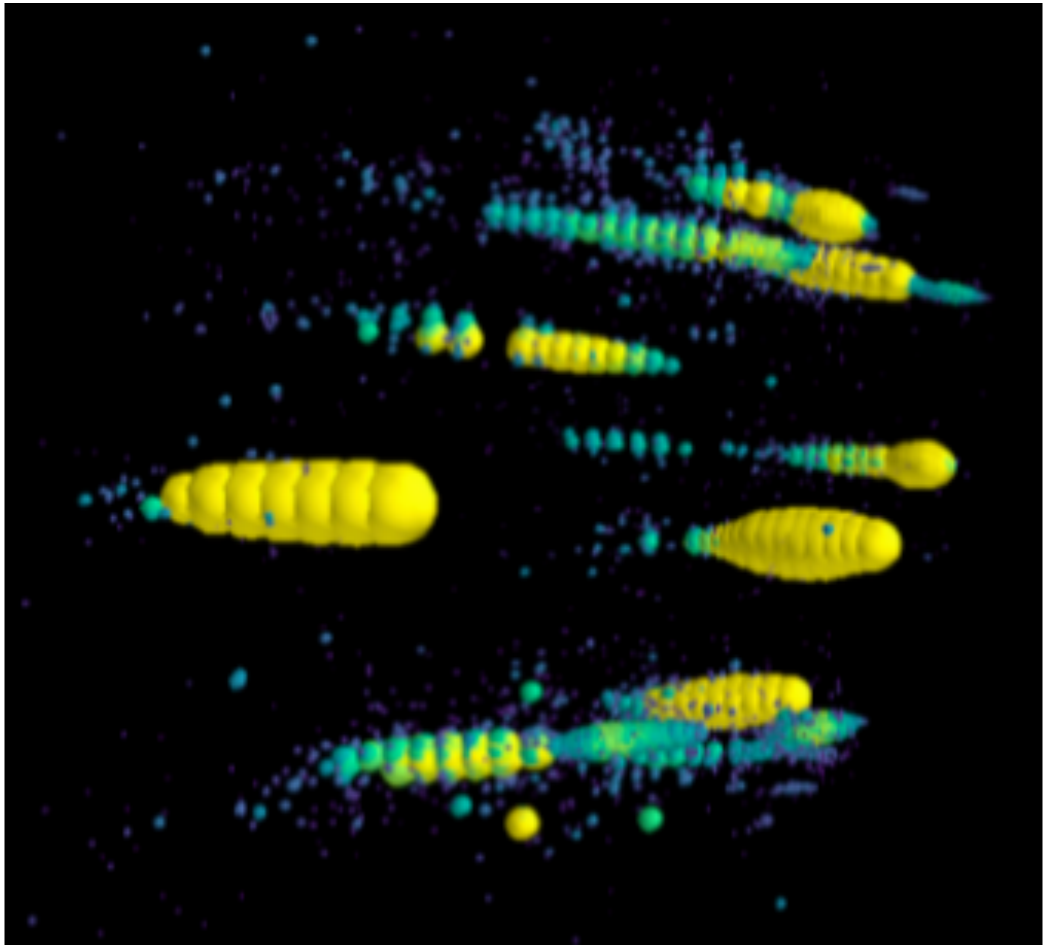
ΔηxΔφ = 0.1x0.1

0.8x16 cm² & 4x4 cm²
σ/E~0.10/√E

FUTURE CMS HIGH GRANULARITY CALORIMETER

Si sensors of 120, 300, 380 μm thickness





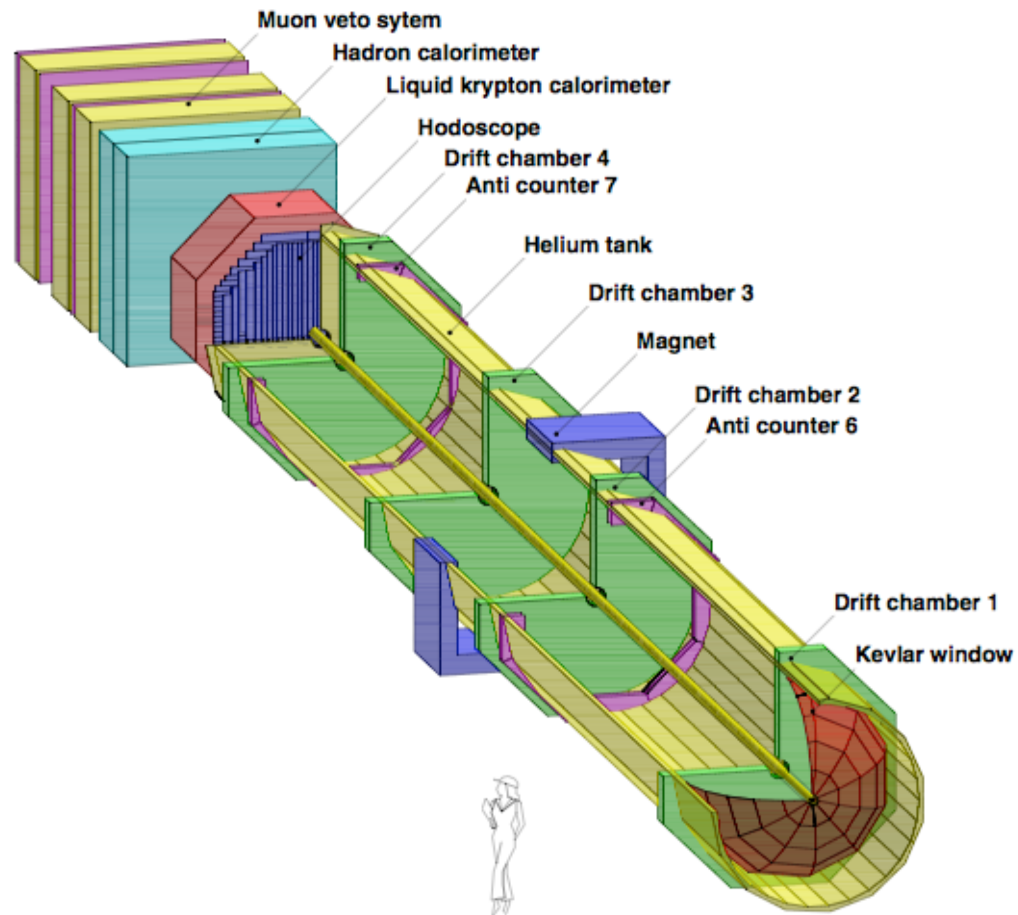
Ten 300 GeV pions

THE NA48 EXPERIMENT

NA48 experiment started data taking in 1997

Now the NA62 experiment, searching for rare Kaon decays is starting data taking with the SAME calorimeter using Liquid Krypton.

The calorimeter has not been warmed up since 1998.

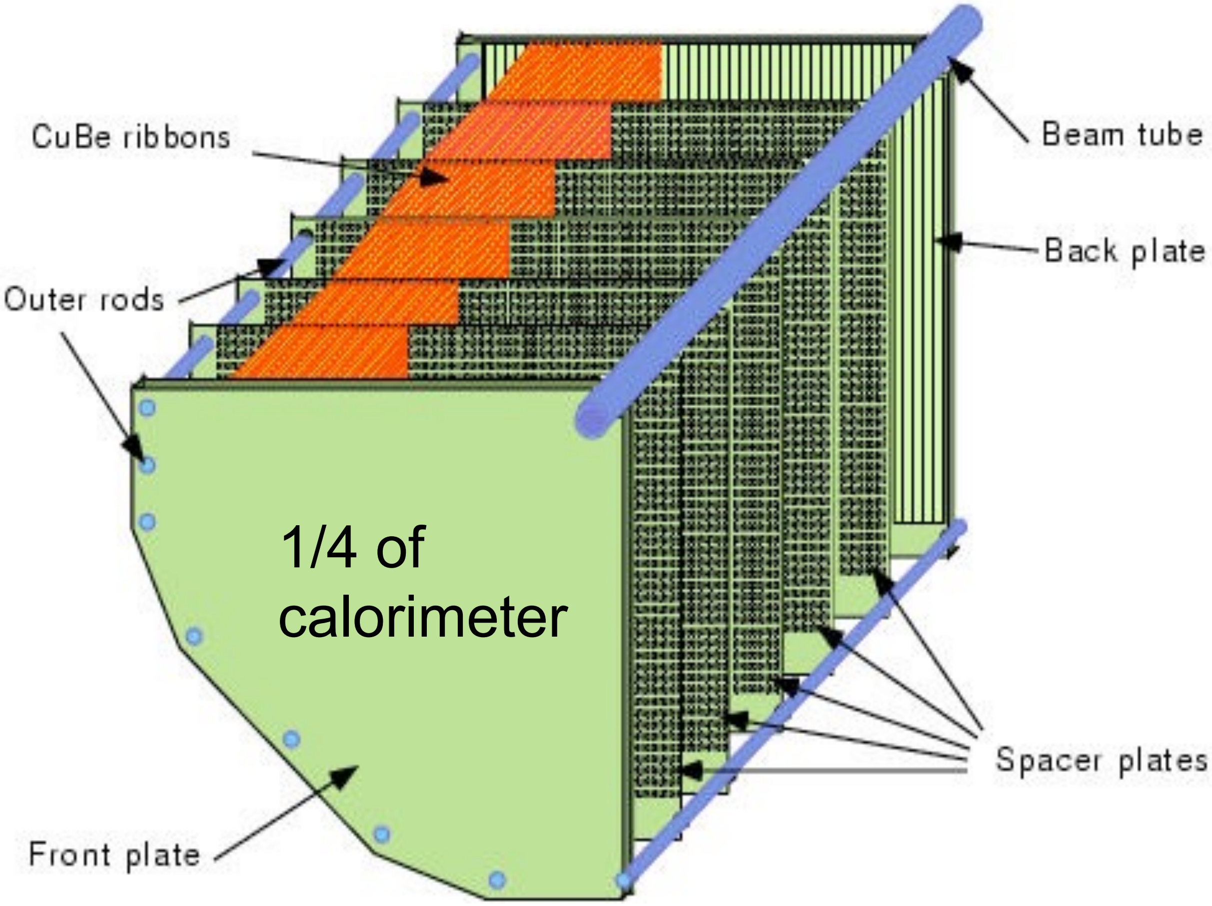


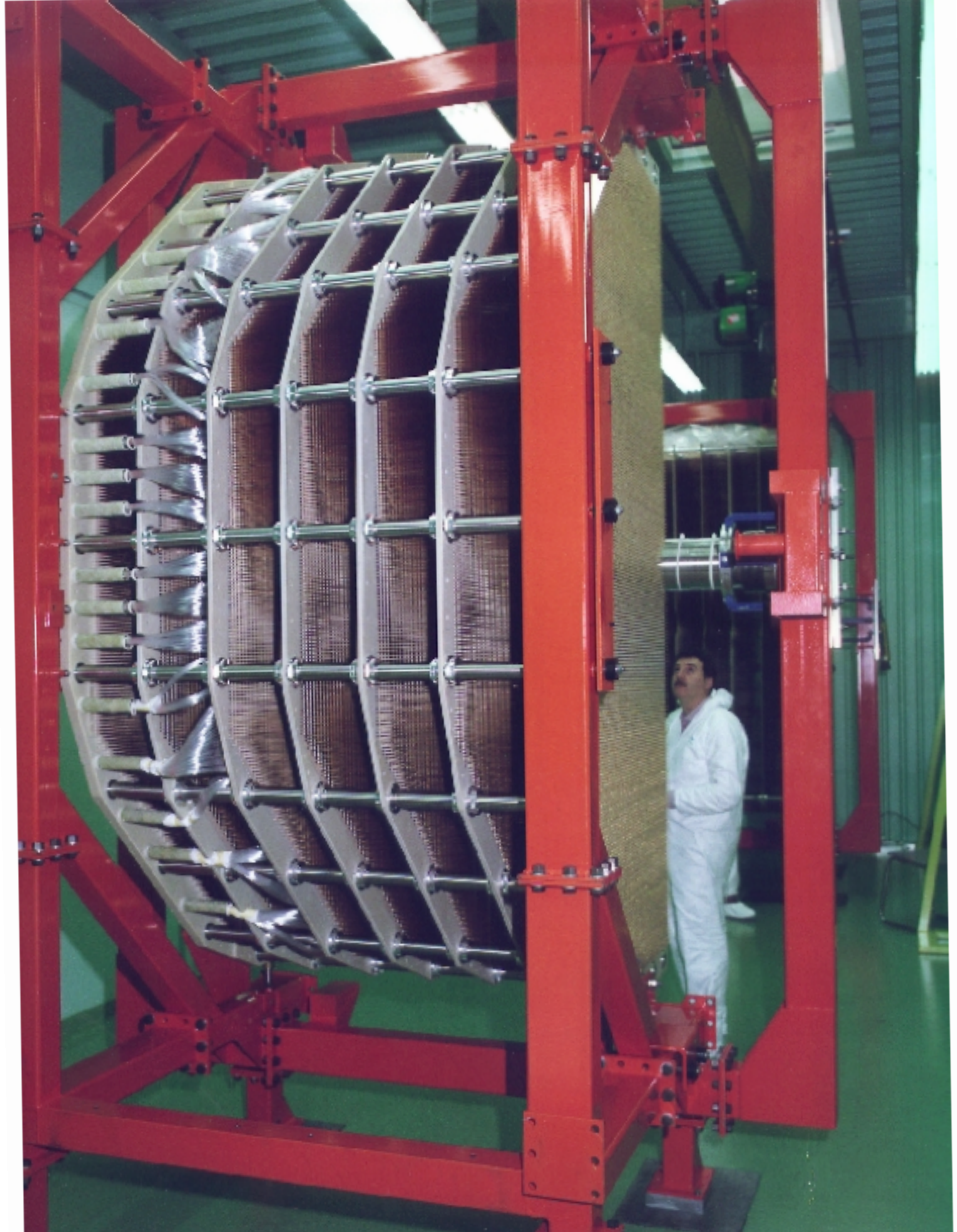
- $K_{L,S} \to \pi^+\pi^-$
  - Magnetic spectrometer ($\sigma_{X,Y} \sim 90\ \mu$m)
  - $\sigma(P)/P \simeq 0.5\,\% \oplus 0.009\ P[\mathrm{GeV}/c]\ \%$ ($\sim 1\ \%$ for 100 GeV/c track momentum)
  - Hodoscope for timing measurements ($\sigma_t \sim 200\ ps$)
  - Muon veto to reject $\pi\mu\nu$ background.

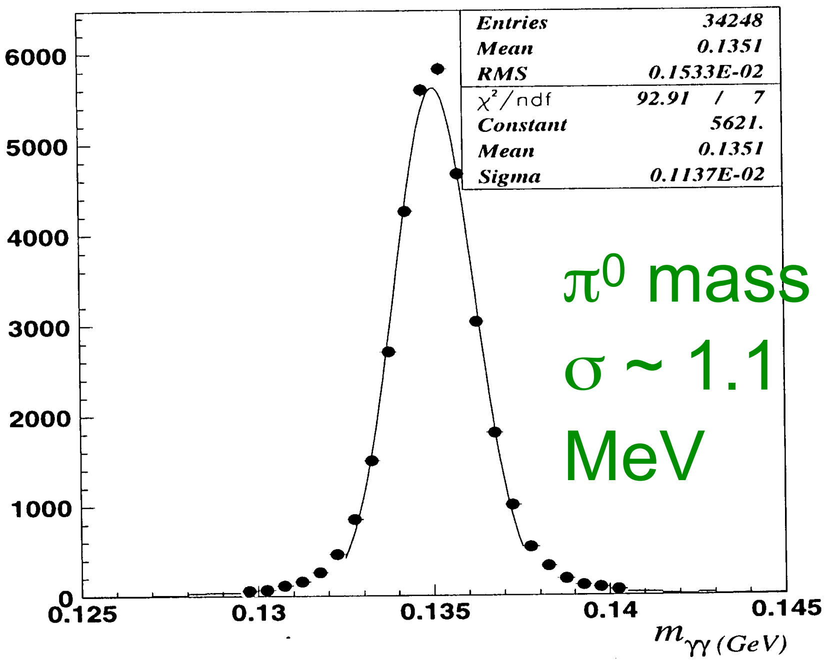
NA48 LIQUID KRYPTON ELECROMAGNETIC CALORIMETER: HOMOGENUOUS CALORIMETER

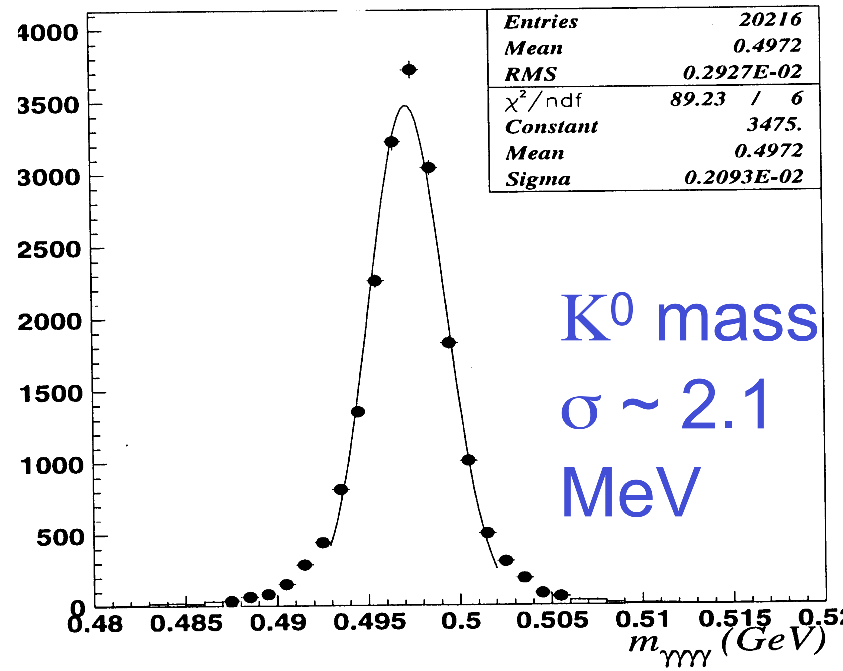
- NA48 has measured Re(ε′/ε) ~10^{-4} by identifying the mode $K_S \rightarrow \pi^0\pi^0$ and $K_L \rightarrow \pi^0\pi^0\pi^0$
- Good resolution on m(π^0) necessary: 1MeV
- (m(π^0) = 135MeV)
- Energy resolution 5%/√E
- LKr bath instrumented with electrodes with a zig-zag sha

Liquid Krypton T = 120 ^{0}K

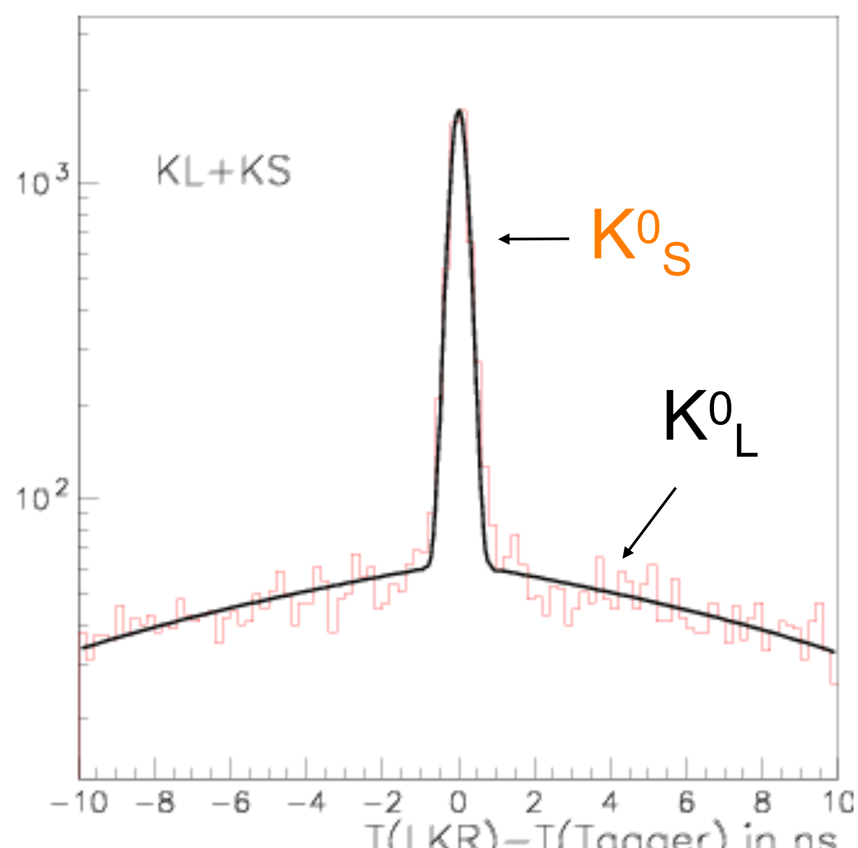








NA48



Calorimeter time resolution σ ~ 220 ps

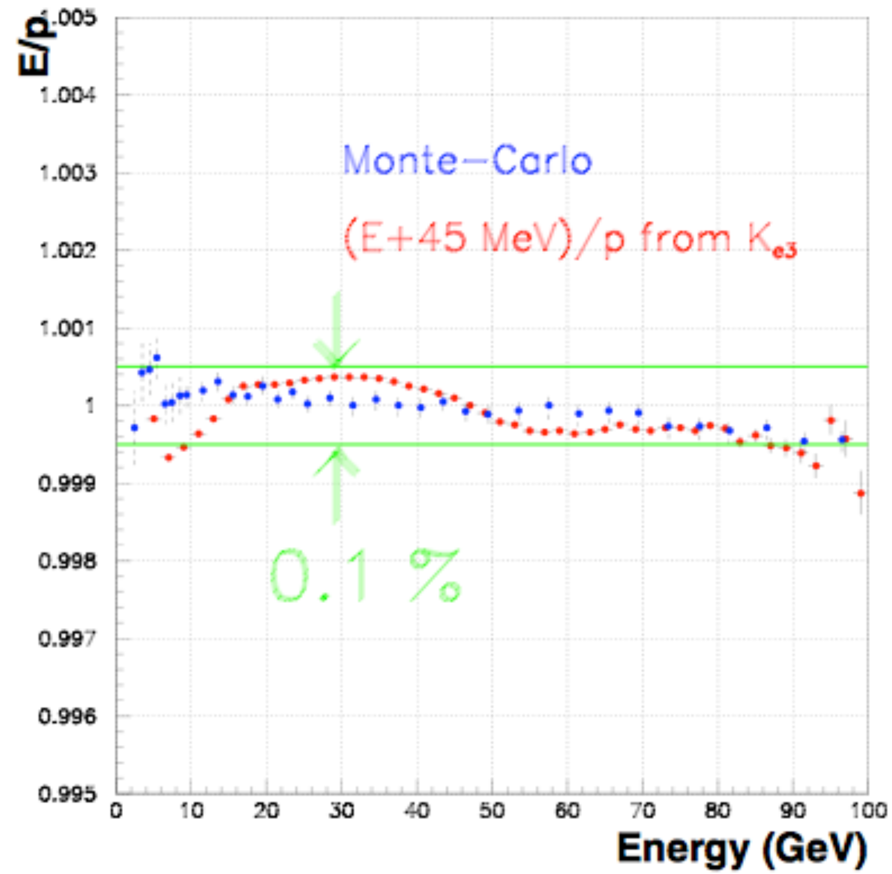
ENERGY LINEARITY

ENERGY RESPONSE LINEARITY is CRITICAL for MASS MEASUREMENT

In NA48, study the calorimeters in-situ selecting $K_L \to \pi^{\pm} e^{\mp} \nu$ decays

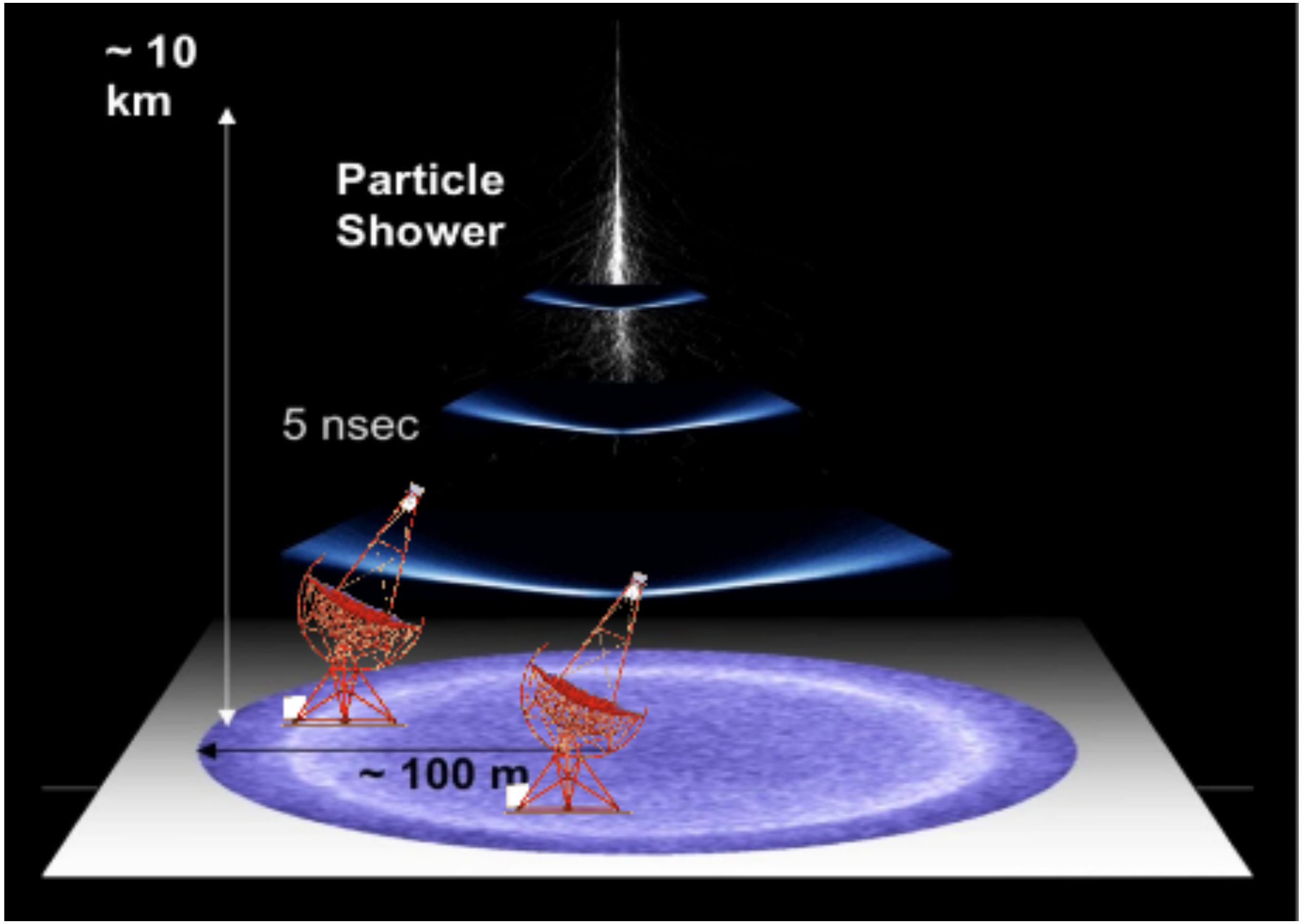
Use the spectrometer to measure p (resolution ~0.5-1%)
and the calorimeter to measure E

In an ideal world: E/p=1

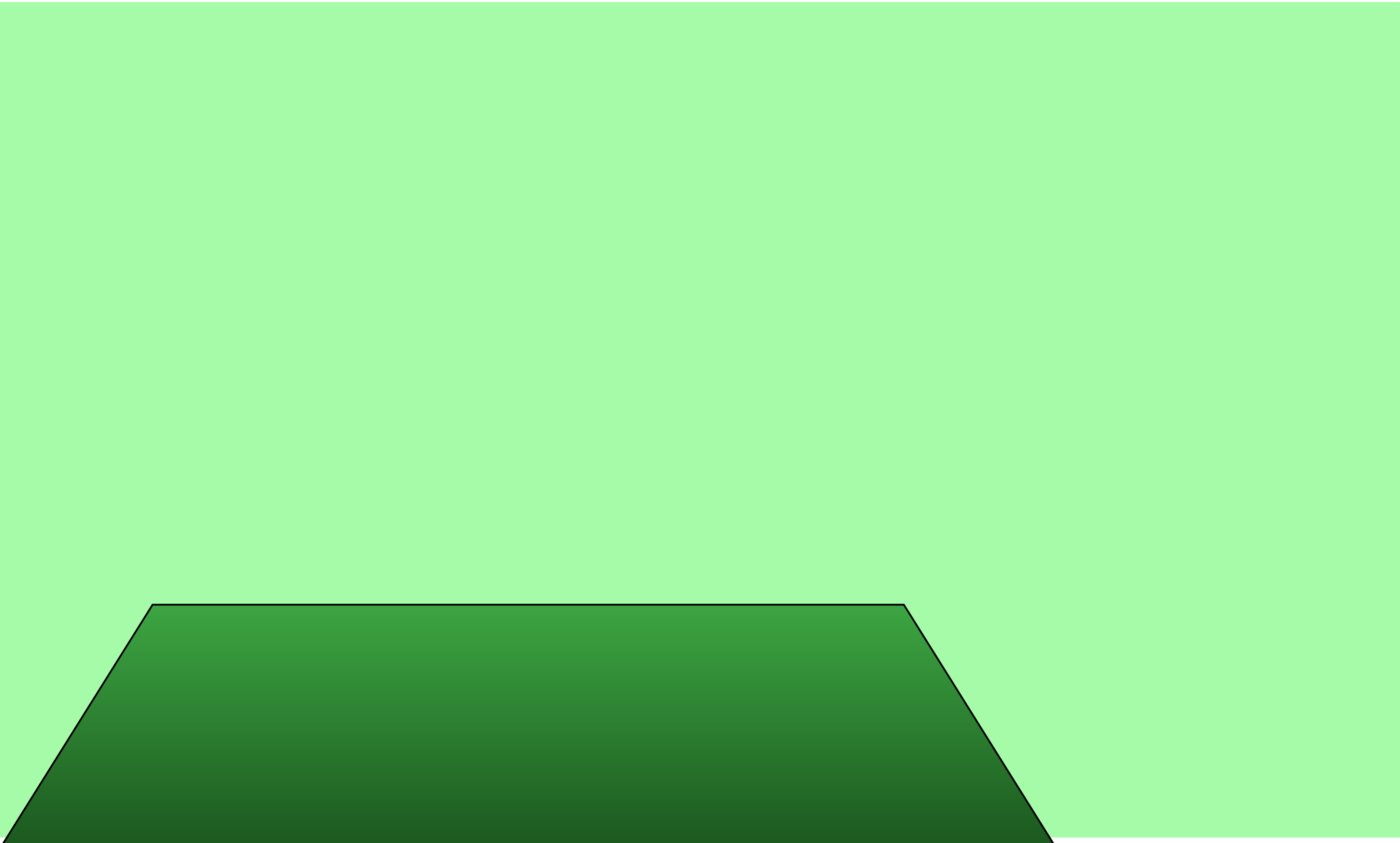


$\Rightarrow$ Non linearity $\approx$ 0.1%
(from 5 to 100 GeV)

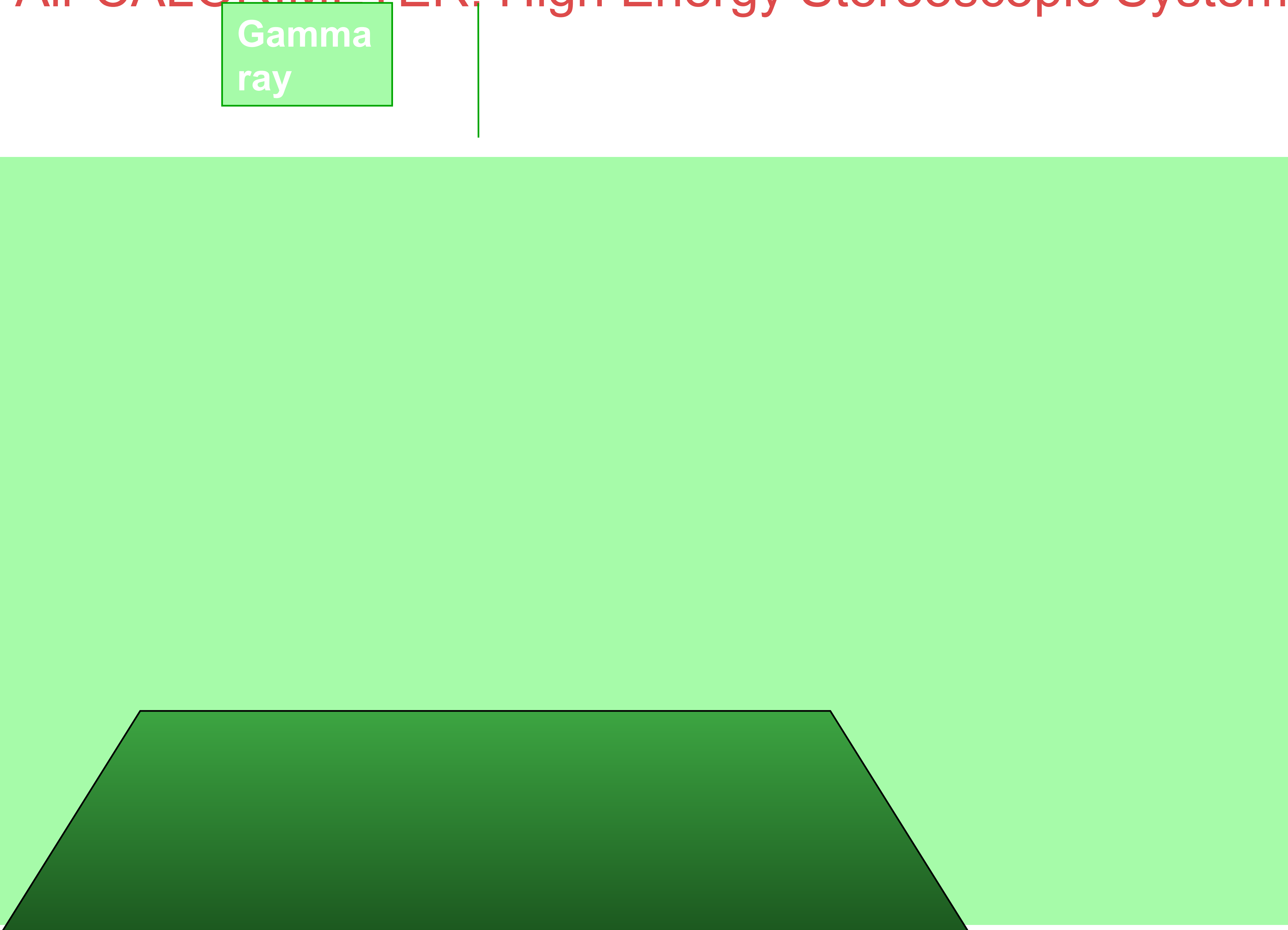
NATURAL CALORIMETER



Air CALORIMETER: High Energy Stereoscopic System



Air CALORIMETER: High Energy Stereoscopic System



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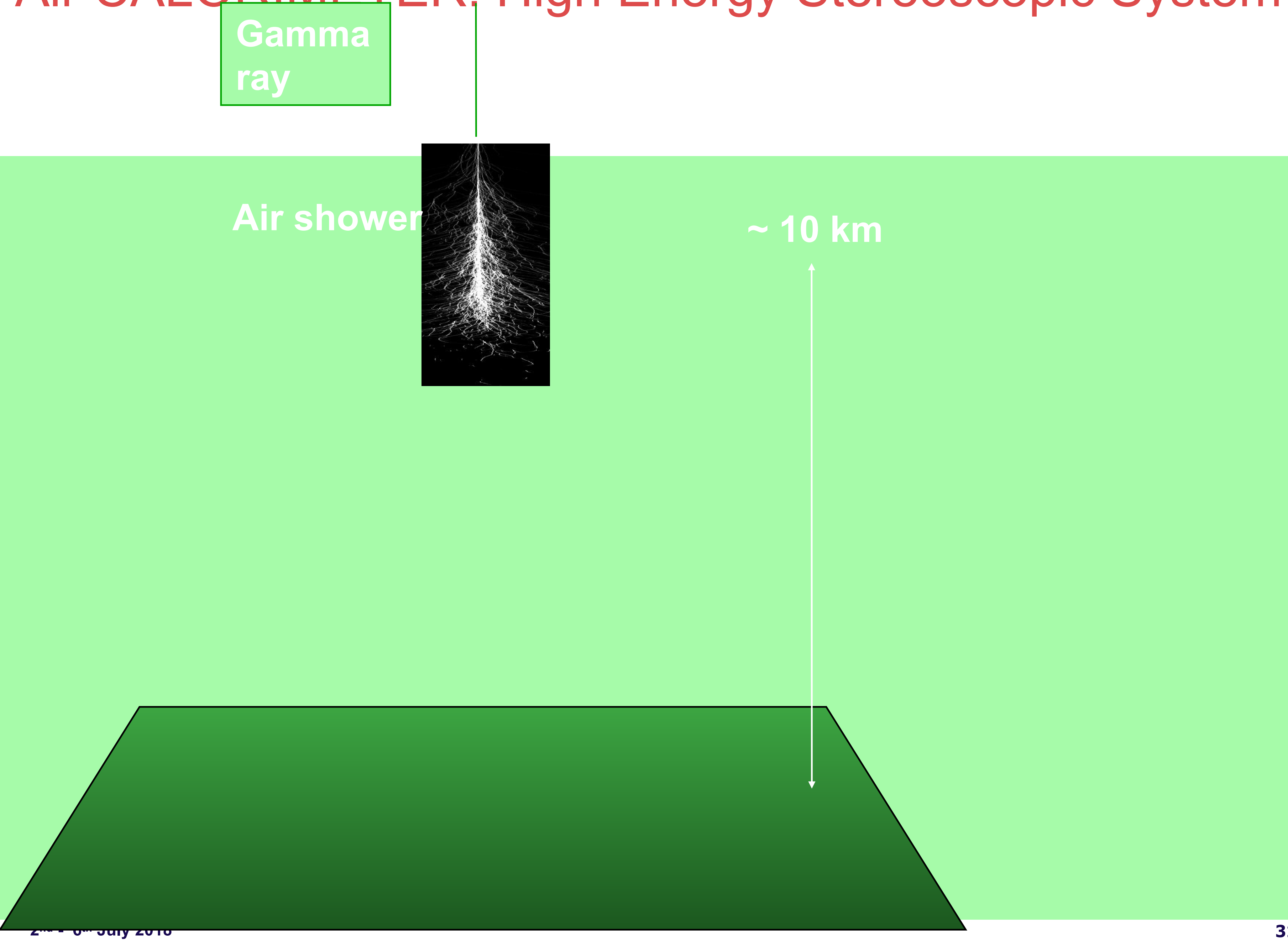

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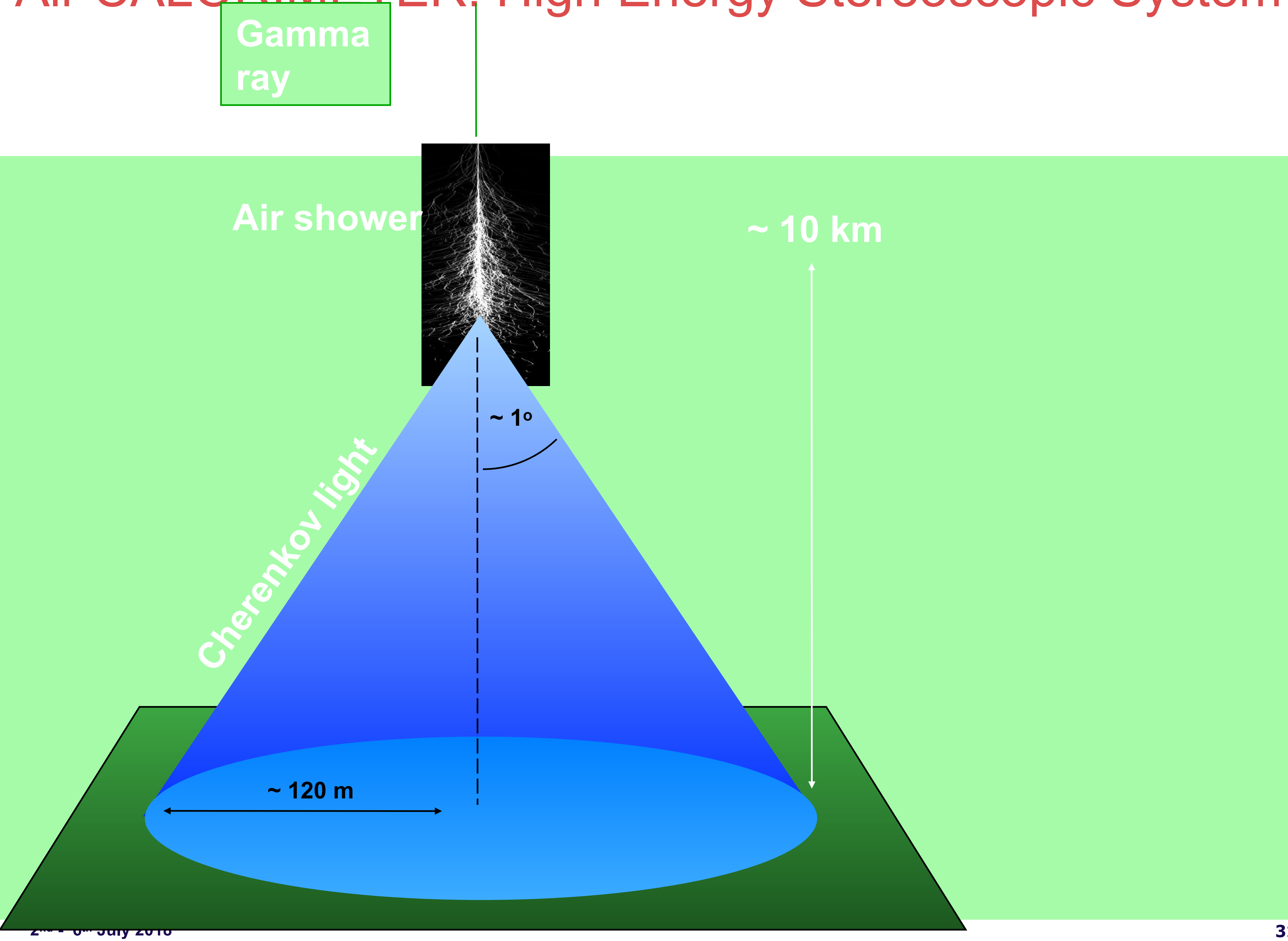
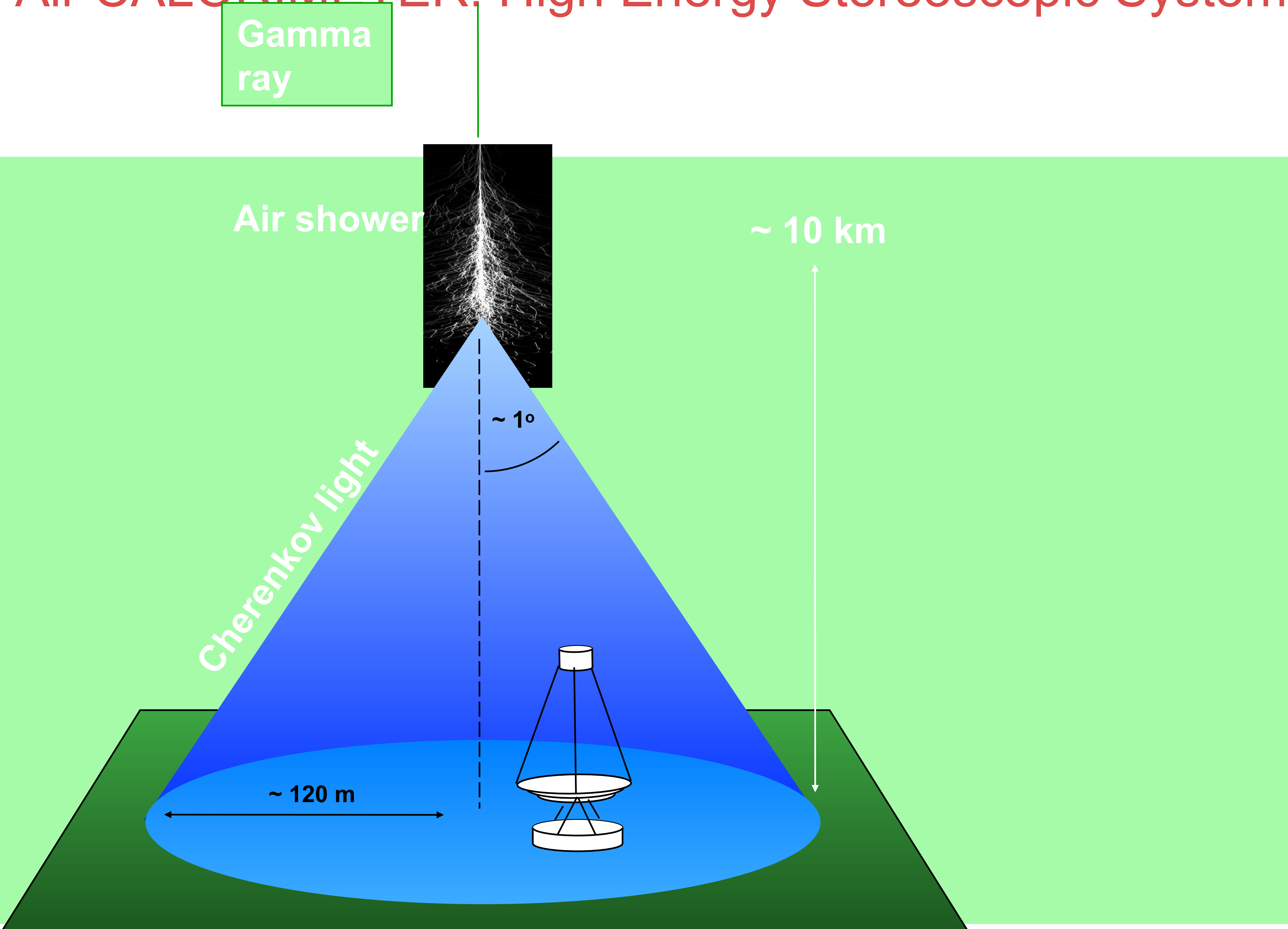
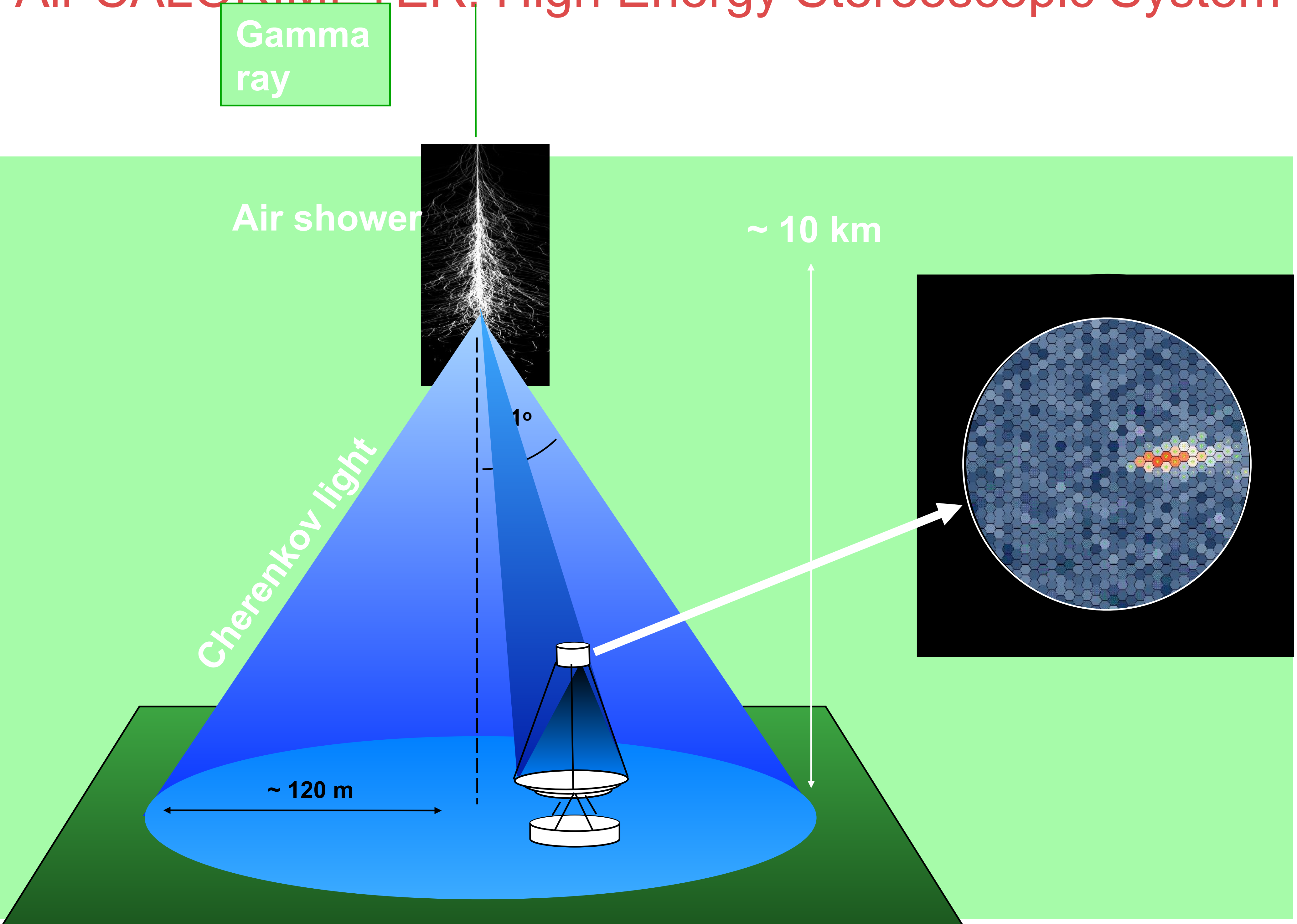


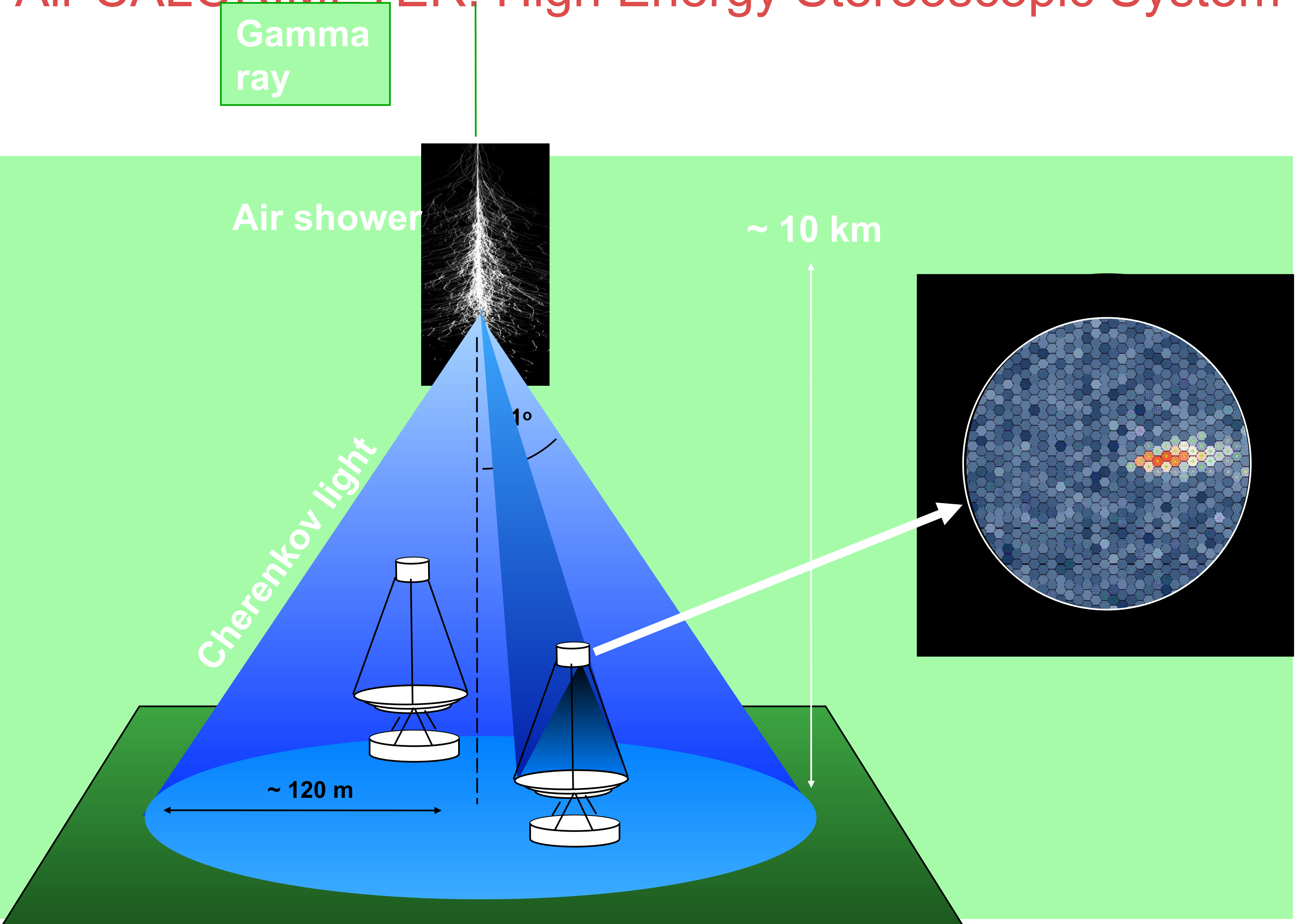
Air CALORIMETER: High Energy Stereoscopic System



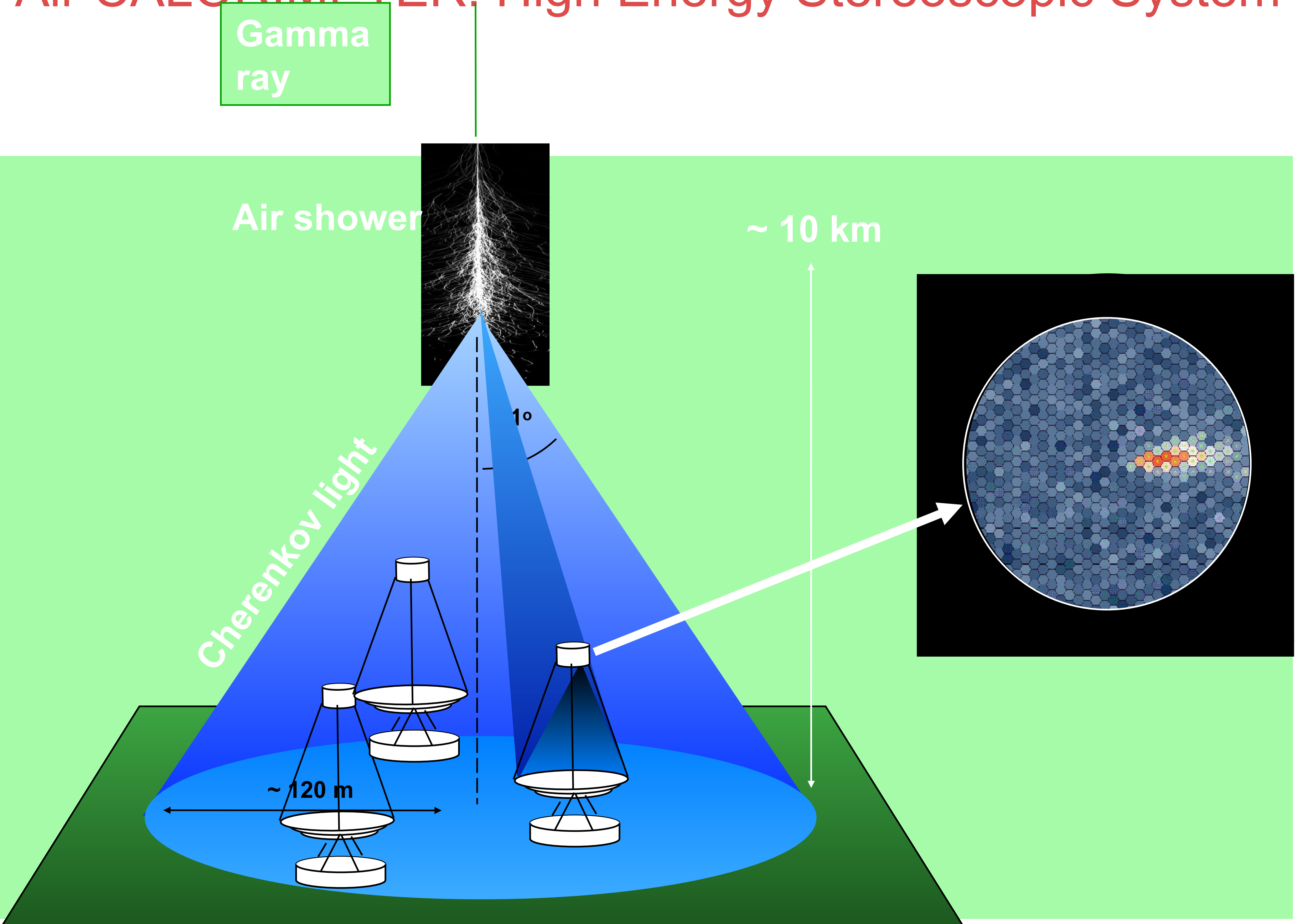
Air CALORIMETER: High Energy Stereoscopic System



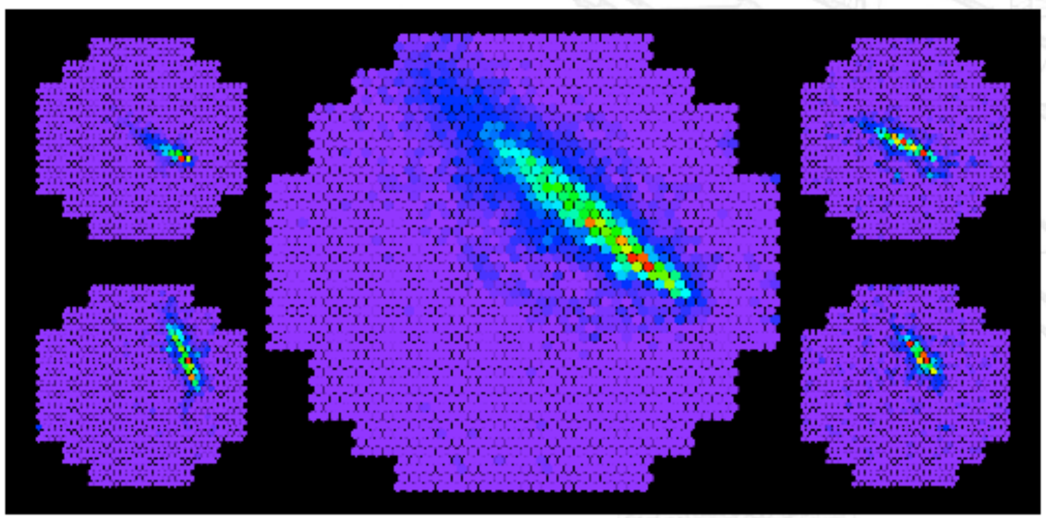
Air CALORIMETER: High Energy Stereoscopic System

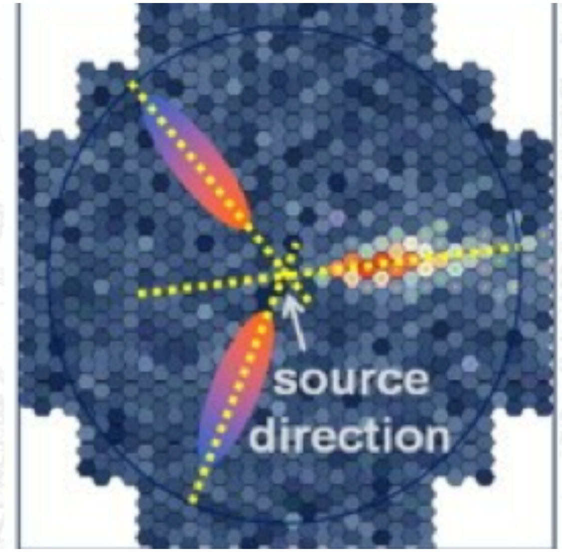


Air CALORIMETER: High Energy Stereoscopic System

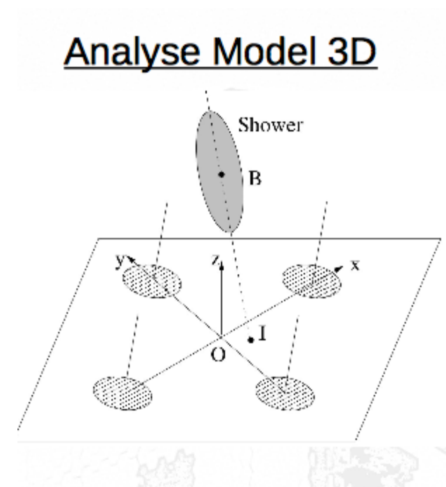


THE METHOD

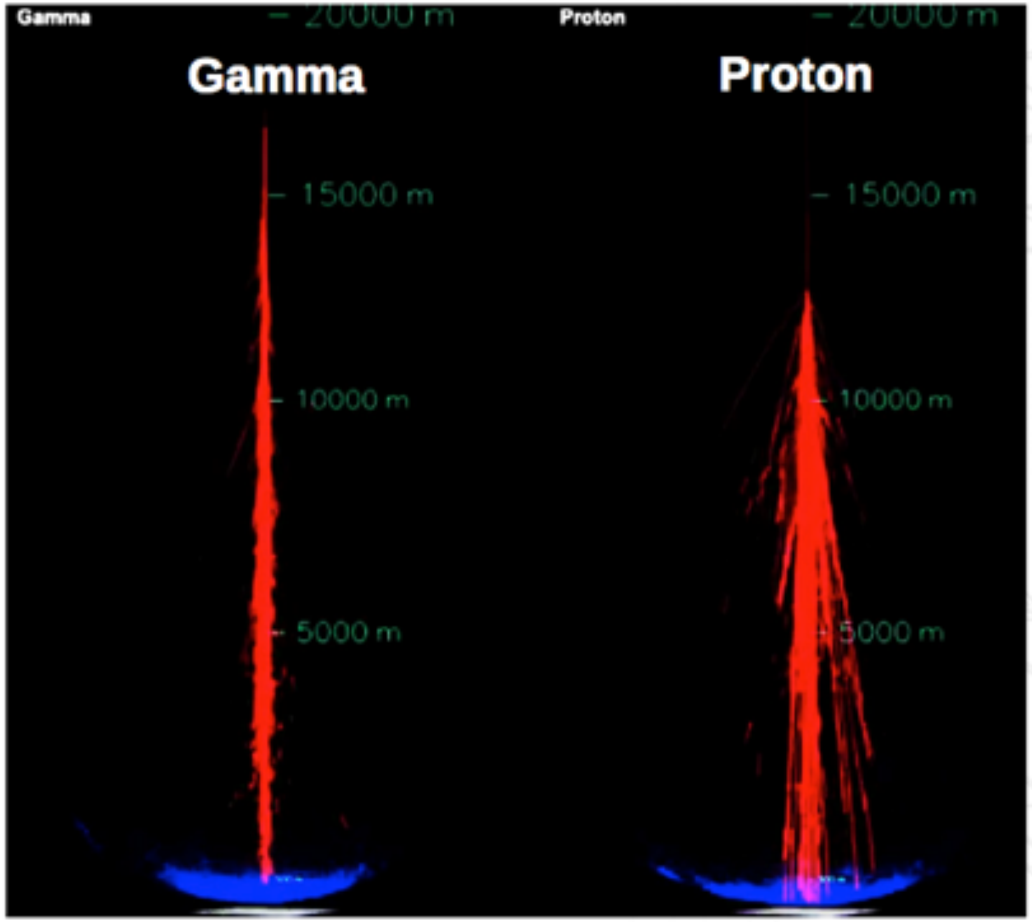




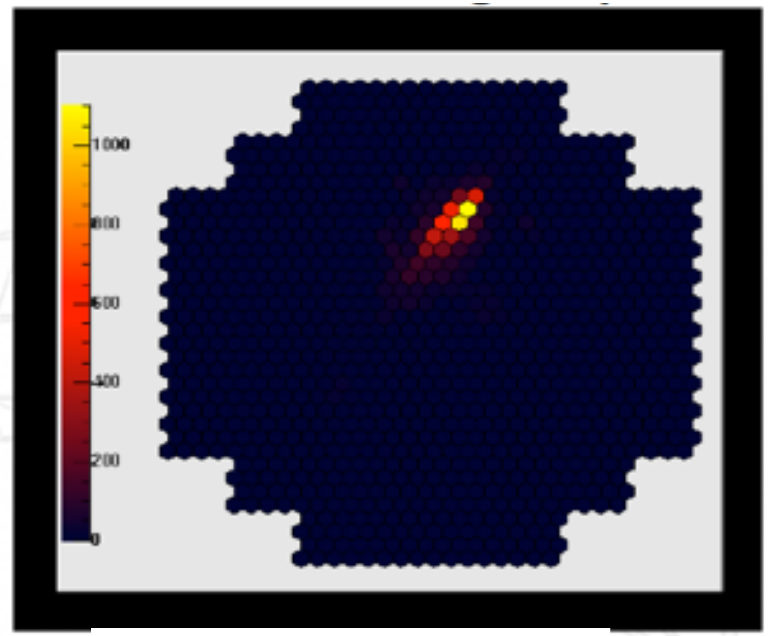
Reconstruct the shower position in atmosphere
Estimate the energy from signal in telescopes + simulation of air showers



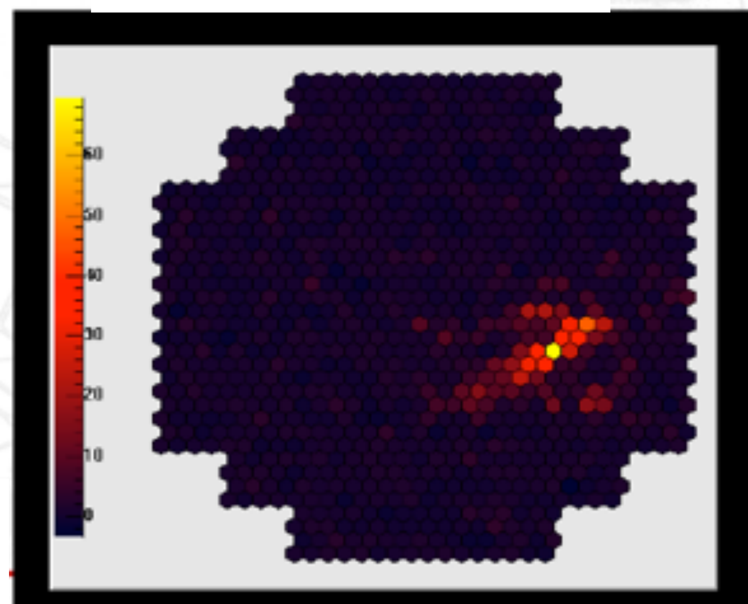
GAMMA RAYS DETECTIONS & SHOWER SHAPES



ELECTROMAGNETIC SHOWER

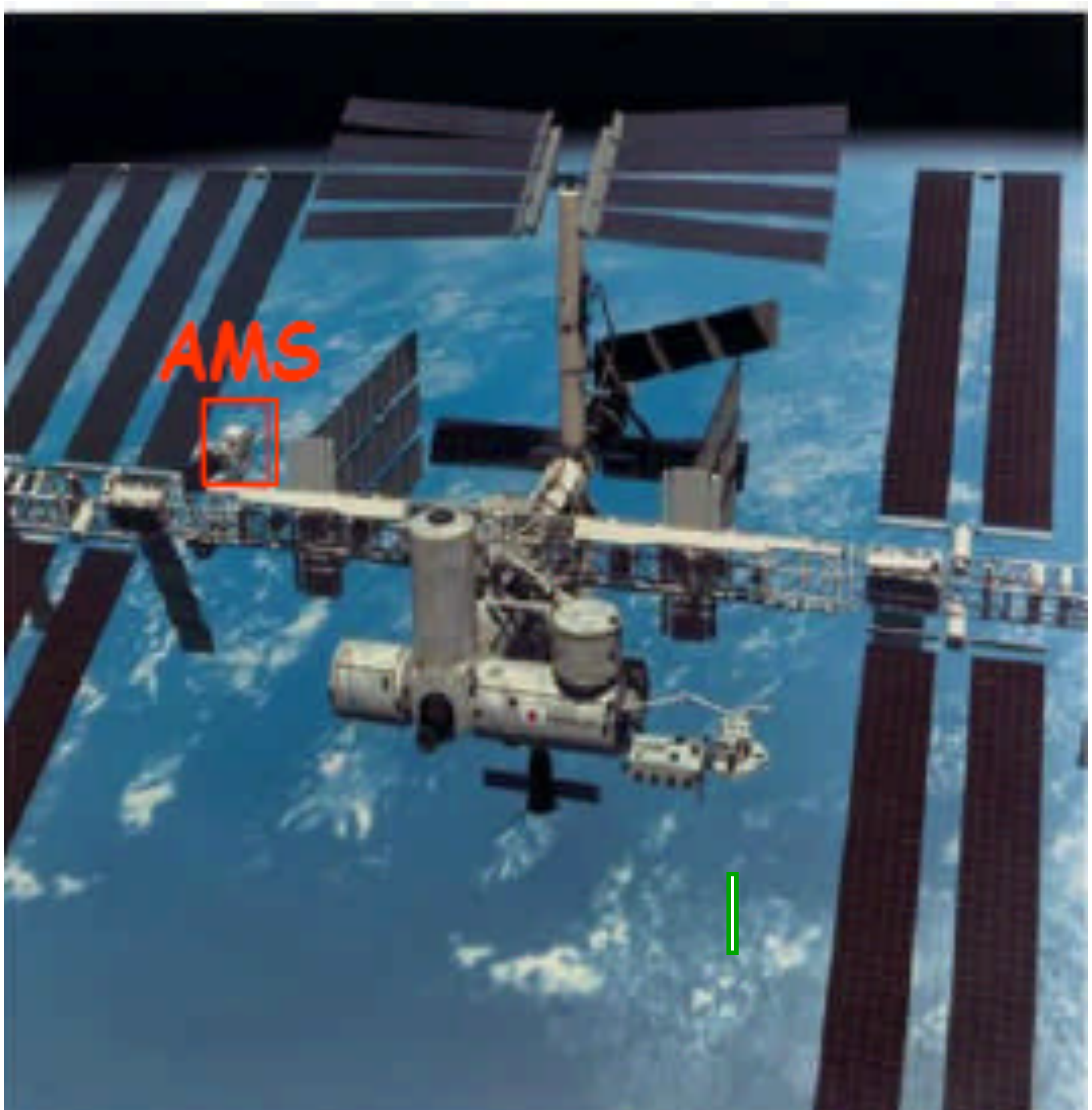


HADRONIC SHOWER



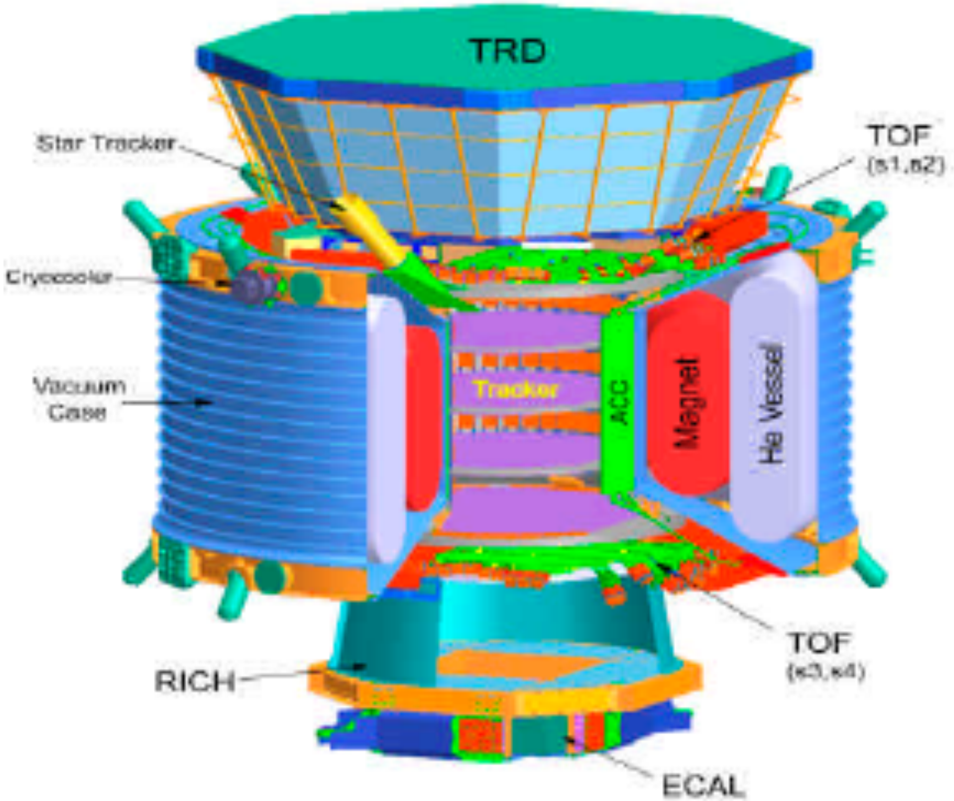
HESS EXPERIMENT INSTALLED in NAMIBIA

ALPHA MAGNETIC SPECTROMETER



- AMS is designed to measure high energy cosmic rays.
- AMS is in particular searching for anti-matter (anti-He)
- AMS is a multi purpose particle detector in space.

AMS DETECTOR



AMS on ISS for 3 years

Transition Radiation Detector
- Foam + drift tubes (Xe/CO_2)

Time of Flight (trigger)
- Scintillators, fine mesh PMT's
- $\sigma_t \sim 120$ ps

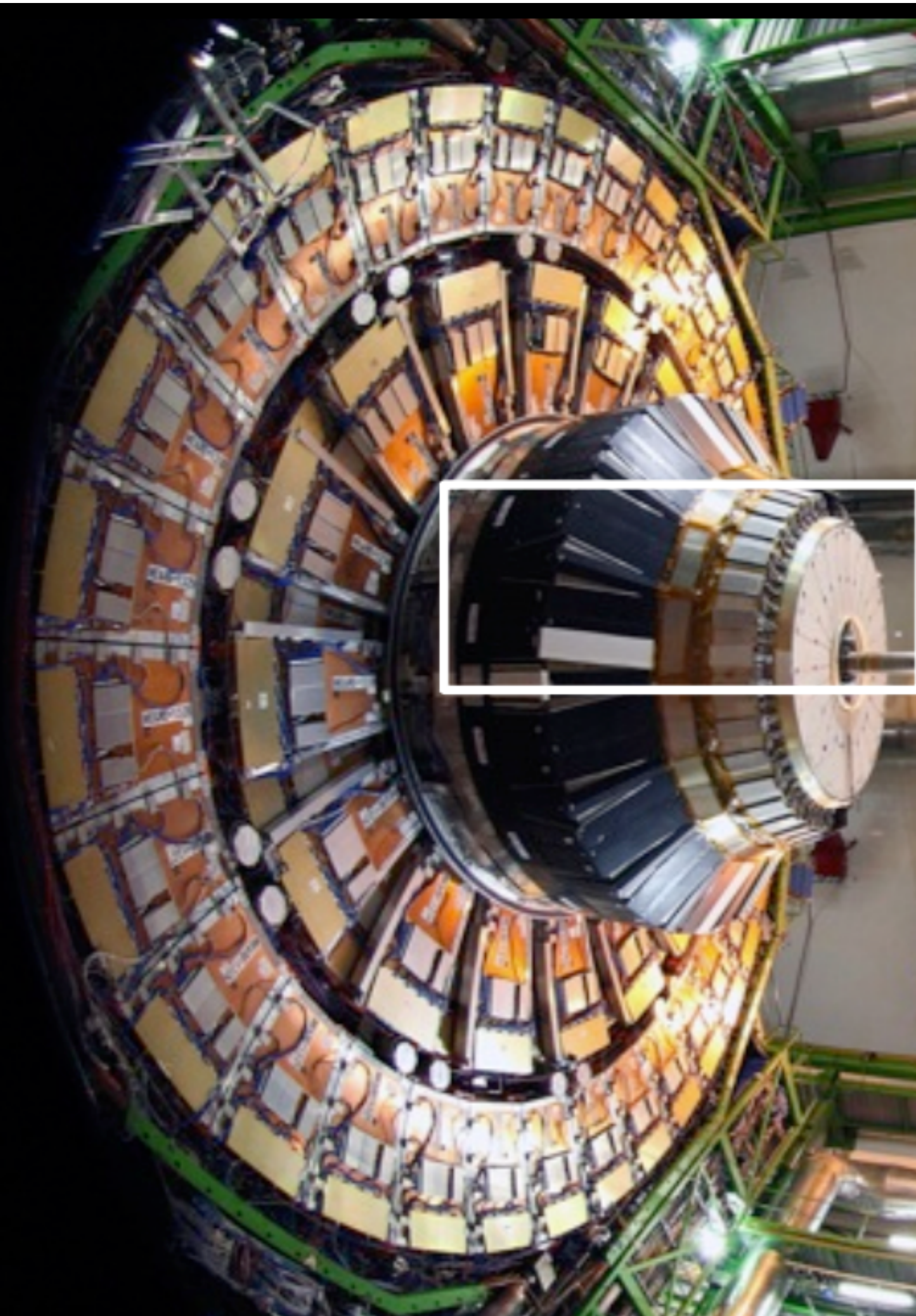
Superconducting magnet (0.86 $T{\cdot}m^2$)

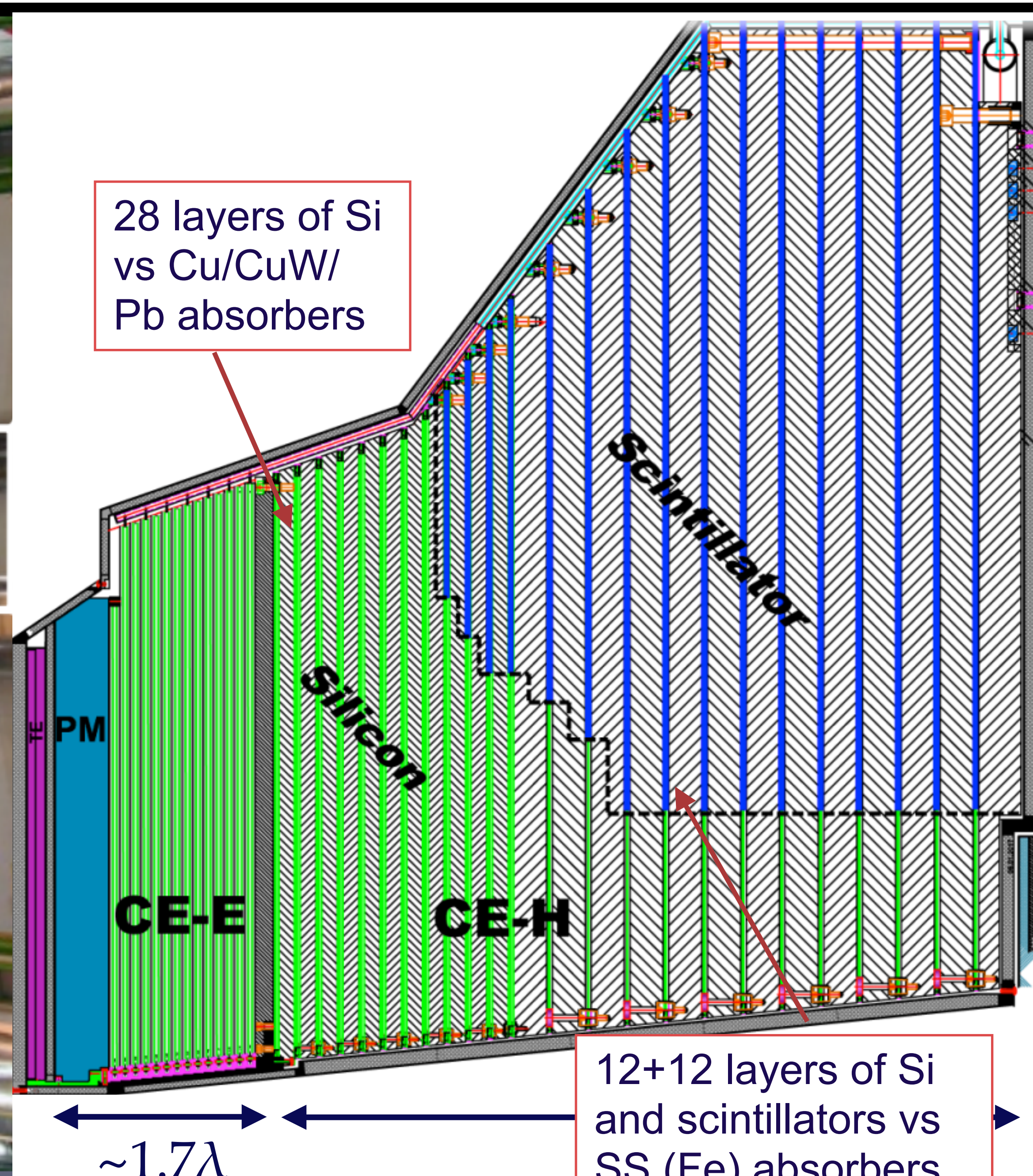
Tracker (8 layers, 6m^2)
- 6 double-sided silicon strips
- σ_x=10 μm in bending plane

RICH
- Radiator (Aerogel+NaF)
- PMT's (16 pixels)

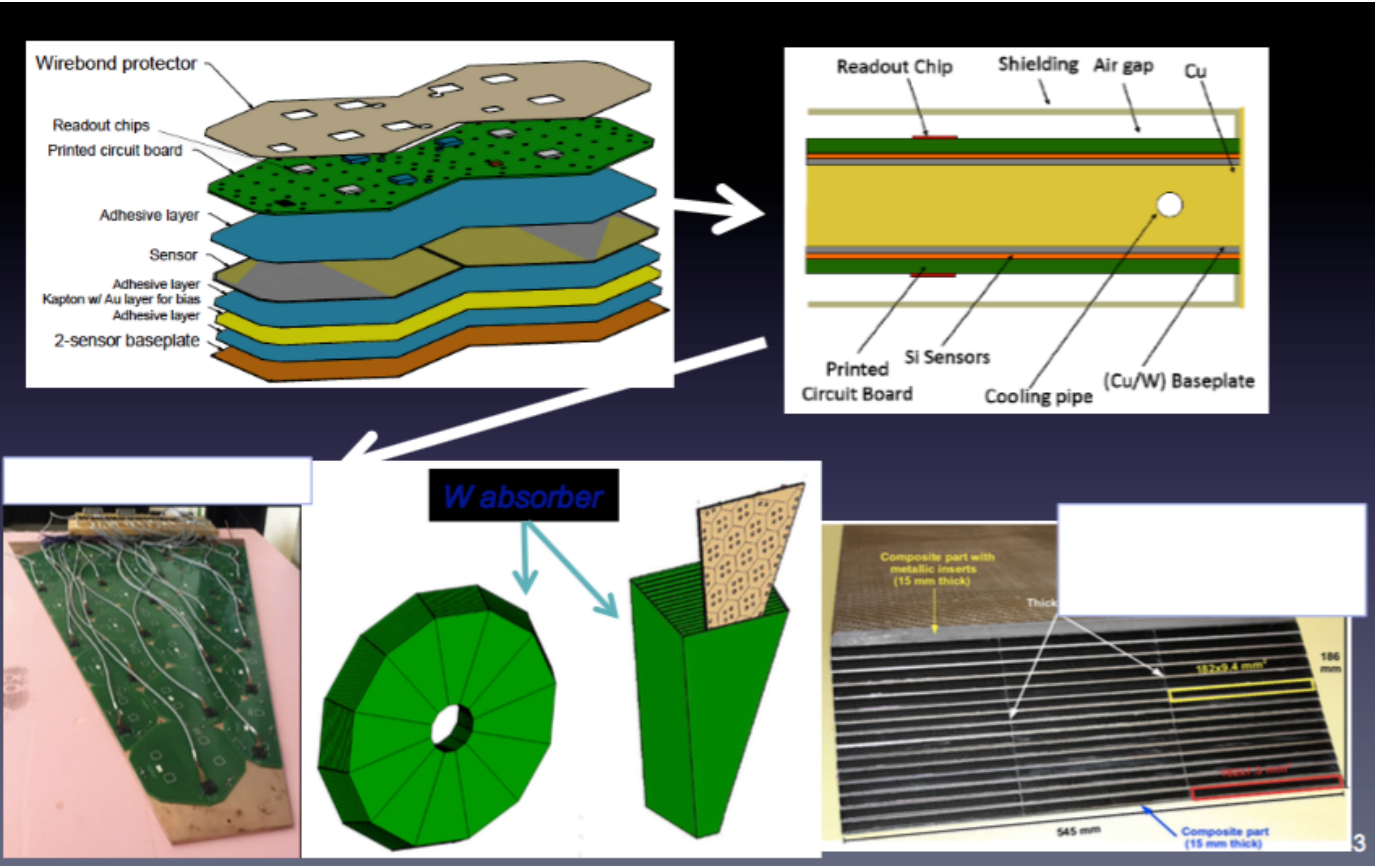
3D-sampling ECAL
- Lead+Scintillating-fibers
- PMT's (4 pixels)

THE FUTURE of the CMS ENDCAP CALORIMETER

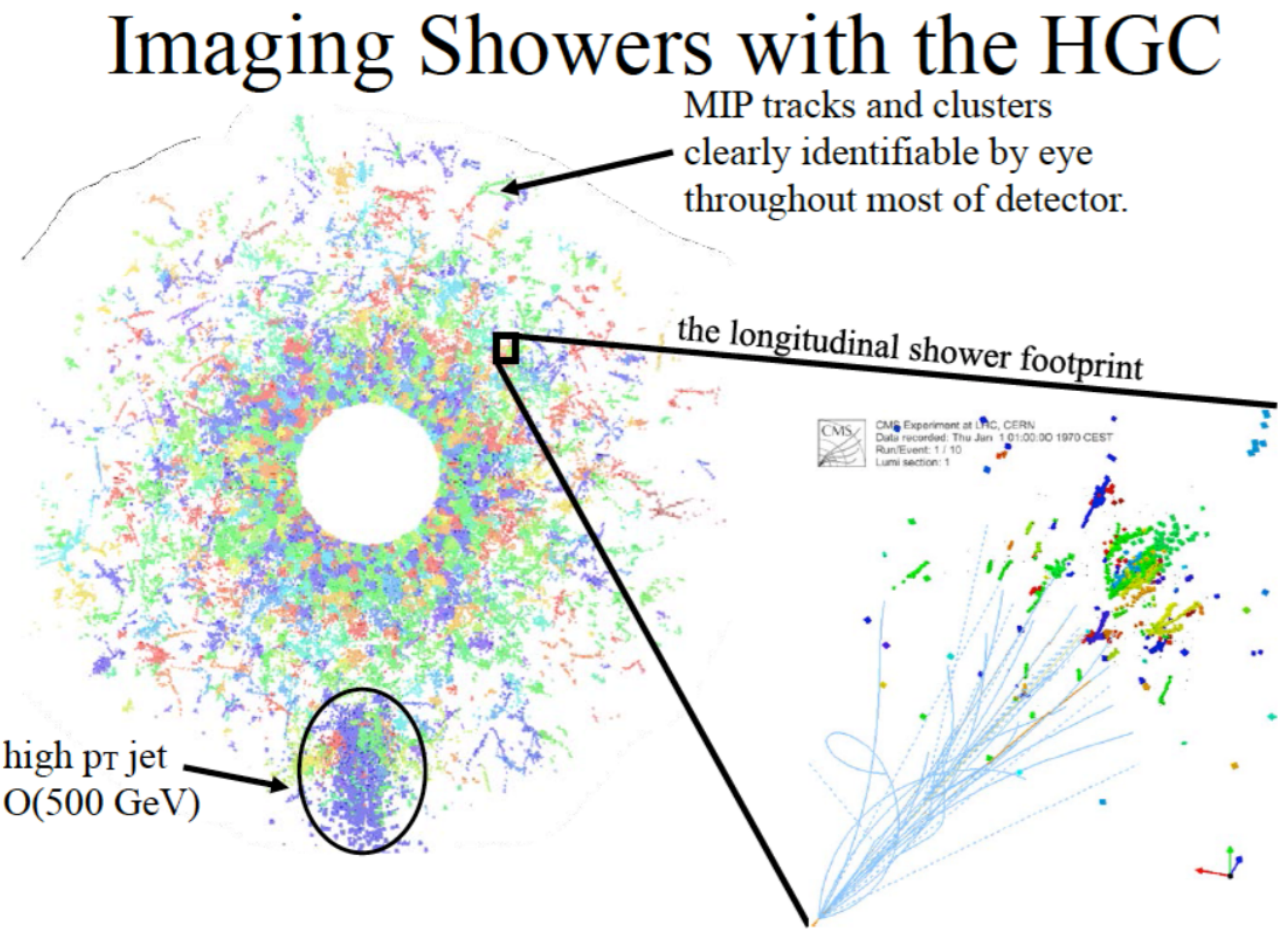




THINTHLY SEGMENTED ENDCAP ECAL FOR CMS



IMAGINING CALORIMETER



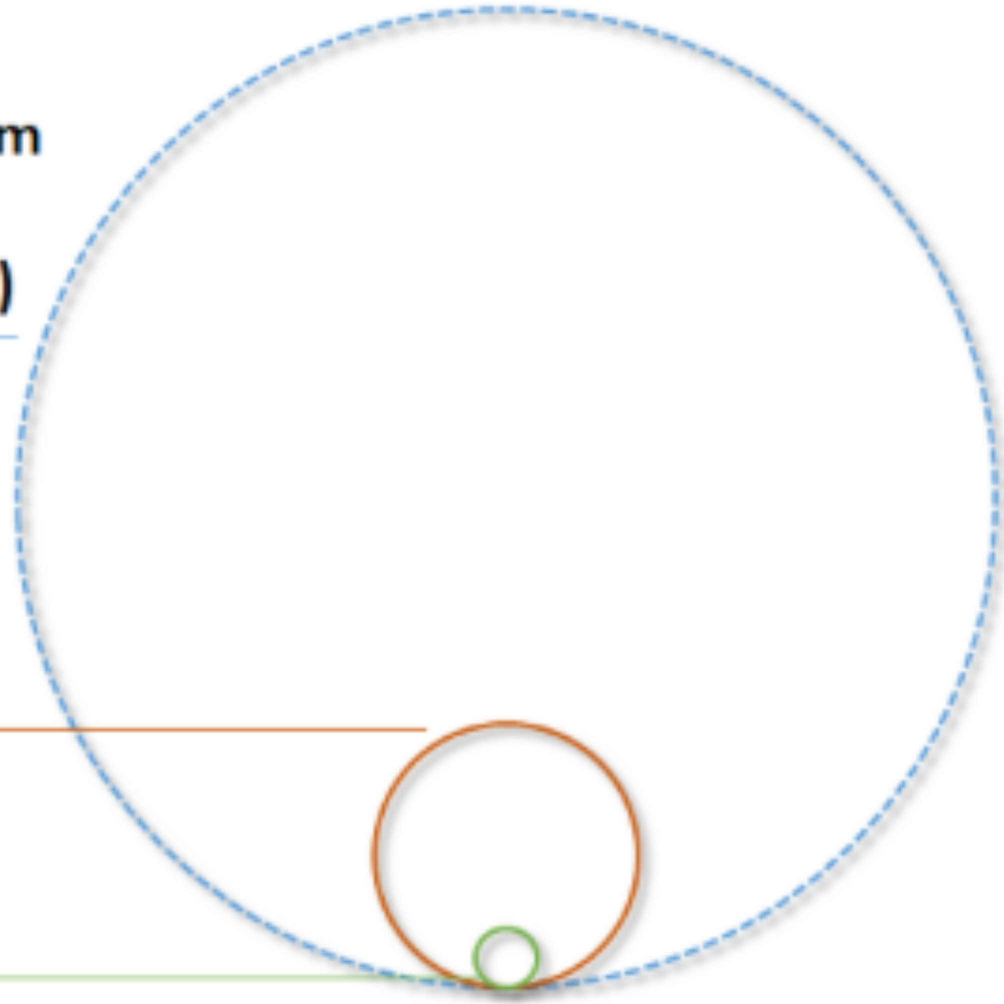
FUTURE CIRCULAR COLLIDER ?

TO PROBE MATTER FURTHER.

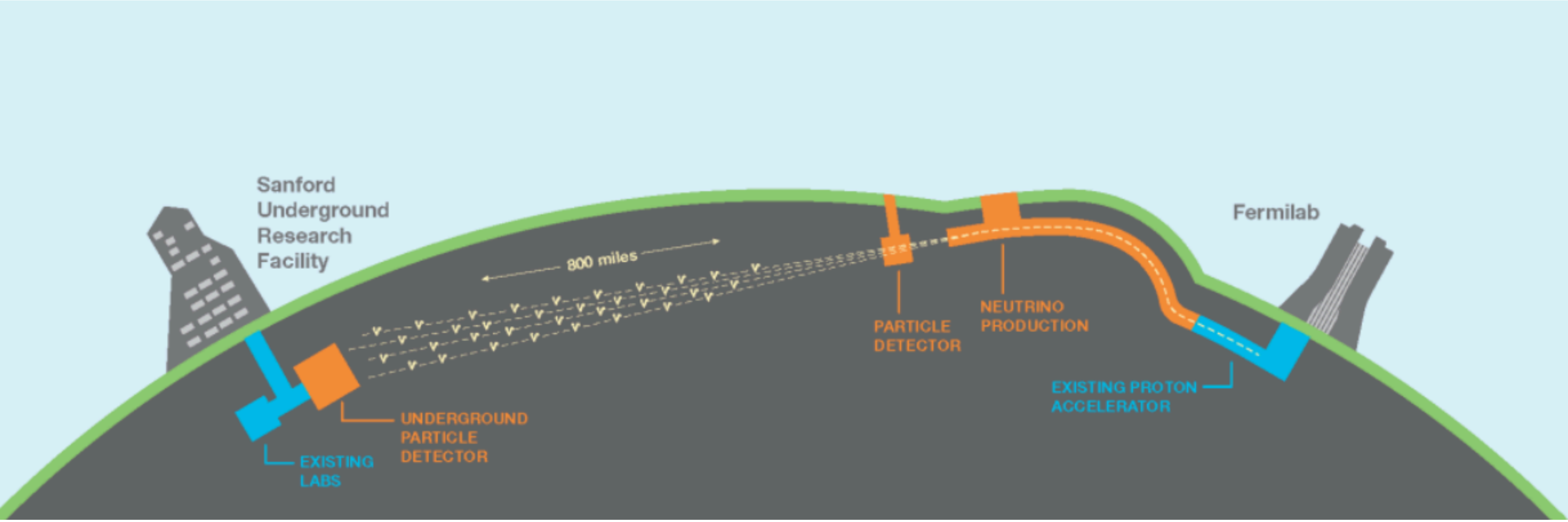
Future Circular Collider
Circumference: **80-100 km**
Energy: **100 TeV (pp)**
>350 GeV (e^+e^-)

Large Hadron Collider
Circumference: **27 km**
Energy: **14 TeV (pp)**
209 GeV (e^+e^-)

Tevatron (closed)
Circumference: **6.2 km**
Energy: **2 TeV**



THE DUNE PROJECT



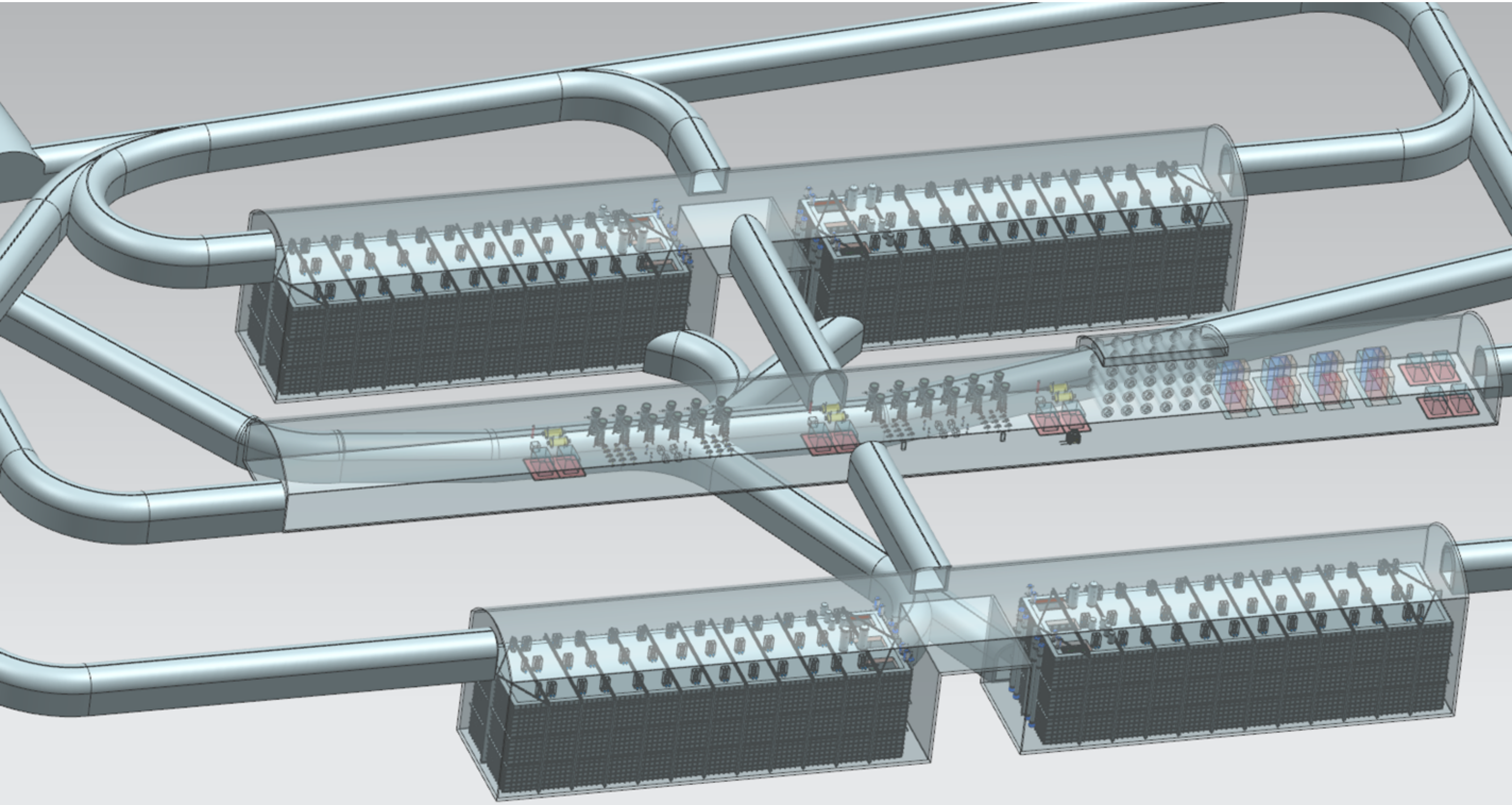
DUNE is an international project based in USA. It is a long base line experiment: neutrinos are produced at Fermilab (near Chicago), travel 800 miles underground before reaching a particle detector.

The aim of the experiment is to precisely measure the neutrino sector.

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\begin{bmatrix} 0.82 \pm 0.01 & 0.54 \pm 0.02 & -0.15 \pm 0.03 \\ -0.35 \pm 0.06 & 0.70 \pm 0.06 & 0.62 \pm 0.06 \\ 0.44 \pm 0.06 & -0.45 \pm 0.06 & 0.77 \pm 0.06 \end{bmatrix}$$

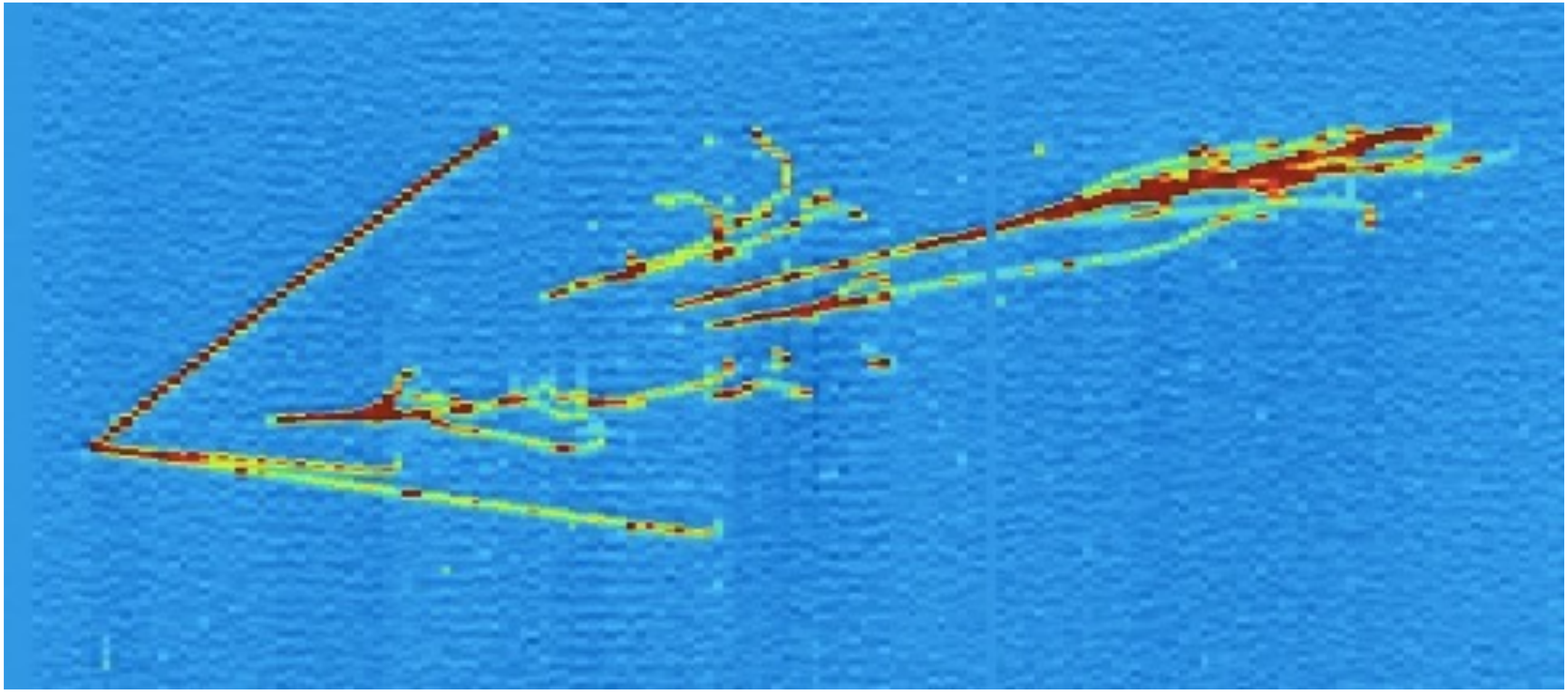
THE DUNE PROJECT



4 large liquid argon TPC - 17000 tons of argon

DUNE Liquid Argon Time Projection Chamber

DUNE Liquid Argon Time Projection Chamber



APPLICATIONS of HEP TECHNIQUES: PET

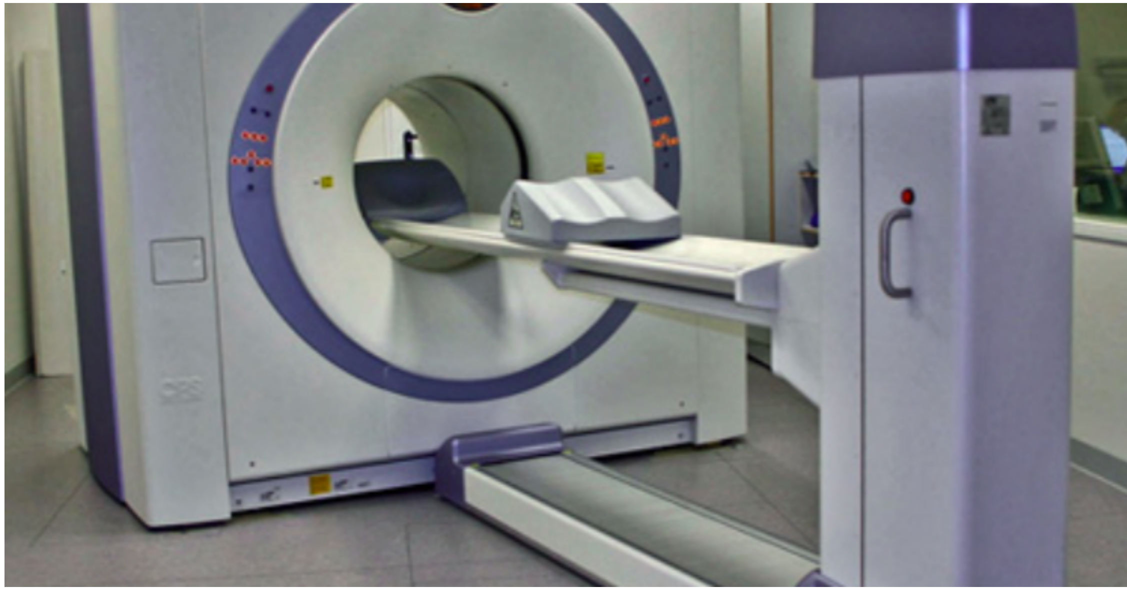
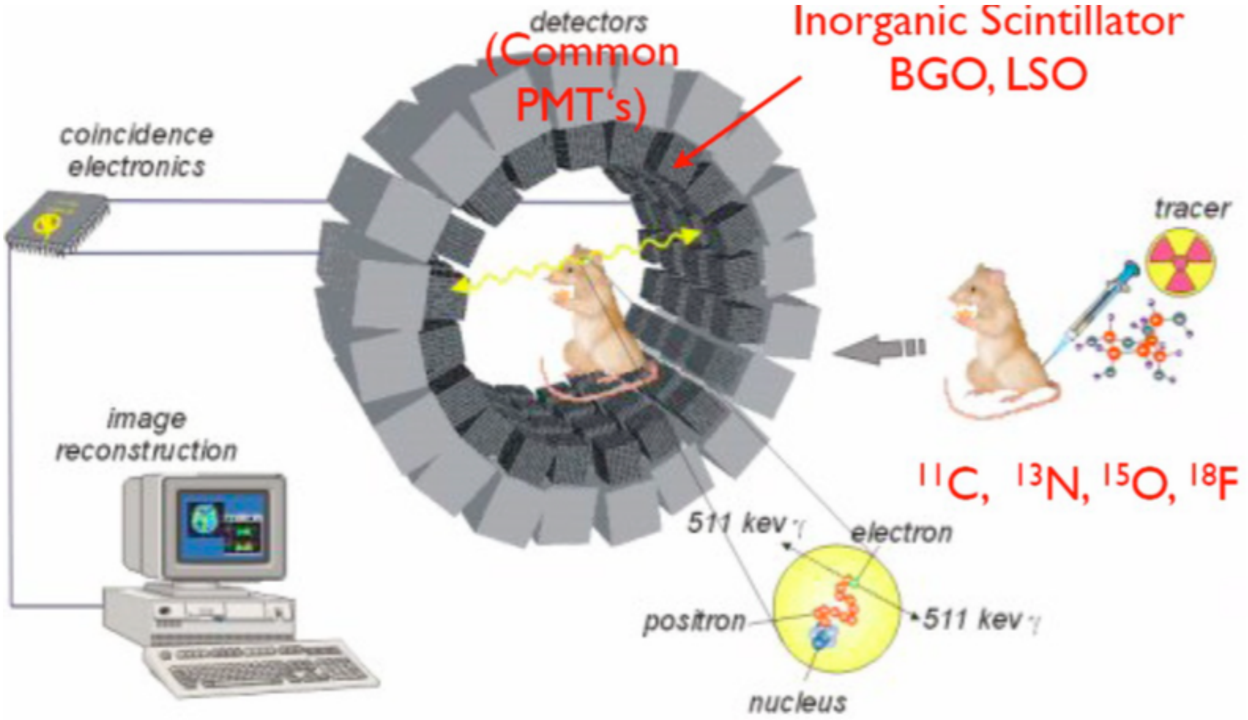
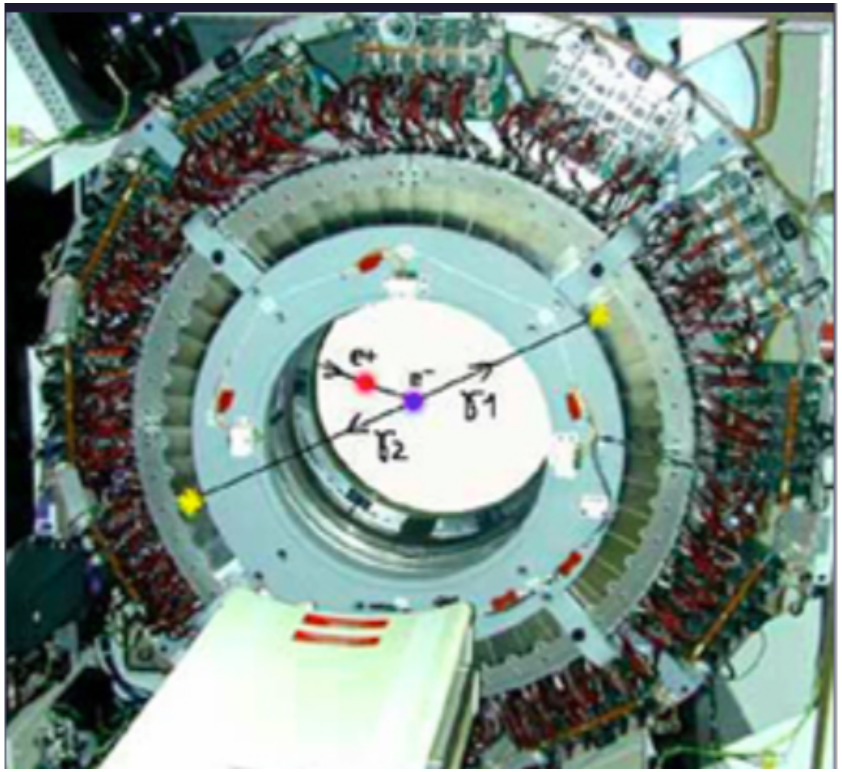


Photo-Electron Tomography





SOME CONCLUSIONS

Detectors are designed and built to make specific physics measurements i.e.
detectors are very specific for each physics subject

Detector techniques are based on particle interaction with matter ultimately on very low energy interactions.

The detector properties and their performance are the key to high quality physics results.

Instrumentation is evolving fast; physics requirements are increasing (rarer and rarer processes, precision measurements): each generation of detector has improved performance with respect to the preceding generation.