PARTICELLE E ACCELERATORI: VIAGGIO AI CONFINI DELLA NATURA

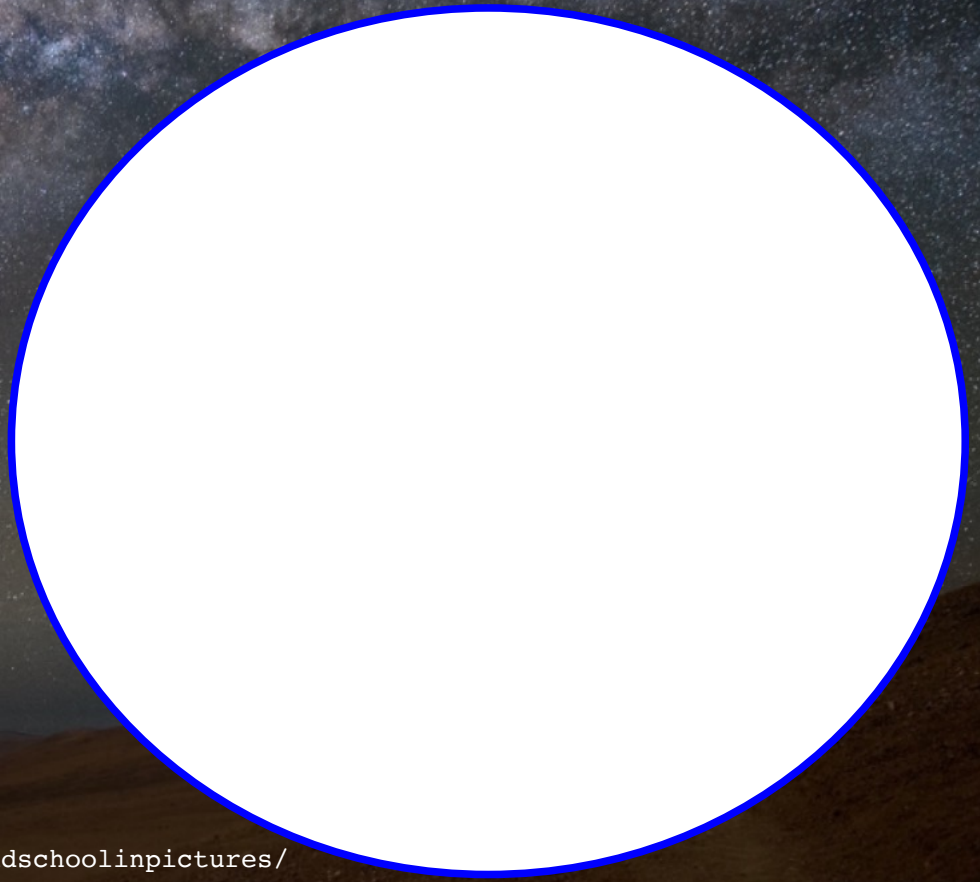
Livia Soffi – Ricercatrice III Liv. INFN

31 Marzo 2023

INFN Istituto Nazionale di Fisica Nucleare Sezione di Roma

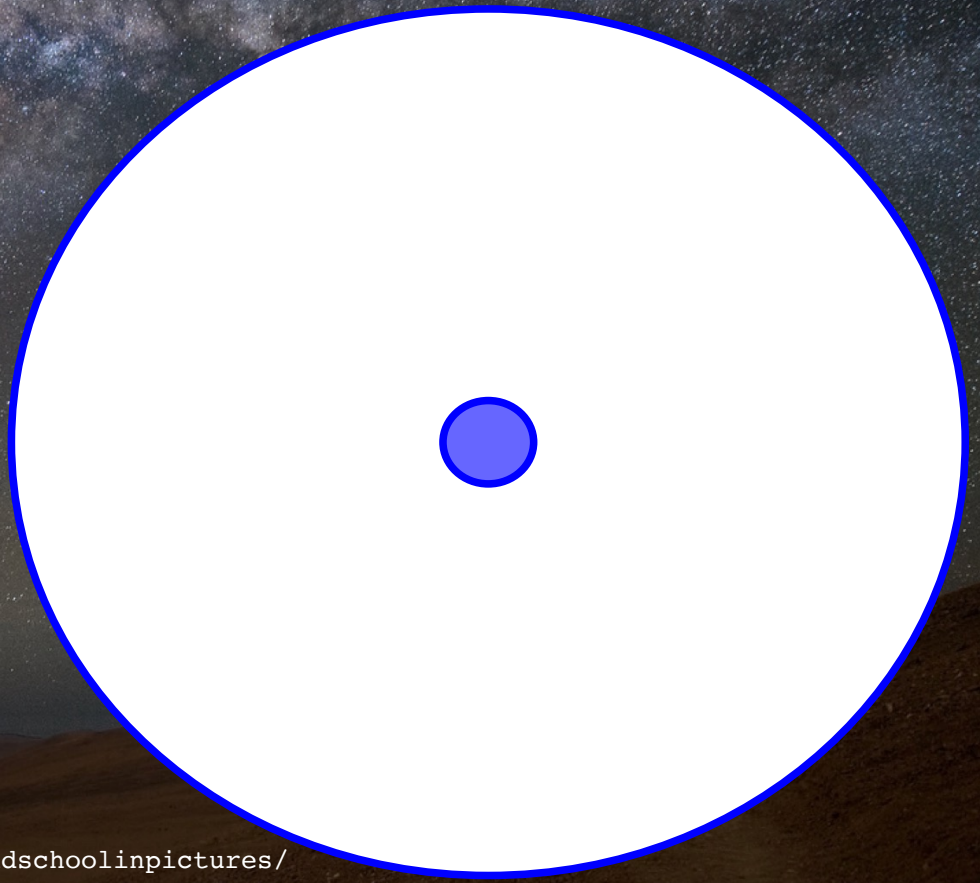
Guida Illustrata al lavoro del ricercatore

Imagine a circle that contains all of human knowledge:



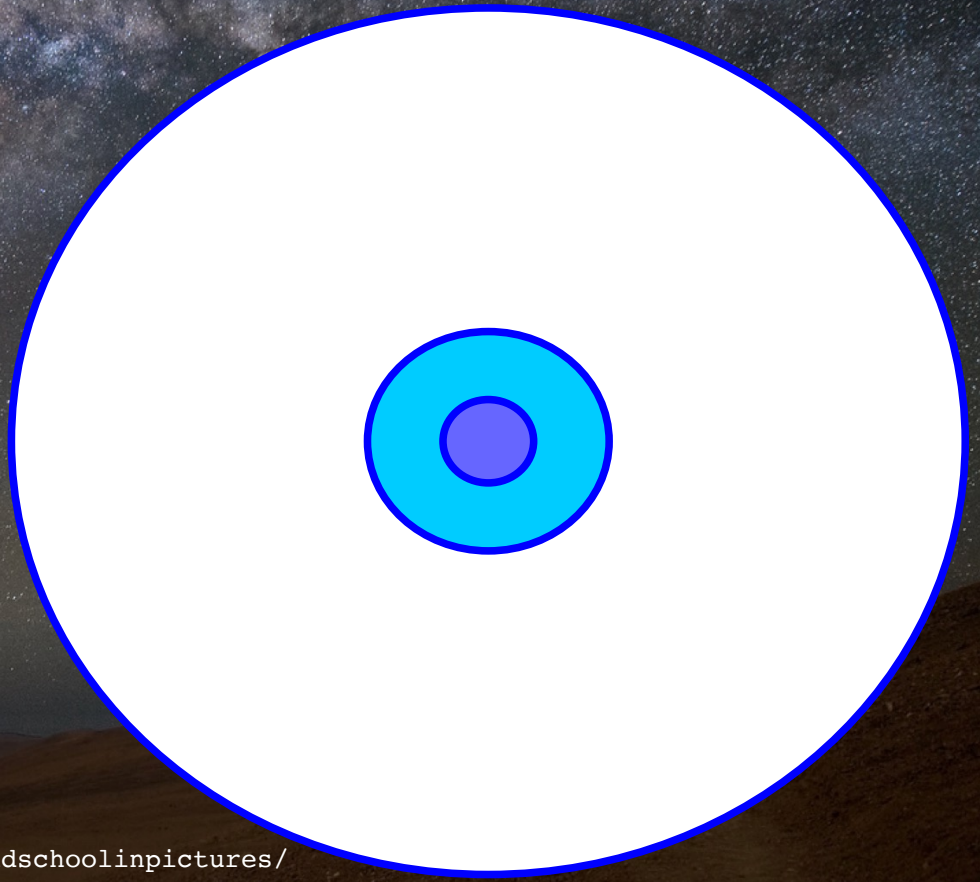
Guida Illustrata al lavoro del ricercatore

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



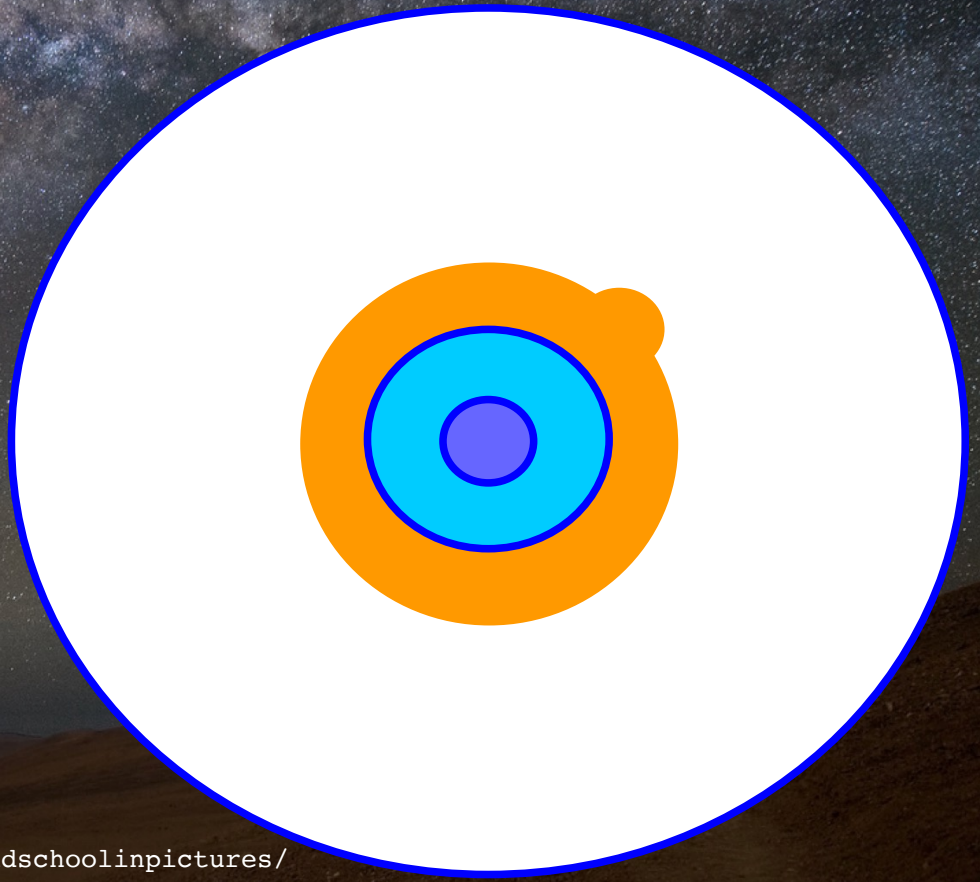
Guida Illustrata al lavoro del ricercatore

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



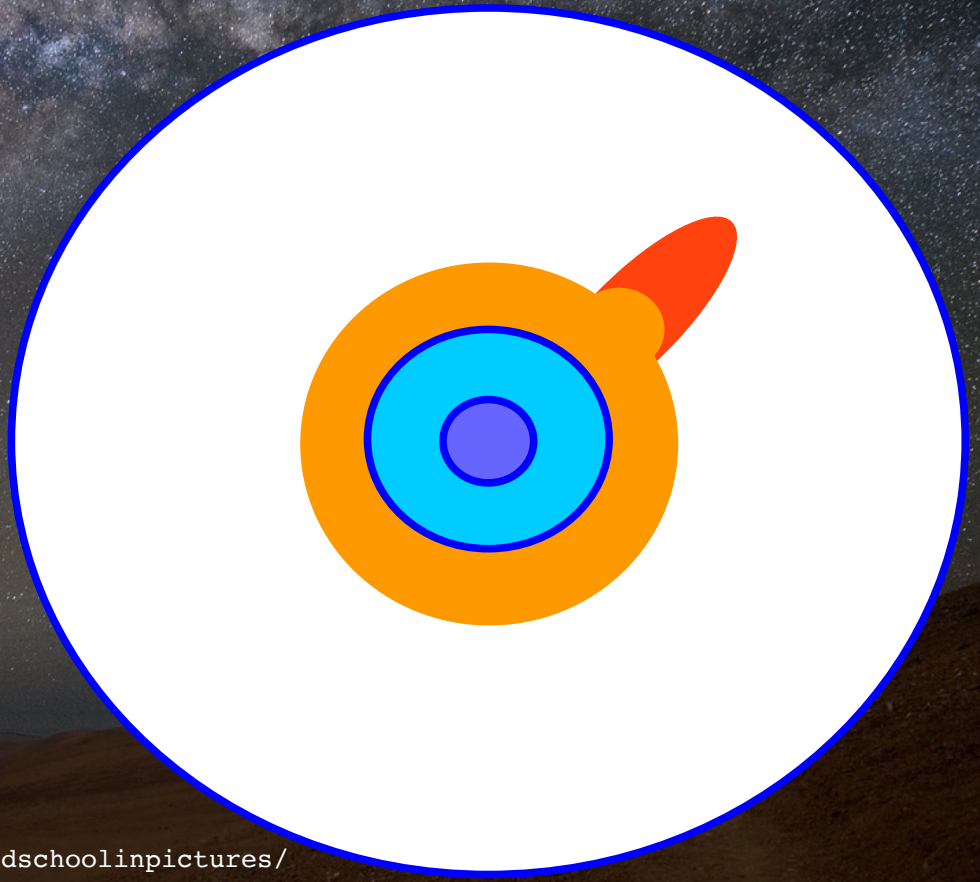
Guida Illustrata al lavoro del ricercatore

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



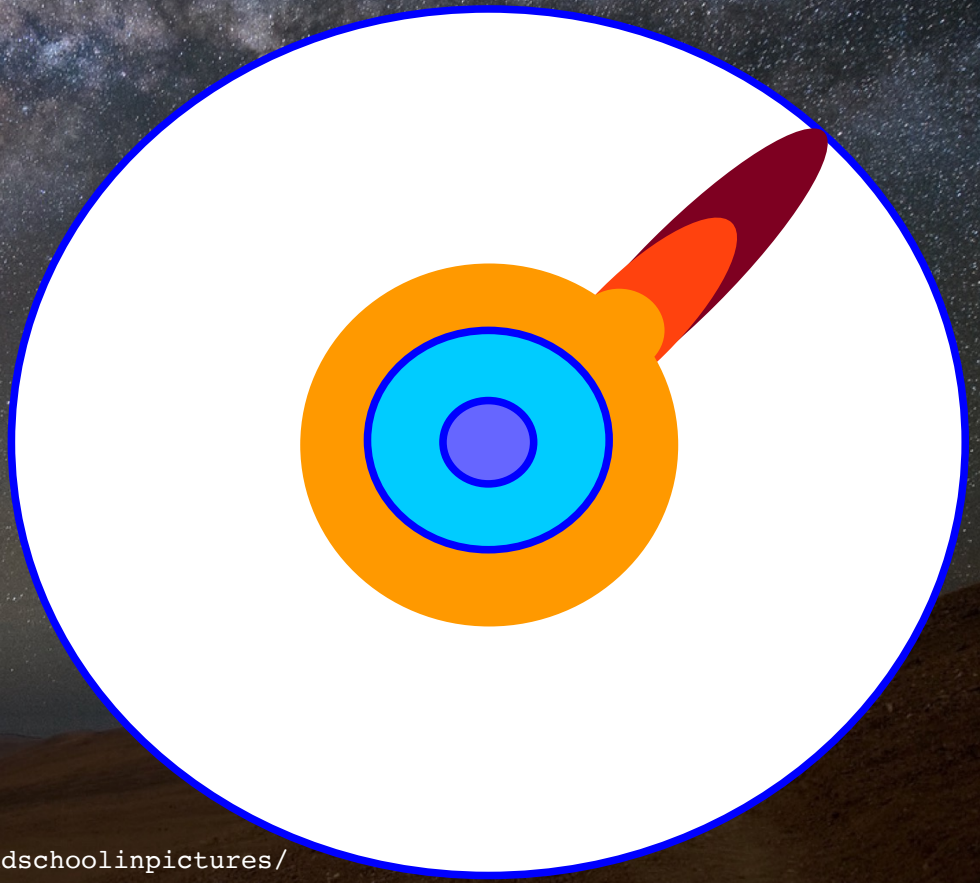
Guida Illustrata al lavoro del ricercatore

A master's degree deepens that specialty:



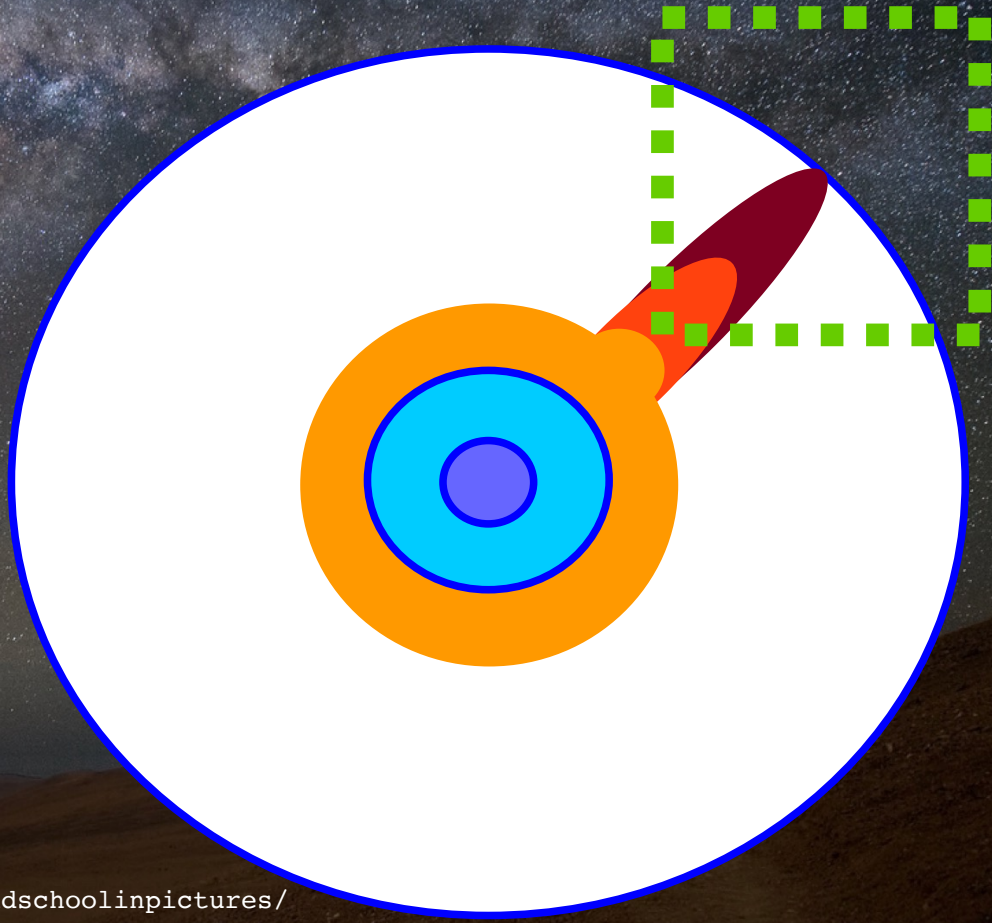
Guida Illustrata al lavoro del ricercatore

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



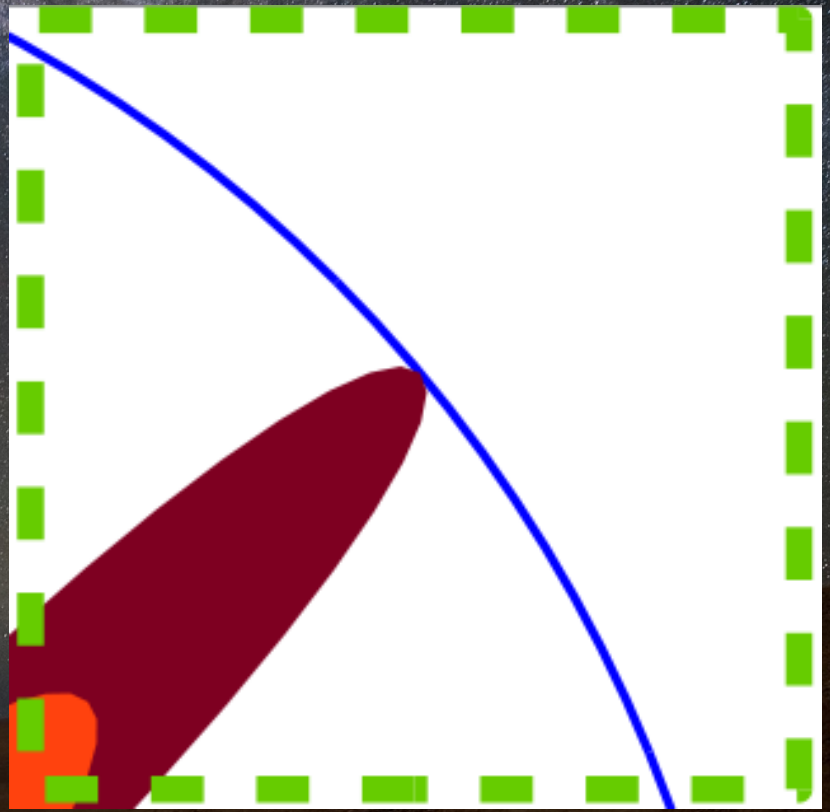
Guida Illustrata al lavoro del ricercatore

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



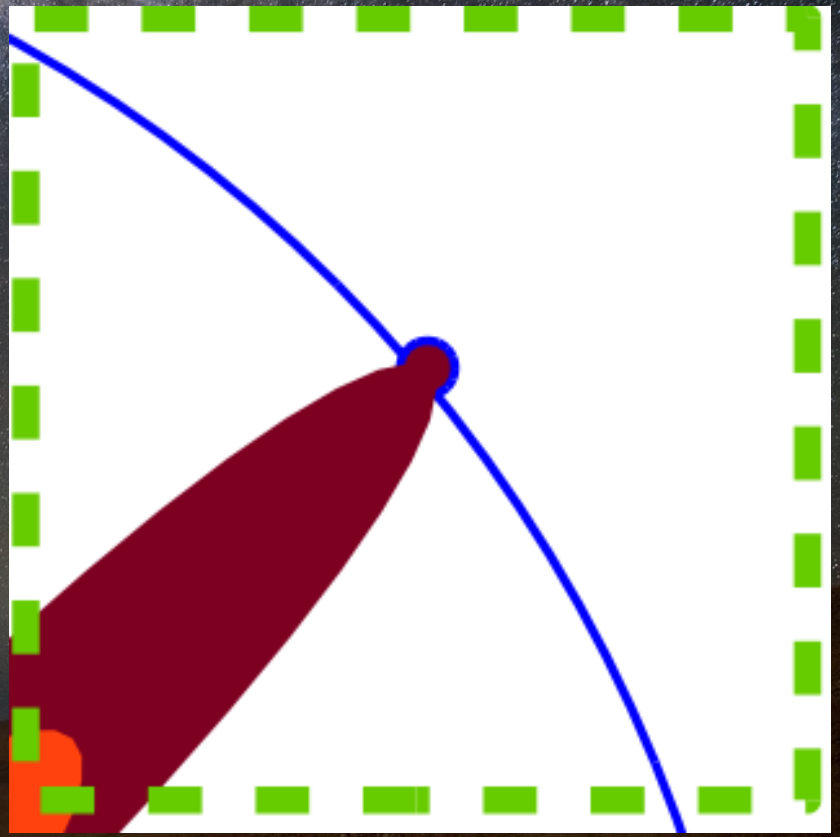
Guida Illustrata al lavoro del ricercatore

You push at the boundary for a few years:



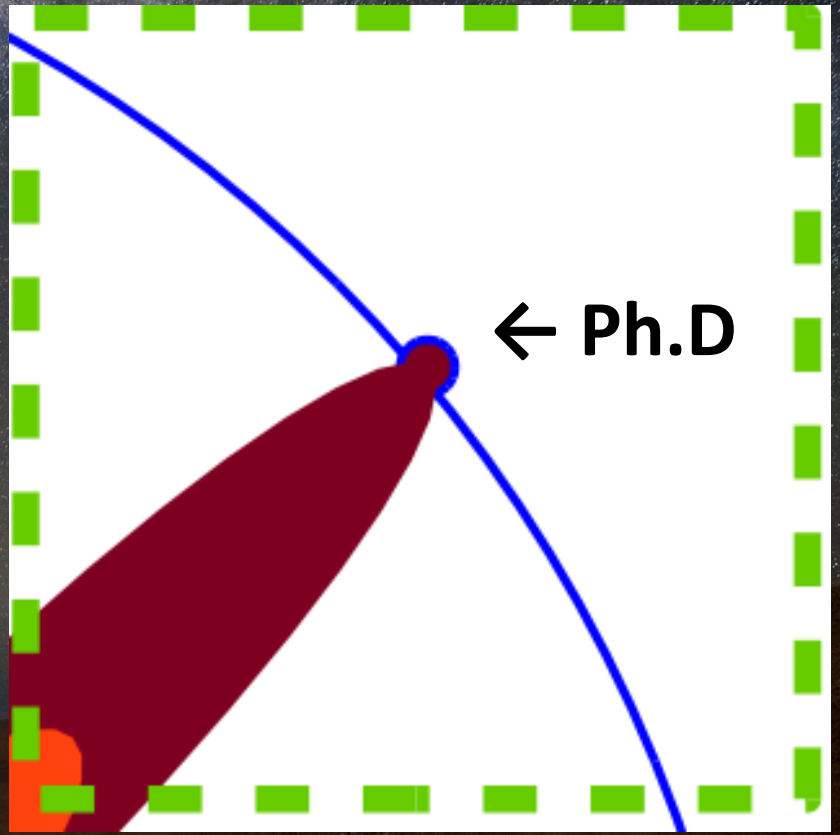
Guida Illustrata al lavoro del ricercatore

Until one day, the boundary goes away:



Guida Illustrata al lavoro del ricercatore

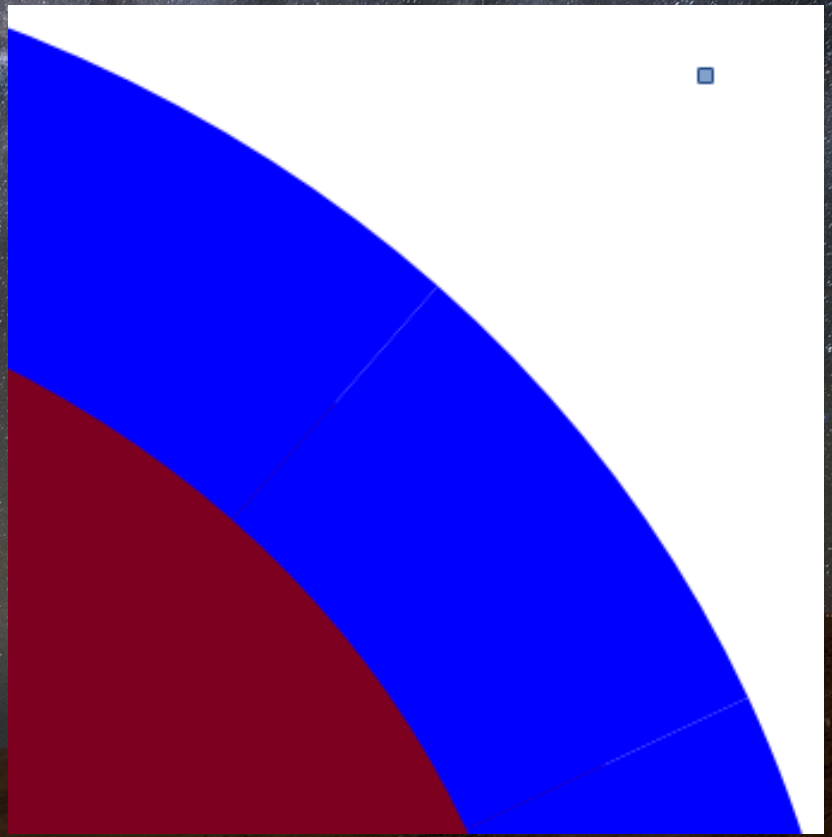
And, that dent you've made is called a **Ph.D**.:



http://matt.might.net/articles/phdschoolinpictures/

Guida Illustrata al lavoro del ricercatore

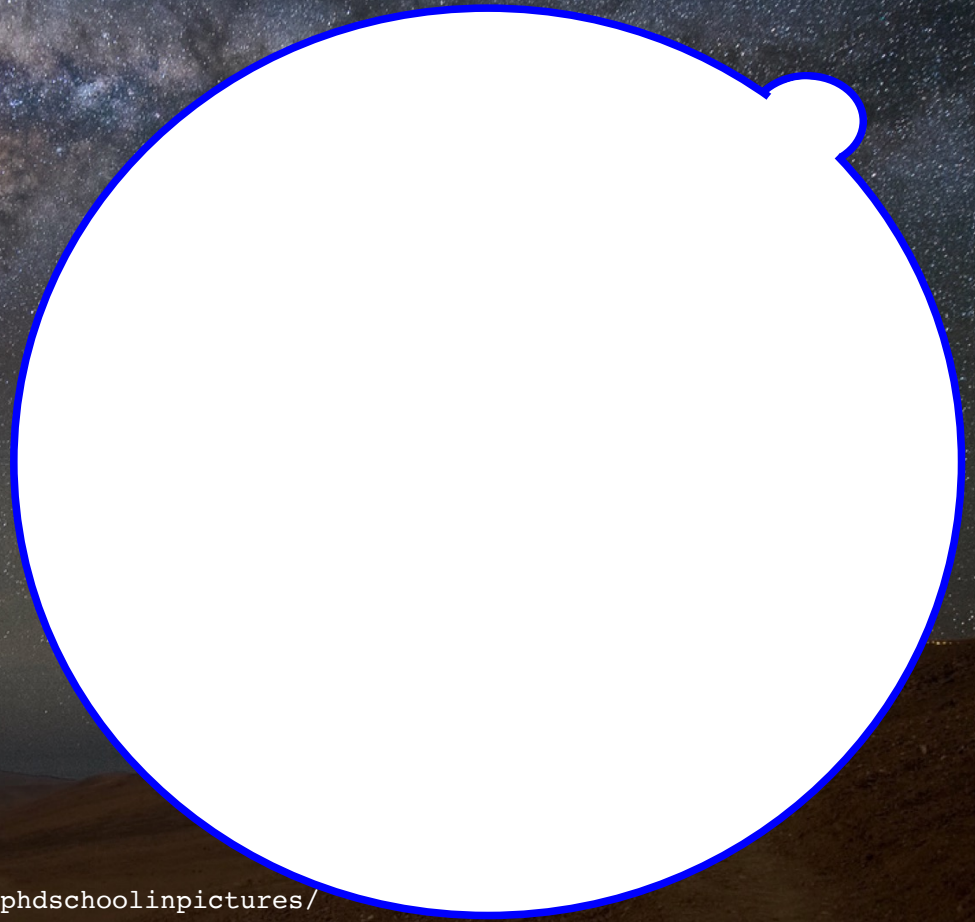
Of course, the world looks different to you now:



Guida Illustrata al lavoro del ricercatore

But don't forget the bigger picture:

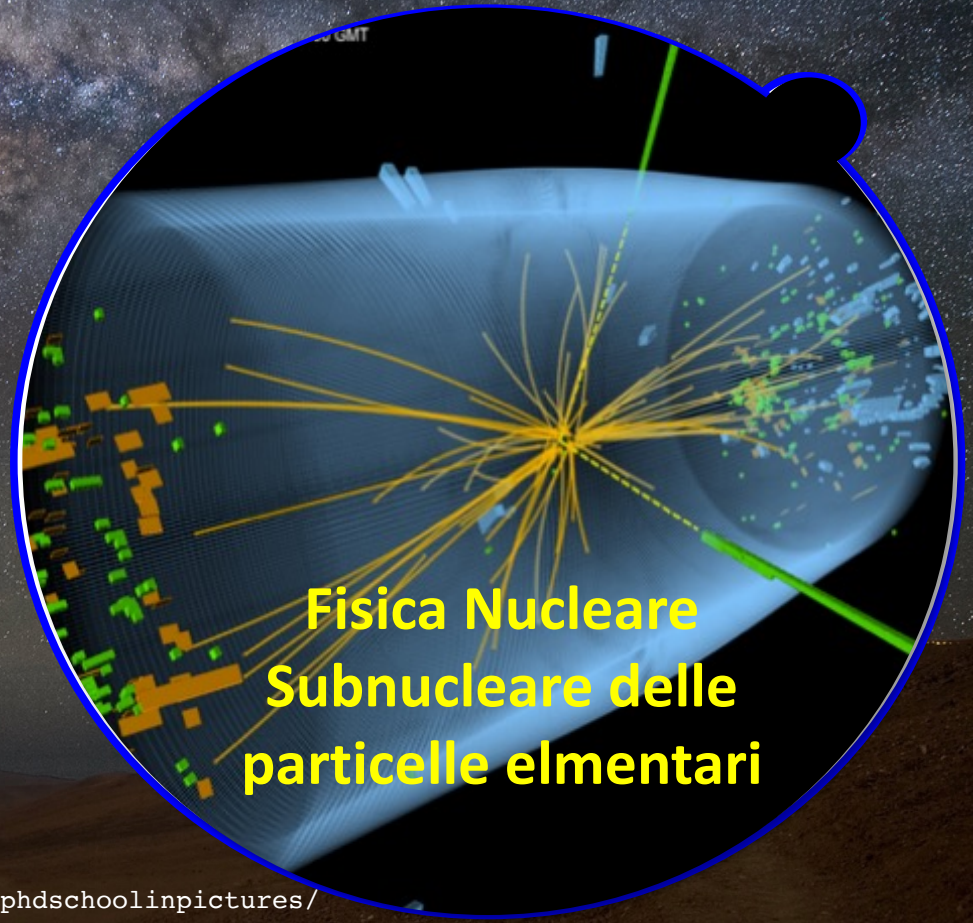
And Keep Pushing!!



Guida Illustrata al lavoro del ricercatore

But don't forget the bigger picture:

And Keep Pushing!!



http://matt.might.net/articles/phdschoolinpictures/

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?

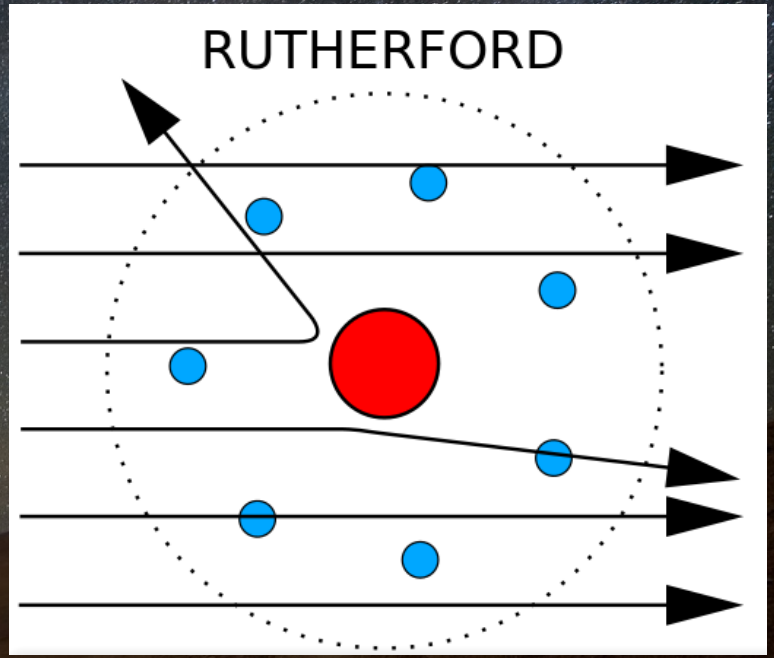
Il Metodo "Tex Willer"

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

OSSERVO LA DEVIAZIONE DEI PROIETTILI

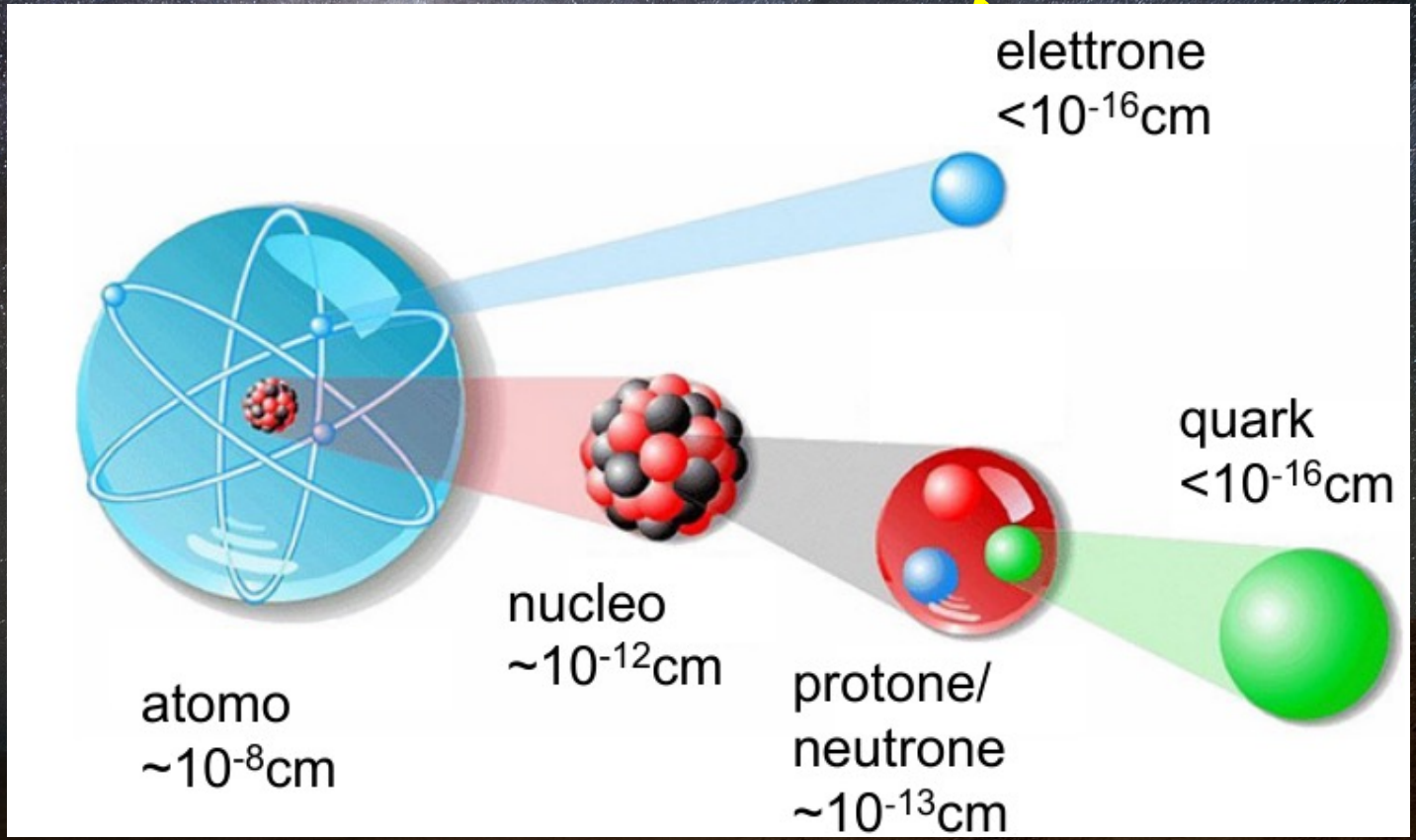
Rutherford, 1909

"Sparo" all'atomo, usando particelle α come proiettili e osservo la loro deviazione.

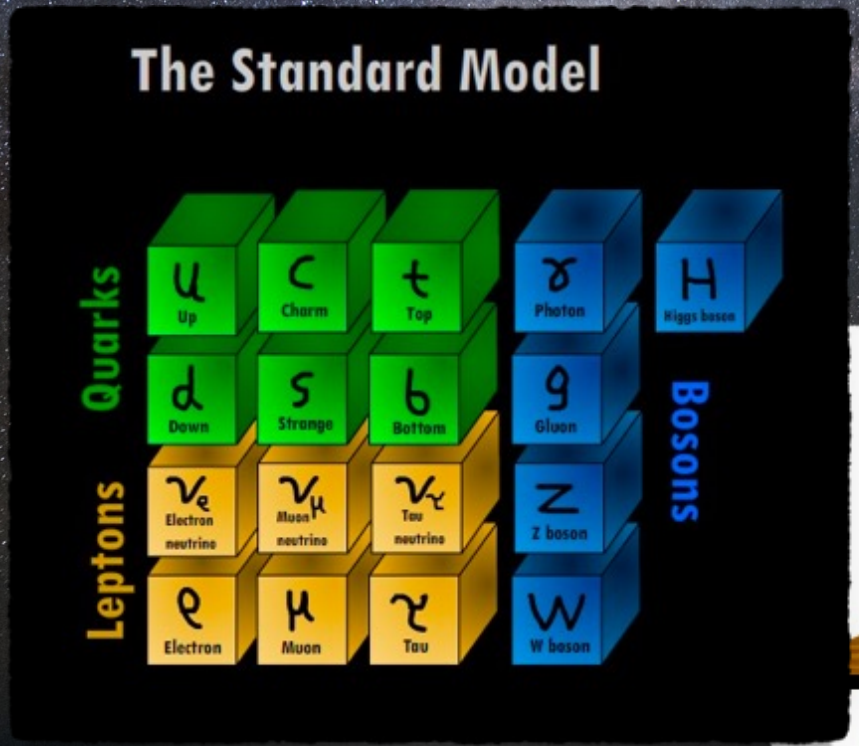


→ L'atomo contiene un nucleo con carica positiva di raggio $<10^{-12}$ cm

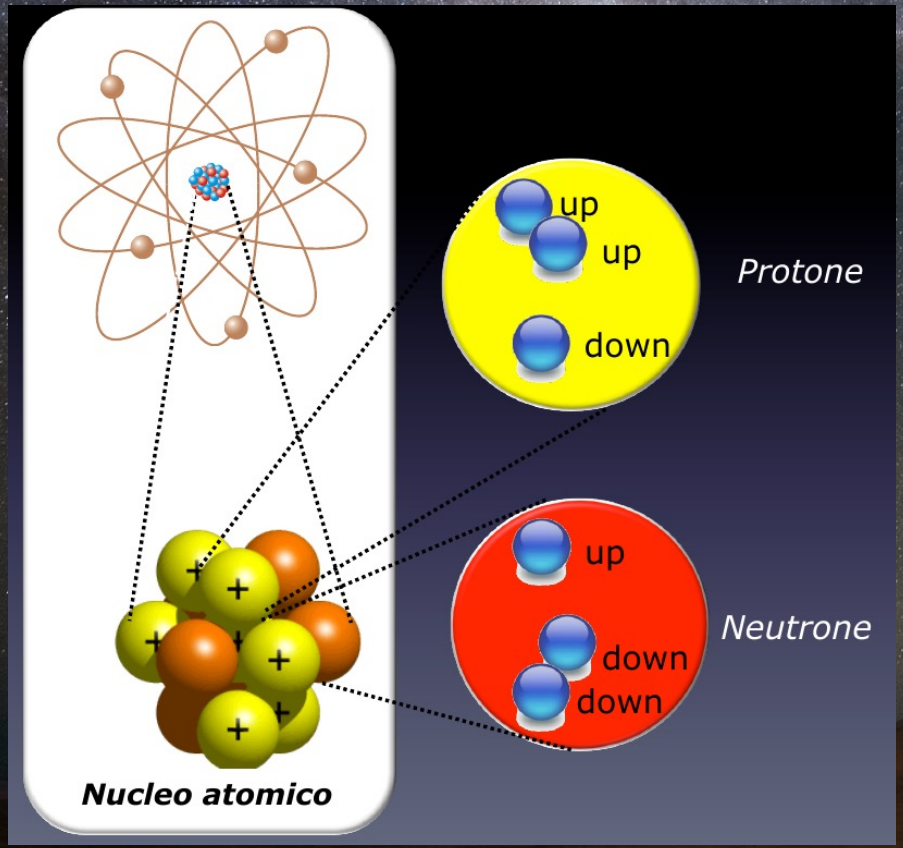
L'infinitamente piccolo

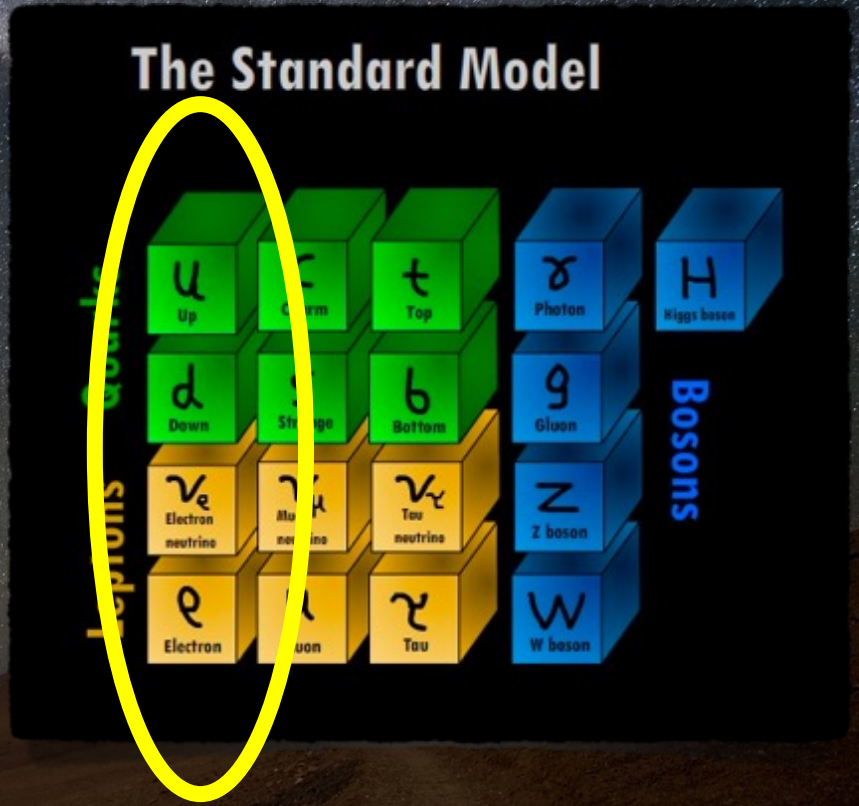


Il Modello Standard



La Materia Ordinaria





La Massa delle Particelle

Meccanica classica (I. Newton, 1687):

massa = quantità di materia

Meccanica relativistica (A. Einstein, 1905):

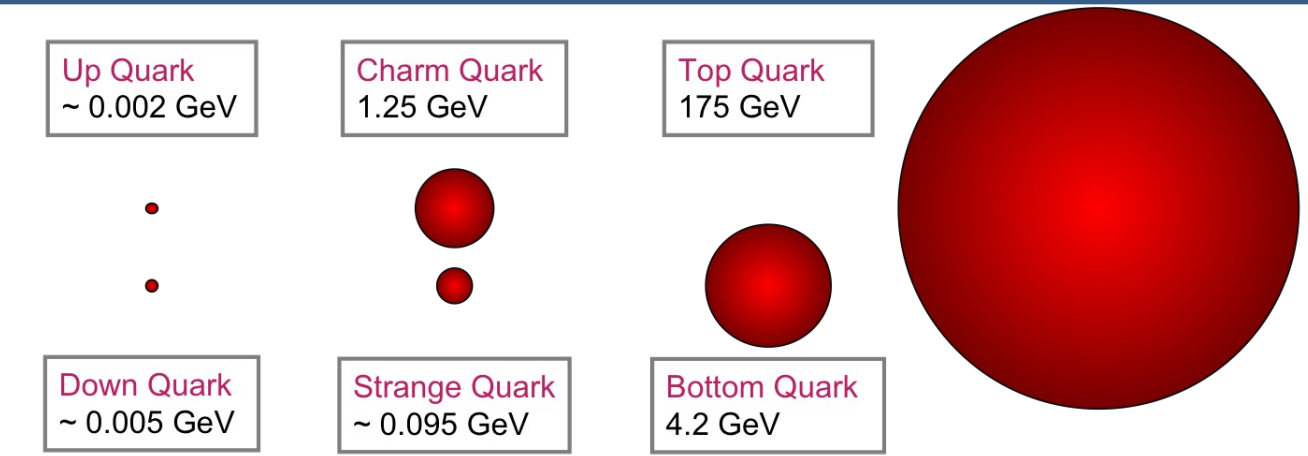
massa = energia

La Massa delle Particelle

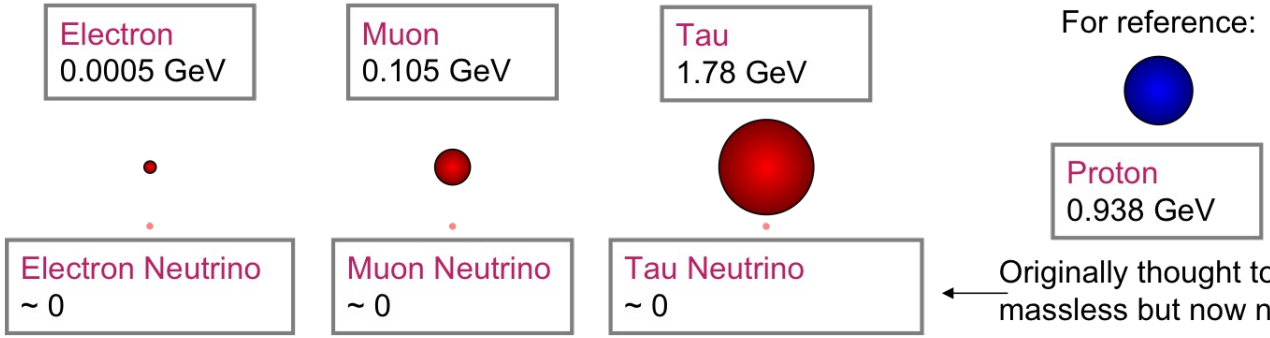
Per noi oggi la massa è una proprietà intrinseca delle particelle:

massa = energia di una particella a riposo

Particelle di un certo peso!



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

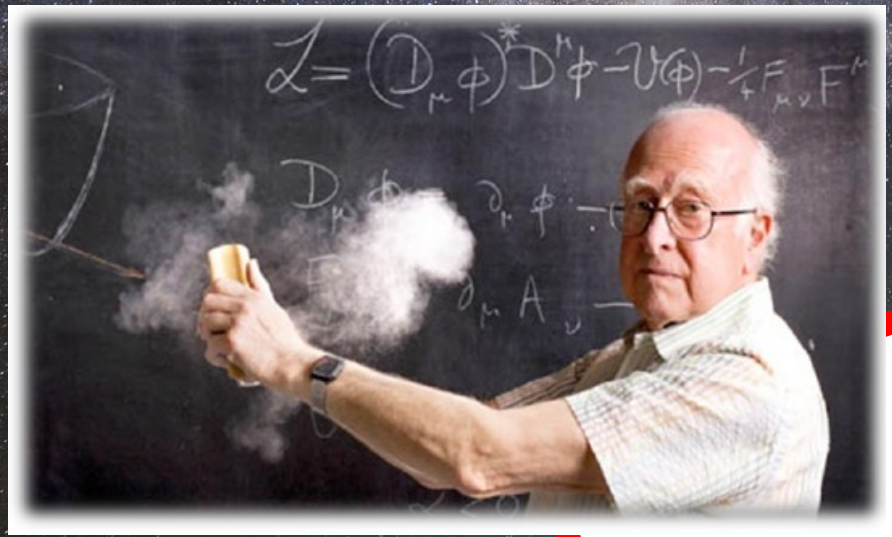


L'idea di Prof. Higgs

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

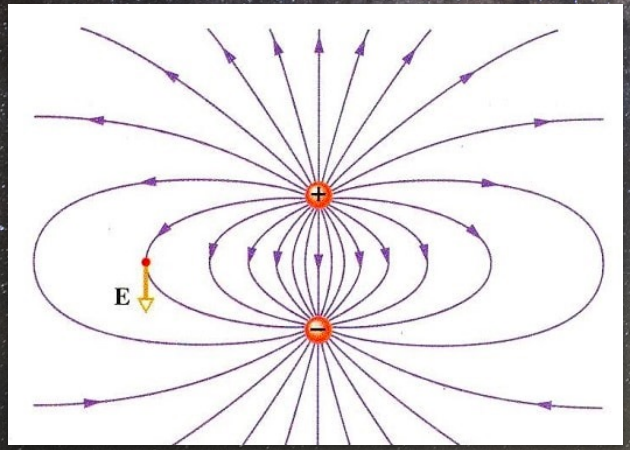


Idea chiave:

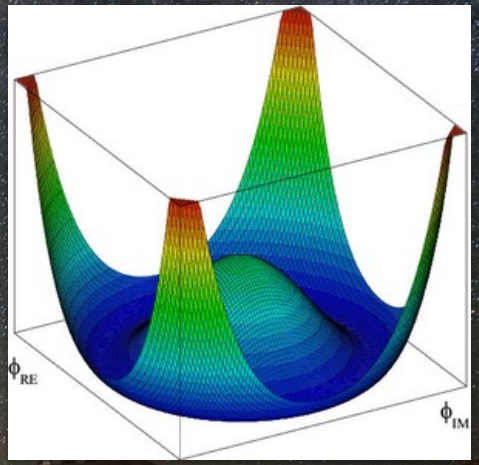
Il campo di Higgs si incolla alle particelle e crea la loro massa

Campi e Particelle

Il **campo elettrico** ha una direzione.



Il **campo di Higgs** è uno scalare.

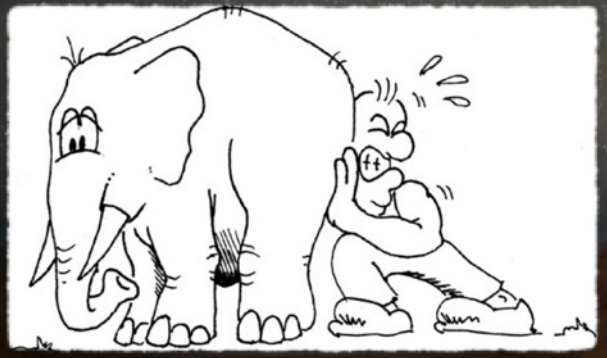


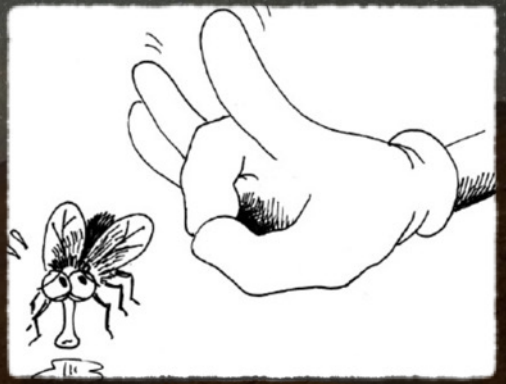
Il **fotone** è la “prova” del campo elettromagnetico.

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"**

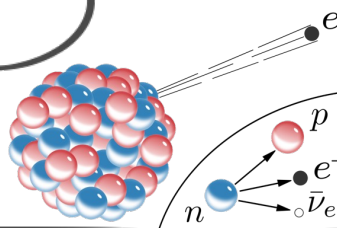


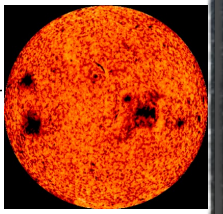


Fant4stic four

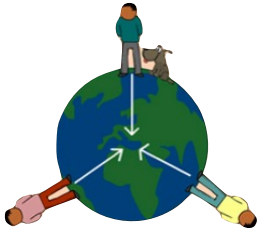
Weak (I=10^{-3})

Electromagnetic (I=1)

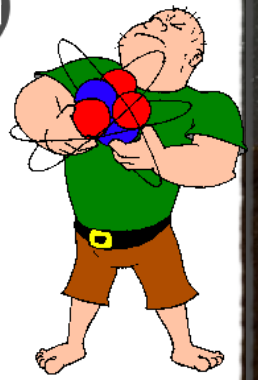




Gravitational (I=10^{-36})



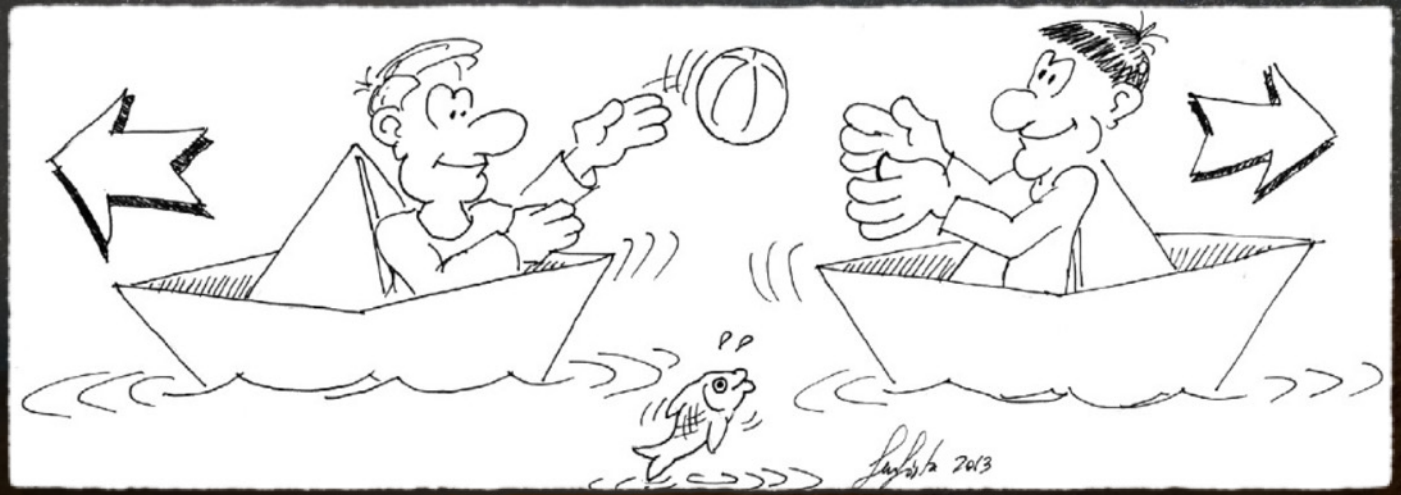
Strong (I=100)



Forze: scambio di particelle

- Le forze tra componenti di materia sono dovute allo **scambio di altre particelle, i bosoni mediatori**

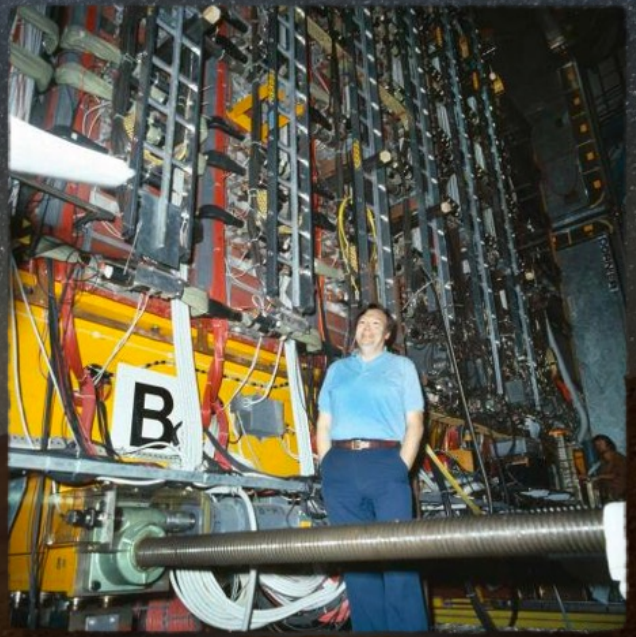
- Questi bosoni sono come palle da basket lanciate tra barchette



Forze: scambio di particelle

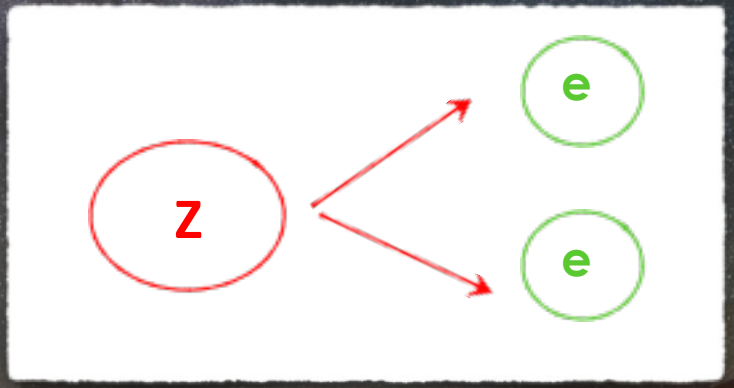
- **Bosone Z predetto nel 1960** per spiegare i decadimenti beta di Fermi

- 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



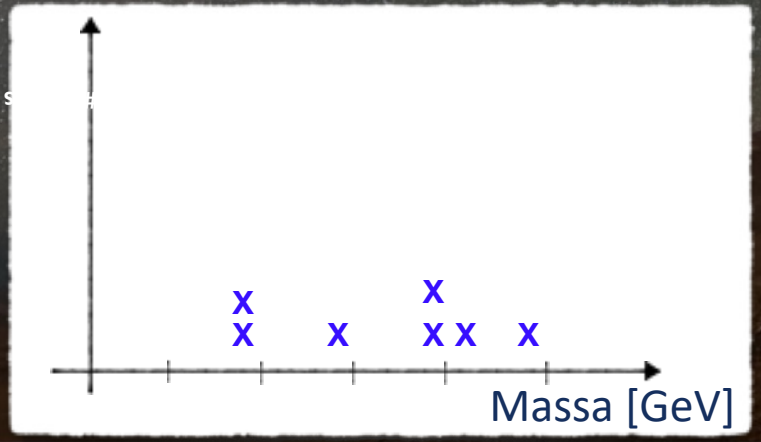
- Quando produciamo una Z in realta` nell'esperimento vediamo due elettroni!

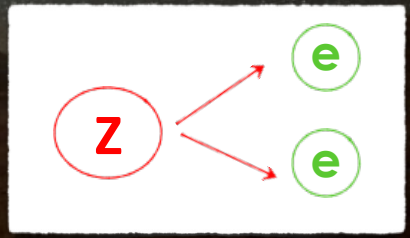
Il bosone Zeta

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

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

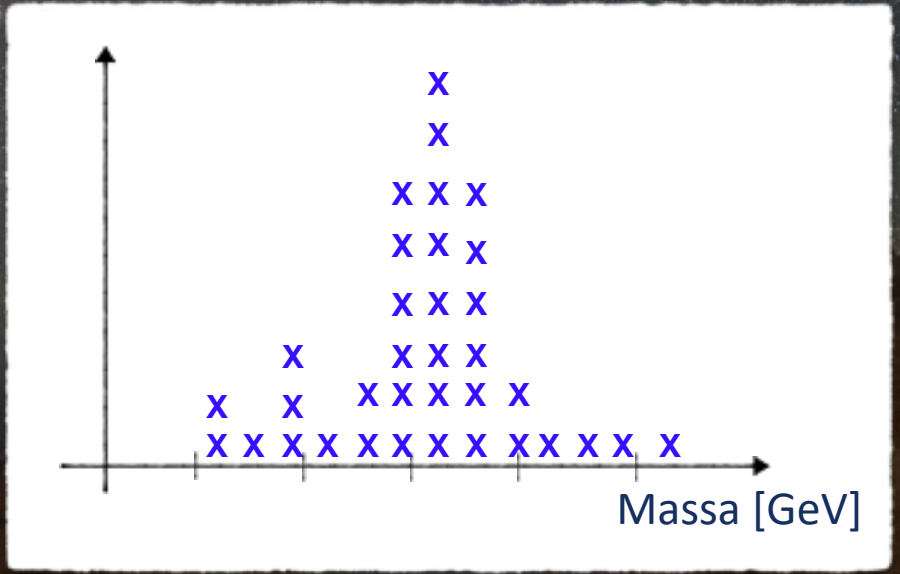
- Ripetiamo per ogni evento (collisione) in cui vediamo due elettroni e riempiamo un istogramma:





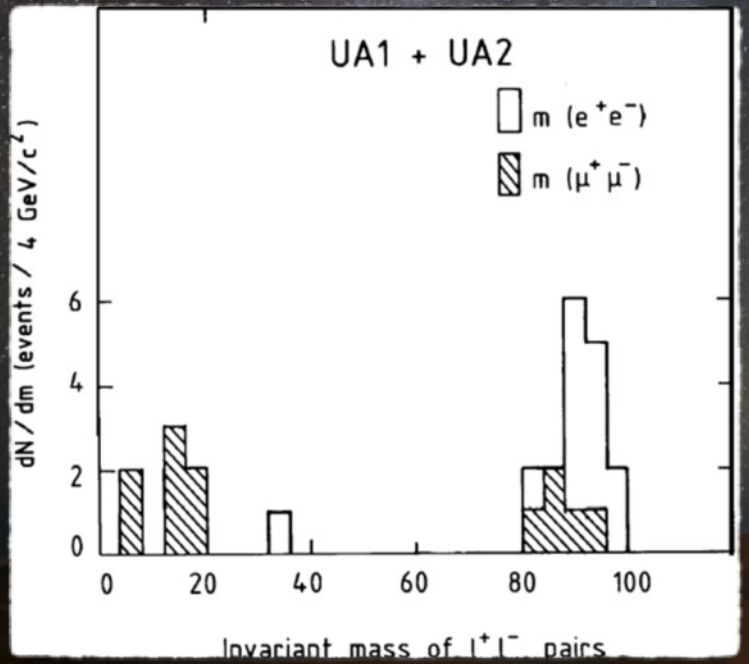
Il bosone Zeta: la sua massa

- 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



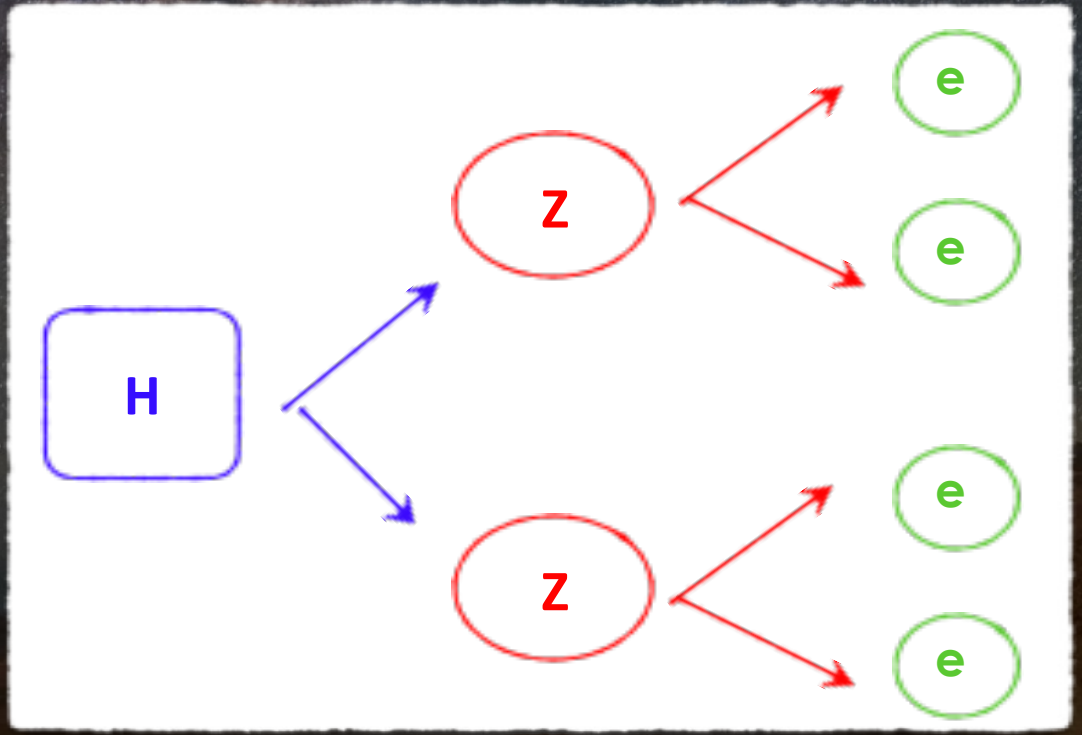
Il nobel di Rubbia

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



Il bosone Zeta e l'Higgs

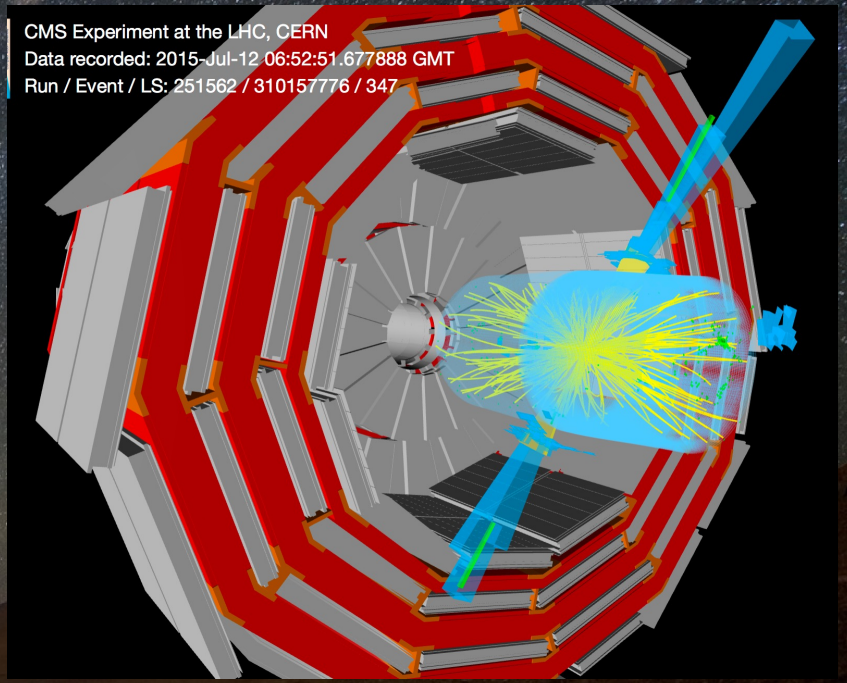
- Il bosone Z "ci serve" per cercare il bosone di Higgs:



Microscopi Potentissimi

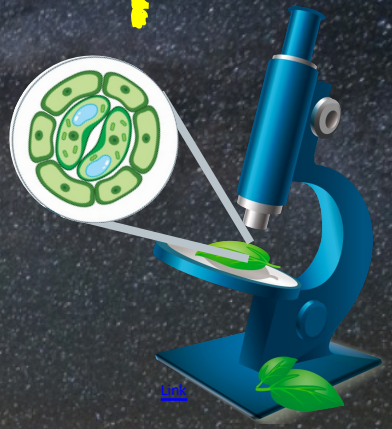
La **dimensione** che riesco a investigare e` **proporzionale a 1/E**

E = energia della mia “sonda”



Vedere l'infinitamente piccolo

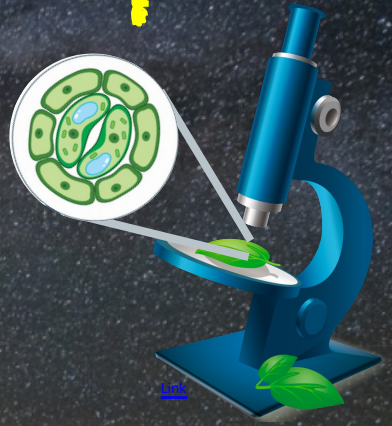
Cellula (d~10^{-5} m): luce visibile E ~eV

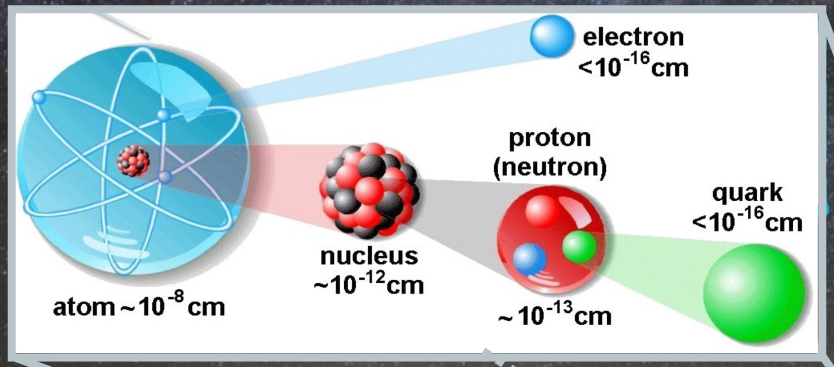


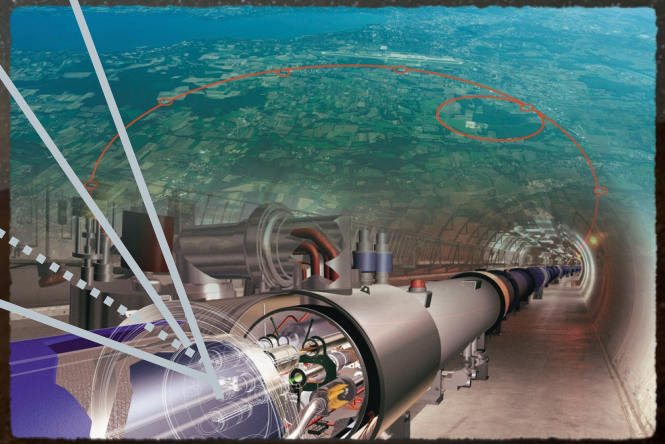
d ↘ E ↗

Vedere l'infinitamente piccolo

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







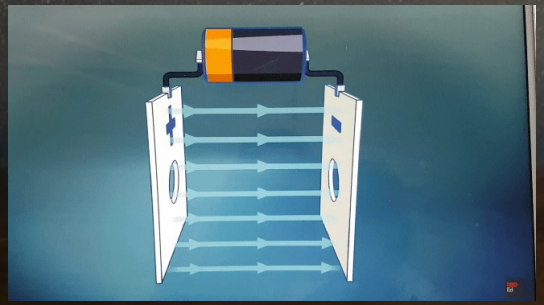
Quark (d~10^{-18} m): LHC E ~TeV

La fisica base degli acceleratori

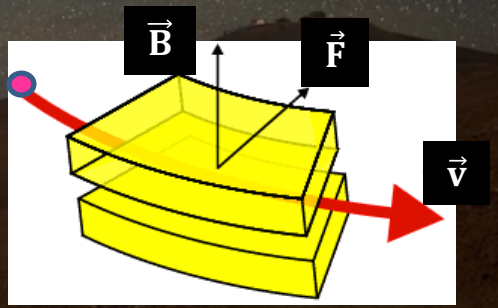
$$\vec{F} = q \cdot (\vec{E} + \vec{v} \times \vec{B})$$

Forza di Lorentz

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

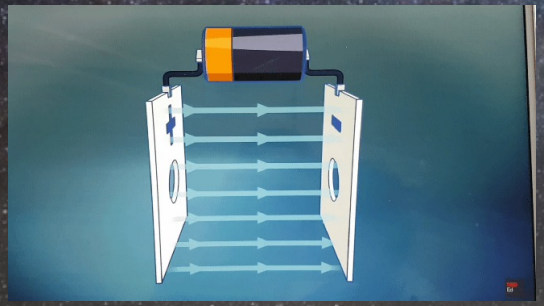


Effetto di un campo magnetico su una particella carica → la particella curva



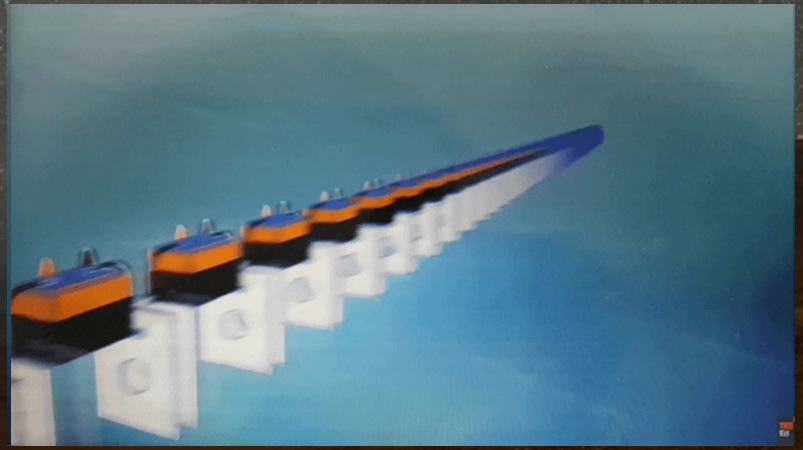
Courtesy of F. Cavallari

Il limite di un acceleratore lineare



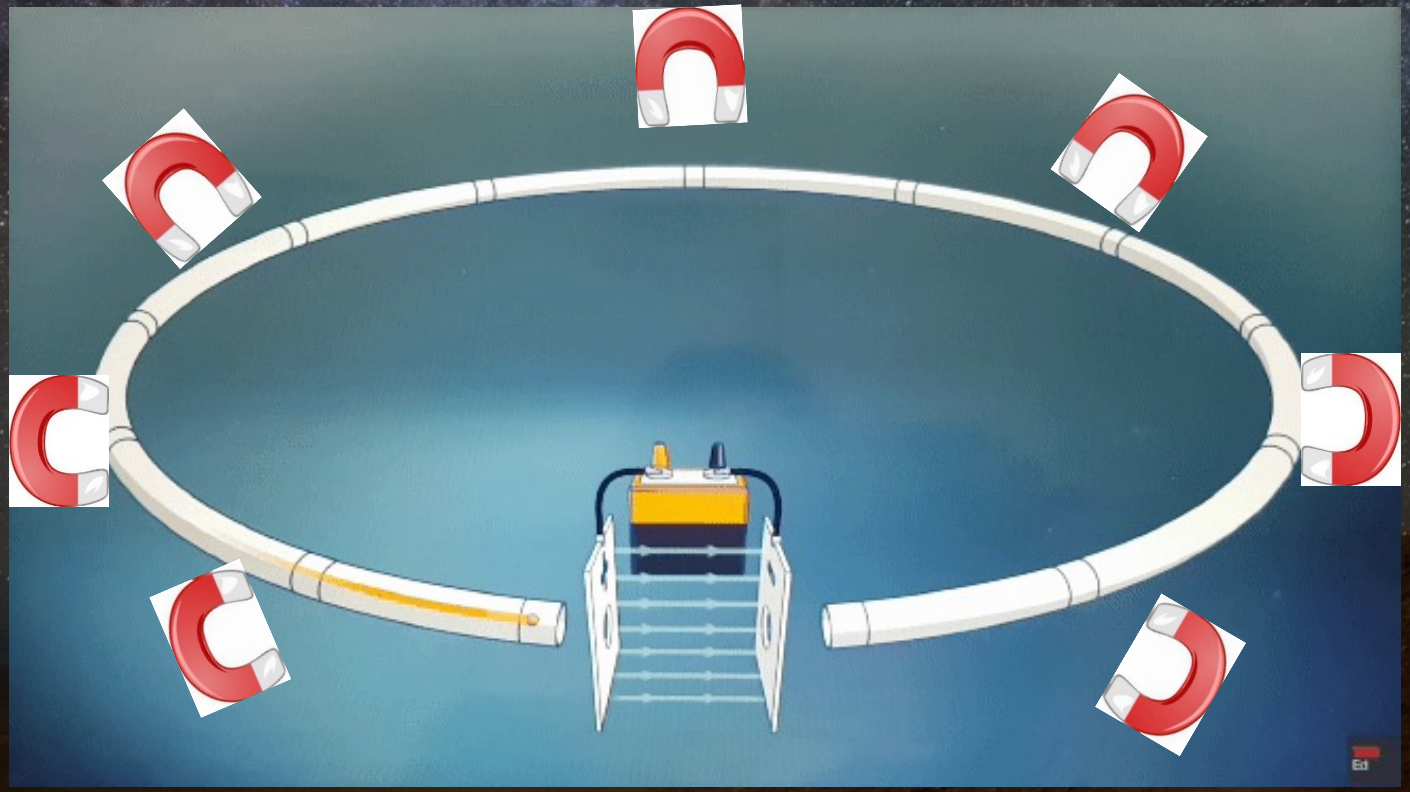
Energia protoni LHC= 7 TeV →

servono 5 triliardi di pile da 1.5V



Courtesy of F. Cavallari

Acceleratore circolare



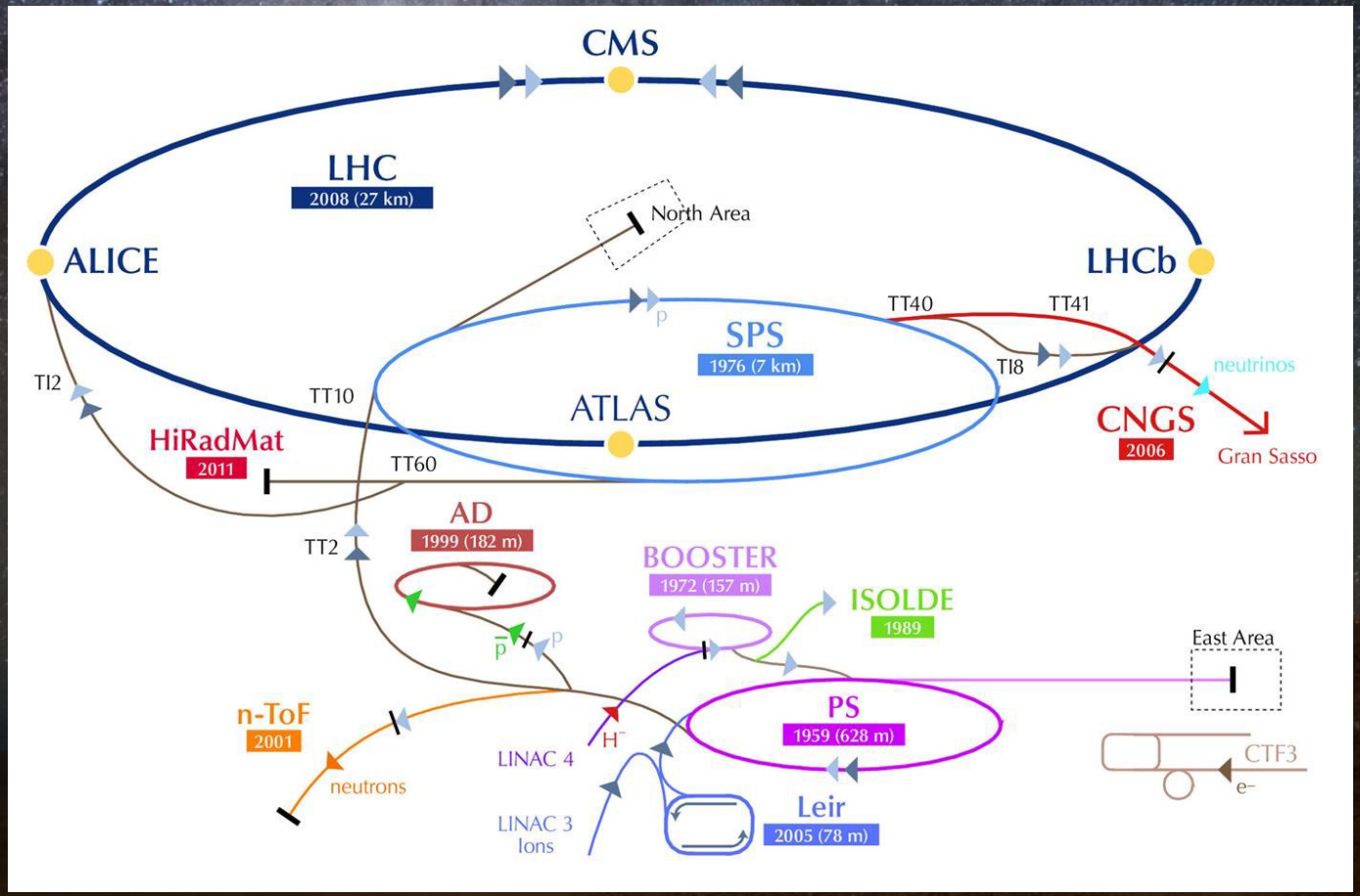
Courtesy of F. Cavallari

AdA (Frascati 1961)

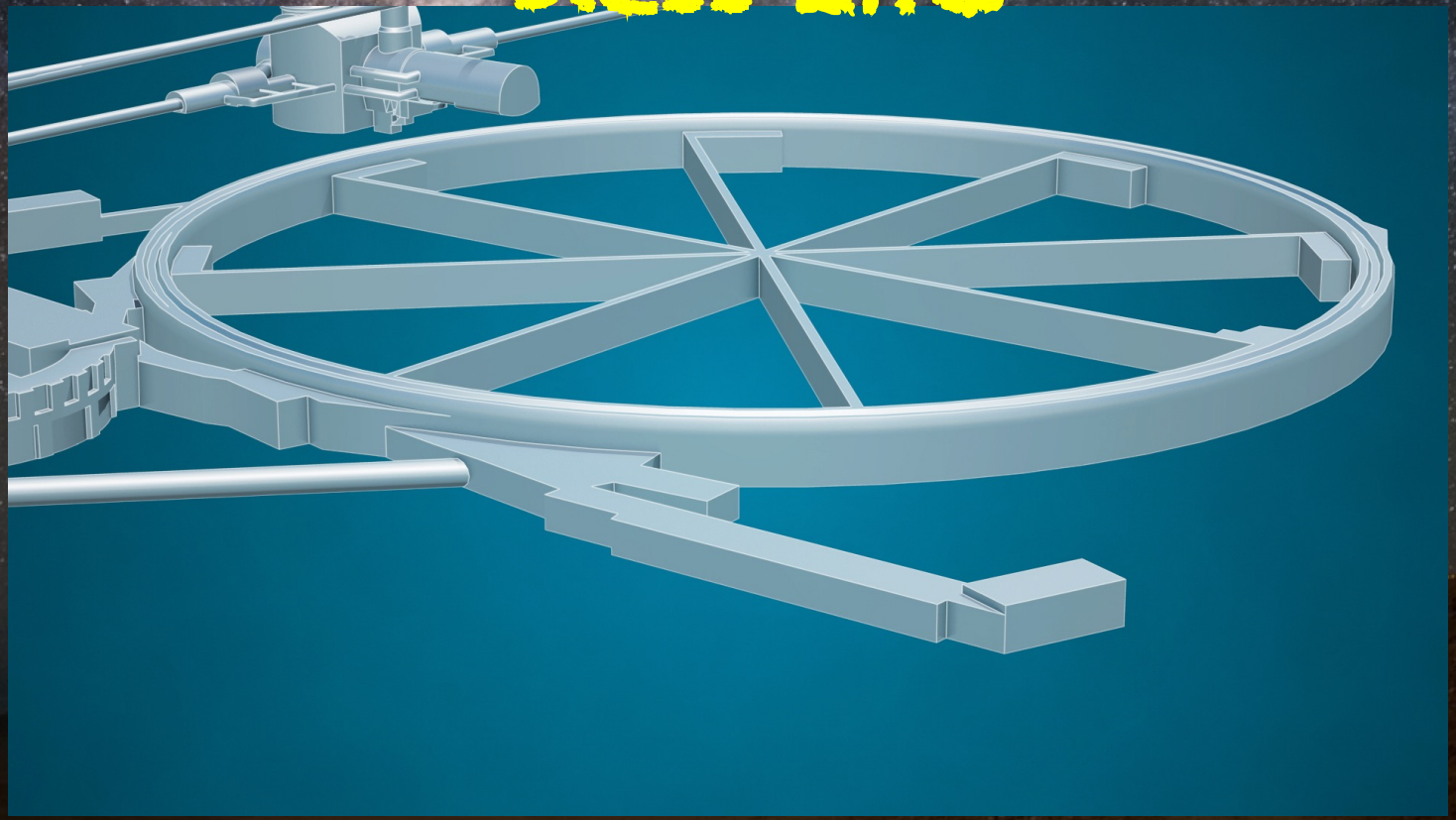
Courtesy of F. Cavallari

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

Gli acceleratori del CERN



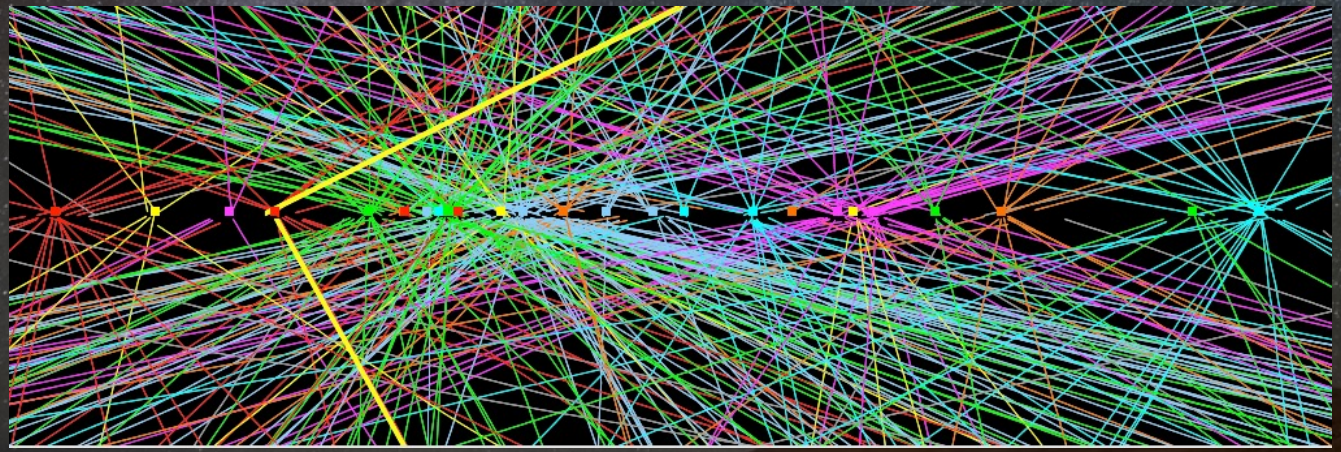
Sorgente di particelle dell'LHC



Courtesy of F. Cavallari

Le Collisioni nel LHC

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

Courtesy of F. Cavallari

Un grande laboratorio europeo: il CERN

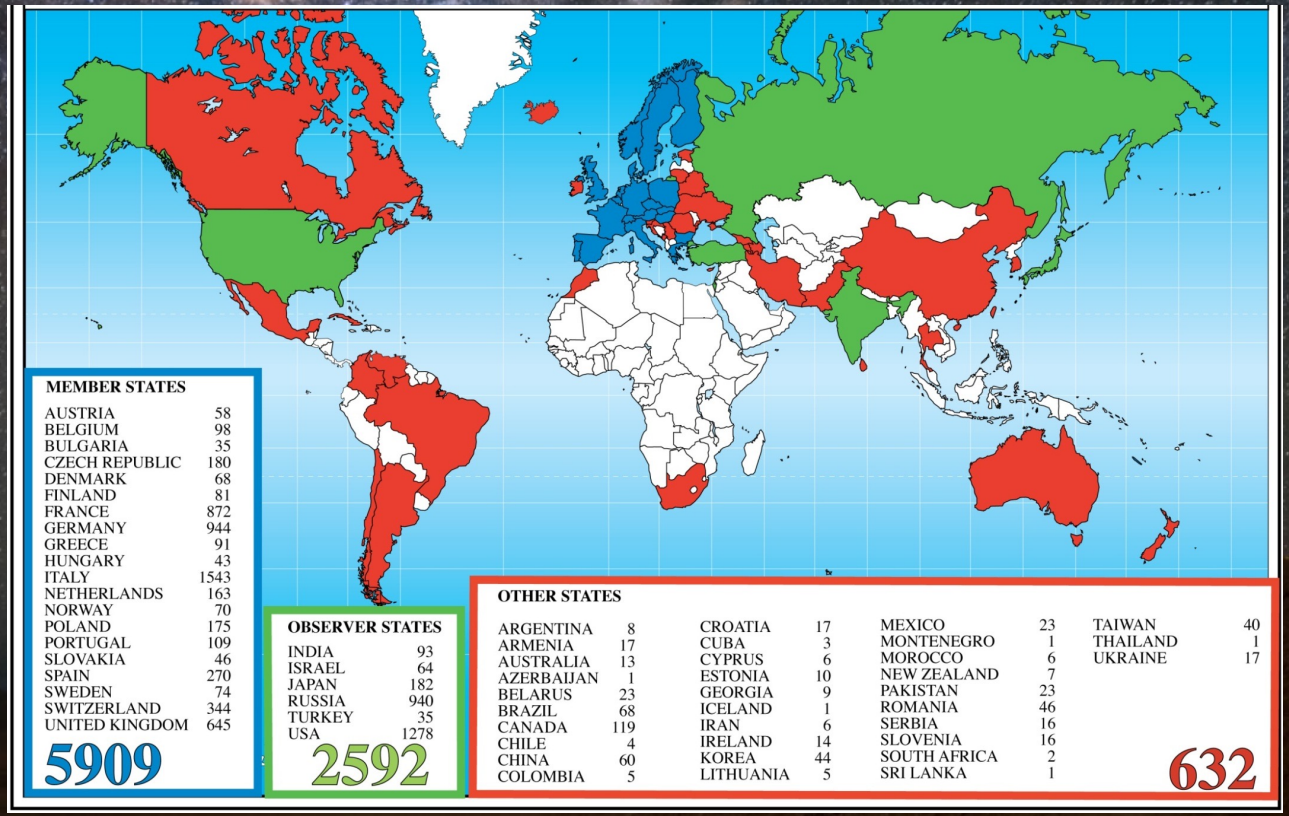
Nel 1954 12 paesi europei tra cui l'Italia costituiscono il CERN (organizzazione europea per la ricerca nucleare)

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:
Edoardo Amaldi, Carlo Rubbia, Luciano Maiani e Fabiola Gianotti (2)

Courtesy of F. Cavallari

Gli scienziati che lavorano al CERN



Courtesy of F. Cavallari

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

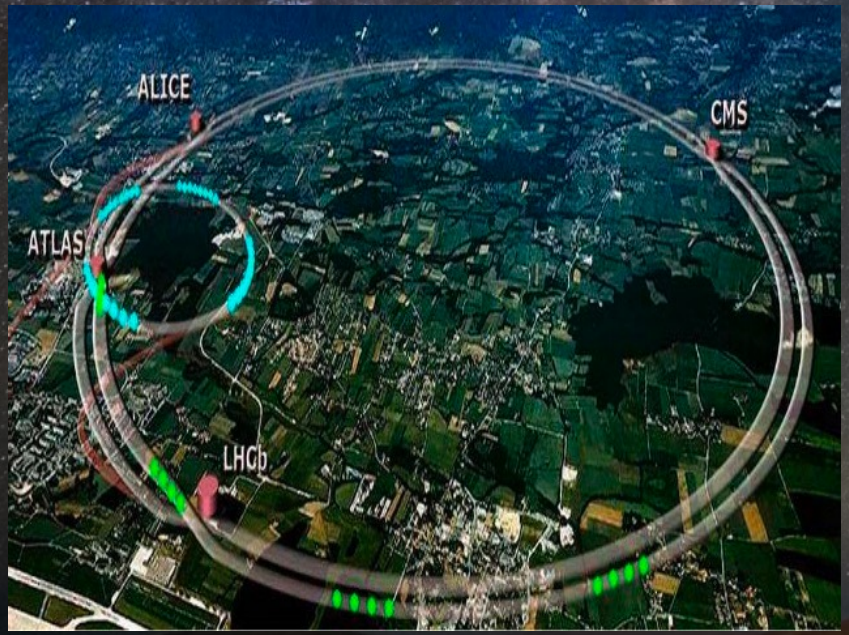
Il Large Hadron Collider LHC

→ Lungo 27 km

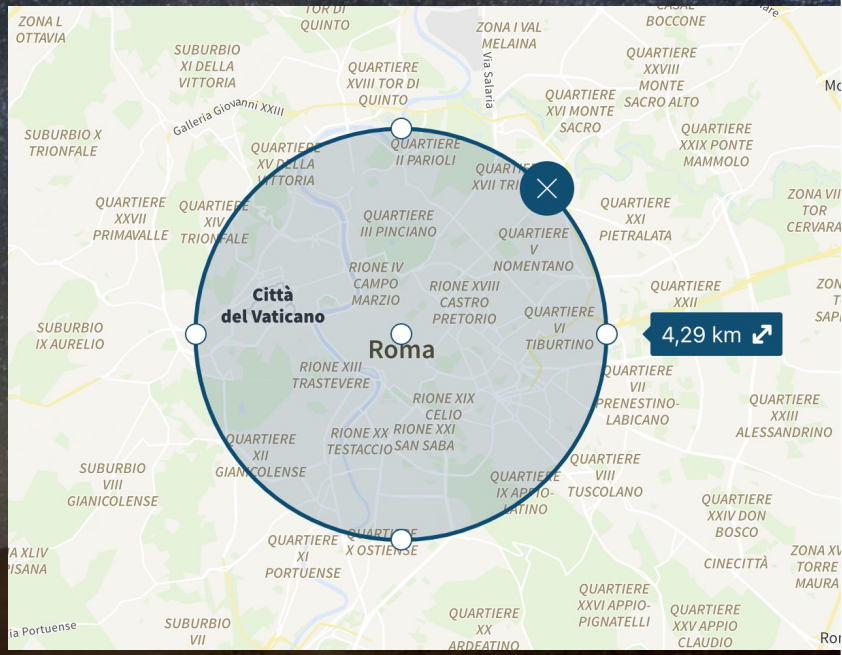
→ Posto a 100m di profondità` sottoterra

Il Large Hadron Collider LHC

→ Lungo 27 km



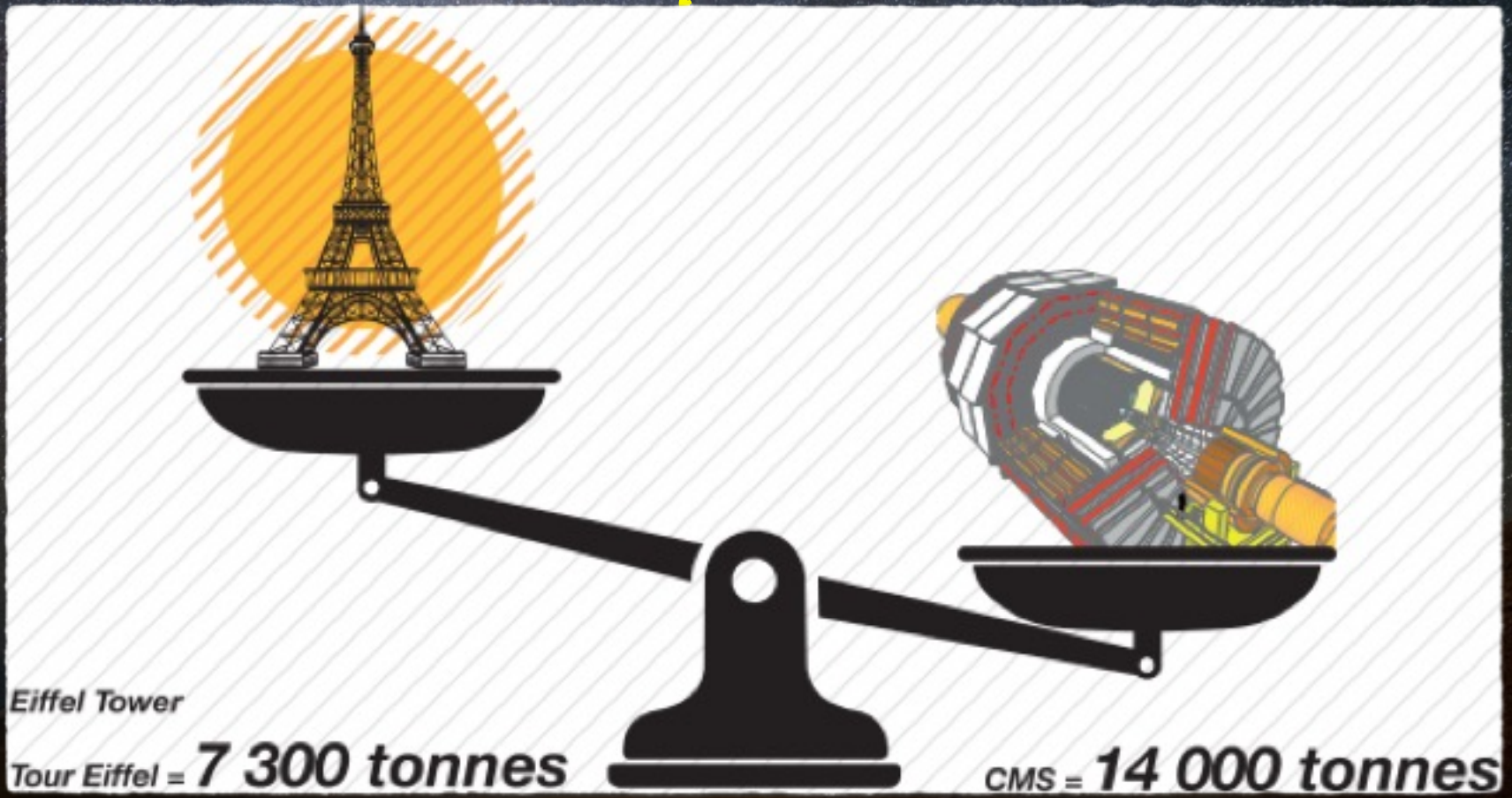
≈



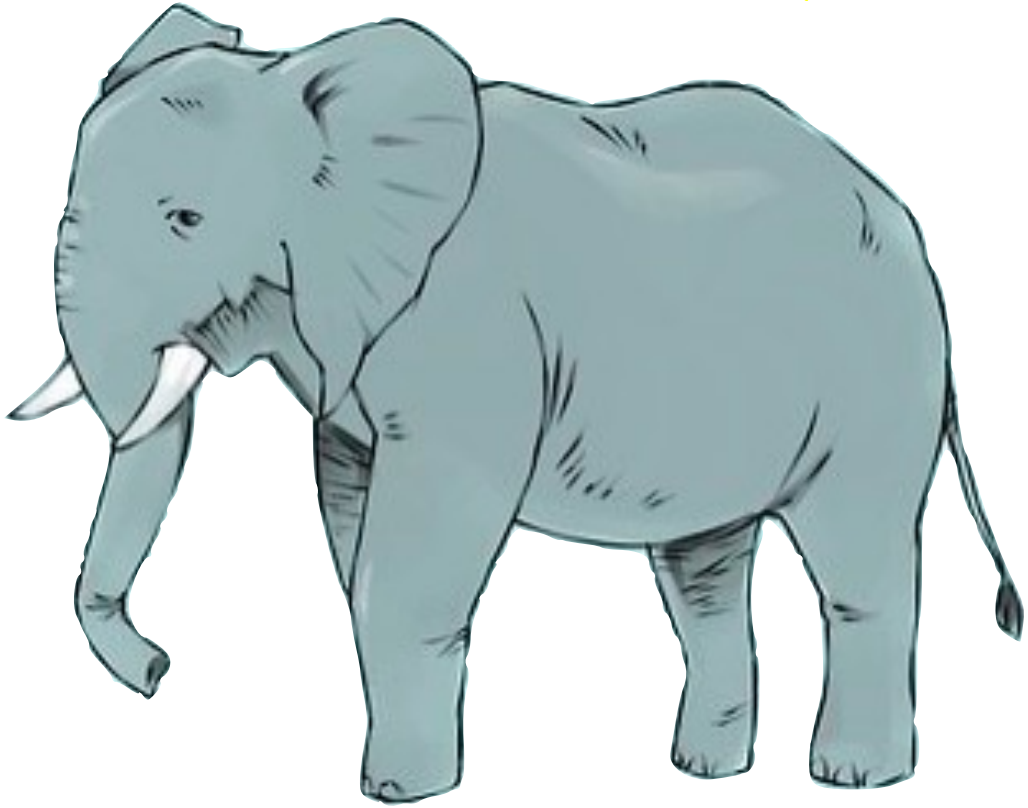
L'esperimento CMS @ LHC

L'esperimento CMS @ LHC

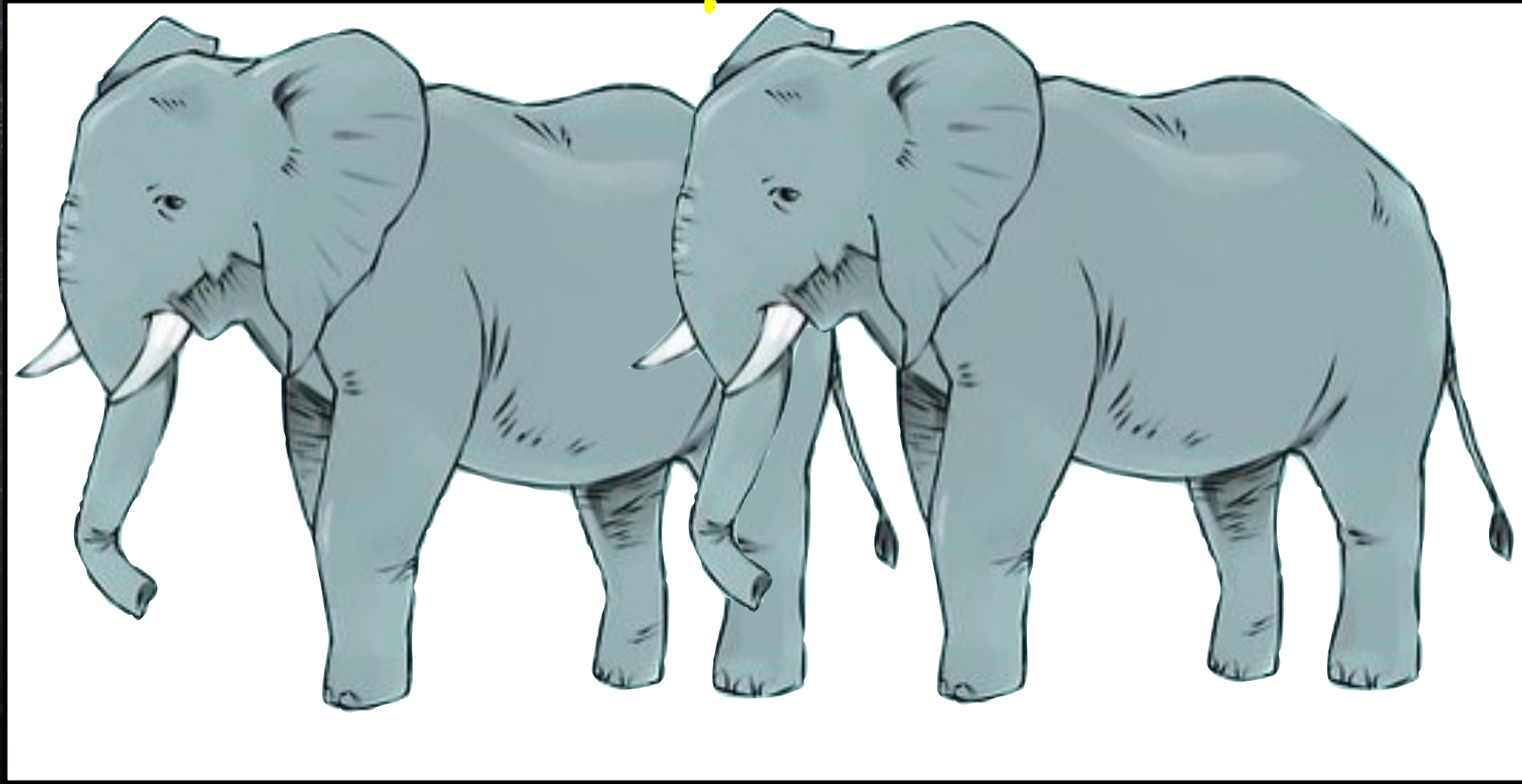
Quanto pesa CMS?



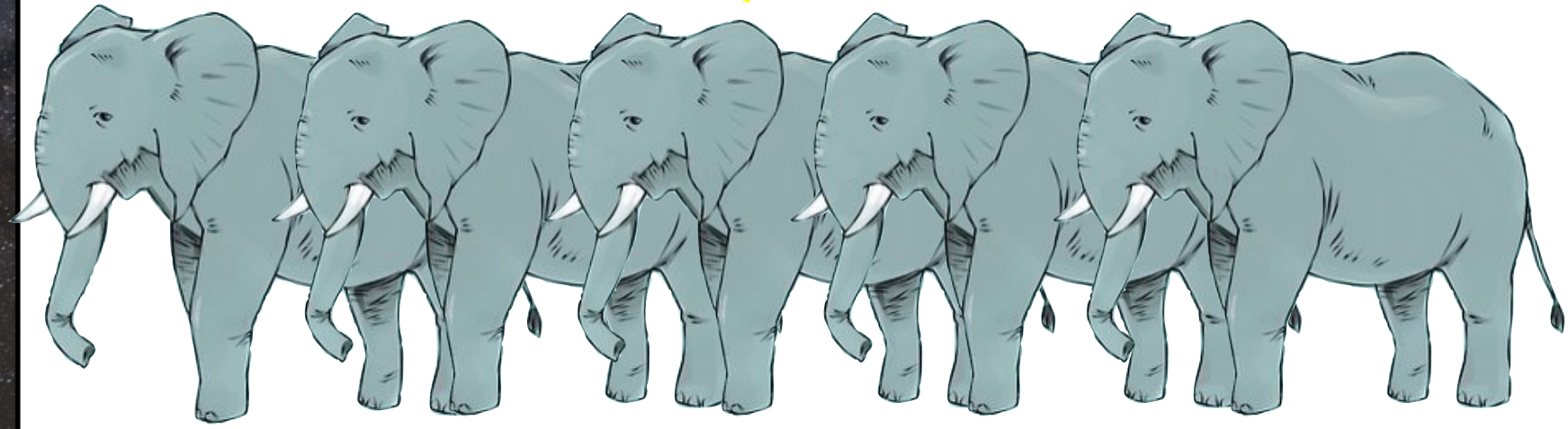
Quanto pesa CMS?



Quanto pesa CMS?



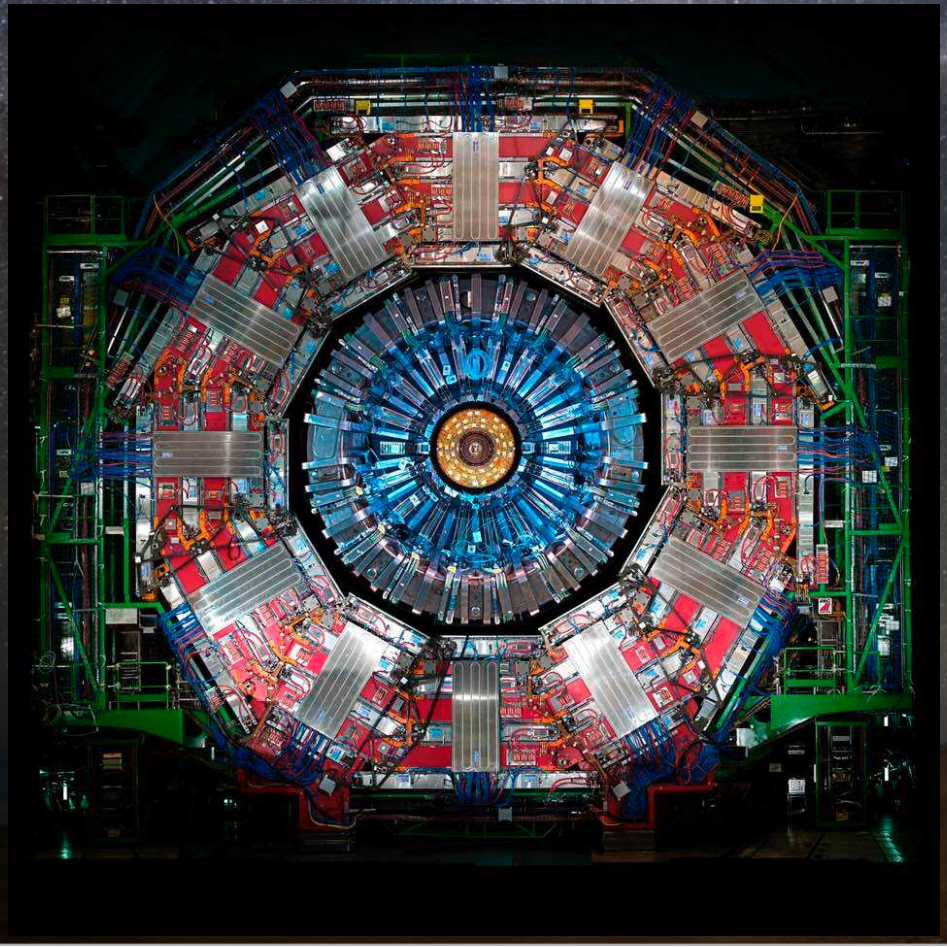
Quanto pesa CMS?



Quanto pesa CMS?

CMS pesa come 14000 elefanti!

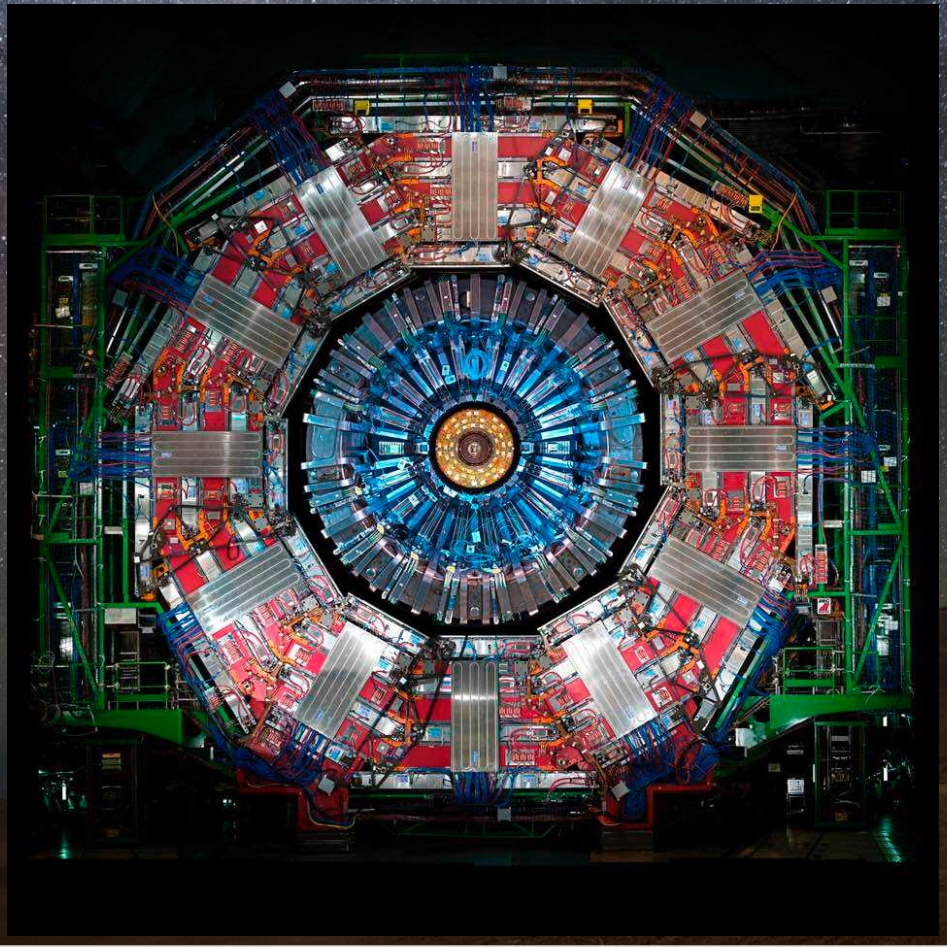
Una macchina fotografica gigante!



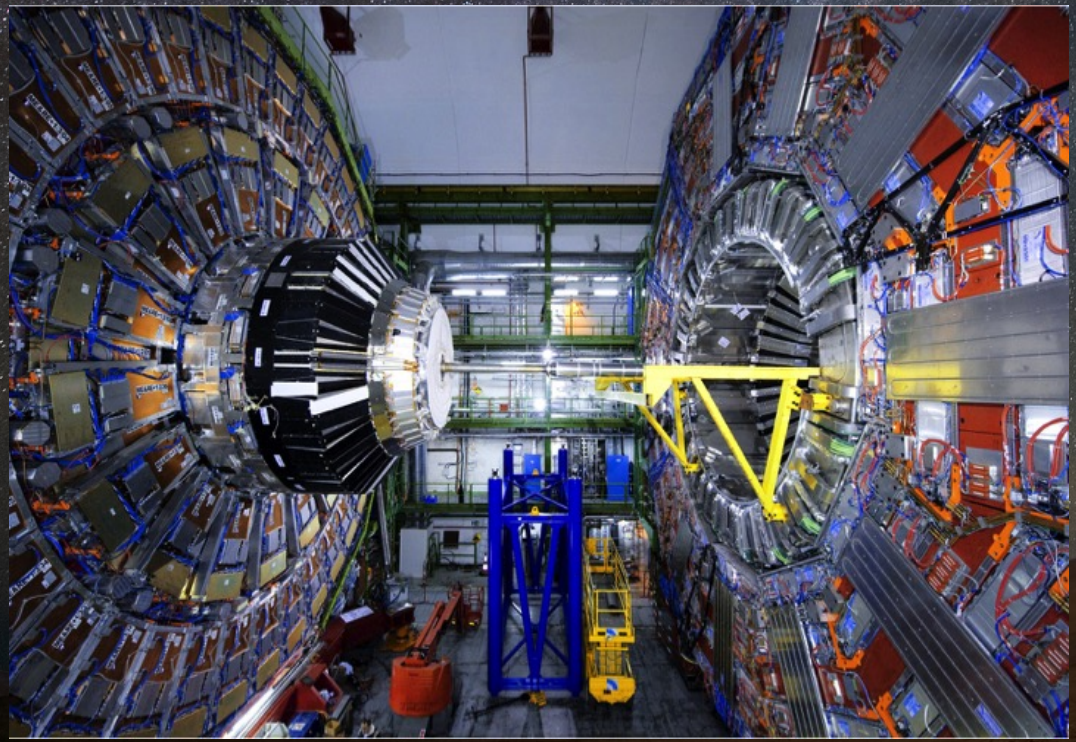
≈

Link

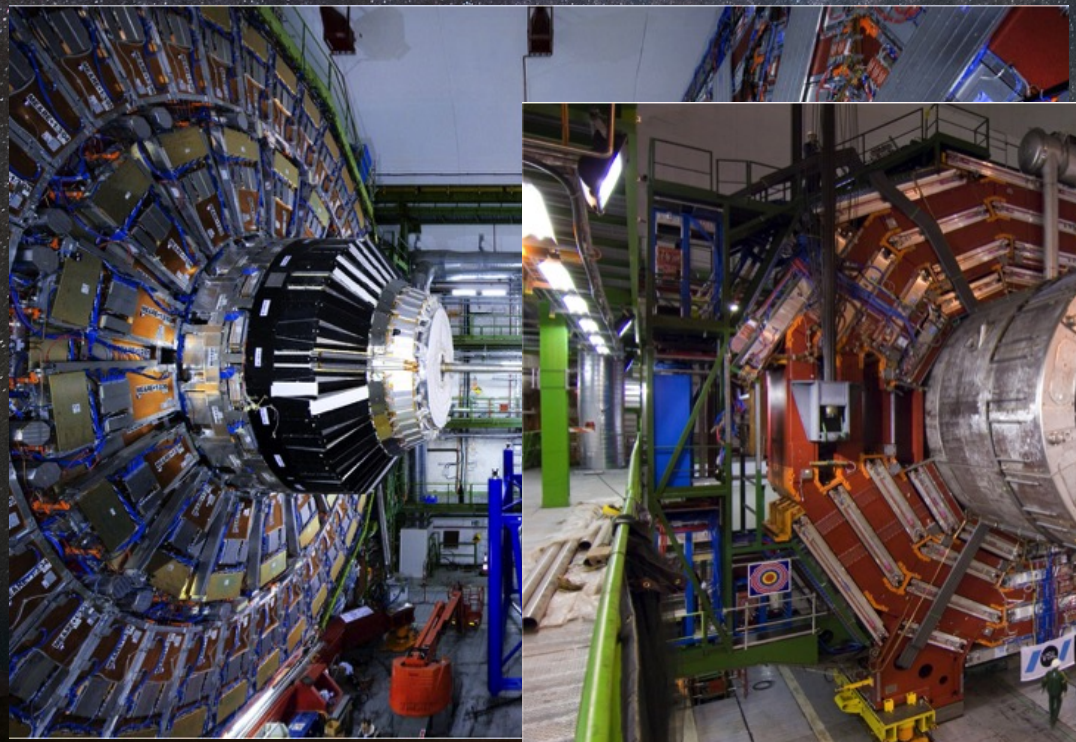
L'esperimento CMS @ LHC

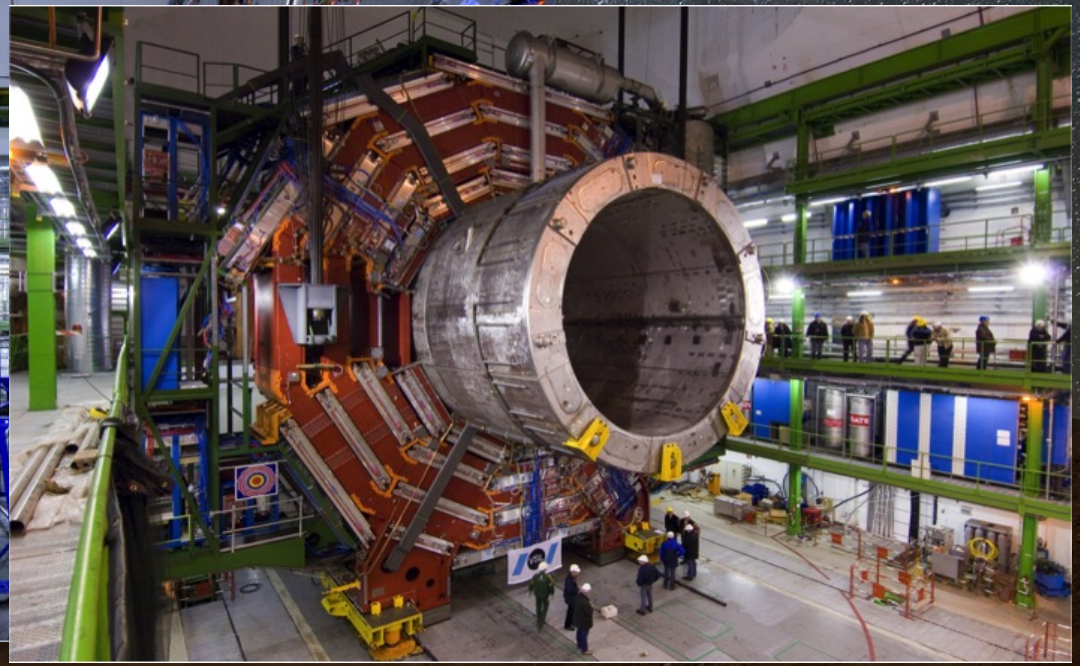


La costruzione di CMS

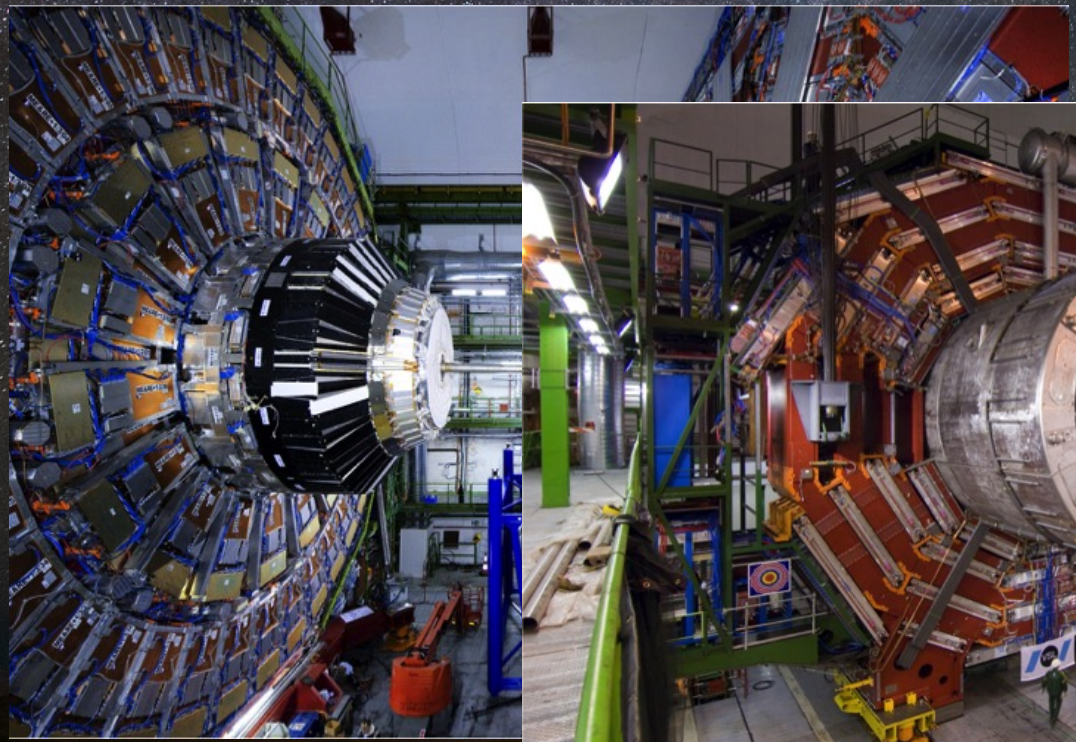


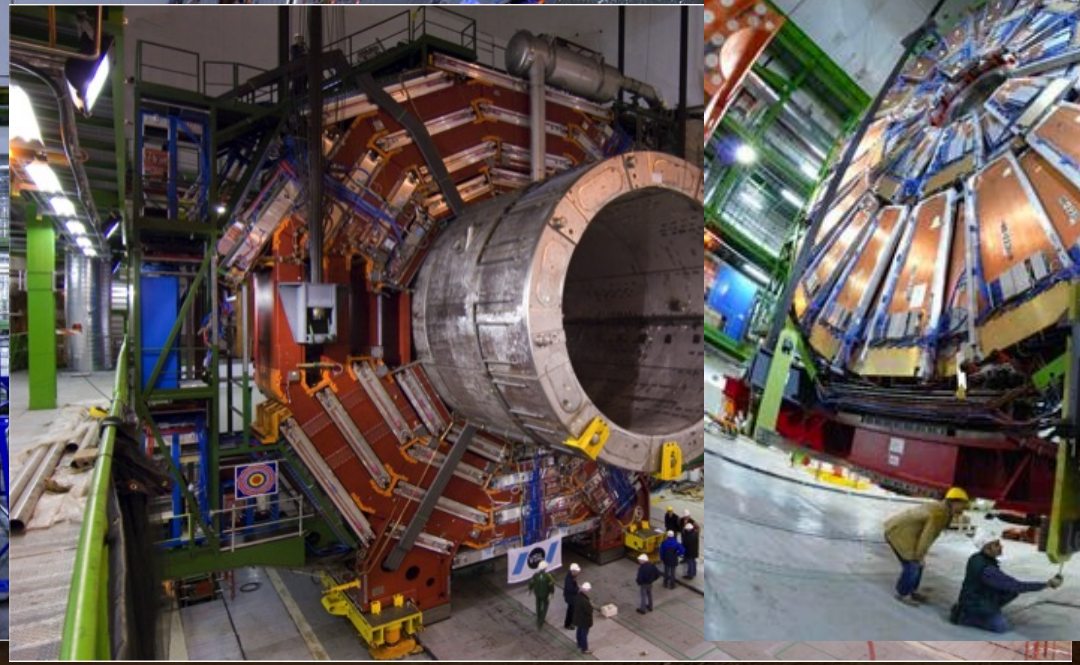
La costruzione di CMS



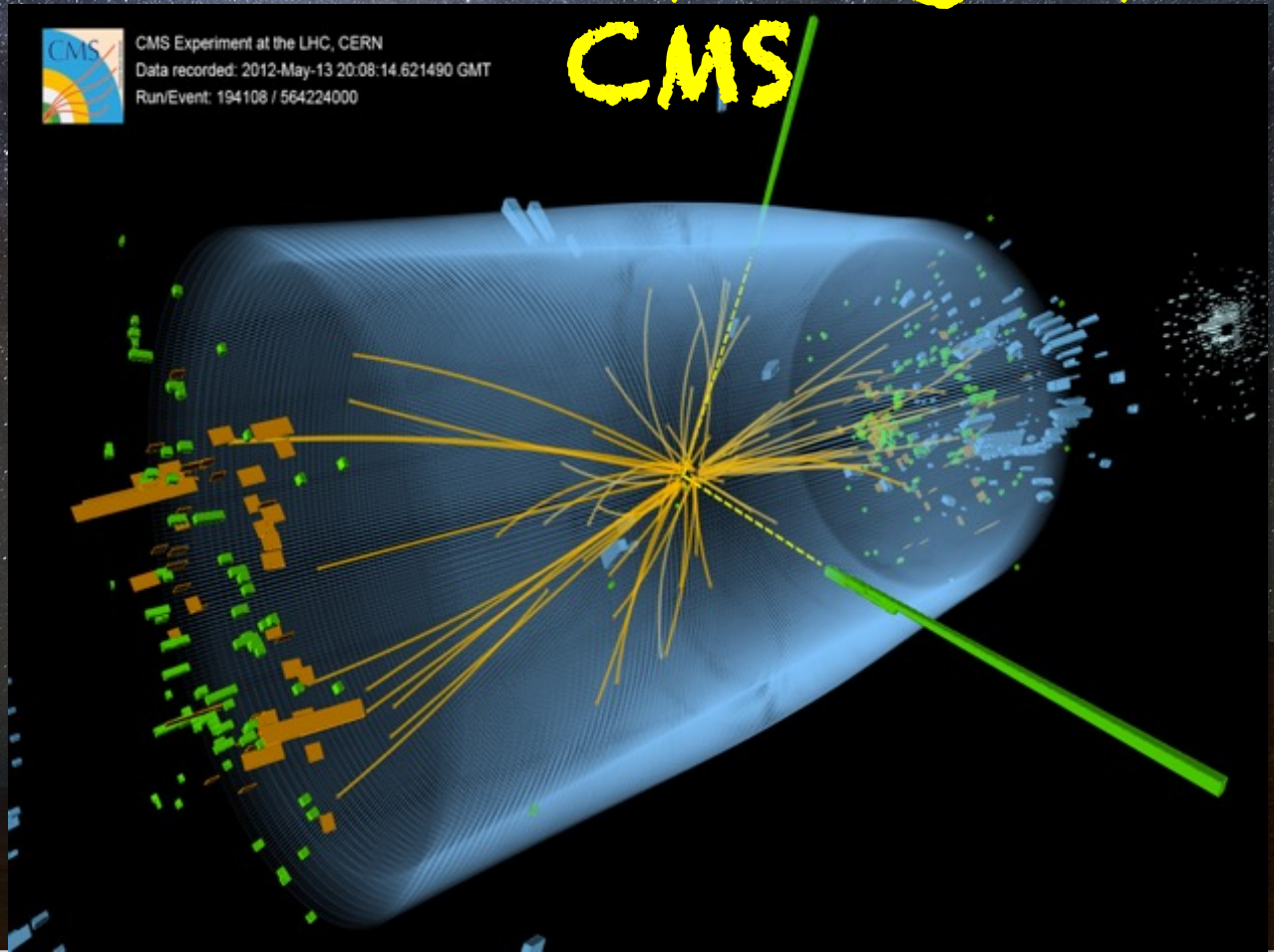


La costruzione di CMS





Le Collisioni fotografate da CMS

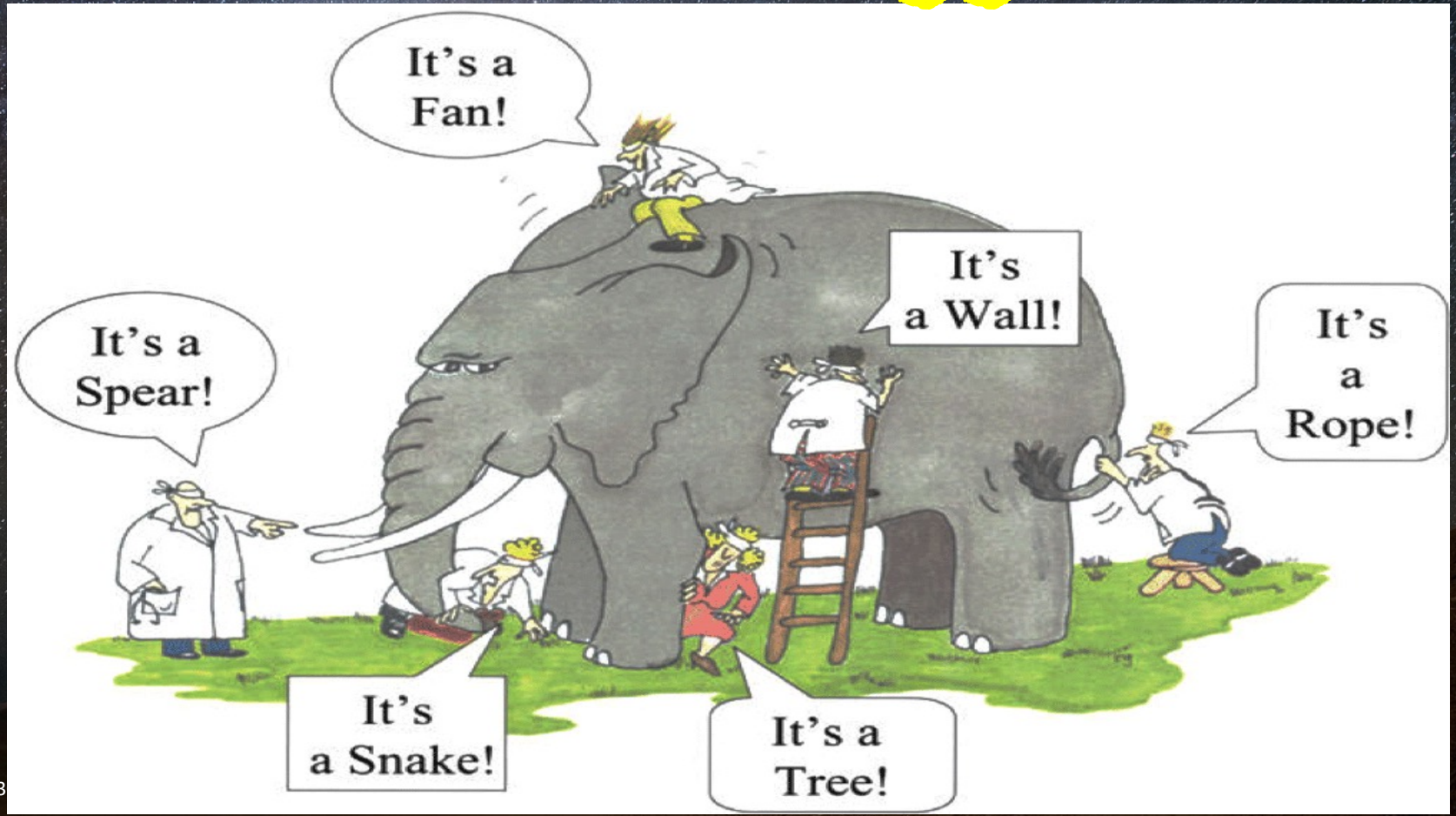


Cosa c'e' oltre l'Higgs?

Cosa c'e' oltre l'Higgs?

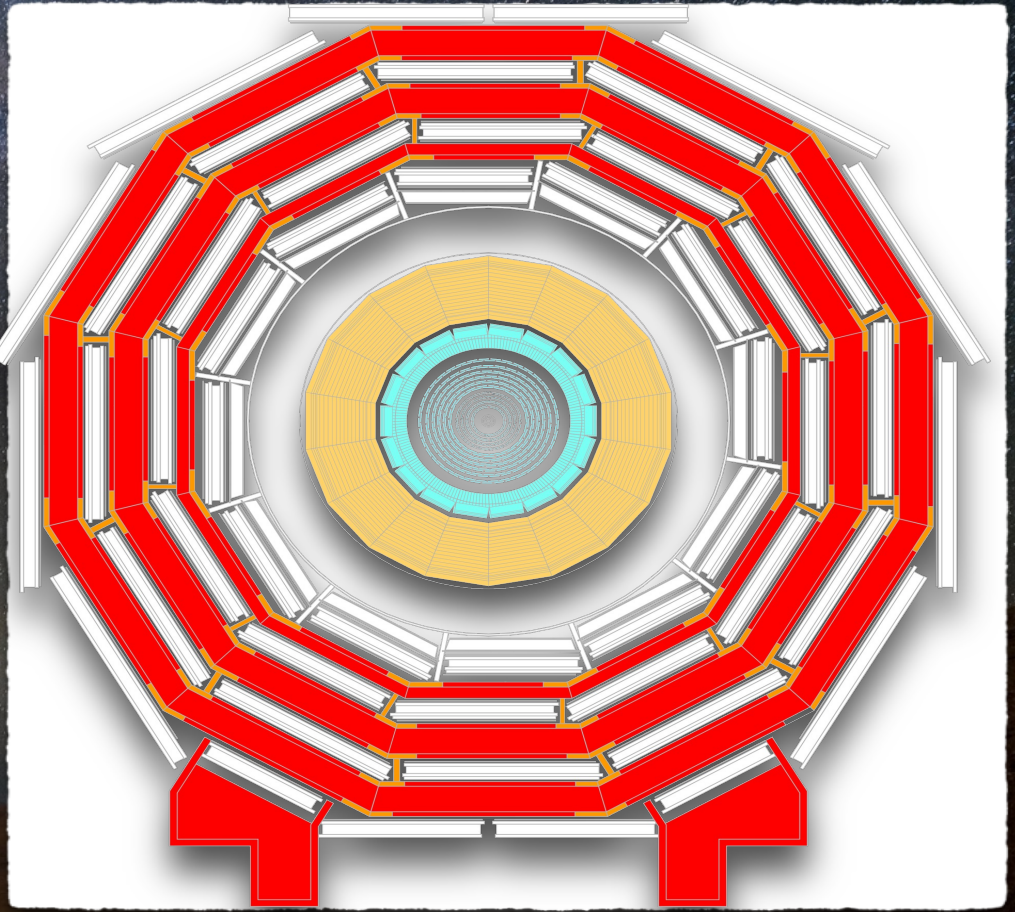
Cosa c'e' oltre l'Higgs?

Cosa c'e' oltre l'Higgs?



Come si cerca la nuova fisica?

Processo noto:



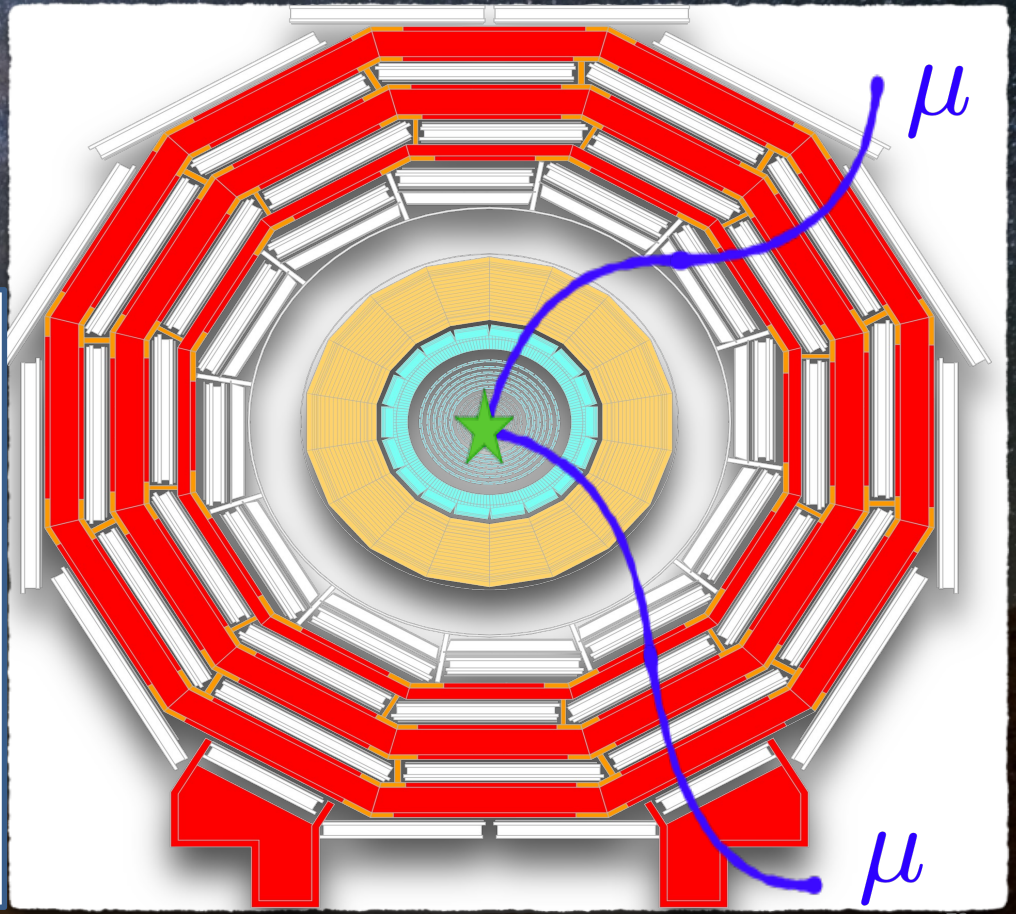
Come si cerca la nuova fisica?

Processo noto:

$$Z \rightarrow \mu\mu$$

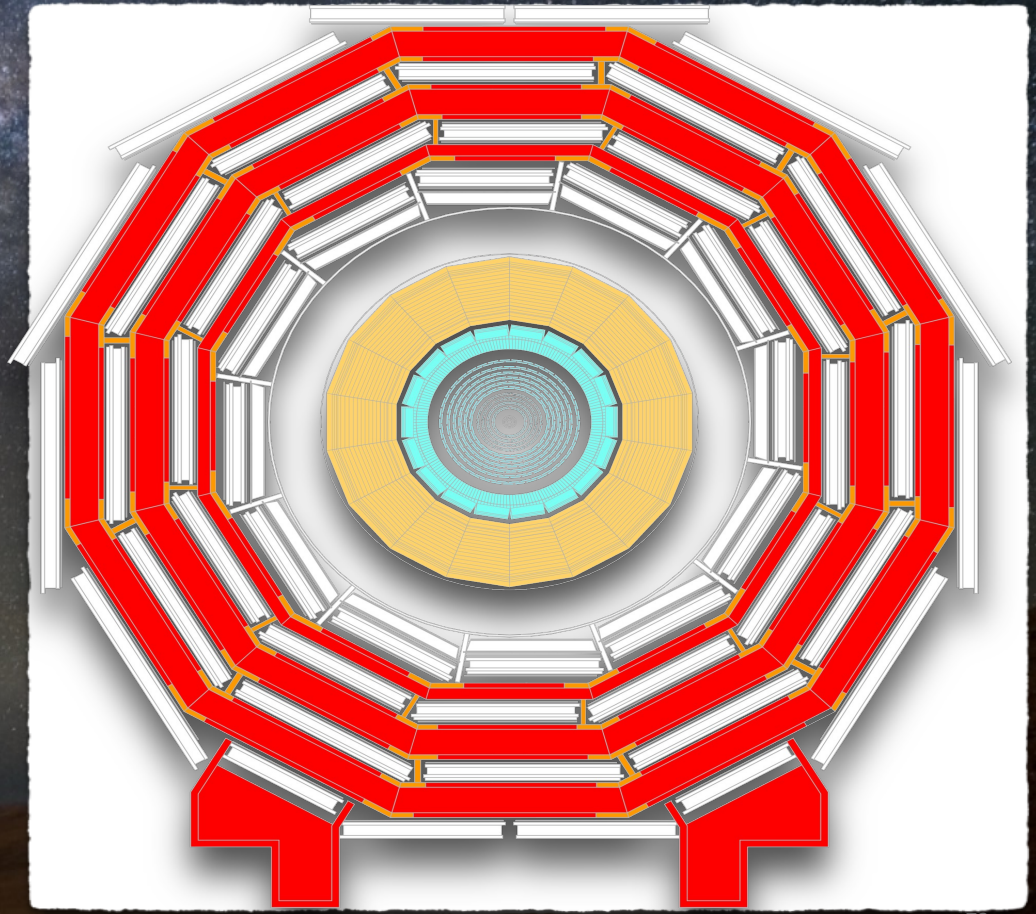
Z

si disintegra **instantaneamente** in **due muoni**!



Come si cerca la nuova fisica?

Processo nuovo:



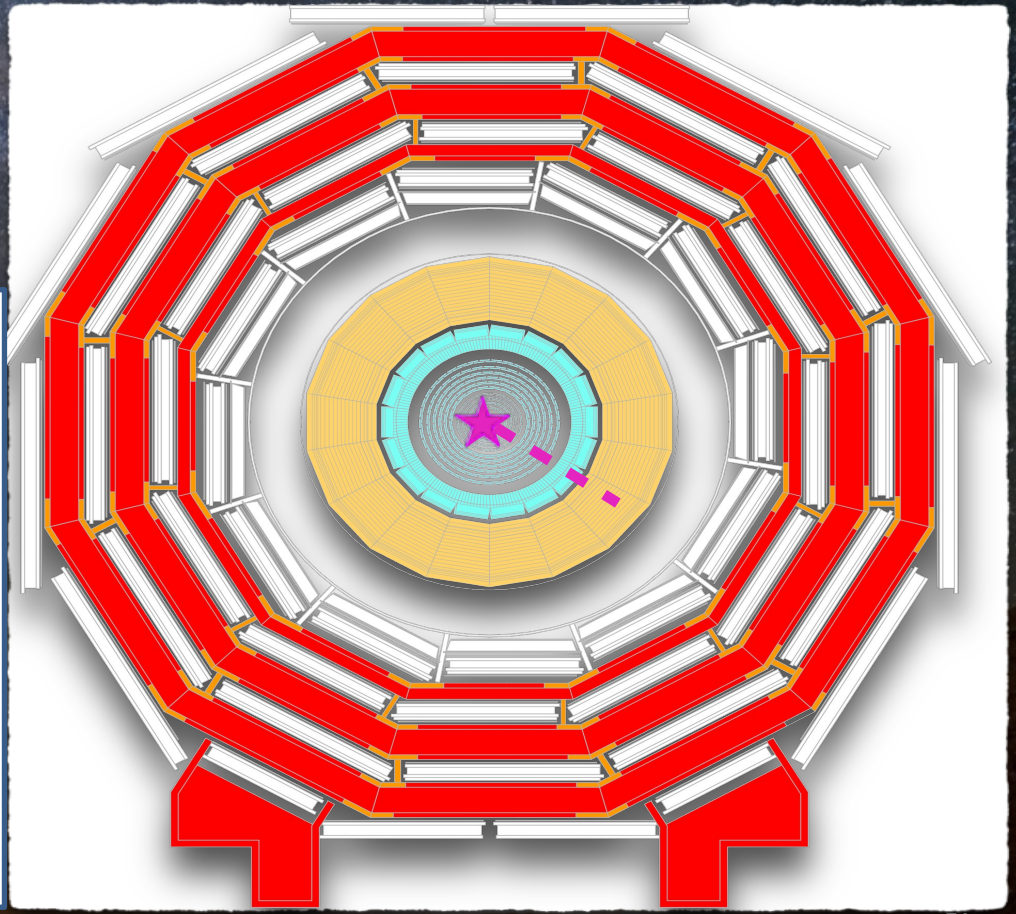
Come si cerca la nuova fisica?

Processo nuovo:

$$X \rightarrow \mu\mu$$

x

cammina un po` nel rivelatore

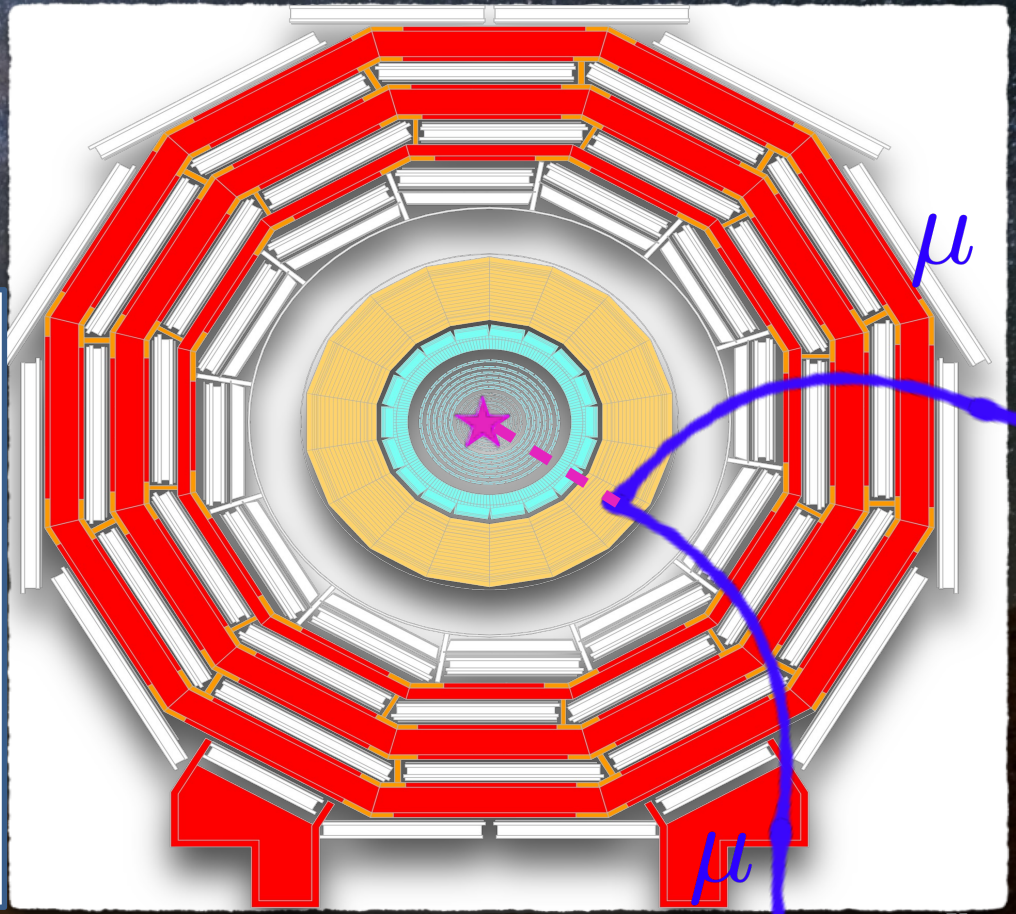


Come si cerca la nuova fisica?

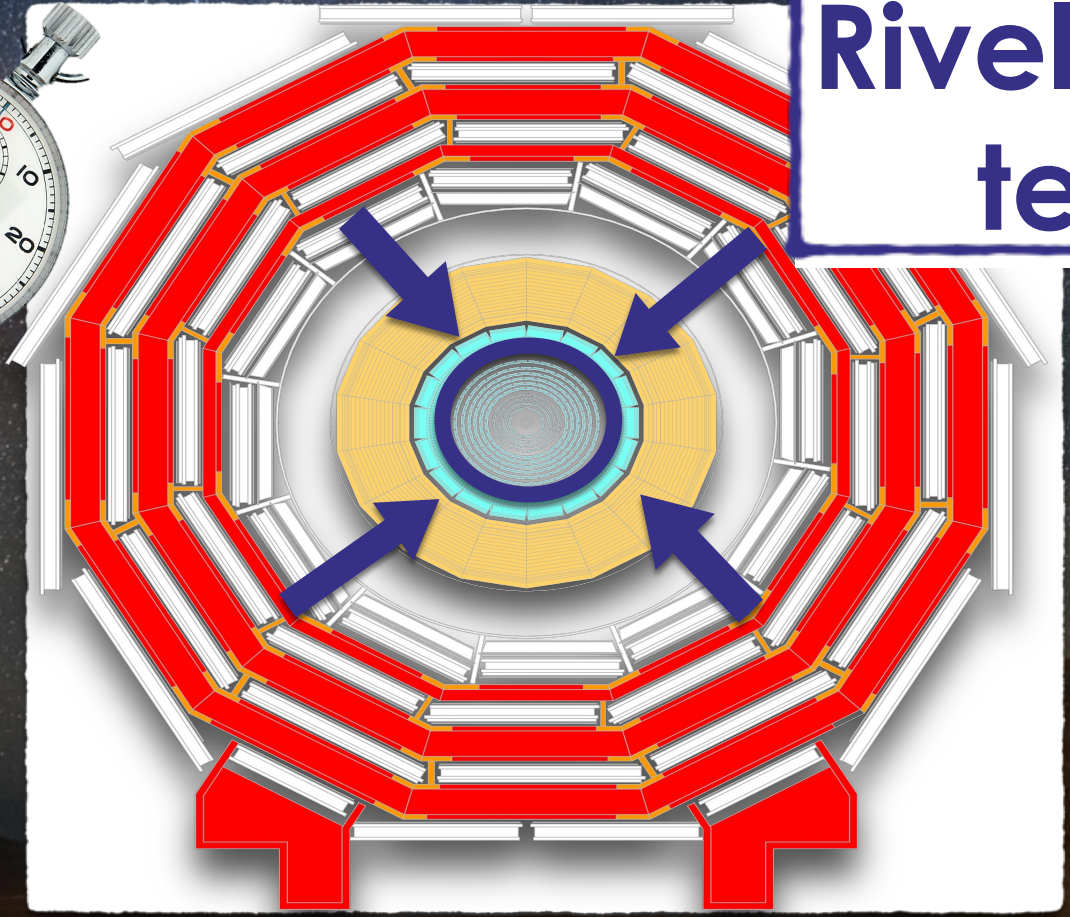
Processo nuovo:

$$X \xrightarrow[X]{} \mu\mu$$

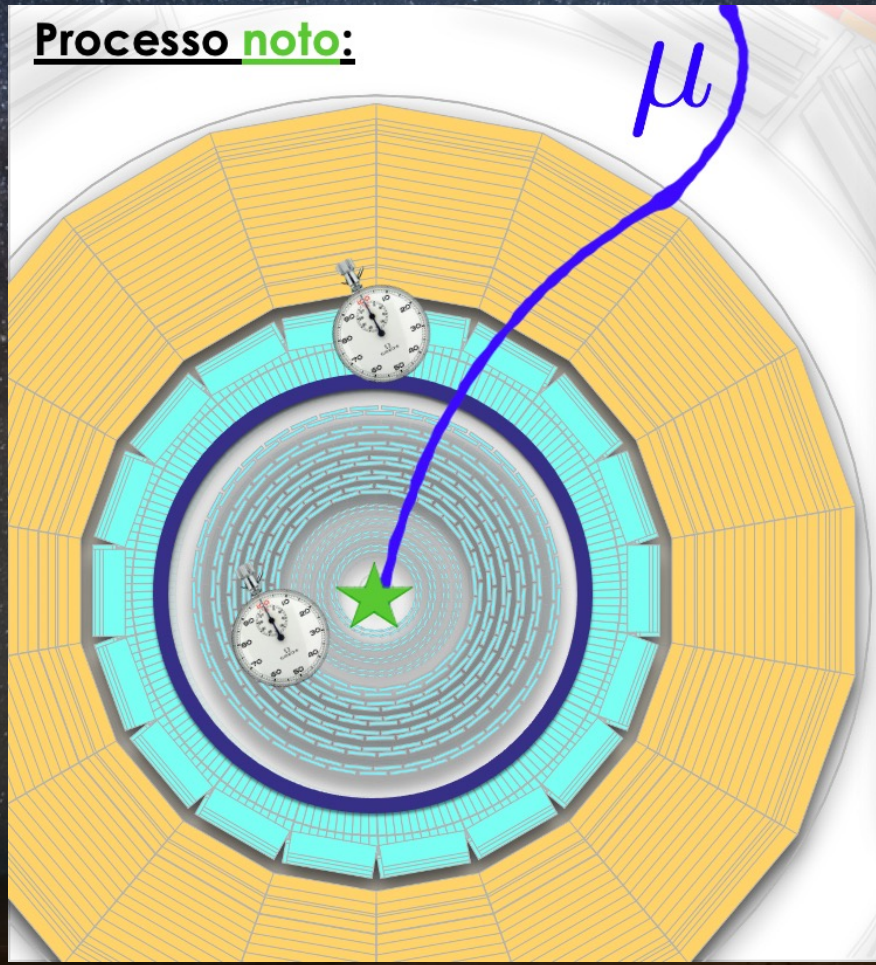
cammina un po` poi decade in due muoni



Rivelatore di tempo



Processo noto:



Tempo della collisione:

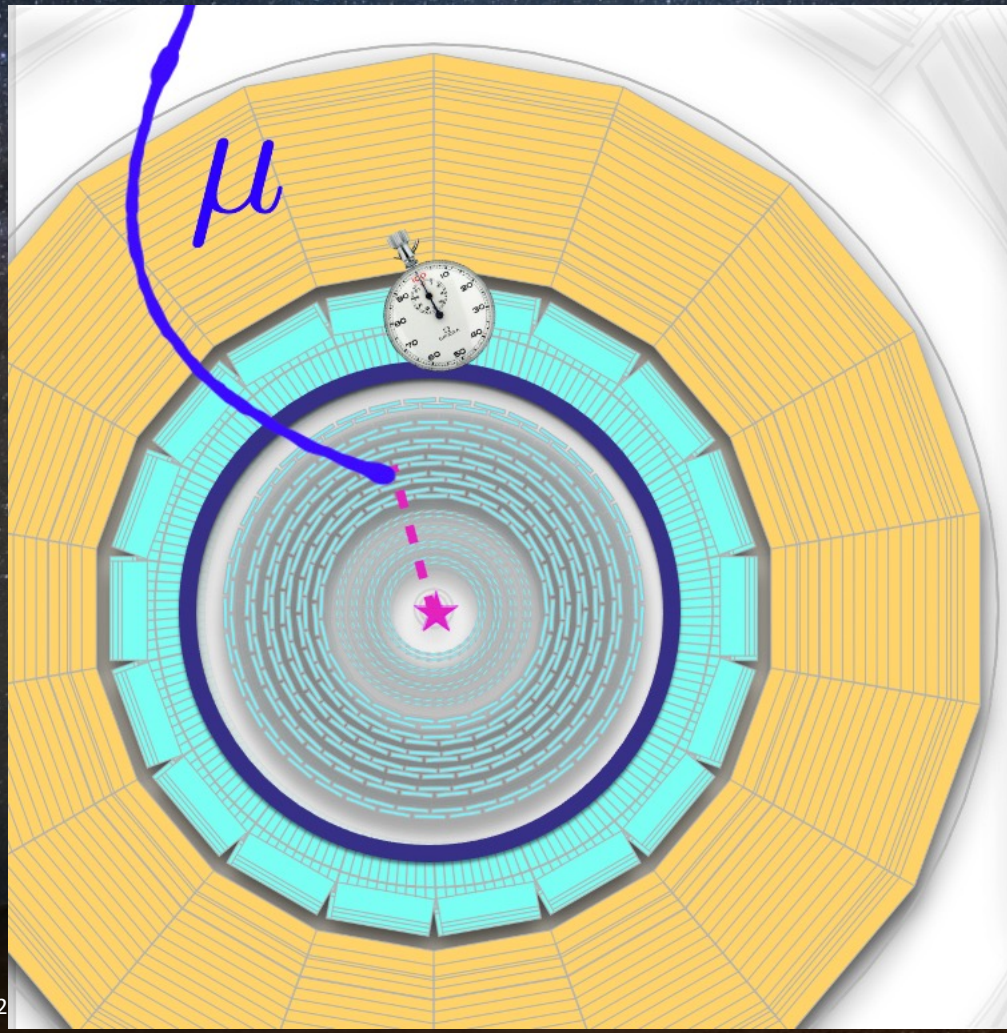
t_0

Tempo di passaggio:

t_μ

Tempo di volo del muone:

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

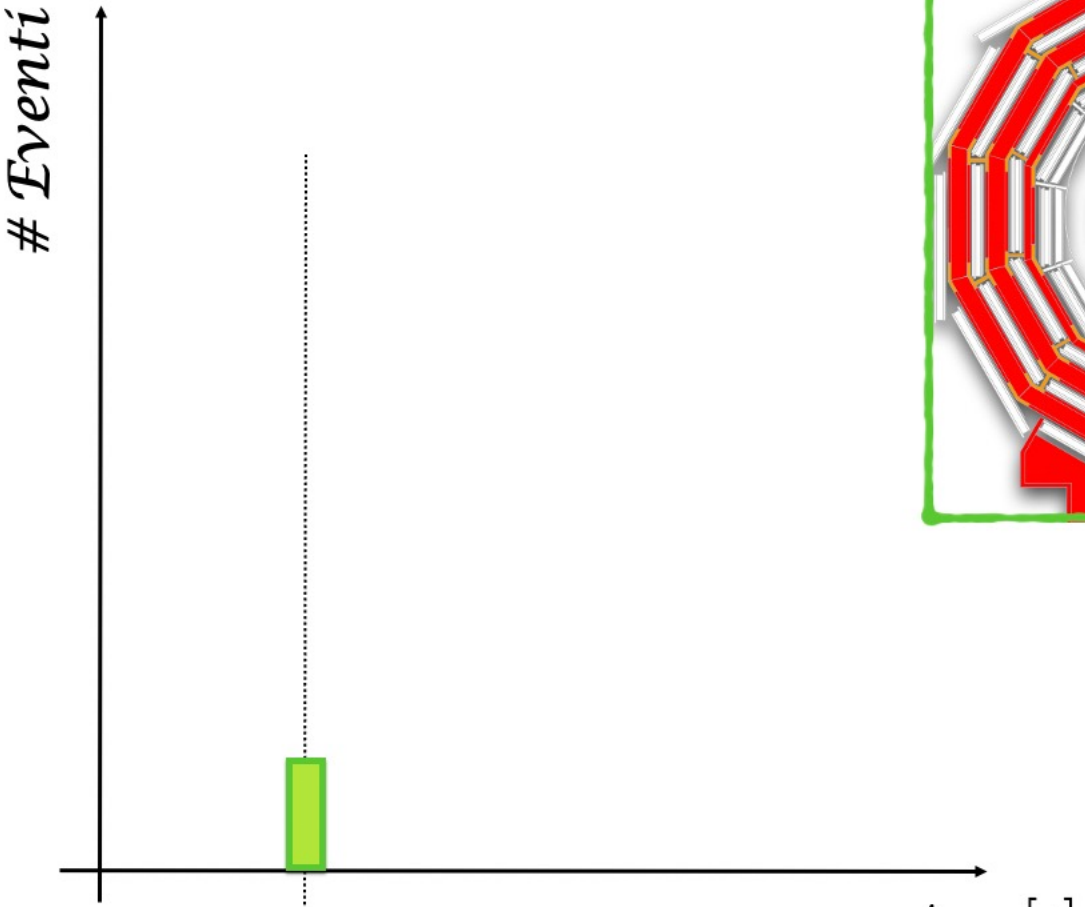


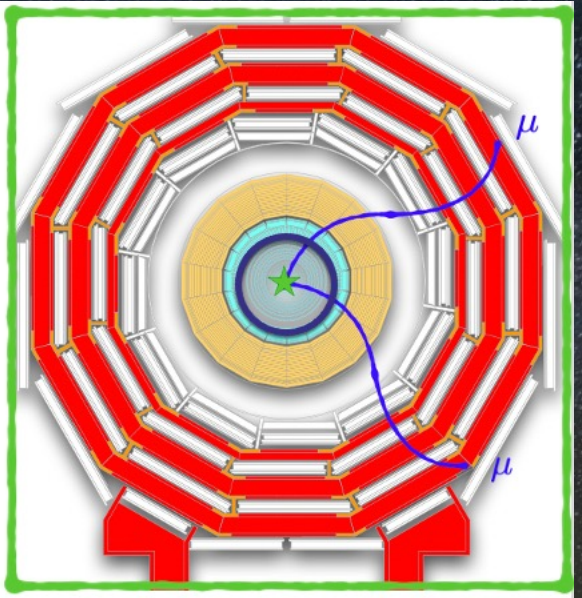
X si muove lentamente prima di disintegrarsi

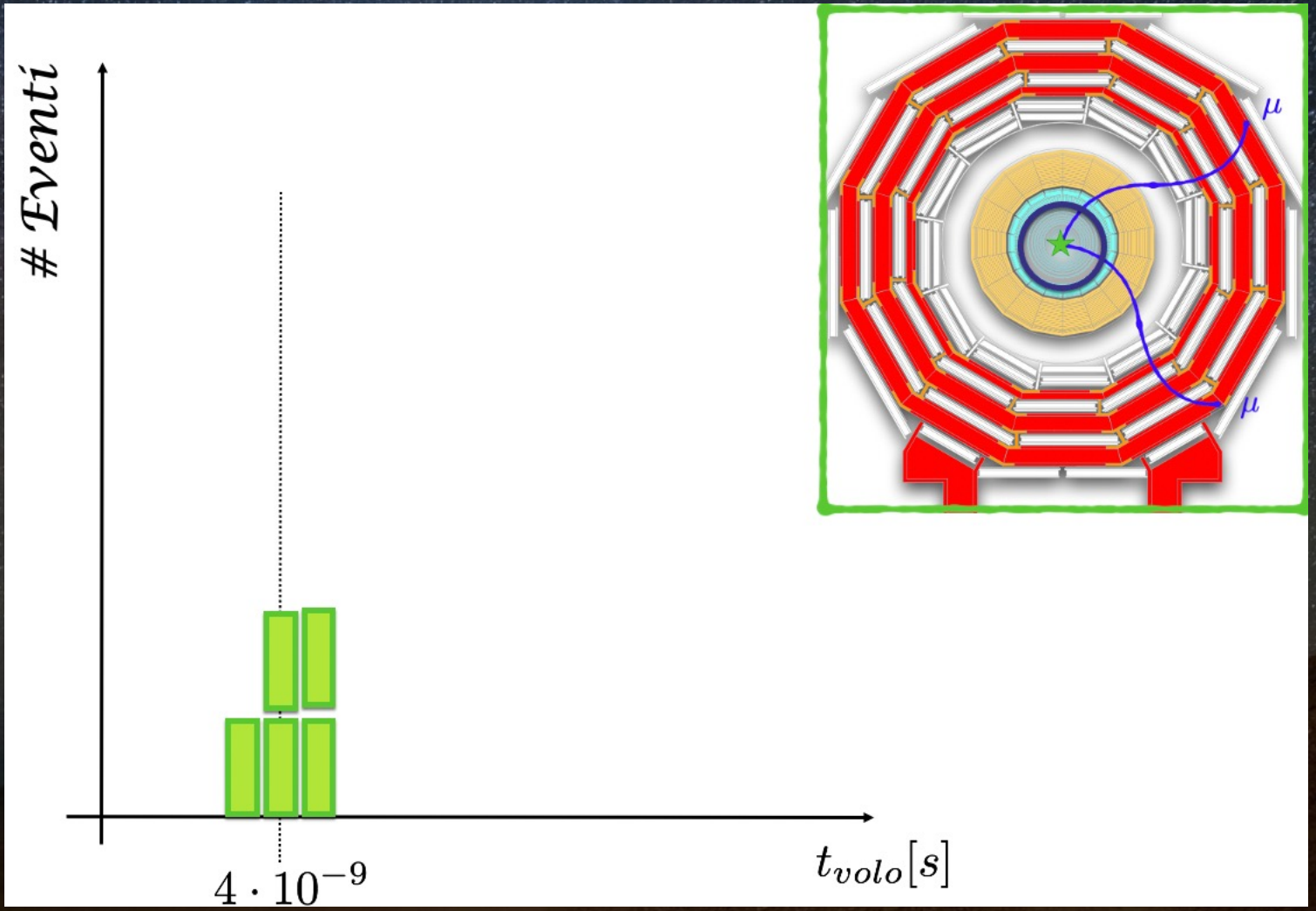
$m_X \nearrow \; v_X \searrow$

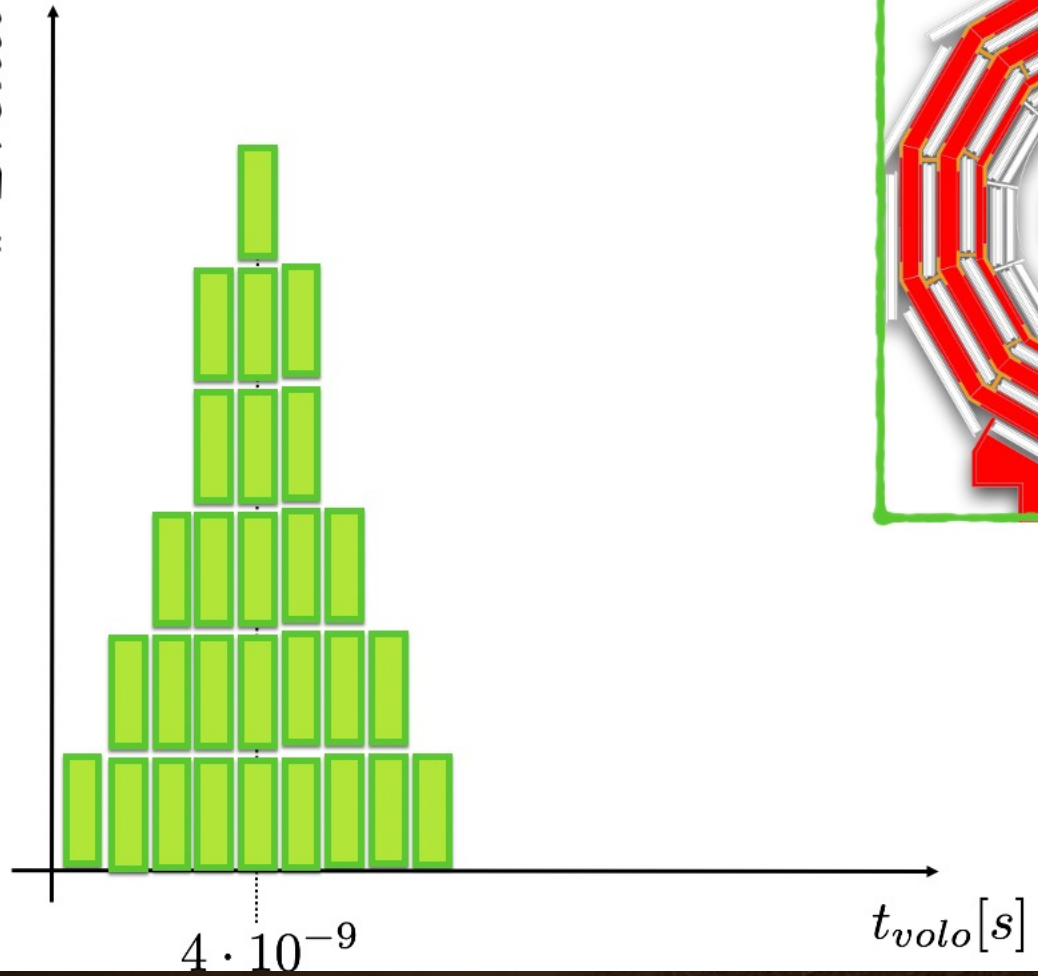
I muoni arrivano in ritardo sul rivelatore:

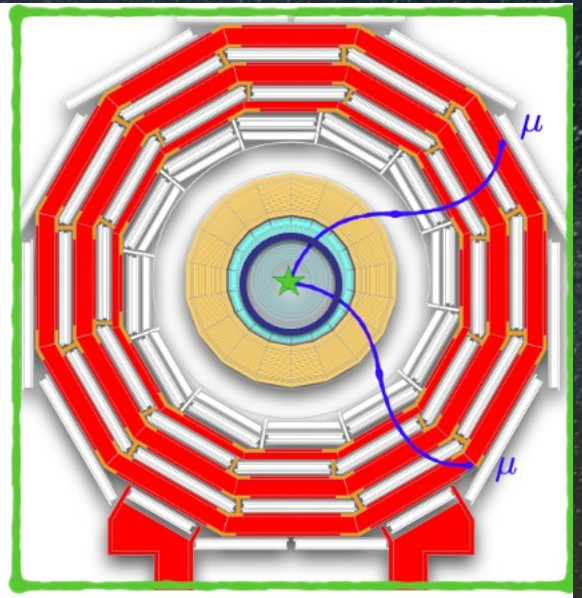
$t_{volo} = t_X + t_\mu - t_0$

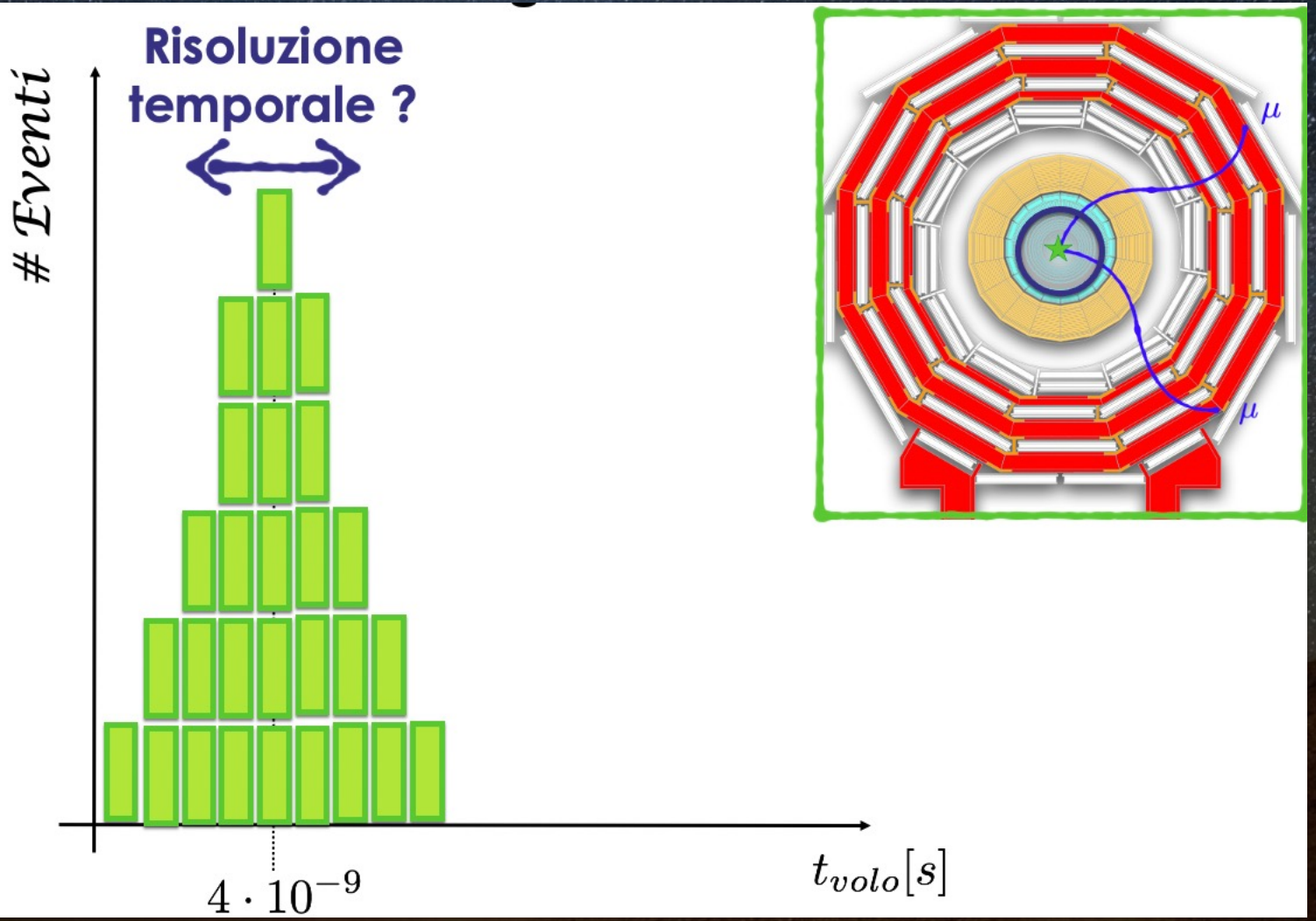

Eventi
$4 \cdot 10^{-9}$
$t_{volo}[s]$

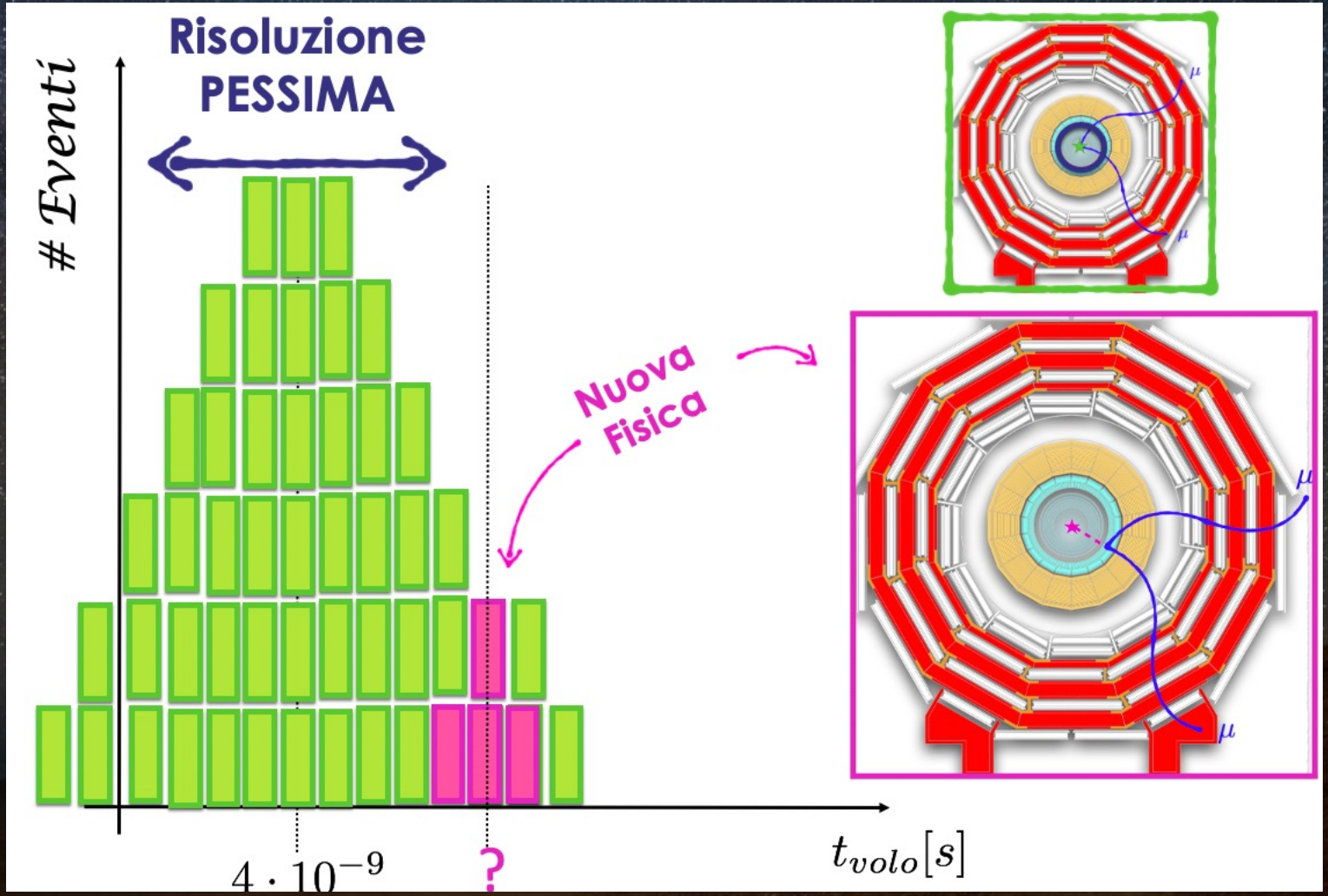

μ
μ

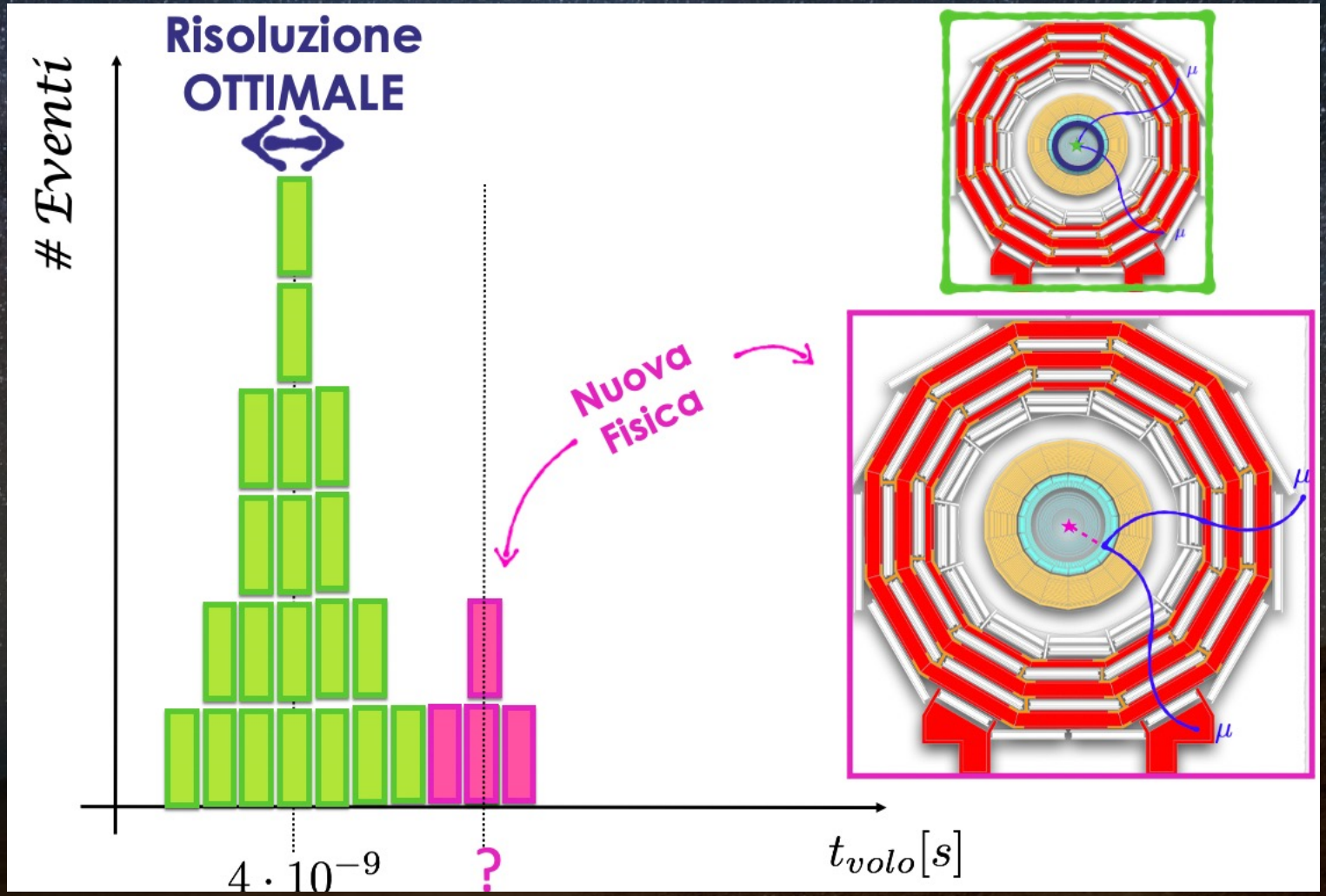

Eventi
$4 \cdot 10^{-9}$
$t_{volo}[s]$
μ
μ

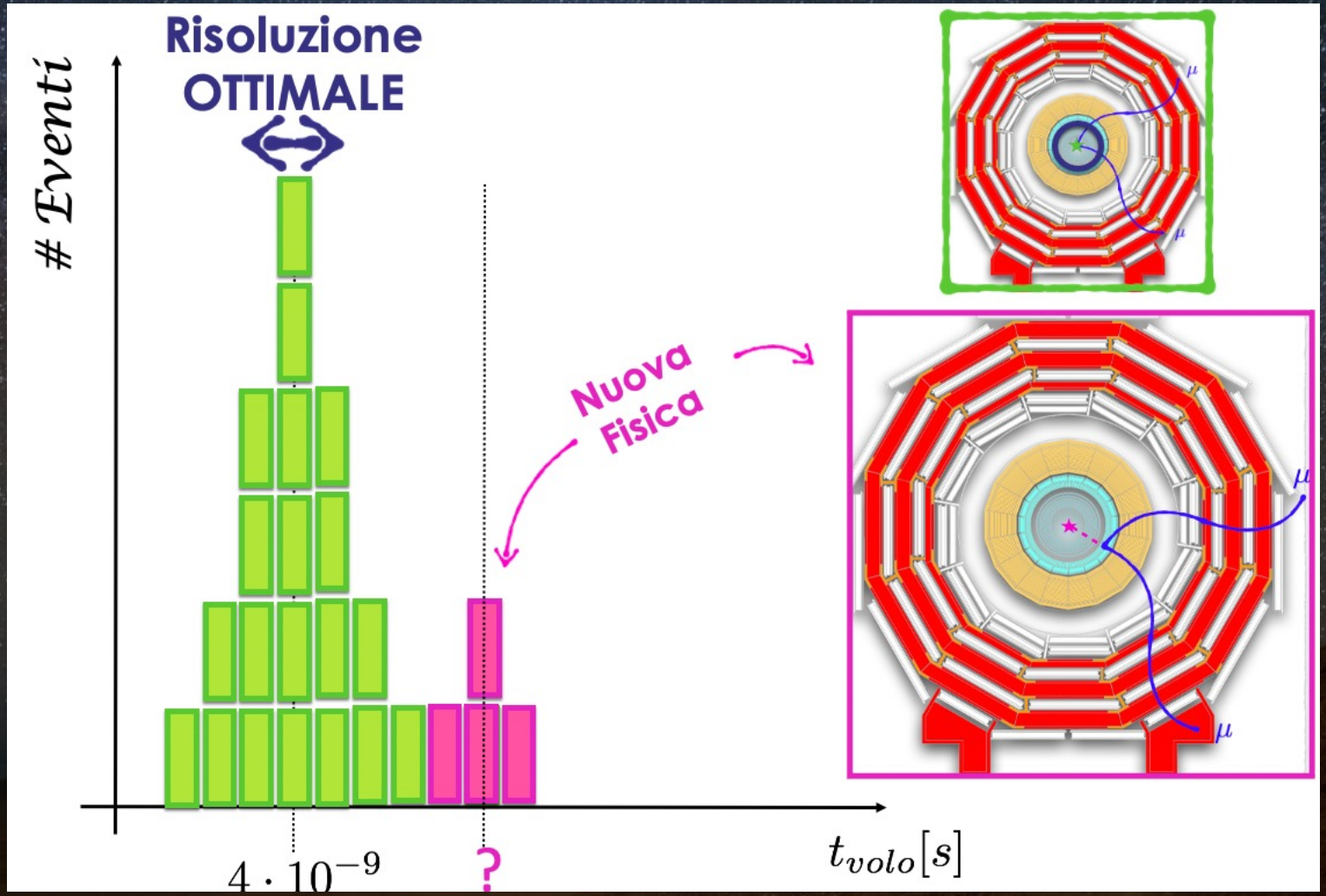

Eventi
$4 \cdot 10^{-9}$
$t_{volo}[s]$


μ
μ


Risoluzione temporale ?
Eventi
$4 \cdot 10^{-9}$
$t_{volo}[s]$
μ
μ


Risoluzione
PESSIMA
Eventi
Nuova
Fisica
μ
μ
μ
μ
$4 \cdot 10^{-9}$
?
$t_{volo}[s]$


Risoluzione
OTTIMALE
Eventi
Nuova
Fisica
$4 \cdot 10^{-9}$
?
$t_{volo}[s]$
μ
μ
μ
μ


Risoluzione
OTTIMALE
Eventi
Nuova
Fisica
$4 \cdot 10^{-9}$
?
$t_{volo}[s]$
μ
μ
μ
μ

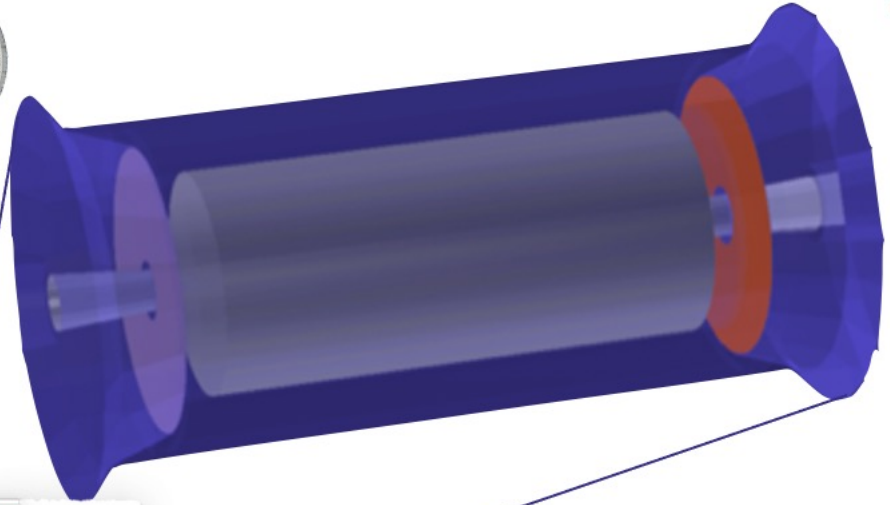
Risoluzione temporale

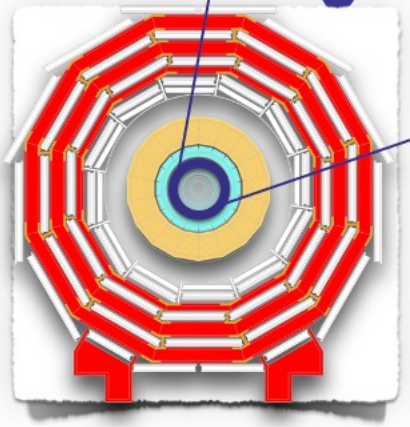
Identificazione nuove particelle

Risoluzione temporale OTTIMALE:

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

Operativo nel 2027!



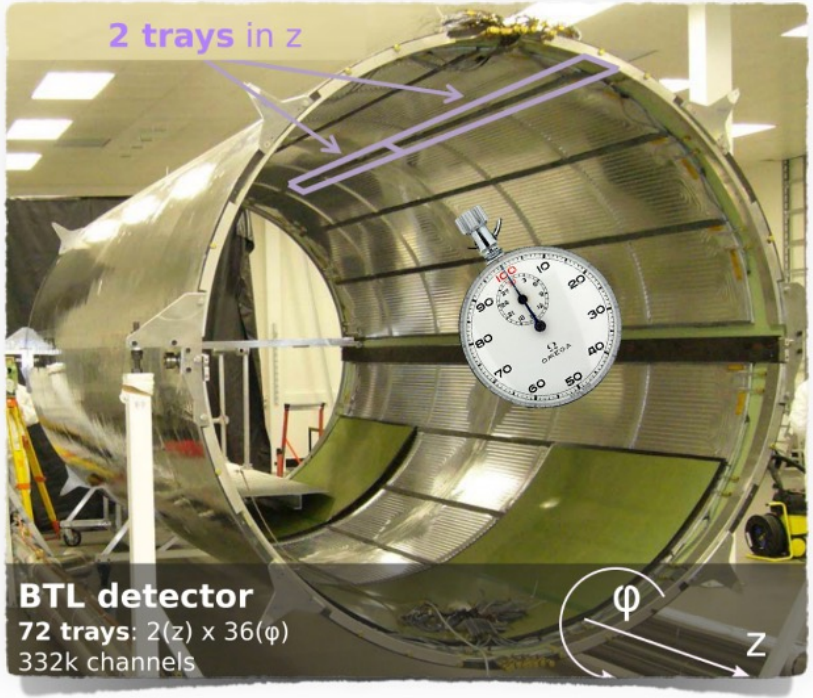


Materiale: **cristalli scintillanti**

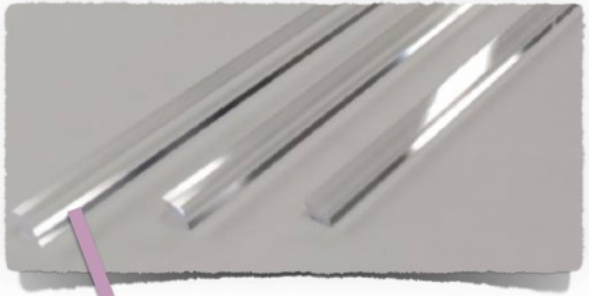
Numero di sensori: **~ 6 Milioni**

Risoluzione Temporale: **30 ps**

Struttura di sostegno



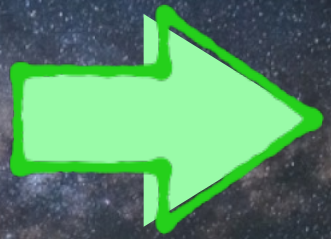
Cristalli 5 x 0.3 cm, singoli sensori



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

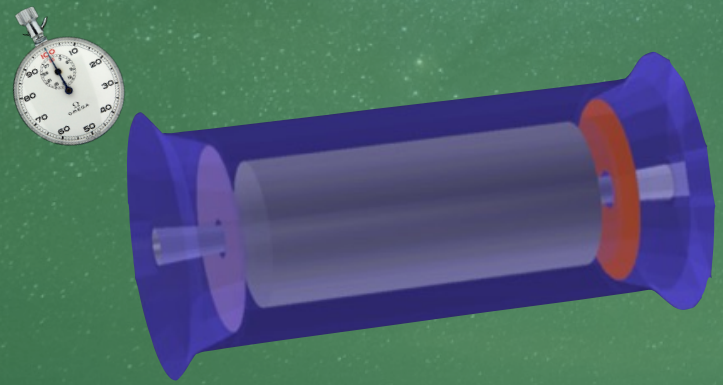
1991 CERN: Where the Web Was born!

RICERCA DI BASE

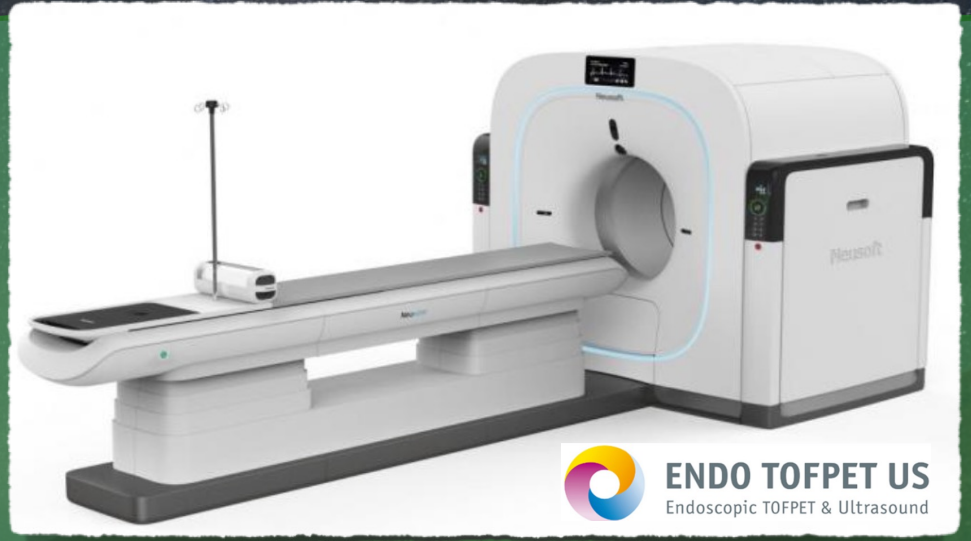
INNOVAZIONE TECNOLOGICA

RICERCA DI BASE

INNOVAZIONE TECNOLOGICA



2022- Rivelatore di tempo di particelle



2000- Time of Flight Photon eMission Tomography

Per qualsiasi domanda:
livia.soffi@roma1.infn.it