Beyond the Standard Model

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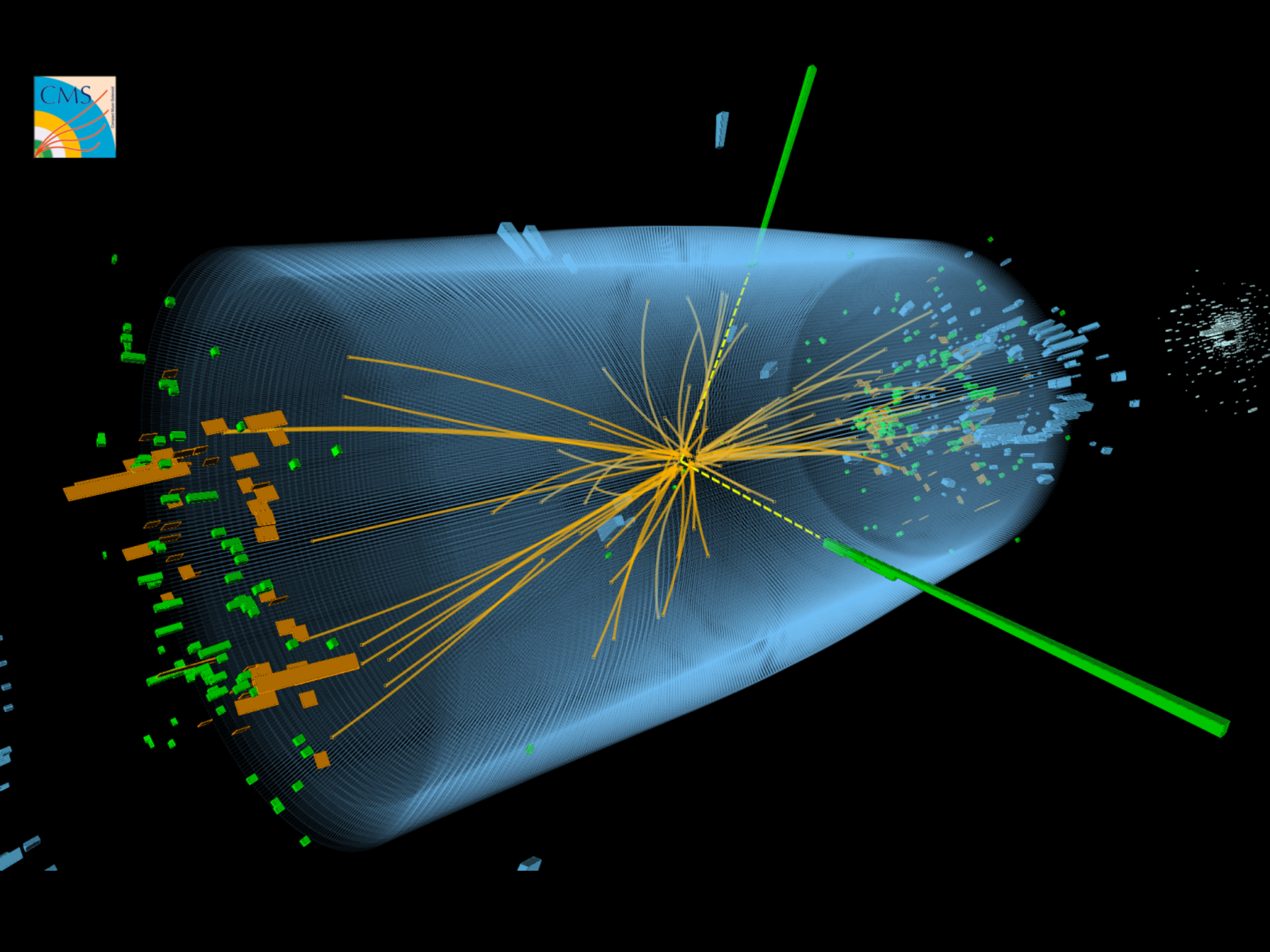
Lecture 1

CERN Summer Student
Programme 2013

The LHC is a project aiming at exploring a new energy regime

The goal is the exploration of small distances ($< 10^{-19}$ m) searching for new phenomena

- The engine that drives us to build accelerators is our understanding that the key to physical laws is hidden in the microcosm.
- The same laws help us to understand the large-scale structure of the universe and its early history.


CMS

The problem of electroweak symmetry breaking

Concept of **symmetry** central in modern physics

invariance of physics laws under transformation of dynamical variables

Now fundamental and familiar concept, but hard to accept in the beginning

Ex.: Earth's motion does not affect *c*

Lorentz tried to derive it from EM

dynamics determine symmetries

Einstein postulates *c* is constant (invariance under velocity changes of observer)

symmetries determine dynamics

Einstein simply postulates what we have deduced, with some difficulty and not always satisfactorily, from the fundamental equations of the electromagnetic field

All physical phenomena in the microcosm can be understood in terms of a single symmetry principle

(simply connected) spherically symmetric object

gauge symmetry

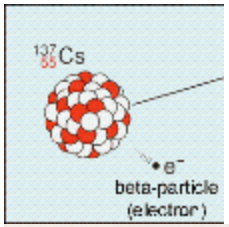
space-time

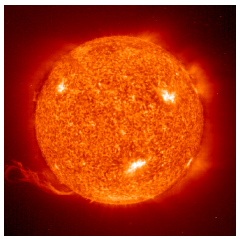
fields

gravity

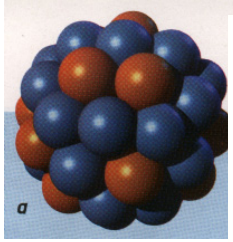
electro-magnetism

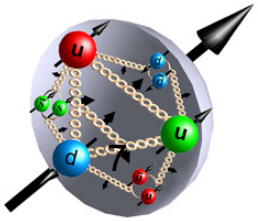
weak force





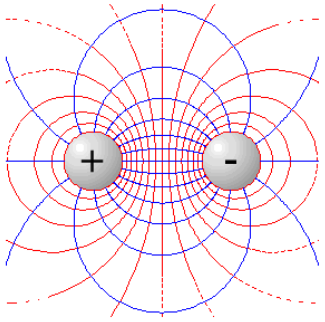
strong force



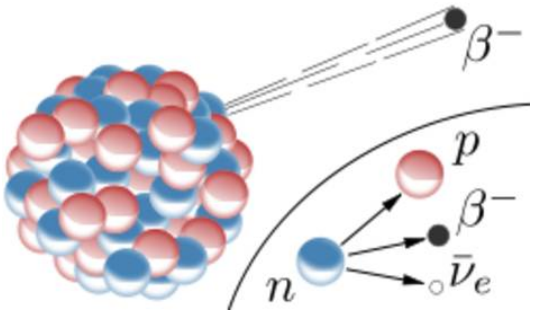


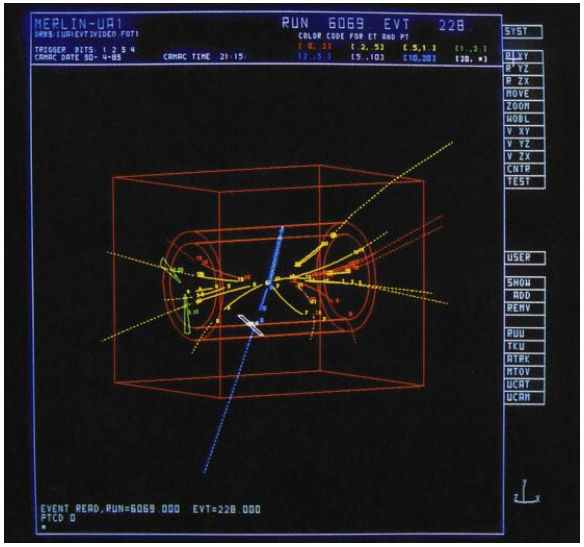
One important difference

Electromagnetism ➔ infinite range ➔ photon mass =0

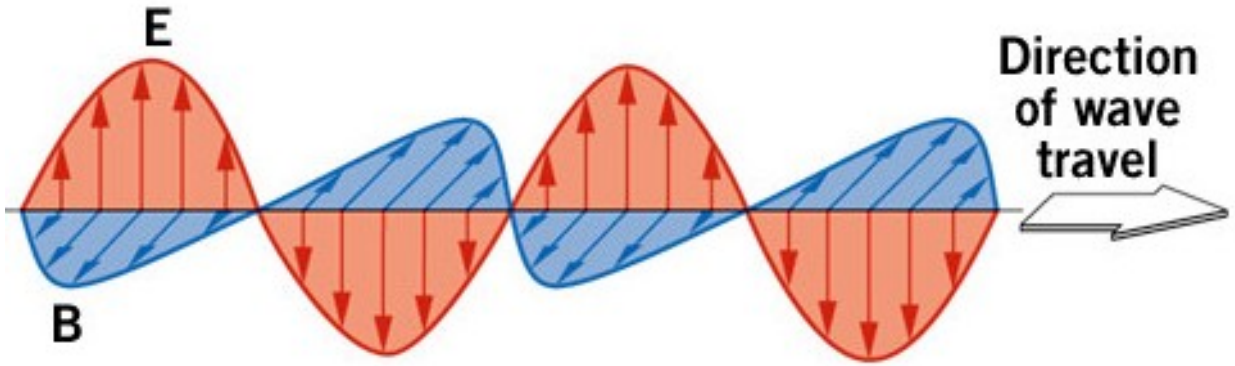


Weak force ➔ 10^{-18} m (10^{-3} *p* radius) ➔ *W*, *Z* massive



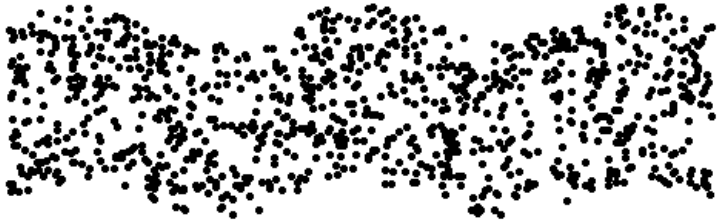


The problem of electroweak breaking

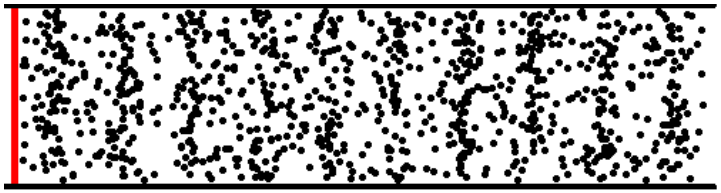


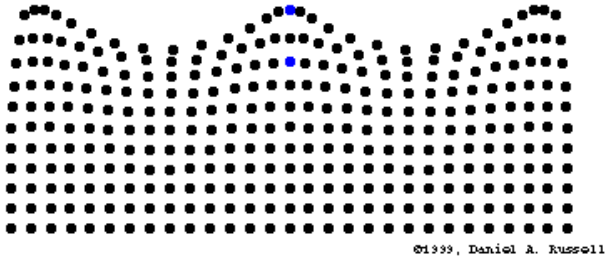
Oscillations perpendicular to direction of motion

Transverse wave



Longitudinal wave



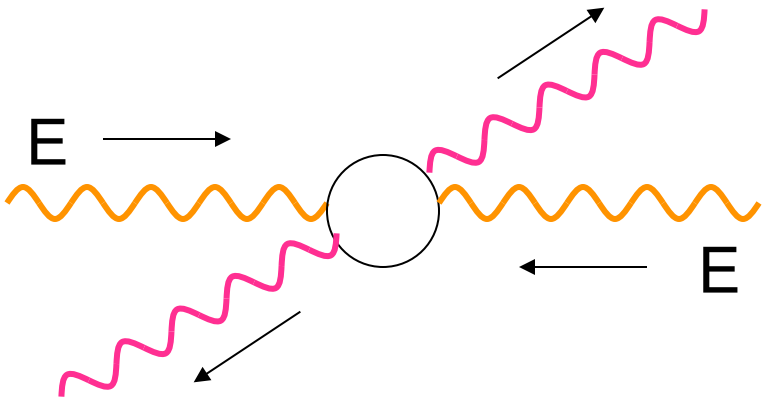


Water wave

The EM wave has only 2 independent polarizations

Just an empirical fact, but a very lucky one

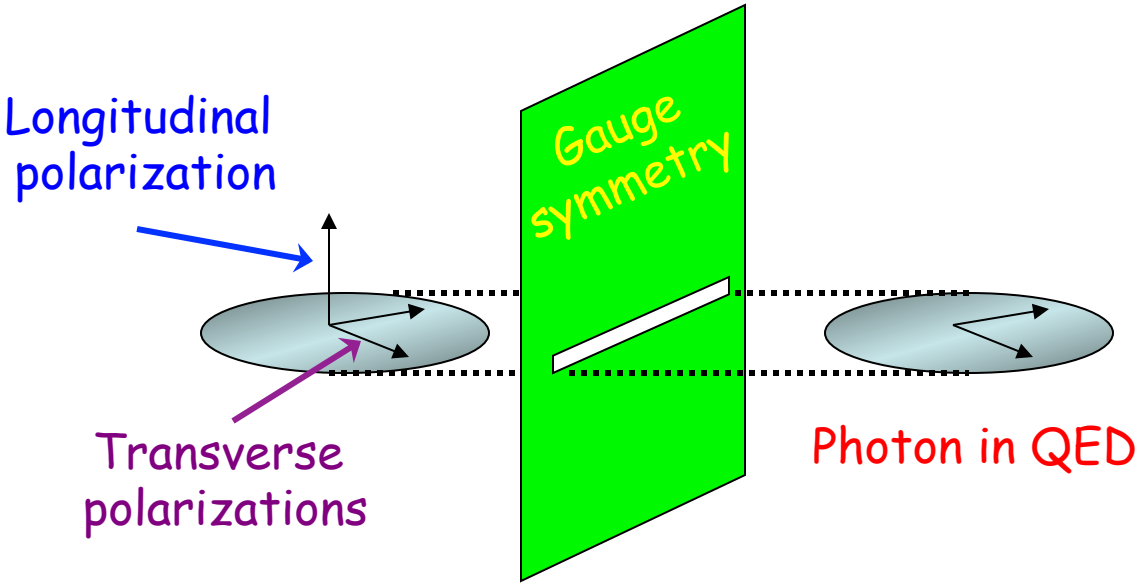
If 3rd polarization existed



Scattering probability grows with E

Nonsense at large E: probability larger than 100%

In QED, 3rd pol. does not exist ⇒ gauge symmetry

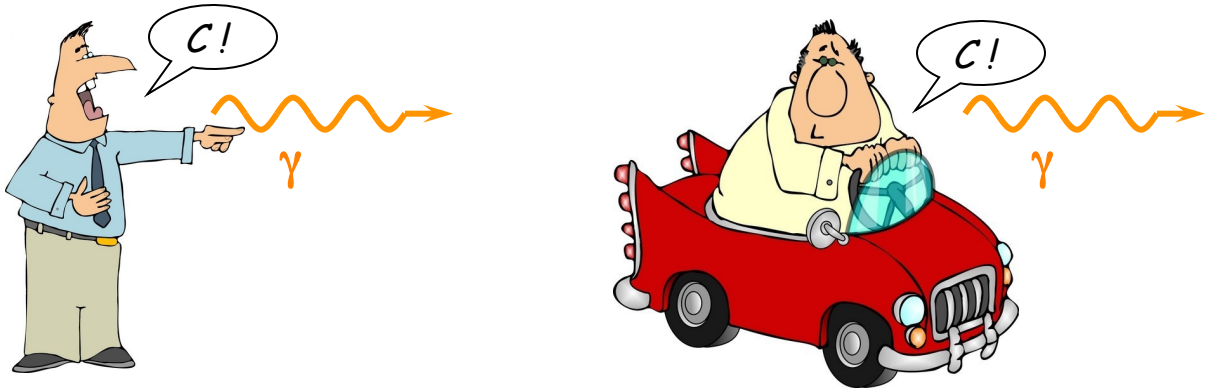


Gauge symmetry is essential to make theory free of nonsense

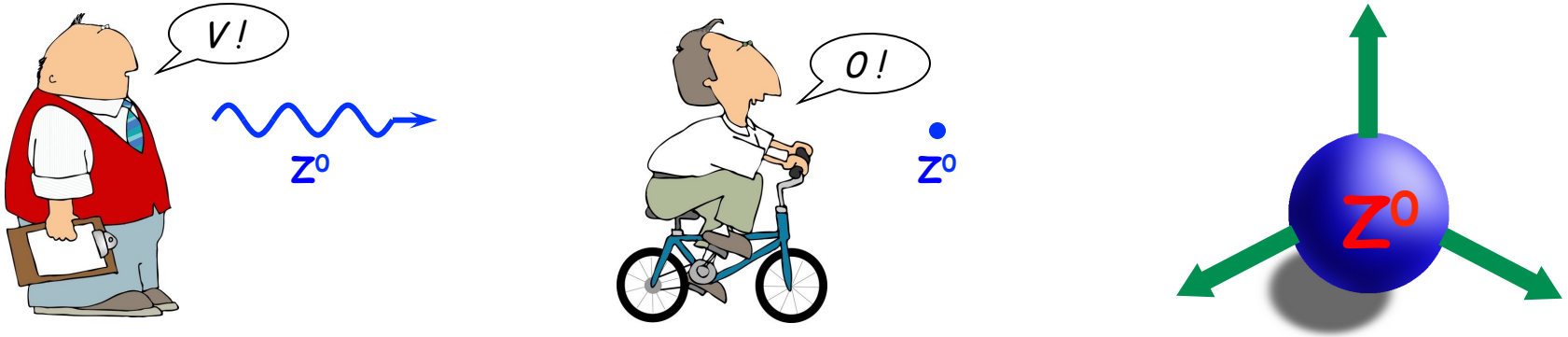
The “gauge trick” cannot work for massive particles

Why?

Einstein relativity: *c* is the same in every reference frame



I can choose a frame where a massive particle is at rest



In that frame: how can I distinguish longitudinal from transverse polarizations?

We have to live with 3 pol. ⇒ nonsense in HE scattering!

The root of the problem:

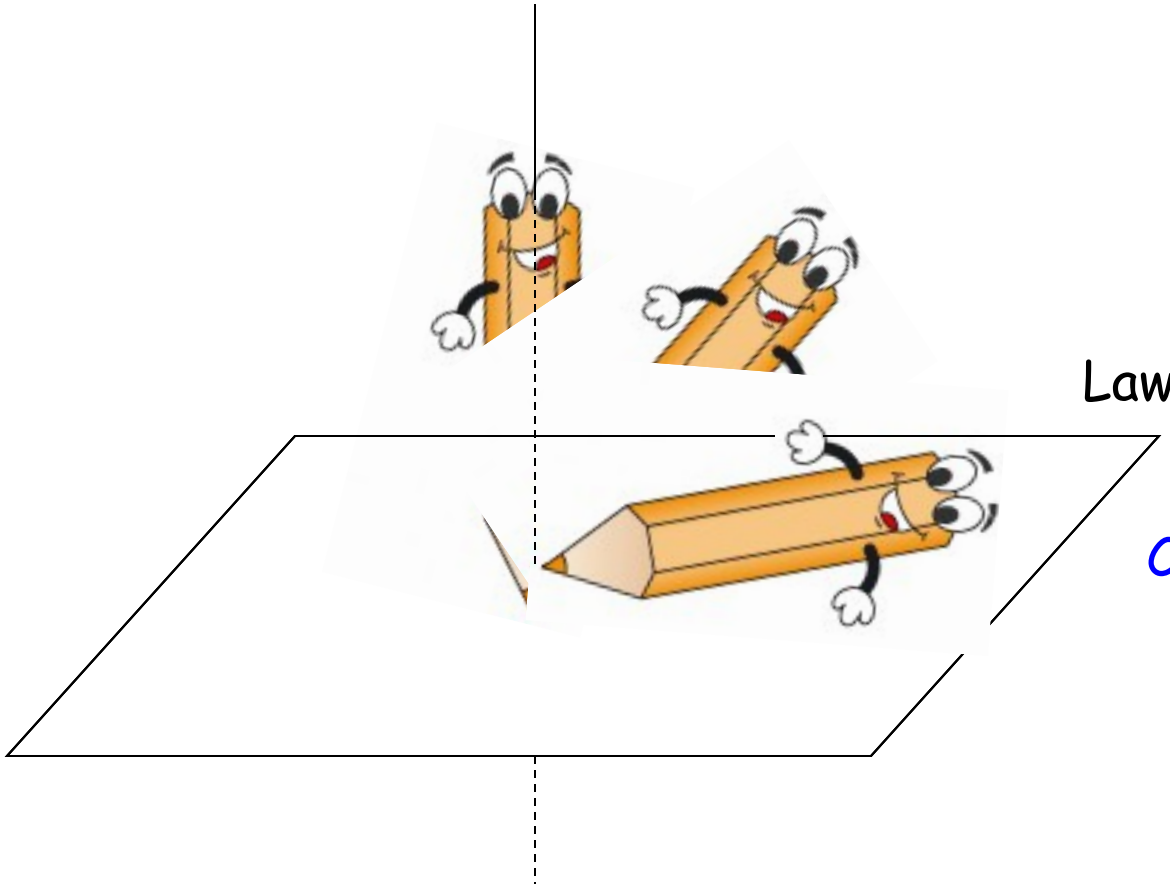
gauge symmetry ⇔ massless force carrier ⇔ controllable HE theory

How can we reconciliate *W, Z* masses (short-range weak force) with gauge symmetry?

Solution: EW symmetry is spontaneously broken

What does it mean?

Symmetry of equations, not of solutions

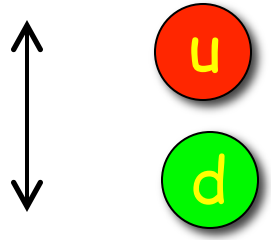


Laws invariant under rotation

Configuration not invariant

With spontaneously broken symmetry, mass relations implied by exact symmetry can be modified

Equations invariant under exchange



⇒ solutions with $M_u = M_d$

or solutions with $M_u > M_d$ possible,

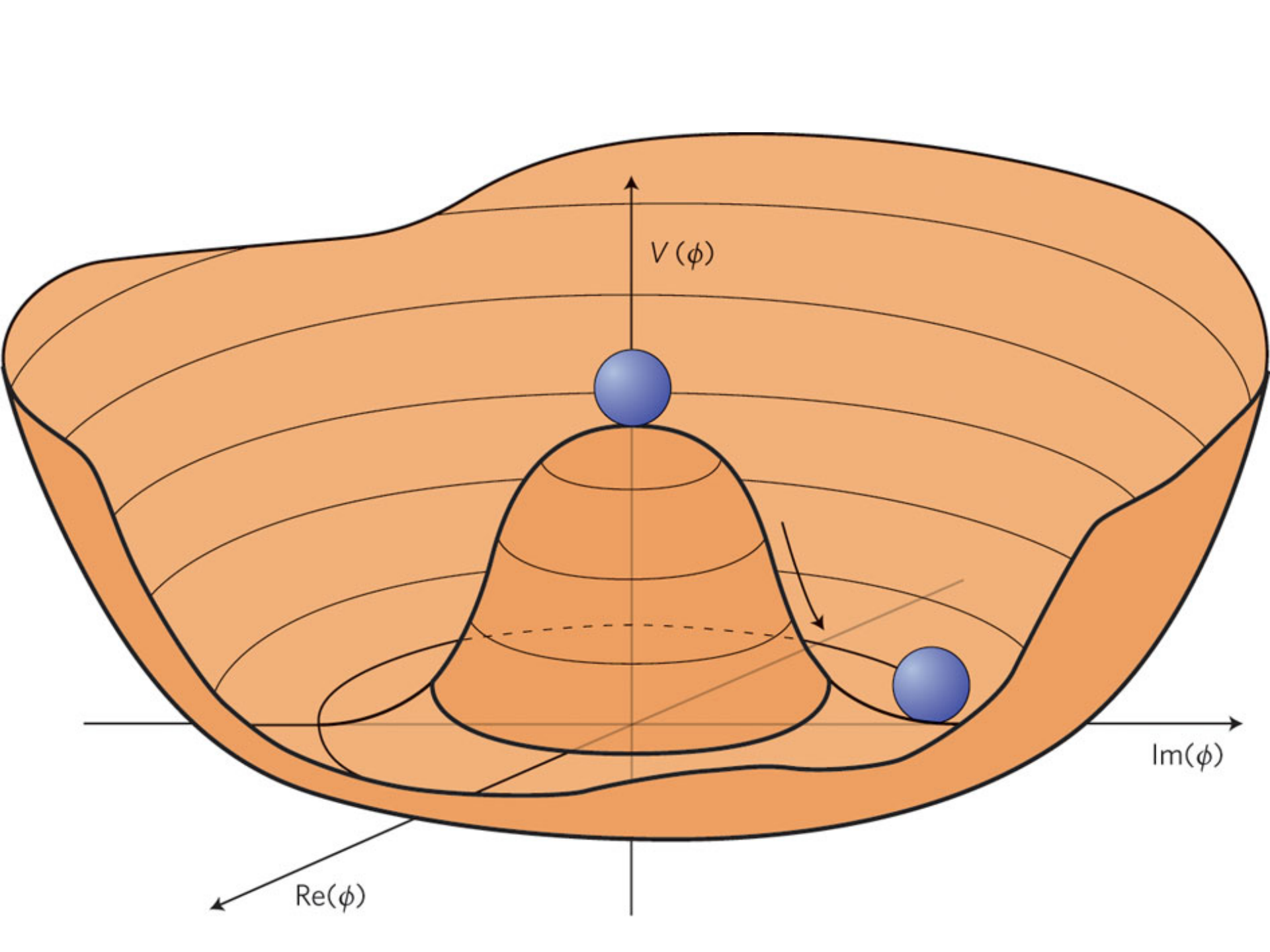
as long as $M_d > M_u$ also exists

Characteristic of SBS ⇒ degeneracy of solutions

Quantum interpretation ⇒ zero-energy excitation ⇒ massless particle

Goldstone 1961

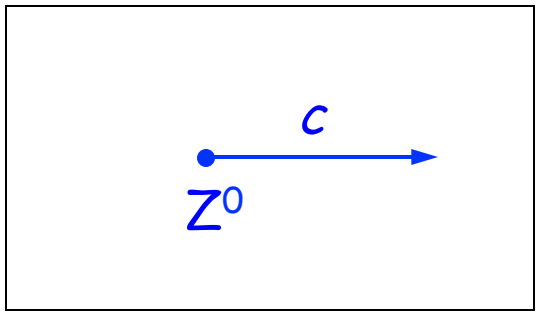
Goldstone boson main obstacle to apply SBS to EW


V (ϕ)
Im(ϕ)
Re(ϕ)

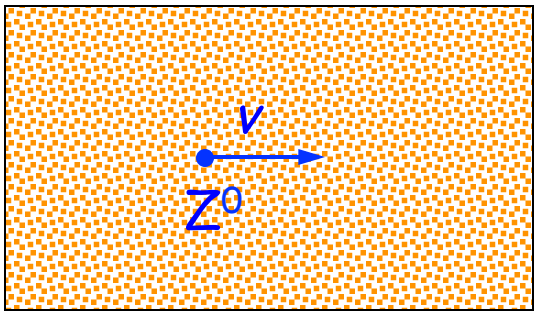
The Higgs mechanism is the solution!!!

Higgs field fills space with uniform distribution of EW charge

This distribution affects particle propagation



empty space



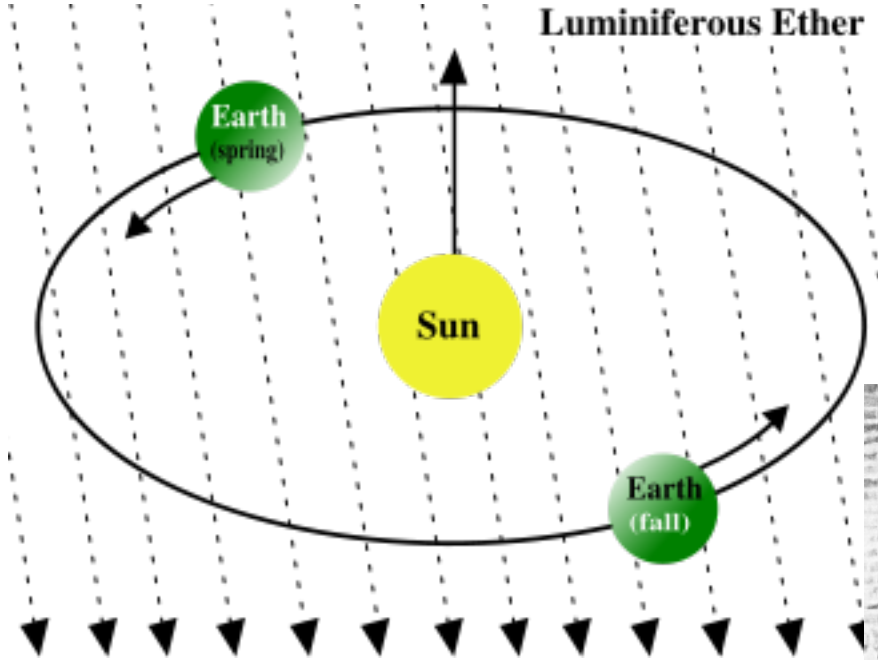
Higgs-filled space

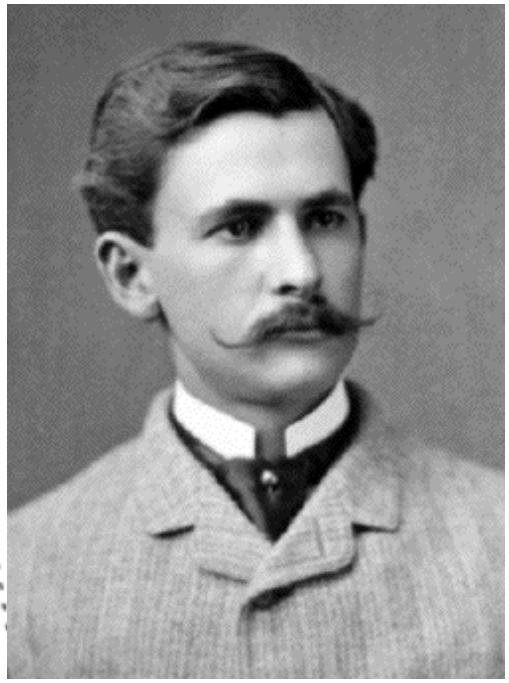
- large distances → mass
- small distances → longitudinal waves are part of the harmless Higgs field → no nonsense

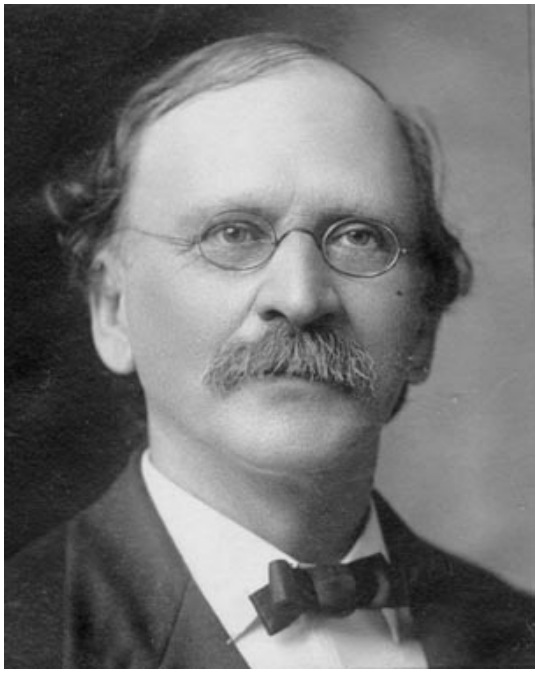
Spontaneous symmetry breaking:
configuration lacks the symmetry of the physical laws

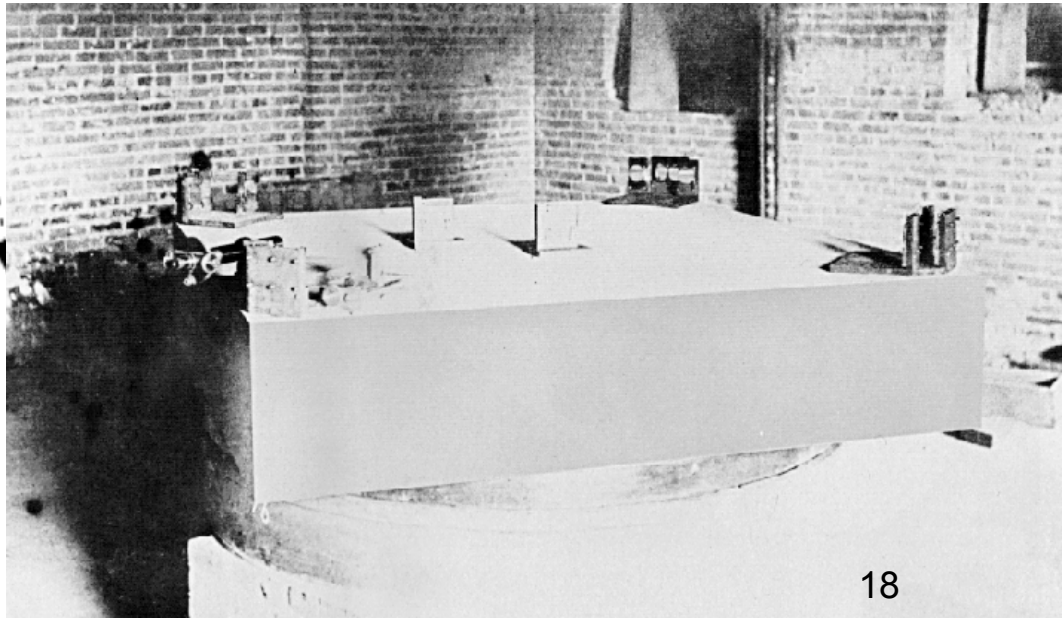
The Higgs mechanism gives a new understanding of the nature of space-time

A new form of aether?

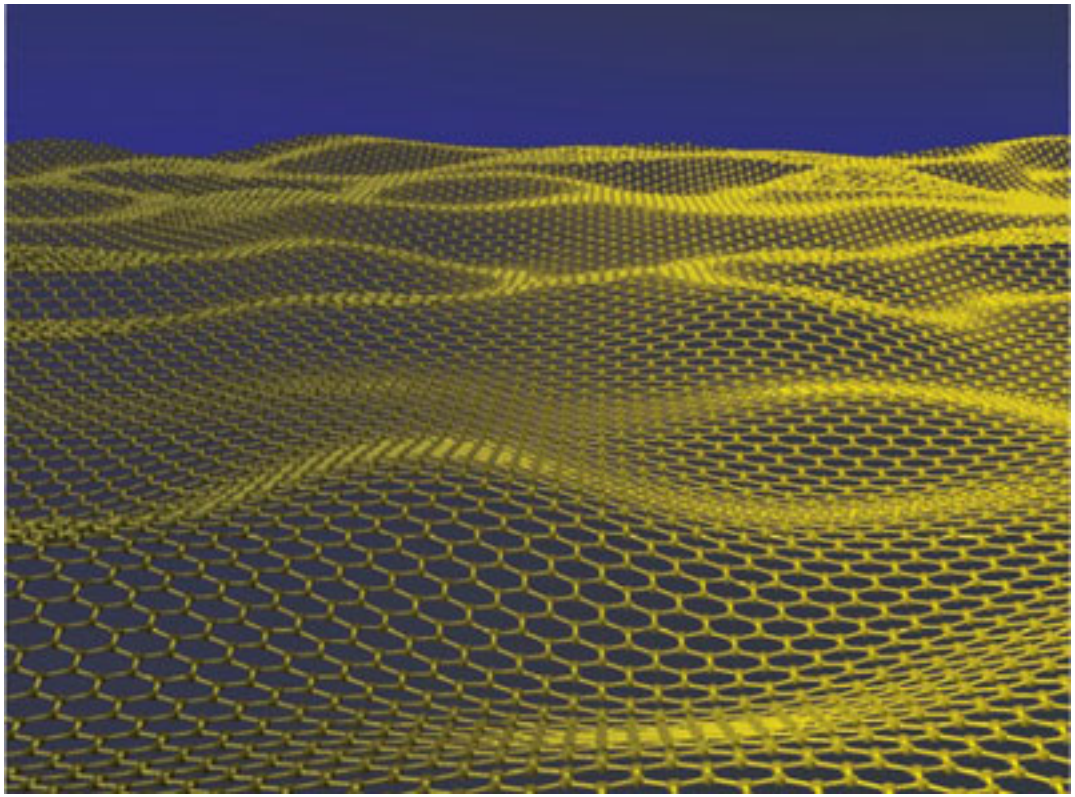






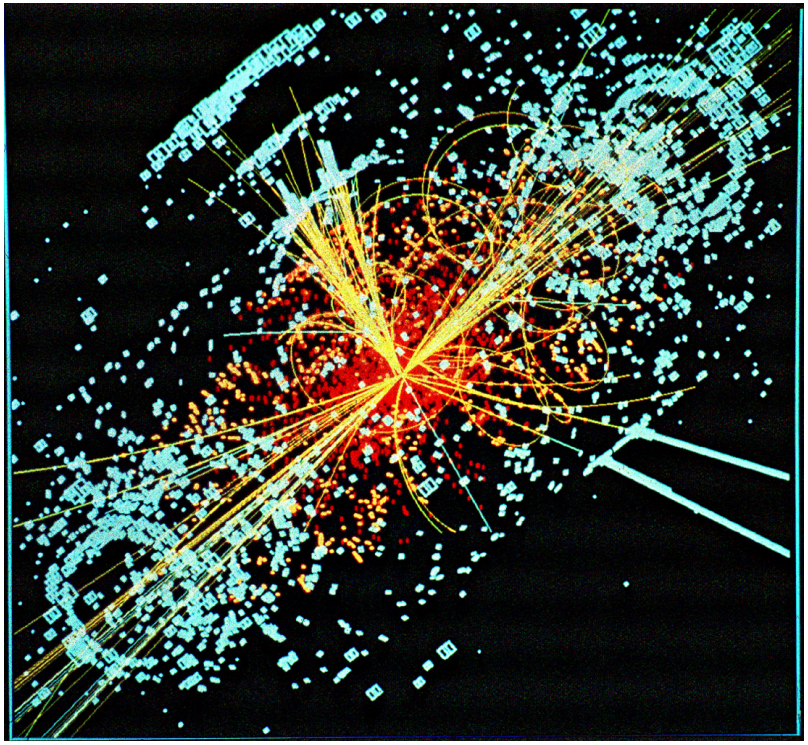


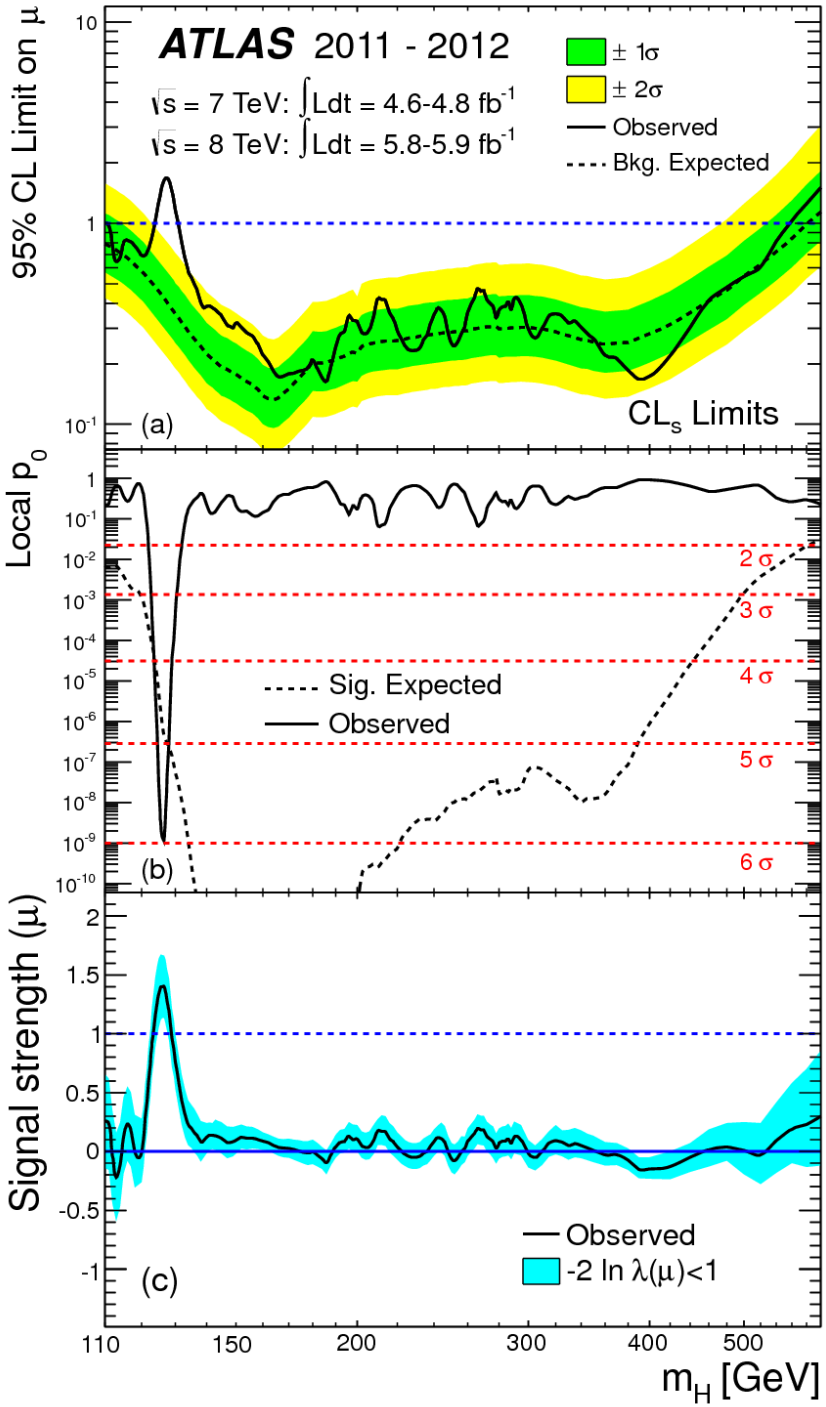
At 10^{-10} seconds after the Big Bang:
Space crystallized into a new form
Nature filled space because she saved energy



No difference, no matter how you move
with respect to this substance

s boson at the LHC





In relativistic quantum theories field $\Leftrightarrow$ particle $\Rightarrow$ Higgs boson

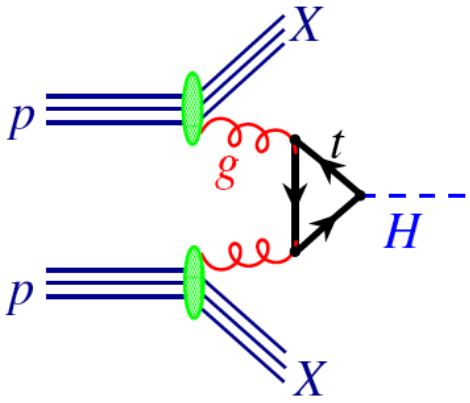
Particle mass $\Rightarrow$ how much it is dragged by Higgs field

Coupling of Higgs to 

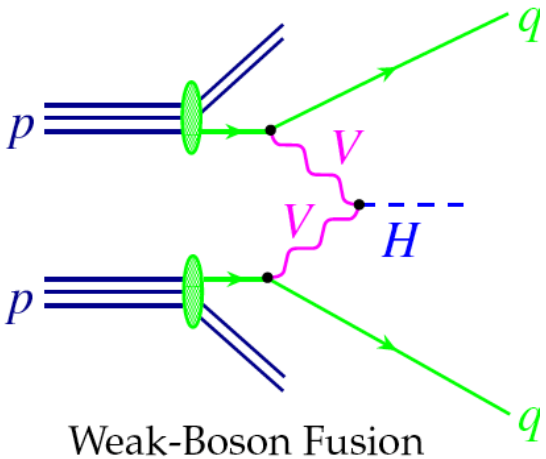
are proportional to M_p

M_H only free parameter: it measures Higgs self-coupling

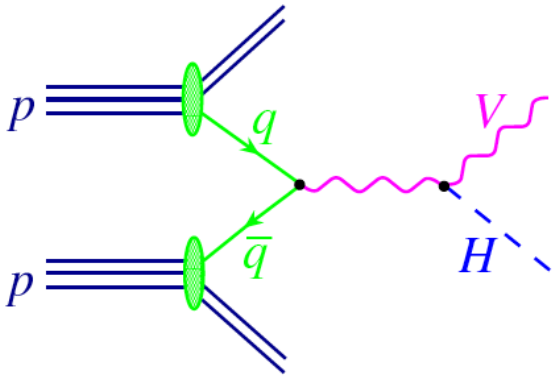
(but Higgs contributes to only 1% of my weight)



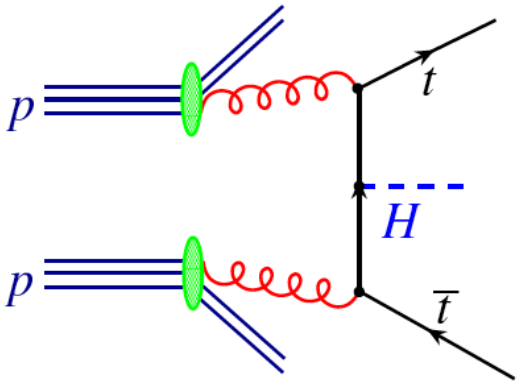
Gluon fusion



Weak-Boson Fusion



Higgs Strahlung



$t\bar{t}H$

Higgs decays in 10^{-22} seconds

Decay	Probability
H ➔ bb	58 %
H ➔ WW	21 %
H ➔ gg	9 %
H ➔ ττ	6 %
H ➔ cc	3 %
H ➔ ZZ	3 %
H ➔ γγ	0.2%
H ➔ Zγ	0.2%
H ➔ μμ	0.02%

Fit to Higgs couplings