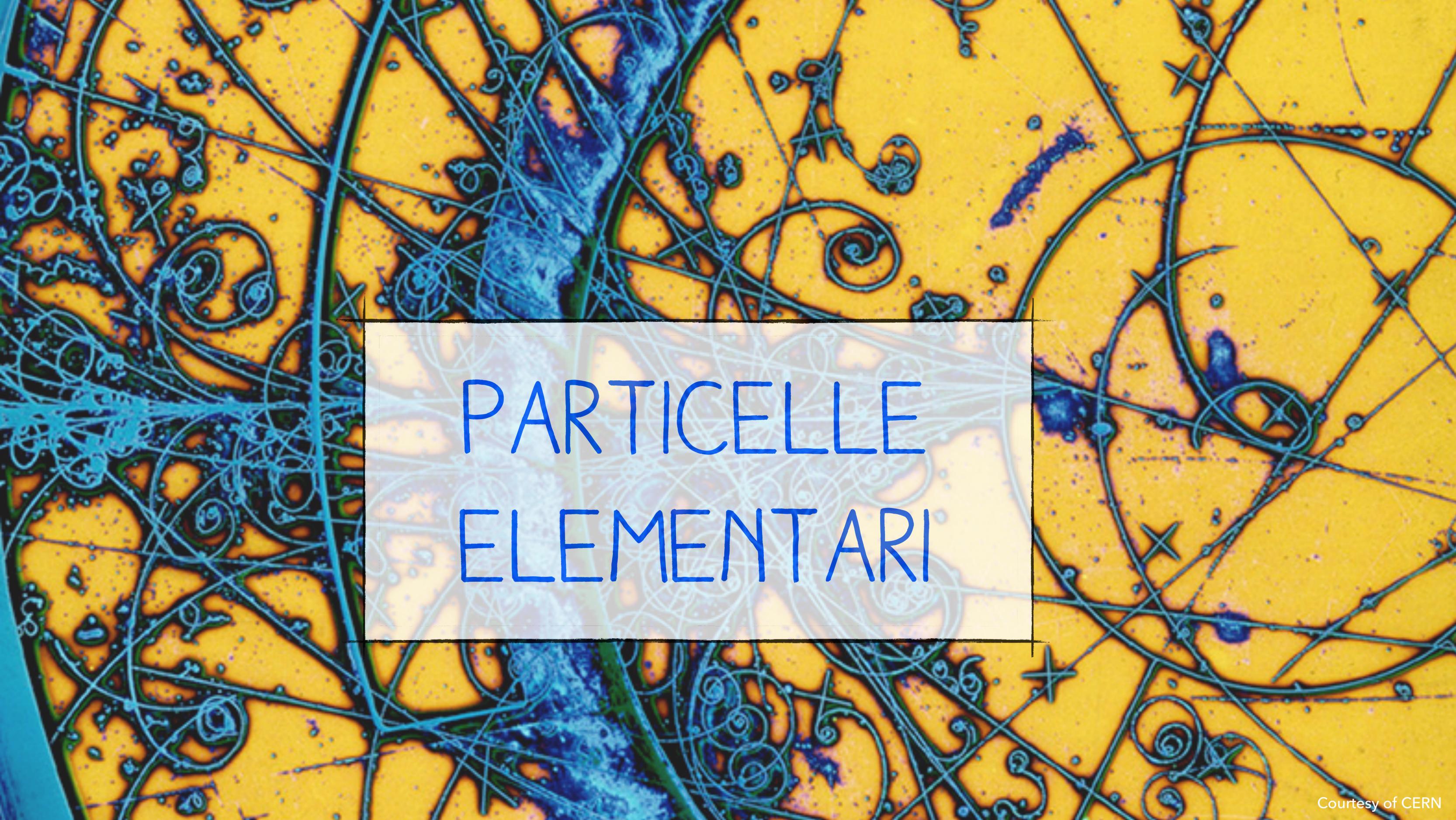




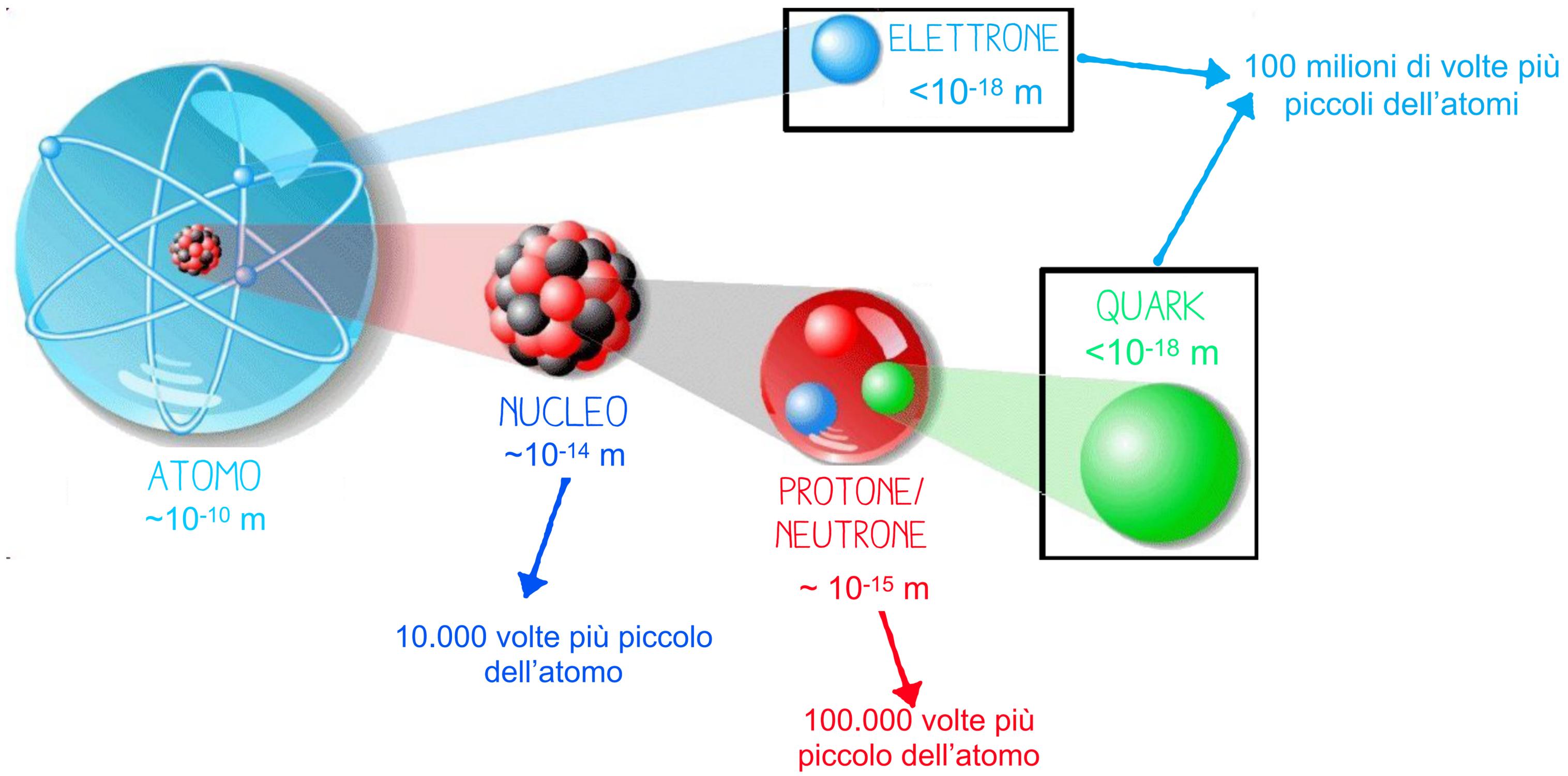
TECNICHE DI RIVELAZIONE DELLE PARTICELLE

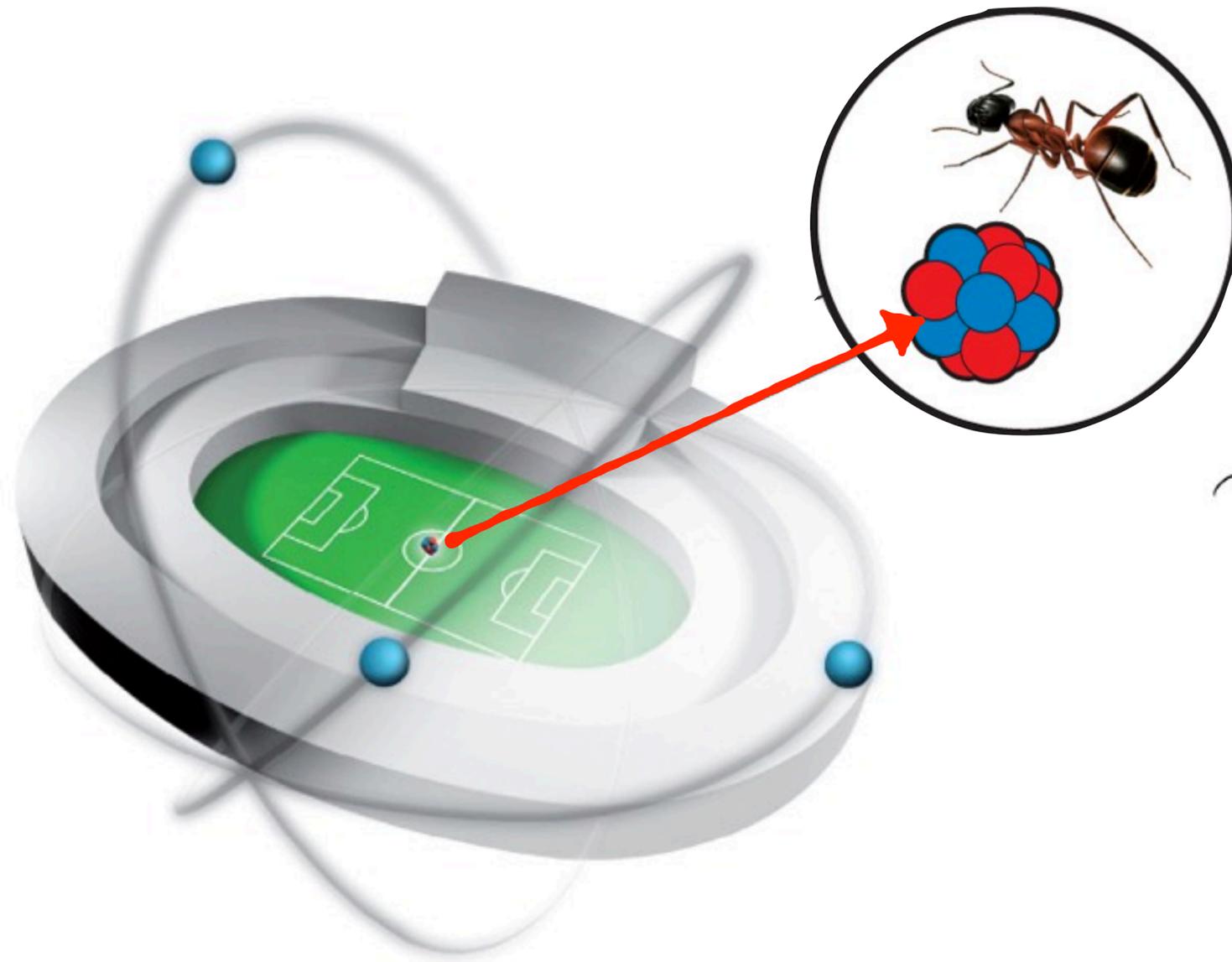
Chiara Oppedisano
INFN Torino

A complex visualization of particle tracks, likely from a bubble chamber or cloud chamber. The tracks are represented by thin, dark lines of varying thickness and color (blue, green, yellow) against a lighter, textured background. Some tracks are straight, while others are curved or spiral. There are also some larger, more diffuse blue and purple regions. The overall appearance is that of a dense network of paths.

PARTICELLE ELEMENTARI

PREFISSO	SIMBOLO	POTENZA DI 10
TERA-	T	10^{12}
GIGA-	G	10^9
MEGA-	M	10^6
KILO-	k	10^3
CENTI-	c	10^{-2}
MILLI-	m	10^{-3}
MICRO-	μ	10^{-6}
NANO-	n	10^{-9}
PICO-	p	10^{-12}





Gli atomi sono sostanzialmente...vuoti!!!
99.99999999999996% dell'atomo di H è vuoto!



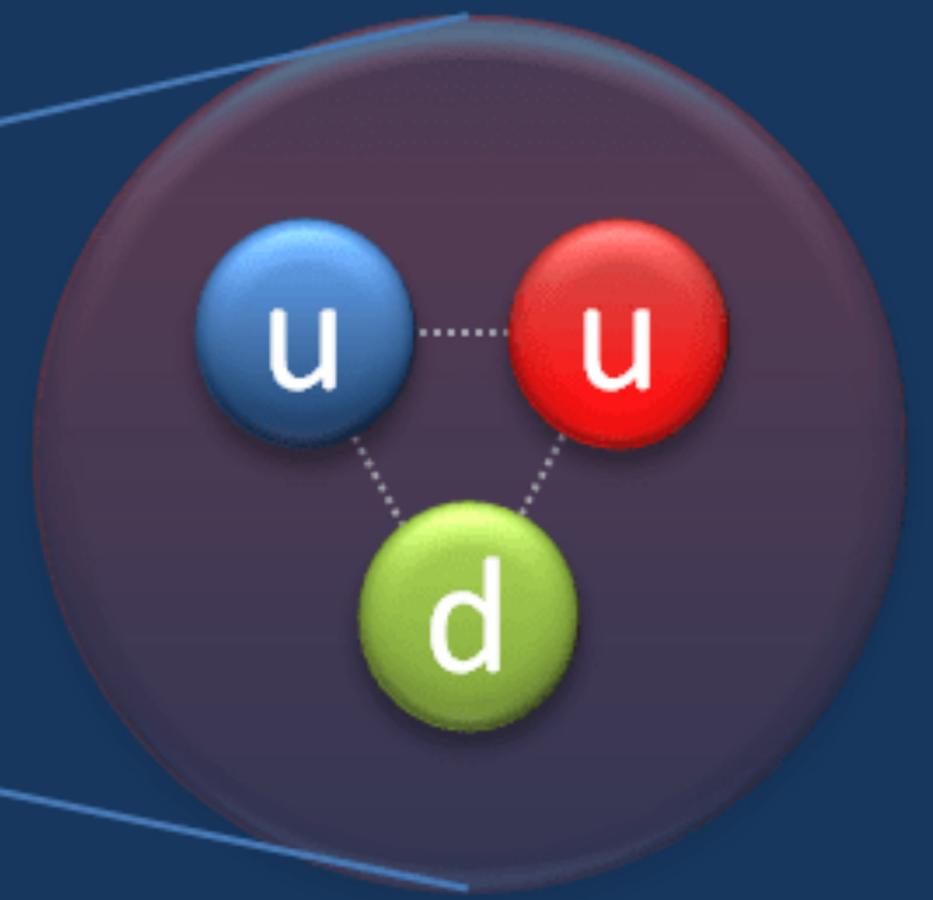
Se l'atomo avesse le dimensioni di uno stadio, il nucleo sarebbe grande quanto una biglia, protoni e neutroni come formiche (gli elettroni come pulci)

Atomo
di idrogeno

— elettrone

+ protone

quarks



PARTICELLE ELEMENTARI

QUARKS

LEPTONI

mass
charge
spin

$\approx 2.2 \text{ MeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
u
up

$\approx 1.28 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
c
charm

$\approx 173.1 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
t
top

0
0
1
g
gluon

$\approx 124.97 \text{ GeV}/c^2$
0
0
0
H
higgs

$\approx 4.7 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
d
down

$\approx 96 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
s
strange

$\approx 4.18 \text{ GeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
b
bottom

0
0
1
 γ
photon

$\approx 0.511 \text{ MeV}/c^2$
-1
 $\frac{1}{2}$
e
electron

$\approx 105.66 \text{ MeV}/c^2$
-1
 $\frac{1}{2}$
 μ
muon

$\approx 1.7768 \text{ GeV}/c^2$
-1
 $\frac{1}{2}$
 τ
tau

$\approx 91.19 \text{ GeV}/c^2$
0
1
Z
Z boson

$< 2.2 \text{ eV}/c^2$
0
 $\frac{1}{2}$
 ν_e
electron neutrino

$< 0.17 \text{ MeV}/c^2$
0
 $\frac{1}{2}$
 ν_μ
muon neutrino

$< 18.2 \text{ MeV}/c^2$
0
 $\frac{1}{2}$
 ν_τ
tau neutrino

$\approx 80.39 \text{ GeV}/c^2$
 ± 1
1
W
W boson

BOSONI DI GAUGE

PARTICELLE ELEMENTARI

mass
charge
spin

$\approx 2.2 \text{ MeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
u
up

$\approx 1.28 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
c
charm

$\approx 173.1 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
t
top

0
0
1
g
gluon

$\approx 4.7 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
d
down

$\approx 96 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
s
strange

$\approx 4.18 \text{ GeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
b
bottom

0
0
1
 γ
photon

$\approx 0.511 \text{ MeV}/c^2$
-1
 $\frac{1}{2}$
e
electron

$\approx 105.66 \text{ MeV}/c^2$
-1
 $\frac{1}{2}$
 μ
muon

$\approx 1.7768 \text{ GeV}/c^2$
-1
 $\frac{1}{2}$
 τ
tau

$\approx 91.19 \text{ GeV}/c^2$
0
1
Z
Z boson

$< 2.2 \text{ eV}/c^2$
0
 $\frac{1}{2}$
 ν_e
electron neutrino

$< 0.17 \text{ MeV}/c^2$
0
 $\frac{1}{2}$
 ν_μ
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$< 18.2 \text{ MeV}/c^2$
0
 $\frac{1}{2}$
 ν_τ
tau neutrino

$\approx 80.39 \text{ GeV}/c^2$
 ± 1
1
W
W boson

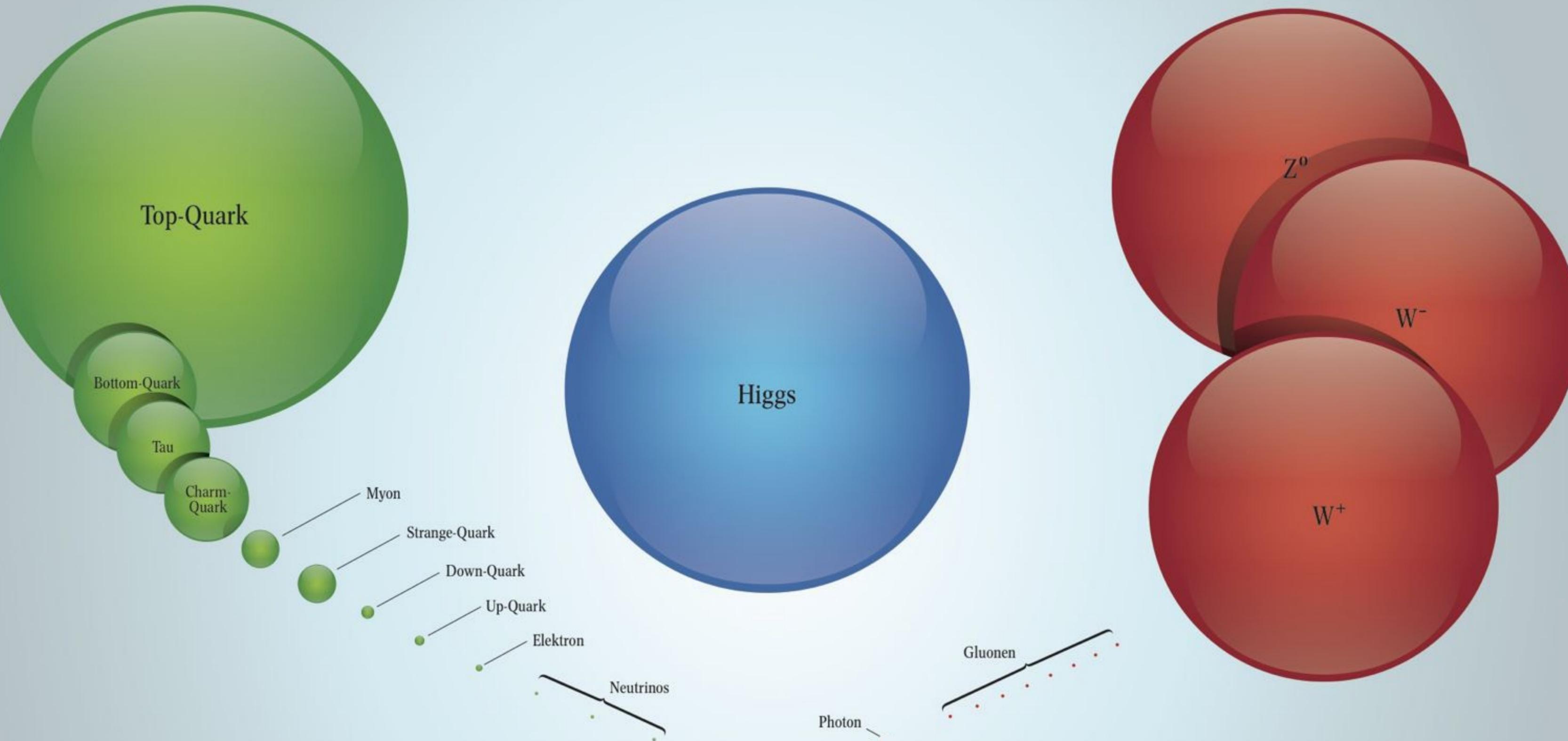
Strong

Electro Magnetic

Weak

INTERAZIONI FONDAMENTALI

MASSA DELLE PARTICELLE FONDAMENTALI





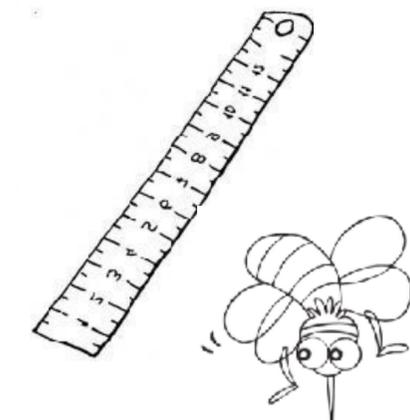
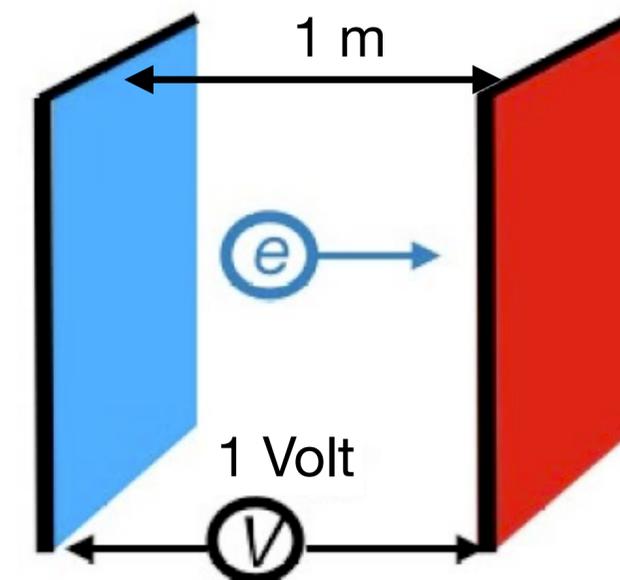
In fisica delle particelle **ENERGIA** e **MASSA** si misurano in **elettronvolt** (eV)

1 eV = aumento di energia di un elettrone che si muove nel vuoto tra due punti posti ad 1 m di distanza tra i quali vi è una differenza di potenziale pari a 1 V

$$1 \text{ eV} = q \Delta V = (1.602 \times 10^{-19} \text{ C}) \times (1 \text{ V})$$

$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$

$$1 \text{ J} = 6.24 \times 10^{18} \text{ eV}$$



Due numeri:

▶ Lisa salta da un'altezza di 1 m ha energia $E = mgh = 60 \text{ kg} \times 9.8 \text{ m/s}^2 \times 1 \text{ m} = 588 \text{ J}$

▶ LHC accelera protoni a: $7 \text{ TeV} = 7 \times 10^{12} \text{ eV} = 1.12 \times 10^{-6} \text{ J}$

zanzara ▶ 1 TeV in $\sim 10^{-2} \text{ m}$

protone ▶ 7 TeV in 10^{-15} m

▶ RELATIVITÀ RISTRETTA

Particelle accelerate a velocità prossime alla velocità della luce ▶ utilizziamo la relatività ristretta

Velocità della luce c (valore limite, invariante = è la stessa per qualsiasi osservatore) $c = 3 \cdot 10^8 \text{ m/s}$

Moto classico ▶ $v \ll c$

momento

$$\vec{p} = m\vec{v}$$

energia cinetica

$$E_{\text{kin}} = \frac{1}{2}mv^2$$



Moto relativistico ▶ $v \sim c$

velocità

$$\beta = \frac{v}{c}$$

fattore γ

$$\gamma = \sqrt{\frac{1}{1-\beta^2}}$$

momento

$$\vec{p} = \gamma m\vec{v}$$

energia cinetica

$$T = (\gamma - 1)mc^2$$

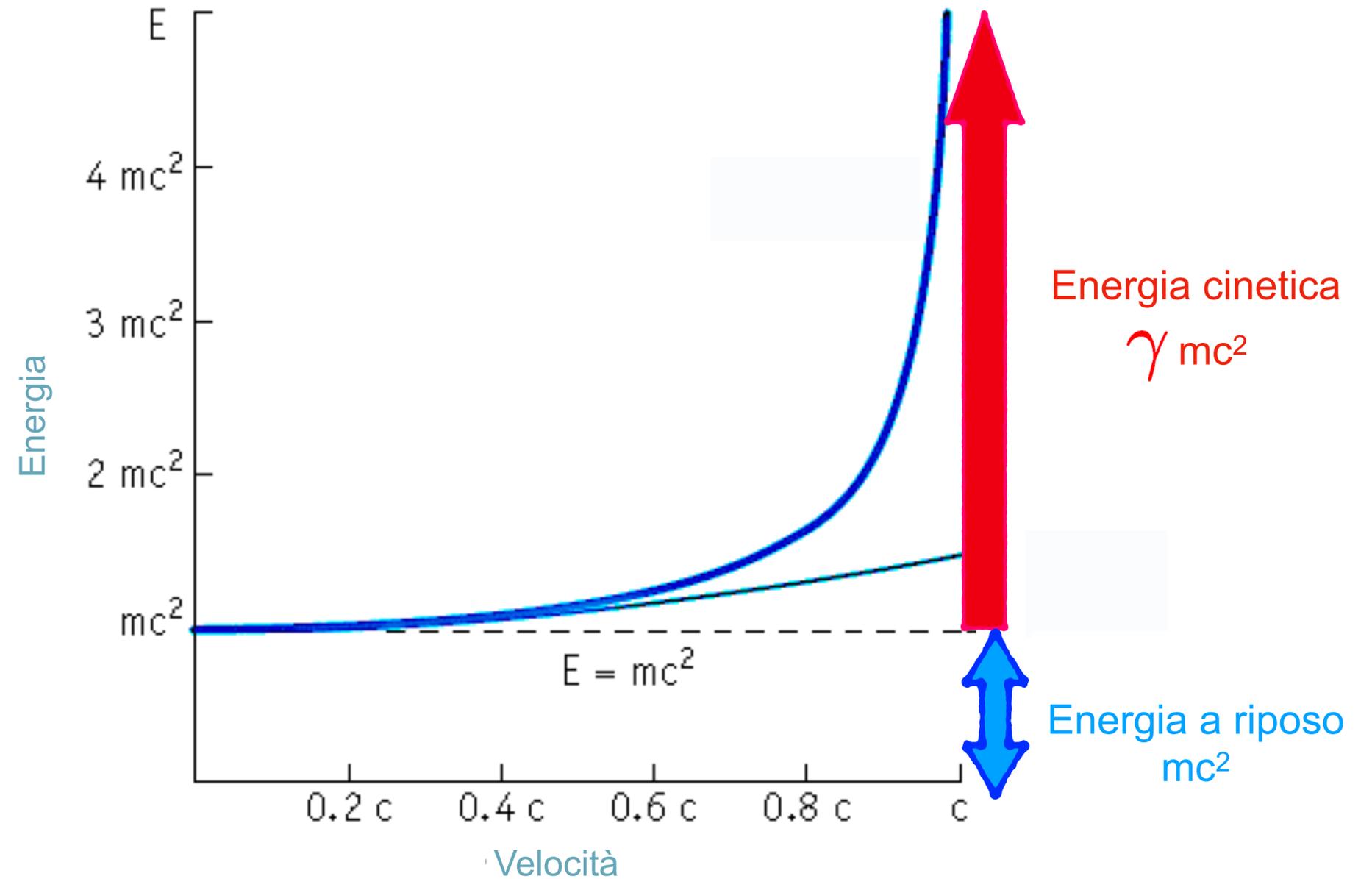
▶ RELATIVITÀ RISTRETTA

Energia invariante relativistico

$$E^2 = p^2 c^2 + m^2 c^4$$

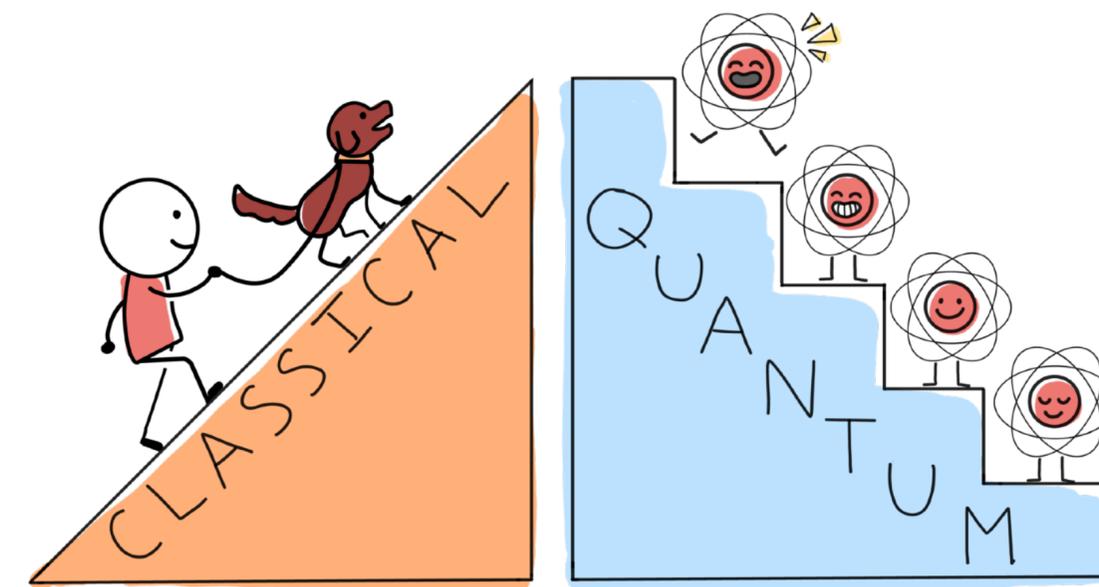
Energia cinetica

Energia a riposo



► MECCANICA QUANTISTICA

Principio di indeterminazione



$$\Delta x \Delta p \geq \hbar$$

Costante di Plank

$$\hbar = h/(2\pi) = 1.05 \cdot 10^{-34} \text{ kg} \cdot \text{m/s}$$

Incertezza sulla misura della POSIZIONE x della particella

Incertezza sulla misura della QUANTITÀ DI MOTO $p = mv$ della particella

Sinner e il principio di
indeterminazione



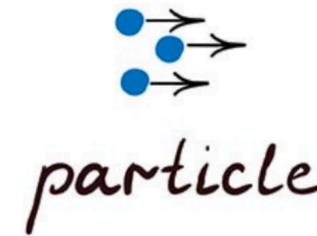
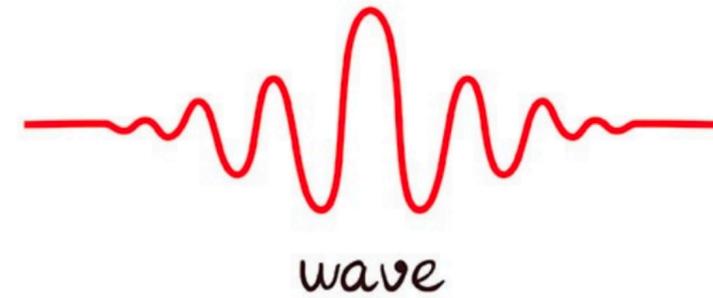
$$\Delta x \Delta p > \hbar$$



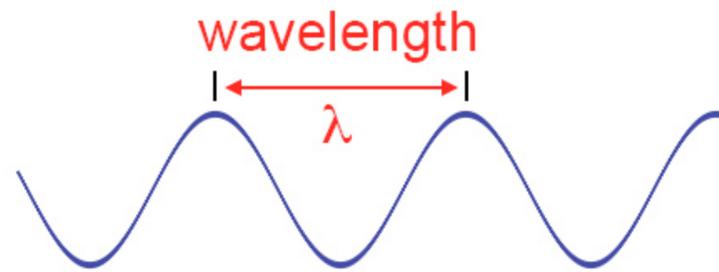
$$\Delta x \Delta p > \hbar$$



► MECCANICA QUANTISTICA



Dualità proprietà particellari e ondulatorie ► lunghezza d'onda associata alla particella



$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

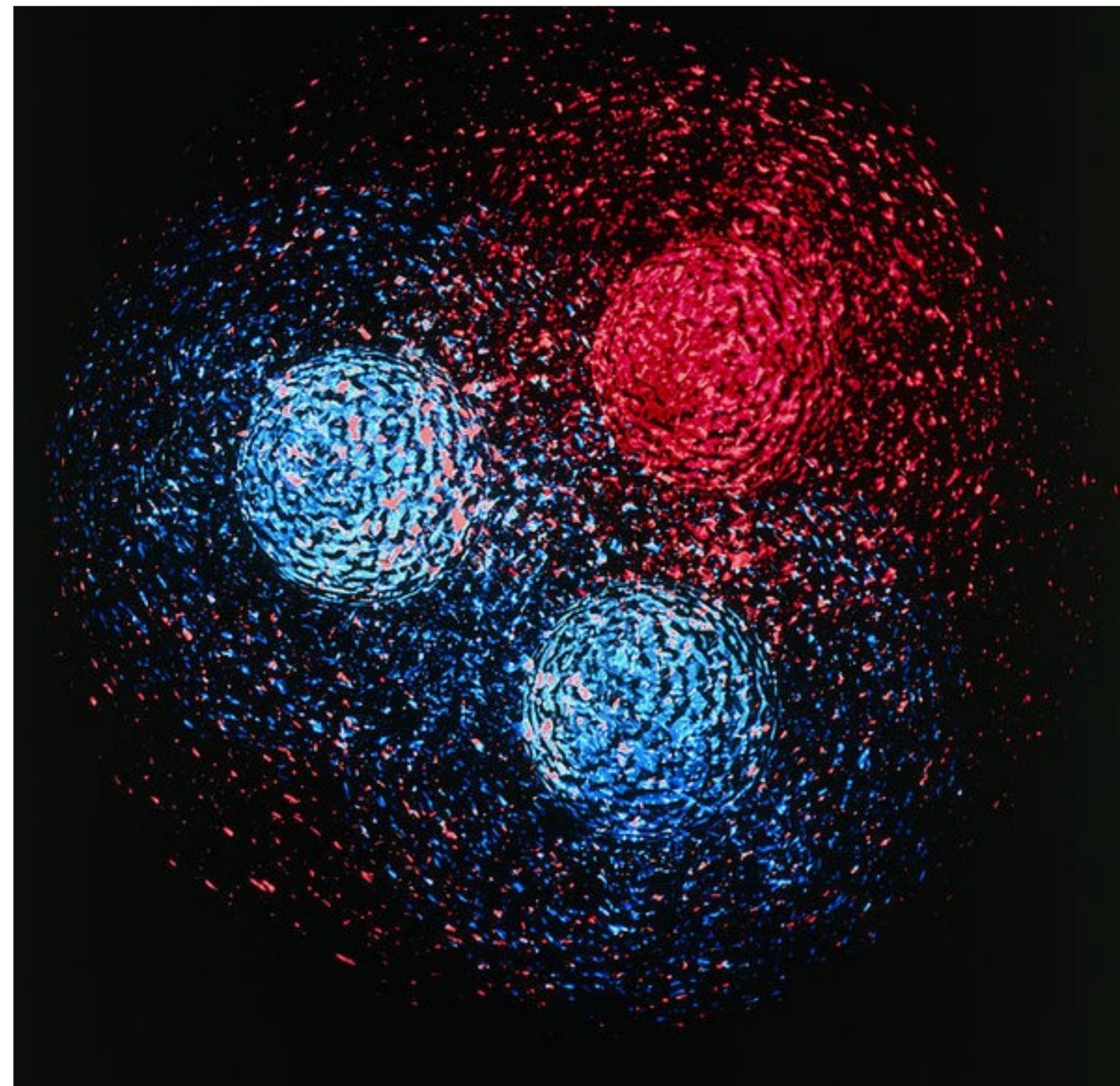
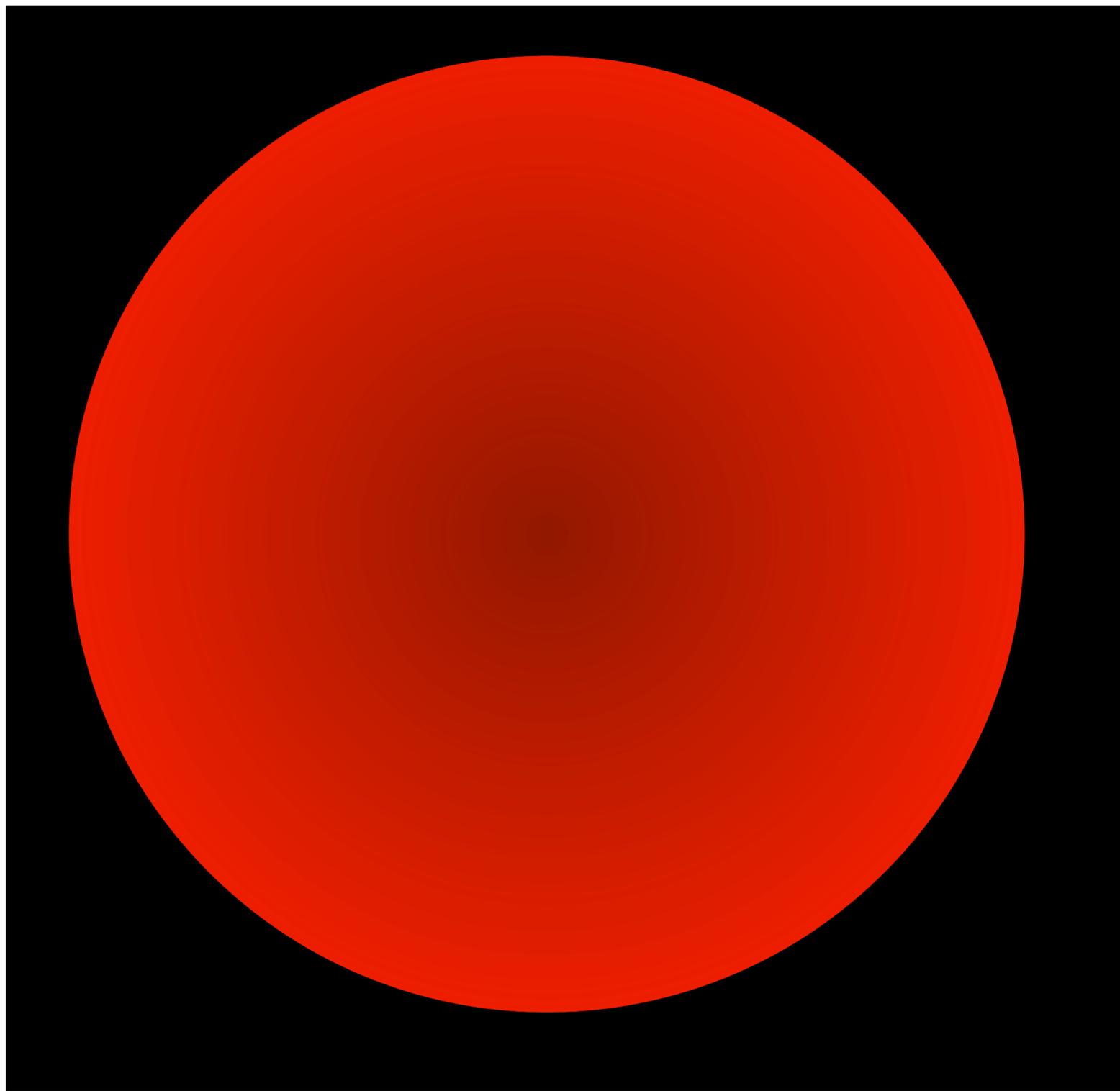
de Broglie

Accelero particelle con grande energia E ► grande momento p (massa \times velocità) ► piccola λ

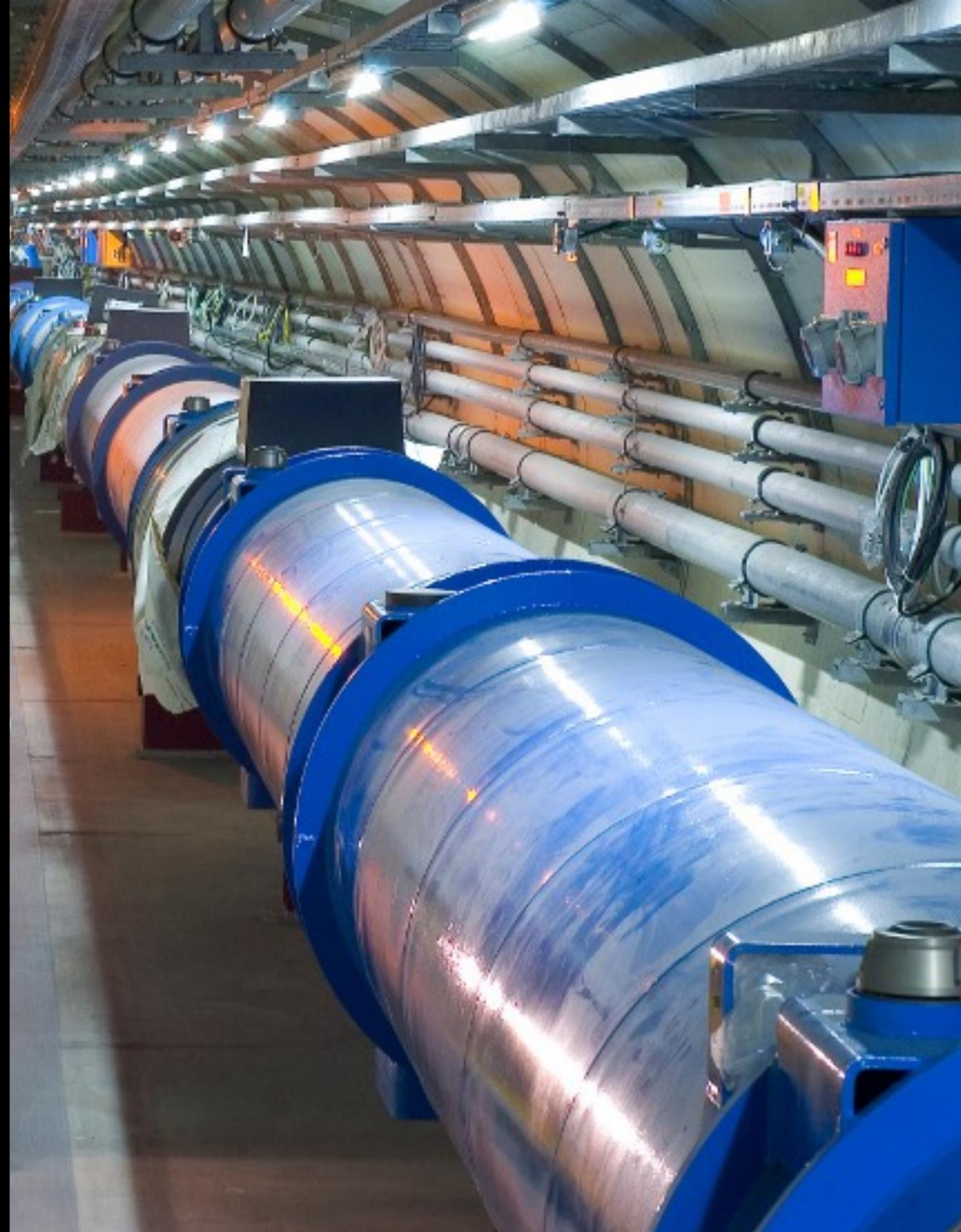
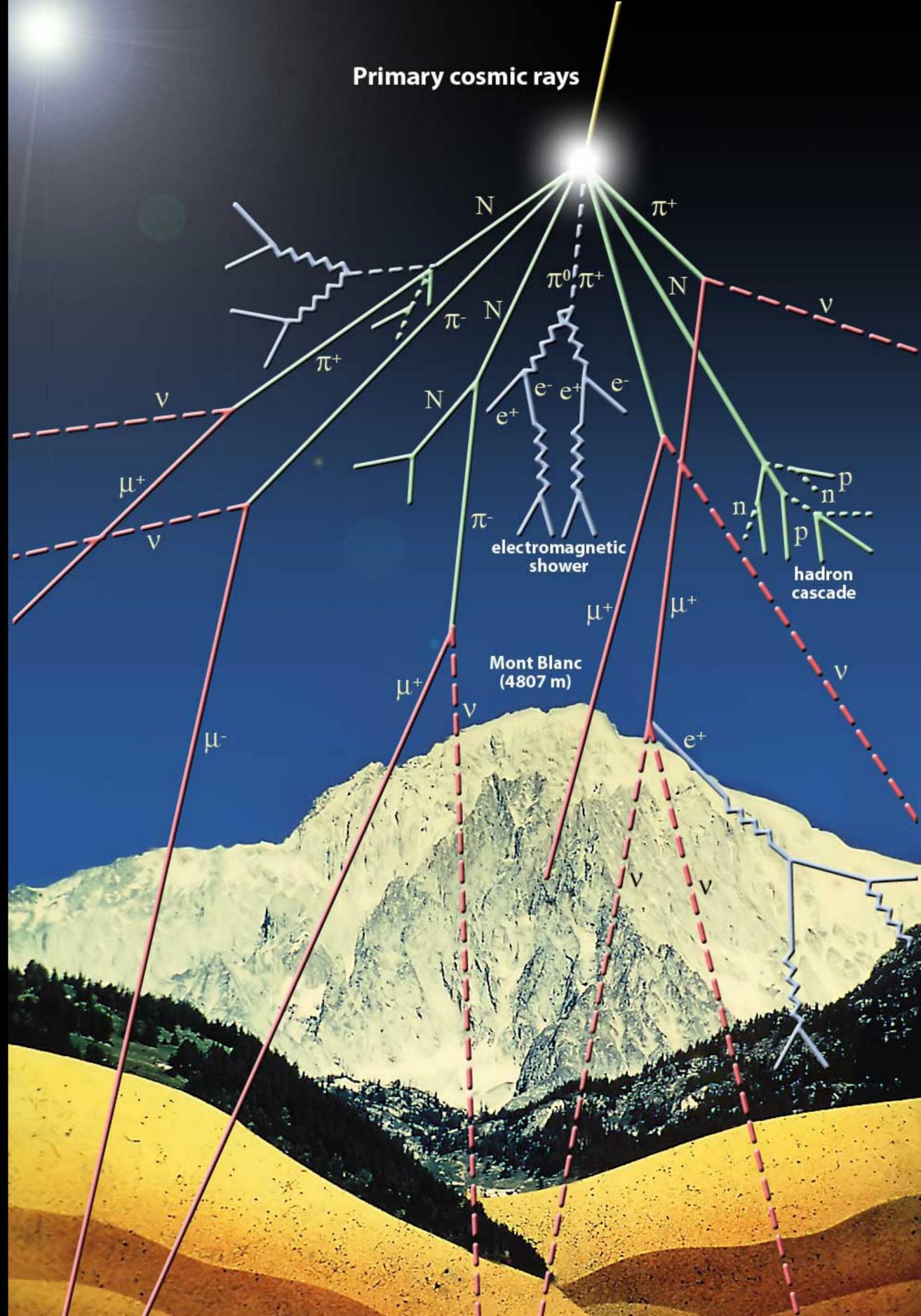
Fasci di protoni accelerati a $13000 \text{ GeV} = 13 \text{ TeV}$ all'LHC:

$$\lambda = \frac{2\pi\hbar c}{pc} = \frac{2\pi \cdot 197 \text{ MeV} \cdot \text{fm}}{13 \text{ TeV}} = \frac{2\pi \cdot 197 \text{ MeV} \cdot \text{fm}}{13 \cdot 10^6 \text{ MeV}} \sim 10^{-4} \text{ fm} = 10^{-20} \text{ m}$$

PROTONE O QUARKS?



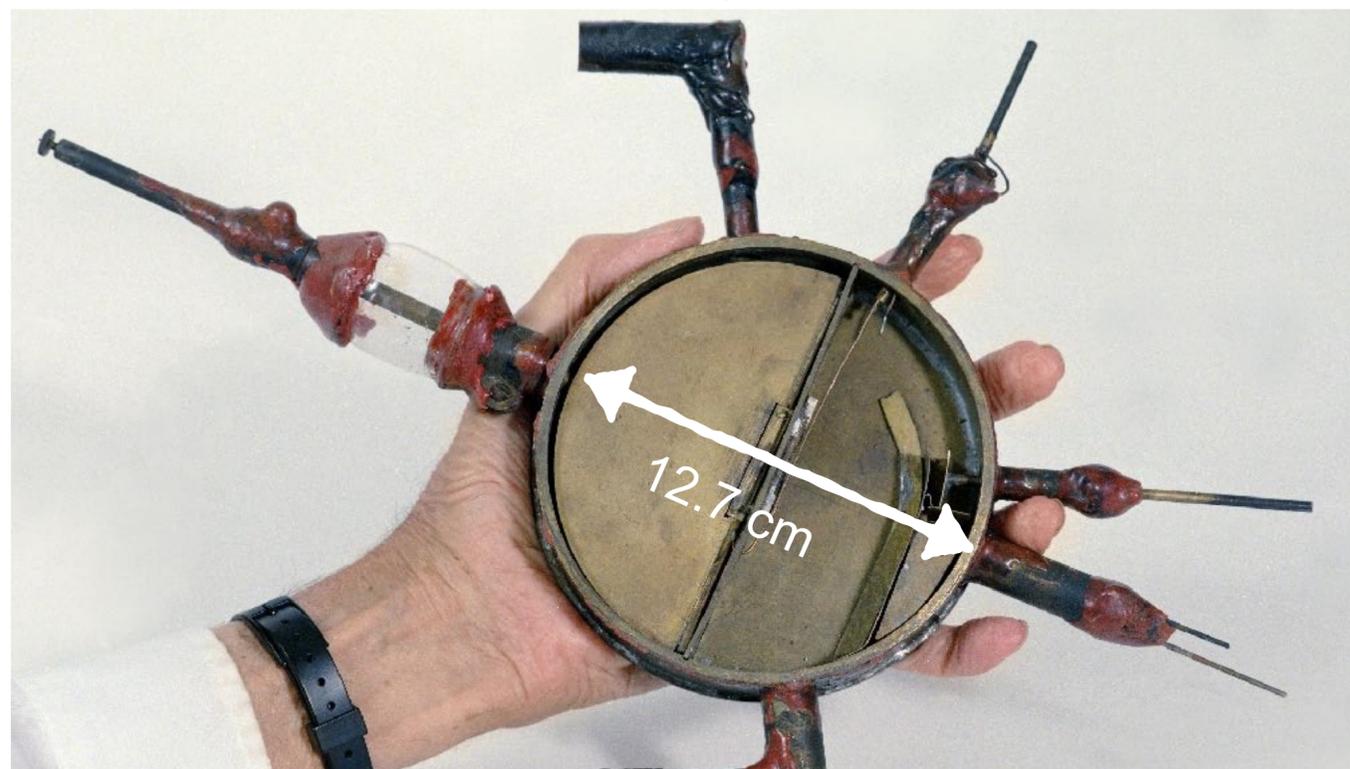
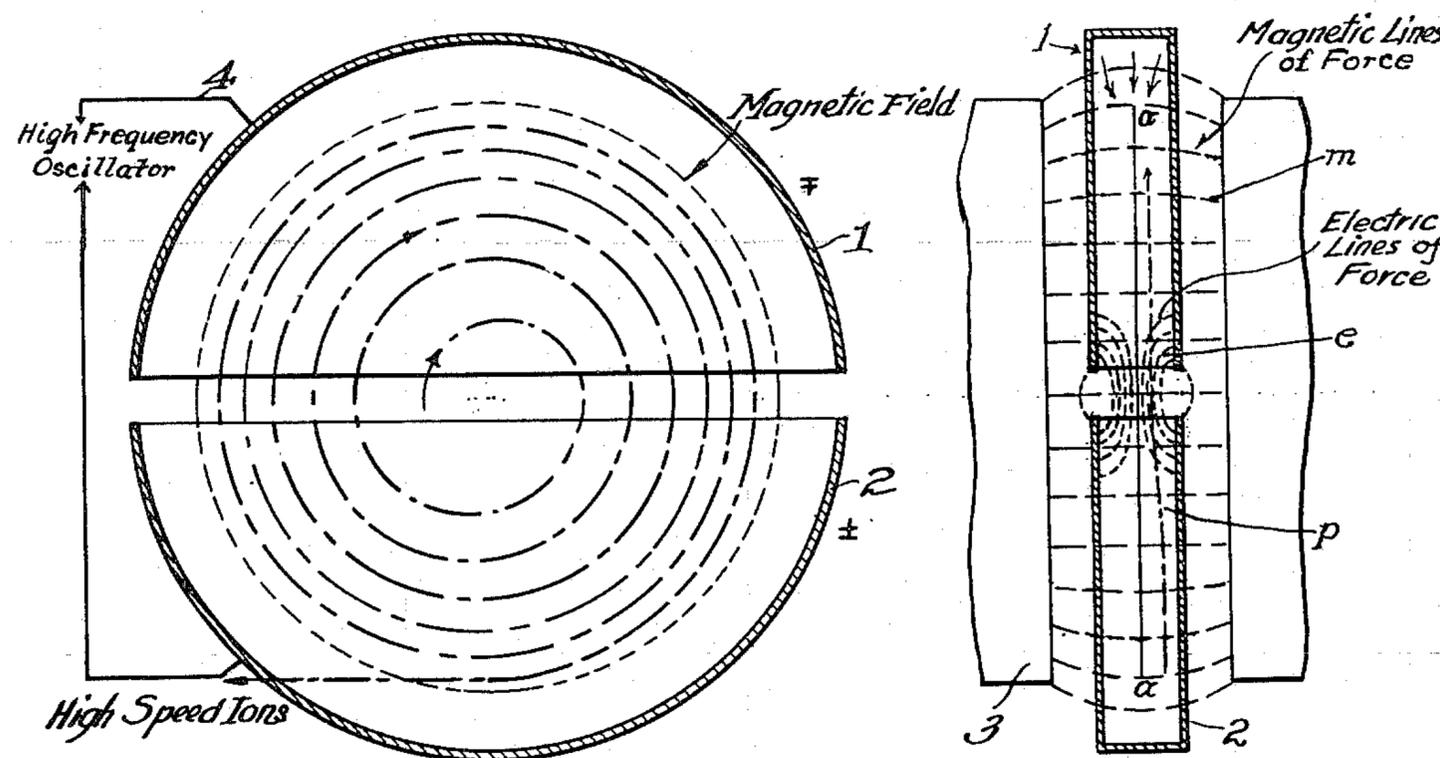
PARTICELLE ELEMENTARI E DOVE TROVARLE...

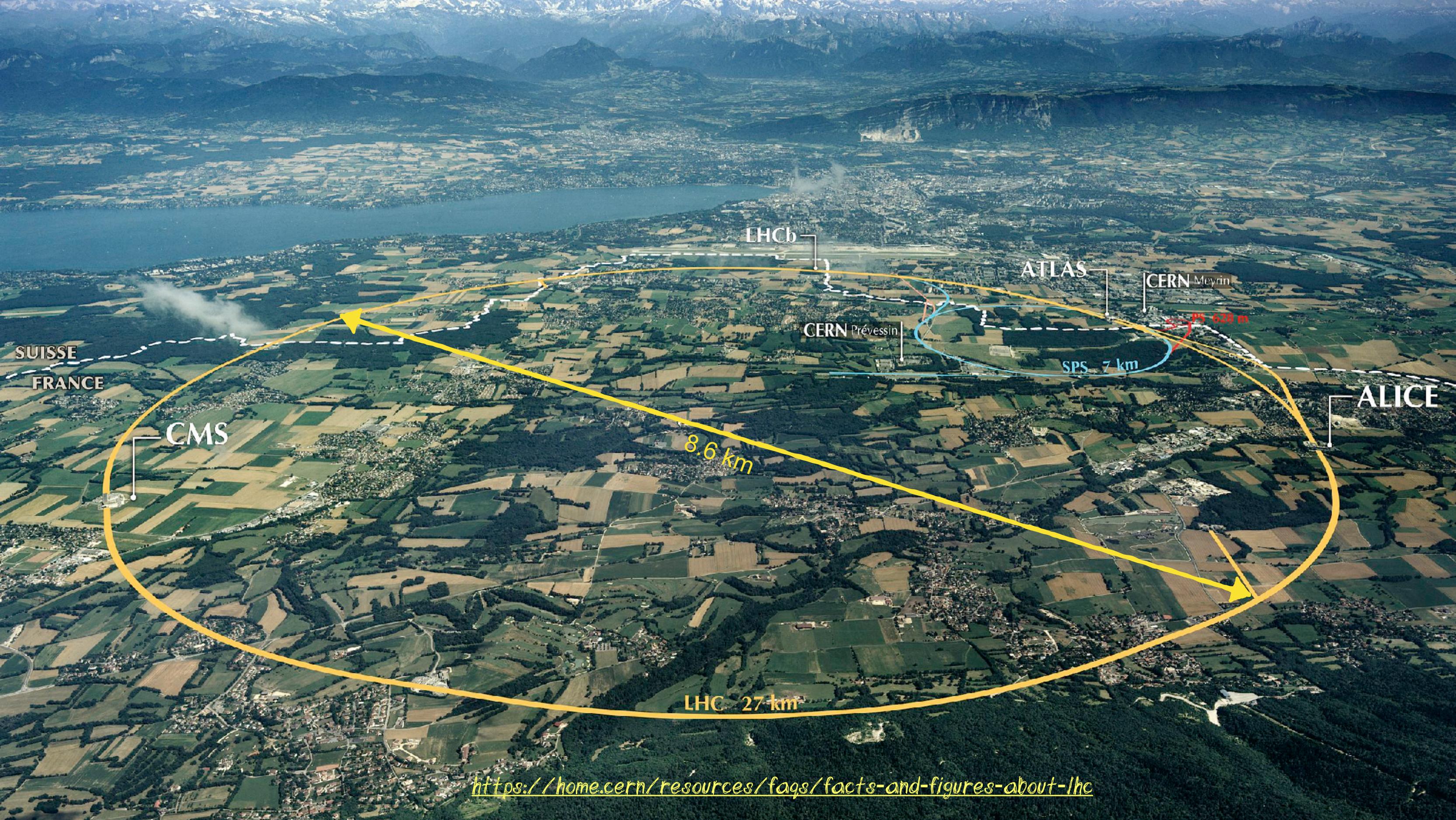




ACCELERATORI DI PARTICELLE

IL PRIMO ACCELERATORE DI PARTICELLE





LHCb

ATLAS

CERN Meyrin

CERN Prévessin

PS 628 m

SPS 7 km

SUISSE
FRANCE

CMS

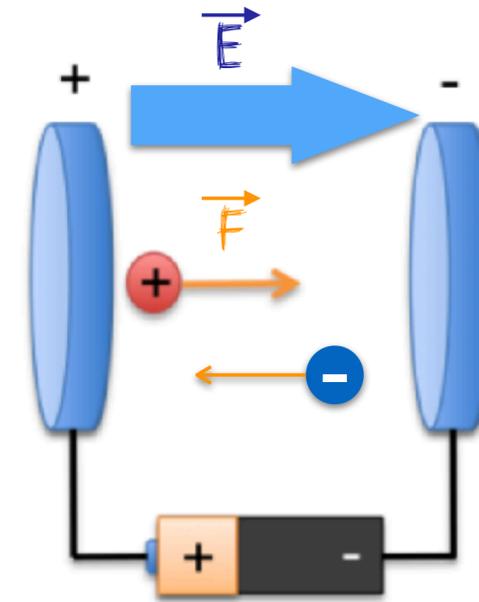
ALICE

8.6 km

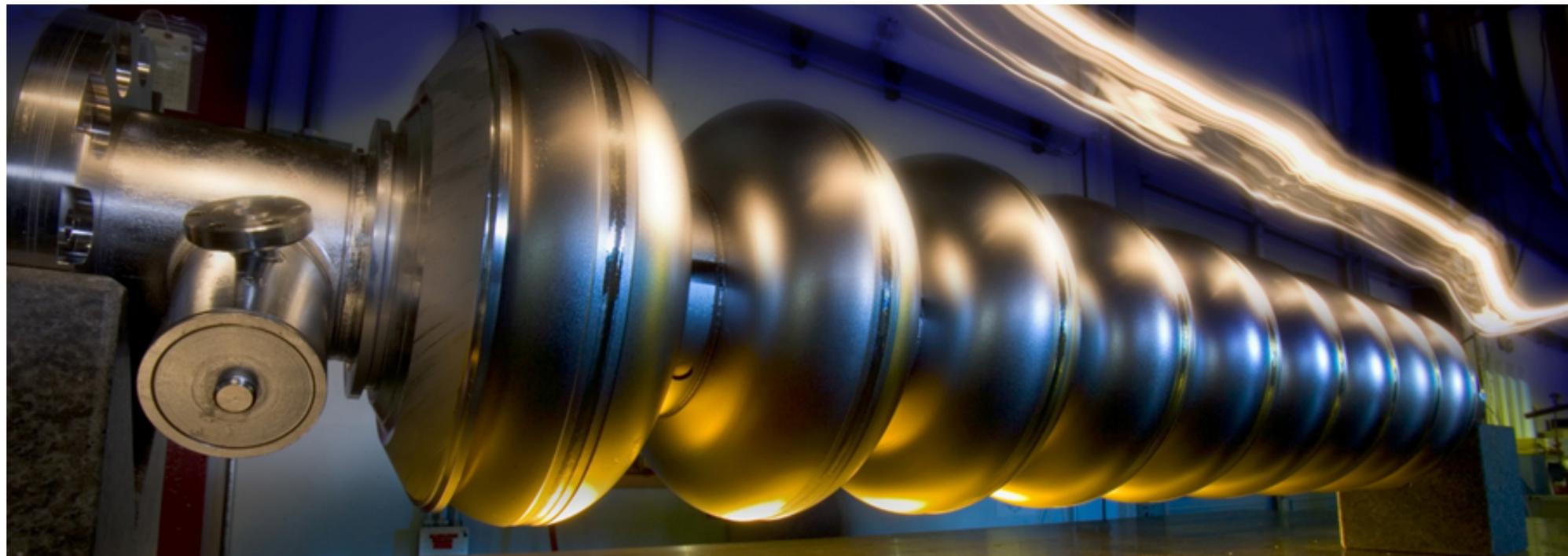
LHC 27 km

□ le **PARTICELLE CARICHE** si accelerano utilizzando **CAMPI ELETTRICI**

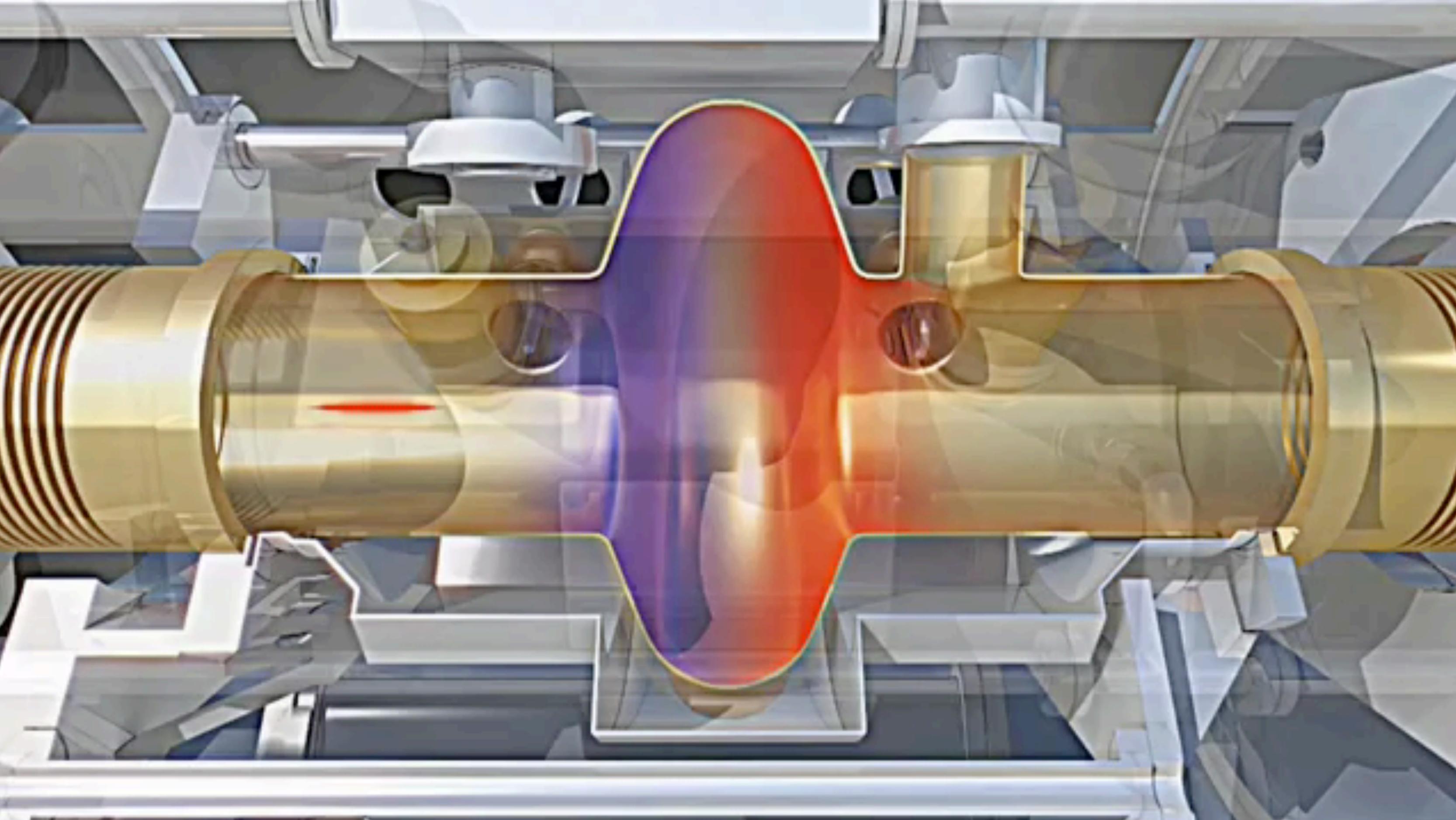
$$\vec{F} = q \cdot \vec{E}$$



□ **CAVITÀ RISONANTI**

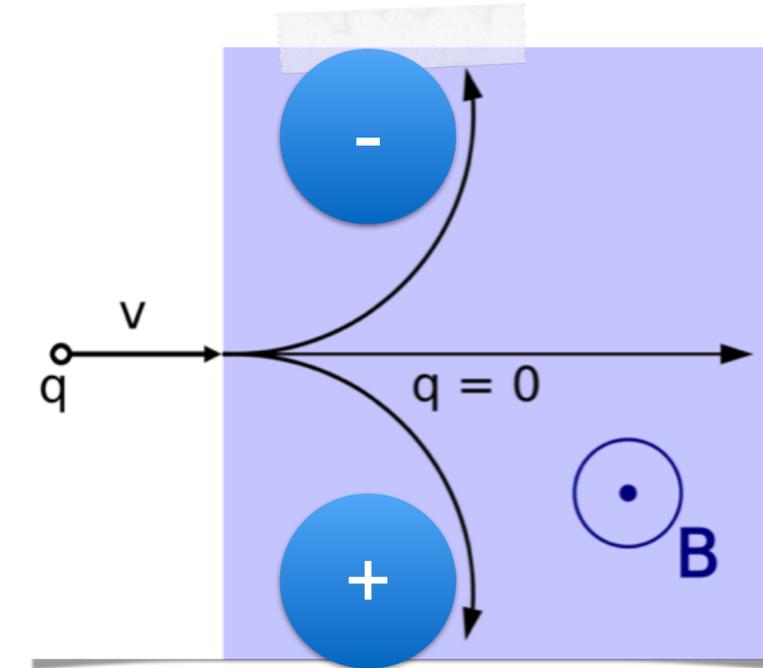
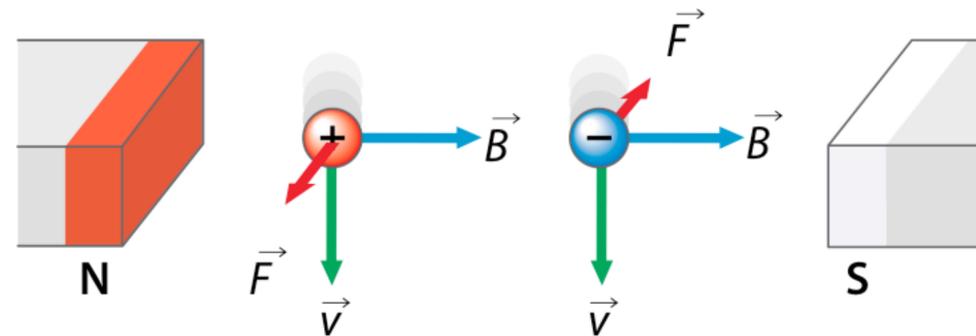


□ i fasci di particelle negli acceleratori hanno una struttura a “**bunches**” ovvero a **pacchetti**



□ per curvare le particelle lungo traiettorie si utilizzano **CAMPI MAGNETICI**

Forza di Lorentz $\vec{F} = q\vec{v} \times \vec{B}$



Per curvare particelle di elevata energia sono necessari campi magnetici molto intensi...oppure acceleratori molto molto grossi!

□ MAGNETI SUPERCONDUTTORI

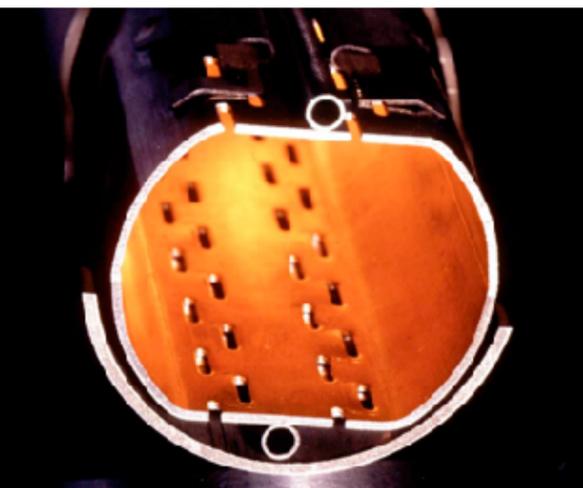
▶ a bassissime temperature hanno bassa resistenza al passaggio di corrente

▶ **campo magnetico 8.3 T a 1.9 K = -271.3 °C (a 4.5 K = -268.7 °C diminuirebbe a 6.8 T)**



LHC ha una circonferenza di 27 km e una potenza di 50 megawatt, se fosse realizzato con tecnologie convenzionali richiederebbe un tunnel di 90-100 km e 1.000 megawatt di potenza per funzionare!

LHC: QUALCHE NUMERO



2 fasci di particelle accelerate a velocità prossime a quelle della luce viaggiano in tubi tenuti sotto vuoto spinto ▶ 10^{-10} to 10^{-11} mbar

Pressione atmosferica in qualche posto nel sistema solare:



1013.25 mbar = 1 atm

~ $3 \cdot 10^{-12}$ mbar

~ 5 mbar

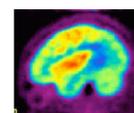


Le particelle sono guidate lungo l'anello da intensi campi magnetici ▶ 8.3 T
1232 magneti superconduttori a basse temperature garantite da sistema di raffreddamento a He liquido ▶ -271.3°C (1.9 K)

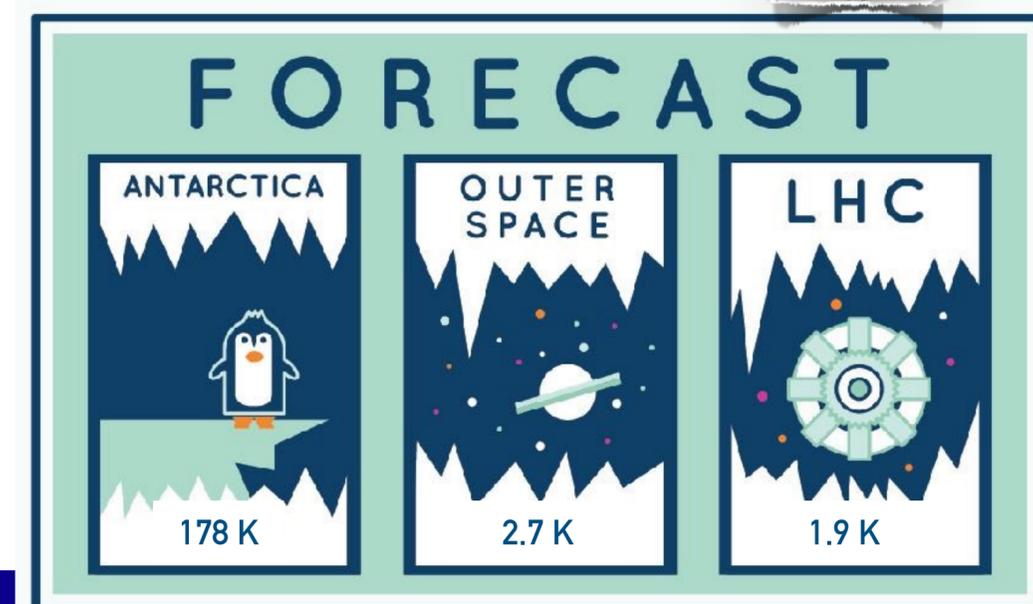
Campo magnetico:

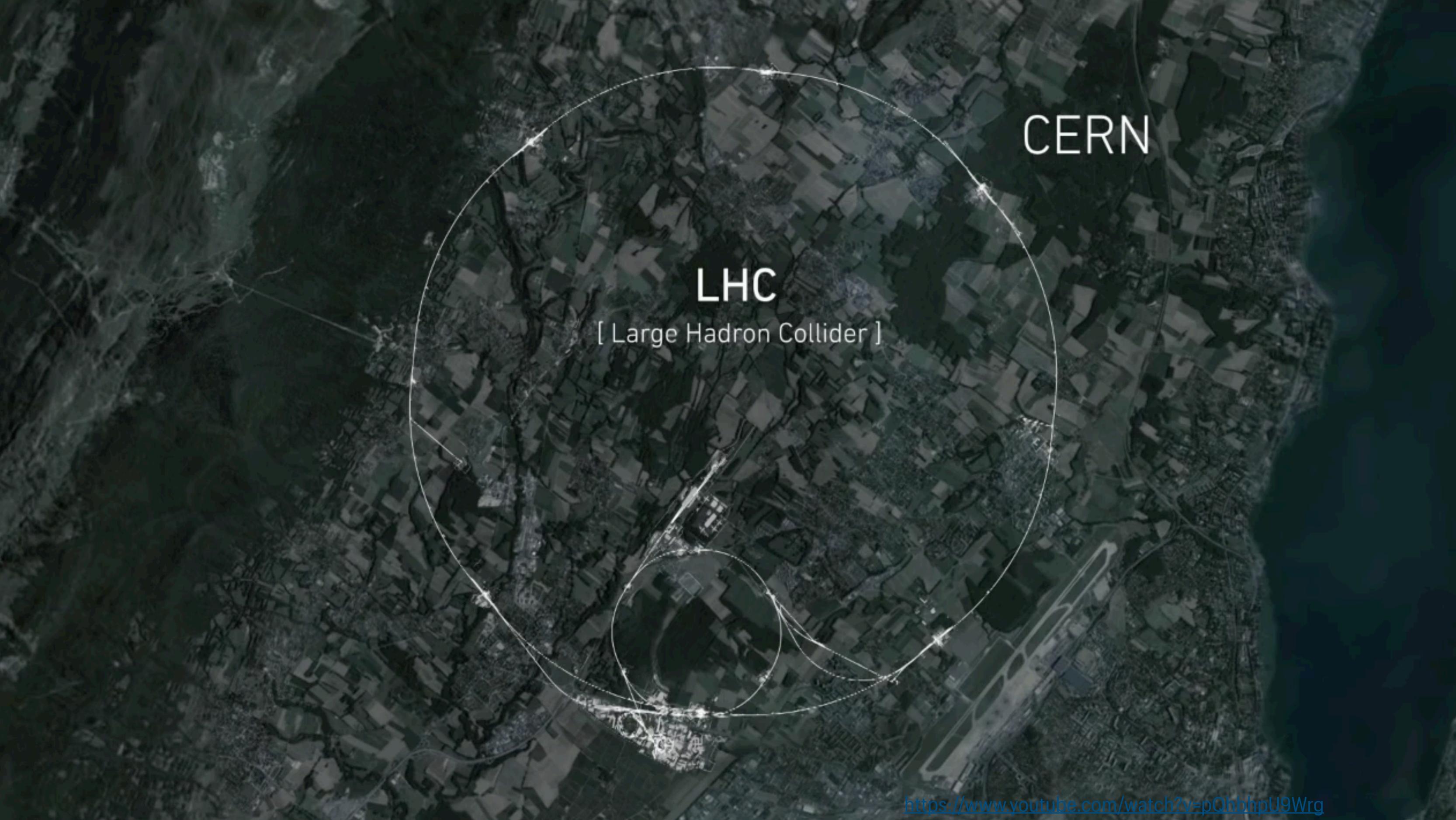


terrestre: 20-70 mT



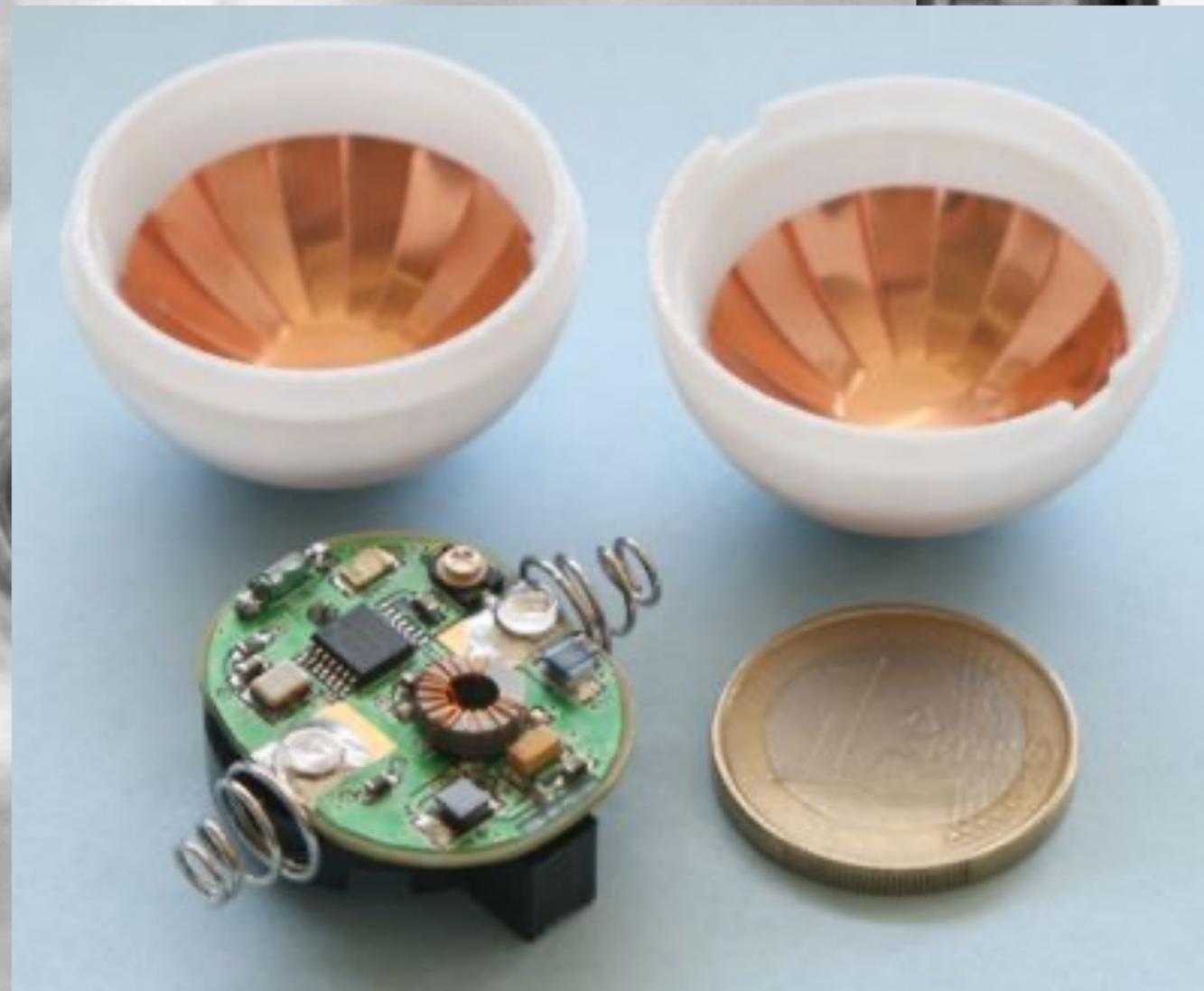
risonanza: 0.7-3 T

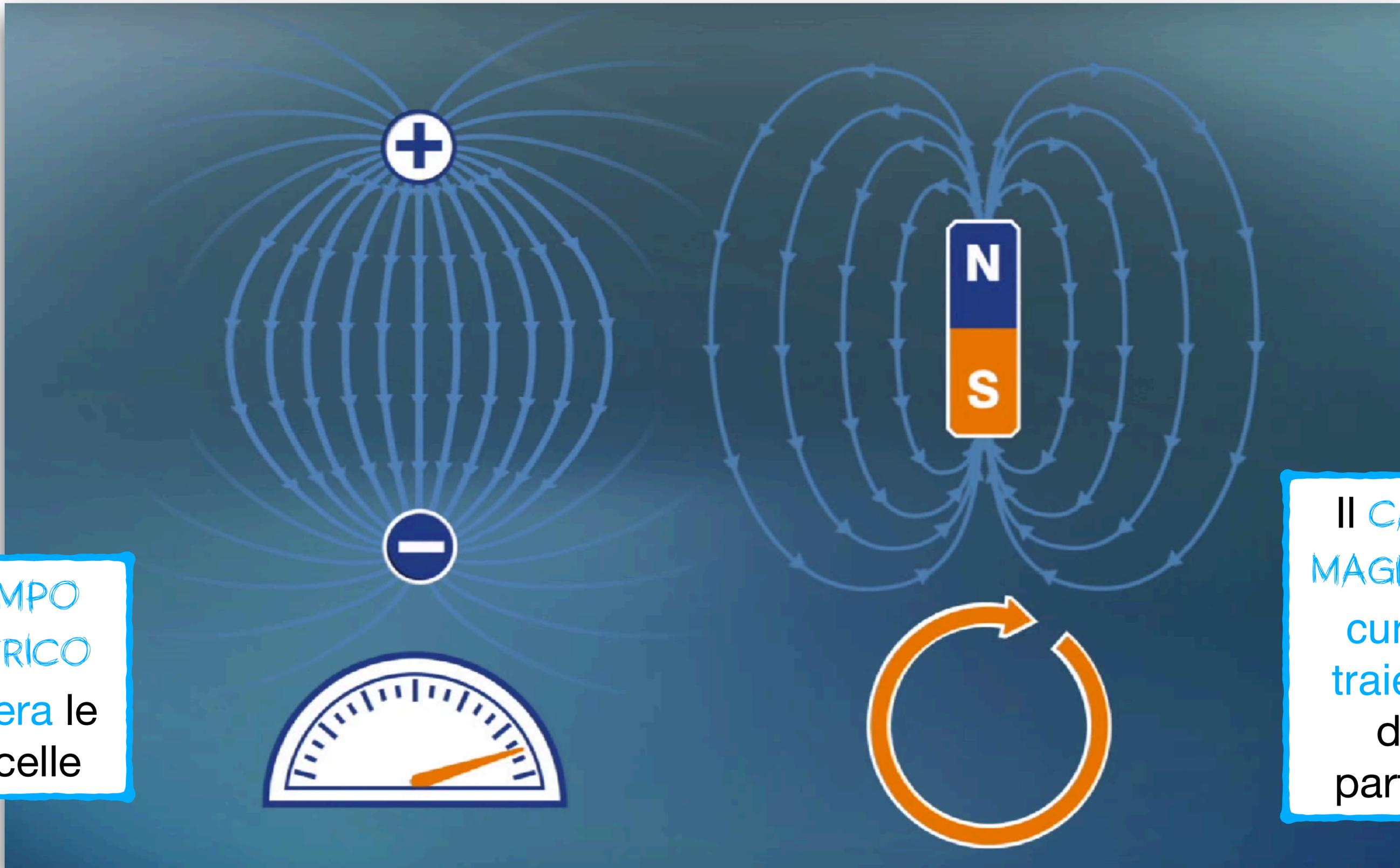


An aerial photograph of the CERN facility in Switzerland, showing the extensive LHC particle accelerator complex. The image is overlaid with white circular lines representing the two main rings of the LHC. The text 'CERN' is positioned in the upper right quadrant, and 'LHC [Large Hadron Collider]' is centered over the main circular structure. The background shows a dense landscape of agricultural fields and some industrial buildings.

CERN

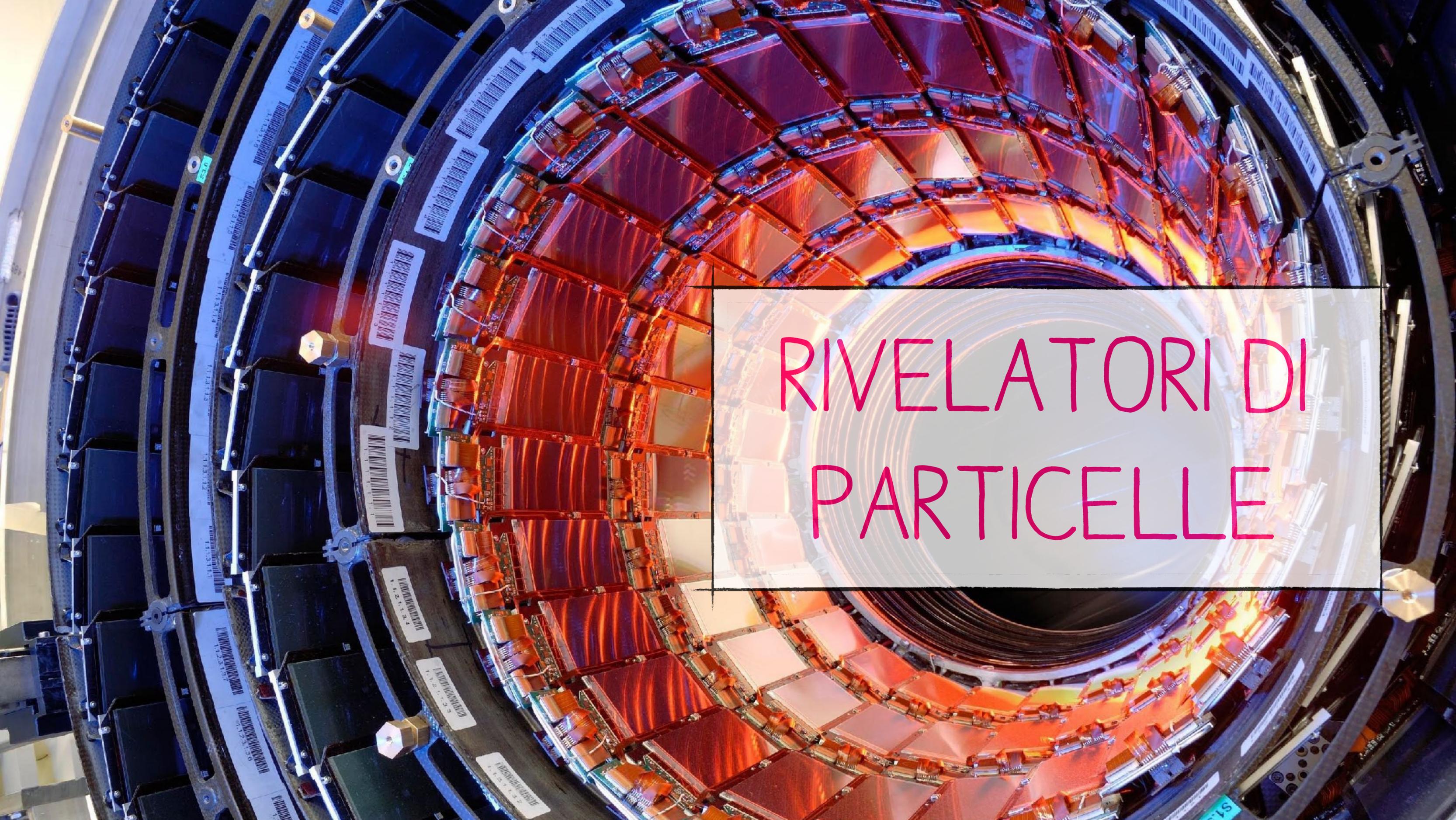
LHC
[Large Hadron Collider]





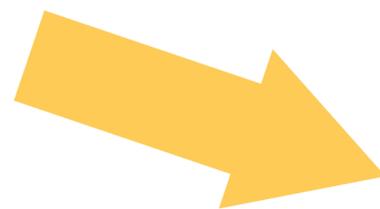
Il CAMPO
ELETTRICO
accelera le
particelle

Il CAMPO
MAGNETICO
curva le
traiettorie
delle
particelle



RIVELATORI DI PARTICELLE

LUCE

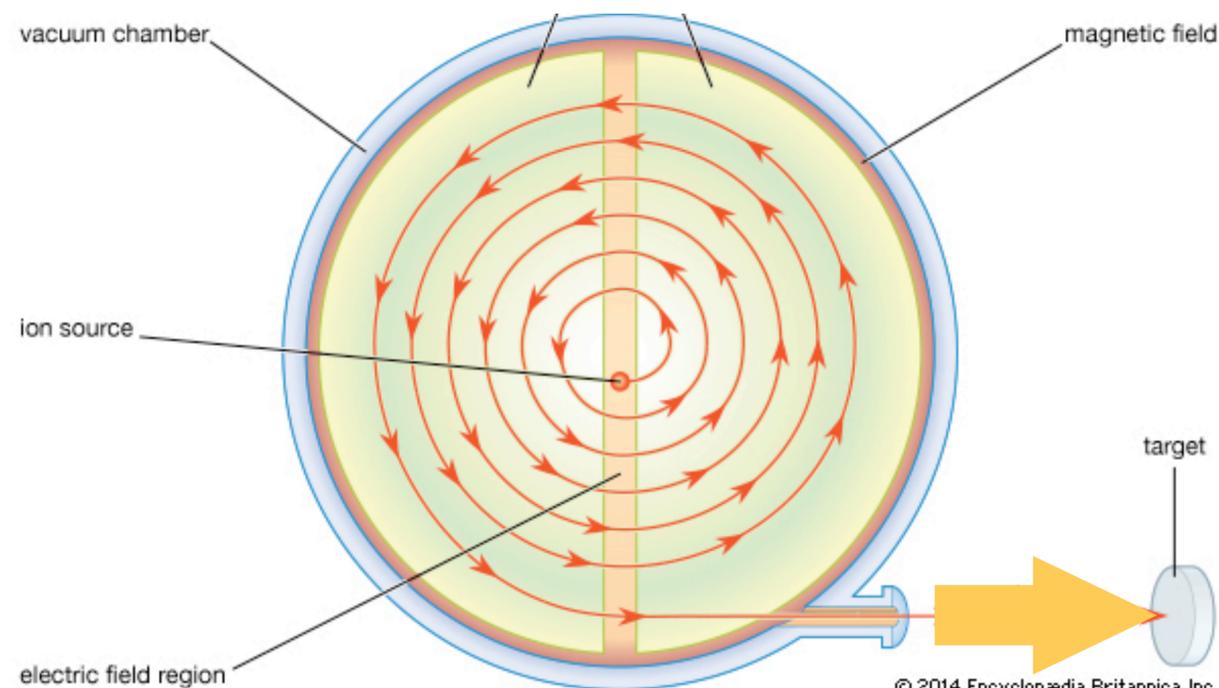


SORGENTE

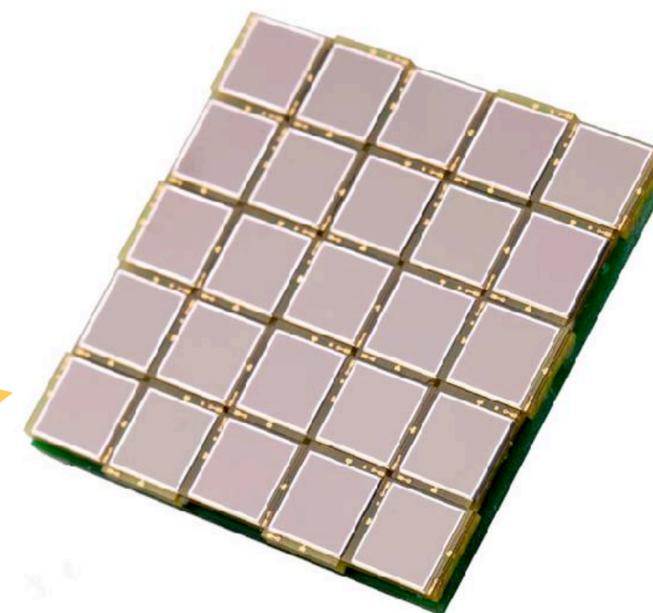
BERSAGLIO

RIVELATORE

PARTICELLE



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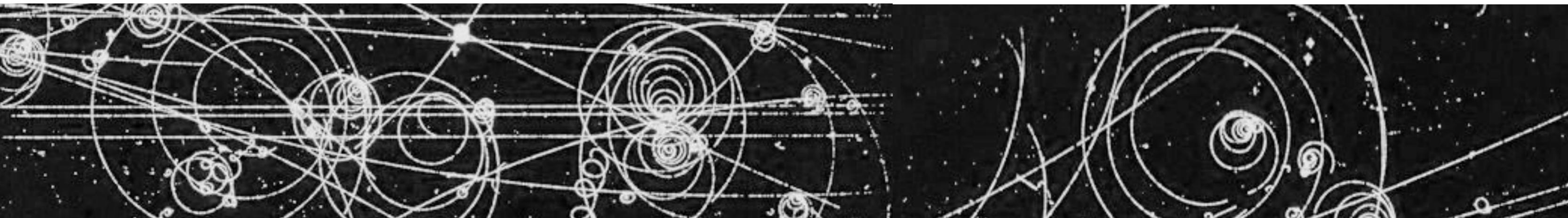


Per rivelare una particella bisogna che interagisca con il materiale del rivelatore

PARTICELLE CARICHE Interazioni elettromagnetica o adronica (ionizzazione)

FOTONI Interazione elettromagnetica

NEUTRINI Interazione debole (bassissima probabilità di interagire)

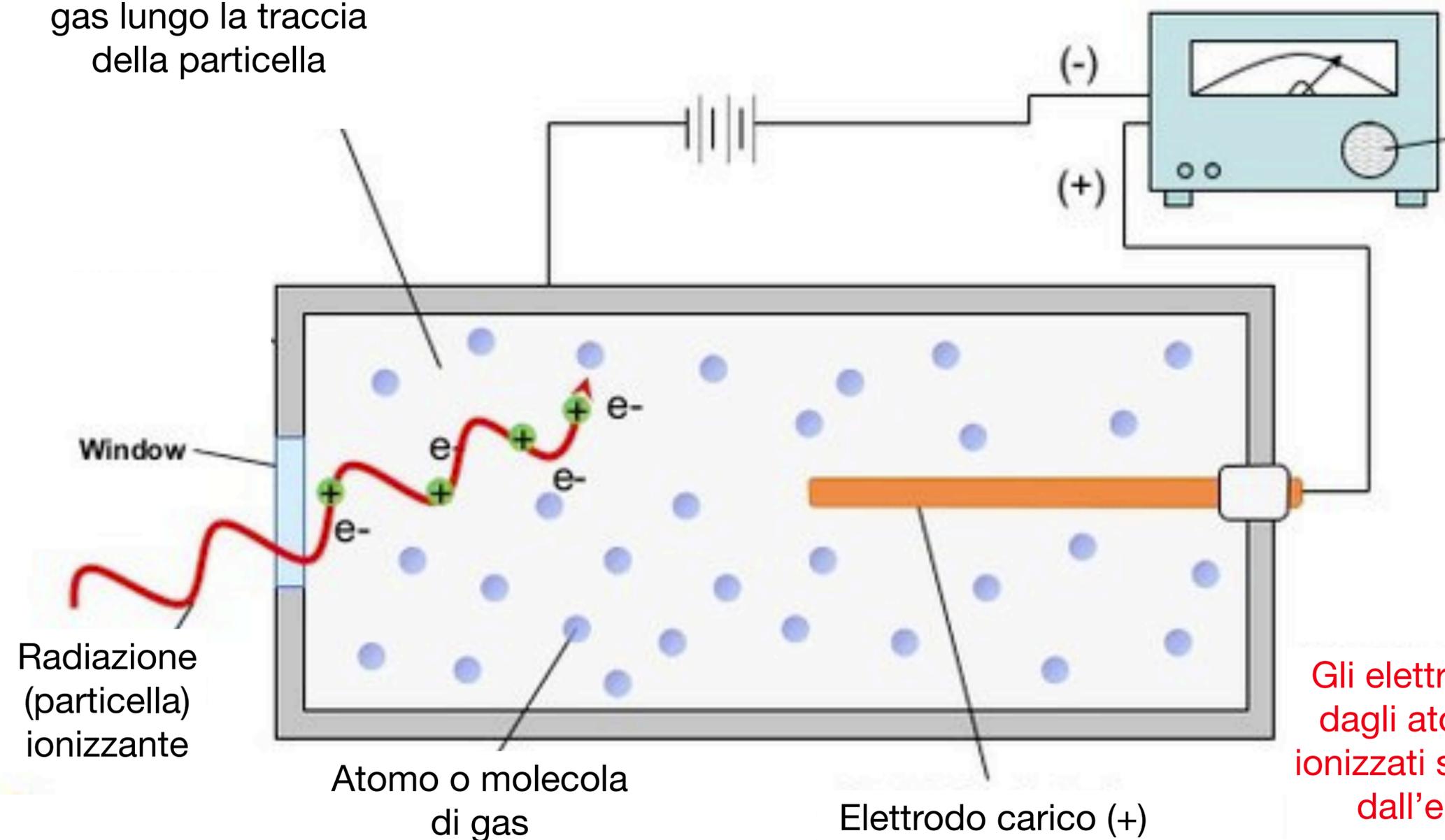


CONTARE ▶ contare numero particelle in un rivelatore

TRACCIARE ▶ ricostruire le tracce delle particelle nel rivelatore

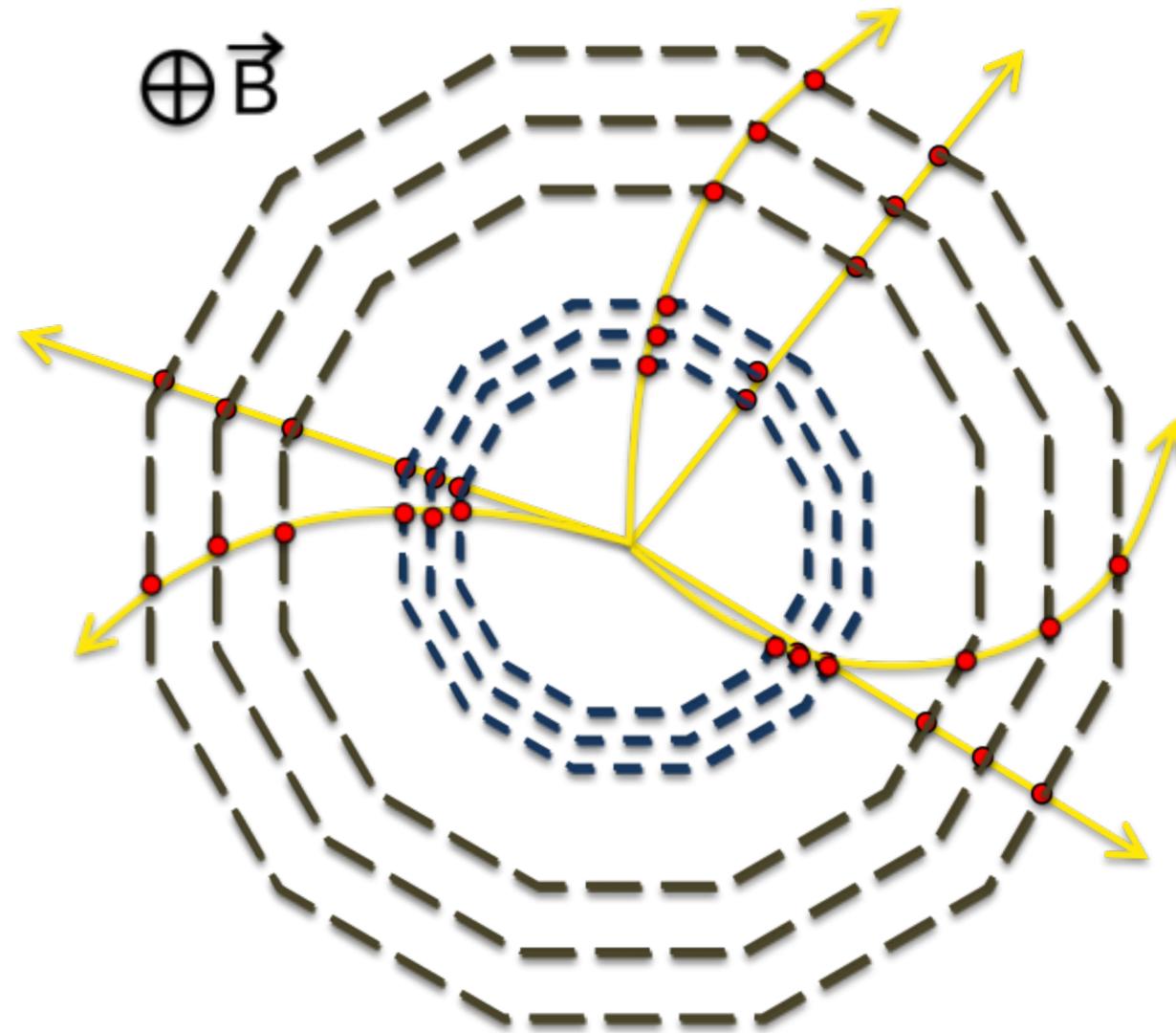
IDENTIFICARE ▶ misurare massa, carica, velocità, energia

IONIZZAZIONE del gas lungo la traccia della particella

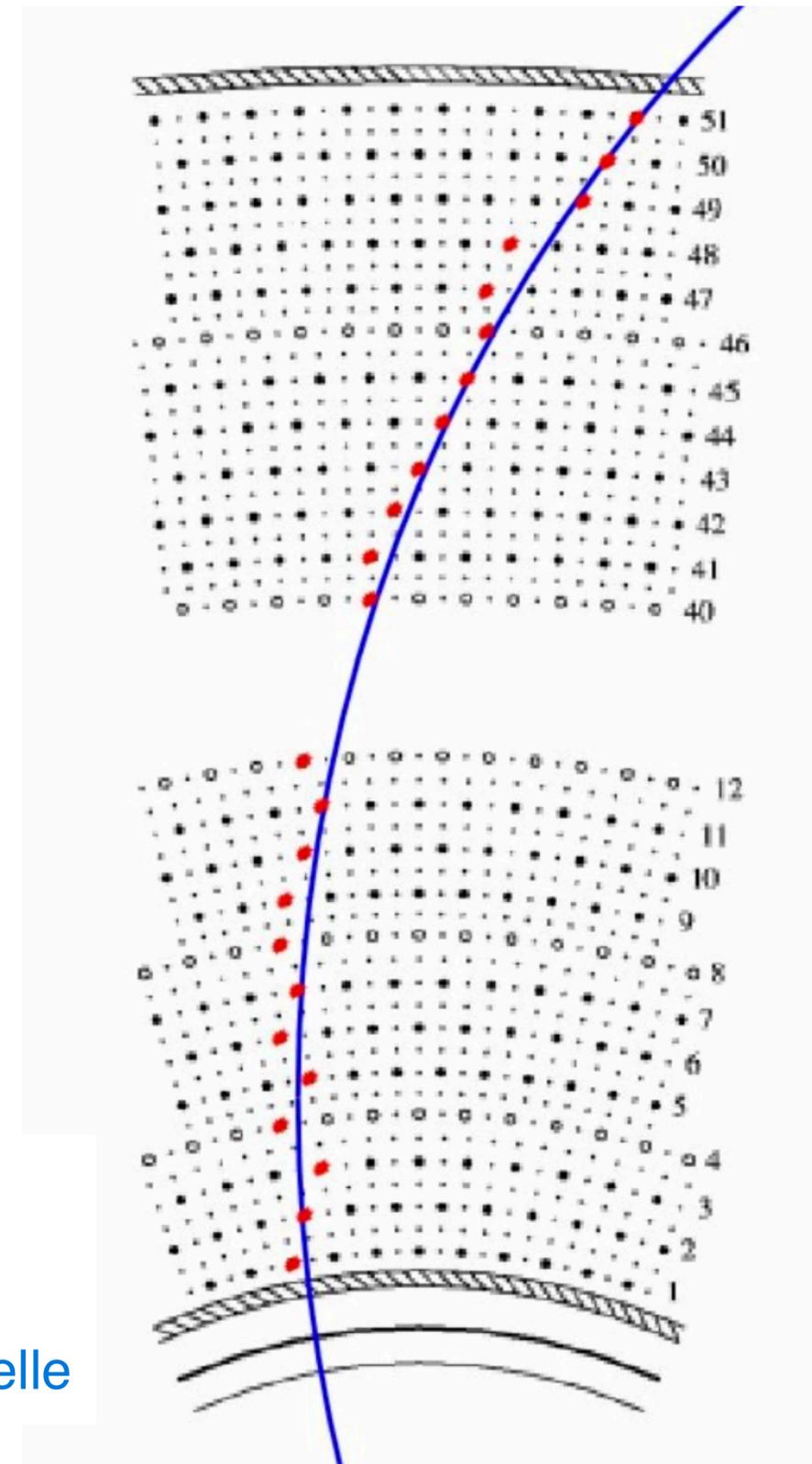


1 suono =
1 particella entrata nel rivelatore

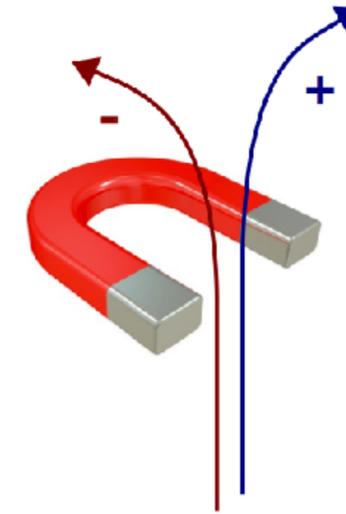
Gli elettroni liberati dagli atomi di gas ionizzati sono attratti dall'elettrodo positivo.



- ▶ si ricostruiscono le **TRACCE** delle particelle partendo dai “punti” lasciati sui rivelatori
- ▶ il campo magnetico consente di misurare il **MOMENTO** delle particelle



□ il segno della **CARICA** si deduce dalla curvatura della traccia



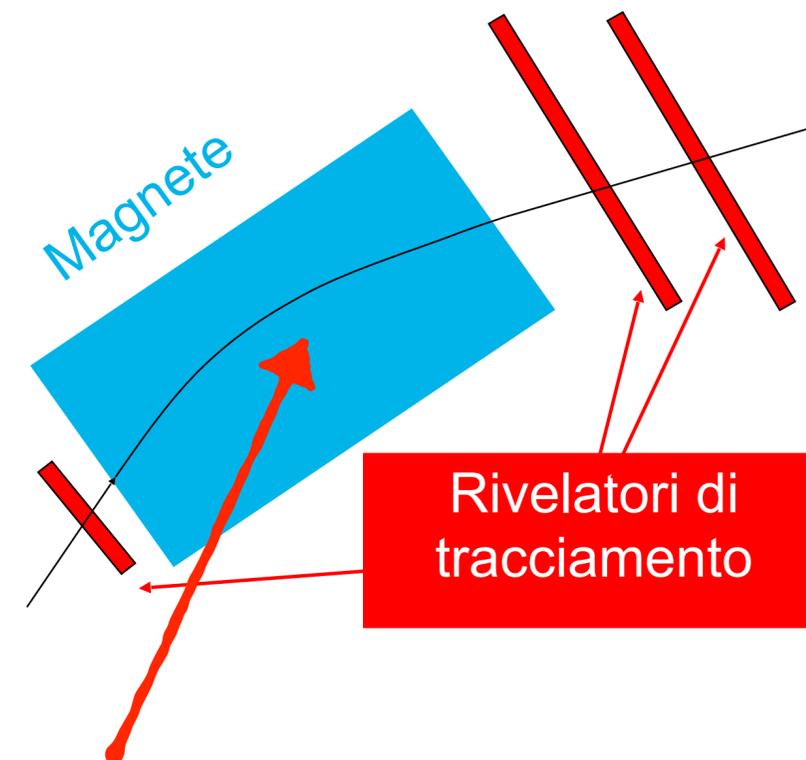
□ il **MOMENTO** (= massa x velocità) si misura in campo magnetico:

$$\vec{F} = q\vec{v} \times \vec{B}$$

usando $\vec{v} \perp \vec{B} \Rightarrow ma = qvB$

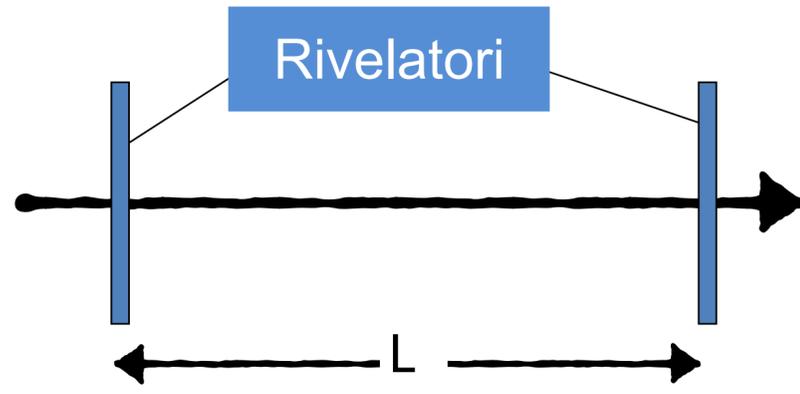
$$mv^2/R = qvB$$

$$p = mv = qBR$$



□ VELOCITÀ

▶ misura del tempo di volo tra 2 rivelatori posti a distanza nota



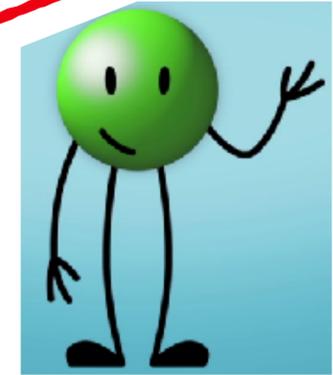
$$\Delta t = L / \beta c \rightarrow \boxed{\beta = L / c \Delta t}$$

□ MASSA

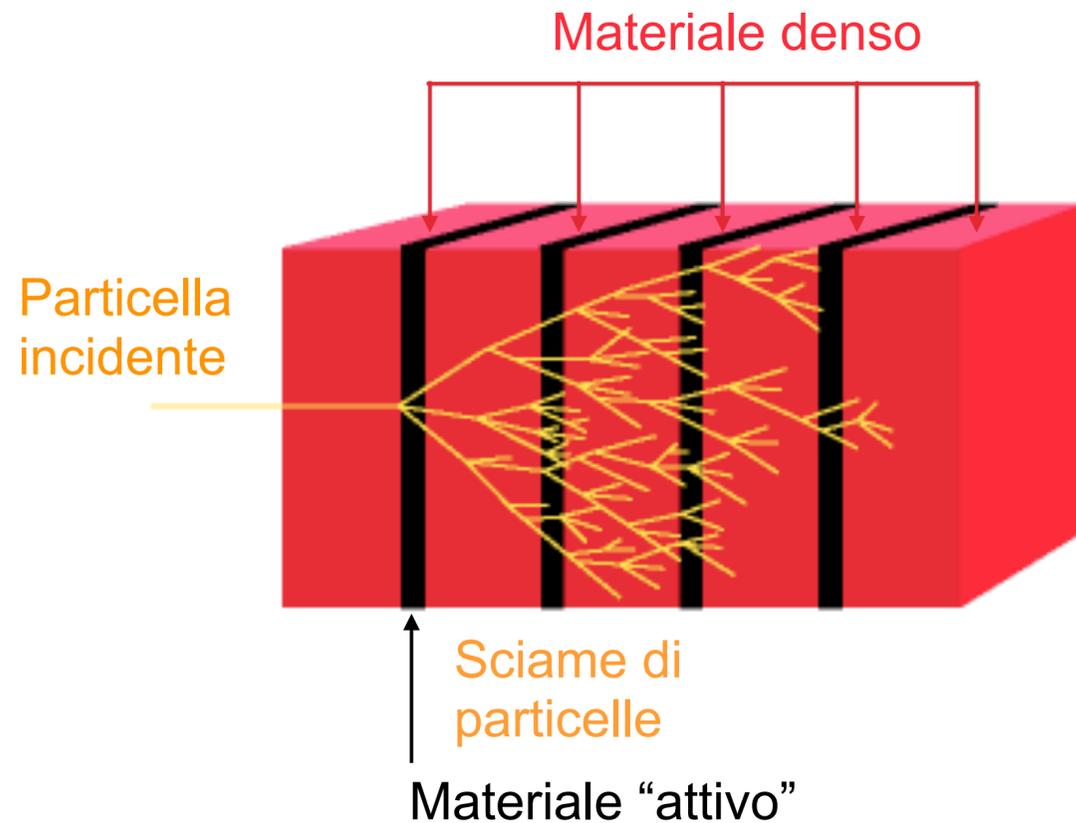
▶ misurati impulso e velocità si ricava la massa

$$p = \gamma m \beta c \rightarrow \boxed{m = p / (\gamma \beta c)}$$

PARTICELLA IDENTIFICATA

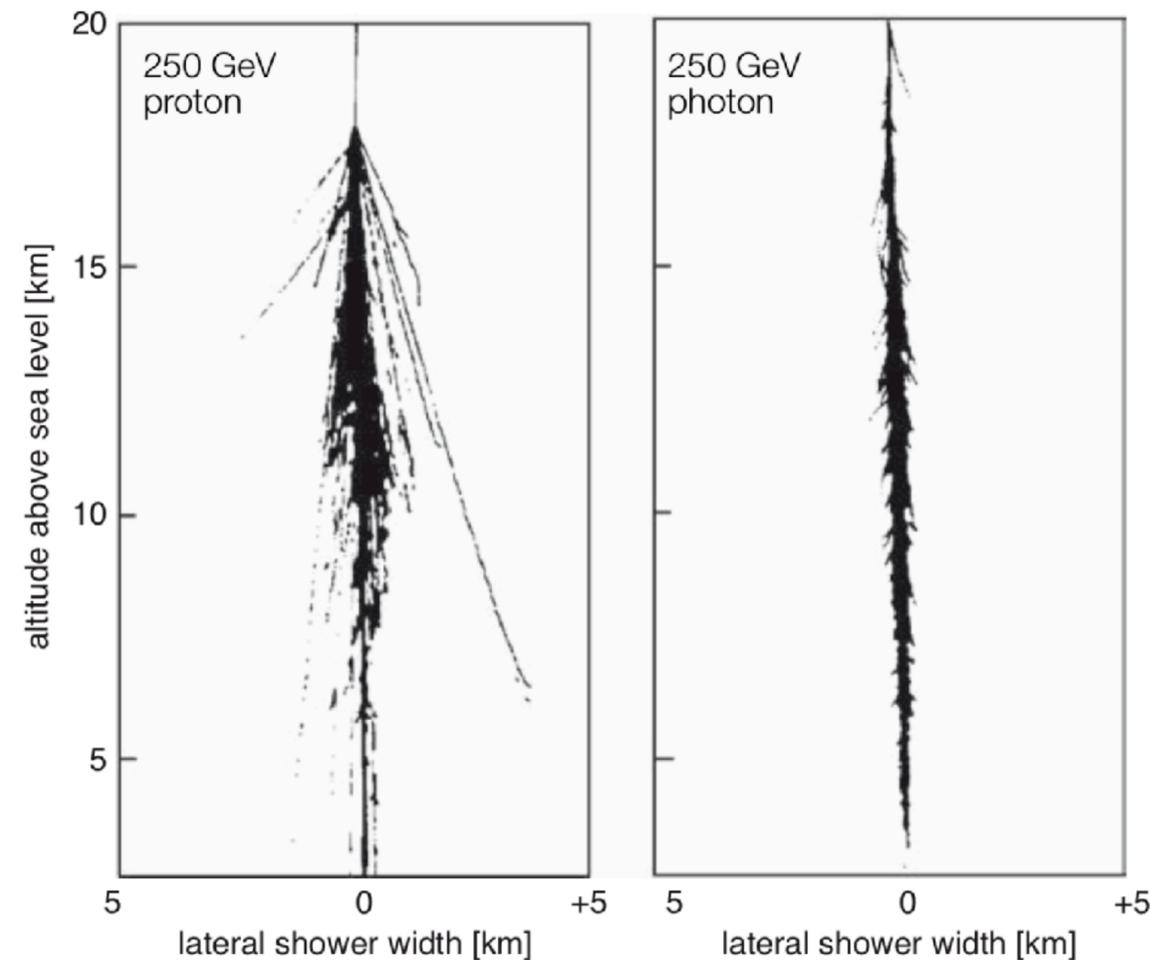


Per misurare l'**ENERGIA** delle particelle prodotte bisogna "bloccarle" (assorbirle)



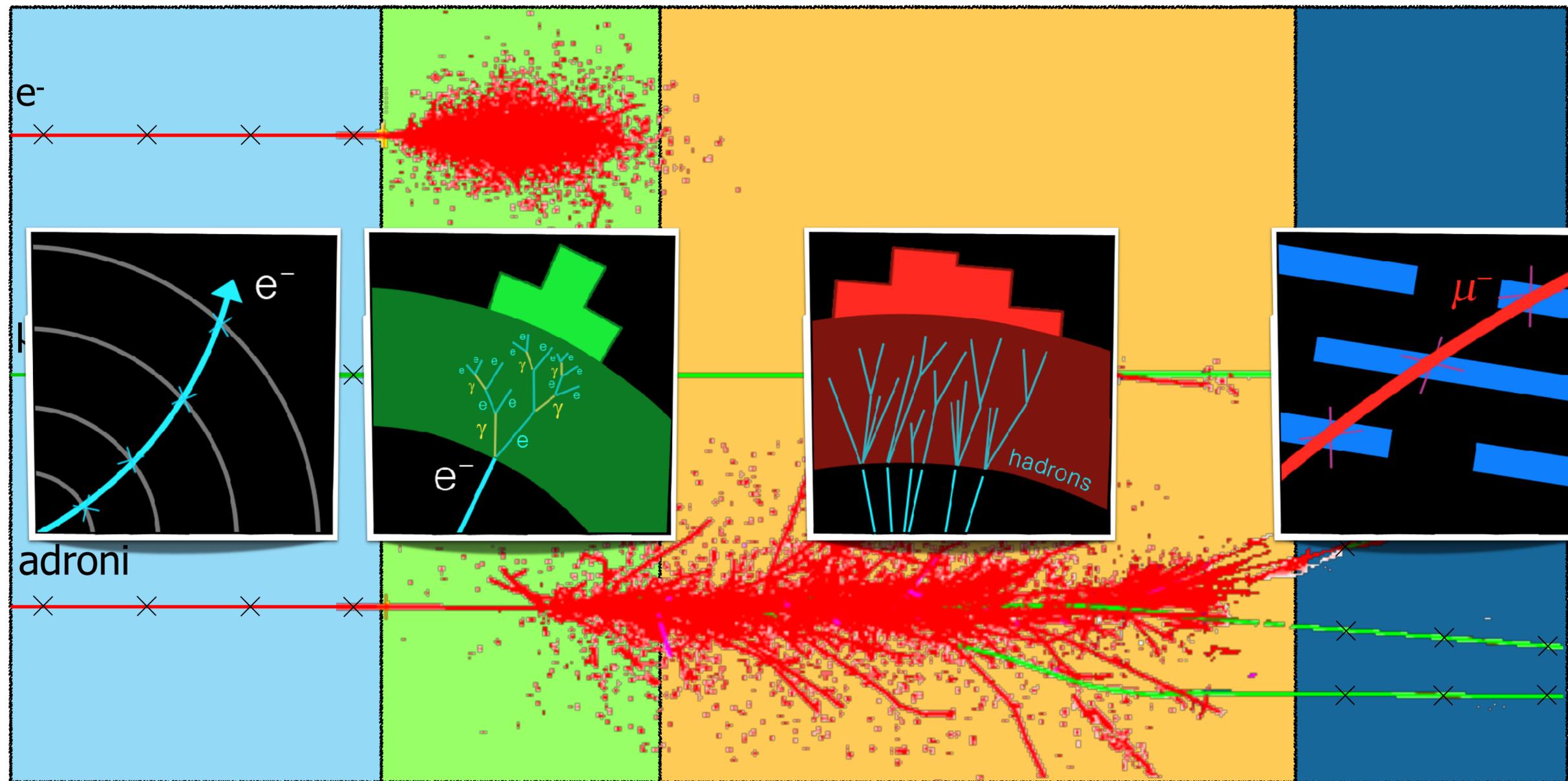
▶ CALORIMETRI

- si utilizza un materiale molto denso per frenare la particella
- strati di materiale sensibile, "attivo", interposti tra strati di materiale pesante ▶ campionamento dell'energia persa dalla particella





APPARATI
SPERIMENTALI



TRACCIAMENTO: poco materiale, misura precisa della posizione

CALORIMETRIA EM: misura dell'energia depositata dagli sciame elettromagnetici

CALORIMETRO ADRONICA: misura dell'energia dello sciame adronico.

RIVELATORE DI MUONI: tracciamento dei μ

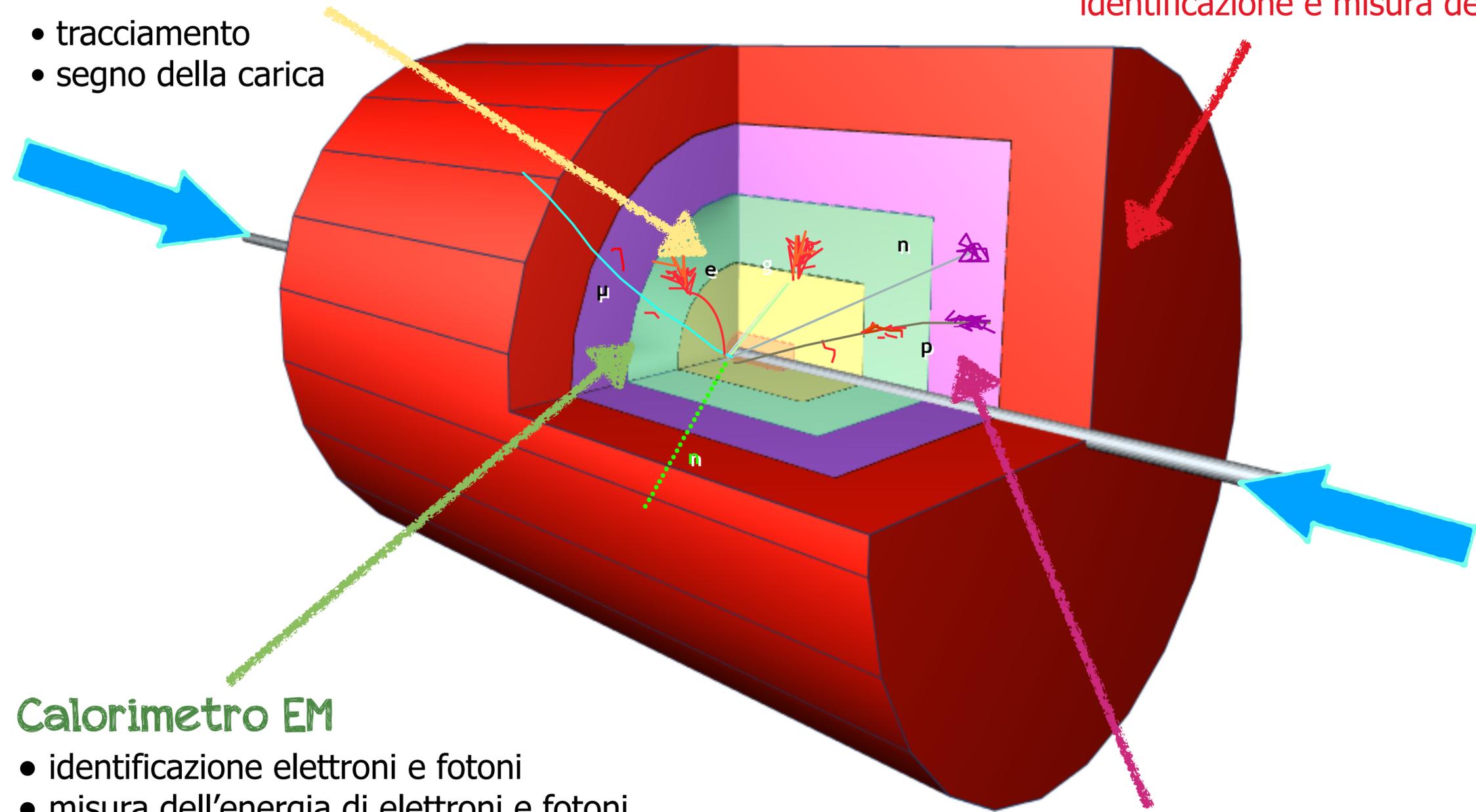
Rivelatori di tracciamento

- tracciamento
- segno della carica

Rivelatori di muoni

identificazione e misura dei μ

fascio di particelle

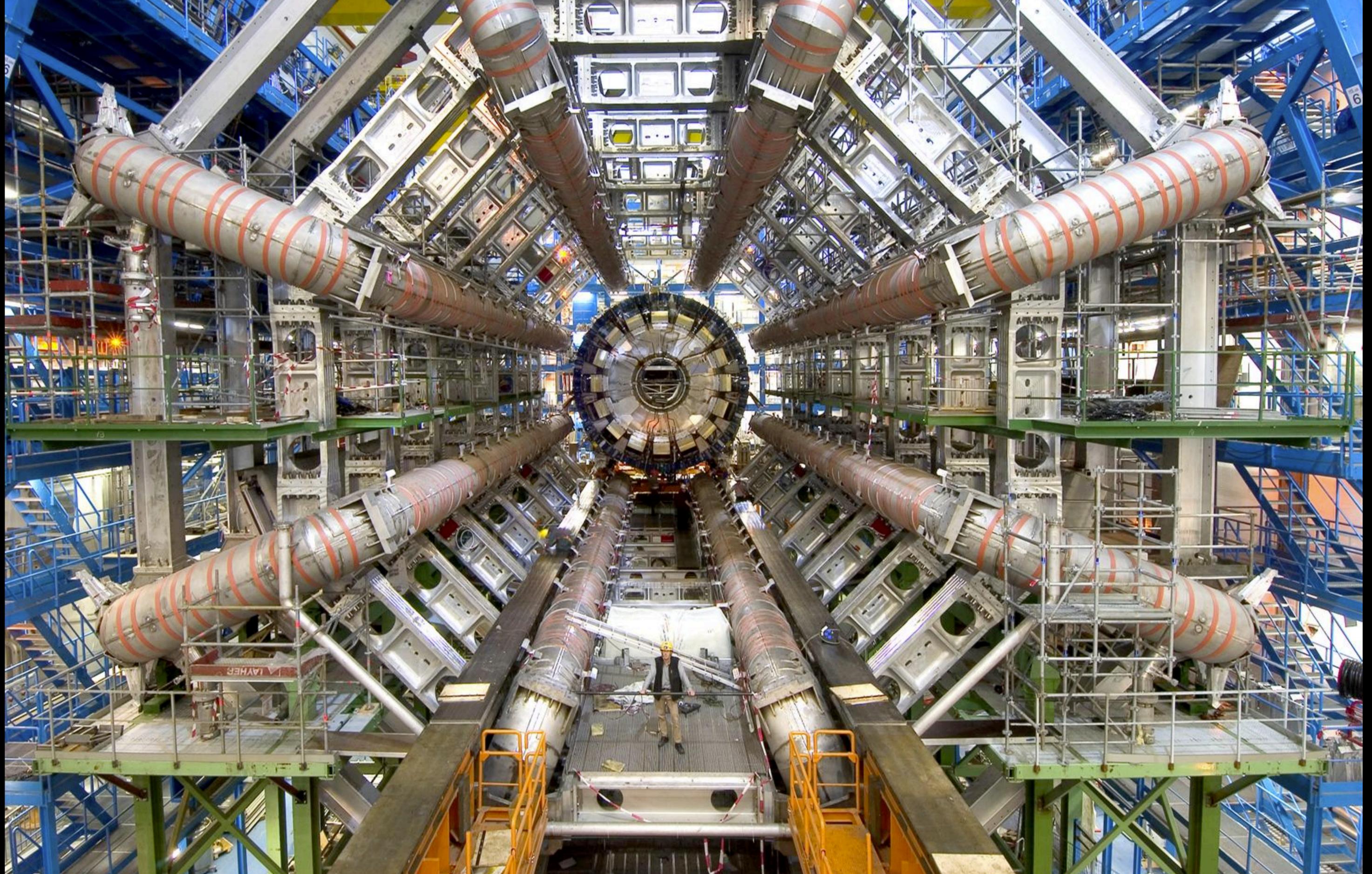


Calorimetro EM

- identificazione elettroni e fotoni
- misura dell'energia di elettroni e fotoni

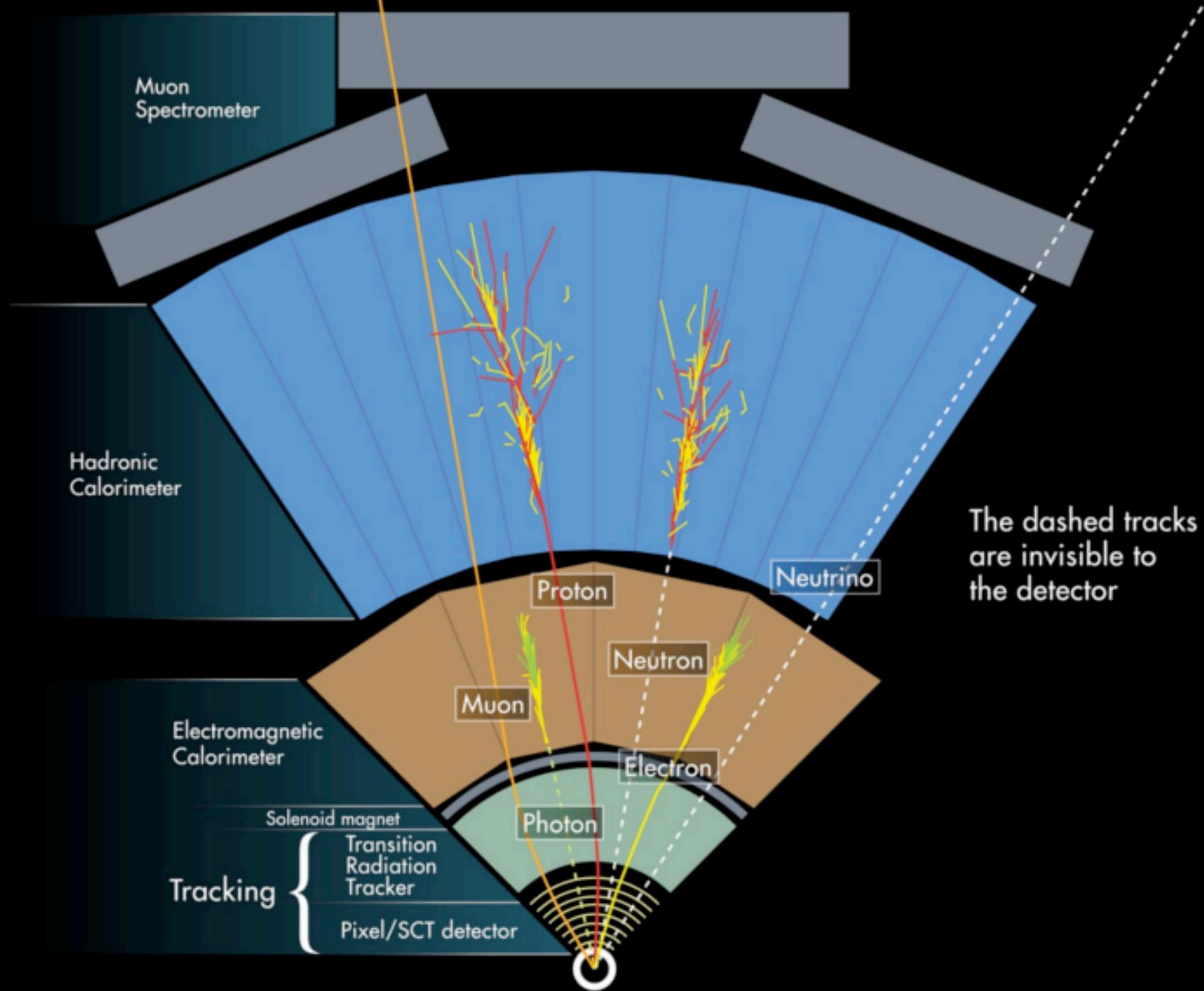
Calorimetro adronico

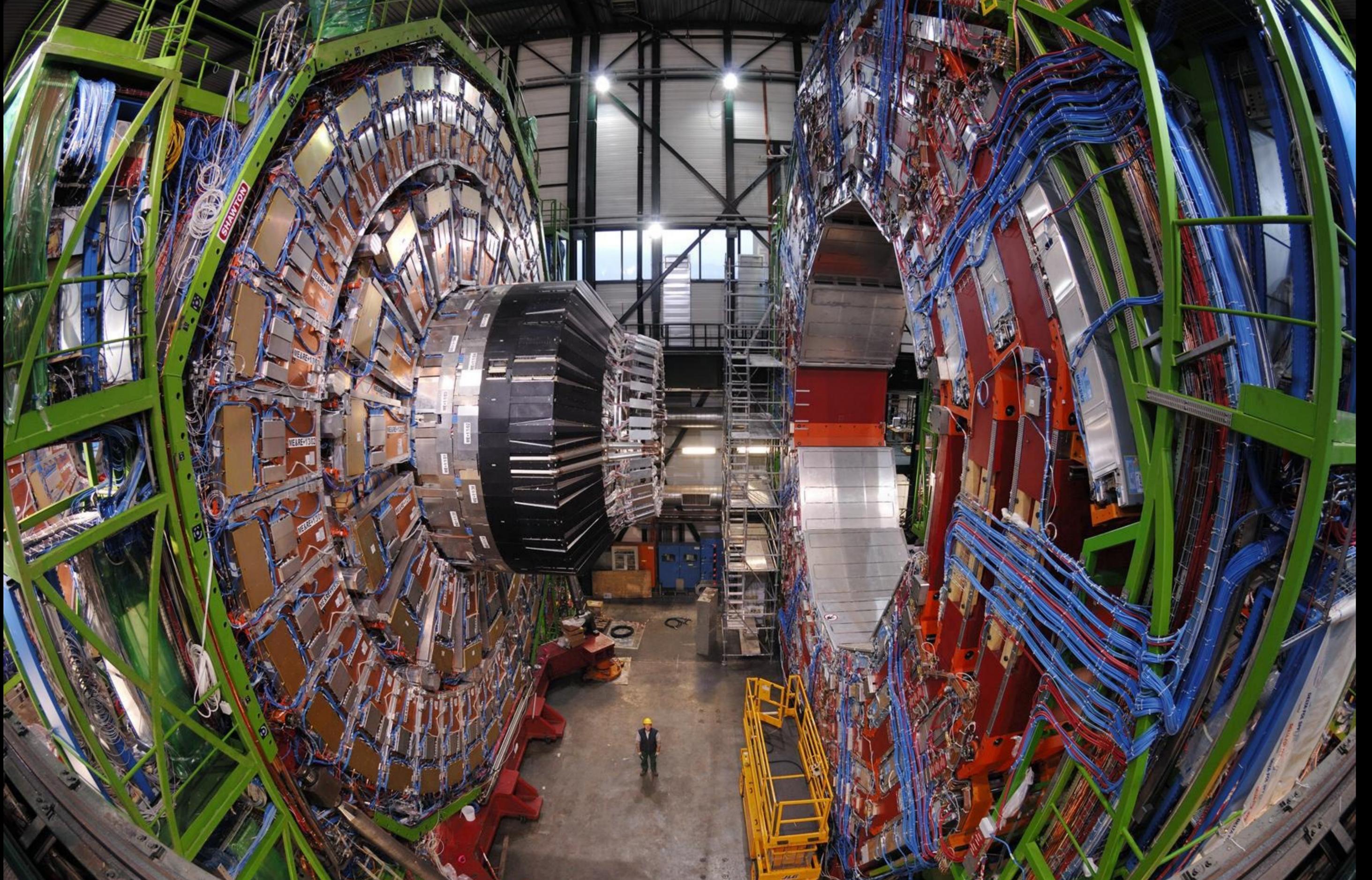
- misura di energia di adroni carichi
- misura energia mancante

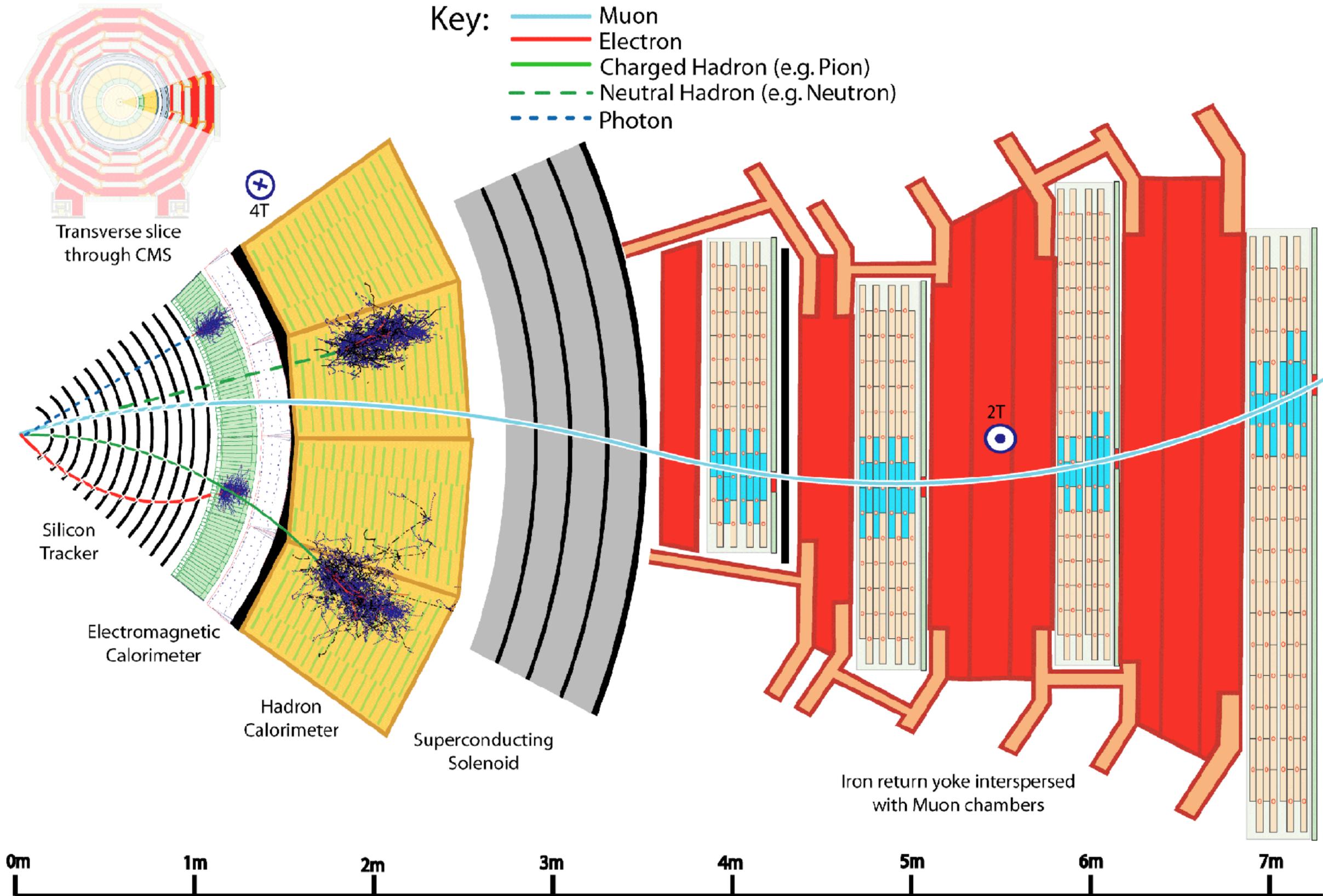


ATLAS

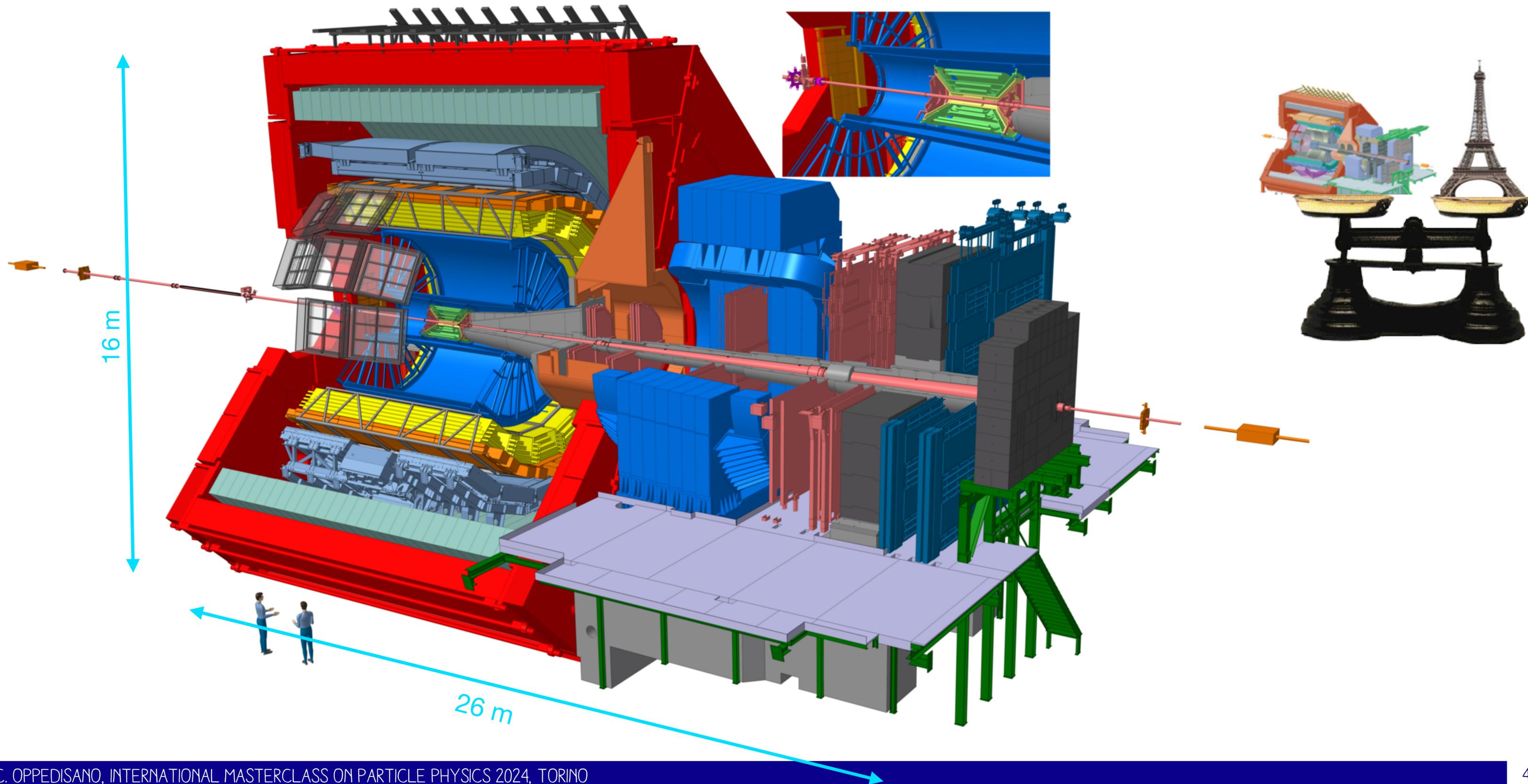
https://atlas.physicsmasterclasses.org/en/zpath_playwithatlas.htm

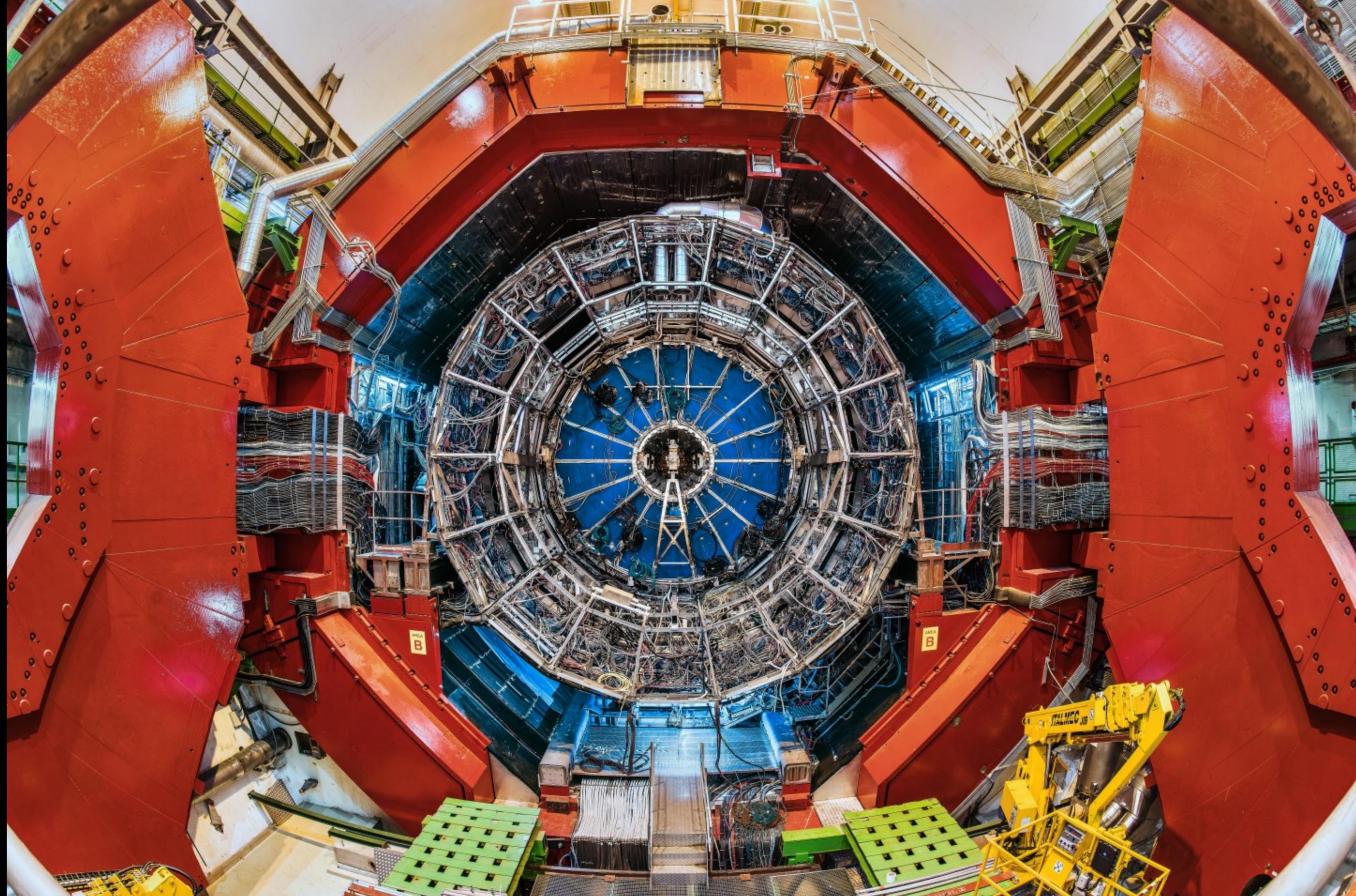


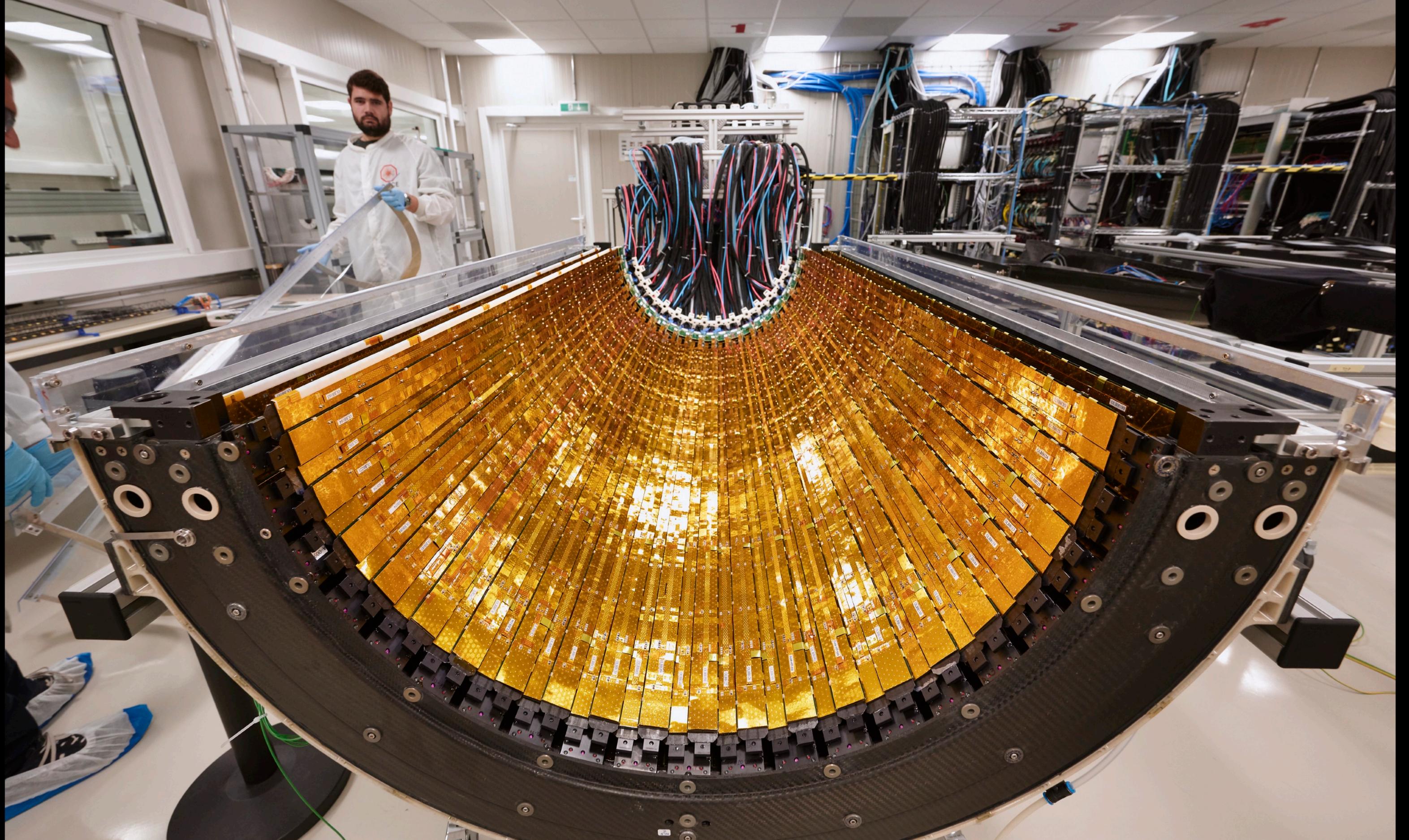


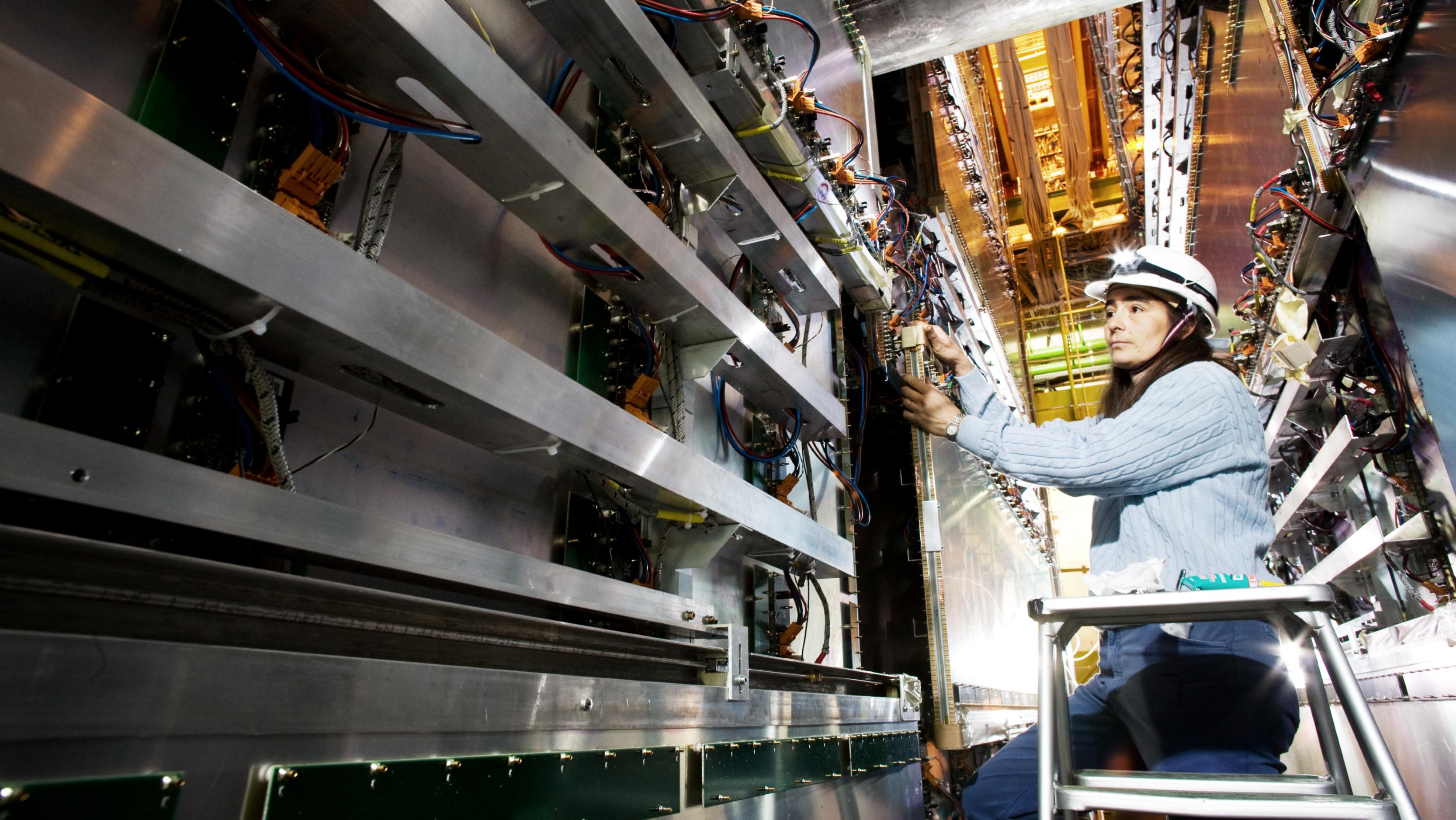


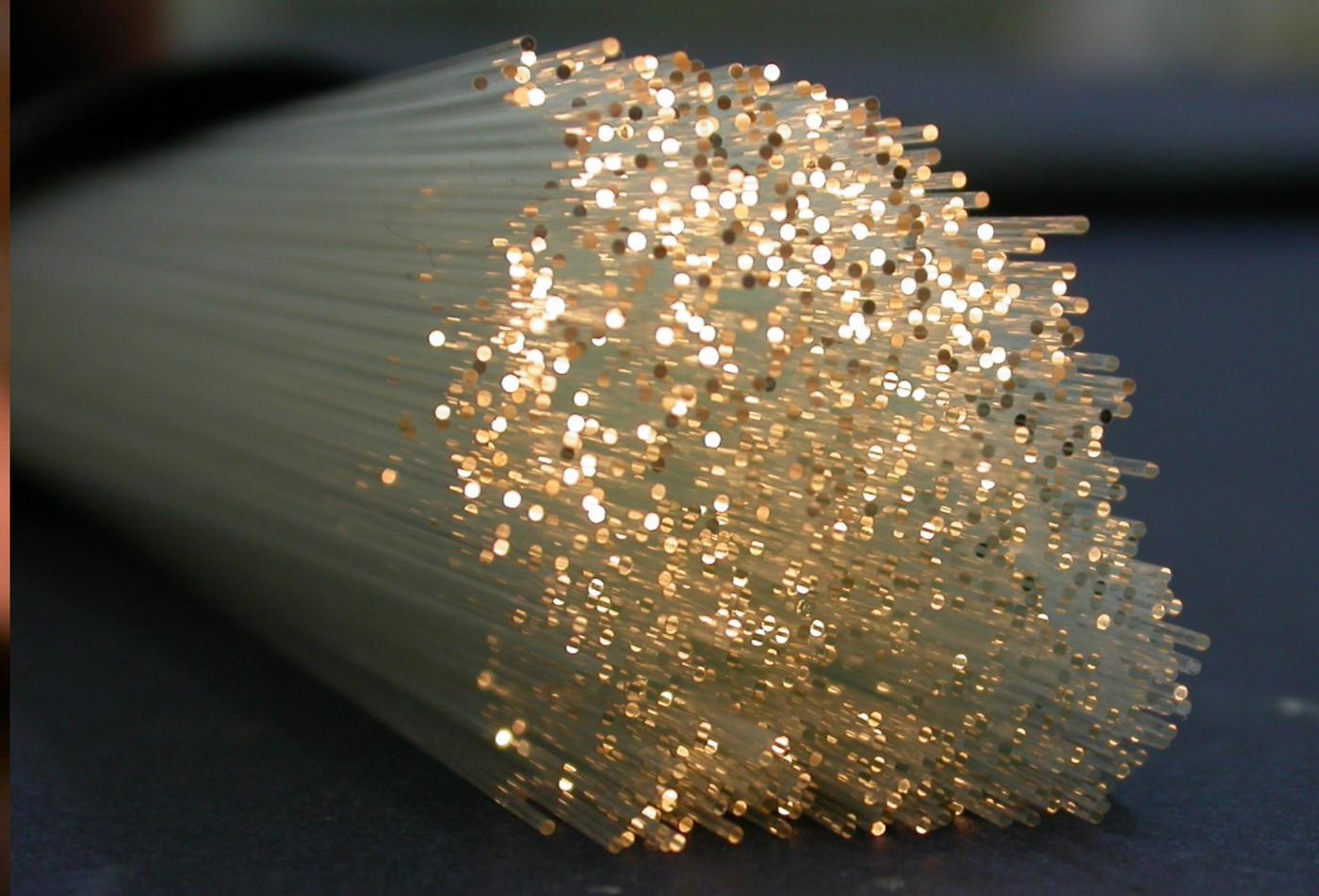
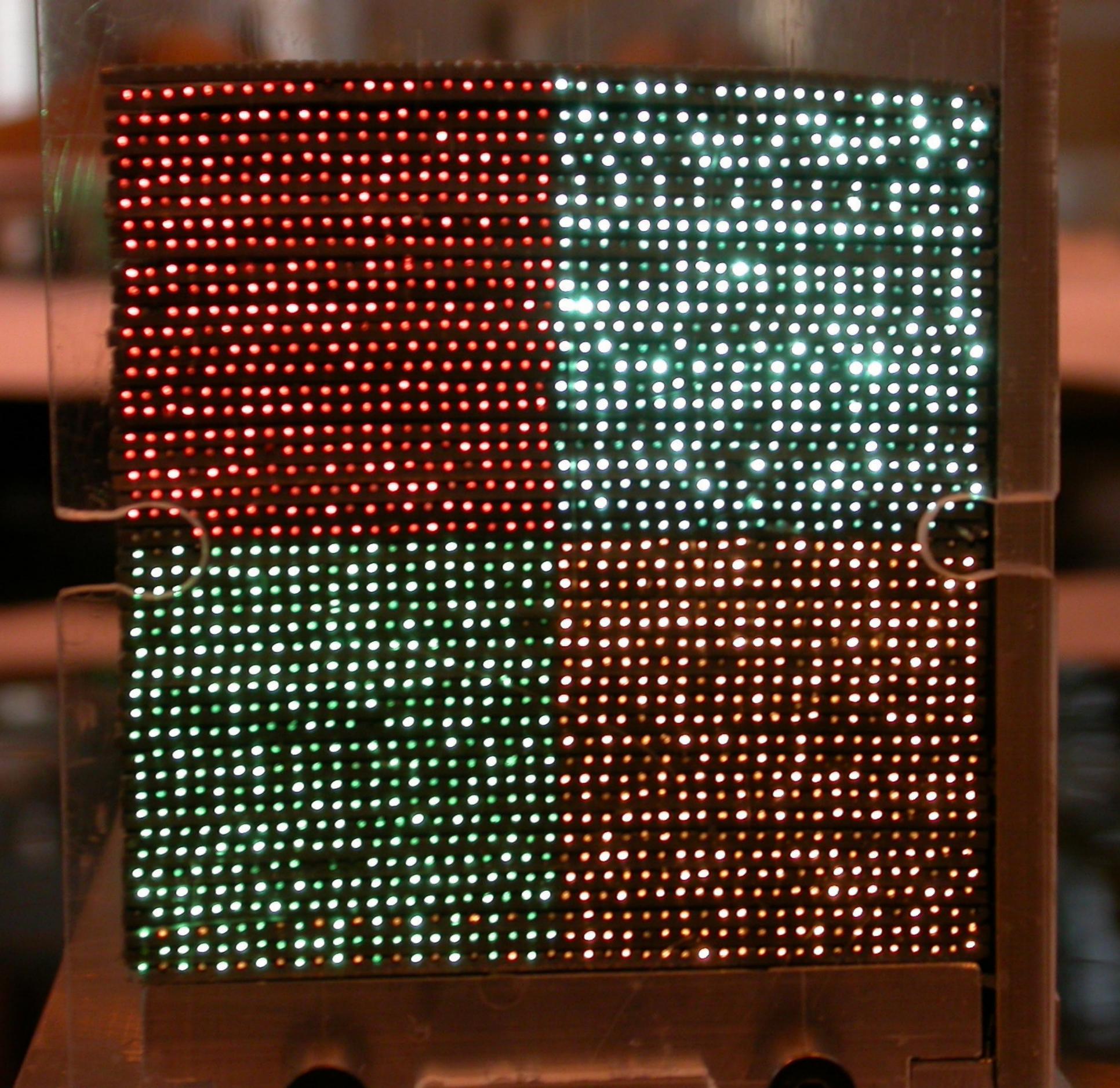
L'ESPERIMENTO ALICE













DAL SEGNALE
AL RISULTATO

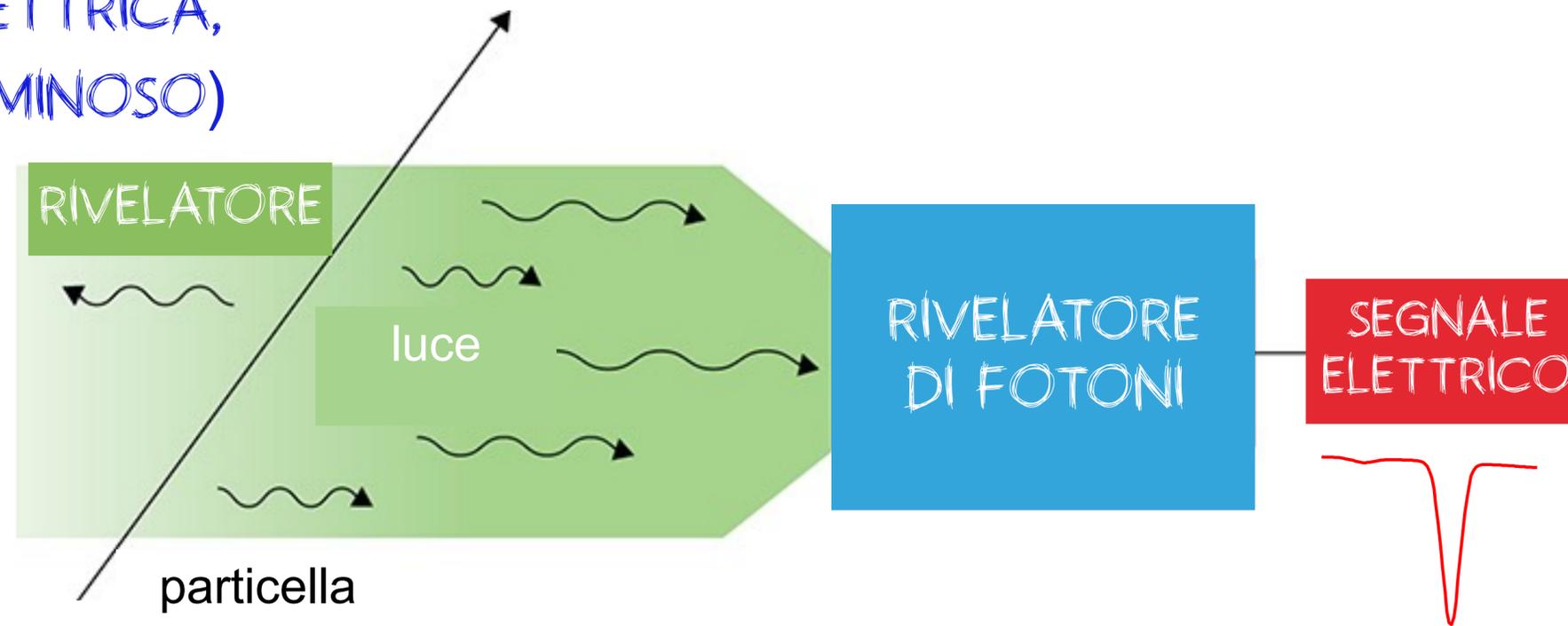
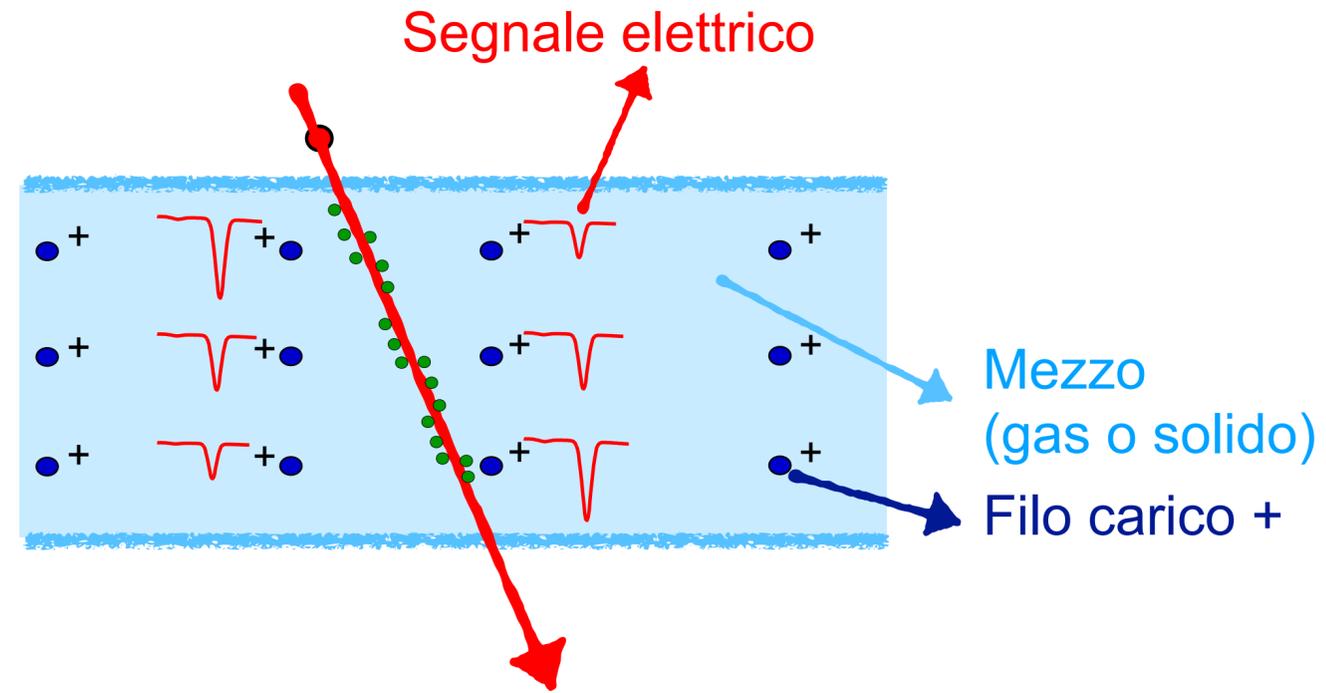
DALLA PARTICELLA AL "SEGNALE"

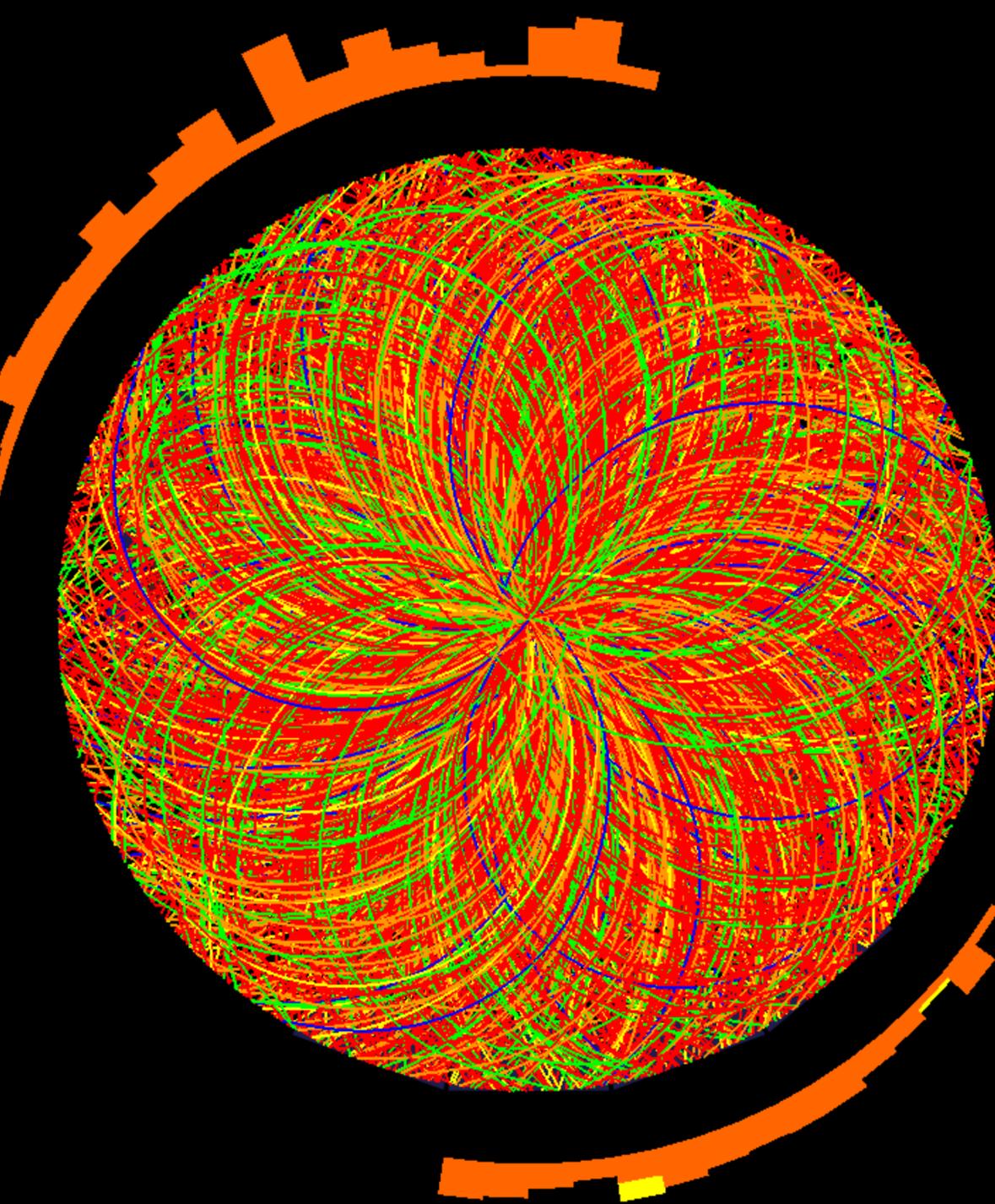
PARTICELLA INTERAGISCE CON
LA MATERIA (RIVELATORE)

PROCESSO FISICO

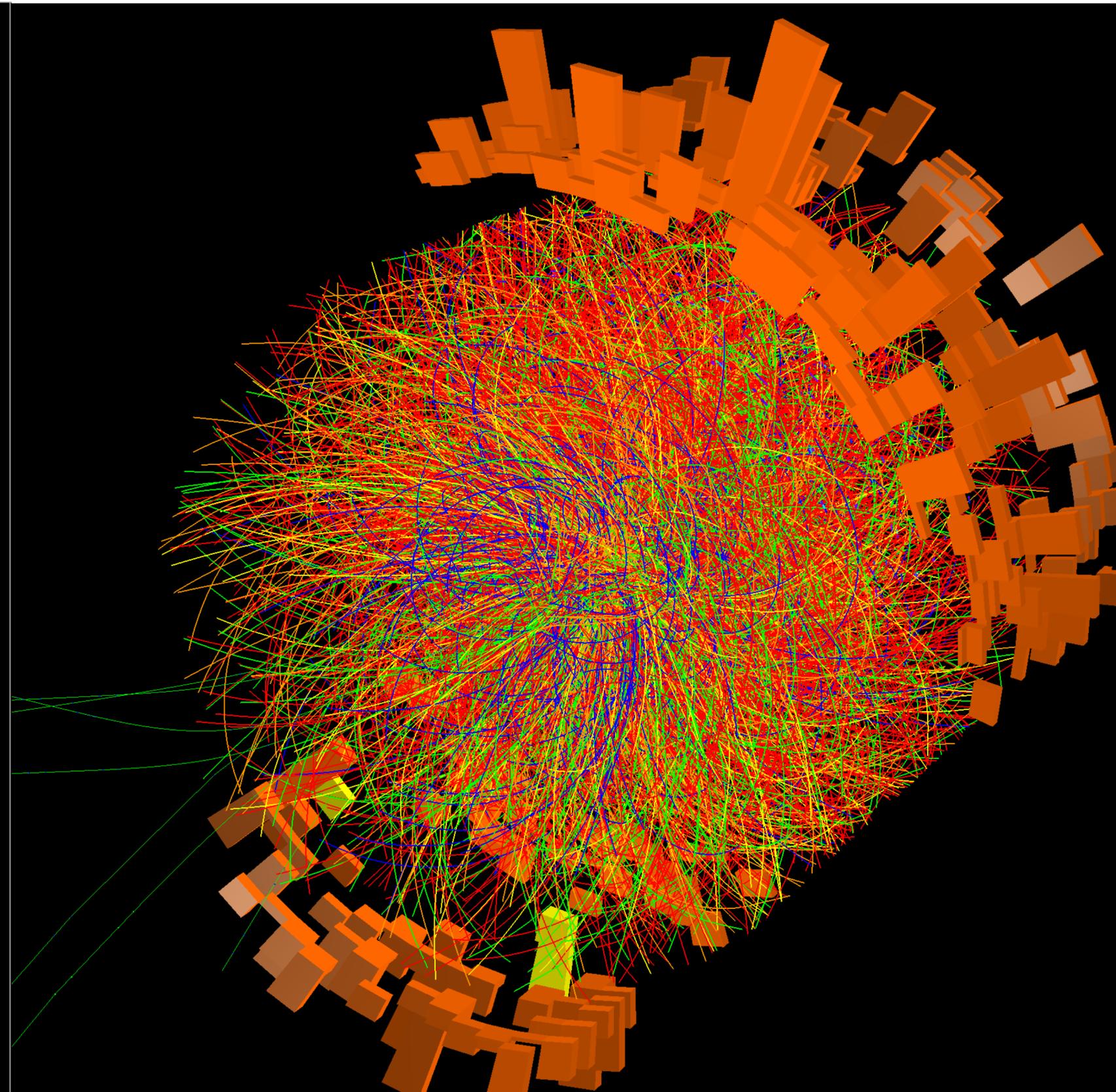
SEGNALE MISURABILE

RACCOLTA DEL SEGNALE
(CARICA ELETTRICA,
SEGNALE LUMINOSO)





ALICE





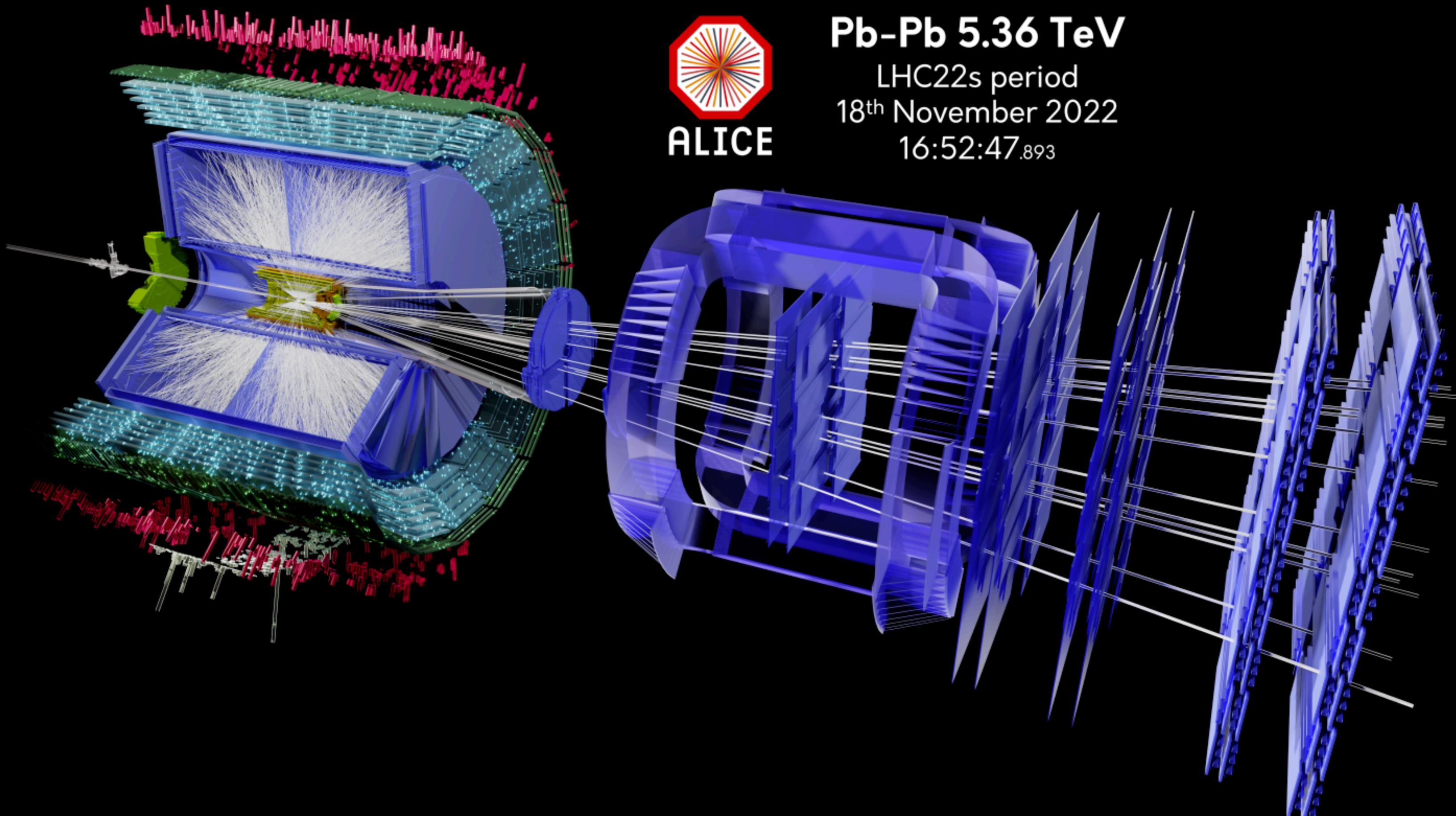
ALICE

Pb-Pb 5.36 TeV

LHC22s period

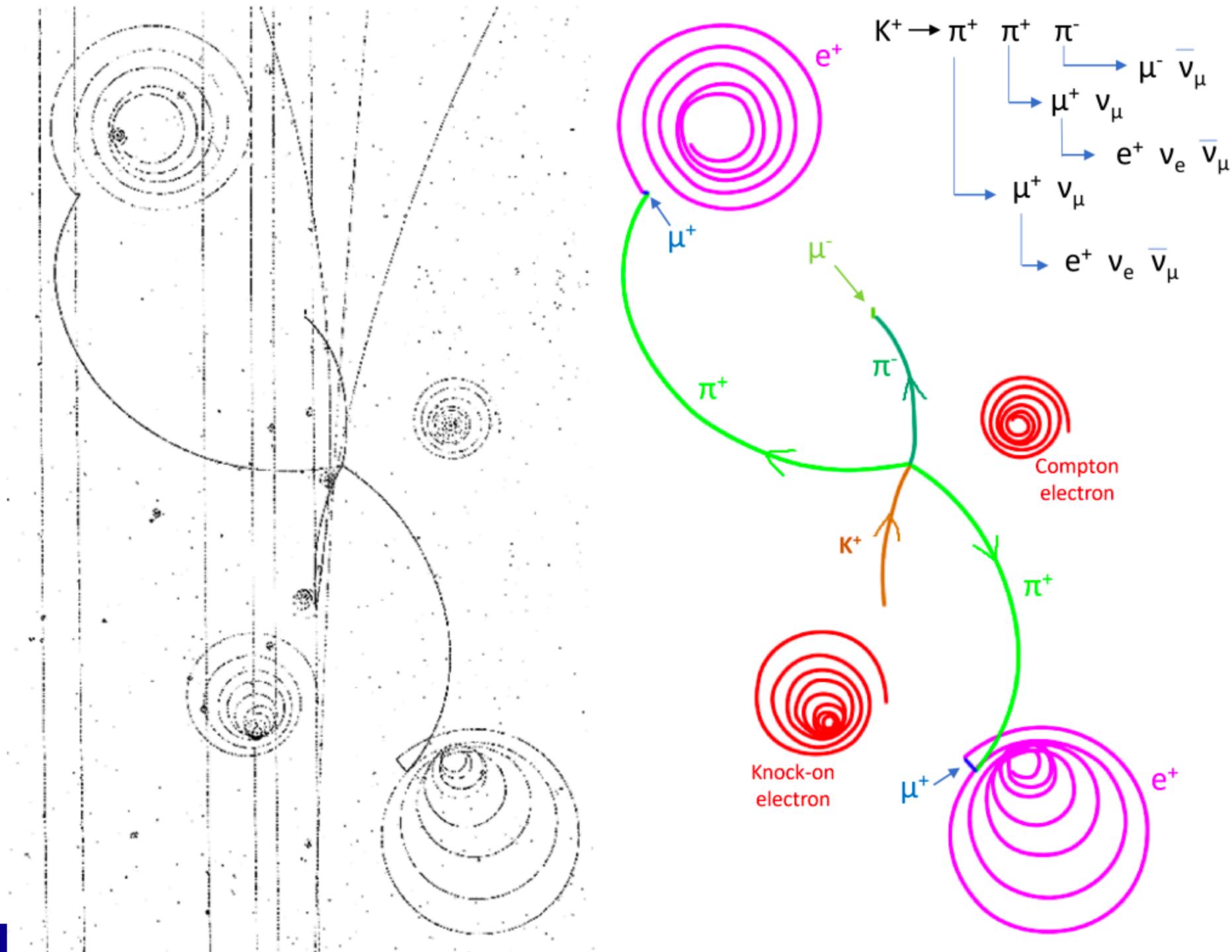
18th November 2022

16:52:47.893



DALLA PARTICELLA AL "SEGNALE"

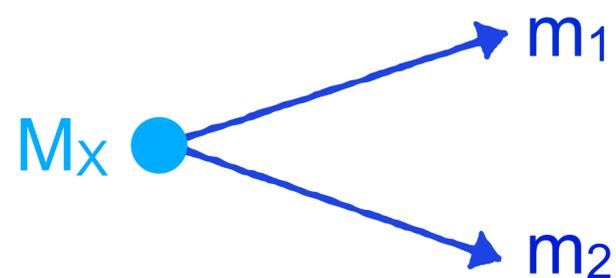
Le particelle **INSTABILI** decadono in particelle **STABILI** prima di raggiungere i rivelatori
Vite medie dell'ordine di 10^{-20} s, viaggiando alla velocità della luce, decadono in $\sim 10^{-12}$ m!



MASSA INVARIANTE = LA MASSA SI CONSERVA!

La massa invariante è una quantità conservata

Particella instabile che decade

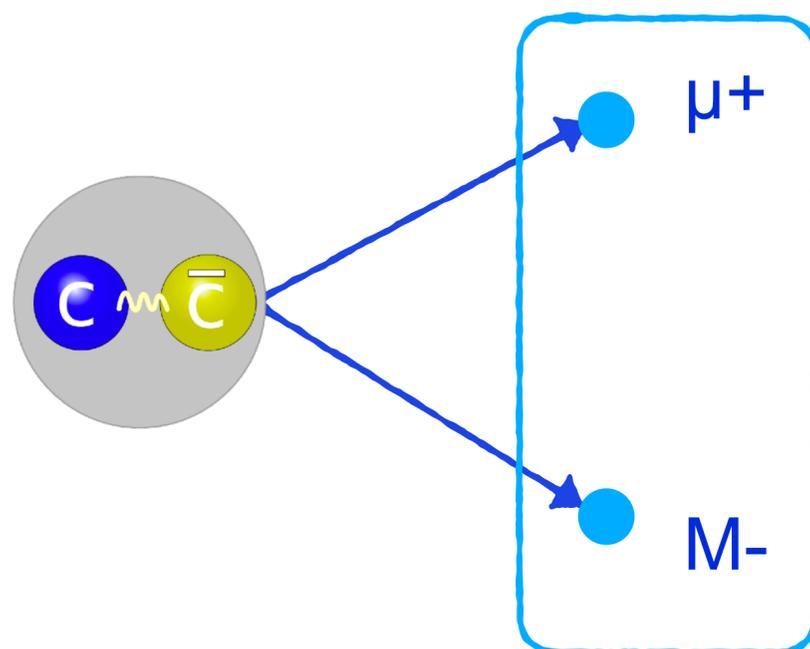


Particelle prodotte nel decadimento di M_X

$$M_X = \sqrt{(E_1 + E_2)^2 - (p_1 + p_2)^2}$$

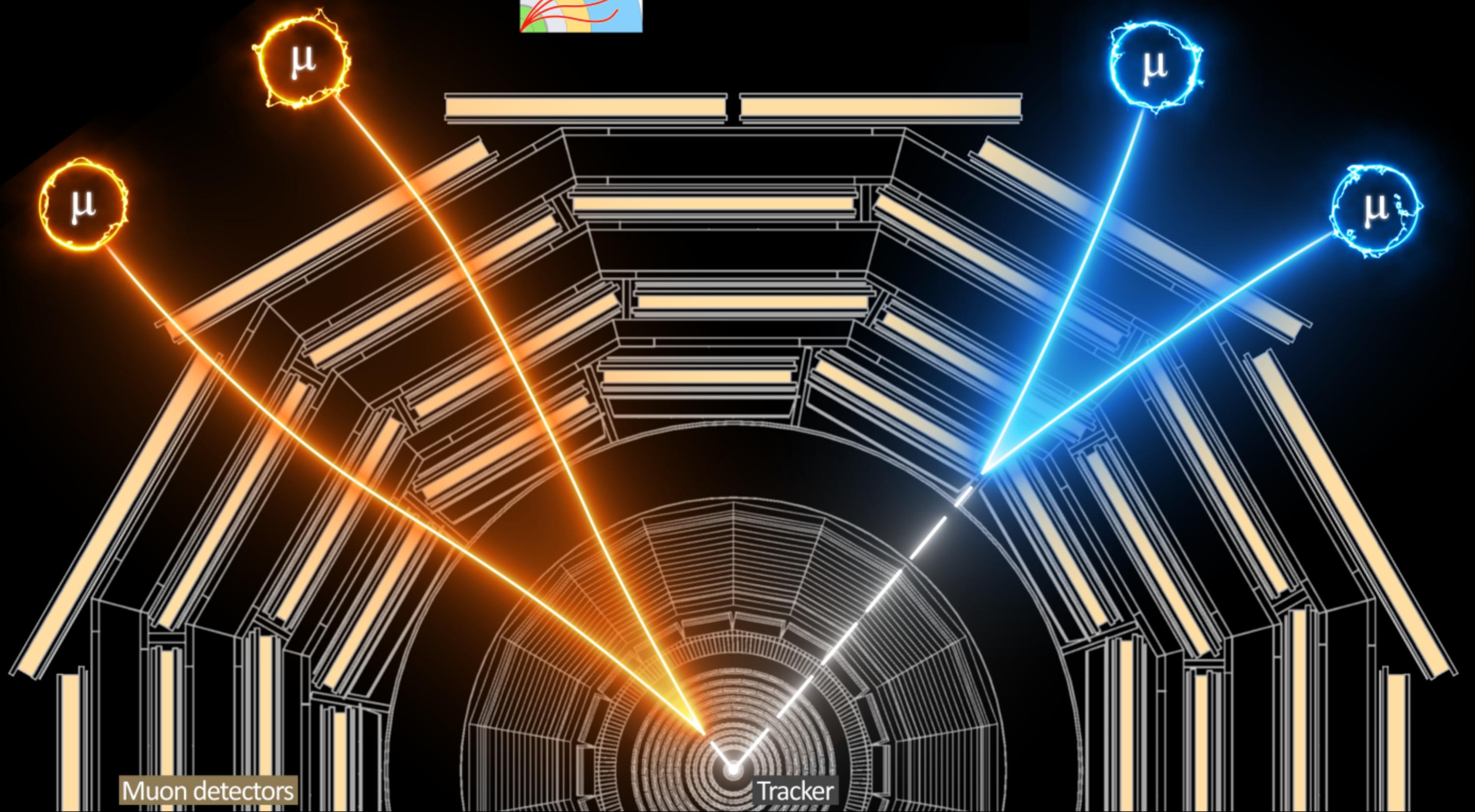
massa X = massa invariante prodotti decadimento

J/ψ



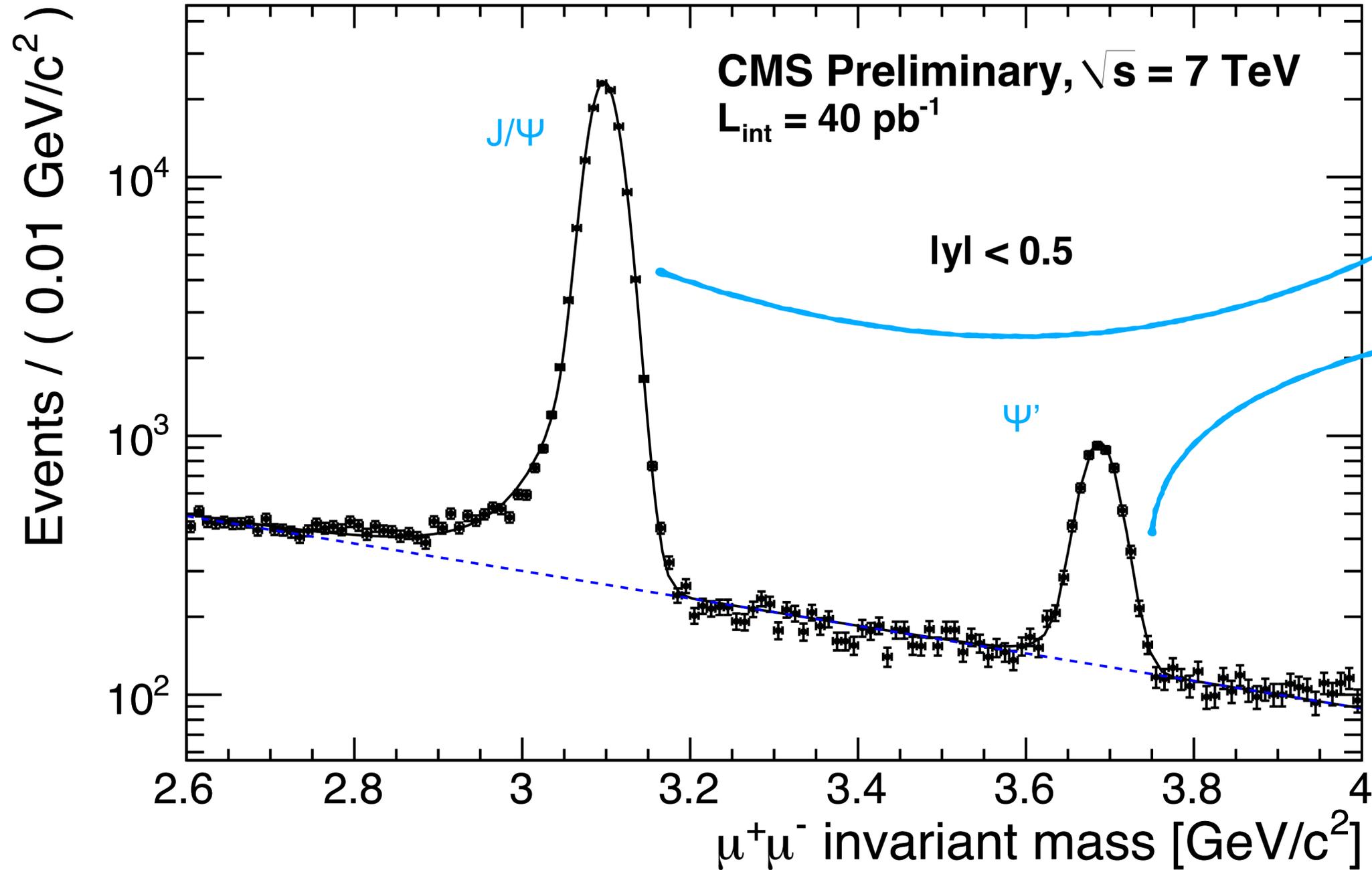
Nel rivelatore misuro le proprietà dei 2 muoni

► costruisco un istogramma con la distribuzione della massa invariante delle coppie di muoni μ^+ , μ^- rivelati



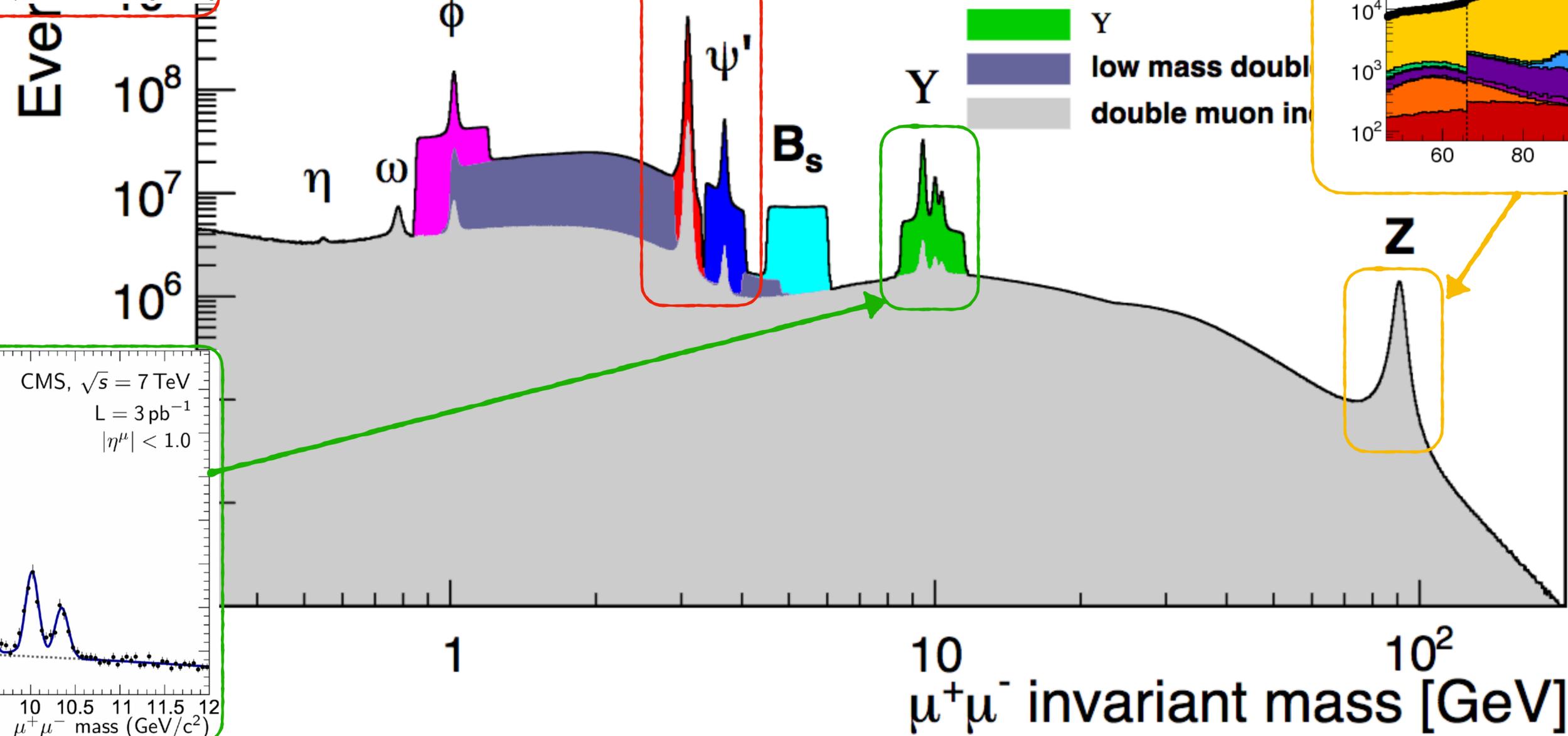
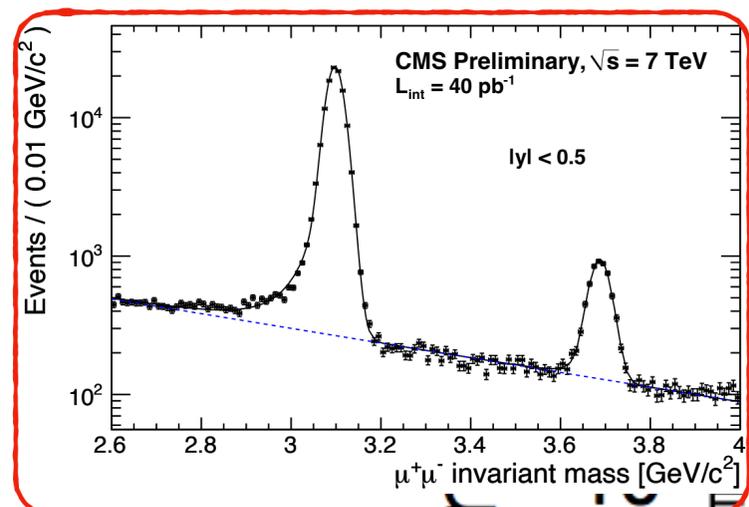
Muondetectors

Tracker

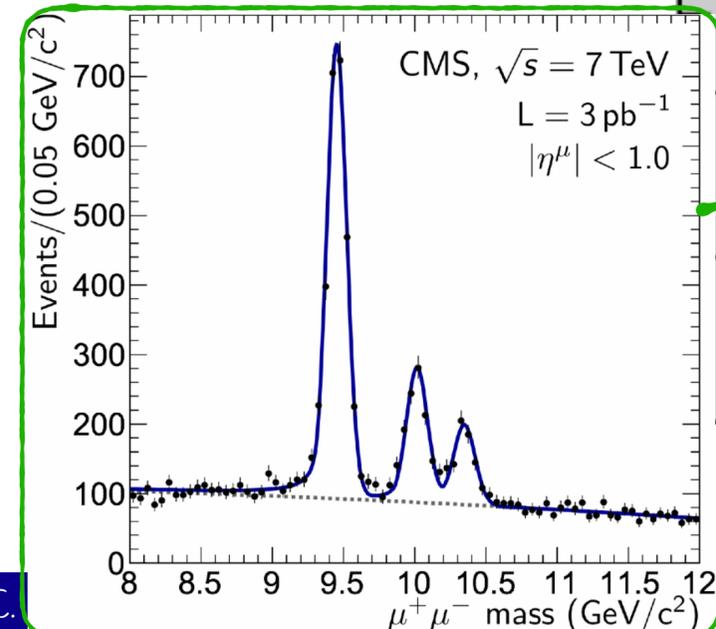
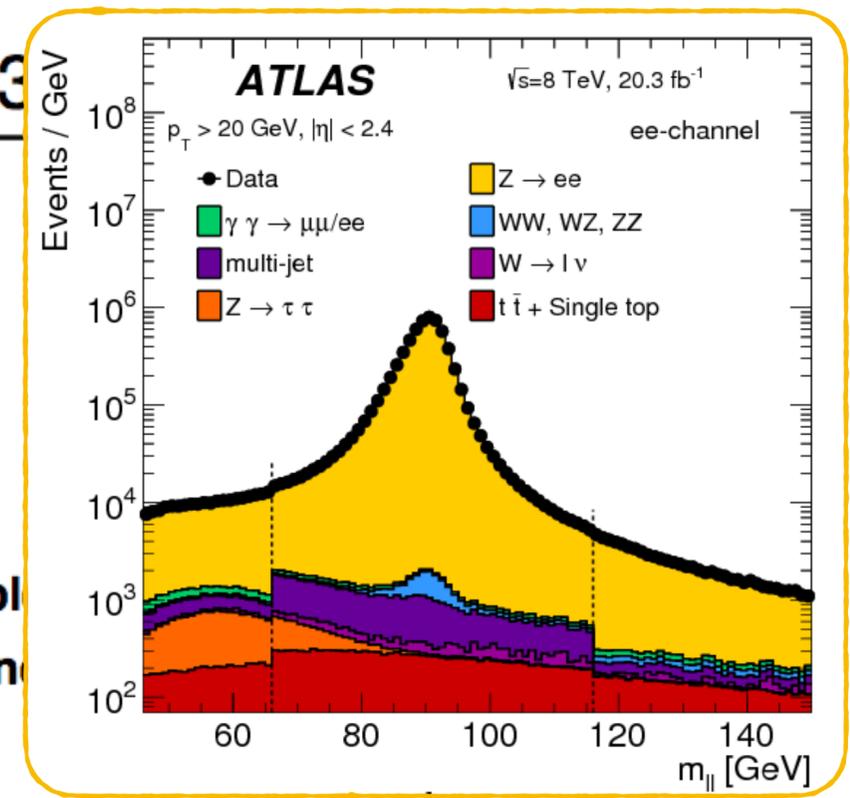


Osserverò un PICCO intorno al valore di massa delle particelle INSTABILI decadute nelle particelle STABILI che ho misurato per calcolare la massa invariante

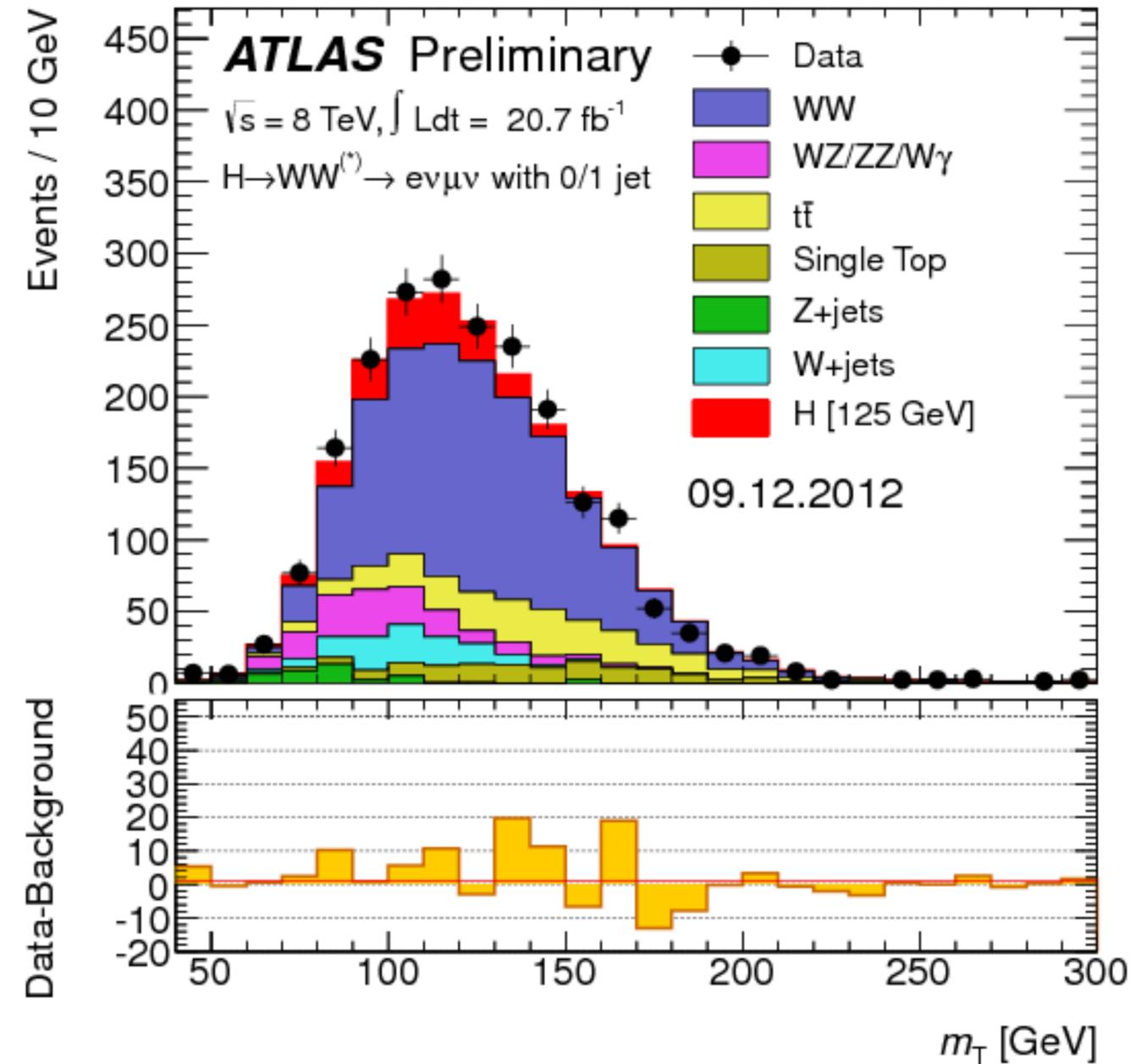
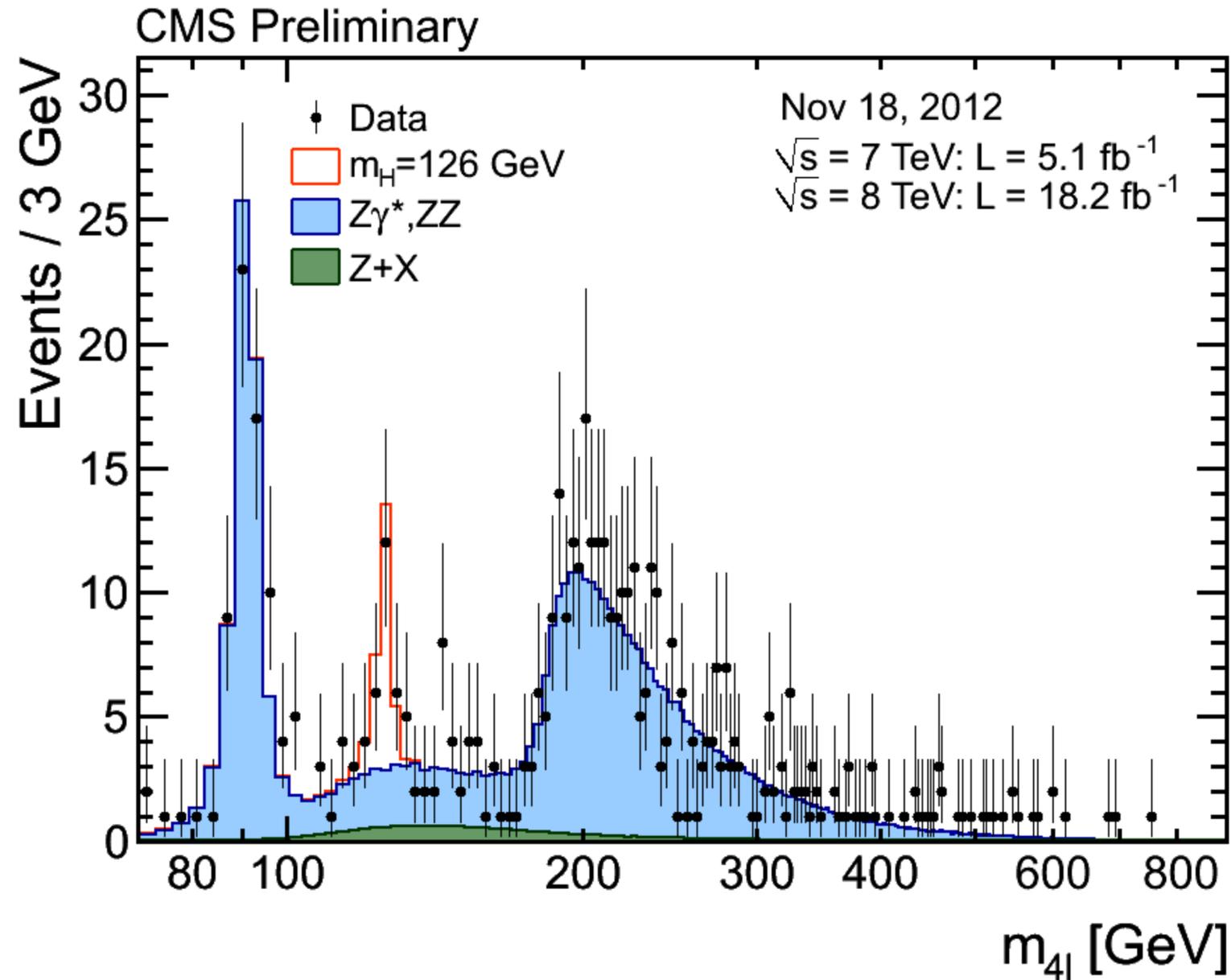
SPETTRO DI MASSA INVARIANTE



13.1 fb⁻¹ (13)



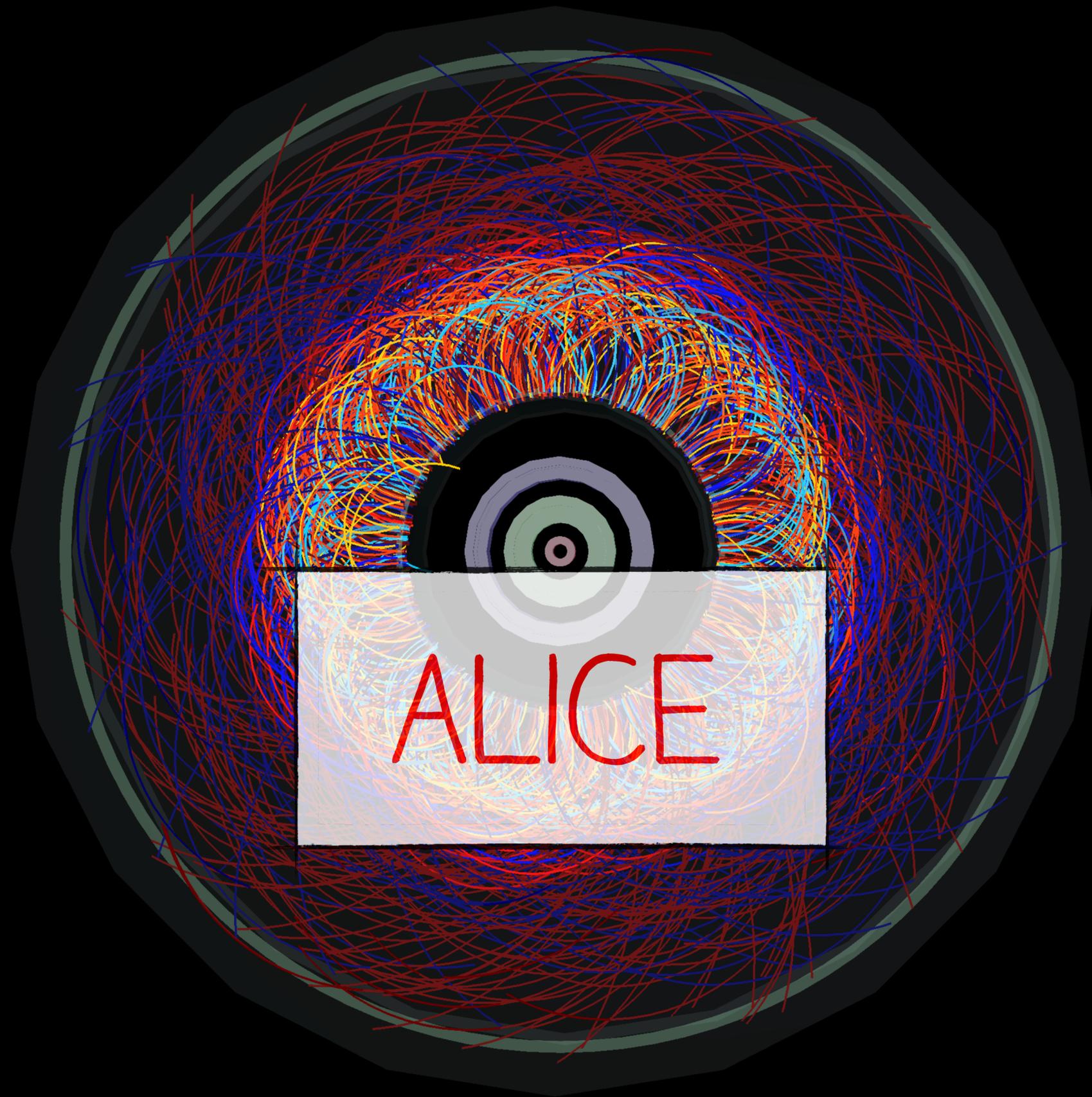
Risultati, pubblicazioni su riviste scientifiche internazionali, scoperte!





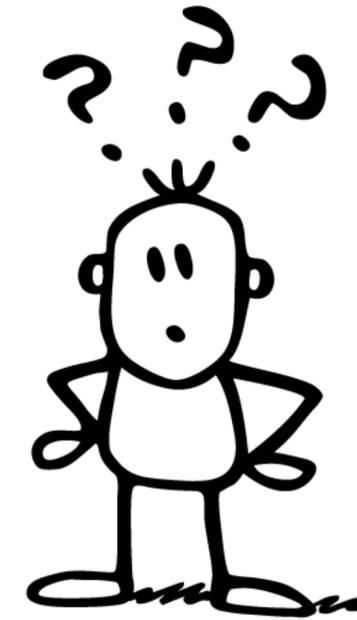
CI SONO SOLTANTO DUE POSSIBILI CONCLUSIONI DI UN ESPERIMENTO: SE IL RISULTATO CONFERMA LE IPOTESI, ALLORA HAI APPENA FATTO UNA MISURA; SE IL RISULTATO È CONTRARIO ALLE IPOTESI, ALLORA HAI FATTO UNA SCOPERTA.

Enrico Fermi



ALICE

MA QUINDI... COSA SI STUDIA AD ALICE?



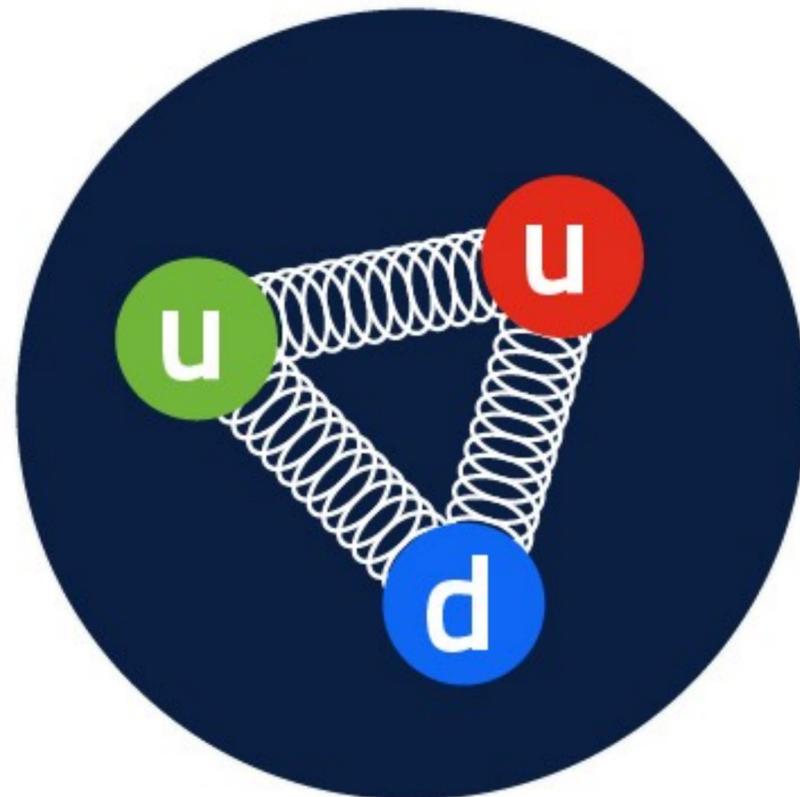
Le particelle formate da quark si chiamano **ADRONI**

Gli adroni si differenziano per il loro contenuto di quark in due tipi di particelle:

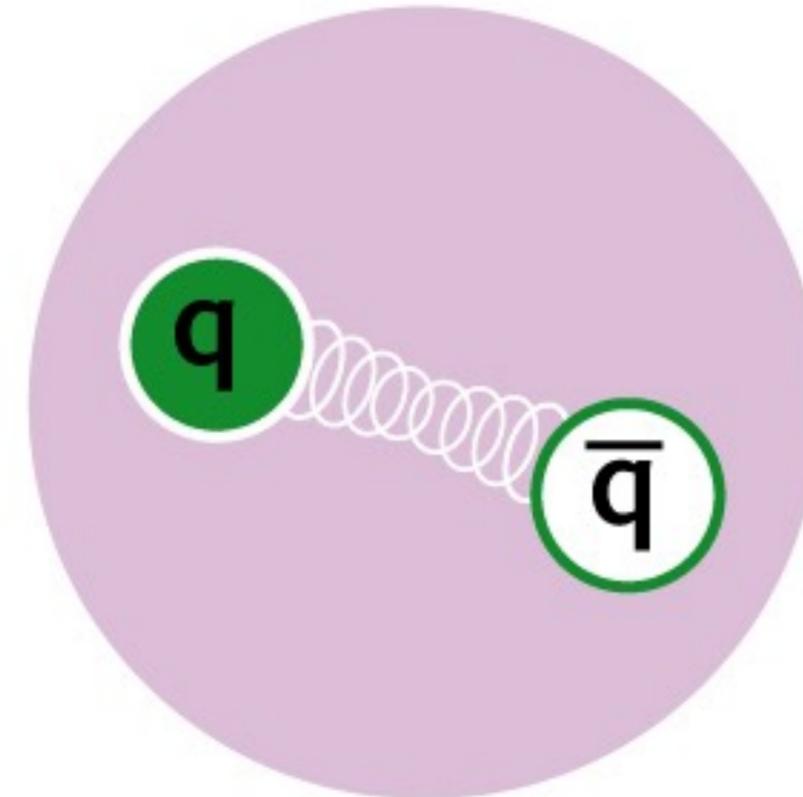
BARIONI ► formati da 3 quark

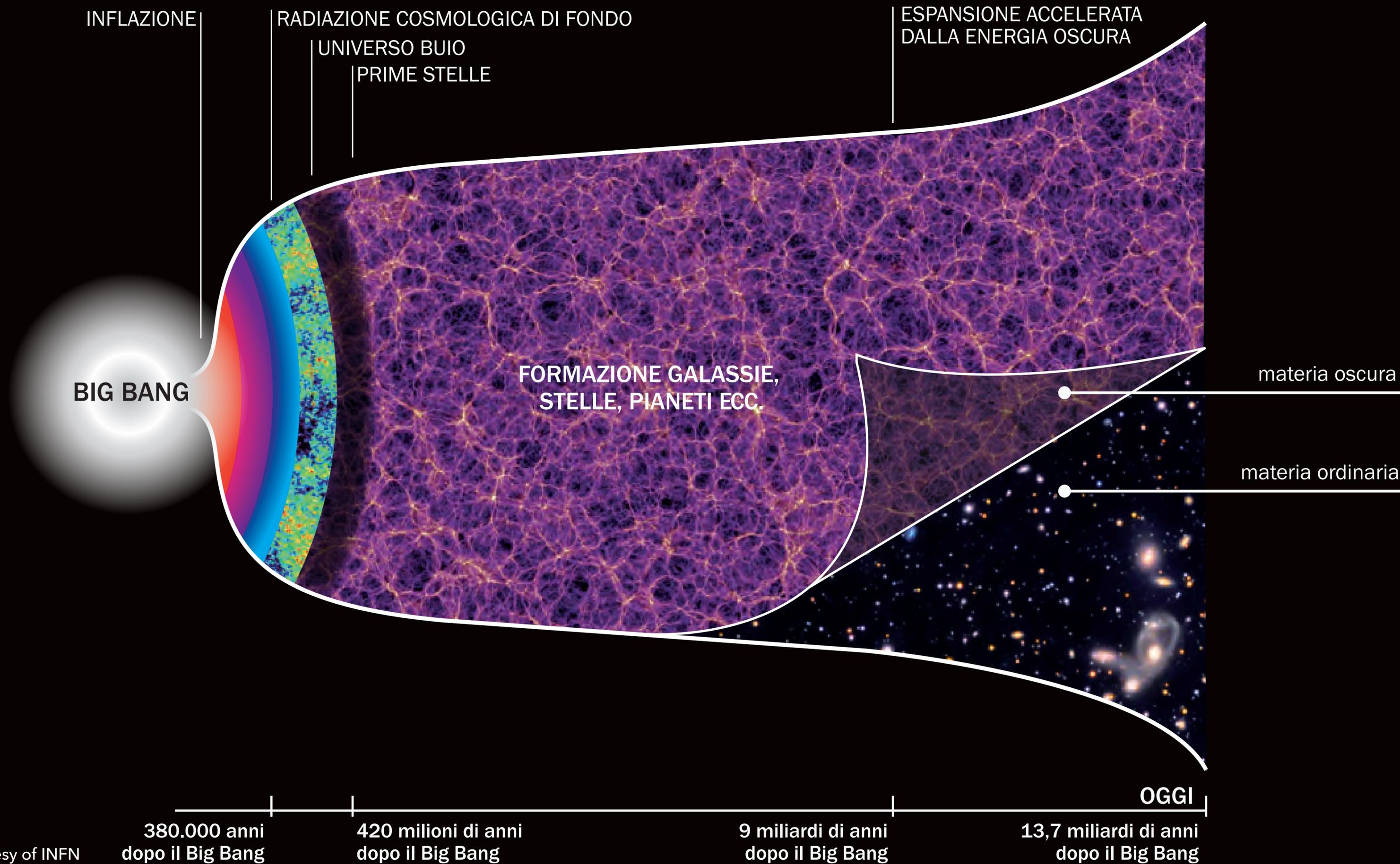
MESONI ► formati da una coppia quark+anti-quark

BARIONI

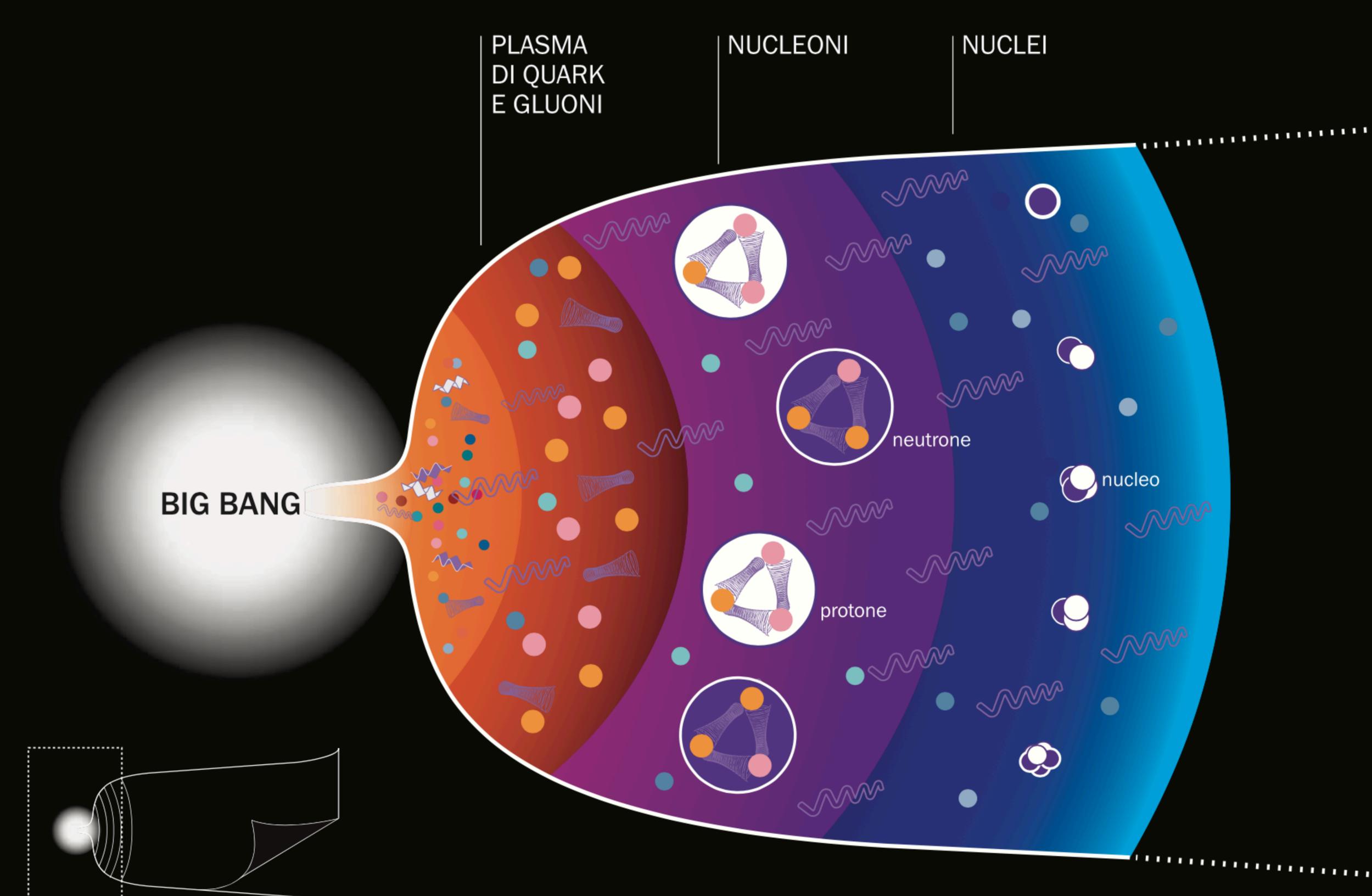


MESONI

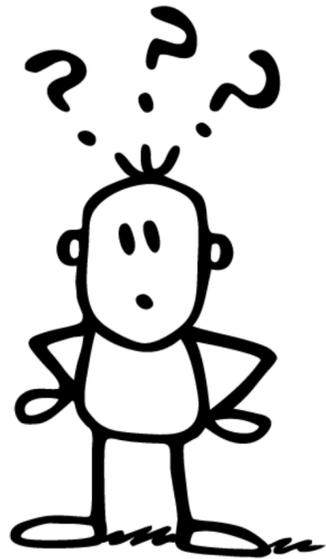
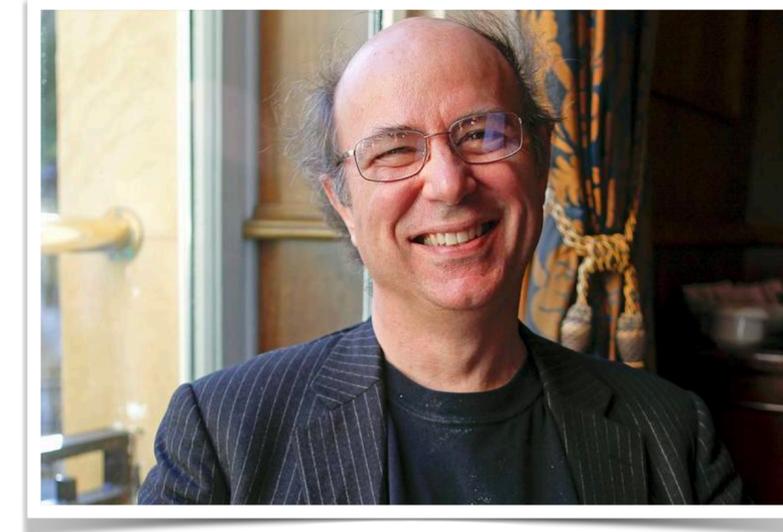




ALL'INIZIO L'UNIVERSO ERA...UNA ZUPPA DI QUARK E GLUONI



“I QUARK SONO NATI LIBERI
E ORA SONO IN CATENE”



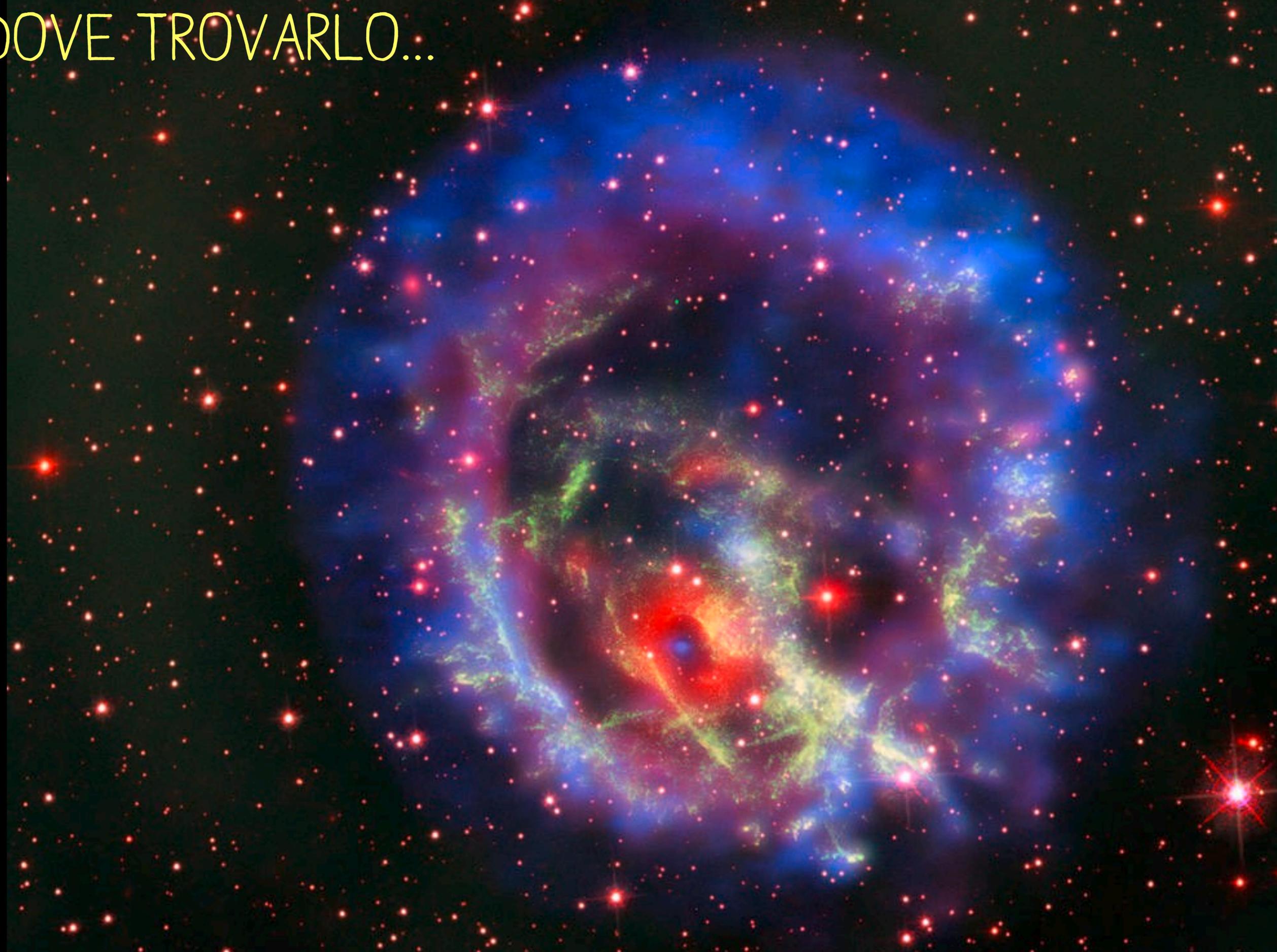
Perché non si osservano quark liberi in natura?

Clay Mathematics Institute has offered a prize of
US\$1,000,000 to the one who provides scientific explanation
from a mathematical point of view for confinement of particles



COME/DOVE SI POSSONO OSSERVARE QUARK E GLUONI
LIBERI COME NELL'UNIVERSO PRIMORDIALE?

QGP E DOVE TROVARLO...

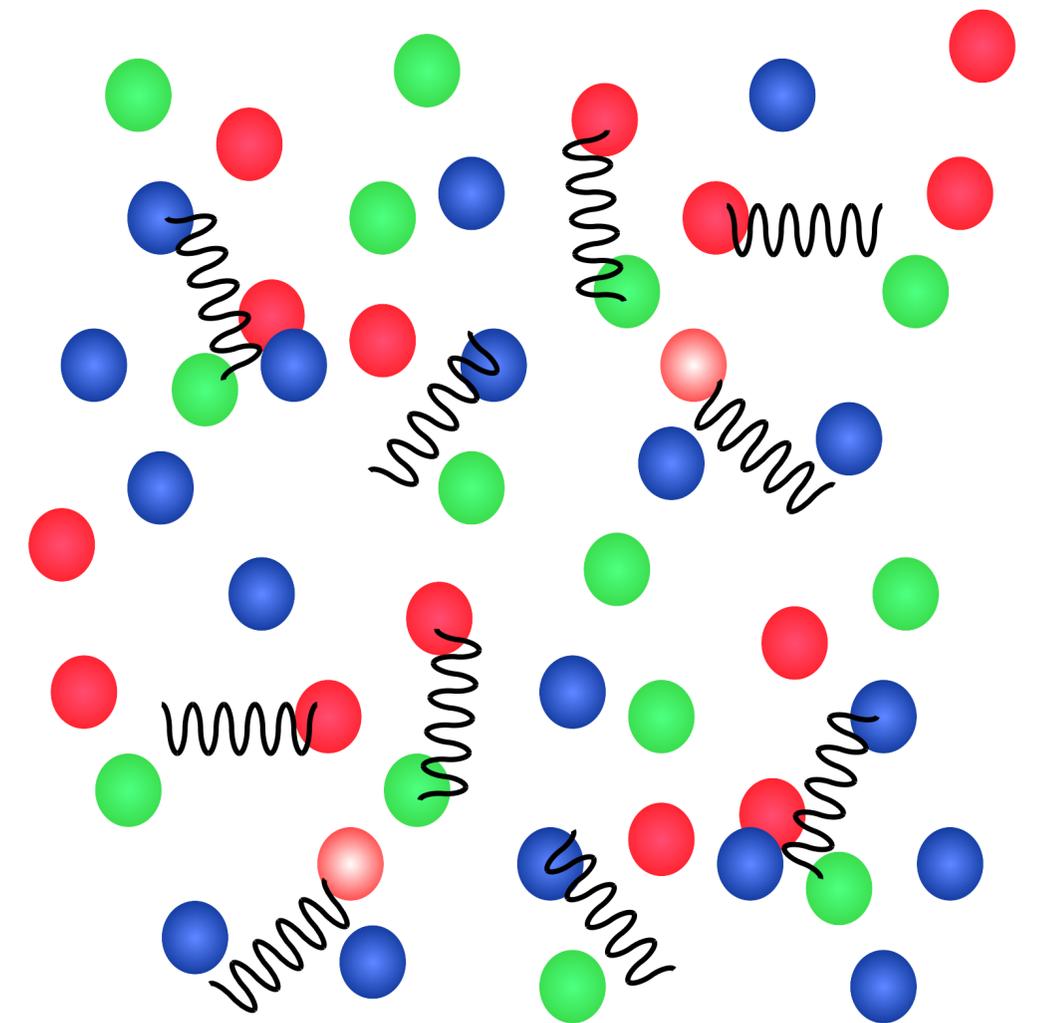
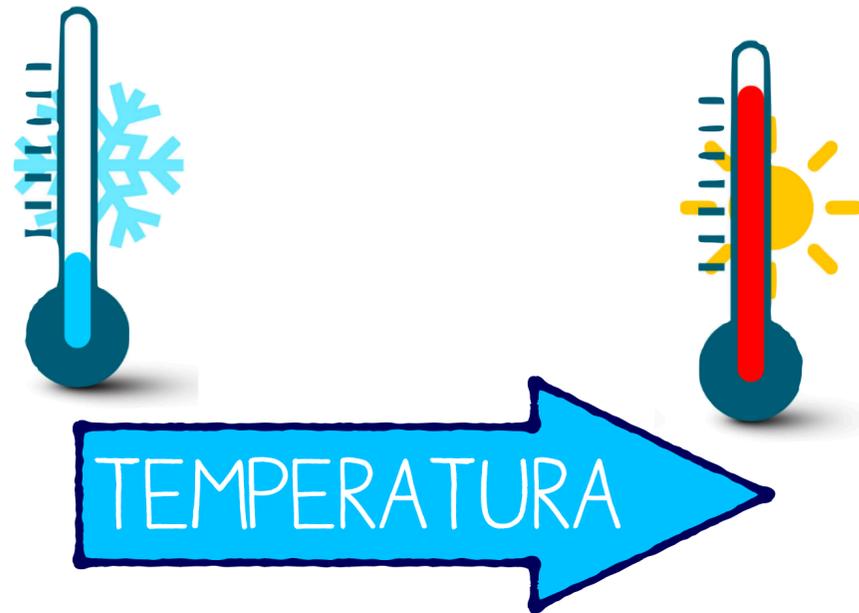
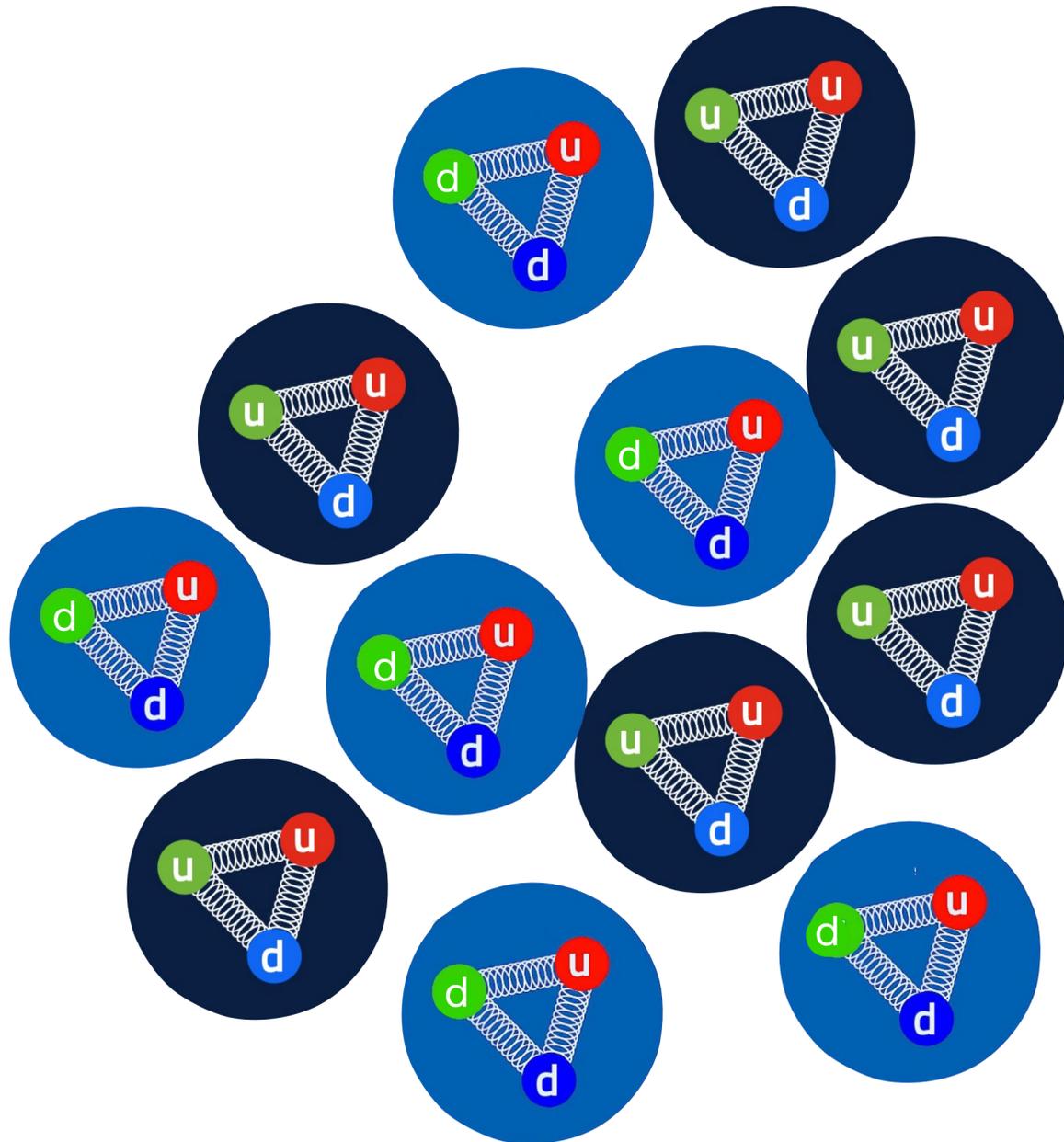


RICETTA PER CREARE IL QGP



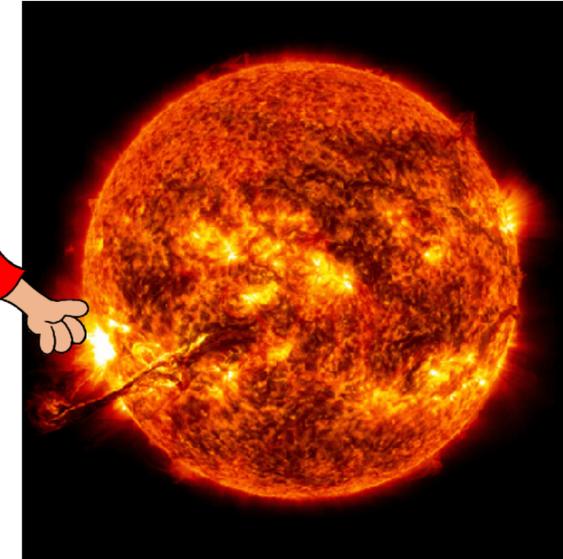
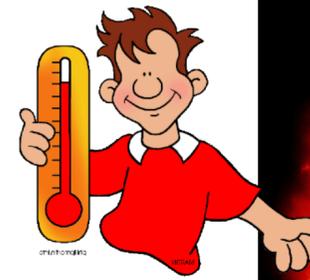
MATERIA NUCLEARE "ORDINARIA"

QUARK GLUON PLASMA



ALICE studia uno stato della materia che non si trova da nessun'altra parte nell'Universo

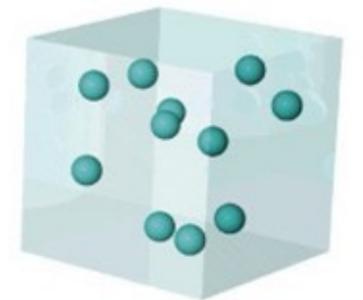
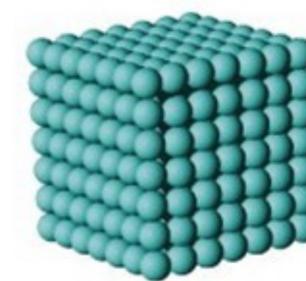
~300.000 volte più caldo del centro del Sole!



con densità paragonabili a quelle delle stelle di neutroni

ALICE studia l'Universo 10^{-6} seconds dopo Big-Bang!

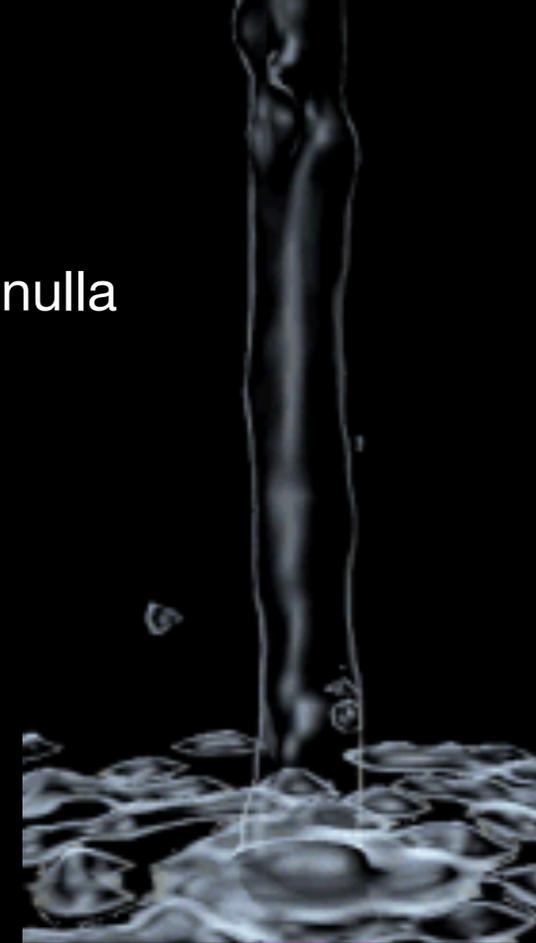
uno stato liquido con bassissima viscosità



BBC FOUR



He superfluido ▶ viscosità nulla



VISCOITÀ



Explore more than **four petabytes**
of open data from particle physics!

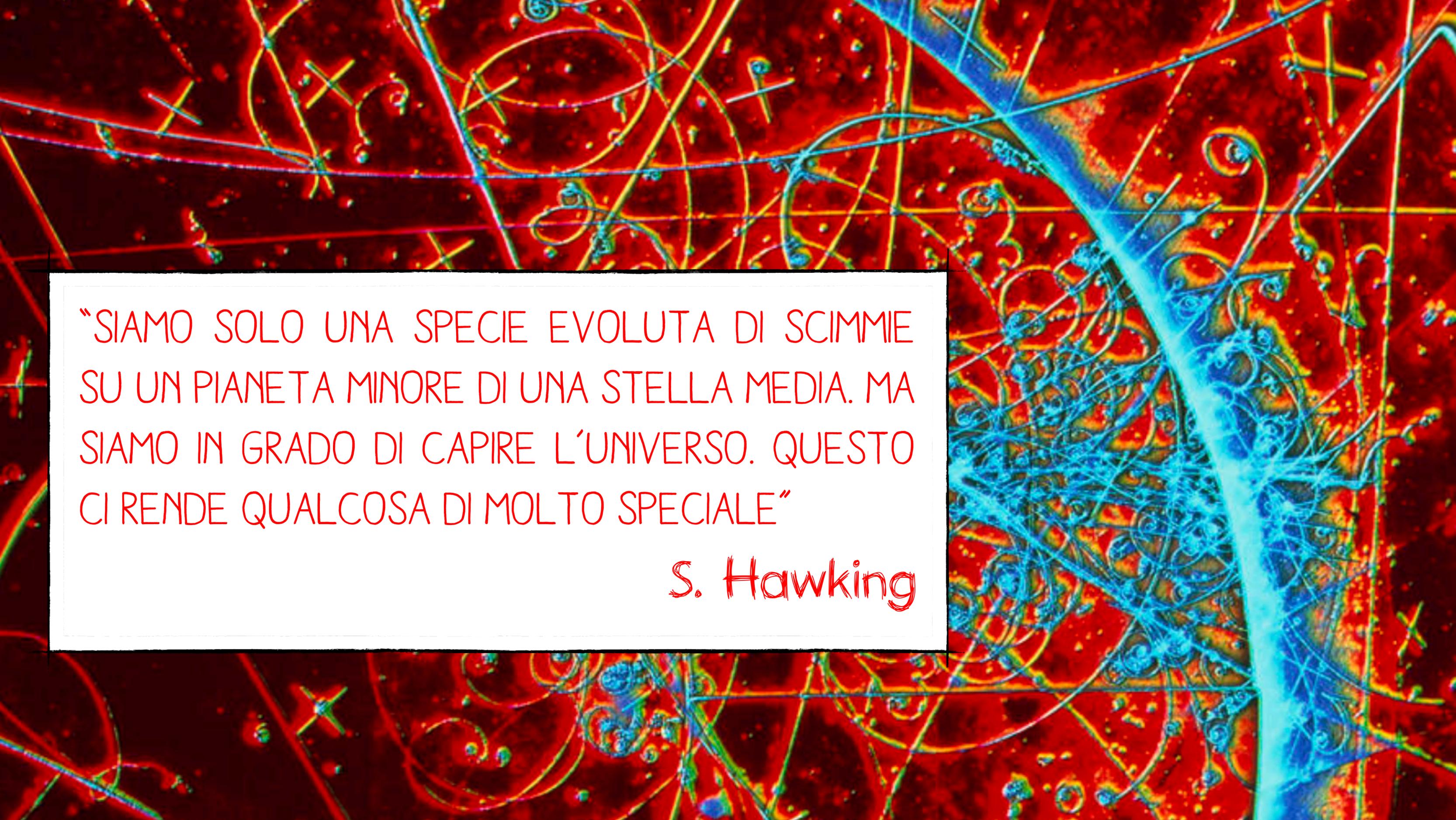
search examples: [collision datasets](#), [keywords:education](#), [energy:7TeV](#)

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“SIAMO SOLO UNA SPECIE EVOLUTA DI SCIMMIE
SU UN PIANETA MINORE DI UNA STELLA MEDIA. MA
SIAMO IN GRADO DI CAPIRE L’UNIVERSO. QUESTO
CI RENDE QUALCOSA DI MOLTO SPECIALE”

S. Hawking