Nature is so extra!

An Introduction to the Standard Model of Particle Physics
Lecture I: An overview

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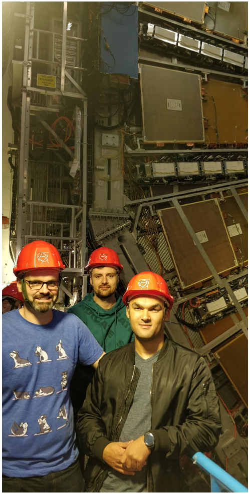
African School of Physics 2022

many diagrams from *Modern Particle Physics* by M. Thomson

Particle Physics in South Africa

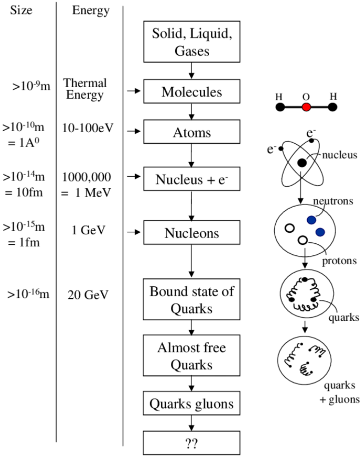


Major involvement in ATLAS & ALICE experiments via **SA-CERN**

Particle Physics as *Reductionism*

- **Methodological reductionism**: the scientific attempt to provide explanation in terms of ever smaller entities.

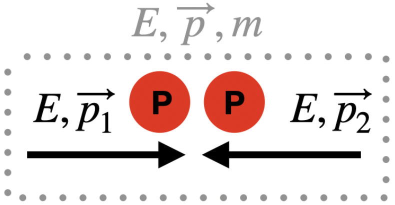
- Particle physics represents (for now) the culmination of the reductionist approach to understanding the universe



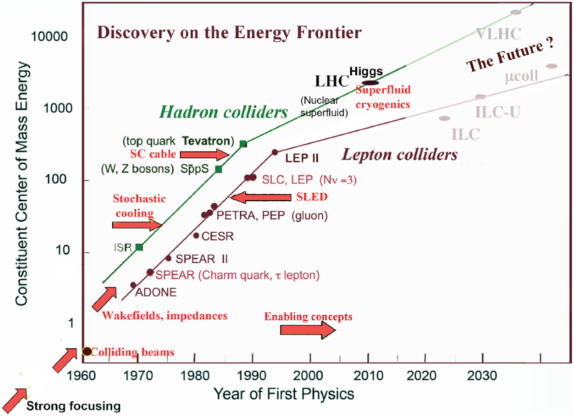
R.Godbole, *The Heart of Matter*, 2010

Physics at the end of the (experimental) road

- Following the reductionist approach means experimentally probing smaller and smaller distance scales ℓ
- From QM we know $\ell = \hbar c / E$
- Smaller distance scales means larger energy scales! $\ell \downarrow \equiv E \uparrow$
- **Colliding particles at the highest-ever energies allows us to probe nature at the smallest-ever distance scales**

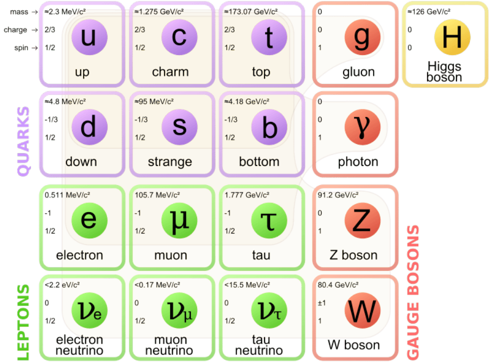


Colliders as microscopes



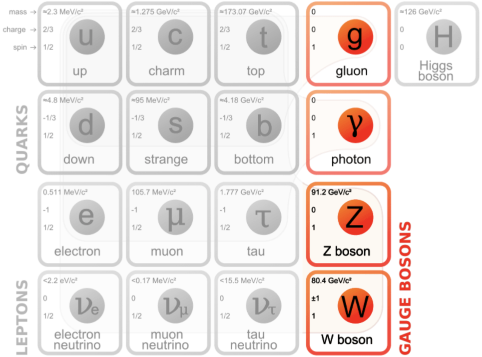
- LHC has been colliding protons at 13 TeV since 2015

So what do we know?



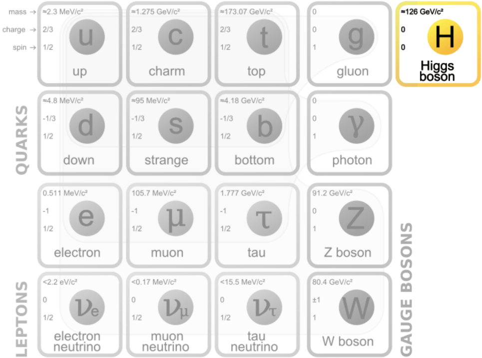
- The Elementary Particles

So what do we know?



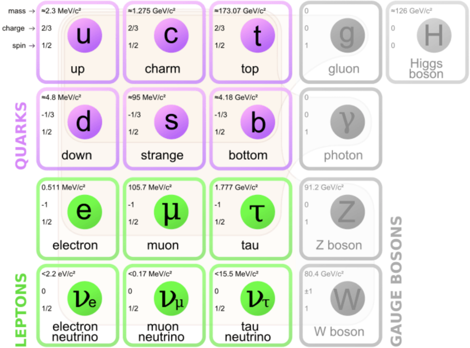
- Gauge Bosons

So what do we know?



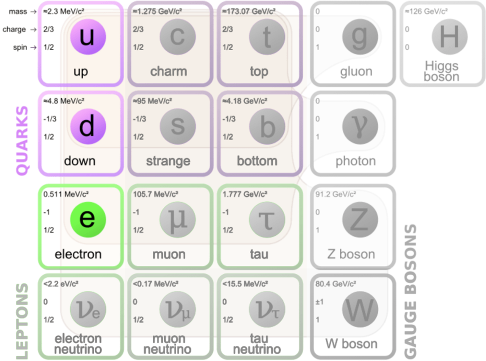
- Higgs Bosons

So what do we know?



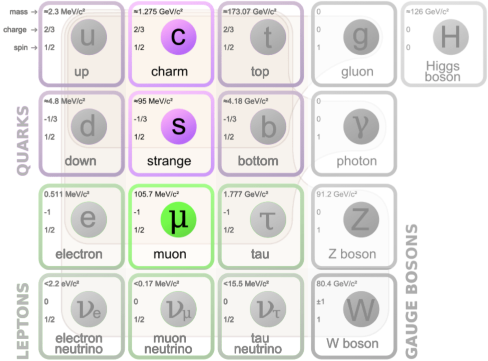
- Fermions

So what do we know?



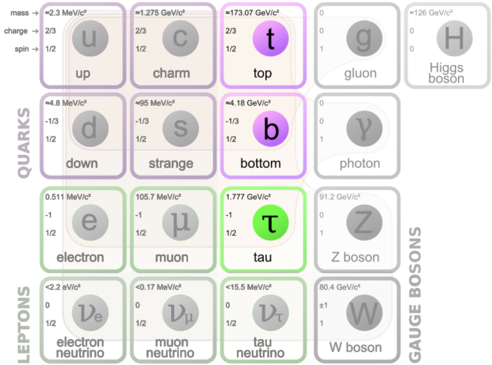
- First Generation: enough for *everyday* matter

So what do we know?



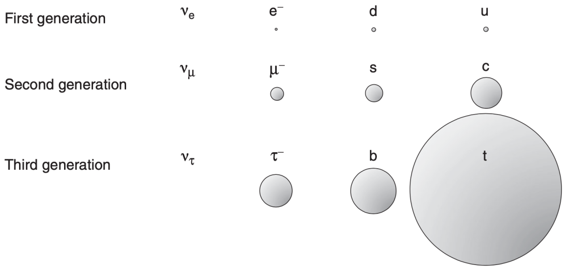
- Second Generation: not strictly needed

So what do we know?



- Third Generation: not strictly needed

So what do we know? masses

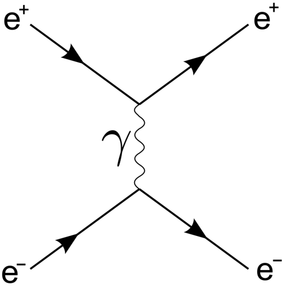


fundamental particles drawn as spheres with $V \propto m$

- Why are there three *generations*?🤨
- Why the random masses if these are fundamental? 🤔
- $m_{top} \approx m_{Au\ atom}$!! 🤯
- **Nature is so extra...**

So what do we know? forces through boson *exchange*

- fundamental particles *interact*: scatter, decay, annihilate...

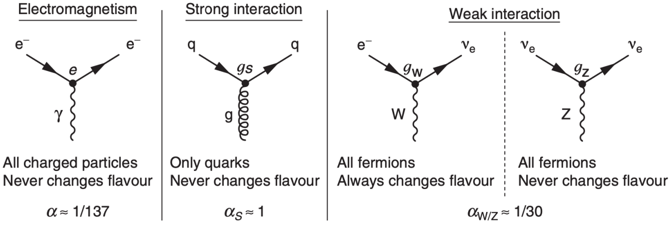


Feynman diagram for Bhabha scattering ($e^+e^- \to e^+e^-$)

- basic interactions (EM, weak, strong) understood as due to boson exchange (γ, $W^{\pm}$ or Z, g)

What interacts with what

- the nature of each force is determined by the properties of the boson that mediates it



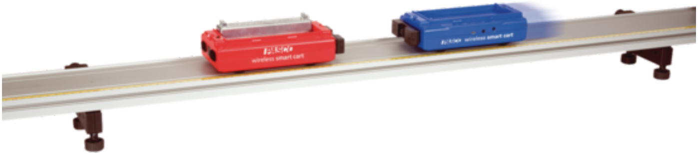
basic interaction vertices for each fundamental forces and fermions

- no explanation of gravity in the Standard Model! 🧐

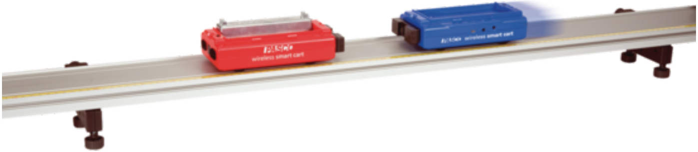
Interactions and conservation laws

- Particle interactions obey certain **conservation laws:**
- Always conserved:
  - energy, momentum
  - electric, color charge
  - lepton number
  - Baryon number? $B = \frac{1}{3}(n_\mathrm{q} - n_{\bar{\mathrm{q}}})$, can a proton decay?
  - more...
- Sometimes conserved:
  - parity (P)
  - lepton/quark flavour numbers: e.g. $L_\tau = N_\tau - N_{\bar{\tau}}$
  - many more...
- **Noether's theorem:** for theories described by a Lagrangian:
  - **conservation law** $\longleftrightarrow$ **symmetry**
- requiring symmetries defines much of the Standard Model

Conservation...that sounds familiar



Conservation...that sounds familiar



- conservation of linear momentum is associated with a symmetry under spatial transformations

From Electromagnetism to QED

- Recall something interesting from Electromagnetism:
- The physical $\vec{E}$ and $\vec{B}$ fields are derived from underlying *scalar* and *vector potentials* ϕ and $\vec{A}$. $A_\mu = (\phi, -\vec{A})$

$$\vec{E} = -\nabla\phi - \frac{\partial\vec{A}}{\partial t}, \vec{B} = \nabla \times \vec{A}$$

Apply a *gauge* transformations to ϕ and $\vec{A}$

$$\phi \to \phi' = \phi - \frac{\partial\chi}{\partial t}, \vec{A} \to \vec{A}' = \vec{A} + \nabla\chi$$

where $A_\mu = (\phi, -\vec{A})$ and $\partial_\mu = (\partial_0, \nabla)$

- $\vec{E}$ and $\vec{B}$ are unchanged and Maxwell's equations still apply
- We call this a *Gauge Symmetry*

Quantum Electrodynamics (QED)

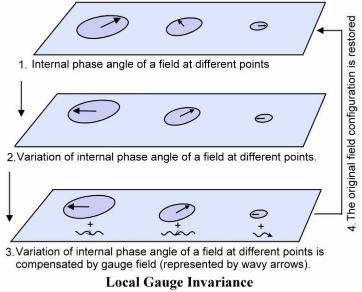
Ignoring interactions, fermions governed by the **free-particle** Dirac equation:

$$i\gamma^{\mu}\partial_{\mu}\psi = m\psi$$

imagine changing the phase of ψ according to some function $\chi(x)$ ($\chi(x)$ is a function of position)

$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi(x)}\psi(x)$$

Does the free-particle Dirac equation still apply?



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Quantum Electrodynamics (QED)

Does the free-particle Dirac equation still apply?

Add a new field A_μ. Dirac equation is now

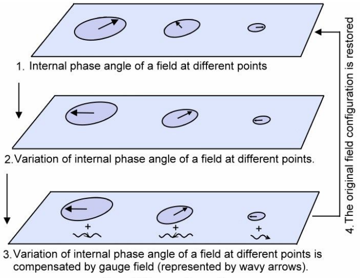
$$i\gamma^\mu(\partial_\mu + iqA_\mu)\psi = m\psi$$

the local phase invariance is restored as long as:

$$A_\mu \rightarrow A'_\mu = A_\mu - \partial_\mu \chi$$

We had to add a field A_μ that transforms exactly as the classical EM 4-potential to ensure local phase invariance

We interpret A_μ as the photon field!



Local Gauge Invariance

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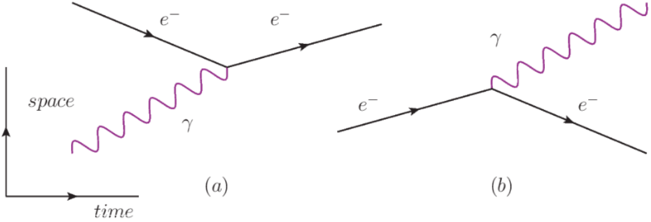
Quantum Electrodynamics (QED)

- There is now a term in the Dirac equation

$$q\gamma^\mu A_\mu \psi$$

- It ***couples*** the fermion field ψ to the photon field A_μ



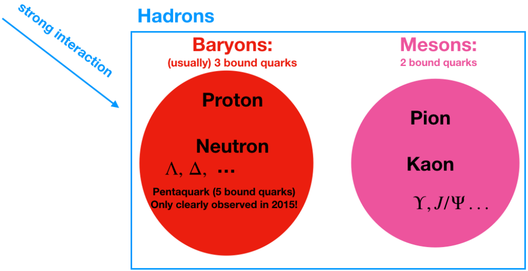
- All of QED (including Maxwell's equations) can be derived from requiring invariance of physics under transformations of the form $\hat{U} = e^{iq\chi(x)}$.

QCD - the theory of the strong interaction

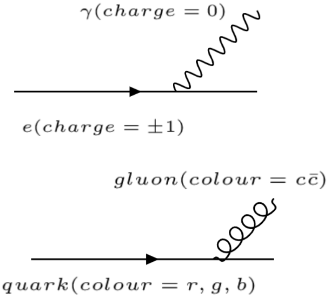
- in the 50 & 60s a spectra of hadronic particles was observed
- the *quark model* was developed to explain these particles as bound states of point-like (fundamental?) quarks
- strong interaction binds quarks to form *hadrons*

6 quark *flavours*

Up	**Charm**	**Top**
Down	**Strange**	**Bottom**



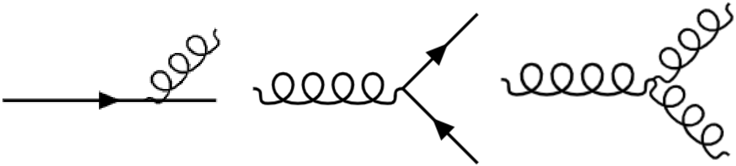
The 8 gluons



- Contrary to QED, the gluon carries the charge (colour) that it couples to
- Quarks or anti-quarks carry one of the colours r, g, b and $\bar{r}, \bar{g}, \bar{b}$ respectively
- Gluons carry the colour of a quark-antiquark pair, $r\bar{g}$, or $b\bar{r}$

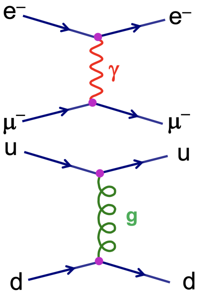
Colour interactions

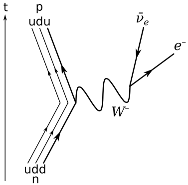
- Basic Feynman diagrams of QCD
  1. emission/absorbtion of a gluon by a quark
  2. gluon *splits* into $q\bar{q}$
  3. gluon *self-interactions*



QCD vs QED vs Weak Interactions

- Superficially QCD and QED are similar
  - both mediated by massless, neutral spin-1 bosons
  - interacting current have the form $\bar{u}(p')\gamma^{\mu}u(p)$
  - always conserve parity
- Charged weak interactions are very different
  - mediated by massive, charged, spin-1, $W^{\pm}$ bosons
  - couples fermions that differ by one unit of electric charge
  - **do not conserve parity**

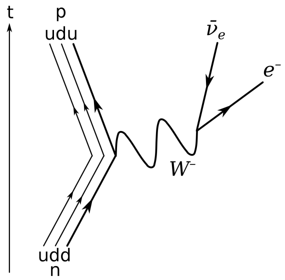




Charged Weak Interactions & Parity

1950s parity violation observed in β decays mirror image of interaction occur at different rates theoretically explained by replacing vector currents of QED/QCD with **Vector - Axial Vector structure**

$$\bar{u}(p')\gamma^{\mu}u(p) \rightarrow \bar{u}\gamma^{\mu}(1-\gamma^5)u$$



- $W^{\pm}$ couples to **left-handed particles** and **right-handed anti-particles** only
- *Weakness* of interaction due to heavy $W^{\pm}$ boson

Mass terms

- Mass: the energy associated with 0 momentum
  - $E^2 = (pc)^2 + \left(mc^2\right)^2$
- fermion mass term appears in the Lagrangian multiplied by the field squared: $m\bar{\psi}\psi$
- Why not just insert a mass term for massive particles, e.g, the electron
- Let's try that out in the QED Lagrangian:

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

- However, $\mathcal{L}$ must be invariant under SU(2) for consistency with the weak theory
- Naive mass term, e.g, $m\bar{\psi}\psi$ not invariant under SU(2)*

*simple explanation in backup

The Brout-Englert-Higgs mechanism

- **Introduce a new complex scalar field (ϕ) in order to recover the gauge invariance of $m\bar{\psi}\psi$**
- The new field is a *doublet* under SU(2)

$$\phi \to \phi' = (I + ig_W \epsilon(x) \cdot T)\phi$$

- The same transformation will affect the left-handed doublet of fermion fields L

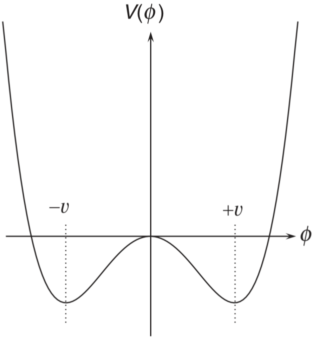
$$\bar{L} \to \bar{L}' = \bar{L}(I - ig_W \epsilon(x) \cdot T)$$

- The combination $\bar{L}\phi$ is invariant under $SU(2)$ transformations
- If we add the right-handed singlet, to give $\bar{L}\phi R$ the combination is invariant

Spontaneous symmetry breaking

- A scalar field that couples to fermions generates a fermion mass term if it has a non-zero vacuum expectation value
- But how does it get this non-zero vacuum expectation value?
- Suppose this new scalar field has a potential of the form

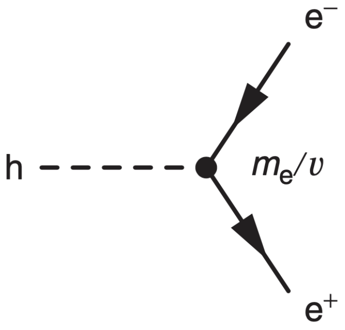
$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$



- If $\lambda > 0$ and $\mu^2 > 0$ the potential looks like this
- After SSB, we end up with a Lagrangian $\mathcal{L}_e = -m_e\bar{e}e + \frac{m_e}{\nu}\bar{e}eh$

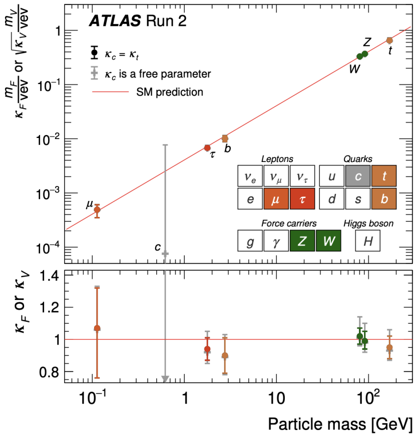
The Higgs boson, experimentally

- After SSB, we can end up with a Lagrangian $\mathcal{L}_e = -m_e\bar{e}e + \frac{m_e}{\nu}\bar{e}eh$
- What should we look for?
- A coupling between the Higgs and fermions that depends on the fermion mass!

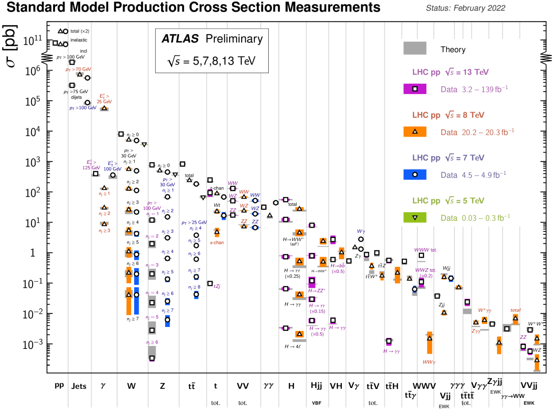


The Higgs boson, experimentally

- So what do we find in the data?
- ATLAS & CMS have measured couplings of the Higgs boson to numerous SM particles
- measured coupling vs particle mass agrees very well with SM prediction! 😎



The Standard Model Stairway



- Nature **is** so extra!
- But the Standard Model is too...

Backup slides

Fermion mass and SU(2)

- the mass term can be written as

$$
\begin{aligned}
-m_e\bar{\psi}\psi &= -m_e\bar{\psi}\Big[\frac{1}{2}(1-\gamma^5)+\frac{1}{2}(1+\gamma^5)\Big]\psi \\
&= -m_e\bar{\psi}\Big[\frac{1}{2}(1-\gamma^5)\psi_L+\frac{1}{2}(1+\gamma^5)\psi_R\Big] \\
&= -m_e\big[\bar{\psi_R}\psi_L+\bar{\psi_L}\psi_R\big]
\end{aligned}
$$

- ψ_L states transform under SU(2), ψ_R states don't
- The mass term is not invariant under SU(2).
- Our Lagrangian doesn't permit massive fermions under SU(2)!
- Similar problems for gauge boson masses