The background of the slide is a repeating pattern of various Feynman diagrams. These diagrams represent particle interactions, featuring solid lines with arrows for fermions and wavy lines for bosons. Some diagrams show simple scattering, while others include loops and more complex vertex structures.

# Le Modèle Standard de la physique des particules

Pourquoi avons-nous construit le LHC?

# Plan

- Les origines du modèle Standard: la TQC (QFT):
  - Motivations de la TQC
  - Diagrammes de Feynman
- Les particules élémentaires et leurs interactions
  - L'interaction électromagnétique
  - L'interaction faible
  - L'interaction forte
  - Le boson de Higgs

# Théorie quantique des champs

- Mécanique quantique

- Plusieurs particules : difficile!

- Pas de relativité (restreinte)

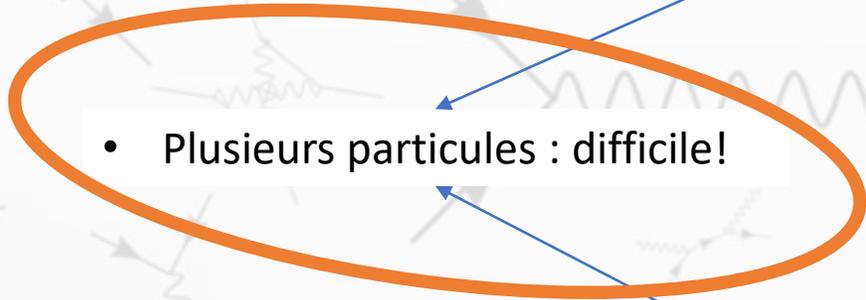
# Théorie quantique des champs

- Mécanique quantique

- Plusieurs particules : difficile!

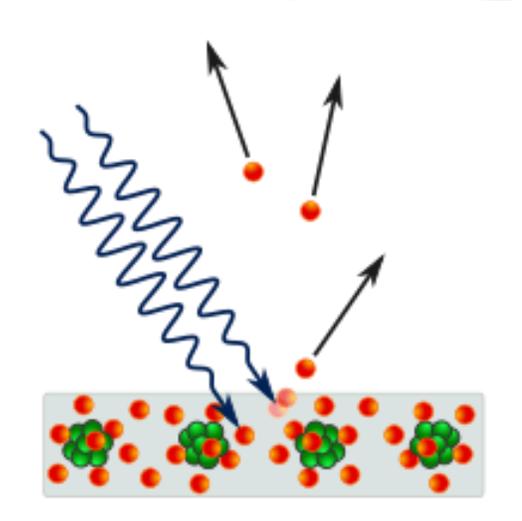
- Pas de relativité (restreinte)

- Résolu par Dirac (mécanique quantique relativiste)



Old Way

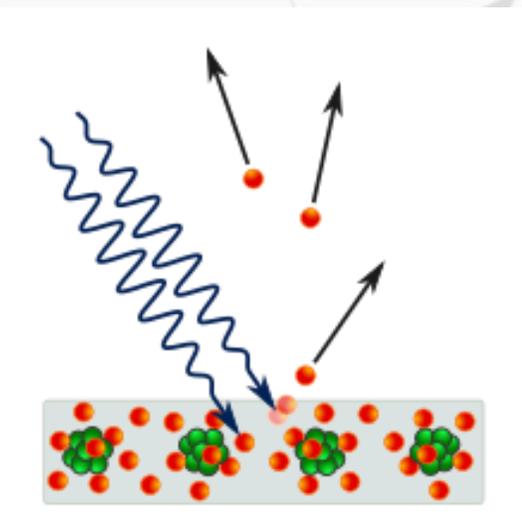
Particules avec coordonnées  $(x,p)$



# Théorie quantique des champs

Old Way

Particules avec coordonnées  $(x,p)$



New Way

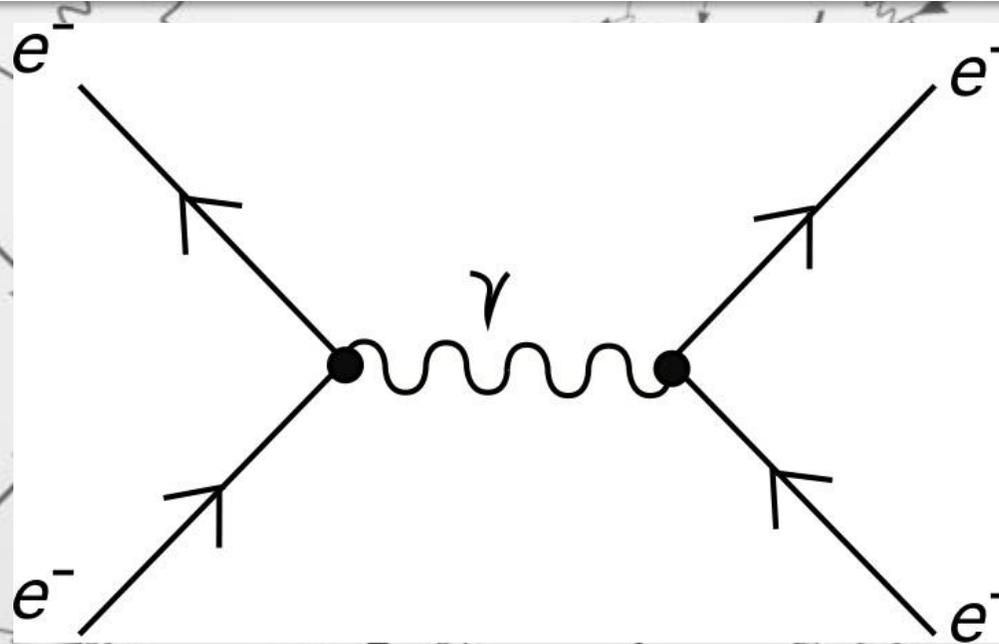
Excitations d'un champs



# Théorie quantique des champs

- Avantages et avancées:
  - Plusieurs particules
  - Relativité restreinte
  - Désintégrations
  - Formulation quantique du champ électromagnétique (QED)
  - + quantification de théories de jauge
- Inconvénients:
  - Calculs difficiles : approche perturbative requise
  - Apparitions de quantités infinies

# Diagrammes de Feynman

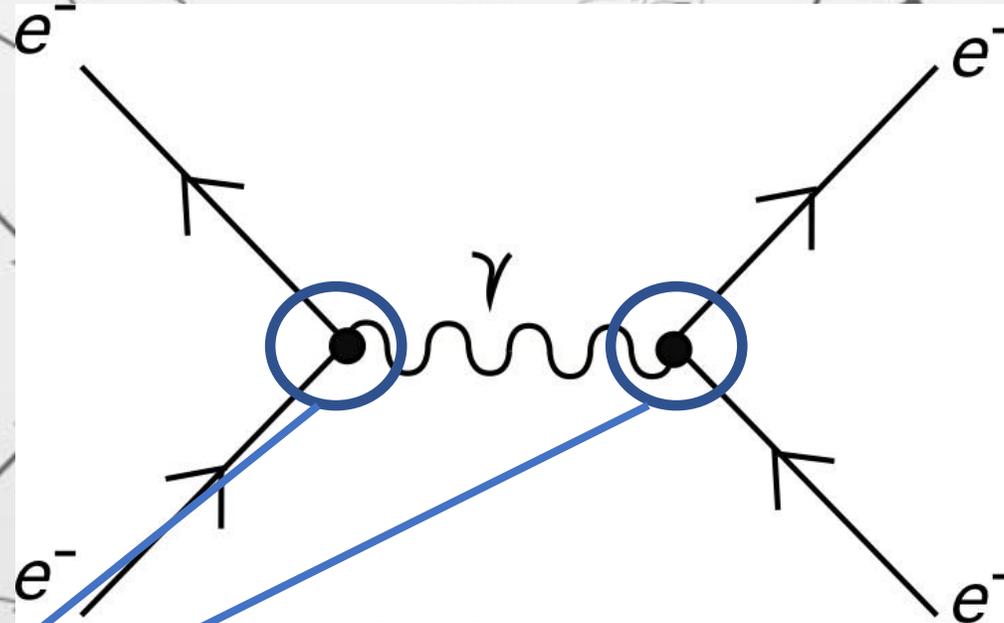


Calcul : probabilités de dispersion, désintégration, section efficace

Outil

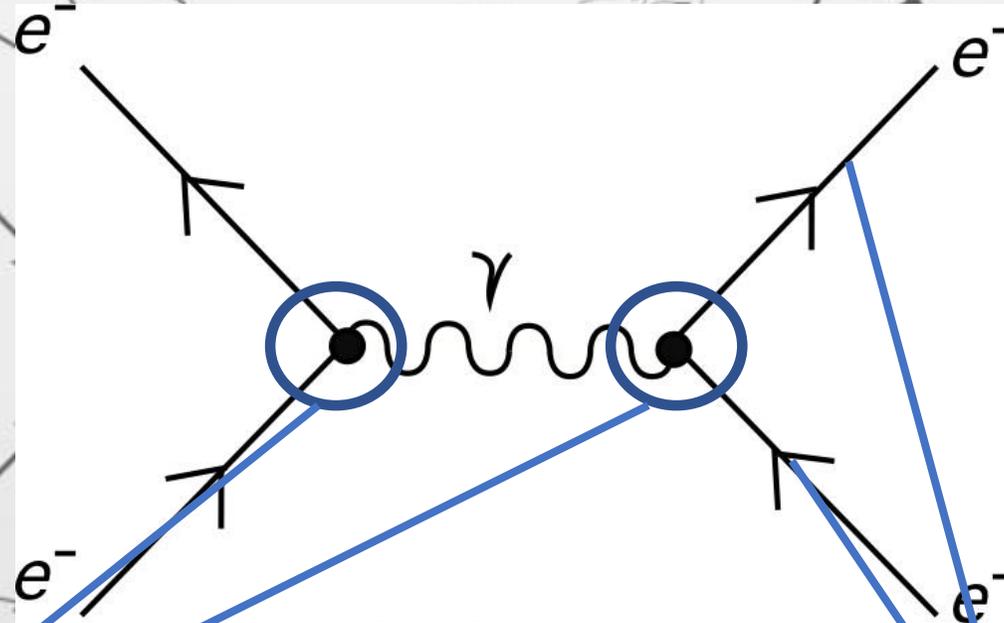
Interprétation : comprendre le « mouvement » des particules

# Diagrammes de Feynman



Vertex : intensité  
de l'interaction

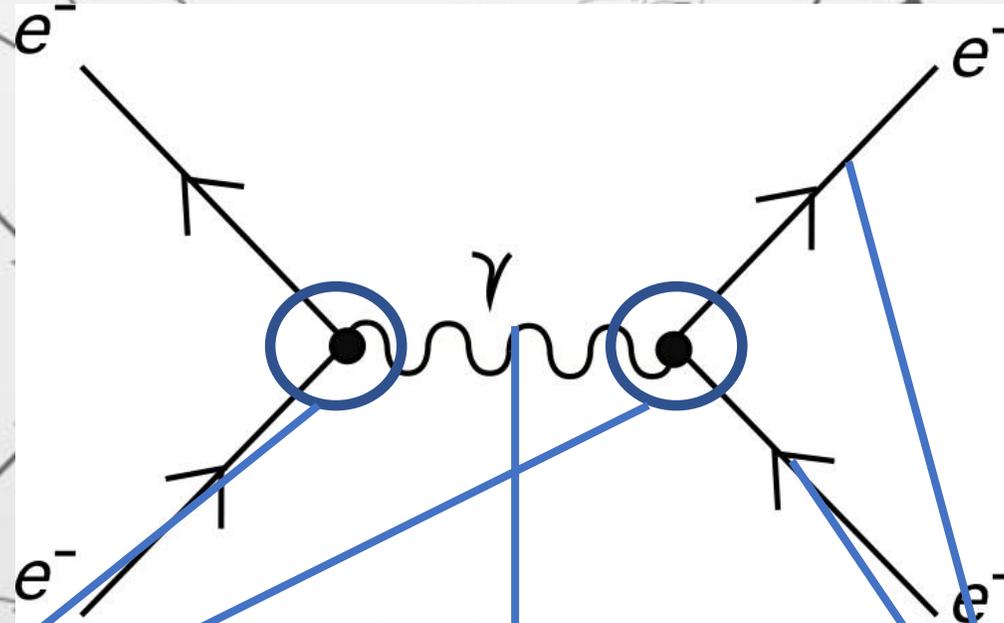
# Diagrammes de Feynman



Vertex : intensité  
de l'interaction

Lignes externes :  
états externes

# Diagrammes de Feynman



Vertex : intensité  
de l'interaction

Lignes internes :  
particules virtuelles

Lignes externes :  
états externes

# Le modèle Standard

Théorie la plus complète qui décrit les particules élémentaires (leptons et quarks) et leurs interactions (bosons)

Développé dans les années 1960-70

## Standard Model of Elementary Particles

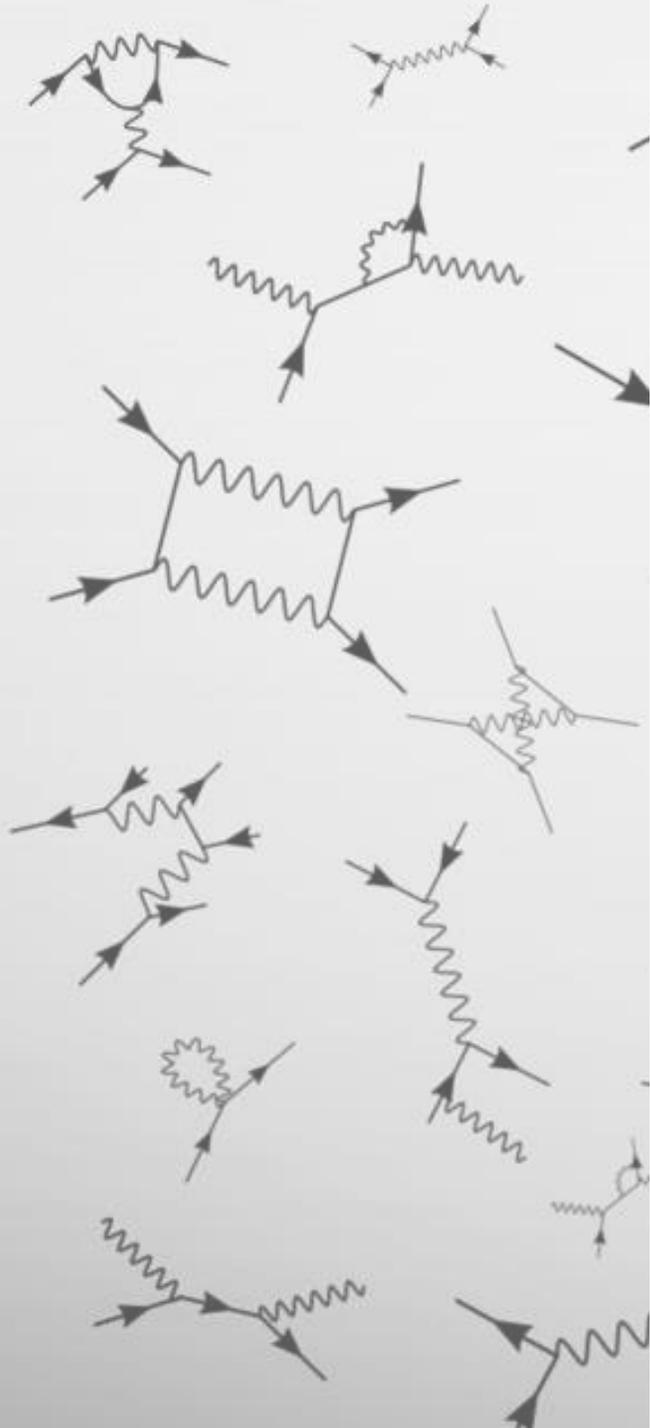
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
QUARKS	$\approx 2.2 \text{ MeV}/c^2$ mass $\frac{2}{3}$ charge $\frac{1}{2}$ spin <b>u</b> up	$\approx 1.28 \text{ GeV}/c^2$ mass $\frac{2}{3}$ charge $\frac{1}{2}$ spin <b>c</b> charm	$\approx 173.1 \text{ GeV}/c^2$ mass $\frac{2}{3}$ charge $\frac{1}{2}$ spin <b>t</b> top	0 0 1 <b>g</b> gluon	$\approx 124.97 \text{ GeV}/c^2$ mass 0 0 0 <b>H</b> higgs
	$\approx 4.7 \text{ MeV}/c^2$ mass $-\frac{1}{3}$ charge $\frac{1}{2}$ spin <b>d</b> down	$\approx 96 \text{ MeV}/c^2$ mass $-\frac{1}{3}$ charge $\frac{1}{2}$ spin <b>s</b> strange	$\approx 4.18 \text{ GeV}/c^2$ mass $-\frac{1}{3}$ charge $\frac{1}{2}$ spin <b>b</b> bottom	0 0 1 <b><math>\gamma</math></b> photon	
	$\approx 0.511 \text{ MeV}/c^2$ mass -1 $\frac{1}{2}$ spin <b>e</b> electron	$\approx 105.66 \text{ MeV}/c^2$ mass -1 $\frac{1}{2}$ spin <b><math>\mu</math></b> muon	$\approx 1.7768 \text{ GeV}/c^2$ mass -1 $\frac{1}{2}$ spin <b><math>\tau</math></b> tau	0 1 <b>Z</b> Z boson	
LEPTONS	$< 1.0 \text{ eV}/c^2$ mass 0 $\frac{1}{2}$ spin <b><math>\nu_e</math></b> electron neutrino	$< 0.17 \text{ MeV}/c^2$ mass 0 $\frac{1}{2}$ spin <b><math>\nu_\mu</math></b> muon neutrino	$< 18.2 \text{ MeV}/c^2$ mass 0 $\frac{1}{2}$ spin <b><math>\nu_\tau</math></b> tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ mass $\pm 1$ 1 <b>W</b> W boson	<b>GAUGE BOSONS</b> VECTOR BOSONS

SCALAR BOSONS

# Le modèle Standard

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \mathcal{D}_\mu - m_e)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+)) - \\
& ig s_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
& W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
& Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
& \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\
& g\alpha_h M (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
& \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
& gM W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
& \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
& \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
& M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+)) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
& \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)\phi^+ \phi^-) - \\
& \frac{1}{2}g^2 \frac{2s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
& g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a - \bar{e}^\lambda (\gamma^\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma^\partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\partial + \\
& m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\
& \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
& (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
& \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep}{}_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
& \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 - \gamma^5) \nu^\kappa)) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
& \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa - \\
& \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa)) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
& \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
& \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
& \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
& \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
& \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
\end{aligned}$$



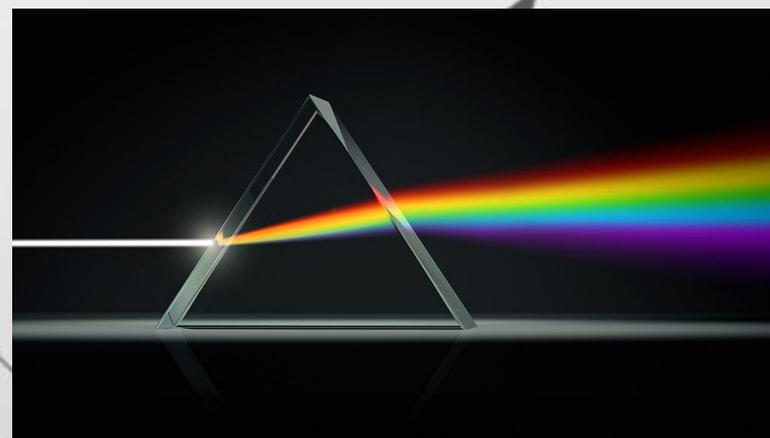
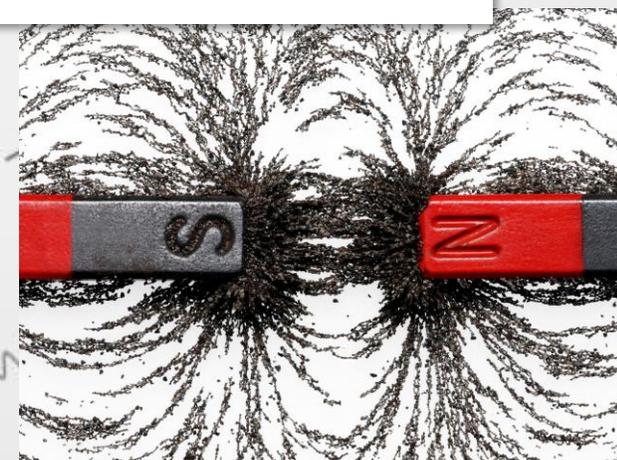
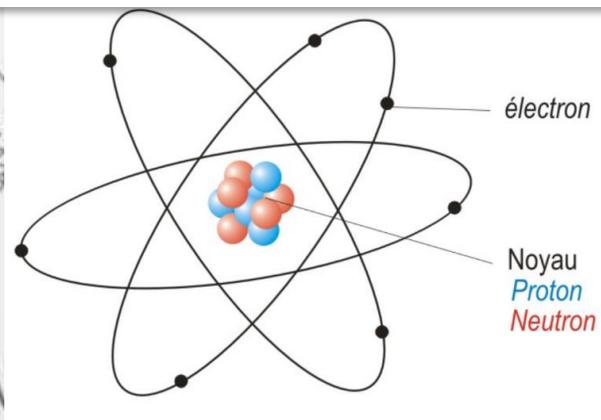
# L'interaction électromagnétique

$$\operatorname{div}(\vec{E}) = \frac{\rho}{\epsilon_0} \quad \operatorname{rot}(\vec{E}) = -\frac{\partial \vec{B}}{\partial t}$$

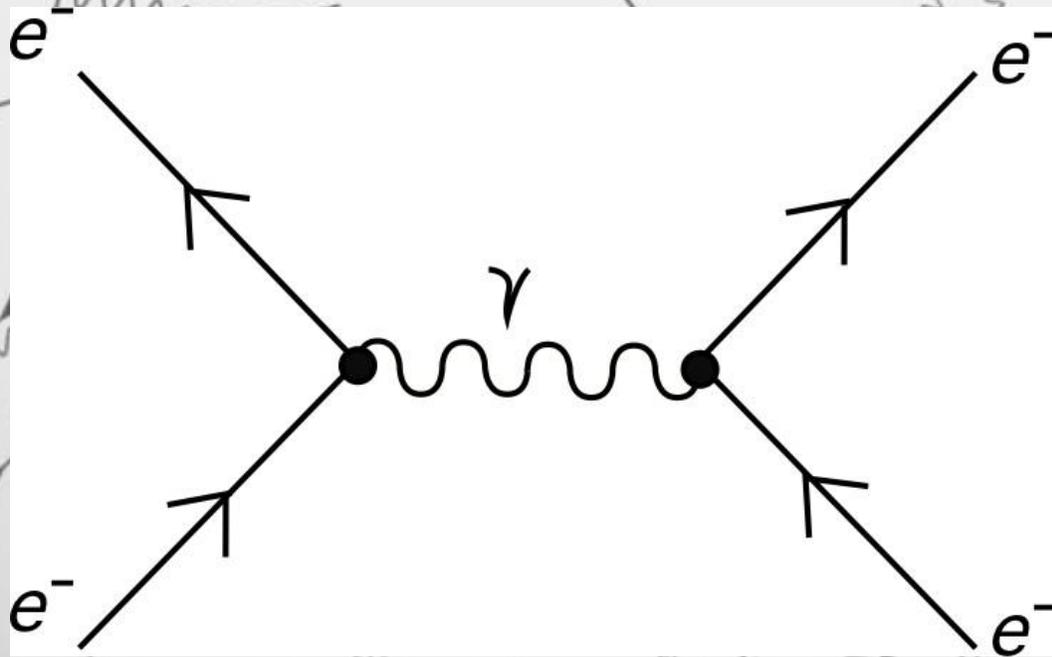
(Maxwell-Gauss) (Maxwell-Faraday)

$$\operatorname{div}(\vec{B}) = 0 \quad \operatorname{rot}(\vec{B}) = \mu_0 \vec{J} + \frac{1}{c^2} \frac{\partial \vec{E}}{\partial t}$$

(Maxwell-Flux) (Maxwell-Ampère)



# L'interaction électromagnétique



Médiateur : le photon

Interagit avec des particules chargées

Ne possède pas de masse, ni de charge

# L'interaction électromagnétique

## Standard Model of Elementary Particles

three generations of matter (fermions)      interactions / force carriers (bosons)

	three generations of matter (fermions)			interactions / force carriers (bosons)	
QUARKS	mass: $\approx 2.2 \text{ MeV}/c^2$ charge: $\frac{2}{3}$ spin: $\frac{1}{2}$ <b>u</b> up	mass: $\approx 1.28 \text{ GeV}/c^2$ charge: $\frac{2}{3}$ spin: $\frac{1}{2}$ <b>c</b> charm	mass: $\approx 173.1 \text{ GeV}/c^2$ charge: $\frac{2}{3}$ spin: $\frac{1}{2}$ <b>t</b> top	mass: 0 charge: 0 spin: 1 <b>g</b> gluon	mass: $\approx 124.97 \text{ GeV}/c^2$ charge: 0 spin: 0 <b>H</b> higgs
	mass: $\approx 4.7 \text{ MeV}/c^2$ charge: $-\frac{1}{3}$ spin: $\frac{1}{2}$ <b>d</b> down	mass: $\approx 96 \text{ MeV}/c^2$ charge: $-\frac{1}{3}$ spin: $\frac{1}{2}$ <b>s</b> strange	mass: $\approx 4.18 \text{ GeV}/c^2$ charge: $-\frac{1}{3}$ spin: $\frac{1}{2}$ <b>b</b> bottom	mass: 0 charge: 0 spin: 1 <b><math>\gamma</math></b> photon	mass: 0 charge: 0 spin: 1 <b>Z</b> Z boson
	mass: $\approx 0.511 \text{ MeV}/c^2$ charge: -1 spin: $\frac{1}{2}$ <b>e</b> electron	mass: $\approx 105.66 \text{ MeV}/c^2$ charge: -1 spin: $\frac{1}{2}$ <b><math>\mu</math></b> muon	mass: $\approx 1.7768 \text{ GeV}/c^2$ charge: -1 spin: $\frac{1}{2}$ <b><math>\tau</math></b> tau		
LEPTONS	mass: $< 1.0 \text{ eV}/c^2$ charge: 0 spin: $\frac{1}{2}$ <b><math>\nu_e</math></b> electron neutrino	mass: $< 0.17 \text{ MeV}/c^2$ charge: 0 spin: $\frac{1}{2}$ <b><math>\nu_\mu</math></b> muon neutrino	mass: $< 18.2 \text{ MeV}/c^2$ charge: 0 spin: $\frac{1}{2}$ <b><math>\nu_\tau</math></b> tau neutrino	mass: $\approx 80.39 \text{ GeV}/c^2$ charge: $\pm 1$ spin: 1 <b>W</b> W boson	GAUGE BOSONS VECTOR BOSONS

Charge :  $\frac{2}{3}$

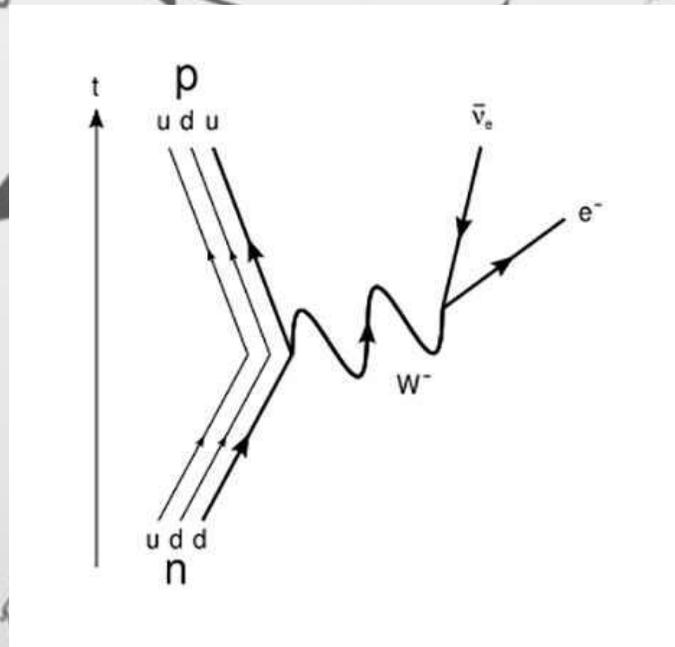
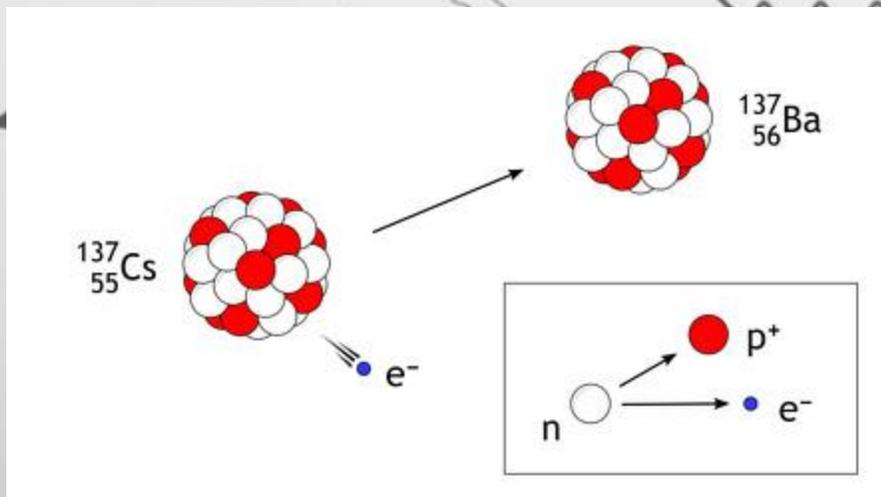
Charge :  $-\frac{1}{3}$

Charge : -1

Charge :  $\pm 1$

# L'interaction faible

## La désintégration bêta



# L'interaction faible

5 bosons

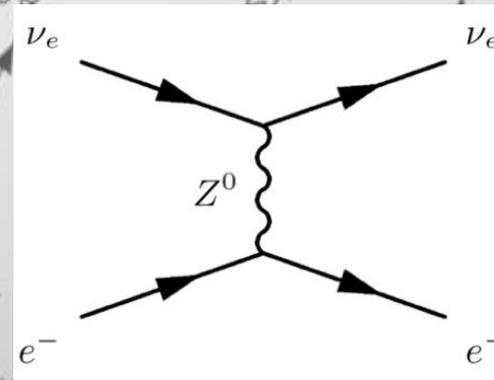
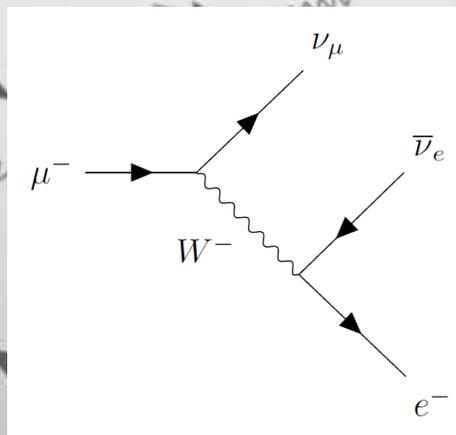
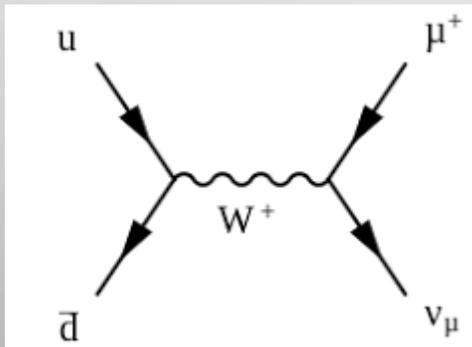
Chargé

80.4 GeV/c<sup>2</sup>  
 $\pm 1$   
**W<sup>±</sup>**  
1  
W boson

Neutre

91.2 GeV/c<sup>2</sup>  
0  
**Z<sup>0</sup>**  
1  
Z boson

Se désintègrent



# L'interaction faible

**Standard Model of Elementary Particles**

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
<b>QUARKS</b>	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
<b>LEPTONS</b>	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	

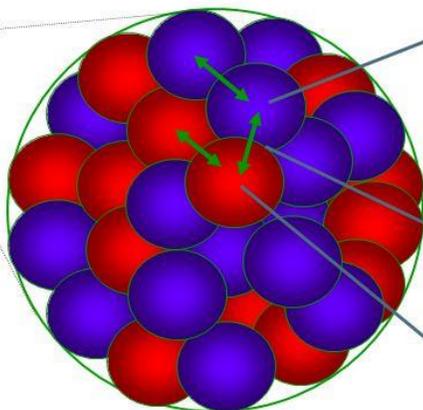
**GAUGE BOSONS VECTOR BOSONS**

**SCALAR BOSONS**

# L'interaction forte

## Structure du noyau

5



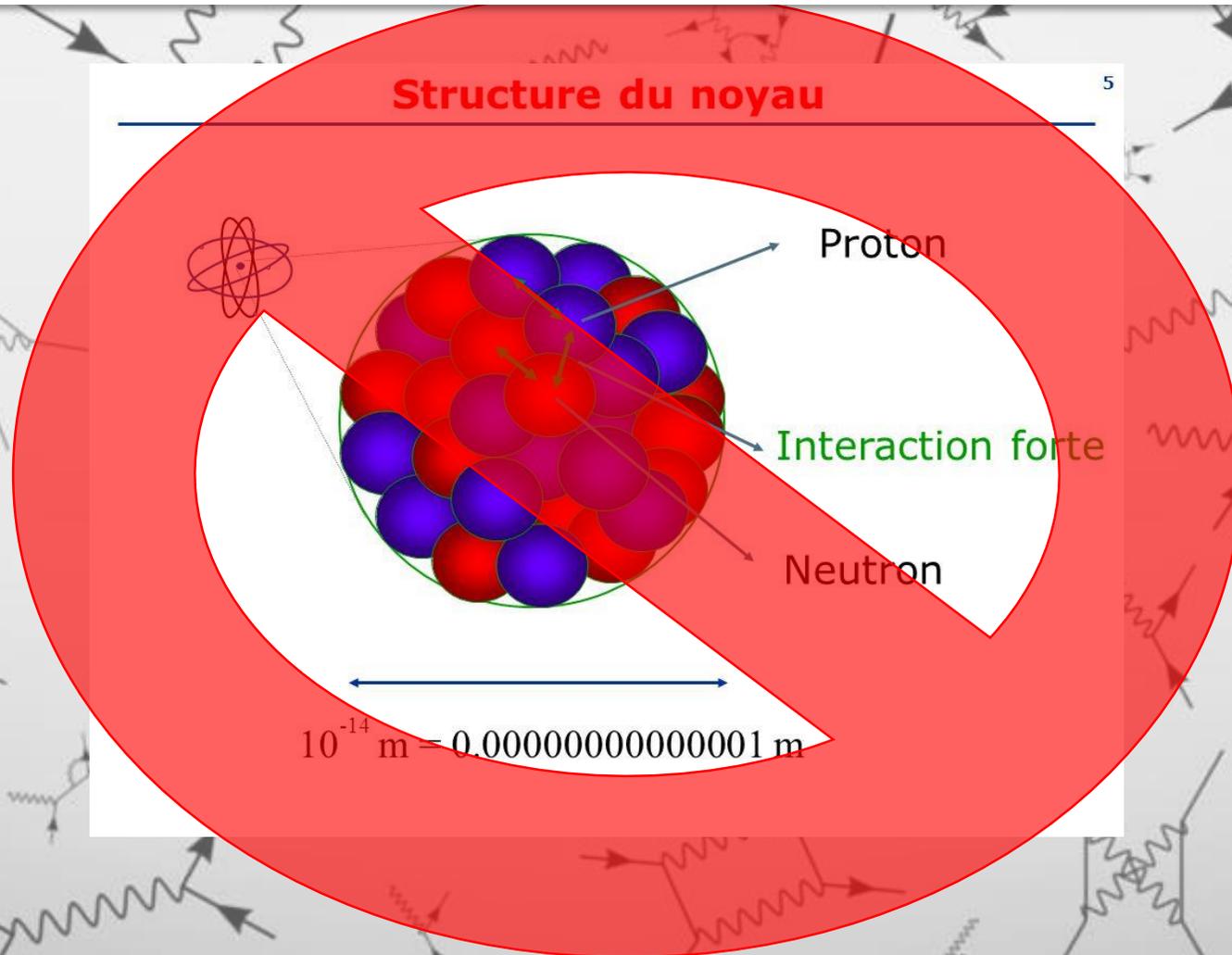
Proton

Interaction forte

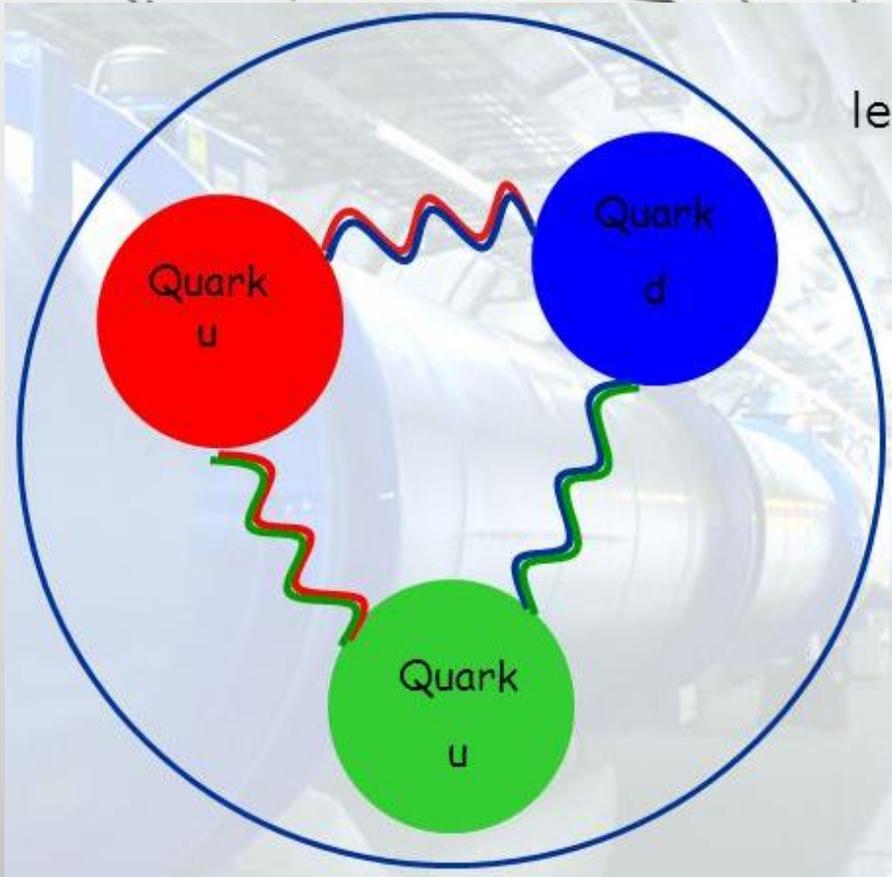
Neutron

$10^{-14}$  m = 0.00000000000001 m

# L'interaction forte



# L'interaction forte



Agit sur les quarks

1 charge de couleur : « Bleu, vert, rouge »

Médiateur: le gluon

2 couleurs: « Bleu, vert, rouge » et  
« Anti-bleu, anti-vert, anti-rouge »

# L'interaction forte

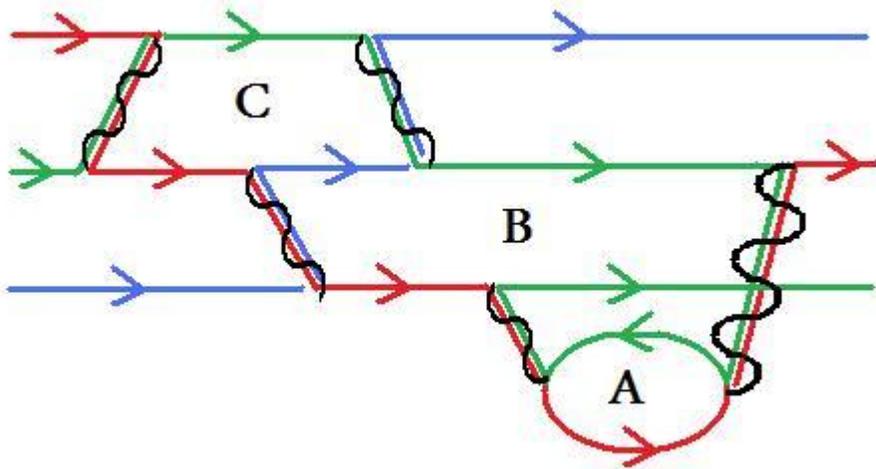
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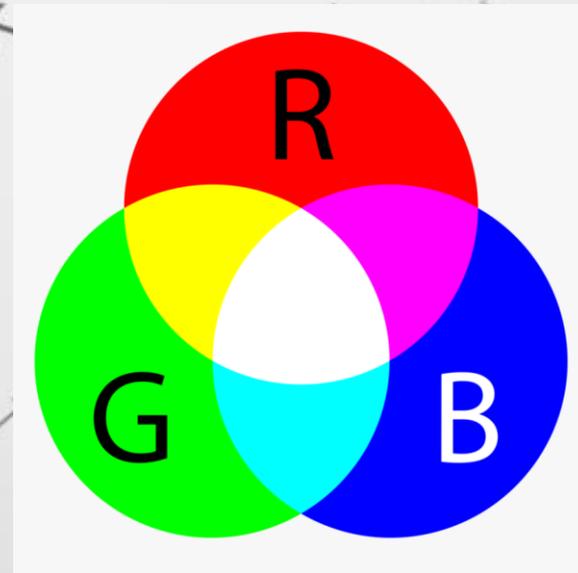
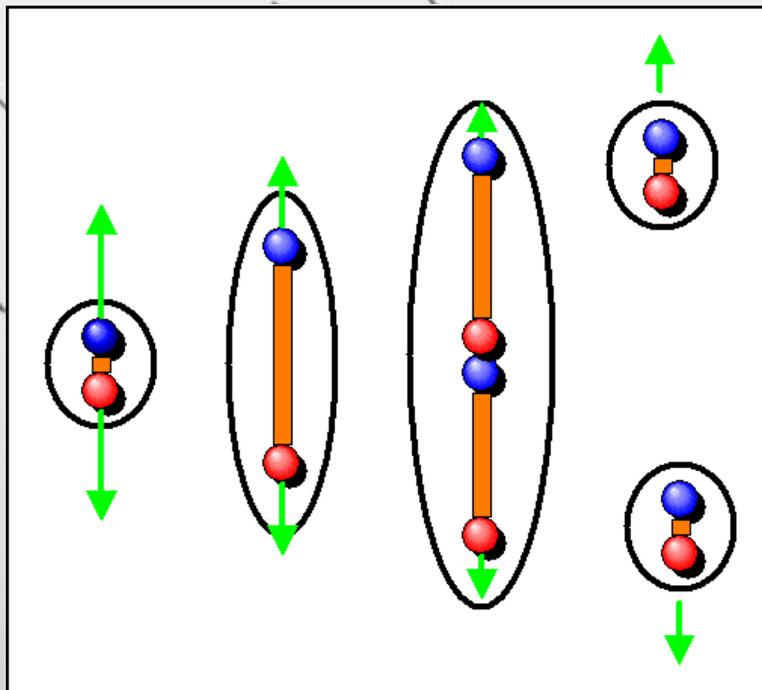
2 couleurs: « Bleu, vert, rouge » et  
« Anti-bleu, anti-vert, anti-rouge »

Pas de charge électrique, sans masse



# L'interaction forte

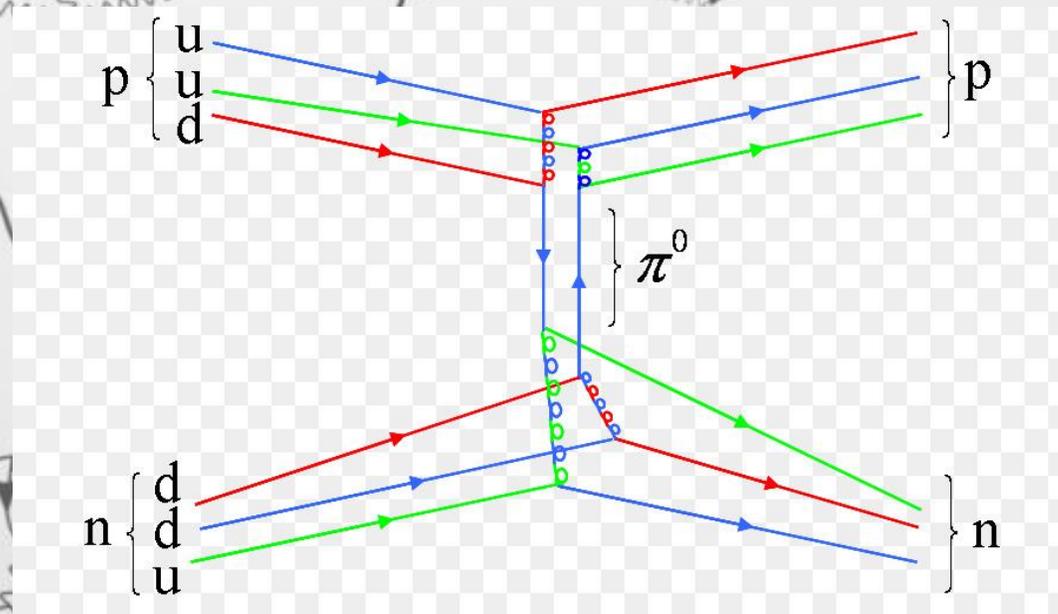
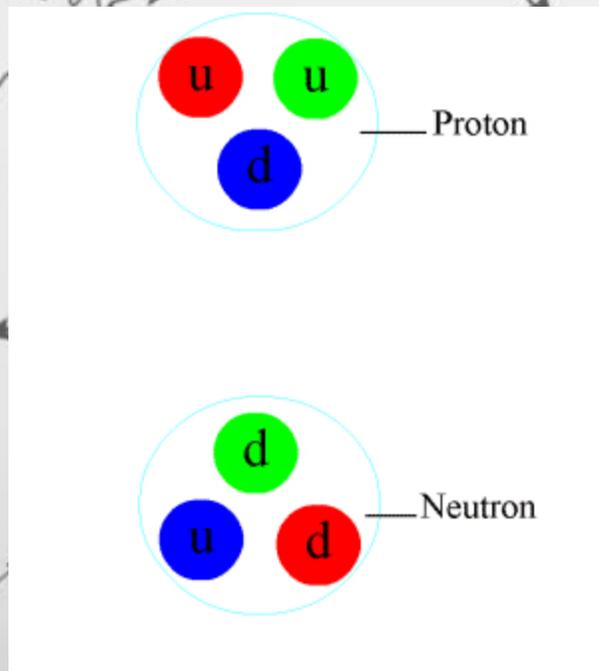
## Le confinement des quarks



Une particule observée doit être blanche (hadrons ou baryons)



# L'interaction nucléaire forte



# Le boson de **Englert-Brout**-Higgs

- Mécanisme de Higgs: Le champ de Higgs confère aux particules élémentaires (massifs) leur masse par une brisure de symétrie spontanée
- Attention: Champ de Higgs  $\neq$  Boson de Higgs
- Découverte expérimentale en 2012 au Large Hadron Collider (CERN)

# Questions ouvertes

- Pas de gravité, ni relativité restreinte
- Matière noire, énergie noire?
- Masse des neutrinos
- Strong CP Problem
- Matière vs antimatière