

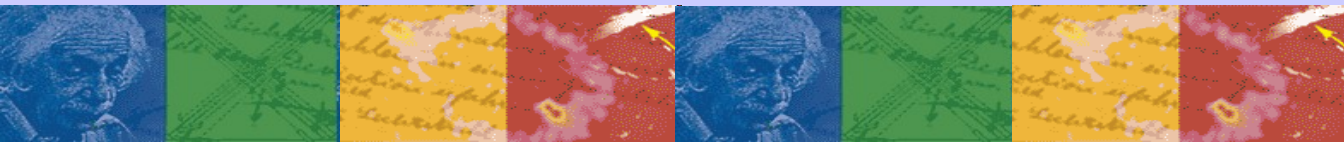
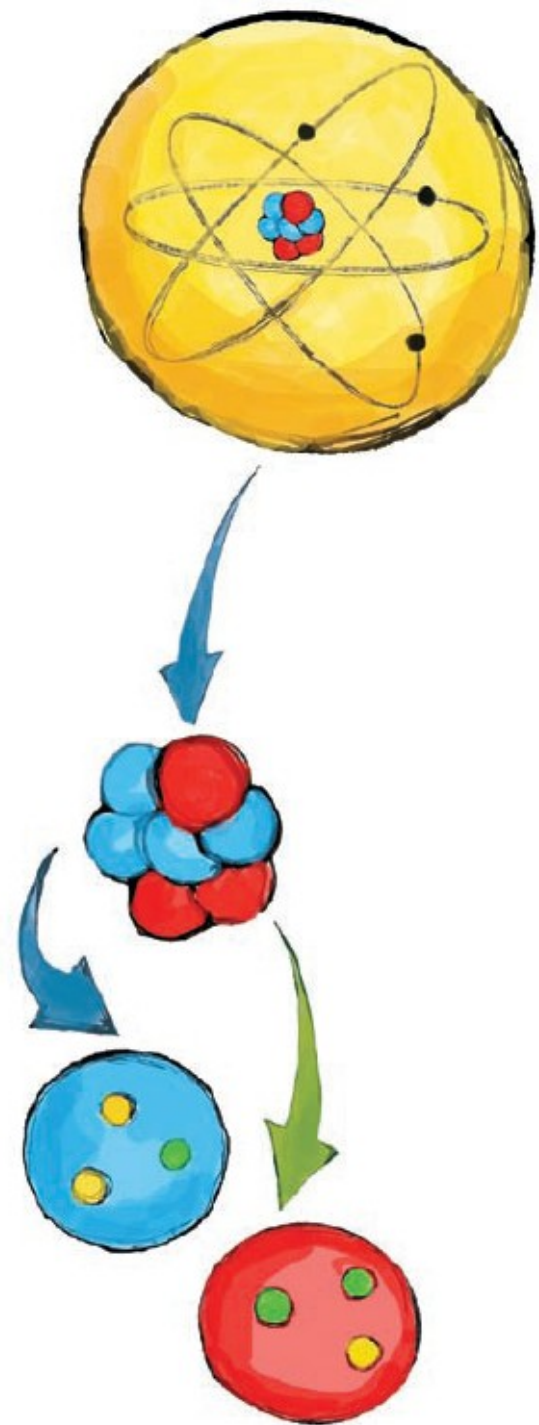
Particules et Interactions

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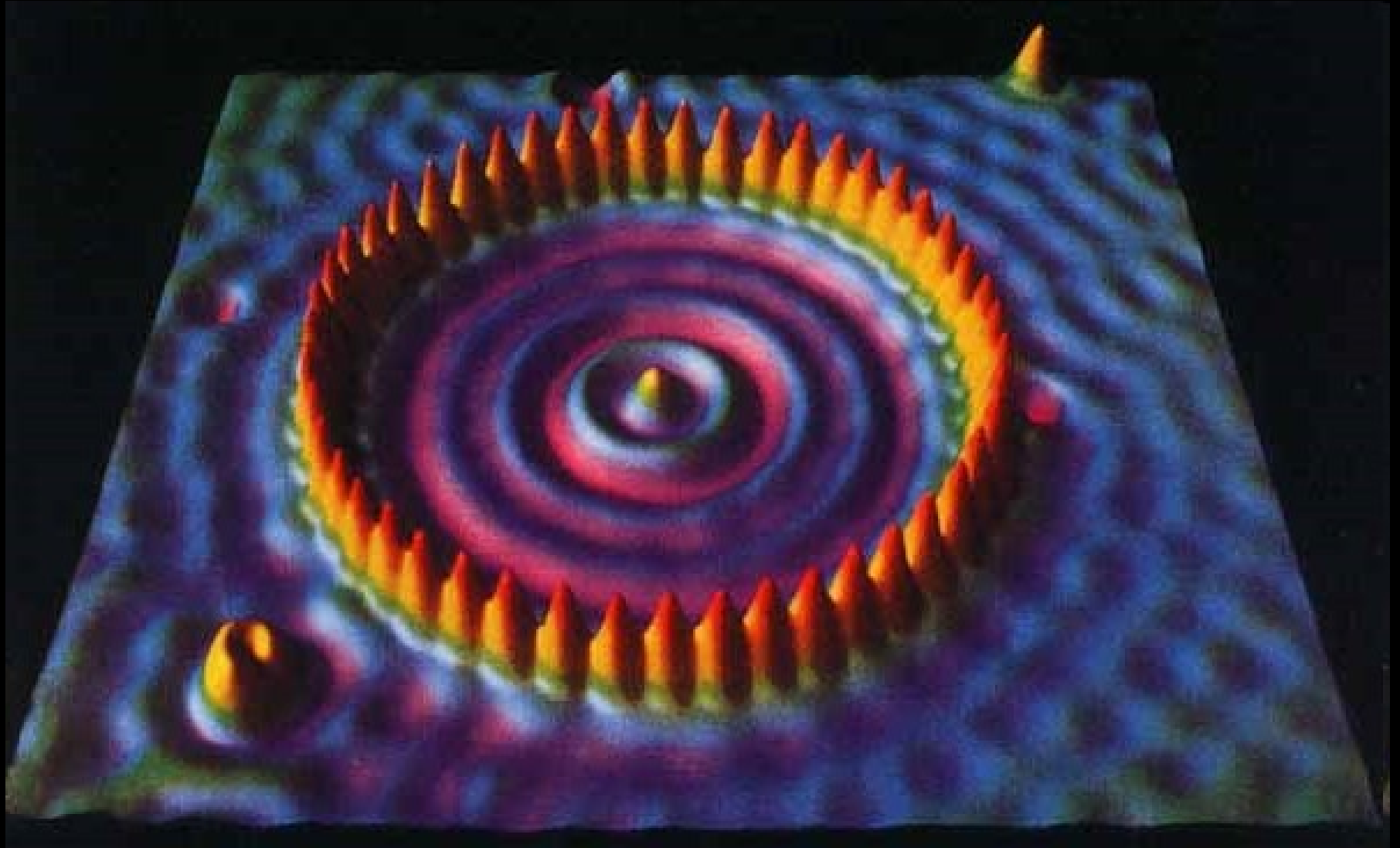
Masterclasses 2024



**Les particules élémentaires :
des blocs fondamentaux (sans structure interne)
qui constituent l'ensemble de la matière**



L'atome



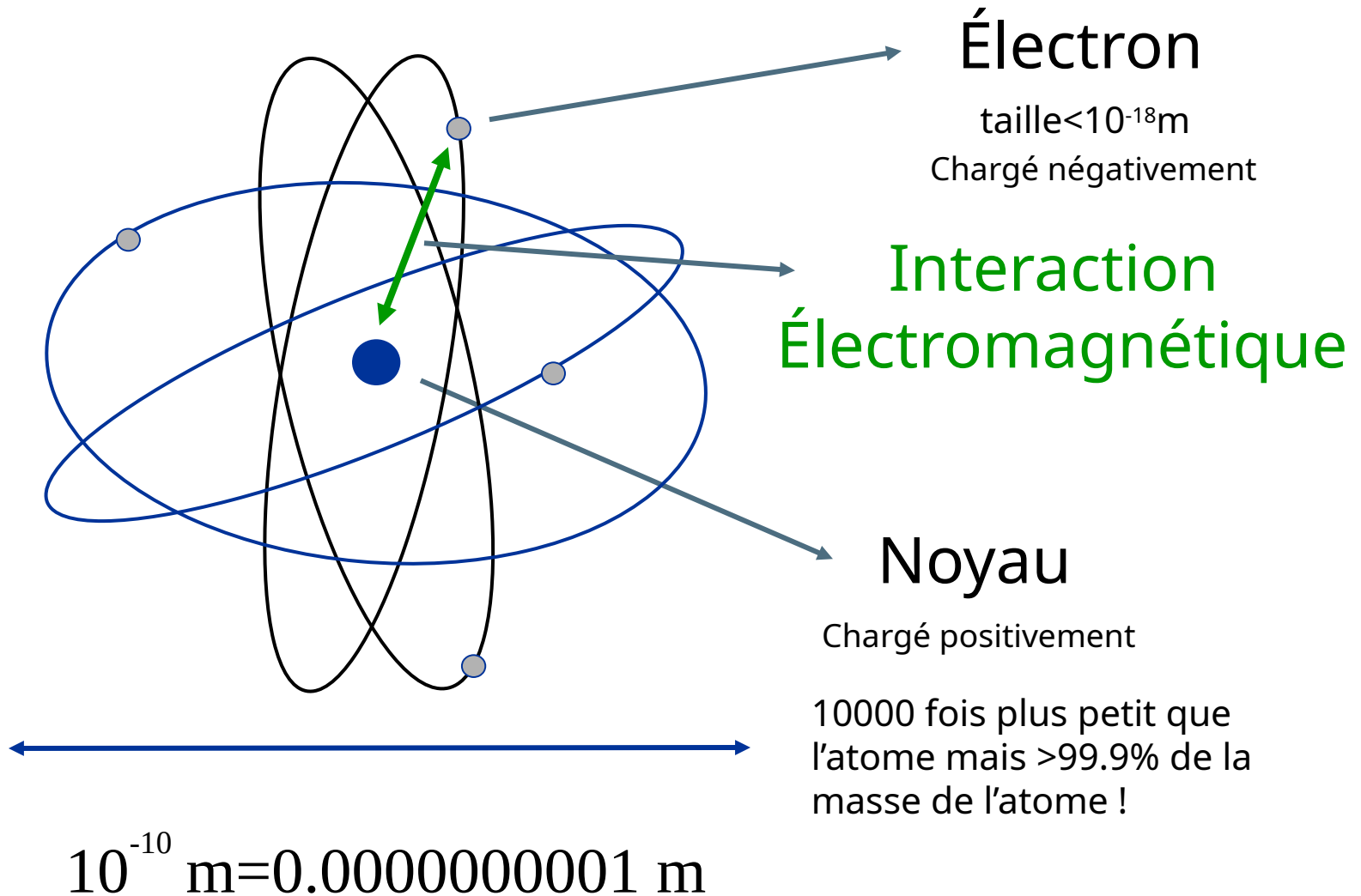
Taille d'un atome: 10^{-10} m = 0.0000000001 m

10 millions de fois plus petit qu'une fourmi

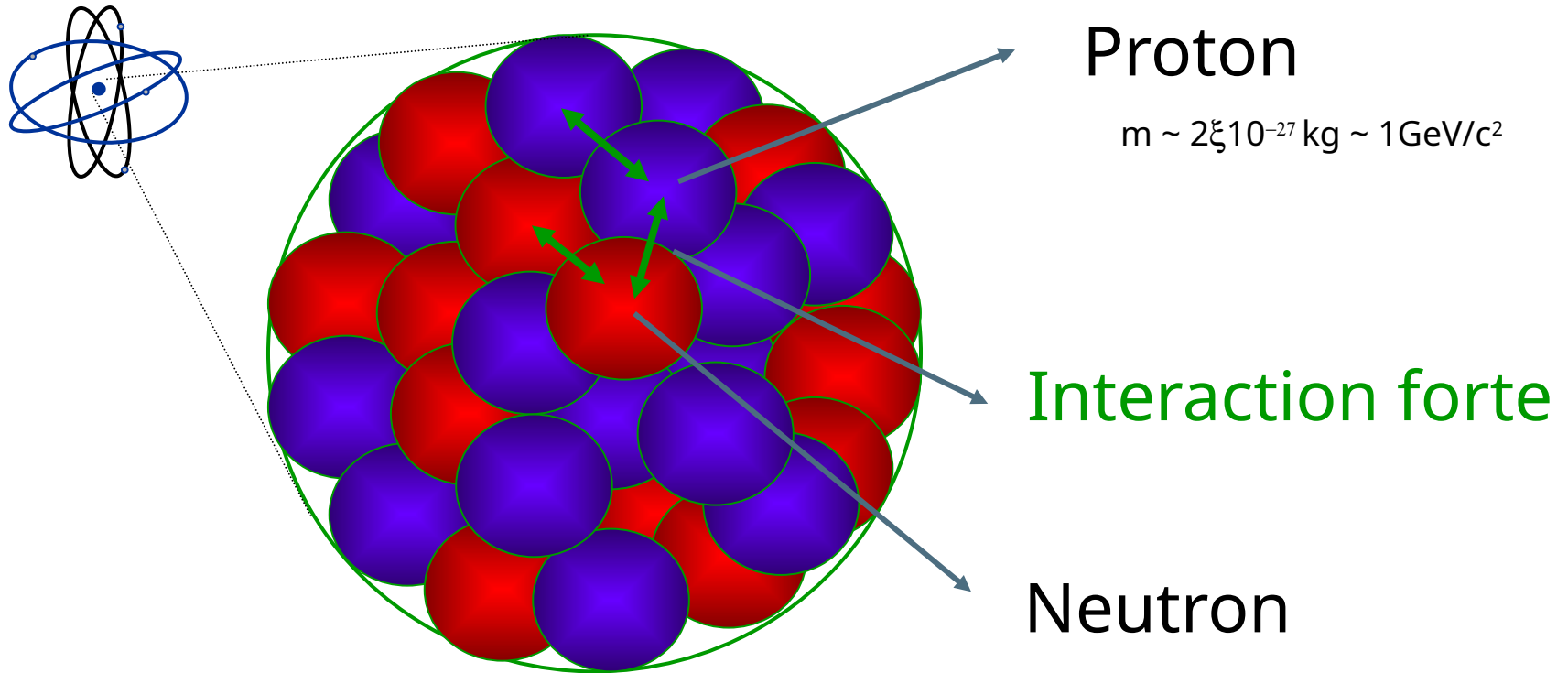
Entre 10 et 100 mille fois plus petit qu'une bactérie



Structure de l'atome



Structure du noyau



Proton

$$m \sim 2 \times 10^{-27} \text{ kg} \sim 1 \text{ GeV}/c^2$$

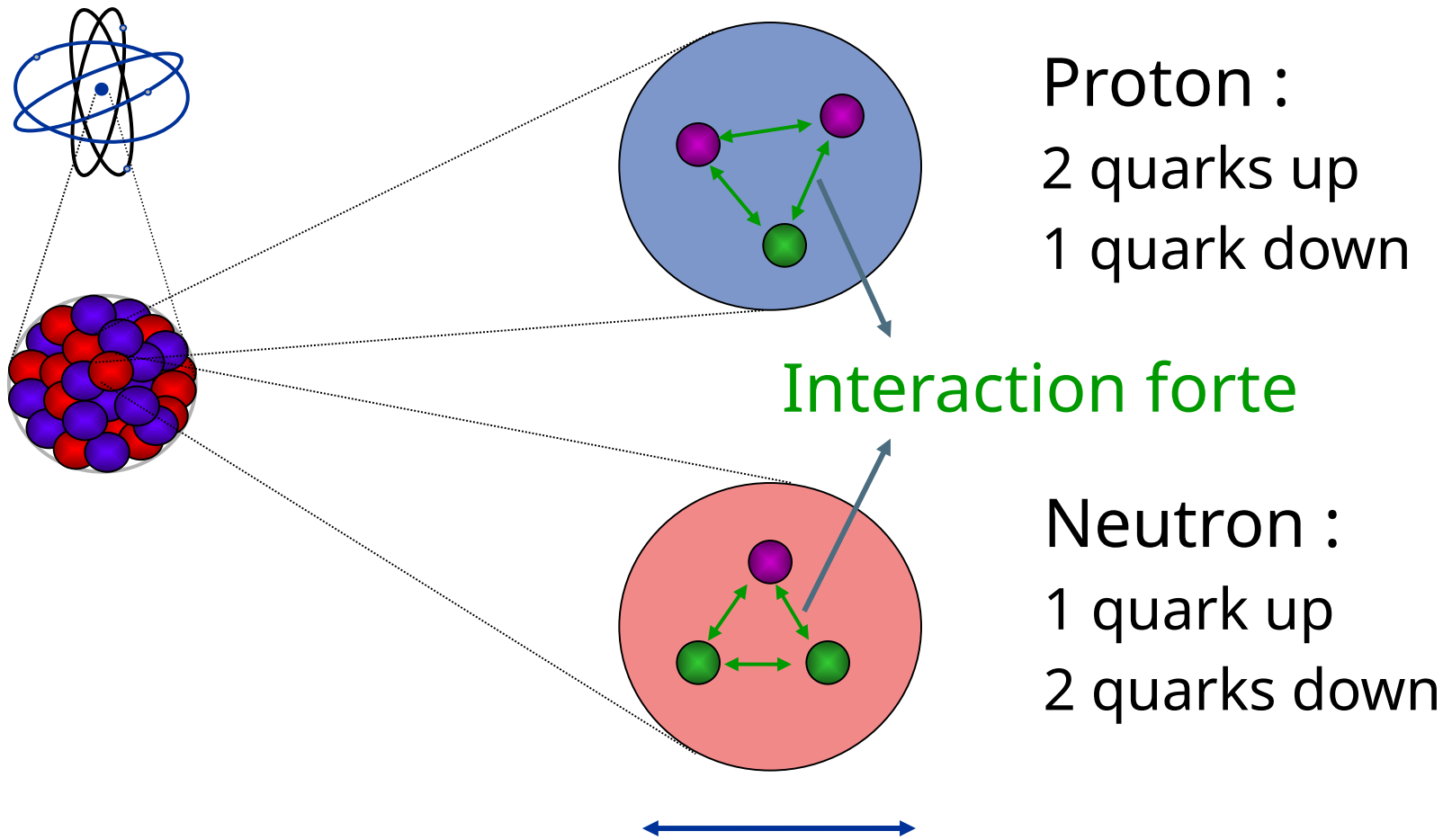
Interaction forte

Neutron



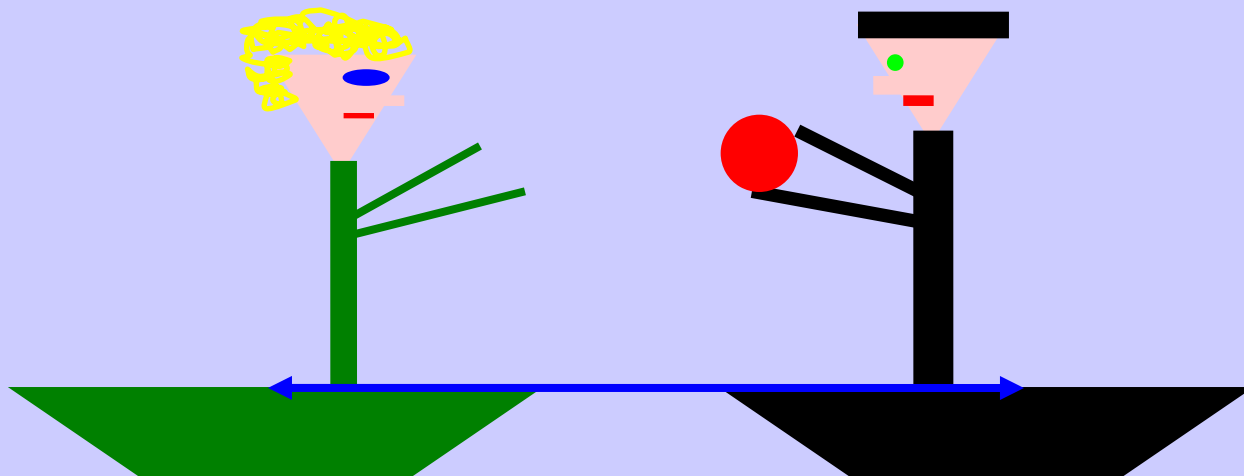
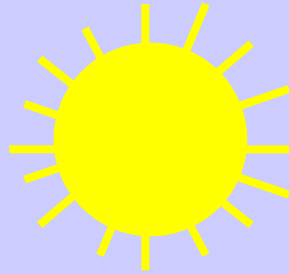
$$10^{-14} \text{ m} = 0.000000000000001 \text{ m}$$

Structure des protons et des neutrons



$$10^{-15} \text{ m} = 0.0000000000000001 \text{ m}$$

Interagir = échanger une particule



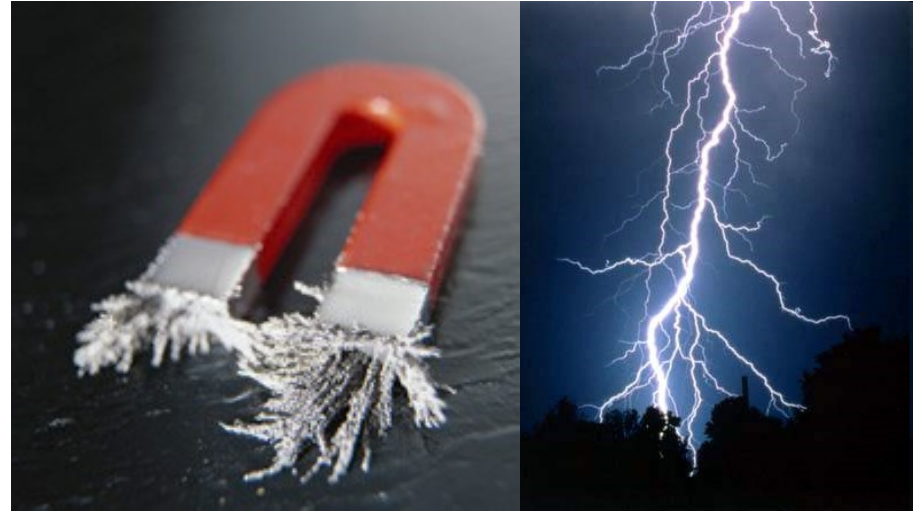
- Les **ballons** sont les **médiateurs** de la force qui écarte les 2 bateaux.
- La **portée** dépend de la **masse** du ballon

Bosons de jauge : médiateurs des interactions fondamentales



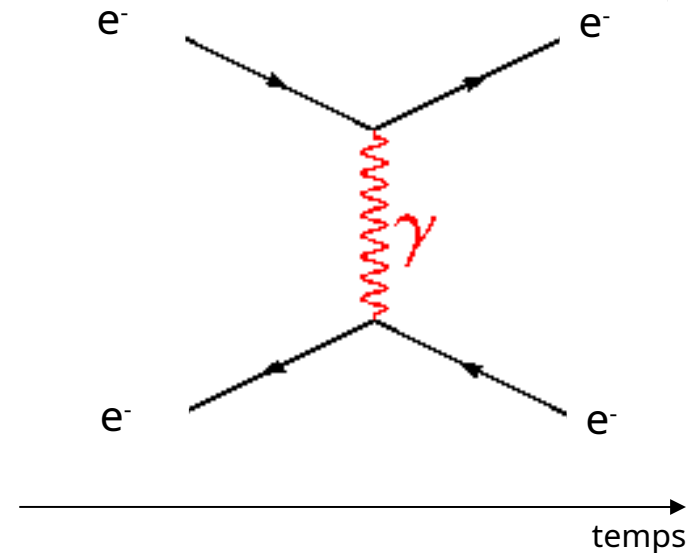
L'interaction électromagnétique

Responsable des phénomènes **électriques et magnétiques** :
aimantation, lumière, cohésion des atomes,...



Médiateur : **photon**

$m=0$ (vitesse= c)
portée infinie



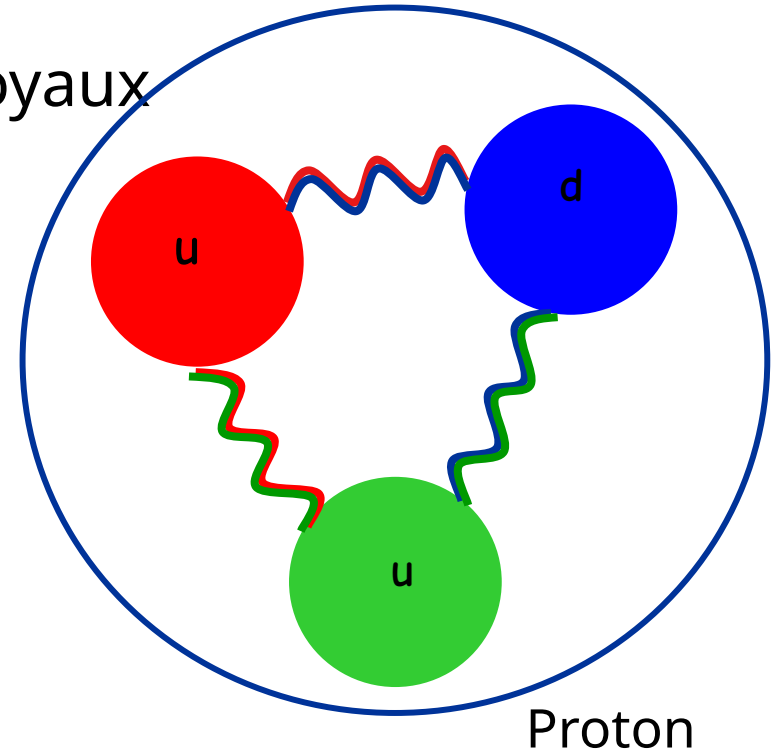
L'interaction nucléaire forte

Responsable de la stabilité des noyaux
ainsi que du proton

Médiateurs: **8 gluons**

$m=0$

Portée : 10^{-15} m

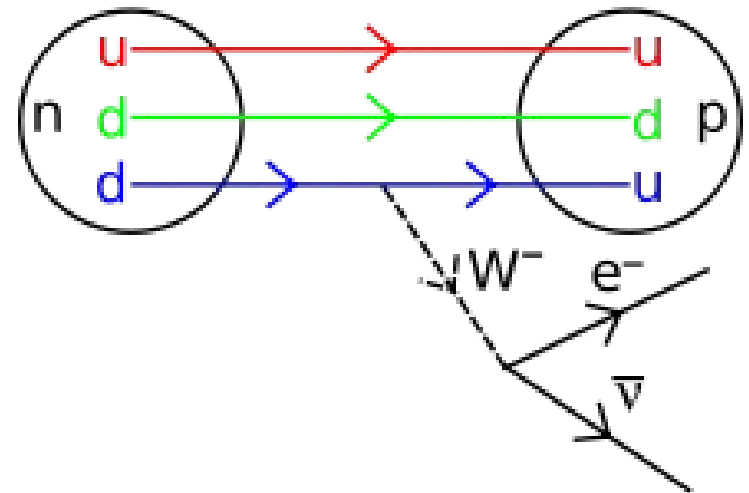


Les quarks n'existent pas à l'état libre: ils sont confinés à l'intérieur de **hadrons** (assemblages de quarks) collés par les **gluons**

L'interaction nucléaire faible

- Responsable de:
 - Radioactivité β
 - Participe aux réactions nucléaires au coeur du Soleil

Médiateurs : W^+ , W^- et Z^0

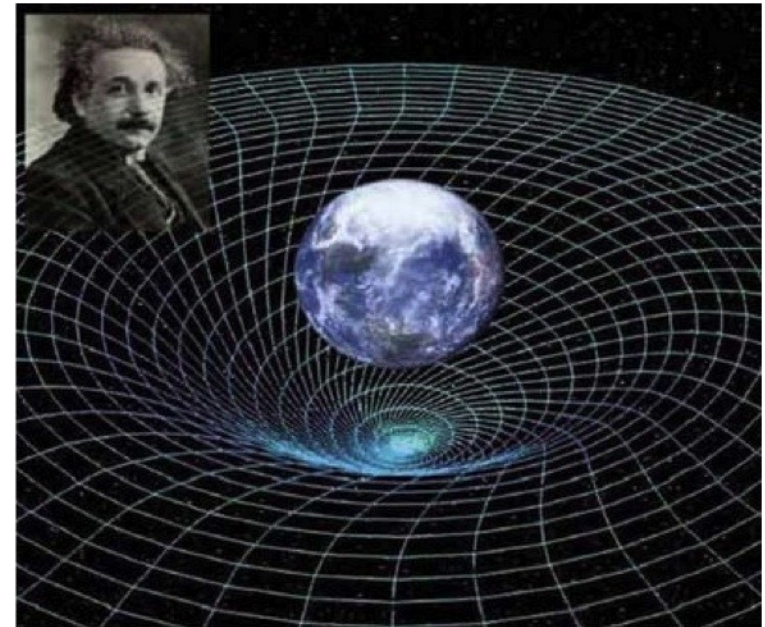


- 10 000 fois plus faible que l'interaction forte
- Portée: 10^{-18} m
 - Expliquée par la grande masse des bosons de jauge de l'interaction faible.



La gravitation

- Responsable de la pesanteur, des marées, des mouvements des astres, ...
- Force complètement négligeable à l'échelle du noyau
 - 10^{-33} fois plus faible que l'interaction faible
 - Mais portée infinie et interaction uniquement attractive
→ dominante à grande échelle
- Décrite par la relativité générale
 - La gravitation est issue d'une déformation de l'espace temps



Médiateur hypothétique : **graviton**

Matière

Leptons

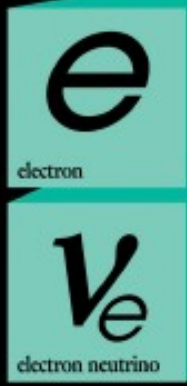
Quarks



Matière

Leptons

Quarks



Matière

Quarks

u up	c charm	t top
d down	s strange	b bottom

Leptons

e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

stable

instable

Matière

Quarks

u up	c charm	t top
d down	s strange	b bottom

Leptons

e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

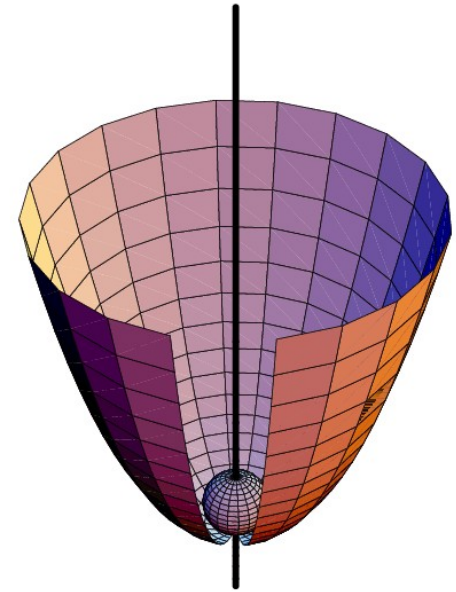
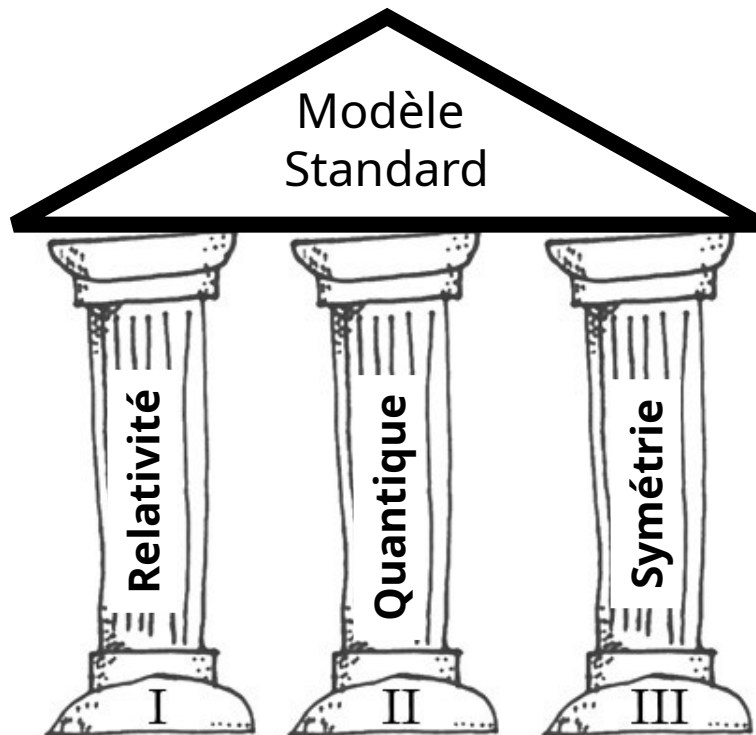
Forces

Z Z boson	γ photon
W W boson	g gluon

$$\begin{aligned}
\mathcal{L}_{\text{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 + \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c \\
& -\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 \Lambda_\nu \partial_\mu \Lambda_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- \\
& -M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \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 \\
& -igc_w \left[\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^+) \right] \\
& -igs_w \left[\partial_\nu \Lambda_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - \Lambda_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + \Lambda_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^- \partial_\nu W_\mu^+) \right] \\
& -\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_\mu^0 W_\nu^+ W_\nu^-) + g^2 s_w^2 (\Lambda_\mu W_\mu^+ \Lambda_\nu W_\nu^- - \Lambda_\mu \Lambda_\mu W_\nu^+ W_\nu^-) \\
& +g^2 s_w c_w [\Lambda_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - 2\Lambda_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha [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) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + igs_w M \Lambda_\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^+) + igs_w \Lambda_\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}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 \\
& +2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_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 \Lambda_\mu \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) \\
& +\frac{1}{2}ig^2 s_w \Lambda_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 \Lambda_\mu \phi^+ \phi^- - g^1 s_w^2 \Lambda_\mu \Lambda_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \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 + igs_w \Lambda_\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 \left[(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda) \right] \\
& +\frac{ig}{2\sqrt{2}} W_\mu^+ \left[(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa) \right] + \frac{ig}{2\sqrt{2}} W_\mu^- \left[(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda) \right] \\
& +\frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} \left[-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda) \right] - \frac{g}{2} \frac{m_e^\lambda}{M} \left[H(\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) \right] \\
& +\frac{ig}{2M\sqrt{2}} \phi^+ \left[-m_d^\lambda (\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) \right] + \frac{ig}{2M\sqrt{2}} \phi^- \left[m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) \right] \\
& -\frac{g}{2} \frac{m_u^\lambda}{M} H(\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H(\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{\chi}^+ (\partial^2 - M^2) \chi^+ + \bar{\chi}^- (\partial^2 - M^2) \chi^- \\
& +\bar{\chi}^0 \left(\partial^2 - \frac{M^2}{c_w^2} \right) \chi^0 + \bar{\Upsilon} \partial^2 \Upsilon + igc_w W_\mu^+ (\partial_\mu \bar{\chi}^0 \chi^- - \partial_\mu \bar{\chi}^+ \chi^0) + igs_w W_\mu^+ (\partial_\mu \bar{\Upsilon} \chi^- - \partial_\mu \bar{\chi}^+ \Upsilon) + igc_w W_\mu^- (\partial_\mu \bar{\chi}^- \chi^0 - \partial_\mu \bar{\chi}^0 \chi^+) \\
& +igs_w W_\mu^- (\partial_\mu \bar{\chi}^- \Upsilon - \partial_\mu \bar{\Upsilon} \chi^+) + igc_w Z_\mu^0 (\partial_\mu \bar{\chi}^+ \chi^+ - \partial_\mu \bar{\chi}^- \chi^-) + igs_w \Lambda_\mu (\partial_\mu \bar{\chi}^+ \chi^+ - \partial_\mu \bar{\chi}^- \chi^-) - \frac{1}{2}gM[\bar{\chi}^+ \chi^+ H + \bar{\chi}^- \chi^- H \\
& +\frac{1}{c_w^2} \bar{\chi}^0 \chi^0 H] + \frac{1-2c_w^2}{2c_w} igM[\bar{\chi}^+ \chi^0 \phi^+ - \bar{\chi}^- \chi^0 \phi^-] + \frac{1}{2c_w} igM[\bar{\chi}^0 \chi^- \phi^+ - \bar{\chi}^0 \chi^+ \phi^-] + igM s_w [\bar{\chi}^0 \chi^- \phi^+ - \bar{\chi}^0 \chi^+ \phi^-] \\
& +\frac{1}{2}igM[\bar{\chi}^+ \chi^+ \phi^0 - \bar{\chi}^- \chi^- \phi^0]
\end{aligned}$$

Le Modèle Standard

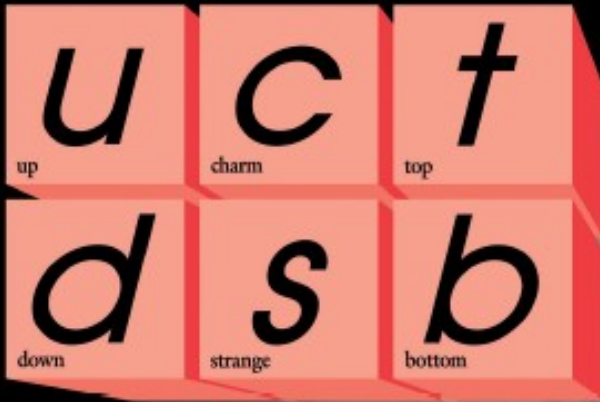
- Elaboré dans les années 1960-70
- Décrit dans un même cadre les **particules élémentaires** et les **interactions forte et électrofaible**
 - Mais pas la gravitation!
- Testé expérimentalement avec **grande précision**



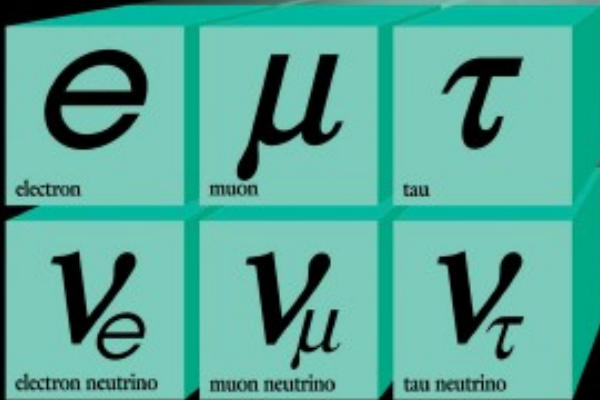
- Un système est symétrique quand on le transforme en laissant sa forme inchangée.
- Groupe de symétrie (Invariance de jauge) détermine complètement la structure de l'interaction!

Matière

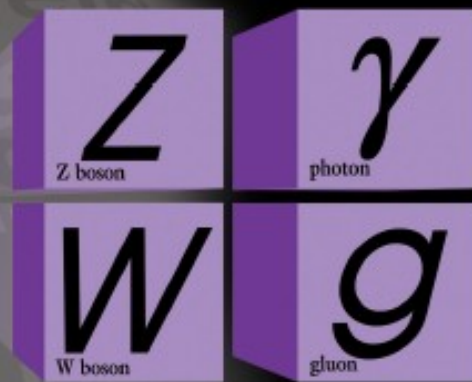
Quarks



Leptons

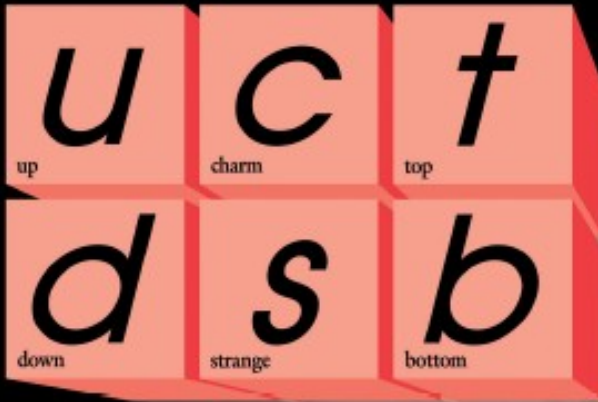


Forces

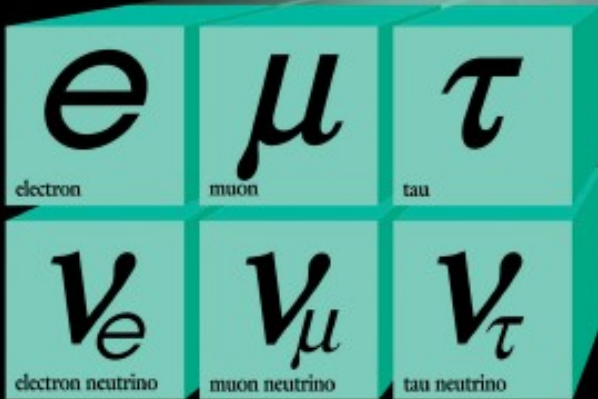


Matière

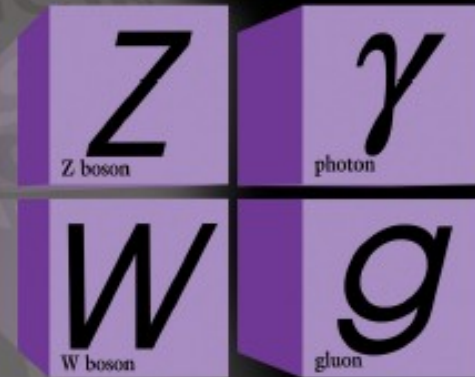
Quarks



Leptons

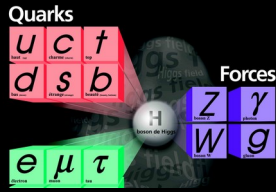


Forces

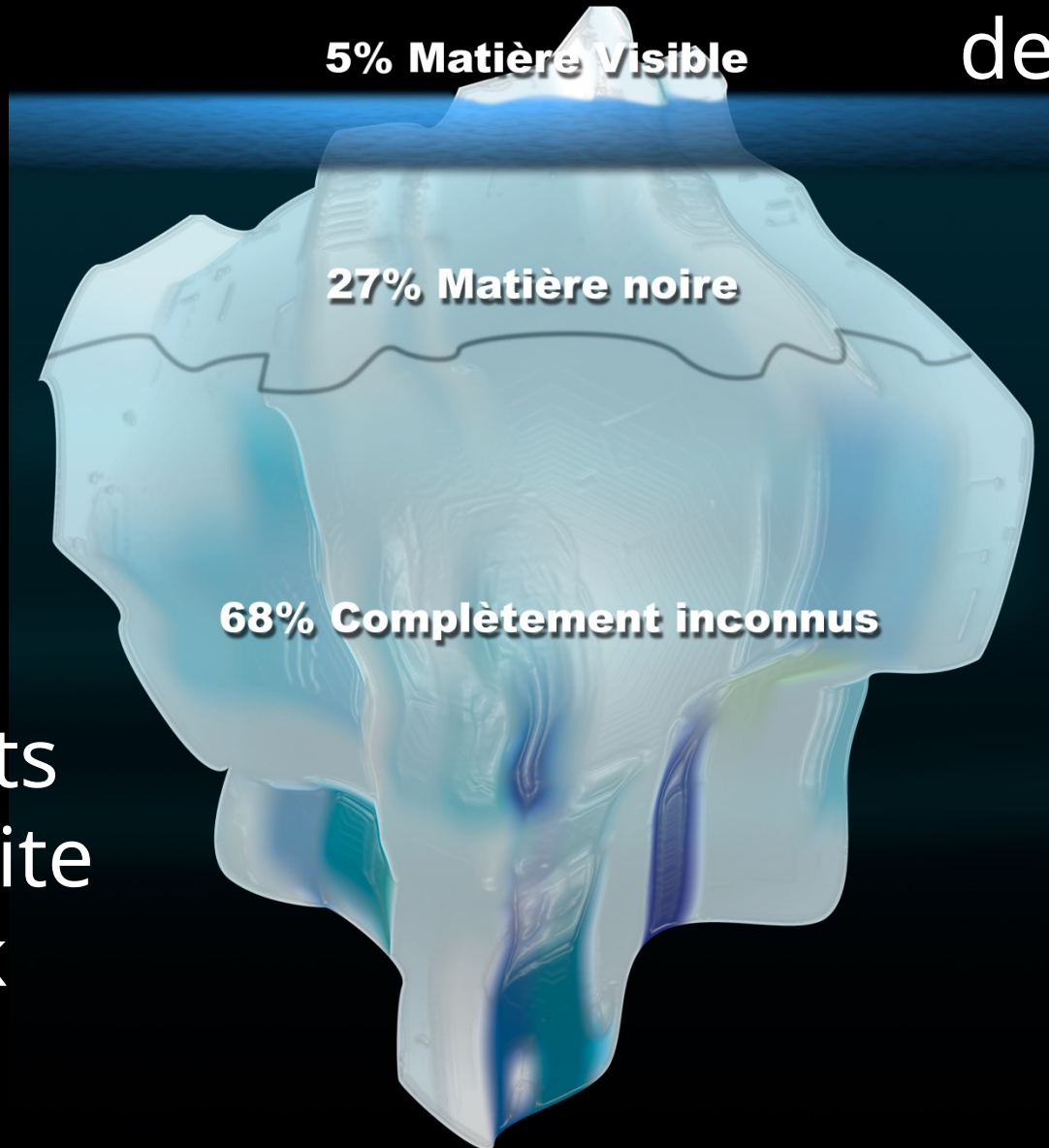


5% Matière Visible





Le contenu énergétique de l'Univers



Résultats
du satellite
Planck
(2013)

Résumé

■ Particules de matières: **fermions**

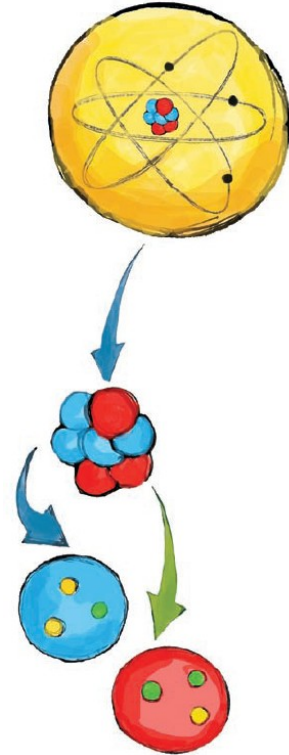
- Particules stables et « utiles » pour bâtir l'univers:
 - électron, quark up et quark down
 - proton = 2 quarks u et un quark d
- Particules instables:
 - muon, tau, quark étrange,...
- A chaque particule est associée une antiparticule

■ Particules d'interactions: **bosons**

- Photon: interaction électromagnétique
- Boson Z/W: interaction faible
- Gluon: interaction forte

- Le **Modèle Standard** est le cadre théorique qui permet de décrire les particules et leurs interactions

- La **masse des particules élémentaires** provient de l'interaction avec le **champ de Higgs** qui se manifeste également par l'existence du **boson de Higgs**

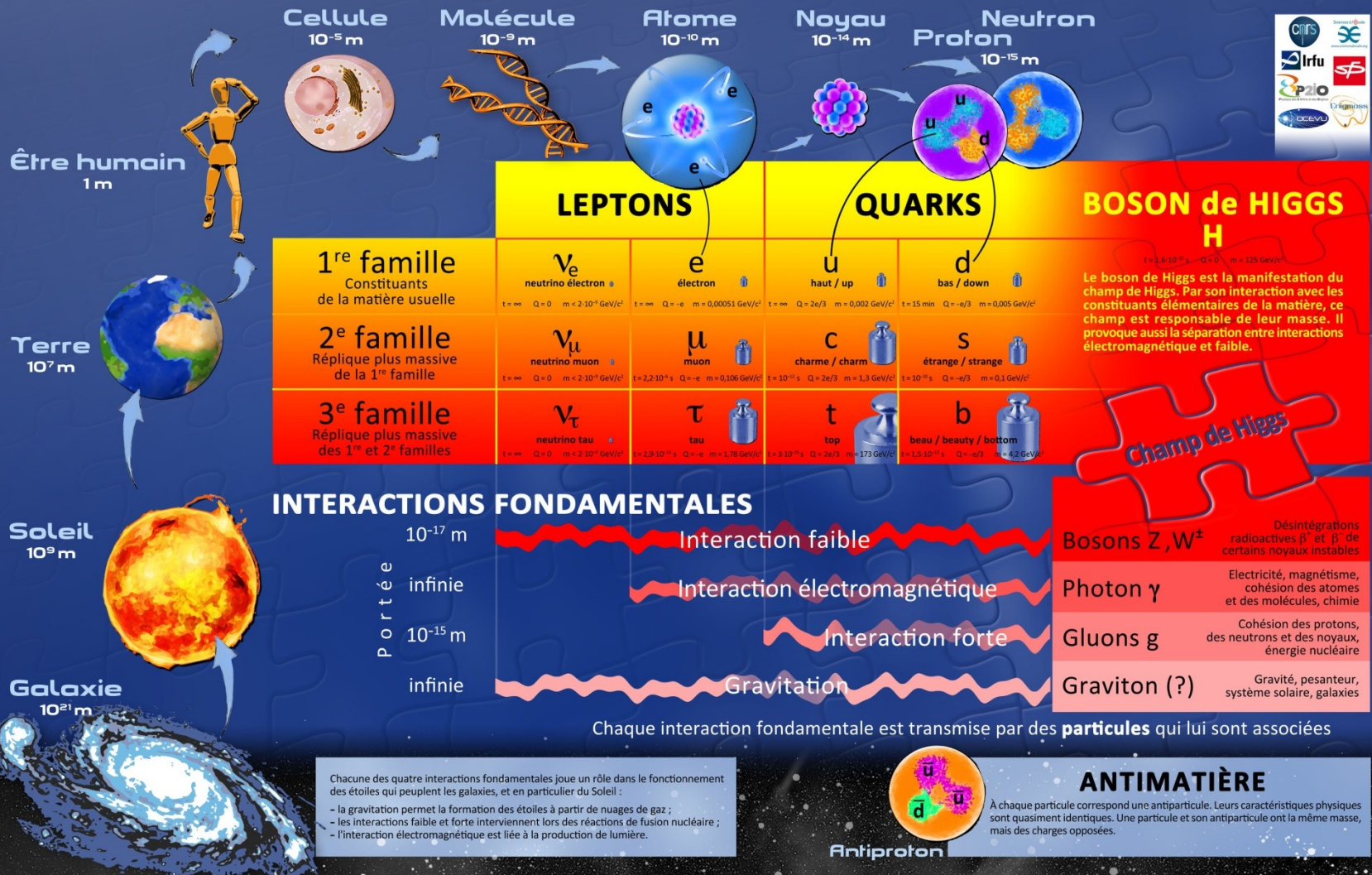




That's all Folks!

Nouvelle affiche des composants élémentaires (2014)

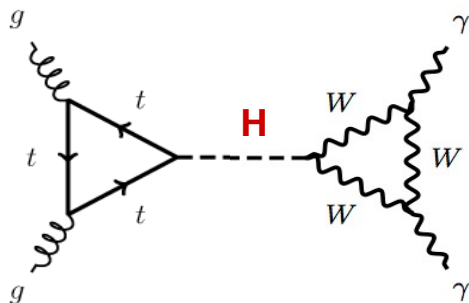
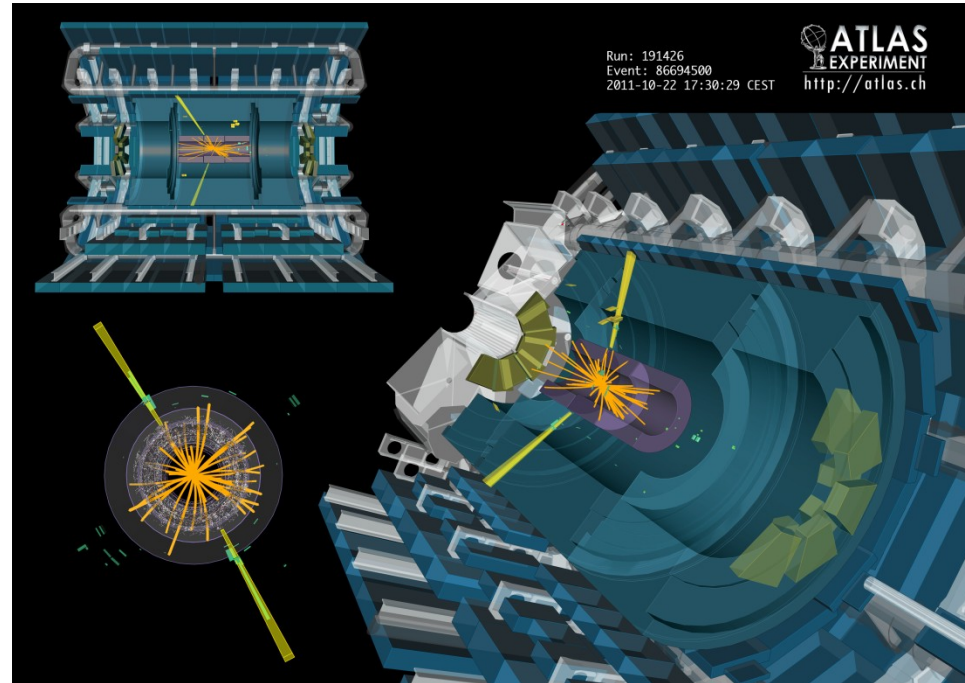
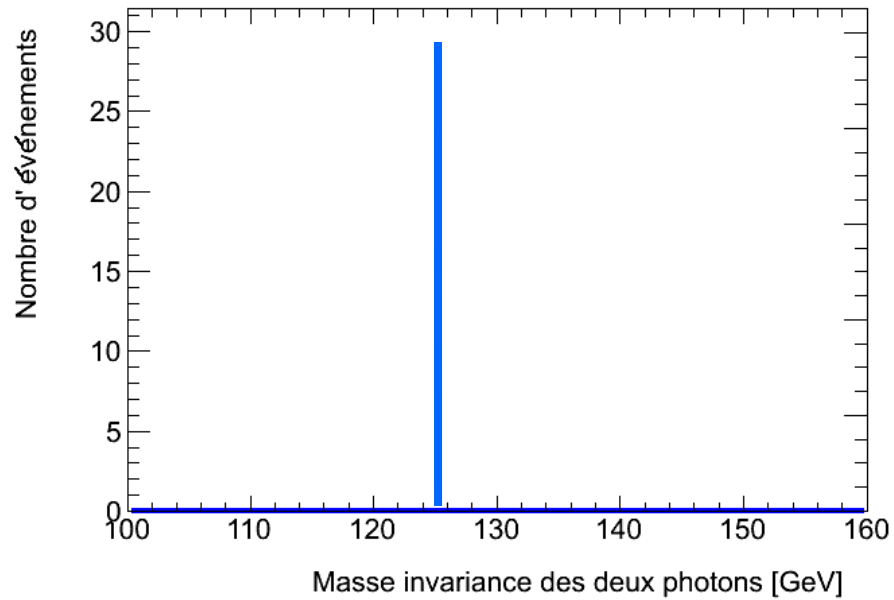
Composants élémentaires de la matière



Le canal $H \rightarrow \gamma\gamma$

$$m_{\gamma\gamma} = \sqrt{\left(\frac{E_1 + E_2}{c^2}\right)^2 - \left(\frac{\vec{p}_1 + \vec{p}_2}{c}\right)^2}$$

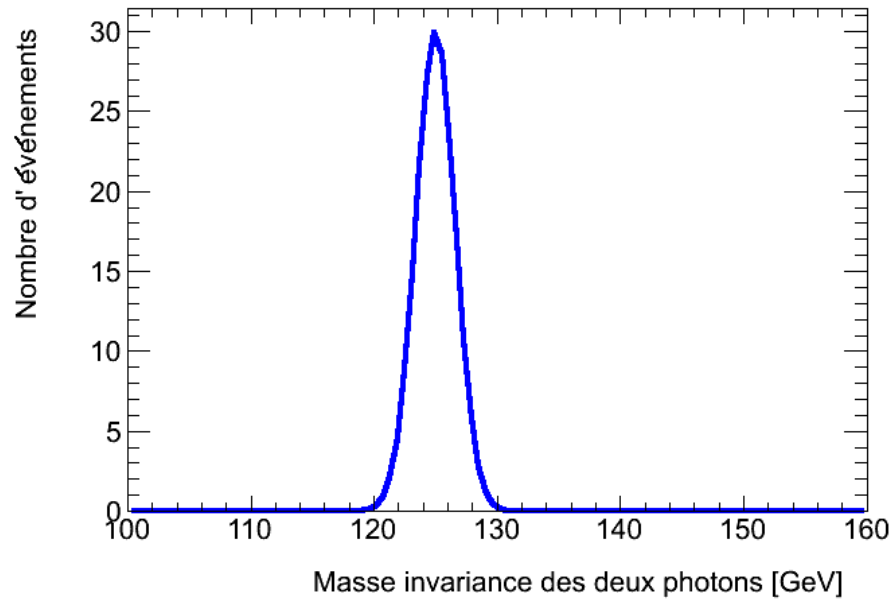
Higgs ($m_H = 125$ GeV)



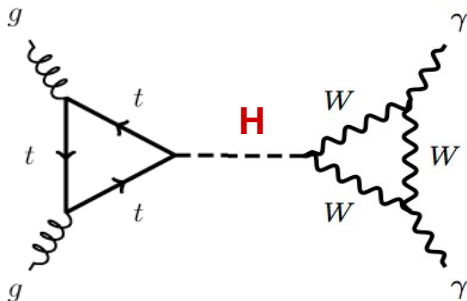
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Higgs ($m_H = 125$ GeV)



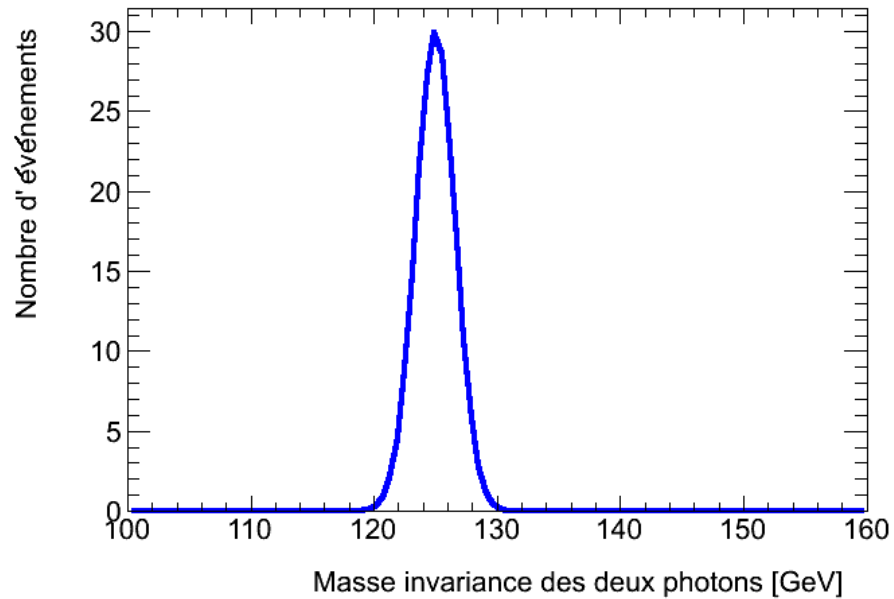
Résolution
du
détecteur



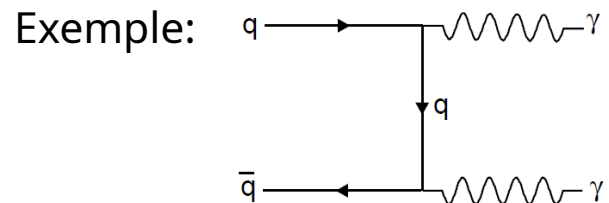
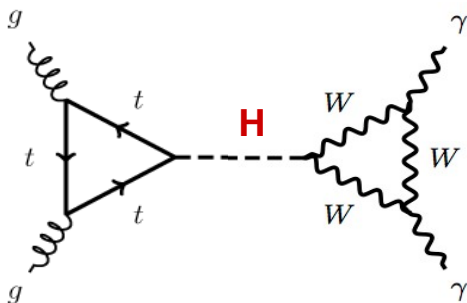
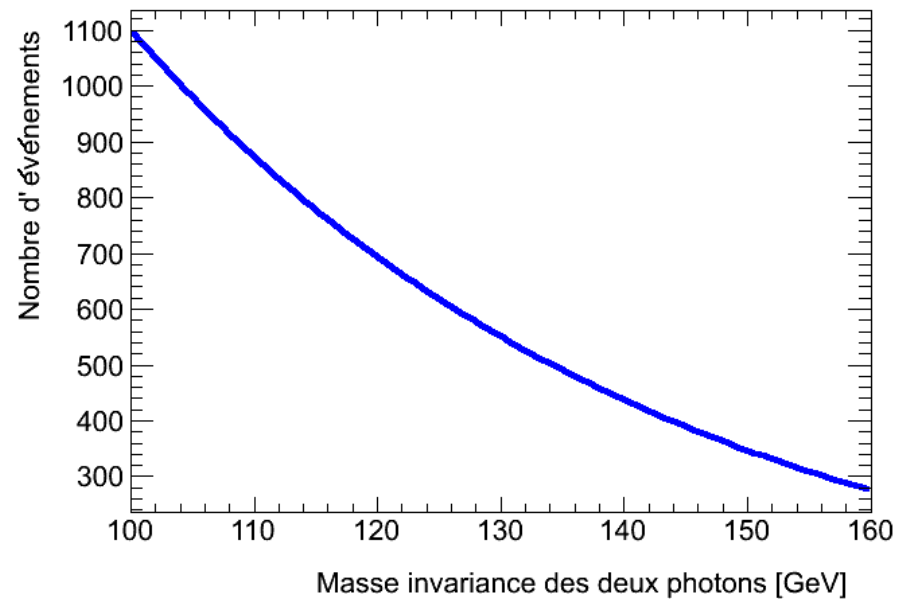
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Higgs ($m_H = 125$ GeV)



Bruit de fond



Le mécanisme de Brout-Englert-Higgs

- La masse quantifie l'inertie du corps

- Plus un objet est massif plus il est difficile à mettre en mouvement



- Invariance de jauge

- ▬ masse=0
 - ▬ $v=c$

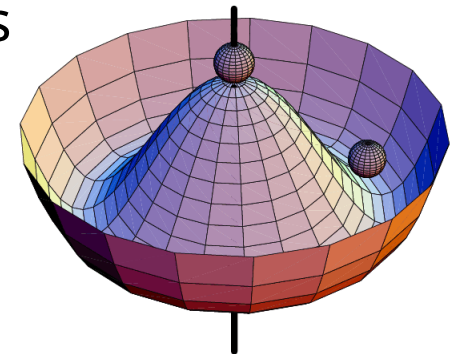
- ▬ contradiction avec l'expérience

- Mécanisme de Brout-Englert-Higgs

- La masse n'est pas une propriété intrinsèque des particules, mais le résultat de l'interaction de la particule avec le champ de Brout-Englert-Higgs

- Découvert en 1964 par:

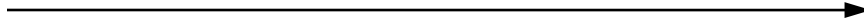
- R. Brout and F. Englert
- P.Higgs
- G. Guralnik, C. R. Hagen, and T. Kibble



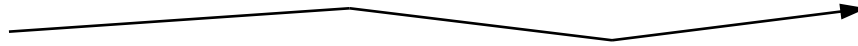


Le mécanisme de Brout-Englert-Higgs

Le photon: masse nulle



L'électron: petite masse



Le boson Z: grande masse



Plus difficile à mettre en mvmt

L'action du champ de Higgs est équivalent à une sorte de viscosité du vide

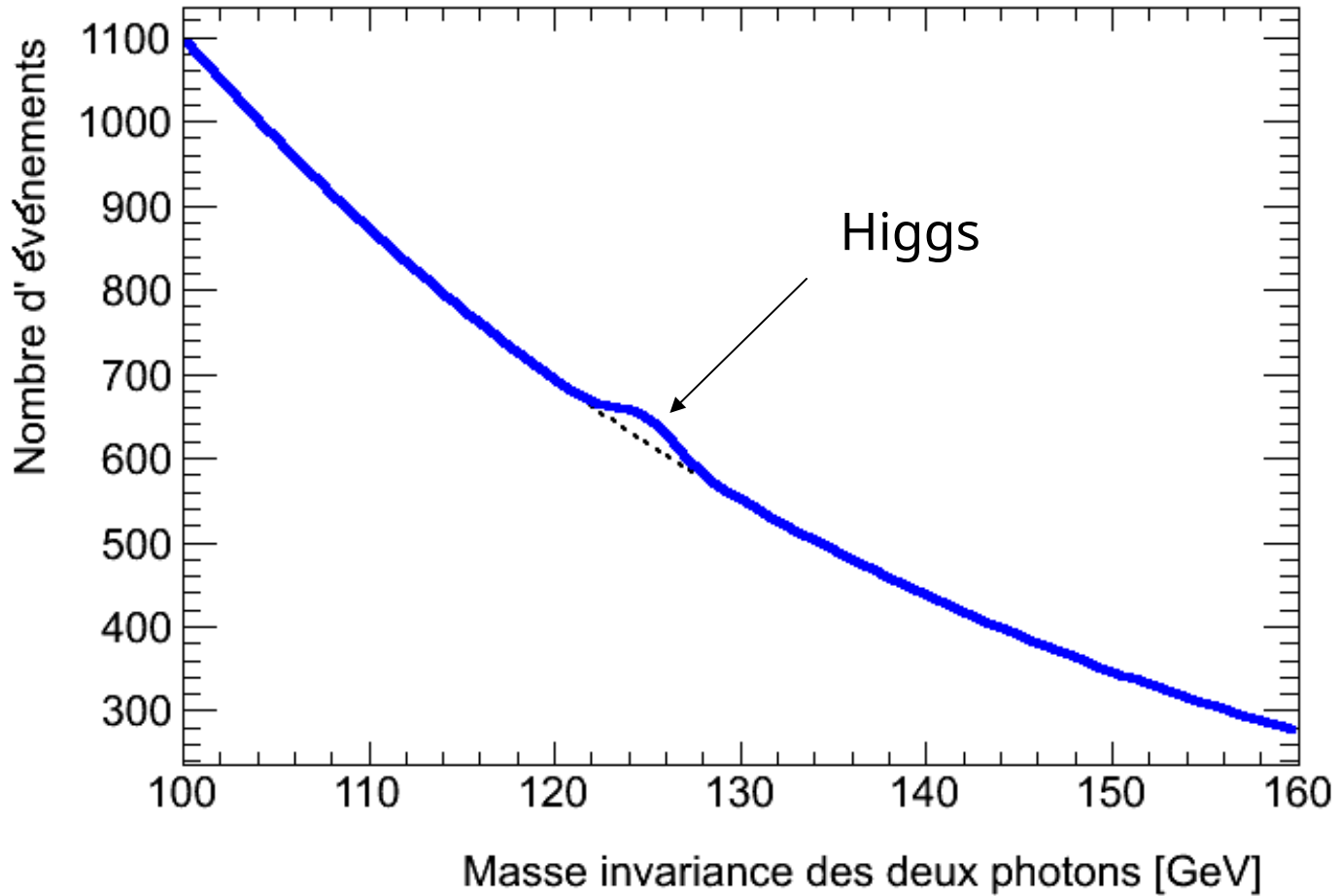
Le boson de Higgs

Boson de Higgs = quanta du champ de Higgs



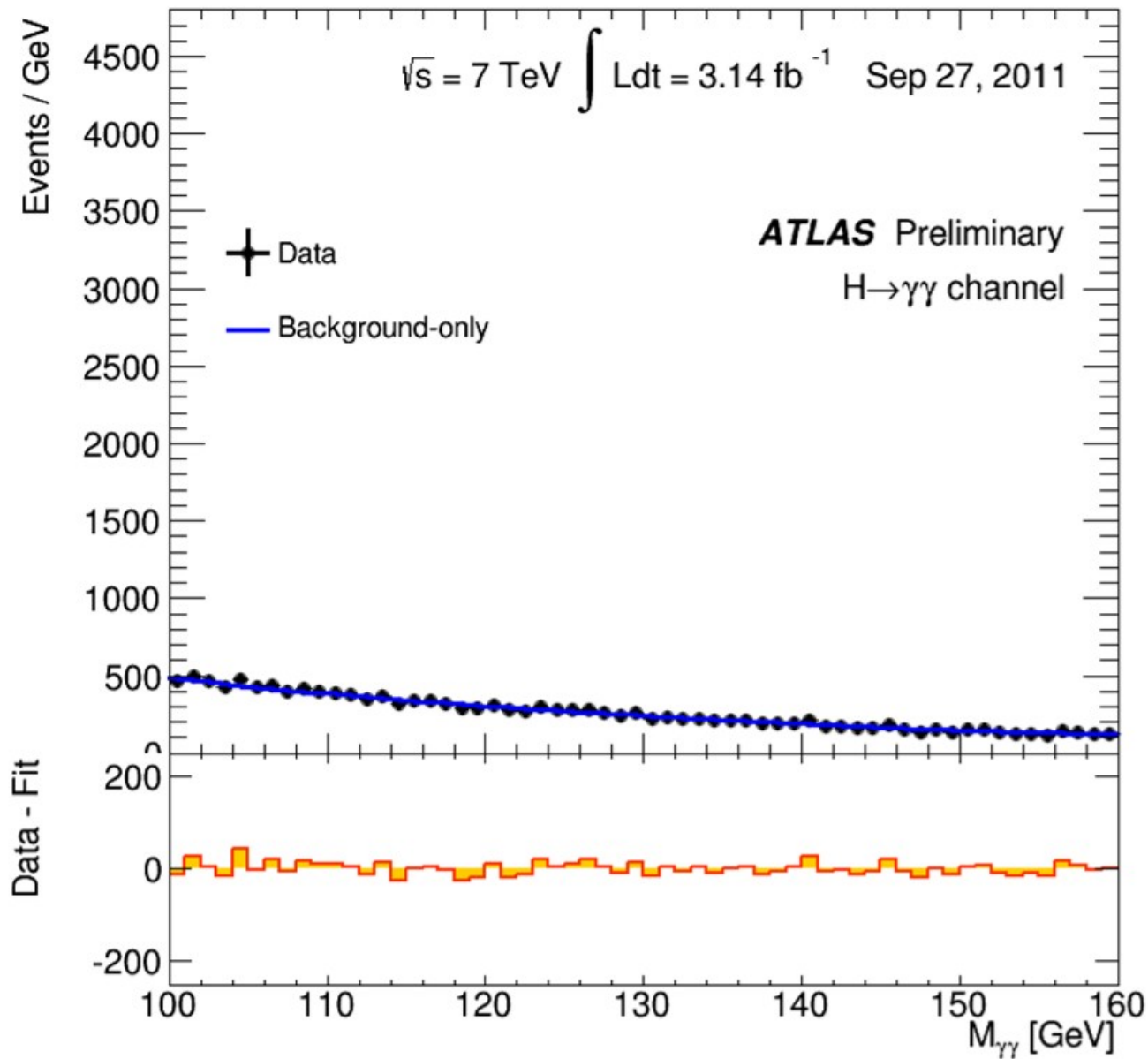
Le boson de Higgs joue un rôle central dans le mécanisme qui explique la masse des particules élémentaires

Le canal $H \rightarrow \gamma\gamma$: simulation

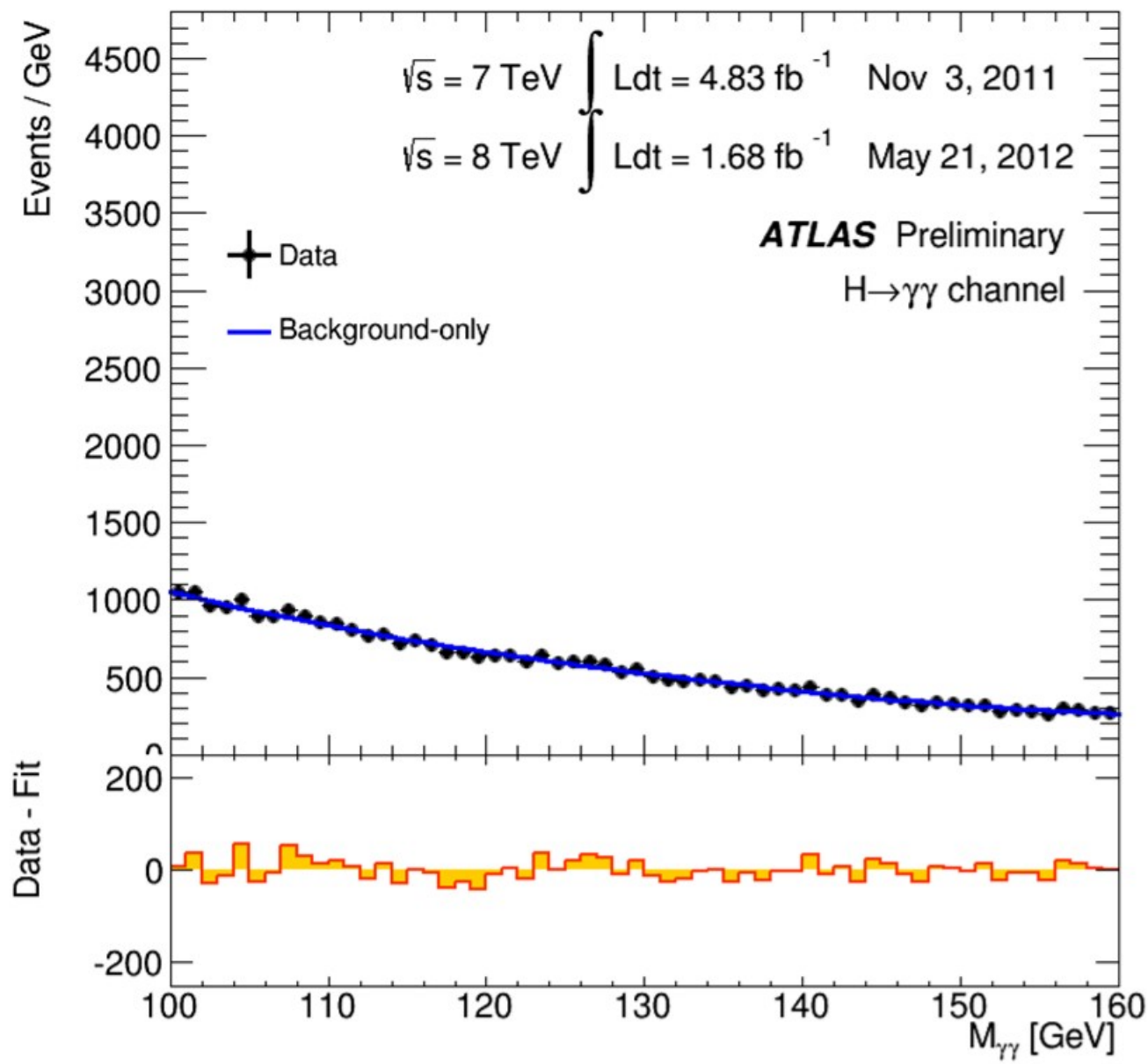


Bosse = signature du boson de Higgs

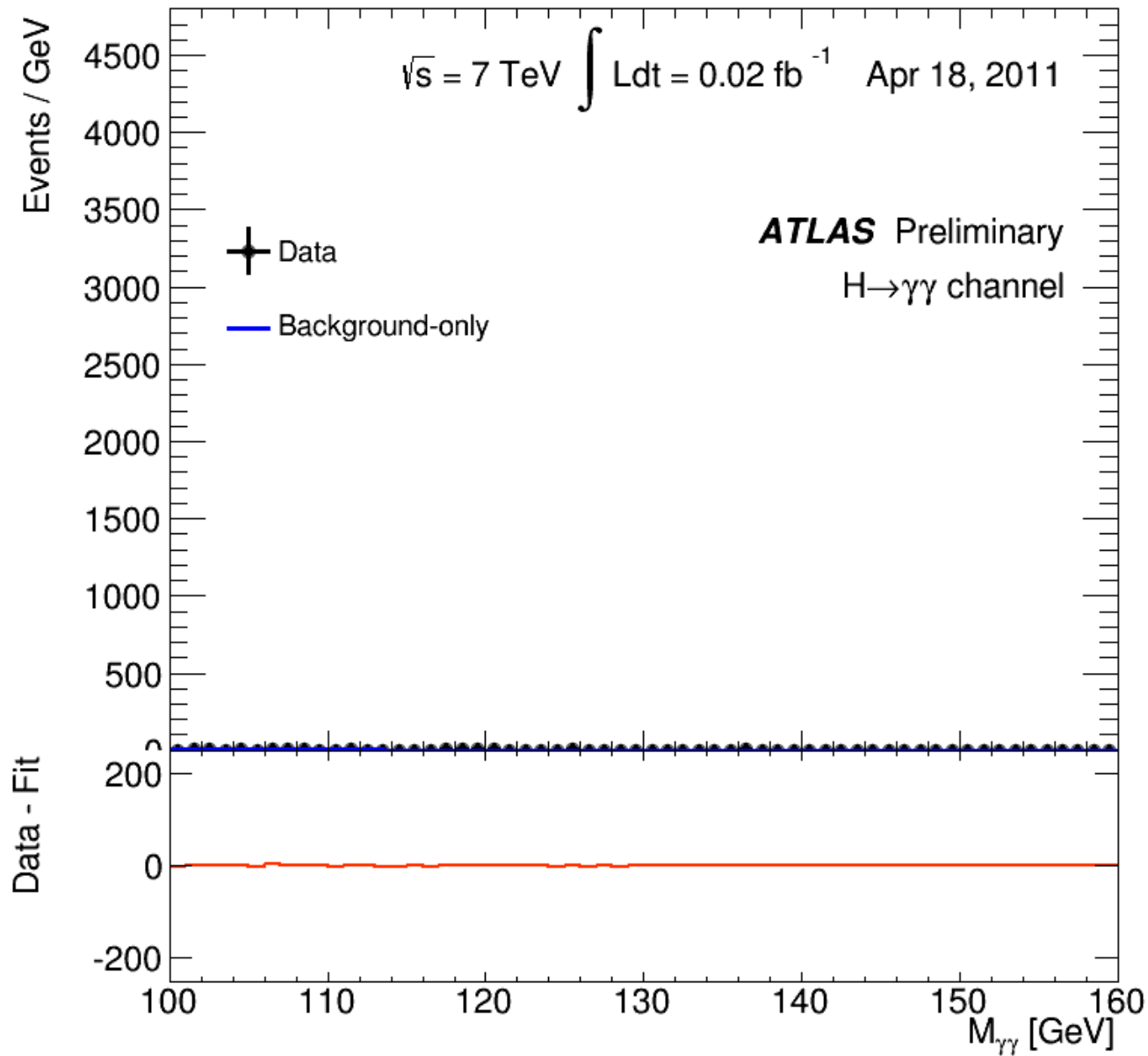
Découverte d'une nouvelle particule au CERN



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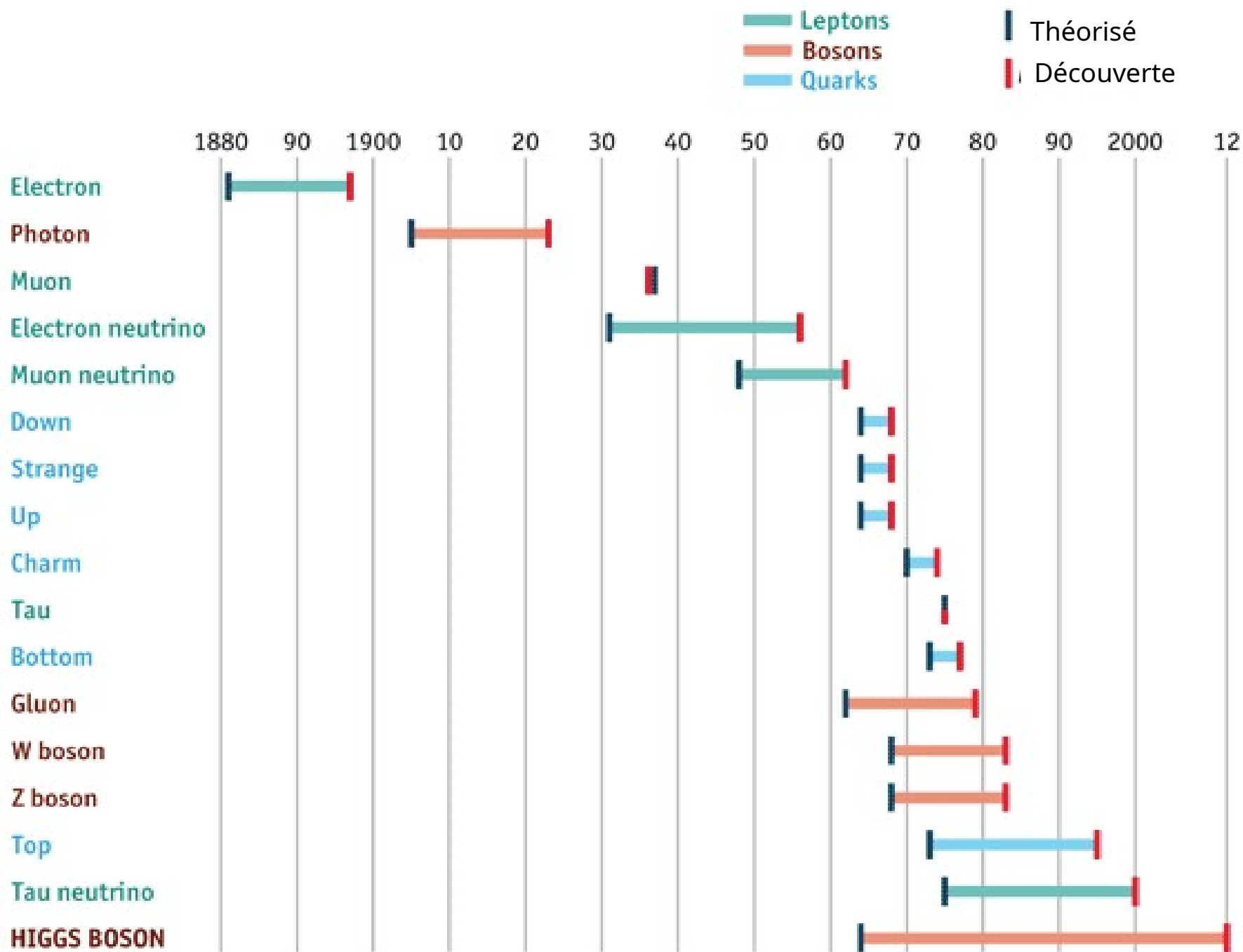


4 Juillet 2012

Libération

35





Matière

Quarks

u up	c charm	t top
d down	s strange	b bottom

Leptons

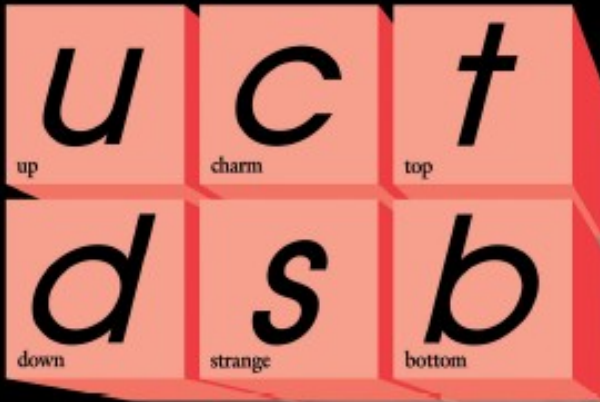
e electron	μ muon	τ tau
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Forces

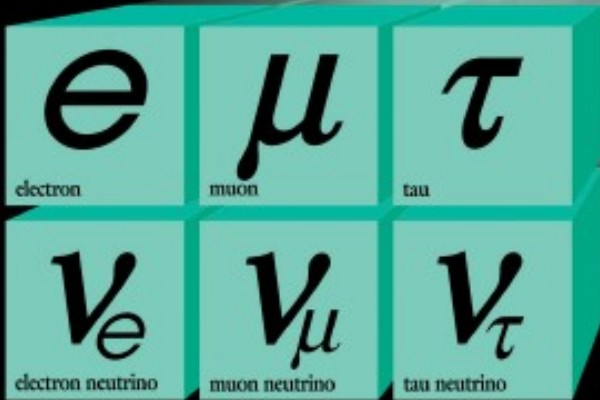
Z Z boson	γ photon
W W boson	g gluon

Matière

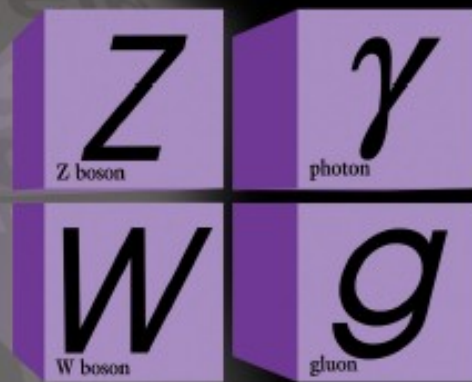
Quarks

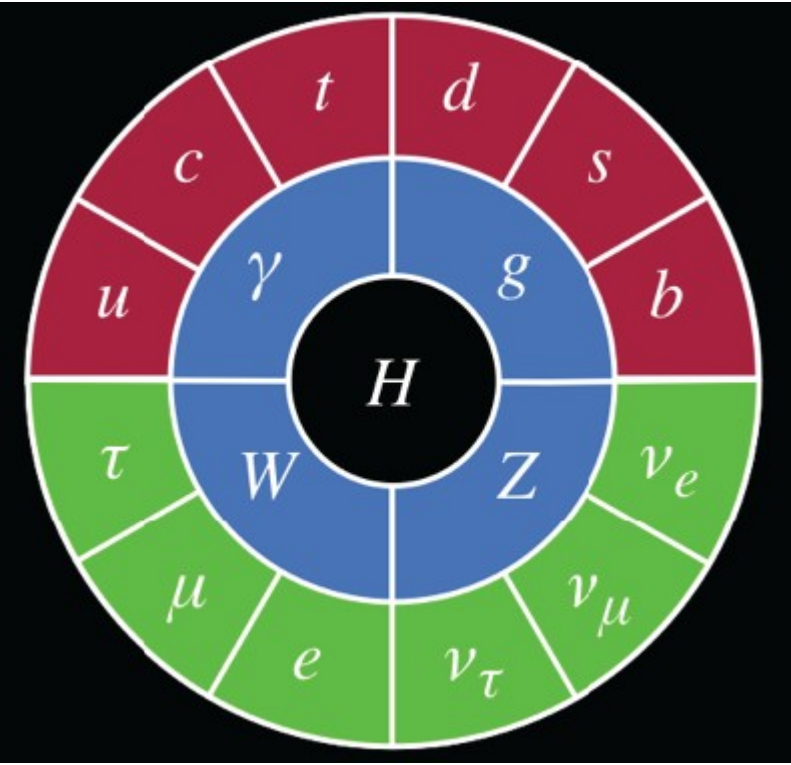


Leptons



Forces



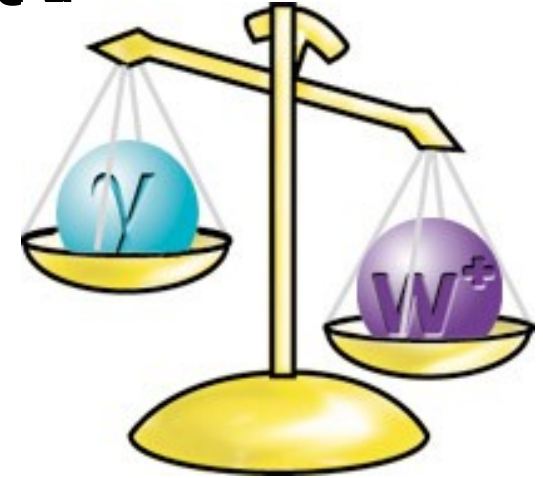


$$\begin{aligned}
& -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
& \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
\mathbf{2} \quad & 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 - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
& \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
& \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - 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_\nu^+ W_\nu^-) + \\
& g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\nu^+ 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^-] - g\alpha [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] - \\
& g M 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) - 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}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_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^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \\
\mathbf{3} \quad & \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{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
& 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
& (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
& \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
\mathbf{4} \quad & \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \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^\lambda) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
& \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
& \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda)] + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
\mathbf{5} \quad & \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}g M [\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} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
& ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}$$

Le mécanisme de Brout-Englert-Higgs

- La masse quantifie l'inertie du corps

- Plus un objet est massif plus il est difficile à mettre en mouvement



- Invariance de jauge

- ▬ masse=0
 - ▬ $v=c$

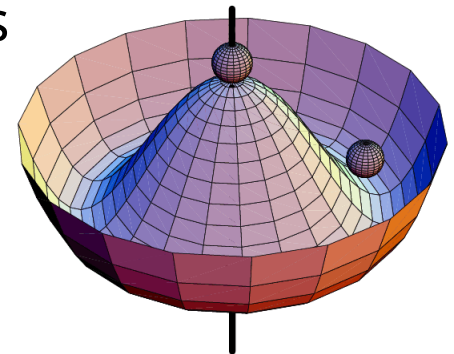
- ▬ contradiction avec l'expérience

- Mécanisme de Brout-Englert-Higgs

- La masse n'est pas une propriété intrinsèque des particules, mais le résultat de l'interaction de la particule avec le champ de Brout-Englert-Higgs

- Découvert en 1964 par:

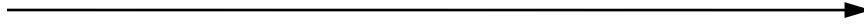
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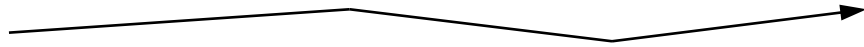


Le mécanisme de Brout-Englert-Higgs

Le photon: masse nulle



L'électron: petite masse



Le boson Z: grande masse



Plus difficile à mettre en mvt

L'action du champ de Higgs est équivalent à une sorte de viscosité du vide

Le boson de Higgs

Boson de Higgs = quanta du champ de Higgs



Le boson de Higgs joue un rôle central dans le mécanisme qui explique la masse des particules élémentaires