



UNIVERSITÀ  
DI PAVIA



INTERNATIONAL  
**MASTERCLASSES**

hands on particle physics

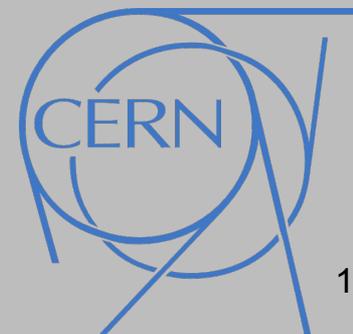
**ALICE & CMS & ATLAS @ Pavia**

29 Febbraio 2024

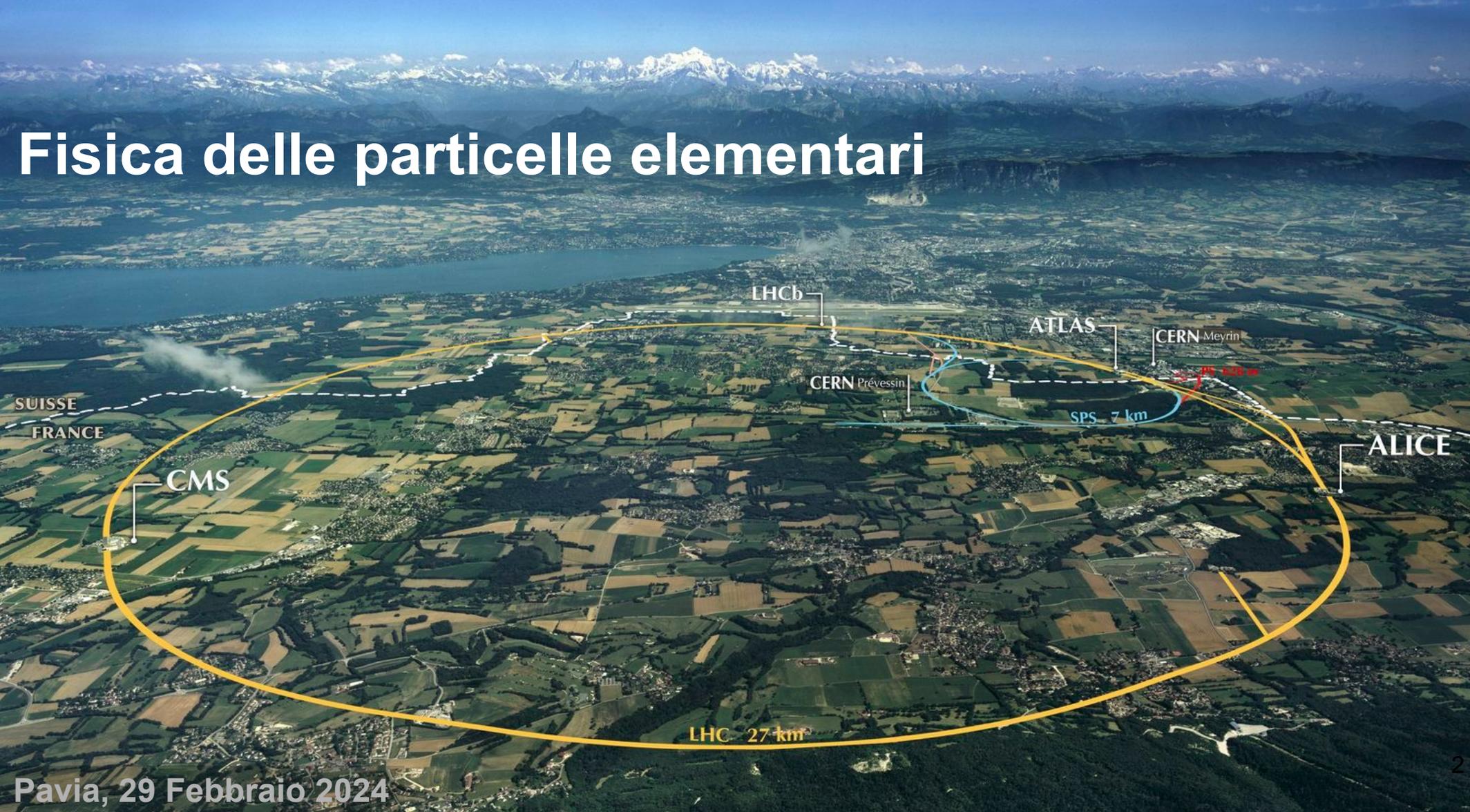
**Tommaso Cresta, Giulia Manco**



International Particle  
Physics Outreach Group



# Fisica delle particelle elementari



SUISSE  
FRANCE

CMS

LHCb

ATLAS

CERN Meyrin

CERN Prévessin

SPS 7 km

PS 430 m

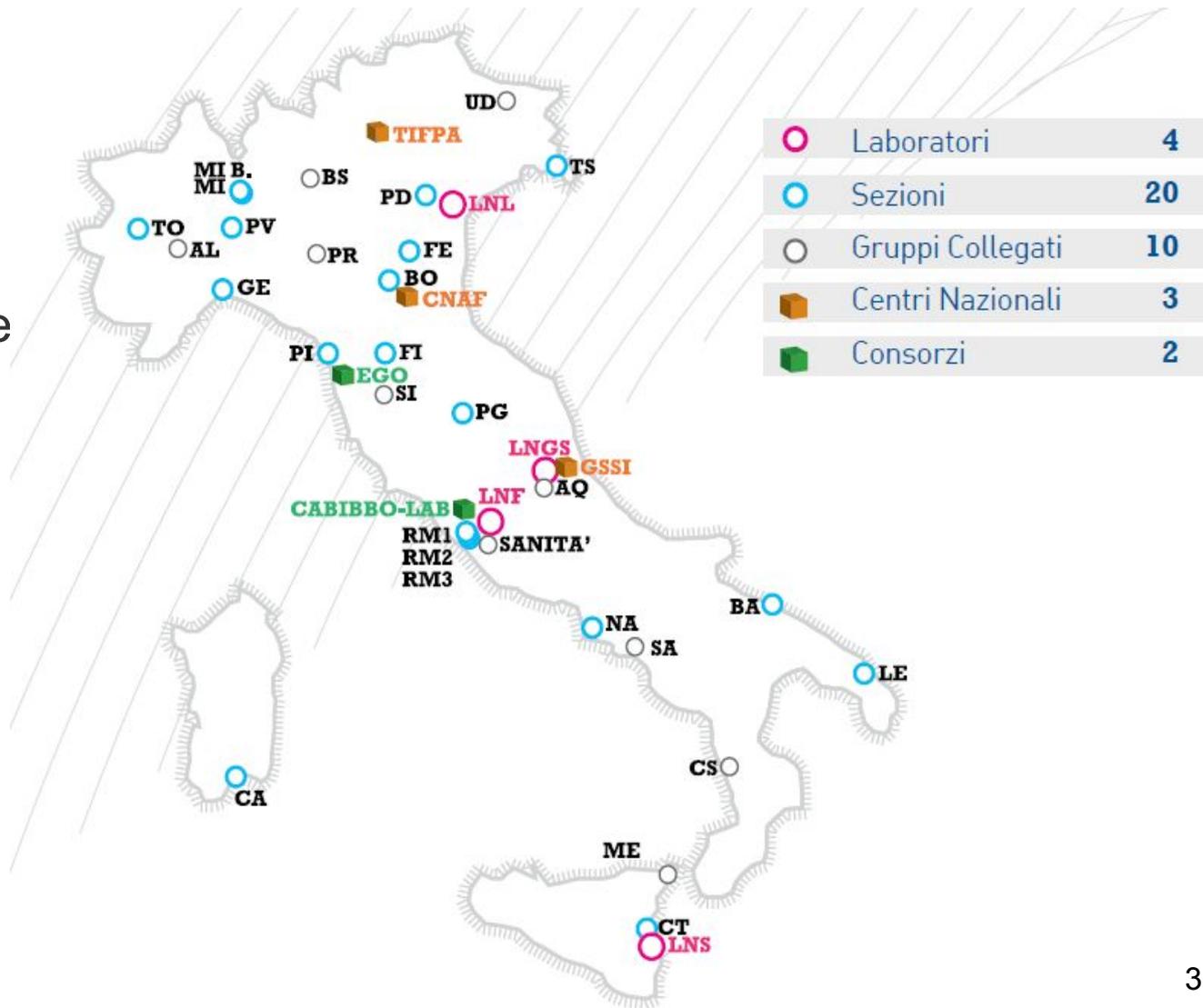
ALICE

LHC 27 km

- Istituto Nazionale di Fisica Nucleare
  - fondi per costruzione apparati e per le trasferte di fisici e tecnici



Istituto Nazionale di Fisica Nucleare



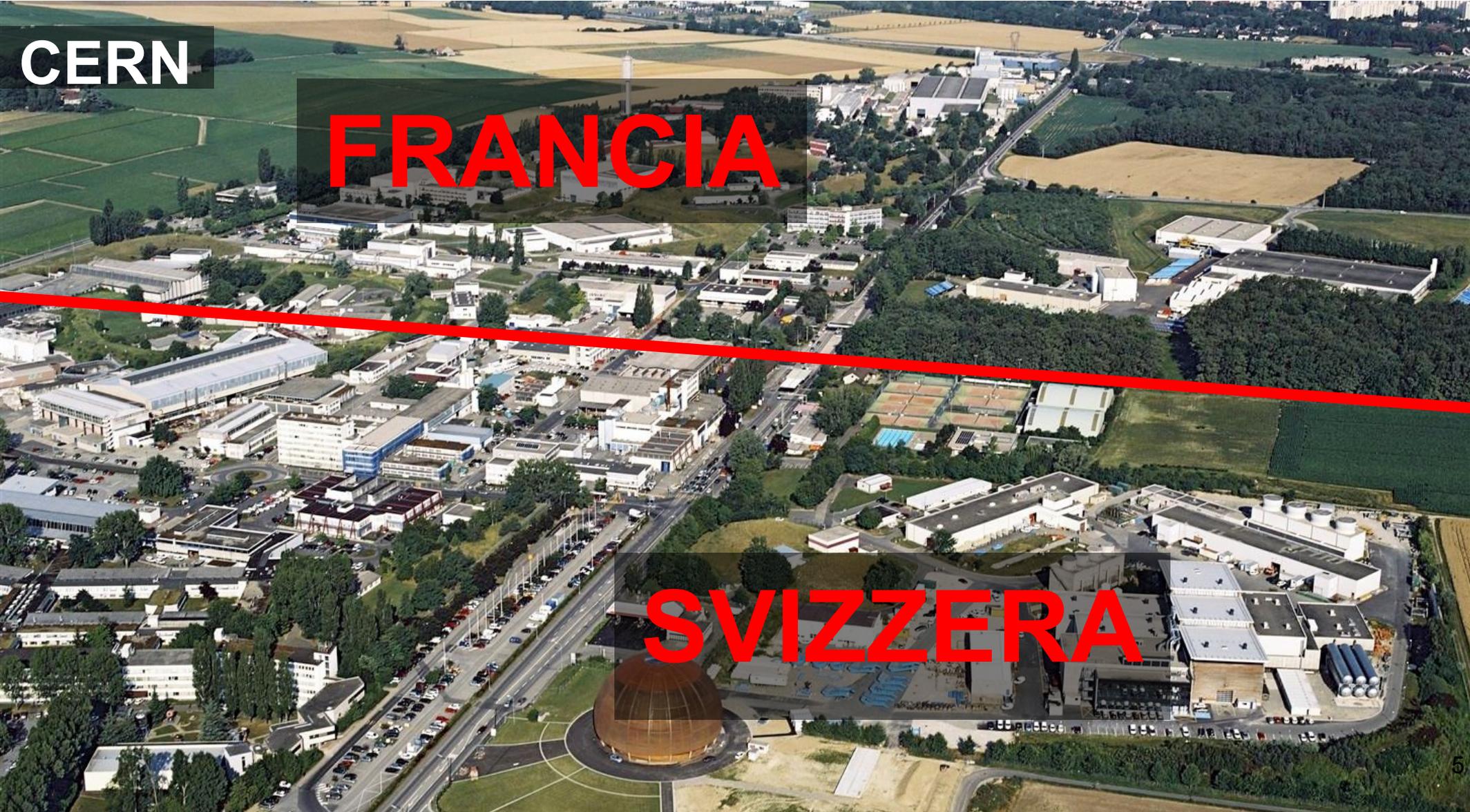
# CERN



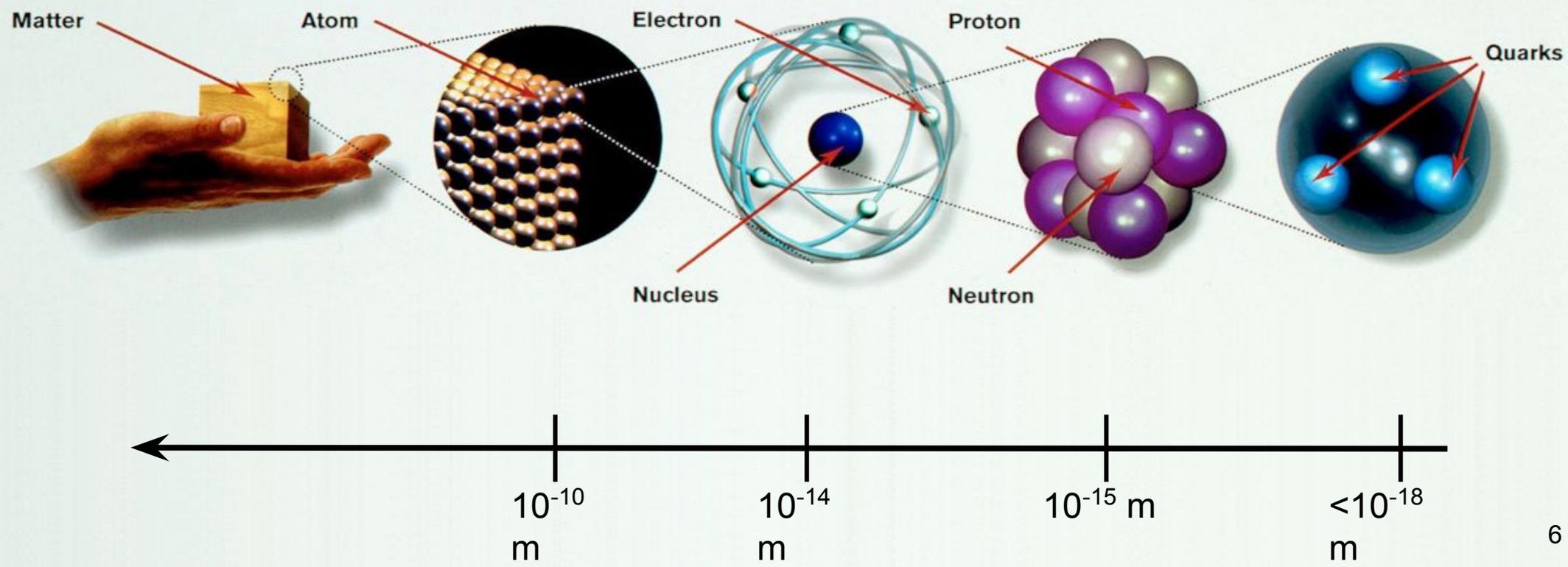
**CERN**

**FRANCIA**

**SVIZZERA**



# Fisica delle Particelle Elementari

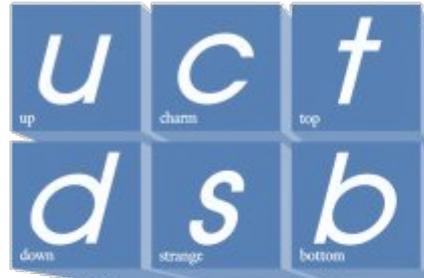


**Tutto è fatto di  
particelle**

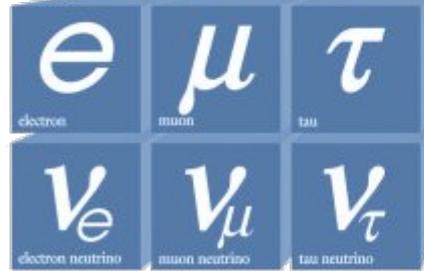
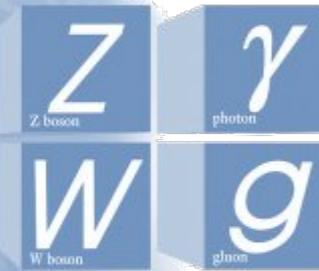


# Tutto è fatto di particelle

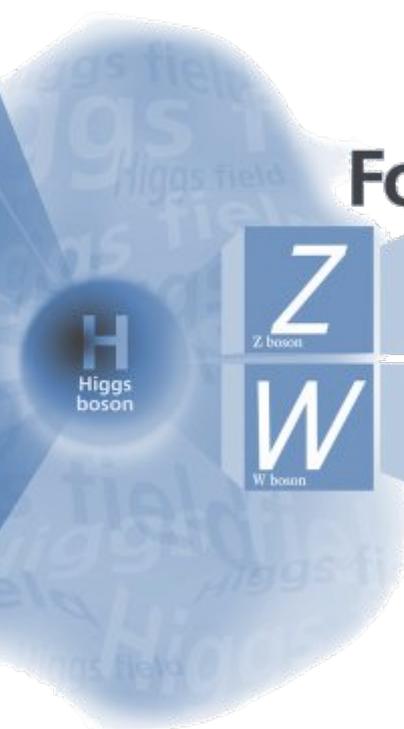
## Quarks



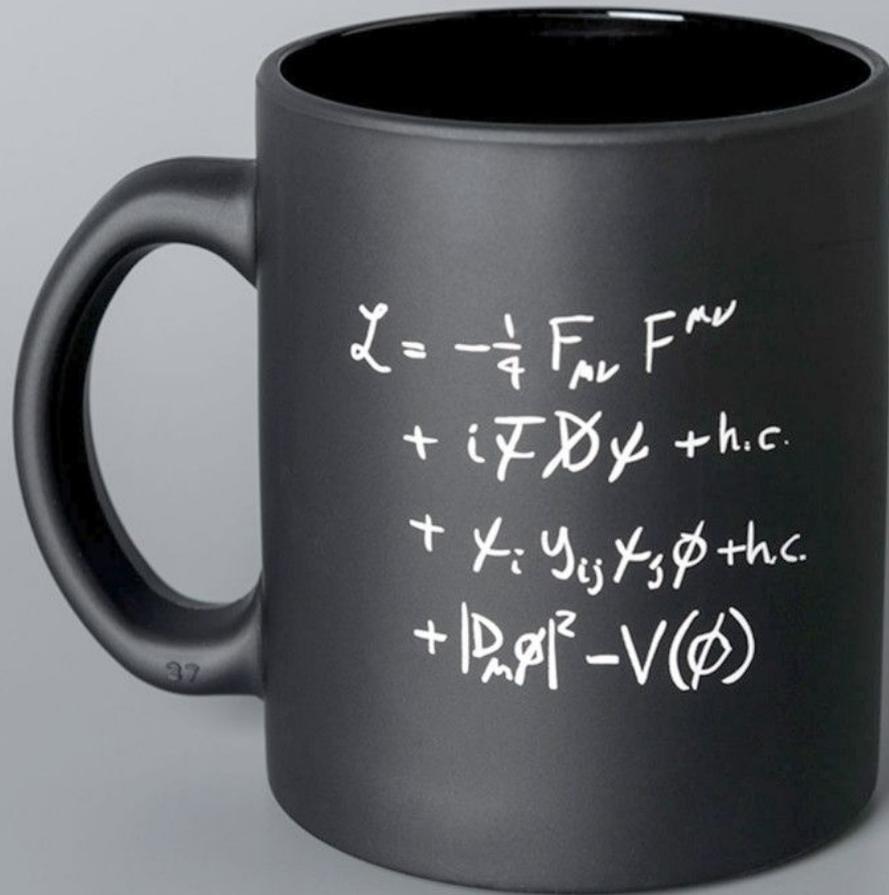
## Forces



## Leptons



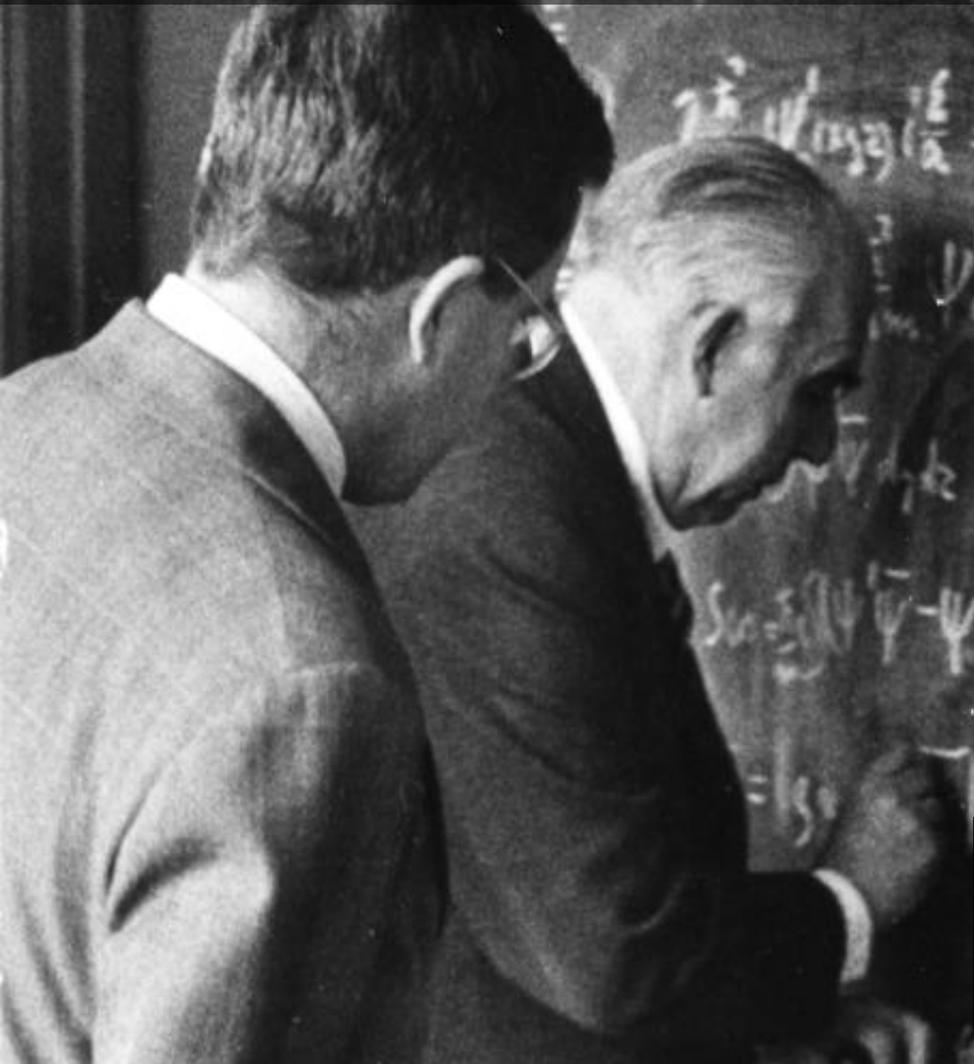
# Modello Standard



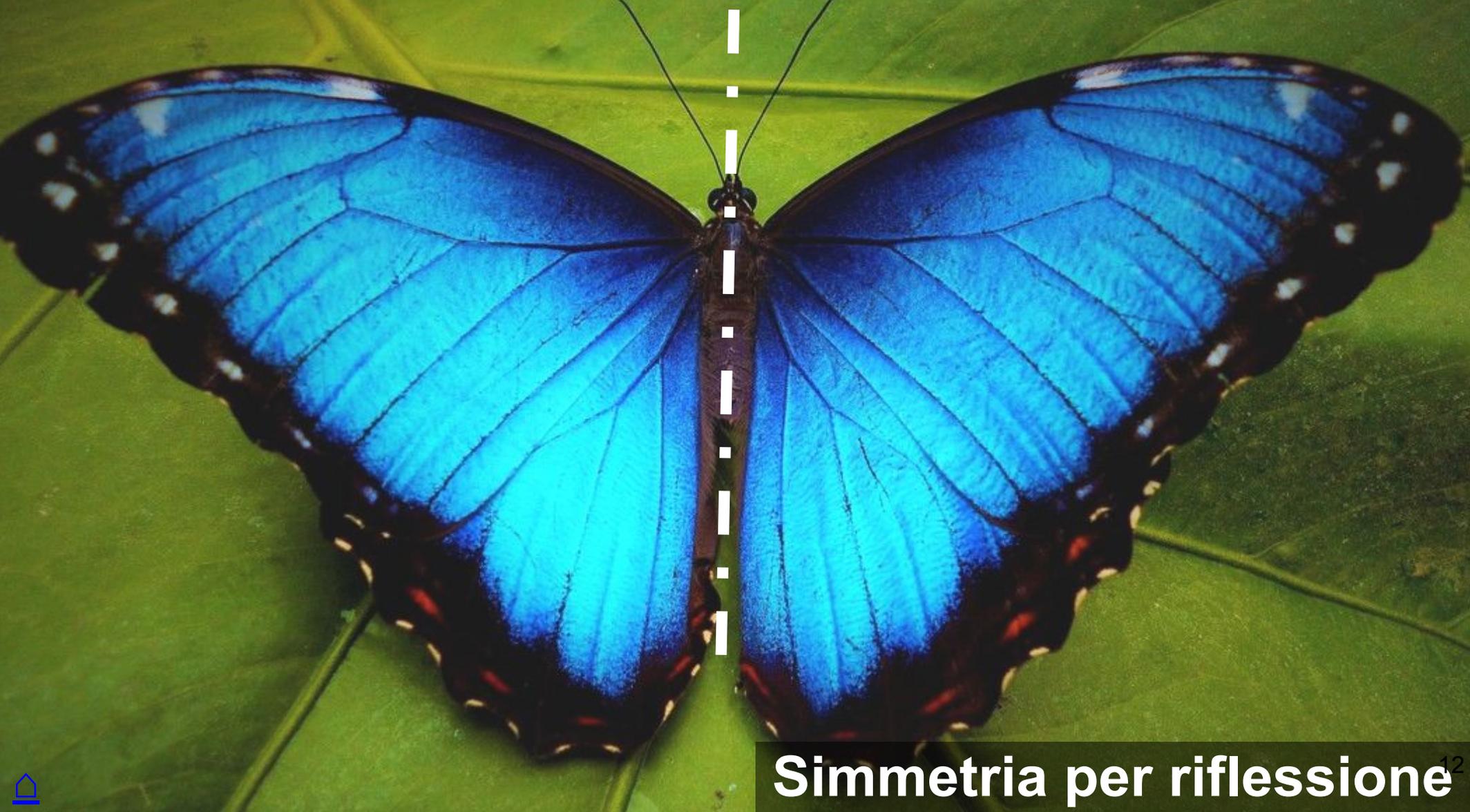
$$\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
& \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
& \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[ \frac{2M^2}{g^2} + \right. \\
& \left. \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
& W_\nu^- \partial_\nu W_\mu^+)] - igs_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
& W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
& \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) + \\
& g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
& \frac{1}{8}g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] - \\
& gMW_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2}ig [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
& W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
& \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
& igs_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
& igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
& \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- +
\end{aligned}$$

**ecc...**

# Alla base della fisica: **simmetria**



**Trasformazione che lascia  
invariato un oggetto**



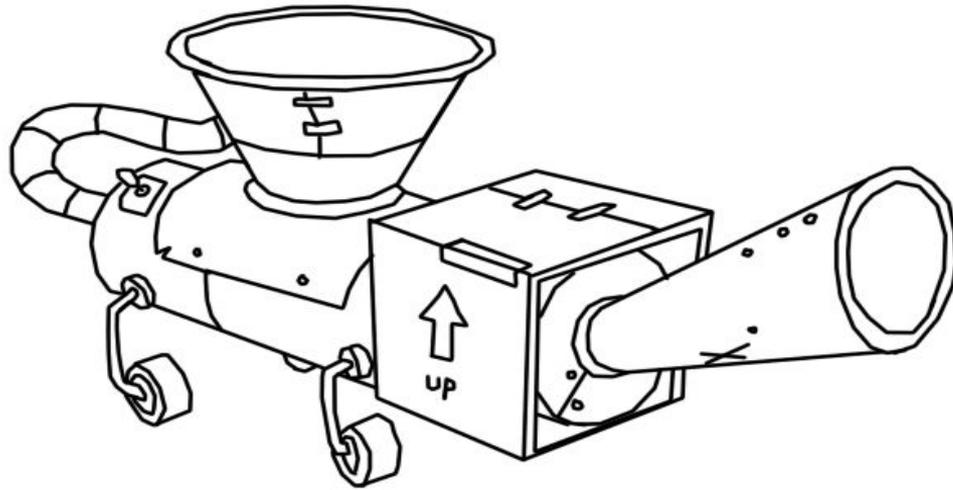
**Simmetria per riflessione**





**Simmetria per  
rotazioni**

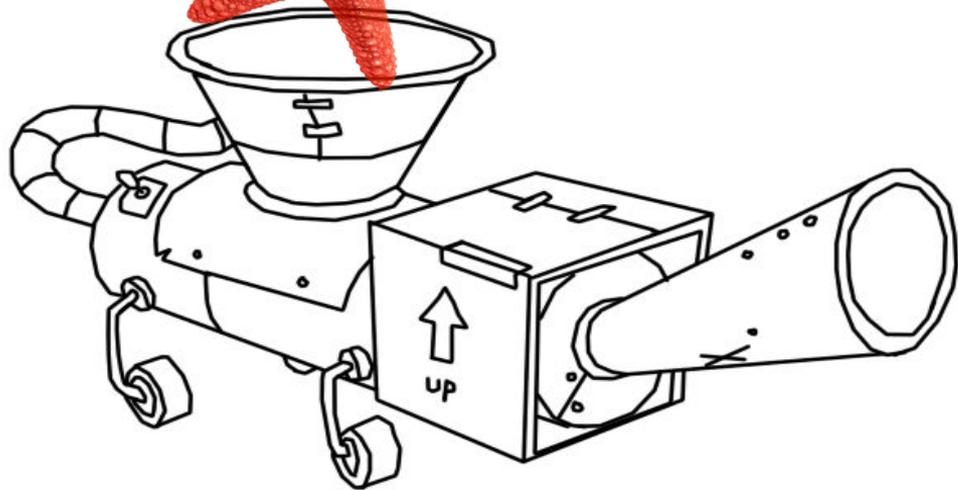
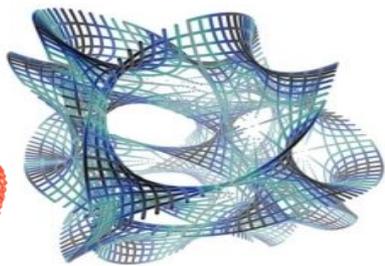
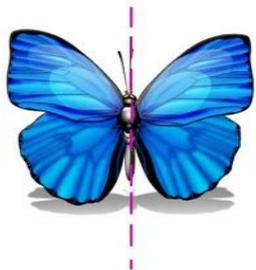
## Simmetrie



**Equazioni**

# Macchina per teorie

## Simmetrie



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c. + \bar{\Psi}_i\gamma_{ij}\Psi_j\Phi + h.c. + |D_\mu\Phi|^2 - V(\Phi)$$

**Equazioni**

# Simmetria



Ad ogni **simmetria** di un sistema fisico è associata una legge di **conservazione**

**Emmy Noether, 1915**

# Teorema di Noether

Invarianza per  
traslazioni temporali



$$dU = \delta Q - \delta L$$

Invarianza per  
traslazioni spaziali



$$\frac{d \sum \vec{p}_i}{dt} = 0$$

Invarianza della  
velocità della luce



$$E = mc^2$$

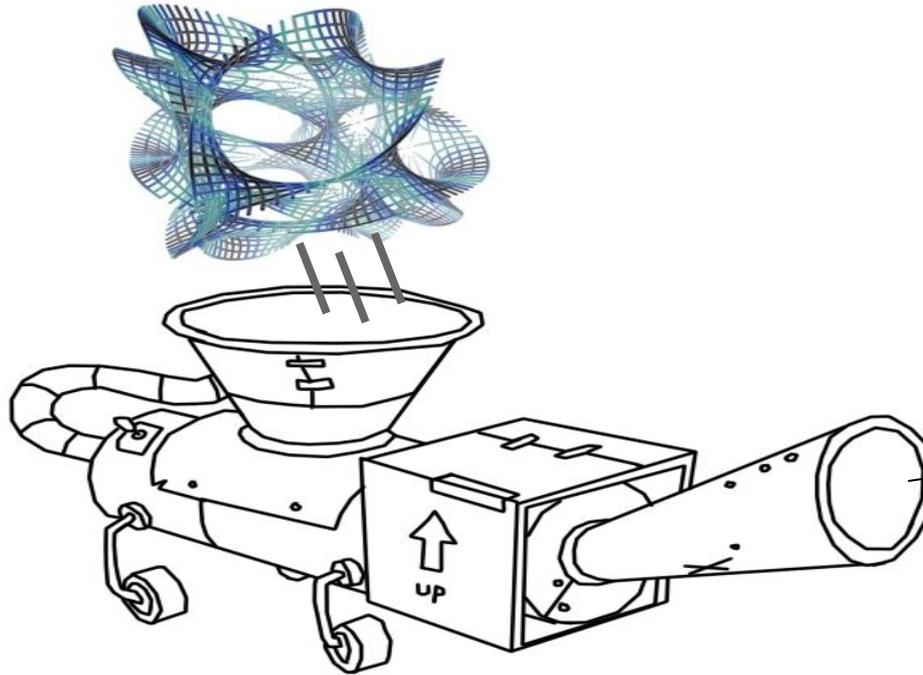
Principio di equivalenza



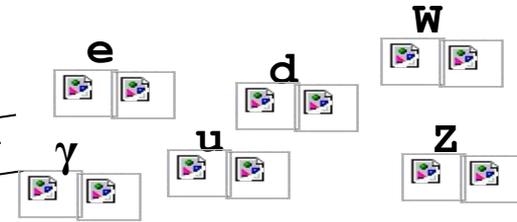
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8 \pi G T_{\mu\nu}$$

# Modello standard delle particelle

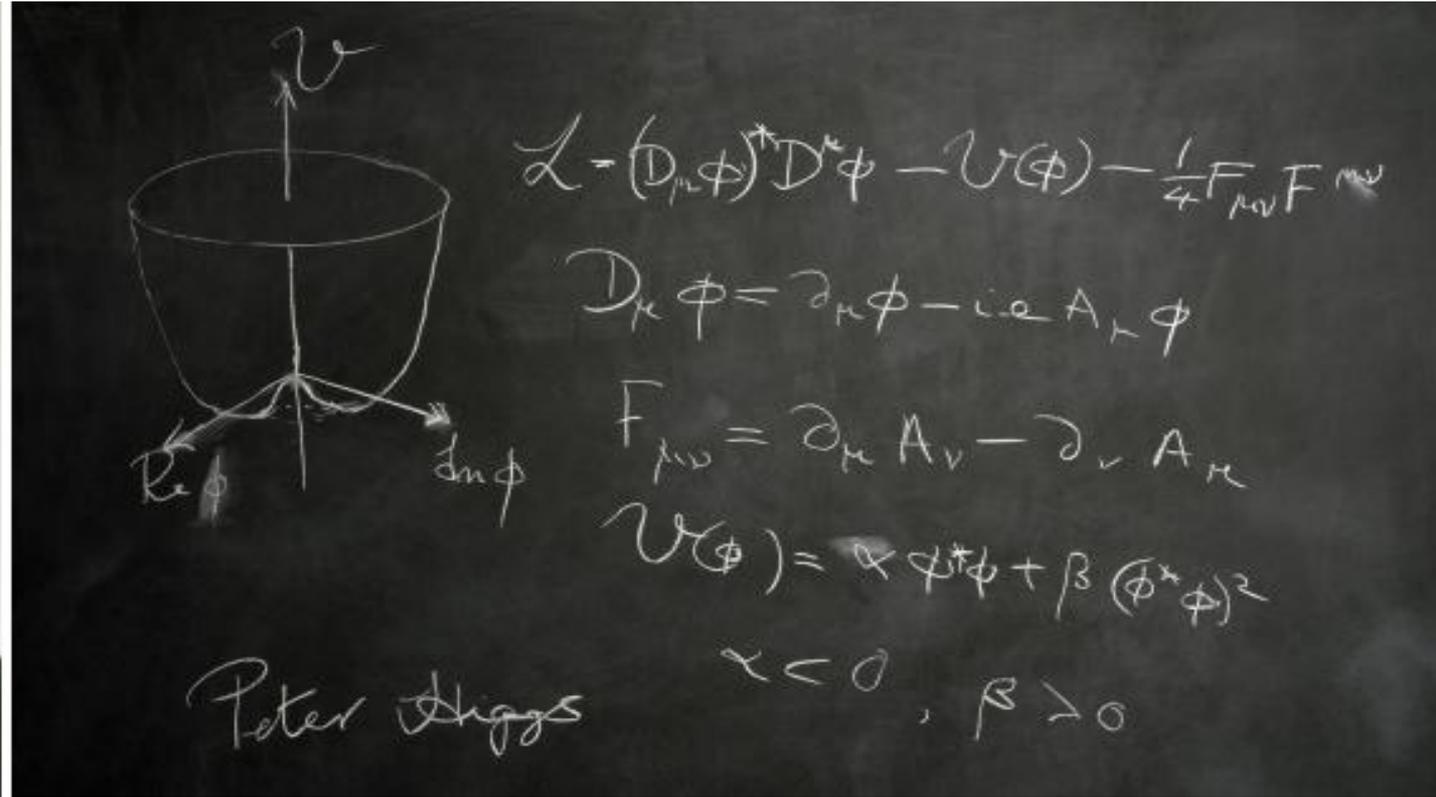
Simmetria  $SU(2)_L \times U(1)$



Descrive tutte le particelle  
Ma .. tutte con **massa nulla**



# E se la simmetria fosse **rotta**?

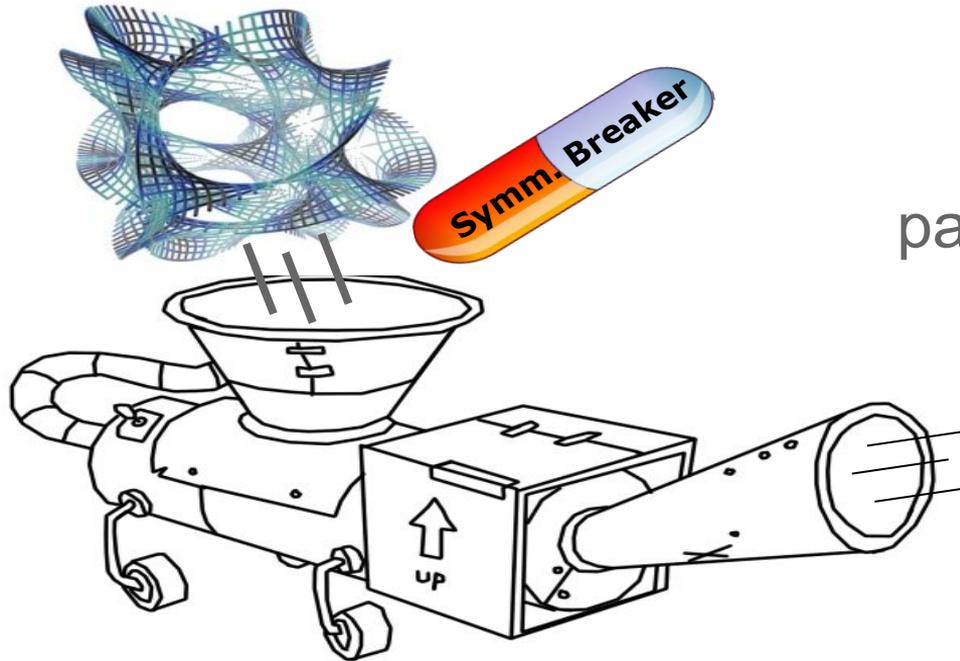


Robert Brout, François Englert, **Peter Higgs** @1964<sub>9</sub>

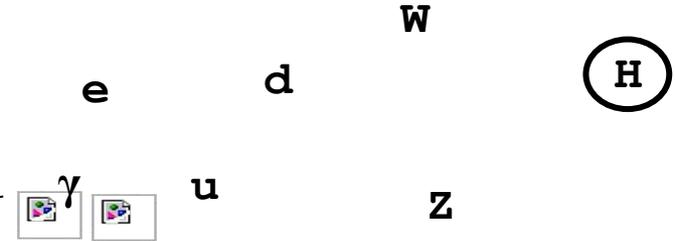
# Modello standard delle particelle

## Simmetria $SU(2)_L \times U(1)$

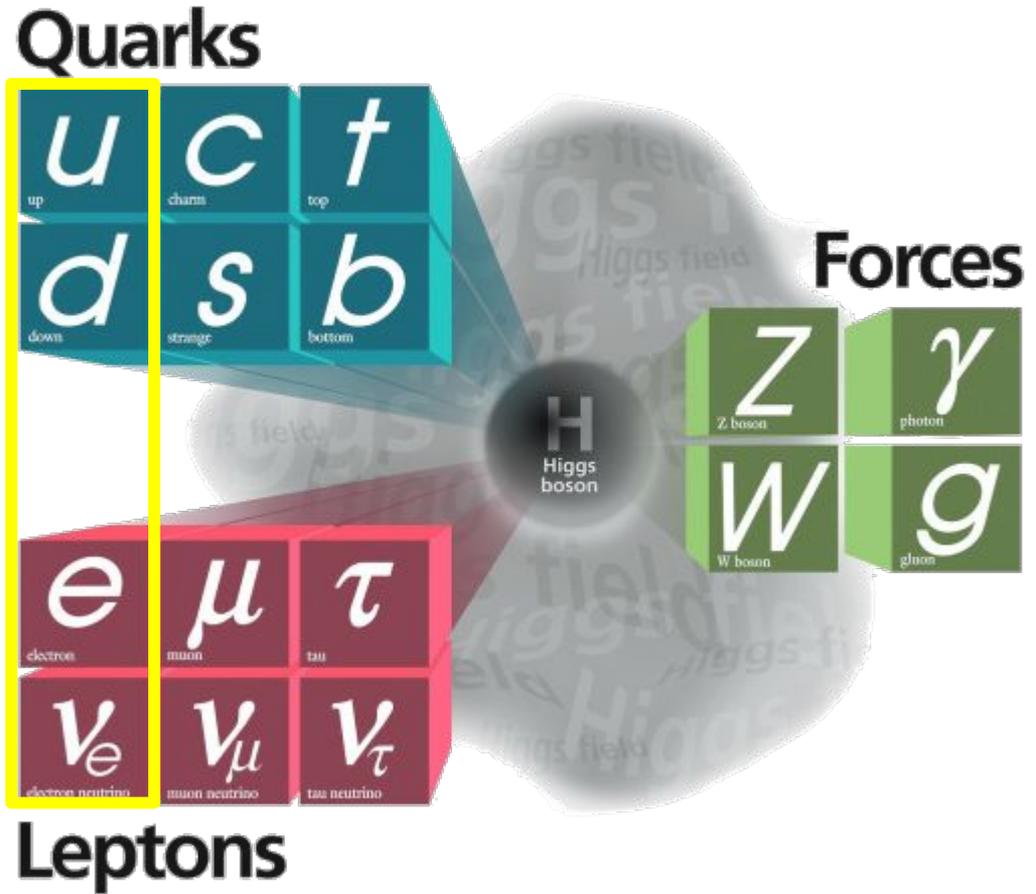
- Meccanismo di **Higgs**:  
in natura la simmetria è “**rotta**”



Descrizione corretta delle  
particelle note + ... una nuova



# Tutto è fatto di particelle



# Tutto è fatto di particelle

## Quarks

$u$ up	$c$ charm	$t$ top
$d$ down	$s$ strange	$b$ bottom

$e$ electron	$\mu$ muon	$\tau$ tau
$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino

## Leptons

## Forces

$Z$ Z boson	$\gamma$ photon
$W$ W boson	$g$ gluon

$H$   
Higgs boson

# I fermioni La materia

# I bosoni Le forze

## Quarks

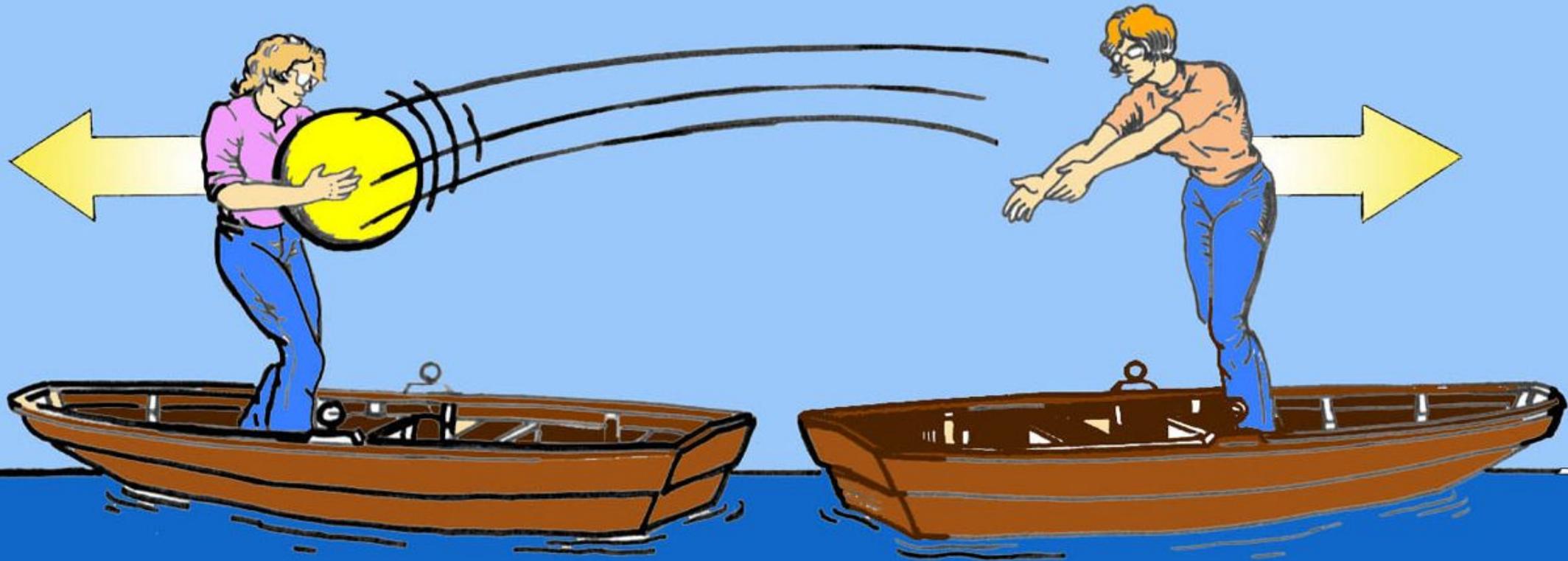


## Leptons

## Forces



# Interazioni mediate da bosoni



# Interazioni mediate da bosoni

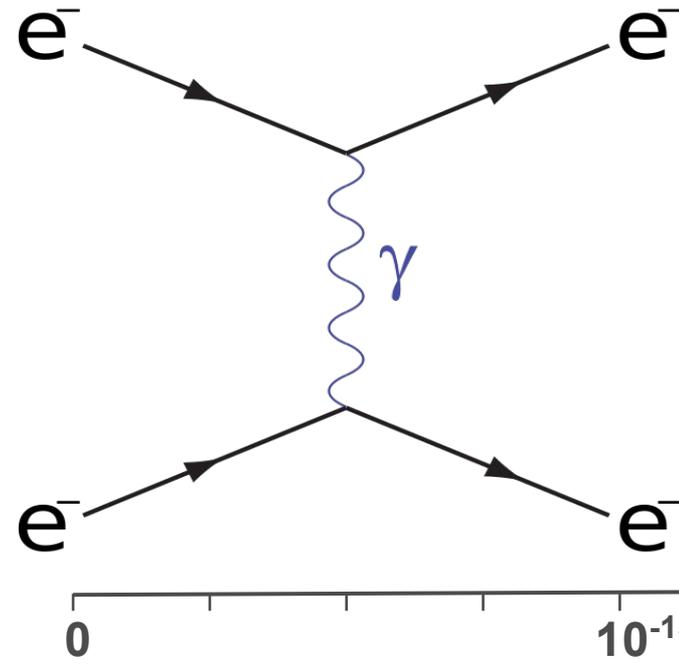


A volte la particella emittente si trasforma



# Diagrammi di Feynman

- Ogni elemento è un pezzo dell'equazione
- Ad ogni vertice si conserva: carica, energia, impulso



Interazione tra  
due elettroni  
mediata da  
un fotone

Masse



# Masse

- Unità di misura di energia

- $E=mc^2$

- **ElectronVolt**

- **1 eV** =  $1.6 \cdot 10^{-19}$  J

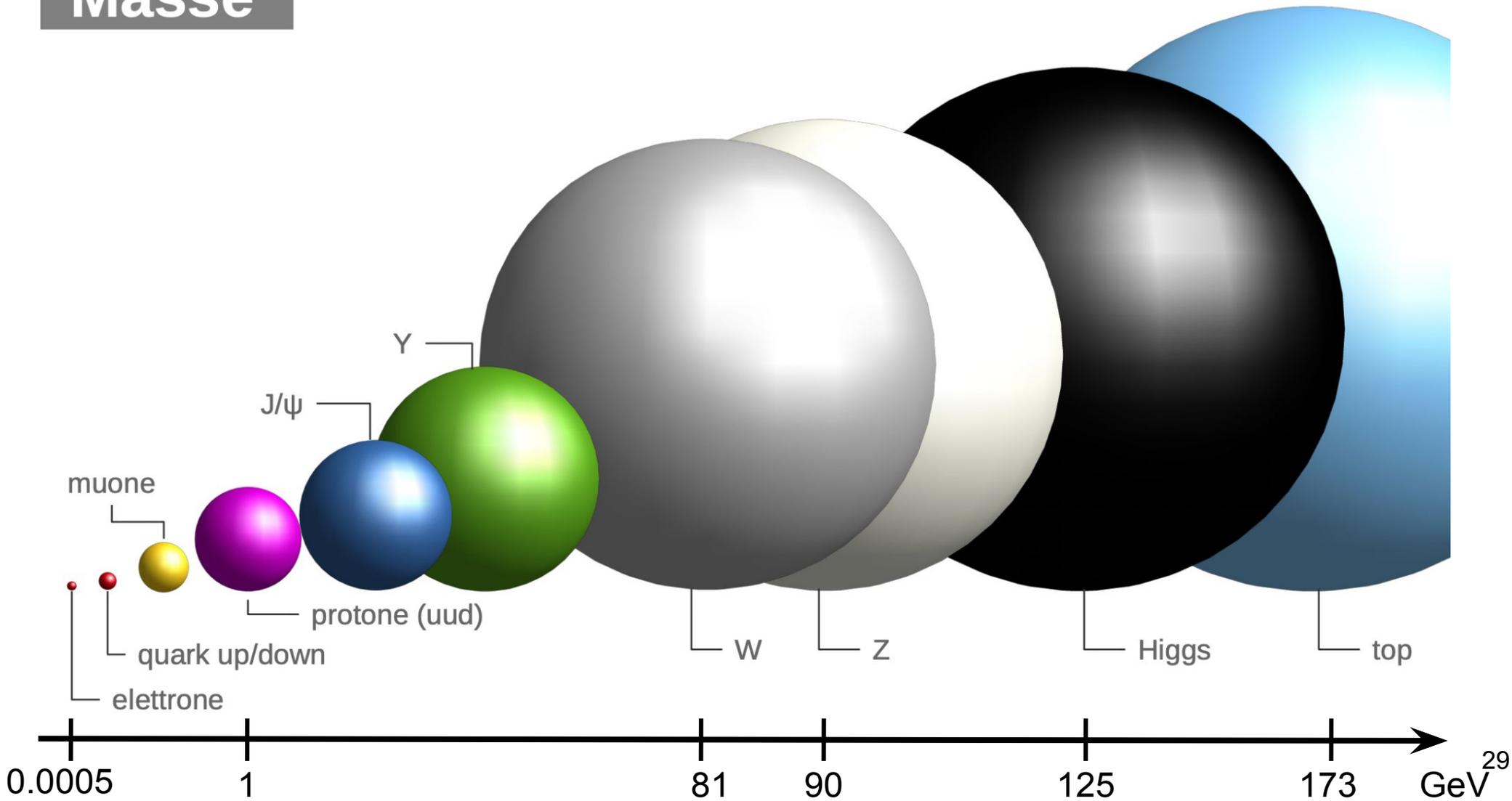
- **1 GeV** =  $10^9$  eV

- **1 TeV** =  $10^{12}$  eV

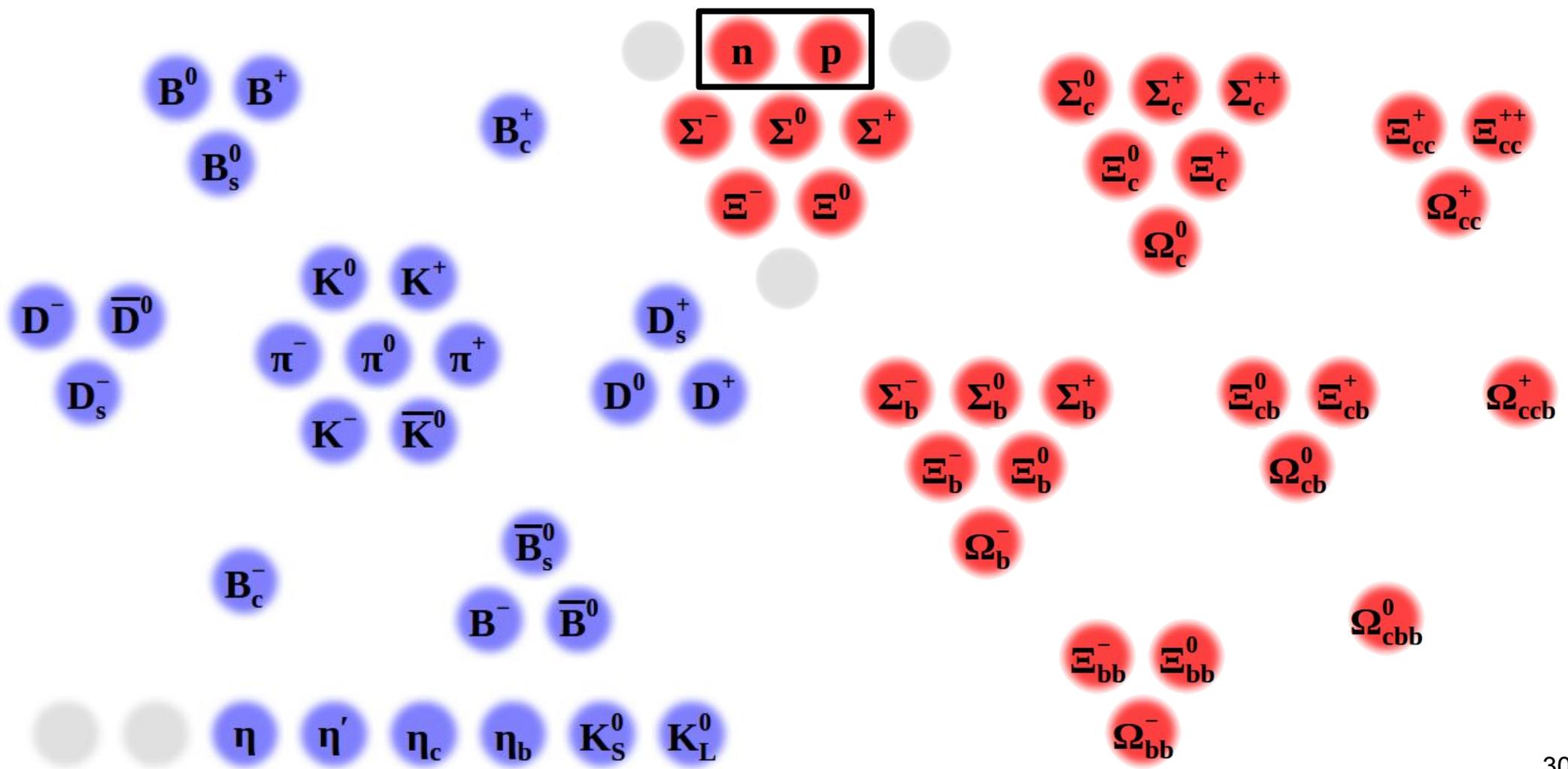
- **Protone = 1 GeV**



# Masse



# LO ZOO



# Da ricordare



- La natura è **matematica**
- Equazioni dalle **simmetrie**
- Tutto è fatto di **particelle**
- **Masse** misurate in GeV
  - Protone                      1 GeV
  - Bosone Z                      90 GeV
  - Bosone Higgs                125 GeV

# Decadimenti



# Decadimenti

- Poche particelle sono stabili
  - Elettrone, protone e neutrini
- Le altre **decadono** in quelle più stabili
  - Con un tempo caratteristico
- Più tardi vedremo
  - **Z**  $\rightarrow e^+e^-$ ,  $\rightarrow \mu^+\mu^-$ , ...
  - **J/Y(cc)**  $\rightarrow e^+e^-$ ,  $\rightarrow \mu^+\mu^-$ , ...
  - **U** (bb)  $\rightarrow e^+e^-$ ,  $\rightarrow \mu^+\mu^-$ , ...



# Decadimenti

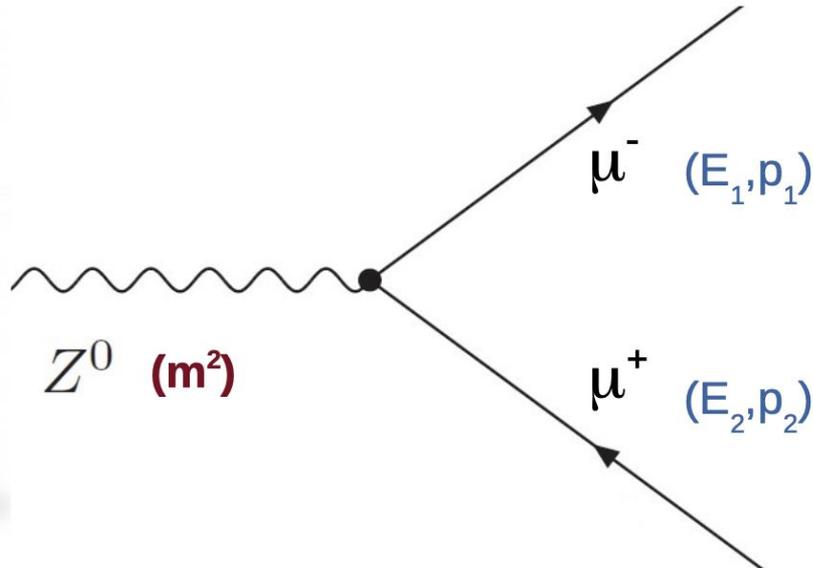
- Poche particelle sono stabili
  - Elettrone, protone e neutrini
- Le altre **decadono** in quelle più stabili
  - Con un tempo caratteristico
- Più tardi vedremo
  - **Z**  $\rightarrow e^+e^-$ ,  $\rightarrow \mu^+\mu^-$ , ...
  - **J/Y(cc)**  $\rightarrow e^+e^-$ ,  $\rightarrow \mu^+\mu^-$ , ...
  - **U** (bb)  $\rightarrow e^+e^-$ ,  $\rightarrow \mu^+\mu^-$ , ...



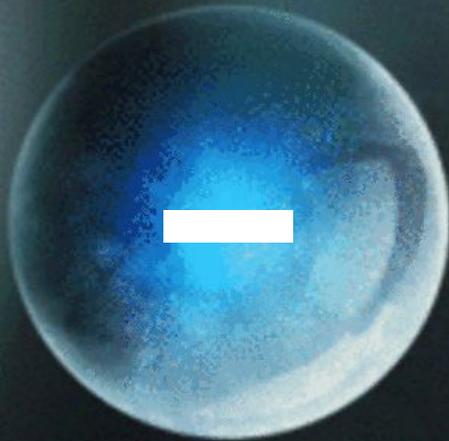
# Conservazione energia e impulso

Misurando **energia** e **impulso** dei prodotti di decadimento  
→ si può risalire alla **massa** della particella iniziale

$$m^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$



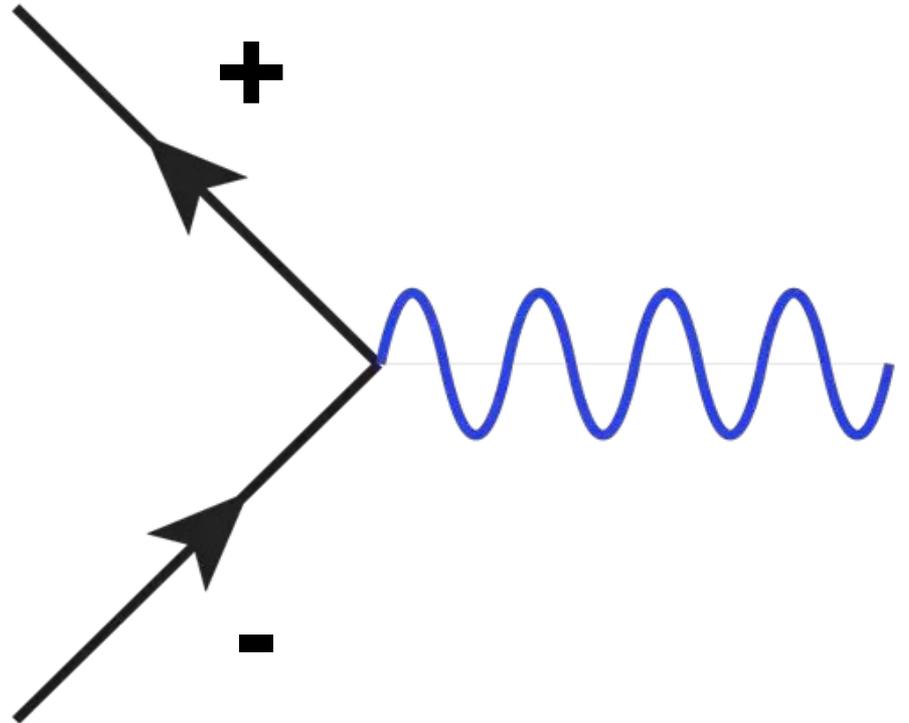
# Antimateria



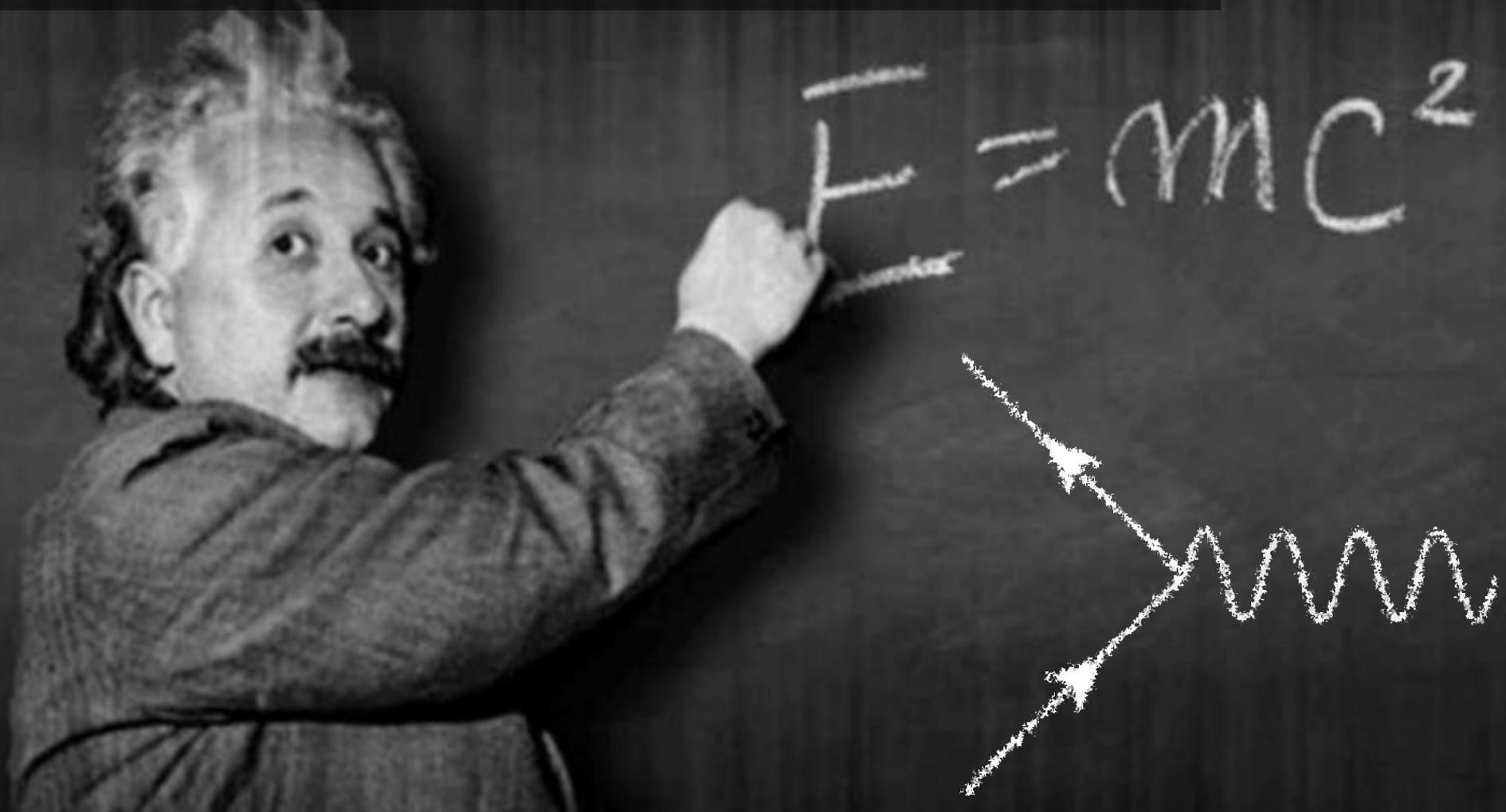
Ogni particella → antiparticella  
stessa massa ma carica opposta

# Antimateria

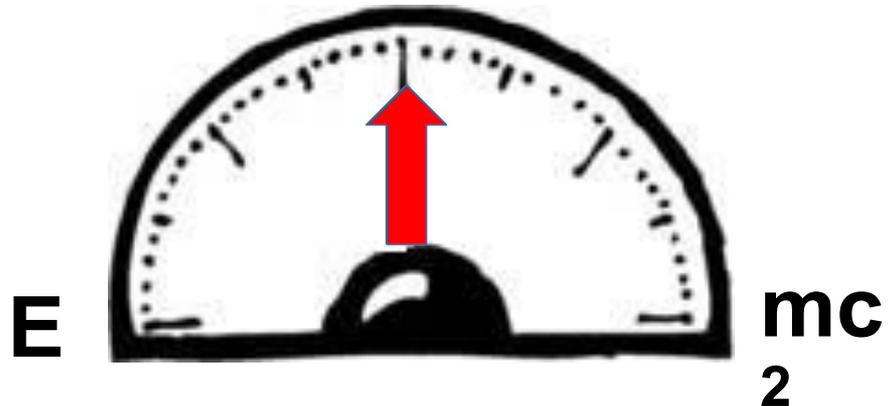
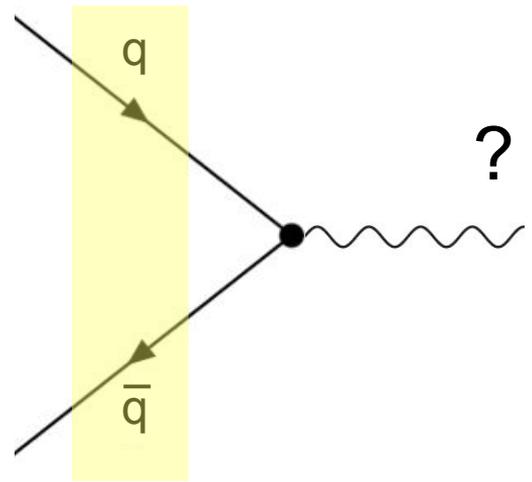
- Se una **particella** incontra la sua **anti-particella** si **annichilano**
  - La **massa** diventa **energia**  
 $E=mc^2$
  - Particelle a carica neutra: fotoni, gluoni o il bosone Z



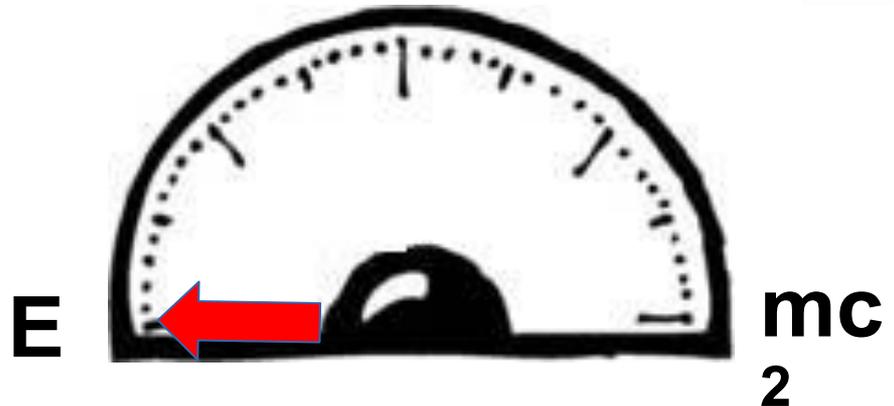
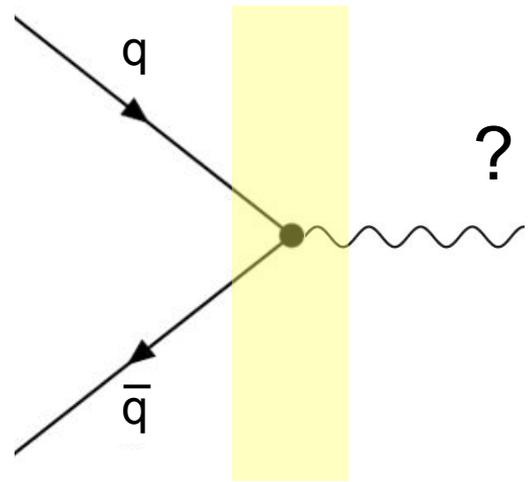
# Come produrre nuove particelle?



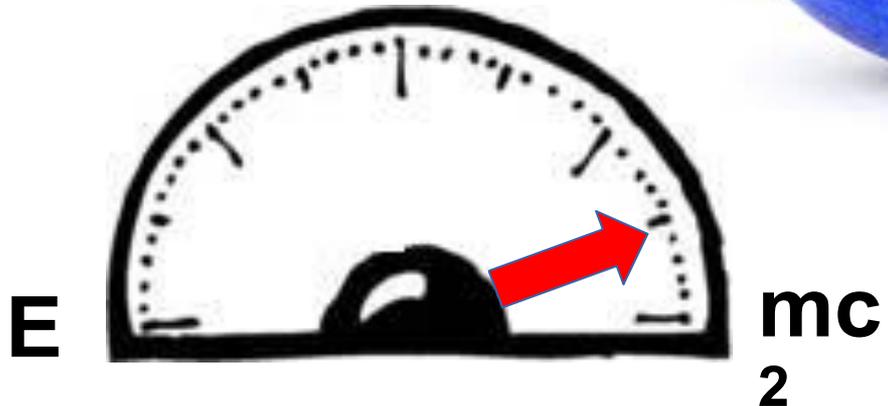
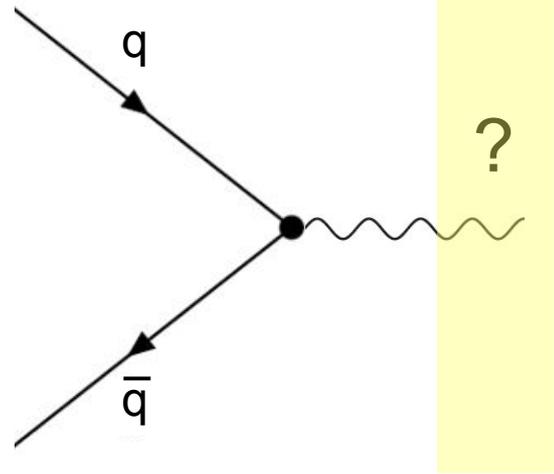
# Collider



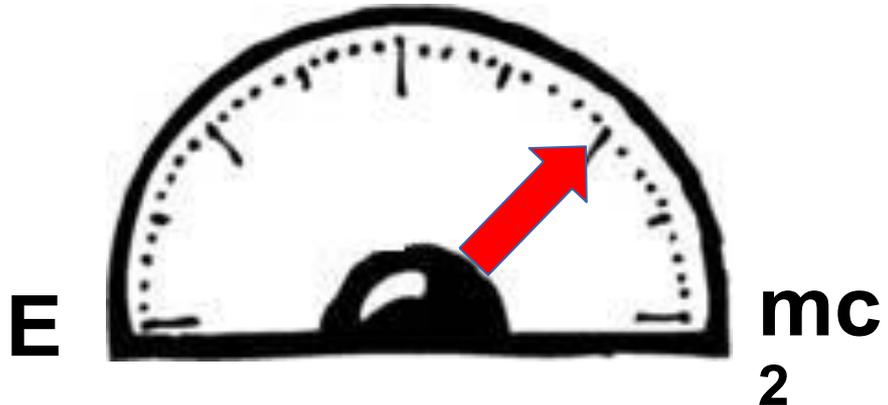
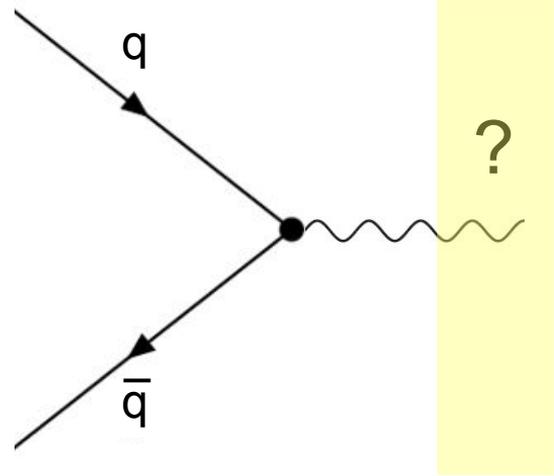
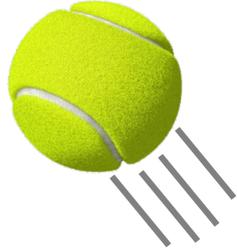
# Collider



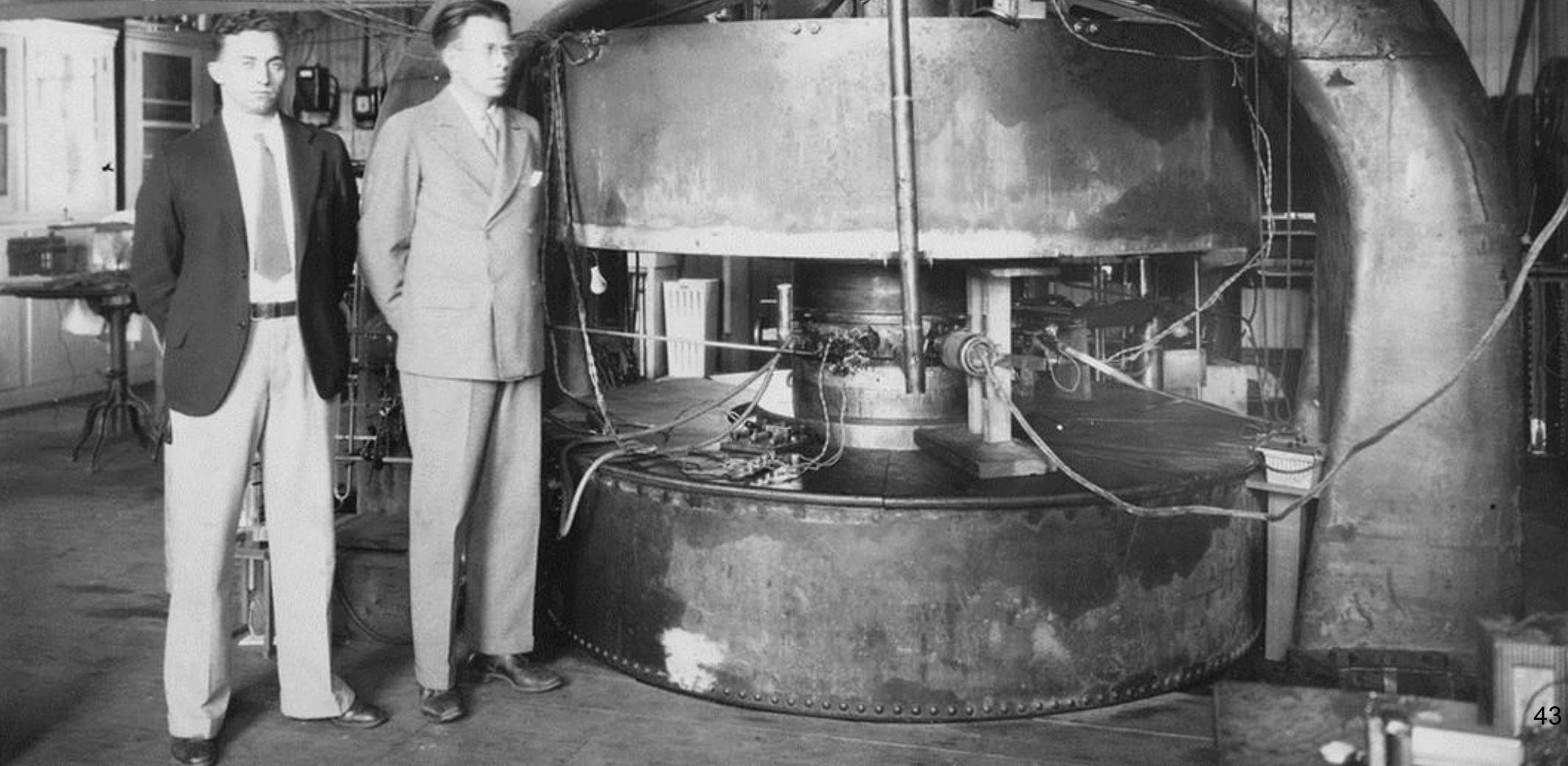
# Collider



# Collider



# Livingstone Lawrence '32



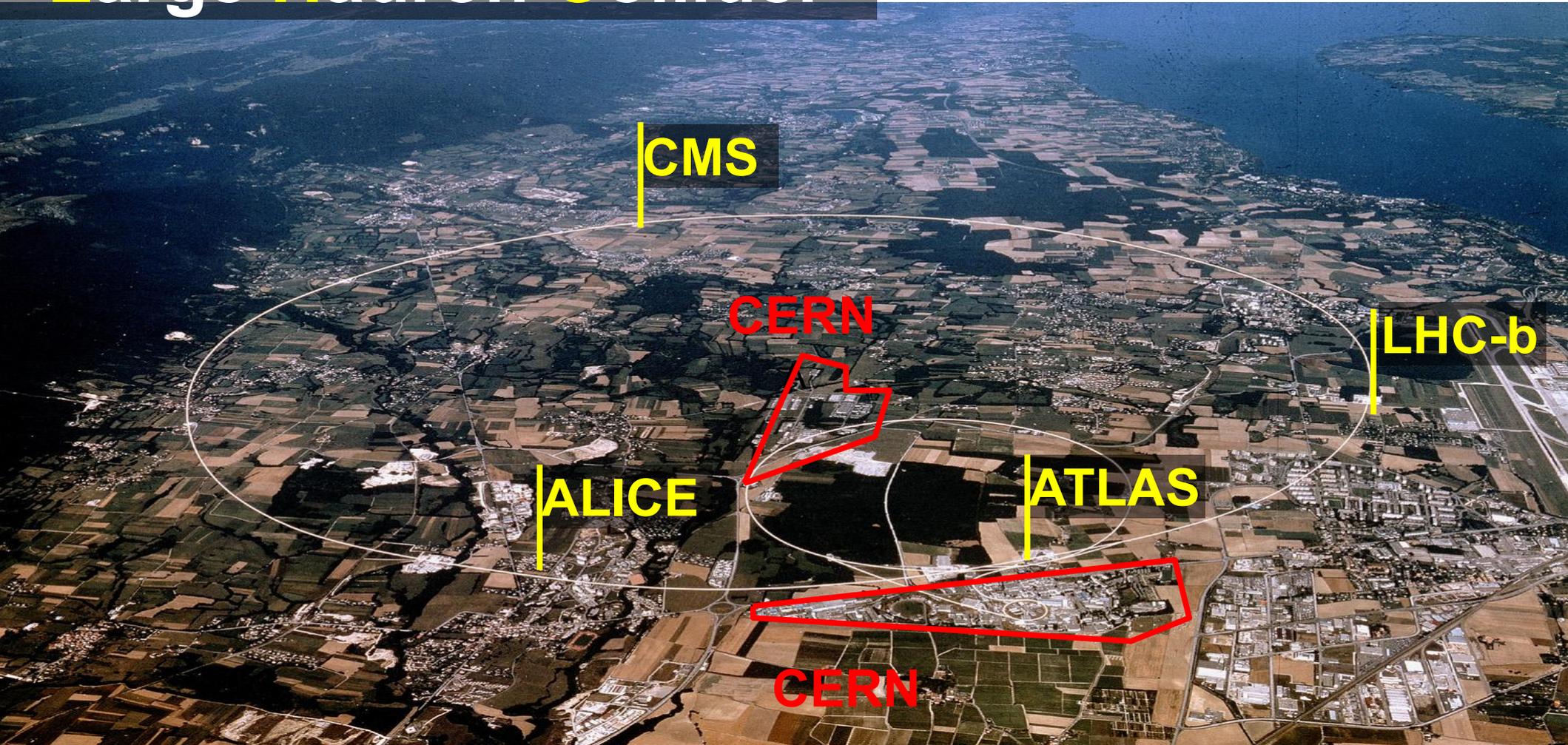
# Anello di Accumulazione '60



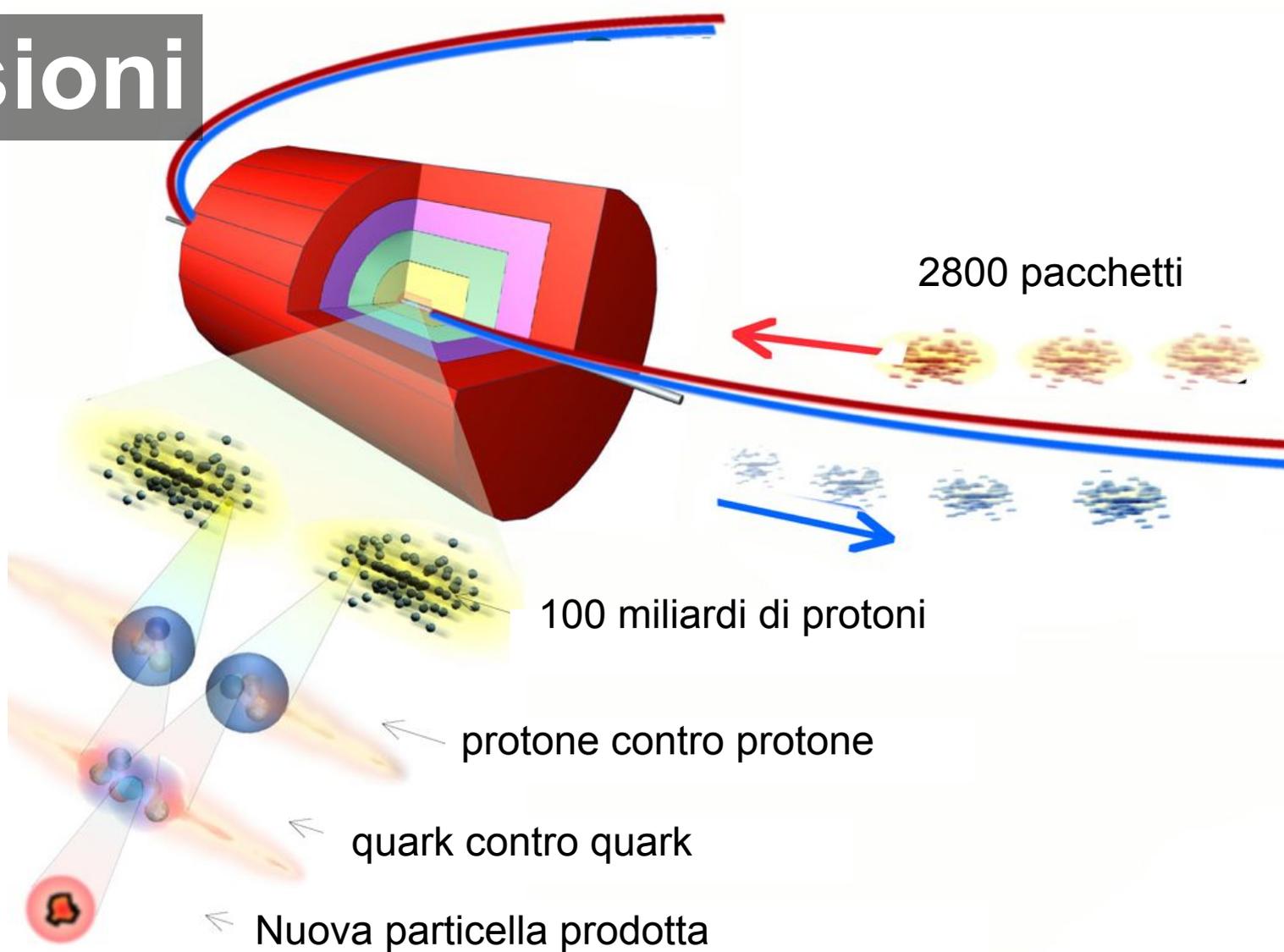
# Large Hadron Collider



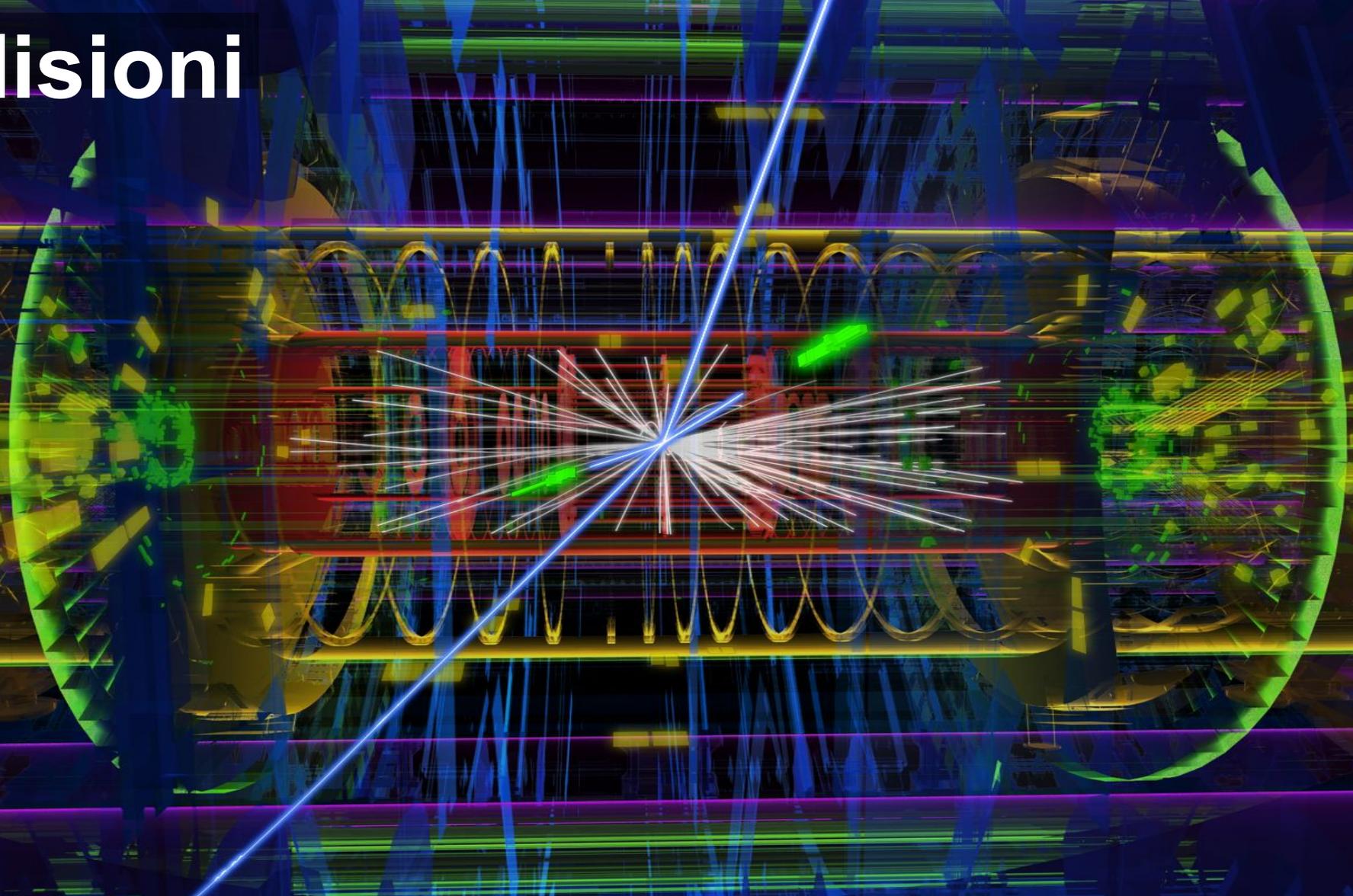
# Large Hadron Collider



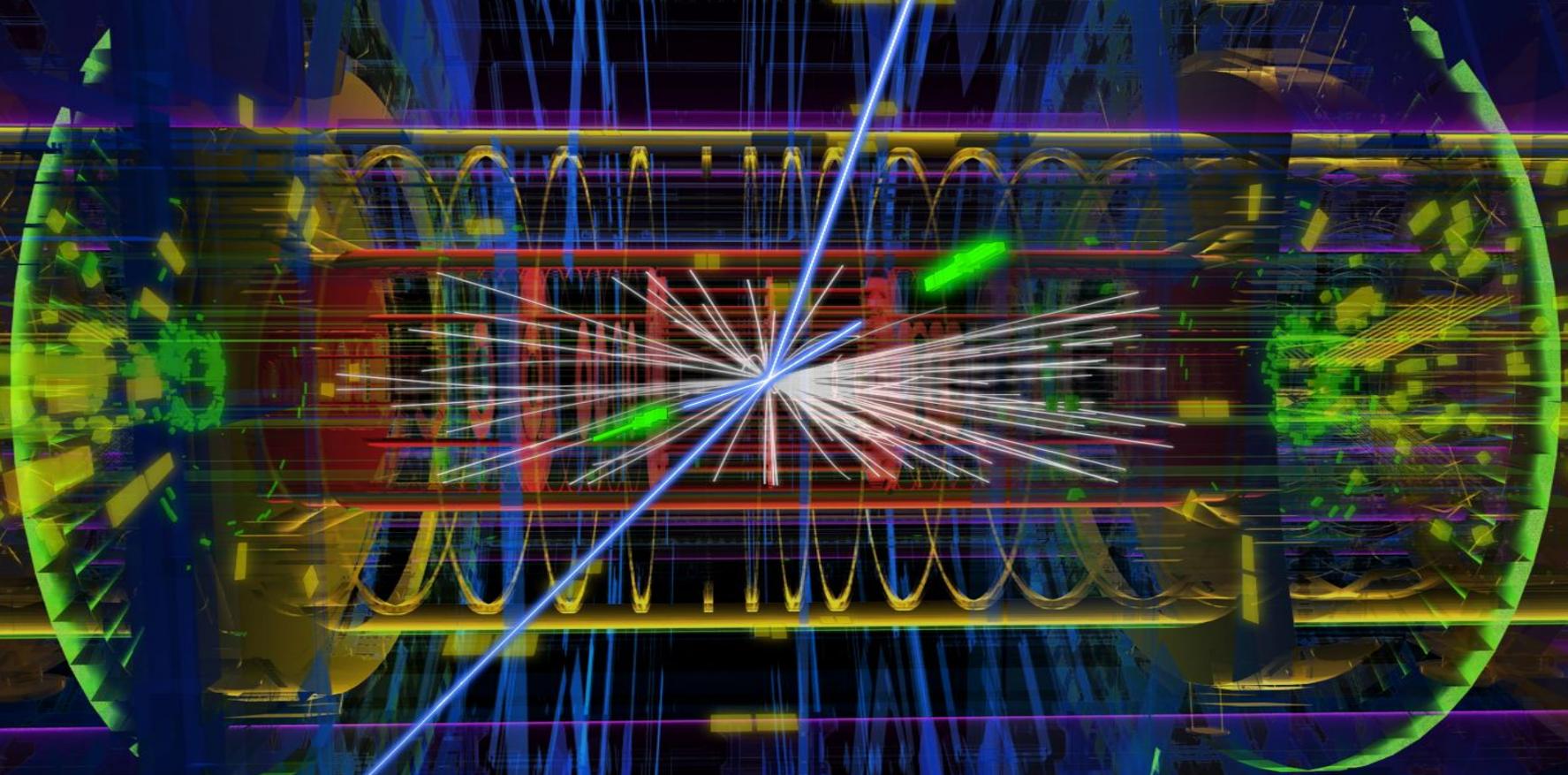
# Collisioni



# Collisioni



**Collisioni: 40 milioni al secondo**



# Eventi rari

Segnale/fondo:

$$1/10^{10}$$

- 1 granello ogni 400 secchielli



# Da ricordare



- Acceleratore da **27 km**
  - Per far collidere ad alta energia particelle leggere
- Per produrre **particelle massive**
  - $E=mc^2$  e annichilazione
- Le particelle massive **decadono** in quelle stabili, che riveliamo
- **Eventi rari**, necessari milioni di scontri al secondo

# Rivelatori di particelle



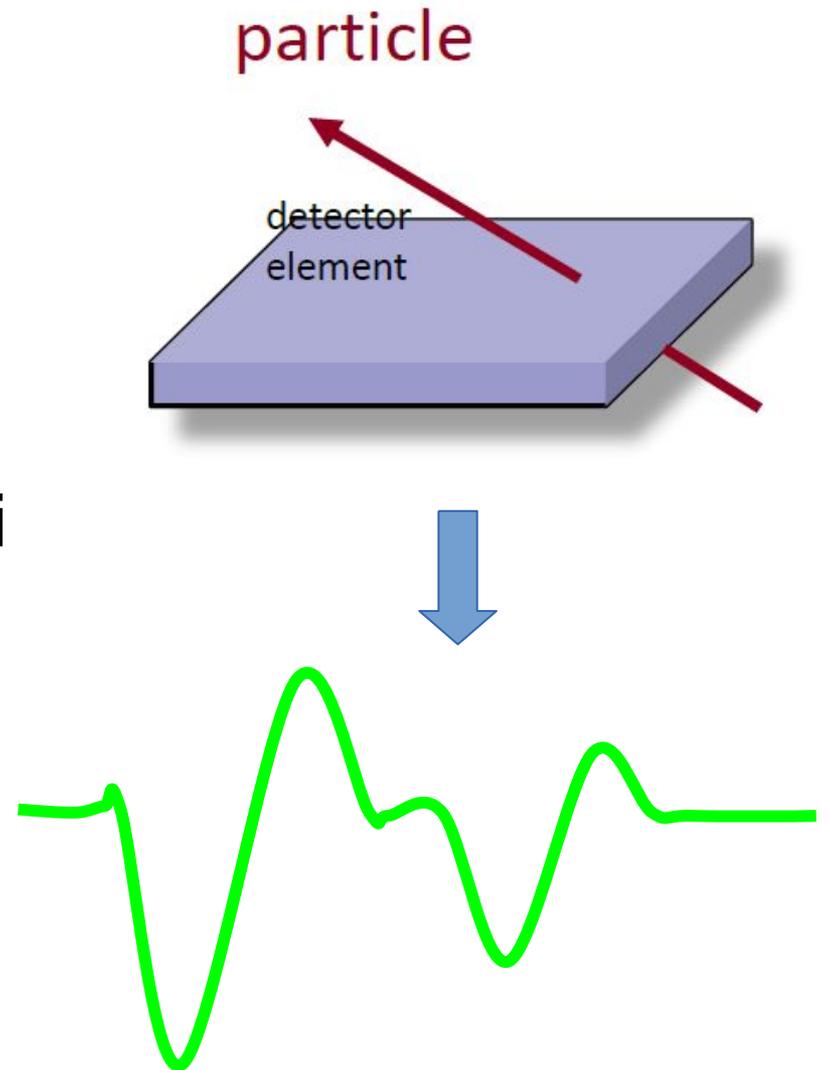


## **Sempre lui:**

“It doesn’t matter how beautiful your theory is. If it doesn’t agree with experiment, it’s wrong.”

# Rivelatori di particelle

- **Interazione** delle particelle con la materia
- Liberazione di elettroni, ioni, fotoni
- Raccolta di **segnali elettrici**

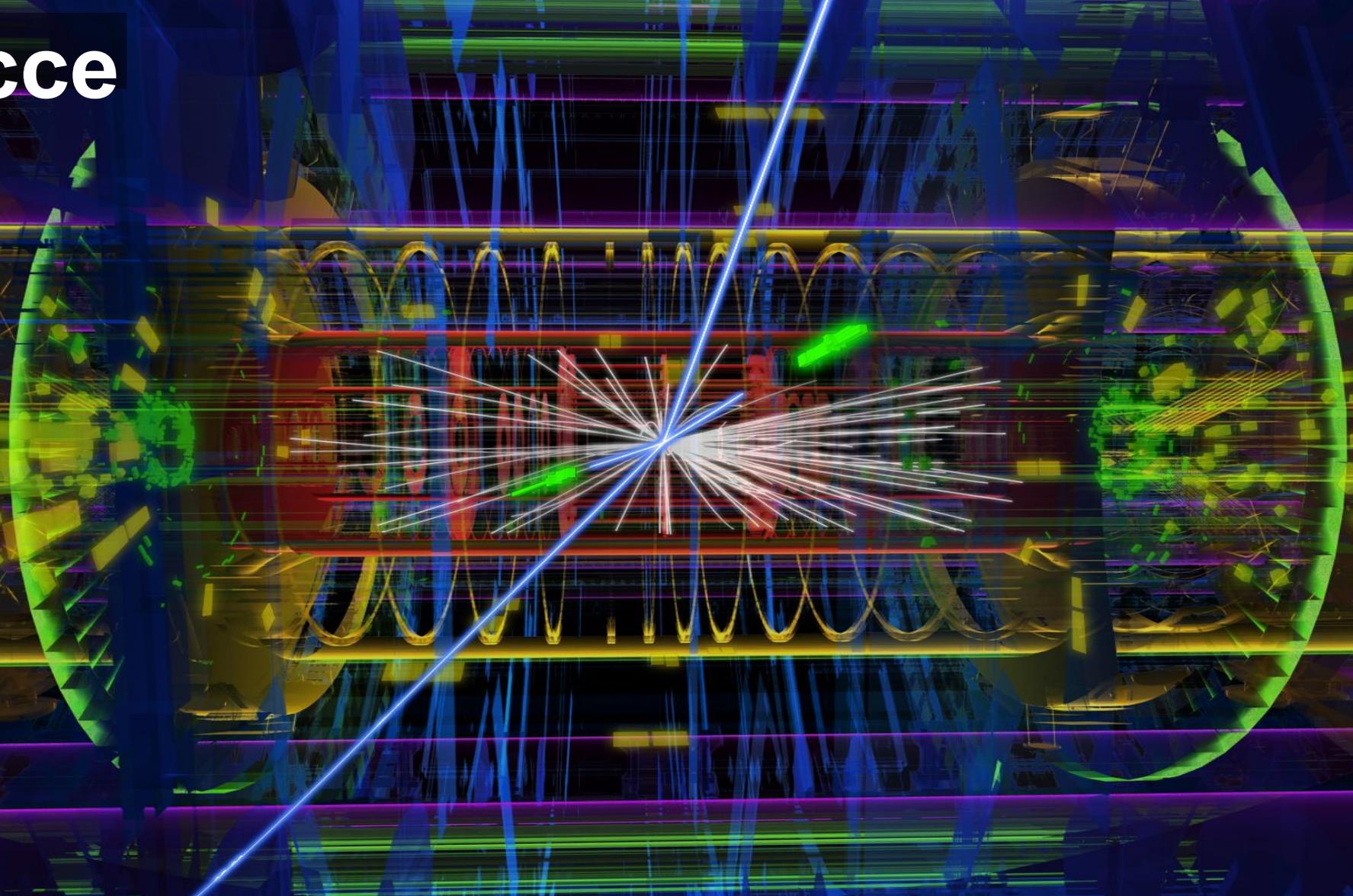


An aerial photograph of a particle detector, likely the ATLAS experiment at CERN, showing a complex network of white tracks crisscrossing a clear blue sky. The tracks are made of small droplets or ice crystals, forming a dense web of lines that intersect at various angles. The tracks are most prominent in the lower half of the image, where they form a grid-like pattern. The sky is a deep, clear blue, providing a high-contrast background for the white tracks.

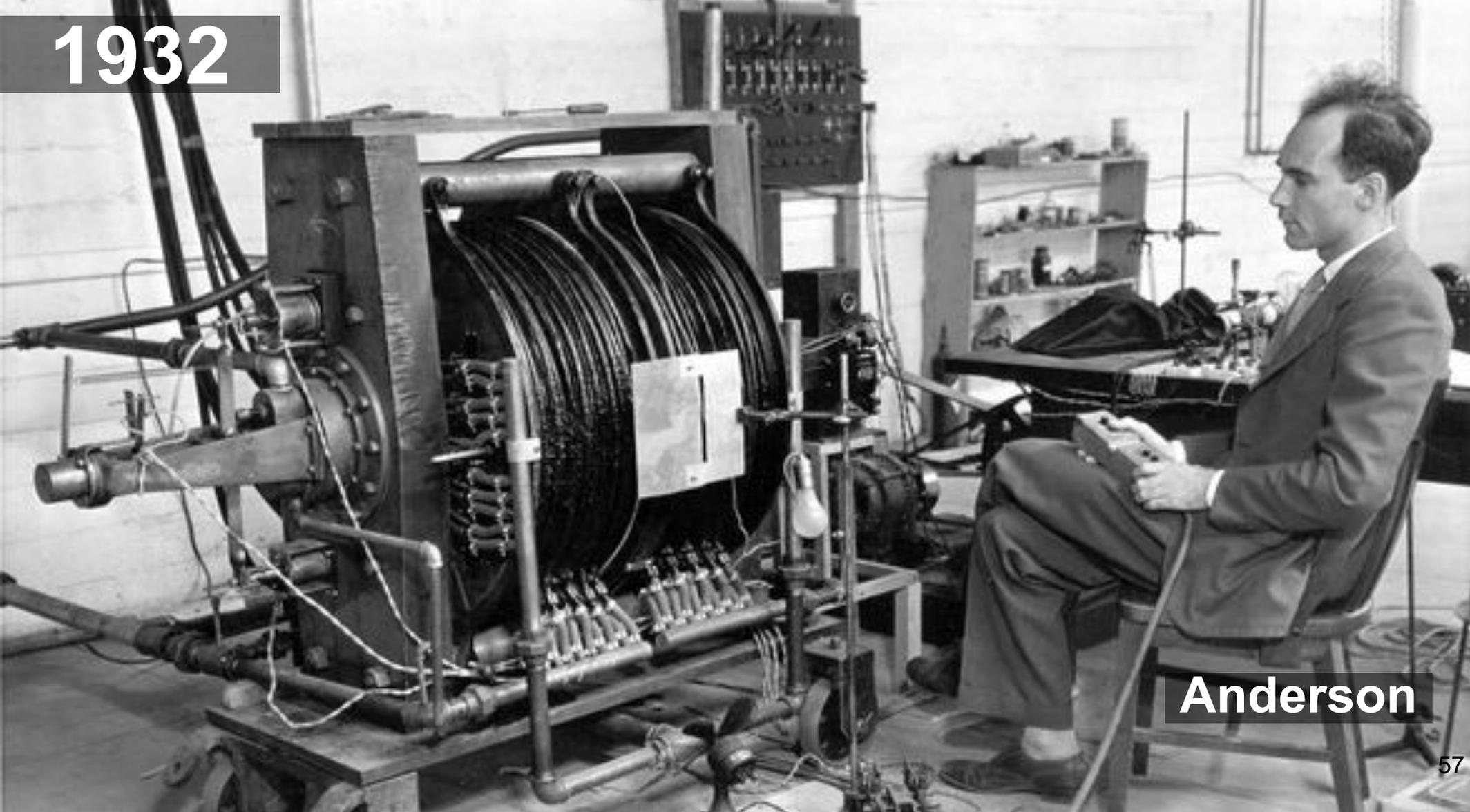
**Rivelatori di  
particelle**

**Seguire le  
scie**

# Tracce

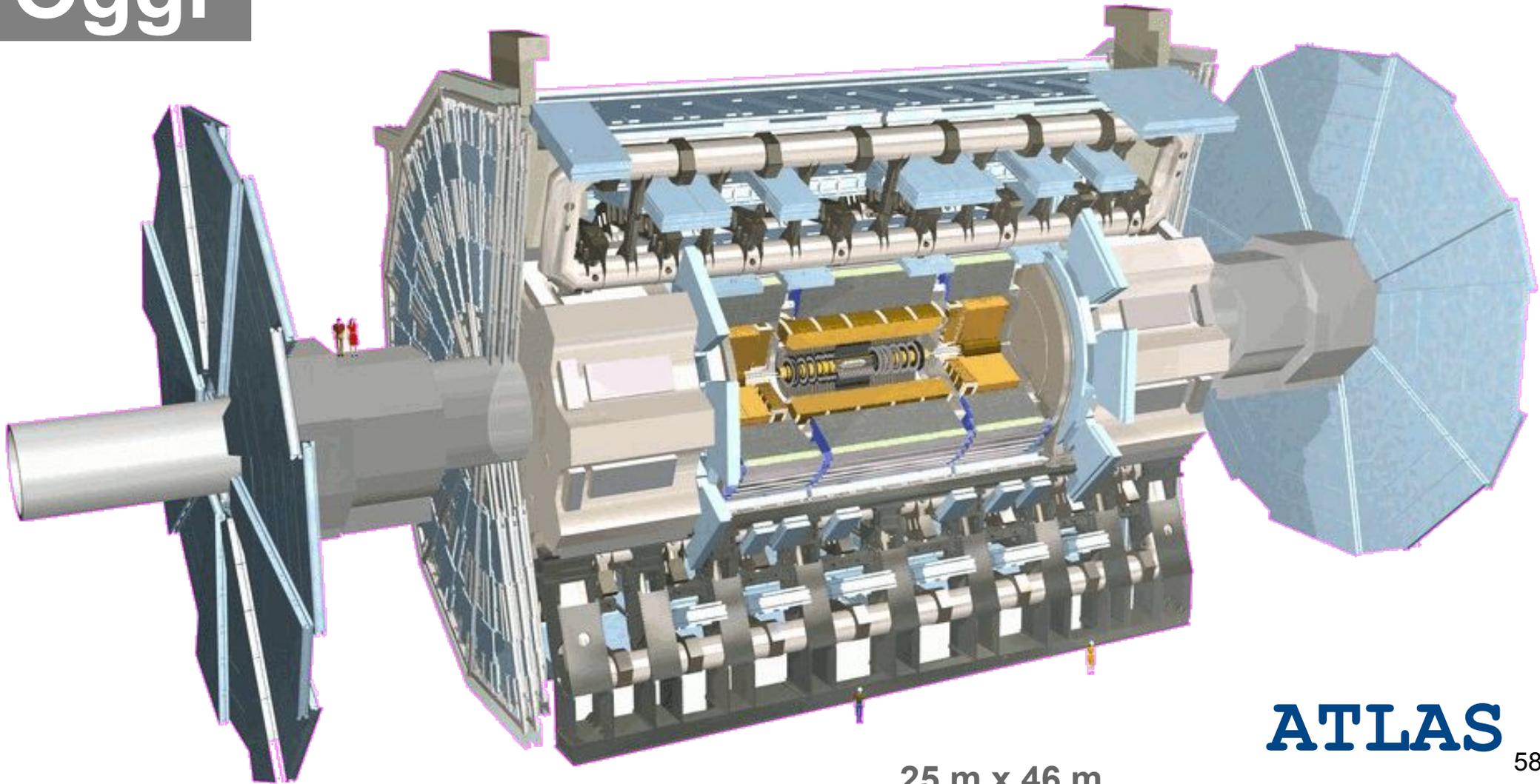


1932



Anderson

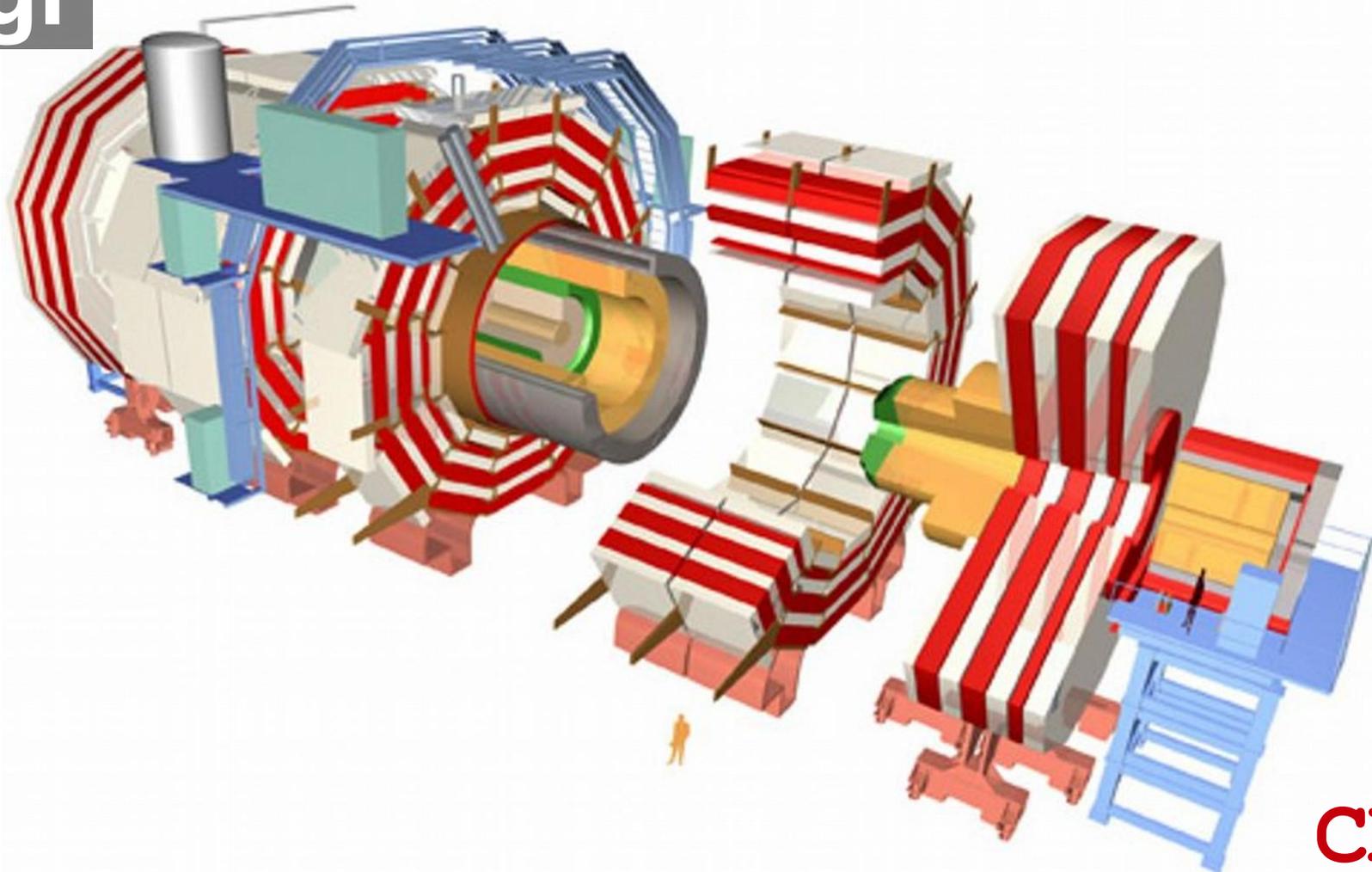
Oggi



25 m x 46 m

**ATLAS**

Oggi



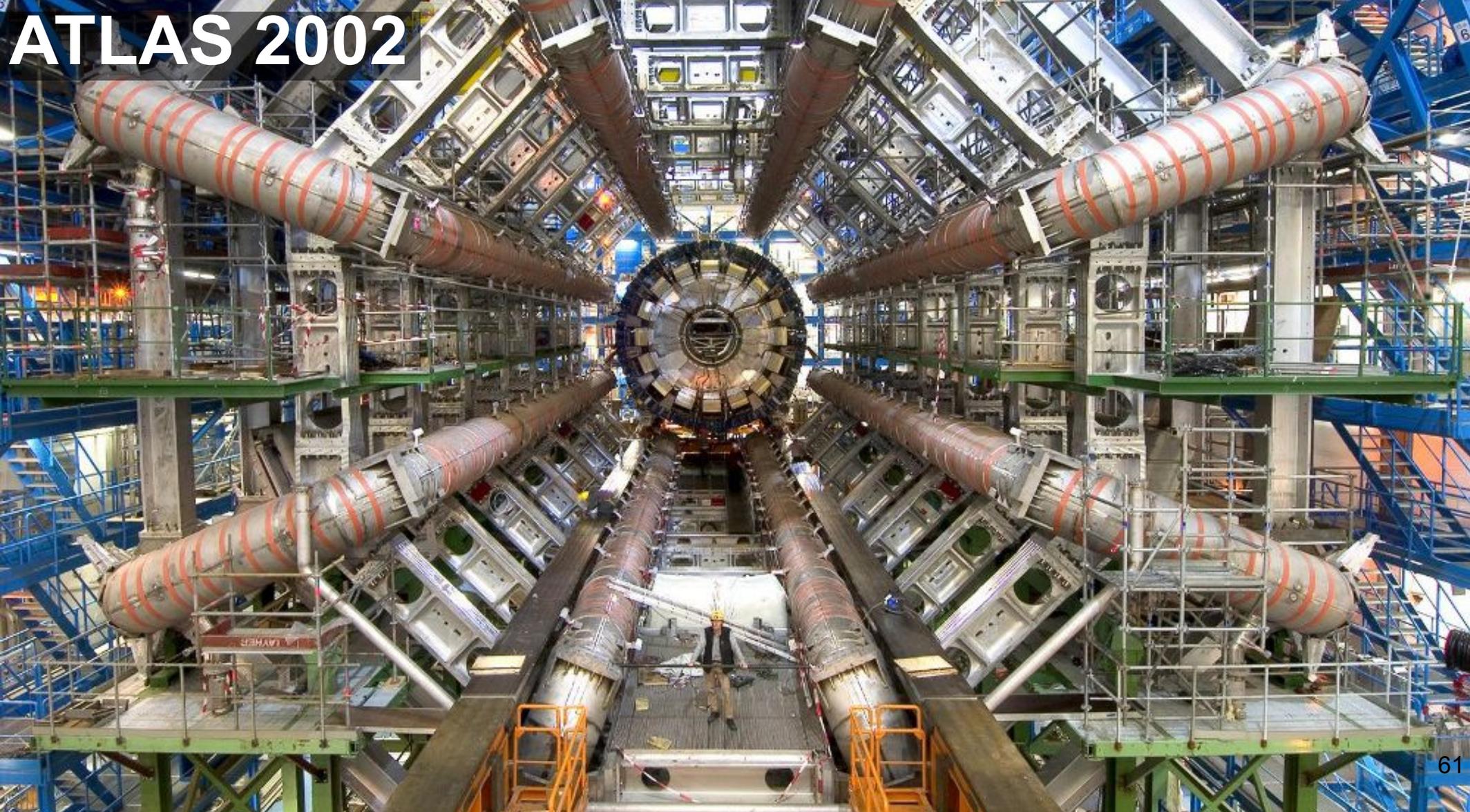
15 m x 21 m

**CMS**

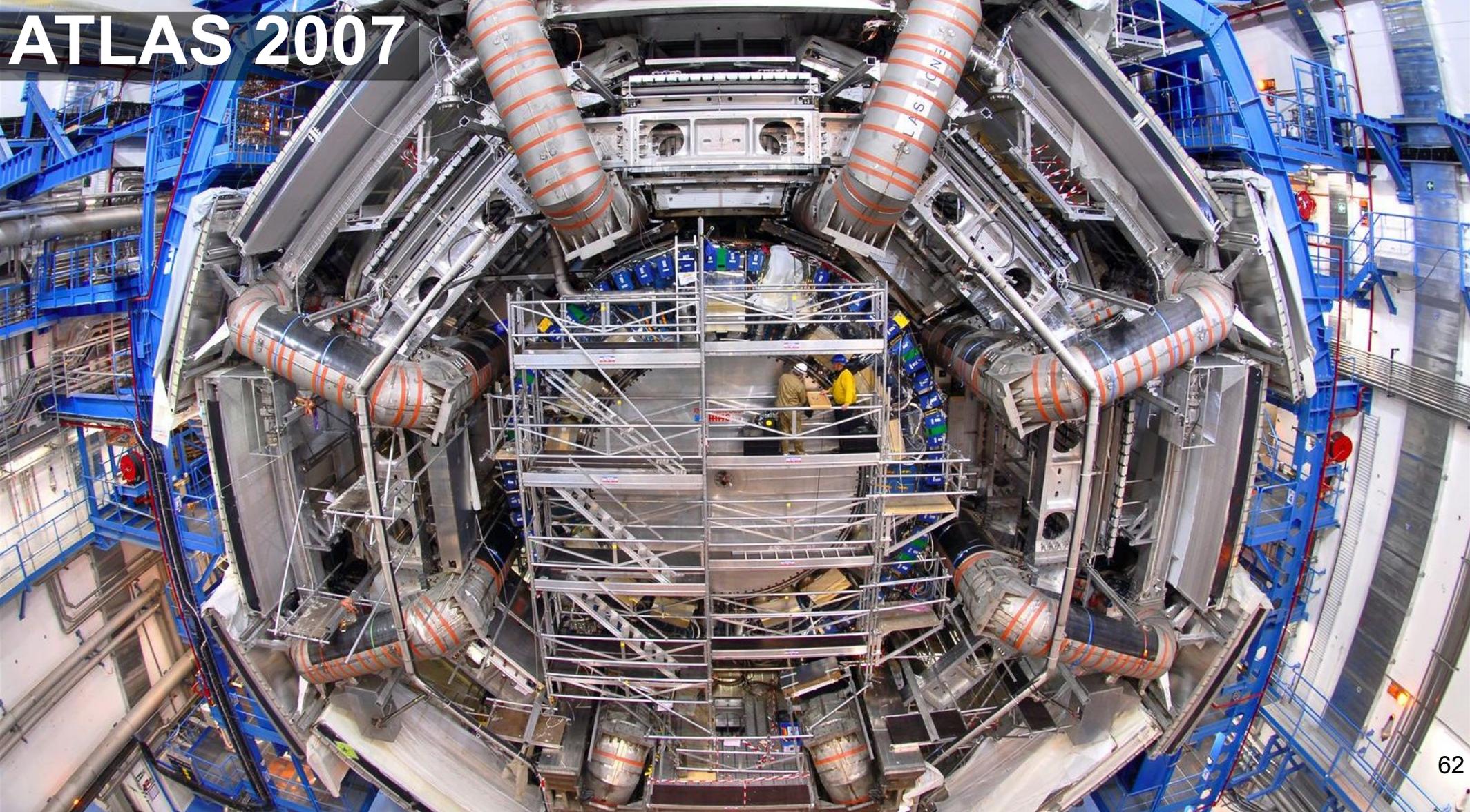
# ATLAS 2001



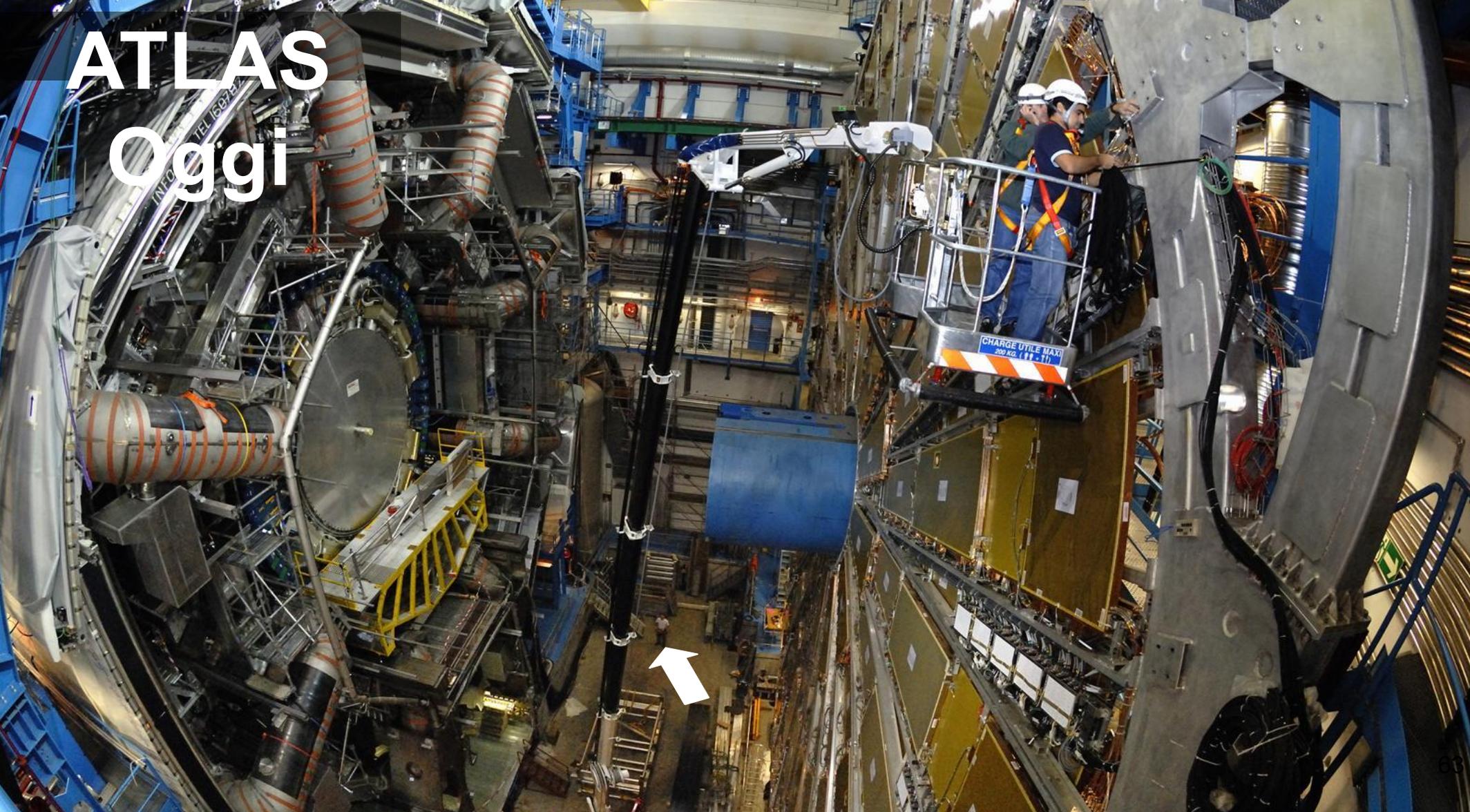
# ATLAS 2002



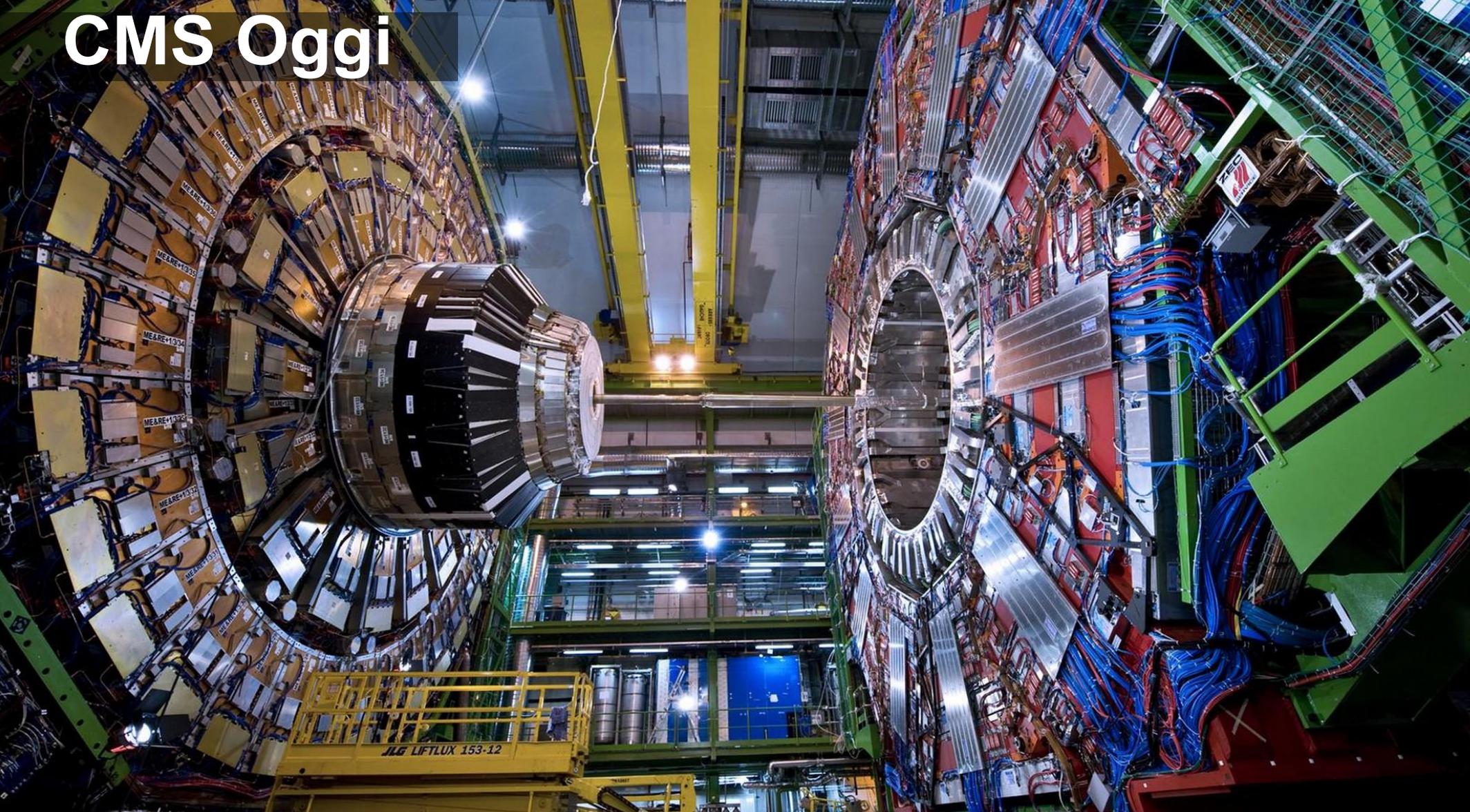
# ATLAS 2007



# ATLAS Oggi



# CMS Oggi



# ALICE Oggi



**Presa dati: 2010-12, 2015-18,  
2022-2025 ... 2038**

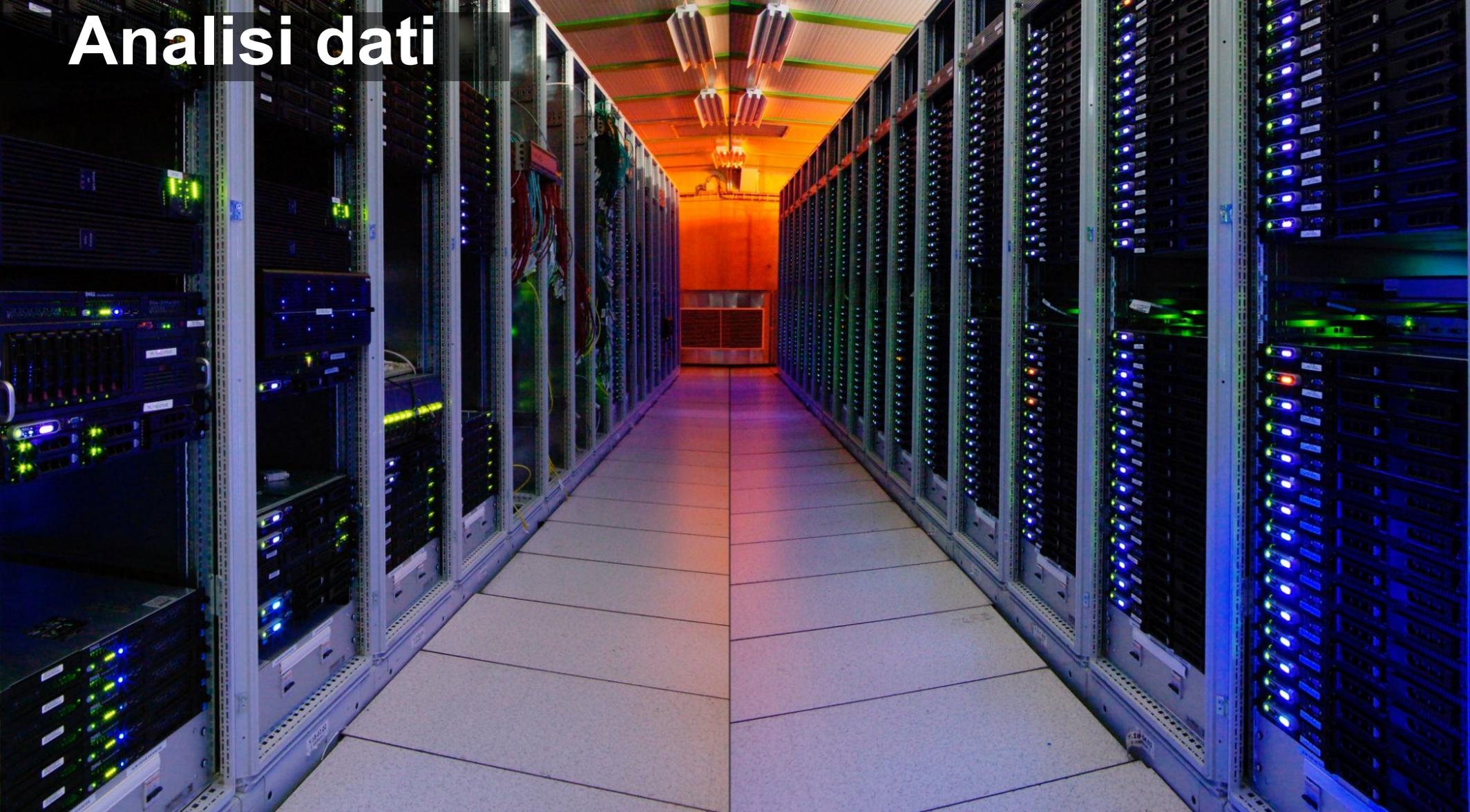


**Big data**



**~10 PB/anno**

# Analisi dati





CERN  
Ginevra

## CHE COS'È

È una **rete planetaria** che unisce e utilizza contemporaneamente la potenza di calcolo e la memoria di decine di migliaia di differenti computer sparsi nel mondo

### Nodi di I livello

- CNAF - Bologna, ITA
- In2p3 - Lione, FRA
- SARA - Amsterdam, OLA
- Ral - Oxford, GBR
- GridKa, Karlsruhe - Stoccarda, GER
- Fermilab - Chicago, USA
- Triumf - Vancouver, CAN
- Brookhaven - Long Island, USA
- Nordic - SVE-FIN-NOR
- Pic - Barcellona, SPA
- Assc - Taiwan, CIN

Fibra ottica  
dedicata  
per i nodi  
di I livello



L'utente può collegarsi alla Grid dal proprio pc e usare le risorse di calcolo che gli servono



**140** centri  
di calcolo  
in 33 Paesi

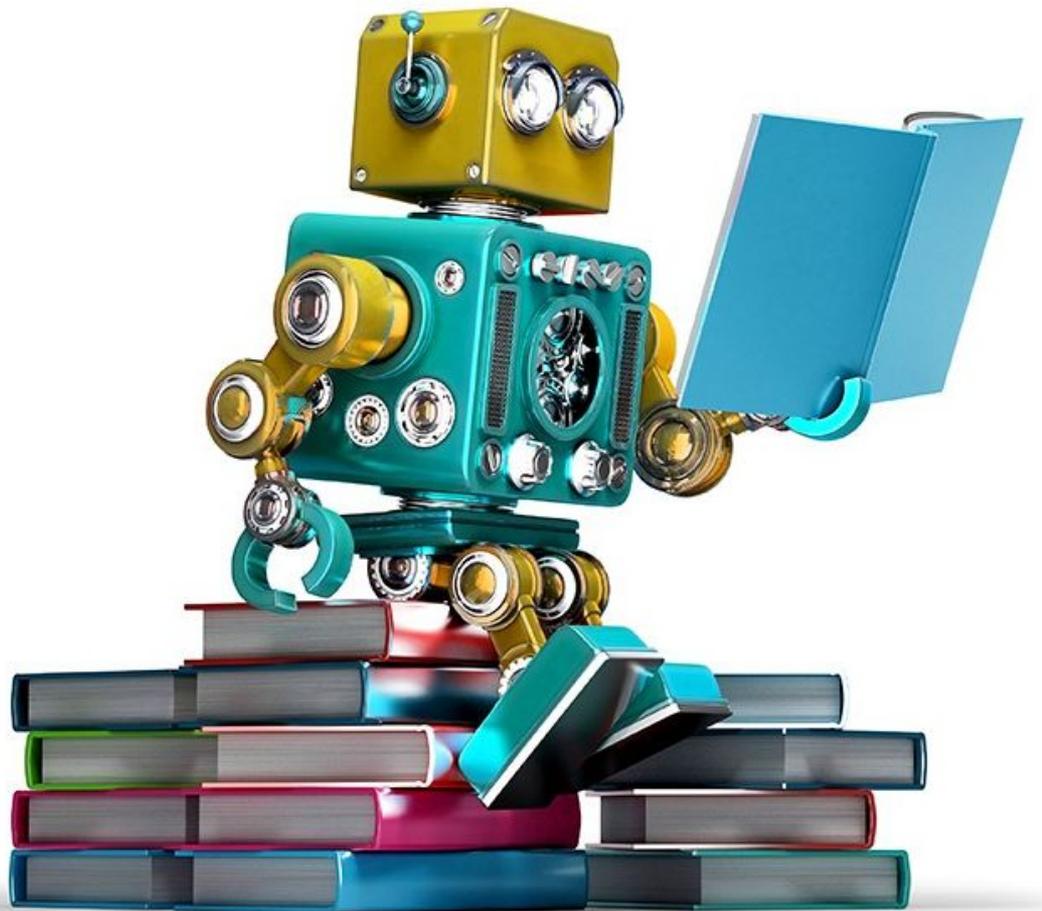


**Oltre 10.000**  
gli utenti che  
utilizzano Grid



La potenza  
di calcolo prodotta  
è pari a quella di **100.000** computer

# Machine Learning



Higgs  
challenge

**the HiggsML challenge**

May to September 2014

When High Energy Physics meets Machine Learning



Info to participate and compete : <https://www.kaggle.com/c/higgs-boson>



## Organization committee

Balázs Kégl - *Appstat/LAL*  
Claire Germain - *TAC/LRI*

David Rousseau - *Atlas/LAL*  
Glen Cowan - *Atlas-RHUL*

Isabelle Guyon - *Chaleam*  
Claire Adam-Bourdarios - *Atlas-LAL*

## Advisory committee

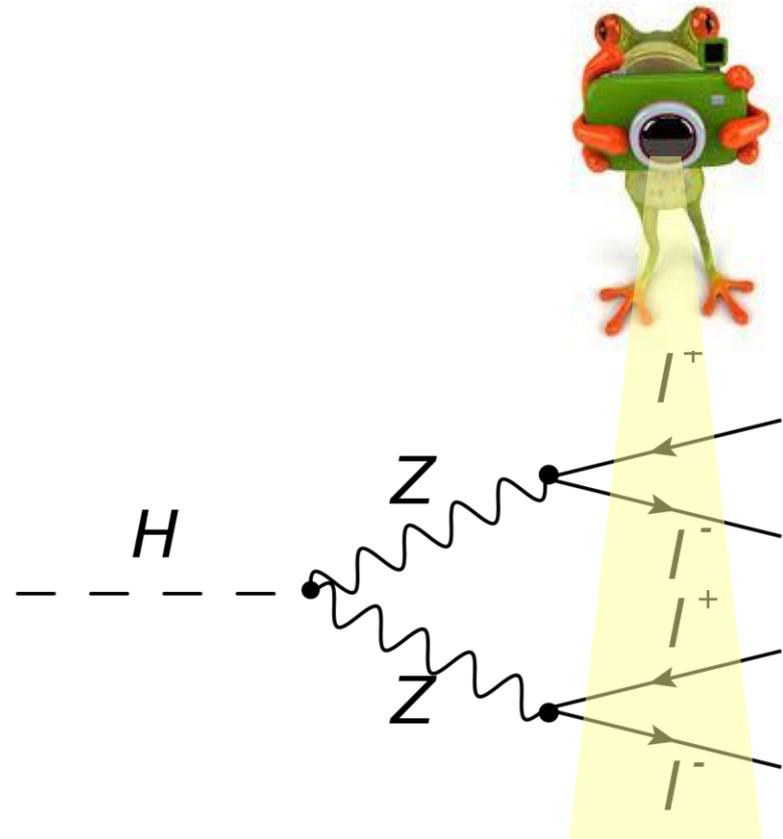
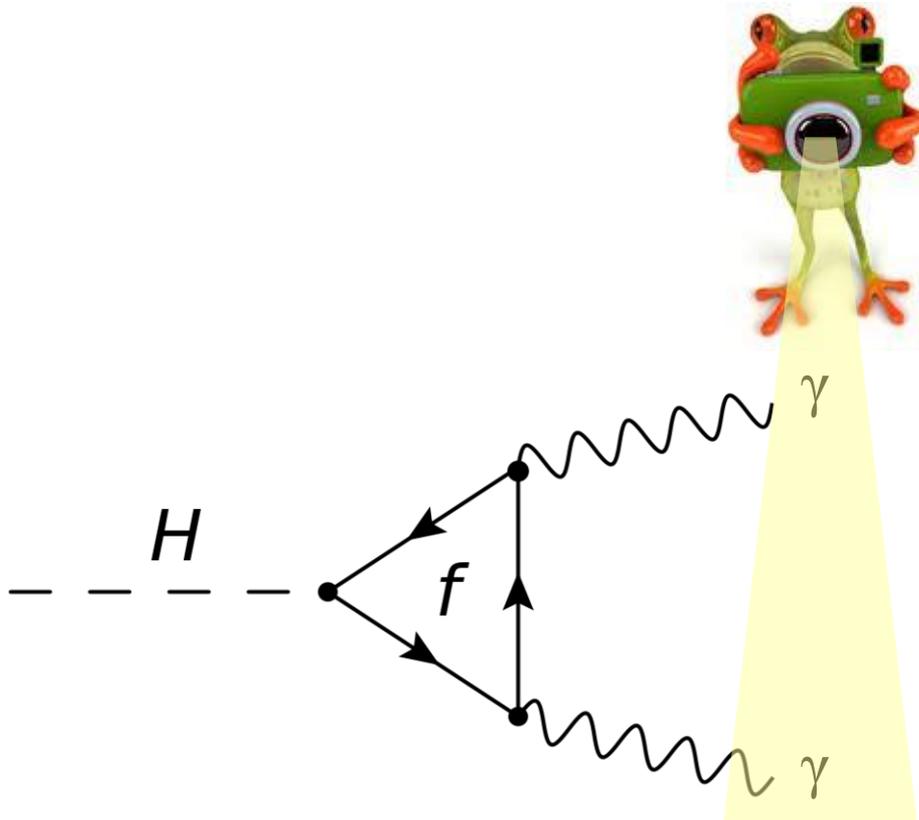
Thorsten Wengler - *Atlas-CERN*  
Andreas Hoecker - *Atlas-CERN*

Joerg Stelzer - *Atlas-CERN*  
Marc Schoenauer - *INRIA*

# Ricerca bosone di Higgs

L'Higgs non è stabile, **decade** in fotoni o leptoni

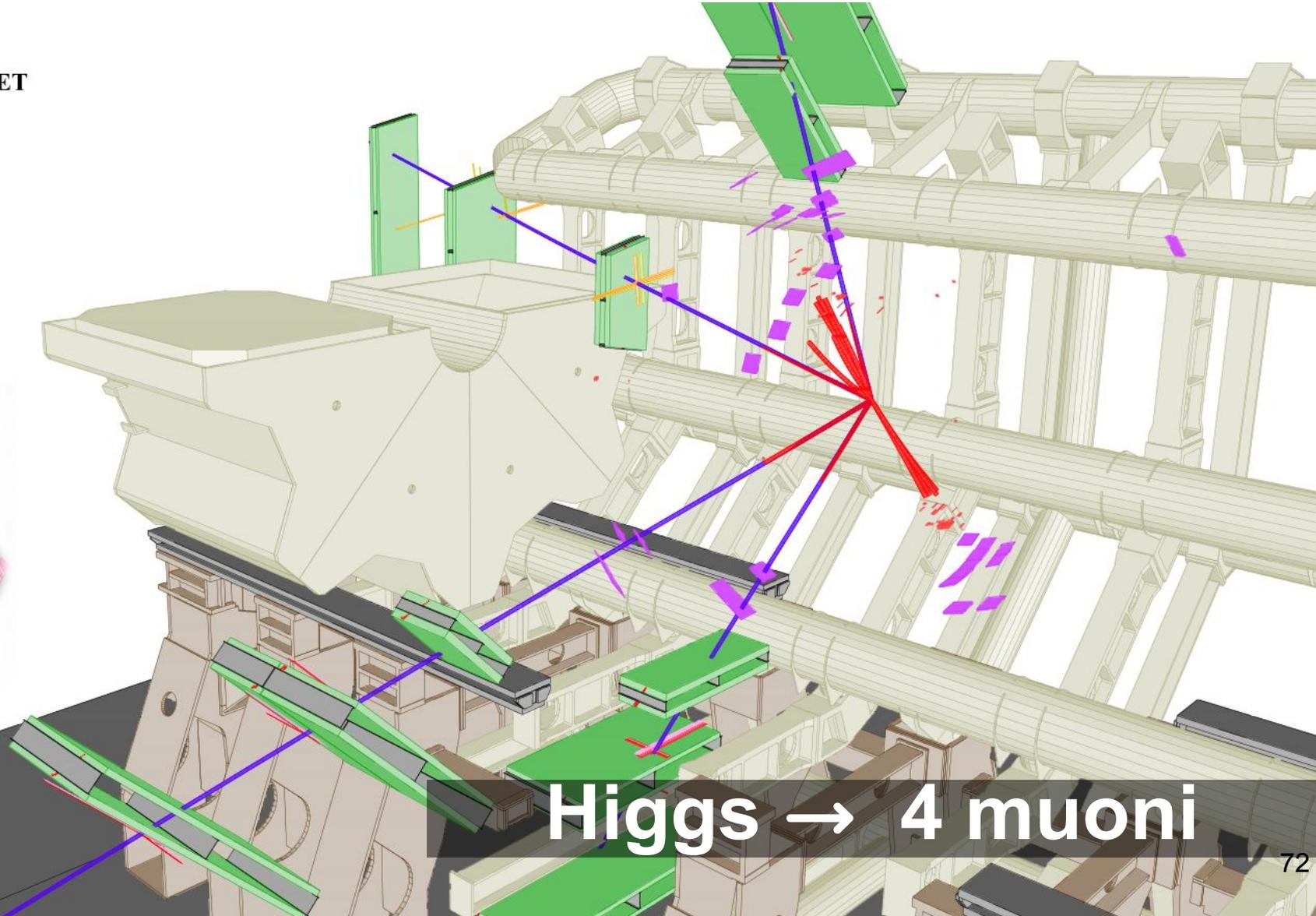
- Identificato partendo dai prodotti del suo decadimento



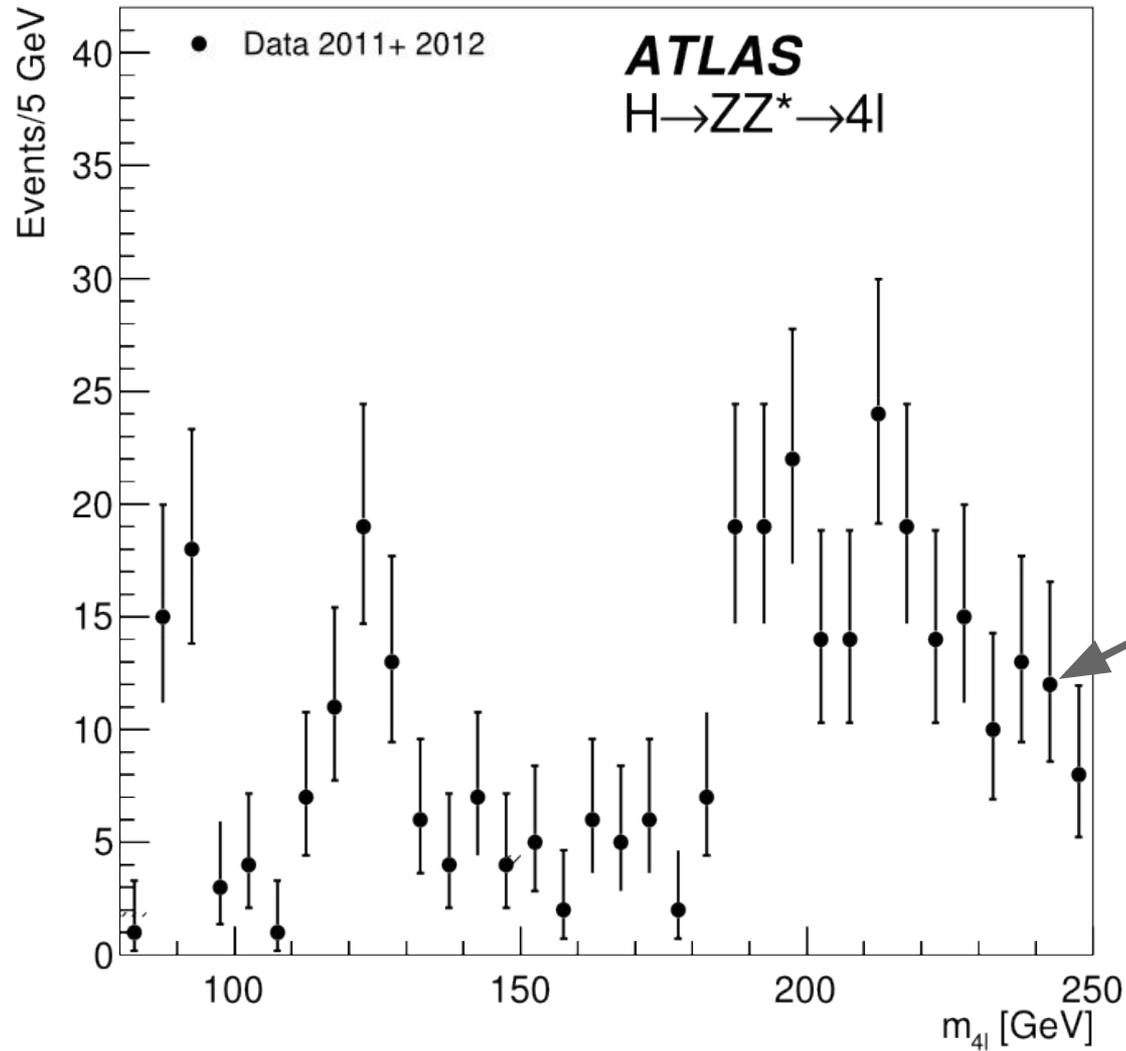
Run Number: 189280,  
Event Number: 143576946  
Date: 2011-09-14, 11:37:11 CET

EtCut > 0.3 GeV  
PtCut > 3.0 GeV  
Vertex Cuts:  
Z direction < 1cm  
Rphi < 1cm

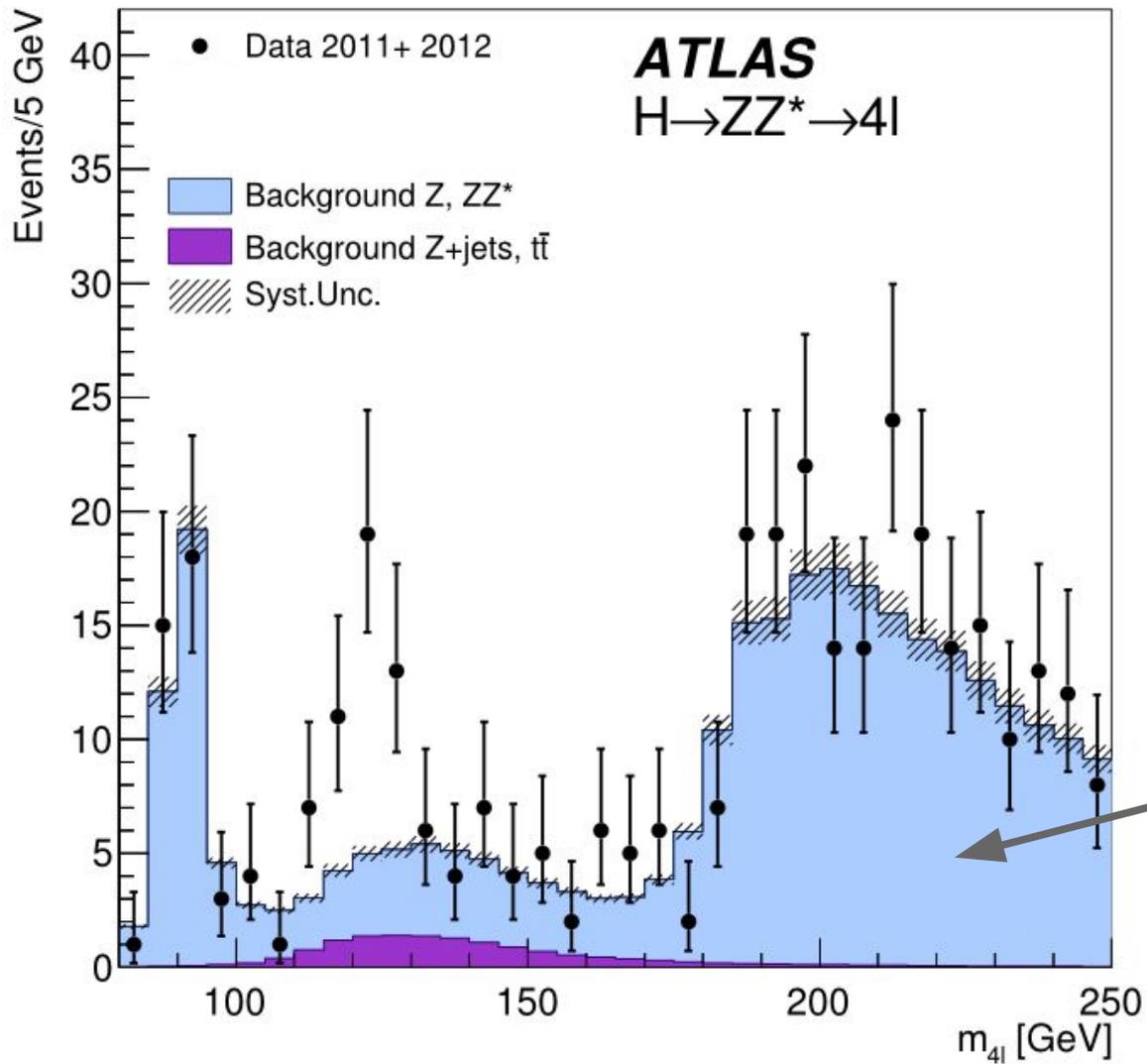
Muon: blue  
Cells: Tiles, EMC



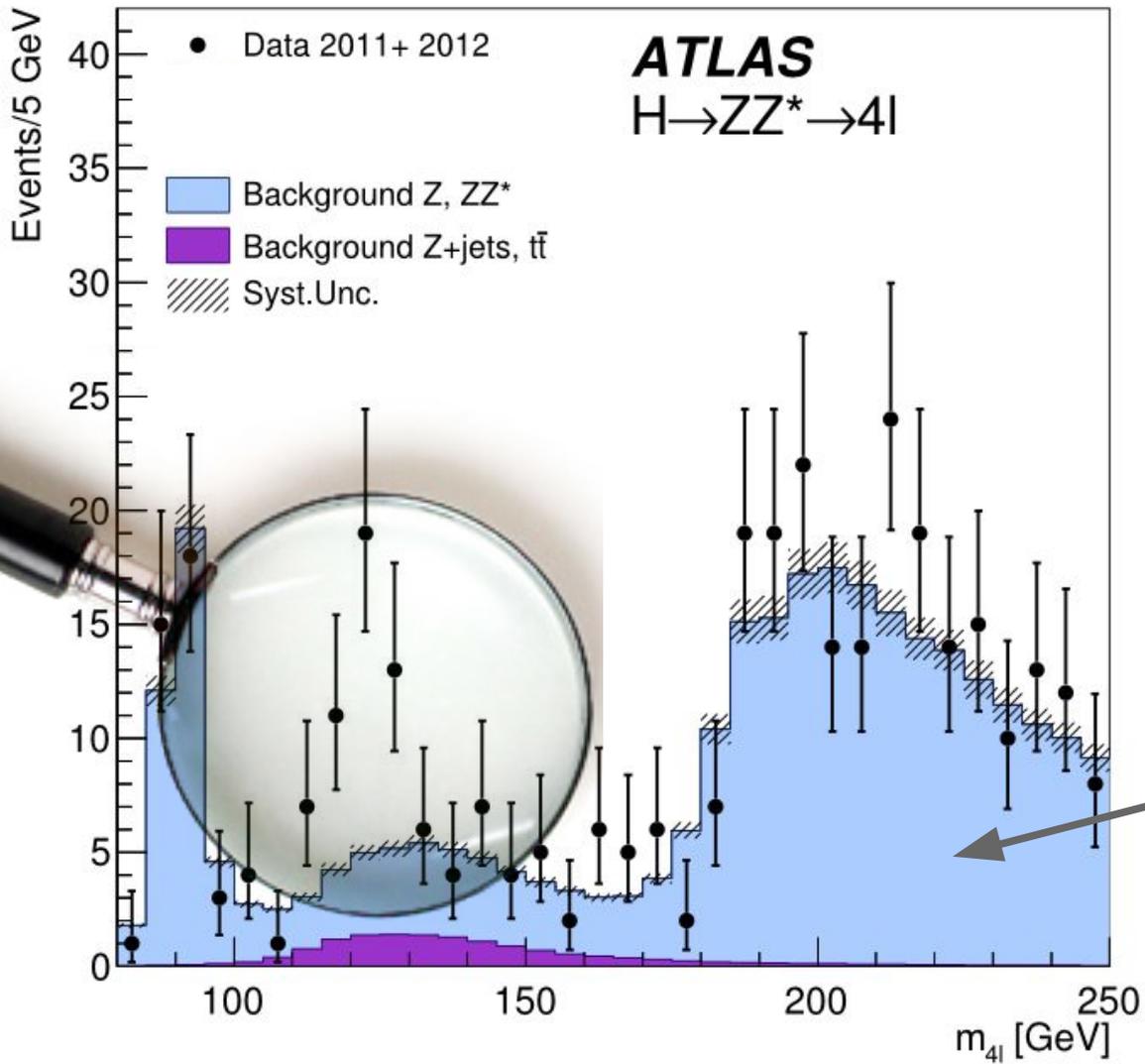
Higgs → 4 muoni



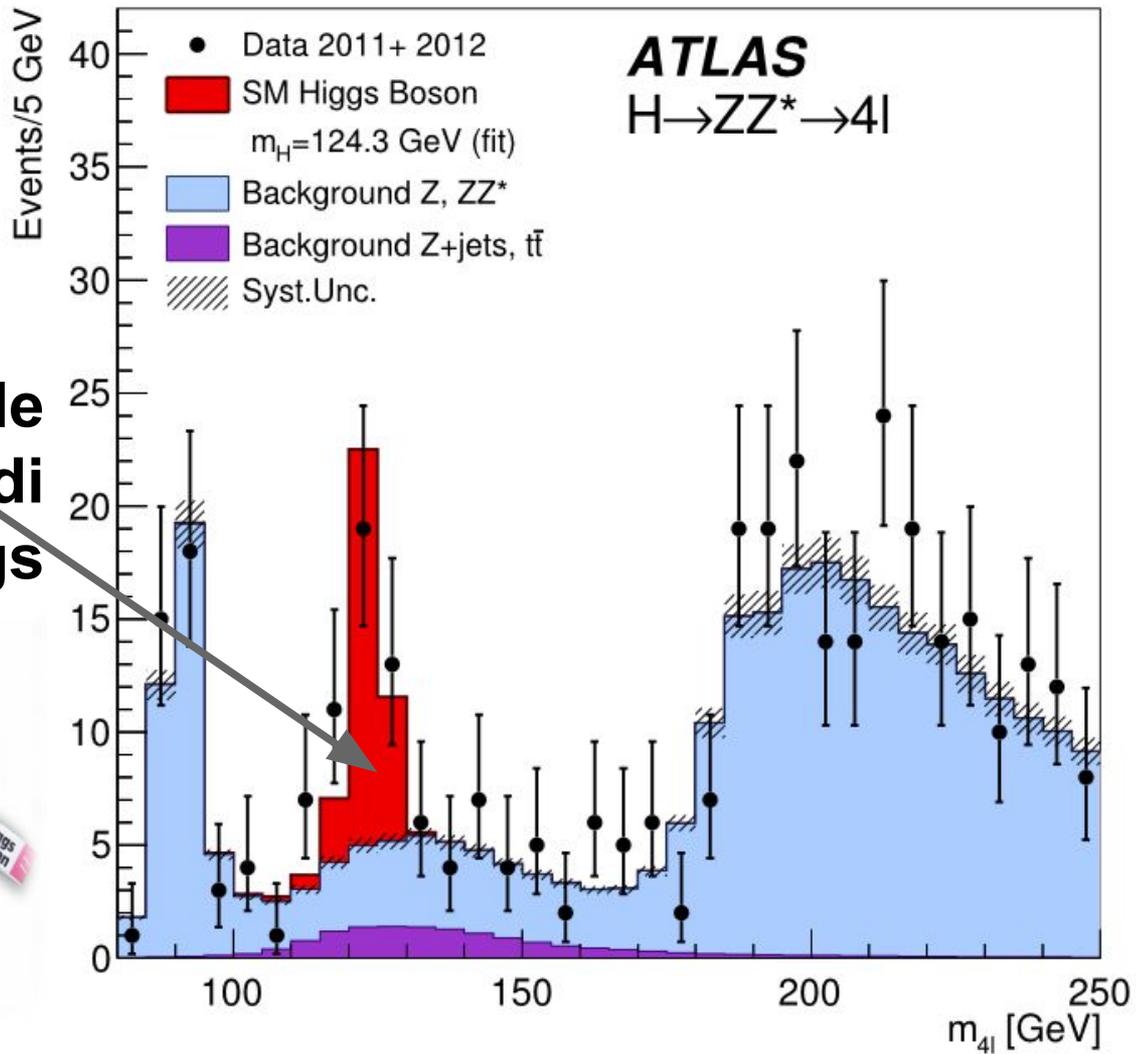
**Dati  
sperimentali**



**Fondo  
atteso**

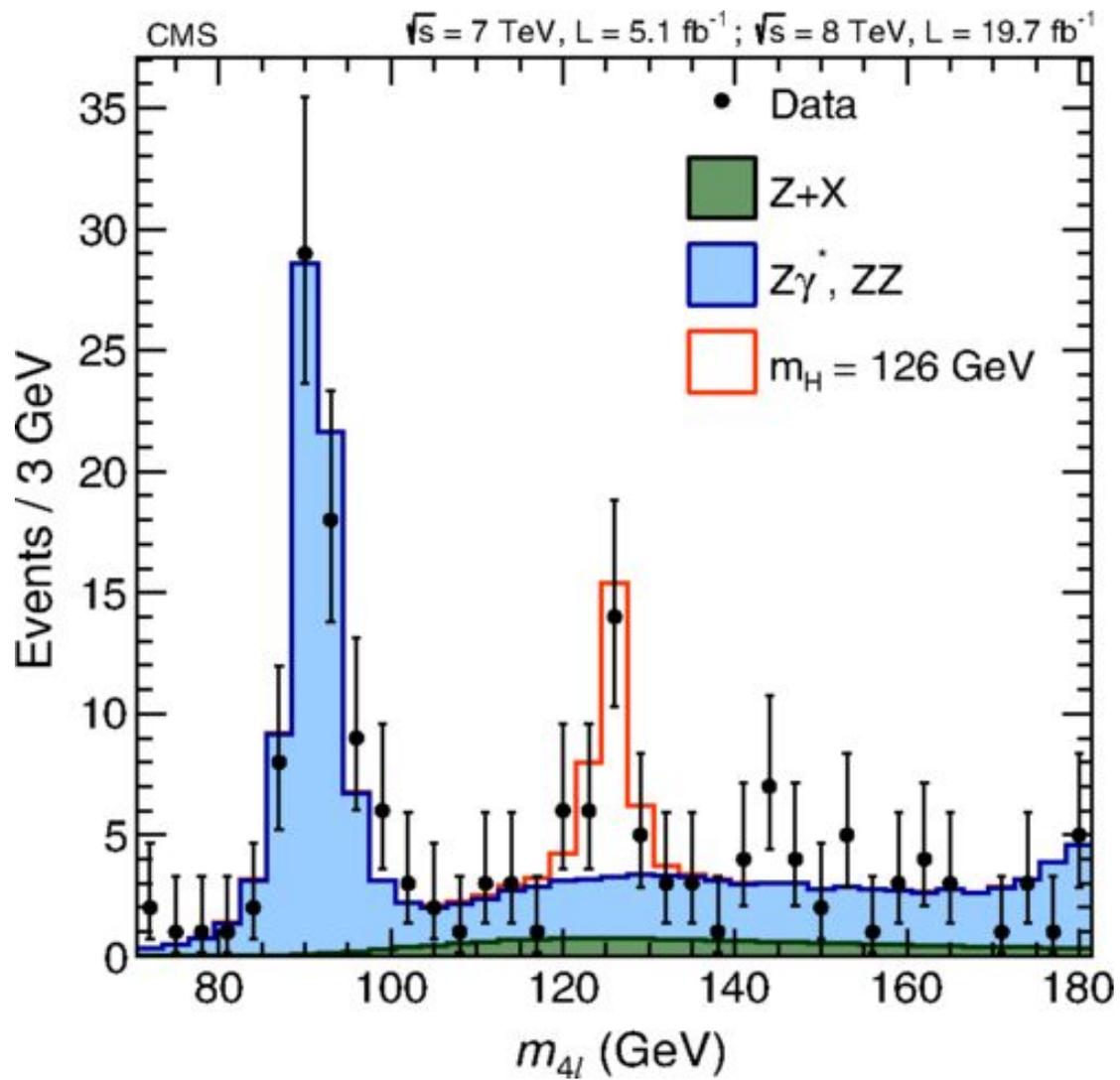


Fondo  
atteso



Segnale  
atteso di  
Higgs





# Bosone di Higgs



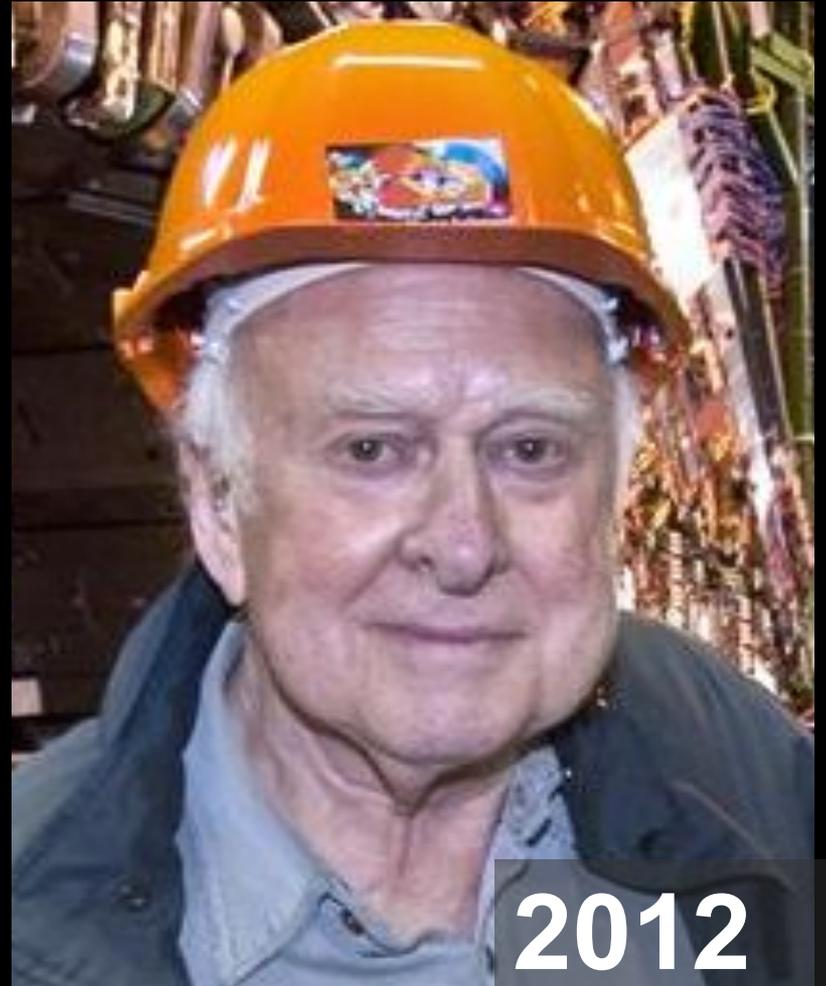
Prof. Peter Higgs



# Prof. Peter Higgs



1964



2012

# Premio Nobel 2013



8 October 2013

# The Nobel Prize in Physics 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

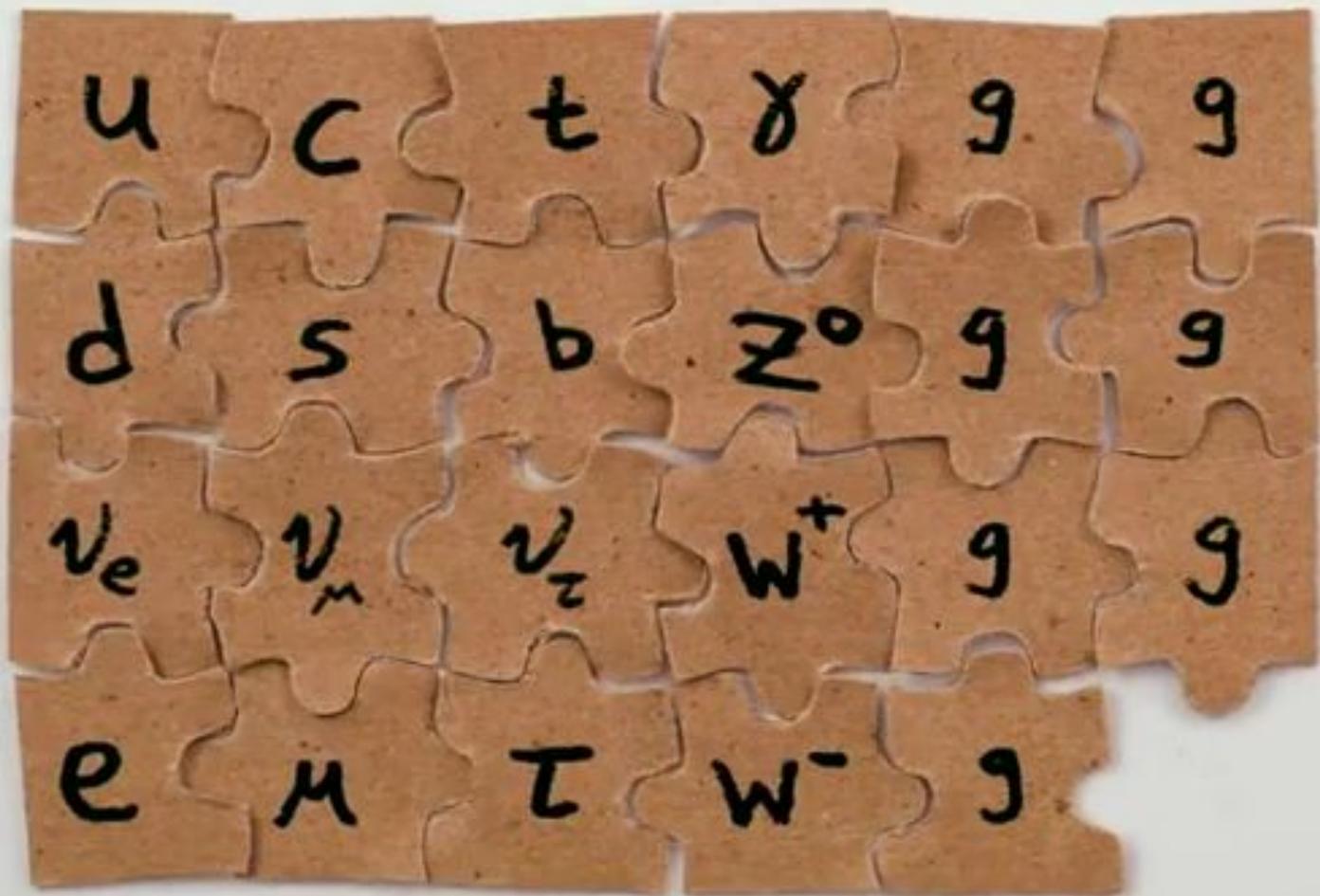
**François Englert**

Université Libre de Bruxelles, Brussels, Belgium

**Peter W. Higgs**

University of Edinburgh, UK

*“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”*



u

c

t

$\gamma$

g

g

d

s

b

$Z^0$

g

g

$\nu_e$

$\nu_\mu$

$\nu_\tau$

$W^+$

g

g

e

$\mu$

$\tau$

$W^-$

g

h

Cosa sappiamo?



# Cosa sappiamo? Poco

- I quark sono **indivisibili**?
- Dov'è finita l'antimateria?
- Esistono altre **dimensioni**?
- Esiste una teoria che unisca tutte le forze fondamentali?
- Cos'è la **materia oscura**?
- Cos'è l'**energia oscura**?



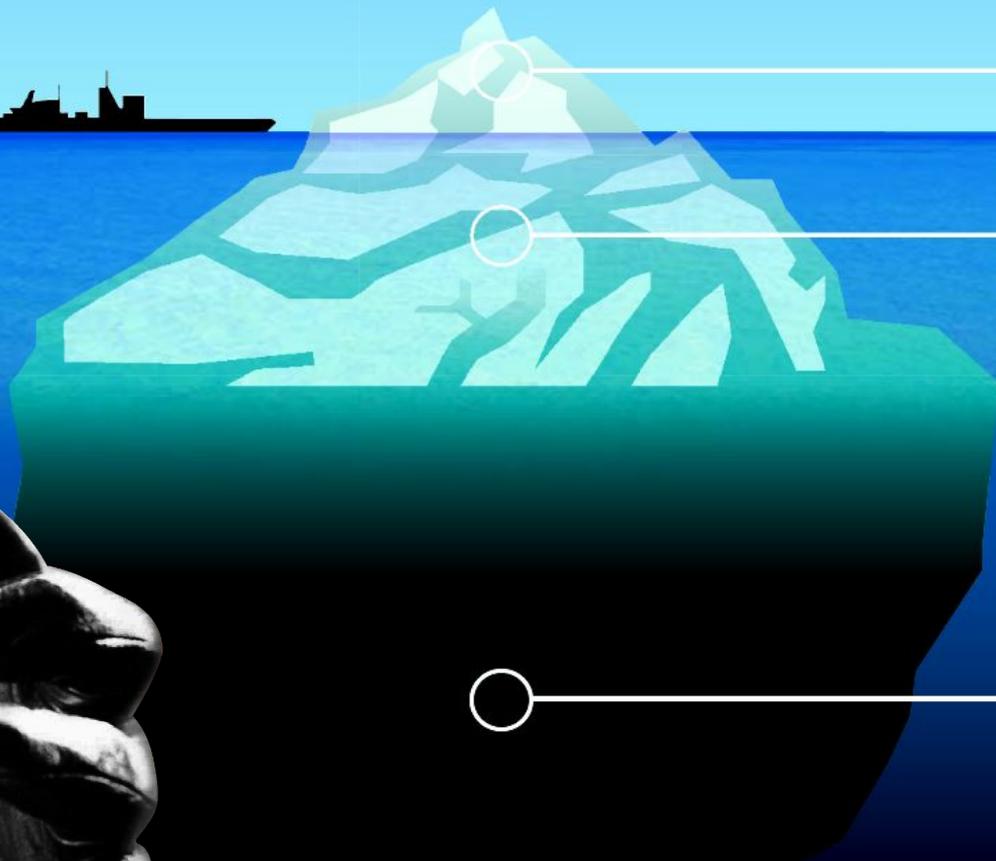
# Il lato oscuro



5% materia ordinaria

22% materia oscura

73% energia oscura



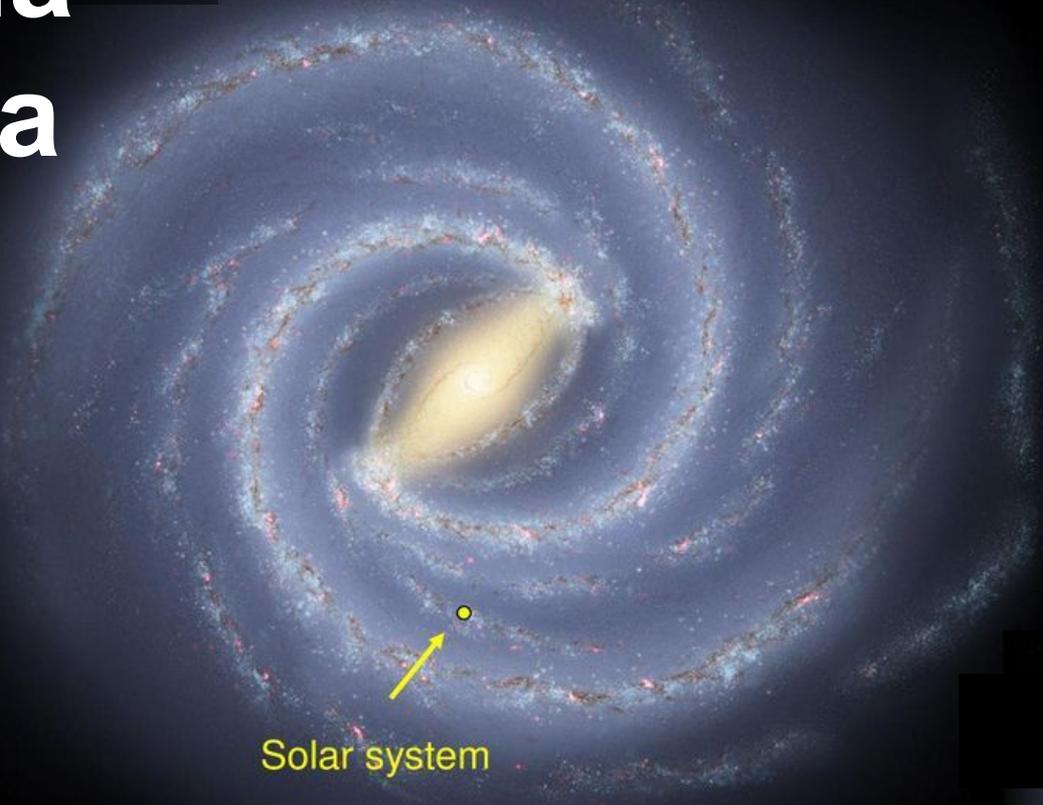
# La massa mancante



'30: Ian Ort, Fritz Zwicky  
'60: Vera Rubin

← 100,000 light years →

# Materia oscura

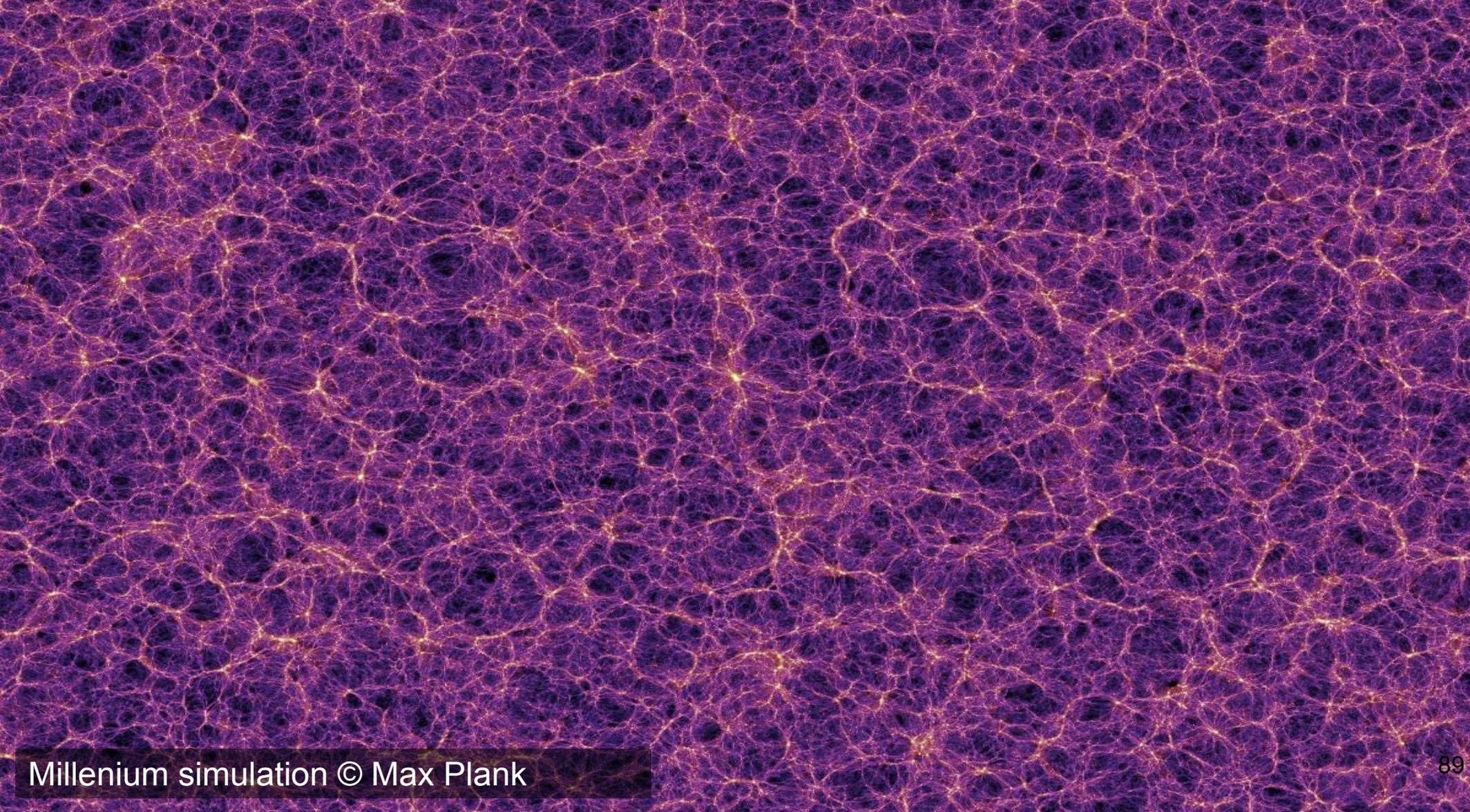


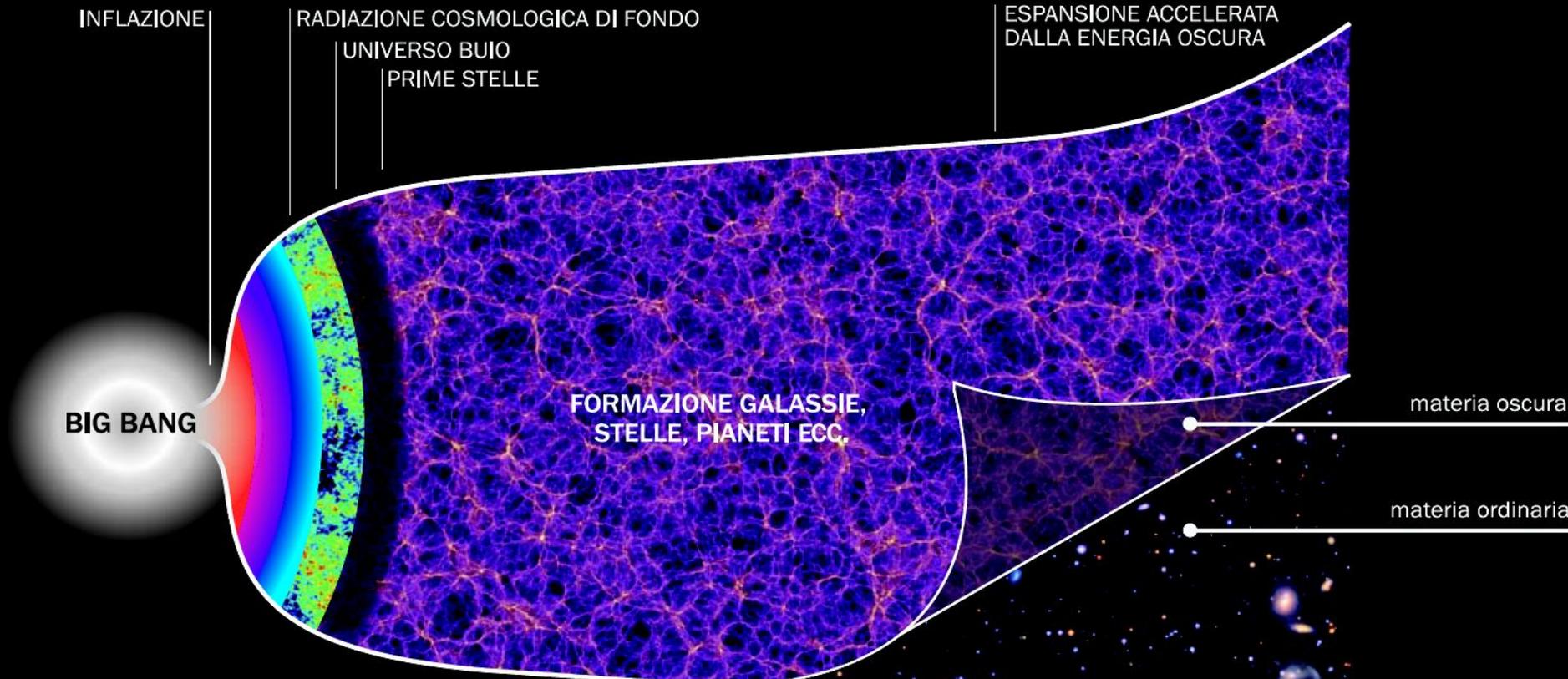
Solar system

Dark  
matter halo

Materia  
oscura

Disco galattico





INFLAZIONE

RADIAZIONE COSMOLOGICA DI FONDO

ESPANSIONE ACCELERATA  
DALLA ENERGIA OSCURA

UNIVERSO BUIO  
PRIME STELLE

**BIG BANG**

FORMAZIONE GALASSIE,  
STELLE, PIANETI ECC.

materia oscura

materia ordinaria

# Storia dell'universo

380.000 anni  
dopo il Big Bang

420 milioni di anni  
dopo il Big Bang

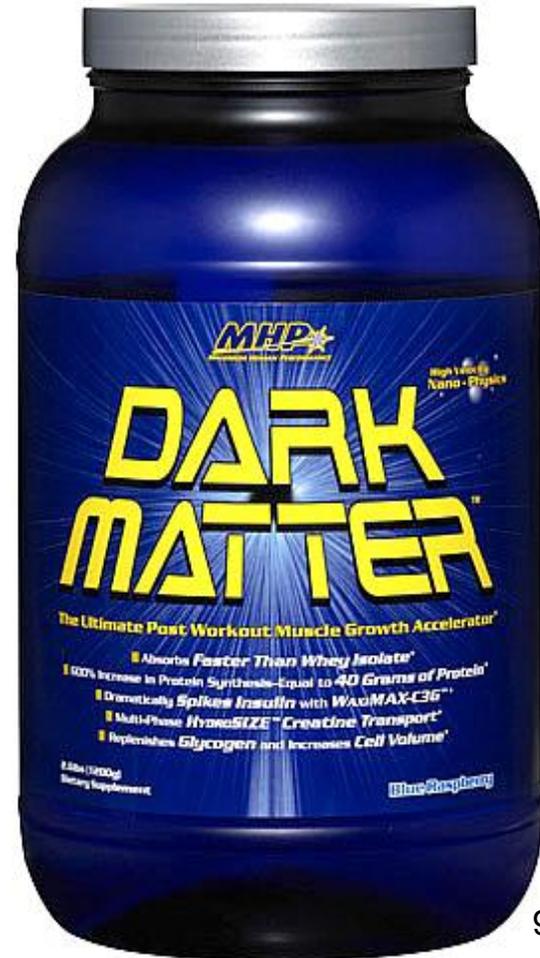
9 miliardi di anni  
dopo il Big Bang

13,7 miliardi di anni  
dopo il Big Bang

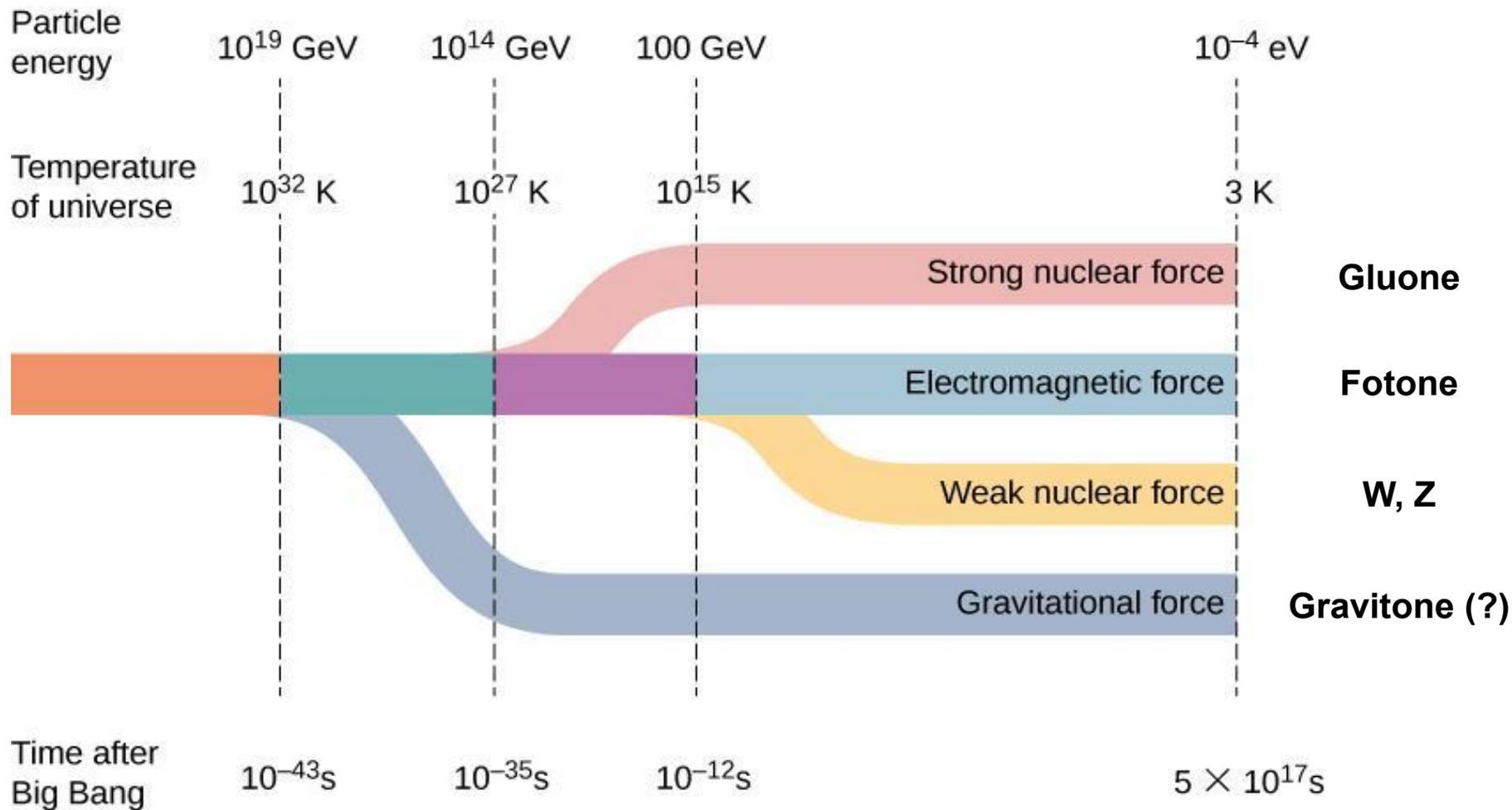
OGGI

# Materia oscura

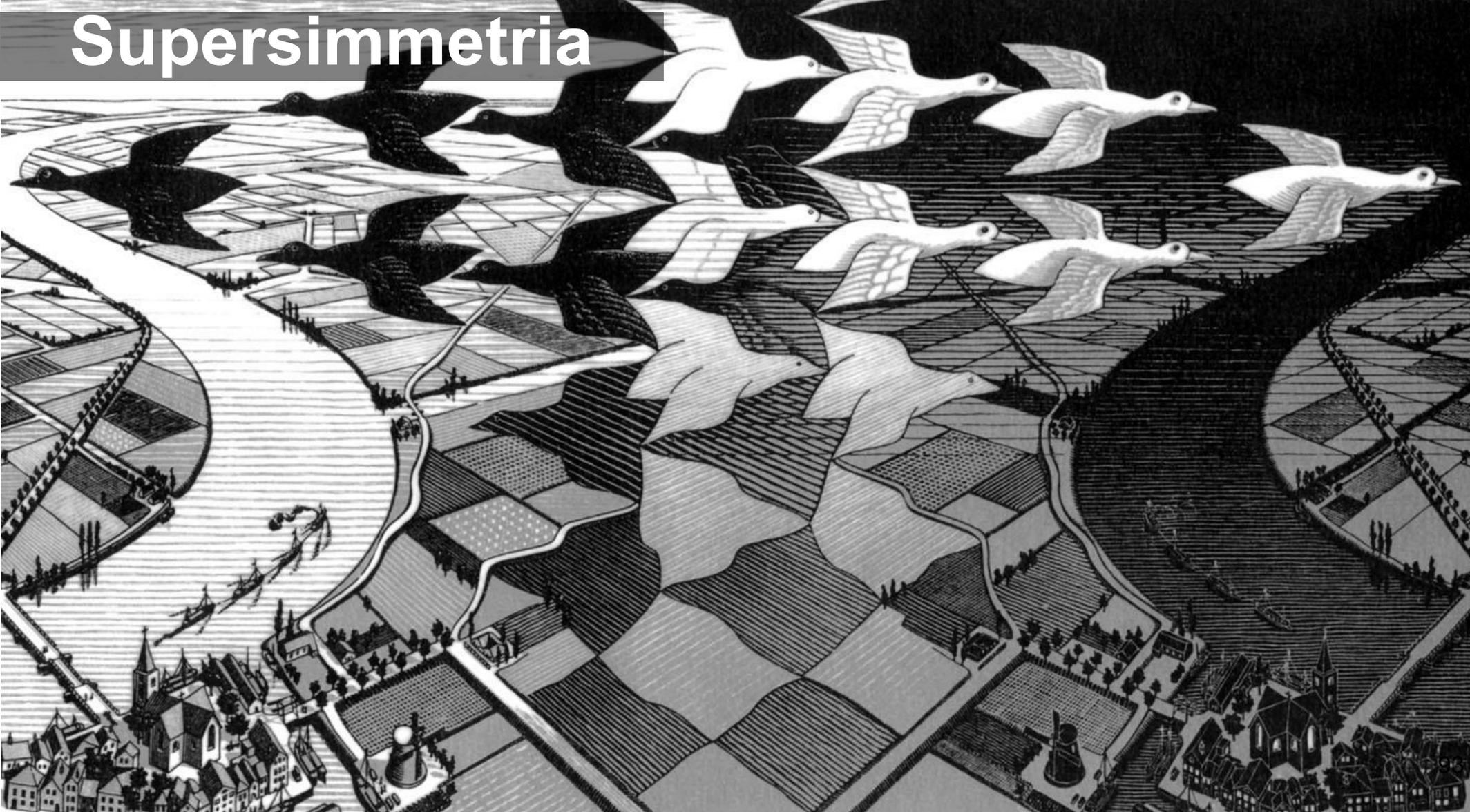
- **Permea** lo spazio
- Interagisce solo **gravitazionalmente**
- Seme per formazione **galassie**
- **Non compatibile** con il modello standard delle particelle elementari
  - Possibili spiegazioni nelle teorie di unificazione delle forze



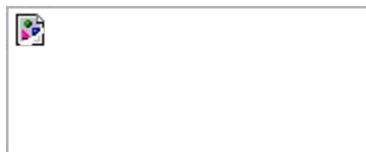
# Teorie di unificazione



# Supersimmetria

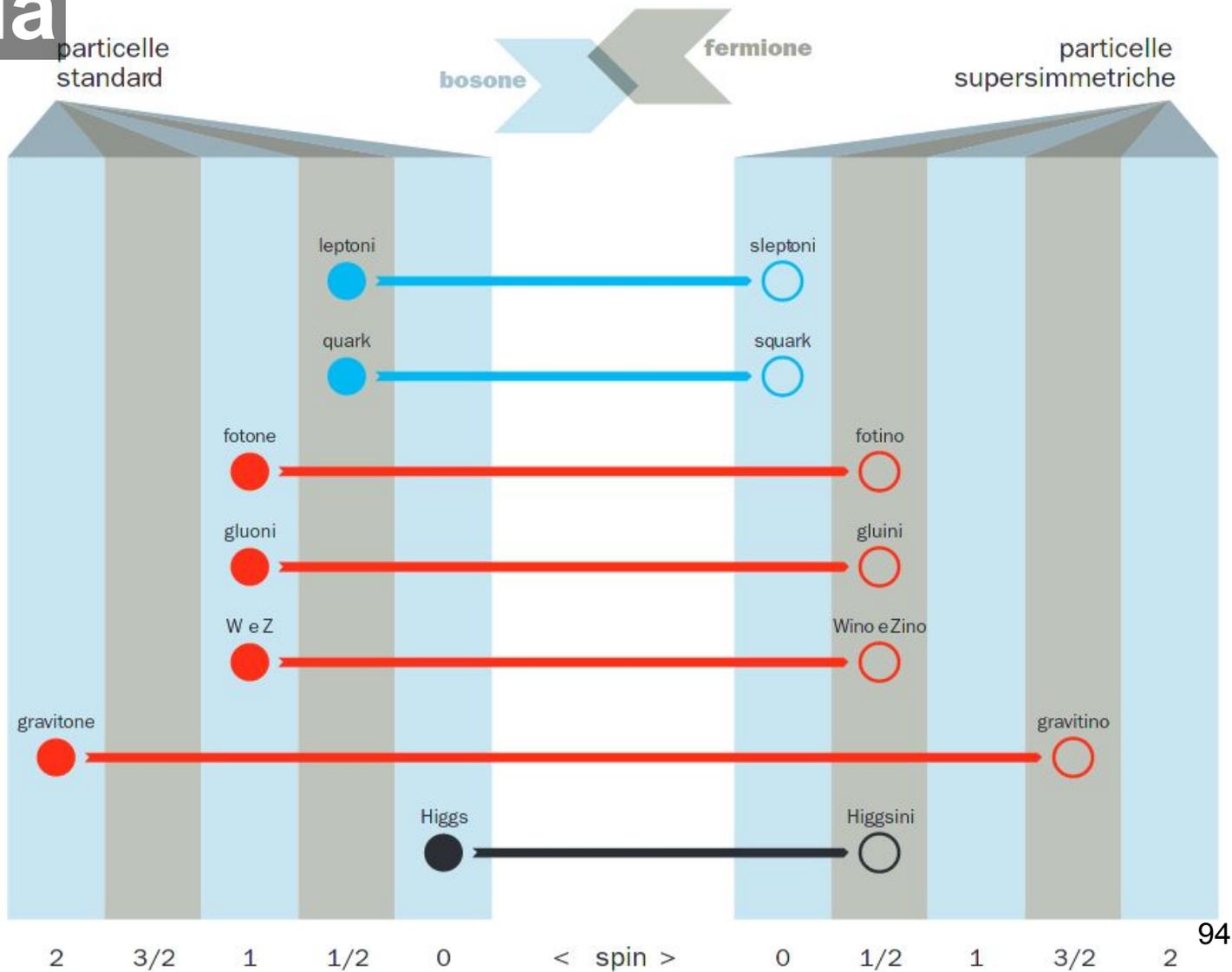


# Supersimmetria

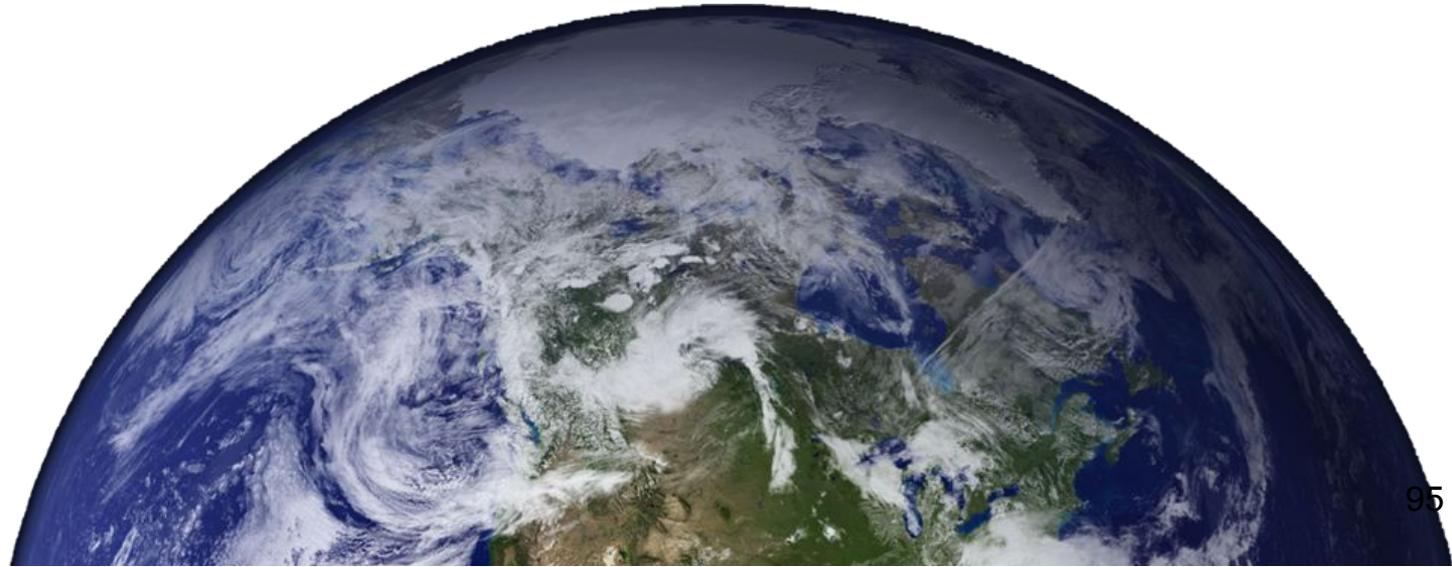


● mediatori

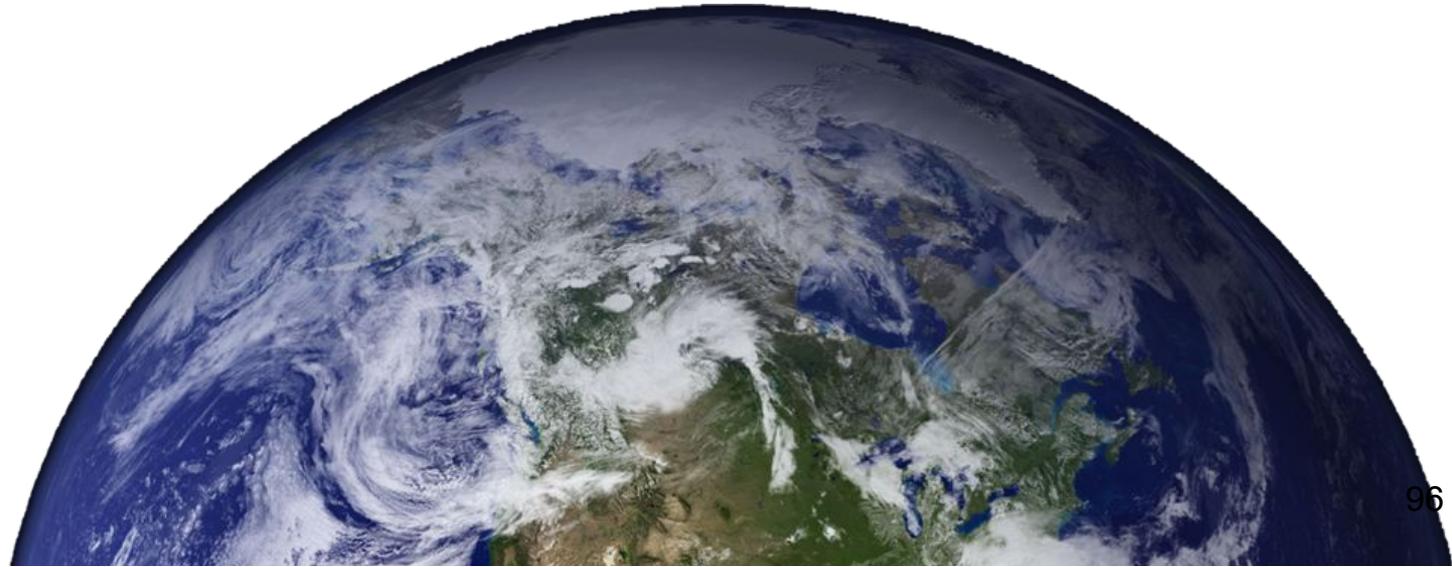
● massa



# La gravità è ...?



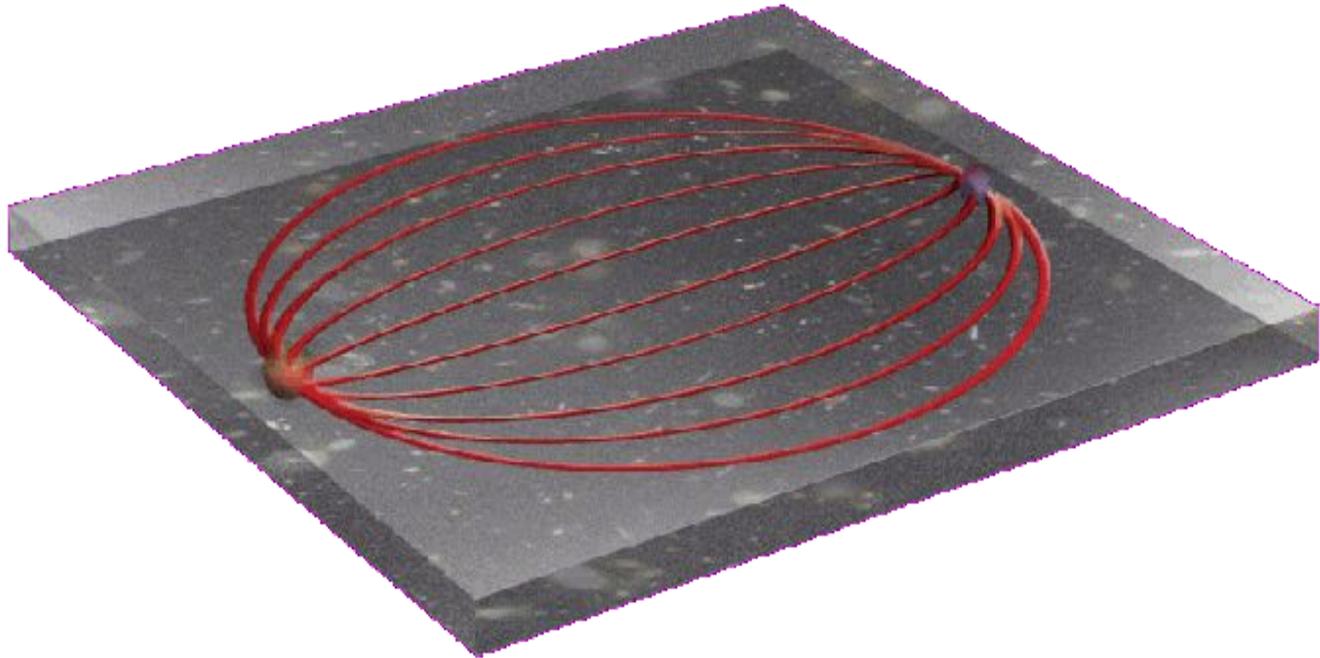
La gravità è **debole!**



# Dimensioni aggiuzionali?

Potrebbero spiegare debolezza forza gravitazionale

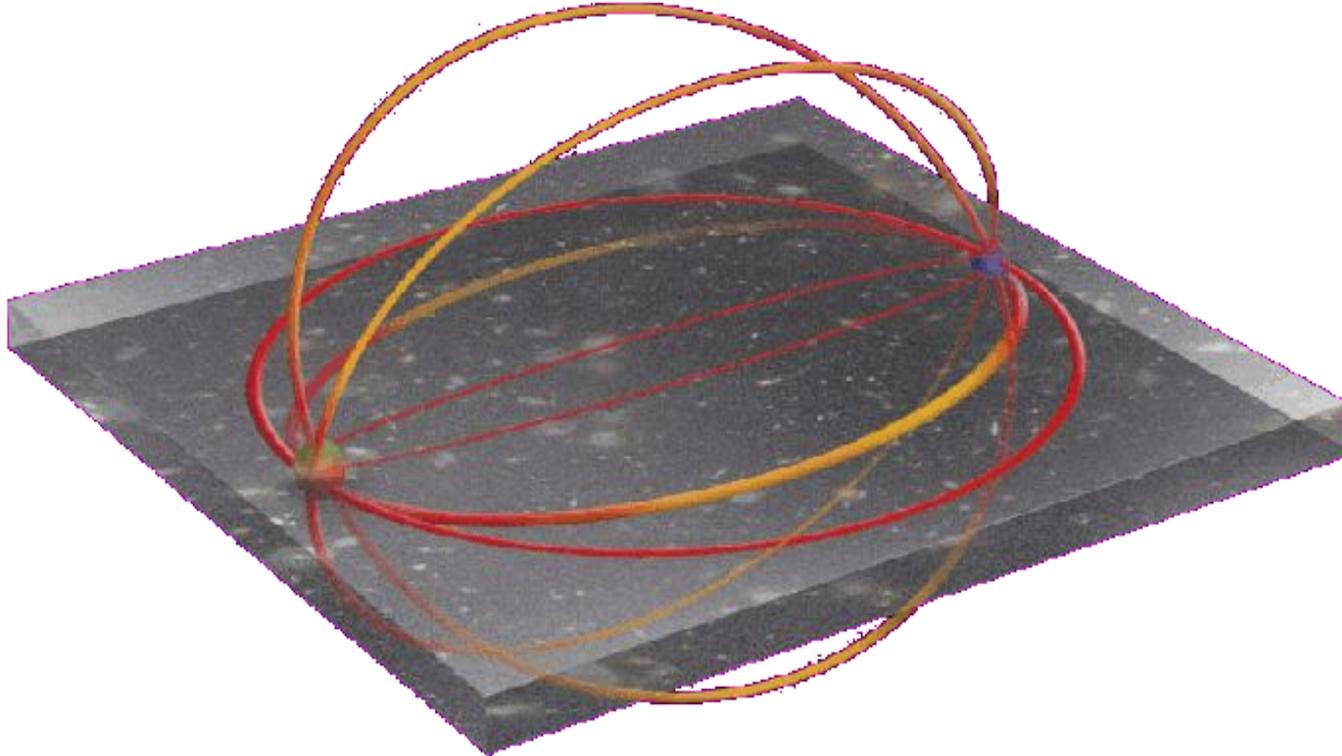
- Le altre forze sono **confinare** in 3D
- La gravità si **distribuisce** invece in tutte le dimensioni



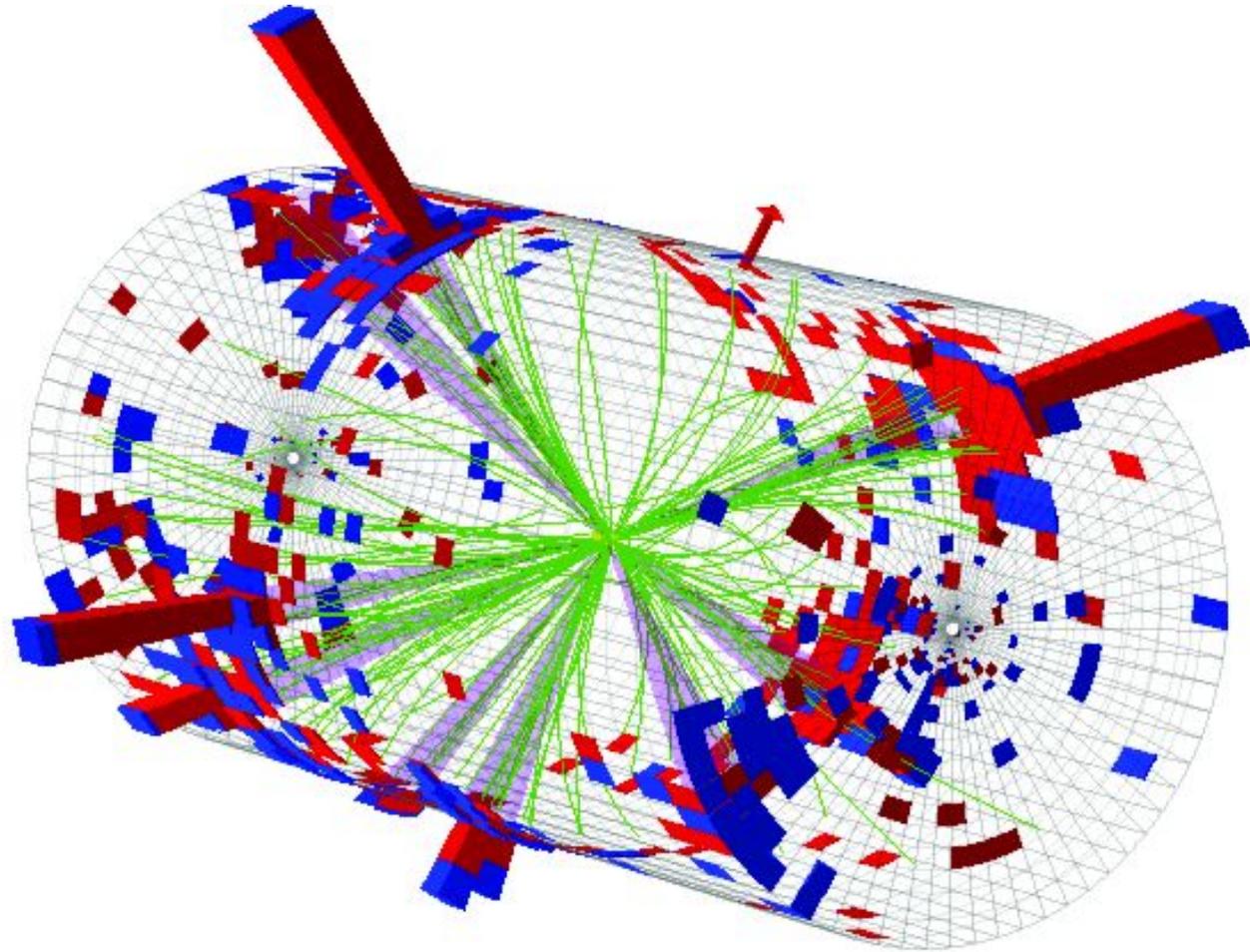
# Dimensioni aggiuntive?

Potrebbero spiegare debolezza forza gravitazionale

- Le altre forze sono **confinata** in 3D
- La gravità si **distribuisce** invece in tutte le dimensioni



# Micro buchi neri





LHC fino a **2038**



Last updated: January 2022

- Shutdown/Technical stop
- Protons physics
- Ions
- Commissioning with beam
- Hardware commissioning/magnet training

# LHC fino a 2038

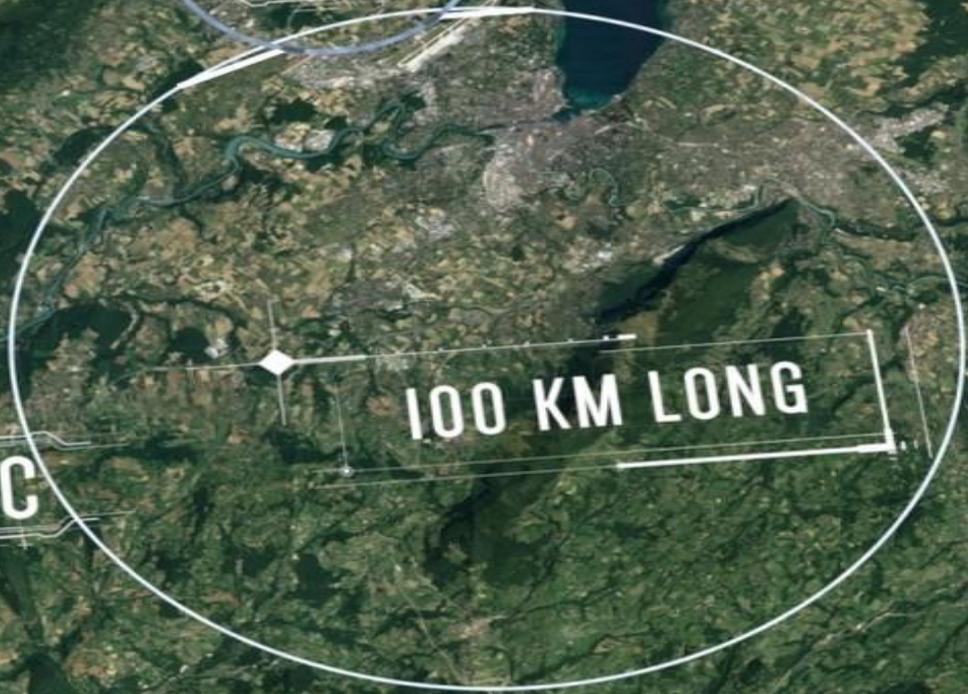
# Futuri acceleratori



SWITZERLAND

FRANCE

FCC



100 KM LONG

100 km Circumference



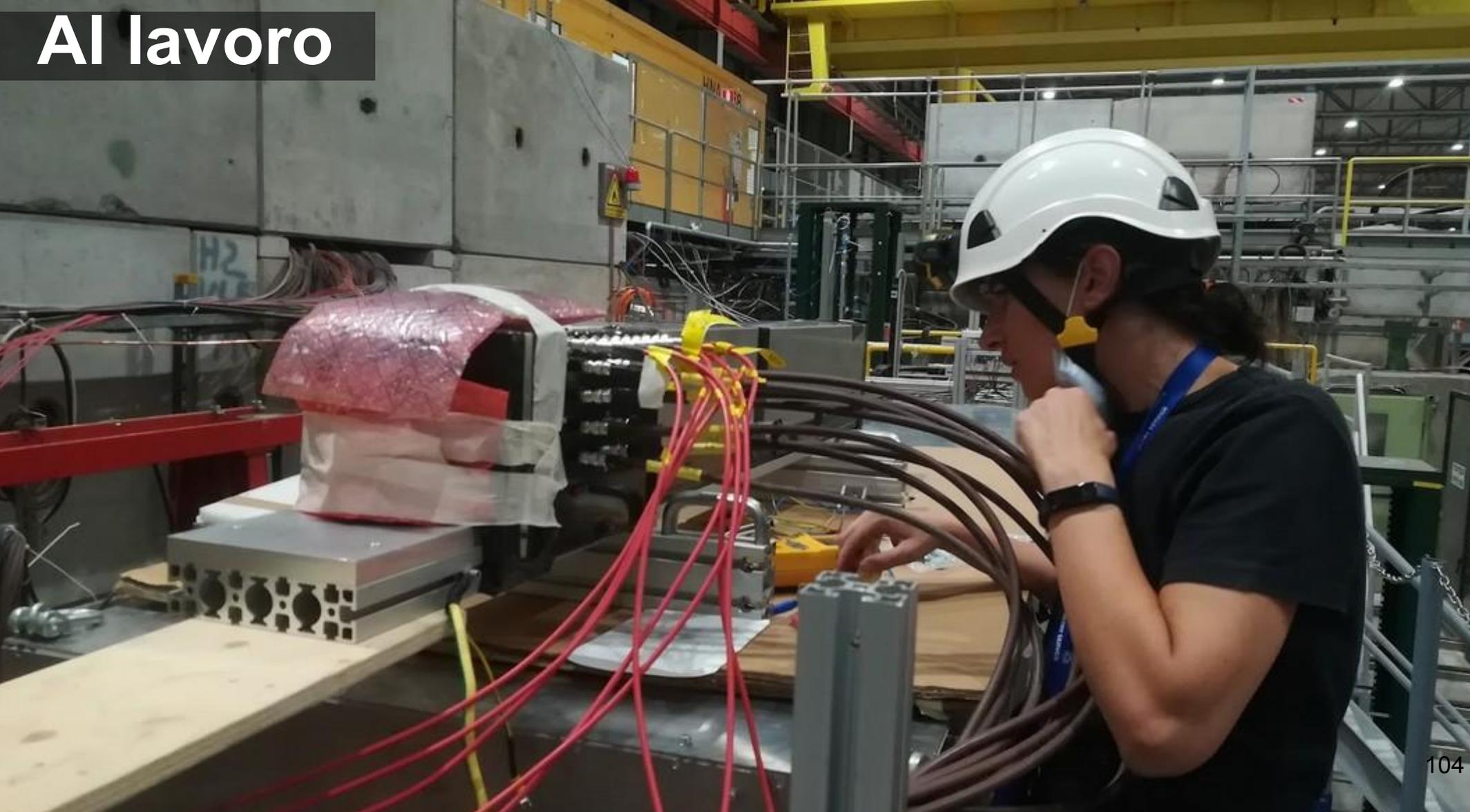
# Al lavoro



UNIVERSITÀ  
DI PAVIA



# Al lavoro



# Al lavoro



# Ricadute sulla società

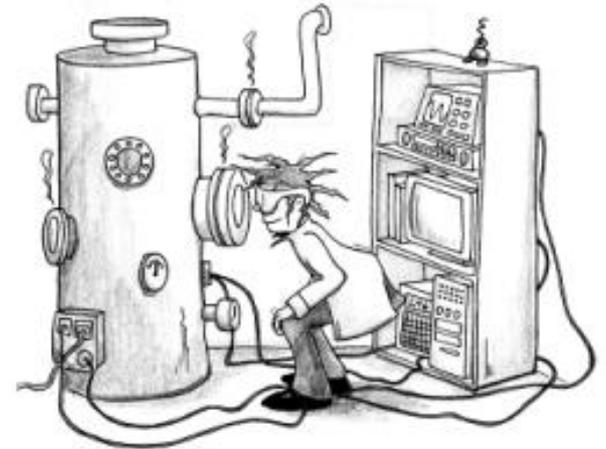


**Teorici**  
**Thinkers**

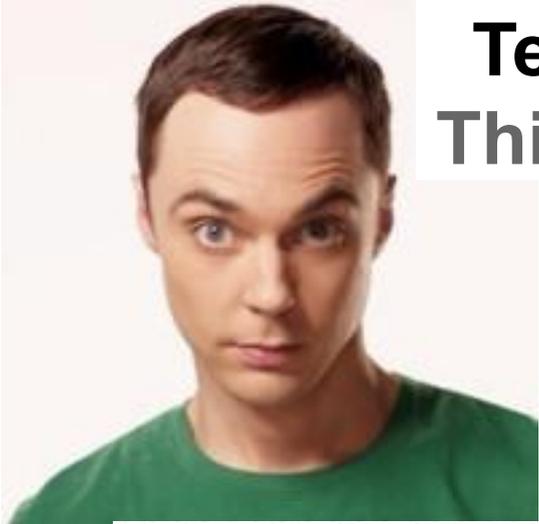
$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\Psi + h.c. \\ & + \Psi_i\gamma_{ij}\Psi_j\Phi + h.c. \\ & + |D_\mu\Phi|^2 - V(\Phi) \end{aligned}$$



**Sperimentali**  
**Makers**



# Ricadute sulla società



**Teorici**  
**Thinkers**

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\Psi + h.c. \\ & + \Psi_i\gamma_{ij}\Psi_j\phi + h.c. \\ & + |D_\mu\phi|^2 - V(\phi) \end{aligned}$$

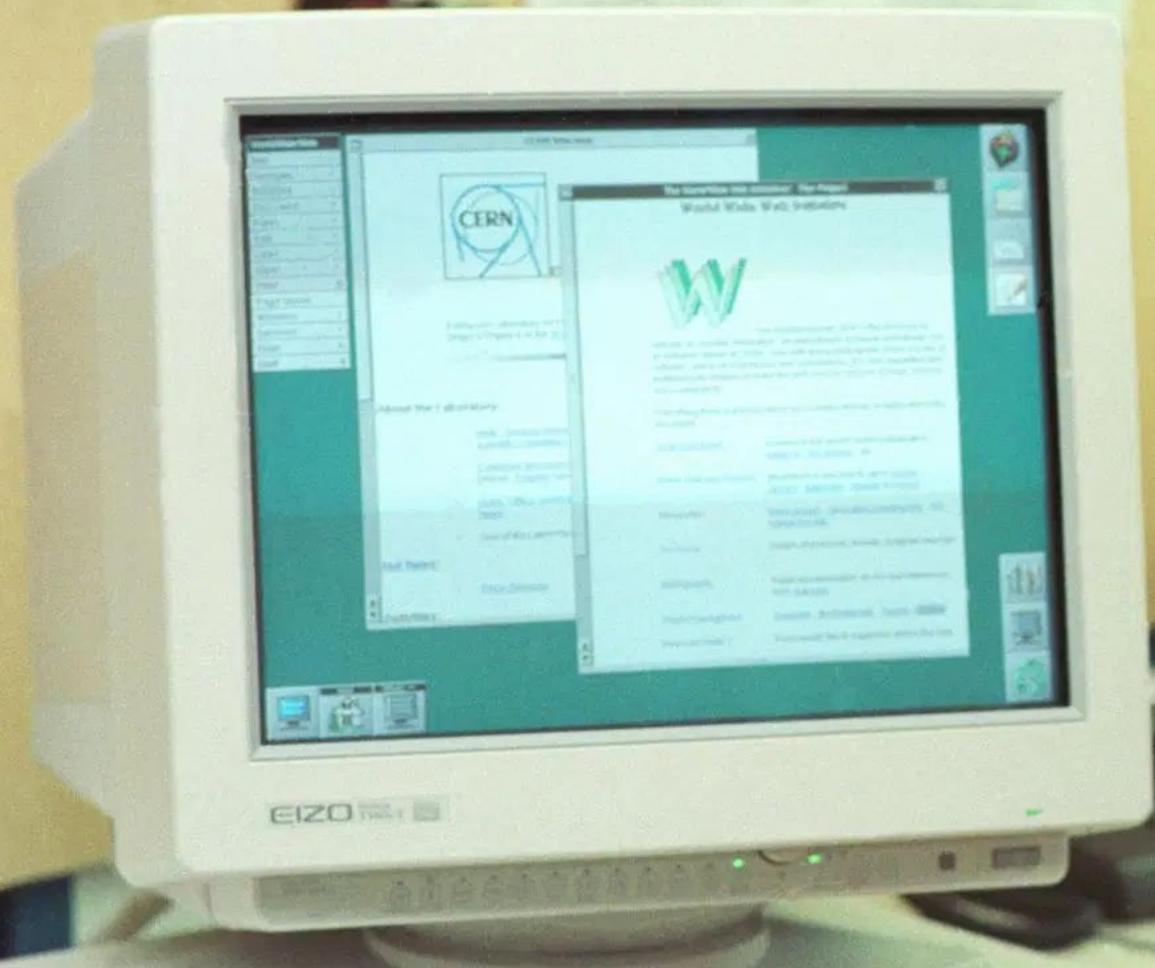


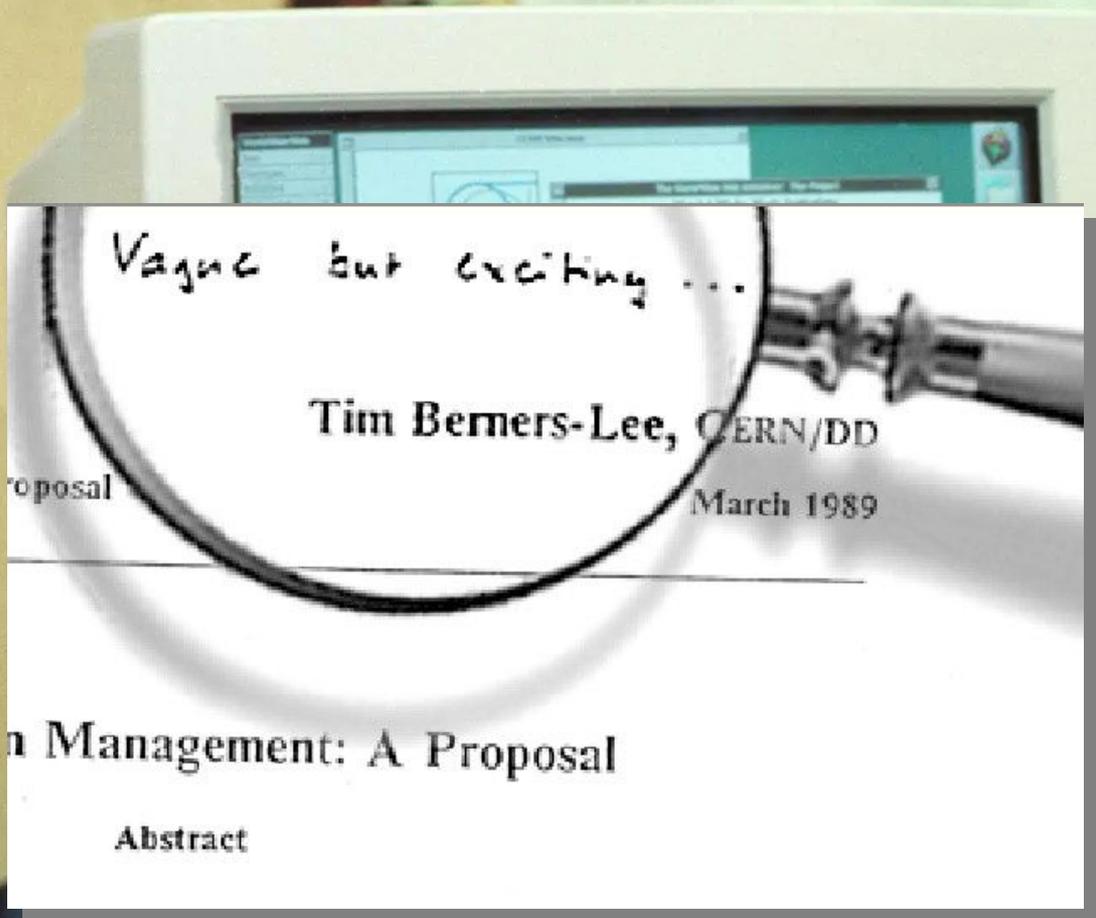
**Sperimentali**  
**Makers**



# Disegnare il futuro







# Centro Nazionale Adroterapia Oncologica





Ricerca di base

Non un **frutto** pronto

A low-angle shot of a massive, ancient tree trunk covered in vibrant green moss. The tree's thick, gnarled branches spread out across the top of the frame, creating a dense canopy of bright green leaves. Sunlight filters through the foliage, creating a soft, ethereal glow and casting long, thin shadows of the surrounding forest onto the ground. The overall atmosphere is one of natural beauty and tranquility.

Ricerca di base

Ma un **seme** che produrrà un  
albero con frutti inimmaginabili