A brief ancestral history of the Higgs boson

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(dedicated to the memory of our Rajaji)

Taming the Infinity

- Maxwell's electromagnetism, Einstein's special relativity, Quantum mechanics worked too well.
- QED, created from their union, to describe how light interacts with atoms faced an ugly roadblock.
- Vacuum is not empty, bubbling with transient particle anti-particle pair. Electron interacts with the EM field. QM allows for non-conservation of energy for virtual particles for a very short time.
- Calculations of electron mass and charge, summing up all intermediate virtual possibilities, yield infinity!
- Lamb measured one part in a million split in the electron energy levels in hydrogen atom. Dirac equation says `no splitting'. QED calculation gives infinity again.
- Use experimentally measured value of mass and charge to calculate Lamb shift or anomalous magnetic moment of electron. This technique of using known values to calculate other values became known as **Renormalization**.

Gauge theory

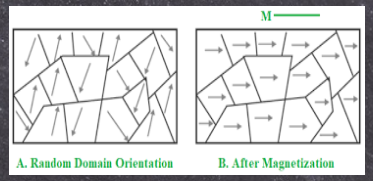
- **What is QED?** It is a gauge theory which relies on invariance under a phase (gauge) transformation at each point in space time. Photon is the carrier of EM force.
- Gauge invariance means that regardless of the accountancy of computational scheme one gets the same result.
- It is a profound scheme that causes the EM force to exist and ensures that photon is strictly massless.
- Next, gauge theory involving more than one fermion (n,p) was constructed (QED involves only one, namely, electron). Algebra involved marices.
- Electrically charged massless photon-like object emerged. This is again an impossible situation.
- Role of weak interaction in burning the solar fuel and giving us day light became known, and its triggering of beta decay required a massive charged gauge boson.
- Meanwhile, (V-A) nature of weak interaction fueled speculation that EM and weak interaction may have a common connection.
- **How to reconcile gauge invariance with massive gauge boson? Infinities shouldn't come back!**

Hidden symmetry

Salam's banquet: Think of a round dinner table

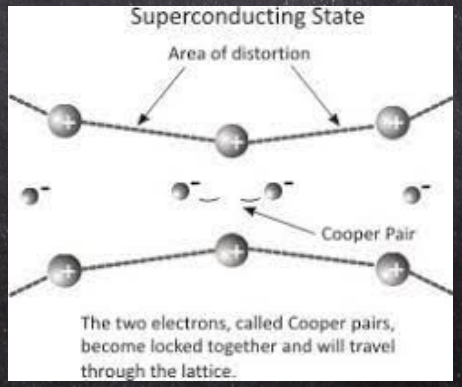
Rotational symmetry of water molecules reduced to Discrete symmetries in subzero temp snowflakes.

Ferromagnetism: Alignment in the direction of external Magnetic field below a certain temperature.



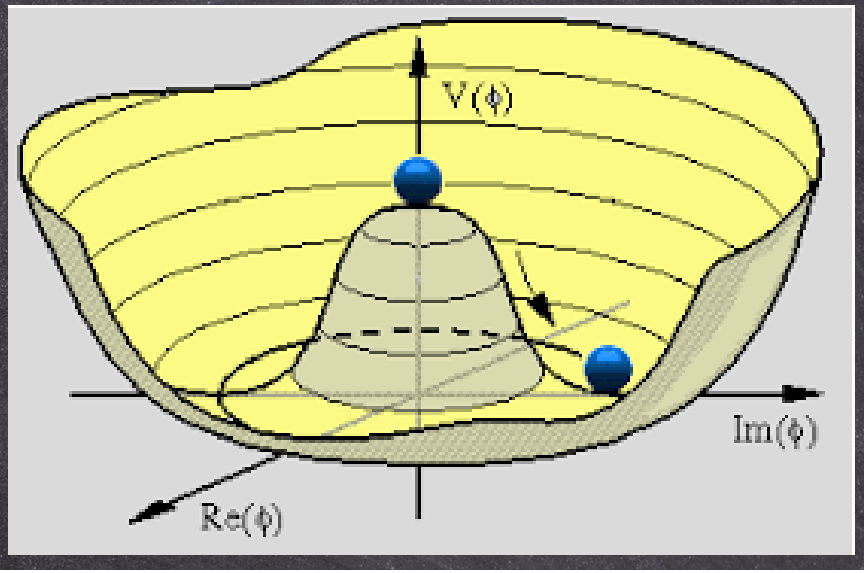
Spontaneous breaking: 'Somehow' transition from phase w/ Full symmetry to a phase having lesser symmetry.

In superconductivity, the symmetry that gets hidden is gauge invariance of electromagnetism, leading to organized Cooper pair bonding.



Spontaneous breaking of global symmetry

- Whenever there is a spontaneous breaking of a continuous global symmetry, massless Nambu-Goldstone bosons appear.
- *Problem or opportunity?*
- **Problem of massive gauge boson + Problem of existence of massless NG boson = More problem OR an earth-shaking solution**
- **And, what about the 'other boson'?**



$$\phi^i = \exp\left(\frac{i}{v}\sum_{n=1}^{N-M}\xi_n T^n_{broken}\right)\begin{pmatrix}0\\0\\\vdots\\0\\v+\sigma(x)\end{pmatrix}$$

Mass generation mechanism

- Anderson: In a superconductor EM field is short ranged, implying that photon becomes massive. It might be a result of zero mass of photon in QED and massless NGB arising from SSB marrying each other. Thus the embarrassing massless boson can be avoided in nonrelativistic plasma.
- Klein and Lee: Goldstone theorem fails in nonrelativistic theories, BUT, also stressed that their argument holds in relativistic theories.
- Gilbert: Presence of GB cannot be avoided in relativistic theories.
- Brout and Englert: Elevated Anderson's assertion from cond mat perspective in relativisitic field theory. Their construction required a massive scalar boson also, but the attention was on **photon mass generation mechanism**.
- Guralnik, Hagen, Kibble: NGB need not be present in locally conserved theories and the force carrier (like W boson in beta decay) could become massive by eating them up. They concentrated **only on mass generation, no massive scalar in their paper.**
- Higgs: If relativistic theory contains gauge fields, Gilbert's argument fails! Impasse lifted! Massless scalar boson avoided, they are devoured by gauge bosons which in turn become massive.
- Importantly, Higgs talked also about the behaviour of the other scalar boson which is massive.

Electroweak theory

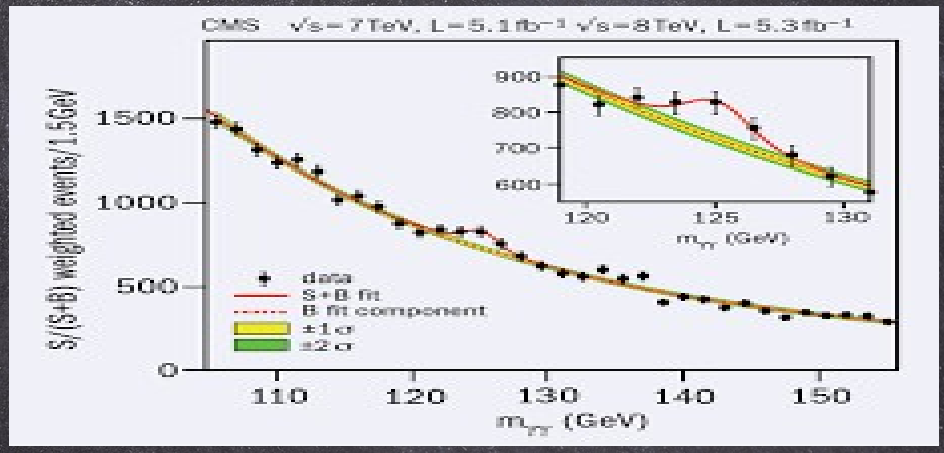
- Glashow constucted a model with a massive triplet (W+, W-, Z) together with a massless QED photon. It is not renormalizable. He only hinted that unification of Weak and EM forces might contain the clue for renormalizability.
- Salam and Ward had independently constructed SU2XU1, but as world experts on renormalization they were unable to digest the masses of the W,Z bosons.
- Kibble incorporated Group Theory into the idea of SSB.

$$2 + 2 = 4 = 3 + 1$$

- Weinberg used the SSB idea in SU2 X U1 model. Salam independently promoted the SU2XU1 model realizing the significance of this mass generation mechanism maintaining gauge invariance.
- ‘t Hooft demonstrated the importance of the real massive scalar `Higgs field’ in keeping the model safe from bad high energy behaviour.

Finally....

- In 2012, CMS and ATLAS Collaborations of the LHC discovered the `other scalar of Goldstone', the Higgs boson.
- The ZZh interaction strength is related to Z-mass. This proves the mass generation mechanism predicted by ABEGHHK'tH.
- The disintegration of the particle into two photons and study of angular momentum confirmed its spin-zero nature.
- Its decay into a pair of fermions implied a new type of spin-zero mediated interaction, proposed by Yukawa in a different context 8 decades previously.
- Unlike EM, weak and strong forces, the Yukawa interaction strength is not quantised.



Outlook

- The Standard Model of Glashow, Weinberg and Salam is now a Standard Theory.
- The mass of the Higgs boson is approx 125 GeV with an error of about 1 GeV.
- This is within the range predicted by precision studies of the weak force carriers.
- But without any protection from ugly quantum mechanical behaviour, why it does not weigh as heavy as the scale where gravity becomes strong?
- Beyond the Standard Model ---

  Extra Dimension (additional length dimensions, curled)?

  Supersymmetry (symmetry between fermions and bosons)?
- Is Higgs elementary or composite?