Tools for High Energies:
Fields, Symmetries and Dualities

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CU' talk
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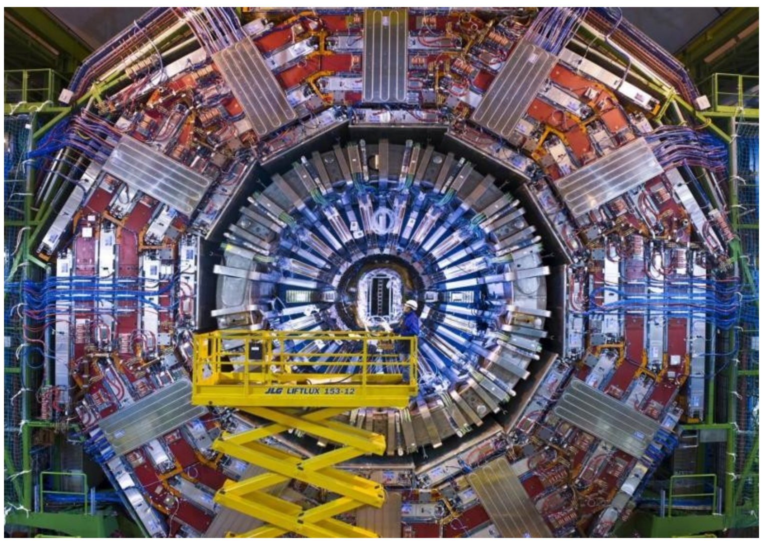
Elementary particle physics



– or –

High energy physics

(Sounds way cooler, and more accurate!)

What is an electron?

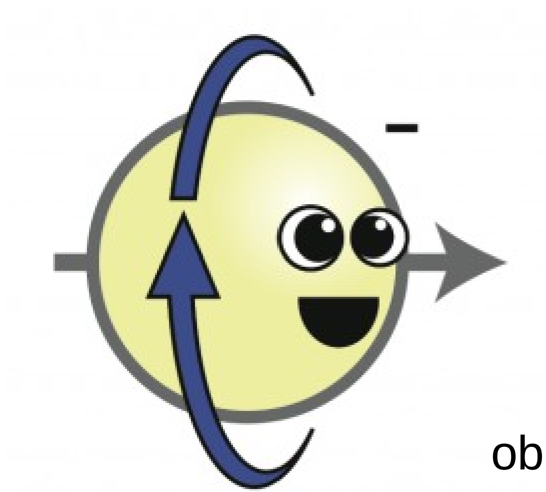
(Why are all electrons the same?)

What is an electron?

mass = 9.109x10^-31 kg

A point particle

charge = -1 e = -1.602x10^-19 C



obeys the Pauli exclusion principle

“intrinsic” angular momentum

Image cred: Flip Tanedo
quantumdiaries.org

The Standard Model – what we know!

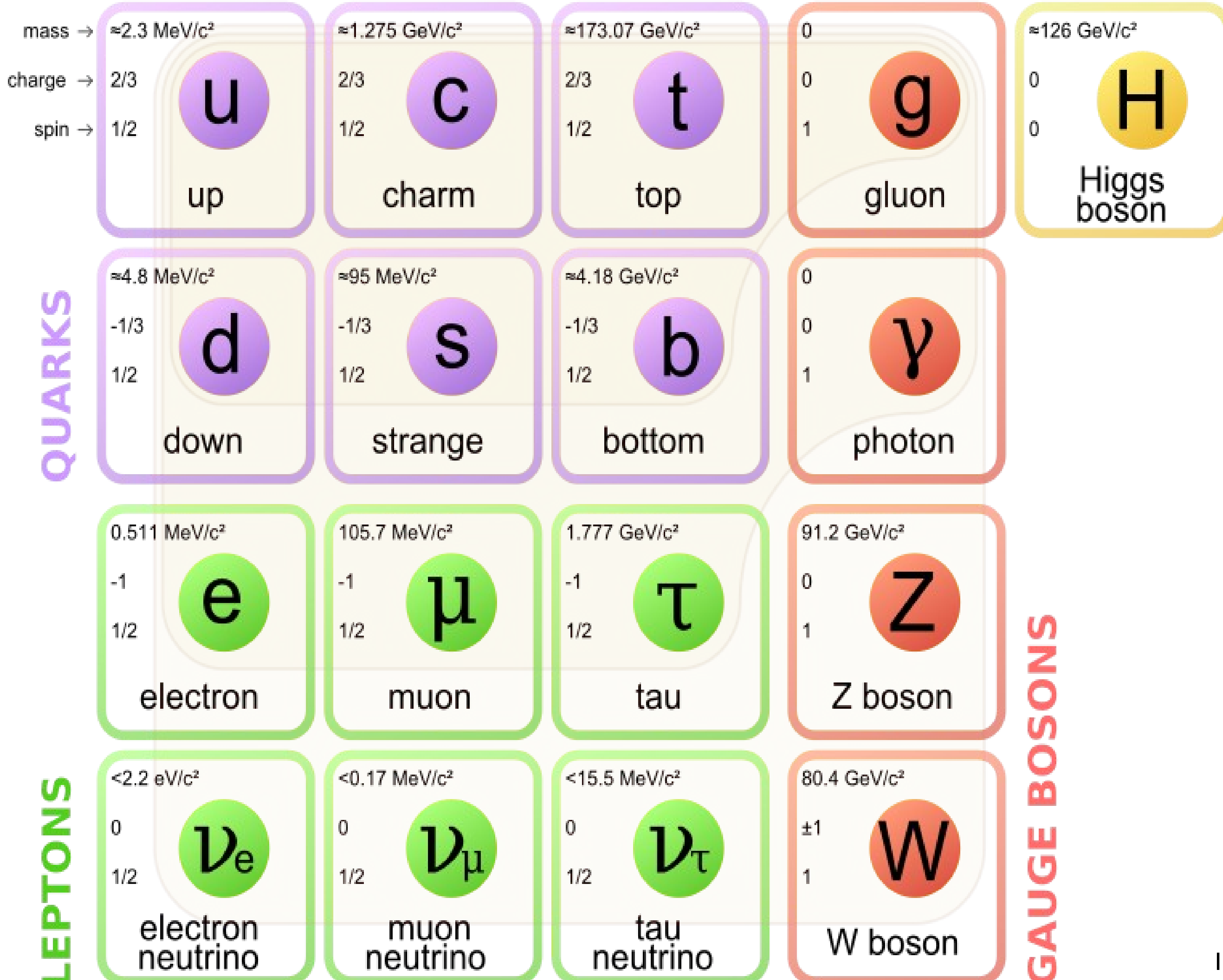
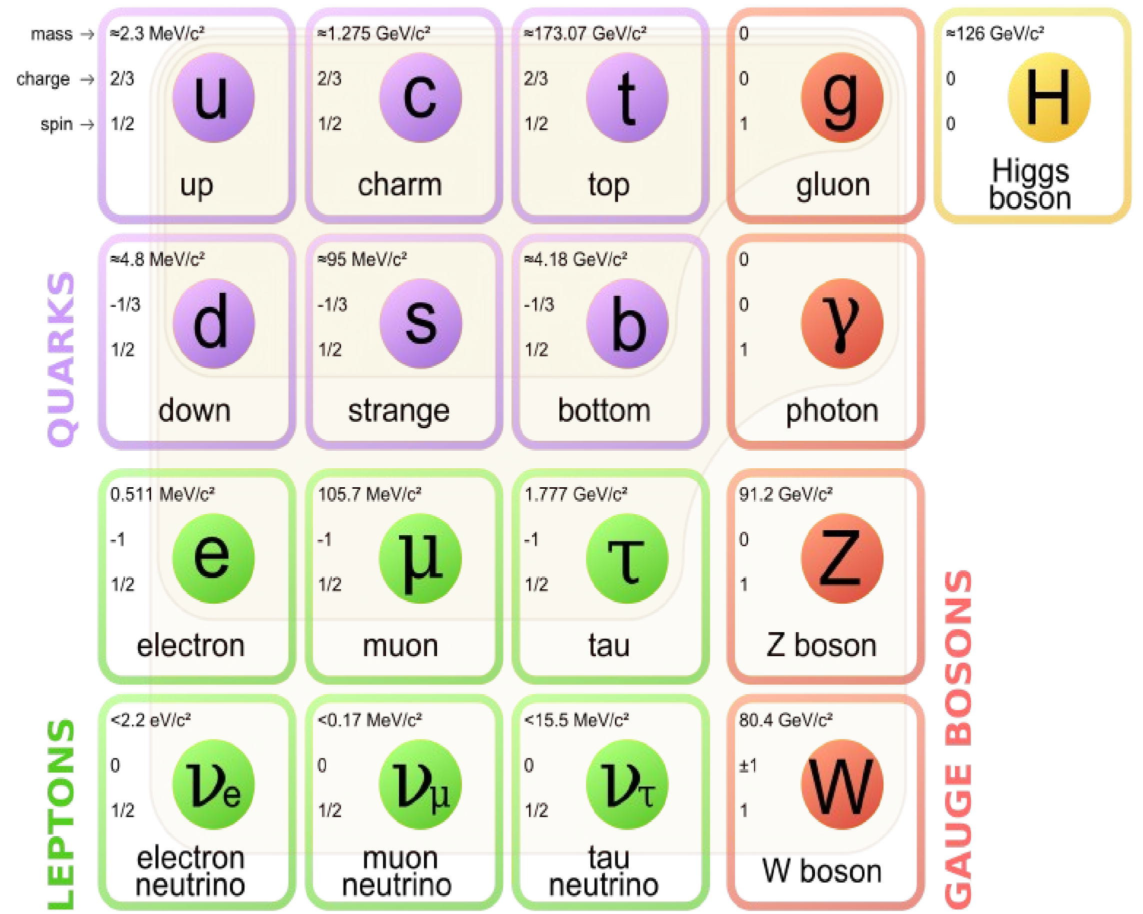


Image cred: Wikipedia

The Standard Model

- Matter is made up of leptons and quarks
- Matter interacts through fundamental forces
- Quarks are “glued” together into protons, neutrons etc.
- There are antiparticles as well



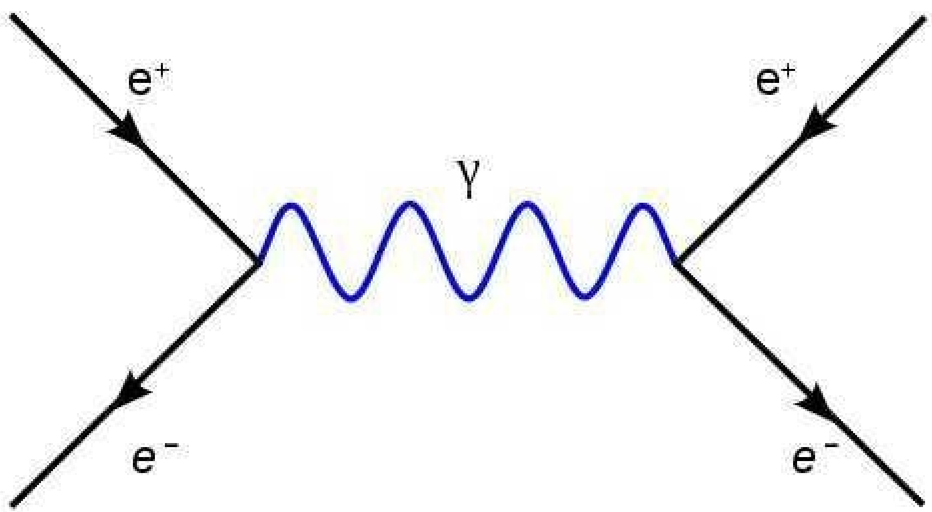
- ...and the Higgs!

...the Standard Model is one example of a

Quantum Field Theory!

→ the main toolbox for all of particle physics

Needed to account for particle creation and annihilation:



Quantum Field Theory

- Many everyday phenomena can be described in terms of fields:

→ Temperature

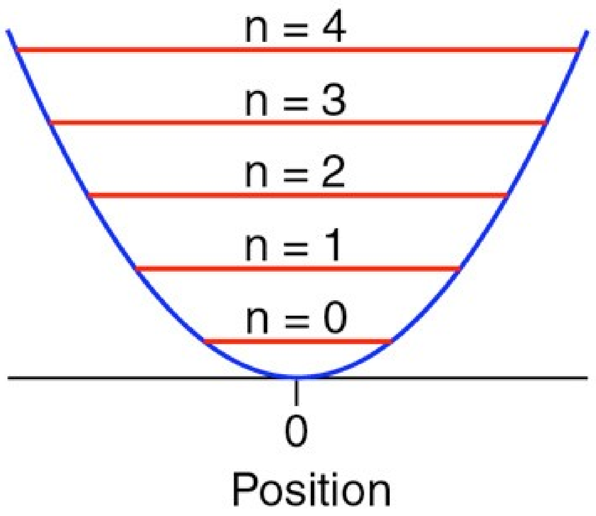
→ Wind

→ Electric & magnetic fields

...and the electron field, quark fields, etc.!

Quantum Field Theory

- Instead of continuous, smooth fields we have discrete, particle-like excitations
- (If you know some QM → like a harmonic oscillator at each point in space)



Quantum Field Theory

= “normal” Field Theory + Quantum Mechanics

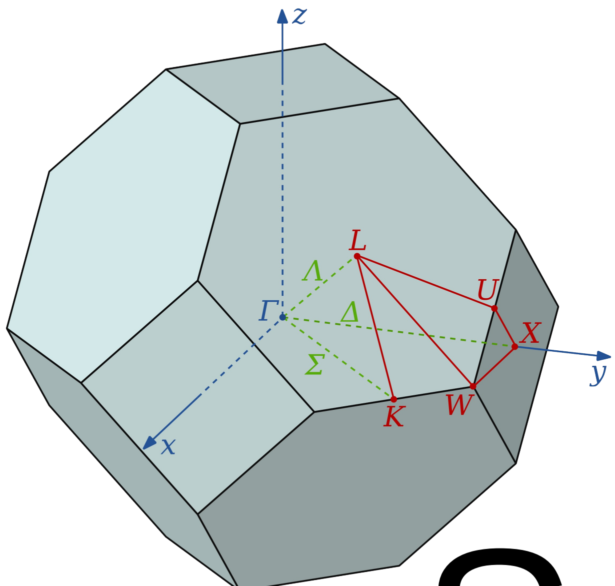
Quantum Field Theory

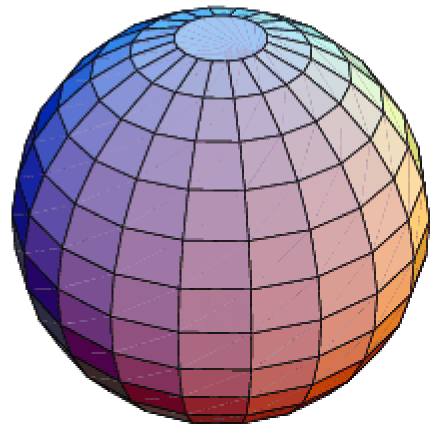
Back to previous question:

→ All electrons are the same because they are all excitations of the same electron field!

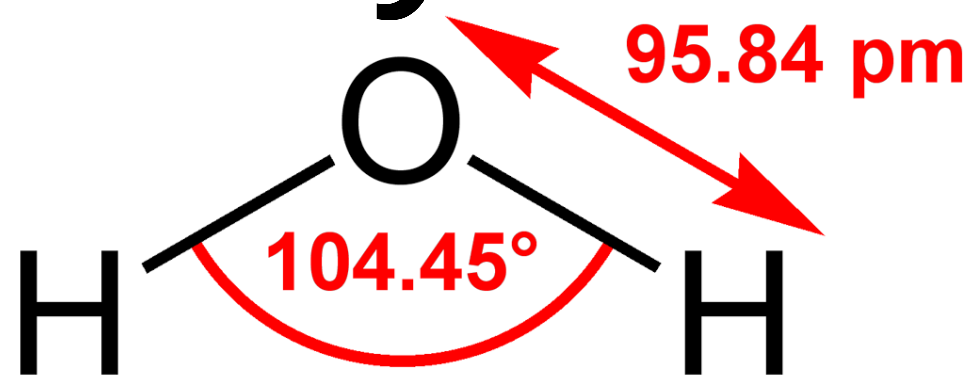
(If they weren't identical → no Pauli exclusion principle → chemistry broken)

What do all of the following have in common?



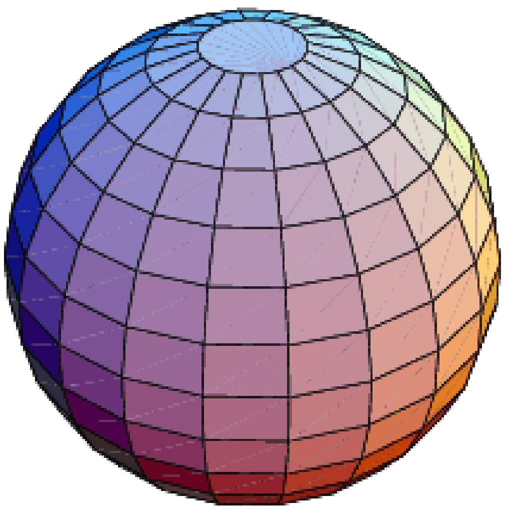


Symmetry!



What is a symmetry? (in physics)

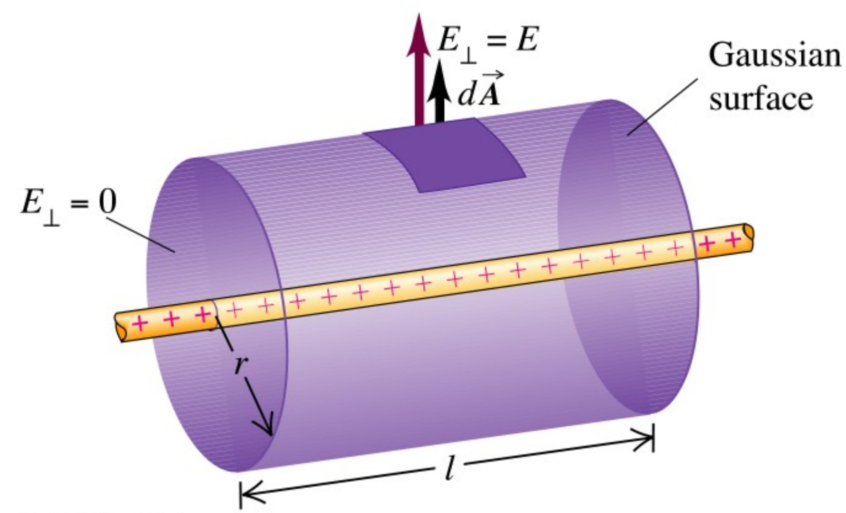
- Under certain changes, or “transformations”, aspects of the system are unchanged
- Examples: reflections, rotations...



Why are symmetries useful?

- Can simplify calculations
- Symmetries → conserved quantities
  - e.g., symmetry of rotations → conservation of angular momentum!
- Needed to describe the fundamental forces

$$\oint \vec{E} \bullet d\vec{A} = \frac{q}{\varepsilon_0}$$



A recipe for fundamental forces

- Start with equations for matter

$$\mathcal{L} = \bar{\psi}(i\,\partial\!\!\!/ - m)\psi$$

- Make equations have a specific ("gauge") symmetry

→Get equations including forces!

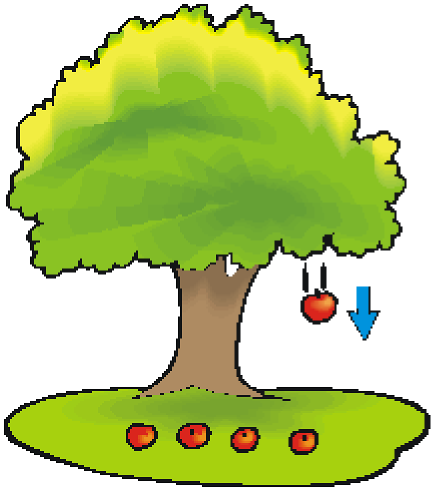
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\partial\!\!\!/ - m)\psi - e\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

Space is said to have rotational symmetry.

But if you rotate something upside down in this room, it will likely behave differently!

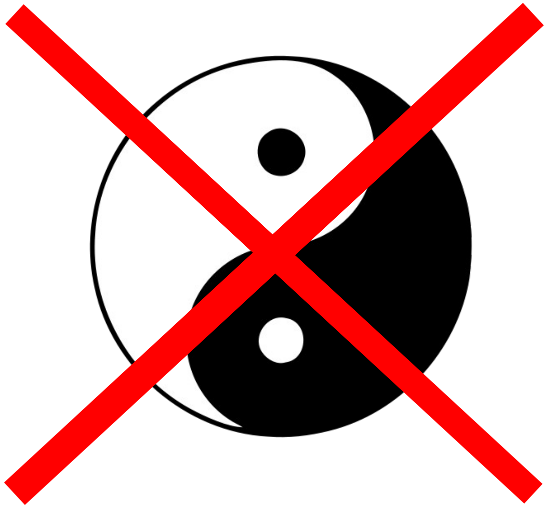
Why?

Answer: Gravity!



Dualities

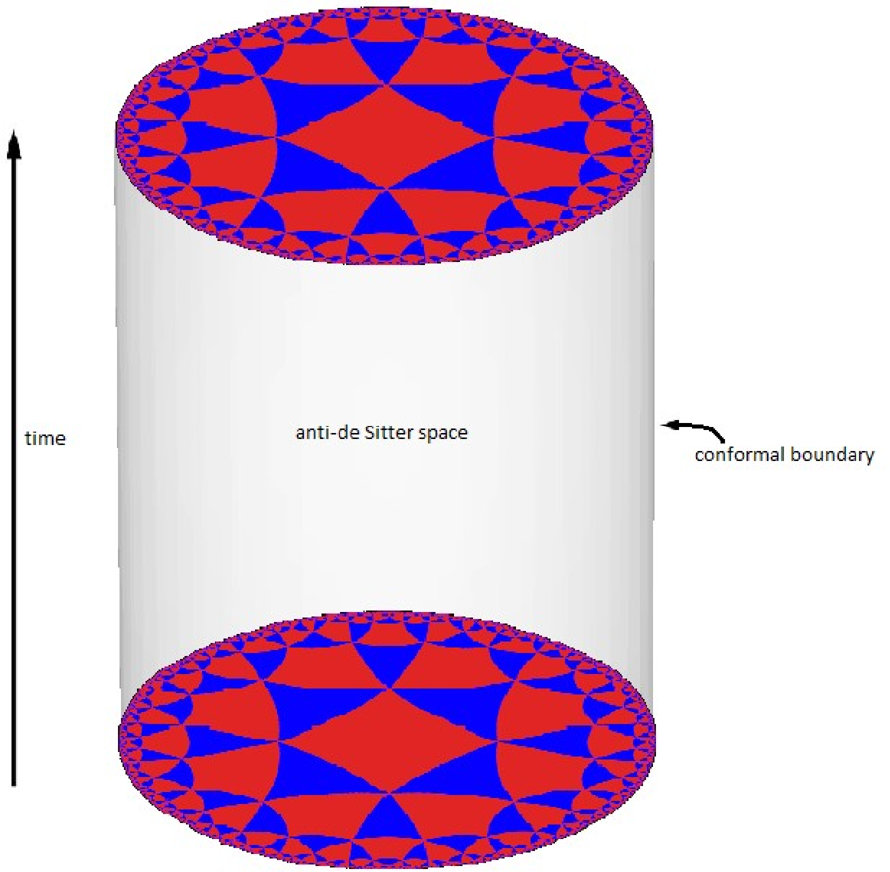
When the same physics can be described by two different sets of equations or variables



My research – AdS/CFT duality

- QFT is hard!
- Some (symmetric) QFTs have a dual theory

  → a very different theory that can describe the same physics
- The dual is a gravity theory in one extra dimension!
- Stuff that is hard to calculate in the QFT is easy in the dual



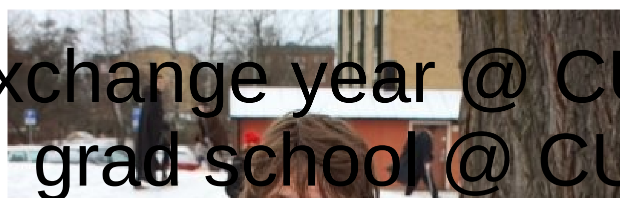
End of physics – Thanks!

What did we learn?

- "Periodic table" of particle physics
- Particles are really <u>quantum fields</u>
- <u>Symmetries</u> are important, especially for describing the fundamental forces
- <u>Dualities</u> can be used to examine difficult QFTs

About me – a not quite random walk

- From Åland, Finland
- Undergrad in Uppsala, Sweden
- Exchange year @ CU → grad school @ CU!



My way of physics

- Became interested in physics in high school
- Started doing Engineering physics, switched to “pure” physics
- Took a long time before I was sure I wanted to do research
- “Randomly” ended up in Boulder!

End of it all – Thanks!

Questions?

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→ Office in the Gamow Tower, 4th floor

More “advanced” symmetries

- Internal symmetries

  → more abstract, but the same principles

  → e.g., can multiply all fields in SM by a phase e^{ix}
- Local, or gauge, symmetries

  (→ exist in “standard” electromagnetism)

  → transformations depend on position

  → super important in particle physics:

  start from matter → demand particular gauge symmetries → get all fundamental forces (except gravity)!

Symmetry breaking & the Higgs mechanism

- Weak force carriers have mass (and so do matter fields!)
- This is not directly compatible with gauge symmetry → need to break symmetry!
- The Higgs field is not zero in vacuum → singles out a direction
- This vacuum number becomes the mass of matter and the W & Z bosons!!

Quantum Field <u>Theory</u>

“ ...a theory is a set of mathematical equations, along with a set of accompanying concepts, that can be used to make predictions for how physical objects will behave, on their own and in combination... ”

– prof. Matt Strassler

The Standard Model from a different (more accurate) perspective!

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Dirac} + \mathcal{L}_{\rm mass} + \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm gauge/\psi} \ . \tag{1}$$

Here,

$$\mathcal{L}_{\rm Dirac} = i\bar{e}^i_{\rm L}\partial\!\!\!/ e^i_{\rm L} + i\bar{\nu}^i_{\rm L}\partial\!\!\!/ \nu^i_{\rm L} + i\bar{e}^i_{\rm R}\partial\!\!\!/ e^i_{\rm R} + i\bar{u}^i_{\rm L}\partial\!\!\!/ u^i_{\rm L} + i\bar{d}^i_{\rm L}\partial\!\!\!/ d^i_{\rm L} + i\bar{u}^i_{\rm R}\partial\!\!\!/ u^i_{\rm R} + i\bar{d}^i_{\rm R}\partial\!\!\!/ d^i_{\rm R} \ ; \tag{2}$$

$$\mathcal{L}_{\rm mass} = -v\left(\lambda^i_e\bar{e}^i_{\rm L}e^i_{\rm R} + \lambda^i_u\bar{u}^i_{\rm L}u^i_{\rm R} + \lambda^i_d\bar{d}^i_{\rm L}d^i_{\rm R} + {\rm h.c.}\right) - M_W^2W^+_\mu W^{-\mu} - \frac{M_W^2}{2\cos^2\theta_W}Z_\mu Z^\mu \ ; \tag{3}$$

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \mathcal{L}_{WZA} \ , \tag{4}$$

where

$$\begin{aligned} G^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_3 f^{abc}A^b_\mu A^c_\nu \\ W^\pm_{\mu\nu} &= \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu \\ Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\ F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \ , \end{aligned} \tag{5}$$

and

$$\begin{aligned} \mathcal{L}_{WZA} = \; & ig_2\cos\theta_{\rm W}\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu Z^\nu + W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu\right] \\ & + ie\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu A^\nu + W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu\right] \\ & + g_2^2\cos^2\theta_{\rm W}\left(W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu}Z_\nu Z^\nu\right) \\ & + g_2^2\left(W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu}A_\nu A^\nu\right) \\ & + g_2 e\cos\theta_{\rm W}\left[W^+_\mu W^-_\nu\left(Z^\mu A^\nu + Z^\nu A^\mu\right) - 2W^+_\mu W^{-\mu}Z_\nu A^\nu\right] \\ & + \frac{1}{2}g_2^2\left(W^+_\mu W^-_\nu\right)\left(W^{+\mu}W^{-\nu} - W^{+\nu}W^{-\mu}\right) \ ; \end{aligned} \tag{6}$$

and

$$\mathcal{L}_{\rm gauge/\psi} = -g_3 A^a_\mu J^{\mu a}_{(3)} - g_2\left(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z\right) - eA_\mu J^\mu_A \ , \tag{7}$$

where

$$\begin{aligned} J^{\mu a}_{(3)} &= \bar{u}^i\gamma^\mu T^a_{(3)}u^i + \bar{d}^i\gamma^\mu T^a_{(3)}d^i \\ J^\mu_{W^+} &= \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\rm L}\gamma^\mu e^i_{\rm L} + V^{ij}\bar{u}^i_{\rm L}\gamma^\mu d^j_{\rm L}\right) \\ J^\mu_{W^-} &= \left(J^\mu_{W^+}\right)^* \\ J^\mu_Z &= \frac{1}{\cos\theta_{\rm W}}\left[\frac{1}{2}\bar{\nu}^i_{\rm L}\gamma^\mu\nu^i_{\rm L} + \left(-\frac{1}{2} + \sin^2\theta_{\rm W}\right)\bar{e}^i_{\rm L}\gamma^\mu e^i_{\rm L} + (\sin^2\theta_{\rm W})\bar{e}^i_{\rm R}\gamma^\mu e^i_{\rm R}\right. \\ & \quad + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm L}\gamma^\mu u^i_{\rm L} + \left(-\frac{2}{3}\sin^2\theta_{\rm W}\right)\bar{u}^i_{\rm R}\gamma^\mu u^i_{\rm R} \\ & \quad \left. + \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm L}\gamma^\mu d^i_{\rm L} + \left(\frac{1}{3}\sin^2\theta_{\rm W}\right)\bar{d}^i_{\rm R}\gamma^\mu d^i_{\rm R}\right] \\ J^\mu_A &= (-1)\bar{e}^i\gamma^\mu e^i + \left(\frac{2}{3}\right)\bar{u}^i\gamma^\mu u^i + \left(-\frac{1}{3}\right)\bar{d}^i\gamma^\mu d^i \ . \end{aligned} \tag{8}$$