

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

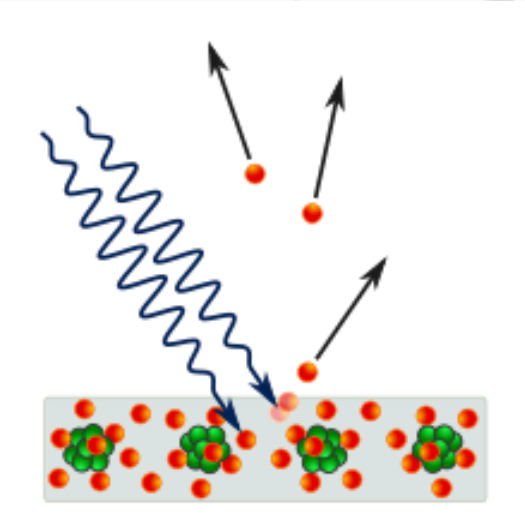
- Plusieurs particules : difficile!

- Pas de relativité (restreinte)

- Résolu par Dirac (mécanique quantique relativiste)

Old Way

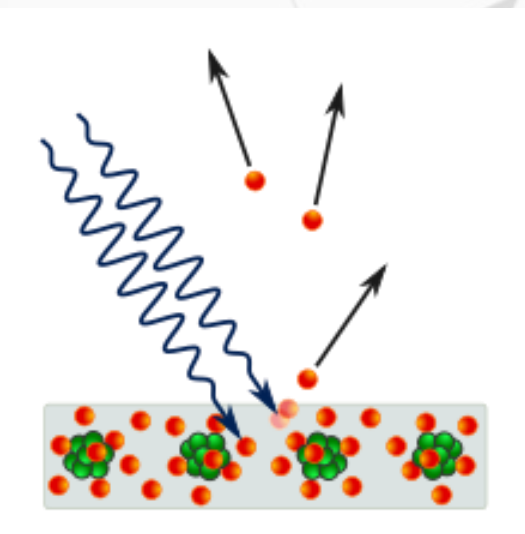
Particules avec coordonnées (x,p)



Théorie quantique des champs

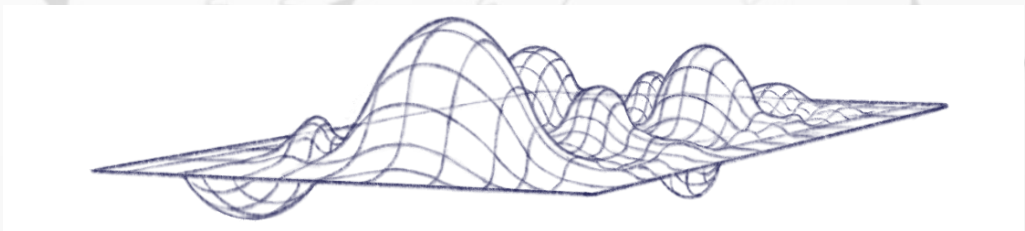
Old Way

Particules avec coordonnées (x,p)



New Way

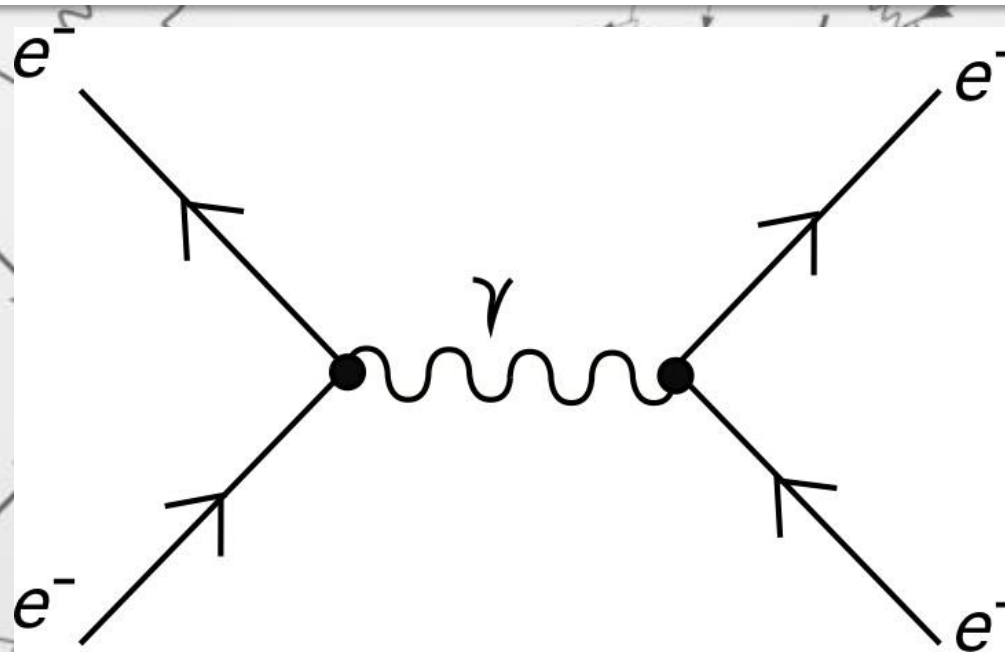
Excitations d'un champs



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

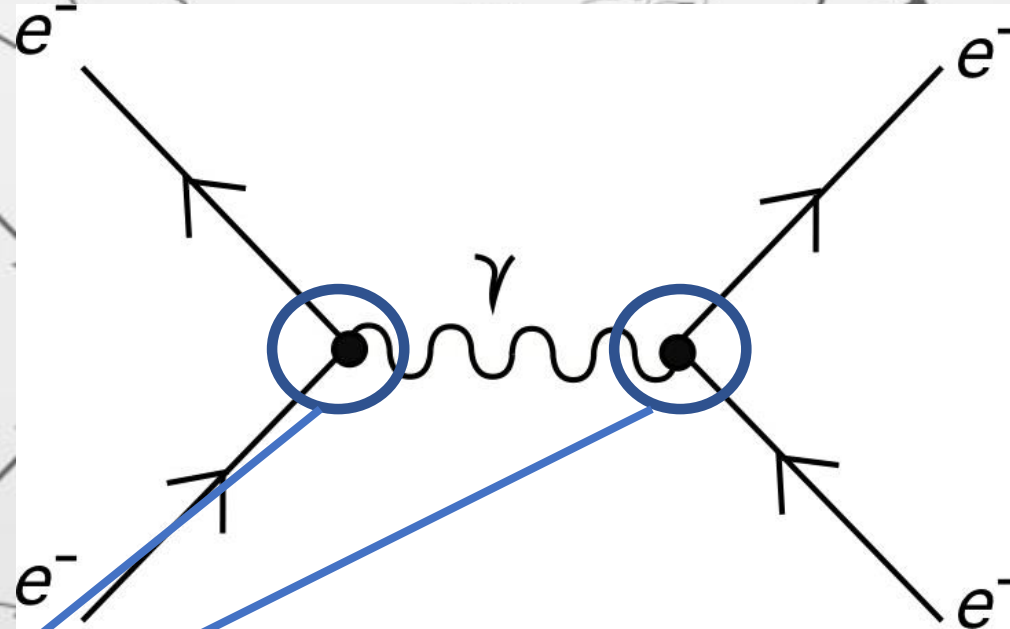


Calcul : probabilités de dispersion, désintégration, section efficace

Outil

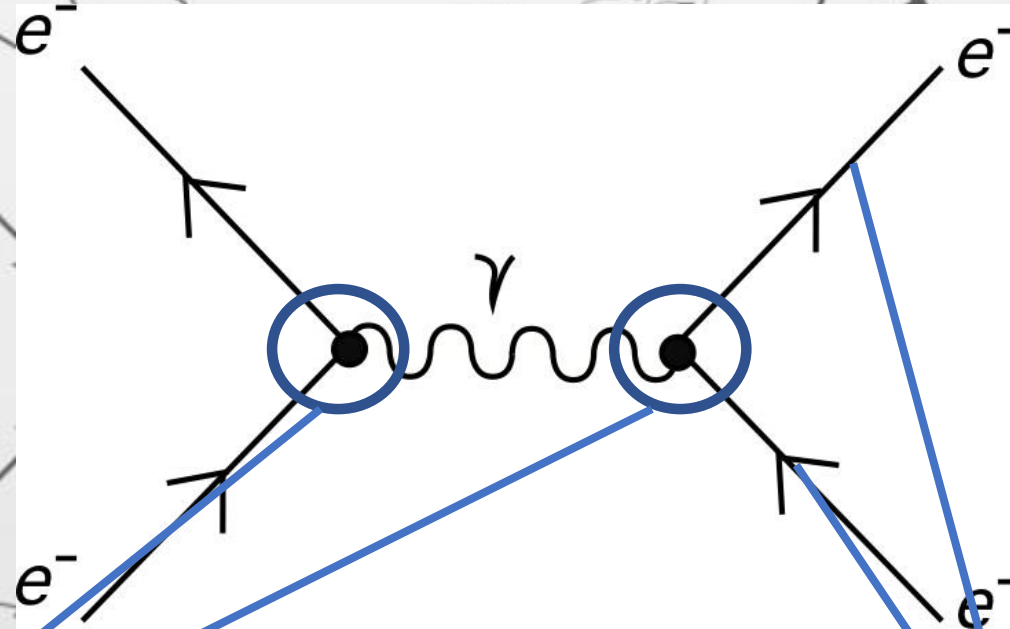
Interprétation : comprendre le « mouvement » des particules

Diagrammes de Feynman



Vertex : intensité
de l'interaction

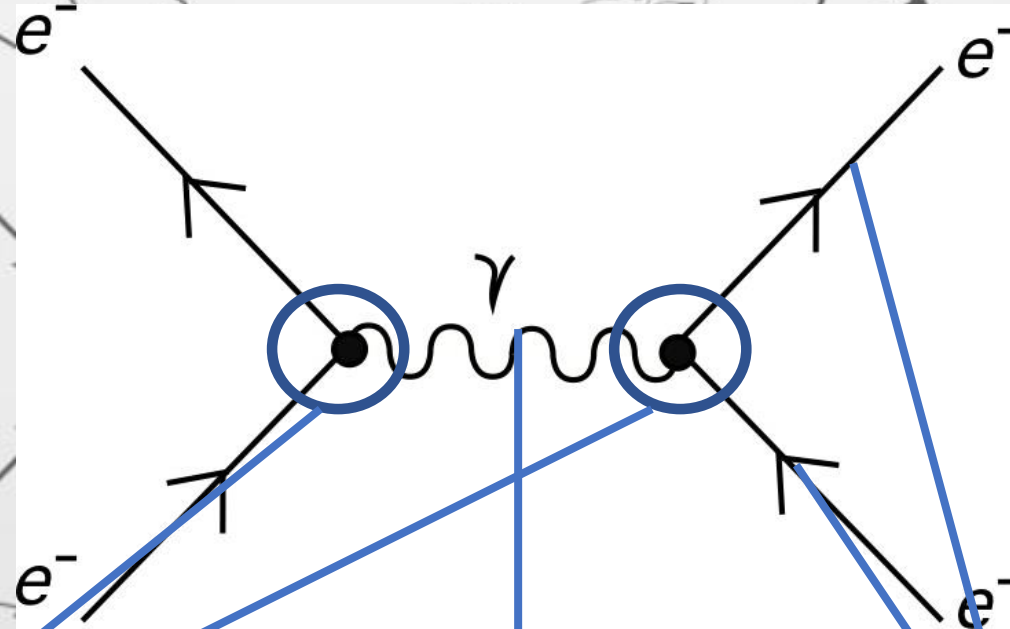
Diagrammes de Feynman



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

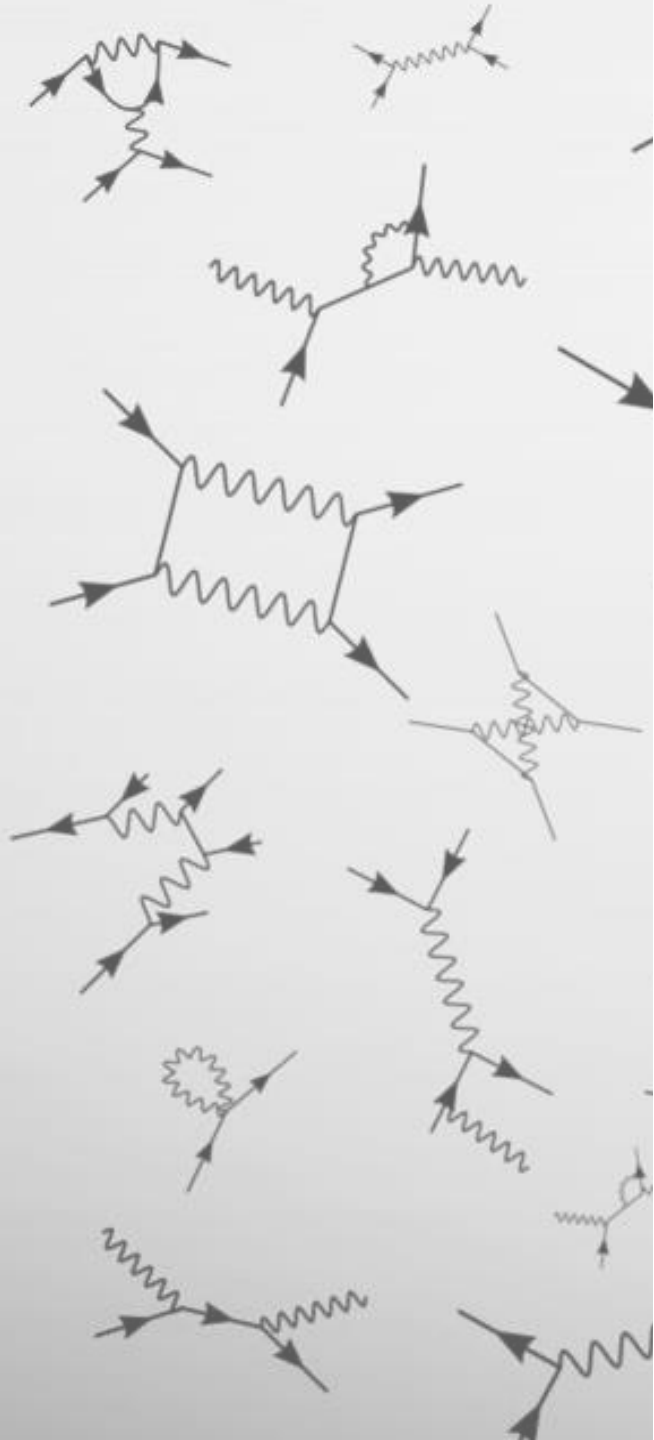
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
QUARKS	$\approx 2.2 \text{ MeV}/c^2$ 2/3 1/2 u up	$\approx 1.28 \text{ GeV}/c^2$ 2/3 1/2 c charm	$\approx 173.1 \text{ GeV}/c^2$ 2/3 1/2 t top	0 0 1 g gluon	$\approx 124.97 \text{ GeV}/c^2$ 0 0 0 H higgs
	$\approx 4.7 \text{ MeV}/c^2$ -1/3 1/2 d down	$\approx 96 \text{ MeV}/c^2$ -1/3 1/2 s strange	$\approx 4.18 \text{ GeV}/c^2$ -1/3 1/2 b bottom	0 0 1 γ photon	
	$\approx 0.511 \text{ MeV}/c^2$ -1 1/2 e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 1/2 μ muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 1/2 τ tau	0 1 1 Z Z boson	
LEPTONS	$< 1.0 \text{ eV}/c^2$ 0 1/2 ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 1/2 ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 1/2 ν_τ tau neutrino	$\approx 80.39 \text{ GeV}/c^2$ ± 1 1 W W boson	GAUGE BOSONS 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^\kappa (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\kappa (\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^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\kappa (\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}$$



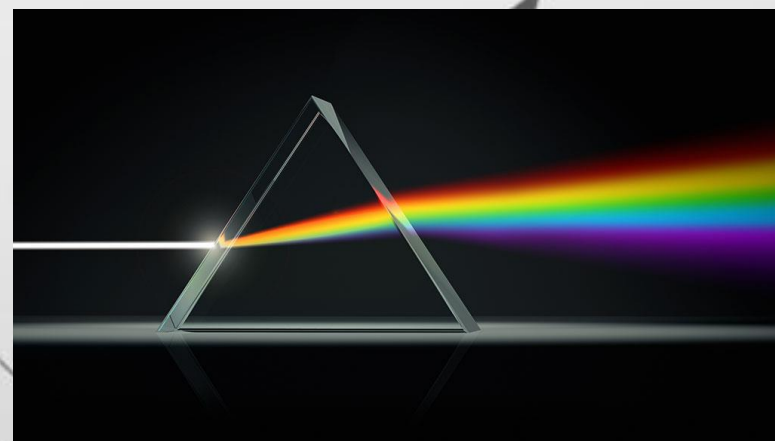
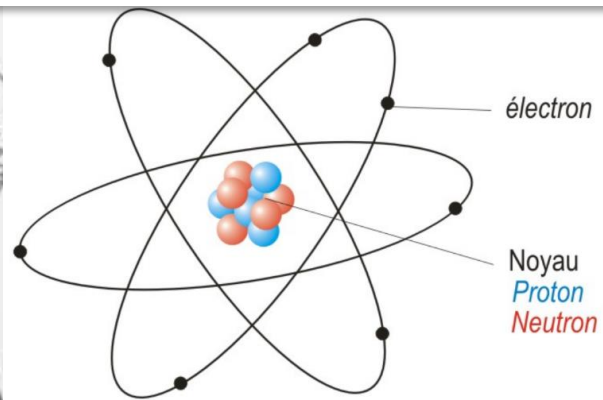
L'interaction électromagnétique

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

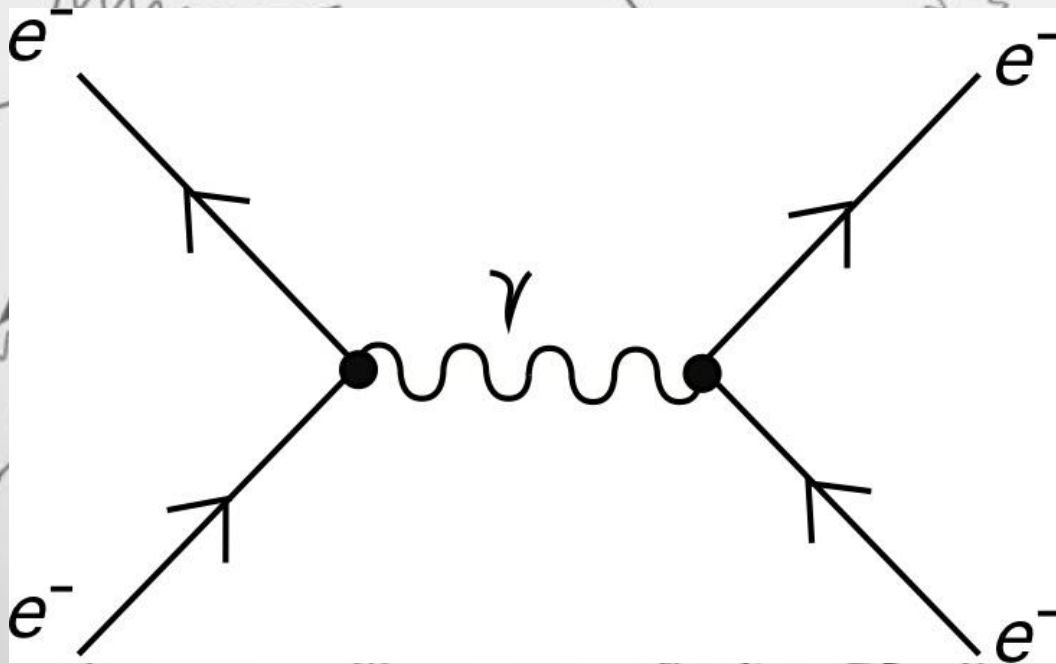
(Maxwell-Gauss) (Maxwell-Faraday)

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

(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: $2/3$ spin: $1/2$ u up	mass: $\approx 1.28 \text{ GeV}/c^2$ charge: $2/3$ spin: $1/2$ c charm	mass: $\approx 173.1 \text{ GeV}/c^2$ charge: $2/3$ spin: $1/2$ t top	mass: 0 charge: 0 spin: 1 g gluon	mass: $\approx 124.97 \text{ GeV}/c^2$ charge: 0 spin: 0 H higgs
	mass: $\approx 4.7 \text{ MeV}/c^2$ charge: $-1/3$ spin: $1/2$ d down	mass: $\approx 96 \text{ MeV}/c^2$ charge: $-1/3$ spin: $1/2$ s strange	mass: $\approx 4.18 \text{ GeV}/c^2$ charge: $-1/3$ spin: $1/2$ b bottom	mass: 0 charge: 0 spin: 1 γ photon	mass: 0 charge: 0 spin: 0 Z Z boson
	mass: $\approx 0.511 \text{ MeV}/c^2$ charge: -1 spin: $1/2$ e electron	mass: $\approx 105.66 \text{ MeV}/c^2$ charge: -1 spin: $1/2$ μ muon	mass: $\approx 1.7768 \text{ GeV}/c^2$ charge: -1 spin: $1/2$ τ tau		
LEPTONS	mass: $< 1.0 \text{ eV}/c^2$ charge: 0 spin: $1/2$ ν_e electron neutrino	mass: $< 0.17 \text{ MeV}/c^2$ charge: 0 spin: $1/2$ ν_μ muon neutrino	mass: $< 18.2 \text{ MeV}/c^2$ charge: 0 spin: $1/2$ ν_τ tau neutrino	mass: 0 charge: ± 1 spin: 1 W W boson	GAUGE BOSONS VECTOR BOSONS

Charge : $2/3$

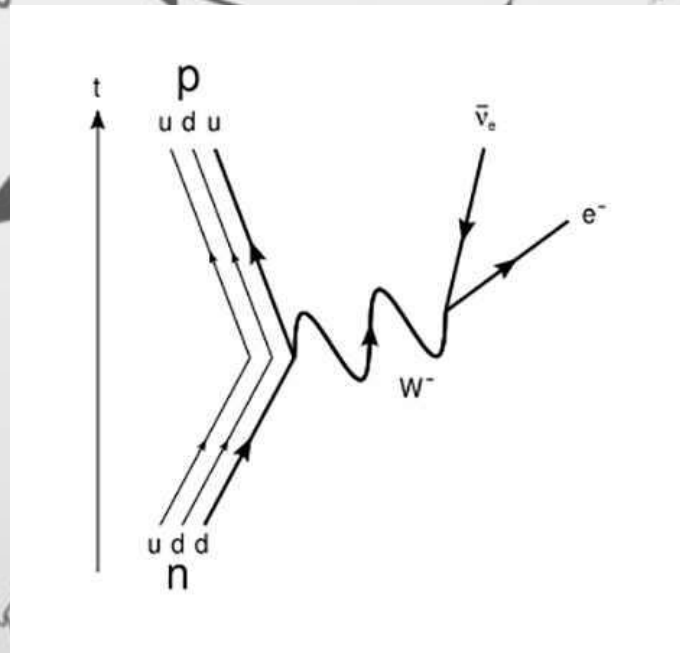
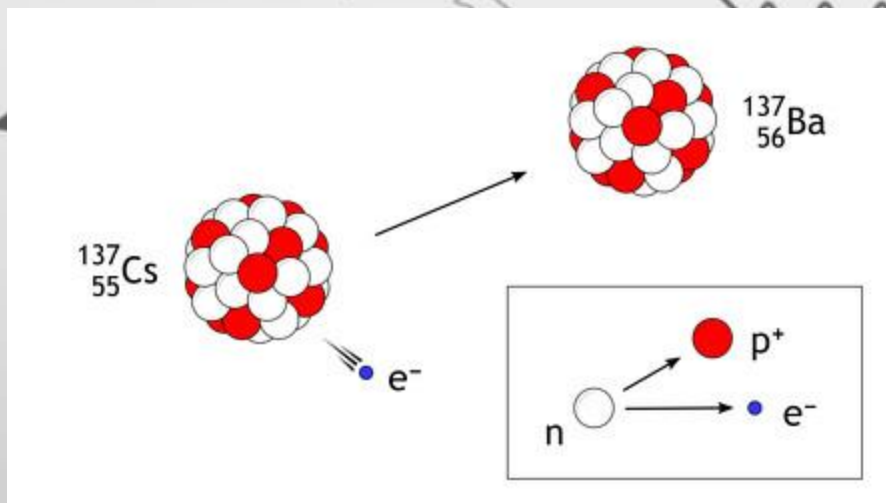
Charge : $-1/3$

Charge : -1

Charge : ± 1

L'interaction faible

La désintégration bêta



L'interaction faible

5 bosons

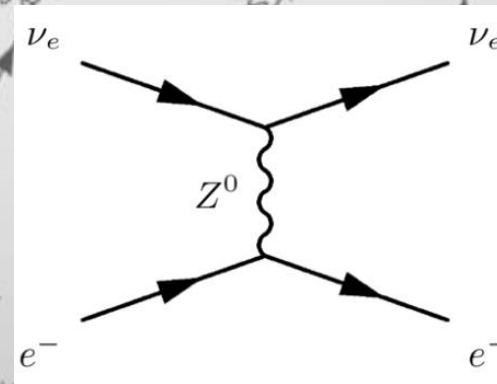
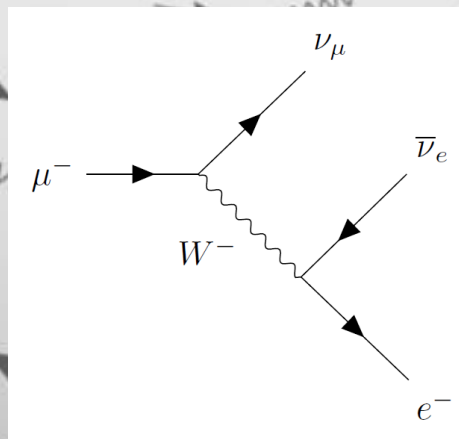
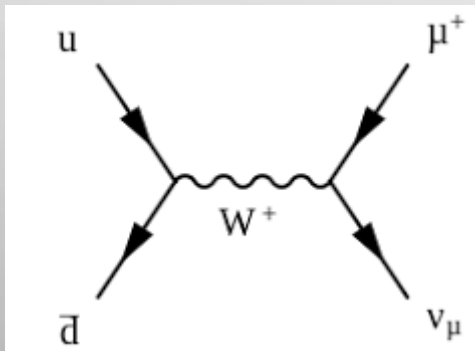
Chargé

80.4 GeV/c²
 ± 1
W[±]
1
W boson

Neutre

91.2 GeV/c²
0
Z⁰
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
QUARKS	u up	c charm	t top	g gluon	H 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	
	d down	s strange	b bottom	γ 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	
LEPTONS	e electron	μ muon	τ tau	Z 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	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

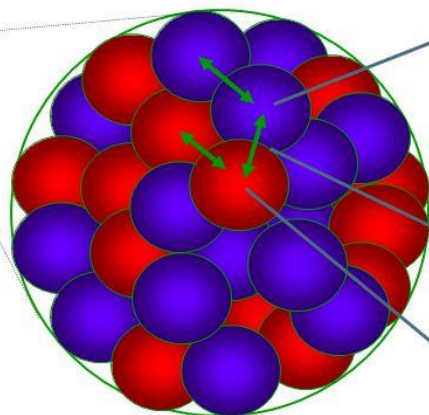
GAUGE BOSONS VECTOR BOSONS

SCALAR BOSONS

L'interaction forte

Structure du noyau

5



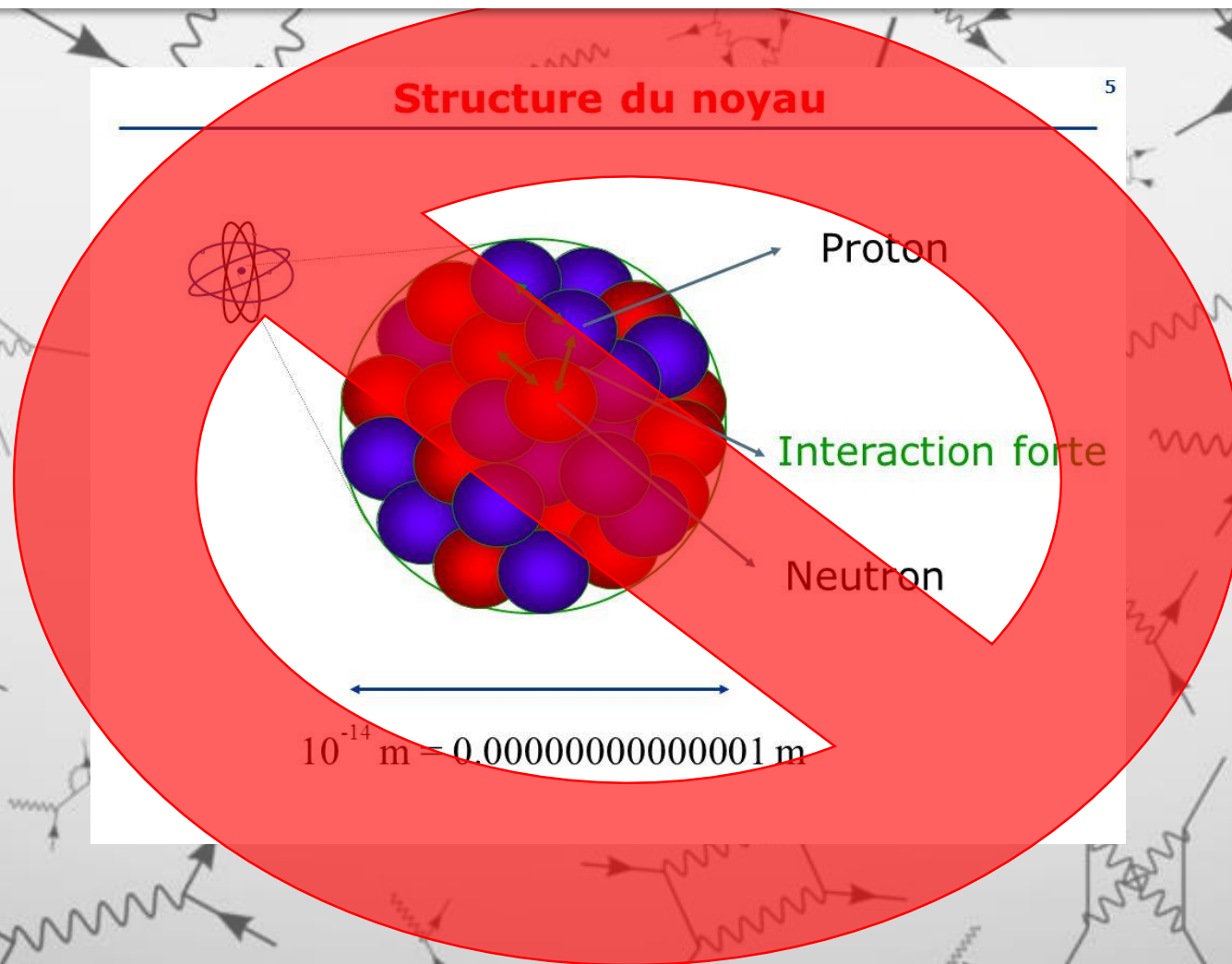
Proton

Interaction forte

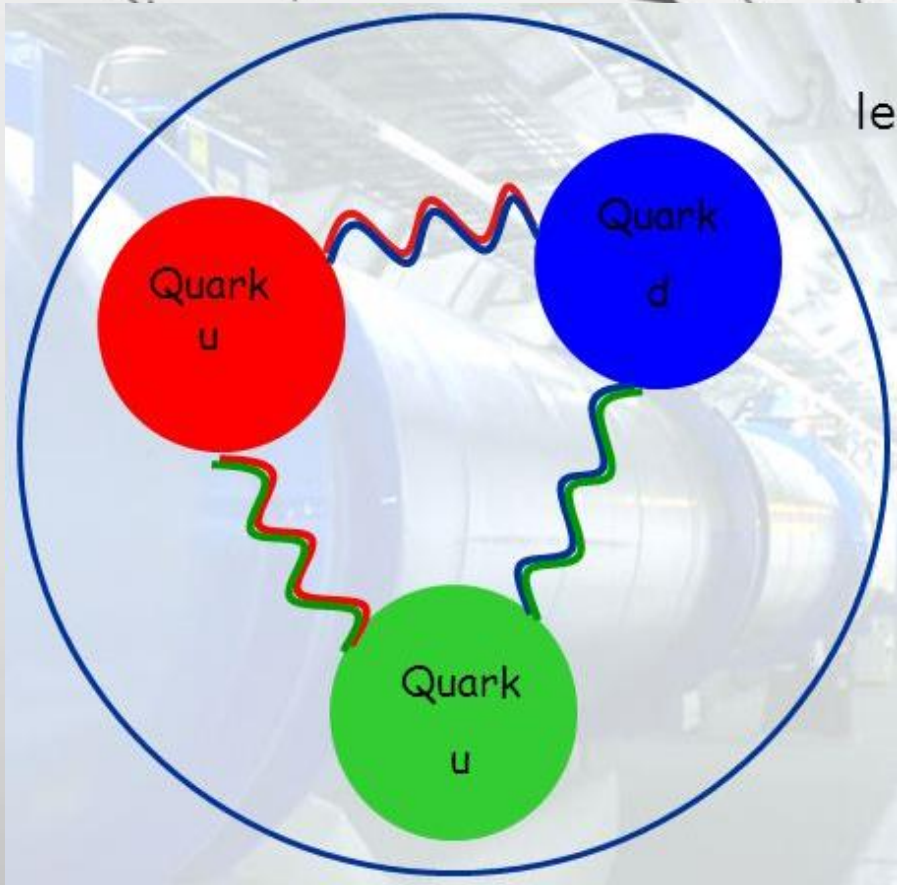
Neutron

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

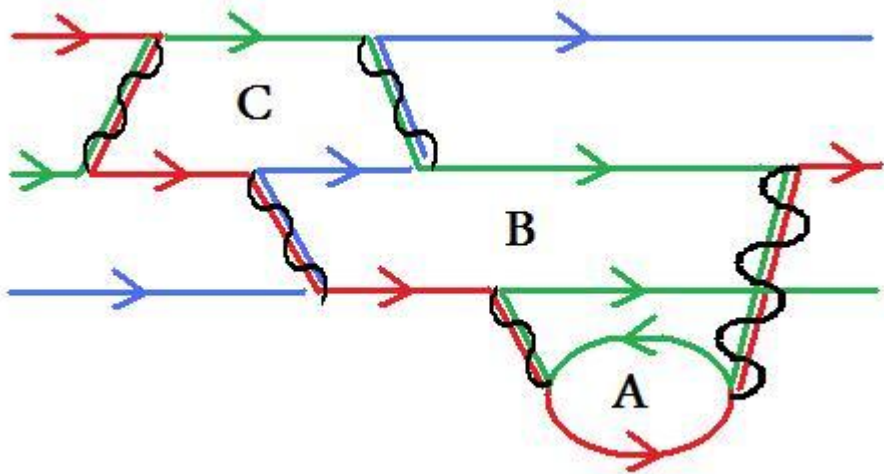
Agit sur les quarks

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

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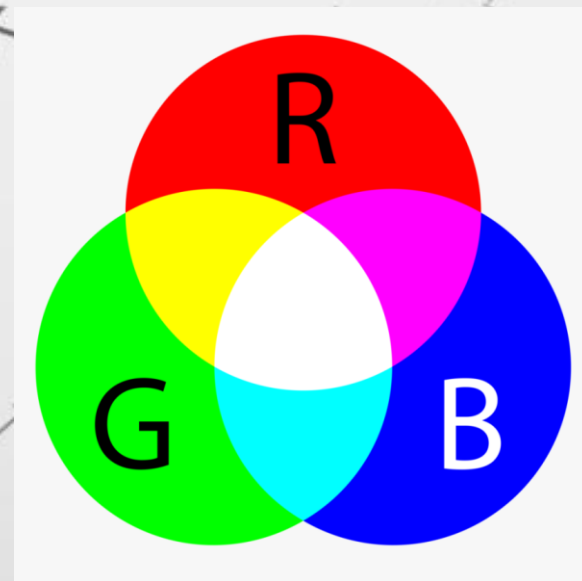
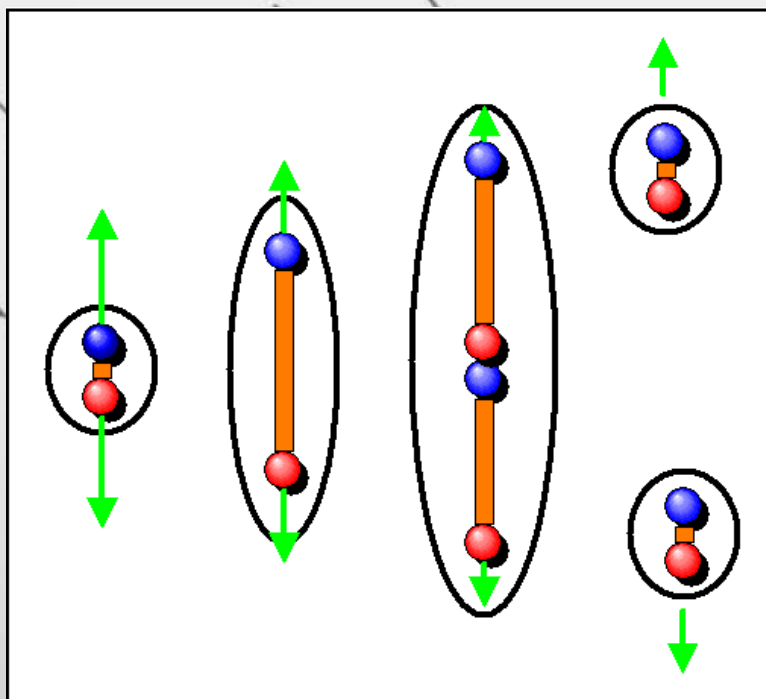
2 couleurs: « Bleu, vert, rouge » et
« Anti-bleu, anti-vert, anti-rouge »

Pas de charge électrique, sans masse



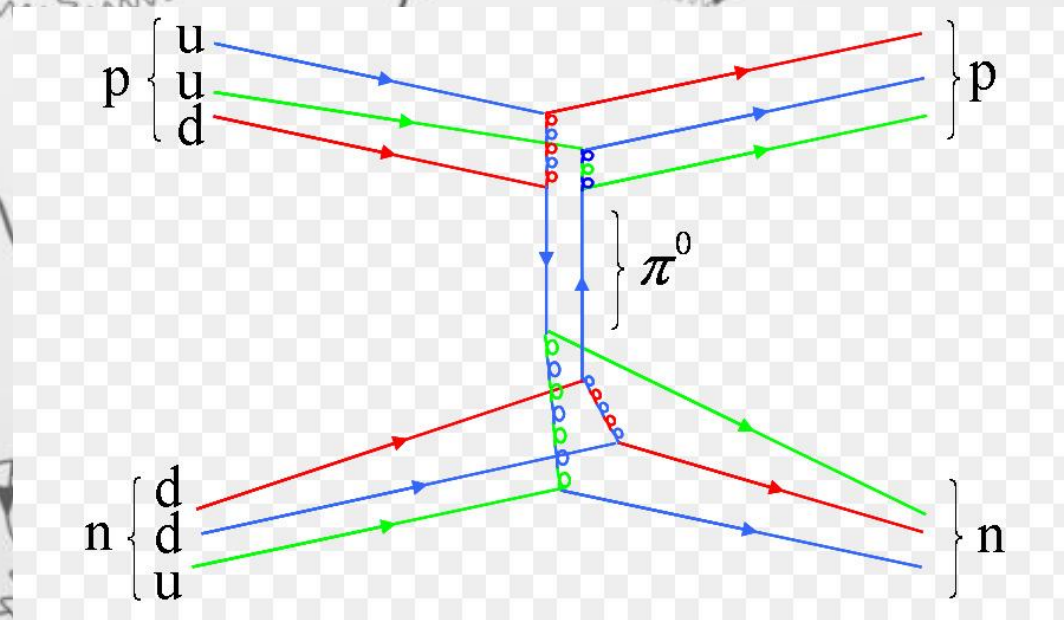
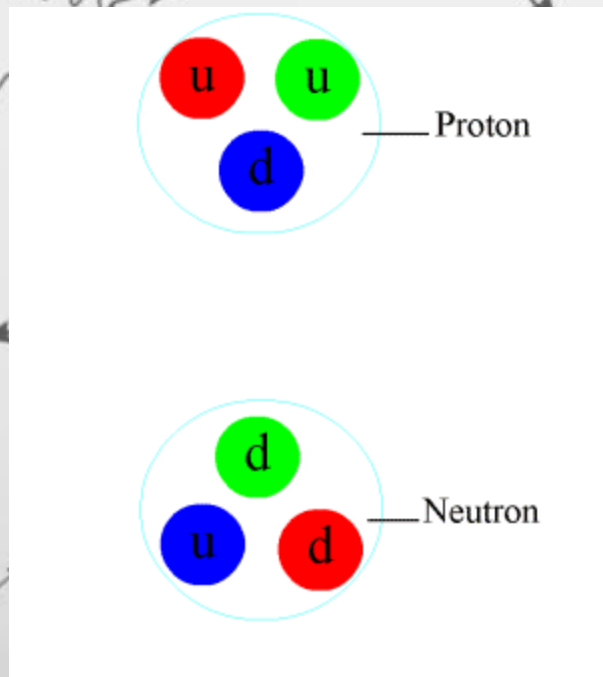
L'interaction forte

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