DE LA RECHERCHE À L'INDUSTRIE

Mesurer l'infiniment petit et observer l'infiniment grand

Stages : http://irfu.cea.fr/Phocea/stages/index.php

Maxence Vandenbroucke

07/2019

université PARIS-SACLAY

PLAN DES COURS

Cours 1 : Généralités

-Introduction générale sur l'importance de la mesure

-Qu'est-ce qu'une expérience de physique subatomique ?

-Que veut-on observer à propos d'une particule?

-Architecture générale d'une expérience en physique subatomique

Cours 2 : Les détecteurs dans le détails

- Interaction particule-matière
- Les Détecteurs à ionisations
- L'exemple des détecteurs gazeux

Cours 3 : Exemples d'expériences (?)

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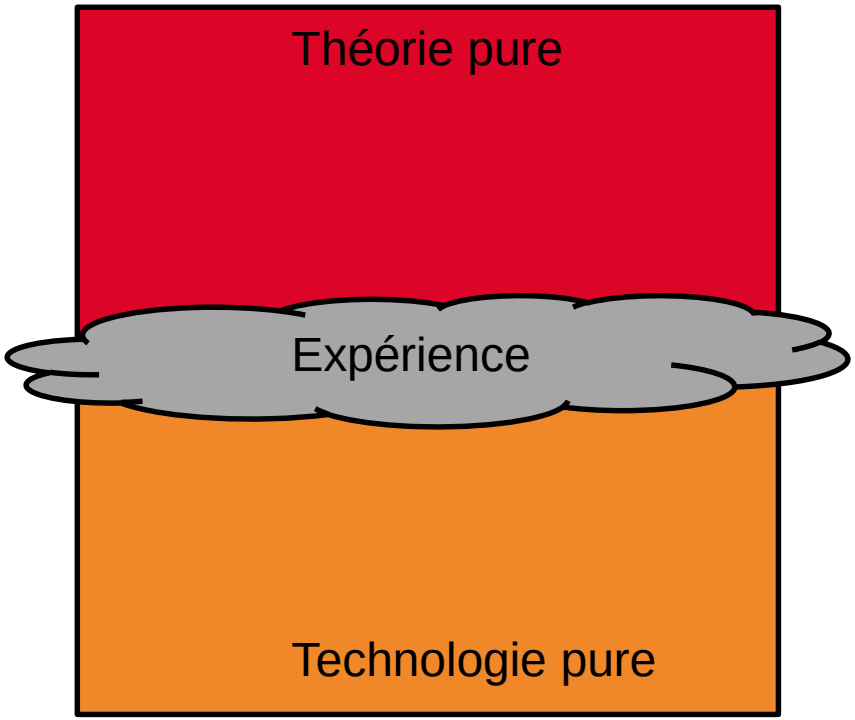
La theorie et la Pratique



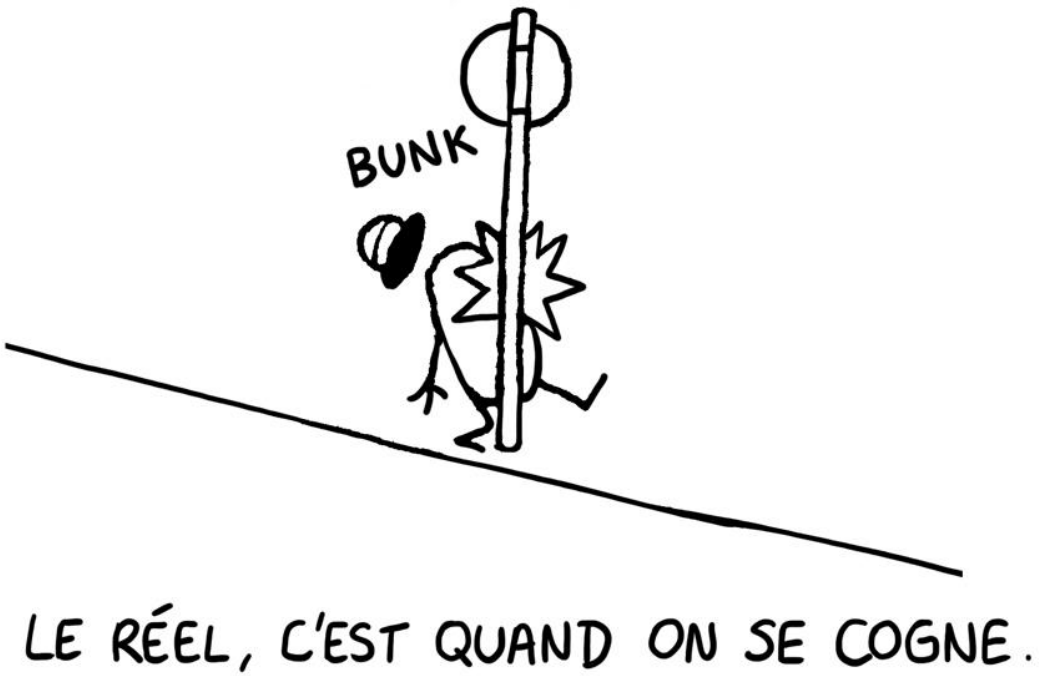
- Théorie
- Construction des Modèles
- Prédiction avec des Modèles
- Simulation de l'expérience

- Design d'expérience
- Choix du dispositif experimental
- Electronique/acquisition
- Reconstruction des évènements
- Comparaison avec la simulation/calcul
- Papier !

Le physicien complet est à la fois proche des interrogations fondamentales, mais aussi des avancés technologiques pour trouver un espace de découverte potentielle

(vision un peu naïve)

MESURER C'EST QUOI ?



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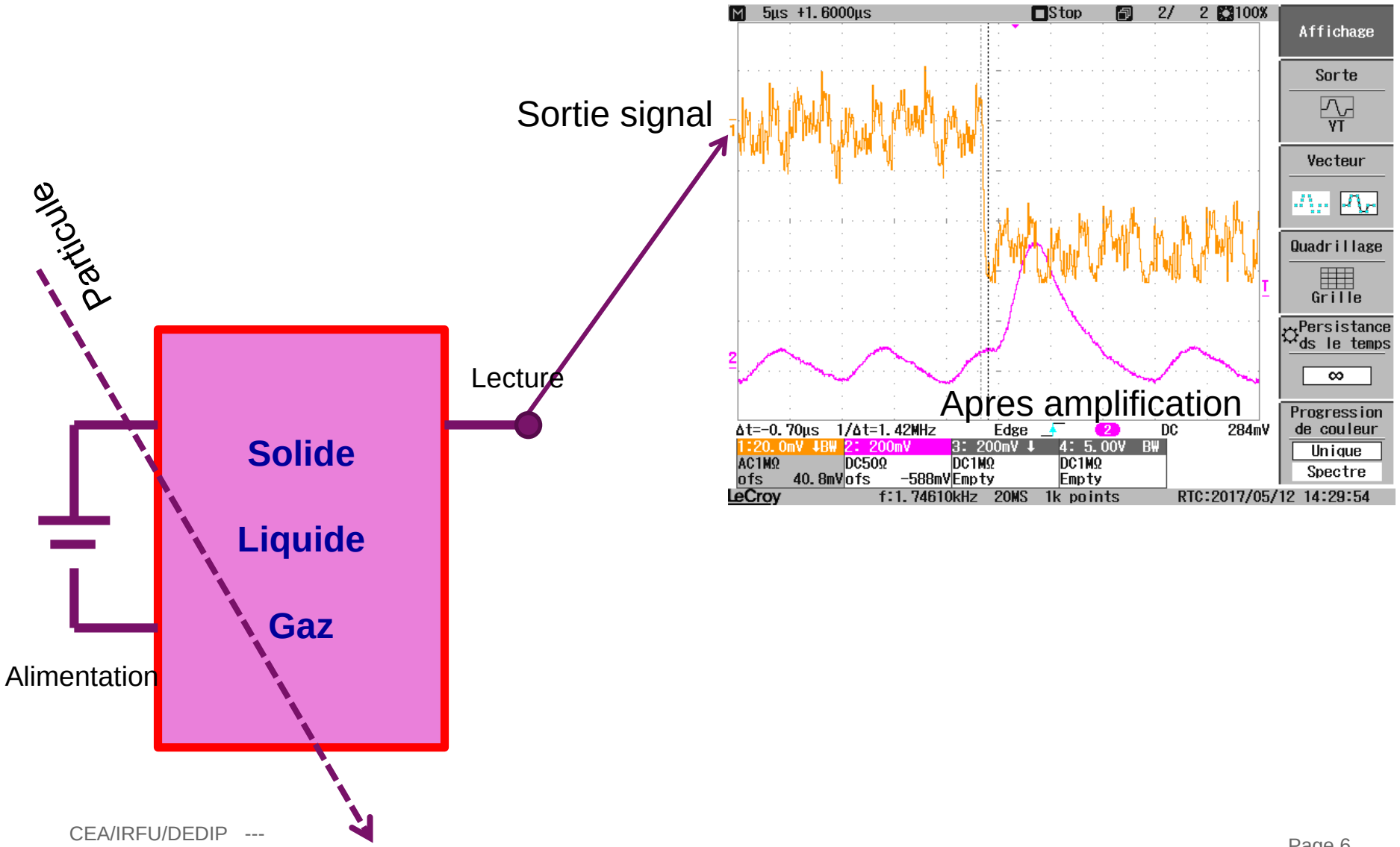
MESURER C'EST QUOI ?



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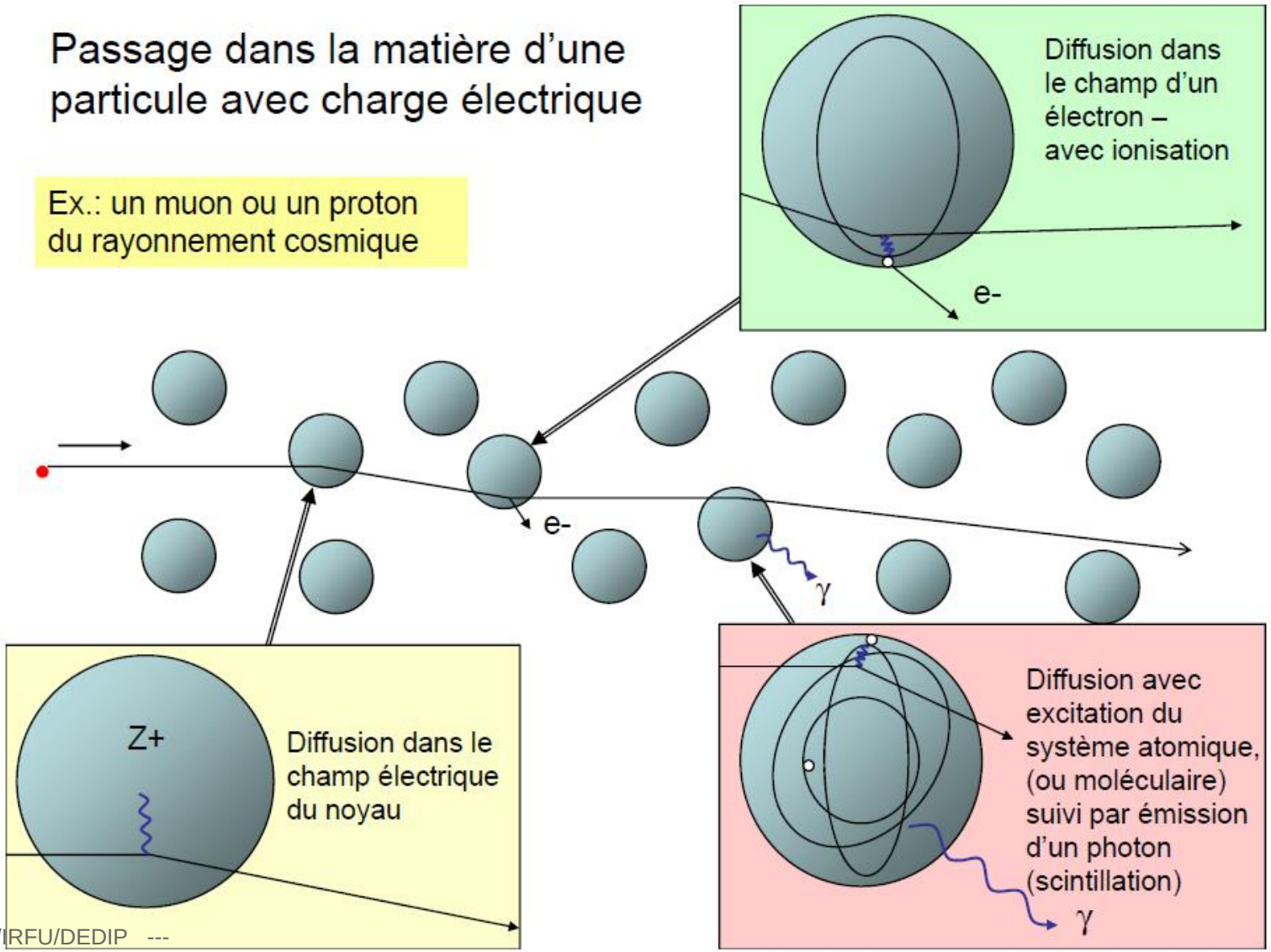
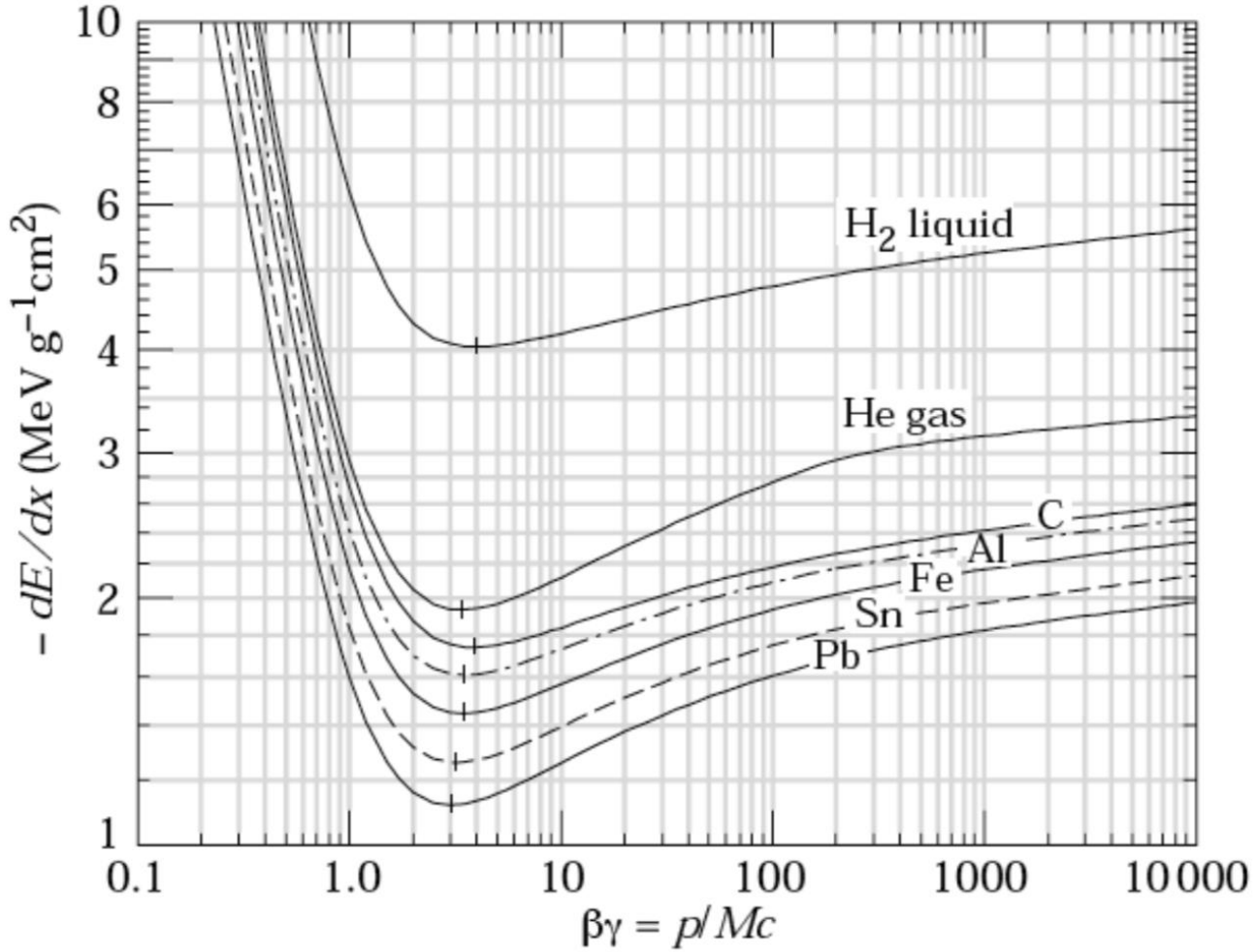
INTERACTIONS PARTICULE-MATIERE

Passage dans la matière d'une particule avec charge électrique

Ex.: un muon ou un proton du rayonnement cosmique

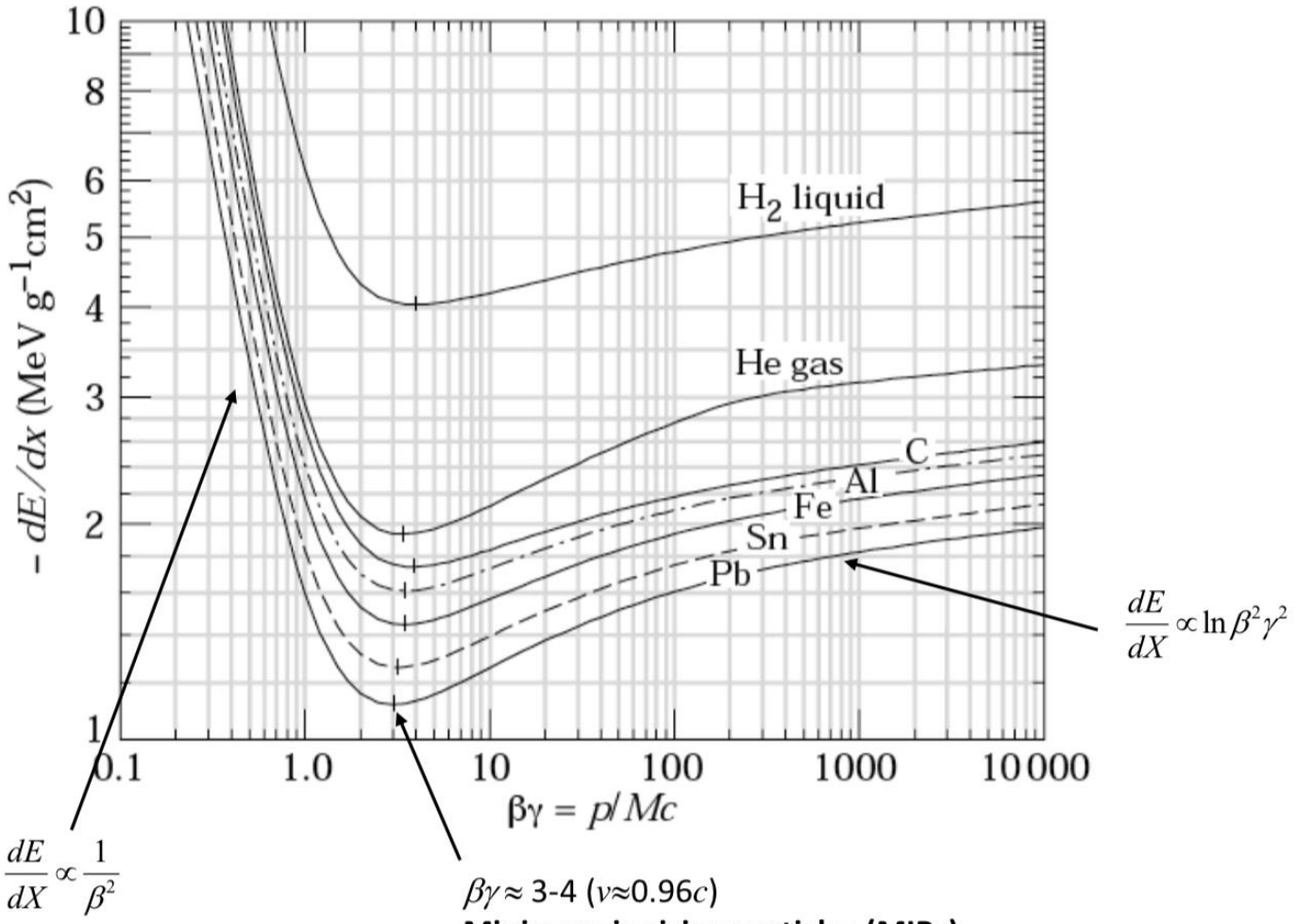


INTERACTIONS PARTICULE-MATIERE

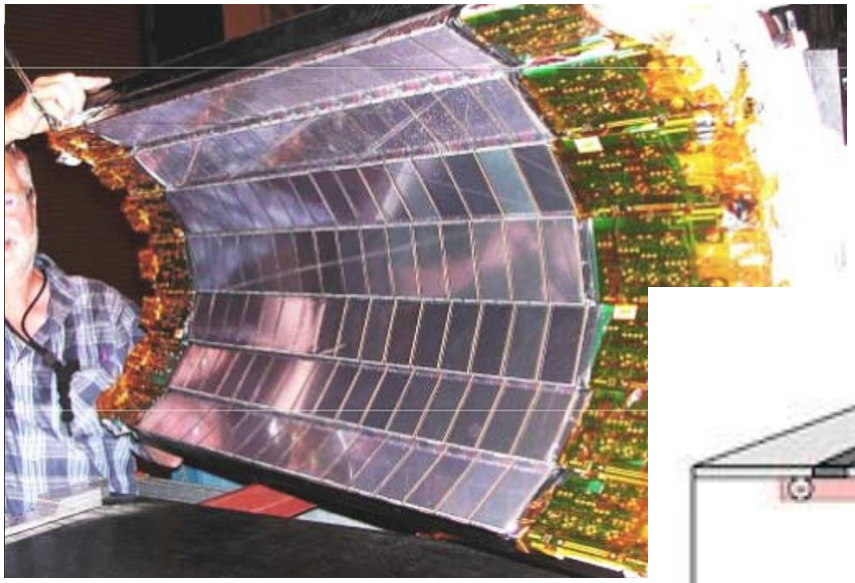


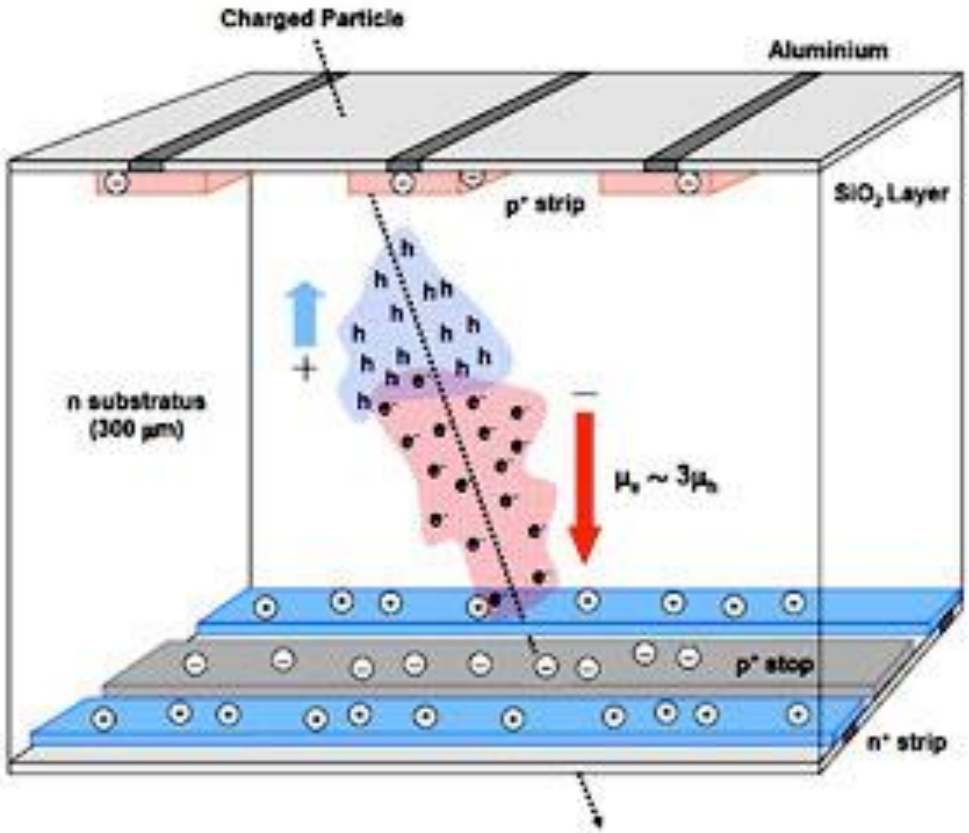
INTERACTIONS PARTICULE-MATIERE

$$-\frac{dE}{dX} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\rho\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{C}{Z}\right]$$



DÉTECTION : TRACKER SILICIUM





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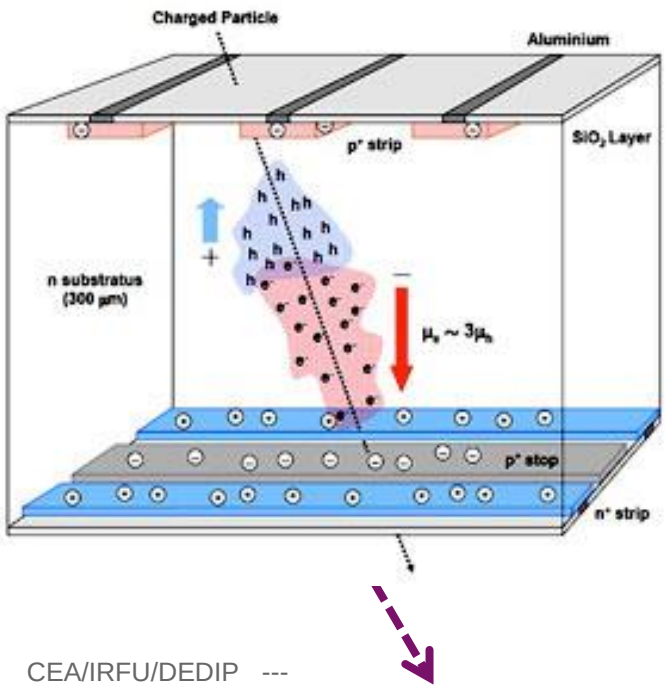
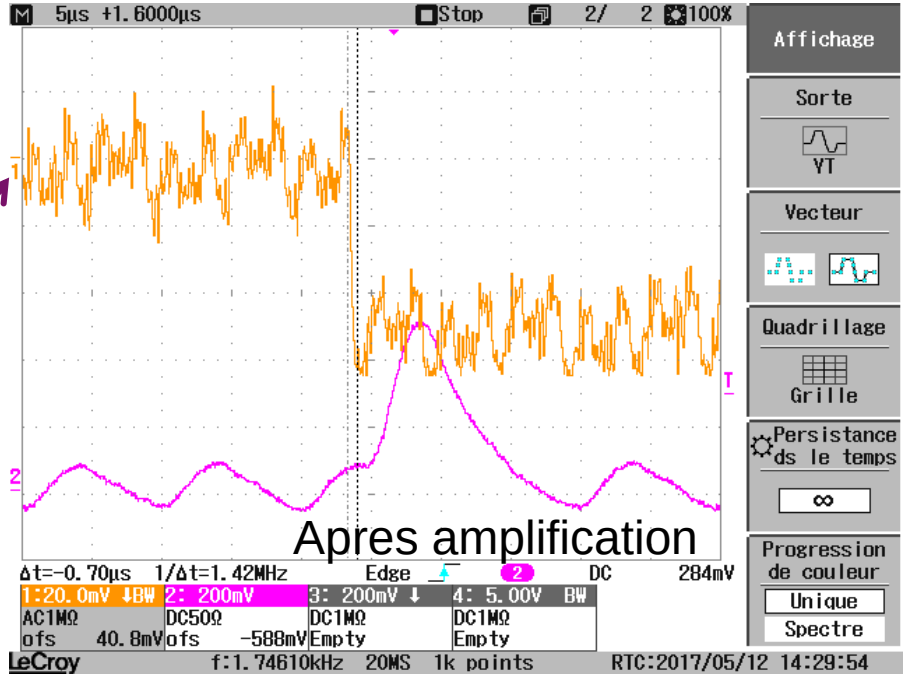
MESURER C'EST QUOI ?

Sortie signal

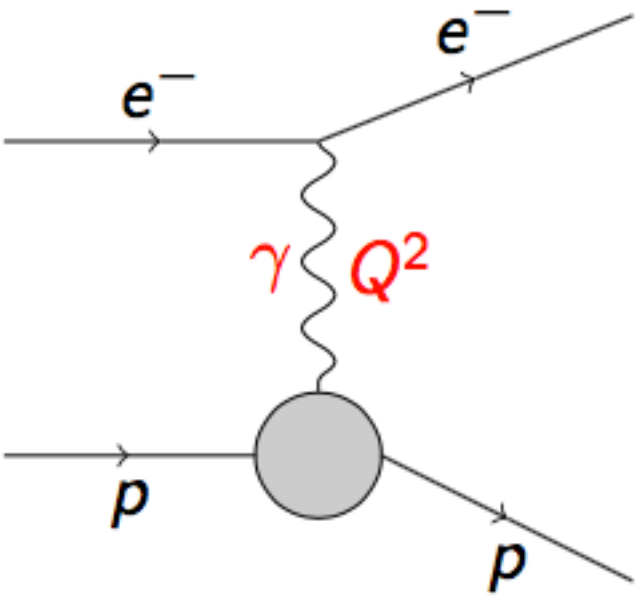
Particule

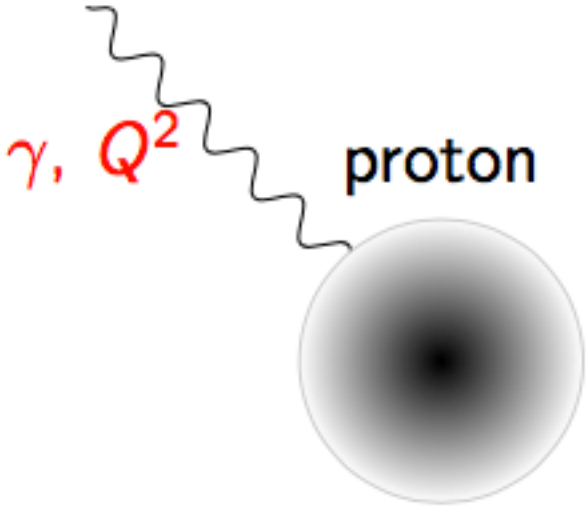




Ali

MESURER QUOI ?





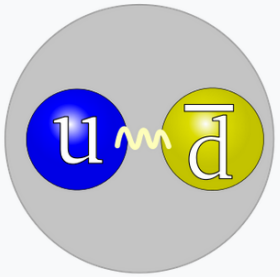
Diffusion élastique.

Pas élastique du tou

MESURER QUOI ?

Déterminer la carte d'identité d'une particule :

Pion



The quark structure of the pion.

Composition	π^+: $u\bar{d}$ π^0: $u\bar{u}$ or $d\bar{d}$ π^-: $d\bar{u}$
Statistics	Bosonic
Interactions	Strong, Weak, Electromagnetic and Gravity
Symbol	π^+, π^0, and π^-
Theorized	Hideki Yukawa (1935)
Discovered	César Lattes, Giuseppe Occhialini (1947) and Cecil Powell
Types	3
Mass	$\pi^\pm$: 139.570 18(35) MeV/c^2 π^0: 134.9766(6) MeV/c^2
Electric charge	π^+: +1 e π^0: 0 e π^-: −1 e
Spin	0
Parity	−1

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Mesure de l'impulsion

$$p=mv$$

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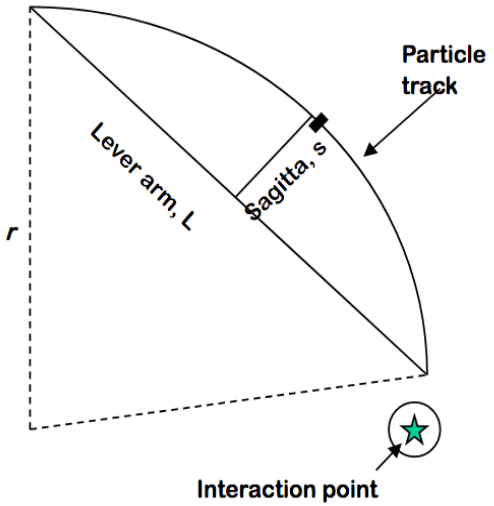
Mesure de l'impulsion

- Technique de spectrométrie magnétique (ou du B-rho)

$$qvB = mv_2/\rho \quad \rightarrow \quad p_\perp = p\cos\vartheta = qB\rho$$

- **Tracking measures particle 3-momenta**



$$p = qBr \approx \frac{qBL^2}{8s}$$

$$\frac{\sigma_p}{p} = \frac{\sigma_s}{s} = \frac{8p}{qBL^2}\sigma_s$$

Precision of sagitta measurement: $\sigma_s \approx \sqrt{\frac{3}{N}}\sigma_{hit}$ (***N*** **position measurements)**

Mesure de l'impulsion

- Technique de spectrométrie magnétique (ou du B-rho)

$$qvB = mv_2/\rho \quad \rightarrow \quad p_\perp = p\cos\vartheta = qB\rho$$

- Technique de temps de vol (TOF pour Time Of Flight)

$$L = v\tau = \beta c\tau = \beta c\gamma\tau_0 = p\tau_0/m$$

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- Effet Vavilov-Tcherenkov

$$\cos\theta_c = \frac{c}{n\beta c} = \frac{1}{n\beta} .$$

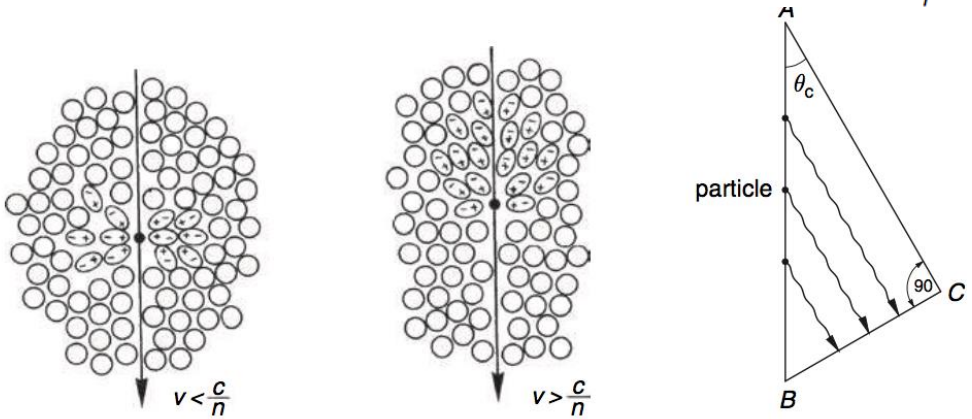

Fig. 5.39. Illustration of the Cherenkov effect [140, 141] and geometric determination of the Cherenkov angle.

DES OBSERVABLES A LA TECHNIQUE DE MESURE

Mesure de l'impulsion

- Technique de spectrométrie magnétique (ou du B-rho)
- Technique de temps de vol (TOF pour Time Of Flight)
- Effet Vavilov-Tcherenkov

Mesure de l'énergie

- Calorimétrie
- Perte d'energie dE/dx

DES OBSERVABLES A LA TECHNIQUE DE MESURE

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Mesure de l'énergie

- Calorimétrie
- Perte d'energie dE/dx
- Frequence

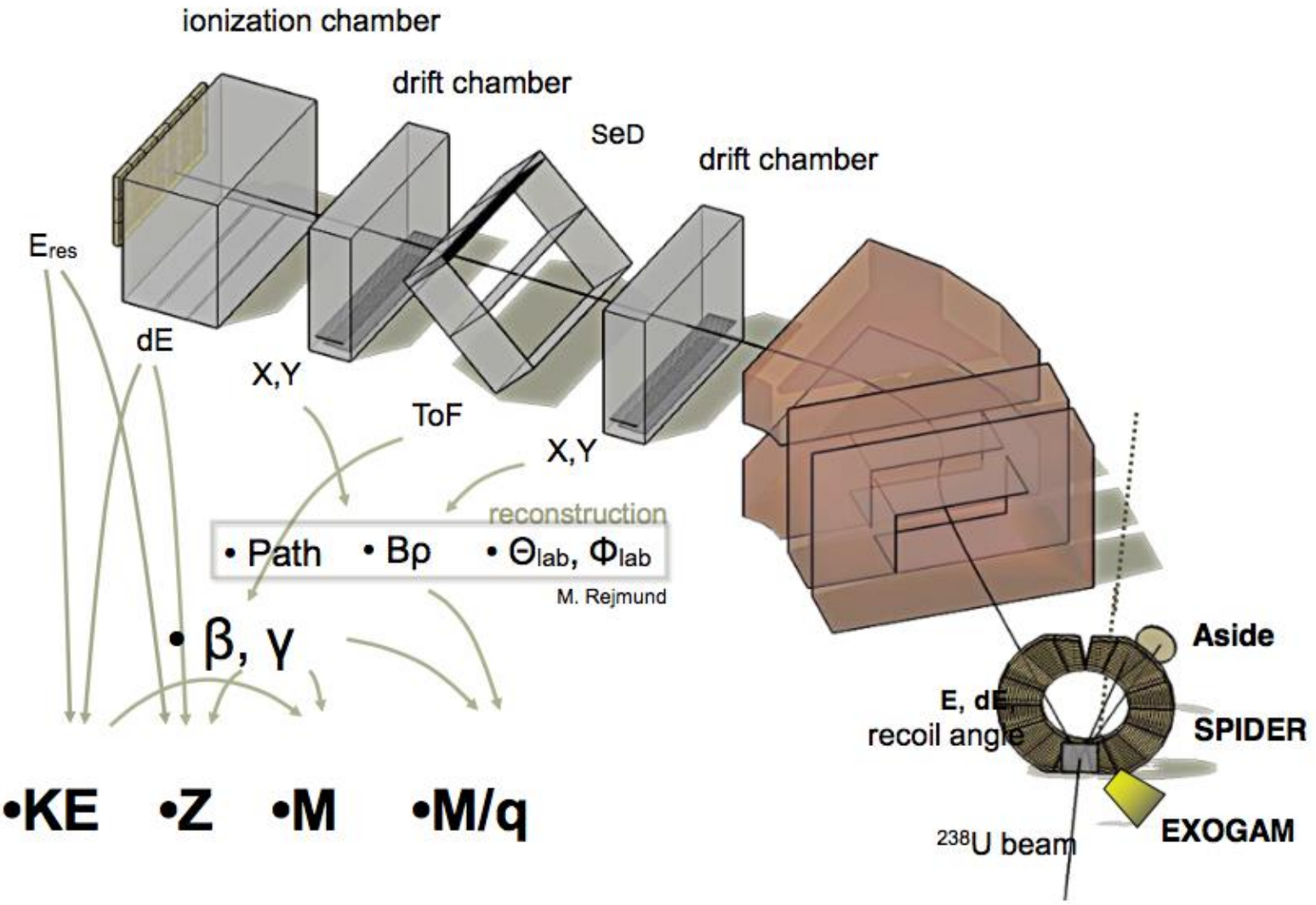
Mesure de spin et de la parité

- (Pas traitée ici)
- Avec un polarimetre indirectement
- Par selection

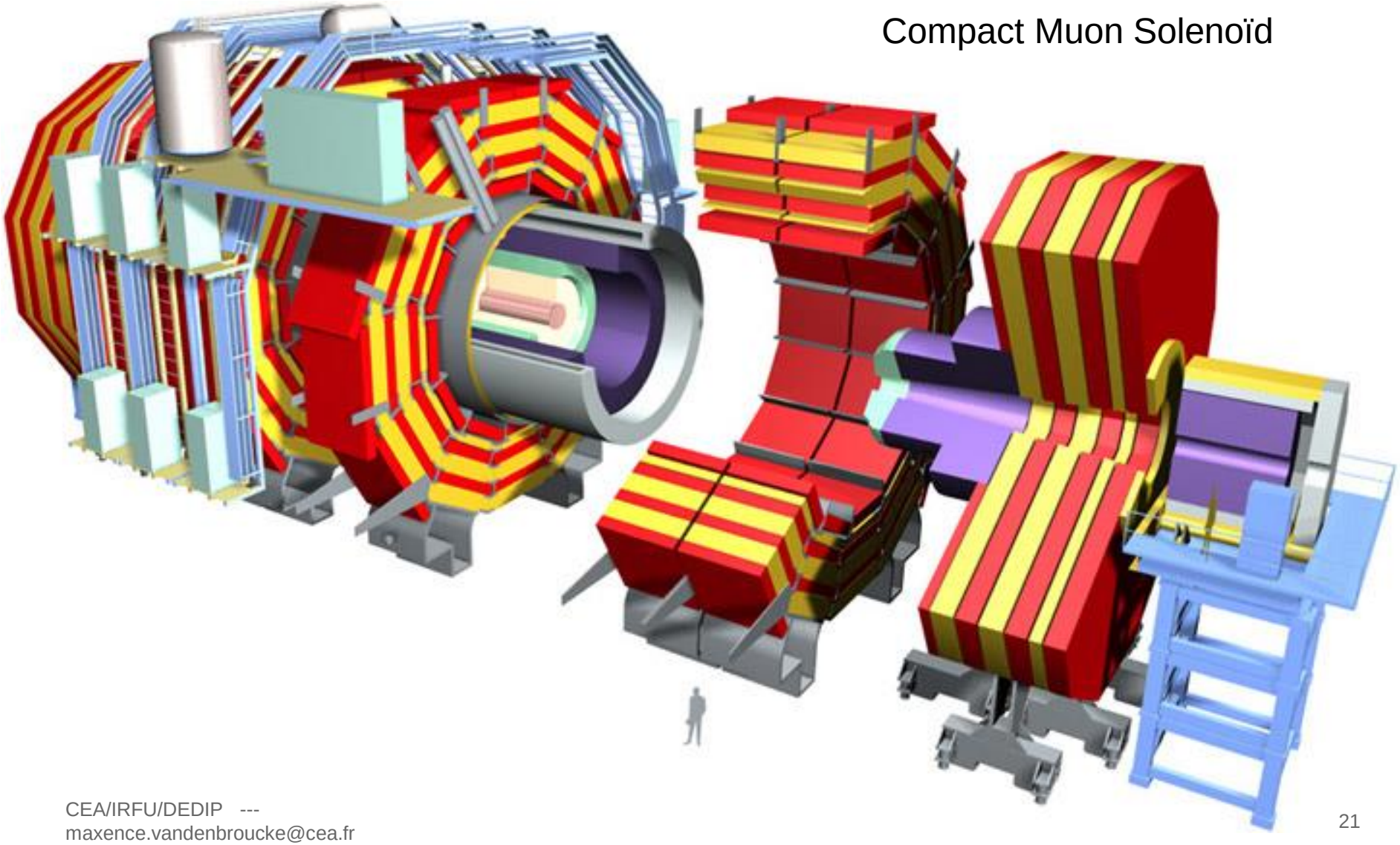
Mesure de la masse et de la charge (PID)

- Combinaison B-rho et TOF
- Combinaison B-rho et dE/dx
- Masse manquante …
- Direction de la courbure dans un spectromètre magnétique
- Mesure de la perte d'énergie dE/dx qui dépend de la charge
- L'electrometre

UN EXEMPLE


ionization chamber
drift chamber
SeD
drift chamber
Eres
dE
X,Y
ToF
X,Y
reconstruction
• Path • Bρ • Θlab, Φlab
M. Rejmund
• β, γ
•KE •Z •M •M/q
Aside
E, dE
recoil angle
SPIDER
EXOGAM
238U beam

UN PLUS GROS



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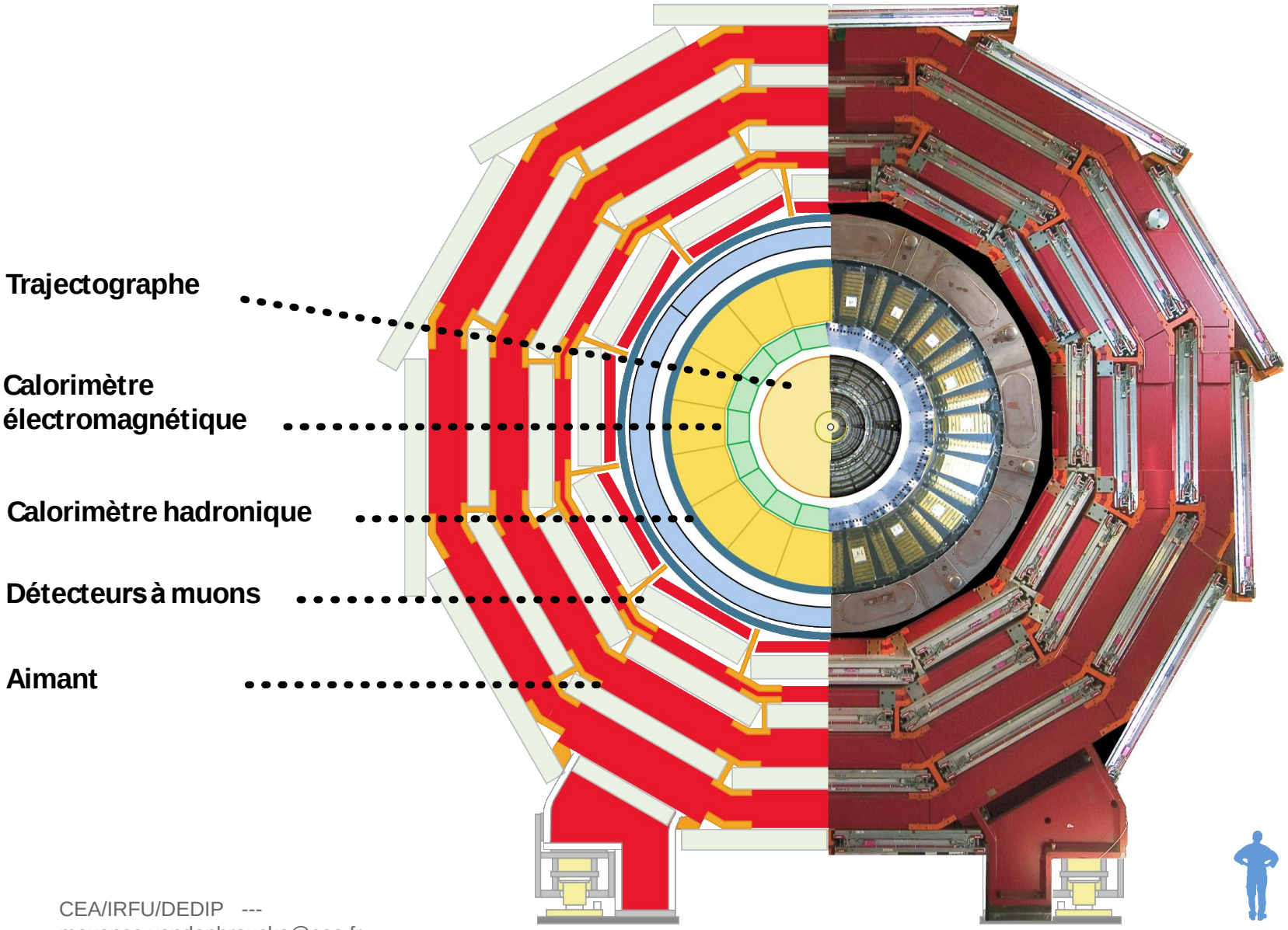
CMS



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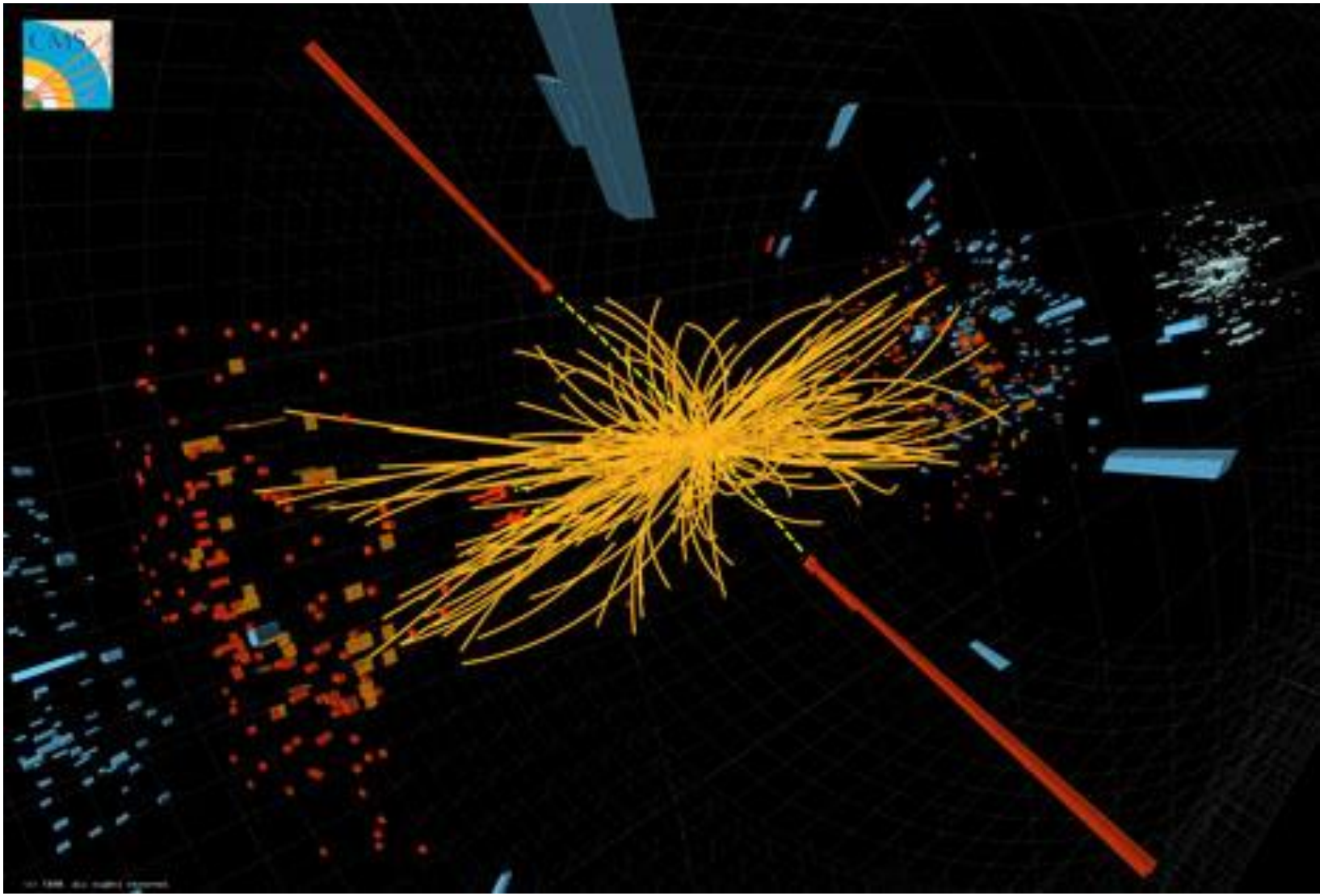
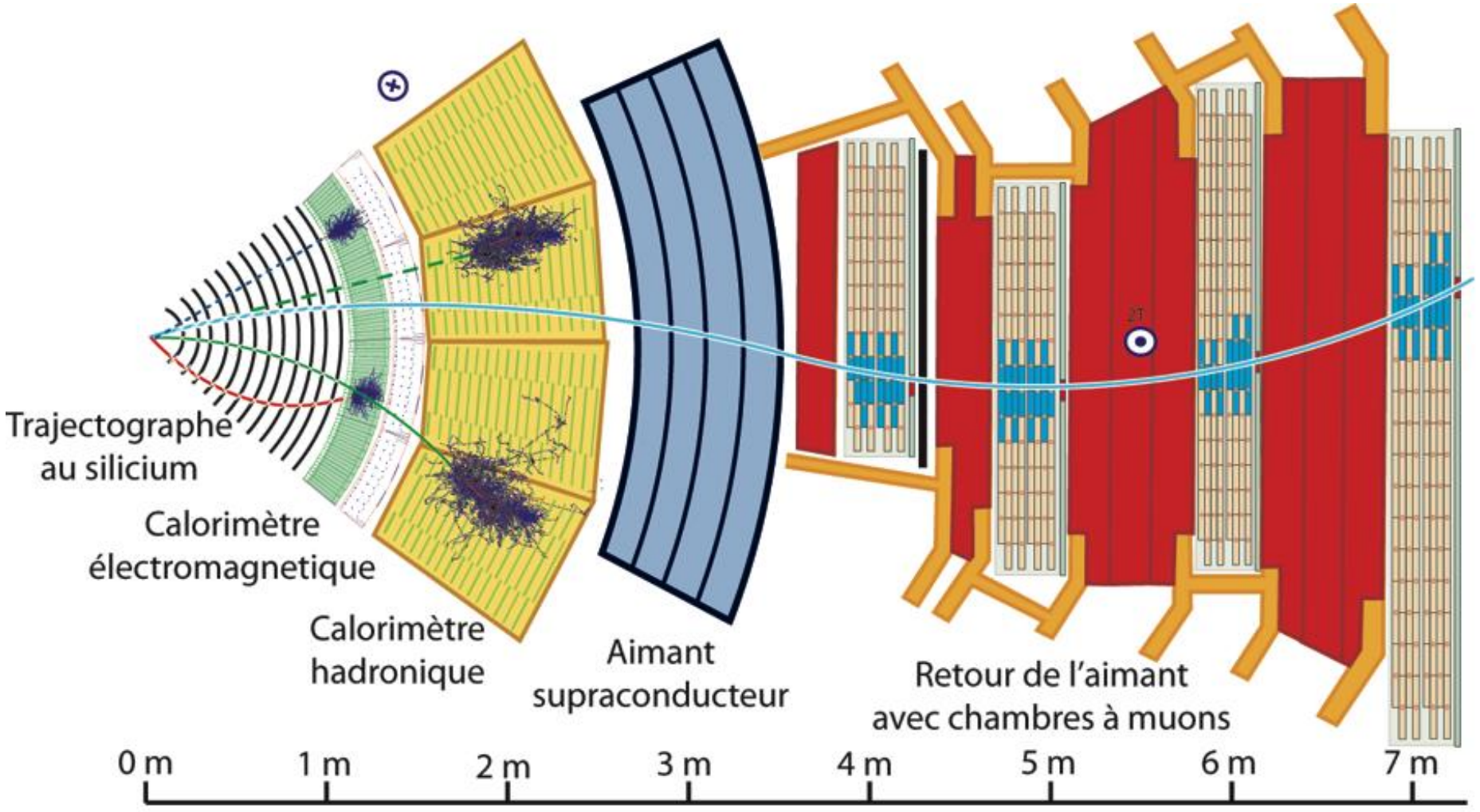
CMS EVENT

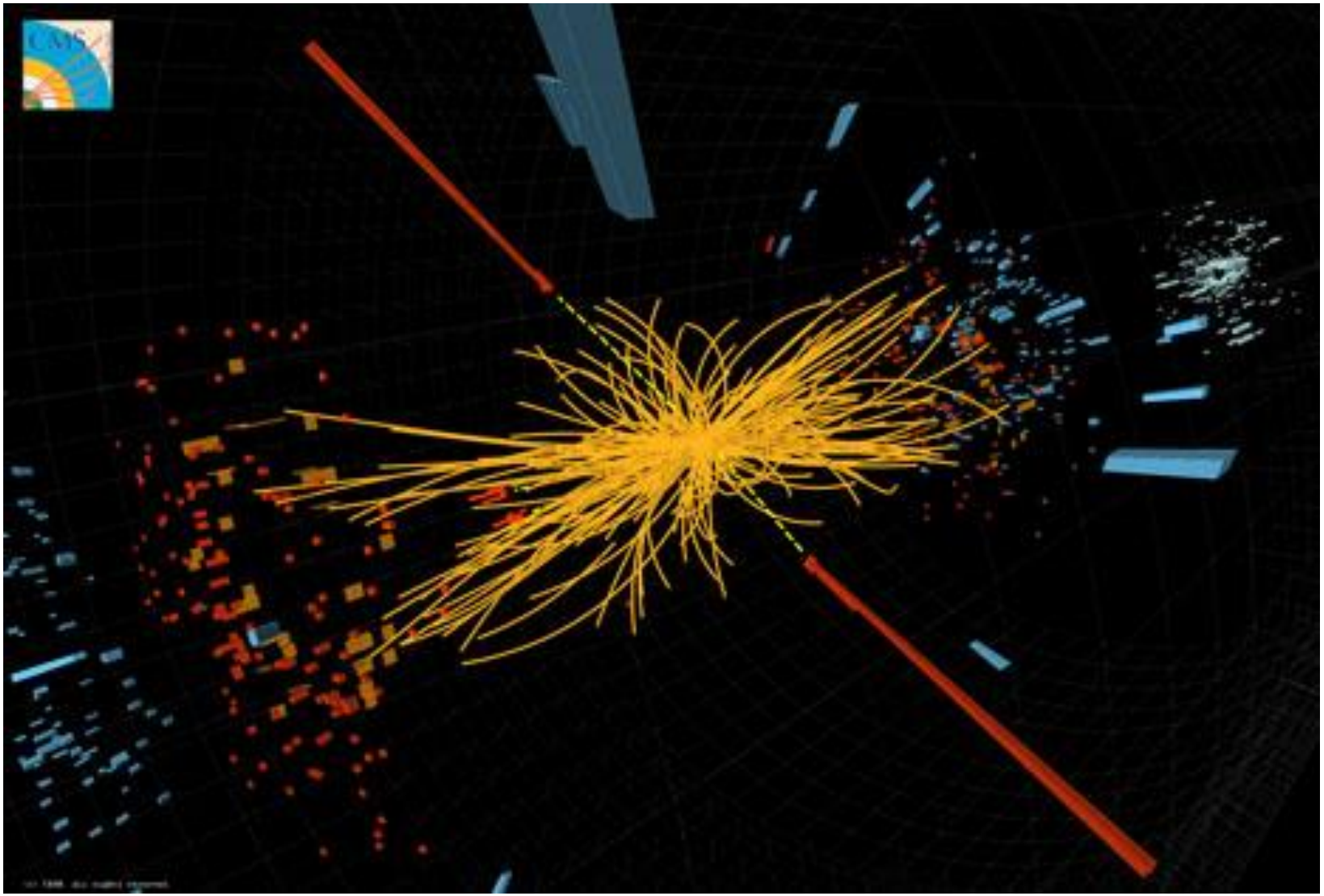


Courbes = trajectoire mesurée par les trajectographes

CMS 3


Trajectographe au silicium
Calorimètre électromagnetique
Calorimètre hadronique
Aimant supraconducteur
Retour de l'aimant avec chambres à muons
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
légende :
Muon
Électron
Hadron chargé
Hadron neutre
Photon

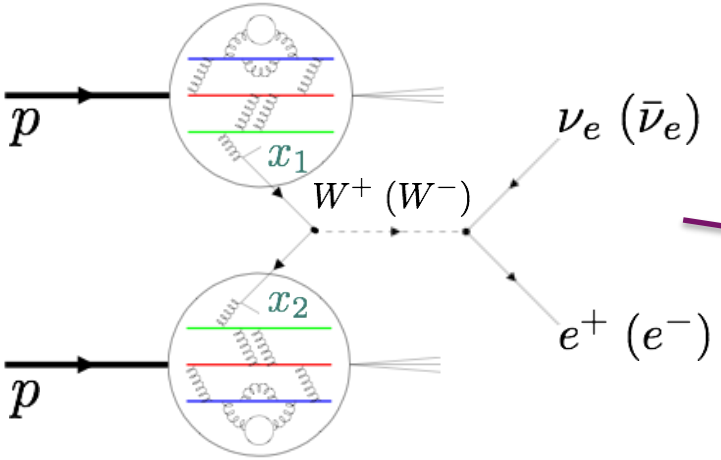
CMS EVENT

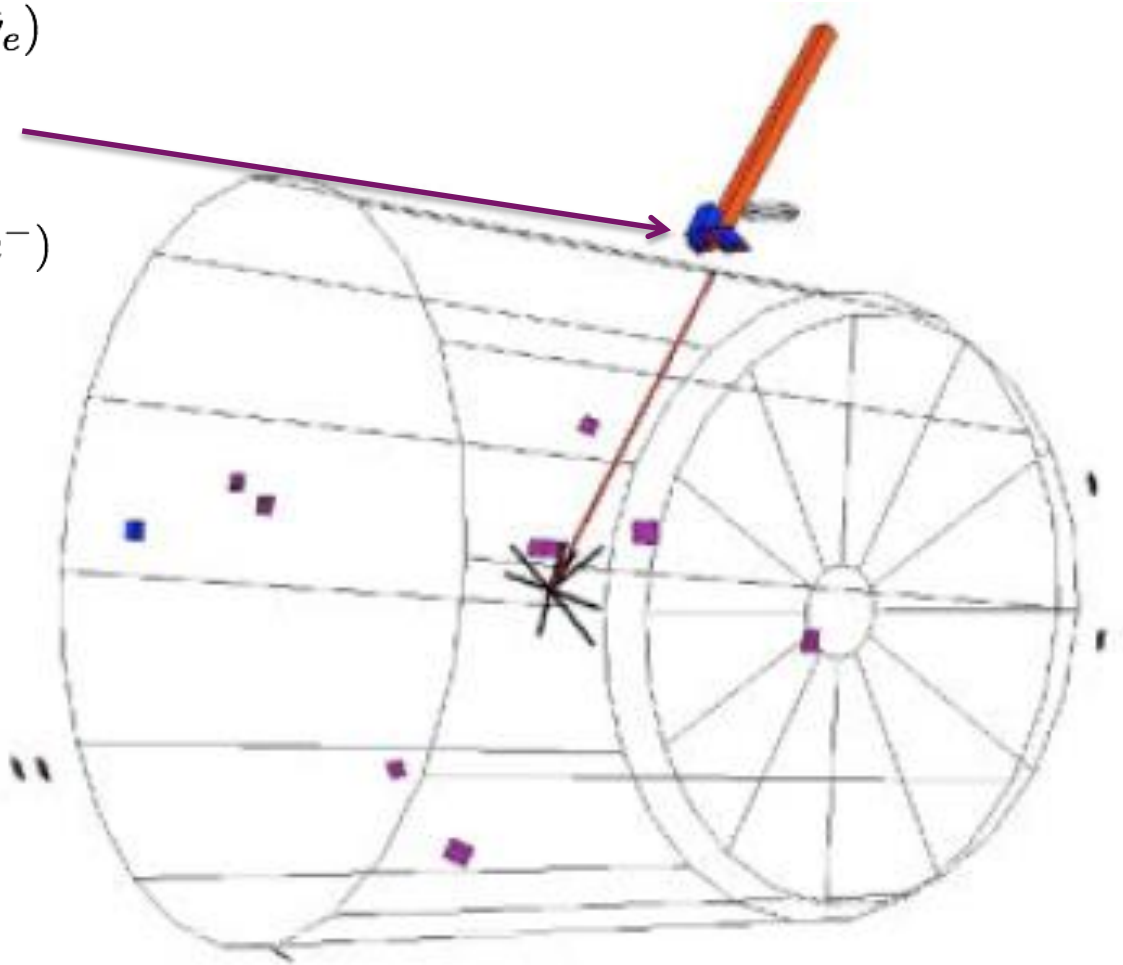


Courbes = trajectoire mesurée par les trajectographes

QCD EXAMPLE – W CROSS-SECTION

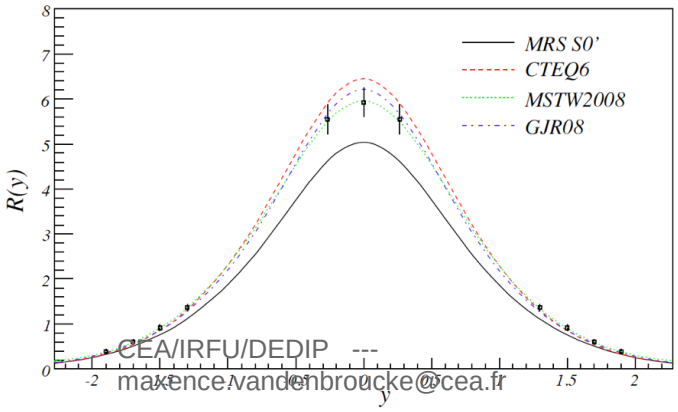
W EVENT -> ISOLATED LEPTON





STAR experiment at BNL

W+/W-



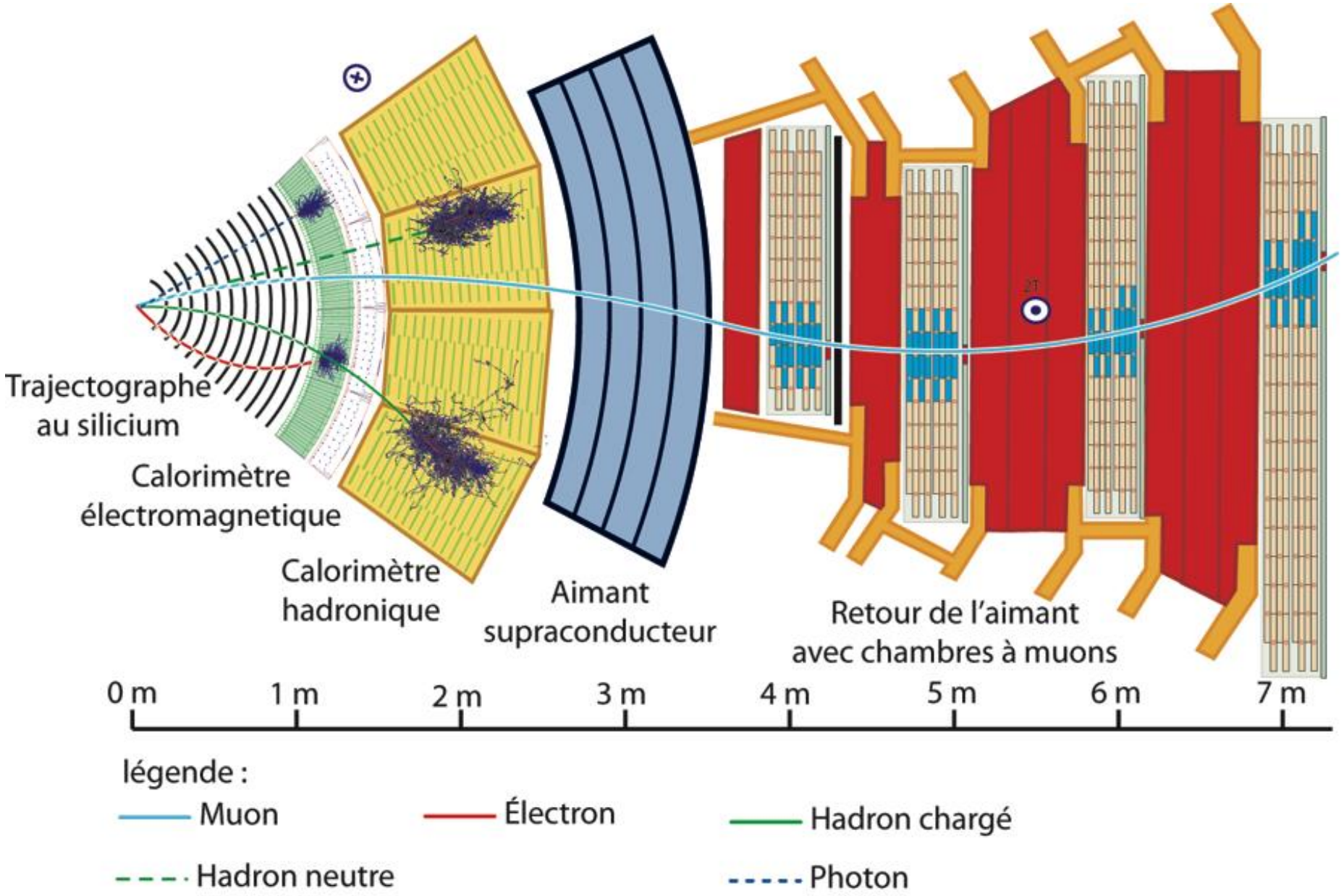
Mesurer l'infiniment petit et observer l'infiniment grand

Cours 2 : Les détecteurs de particules

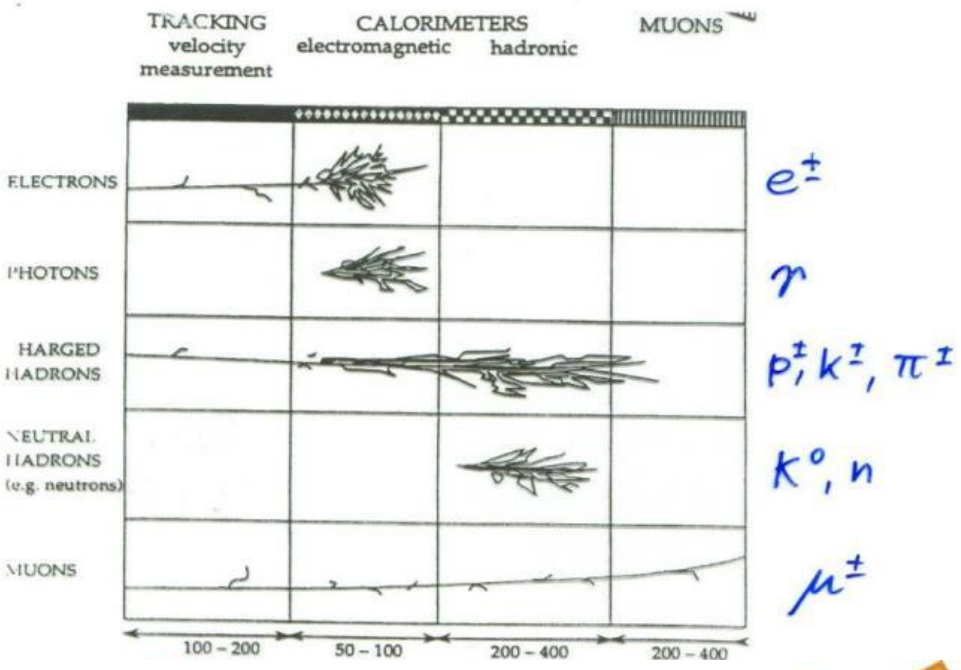
- **Trajectographie :**
  - **-Détecteurs Gazeux**
  - **-Détecteurs au Silicium**
- **Calorimétrie**
- **Scintillation**

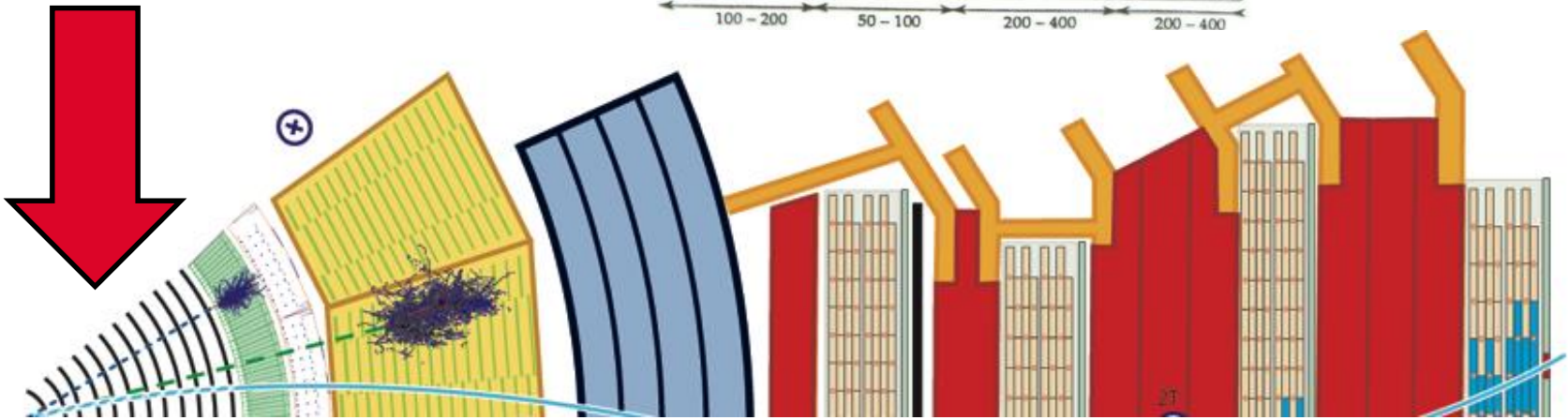
Basé sur les cours de Stefano Panebianco (CEA/IRFU), et le cours de Werner Riegler (CERN), Particle Detectors , Second Edition, C. Grupen & B. Shwartz

CMS 3

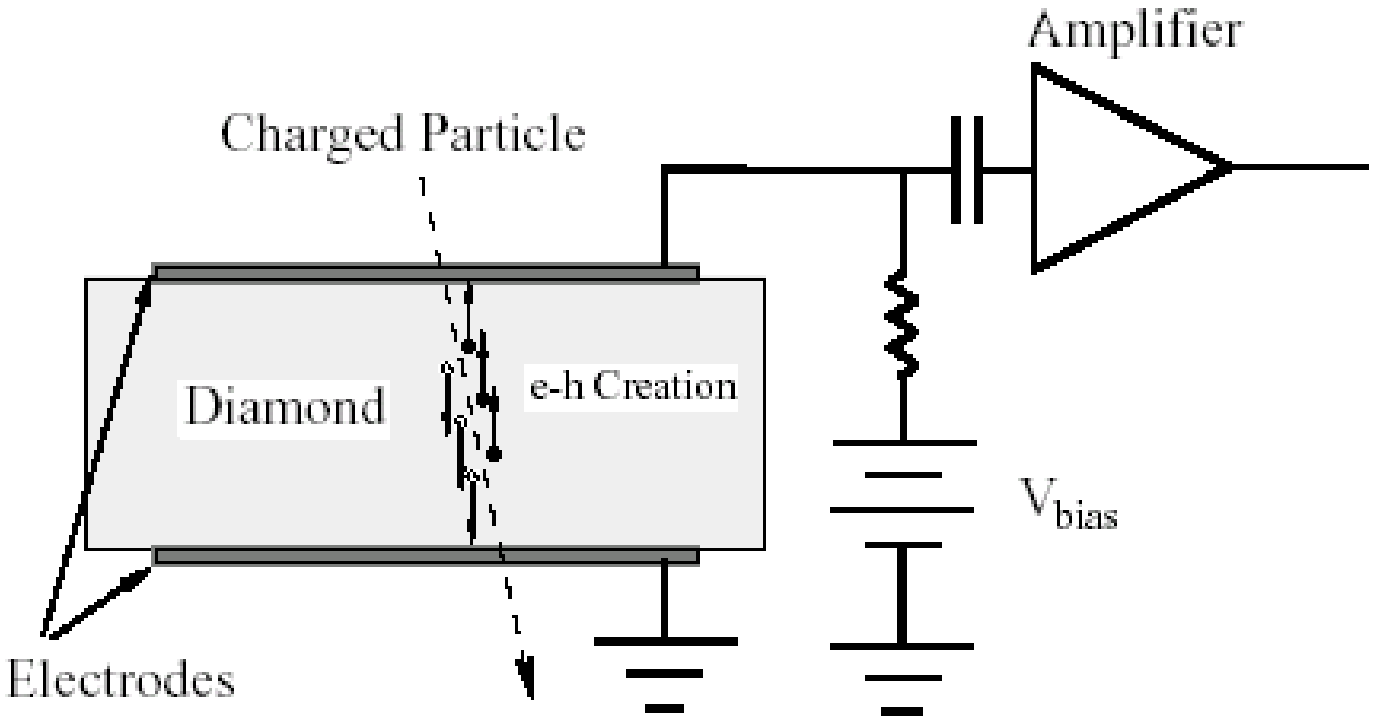

Trajectographe au silicium
Calorimètre électromagnetique
Calorimètre hadronique
Aimant supraconducteur
Retour de l'aimant avec chambres à muons
2T
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
légende :
Muon
Électron
Hadron chargé
Hadron neutre
Photon

Trajectographes Semi-Conducteur

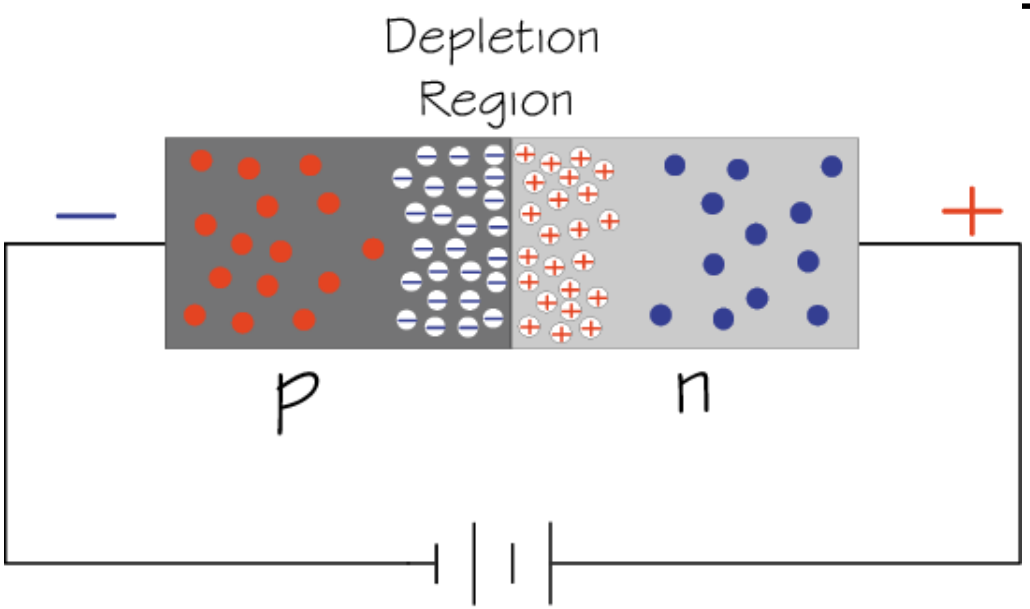




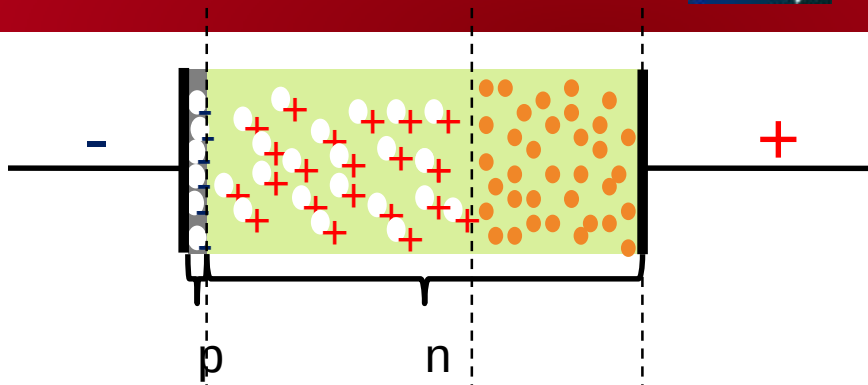
Les Détecteurs à base de Semi-Conducteur



Les Détecteurs à base de Semi-Conducteur

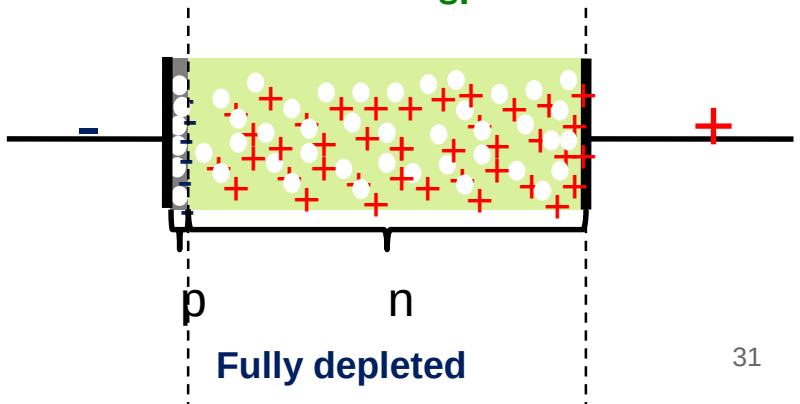


- Electron
- Positive ion from removal of electron in n-type impurity
- Negative ion from filling in p-type vacancy
- Hole



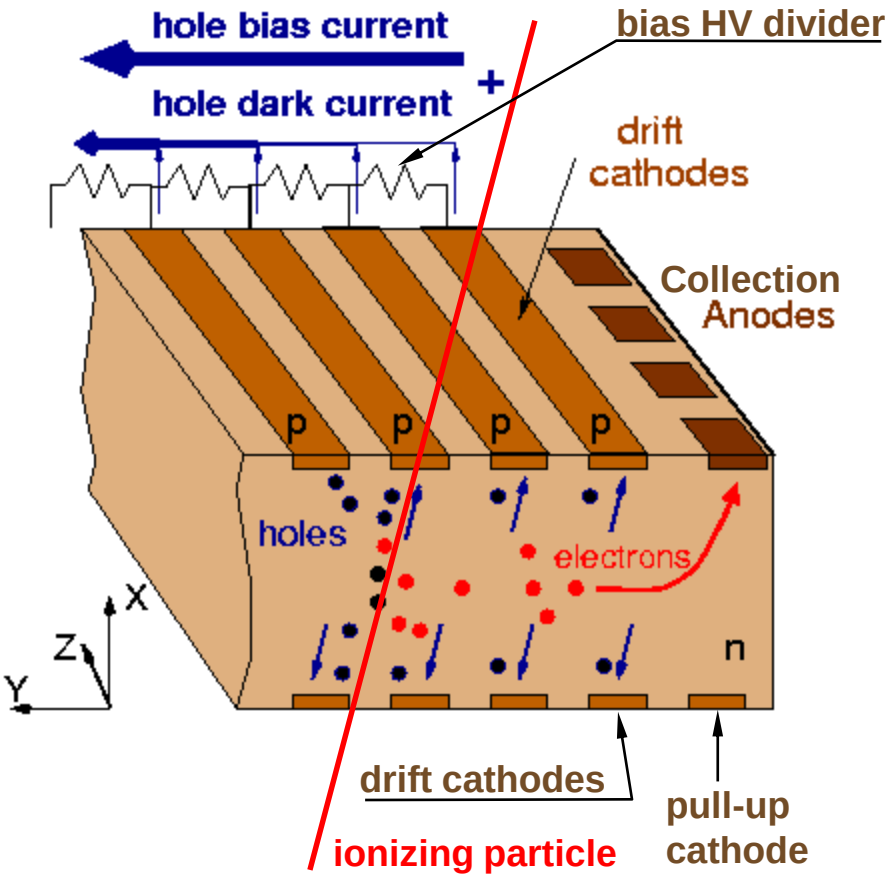
Zone without free charge carriers positively charged. Sensitive Detector Volume.

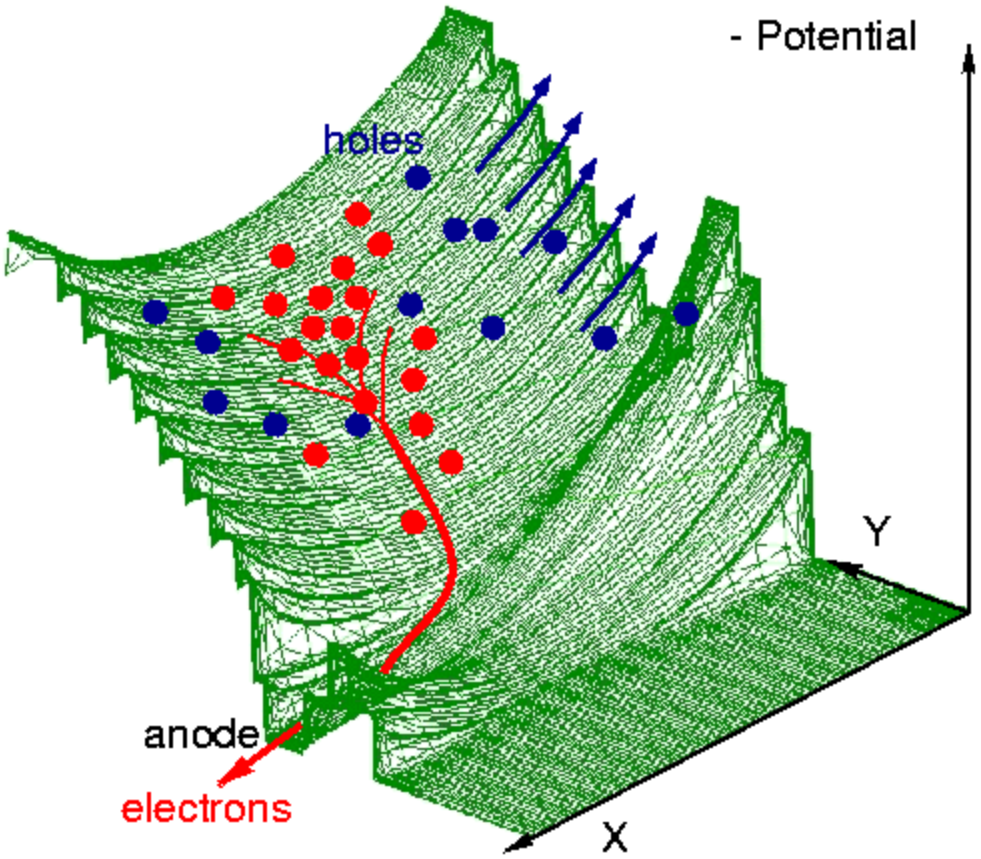
Zone with free electrons. Conductive. Insensitive to particles.



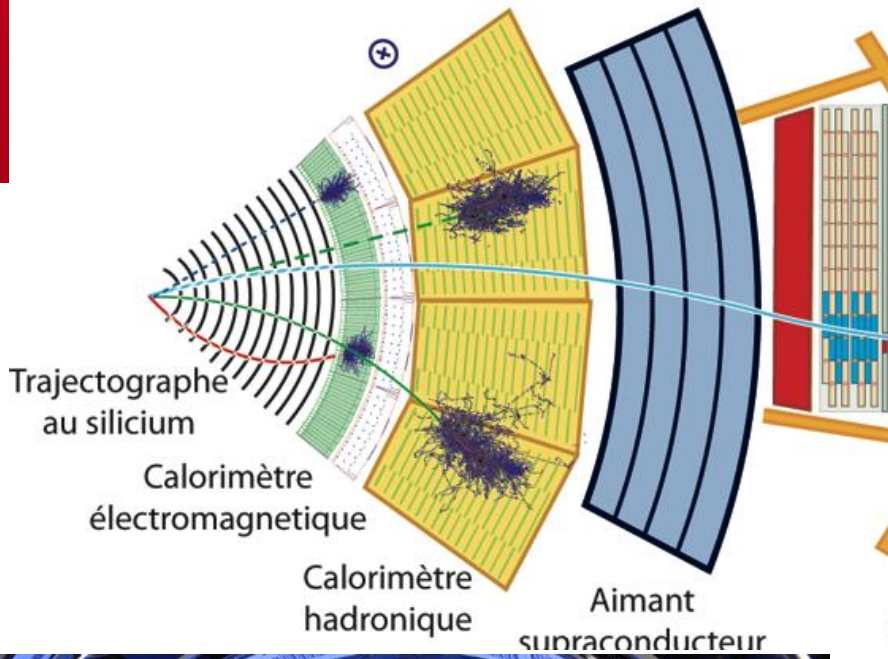
Fully depleted

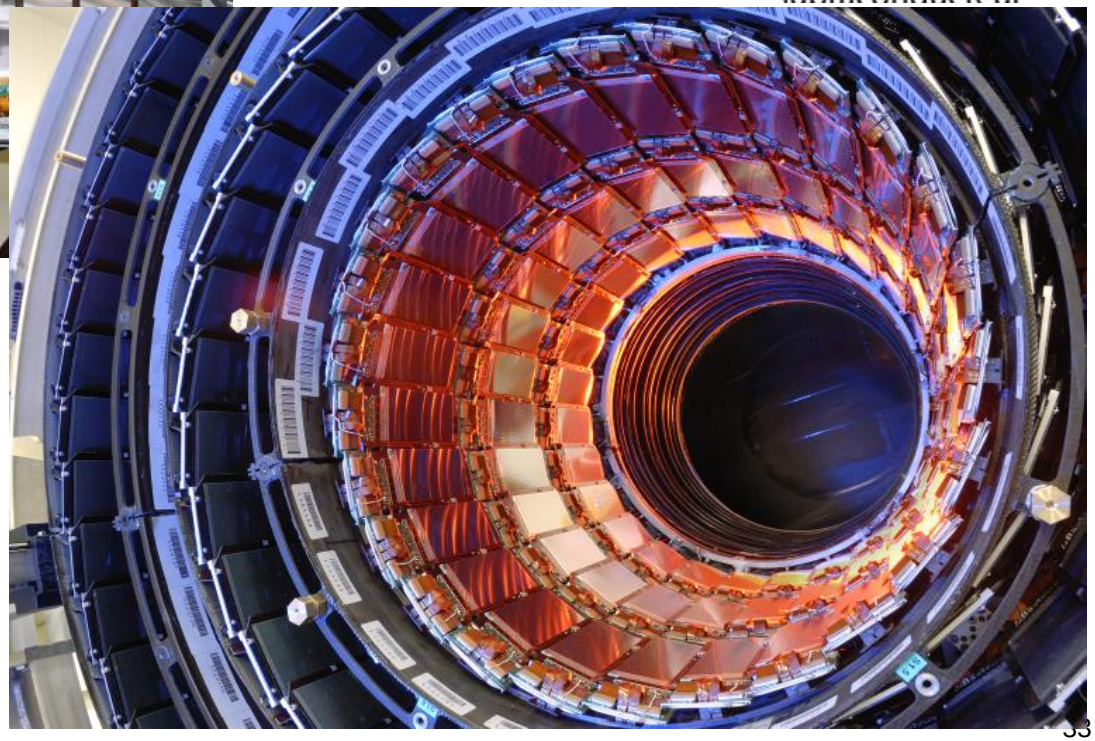
Silicon Drift Detector

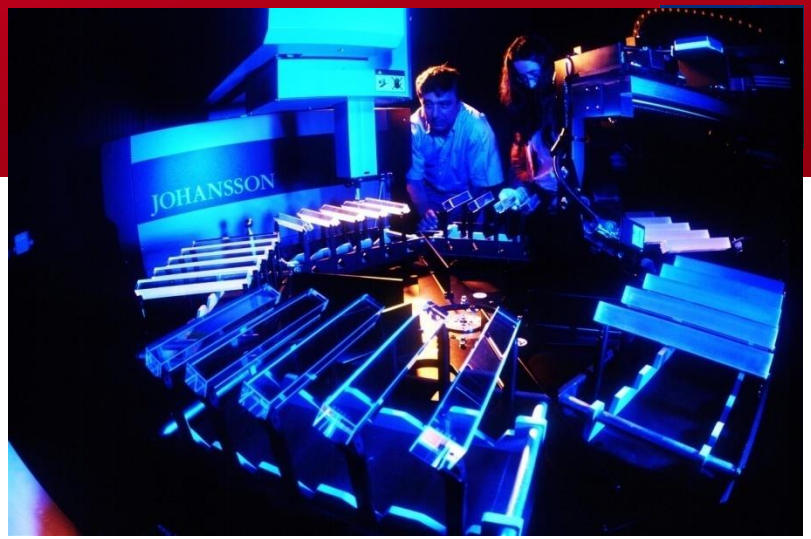




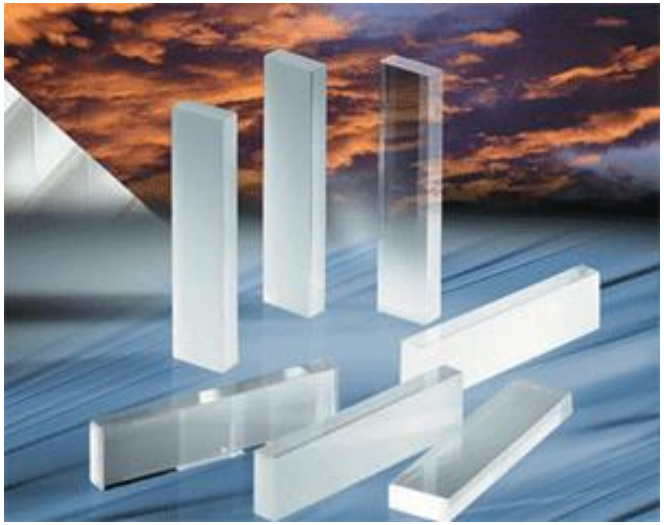
CMS Tracker

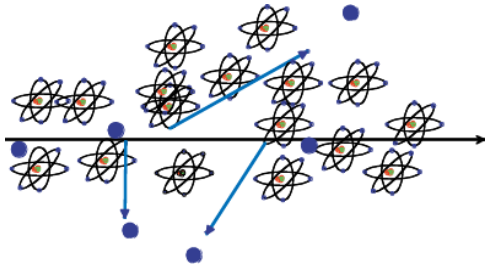

Trajectographe
au silicium
Calorimètre
électromagnetique
Calorimètre
hadronique
Aimant
supraconducteur





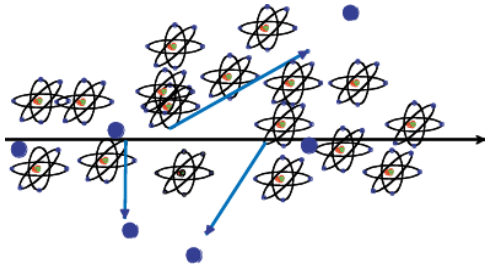
Les Détecteur à base de scintillation





Detectors based on Registration of excited Atoms → Scintillators

Emission of photons of by excited Atoms, typically UV to visible light.



Detectors based on Registration of excited Atoms → Scintillators

Emission of photons of by excited Atoms, typically UV to visible light.

a) **Observed in Noble Gases (even liquid !)**

b) **Inorganic Crystals**

→ **Substances with largest light yield. Used for precision measurement of energetic Photons. Used in Nuclear Medicine.**

c) **Polyzyclic Hydrocarbons (Naphtalen, Anthrazen, organic Scintillators)**

→ ***Most important category. Large scale industrial production, mechanically and chemically quite robust. Characteristic are one or two decay times of the light emission.***

Organic ('Plastic') Scintillators

Inorganic (Crystal) Scintillators

Low Light Yield **Fast: 1-3ns**

Type	Light output[a]	λ_{max}[b] (nm)	Attenuation length[c] (cm)	Risetime (ns)	Decay time[d] (ns)	Pulse FWHM (ns)
NE 102A	58–70	423	250	0.9	2.2–2.5	2.7–3.2
NE 104	68	406	120	0.6–0.7	1.7–2.0	2.2–2.5
NE 104B	59	406	120	1	3.0	3
NE 110	60	434	400	1.0	2.9–3.3	4.2
NE 111	40–55	375	8	0.13–0.4	1.3–1.7	1.2–1.6
NE 114	42–50	434	350–400	~1.0	4.0	5.3
Pilot B	60–68	408	125	0.7	1.6–1.9	2.4–2.7
Pilot F	64	425	300	0.9	2.1	3.0–3.3
Pilot U	58–67	391	100–140	0.5	1.4–1.5	1.2–1.9
BC 404	68	408	—	0.7	1.8	2.2
BC 408	64	425	—	0.9	2.1	~2.5
BC 420	64	391	—	0.5	1.5	1.3
ND 100	60	434	400	—	3.3	3.3
ND 120	65	423	250	—	2.4	2.7
ND 160	68	408	125	—	1.8	2.7

Large Light Yield **Slow: few 100ns**

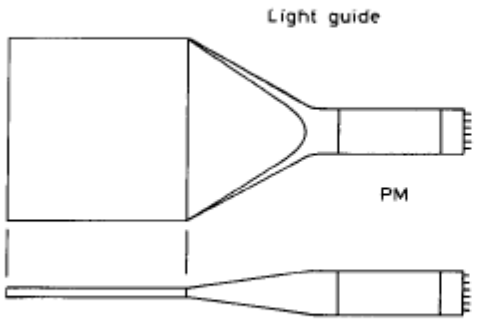
	Relative light output	λ_{max} emission (nm)	Decay time (ns)	Density (g/cm³)
Inorganic crystals				
NaI(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
$Bi_4Ge_3O_{12}$ (BGO)	23–86	480	300	7.13
Organic crystals				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330–348	76–96	1.03
p,p'-Quarterphenyl	94	437	7.5	1.20
Primary activators				
2,5-Diphenyl-oxazole (PPO)	75	360–416	5[a]	
2-Phenyl-5-(4-biphenylyl)-1,3,4-oxadiazole (PBD)	96	360–5		
4,4"-Bis(2-butyloctyloxy)-*p*-quaterphenyl (BIBUQ)	60	365,393	1.30[b]	

LHC bunchcrossing 25ns

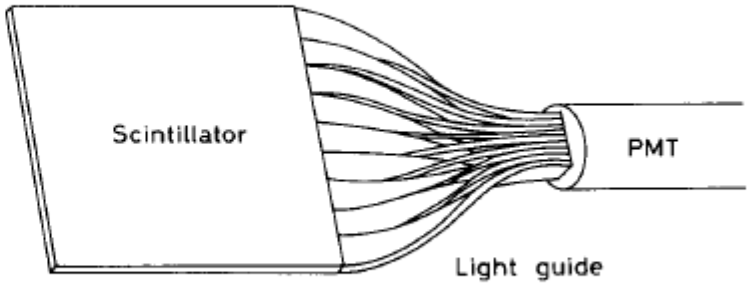
LEP bunchcrossing 25μs

Typical Geometries:

- Light guides: transfer by total internal reflection (+outer reflector)

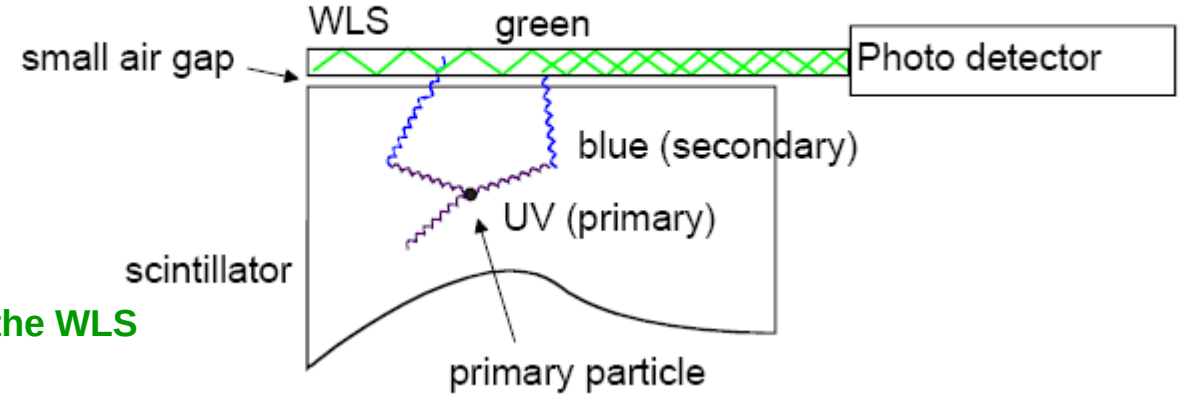


"fish tail"



adiabatic

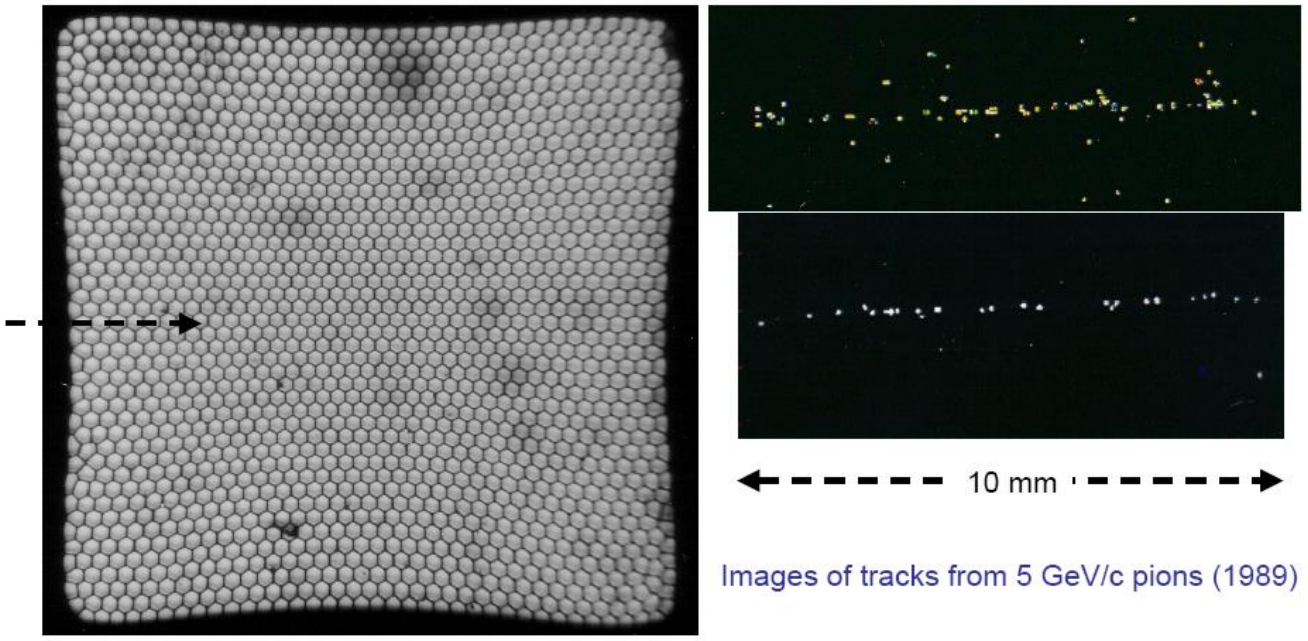
- wavelength shifter (WLS) bars



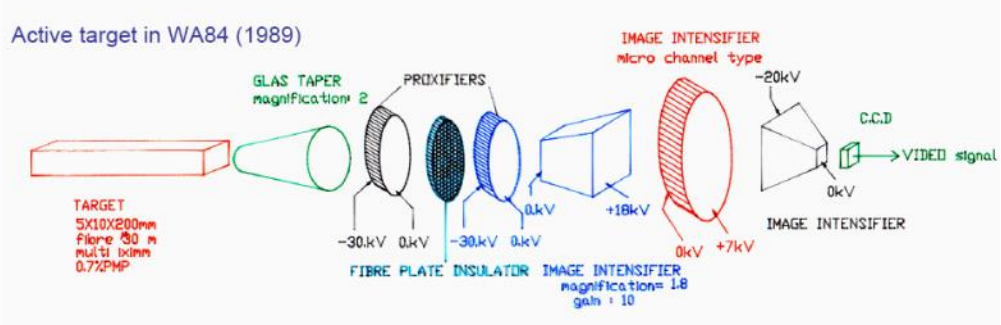
UV light enters the WLS material
Light is transformed into longer wavelength
→Total internal reflection inside the WLS material
→ 'transport' of the light to the photo detector

From C. Joram

Fiber Tracking

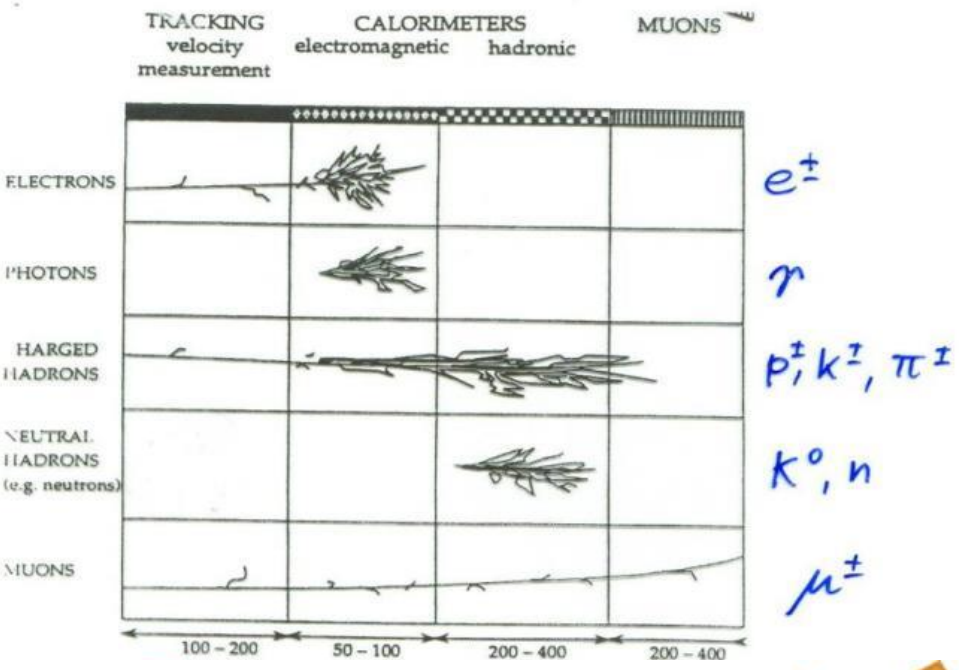


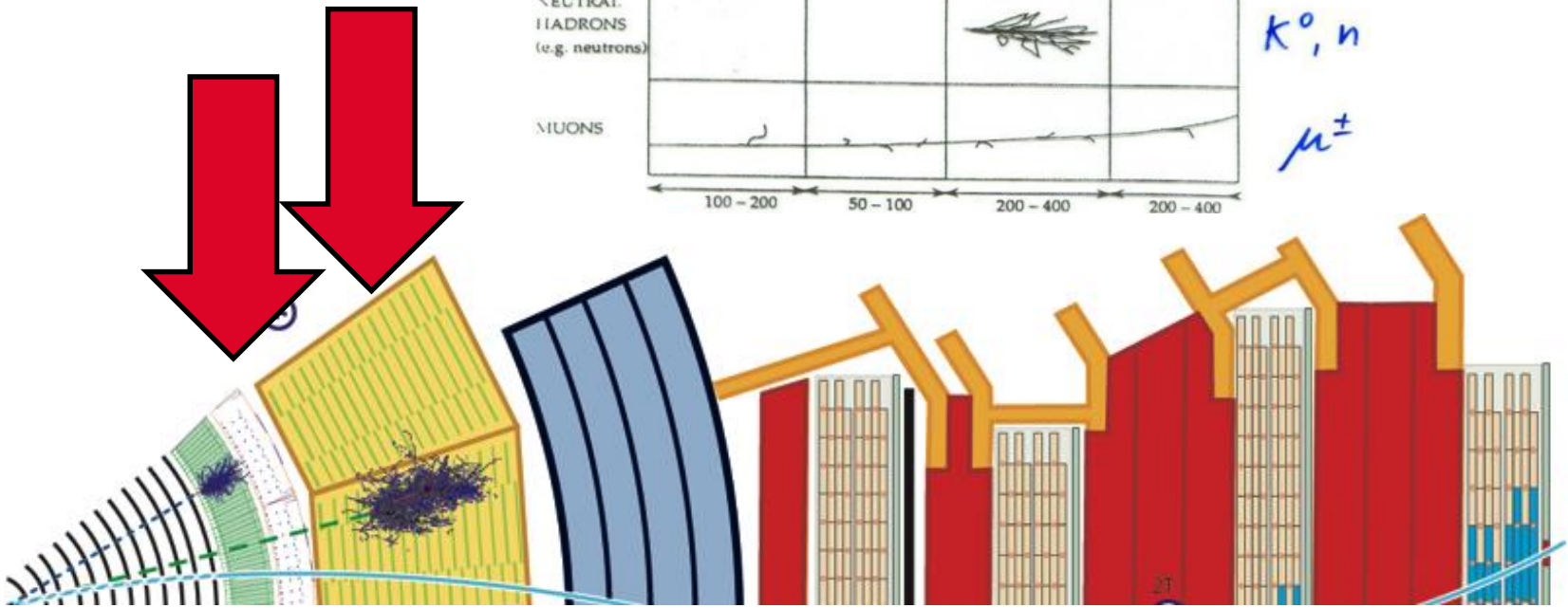
Images of tracks from 5 GeV/c pions (1989)



Readout of photons in a cost effective way is rather challenging.

Calorimétrie





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:

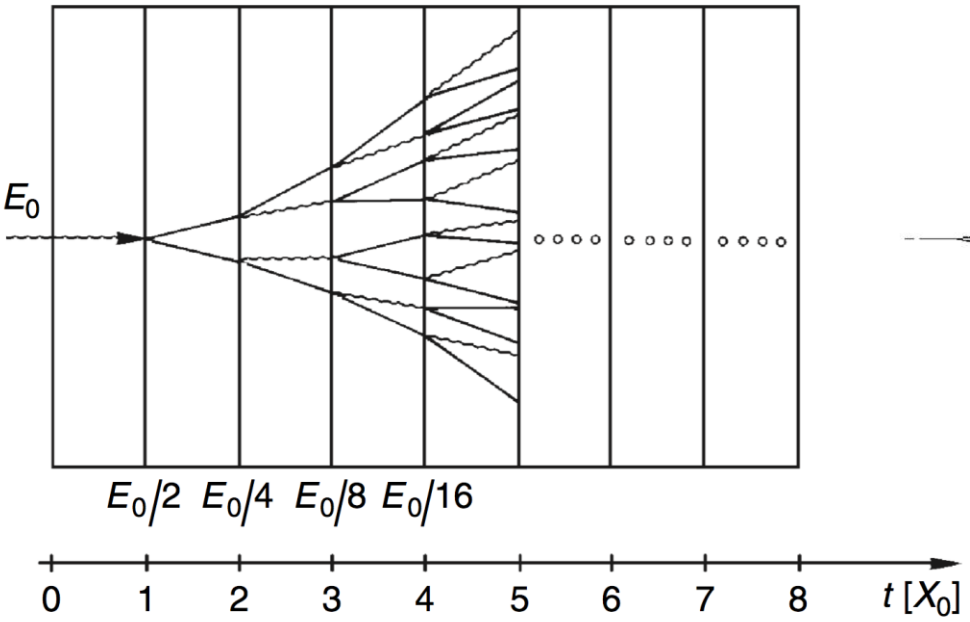
Homogeneous Calorimeters,
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

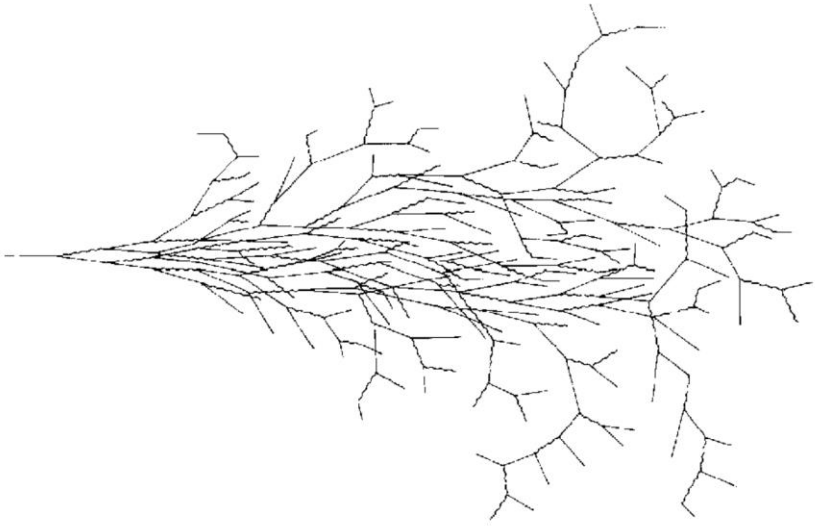
Sampling Calorimeters,
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

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

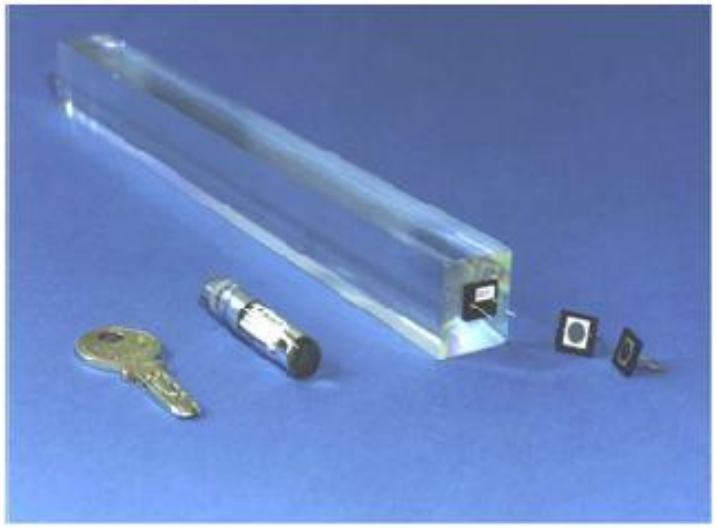
EM Calorimetry

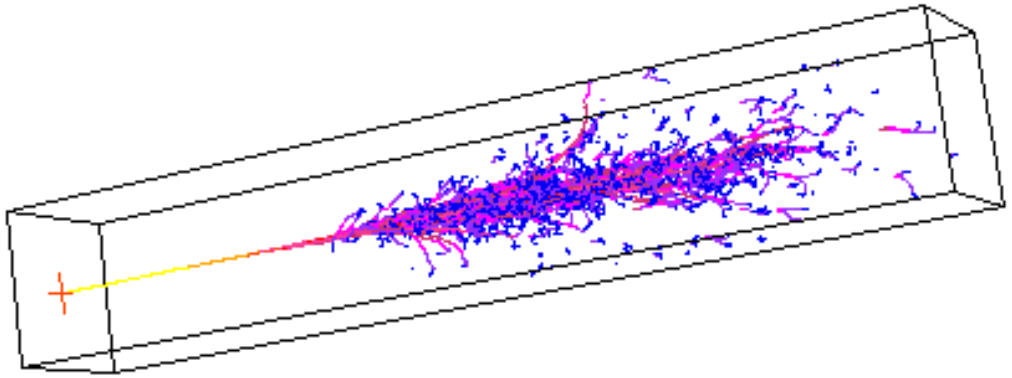
At high energies (higher than 100 MeV) electrons lose their energy almost exclusively by bremsstrahlung while photons lose their energy by electron–positron pair production

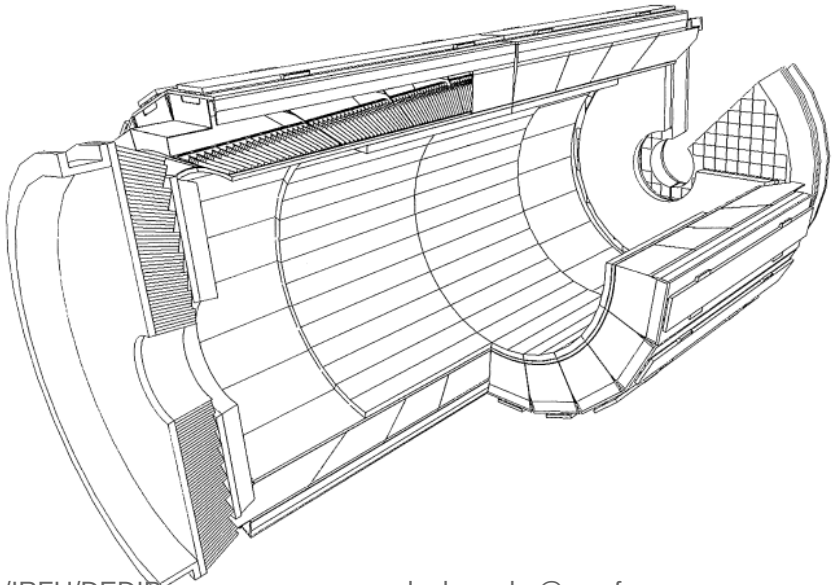




Crystals for Homogeneous EM Calorimetry







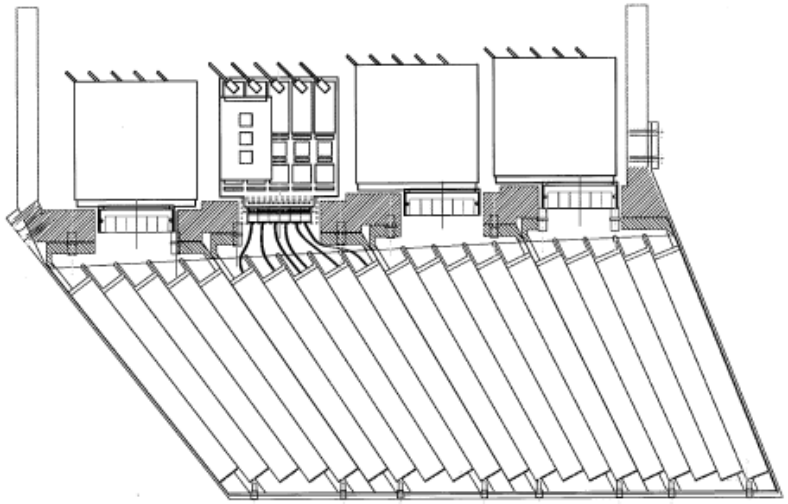


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Hadron Calorimeters are Large because is large

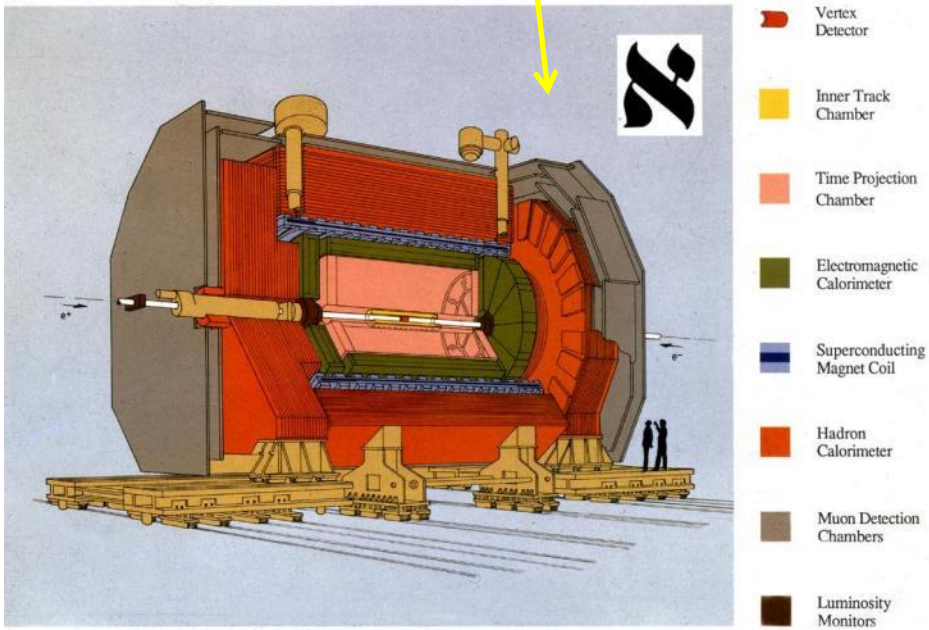
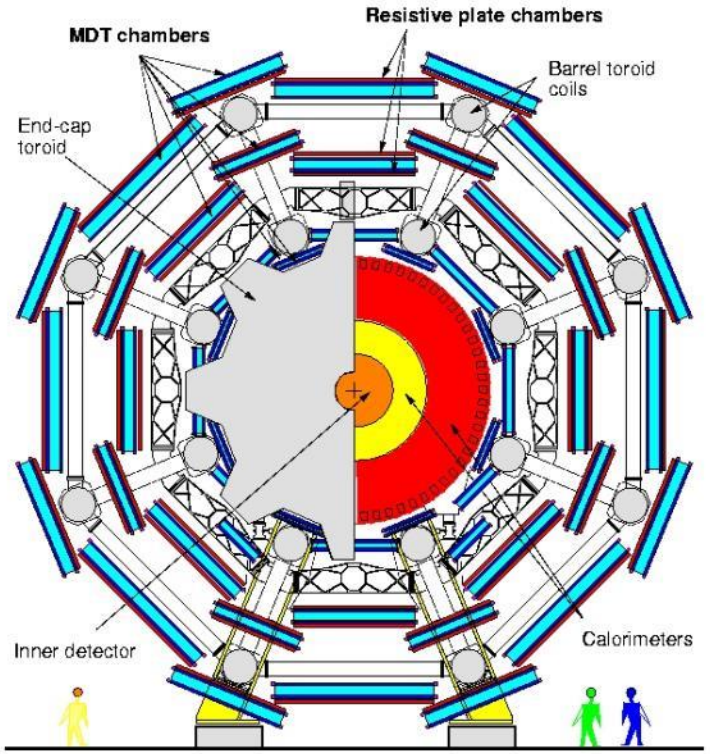
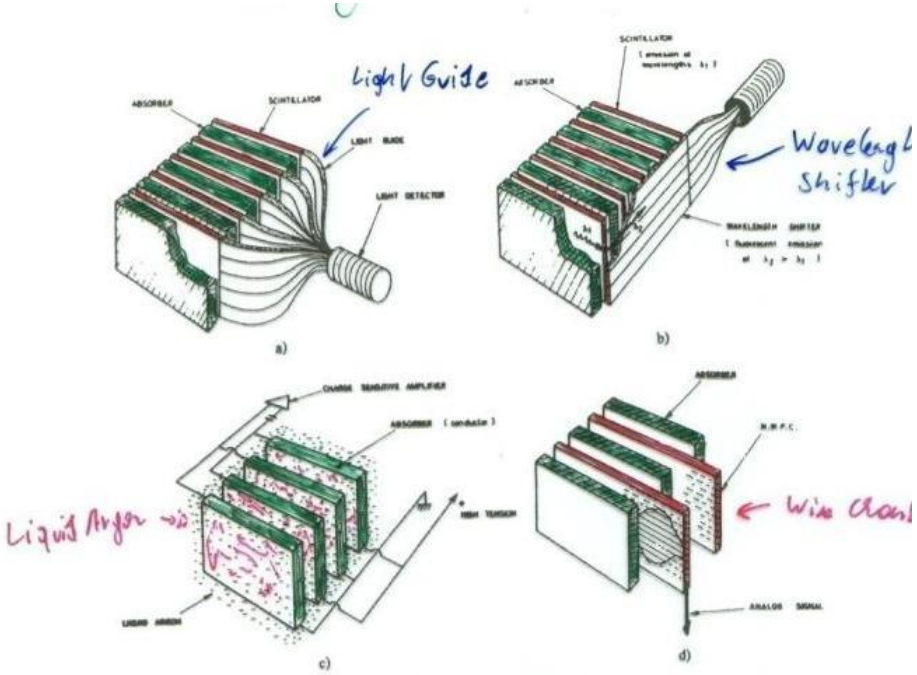


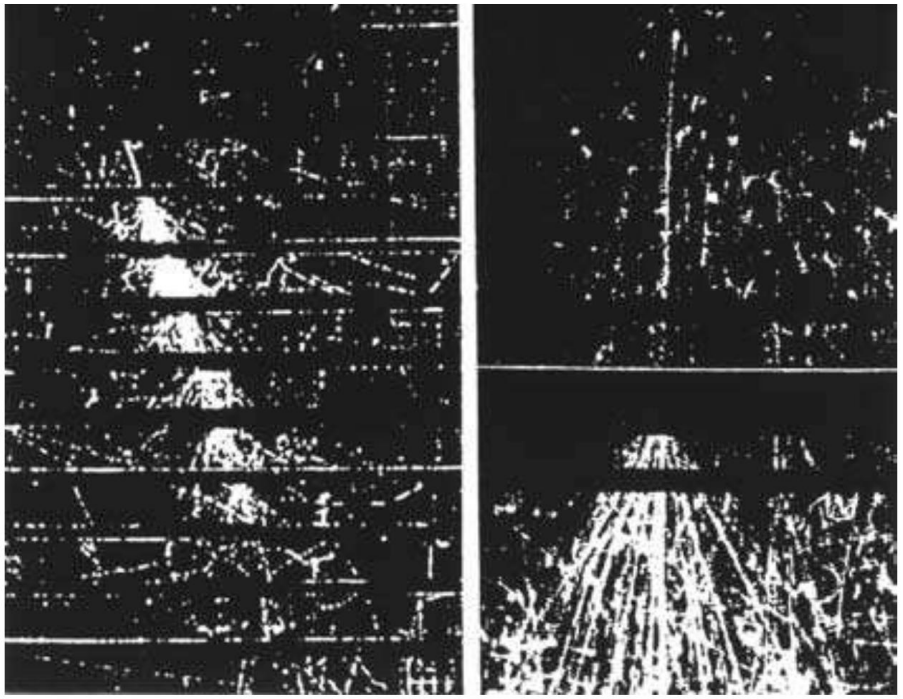
Fig. 1 - The ALEPH Detector

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

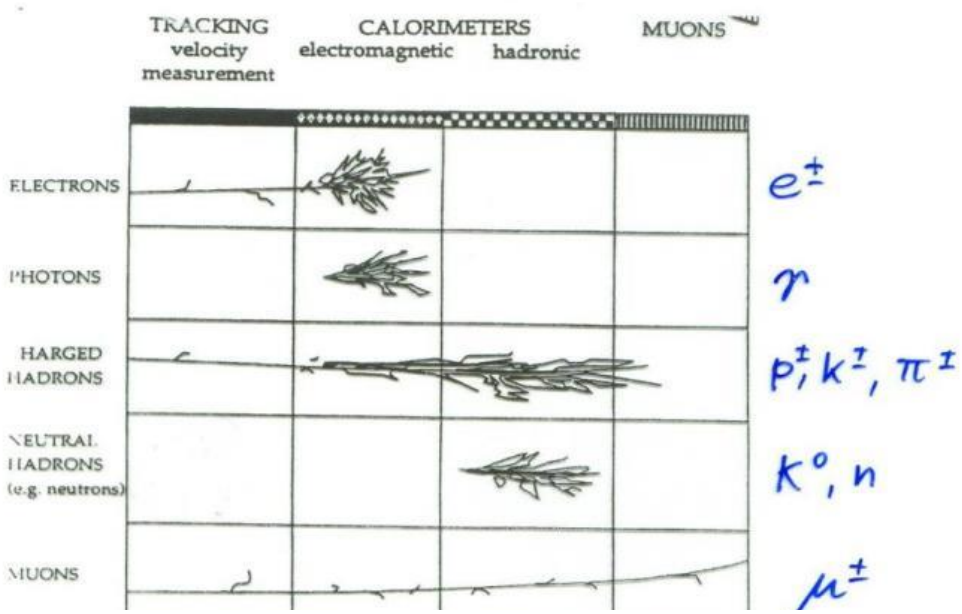


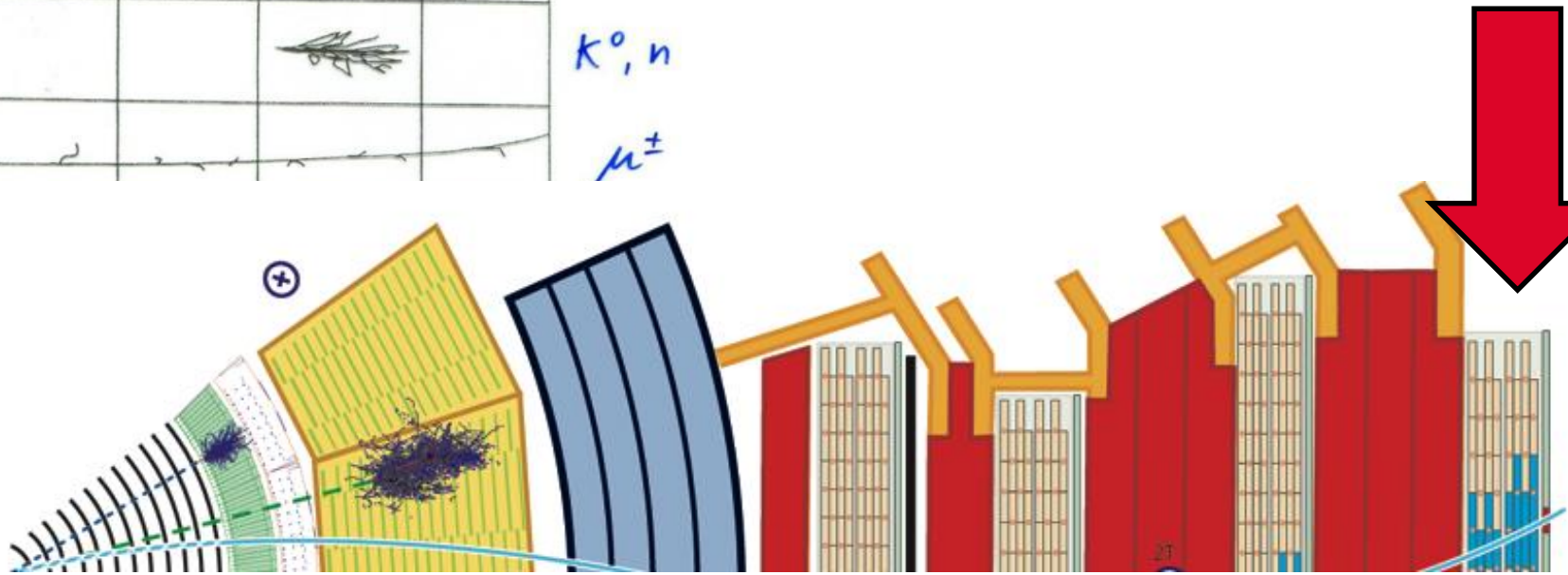
Sampling Calorimeters



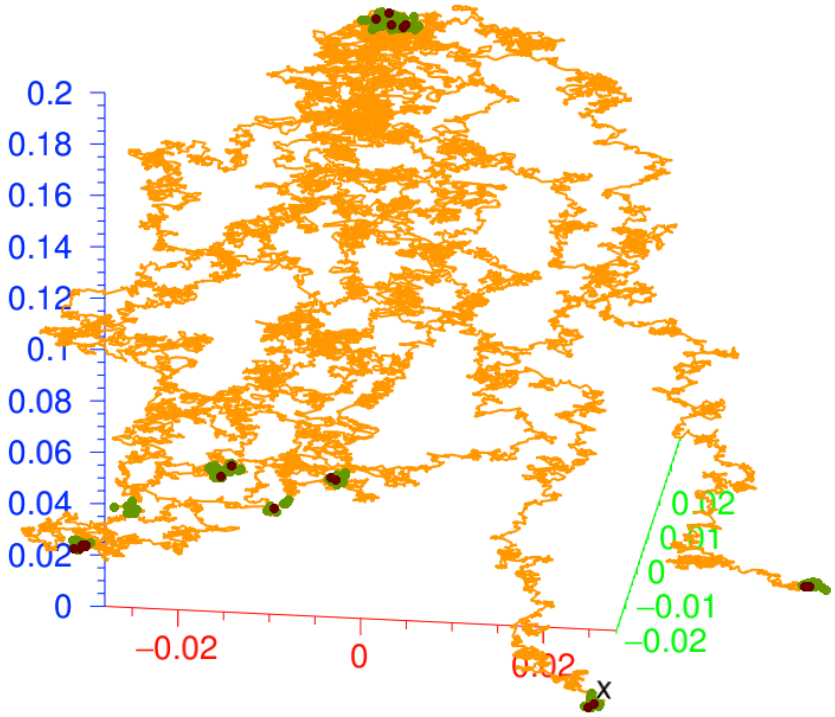


Détecteurs Gazeux

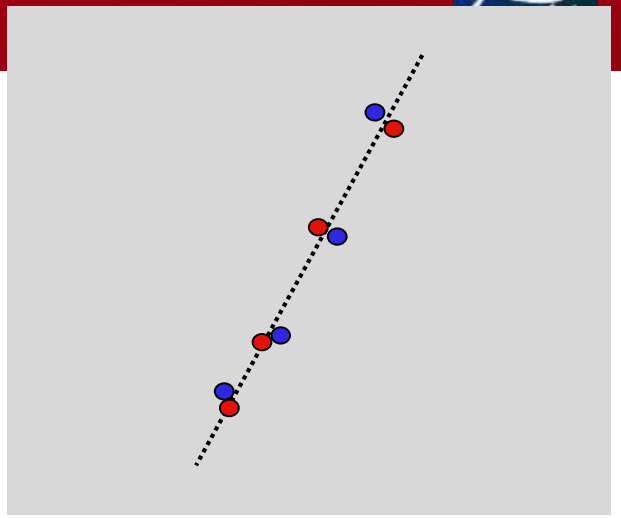




La détection des particules: exemple des détecteurs gazeux



Production de paires électron-ion :

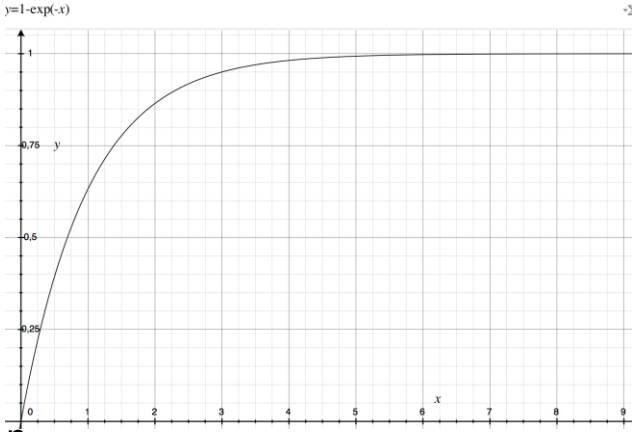


- Les interactions Coulombiennes entre le champ électrique de la particule et les atomes du milieu produisent des paires électron-ion.
- Les ionisations multiples suivent une statistique de Poisson:

$$P_k^n = \frac{n^k}{k!} e^{-n}$$

n : moyen

k : mesuré

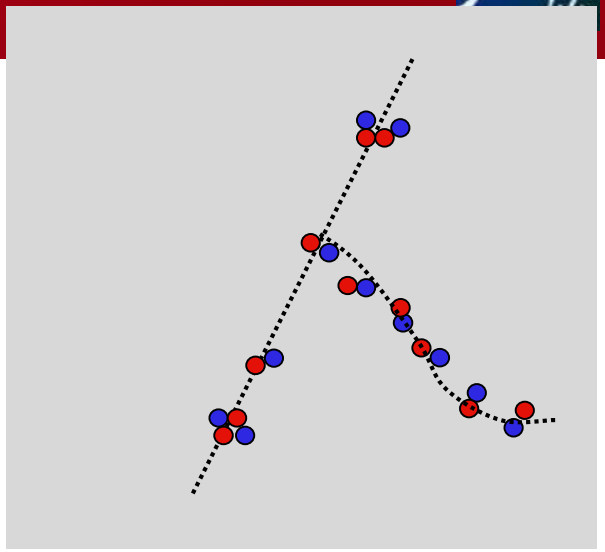


- Efficacité de détection: $e = 1 - P_0^n = 1 - e^{-n}$
- Mécanismes d'ionisation :

- Excitation: $X + p \rightarrow X^* + p$ puis $X^* \rightarrow X^+ + e^-$
- Ionisation: $X + p \rightarrow X^+ + p + e^-$
- *Effet Penning*: $Ne^* + Ar \rightarrow Ne + Ar^+ + e^-$

CEA/IRFU/DEDIP --- maxence.vandenbroucke@cea.fr

IONISATION TOTALE



- Les électrons primaires ionisent à nouveau le milieu et produisent localement de nouveaux groupes de paires électron-ion. Si l'électron secondaire a suffisament d'énergie il peut produire une longue trace (électronδ).

- Nombre total de paires:

$$n_T = \frac{\Delta E}{w_i}$$

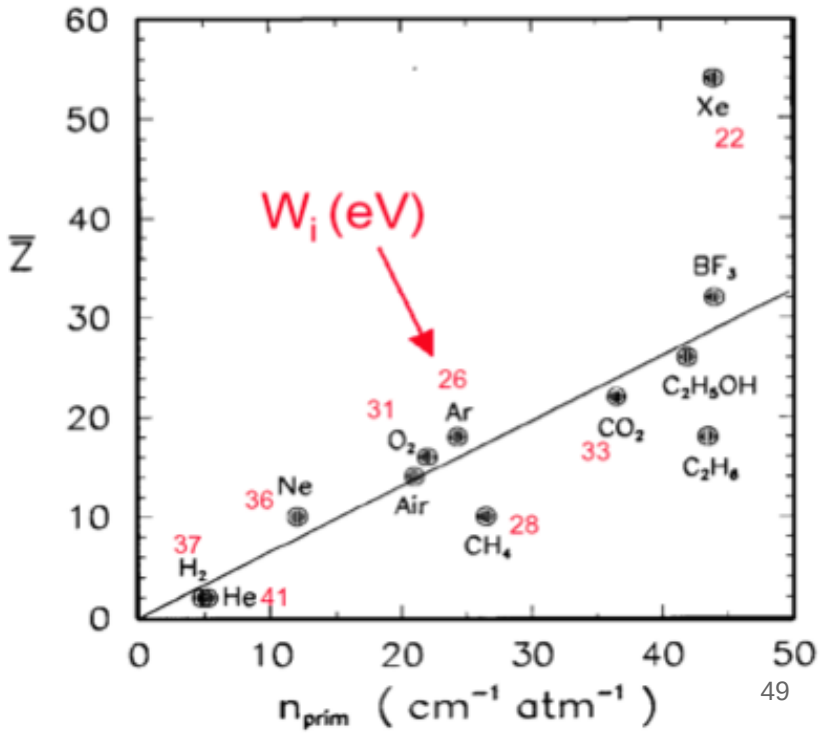
ΔE : perte d'énergie de la particule

w_i : énergie moyenne par paire

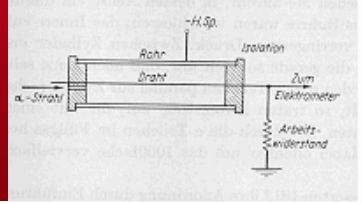
M.I.P. dans l'argon:

– ΔE= 2,65 keV/cm $\quad w_i$ = 25 eV

– $n_T \approx 106$ paires électron-ion/cm

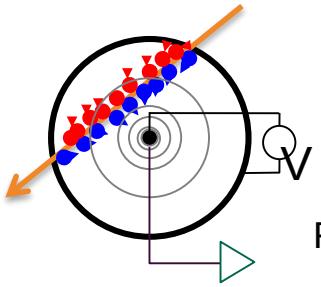


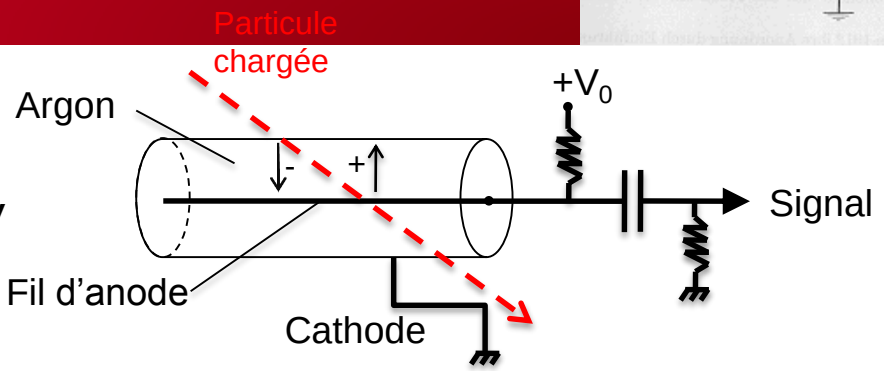
EXEMPLE SIMPLE DE DÉTECTEUR

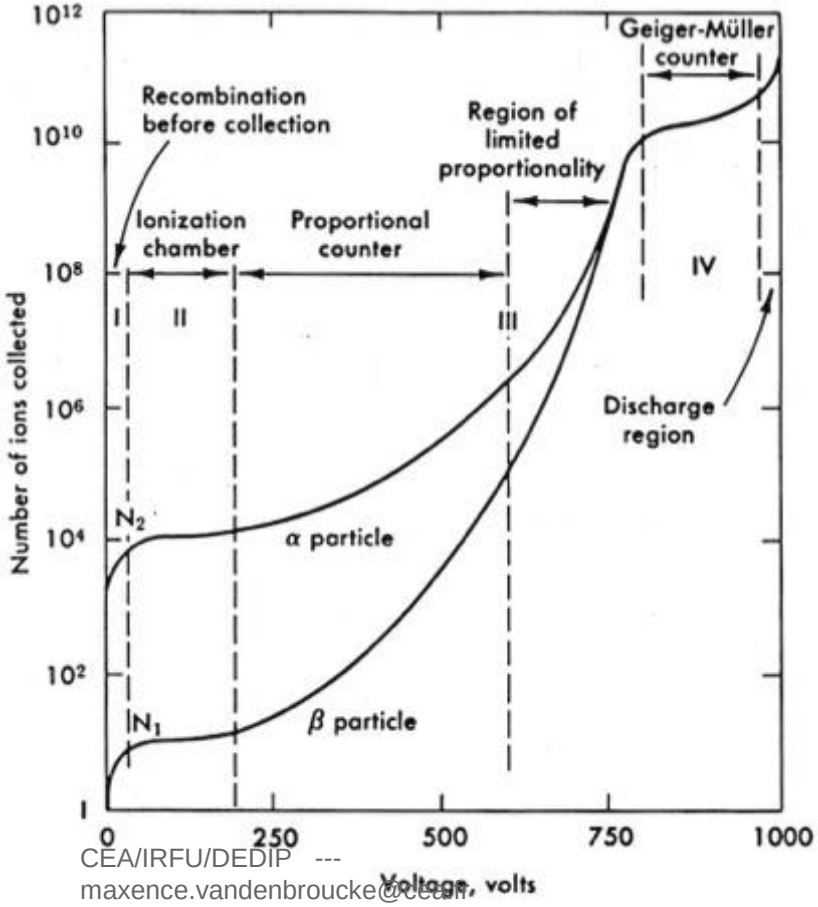


(RADIAL) AVEC: $E = \frac{1}{r}\frac{V_0}{\ln(b/a)}$

- R : DISTANCE RADIALE À L'AXE
- B : RAYON INTERNE DU CYLINDRE
- A : RAYON DU FIL D'ANODE







I: tension trop faible→ recombinaison

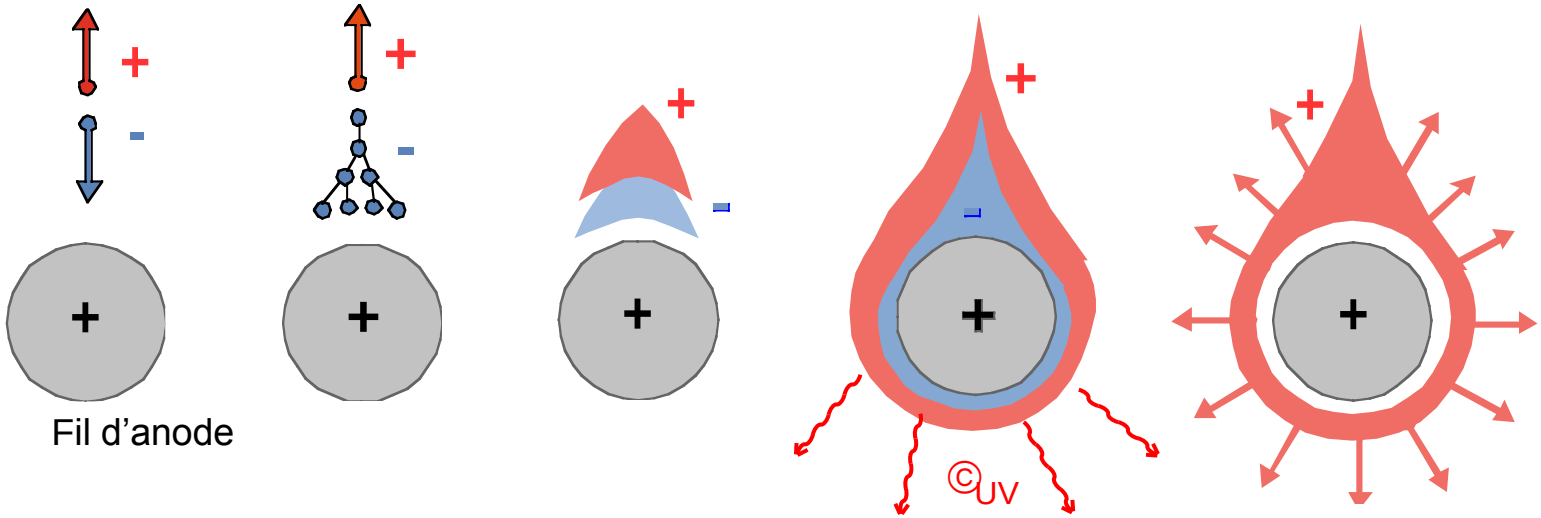
II: Chambre d'ionisation. Collection des charges sans amplification.

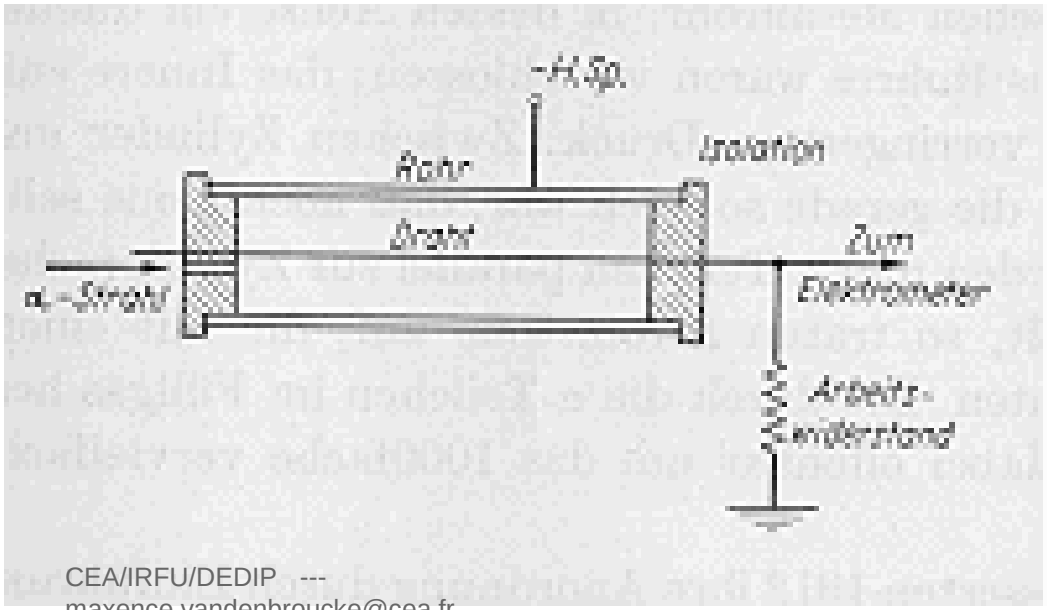
IIIa: Mode **proportionnel**. Le signal est amplifié et proportionnel à l'énergie déposée.

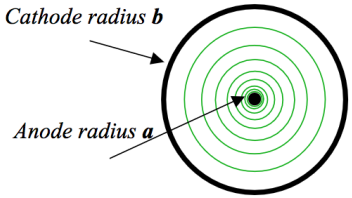
IIIb: Mode **Streamer**. Phénomènes secondaires induits par les photons de la première avalanche → Gaz quencher

IV: Mode **Geiger-Müller**. Avalanche dans tout le détecteur. Le courant de sortie est saturé.

PHÉNOMÈNE D'AVALANCHE AUTOUR D'UN FILS







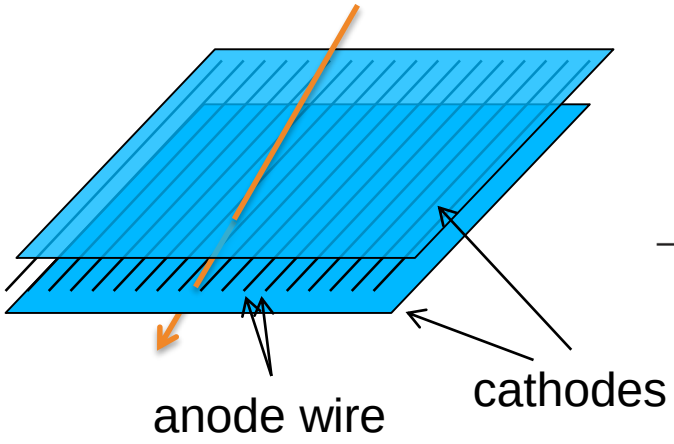
ELECTRIC FIELD AND POTENTIAL:

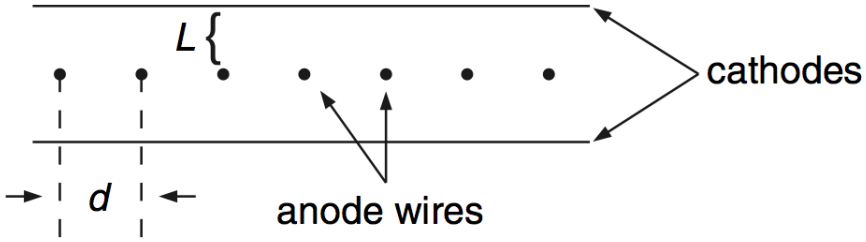
$$E(r) = \frac{CV_0}{2\pi\varepsilon_0}\frac{1}{r}$$

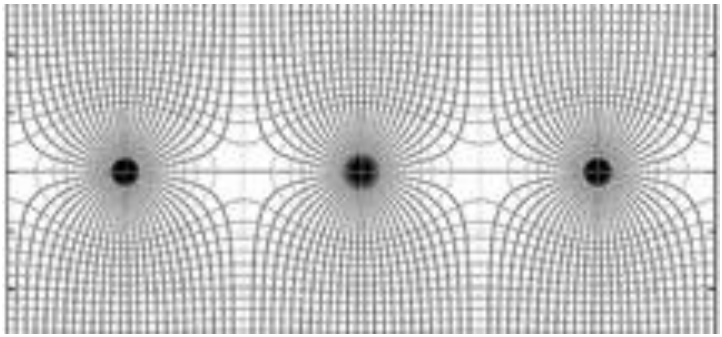
$$V(r) = \frac{CV_0}{2\pi\varepsilon_0}\ln\frac{r}{a}$$

$$C = \frac{2\pi\varepsilon_0}{\ln(b/a)}$$ capacitance per unit length

MWPCS







GRANDE CHAMBRE À FILS (1972)

En comparaison des chambres à étincelles et des chambres à bulles, les chambres à fils sont plus rapides, présentent de meilleures résolutions spatiale et temporelle, sans temps mort significatif et résistantes aux radiations.

PRIX NOBEL DE PHYSIQUE 1992

The Royal Swedish Academy of Sciences awards the 1992 Nobel Prize in Physics to **Georges Charpak** for his invention and development of particle detectors, in particular the multiwire proportional chamber.

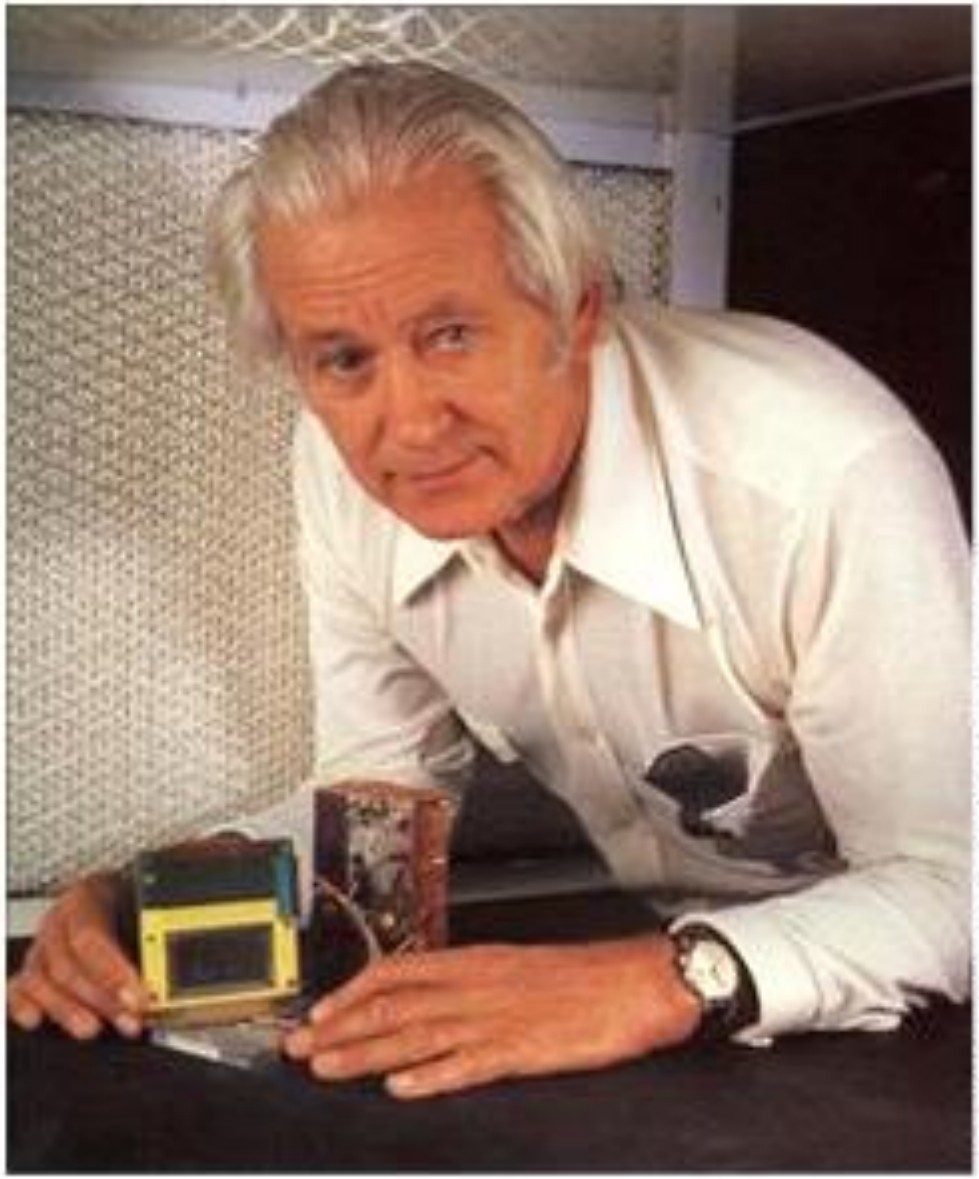


Photo: D. Parker, Science Photo Lab. UK

Georges Charpak
CERN, Geneva, Switzerland

NOBEL PRICES FOR INSTRUMENTATION

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron & Discoveries
1948: P.M.S. Blacket, Cloud Chamber & Discoveries
1950: C. Powell, Photographic Method & Discoveries
1954: Walter Bothe, Coincidence method & Discoveries
1960: Donald Glaser, Bubble Chamber
1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries
1992: Georges Charpak, Multi Wire Proportional Chamber
2009: Boyle and Smith for the CCD sensor

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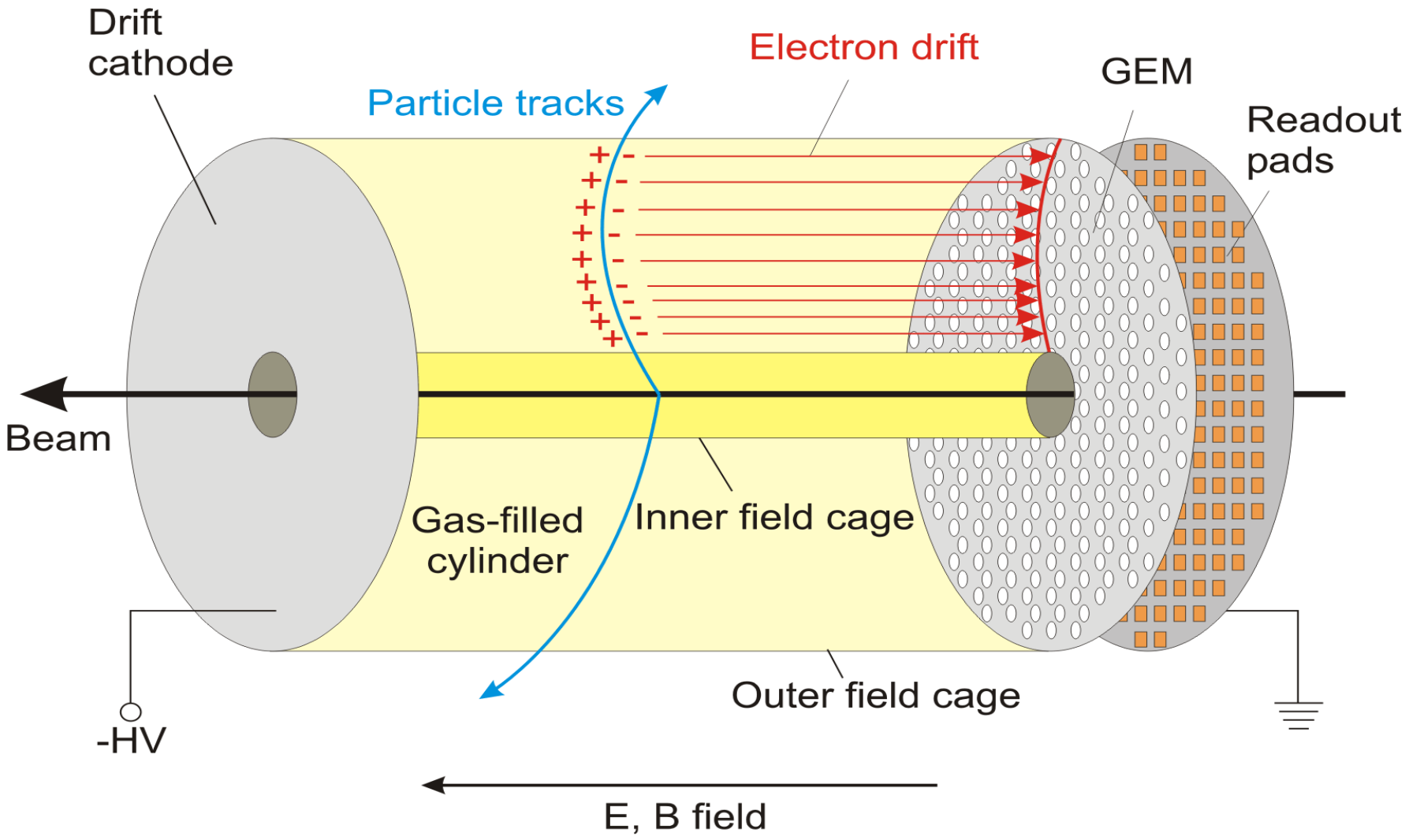
DEDIP ---
maxence.va
ndenbrouck

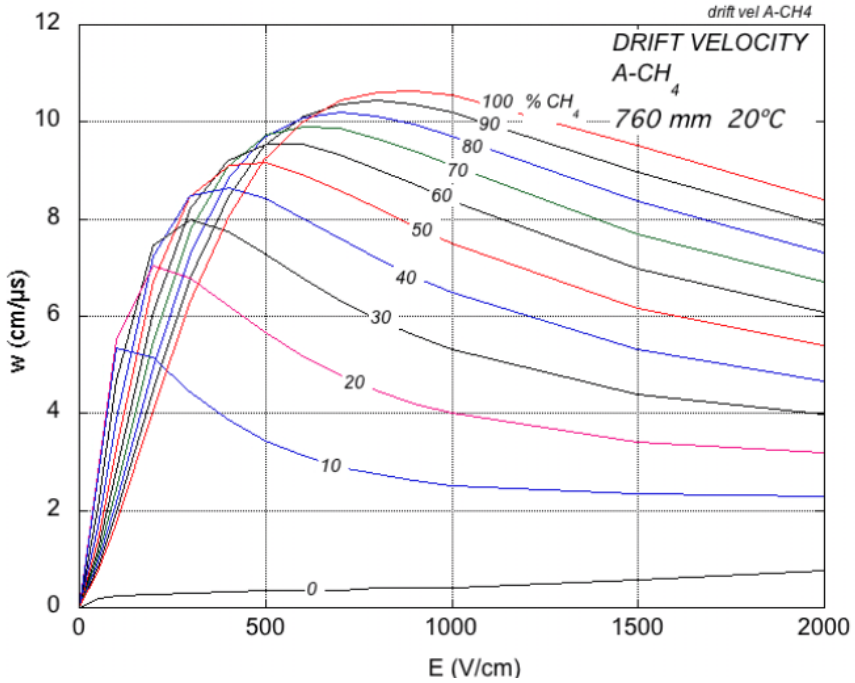
Time Projection Chamber (TPC):

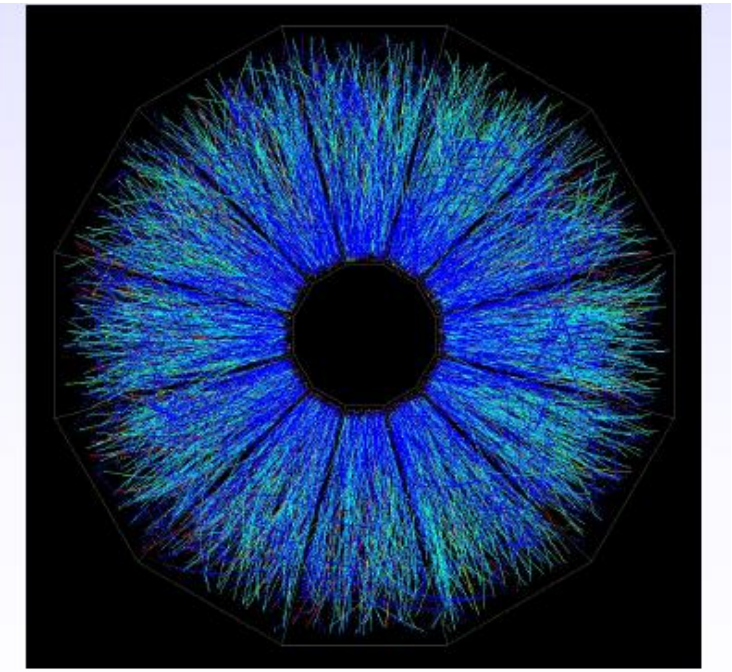


Time Projection Chamber (TPC):

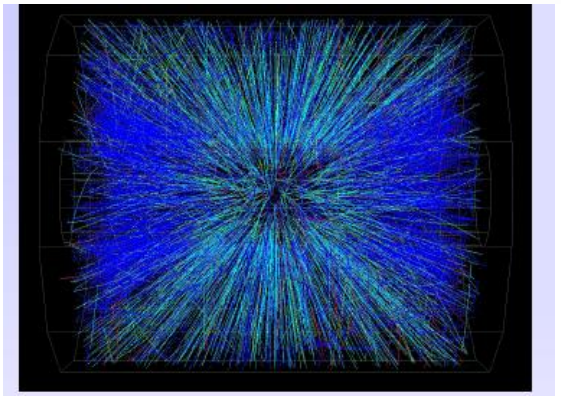
Event display of a Au Au collision at CM energy of 130 GeV/n.

Typically around 200 tracks per event.

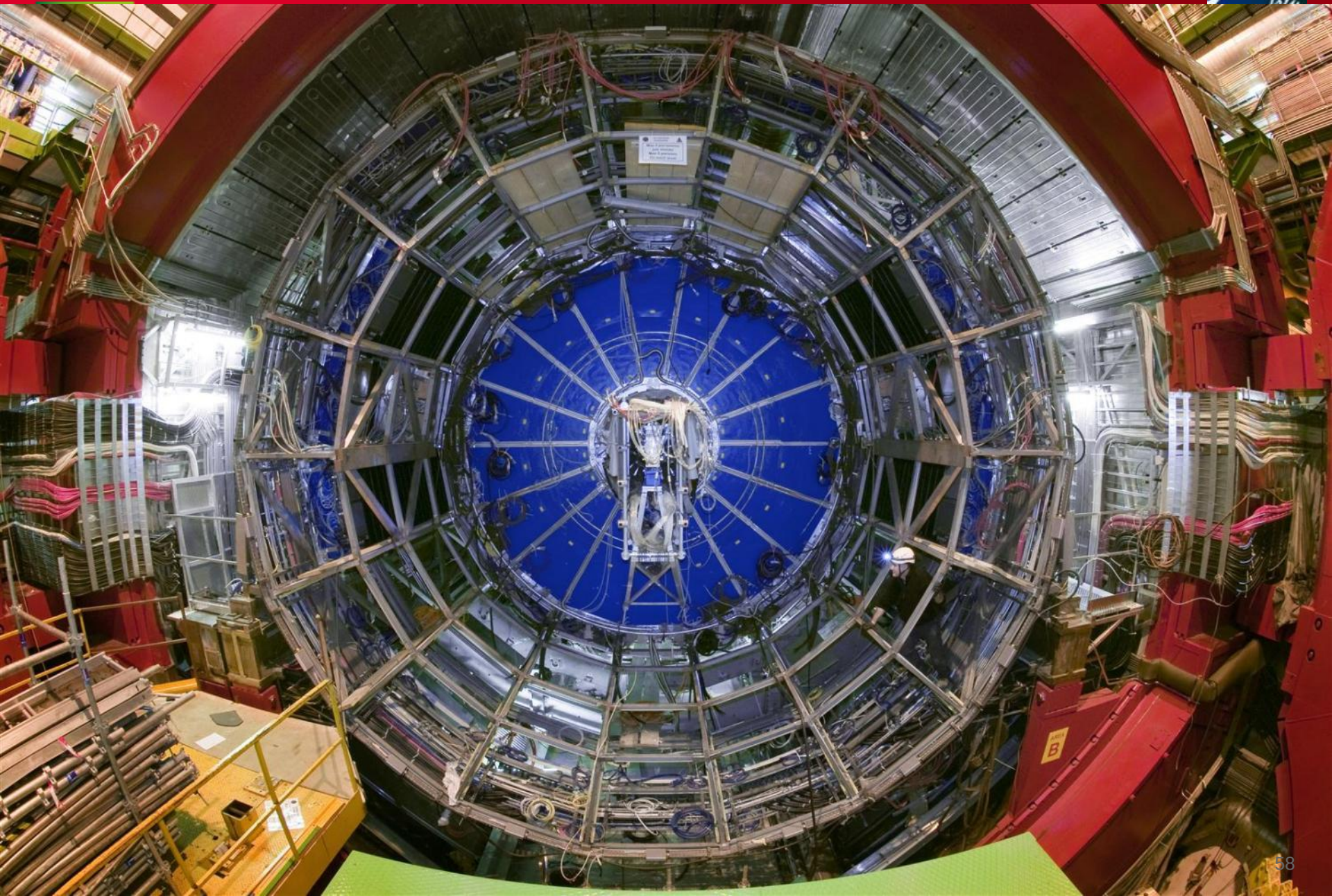




EXAMPLE: Ar-CH_4 90-10 , E=1kVcm^{-1} w$^-$ = 2.5 cm µs^{-1}



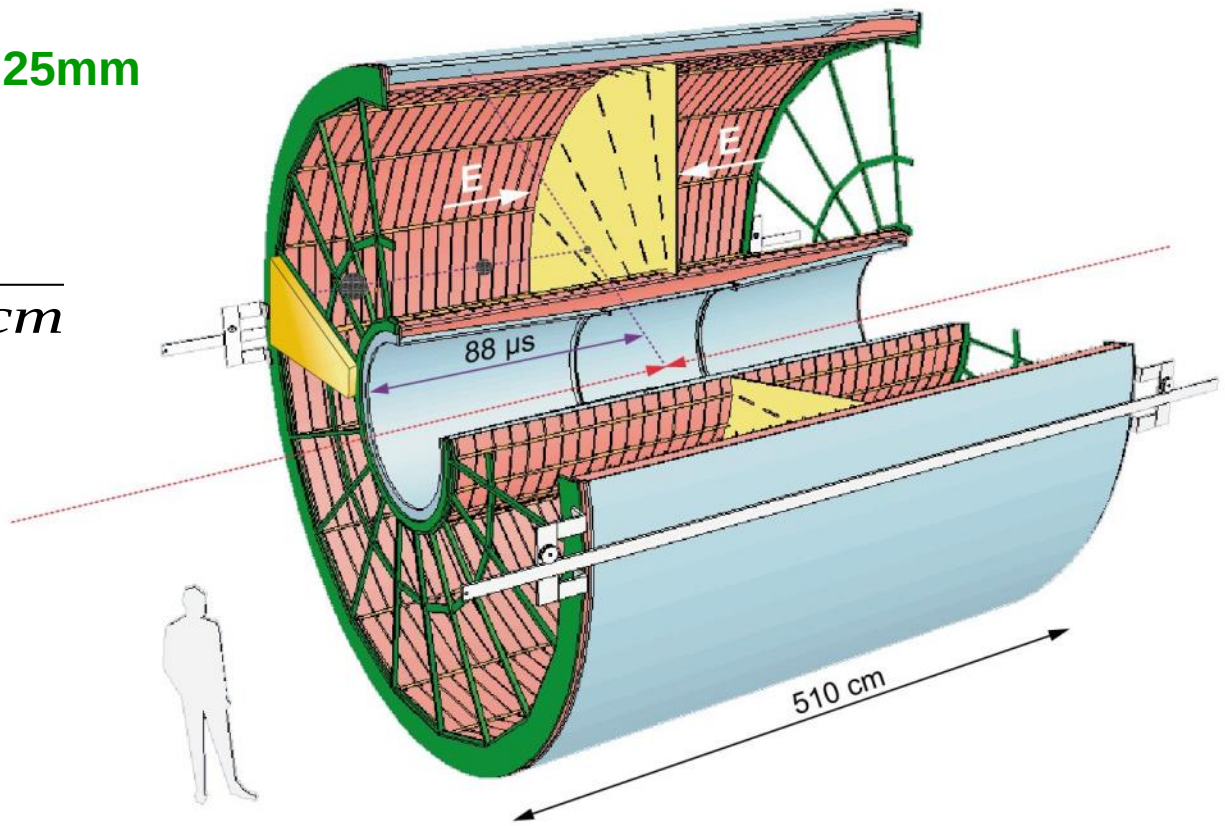
TPC installed in the ALICE Experiment



ALICE TPC: Detector Parameters

- Gas Ne/ CO_2 90/10%
- Field 400V/cm
- Gas gain >10^4
- Position resolution σ= 0.25mm
- Diffusion: σ_t= 250μm
- Pads inside: 4x7.5mm
- Pads outside: 6x15mm
- B-field: 0.5T
- Largest TPC:
  - Length 5m
  - Diameter 5m
  - Volume 88m^3
  - Detector area 32m^2
  - Channels ~570 000

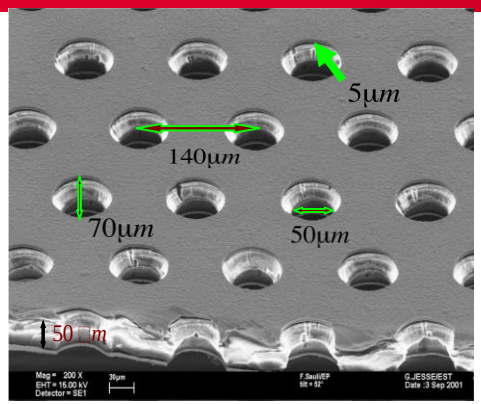
$\sqrt{cm}$

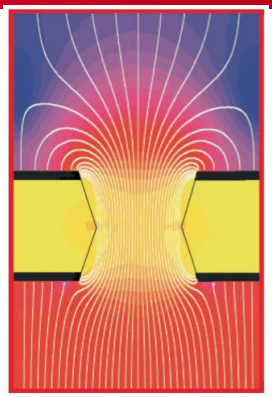


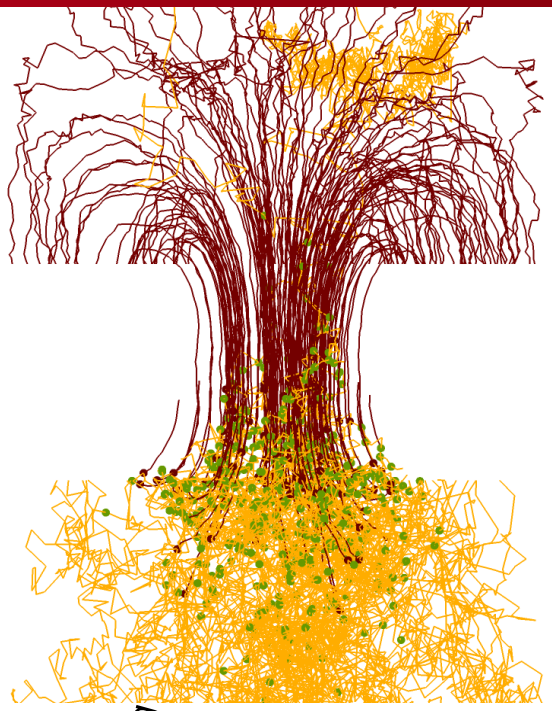
- High Voltage:
  - Cathode -100kV

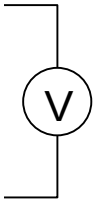
=> Gated grid ~15kHz max

GEM : GASEOUS ELECTRON MULTIPLIER

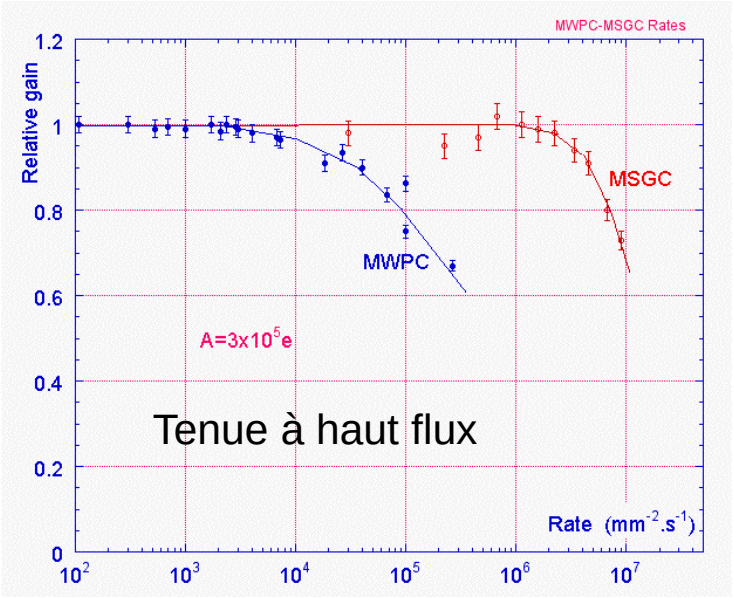


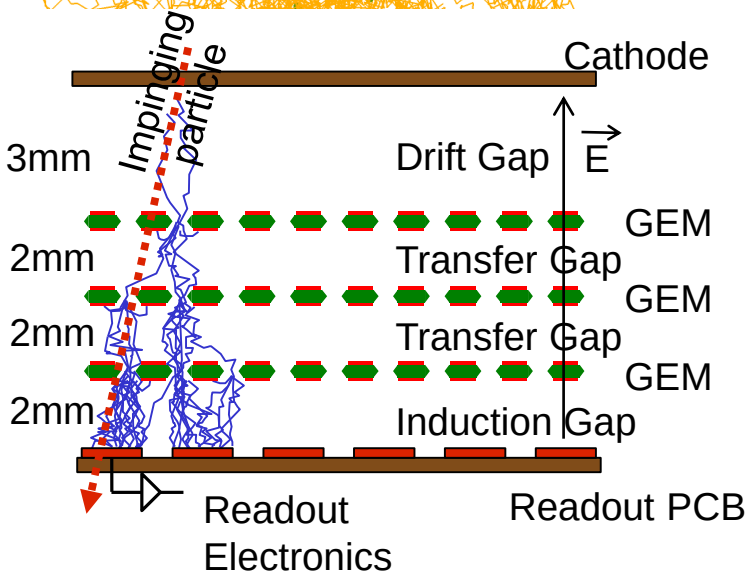






$\Delta V \sim 360V$





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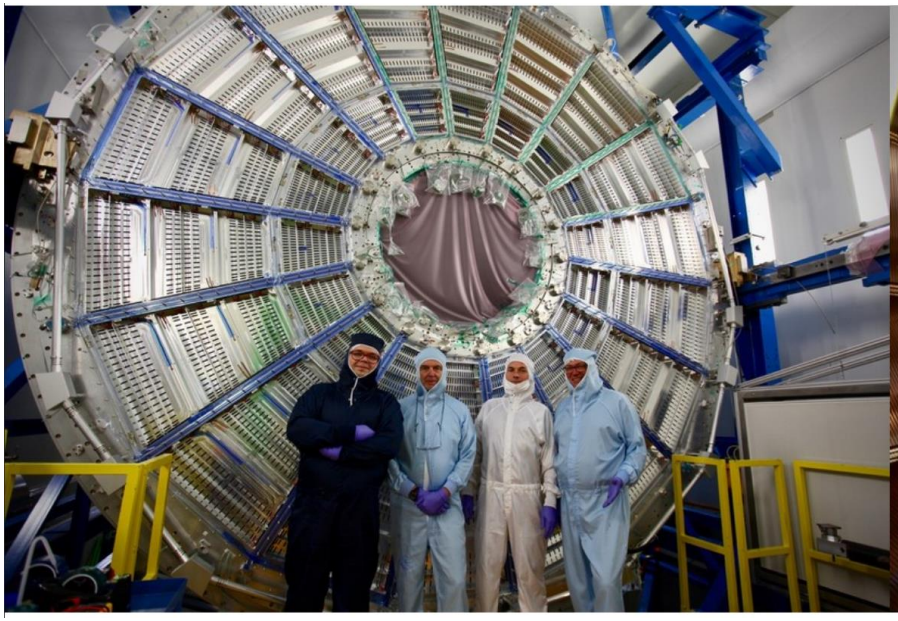
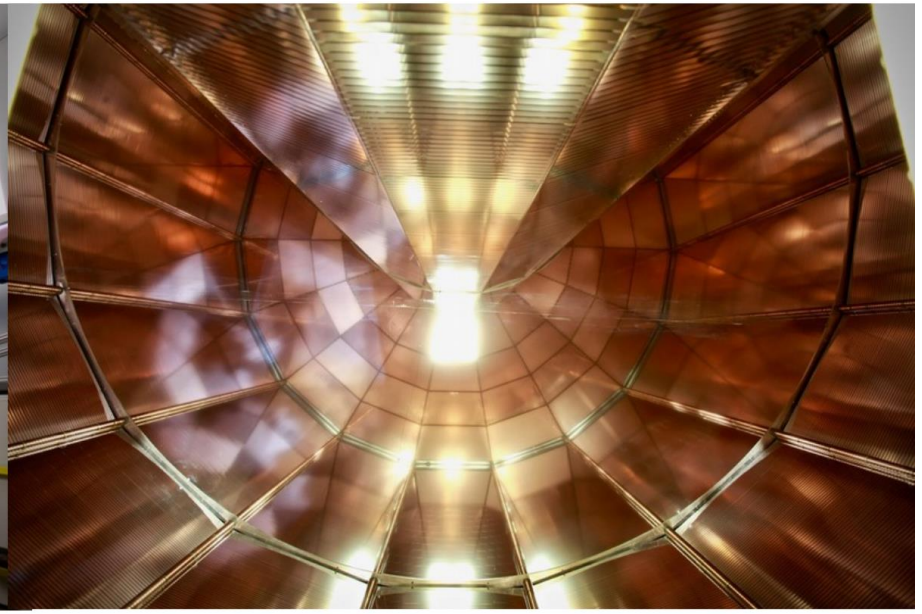
ALICE UPGRADE

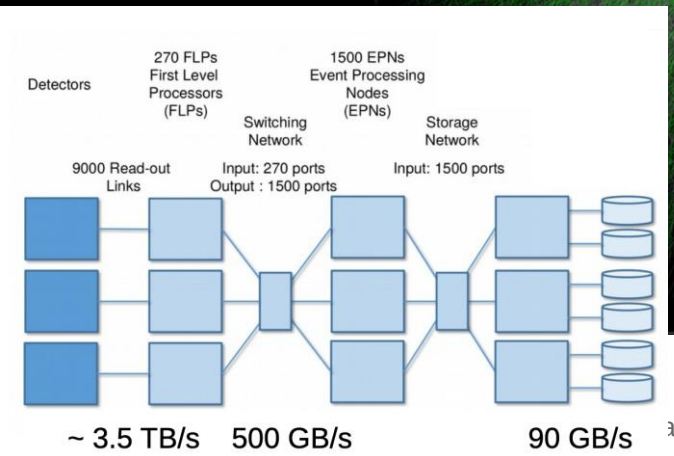




ALICE UPGRADE

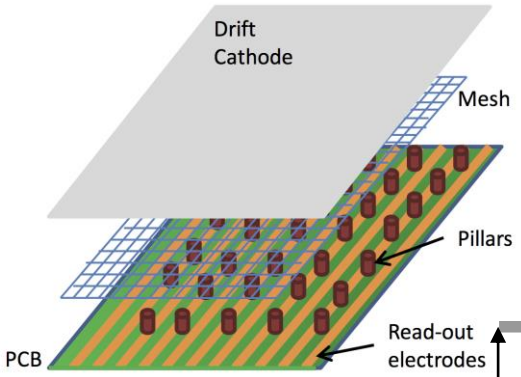
50 kHz Pb-Pb interactions in the TPC

- Enormous raw data rate (~3.5 TB/s)
  - Requires online data compression

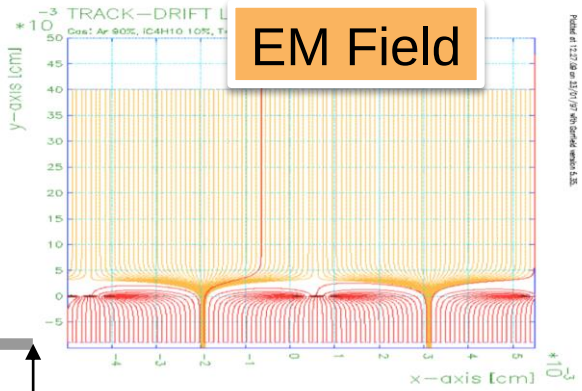


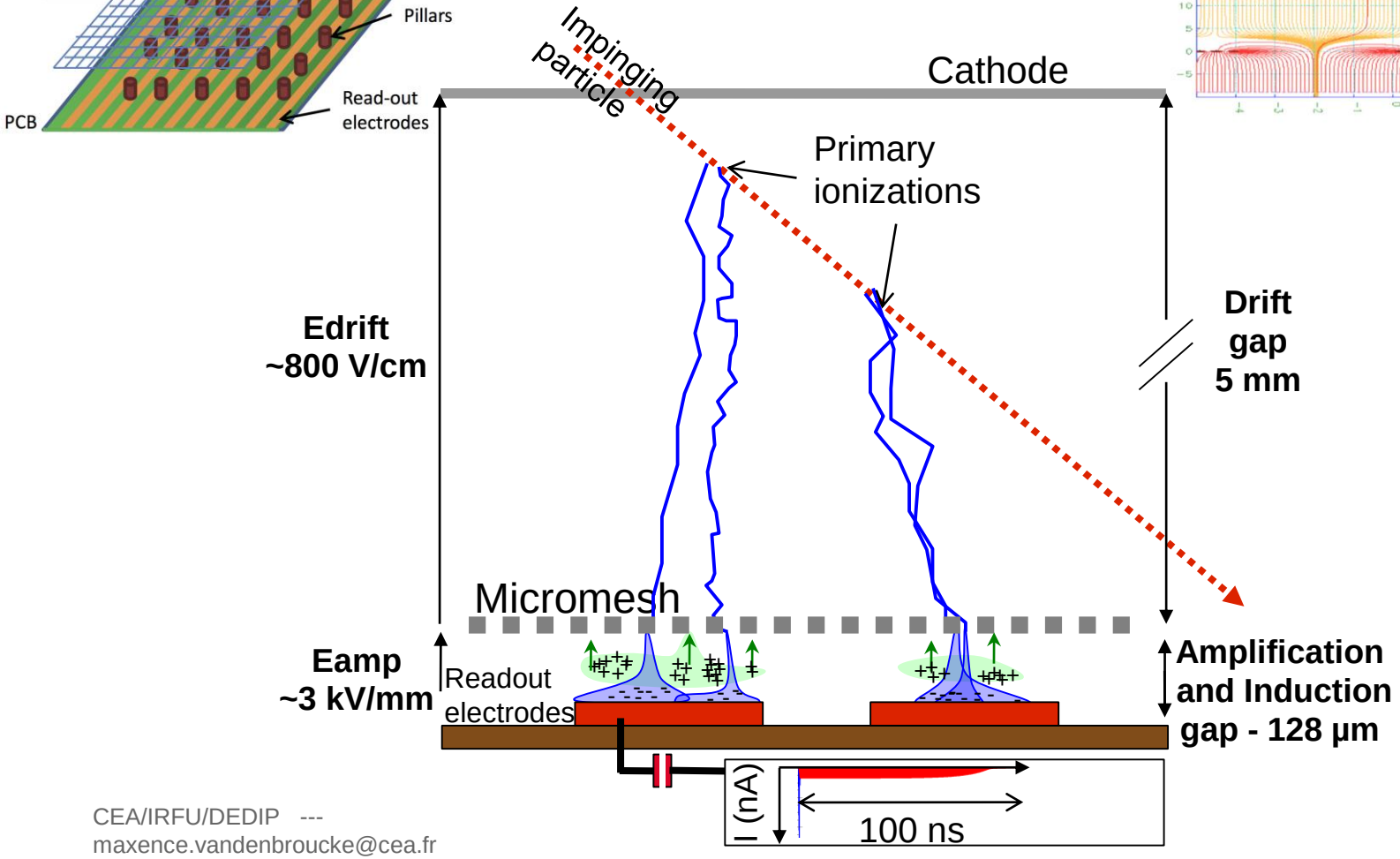
20 x TPC drift time (= 2 ms)

MICROMEGAS



EM Field



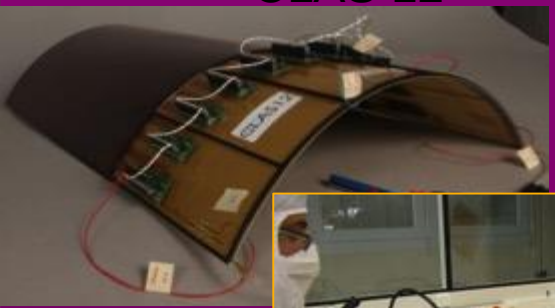


APPLICATIONS EN PHYSIQUE…

Grands détecteurs pour le système à muons d'ATLAS/HL-LHC

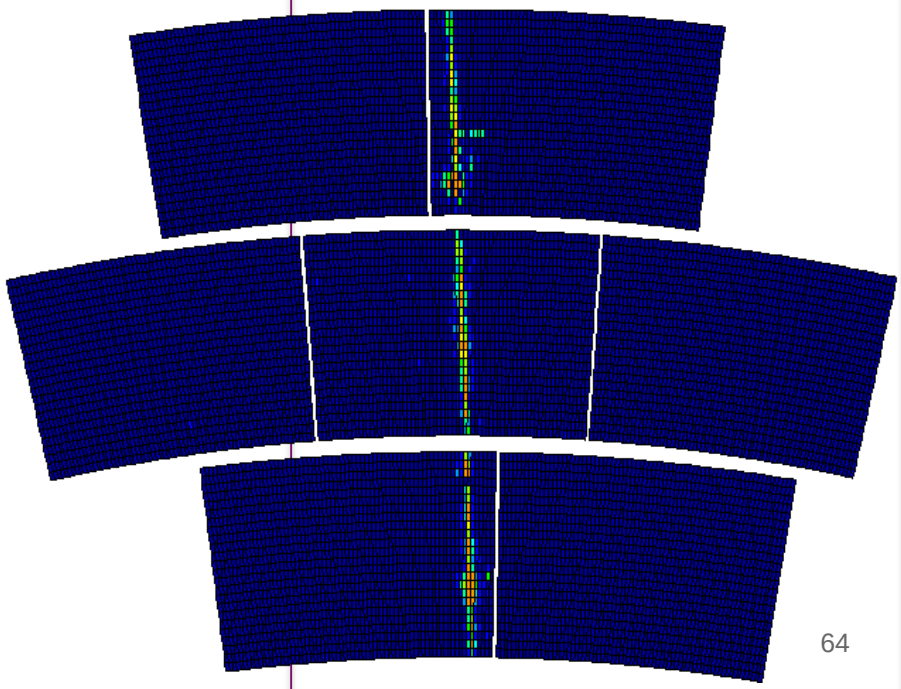
TPC pour l'ILC

CLAS 12

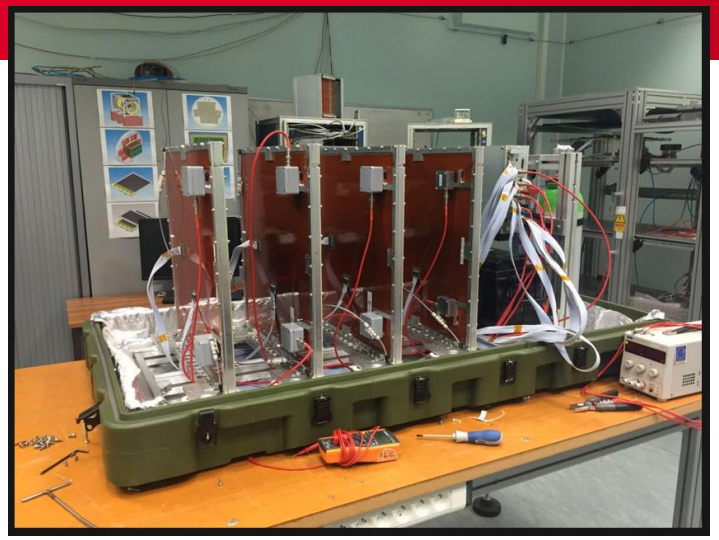


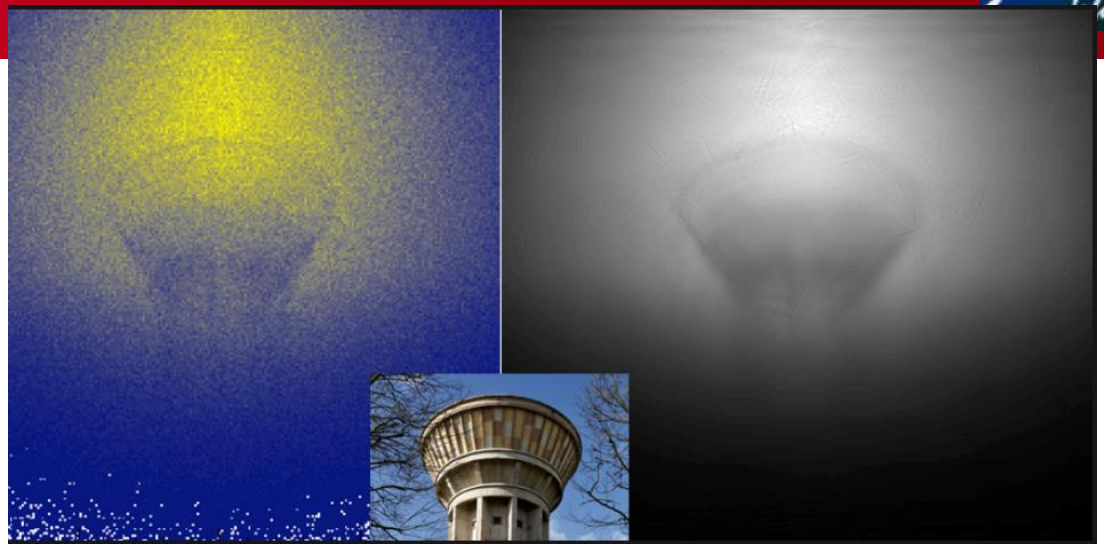
Tuile pour le trajectographe cylindrique

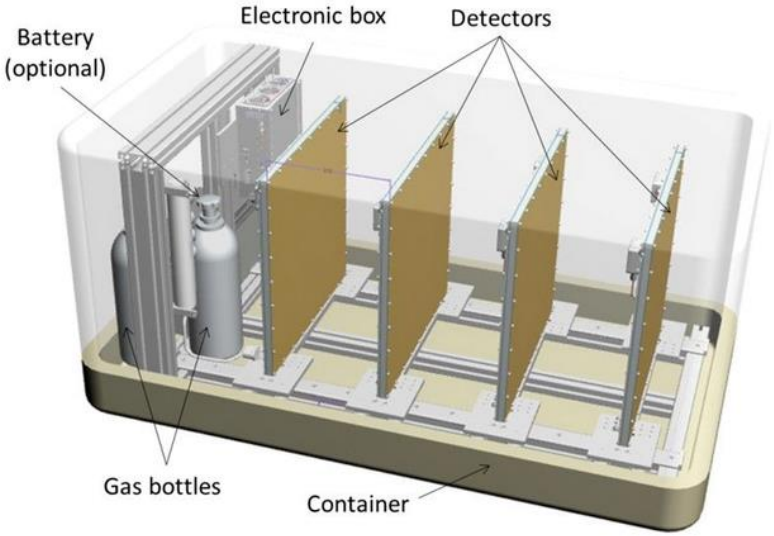
Mise en place de l'électrode de dérive

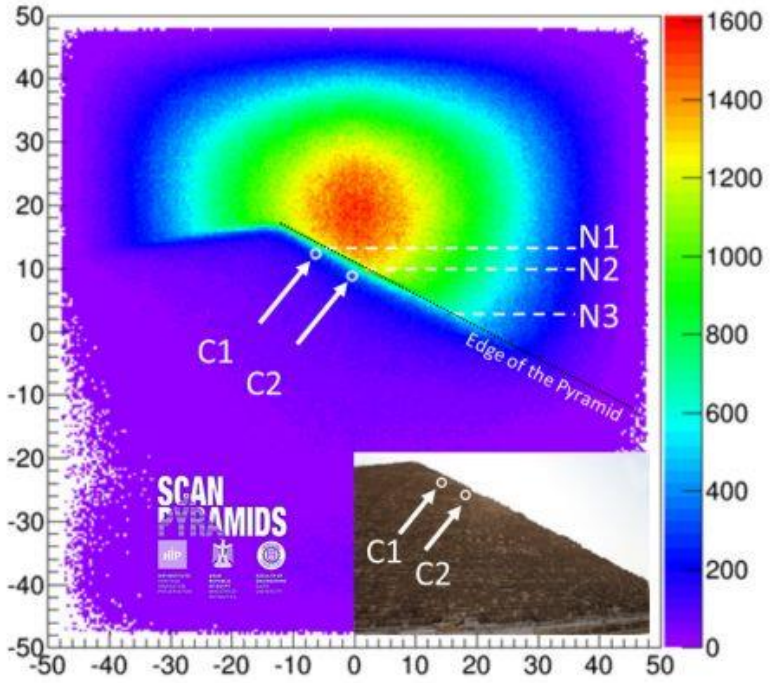


MUONGRAPHY









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DE LA RECHERCHE À L'INDUSTRIE

Mesurer l'infiniment petit et observer l'infiniment grand

Stages : http://irfu.cea.fr/Phocea/stages/index.php

Maxence Vandenbroucke

07/2019

université PARIS-SACLAY

PLAN DES COURS

Cours 1 : Généralités

-Introduction générale sur l'importance de la mesure

-Qu'est-ce qu'une expérience de physique subatomique ?

-Que veut-on observer à propos d'une particule?

-Architecture générale d'une expérience en physique subatomique

Cours 2 : Les détecteurs de particules

- Trajectographie :
  - -Détecteurs Gazeux
  - -Détecteurs au Silicium
- Calorimétrie
- Scintillation

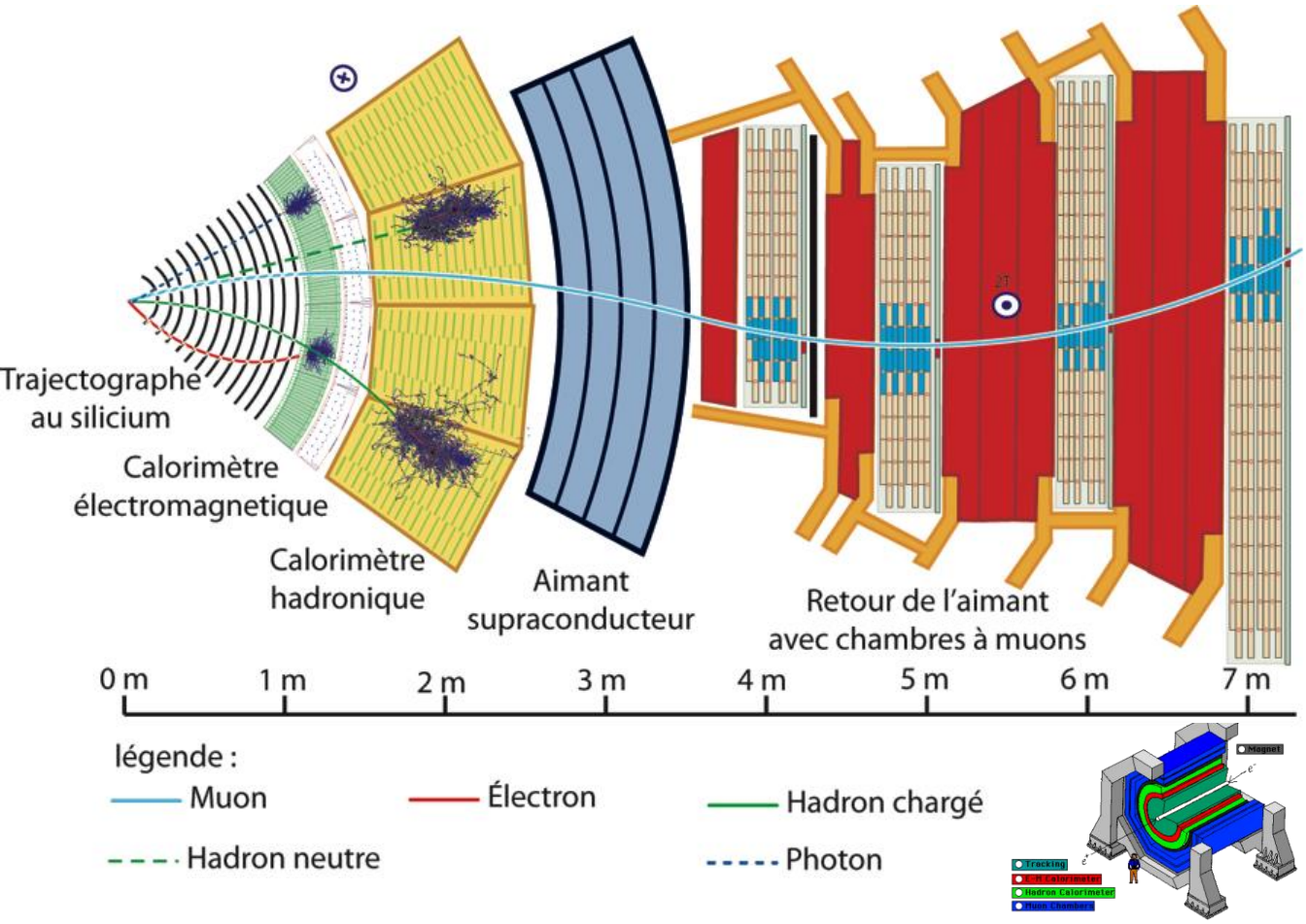
Cours 3 : Exemple d'expériences

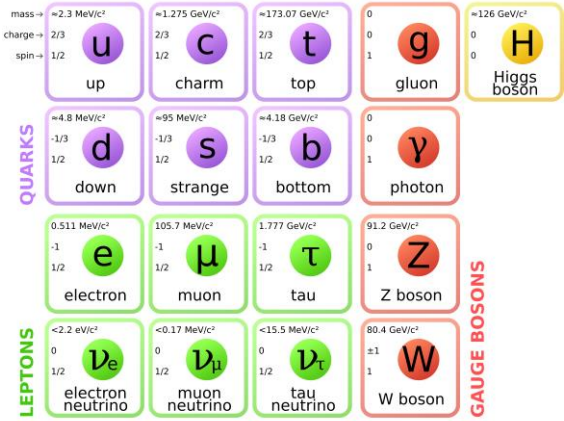
- Autour du Neutrino
- Nucléaire et Hadronique
- Rayons Cosmiques
- Antimatière

Mesurer l'infiniment petit et observer l'infiniment grand

Cours 3 : Exemple d'expériences

- **Autour du Neutrino**
- **Nucléaire et Hadronique**
- **Rayons Cosmiques**
- **Antimatière**
- **Matière sombre**





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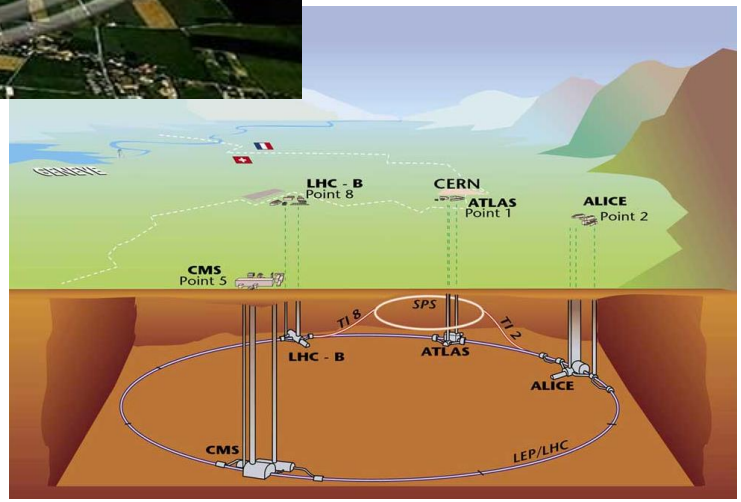
Le Large Hadron Collider



8.3 T

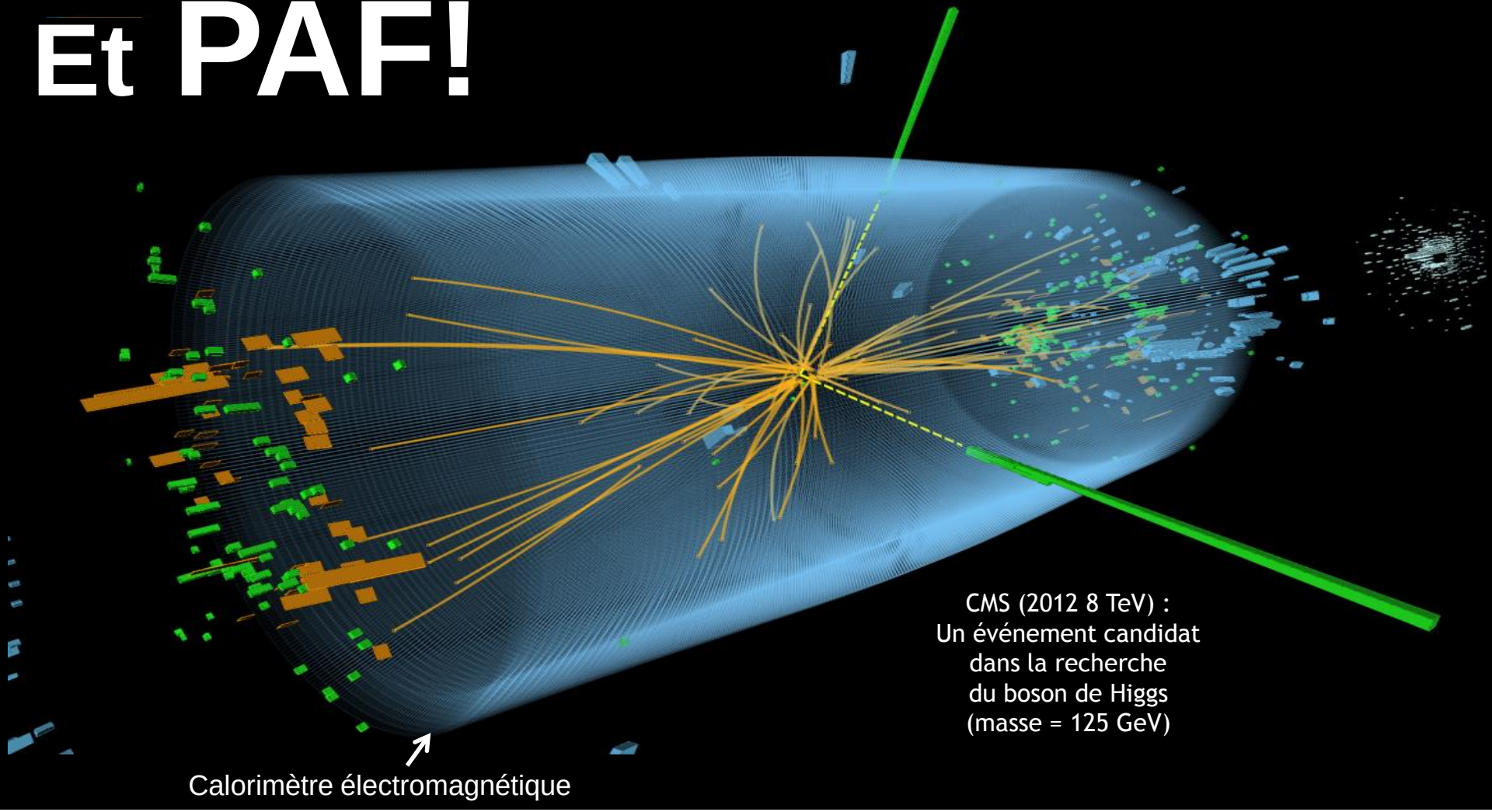
27 km

1.9 K (-271.3 °C)

10^{-13} atm

362 MJ

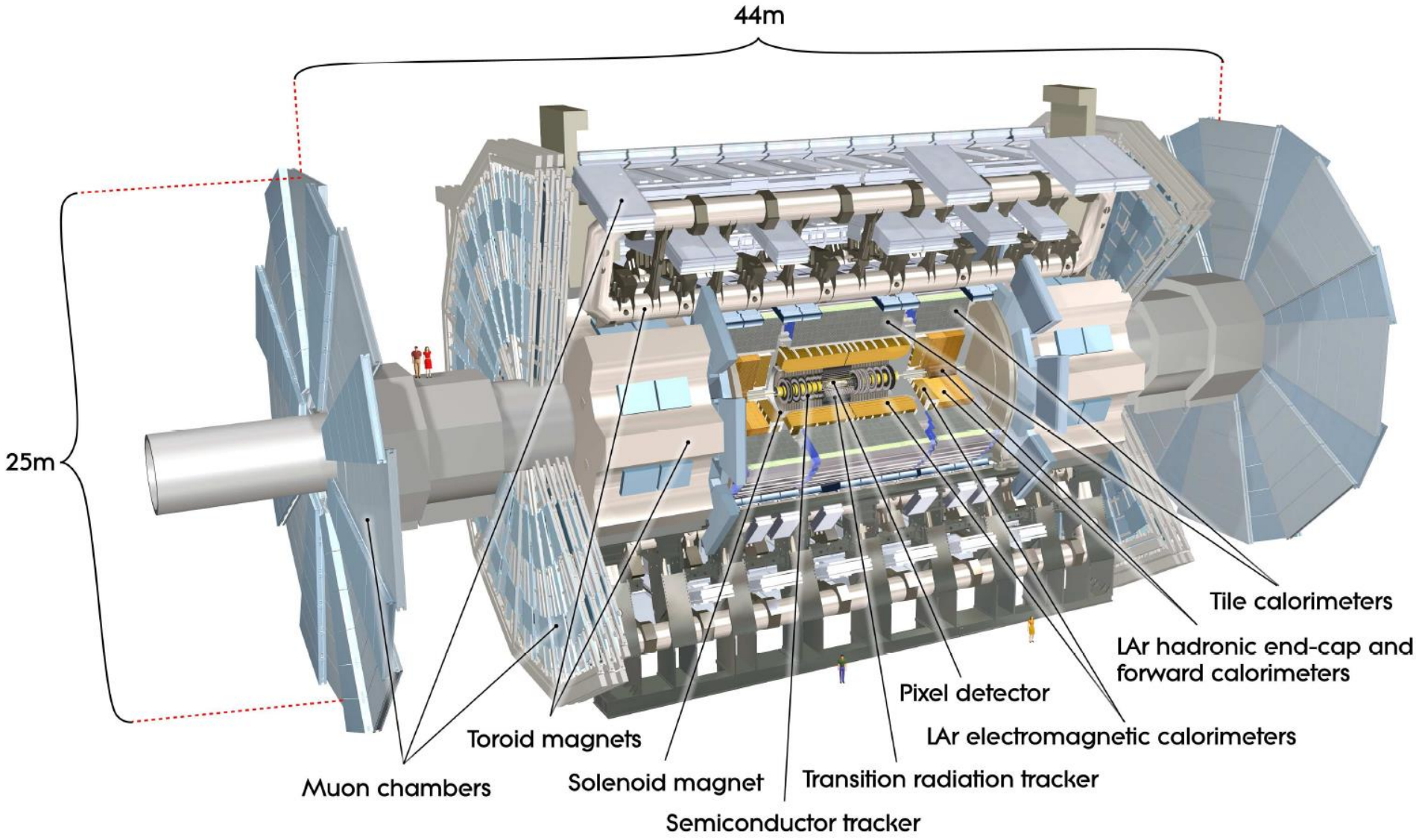
Et PAF!



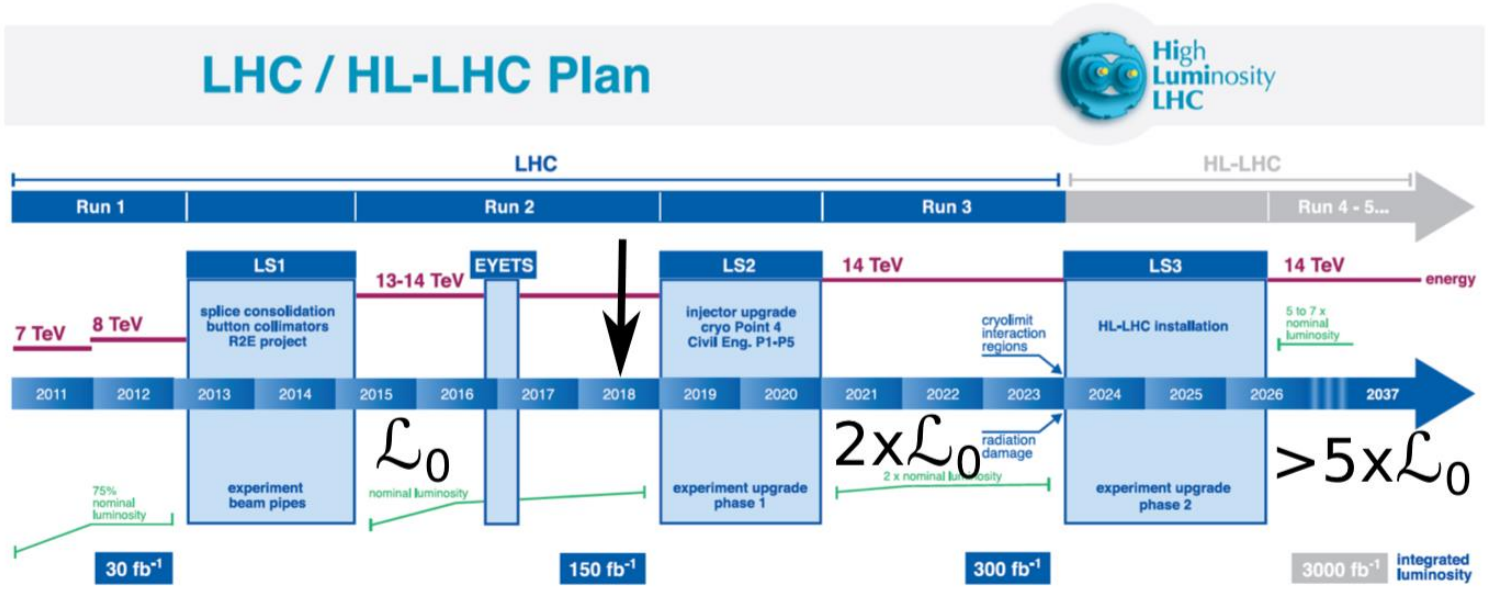
CMS (2012 8 TeV) :
Un événement candidat
dans la recherche
du boson de Higgs
(masse = 125 GeV)

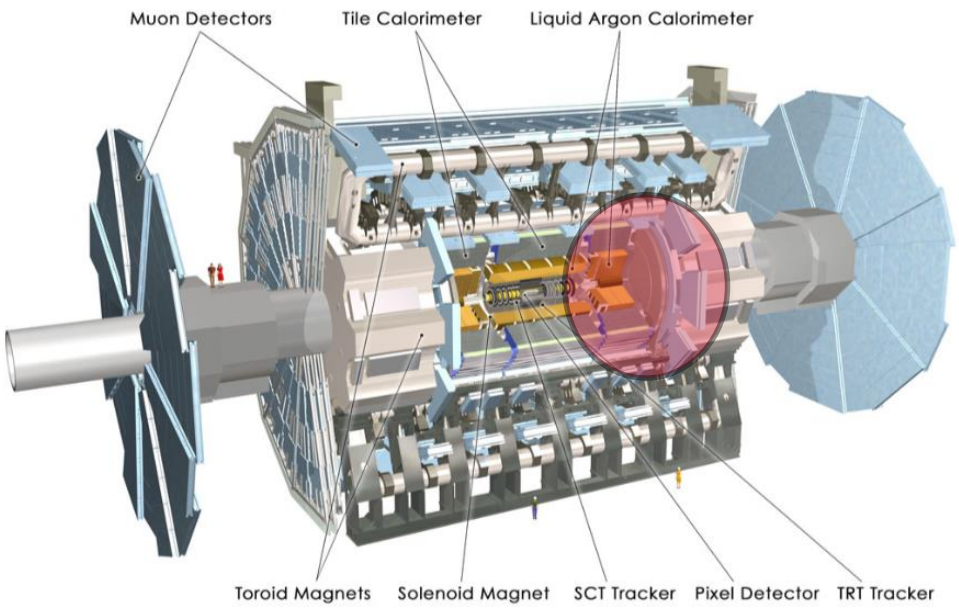
Calorimètre électromagnétique

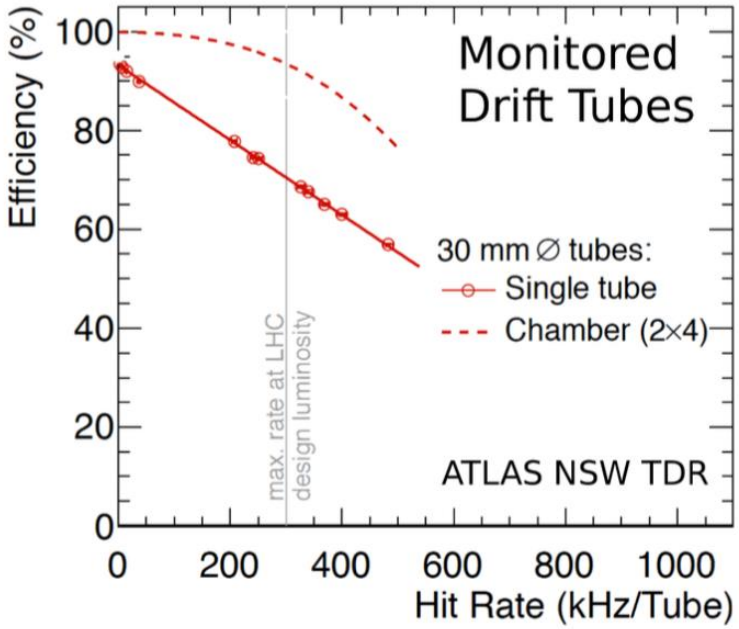
The LHC accelerator


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Transition radiation tracker
Muon chambers
Solenoid magnet
Semiconductor tracker

ATLAS - UPGRADE



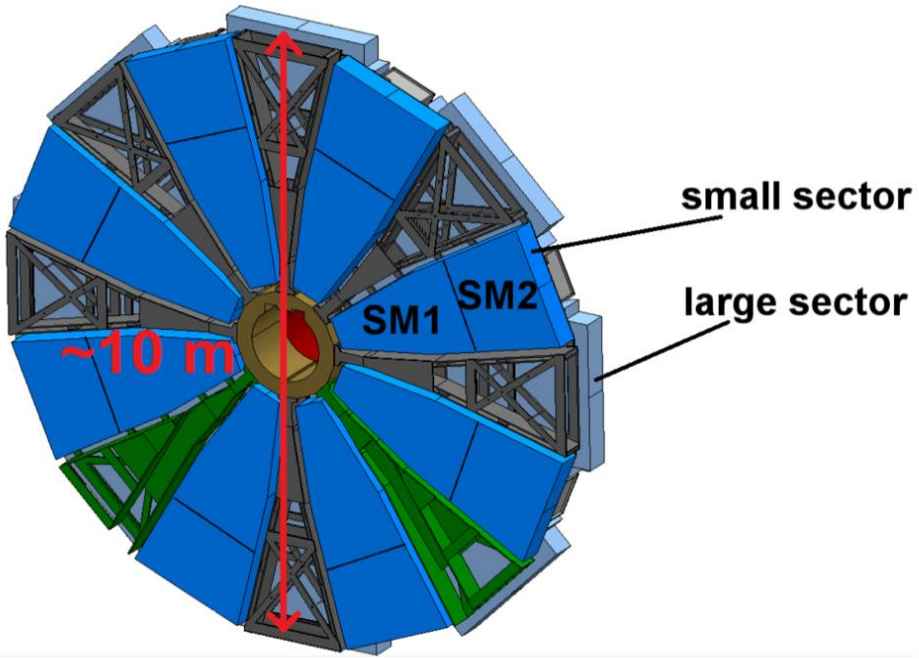




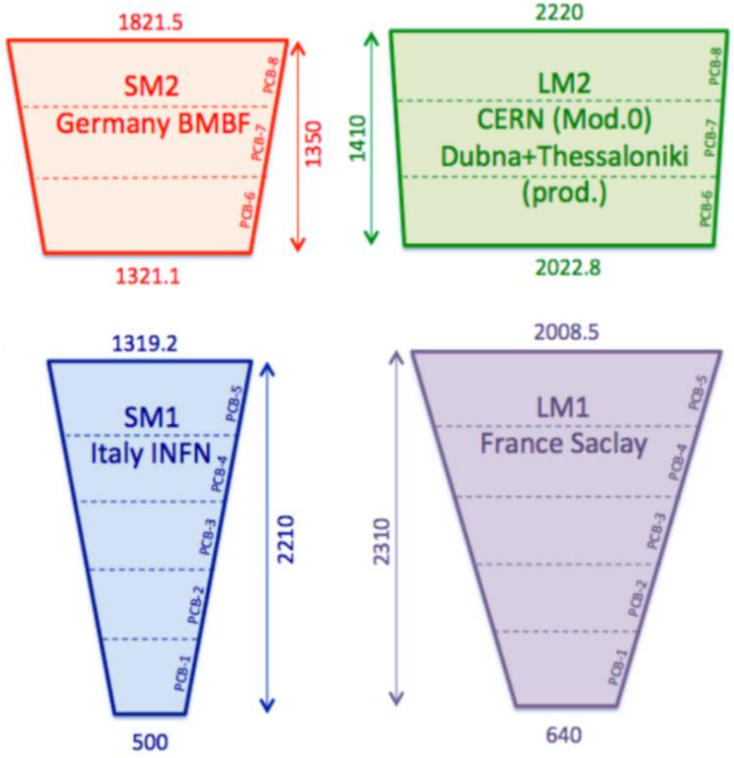
Upgrade of the Muon Small Wheels

replacement of the current end caps of the muon spectrometer by small-strip Thin Gap Chamber (sTGC) and Micromegas quadruplets

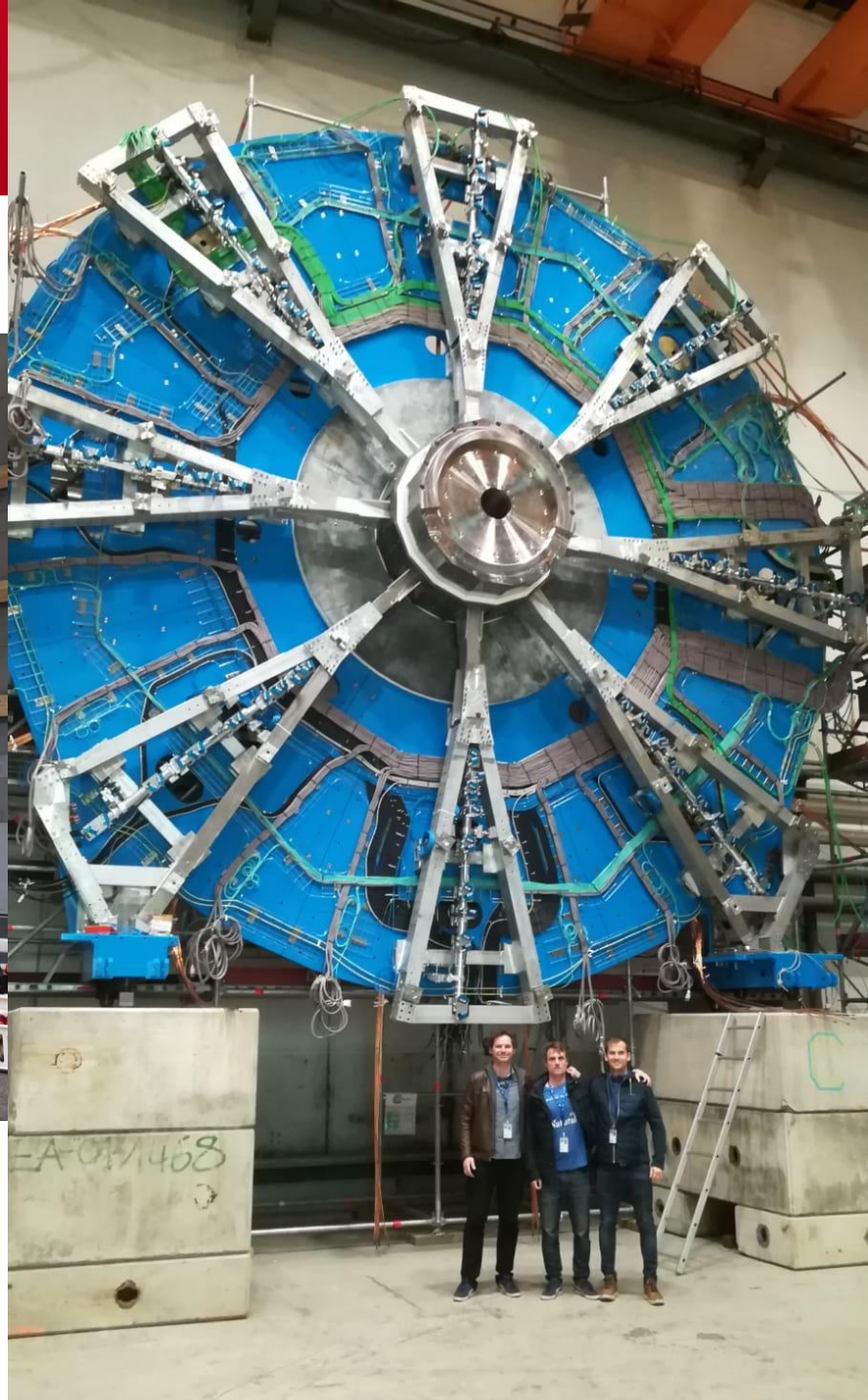
New Small Wheel Sectors



Micromegas quadruplets



NSW



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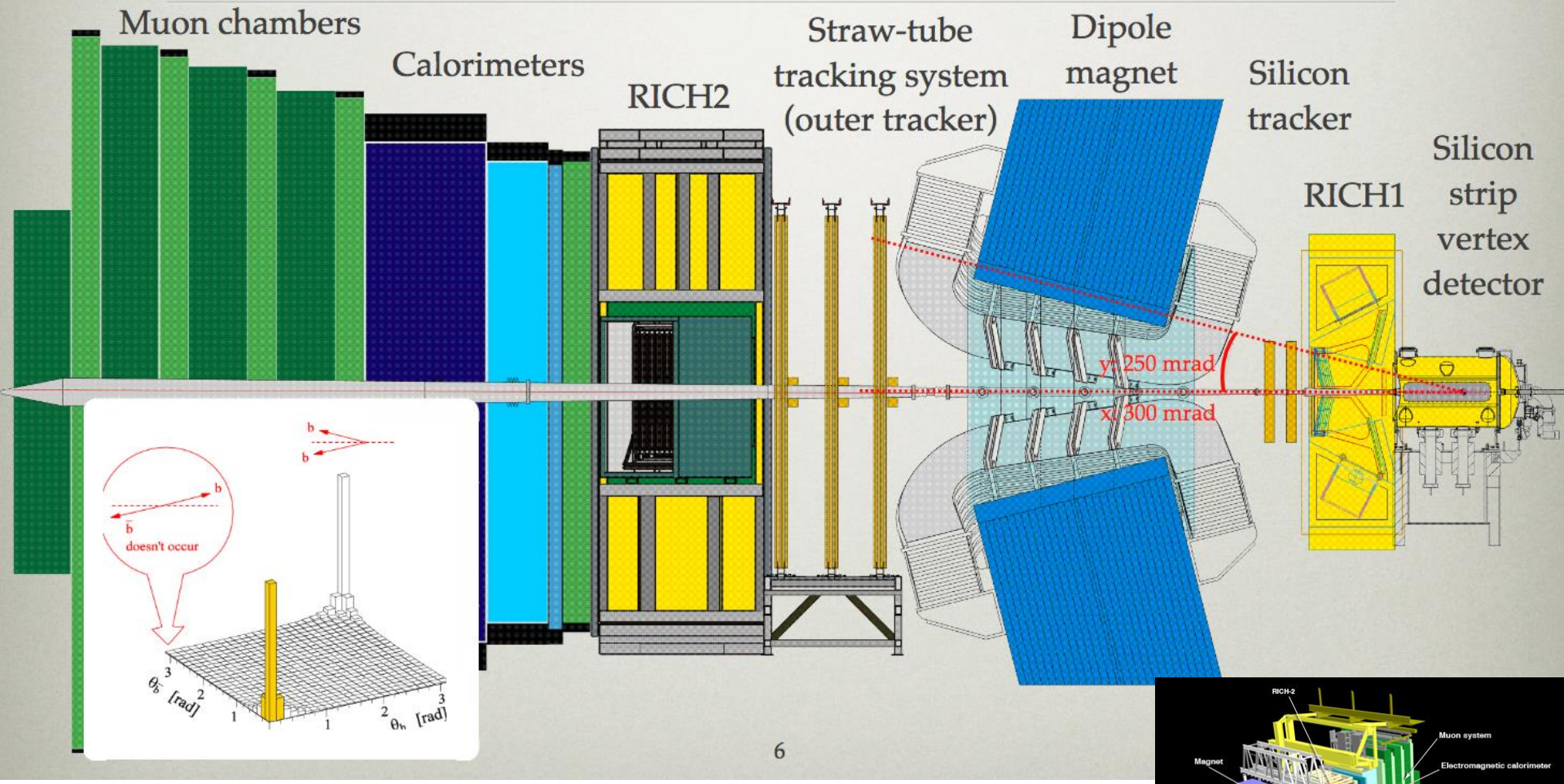
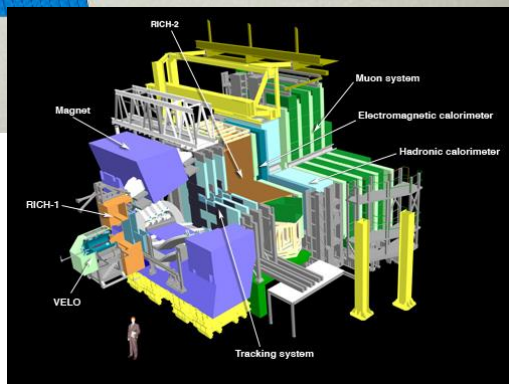
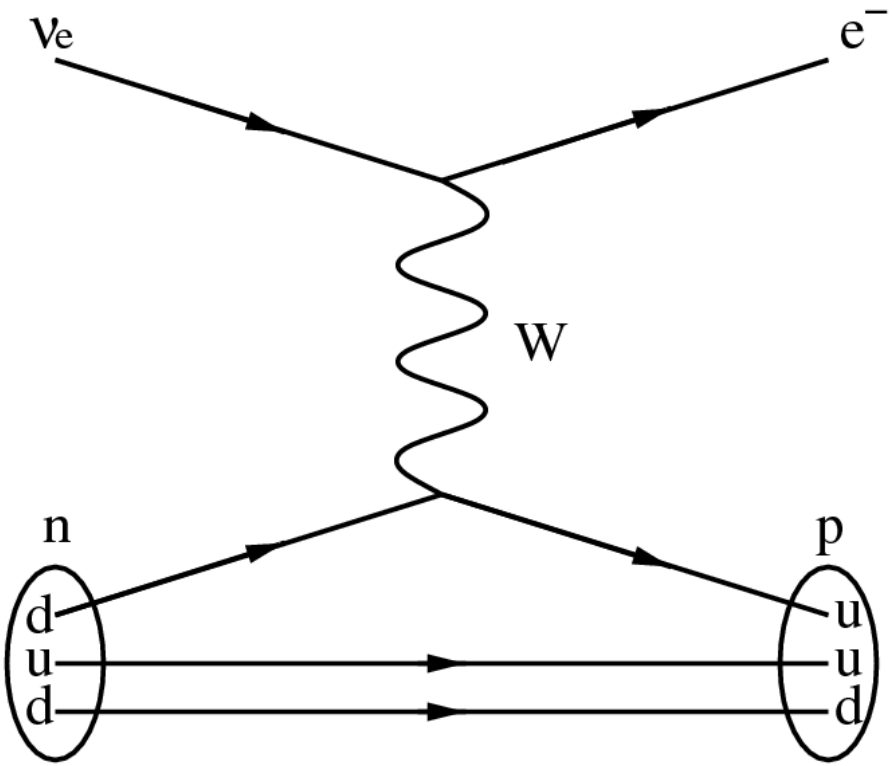
LHCb instruments $2<\eta_{LHC}<5$

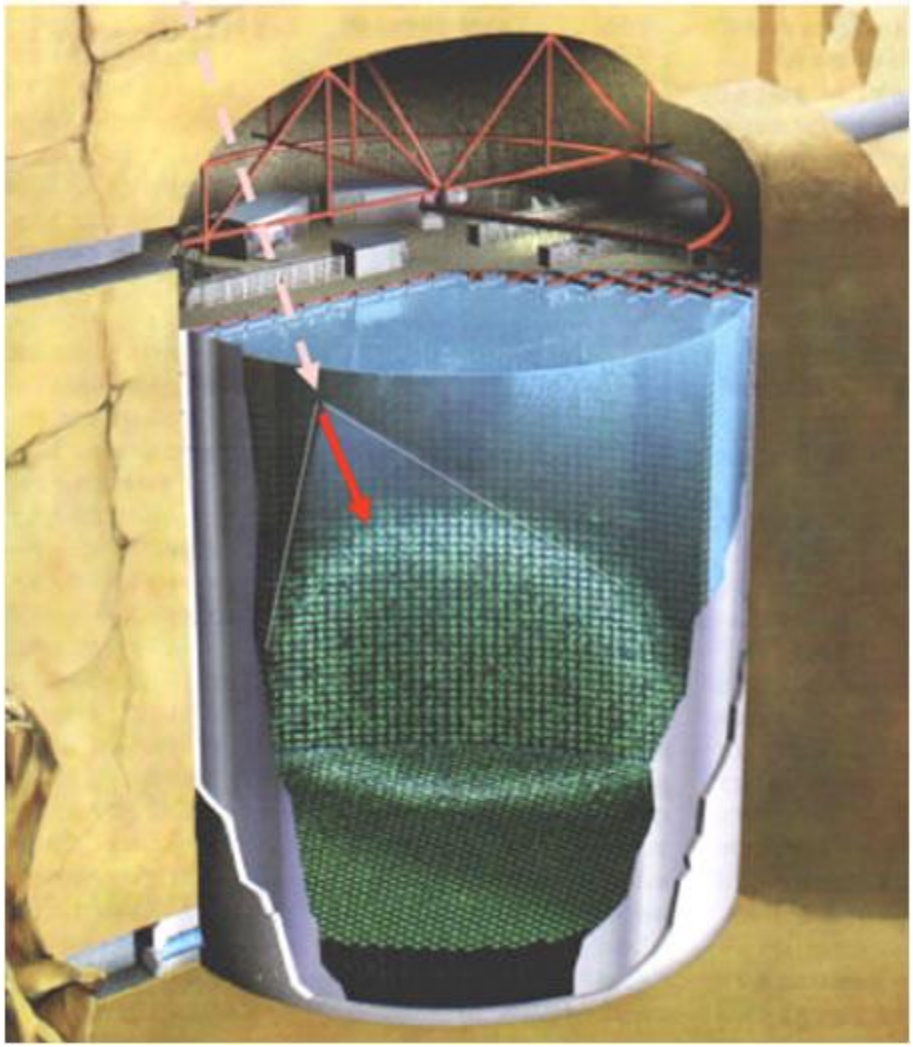


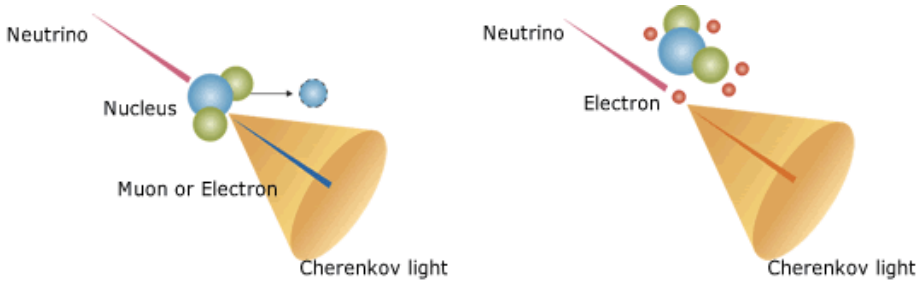


Observer les neutrinos

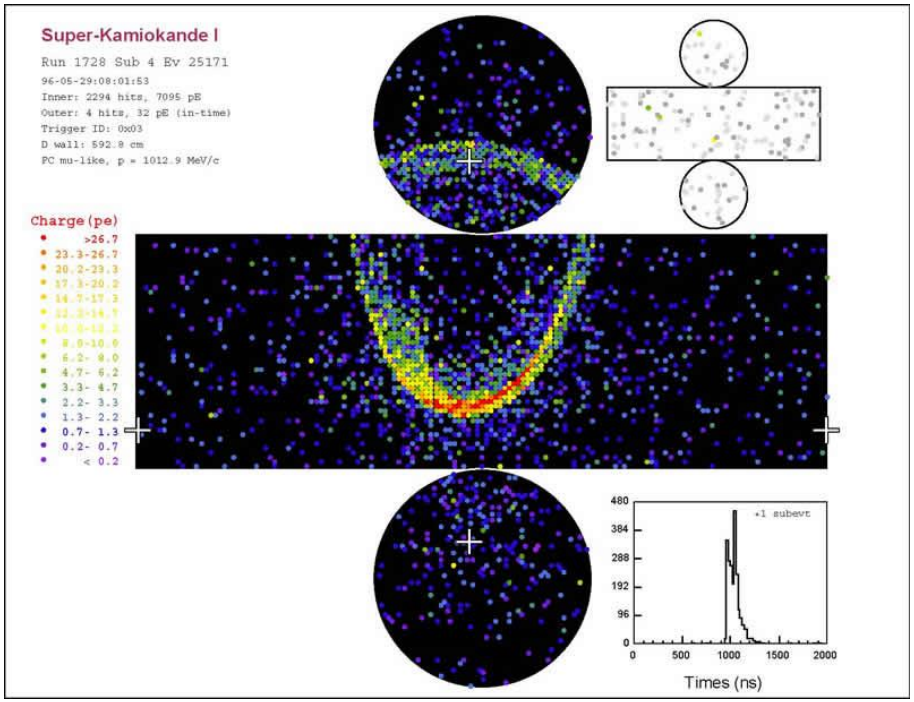


Super Kamiokande

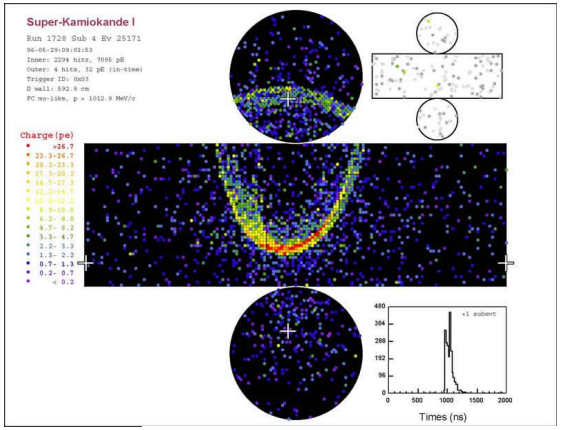


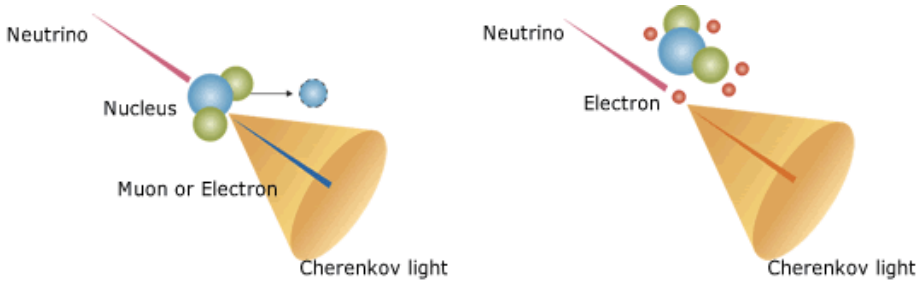


The generated charged particle emits the Cherenkov light.



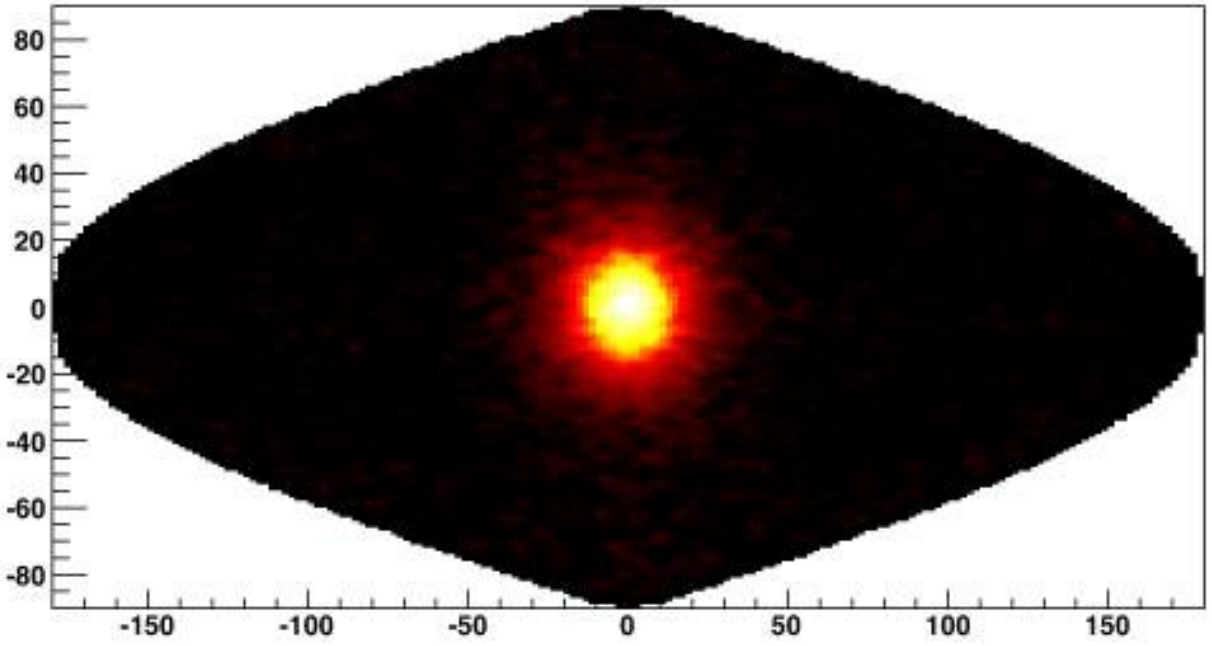
Super Kamiokande





The generated charged particle emits the Cherenkov light.

Image du soleil en Neutrino Electronique



Antares

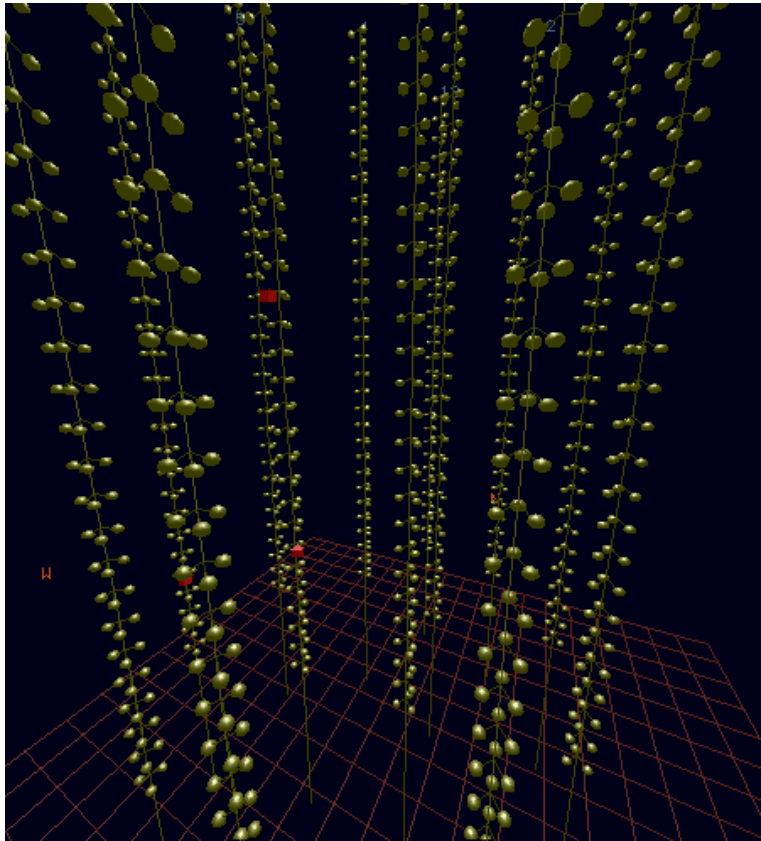
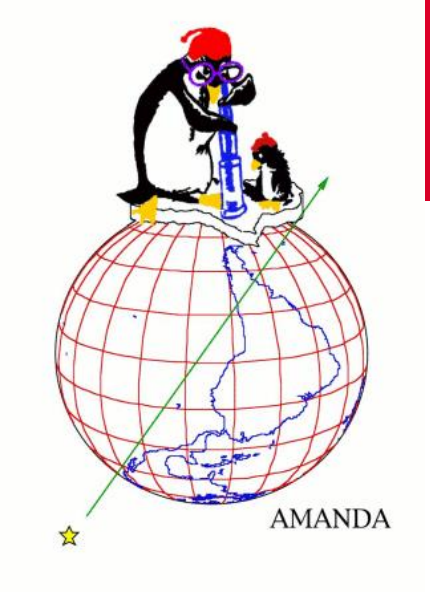
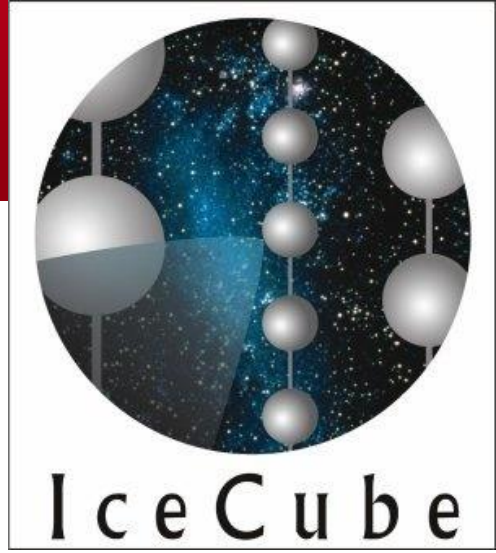


FIG. (II) 1.7: *Photographie d'un individu bioluminescent prise par l'une des caméras installées sur la ligne d'instrumentation IL07 (lire le paragraphe* (II) 3.1*). L'échelle n'est pas précisément connue (elle dépend de la distance à la caméra).*

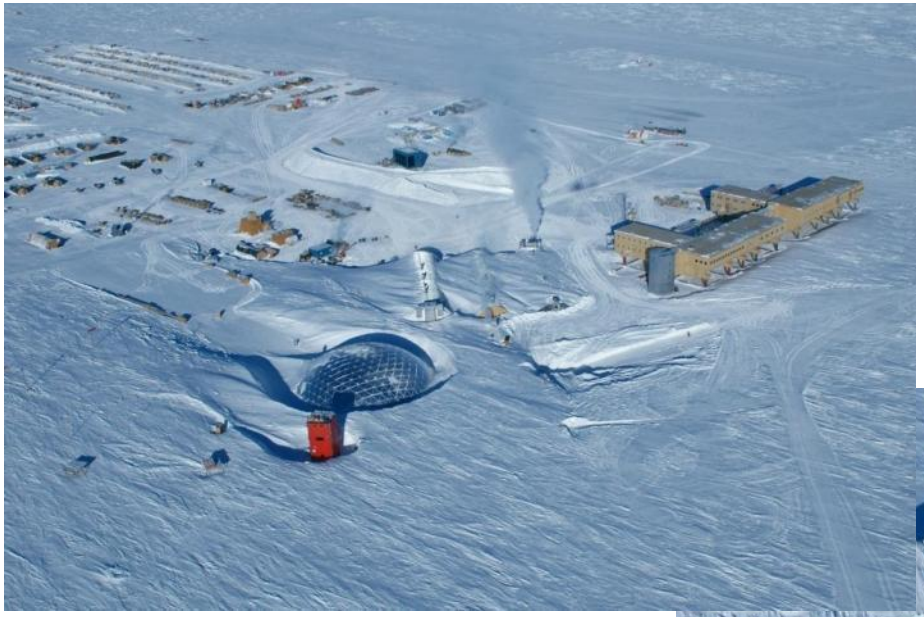




AMANDA

Antarctic **M**uon **A**nd **N**eutrino **D**etector **A**rray

AMANDA



South Pole

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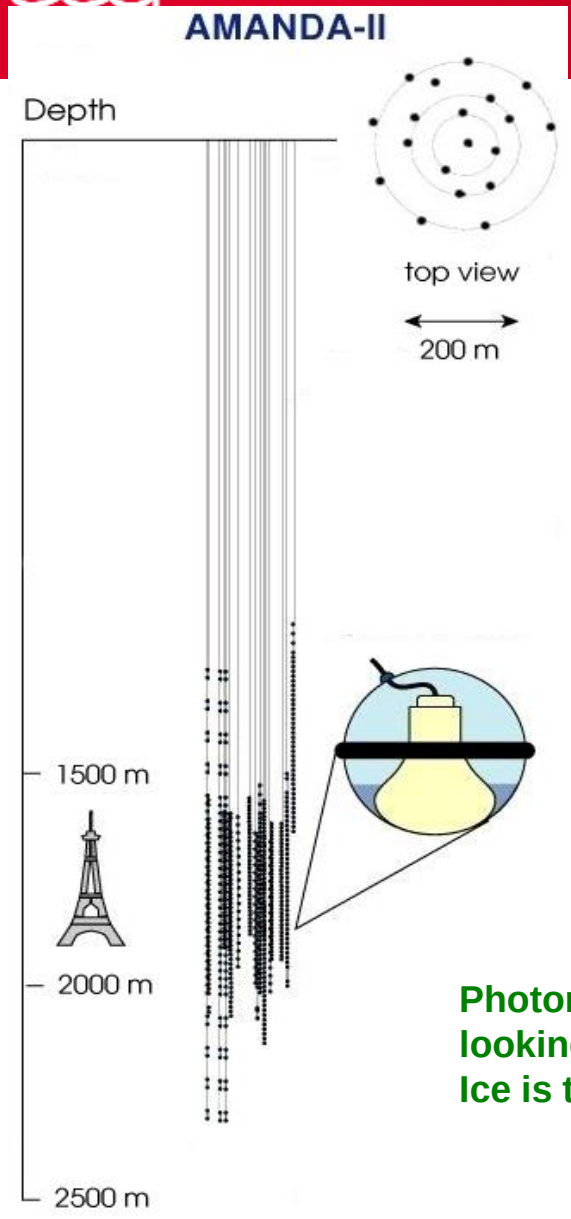
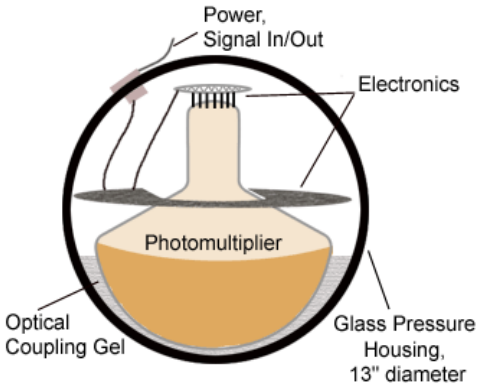
AMANDA



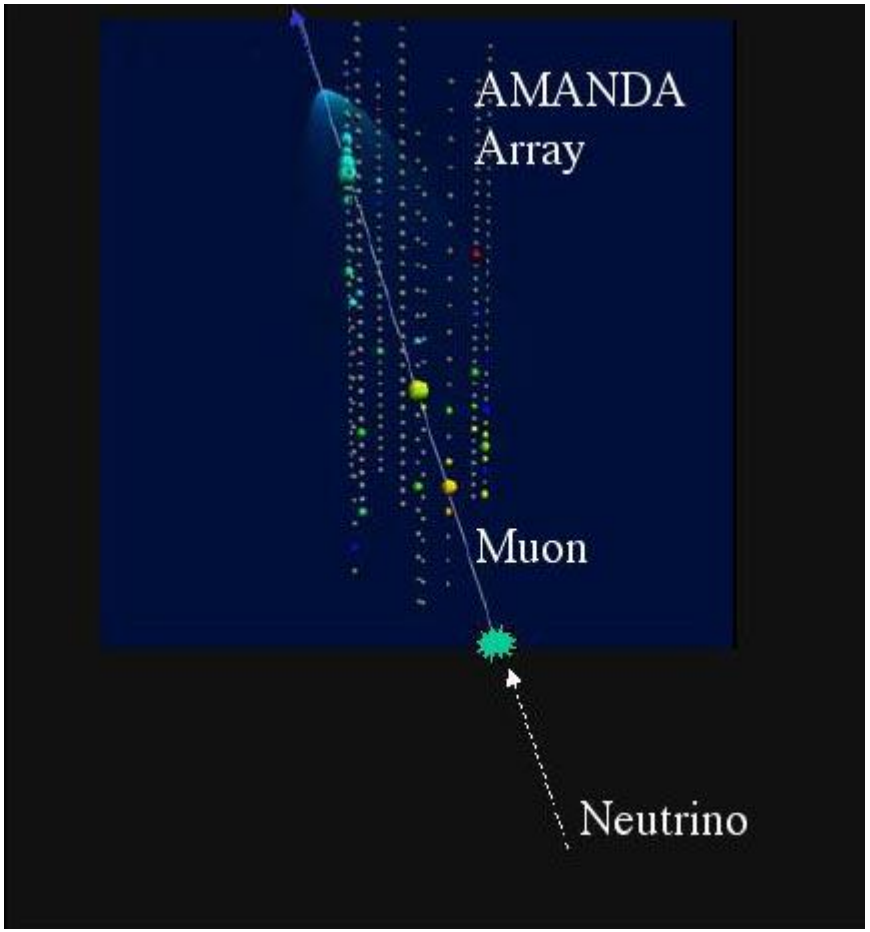


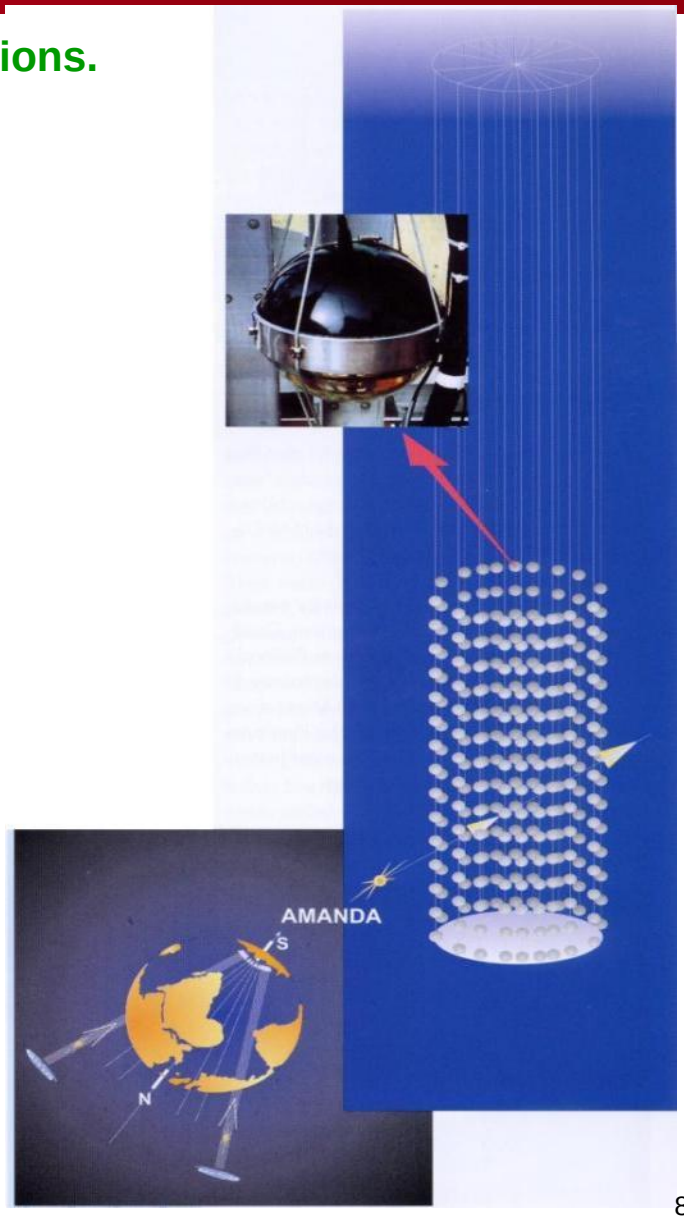
Photomultipliers in the Ice,
looking downwards.
Ice is the detecting medium.

AMANDA

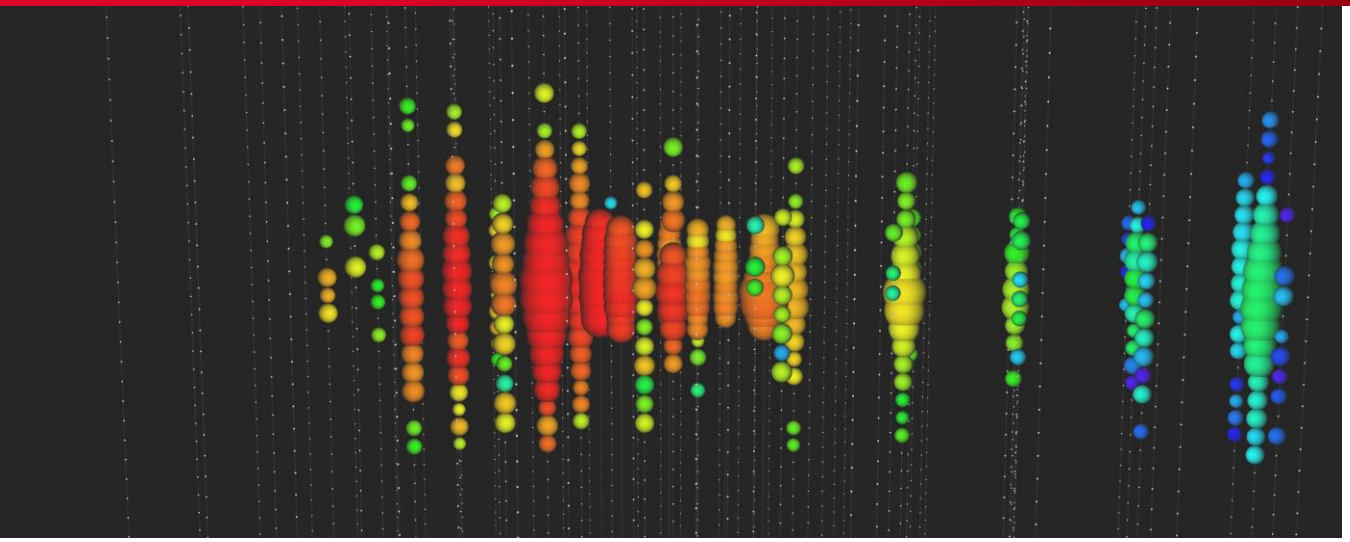
Look for upwards going Muons from Neutrino Interactions.
Cherekov light propagating through the ice.

→ Find neutrino point sources in the universe !

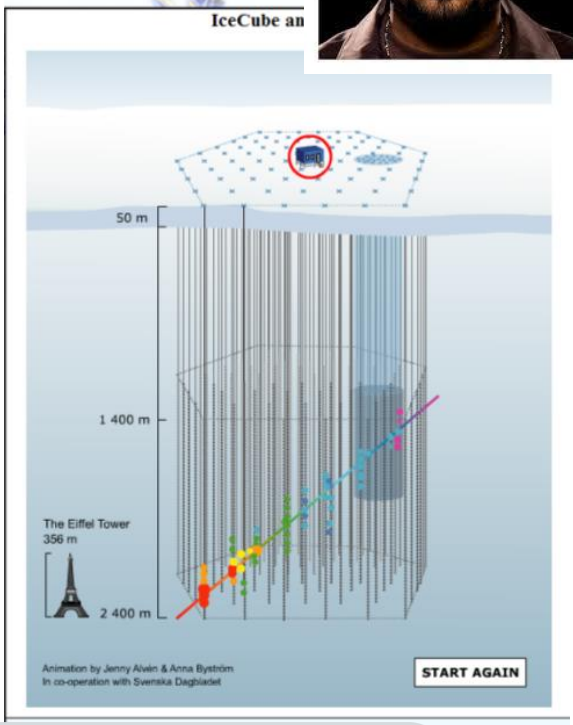


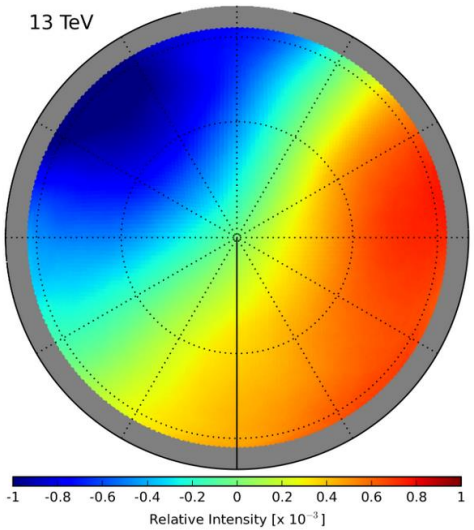


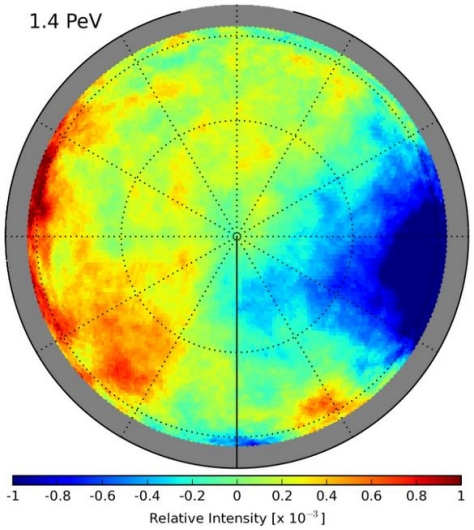
AMANDA – ICE CUBE

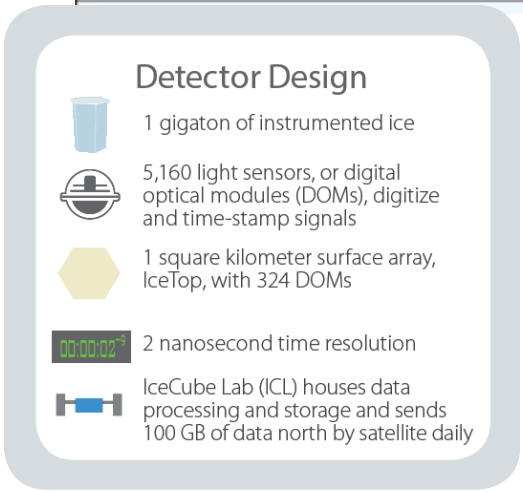


A very high energy neutrino detected in IceCube on November 12, 2010, with an energy of 71 TeV.
Image: IceCube Collaboration







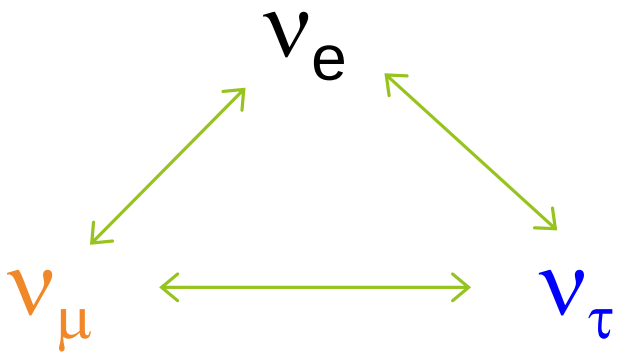


CERN Neutrino Gran Sasso

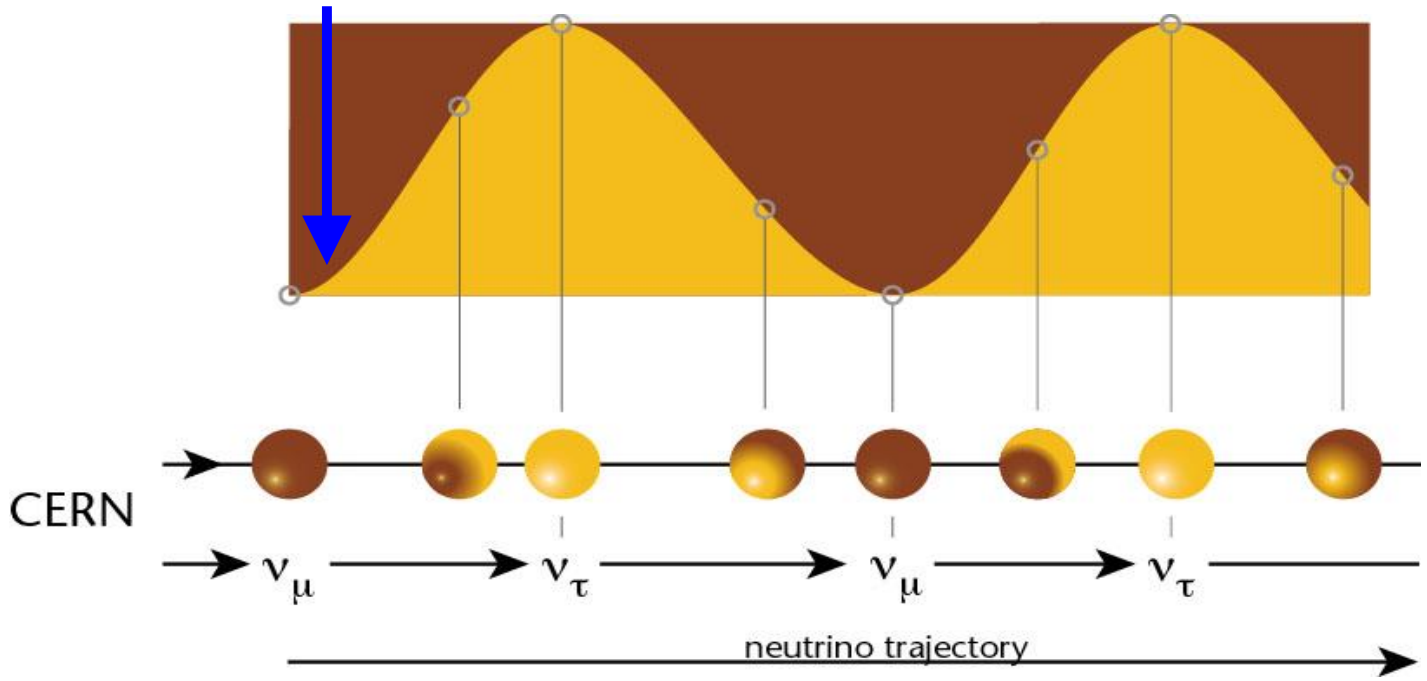
(CNGS)

CNGS

If neutrinos have mass:



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



CNGS PROJECT

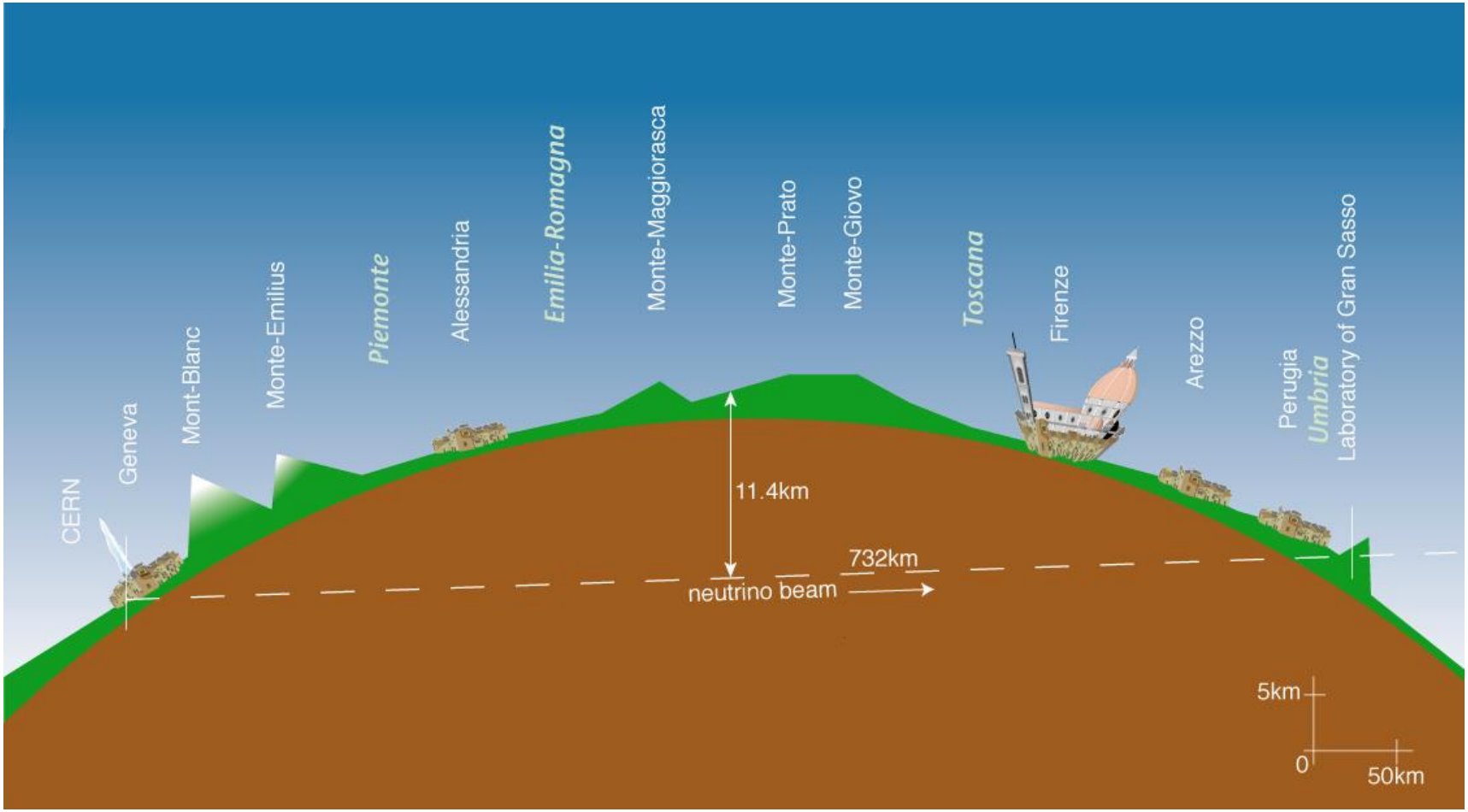
CNGS (CERN NEUTRINO GRAN SASSO)

- A LONG BASE-LINE NEUTRINO BEAM FACILITY (732KM)
- SEND ν_M BEAM PRODUCED AT CERN
- DETECT ν_T APPEARANCE IN OPERA EXPERIMENT AT GRAN SASSO

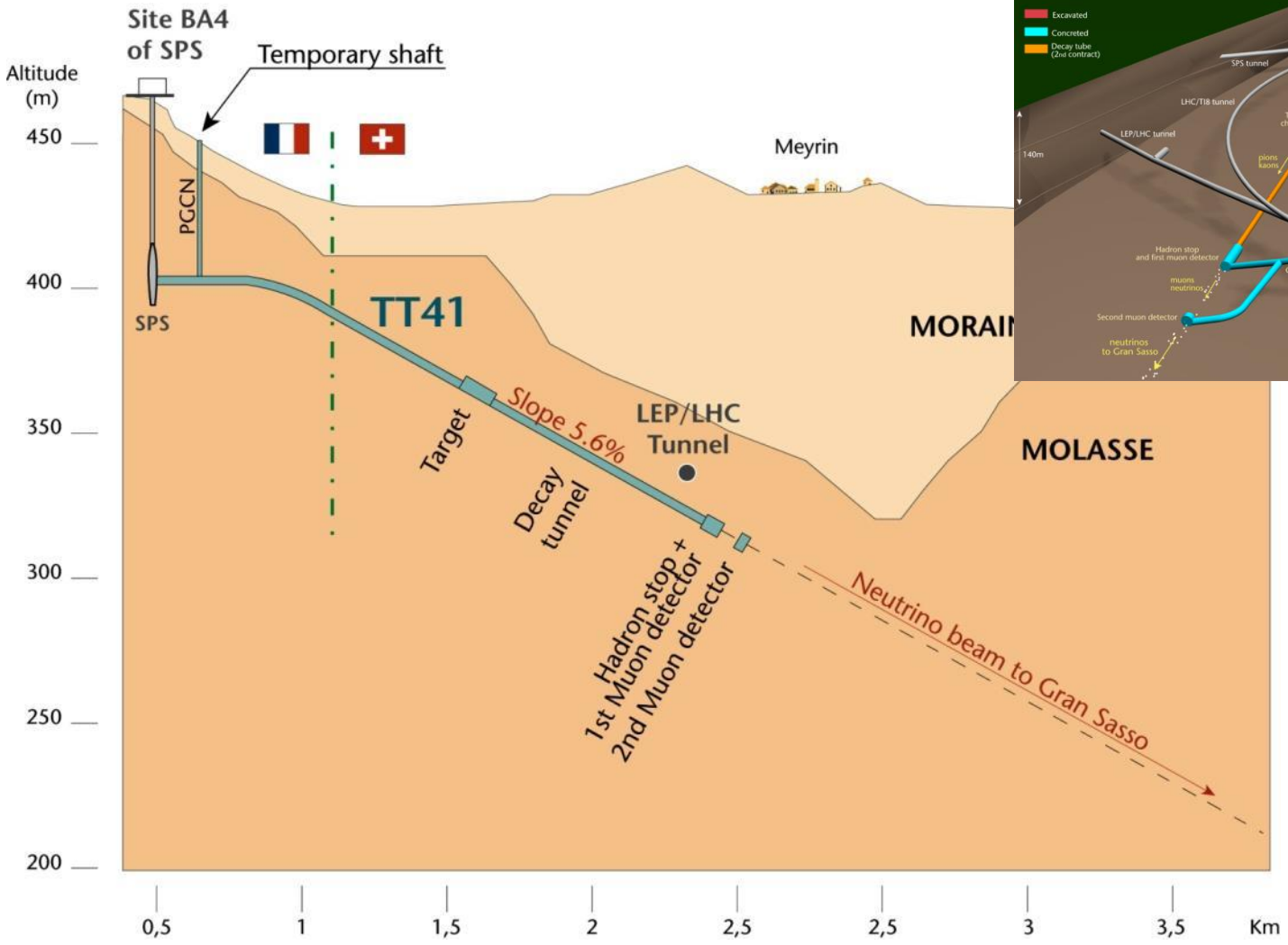
➔ direct proof of ν_μ - ν_τ oscillation (appearance experiment)

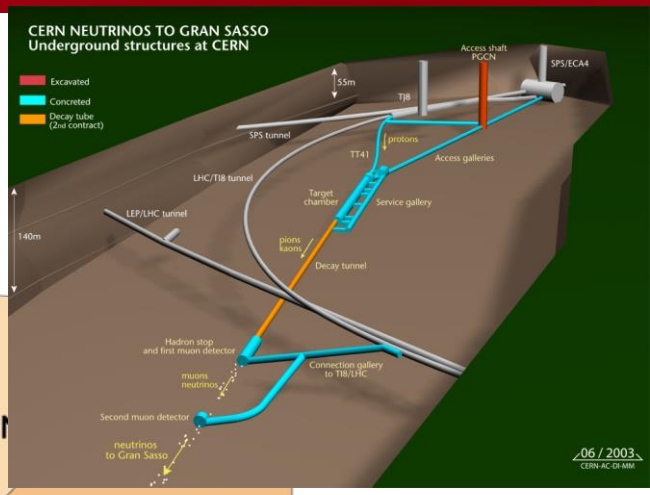
CEA/IRFU/DEDIP ---
maxence.vandenbroucke@cea.fr

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


Site BA4
of SPS
Temporary shaft
Altitude
(m)
450
400
350
300
250
200
PGCN
SPS
TT41
Meyrin
MORAI
MOLASSE
Target
Slope 5.6%
LEP/LHC
Tunnel
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


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

NEUTRINOS AT CNGS: SOME NUMBERS

For 1 day of CNGS operation, we expect:

protons on target	**2×10^{17}**
pions / kaons at entrance to decay tunnel	**3×10^{17}**
ν_μ in direction of Gran Sasso	**10^{17}**
ν_μ in 100 m^2 at Gran Sasso	**3×10^{12}**

ν_μ events per day in OPERA	$\approx$ 25 per day
ν_τ events (from oscillation)	$\approx$ 2 per year

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Opera Experiment at Gran Sasso

$$\nu_\tau N \rightarrow \tau^- X$$

$$\tau^- \rightarrow \mu^- \nu_\mu \bar{\nu}_\tau \quad with \quad BR = 17.36 \pm 0.05\% \tag{1}$$

$$\tau^- \rightarrow e^- \nu_e \bar{\nu}_\tau \quad with \quad BR = 17.85 \pm 0.05\% \tag{2}$$

$$\tau^- \rightarrow h^- (n\pi^0) \bar{\nu}_\tau \quad with \quad BR = 49.52 \pm 0.07\% \tag{3}$$

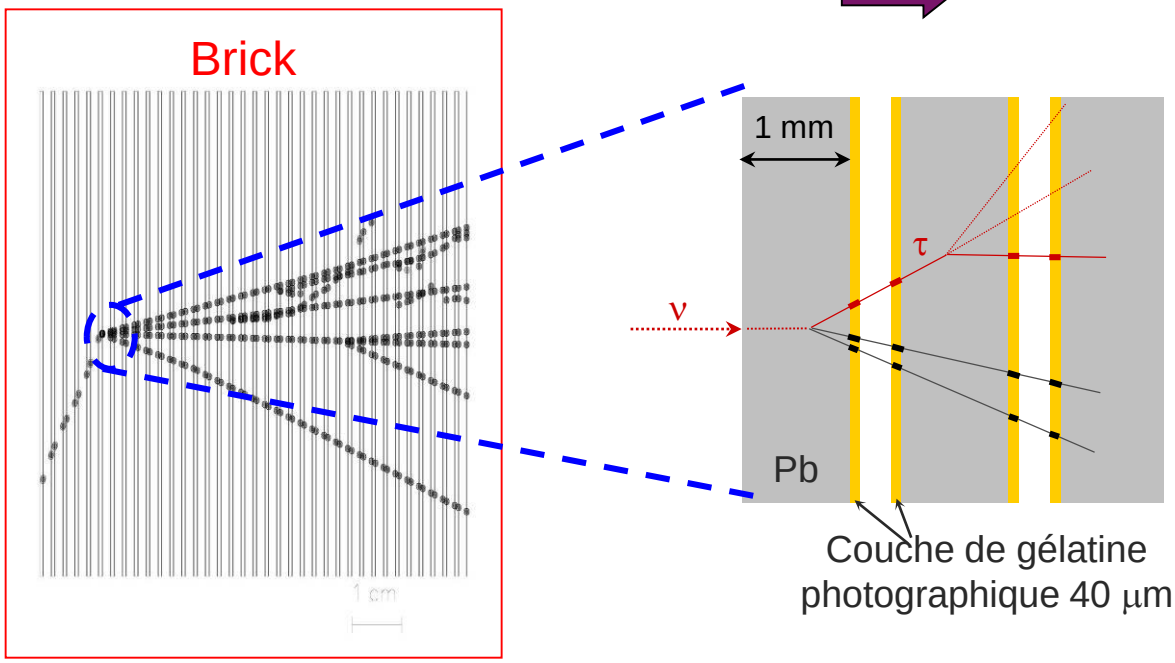
$$\tau^- \rightarrow 2h^- h^+ (n\pi^0) \bar{\nu}_\tau \quad with \quad BR = 15.19 \pm 0.08\%. \tag{4}$$

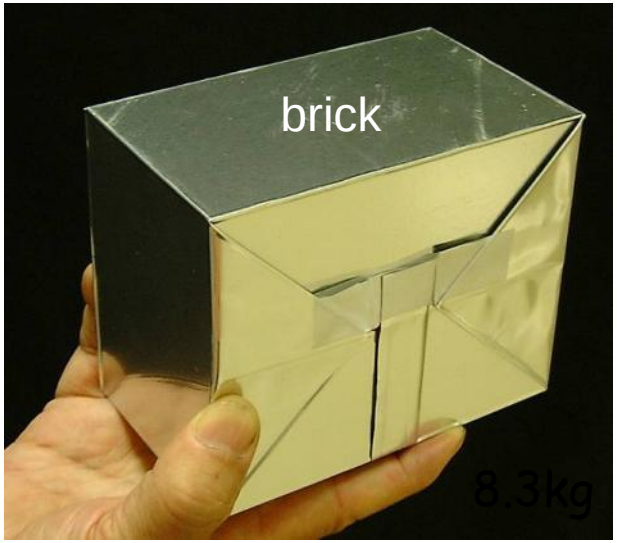
https://arxiv.org/pdf/1305.2513.pdf

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

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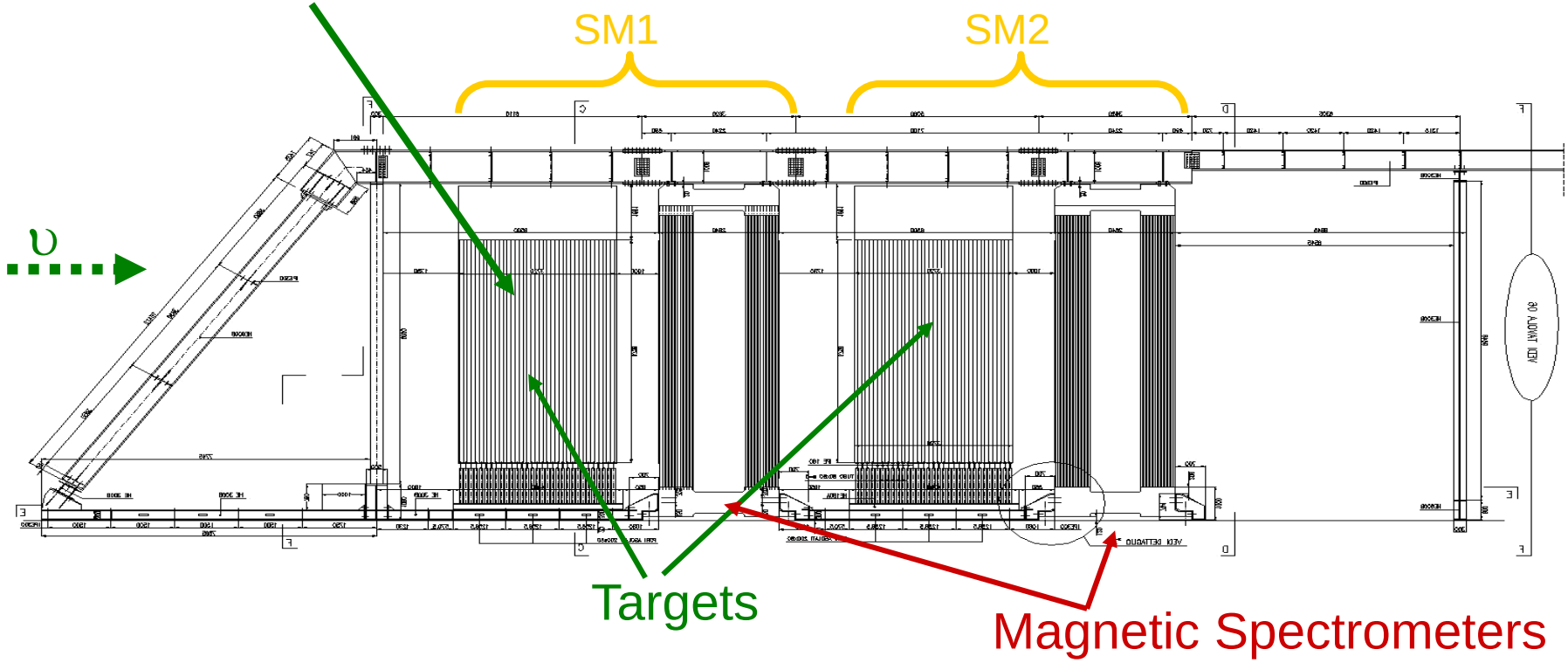
Opera Experiment at Gran Sasso

31 target planes / supermodule

In total: 206336 bricks, 1766 tons



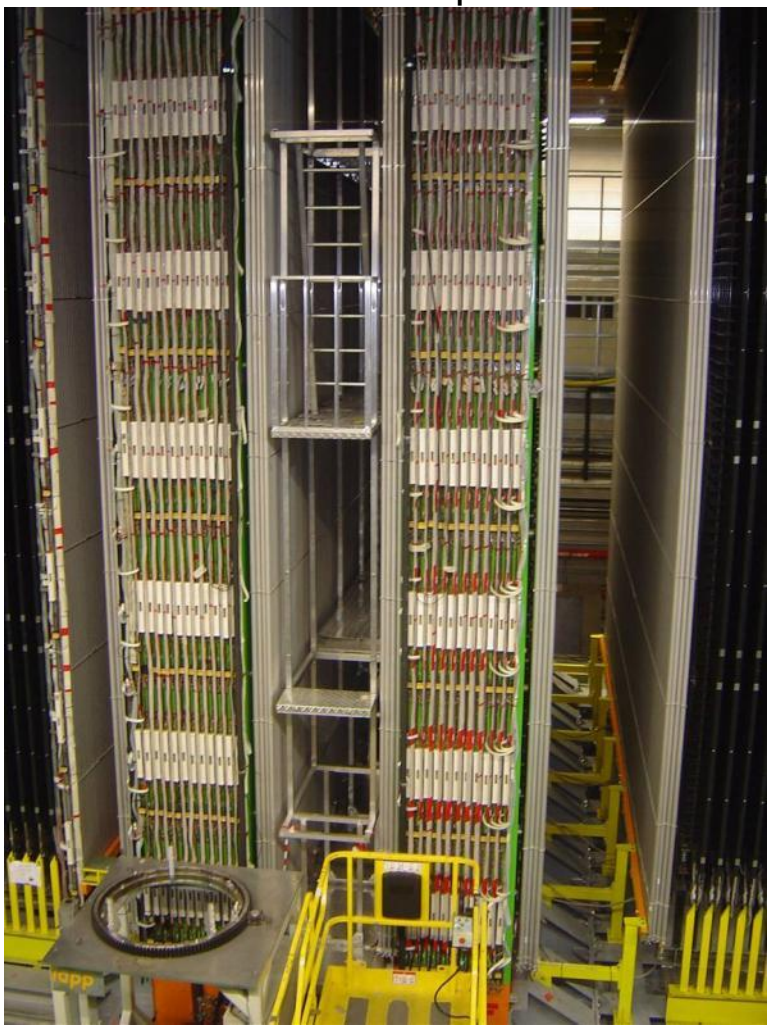
First observation of CNGS beam neutrinos : August 18th, 2006

Opera Experiment at Gran Sasso

Second Super-module

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

Details of the first spectrometer

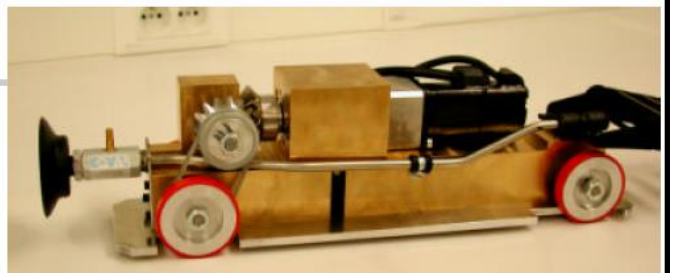


3050 m^2 Resistive Plate Counters
2000 tons of iron for the two magnets

Opera Experiment at Gran Sasso

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

Tests with the prototype wall



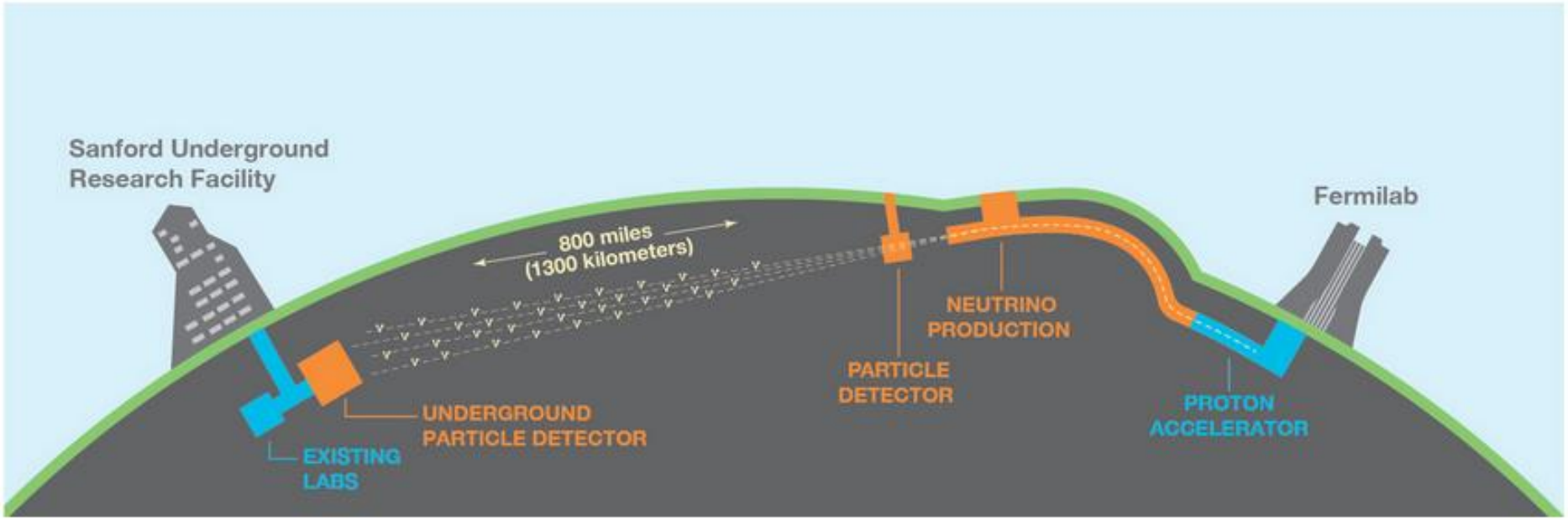
The robotised "Ferrari" for insertion/extraction of bricks with vacuum grip by Venturi valve

"Carousel" brick dispensing and storage system

Dune

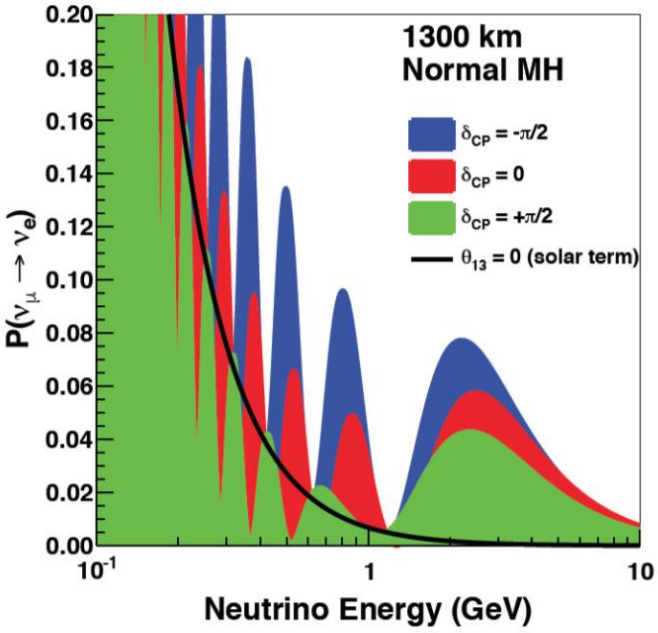
An international mega-science project

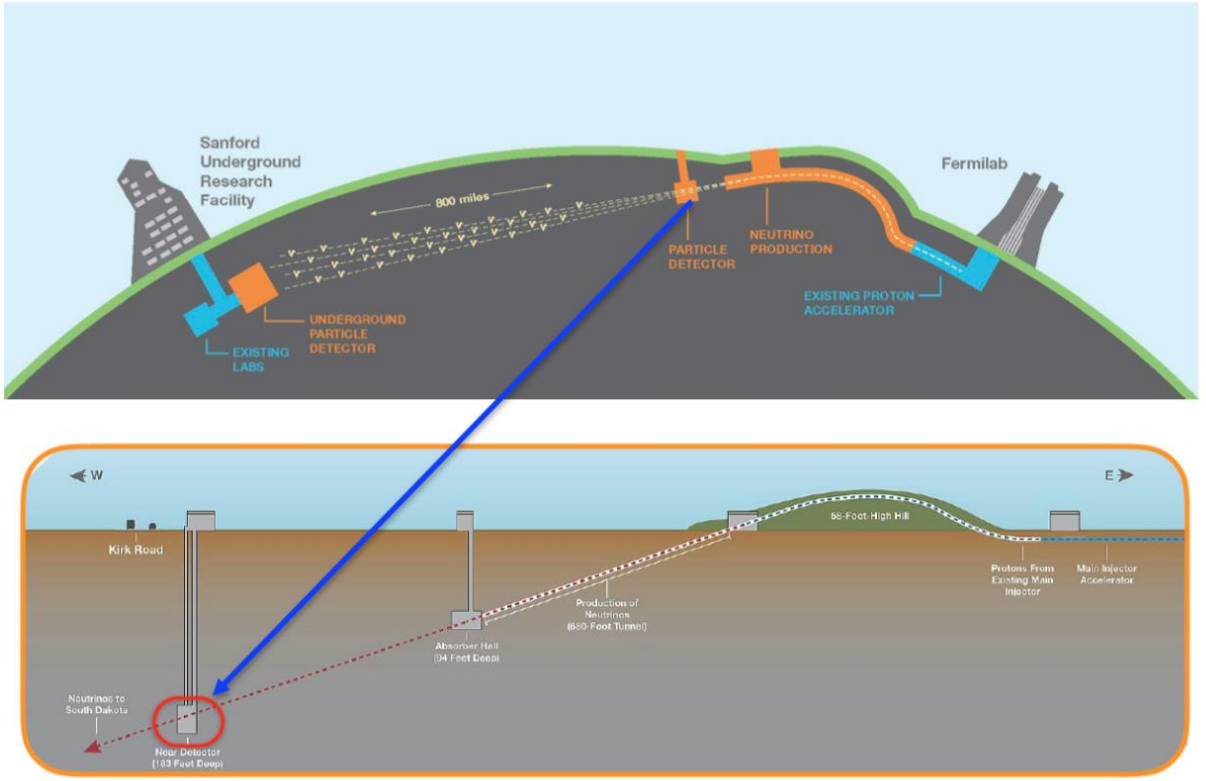
The Deep Underground Neutrino Experiment (DUNE) is a leading-edge, international experiment for neutrino science and proton decay studies. Discoveries over the past half-century have put neutrinos, the most abundant matter particles in the universe, in the spotlight for further research into several fundamental questions about the nature of matter and the evolution of the universe — questions that DUNE will seek to answer.



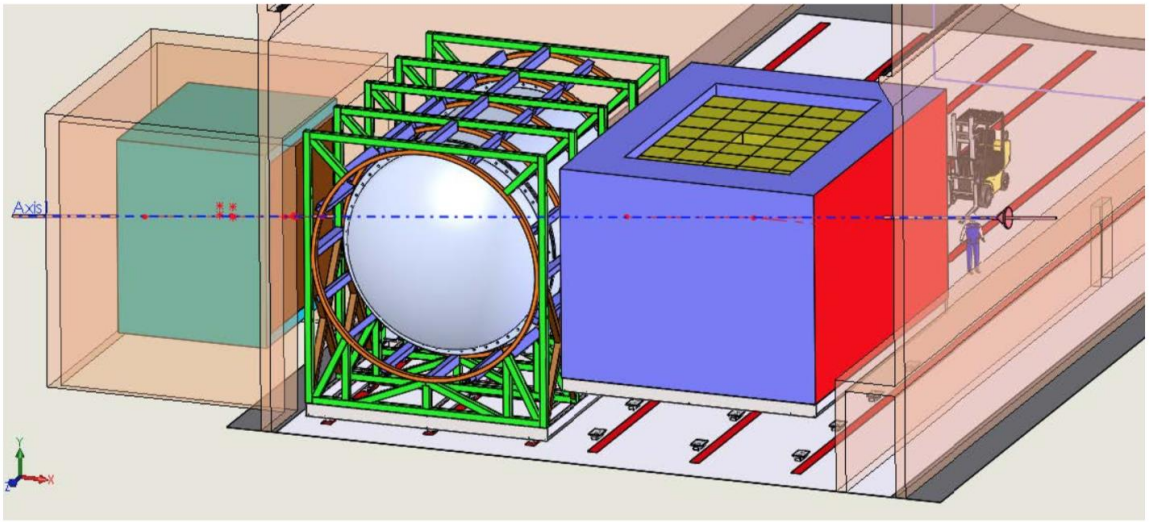
DUNE

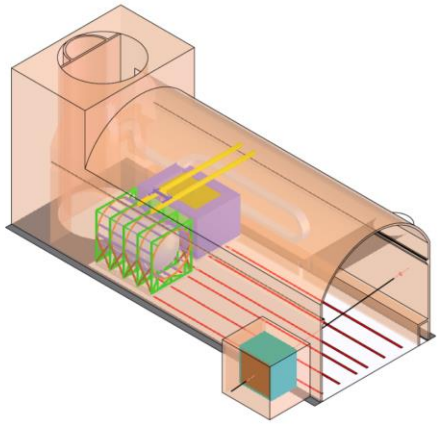
- Observe ν_e appearance and ν_μ disappearance at long baseline in a wideband beam to precisely measure the neutrino oscillation parameters δ_{CP}, θ_{23}, θ_{13}, and Δm^2_{32} in a single experiment.





Reference Design

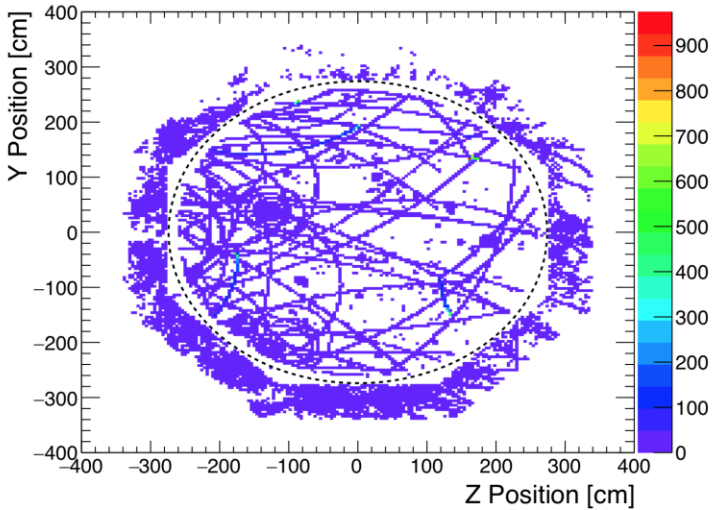




- 3 components (Right-to-left)
  - LAr TPC with pixelated readout (50t)
  - Multi-Purpose Detector - MPD
    - HPgTPC(1t) + ECAL + magnet
  - 3DST-S: Three-Dimensional Scintillator Track

Z-Y projection full spill & event

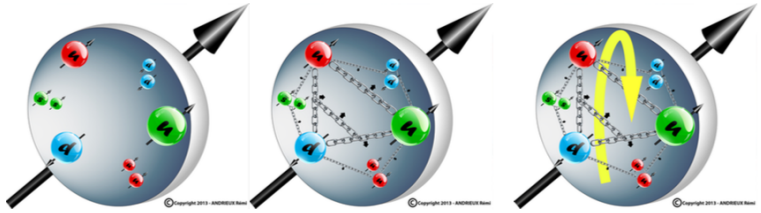
- Corresponds to full spill exposure
- Overlay of test event plus 60 events in the ECAL



Physique Hadronique

COMPASS et CLAS12

COMPASS at CERN



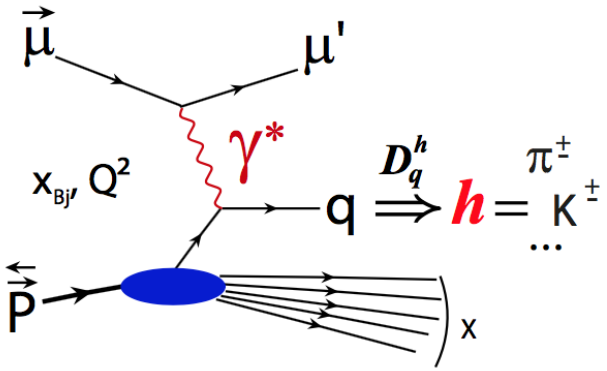
Différentes contributions

$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta u + \Delta d + \Delta s)} + \underbrace{\Delta G} + \underbrace{L_g + L_q}$$

Spin des quarks
$\Delta\Sigma \sim 0.3$

Spin des gluons
$|\Delta G| < 0.5$

Moments orbitaux
$L_{q+g} = ??$



Section efficace DIS

$$\frac{d^2\sigma}{dxdQ^2} = \underbrace{c_1 F_1(x,Q^2) + c_2 F_2(x,Q^2)}_{\text{fonctions de structure non-polarisées}} + \underbrace{c_3^{s,S} g_1(x,Q^2) + c_4^{s,S} g_2(x,Q^2)}_{\text{fonctions de structure polarisées}}$$

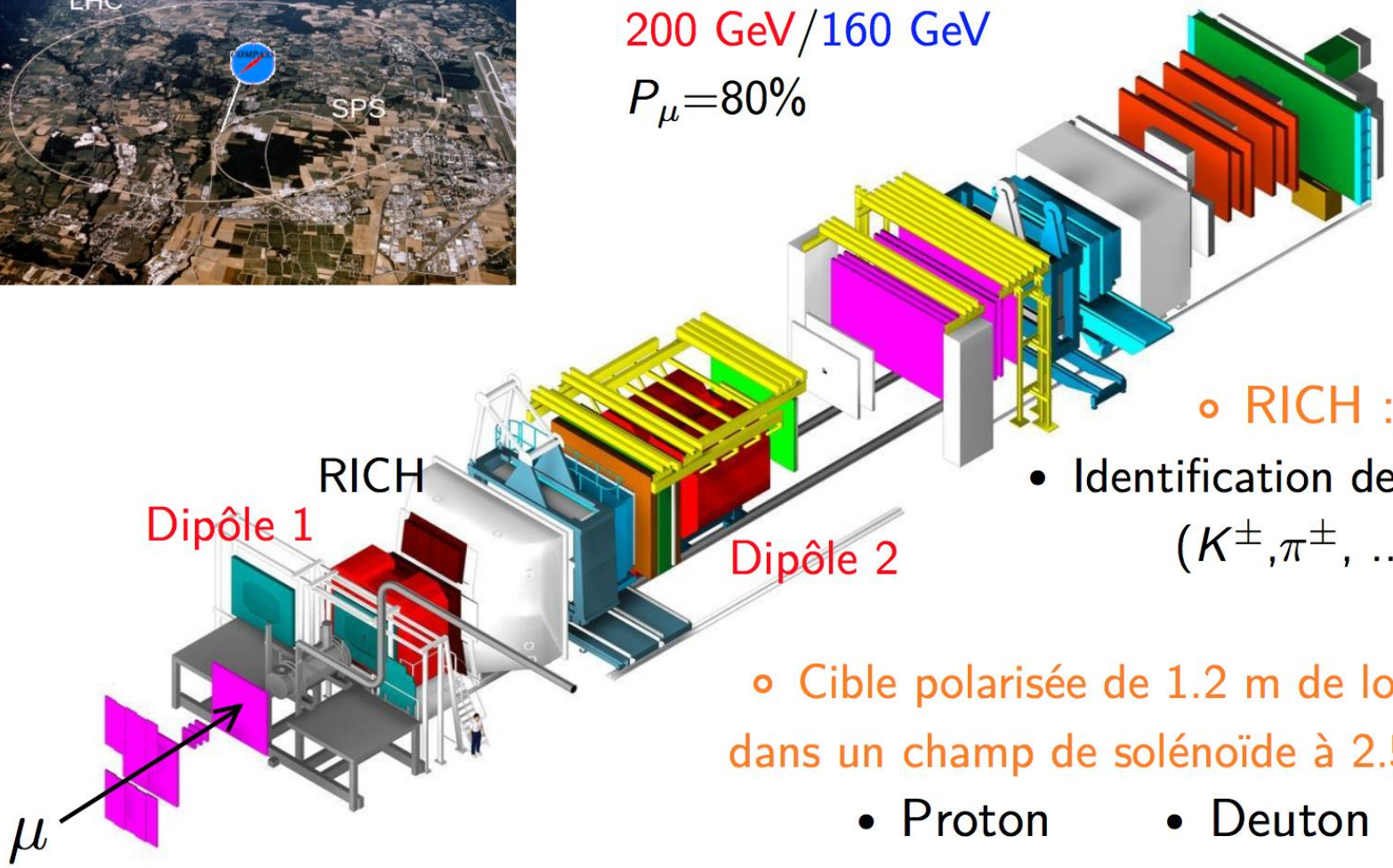
COMPASS at CERN

- Faisceau polarisé de μ^+ du SPS

  $1 \cdot 10^8/2 \cdot 10^8$ μ par déversement de $\sim$ 10 s

  200 GeV/160 GeV

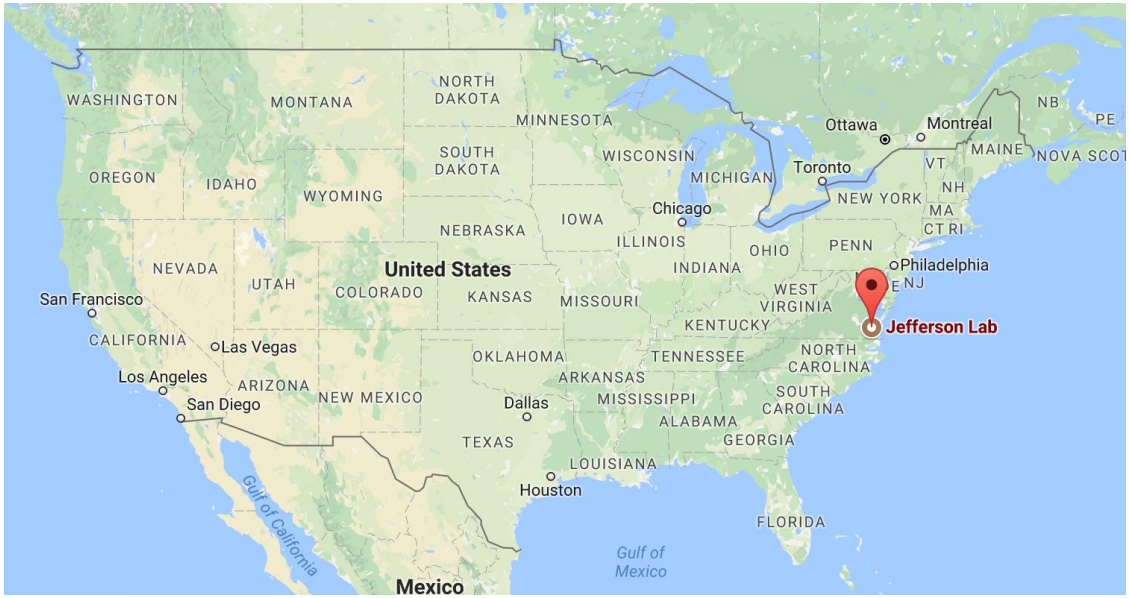
  P_μ=80%

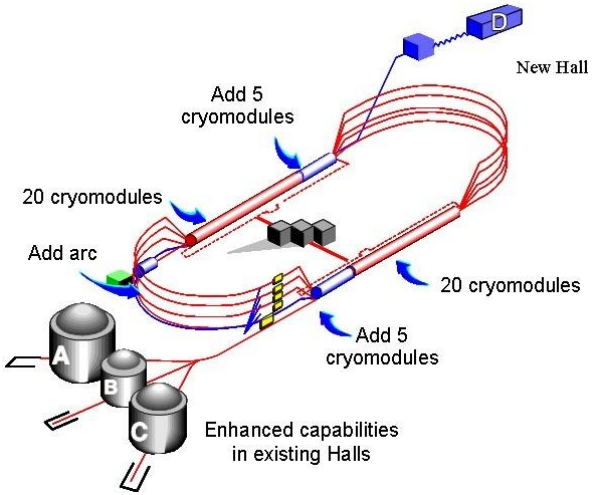


- RICH :
  - Identification des hadrons ($K^\pm$,$\pi^\pm$, ...)

- Cible polarisée de 1.2 m de long dans un champ de solénoïde à 2.5 T
  - Proton
  - Deuton

CLAS12 at Jefferson Lab





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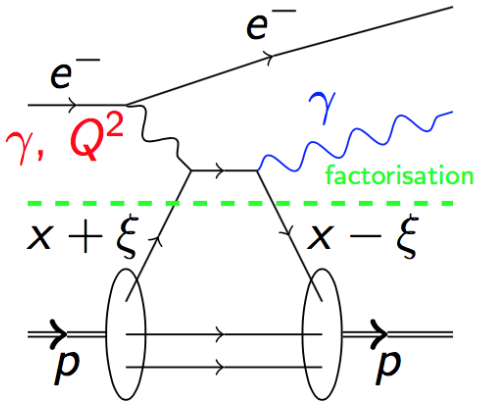
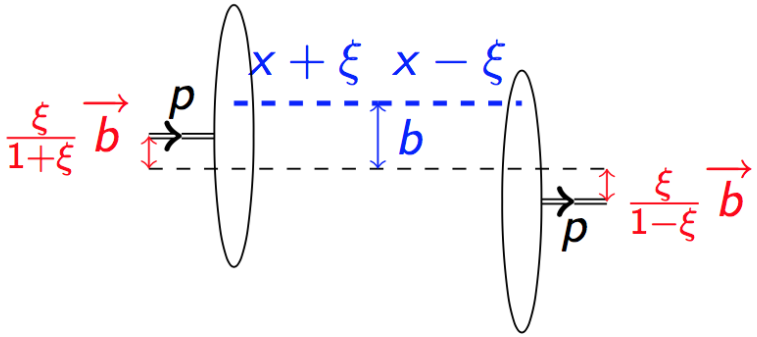
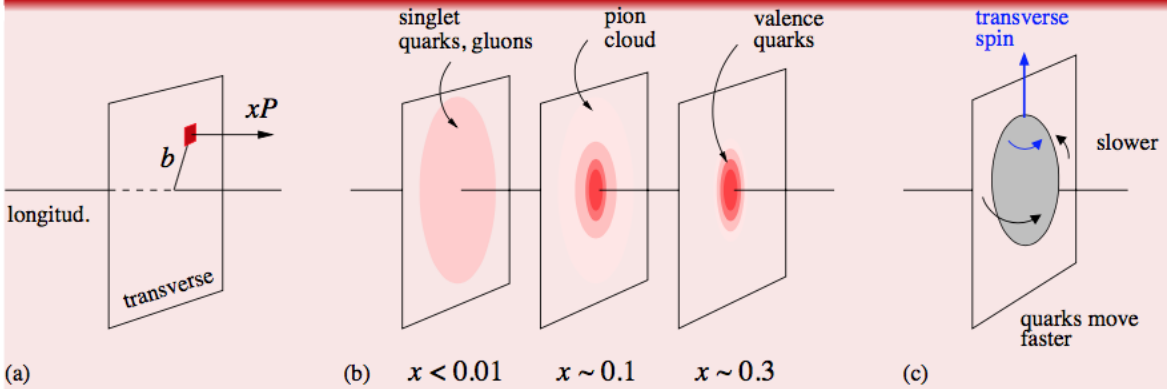
CLAS12 at Jefferson Lab

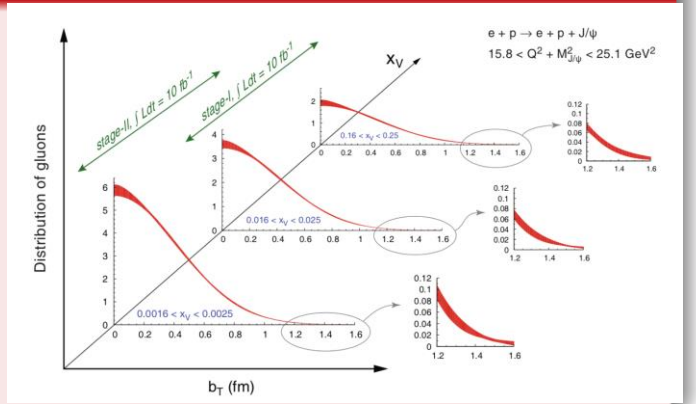
Diffusion Compton profondément virtuelle (DVCS)

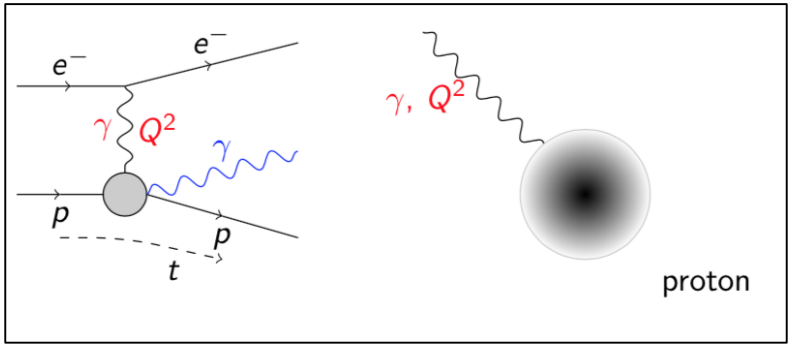




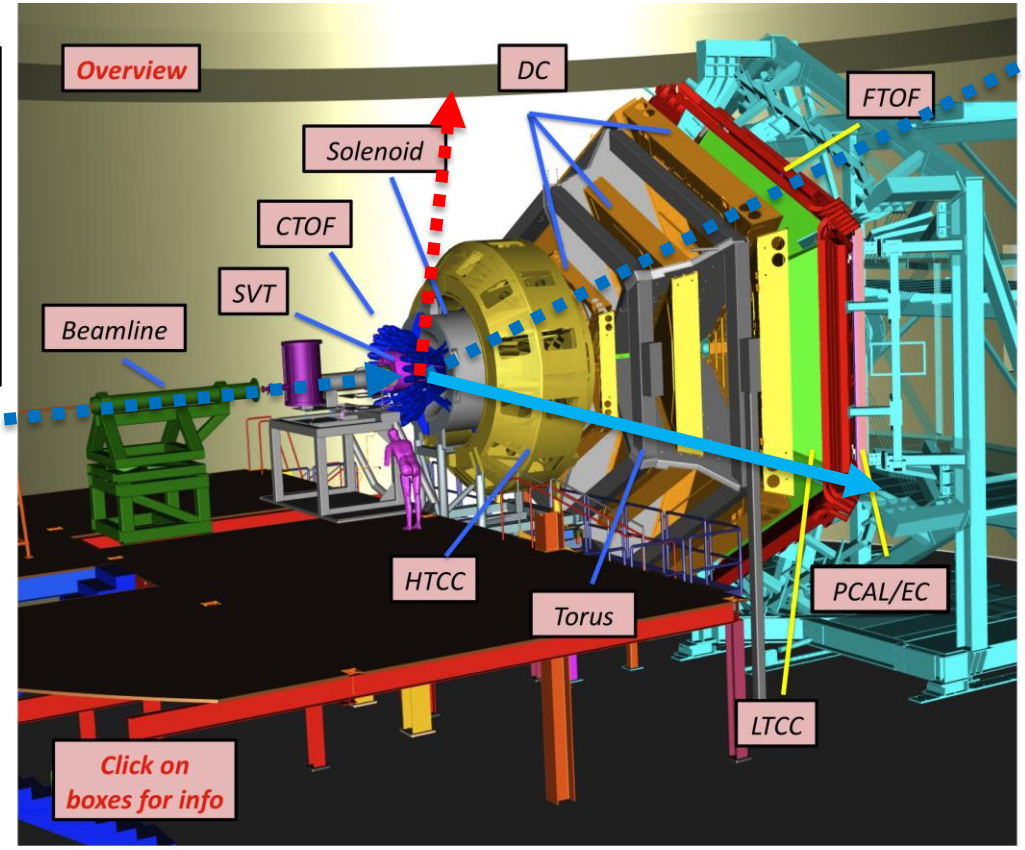
Vers une visualisation en 3d du nucléon !



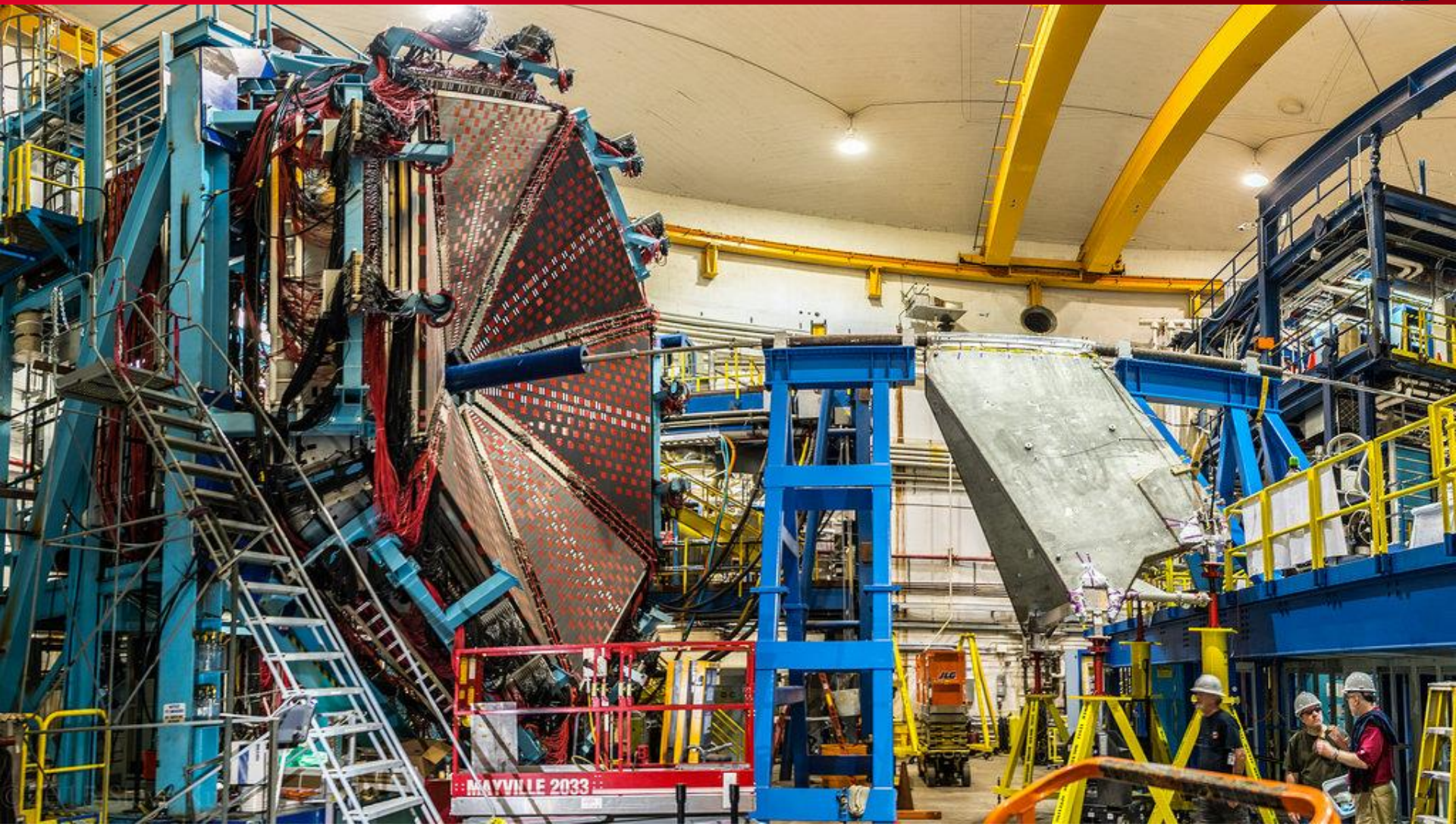



e^-
e^-
γ Q^2
γ
p
p
t
γ, Q^2
proton

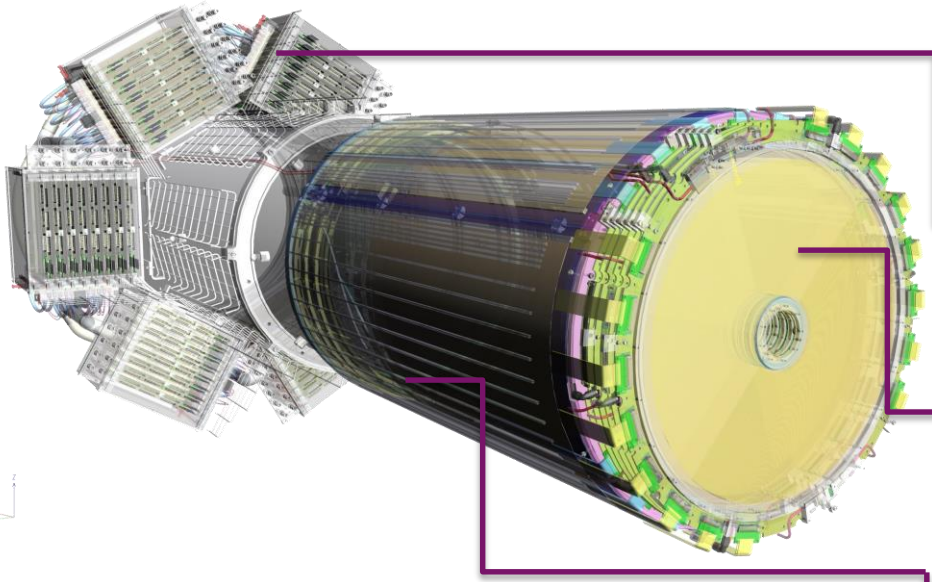
proton

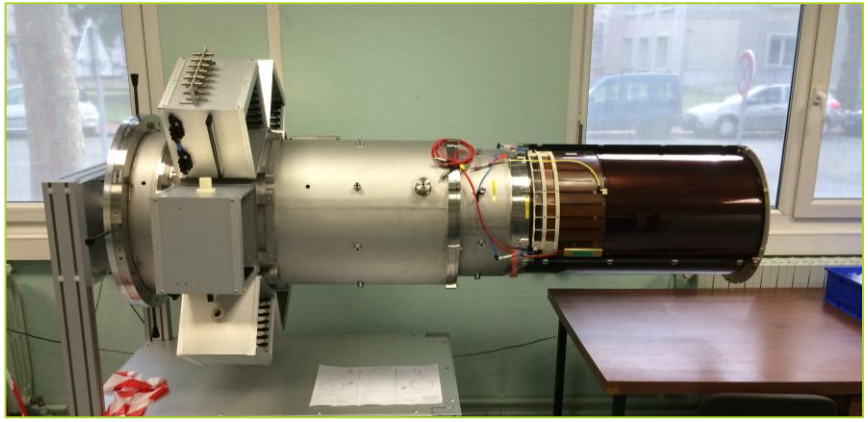

Overview
DC
FTOF
Solenoid
CTOF
SVT
Beamline
HTCC
Torus
PCAL/EC
LTCC
Click on boxes for info

CLAS12 at Jefferson Lab



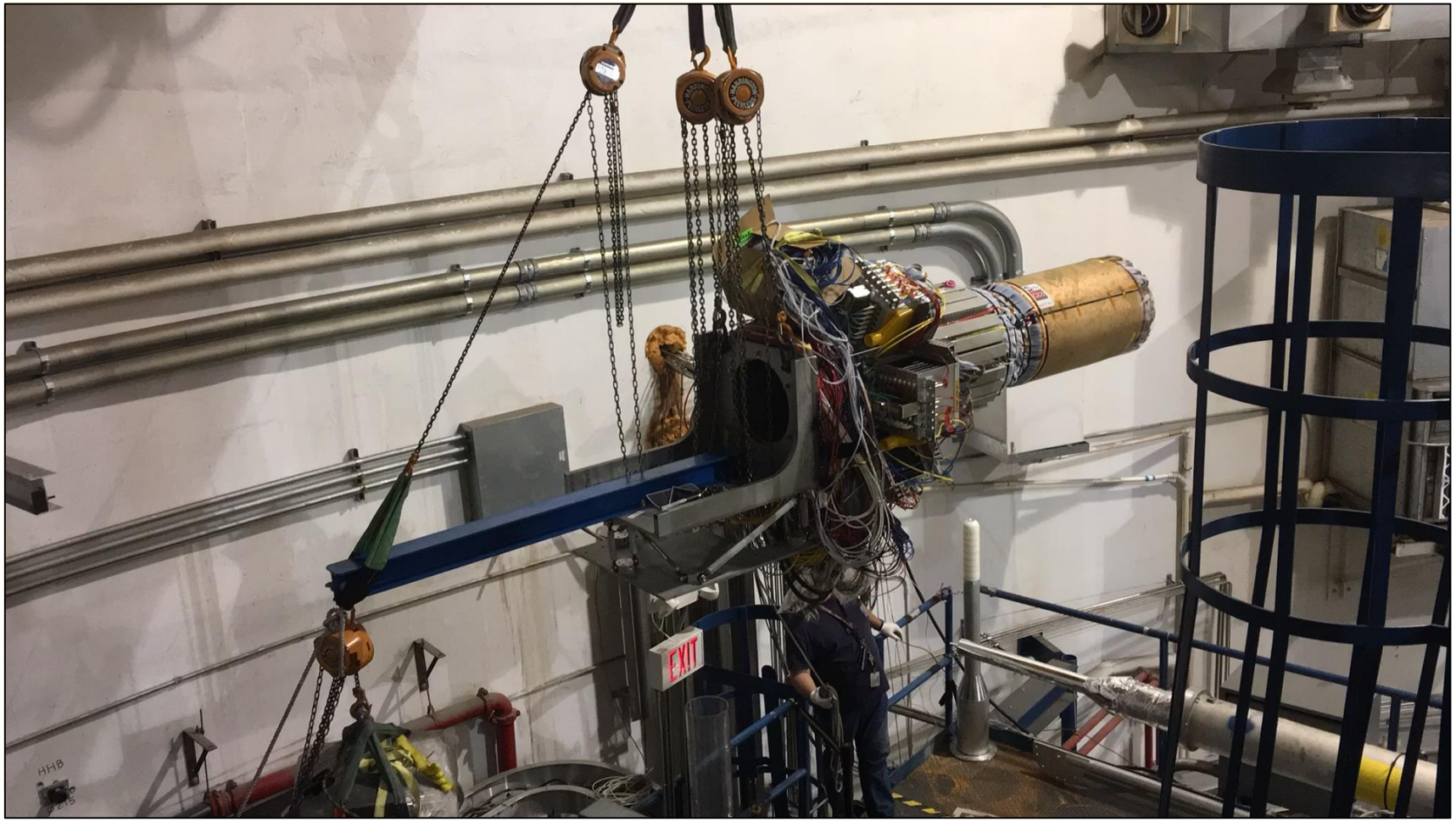
CLAS12 - THE MICROMEGAS VERTEX TRACKER



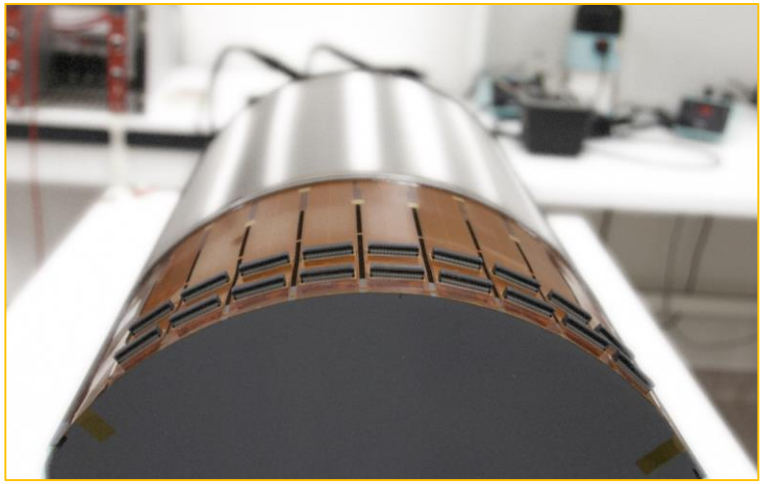


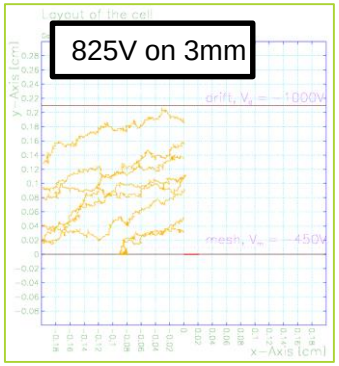
- 4 m² of Micromegas detectors to be installed in 2017
- DREAM based Front-End Electronics
- Remote off-detector frontend electronics connected with 2m micro-coaxial cables
- Forward Detectors
  - High particle rate (30MHz) => Fast detectors
  - Resistive strips divided in 2 zones inner/outer
  - Dimensions: 6x 430 mm diameter disk with a 50 mm diameter hole at the center
- Cylindrical Barrel
  - Low momentum particles => Light Detectors
  - Limited space of ~10 cm for 6 layers
  - High magnetic field (5T)
  - Phase 1 (2016) : 2 Layers (6 Det. of 120°)
  - Phase 2 (2017) : 6 Layers (18 Det.)

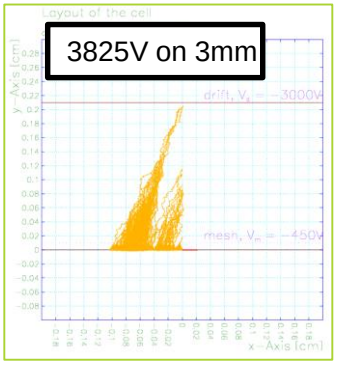
CLAS12 at Jefferson Lab

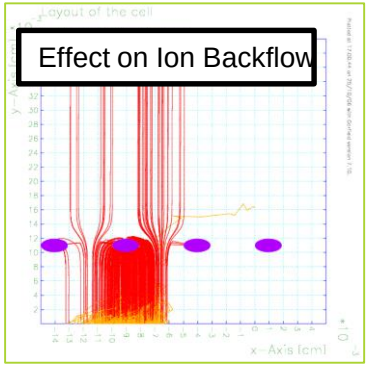


CLAS12 - THE MICROMEGAS VERTEX TRACKER

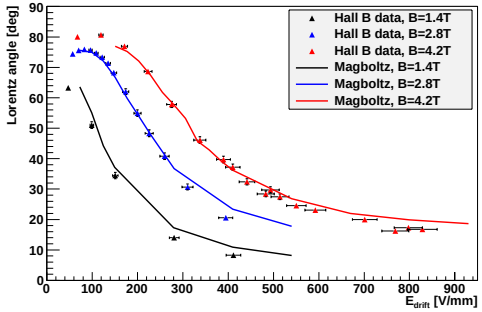




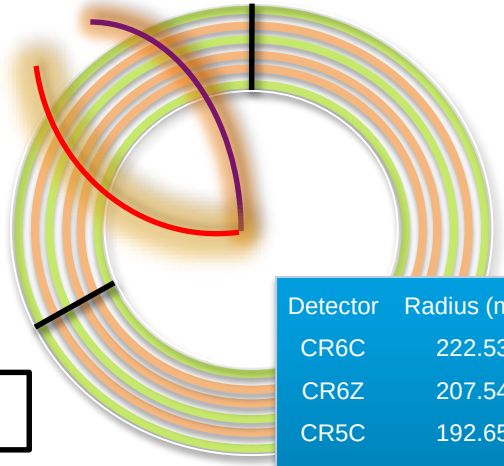




Lorentz Angle Vs HV



=> Clas-note 2007-004: Simulations of Micromegas detectors for the CLAS12 experiment (S. Procureur)



Detector	Radius (mm)
CR6C	222.53
CR6Z	207.54
CR5C	192.65
CR5Z	177.57
CR4Z	162.56
CR4C	147.57

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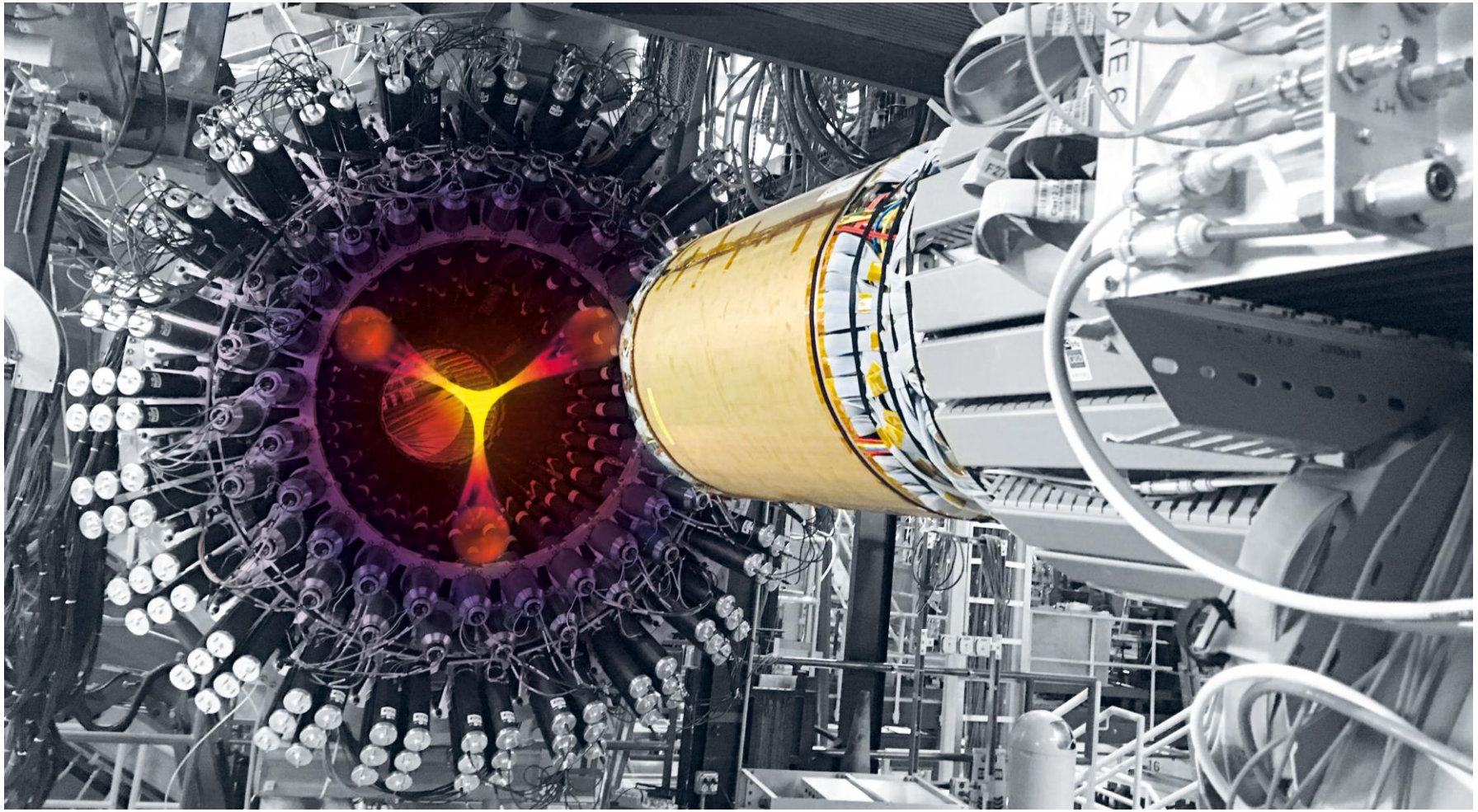
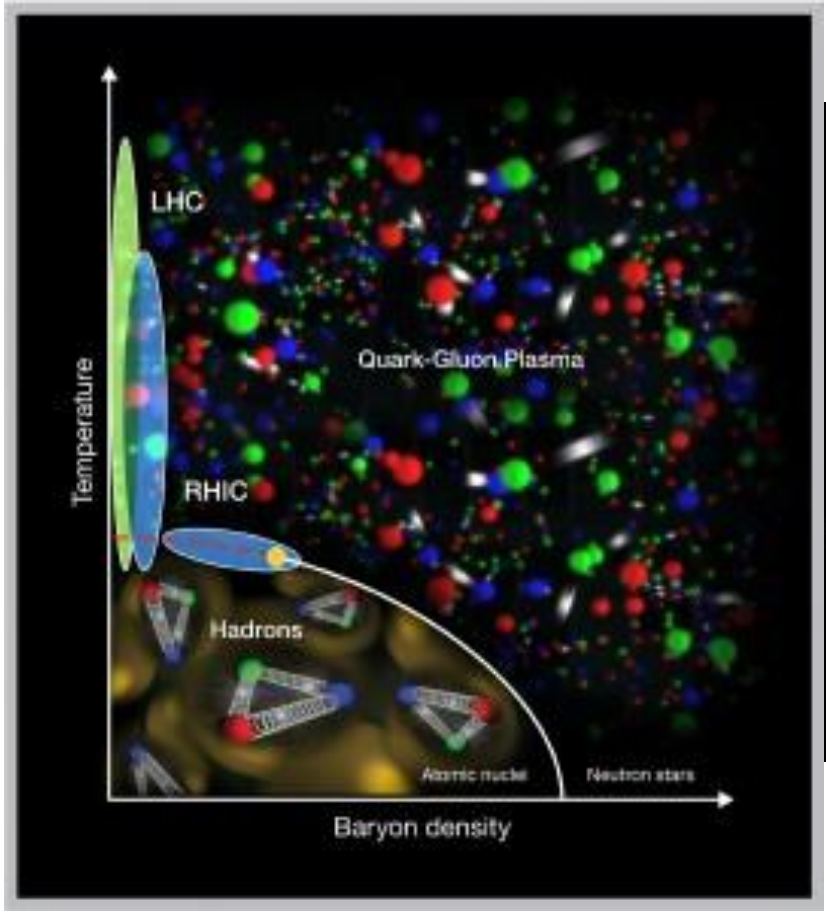
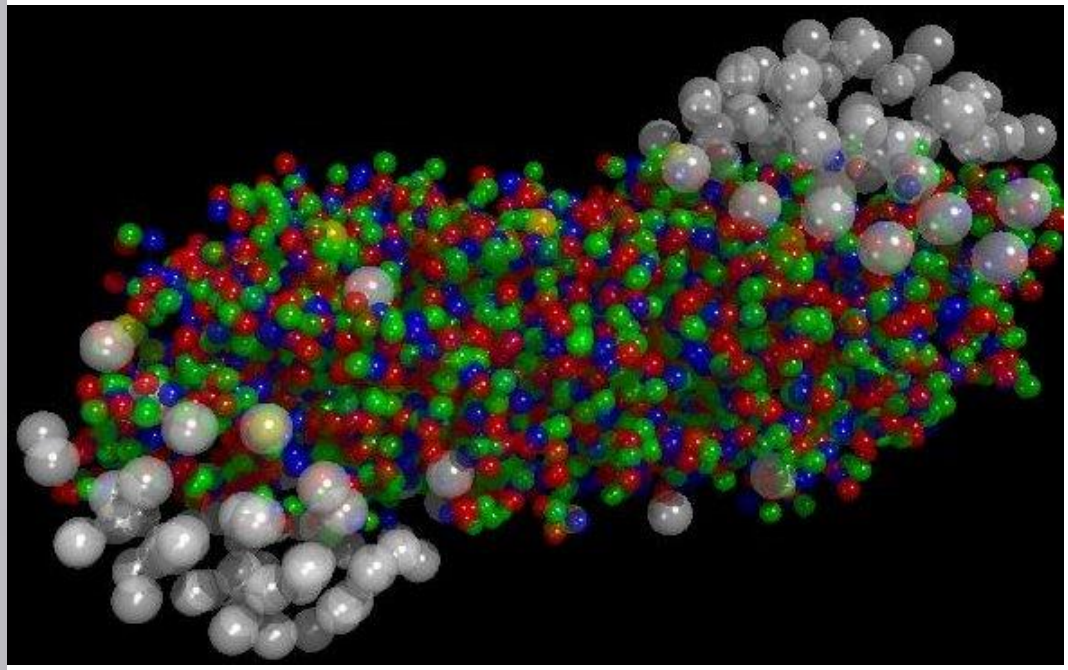
CLAS12 – Central Tracker



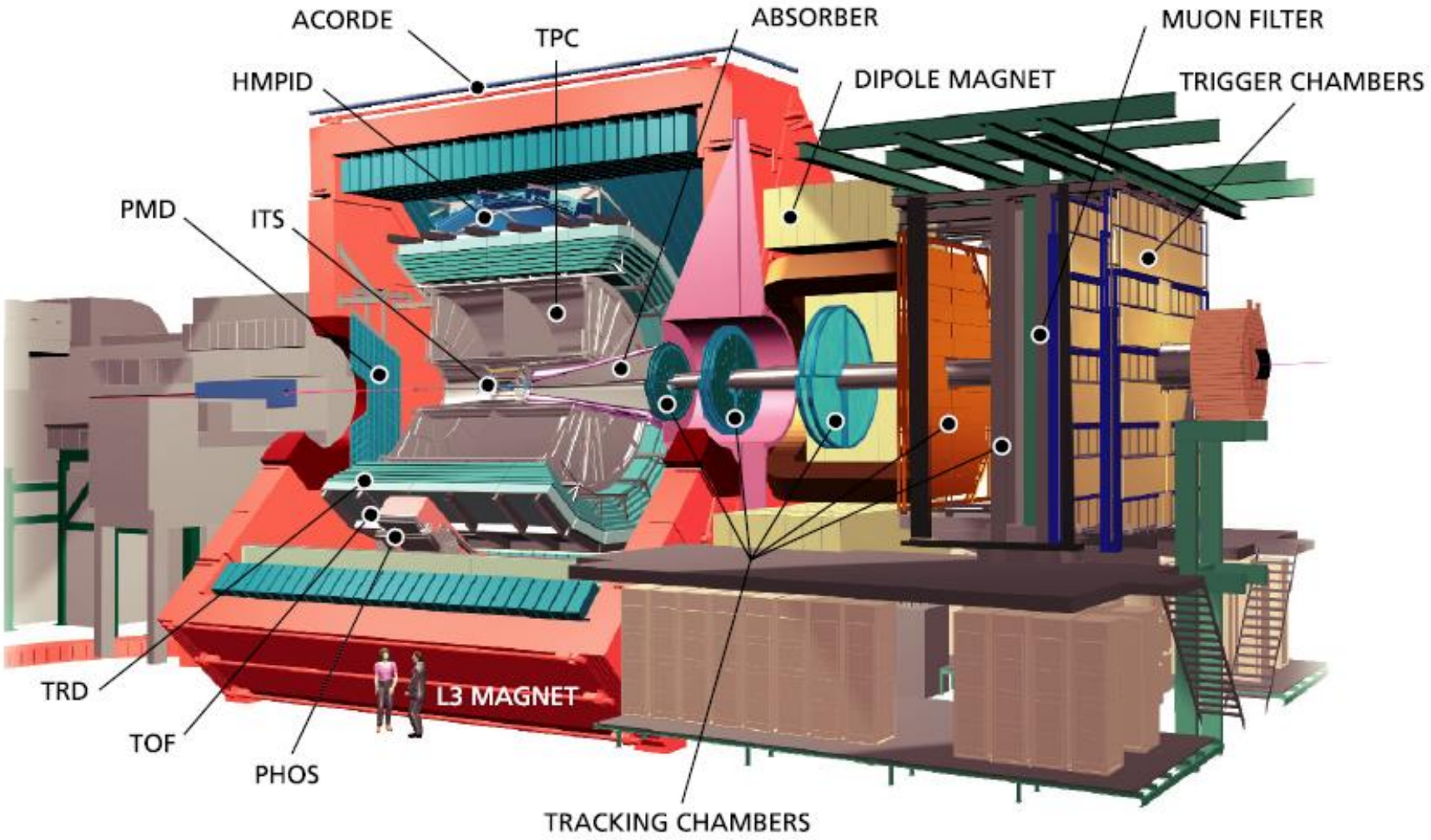
ALICE

A heavy Ion Experiment at the LHC

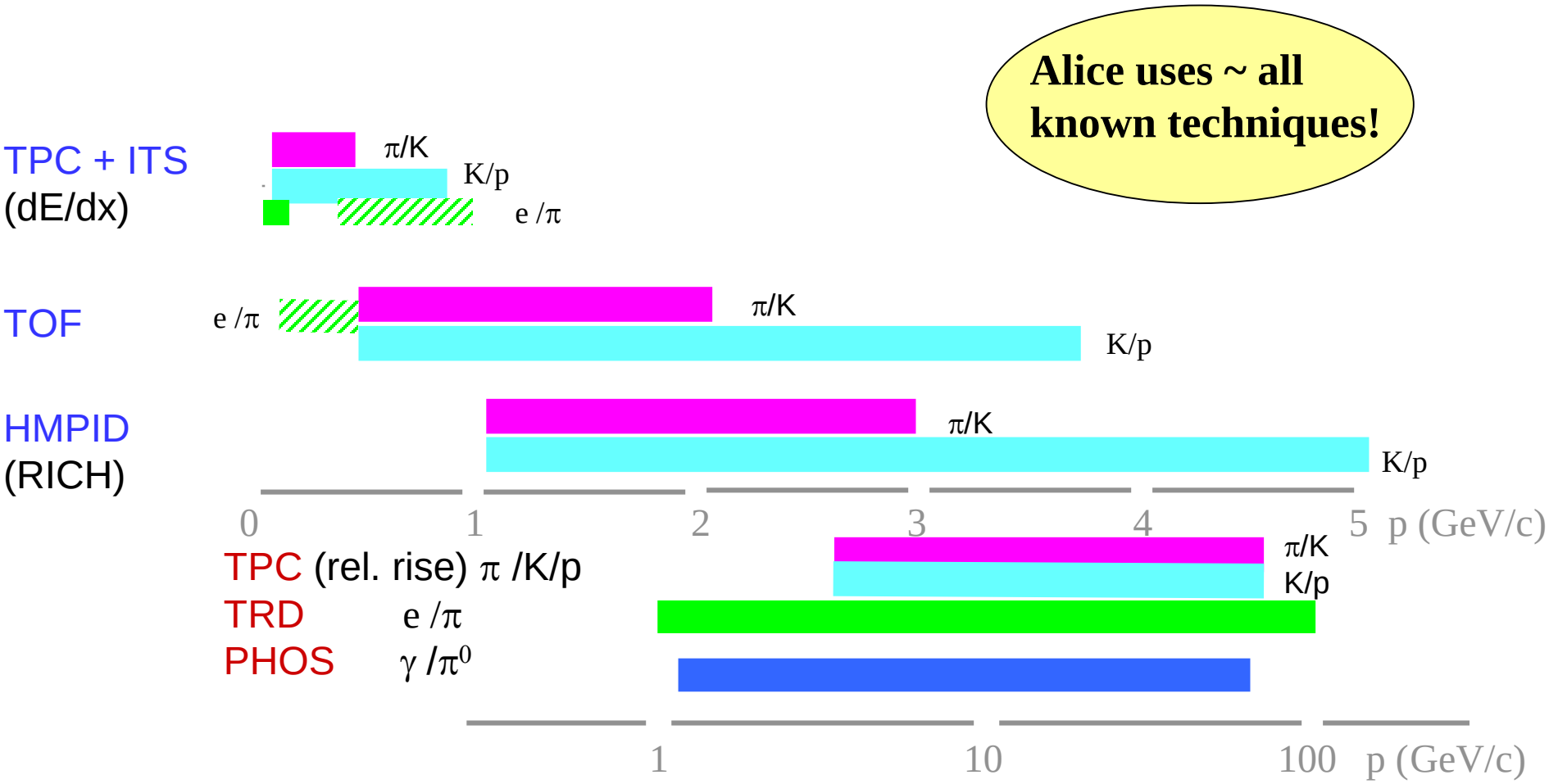




ALICE


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

ALICE Particle ID



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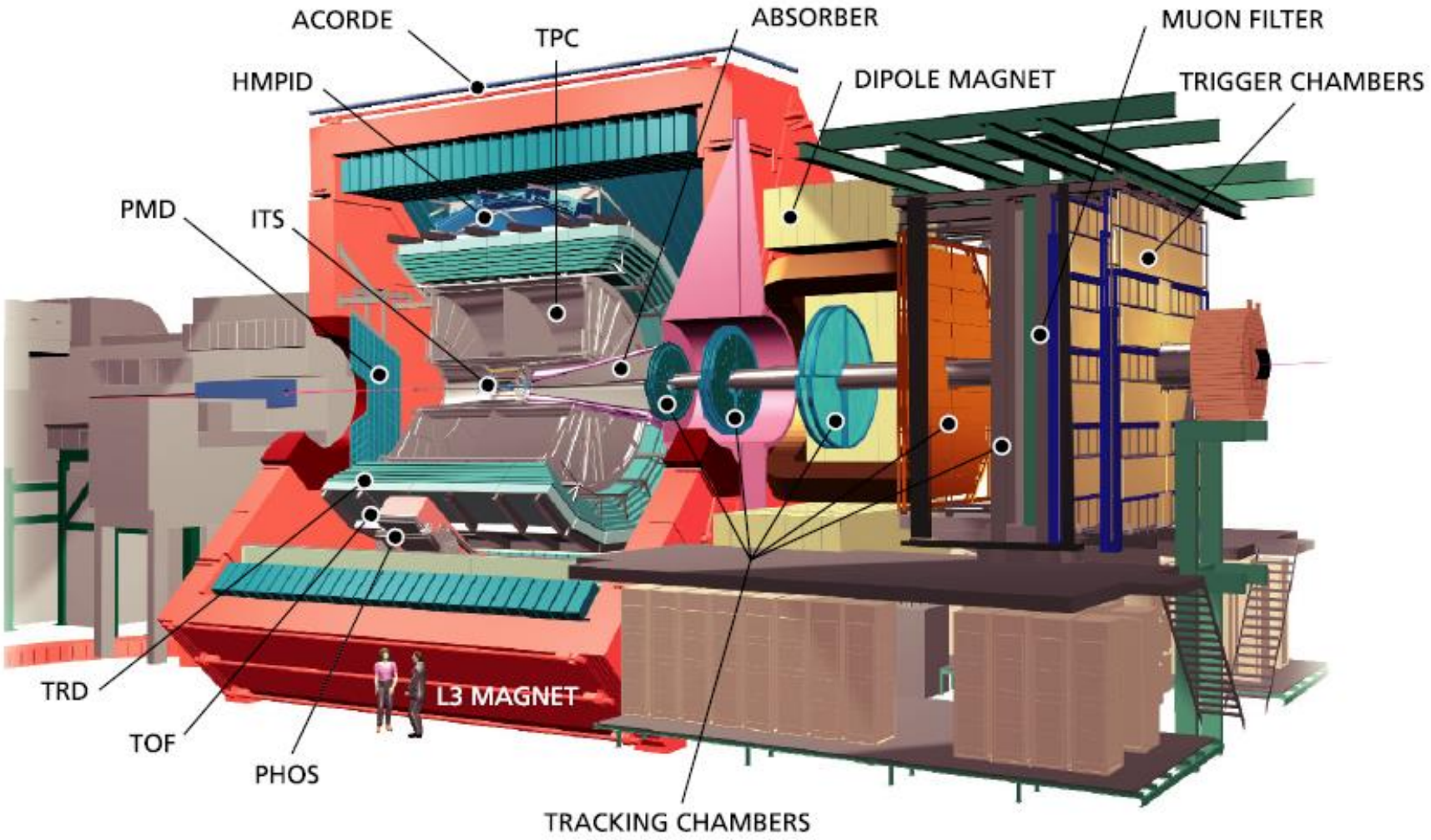
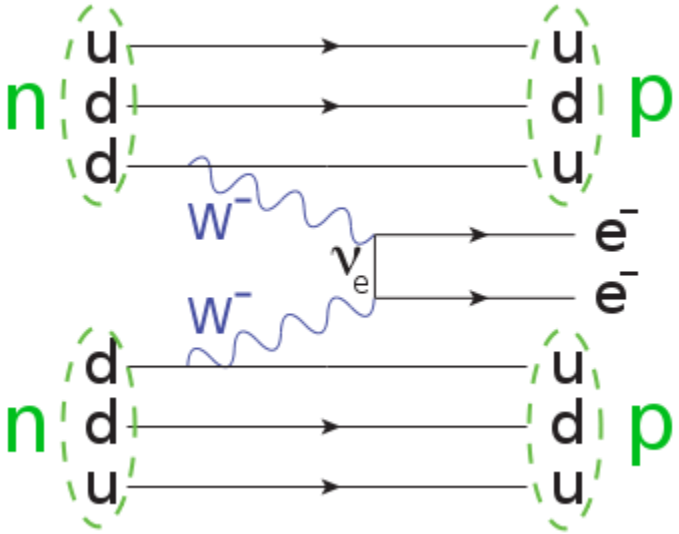

ACORDE
TPC
ABSORBER
MUON FILTER
HMPID
DIPOLE MAGNET
TRIGGER CHAMBERS
PMD
ITS
TRD
L3 MAGNET
TOF
PHOS
TRACKING CHAMBERS

DOUBLE BETA DECAY



$$0\nu\beta\beta \text{ of } {}^{136}Xe : {}^{136}Xe \rightarrow {}^{136}Ba + 2e^{-}$$

PandaX

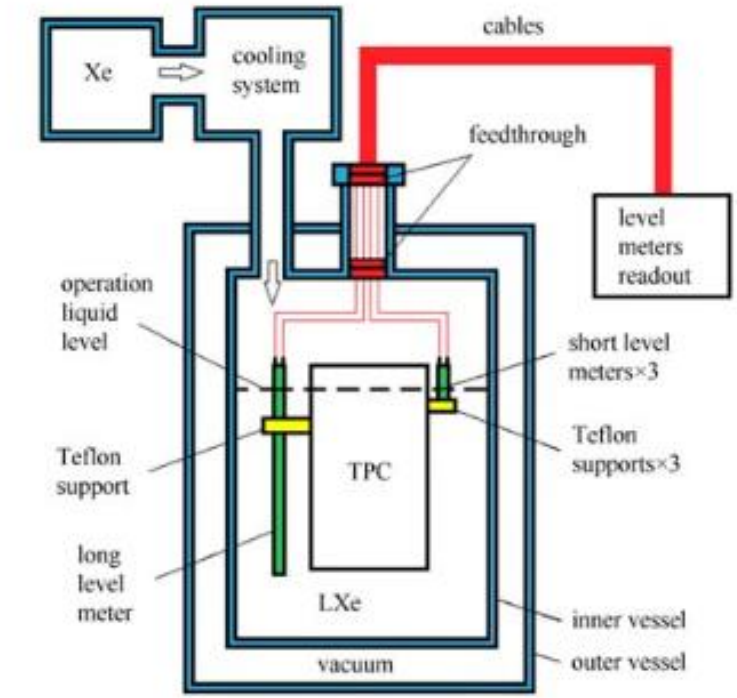
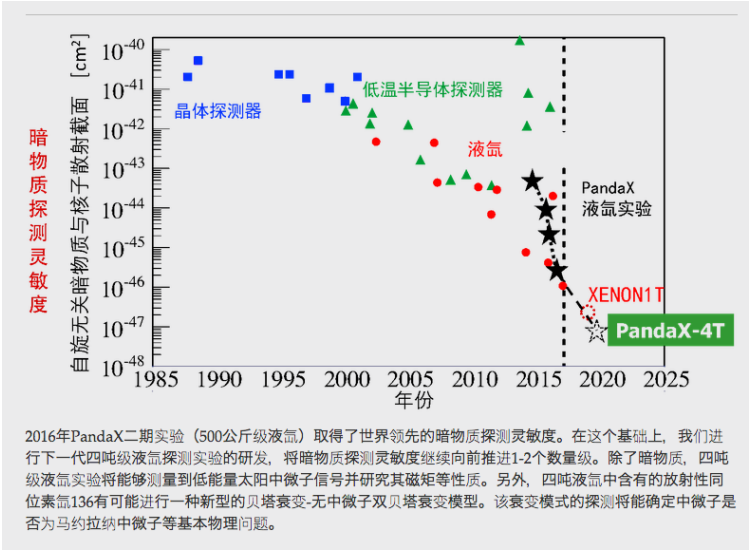
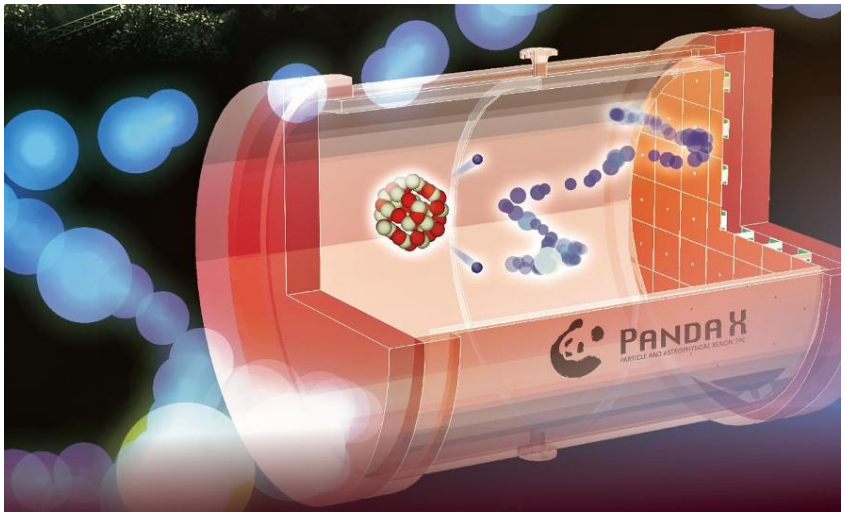


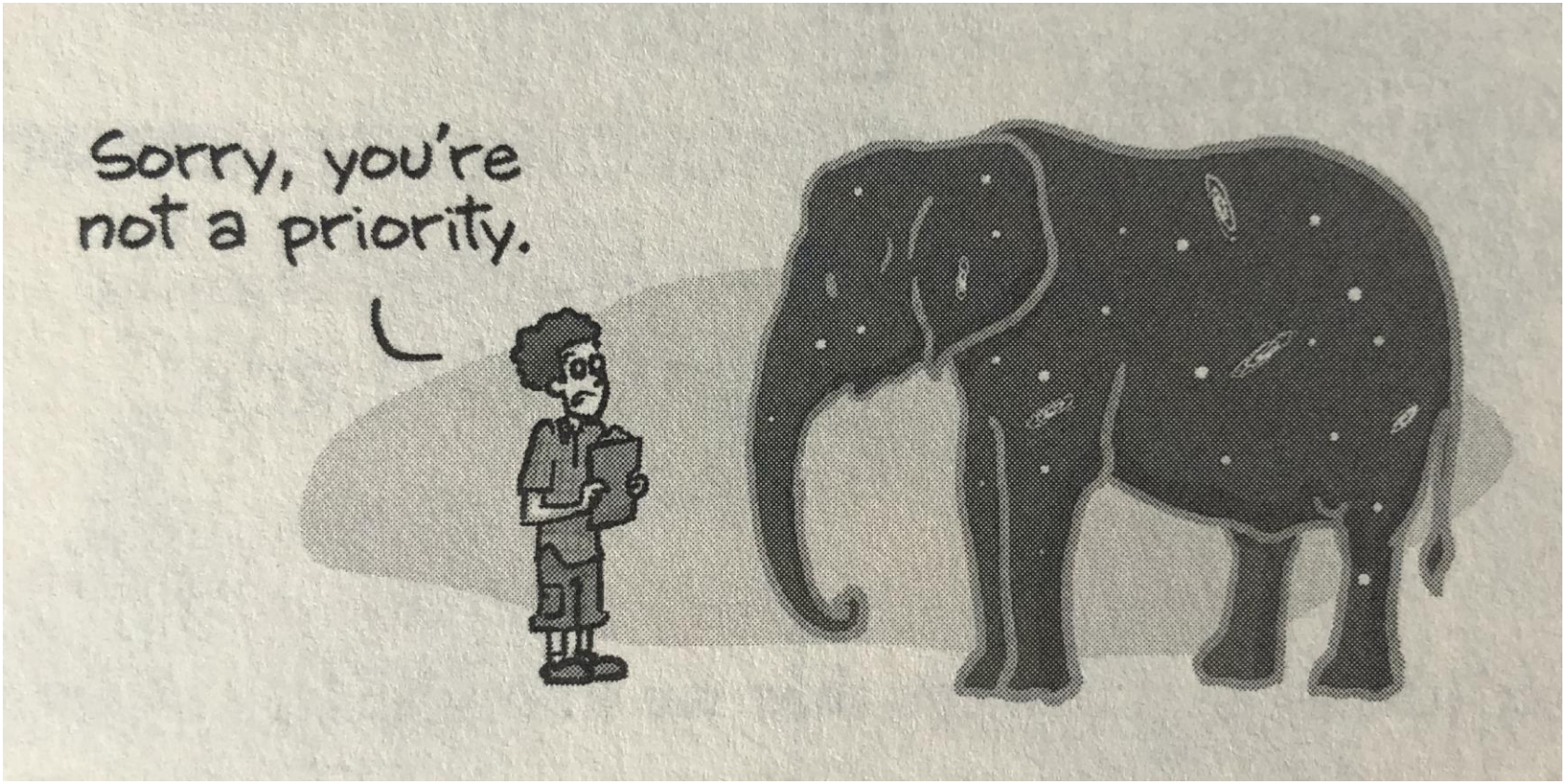
Fig. 1. Schematics of the two-phase xenon detector as used in PandaX. LXe is contained in an inner vessel insulated by vacuum from the outside. One long liquid level meter monitors the overall liquid xenon height and three short level meters monitor the height of the liquid-gas interface around the TPC.



2016年PandaX二期实验（500公斤级液氙）取得了世界领先的暗物质探测灵敏度。在这个基础上，我们进行下一代四吨级液氙探测实验的研发，将暗物质探测灵敏度继续向前推进1-2个数量级。除了暗物质，四吨级液氙实验将能够测量到低能量太阳中微子信号并研究其磁矩等性质。另外，四吨液氙中含有的放射性同位素氙136有可能进行一种新型的贝塔衰变-无中微子双贝塔衰变模型。该衰变模式的探测将能确定中微子是否为马约拉纳中微子等基本物理问题。



MATIERE SOMBRE



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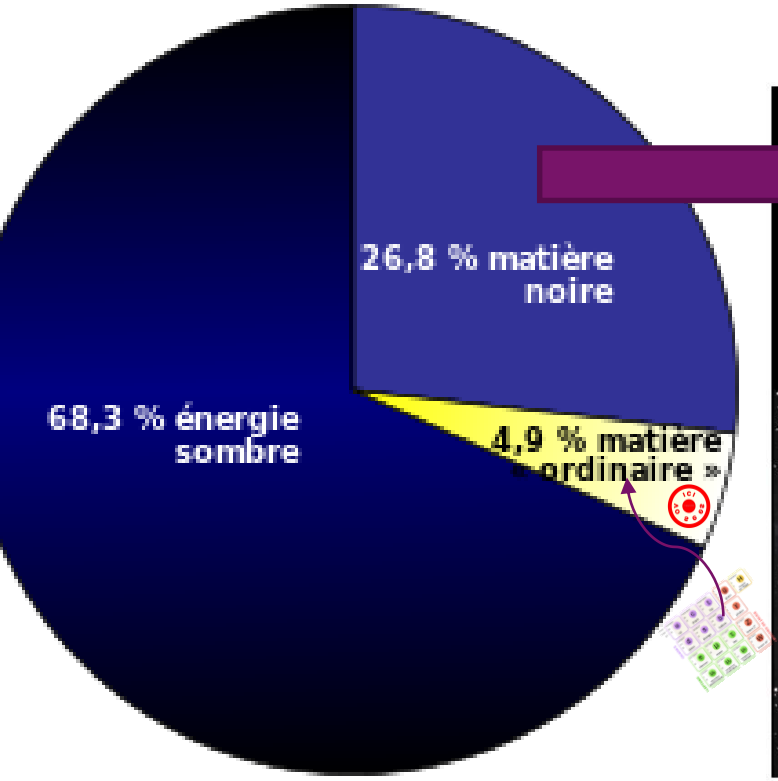
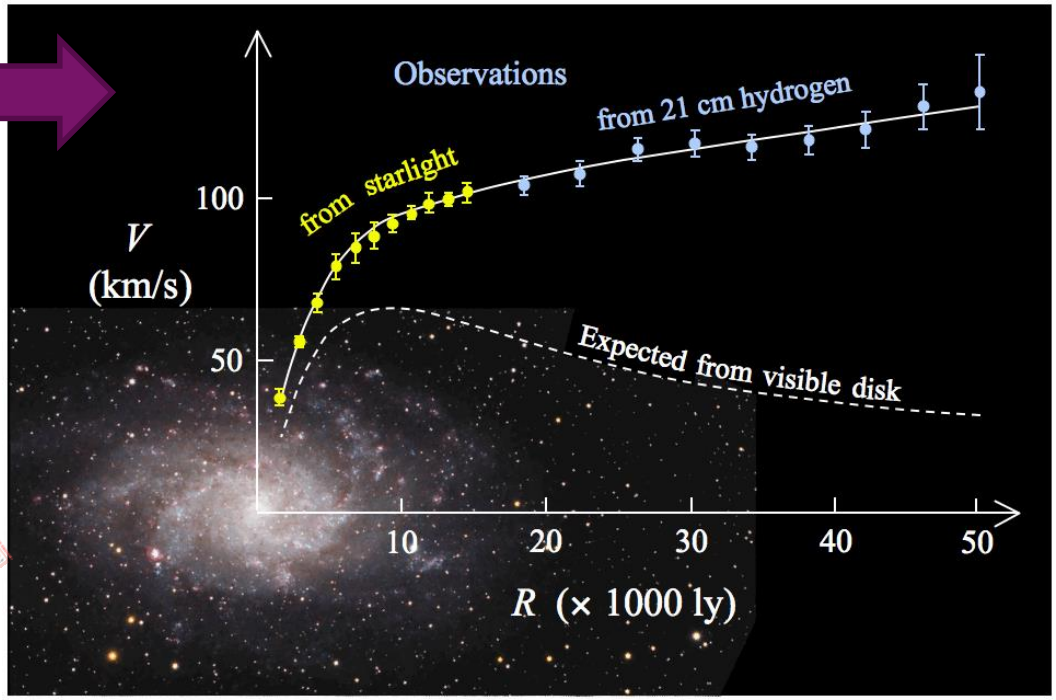
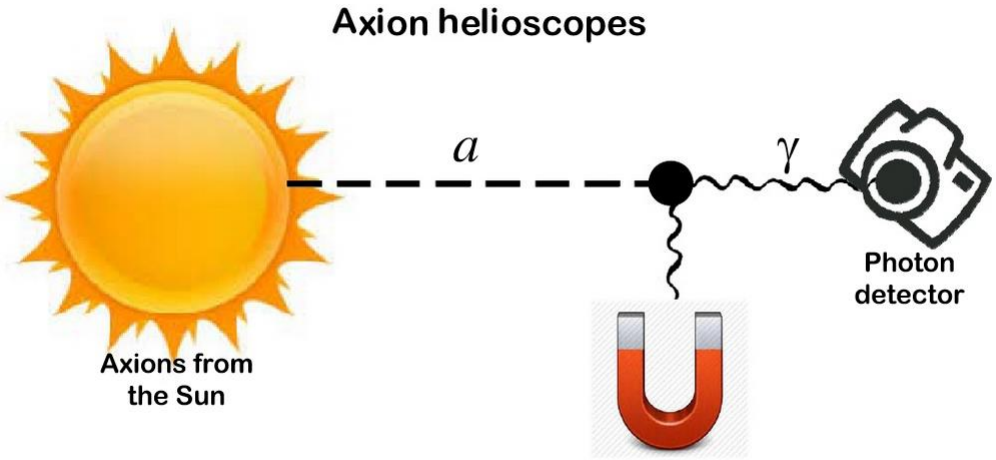

26,8 % matière noire
68,3 % énergie sombre
4,9 % matière « ordinaire »


Observations
from 21 cm hydrogen
from starlight
100
V
(km/s)
50
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

AXIONS



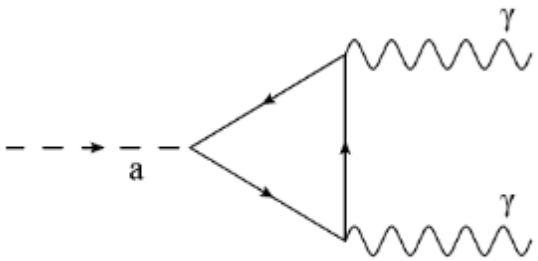
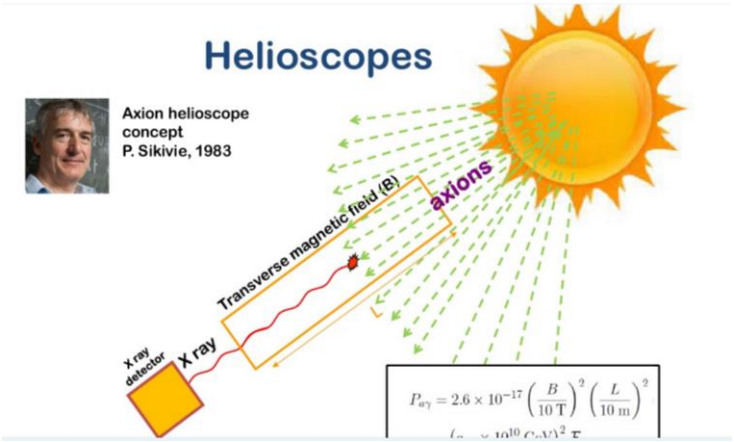
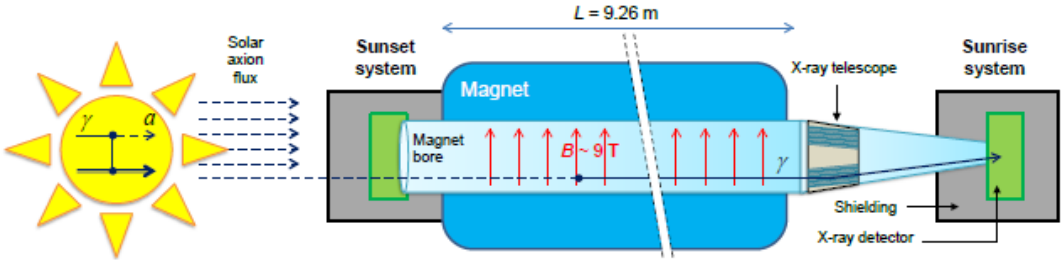


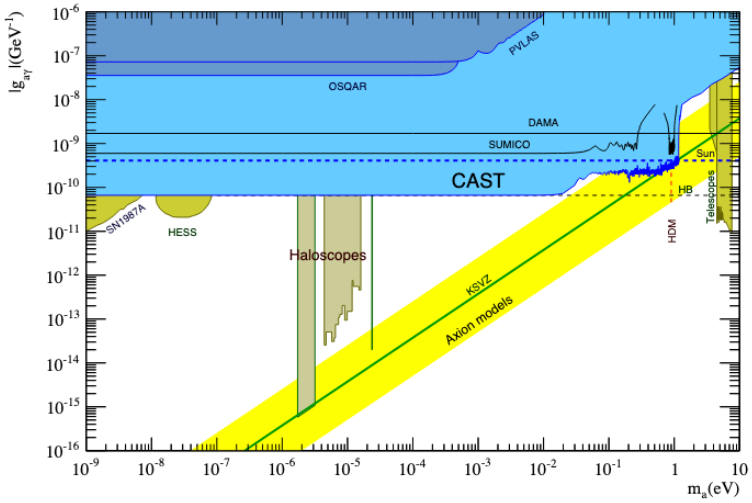
Figure 2: Feynman diagram, associated with the coupling between an axion and two photons.

© Igor G. Irastorza

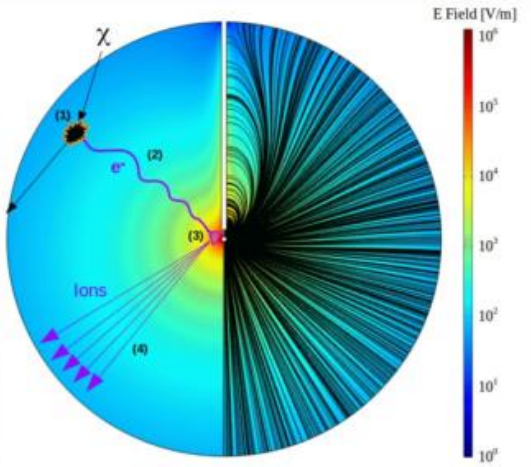
CAST - IAXO

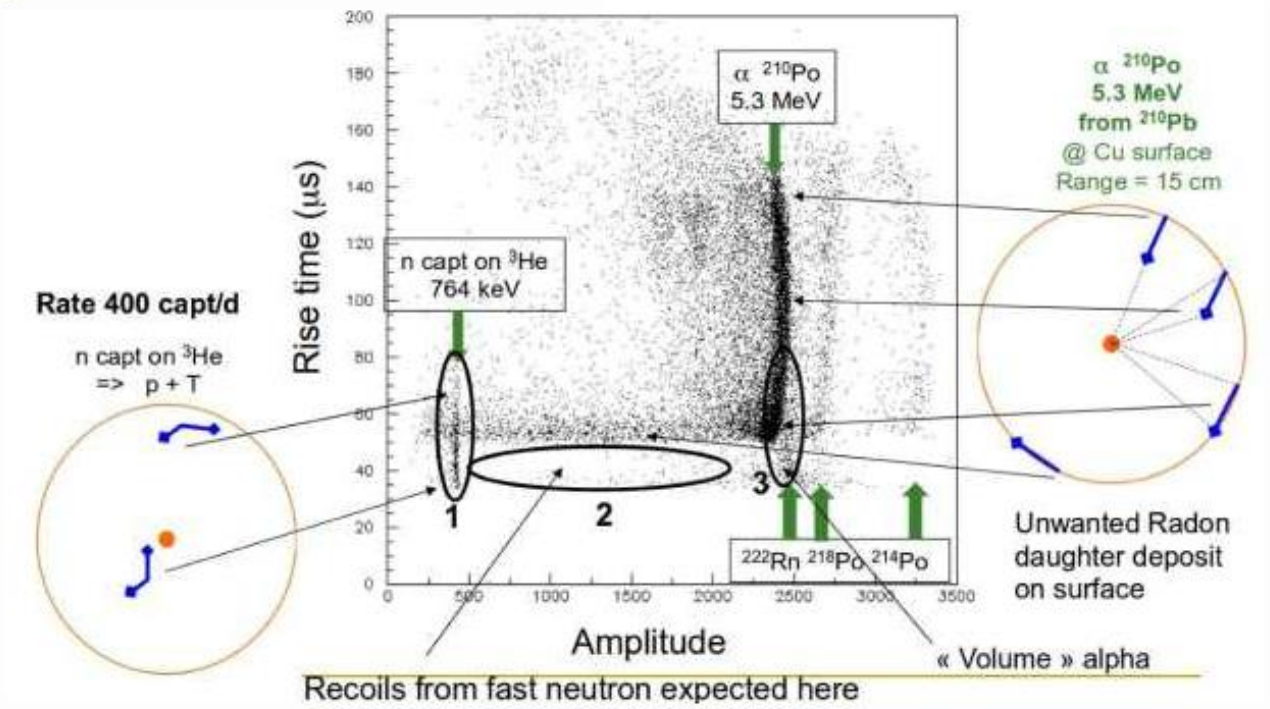

Helioscopes
Axion helioscope concept
P. Sikivie, 1983
axions
Transverse magnetic field (B)
X ray
X ray detector
$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\,\mathrm{T}}\right)^2 \left(\frac{L}{10\,\mathrm{m}}\right)^2$


L = 9.26 m
Solar axion flux
Sunset system
Magnet
Magnet bore
B ~ 9 T
X-ray telescope
Sunrise system
Shielding
X-ray detector


PVLAS
OSQAR
DAMA
SUMICO
CAST
Sun
HB
Telescopes
HDM
SN1987A
HESS
Haloscopes
KSVZ
Axion models
m_a(eV)

NEWS





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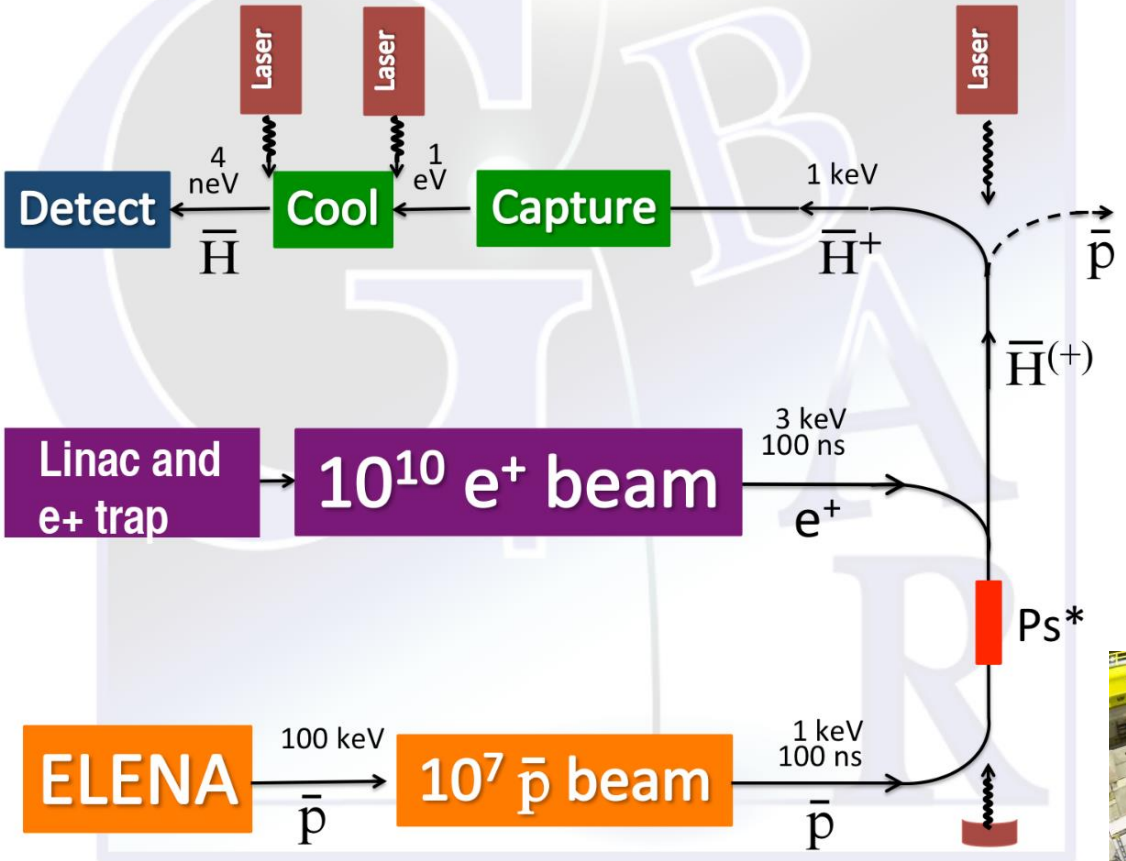
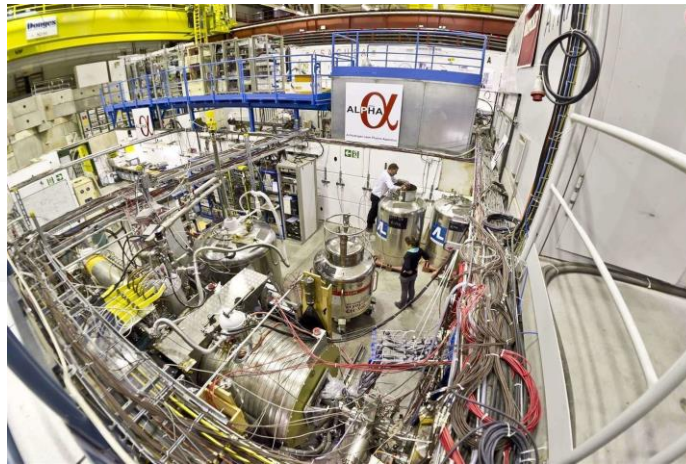
ANTI-MATIERE

GBAR at CERN

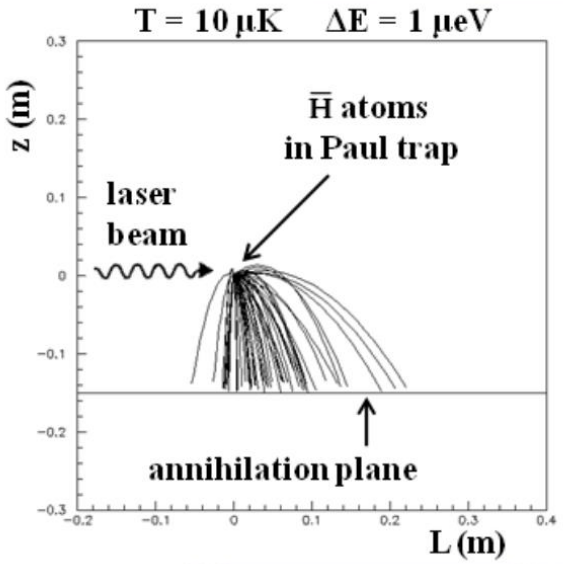
Schematic

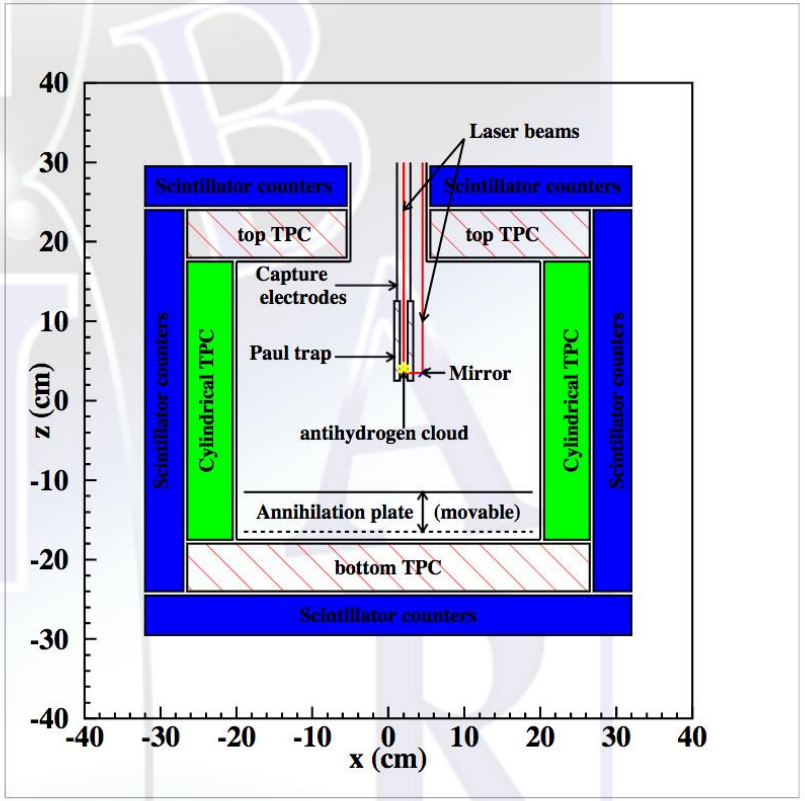




GBAR at CERN

Detection





Detection requirement:

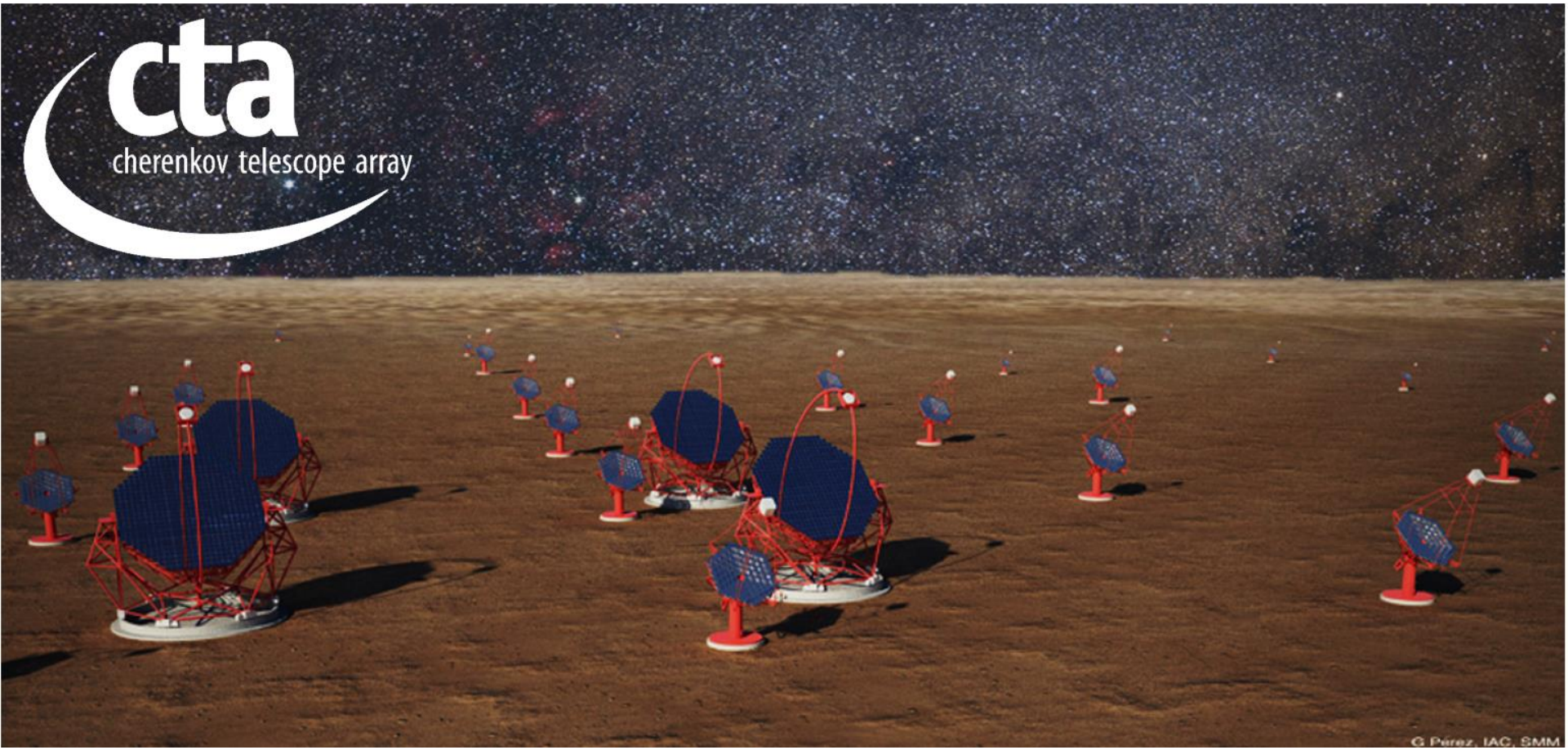
- TOF precision : 150 μs
- Annihilation vertex precision : 1 mm
- Background rejection through event topology

Scheme under design: TPC with micromegas chamber (as in T2K near detector)

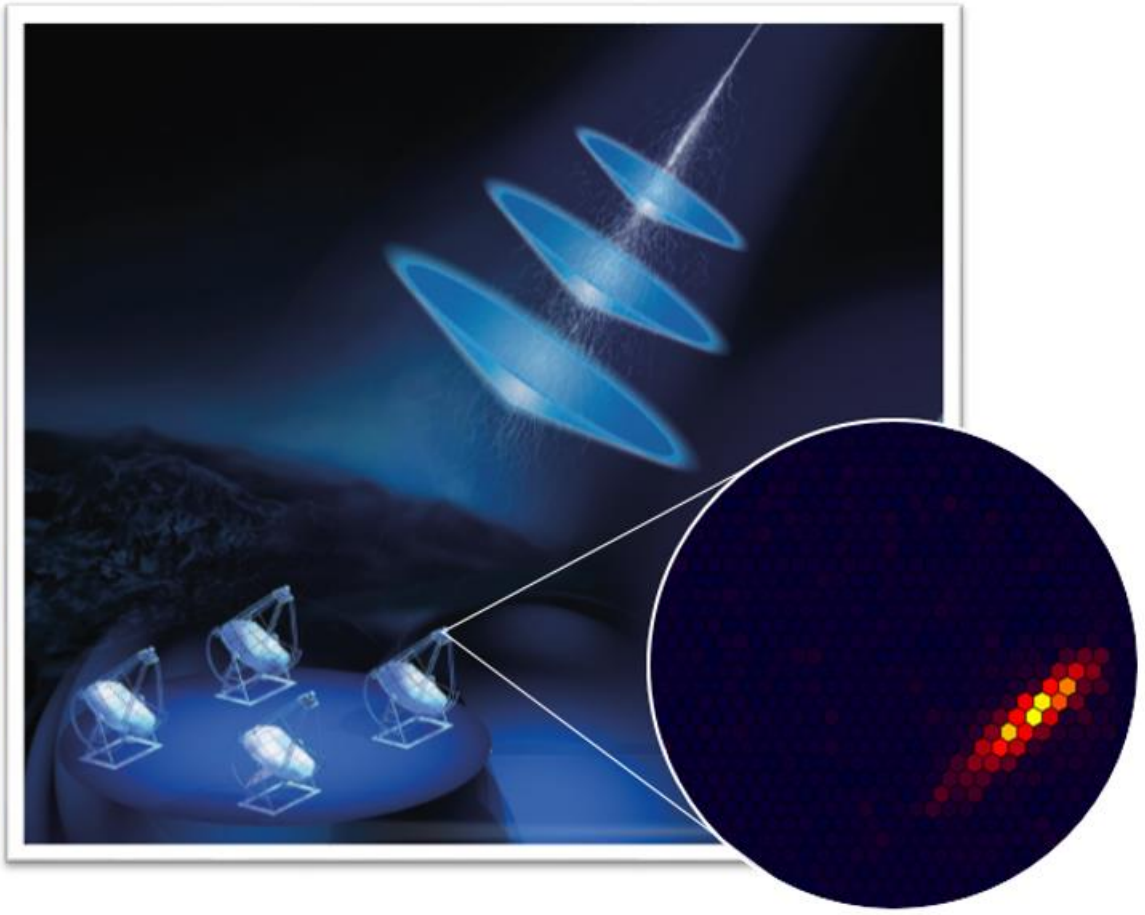
$$\frac{\Delta \bar{g}}{\bar{g}} \approx 10^{-2}$$

ASTRO-PHYSIQUE

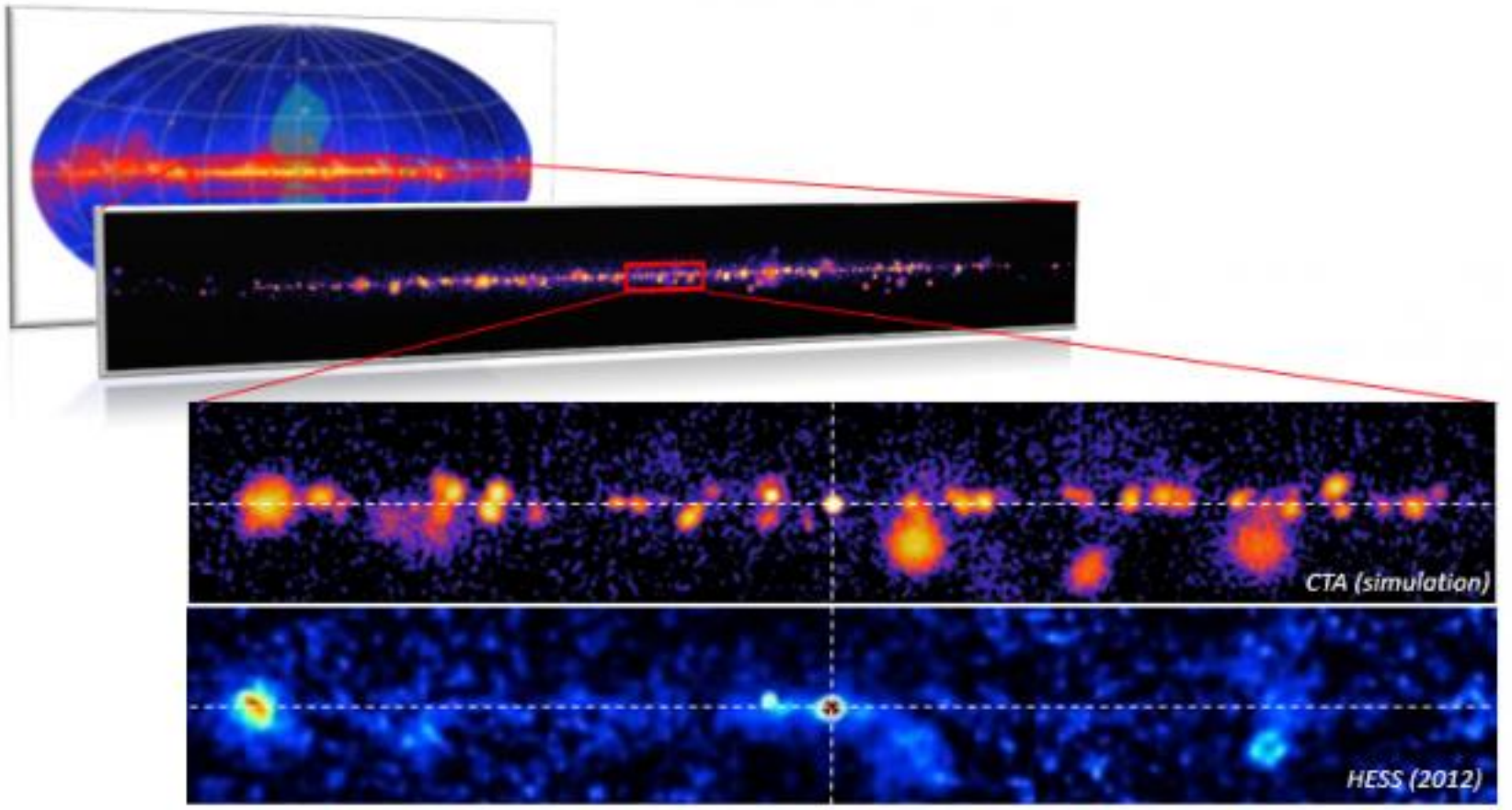
CTA



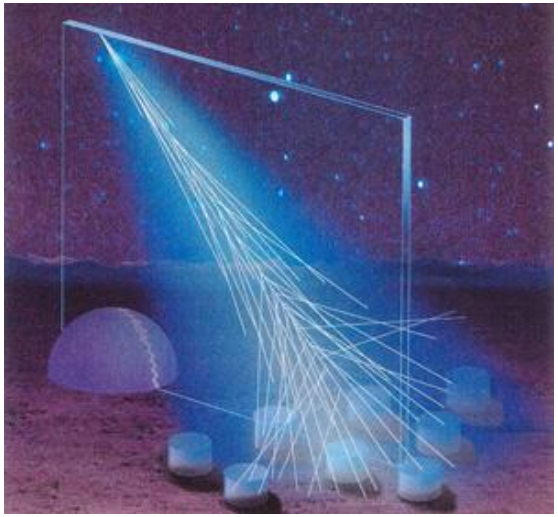
CTA



CTA



Pierre Auger Cosmic Ray Observatory



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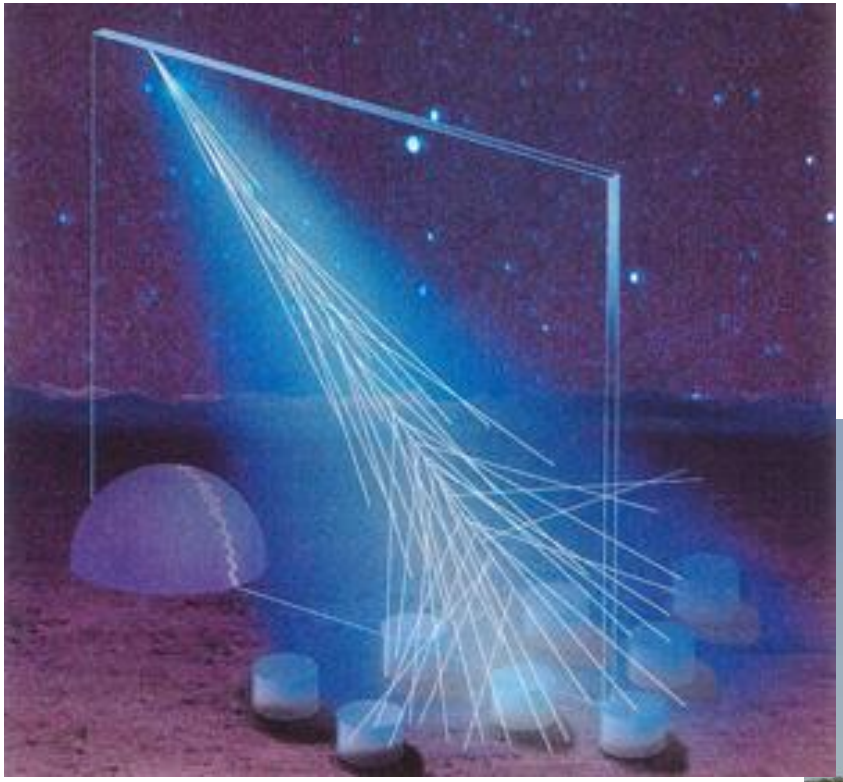
Pierre Auger Cosmic Ray Observatory



Use earth's atmosphere as a calorimeter. 1600 water Cherenkov detectors with 1.5km distance.

Placed in the Pampa Amarilla in western Argentina.

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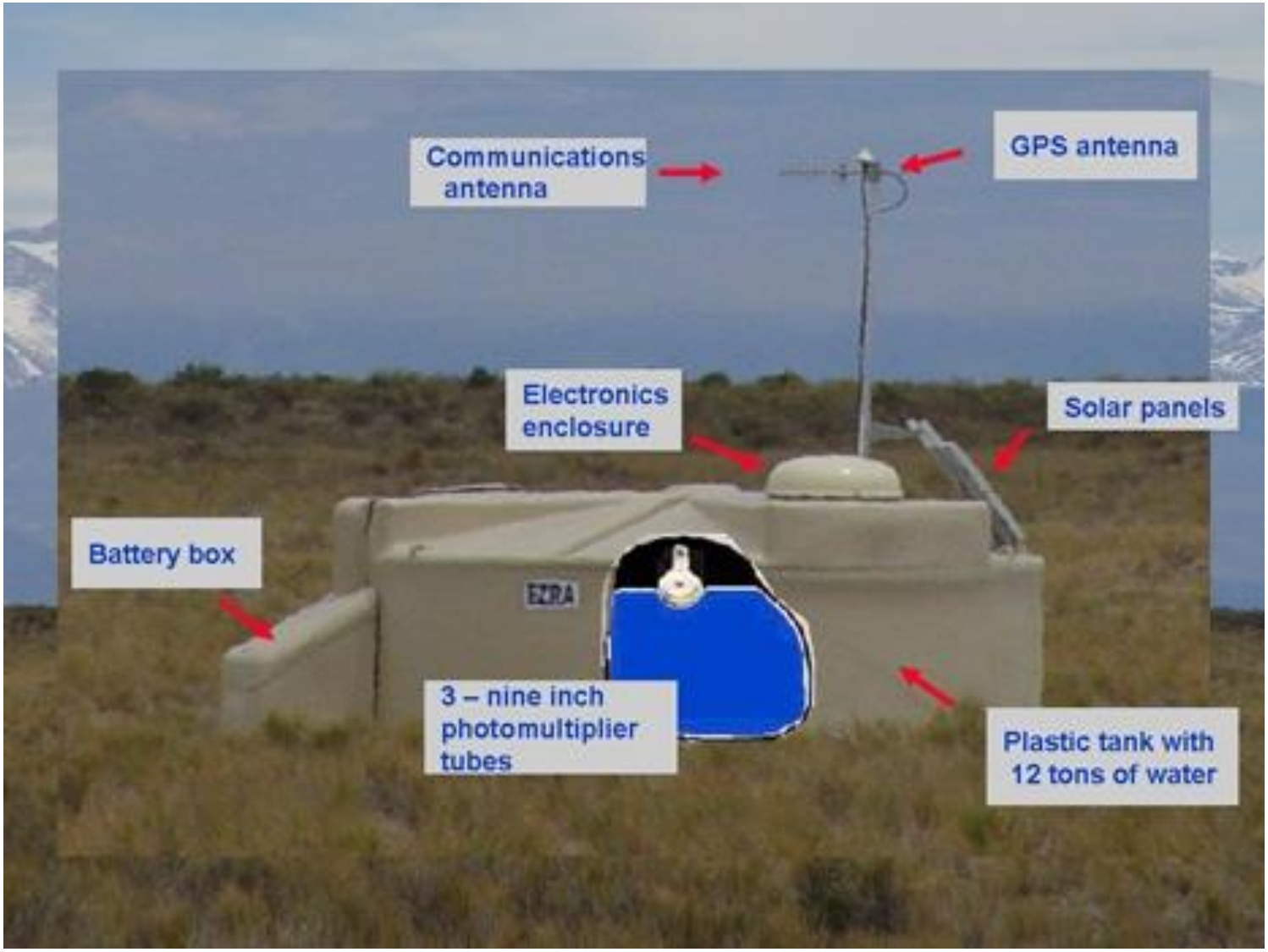
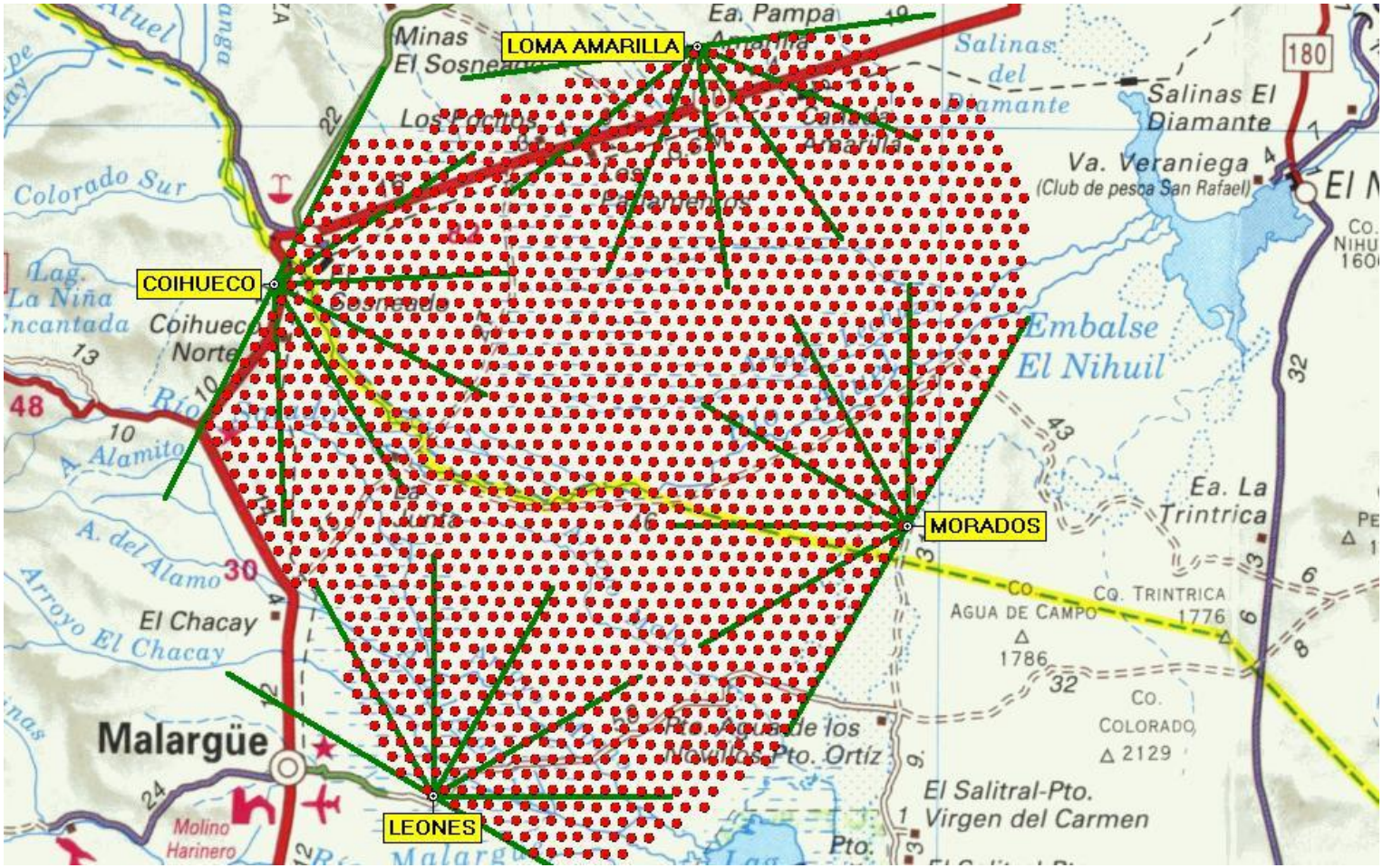
Pierre Auger Cosmic Ray Observatory



Pierre Auger Cosmic Ray Observatory



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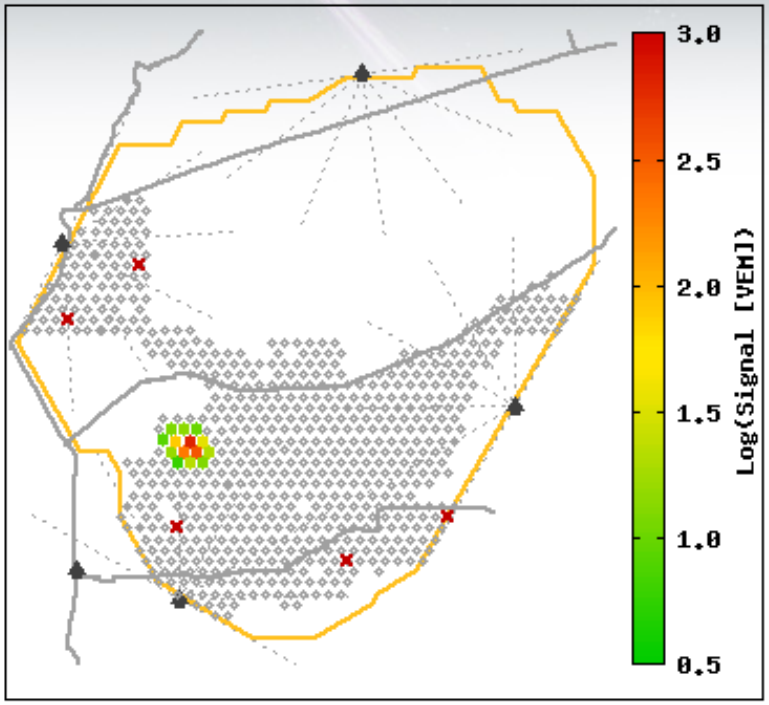
Event 1234800

See CR incoming direction | See individual station data

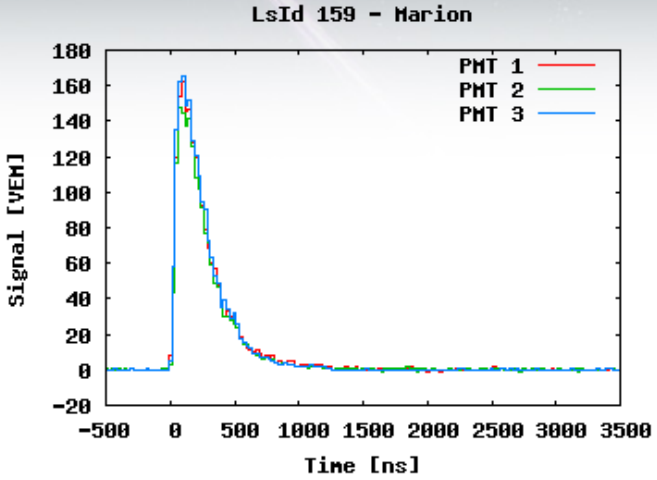


37 EeV = Exa Electron Volt = 37 x 10^{18} eV

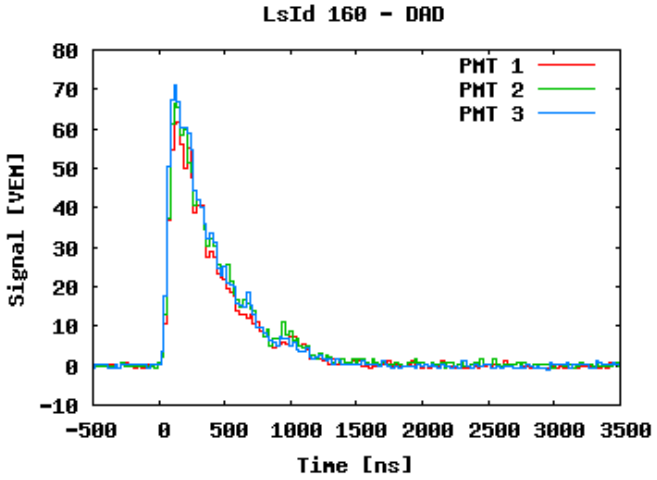
Generic Information	
Id	1234800
Date	Sat Mar 5 15:54:48 2005
Nb Station	14
Energy	37.4 ± 1.2 EeV
Theta	43.4 ± 0.1 deg
Phi	-27.3 ± 0.2 deg
Curvature	15.8 ± 0.8 km
Core Easting	460206 ± 20 m
Core Northing	6089924 ± 11 m
Reduced Chi^2	2.30

Event 1234800

See event reconstruction data | See CR incoming direction



Signal in VEM for the 3 PMTs of station 159 (Marion) as a function of time



Signal in VEM for the 3 PMTs of station 160 (DAD) as a function of time

AMS

ALPHA MAGNETIC SPECTROMETER

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

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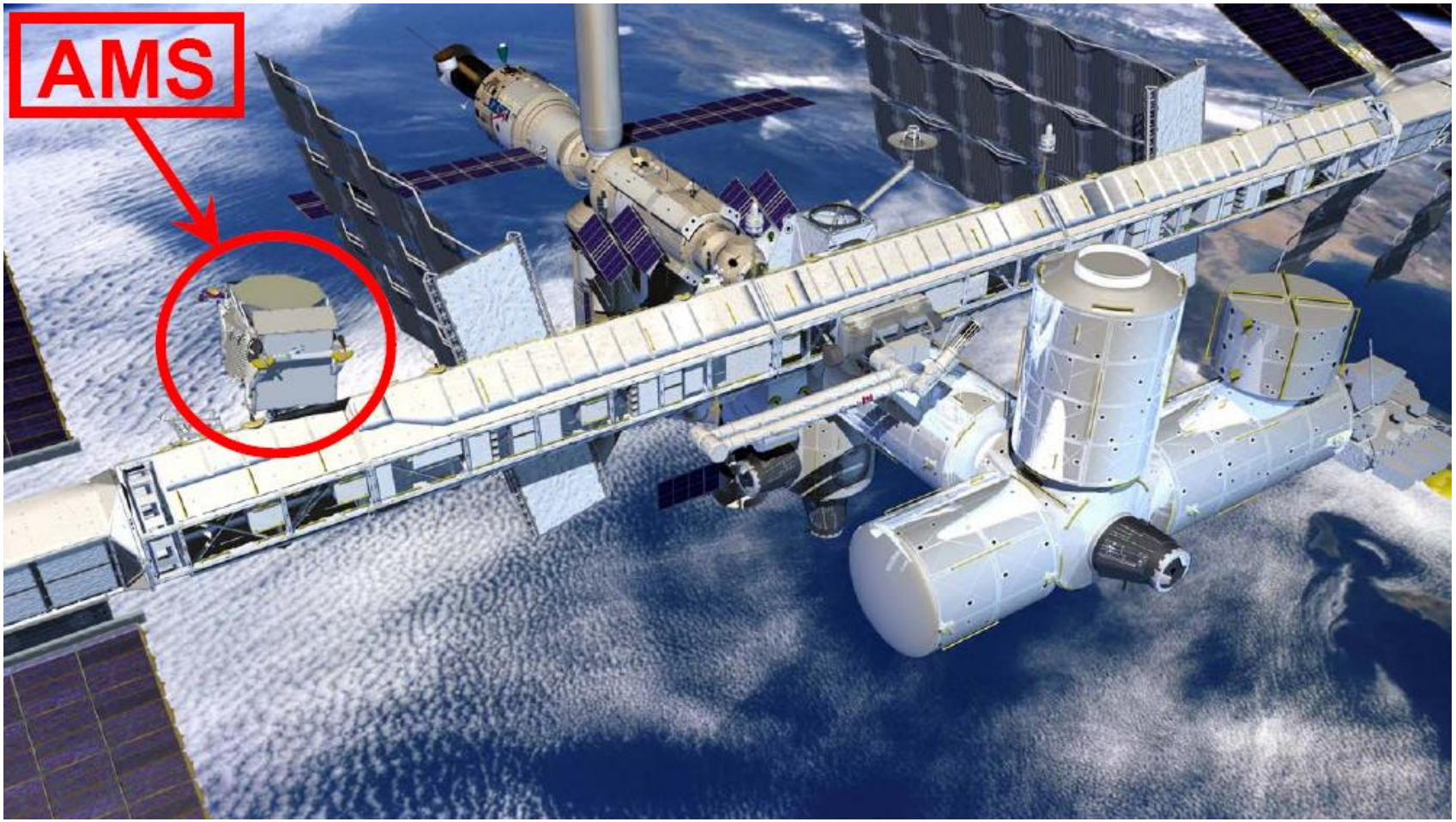
Will be installed on the space station.



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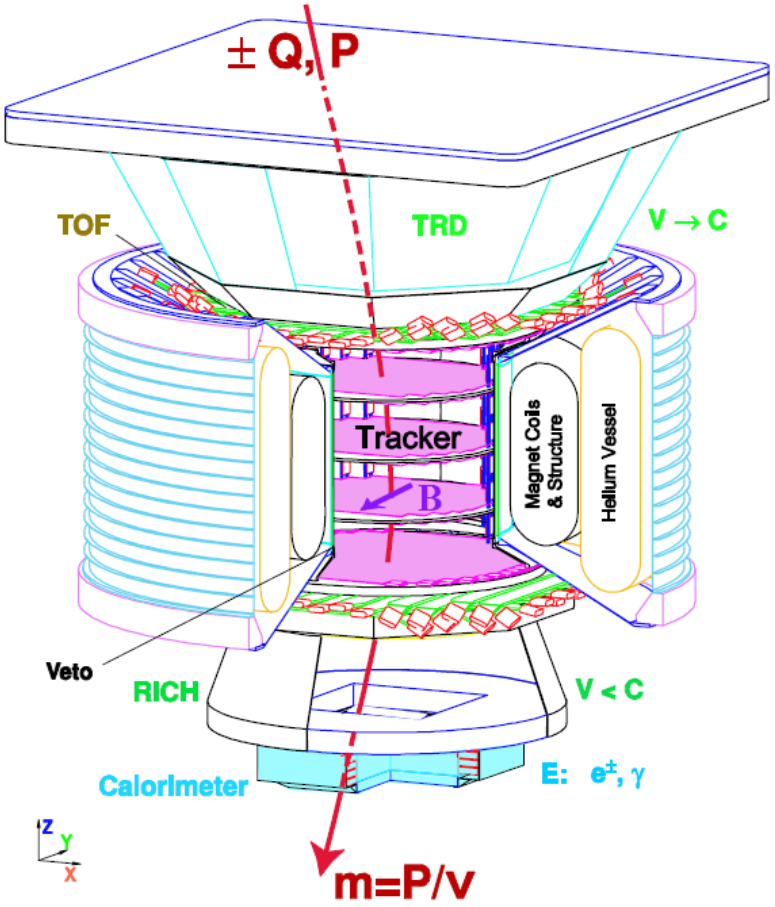
AMS



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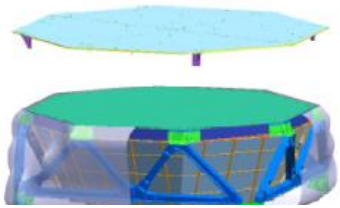

Zenith Radiator

TRD:
Transition Radiation Detector

USS:

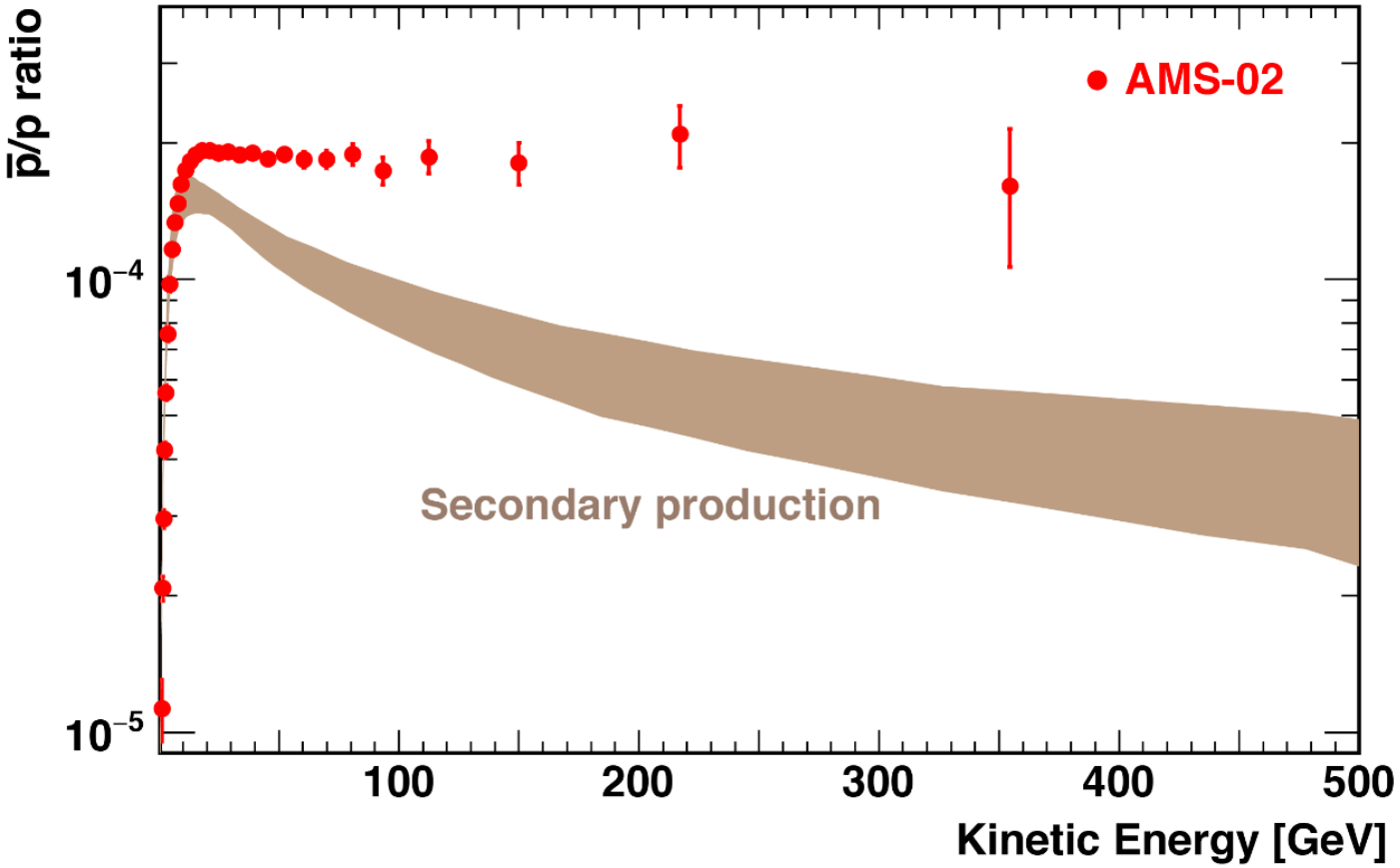

Figure 1. Antiproton to proton ratio measured by AMS. As seen, the measured ratio cannot be explained by existing models of secondary production.

PAS:
Payload Attach System

MUON TOMOGRAPHY

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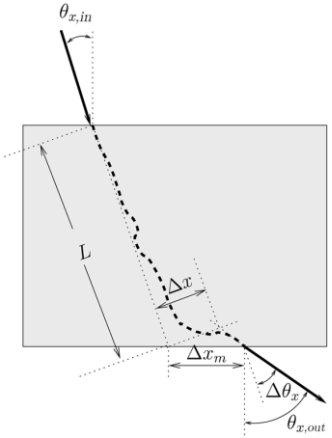
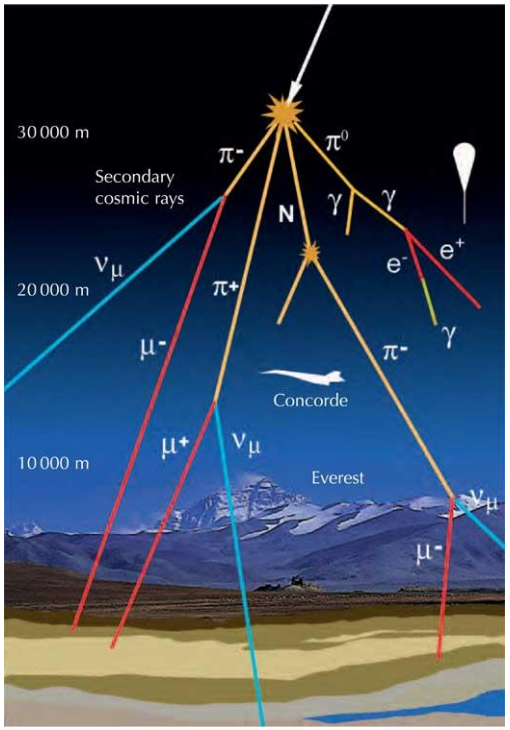
MUON TOMOGRAPHY

- Cosmic muons produced by cascade of reactions induced by cosmic rays in the upper atmosphere
  - Flux: ~150/m²/s ~ $\cos^2\theta$ (maximum in zenith direction)
  - Mean energy: 4 GeV
  - Life-time: 2 μs
  - Natural, free and harmless radiation
  - Straight propagation (in mean)





- Muon interaction with matter
  - Bethe-Bloch ionization stopping power

$$-\frac{dE}{ds} = \rho q^2 \frac{N_A e^4}{4\pi\epsilon_0^2 m_e c^2}\frac{Z}{A}\frac{1}{\beta^2}\left(\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right)$$

  - Standard deviation of the scattering angle

$$\sigma_\theta = \frac{19.2MeV}{\beta pc}\sqrt{\frac{\rho s}{X_0}}\left(1 + 0.038\ln\frac{\rho s}{X_0}\right)$$

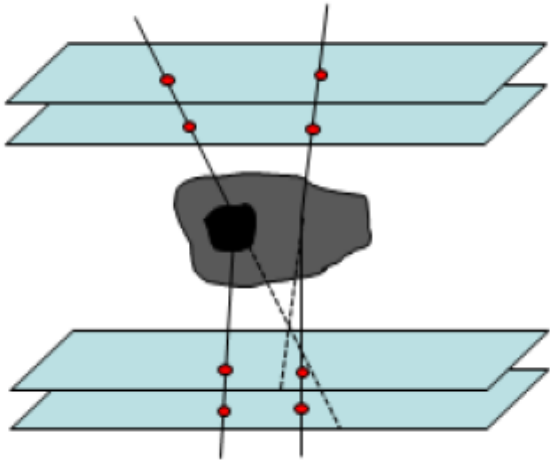
  - Radiation length

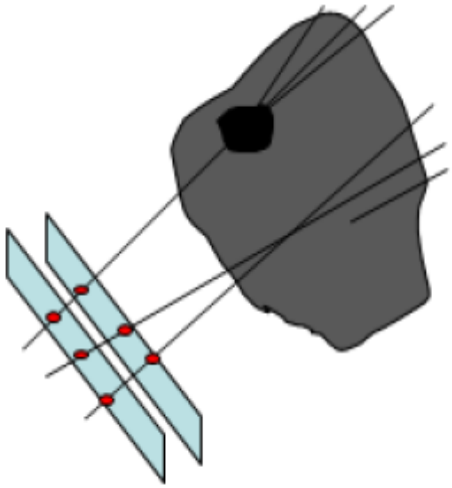
$$X_0 = 716.4 g cm^{-2}\frac{A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}$$

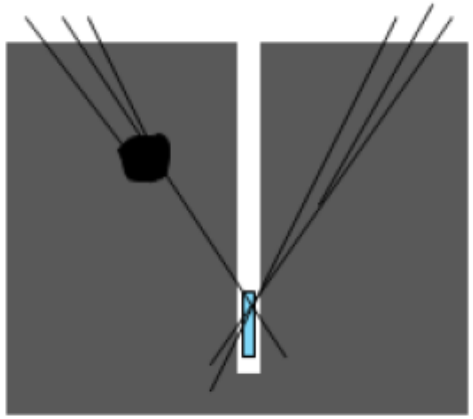
Material	Thickness	θ (°)	$P_{absorption}$
Air	100 m	0.094	0.78%
Lead	10 cm	1.01	2.9%
Water	1 m	0.35	4.2%
Ground	100 m		99%

MUON TOMOGRAPHY USING GASEOUS DETECTORS

- Muons can be stopped (decay) or their trajectory can be changed
- Two modes of muon tomography can be extracted from muon flux
  - Absorption muography
  - Deviation muography





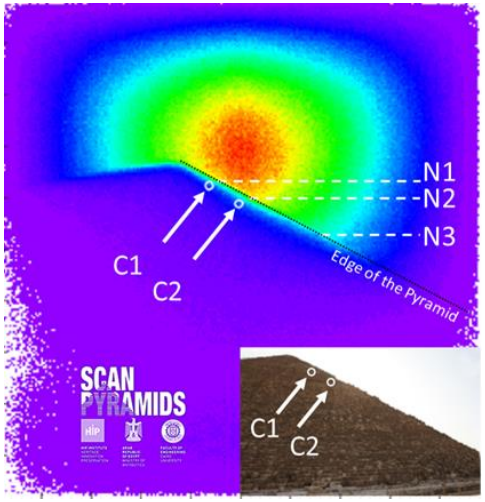


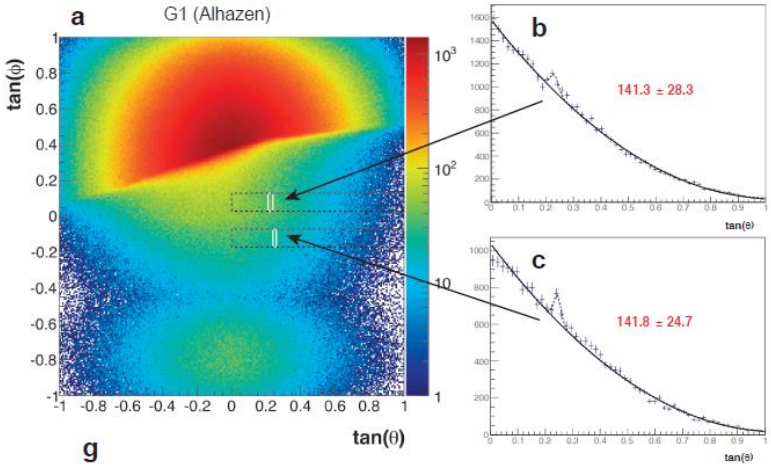
- High potential of societal applications in many fields:
  - volcanology, archaeology
  - mineral exploration, civil engineering, …

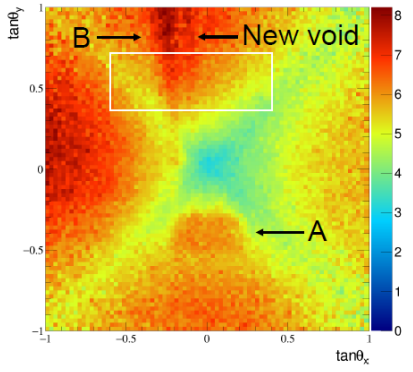
RESULTS

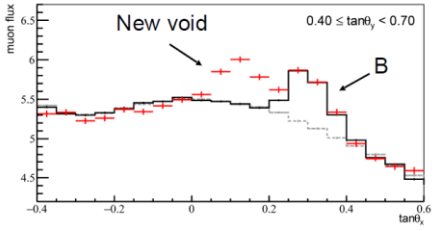
- Discoveries of new cavities large void above the Grand Gallery

2016 — *CEA* — 2017 — *Nagoya*

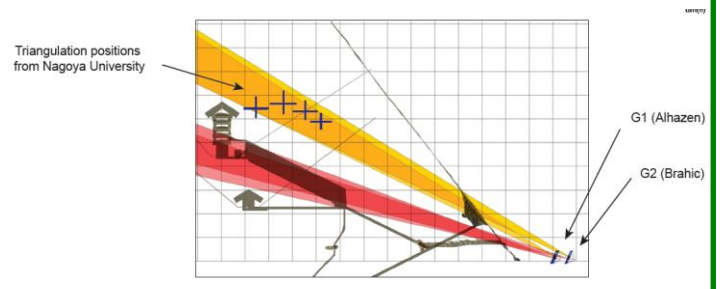








- *Only 2 such voids detected*
- *1st detection ever from outside of a deep structure*



PLAN DES COURS

Cours 1 : Généralités

-Introduction générale sur l'importance de la mesure

-Qu'est-ce qu'une expérience de physique subatomique ?

-Que veut-on observer à propos d'une particule?

-Architecture générale d'une expérience en physique subatomique

Cours 2 : Les détecteurs de particules

- Trajectographie :
  - -Détecteurs Gazeux
  - -Détecteurs au Silicium
- Calorimétrie
- Scintillation

Cours 3 : Exemple d'expériences

- Autour du Neutrino
- Nucléaire et Hadronique
- Rayons Cosmiques
- Antimatière

CEA/IRFU/DEDIP --- maxence.vandenbroucke@cea.fr

SOURCES

Basé sur les cours de Stefano Panebianco (CEA/IRFU) rencontre d'ete 2016

Le cours de Werner Riegler (CERN Summer Student Lecture Program 2009)

Particle Detectors , Second Edition, C. Grupen & B. Shwartz