The Origin of Mass in Subatomic Particles

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Introduction

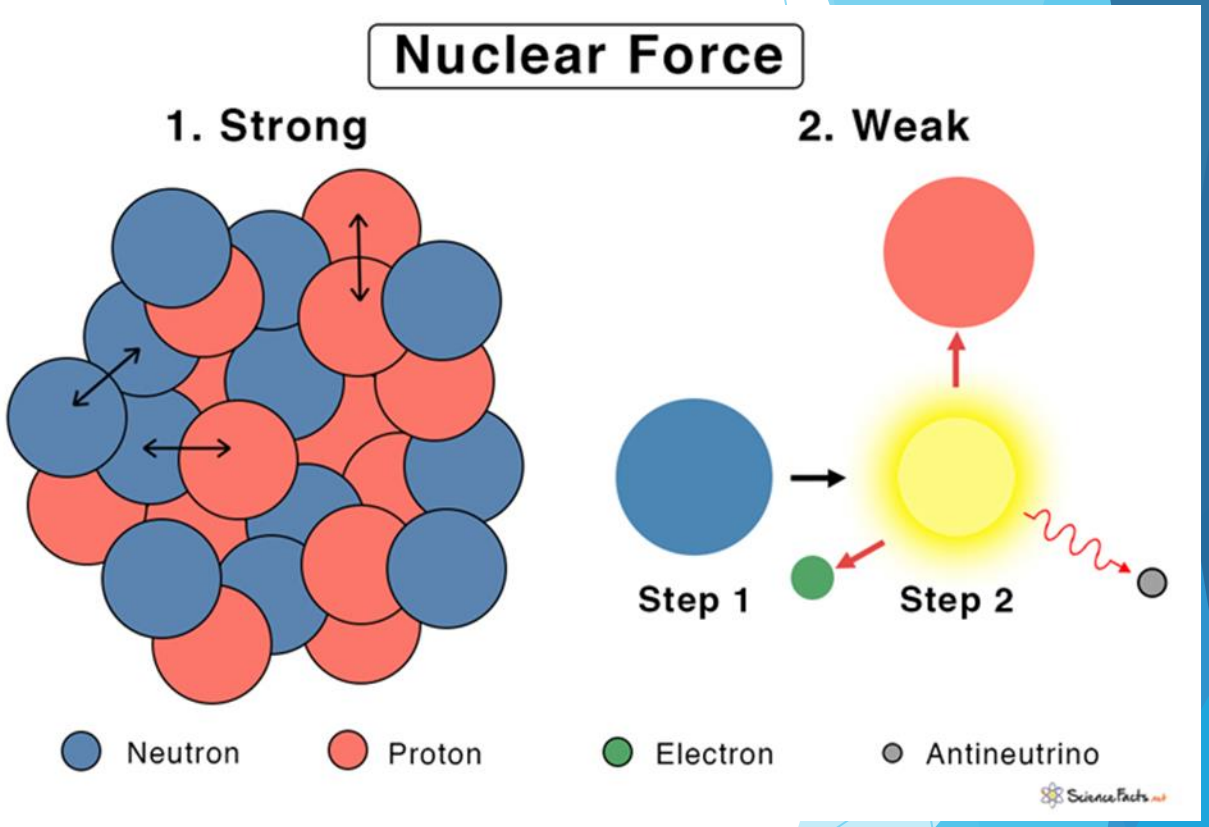
- Rest mass energy
  - $E=mc^2$
- Nuclear reactions
  - Binding energy
    - Found using the difference in mass of a nucleus and the masses of the protons and neutrons that make it up

How Does Energy Condense into Matter?

- How do you get the formation of particles like protons and electrons from energy?

A separate issue

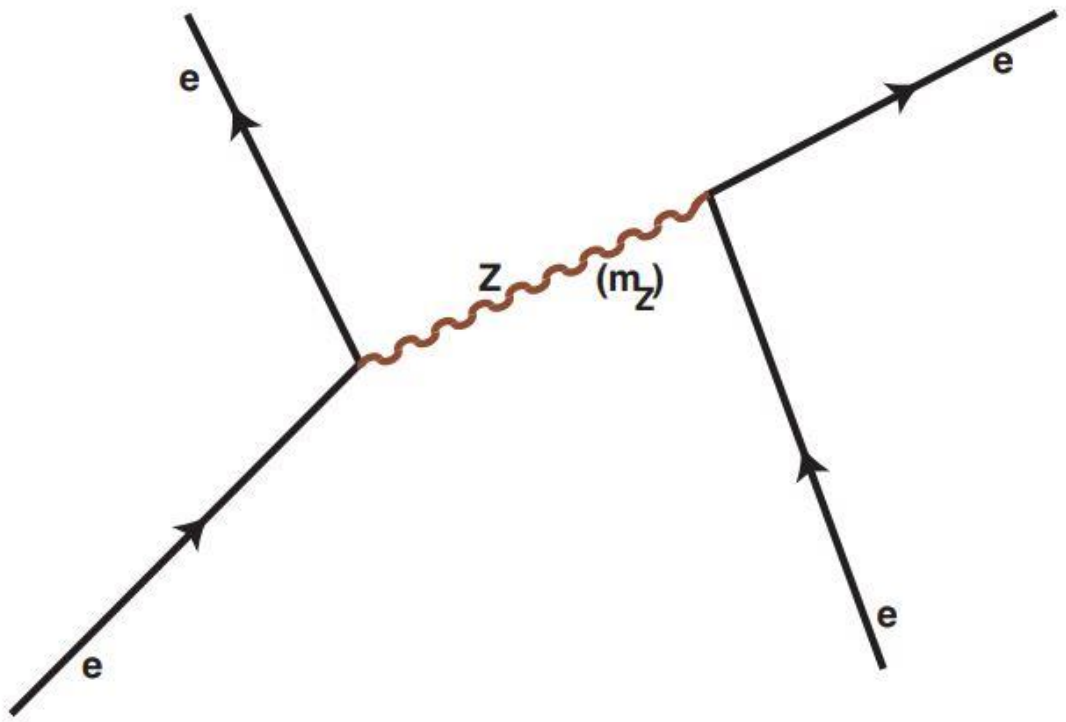
- Extending knowledge of long range forces(gravity, electromagnetism) to short range nuclear forces
  - Have general relativity for gravity
  - Photons/field theory for electromagnetic forces
- Harder to develop for nuclear forces

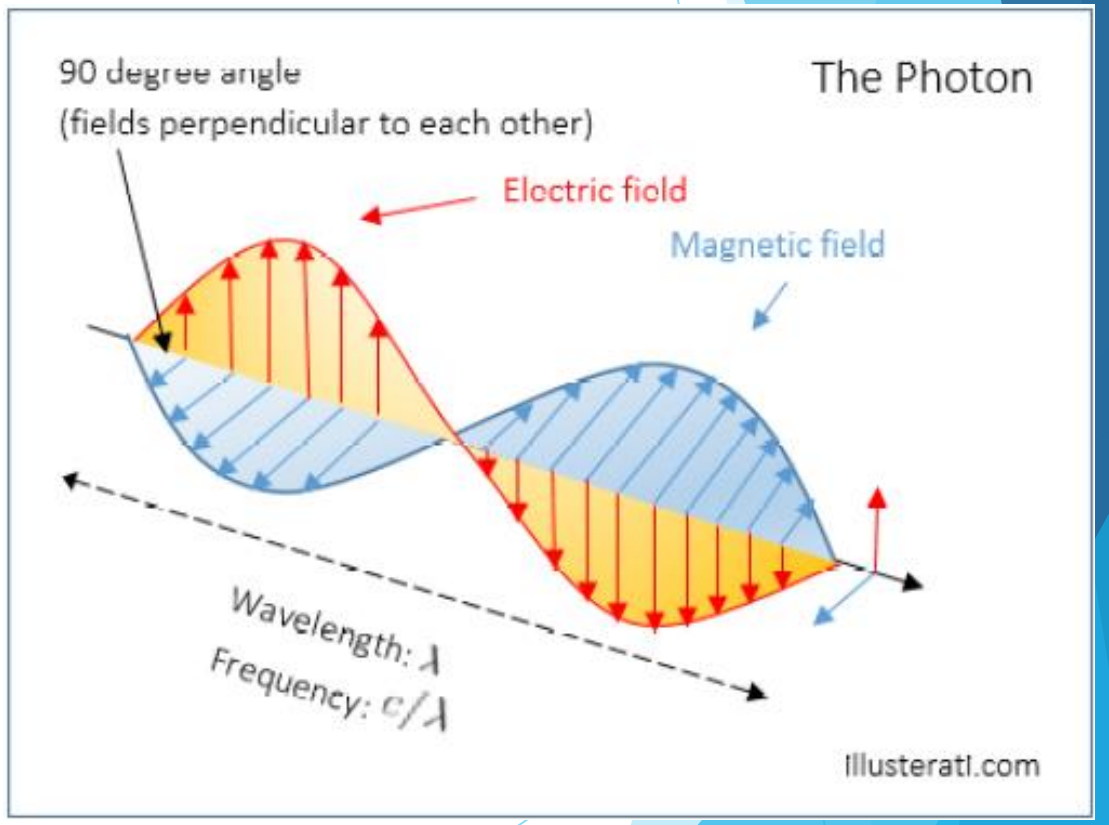


Answer

- Brout-Englert-Higgs (BEH) Mechanism

Force carrying particles

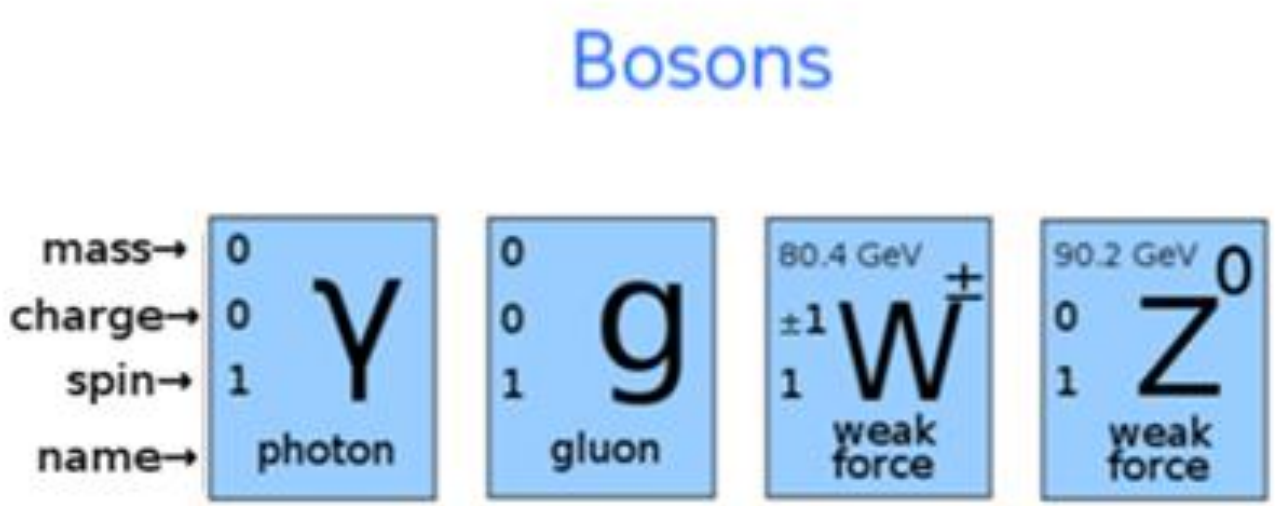




https://www.differencebetween.com/difference-between-photon-and-vs-electron/

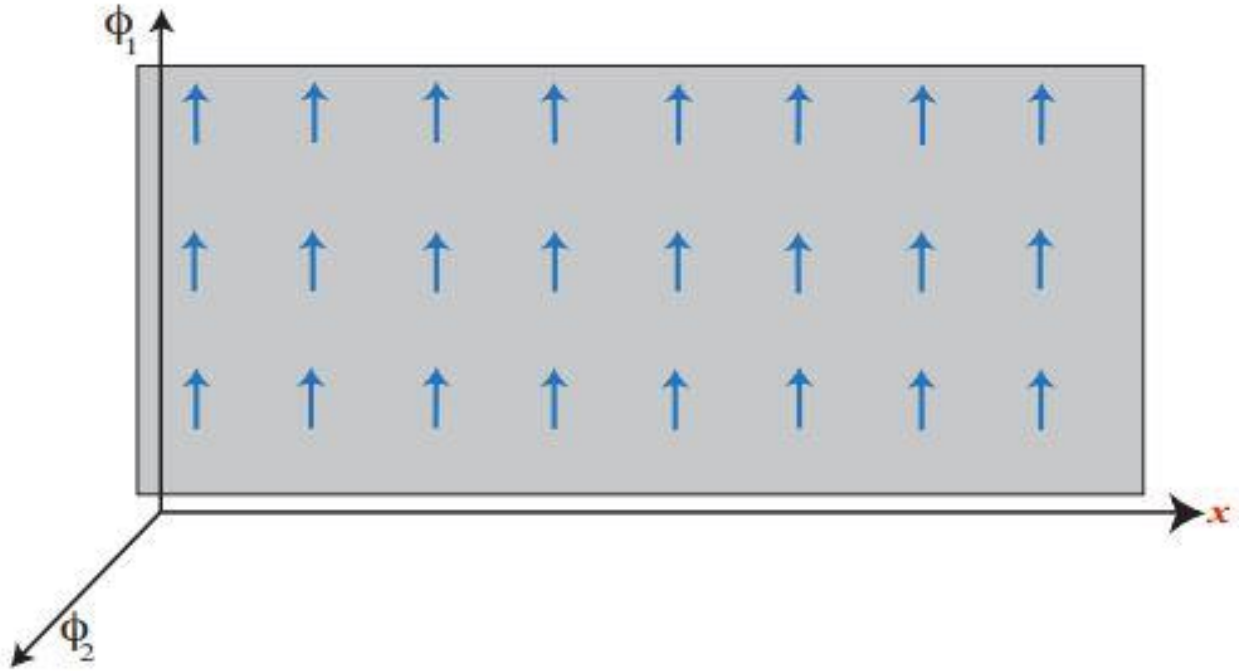
Boson

- Integer spin(not ½ like fermions)

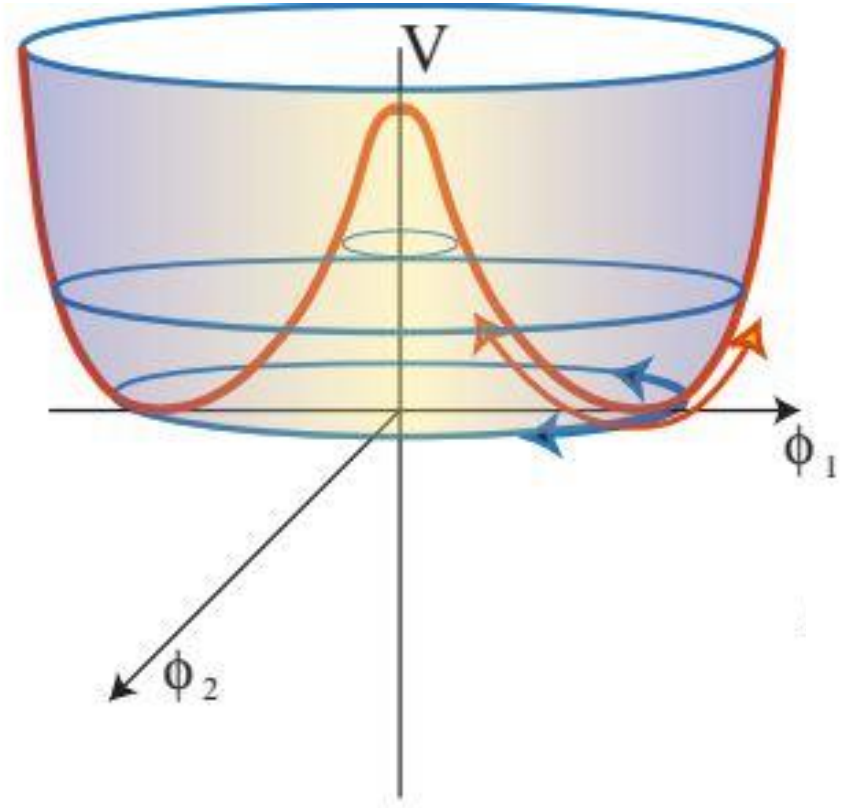


https://www.quora.com/What-is-gauge-boson

Condensate

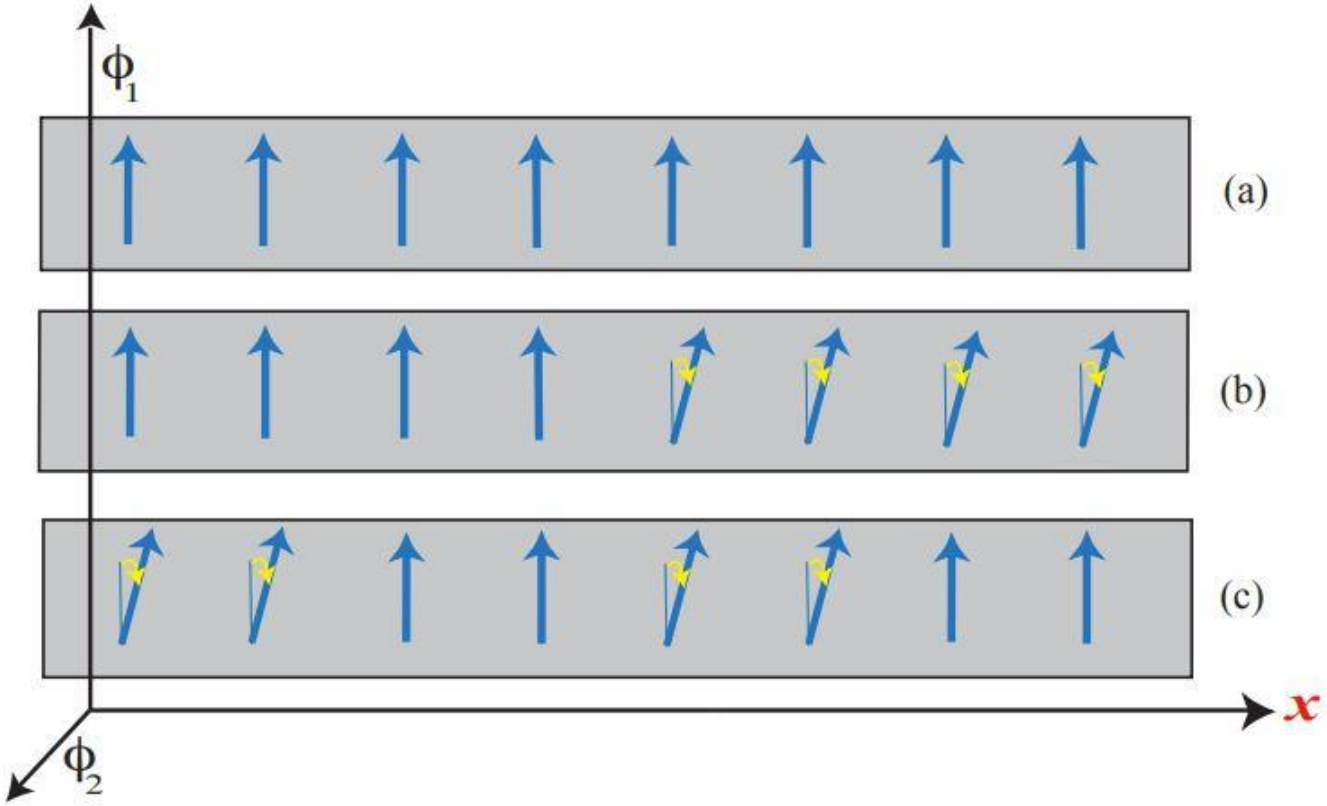


The potential



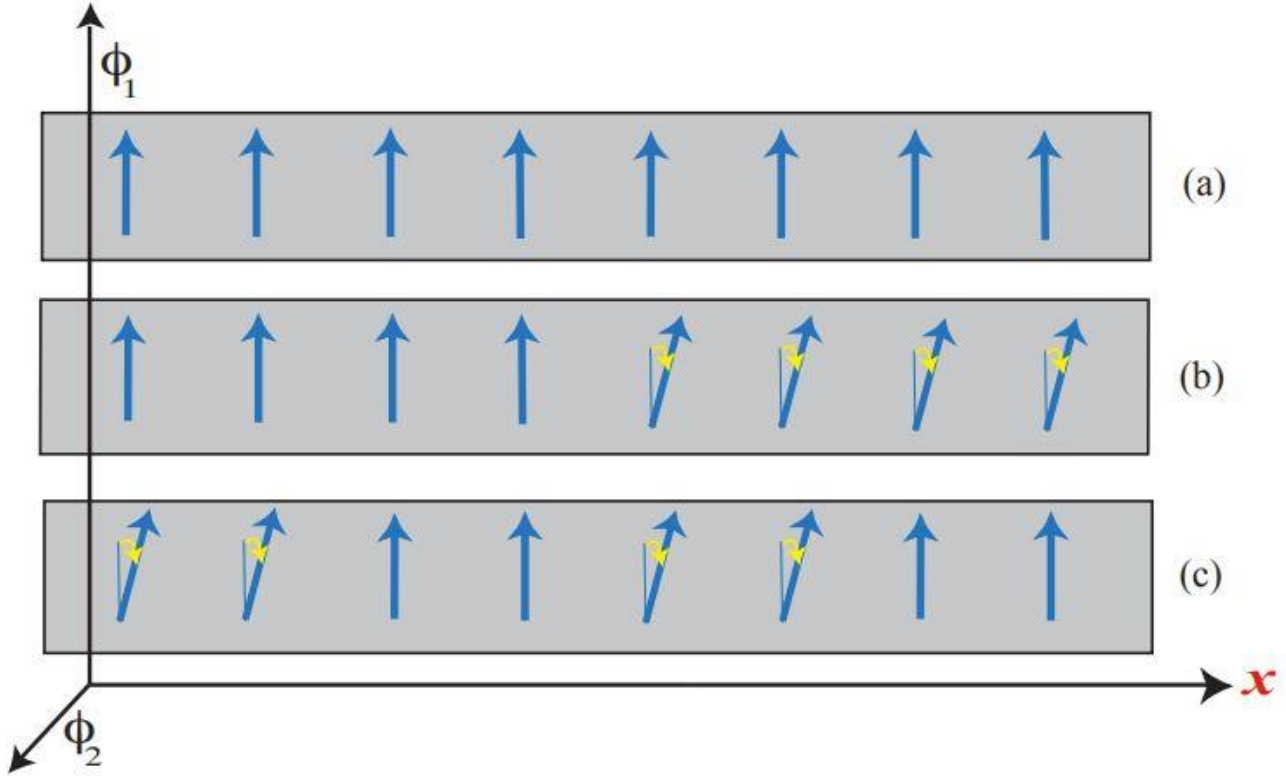
- Moving around well gives massless bosons
- Up the well gives massive

Symmetry

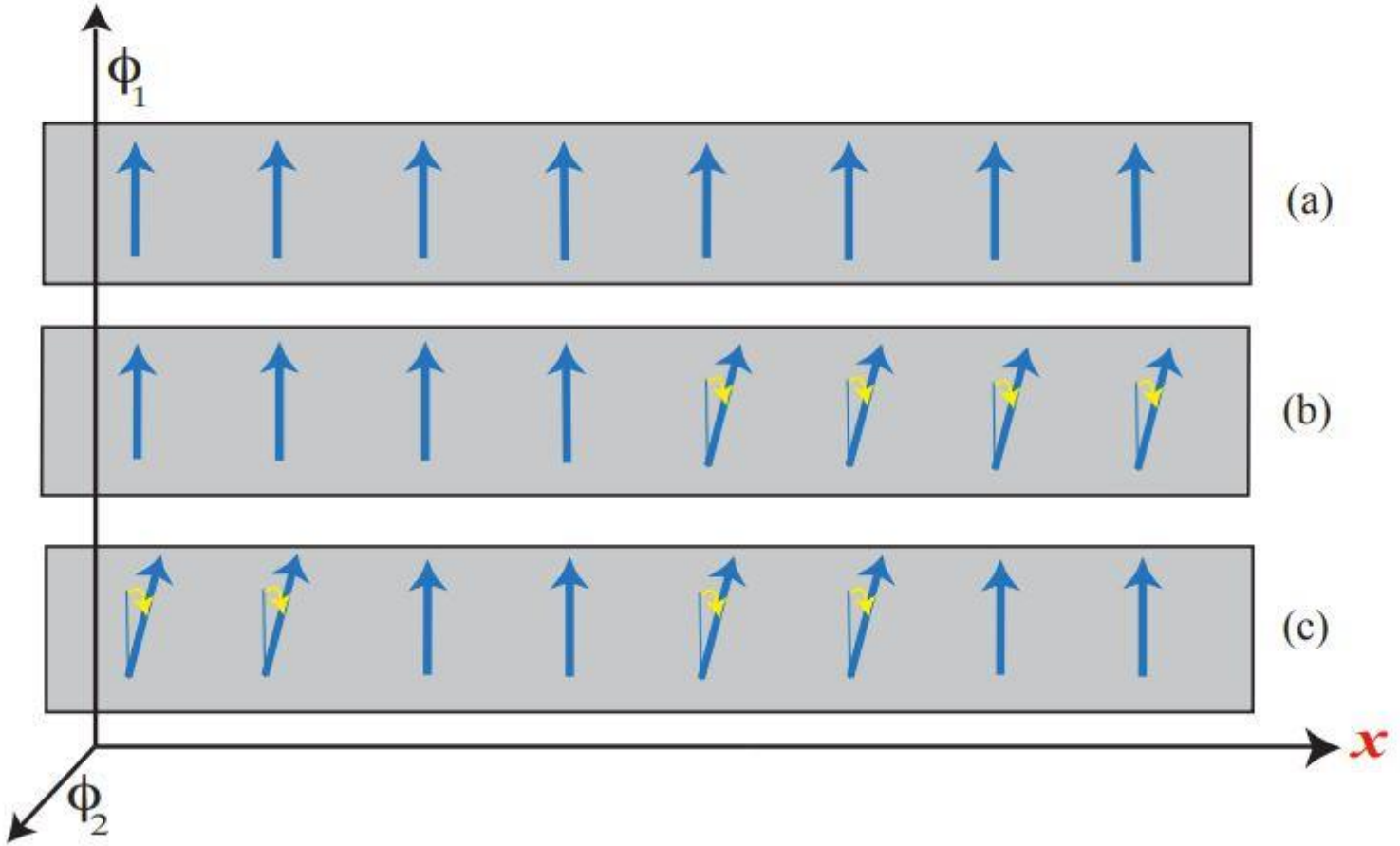


Spontaneous Symmetry breaking(SBB)

- Caused by expectation value of the fields

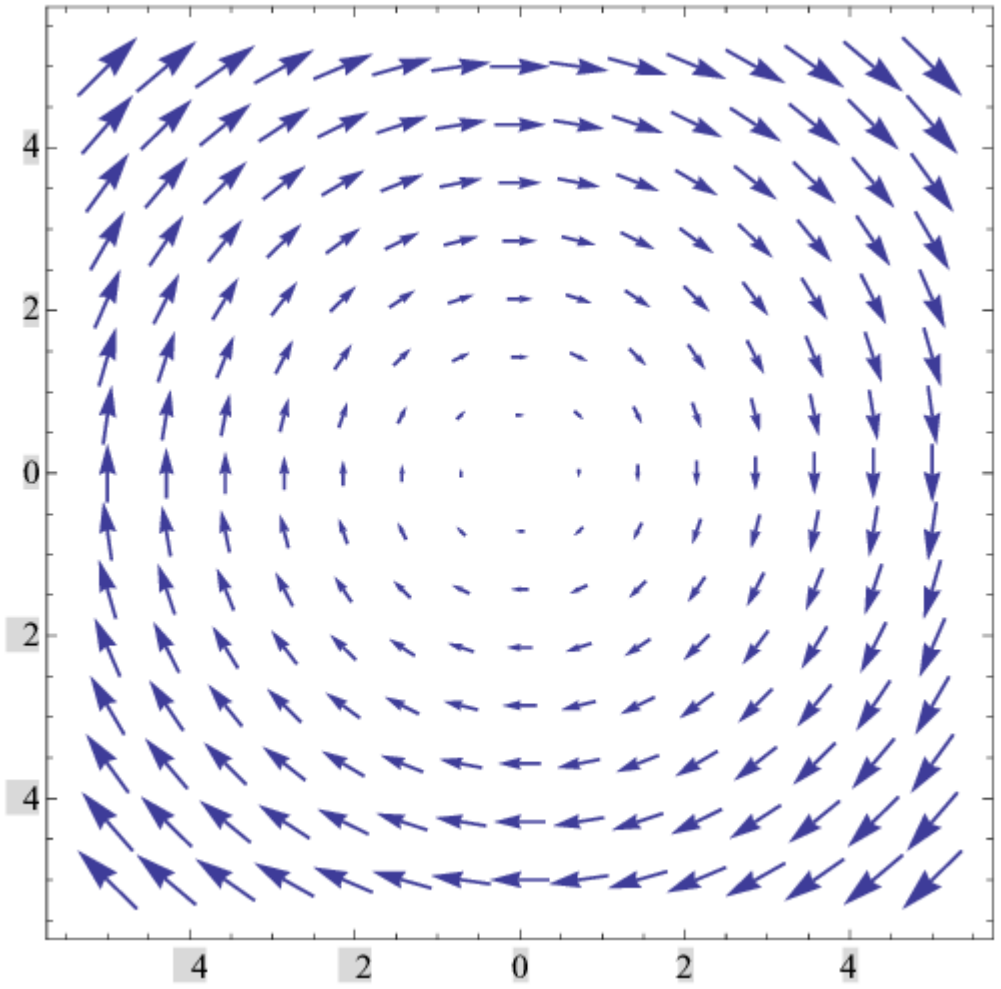


Nambu-Goldstone(NG) Massless Boson



Gauge vector field

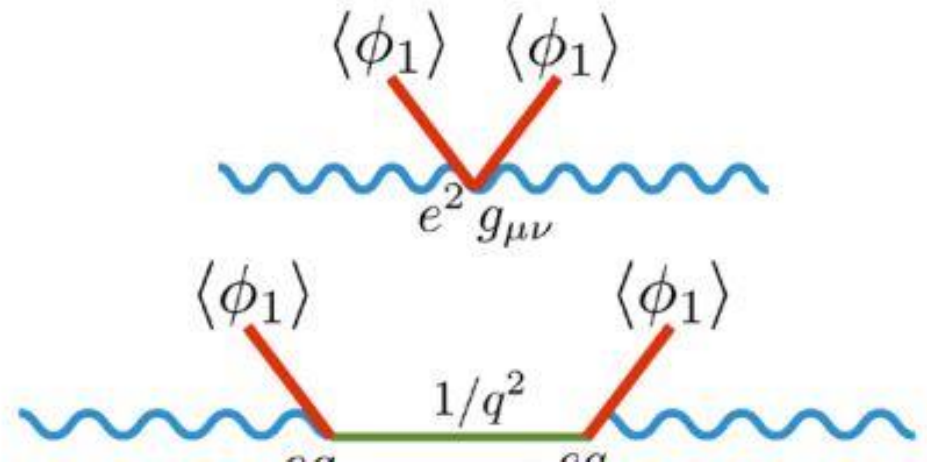
- Chosen for local symmetry
- The gauge vector field accounts for the change in energy due to local transformations

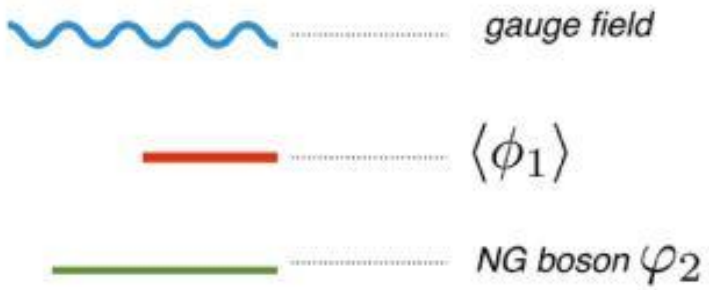


https://www.researchgate.net/figure/Pseudo-gauge-field-produced-using-the-deformation-vector-u-2xy-x-2-y-2-u-0-L_fig9_280773267

Boson coupling produces longitudinal propagation

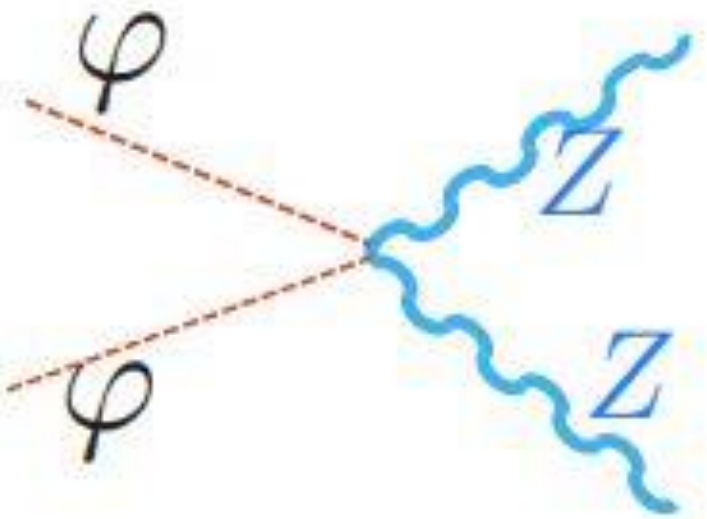
- The NG boson cannot exist due to local symmetry
- Massless particles cannot have longitudinal propagation





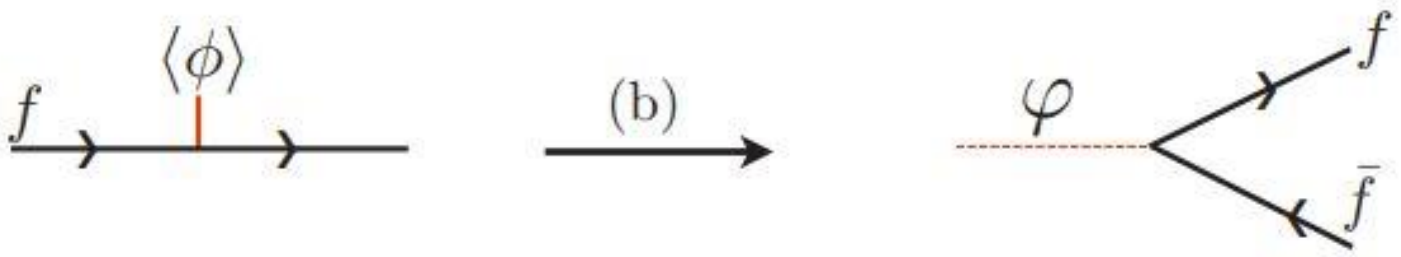
These can couple to other particles

- W, Z
- These are the force carrying particles of the weak force



A similar process gives massive fermions

- This same process with a massless fermion leads to massive fermions



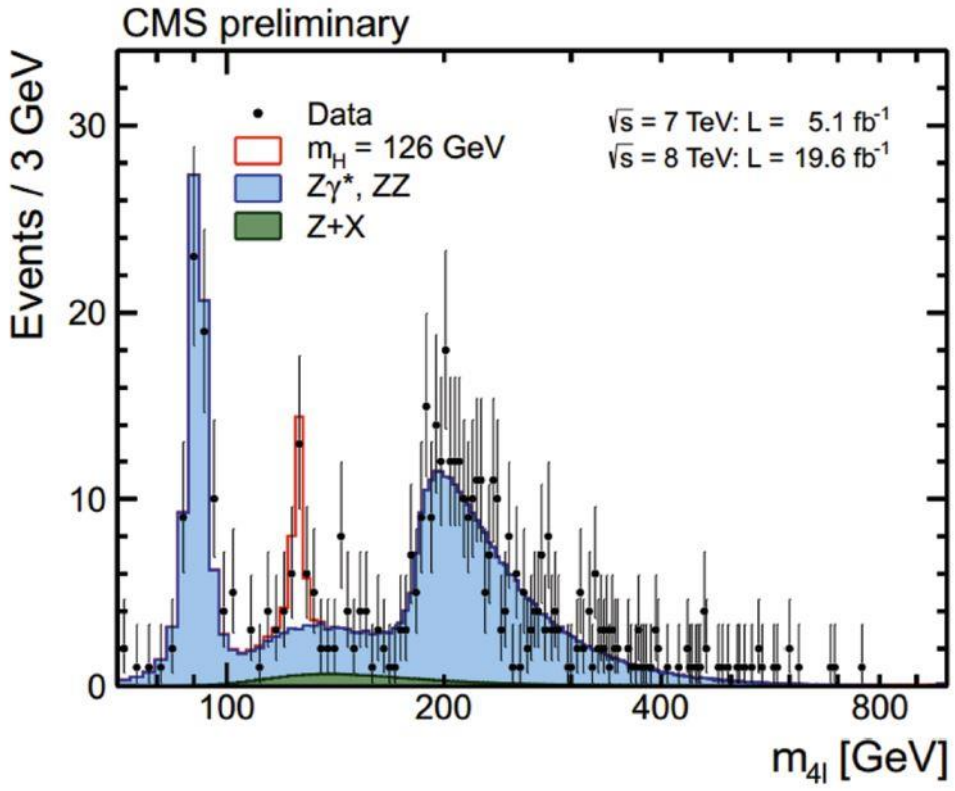
particles (charge)				
$e\,(-1)$	$\nu_e\,(0)$	$u\,u\,u\,(\frac{2}{3})$	$d\,d\,d\,(-\frac{1}{3})$	q= + 1 p; q= 0 n
$\mu\,(-1)$	$\nu_\mu\,(0)$	$c\,c\,c\,(\frac{2}{3})$	$s\,s\,s\,(-\frac{1}{3})$	+ antiparticles
$\tau\,(-1)$	$\nu_\tau\,(0)$	$t\,t\,t\,(\frac{2}{3})$	$b\,b\,b\,(-\frac{1}{3})$	

Summary of the mechanism

- Condensate
- SSB
- NG Boson
- Gauge vector field and local symmetry
- Coupling of NG boson and Gauge vector field
- Longitudinal propagation
- Massive particle

Experimental Discovery

- The Higgs boson breaks down into leptons in a predictable way
- These breakdowns give readings in the LHC than can be picked out of the other reactions



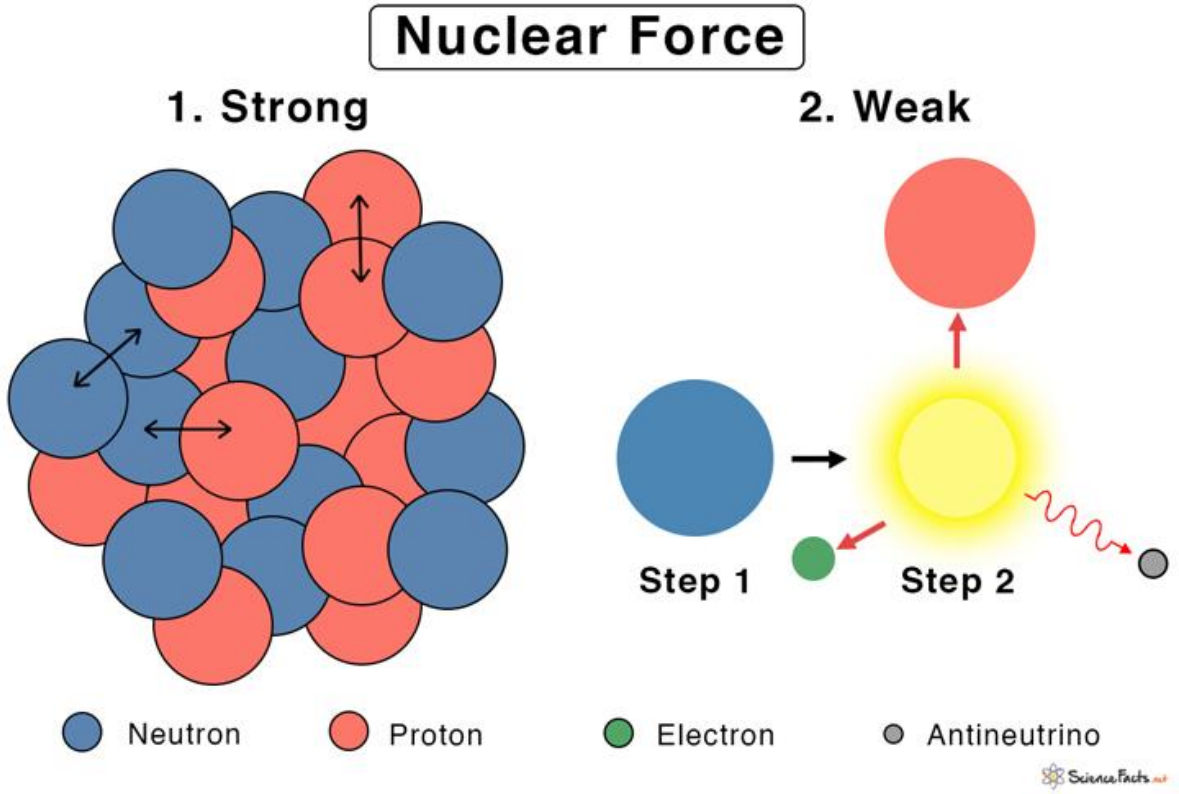
Other conclusions

- This also gives a mechanism for weak and strong interactions between particles
  - Z and W bosons for the Weak interaction
  - Eight gluons for the Strong interaction

Sources

- Englert, Fransois. *Nobel Lecture: The BEH Mechanism and its Scalar Boson*. 2013. https://www.nobelprize.org/uploads/2018/06/englert-lecture.pdf

Short Range vs. Long Range Forces



https://www.sciencefacts.net/nuclear-force.html