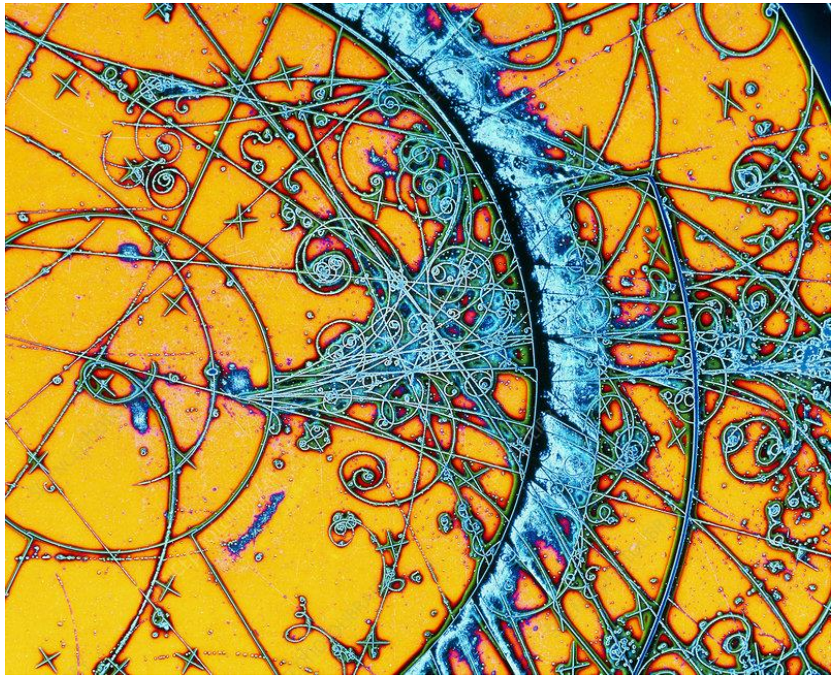
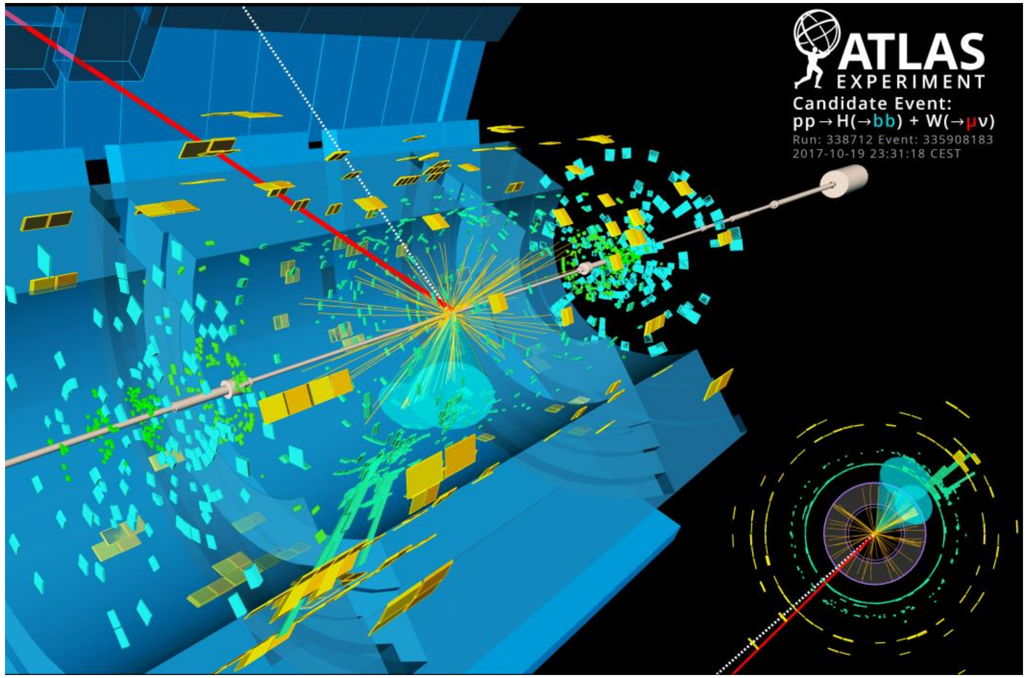
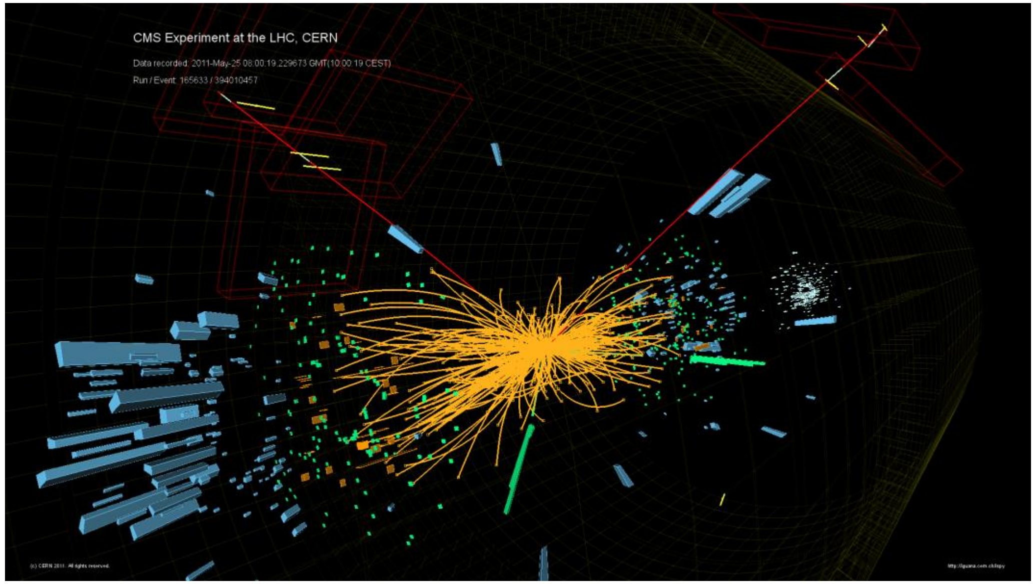



ATLAS
EXPERIMENT
Candidate Event:
pp → H(→bb) + W(→μν)
Run: 338712 Event: 335908183
2017-10-19 23:31:18 CEST


CMS Experiment at the LHC, CERN
Data recorded: 2011-May-25 08:00:19.229673 GMT(10:00:19 CEST)
Run / Event: 165633 / 394010457
(c) CERN 2011. All rights reserved.
http://iguana.cern.ch/ispy

Particle Detectors

Summer Student Lectures 2022

Werner Riegler, CERN, werner.riegler@cern.ch

History of Instrumentation ↔ History of Particle Physics

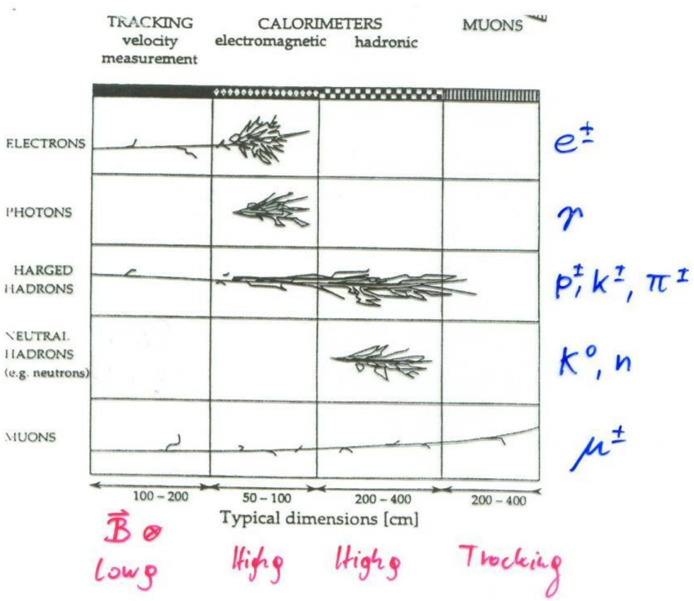
The ‘Real’ World of Particles

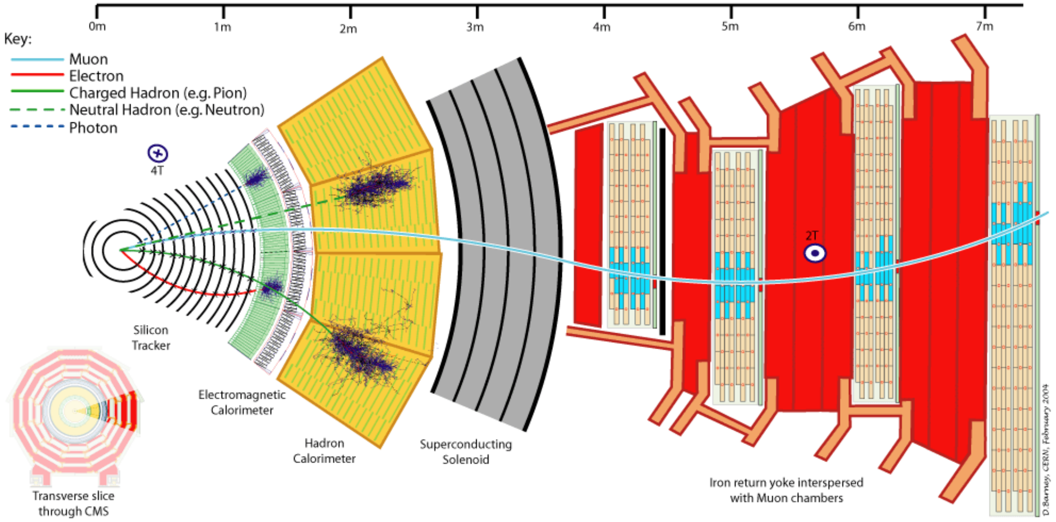
Interaction of Particles with Matter

Tracking Detectors, Calorimeters, Particle Identification

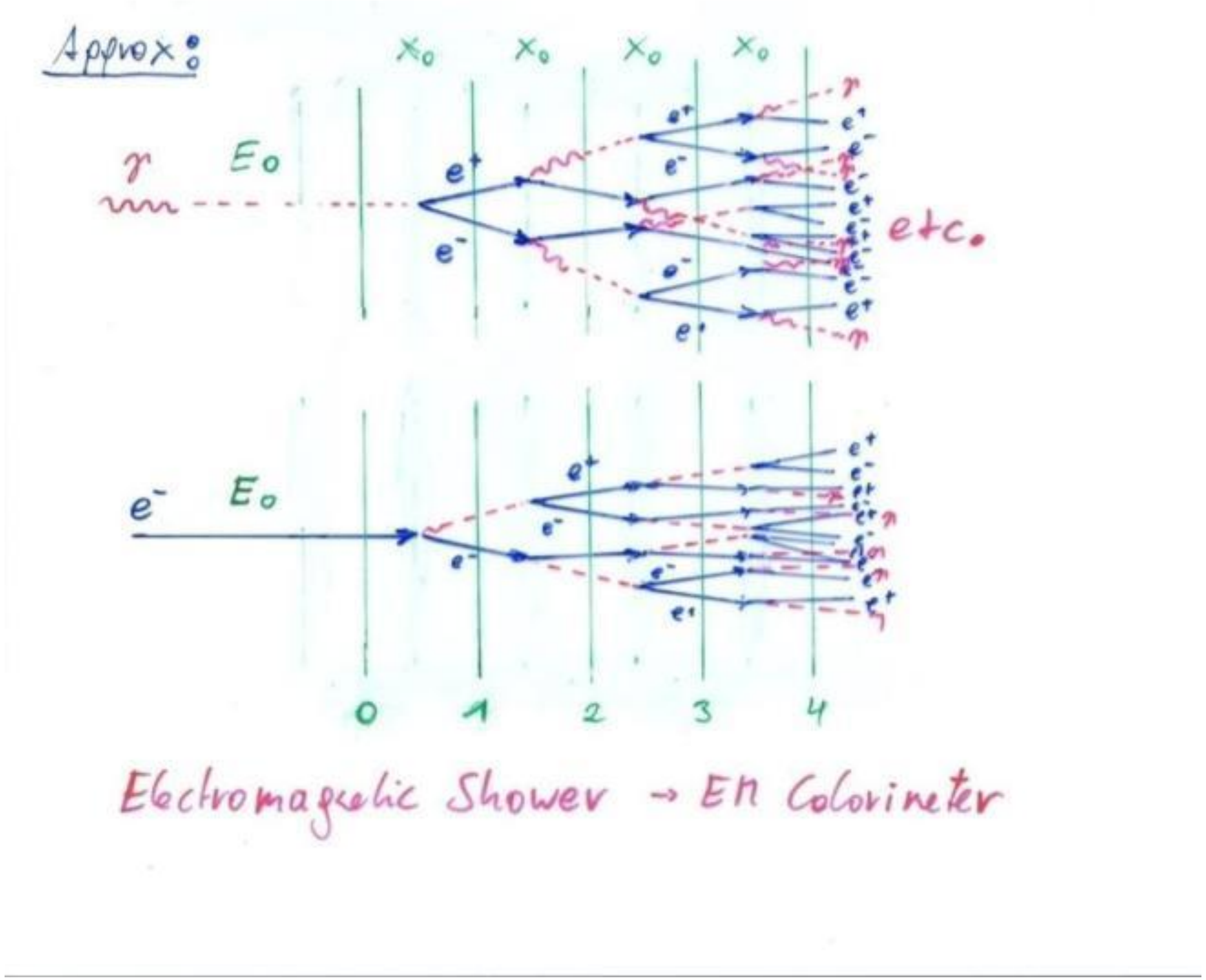
Detector Systems

Calorimetry

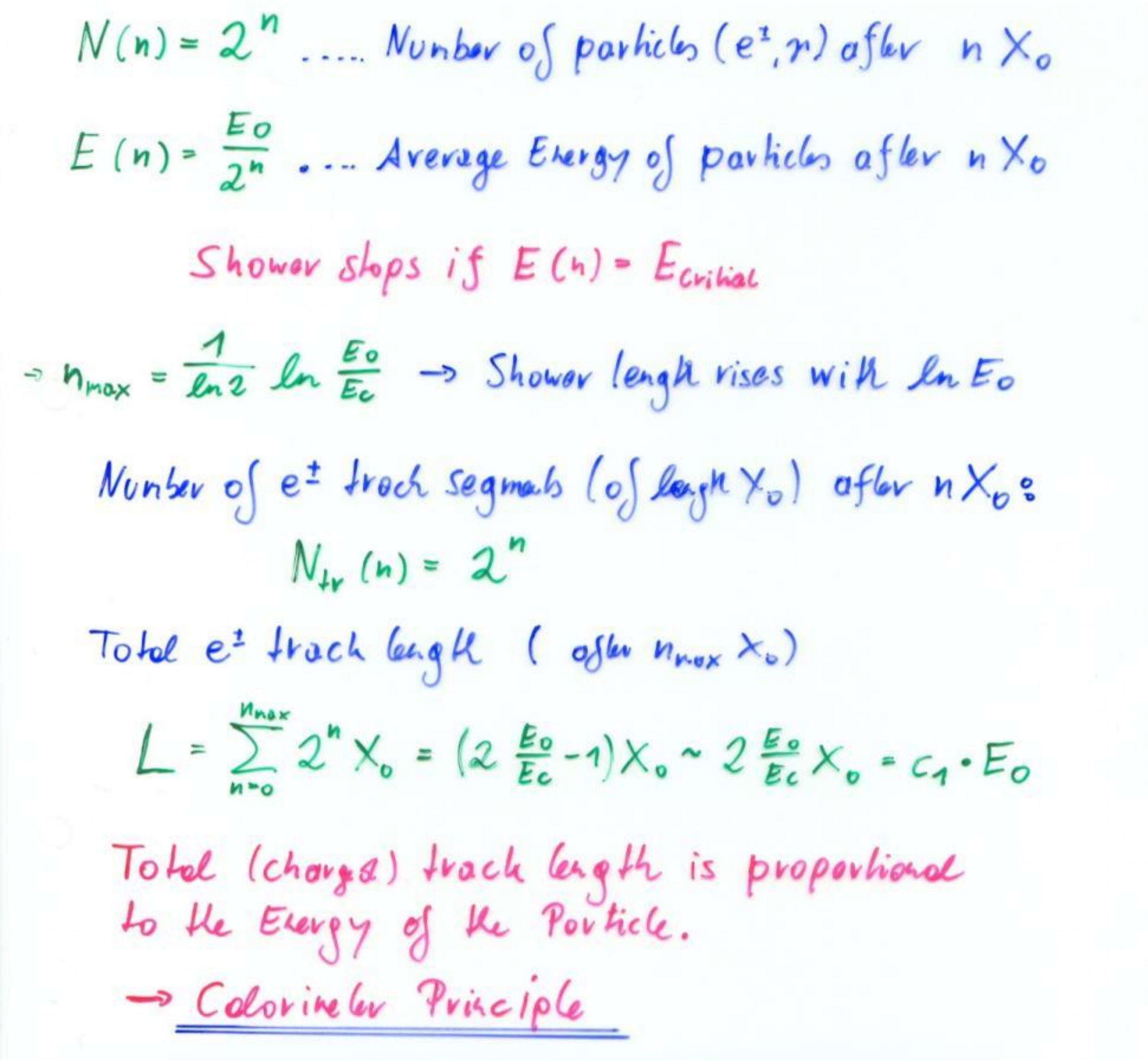




Bremsstrahlung + Pair Production → EM Shower



Electro-Magnetic Shower of High Energy Electrons and Photons



$N(n) = 2^n$ ….. Number of particles ($e^\pm, \gamma$) after $n X_0$

$E(n) = \frac{E_0}{2^n}$ …. Average Energy of particles after $n X_0$

Shower stops if $E(n) = E_{critical}$

→ $n_{max} = \frac{1}{\ln 2} \ln \frac{E_0}{E_c}$ → Shower length rises with $\ln E_0$

Number of $e^\pm$ track segments (of length X_0) after $n X_0$:

$$N_{tr}(n) = 2^n$$

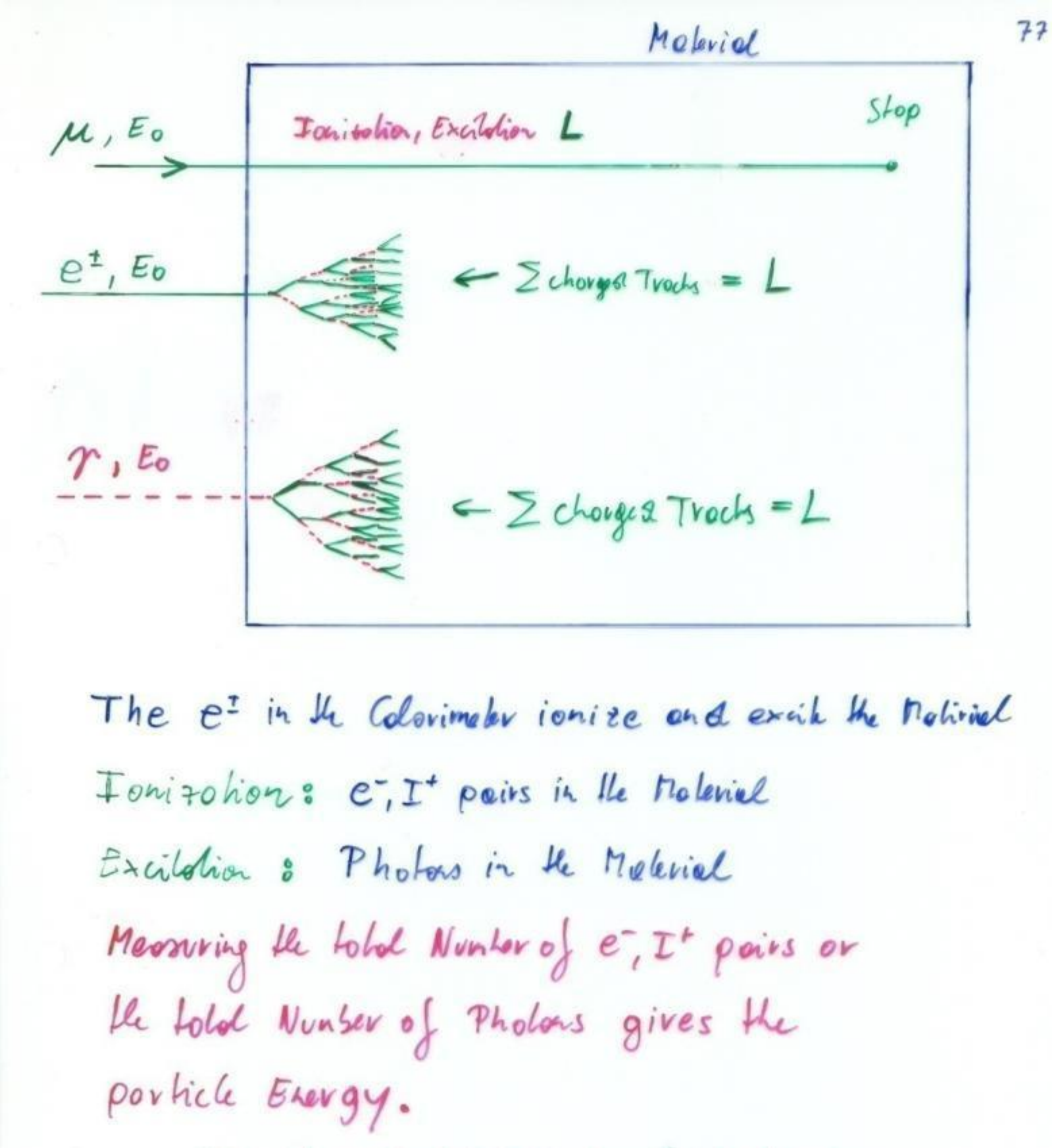
Total $e^\pm$ track length (after $n_{max} X_0$)

$$L = \sum_{n=0}^{n_{max}} 2^n X_0 = \left(2\frac{E_0}{E_c} - 1\right) X_0 \sim 2\frac{E_0}{E_c} X_0 = c_1 \cdot E_0$$

Total (charged) track length is proportional to the Energy of the Particle.

→ Calorimeter Principle

Calorimetry: Energy Measurement by total Absorption of Particles

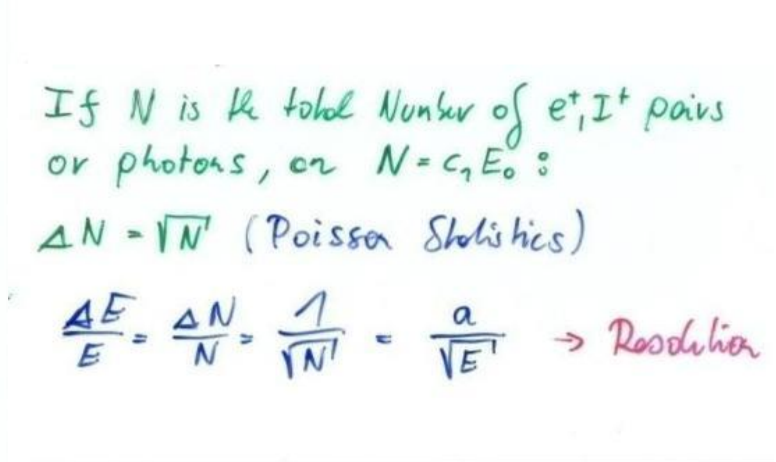


The $e^\pm$ in the Calorimeter ionize and excite the Material

Ionization: e^-, I^+ pairs in the Material

Excitation: Photons in the Material

Measuring the total Number of e^-, I^+ pairs or the total Number of Photons gives the particle Energy.



If N is the total Number of e^+, I^+ pairs or photons, or $N = c_1 E_0$:

$\Delta N = \sqrt{N}$ (Poisson Statistics)

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{a}{\sqrt{E}} \rightarrow \text{Resolution}$$

Only Electrons and High Energy Photons show EM cascades at current GeV-TeV level Energies.

Strongly interacting particles like Pions, Kaons, produce hadonic showers in a similar fashion to the EM cascade
→Hadronic calorimetry

Momentum Spectrometer: Δp/p α p

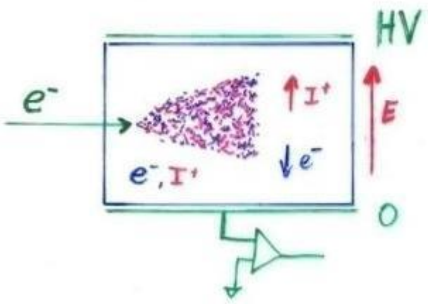
Calorimeter: Δ E/E α 1/ √ E

Energy measurement improves with higher particle energies – LHC !

Calorimetry: Energy Measurement by total Absorption of Particles

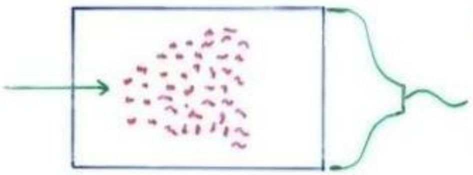
The Measurement is destructive. The particle can not be subject to further study.

Energy Measurement by



Collecting the produced Charge

Liquid Nobel Gases
(Nobel Liquids)



Measuring the Photons produced by the collision of the e± with Atom Electrons of the Material.

Scintillating Crystals,
Plastic Scintillators

Total Amount of e^-, I^+ pairs or Photons is proportional to the total track length is proportional to the particle Energy.

Calorimetry

Calorimeters can be classified into:

Electromagnetic Calorimeters,
to measure electrons and photons through their EM interactions.

Hadron Calorimeters,
Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

Homogeneous Calorimeters,
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

Sampling Calorimeters,
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

Calorimetry

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.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

EM Calorimetry

Approximate longitudinal shower development

$N(n) = 2^n$ .... Number of particles $(e^\pm, \gamma)$ after $n\,X_0$

$E(n) = \frac{E_0}{2^n}$ ... Average Energy of particles after $n\,X_0$

Shower stops if $E(n) = E_{critical}$

$\rightarrow n_{max} = \frac{1}{\ln 2} \ln \frac{E_0}{E_c}$ → Shower length rises with $\ln E_0$

Radiation Length X_0 and Moliere Radius are two key parameters for choice of calorimeter materials

Approximate transverse shower development

The transverse Shower Dimension is mainly related to the Multiple scattering of the low Energy Electrons.

$$\theta_0 \sim \frac{21\,[\mathrm{MeV}]}{\beta\, p\left[\frac{\mathrm{MeV}}{c}\right]}\, z_1 \cdot \sqrt{\frac{x}{X_0}}$$

Electrons E_c , $E \sim p \cdot c$

$$\theta_0 \sim \frac{21\,[\mathrm{MeV}]}{\beta\, E_c\,[\mathrm{MeV}]} \cdot z_1 \cdot \sqrt{\frac{x}{X_0}} \qquad z_1 = 1,\ \beta \sim 1$$

$$E_c \sim \frac{610}{Z+1.24}\,\mathrm{MeV} \sim \frac{610}{Z}\,\mathrm{MeV}$$

$$\theta_0 = 0.0344 \cdot Z \cdot \sqrt{\frac{x}{X_0}}$$

Moliere Radius ρ_M = Lateral Shower Radius after $1\,X_0$:

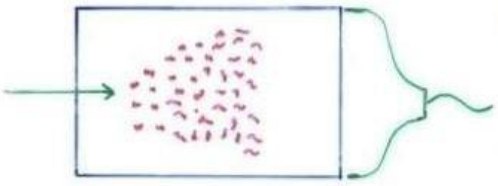
$$\underline{\underline{\rho_M \approx 0.0344 \cdot Z \cdot X_0}}$$

95% of Energy are in a Cylinder of $2\rho_M$ Radius.

Crystals for Homogeneous EM Calorimetry

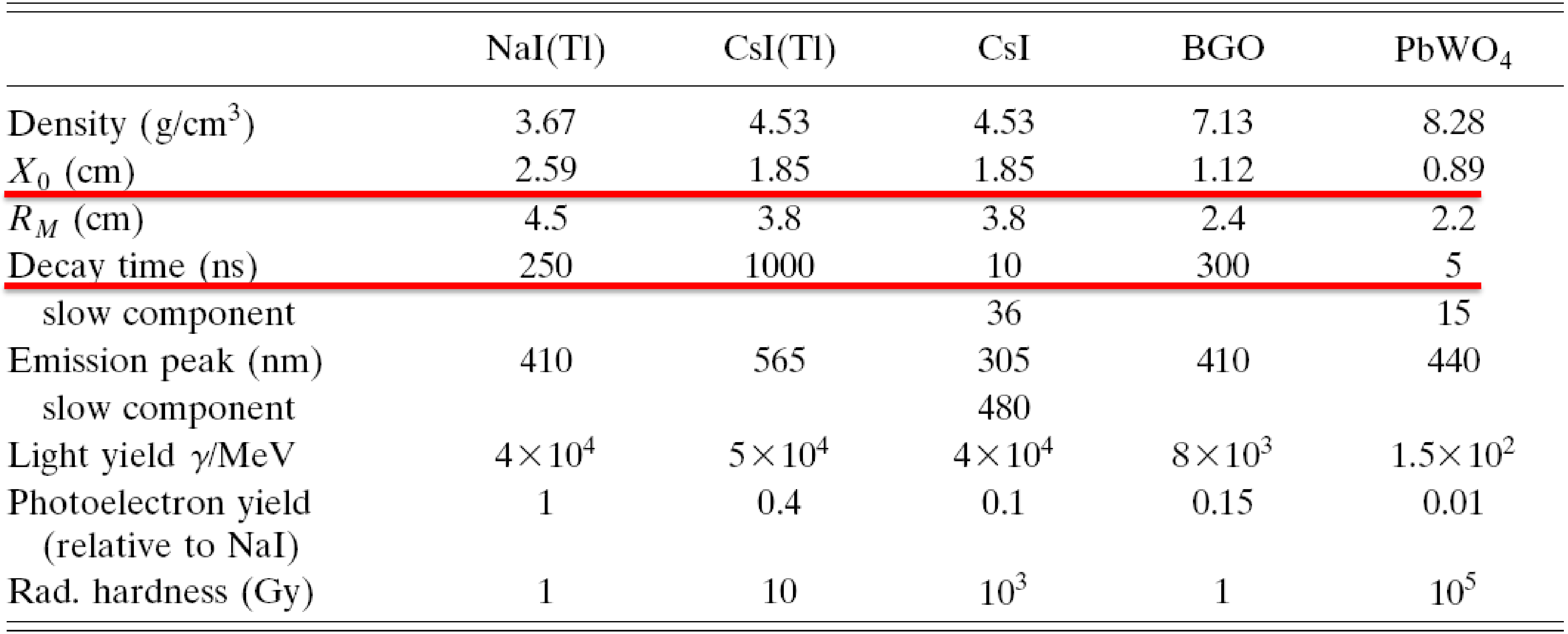
In crystals the light emission is related to the crystal structure of the material. Incident charged particles create electron-hole pairs and photons are emitted when electrons return to the valence band.

The incident electron or photon is completely absorbed and the produced amount of light, which is reflected through the transparent crystal, is measured by photomultipliers or solid state photon detectors.



Measuring the Photons
produced by the collision
of the $e^\pm$ with Atom Electrons
of the Material.

Crystals for Homogeneous EM Calorimetry



	NaI(Tl)	CsI(Tl)	CsI	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.53	4.53	7.13	8.28
X_0 (cm)	2.59	1.85	1.85	1.12	0.89
R_M (cm)	4.5	3.8	3.8	2.4	2.2
Decay time (ns)	250	1000	10	300	5
slow component			36		15
Emission peak (nm)	410	565	305	410	440
slow component			480		
Light yield γ/MeV	4×10^4	5×10^4	4×10^4	8×10^3	1.5×10^2
Photoelectron yield (relative to NaI)	1	0.4	0.1	0.15	0.01
Rad. hardness (Gy)	1	10	10^3	1	10^5

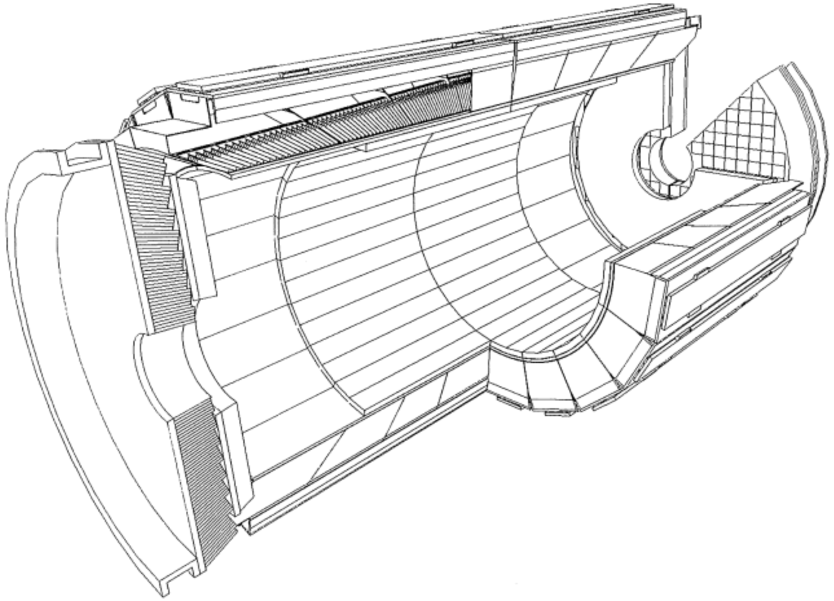
Barbar@PEPII, 10ms interaction rate, good light yield, good S/N

KTeV@Tevatron, High rate, Good resolution

L3@LEP, 25us bunch crossing, Low radiation dose

CMS@LHC, 25ns bunch crossing, high radiation dose

Crystals for Homogeneous EM Calorimetry



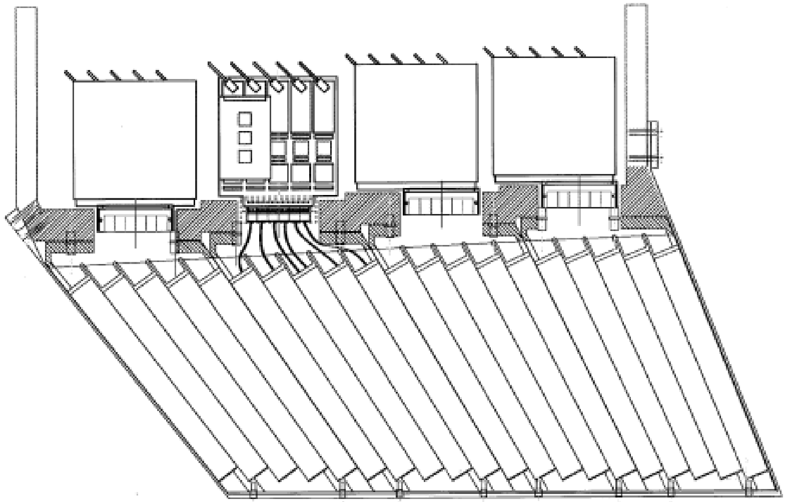
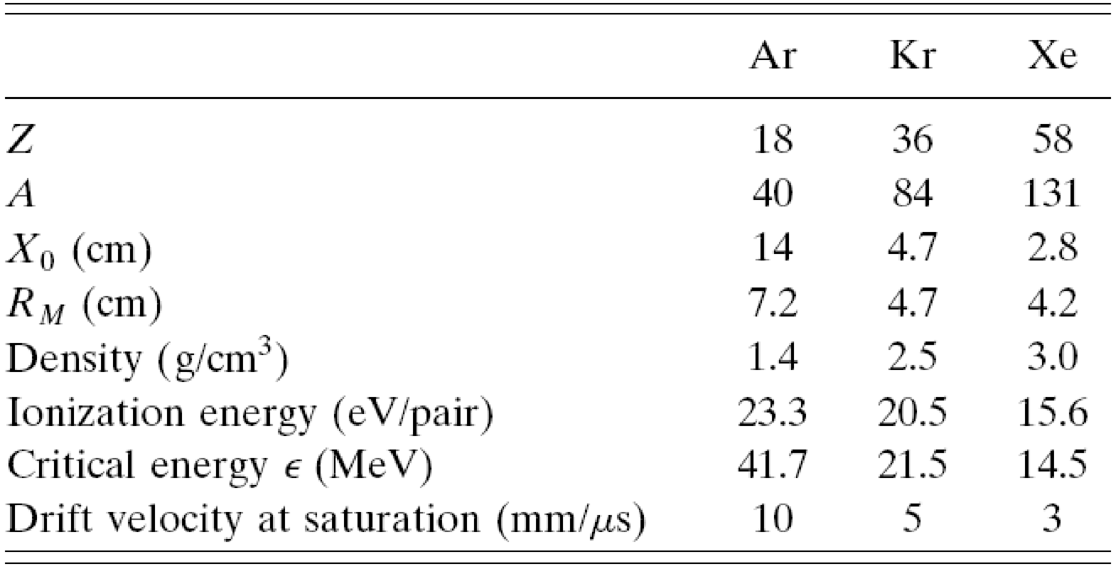
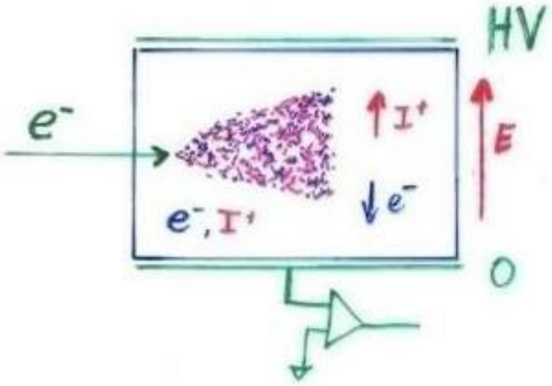


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Noble Liquids for Homogeneous EM Calorimetry



	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.8
R_M (cm)	7.2	4.7	4.2
Density (g/cm^3)	1.4	2.5	3.0
Ionization energy (eV/pair)	23.3	20.5	15.6
Critical energy ϵ (MeV)	41.7	21.5	14.5
Drift velocity at saturation (mm/μs)	10	5	3

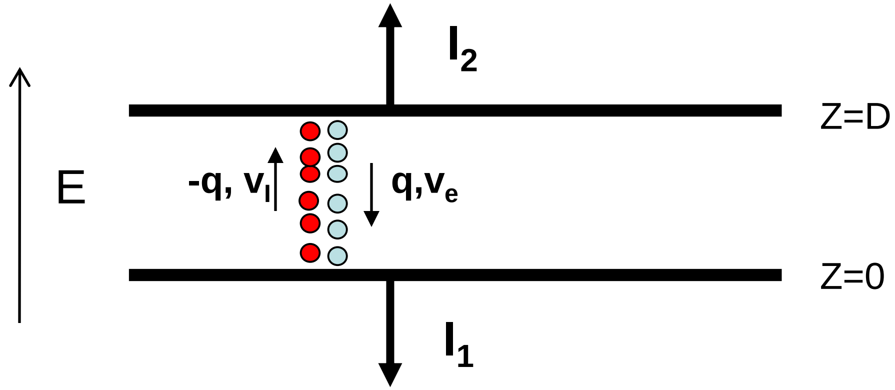


When a charge particle traverses these materials, about half the lost energy is converted into ionization and half into scintillation.

The best energy resolution would obviously be obtained by collecting both the charge and light signal. This is however rarely done because of the technical difficulties to extract light and charge in the same instrument.

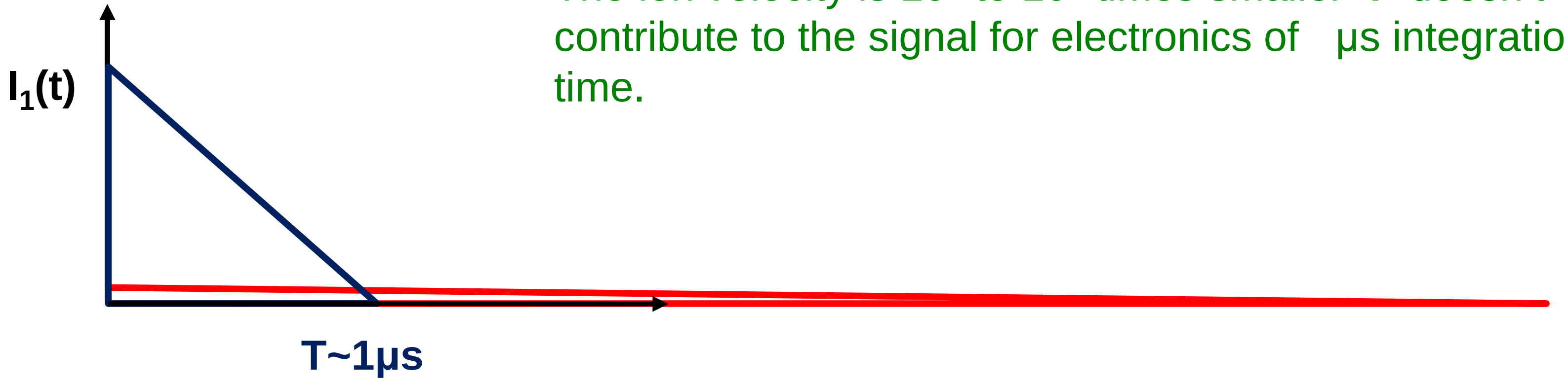
Krypton is preferred in homogeneous detectors due to small radiation length and therefore compact detectors. Liquid Argon is frequently used due to low cost and high purity in sampling calorimeters.

Noble Liquids for Homogeneous EM Calorimetry



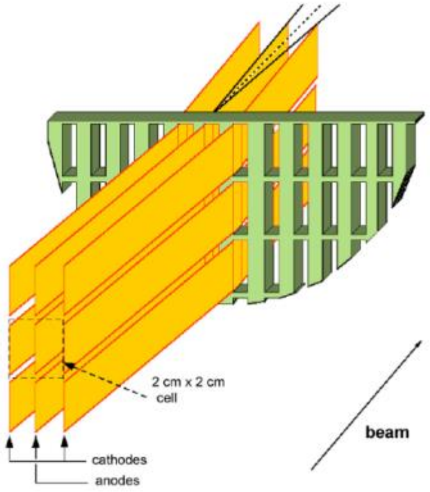
E.g. Liquid Argon, 5mm/ μs at 1kV/cm, 5mm gap → 1 μs for all electrons to reach the electrode.

The ion velocity is 10^3 to 10^5 times smaller → doesn't contribute to the signal for electronics of μs integration time.



Homogeneous EM Calorimeters, Examples

NA48/62 Liquid Krypton
2cmx2cm cells
X_0 = 4.7cm
125cm length ($27X_0$)
ρ = 5.5cm



KTeV CsI
5cmx5cm and
X_0 = 1.85cm
2.5cmx2.5cm crystals
50cm length ($27X_0$)
ρ = 3.5cm

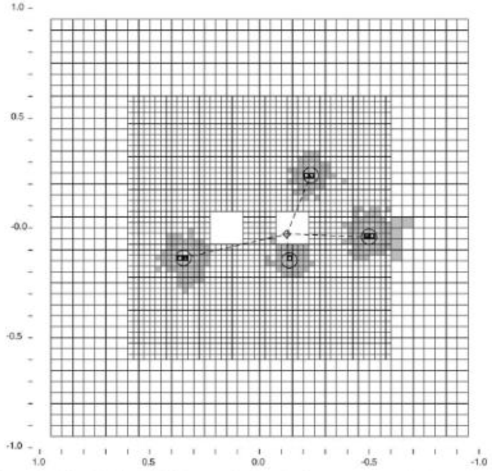
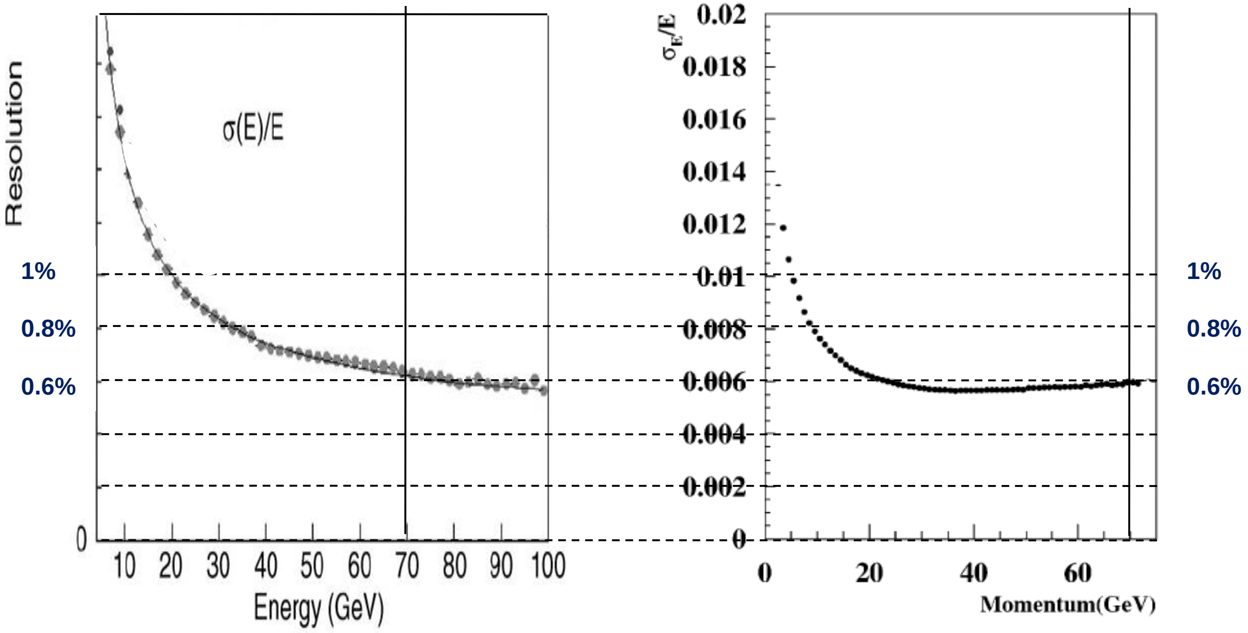
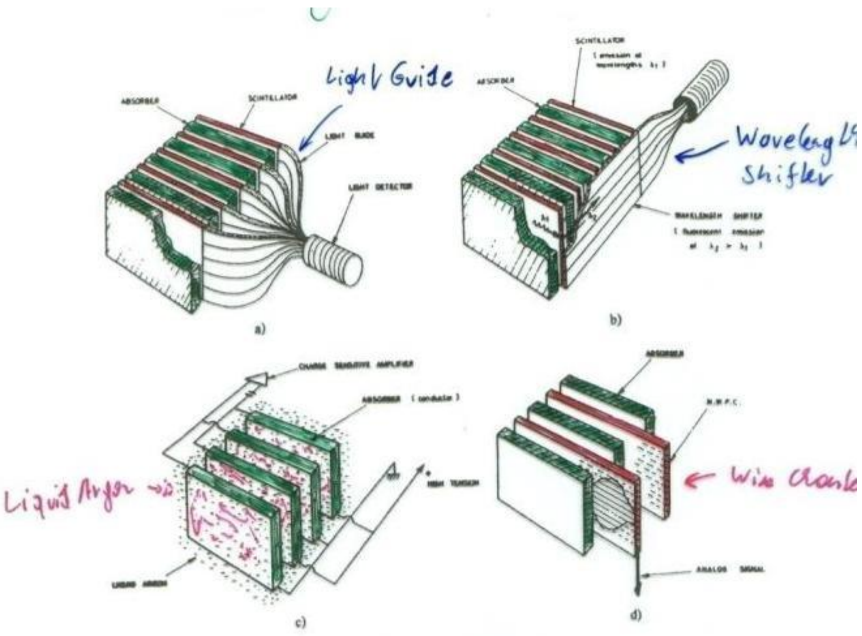


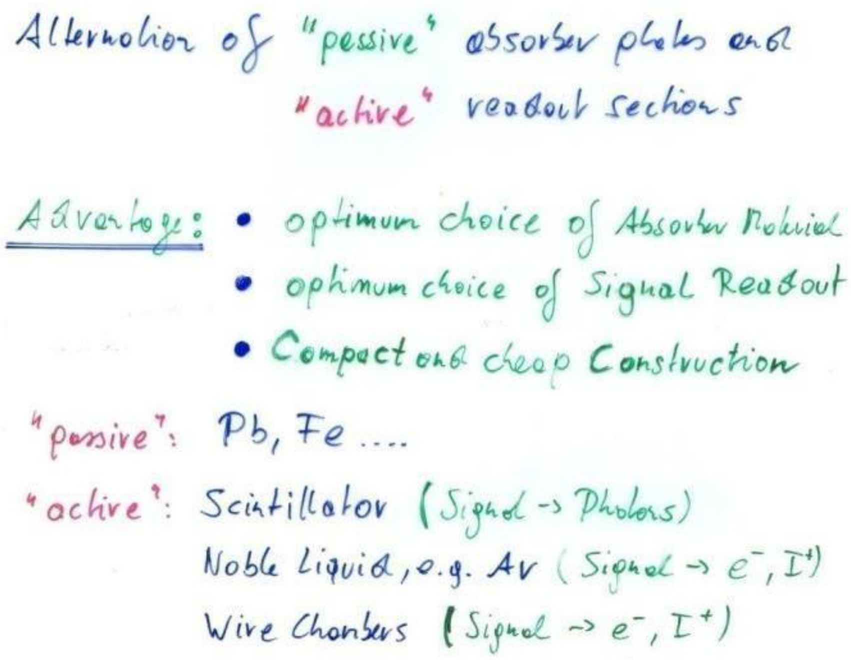
Fig. 1. Schematic of the KTeV CsI Calorimeter showing the cluster energy profiles due to four photons.

NA48 Experiment at CERN and KTeV Experiment at Fermilab, both built for measurement of direct CP violation. Homogenous calorimeters with Liquid Krypton (NA48) and CsI (KTeV). Excellent and very similar resolution.



Sampling Calorimeters





Alternation of "passive" absorber plates and "active" readout sections

Advantage:
- optimum choice of Absorber Material
- optimum choice of Signal Readout
- Compact and cheap Construction

"passive": Pb, Fe ....

"active": Scintillator (Signal -> Photons)

Noble Liquid, e.g. Ar (Signal -> e^-, I^+)

Wire Chambers (Signal -> e^-, I^+)

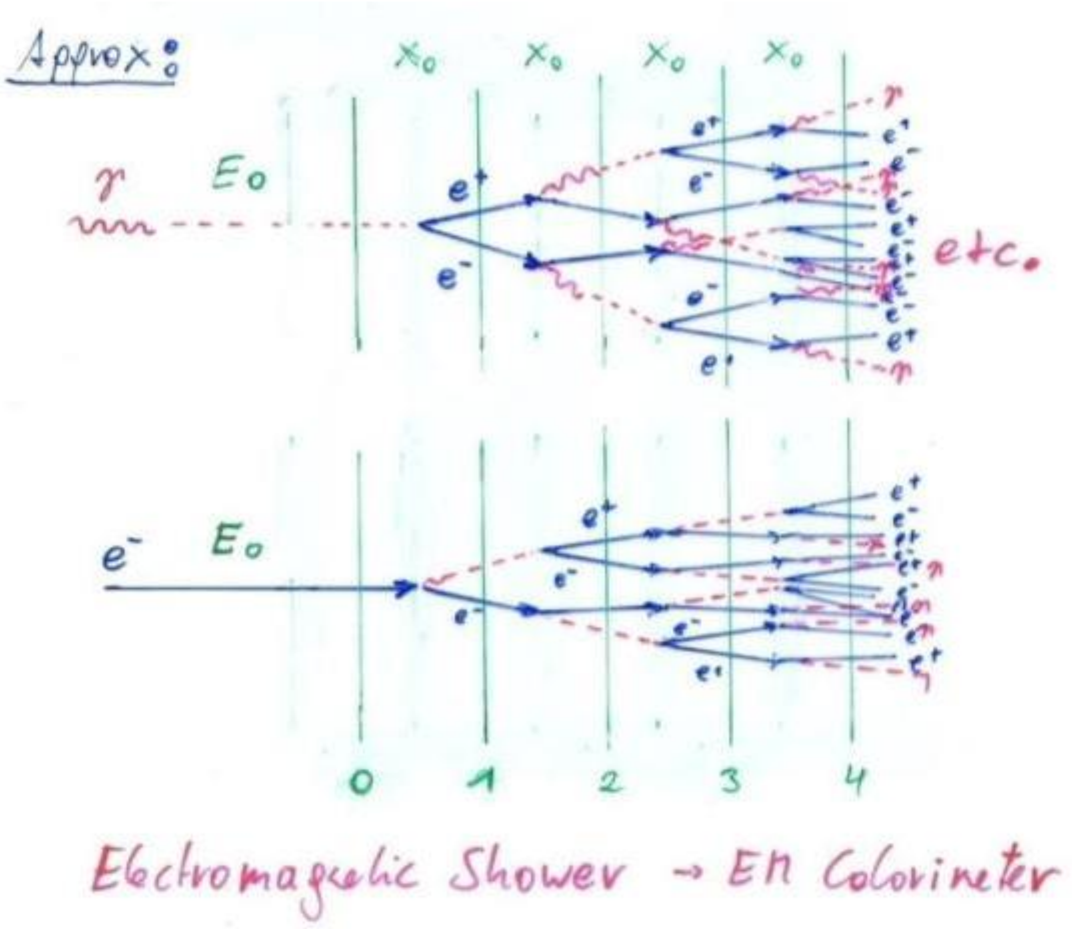
Energy resolution of sampling calorimeters is in general worse than that of homogeneous calorimeters, owing to the sampling fluctuations – the fluctuation of ratio of energy deposited in the active and passive material.

The resolution is typically in the range 5-20%/Sqrt[E(GeV)] for EM calorimeters. On the other hand they are relatively easy to segment longitudinally and laterally and therefore they usually offer better space resolution and particle identification than homogeneous calorimeters.

The active medium can be scintillators (organic), solid state detectors, gas detectors or liquids.

Sampling Fraction = Energy deposited in Active/Energy deposited in passive material.

EM Calorimetry → Hadron Calorimetry

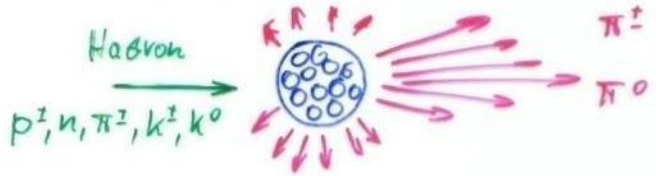


Similar process for Hadrons.

The equivalent to EM Bremsstrahlung is Pion radiation.

The equivalent to the radiation length is the nuclear interaction length.

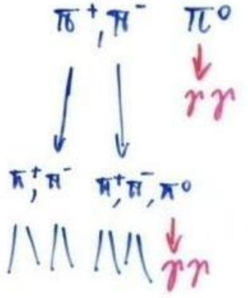
Hadronic Calorimetry



Strong Interaction

Approximate Energy Distribution

~50%	~20%	~30%
π^+, π^- $\pi^0 \to \gamma\gamma$	Nuclear Excitation 5-30 MeV p, n, γ	Slow Nucleons



Hadron kaskade

$\pi^0 \to \gamma\gamma \to$ Electromagnetic Component

In Hadronic Cascades the Longitudinal Shower is given by the Absorbtion Length λ_a $I \sim e^{-\frac{x}{\lambda_a}}$

In typical Detector Materials λ_a is much larger than X_0

$$\lambda \sim \frac{1}{\rho} \cdot 35\, A^{\frac{1}{3}}$$

	ρ	X_0	λ
Fe	7.87	1.76 cm	~17 cm
Pb	11.35	0.56 cm	~17 cm

Energy Resolution:

- A large Fraction of the Energy 'disappears' into
  - Binding Energy of emitted Nucleons
  - $\pi \to \mu + \nu$ which are not absorbed
- π^0's Decaying into $\gamma\gamma$ start an EM Cascade ($\tau \sim 10^{-14}$ s)

– Energy Resolution is worse than for EM Calorimeters

Hadron Calorimeters are Large because λ is large

Hadron Calorimeters are large and heavy because the hadronic interaction length λ, the ‘strong interaction equivalent’ to the EM radiation length X_0, is large (5-10 times larger than X_0)

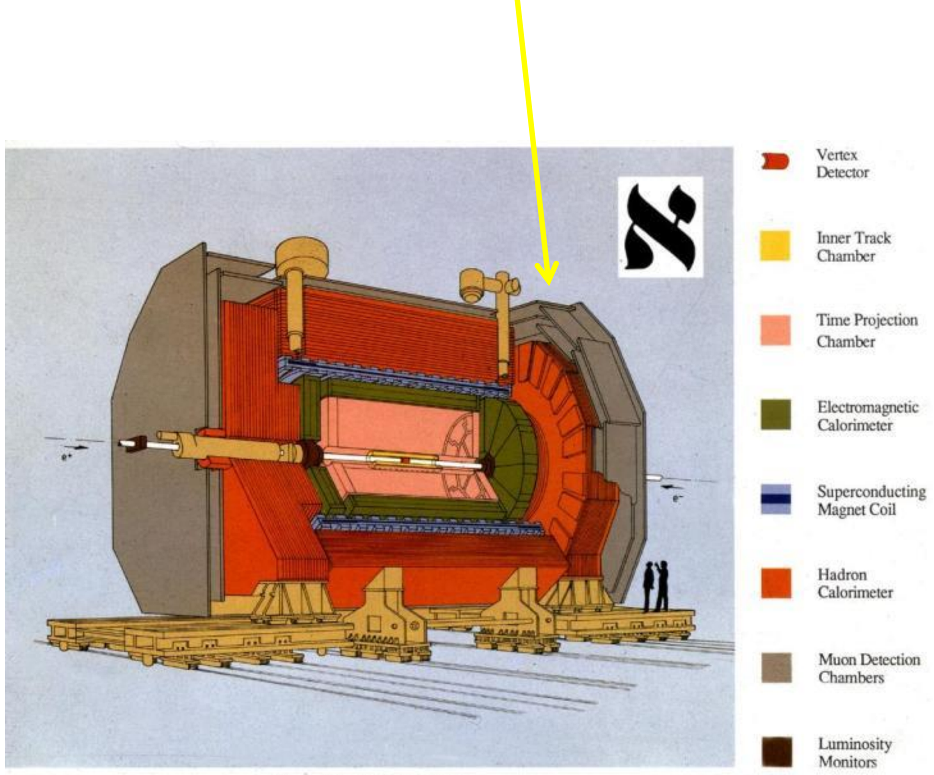
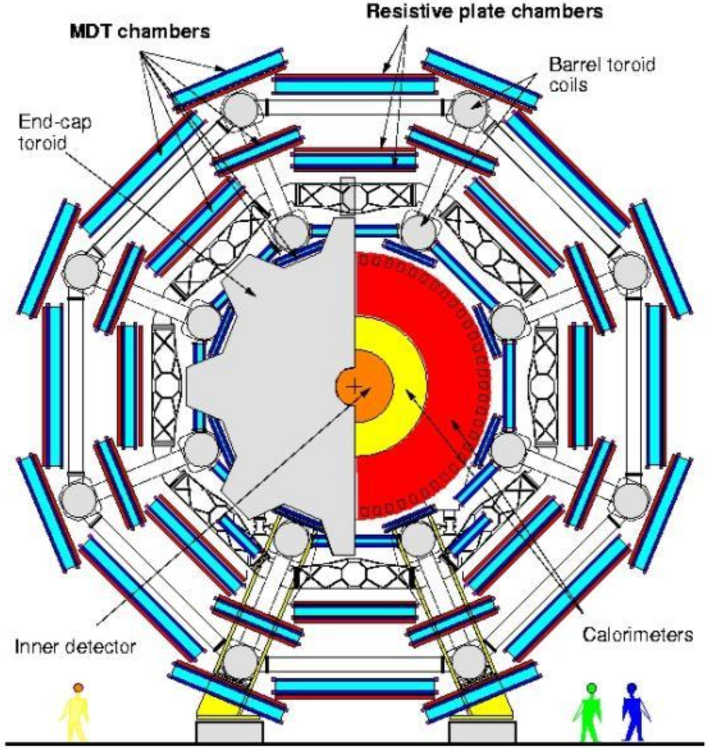


Fig. 1 - The ALEPH Detector



Because part of the energy is ‘invisible’ (nuclear excitation, slow nucleons), the resolution of hadron calorimeters is typically worse than in EM calorimeters 20-100%/√E(GeV).

A few Reasons why you want to become an Experimental Particle Physicist

The Standard Model of Particles Physics, a theory that was established in the early 1970ies, is in excellent agreement with experiments. Experiments at LEP/Tevatron/LHC/KEK etc. verified the theory to impressive precision.

The Higgs Particle, a necessary element of the standard model, was found at the LHC.

Although the standard model is perfectly fitting the experiment, we know/think that it cannot be the final answer:

CP violation and the other CKM matrix elements are put into the model explicitly and they are not derived from a theory.

The Matter- Antimatter asymmetry in the Universe cannot be explained by the level of standard model CP violation.

The masses of the particles are also unexplained.

The cosmological constant predicted by the standard model differs by many orders of magnitude from the observed one.

The Higgs mass renormalization requires fine tuning operations etc. etc.

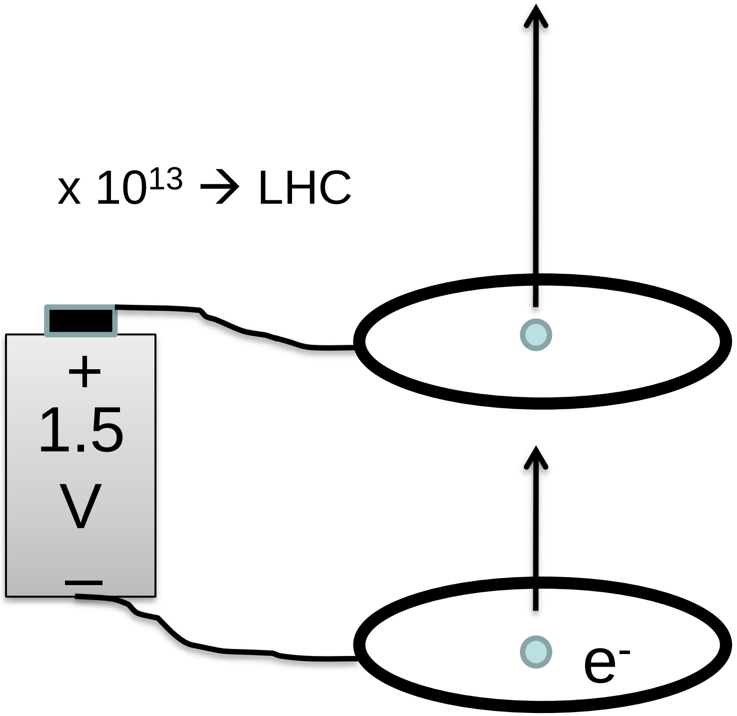
A few Reasons why you want to become an Experimental Particle Physicist

Substantial theory efforts did not really advance on these questions and did not touch base with experiment.

It is very difficult to find out what is wrong with the theory if all experimental results are in agreement with the theory.

The next step in advancing our knowledge will come from experiment. Maybe LHC or some telescope, or some astrophysics experiment or some other future accelerator …

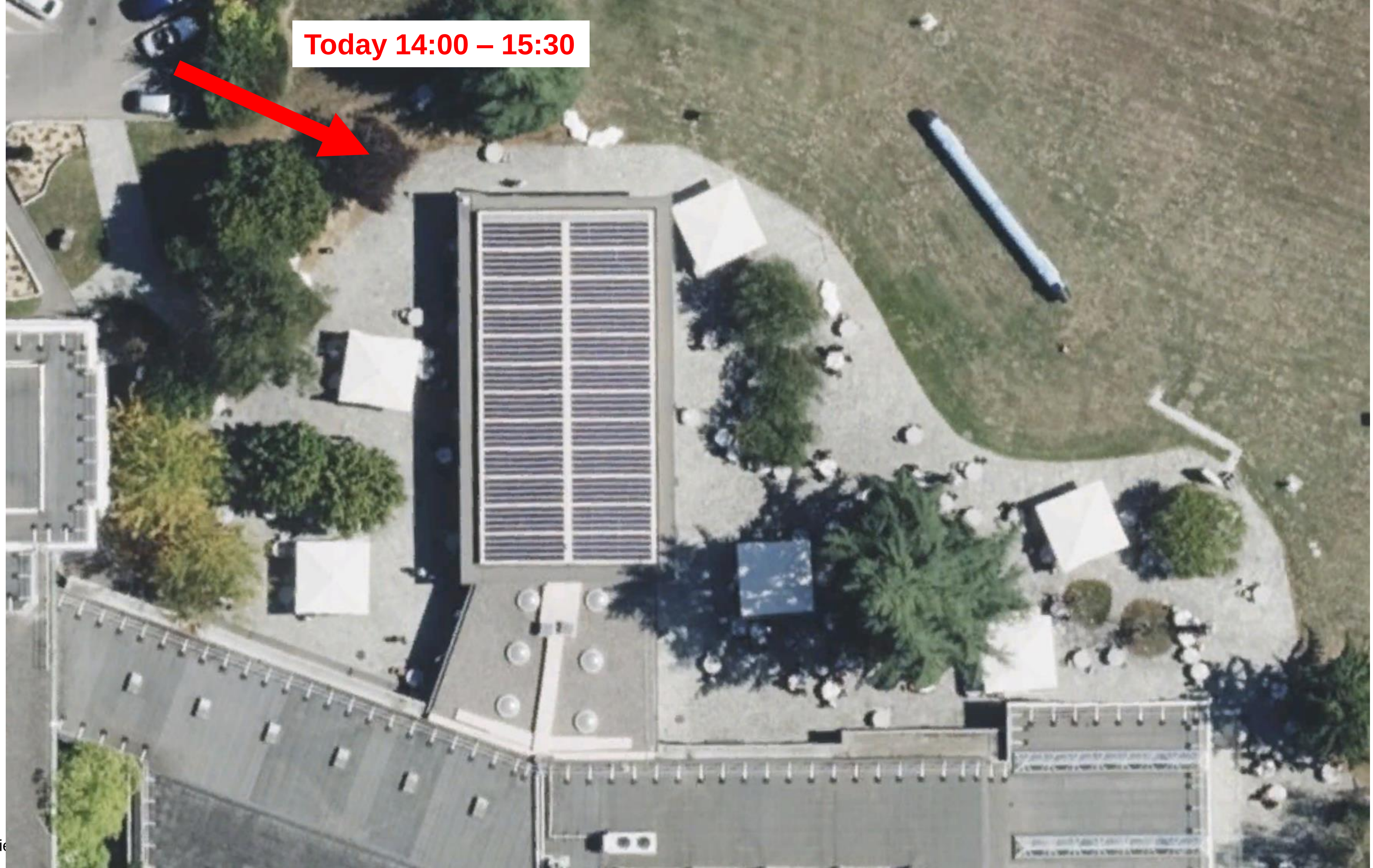
We have to invent new technologies for future accelerators and experiments !



x 10^{13} → LHC

You

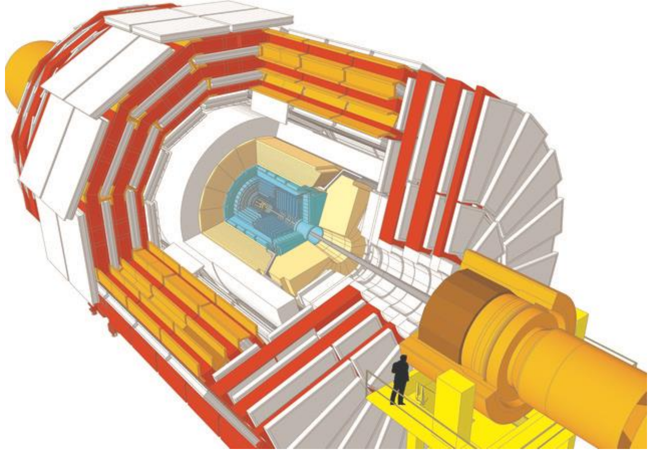
have to develop the tricks and technologies to advance on the most fundamental questions in Physics !

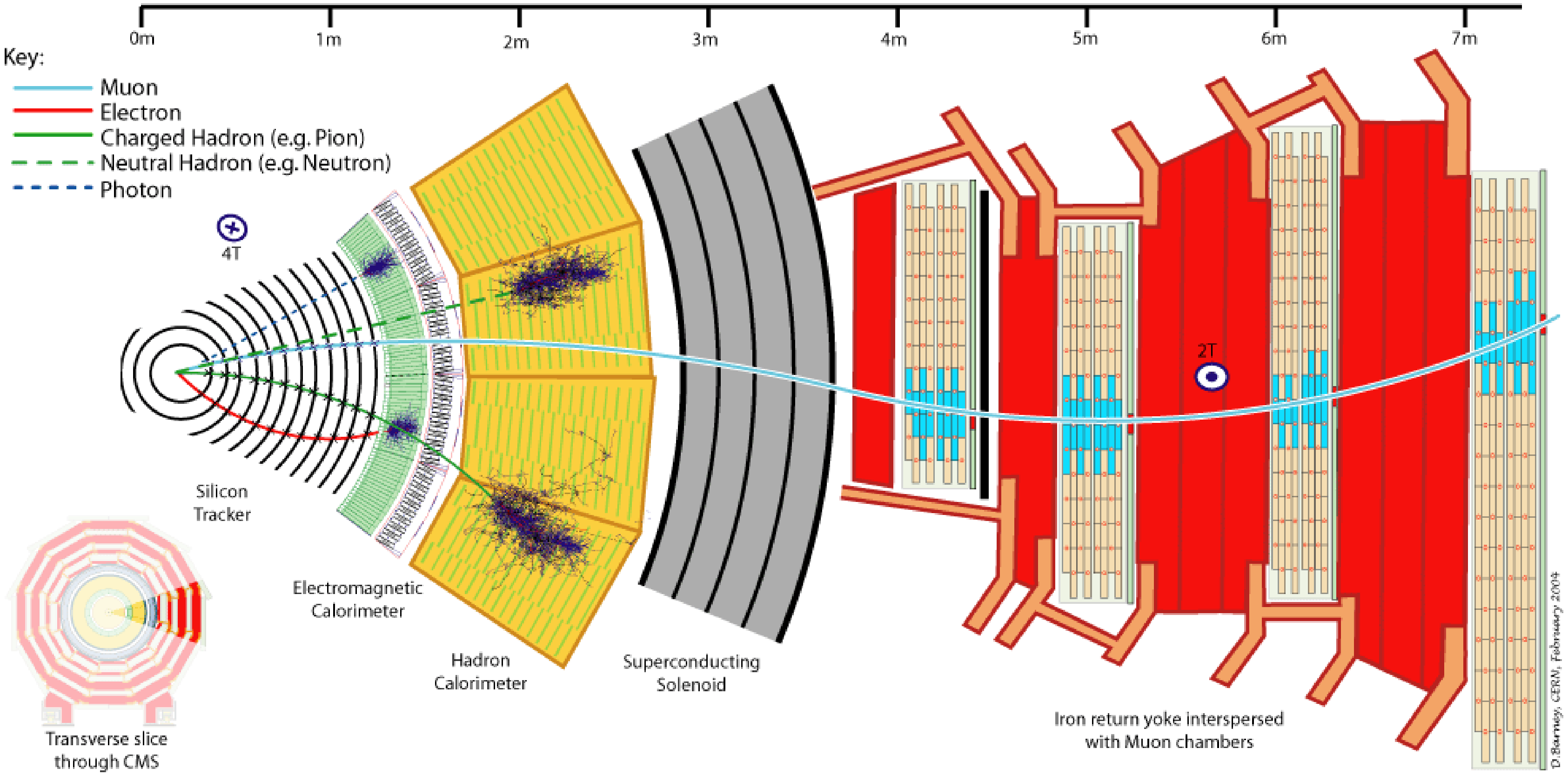


Today 14:00 – 15:30

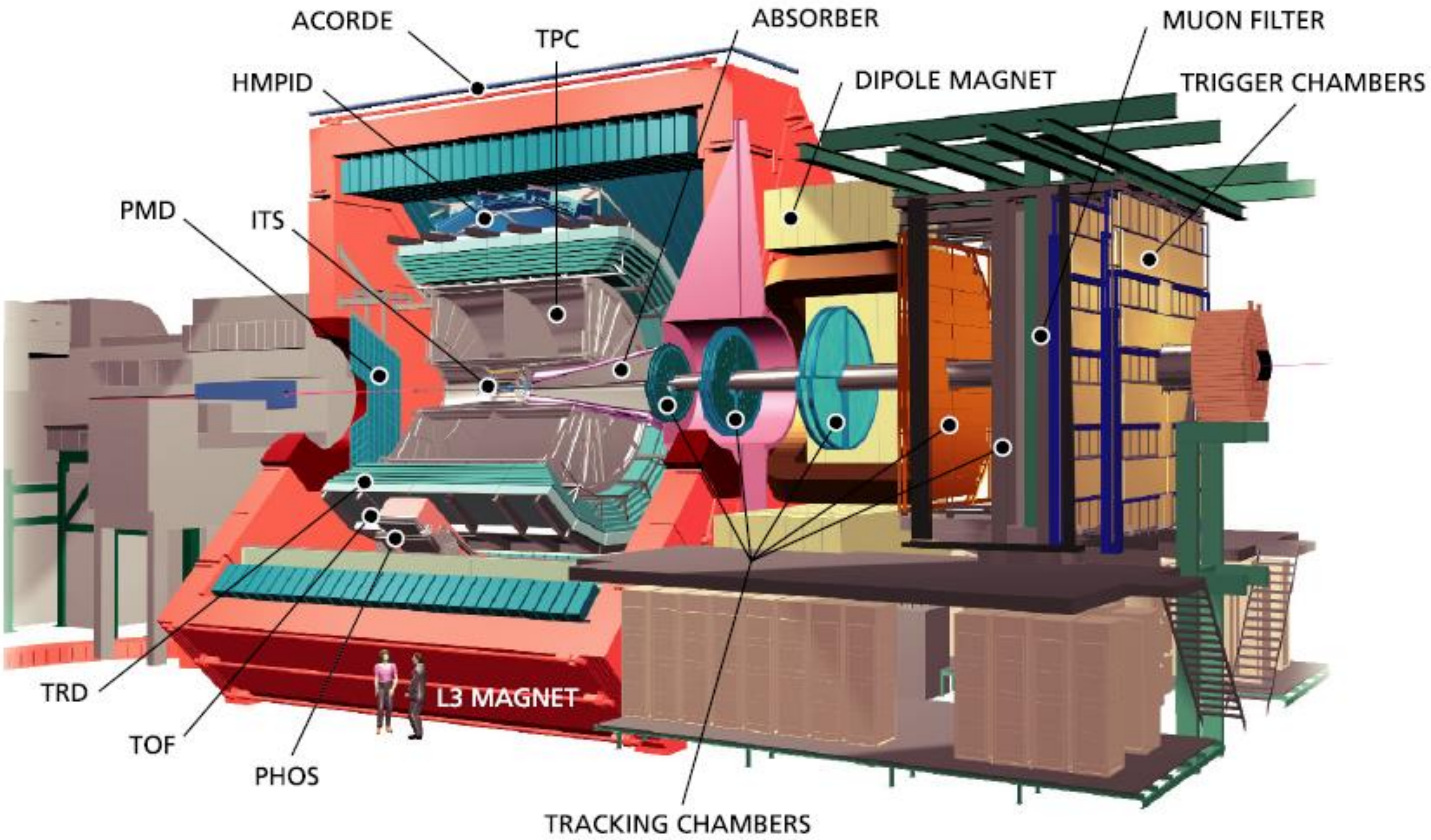
Detector Systems

CMS Detector



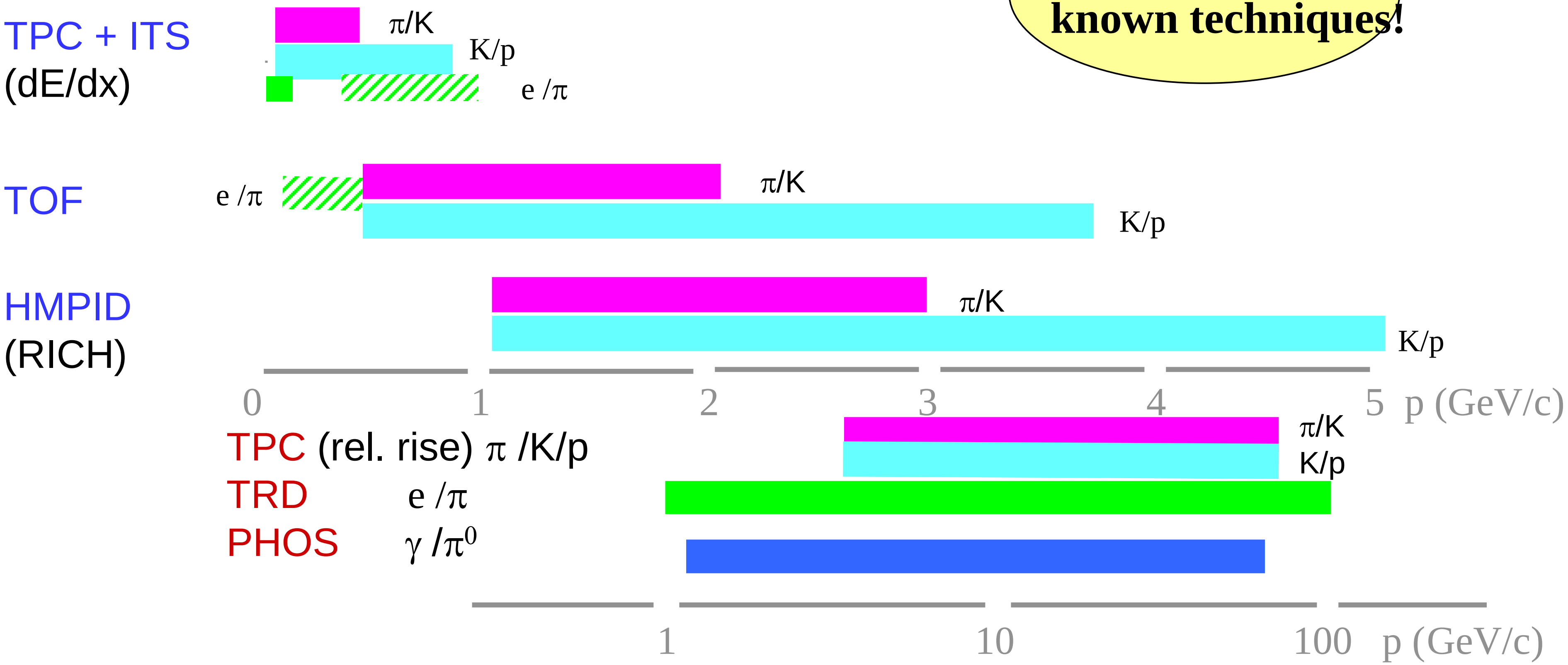


ALICE

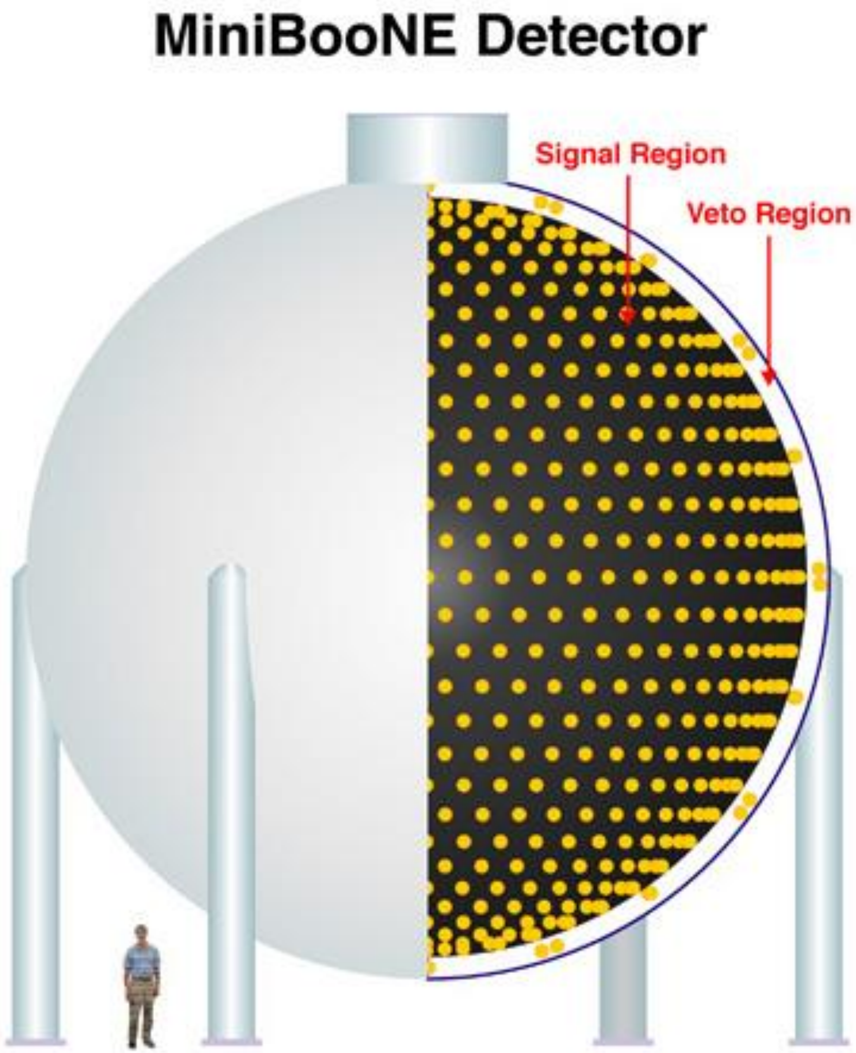

ACORDE
TPC
ABSORBER
MUON FILTER
HMPID
DIPOLE MAGNET
TRIGGER CHAMBERS
PMD
ITS
TRD
L3 MAGNET
TOF
PHOS
TRACKING CHAMBERS

ALICE Particle ID

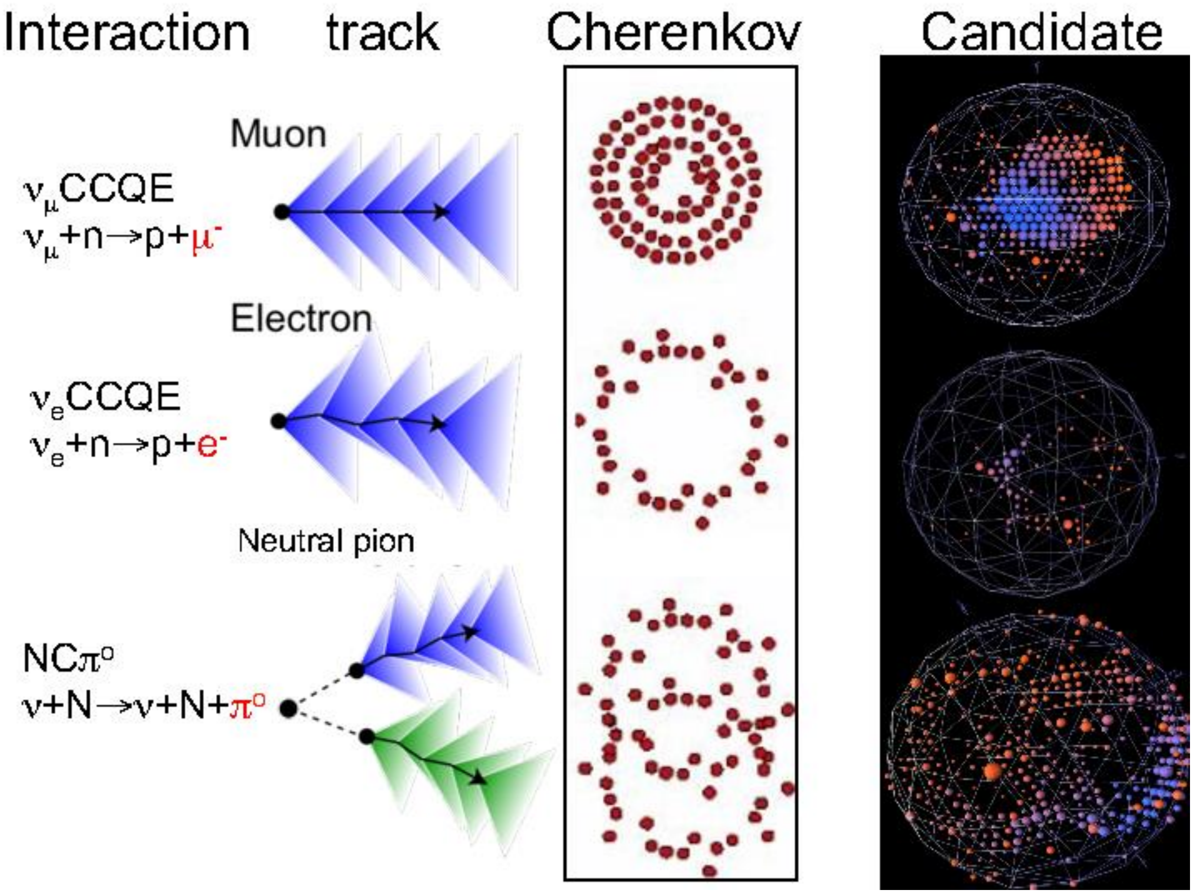
Alice uses ~ all known techniques!



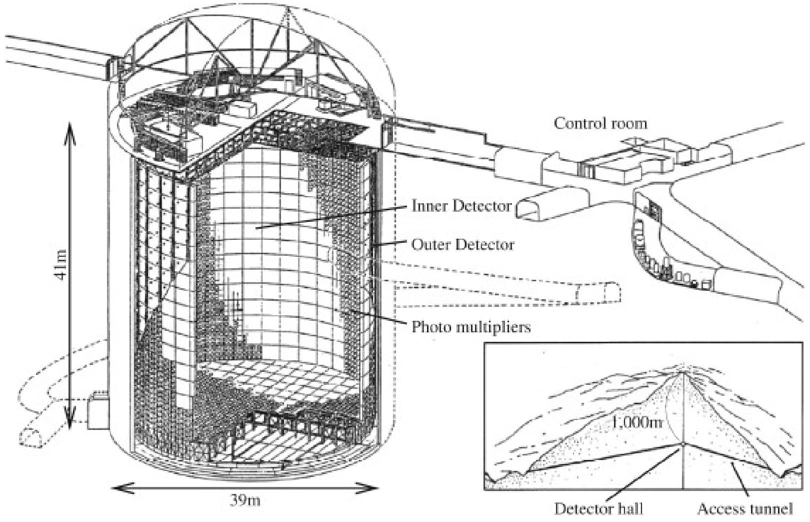
MiniBooNE detector, Neutrinos

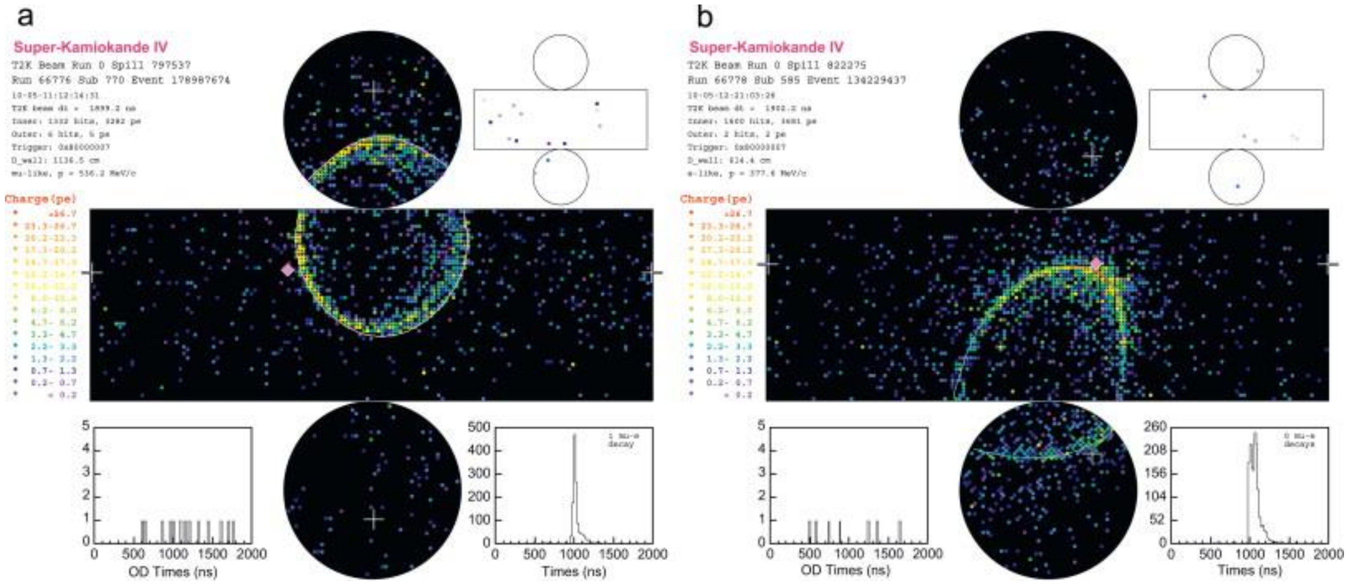


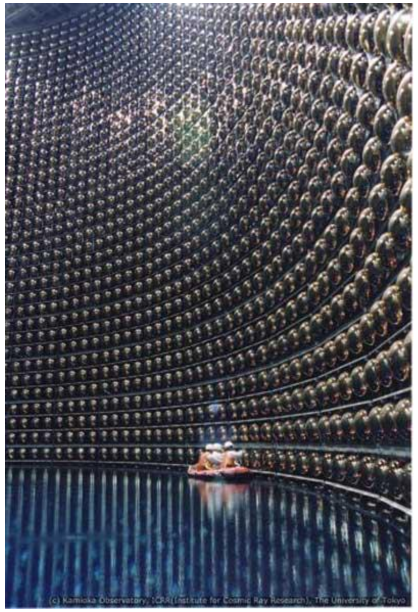
800 tons of mineral oil
1280 photomultipliers



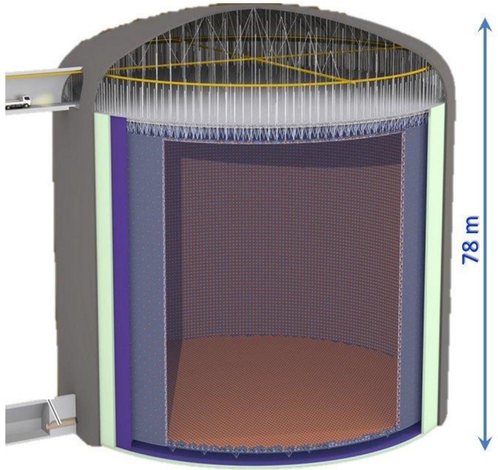
Super-Kamiokande, Neutrinos





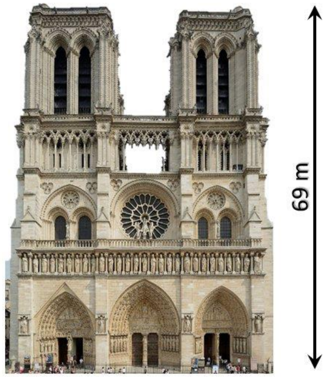


Hyper-Kamiokande



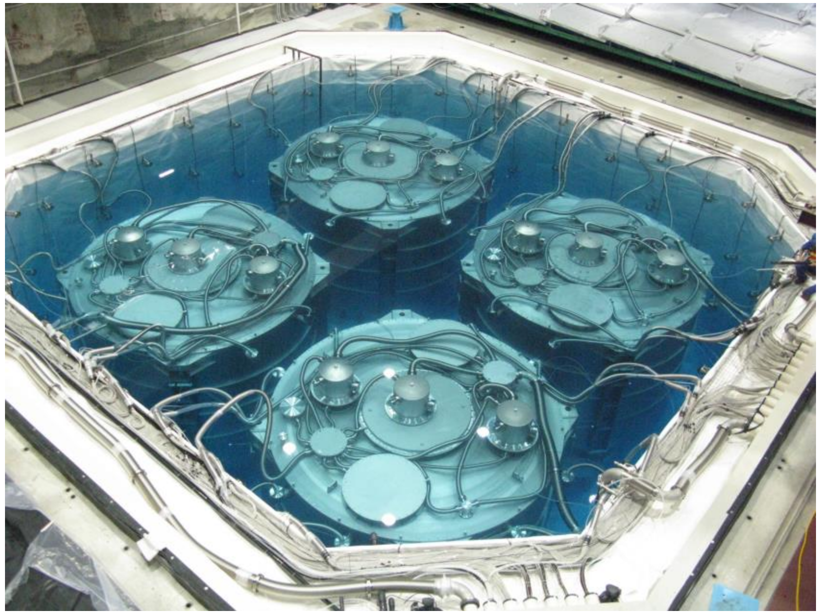
~ 260.000 m^3

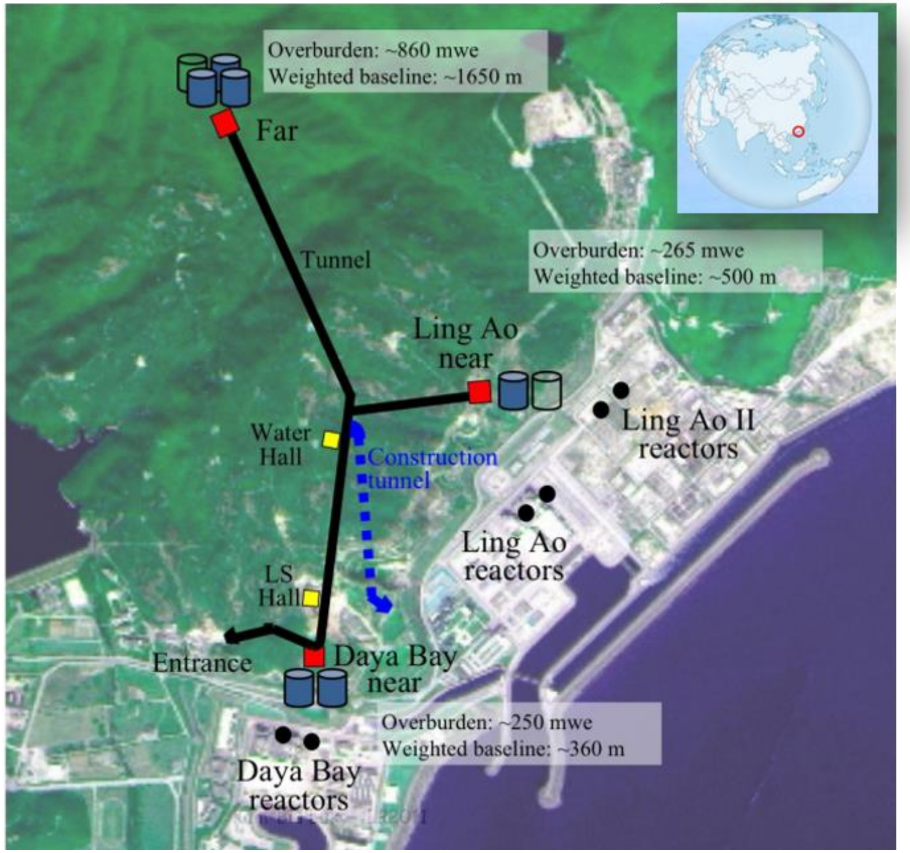
Notre-Dame de Paris



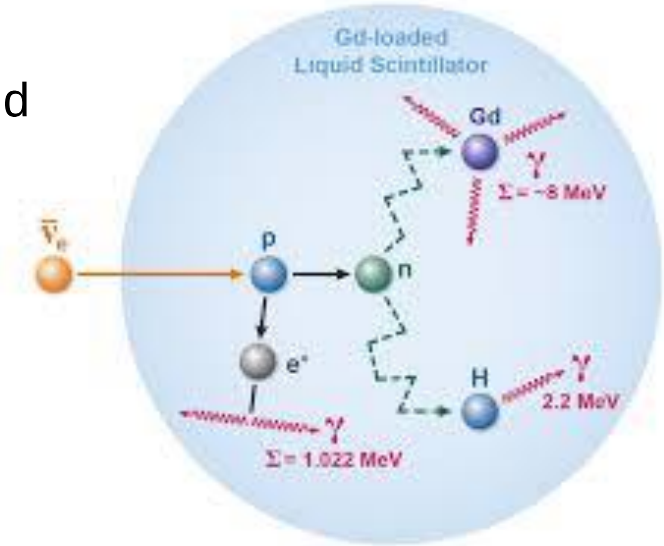
~ 180.000 m^3

Daya Bay, Neutrinos

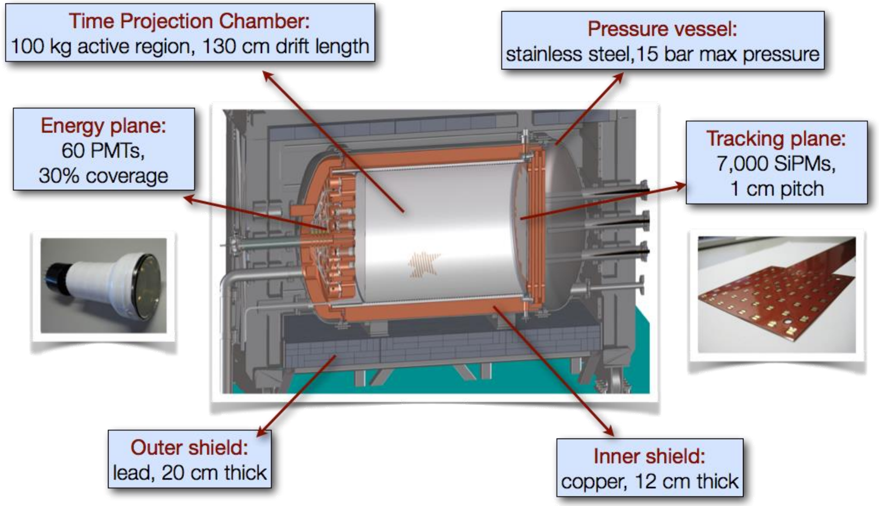




20 tons of liquid scintillator



NEXT experiment, double β decay



Time Projection Chamber: 100 kg active region, 130 cm drift length

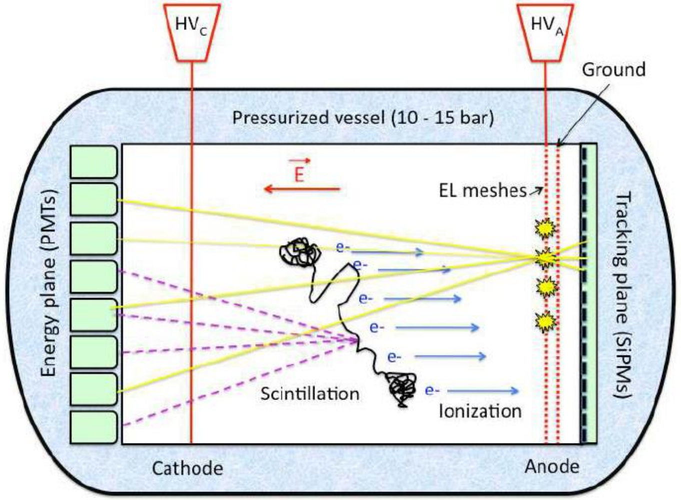
Pressure vessel: stainless steel,15 bar max pressure

Energy plane: 60 PMTs, 30% coverage

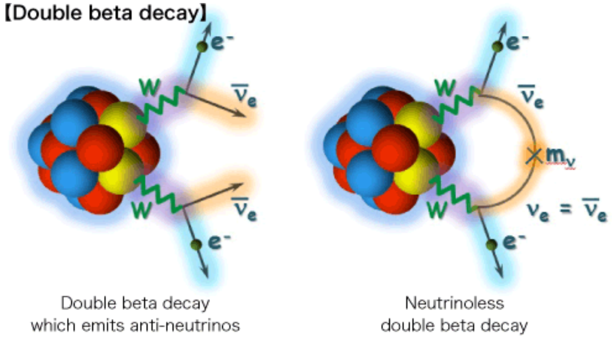
Tracking plane: 7,000 SiPMs, 1 cm pitch

Outer shield: lead, 20 cm thick

Inner shield: copper, 12 cm thick

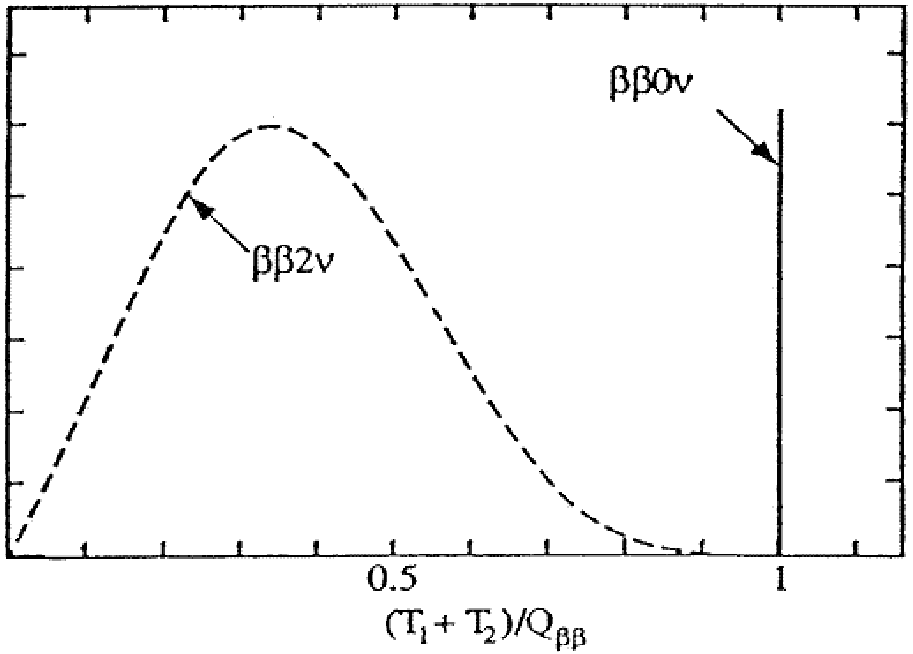


【Double beta decay】



Double beta decay which emits anti-neutrinos

Neutrinoless double beta decay

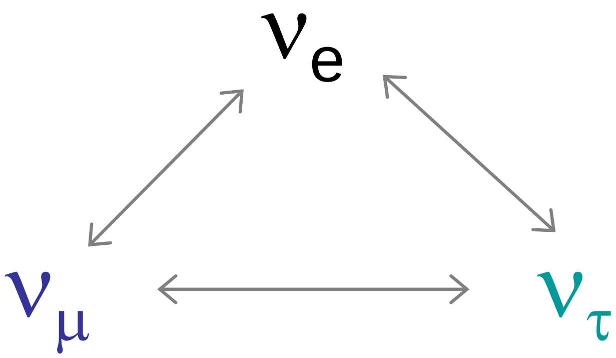


CERN Neutrino Gran Sasso

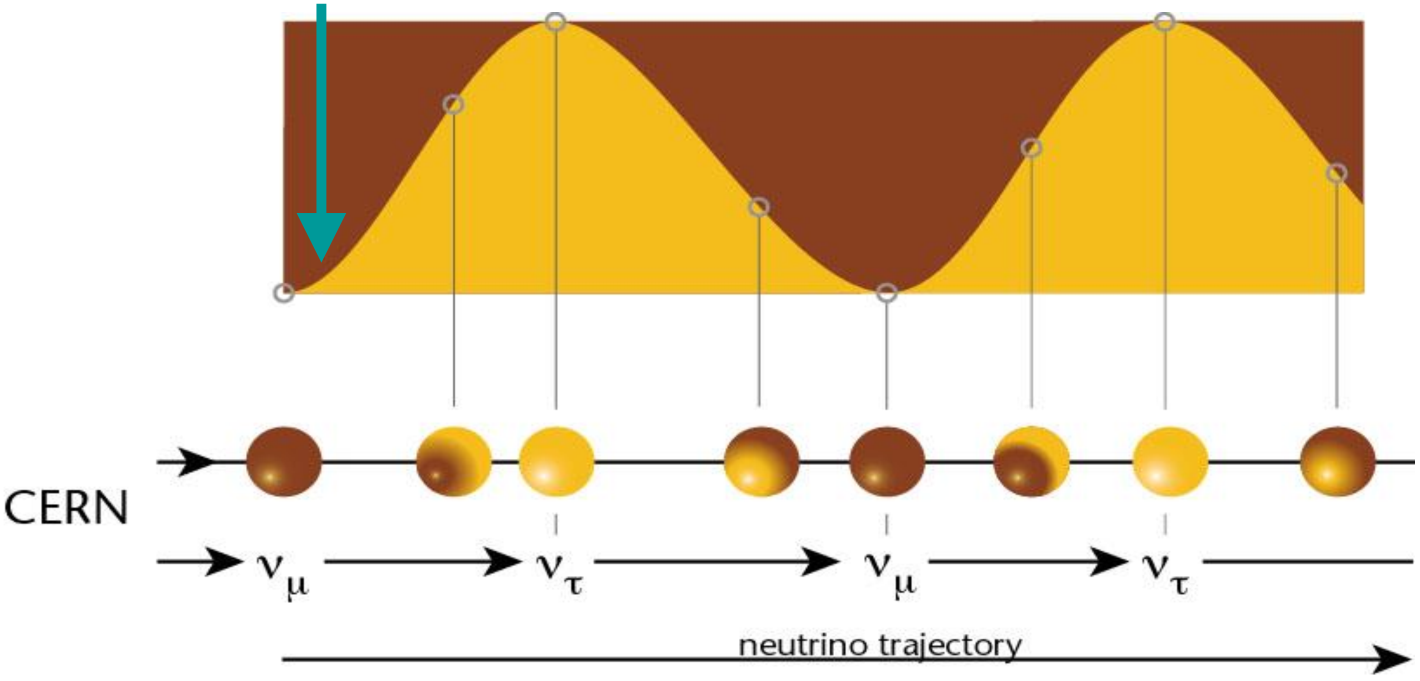
(CNGS)

CNGS

If neutrinos have mass:



Muon neutrinos produced at CERN.
See if tau neutrinos arrive in Italy.



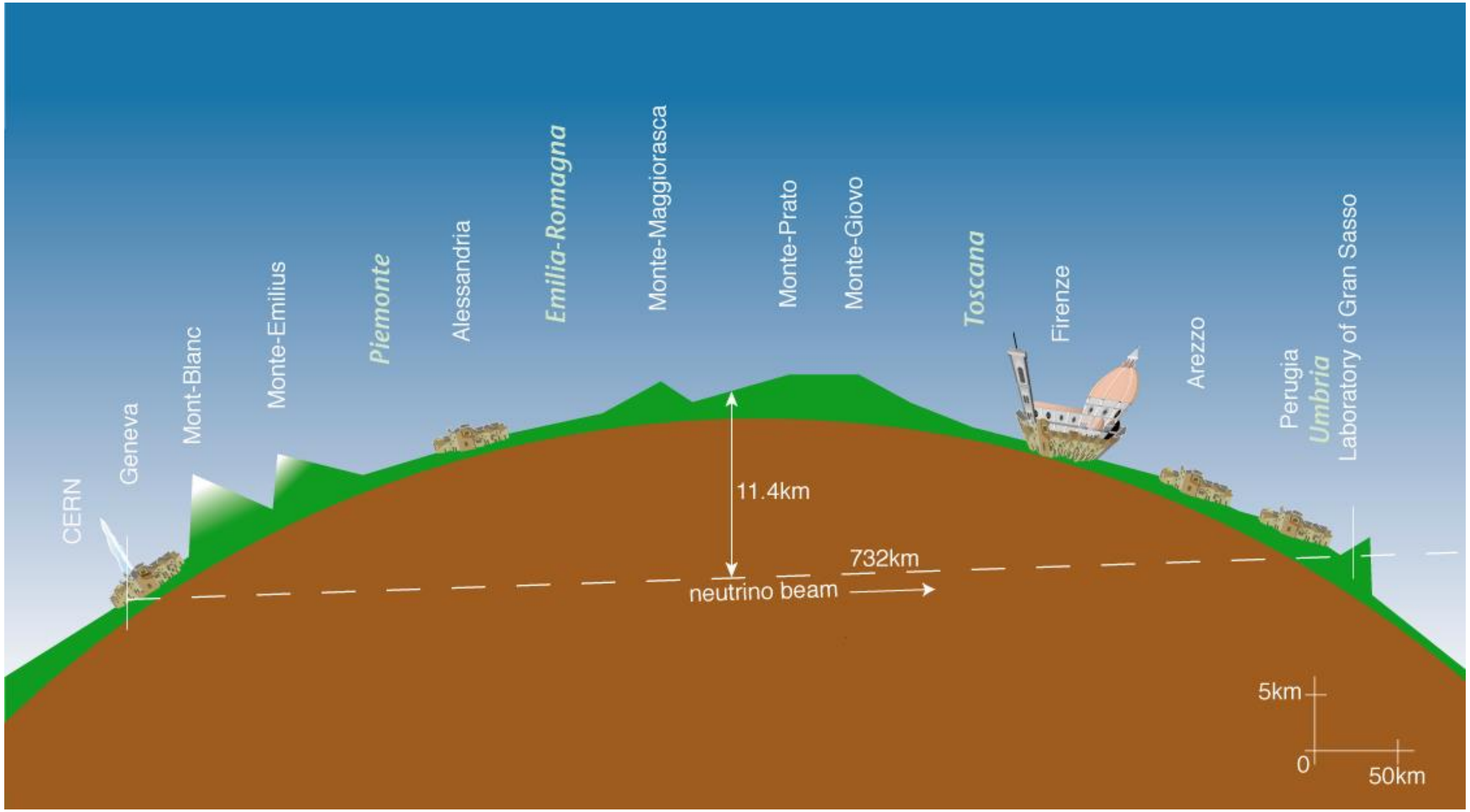
CNGS Project

CNGS (CERN Neutrino Gran Sasso)

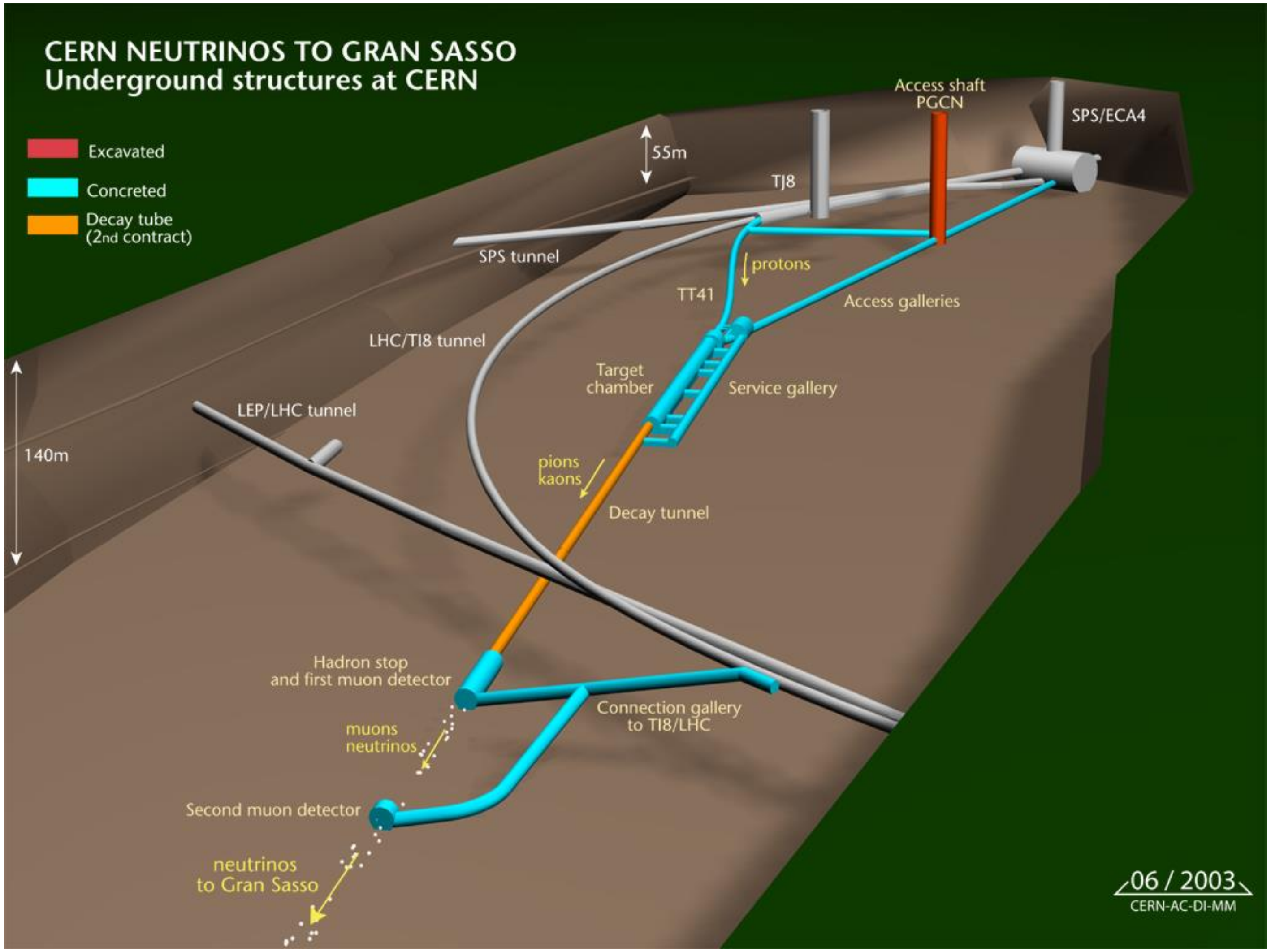
- A long base-line neutrino beam facility (732km)
- send ν_μ beam produced at CERN
- detect ν_τ appearance in OPERA experiment at Gran Sasso

➔ direct proof of ν_μ - ν_τ oscillation (appearance experiment)

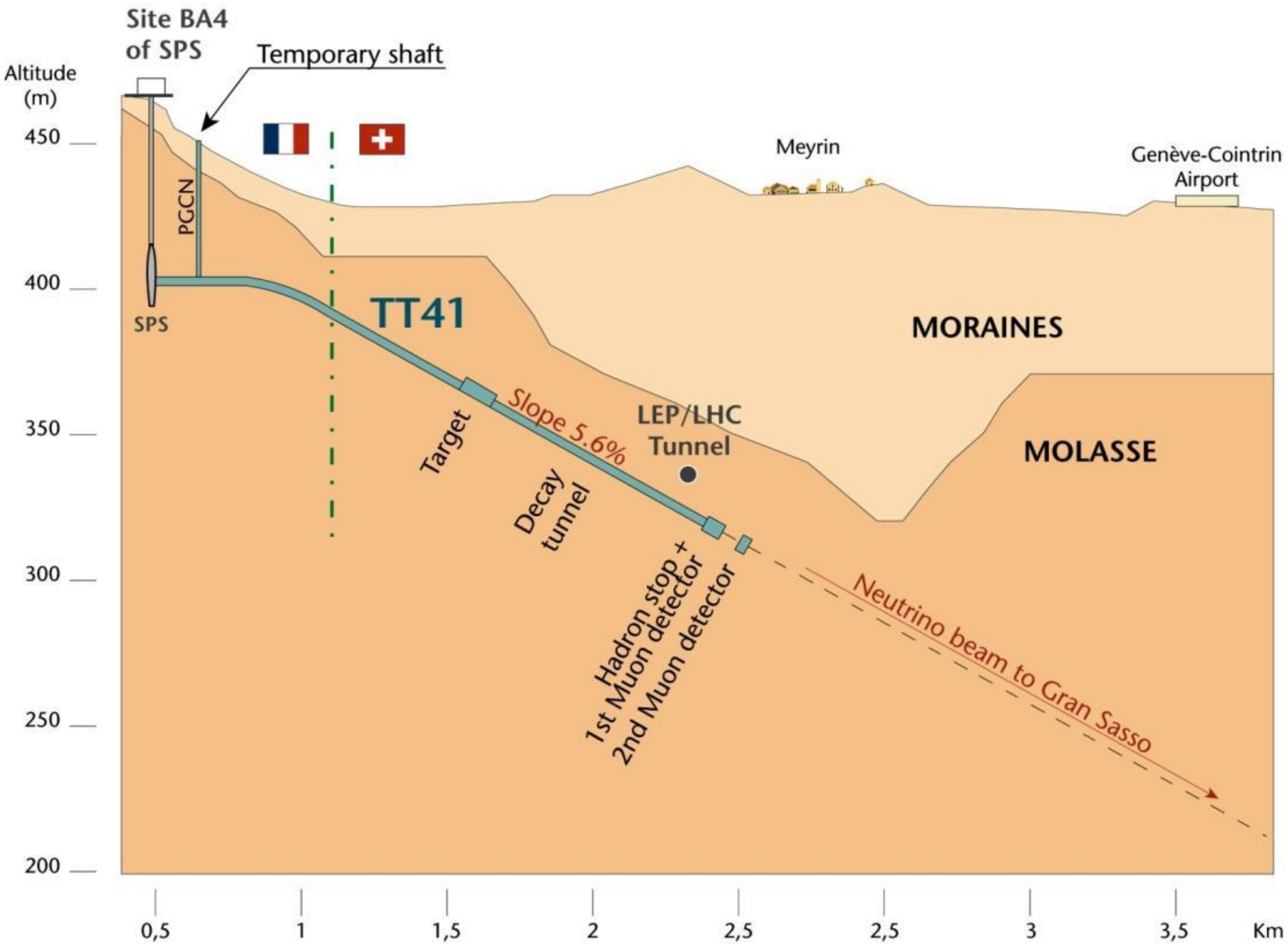
CNGS


CERN
Geneva
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
5km
0
50km

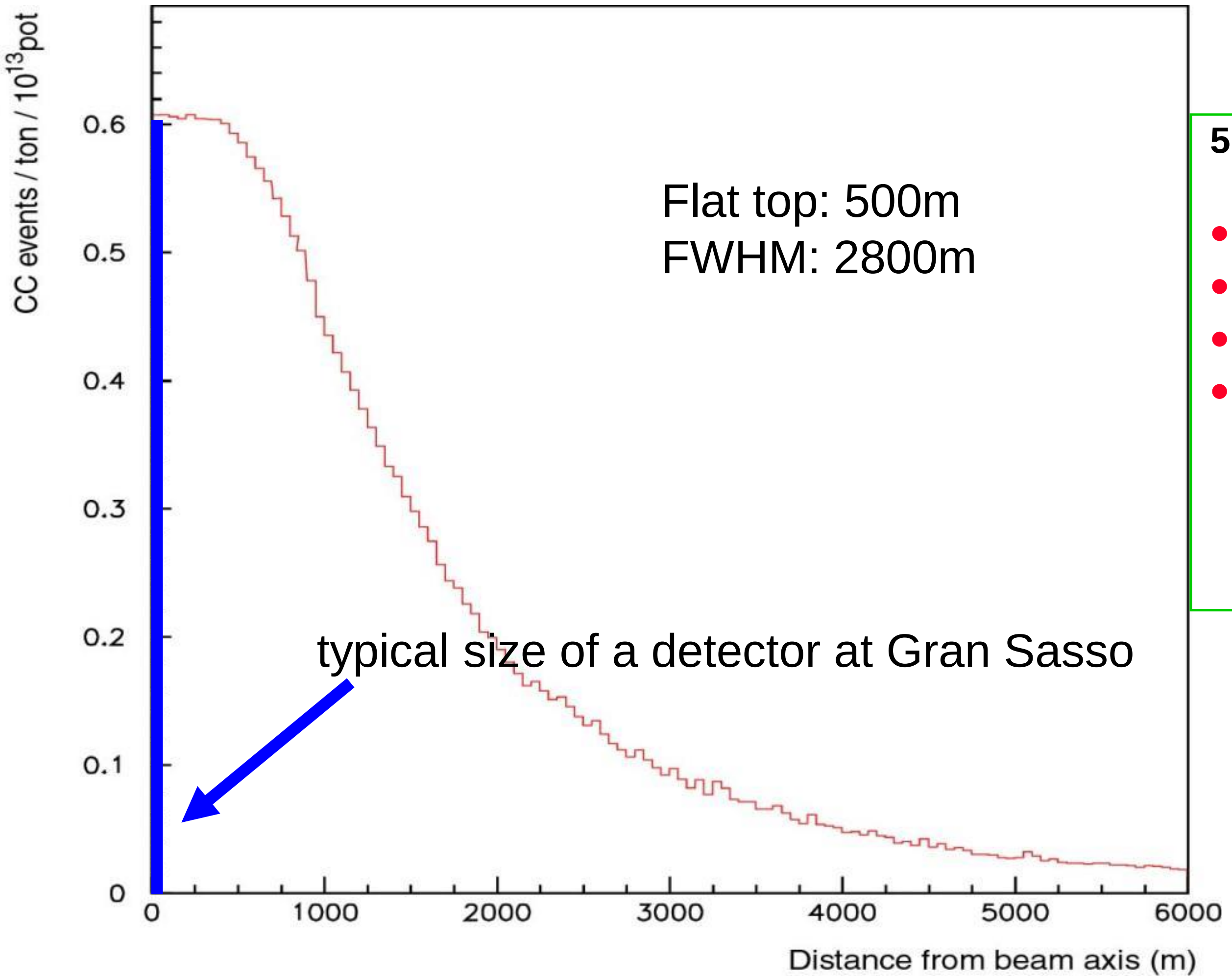
CNGS


CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
🟥 Excavated
🟦 Concreted
🟧 Decay tube (2nd contract)
55m
140m
TJ8
Access shaft PGCN
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target chamber
Service gallery
LEP/LHC tunnel
pions kaons
Decay tunnel
Hadron stop and first muon detector
Connection gallery to TI8/LHC
muons neutrinos
Second muon detector
neutrinos to Gran Sasso
06 / 2003
CERN-AC-DI-MM

CNGS


Site BA4
of SPS
Temporary shaft
Altitude
(m)
450
400
350
300
250
200
PGCN
SPS
TT41
Meyrin
Genève-Cointrin
Airport
MORAINES
MOLASSE
LEP/LHC
Tunnel
Slope 5.6%
Target
Decay
tunnel
Hadron stop +
1st Muon detector
2nd Muon detector
Neutrino beam to Gran Sasso
0,5
1
1,5
2
2,5
2,5
3
3,5
Km

Radial Distribution of the ν_μ-Beam at GS



Flat top: 500m
FWHM: 2800m

typical size of a detector at Gran Sasso

5 years CNGS operation, 1800 tons target:

- **30000 neutrino interactions**
- **~150 ν_τ interactions**
- **~15 ν_τ identified**
- **< 1 event of background**

Neutrinos at CNGS: Some Numbers

For 1 year of CNGS operation, we expect:

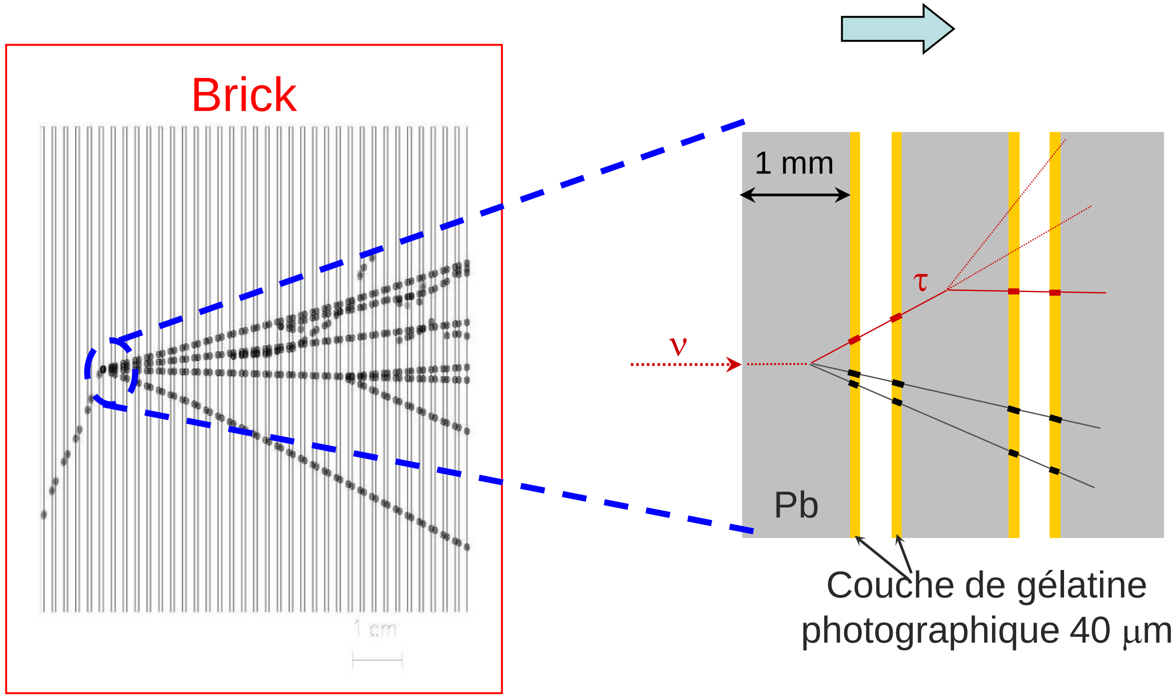
protons on target	2×10^{19}
pions / kaons at entrance to decay tunnel	3×10^{19}
ν_μ in direction of Gran Sasso	10^{19}
ν_μ in 100 m^2 at Gran Sasso	3×10^{14}
ν_μ events per day in OPERA	≈ 2500
ν_τ events (from oscillation)	≈ 2

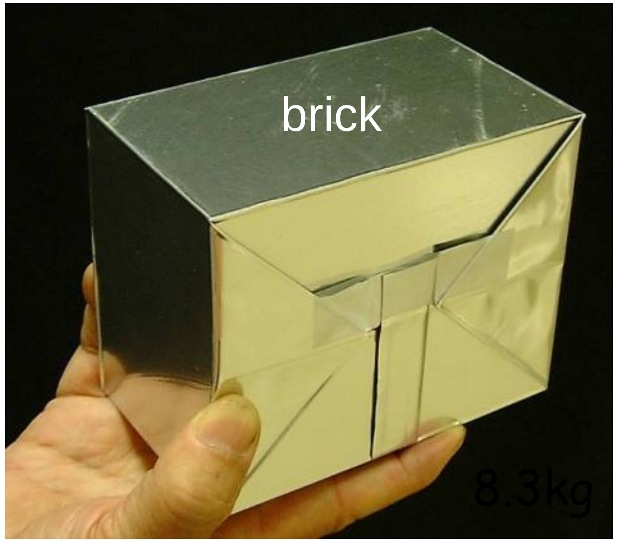
Opera Experiment at Gran Sasso

Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target
Emulsions: micrometric precision



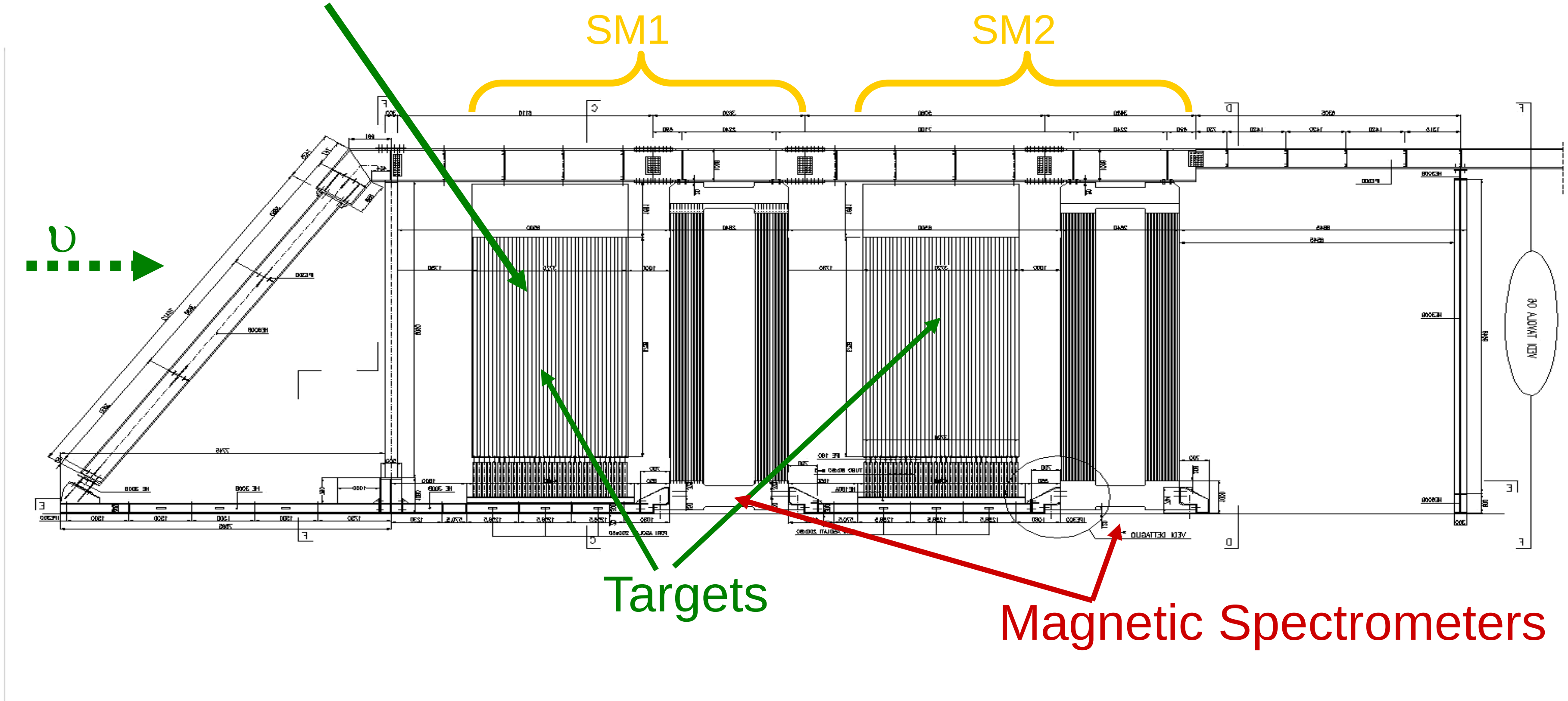


10.2 x 12.7 x 7.5 cm^3

Opera Experiment at Gran Sasso

31 target planes / supermodule

In total: 206336 bricks, 1766 tons



SM1

SM2

υ

Targets

Magnetic Spectrometers

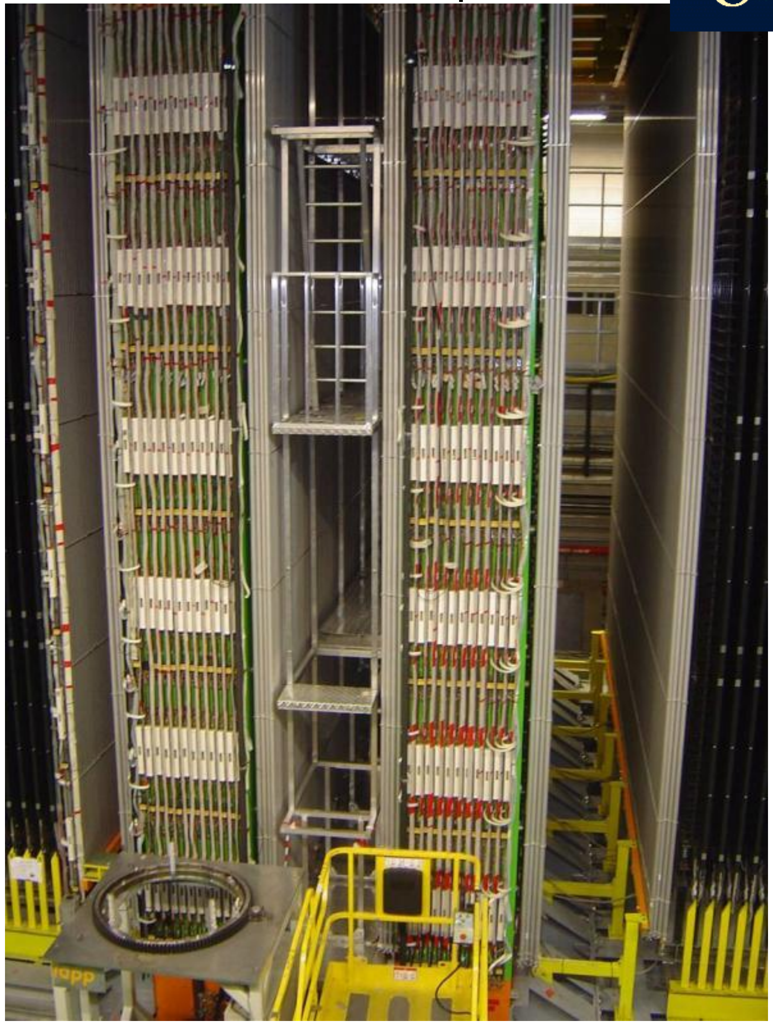
First observation of CNGS beam neutrinos : August 18th, 2006

Opera Experiment at Gran Sasso

Second Super-module

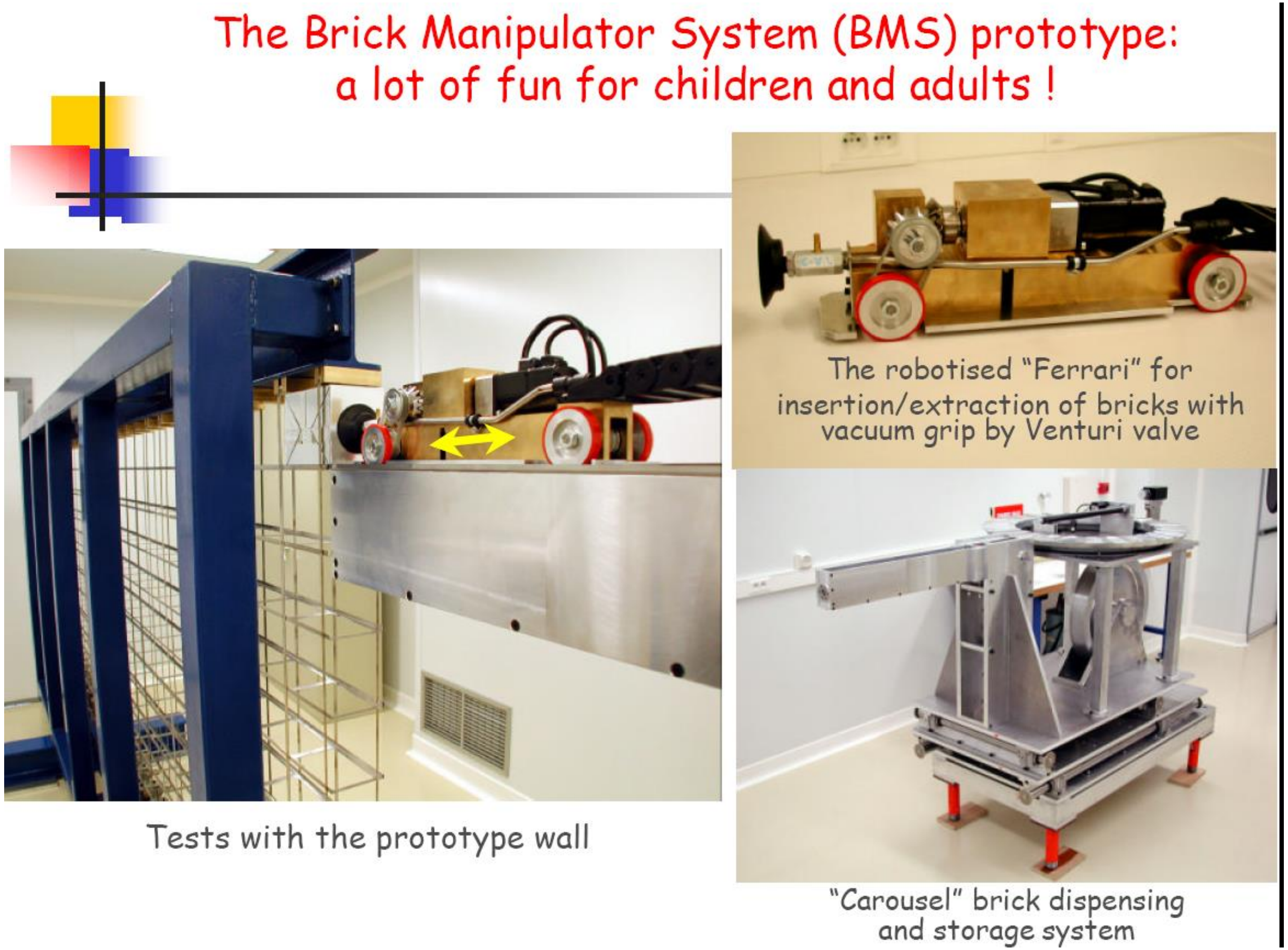
Scintillator planes 5900 m^2
8064 7m long drift tubes

Details of the first spectrometer



3050 m^2 Resistive Plate Counters
2000 tons of iron for the two magnets

Opera Experiment at Gran Sasso



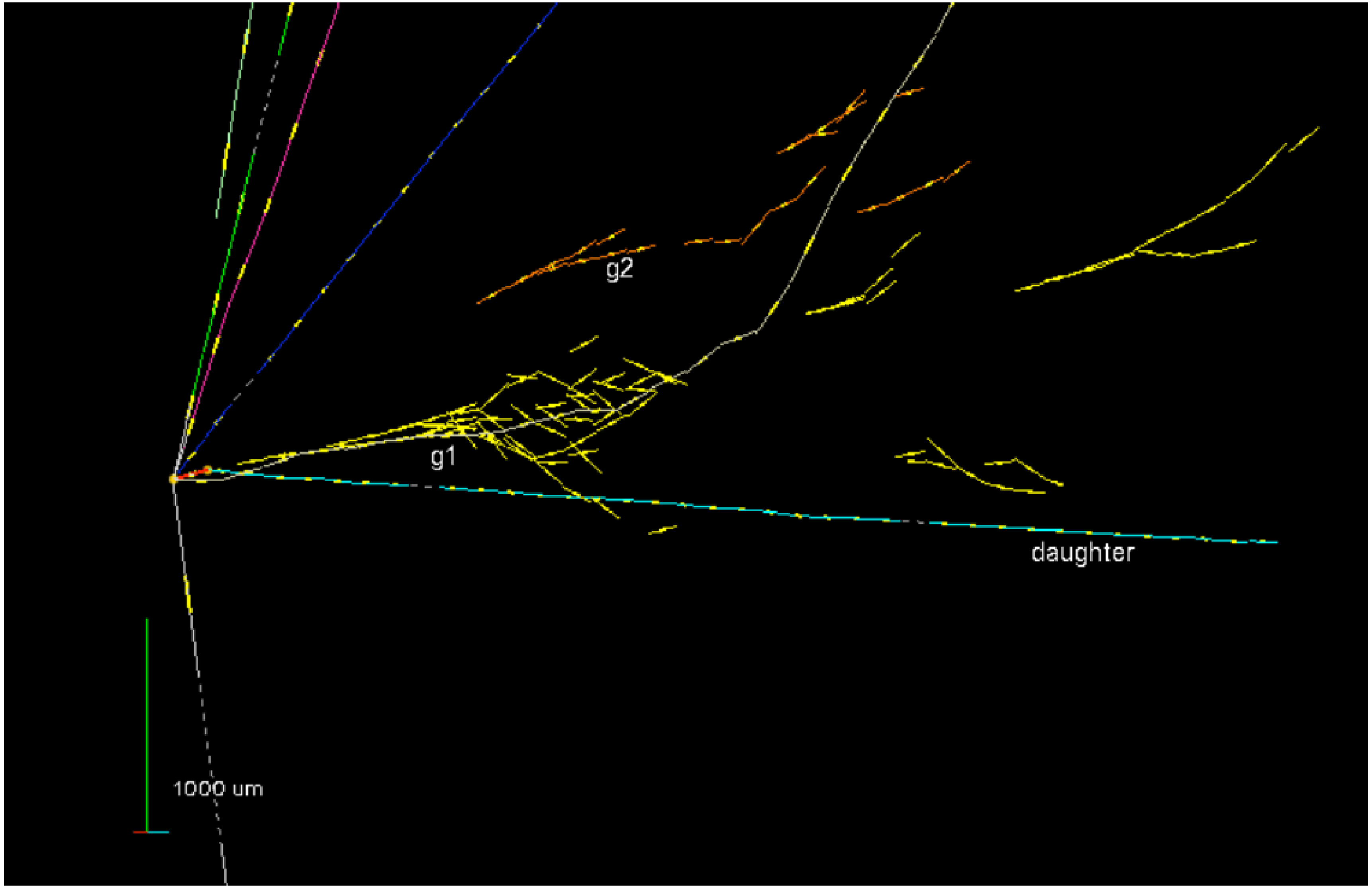
The Brick Manipulator System (BMS) prototype:
a lot of fun for children and adults !

The robotised "Ferrari" for insertion/extraction of bricks with vacuum grip by Venturi valve

Tests with the prototype wall

"Carousel" brick dispensing and storage system

First Tau Candidate !



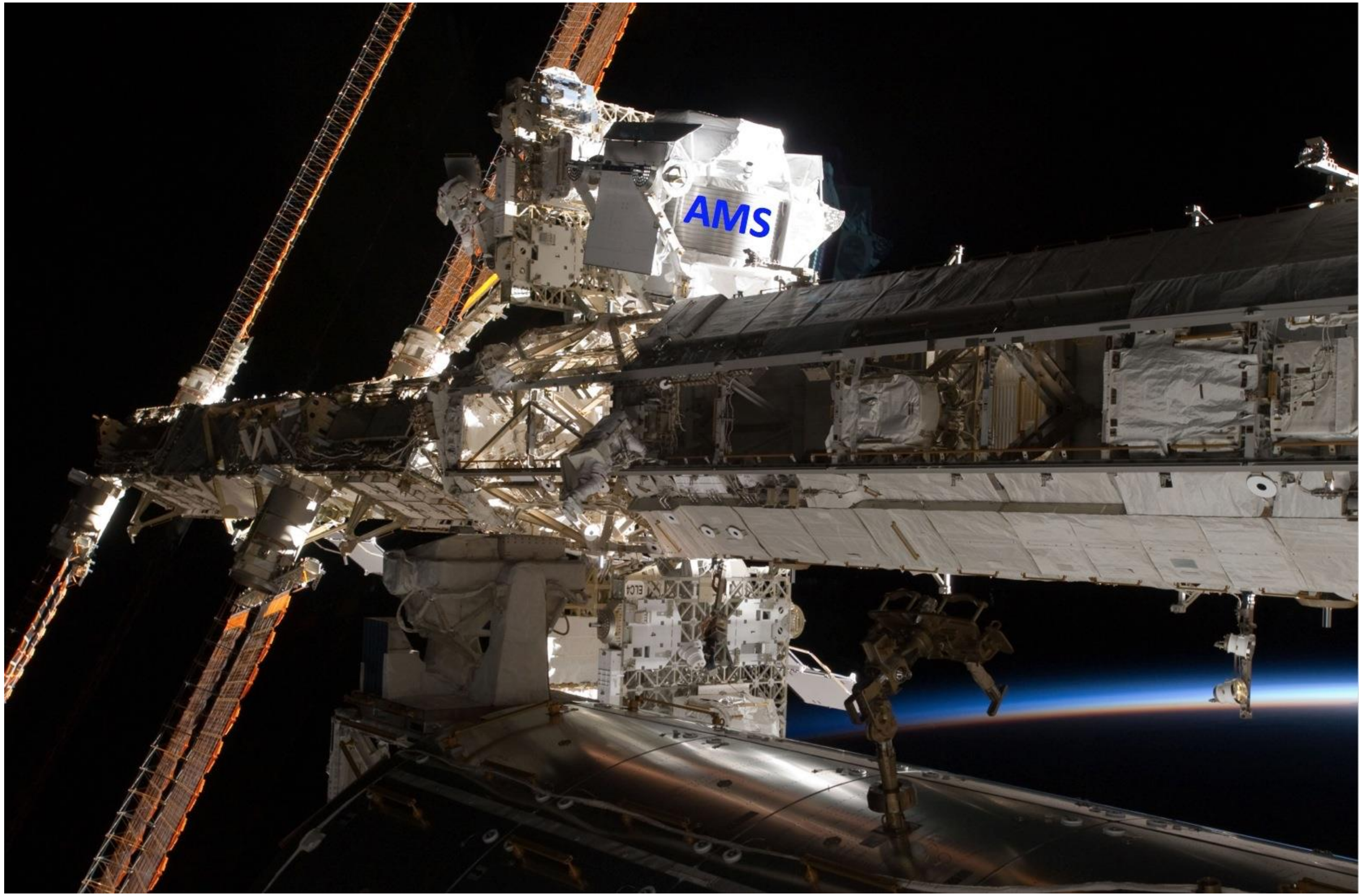
AMS

Alpha **M**agnetic **S**pectrometer

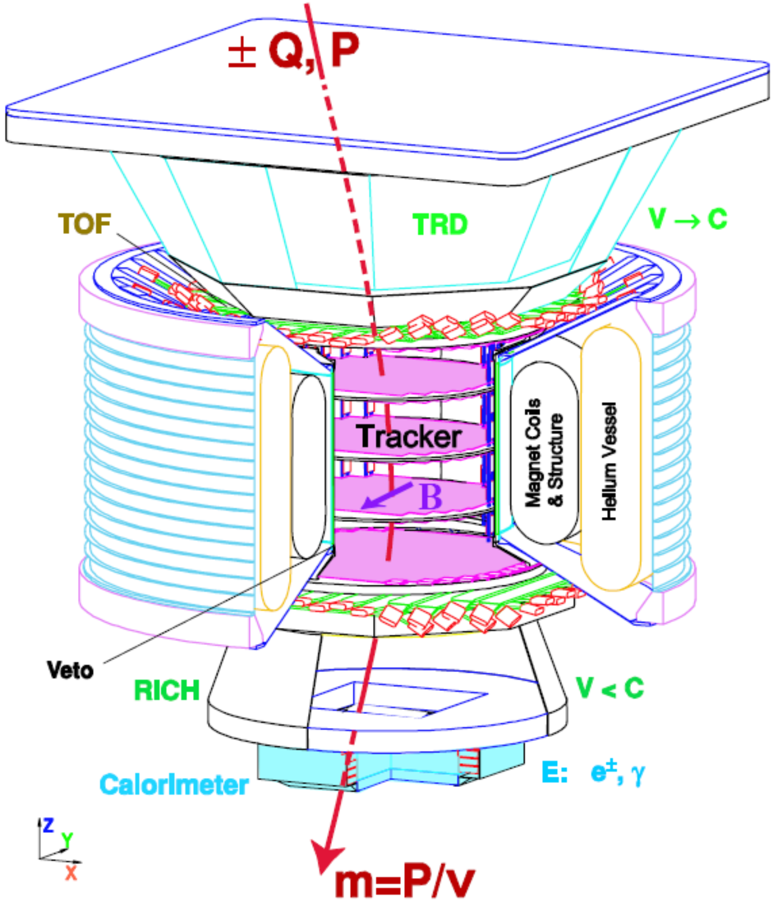
Try to find Antimatter in the primary cosmic rays.
Study cosmic ray composition etc. etc.

AMS

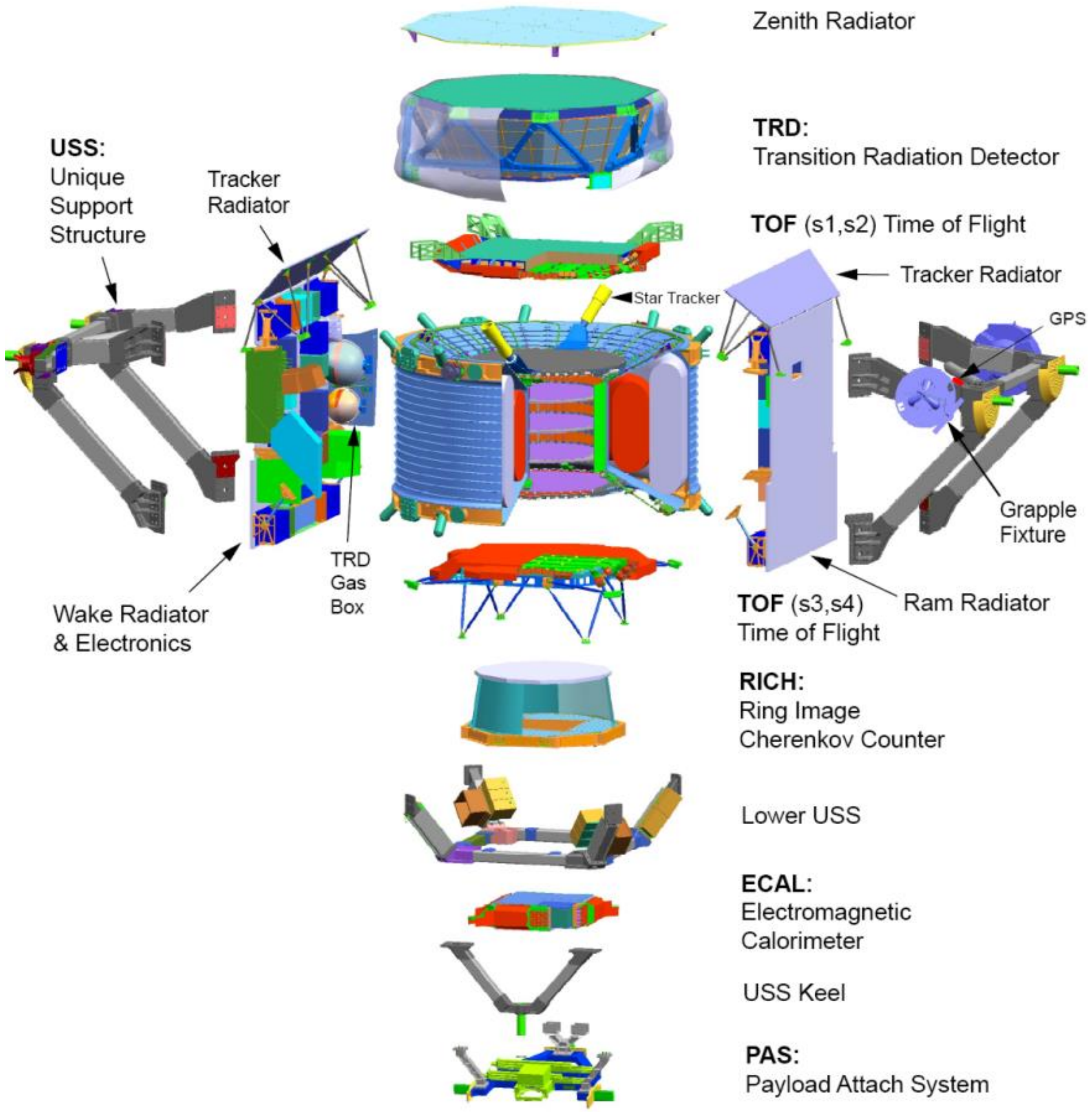
Installed on the space station.



AMS


± Q, P
TOF
TRD
V → C
Tracker
B
Magnet Coils & Structure
Helium Vessel
Veto
RICH
V < C
Calorimeter
E: e±, γ
Z
Y
X
m=P/v

AMS


Zenith Radiator
TRD:
Transition Radiation Detector
USS:
Unique
Support
Structure
Tracker
Radiator
TOF (s1,s2) Time of Flight
Tracker Radiator
Star Tracker
GPS
Grapple
Fixture
TRD
Gas
Box
Wake Radiator
& Electronics
TOF (s3,s4)
Time of Flight
Ram Radiator
RICH:
Ring Image
Cherenkov Counter
Lower USS
ECAL:
Electromagnetic
Calorimeter
USS Keel
PAS:
Payload Attach System