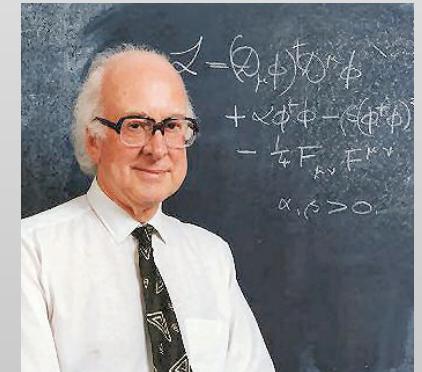
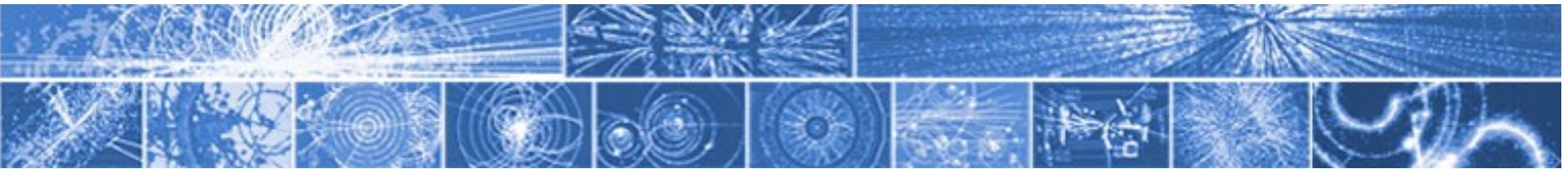


# Il bosone di Higgs



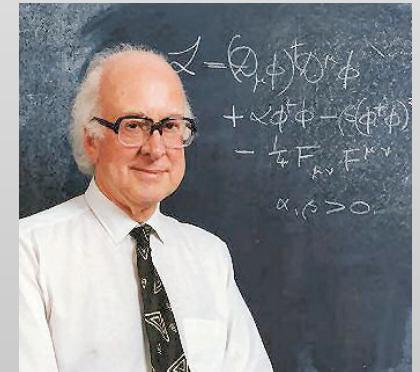
$$\begin{aligned} \mathcal{L} = & (\partial_\mu \phi)^\dagger \partial^\mu \phi \\ & + \frac{\lambda}{2} \phi^\dagger \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & - \frac{1}{2} F_{\mu\nu} F^{\mu\nu} \end{aligned}$$

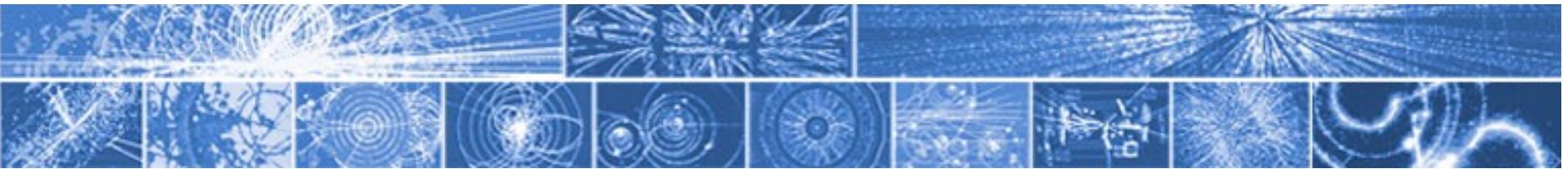
$$\alpha, \beta > 0$$



# Il bosone di ~~Higgs~~

Englert-Brout-Higgs-Guralnik-Hagen-Kibble



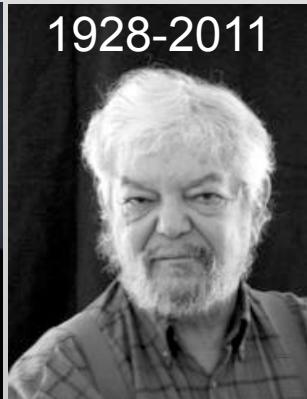


# Il bosone di ~~Higgs~~

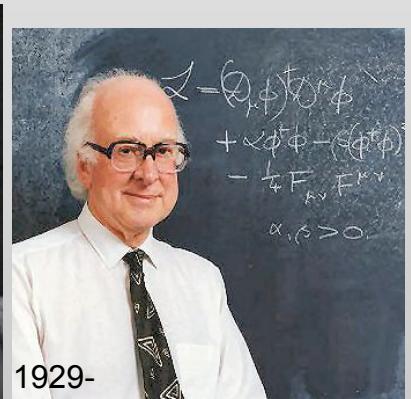
Englert-Brout-Higgs-Guralnik-Hagen-Kibble



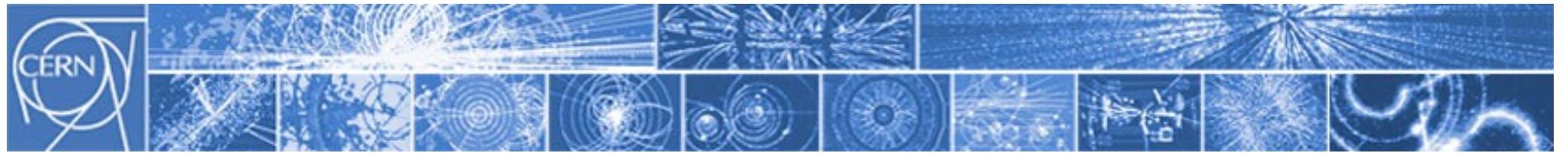
1932-



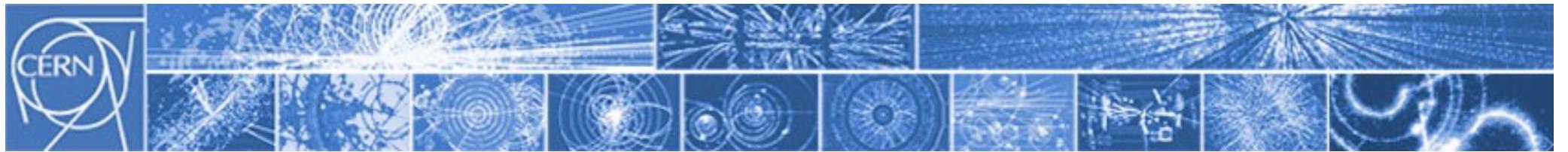
1928-2011



1929-

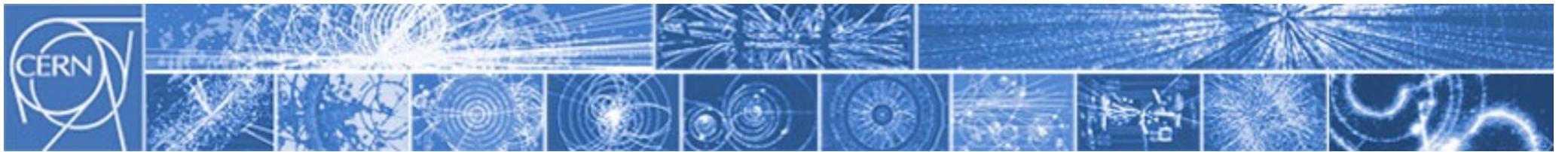


Q. Perché una particella ha massa  $m$ ?



## Q. Perché una particella ha massa $m$ ?

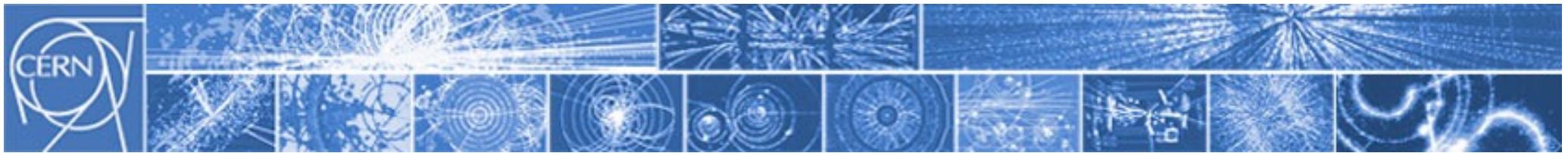
$$\begin{aligned}\mathcal{L} \simeq & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & + i\bar{\Psi}\not{D}\Psi \\ & + y_{ij}\Psi_i\Psi_j\phi \\ & + |D_\mu\phi|^2 - V(\phi)\end{aligned}$$



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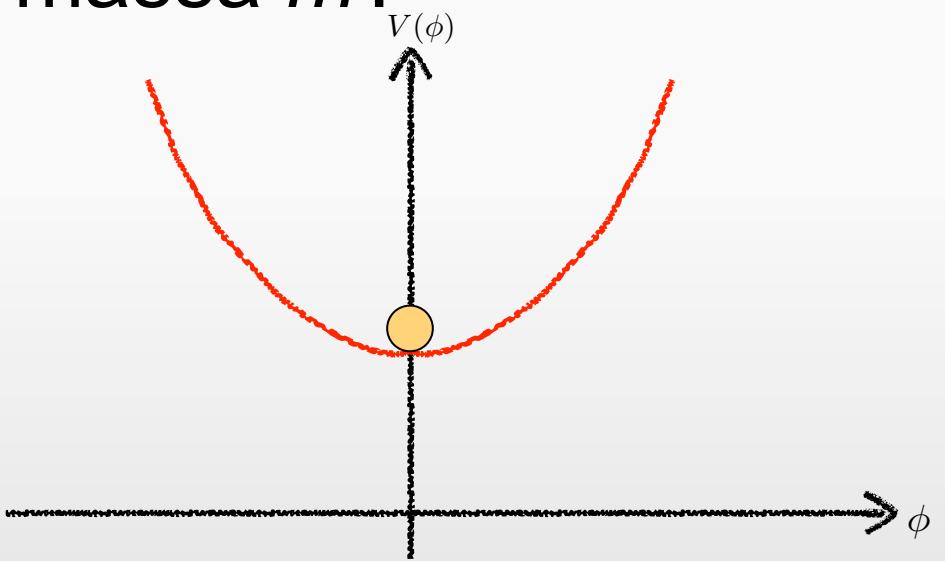
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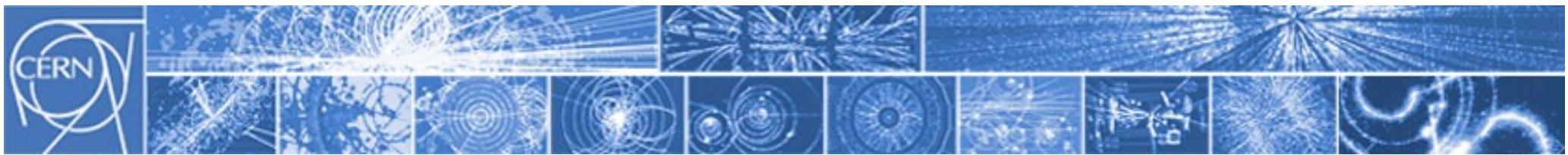
$-m^2 |\phi|^2 + \lambda |\phi|^4$



## Q. Perché una particella ha massa $m$ ?

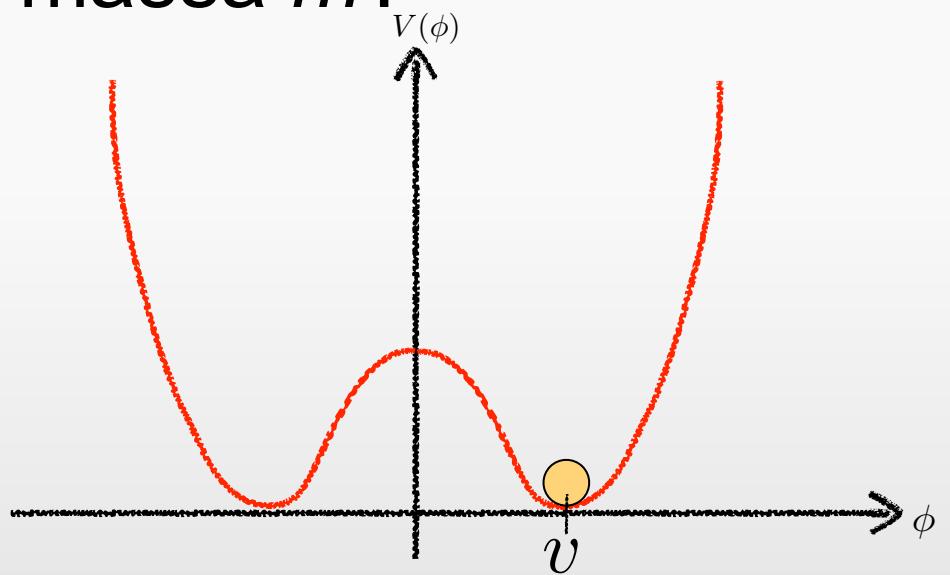
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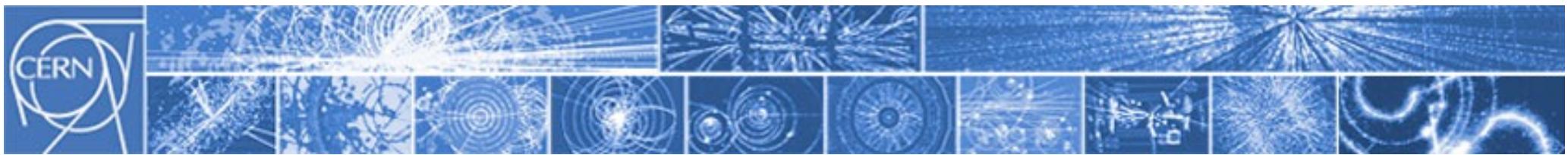


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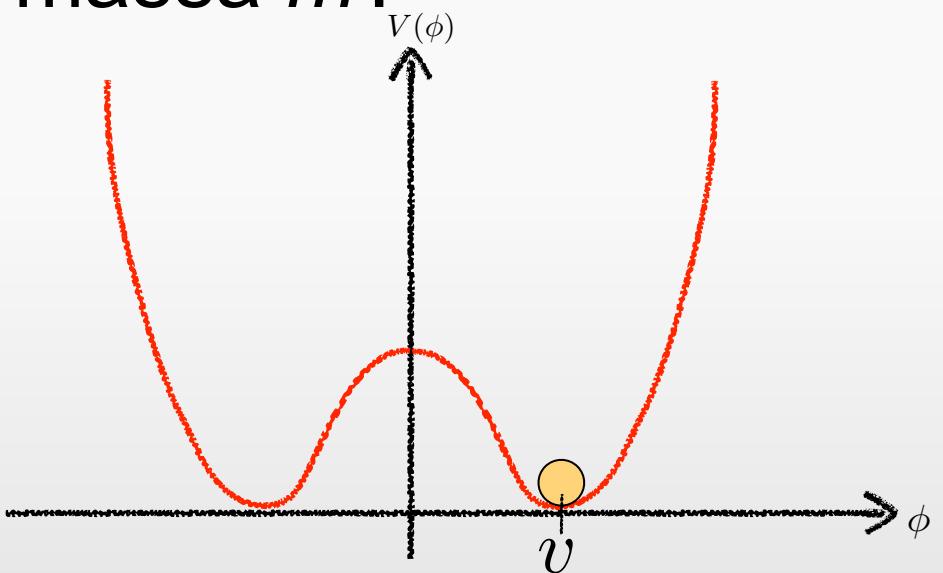


$$\phi \simeq v + h$$

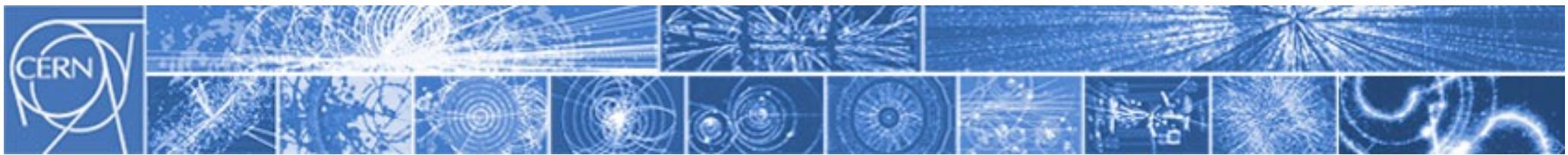


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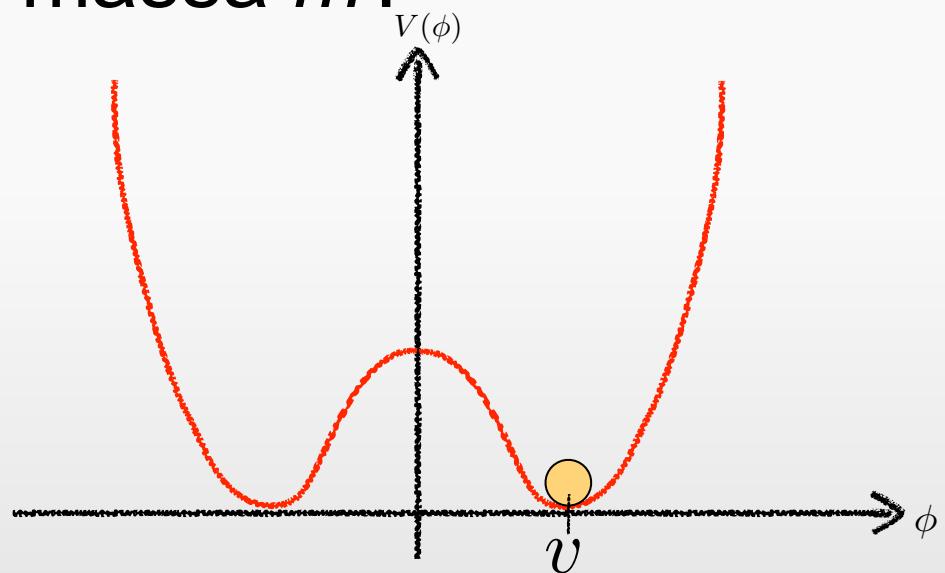


$$\phi = \frac{1}{\sqrt{2}}(v + h)$$



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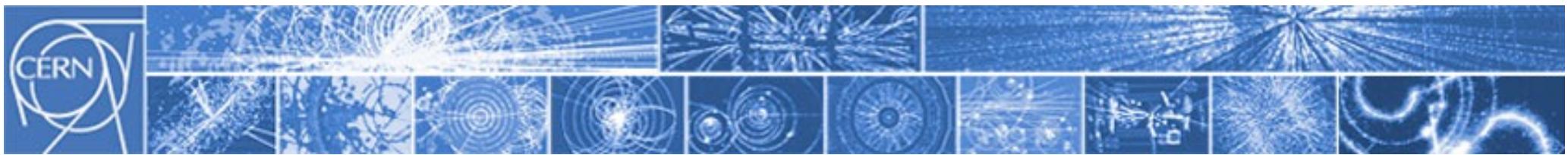
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$$y_{ij}\Psi_i\Psi_j \frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h$$

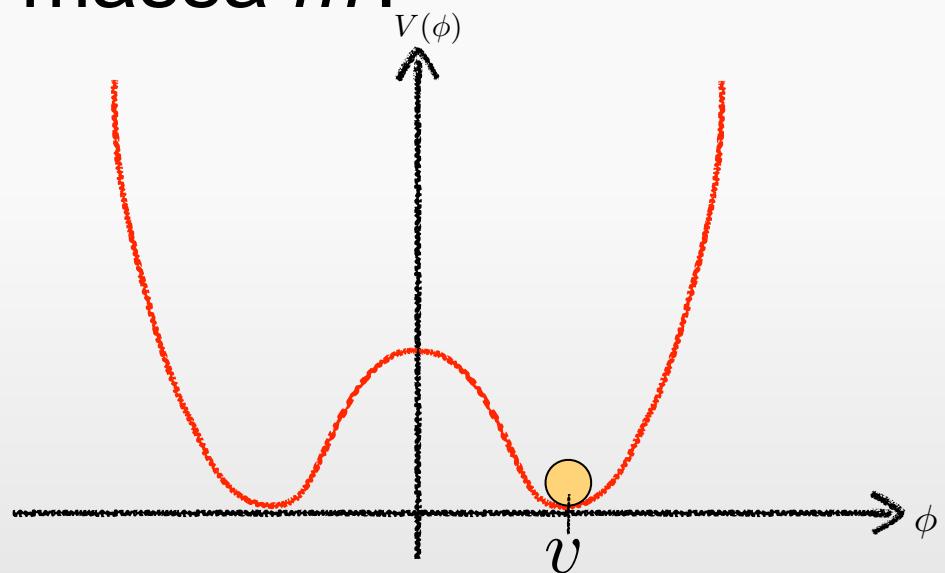
$$\frac{\mu}{\mu} + \frac{\mu}{\mu} \cdot \cdots \cdot h$$

$$\phi = \frac{1}{\sqrt{2}}(v+h)$$



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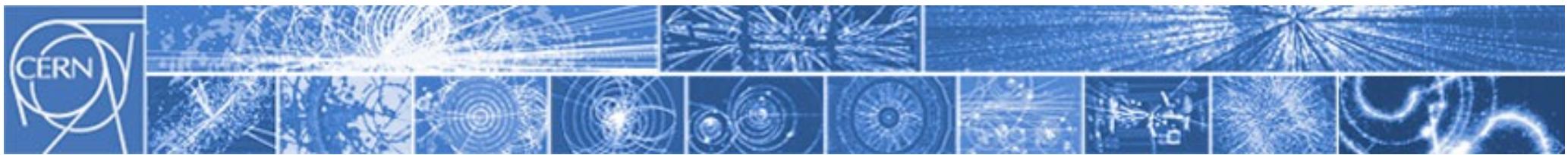
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$$y_{ij}\Psi_i\Psi_j \frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h = \frac{\mu}{\mu} + \frac{y_\mu}{\sqrt{2}}h$$

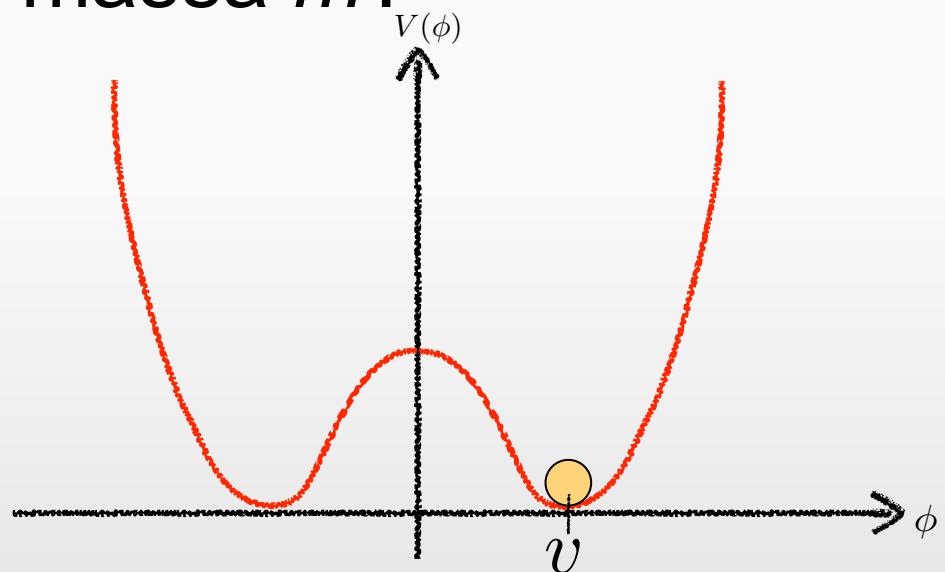
$$\phi = \frac{1}{\sqrt{2}}(v+h)$$

μ + h  
μ y<sub>μ</sub>/√2



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

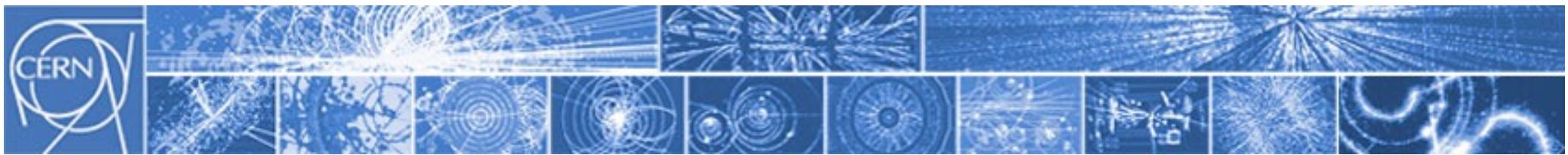


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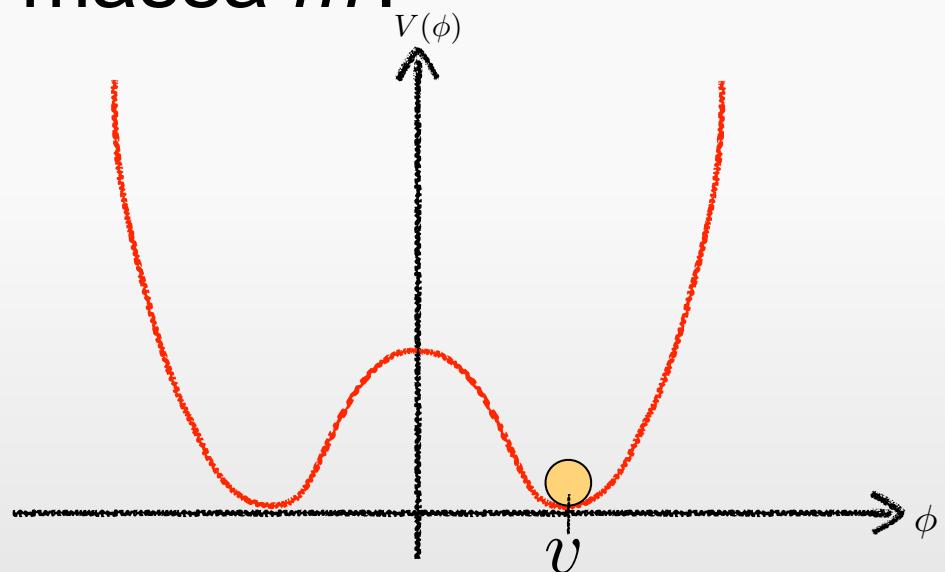
μ + h  
μ y<sub>μ</sub>/√2

$$|D_\mu\phi|^2 \rightsquigarrow \frac{g}{2}vW^+W^-$$



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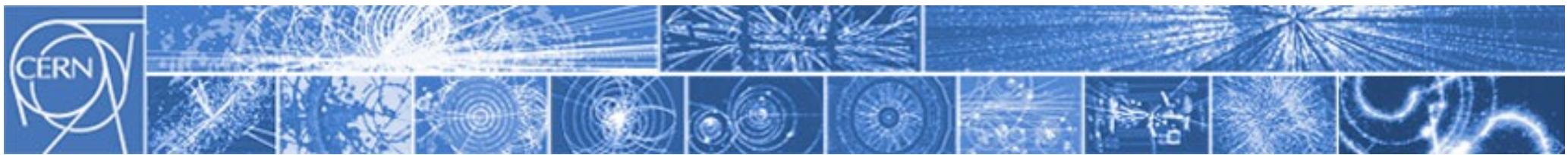


$$y_{ij}\Psi_i\Psi_j \frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h =$$

$$|D_\mu\phi|^2 \rightsquigarrow \frac{g v}{2}W^+W^-$$

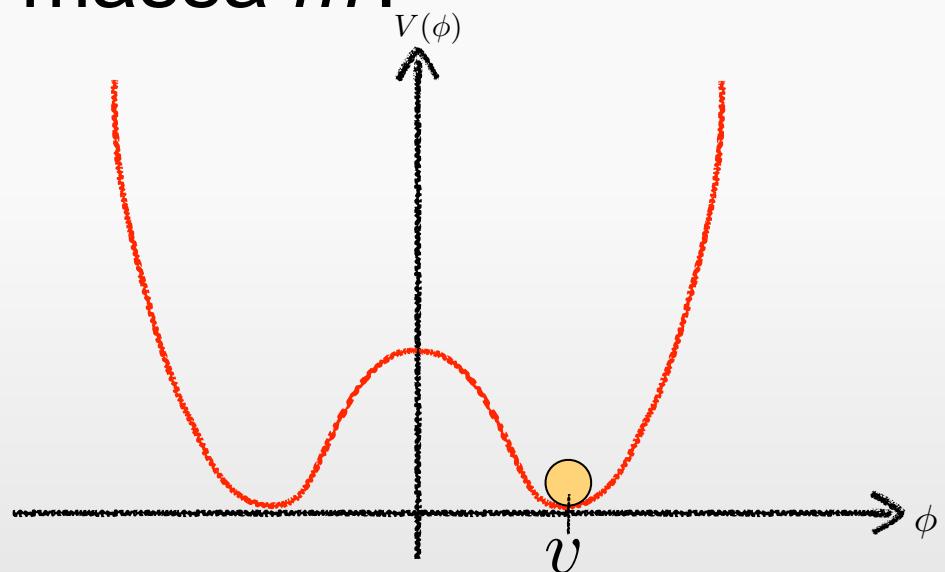
$M_W$

$$\frac{\mu}{\mu} + \frac{\phi = \frac{1}{\sqrt{2}}(v+h)}{h} = \frac{\mu}{\mu} + \frac{y_\mu/\sqrt{2}}{h}$$



# Q. Perché una particella ha massa $m$ ?

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

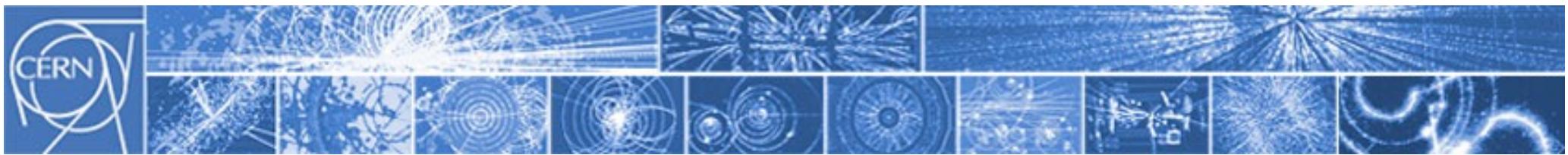


$$y_{ij}\Psi_i\Psi_j \frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h$$

$$|D_\mu\phi|^2 \rightsquigarrow \frac{g v}{2}W^+W^-$$

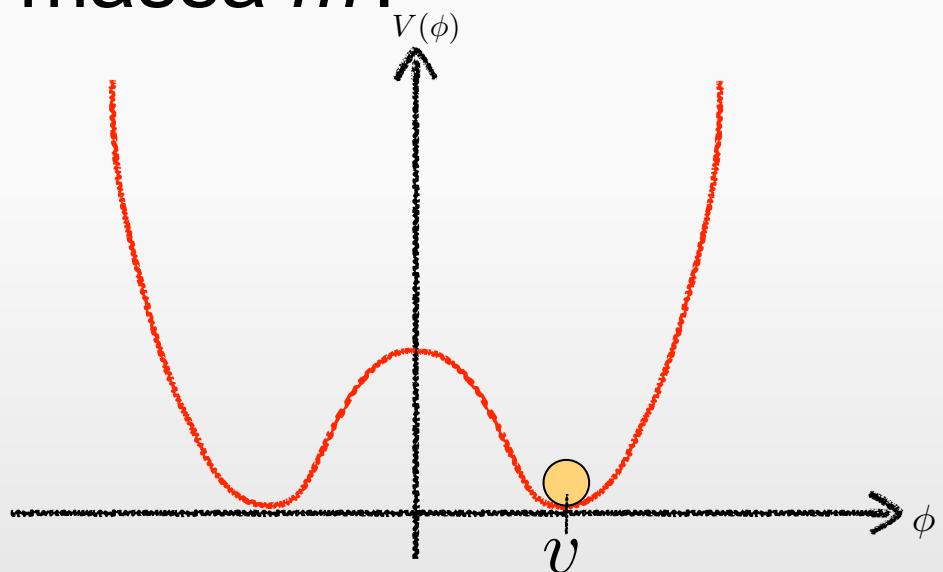
$$V(\phi) \rightsquigarrow \frac{1}{2}(2\lambda v^2)hh$$

$$\begin{aligned}\phi &= \frac{1}{\sqrt{2}}(v+h) \\ \mu &\quad \text{---} \quad h \\ \mu &\quad \text{---} \quad y_\mu/\sqrt{2}\end{aligned}$$



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$$y_{ij}\Psi_i\Psi_j \frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h = \frac{\mu}{\mu} +$$

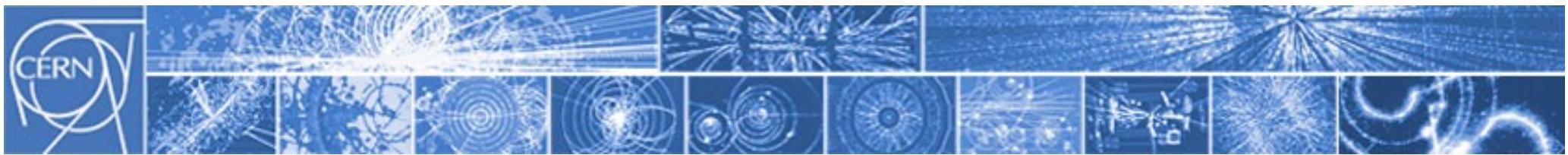
$$\phi = \frac{1}{\sqrt{2}}(v+h)$$

μ → μ + h  
μ → y<sub>μ</sub>/√2

$$|D_\mu\phi|^2 \rightsquigarrow \frac{g v}{2} W^+W^-$$

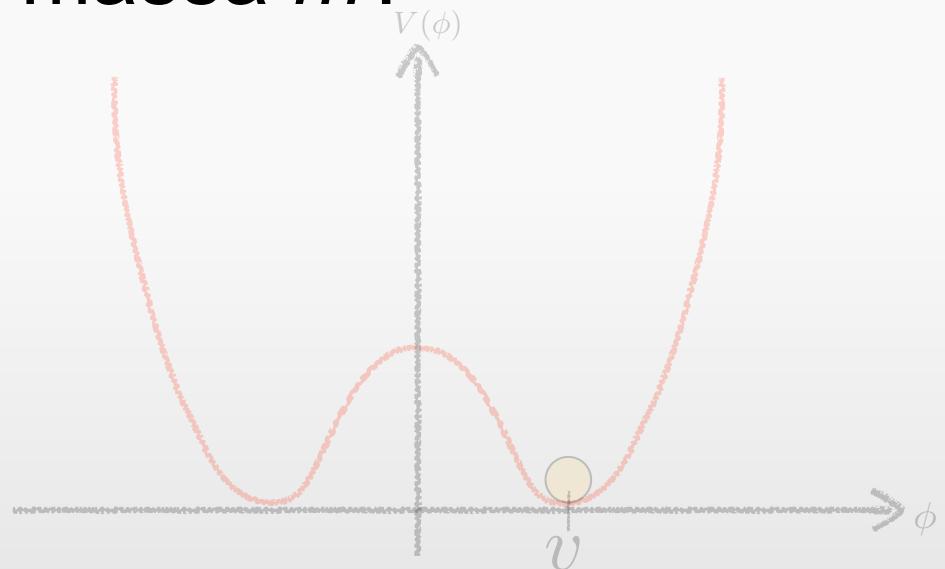
M<sub>W</sub> ↑  
m<sub>μ</sub>

$$V(\phi) \rightsquigarrow \frac{1}{2} \frac{m_h^2}{(2\lambda v^2)} hh$$



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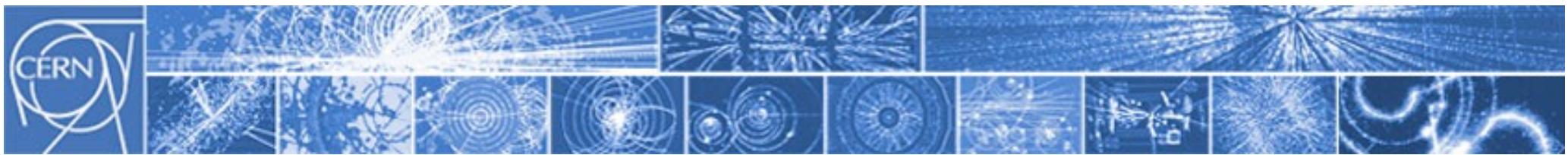
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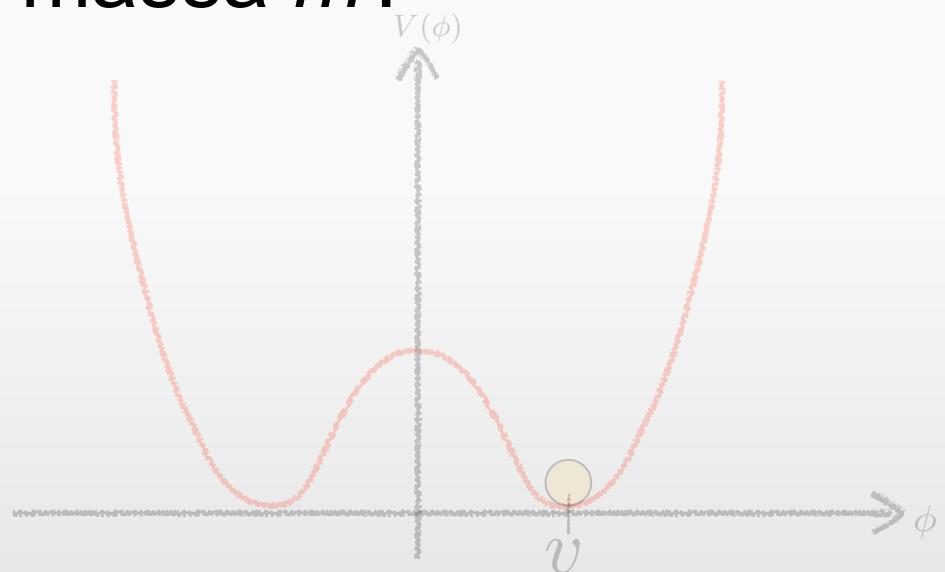
$$\begin{aligned}\phi &= \frac{1}{\sqrt{2}}(v+h) \\ \mu &\quad \text{---} \quad \mu \\ \mu &\quad \text{---} \quad h \\ &\quad \quad \quad y_\mu/\sqrt{2}\end{aligned}$$

A. Perché interagisce con l'higgs con intensità  $y=\sqrt{2}m/v!$



# Q. Perché una particella ha massa $m$ ?

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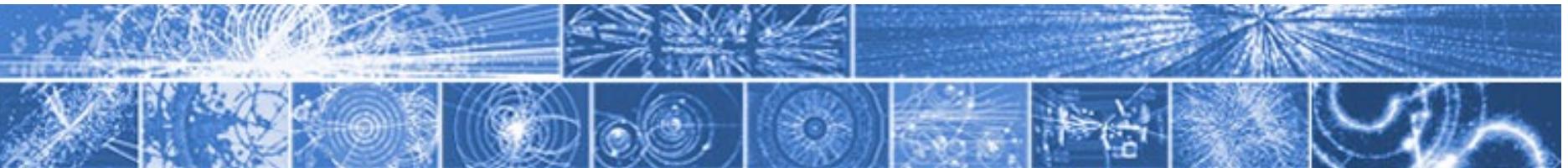
$$y_{ij}\Psi_i\Psi_j \frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \boxed{\frac{y_\mu v}{\sqrt{2}}} \mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h$$

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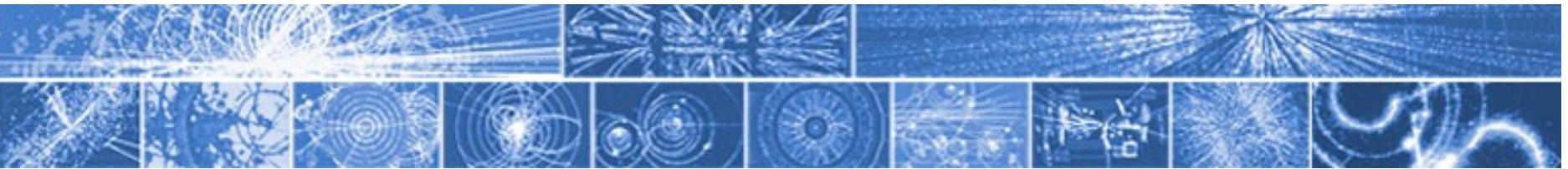
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Q. E se il campo di higgs non esistesse?



## Q. Perché una particella ha massa $m$ ?

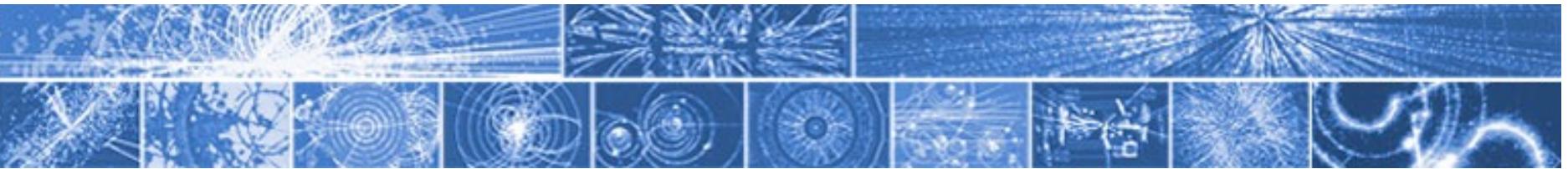
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## Q. Perché una particella ha massa $m$ ?

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

$$F_{\mu\nu} F^{\mu\nu} \rightsquigarrow \partial_\mu W_\nu \partial_\nu W_\mu + \dots$$



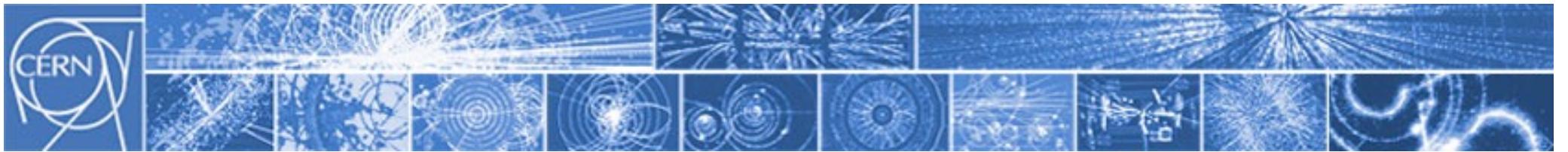
## Q. Perché una particella ha massa $m$ ?

$$\mathcal{L} \simeq -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} D\Psi$$
$$F_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$$
$$D \simeq \partial - igW$$

$$+y_{ij}\Psi_i\Psi_j\phi$$
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$$F_{\mu\nu} F^{\mu\nu} \rightsquigarrow \partial_\mu W_\nu \partial_\nu W_\mu + \dots$$

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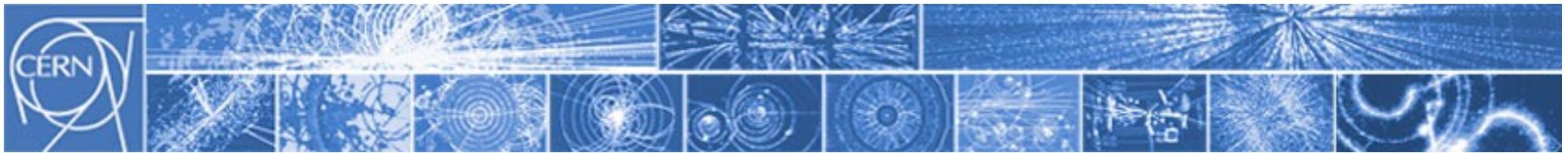
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niente termini di massa!

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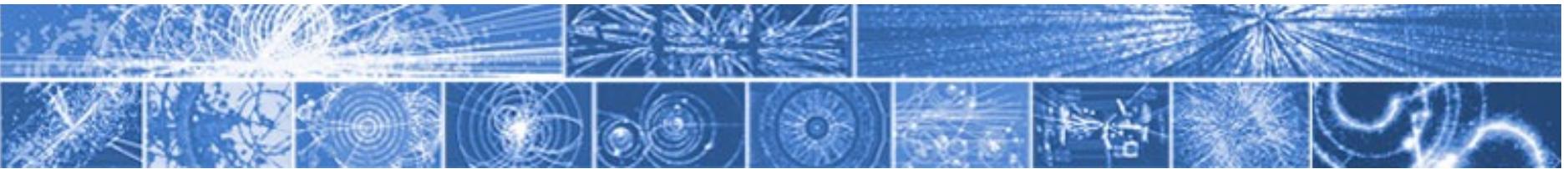
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E se li mettessimo a mano?

$$+\textcolor{red}{M} W\bar{W} \dots +\textcolor{red}{m} \mu\bar{\mu} \dots$$



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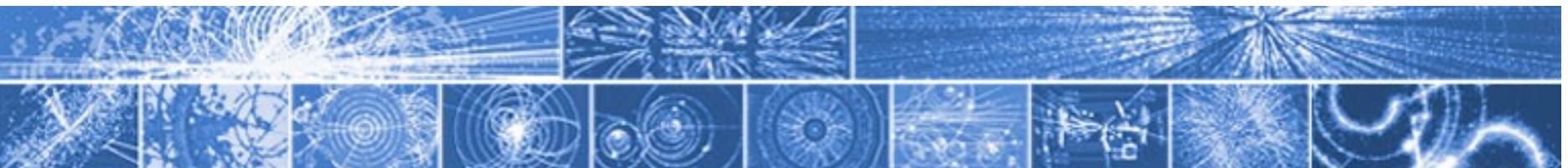
E se li mettessimo a mano?

$$+\textcolor{red}{M} W\bar{W} \dots$$

$$+\textcolor{red}{m} \mu\bar{\mu} \dots$$



rottura esplicita della simmetria di gauge



Q. P. and  $\bar{P}$  are the quarks and antiquarks in the

$\mathcal{L}$

,  $- \partial_\nu W_\mu$

$W$

$F_{\mu\nu} F^{\mu\nu}$

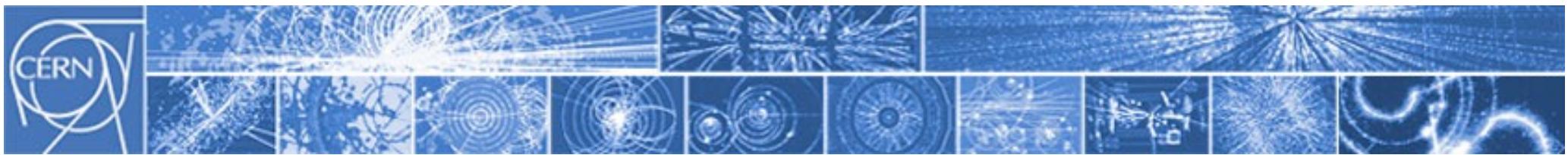
$i\bar{\Psi} D^\mu \Psi$

E s

+  $M$

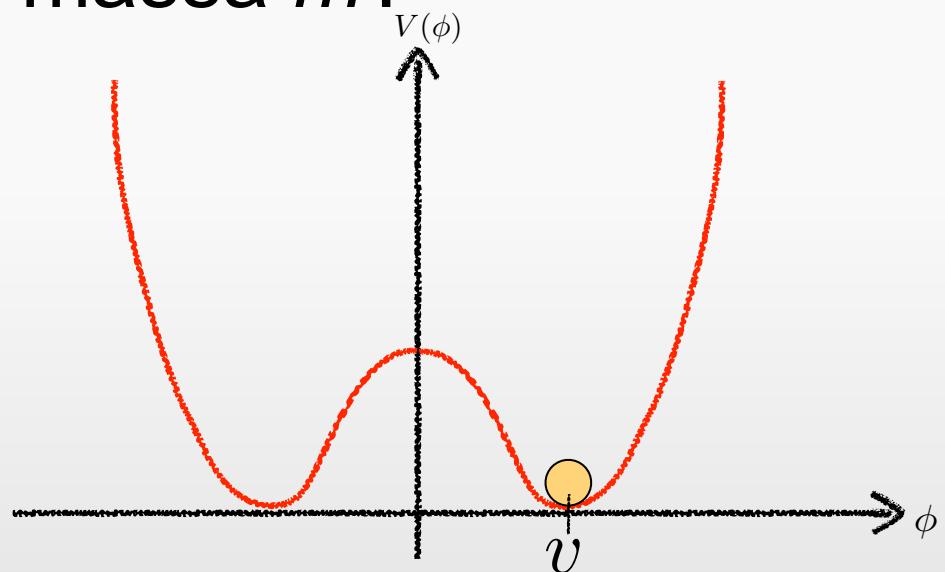
di gauge





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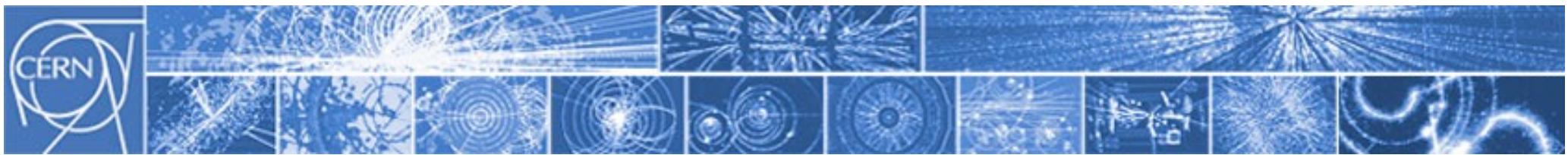


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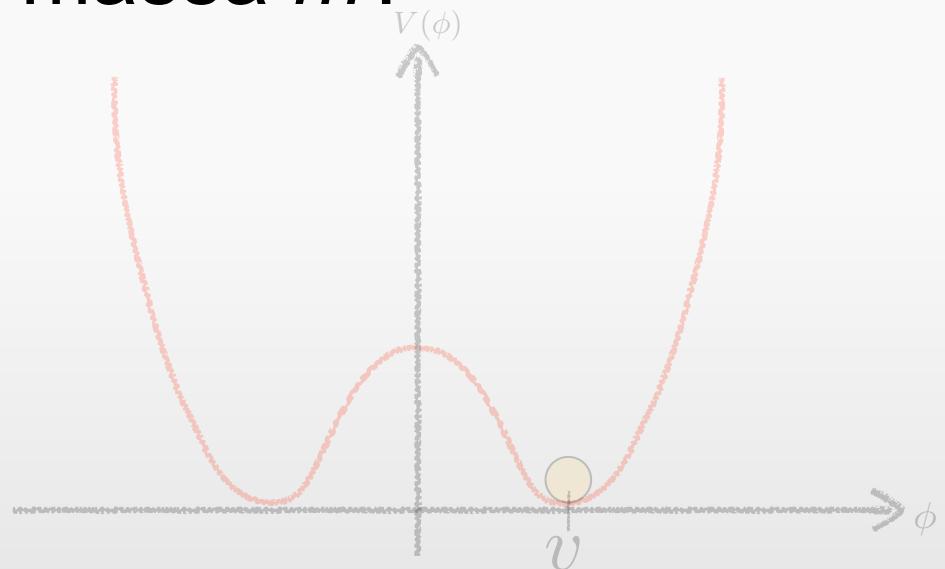
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$$\begin{aligned}\phi &= \frac{1}{\sqrt{2}}(v+h) \\ \mu &\quad \text{---} \quad h \\ \mu &\quad \text{---} \quad y_\mu/\sqrt{2}\end{aligned}$$



# Q. Perché una particella ha massa $m$ ?

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



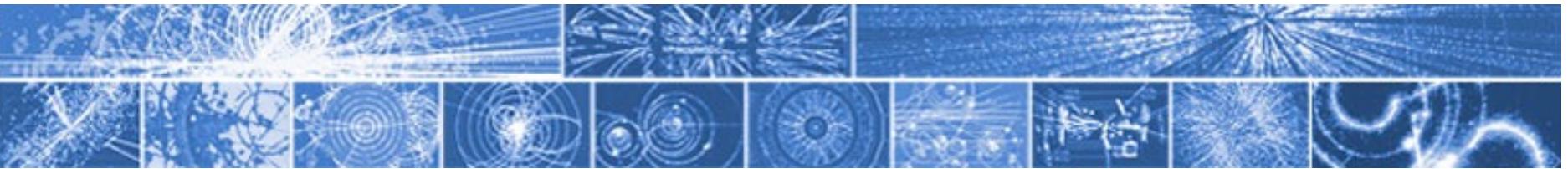
$$y_{ij}\Psi_i\Psi_j \frac{1}{\sqrt{2}}(v+h) \rightsquigarrow \frac{y_\mu v}{\sqrt{2}}\mu\mu + \frac{y_\mu}{\sqrt{2}}\mu\mu h$$

$$|D_\mu\phi|^2 \rightsquigarrow \frac{gv}{2}W^+W^-$$

$$V(\phi) \rightsquigarrow \frac{1}{2}(2\lambda v^2)hh$$

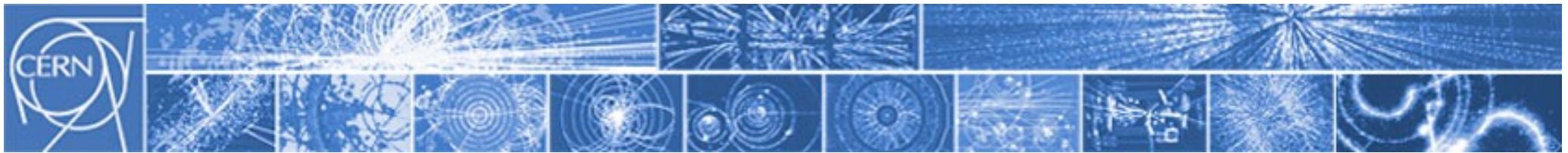
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A. Perché interagisce con l'higgs con intensità  $y=\sqrt{2}m/v!$



Q. Perché una particella ha massa  $m$ ?

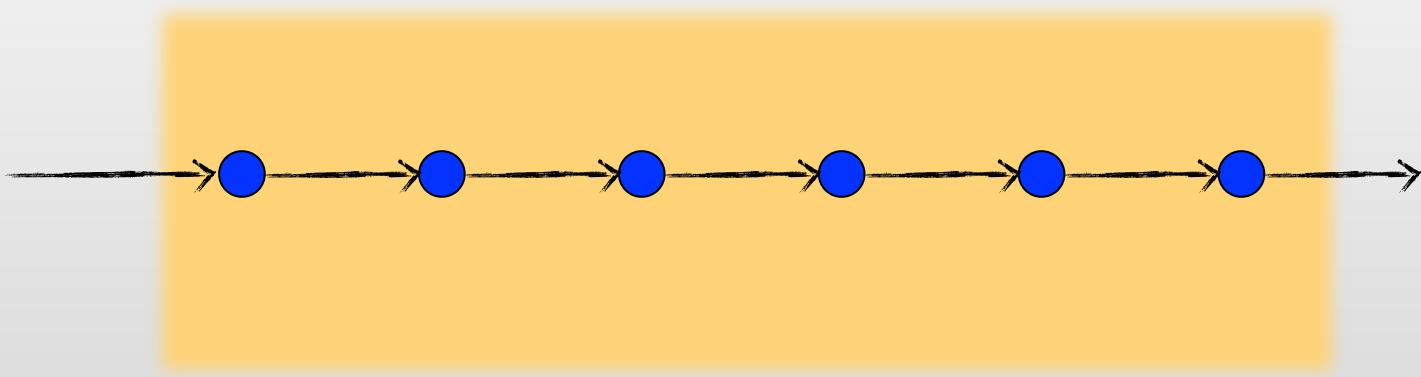
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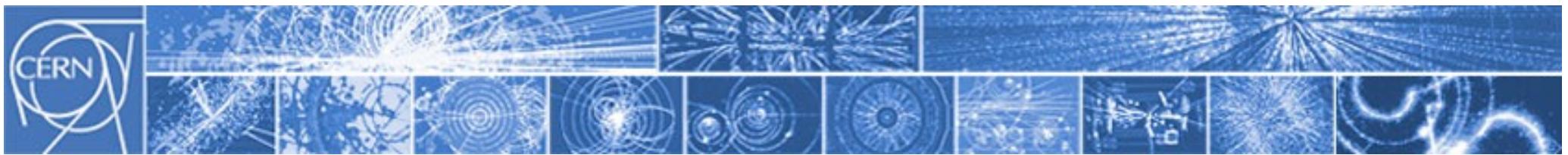


Q. Perché una particella ha massa  $m$ ?

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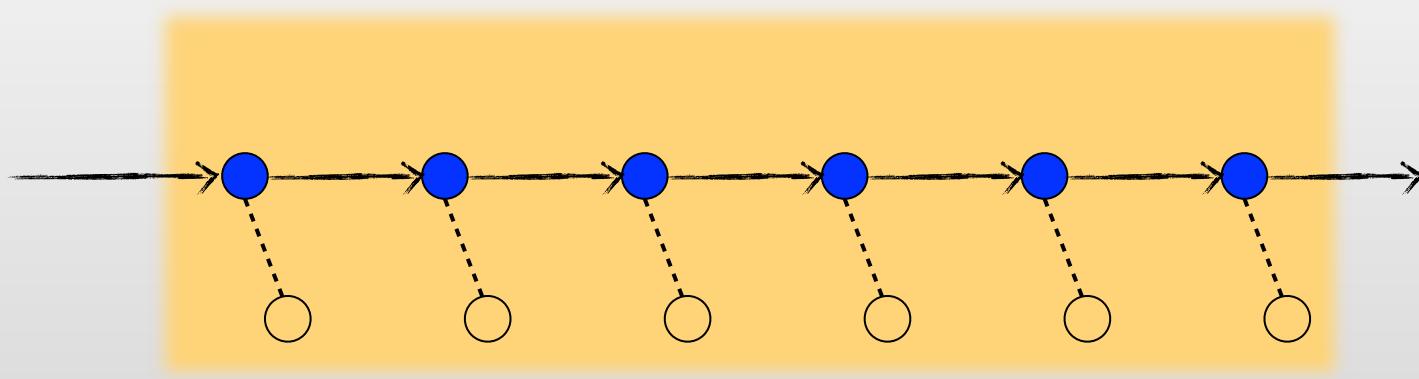




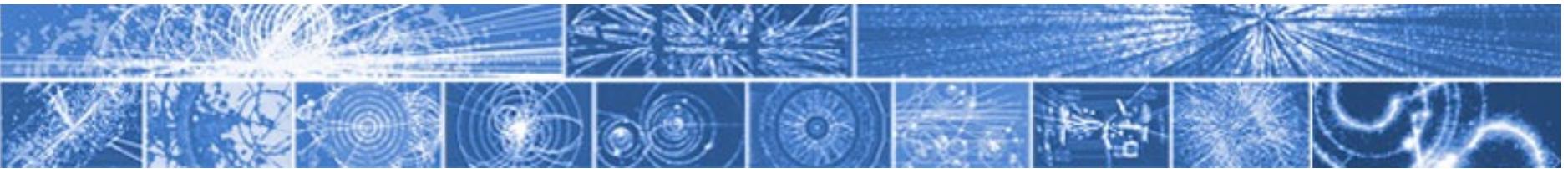
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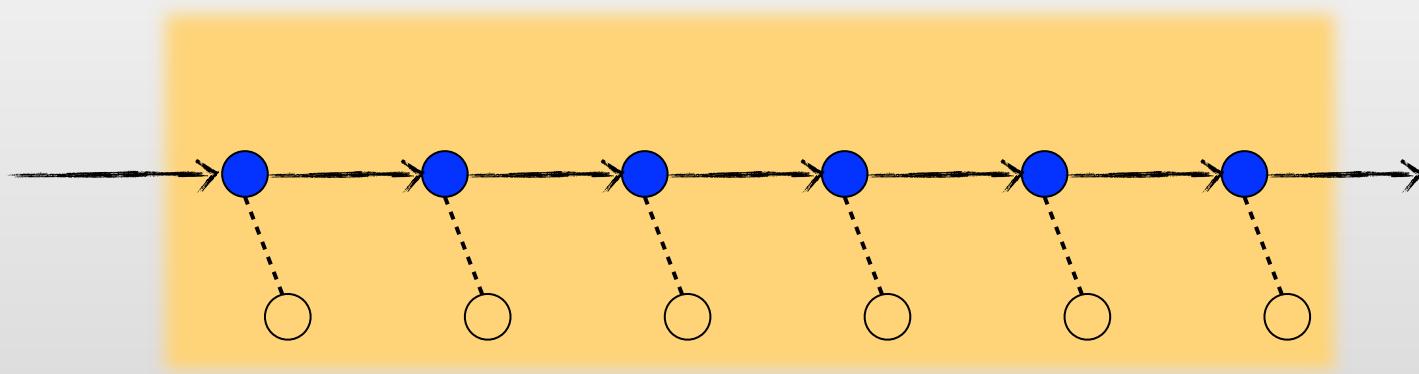
Credit: Michelangelo Mangano



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Le 'onde' del campo di Higgs sono una *particella*:  
la particella di Higgs (bosone).

Equation (2b) describes waves whose quanta have  
(bare) mass  $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$

VOLUME 13, NUMBER 9

PHYSICAL REVIEW LETTERS

31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS\*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium  
(Received 26 June 1964)

VOLUME 13, NUMBER 16

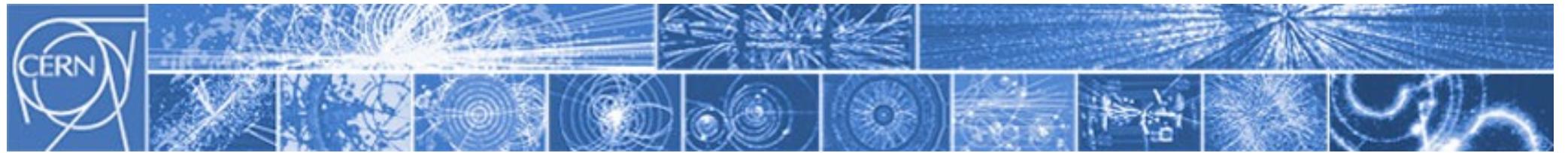
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19 OCTOBER 1964

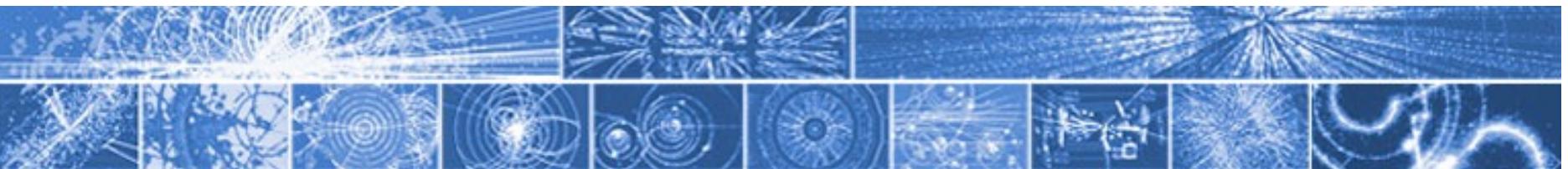
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Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland  
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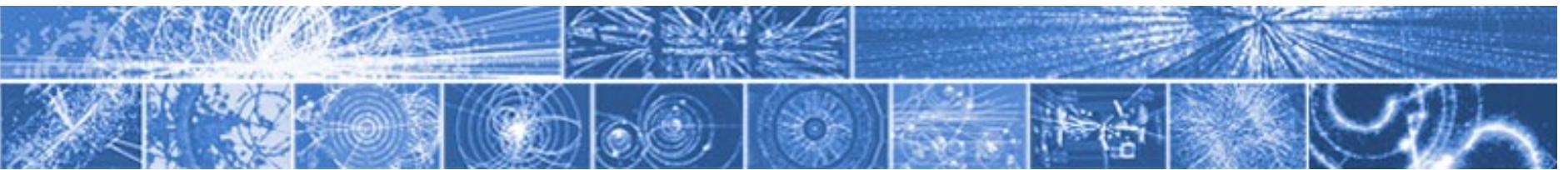


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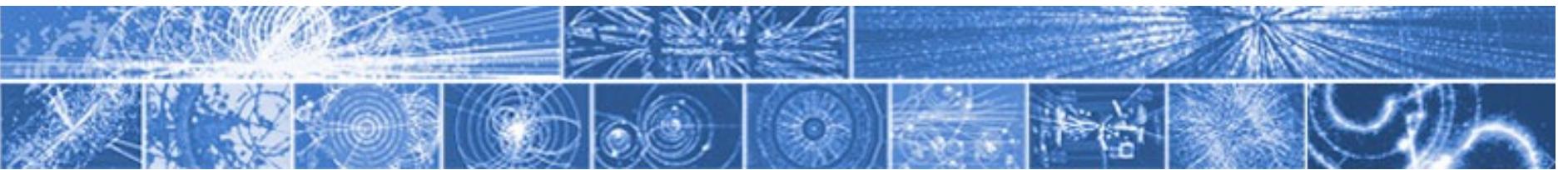
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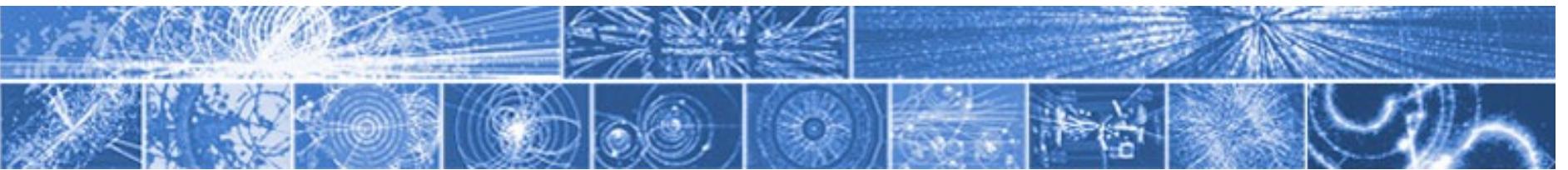
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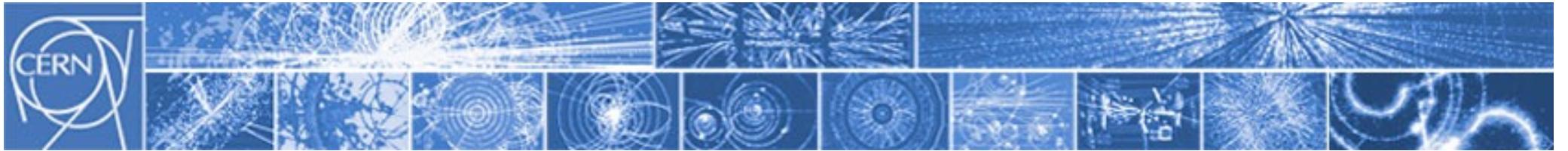
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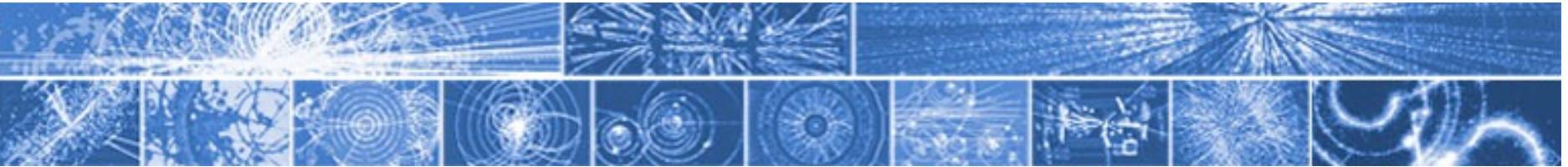


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# Recap: Origine della massa

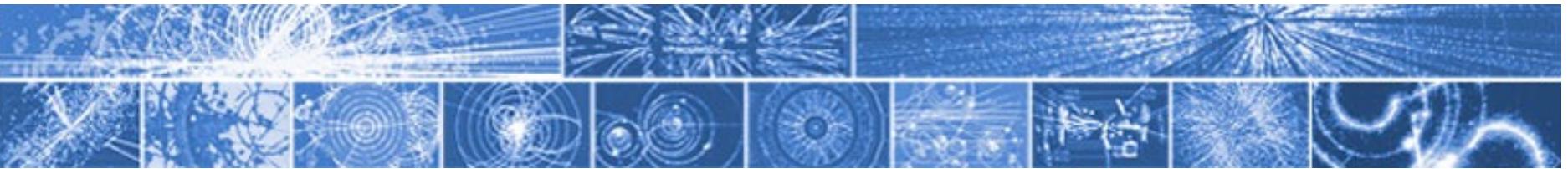


# Recap: Origine della massa

*Microfisica* ‘spiega’ da dove viene la massa

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*Scienze naturali, Chimica*



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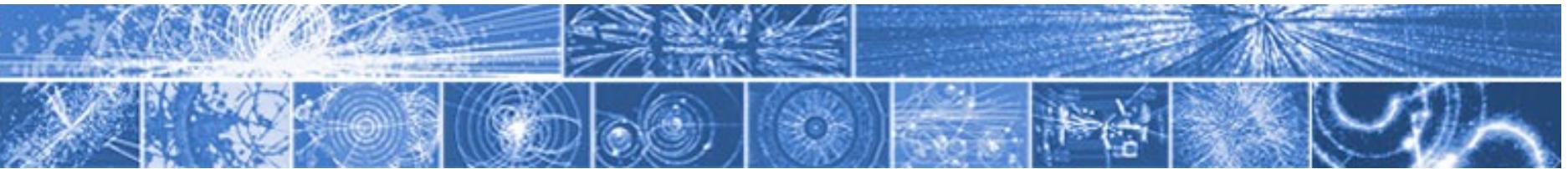
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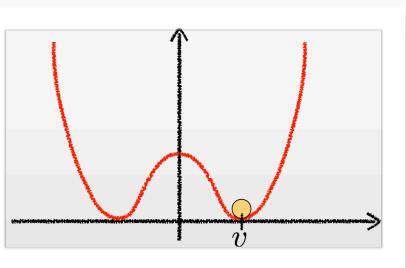
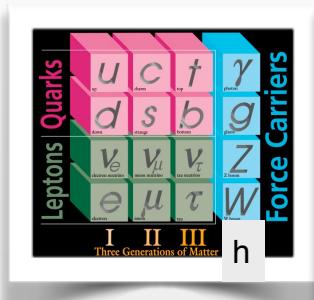
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Particelle elementari



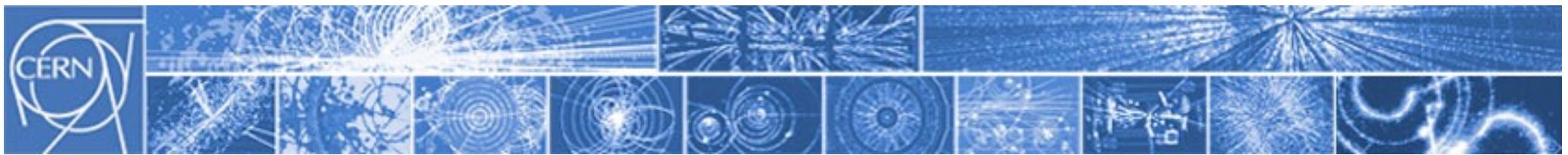
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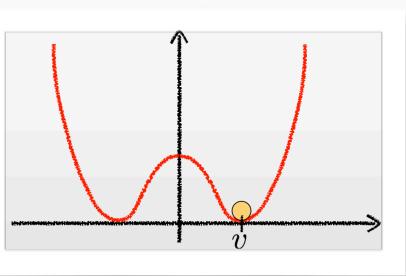
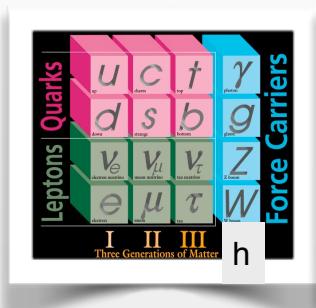
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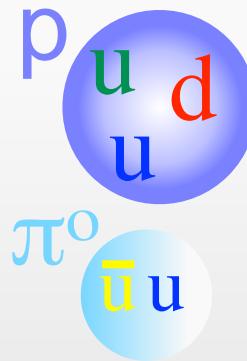
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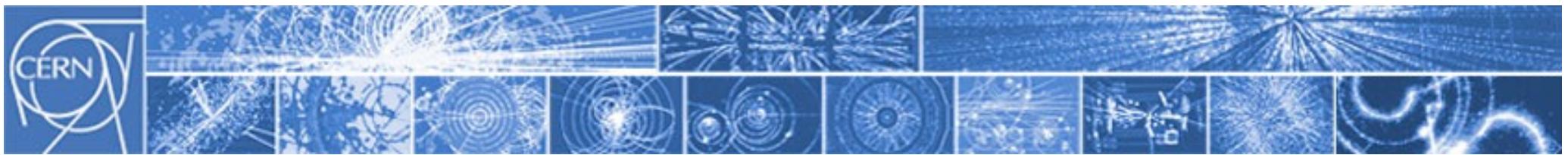
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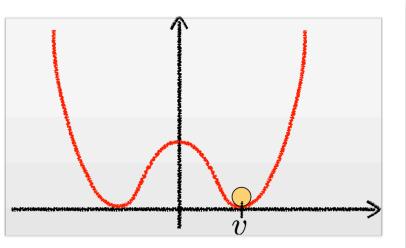
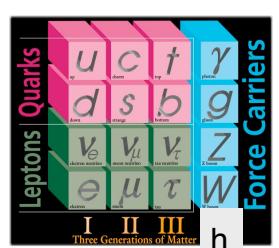
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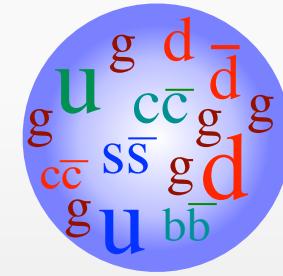
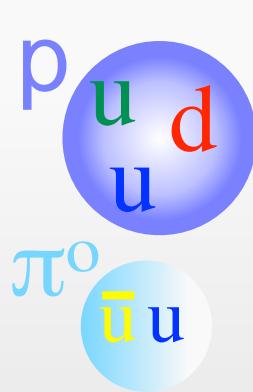
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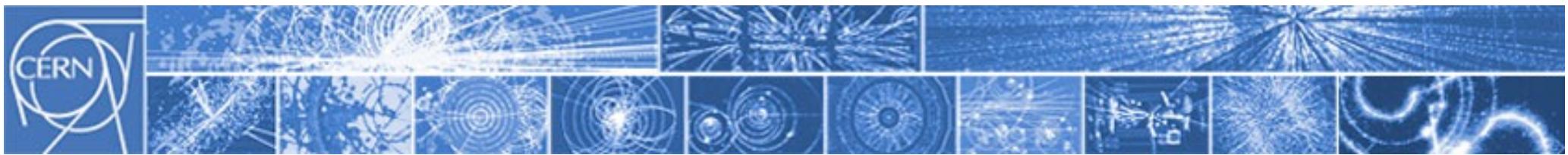


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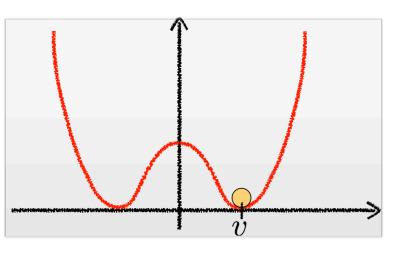
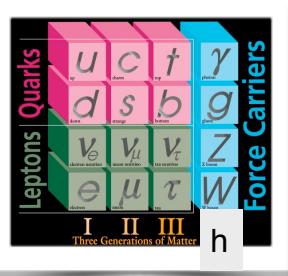
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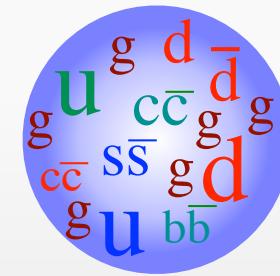
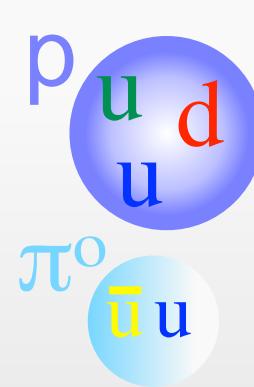
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$$\Lambda_{\text{QCD}} \sim 300 \text{ MeV}$$

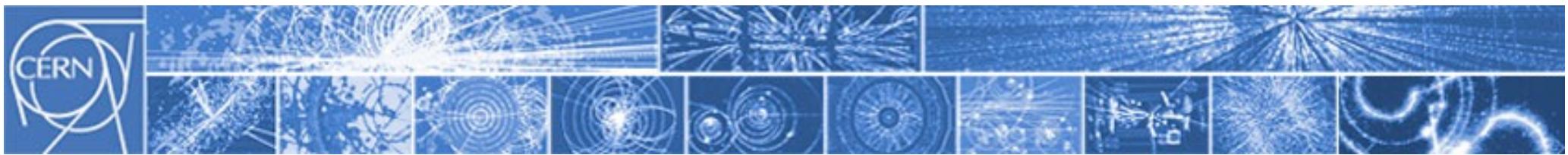
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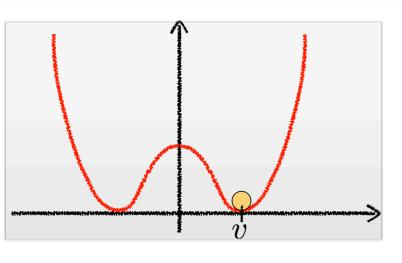
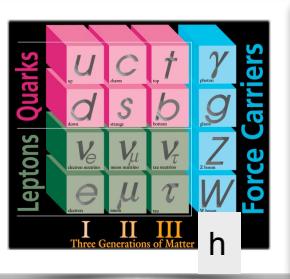
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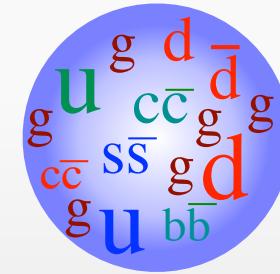
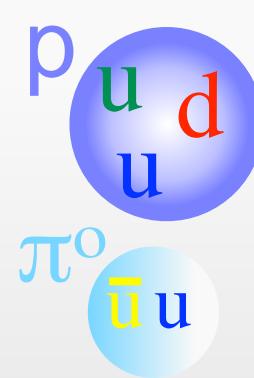
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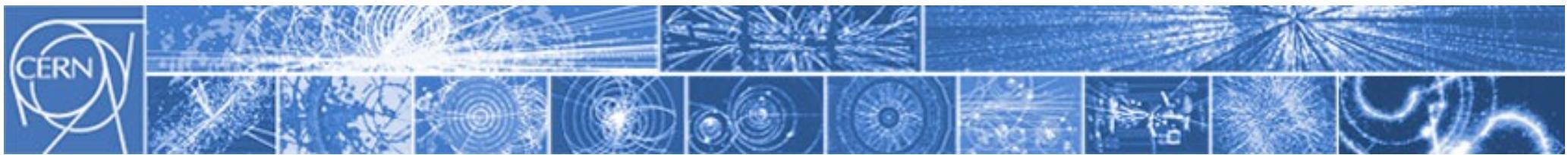
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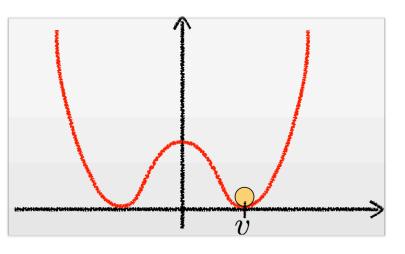
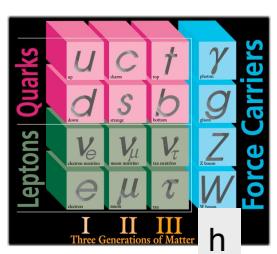
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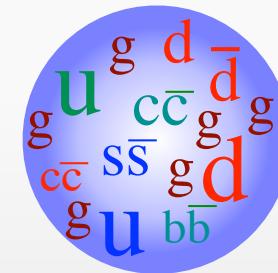
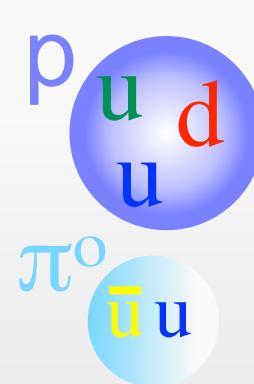
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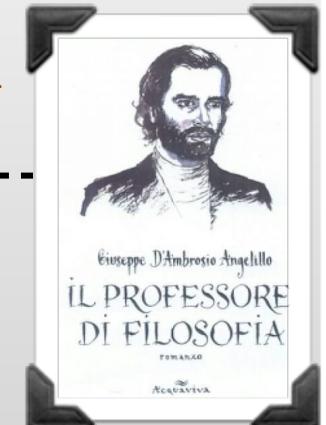
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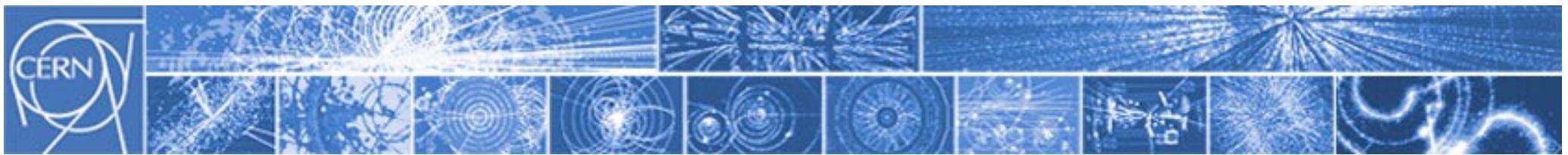


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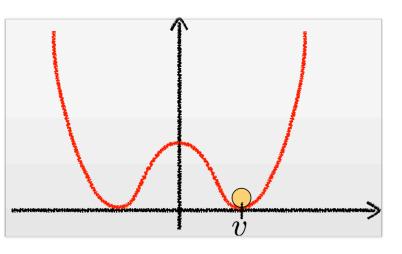
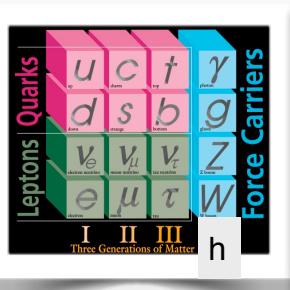
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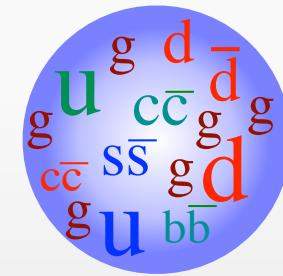
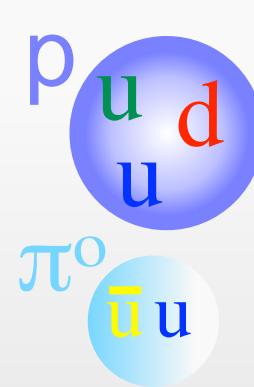
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resistenza opposta a una forza

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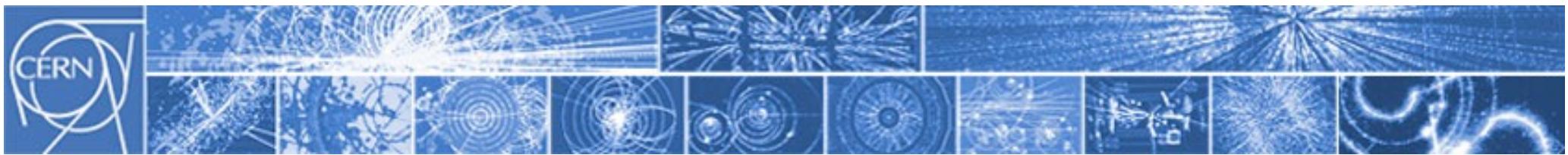
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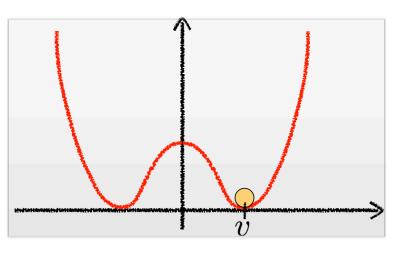
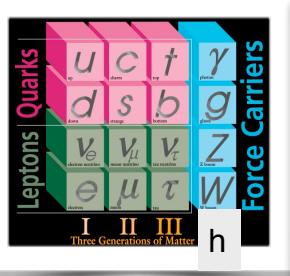
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$$F = G_N \frac{m_1 m_2}{r^2}$$



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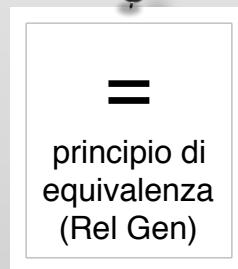
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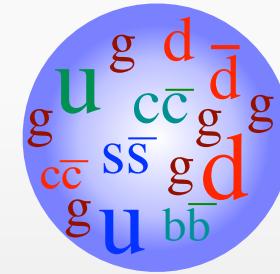
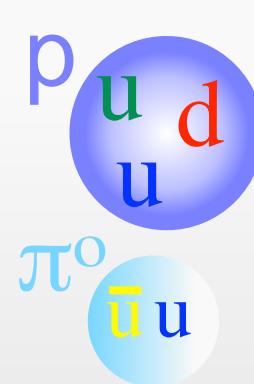
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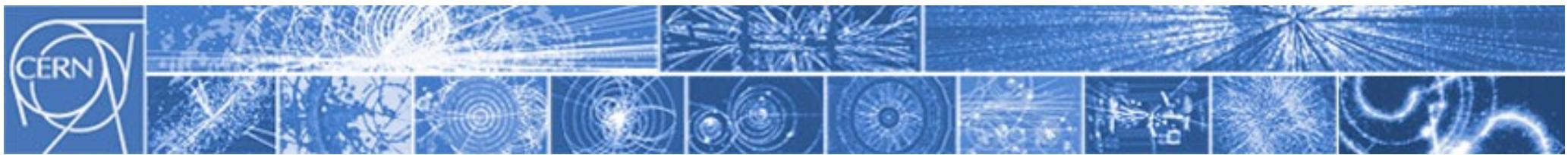
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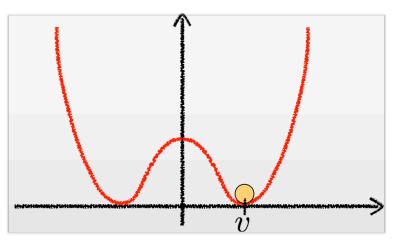
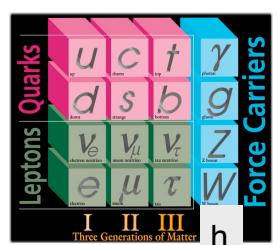
libertà asintotica (QCD):  
i quarks si rivestono di  
quarks e gluoni soffici,  
l'energia associata al  
ribollio è la massa

$M \gg \Lambda_{QCD}$  : break-up  
 $M \ll \Lambda_{QCD}$  : dress-up



# Recap: Origine della massa

## Particelle elementari



$$v \neq 0$$

(la proprietà intrinseca è  $y_i$ , non  $m_i$ )

La sorgente ultima è la porzione di energia del Big Bang cristallizzata nella transizione (di fase) EW e di QCD.

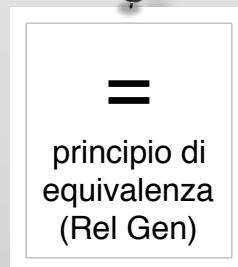
*Microfisica* spiega' da dove viene la massa

*Macrofisica* descrive come la massa determina il comportamento di un corpo

## Massa Inerziale

resistenza opposta a una forza

$$\vec{F} = m \vec{a}$$



## Massa Gravitazionale

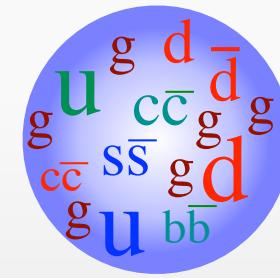
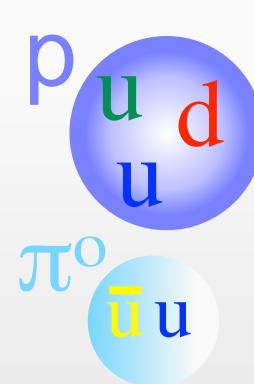
sorgente dell'attrazione gravitazionale

$$F = G_N \frac{m_1 m_2}{r^2}$$

*Scienze naturali, Chimica*

"La massa è il contenuto di materia di un corpo"

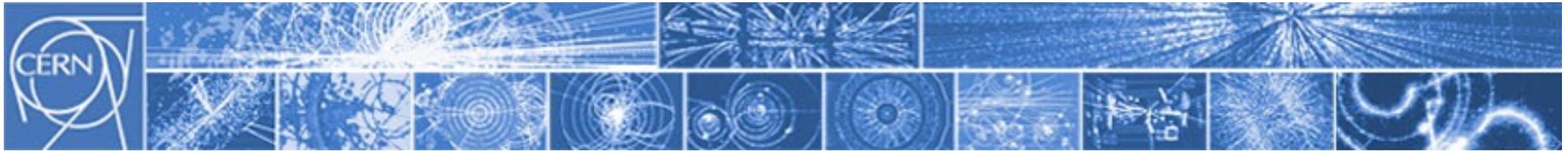
## Particelle composte (il 99.9% della massa di un oggetto quotidiano)



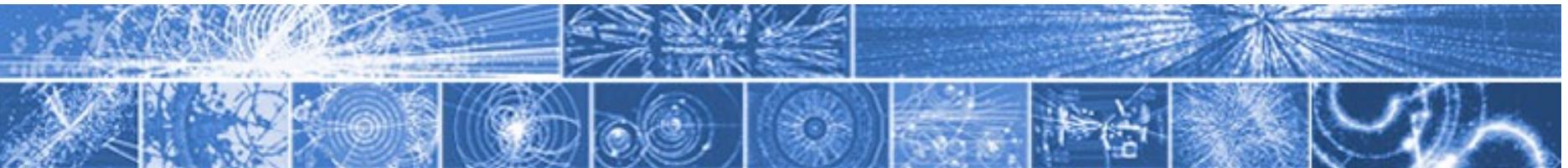
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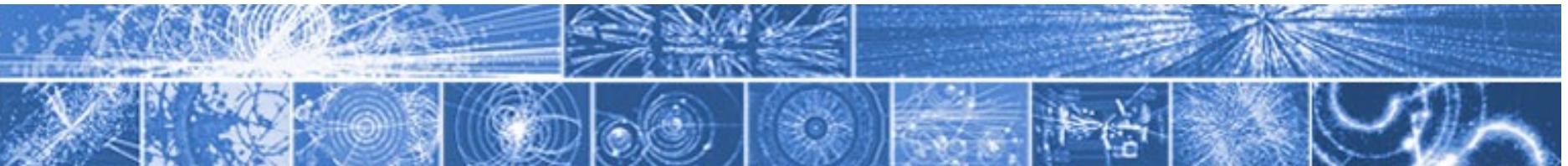
# Oltre il Modello Standard



## Problemi aperti in Fisica delle Particelle

- il *pattern* delle masse e le proprietà dell'higgs

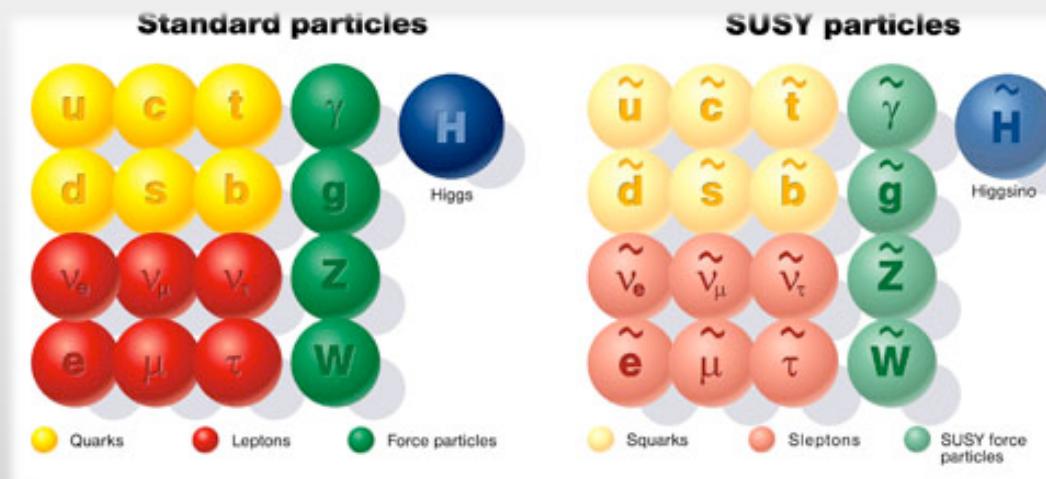


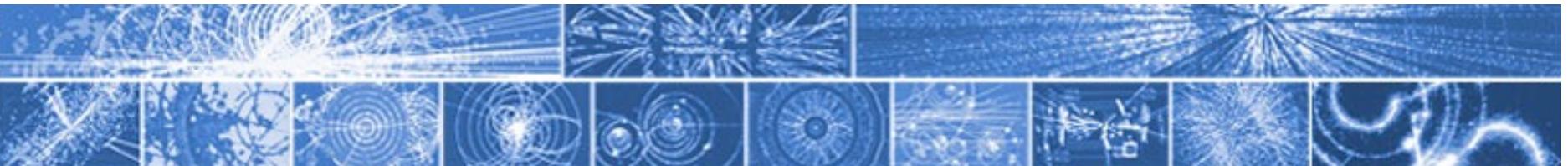


## Problemi aperti in Fisica delle Particelle



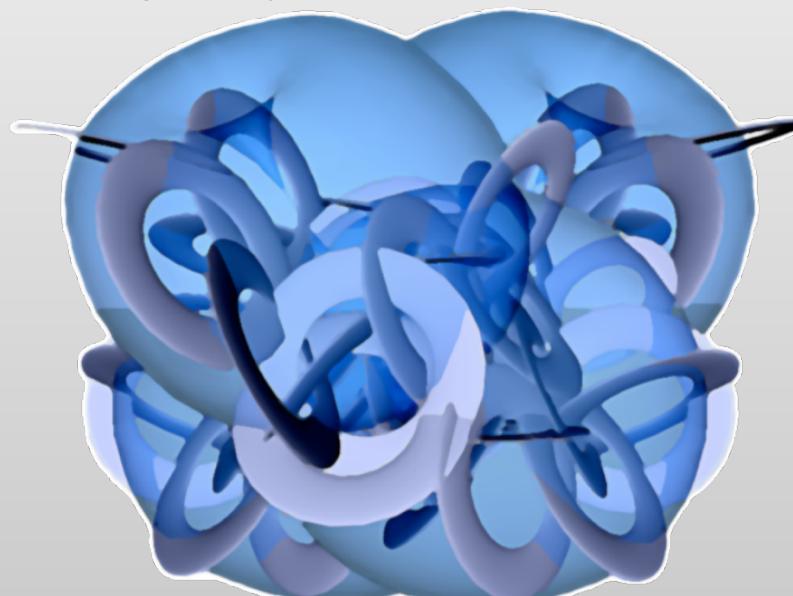
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- la supersimmetria  
(forse c'è un partner supersimmetrico per ogni tipo di particella nota!)

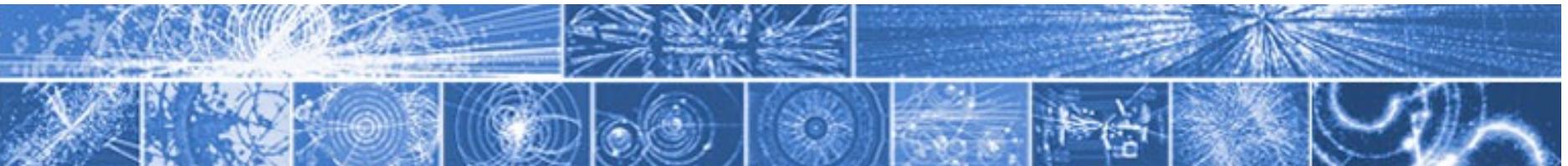




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- la supersimmetria  
(forse c'è un partner supersimmetrico per ogni tipo di particella nota!)
- le dimensioni dello spazio-tempo  
(forse ci sono più di 3 dimensioni spaziali!)





## Problemi aperti in Fisica delle Particelle

- il *pattern* delle masse e le proprietà dell'higgs



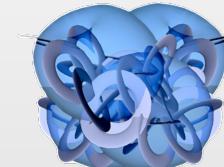
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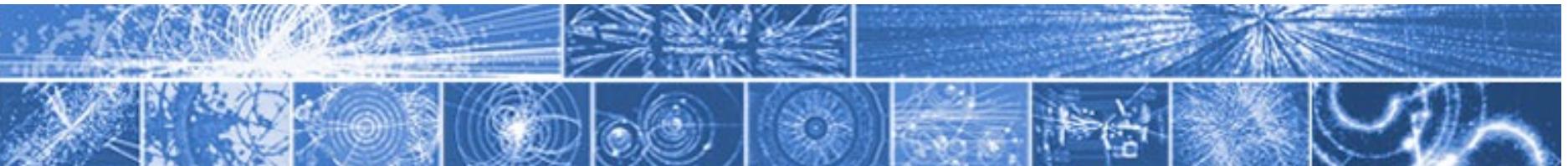
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- la Materia Oscura

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





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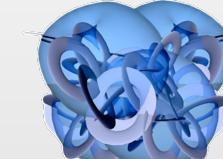
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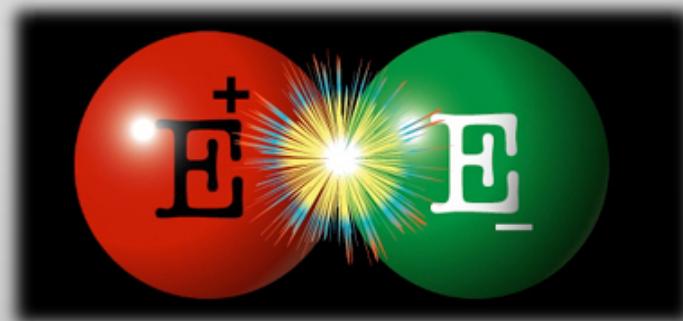


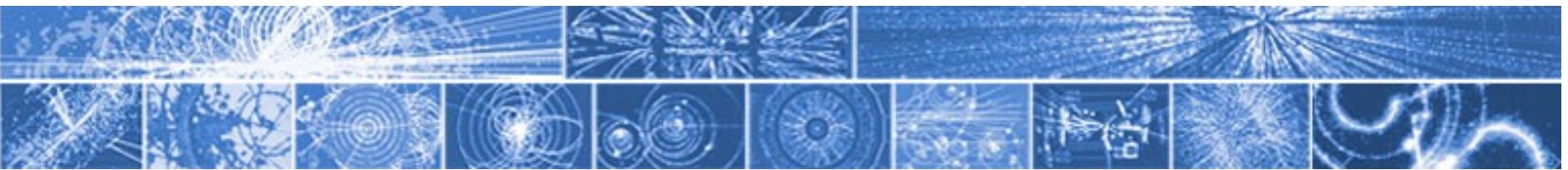
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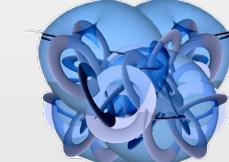
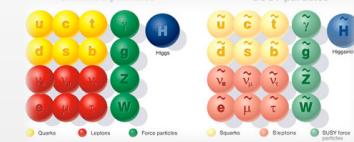
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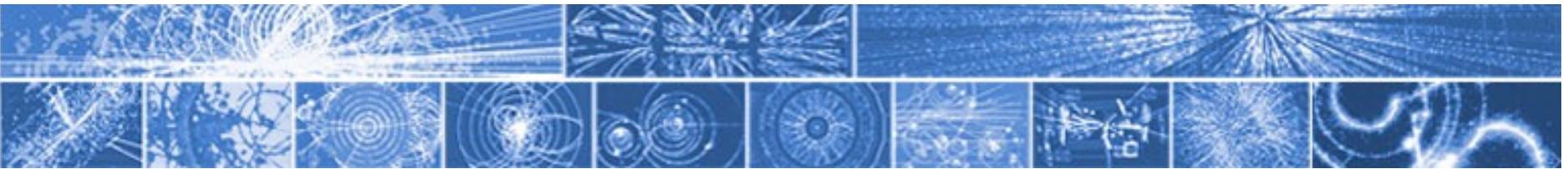




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(dove è finita tutta l'antimateria dell'Universo?)
- le masse e la natura dei neutrini  
(perché particelle così speciali?)
- ...





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