



# Lo straordinario mondo dell'infinitamente piccolo

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Istituto Nazionale di Fisica Nucleare - Roma



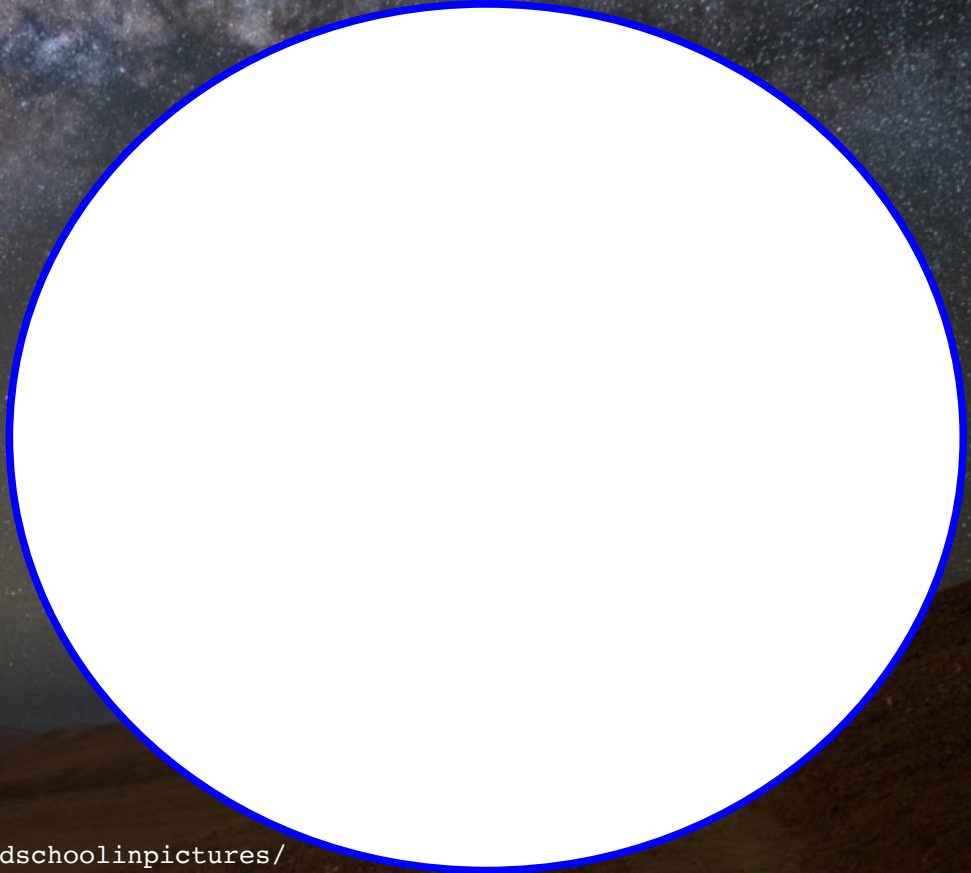
Istituto Nazionale di Fisica Nucleare

Sezione di Roma



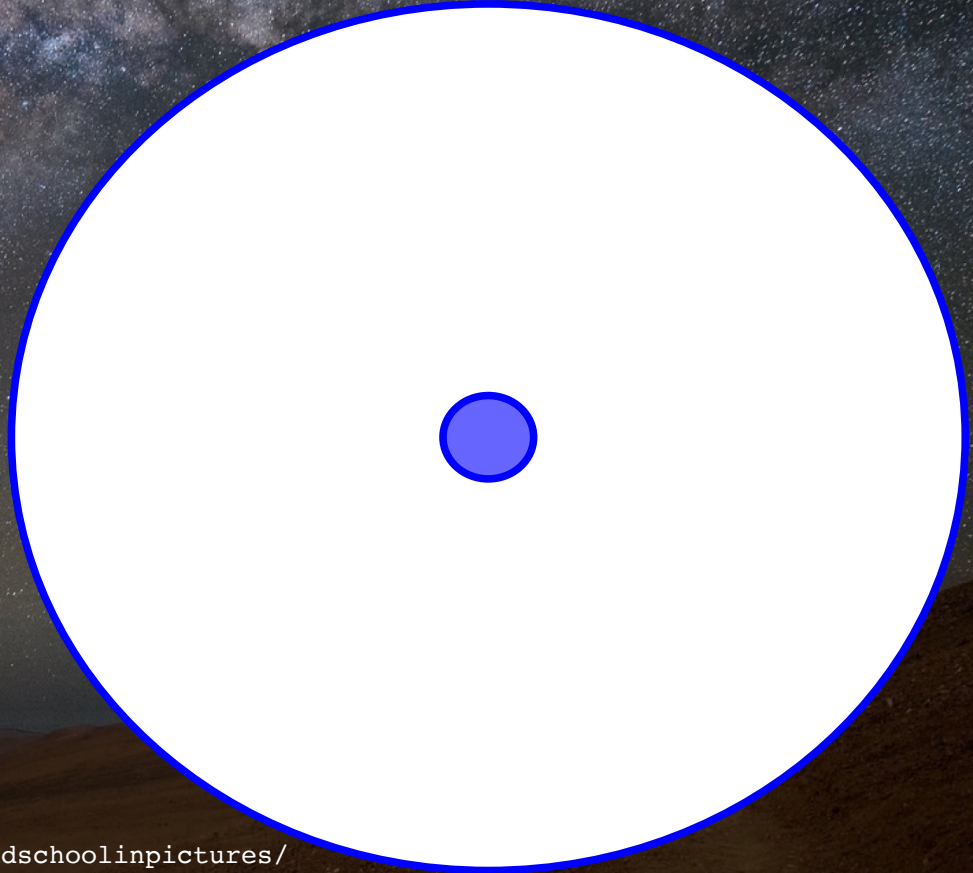
# Guida Illustrata al lavoro del ricercatore

Imagine a circle  
that contains all  
of human  
knowledge:



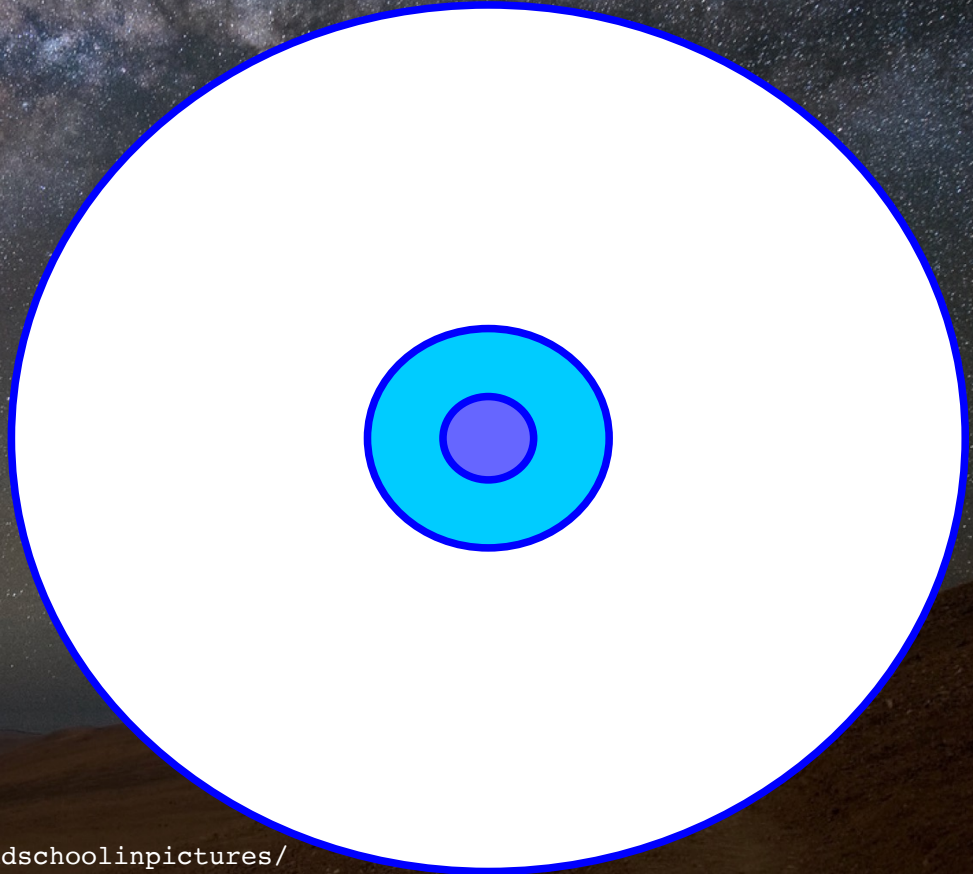
# Guida Illustrata al lavoro del ricercatore

By the time you finish elementary school, you know a little:



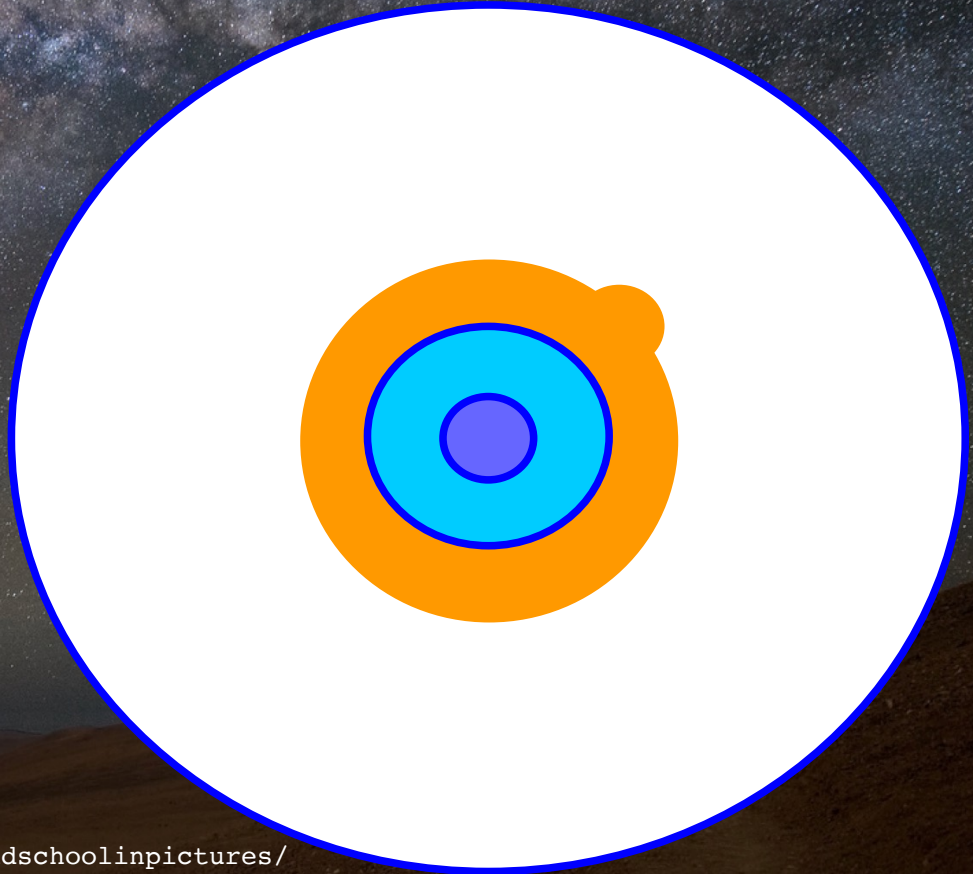
# Guida Illustrata al lavoro del ricercatore

By the time you finish high school, you know a bit more:



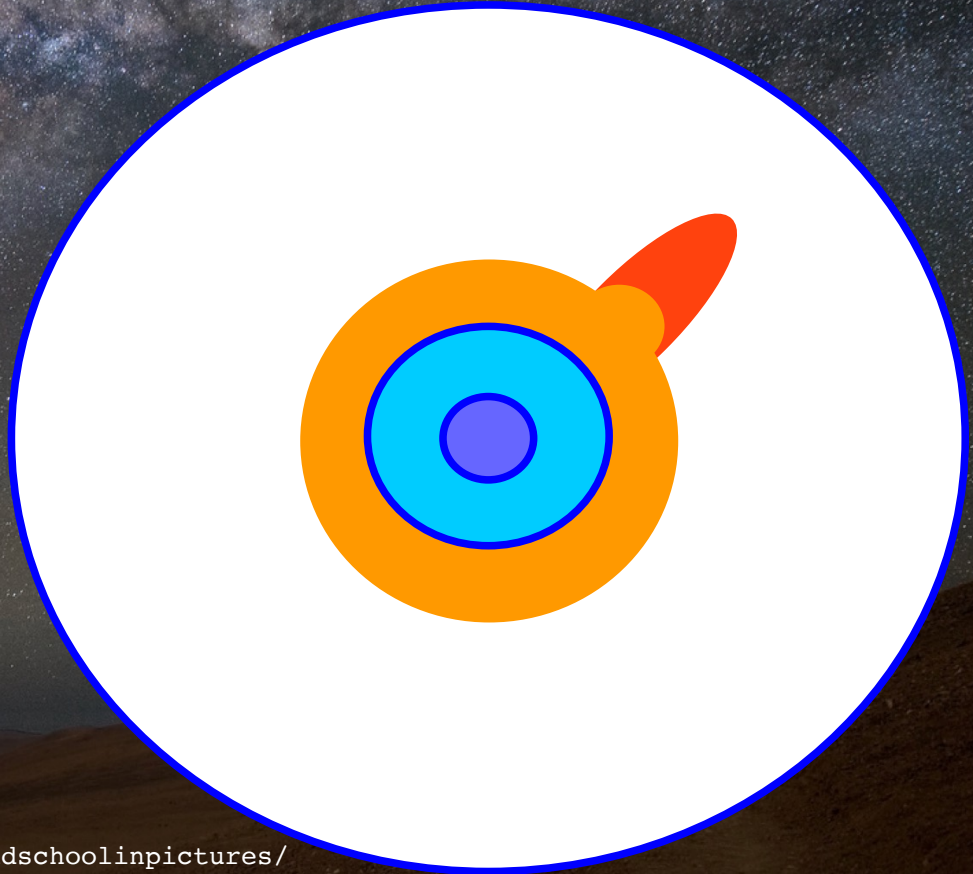
# Guida Illustrata al lavoro del ricercatore

With a bachelor's degree, you gain a specialty:



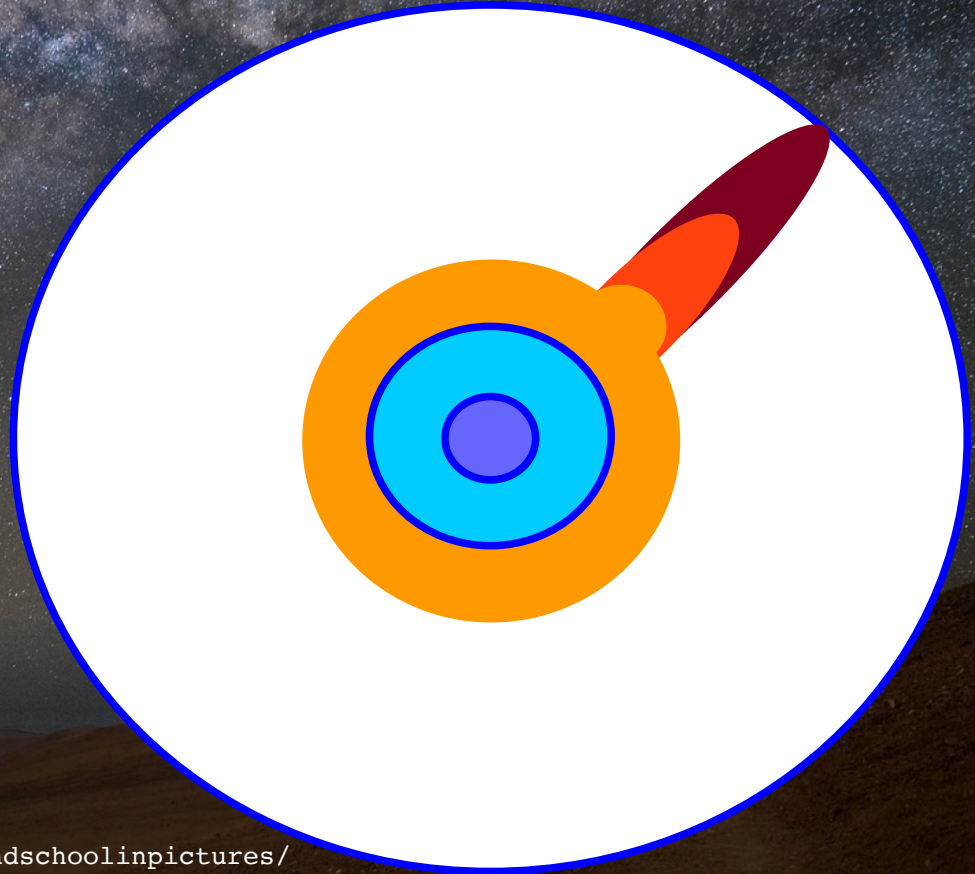
# Guida Illustrata al lavoro del ricercatore

A master's degree **deepens** that specialty:



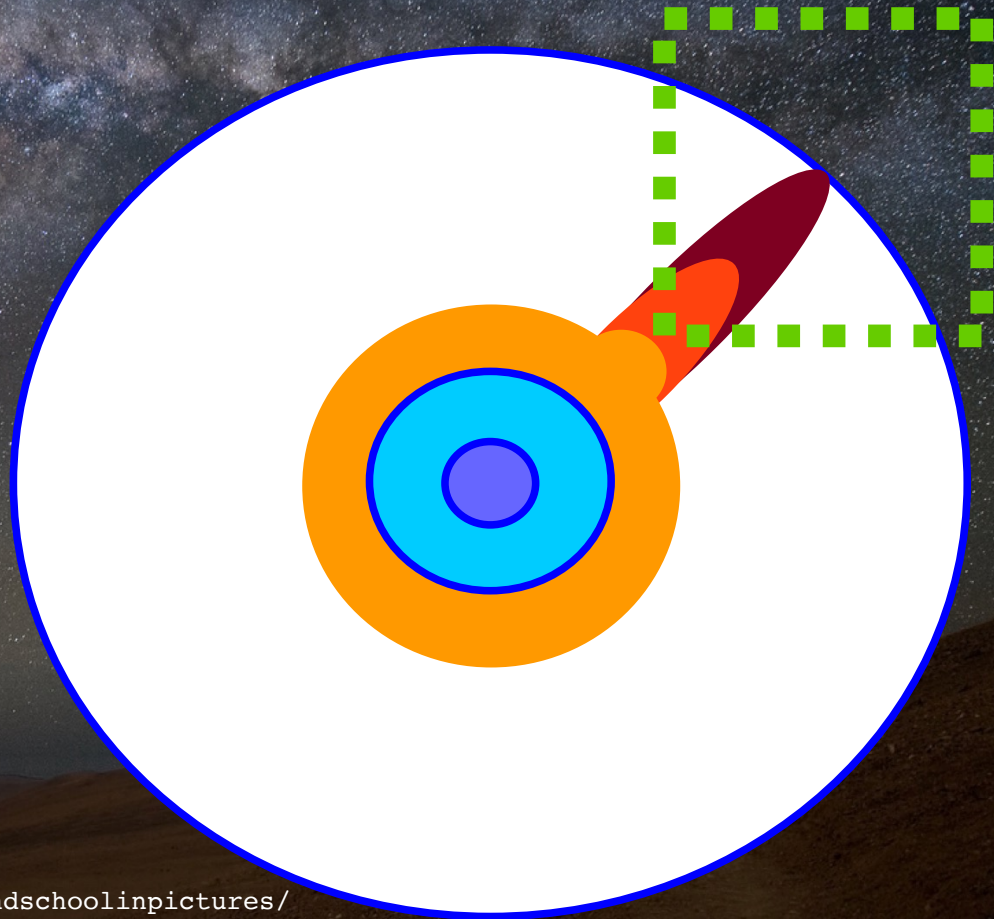
# Guida Illustrata al lavoro del ricercatore

Reading  
research papers  
takes you to the  
edge of human  
knowledge:



# Guida Illustrata al lavoro del ricercatore

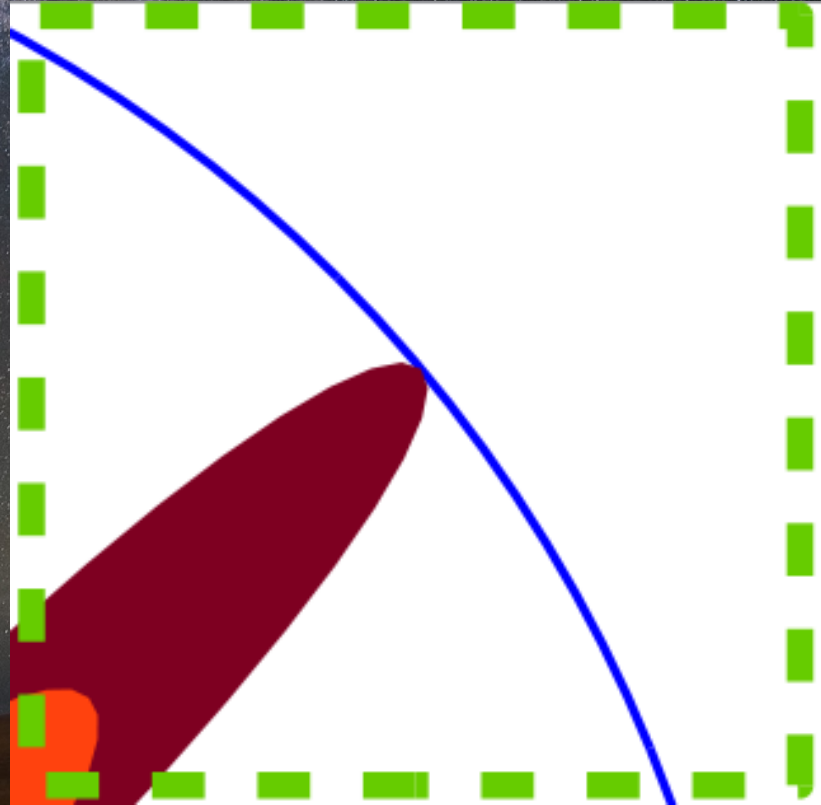
Once you are at the boundary you **focus**:





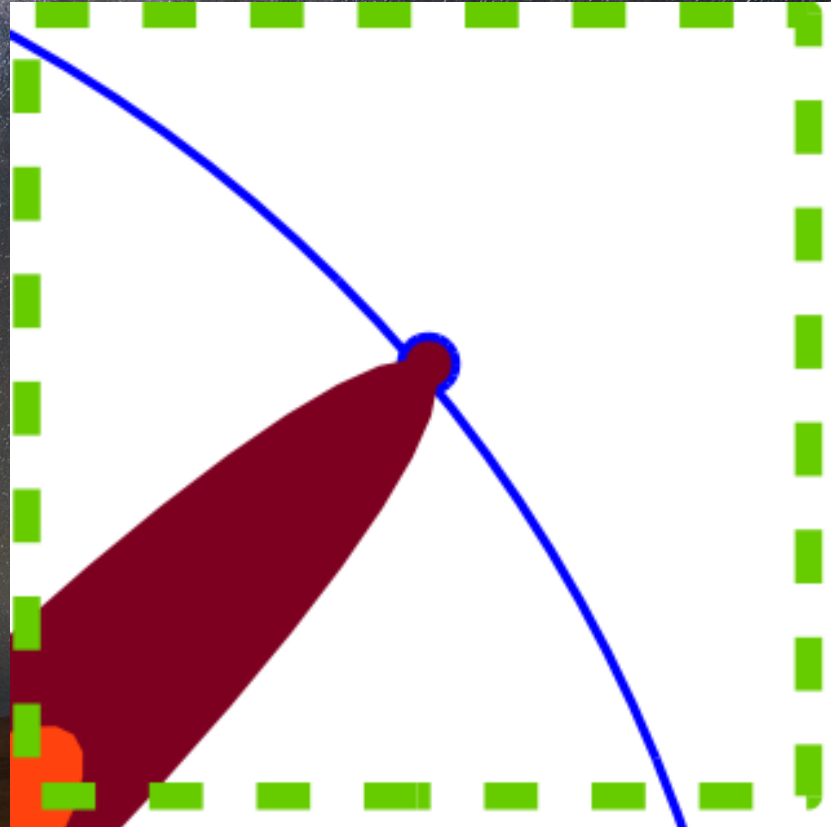
# Guida Illustrata al lavoro del ricercatore

You push at the boundary for a few years:



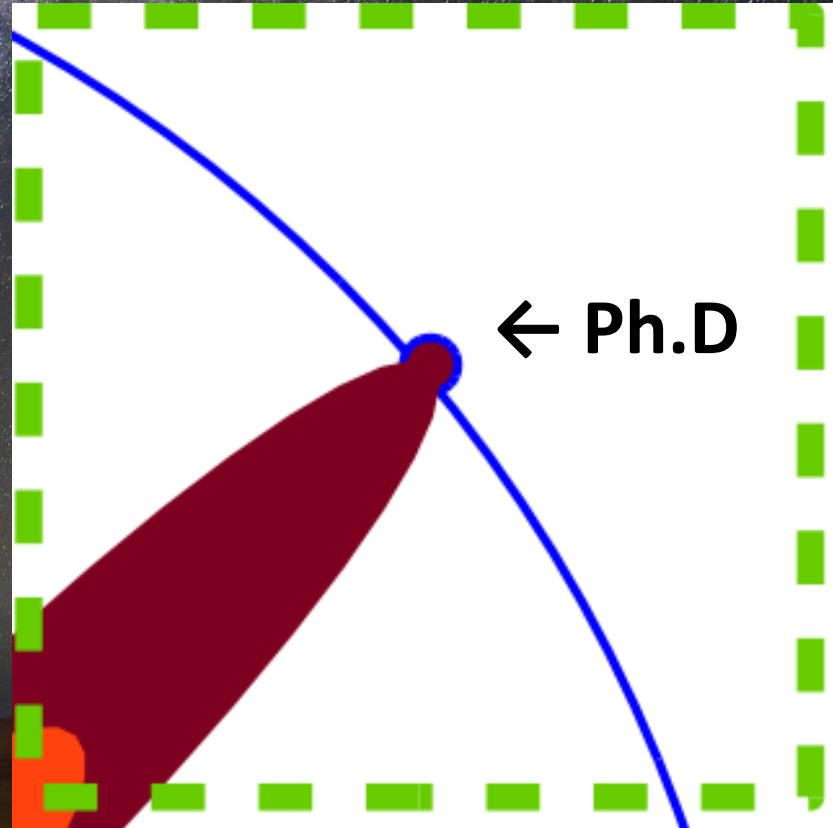
# Guida Illustrata al lavoro del ricercatore

Until one day,  
the boundary  
goes away:



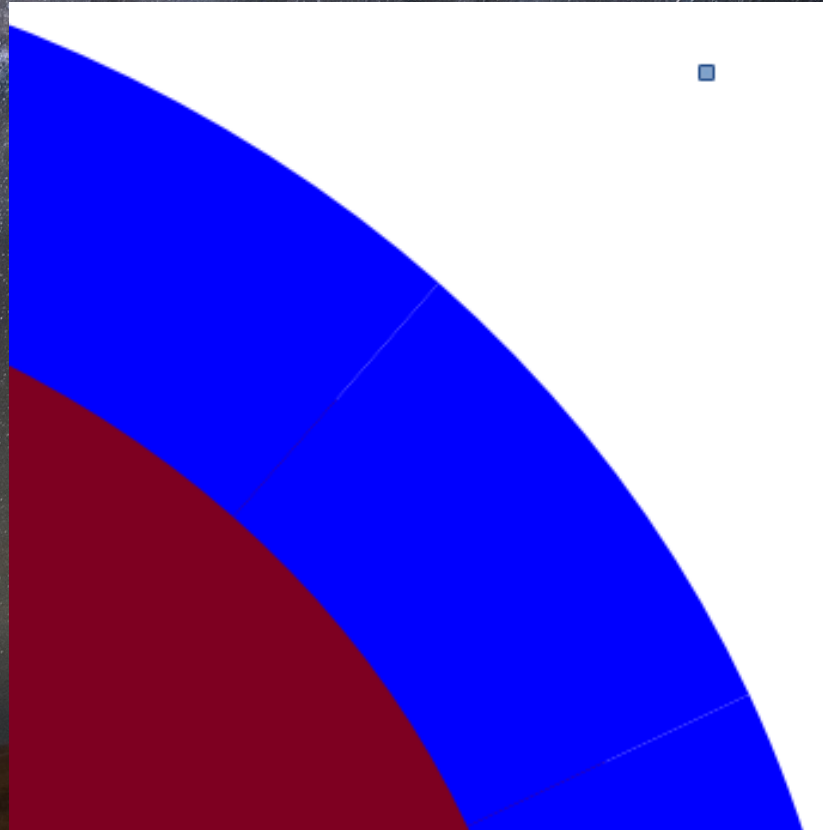
# Guida Illustrata al lavoro del ricercatore

And, that dent  
you've made is  
called a **Ph.D.**:



# Guida Illustrata al lavoro del ricercatore

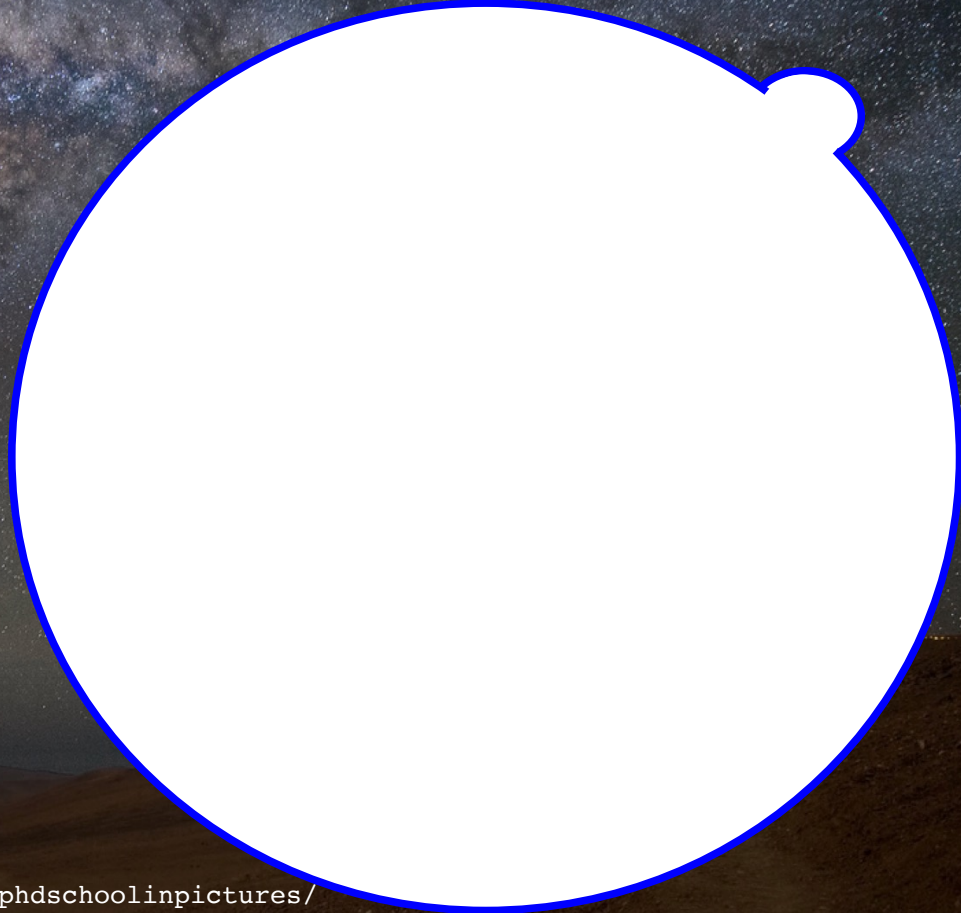
Of course, the **world** looks different to you now:



# Guida Illustrata al lavoro del ricercatore

But don't forget  
the bigger  
picture:

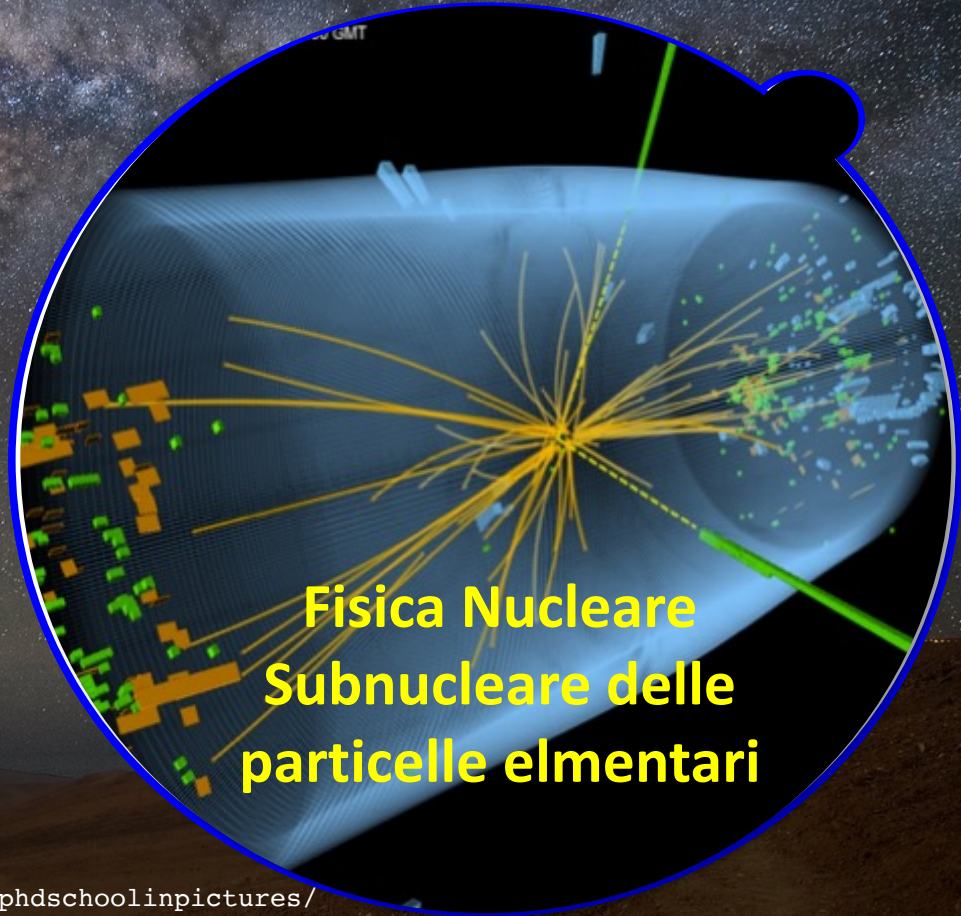
**And Keep  
Pushing!!**



# Guida Illustrata al lavoro del ricercatore

But don't forget  
the bigger  
picture:

**And Keep  
Pushing!!**



# La ricerca fondamentale

Ricerca di Base ↔ Ricerca Applicata

Oggi parleremo di fisica delle particelle  
elementari e delle sue applicazioni

# Particelle Elementari

1. Puntiformi = che non si possono più dividere

2. Composte = che contengono altre particelle

Una particella può sembrare puntiforme ma non esserlo quando la si “guarda” meglio:



particelle che oggi riteniamo puntiformi possono in realta' essere composte.



# L'atomo e' elementare?

Il Metodo "Tex Willer"



Un sacco contiene sabbia, l'altro pepite d'oro: come faccio a scegliere senza toccarli?

# L'atomo e' elementare?

Il Metodo "Tex Willer"



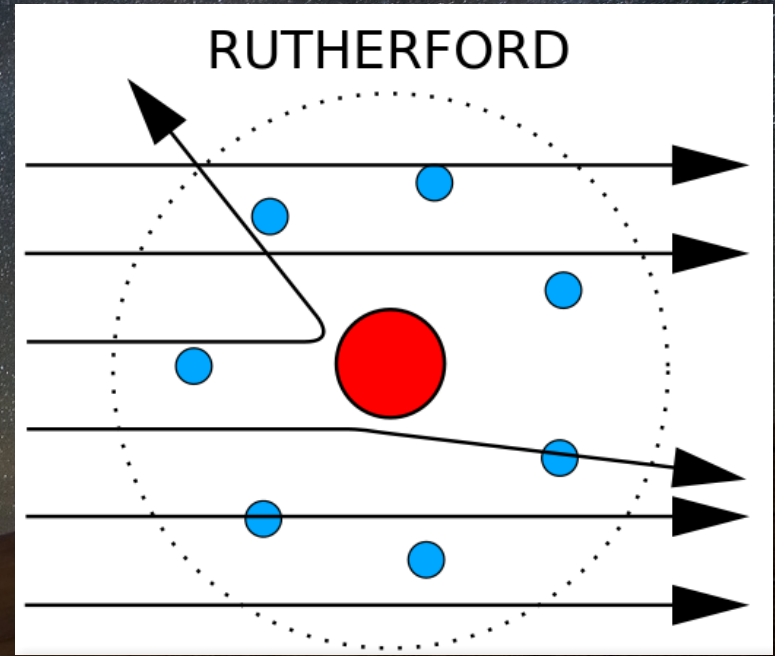
Un sacco contiene sabbia,  
l'altro pepite d'oro: come  
faccio a scegliere senza  
toccarli?

**OSSERVO LA  
DEVIAZIONE DEI  
PROIETTILI**

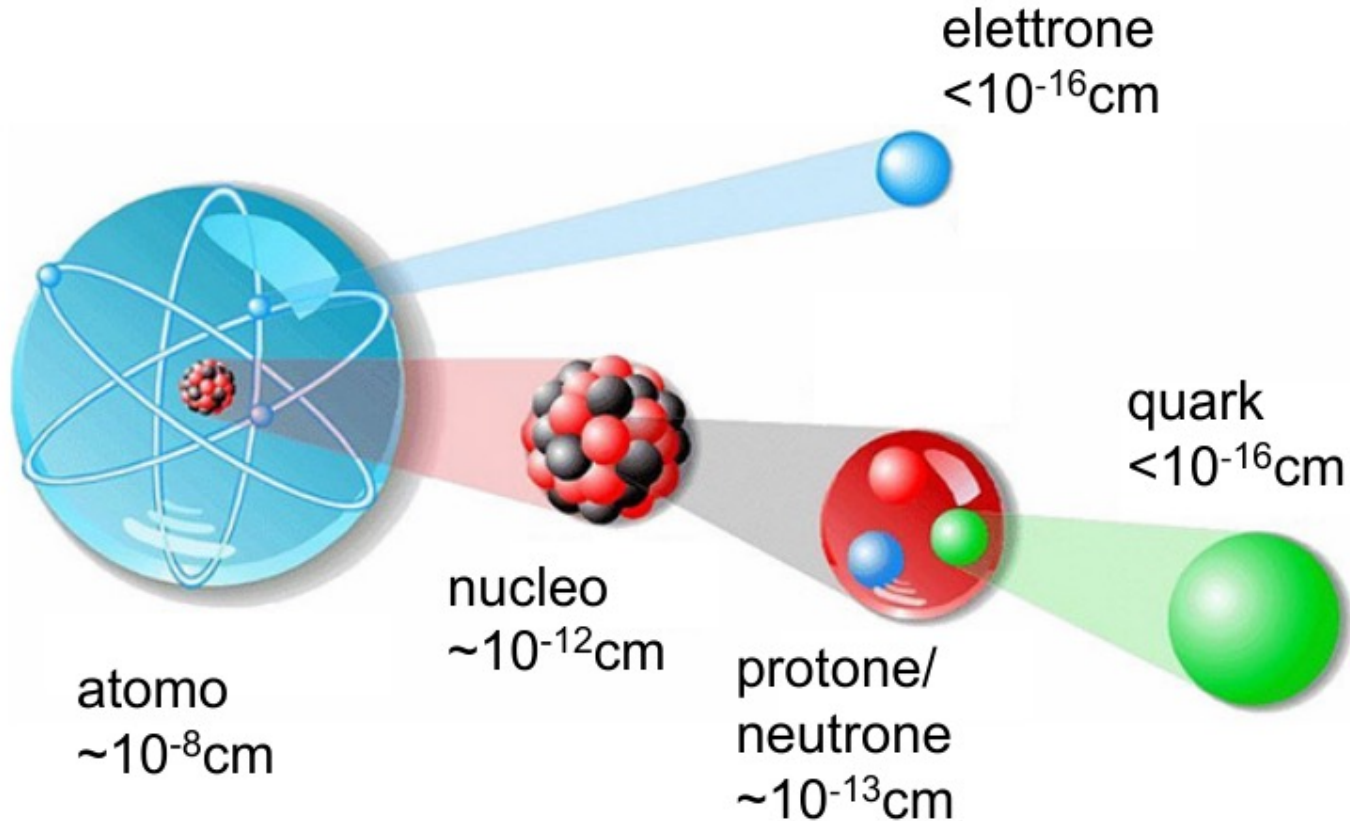
# Rutherford, 1909

“Sparo” all'atomo, usando particelle  $\alpha$  come proiettili e osservo la loro deviazione.

→ L'atomo contiene un nucleo con carica positiva di raggio  $<10^{-12}$  cm

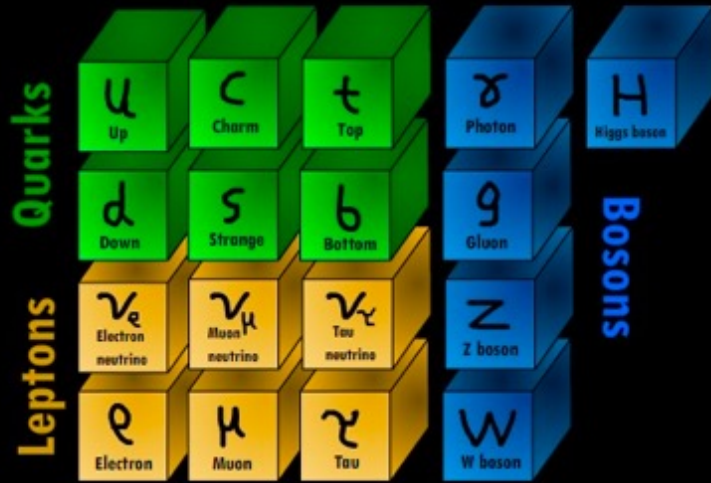


# L'infinitamente piccolo

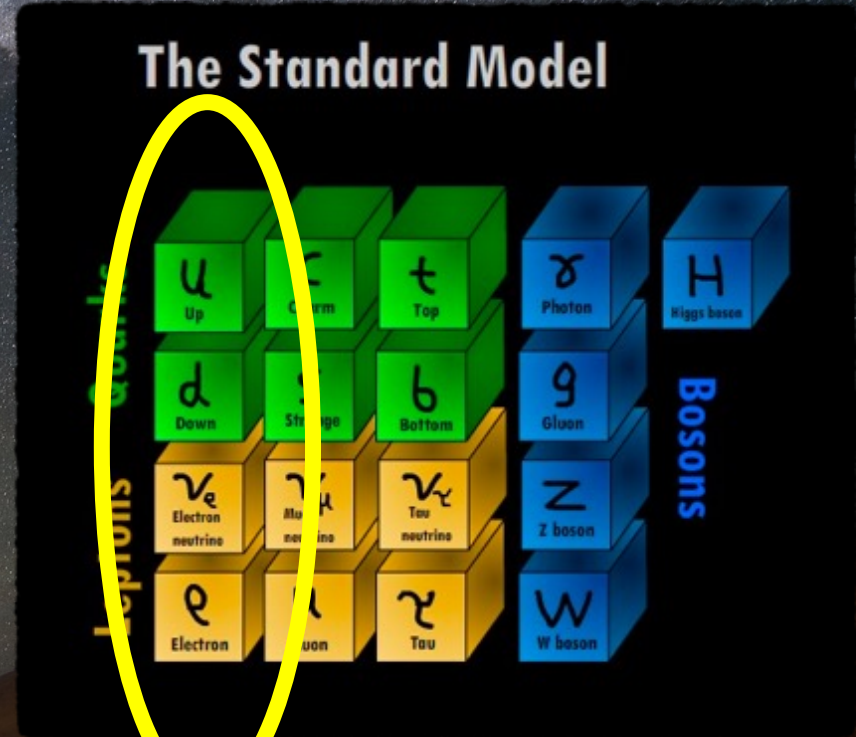
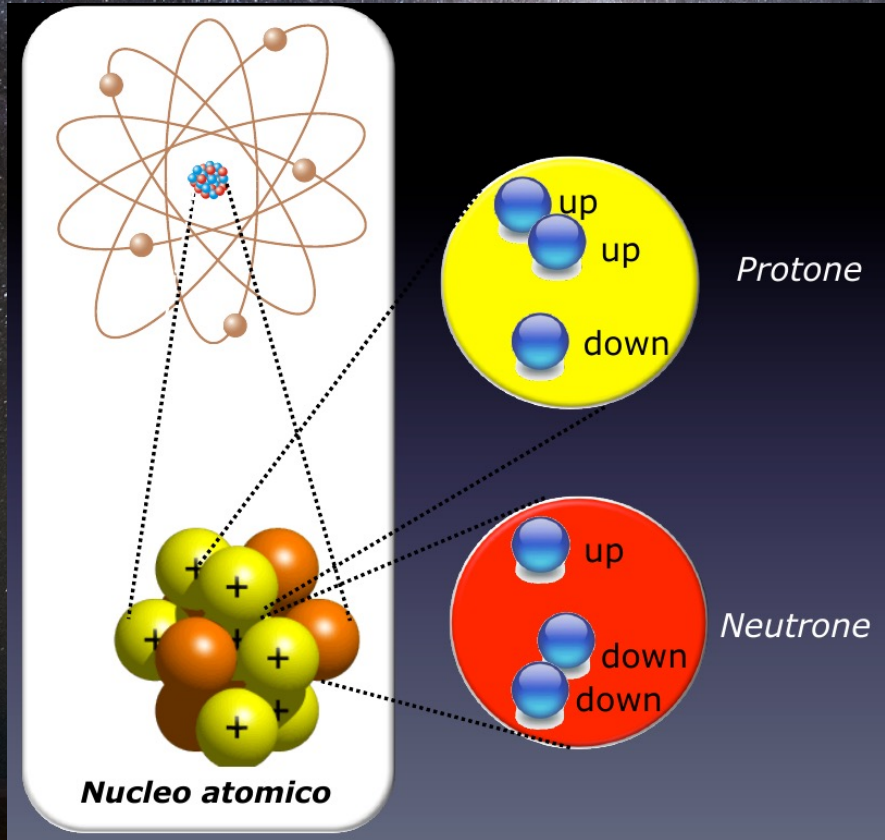


# IL Modello Standard

## The Standard Model



# La Materia Ordinaria



# La Massa delle Particelle

Meccanica classica (I. Newton, 1687):

**massa = quantità di materia**



Meccanica relativistica (A. Einstein, 1905):

**massa = energia**



# La Massa delle Particelle

**Per noi oggi la massa è una proprietà  
intrinseca delle particelle:**

**massa = energia di una particella a  
riposo**

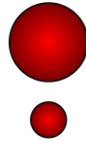


# Particelle di un certo peso!

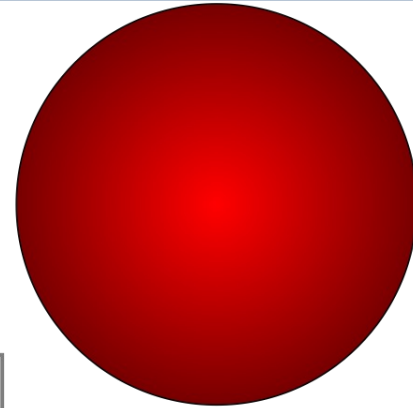
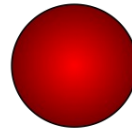
Up Quark  
~ 0.002 GeV



Charm Quark  
1.25 GeV



Top Quark  
175 GeV



Down Quark  
~ 0.005 GeV

Strange Quark  
~ 0.095 GeV

Bottom Quark  
4.2 GeV

These are relative masses not size – they have no measurable size

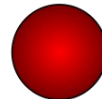
Electron  
0.0005 GeV



Muon  
0.105 GeV



Tau  
1.78 GeV



For reference:



Proton  
0.938 GeV

Electron Neutrino  
~ 0

Muon Neutrino  
~ 0

Tau Neutrino  
~ 0

← Originally thought to be massless but now not

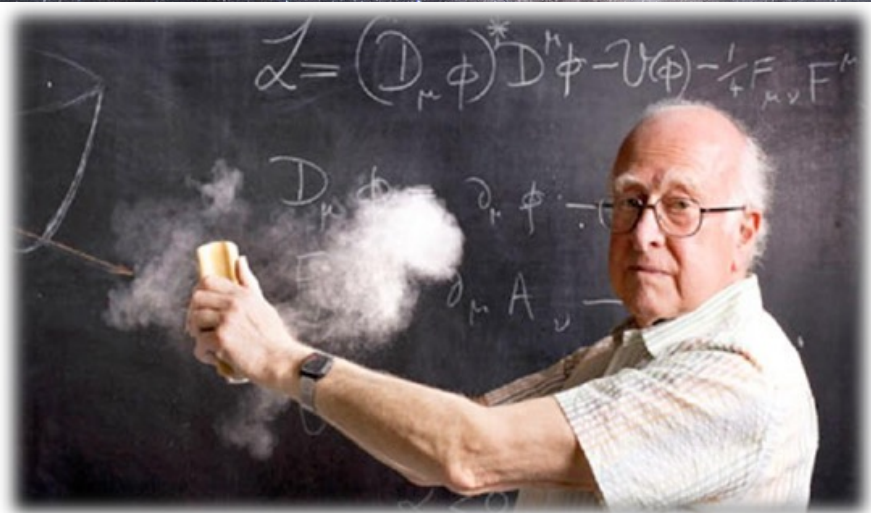
# L'idea di Prof. Higgs

Le particelle che interagiscono con il campo di Higgs vengono rallentate



Più una particella “sente” il campo di Higgs, maggiore è la sua massa

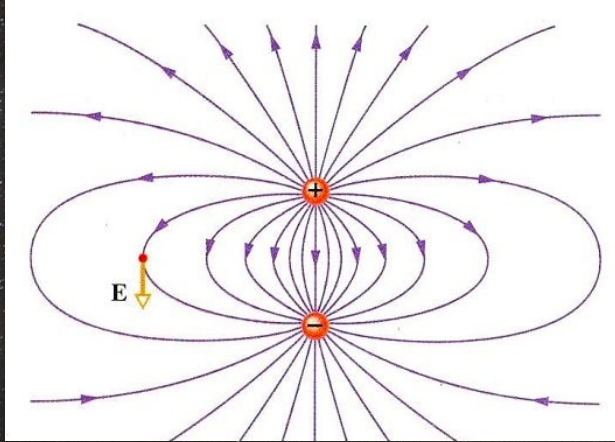
# L'idea di Prof. Higgs



**Idea chiave:  
Il campo di Higgs si incolla  
alle particelle e crea la loro  
massa**

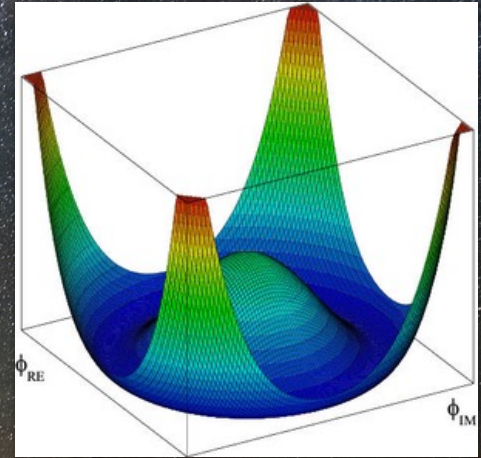
# Campi e Particelle

Il **campo elettrico** ha una direzione.



Il **fotone** è la “prova” del campo elettromagnetico.

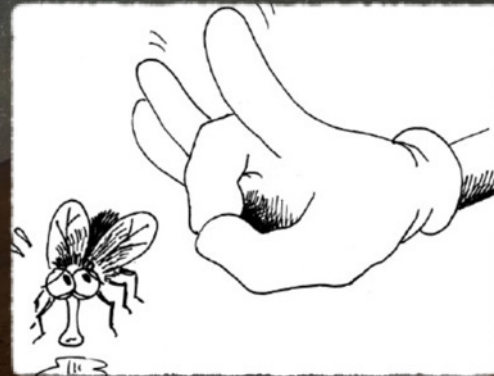
Il **campo di Higgs** è uno scalare.



La **particella di Higgs** è la “prova” del campo di Higgs.

# Forze e Interazioni

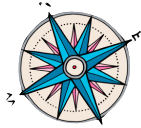
- Le particelle di materia interagiscono tramite **le forze**
- Quando applichiamo una forza ad un oggetto **cambiamo il suo stato di moto**
- **Minore la massa piu` facile sara` "spostarlo"**



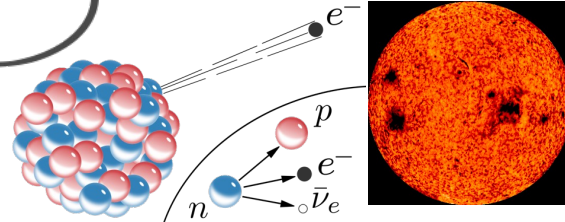
# Fantastic four



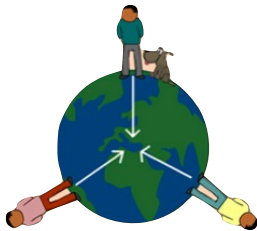
Electromagnetic ( $I=1$ )



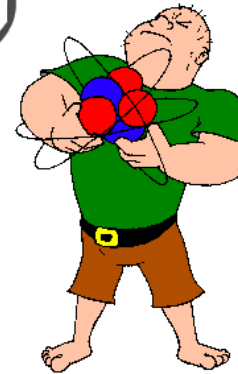
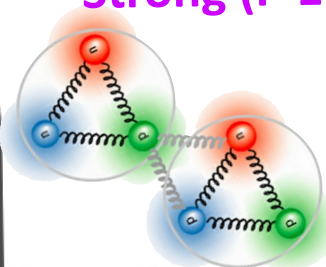
Weak ( $I=10^{-3}$ )



Gravitational ( $I=10^{-36}$ )

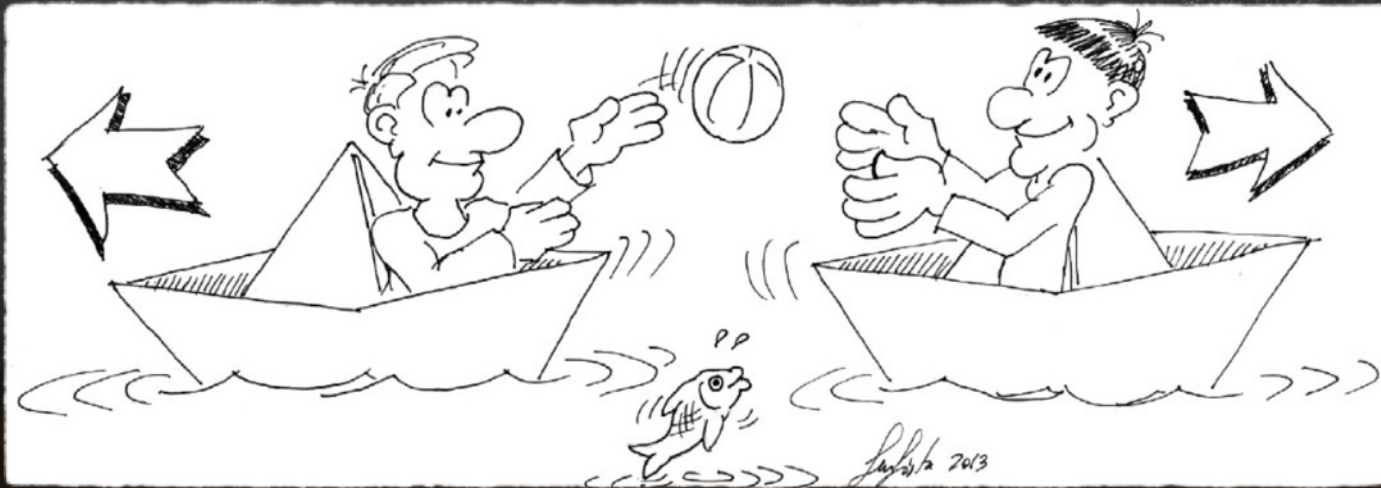


Strong ( $I=100$ )



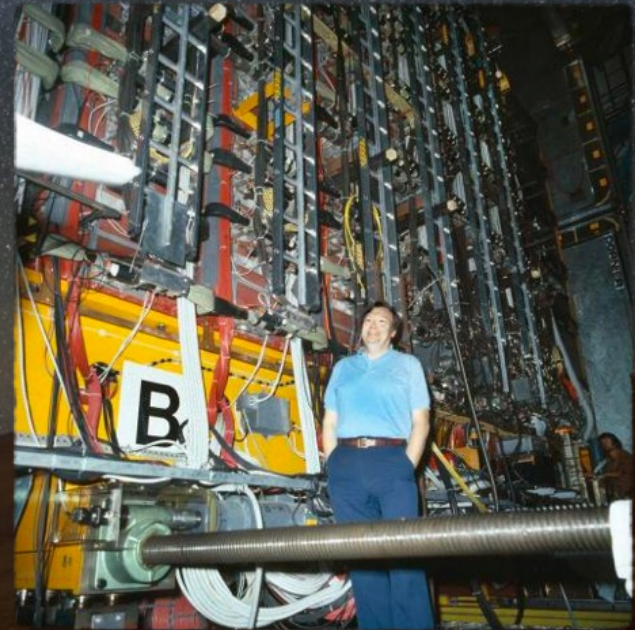
# Forze: scambio di particelle

- Le forze tra componenti di materia sono dovute allo **scambio di altre particelle, i bosoni mediatori**
- Questi bosoni sono come palle da basket lanciate tra barchette



# Forze: scambio di particelle

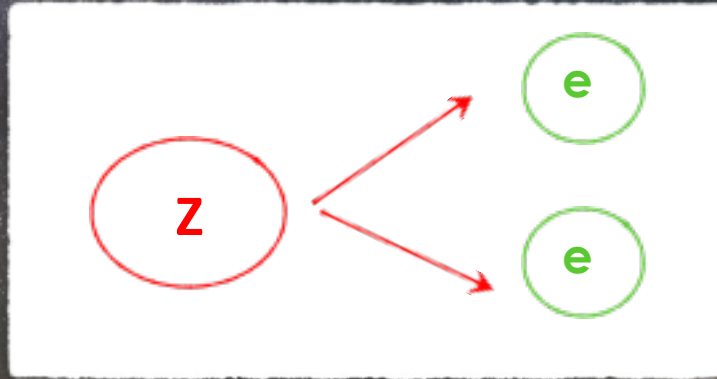
- **Bosone Z** predetto nel **1960** per spiegare i decadimenti beta di Fermi
- La teoria prevede la massa del **bosone Z** attorno a **90 GeV** e i fisici del **CERN** nel **1980** costruirono il primo acceleratore in grado di produrlo e rivelarlo





# IL bosone Zeta

- La Z non vive molto ma **si disintegra subito in due elettroni** che possono essere rivelati



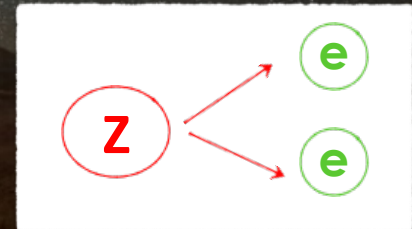
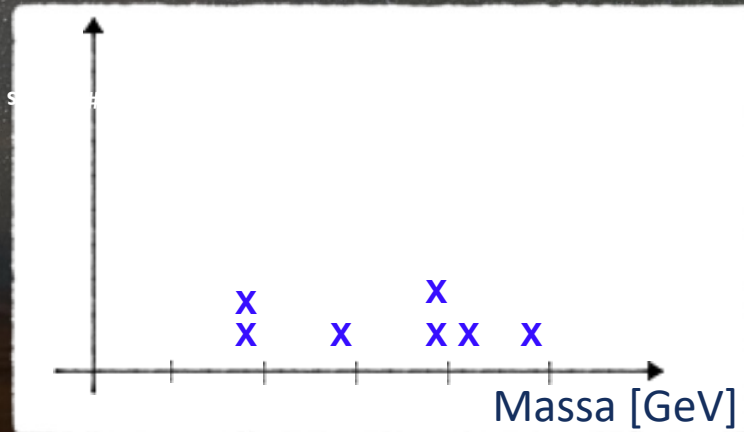
- Quando **produciamo una Z** in realta` nell'esperimento **vediamo due elettroni!**

# IL bosone Zeta

- Misuriamo le **energie** e la **direzione** dei due elettroni e calcoliamo la massa della Z:

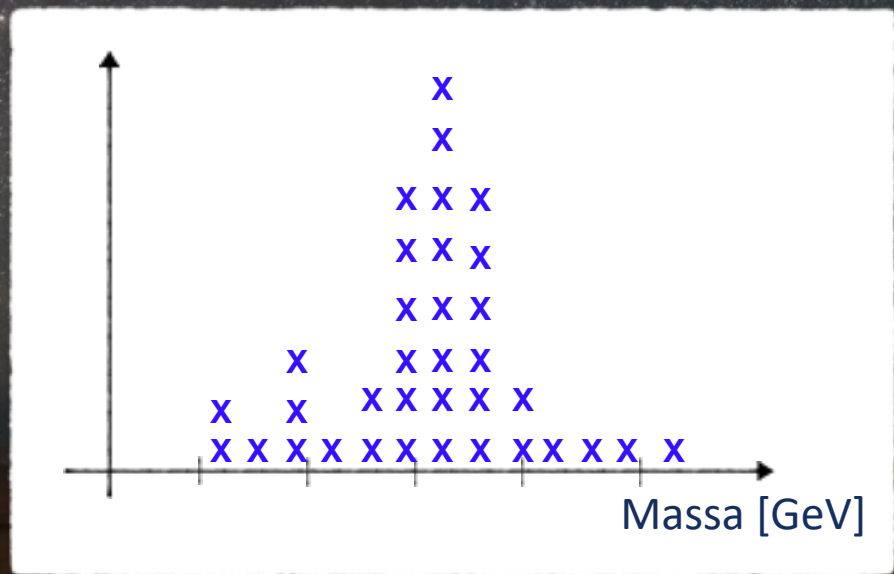
$$m_X = \sqrt{2E_1E_2(1 - \cos\theta)}$$

- Ripetiamo per **ogni evento** (collisione) in cui vediamo due elettroni e riempiamo un **istogramma**:



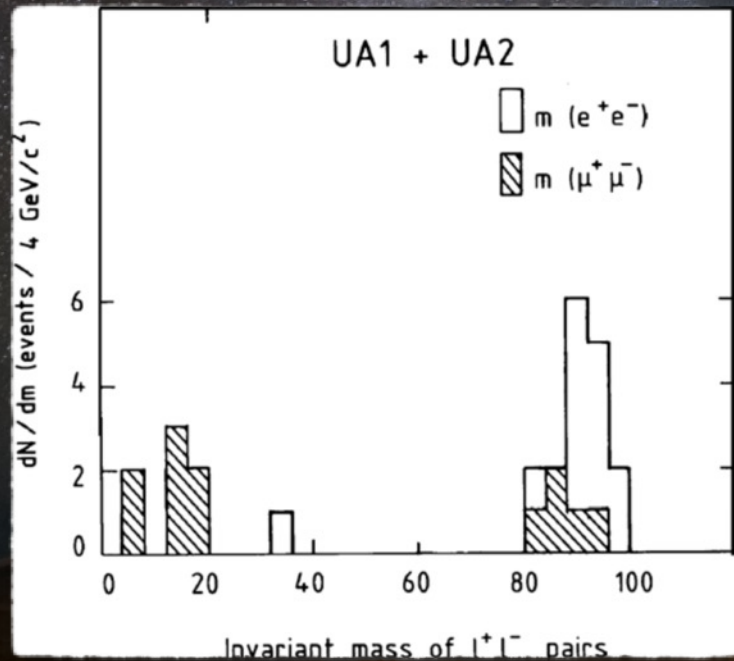
# IL bosone Zeta: La sua massa

- Un **picco di eventi** appare in prossimita` del **valore vero della massa della Z**
- Se l'eccesso di eventi e` molto grande **abbiamo scoperto una nuova particella**



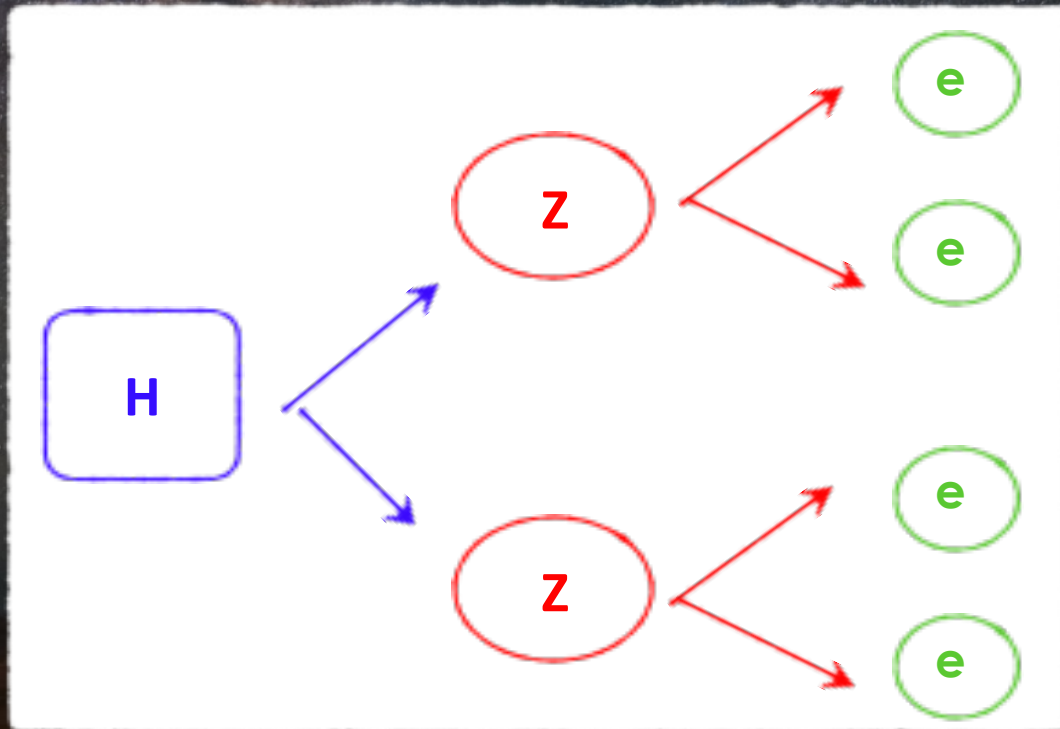
# IL nobel di Rubbia

- 1983 gli esperimenti UA1 e UA2 al CERN scoprono il bosone Z



# IL bosone Zeta e L'Higgs

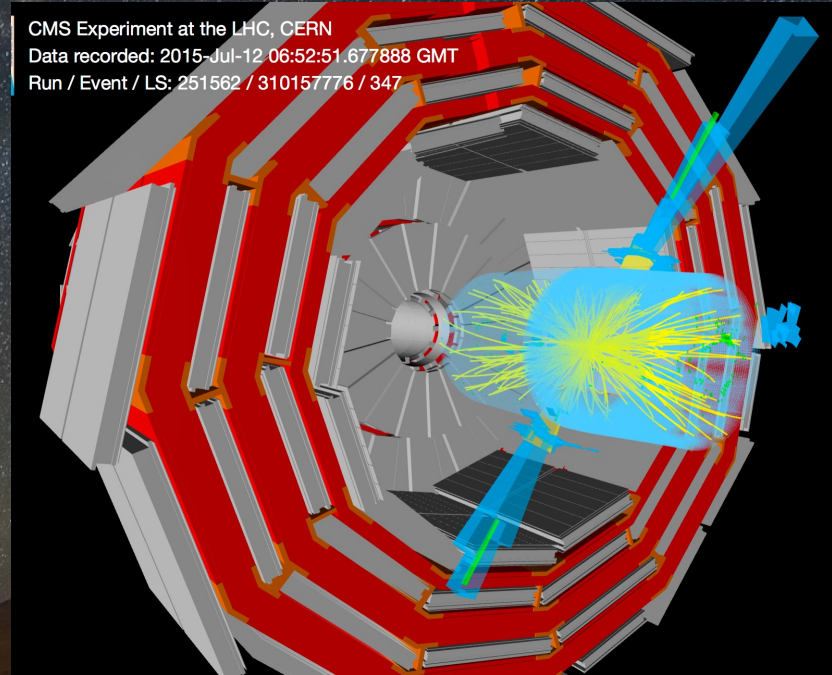
- Il **bosone Z** "ci serve" per cercare il **bosone di Higgs**:



# Microscopi Potentissimi

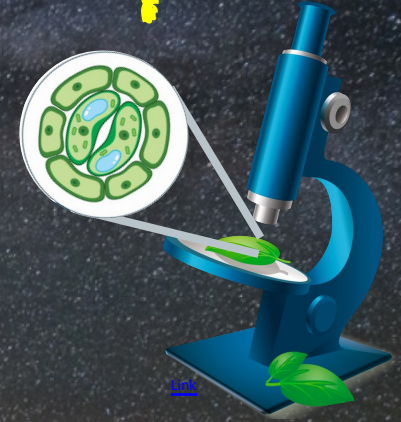
La **dimensione** che riesco a investigare e' **proporzionale a  $1/E$**

$E$  = energia della mia "sonda"



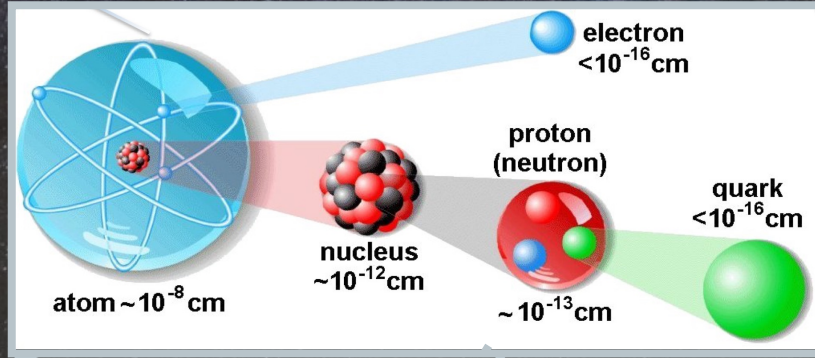
# Vedere l'infinitamente piccolo

Cellula ( $d \sim 10^{-5} \text{ m}$ ): luce visibile  $E \sim \text{eV}$

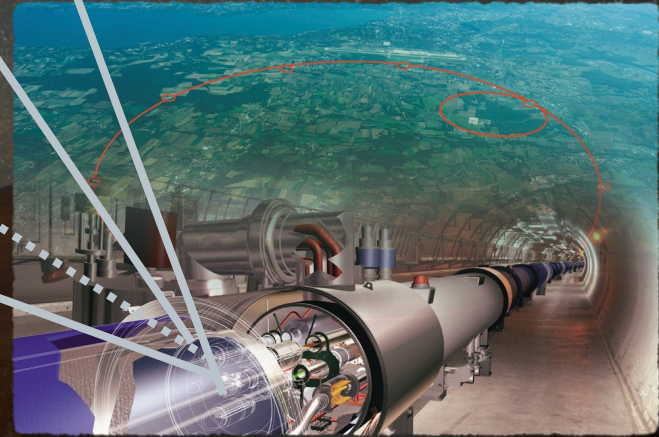


# Vedere l'infinitamente piccolo

Cellula ( $d \sim 10^{-5}$  m): luce visibile  $E \sim eV$



Quark ( $d \sim 10^{-18}$  m): LHC  $E \sim TeV$





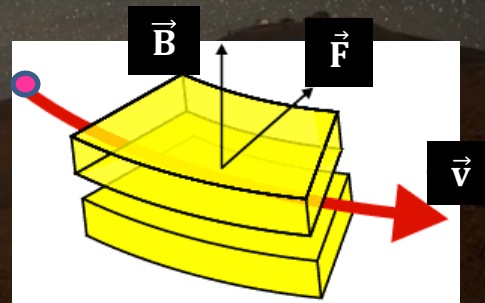
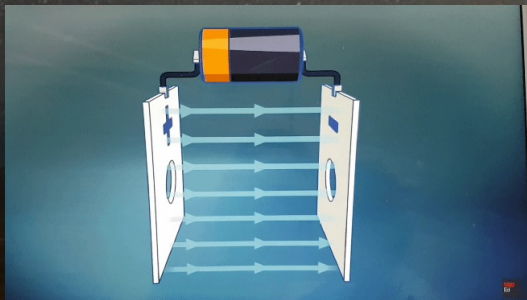
# La fisica base degli acceleratori

$$\vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B})$$

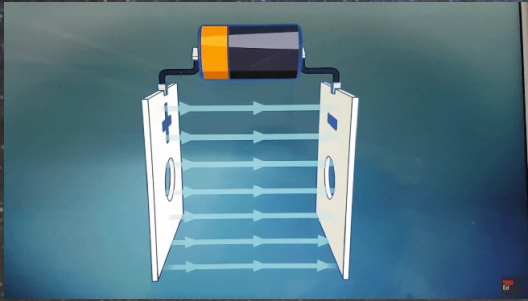
Forza di Lorentz

Effetto di un campo elettrico su una particella carica → la particella accelera

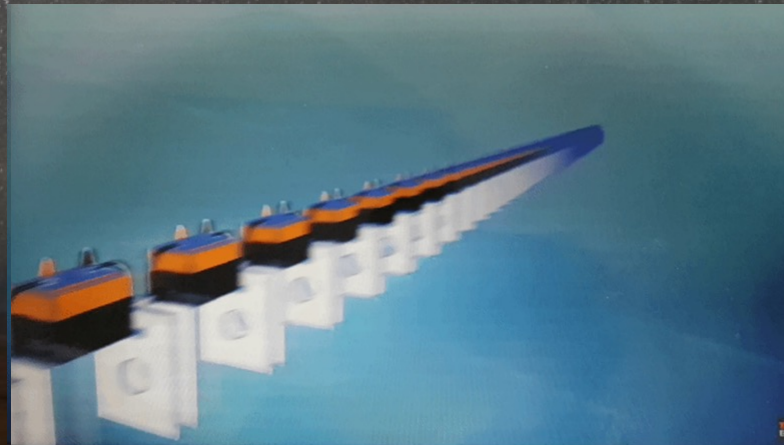
Effetto di un campo magnetico su una particella carica → la particella curva



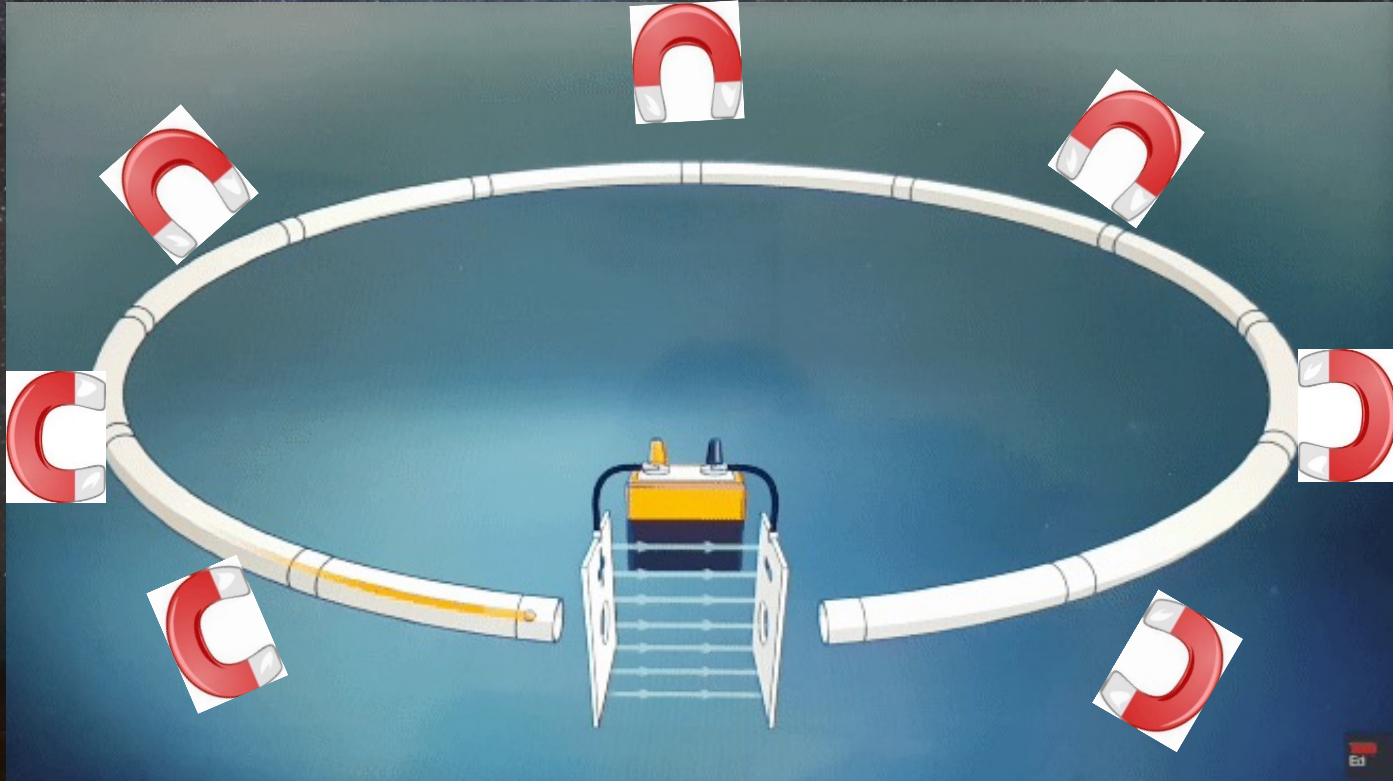
# Il limite di un acceleratore lineare



Energia protoni LHC= 7 TeV →  
servono 5 triliardi di pile da 1.5V



# Acceleratore circolare

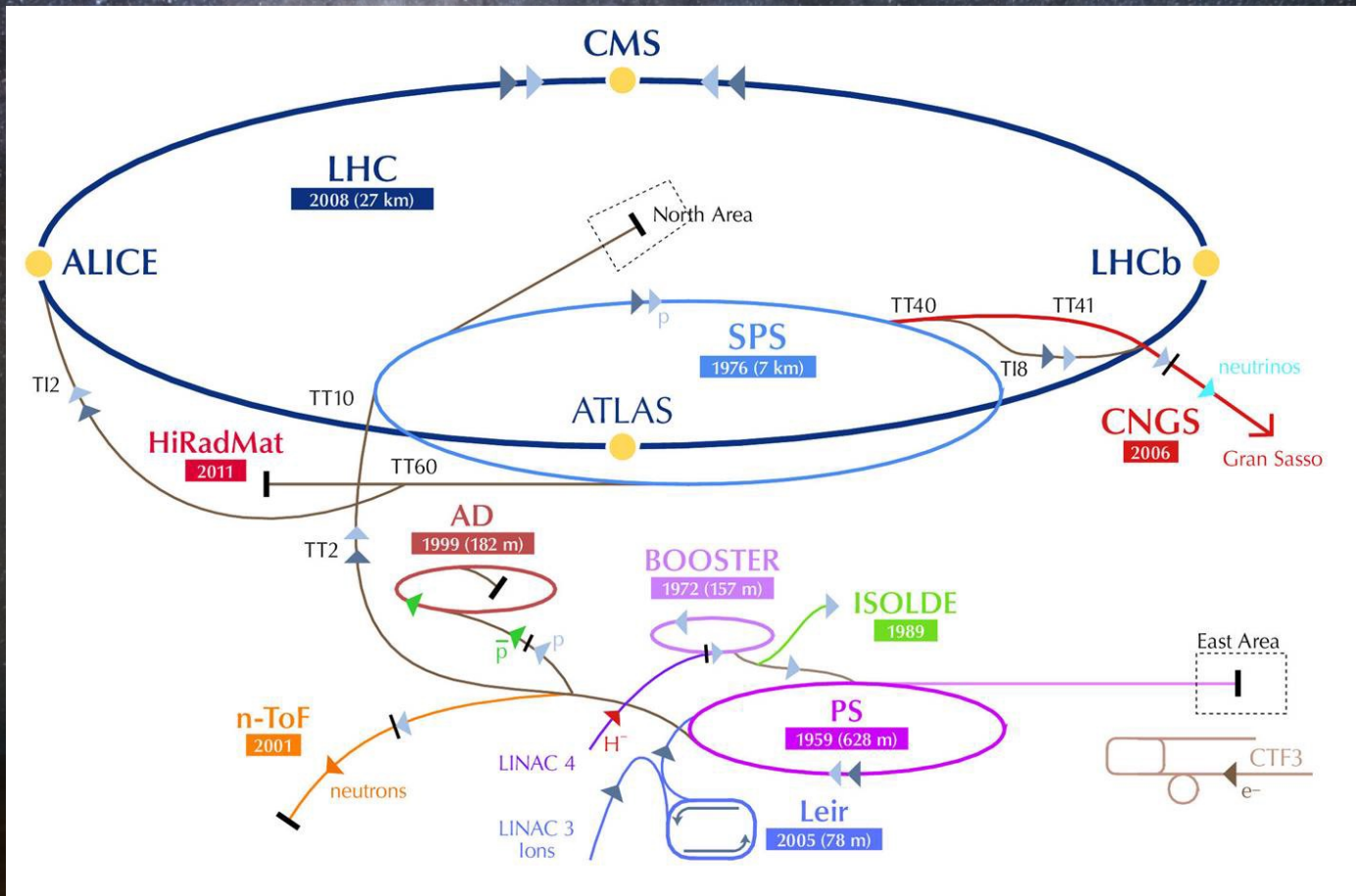


# AdA (Frascati 1961)

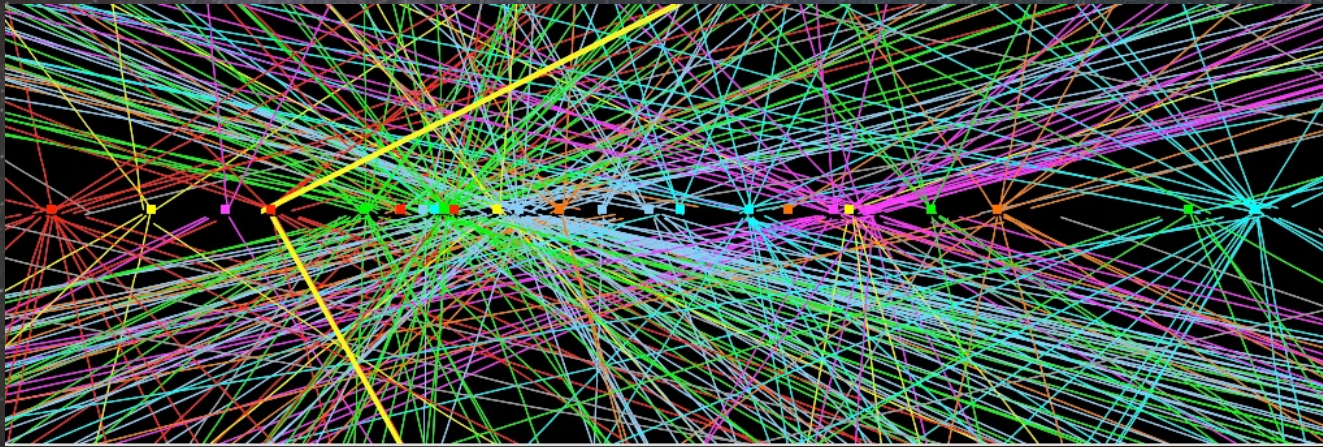
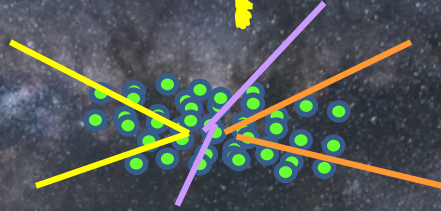


**Idea di far circolare due fasci di carica opposta nello stesso acceleratore e mandarli in collisione**

# Gli acceleratori del CERN



# Incroci di particelle



I fasci dell'LHC sono così intensi che quando si incrociano, circa 30-50 coppie di protoni si scontrano. Fra qualche anno aumenteremo l'intensità dei fasci di protoni e raggiungeremo 140-200 urti per incrocio dei fasci

# Un grande laboratorio europeo: il CERN

Nel 1954 12 paesi europei tra cui l'Italia costituiscono il CERN (organizzazione europea per la ricerca nucleare)

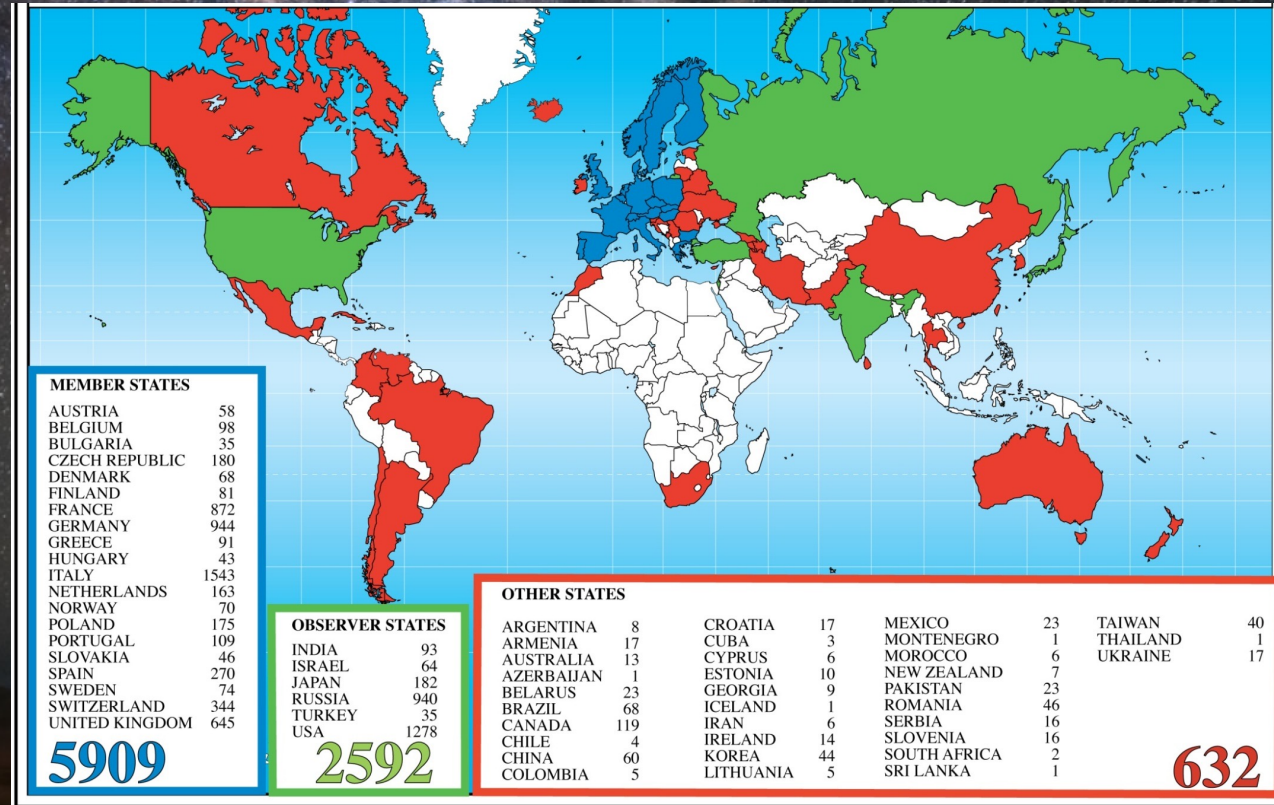


Oggi 23 stati membri.  
Ogni paese contribuisce in base al PIL  
L'Italia contribuisce per circa il 12% al budget del laboratorio

Quattro sono stati i direttori Italiani del CERN:  
Eduardo Amaldi, Carlo Rubbia, Luciano Maiani e Fabiola Gianotti (2)



# Gli scienziati che lavorano al CERN





# Laboratori del CERN di Ginevra: Centro Europeo per la Ricerca Nucleare



# Il Large Hadron Collider LHC

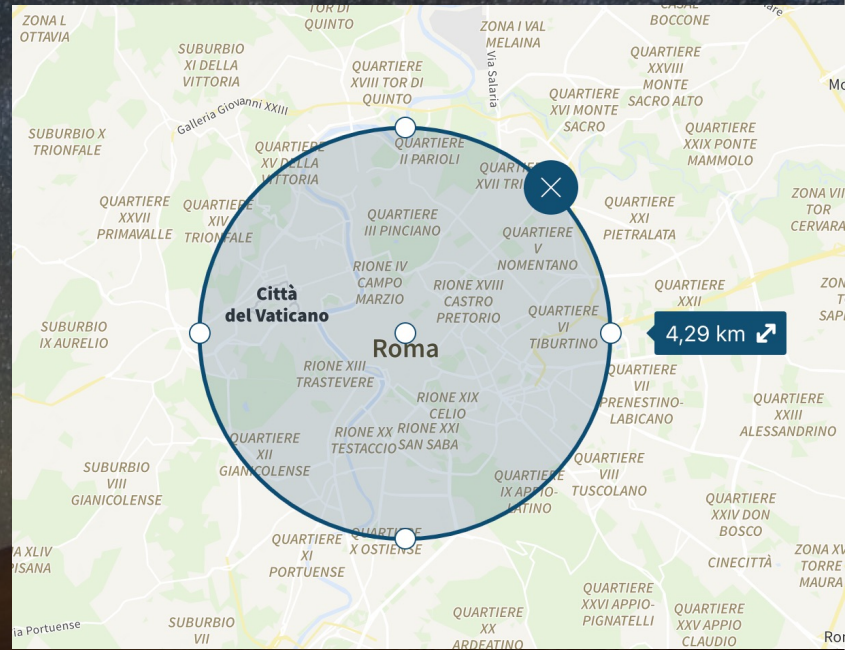
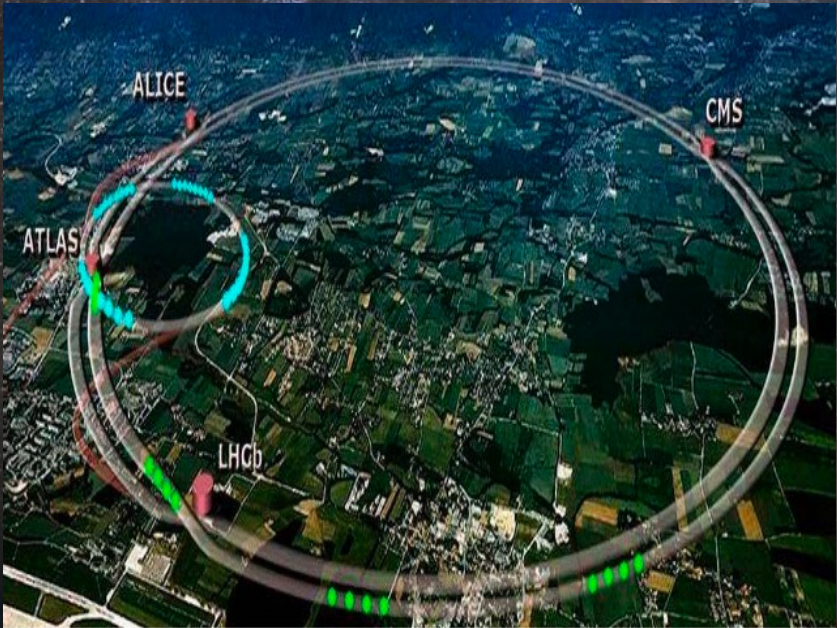


→ Lungo 27 km

→ Posto a 100m di profondità` sottoterra

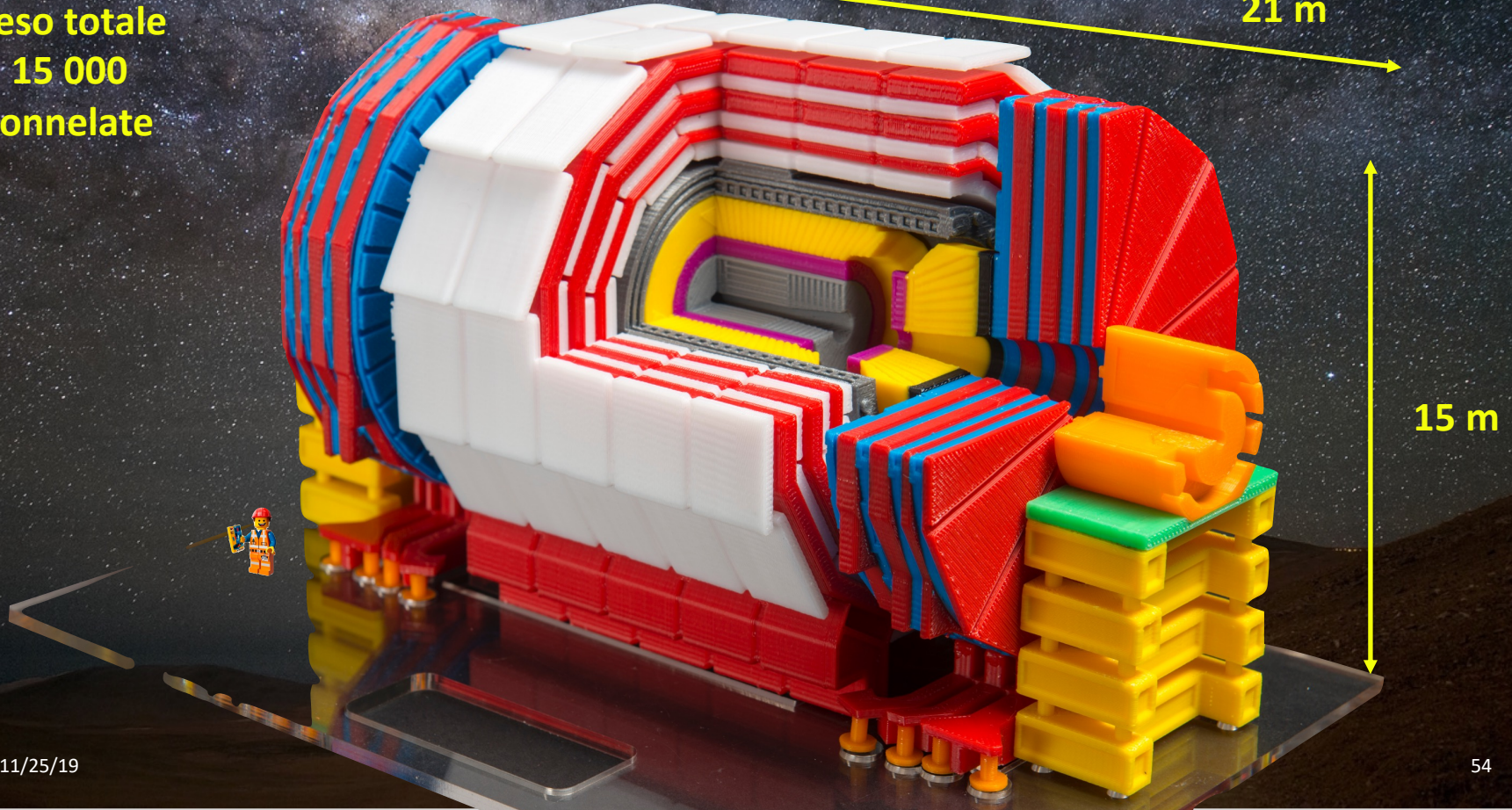
# IL Large Hadron Collider LHC

→ Lungo 27 km



# L'esperimento CMS @ LHC

Peso totale  
15 000  
tonnelate

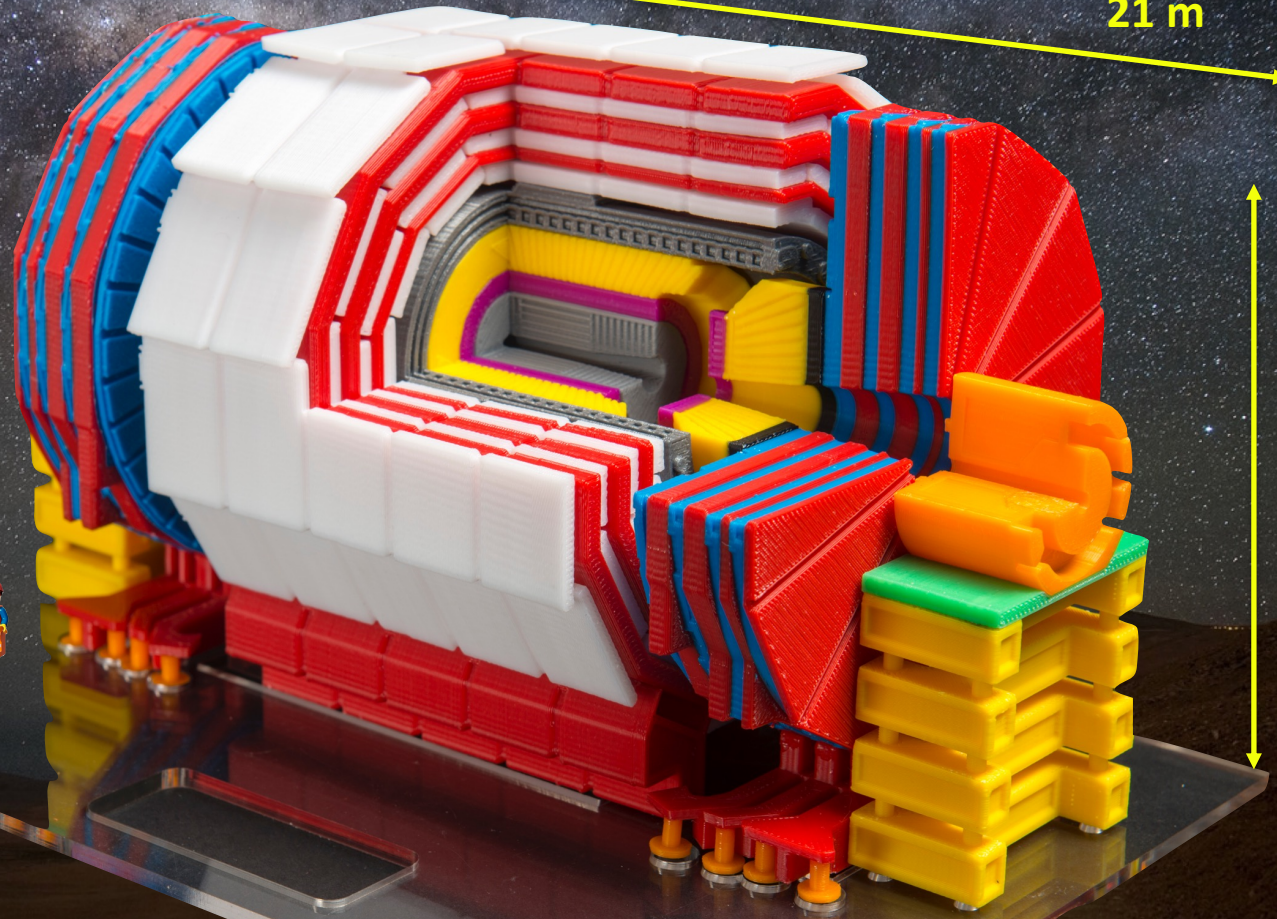


# L'esperimento CMS @ LHC

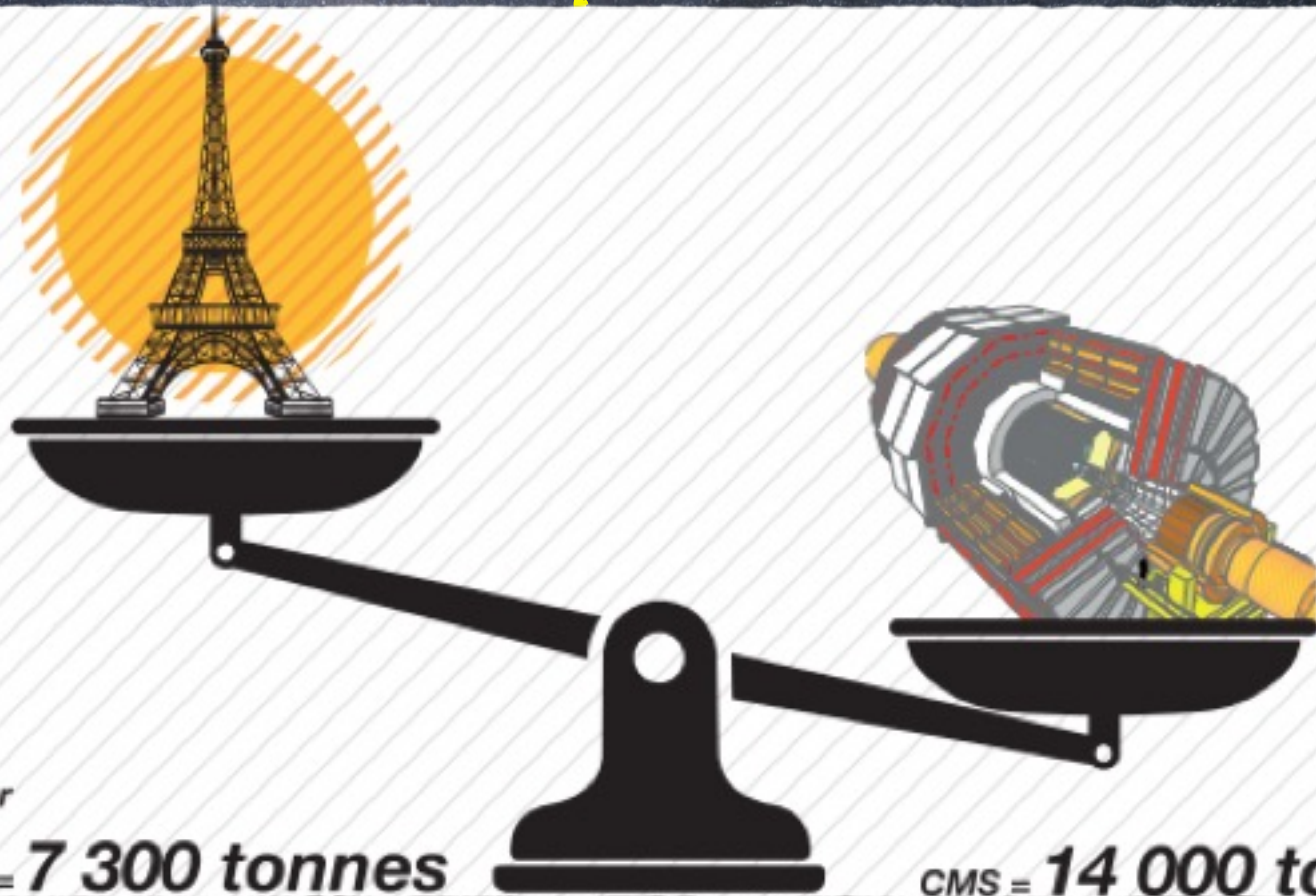
Peso totale  
15 000  
tonnelate

21 m

15 m



# Quanto pesa CMS?

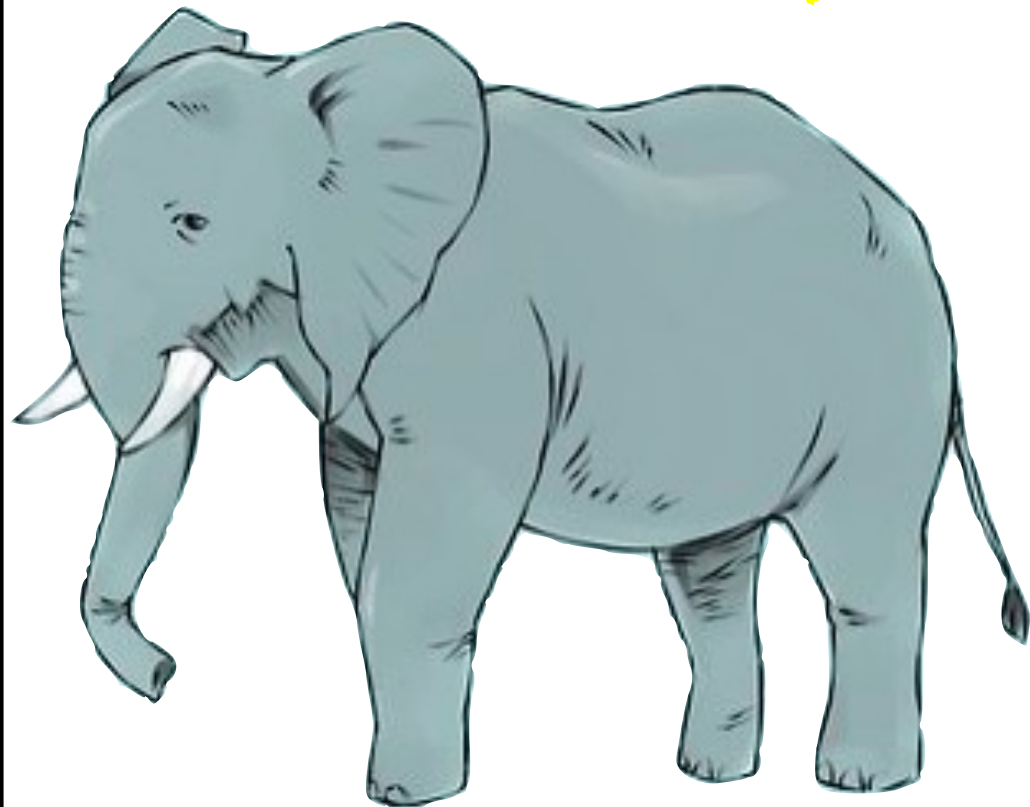


Eiffel Tower

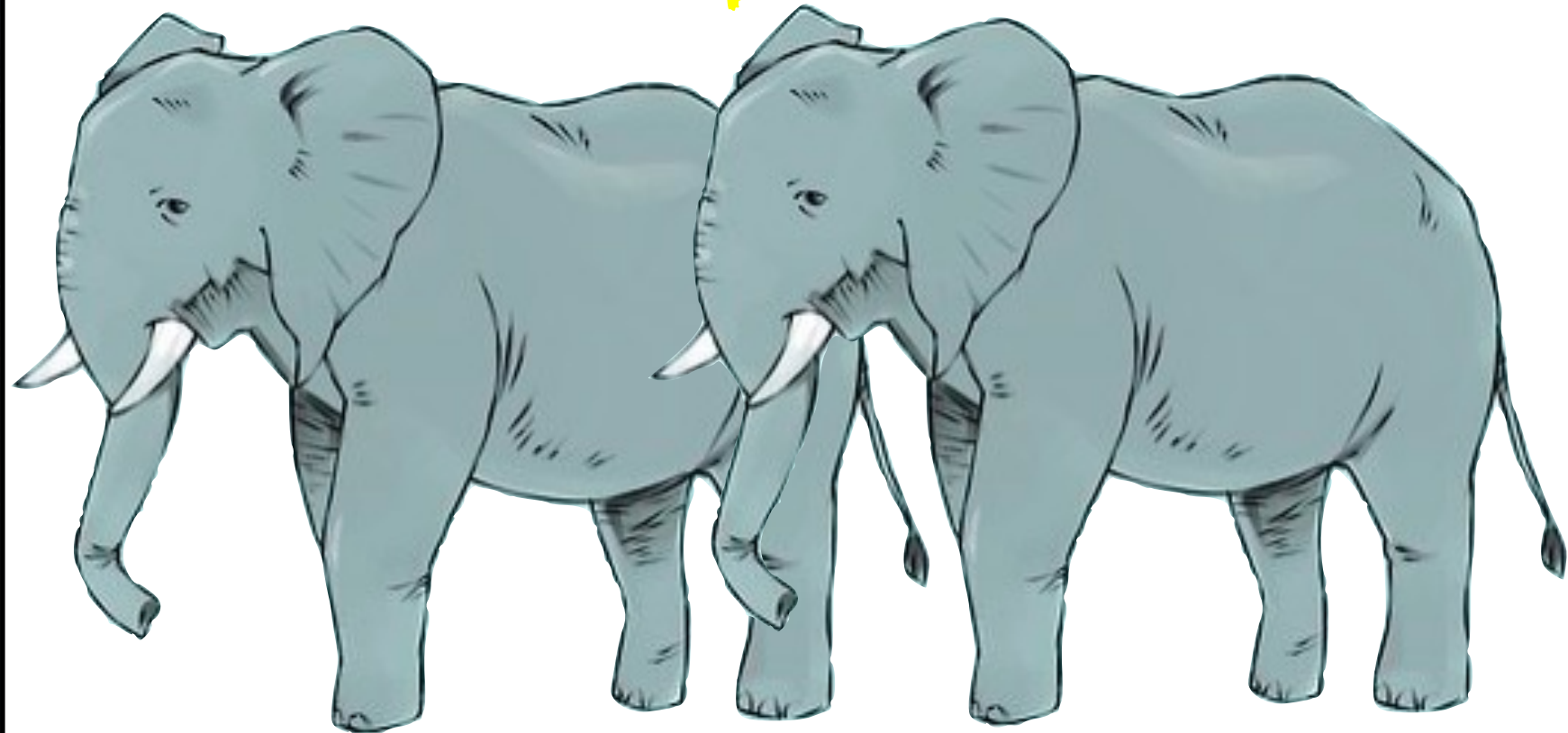
Tour Eiffel = 7 300 tonnes

CMS = 14 000 tonnes

Quanto pesa CMS?

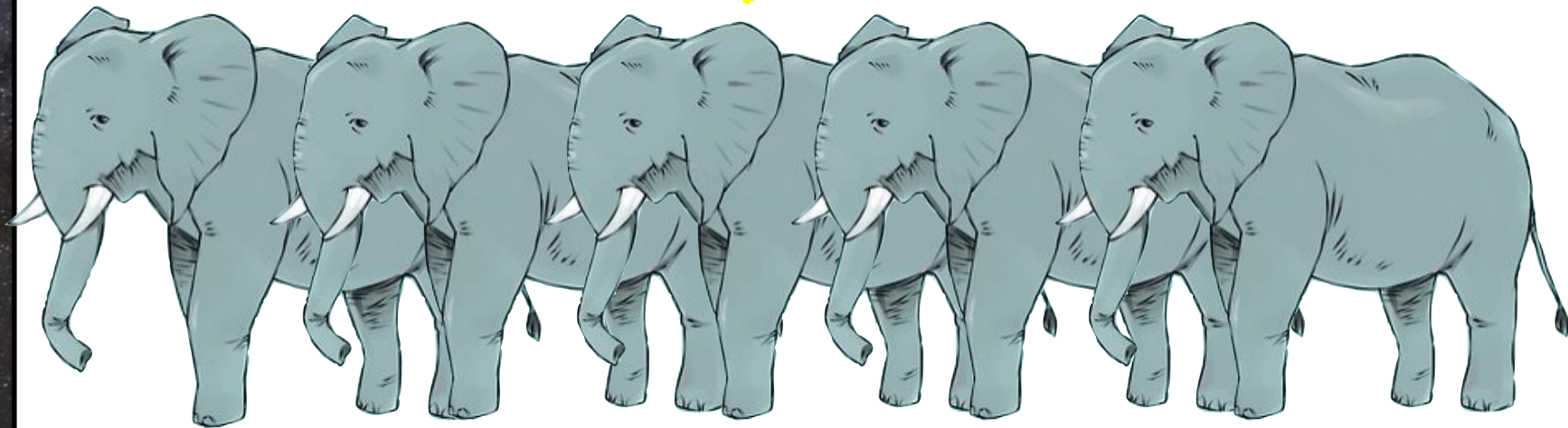


Quanto pesa CMS?

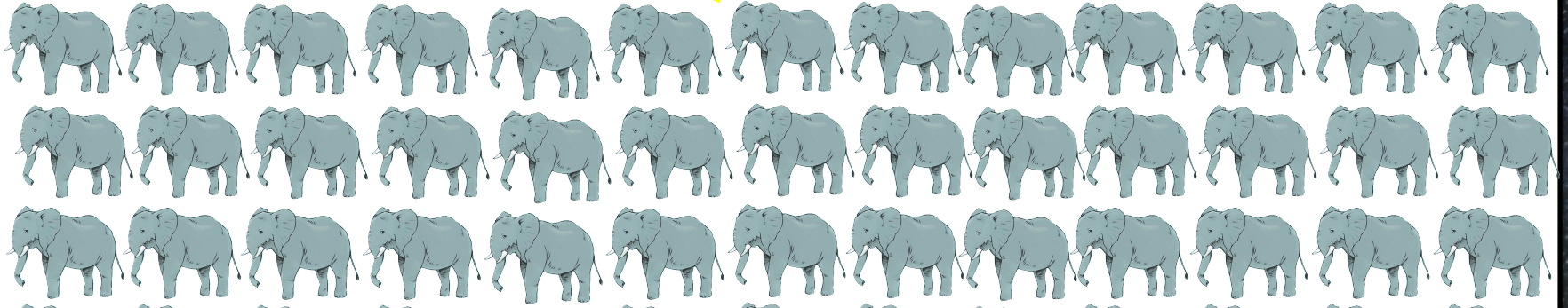




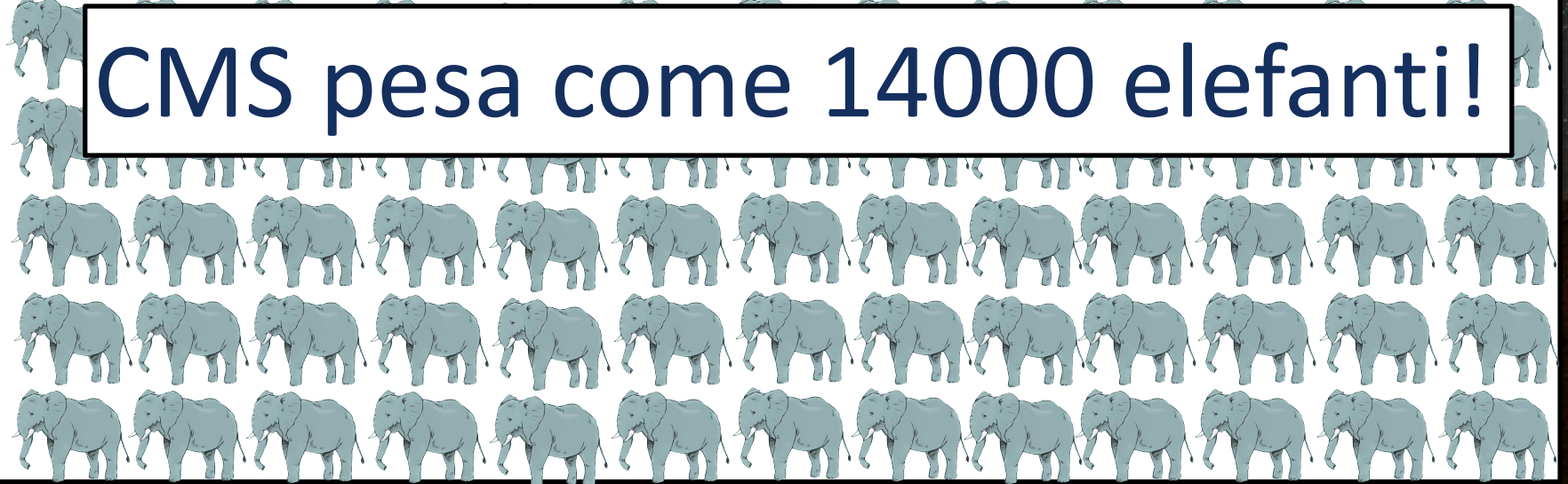
Quanto pesa CMS?



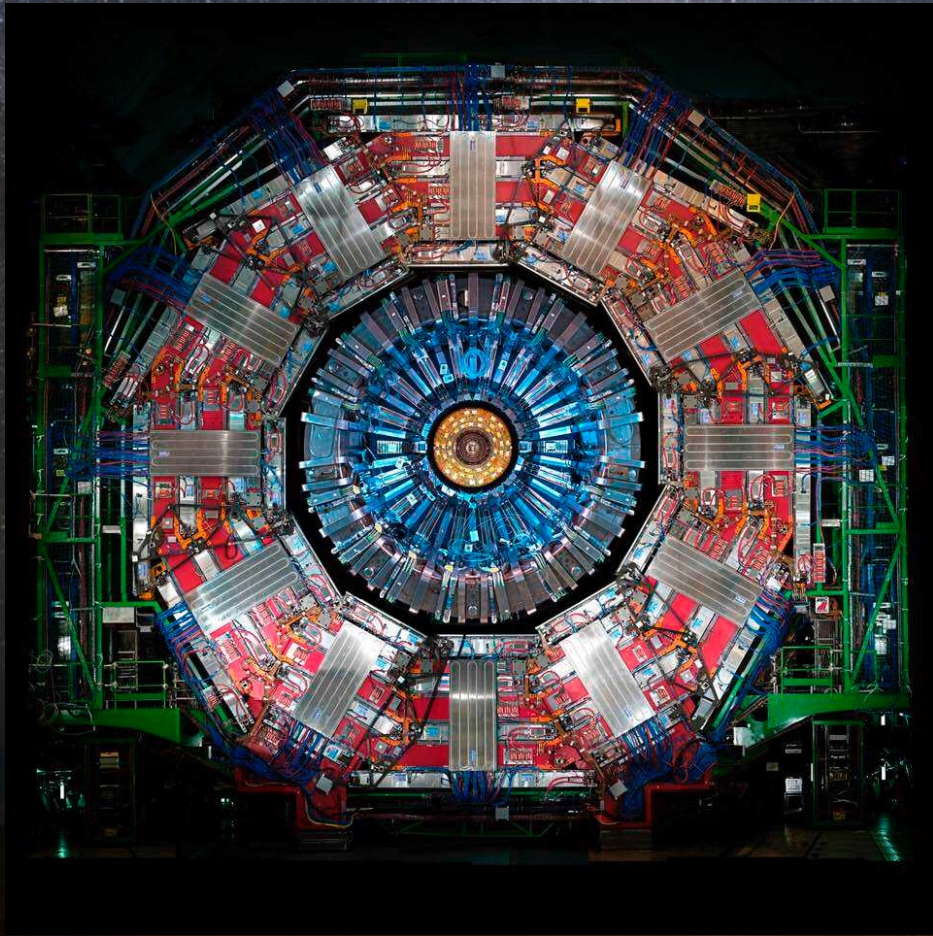
# Quanto pesa CMS?



**CMS pesa come 14000 elefanti!**

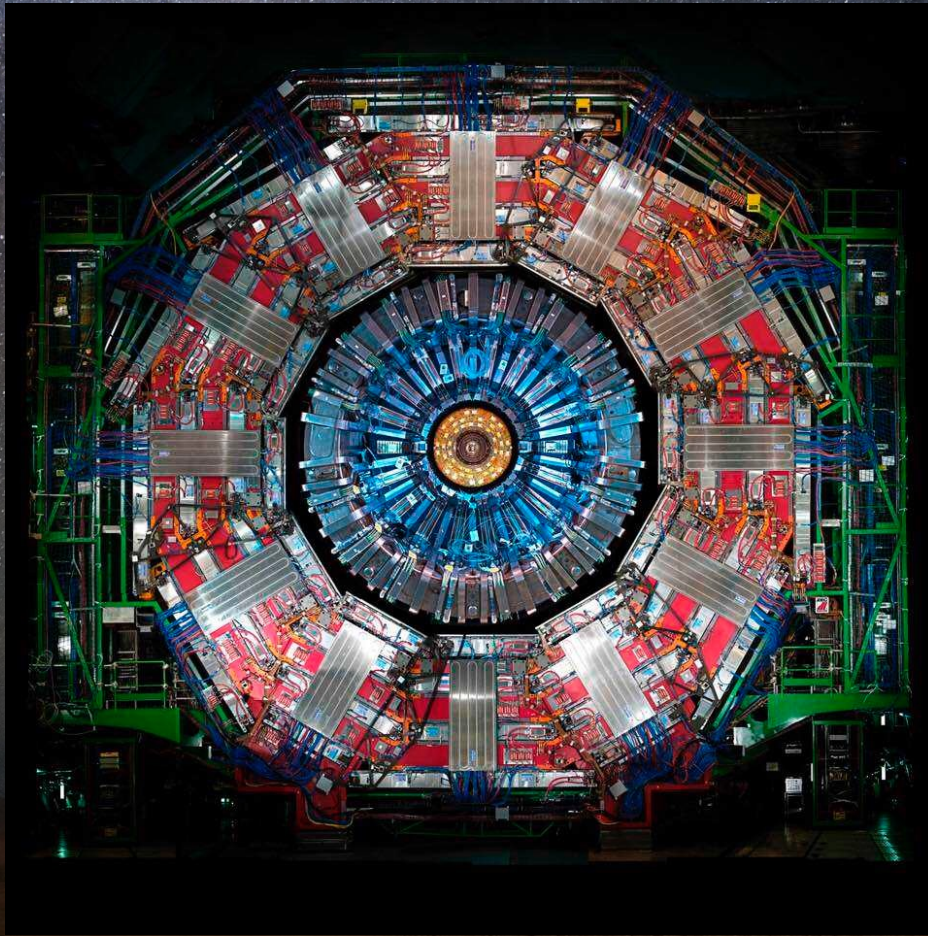


# Una macchina fotografica gigante!

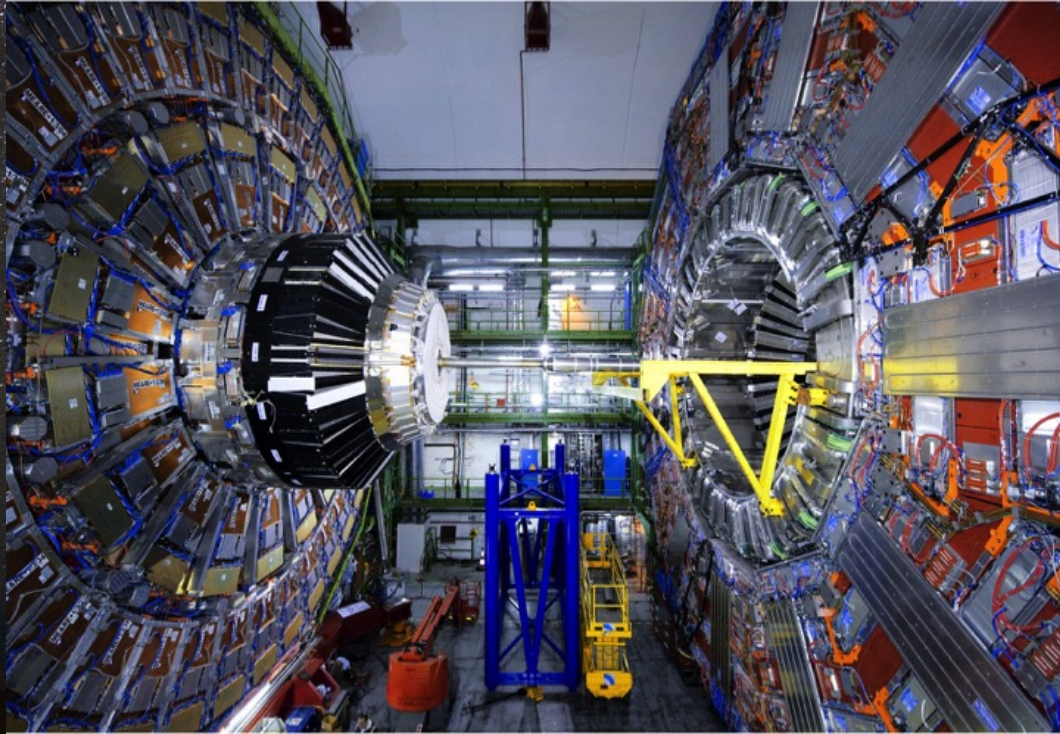


[Link](#)

# L'esperimento CMS @ LHC

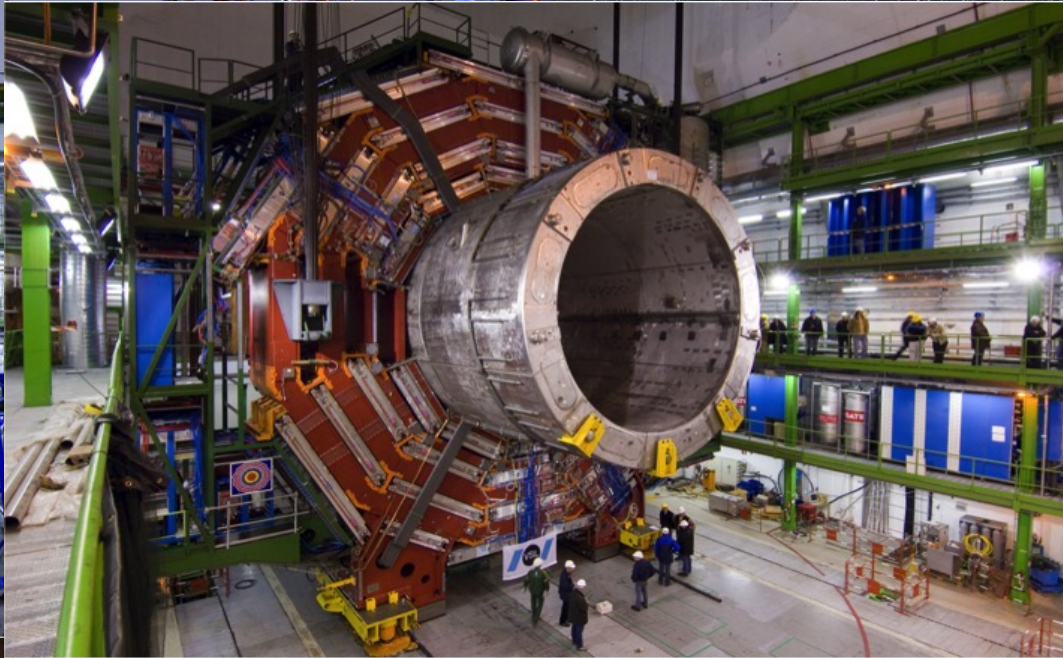
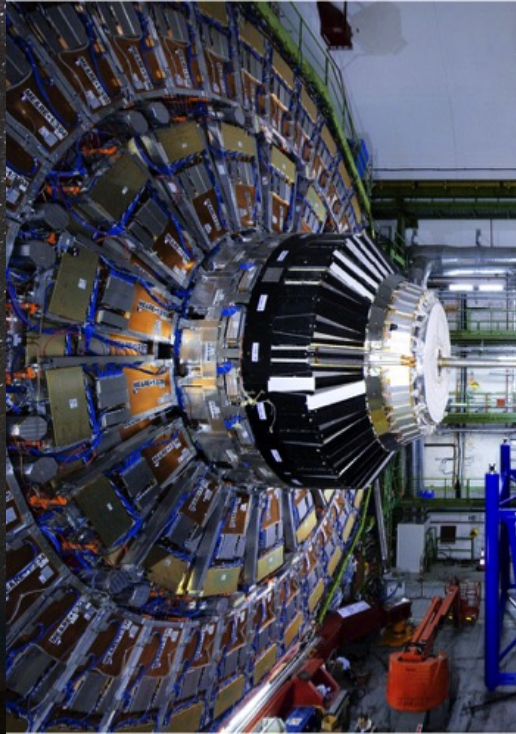


# La costruzione di CMS

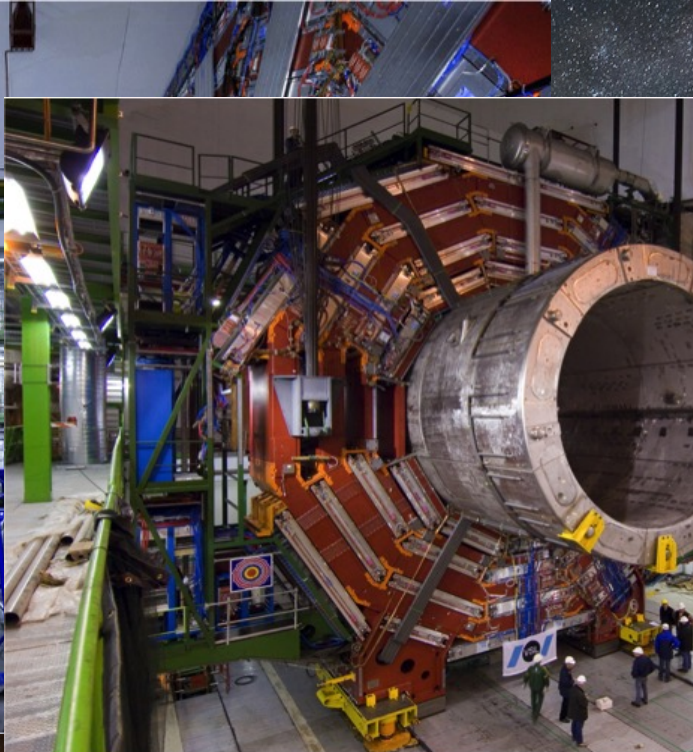
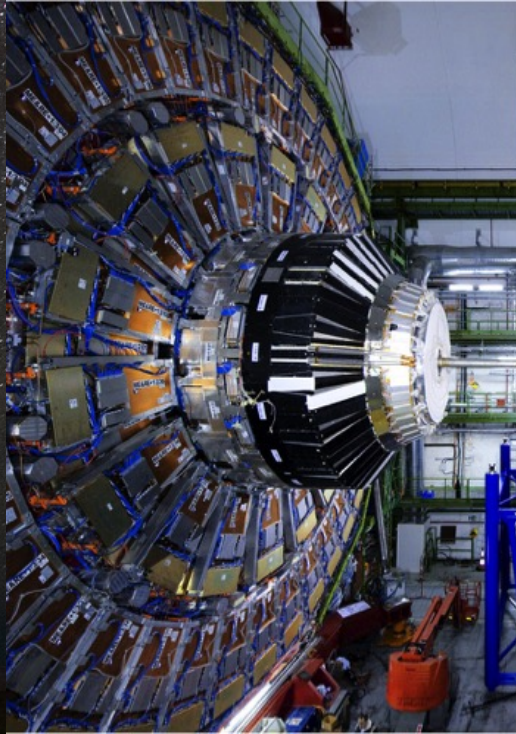


3/30/23

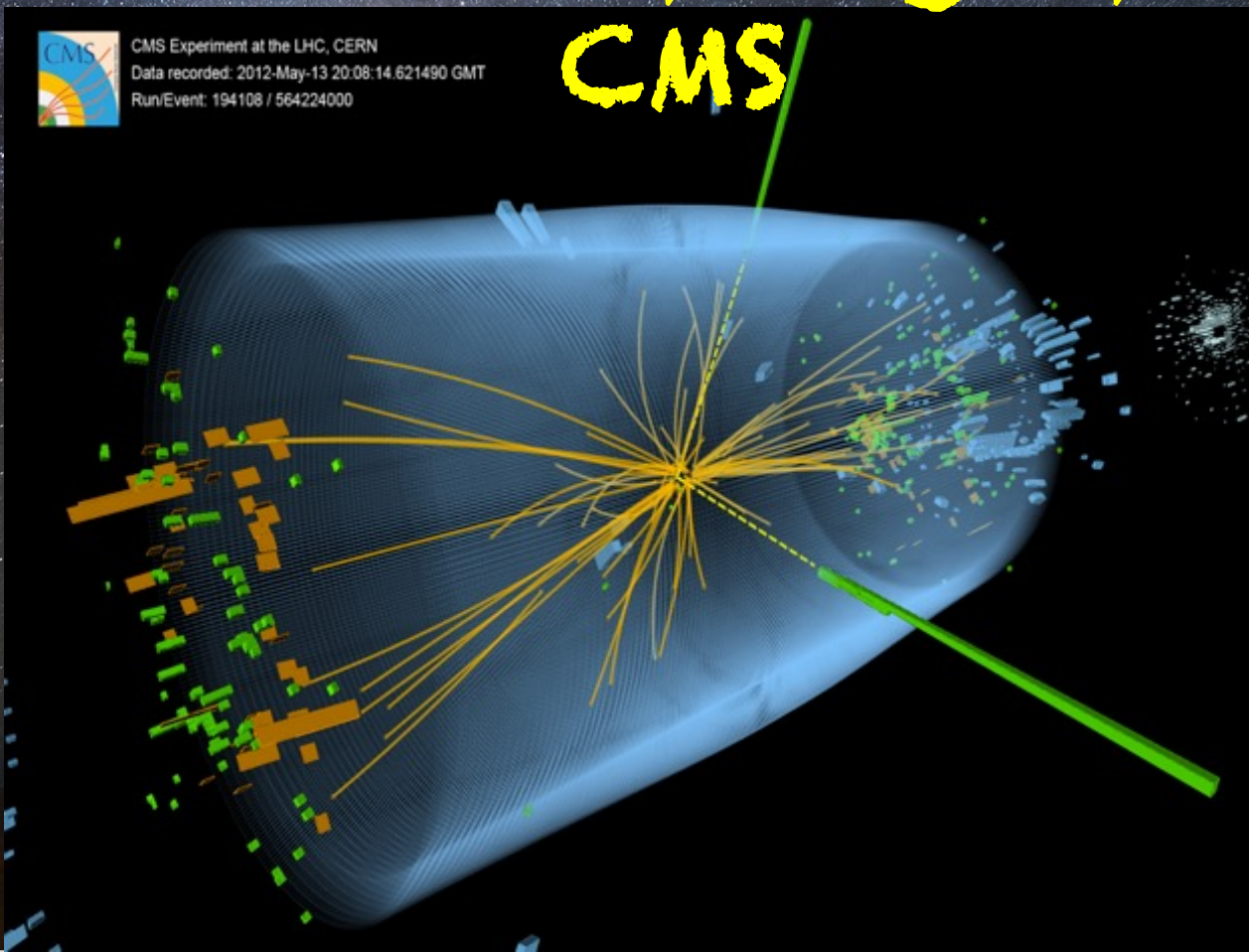
# La costruzione di CMS



# La costruzione di CMS



# Le Collisioni fotografate da





# Cosa c'e' oltre L'Higgs?



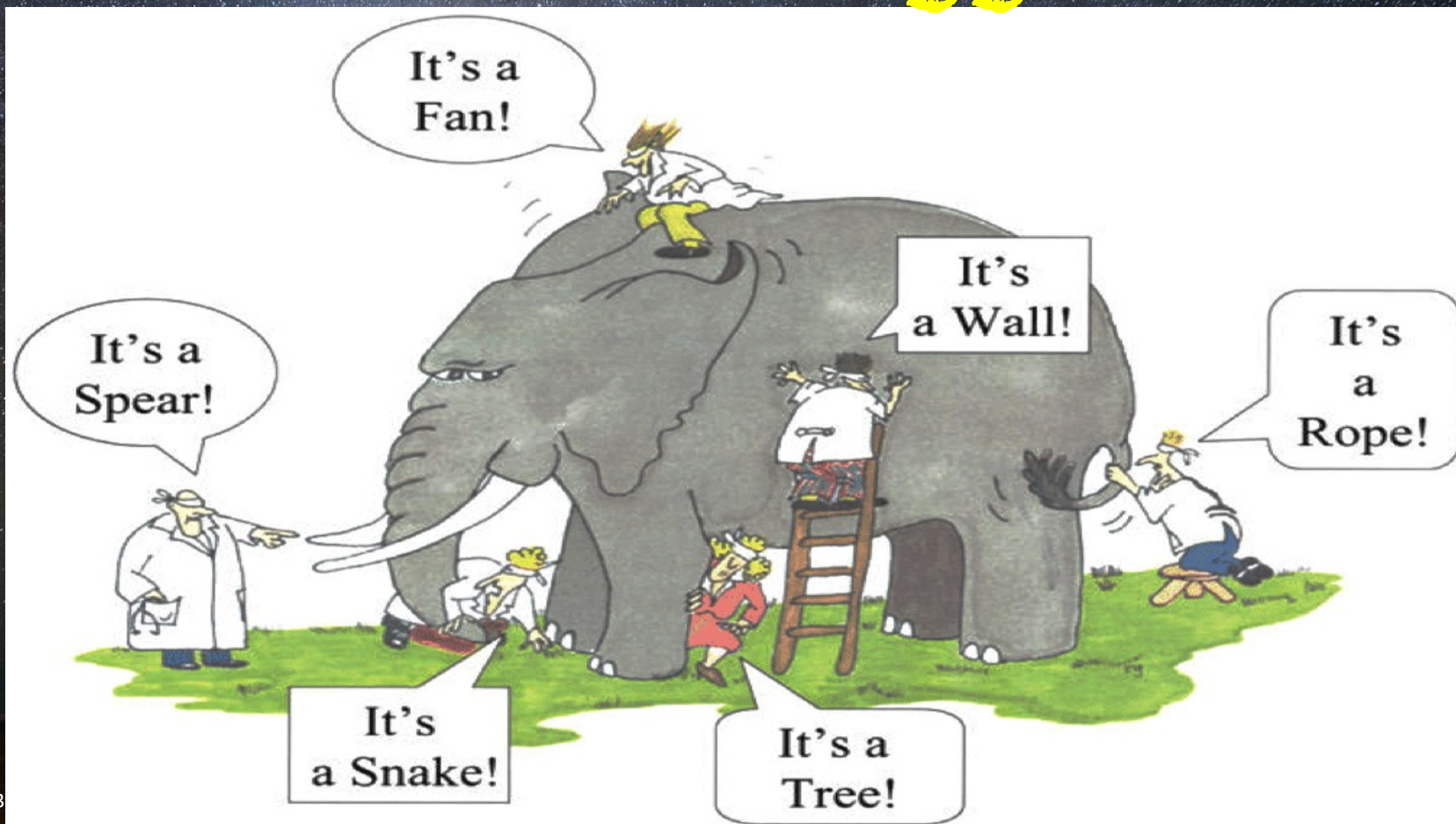
# Cosa c'e' oltre L'Higgs?



# Cosa c'e' oltre L'Higgs?

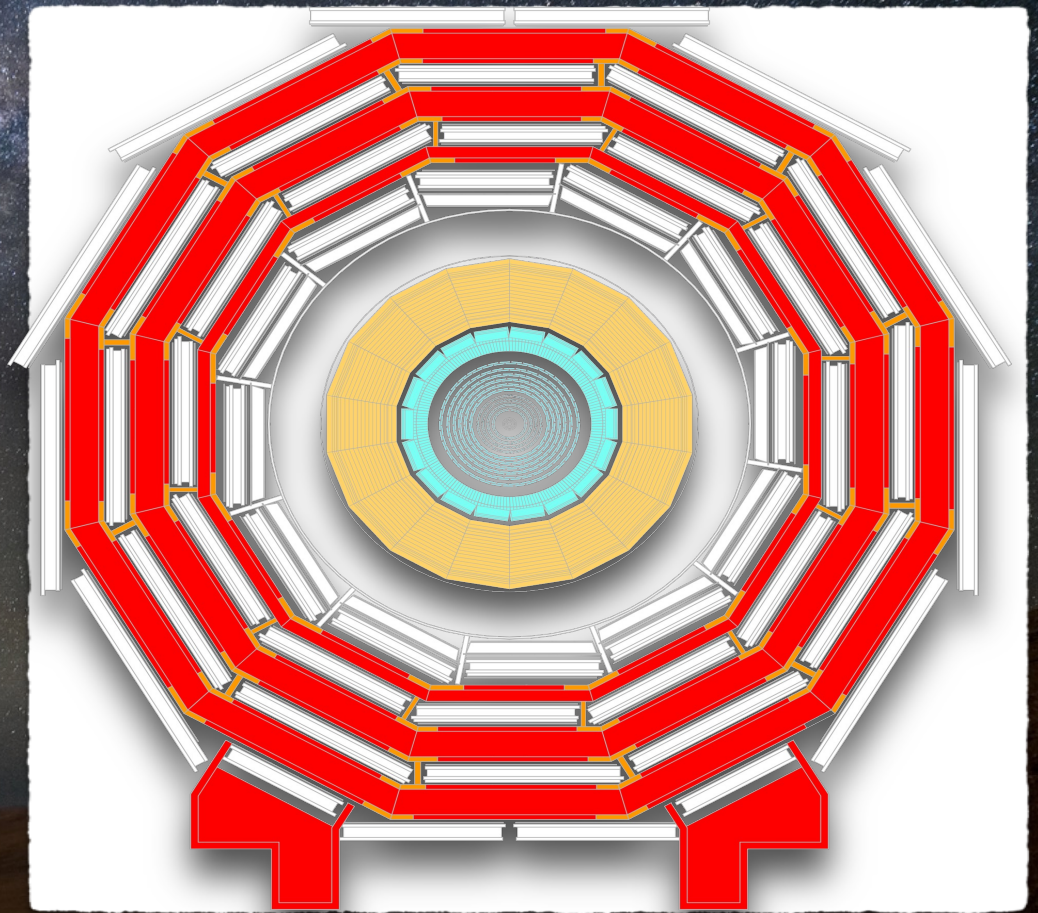


# Cosa c'e' oltre L'Higgs?



# Come si cerca la nuova fisica?

Processo noto:



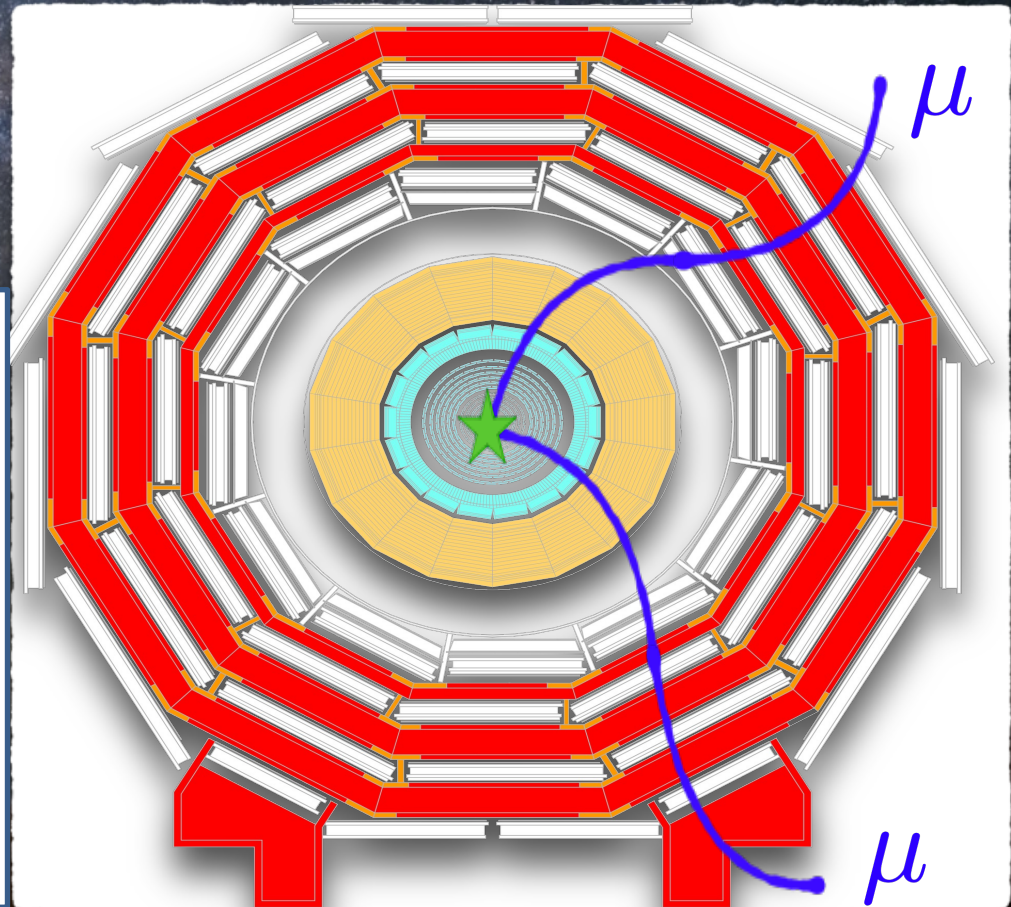
# Come si cerca la nuova fisica?

Processo noto:

$$Z \rightarrow \mu\mu$$

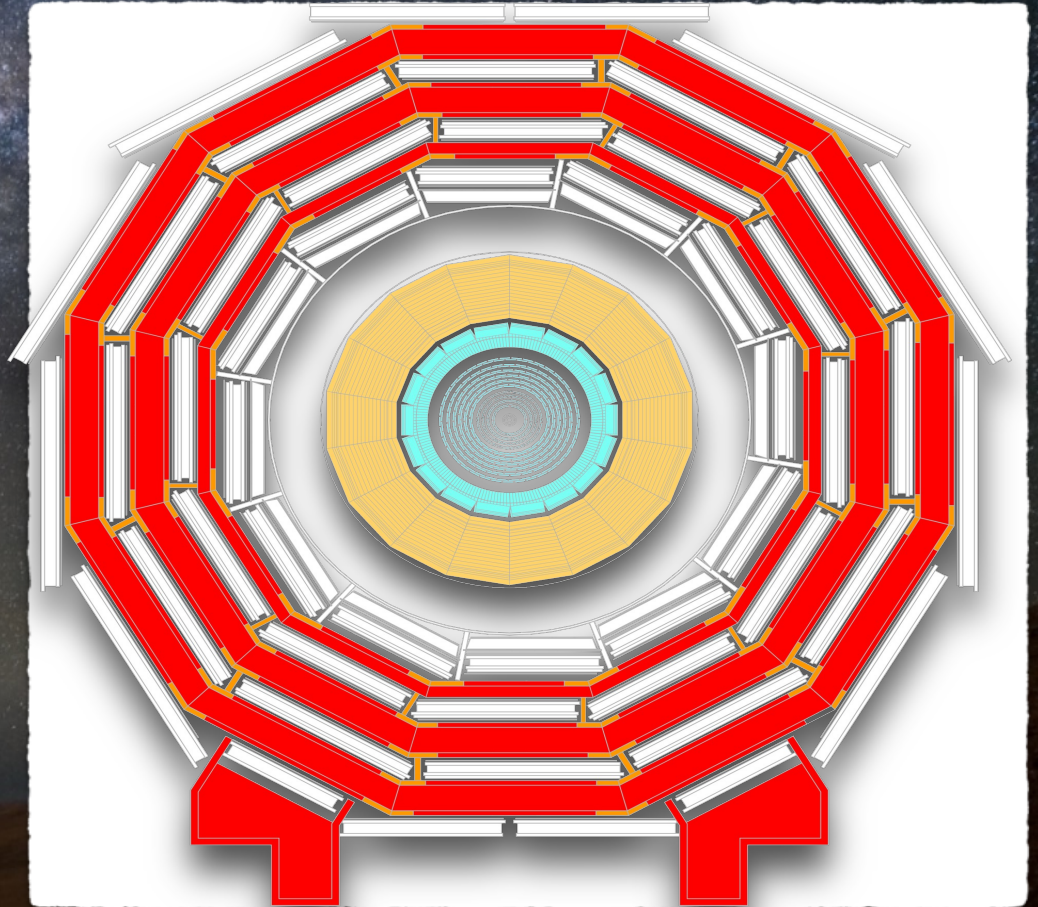
$Z$

si disintegra  
**istantaneamente**  
in **due muoni!**



# Come si cerca la nuova fisica?

Processo nuovo:



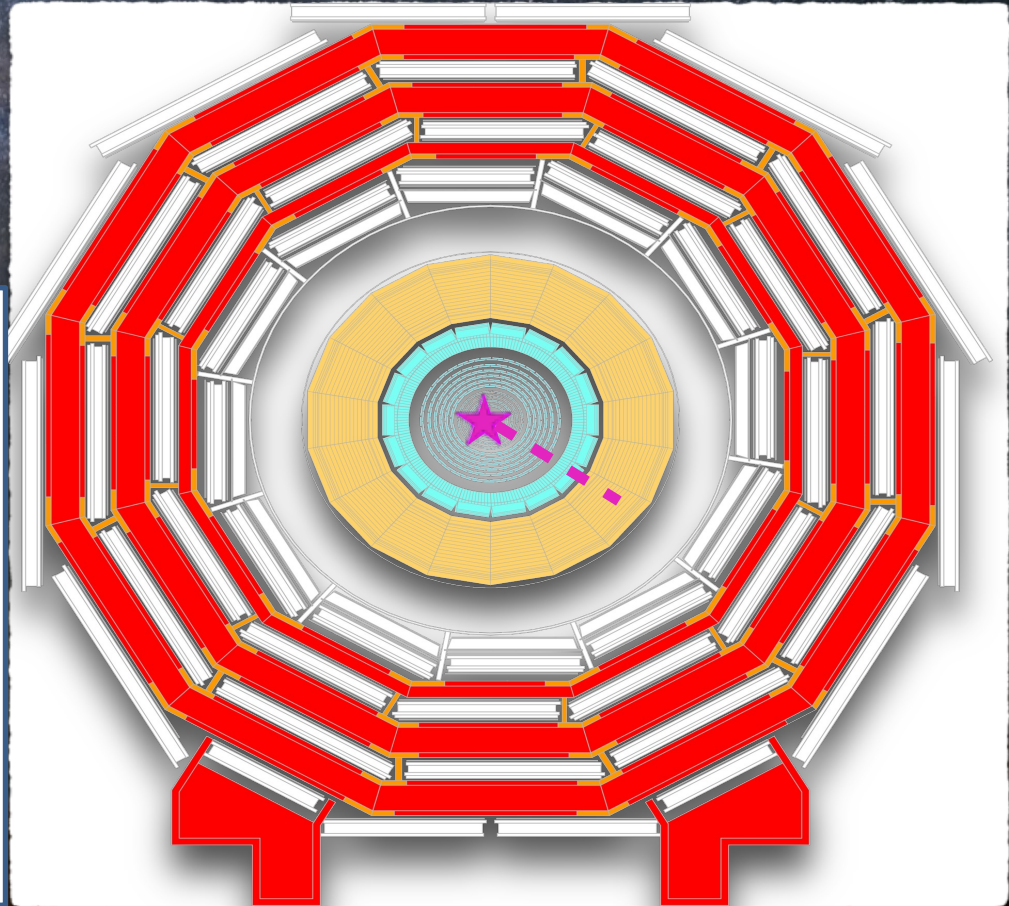
# Come si cerca la nuova fisica?

Processo nuovo:

$$X \rightarrow \mu\mu$$

X

cammina un po'  
nel rivelatore



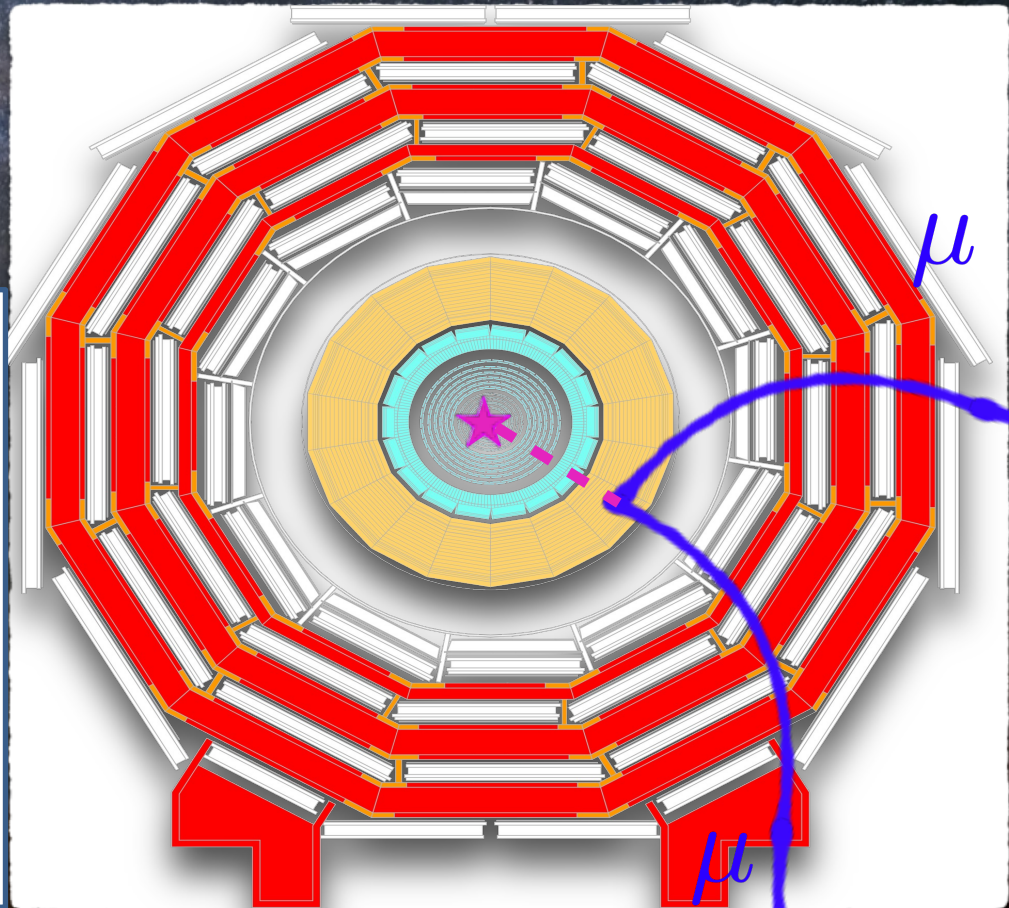


# Come si cerca la nuova fisica?

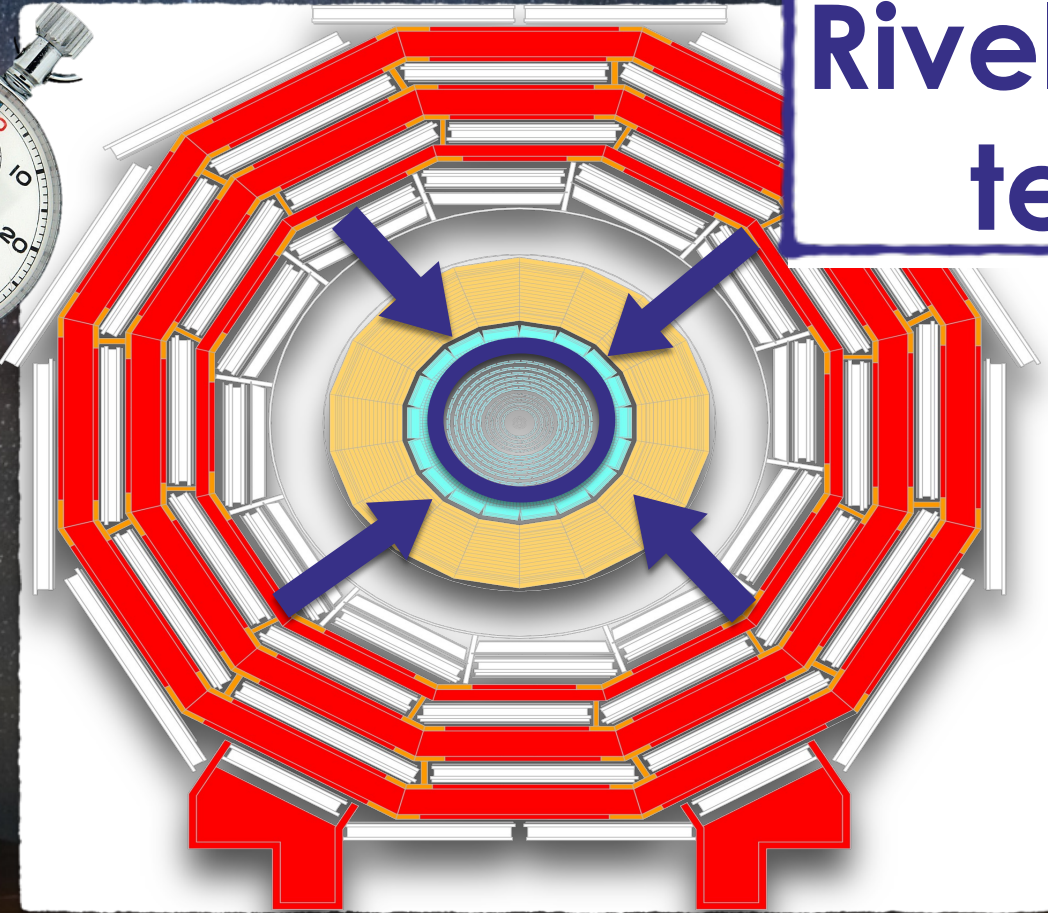
Processo nuovo:

$$X \xrightarrow{x} \mu\mu$$

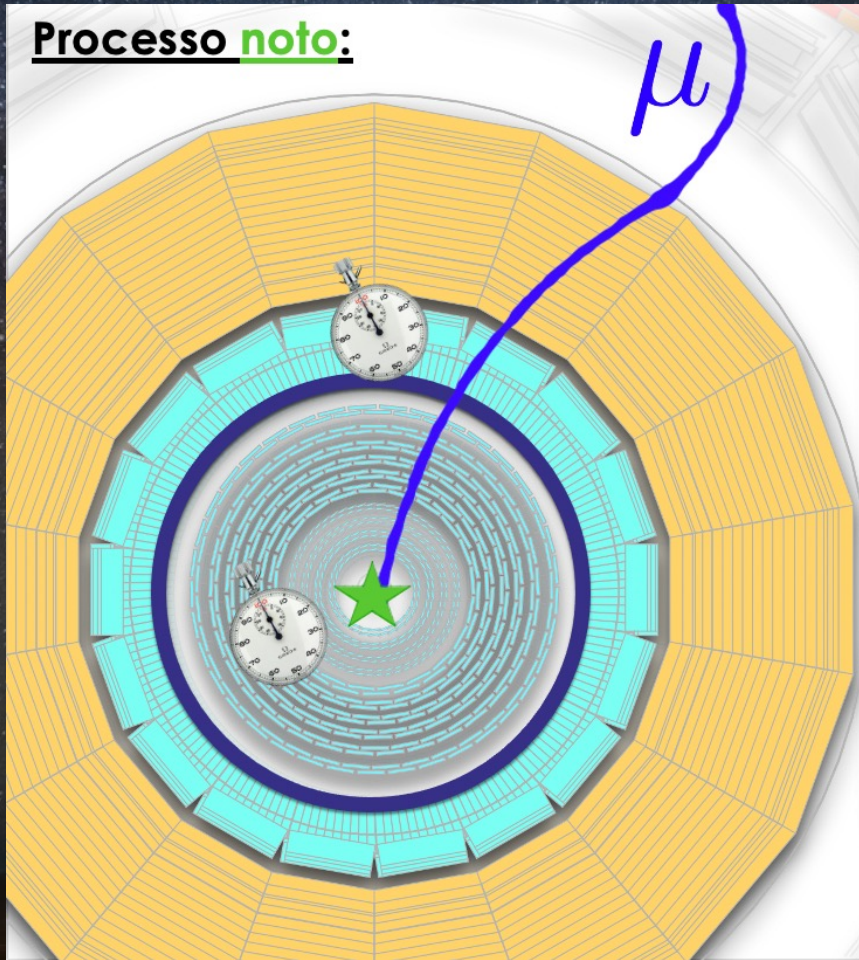
cammina un po'  
poi decade in due  
muoni



# Rivelatore di tempo



Processo noto:



Tempo della  
collisione:

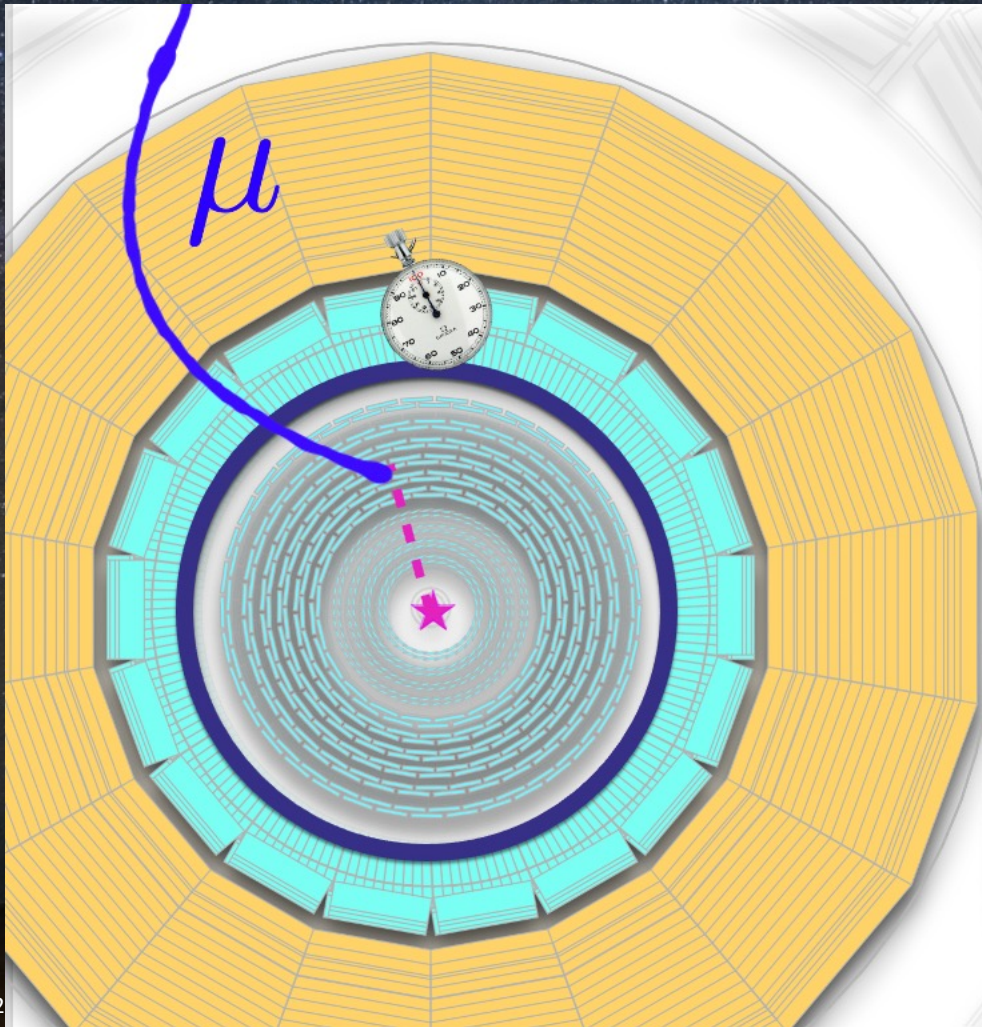
$$t_0$$

Tempo di  
passaggio:

$$t_\mu$$

Tempo di volo del  
muone:

$$t_{\text{volo}} = t_\mu - t_0$$



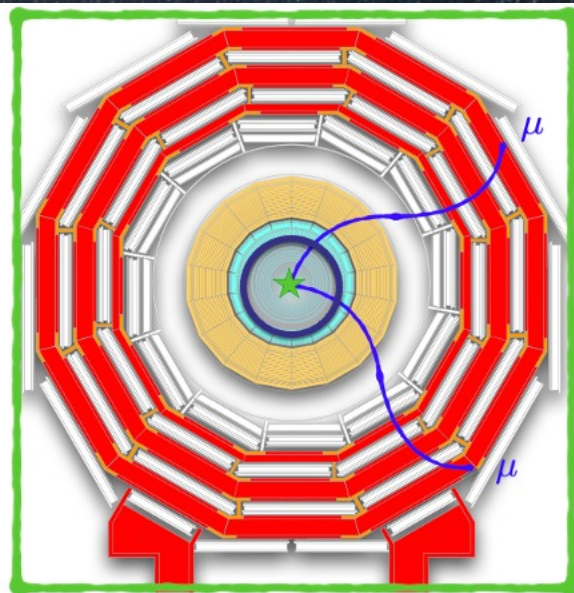
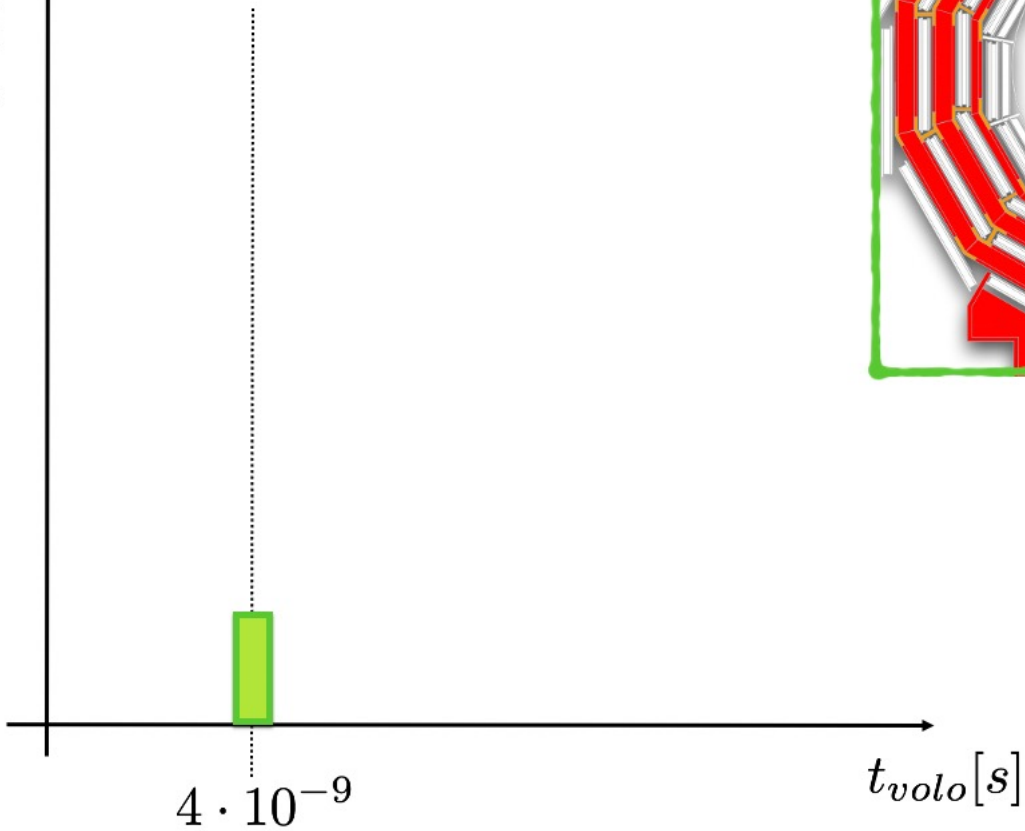
$X$  si muove  
lentamente prima  
di disintegrarsi

$$m_X \nearrow v_X \searrow$$

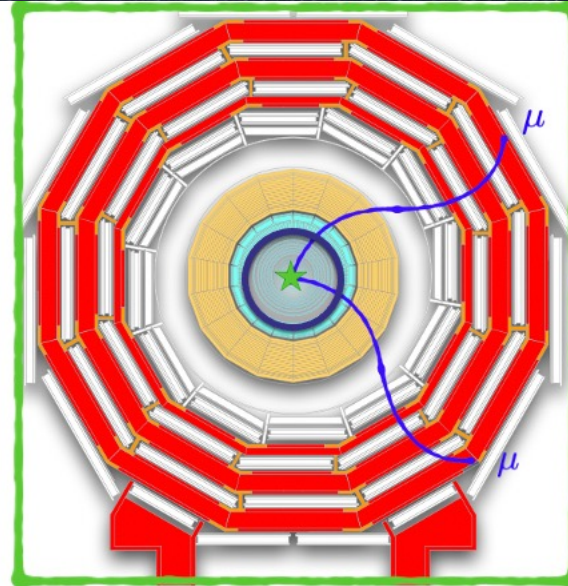
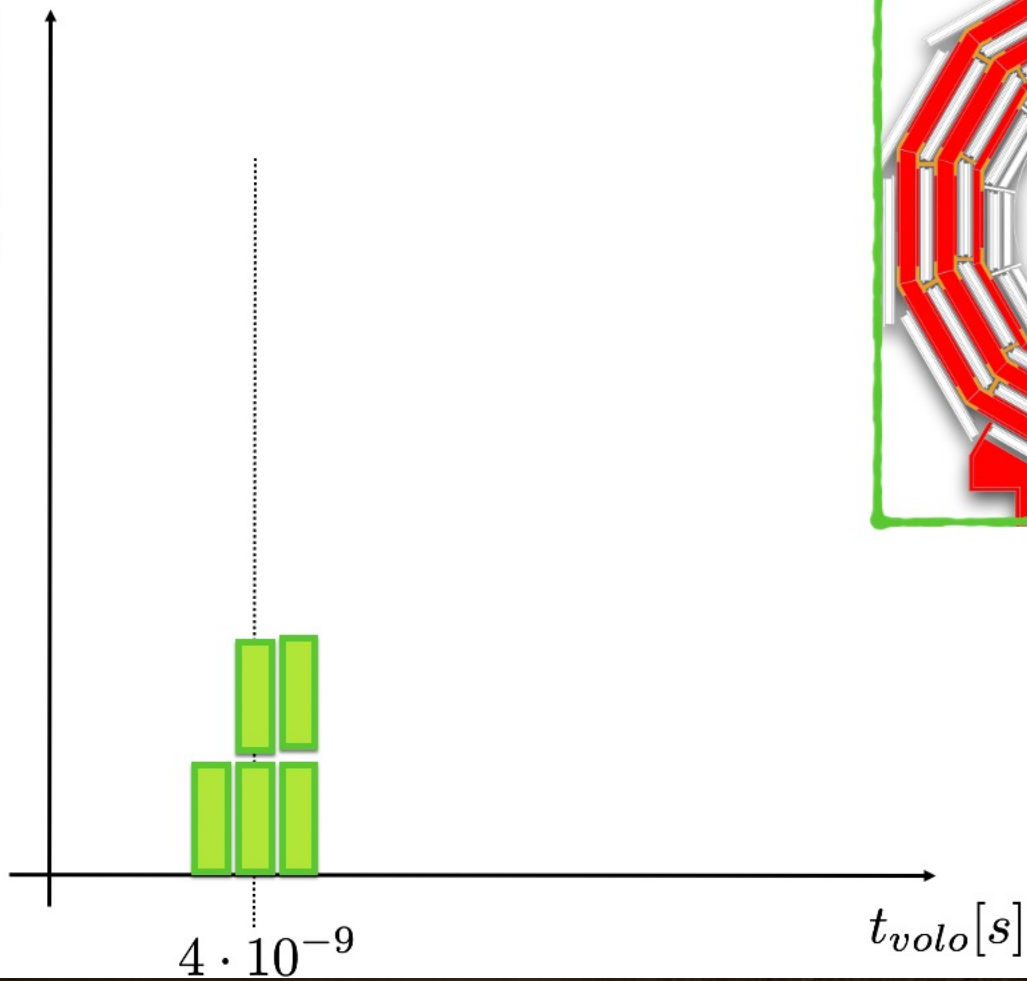
I muoni arrivano in  
ritardo sul rivelatore:

$$t_{\text{volo}} = t_X + t_\mu - t_0$$

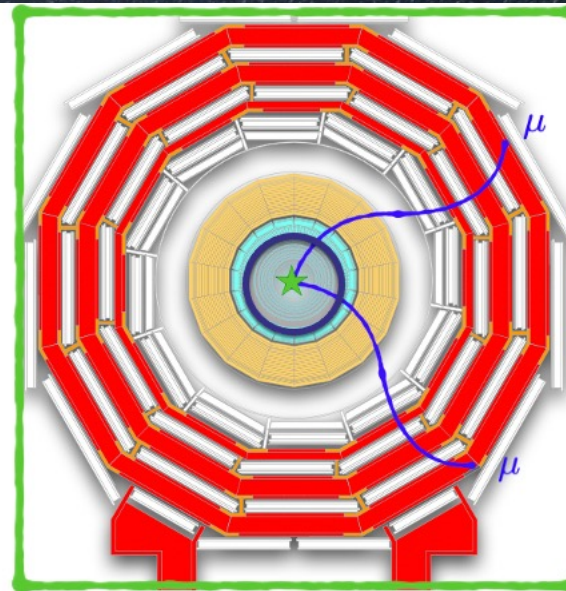
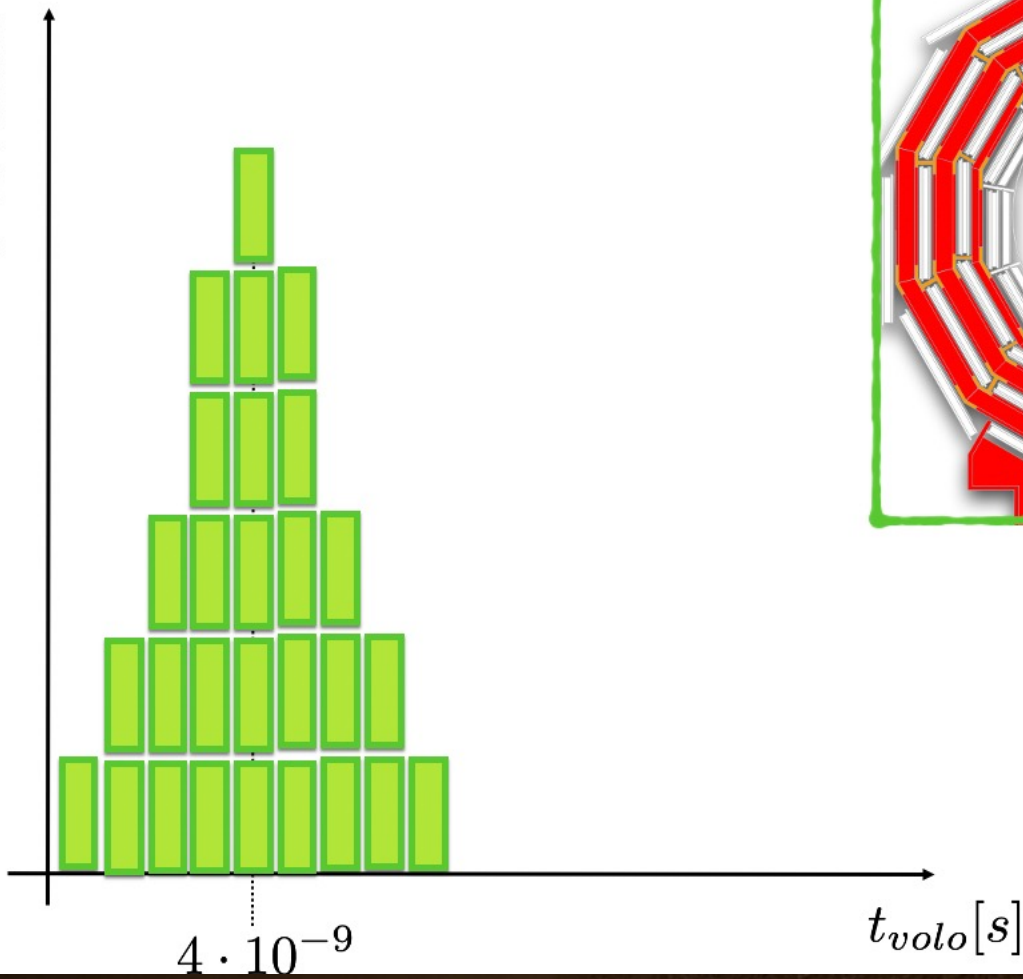
# Eventi



# Eventi

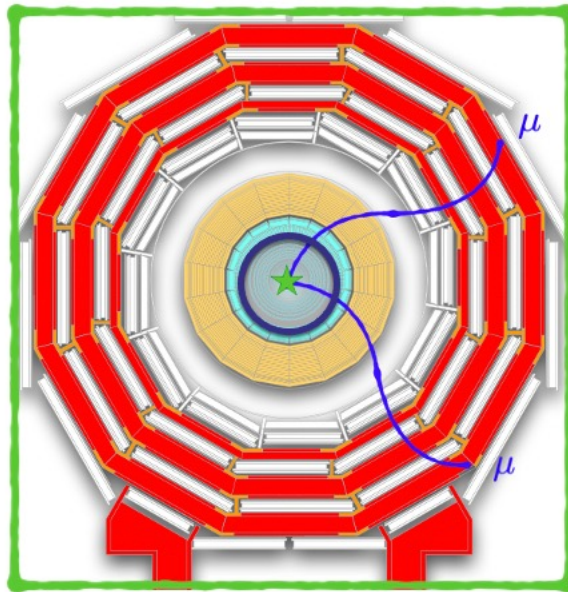
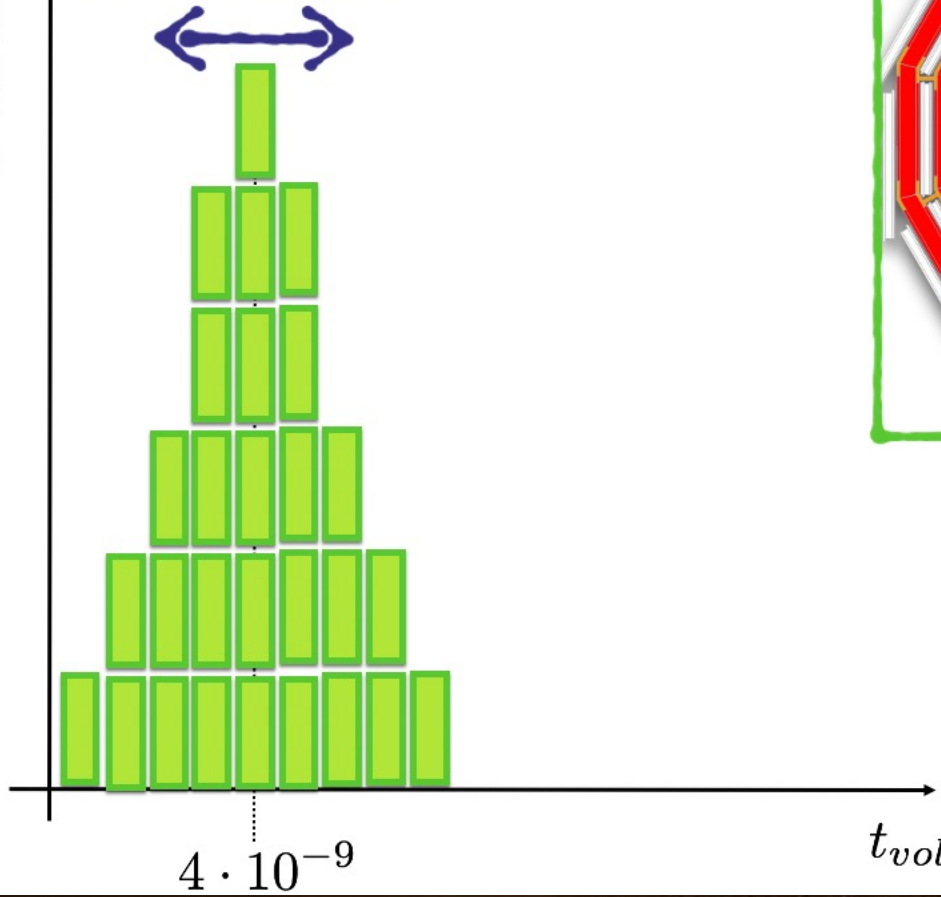


# Eventi

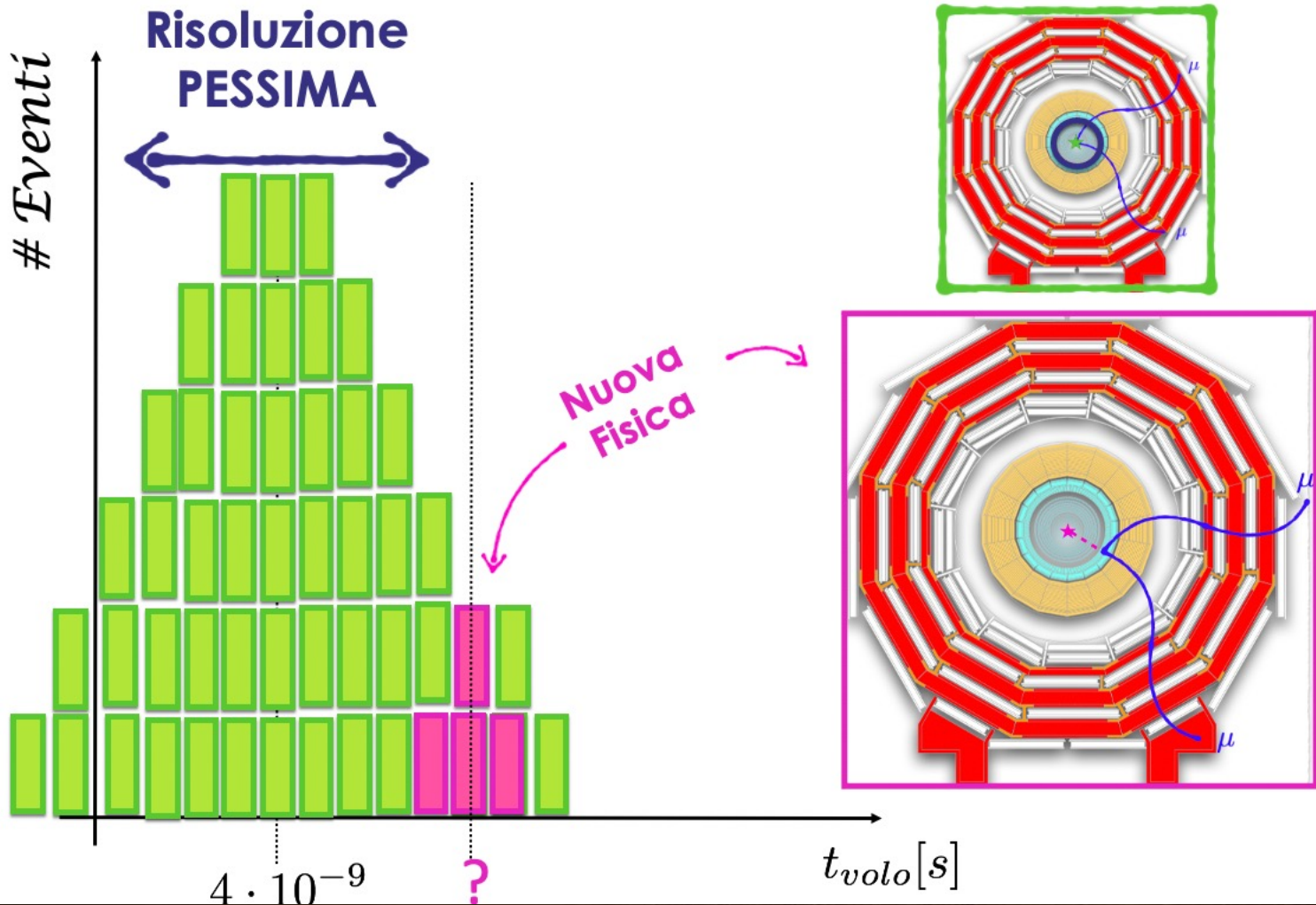


Risoluzione  
temporale ?

# Eventi

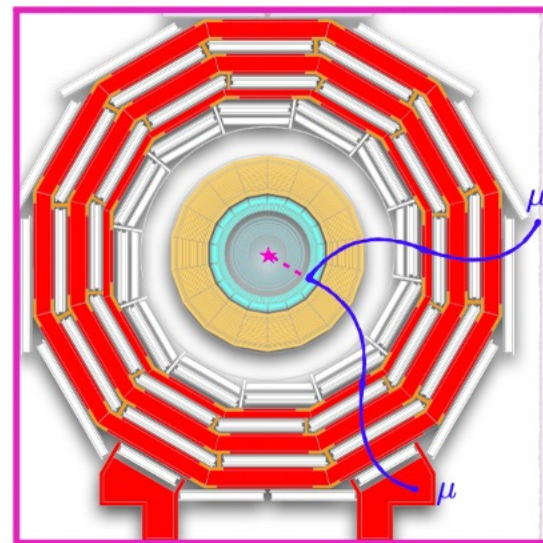
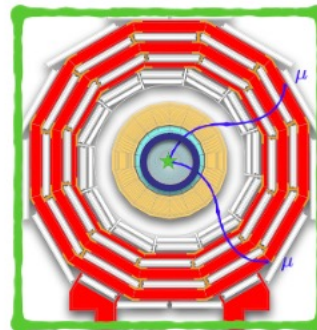
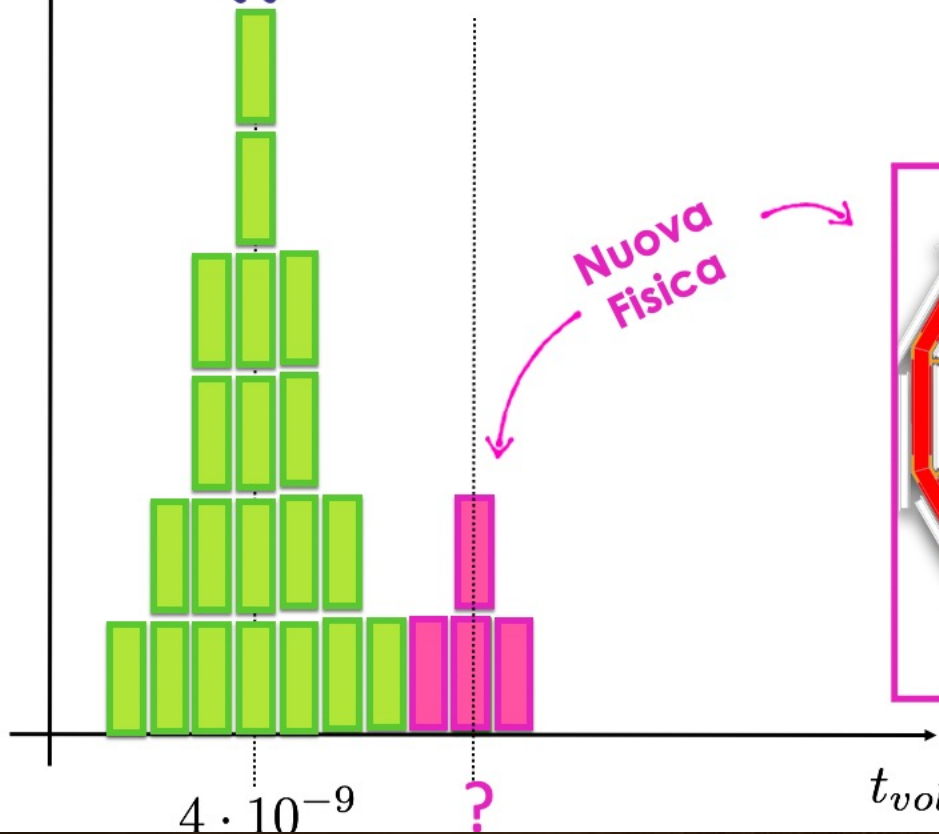






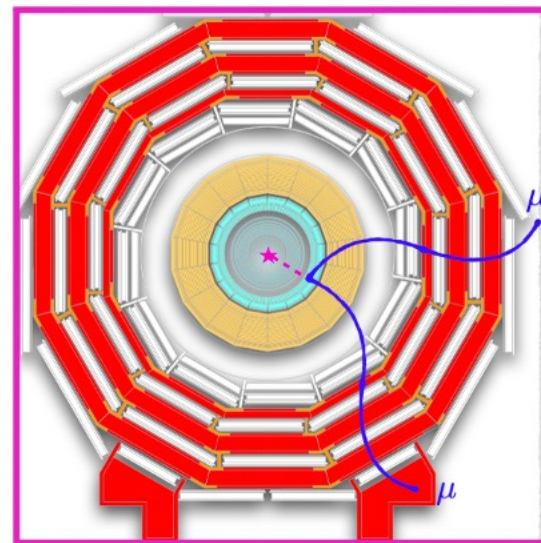
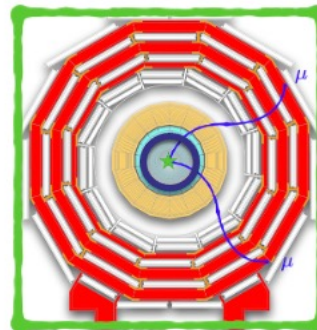
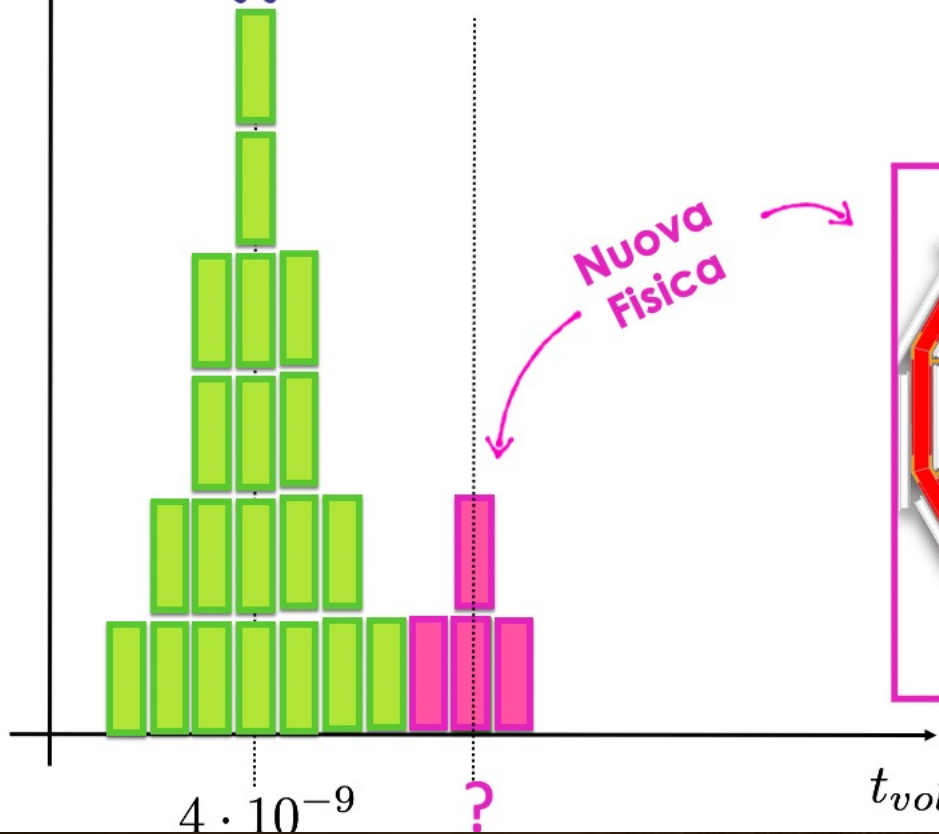
# Eventi

Risoluzione  
OTTIMALE



# Eventi

Risoluzione  
OTTIMALE



**Risoluzione  
temporale**



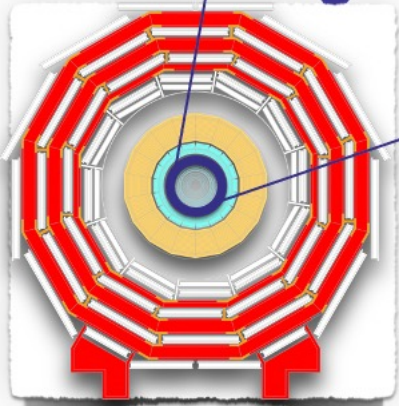
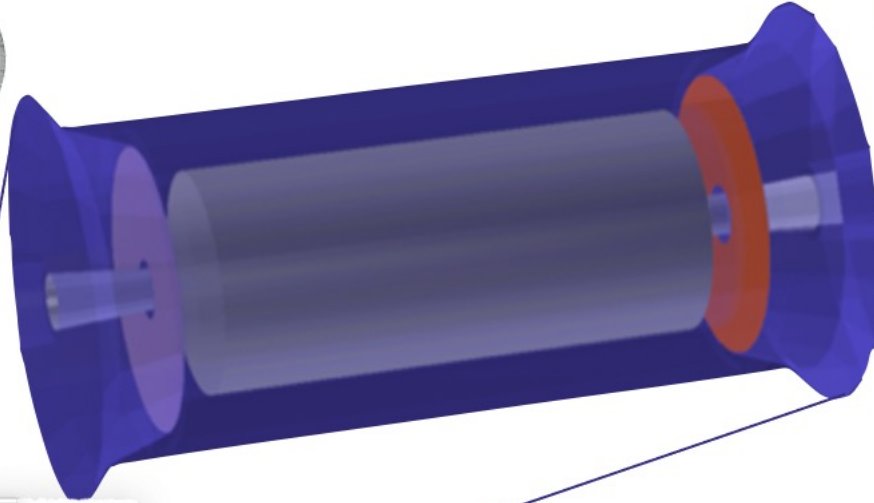
**Identificazione  
nuove  
particelle**



**Risoluzione temporale  
OTTIMALE:**

$$\sigma_t = 30 \cdot 10^{-12} \text{ s}$$

Operativo  
nel 2027!

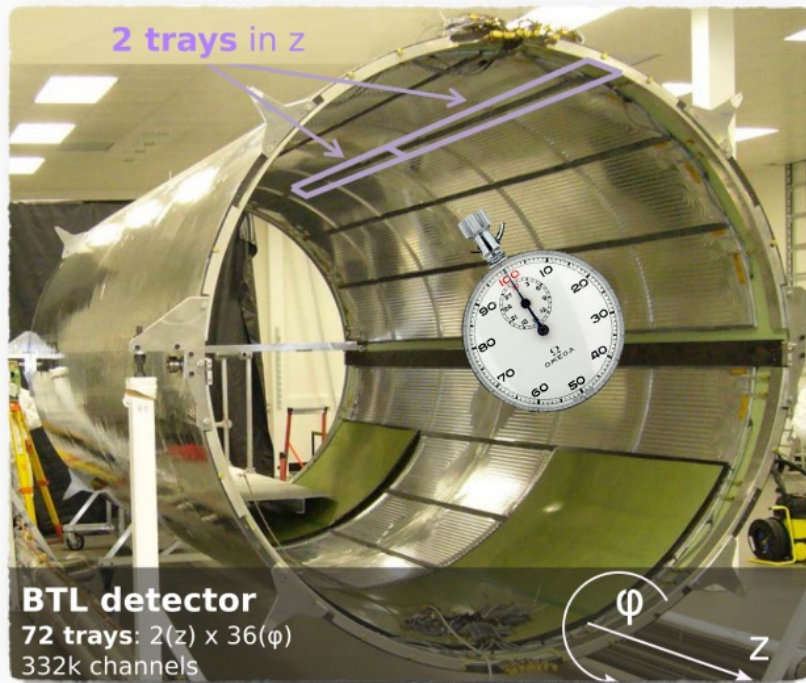


Materiale: **cristalli scintillanti**

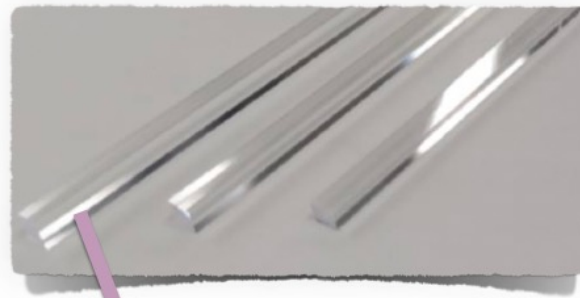
Numero di sensori: ~ **6 Milioni**

Risoluzione Temporale: **30 ps**

## Struttura di sostegno



Cristalli 5 x 0.3 cm,  
singoli sensori

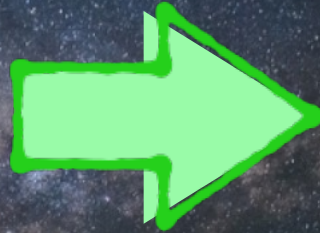




Robert Wilson,  
USA (1914-2000)

*“... this new knowledge ...  
has nothing to do directly  
with defending our country,  
except to help make it  
worth defending”*

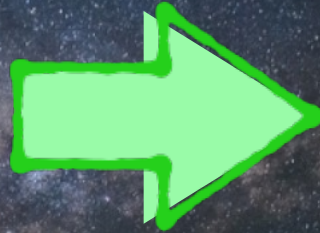
RICERCA DI  
BASE



INNOVAZIONE  
TECNOLOGICA



RICERCA DI  
BASE

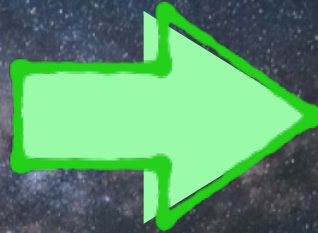


INNOVAZIONE  
TECNOLOGICA



1973 **GPS**: Verifica  
della teoria di  
Einstein

RICERCA DI  
BASE



INNOVAZIONE  
TECNOLOGICA

1991 CERN: **W**here  
the **W**eb **W**as born!



RICERCA DI  
BASE

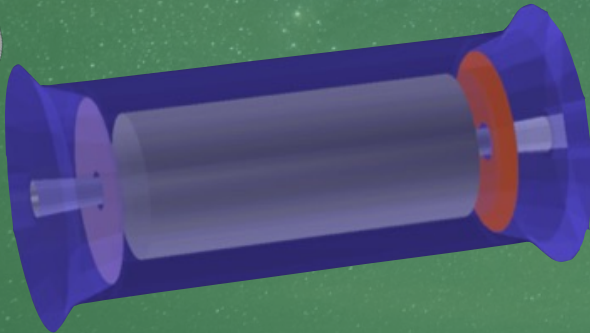


INNOVAZIONE  
TECNOLOGICA

RICERCA DI  
BASE

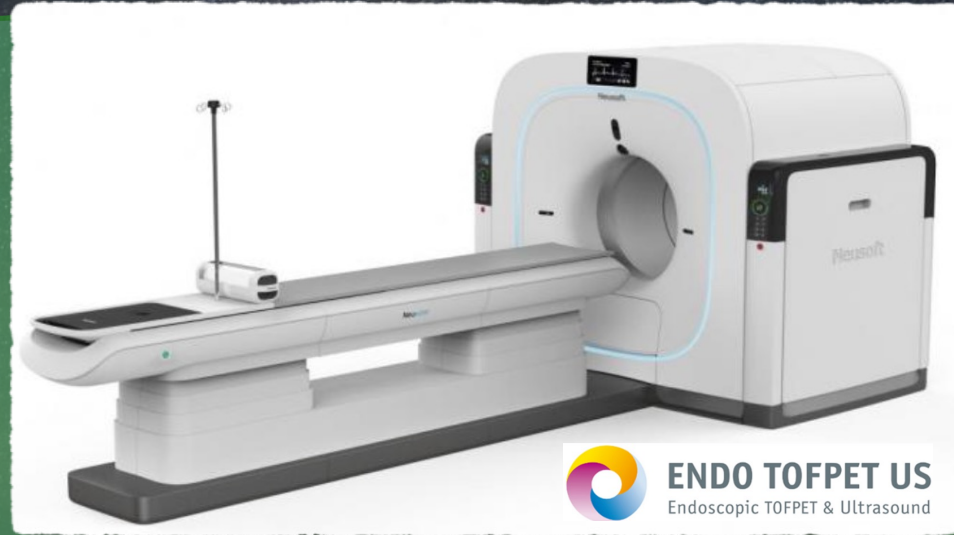


INNOVAZIONE  
TECNOLOGICA



2022- Rivelatore di  
tempo di particelle

3/30/23



2000- Time of Flight Photon  
eMission Tomography



Grazie per l'attenzione

Per qualsiasi domanda:  
[livia.soffi@roma1.infn.it](mailto:livia.soffi@roma1.infn.it)