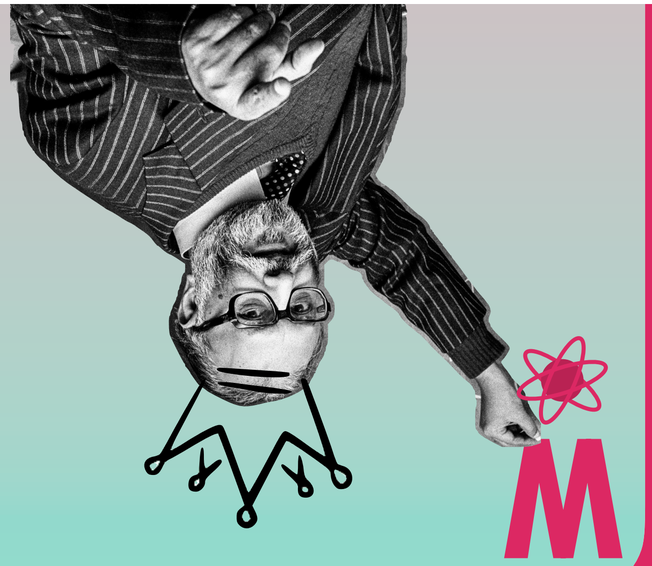
# il MODELLO STANDARD

# il MODELLO STANDARD È MORTO



# VIVA il MODELLO STANDARD!

UNIVERSITÀ
DI PAVIA

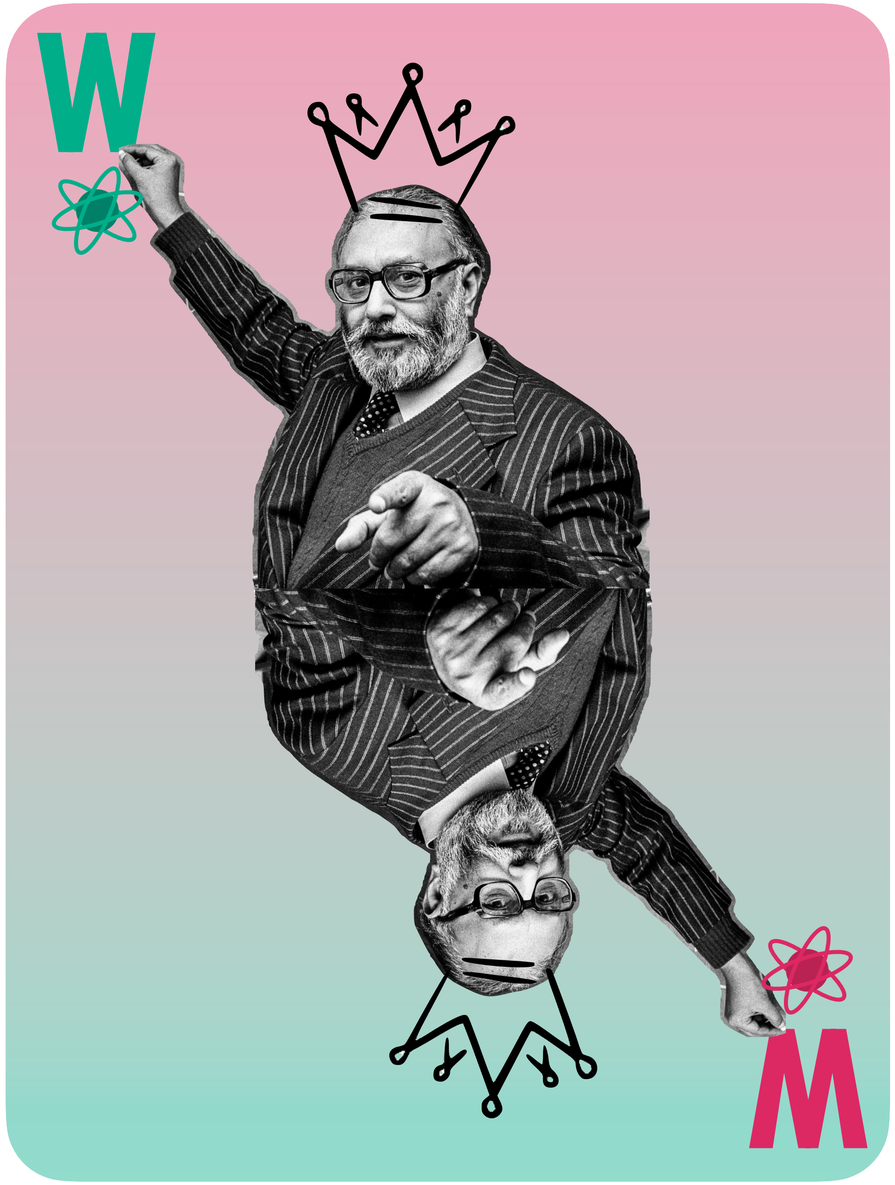
INFN

Incontri di Fisica Moderna
17.12.2024

# VIVA il MODELLO STANDARD È MORTO

**Andrea Pareti**
ATLAS - RD_FCC

**Francesco P. Ucci**
QFT@Colliders



# Cos'è il MODELLO STANDARD

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Una teoria che descrive la Natura

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Una teoria che descrive la Natura

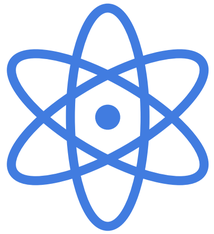
verificata sperimentalmente

# Cos'è il MODELLO STANDARD delle Particelle Elementari?

Una teoria che descrive la Natura

verificata sperimentalmente

Su scala microscopica

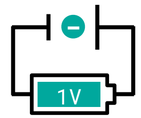


# Particelle Elementari

$$E = h\nu = h\frac{c}{\lambda}$$

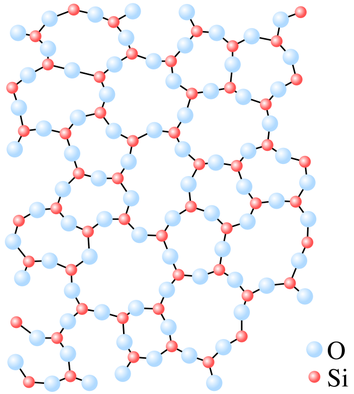
**unità di misura**

1 eV = 1.6 x $10^{-19}$ J




h = 4.135667696...x$10^{-15}$ eV s

**Legami molecolari**




~$10^{-9}$ m

O(keV)

Struttura della Materia

# Particelle Elementari

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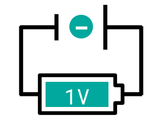


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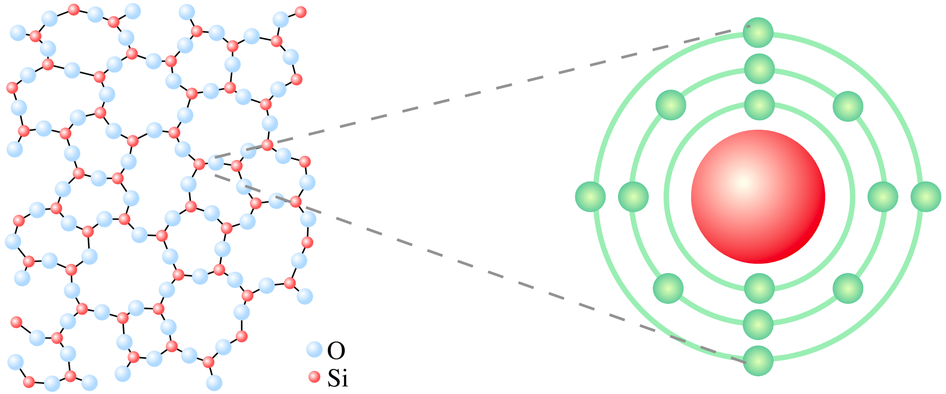




~$10^{-9}$ m

~$10^{-10}$ m

O(keV)

O(10-100 keV)

Struttura della Materia

Orbitali atomici

# Particelle Elementari

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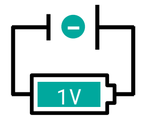


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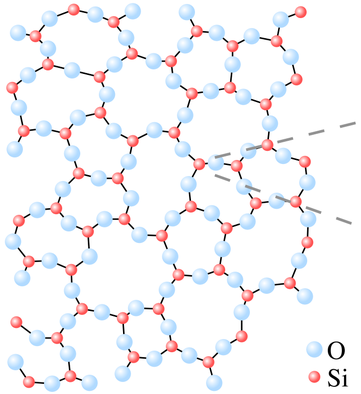


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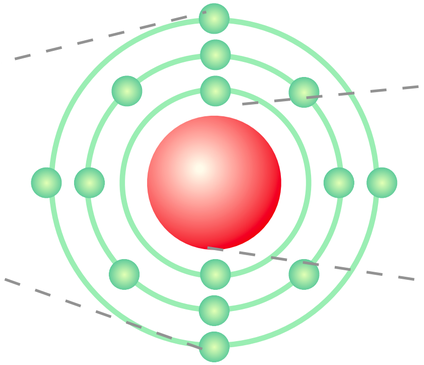
O(keV)

Struttura della Materia

**Atomi**

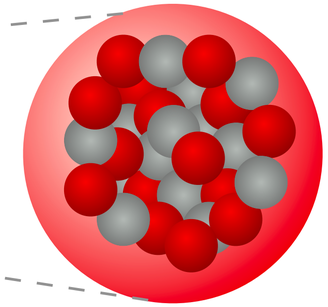


~$10^{-10}$ m

O(10-100 keV)

Orbitali atomici

**Nuclei atomici**



~$10^{-14}$ m

100 MeV

Fisica Nucleare

# Particelle Elementari

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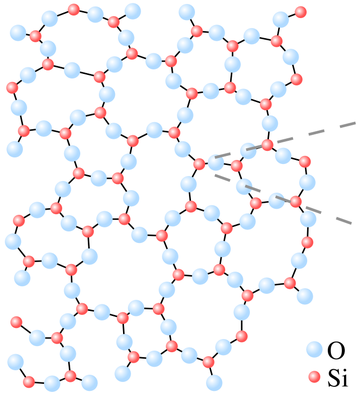


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O(keV)

Struttura della Materia

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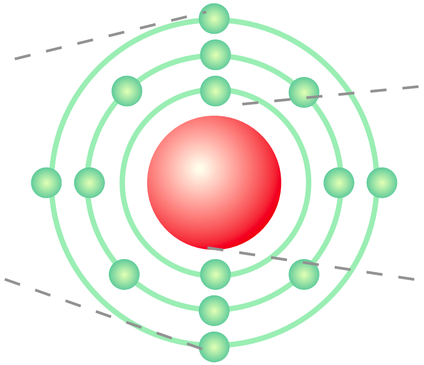
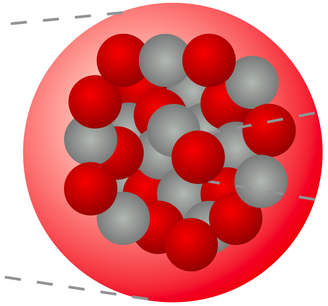


~$10^{-10}$ m

O(10-100 keV)

Orbitali atomici

**Nuclei atomici**

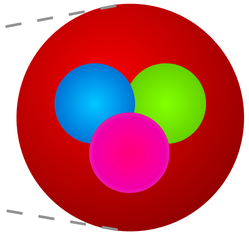


~$10^{-14}$ m

100 MeV

Fisica Nucleare

**Protoni**



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1 GeV

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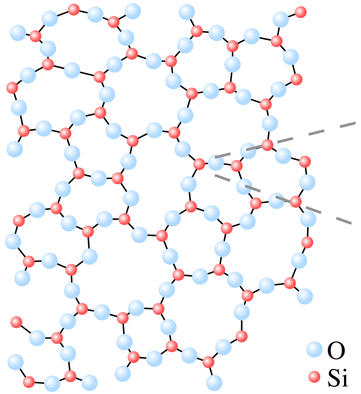
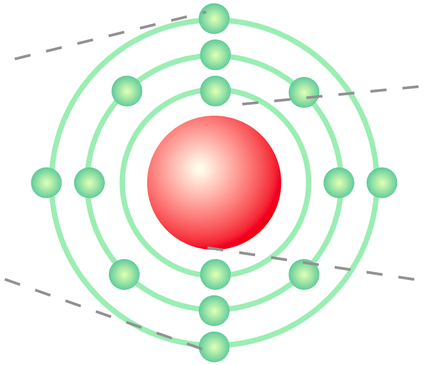



~$10^{-9}$ m

O(keV)

Struttura della Materia

**Atomi**

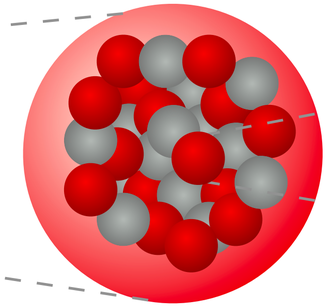


~$10^{-10}$ m

O(10-100 keV)

Orbitali atomici

**Nuclei atomici**



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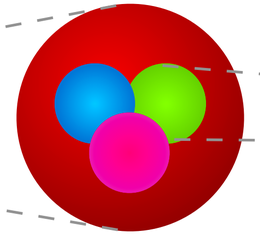
100 MeV

Fisica Nucleare

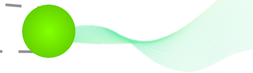
**Protoni**



~$10^{-15}$ m

1 GeV

**Particelle elementari**



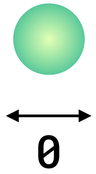
<$10^{-17}$ m

O(100 GeV)

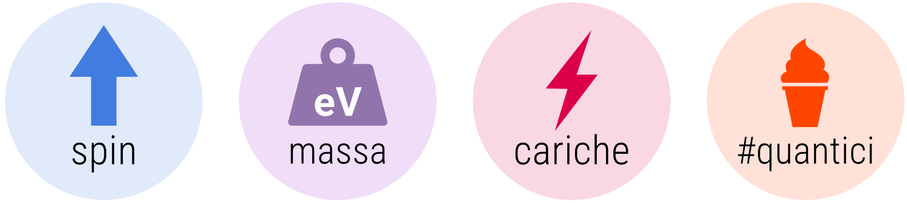
Teoria Quantistica dei Campi

# Particelle Elementari

**Puntiforme**
non ulteriormente divisibile



# Particelle Elementari




**Puntiforme**
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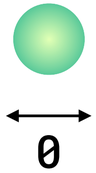

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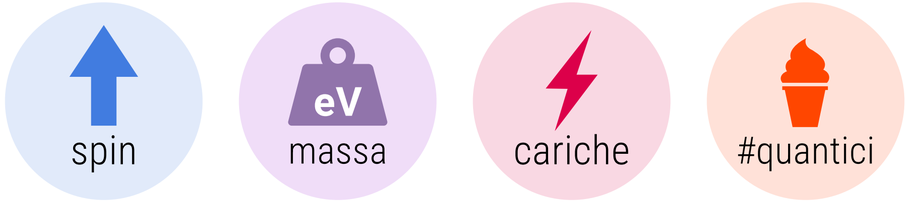


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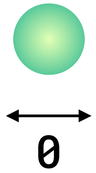

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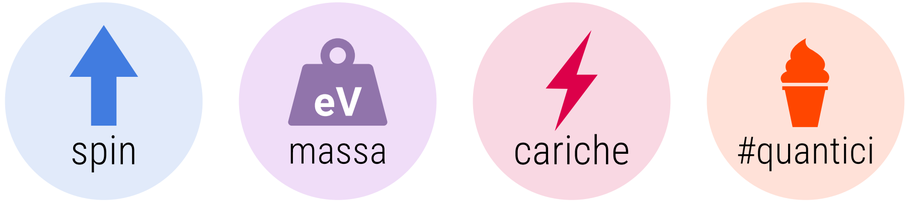


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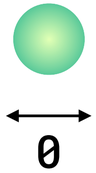



**Fermioni**

**Bosoni**

# Particelle Elementari

spin

eV
massa

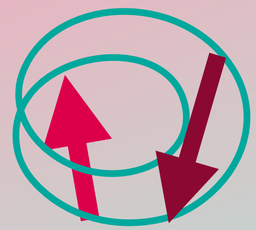
cariche

#quantici

**Puntiforme**
non ulteriormente divisibile

0

**F**



**S** = 1/2, 3/2,… n/2

**Spinori**

**Materia ordinaria**

**Bosoni**

# Particelle Elementari

spin

eV
massa

cariche

#quantici

**Puntiforme**
non ulteriormente divisibile

0

**F**

S = 1/2, 3/2,… n/2

Spinori

**B**

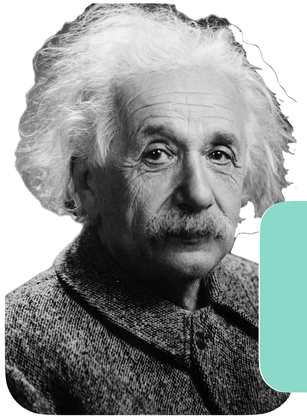
S = 0,1,… n

Vettori

Materia ordinaria

Forze

# Particelle Elementari

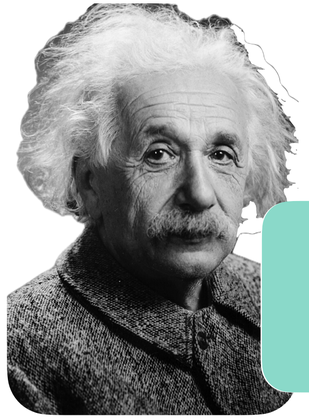


**Relatività**

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

Equivalenza massa-energia

# Particelle Elementari



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Equivalenza massa-energia

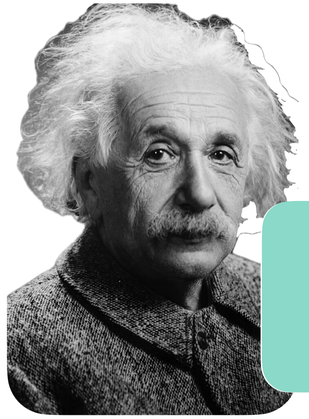
+

**Meccanica Quantistica**

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right)\psi = i\frac{\partial\psi}{\partial t}$$

Equazione di Schrödinger

# Particelle Elementari



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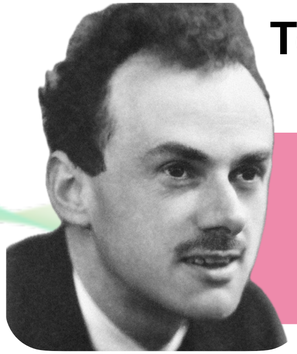


**Teoria Quantistica dei Campi**

$$(\gamma^\mu\partial_\mu - m)\psi = 0$$

Eq. di Dirac

$$\psi = \psi(\vec{x}, t)$$

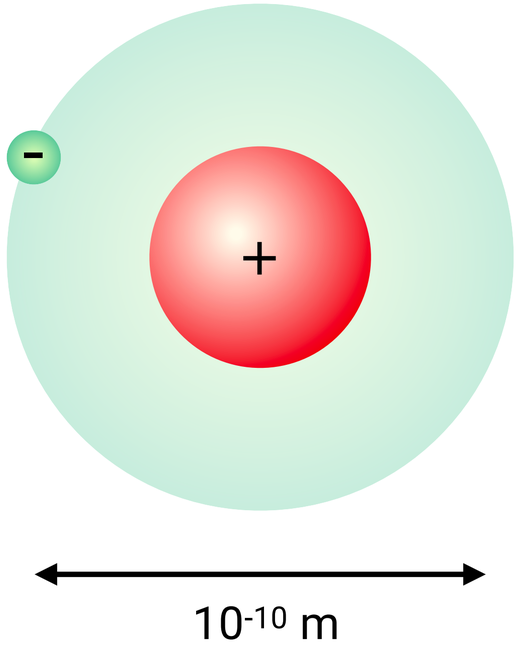
Eccitazioni di campi fondamentali

-

+

Le soluzioni dell'equazione prevedono l'esistenza delle **antiparticelle**

# Guardiamo in un atomo…

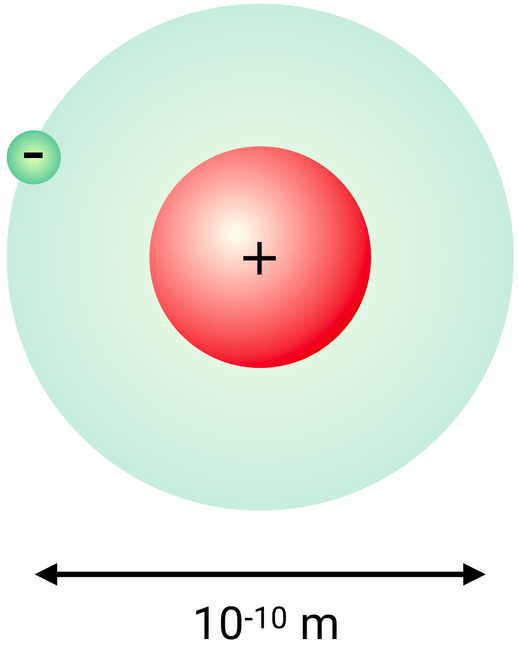


# Il campo elettromagnetico

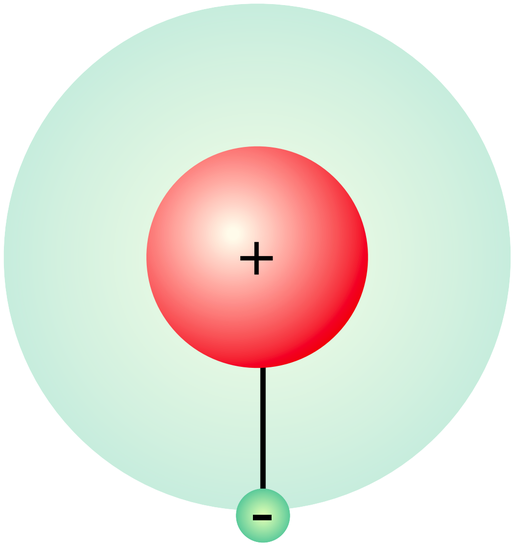
~0.5 MeV

La particella carica più leggera in natura! (e anche stabile)

La materia ordinaria a carica **negativa** è fatta di elettroni

# Il campo elettromagnetico


**Classicamente**
L'elettrone è legato al nucleo attraverso la forza elettrica

$$F = \frac{1}{4\pi\epsilon_0}\frac{q_e q_N}{r^2}$$

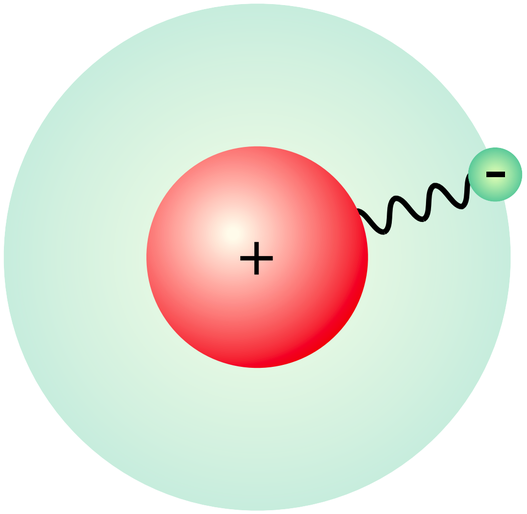
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$
$$\nabla \times \vec{B} = \mu_0\epsilon_0\frac{\partial \vec{E}}{\partial t} + \mu_0\vec{J}$$
$$\nabla \cdot \vec{B} = 0$$

**Equazioni di Maxwell**

$$F^{\mu\nu} = \begin{bmatrix} 0 & -E_x/c & -E_y/c & -E_z/c \\ E_x/c & 0 & -B_z & B_y \\ E_y/c & B_z & 0 & -B_x \\ E_z/c & -B_y & B_x & 0 \end{bmatrix}$$

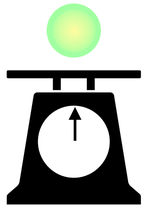
**Campo Elettromagnetico classico**

# Il campo elettromagnetico

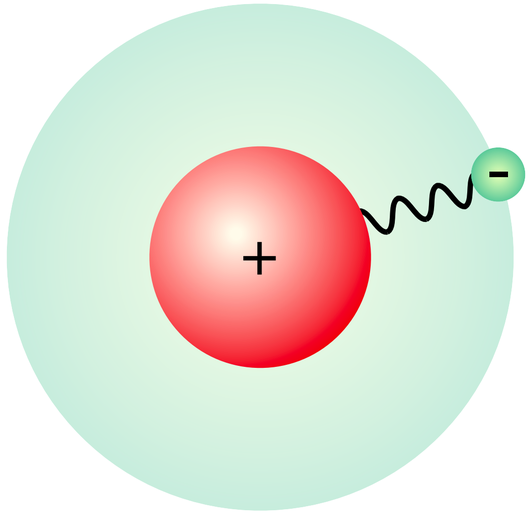

**Quantisticamente**
L'elettrone scambia fotoni con il nucleo

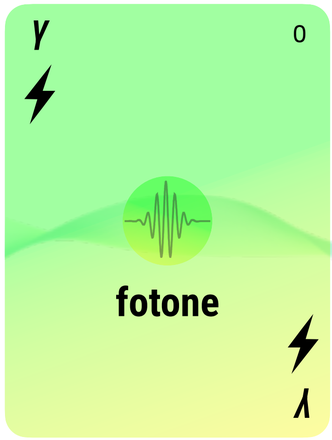

$$E^2 = m^2c^4 + p^2c^2$$

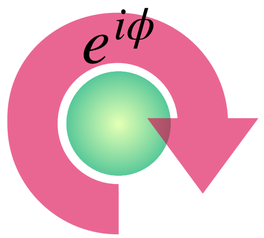


0
si muove a v=c

# Il campo elettromagnetico




Risultato dell'invarianza per "rotazioni" del campo dell'elettrone

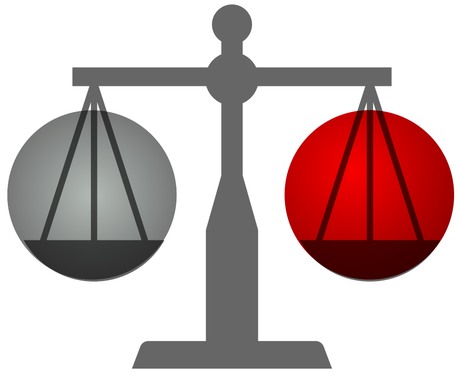
**Elettrodinamica Quantistica**

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - ej_{\mu}A^{\mu}$$

Il fotone è il **quanto** che media la forza elettromagnetica

intensità proporzionale alla **carica**

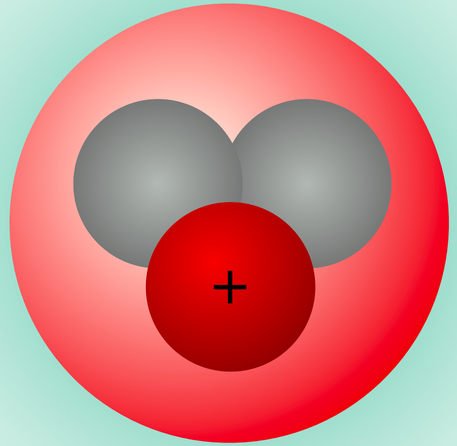
# Il nucleo



~ 1 GeV

~**2000 volte** la massa dell'elettrone!

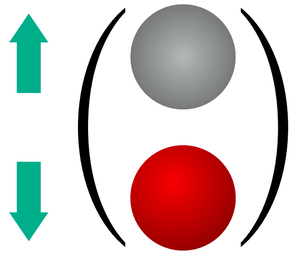
Il nucleo è composto da **protoni** e **neutroni**



$10^{-14}$ m

La forza nucleare è circa uguale per **p** e **n**

**Simmetria di *isospin***

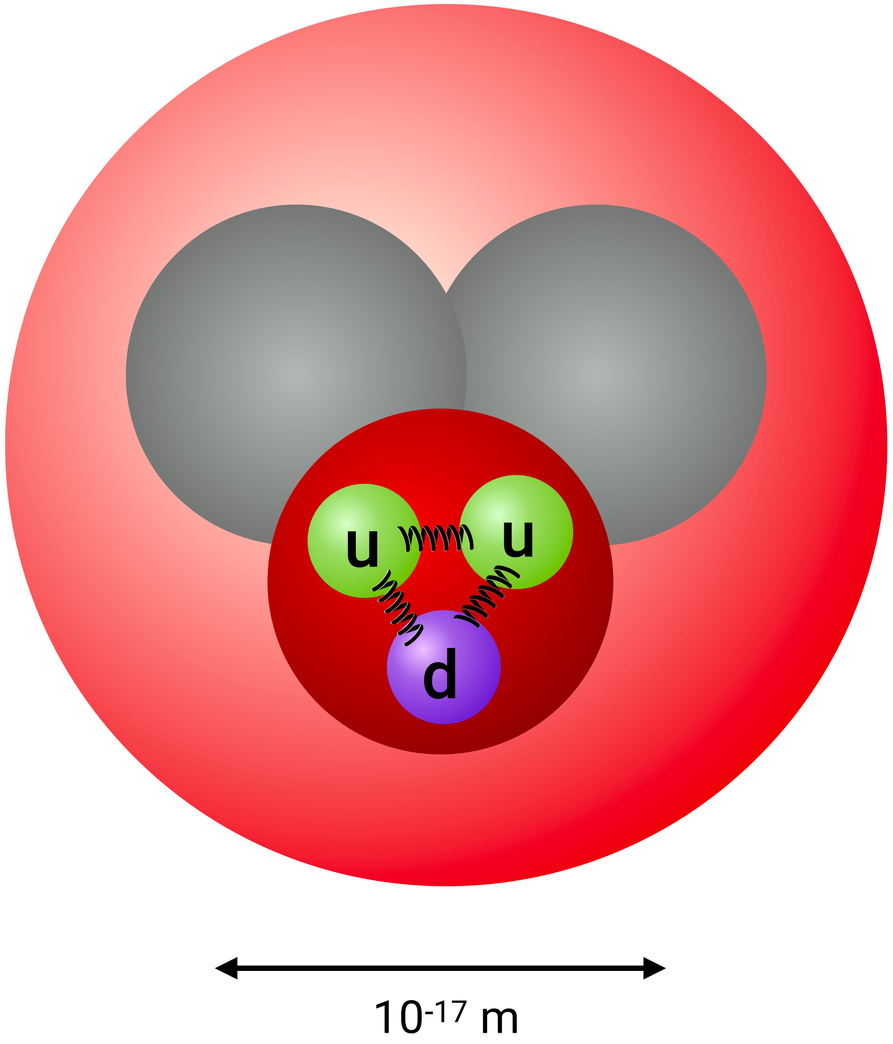


**p** e **n** sono due manifestazioni della stessa particella: il **nucleone**

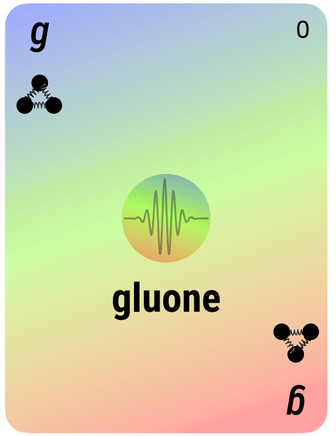
# Dentro il nucleo

$$V_{\text{Yukawa}} = -g^2 \frac{e^{-\mu r}}{r}$$

I nucleoni interagiscono attraverso un potenziale residuo dell'**interazione forte**




**Cromodinamica Quantistica**

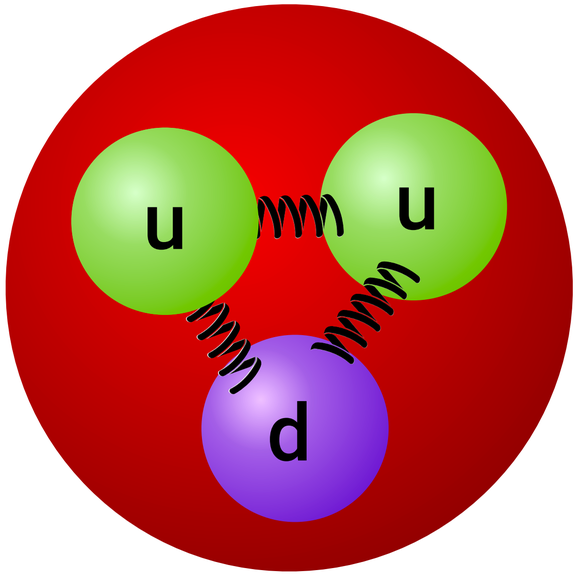


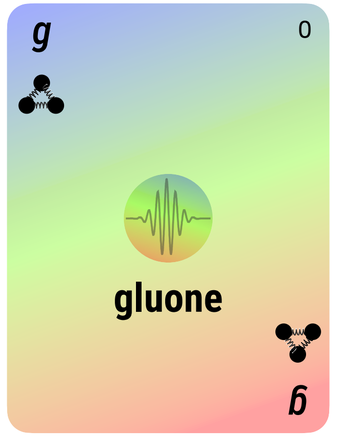

La forza forte è dovuta allo scambio di **gluoni**

# Dentro il protone

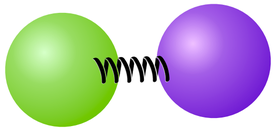
I nucleoni non sono particelle elementari.
Al loro interno ci sono i **quark**

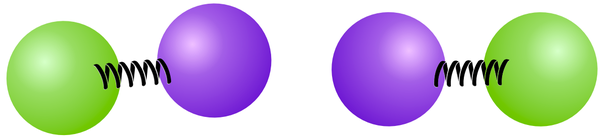




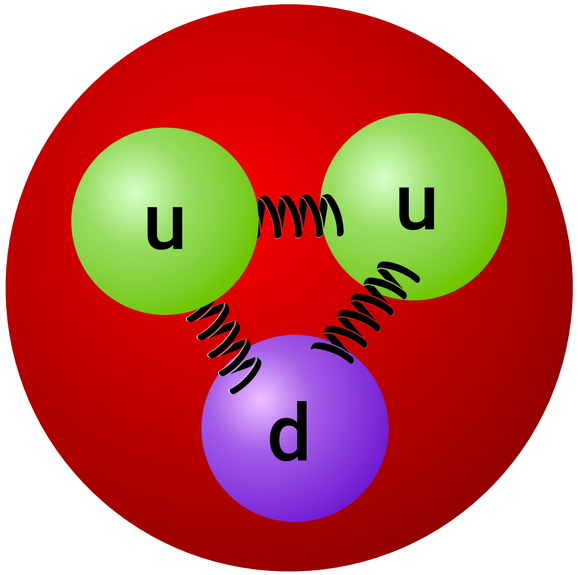




Sono particelle “appiccicose”!
con una **carica di colore**

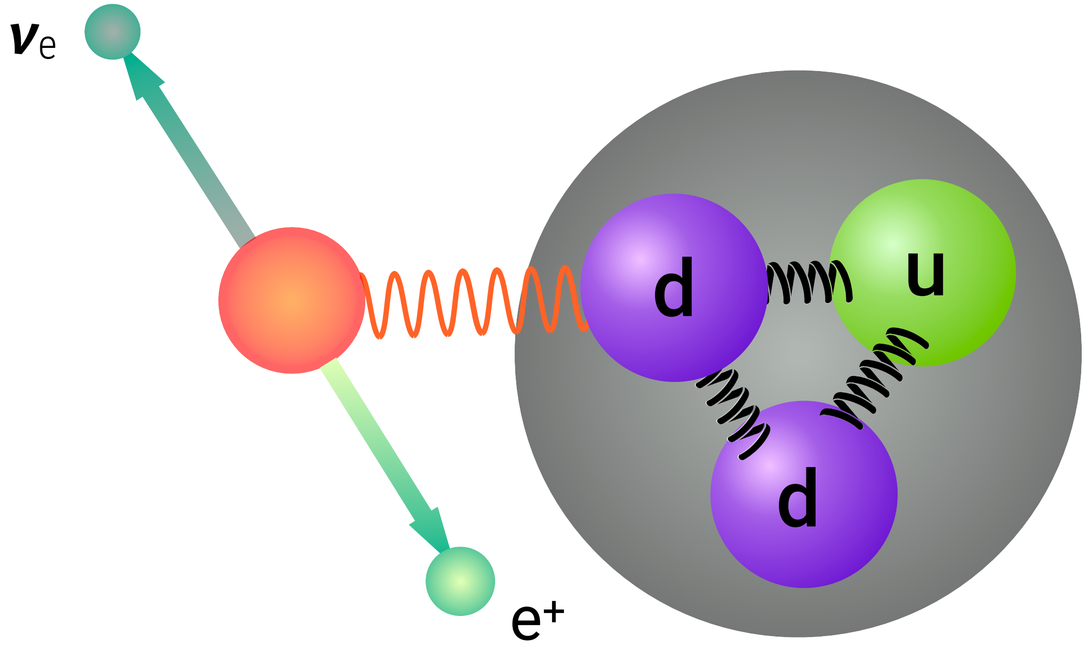




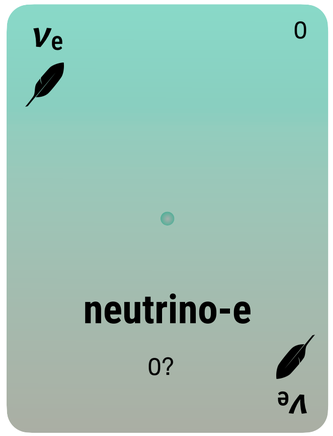
# Dentro il protone



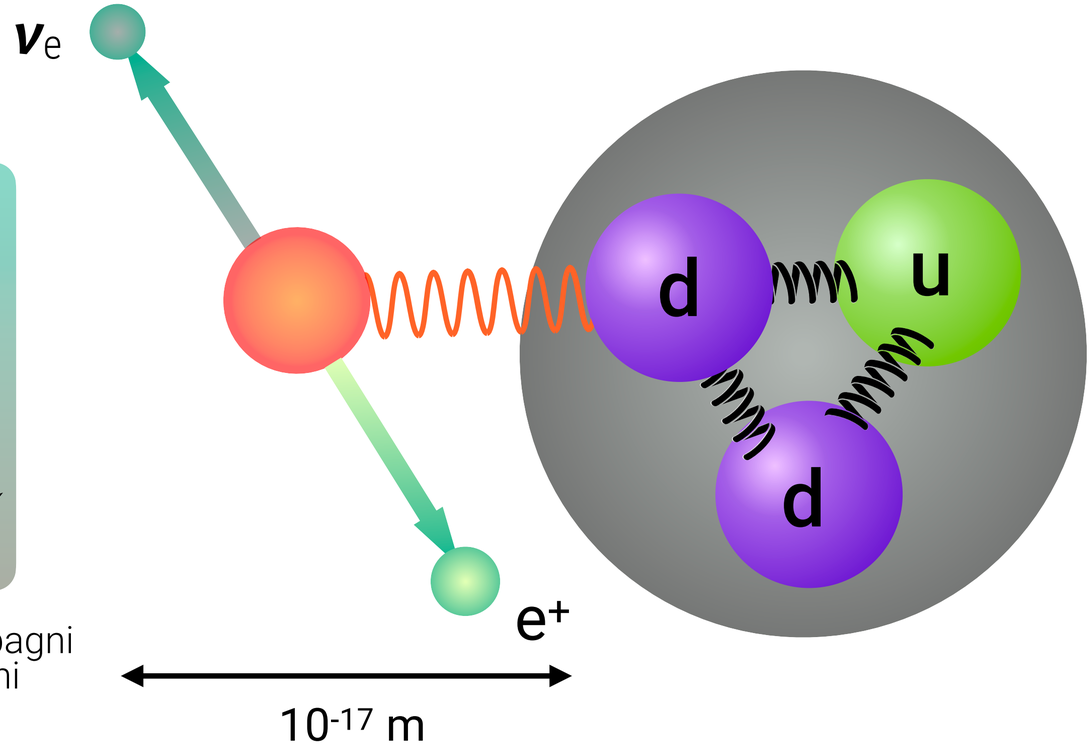
# I decadimenti deboli



# I decadimenti deboli

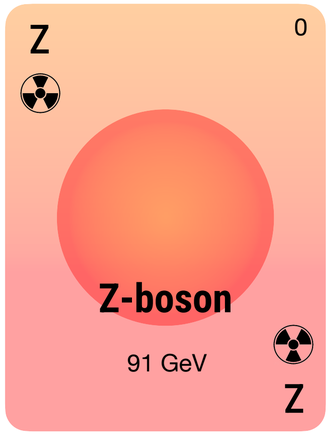


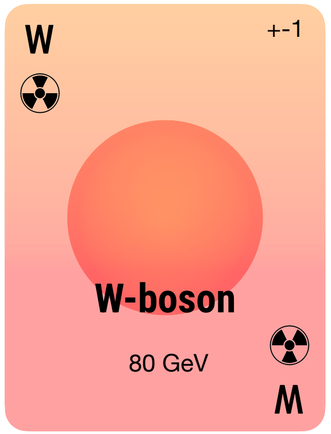

I **neutrini** sono i compagni neutri degli elettroni




$$\lambda \simeq \frac{hc}{M_W}$$

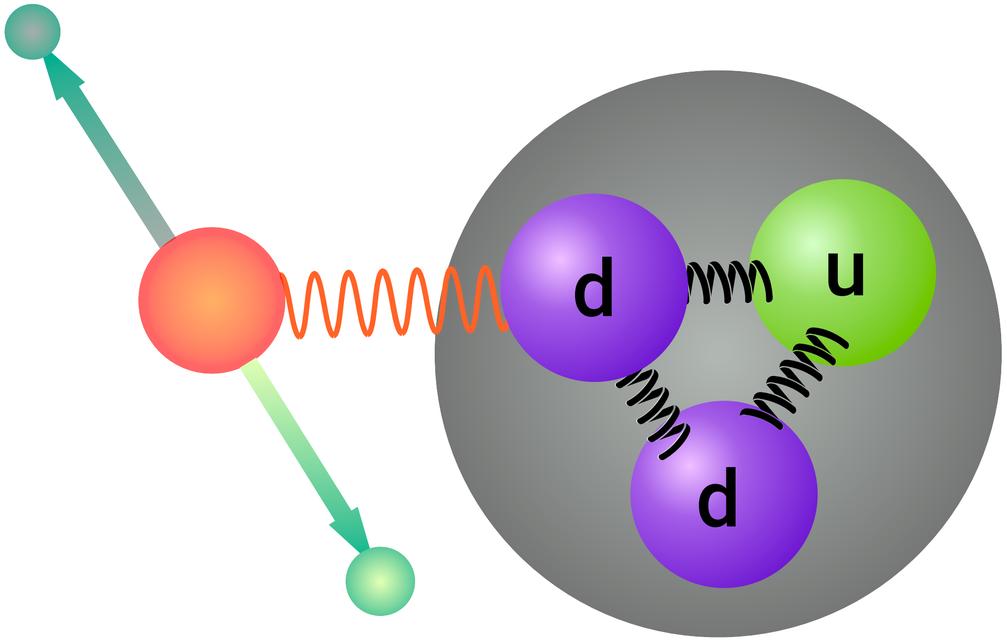
Sono molto massivi:
forza a corto range e debole

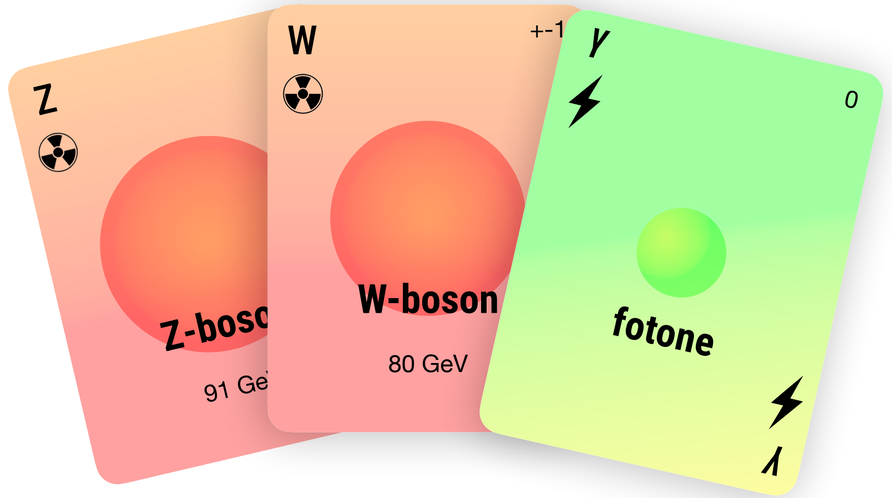



I bosoni **W** e **Z** sono i mediatori dei decadimenti nucleari

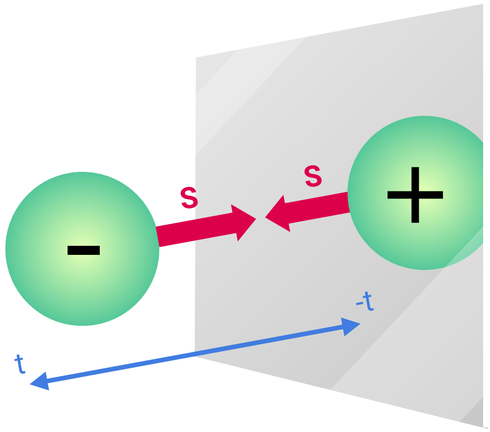
# I decadimenti deboli




**Unificazione elettrodebole**
La forza debole ed elettromagnetica
sono facce della stessa medaglia!

# Una teoria fatta di simmetrie

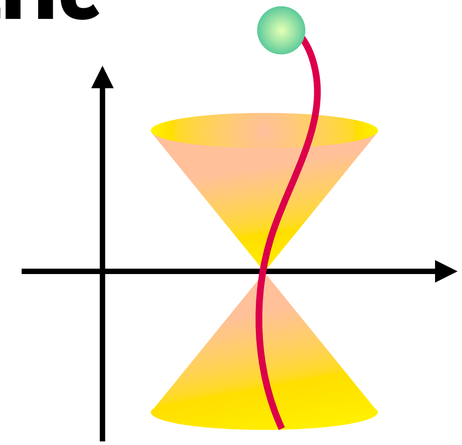



**C**arica $q \rightarrow -q$

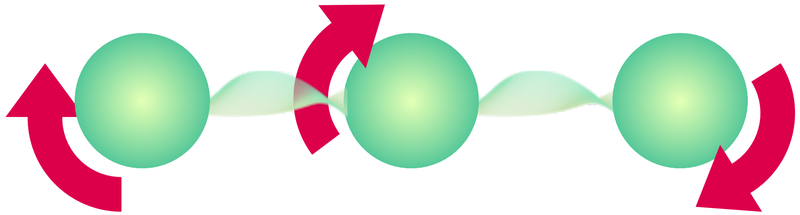
**P**arità $\vec{x} \rightarrow -\vec{x}$

**T**empo $t \rightarrow -t$

Le interazioni fondamentali sono uguali allo specchio

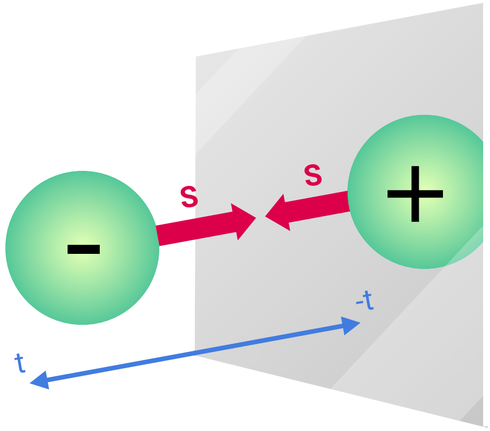


Rispettano le simmetrie dello spaziotempo



Le interazioni fondamentali sono ricavate a partire dalle **simmetrie di gauge**

# Una teoria fatta di simmetrie




**C**arica $q \rightarrow -q$

**P**arità $\vec{x} \rightarrow -\vec{x}$

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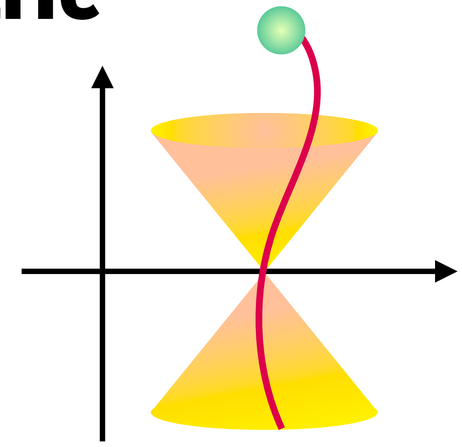
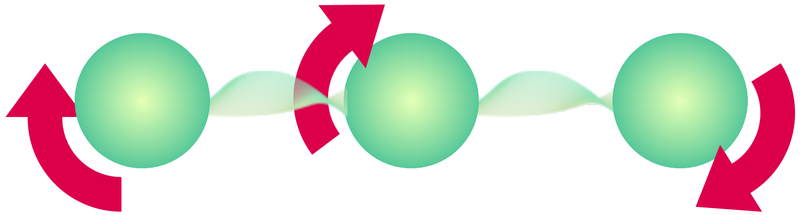
Le interazioni fondamentali sono uguali allo specchio



Rispettano le simmetrie dello spaziotempo



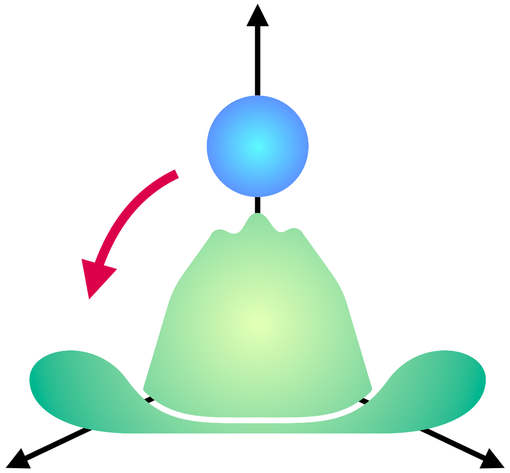
Le interazioni fondamentali sono ricavate a partire dalle **simmetrie di gauge**

## ma alcune si rompono...

$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

una funzione che dopo la **rottura spontanea di simmetria** assume un particolare valore

le particelle elementari acquistano **massa**



# Il Modello Standard delle Particelle

La materia di cui siamo fatti

## Quark

u +2/3
up
2.1 MeV
u n

d -1/3
down
4.7 MeV
d p

## Leptoni

$e^-$ -1
elettrone
0.511 MeV
$e^-$

$\nu_e$ 0
neutrino-e
0?
$\nu_e$

E le sue interazioni

## Strong Force

g 0
gluone
g

## Electroweak Force

γ 0
fotone
γ

Z 0
Z-boson
91 GeV
Z

W +-1
W-boson
80 GeV
W

## Higgs Mechanism

H H H H
Higgs
125 GeV

# Il Modello Standard delle Particelle

Quark

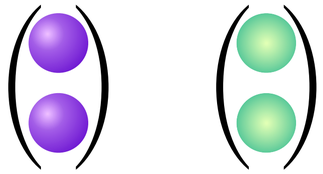
u +2/3
up
2.1 MeV
n

d -1/3
down
4.7 MeV
p

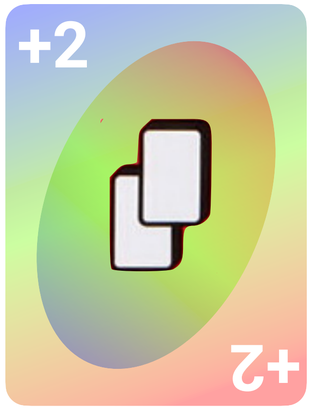
Leptoni

e⁻ -1
elettrone
0.511 MeV
e⁻

$\nu_e$ 0
neutrino-e
0?
$\nu_e$



Da argomenti di simmetria quark e leptoni sono organizzati in doppietti




Si osservano altre 2 generazioni di materia

Strong Force

g 0
gluone
g

γ 0
fotone
γ

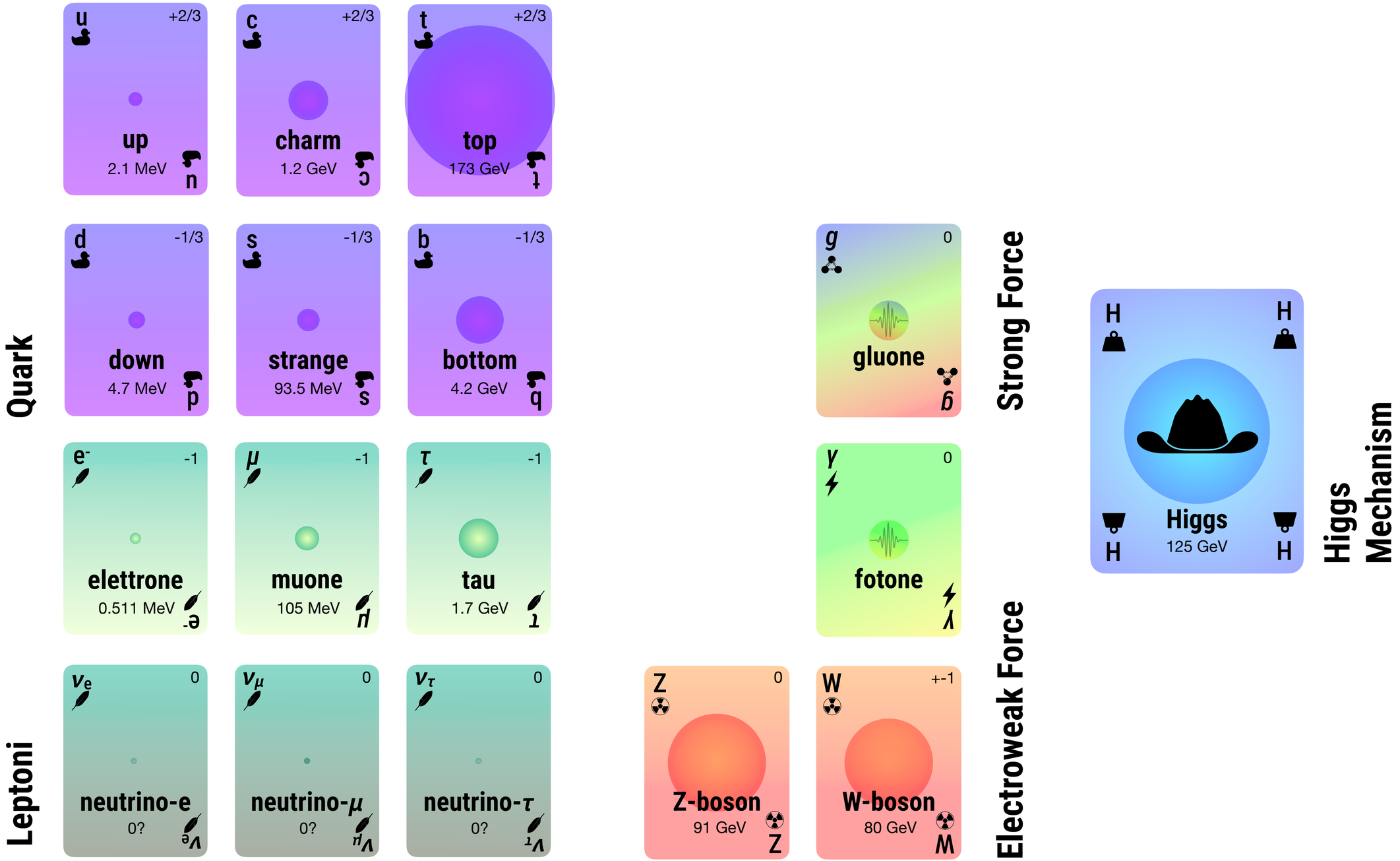
Electroweak Force

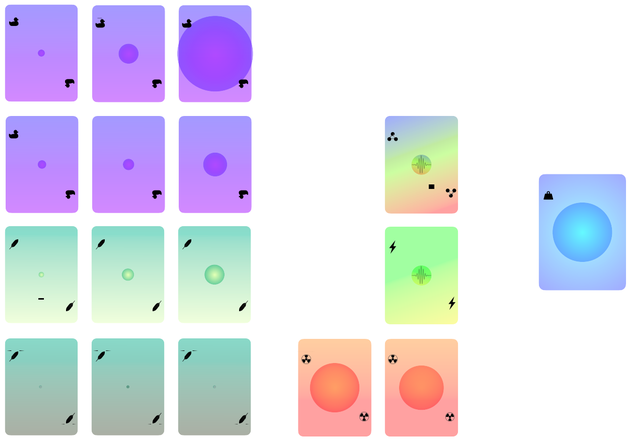
Z 0
Z-boson
91 GeV
Z

W +-1
W-boson
80 GeV
W

Higgs Mechanism

# Il Modello Standard delle Particelle

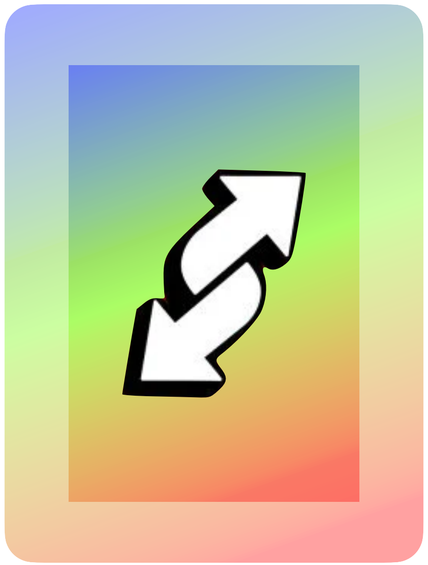




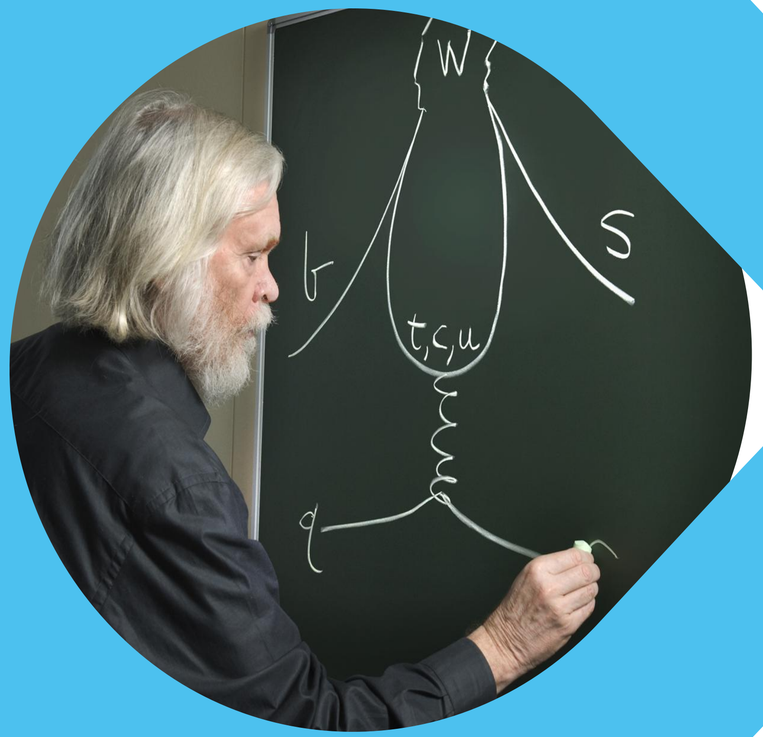

Ma...

# il MODELLO STANDARD

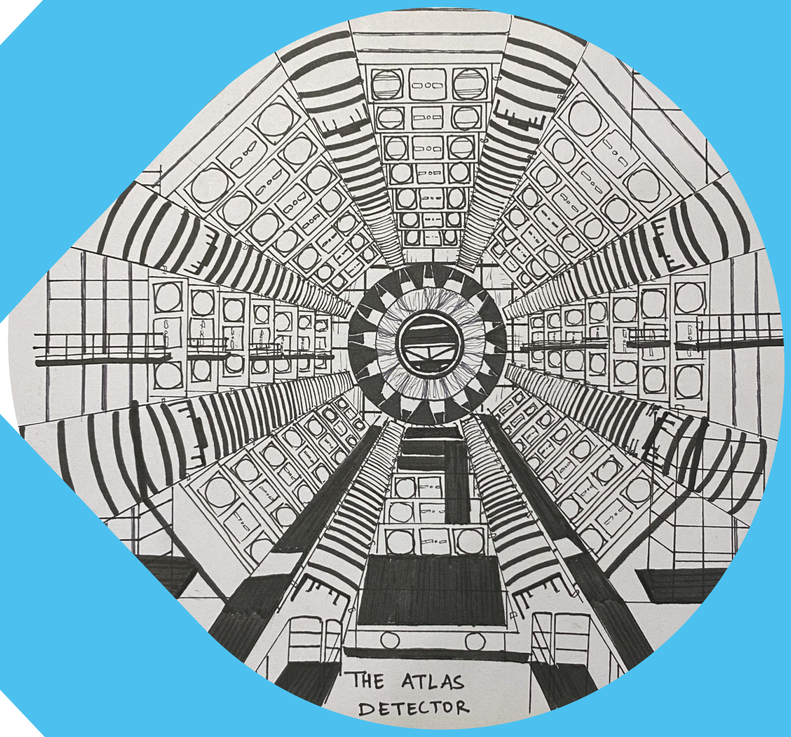
...funziona?



# Il metodo scientifico



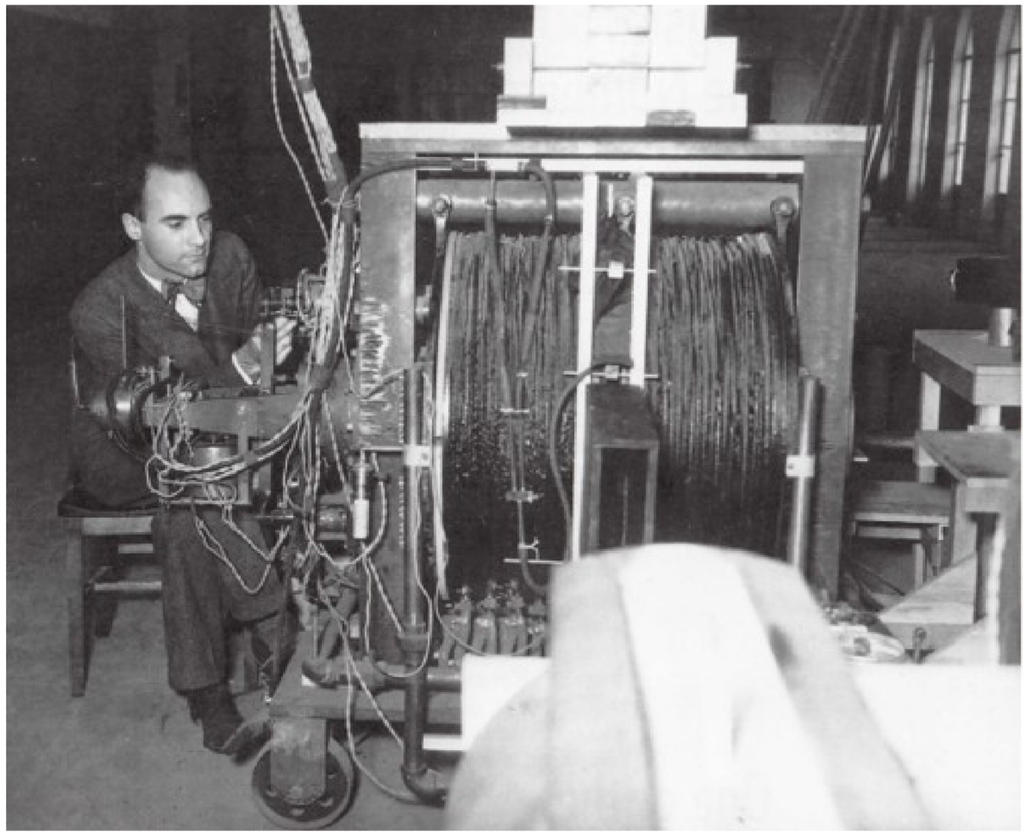

Teoria



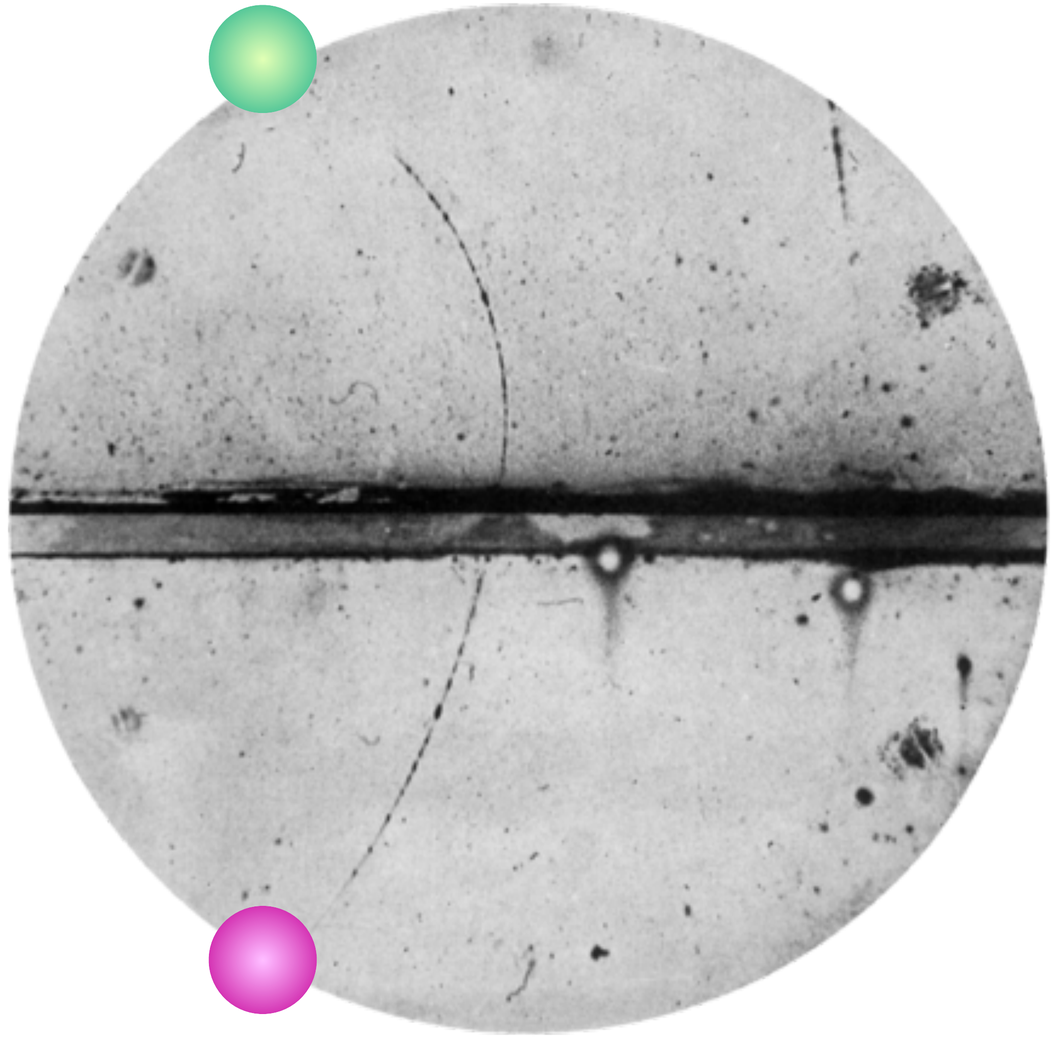

Esperimenti

# Gli esperimenti

Scoperta del positrone (antimateria)
**Anderson**, 1932

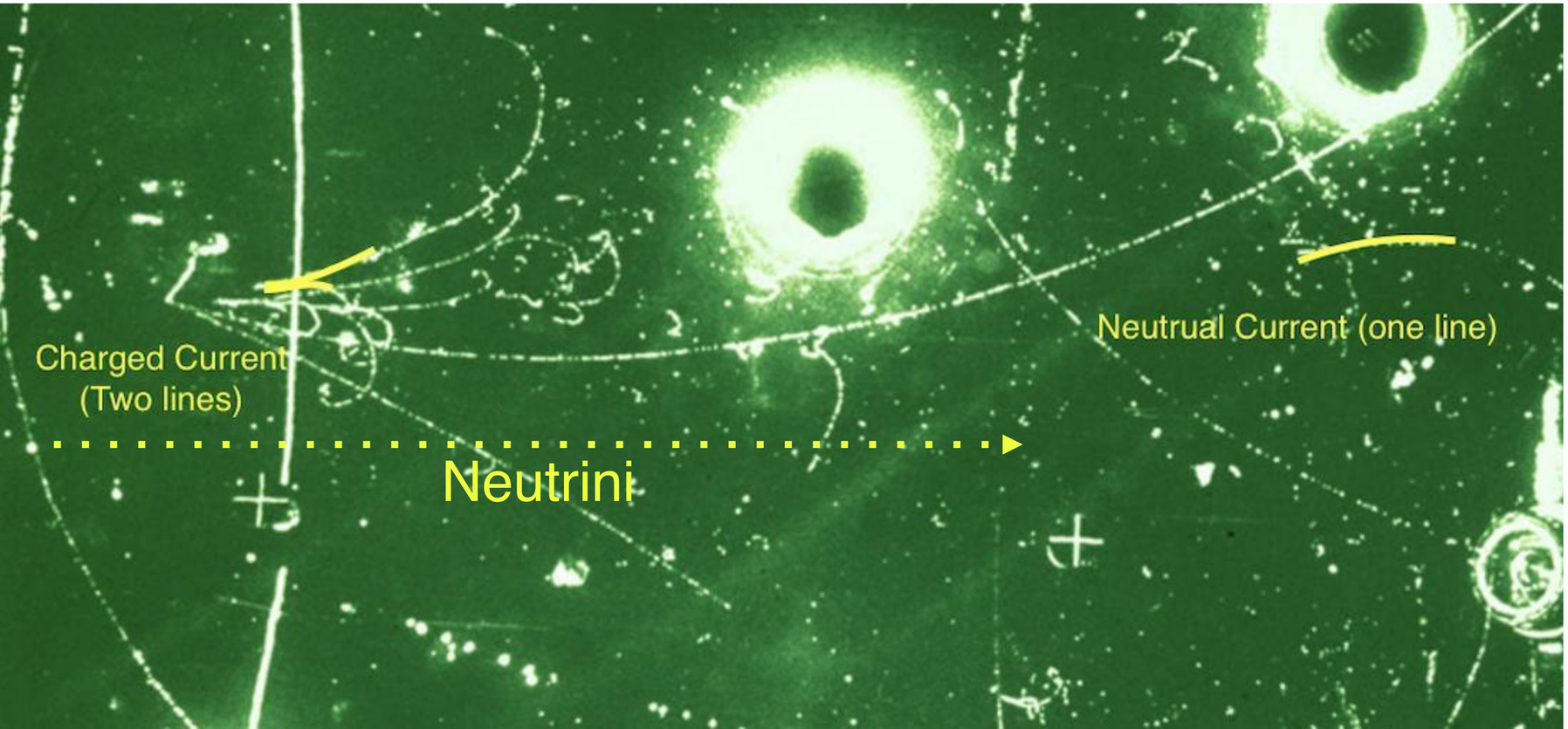






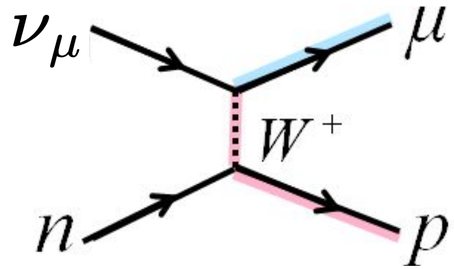
# Gli esperimenti

Gargamelle, scoperta delle correnti deboli neutre (1973)




## Corrente debole carica

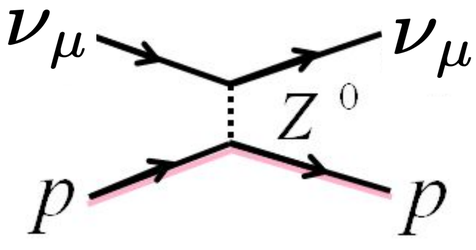
$$\nu_\mu + n \rightarrow \mu + p$$




$W^\pm$ boson

## Corrente debole neutra

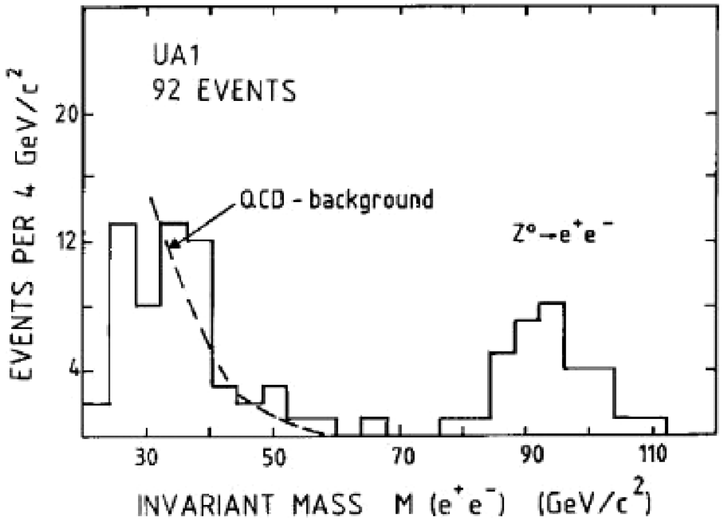
$$\nu_\mu + p \rightarrow \nu_\mu + p$$

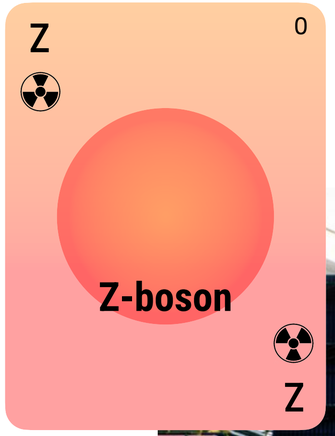


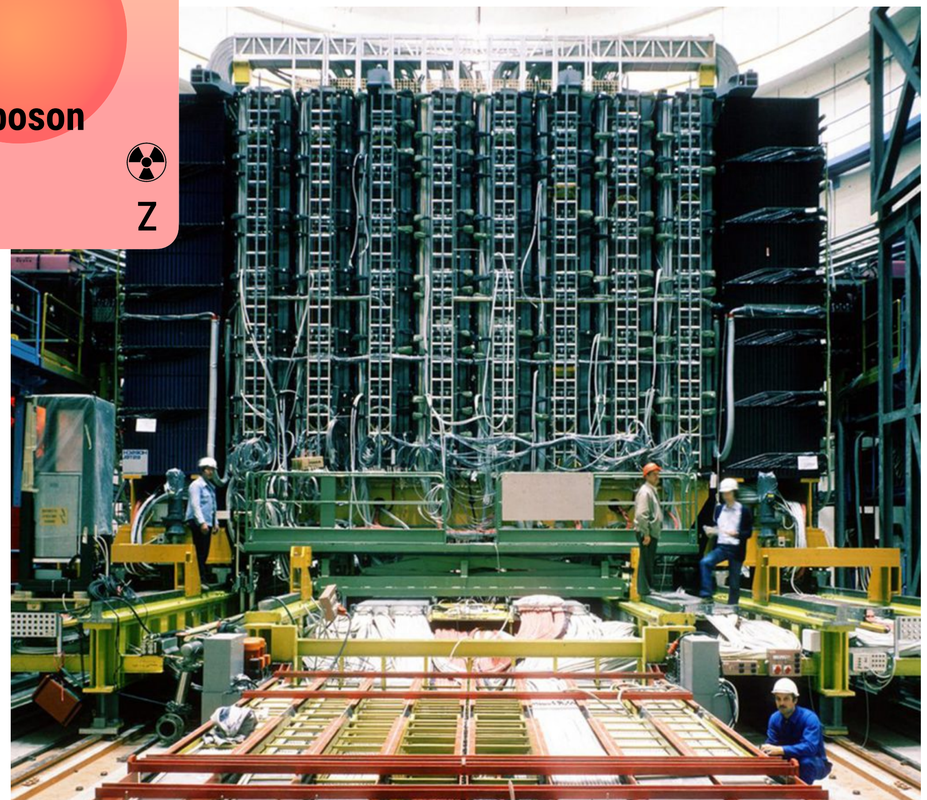

$Z^0$ boson

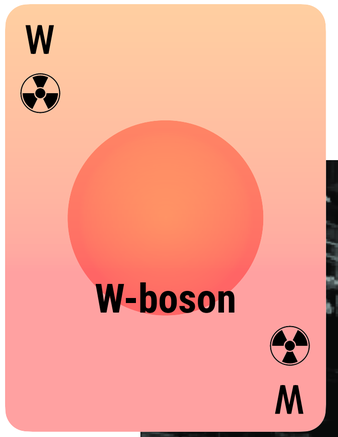
# Gli esperimenti

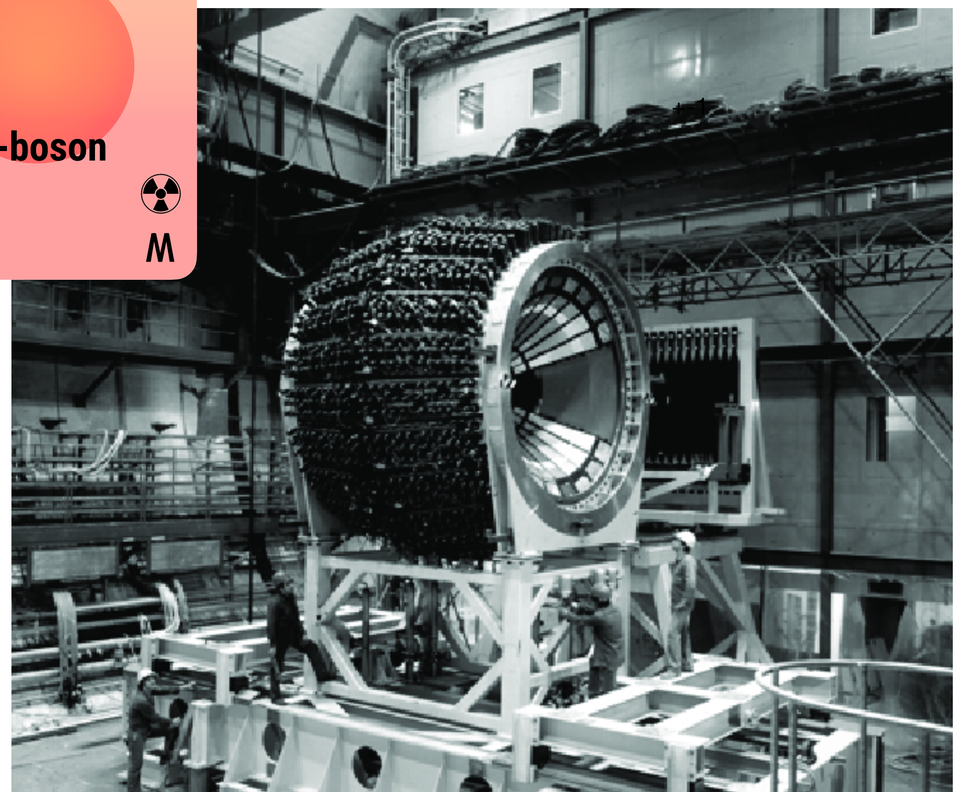
UA1 e UA2, scoperta dei bosoni $W^{+/-}$ e $Z^0$ (1983)



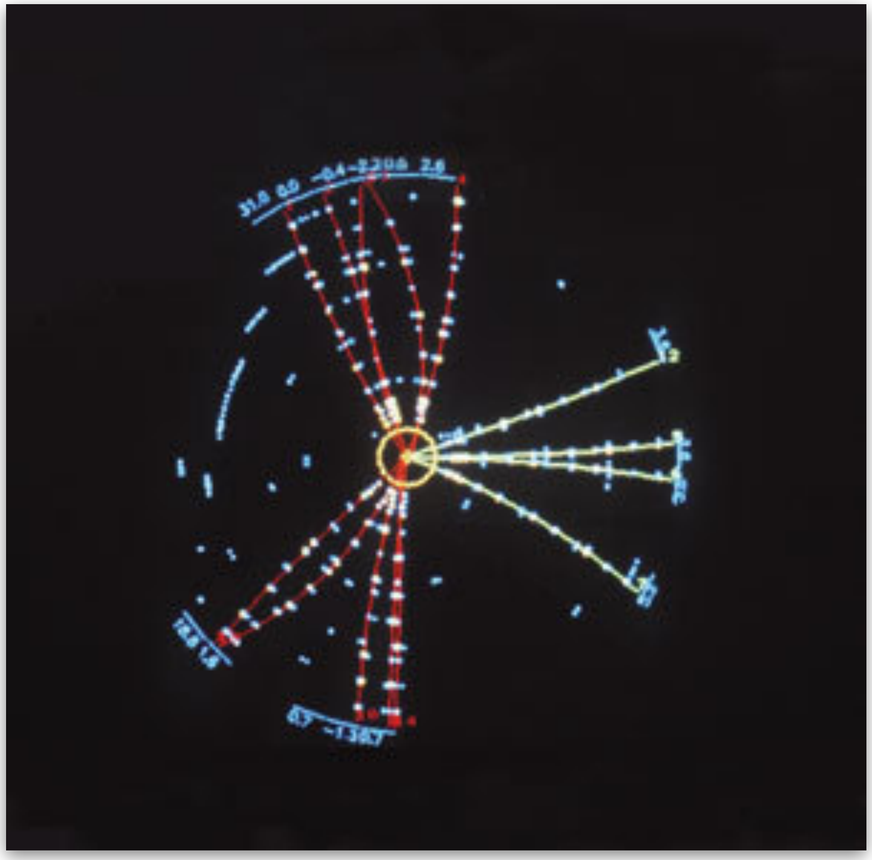





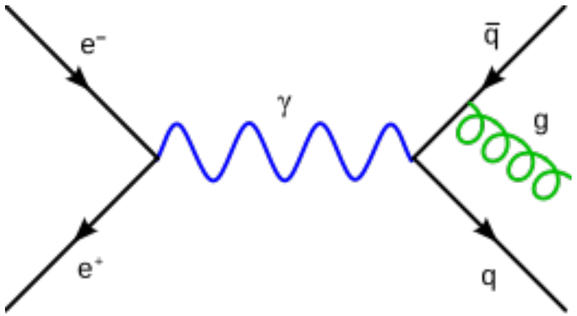



# Gli esperimenti

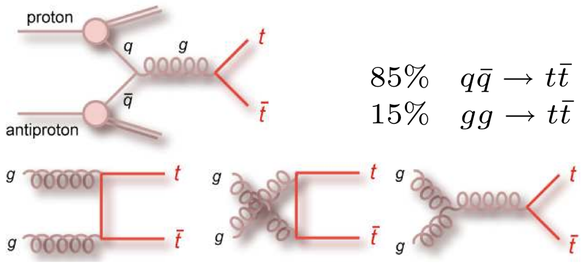
Esistenza dei **gluoni**,
quark **charm**, e **terza famiglia** di quark e leptoni (tau e neutrino tau, quark bottom e top)



Scoperta del gluone
@ DESY (1979)

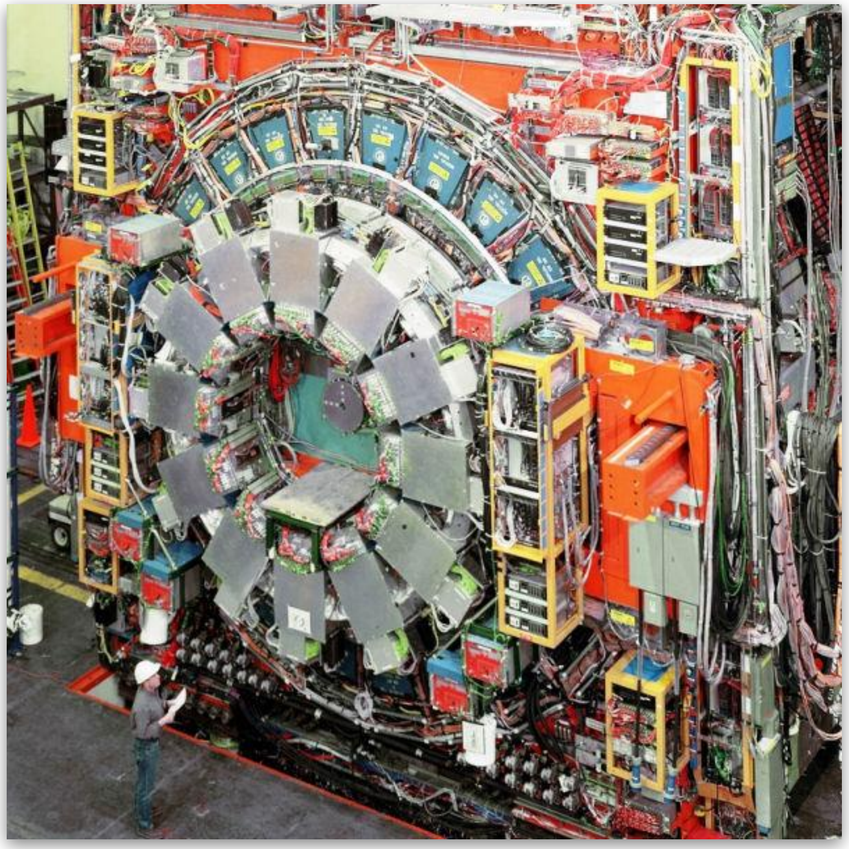



**Strong top production**




$85\%\quad q\bar{q} \to t\bar{t}$
$15\%\quad gg \to t\bar{t}$

Scoperta del quark top
@ Tevatron (1995)



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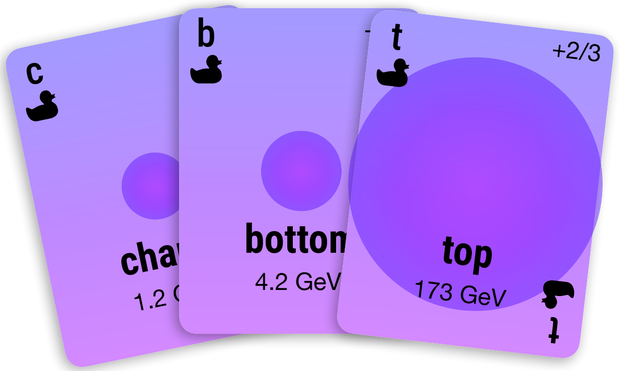
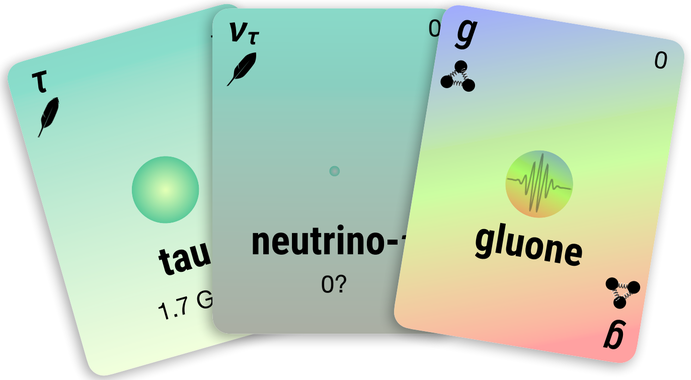
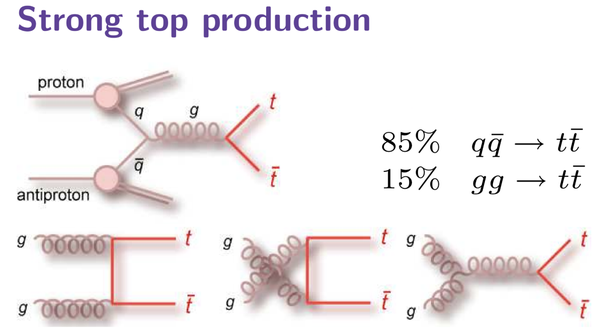
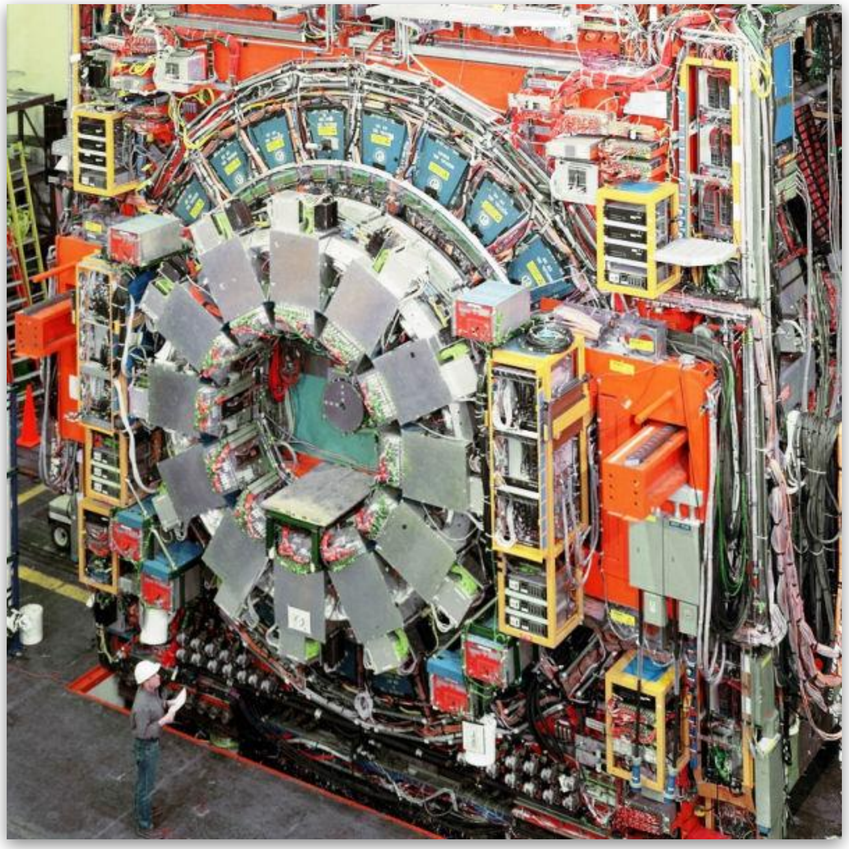


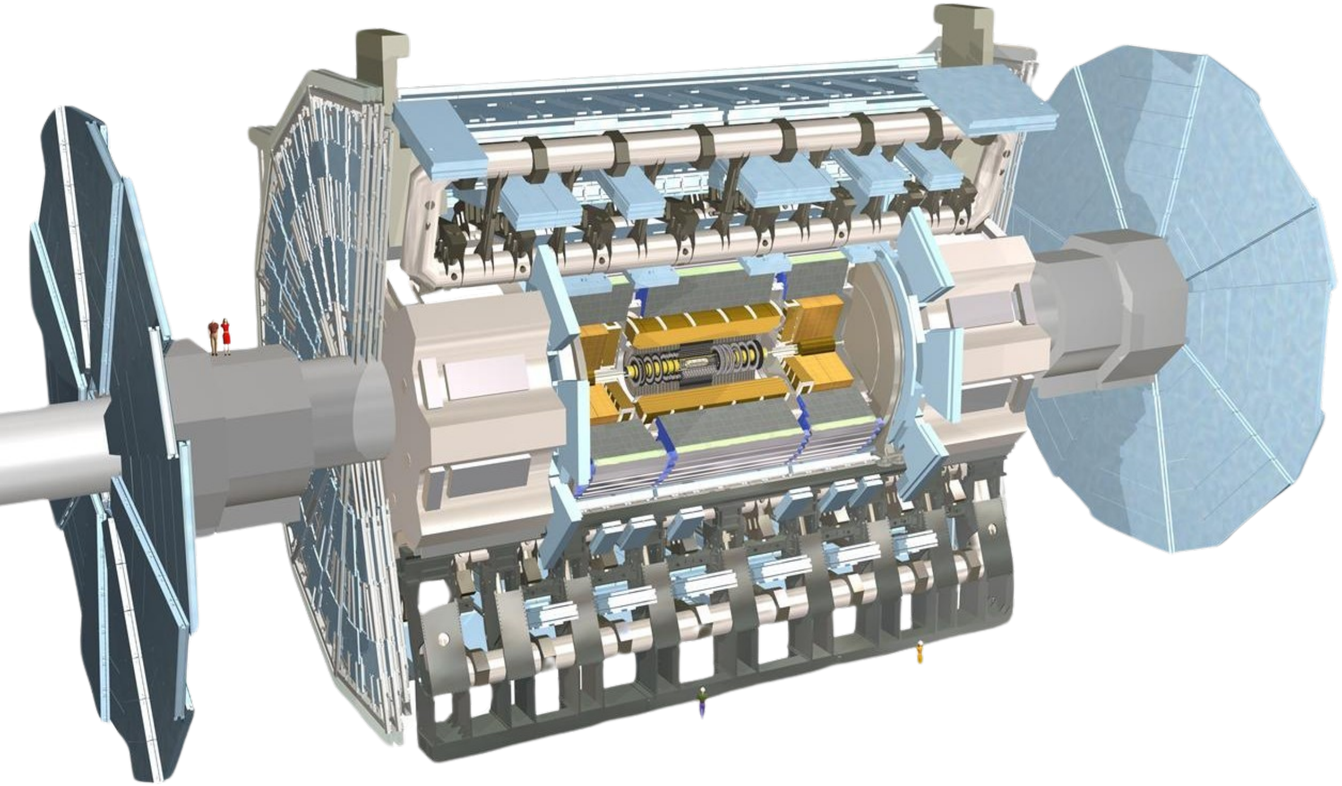




Scoperta del quark top @ Tevatron (1995)



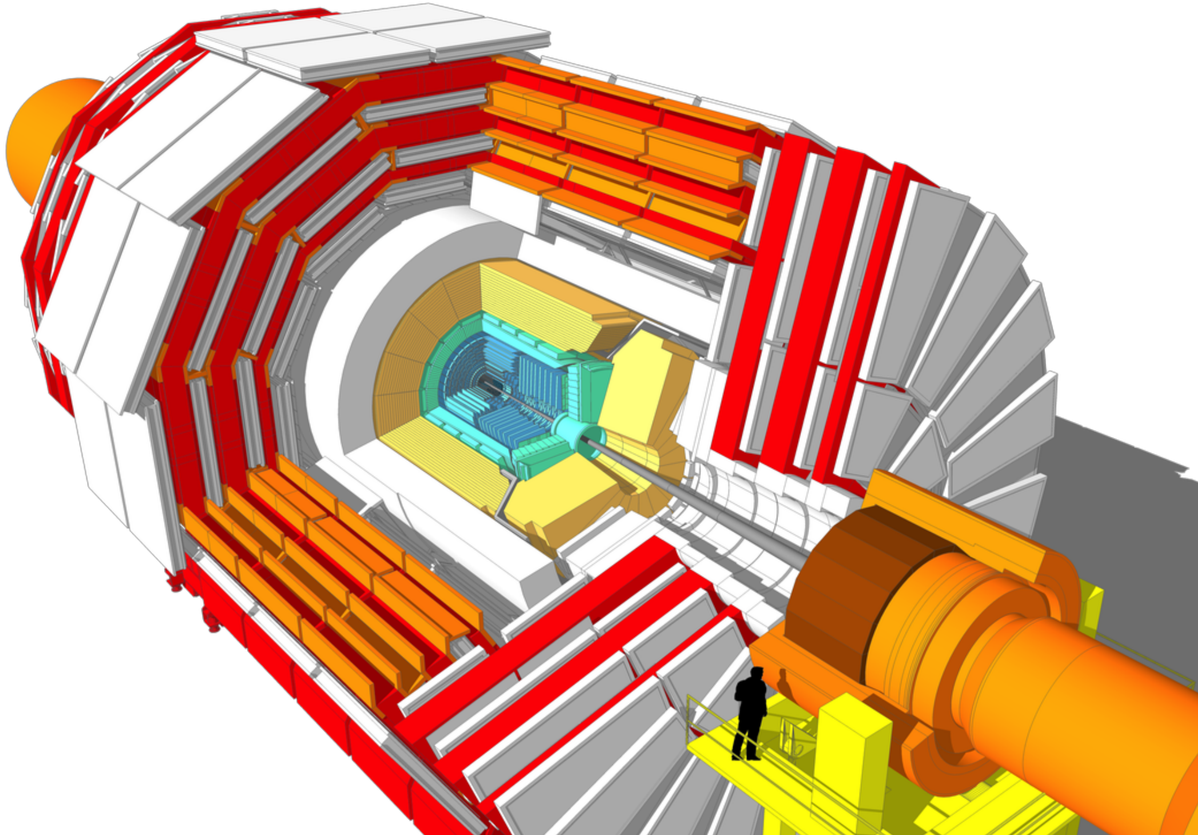
# Gli esperimenti

ATLAS e CMS, scoperta del bosone di Higgs (2012)



**ATLAS**

**CMS**



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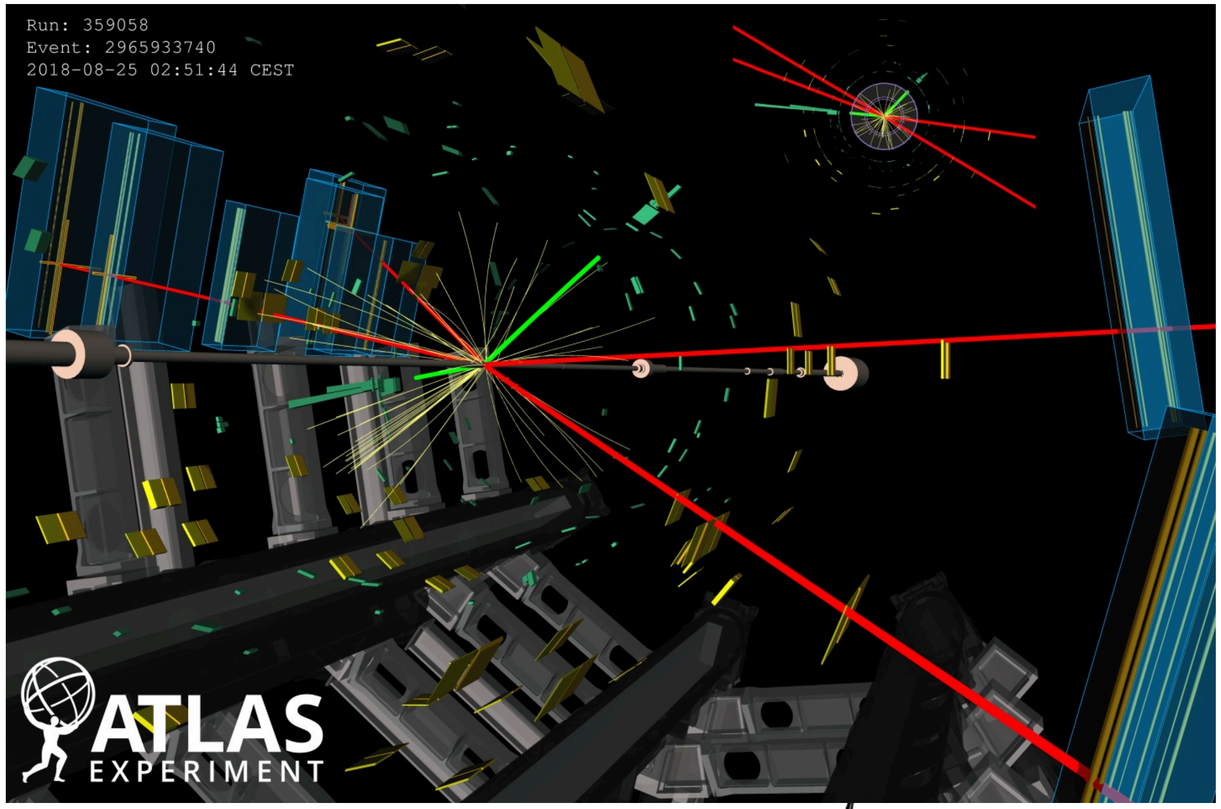
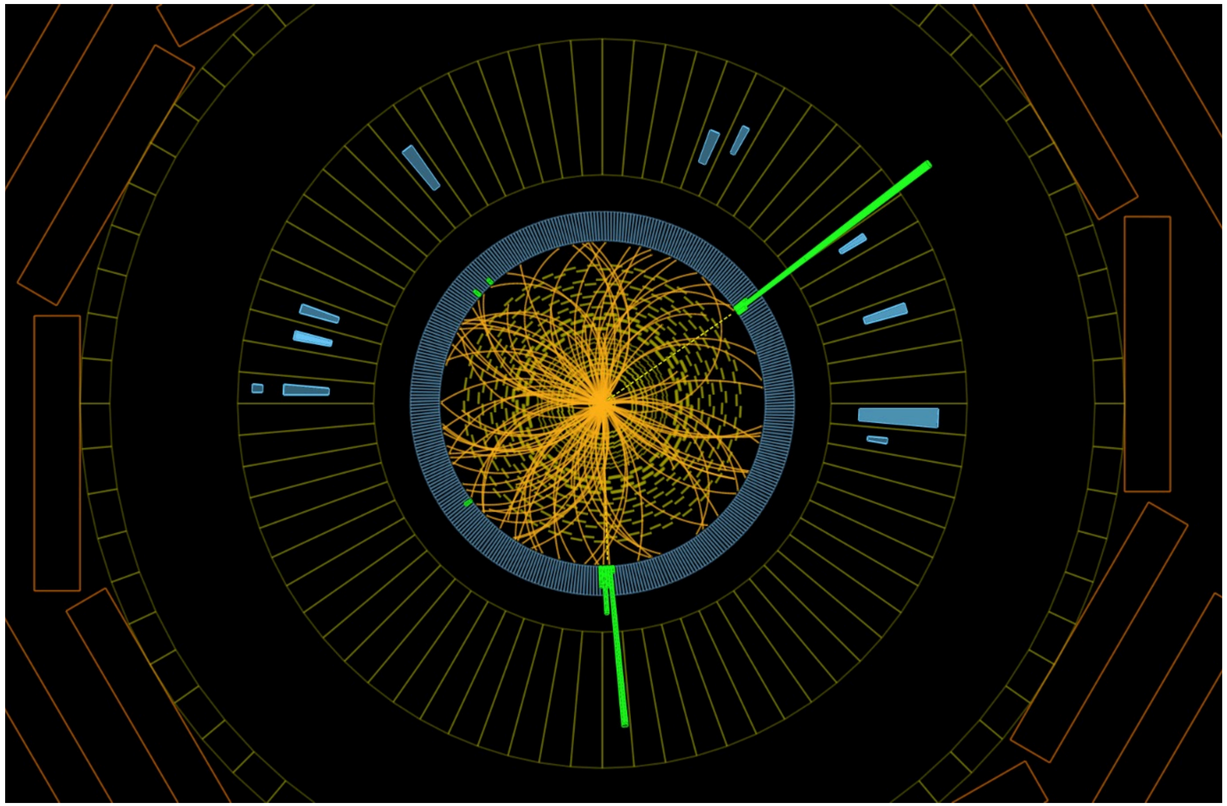
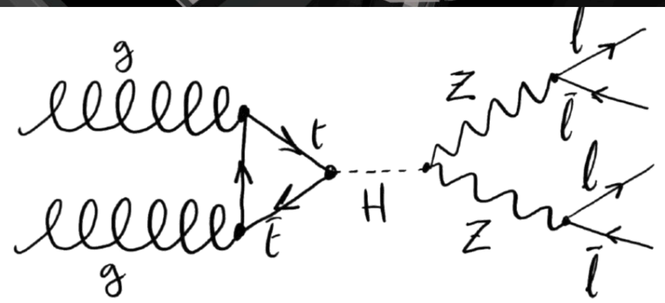
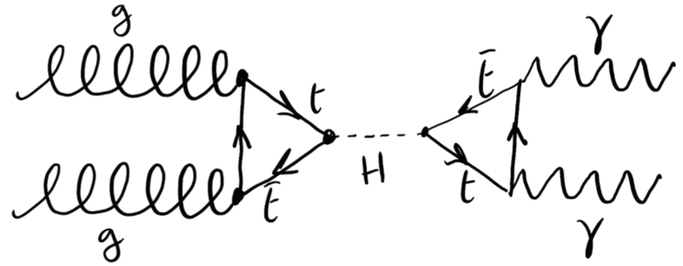


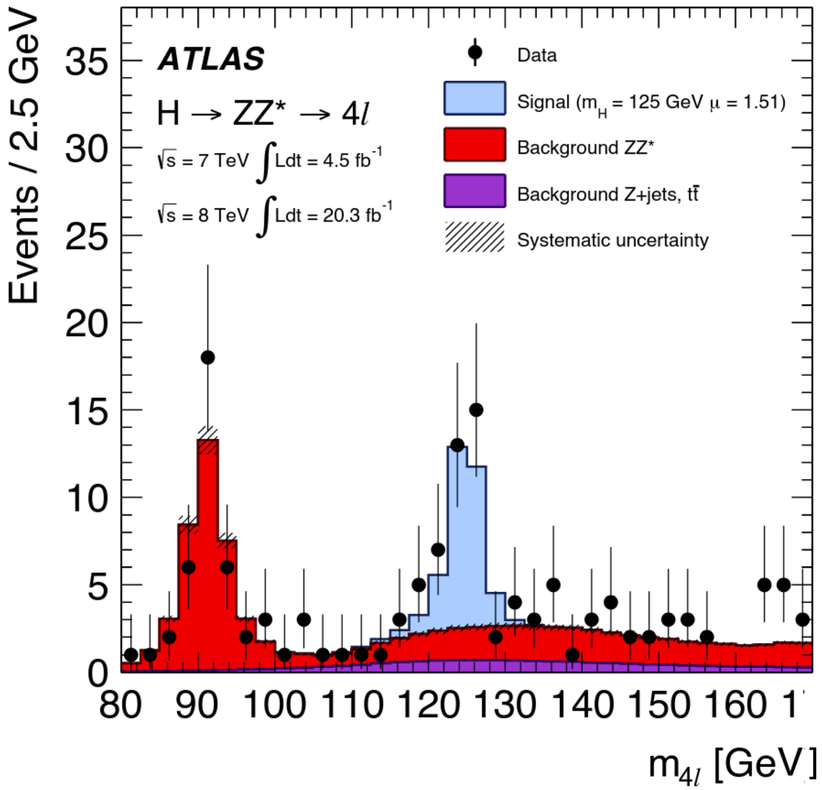





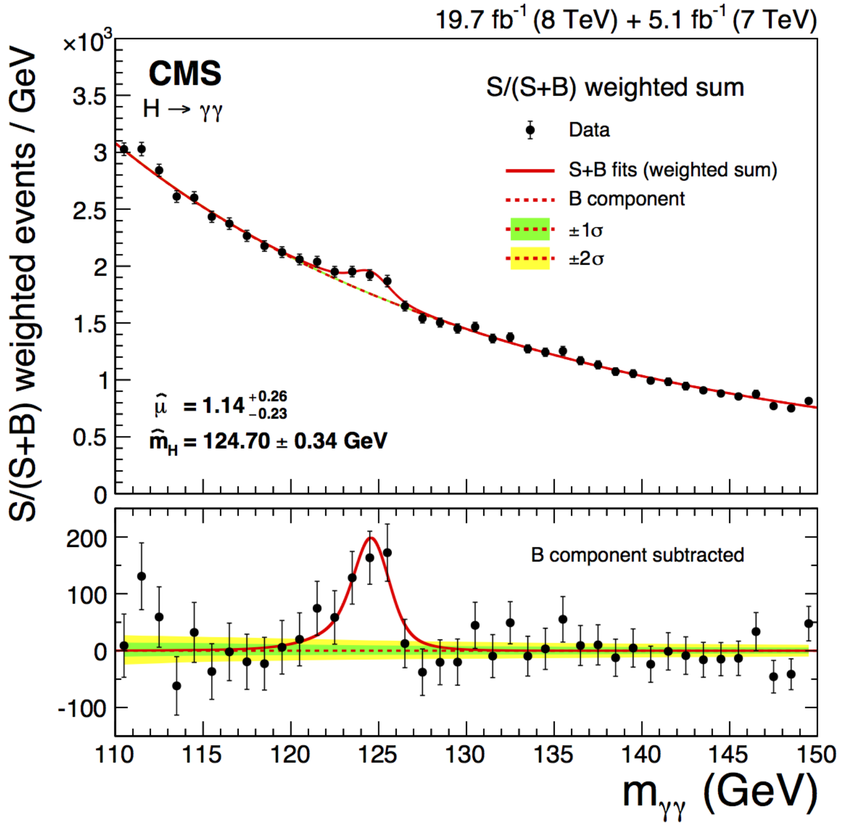



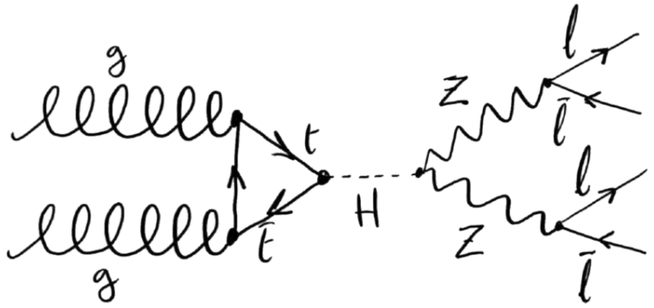
# Gli esperimenti

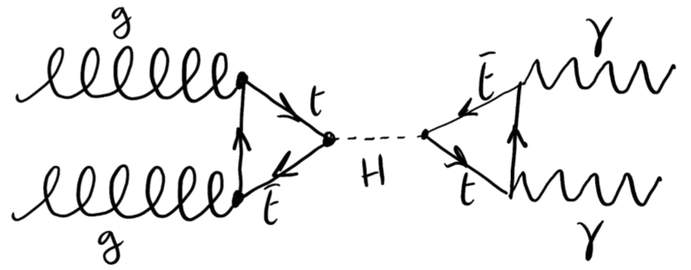
ATLAS e CMS, scoperta del bosone di Higgs (2012)







# Come ci si confronta con la teoria?

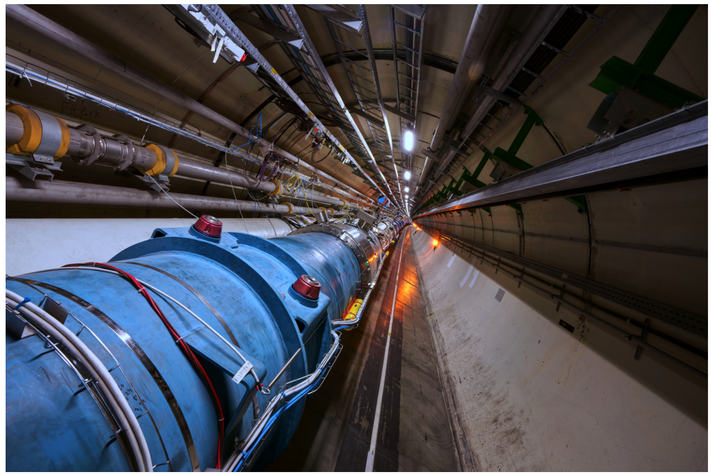
**Numero di Eventi**
Che misuriamo

$$N = \sigma \cdot L$$

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

**Sezione d'urto**
(il Modello Standard o un'altra teoria che vogliamo testare)

**Luminosità**
La macchina che vogliamo utilizzare (acceleratore)

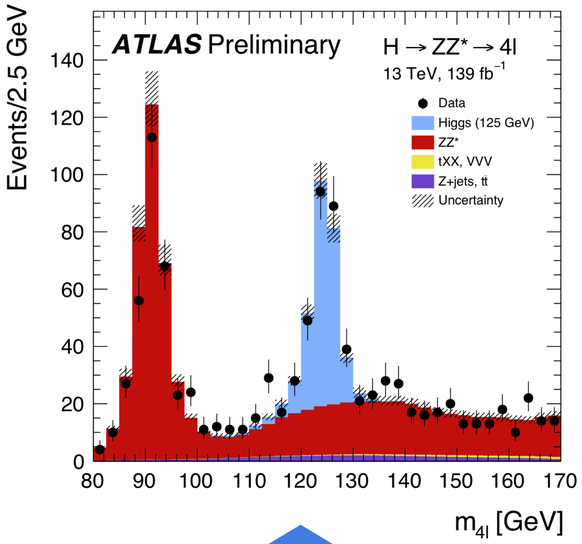


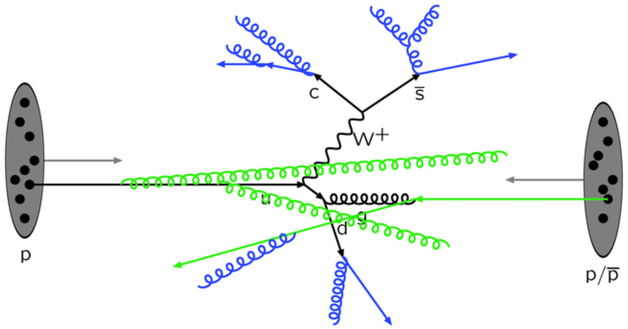
# Come ci si confronta con la teoria?

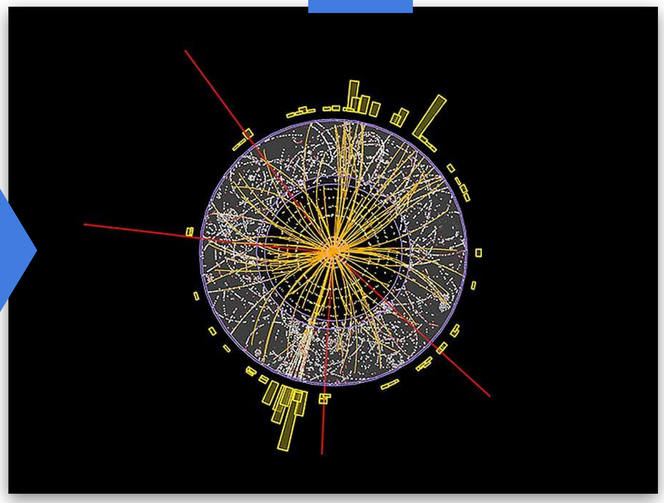
**Numero di Eventi**
Che misuriamo

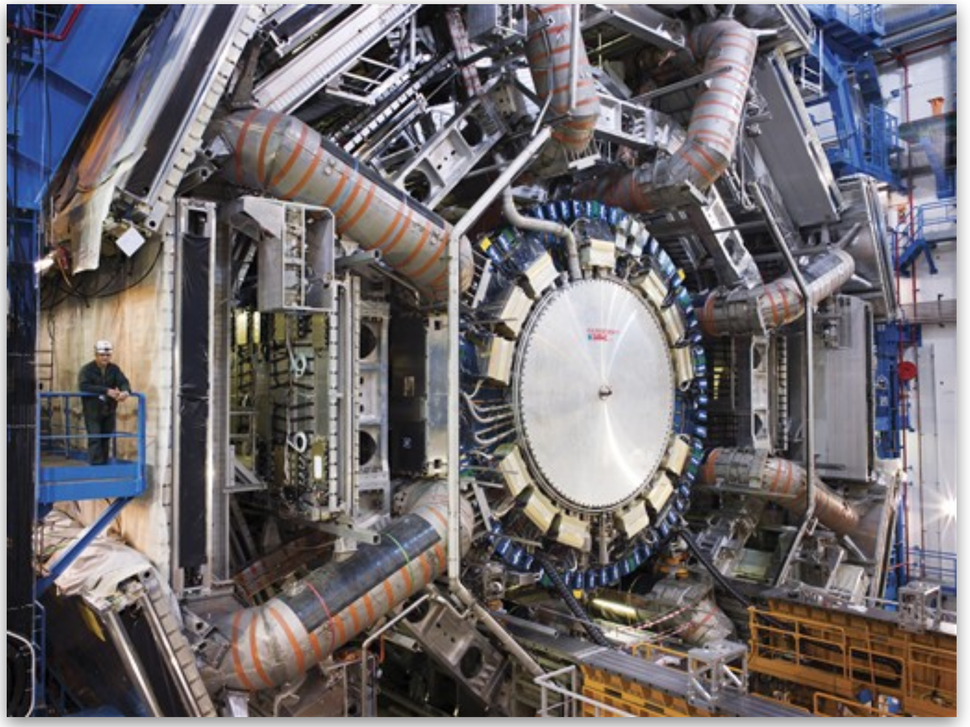
$$N = \sigma \cdot L$$

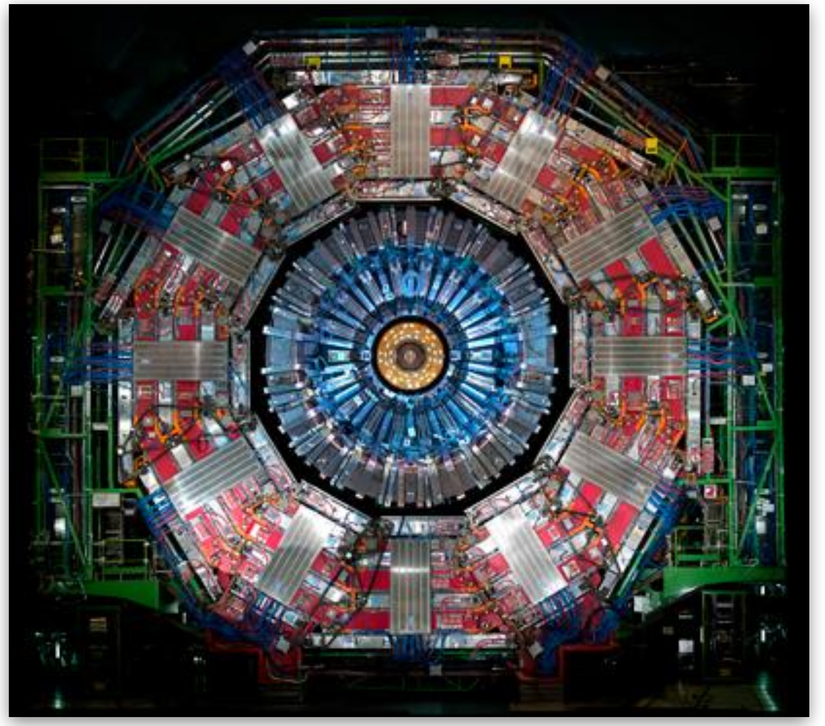
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



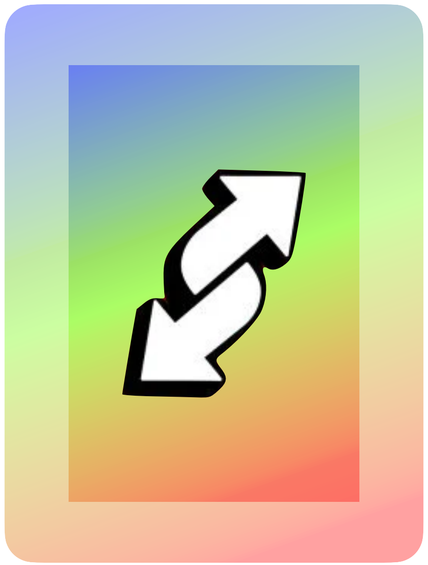







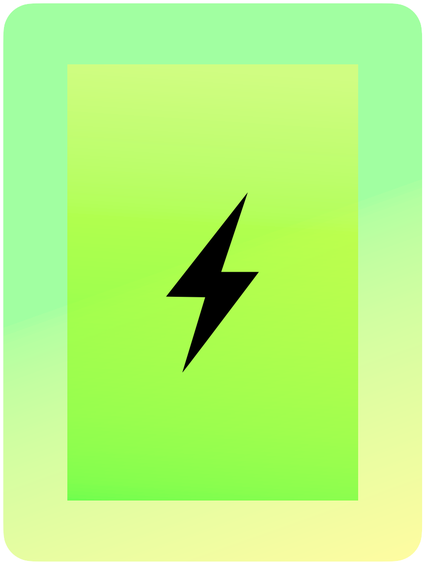
Uno ( *O* (1000) ) sperimentale all'opera:

- Hardware ed elettronica di basso/alto livello
- Acquisizione dati, processing & computing
- Analisi dei dati raccolti
- Confronto con fenomenologia e simulazioni Monte Carlo
- Statistica
- Sviluppo tecniche di analisi (unfolding, machine learning, ecc.)
- E (tantissimo) altro

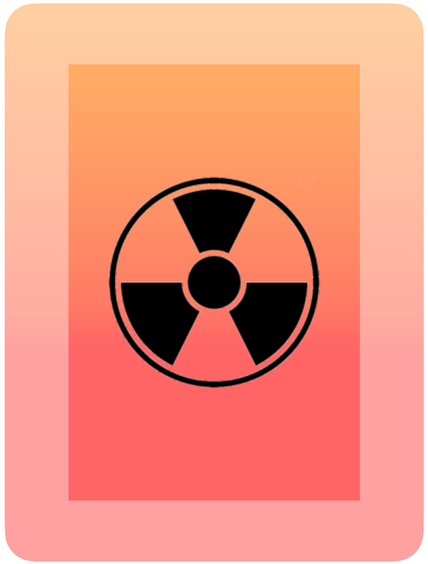


# E la gravità?

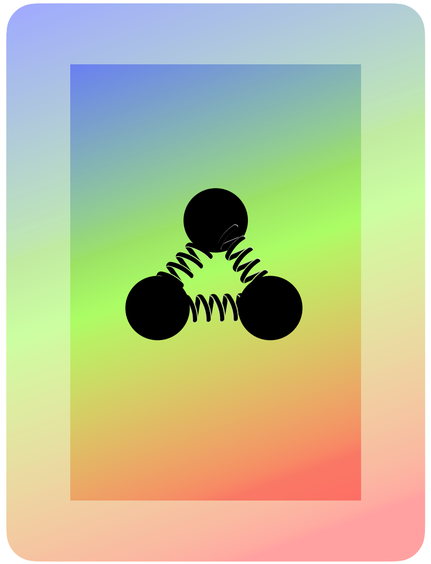
Il Modello Standard descrive
**3 delle 4** interazioni fondamentali
nello spaziotempo **piatto**



**Elettromagnetismo**



**Debole**

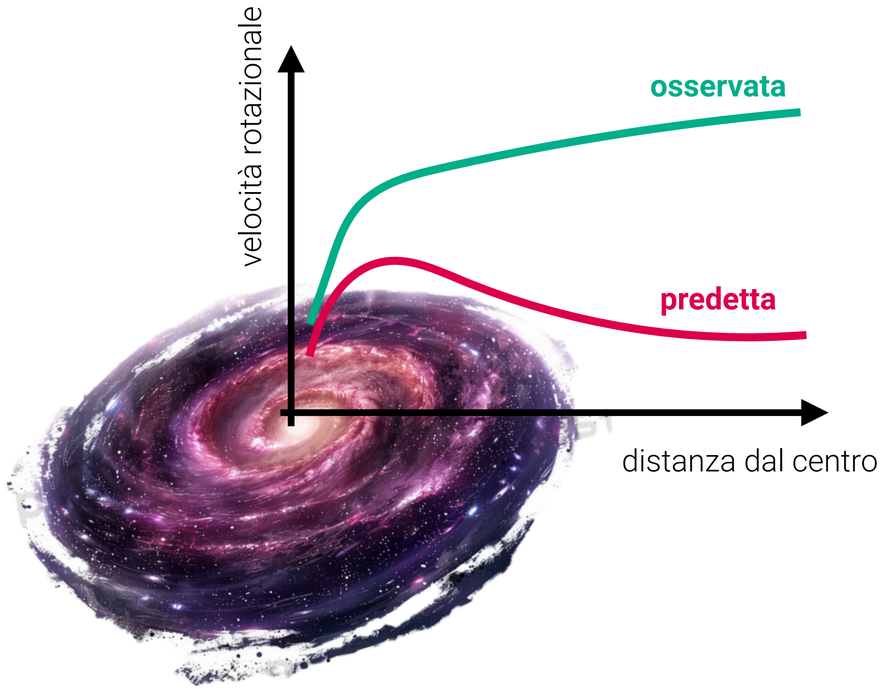


**Forte**


**Gravità**

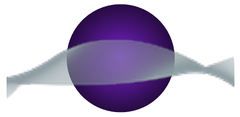
I tentativi di descrivere la gravità
con lo stesso formalismo del
modello standard **falliscono**

# Materia e energia oscure

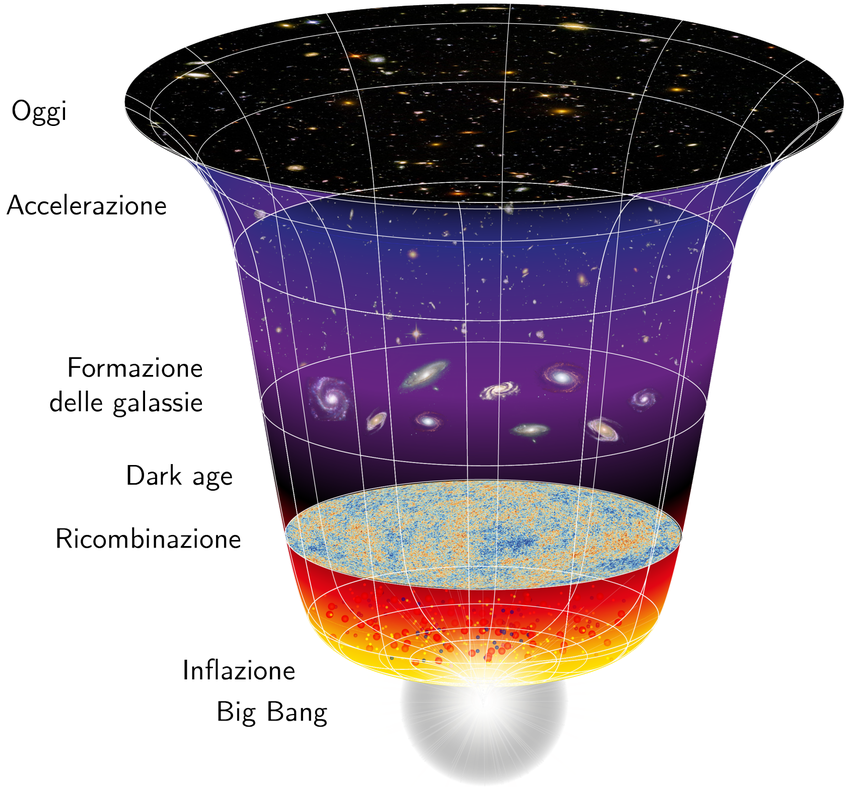



La materia osservata è solo il 5% della materia contenuta nelle galassie:
**materia oscura**

Nessuna particella del MS può spiegare questo fenomeno

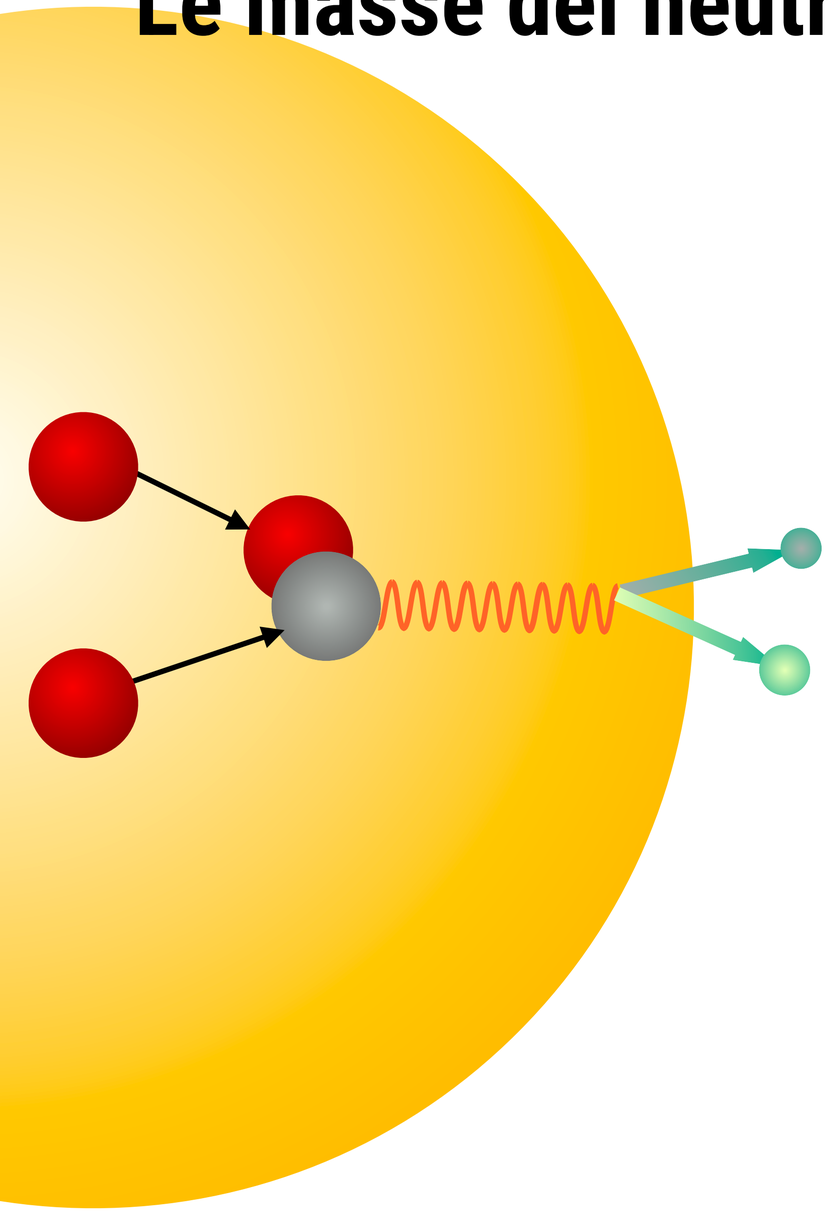


L'universo si espande in modo accelerato:
**energia oscura**

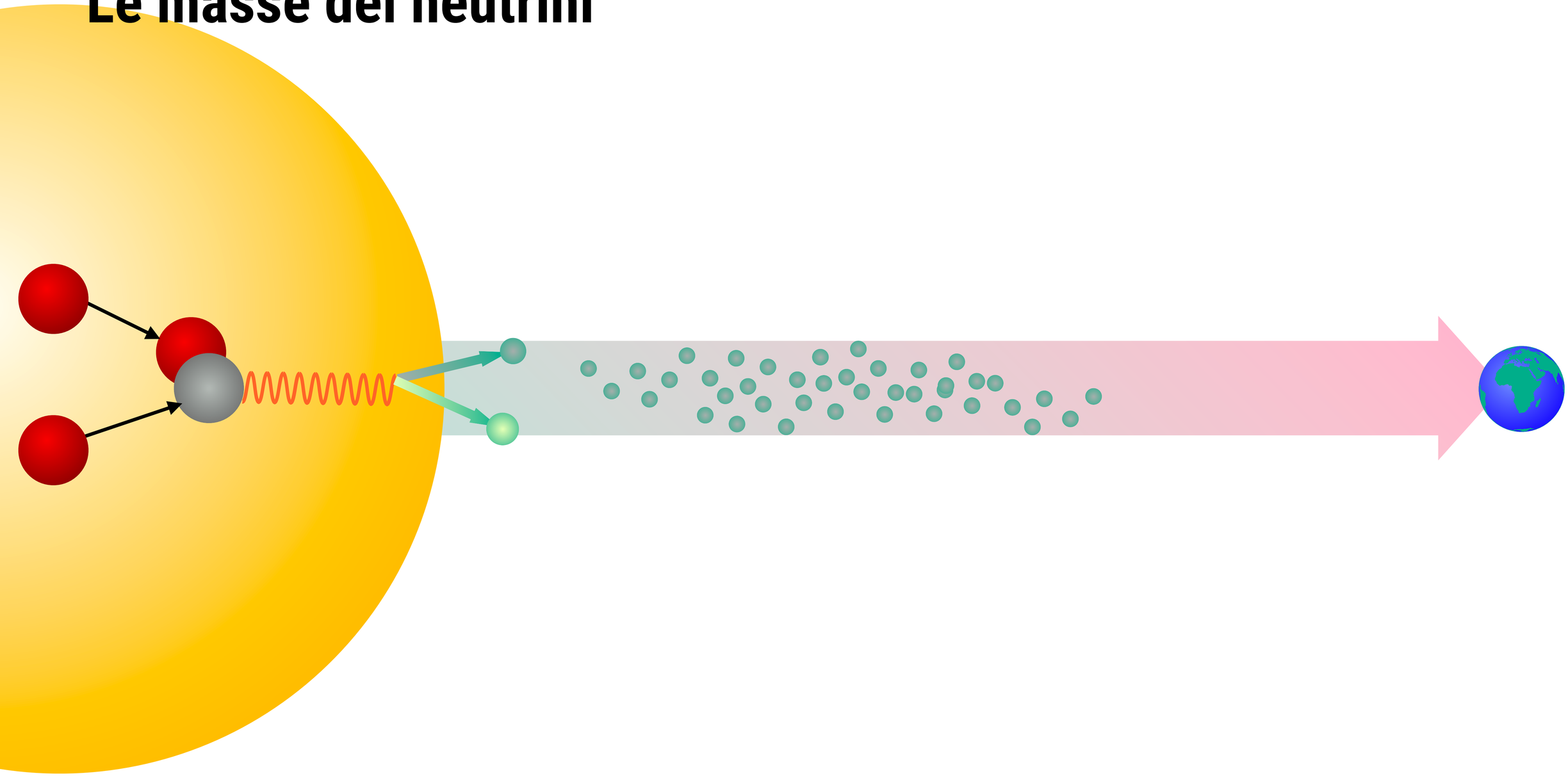



**Inflazione**
potrebbe avere origine particellare non spiegata dal MS

# Le masse dei neutrini



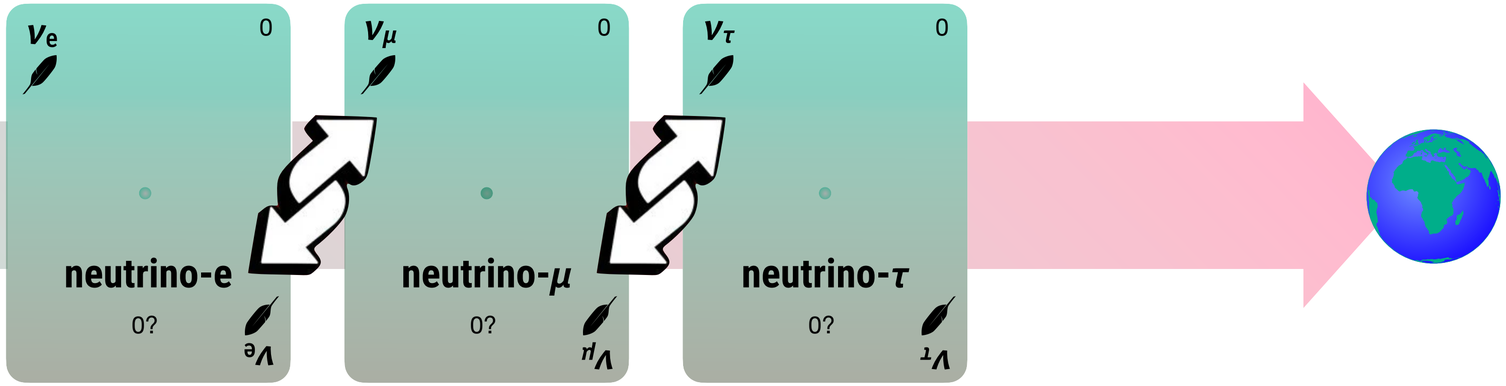
# Le masse dei neutrini



# Le masse dei neutrini

**Oscillazioni dei neutrini**
sperimentalmente si osserva che i neutrini hanno massa

$$P(\nu_i \to \nu_j) \propto sin\left(\frac{\Delta m_{ij}^2 L}{E}\right)$$

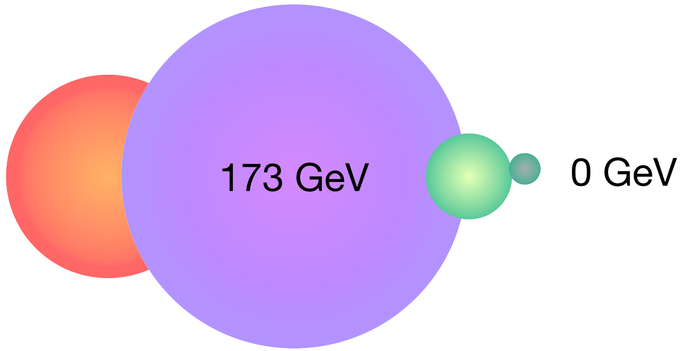



Nel MS $m_\nu = 0.$
Unica particella elementare **neutra**

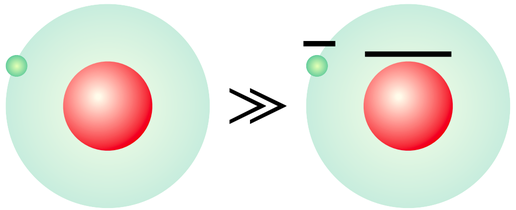
$\overline{\bullet} \stackrel{?}{=} \bullet$

Non è chiaro se sia
l'**antiparticella di se stessa**

# E altri problemi…

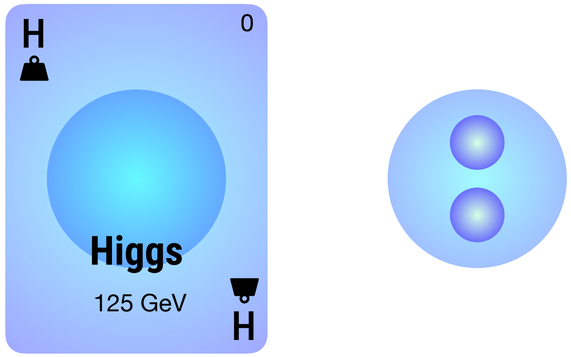



I valori delle masse
sono **parametri liberi**



Asimmetria materia/**antimateria**

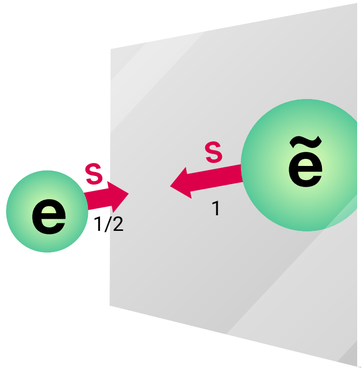

Perché ci sono tre
**generazioni** di materia?



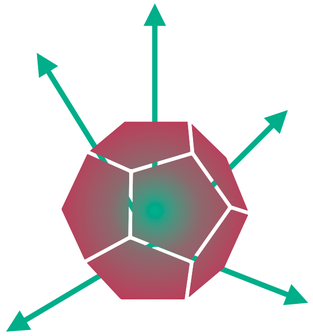

Higgs è elementare o **composito?**

# E possibili soluzioni

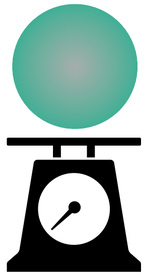
Supersimmetrie



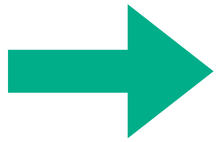

Dimensioni extra

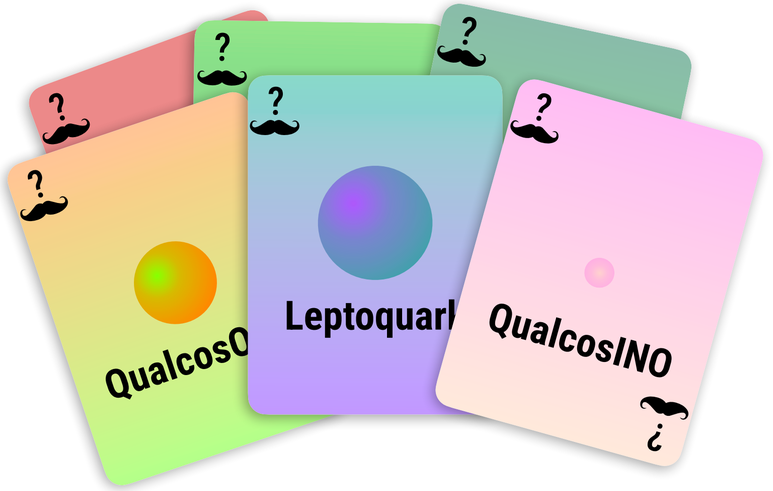


Neutrini pesanti



**Nuovi modelli teorici**

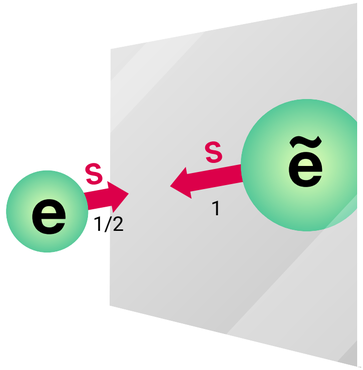




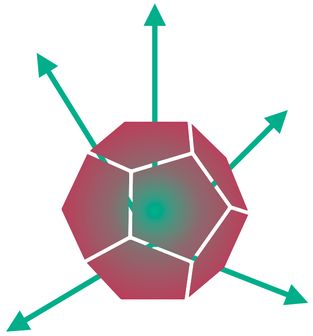

**Nuove particelle**


# E possibili soluzioni

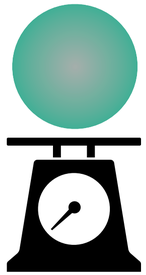
Supersimmetrie



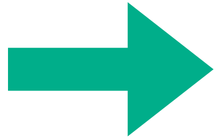

Dimensioni extra

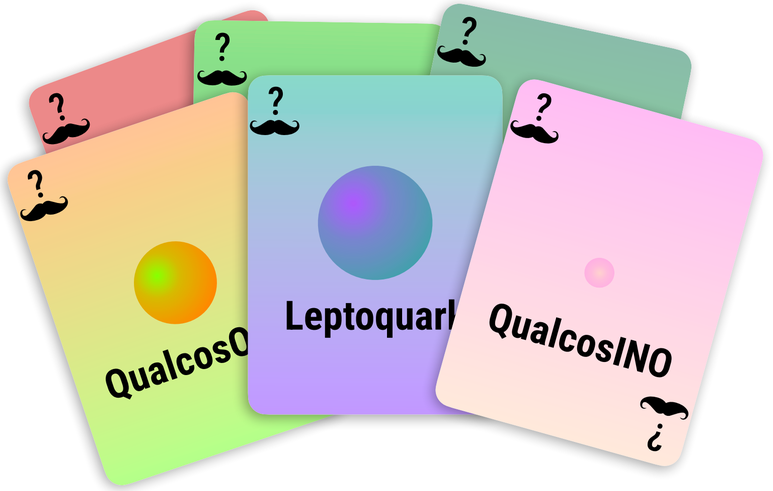


Neutrini pesanti



**Nuovi modelli teorici**



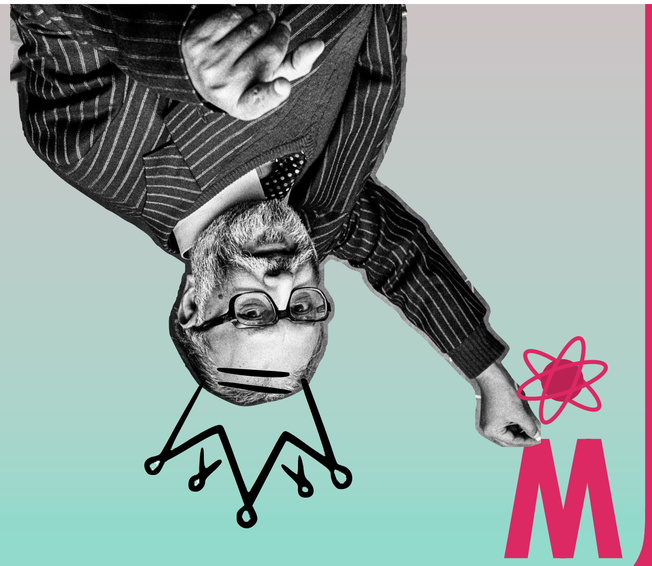


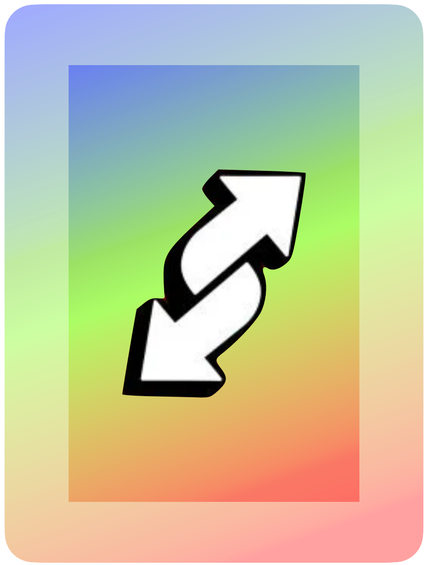

**Nuove particelle**

Il Modello standard potrebbe essere solo il **limite a “bassa” energia** di una teoria più completa

Ma se le carte sono mescolate… non sappiamo dove cercare!

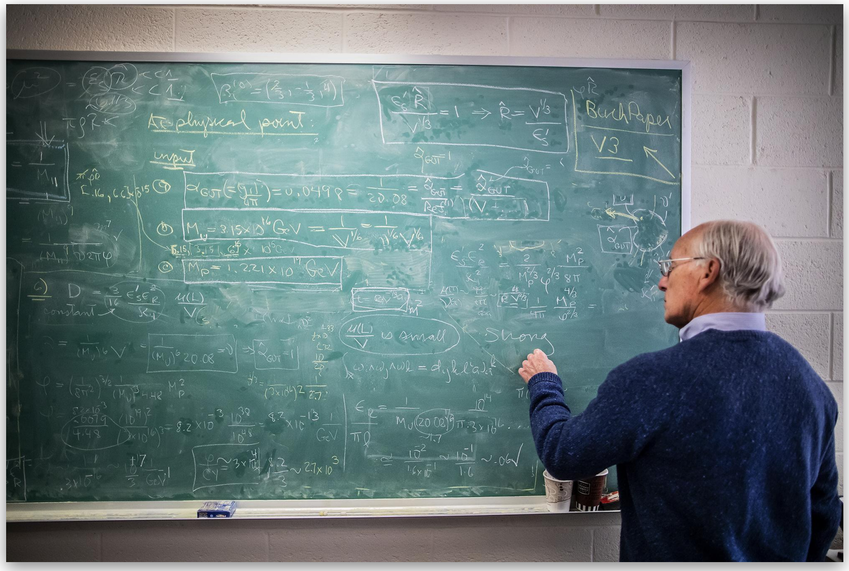
# il MODELLO STANDARD È MORTO

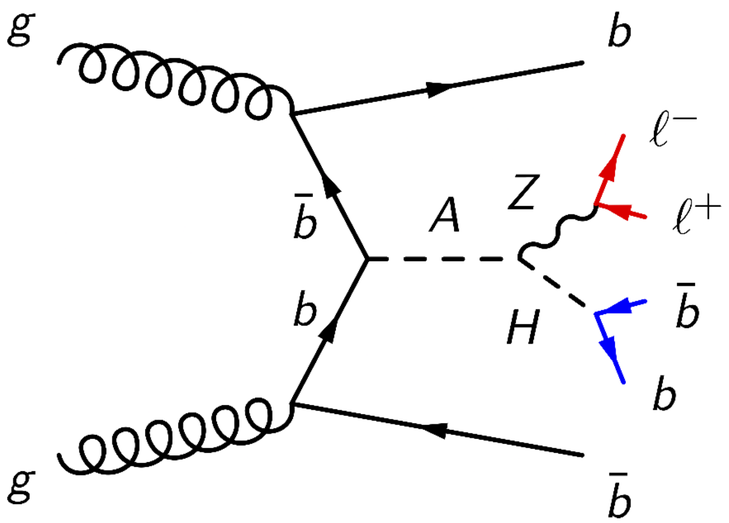


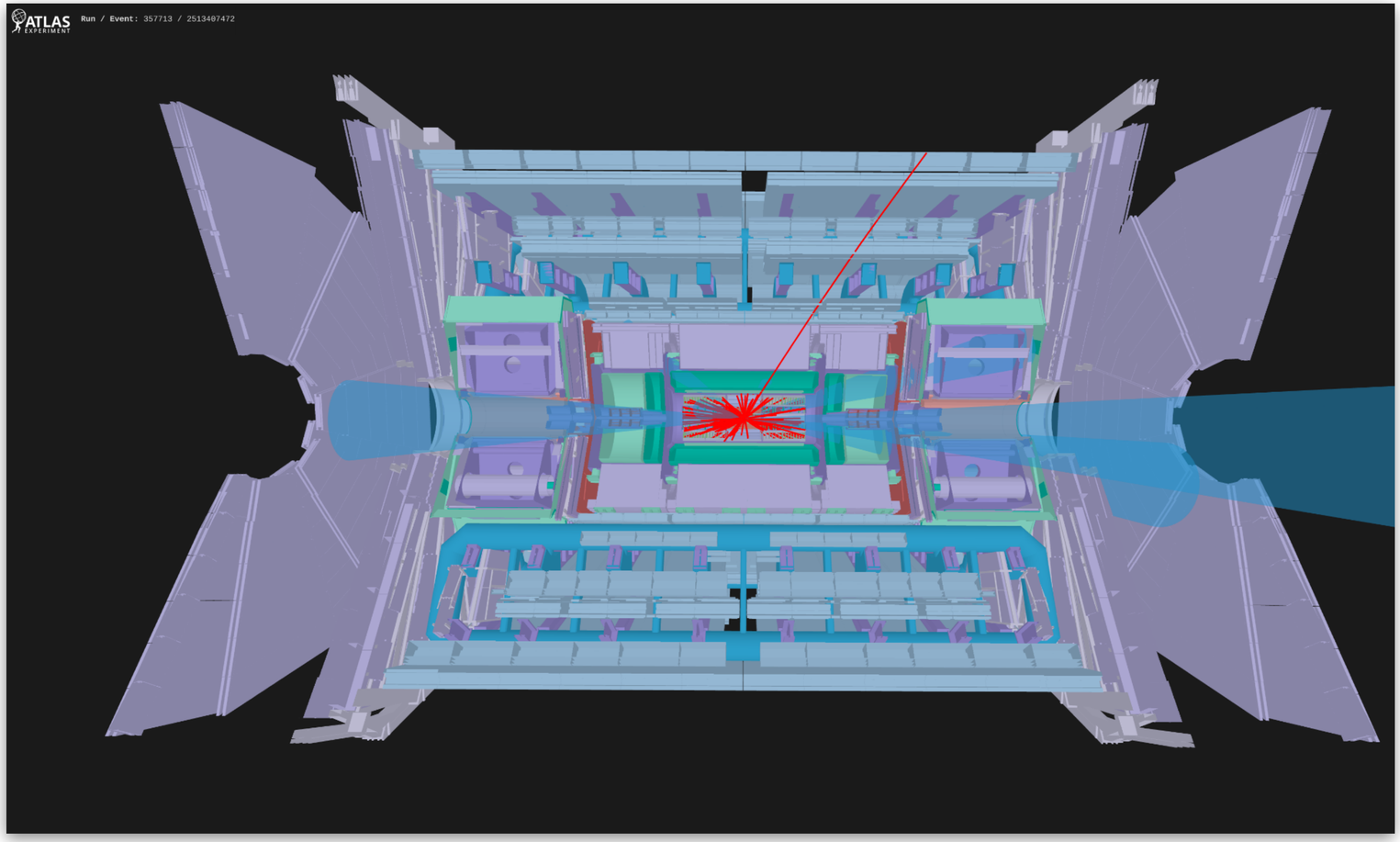


# Ricerche dirette e indirette

# Ricerche dirette

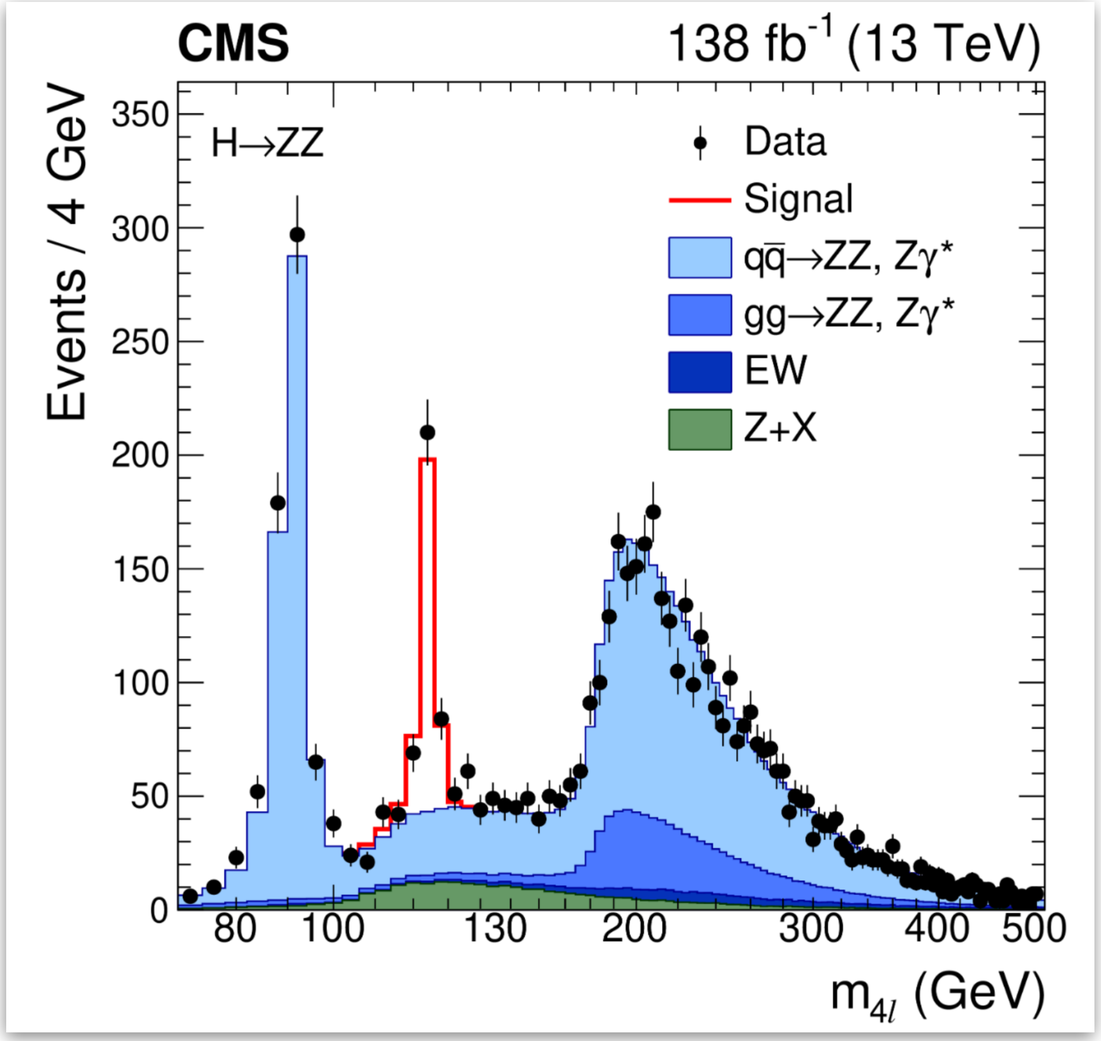




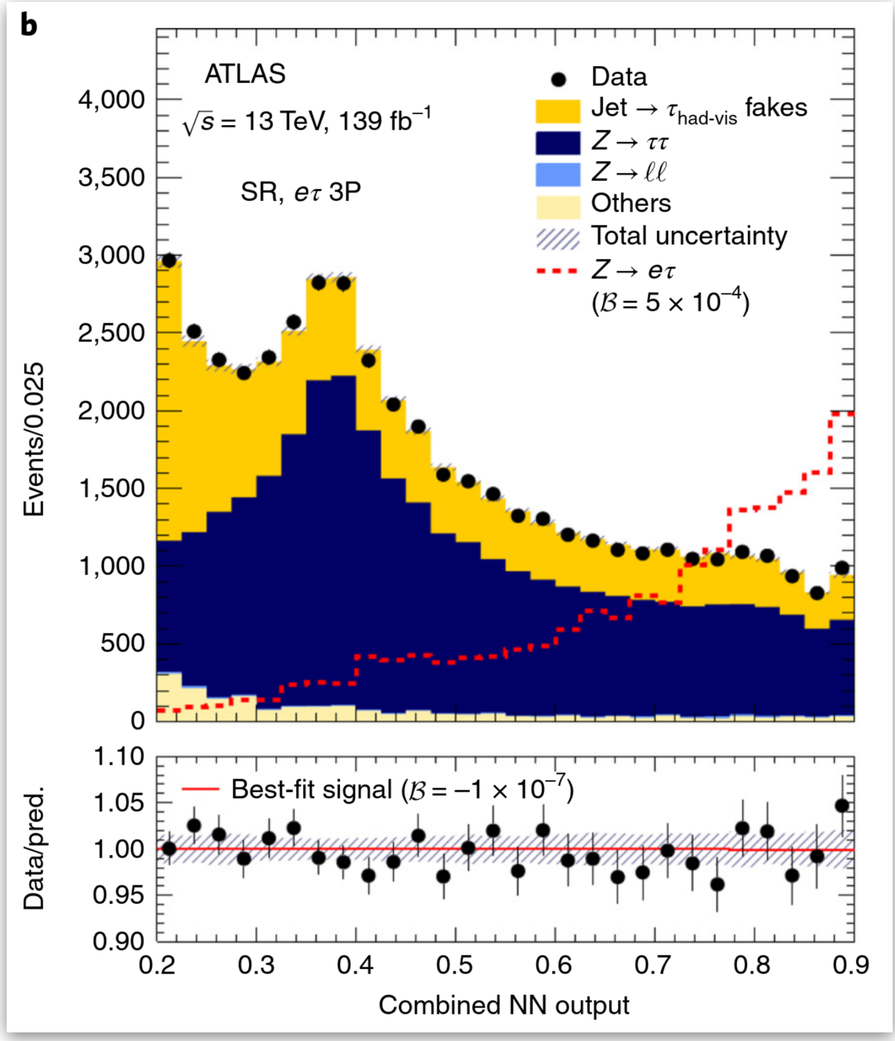



# Ricerche dirette

## Quando va bene




## Quando va meno bene



# ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024

**ATLAS** Preliminary

$\sqrt{s}$ = 13 TeV

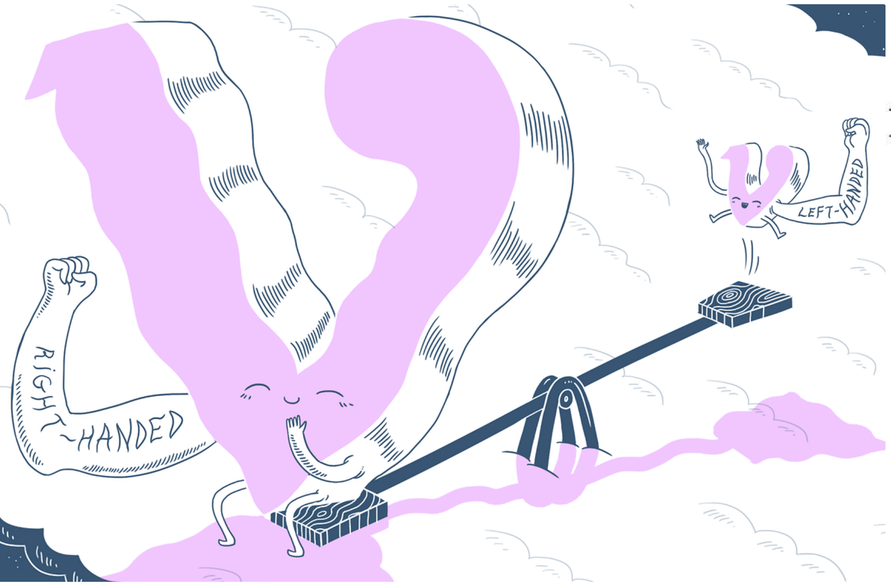
| | Model | Signature | | | $\int \mathcal{L}\,dt$ [fb$^{-1}$] | Mass limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | $\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 $e,\mu$ | 2-6 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{q}$ [1×, 8× Degen.] 1.0 1.85 | $m(\tilde{\chi}_1^0)$<400 GeV | 2010.14293 |
| | | mono-jet | 1-3 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{q}$ [8× Degen.] 0.9 | $m(\tilde{q})$-$m(\tilde{\chi}_1^0)$=5 GeV | 2102.10874 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 $e,\mu$ | 2-6 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{g}$ 2.3 | $m(\tilde{\chi}_1^0)$=0 GeV | 2010.14293 |
| | | | | | | $\tilde{g}$ Forbidden 1.15-1.95 | $m(\tilde{\chi}_1^0)$=1000 GeV | 2010.14293 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$ | 1 $e,\mu$ | 2-6 jets | | 140 | $\tilde{g}$ 2.2 | $m(\tilde{\chi}_1^0)$<600 GeV | 2101.01629 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$ | $ee,\mu\mu$ | 2 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{g}$ 2.2 | $m(\tilde{\chi}_1^0)$<700 GeV | 2204.13072 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$ | 0 $e,\mu$ | 7-11 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{g}$ 1.97 | $m(\tilde{\chi}_1^0)$ <600 GeV | 2008.06032 |
| | | SS $e,\mu$ | 6 jets | | 140 | $\tilde{g}$ 1.15 | $m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=200 GeV | 2307.01094 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | 3 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{g}$ 2.45 | $m(\tilde{\chi}_1^0)$<500 GeV | 2211.08028 |
| | | SS $e,\mu$ | 6 jets | | 140 | $\tilde{g}$ 1.25 | $m(\tilde{g})$-$m(\tilde{\chi}_1^0)$=300 GeV | 1909.08457 |
| 3rd gen. squarks direct production | $\tilde{b}_1\tilde{b}_1$ | 0 $e,\mu$ | 2 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{b}_1$ 1.255 | $m(\tilde{\chi}_1^0)$<400 GeV | 2101.12527 |
| | | | | | | $\tilde{b}_1$ 0.68 | 10 GeV<$\Delta m(\tilde{b}_1,\tilde{\chi}_1^0)$<20 GeV | 2101.12527 |
| | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$ | 0 $e,\mu$ | 6 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{b}_1$ Forbidden 0.23-1.35 | $\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=130 GeV, $m(\tilde{\chi}_1^0)$=100 GeV | 1908.03122 |
| | | 2 $\tau$ | 2 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{b}_1$ 0.13-0.85 | $\Delta m(\tilde{\chi}_2^0,\tilde{\chi}_1^0)$=130 GeV, $m(\tilde{\chi}_1^0)$=0 GeV | 2103.08189 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | ≥ 1 jet | $E_T^{\text{miss}}$ | 140 | $\tilde{t}_1$ 1.25 | $m(\tilde{\chi}_1^0)$=1 GeV | 2004.14060, 2012.03799 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ | 1 $e,\mu$ | 3 jets/1 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{t}_1$ Forbidden 1.05 | $m(\tilde{\chi}_1^0)$=500 GeV | 2012.03799, 2401.13430 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 bv, \tilde{\tau}_1\to\tau\tilde{G}$ | 1-2 $\tau$ | 2 jets/1 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{t}_1$ Forbidden 1.4 | $m(\tilde{\tau}_1)$=800 GeV | 2108.07665 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$ | 0 $e,\mu$ | 2 $c$ | $E_T^{\text{miss}}$ | 36.1 | $\tilde{c}$ 0.85 | $m(\tilde{\chi}_1^0)$=0 GeV | 1805.01649 |
| | | 0 $e,\mu$ | mono-jet | $E_T^{\text{miss}}$ | 140 | $\tilde{t}_1$ 0.55 | $m(\tilde{t}_1,\tilde{c})$-$m(\tilde{\chi}_1^0)$=5 GeV | 2102.10874 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_2^0, \tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$ | 1-2 $e,\mu$ | 1-4 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{t}_1$ 0.067-1.18 | $m(\tilde{\chi}_2^0)$=500 GeV | 2006.05880 |
| | $\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$ | 3 $e,\mu$ | 1 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{t}_2$ Forbidden 0.86 | $m(\tilde{\chi}_1^0)$=360 GeV, $m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$= 40 GeV | 2006.05880 |
| EW direct | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via $WZ$ | Multiple $\ell$/jets | | $E_T^{\text{miss}}$ | 140 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.96 | $m(\tilde{\chi}_1^0)$=0, wino-bino | 2106.01676, 2108.07586 |
| | | $ee,\mu\mu$ | ≥ 1 jet | $E_T^{\text{miss}}$ | 140 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205 | $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV, wino-bino | 1911.12606 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $WW$ | 2 $e,\mu$ | | $E_T^{\text{miss}}$ | 140 | $\tilde{\chi}_1^\pm$ 0.42 | $m(\tilde{\chi}_1^0)$=0, wino-bino | 1908.08215 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via $Wh$ | Multiple $\ell$/jets | | $E_T^{\text{miss}}$ | 140 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidden 1.06 | $m(\tilde{\chi}_1^0)$=70 GeV, wino-bino | 2004.10894, 2108.07586 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$ | 2 $e,\mu$ | | $E_T^{\text{miss}}$ | 140 | $\tilde{\chi}_1^\pm$ 1.0 | $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$) | 1908.08215 |
| | $\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}_1^0$ | 2 $\tau$ | | $E_T^{\text{miss}}$ | 140 | $\tilde{\tau}$ [$\tilde{\tau}_R\tilde{\tau}_R$] 0.35 0.5 | $m(\tilde{\chi}_1^0)$=0 | 2402.00603 |
| | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{\ell}$ 0.7 | $m(\tilde{\chi}_1^0)$=0 | 1908.08215 |
| | | $ee,\mu\mu$ | ≥ 1 jet | $E_T^{\text{miss}}$ | 140 | $\tilde{\ell}$ 0.26 | $m(\tilde{\ell})$-$m(\tilde{\chi}_1^0)$=10 GeV | 1911.12606 |
| | $\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$ | 0 $e,\mu$ | ≥ 3 $b$ | $E_T^{\text{miss}}$ | 140 | $\tilde{H}$ 0.94 | $BR(\tilde{\chi}_1^0\to h\tilde{G})$=1 | 2401.14922 |
| | | 4 $e,\mu$ | 0 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{H}$ 0.55 | $BR(\tilde{\chi}_1^0\to Z\tilde{G})$=1 | 2103.11684 |
| | | 0 $e,\mu$ | ≥ 2 large jets | $E_T^{\text{miss}}$ | 140 | $\tilde{H}$ 0.45-0.93 | $BR(\tilde{\chi}_1^0\to Z\tilde{G})$=1 | 2108.07586 |
| | | 2 $e,\mu$ | ≥ 2 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{H}$ 0.77 | $BR(\tilde{\chi}_1^0\to Z\tilde{G})$=$BR(\tilde{\chi}_1^0\to h\tilde{G})$=0.5 | 2204.13072 |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | $E_T^{\text{miss}}$ | 140 | $\tilde{\chi}_1^\pm$ 0.66 | Pure Wino | 2201.02472 |
| | | | | | | $\tilde{\chi}_1^\pm$ 0.21 | Pure higgsino | 2201.02472 |
| | Stable $\tilde{g}$ R-hadron | pixel dE/dx | | $E_T^{\text{miss}}$ | 140 | $\tilde{g}$ 2.05 | | 2205.06013 |
| | Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$ | pixel dE/dx | | $E_T^{\text{miss}}$ | 140 | $\tilde{g}$ [$\tau(\tilde{g})$ =10 ns] 2.2 | $m(\tilde{\chi}_1^0)$=100 GeV | 2205.06013 |
| | $\tilde{\ell}\tilde{\ell}, \tilde{\ell}\to t\tilde{G}$ | Displ. lep | | $E_T^{\text{miss}}$ | 140 | $\tilde{e},\tilde{\mu}$ 0.74 | $\tau(\tilde{l})$ = 0.1 ns | ATLAS-CONF-2024-011 |
| | | | | | | $\tilde{\tau}$ 0.36 | $\tau(\tilde{l})$ = 0.1 ns | ATLAS-CONF-2024-011 |
| | | pixel dE/dx | | $E_T^{\text{miss}}$ | 140 | $\tilde{\tau}$ 0.36 | $\tau(\tilde{l})$ = 10 ns | 2205.06013 |
| RPV | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0, \tilde{\chi}_1^\pm\to Z\ell\to\ell\ell\ell$ | 3 $e,\mu$ | | | 140 | $\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR($Ze$)=1] 0.625 1.05 | Pure Wino | 2011.10543 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$ | 4 $e,\mu$ | 0 jets | $E_T^{\text{miss}}$ | 140 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55 | $m(\tilde{\chi}_1^0)$=200 GeV | 2103.11684 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$ | | ≥8 jets | | 140 | $\tilde{g}$ [$m(\tilde{\chi}_1^0)$=50 GeV, 1250 GeV] 1.6 2.34 | Large $\lambda''_{112}$ | 2401.16333 |
| | $\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$ | | Multiple | | 36.1 | $\tilde{t}$ [$\lambda''_{323}$=2e-4, 1e-2] 0.55 1.05 | $m(\tilde{\chi}_1^0)$=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{t}\tilde{t}, \tilde{t}\to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm\to bbs$ | | ≥ 4$b$ | | 140 | $\tilde{t}$ Forbidden 0.95 | $m(\tilde{\chi}_1^\pm)$=500 GeV | 2010.01015 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$ | | 2 jets + 2 $b$ | | 36.7 | $\tilde{t}_1$ [$qq, bs$] 0.42 0.61 | | 1710.07171 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to q\ell$ | 2 $e,\mu$ | 2 $b$ | | 140 | $\tilde{t}_1$ 0.4-1.85 | BR($\tilde{t}_1\to be/b\mu$)>20% | 2406.18367 |
| | | 1 $\mu$ | DV | | 136 | $\tilde{t}_1$ [1e-10< $\lambda'_{23k}$ <1e-8, 3e-10< $\lambda'_{23k}$ <3e-9] 1.0 1.6 | BR($\tilde{t}_1\to q\mu$)=100%, $\cos\theta_t$=1 | 2003.11956 |
| | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0\to tbs, \tilde{\chi}_1^+\to bbs$ | 1-2 $e,\mu$ | ≥6 jets | | 140 | $\tilde{\chi}_1^0$ 0.2-0.32 | Pure higgsino | 2106.09609 |

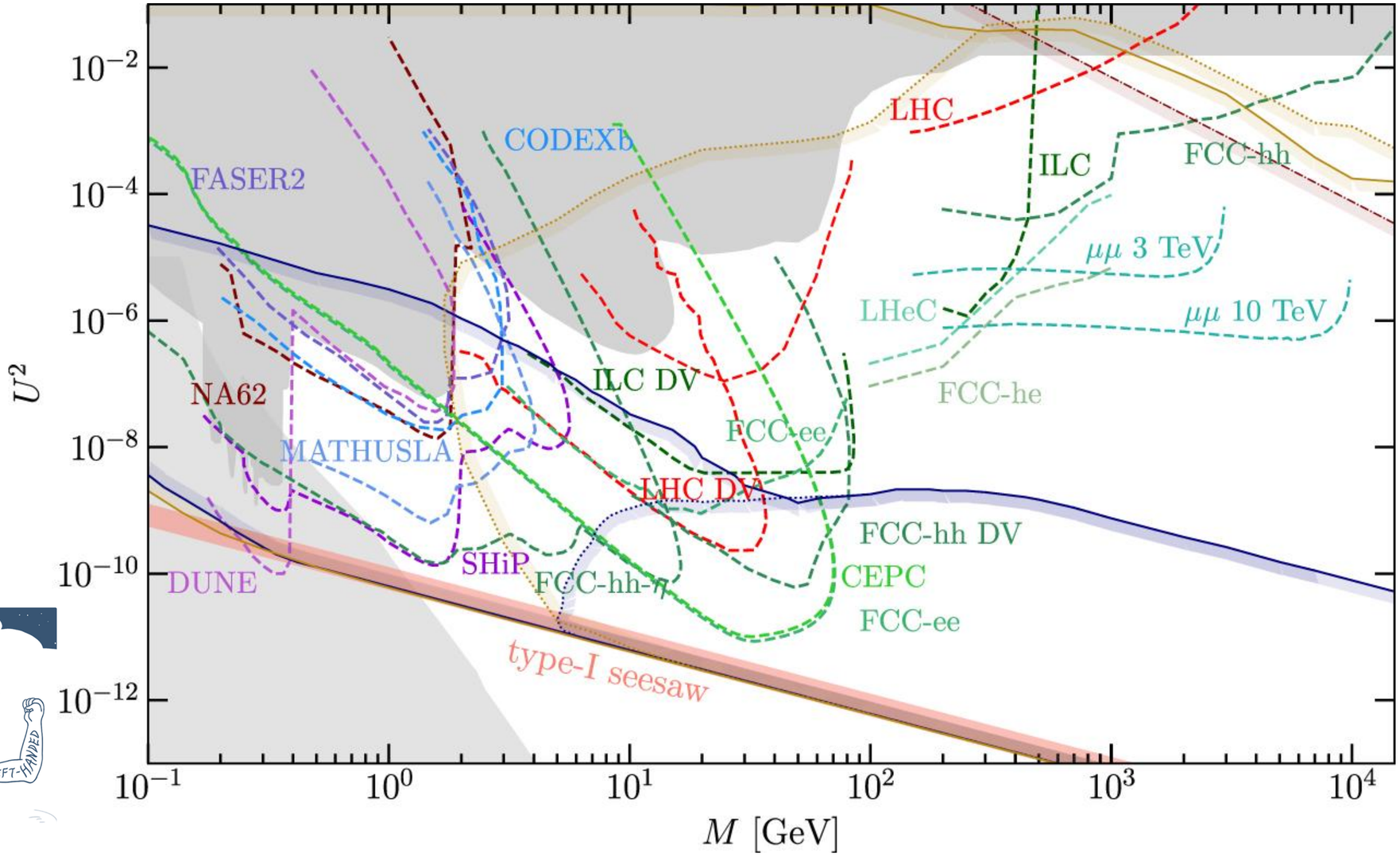
$10^{-1}$ 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Esempi di analisi fatte in ATLAS per ricerca di supersimmetrie

Limiti sull’angolo di mixing di un possibile neutrino di Majorana con il corrispondente neutrino presente nel modello standard, per diverse possibili masse



# EXECUTIVE SUMMARY

We haven't found Supersymmetry

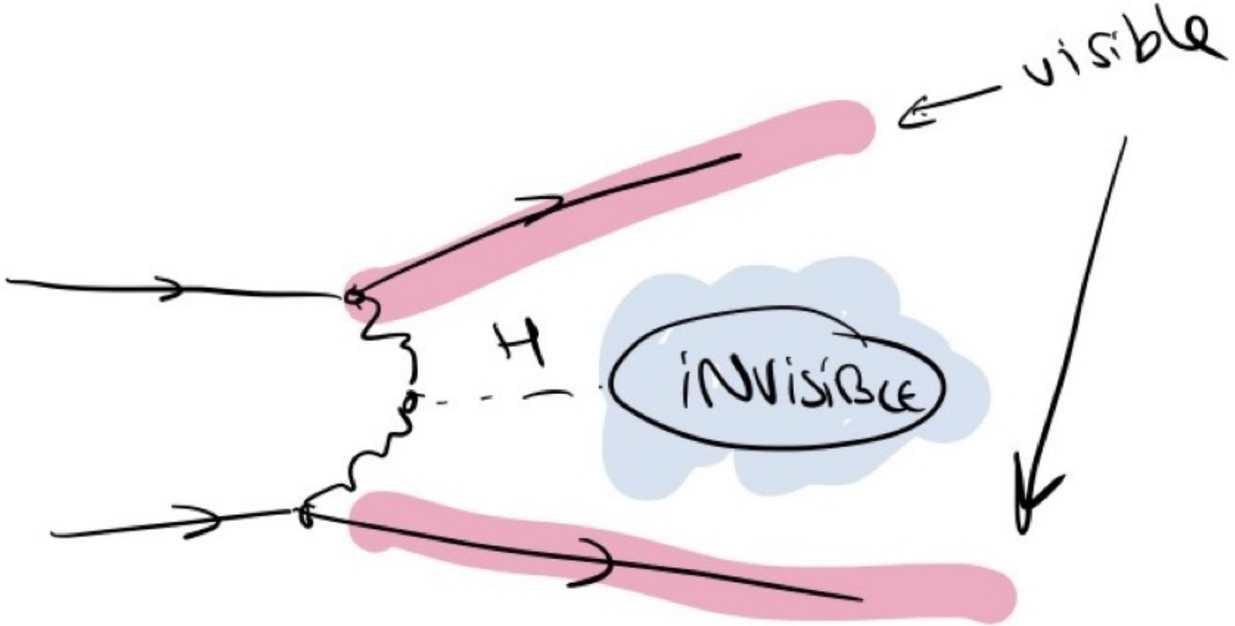
We haven't found Dark Matter either

Let me elaborate on that...

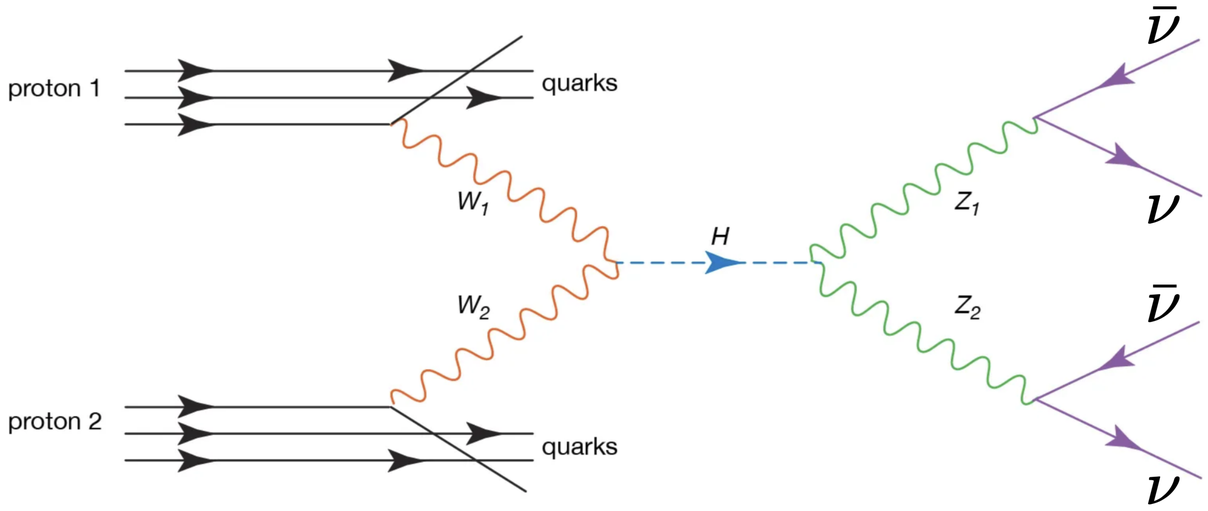


Risultati dalla conferenza Moriond 2024

# Ricerche indirette

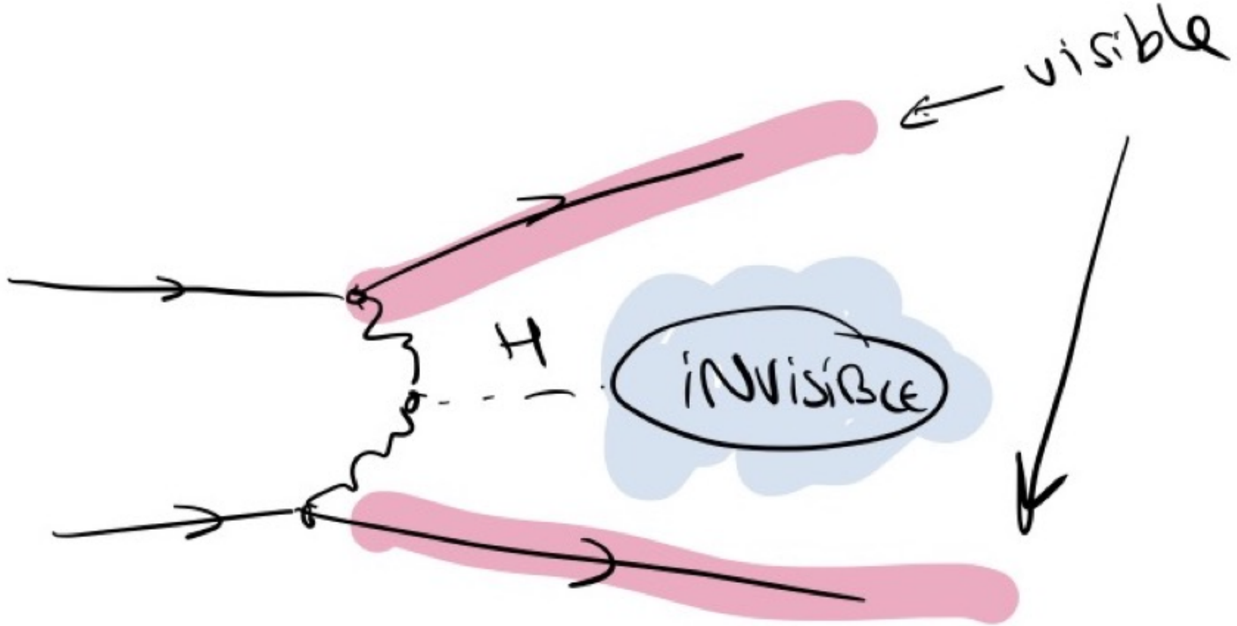



# Ricerche indirette

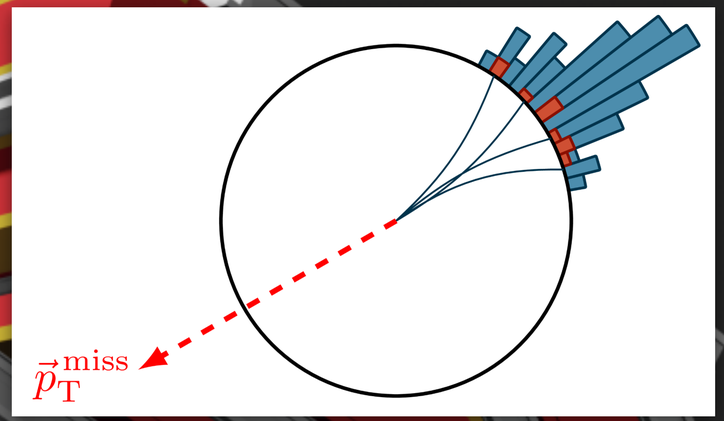


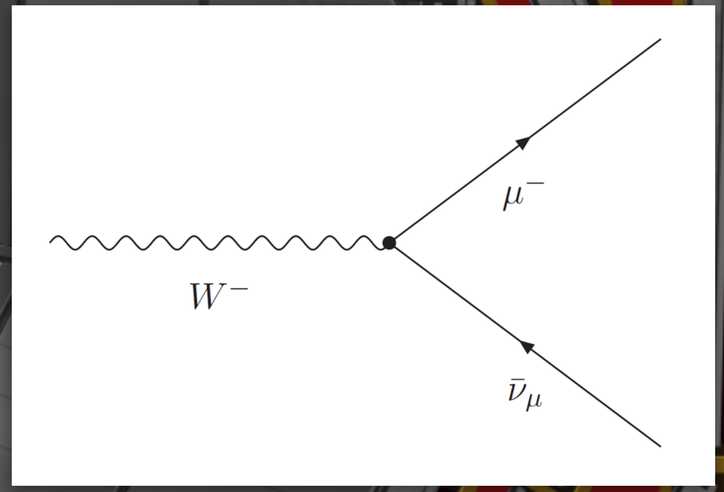

Percentuale di decadimenti prevista dal MS: ~0.12%

$$H \rightarrow ZZ^{\star} \rightarrow \nu\bar{\nu}\nu\bar{\nu}$$




# Massa del bosone W



# Massa del bosone W

## Comparison of W boson mass measurements

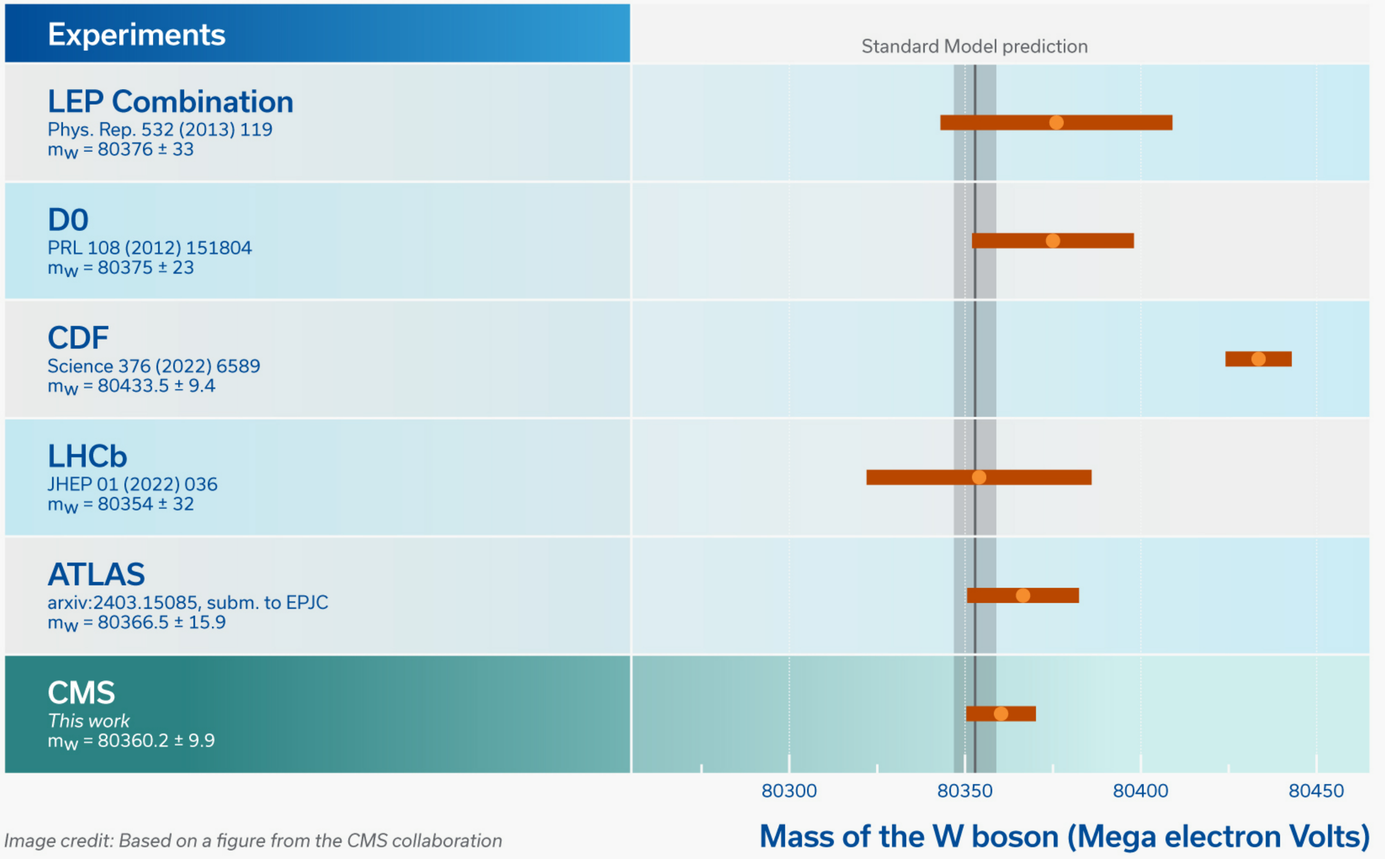


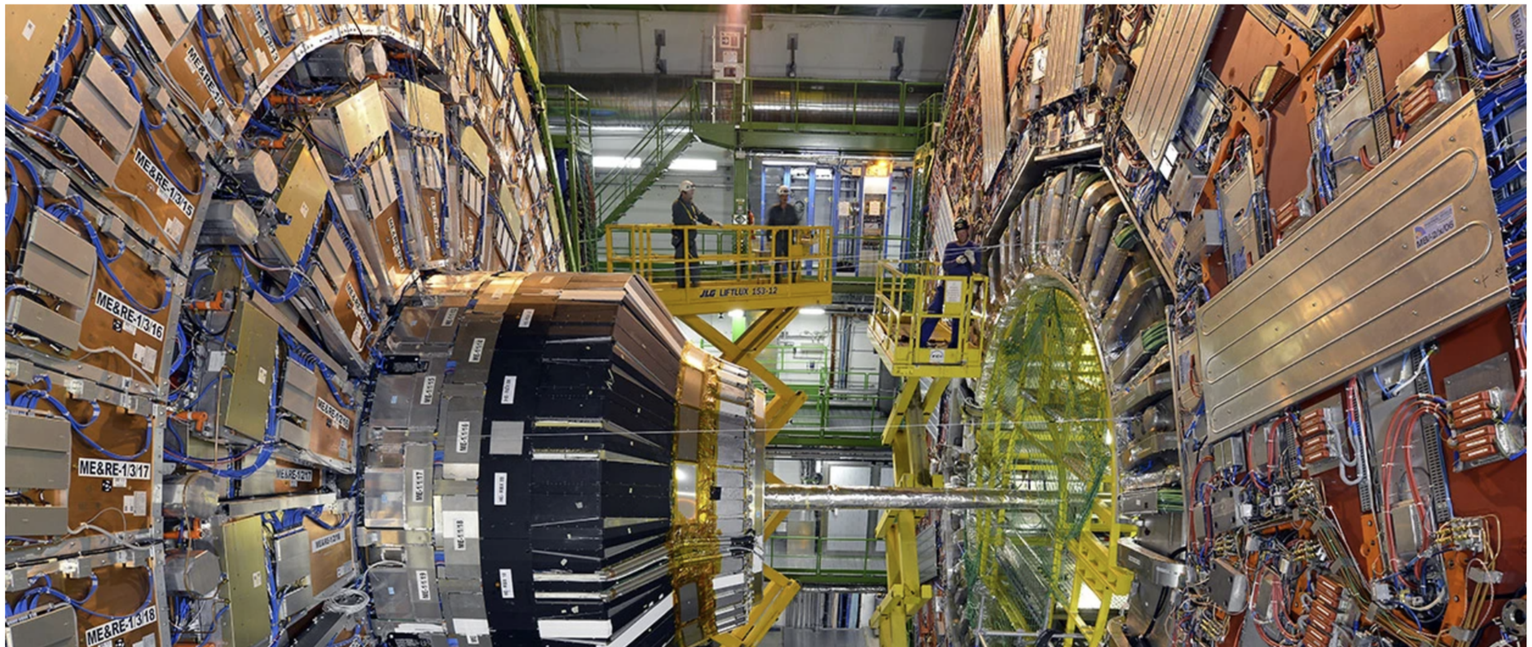

*Image credit: Based on a figure from the CMS collaboration*

NEWS | 17 September 2024

# ‘The standard model is not dead’: ultra-precise particle measurement thrills physicists

**CERN’s calculation of the *W* boson’s mass agrees with theory, contradicting a previous anomaly that had raised the possibility of new physics.**

By Elizabeth Gibney



# VIVA il MODELLO STANDARD!

# Il momento magnetico anomalo del muone

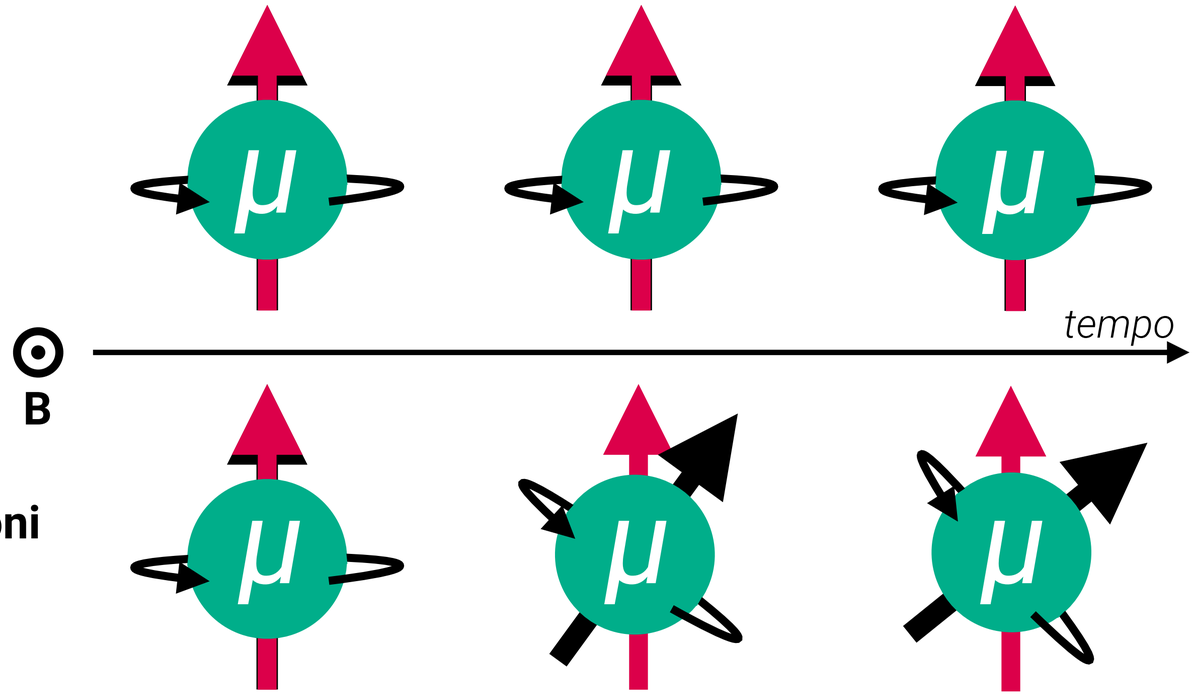
$$\vec{\mu} = g \frac{Qe}{2m_\mu} \frac{\vec{\sigma}}{2}$$

**Momento magnetico**
associato allo **spin**
di una particella

$$a_\mu = \frac{(g-2)_\mu}{2} \neq 0$$

**Dirac**
g=2

**Correzioni**
g!=2




$a_\mu$ (exp) =116 592 059(22) × $10^{-11}$

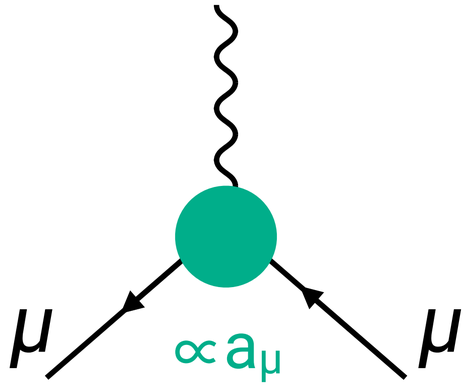
# Ma perché aμ!=0?

Muone + Campo Magnetico

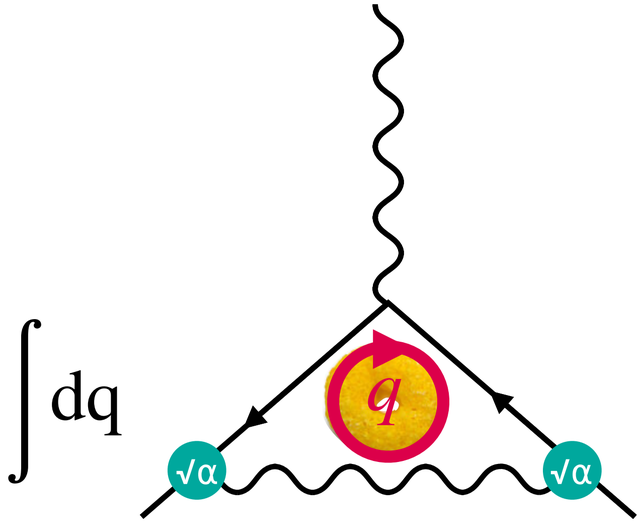

**Lagrangiana**
una funzione che descrive le proprietà della teoria

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - ej_{\mu}A^{\mu} + \bar{\psi}(\gamma^{\mu}\partial_{\mu} - m)\psi$$

**Fattore di Forma**
elettromagnetico



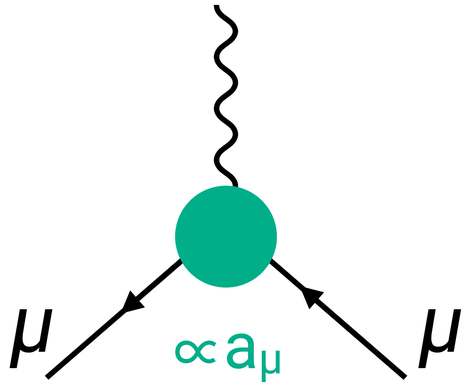

**Diagrammi di Feynman**
per rappresentare le interazioni




**Loop**
ogni volta che ho una linea chiusa devo integrare su tutti i possibili valori del momento

# Ma perché aμ!=0?


**Non è una teoria esatta**
I conti possono essere espansi in una “**Serie di Taylor”**



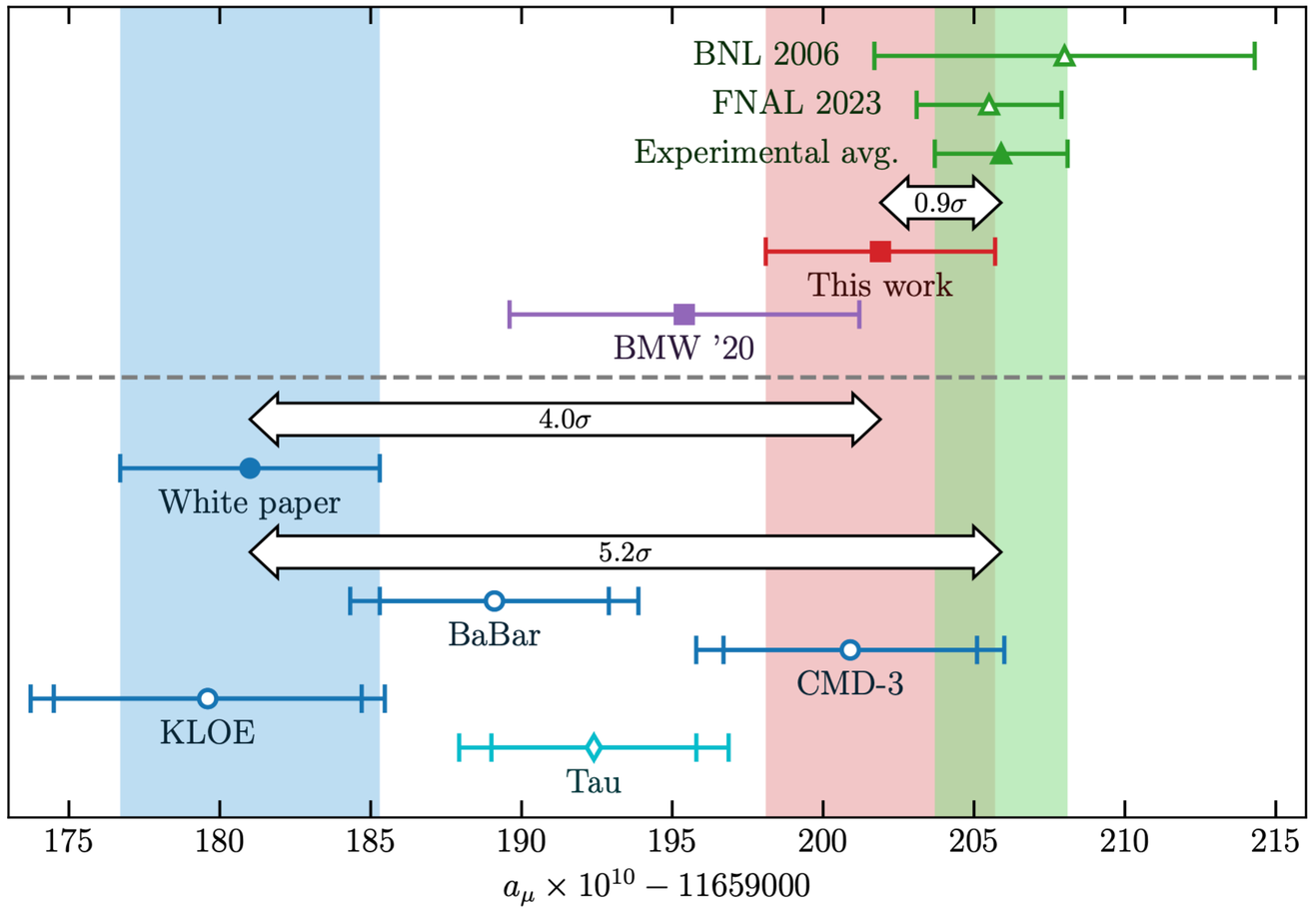

**Intensità della forza**

$\alpha = e^2/4\pi = 1/137$

È un numero piccolo, quindi un buon parametro di espansione

$$0 + \frac{\alpha}{\pi} + \left(\frac{\alpha}{\pi}\right)^2 + \left(\frac{\alpha}{\pi}\right)^3 + \left(\frac{\alpha}{\pi}\right)^4 + \left(\frac{\alpha}{\pi}\right)^5$$

# Se si fanno esperimenti…

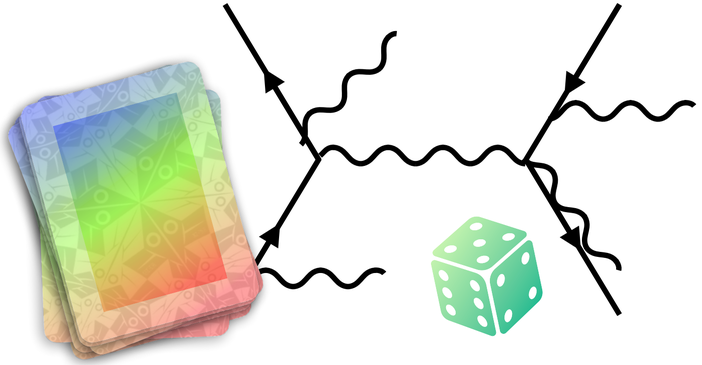


# il MODELLO STANDARD è VIVO & MORTO

$$\frac{1}{\sqrt{2}}\left|\ \right\rangle \pm \left|\ \right\rangle$$


# Fenomenologia

**Simulazioni Monte Carlo**

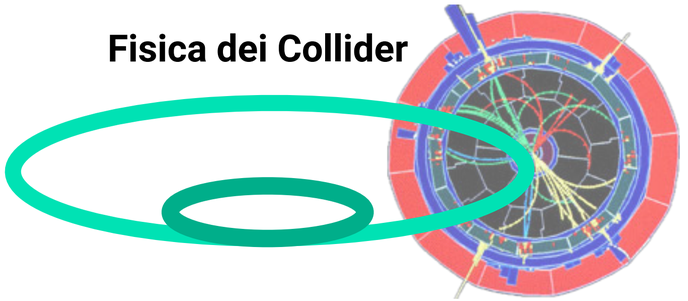


**Teoria Quantistica dei Campi**

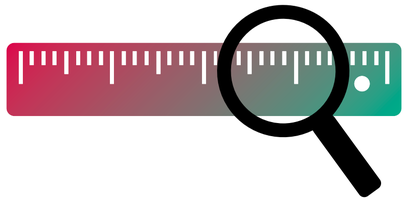
**Fenomenologia delle particelle elementari**

Studiare come la **teoria** si manifesta negli **esperimenti**

**Fisica dei Collider**



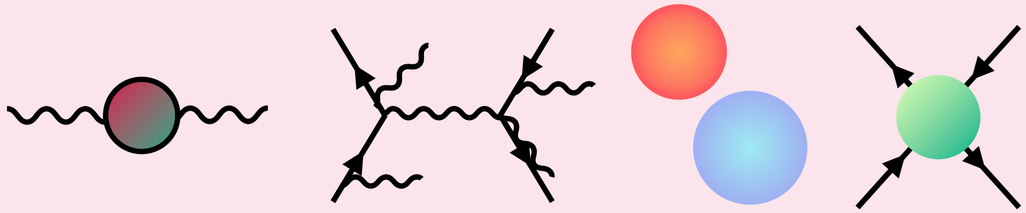
**Fisica di Precisione**



# Fenomenologia del MS a Pavia

Calame, Chiesa, Montagna, Nicrosini, Piccinini

**Teoria Quantistica dei Campi**



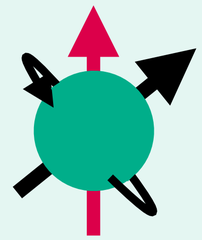
Rinormalizzazione

Tecniche di risommazione

Fisica elettrodebole

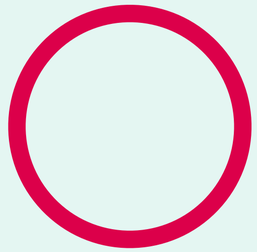
Teorie effettive

**Applicazioni**

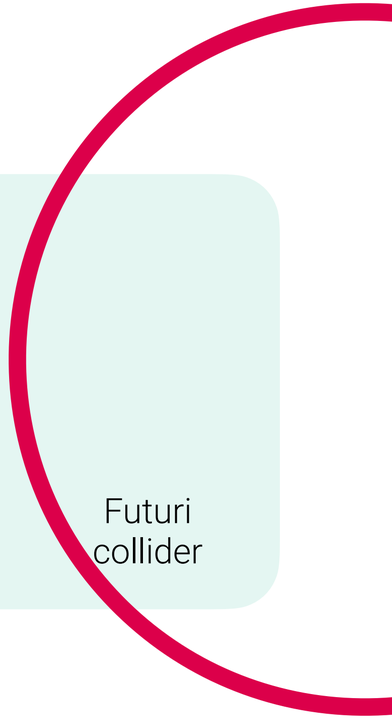


MUonE

Collider e+e- a bassa energia



LHC

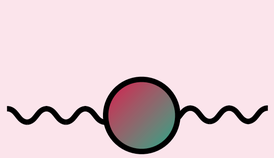


Futuri collider

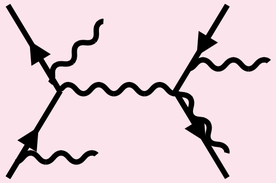
# Fenomenologia del MS a Pavia

Calame, Chiesa, Montagna, Nicrosini, Piccinini

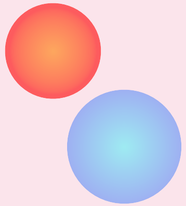
## Teoria Quantistica dei Campi



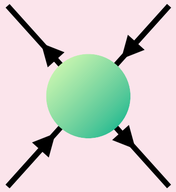
Rinormalizzazione



Tecniche di risommazione

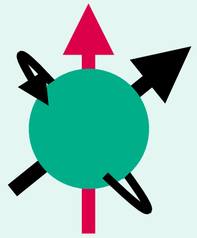


Fisica elettrodebole



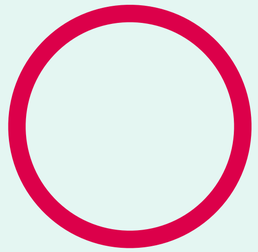
Teorie effettive

## Applicazioni



MUonE

Collider e+e- a bassa energia

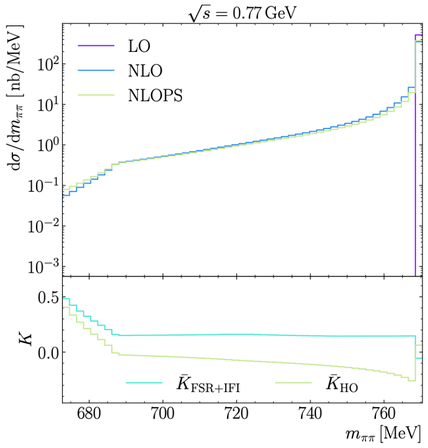


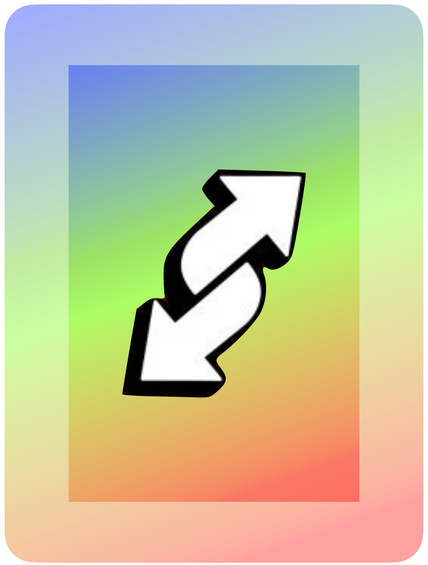
LHC

Futuri collider

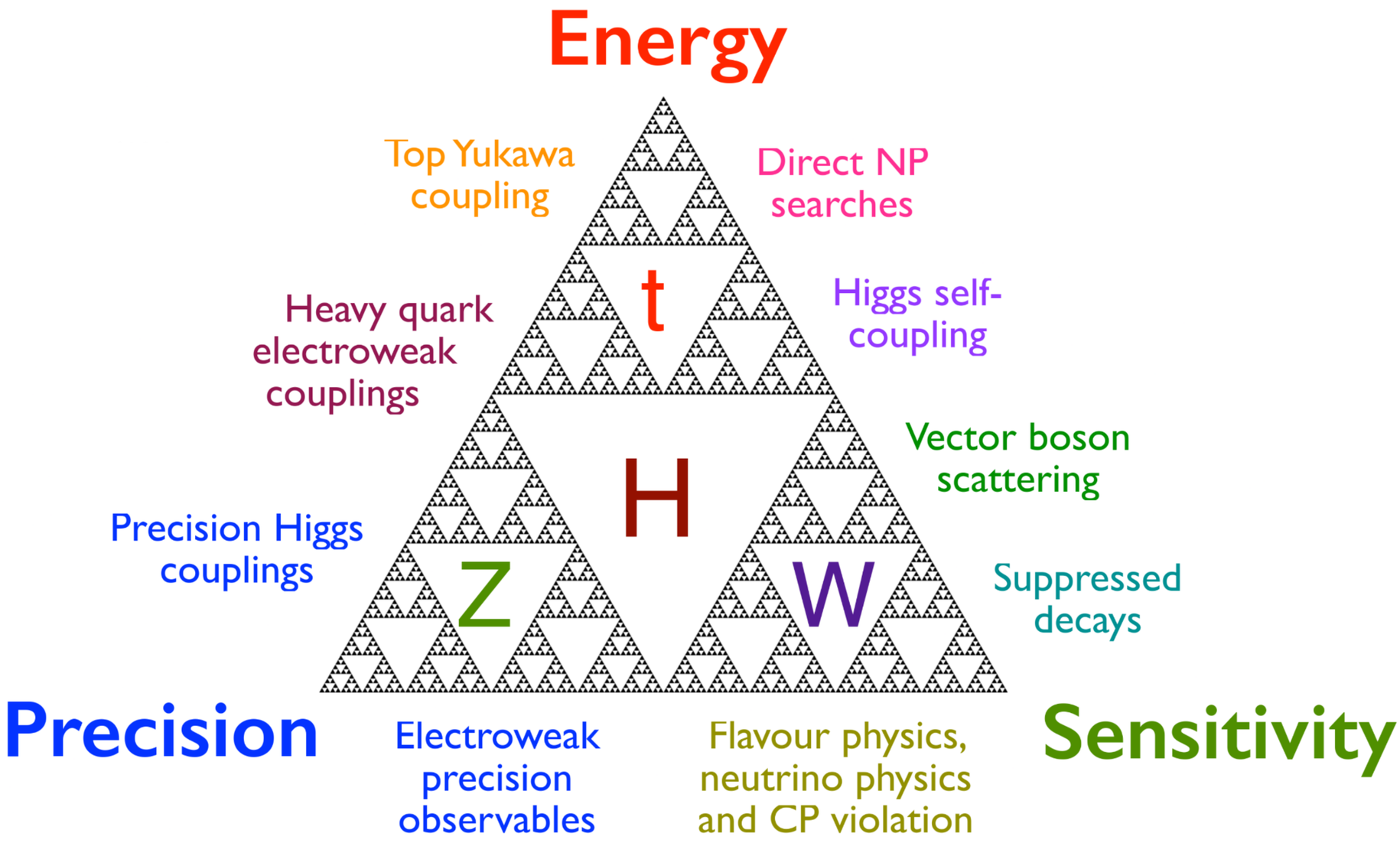
BabaYaga@NLO
Mesmer
PowegBOX
…
Horace
MessPV

## Sviluppo di Monte Carlo





# Cosa ci aspetta?



# Cosa ci aspetta?

Forza di Lorentz

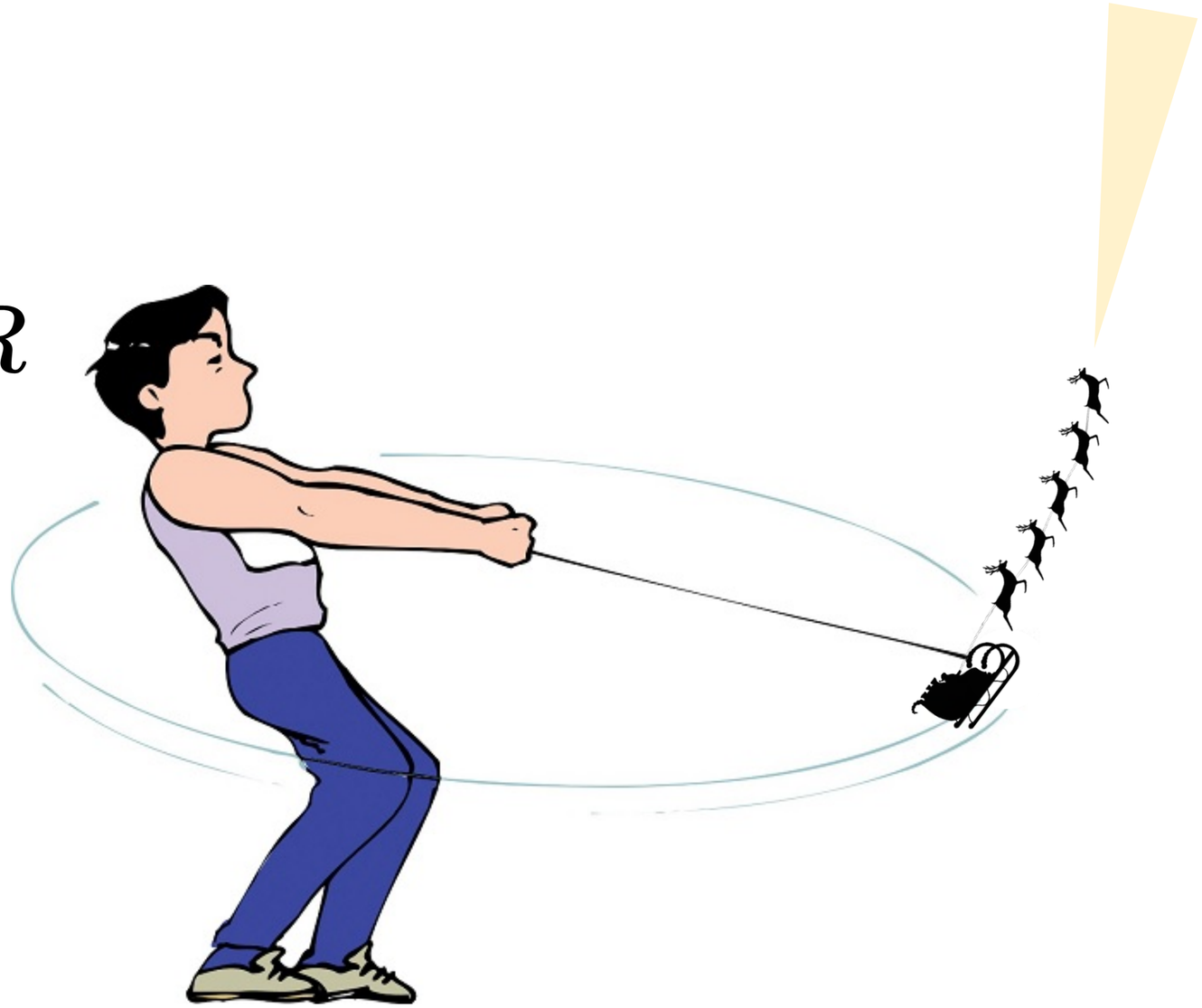
$$F_L = e\,v\,B$$

Forza Centrifuga

$$F_c = \frac{mv^2}{R}$$

$$\frac{p}{e} = B\,R$$

L’energia che ci serve per produrre nuove particelle



# Cosa ci aspetta?

Forza di Lorentz

$$F_L = e\,v\,B$$

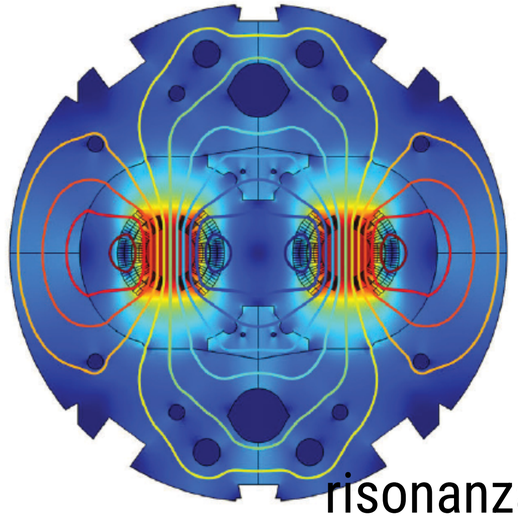
Forza Centrifuga

$$F_c = \frac{mv^2}{R}$$

$$\frac{p}{e} = B\,R$$

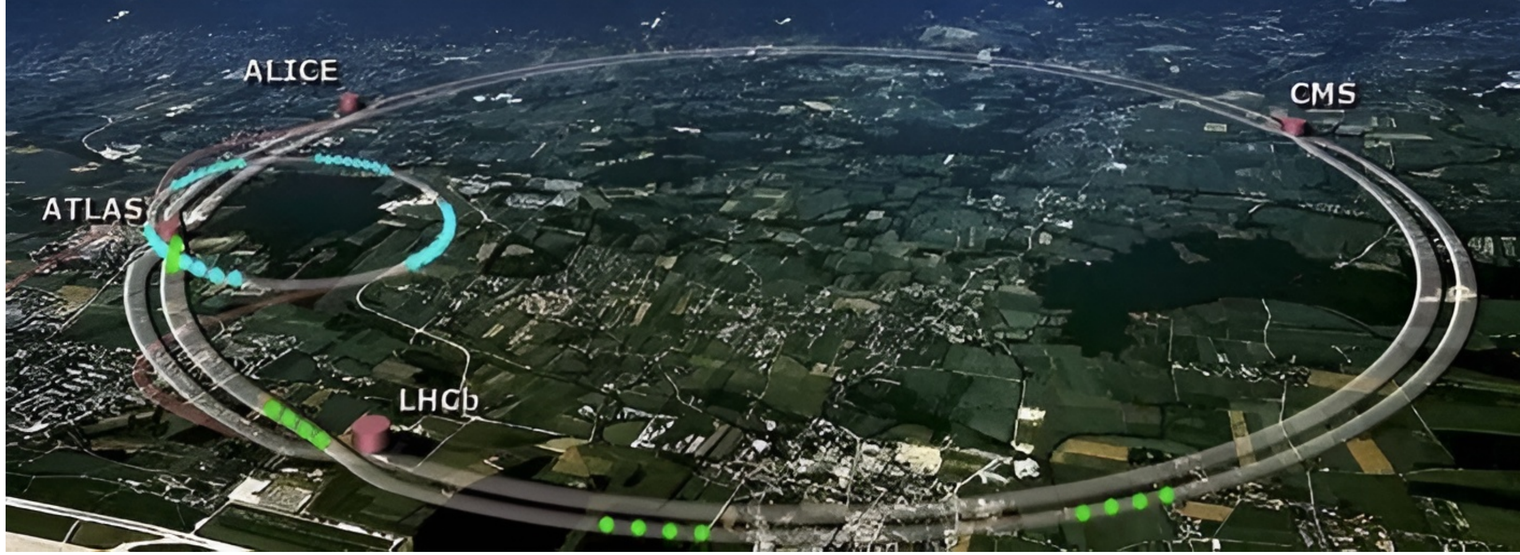
L'energia che ci serve per produrre nuove particelle

Il campo magnetico che siamo in grado di utilizzare



@ LHC: B ~ 8.33 T
Magneti per risonanza magnetica ~ 3 T

# Cosa ci aspetta?




Forza di Lorentz

$$F_L = e\,v\,B$$

Forza Centrifuga

$$F_c = \frac{mv^2}{R}$$

$$\frac{p}{e} = B\,R$$

L'energia che ci serve per produrre nuove particelle

L'acceleratore che ci permettono di costruire

$R \sim 4.3\,\mathrm{km}$

$B \sim 8.3\,\mathrm{T}$

$E \sim 14\,\mathrm{TeV}$

# Cosa ci aspetta?

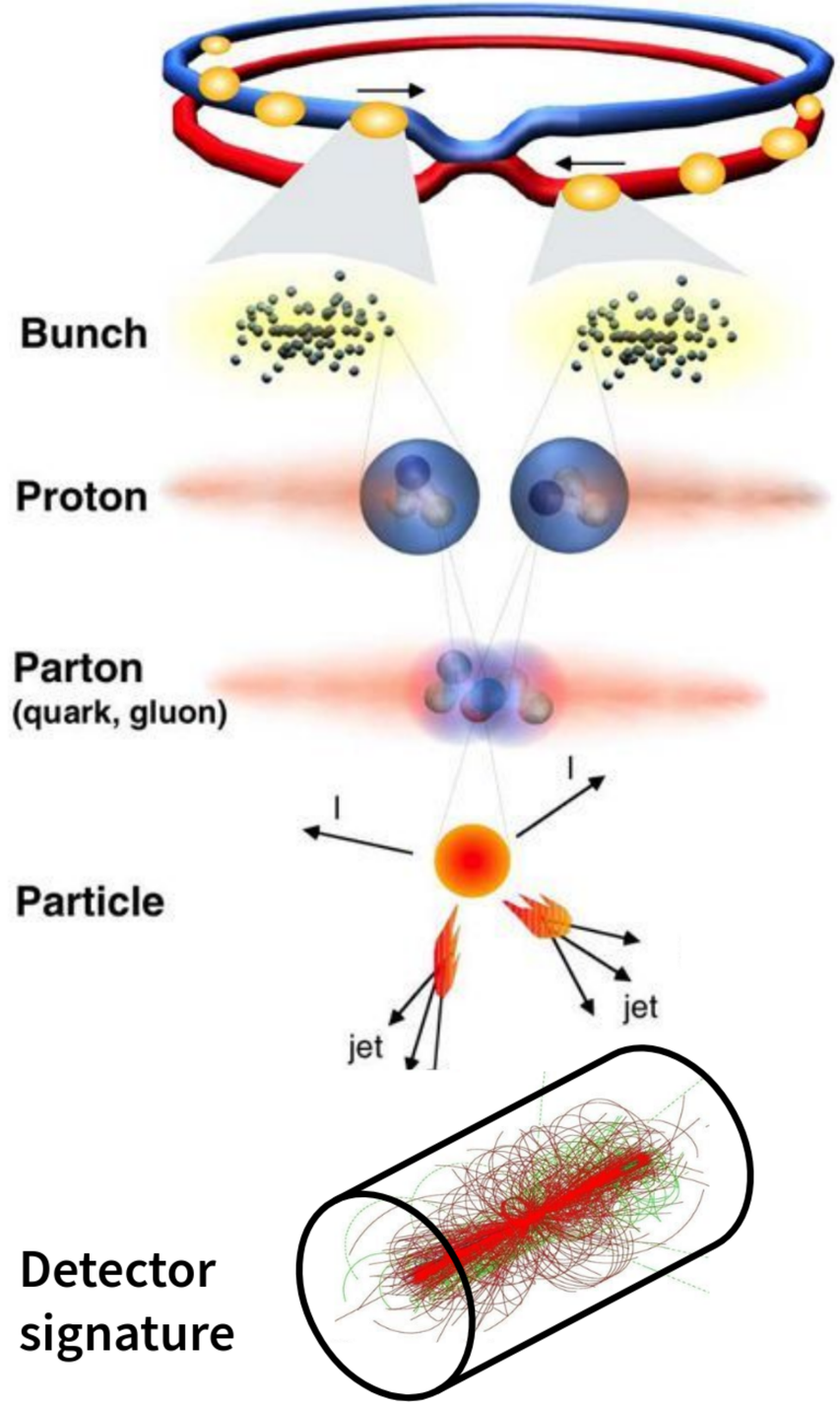
Frequenza di rivoluzione

Numero di particelle nei bunch

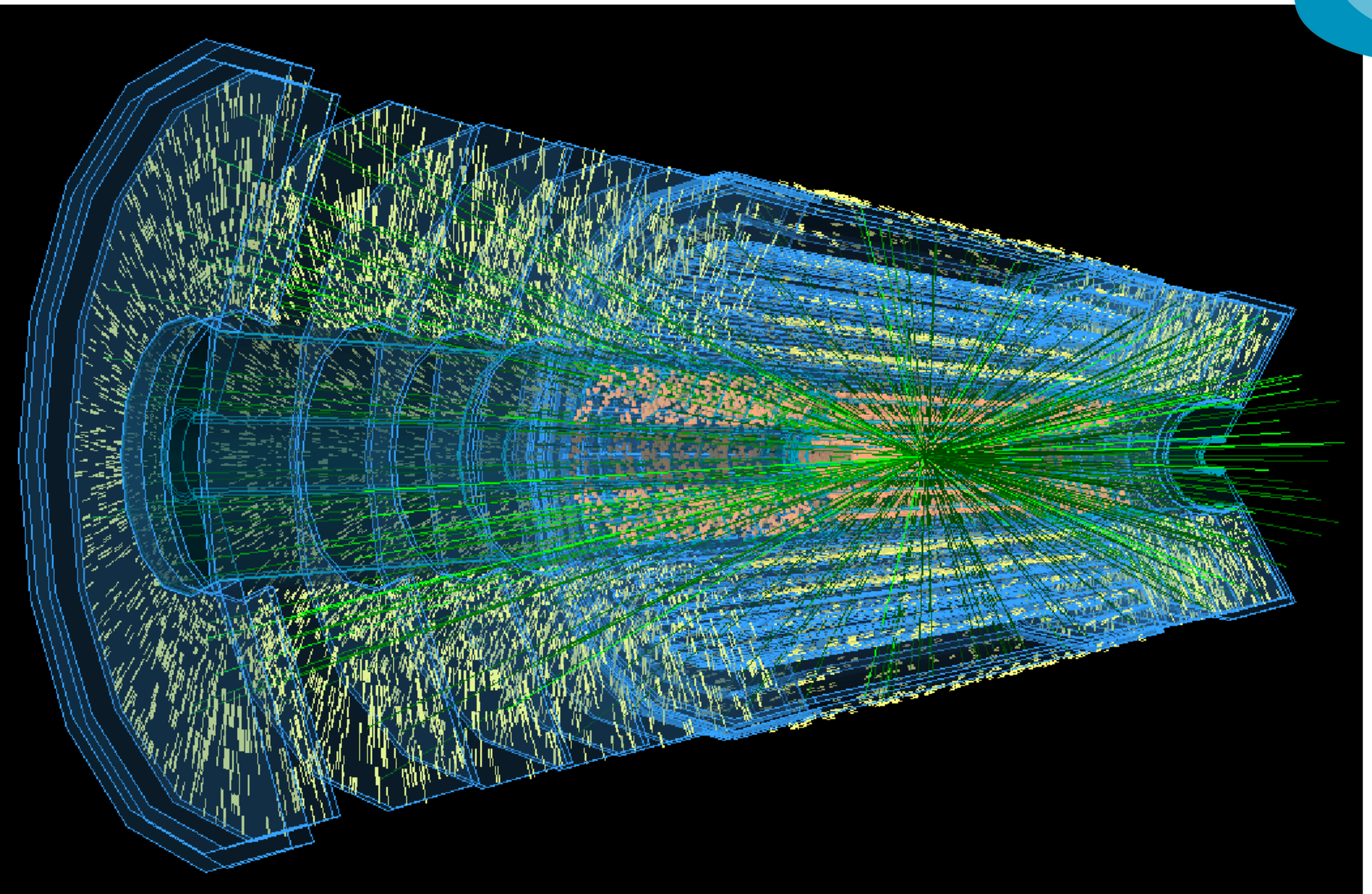
Numero di bunch

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

“Dimensione” dei bunch



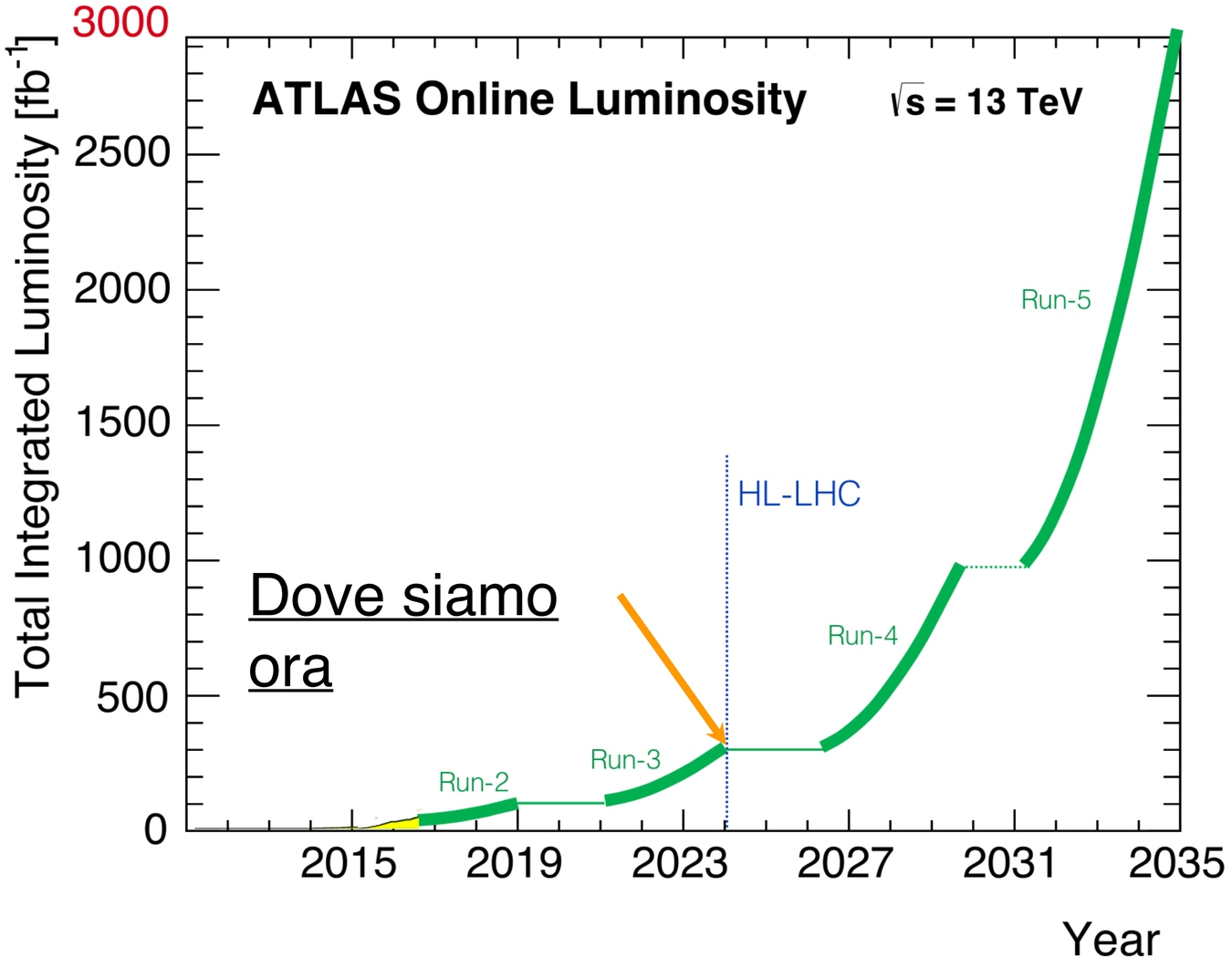
# Cosa ci aspetta?



Upgrade dei rivelatori e dei sistemi di acquisizione dati per sopportare i rate di collisioni molto più elevati

Gruppi a Pavia:
ATLAS
CMS
ALICE

# Cosa ci aspetta?




Upgrade dei rivelatori e dei sistemi di acquisizione dati per sopportare i rate di collisioni molto più elevati

→ Più dati per le analisi!

Gruppi a Pavia:

ATLAS

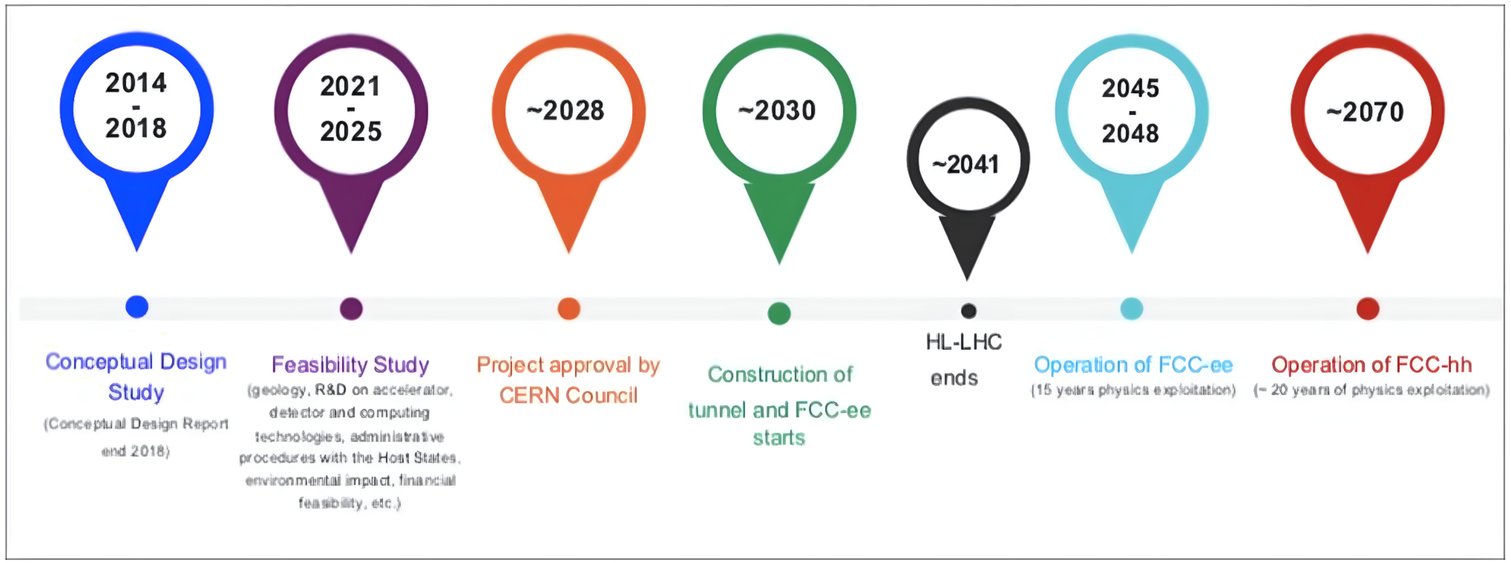
CMS

ALICE

# Cosa ci aspetta?

3 !

## High-priority future initiatives




A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

***• the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

***• Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.***

***The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.***

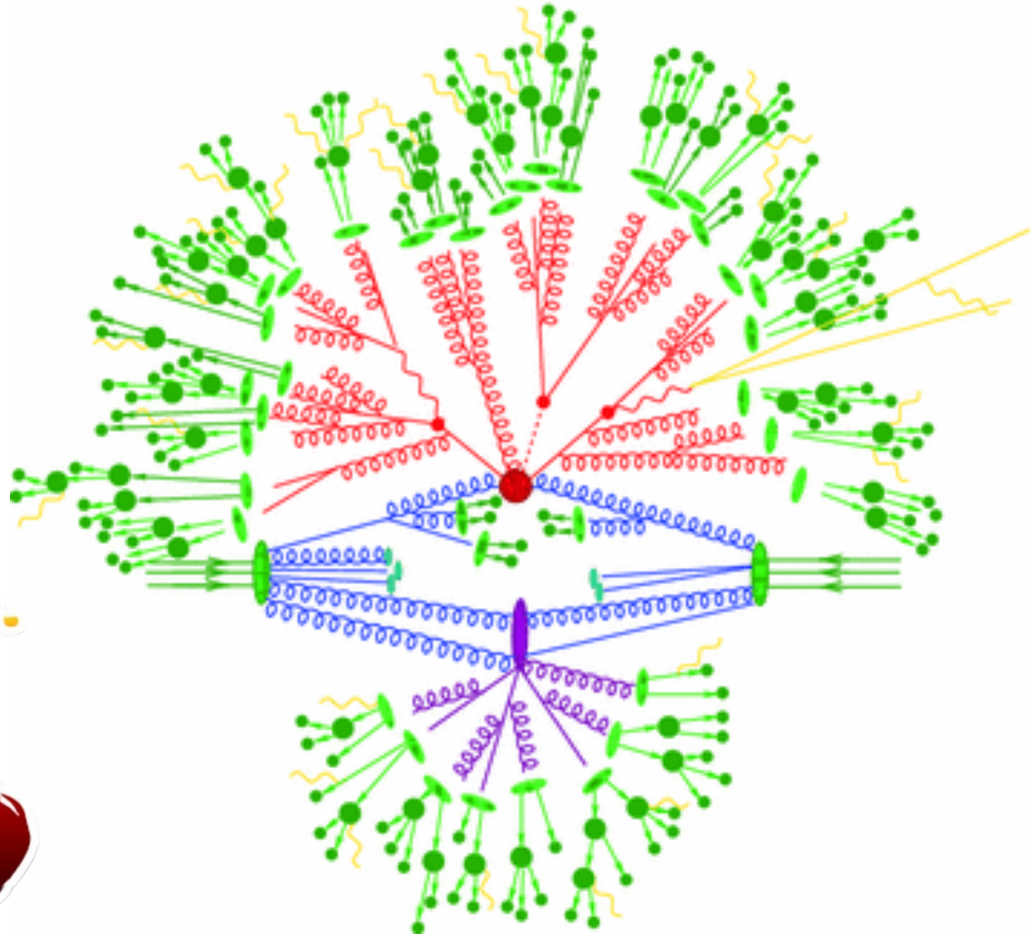
FUTURE CIRCULAR COLLIDER

# Collisioni pp Vs $e^+e^-$

Perdita di energia per radiazione di sincrotrone

$m_{protone} \sim 2000\ m_{elettrone}$

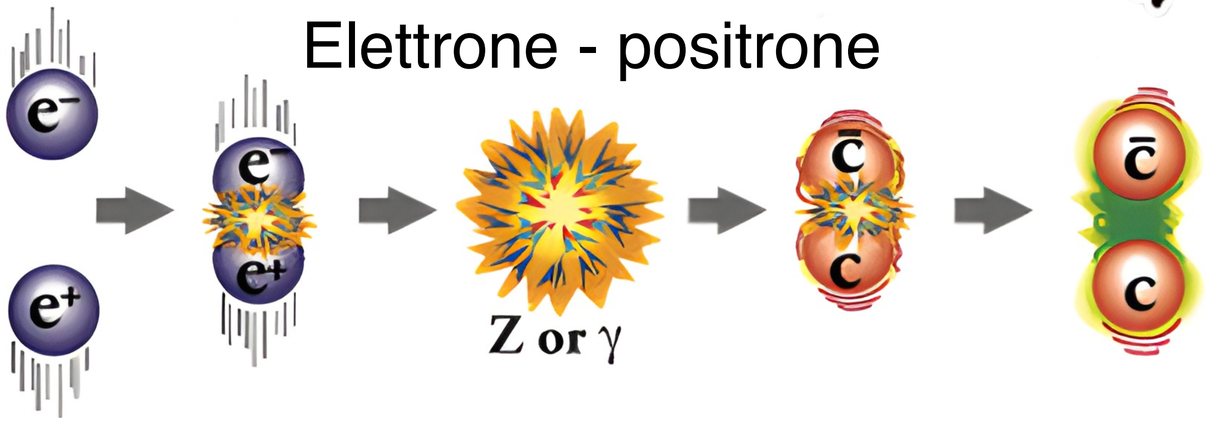
$$\Delta E \propto \left(\frac{E}{m}\right)^4$$



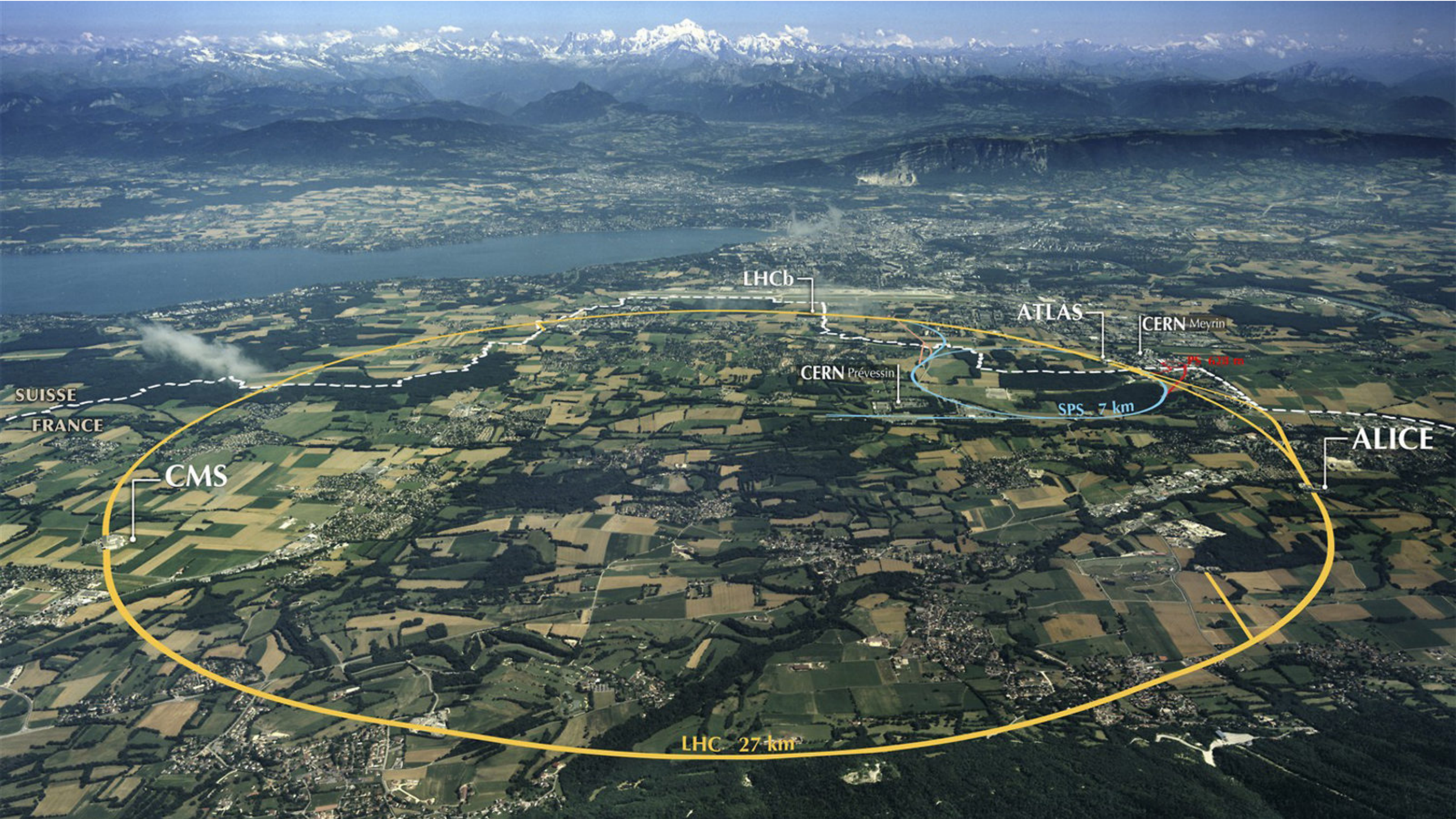
Protone - protone

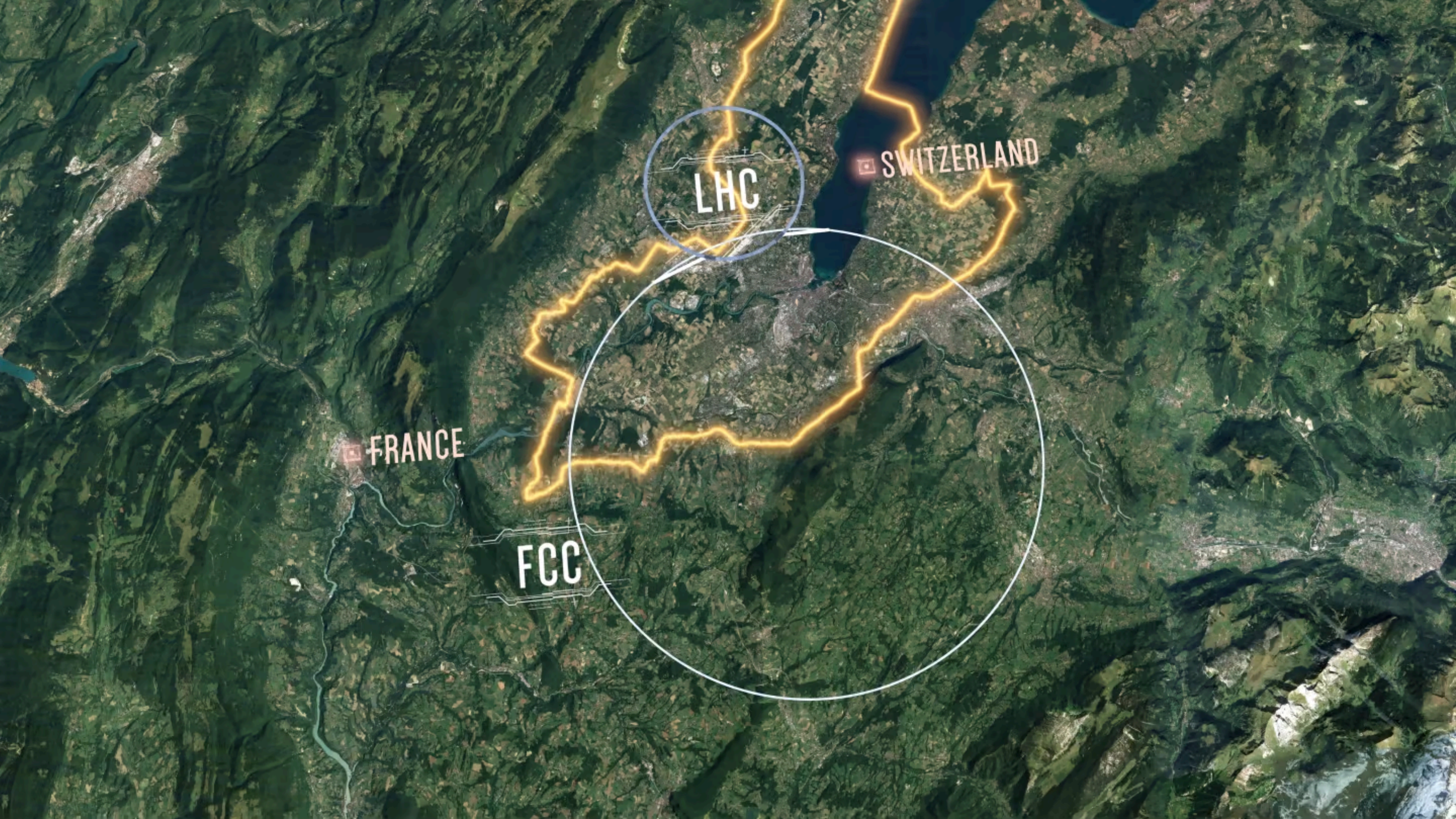
VS

Elettrone - positrone



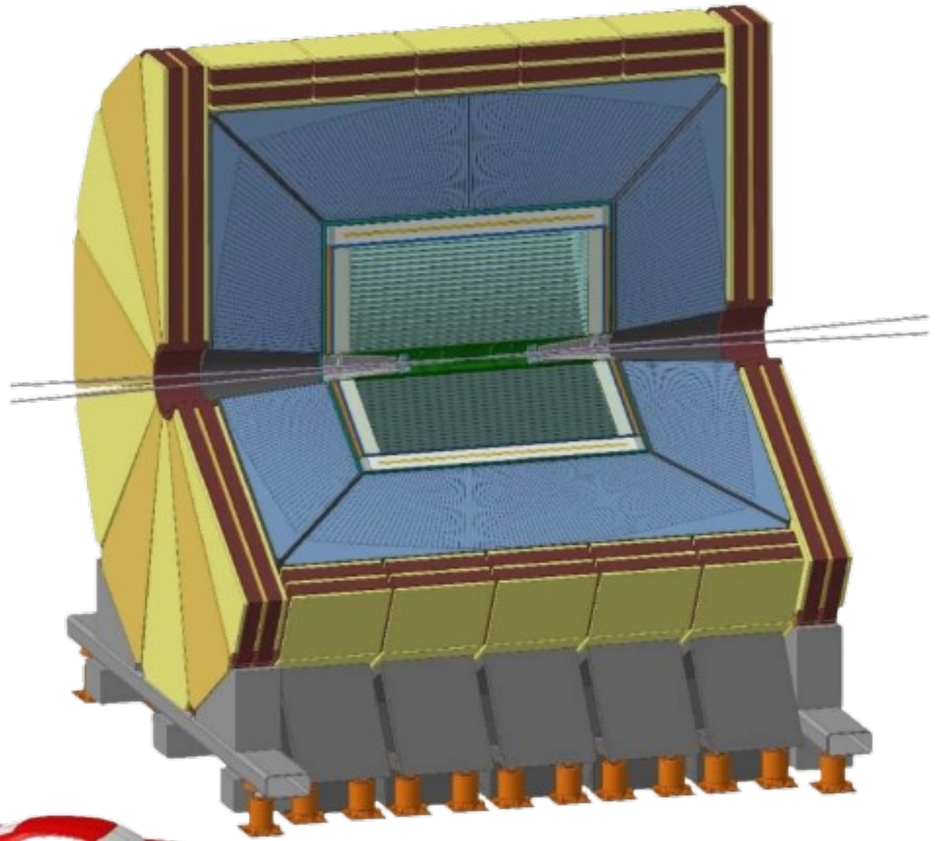

<u>Da considerare</u>:
Particelle elementari / composite
Energia nel centro di massa
Complessità dello stato finale


LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km

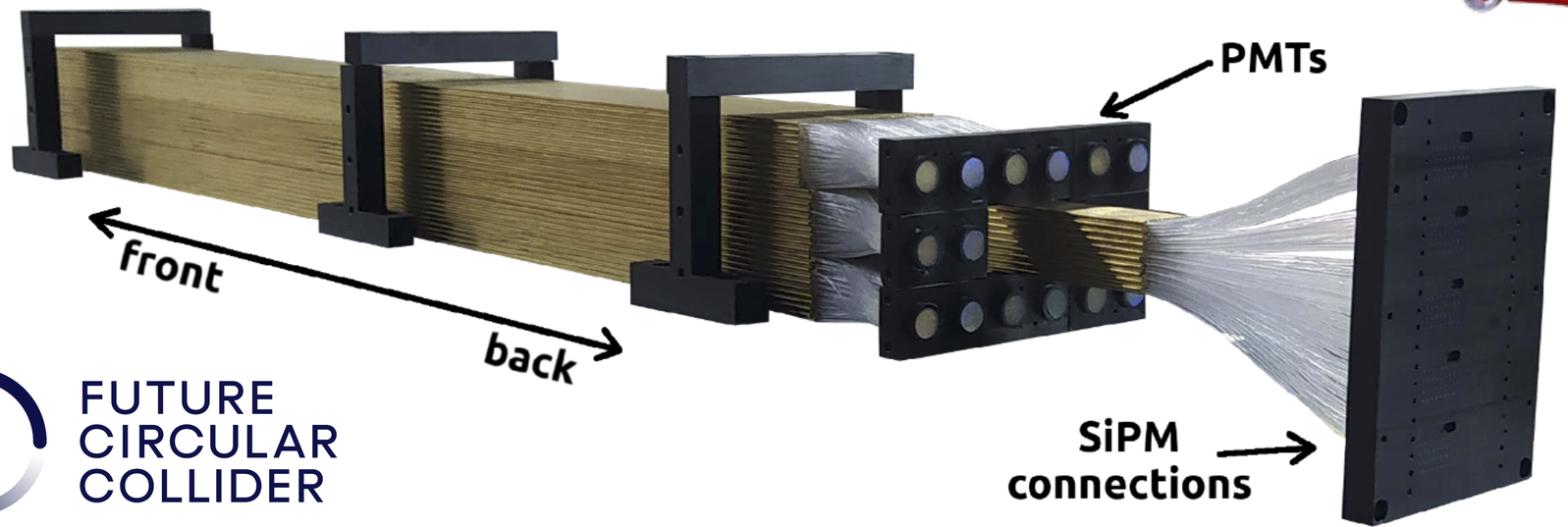

LHC
SWITZERLAND
FRANCE
FCC

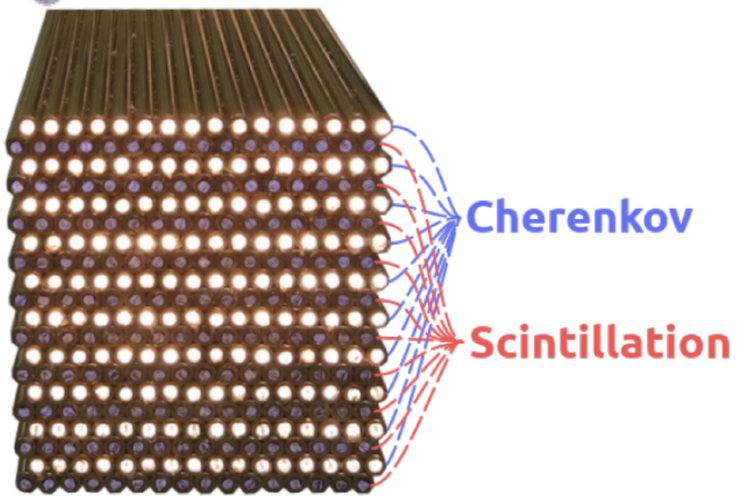
# Cosa ci aspetta a FCC?

Esperimento IDEA @ FCC-ee
(Innovative Detector for Electron-positron Accelerators)



RD_FCC @ Pavia:
Sviluppo di una nuova tipologia di calorimetri (dual-readout), per migliorare notevolmente la precisione nella ricostruzione di jet adronici



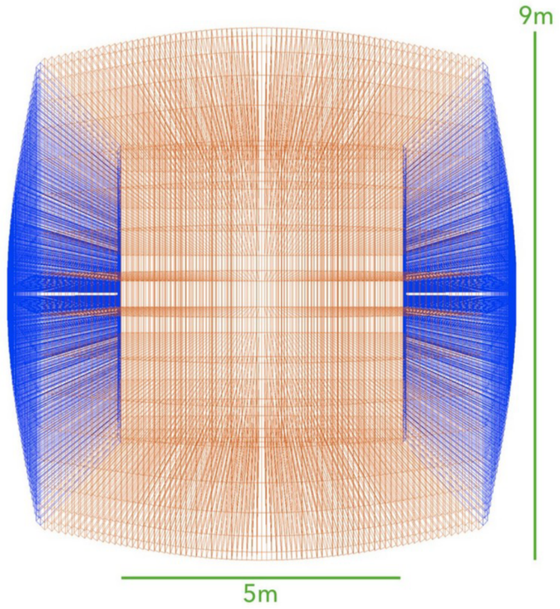

FUTURE
CIRCULAR
COLLIDER

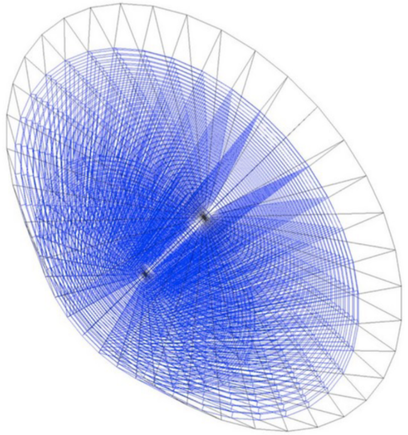
# Cosa ci aspetta a FCC?

Attività in corso (lato sperimentale):

- Costruzione di prototipi dimostrativi per valutare le performance dei rivelatori

- Analisi dei dati raccolti durante campagne al CERN, confronto con simulazioni e applicazioni ML



- Analisi di fisica, principalmente oltre il Modello Standard, attraverso simulazioni Monte Carlo per valutare le potenzialità dell’esperimento IDEA

# Ma i muoni?

International MUON Collider Collaboration

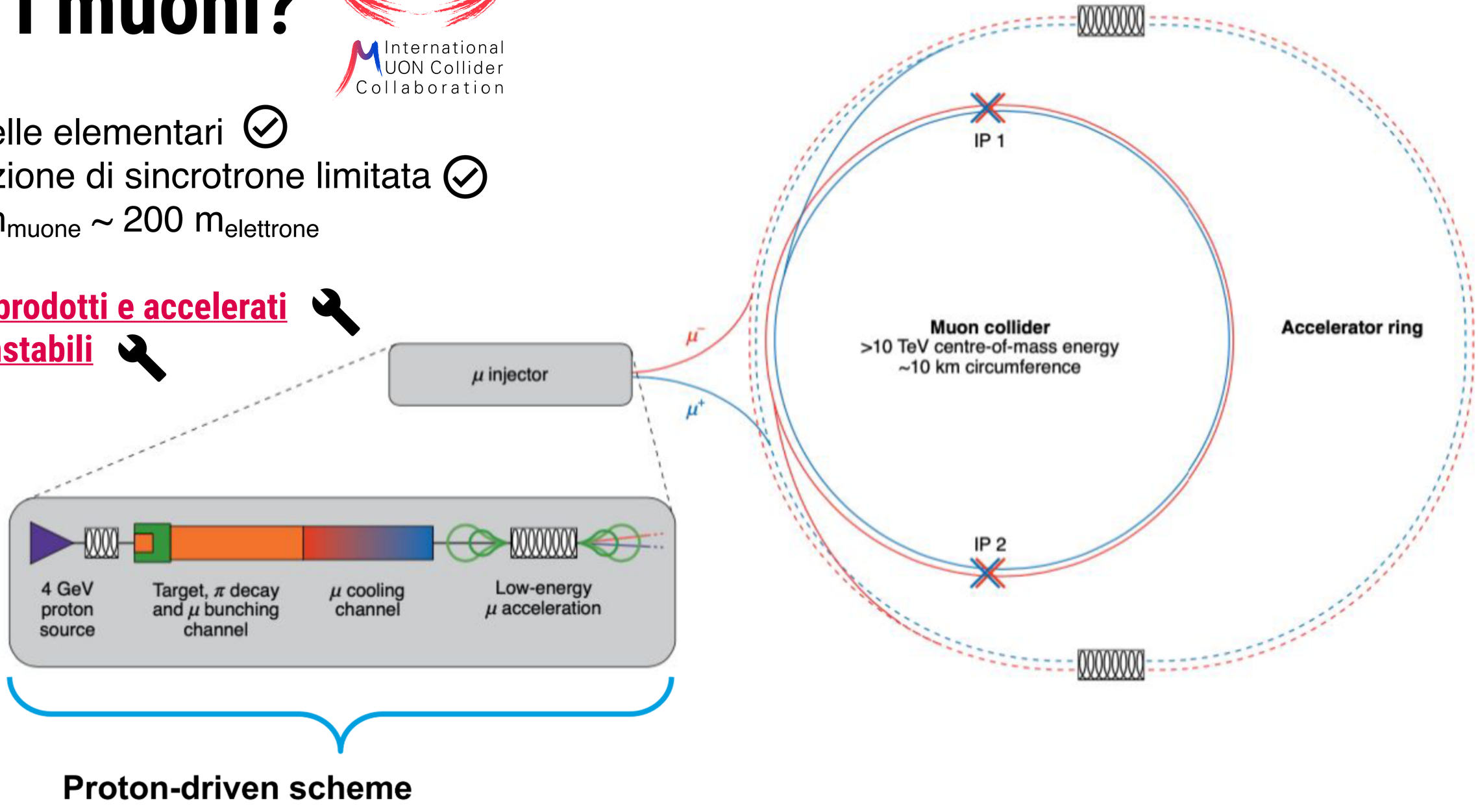
Particelle elementari ✓

Radiazione di sincrotrone limitata ✓

$m_{muone} \sim 200\ m_{elettrone}$

**Vanno prodotti e accelerati** 🔧

**Sono instabili** 🔧

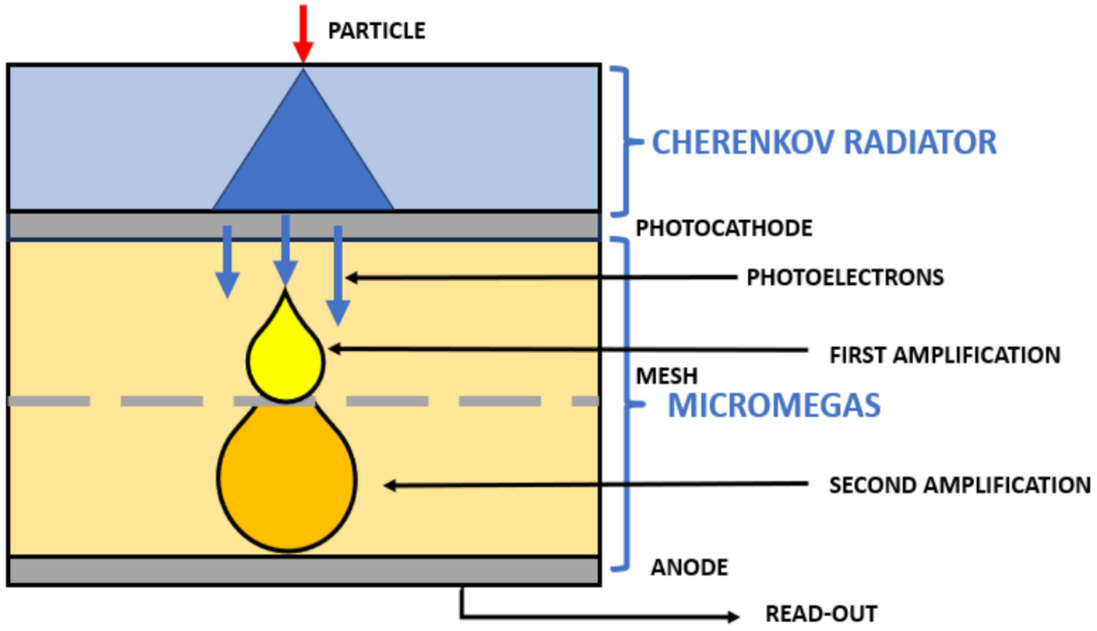


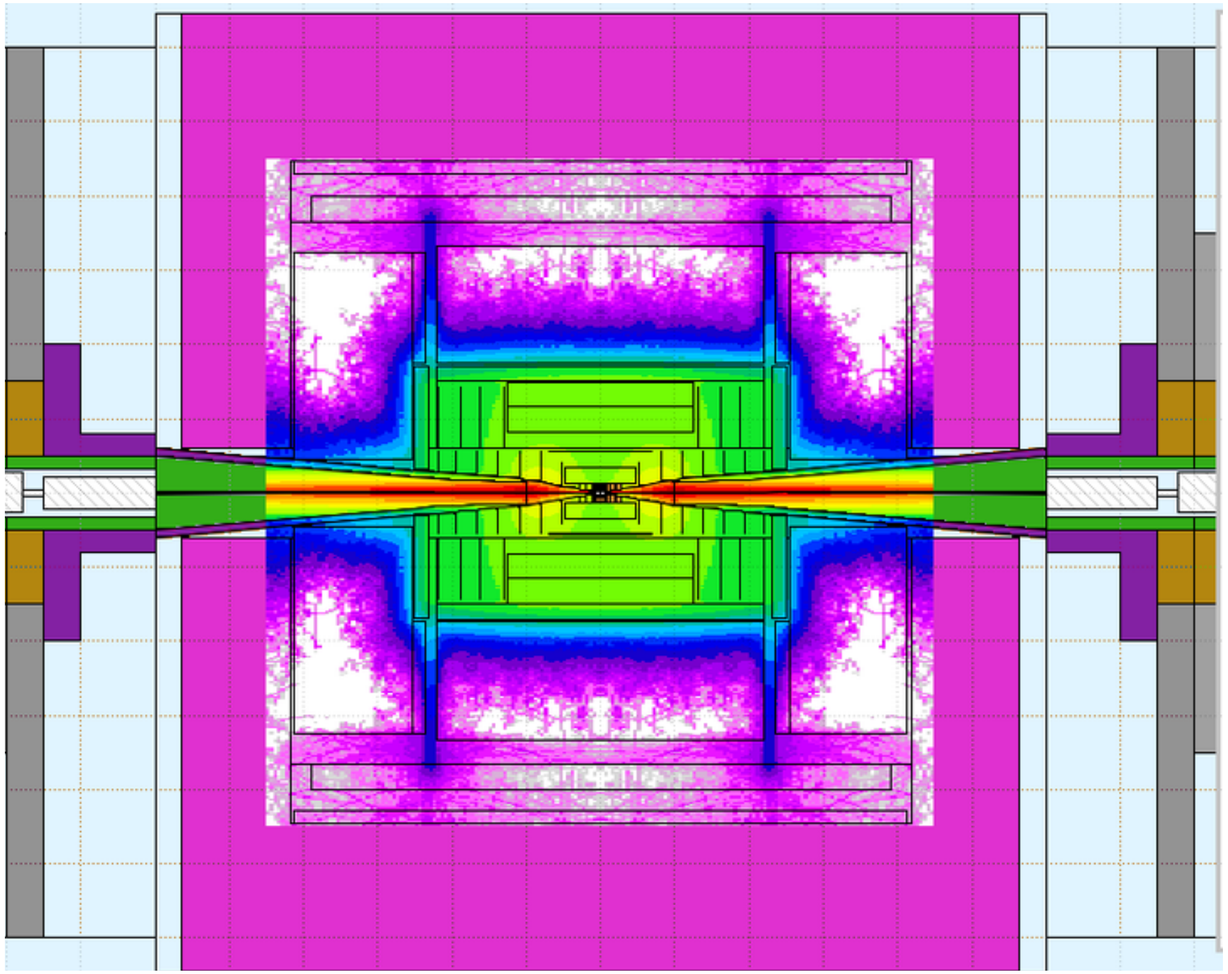
# Ma i muoni?

International MUON Collider Collaboration

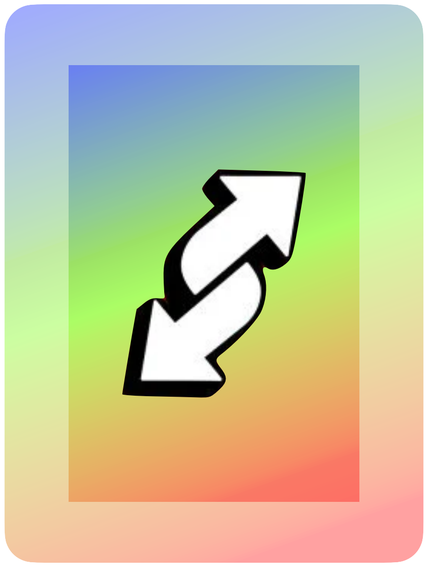
RD_MUCOL @ Pavia:
Sviluppo di rivelatori a gas con eccellente risoluzione temporale, per separare i segnali prodotti nella collisione di interesse dal background

Simulazioni per verificare le performance del sistema a muoni usando canali di fisica (SM e Beyond SM)



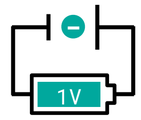



Beam Induced Background (BIB):
Interazioni nel rivelatore dovute alle particelle prodotte dal decadimento dei muoni, nell'area vicina al punto di collisione



**unità di misura**

1 eV = 1.6 x $10^{-19}$ J




**Collider**

**Passato**

DAΦNE

LEP I-II

**Presente**

CMD

Belle II

(HL) LHC

**Futuro**

FCC-ee

Muon Collider

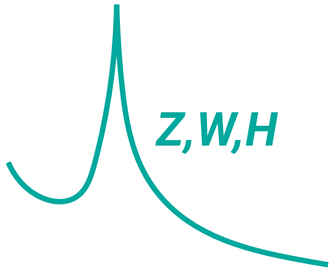
FCC-hh

Energy

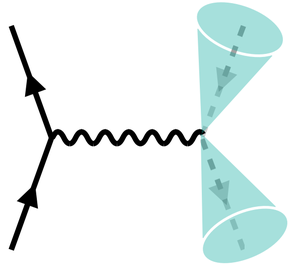
1 GeV | 10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

**Osservabili**

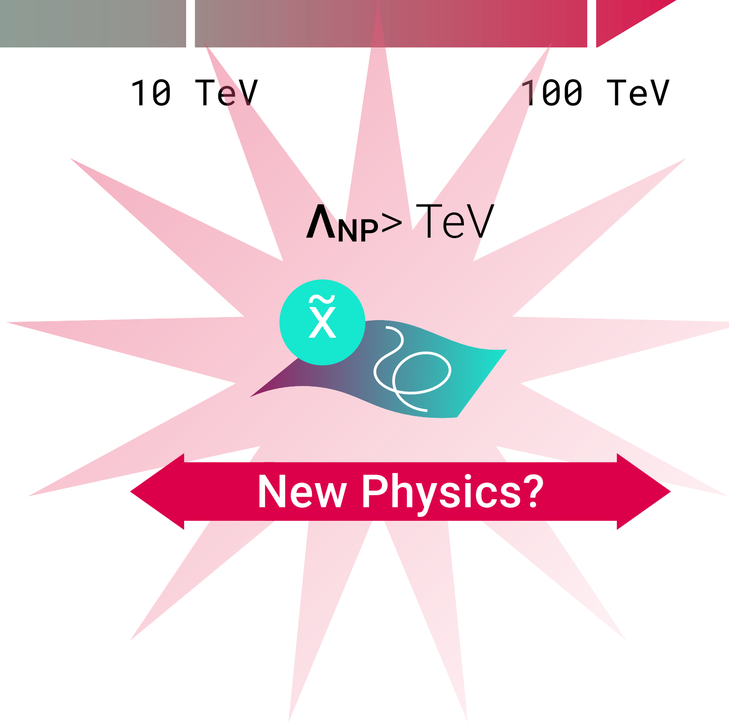
lepton g-2




EWPO



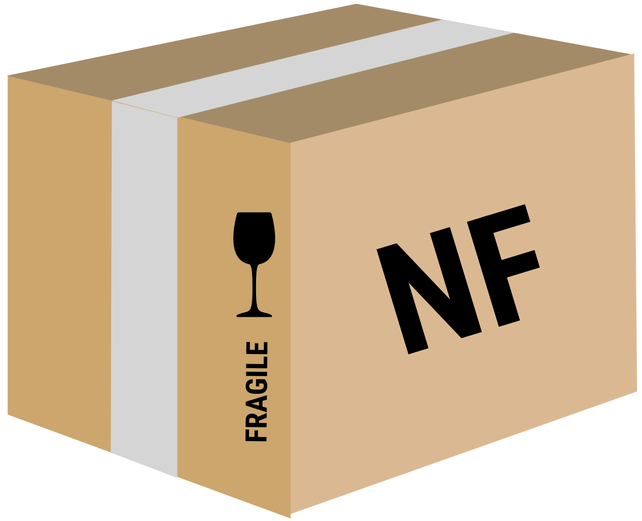
$e^+e^- \rightarrow$ *hadrons*




New Physics?

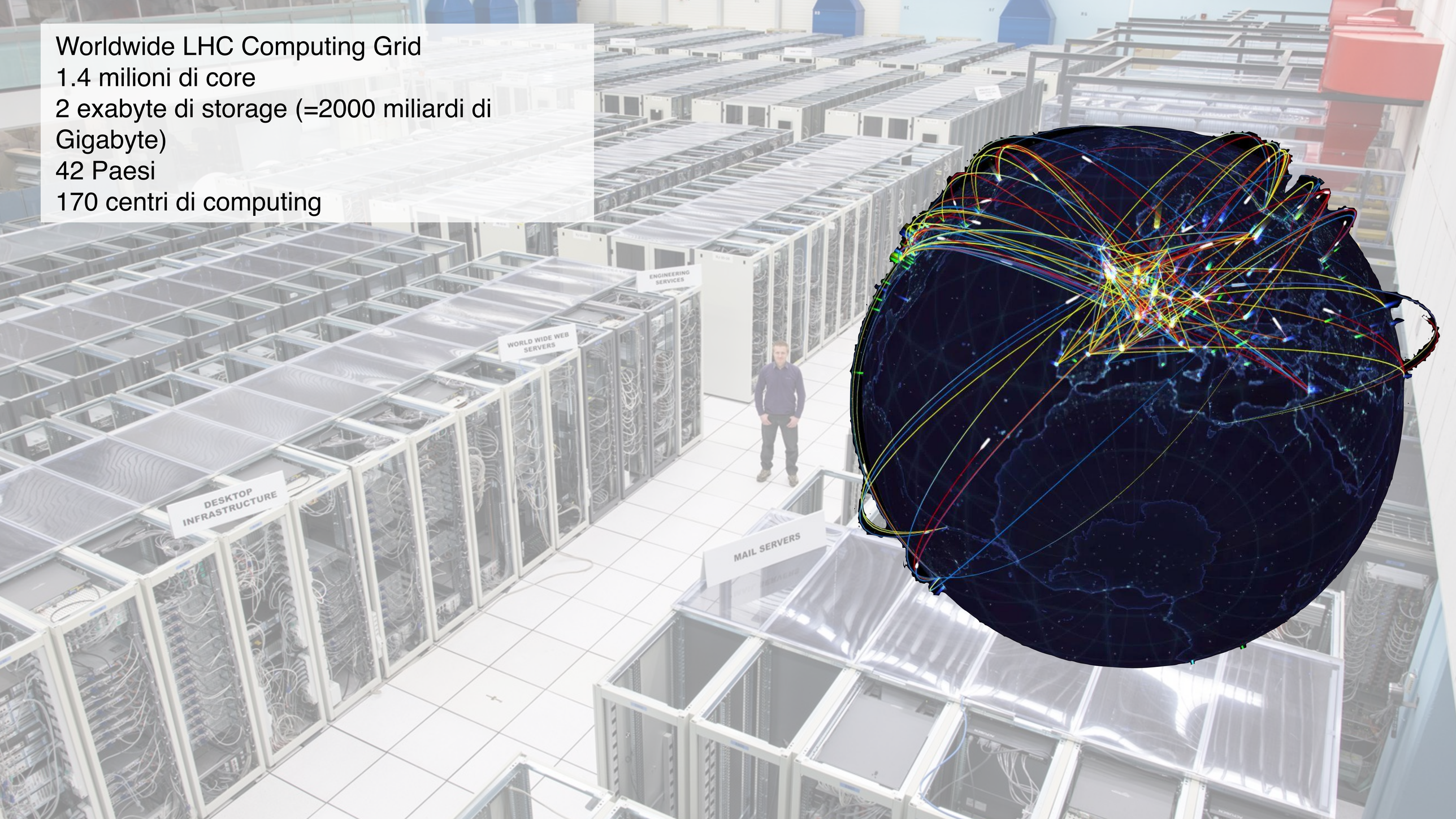
$$\frac{1}{\sqrt{2}} \left| \text{  } \right\rangle \pm \left| \text{  } \right\rangle$$

Se il Modello Standard è
**vivo e morto** allo stesso tempo




Non resta che **aprire la scatola**
della Nuova Fisica!

Worldwide LHC Computing Grid
1.4 milioni di core
2 exabyte di storage (=2000 miliardi di Gigabyte)
42 Paesi
170 centri di computing




Worldwide LHC Computing Grid
1.4 milioni di core
2 exabyte di storage (=2000 miliardi di Gigabyte)
42 Paesi
170 centri di computing

# Da grandi moli di dati derivano grandi potenzialità

Numero di eventi osservati in ATLAS

Numero di bosoni di Higgs prodotti da LHC