

Meccanismo di Higgs nell'Unificazione Elettrodebole

22 giugno 2007
Giuseppe Genovese

Partiamo da...

La simmetria di gauge elettrodebole è $SU(2)_L \times U(1)_Y$

Bosoni vettoriali intermedi $W_\mu^{1,2,3}, B_\mu$

$$W_\mu = \frac{W_\mu^1 + iW_\mu^2}{\sqrt{2}}$$

$$W_\mu^\dagger = \frac{W_\mu^1 - iW_\mu^2}{\sqrt{2}}$$

$$Z_\mu = \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}}$$

$$A_\mu = \frac{gW_\mu^3 + g'B_\mu}{\sqrt{g^2 + g'^2}}$$

... e i campi dei fermioni

$$\psi_L = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix}, \quad l_R \quad l = e, \mu, \tau$$

+ quark

la lagrangiana per le interazioni elettrodeboli è

$$\mathcal{L} = -\frac{1}{4}W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4}F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}_L \gamma_\mu D_\mu \psi_L + i\bar{l}_R \gamma_\mu D_\mu l_R$$

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INCOMPLETA

Dove sono le masse?

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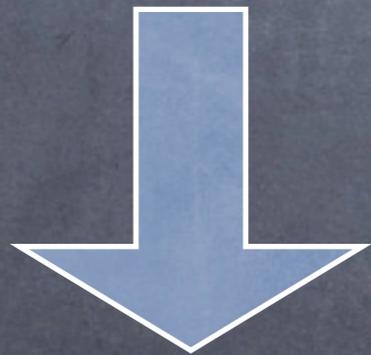
Le interazioni e. m.
hanno range infinito ($1/r$)

Le interazioni deboli
hanno range finito

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Mediatore senza massa

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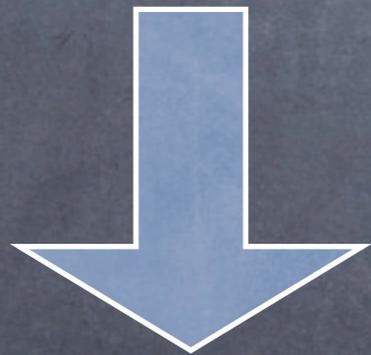


Mediatori massivi

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hanno range infinito ($1/r$)



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$$\frac{1}{2}M_W^2 W_\mu W^\mu$$

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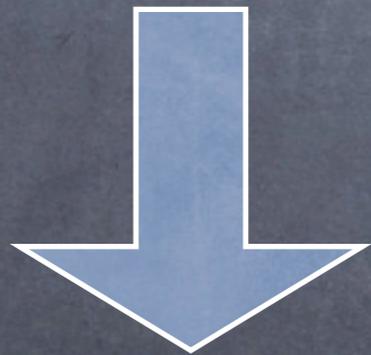


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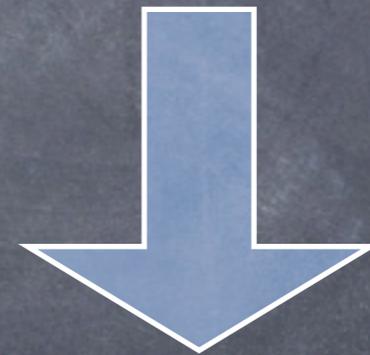
Le interazioni e. m.
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Mediatore senza massa

$$\frac{1}{2}M_W^2 W_\mu W^\mu \xrightarrow{\text{teoria}}$$

Le interazioni deboli
hanno range finito



Mediatori massivi

non invariante di gauge
non rinormalizzabile

Dove sono le masse? (bis)

i leptoni carichi $-m_l \bar{\psi}\psi = -m_l(\bar{l}_R l_L + \bar{l}_L l_R)$

distrugge la simmetria $SU(2)_L$

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distrugge la simmetria $SU(2)_L$

In definitiva:

Si deve trovare come scrivere una lagrangiana che:

- predica le masse dei bosoni di gauge
- sia invariante di gauge
- conduca ad una teoria rinormalizzabile

Rottura spontanea della simmetria

“Consider a chair. The equations governing the atoms of the chair are rotationally symmetric, but the solution of these equations, the chair, has a definite direction in space”

S. Weinberg

Rottura spontanea della simmetria

$$V(\phi) = \mu^2 \phi^2 + \lambda \phi^4 \quad \lambda > 0$$

$$V(\phi) = V(-\phi)$$

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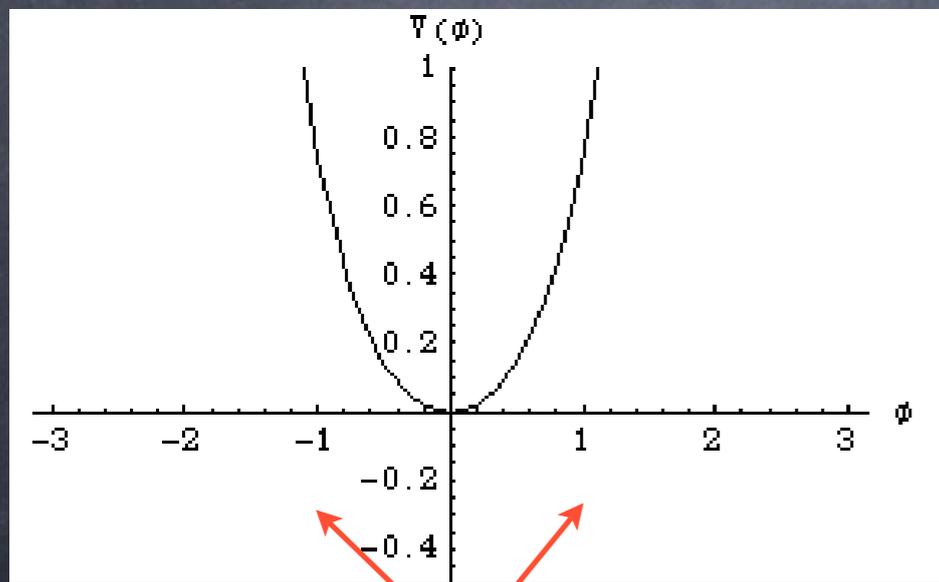
$$\begin{array}{l} \mu^2: \quad |\mu^2| \quad \longrightarrow \quad -|\mu^2| \\ v: \quad 0 \quad \longrightarrow \quad \pm \sqrt{\frac{-\mu^2}{\lambda}} \end{array}$$

 minimo del potenziale
(valore di aspettazione nel vuoto)

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Il vuoto si sdoppia: se ne deve scegliere uno rompendo la simmetria

$$\phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$

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

Invariante sotto U(1)

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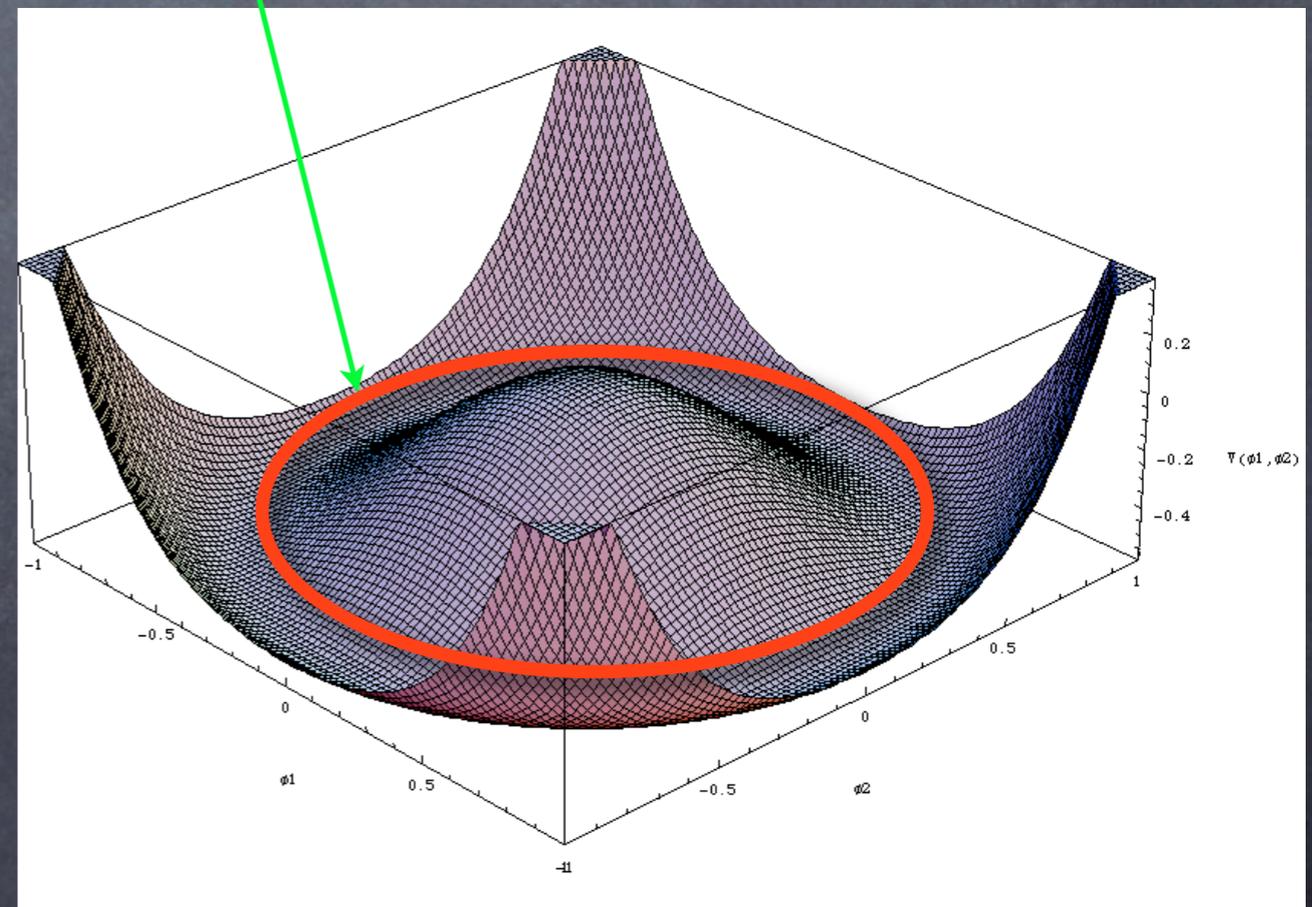
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Invariante sotto U(1)

$$v = e^{i\theta} \sqrt{\frac{\mu^2}{\lambda}}$$

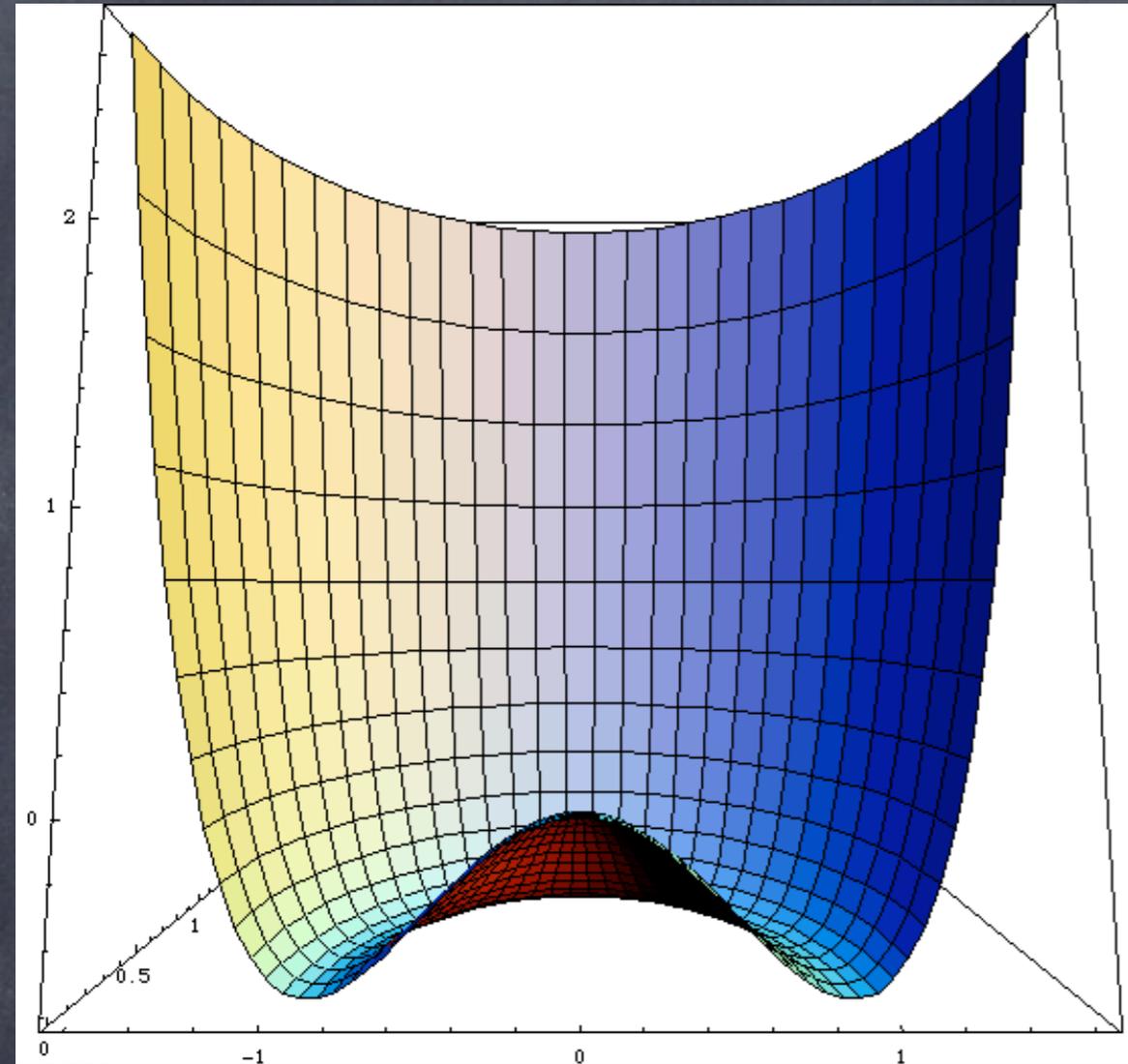
bisogna scegliere un punto sulla circonferenza

$$\begin{aligned} \mu^2 &< 0 \\ \lambda &> 0 \end{aligned}$$



Rottura di U(1) globale

$$\phi(x) = \frac{\rho(x)}{\sqrt{2}} e^{-i\alpha(x)/v}$$

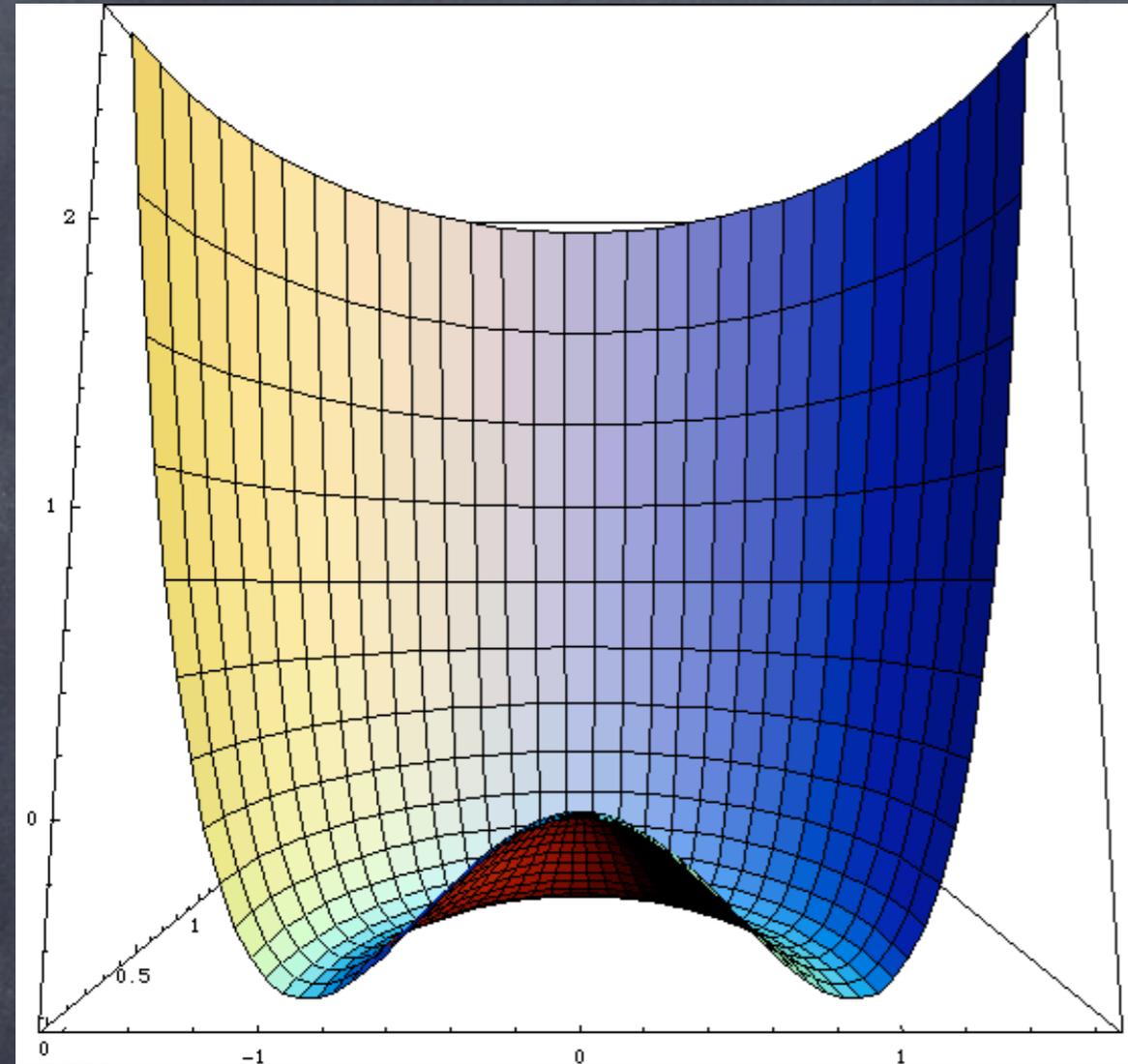


$$\mathcal{L} = \partial_\mu \phi^\dagger \partial^\mu \phi - \mu^2 |\phi|^2 - \lambda |\phi|^4 \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

$$|\phi_{min}| = \frac{v}{\sqrt{2}} \implies \langle 0 | \rho | 0 \rangle = v$$

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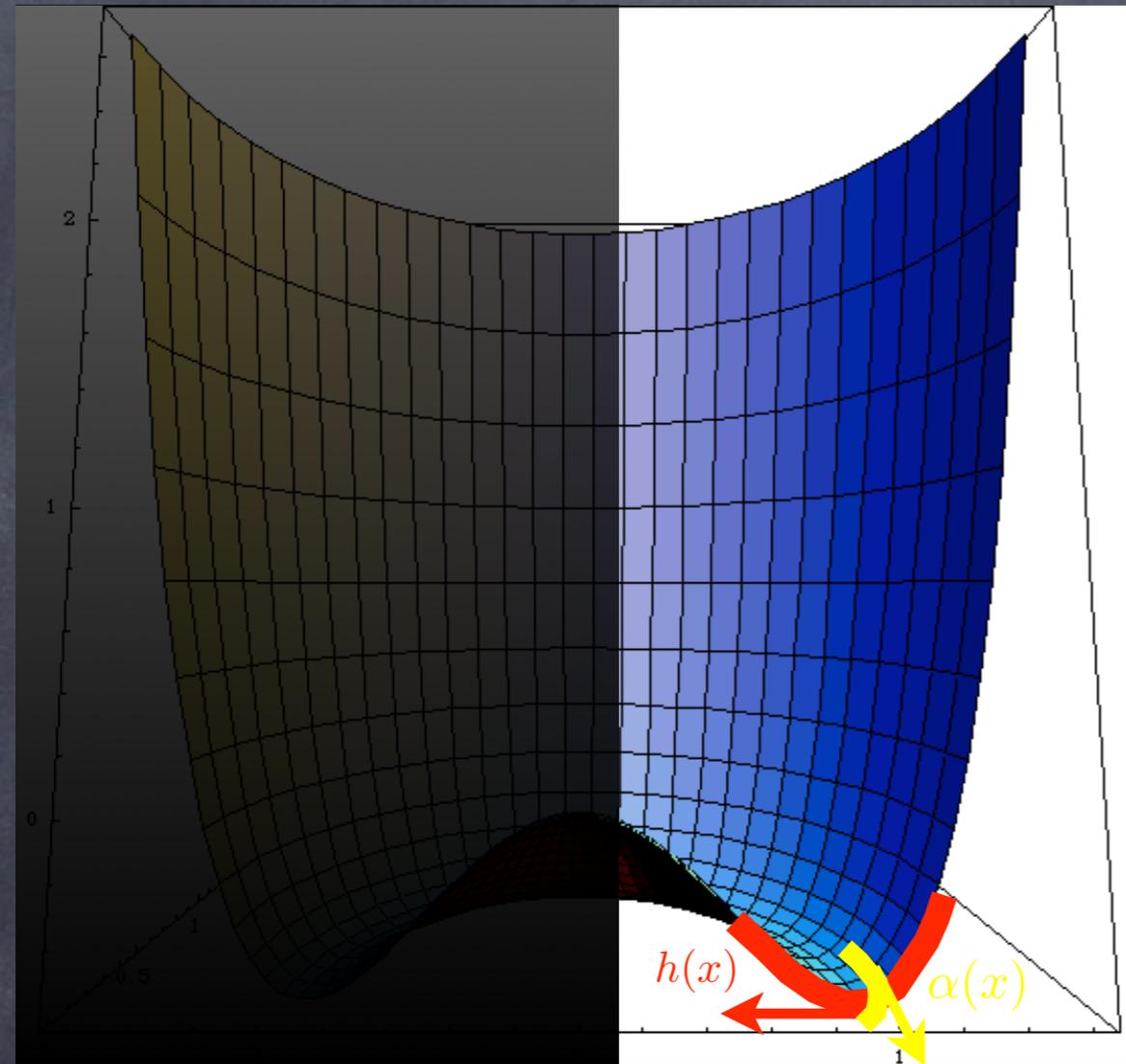
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Rottura di U(1) globale



$$\phi(x) = \frac{\rho(x)}{\sqrt{2}} e^{-i\alpha(x)/v}$$

$$\phi(x) = \frac{(v + h(x))}{\sqrt{2}} e^{-i\alpha(x)/v}$$

$$\langle 0|h|0\rangle = 0$$

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il campo $\alpha(x)$ non sente il potenziale \Rightarrow senza massa
il campo $h(x)$ oscilla attorno al vuoto \Rightarrow ha massa

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m_h^2

$$m_h = \sqrt{-2\mu^2}$$

bosone di Goldstone

Teorema di Goldstone

- Per ogni simmetria rotta spontaneamente la teoria prevede la presenza di particelle (spin-0) senza massa, i bosoni di Goldstone.
- Il numero di bosoni di Goldstone è uguale al numero di generatori "rotti".

Per $U(1)$ 1 generatore rotto \Rightarrow campo $\alpha(x)$

Rottura di simmetrie di gauge: $SU_L(2) \times U_Y(1)$

$$\mathcal{L} = -\frac{1}{4}W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4}F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}_L \gamma_\mu D_\mu \psi_L + i\bar{l}_R \gamma_\mu D_\mu l_R$$
$$+ \mathcal{L}_{SB} = D_\mu \phi^\dagger D^\mu \phi - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \frac{\alpha^2(x) + i\alpha^1(x)}{\sqrt{2}} \\ \frac{\sigma(x) - i\alpha^3(x)}{\sqrt{2}} \end{pmatrix}$$

$$\langle 0 | \phi^\dagger \phi | 0 \rangle = \langle 0 | [\sigma^2 + (\alpha^1)^2 + (\alpha^2)^2 + (\alpha^3)^2] | 0 \rangle = v^2$$

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elettricamente carico

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elettricamente neutro

$$\langle 0 | \phi^\dagger \phi | 0 \rangle = \langle 0 | [\sigma^2 + (\alpha^1)^2 + (\alpha^2)^2 + (\alpha^3)^2] | 0 \rangle = v^2$$

$$\sigma(x) = v + H(x)$$

$$\phi(x) = \begin{pmatrix} \frac{\alpha^2(x) + i\alpha^1(x)}{\sqrt{2}} \\ \frac{v + H(x) - i\alpha^3(x)}{\sqrt{2}} \end{pmatrix} = e^{-i\alpha^j(x)\tau_j/2v} \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix}$$

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gauge unitaria: elimina i bosoni di Goldstone

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$H(x)$ è il campo di Higgs

$$\mathcal{L}_{SB} = D_\mu \phi^\dagger D^\mu \phi - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

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$$\frac{1}{2} \partial_\mu H \partial^\mu H + \frac{g^2}{8} (v + H)^2 W_\mu^\dagger W^\mu + \frac{1}{8} (v + H)^2 (g^2 + g'^2) Z_\mu Z^\mu$$

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$$\mathcal{L} = \mathcal{L}_H + \mathcal{L}_{gauge} + \mathcal{L}_f + \mathcal{L}_{Int}$$

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$$\mathcal{L}_H = \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{1}{2} m_H^2 H^2$$

con

$$m_H = \sqrt{-2\mu^2}$$

Caso del fotone

$$\frac{1}{2} \partial_\mu H \partial^\mu H + \frac{g^2}{8} (v + H)^2 W_\mu^\dagger W^\mu + \frac{1}{8} (v + H)^2 (g^2 + g'^2) Z_\mu Z^\mu$$
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ortogonale, senza termine di massa

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ortogonale, senza termine di massa

$$\Rightarrow \mathcal{L}_\gamma = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \mathcal{L}_\gamma W, Z$$

Lagrangiana per i bosoni di gauge

$$\mathcal{L}_{gauge} = -\frac{1}{2}W_{\mu\nu}^\dagger W^{\mu\nu} + \frac{M_W^2}{2}W_\mu^\dagger W^\mu - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} \\ + \frac{M_Z^2}{2}Z_\mu Z^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_{intbg}$$

$$M_W = g \frac{v}{2}$$

$$M_Z = \sqrt{g^2 + g'^2} \frac{v}{2}$$

Accoppiamenti di Yukawa per i fermioni

Per gli elettroni:
$$\mathcal{L}_{M_e} = -g_e (\bar{l}_L^e \phi e_R + \bar{e}_R \phi^\dagger l_L^e)$$
$$= -\left(\frac{g_e v}{\sqrt{2}}\right) (\bar{e}_L e_R + \bar{e}_R e_L)$$

ne resta un altro termine d'interazione nella lagrangiana:

$$-\frac{g_e}{\sqrt{2}} H \bar{e} e = -\frac{M_e}{v} H \bar{e} e$$

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$$D = \begin{pmatrix} D^+ \\ D^- \end{pmatrix}$$

Diagram showing the definition of the doublet D . An arrow points from a question mark to D^+ , and another arrow points from ϕ to D^- .

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Diagram: An arrow points from a question mark '?' to the D^+ component, and another arrow points from the symbol ϕ to the D^- component.

ad esempio $\begin{pmatrix} u \\ d \end{pmatrix}$

Accoppiamenti di Yukawa per i fermioni

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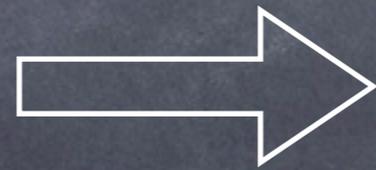
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Arrows: $\phi \rightarrow D^-$, $? \rightarrow D^+$



$$\begin{cases} Y_\phi = 1 \\ Y_{\tilde{\phi}} = -1 \end{cases}$$

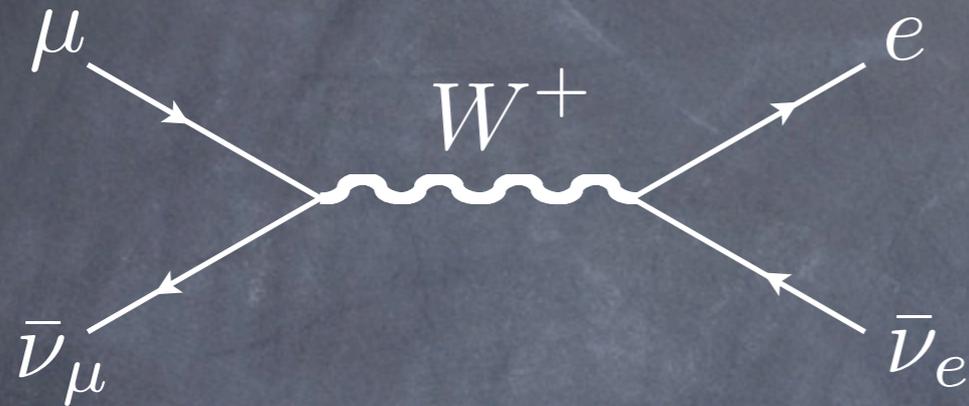
ad esempio $\begin{pmatrix} u \\ d \end{pmatrix}$

$$\tilde{\phi} = i\tau_2 \phi^*$$

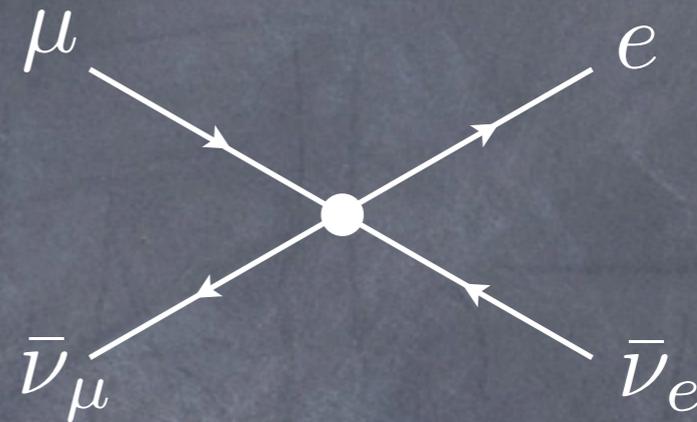
Termini di interazione

$$\mu \rightarrow e \bar{\nu}_e \nu_\mu$$

EW unificata



Fermi



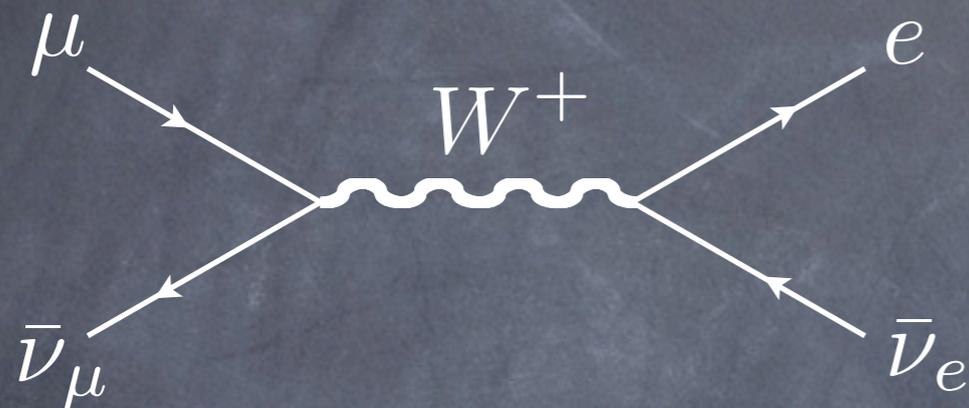
$$\frac{g^2}{16} \bar{\nu}_{\mu L} i \gamma_\rho \mu_L \left(\frac{-g^{\sigma\rho}}{p^2 - M_W^2} \right) \bar{e}_L i \gamma_\sigma \nu_{eL}$$

$$\frac{G_\mu}{\sqrt{2}} \bar{\nu}_{\mu L} \mu_L \bar{e}_L \nu_{eL}$$

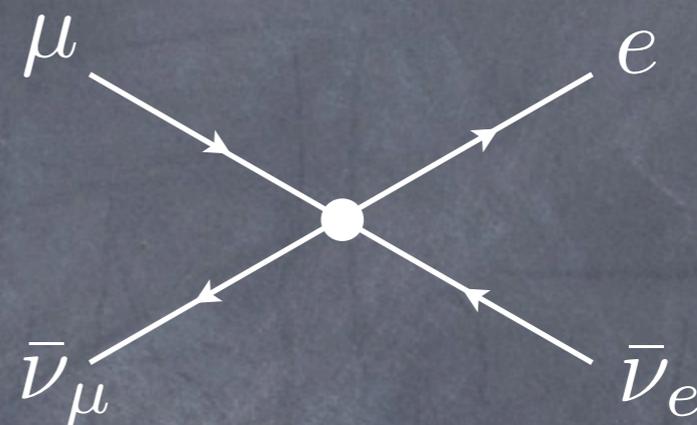
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Fermi



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$$\frac{G_\mu}{\sqrt{2}} \bar{\nu}_{\mu L} \mu_L \bar{e}_L \nu_{eL}$$

$$M_W \gg Q \quad \Downarrow$$

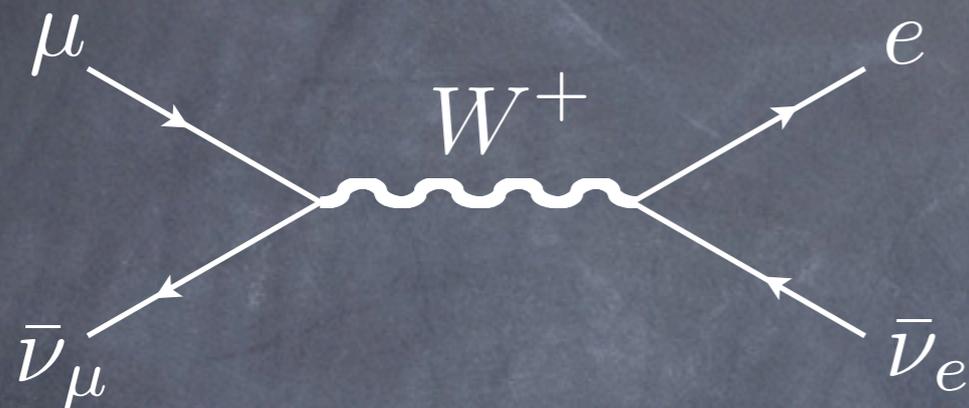
$$\frac{g^2}{8M_W^2} \bar{\nu}_{\mu L} \mu_L \bar{e}_L \nu_{eL}$$

Termini di interazione

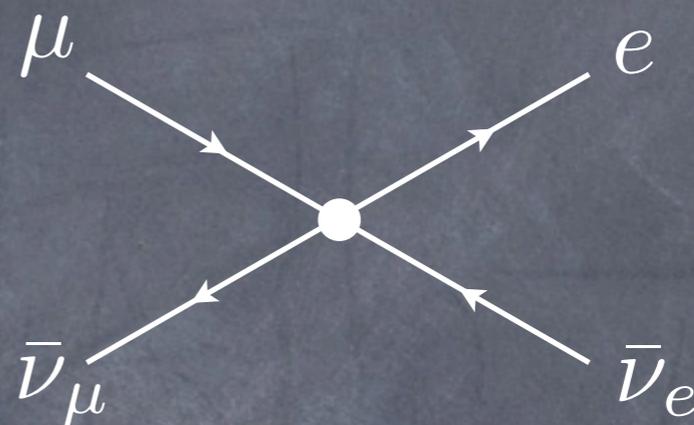
$$M_W^2 = \frac{g^2 v^2}{4}$$

$$\mu \rightarrow e \bar{\nu}_e \nu_\mu$$

EW unificata



Fermi



$$\frac{g^2}{16} \bar{\nu}_{\mu L} i \gamma_\rho \mu_L \left(\frac{-g^{\sigma\rho}}{p^2 - M_W^2} \right) \bar{e}_L i \gamma_\sigma \nu_{eL} \rightarrow \frac{G_\mu}{\sqrt{2}} \bar{\nu}_{\mu L} \mu_L \bar{e}_L \nu_{eL}$$

$$M_W \gg Q \quad \Downarrow$$

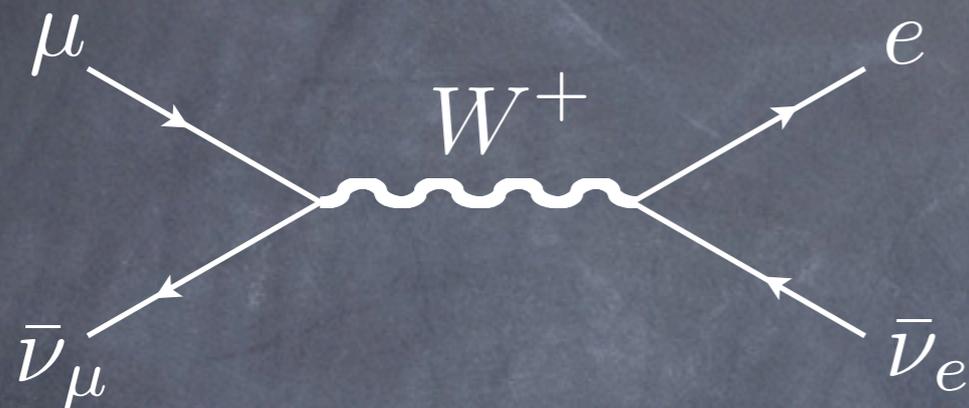
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Termini di interazione

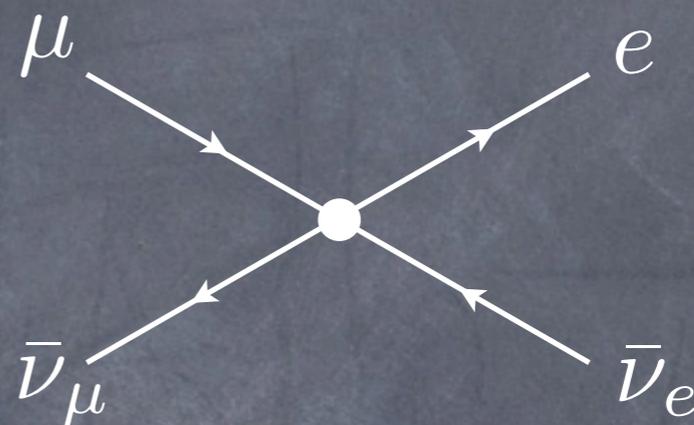
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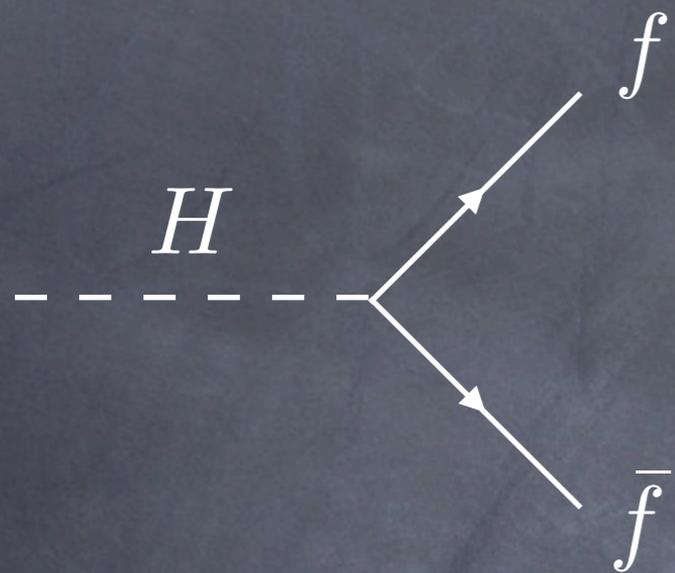
$$\frac{g^2}{16} \bar{\nu}_{\mu L} i \gamma_\rho \mu_L \left(\frac{-g^{\sigma\rho}}{p^2 - M_W^2} \right) \bar{e}_L i \gamma_\sigma \nu_{eL} \rightarrow \frac{G_\mu}{\sqrt{2}} \bar{\nu}_{\mu L} \mu_L \bar{e}_L \nu_{eL}$$

$$M_W \gg Q$$



$$\frac{g^2}{8M_W^2} \bar{\nu}_{\mu L} \mu_L \bar{e}_L \nu_{eL}$$

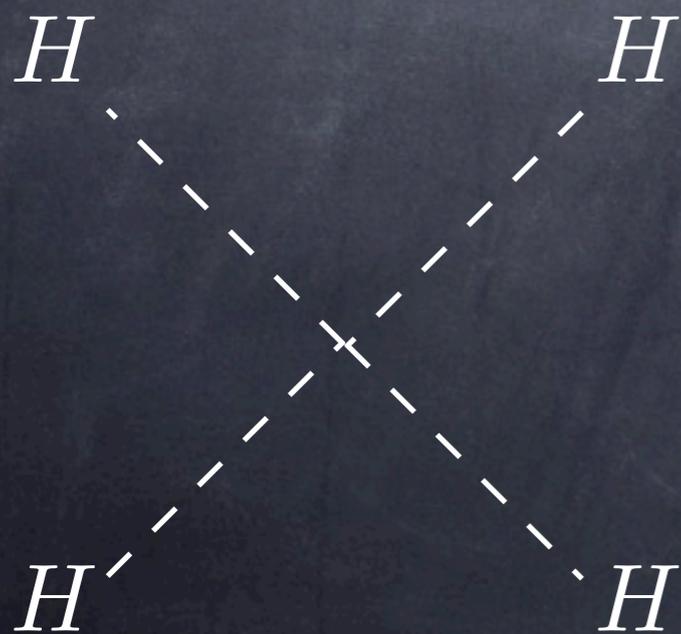
$$v = \sqrt{\sqrt{2} G_\mu} \sim 246 \text{ GeV}$$



$$g_{Hff} = i\sqrt{\sqrt{2}G_\mu}M_f$$



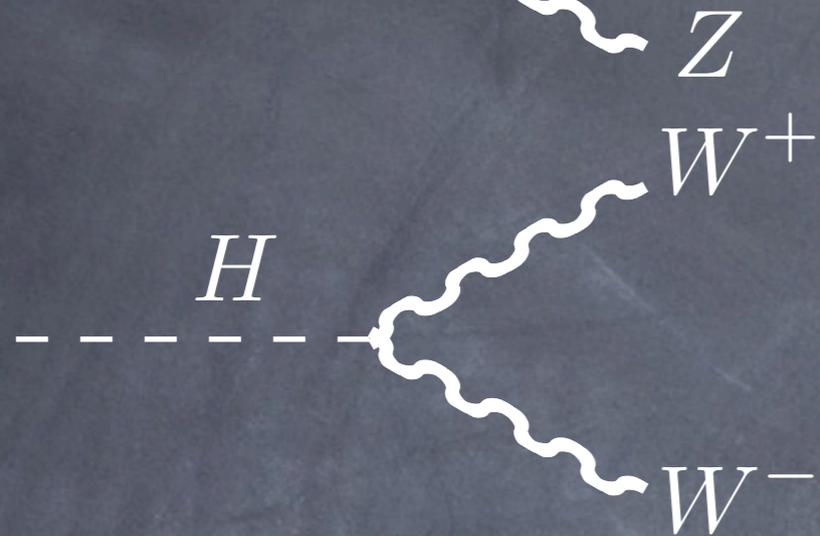
$$g_{HHH} = i3\sqrt{\sqrt{2}G_\mu}M_H^2$$



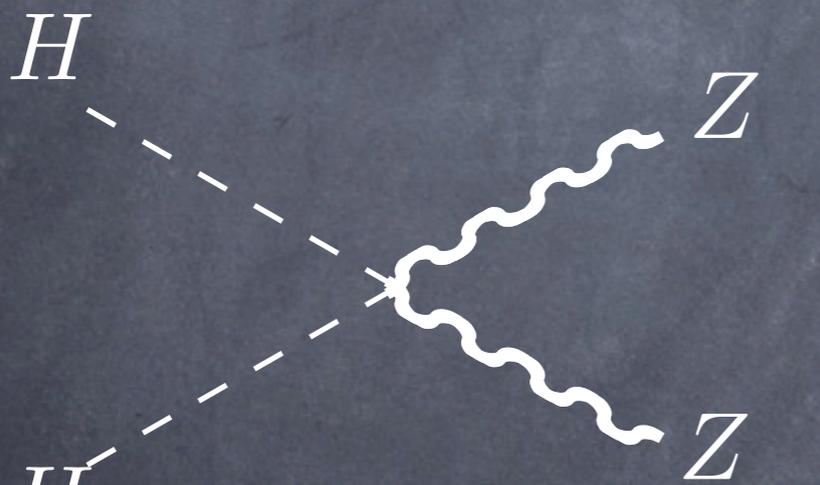
$$g_{HHHH} = i3\sqrt{2}G_\mu M_H^2$$



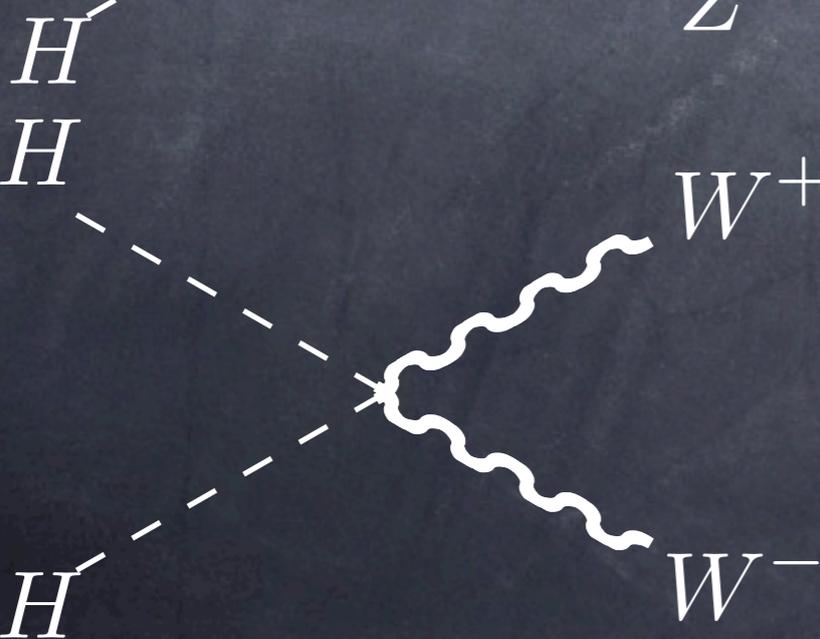
$$g_{HZZ} = -ig_{\mu\nu}2\sqrt{\sqrt{2}G_{\mu}M_Z^2}$$



$$g_{HWW} = -ig_{\mu\nu}2\sqrt{\sqrt{2}G_{\mu}M_W^2}$$

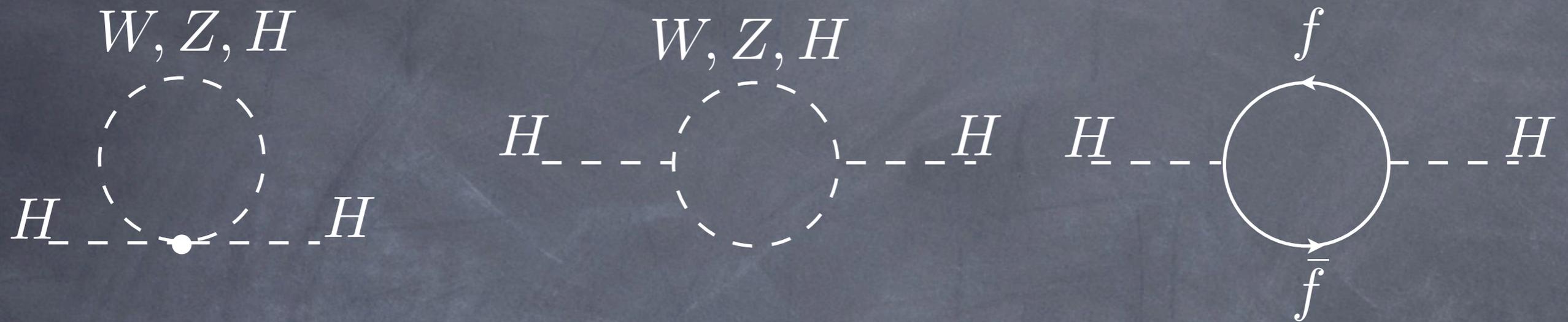


$$g_{HHZZ} = -ig_{\mu\nu}2\sqrt{2}G_{\mu}M_Z^2$$



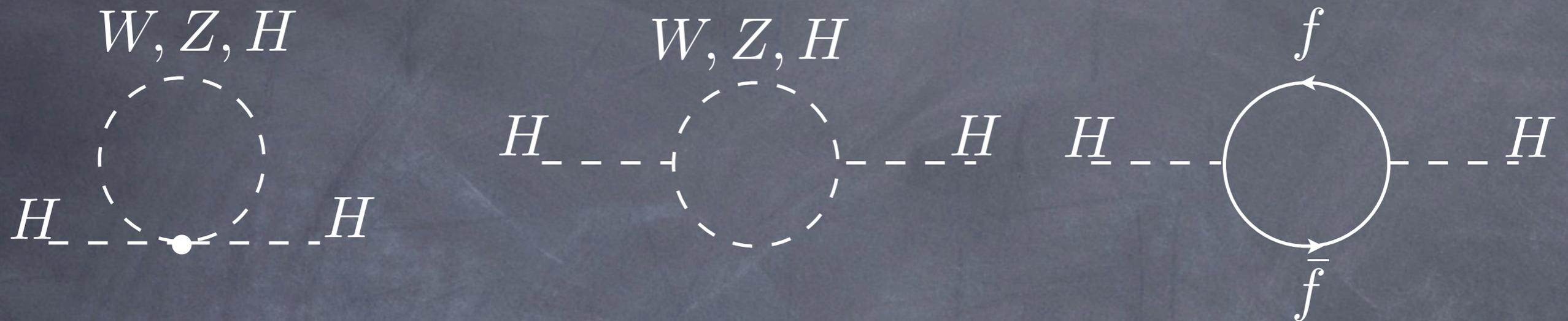
$$g_{HHWW} = -ig_{\mu\nu}2\sqrt{2}G_{\mu}M_W^2$$

Il problema del fine-tuning



$$M_H^2 = (M_H^0)^2 + \frac{3\Lambda^2}{8\pi^2 v^2} (M_H^2 + 2M_W^2 + M_Z^2 - 4m_t^2)$$

Il problema del fine-tuning

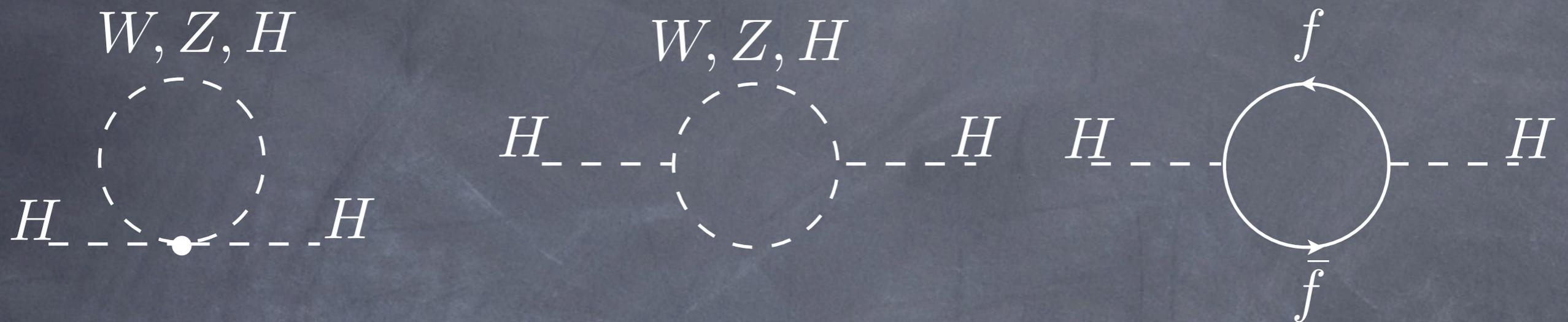


cut-off: dipendenza quadratica!

t è il più pesante

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Il problema del fine-tuning



cut-off: dipendenza quadratica!

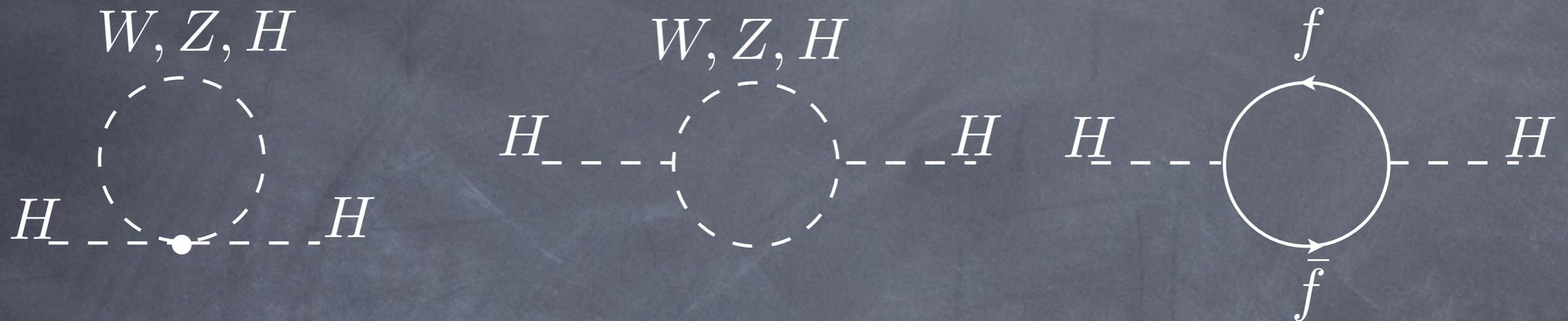
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se $\Lambda \sim 10^{19} \text{ GeV}$ (gravità)

$$M_H \sim 100 \text{ GeV} \rightarrow 1 \text{ TeV}$$

Il problema del fine-tuning



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numeri a 38 cifre che differiscono per le ultime 4 o 5!

se $\Lambda \sim 10^{19} \text{ GeV}$ (gravità)

$$M_H \sim 100 \text{ GeV} \rightarrow 1 \text{ TeV}$$

Conclusioni e Prospettive

- Il meccanismo di Higgs offre la possibilità di introdurre le masse nella teoria con l'unico "scotto" di predire una particella, finora non osservata, corrispondente al campo di Higgs.
- La natura scalare del campo di Higgs dà origine al problema del fine-tuning. Alla luce di ciò, sembra lecito predire un cut-off per la teoria dell'ordine del TeV. LHC porterà informazioni sulla fisica alla scala del cut-off.