

Mesurer l'infiniment petit et observer l'infiniment grand

DE LA RECHERCHE À L'INDUSTRIE



**16-27 JUILLET
2018**

Orsay
Palaiseau
Paris
Saclay

Rencontres
Promotion Chien-Shiung Wu

de L'INFINIMENT
GRAND
à L'INFINIMENT
petit

**VISITES
DE LABOS,
CONFÉRENCES,
DÉBATS**

Niveau L3

Comprendre l'infiniment petit
Les noyaux et leurs interactions
Des particules aux étoiles
jusqu'au cosmos
Mesurer l'infiniment petit,
observer l'infiniment grand
Applications médicales
Maîtriser l'énergie
Enregistrer, analyser, découvrir

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[Stages : http://irfu.cea.fr/Phoceastages/index.php](http://irfu.cea.fr/Phoceastages/index.php)

Maxence Vandembroucke

07/2018

université
PARIS-SACLAY

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

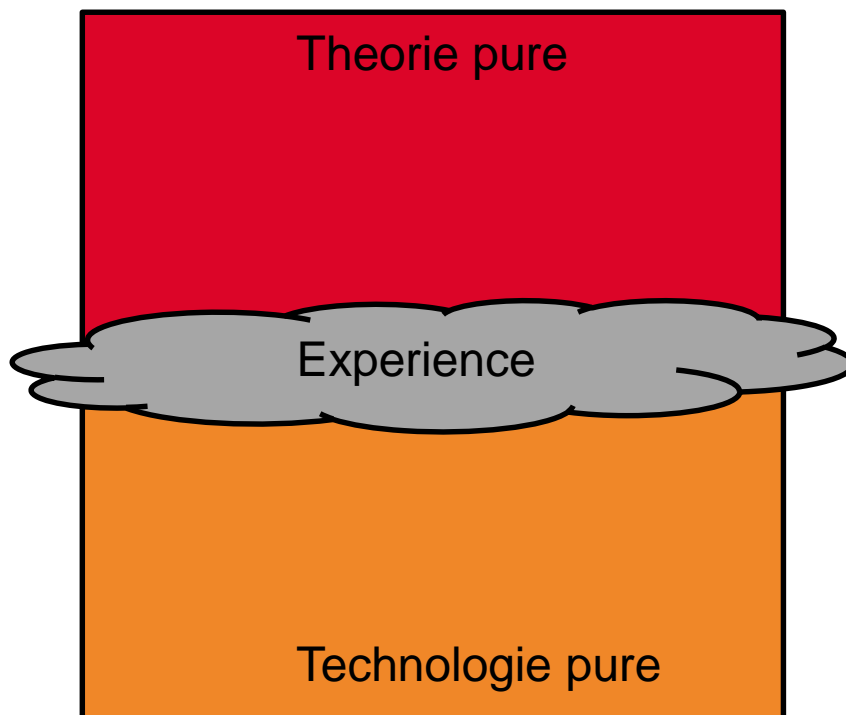
- Interaction particule-matière
- Les Détecteurs à ionisations
- L'exemple des détecteurs gazeux

Cours 3 : Exemples d'expériences (?)

Cours 1 : Généralités

- Introduction générale sur l'importance de la mesure
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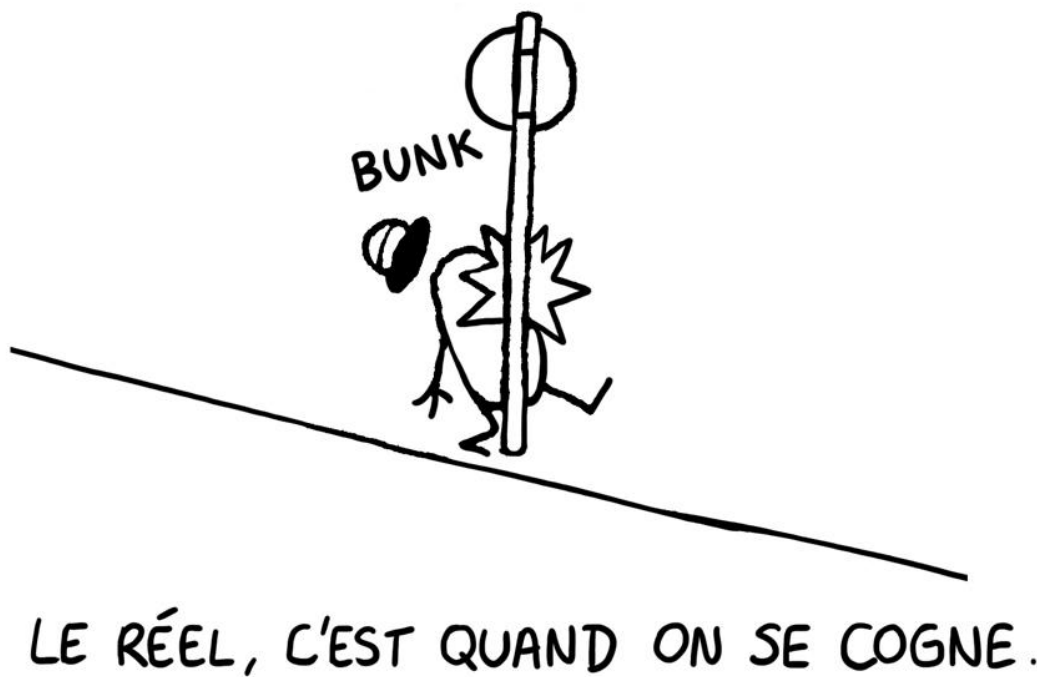




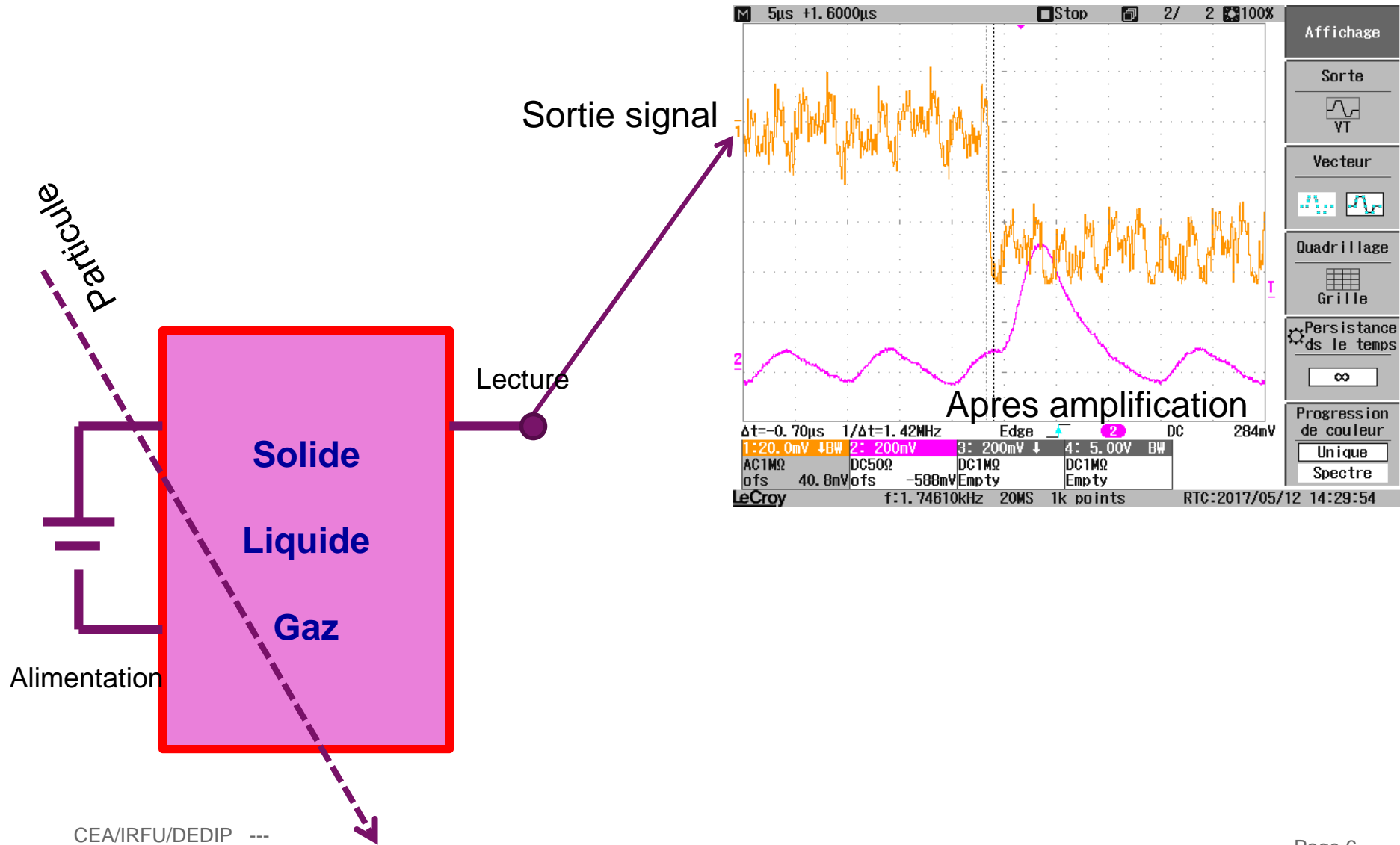
- Théorie
 - Construction des Modèles
 - Prédiction avec des Modèles
 - Simulation d'expérience MC
-
- Design d'expérience
 - Recherche sur les détecteurs
 - Electronique/acquisition
 - Reconstruction des évènements
 - Comparaison avec le MC
 - Papier !

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)

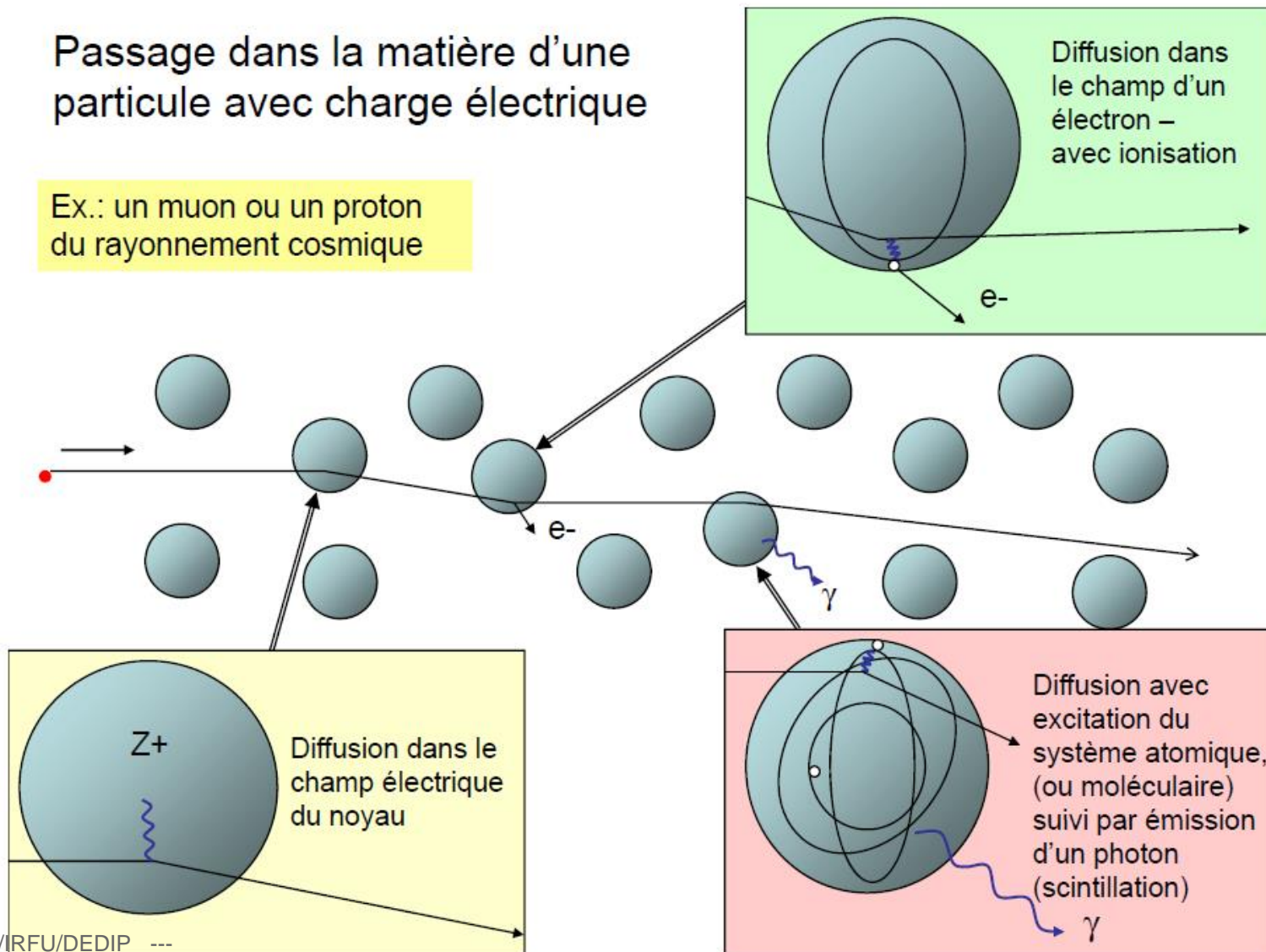


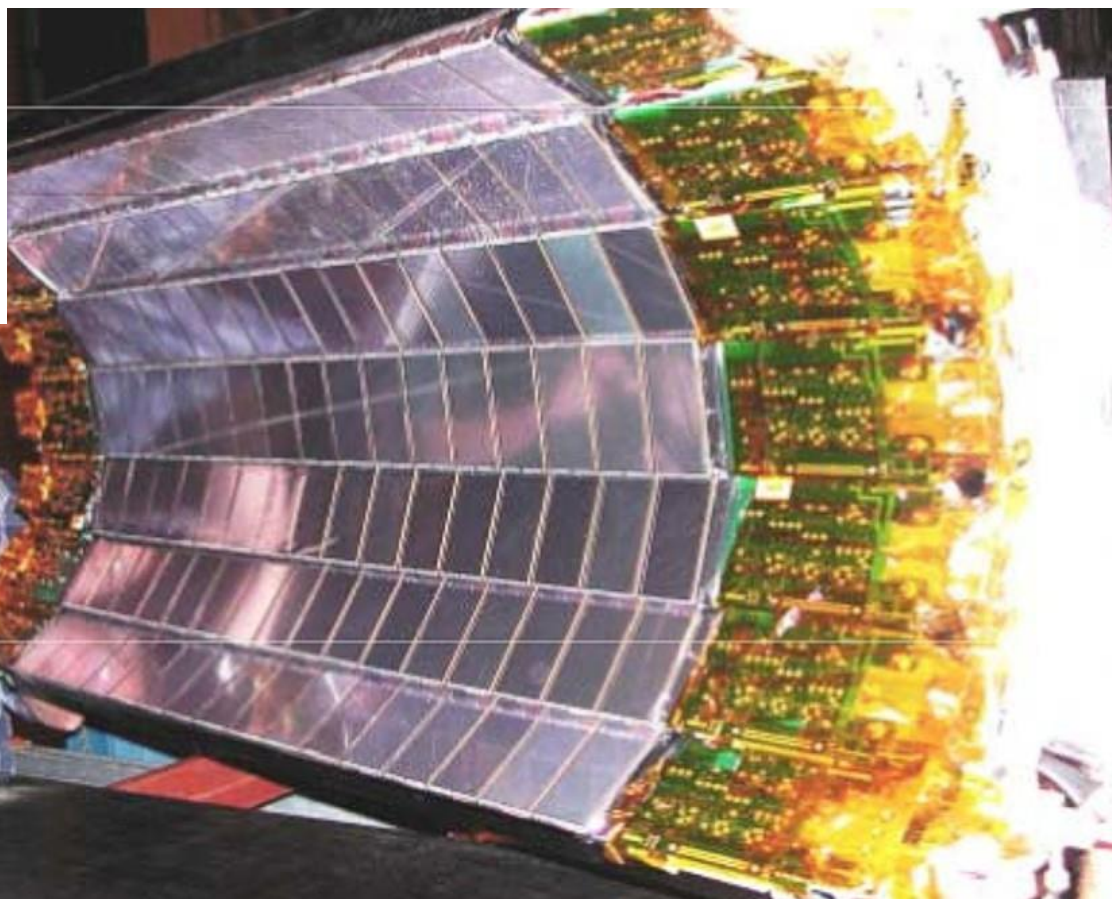
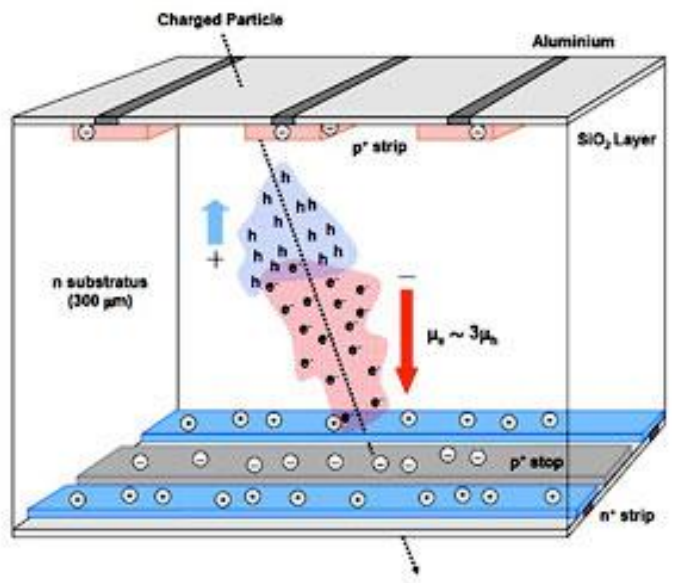
MESURER C'EST QUOI ?



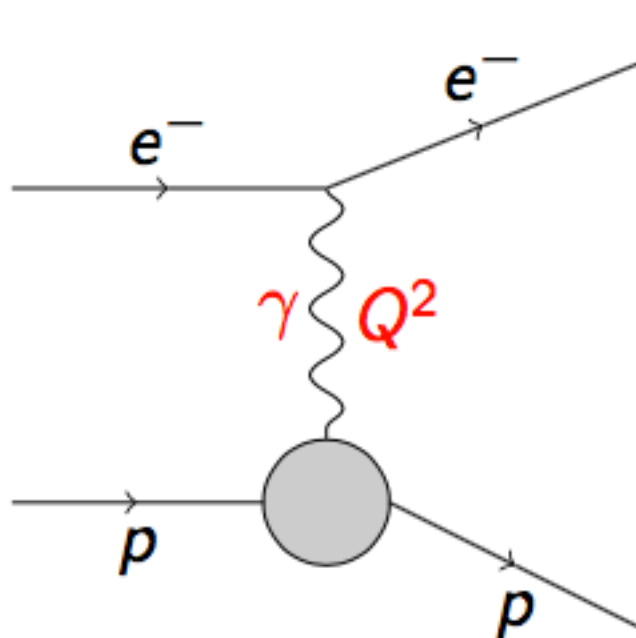
Passage dans la matière d'une particule avec charge électrique

Ex.: un muon ou un proton du rayonnement cosmique

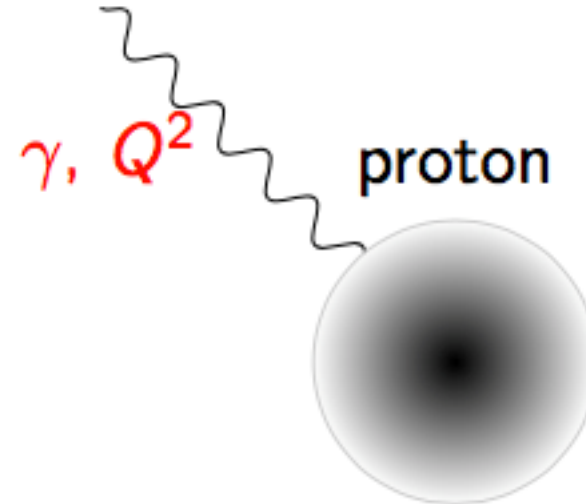




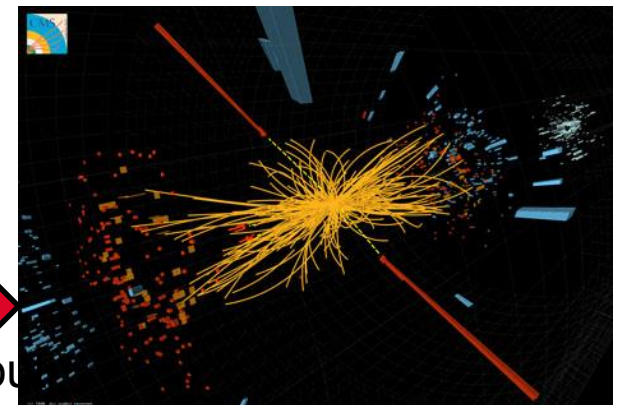
MESURER QUOI ?



Diffusion élastique.



Pas élastique du tout



Déterminer la carte d'identité d'une particule :

Up quarks

Composition	Elementary particle
Statistics	Fermionic
Generation	First
Interactions	Strong, Weak, Electromagnetic force, Gravity
Symbol	u
Antiparticle	Up antiquark (\bar{u})
Theorized	Murray Gell-Mann (1964) George Zweig (1964)
Discovered	SLAC (1968)
Mass	$2.3^{+0.7}_{-0.5} \text{ MeV}/c^2[1]$
Decays into	Stable or Down quark + Positron + Electron neutrino
Electric charge	$+\frac{2}{3} e$
Color charge	Yes
Spin	$\frac{1}{2}$
Weak isospin	LH: $+\frac{1}{2}$, RH: 0
Weak hypercharge	LH: $+\frac{1}{3}$, RH: $+\frac{4}{3}$



Mesure de l'impulsion

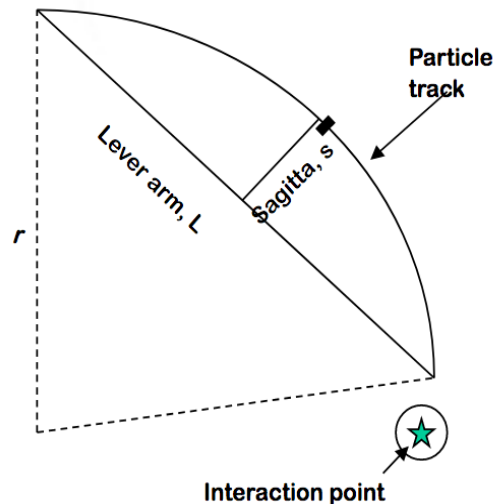
$$p=mv$$

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:

$$\sigma_s \approx \sqrt{\frac{3}{N}} \sigma_{hit} \quad (N \text{ position measurements})$$

Mesure de l'impulsion

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$$qvB = mv^2/\rho \quad \rightarrow \quad p_{\perp} = p \cos \vartheta = qB\rho$$

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

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

Mesure de l'impulsion

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

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

- Effet Vavilov-Tcherenkov

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

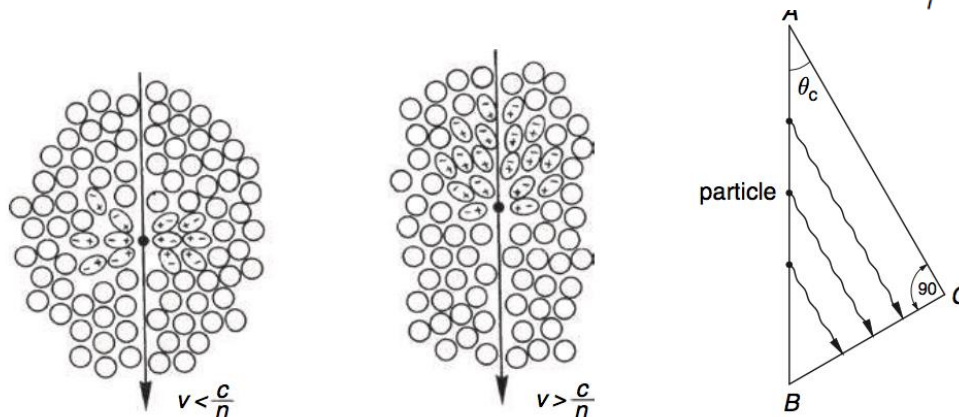


Fig. 5.39. Illustration of the Cherenkov effect [140, 141] and geometric determination of the Cherenkov angle.

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'énergie dE/dx



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

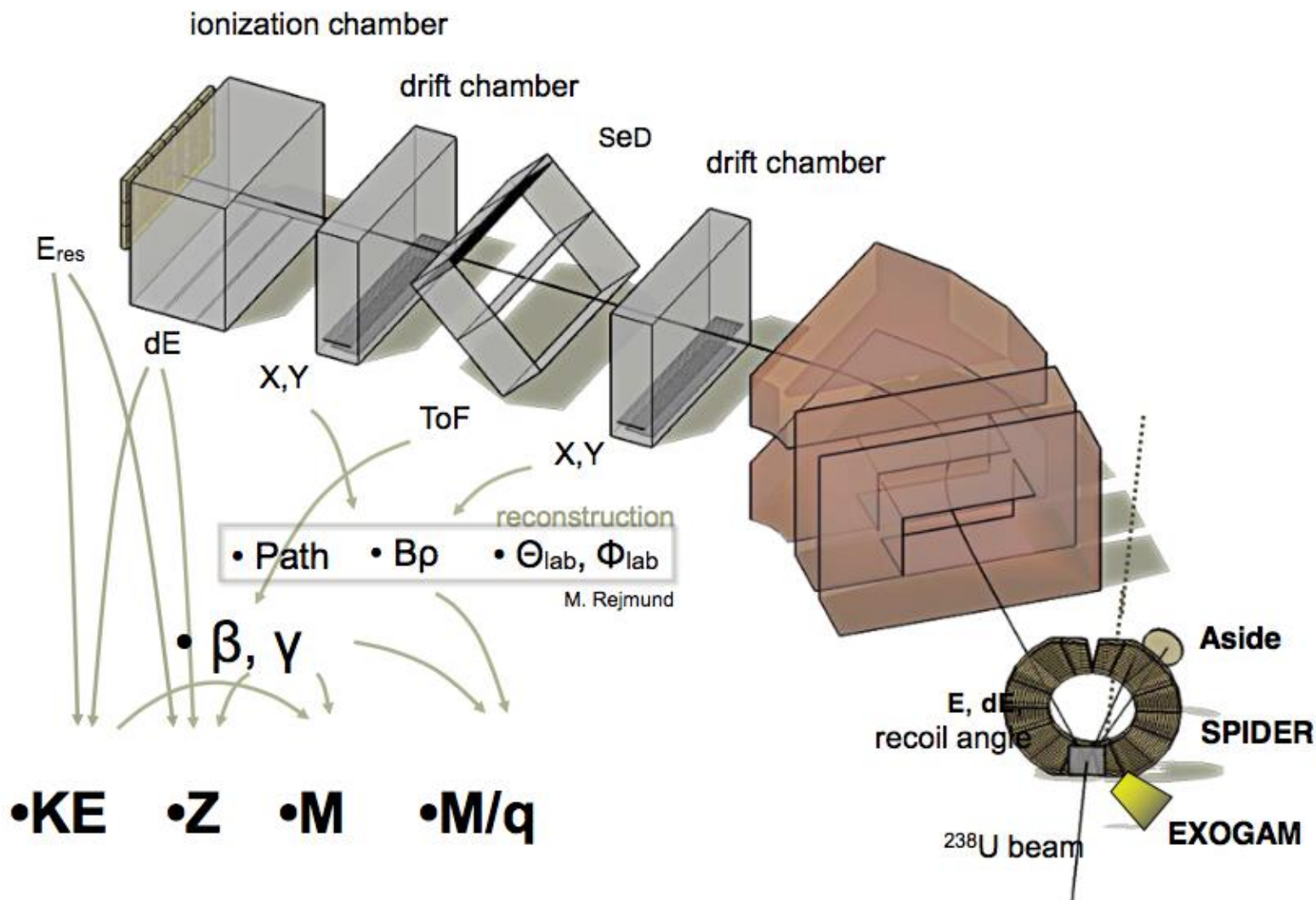
- Calorimétrie
- Perte d'énergie dE/dx
- Fréquence

Mesure de spin et de la parité

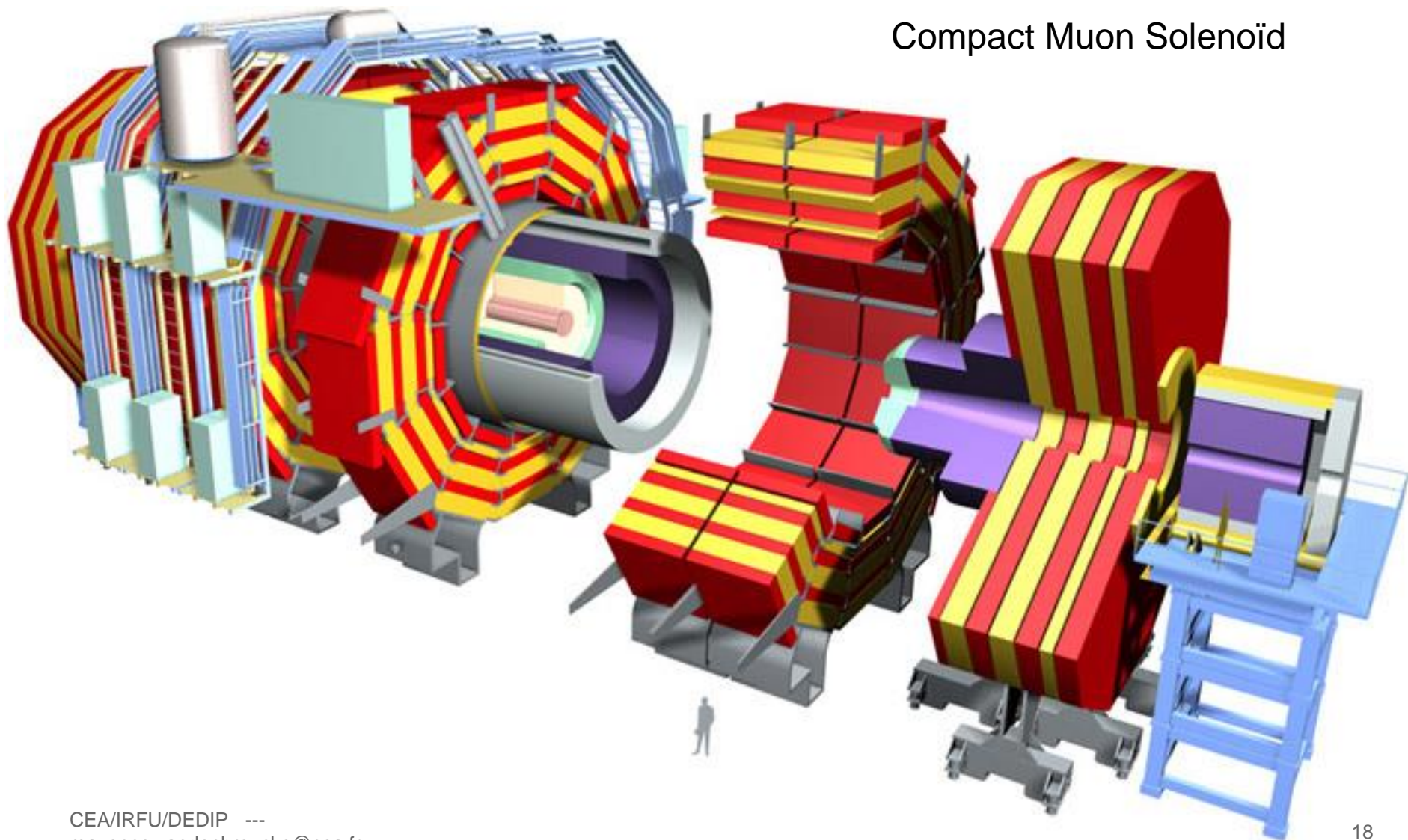
- (Pas traitée ici)
- Avec un polarimètre indirectement
- Par sélection

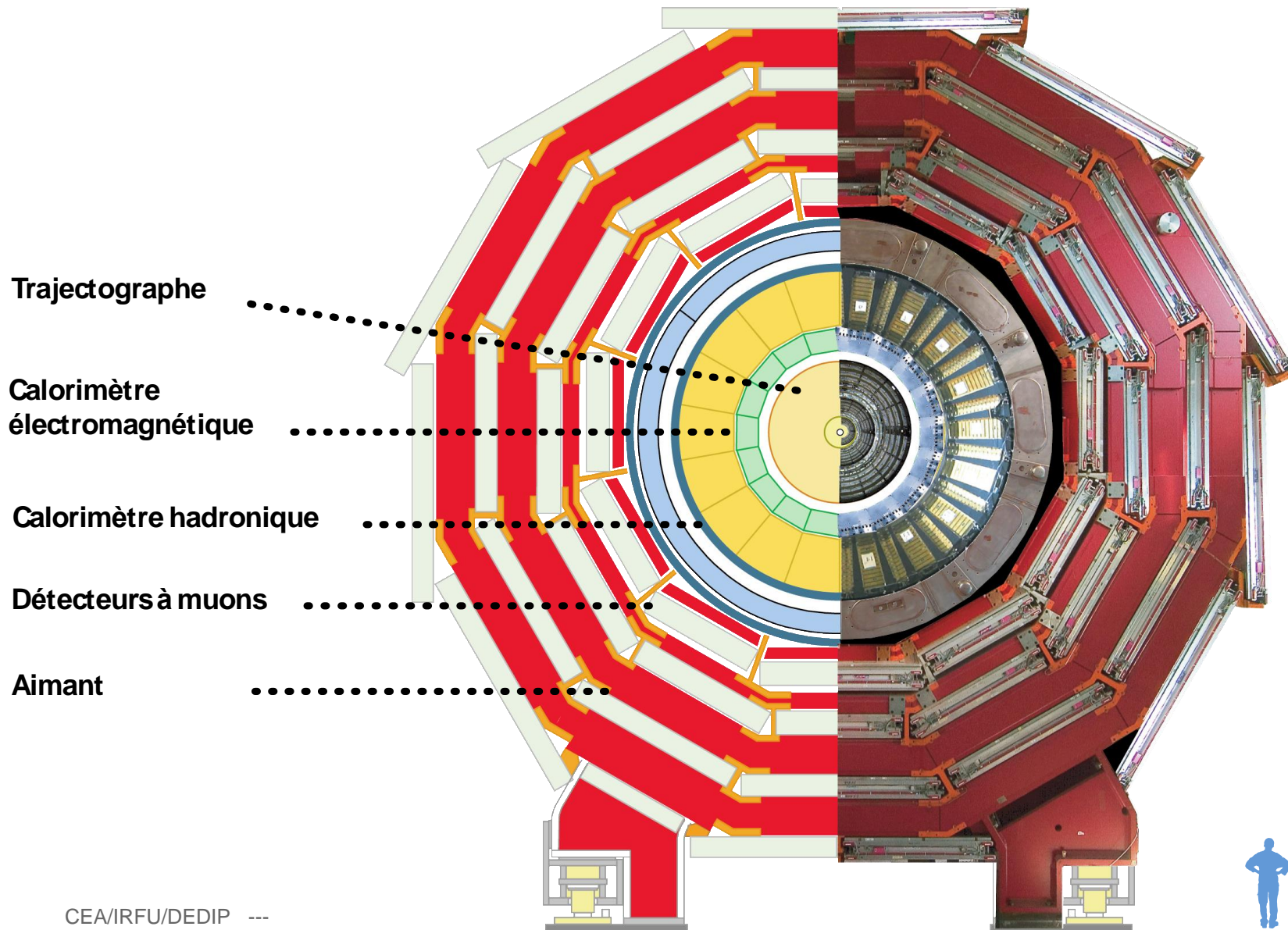
Mesure de la masse et de la charge (PID)

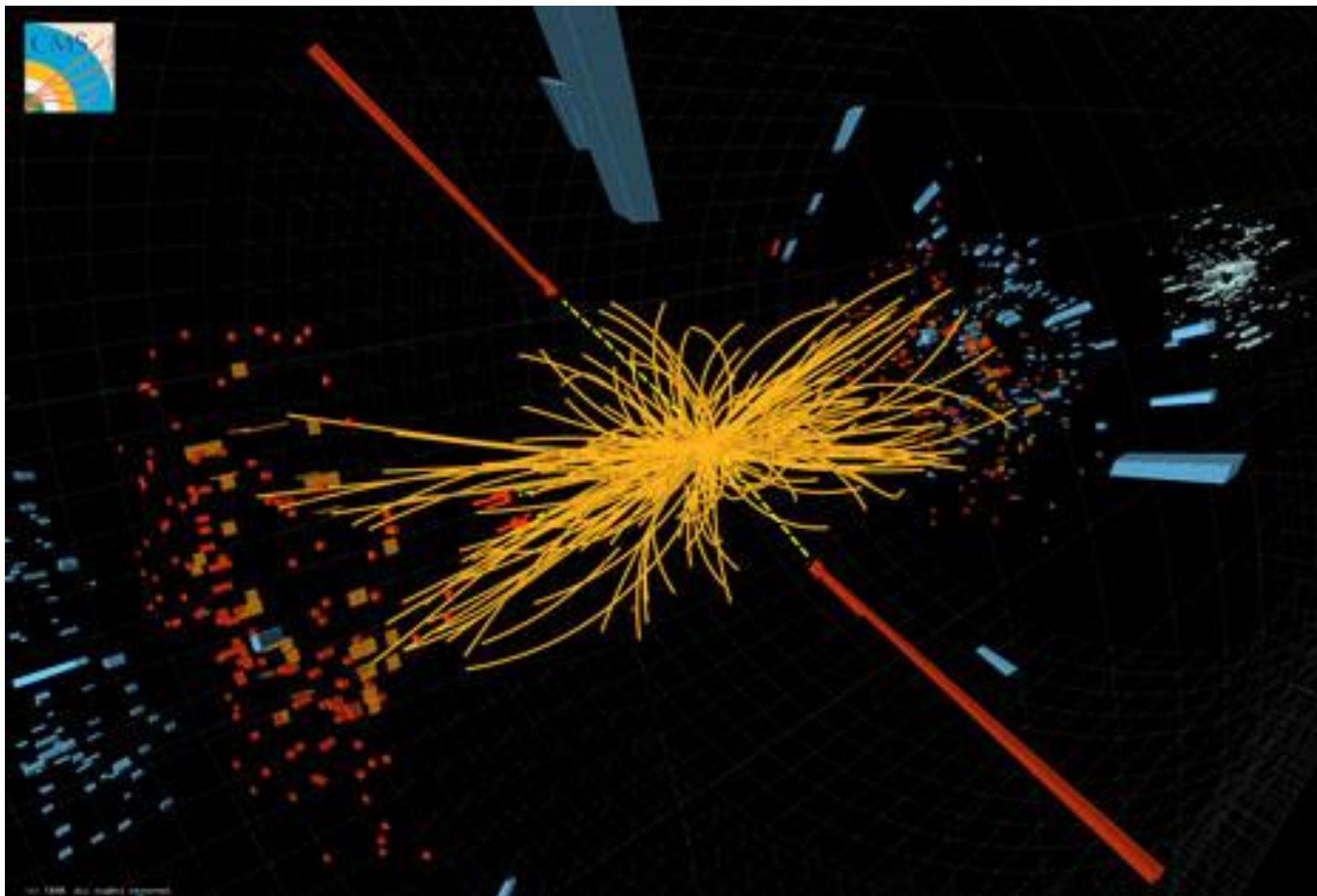
- Combinaison B-rho et TOF
- Combinaison B-rho et dE/dx
- Masse manquante ...
- Direction de la courbure dans un spectromètre magnétique
- Mesure de la perte d'énergie dE/dx qui dépend de la charge
- L'électromètre

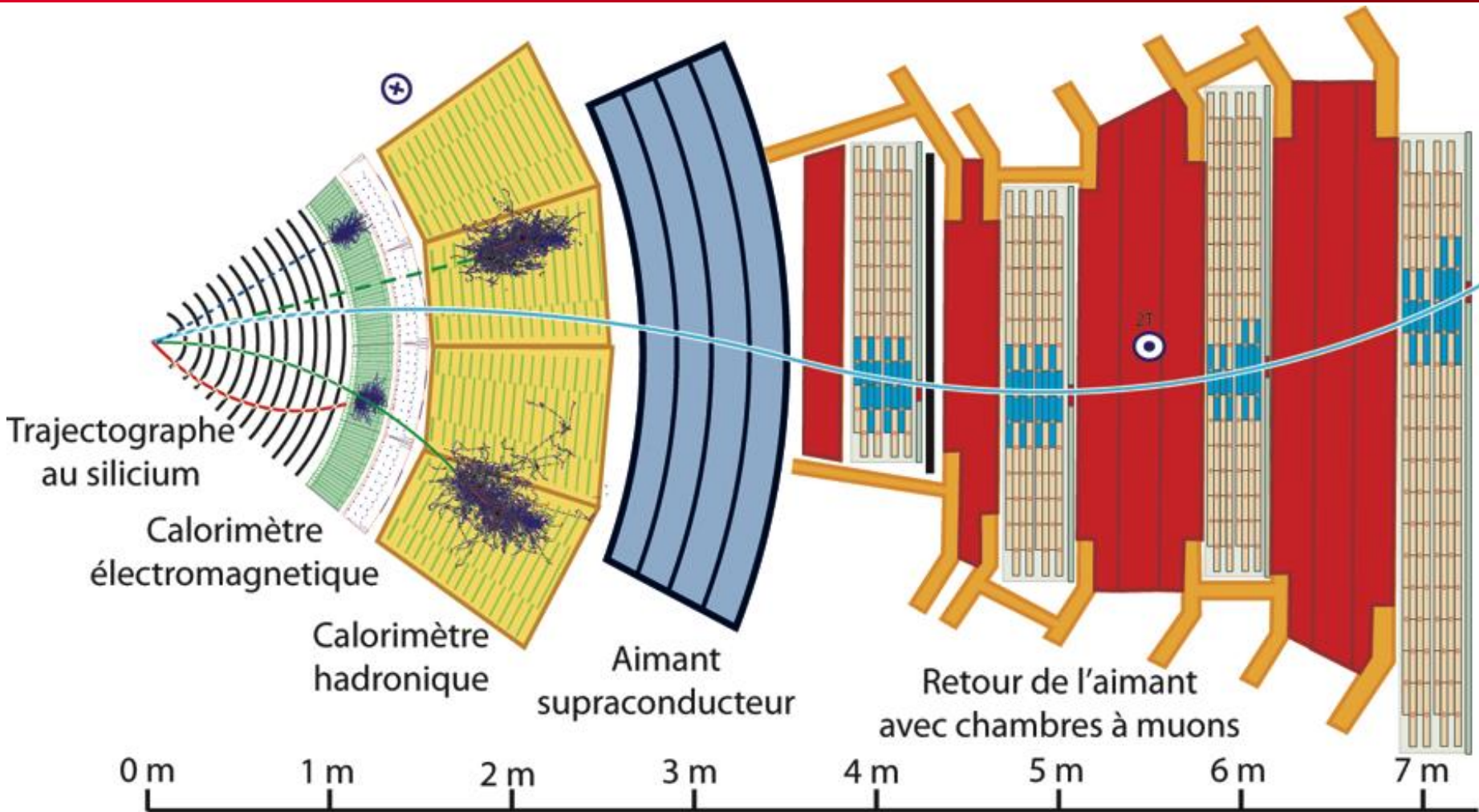


Compact Muon Solenoïd









légende :

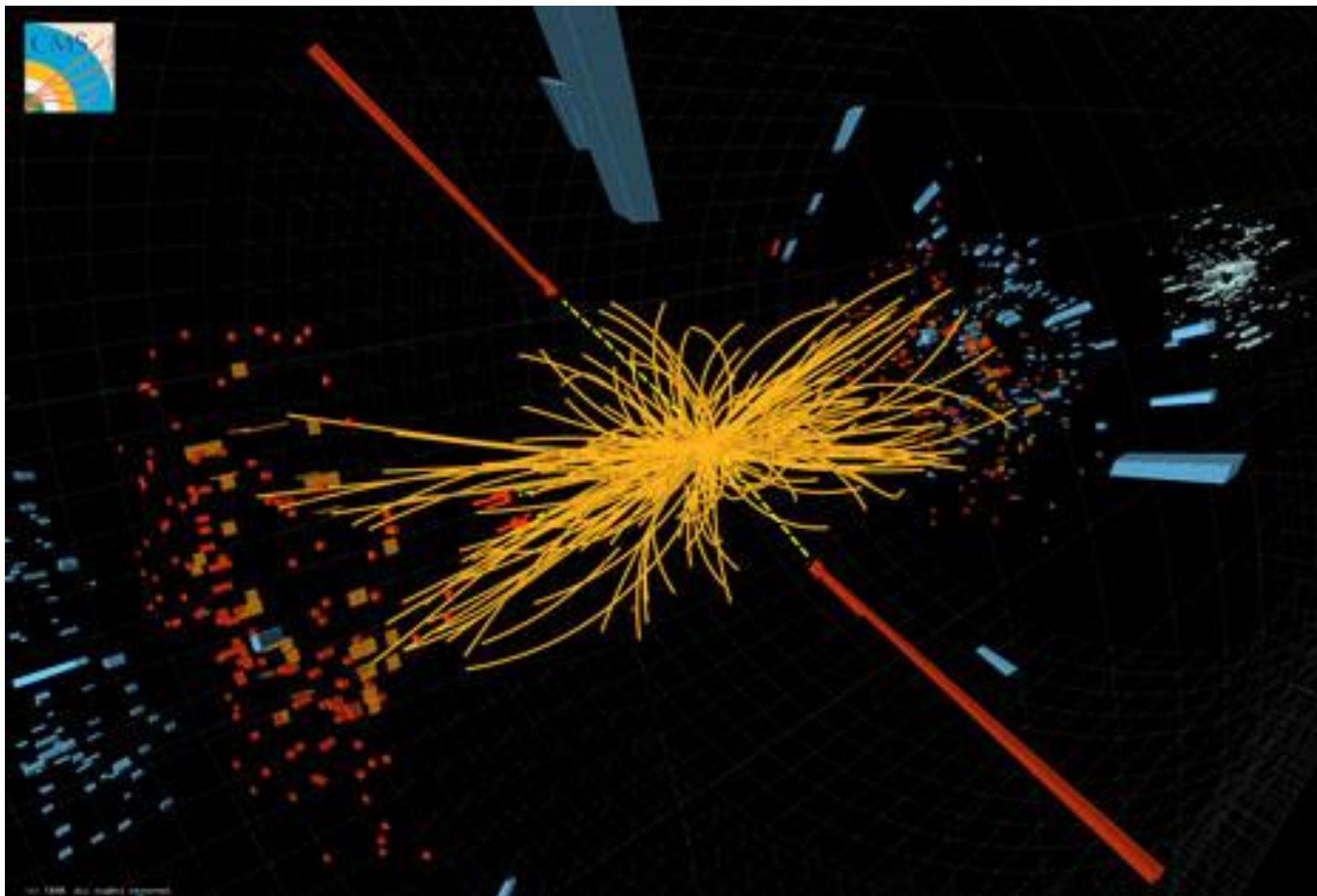
Muon

Électron

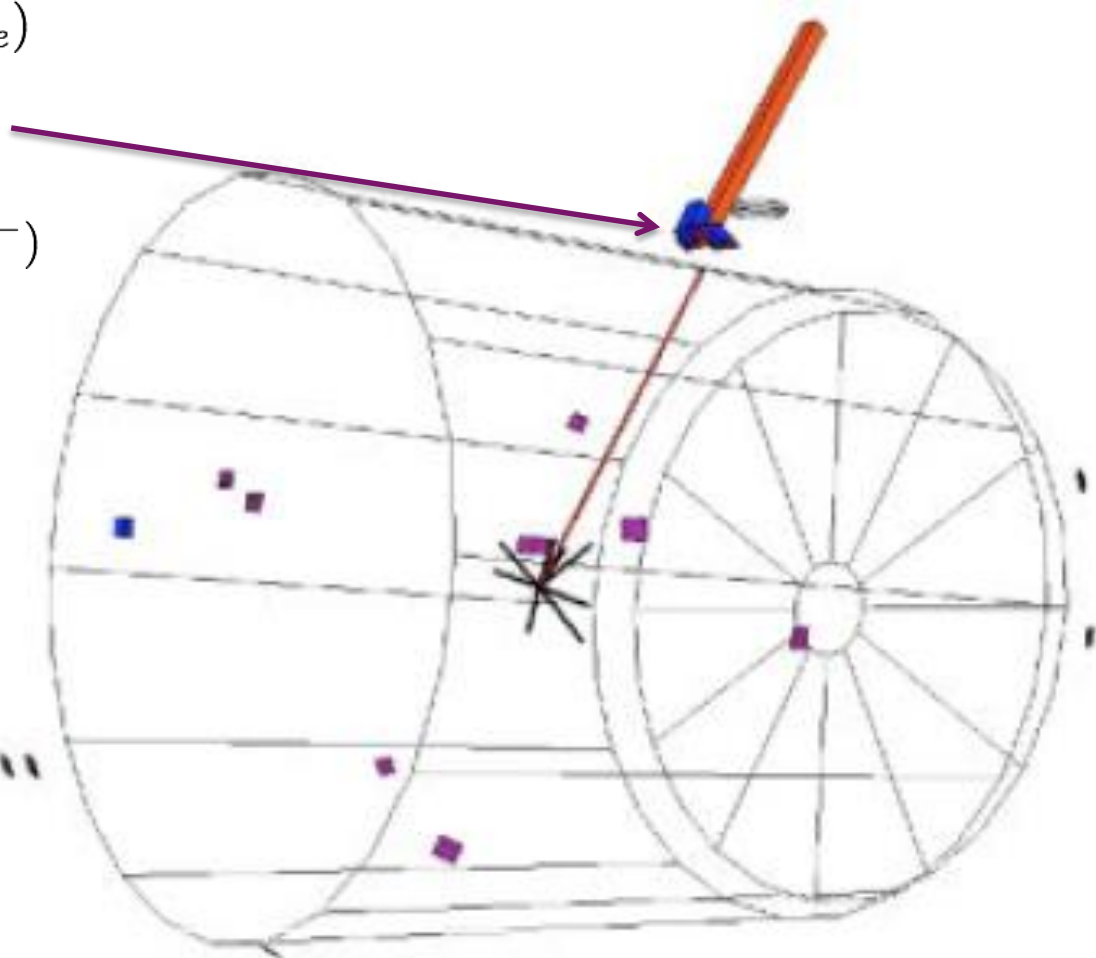
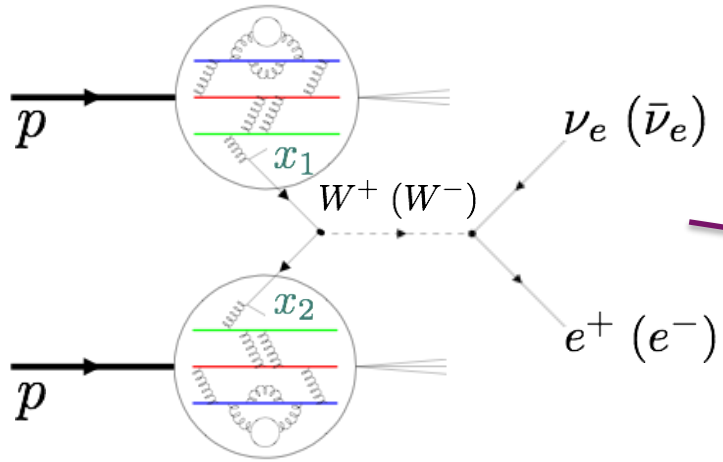
Hadron chargé

Hadron neutre

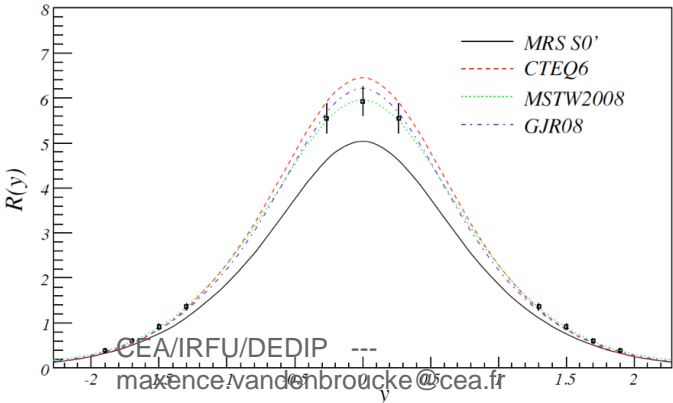
Photon



W EVENT -> ISOLATED LEPTON



W+/W-



STAR experiment at BNL

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

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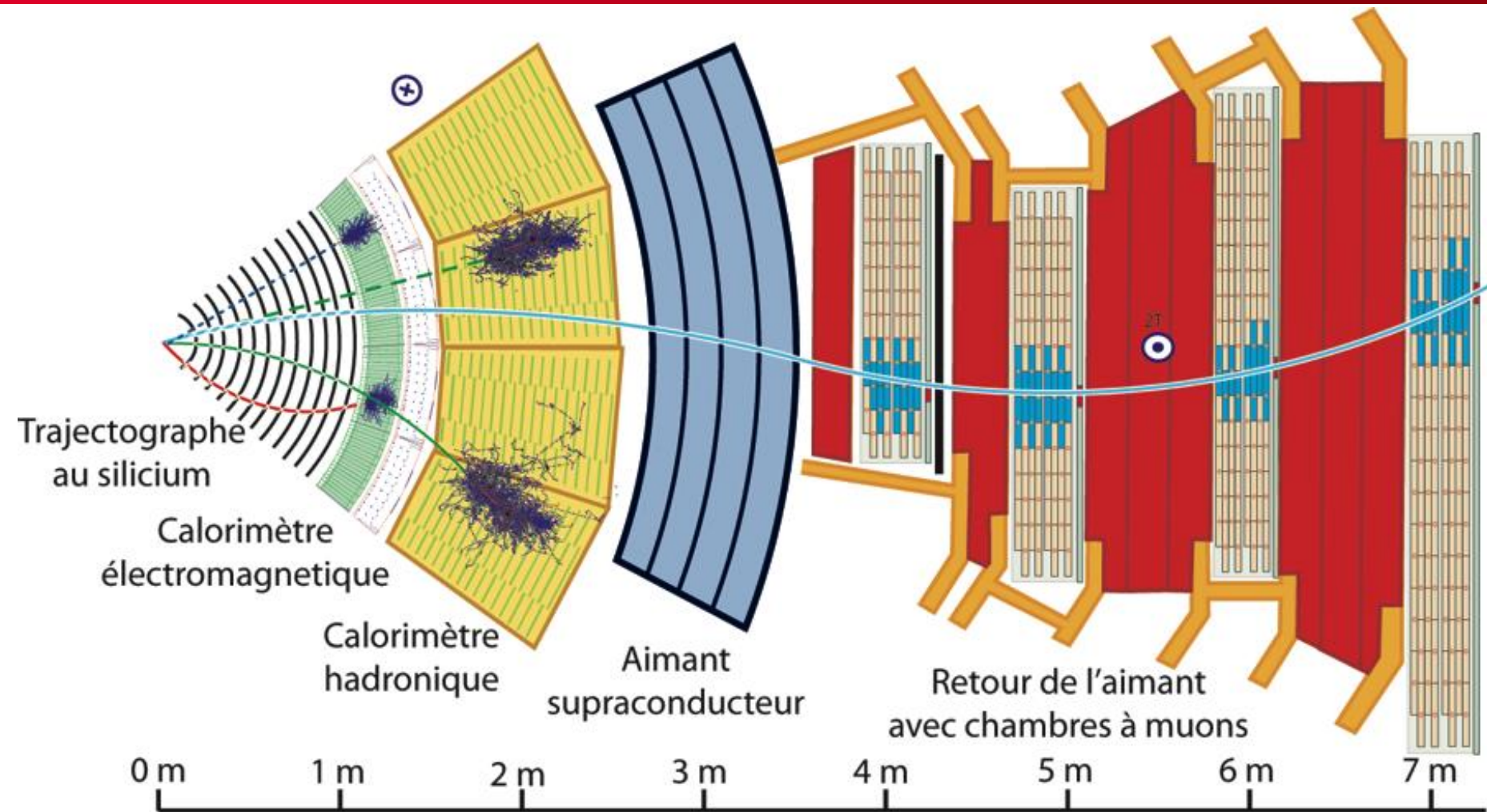
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"Did you see it?"
"No nothing."
"Then it was a neutrino!"





légende :

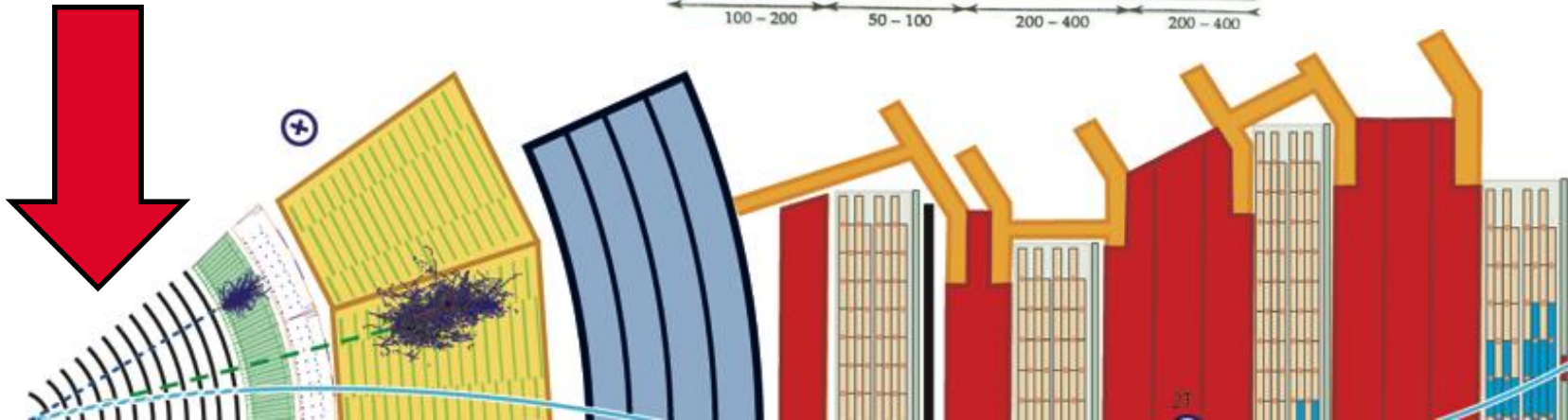
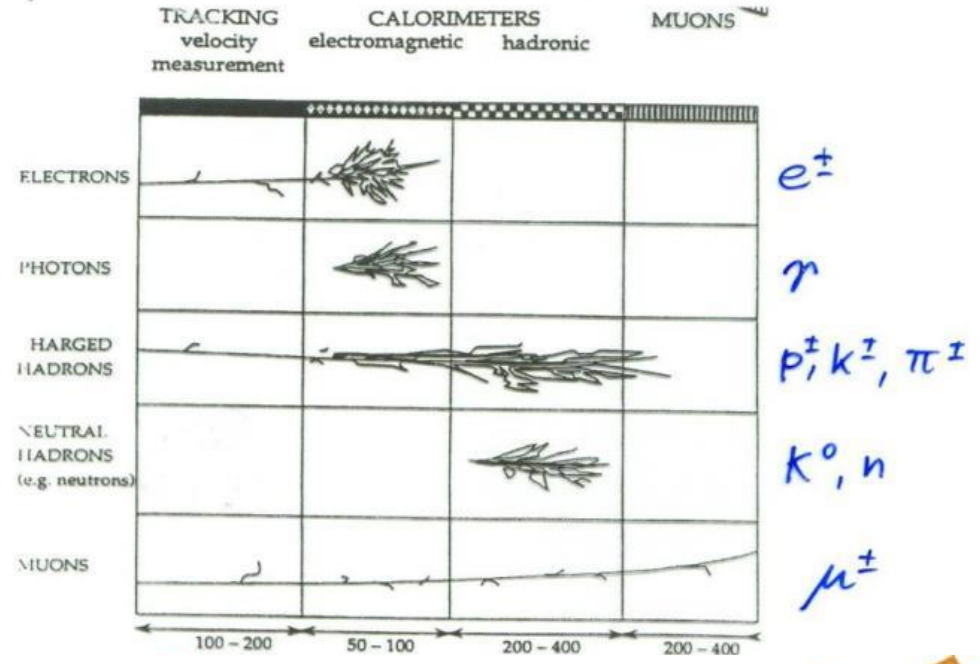
— Muon

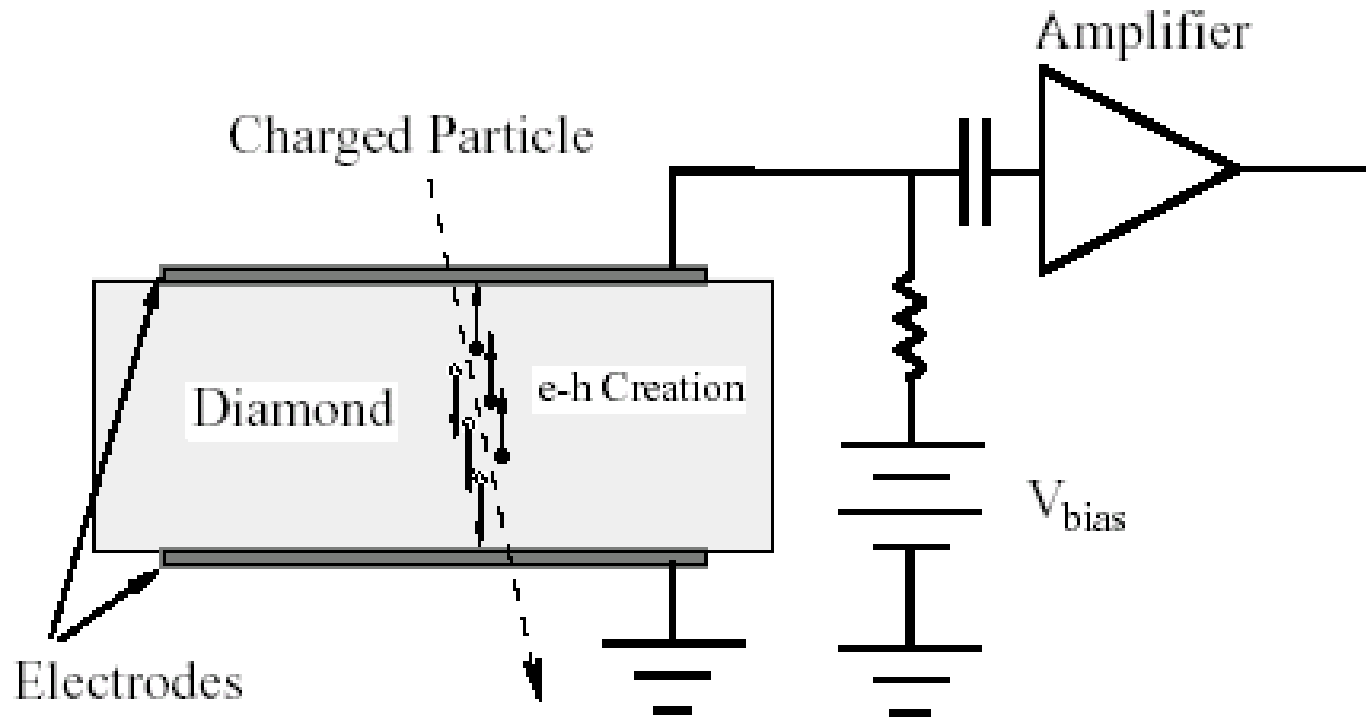
— Électron

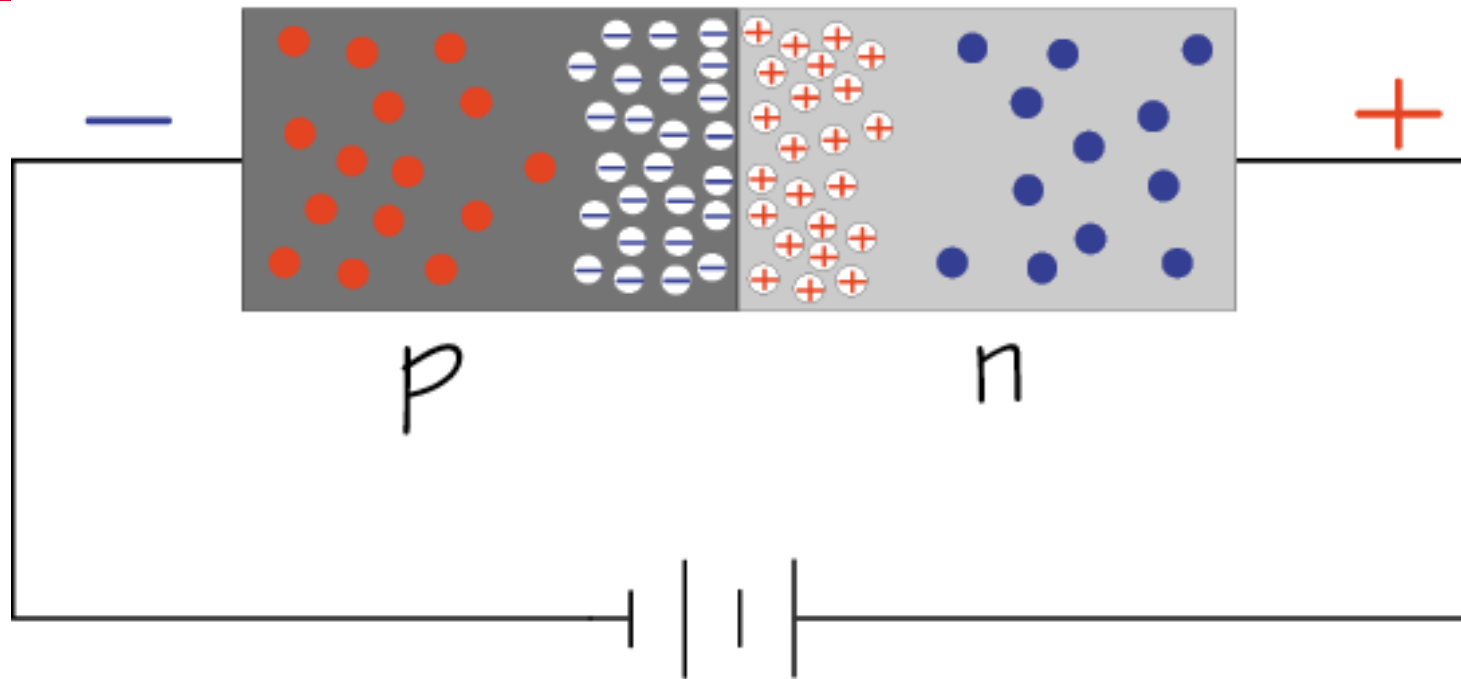
— Hadron chargé

- - - Hadron neutre

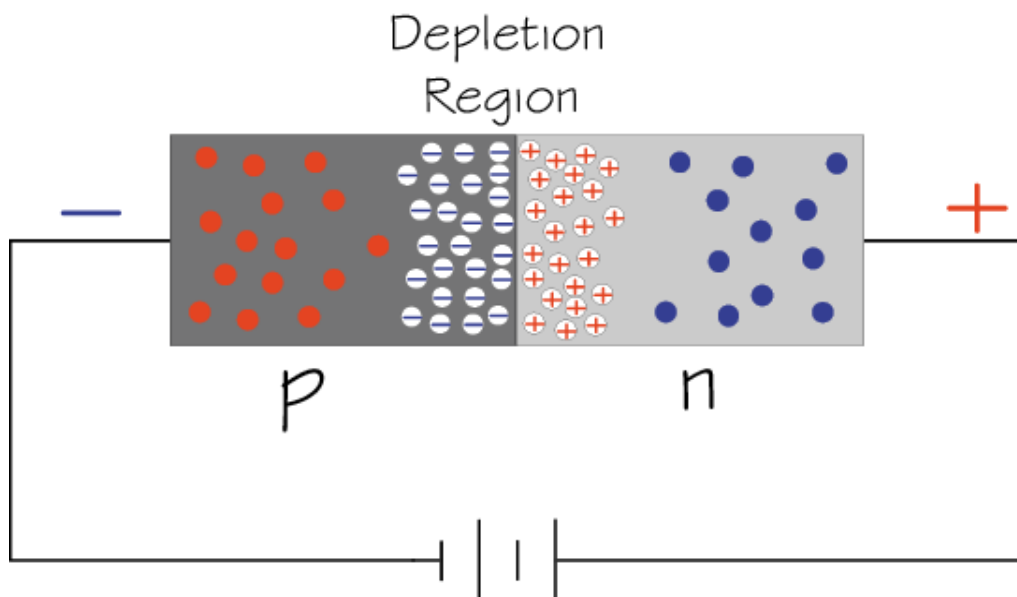
- - - Photon



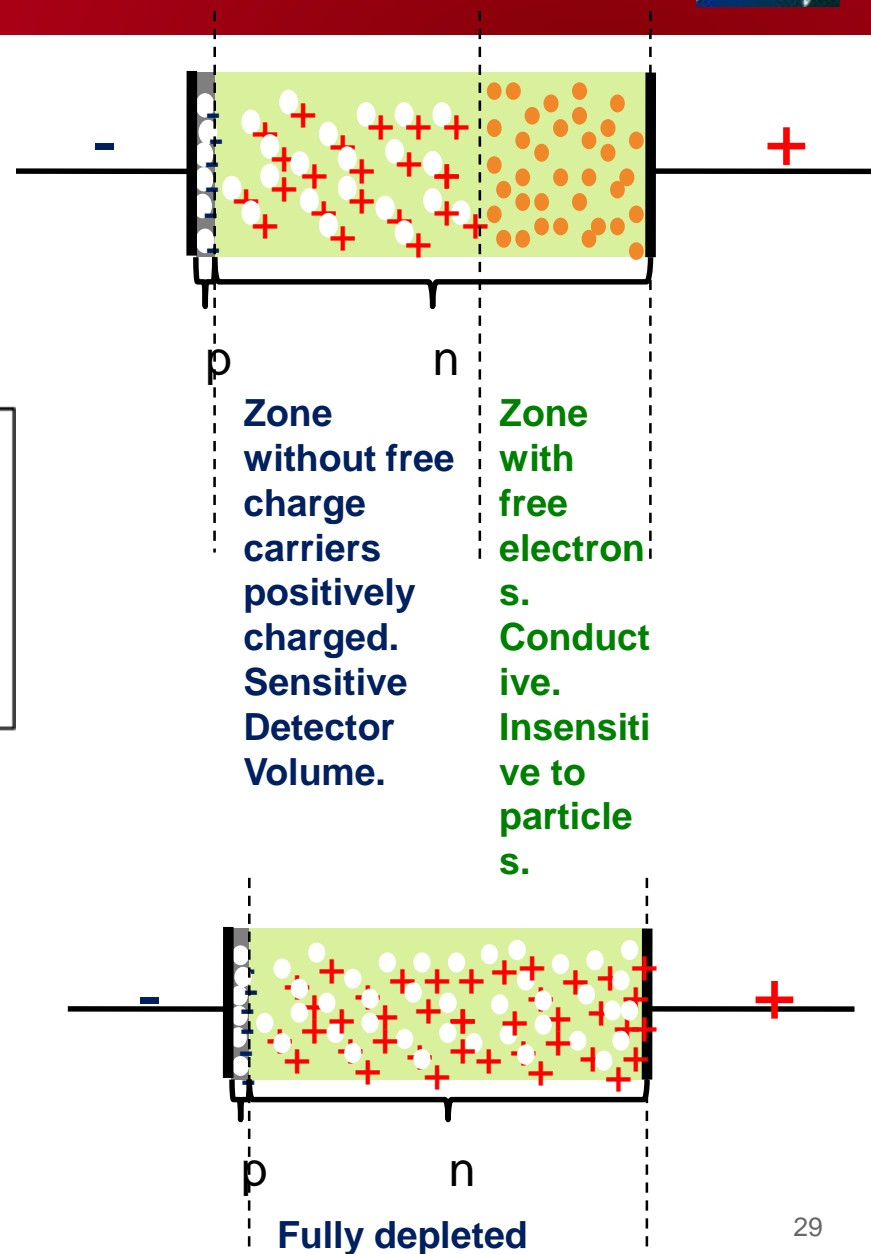


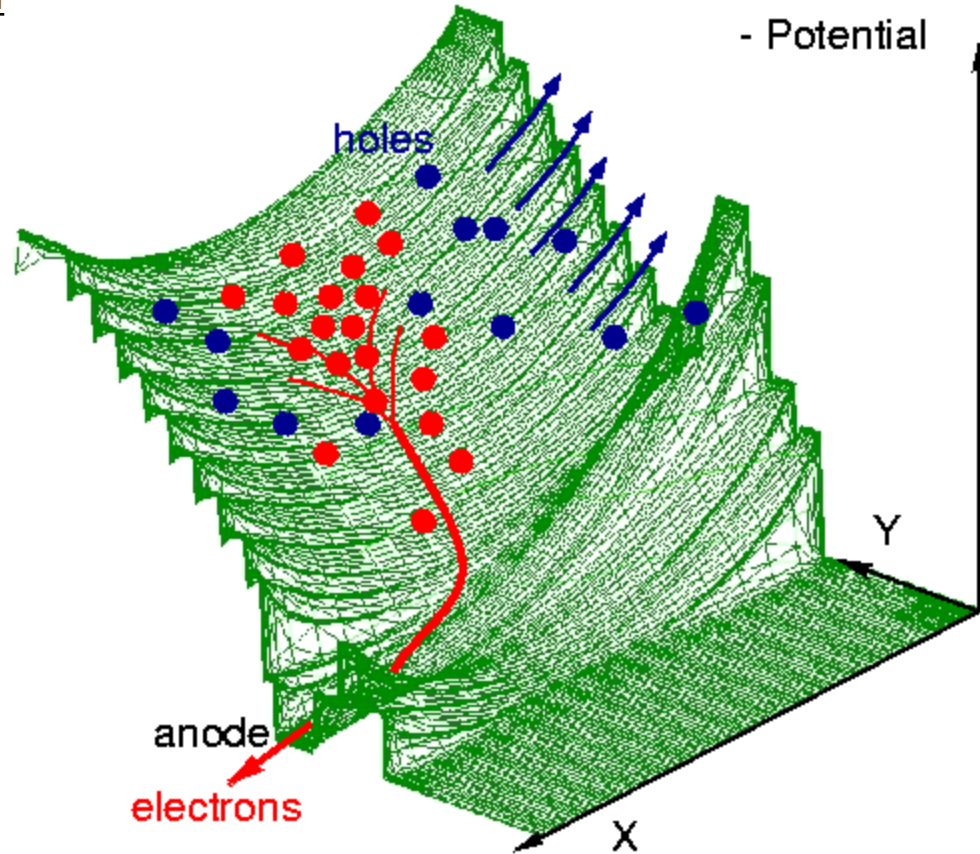
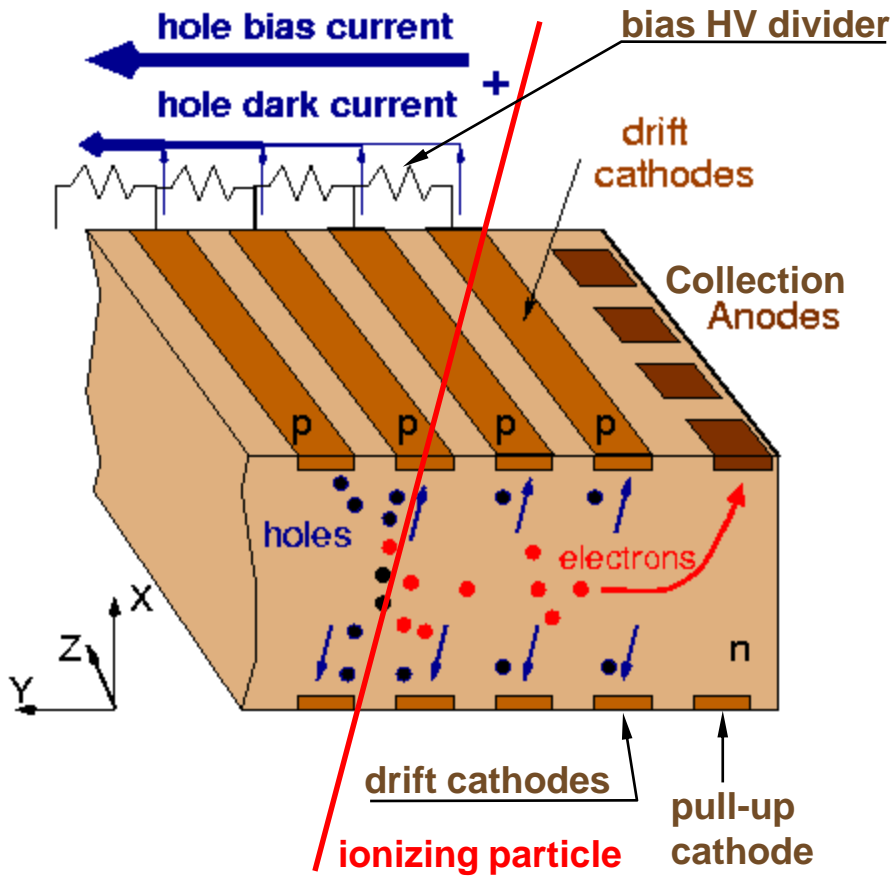


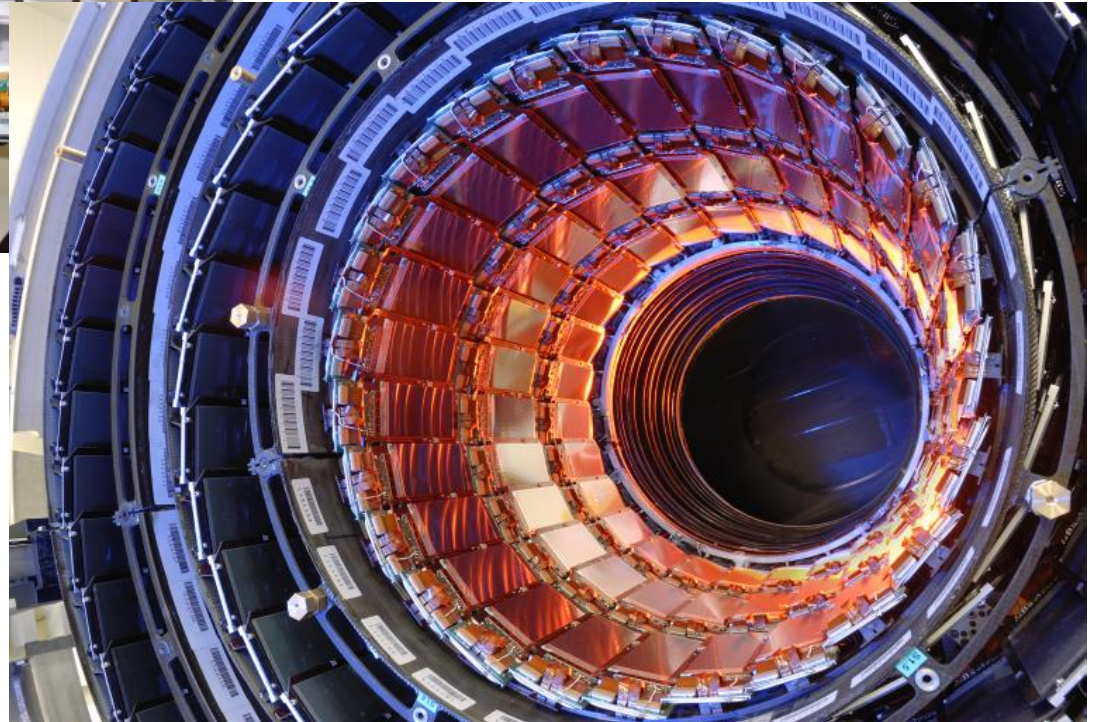
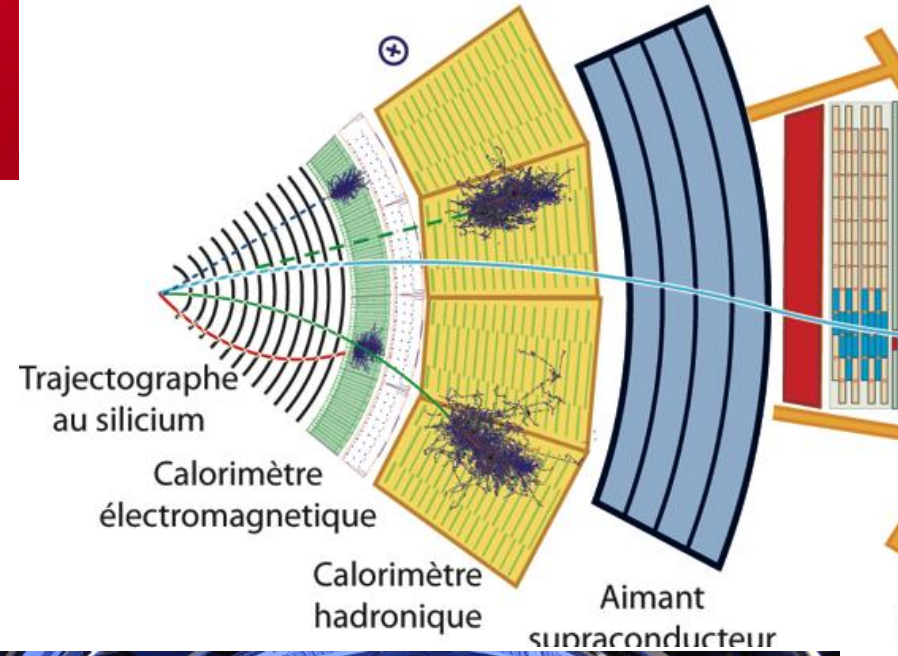
- Electron
- ⊕ Positive ion from removal of electron in n-type impurity
- ⊖ Negative ion from filling in p-type vacancy
- Hole

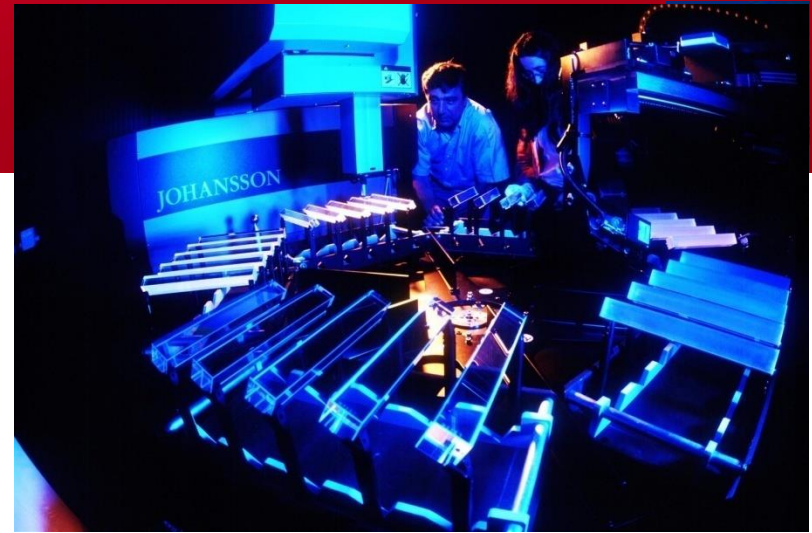


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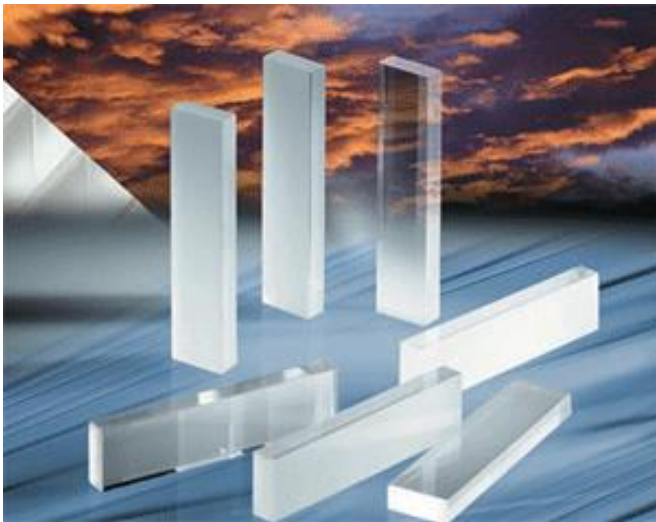


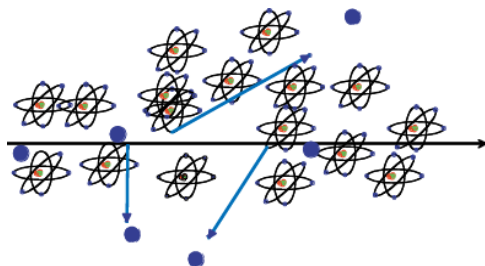






Les Détecteur à base de scintillation

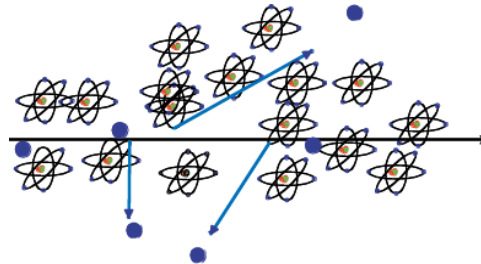




Detectors based on Registration of excited Atoms → Scintillators

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) Polycyclic 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

Low Light Yield

Fast: 1-3ns

Type	Light ^a output	λ_{max}^b (nm)	Attenuation ^c length (cm)	Risetime (ns)	Decay ^d time (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

LHC bunchcrossing 25ns

Inorganic (Crystal) Scintillators

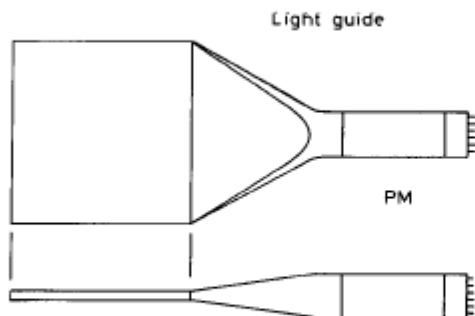
Large Light Yield

Slow: few 100ns

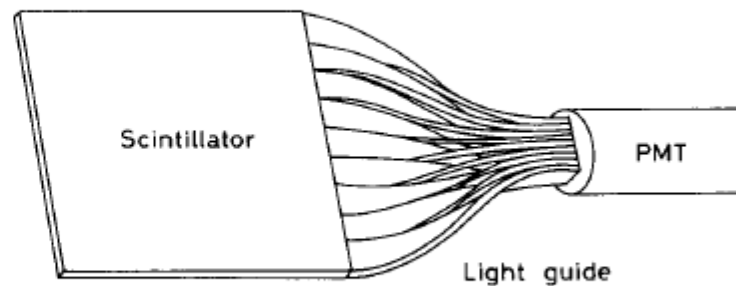
	Relative light output	λ_{max} emission (nm)	Delay time (ns)	Density (g/cm ³)
<i>Inorganic crystals</i>				
Nal(Tl)	230	415	230	3.67
CsI(Tl)	250	560	900	4.51
Bi ₄ Ge ₃ O ₁₂ (BGO)	23-86	480	300	7.13
<i>Organic crystals</i>				
Anthracene	100	448	22	1.25
Trans-stilbene	75	384	4.5	1.16
Naphthalene	32	330-348	76-96	1.03
<i>p,p'</i> -Quarterphenyl	94	437	7.5	1.20
<i>Primary activators</i>				
2,5-Diphenyl-oxazole (PPO)	75	360-416	5*	
2-Phenyl-5-(4-biphenyl)- 1,3,4-oxadiazole (PBD)	96	360-5		
4,4''-Bis(2-butyloctyloxy)- <i>p</i> - quaterphenyl (BIBUQ)	60	365,393	1.30*	

LEP bunchcrossing 25 μ s

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



“fish tail”



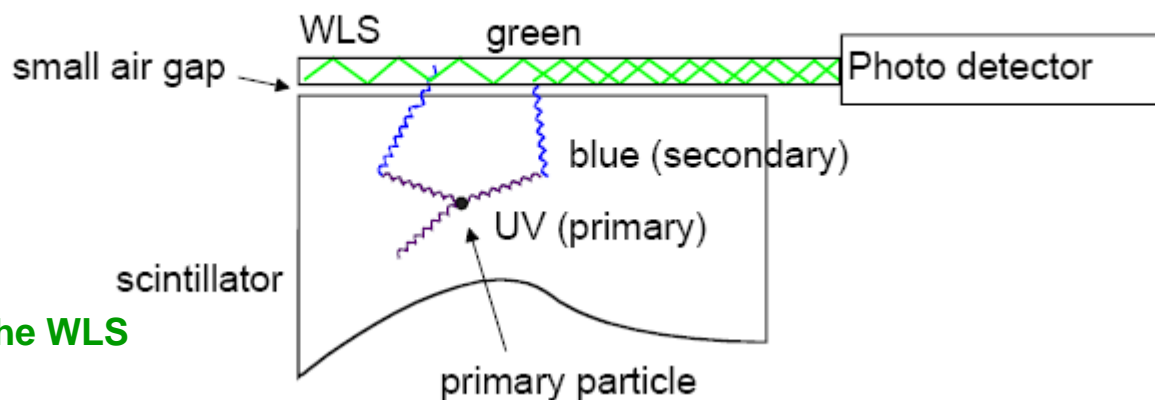
adiabatic

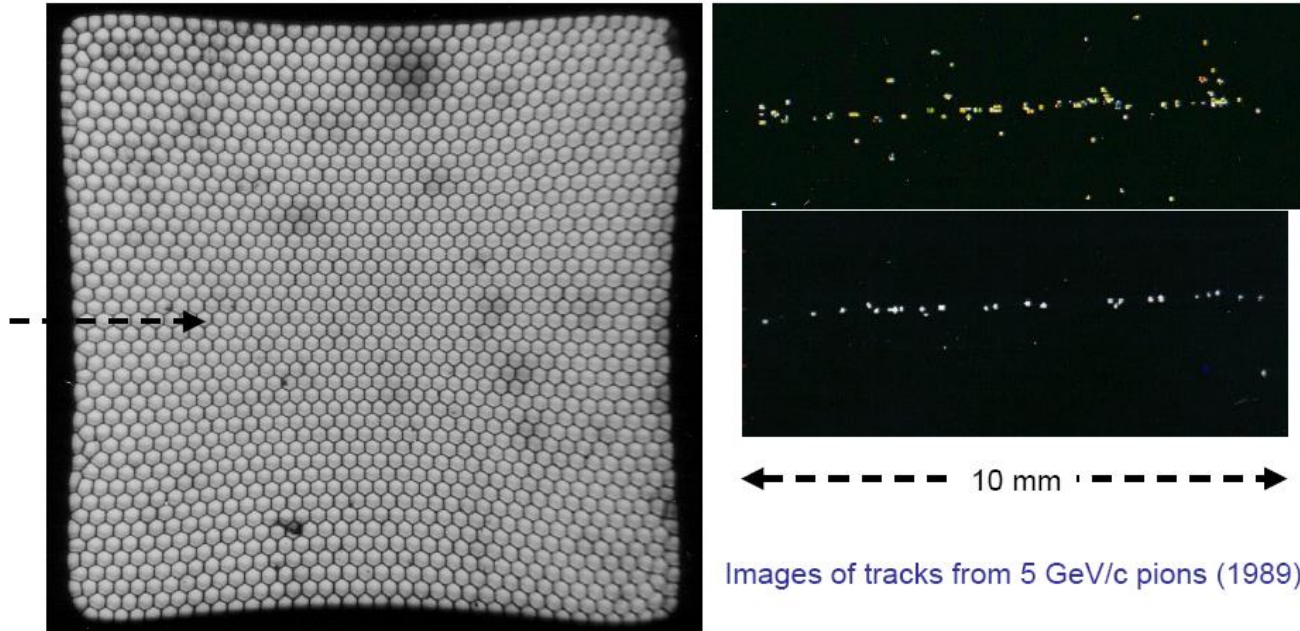
- wavelength shifter (WLS) bars

UV light enters the WLS material
Light is transformed into longer wavelength

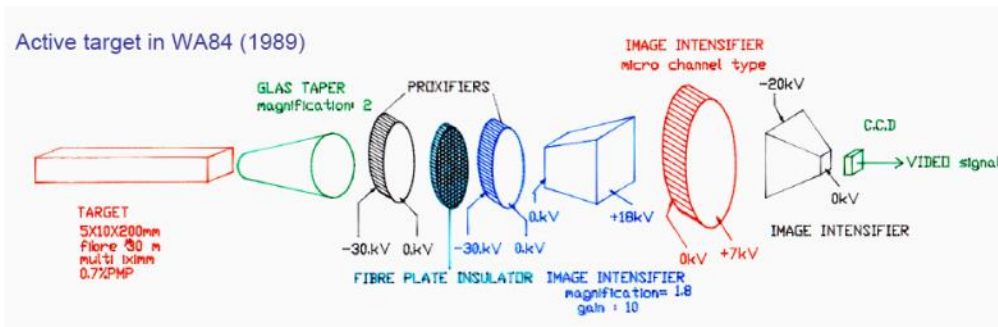
→ Total internal reflection inside the WLS material

→ ‘transport’ of the light to the photo detector

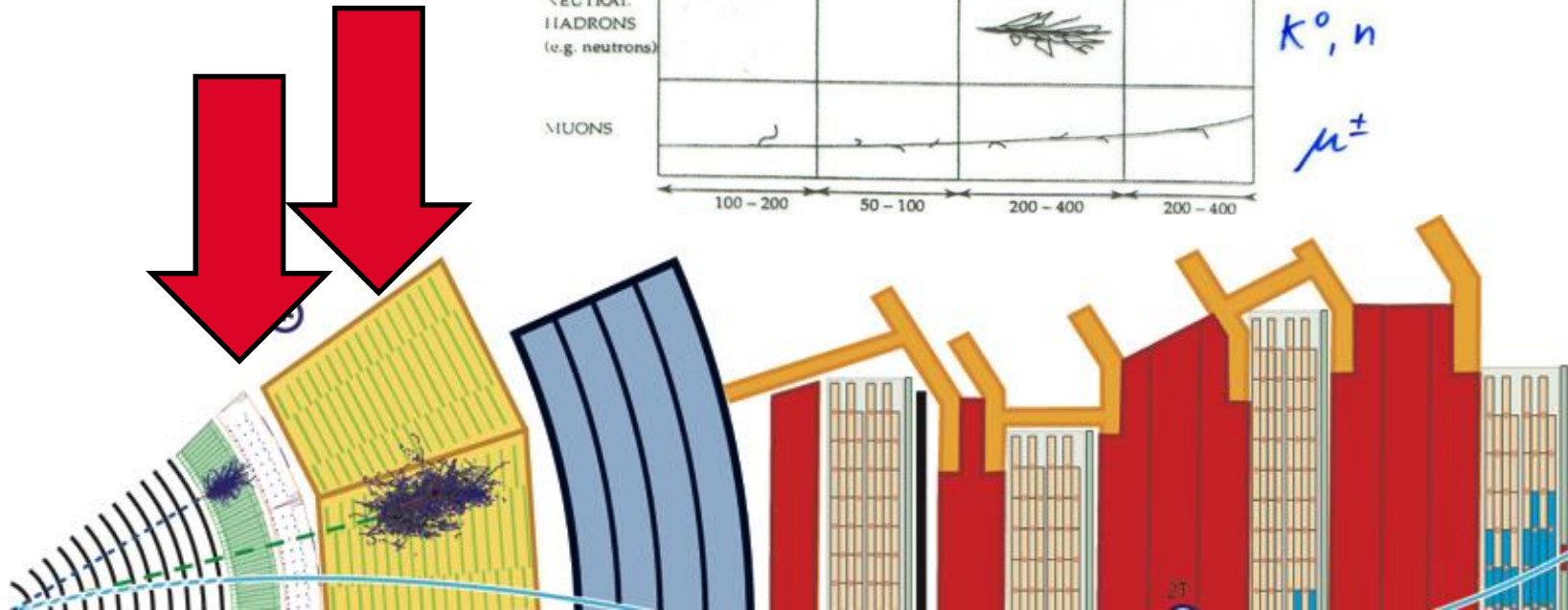
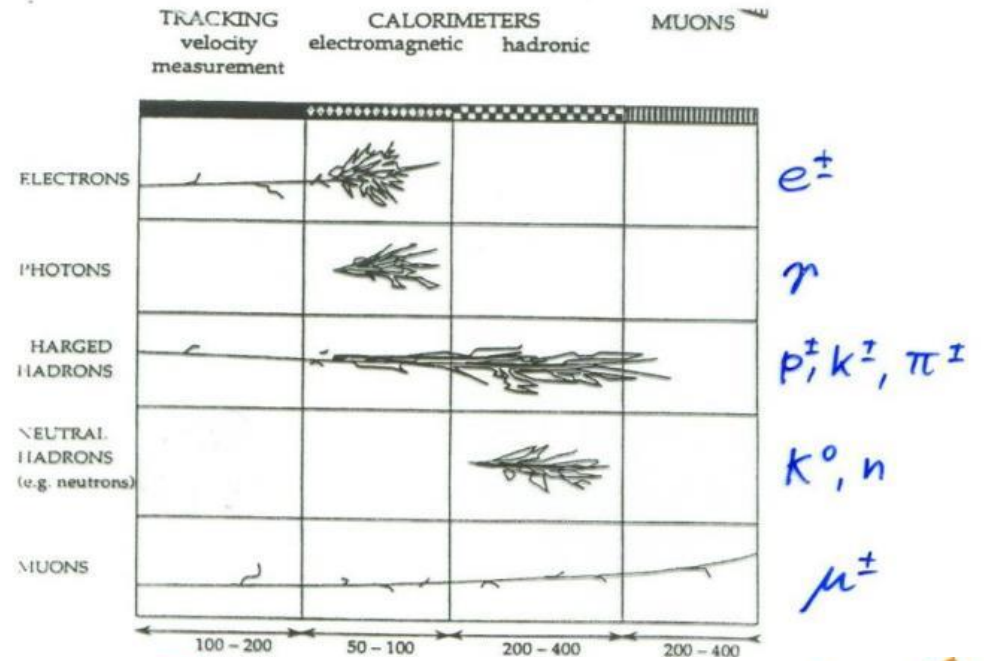




Images of tracks from 5 GeV/c pions (1989)



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



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,

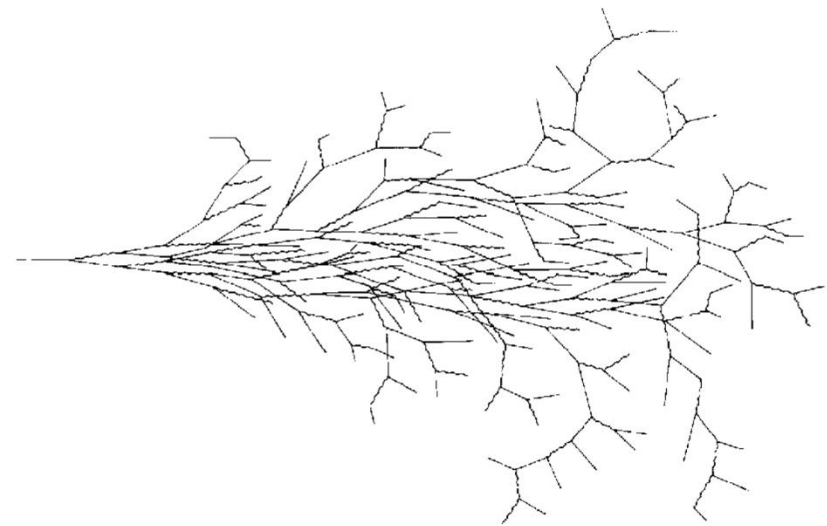
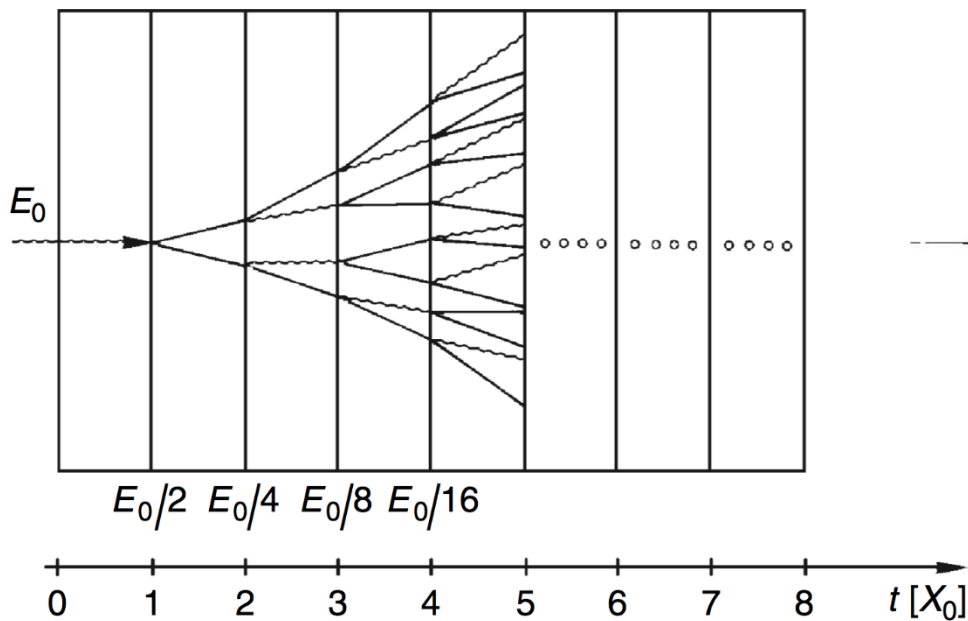
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

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, NO. 4, October 2003

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

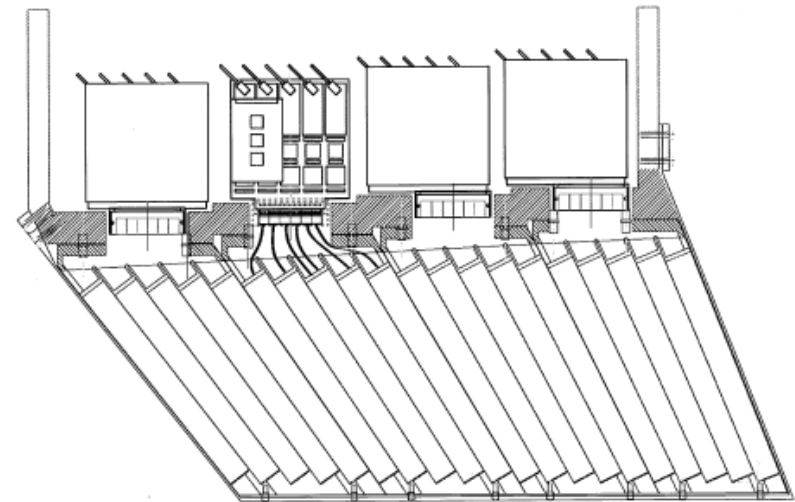
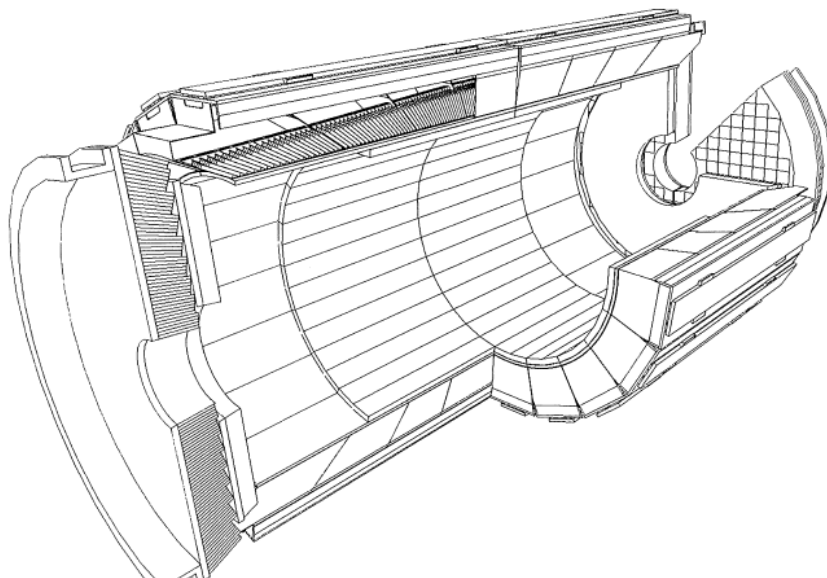
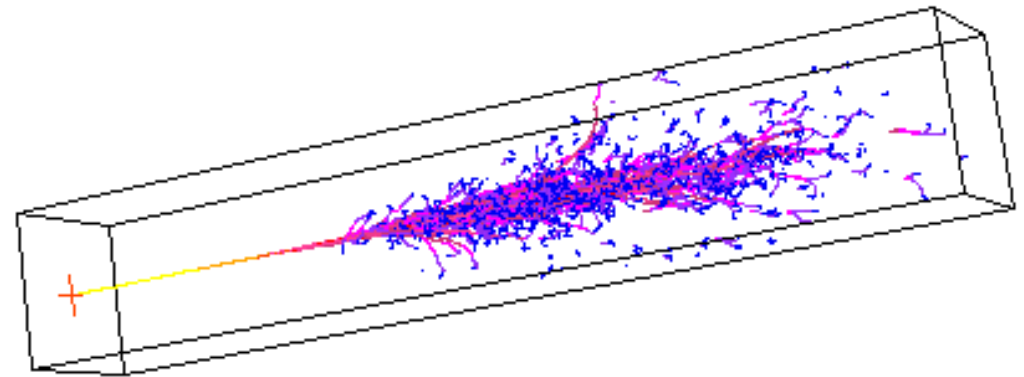
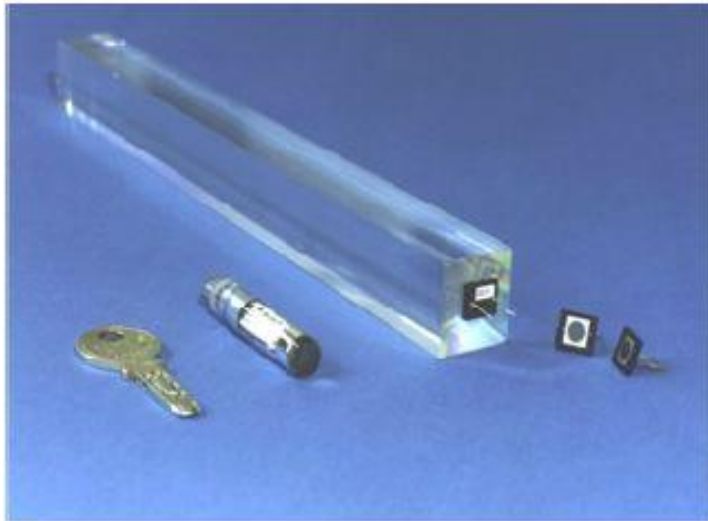


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Hadron Calorimeters are Large because λ is large

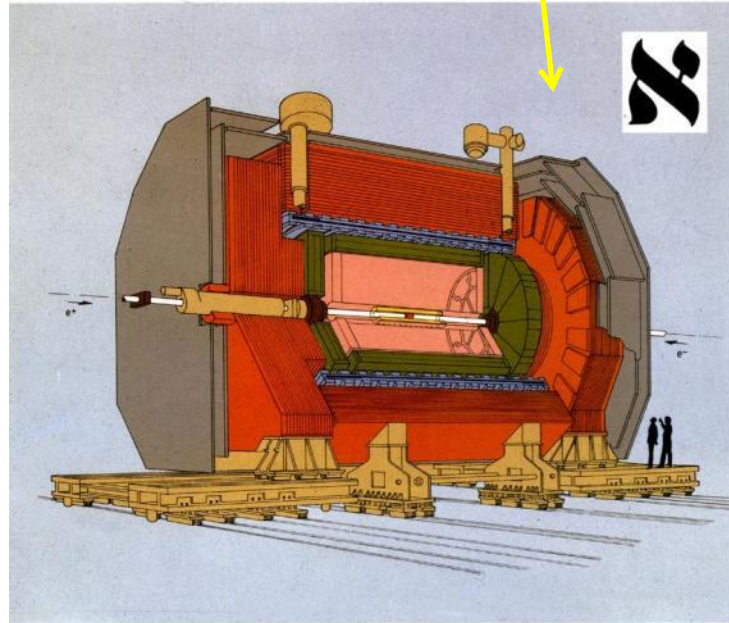
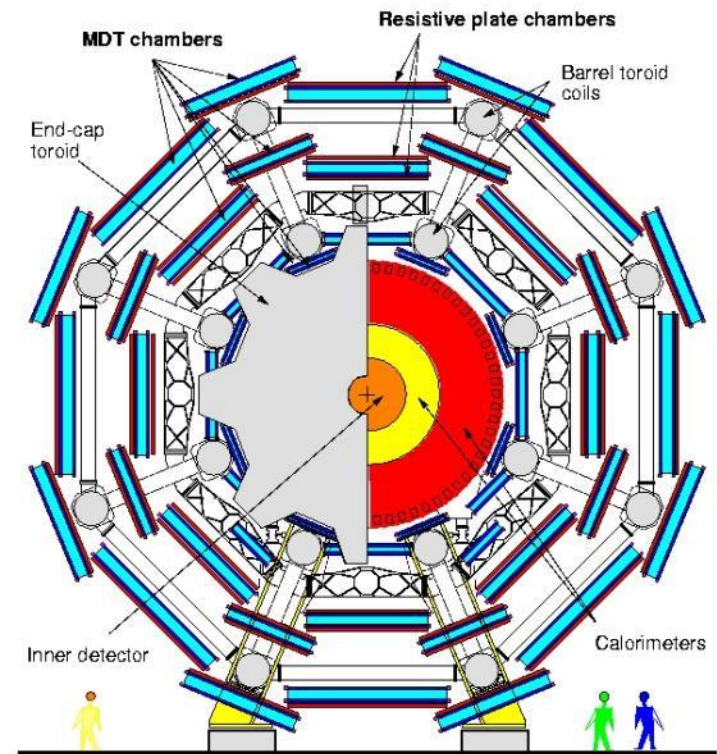
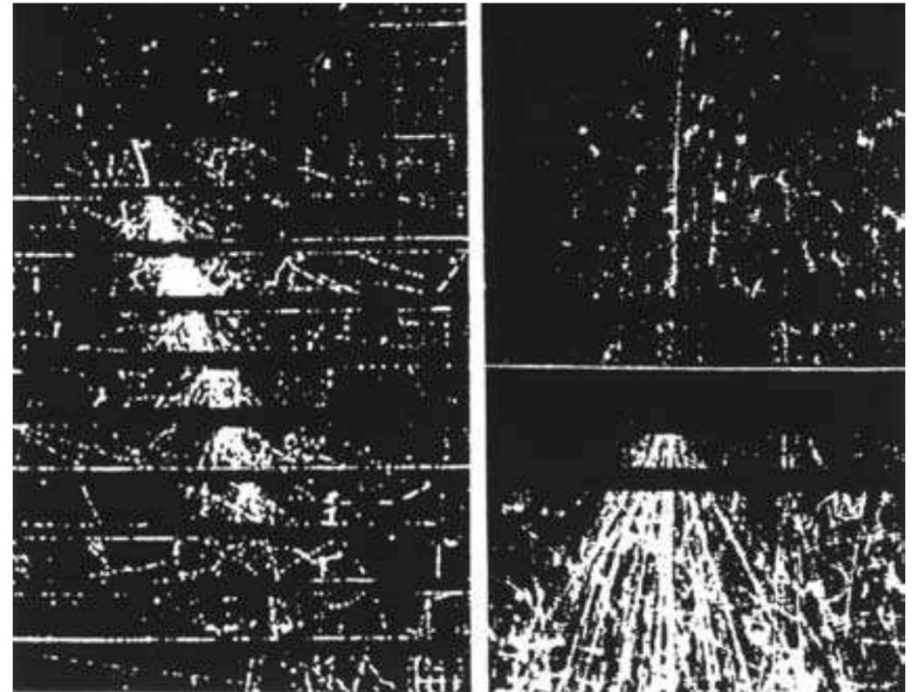
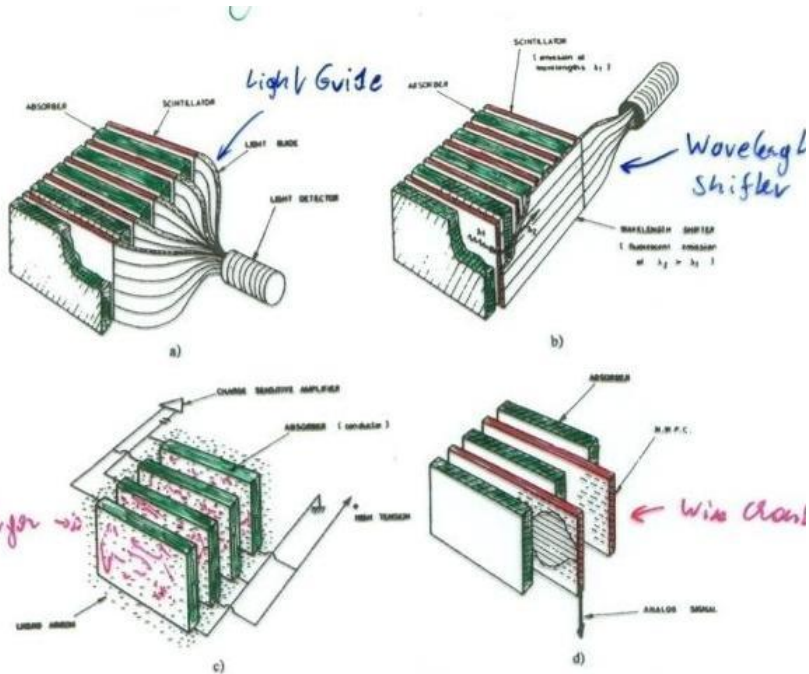


Fig. 1 - The ALEPH Detector

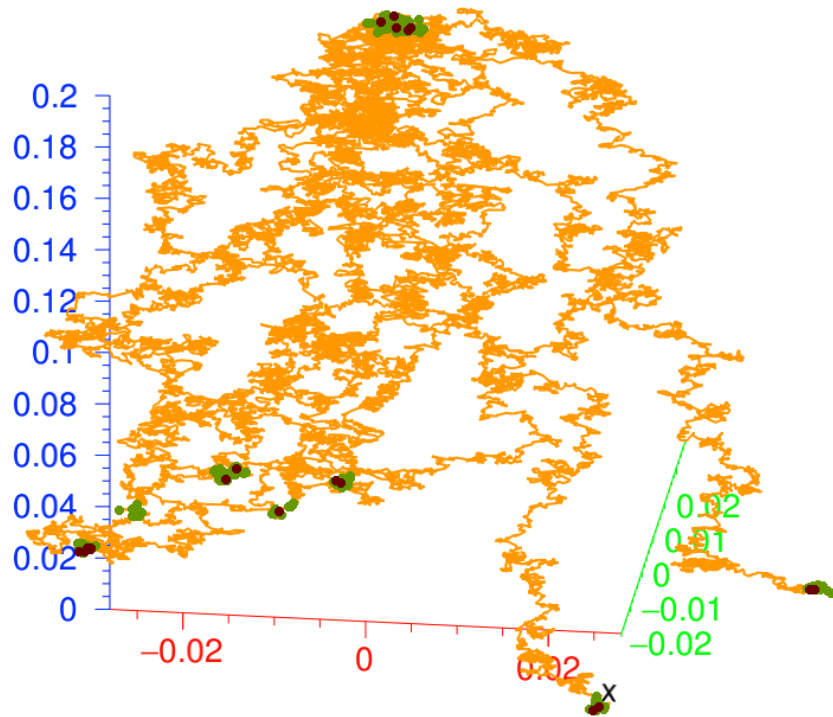
- Vertex Detector
- Inner Track Chamber
- Time Projection Chamber
- Electromagnetic Calorimeter
- Superconducting Magnet Coil
- Hadron Calorimeter
- Muon Detection Chambers
- Luminosity Monitors

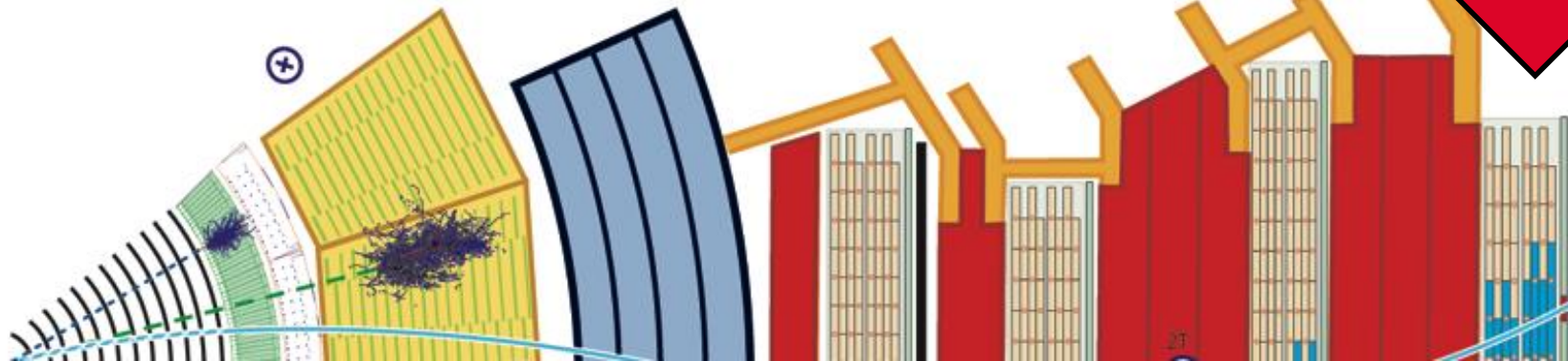
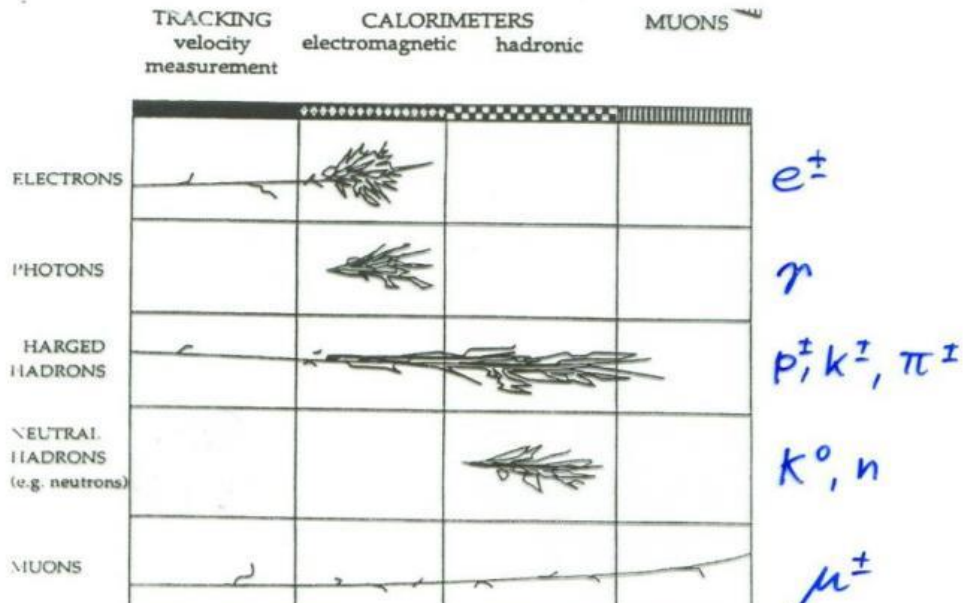
Hadron Calorimeters are large and heavy because the hadronic interaction length λ , the 'strong interaction equivalent' to the EM radiation length X_0 , is large (5-10 times larger than X_0)

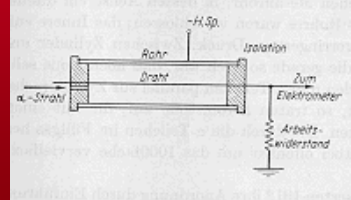




La détection des particules: exemple des détecteurs gazeux

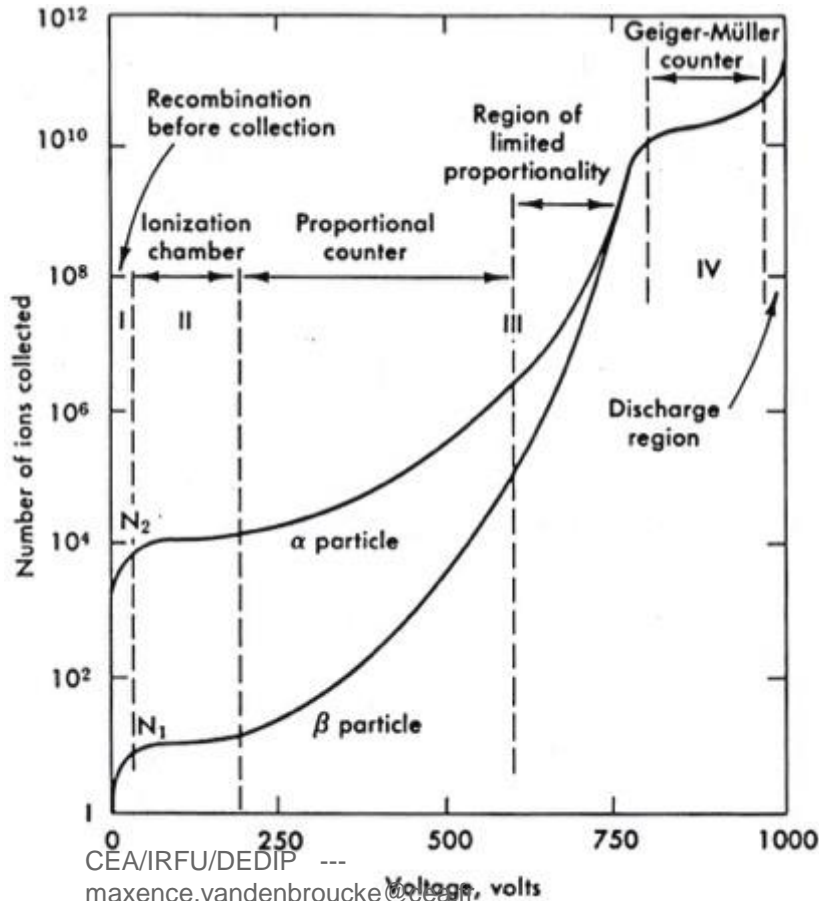
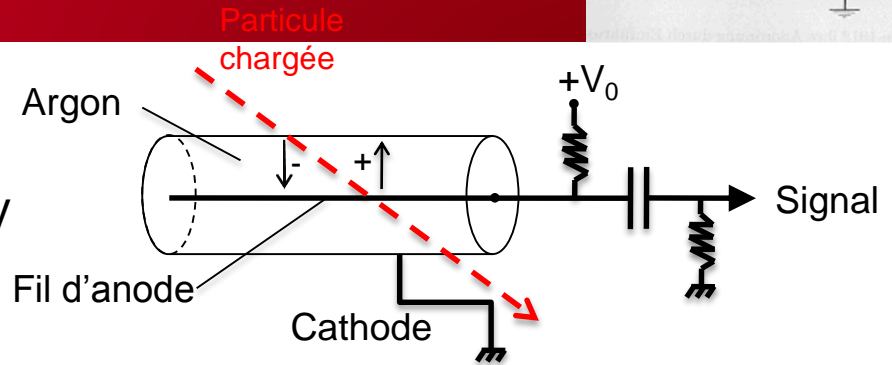
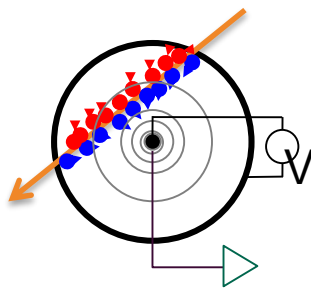






(RADIAL) AVEC:
$$E = \frac{1}{r} \frac{V_0}{\ln(b/a)}$$

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



I: tension trop faible \rightarrow 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 \rightarrow Gaz quencher

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

Production de paires électron-ion :

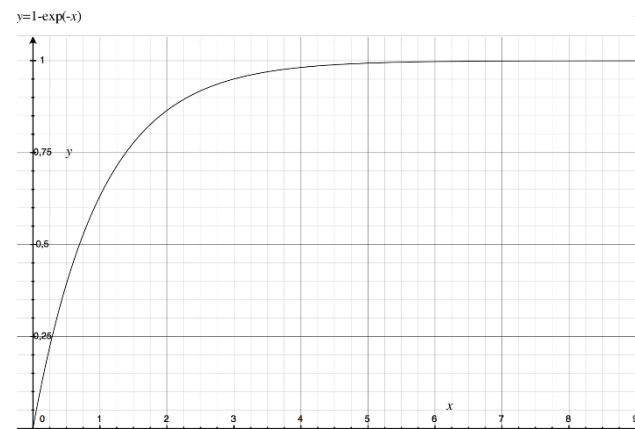
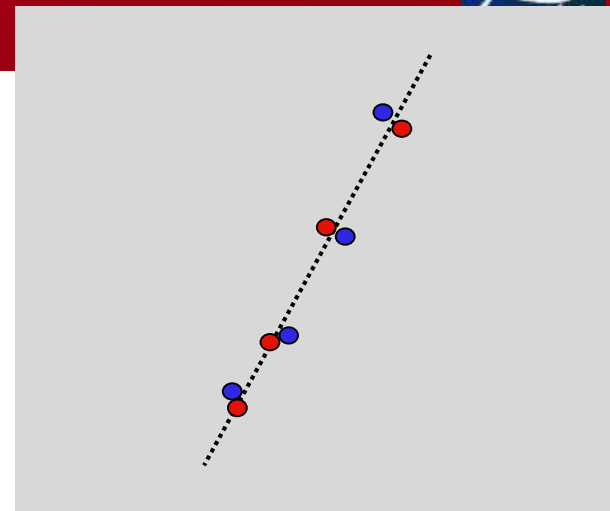
- Les interactions Coulombiennes entre le champ électrique de la particule et les atomes du milieu produisent des paires électron-ion.
- Les ionisations multiples suivent une statistique de Poisson:

$$P_k^n = \frac{n^k}{k!} e^{-n} \quad \begin{array}{l} n : \text{moyen} \\ k : \text{mesuré} \end{array}$$

- 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*: $Ne^* + Ar \rightarrow Ne + Ar^+ + e^-$





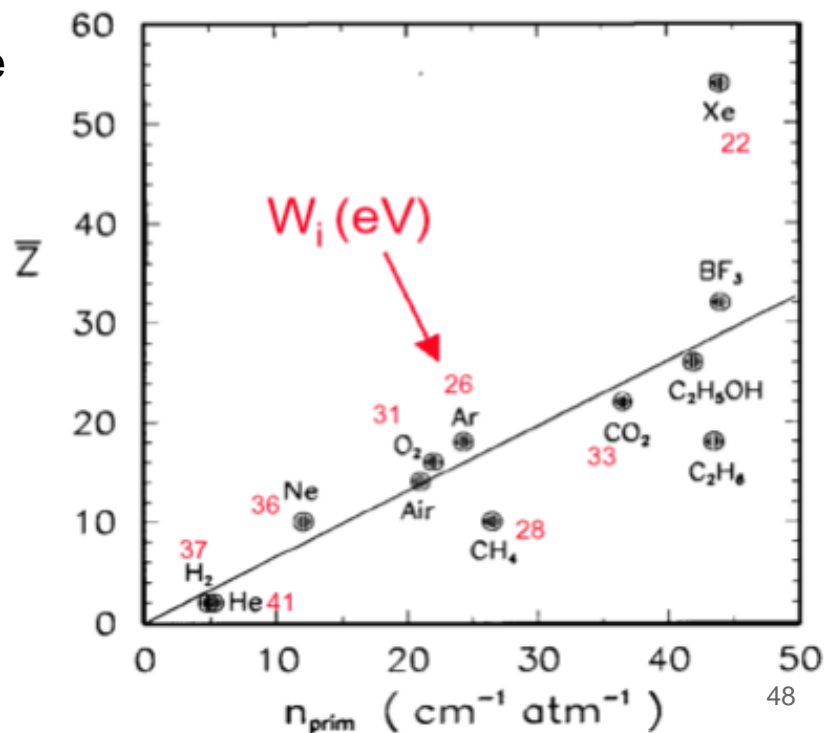
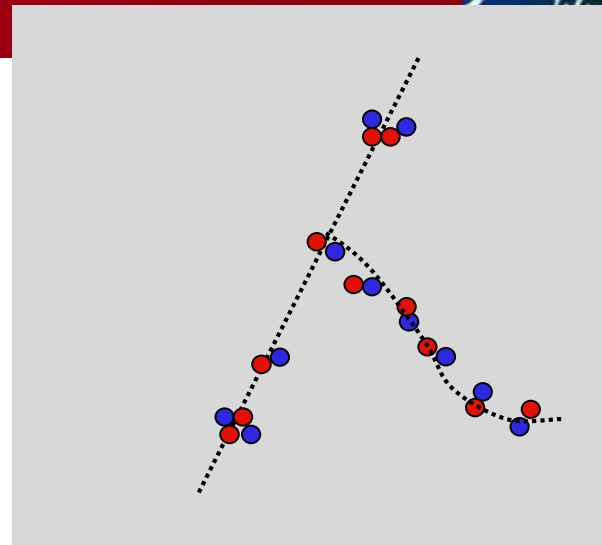
- Les électrons primaires ionisent à nouveau le milieu et produisent localement de nouveaux groupes de paires électron-ion. Si l'électron secondaire a suffisamment d'énergie il peut produire une longue trace (électron δ).
- Nombre total de paires:

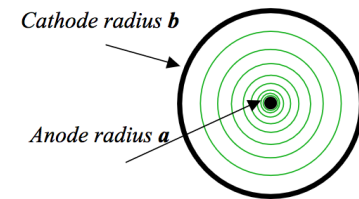
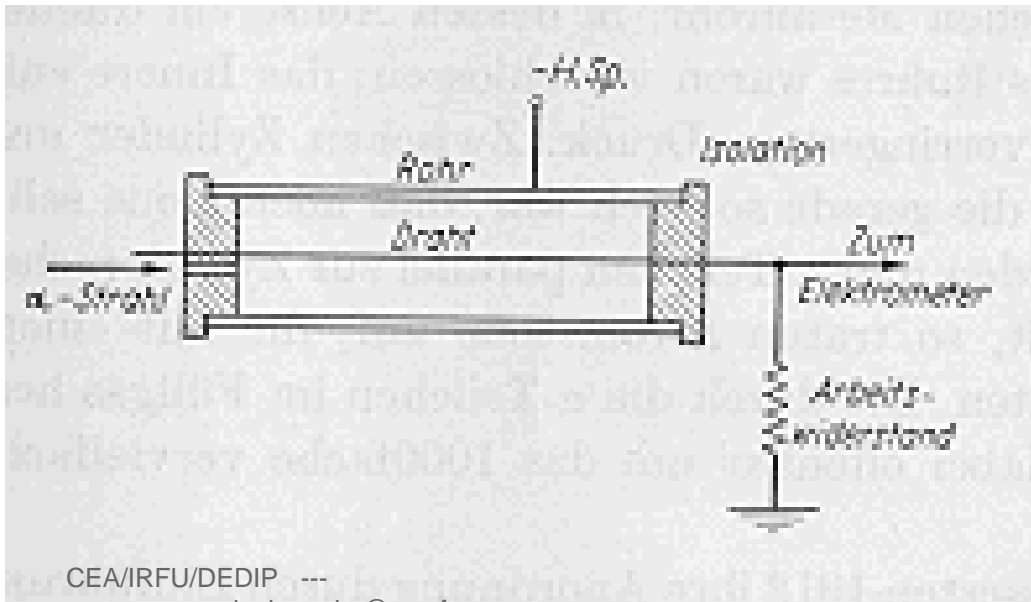
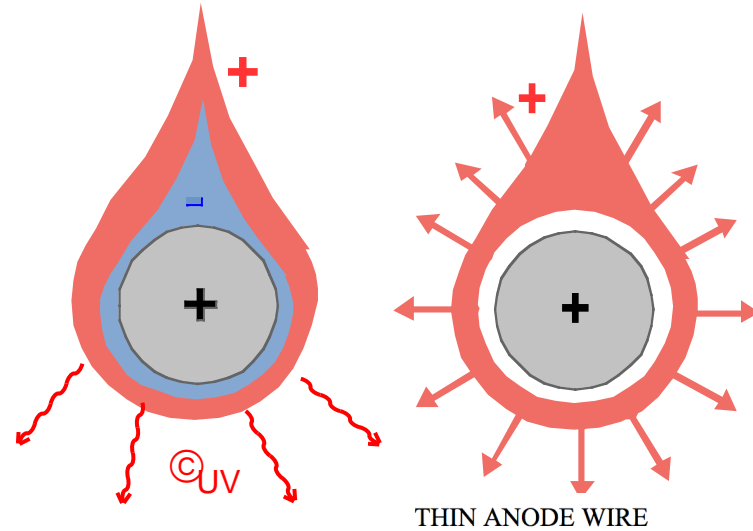
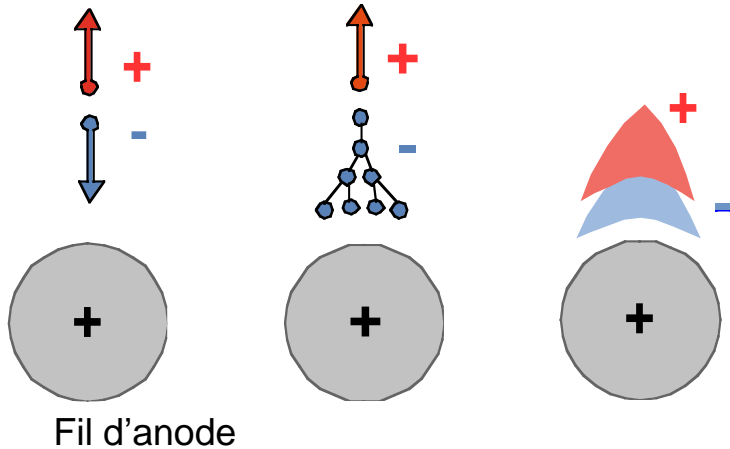
$$n_T = \frac{\Delta E}{w_i}$$

ΔE : perte d'énergie de la particule
 w_i : énergie moyenne par paire

M.I.P. dans l'argon:

- $\Delta E = 2,65 \text{ keV/cm}$ $w_i = 25 \text{ eV}$
- $n_T \approx 106 \text{ paires électron-ion/cm}$



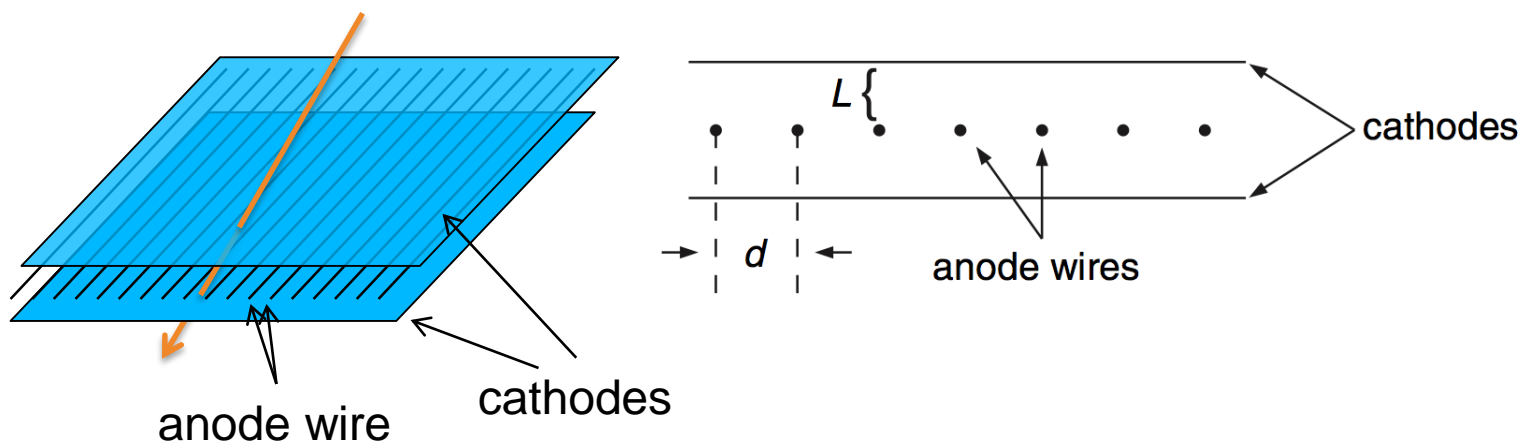


ELECTRIC FIELD AND POTENTIAL:

$$E(r) = \frac{CV_0}{2\pi\epsilon_0} \frac{1}{r}$$

$$V(r) = \frac{CV_0}{2\pi\epsilon_0} \ln \frac{r}{a}$$

$$C = \frac{2\pi\epsilon_0}{\ln(b/a)} \quad \text{capacitance per unit length}$$



EN COMPARAISON DES CHAMBRES À ÉTINCELLES ET DES CHAMBRES À BULLES, LES CHAMBRES À FILS SONT PLUS RAPIDES, PRÉSENTENT DE MEILLEURES RÉOLUTIONS SPATIALE ET TEMPORELLE, SANS TEMPS MORT SIGNIFICATIF ET RÉSISTANTES AUX RADIATIONS.



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.

Georges Charpak
CERN, Geneva, Switzerland

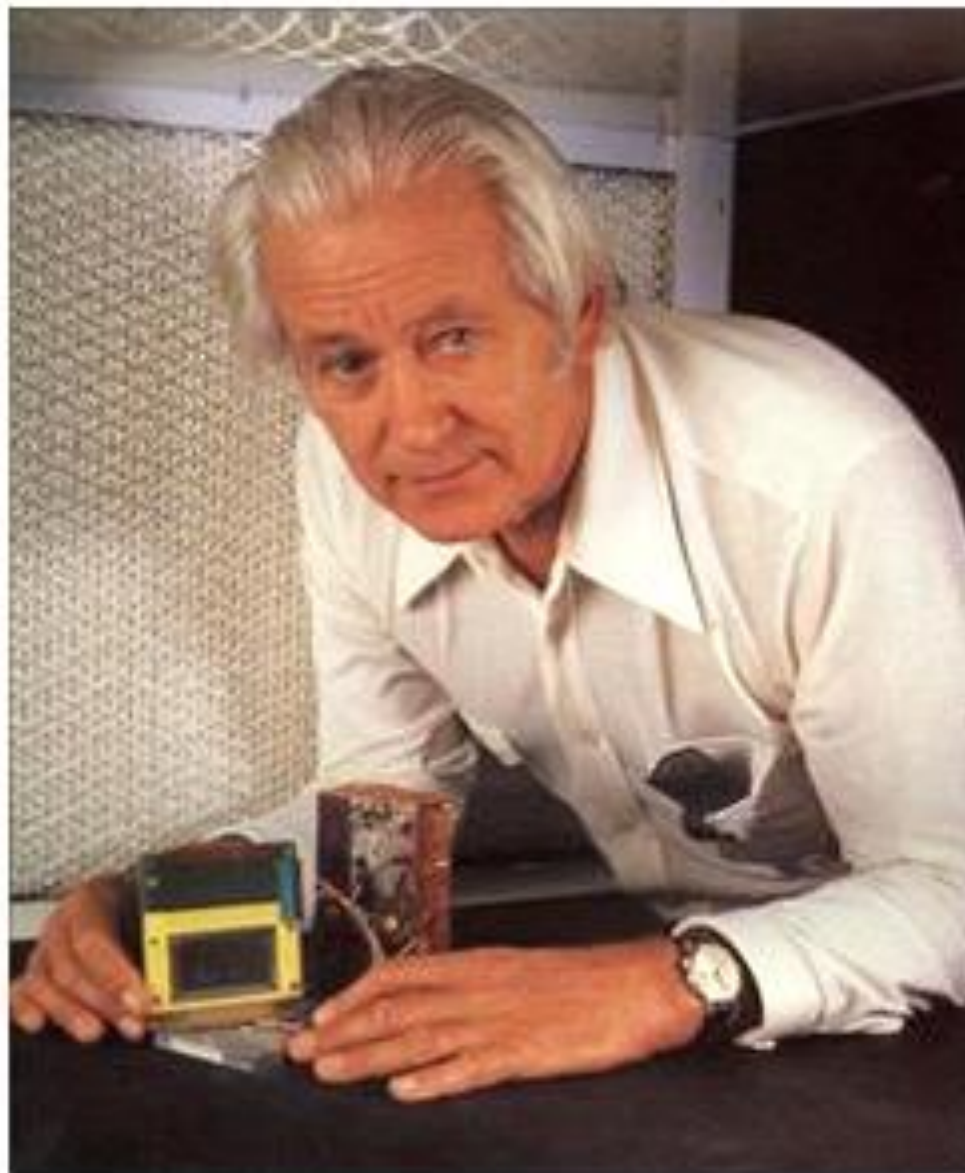
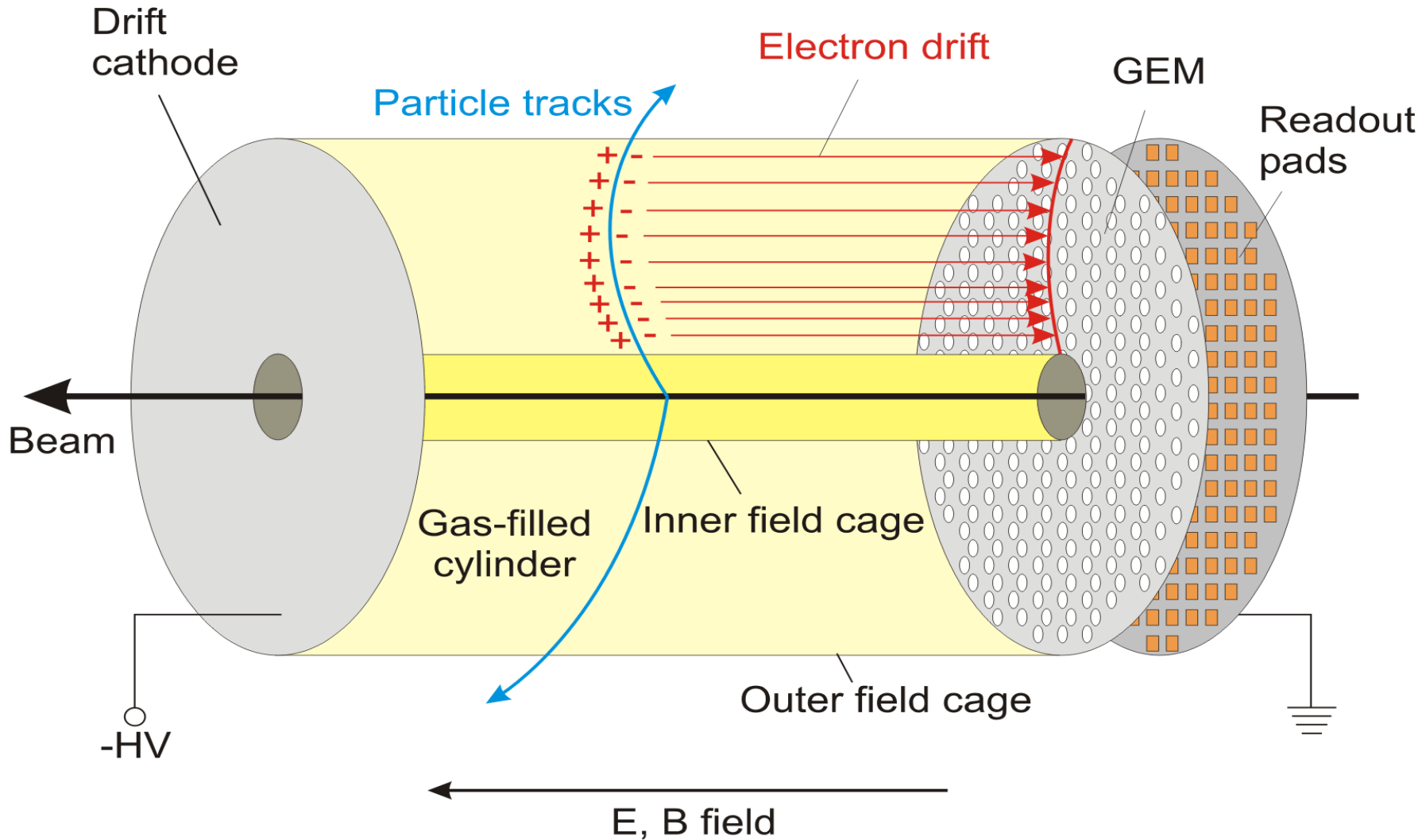
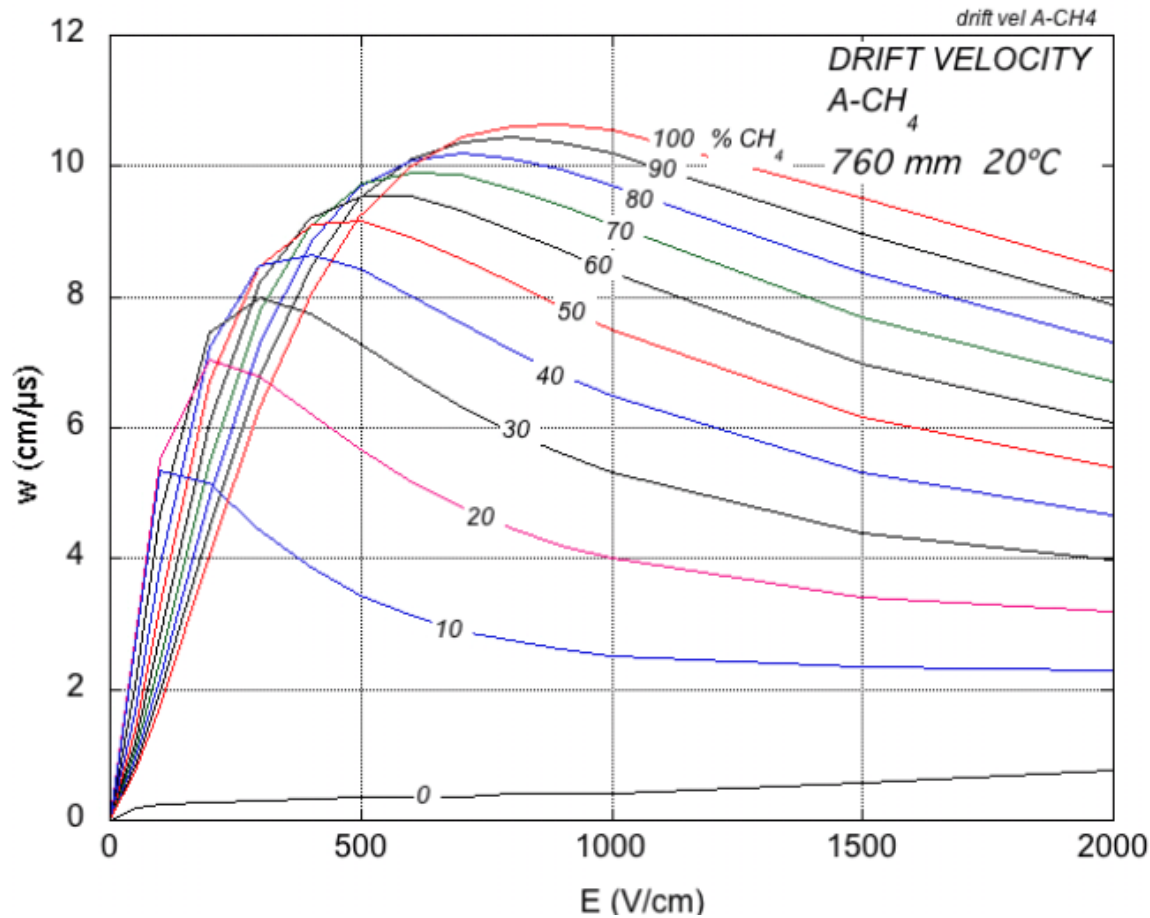


Photo: D. Parker, Science Photo Lab, UK



- 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



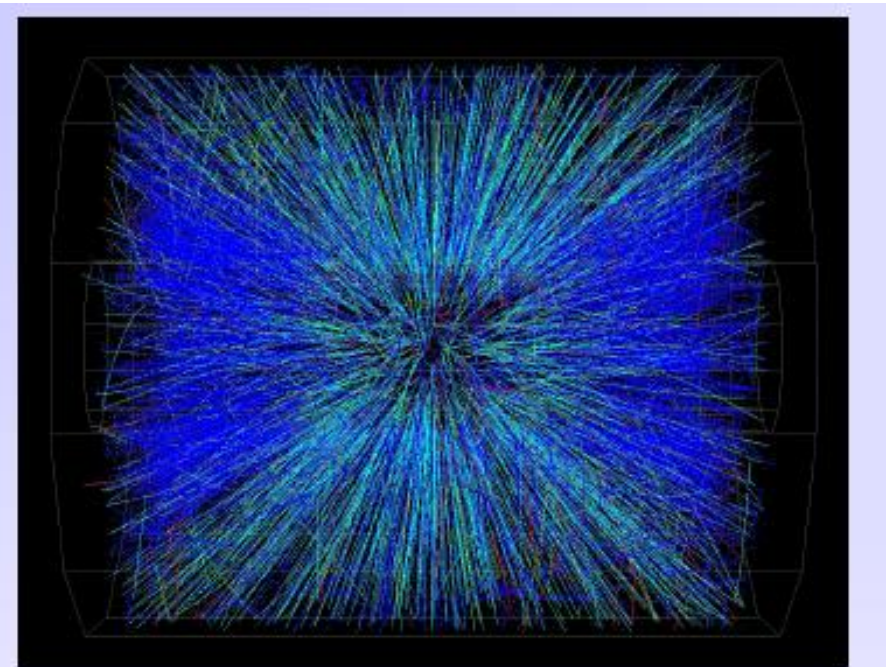
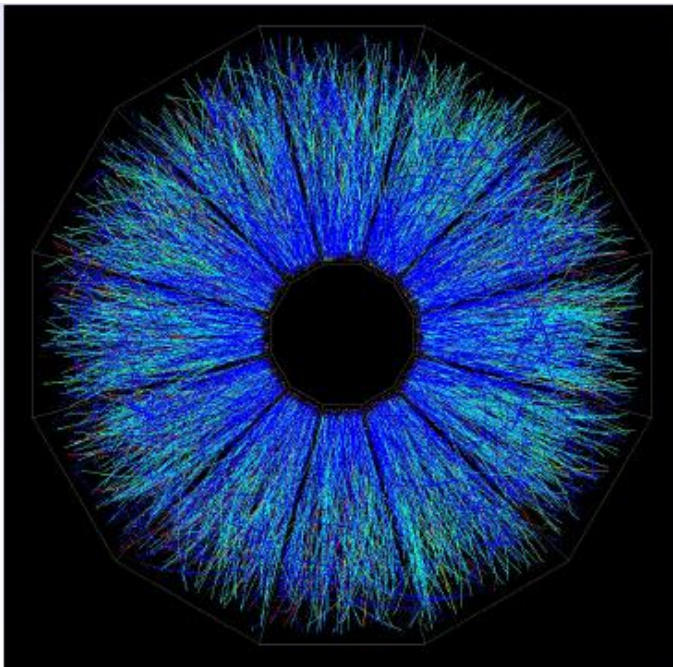


EXAMPLE: Ar-CH₄ 90-10 , $E=1\text{kVcm}^{-1}$ $w = 2.5 \text{ cm } \mu\text{s}^{-1}$

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

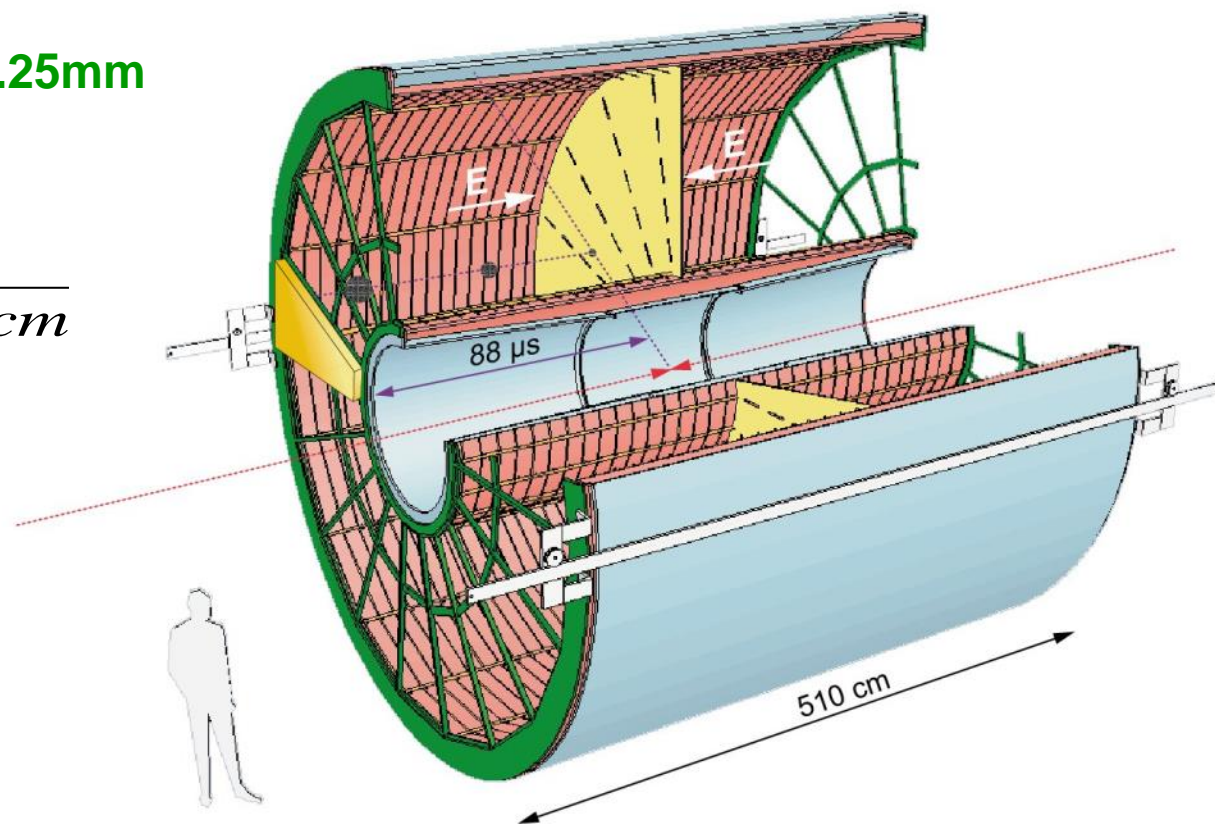
Typically around 200 tracks per event.

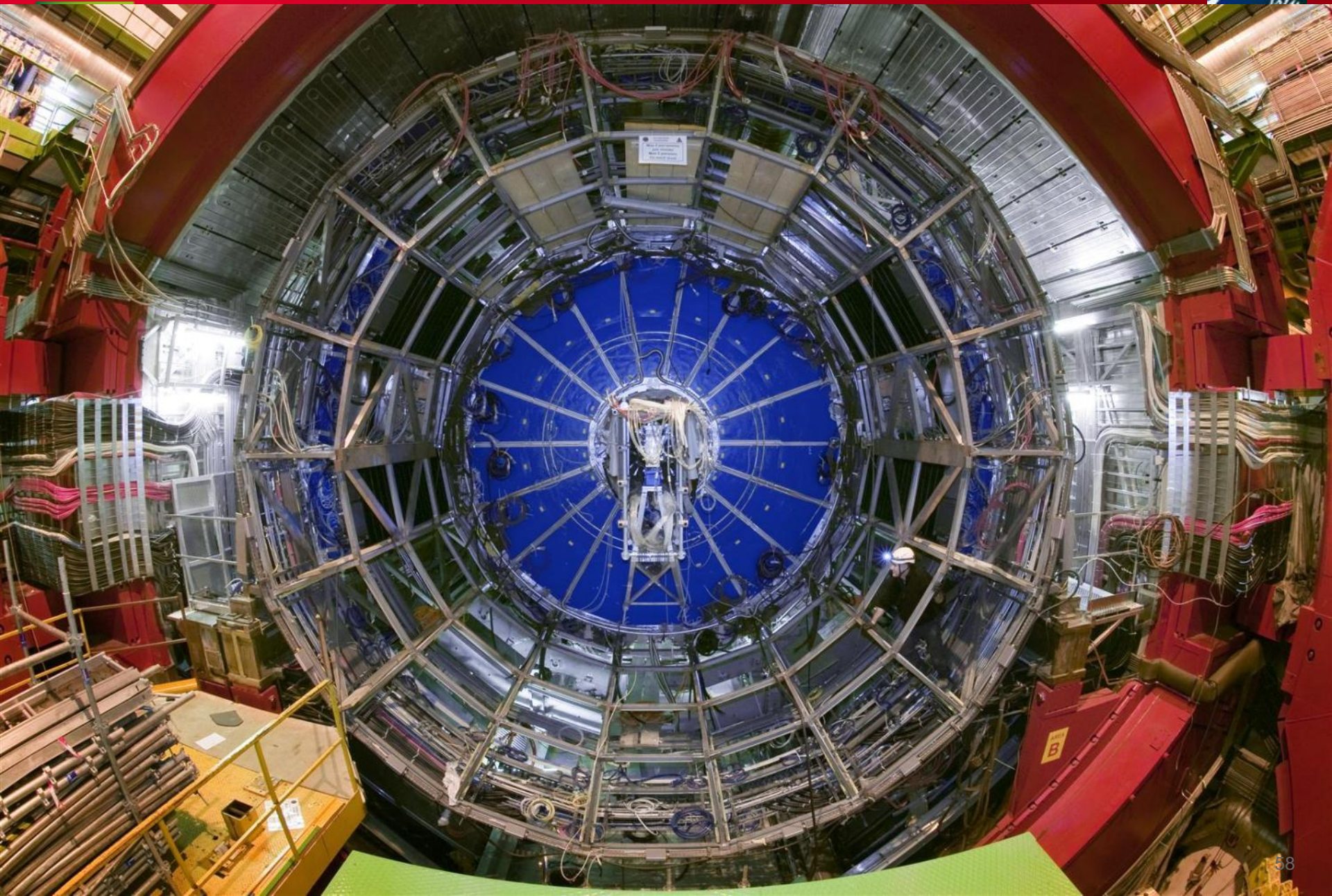
Great advantage of a TPC: The only material that is in the way of the particles is gas → very low multiple scattering → very good momentum resolution down to low momenta !

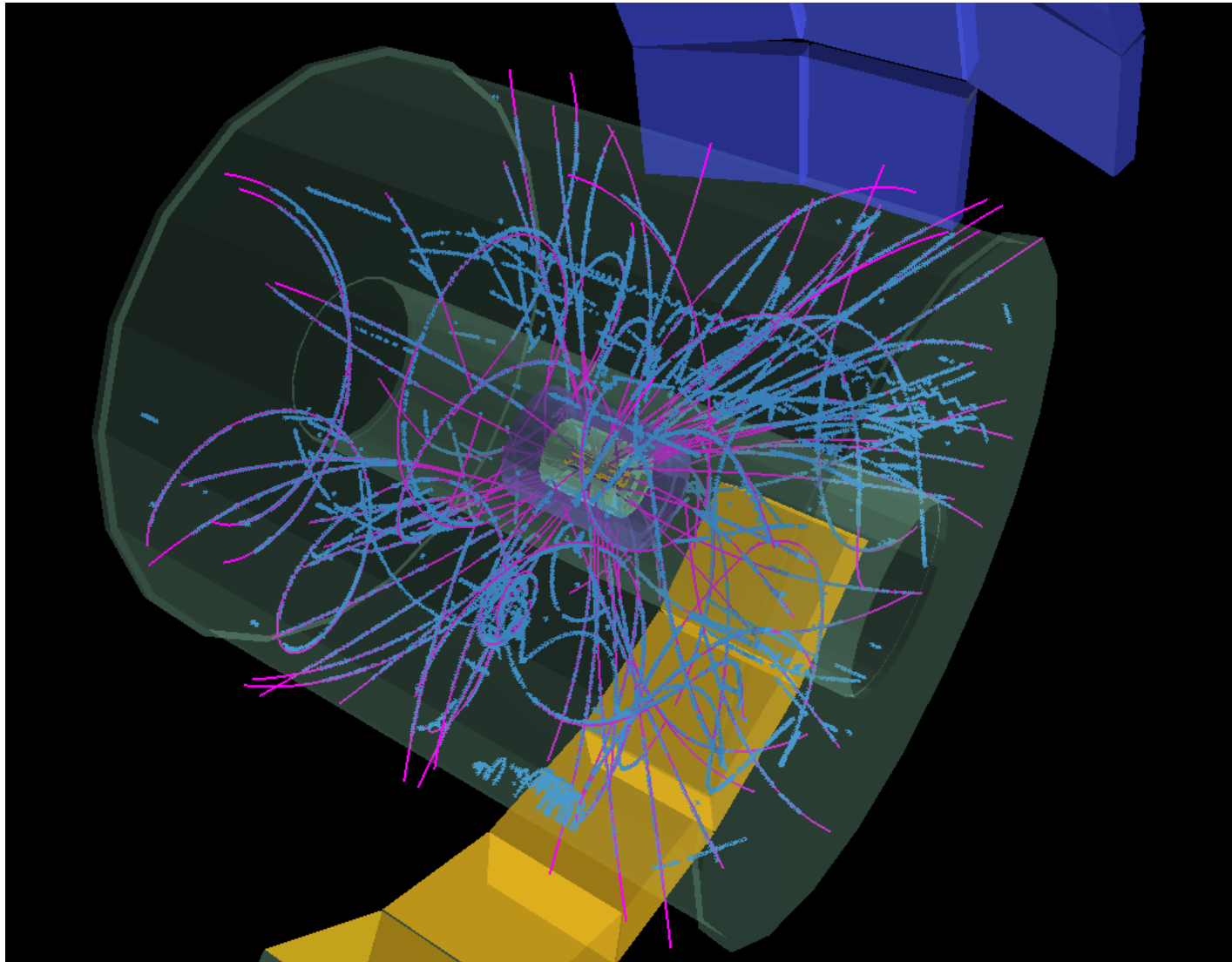


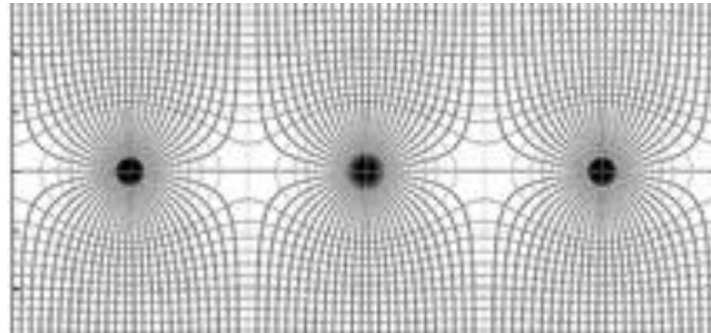
- Gas Ne/ CO₂ 90/10%
- Field 400V/cm
- Gas gain >10⁴
- Position resolution $\sigma = 0.25\text{mm}$
- Diffusion: $\sigma_t = 250\mu\text{m}$
- Pads inside: 4x7.5mm
- Pads outside: 6x15mm
- B-field: 0.5T
- Largest TPC:
 - Length 5m
 - Diameter 5m
 - Volume 88m³
 - Detector area 32m²
 - Channels ~570 000
- High Voltage:
 - Cathode -100kV

$\sqrt{\text{cm}}$

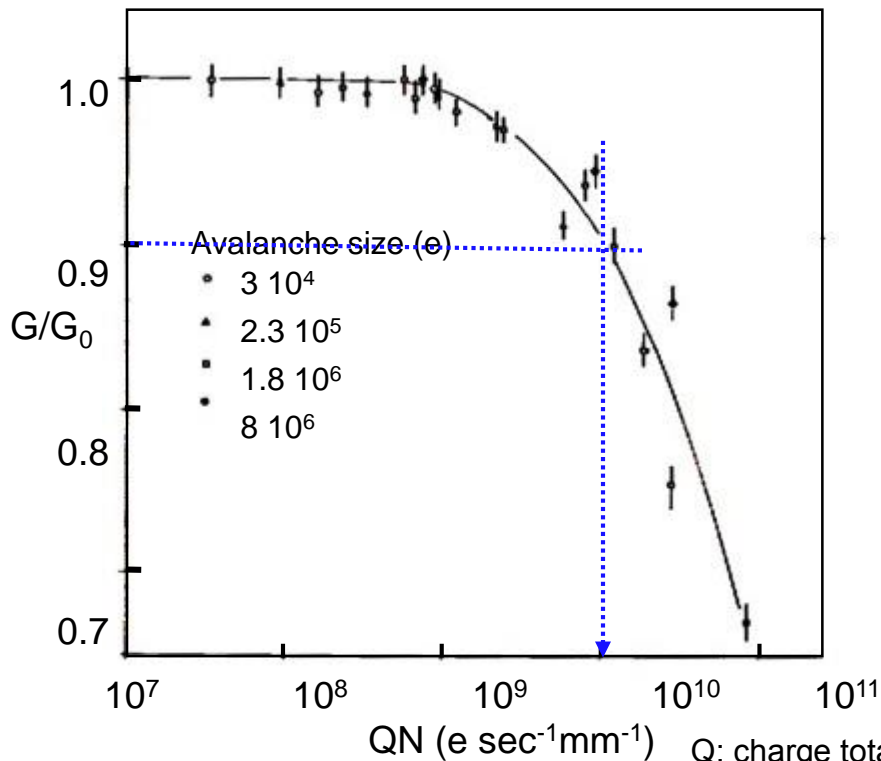




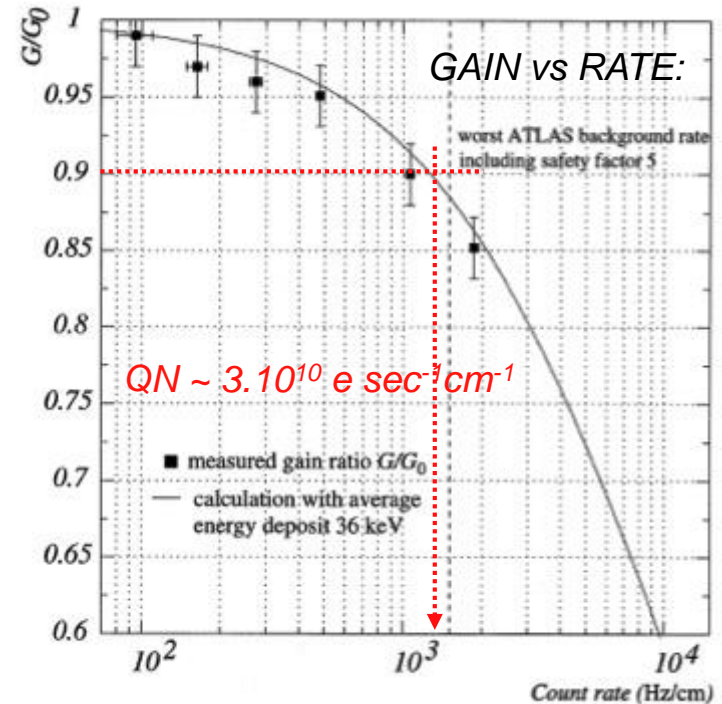




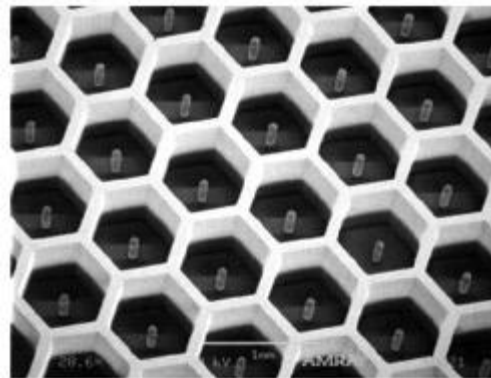
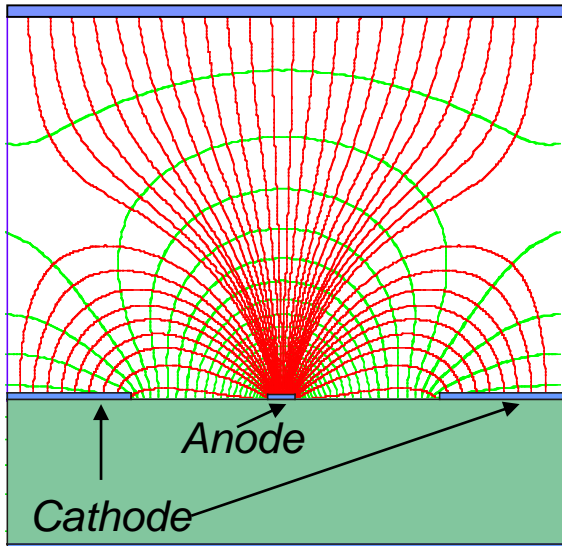
DRIFT CHAMBERS (1980):



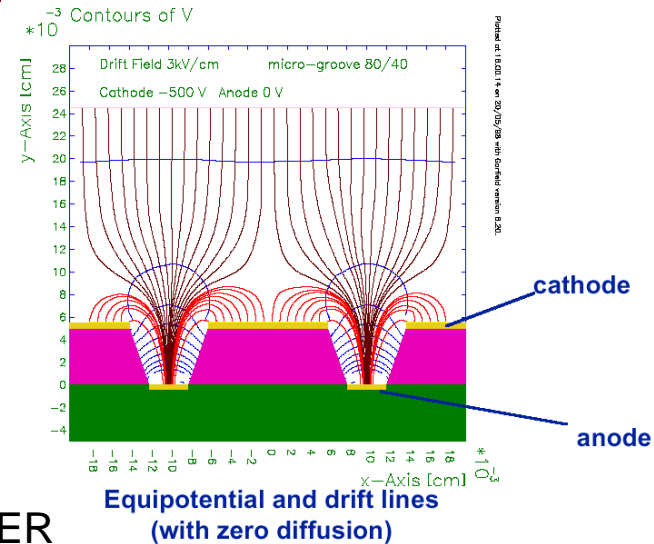
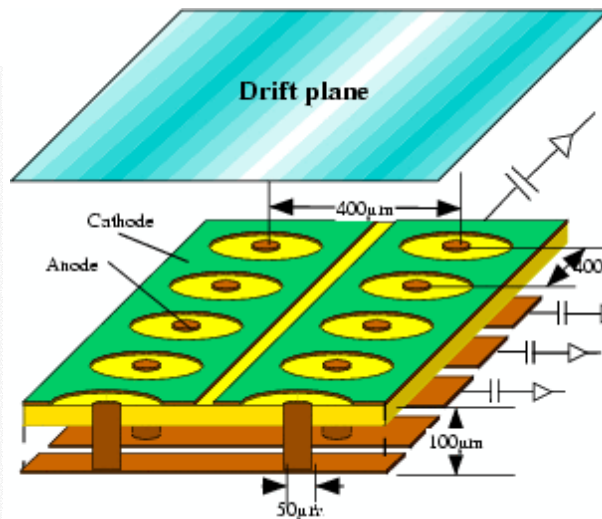
ATLAS MONITORED DRIFT TUBES (2000):



Électrode de dérivation MICRO-PIN ARRAY (MIPA)

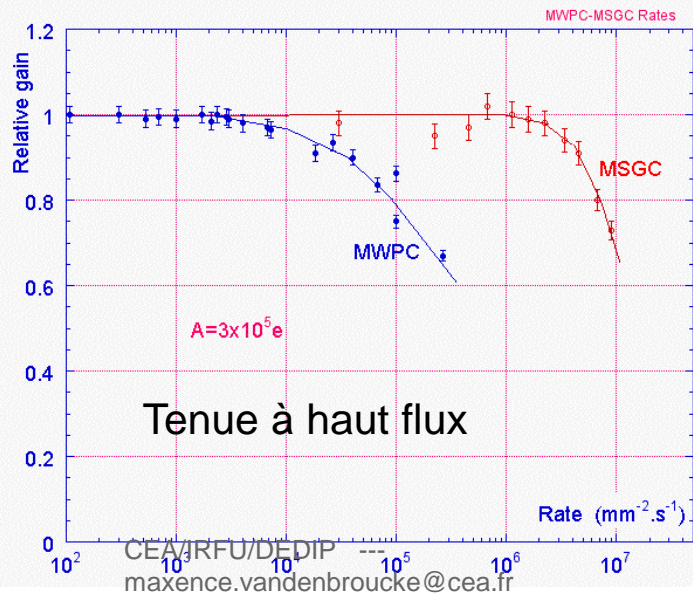
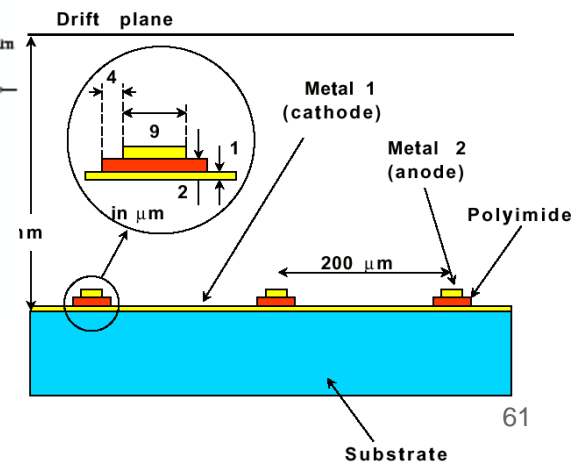


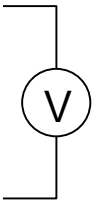
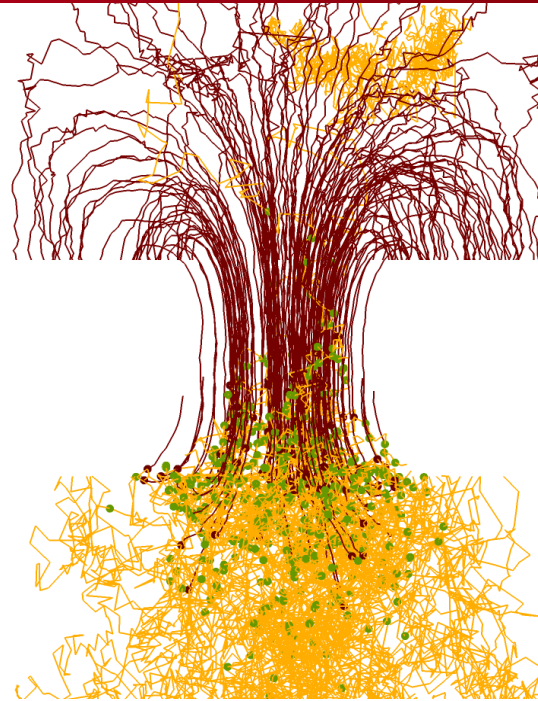
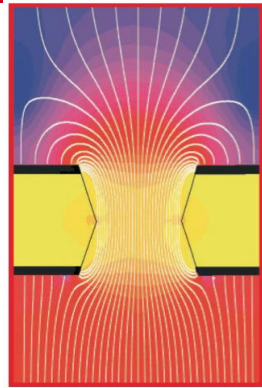
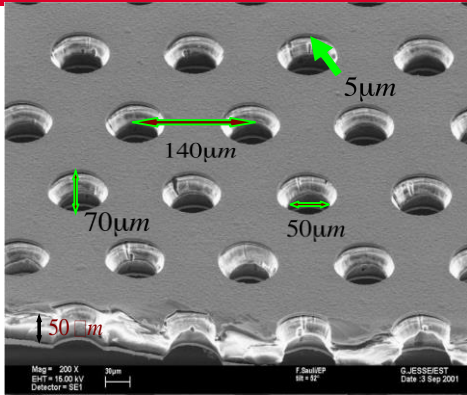
MICRO-PIXEL CHAMBER



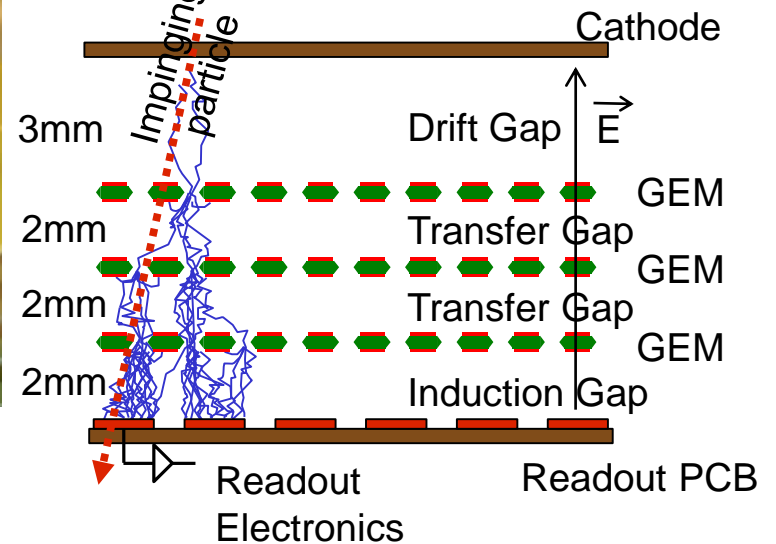
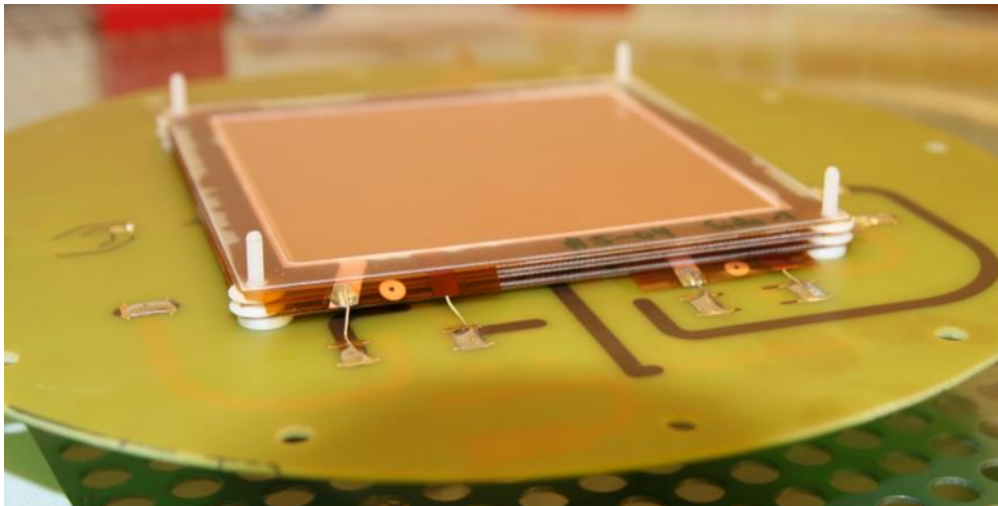
Equipotential and drift lines (with zero diffusion)

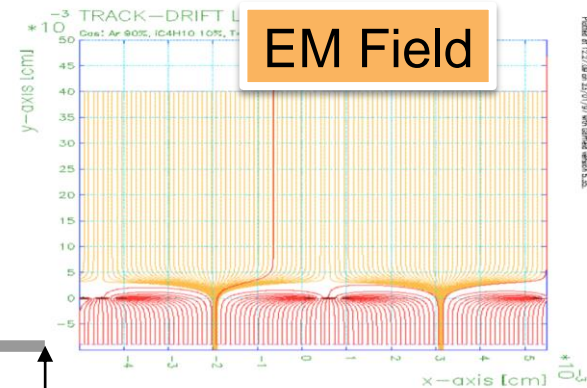
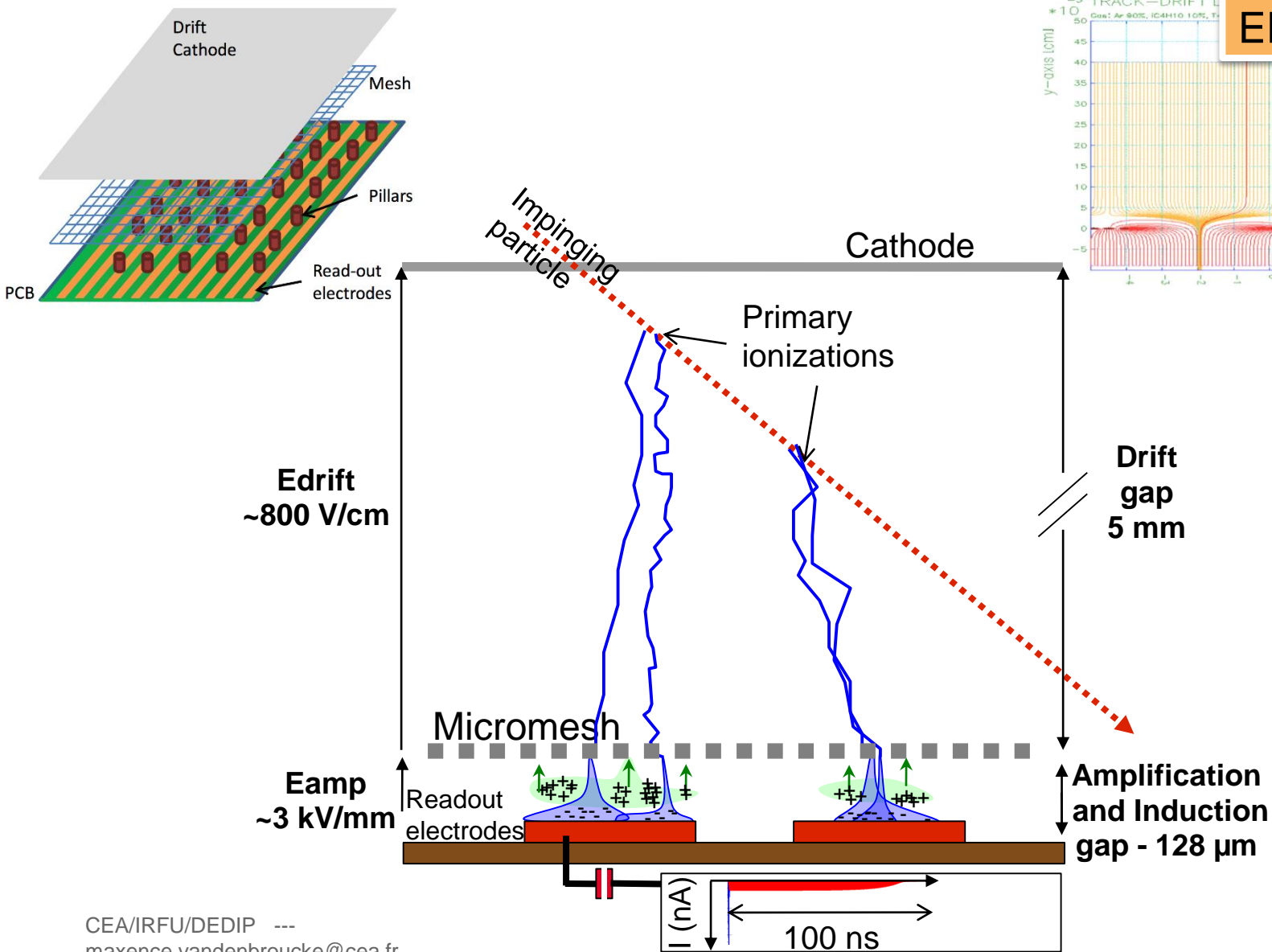
MICRO-GAP CHAMBER





$\Delta V \sim 360V$

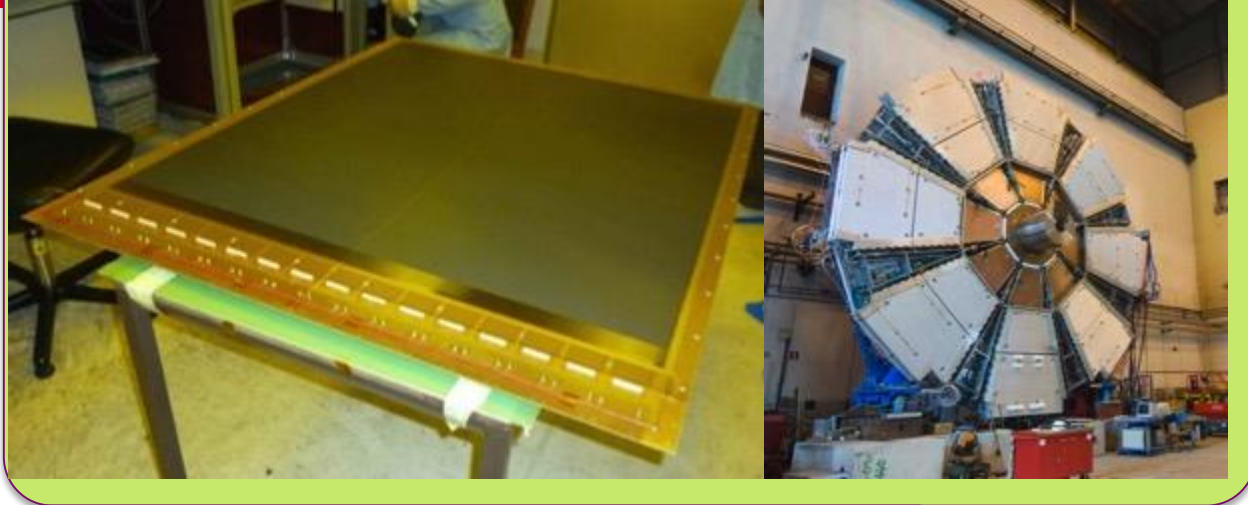




APPLICATIONS EN PHYSIQUE...



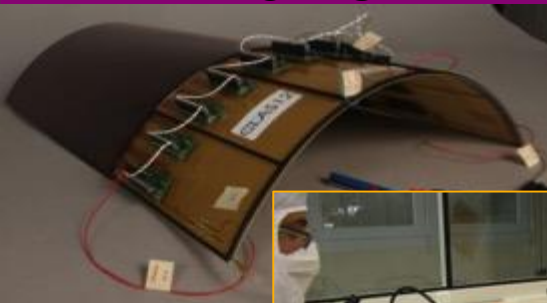
Grands détecteurs pour le système à muons d'ATLAS/HL-LHC



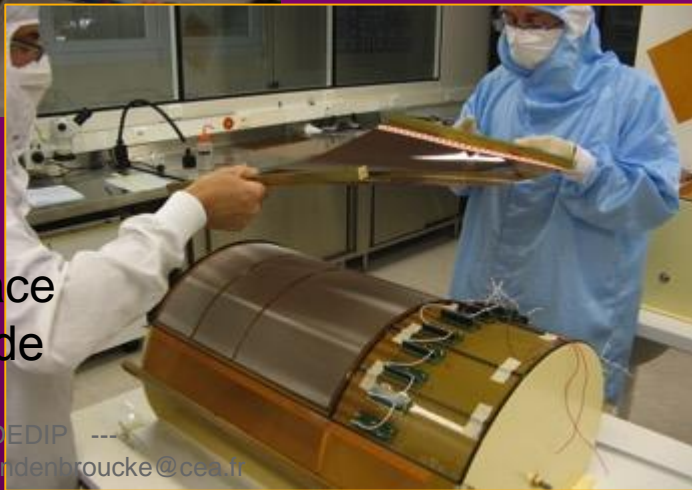
TPC pour l'ILC



CLAS 12

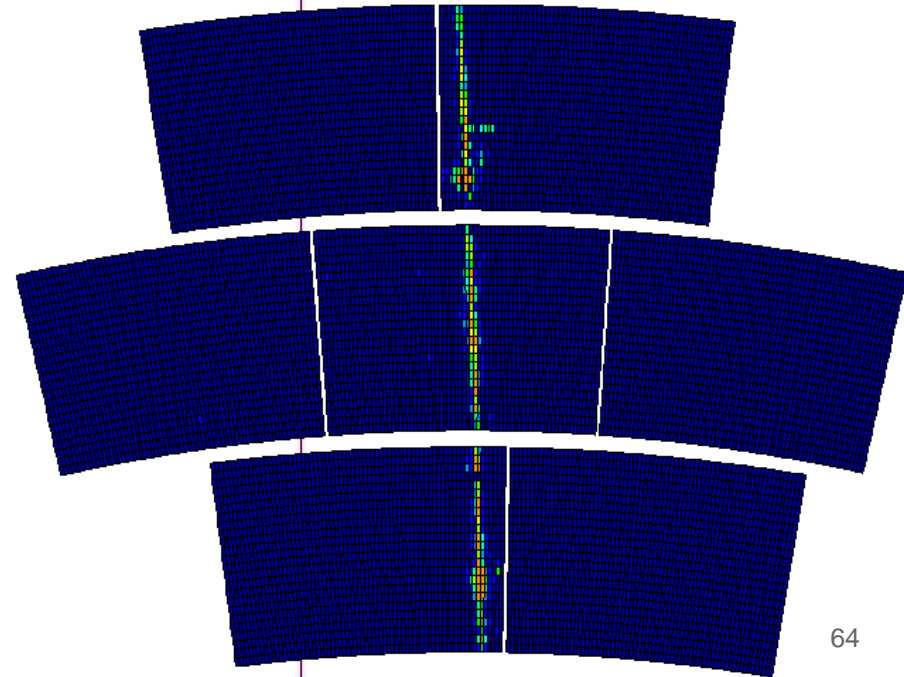


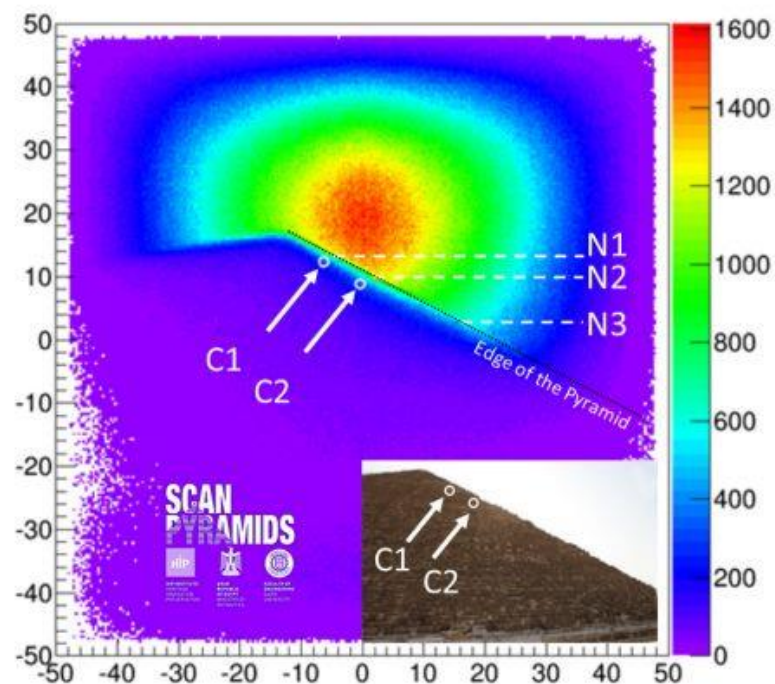
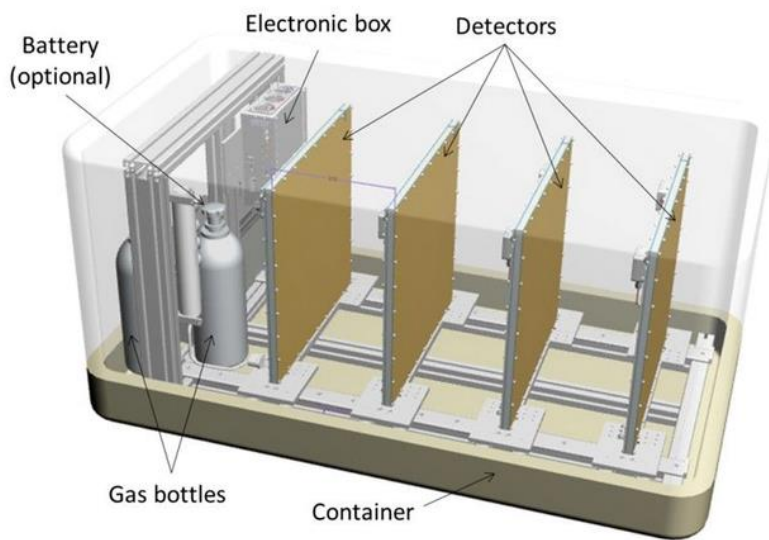
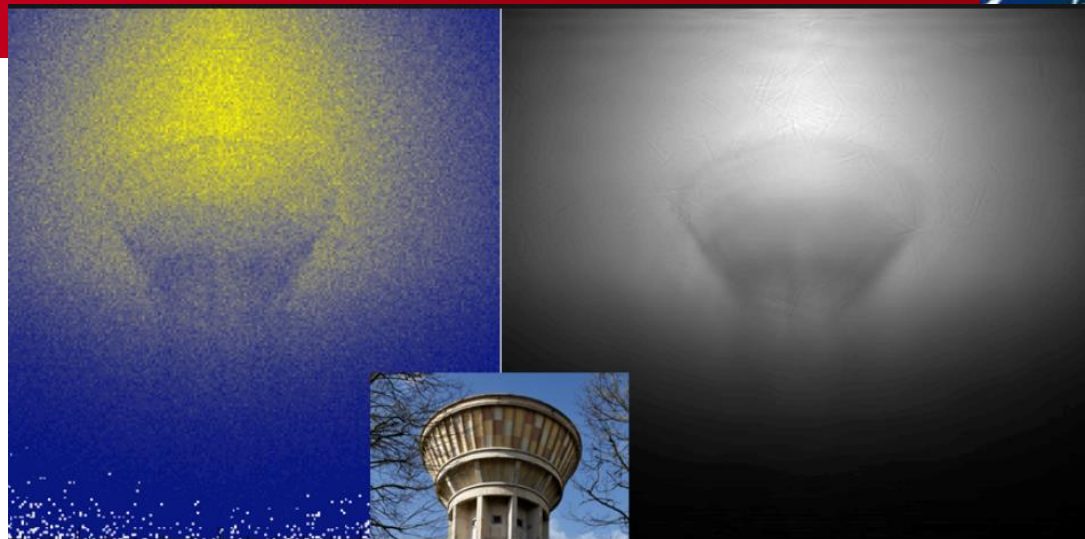
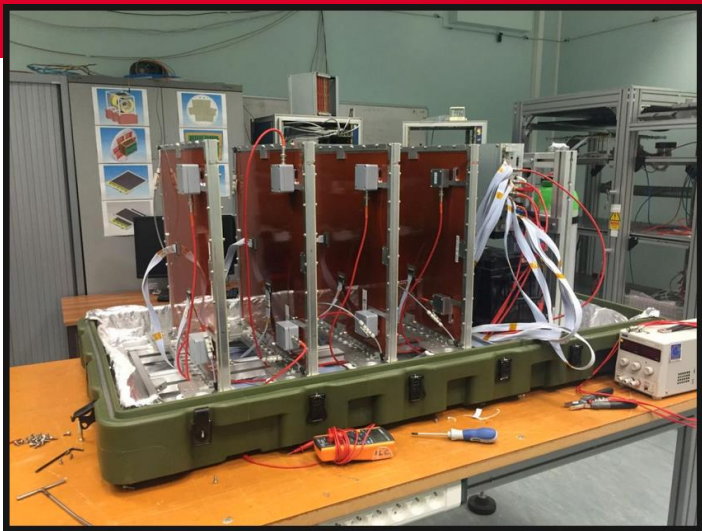
Tuile pour le trajectographe cylindrique



Mise en place de l'électrode de dérive

CEA/IRFU/DEDIP
maxence.vanderbroucke@cea.fr





Mesurer l'infiniment petit et observer l'infiniment grand

DE LA RECHERCHE À L'INDUSTRIE

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Promotion Chien-Shiung Wu
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GRAND
à L'INFINIMENT
petit

VISITES DE LABOS, CONFÉRENCES, DÉBATS

Niveau L3

Comprendre l'infiniment petit
Les noyaux et leurs interactions
Des particules aux étoiles jusqu'au cosmos
Mesurer l'infiniment petit, observer l'infiniment grand
Applications médicales
Maîtriser l'énergie
Enregistrer, analyser, découvrir

CONTACT : SECRETARIAT-INFINIS@IN2P3.FR
WWW.IN2P3.FR/SEVENT/RENCONTRES-PHYSIQUE-INFINIS



Stages : <http://irfu.cea.fr/Phoceastages/index.php>

Maxence Vandembroucke

07/2018

université
PARIS-SACLAY

Cours 1 : Généralités

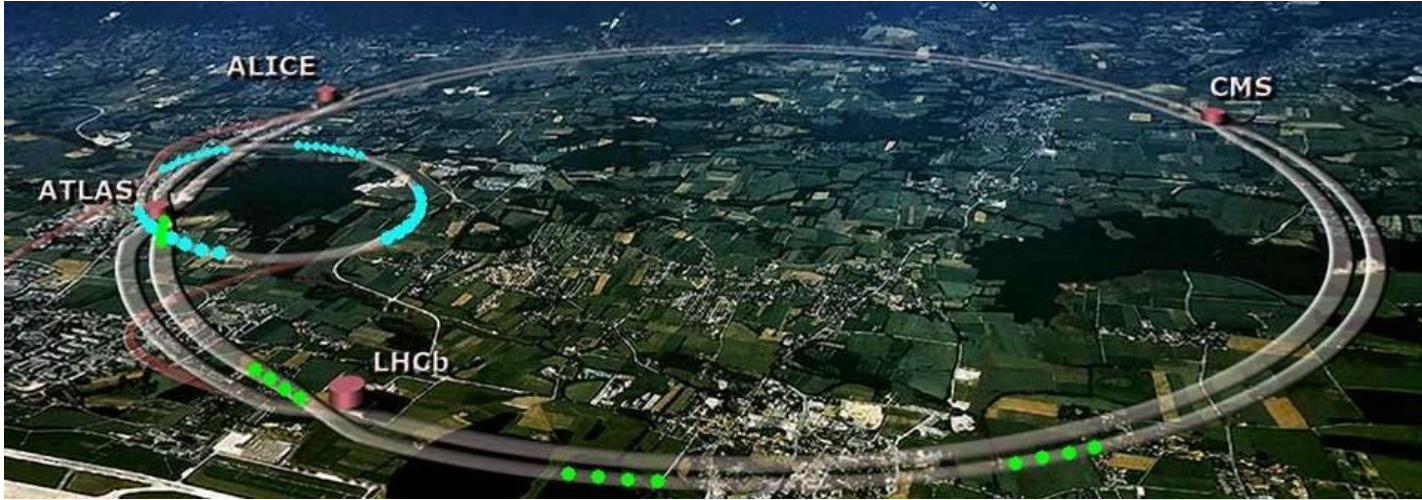
- Introduction générale sur l'importance de la mesure
- Qu'est-ce qu'une expérience de physique subatomique ?
- Que veut-on observer à propos d'une particule?
- Architecture générale d'une expérience en physique subatomique

Cours 2 : Les détecteurs de particules

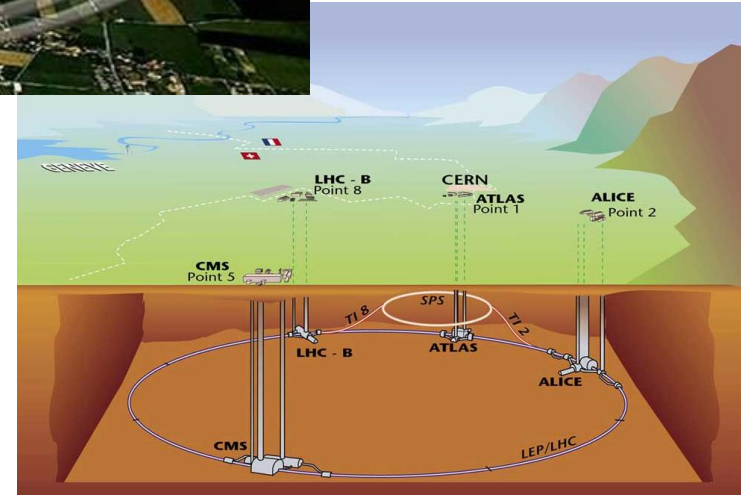
- Trajectographie :
 - Détecteurs Gazeux
 - Détecteurs au Silicium
- Calorimétrie
- Scintillation

Cours 3 : Exemple d'expériences

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



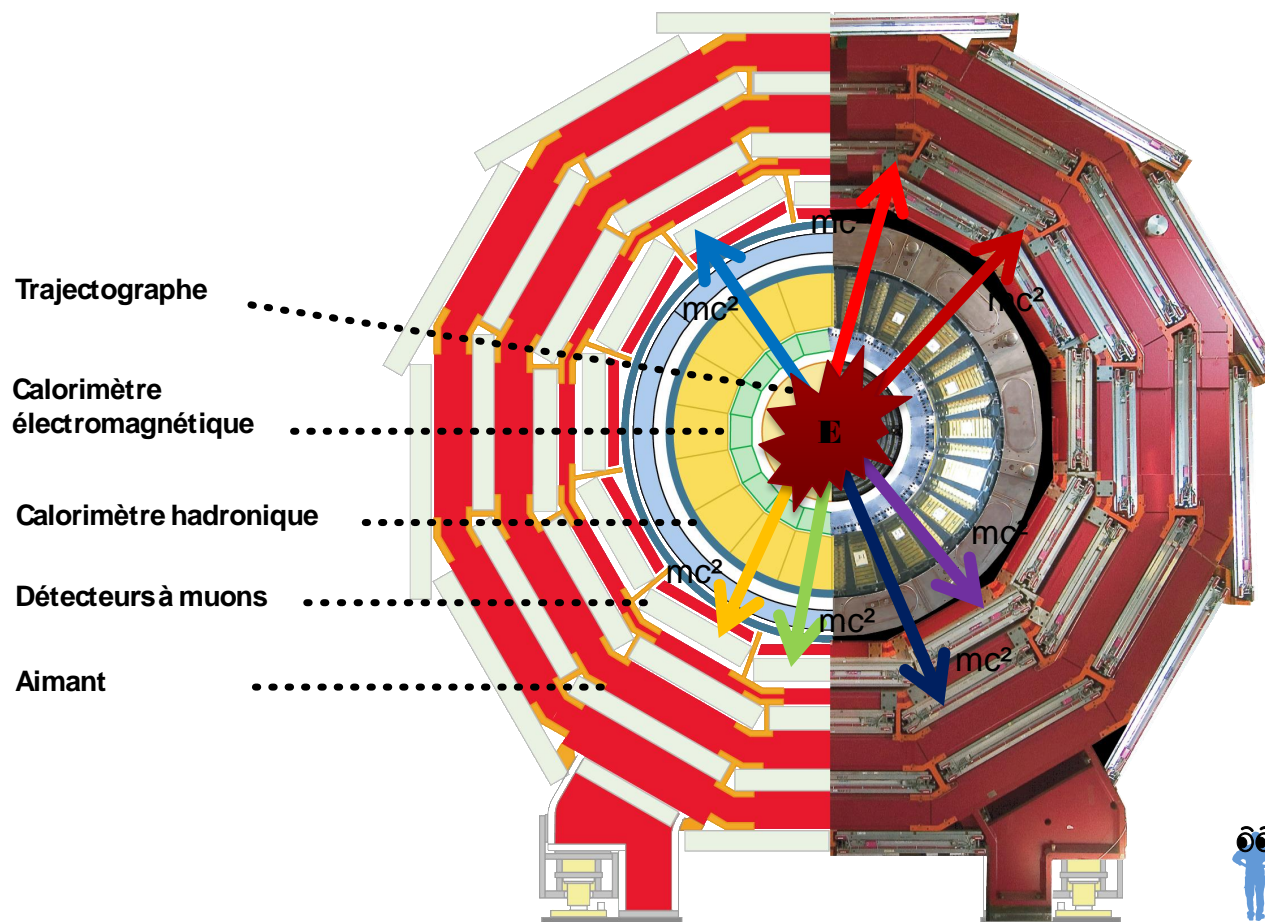
27 km
8.3 T
10⁻¹³ atm
1.9 K (-271.3 °C)
362 MJ

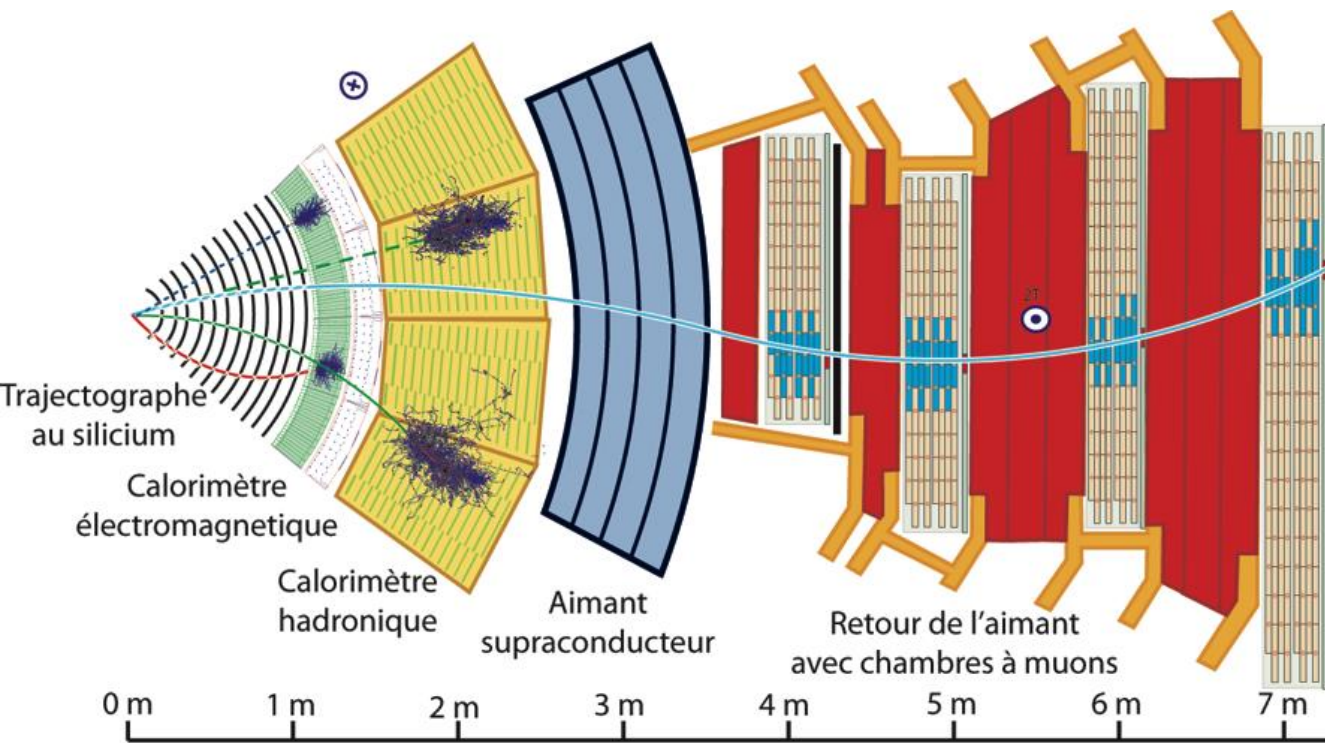


The LHC accelerator

Compact Muon Solenoid

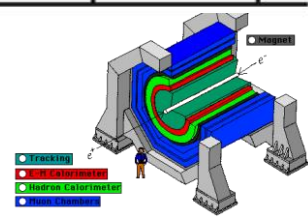






légende :

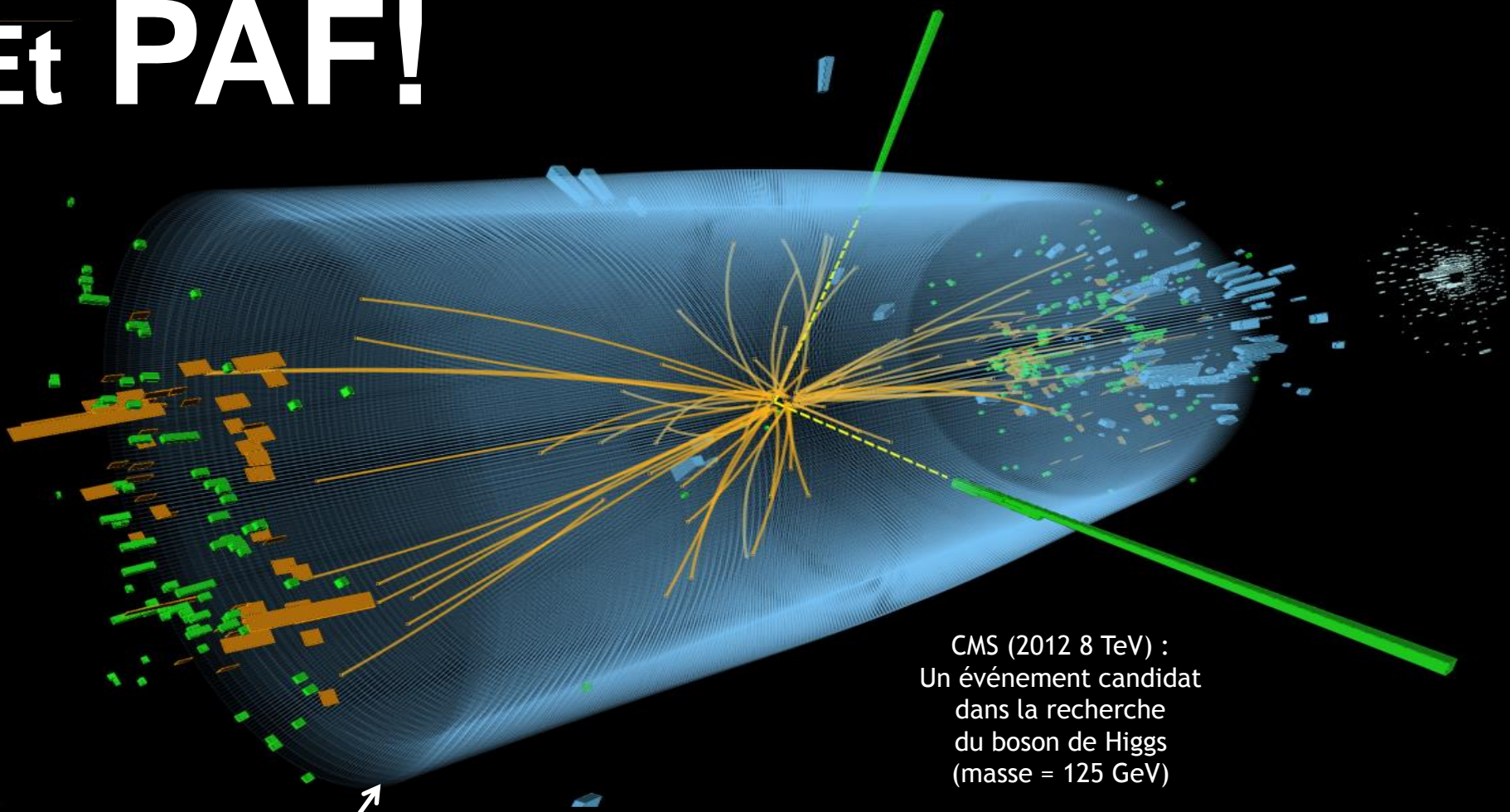
- Muon
- Électron
- Hadron chargé
- - - Hadron neutre
- - - Photon



	mass →	charge →	spin →					
QUARKS	≈2.3 MeV/c ²	2/3	1/2	u	≈1.275 GeV/c ²	2/3	1/2	c
				up				charm
	≈4.8 MeV/c ²	-1/3	1/2	d	≈95 MeV/c ²	-1/3	1/2	s
				down				strange
	≈173.07 GeV/c ²	2/3	1/2	t	≈4.18 GeV/c ²	-1/3	1/2	b
				top				bottom
	0	1	g	0	0	0	γ	
			gluon				photon	
	≈126 GeV/c ²	0	0	H				
			Higgs boson					
LEPTONS	0.511 MeV/c ²	-1	1/2	e	105.7 MeV/c ²	-1	1/2	μ
				electron				muon
	<2.2 eV/c ²	0	1/2	ν_e	<0.17 MeV/c ²	0	1/2	ν_μ
				electron neutrino				muon neutrino
	1.777 GeV/c ²	-1	1/2	τ	≈15.5 MeV/c ²	-1	1/2	ν_τ
				tau				tau neutrino
	81.2 GeV/c ²	0	1	Z	80.4 GeV/c ²	±1	1	W
			Z boson				W boson	

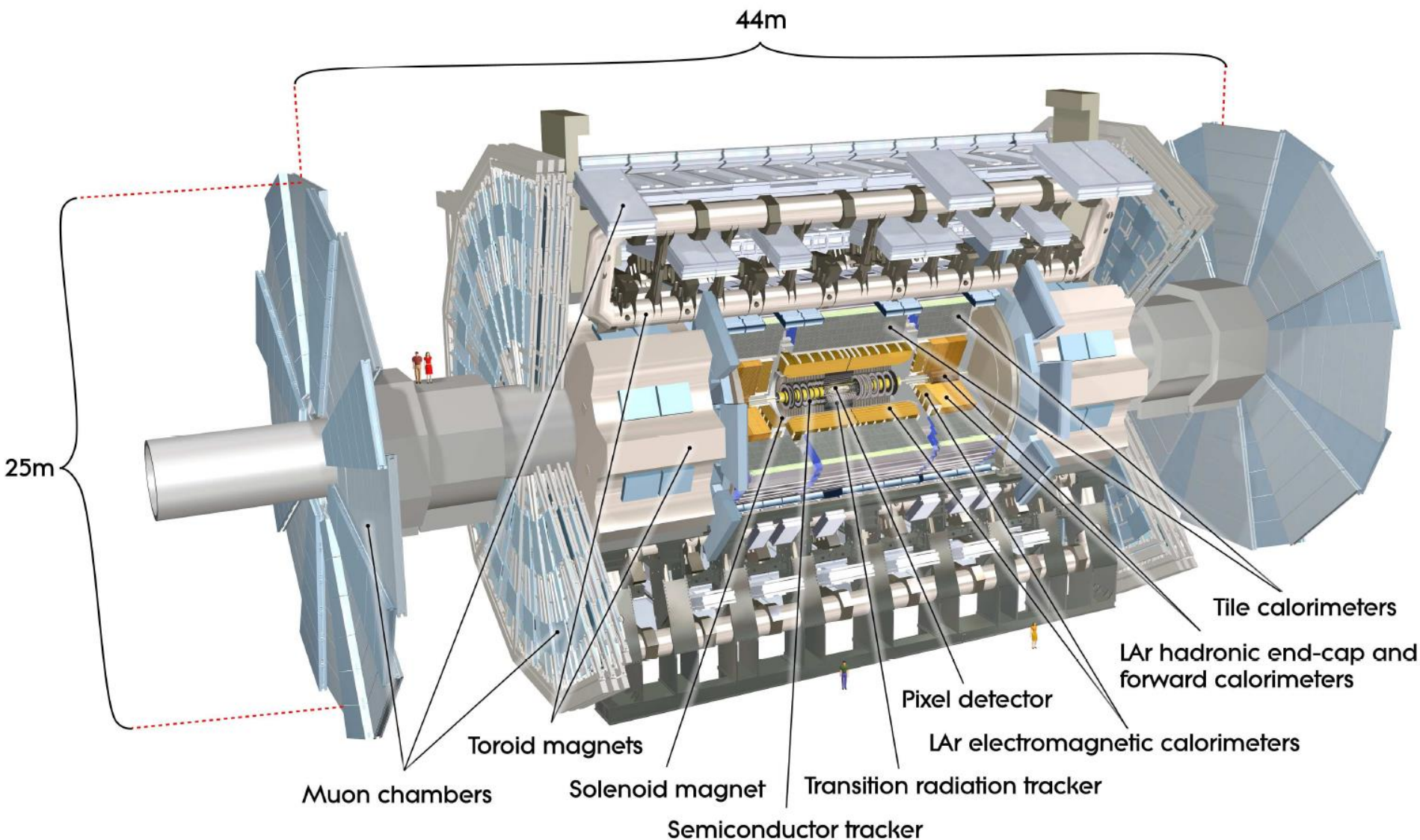
GAUGE BOSONS

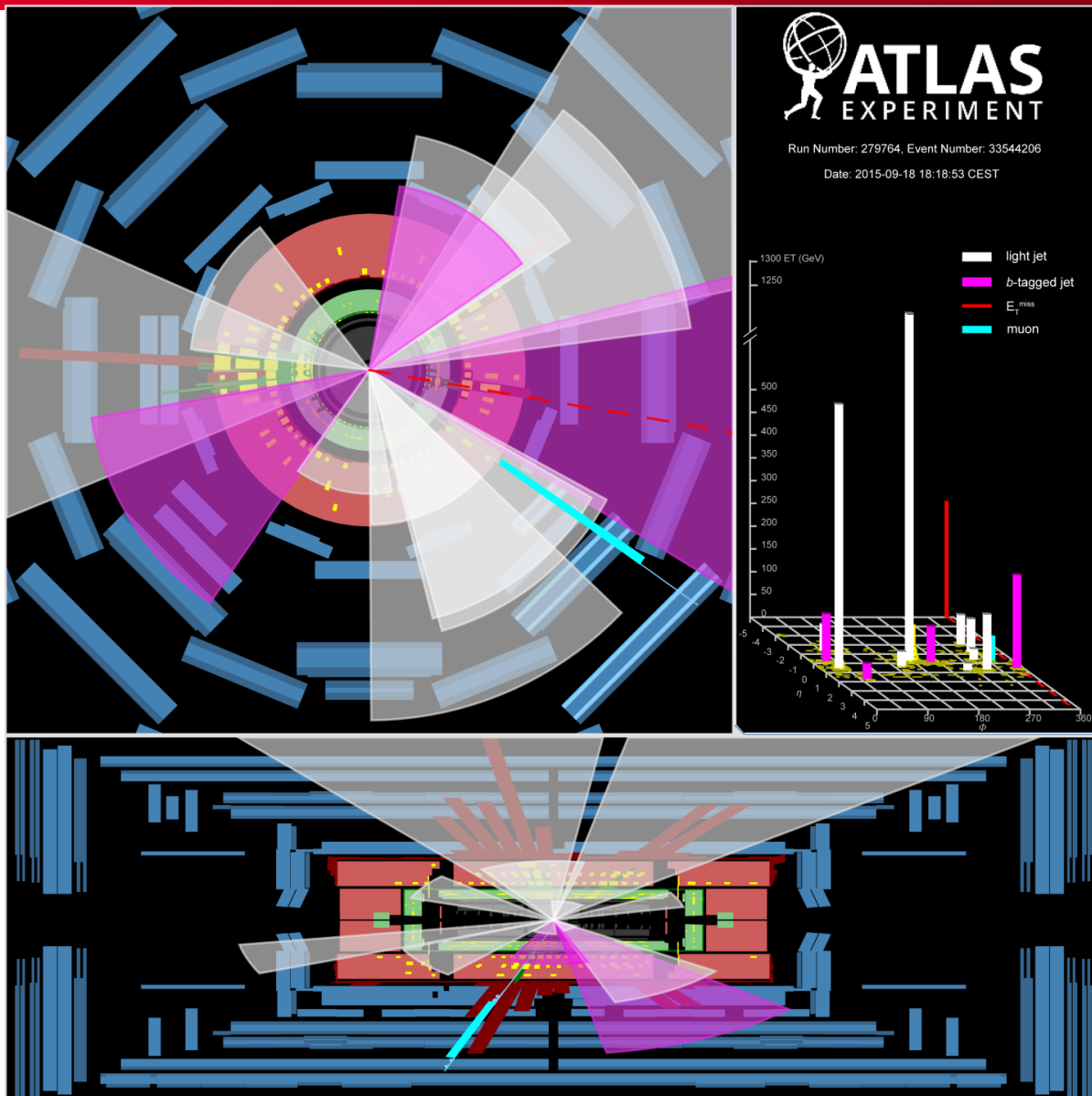
Et PAF!



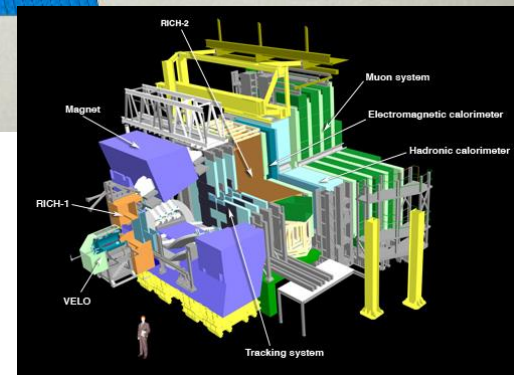
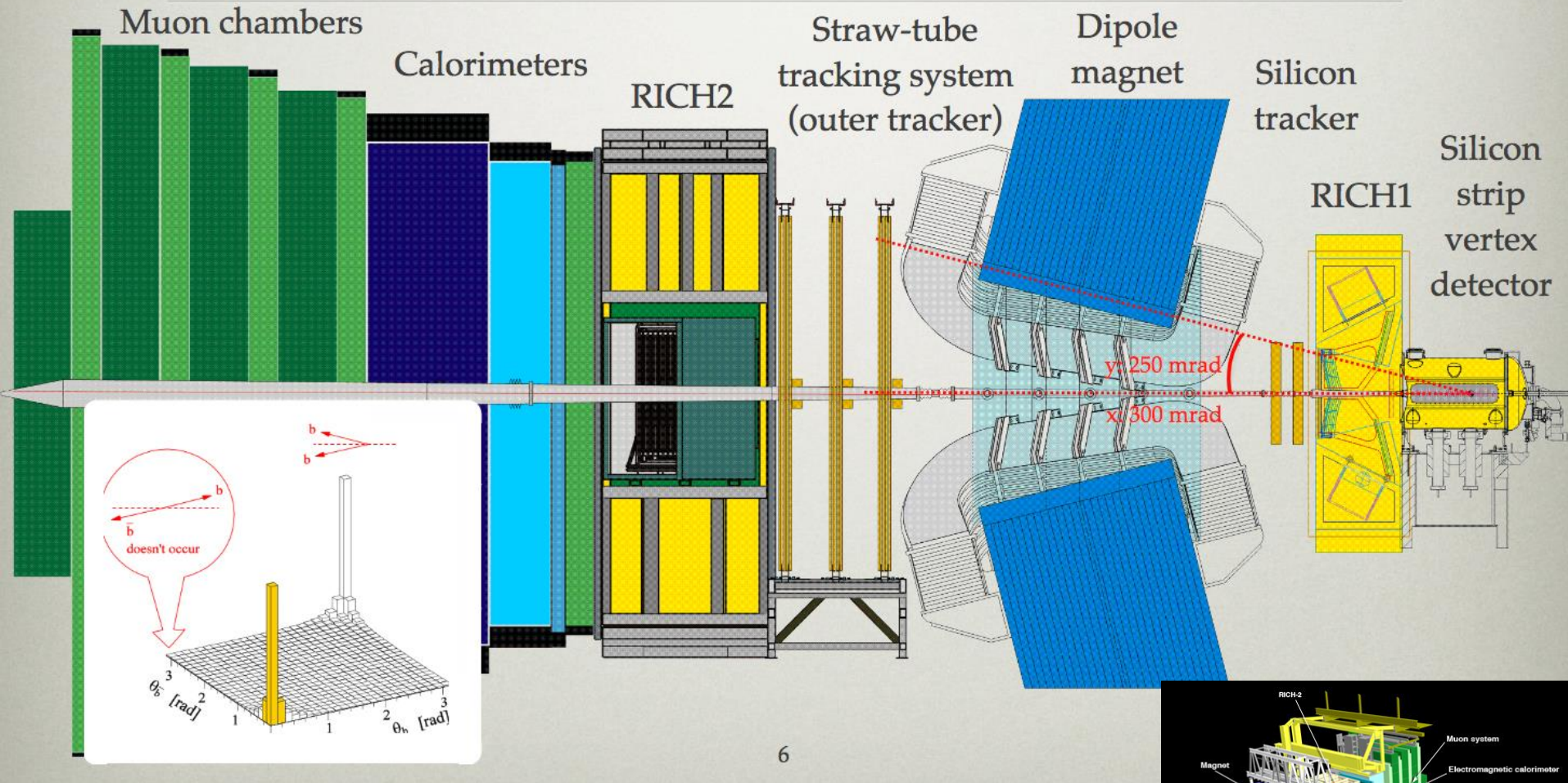
CMS (2012 8 TeV) :
Un événement candidat
dans la recherche
du boson de Higgs
(masse = 125 GeV)

Calorimètre électromagnétique





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



S

ITY

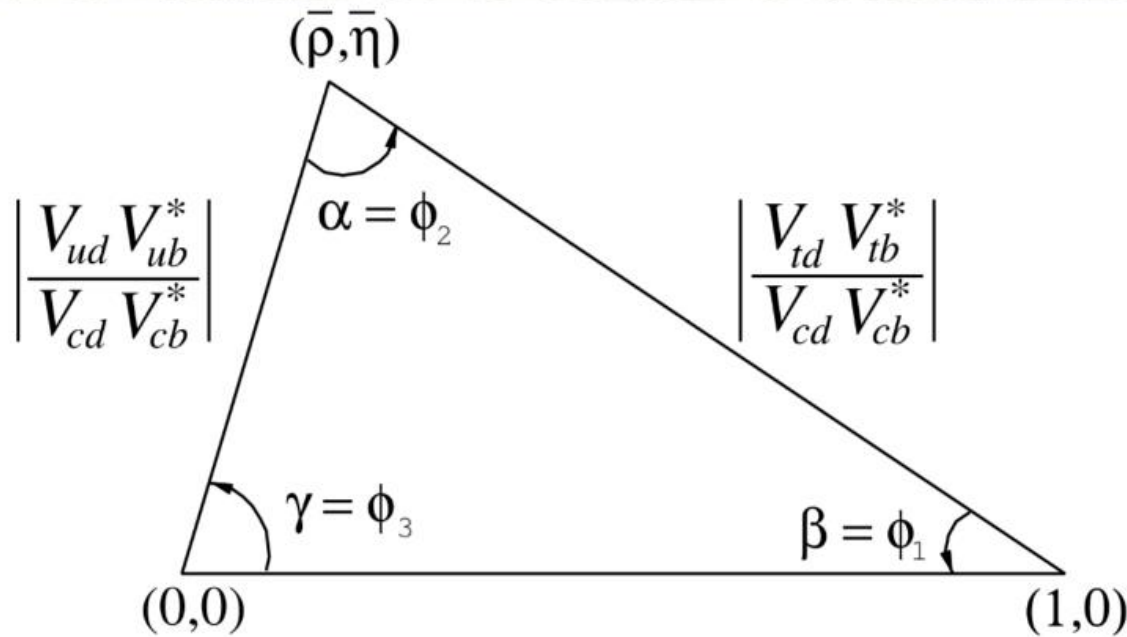


Figure 12.1: Sketch of the unitarity triangle.

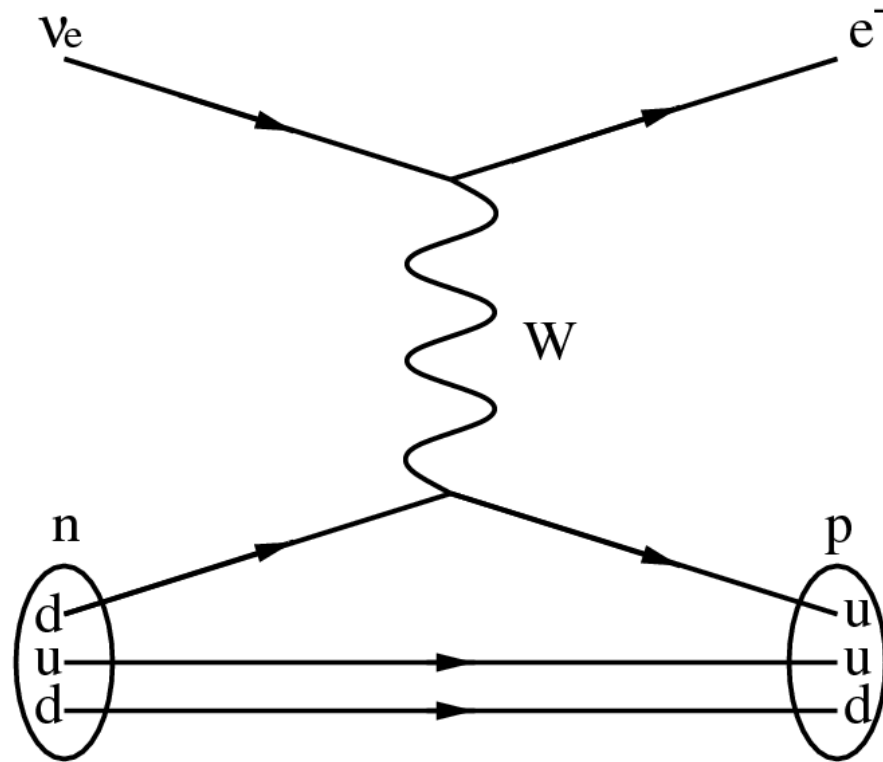
$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\bar{\rho} - i\bar{\eta}) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

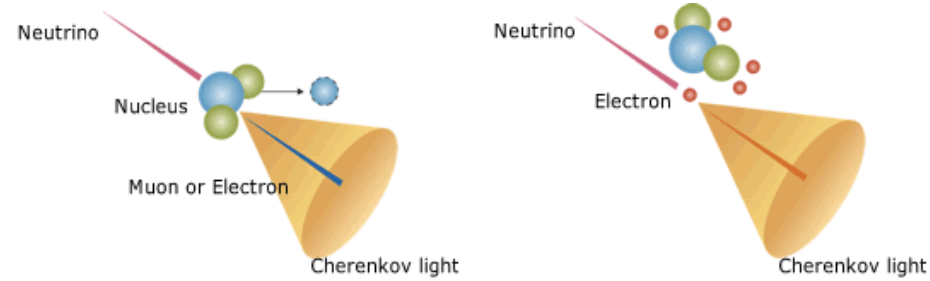
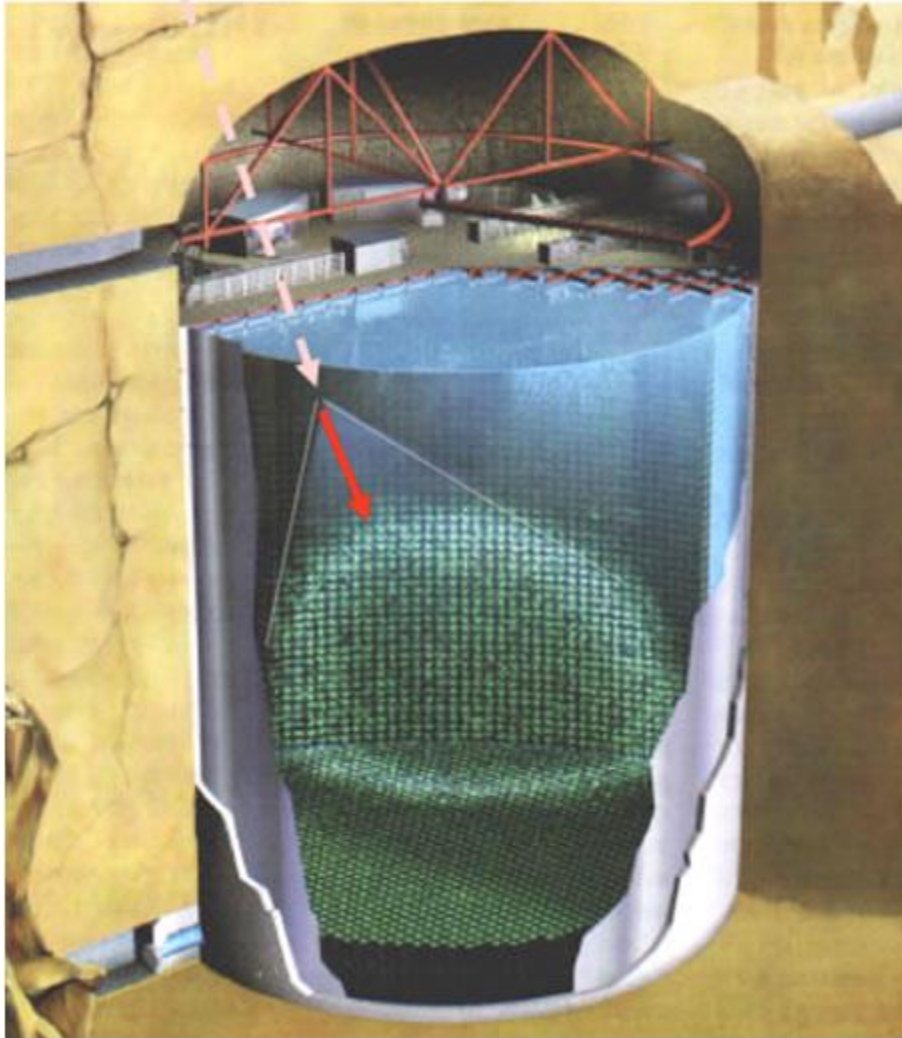
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

$$-(\bar{\rho} + i\bar{\eta}) + 1 + (-1 + \bar{\rho} + i\bar{\eta}) = 0,$$

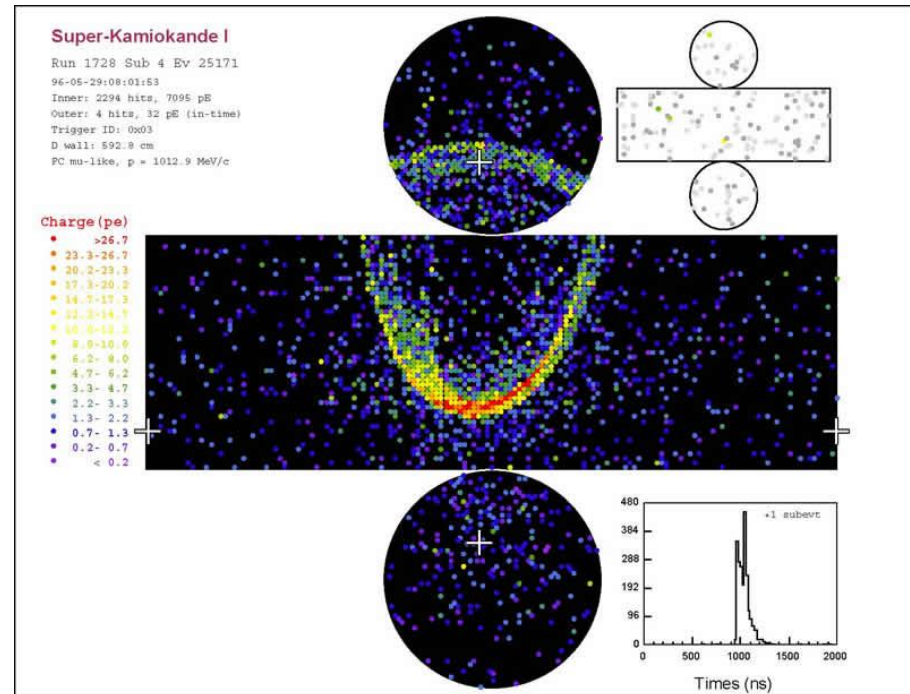
$$\bar{\rho} + i\bar{\eta} = -V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)$$

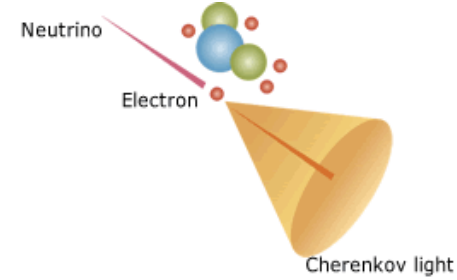
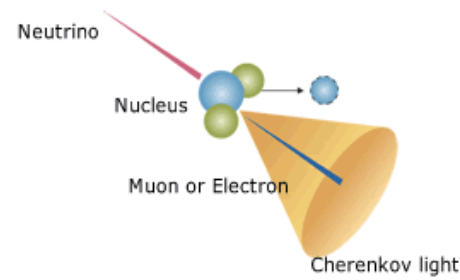
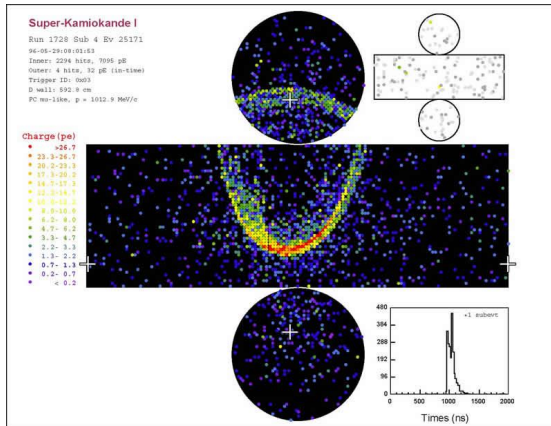


Super Kamiokande



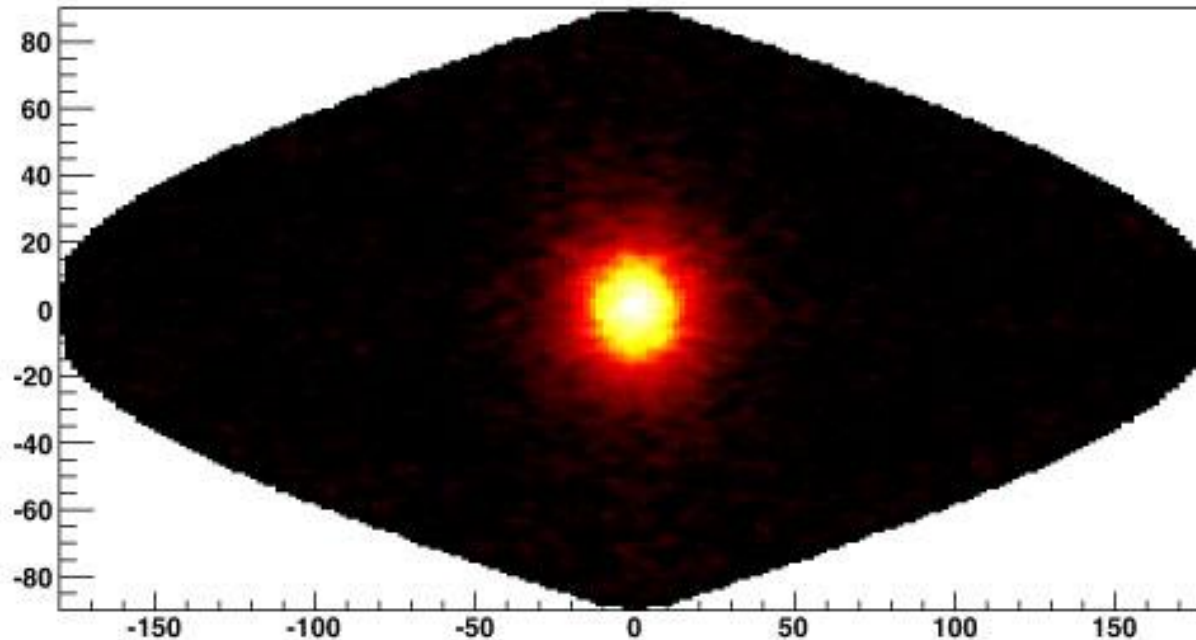
The generated charged particle emits the Cherenkov light.

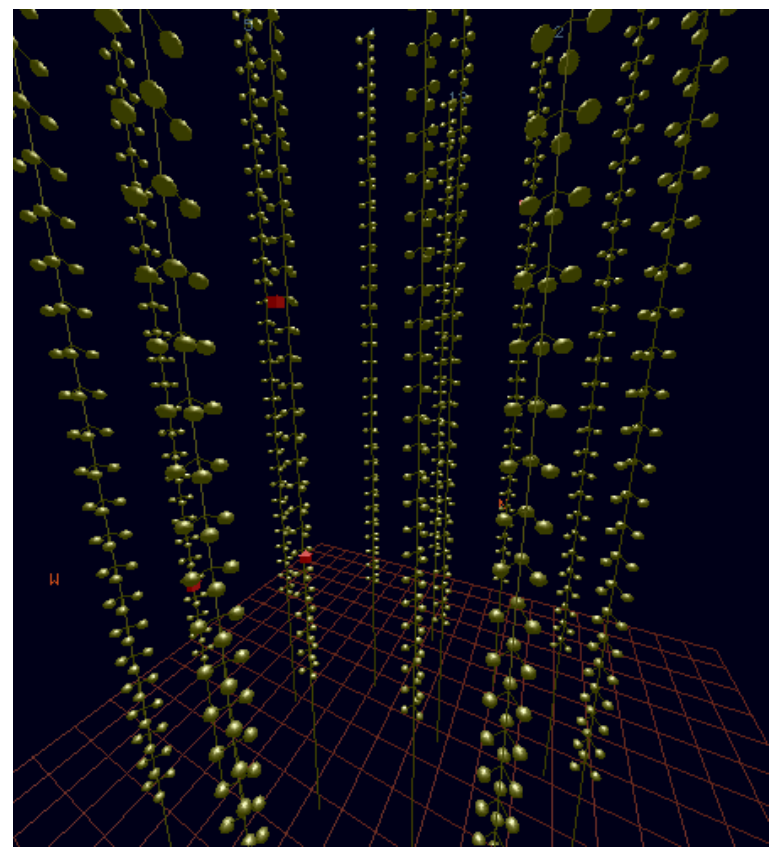


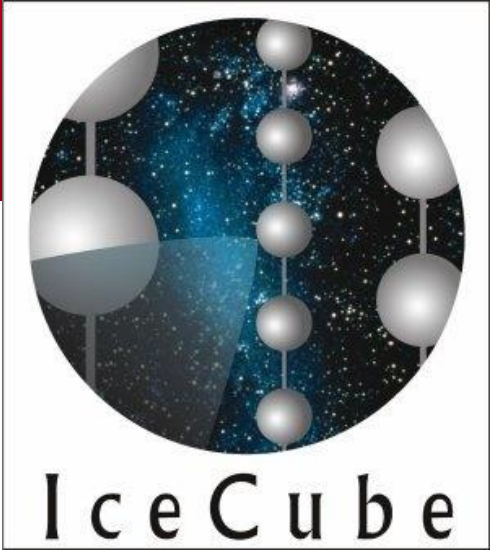
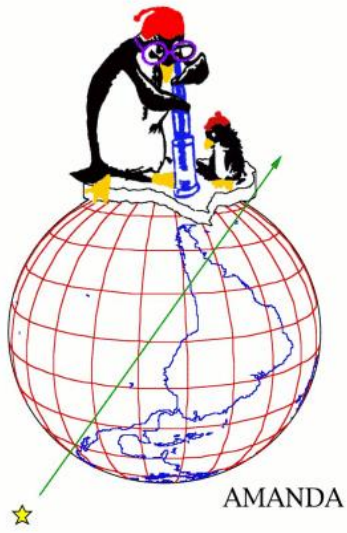


The generated charged particle emits the Cherenkov light.

Image du soleil en Neutrino Electronique







AMANDA

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



South Pole

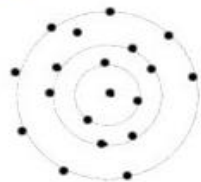


AMANDA



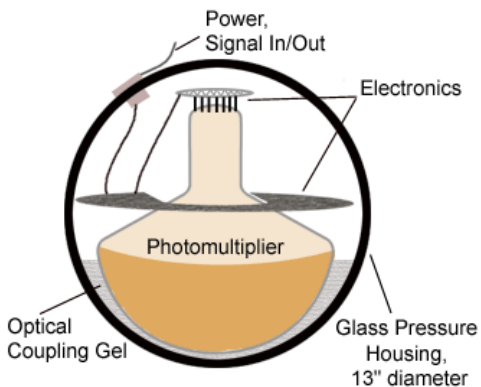
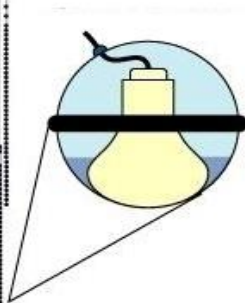
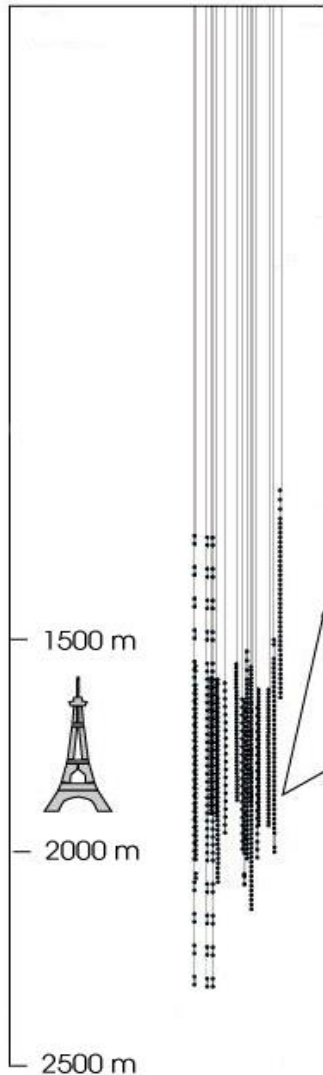
AMANDA-II

Depth



top view

200 m

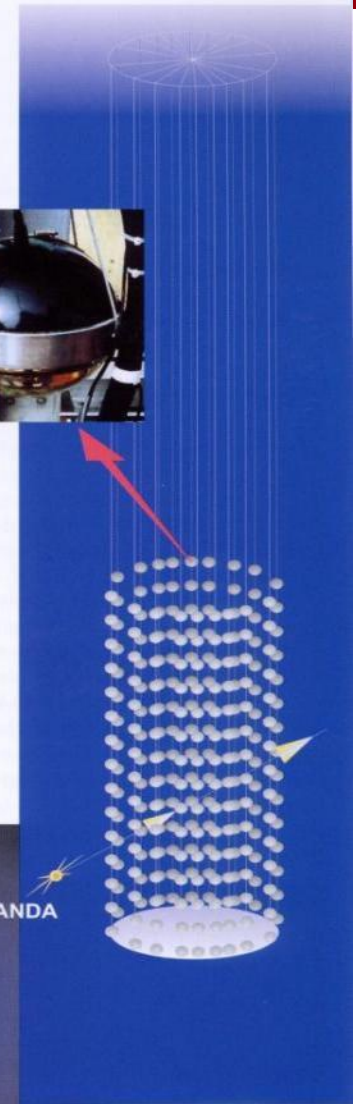
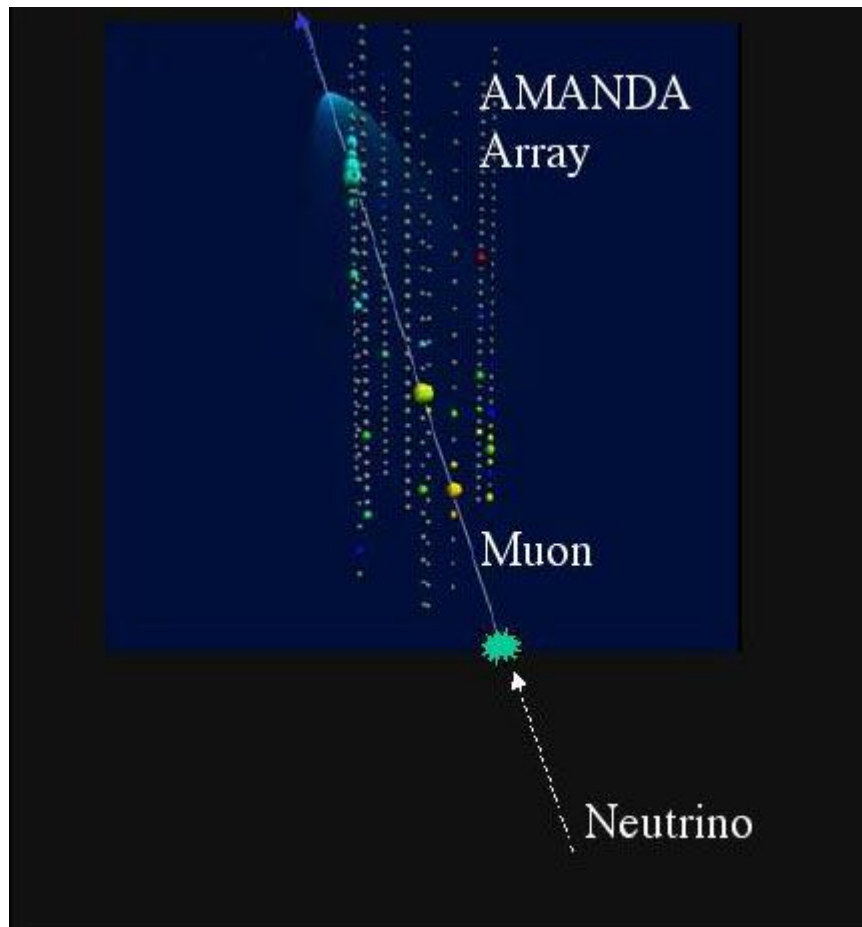


**Photomultipliers in the Ice,
looking downwards.
Ice is the detecting medium.**

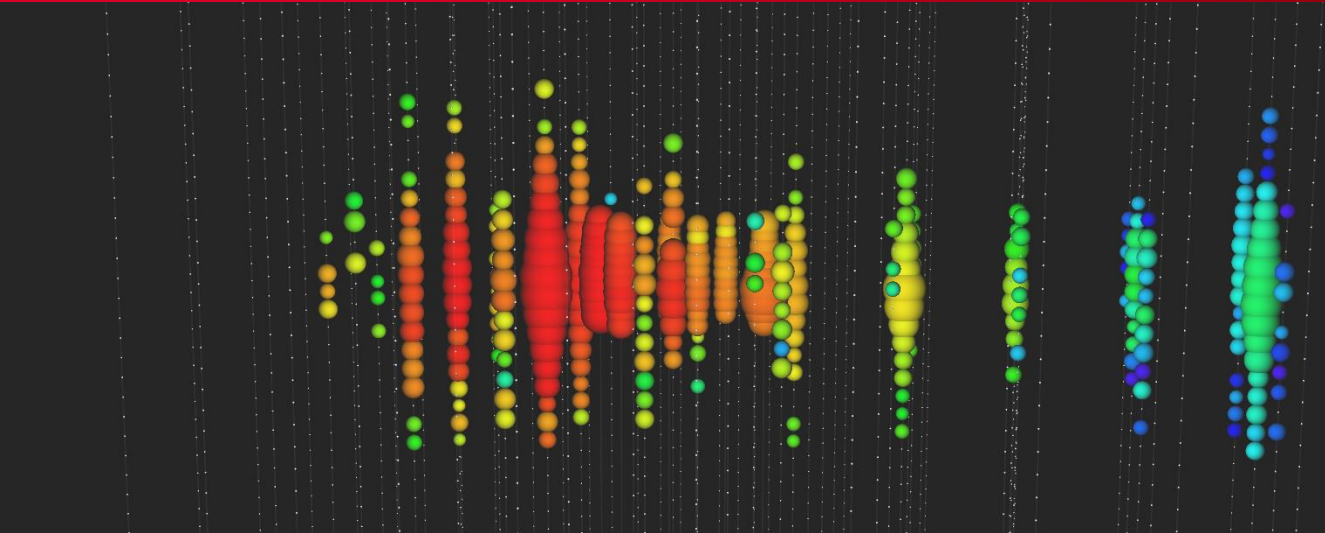


Look for upwards going Muons from Neutrino Interactions.
Cherekov light propagating through the ice.

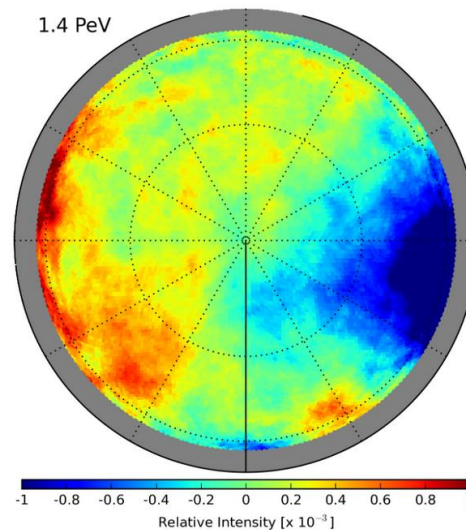
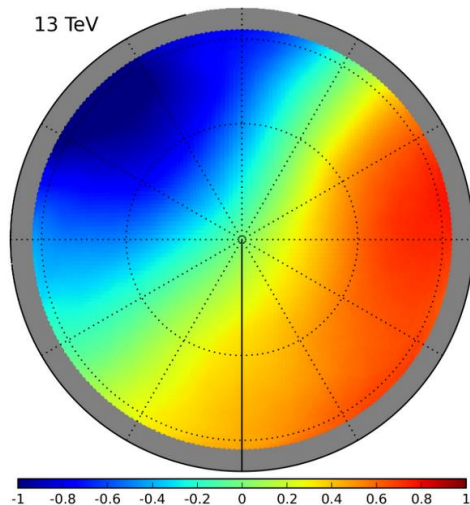
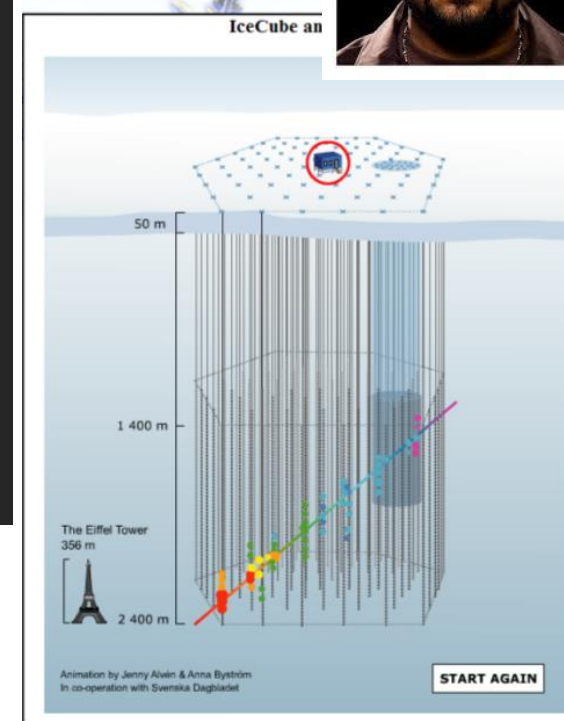
→ Find neutrino point sources in the universe !








AMANDA – ICE CUBE



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



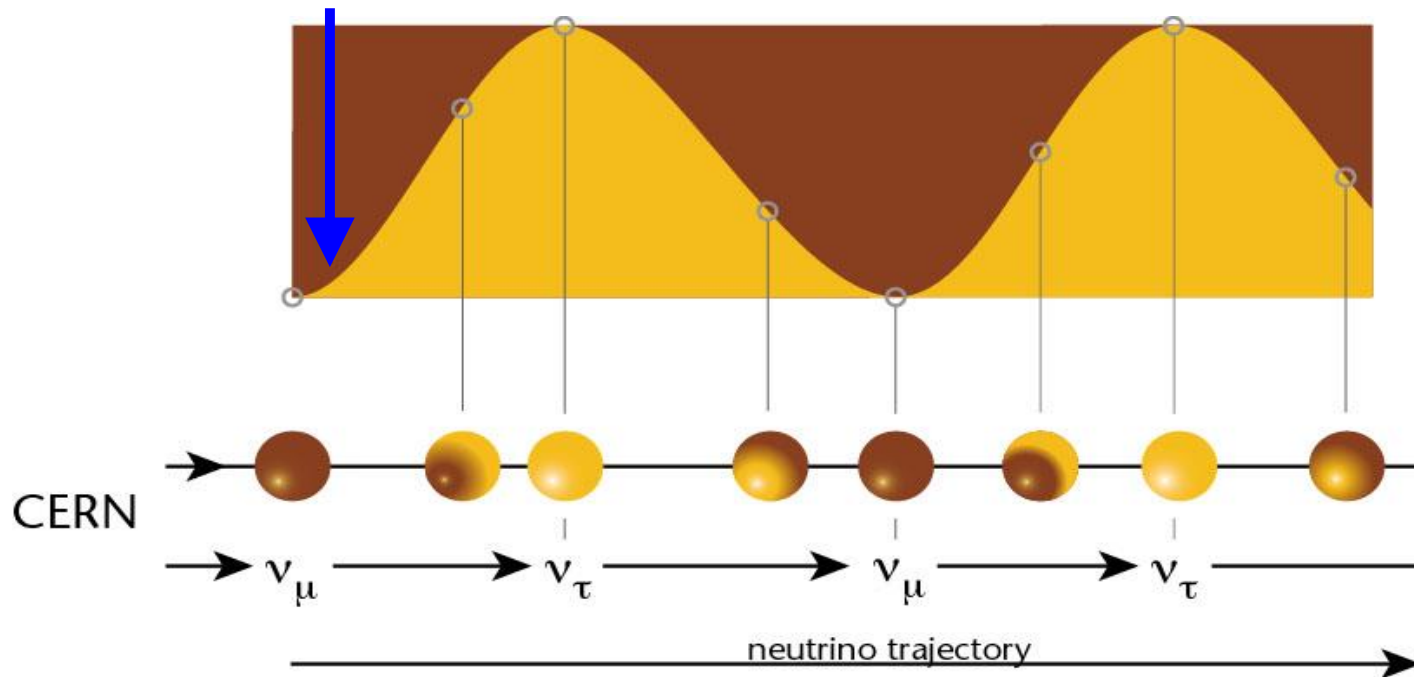
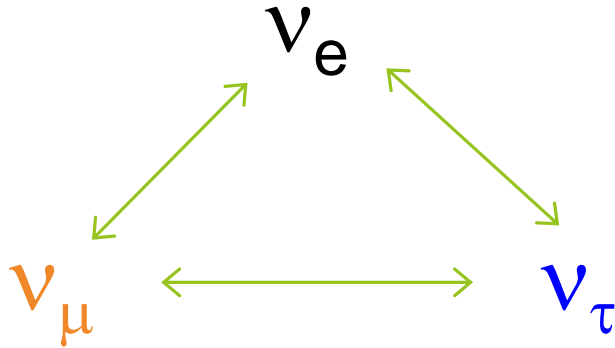
Detector Design

-  1 gigaton of instrumented ice
-  5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
-  1 square kilometer surface array, IceTop, with 324 DOMs
-  2 nanosecond time resolution
-  IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily

CERN Neutrino Gran Sasso (CNGS)

If neutrinos have mass:

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



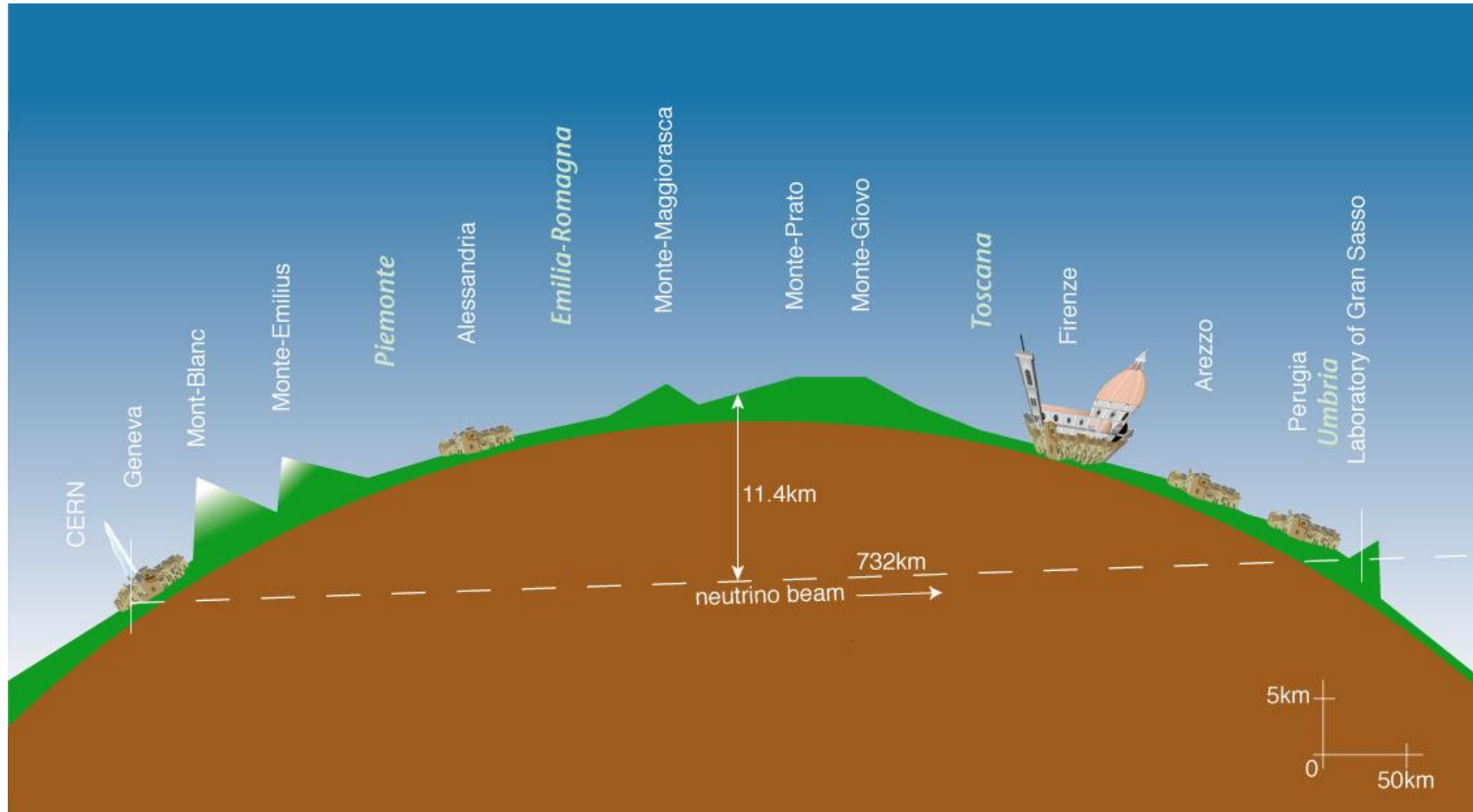
CNGS (CERN NEUTRINO GRAN SASSO)

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

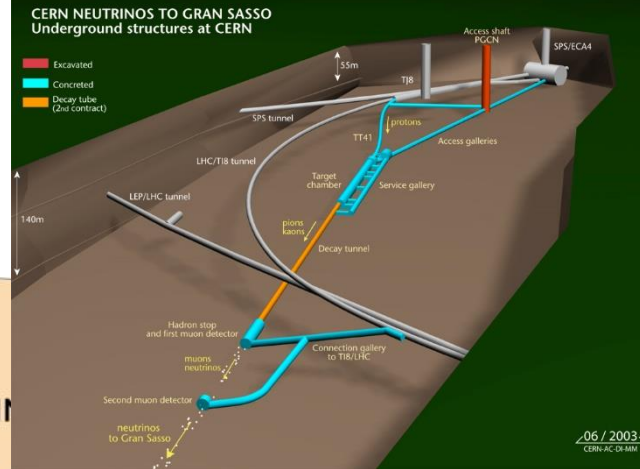
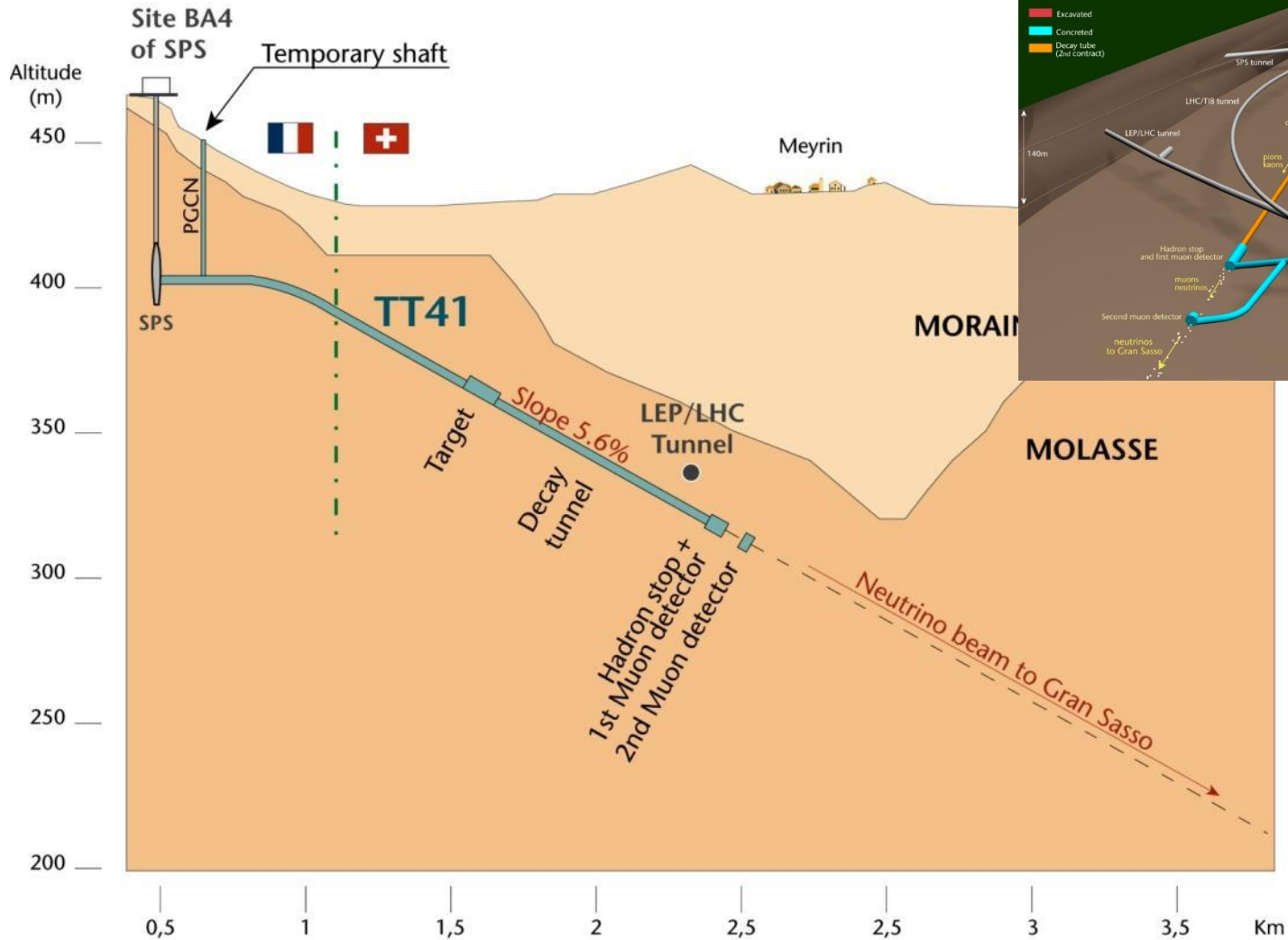


➔ direct proof of $\nu_\mu - \nu_\tau$ oscillation (appearance experiment)

CNGS



CNGS



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 ≈ 25 per day

ν_{τ} events (from oscillation) ≈ 2 per year

$$\nu_{\tau} N \longrightarrow \tau^{-} X$$

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

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

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

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

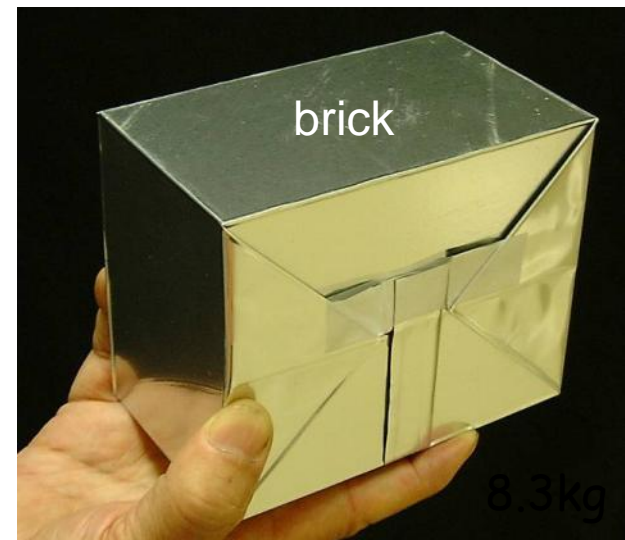
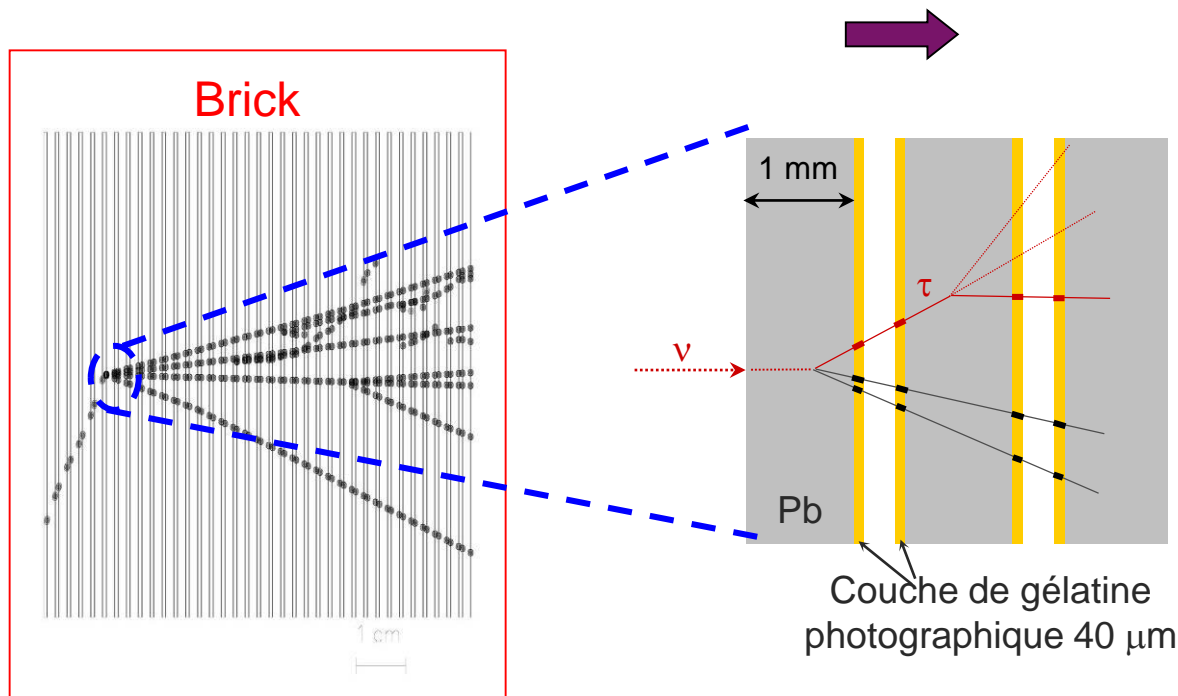
<https://arxiv.org/pdf/1305.2513.pdf>

Basic unit: brick

56 Pb sheets + 56 photographic films (emulsion sheets)

Lead plates: massive target

Emulsions: micrometric precision

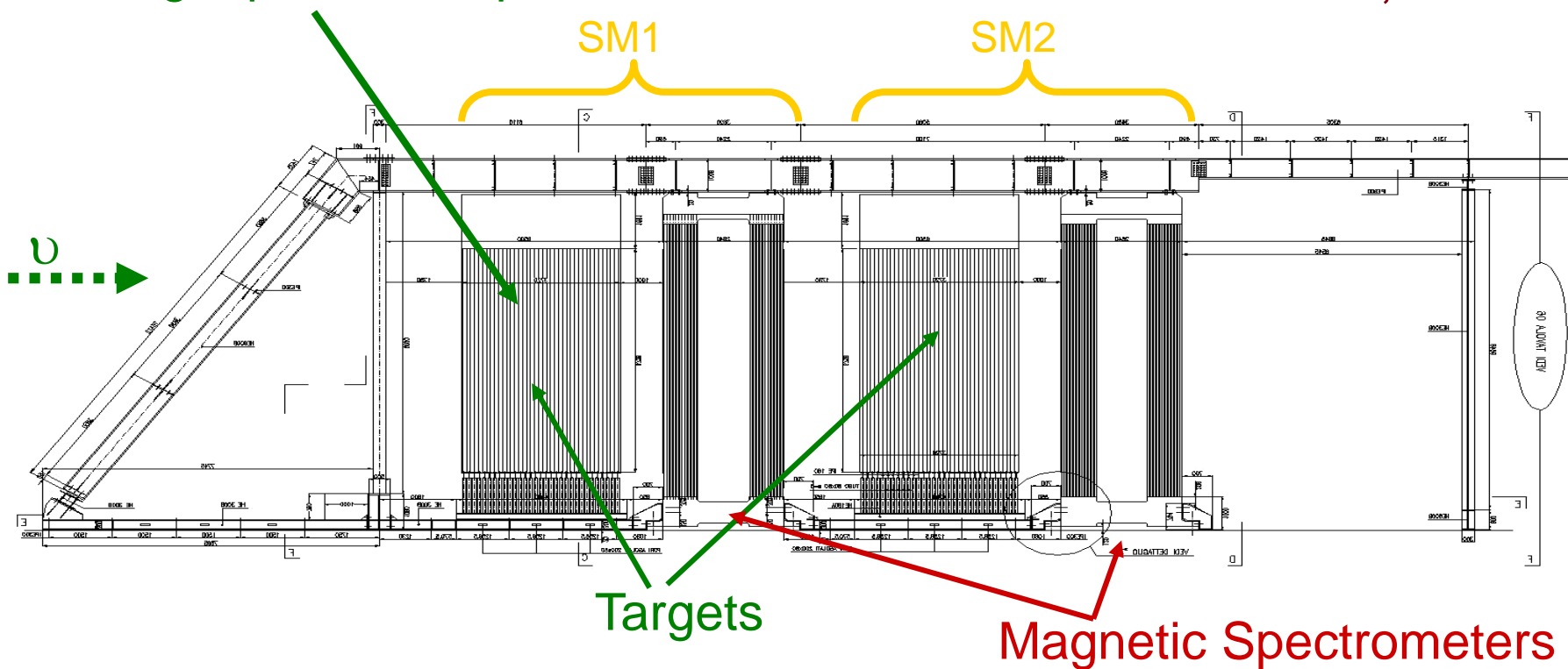


10.2 x 12.7 x 7.5 cm³



31 target planes / supermodule

In total: 206336 bricks, 1766 tons



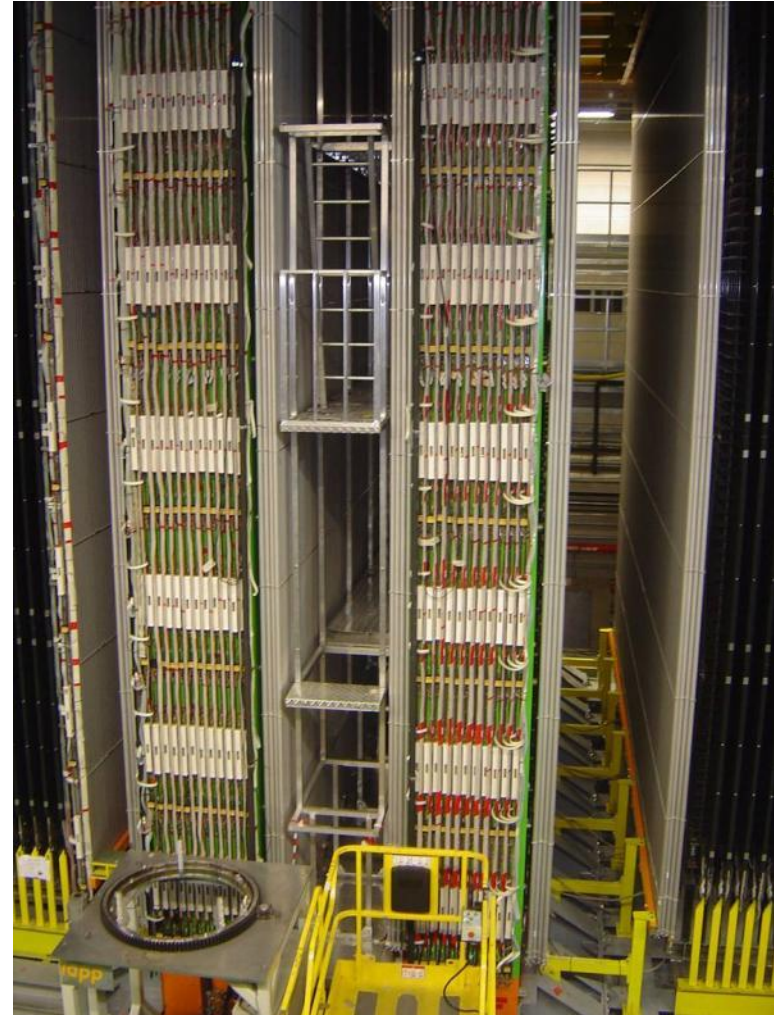
First observation of CNGS beam neutrinos : August 18th, 2006

Second Super-module



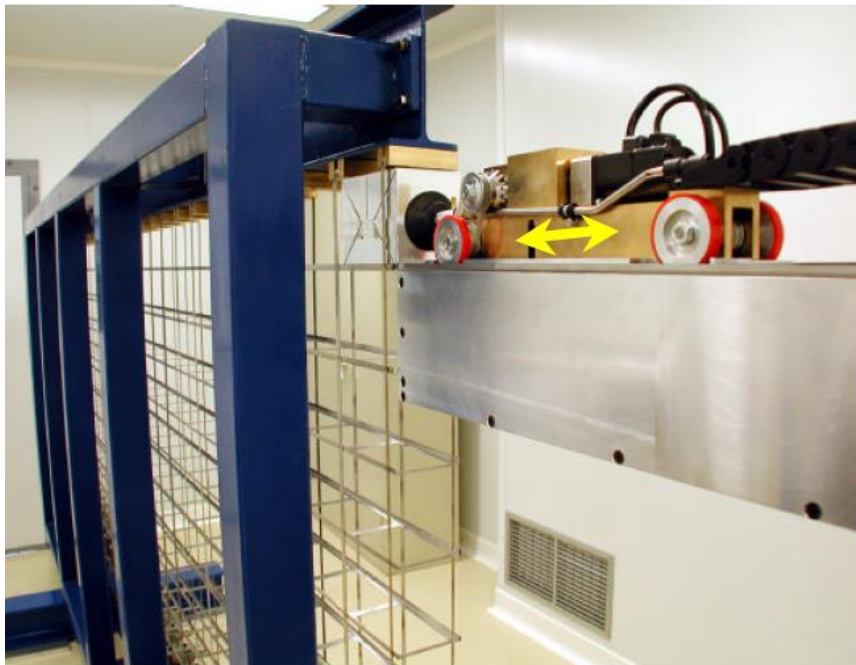
Scintillator planes 5900 m²
8064 7m long drift tubes

Details of the first spectrometer

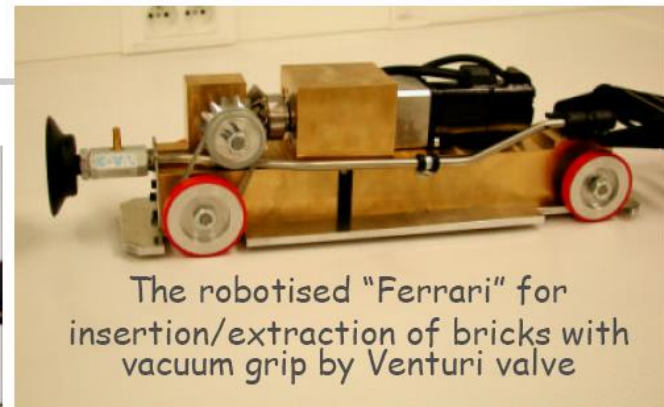


3050 m² Resistive Plate Counters
2000 tons of iron for the two magnets

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



Tests with the prototype wall



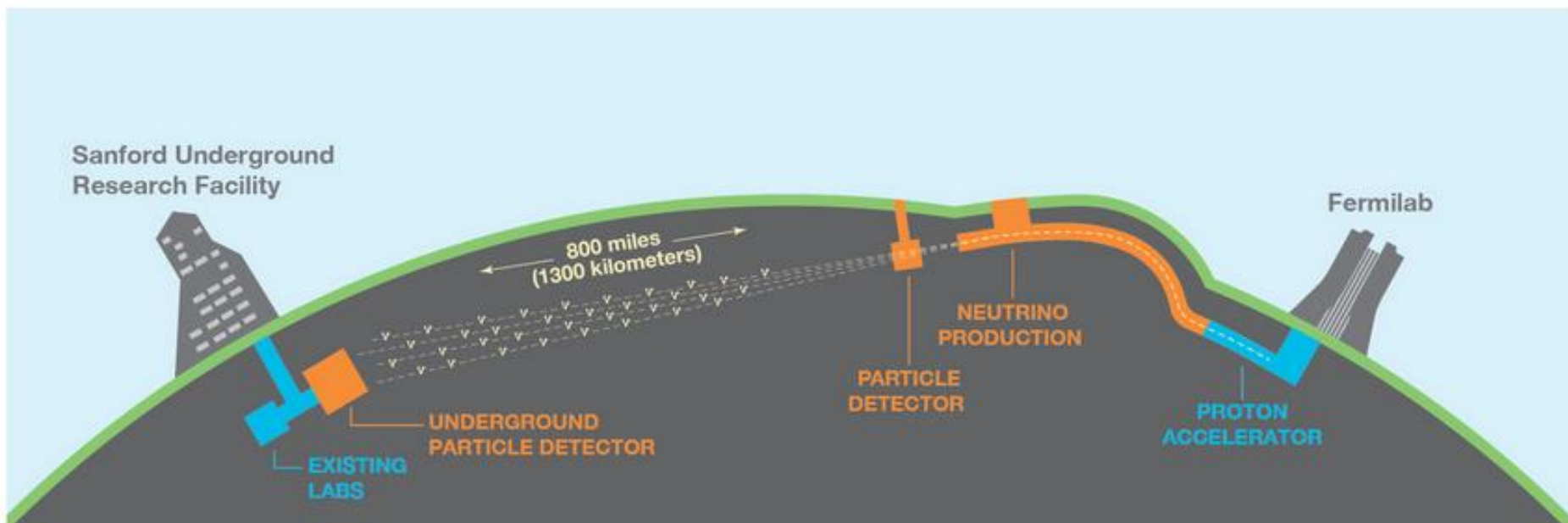
The robotised "Ferrari" for
insertion/extraction of bricks with
vacuum grip by Venturi valve

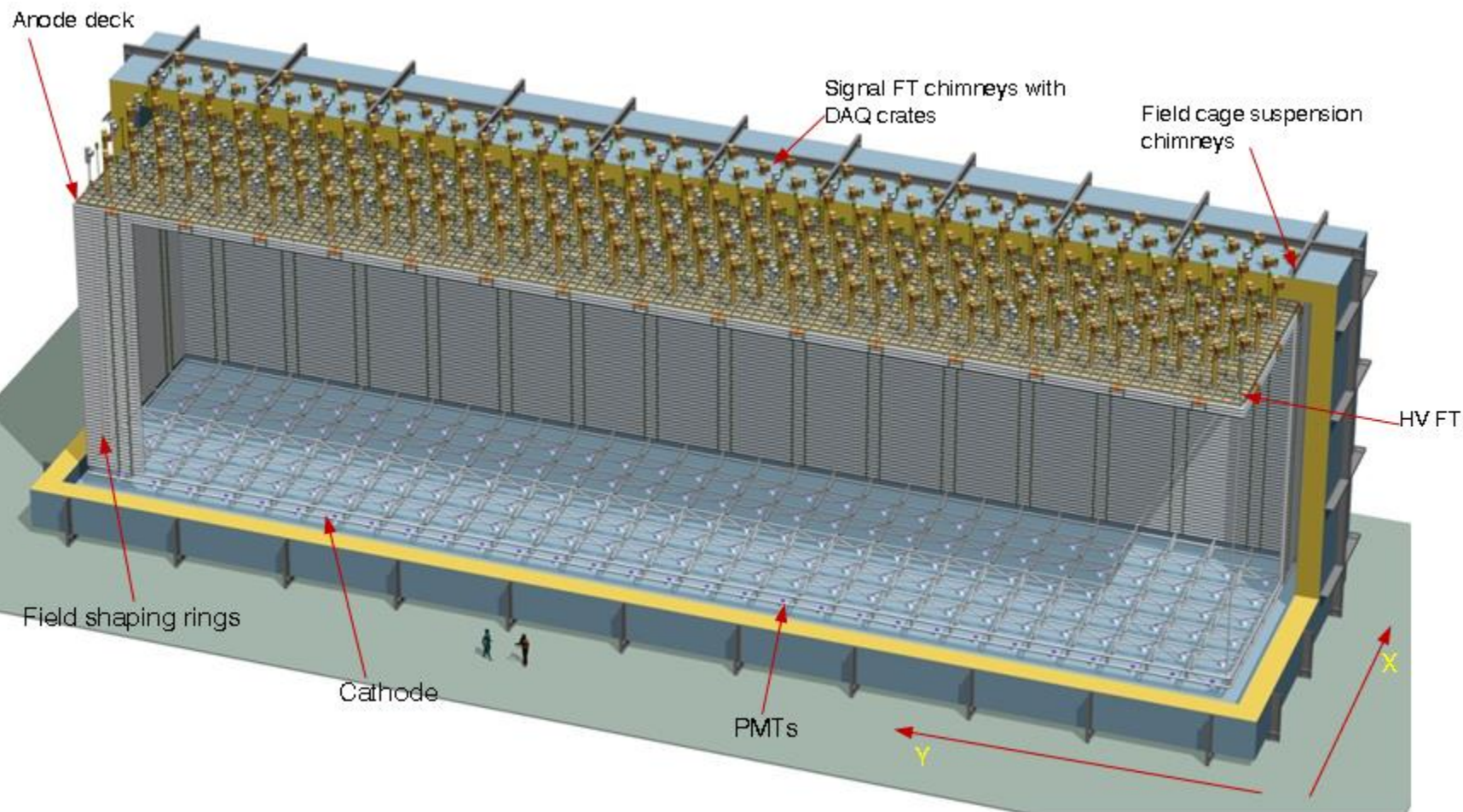


"Carousel" brick dispensing
and storage system

An international mega-science project

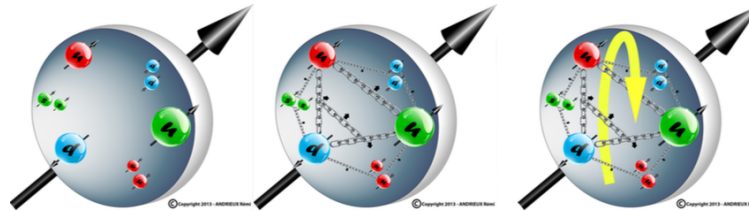
The Deep Underground Neutrino Experiment (DUNE) is a leading-edge, international experiment for neutrino science and proton decay studies. Discoveries over the past half-century have put neutrinos, the most abundant matter particles in the universe, in the spotlight for further research into several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





Physique Hadronique

COMPASS et CLAS12



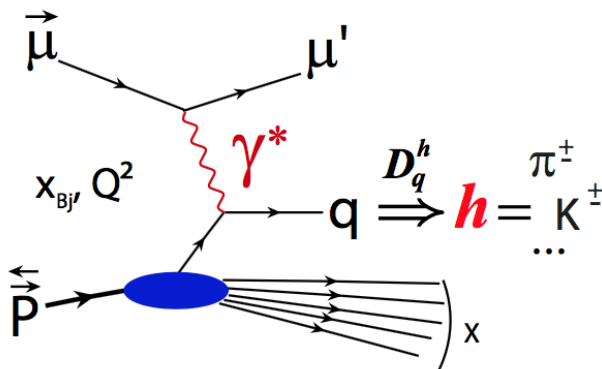
Différentes contributions

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

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

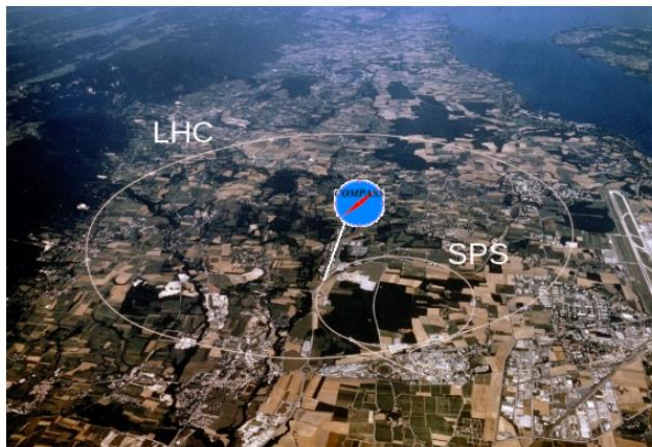
Spin des gluons
 $|\Delta G| < 0.5$

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

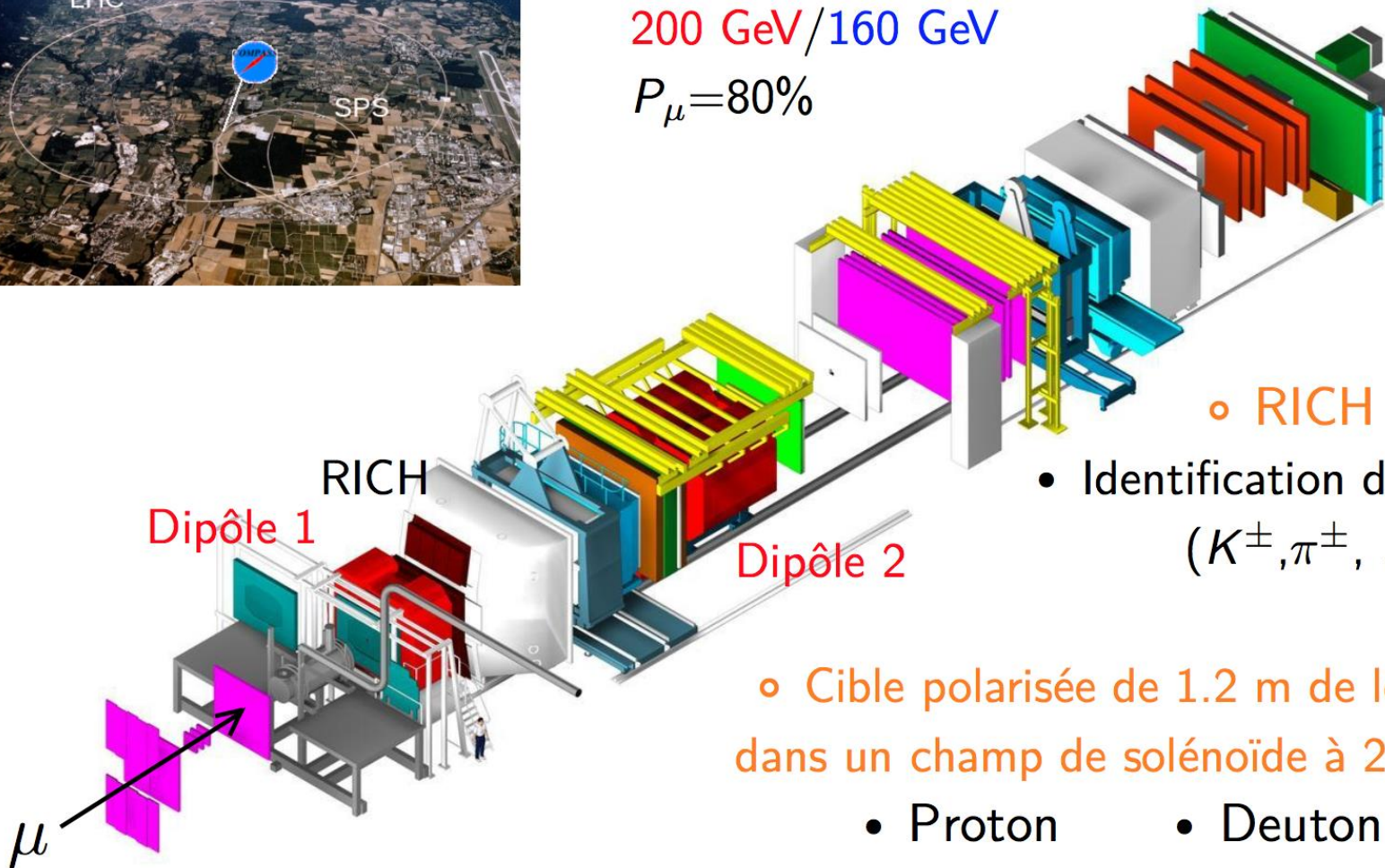


Section efficace DIS

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



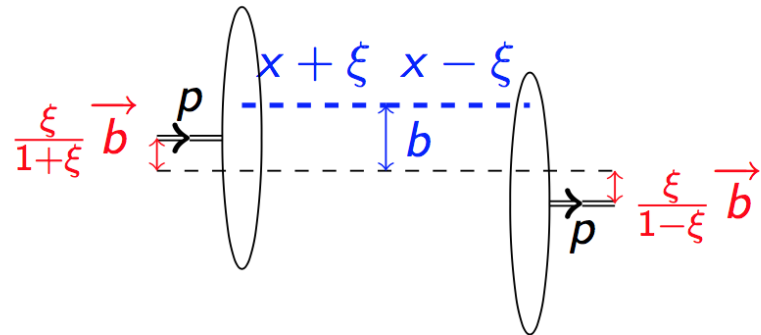
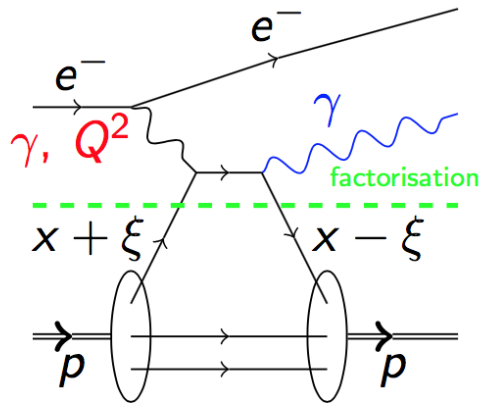
- Faisceau polarisé de μ^+ du SPS
 $1 \cdot 10^8 / 2 \cdot 10^8 \mu$ par déversement de ~ 10 s
 200 GeV / 160 GeV
 $P_\mu = 80\%$



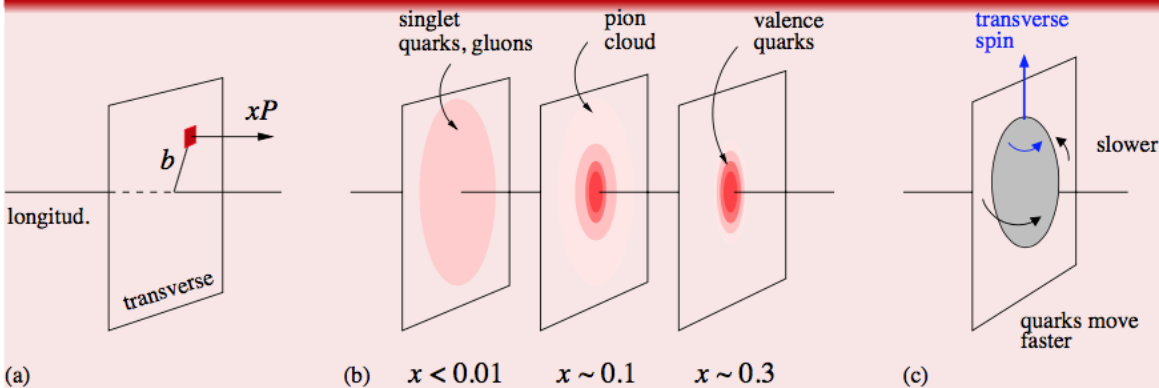
- RICH :
 - Identification des hadrons (K^\pm, π^\pm, \dots)

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

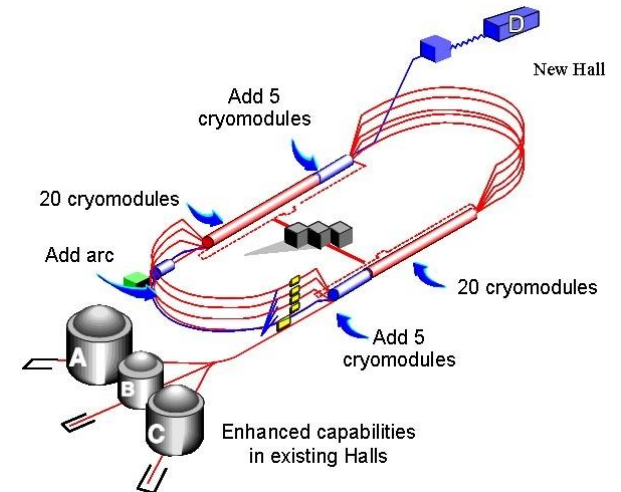
Diffusion Compton profondément virtuelle (DVCS)

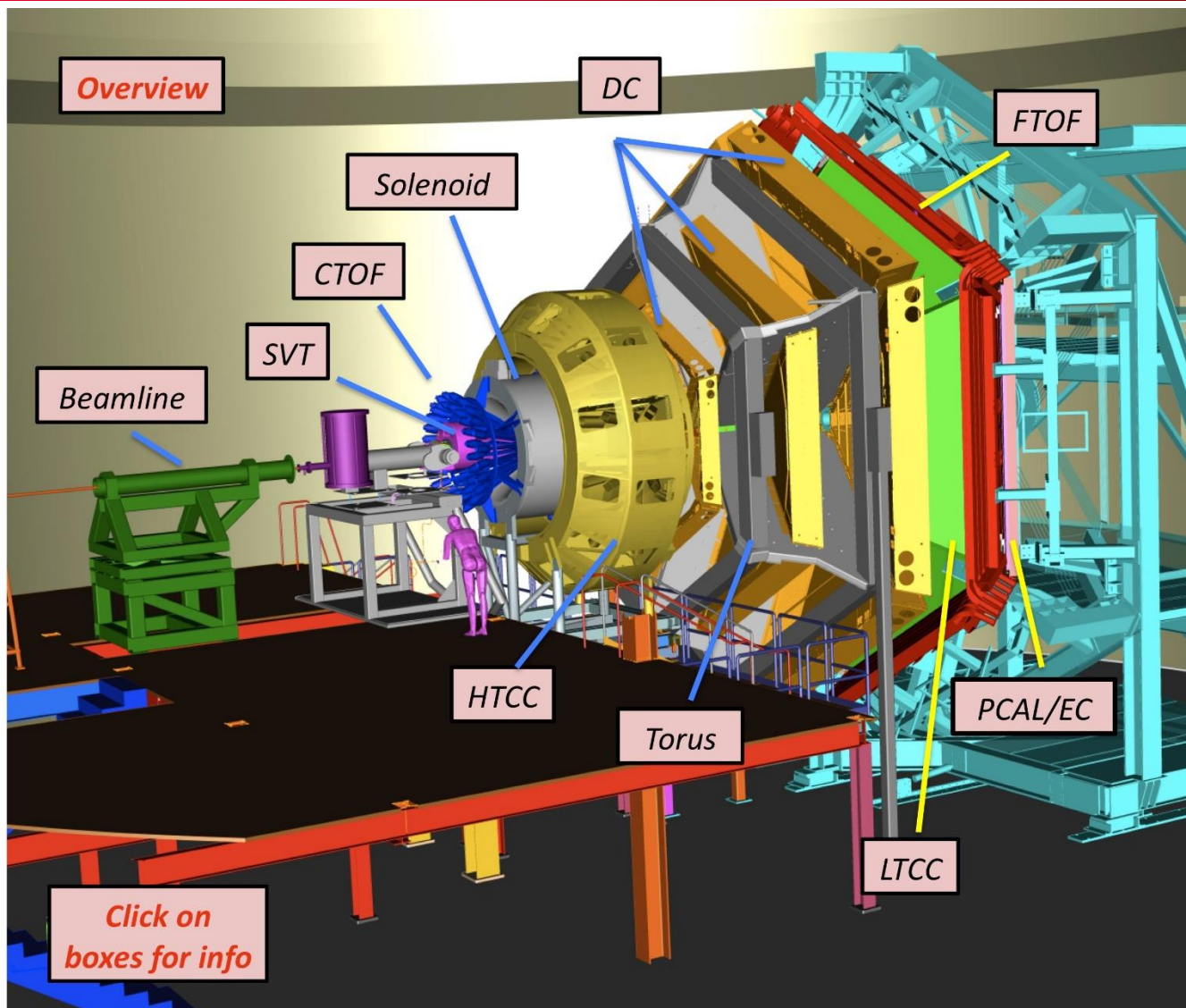


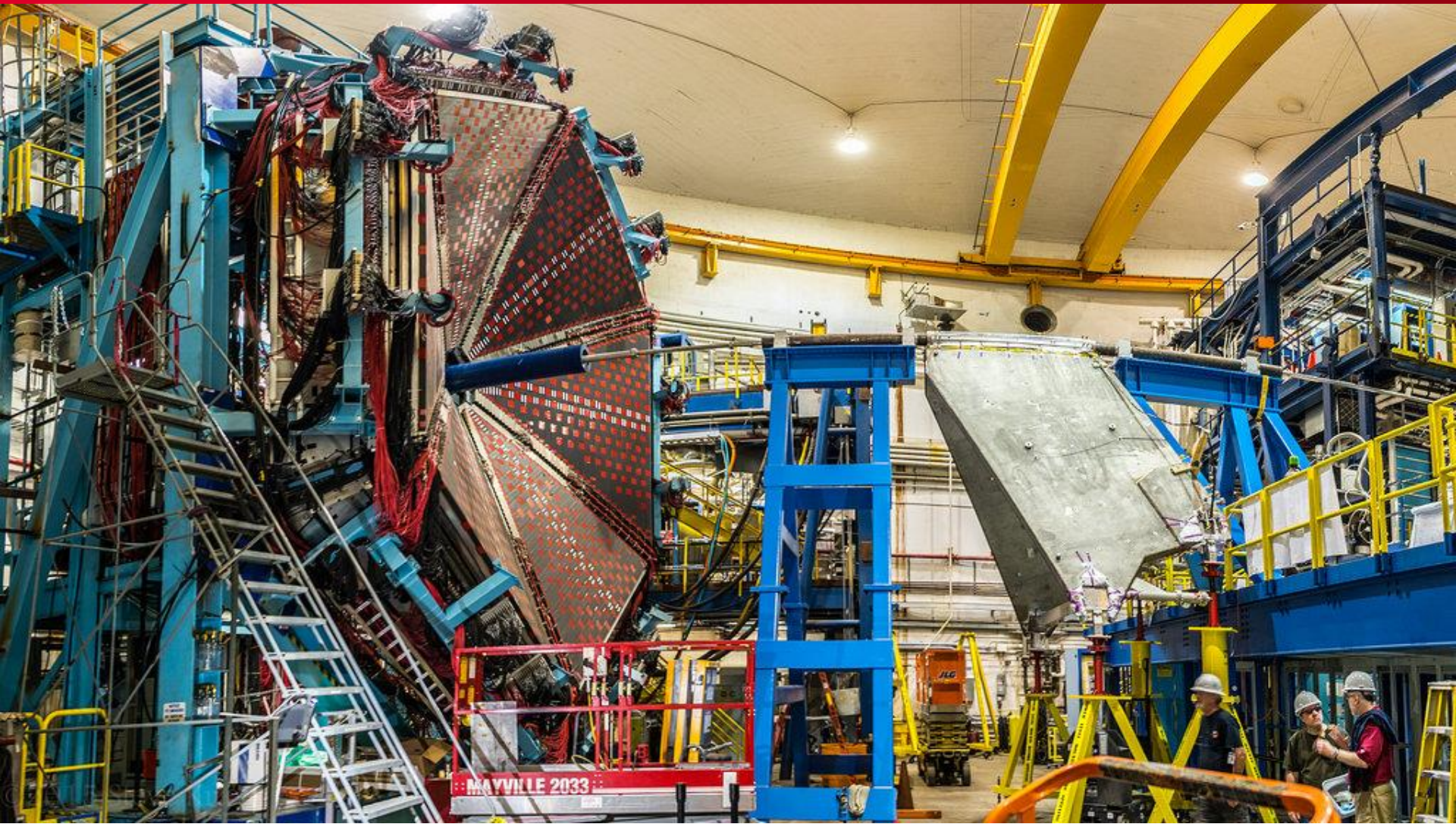
Vers une visualisation en 3d du nucléon !

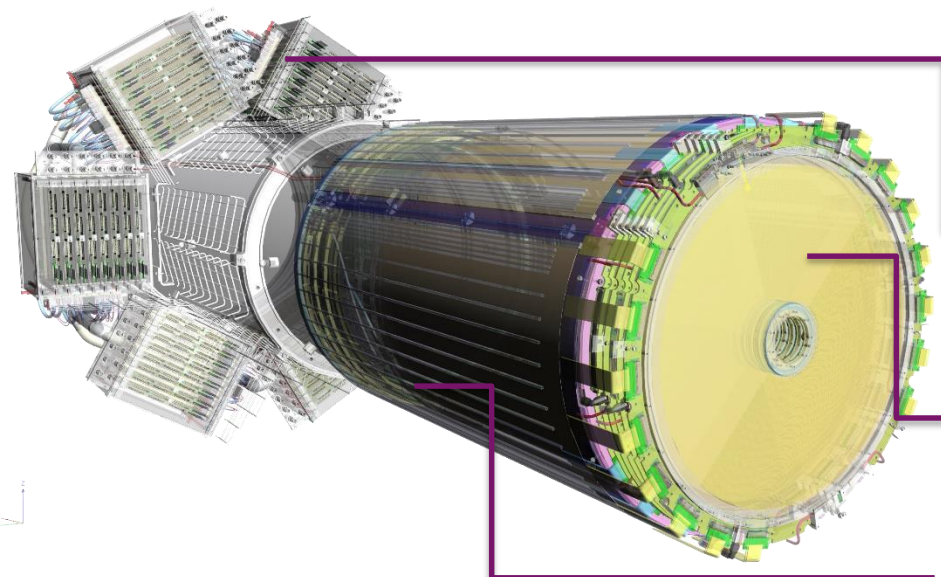


C. Weiss,
AIP Conf.
Proc. 1149,
150 (2009)









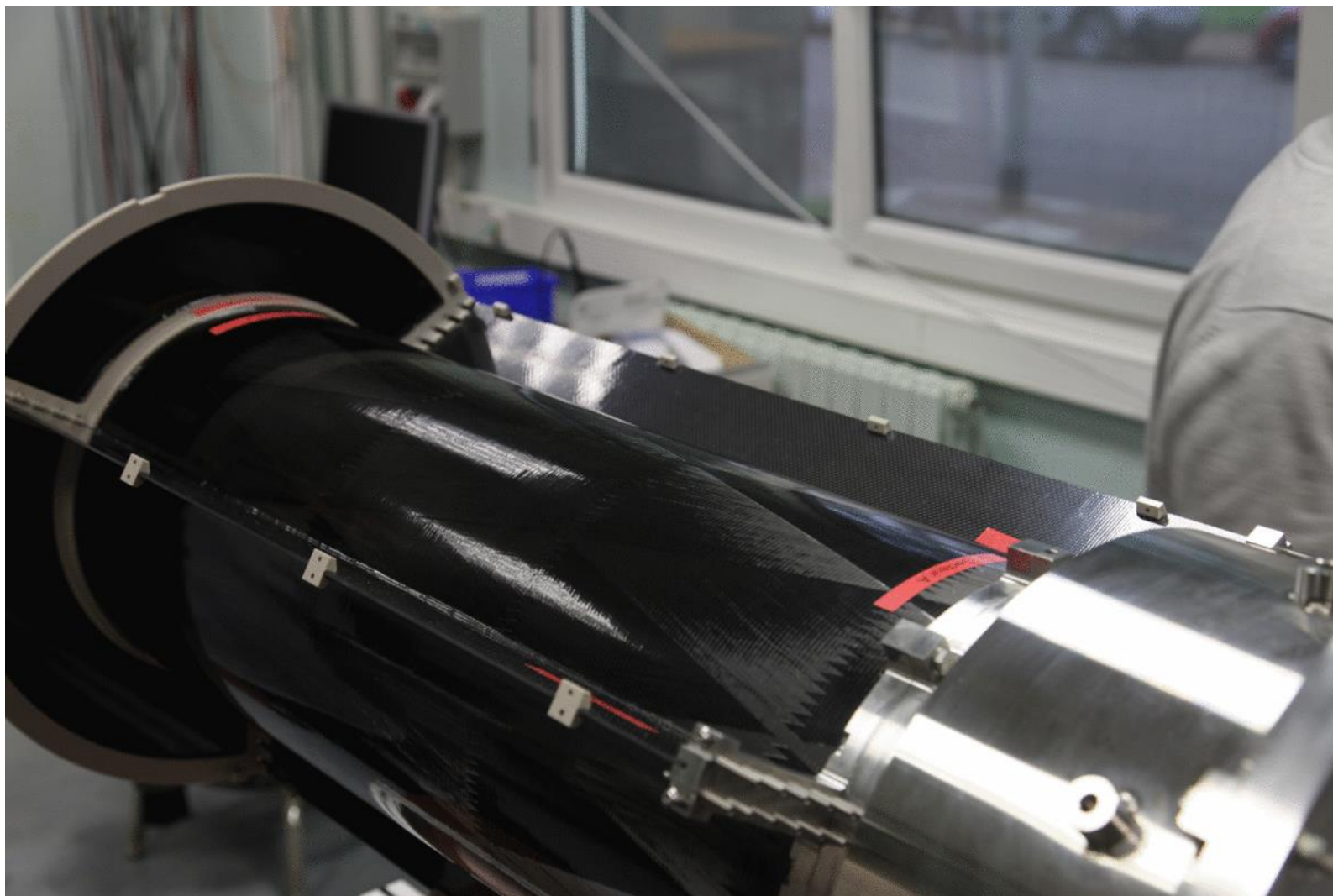
- ▶ 4 m² of Micromegas detectors to be installed in 2017
- ▶ DREAM based Front-End Electronics
- ▶ Remote off-detector frontend electronics connected with 2m micro-coaxial cables

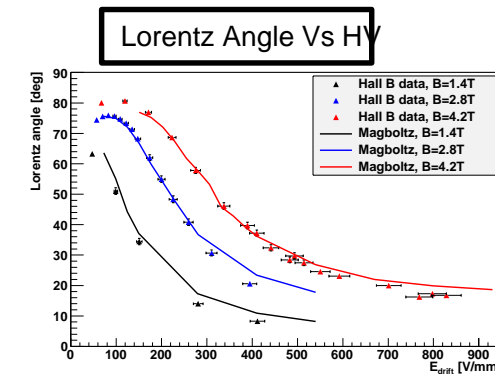
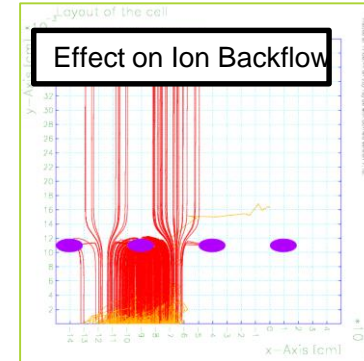
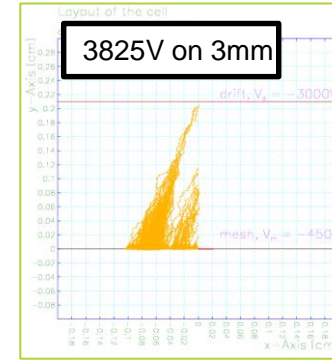
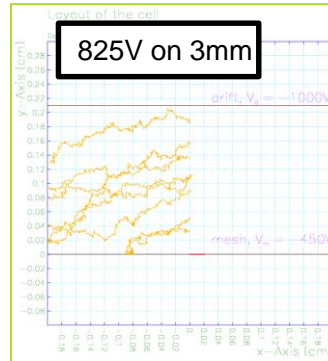
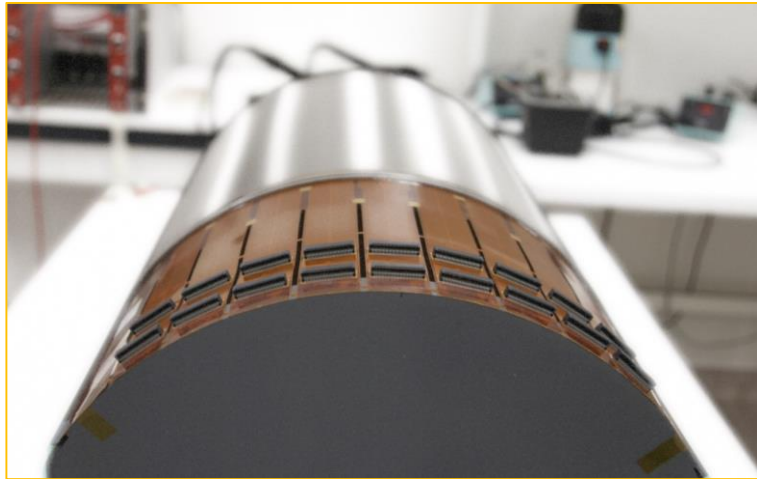
Forward Detectors

- ▶ 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

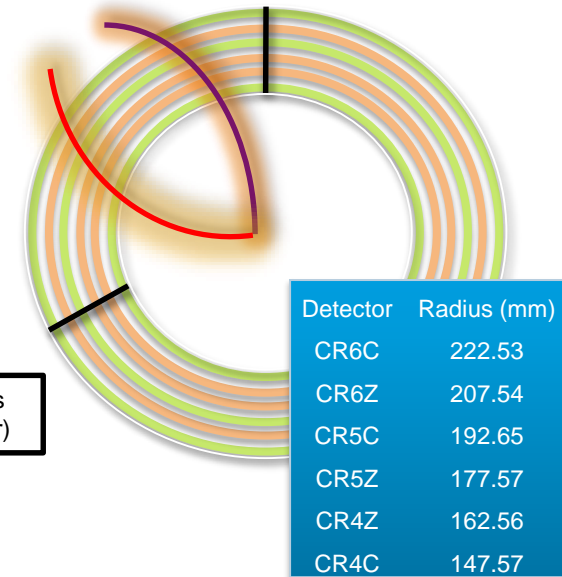
Cylindrical Barrel

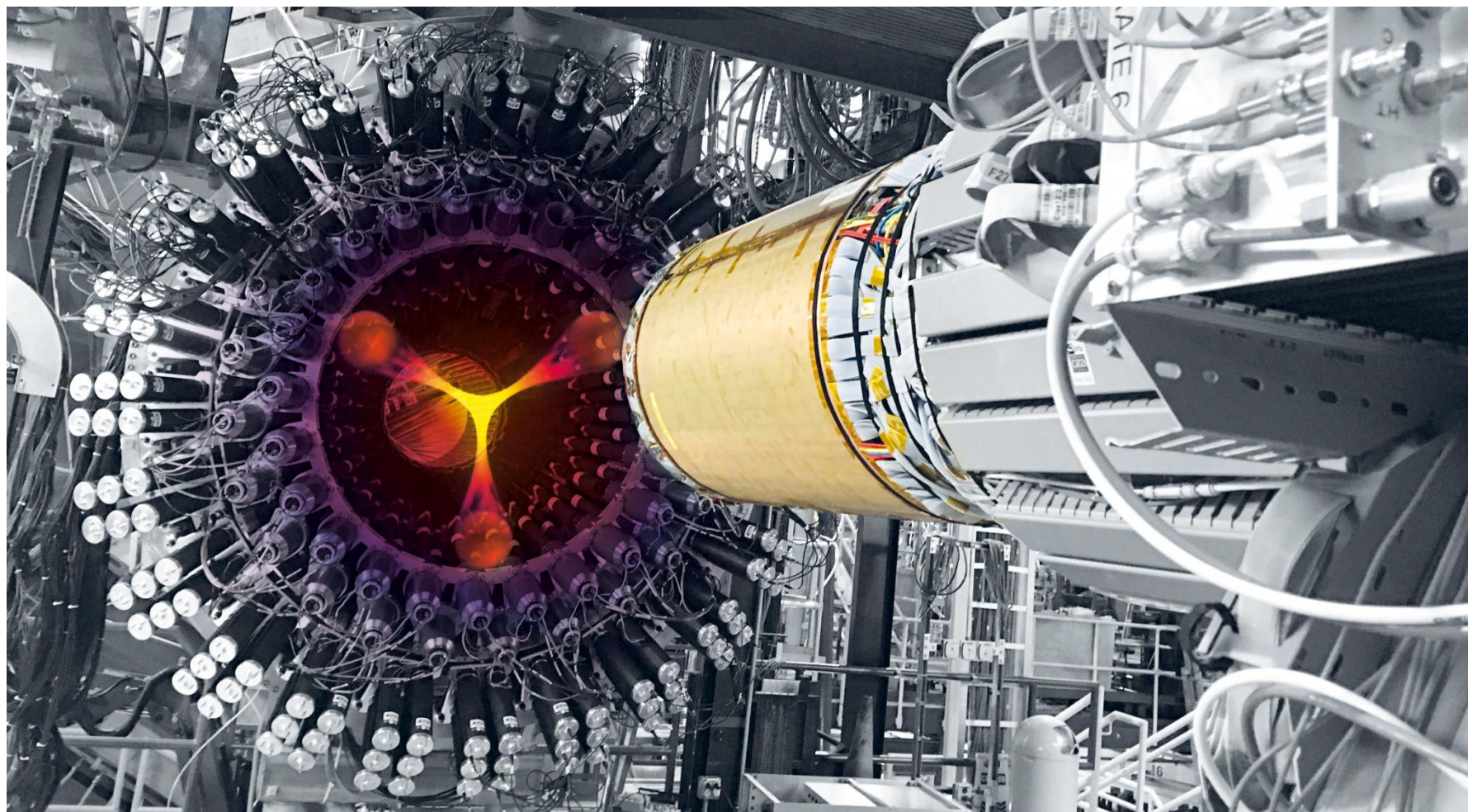
- ▶ Low momentum particles => Light Detectors
- ▶ Limited space of ~10 cm for 6 layers
- ▶ High magnetic field (5T)
- ▶ Phase 1 (2016) : 2 Layers (6 Det. of 120°)
- ▶ Phase 2 (2017) : 6 Layers (18 Det.)





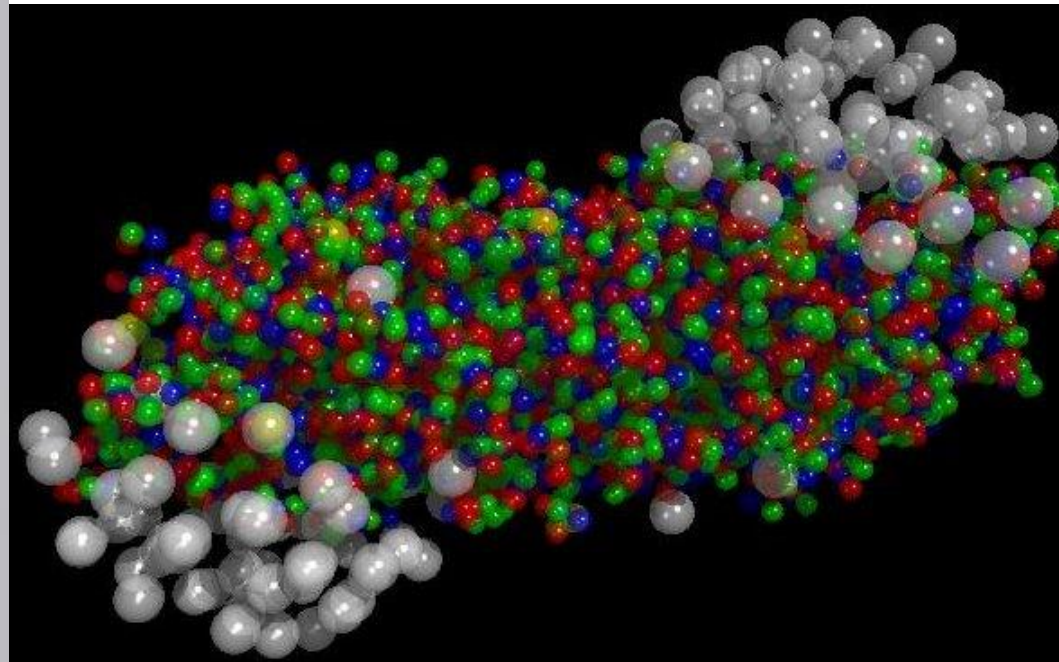
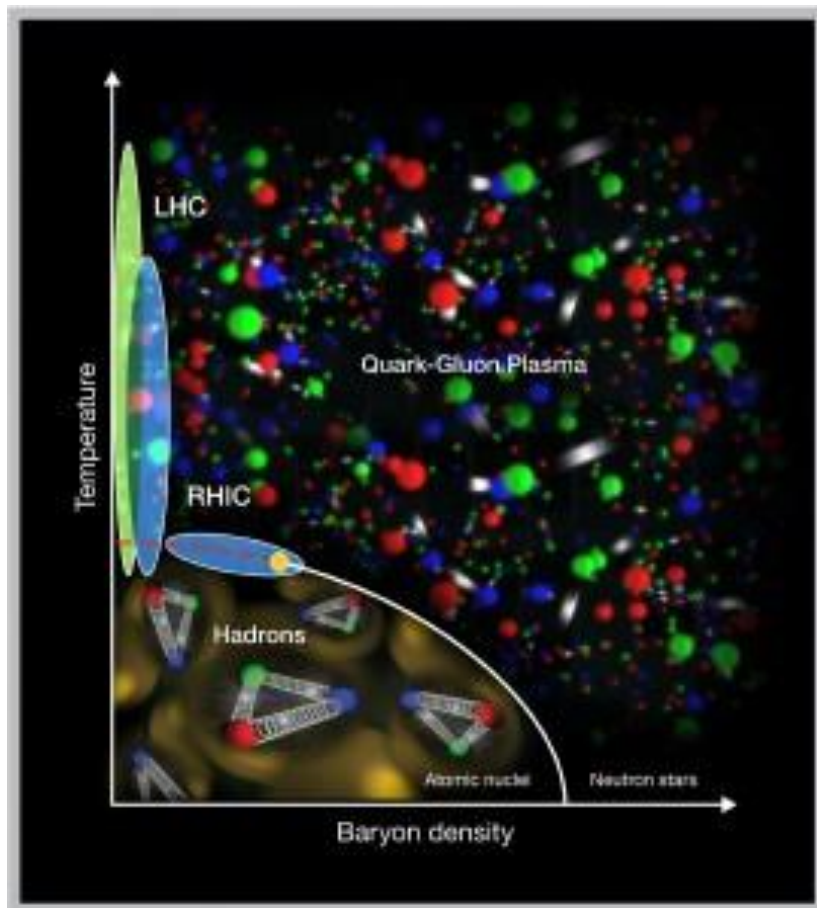
=> Clas-note 2007-004: Simulations of Micromegas detectors for the CLAS12 experiment (S. Procureur)

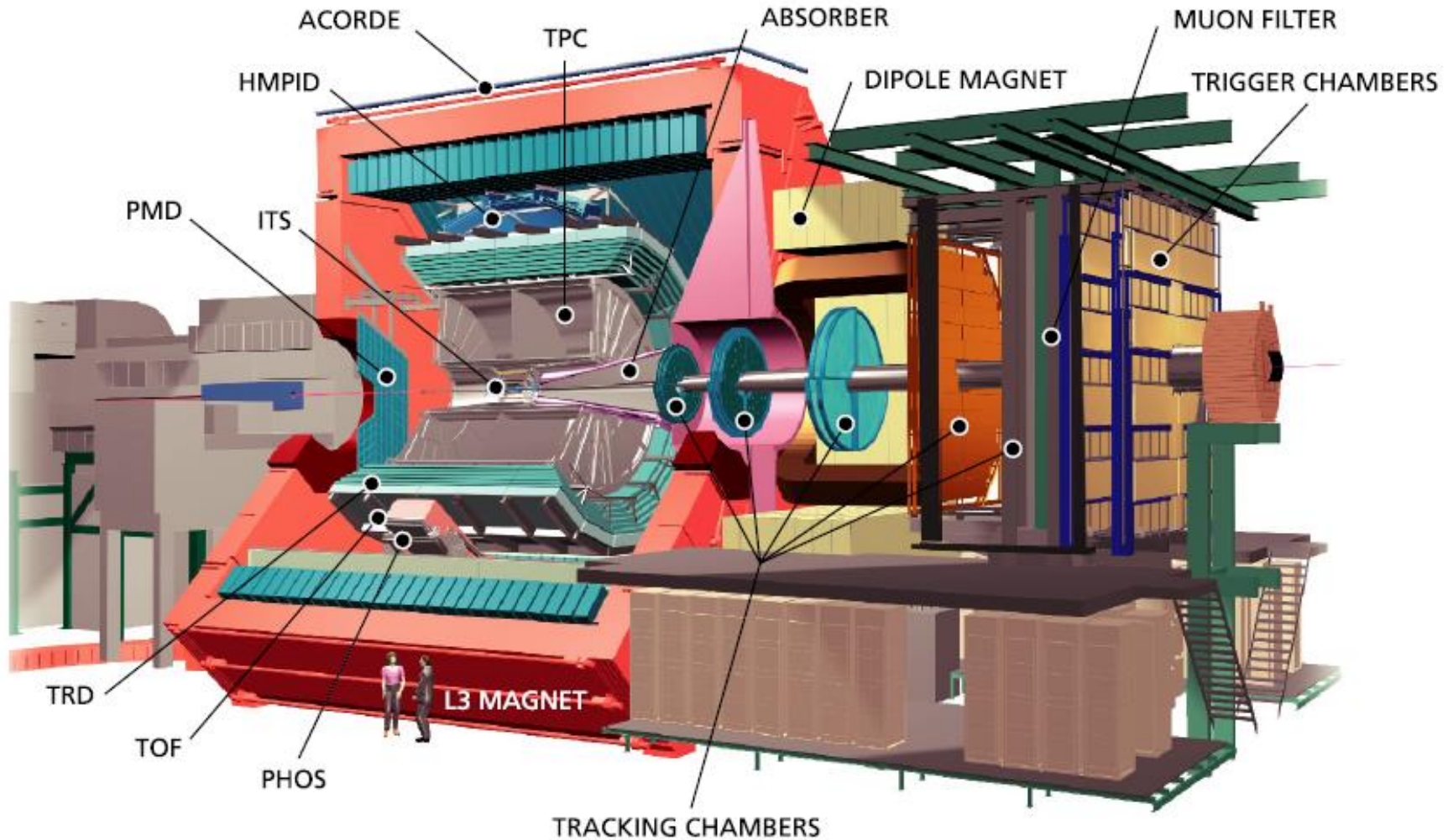




ALICE

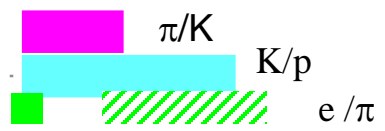
A heavy Ion Experiment at the LHC





Alice uses ~ all known techniques!

TPC + ITS
(dE/dx)



TOF



HMPID
(RICH)



0 1 2 3 4 5 p (GeV/c)

TPC (rel. rise) $\pi/K/p$



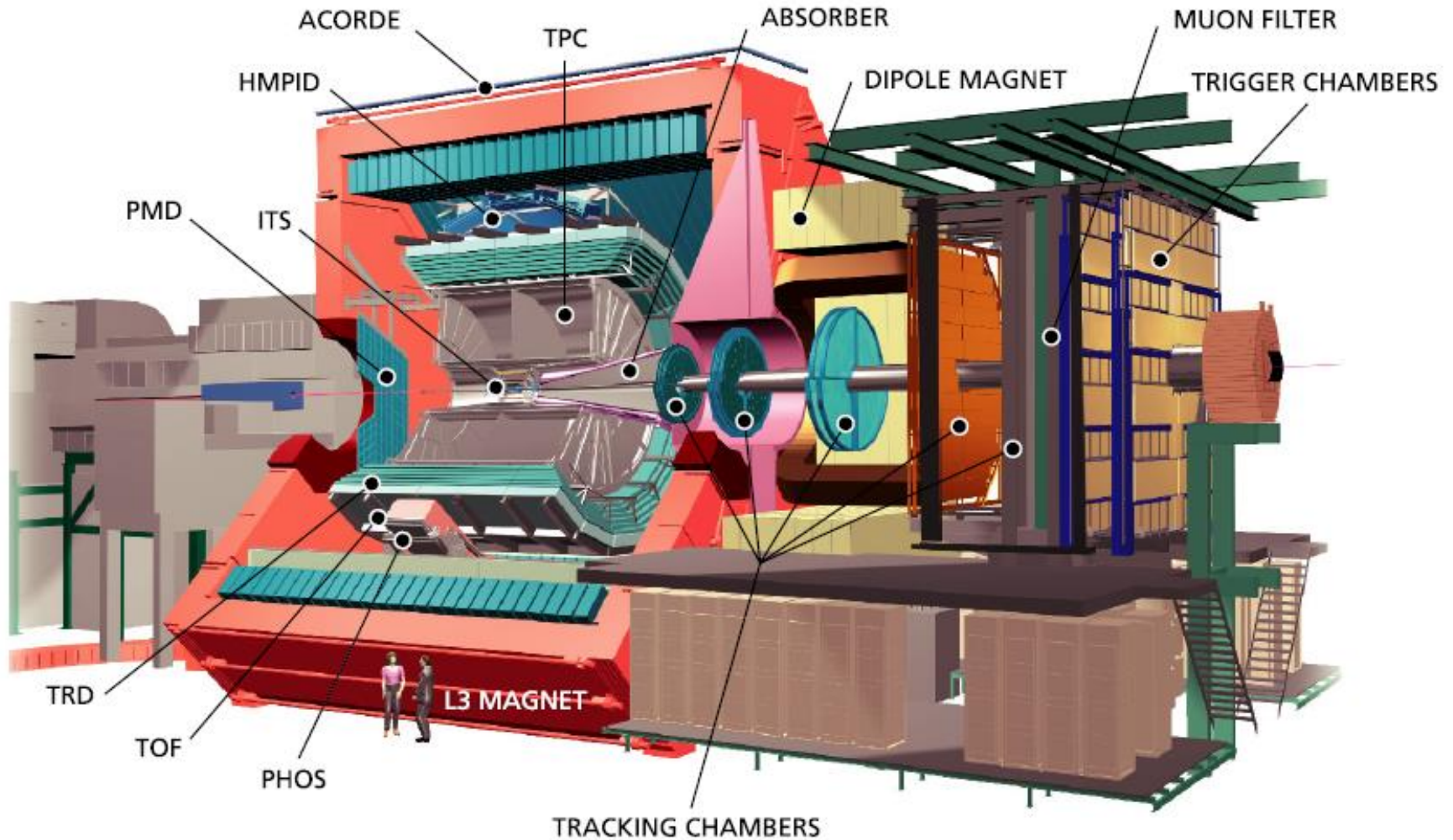
TRD e/π



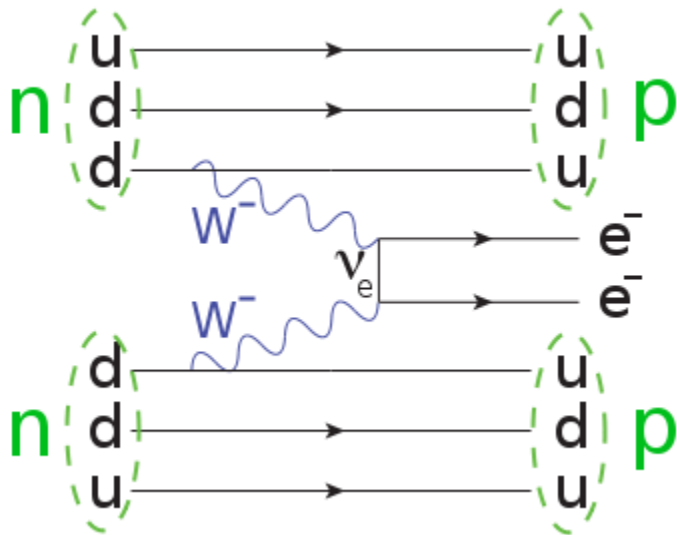
PHOS γ/π^0



1 10 100 p (GeV/c)



DOUBLE BETA DECAY



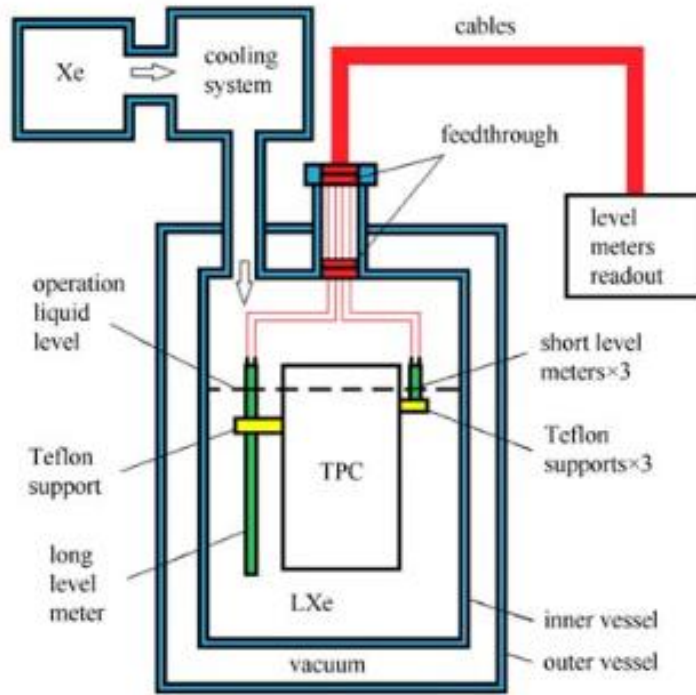
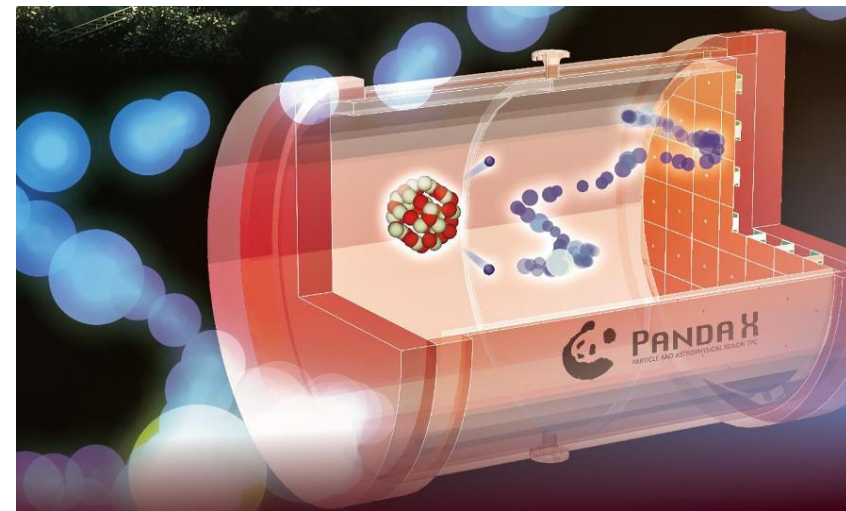
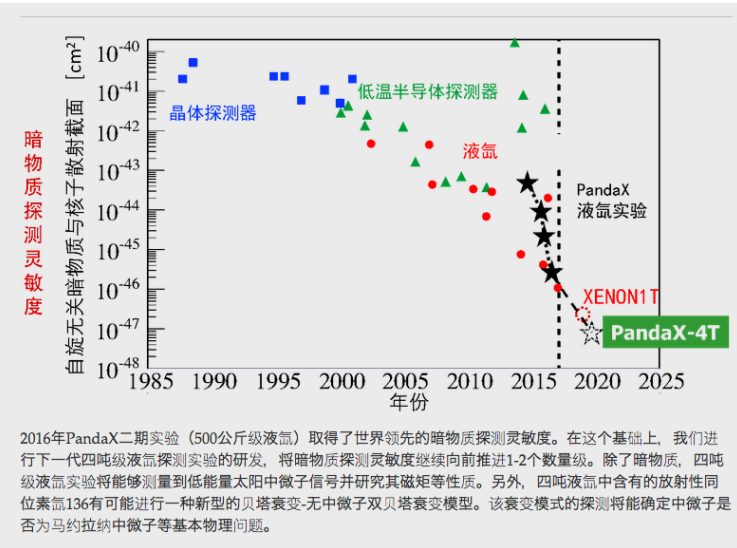
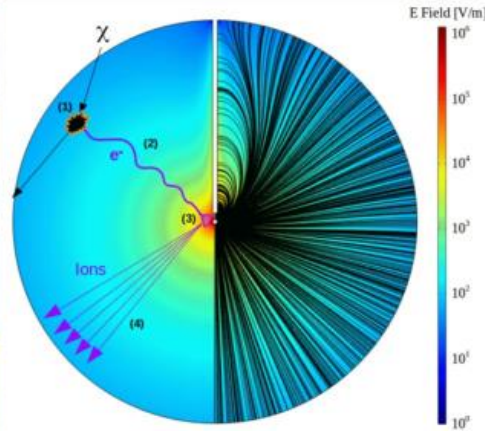


Fig. 1. Schematics of the two-phase xenon detector as used in PandaX. LXe is contained in an inner vessel insulated by vacuum from the outside. One long liquid level meter monitors the overall liquid xenon height and three short level meters monitor the height of the liquid-gas interface around the TPC.

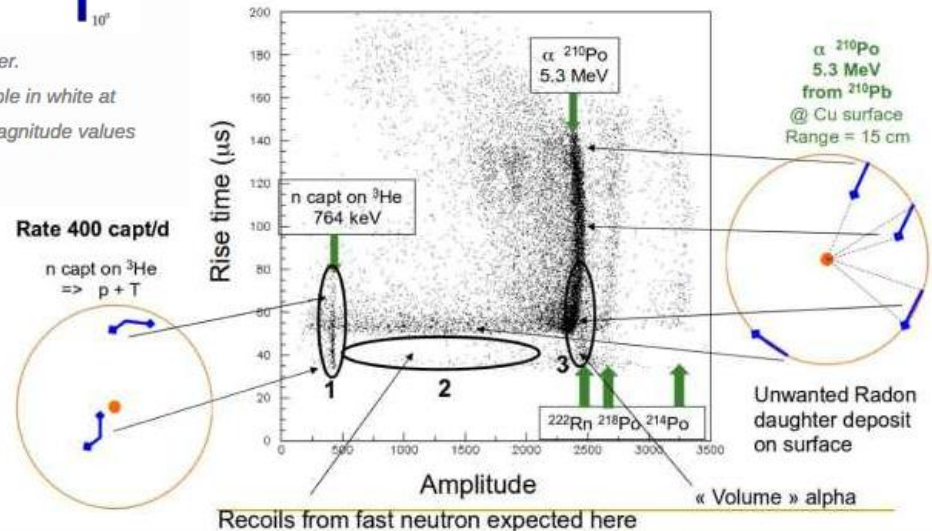


MATIERE SOMBRE



Left: Picture of SEDINE: a 60 cm diameter prototype made of low activity (NOSV) copper.

Right: Cross section of the detector in axial symmetry. The rod and the sensor are visible in white at scale. Field lines are shown on the right part of the picture only to allow the electric-field-magnitude values indicated in log scale by the color code to be properly seen.

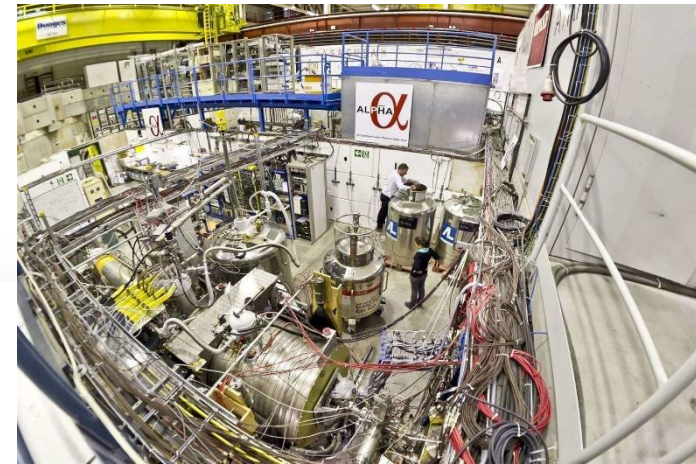
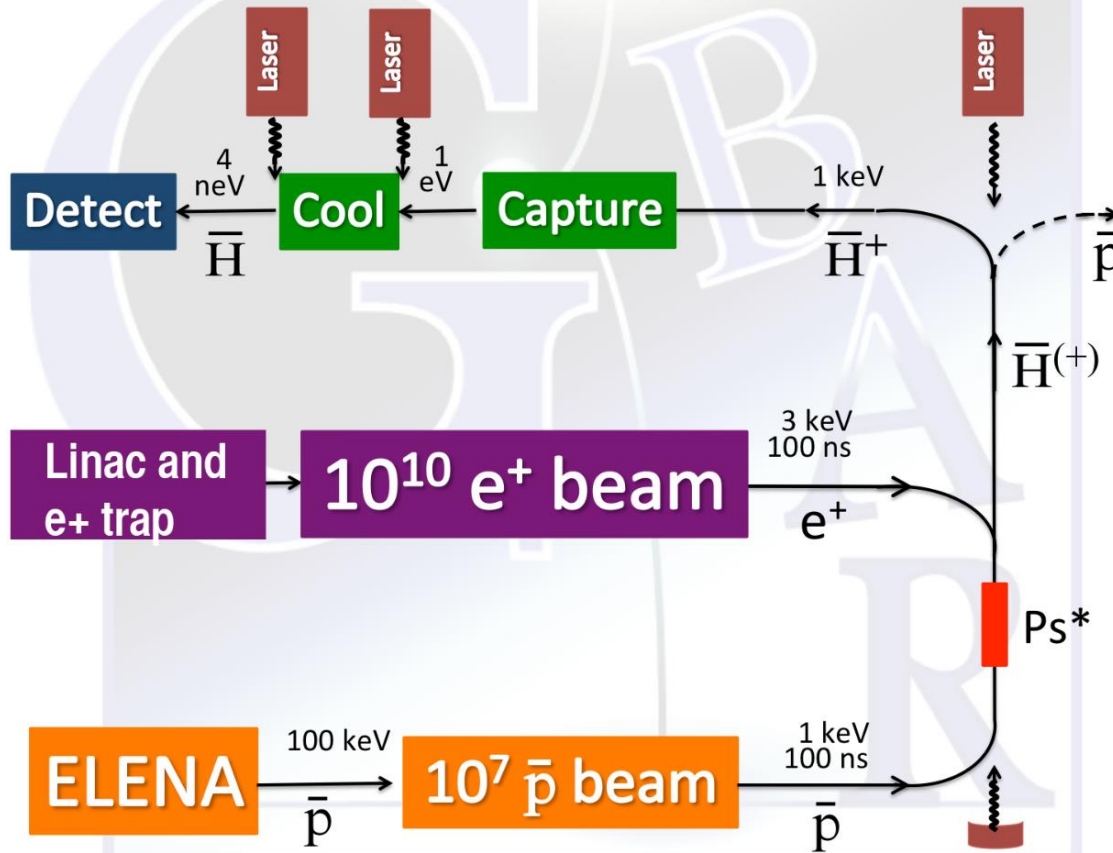


Ultimately, an electronic/nuclear recoil discrimination is feasible with this detector technology. However, this requires operating the SPC at low pressures (~100 mbar) such that electron interactions give rise to sizeable tracks. In such an operating mode, nuclear recoils induced by dark matter particles will still lead to point-like energy depositions while the discrimination of track-like electronic recoils will allow for a rejection of the associated radioactive background.

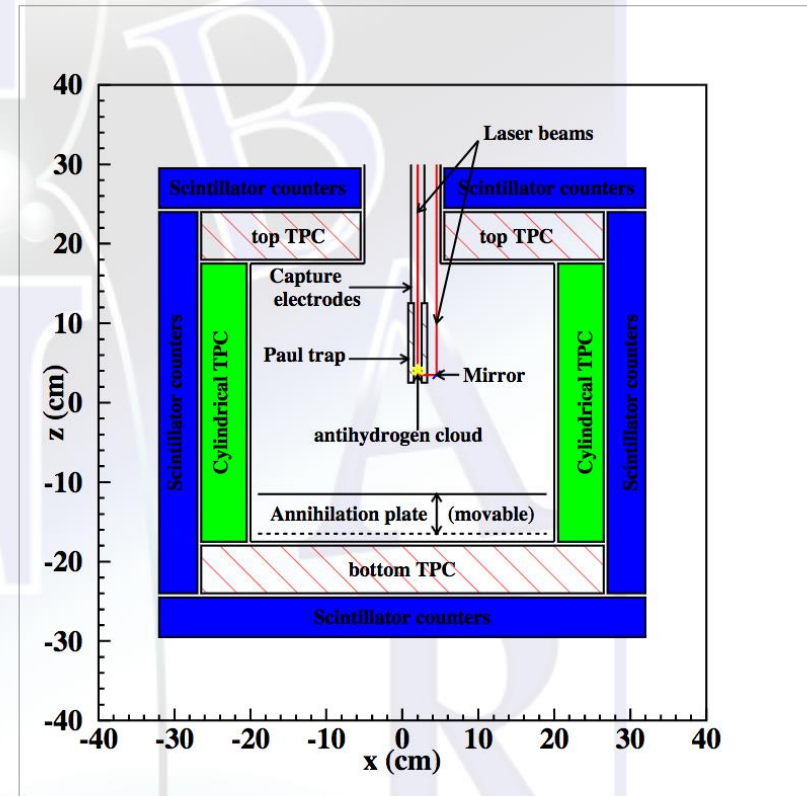
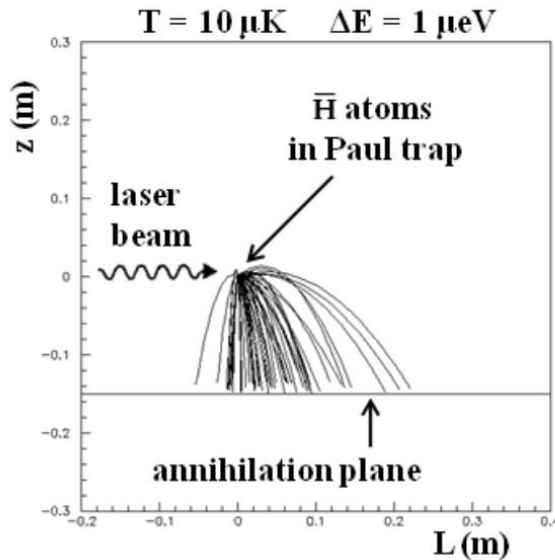
ANTI-MATIERE



Schematic



Detection



Detection requirement:

TOF precision : $150 \mu\text{s}$

Annihilation vertex precision : 1 mm

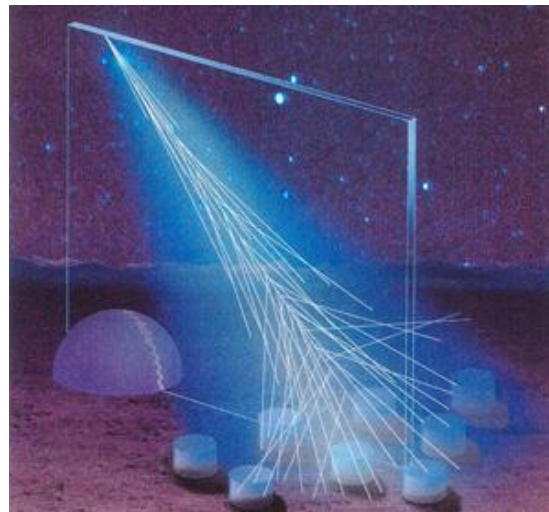
Background rejection through event topology

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

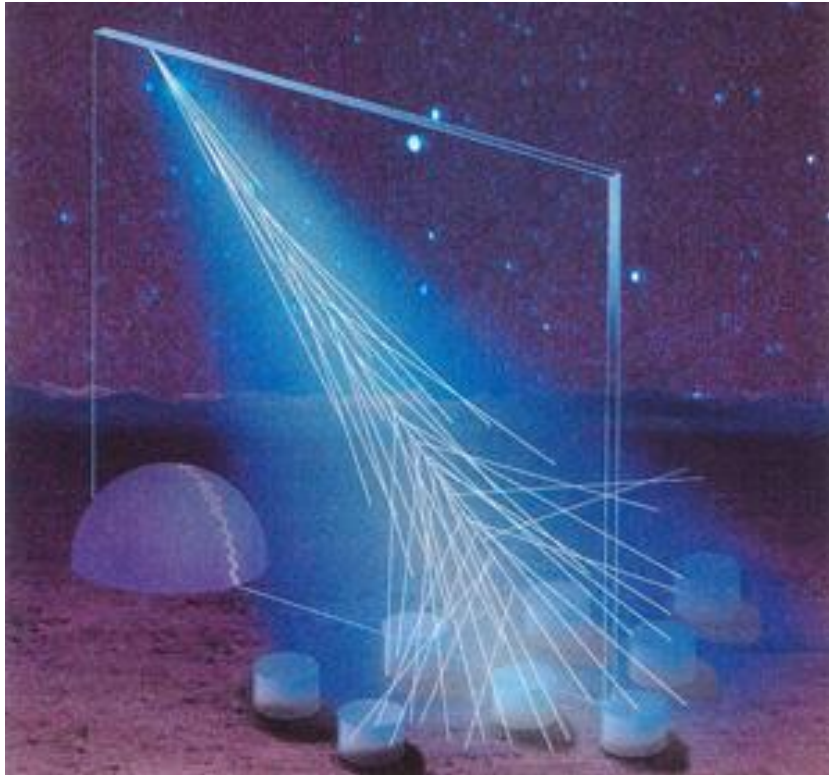
$$\frac{\Delta \bar{g}}{\bar{g}} \approx 10^{-2}$$



Pierre Auger Cosmic Ray Observatory



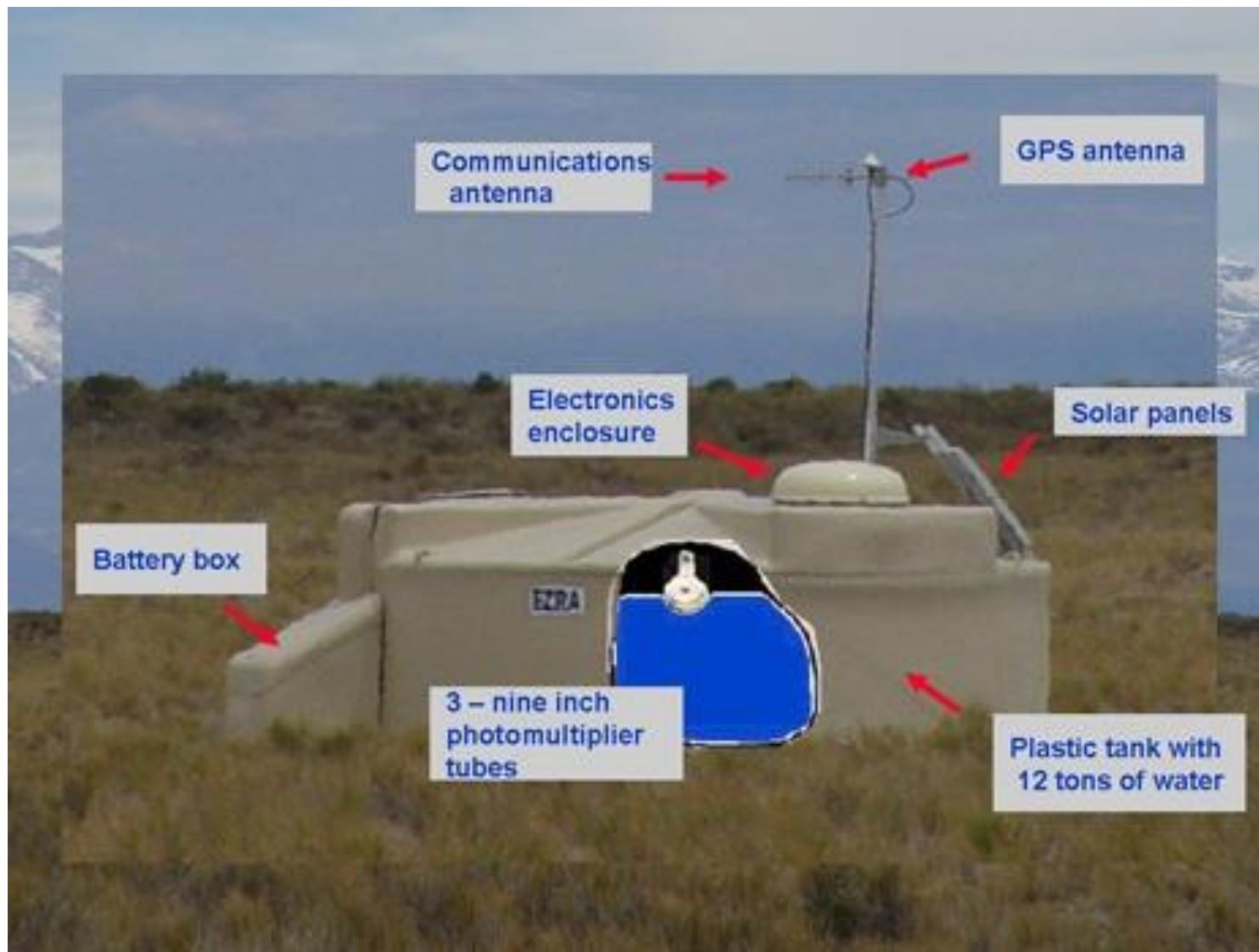
Pierre Auger Cosmic Ray Observatory

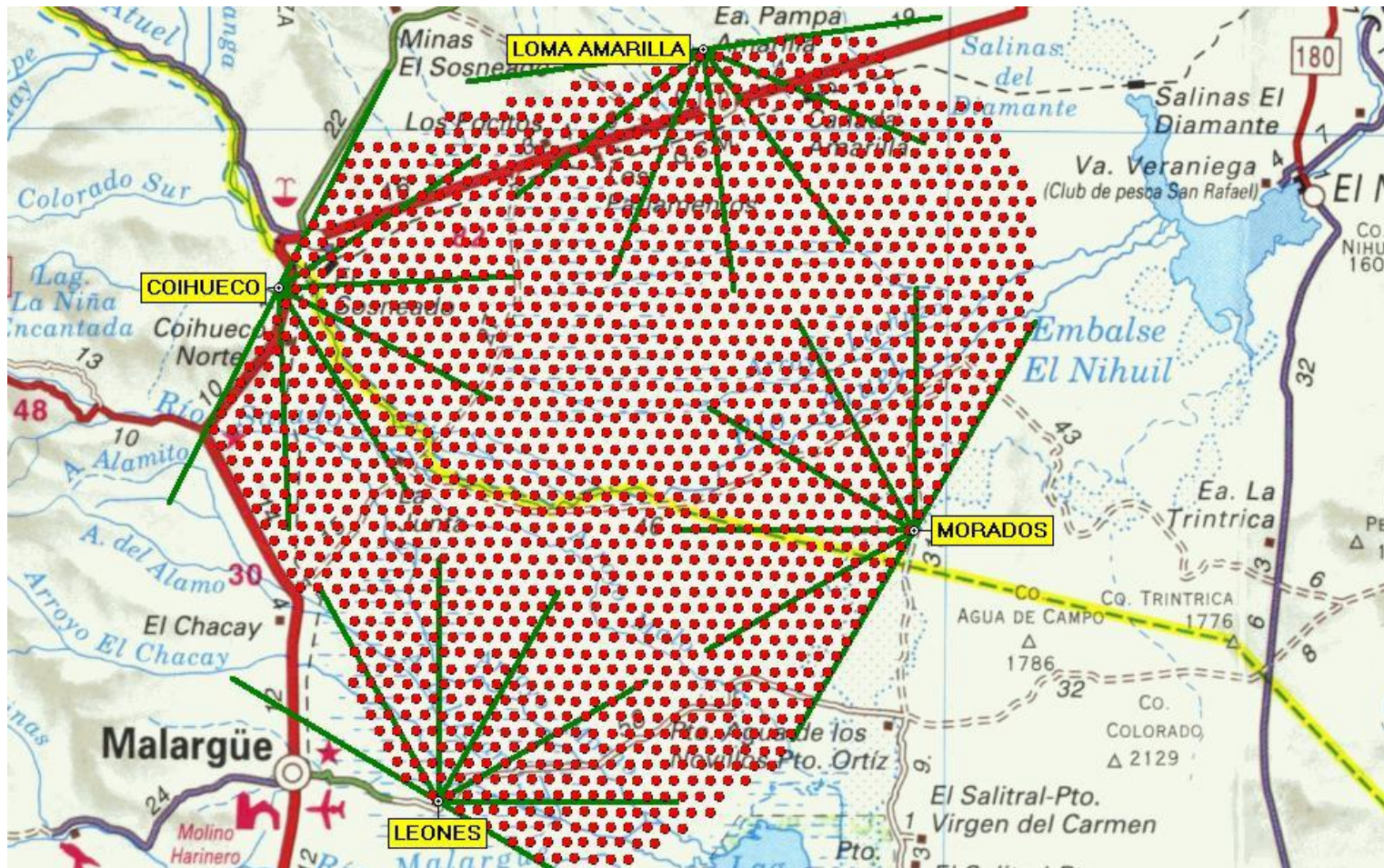


Use earth's atmosphere as a calorimeter. 1600 water Cherenkov detectors with 1.5km distance.

Placed in the Pampa Amarilla in western Argentina.

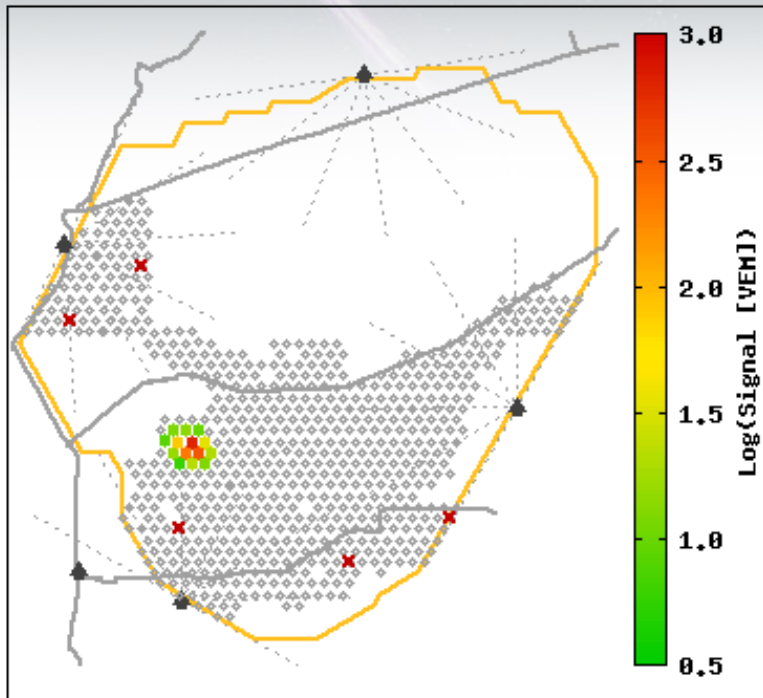






Event 1234800

[See CR incoming direction](#) | [See individual station data](#)

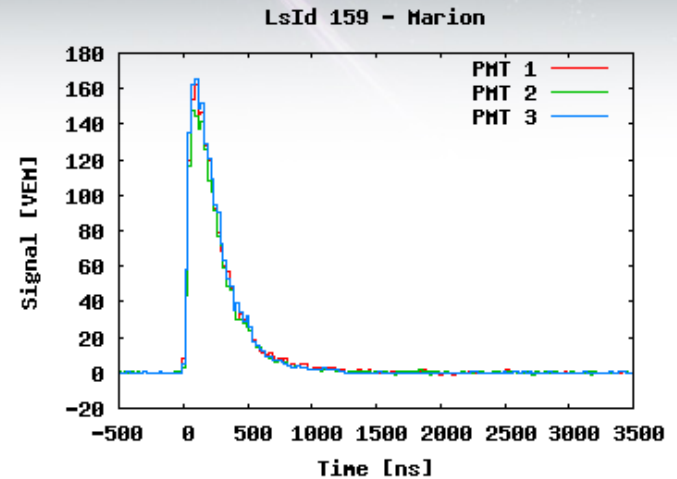


37 EeV = Exa Electron Volt = 37×10^{18} eV

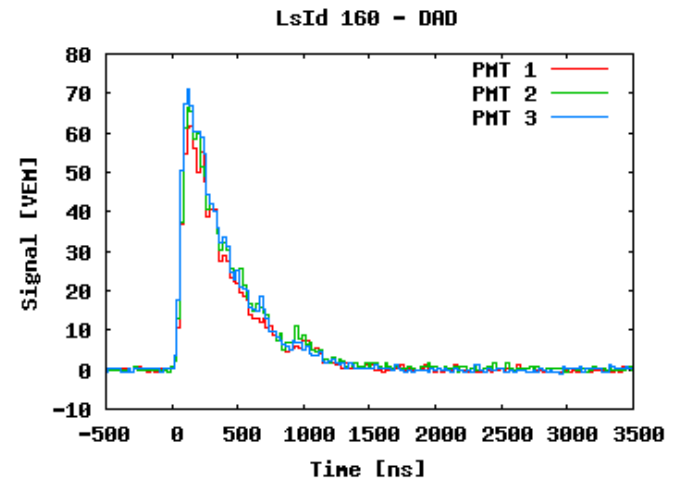
Generic Information	
Id	1234800
Date	Sat Mar 5 15:54:48 2005
Nb Station	14
Energy	37.4 ± 1.2 EeV
Theta	43.4 ± 0.1 deg
Phi	-27.3 ± 0.2 deg
Curvature	15.8 ± 0.8 km
Core Easting	460206 ± 20 m
Core Northing	6089924 ± 11 m
Reduced χ^2	2.30

Event 1234800

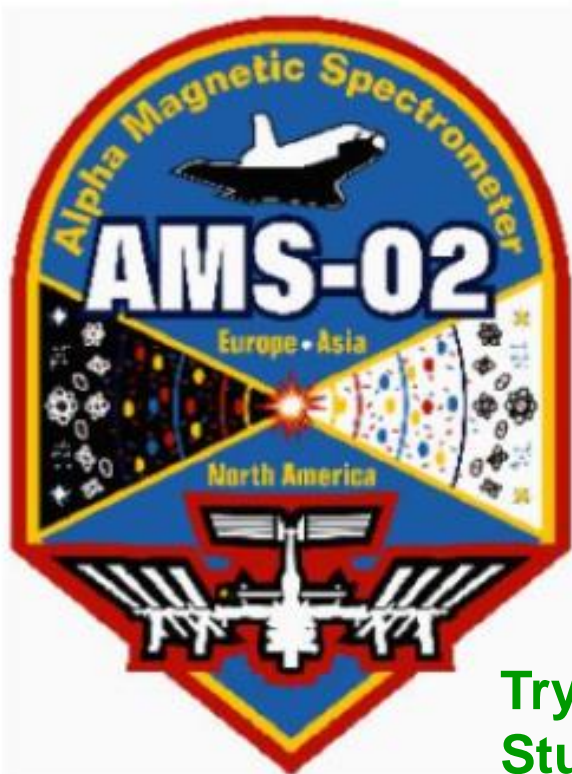
[See event reconstruction data](#) | [See CR incoming direction](#)



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

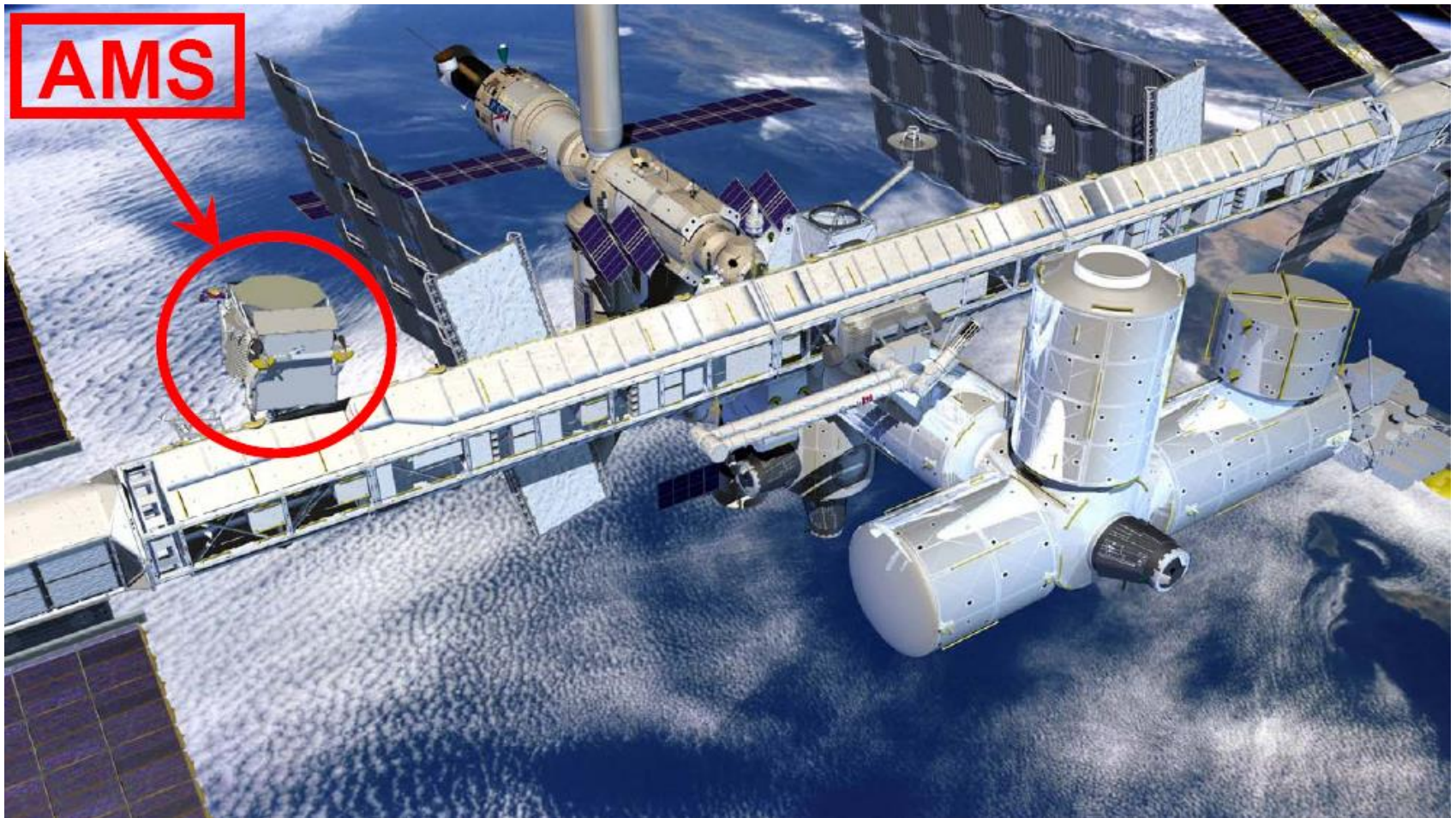


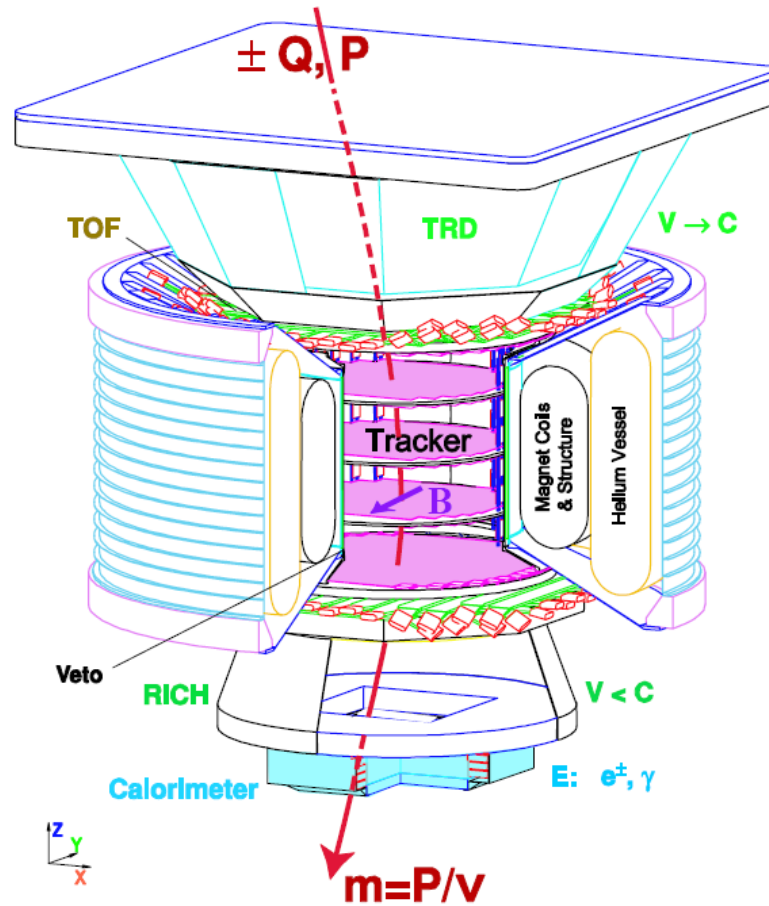
AMS

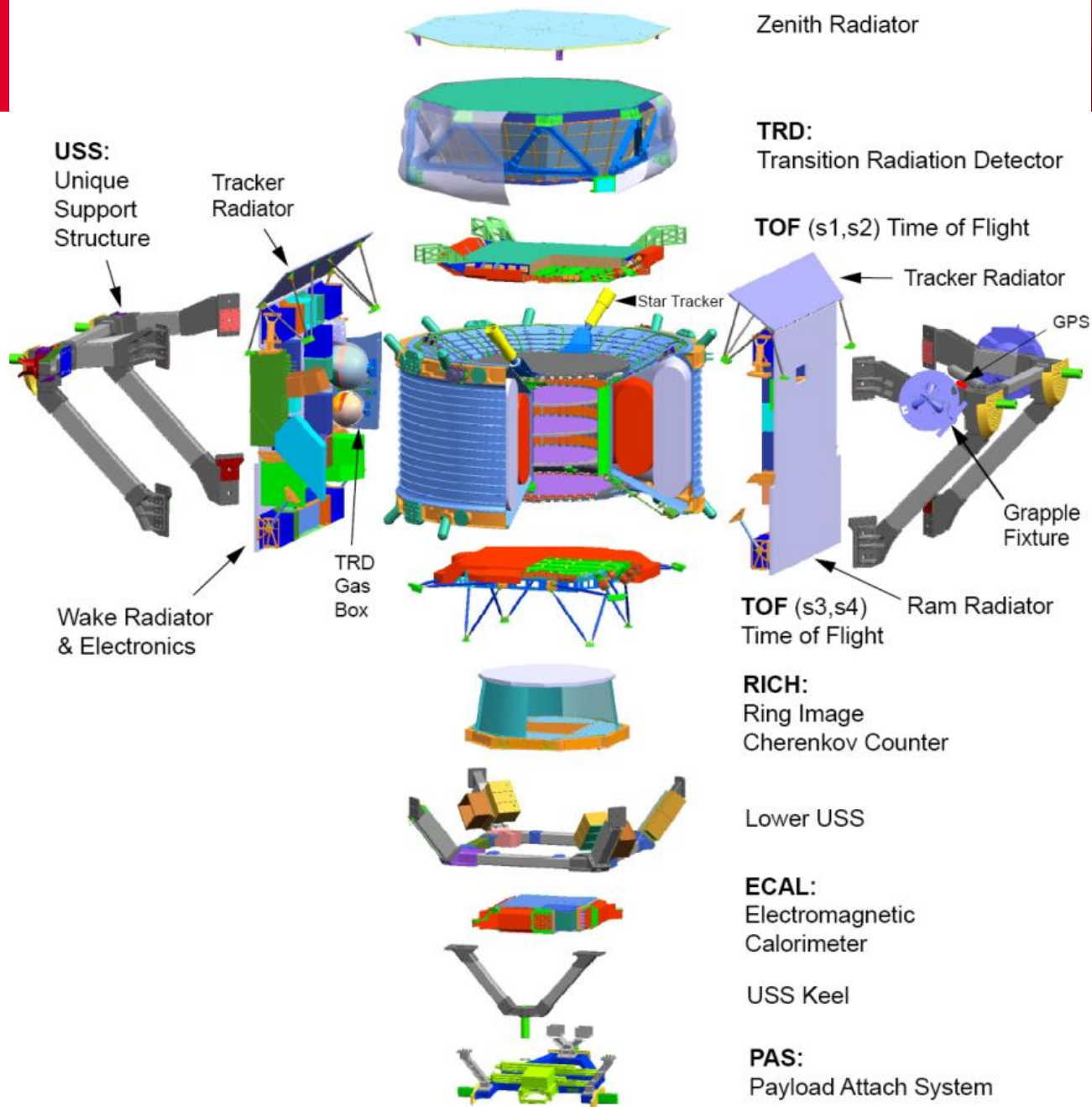
ALPHA MAGNETIC **S**PECTROMETER

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

Will be installed on the space station.

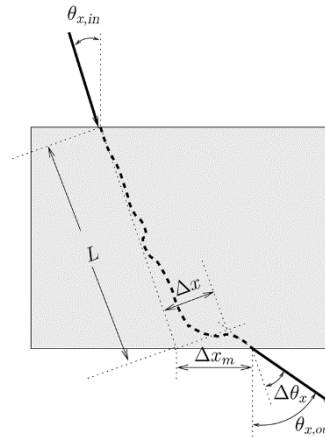






MUON TOMOGRAPHY

- Cosmic muons produced by cascade of reactions induced by cosmic rays in the upper atmosphere
 - Flux: $\sim 150/m^2/s \sim \cos^2\theta$ (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

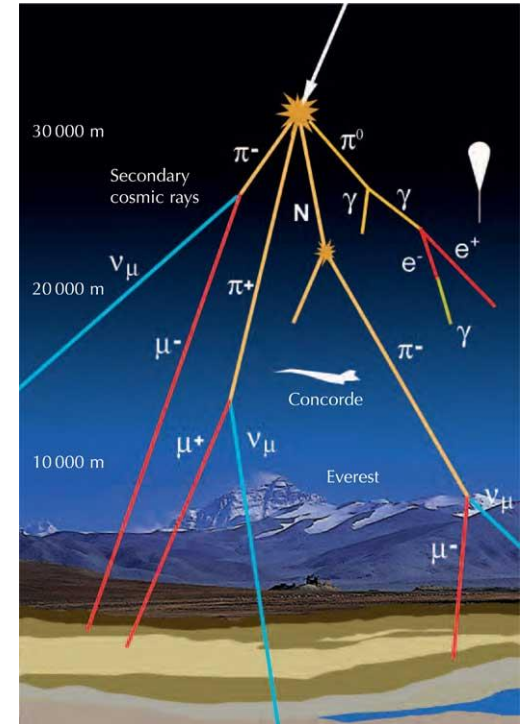
$$-\frac{dE}{ds} = \rho q^2 \frac{N_A e^4}{4\pi\epsilon_0^2 m_e c^2} \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right)$$

- Standard deviation of the scattering angle

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

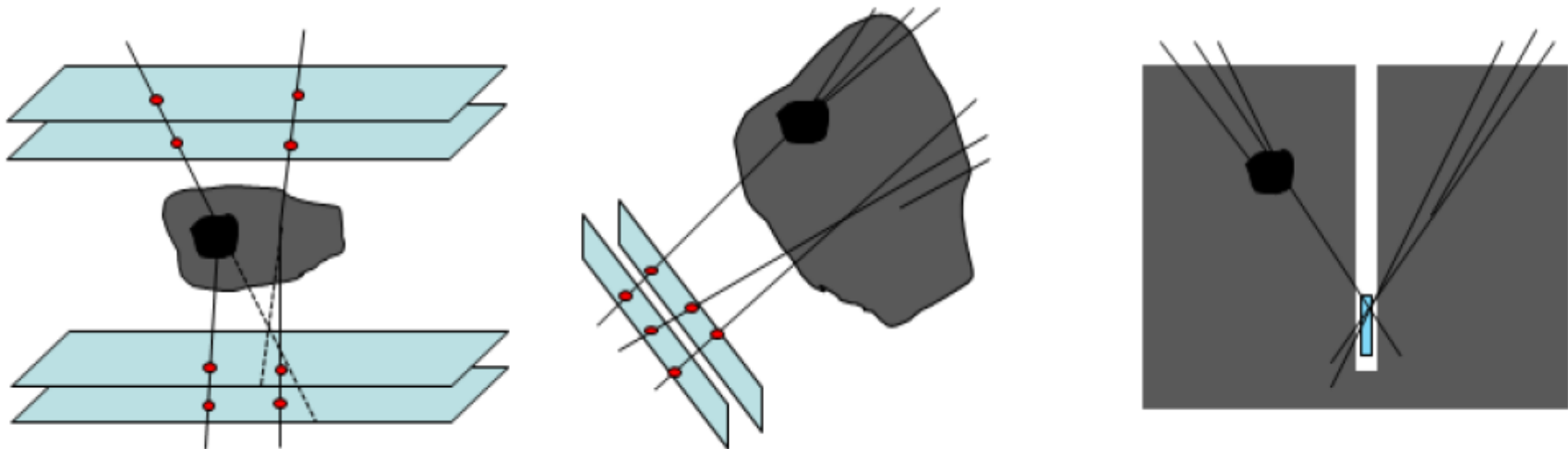
- Radiation length

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



Material	Thickness	θ (°)	$P_{\text{absorption}}$
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%

- 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

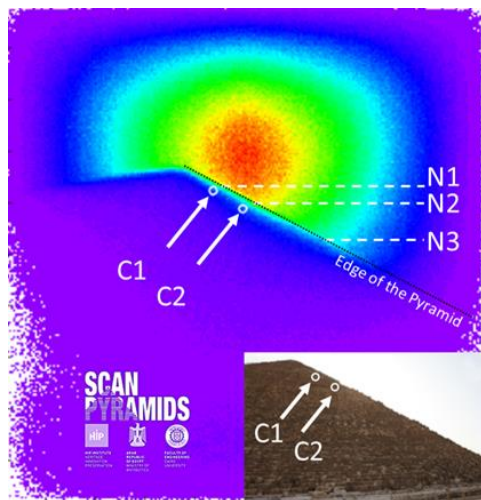


- High potential of societal applications in many fields:
 - volcanology, archaeology
 - mineral exploration, civil engineering, ...

- Discoveries of new cavities large void above the Grand Gallery

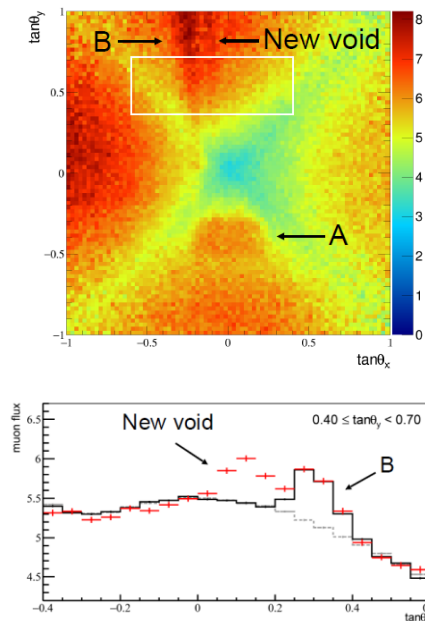
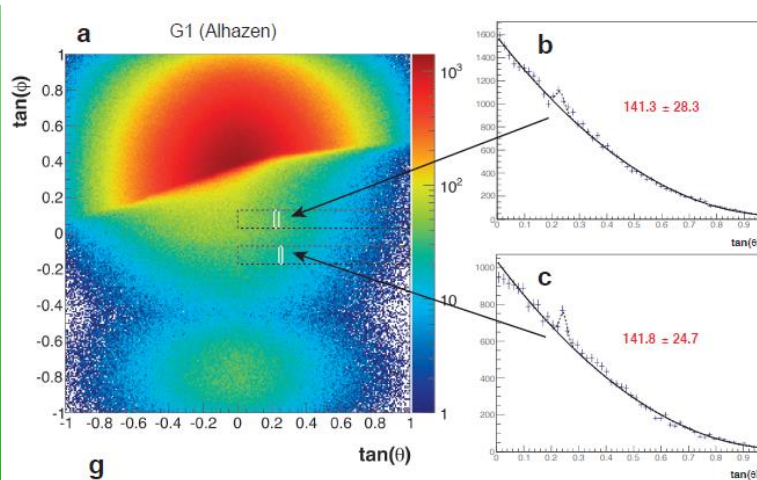
2016

CEA

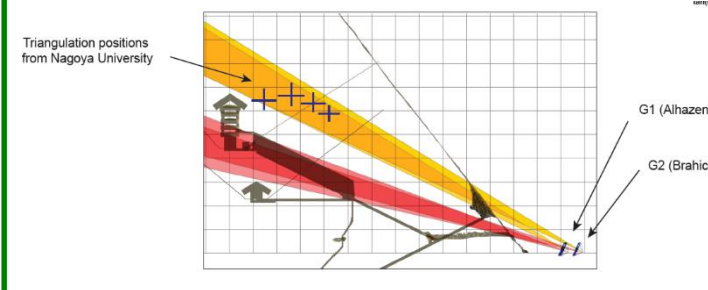


2017

Nagoya



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



Great

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

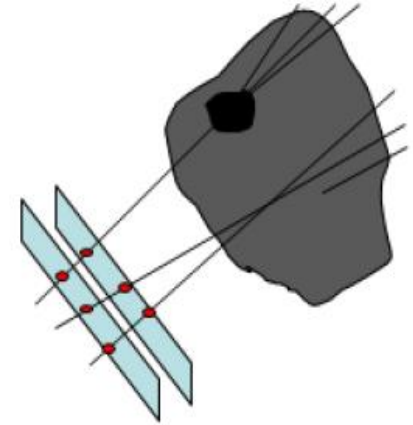
- Autour du Neutrino
- Nucléaire et Hadronique
- Rayons Cosmiques
- Antimatière

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

- Gaseous tracking detector for charge particle detection
- Muon tomography can be extracted from muon flux

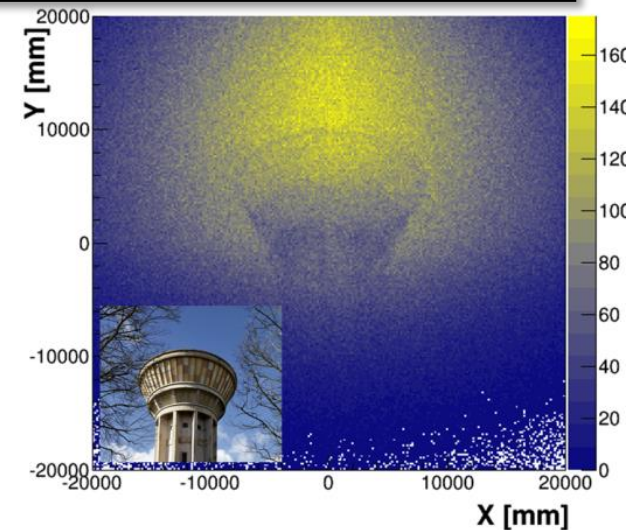


How to read a muography:

- *Each pixel is a number (or a flux) of reconstructed muons in the corresponding direction*
- *Light colour → more muon → less absorption → less matter*
- *Dark colour → less muons → more absorption → more matter*



- A demonstrator telescope was built:
 - transportable and easily functional
 - 4 × 2D resistive Micromegas
 - 3G connection for operation, monitoring and retrieve pre-processed data



- New telescope:
 - transportable and easily functional
 - 4 × 2D resistive Micromegas (version 2)
 - 3G connection for operation, monitoring and retrieve pre-processed data

