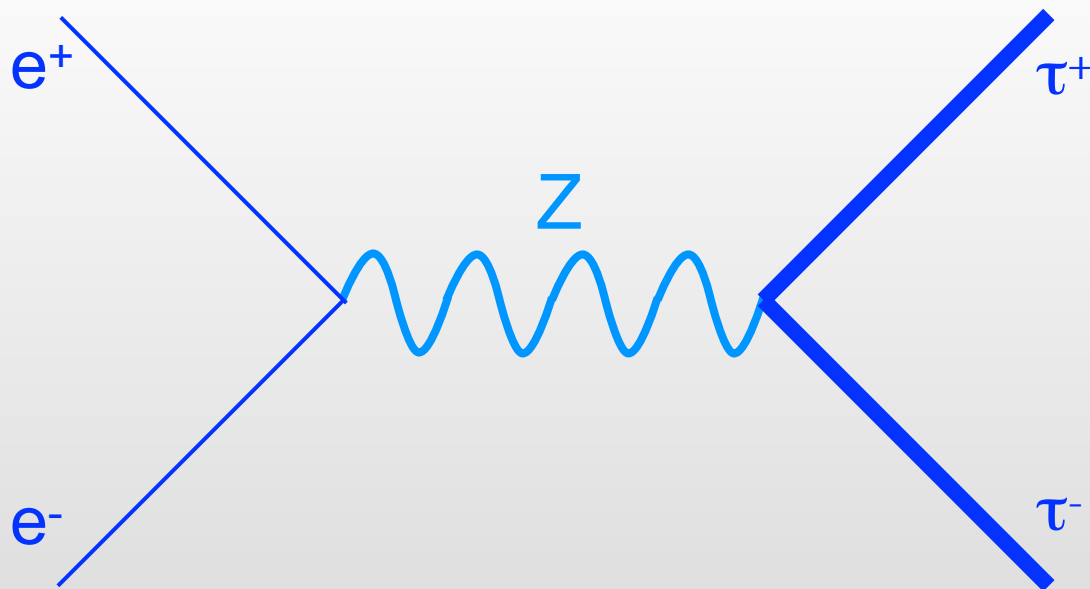


# I diagrammi di Feynman al lavoro

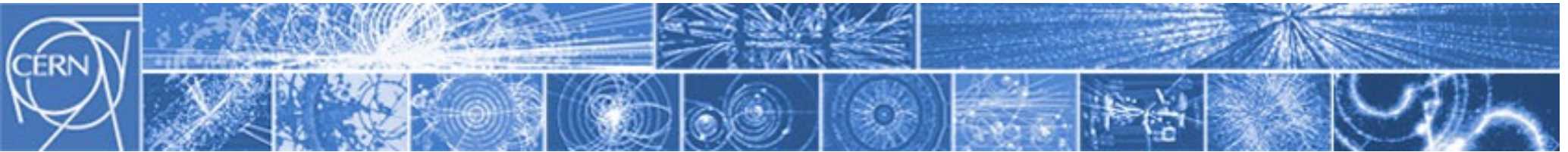
## *Esempio 1: collisione $e^+e^-$*

*(semirigoroso)*

**LEP**  
105 GeV



- carica elettrica
- sapore leptonic indiv.

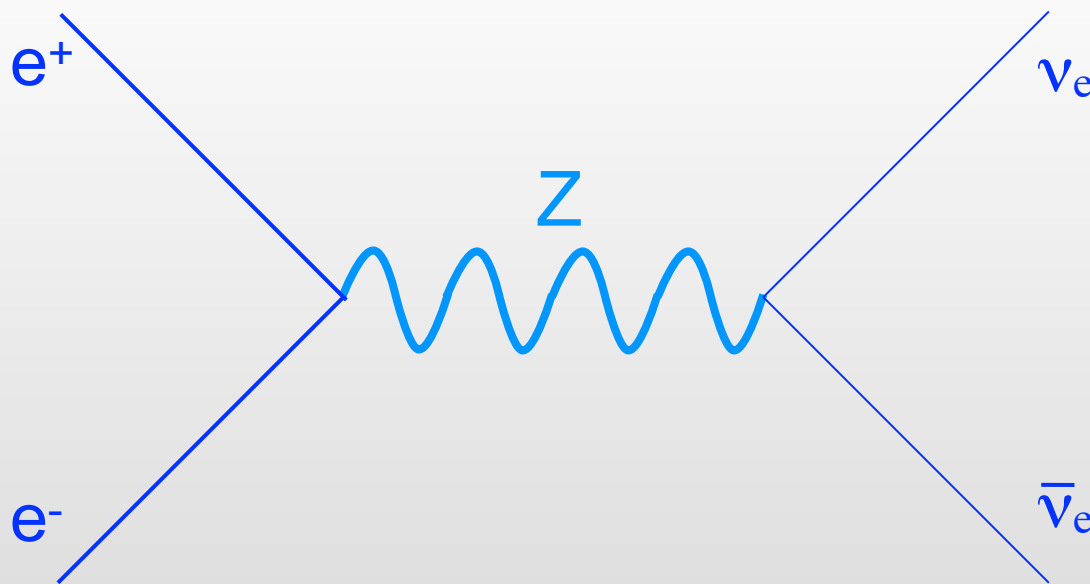


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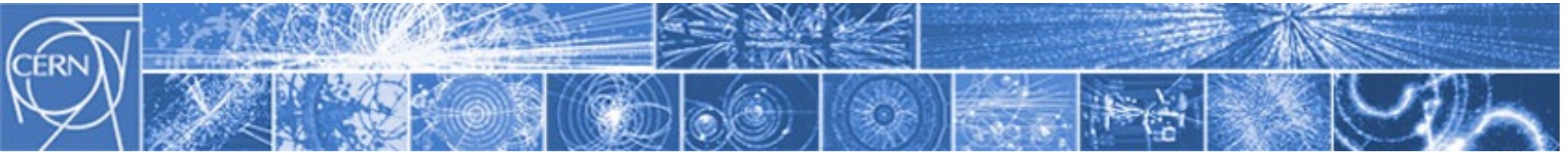
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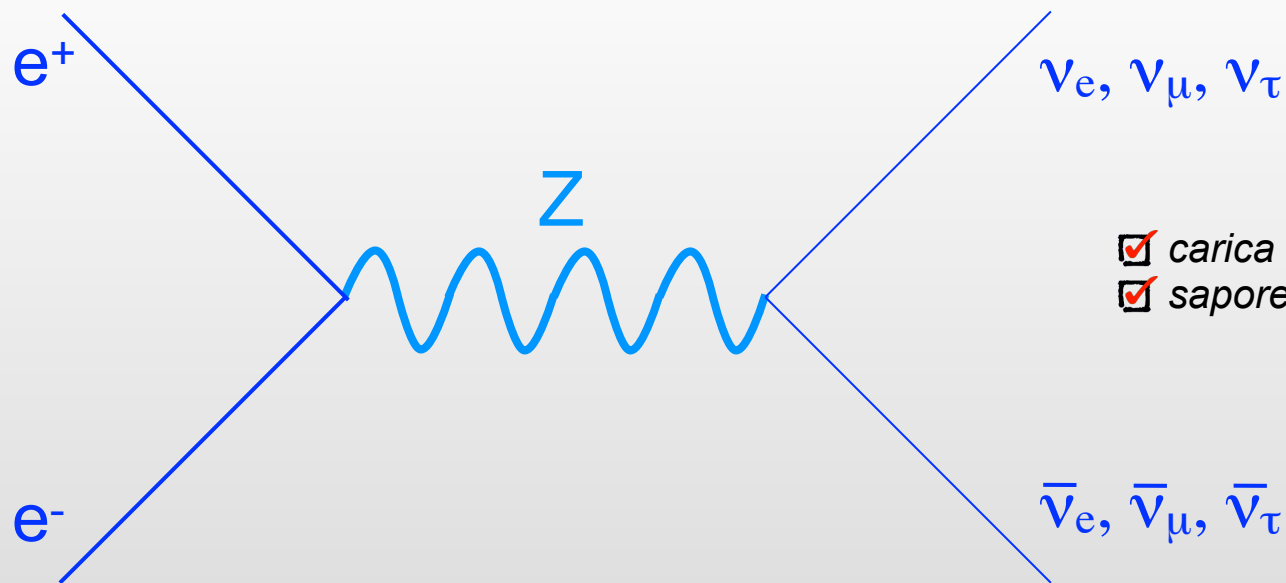


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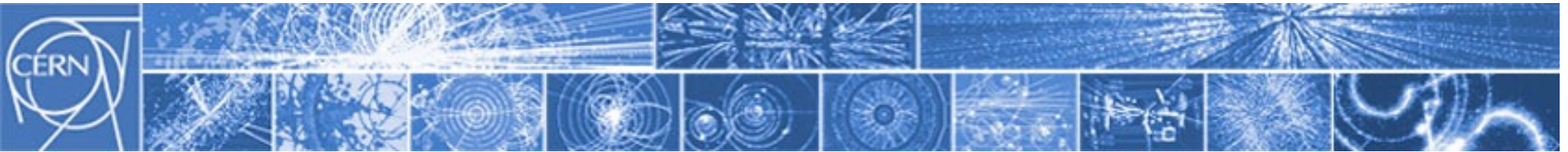
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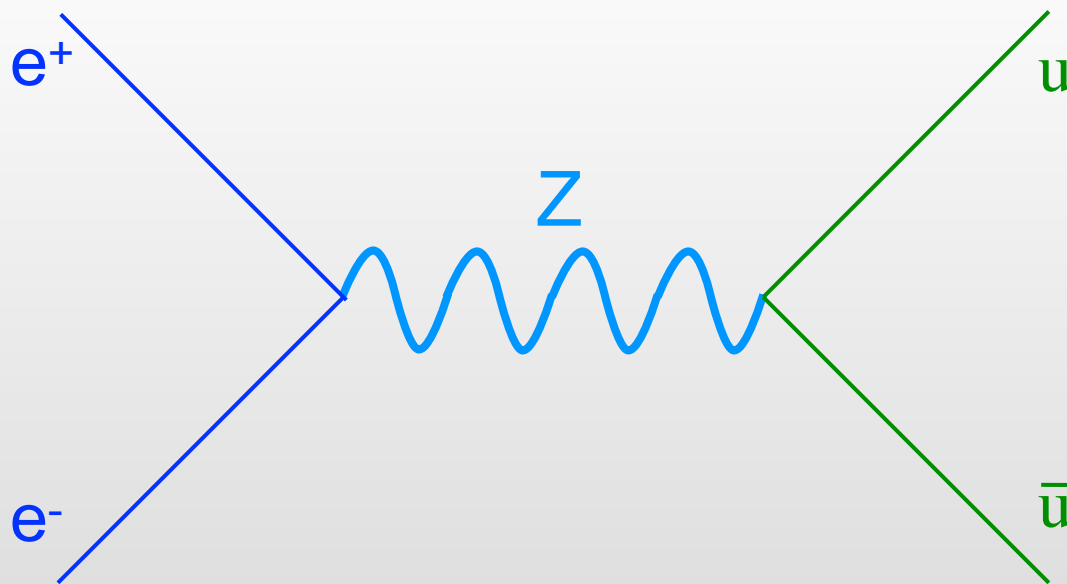


# I diagrammi di Feynman al lavoro

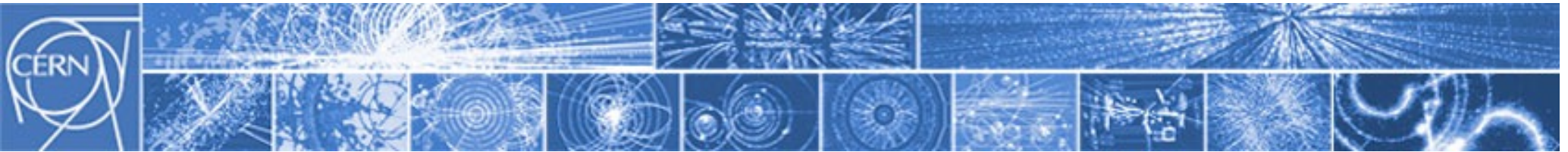
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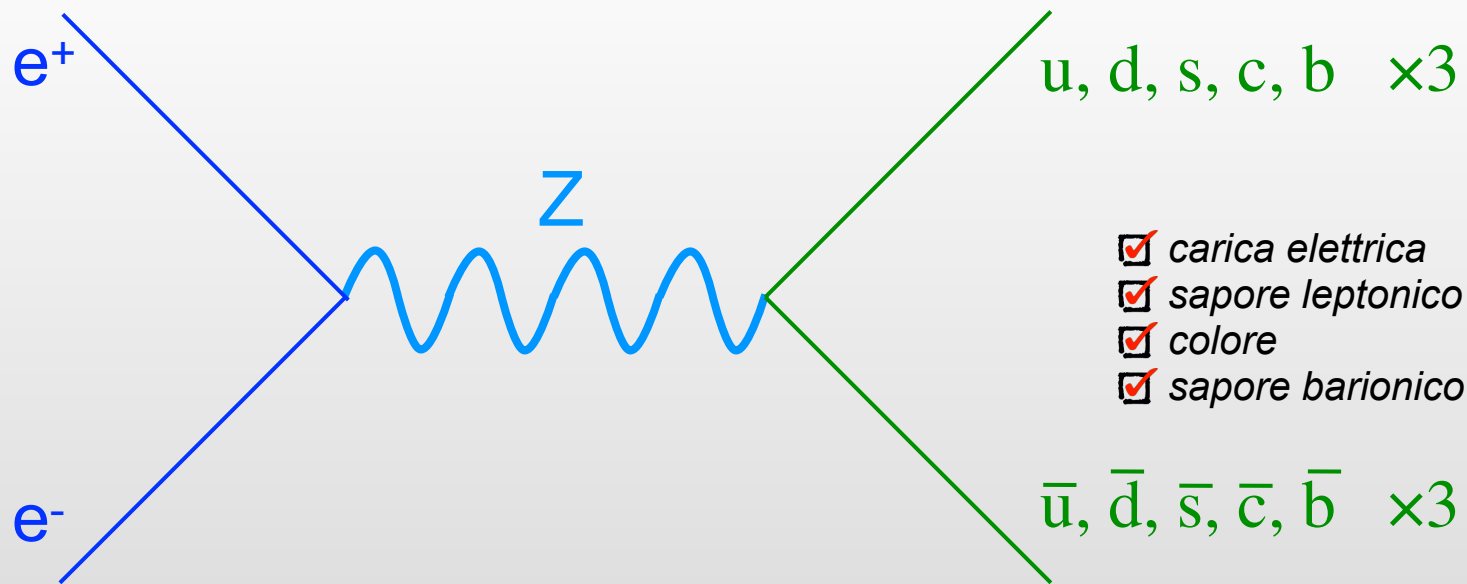


# I diagrammi di Feynman al lavoro

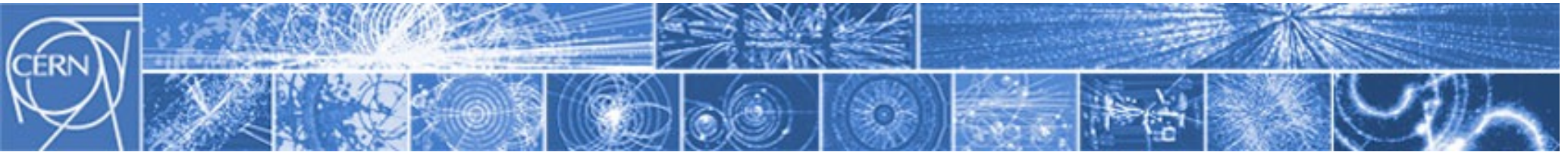
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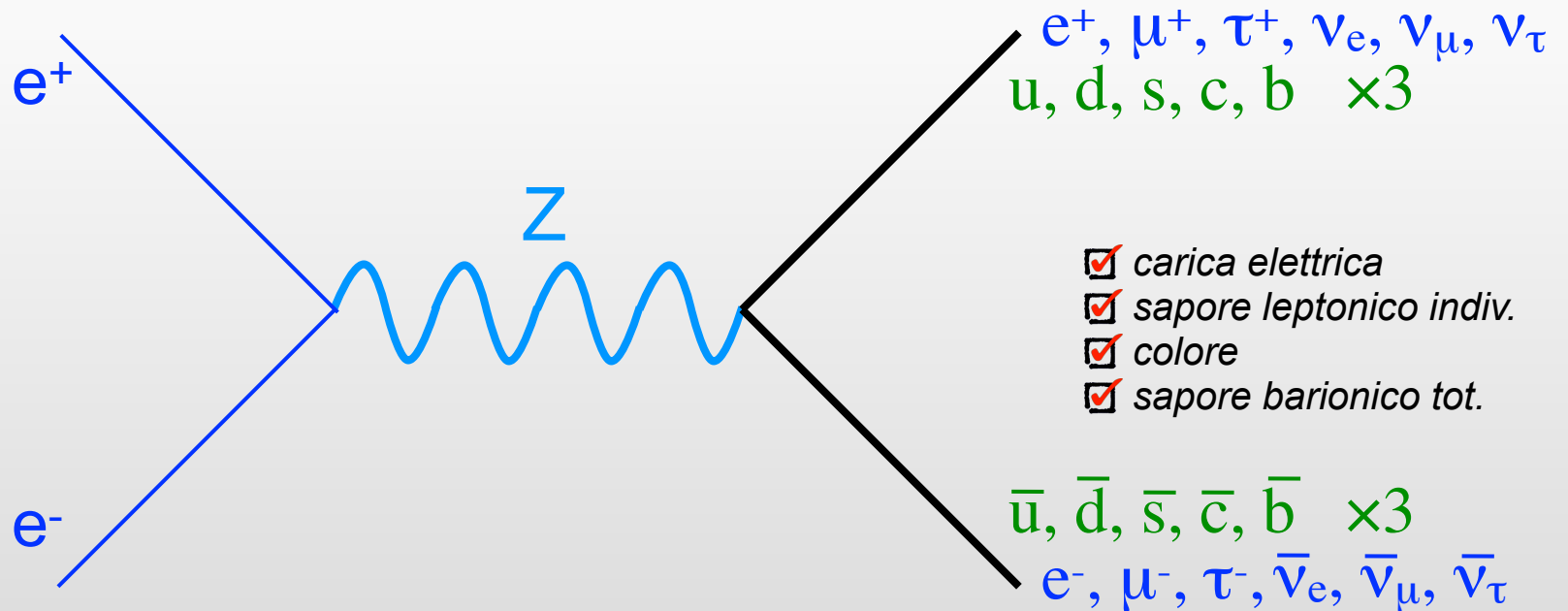


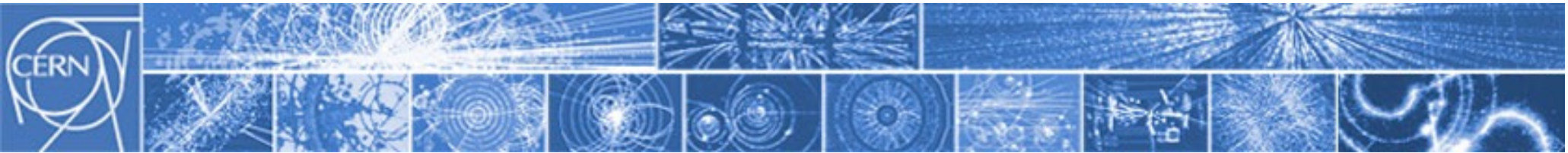
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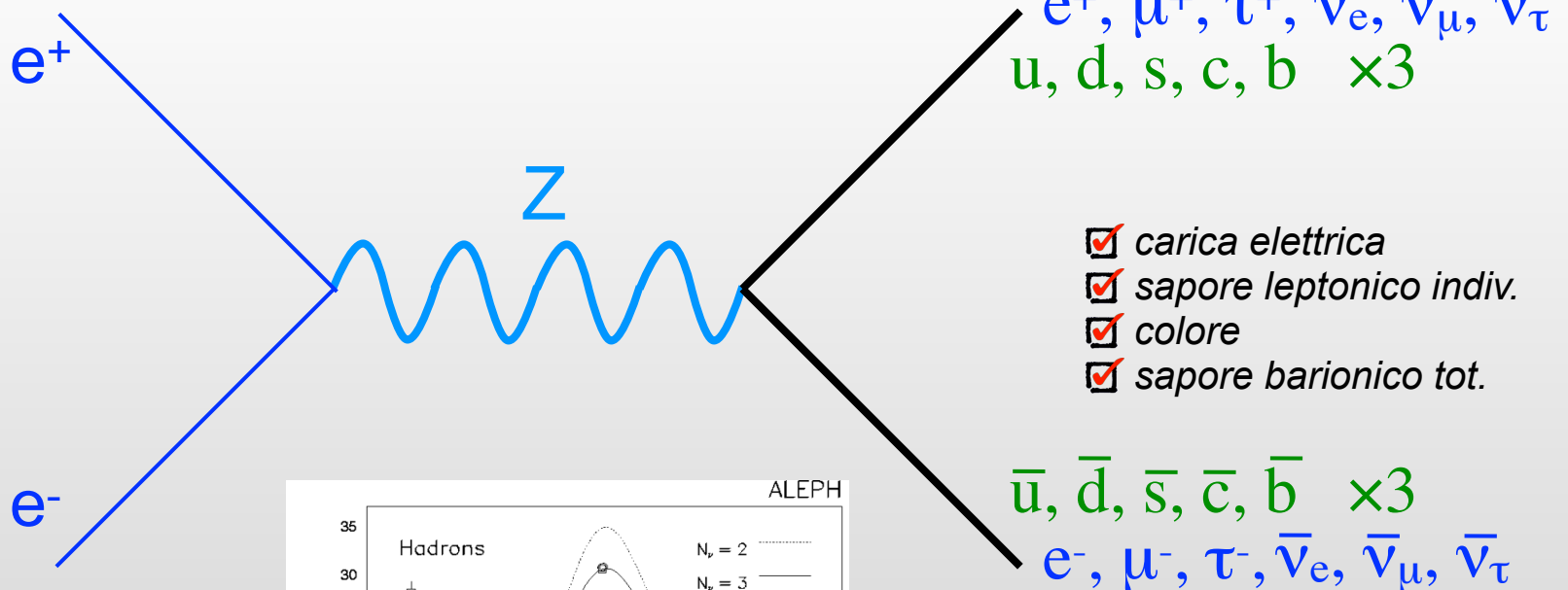




# I diagrammi di Feynman al lavoro

## Esempio 1: collisione $e^+e^-$

(semirigoroso)

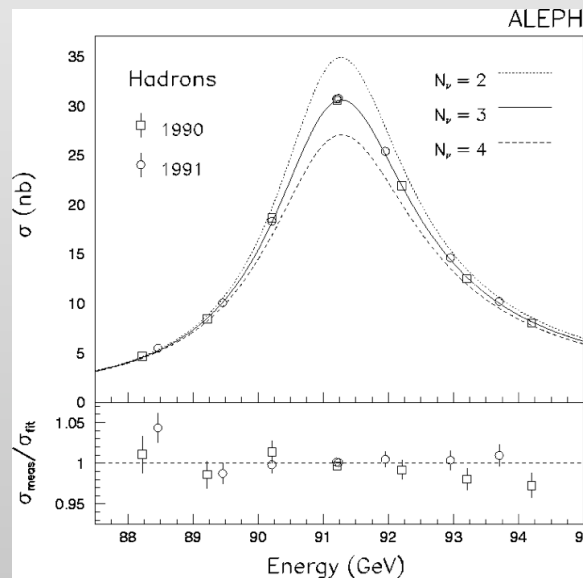


**LEP**  
105 GeV

- carica elettrica
- sapore leptonico indiv.
- colore
- sapore barionico tot.

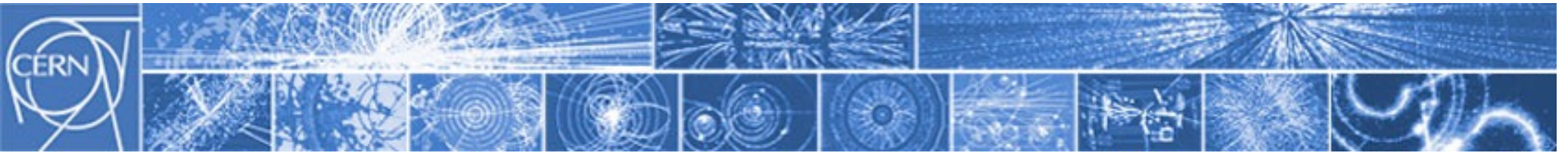
La *larghezza* della Z  
permette di determinare  
il numero di famiglie:

più canali aperti =  
decadimento più veloce =  
più larga



**$\Rightarrow$  3 famiglie!**

(a meno che il quarto neutrino  
non abbia massa  $> \sim 45$  GeV)

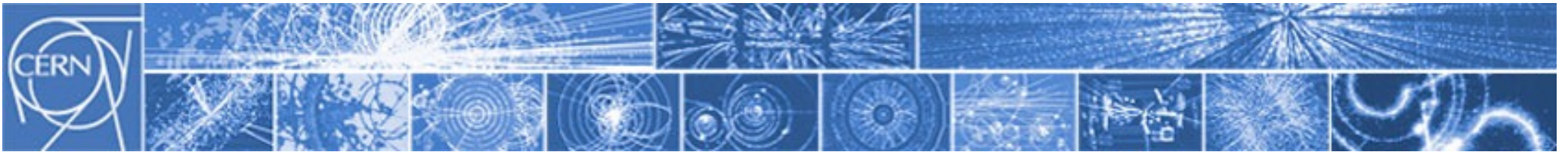


# I diagrammi di Feynman al lavoro

## *Esempio 2: collisione $p\bar{p}$*

*(semirigoroso)*



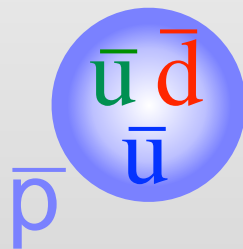
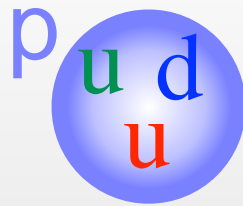


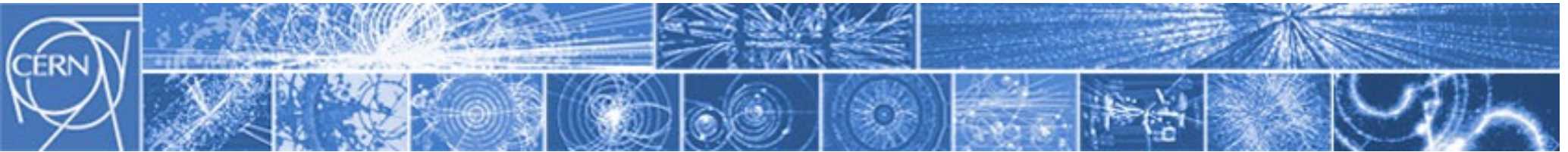
# I diagrammi di Feynman al lavoro

## *Esempio 2: collisione $p\bar{p}$*

(semirigoroso)

**TeVatron**  
2 TeV

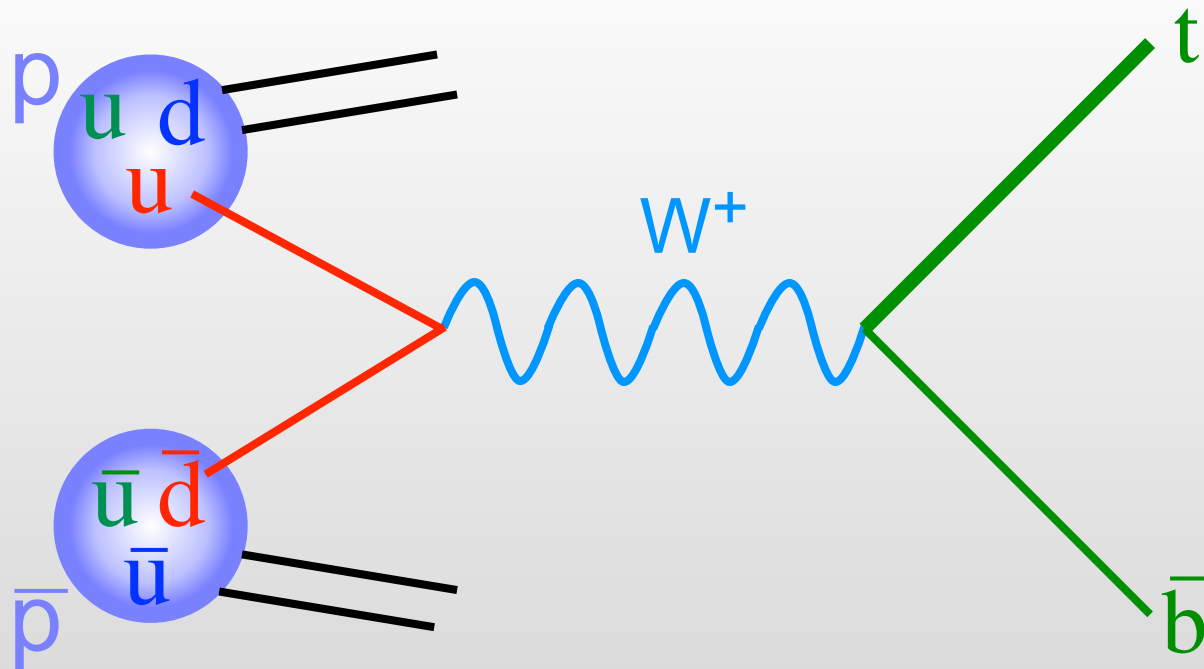




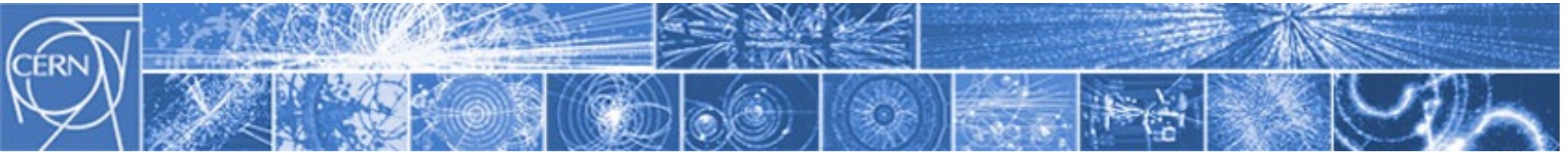
# I diagrammi di Feynman al lavoro

*Esempio 2: collisione  $p\bar{p} \rightarrow$  produzione di quark top*  
(semirigoroso)

**TeVatron**  
2 TeV



*Nota:* non è il canale più efficace per produrre un top quark al Tevatron, ma vabbè.

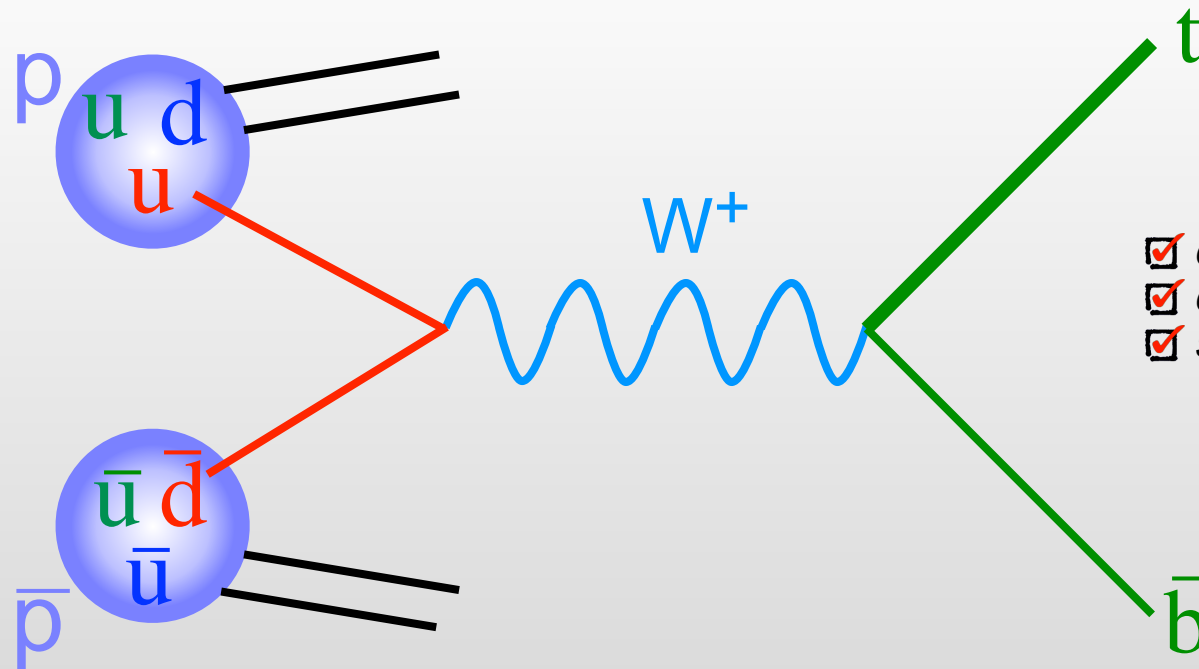


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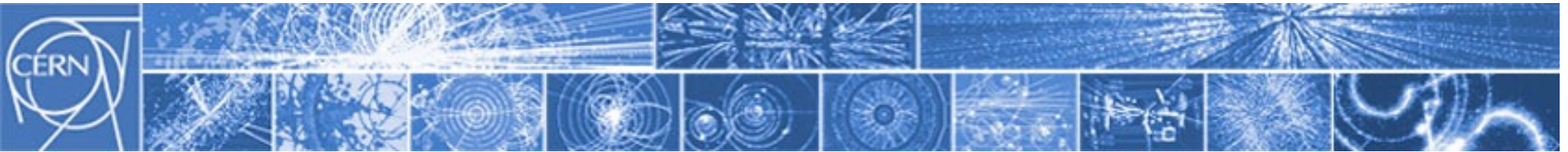
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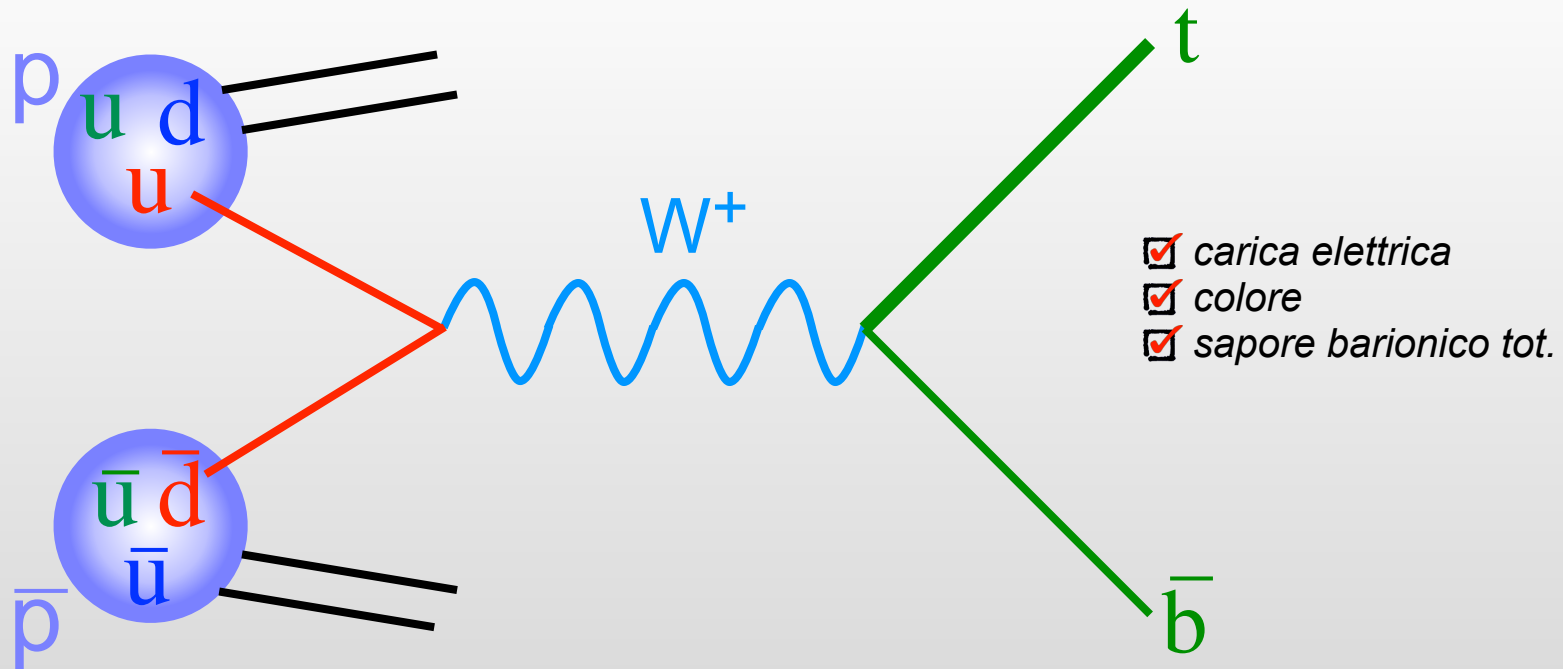


## I diagrammi di Feynman al lavoro

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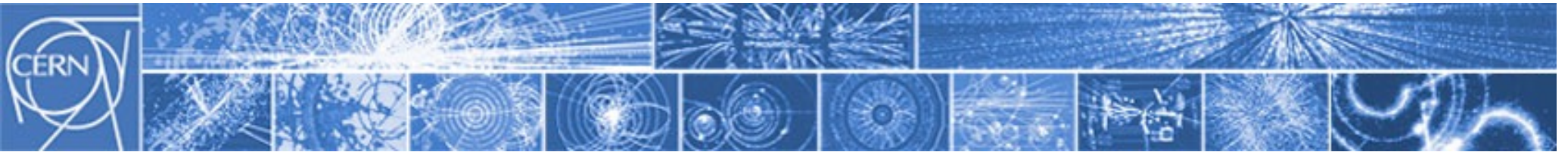
*(semirigoroso)*

**TeVatron**  
2 TeV



Ogni  $q$  porta una frazione del momento del  $p$ : serve una grande energia.

Magari scopriremo così una nuova particella pesante (un *nuovo* 'quark'?).

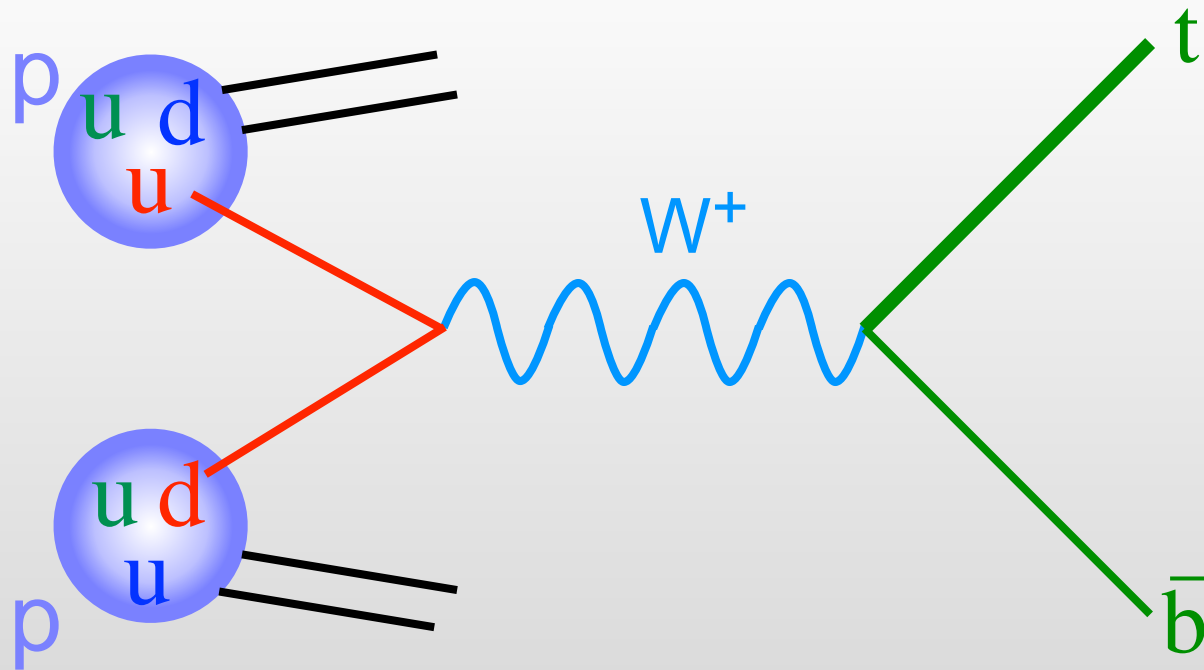


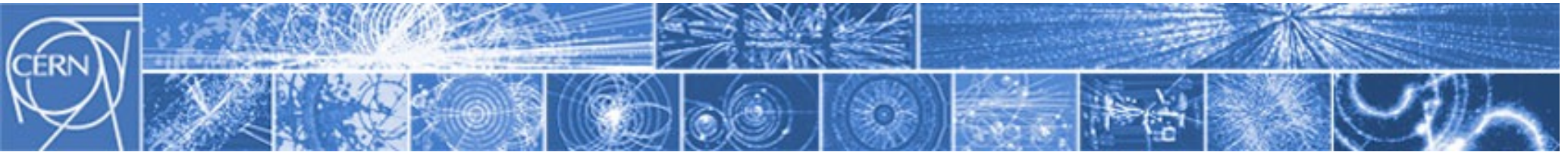
# I diagrammi di Feynman al lavoro

*Esempio 2b: collisione  $pp \rightarrow$  produzione di quark top*

*(semirigoroso)*

**LHC**  
'14 TeV'



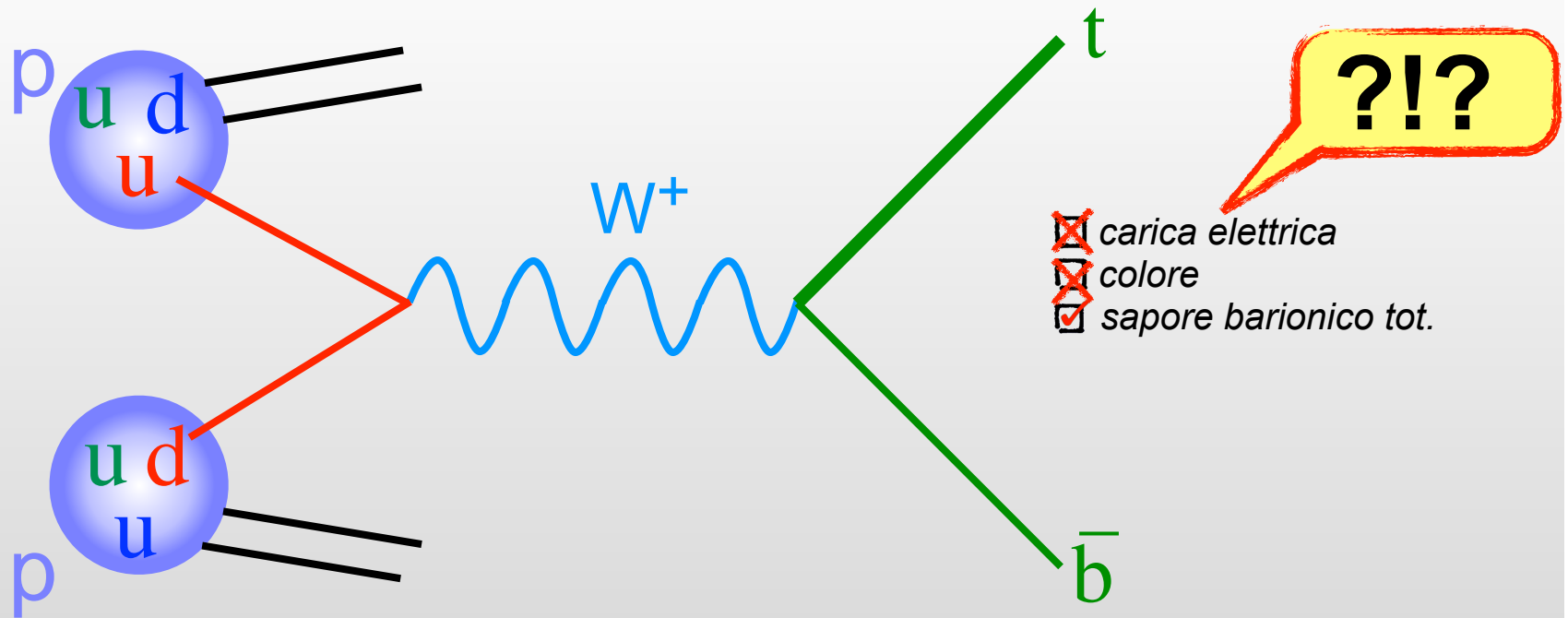


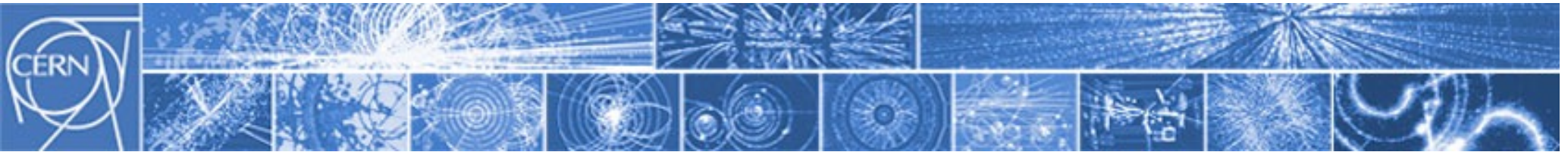
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'14 TeV'



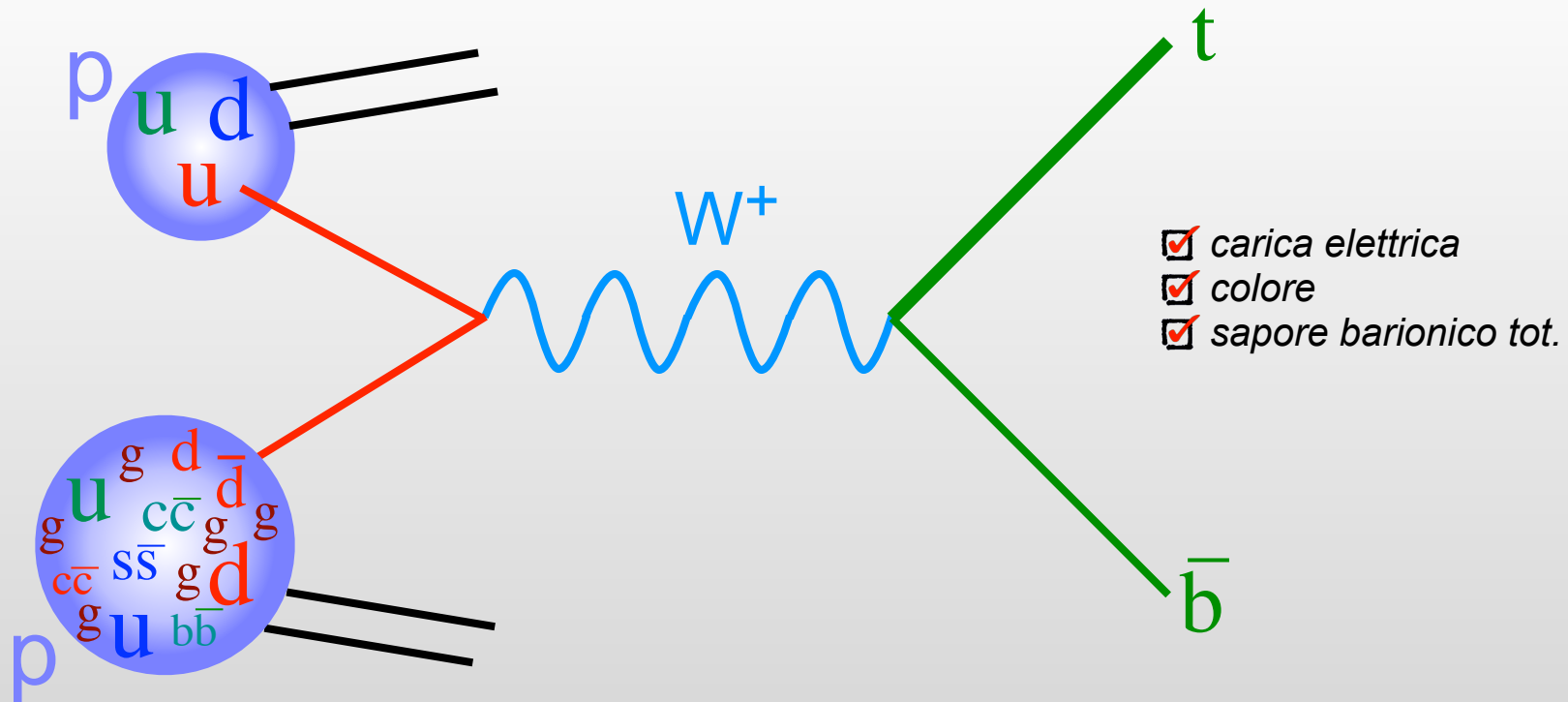


# I diagrammi di Feynman al lavoro

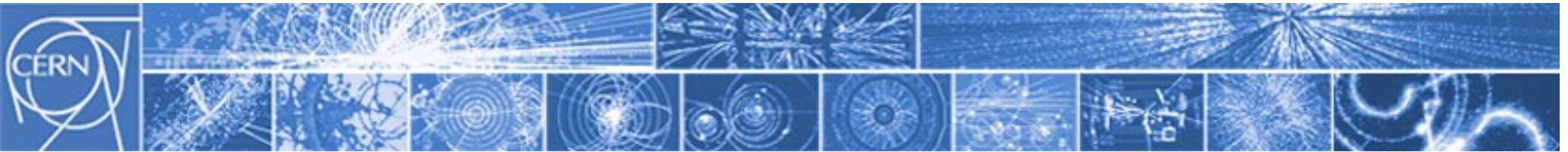
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Un protone 'contiene' *quarks*, *antiquarks* di tutti i sapori (del *mare*, vs *valenza*), e *gluoni*, secondo una certa *distribuzione di probabilità*, funzione dell'energia.

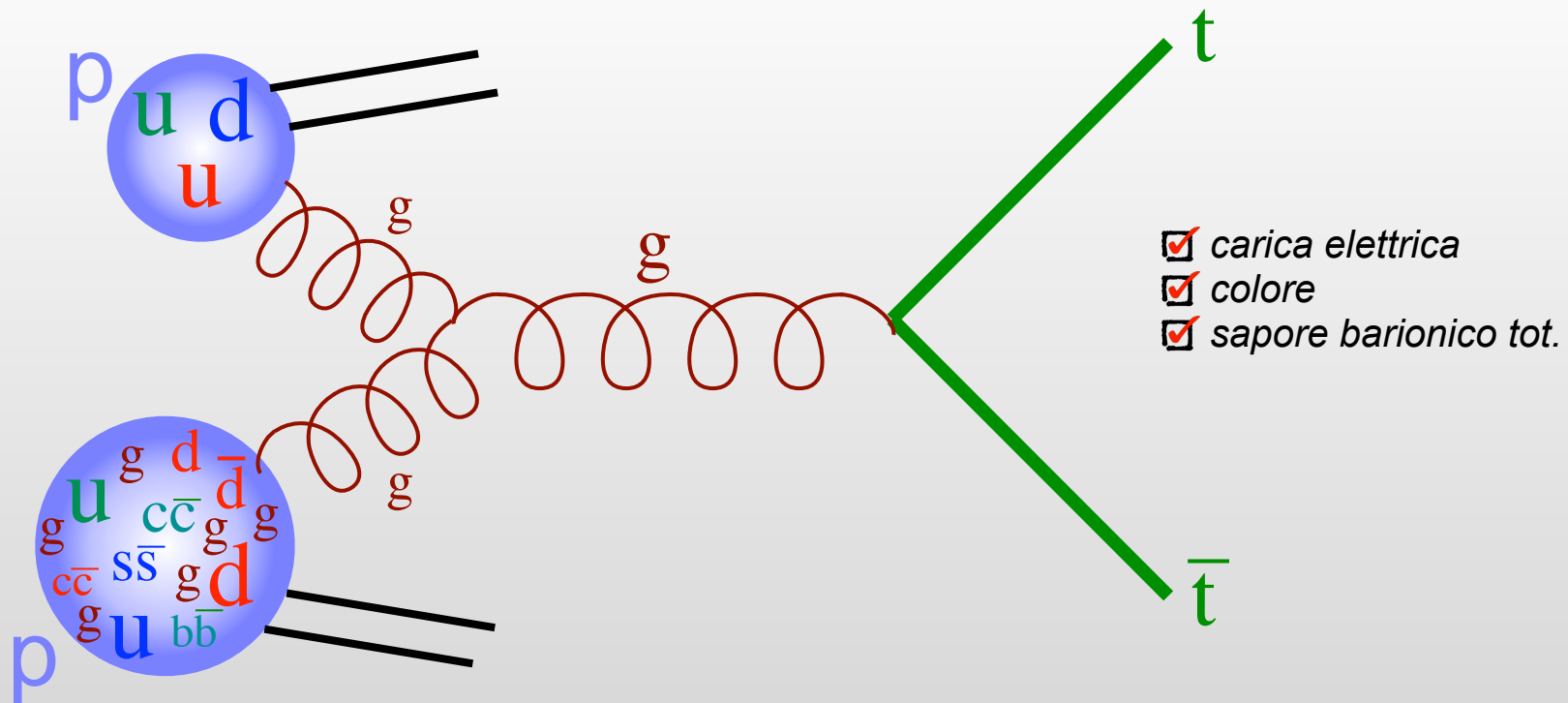


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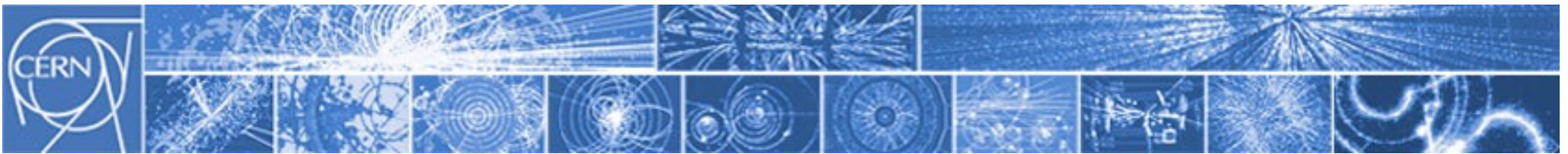
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By the way, ecco uno dei canali più efficaci per produrre un top quark a LHC.



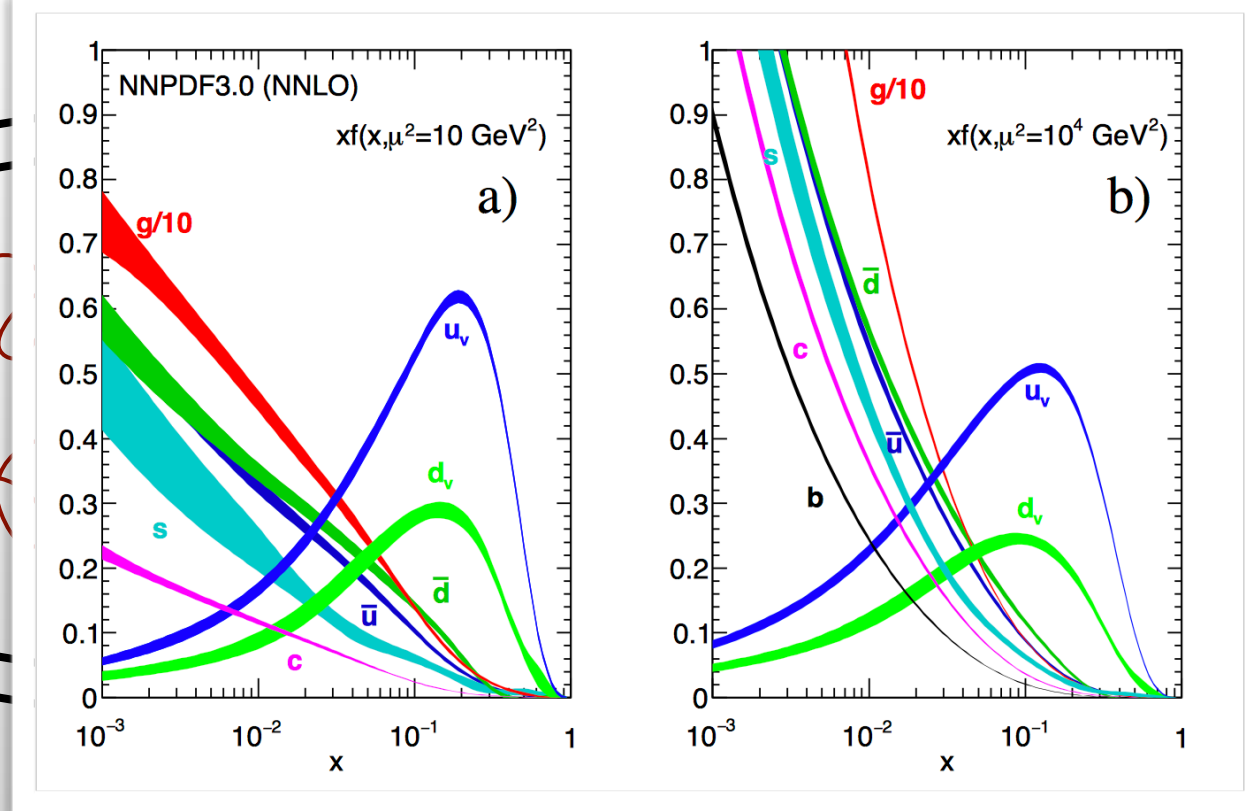
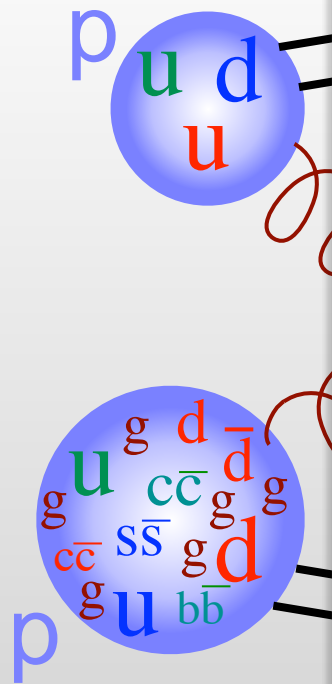


# I diagrammi di Feynman al lavoro

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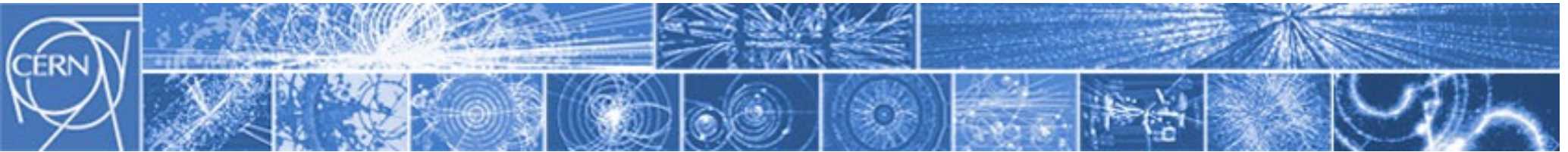
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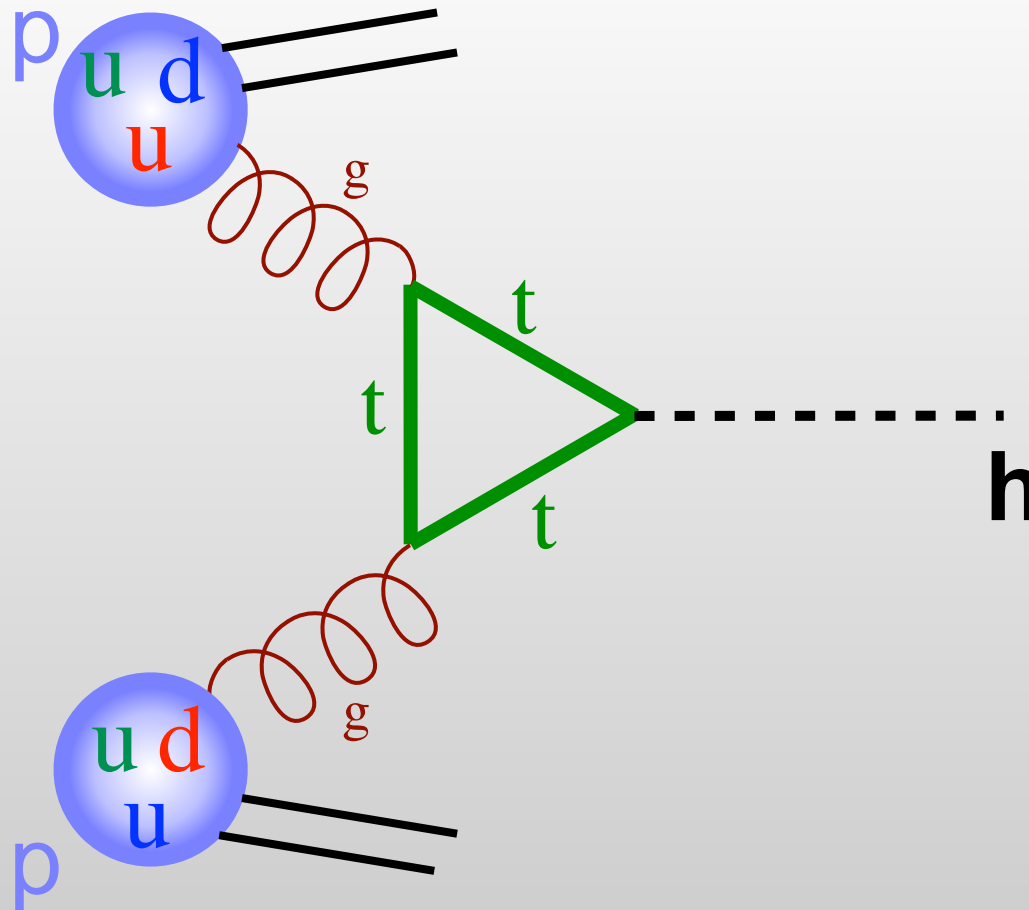


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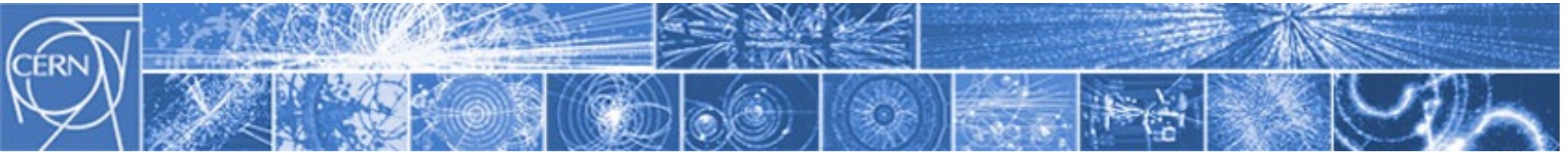
## *Esempio 3: collisione pp → produzione di higgs*

*(semirigoroso)*

**LHC**  
'14 TeV'



- carica elettrica
- colore
- sapore barionico tot.

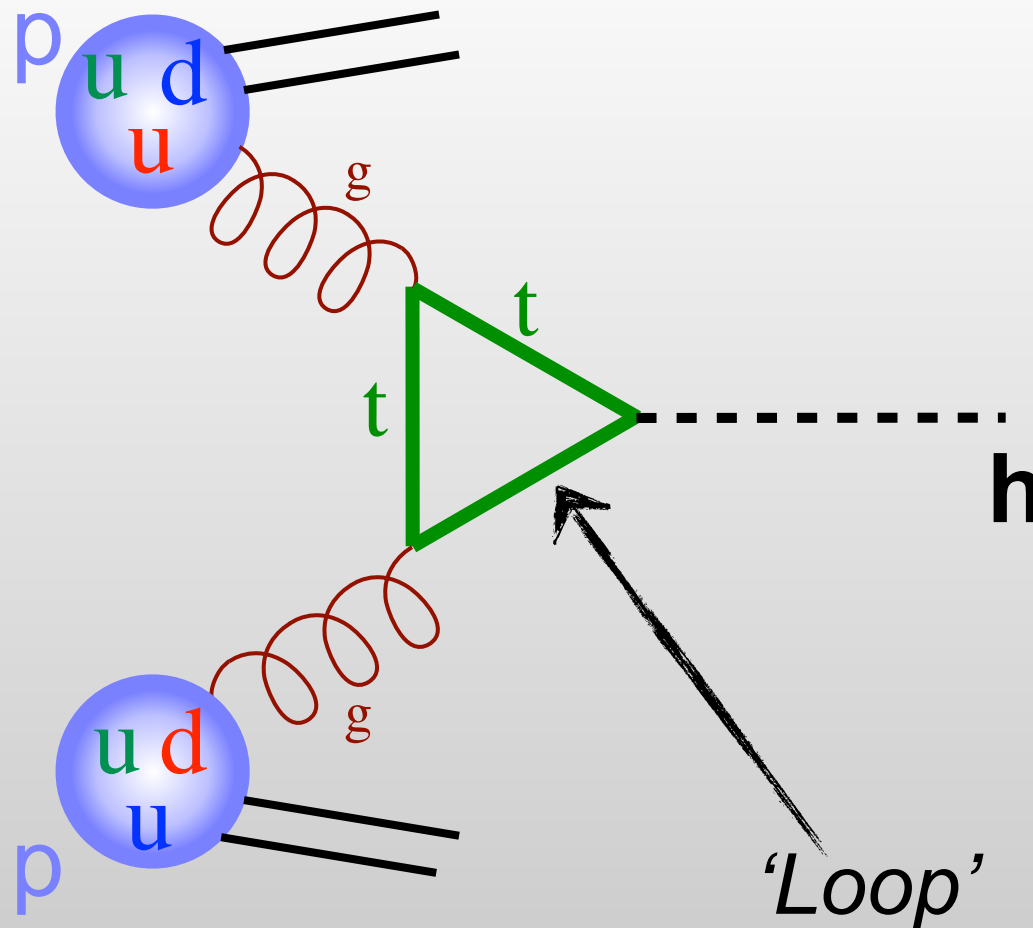


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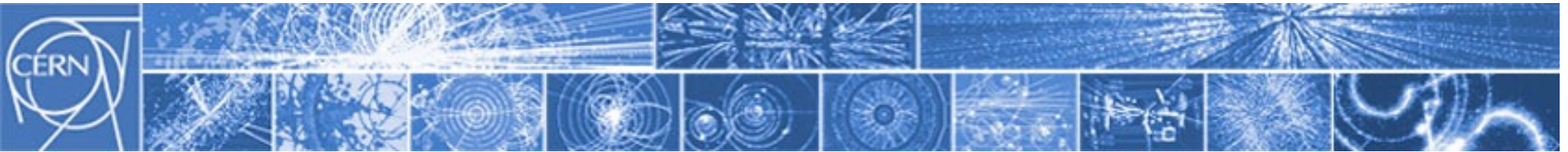
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'14 TeV'



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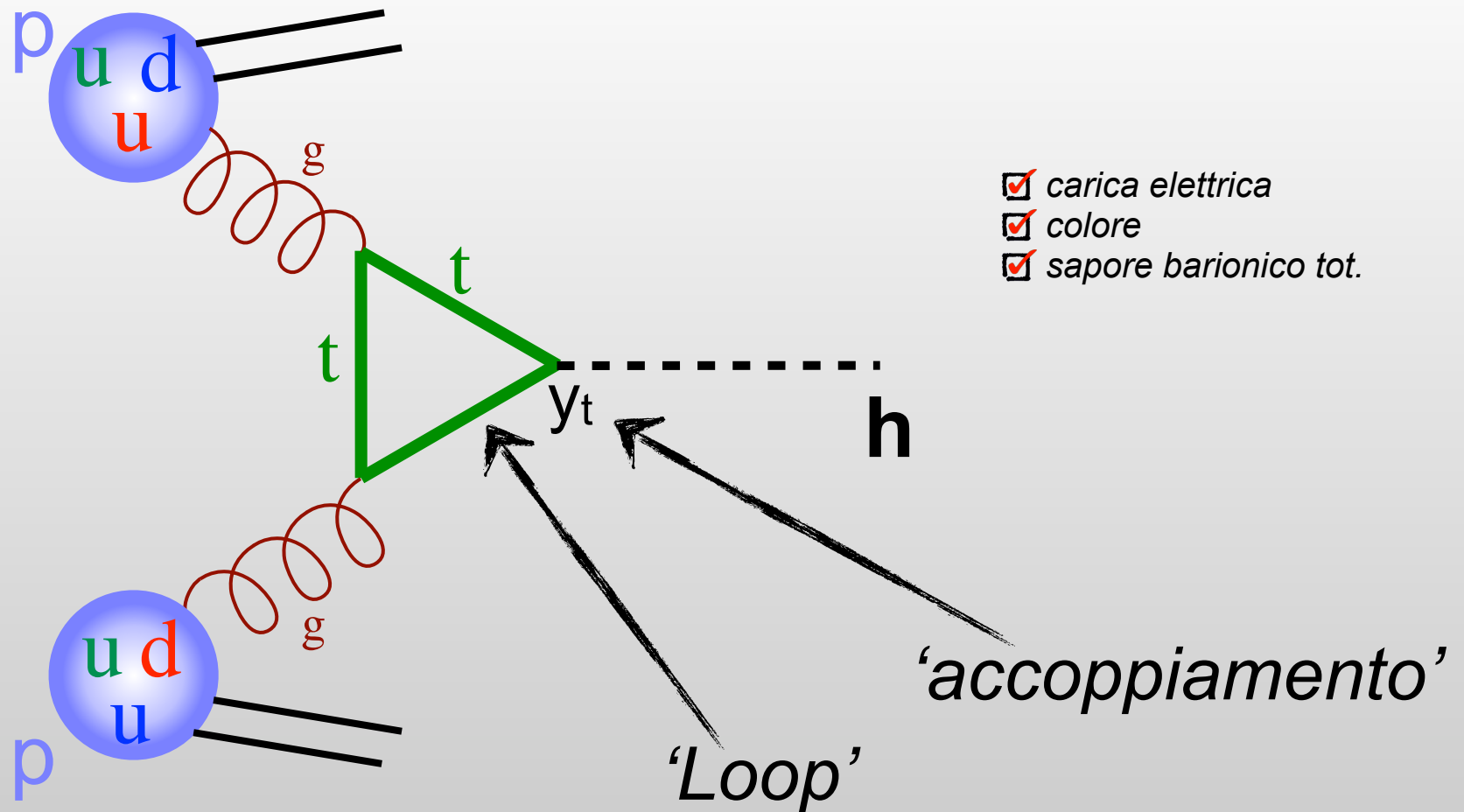


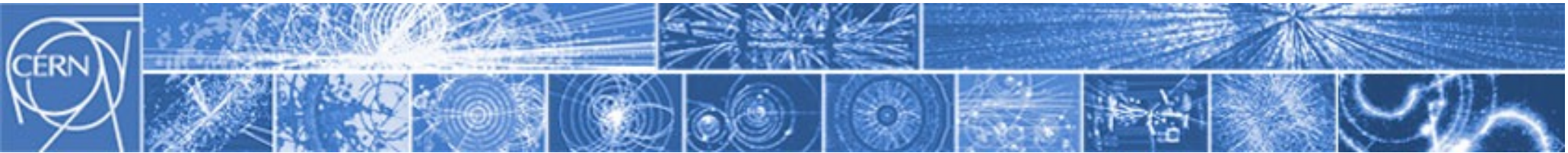
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'14 TeV'





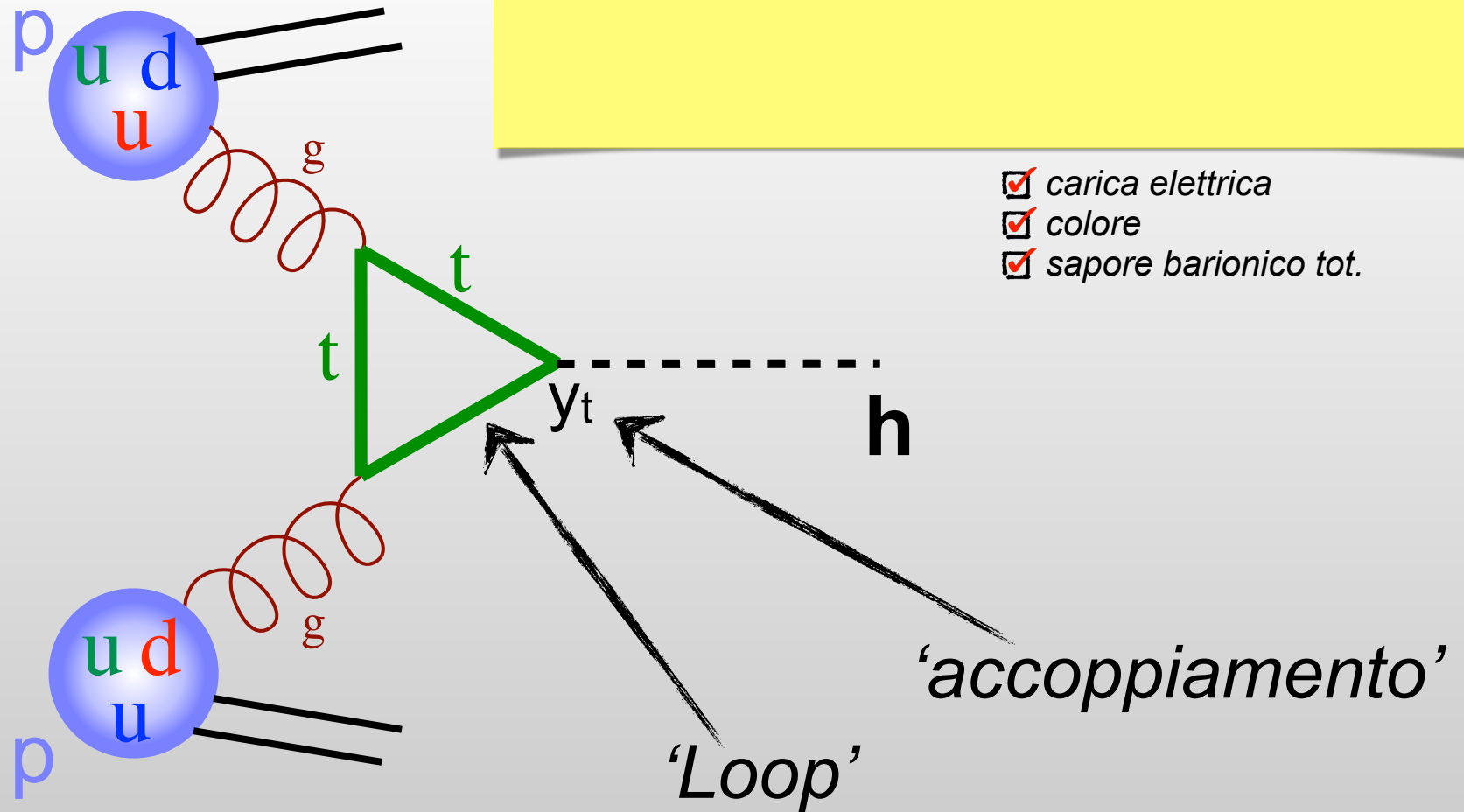
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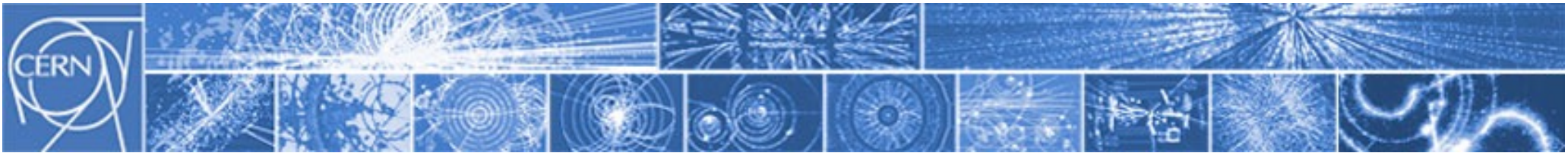
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(semirigoroso)

Q: Ma quindi alla fin fine si può fare un po' tutto?

LHC  
'14 TeV'





# I diagrammi di Feynman al lavoro

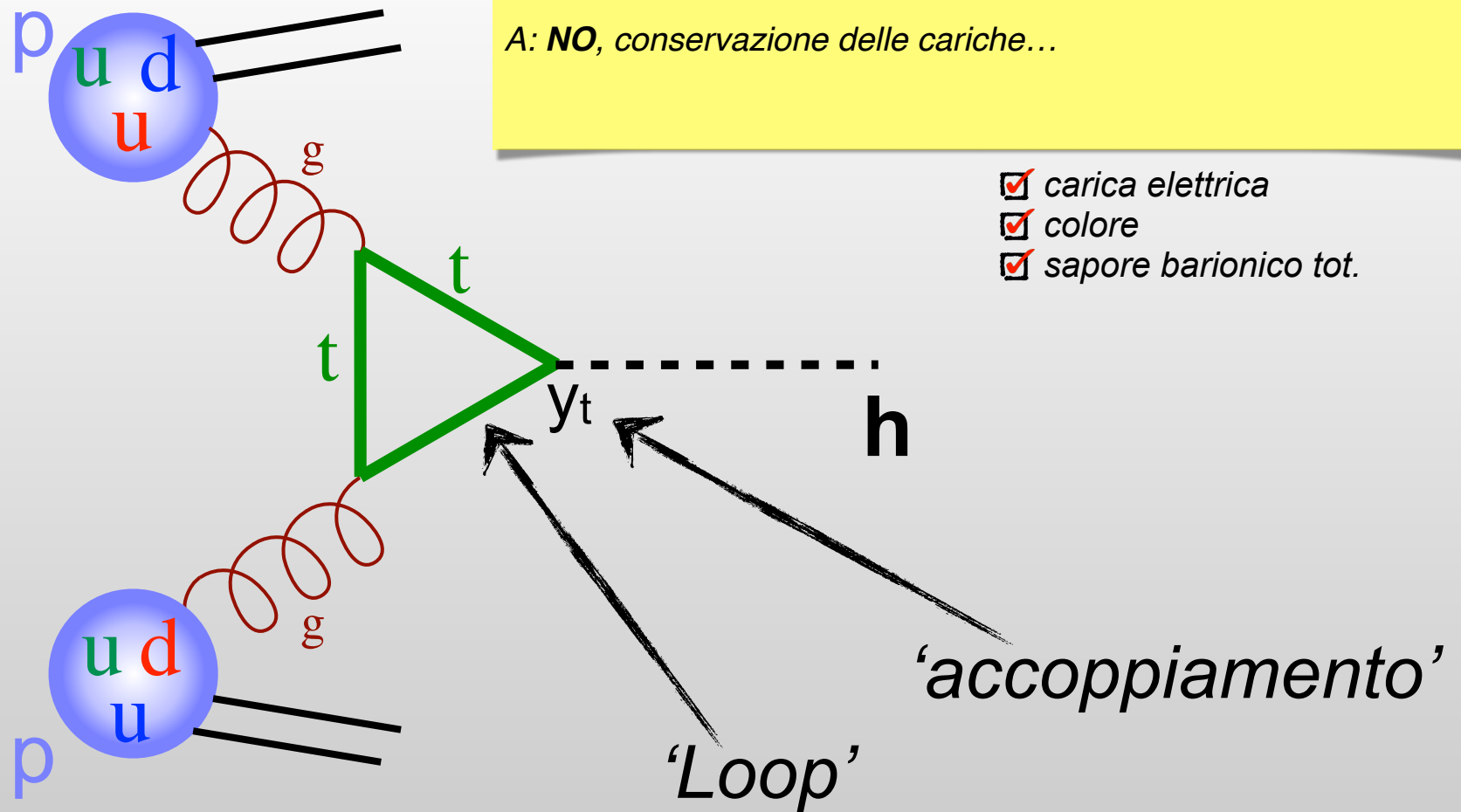
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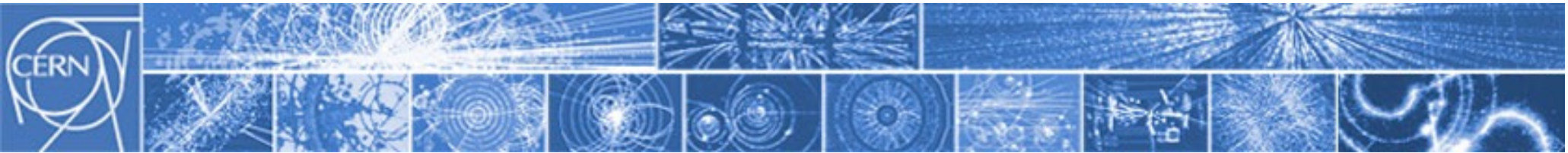
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A: **NO**, conservazione delle cariche...

LHC  
'14 TeV'





# I diagrammi di Feynman al lavoro

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(semirigoroso)

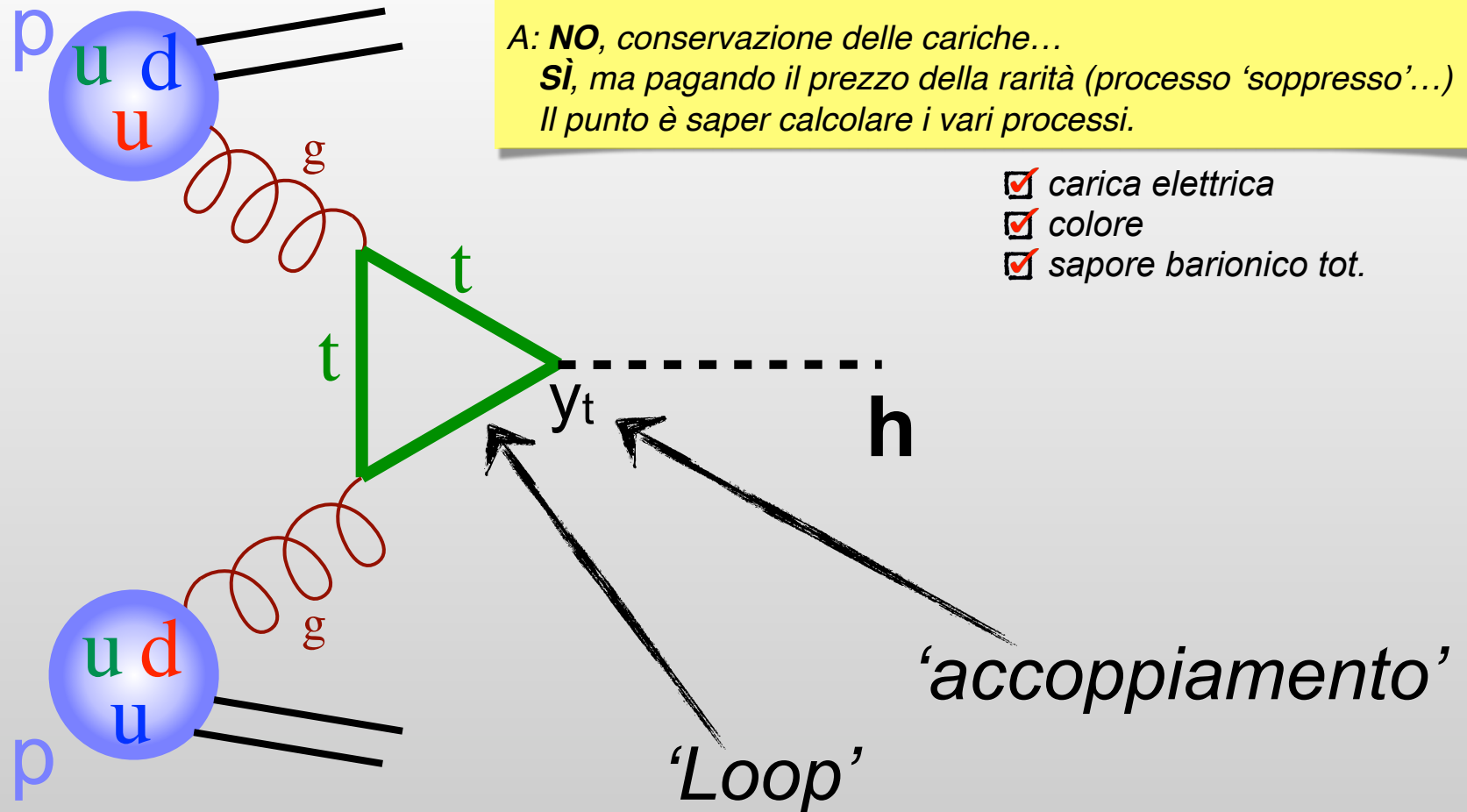
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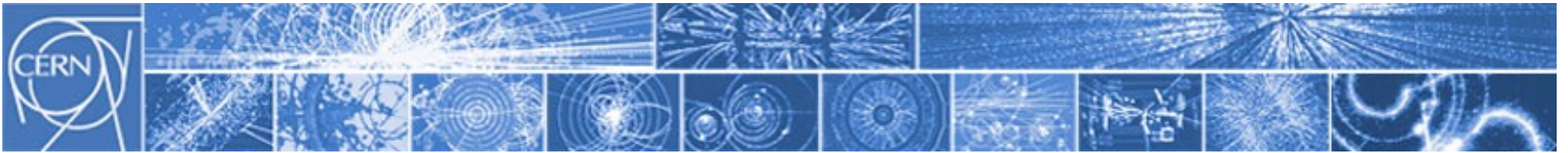
A: **NO**, conservazione delle cariche...

**Sì**, ma pagando il prezzo della rarità (processo 'soppresso'...)

Il punto è saper calcolare i vari processi.

LHC  
'14 TeV'



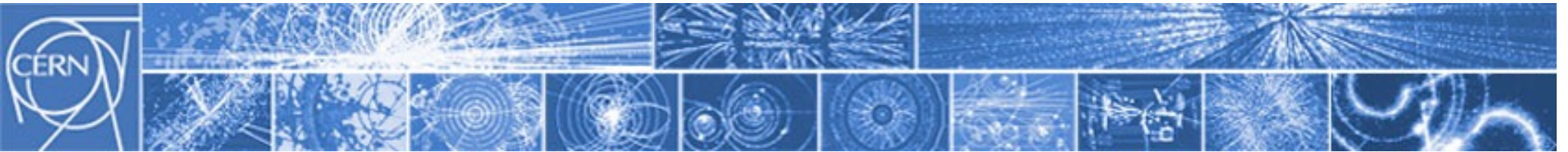


# I diagrammi di Feynman al lavoro

## *Esempio 4: decadimento del muone*

*(piuttosto rigoroso: ma per i dettagli ci vorrebbe un intero corso di QFT!)*

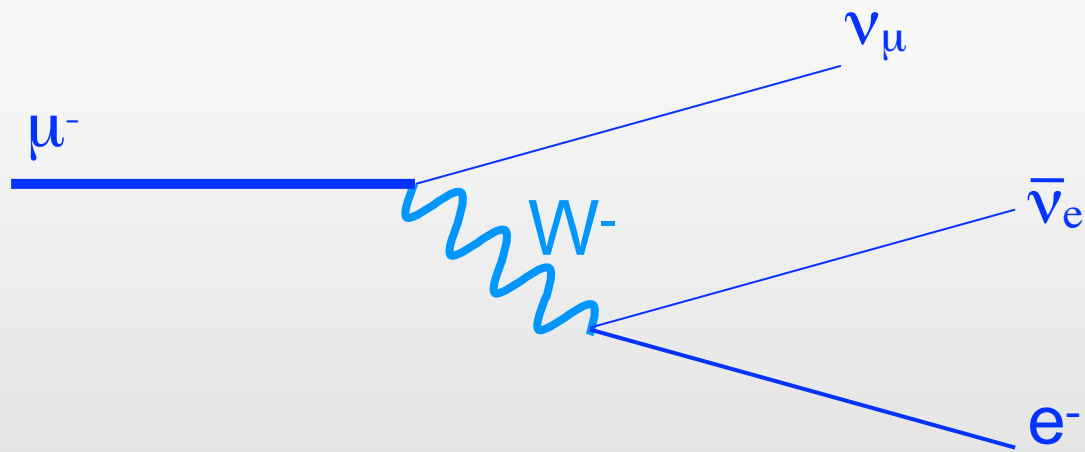


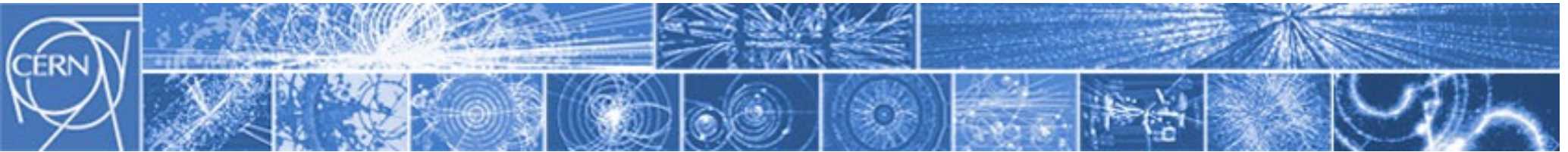


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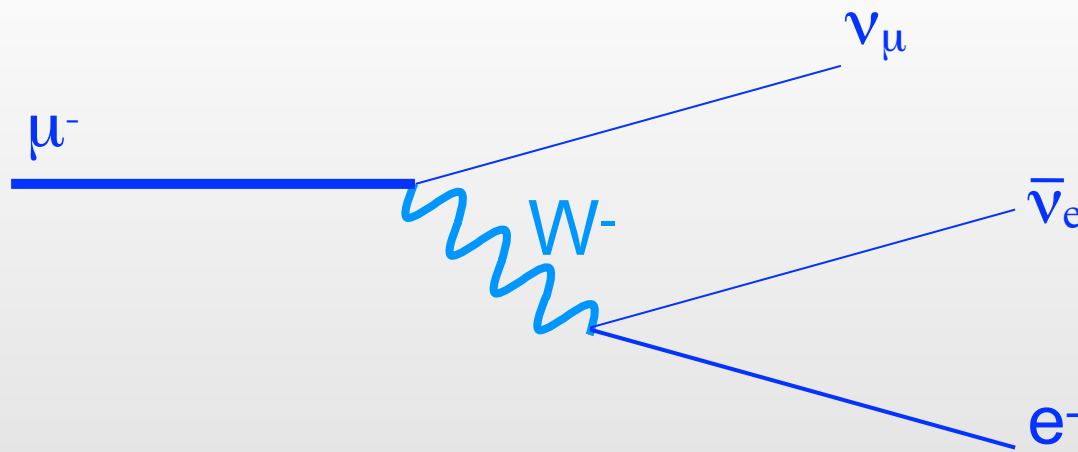




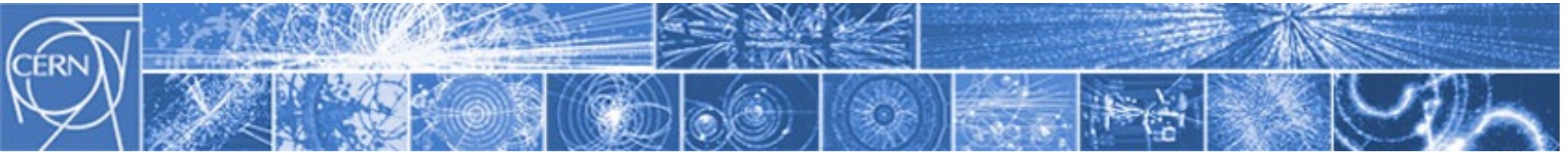
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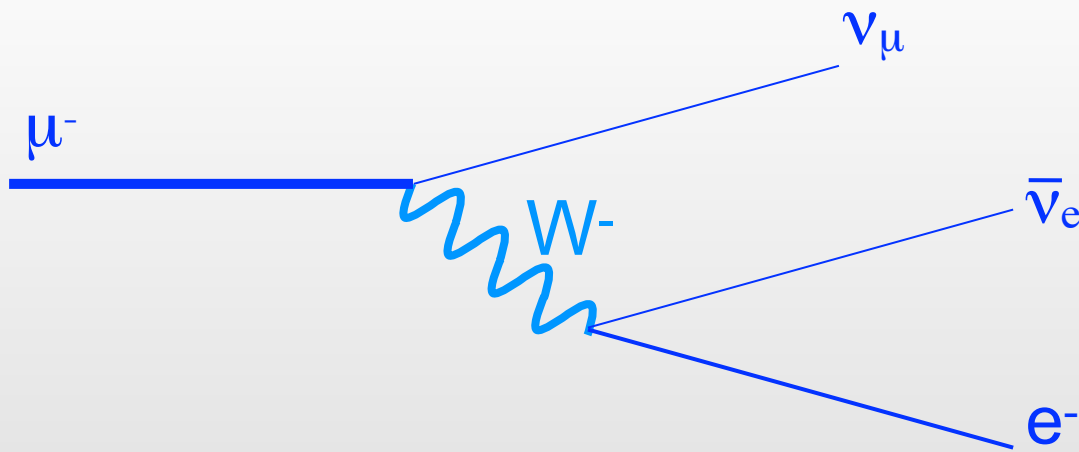
$$\mathcal{L} \simeq -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + y_{ij}\Psi_i\Psi_j\phi + |D_\mu\phi|^2 - V(\phi)$$



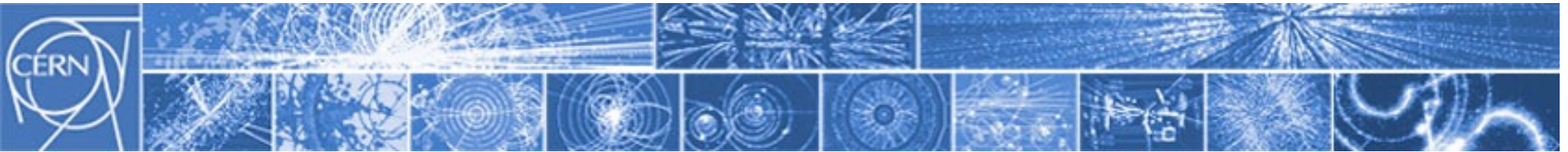
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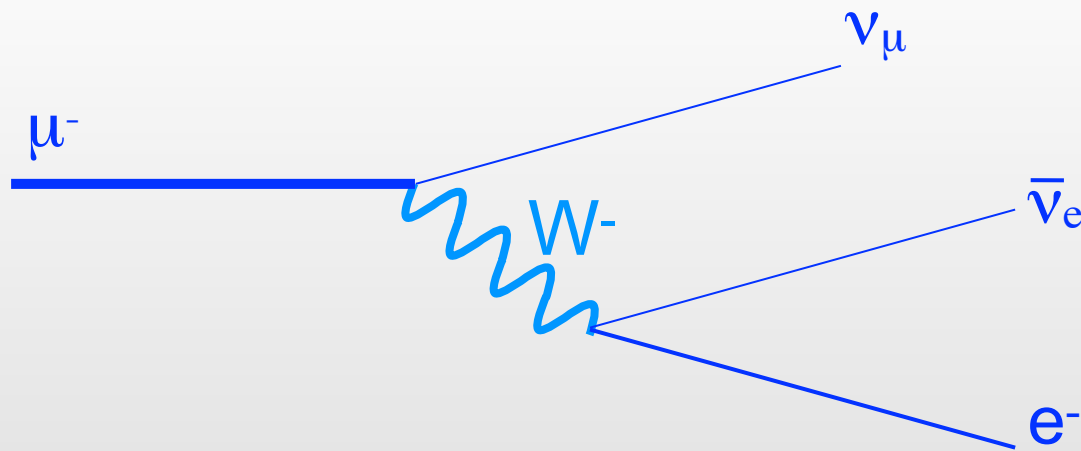
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# I diagrammi di Feynman al lavoro

## Esempio 4: decadimento del muone

(piuttosto rigoroso: ma per i dettagli ci vorrebbe un intero corso di QFT!)



$$\mathcal{L} \simeq -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

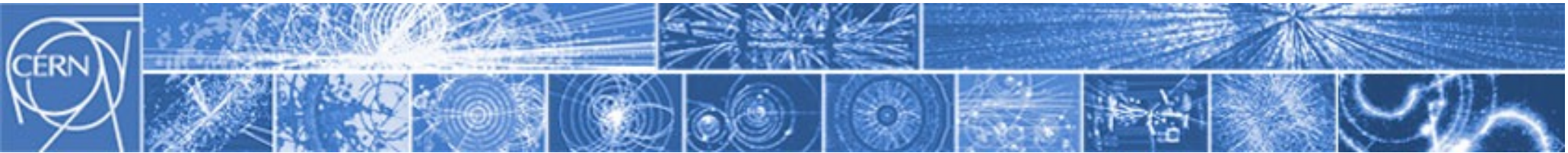
$$+i\bar{\Psi} \not{D} \Psi$$

$$+y_{ij} \Psi_i \Psi_j \phi$$

$$+|D_\mu \phi|^2 - V(\phi)$$

$$\Psi = \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L = \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \frac{1 - \gamma_5}{2}$$

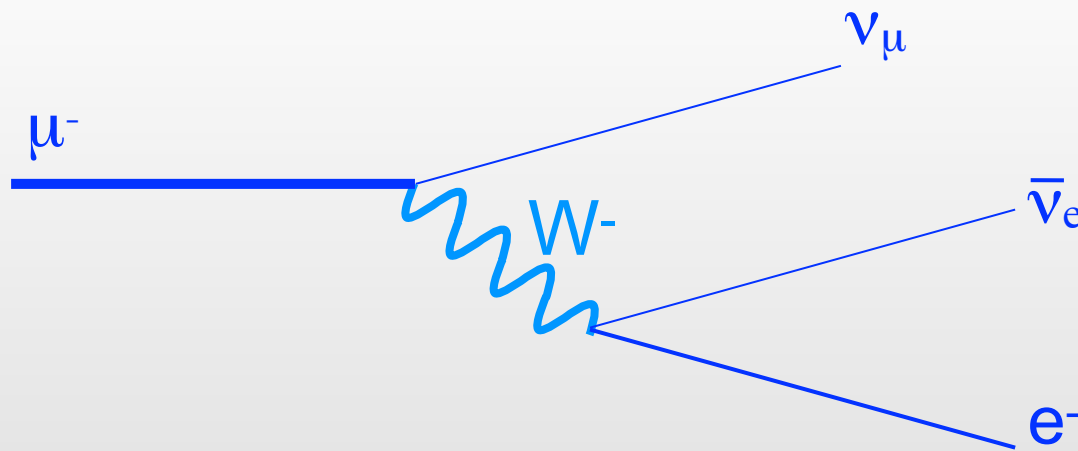
$$\not{D} = \gamma D \supset \gamma \left( -i \frac{g}{\sqrt{2}} W^- \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \right)$$



# I diagrammi di Feynman al lavoro

## Esempio 4: decadimento del muone

(piuttosto rigoroso: ma per i dettagli ci vorrebbe un intero corso di QFT!)



$$\mathcal{L} \simeq -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+i\bar{\Psi} \not{D} \Psi$$

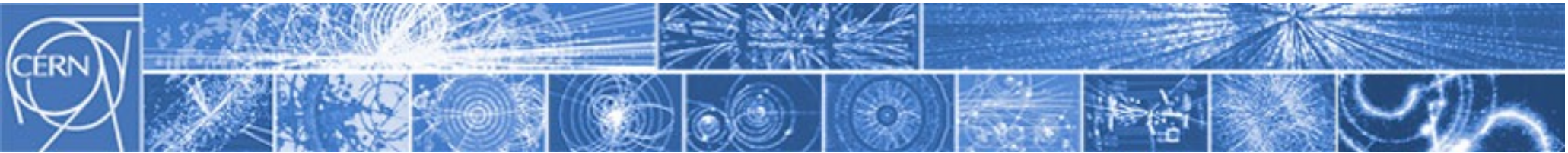
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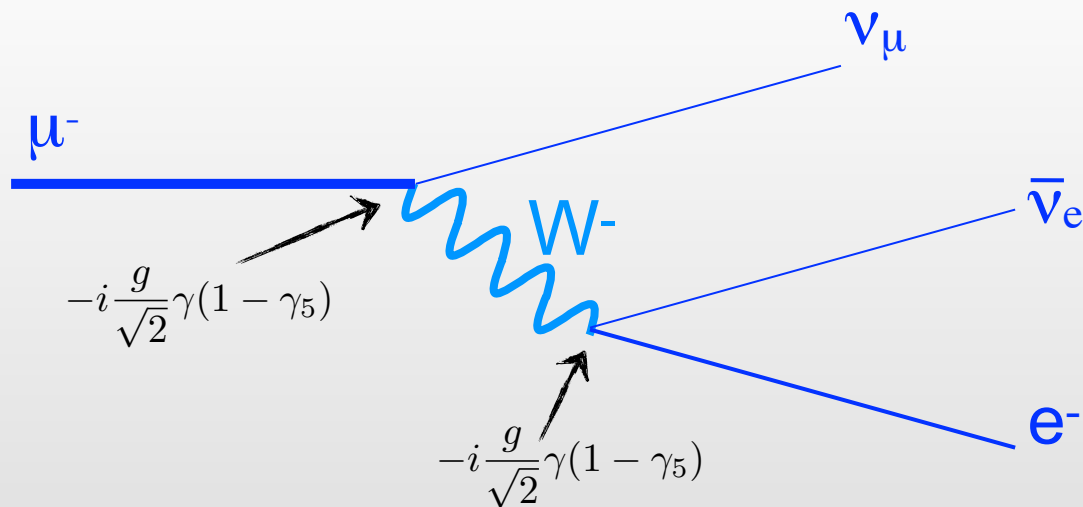
$$\simeq \nu_\mu \left( -i \frac{g}{\sqrt{2}} \right) \gamma (1 - \gamma_5) W^-_\mu$$



# I diagrammi di Feynman al lavoro

## Esempio 4: decadimento del muone

(piuttosto rigoroso: ma per i dettagli ci vorrebbe un intero corso di QFT!)



$$\mathcal{L} \simeq -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+i\bar{\Psi} \not{D} \Psi$$

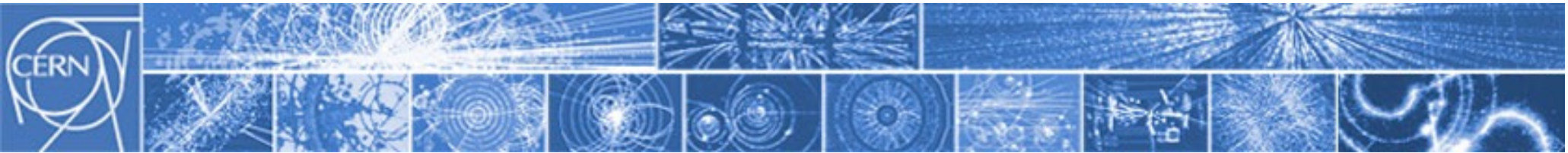
$$+y_{ij} \Psi_i \Psi_j \phi$$

$$+|D_\mu \phi|^2 - V(\phi)$$

$$\Psi = \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L = \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \frac{1 - \gamma_5}{2}$$

$$\not{D} = \gamma D \supset \gamma \left( -i \frac{g}{\sqrt{2}} W^- \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \right)$$

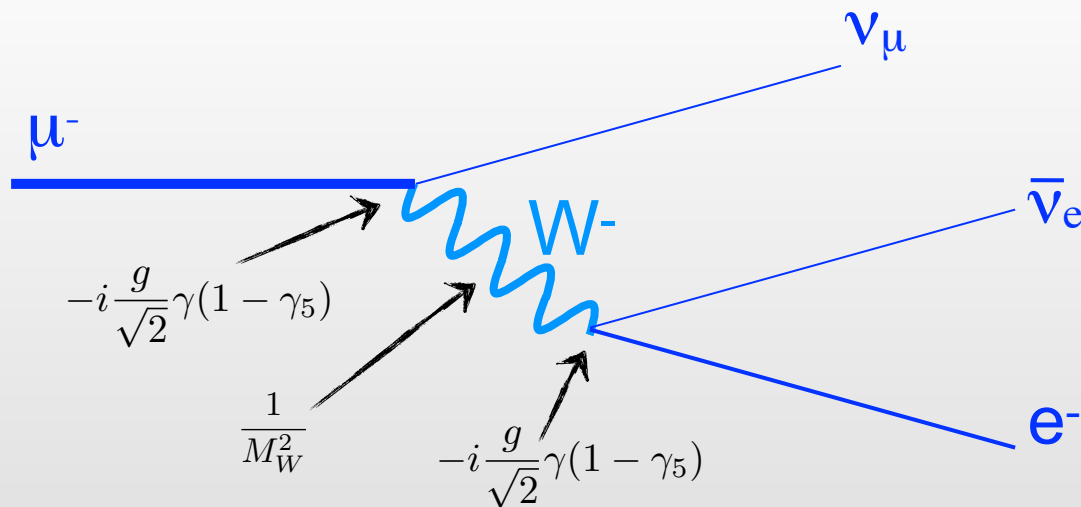
$$\text{[light blue box]} \simeq \nu_\mu \left( -i \frac{g}{\sqrt{2}} \right) \gamma (1 - \gamma_5) W^-_\mu$$



# I diagrammi di Feynman al lavoro

## Esempio 4: decadimento del muone

(piuttosto rigoroso: ma per i dettagli ci vorrebbe un intero corso di QFT!)



$$\mathcal{L} \simeq -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

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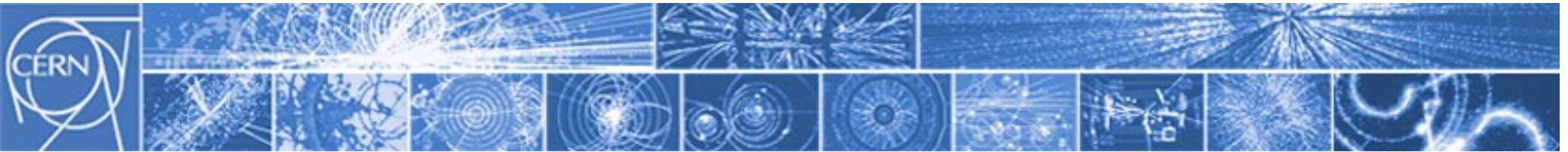
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$$\not{D} = \gamma D \supset \gamma \left( -i \frac{g}{\sqrt{2}} W^- \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \right)$$

$$\text{[Vertex]} \simeq \nu_\mu \left( -i \frac{g}{\sqrt{2}} \right) \gamma(1 - \gamma_5) W^- \mu$$

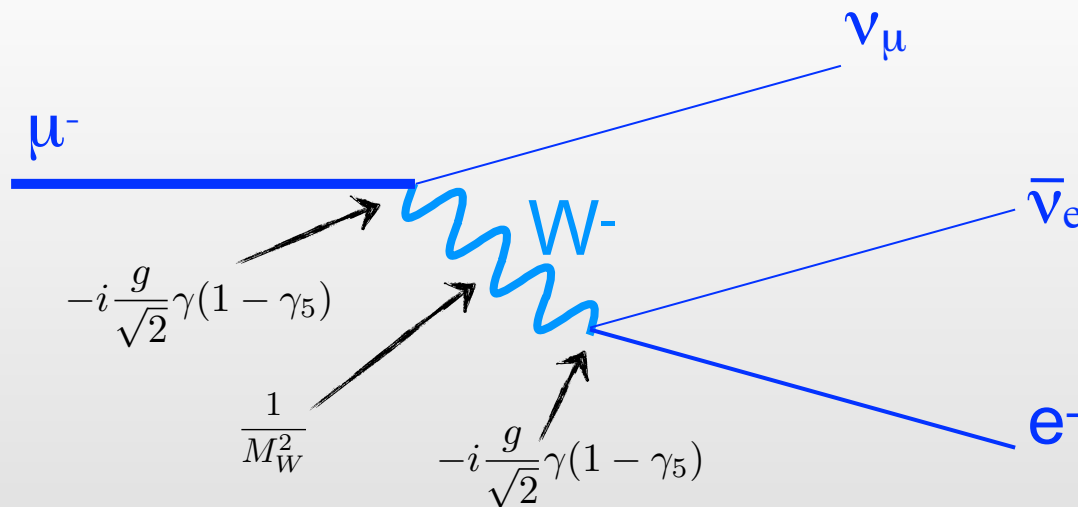
$$\text{[W boson propagator]} \propto \frac{1}{M_W^2 - p^2} \rightarrow \frac{1}{M_W^2}$$



# I diagrammi di Feynman al lavoro

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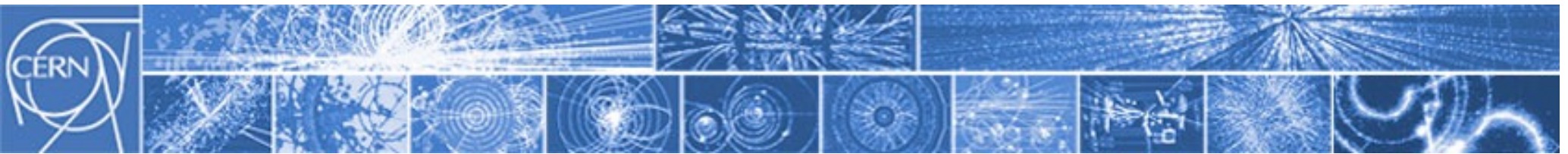
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**ampiezza:**  $|\mathcal{M}| \propto \frac{g^2}{2} [\nu_\mu \gamma(1 - \gamma_5) \mu] \frac{1}{M_W^2} [e \gamma(1 - \gamma_5) \nu_e]$

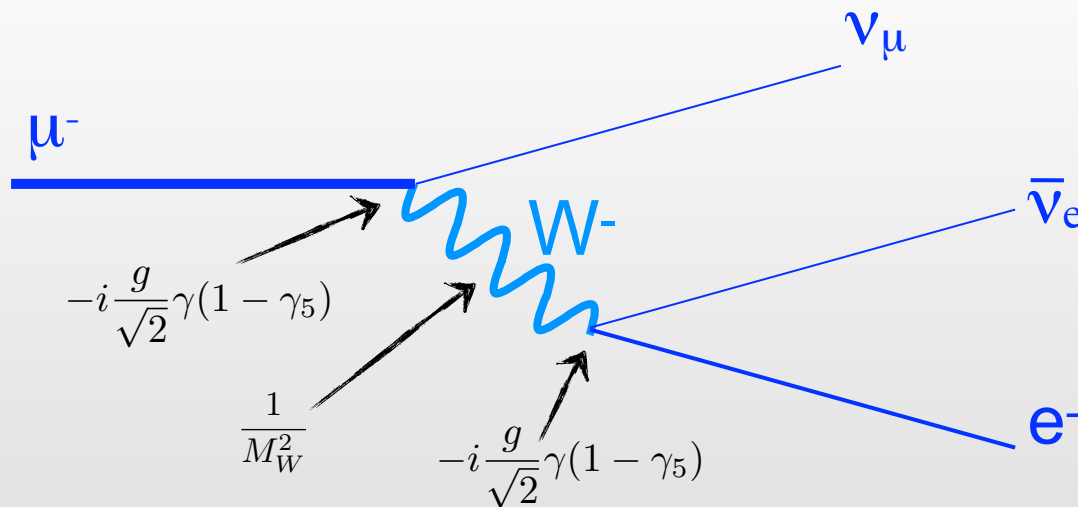




# I diagrammi di Feynman al lavoro

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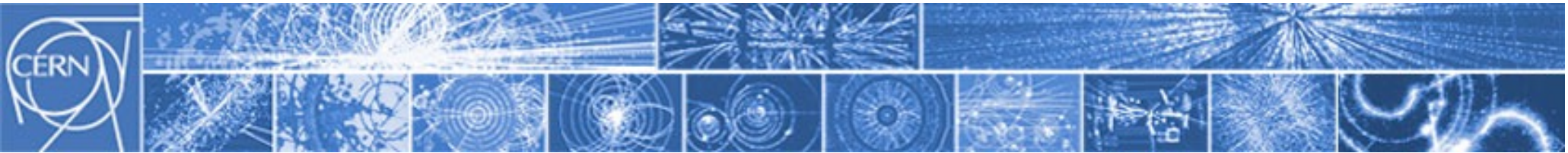
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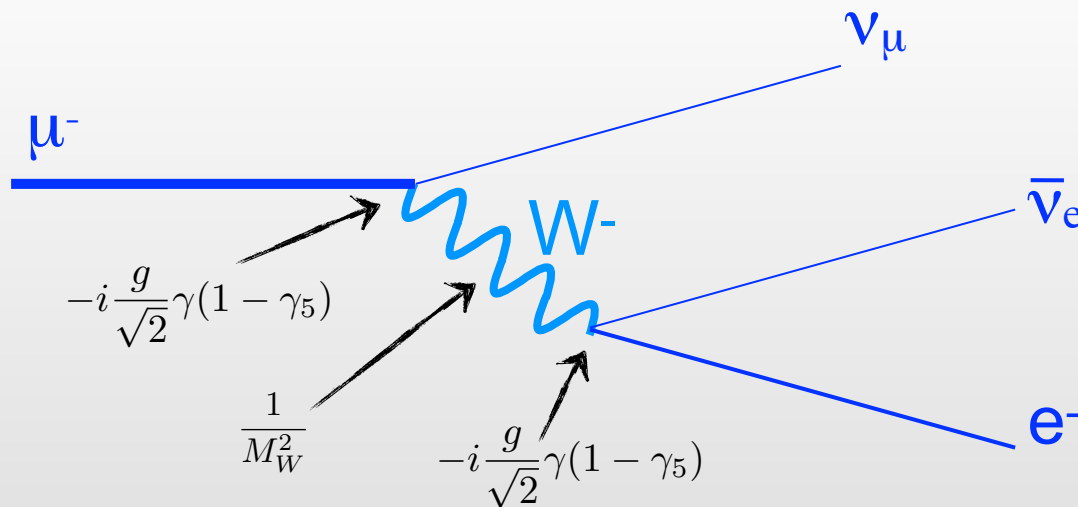
**tasso di decadimento:**  $\Gamma \propto |\mathcal{M}|^2$



# I diagrammi di Feynman al lavoro

## Esempio 4: decadimento del muone

(piuttosto rigoroso: ma per i dettagli ci vorrebbe un intero corso di QFT!)



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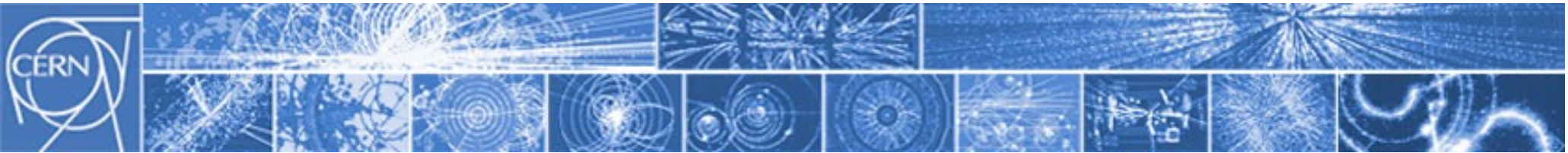
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“...dopo una serie di facili passaggi, si può facilmente dimostrare che...”

$$G_F = \frac{\sqrt{2} g^2}{8 M_W^2}$$

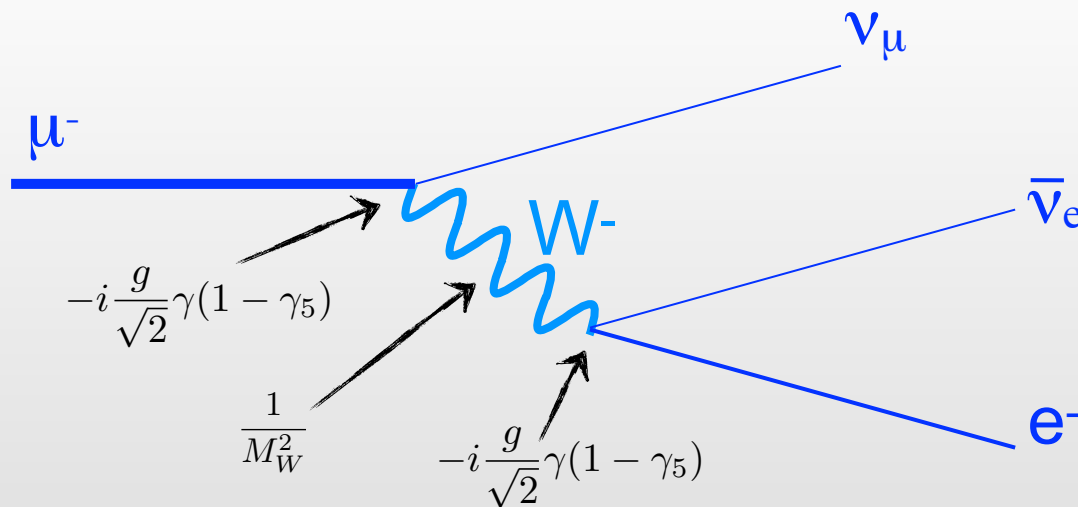
**tasso di decadimento:**  $\Gamma = \frac{1}{192 \pi^3} G_F^2 m_\mu^5$



# I diagrammi di Feynman al lavoro

## Esempio 4: decadimento del muone

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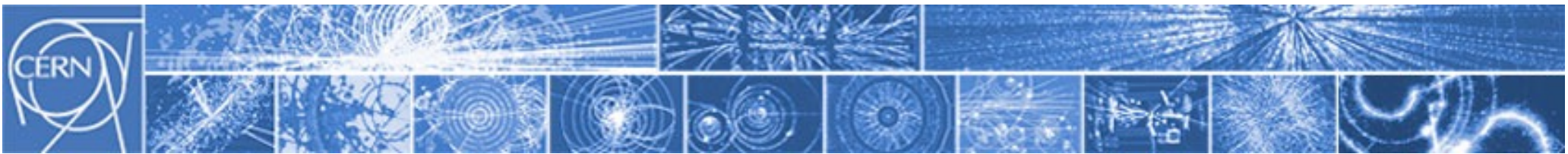
**ampiezza:**  $|\mathcal{M}| \propto \frac{g^2}{2} [\nu_\mu \gamma(1 - \gamma_5) \mu] \frac{1}{M_W^2} [e \gamma(1 - \gamma_5) \nu_e]$

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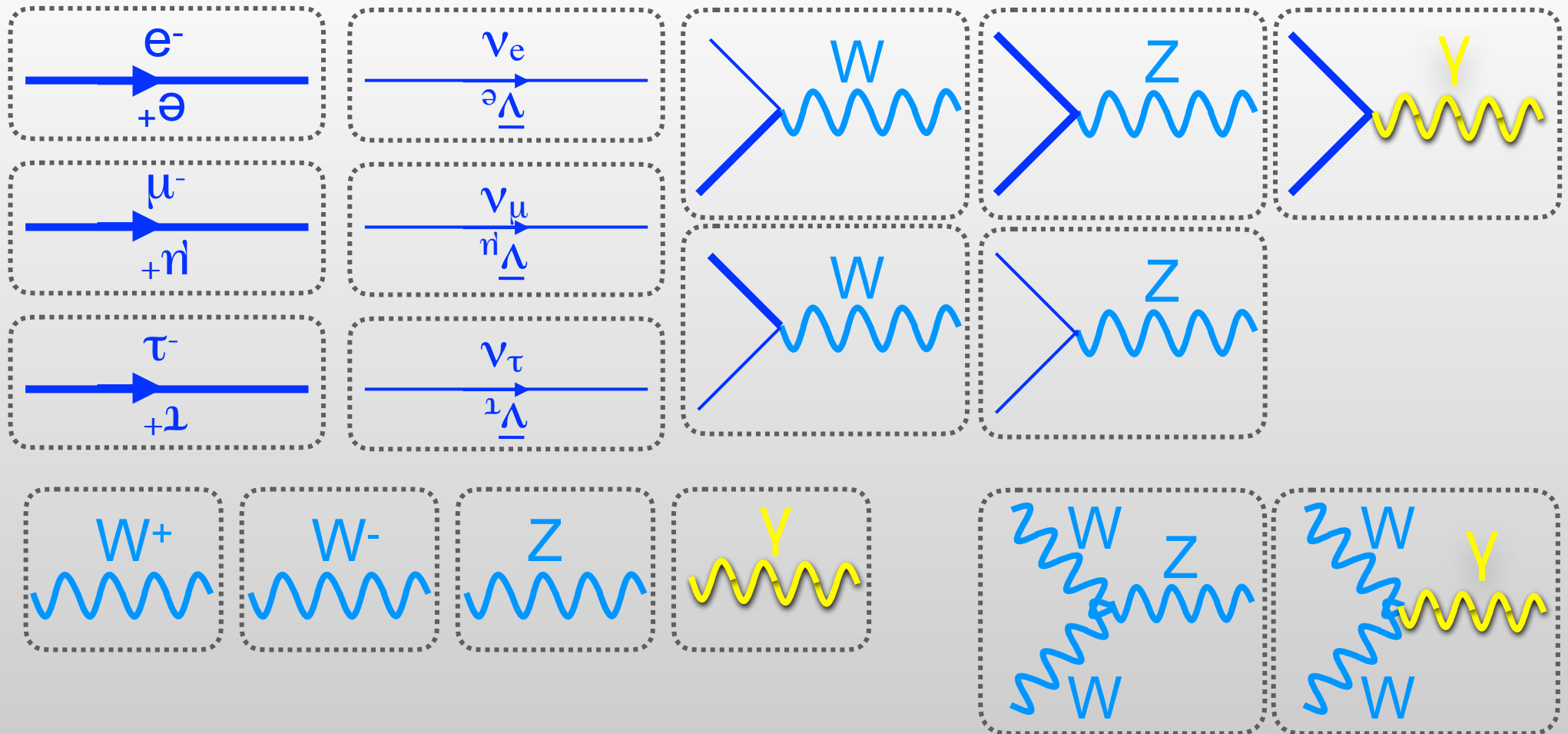
**tasso di decadimento:**  $\Gamma = \frac{1}{192 \pi^3} G_F^2 m_\mu^5$

**vita media:**  $\tau = 1/\Gamma = (2.19703 \pm 0.0004) \times 10^{-6}$  secondi



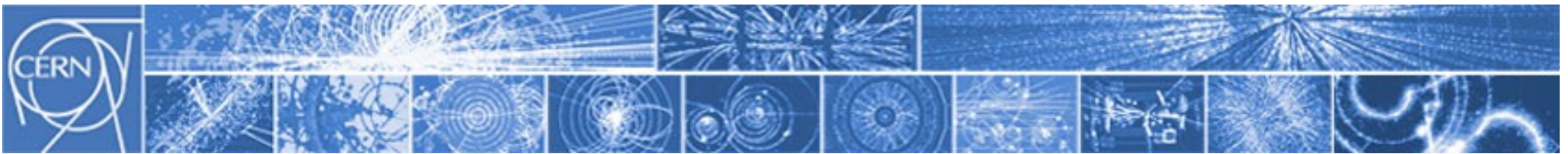
# I diagrammi di Feynman al lavoro: gioco del domino *(un'idea di presentazione/masterclass?)*

EW Feynman rules



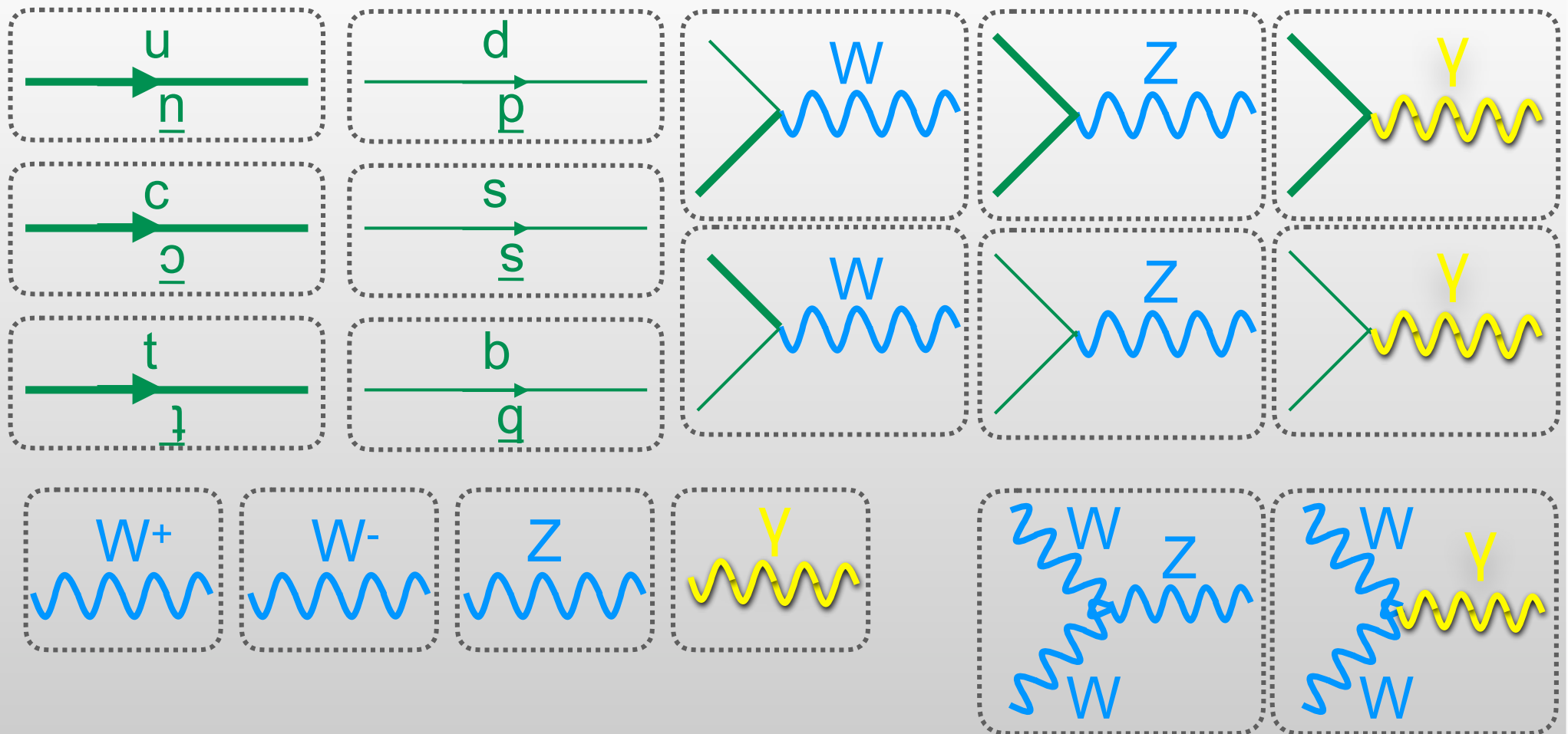
idea ripresa in:

J. Woithe, J. Wiener, F. Van der Veken, *Let's have a coffee with the Standard Model of particle physics!*, Phys. Educ. 52 (2017) 034001



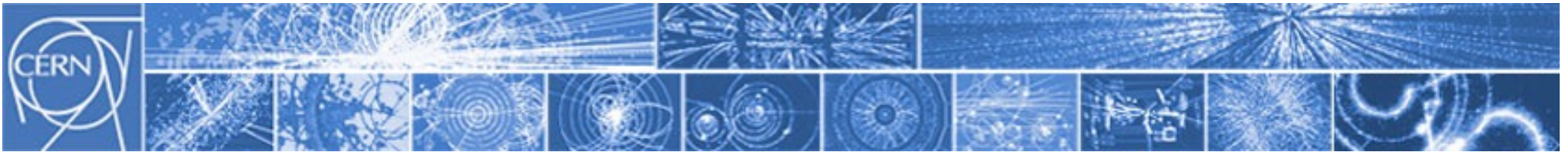
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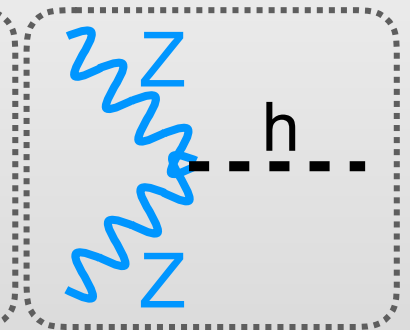
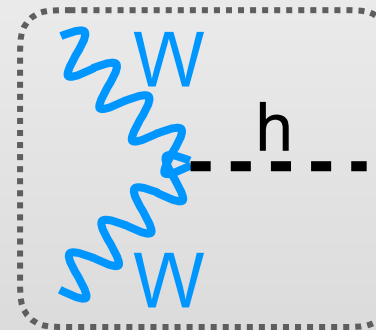
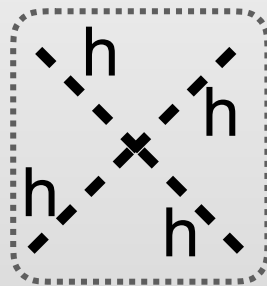
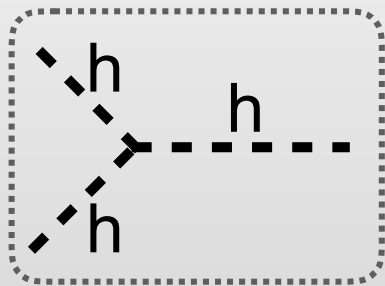
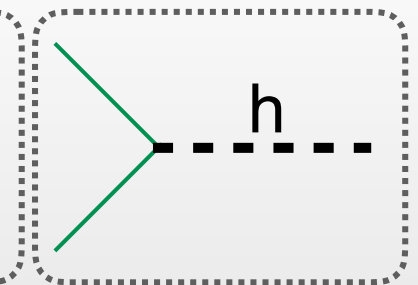
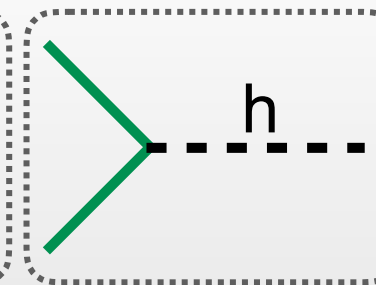
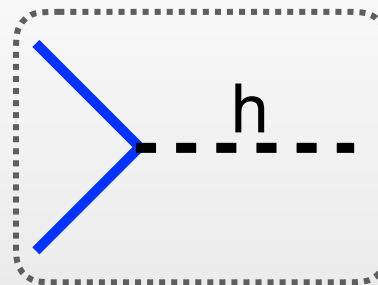
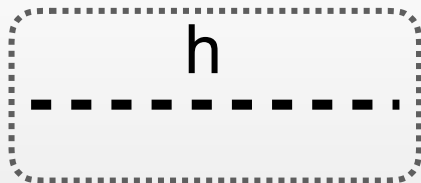
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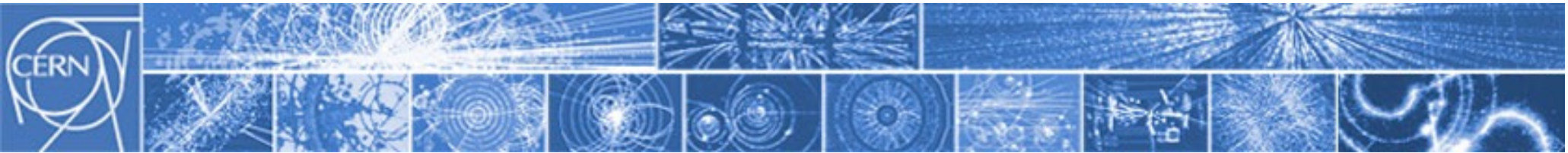
# I diagrammi di Feynman al lavoro: *gioco del domino* (un'idea di presentazione/masterclass?)

Feynman rules higgs sector



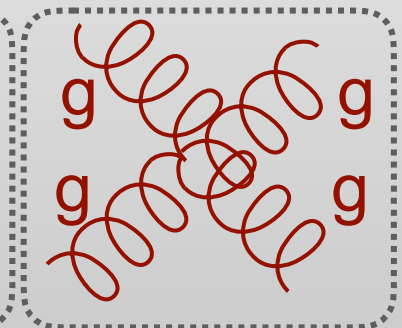
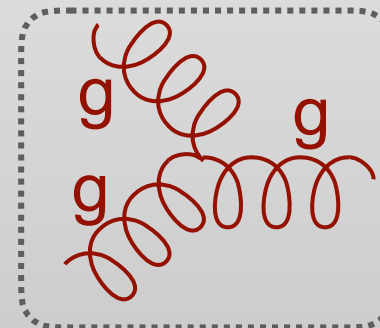
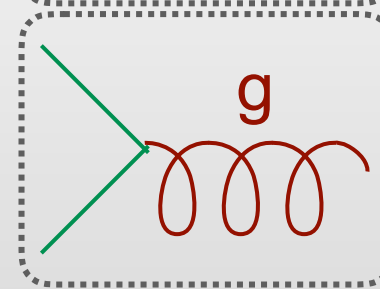
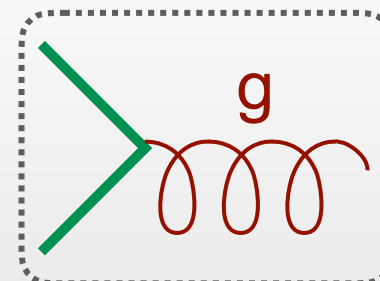
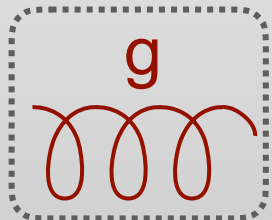
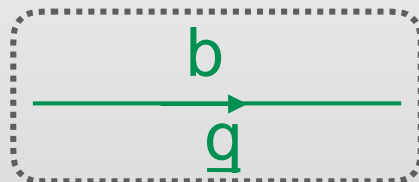
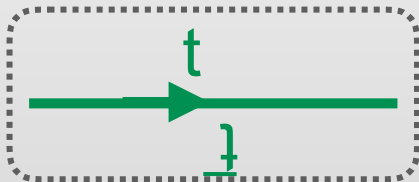
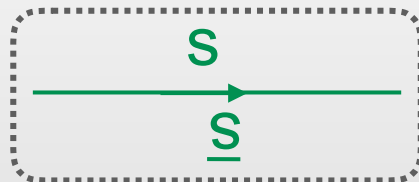
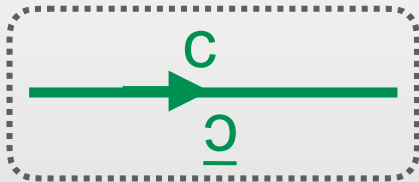
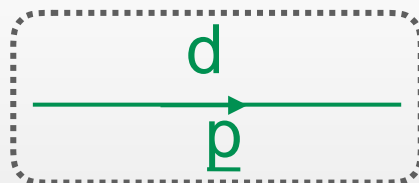
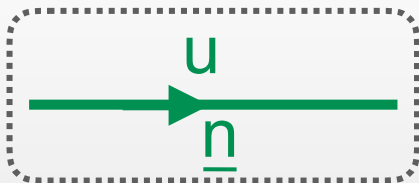
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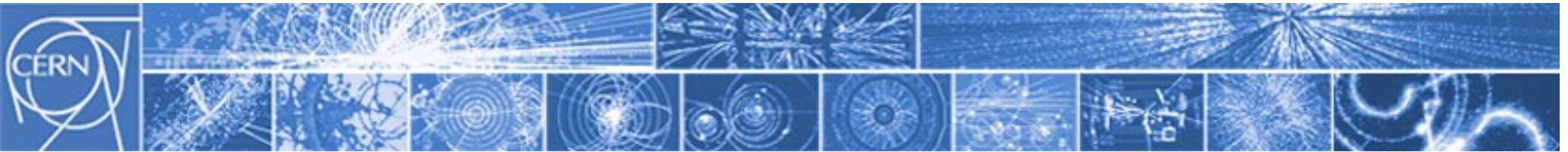
# I diagrammi di Feynman al lavoro: *gioco del domino* (un'idea di presentazione/masterclass?)

QCD Feynman rules



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# I diagrammi di Feynman al lavoro: *gioco del domino* (un'idea di presentazione/masterclass?)

## Processi da riprodurre:

- Bhabha scattering:  $e^+e^- \rightarrow e^+e^-$  [hint: 4 diagrammi possibili (tree-level)]
- Decadimento beta:  $(A,Z) \rightarrow (A,Z+1) e^- \bar{\nu}$
- Decadimento beta<sup>+</sup>:  $(A,Z) \rightarrow (A,Z-1) e^+ \nu$
- Cattura K:  $(A,Z) e^- \rightarrow (A,Z-1) \nu$
- Decadimento del muone
- Decadimento del top (semi-leptonico, hadronico)
- Scattering  $e^+e^- \rightarrow W^+W^-$  [hint: 3 diagrammi possibili (tree-level)]
- Decadimento  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$  [hint: implica sia interazioni deboli che forti]
- ...