

CERN

European Organization for Nuclear Research

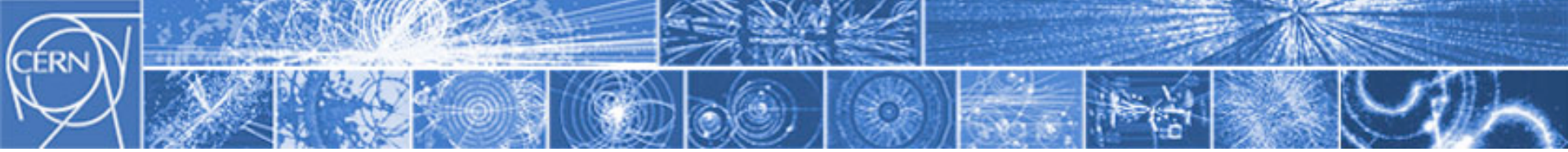
Organisation Européenne pour la Recherche Nucléaire

# Fisica delle particelle oggi

## Il Modello Standard and Beyond

- Bosone di Higgs
- SuperSimmetria
- Materia Oscura

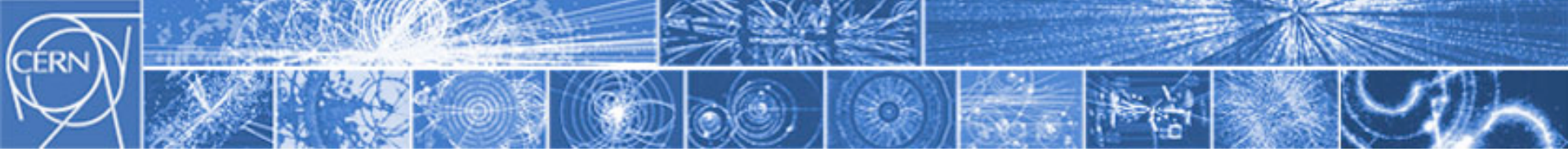
*Marco CIRELLI [CERN, Divisione Teorica]*



## **Cosa si fa al CERN**

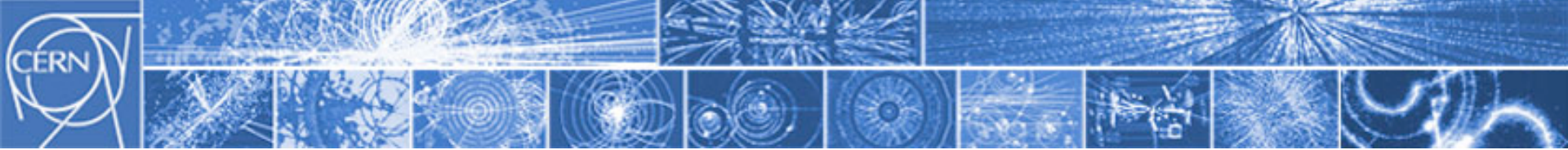
### **Ricerca fondamentale in Fisica delle Particelle**

- i costituenti elementari della materia
- le forze fondamentali che li governano
- l'origine, il contenuto e la struttura dell'Universo



# **Modello Standard**

(della fisica delle particelle elementari)



Il Modello Standard è la costruzione ('scoperta') fondamentale della fisica delle particelle, nella seconda metà del XX secolo.

## **XIX secolo** elettromagnetismo

**1932** teoria di Fermi del decadimento beta - interazioni deboli

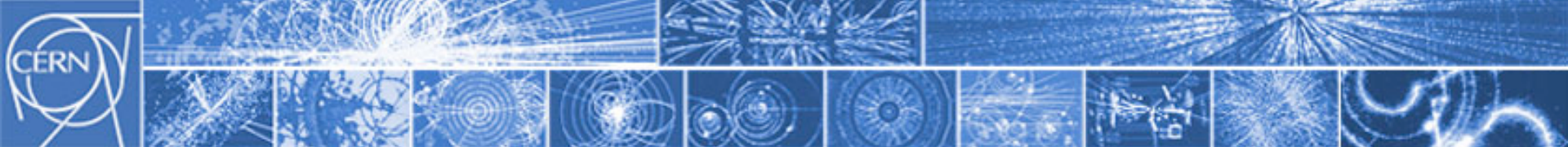
**1960's** unificazione em-debole: teoria ElectroWeak  
(Glashow, Weinberg, Salam)

**1981** scoperta bosoni W e Z (Rubbia)

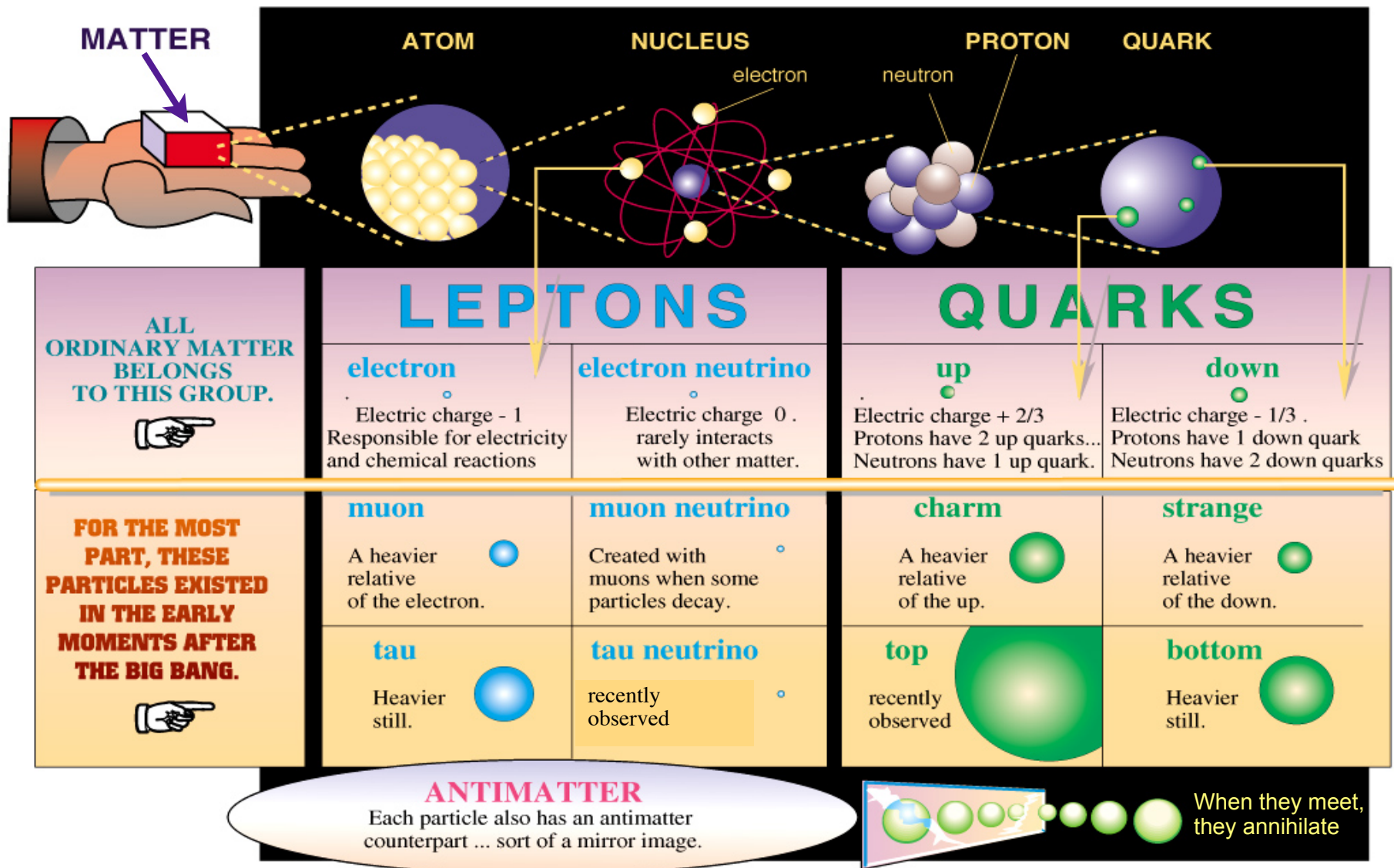
**1970's** teoria della QCD - interazioni nucleari forti  
(Gross, Politzer, Wilczek)

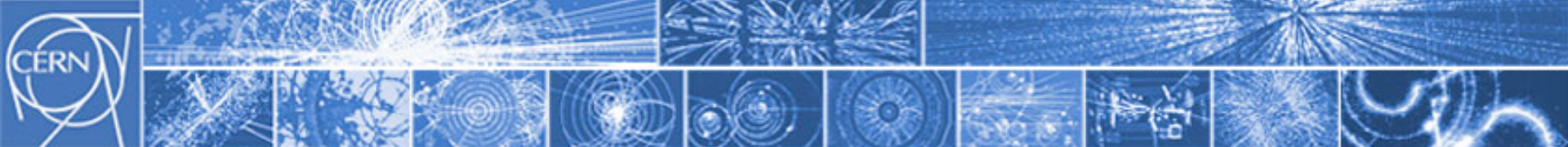
|      |            |      |           |
|------|------------|------|-----------|
| 1936 | $\mu$      | 1968 | $s$ quark |
| 1956 | $\nu_e$    | 1974 | $c$ quark |
| 1962 | $\nu_\mu$  | 1977 | $b$ quark |
| 1974 | $\tau$     | 1995 | $t$ quark |
| 2000 | $\nu_\tau$ |      |           |



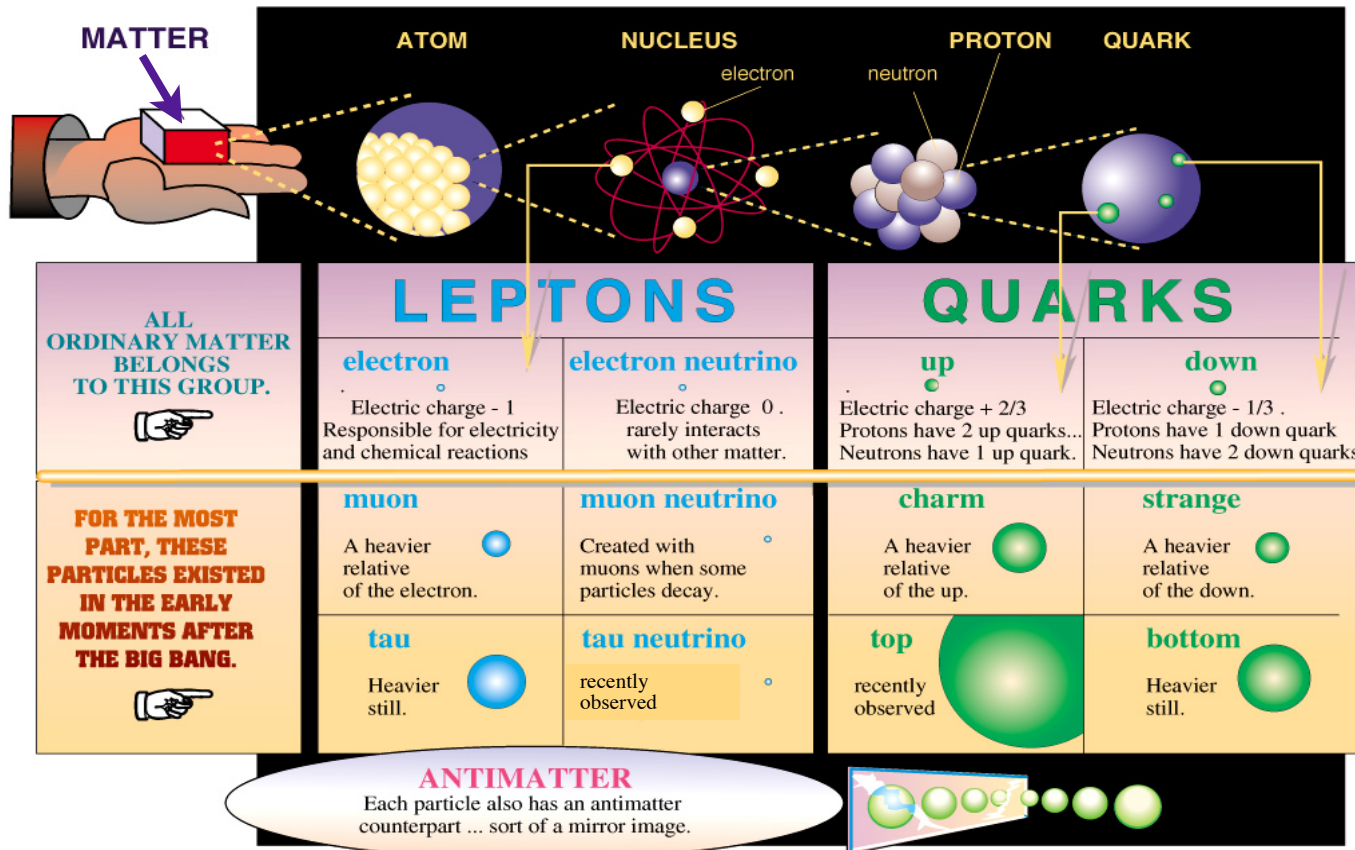


# STANDARD MODEL

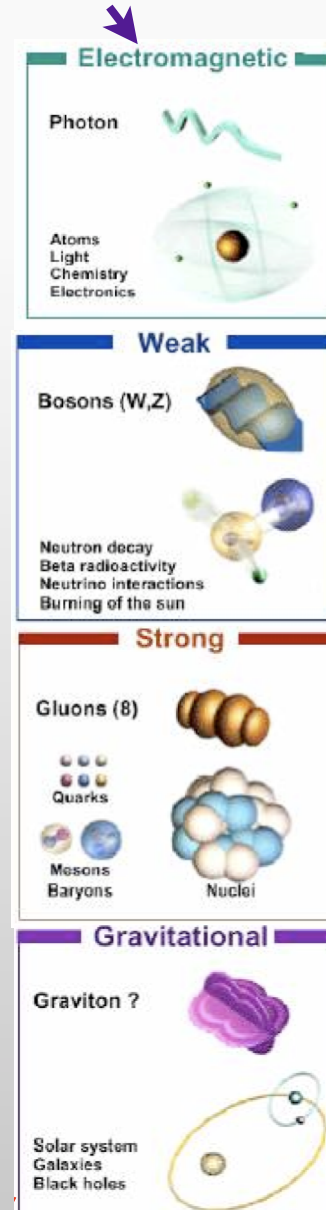




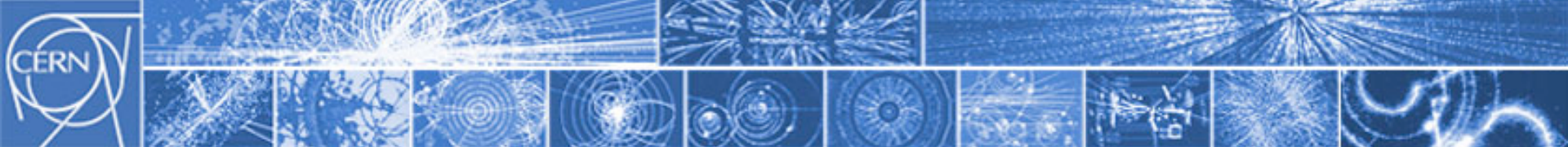
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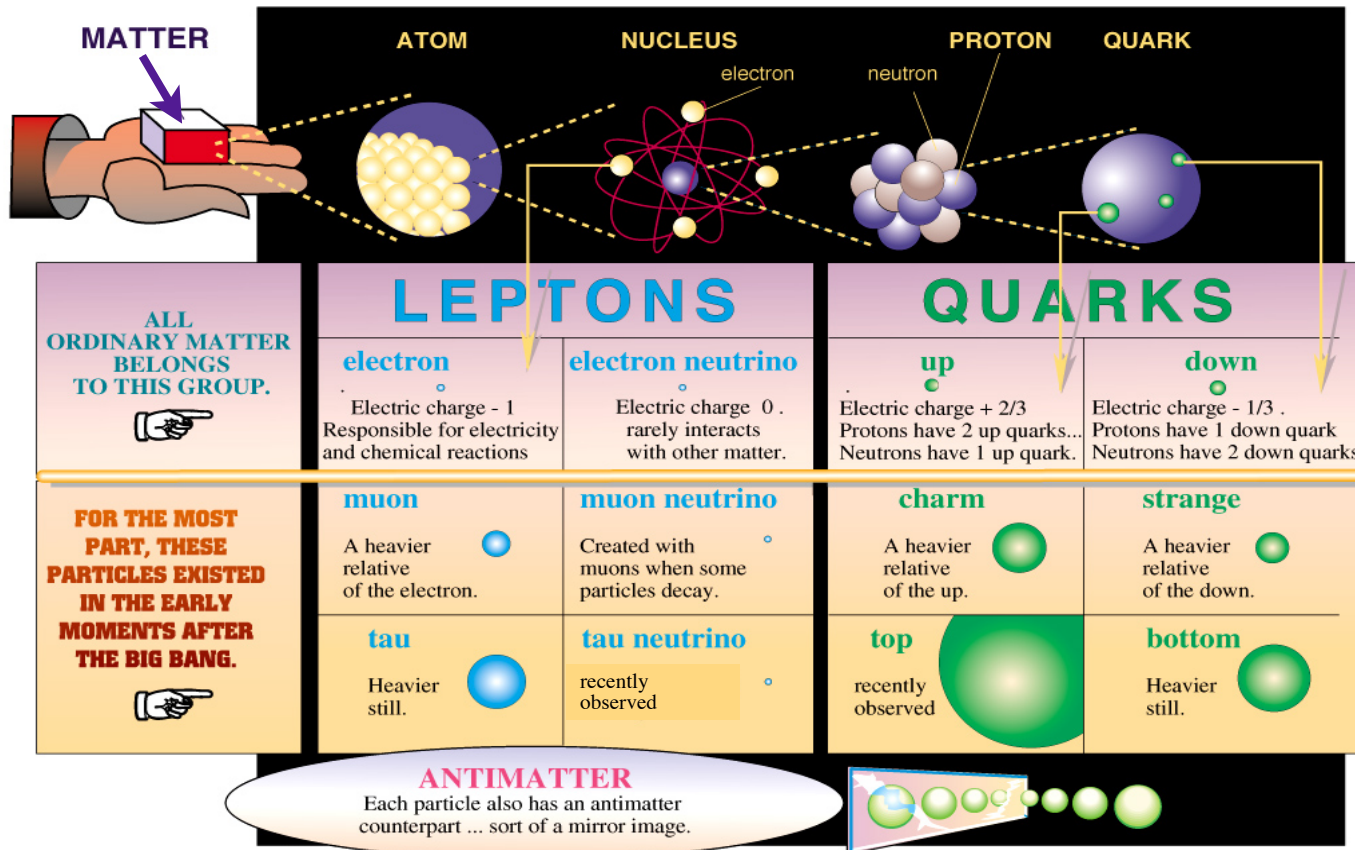
# FORCES







# STANDARD MODEL



from Time magazine

CERN AC \_ E11-7

# FORCES

**Electromagnetic**

Photon

Atoms  
Light  
Chemistry  
Electronics

**Weak**

Bosons (W,Z)

Neutron decay  
Beta radioactivity  
Neutrino interactions  
Burning of the sun

**Strong**

Gluons (8)

Quarks

Mesons

Baryons

Nuclii

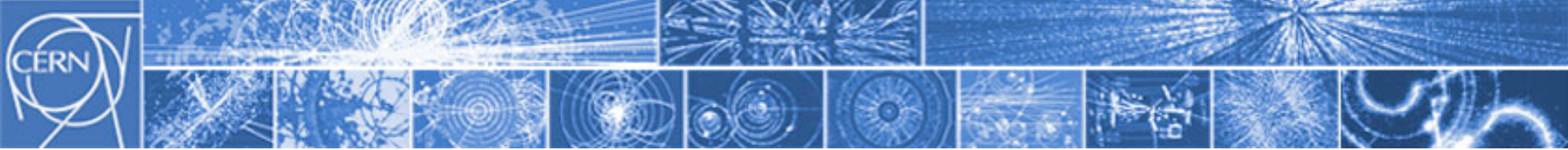
**Gravitational**

Graviton ?

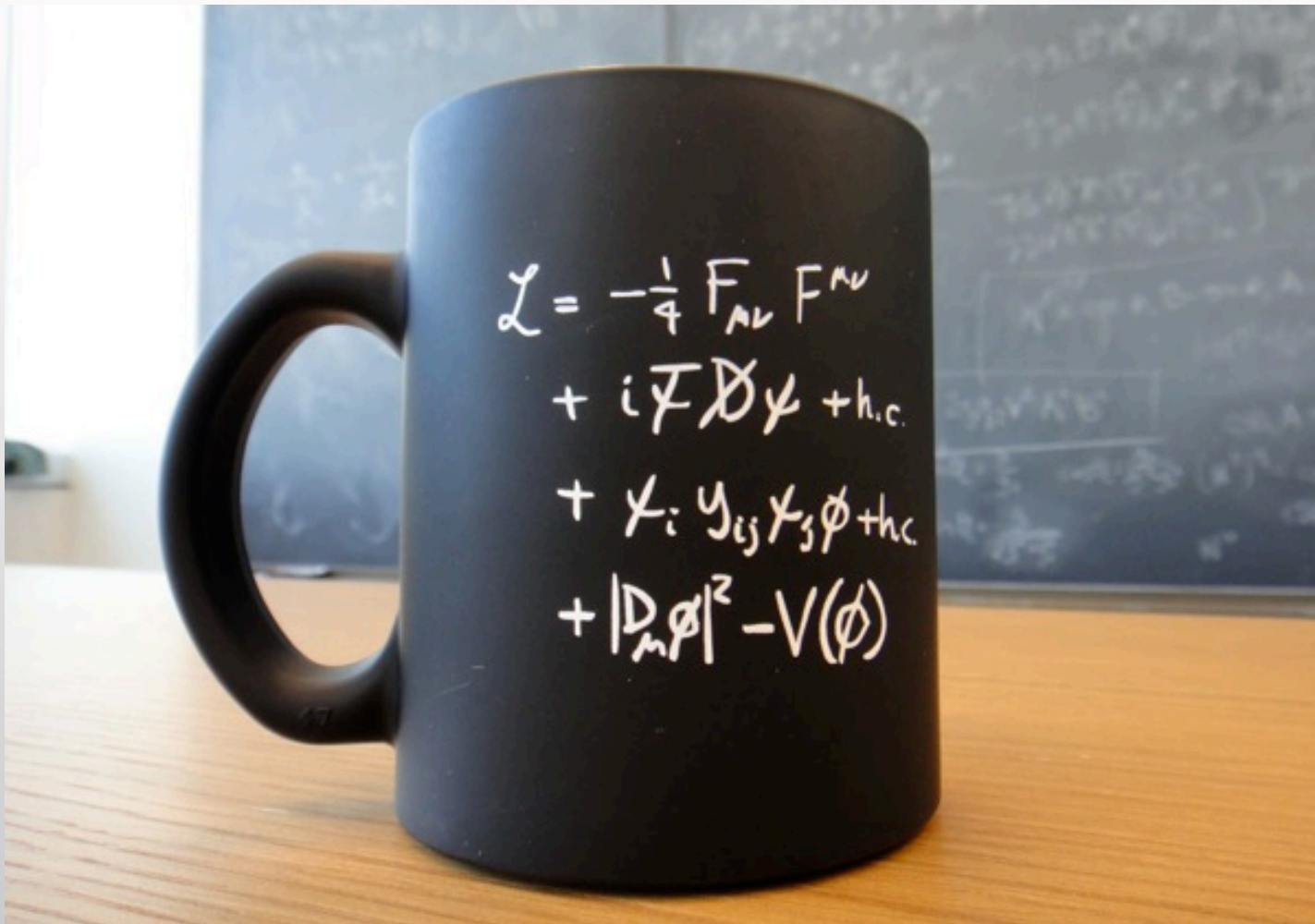
Solar system  
Galaxies  
Black holes

**Higgs boson**

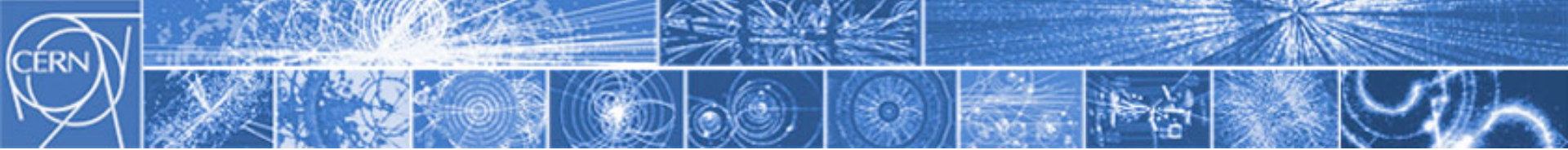
still missing



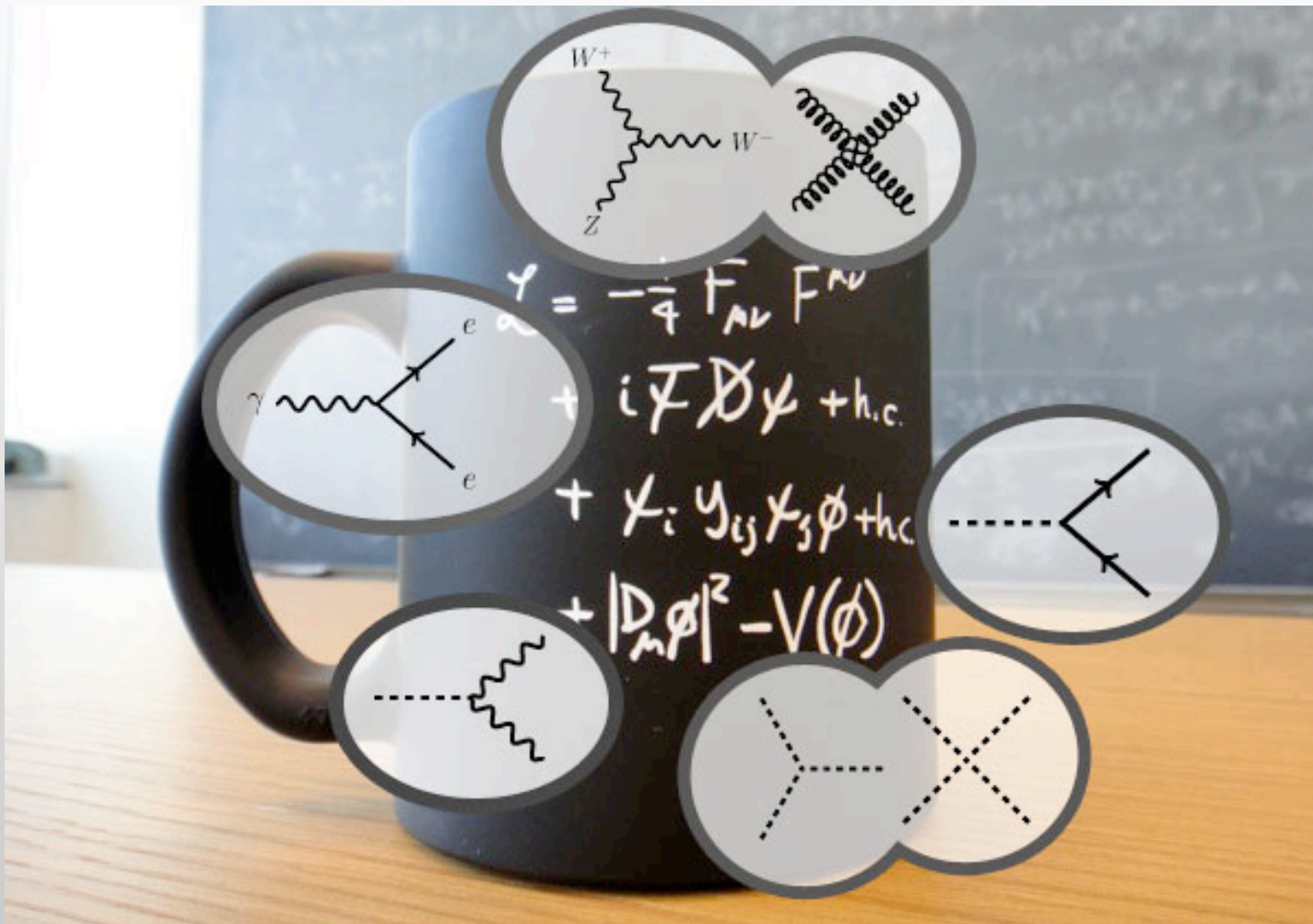
# Standard Model Lagrangian



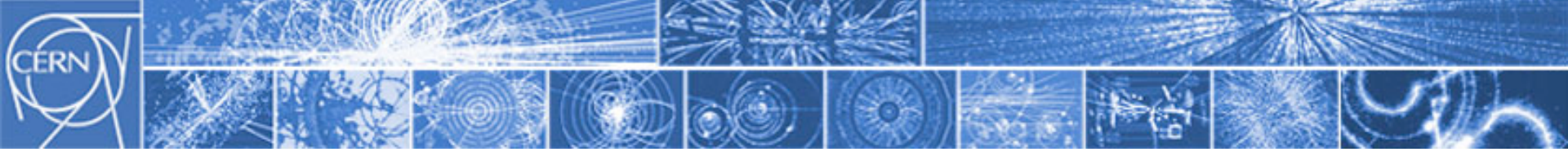




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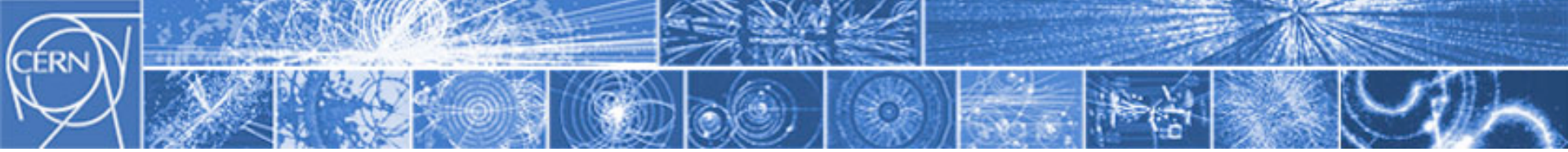






## Problemi aperti in Fisica delle Particelle

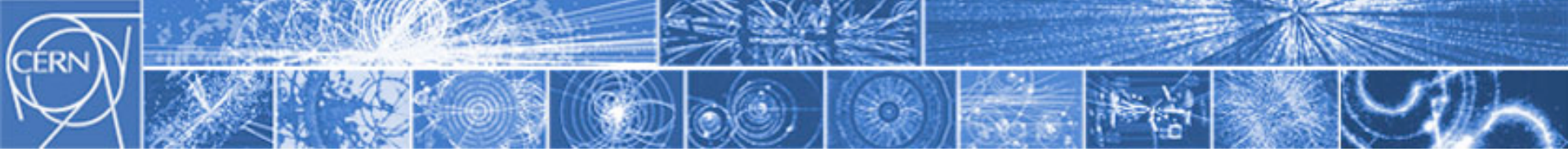
- l'origine della massa e il bosone di Higgs



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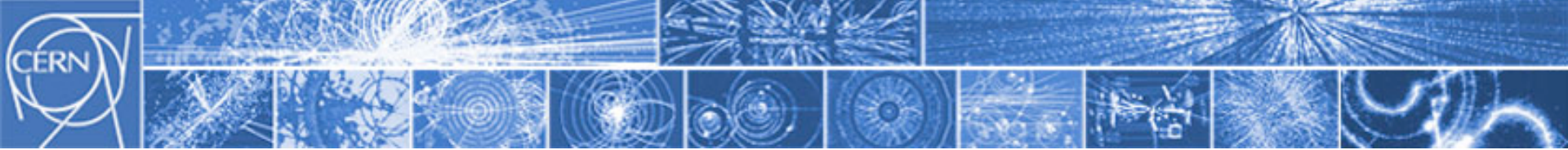




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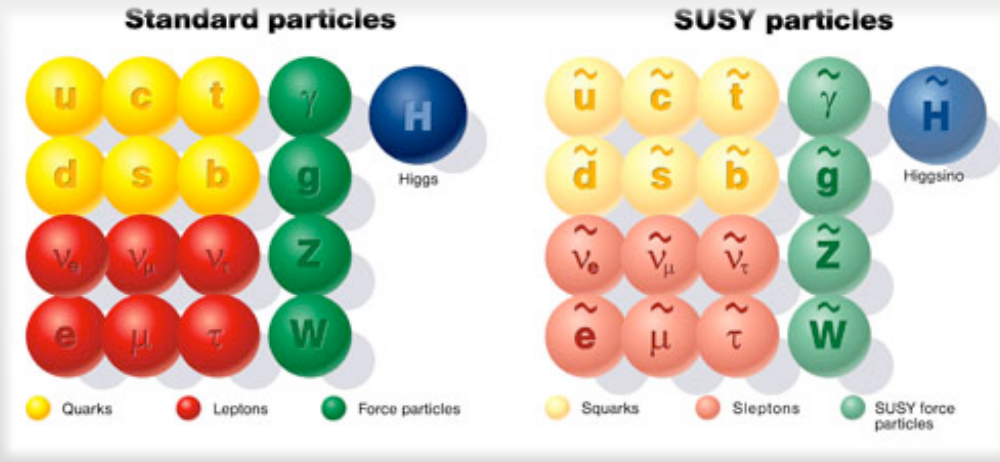
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- la supersimmetria  
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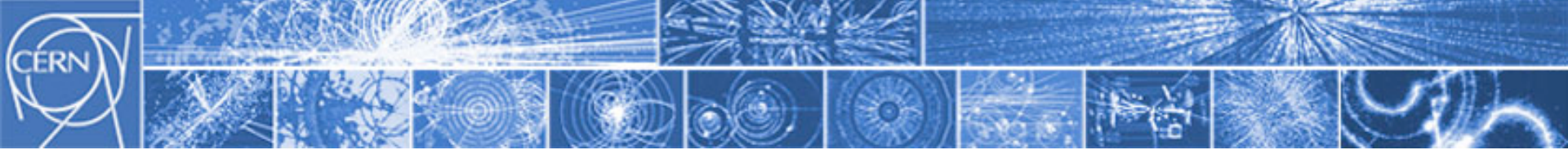




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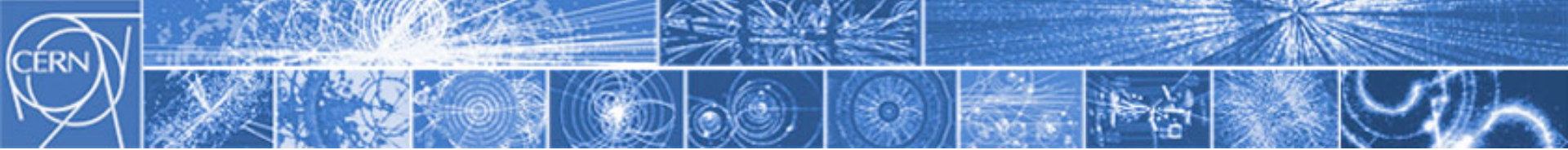


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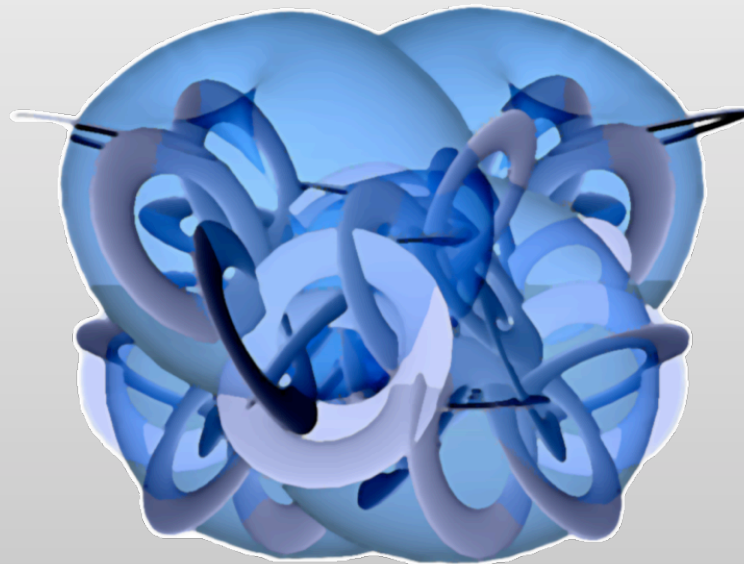
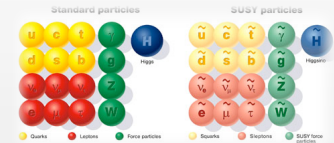


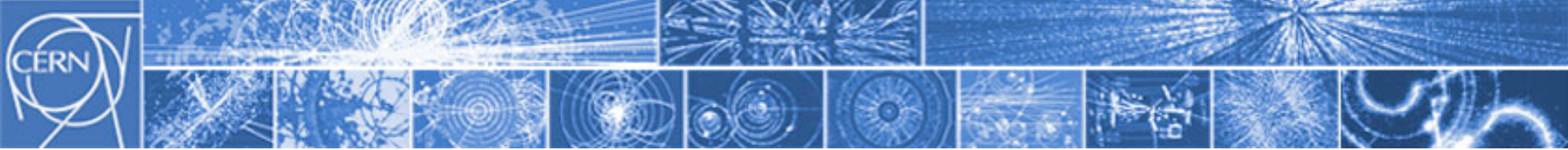




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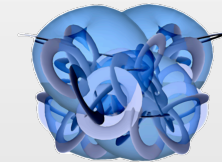
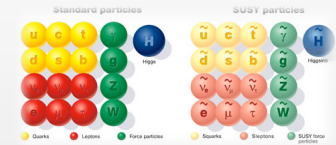
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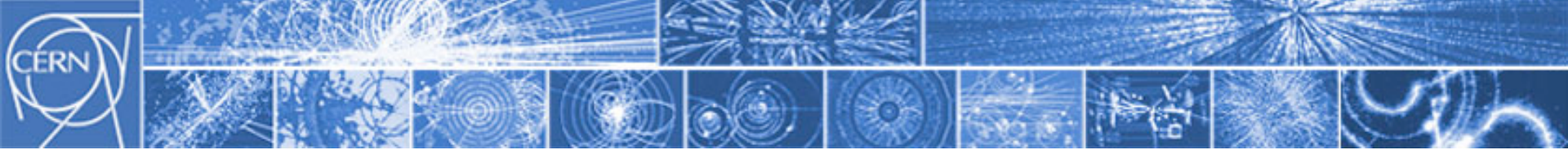




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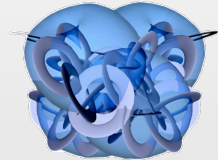
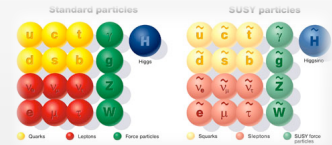
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(una particella sconosciuta che costituisce l'80% della materia dell'Universo!)

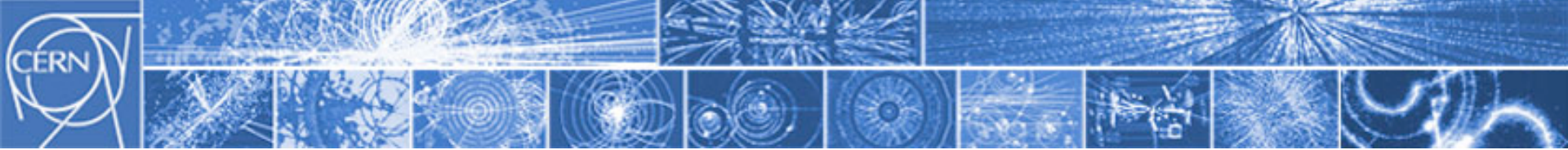




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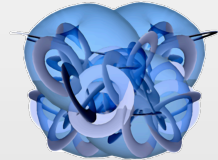
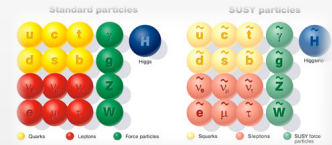
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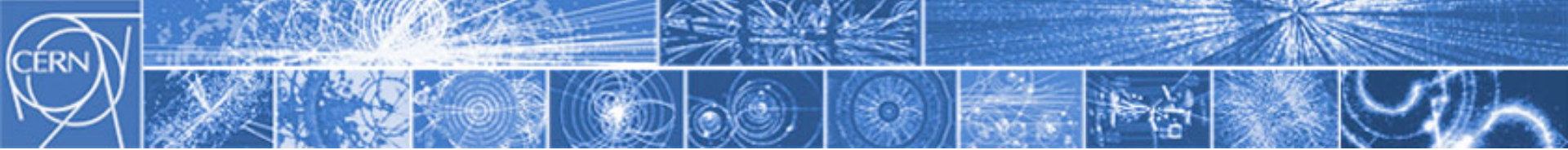


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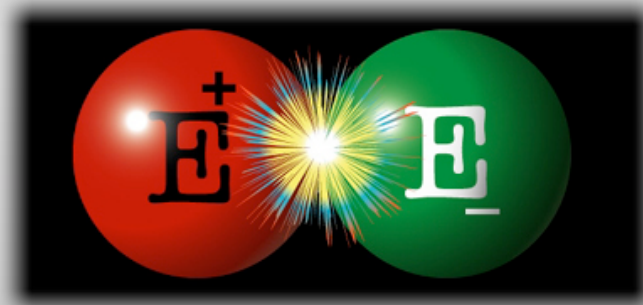
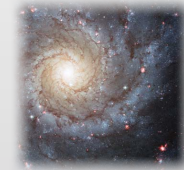
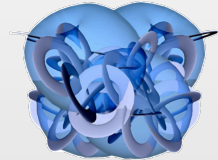
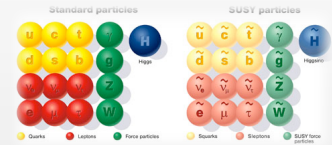




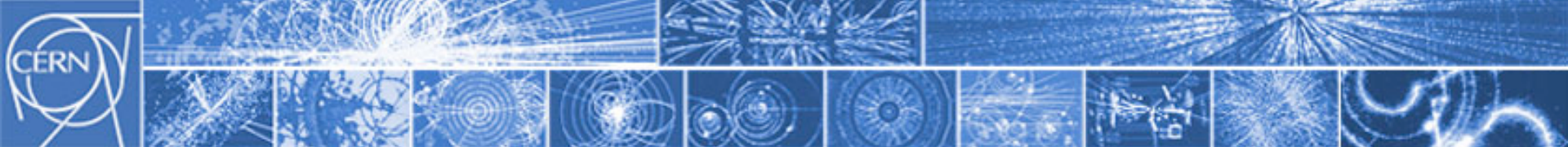


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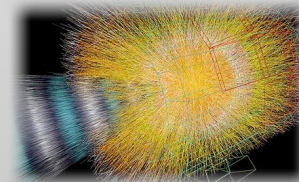
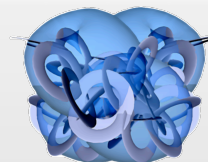
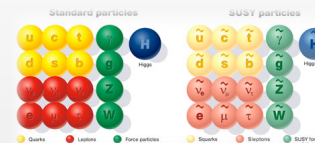


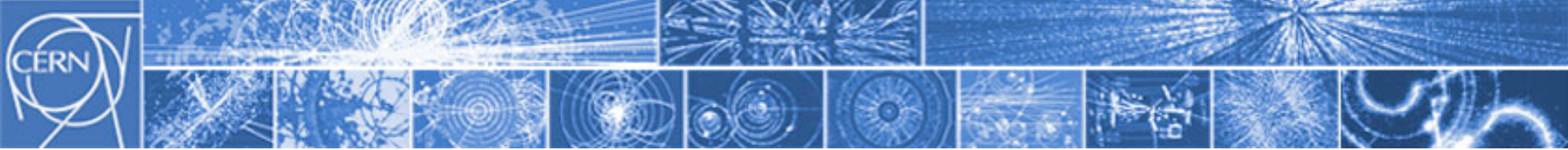




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- l'asimmetria tra materia e antimateria  
(dove è finita tutta l'antimateria dell'Universo?)
- il plasma di quarks e gluoni  
(come diventa la materia nucleare a energie e densità elevatissime?)
- ...





## Come risolvere questi problemi? o... Come si fanno le scoperte?

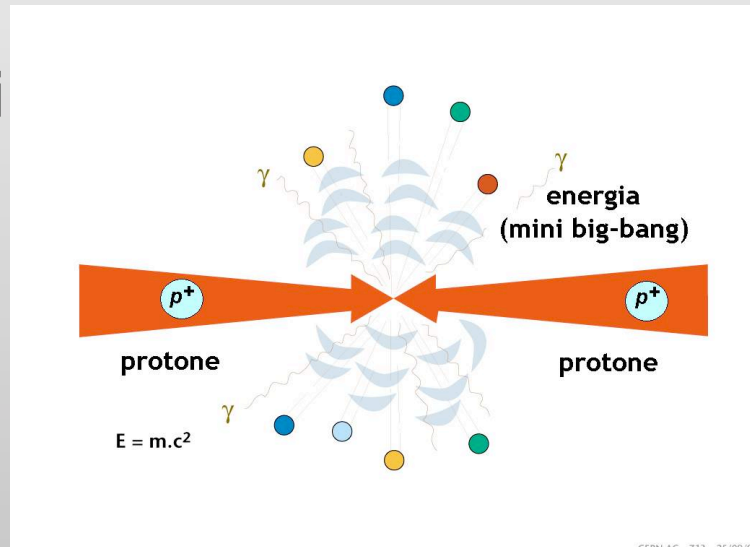
Accelerare le particelle elementari (*protoni, elettroni*)

fino a energie elevatissime (*7 TeV*)

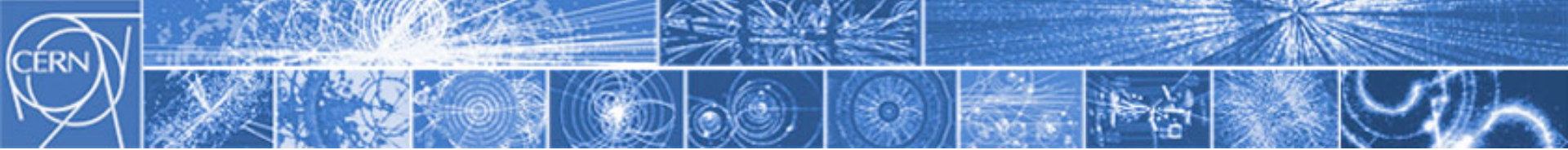
e portarle a collidere.  **$E=mc^2$**

Analizzare accuratamente i prodotti

per scoprire nuove particelle,  
nuove forze,  
nuova fisica...





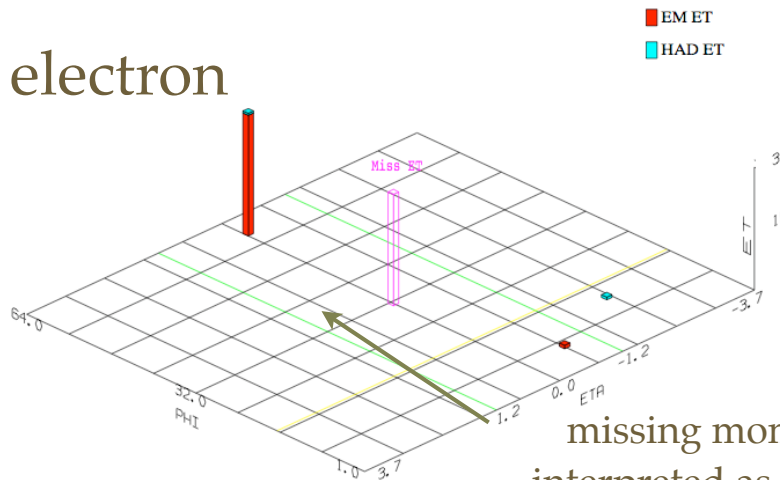


# Examples of reactions in proton collisions

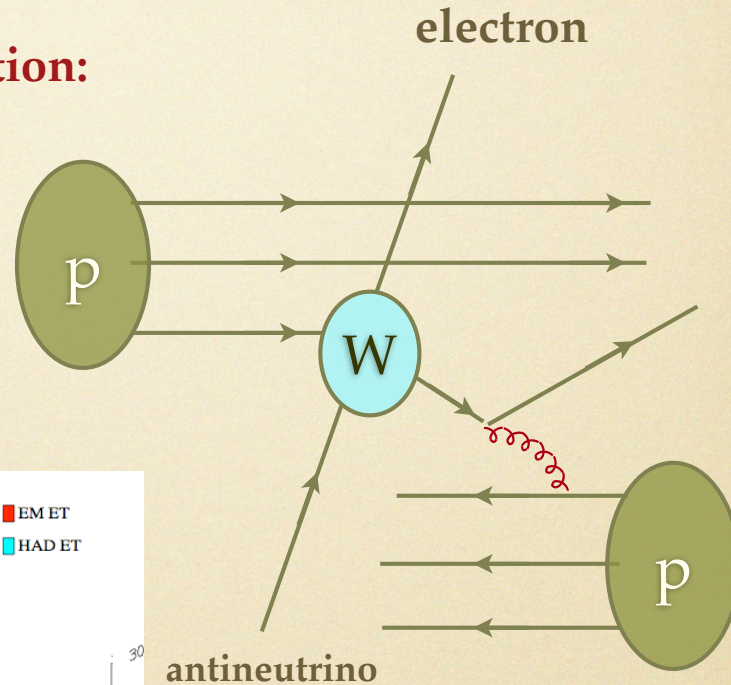
**quark-antiquark annihilation:**  
 $u \text{ dbar} \rightarrow W$

A real-life event from the Tevatron:

electron

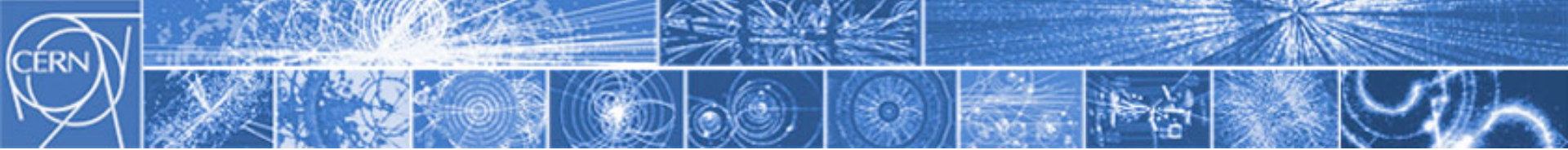


missing momentum,  
 interpreted as a neutrino



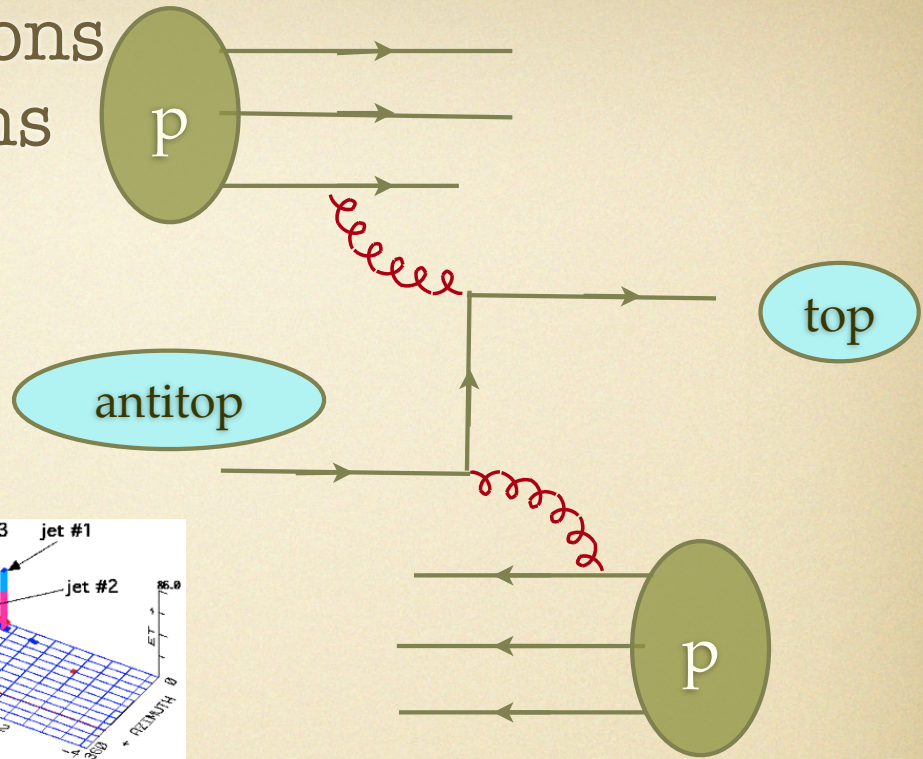
In principle the “force carrier” of new interactions could be created in the same way, provided their mass is not too large





# Examples of reactions in proton collisions

gluon-gluon reactions:  
 $gg \rightarrow top\ antitop$

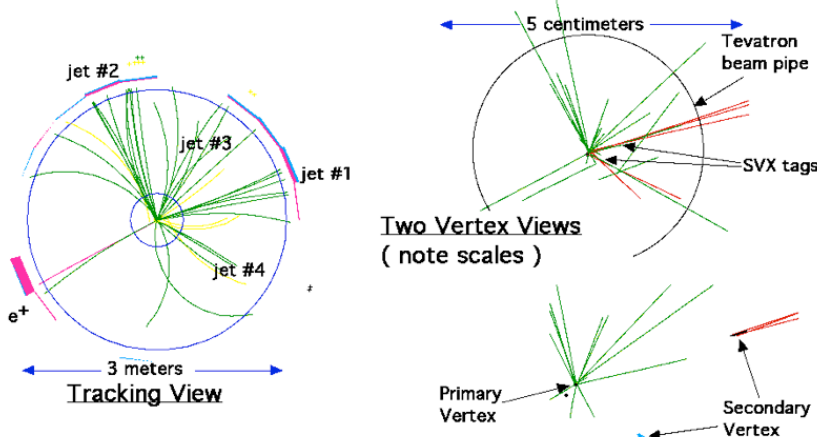
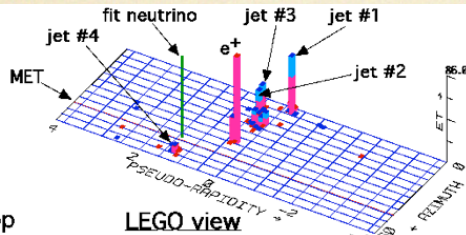


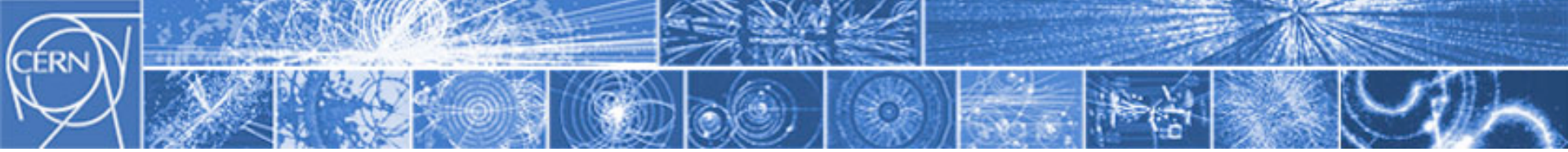
## $e + 4\text{ jet event}$

40758\_44414  
 24-September, 1992

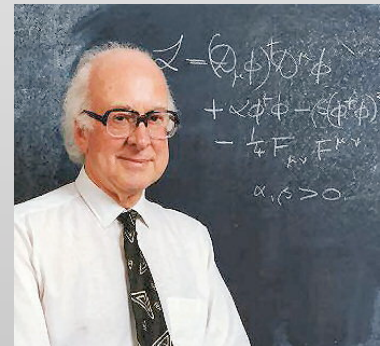
TWO jets tagged by SVX  
 fit top mass is  $170 \pm 10\text{ GeV}$

$e^+$ , Missing  $E_T$ , jet #4 from top  
 jets 1,2,3 from top ( 2&3 from W )

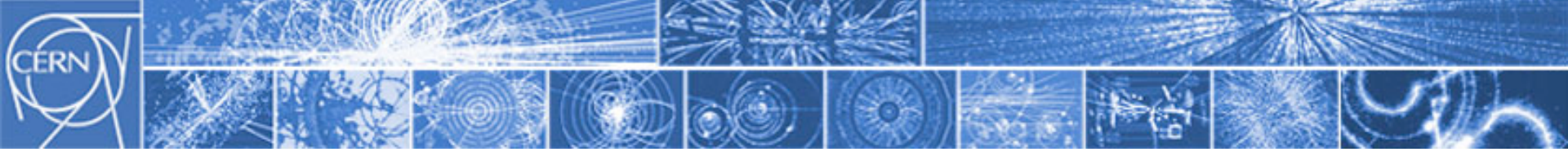




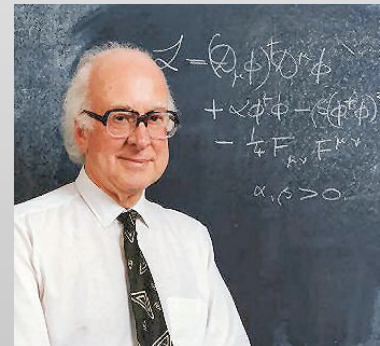
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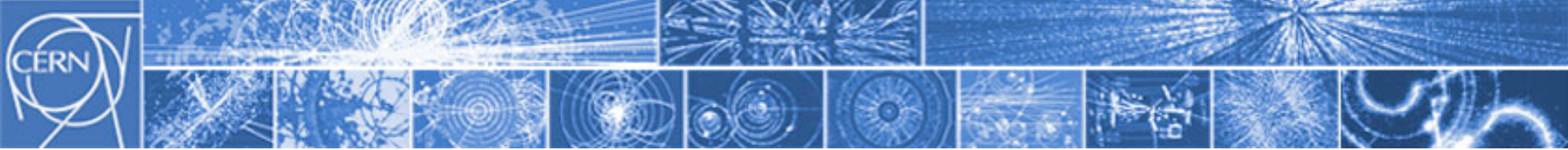






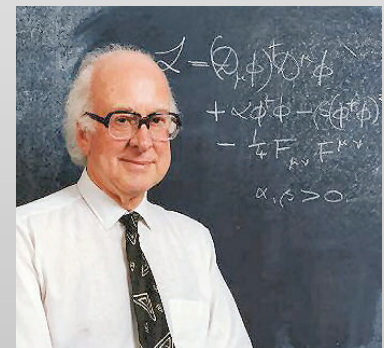
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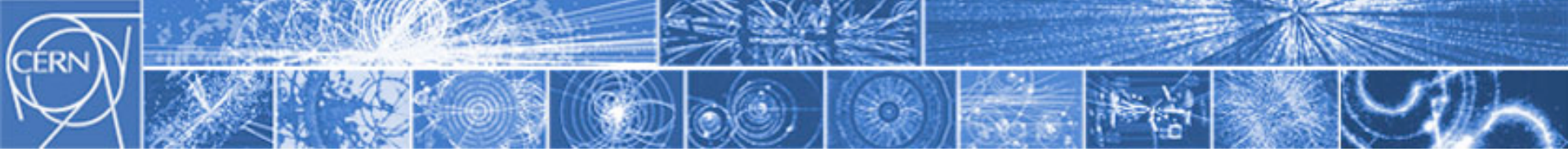




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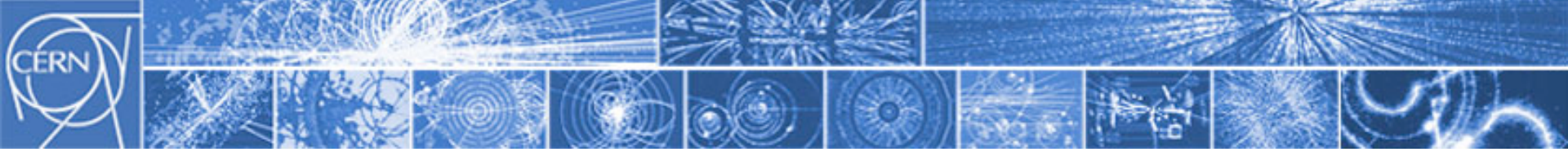
Englert-Brout-Higgs-Guralnik-Hagen-Kibble



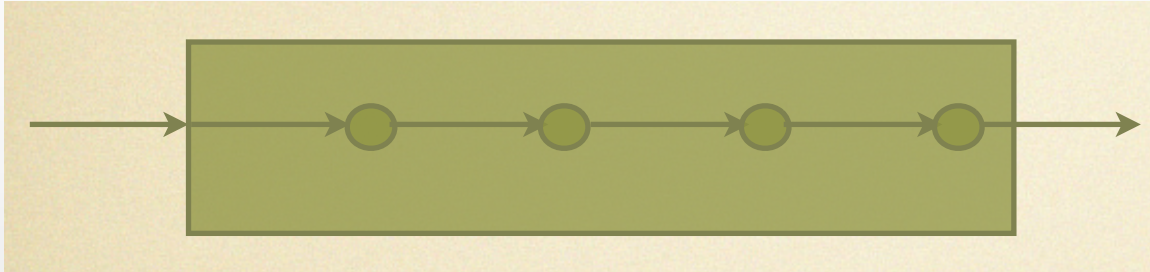


“perche' una certa particella ha massa  $m$ ?”

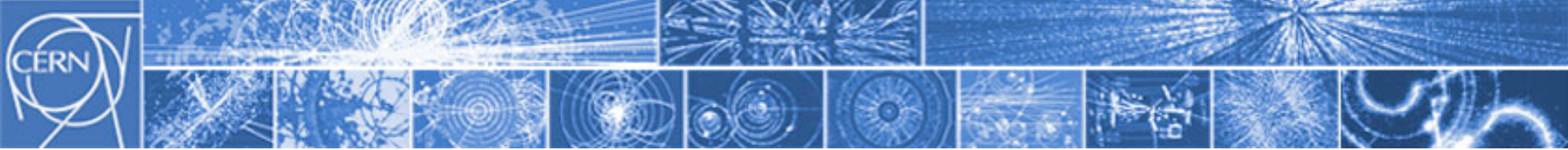




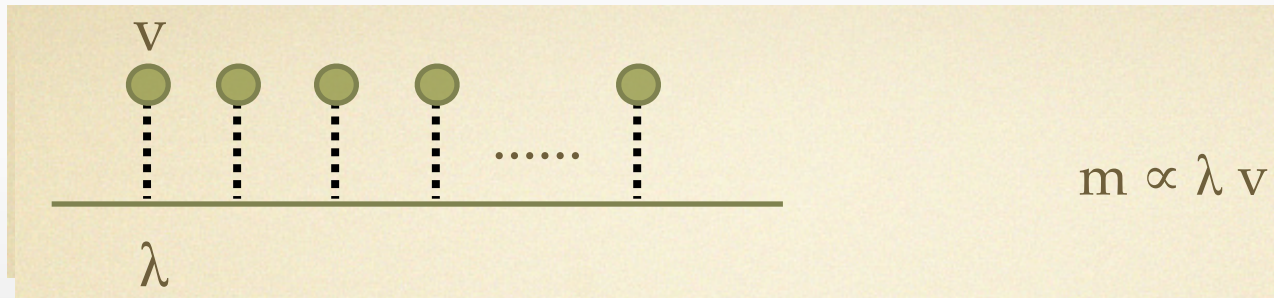
“perche' una certa particella ha massa  $m$ ?”



Il campo di Higgs e' come un mezzo continuo in cui l'universo e' immerso. Le particelle, interagendo con esso, acquistano l'inerzia caratteristica delle particelle con massa.



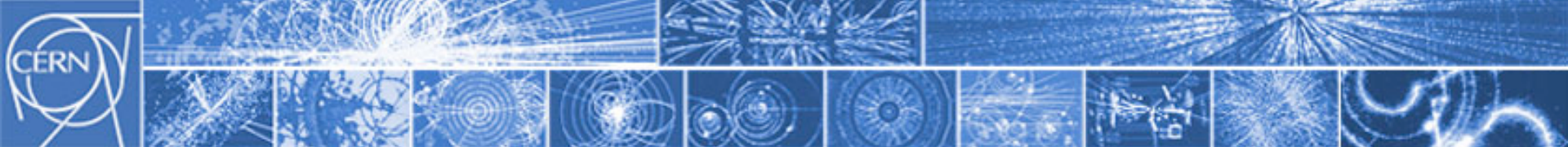
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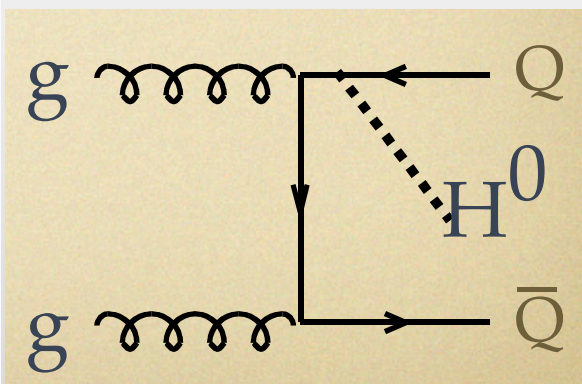
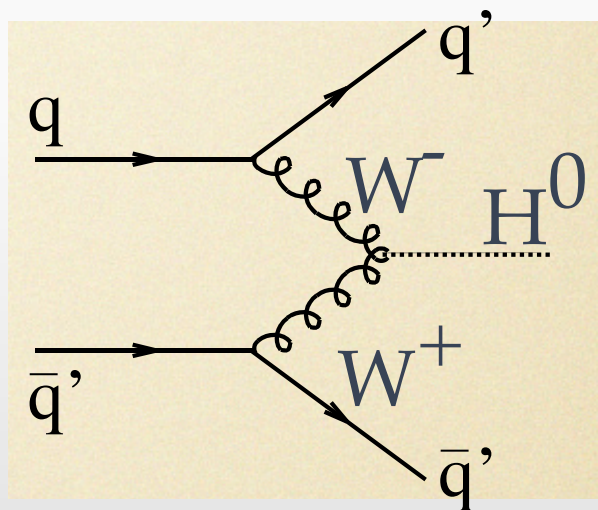
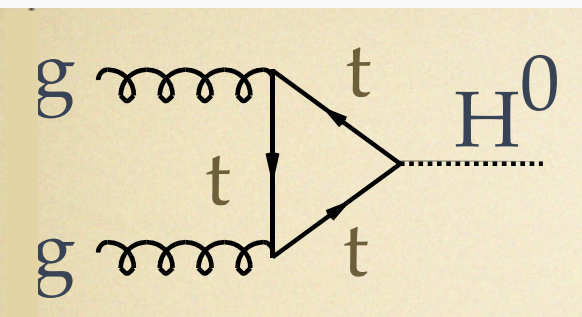
Ora la domanda “perche’ una certa particella ha massa  $m$ ?”  
e’ rimpiazzata da “perche’ una certa particella si accoppia  
al campo di Higgs con intensita’  $\lambda \propto m / v$ ?”

Le ‘onde’ del campo di Higgs sono una particella:  
la particella di Higgs (bosone).

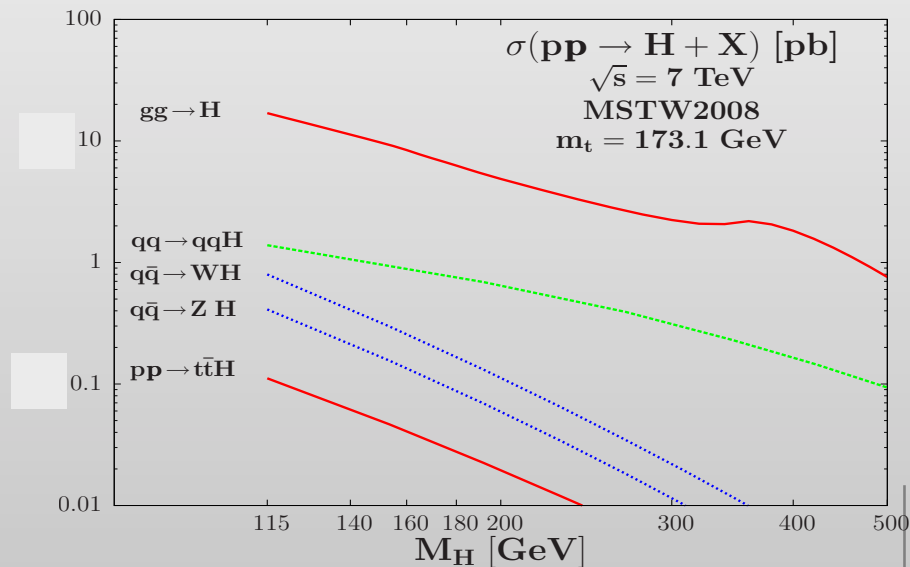
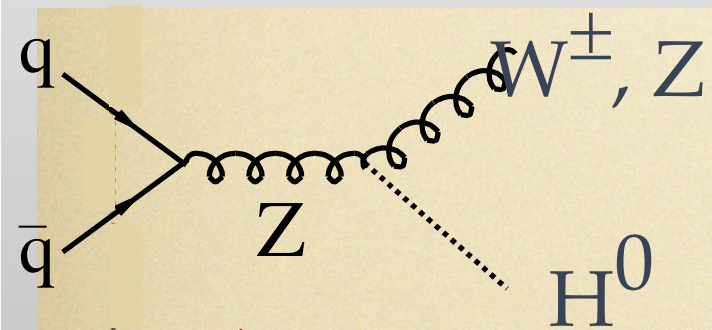




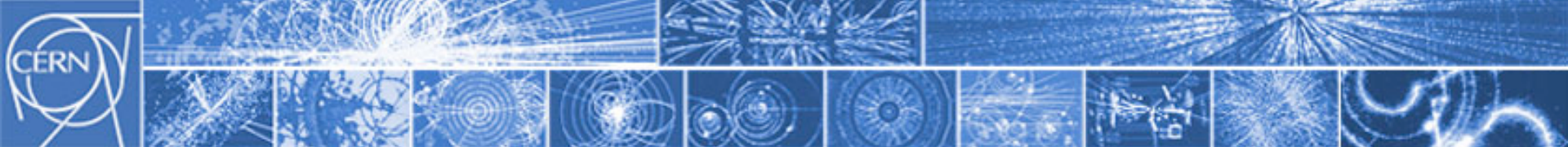
# Produzione del bosone di Higgs a un collider



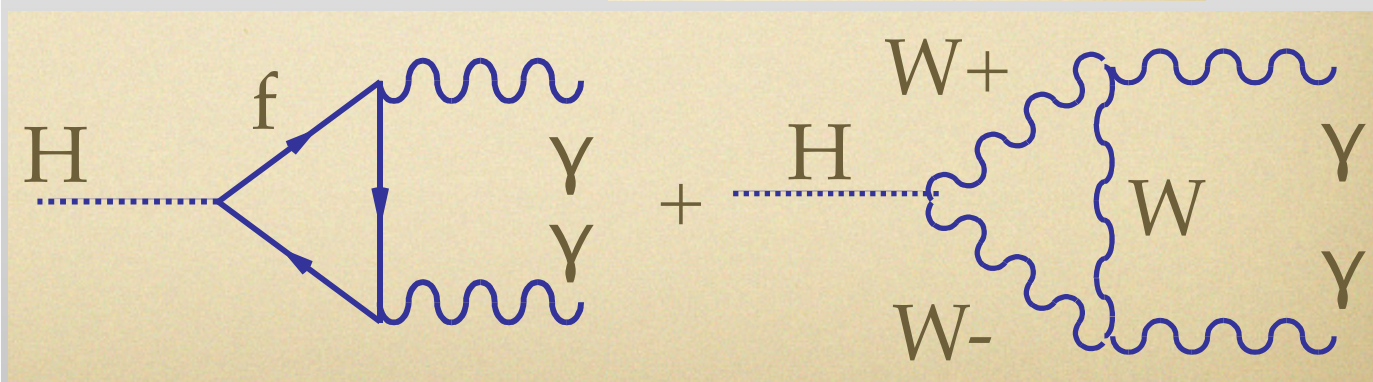
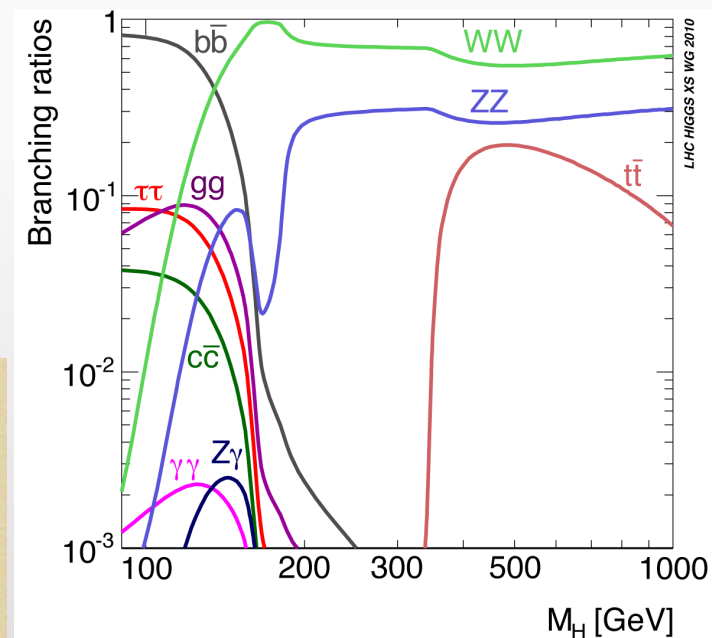
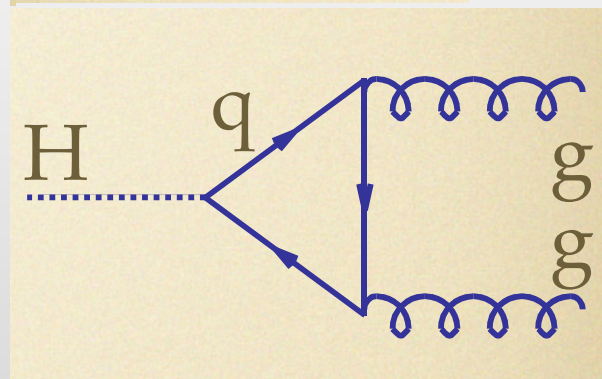
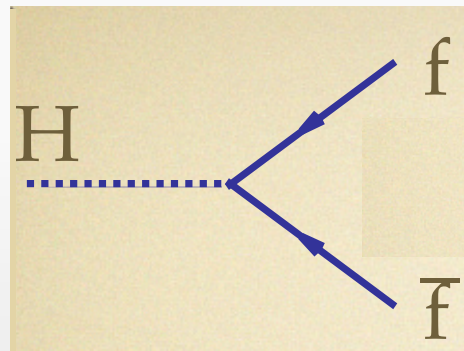
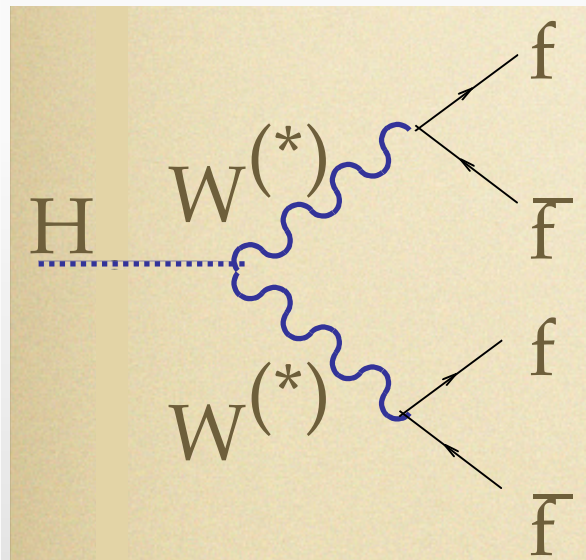
*Diagrammi di Feynman*



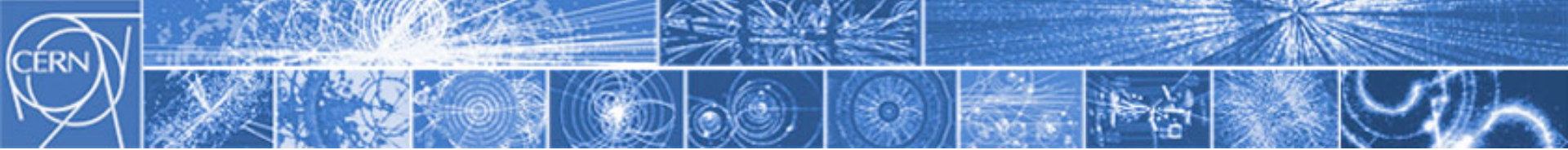




# Decadimento del bosone di Higgs

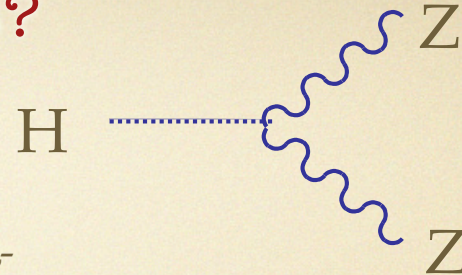




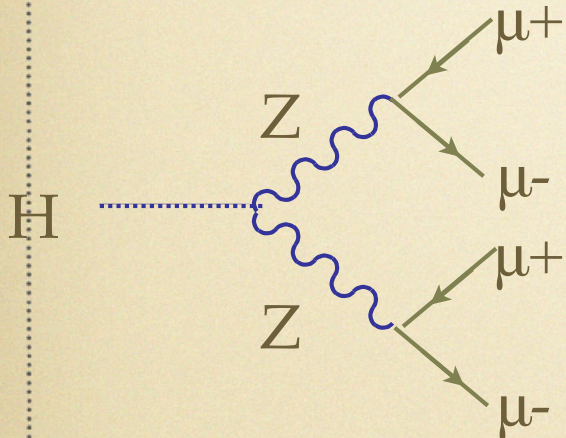


# How can we detect the Higgs?

**Example:** If  $m(H) > 2 m(Z) \Rightarrow H \rightarrow ZZ$



Each Z will decay. Assume for example  $Z \rightarrow \mu^+ \mu^-$

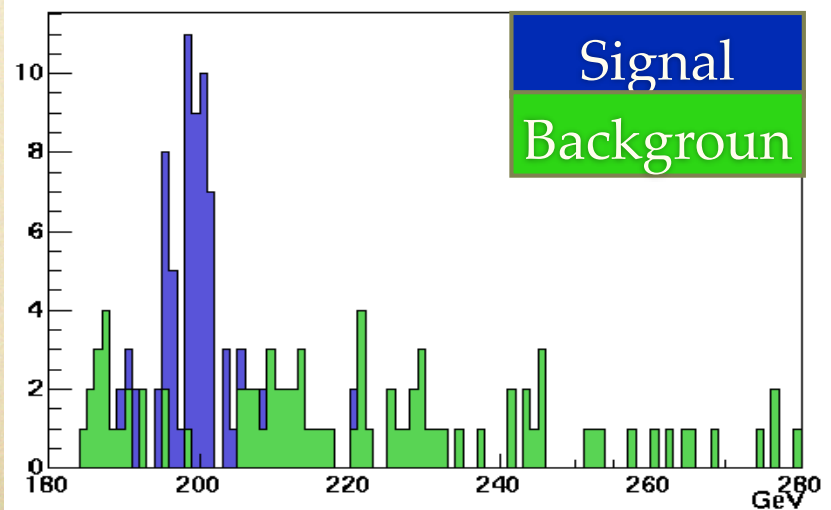


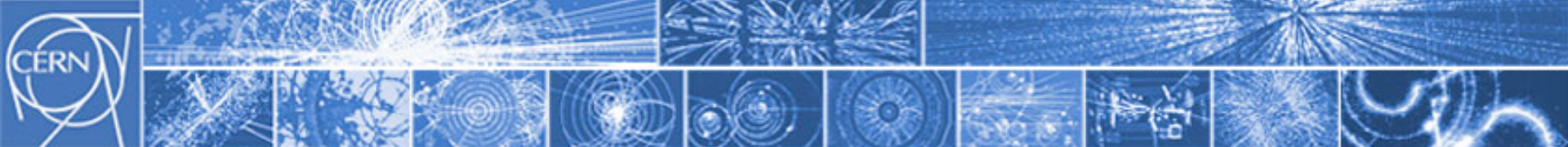
Search for events with 4 muons ( $\mu^+_1 \mu^-_2 \mu^+_3 \mu^-_4$ ) subject to the condition that:

$$m(\mu^+_1 \mu^-_2) = m(\mu^+_3 \mu^-_4) = m(Z)$$

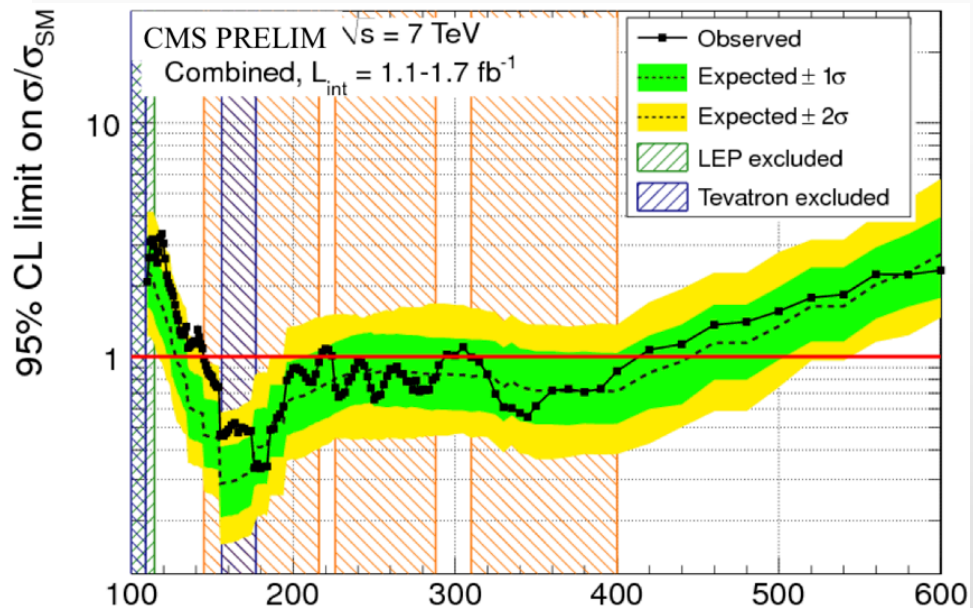
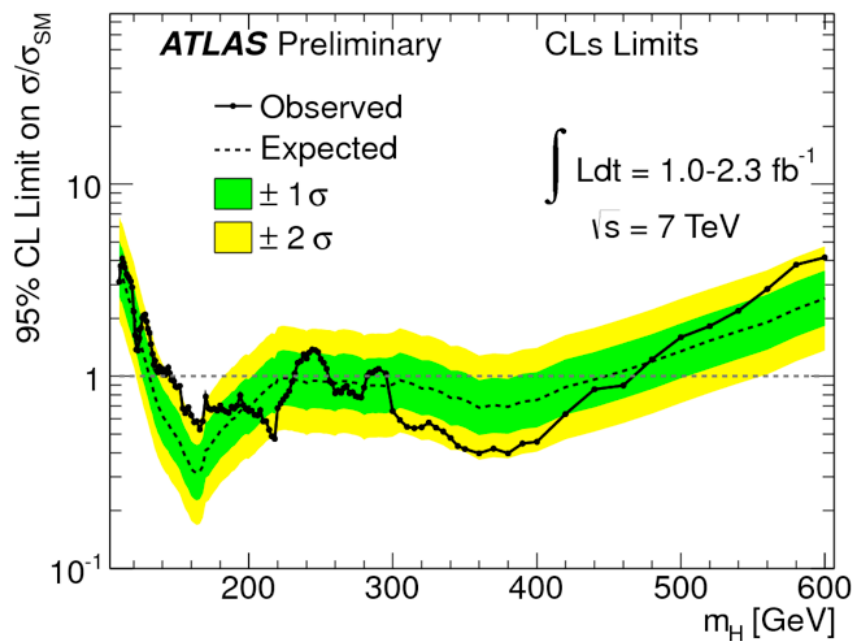
The invariant mass of the 4-muon system will then give  $m(H)$

A computer simulation of how the signal will appear, for  $m_H = 200$  GeV

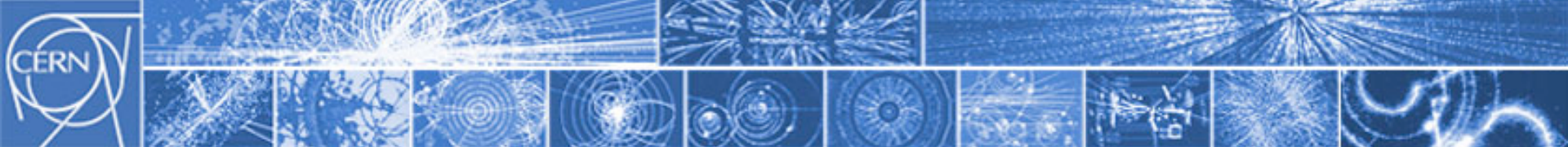




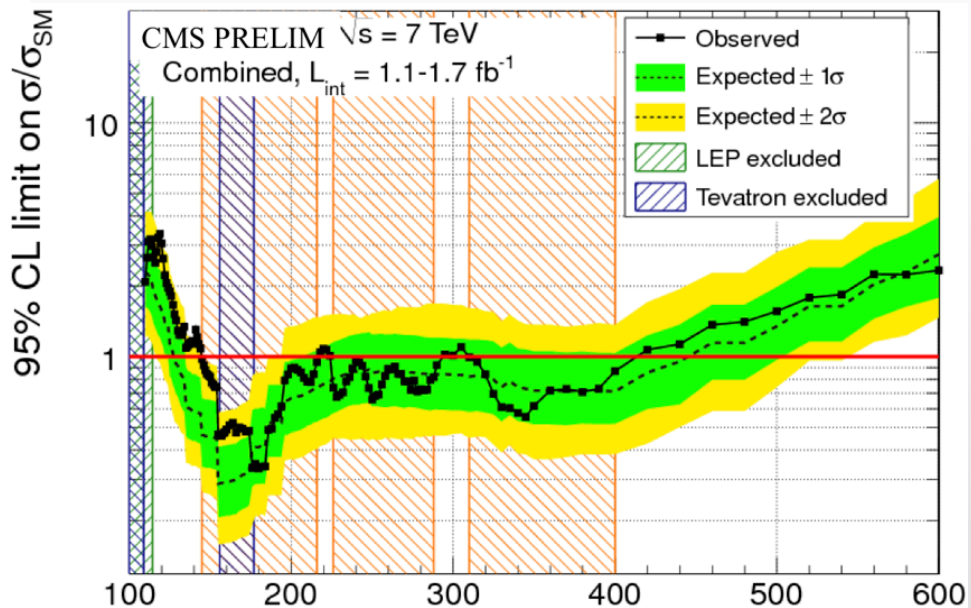
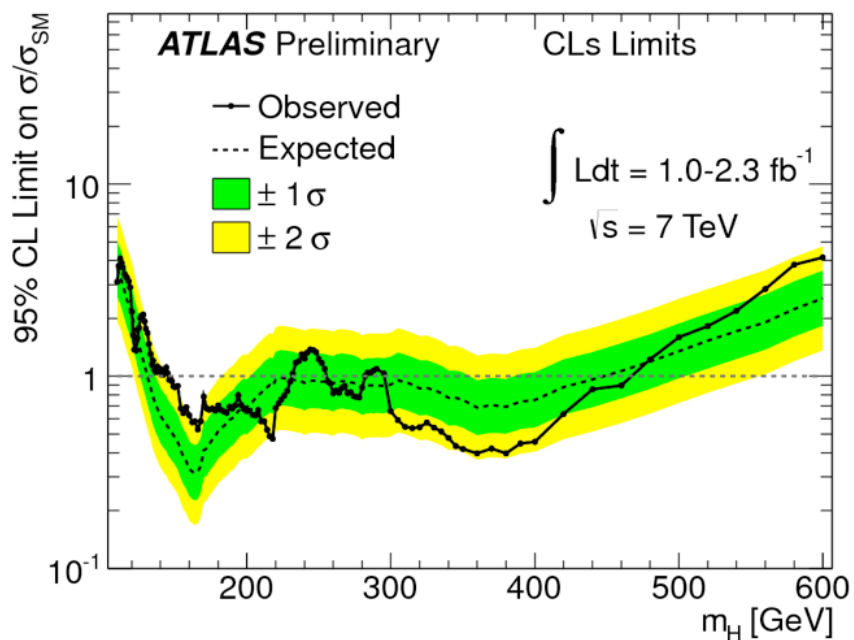
# Status: *Lepton-Photon 2011* a Mumbai





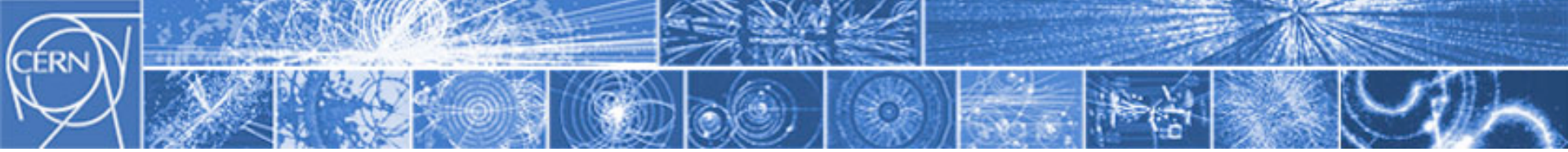


# Status: *Lepton-Photon 2011* a Mumbai



Insomma:

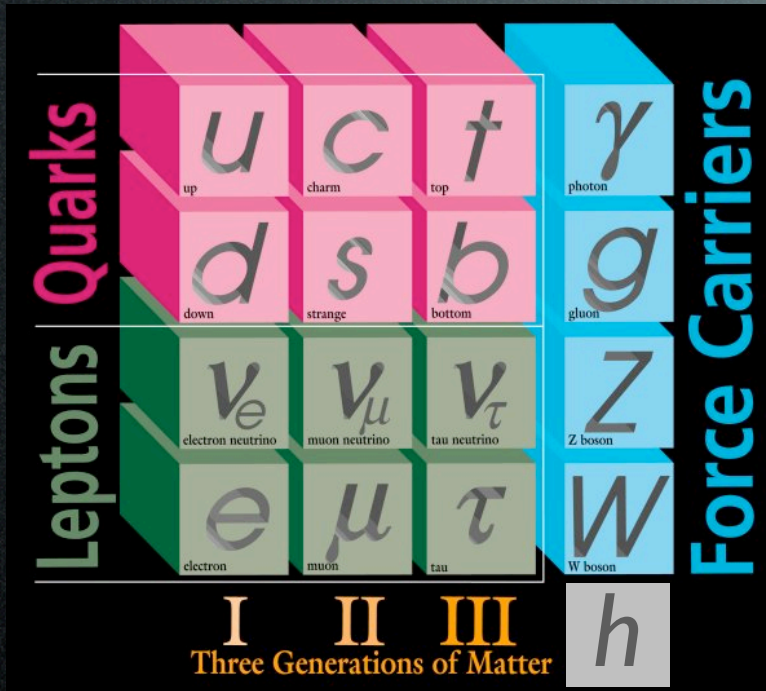
- Standard Model higgs **escluso** nel range  $145 \text{ GeV} < m_h < 466 \text{ GeV}$  (e  $m_h < 115 \text{ GeV}$ )
- entro l'inizio del 2012 copriremo anche l'ultima finestra (115-145)



# SuperSymmetry (SuSy)

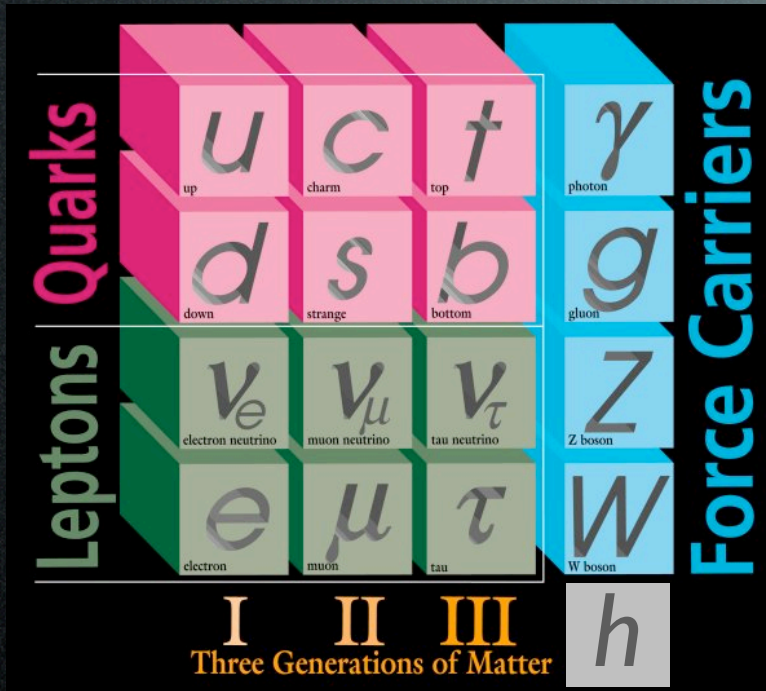


# SuSy in 2 minutes





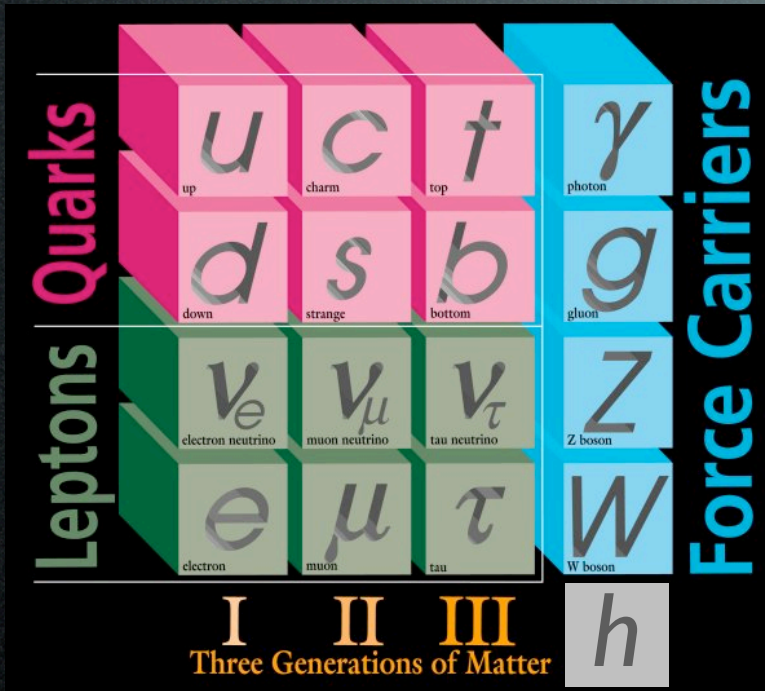
# SuSy in 2 minutes



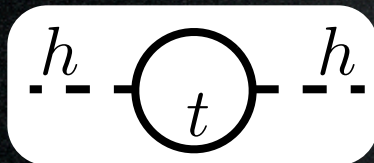
$$m_h \approx 150 \text{ GeV}$$



# SuSy in 2 minutes



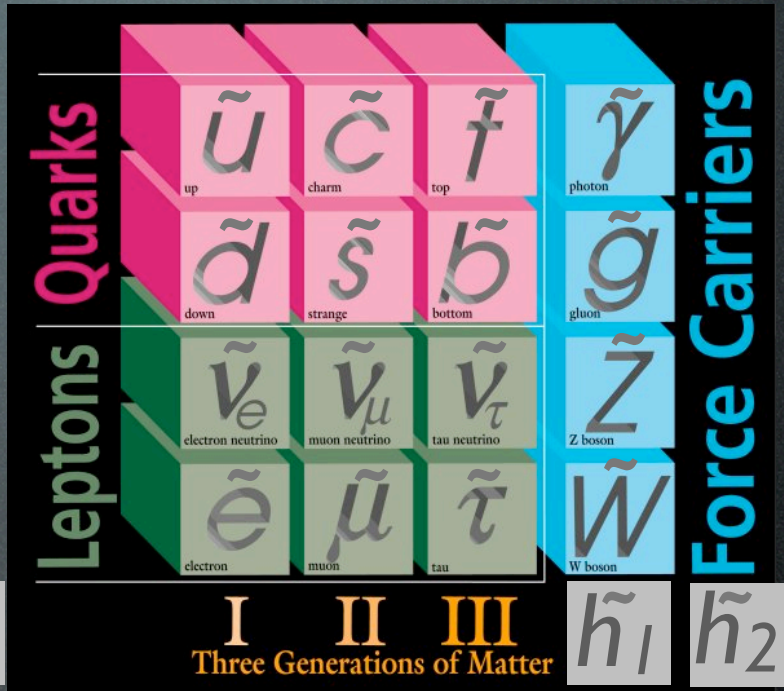
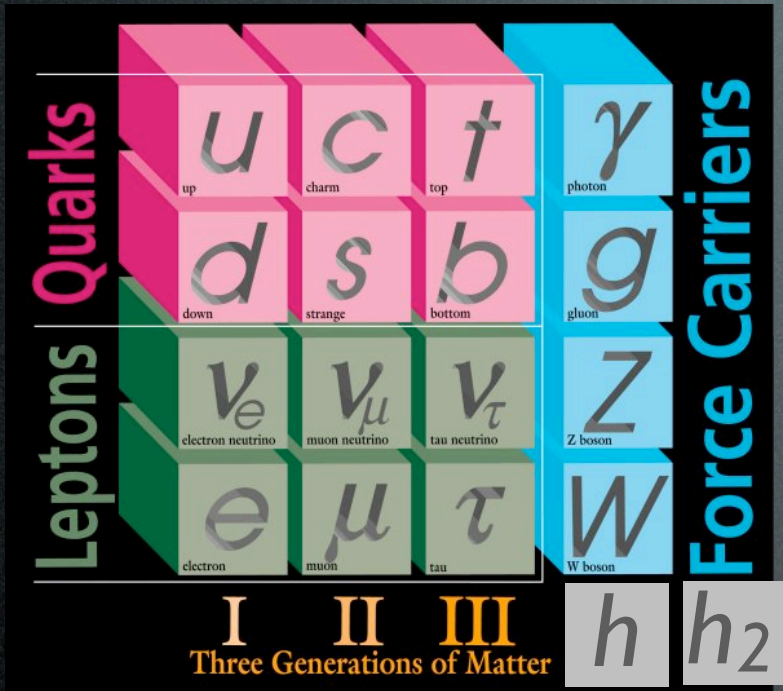
$$m_h \approx 150 \text{ GeV}$$



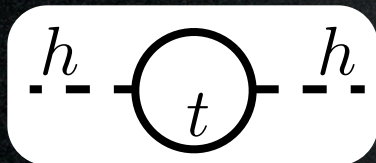
$$\Delta m_h \propto 10^{19} \text{ GeV}$$



# SuSy in 2 minutes



$$m_h \approx 150 \text{ GeV}$$



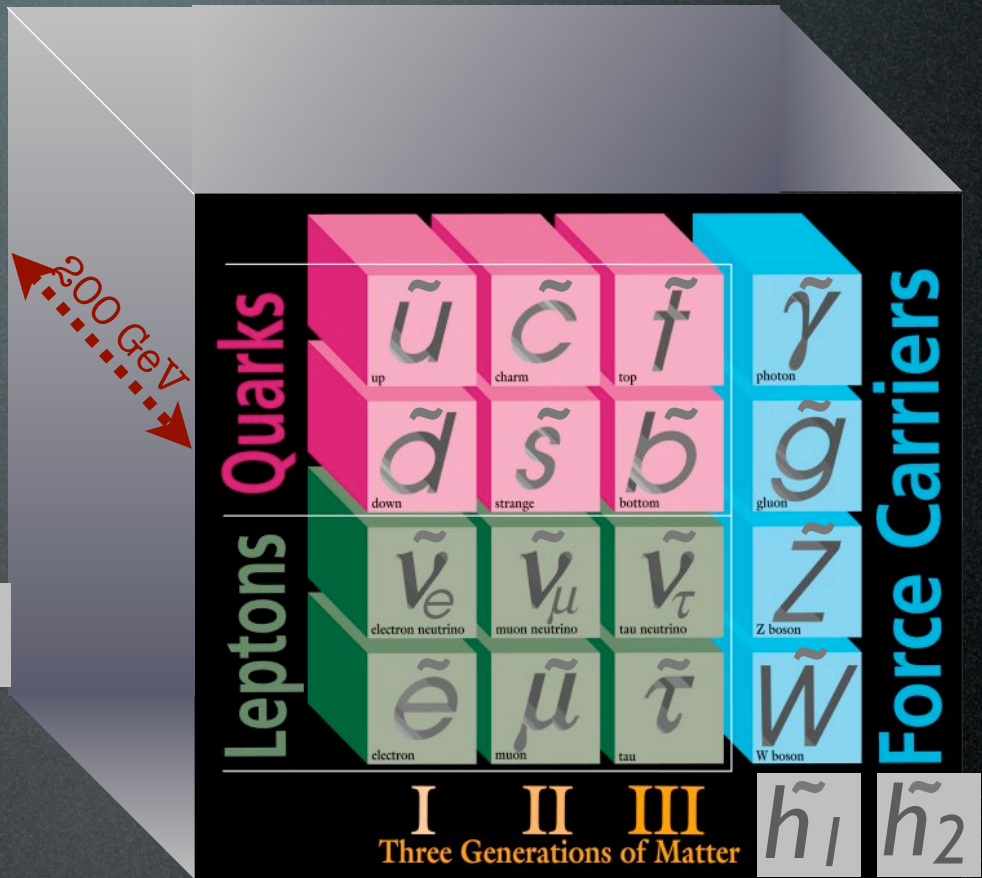
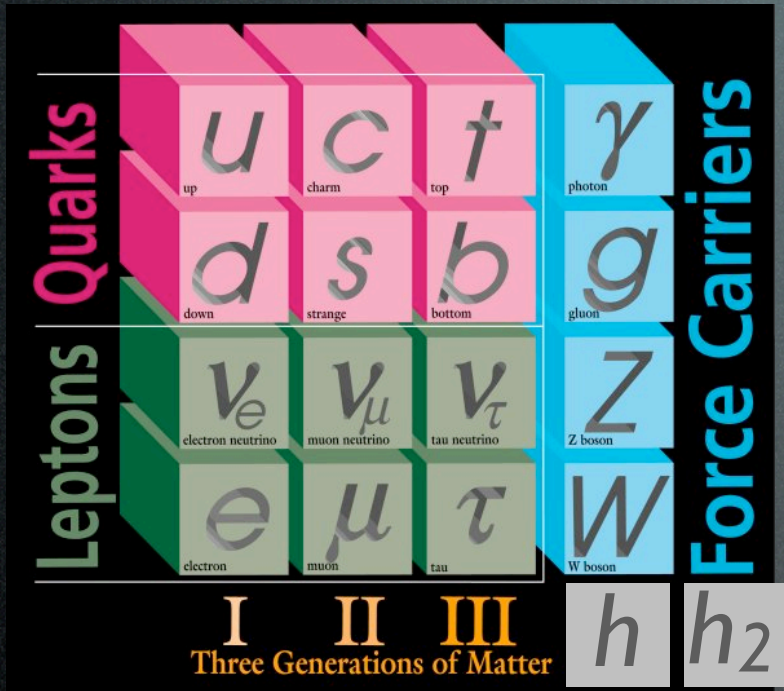
$$\Delta m_h \propto 10^{19} \text{ GeV}$$



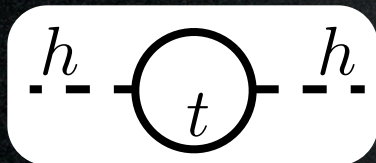
$$\Delta m_h \propto -10^{19} \text{ GeV}$$



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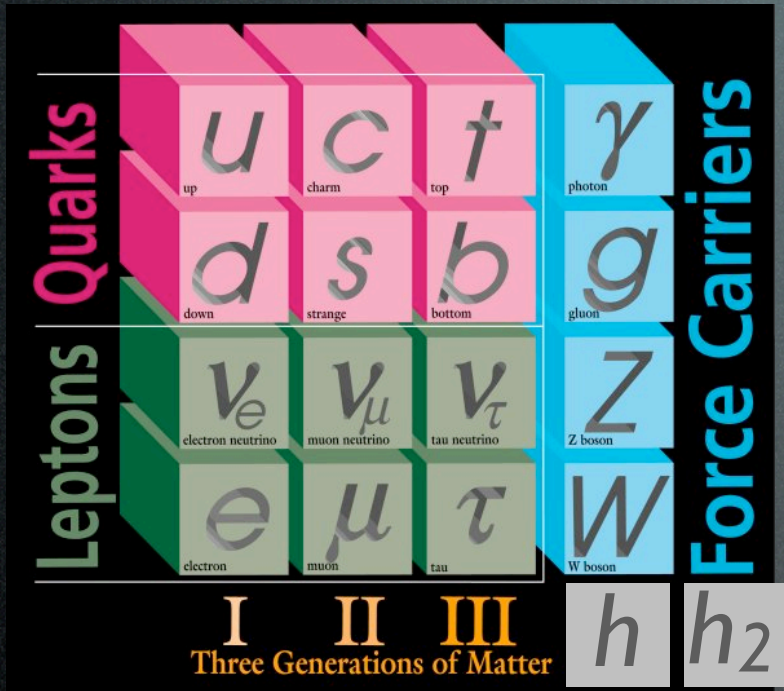
$$\Delta m_h \propto 10^{19} \text{ GeV}$$



$$\Delta m_h \propto -10^{19} \text{ GeV}$$

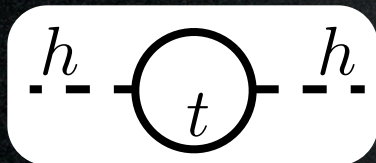


# SuSy in 2 minutes

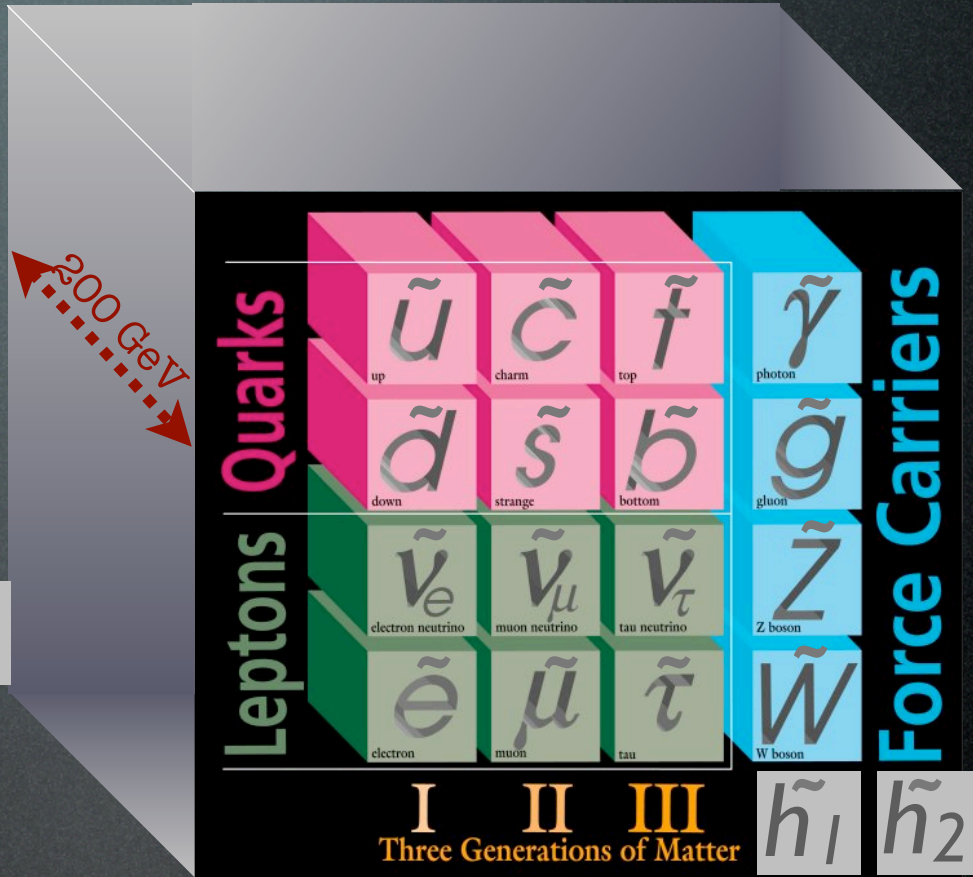


$$R = +1$$

$$m_h \approx 150 \text{ GeV}$$



$$\Delta m_h \propto 10^{19} \text{ GeV}$$



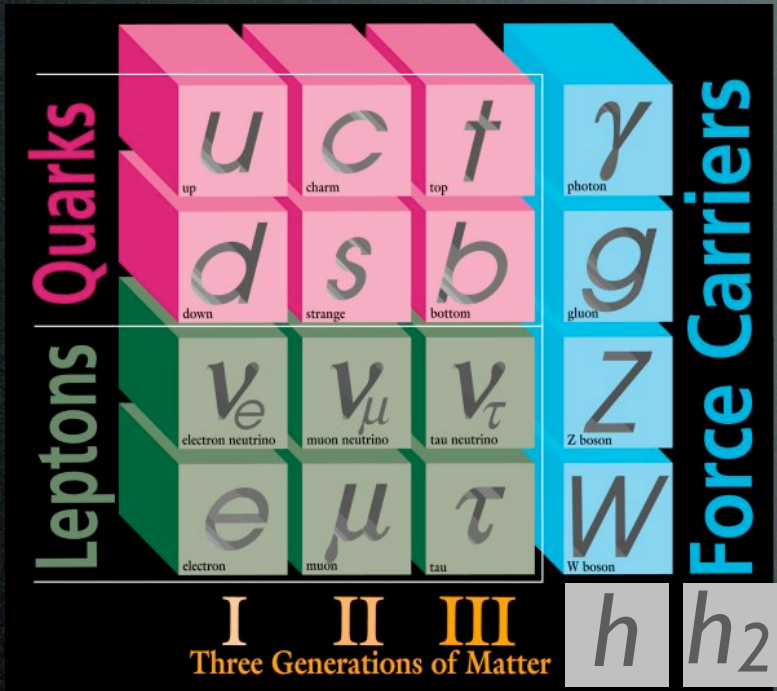
$$R = -1$$



$$\Delta m_h \propto -10^{19} \text{ GeV}$$



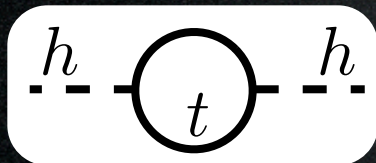
# SuSy in 2 minutes



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$$R = -1$$

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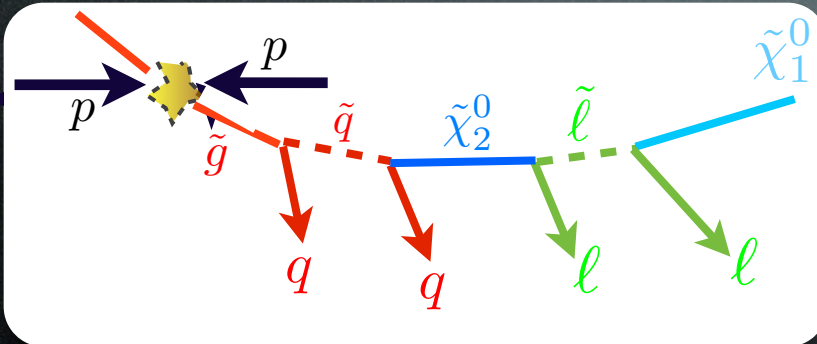
$$\Delta m_h \propto -10^{19} \text{ GeV}$$



# Production at colliders

## Search strategy 1:

look for decay subproducts of particles in the same theory



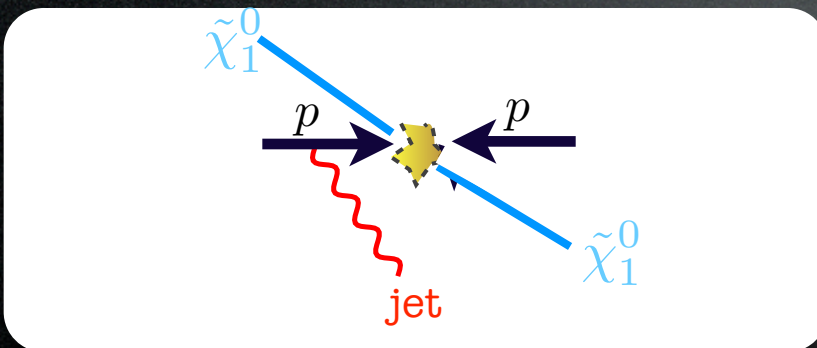
- well studied ( $M_T^2$ ..)
- model dependent

‘trigger on 4j+4l+MET...’

huge literature

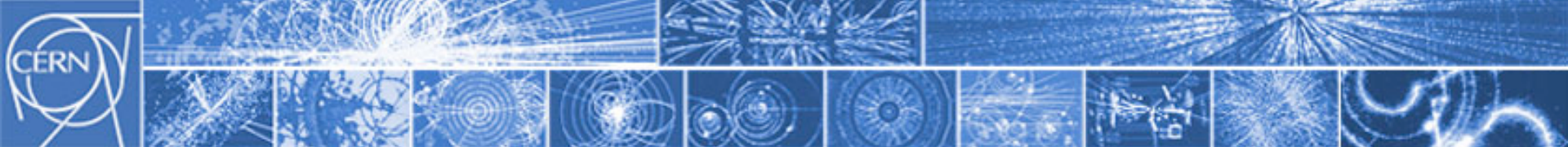
## Search strategy 2: ‘monojets’

e.g. J.Goodman et al., 1008.1783

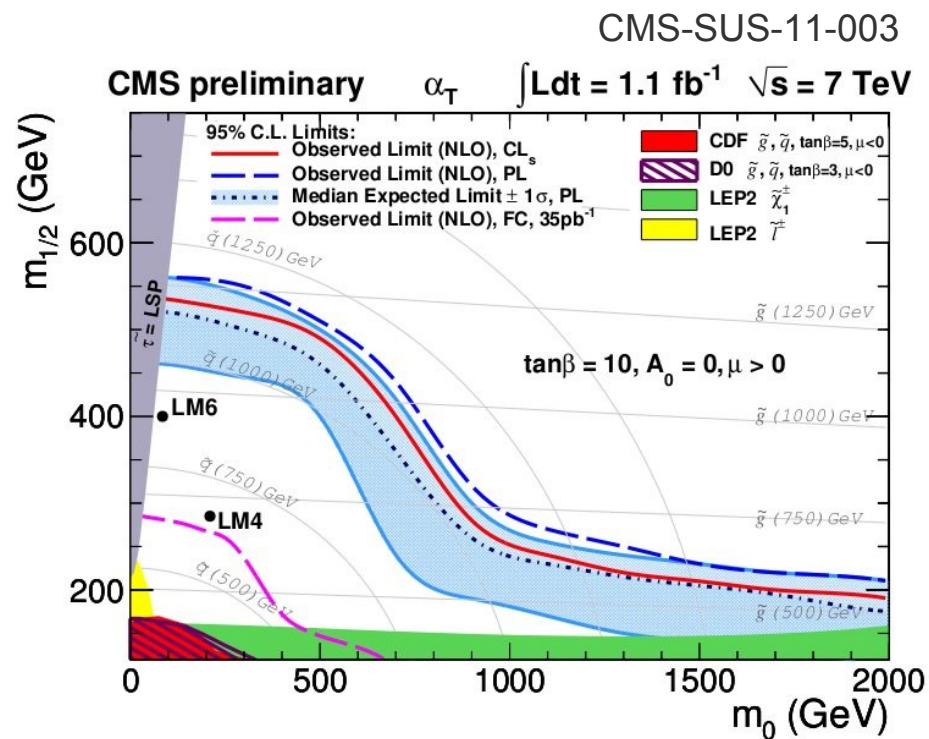
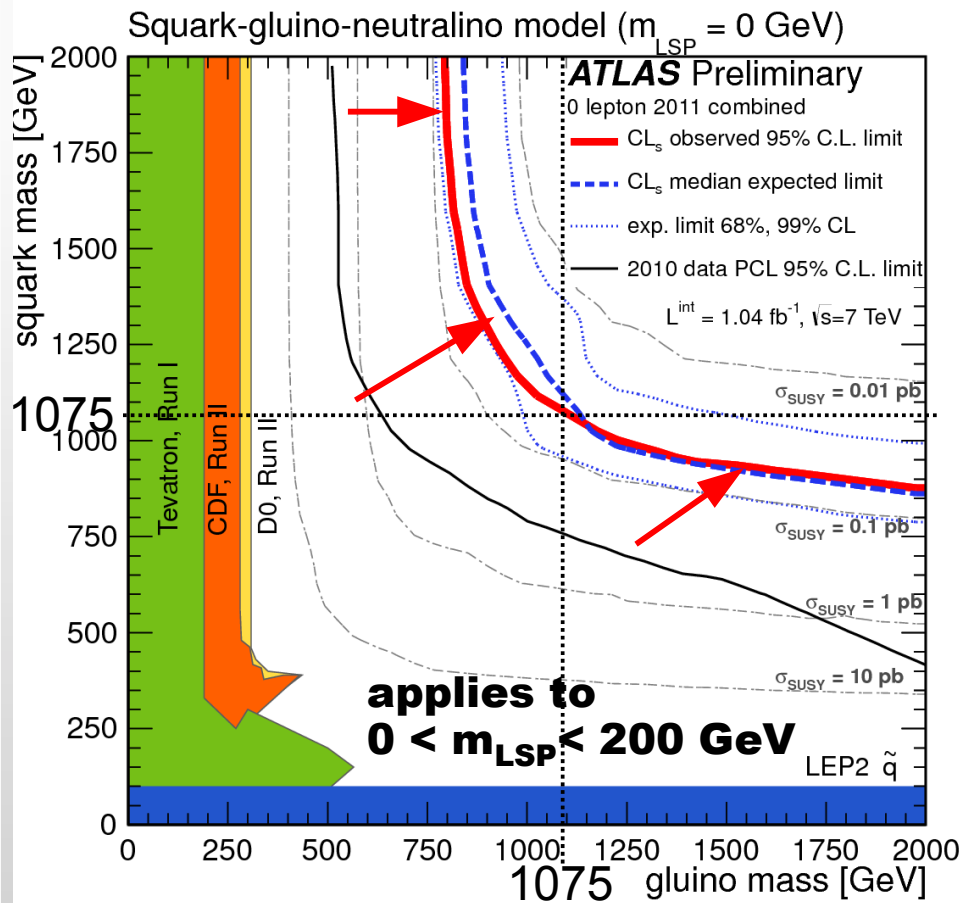


- ‘new’
- more model independent

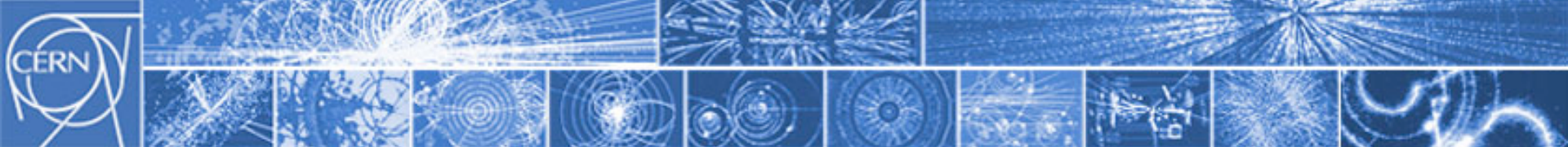




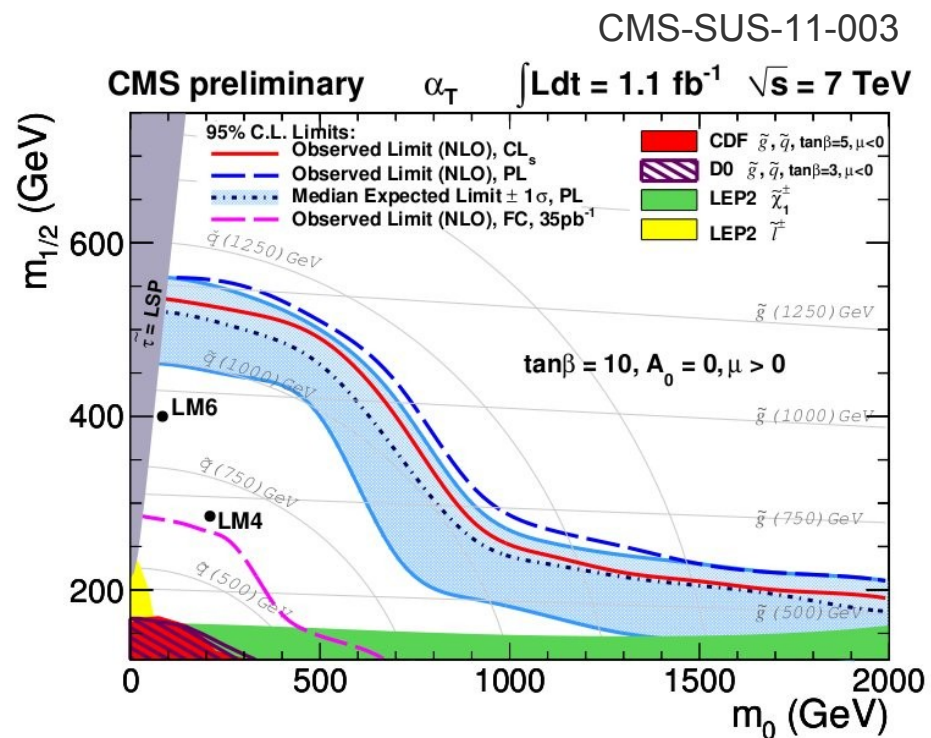
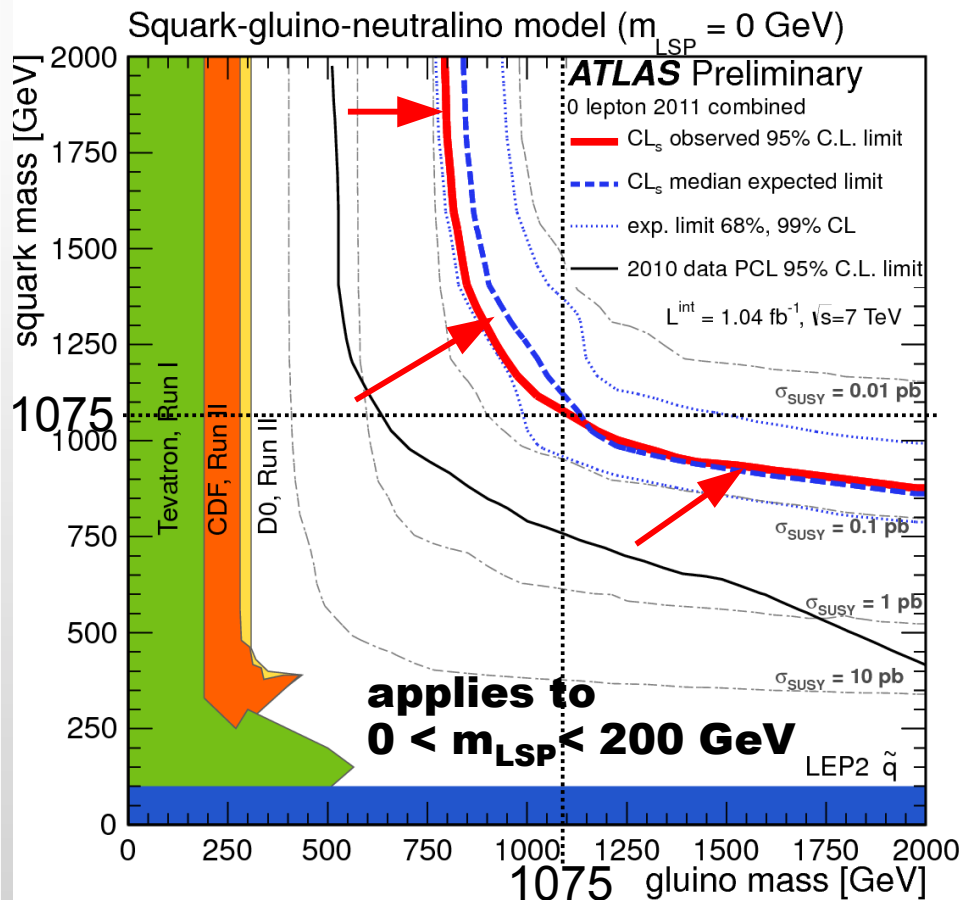
# Status: *Lepton-Photon 2011* a Mumbai





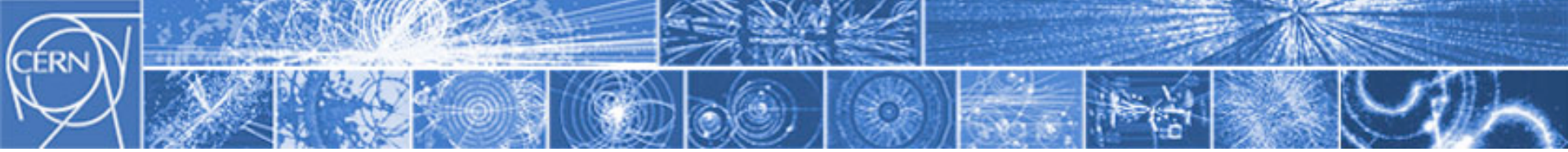


# Status: *Lepton-Photon 2011* a Mumbai



Insomma:

- particelle SuSy **escluse** fino circa 1 TeV
- o sister, where art thou?



# **Materia Oscura** *(Dark Matter)*

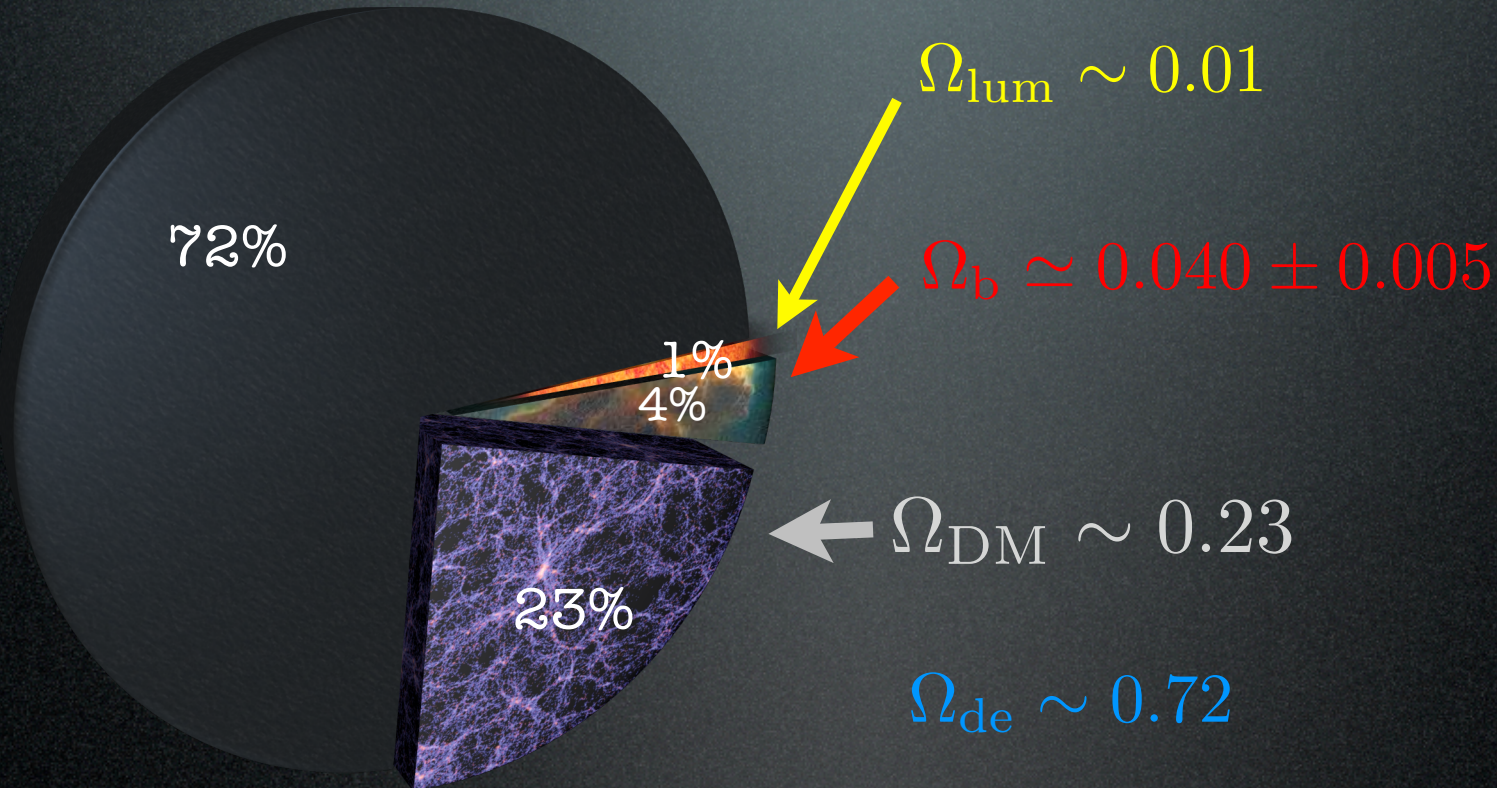


What is the Universe  
made of?



# The cosmic inventory

Most of the Universe is Dark



$$\left( \Omega_x = \frac{\rho_x}{\rho_c}; \text{CMB first peak} \Rightarrow \Omega_{\text{tot}} = 1 \text{ (flat)}; \text{HST } h = 0.71 \pm 0.07 \right)$$



How do we know that  
Dark Matter is out there?



# The Evidence for DM

## 1) galaxy rotation curves

$$m \frac{v_c^2(r)}{r} = \frac{G_N m M(r)}{r^2}$$

'centrifugal'      'centripetal'

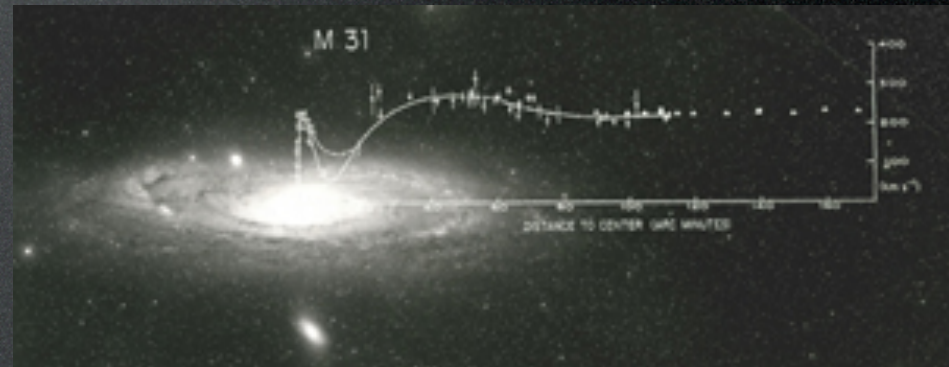
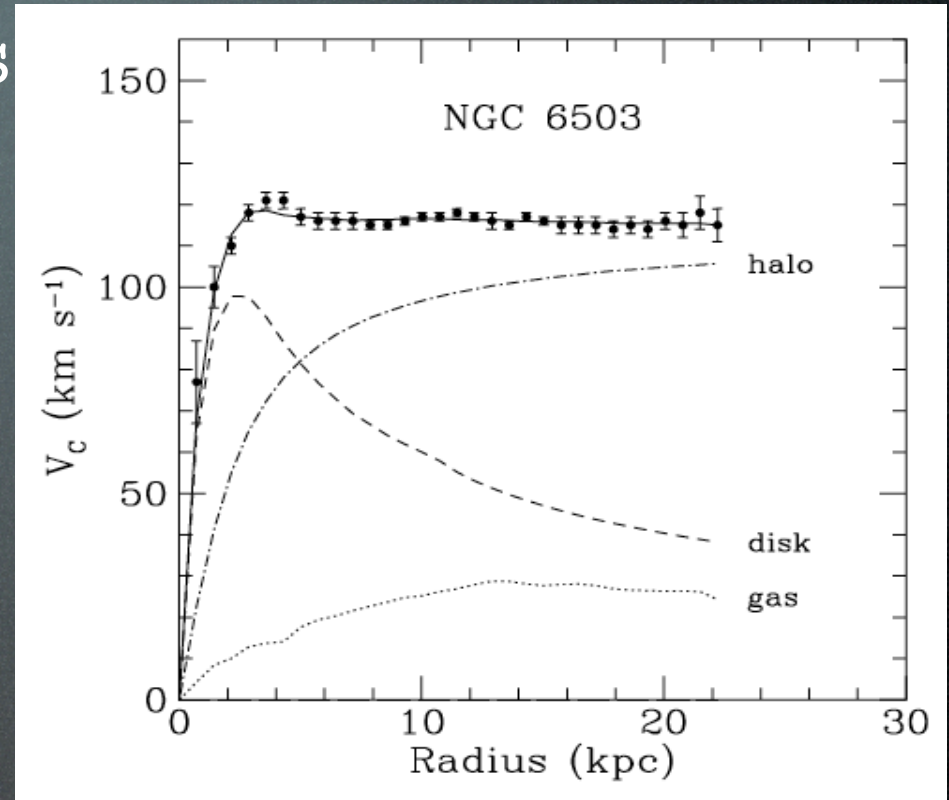
$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

with  $M(r) = 4\pi \int \rho(r) r^2 dr$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$



$$\Omega_M \gtrsim 0.1$$





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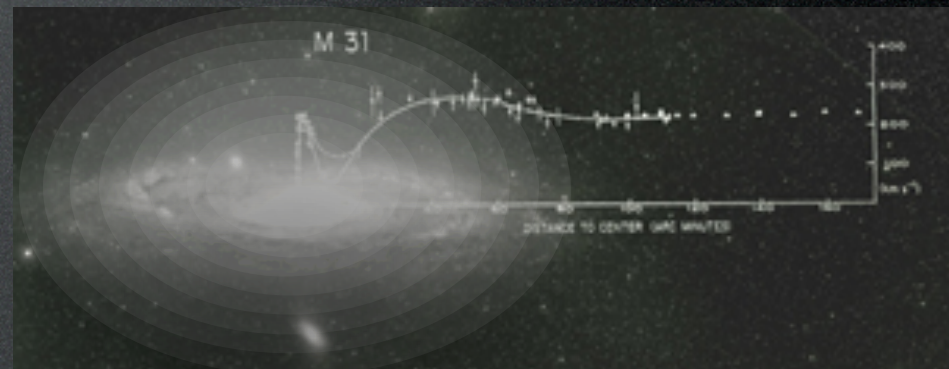
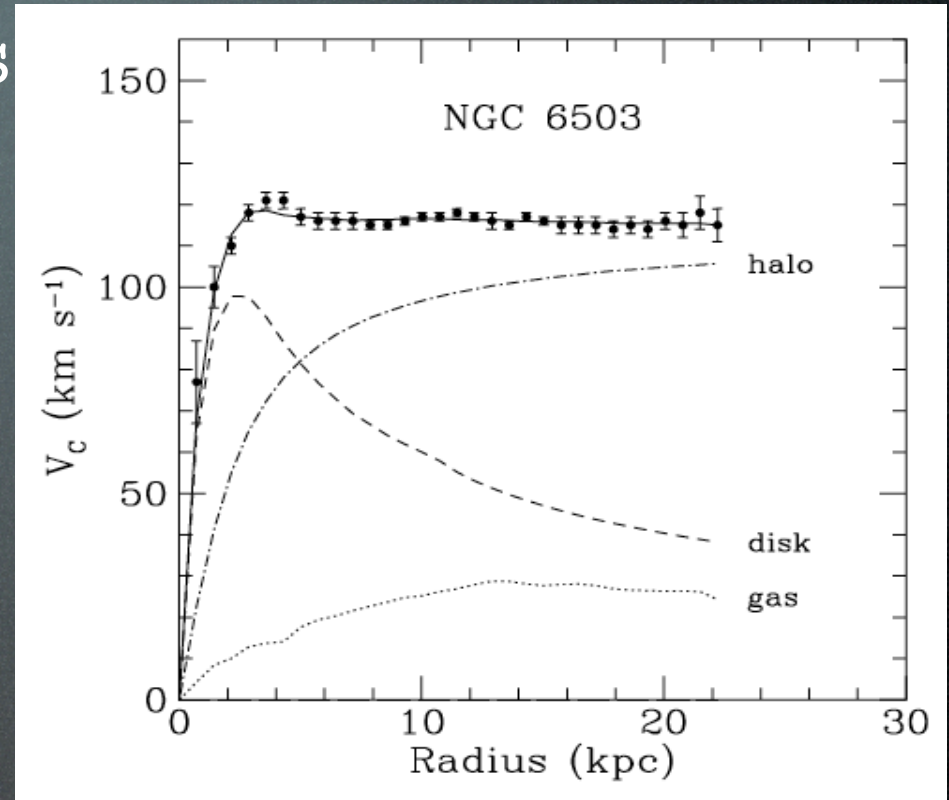
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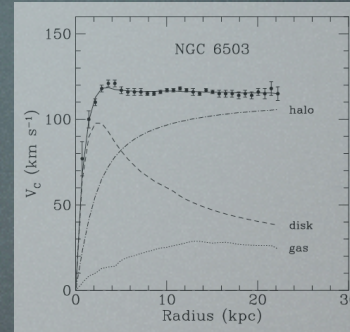
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# The Evidence for DM

1) galaxy rotation curves



$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies

- “rotation curves”
- gravitation lensing



$$\Omega_M \sim 0.2 \div 0.4$$



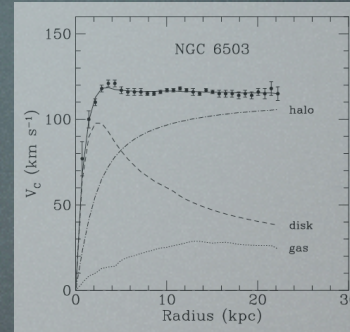
“bullet cluster” - NASA  
astro-ph/0608247

[further developments]



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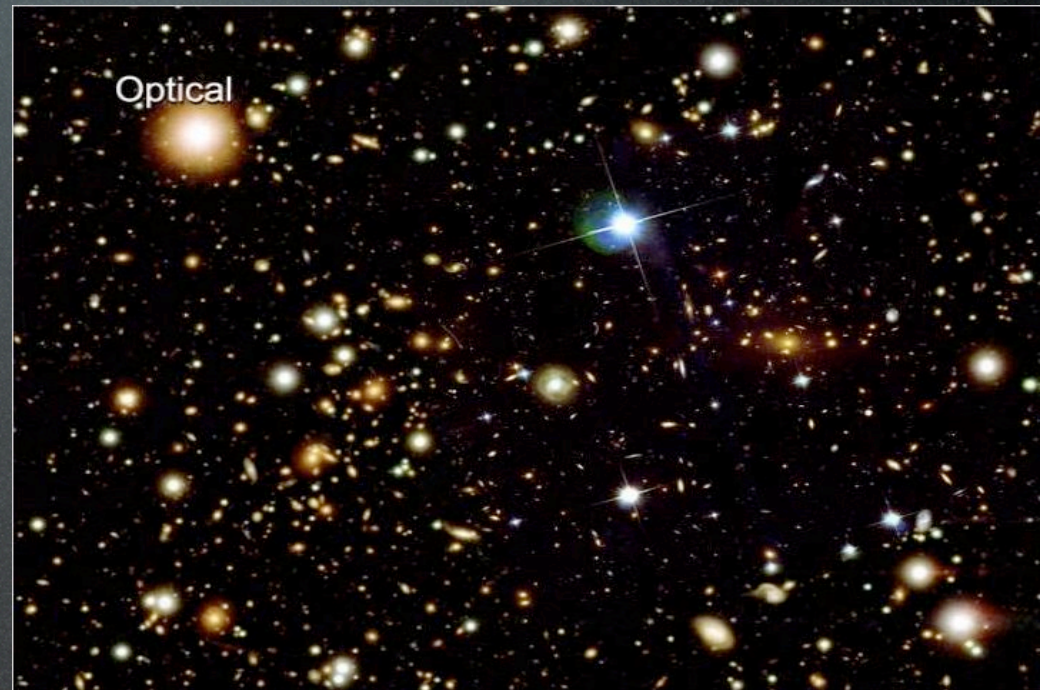
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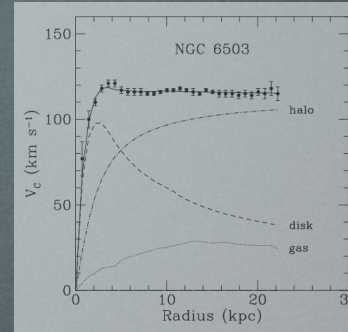
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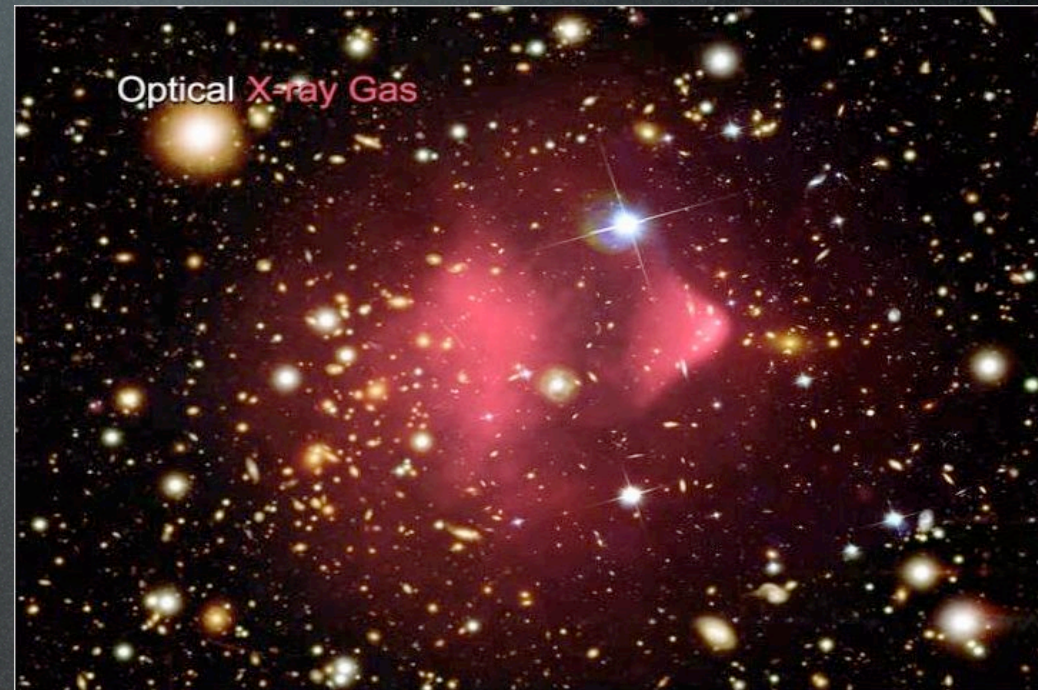
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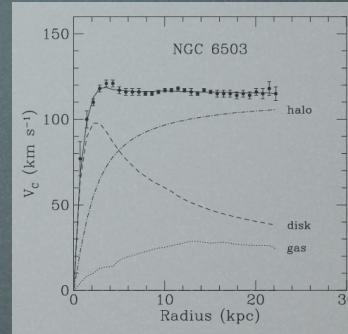
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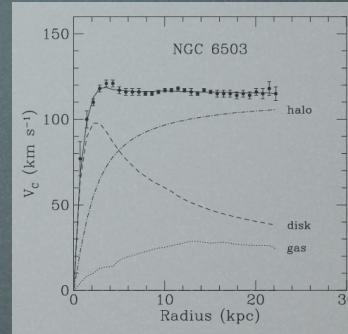
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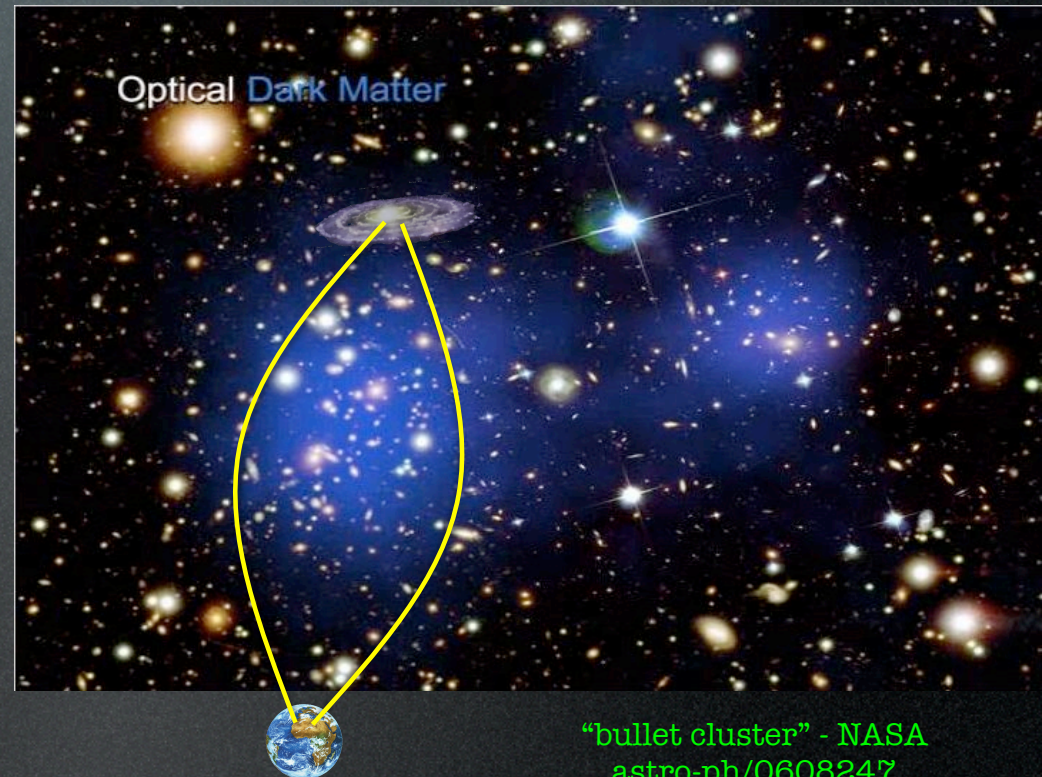
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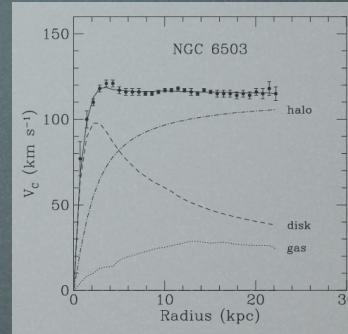
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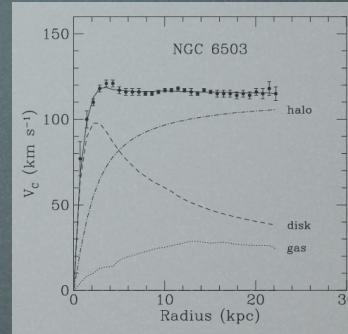
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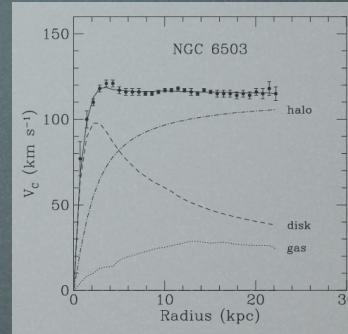
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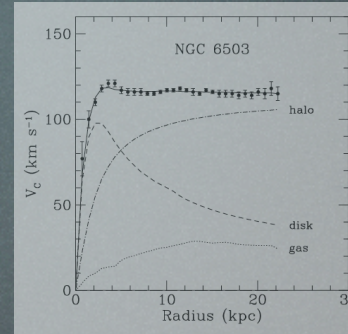


ring of Dark Matter (2007)



# The Evidence for DM

1) galaxy rotation curves



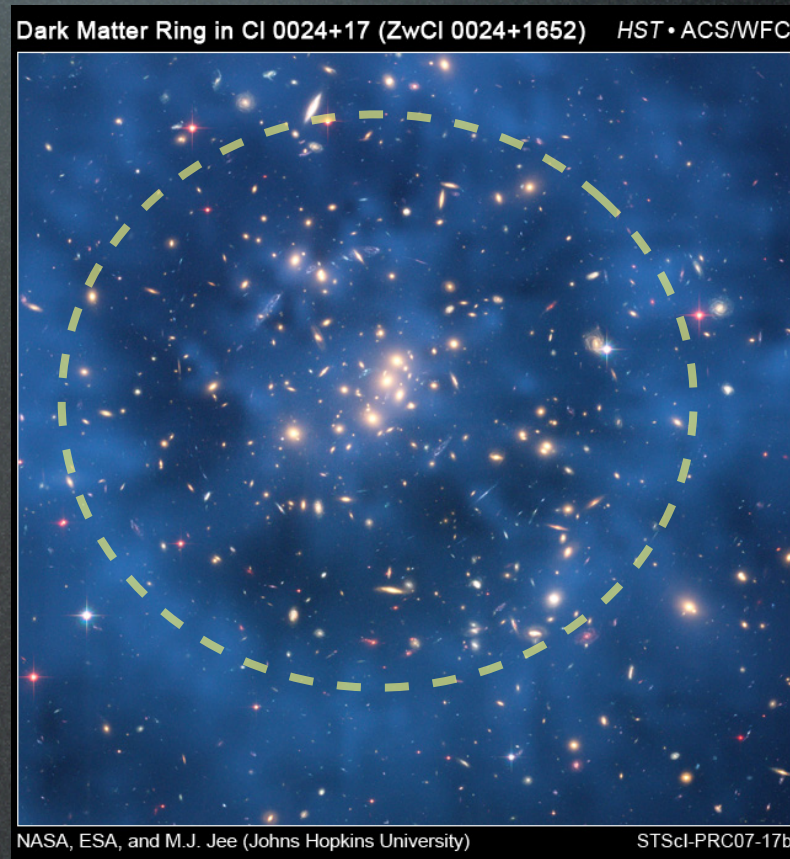
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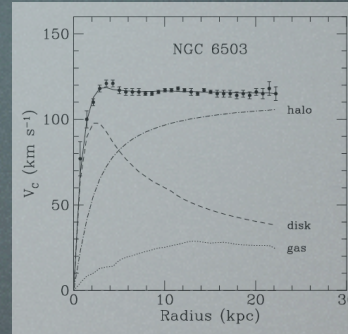


ring of Dark Matter (2007)



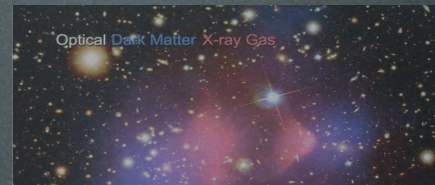
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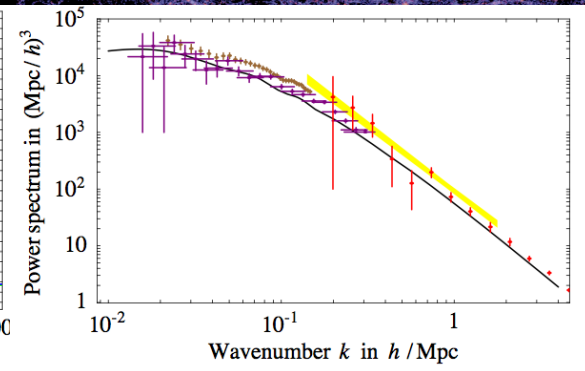
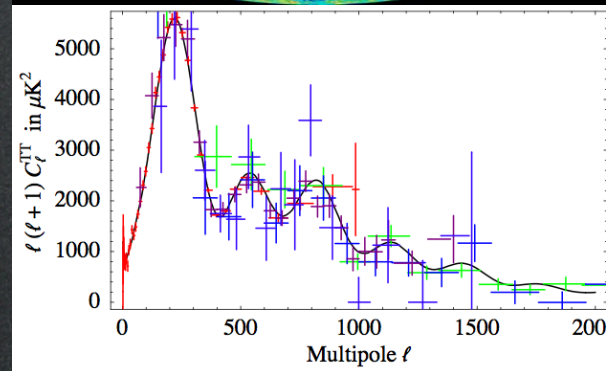
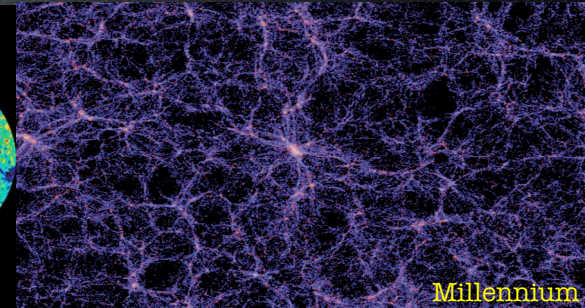
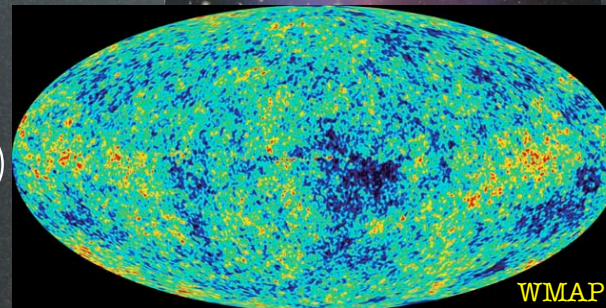
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2) clusters of galaxies



$$\Omega_M \sim 0.2 \div 0.4$$

3) CMB+LSS(+SNIa:)





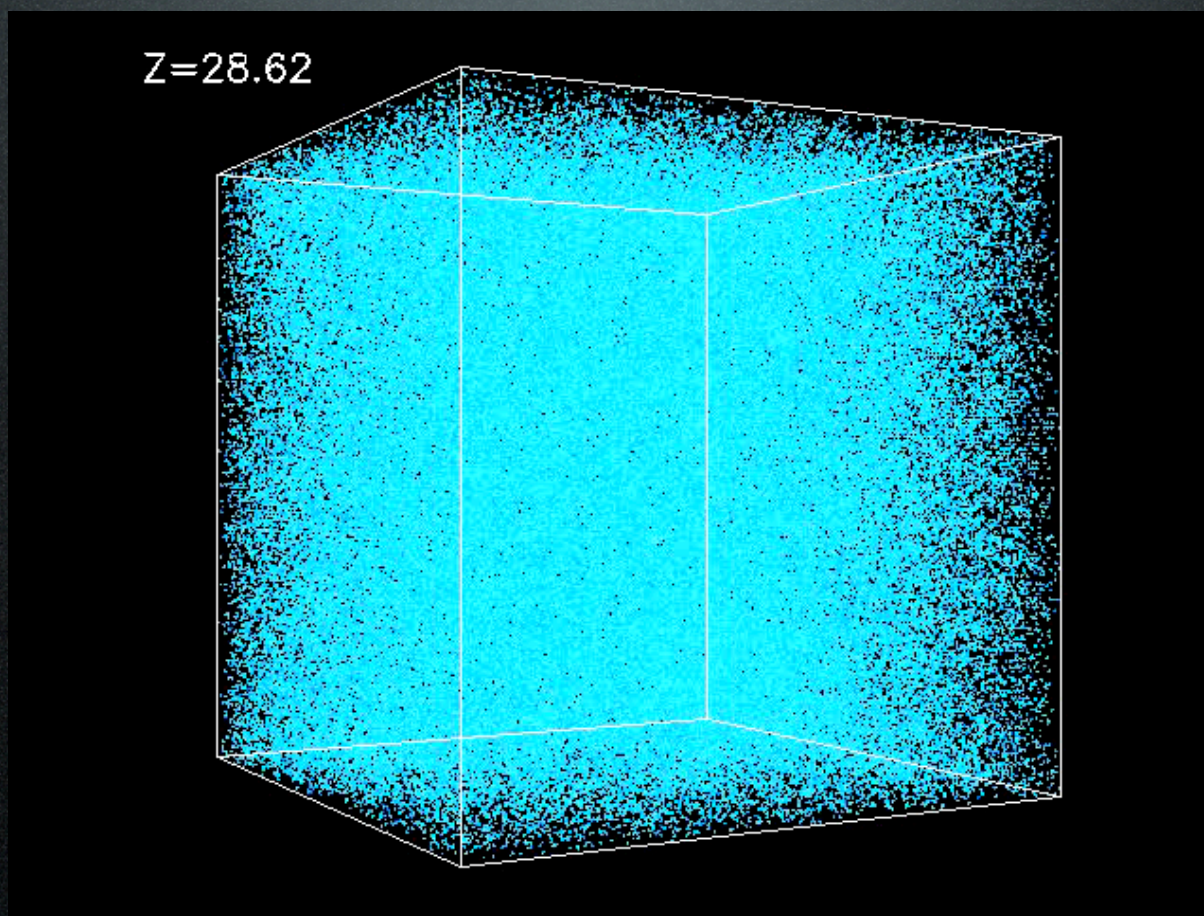
# DM N-body simulations

$2 \times 10^6$  CDM particles, 43 Mpc cubic box



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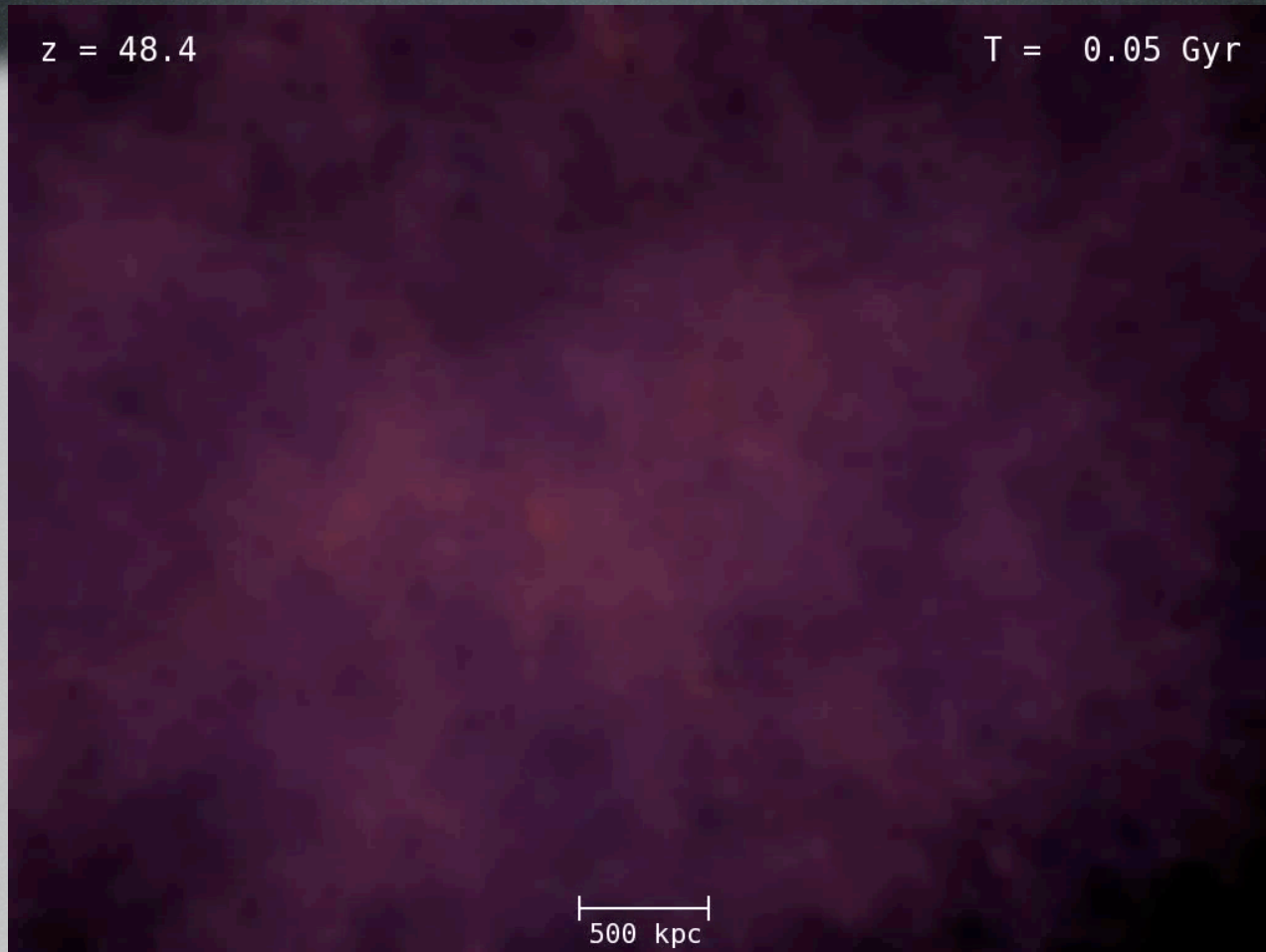




# DM N-body simulations

Aquarius project of the VIRGO coll.:

$1.5 \cdot 10^9$  CDM particles, single galactic halo

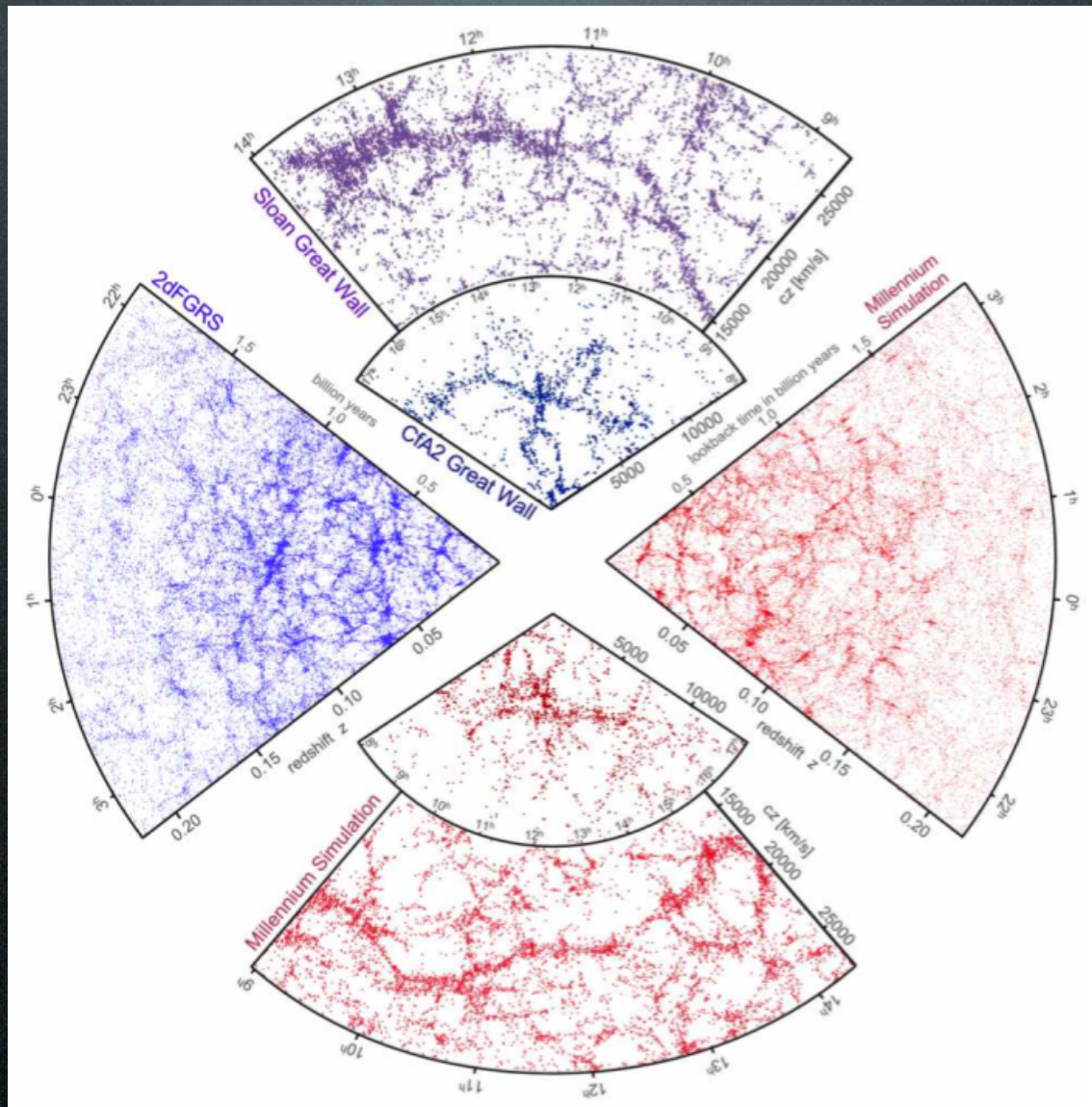




# DM N-body simulations

2dF:  $2.2 \cdot 10^5$  galaxies

SDSS:  $10^6$  galaxies,  
2 billion lyr



Springel, Frenk, White, Nature 440 (2006)

Millennium:  
 $10^{10}$  particles,  
 $500 h^{-1}$  Mpc

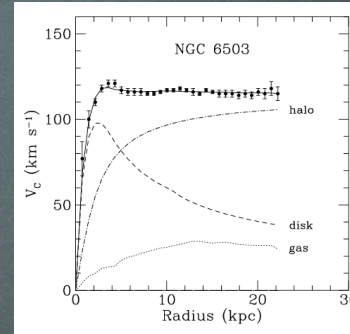
[back]

Of course, you have to  
infer galaxies within the  
DM simulation



# The Evidence for DM

1) galaxy rotation curves



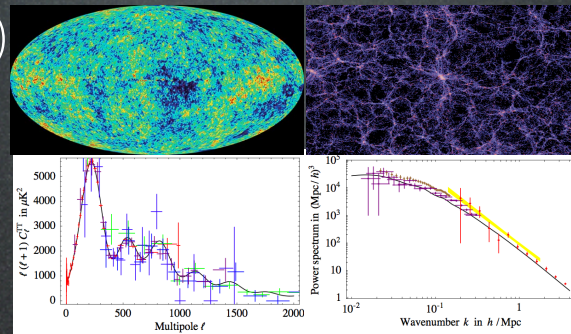
$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies



$$\Omega_M \sim 0.2 \div 0.4$$

3) CMB+LSS(+SNIa:)



$$\Omega_M \approx 0.26 \pm 0.05$$

What is DM?



What do we know of the  
particle physics properties of  
Dark Matter?











DM can **NOT** be:

an astro *je ne sais pas quoi*:



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- neutrons
- gas
- Black Holes
- brown dwarves



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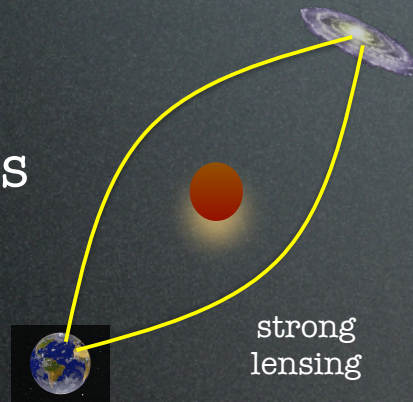
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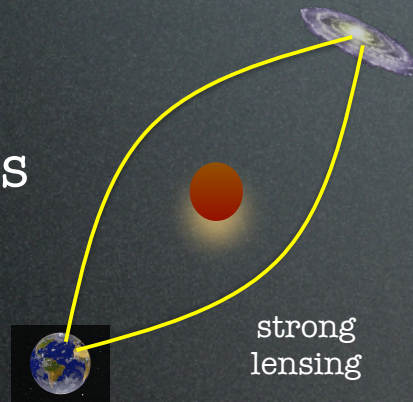
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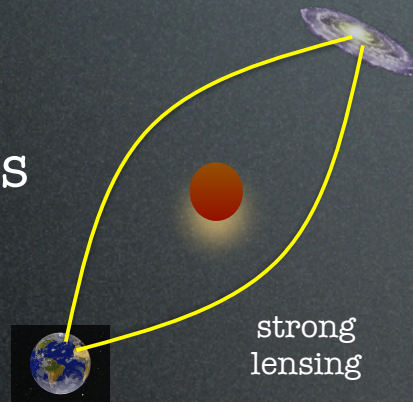
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- BBN computes the abundance of He in terms of primordial baryons:  
too much baryons => Universe full of Helium
- CMB says baryons are 4% max



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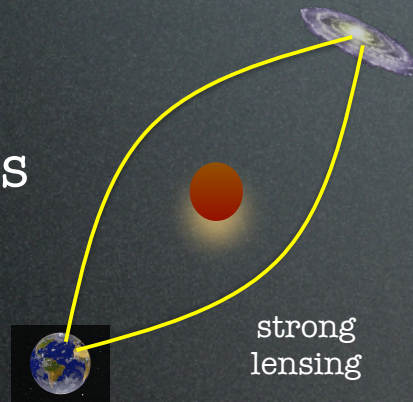
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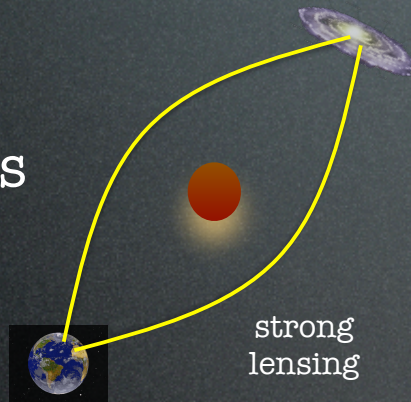
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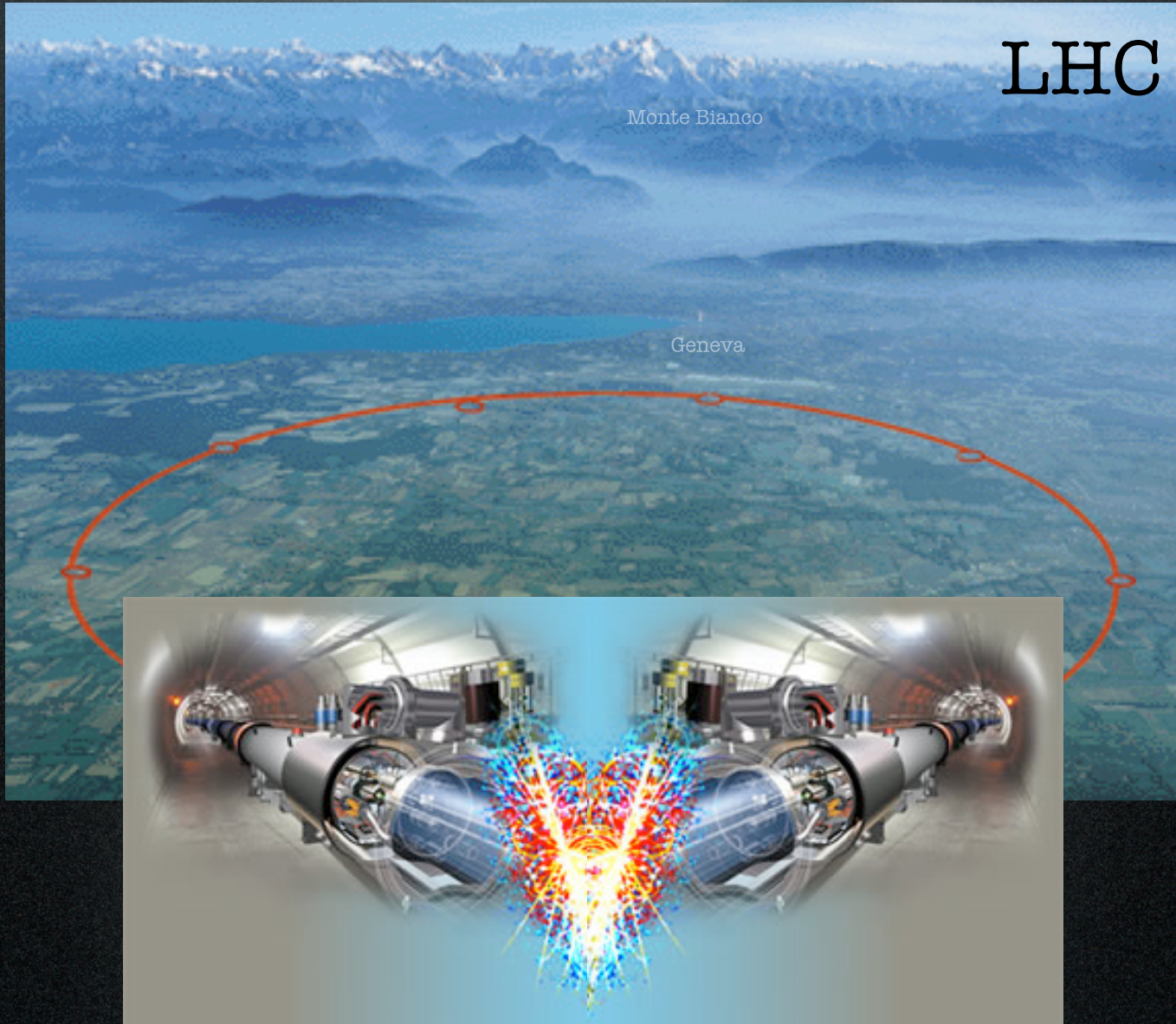
~~neutrinos:~~

too light!  $m_\nu \lesssim 1 \text{ eV}$

do not have enough mass to act as gravitational attractors in galaxy collapse

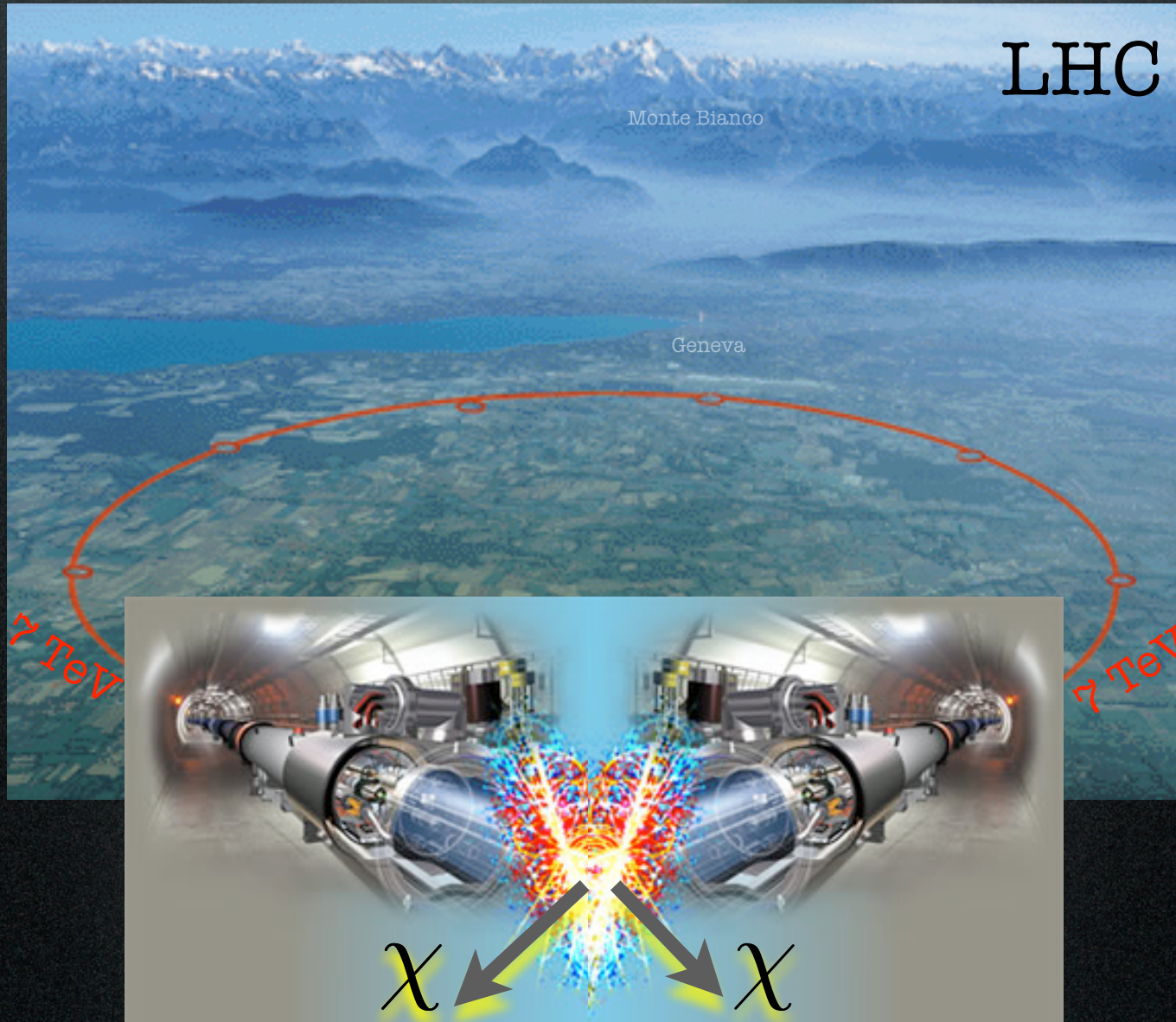


# 2. Production at colliders



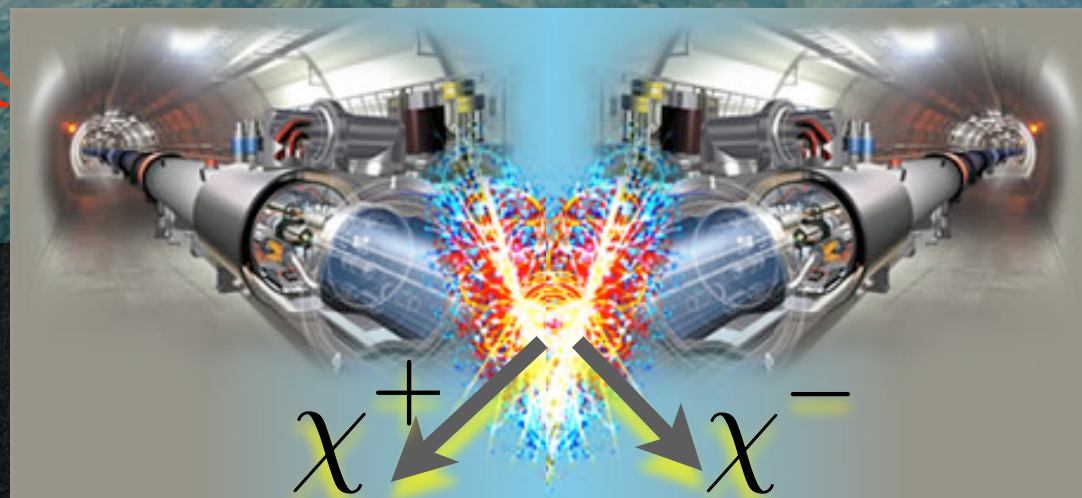
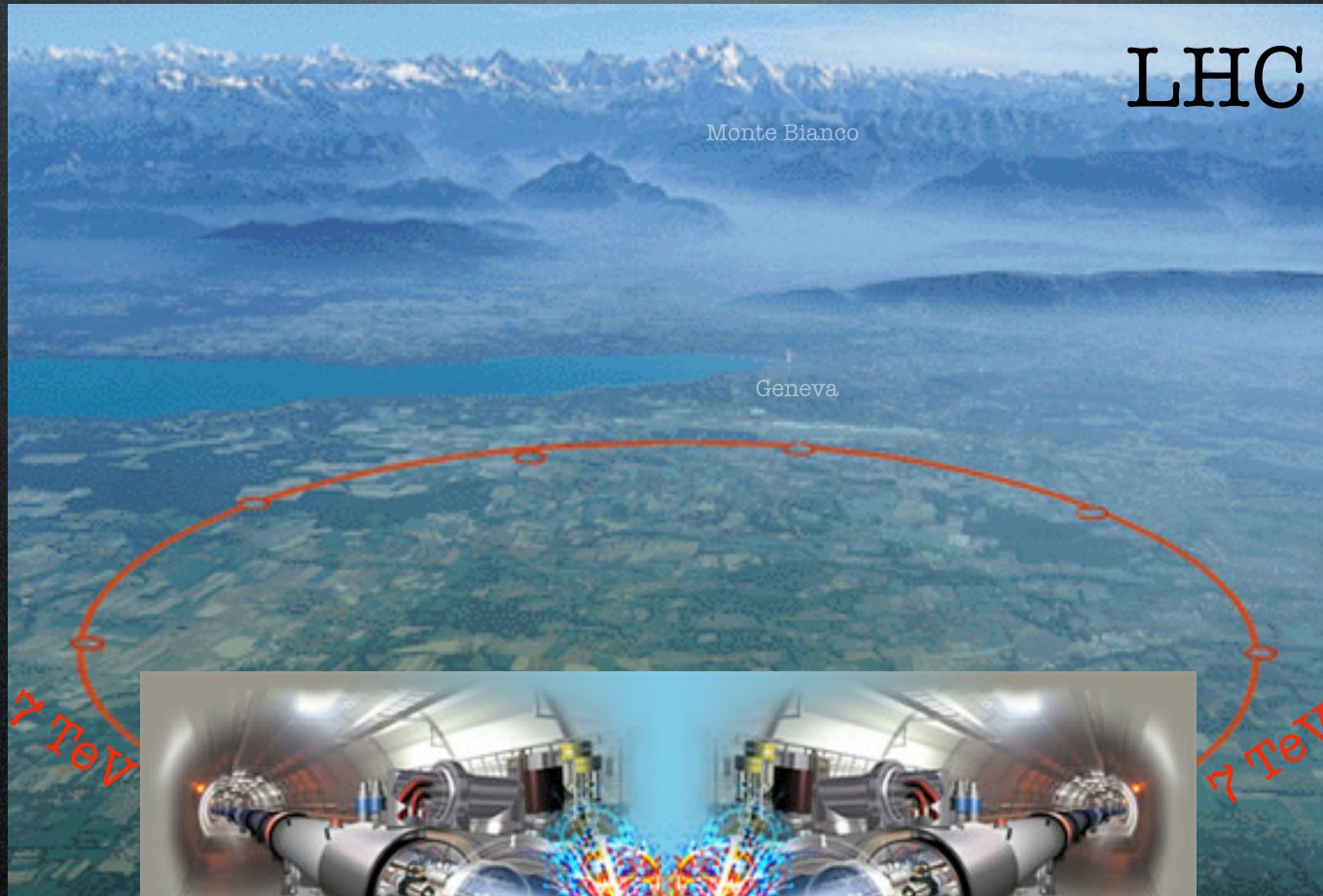


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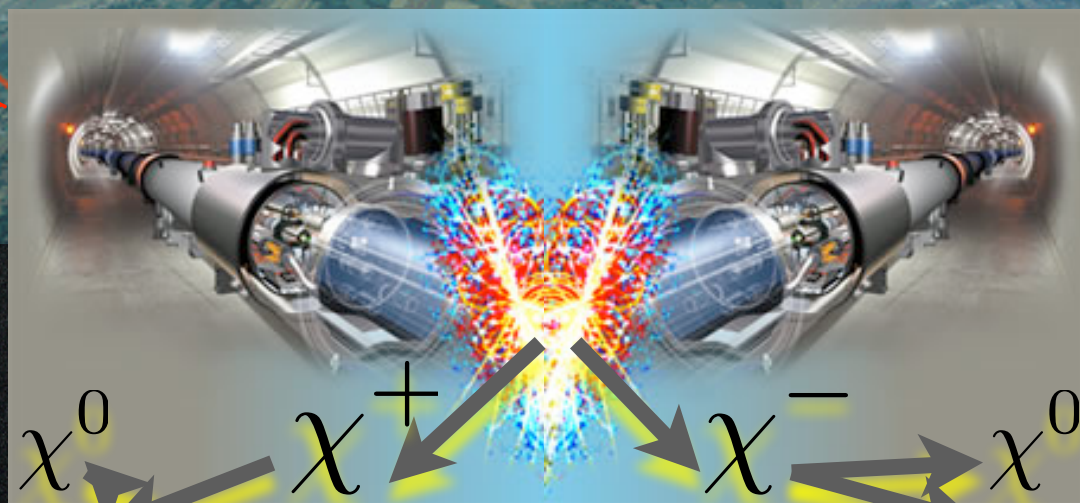


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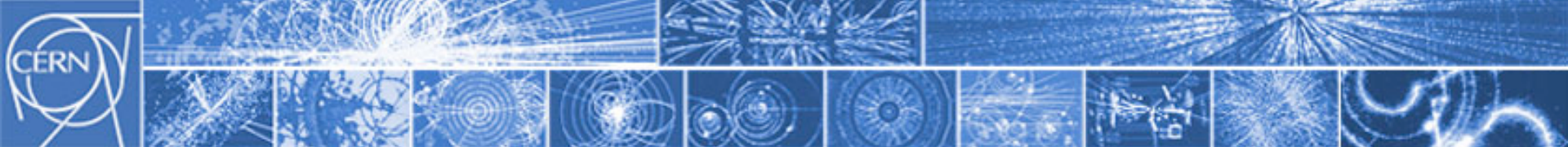
missing energy

missing energy

...

...





# Problemi aperti in Fisica delle Particelle

- l'origine della massa e il bosone di Higgs
- la supersimmetria  
(forse c'è un partner supersimmetrico per ogni tipo di particella nota!)
- le dimensioni dello spazio-tempo  
(forse ci sono più di 3 dimensioni spaziali!)
- la Materia Oscura  
(una particella sconosciuta che costituisce l'80% della materia dell'Universo!)
- l'asimmetria tra materia e antimateria  
(dove è finita tutta l'antimateria dell'Universo?)
- il plasma di quarks e gluoni  
(come diventa la materia nucleare a energie e densità elevatissime?)
- ...

