

Einführung in die Teilchenphysik

Masterclass 2019

Pirmin Berger

Folien von Simon Corrodi. Danke!





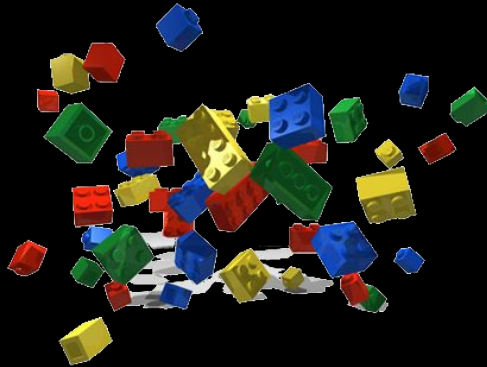
Aufeinanderschiessen



Theorie

Was wird geschehen?

Loch? Explosion?



Vergleichen

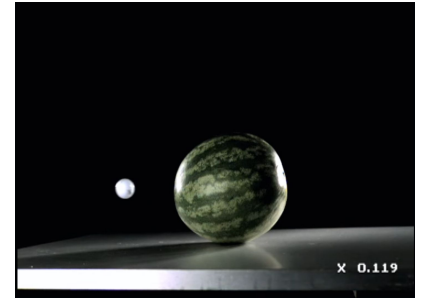
X 3.328

Übersicht

- Aufeinanderschiessen: Beschleuniger (nächste Präsentation)
 - Theorie: Das Standard Modell
 - Vergleichen: Detektoren (nächste Präsentation)
-
- Wie gut ist die gezeigte Analogie?
 - Worum geht es heute?
 - Ok. Und jetzt?

Aufeinanderschiessen

- Was? Teilchen....
- Wie? (nächster Vortrag)

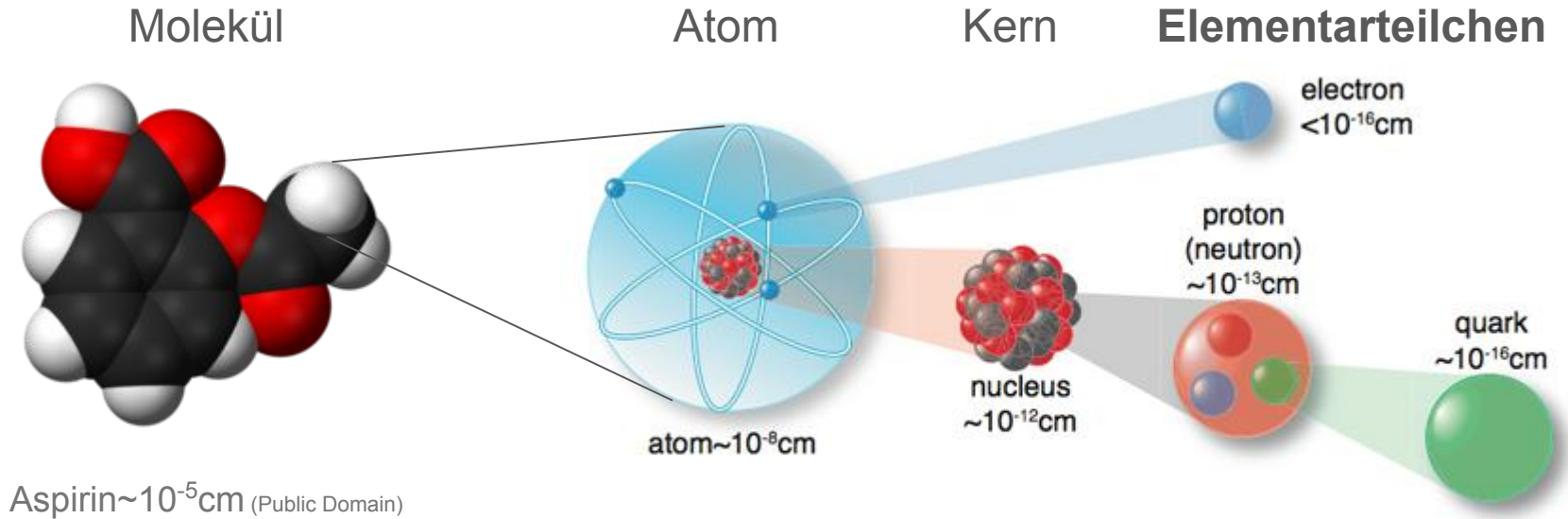
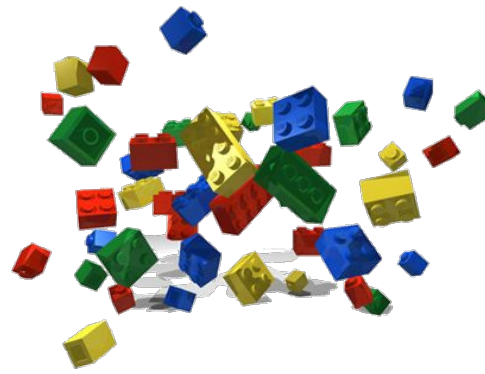


Theorie

Das Standard Modell

Woraus besteht Materie?

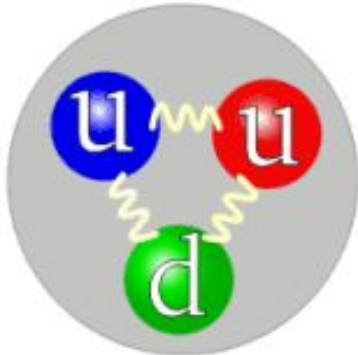
- ca. 600 v. Chr.: 4 Elemente
- heute?



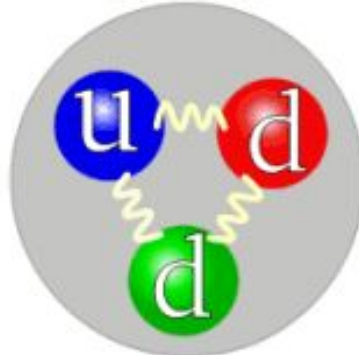
Woraus besteht Materie?

Frage: wie sieht man $<10^{-16}\text{cm}$?

Antwort: de Broglie: $E \sim 1/\lambda$; hohe Energien



Proton



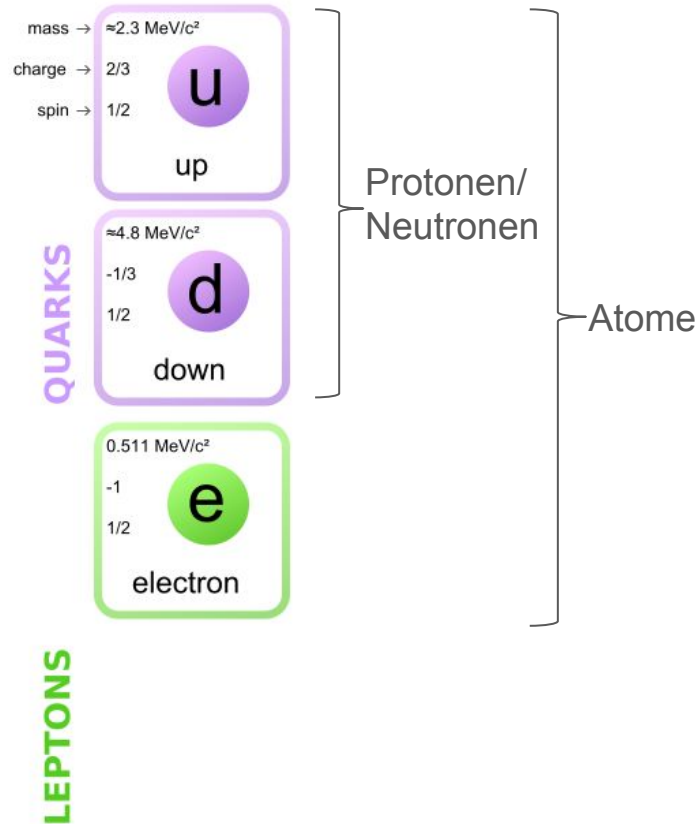
Neutron

Quark composition of a proton and a neutron (diagrams from *Wikipedia*)

Quarks

- Elementarteilchen
- Ladung:
 - up: $+2/3e$
 - down: $-1/3e$
- 3 "Farben"
- nie "alleine"

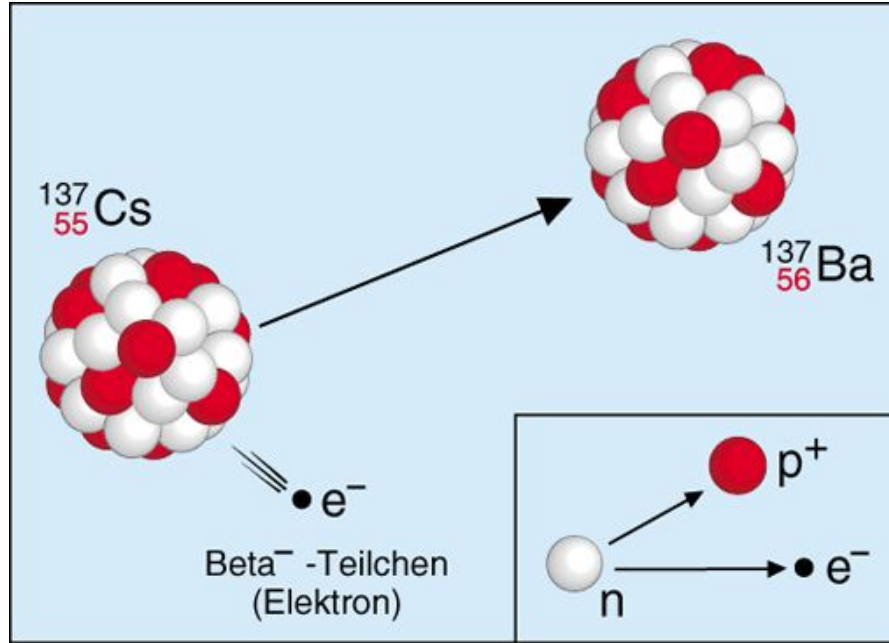
Standard Modell: Teilchen I



Bemerkung

$$1 \text{ MeV}/c^2 = 1.78 \times 10^{-30} \text{ kg}$$

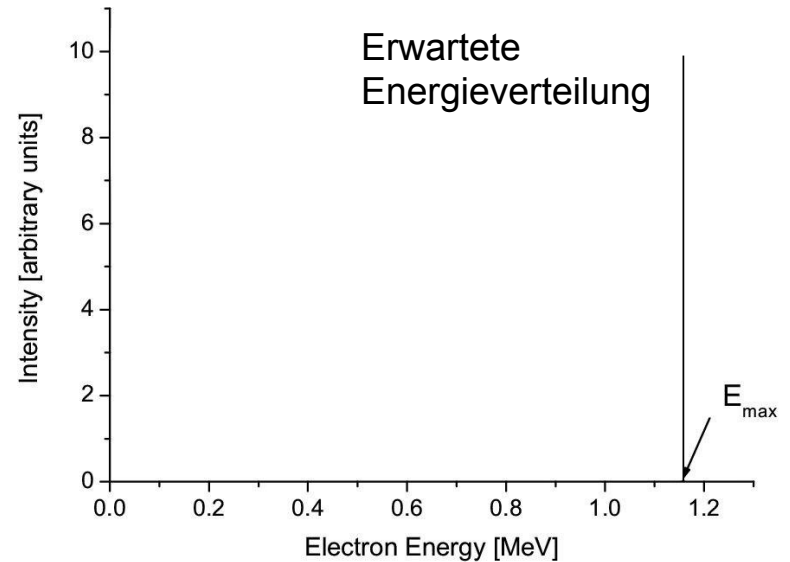
β^- -Zerfall



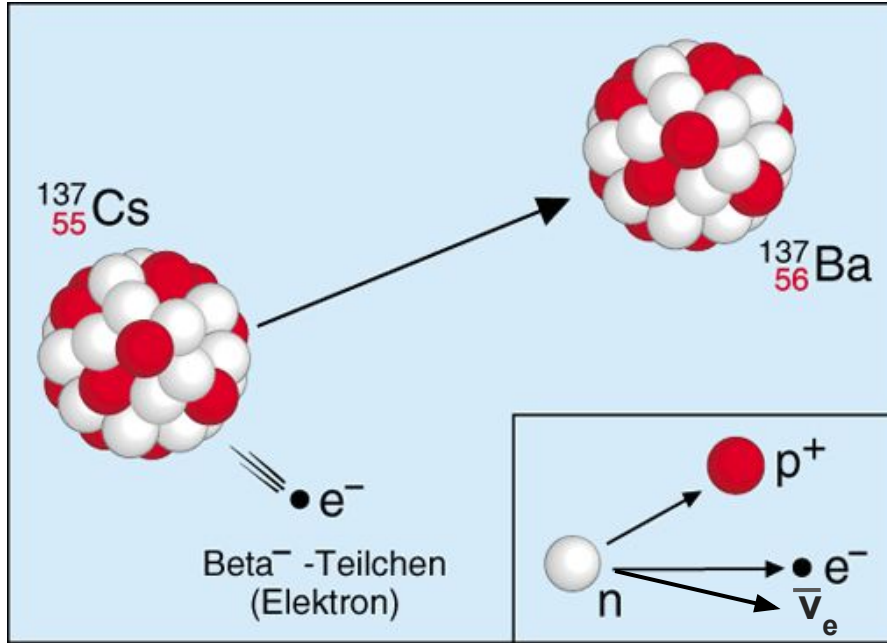
Neutron \rightarrow Proton + Elektron

$$E_{\text{kin}} = m_{\text{Cs}} - (m_{\text{Ba}} + m_{\text{e}}): \text{konstant}$$

2 Teilchen, Impulserhaltung: **“back-to-back”**



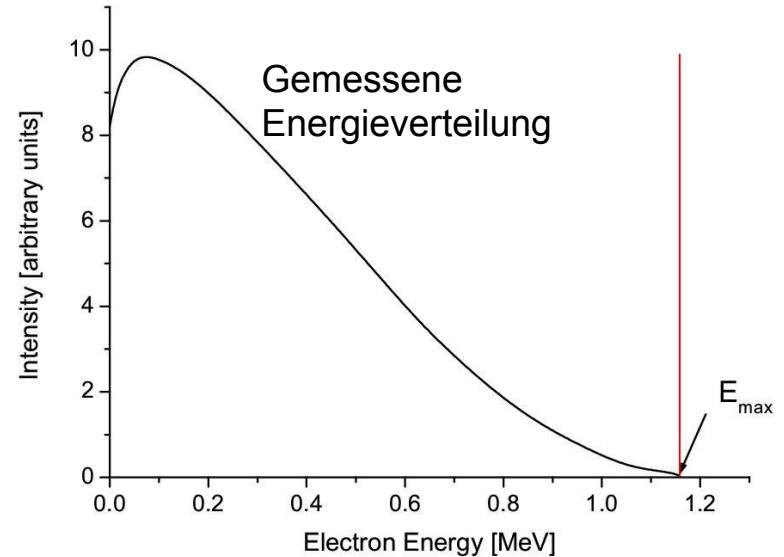
β^- -Zerfall



Neutron \rightarrow Proton + Elektron
+ *Neutrino*

$$E_{\text{kin}} = m_{\text{Cs}} - (m_{\text{Ba}} + m_e): \text{konstant}$$

~~2 Teilchen, Impulserhaltung: "back-to-back"~~



Standard Modell: Neutrinos

mass → $\approx 2.3 \text{ MeV}/c^2$
charge → $2/3$
spin → $1/2$

u

up

QUARKS

mass → $\approx 4.8 \text{ MeV}/c^2$
charge → $-1/3$
spin → $1/2$

d

down

mass → $0.511 \text{ MeV}/c^2$
charge → -1
spin → $1/2$

e

electron

LEPTONS

mass → $< 2.2 \text{ eV}/c^2$
charge → 0
spin → $1/2$

ν_e

electron neutrino

Neutrino

- Elementarteilchen
- Ladung: 0
- Masse: sehr klein
nicht 0

Standard Modell: Familien

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$
spin →	$1/2$	$1/2$	$1/2$
	u up	c charm	t top
QUARKS	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$
	$-1/3$	$-1/3$	$-1/3$
	$1/2$	$1/2$	$1/2$
	d down	s strange	b bottom
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$
	-1	-1	-1
	$1/2$	$1/2$	$1/2$
	e electron	μ muon	τ tau
LEPTONS	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$
	0	0	0
	$1/2$	$1/2$	$1/2$
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

Frage:

Wieso sehen wir fast ausschliesslich u, d (Protonen, Neutronen) und e (Elektronen)?

Antwort:

- a) Neutrino kaum Interaktion
- b) Nicht stabil, Zerfall

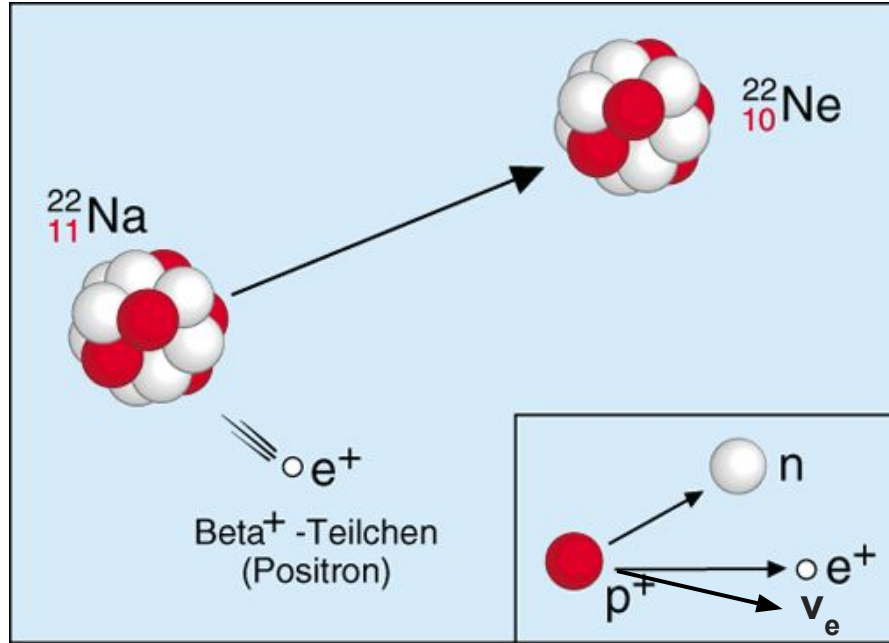
Frage:

Wieso gibt es 3 "Familien"?

Antwort:

???

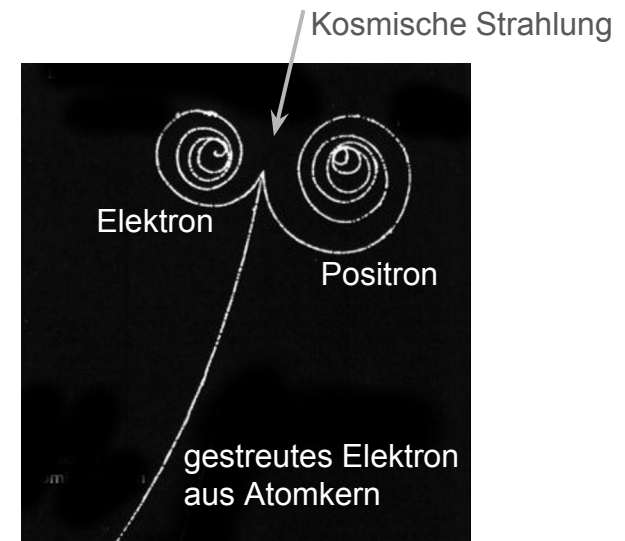
β^+ -Zerfall



**Proton \rightarrow Neutron + *Positron*
+ Neutrino**

Positron (e^+) = Anti-Elektron (\bar{e}^-)

Lorentzkraft: $F_L = qv \times B$



Blasenkammer e^+/e^- Paar

Standard Modell: Anti-Teilchen

mass → $\approx 2.3 \text{ MeV}/c^2$ $\approx 1.275 \text{ GeV}/c^2$ $\approx 173.07 \text{ GeV}/c^2$
 charge → $2/3$ $2/3$ $2/3$
 spin → $1/2$ $1/2$ $1/2$

	u up	c charm	t top
QUARKS	d down	s strange	b bottom
	e electron	μ muon	τ tau
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

$\approx 4.8 \text{ MeV}/c^2$ $\approx 95 \text{ MeV}/c^2$ $\approx 4.18 \text{ GeV}/c^2$
 $-1/3$ $-1/3$ $-1/3$
 $1/2$ $1/2$ $1/2$

$0.511 \text{ MeV}/c^2$ $105.7 \text{ MeV}/c^2$ $1.777 \text{ GeV}/c^2$
 -1 -1 -1
 $1/2$ $1/2$ $1/2$

$< 2.2 \text{ eV}/c^2$ $< 0.17 \text{ MeV}/c^2$ $< 15.5 \text{ MeV}/c^2$
 0 0 0
 $1/2$ $1/2$ $1/2$

mass → $\approx 2.3 \text{ MeV}/c^2$ $\approx 1.275 \text{ GeV}/c^2$ $\approx 173.07 \text{ GeV}/c^2$
 charge → $-2/3$ $-2/3$ $-2/3$
 spin → $1/2$ $1/2$ $1/2$

	\bar{u} up	\bar{c} charm	\bar{t} top
QUARKS	\bar{d} down	\bar{s} strange	\bar{b} bottom
	\bar{e} electron	$\bar{\mu}$ muon	$\bar{\tau}$ tau
	$\bar{\nu}_e$ electron neutrino	$\bar{\nu}_\mu$ muon neutrino	$\bar{\nu}_\tau$ tau neutrino

$\approx 4.8 \text{ MeV}/c^2$ $\approx 95 \text{ MeV}/c^2$ $\approx 4.18 \text{ GeV}/c^2$
 $1/3$ $1/3$ $1/3$
 $1/2$ $1/2$ $1/2$

$0.511 \text{ MeV}/c^2$ $105.7 \text{ MeV}/c^2$ $1.777 \text{ GeV}/c^2$
 1 1 1
 $1/2$ $1/2$ $1/2$

$< 2.2 \text{ eV}/c^2$ $< 0.17 \text{ MeV}/c^2$ $< 15.5 \text{ MeV}/c^2$
 0 0 0
 $1/2$ $1/2$ $1/2$

Wie interagieren Teilchen? Kräfte

Gravitation (Schwerkraft)

Planetenbahnen, Gewichtskraft

- nur positiv
- Reichweite: ∞

Elektromagnetische Kraft

Licht, Elektrizität, Magnetismus,
Elektronen um den Kern -> Chemie

- positiv/negativ
- Reichweite: ∞

Schwache Wechselwirkung

Beta-Zerfall, Fusion (Sonne),

Leptonen \leftrightarrow Quarks

- Reichweite: klein ($\sim 10^{-16}$ cm)

Starke Wechselwirkung

Zusammenhalt der Protonen/Neutronen,

Quarks \leftrightarrow Quarks

- Reichweite: speziell

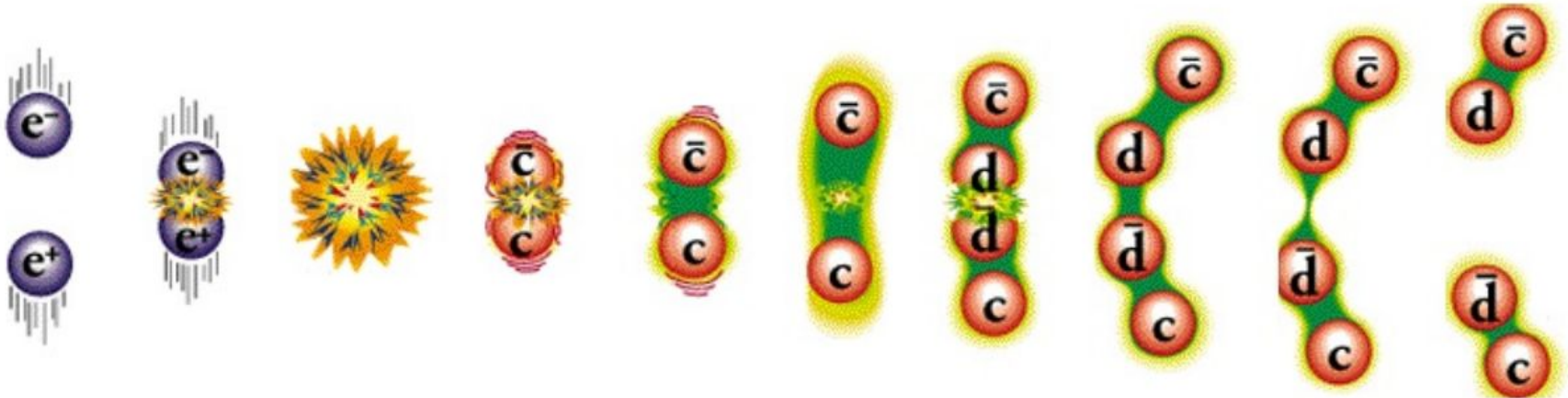
Starke Wechselwirkung

“bekannte Kräfte” (Elektromagnetisch, Gravitation)

$$F \sim 1/r^2$$

Starke Wechselwirkung

stärker je weiter die Teilchen auseinander, Vorstellung: Gummi-Band



Grund weshalb es keine freien Quarks gibt

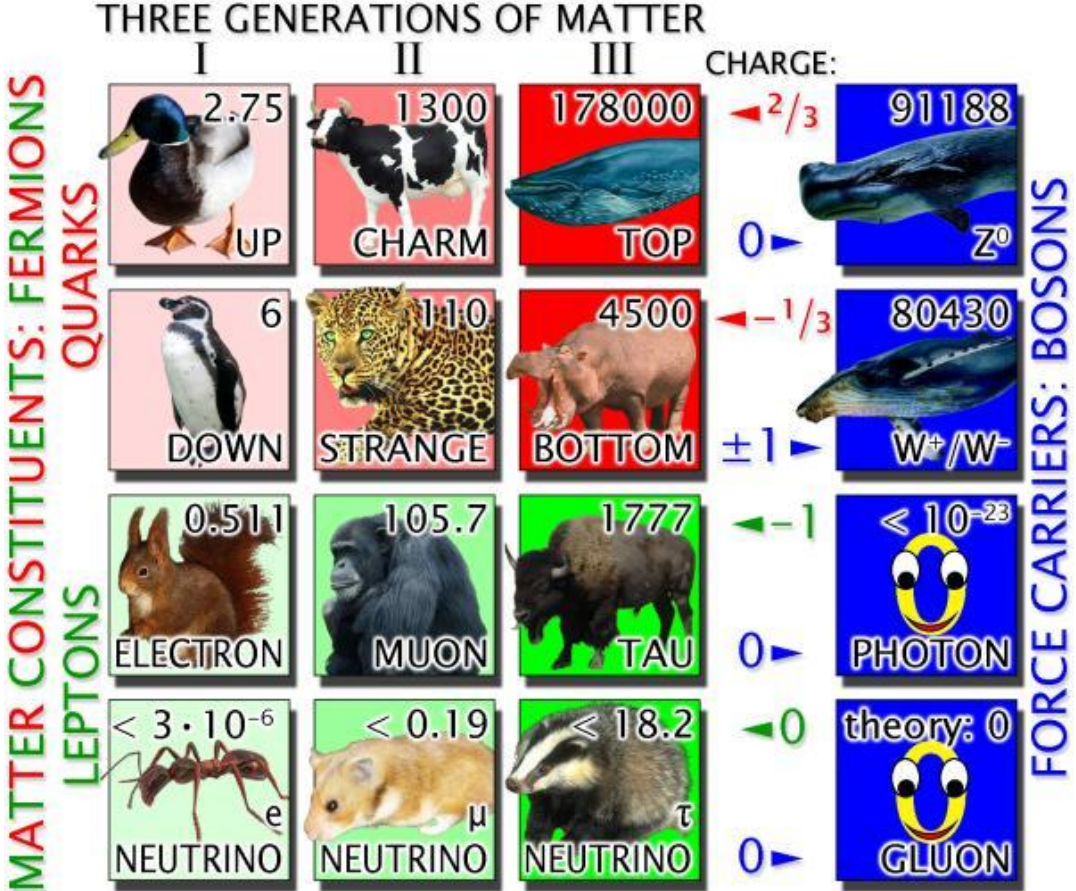
“Botenteilchen”: Bosonen

Wechselwirkungen werden durch “Botenteilchen” (Bosonen) vermittelt.

Wechselwirkung	Teilchen (Boson)	Ladung	Relative Stärke
Elektromagnetisch	Photon (γ)	<i>elektrisch</i>	10^{-2}
Schwach	W^+ , W^- , Z^0	<i>“schwach”</i>	10^{-15}
Stark	Gluon (g)	<i>Farbe</i>	1
Gravitation	Graviton?	<i>Masse</i>	10^{-41}

Standard Modell Teilchen

















	<p>mass → $\approx 2.3 \text{ MeV}/c^2$</p> <p>charge → $2/3$</p> <p>spin → $1/2$</p> <p>u</p> <p>up</p>	<p>mass → $\approx 1.275 \text{ GeV}/c^2$</p> <p>charge → $2/3$</p> <p>spin → $1/2$</p> <p>c</p> <p>charm</p>	<p>mass → $\approx 173.07 \text{ GeV}/c^2$</p> <p>charge → $2/3$</p> <p>spin → $1/2$</p> <p>t</p> <p>top</p>	<p>mass → 0</p> <p>charge → 0</p> <p>spin → 1</p> <p>g</p> <p>gluon</p>	<p>mass → $\approx 126 \text{ GeV}/c^2$</p> <p>charge → 0</p> <p>spin → 0</p> <p>H</p> <p>Higgs boson</p>	
QUARKS	<p>mass → $\approx 4.8 \text{ MeV}/c^2$</p> <p>charge → $-1/3$</p> <p>spin → $1/2$</p> <p>d</p> <p>down</p>	<p>mass → $\approx 95 \text{ MeV}/c^2$</p> <p>charge → $-1/3$</p> <p>spin → $1/2$</p> <p>s</p> <p>strange</p>	<p>mass → $\approx 4.18 \text{ GeV}/c^2$</p> <p>charge → $-1/3$</p> <p>spin → $1/2$</p> <p>b</p> <p>bottom</p>	<p>mass → 0</p> <p>charge → 0</p> <p>spin → 1</p> <p>γ</p> <p>photon</p>		
LEPTONS	<p>mass → $0.511 \text{ MeV}/c^2$</p> <p>charge → -1</p> <p>spin → $1/2$</p> <p>e</p> <p>electron</p>	<p>mass → $105.7 \text{ MeV}/c^2$</p> <p>charge → -1</p> <p>spin → $1/2$</p> <p>μ</p> <p>muon</p>	<p>mass → $1.777 \text{ GeV}/c^2$</p> <p>charge → -1</p> <p>spin → $1/2$</p> <p>τ</p> <p>tau</p>	<p>mass → $91.2 \text{ GeV}/c^2$</p> <p>charge → 0</p> <p>spin → 1</p> <p>Z</p> <p>Z boson</p>	GAUGE BOSONS	
	<p>mass → $< 2.2 \text{ eV}/c^2$</p> <p>charge → 0</p> <p>spin → $1/2$</p> <p>ν_e</p> <p>electron neutrino</p>	<p>mass → $< 0.17 \text{ MeV}/c^2$</p> <p>charge → 0</p> <p>spin → $1/2$</p> <p>ν_μ</p> <p>muon neutrino</p>	<p>mass → $< 15.5 \text{ MeV}/c^2$</p> <p>charge → 0</p> <p>spin → $1/2$</p> <p>ν_τ</p> <p>tau neutrino</p>	<p>mass → $80.4 \text{ GeV}/c^2$</p> <p>charge → ± 1</p> <p>spin → 1</p> <p>W</p> <p>W boson</p>		



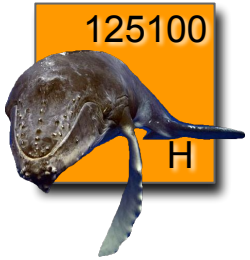
ALL MASSES IN MEV;
ANIMAL MASSES
SCALE WITH
PARTICLE MASSES

The Standard Model fundamental particle zoo

THREE GENERATIONS OF MATTER

	I	II	III	CHARGE:	
MATTER CONSTITUENTS: FERMIONS	QUARKS	 2.75 UP	 1300 CHARM	 178000 TOP	 91188 $\leftarrow \frac{2}{3}$ 0 \blacktriangleright Z^0
		 6 DOWN	 110 STRANGE	 4500 BOTTOM	 80430 $\leftarrow -\frac{1}{3}$ ± 1 \blacktriangleright W^+ / W^-
	LEPTONS	 0.511 ELECTRON	 105.7 MUON	 1777 TAU	 $< 10^{-23}$ 0 \blacktriangleright PHOTON
		 $< 3 \cdot 10^{-6}$ NEUTRINO e	 < 0.19 NEUTRINO μ	 < 18.2 NEUTRINO τ	 theory: 0 0 \blacktriangleright GLUON

FORCE CARRIERS: BOSONS



ALL MASSES IN MEV;
ANIMAL MASSES
SCALE WITH
PARTICLE MASSES

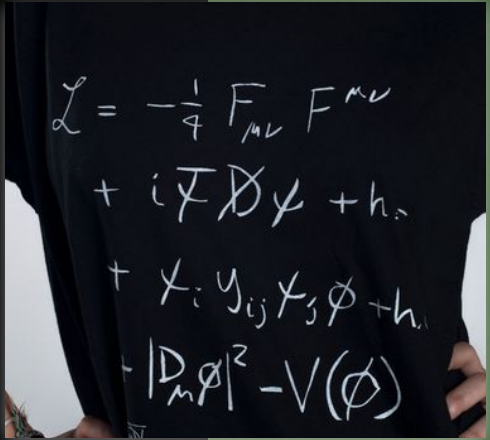
The Standard Model fundamental particle zoo

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

$$+ i\bar{\psi}\not{D}\psi + h.c.$$

$$+ \chi_i y_{ij} \chi_j \phi + h.c.$$

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


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

$$+ i\bar{\psi}\not{D}\psi + h.c.$$

$$+ \chi_i y_{ij} \chi_j \phi + h.c.$$

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



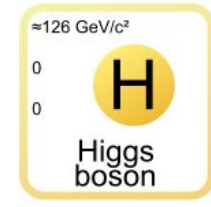
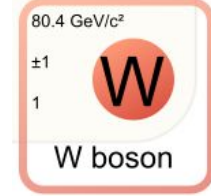
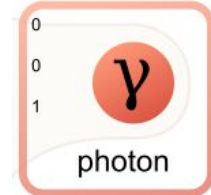
mass: +2.3 MeV/c ²	+1.275 GeV/c ²	+173.0 GeV/c ²
charge: 2/3	2/3	2/3
spin: 1/2	1/2	1/2
u	c	t
up	charm	top
QUARKS		
+4.8 MeV/c ²	+95 MeV/c ²	+4.18 GeV/c ²
-1/3	-1/3	-1/3
1/2	1/2	1/2
d	s	b
down	strange	bottom
0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²
1	1	1
1/2	1/2	1/2
e	μ	τ
electron	muon	tau
LEPTONS		
<2 eV/c ²	+0.17 MeV/c ²	+1.05 MeV/c ²
0	0	0
1/2	1/2	1/2
ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

Elektroschwache Wechselwirkung



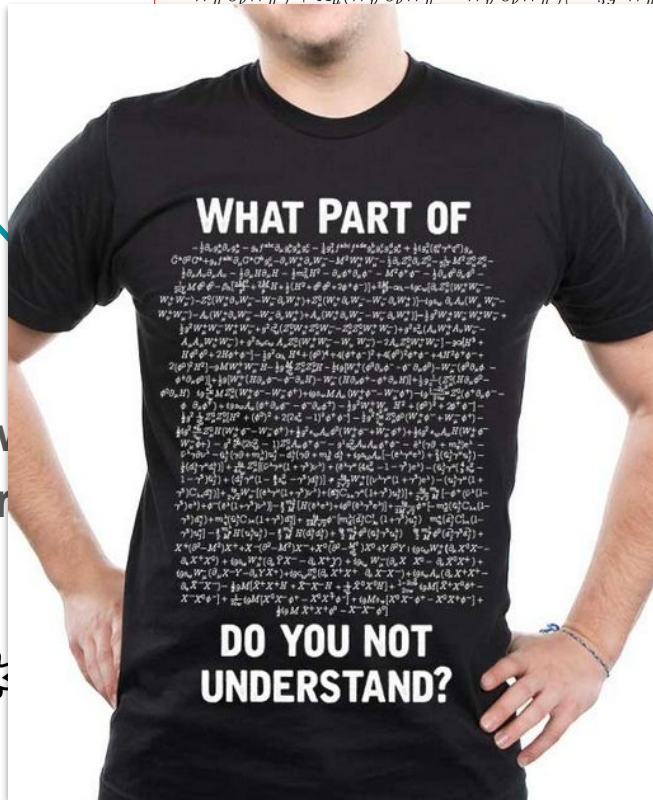
$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2}i g_s^2 (\bar{q}_i^a \gamma^\mu q_j^a) g_\mu^a + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu \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 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} 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_\nu^- \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_\nu^- W_\nu^+ W_\mu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + 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} 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_\nu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\nu^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_\nu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u) u_j^\lambda - \\
 & \bar{d}_j^\lambda (\gamma \partial + m_d) 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 k} d_k^\lambda) + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\lambda \gamma^\mu C_{\lambda k}^\dagger u_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu) + \frac{ig}{2\sqrt{2}} \frac{m_\lambda^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_\lambda^2}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda k} (1 - \gamma^5) d_k^\lambda) + \\
 & m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda k} (1 + \gamma^5) d_k^\lambda) + \frac{ig}{2M\sqrt{2}} \phi^- [m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda k}^\dagger (1 + \gamma^5) u_j^\lambda) - m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda k}^\dagger (1 - \\
 & \gamma^5) u_j^\lambda) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{ig}{2} \frac{m_\lambda^2}{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 - \\
 & \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}{c_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}$$

Starke Wechselwirkung





mass	$\sim 2.3 \text{ MeV}/c^2$	$1.275 \text{ GeV}/c^2$	$173.07 \text{ GeV}/c^2$
charge	2/3	2/3	2/3
spin	1/2	1/2	1/2
	u	c	t
	up	charm	top
	$-1/3$	$-1/3$	$-1/3$
	$-1/2$	$-1/2$	$-1/2$
	d	s	b
	down	strange	bottom
QUARKS			
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$
	1	1	1
	0	0	0
	e	μ	τ
	electron	muon	tau
	$-2/3$	$-1/3$	$-1/3$
	0	0	0
	ν_e	ν_μ	ν_τ
	electron neutrino	muon neutrino	tau neutrino
LEPTONS			

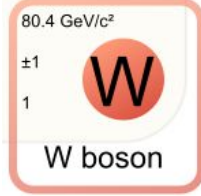
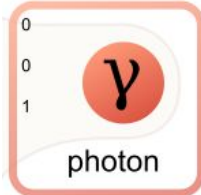


Elektroschwache Wechselwirkung



$$\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}{2} g_s^2 f^{abc} f^{ade} g_\mu^a g_\nu^b g_\mu^c g_\nu^d g_\mu^e \\
 & \frac{1}{2} i g_s^2 (\bar{q}_i^\mu \gamma^\mu q_j^\mu) g_\mu^a + 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 A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H \\
 & \frac{1}{2} m_\nu^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} M \phi^0 \phi^0 - \beta_h \left[\frac{2M_g^2}{g^2} H + \frac{2M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right] + \frac{2M_h^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - 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^+)] - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\nu^- \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^- + W_\mu^+ W_\nu^- + W_\mu^- W_\nu^+ - \partial_\nu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - H \phi^+ \phi^- - 2(\phi^0)^2 H^2 - \phi^0 \partial_\mu \phi^0 - W_\mu^- (H \partial_\mu \phi^+ - \phi^- - W_\mu^- \phi^+) + \phi^- \partial_\mu \phi^+ - \phi^- \partial_\mu \phi^+ + 2 + 2\phi^+ \phi^- - Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + 1) Z_\mu^0 A_\mu \phi^+ \phi^- + \partial_\nu (m_\nu^2 u_j^\nu) + \frac{1}{2} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3} s_w^2 - \mu(1 + \gamma^5) e^\lambda) + (\bar{d}_j^\lambda C_{\lambda c}^\dagger \gamma^\mu (1 + \gamma^5) \nu^\lambda) - (1 - \gamma^5) d_j^\lambda) + m_\nu^2 (\bar{d}_j^\lambda C_{\lambda c}^\dagger (1 - \gamma^5) u_j^\lambda) - \bar{u}_j^\lambda \gamma^\nu u_j^\nu - X^- + X^0 (\partial^2 - \partial_\mu \bar{X} X - \partial_\mu \bar{X} Y - \partial_\mu \bar{X} X + X^0 H) +
 \end{aligned}$$

Starke Wechselwirkung



<http://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation>

Theory: Das Standard Modell

- Elementarteilchen
- Wechselwirkungen (ausser Gravitation)
- 26 freie Parameter (z.B. m_{Higgs} , m_Z)

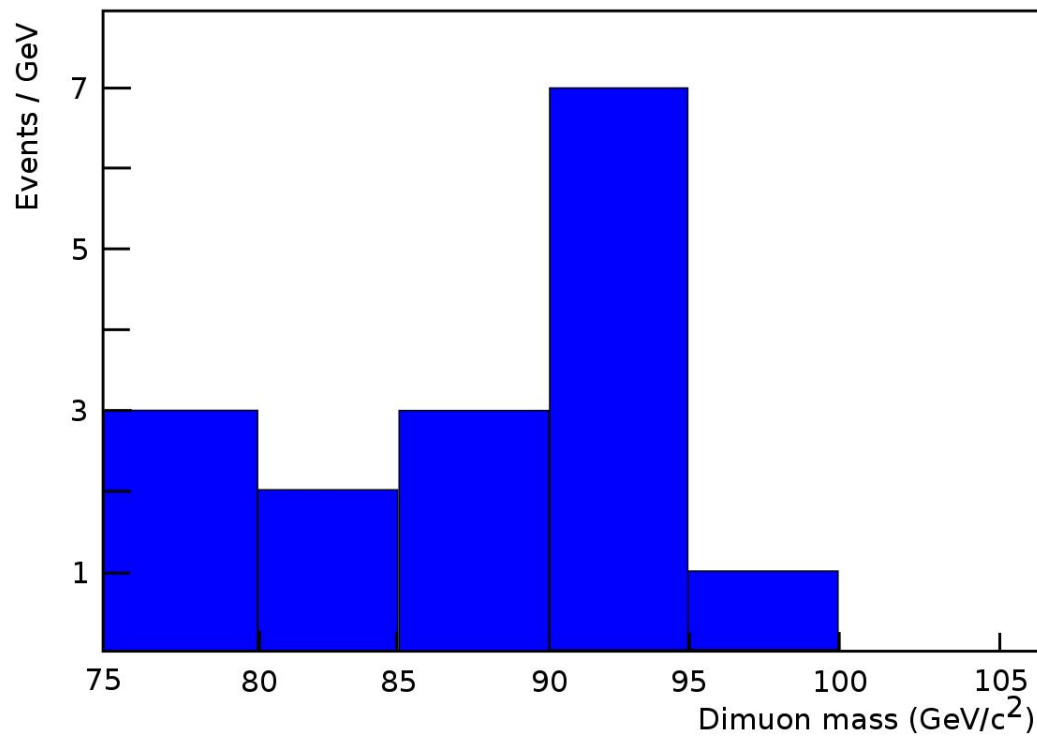
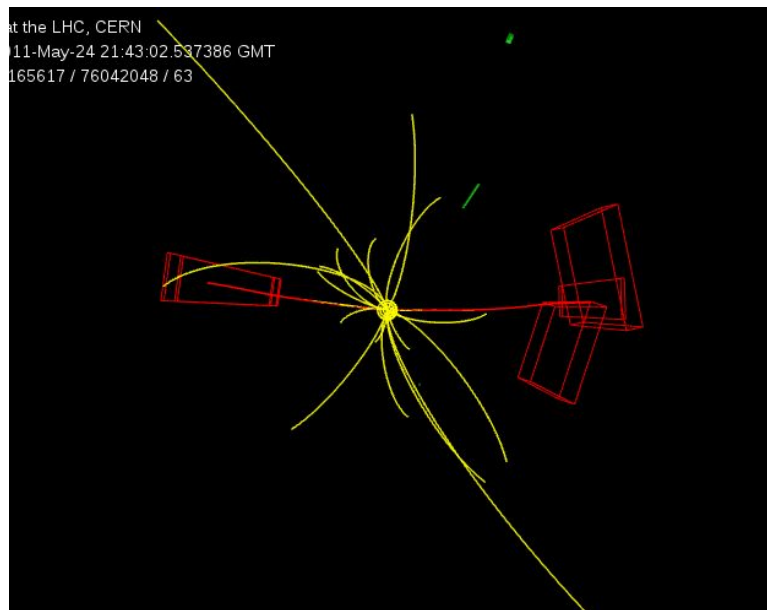
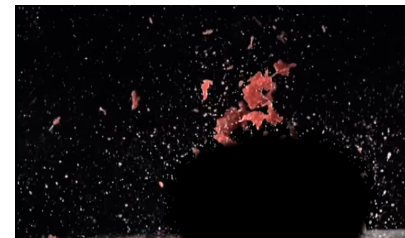
- kompatibel mit der speziellen Relativitätstheorie
- sehr gut getestet: Bsp g_{Elektron}
 - Gemessen: $g_{\text{Elektron}} = -2.00231930436182(52)$
 - Theorie: $g_{\text{Elektron}} = -2.0023193048(8)$

Theorie

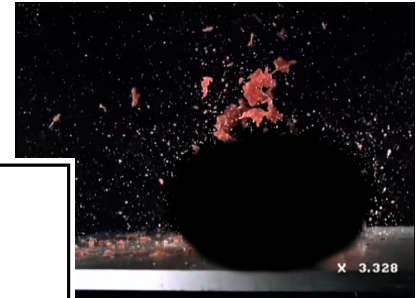
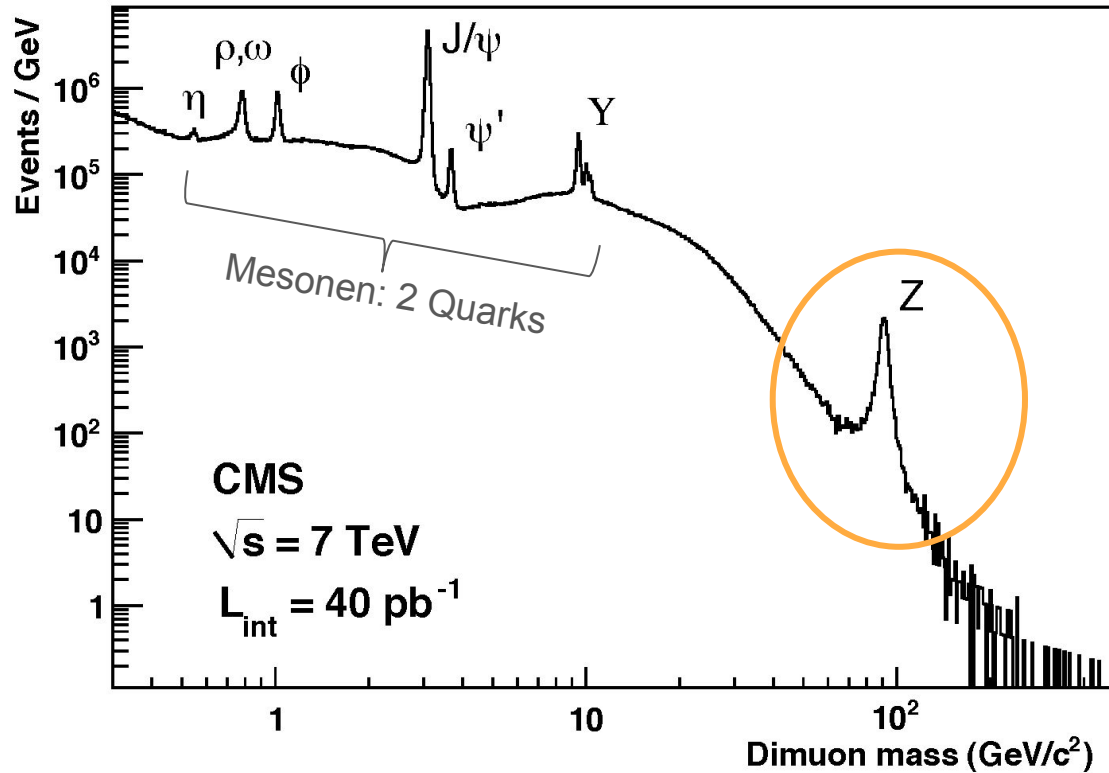


Vergleichen

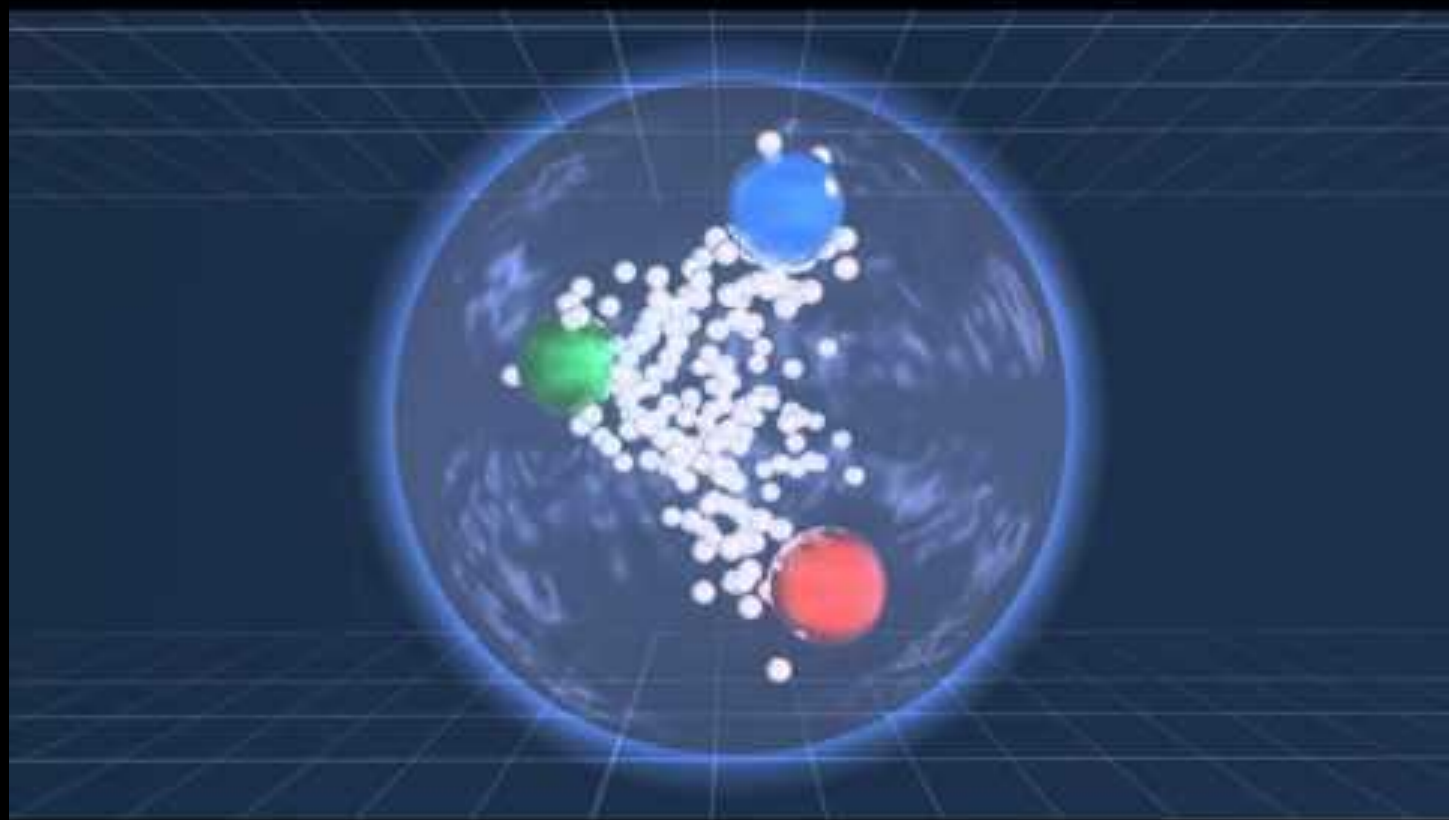
Selektion: 2 muonen
Grösse: Energie/Masse
($E=mc^2$)



Vergleichen



Wie gut ist die
“Golfball - Melonen” Analogie?



Wie gut ist die Analogie?

Golfball <-> Melone

ganze Objekte kollidieren

Melone wird "zerrissen", die Teile werden verteilt

relativ langsam

Proton <-> Proton

einzelne Quarks kollidieren

Quark/Anti-Quark erzeugen ein neues Objekt

Energy <-> Masse

$$\text{Einstein: } E^2 = (mc^2)^2 + (pc)^2$$

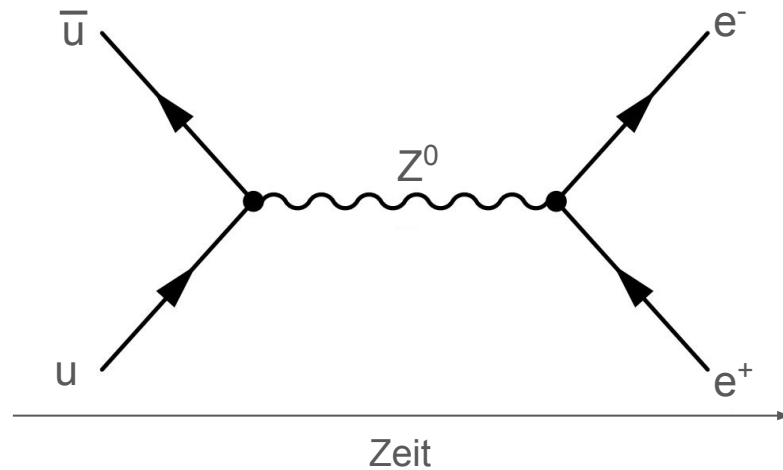
(m: Masse, p: Impuls, c: Lichtgeschwindigkeit)

sehr schnell -> viel Energie für neue Teilchen

Heute:
W- und Z-Bosonen
Standard Modell Test

Heute: W- und Z-Bosonen

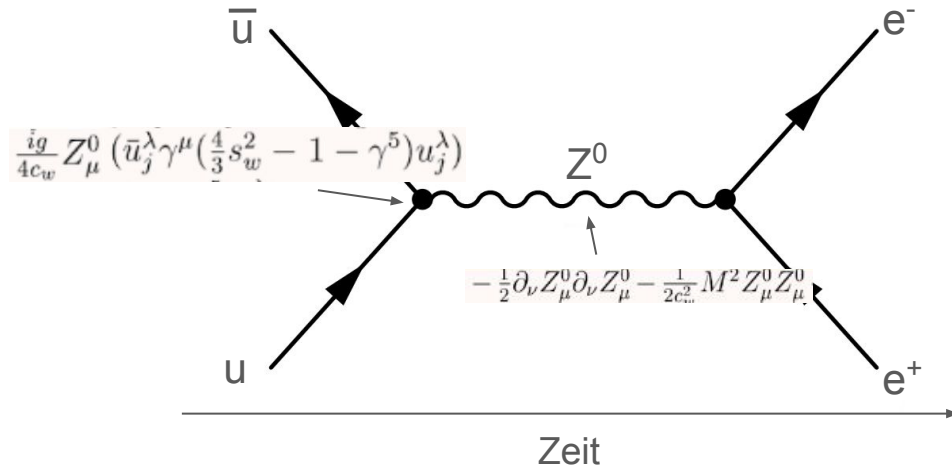
was kann passieren? was schauen wir uns an? was können wir testen?



- “von Links nach Rechts”
- Quark + Anti-Quark $\rightarrow Z^0$
- Z^0 zerfällt sofort in e^+/e^-

Heute: W- und Z-Bosonen

was kann passieren? was schauen wir uns an? was können wir testen?



- “von Links nach Rechts”
- Quark + Anti-Quark $\rightarrow Z^0$
- Z^0 zerfällt sofort in e^+/e^-
- Welche dieser Diagramme es gibt folgt aus dem “Lagrangian”

Starke Wechselwirkung

Elektroschwache Wechselwirkung

$$\frac{ig_s}{4} \bar{\psi} \gamma^\mu T^a \psi G^a_\mu$$

$$\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

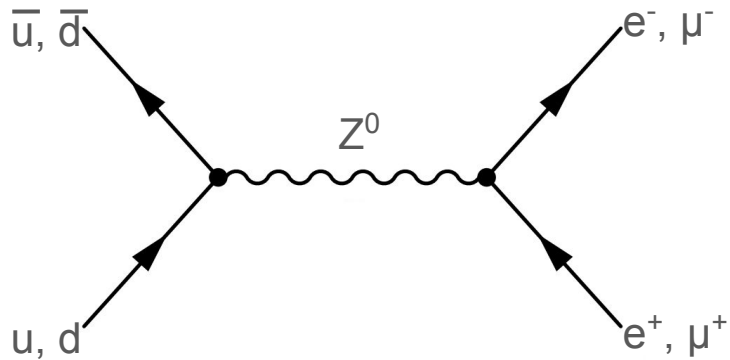
$$\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$\frac{1}{2} (D_\mu \phi)^\dagger (D^\mu \phi) - \frac{1}{2} m^2 \phi^\dagger \phi - \frac{\lambda}{4} (\phi^\dagger \phi)^2$$

<http://www.symmetrymagazine.org/article/the-structured-standard-model-equation>

Z^0 -Boson \rightarrow 2 Leptonen

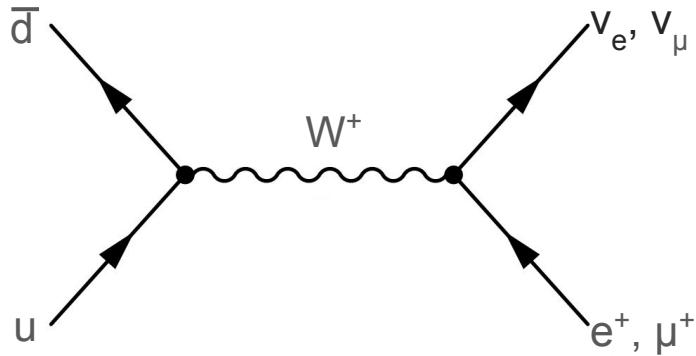
Z^0 zerfällt sofort: im Detektor sehen wir Leptonen (e/μ)



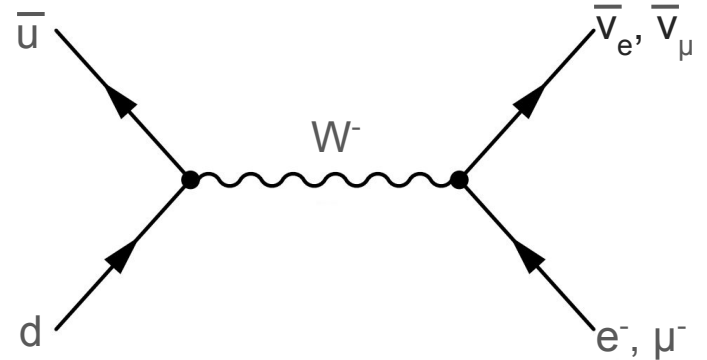
- Quark + Anti-Quark: Ladung 0
- Z^0 : Ladung 0
- e^+/e^- oder μ^+/μ^- : Ladung 0

$W^{-/+}$ -Boson \rightarrow 1 Lepton

$W^{+/-}$ zerfallen sofort, Neutrinos sind "unsichtbar" für den Detektor
im Detektor sehen wir Leptonen (e/μ)



- Up($2/3$) + Anti-Down($1/3$): Ladung +
- W^+ : Ladung +
- e^+/ν_e oder μ^+/ν_μ : Ladung +



- Down($-1/3$) + Anti-Up($-2/3$): Ladung -
- W^- : Ladung -
- $e^-/\bar{\nu}_e$ oder $\mu^-/\bar{\nu}_\mu$: Ladung -

Heute: Was testen/messen wir?

Standard Modell Vorhersagen:

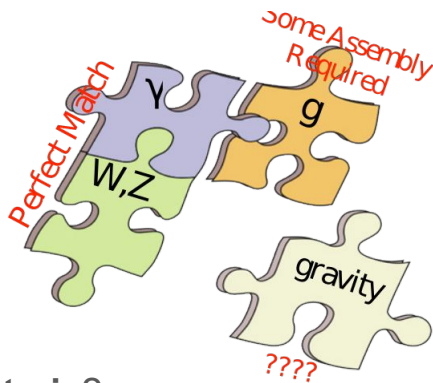
- Verhältnis von Zerfällen nach e und μ (W^- und Z -Bosonen)
- Verhältnis von produzierten W^+ und W^-
- Verhältnis von produzierten Z^0 und $W^{+/-}$

Freier Parameter im Standard Modell:

- Masse Z^0

Ok. Und jetzt?

Ok. Und jetzt?

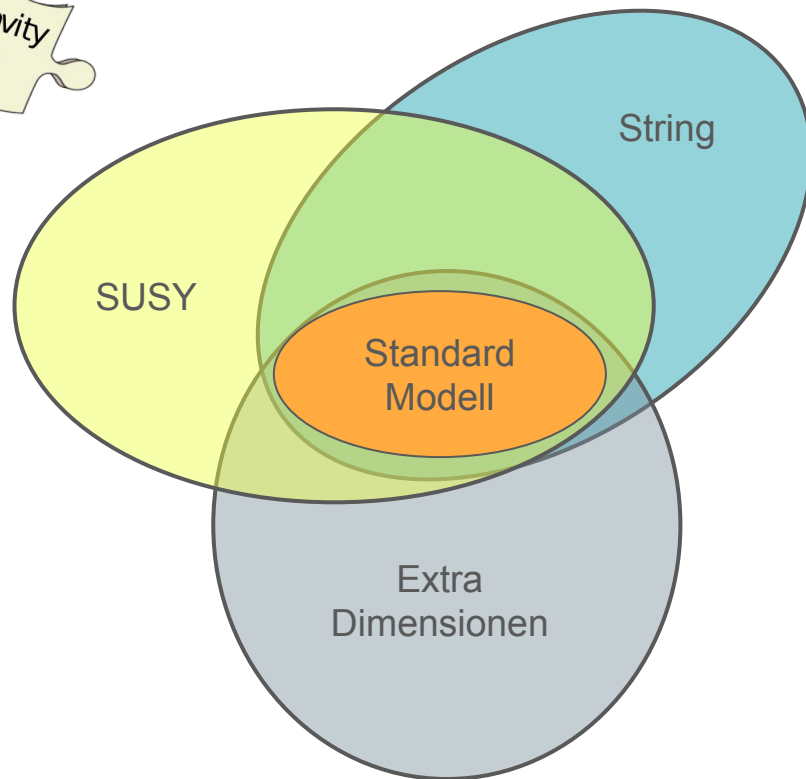


Fragen

- wie passt **Gravitation** ins Bild?
- wieso gibt es mehr **Materie als Anti-Materie**?
- wieso dehnt sich das Universum aus?
- was ist **dunkle Materie**?
- was ist dunkle Energie?

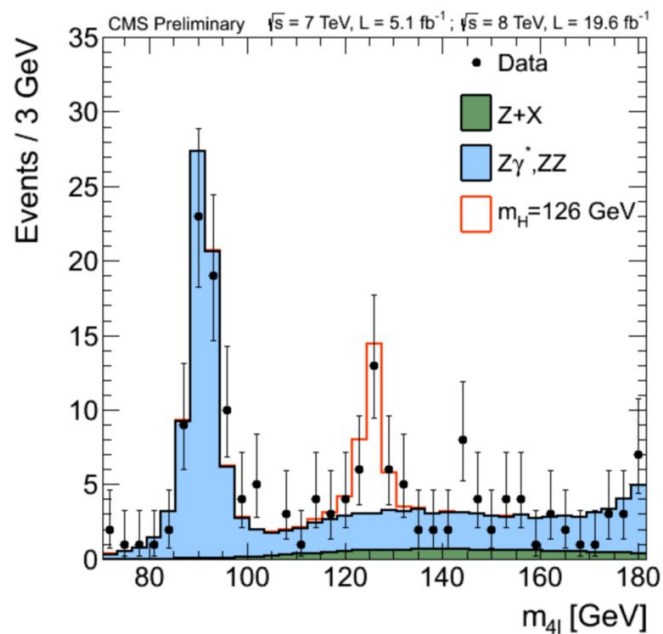
- wieso 26 freie Parameter?
- wieso sind diese so verschieden? (Naturalness)
- wieso 3 Familien?
- wieso ist "**fine-tuning**" notwendig?

viele neuen Theorien

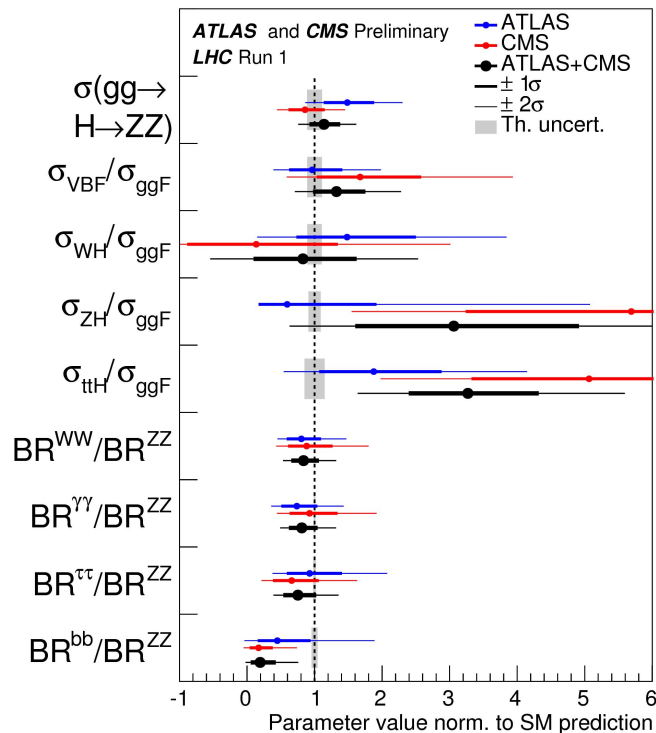


Ok. Und jetzt?

Direkt (neue Teilchen)



Indirekt (stimmt irgend etwas nicht?)

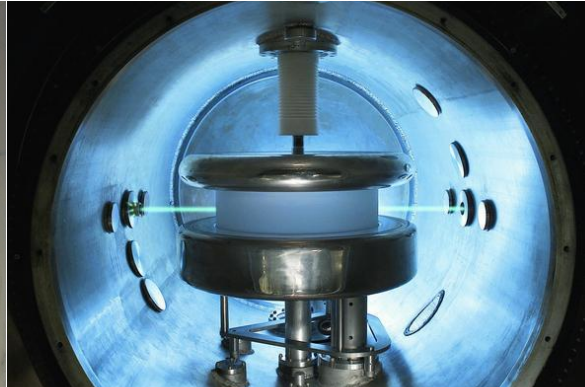
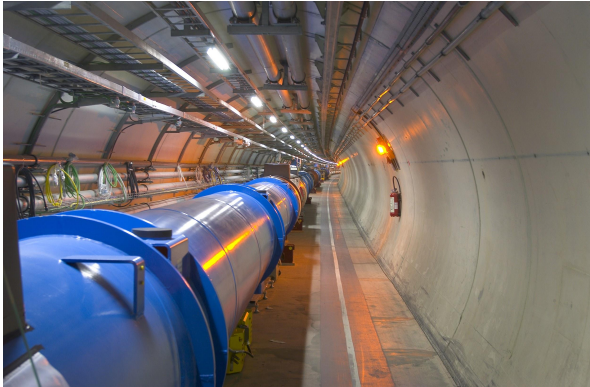


Ok. Und jetzt?

Hohe Energien (~ 13 TeV)

Hohe Intensitäten
(Prazision, \sim MeV)

Kosmisch Strahlung



CERN: **Beschleuniger**
neue Teilchen?
(nachster Vortrag)

nEDM (PSI, Villigen)
stimmt was nicht?
elektrische Dipolmoment des Neutrons

CTA Teleskop
Cherenkov Telescope Array
Teilchen kosmischen Ursprungs

Fragen?

Bildnachweis

Golfball - Melone: <https://youtu.be/fogo9NQ1g6A>

CERN Tunnel: <http://lh-machine-outreach.web.cern.ch/lhc-machine-outreach/images/cern-photos/CE0085M.jpg>

Molekül: http://www.pharma-select.net/s/cc_images/cache_2421886599.png (public domain)

Atom Grössen: <http://www.ipp.phys.ethz.ch/outreach/particle-physics--a-brief-review.html>

Standard Modell:

https://en.wikipedia.org/wiki/Standard_Model#/media/File:Standard_Model_of_Elementary_Particles.svg

Standard Modell Tiere: <http://teoriasperturbativas.wdfiles.com/local--files/blog:9/SM.jpg>

Quarks: https://upload.wikimedia.org/wikipedia/commons/thumb/9/92/Quark_structure_proton.svg/2000px-Quark_structure_proton.svg.png

Wellen Analogie: <https://www.youtube.com/watch?v=RQ95WcCCI9w> (Physikshow, Universität Bonn)

Radioactive Decays: <https://www.euronuclear.org>

Standard Modell Wandtafel: https://cds.cern.ch/record/1561145/files/Formula_image.jpg

Standard Modell: <http://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation>

Dimuon Spektrum: https://inspirehep.net/record/872180/files/denterria_dimuon_mass_spectrum_cms2010.png

SM Puzzle: “Tricks and Traps: Low Energy Searches for High Energy Physics”, Guy Ron.

Z-Produktion Video: www.cern.ch

Higgs Peak: http://sse.royalsociety.org/summer13/media/18946/cms-data_800.png

Standard Modell Testes: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-044/fig_07.png

nEDM: http://www.ipp.phys.ethz.ch/research/nedm-at-psi/_jcr_content/par/fullwidthimage/image.imageformat.lightbox.537890934.png

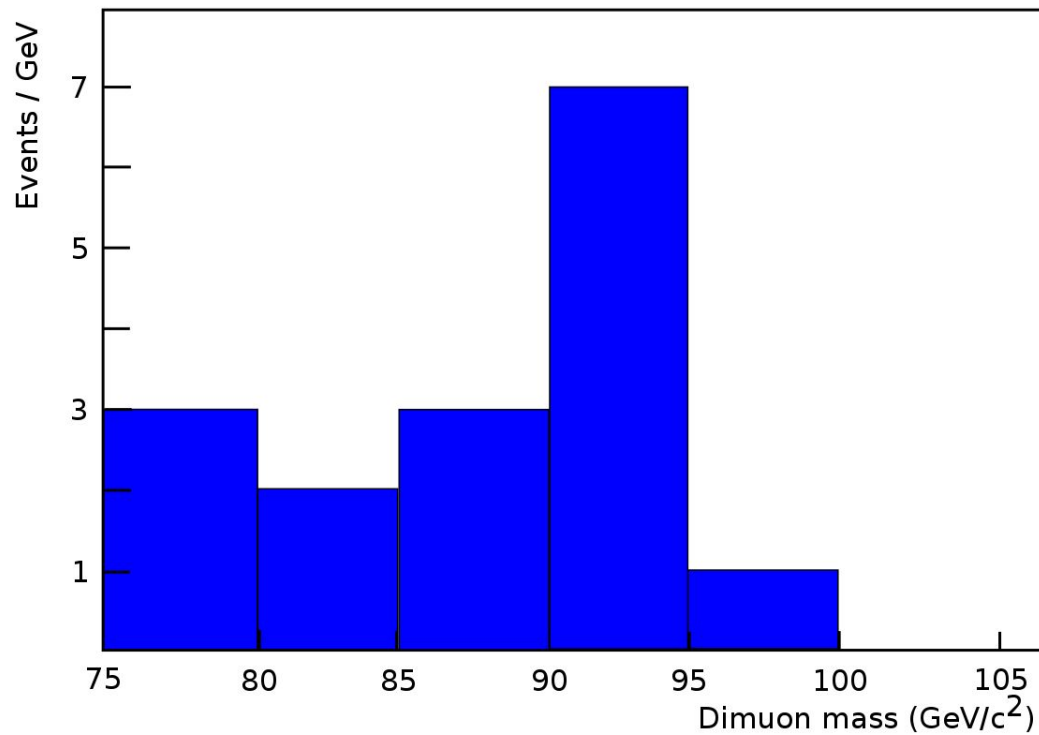
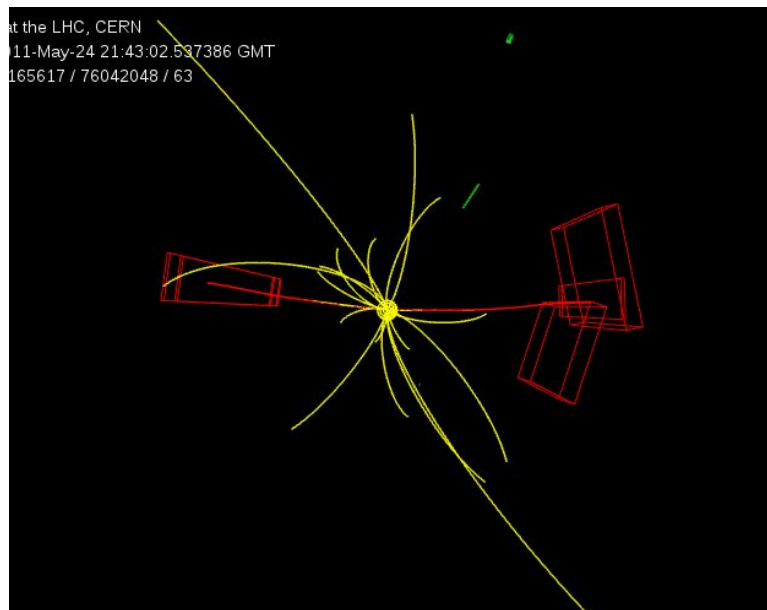


X 1.916

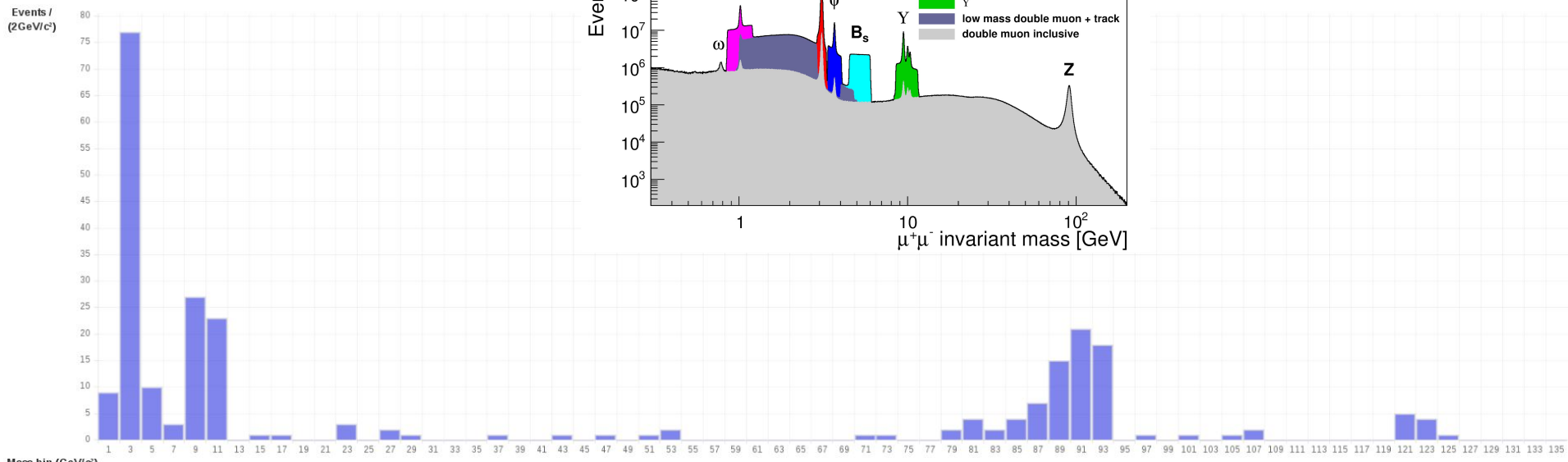
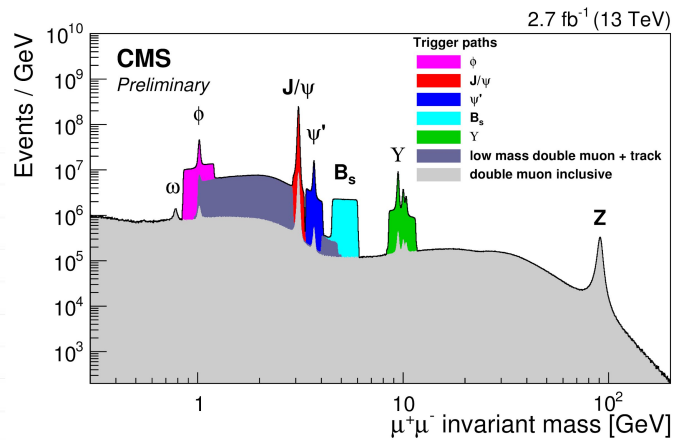
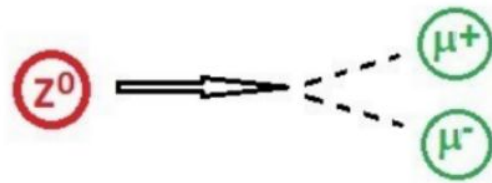
Erinnerung

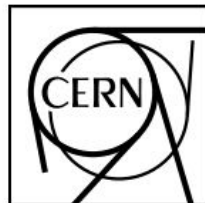
Vergleichen

Selektion: 2 Muonen
Grösse: Energie/Masse
($E=mc^2$)



Heute: Daten





CERN-PH-EP-2012-218

Accepted by: Physics Letters B

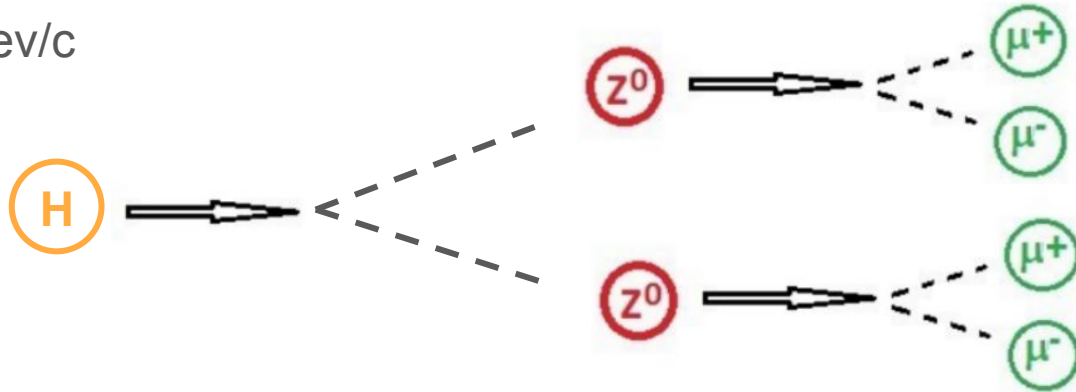
Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

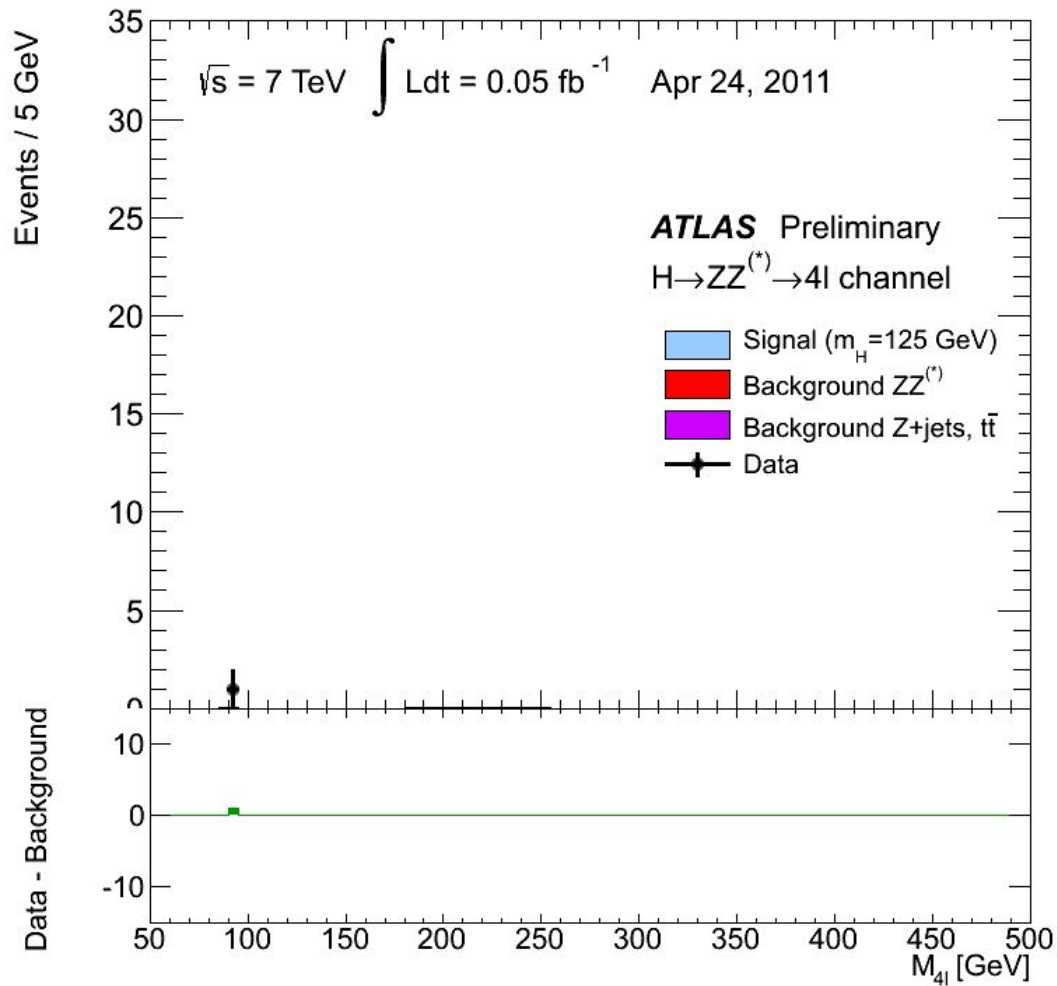
The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

LHC: Higgs Boson

- 2 Muon Paare
- Jeweils +/-
- $p = 25\text{Gev}/c$
-



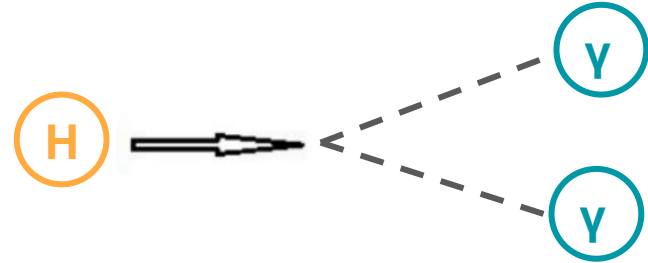


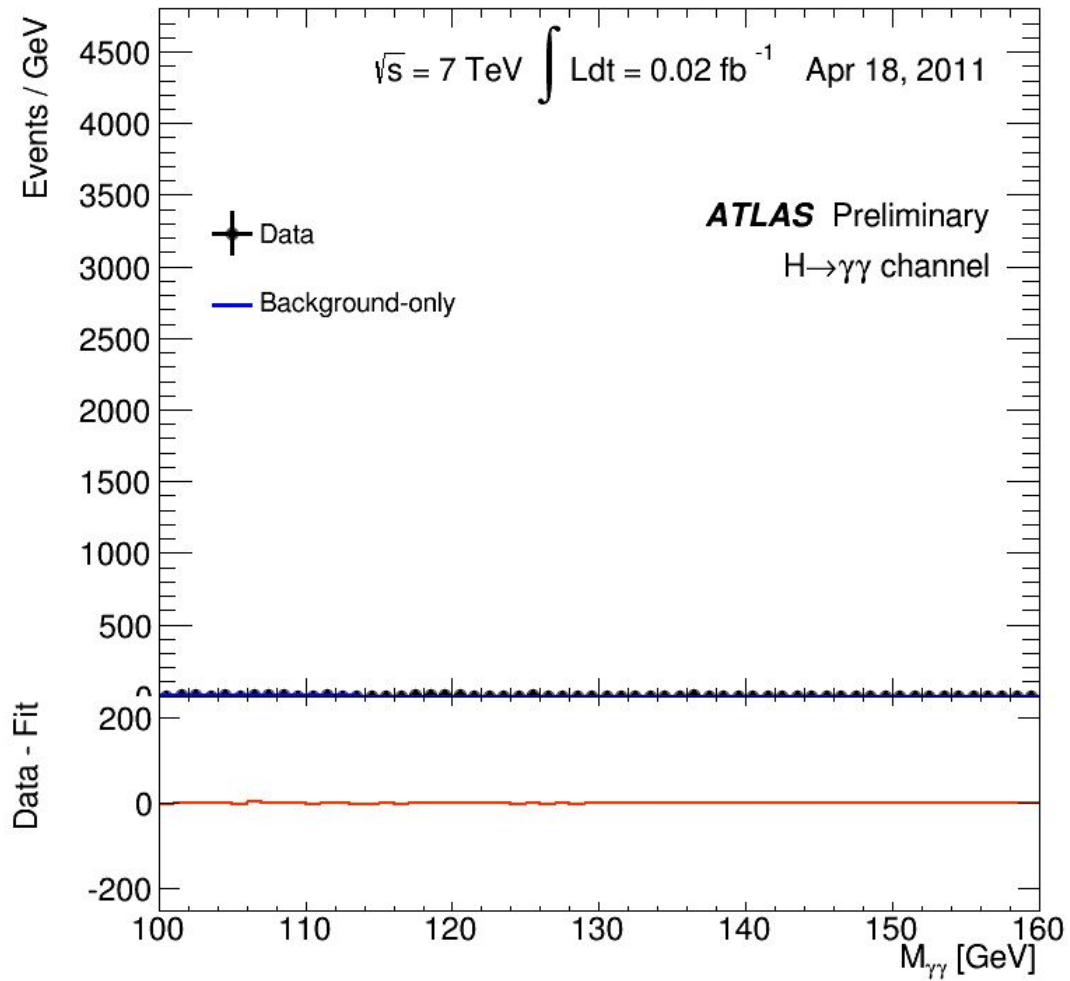
LHC: Higgs Boson

- 2 Photonen
-

5.1. Event selection

The data used in this channel are selected using a diphoton trigger [96], which requires two clusters formed from energy depositions in the electromagnetic calorimeter. An E_T threshold of 20 GeV is applied to each cluster for the 7 TeV data, while for the 8 TeV data the thresholds are increased to 35 GeV on the leading (the highest E_T) cluster and to 25 GeV on the sub-leading (the next-highest E_T) cluster. In addition, loose





Fragen?



UP



CHARM



TOP



PHOTON

STABILER TYP
KOMMUNIKATIV
FEDERLEICHT

W⁺



DOWN



STRANGE



BOTTOM



Z



ELEKTRON



MUON



TAUON



GLUON



W⁻



FEDERLEICHT
GESITERHAFT
WECHSELHAFT
NEUTRINOS



HIGGS