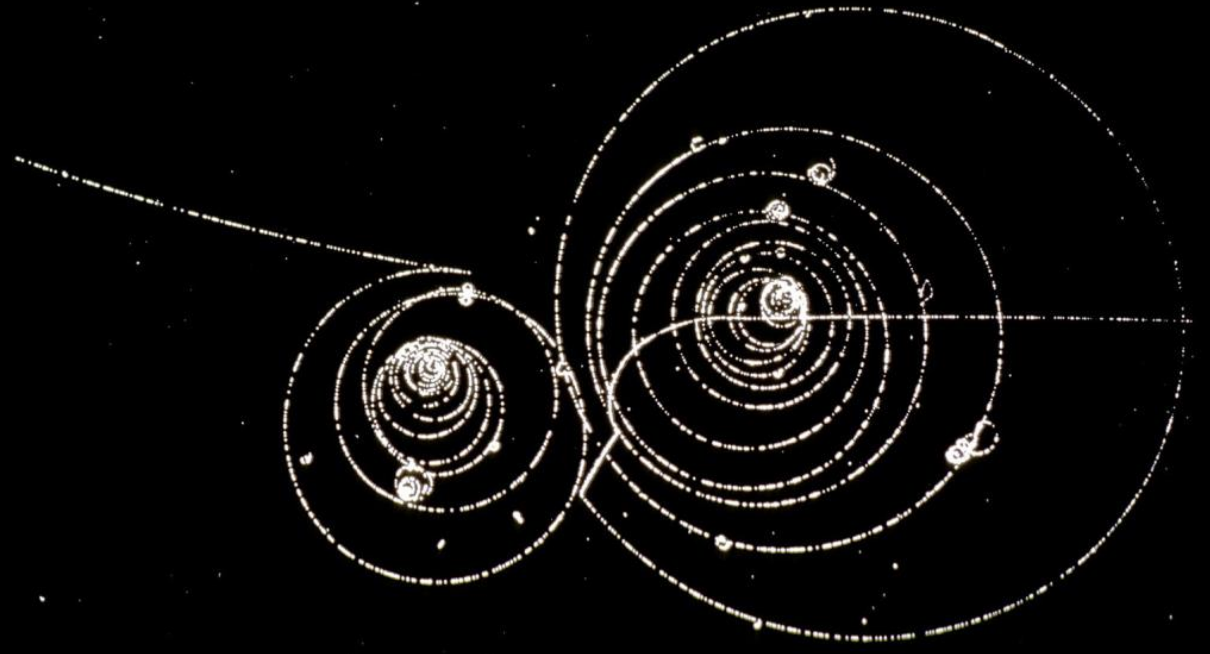
High Energy Physics
Lecture 1: Introduction



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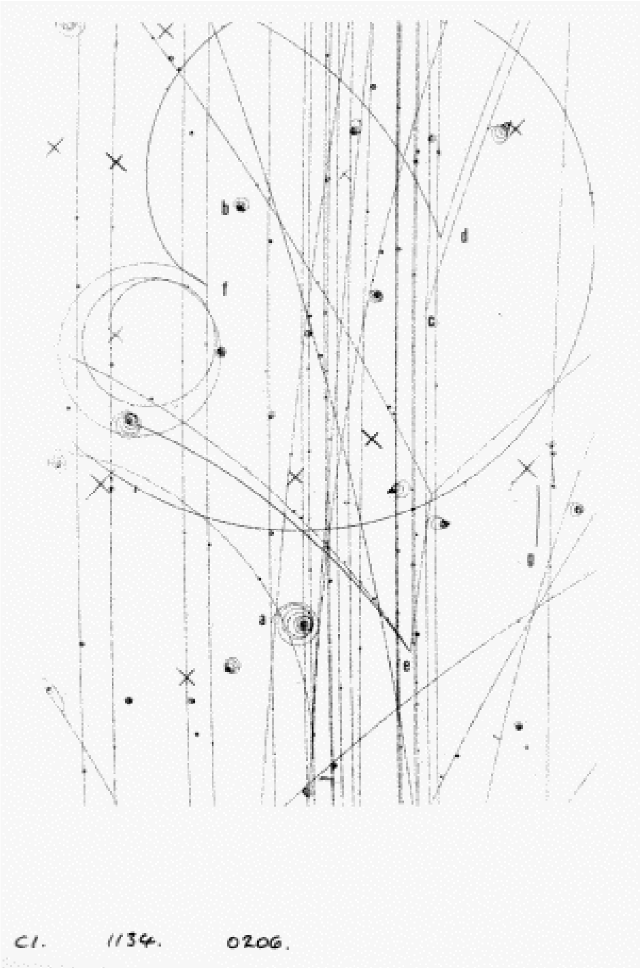
Welcome to High Energy Physics!

- Introductions
- Logistics
- Course structure
- Bibliography
- Quick overview



Introduction and Logistics

- Ricardo Gonçalo
  - Logistics:
  - Email: jgoncalo@uc.pt
  - Office: E.20
  - Office hours: Tuesday 11am?

- Research interests:
  - Higgs boson properties
  - Hadronic jet physics
  - Trigger development
  - Detector upgrade
  - Data analysis
  - etc

Overall learning objectives

- Elementary particles, their spectrum and classification; fundamental interactions and corresponding gauge bosons
- Klein-Gordon and Dirac equations and their free-particle solutions; zero mass and helicity limit; neutrinos and the V-A structure of weak interactions
- Fermion and boson propagators; Yukawa potential of a bosonic field; propagators
- Feynman diagrams; cross section calculation at 1st order for simple processes; higher order diagrams and renormalization
- Proton form factor and structure functions; quarks and gluons; notions of quantum chromodynamics; strong coupling constant; quark confinement and asymptotic freedom
- Neutrino physics; mixing and oscillation
- P, C, and T symmetries; CP and T violation and the CPT theorem
- Unified electroweak theory and the Standard Model; neutral and charged currents, W and Z bosons
- The Higgs mechanism and electroweak symmetry breaking
- High energy collider- and non-collider based experiments; important results
- Limitations of the Standard Model and searches for new physics

Course structure

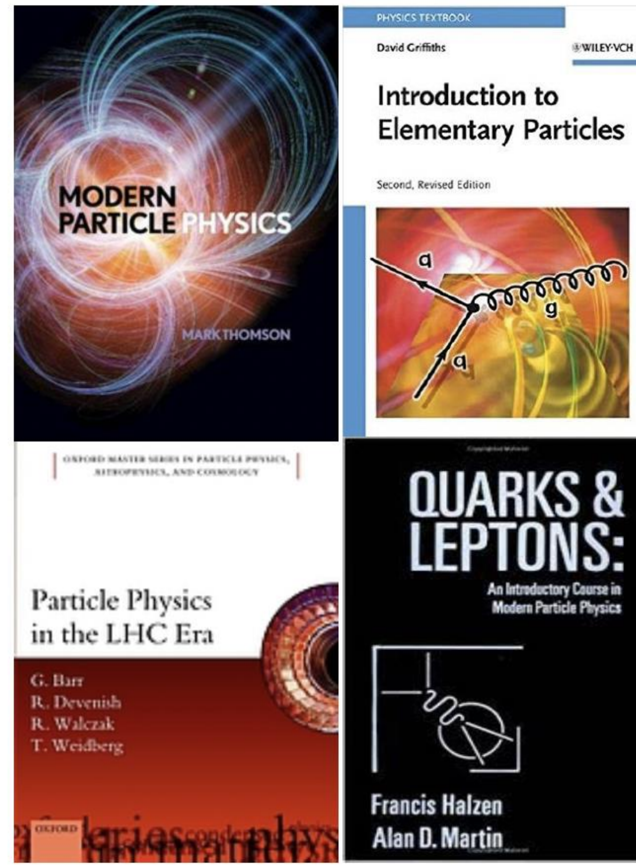
- 14 theory lectures:
  - Mixture of slides and blackboard
  - If time allows: a seminar (to be defined)

- 14 problem sessions:
  - Sometimes will use for theory

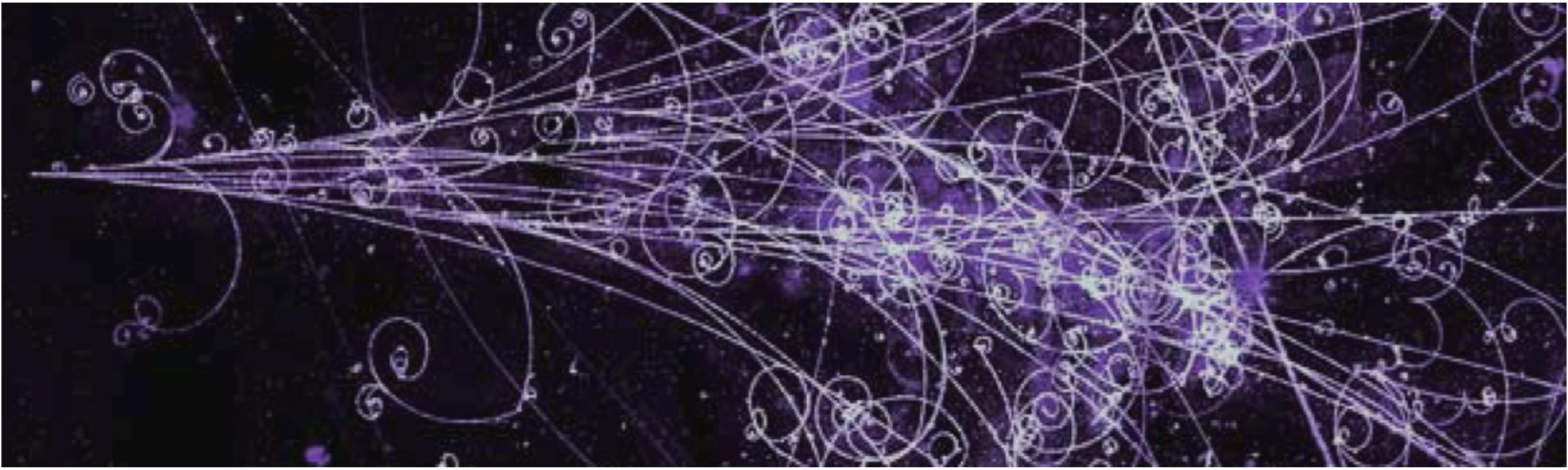
- Grading:
  - Final test during 18th May problem session (50%)
  - Problem sets to deliver individually (50%) in Inforestudante

Bibliography

- Main book (in principle):
  - Mark Thomson “Modern Particle Physics”
- Sometimes I will use:
  - D. J. Griffiths “Introduction to Elementary Particles”
  - G.Barr et al. “Particle Physics in the LHC Era”
  - F. Halzen & A.D. Martin “Quarks & Leptons”
- Encyclopaedia on particle properties and other relevant information
  - PDG: http://pdg.lbl.gov

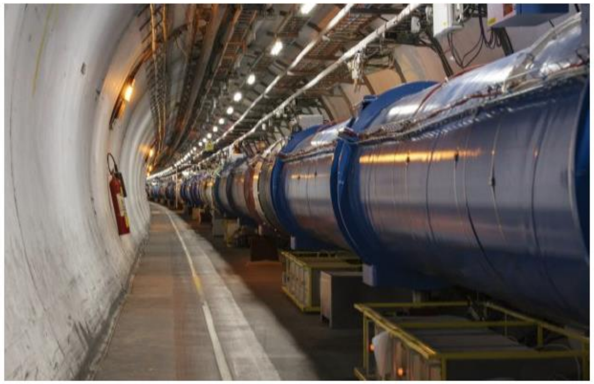


Particle Physics



Particle Physics

- High Energy Physics? Same as particle physics, physics of elementary particles, etc



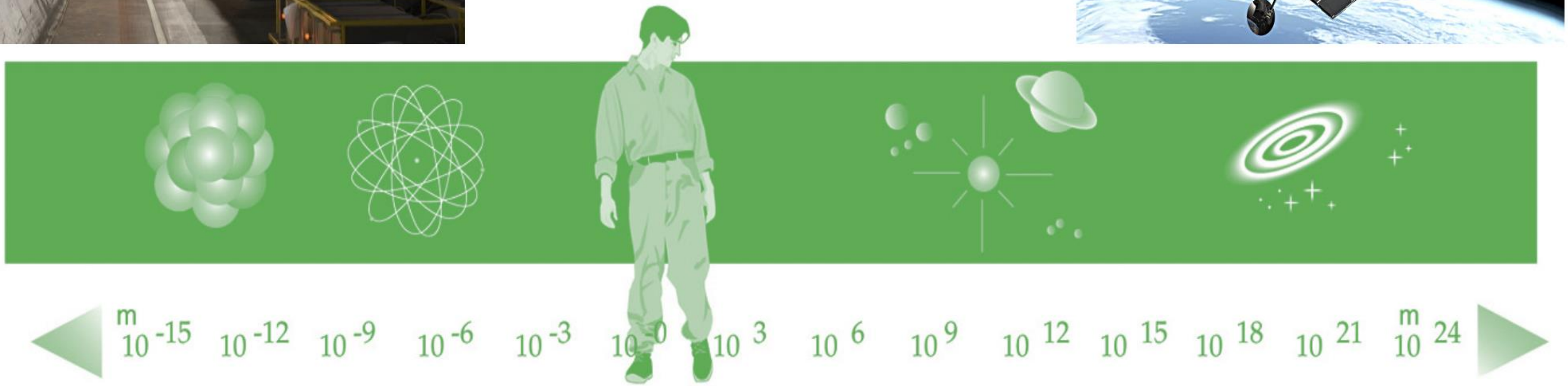
Length: 1 fm = 10^{-15} m (fermi)

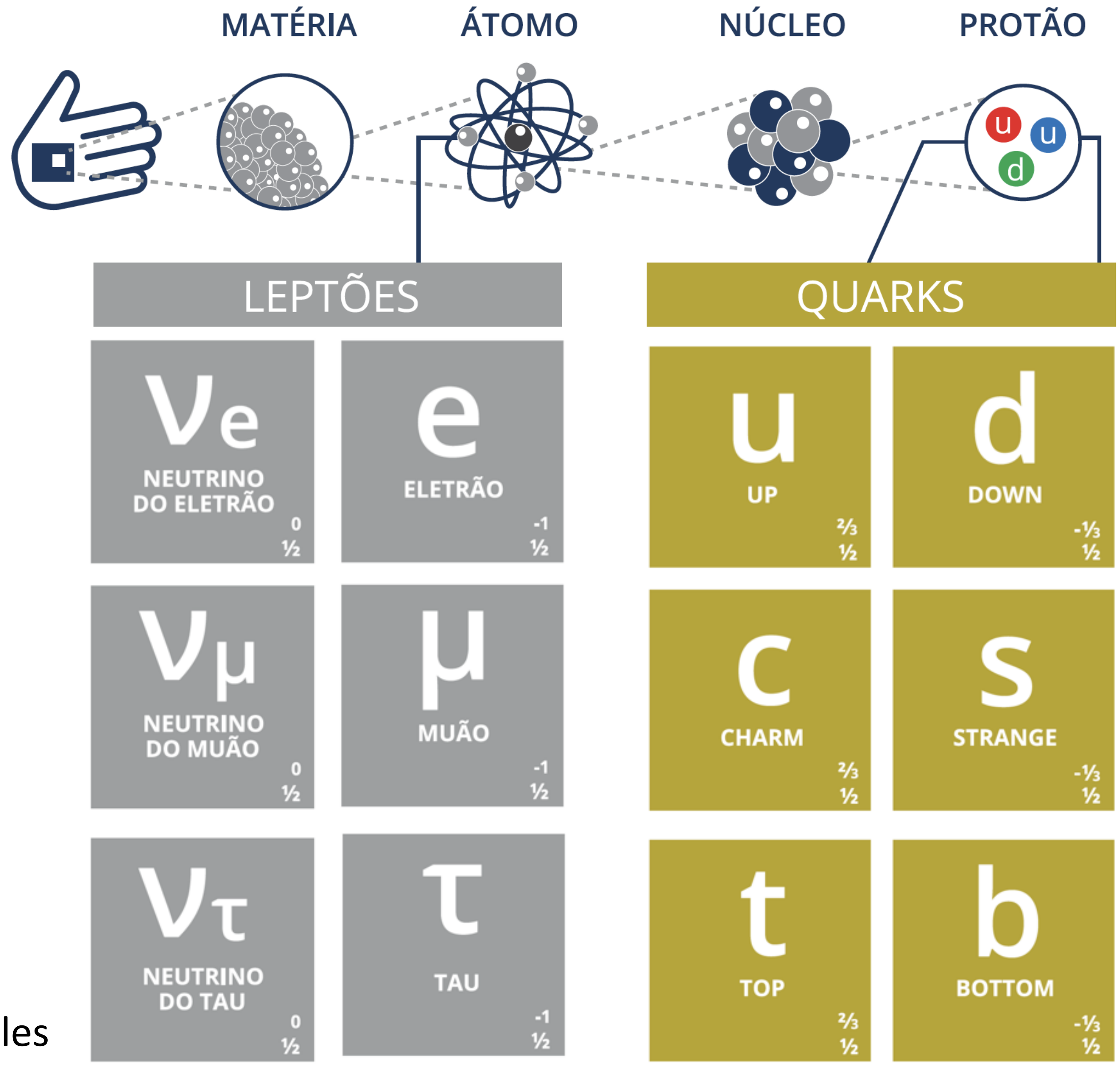
Area: 1 barn = 10^{-28} m^2 1pb=10^{-12}b

Time: 1 ps = 10^{-12} s; 1ns = 10^{-9} s

Energy: 1 GeV = 10^{9} eV

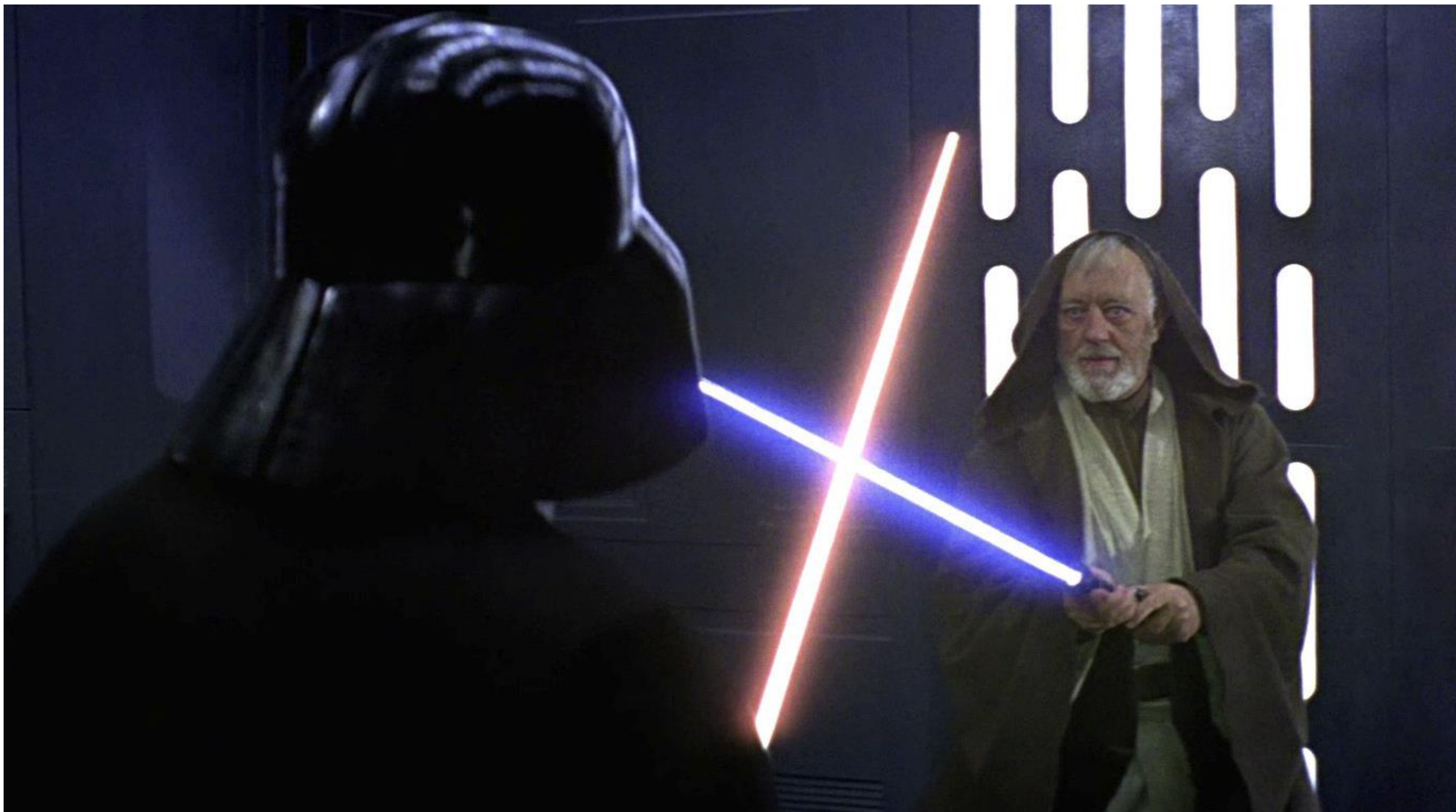
1 eV = 1.602×10^{-19} J





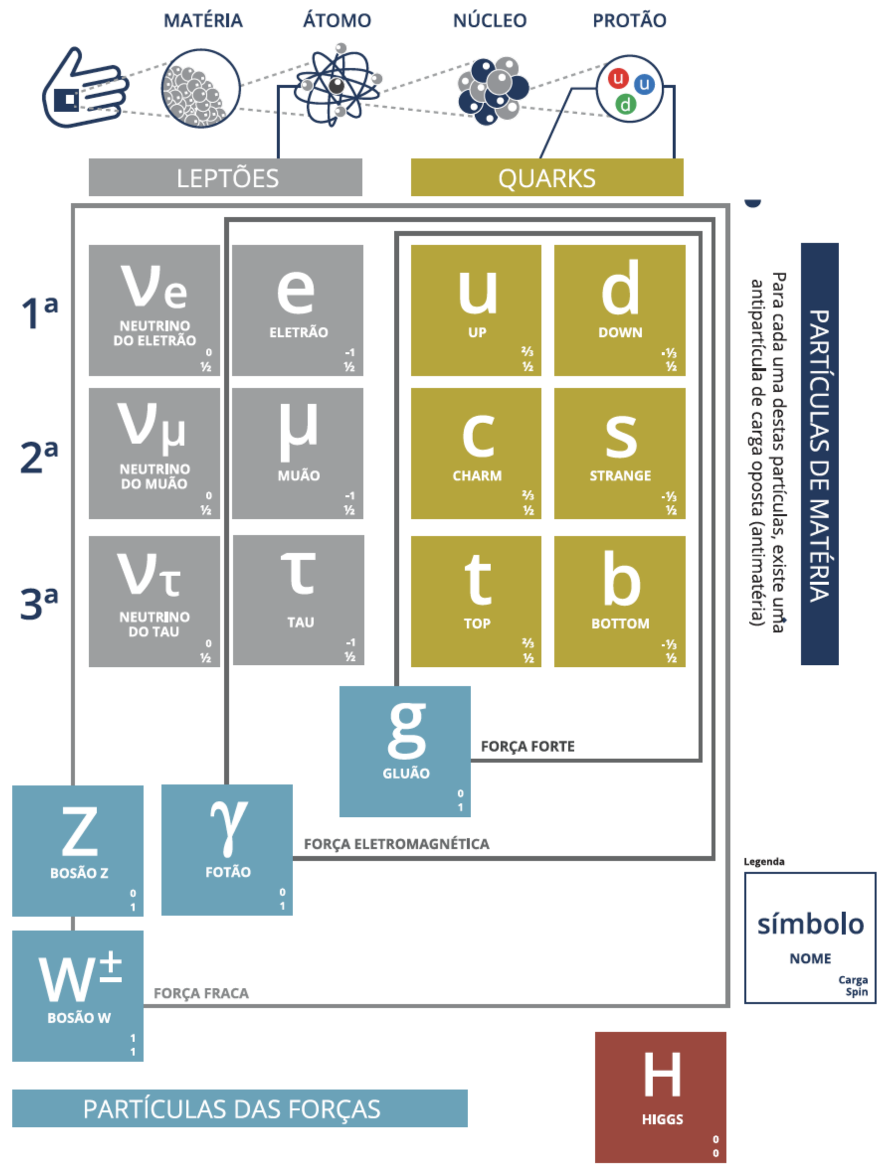
Plus antiparticles

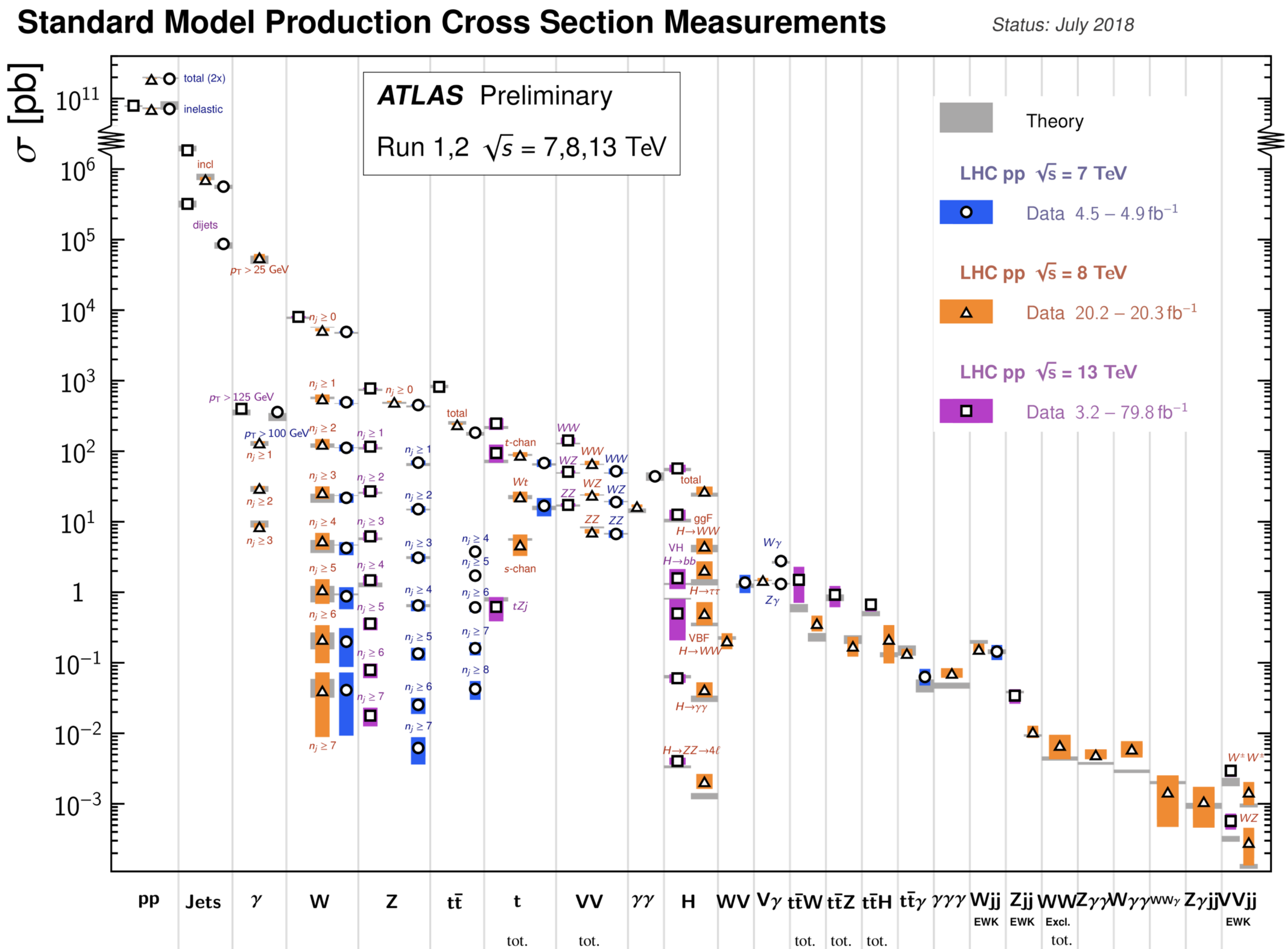
And the forces…

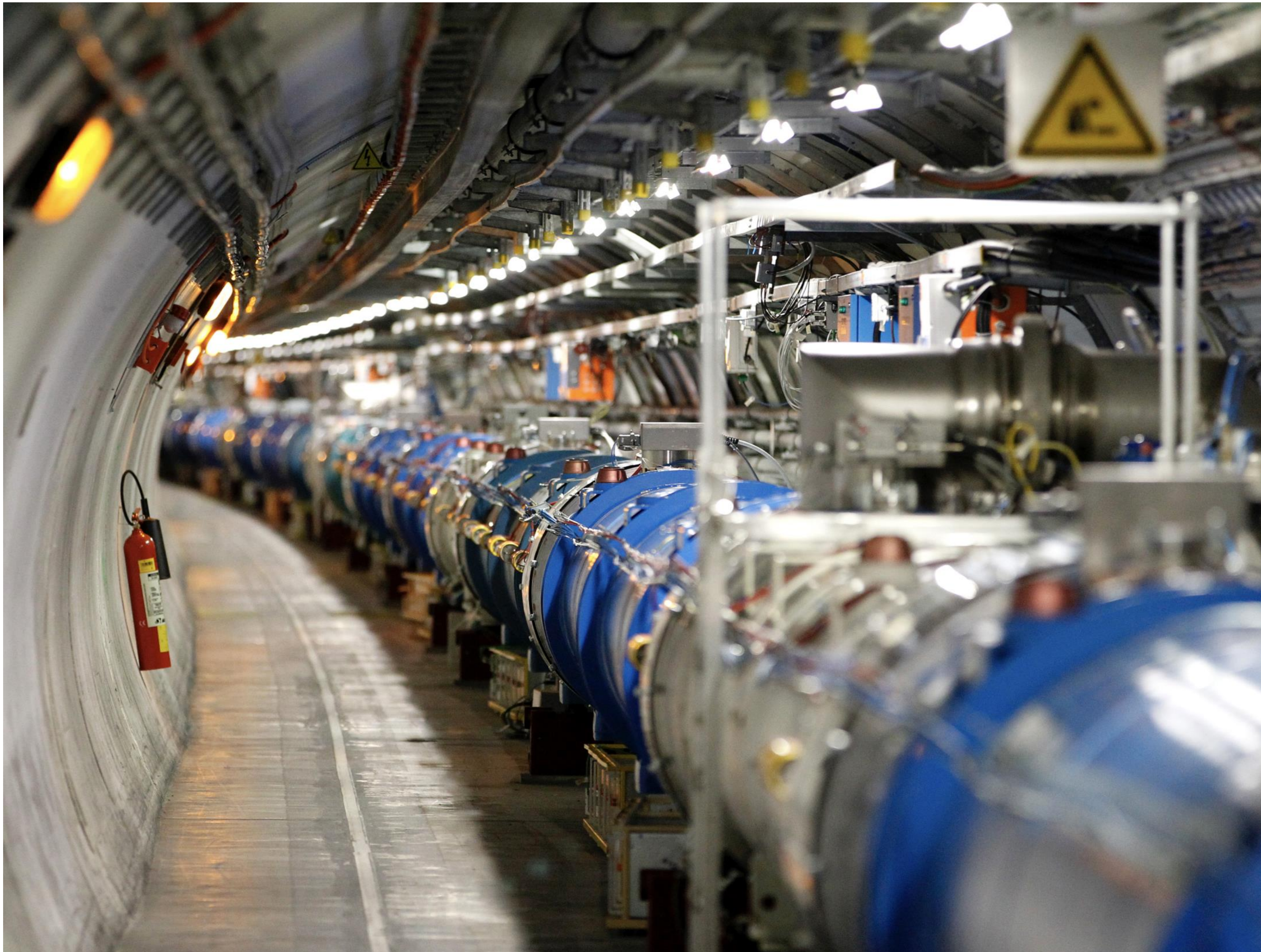


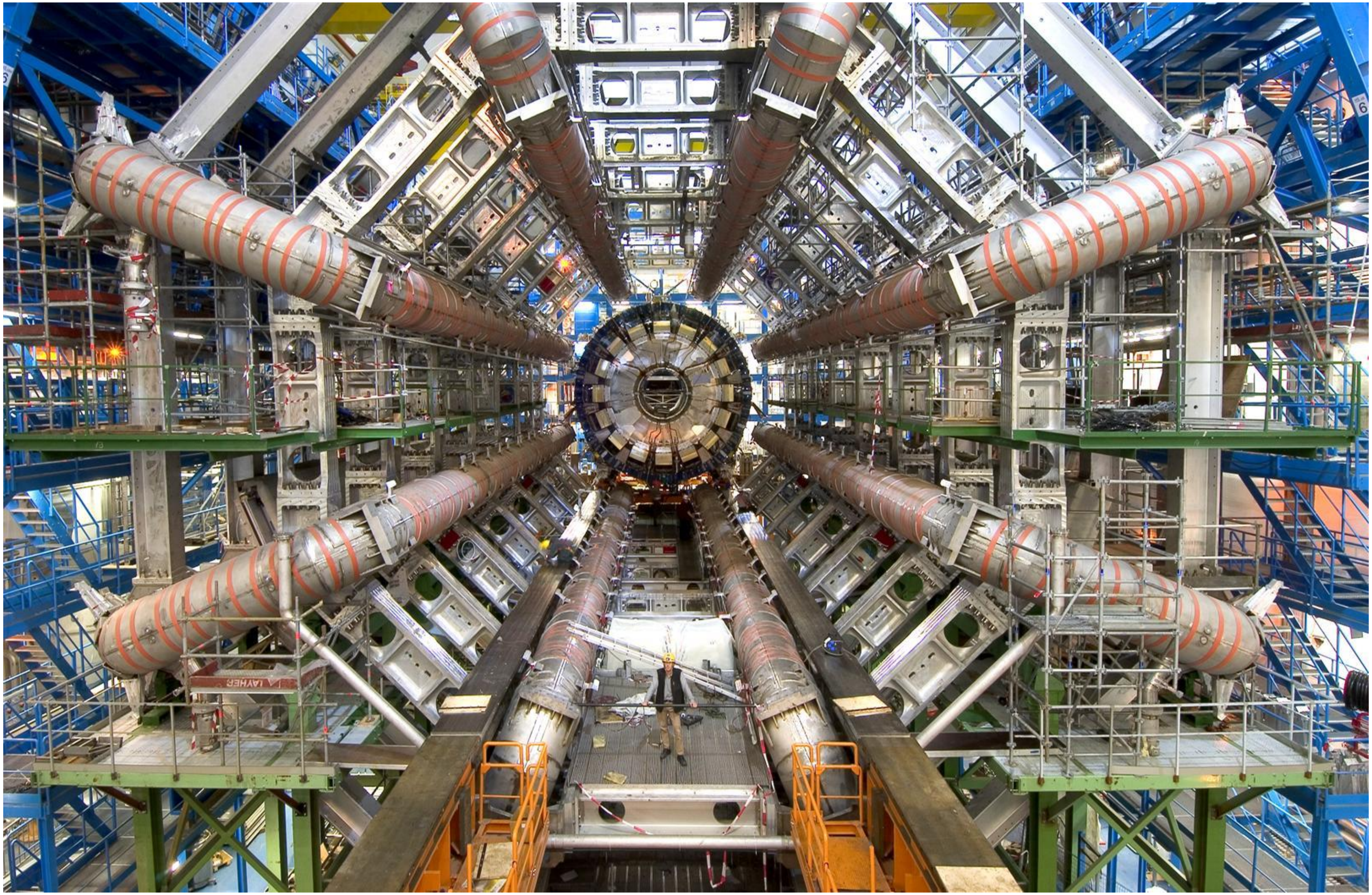
The Standard Model of Particle Physics

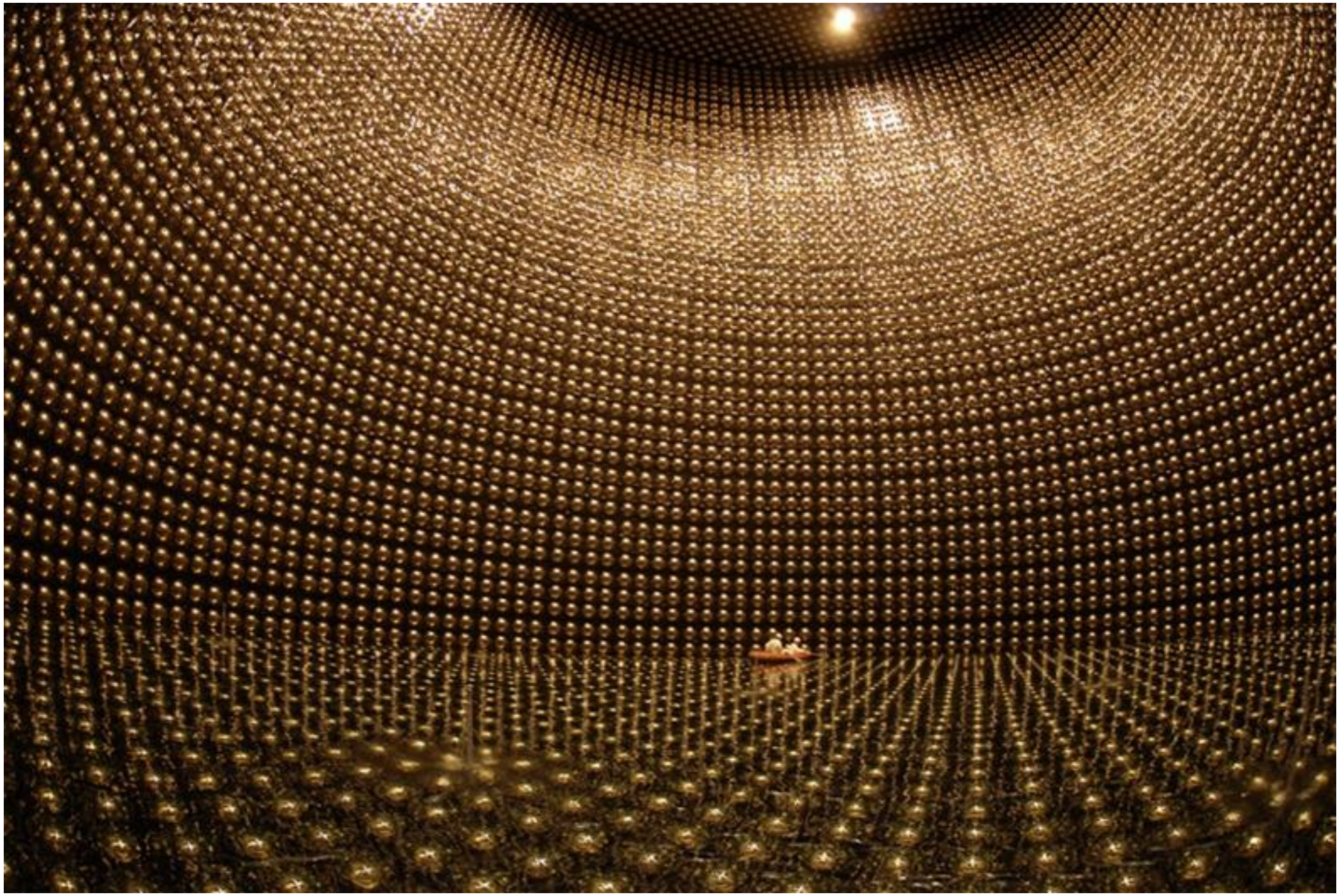
$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_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)) - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8} g^2 \alpha_h \left(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\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2} ig \left(W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \right) + \\
\tfrac{1}{2} g \left(W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H) \right) + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M \left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+ \right) - ig \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
\tfrac{1}{4} g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-\right) - \\
\tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2} ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \tfrac{1}{2} ig_s \lambda^a_{ij} (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda (\gamma\partial + m^\lambda_\nu) \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + \\
m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu \left(-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3} (\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3} (\bar{d}^\lambda_j \gamma^\mu d^\lambda_j) \right) + \\
\tfrac{ig}{4c_w} Z^0_\mu \{ (\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}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - 1 - \gamma^5) d^\lambda_j) + \\
(\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 + \gamma^5) u^\lambda_j) \} + \tfrac{ig}{2\sqrt{2}} W^+_\mu \left((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d^\kappa_j) \right) + \\
\tfrac{ig}{2\sqrt{2}} W^-_\mu \left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) u^\lambda_j) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_e (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1 + \gamma^5) e^\kappa \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_e (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa \right) - \tfrac{g}{2} \tfrac{m^\lambda_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
\tfrac{g}{2} \tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2} \tfrac{m^\lambda_\nu}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2} \tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1 - \gamma_5) \hat{\nu}_\kappa - \\
\tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1 - \gamma_5) \hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \gamma^5) u^\kappa_j \right) - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu + \\
\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{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) + igs_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^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} gM \left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H \right) + \tfrac{1-2c_w^2}{2c_w} igM \left(\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^- \right) + \\
\tfrac{1}{2c_w} igM \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + igMs_w \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + \\
\tfrac{1}{2} igM \left(\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0 \right) .
\end{gathered}
$$

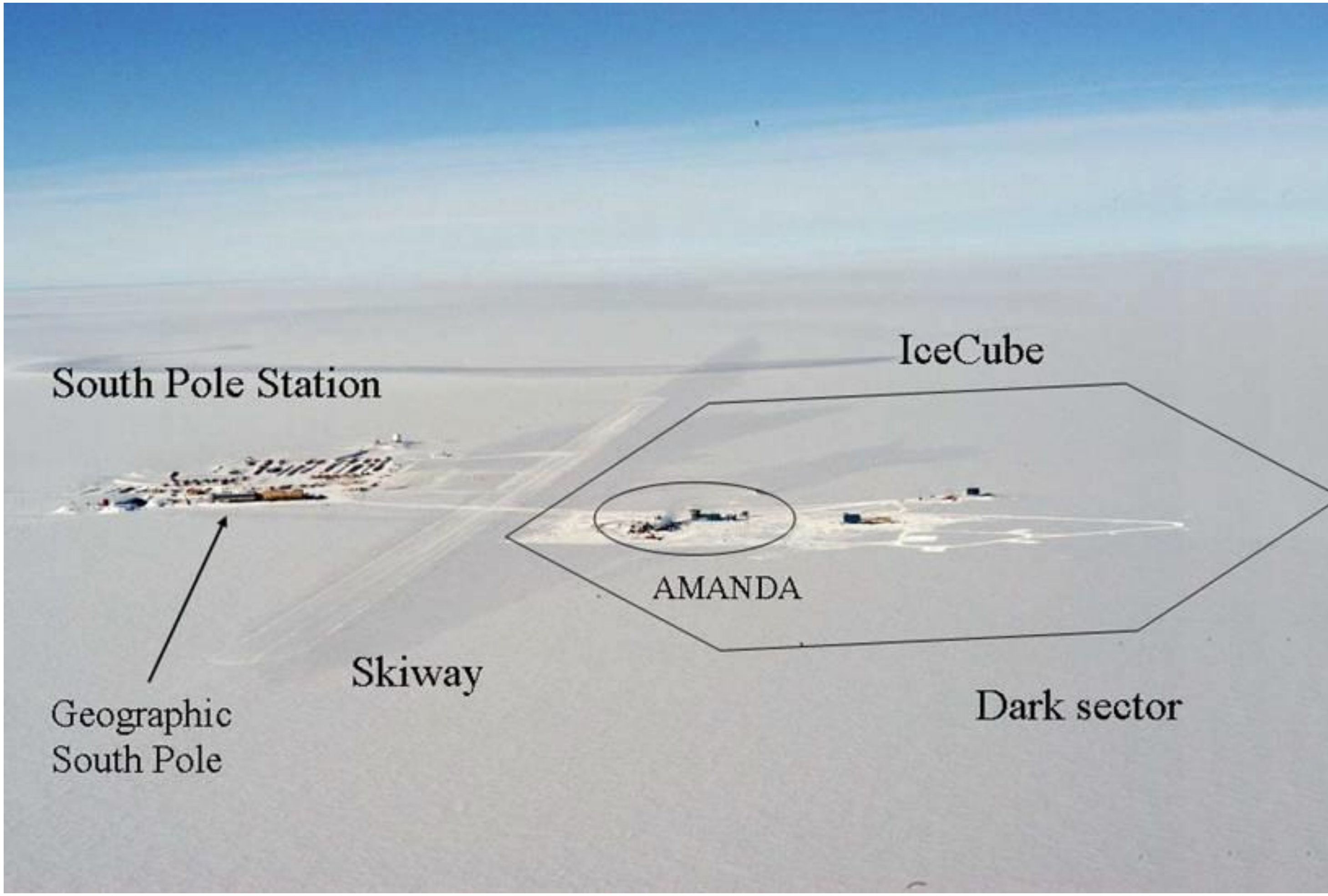



Standard Model Production Cross Section Measurements
Status: July 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
total (2x)
inelastic
incl
dijets
pT > 25 GeV
pT > 125 GeV
pT > 100 GeV
total
t-chan
Wt
s-chan
tZj
WW
WZ
ZZ
ggF
H→WW
VH
H→bb
H→ττ
VBF
H→γγ
H→ZZ→4ℓ
Wγ
Zγ
W±W±
WZ
pp
Jets
γ
W
Z
tt̄
t
VV
γγ
H
WV
Vγ
tt̄W
tt̄Z
tt̄H
tt̄γ
γγγ
Wjj
Zjj
WW
Zγγ
Wγγ
WWγ
Zγjj
VVjj
EWK
Excl.
tot.









South Pole Station
IceCube
AMANDA
Skiway
Geographic
South Pole
Dark sector


AMS

Back to school: Units

Standard Units

Grandeza física	SI	Factor de conversão	Unidades Standard
Comprimento	m	10^{15}	fm
Tempo	s	1	s
Massa	kg	$\frac{c^2}{1.602\times10^{-13}} = 5.609\times10^{29}$	MeV/c^2
Momento linear	kg ms^{-1}	$\frac{c^2}{1.602\times10^{-13}}\frac{1}{c} = 1.871\times10^{21}$	MeV/c Velocidade em unidades de c

Natural Units: $\hbar = c = 1$

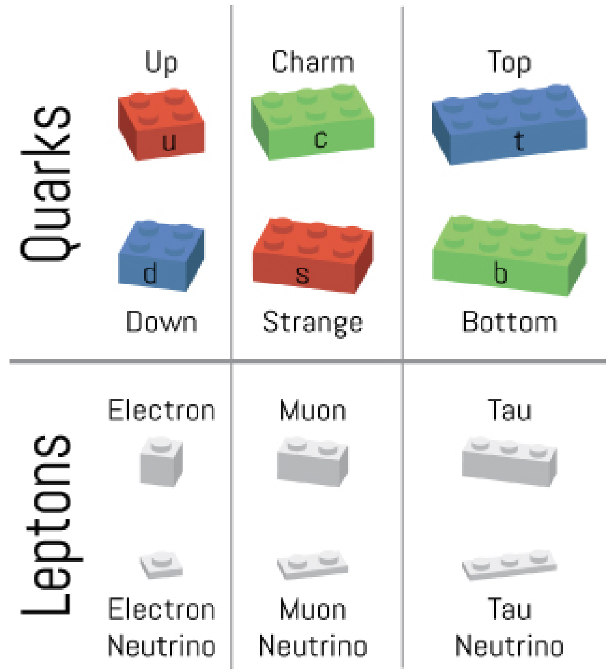
Grandeza física	SI	Factor de conversão	Unidades Naturais
Comprimento	m	$\frac{10^{15}}{\hbar c} = 5.068\times10^{12}$	MeV^{-1}
Tempo	s	$\frac{1}{\hbar} = 1.519\times10^{21}$	MeV^{-1}
Massa	kg	$\frac{c^2}{1.602\times10^{-13}} = 5.609\times10^{29}$	MeV
Momento linear	kg ms^{-1}	$\frac{c^2}{1.602\times10^{-13}}\frac{10^{15}}{\hbar c}\left(\frac{1}{\hbar}\right)^{-1} = 1.871\times10^{21}$	MeV Velocidade em unidades de *c*

Plus the electric charge: $\alpha = \sqrt{4\pi\epsilon_0}\frac{e}{\hbar c} = \frac{1}{137}$

Standard vs Natural Units

Grandeza física	Unidades Standard	Factor de conversão	Unidades Naturais
Comprimento	fm	$\frac{1}{\hbar c} = 5.068\times10^{-3}$	MeV^{-1}
Tempo	s	$\frac{1}{\hbar} = 1.519\times10^{21}$	MeV^{-1}
Massa	MeV/c^2	c^2	MeV
Momento linear	MeV/c Velocidade em unidades de *c*	c	MeV Velocidade em unidades de *c*

Particle Properties



Quarks, Leptons, Gauge bosons

particles

ν_e	ν_μ	ν_τ	no charge, no color
e^-	μ^-	τ^-	-1 charge, no color
u	c	t	+2/3 charge, color
d	s	b	-1/3 charge, color

antiparticles

ν_e	ν_μ	ν_τ	no charge, no color
e^+	μ^+	τ^+	+1 charge, no colo
$\bar{u}$	$\bar{c}$	$\bar{t}$	-2/3 charge, color
$\bar{d}$	$\bar{s}$	$\bar{b}$	+1/3 charge, color

Z W± Mediators of EM interaction

γ Mediator of EM interaction

g Mediator of strong interaction

H agent of spontaneous symmetry breaking

Gauge Bosons

- Spin 1; different charges
- Responsible for properties of interactions
- Massive vs massless bosons

Sector		Q	Colour charge	Mass	Width	J^P
EW	$W^{\pm}$	± 1	0	80.399(23) GeV	2.085(42) GeV	1
	Z^0	0	0	91.1876(21) GeV	2.4952(23) GeV	1
	γ	0	0	0	0 (stable)	1^-
Strong	g	0	$SU(3)_{colour}$ octet	0	0 (stable)	1^-

Leptons

- Unit charge, spin 1/2
- Feel electromagnetic and weak, but not strong force
- Lepton number L_e, L_μ, L_τ
  - Found to be conserved in all known interactions

State	Q	Mass	L_e	L_μ	L_τ	Lifetime
e^-	-1	$0.511\,\mathrm{MeV}$	$+1$	0	0	$> 4.6 \times 10^{26}$ years
ν_e	0	$< 2\,\mathrm{eV}$	$+1$	0	0	Stable
μ^-	-1	$105.7\,\mathrm{MeV}$	0	$+1$	0	$2.197034(21) \times 10^{-6}\,\mathrm{s}$
ν_μ	0	$< 0.19\,\mathrm{MeV}$	0	$+1$	0	Stable
τ^-	-1	$1776.82 \pm 0.16\,\mathrm{MeV}$	0	0	$+1$	$(290.6 \pm 1.0) \times 10^{-15}\,\mathrm{s}$
ν_τ	0	$< 18.2\,\mathrm{MeV}$	0	0	$+1$	Stable

π^+ DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$		[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$		[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$		[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$		[c]	$(7.39 \pm 0.05) \times 10^{-7}$		70
$e^+\nu_e\pi^0$			$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$			$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$			$< 5 \times 10^{-6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
$\mu^+\overline{\nu}_e$	*L*	[d]	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	*LF*	[d]	$< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	*LF*		$< 1.6 \times 10^{-6}$	90%	30

Particle Data Group: https://pdg.lbl.gov

Quarks

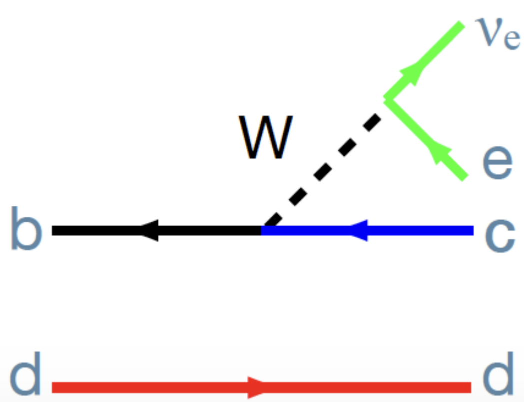
- Fractional electric charge, spin 1/2 (see later about Isospin)
- Always confined in hadrons: mesons (qq); baryons (qqq)
- Explain basic (static) structure of hadrons
- Colour quantum number:
  - 3 values: Red, Green, or Blue
  - Introduced to explain some baryon wavefunctions, for example of Δ^{++} (uuu)
  - Only colour-neutral particles are stable
  - Stable combinations are qqq and $q\bar{q}$
  - Gluons are bi-coloured:

	Q	Mass	I	I_z
d	$-\frac{1}{3}$	4.1–5.8 MeV	$+\frac{1}{2}$	$-\frac{1}{2}$
u	$+\frac{2}{3}$	1.7–3.3 MeV	$+\frac{1}{2}$	$+\frac{1}{2}$
s	$-\frac{1}{3}$	80–130 MeV	0	0
c	$+\frac{2}{3}$	1.18–1.34 GeV	0	0
b	$-\frac{1}{3}$	$4.19^{+0.18}_{-0.06}$ GeV	0	0
t	$+\frac{2}{3}$	172.0 ± 1.6 GeV	0	0

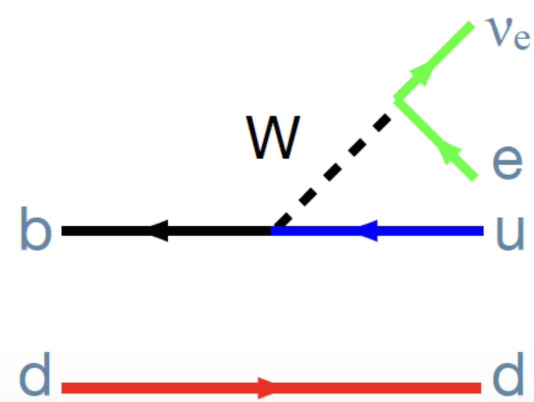
$$r\bar{b},\quad r\bar{g},\quad b\bar{g},\quad b\bar{r},\quad g\bar{r},\quad g\bar{b},\quad \frac{1}{\sqrt{2}}(r\bar{r}-b\bar{b}),\quad \frac{1}{\sqrt{6}}(r\bar{r}+b\bar{b}-2g\bar{g})$$

- In the laboratory, we never see "free quarks" but bound systems:
  - "mesons": quark and antiquark pair
  - "baryons": three quarks bound together
    - "antibaryons": three antiquarks bound together
  - Collectively they are called "hadrons"
- To understand the underlying mechanism for a process involving hadrons, consider the constituent quarks (look it up, no need to memorize)
  - D^{*-} = bound state of anti-c quark and d quark
  - ρ^{-} = bound state of anti-u quark and d quark

$$B^0 \rightarrow D^{*-} + e^+ + \nu_e$$



$$B^0 \rightarrow \rho^- + e^+ + \nu_e$$



≈140 known mesons
≈65 baryons plus resonances
59 hadrons found at the LHC until 2021

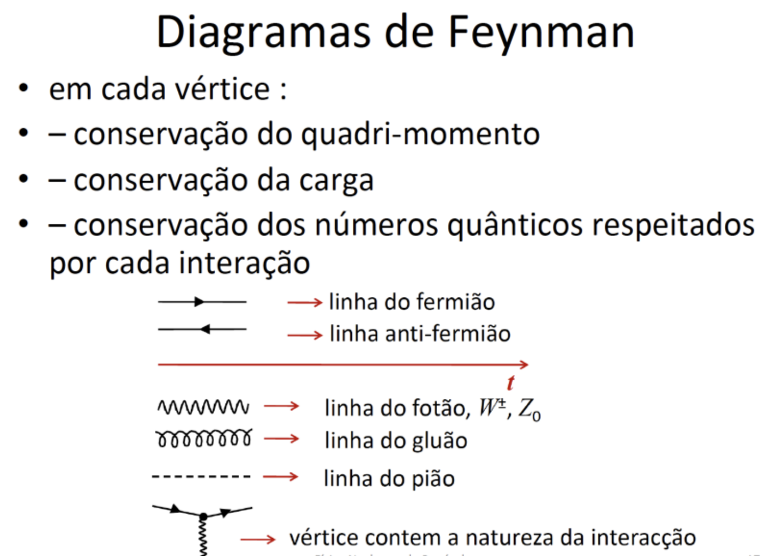
Name		Mass (MeV/c^2)	Lifetime (s)	Spin $\mathcal{J}^{\mathcal{P}}$ [$\hbar$]	Charge Q/e	Isospin $\mathcal{I}$	Strangeness $\mathcal{S}$
QUARKS:							
"up"	u	411?	∞?	$\frac{1}{2}$	$+\frac{2}{3}$	$\frac{1}{2}$	0
"down"	d	411?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{2}$	0
"strange"	s	558?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	0	-1
MESONS:							
pion	π	139	$\pi^\pm$: 2.6×10^{-8} π^0 : 8.3×10^{-17}	0^-	$-1, 0, +1$	1	0
kaon	K	495	$K^\pm$: 1.2×10^{-8} K^0 : ambiguous	0^-	$-1, 0, +1$	$\frac{1}{2}$	K^0, K^+ : $+1$ $\bar{K}^0, K^-$: -1
eta	η	549	8.9×10^{-15}	0^-	0	0	0
rho	ρ	770	4.3×10^{-24}	1^-	$-1, 0, +1$	1	0
omega	ω	783	6.58×10^{-23}	1^-	0	0	0
phi	ϕ	1020	1.6×10^{-22}	0^-	0	0	0
	K^*	892	1.33×10^{-23}	1^-	$-1, 0, +1$	$\frac{1}{2}$	K^{*0}, K^{*+} : $+1$ $\bar{K}^{*0}, K^{*-}$: -1
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
BARYONS:							
nucleon	N	938	proton (p) : ∞ neutron (n) : 920	$\frac{1}{2}^+$	$0, +1$	$\frac{1}{2}$	0
lambda	Λ	1116	2.6×10^{-10}	$\frac{1}{2}^+$	0	0	-1
sigma	Σ	1190	$\Sigma^\pm$: $\approx 10^{-10}$ Σ^0 : $< 10^{-14}$	$\frac{1}{2}^+$	$-1, 0, +1$	1	-1
cascade	Ξ	1320	$\approx 2 \times 10^{-10}$	$\frac{1}{2}^+$	$-1, 0$	$\frac{1}{2}$	-2
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
delta	Δ	1232	5×10^{-24}	$\frac{3}{2}^+$	$-1, 0, +1, +2$	$\frac{3}{2}$	0
	Σ^*	1383	1.6×10^{-23}	$\frac{3}{2}^+$	$-1, 0, +1$	1	-1
	Ξ^*	1530	6.6×10^{-23}	$\frac{3}{2}^+$	$-1, 0$	$\frac{1}{2}$	-2
Omega	Ω	1672	1.3×10^{-10}	$\frac{3}{2}^+$	-1	0	-3
	⋮	⋮	⋮	⋮	⋮	⋮	⋮

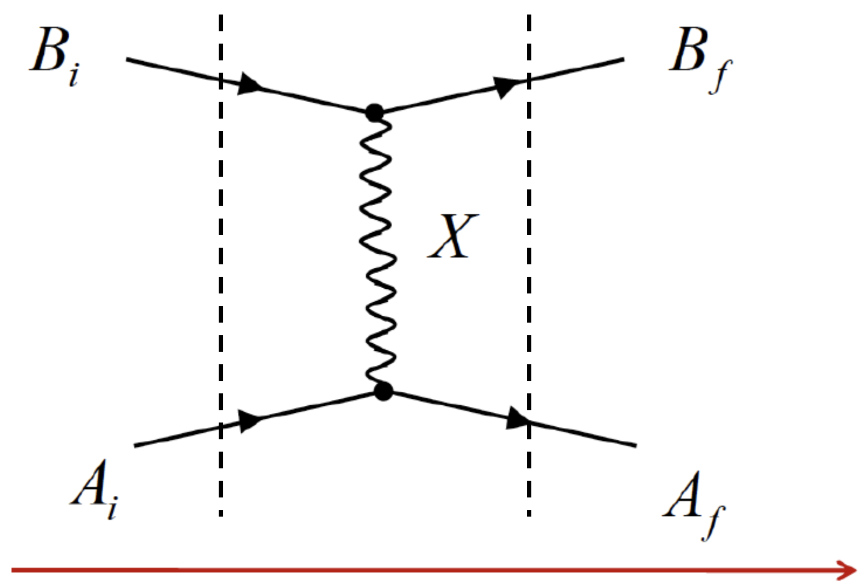
Feynman Diagrams

Intreractions

- Interaction between two particles A and B interpreted as exchange of mediating particle X
- Left hand side: initial state
- Right hand side: final state
- Middle: how transition happened
- Time runs from left to right(*)

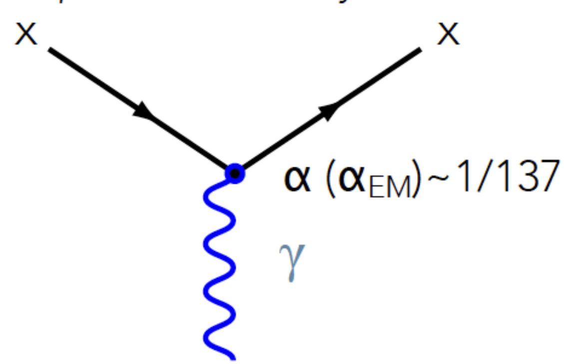
(*) But only in the sense that "before" is initial state and "after" is final state





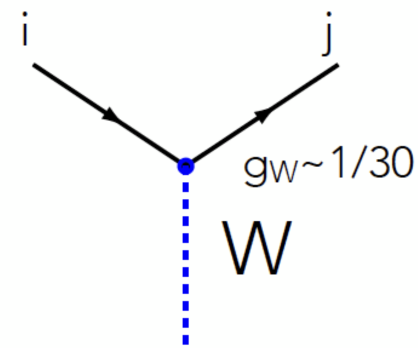
- Fundamental building block of an interaction is the "vertex"

electromagnetism
"quantum electrodynamics"



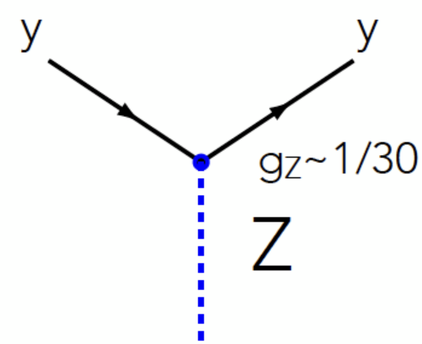
x is any charged particle

weak charged current



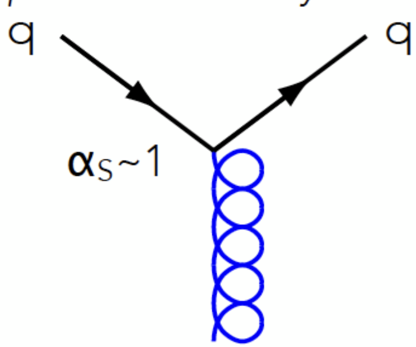
i:+2/3 quark, j: -1/3 quark
or
i: ν_l, j: l^-

weak neutral current



y is quark or lepton

strong interaction
"quantum chromodynamics"

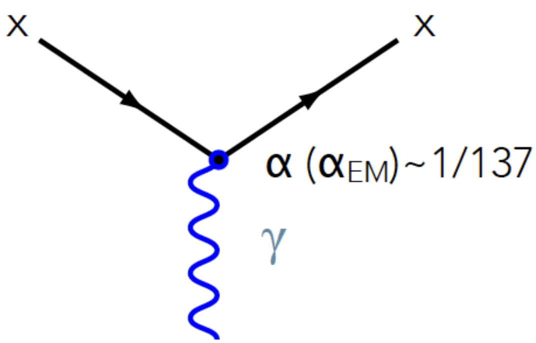


q is any quark (colored object)

- Some "laws" are automatically built into the diagrams
- Conservation of electric charge
- Conservation of lepton number
  - "e", "μ" "τ"
- Baryon number
  - number of quarks

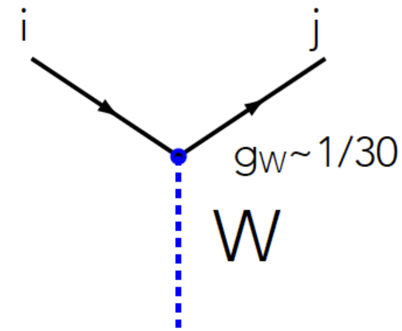
- Fundamental building block of an interaction is the “vertex”

electromagnetism
“quantum electrodynamics”



x is any charged particle

weak charged current



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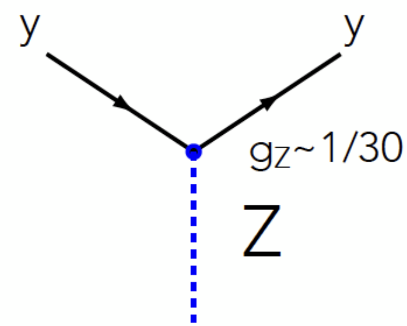
weak neutral current



y is quark or lepton

strong interaction
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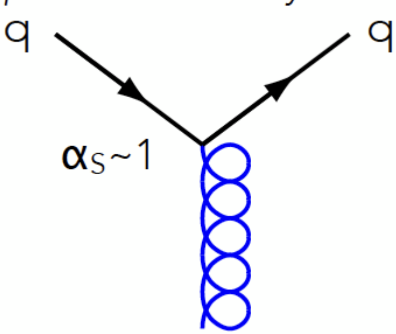
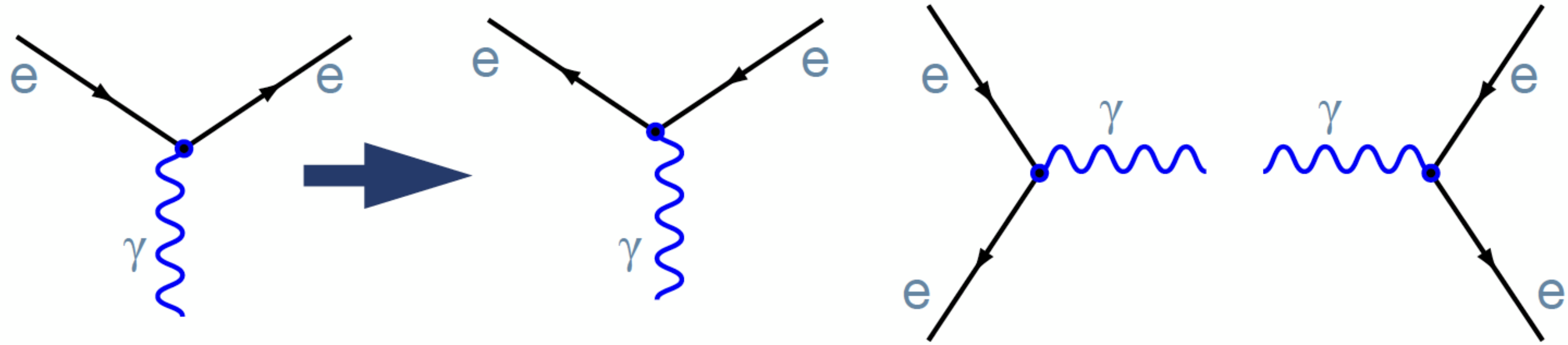
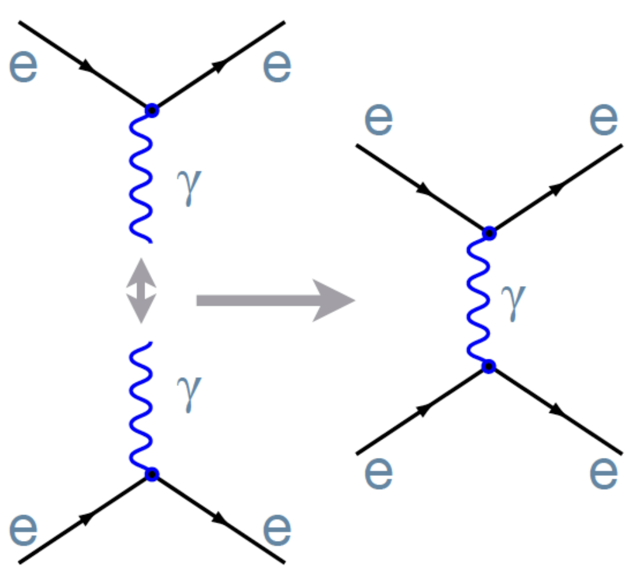


q is any quark (colored object)

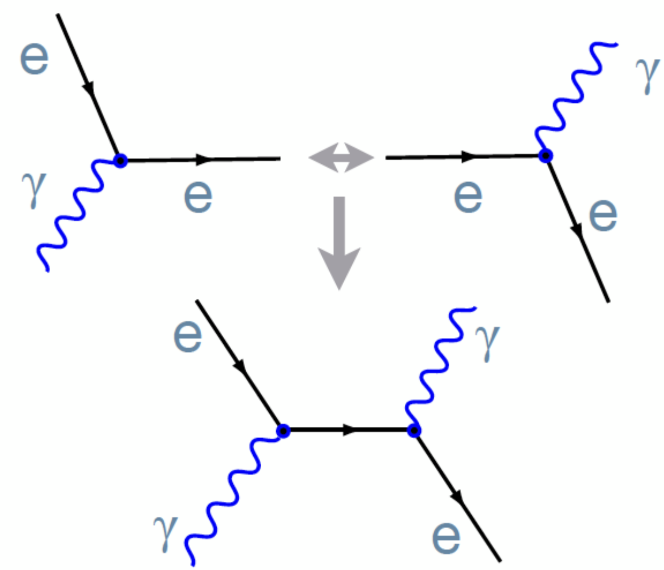
- arrows: direction matters!
  - backward arrow means “antiparticle” (opposite charges)
  - don’t mix up arrow and label
- same letter means same particle
- vertex factor “coupling constant”
  - not part of diagram but indicates “strength” of interaction

- Vertices can be rotated and connected by common particles (“propagator”)

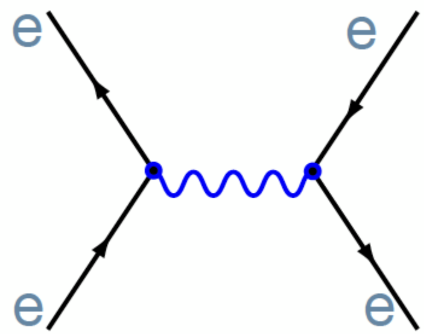


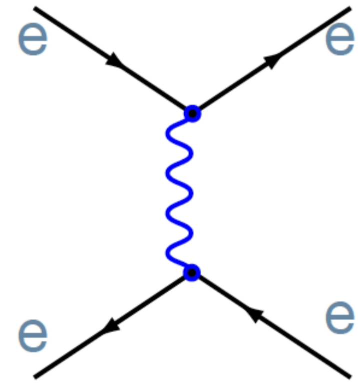


$$e^- + e^- \to e^- + e^-$$

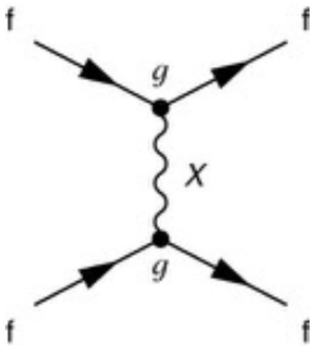


$$e^- + \gamma \to e^- + \gamma$$





- In fact, any allowed process has an infinite number of possible diagrams
- The coupling constant:
  - diagrams with more vertices have vertex factors
  - if this is small, diagrams with more vertices contribute less
  - we do calculation at “order N” where N is the number of vertices.
    - must consider all diagrams of “order N”
    - if we want more precise calculation we go to higher order



Cross-section calculation from diagrams:

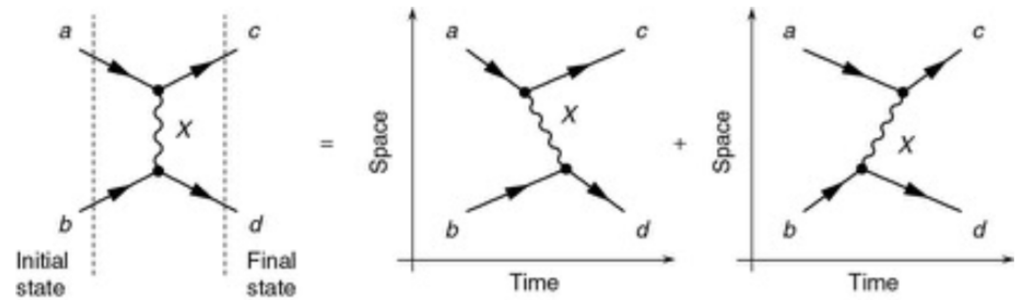
from probabilities, and in turn,from quantum mechanical transition matrix elements.

these contain one g factor for each vertex.

$$\mathcal{M} \propto g^2 \sim \alpha \qquad |\mathcal{M}|^2 \propto g^4 \sim \alpha^2$$

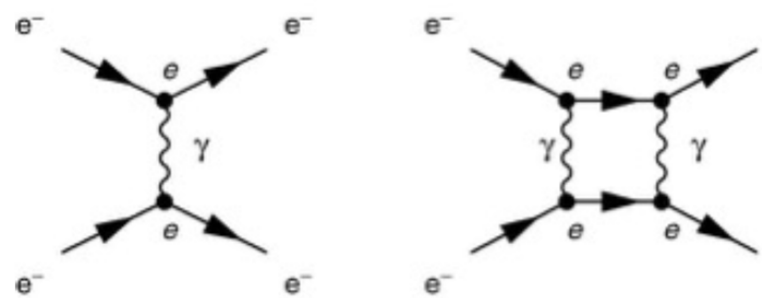
Time-ordering is left - to -right.

But due to the uncertainty principle, we cannot know all about the "virtual" particle being exchanged. A vertical line represent all possible time-orderings.



An infinite number of diagrams is possible for the same initial and final state.

classified according to the number of vertices



$$|\mathcal{M}_\gamma|^2 \propto \alpha^2 >> |\mathcal{M}_{\gamma\gamma}|^2 \propto \alpha^4$$