The Standard Model, the Higgs and beyond

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CP3 - Origins
Particle Physics & Cosmology

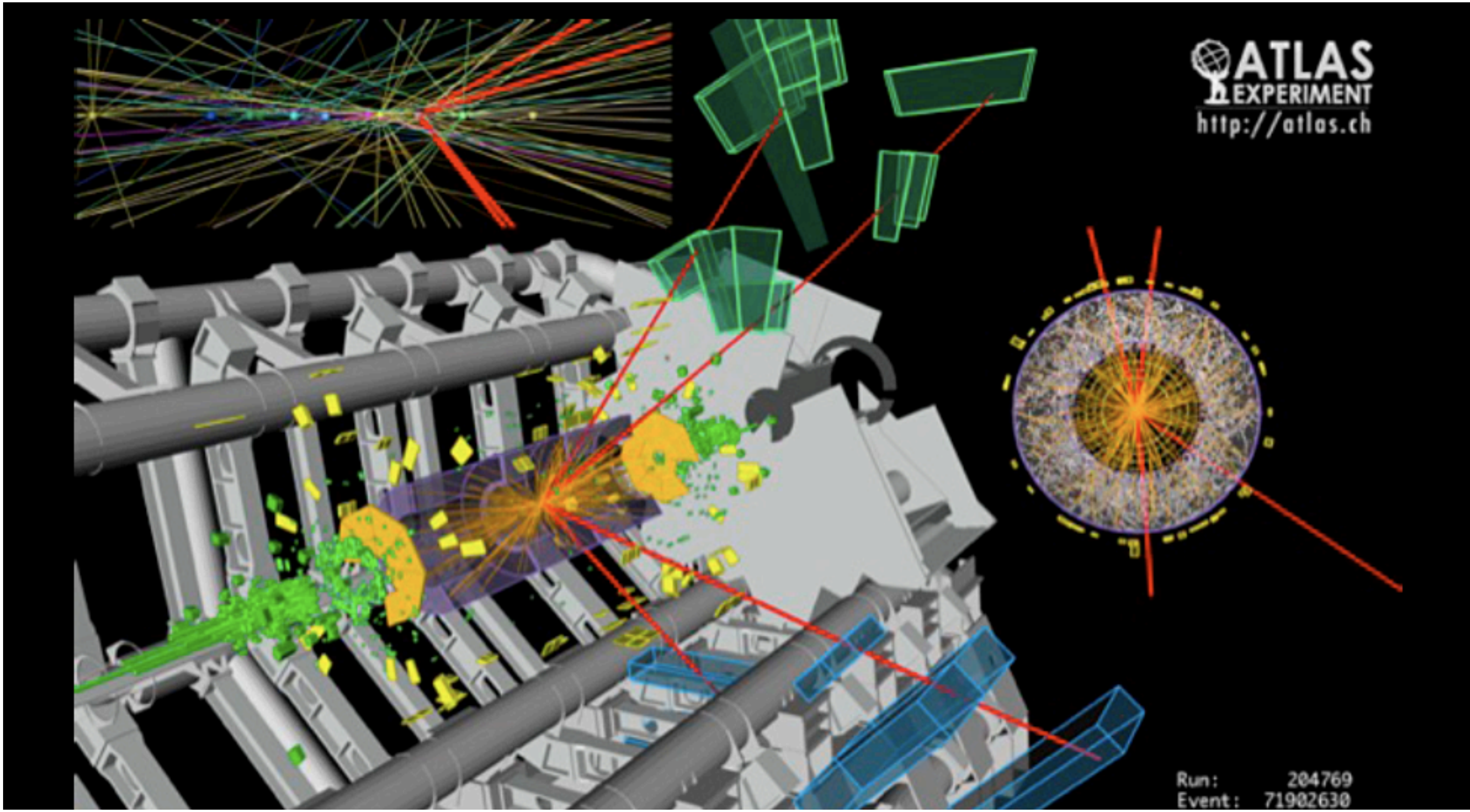
My life as a boson: by Professor Peter Higgs

http://www.swan.ac.uk/media-centre/livestreaming/higgs-boson/

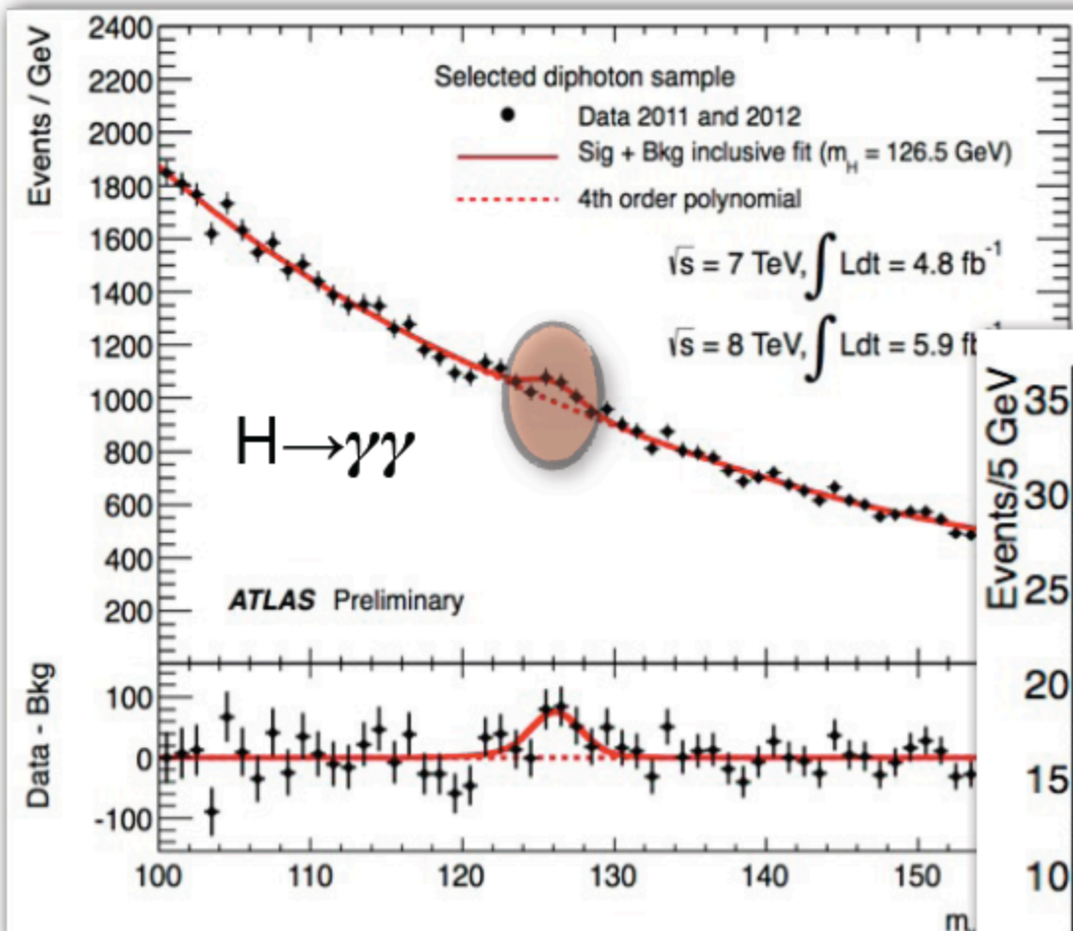
Based in part on lectures by Professor Graham Ross
http://indico.cern.ch/scripts/SSLPdisplay.py?stdate=2008-06-30&nbweeks=6

Visit www.cp3-origins.dk for various lectures and info

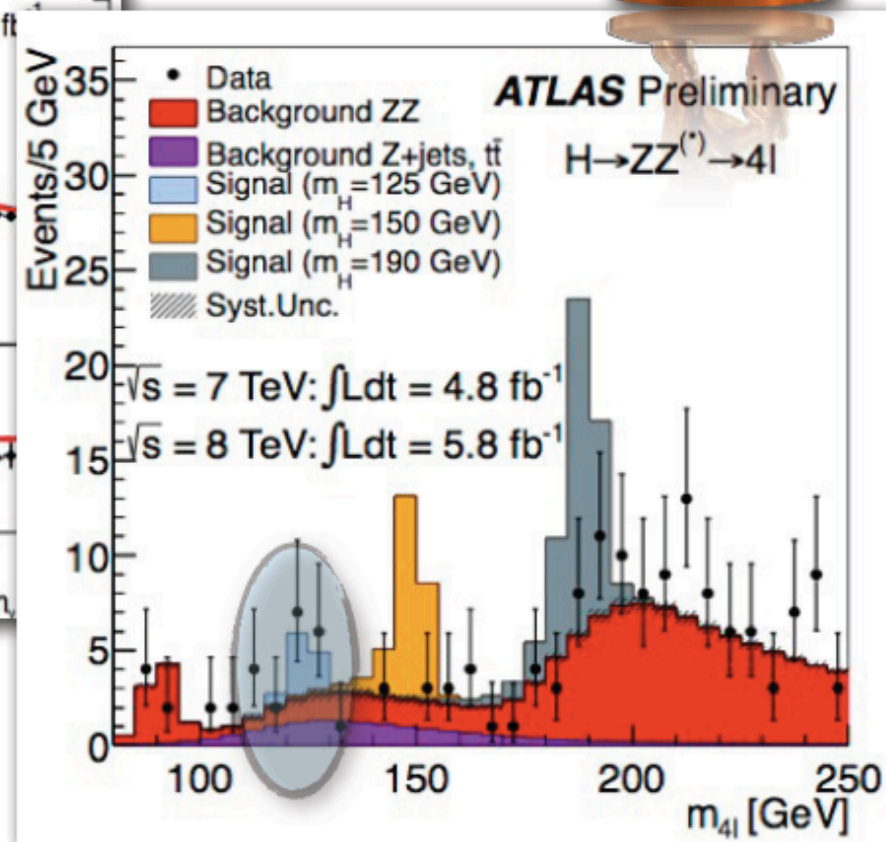
Nordita Master Class in Physics July-August 2012


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630

2 bumps

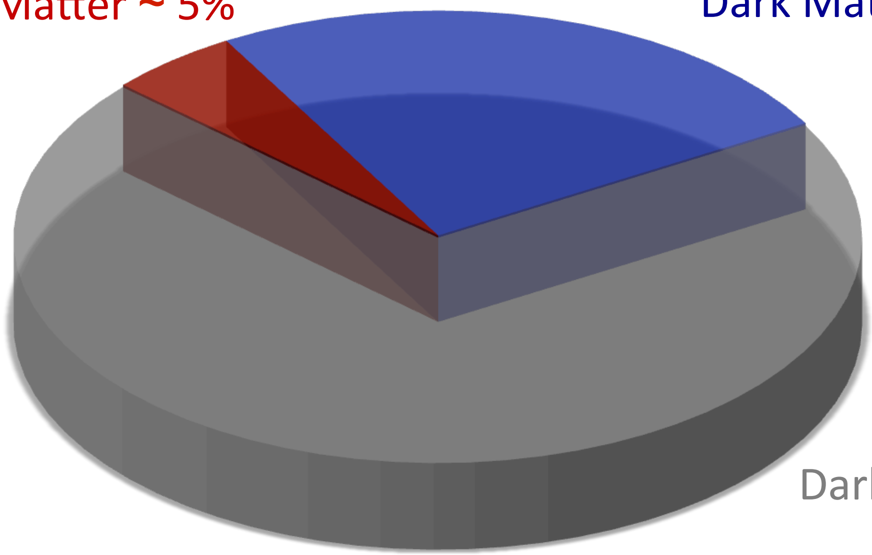


Events / GeV
Selected diphoton sample
Data 2011 and 2012
Sig + Bkg inclusive fit (m_H = 126.5 GeV)
4th order polynomial
$\sqrt{s}$ = 7 TeV, $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 5.9 fb^{-1}
H→γγ
ATLAS Preliminary
Data - Bkg
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
100
0
-100
100
110
120
130
140
150



Events/5 GeV
Data
Background ZZ
Background Z+jets, $t\bar{t}$
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
ATLAS Preliminary
H→ZZ$^{(*)}$→4l
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8 fb^{-1}
35
30
25
20
15
10
5
0
100
150
200
250
m_{4l} [GeV]

What is the world made of?



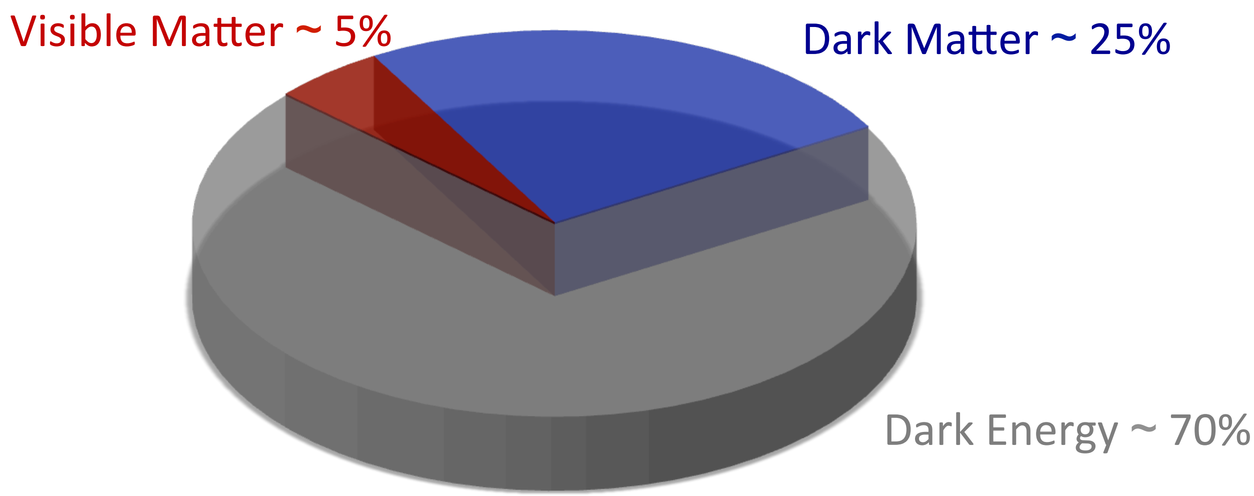
See lectures by Elgarøy for discussions of dark matter and dark energy

What is the world made of?

Two outstanding problems of the Standard Models of particle physics and cosmology:

What is the *origin* of mass?

What is the *nature* of Dark Matter?



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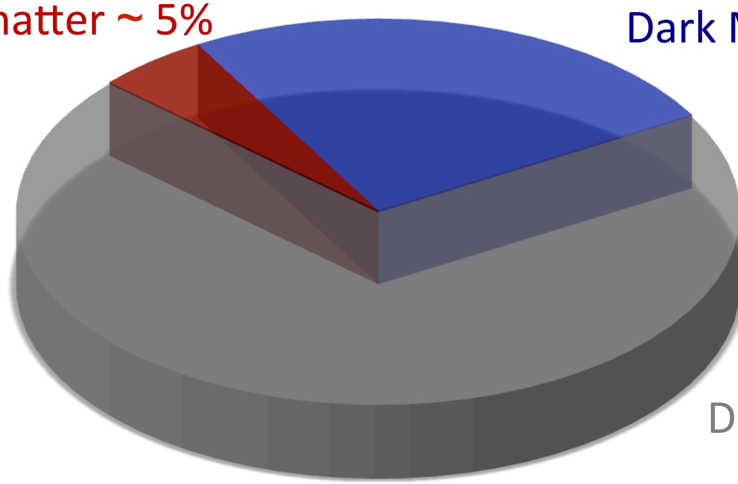

No obvious particle physics scale associated with the problem of dark energy

Many proposed particle physics scales associated with the nature and origin of DM

A definite particle physics scale related to (part of!) the origin of mass, i.e. Higgs-mechanism …though not necessarily the Higgs boson!

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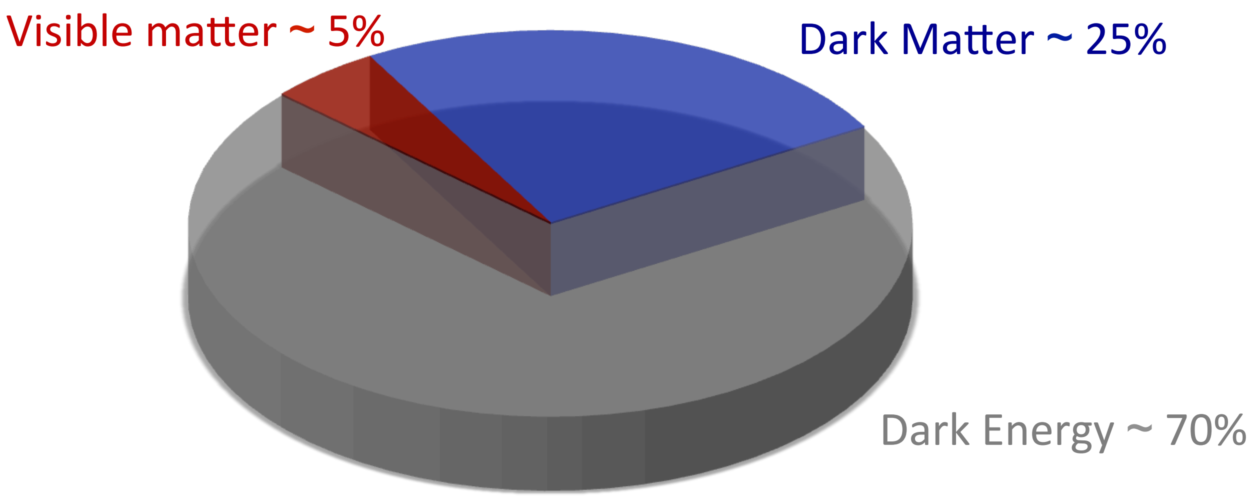


In these lectures we will discuss the SM describing the visible matter in the universe, and the origin of mass for the SM particles – the Higgs mechanism

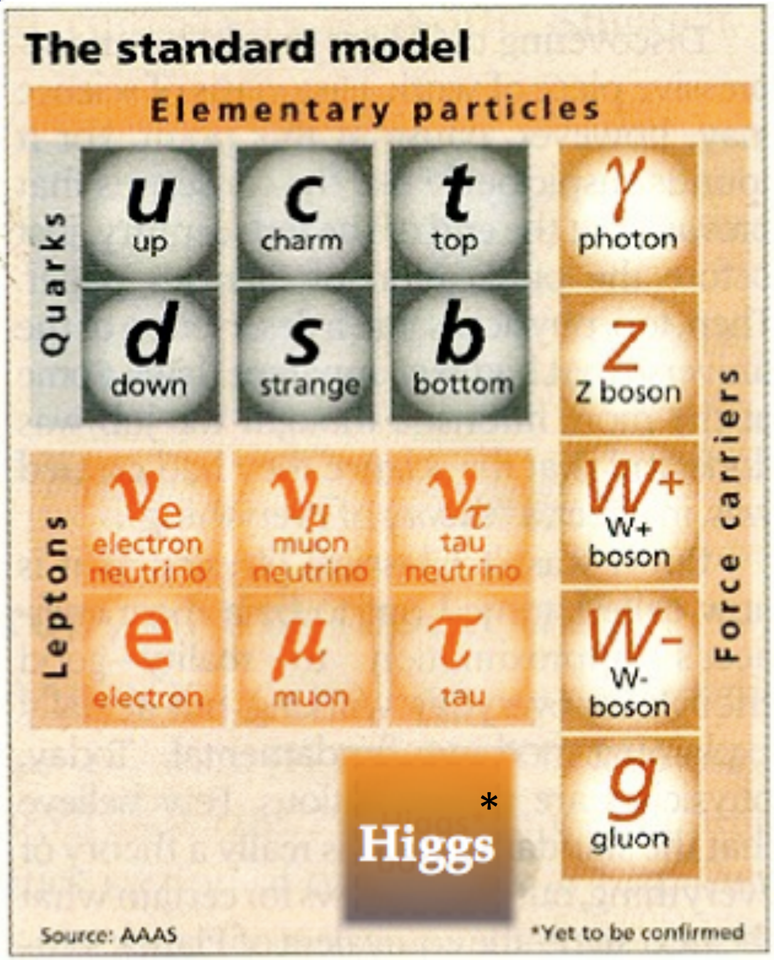
The SM, the Higgs and beyond

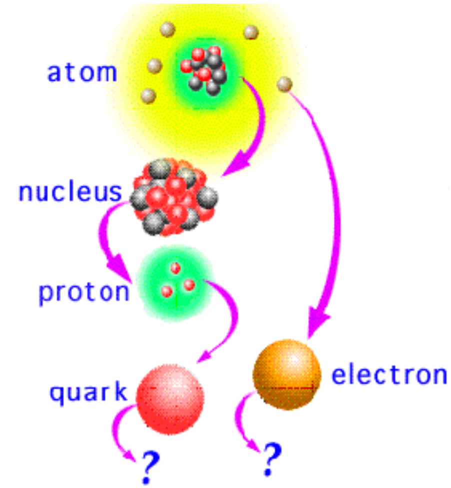
Tentative Outline

- Lecture 1 – Fundamental particles and interactions, Higgs teaser
- Lecture 2 - Symmetries, Quantum Field Theory, Gauge Theory
- Lecture 3 - The SM, the Higgs Mechanism of the Standard Model
- Lecture 4 – Beyond the SM, curing the ills of the SM Higgs boson?

The accompanying notes and exercises, which you should work through will provide the details omitted in the lecture slides

The Standard Model on a stamp





U(1)

SU(2)

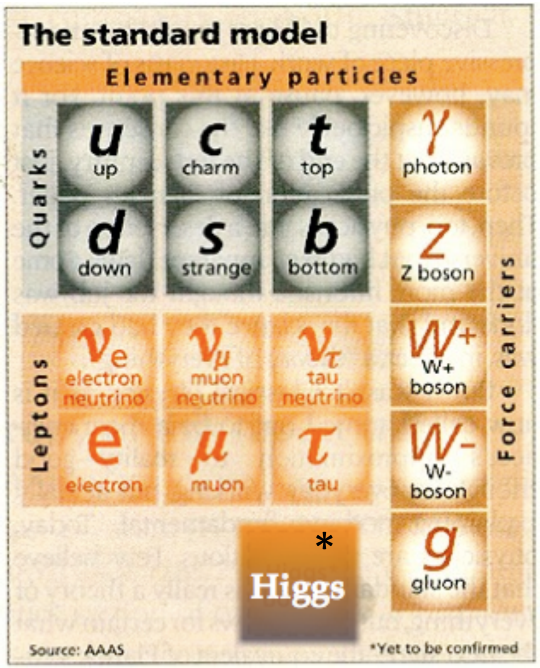
SU(3)

4 known Fundamental Interactions

	Strength
Strong	$\alpha_s = \frac{g_s^2}{4\pi\hbar c} \sim 1^{\dagger}$
Electromagnetic	$\alpha_{em} = \frac{e^2}{4\pi\hbar c} \sim \frac{1}{137}$
Weak	$G_F m_p^2 \sim 10^{-5\dagger}$
Gravitational	$G_N m_p^2 \sim 10^{-36}$

† *Short range* (Do you know why?)

The Standard Model



Each particle defined by a few charges or *quantum numbers:*

U(I) Electric-, weak-, strong charge, mass and in addition spin.

SU(2) For each charge there is a corresponding force acting on the charge – described by a gauge theory

SU(3)

Matter particles are spin-1/2

Force particles are spin -1

Higgs Boson in the SM is spin-0

Fundamental Interactions

	Strength
$Strong - SU(3)$	$\alpha_s = \frac{g_s^2}{4\pi\hbar c} \sim 1^{1\dagger}$
$EM - U(1)$	$\alpha_{em} = \frac{e^2}{4\pi\hbar c} \sim \frac{1}{137}$
$Weak - SU(2)$	$G_F m_p^2 \sim 10^{\ddagger 5}$
$Gravitational$	$G_N m_p^2 \sim 10^{-36}$

THE PERIODIC TABLE

Particles like the electron (fermions, spin 1/2)

	Leptons		Quarks (each in 3 "colors")	
	e 0.511 MeV	ν_e < 0.000003	d 7	u 3
	μ 106	ν_μ < 0.2	s 120	c 1200
	τ 1777	ν_τ < 20	b 4300	t 175,000
← charge	-1	0	$-1/3$	$2/3$

Particles like the photon (bosons, spin 1)

γ 0	photon	"electromagnetism"
g 0	gluon (8 "colors")	"strong interaction"
$W^\pm$ 80,420	Z^0 91,188	"weak interaction"

Forces

Can we understand forces as particle exchange clasically?

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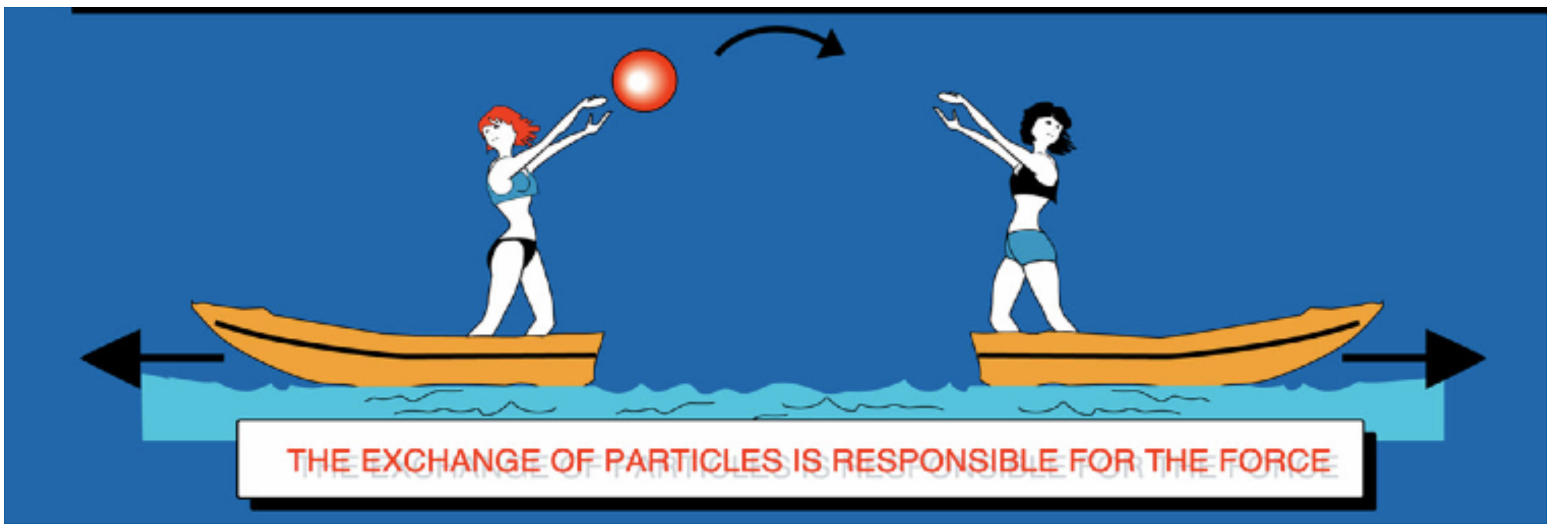
Repulsive force as particle exchange:



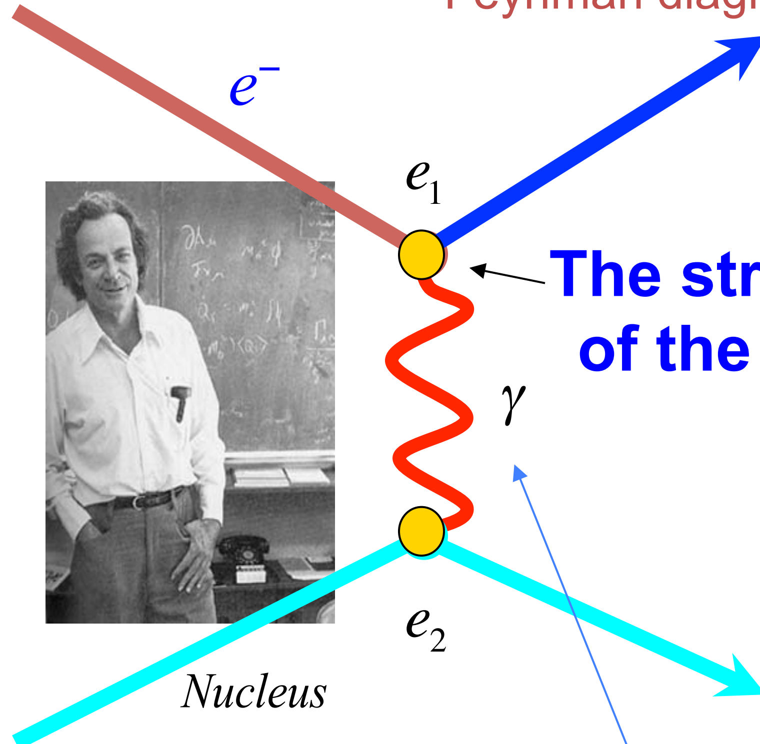
What about an attractive force?

Exchange forces

Electromagnetism

$$V_{em}(r) = \frac{e_1\, e_2}{4\pi}\,\frac{1}{r}$$

Feynman diagram



The strength of the force

In momentum space :

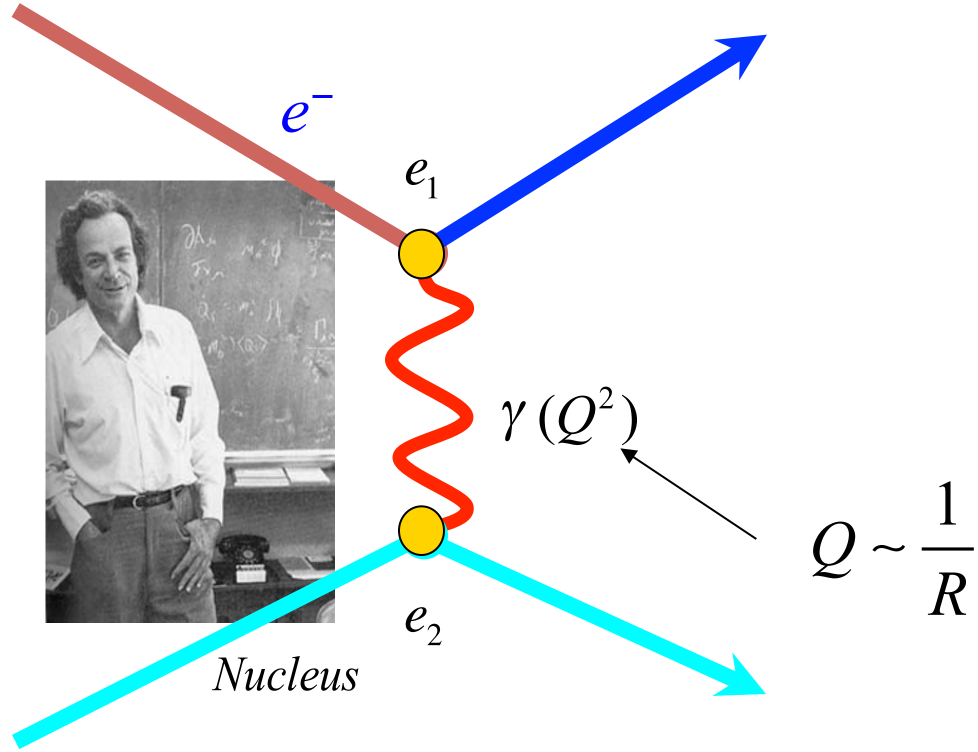
$$V_{em}(|\mathbf{q}|) \sim \int V_{em}(|\mathbf{r}|)e^{-i\mathbf{k}.\mathbf{r}}d^3\mathbf{r} \sim \frac{\alpha}{|\mathbf{k}|^2}$$

Photon “propagator”

Exchange forces

Electromagnetism

$$V_{em}(r) = \frac{e_1\, e_2}{4\pi}\,\frac{1}{r}$$



Experiments conducted in momentum space :

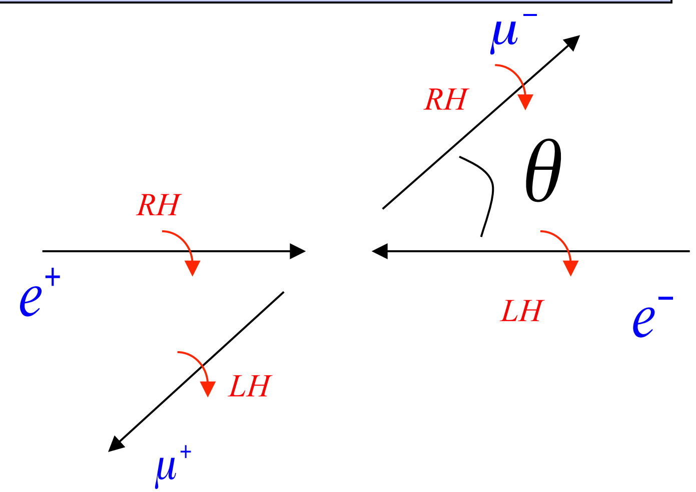
$$V_{em}(|\mathbf{q}|) \sim \int V_{em}(|\mathbf{r}|)\, e^{-i\mathbf{k}.\mathbf{r}}\, d^3\mathbf{r} \sim \frac{\alpha}{|\mathbf{k}|^2}$$

$$Q^2 \equiv -\mathbf{k}^2$$

"*virtual photon*"

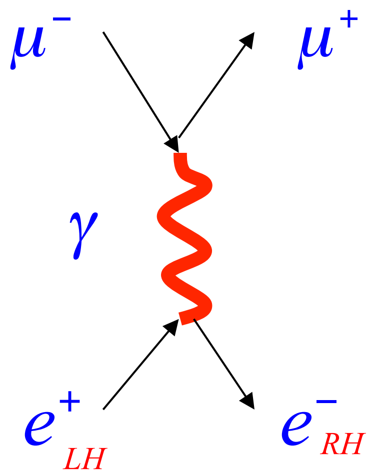
Application to a scattering processes

$$e^+e^- \to \mu^+\mu^-$$



$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 E_{CM}^2}|M|^2$$

Feynman diagram



QM : Transition amplitude <final state$|H_I|$initial state>

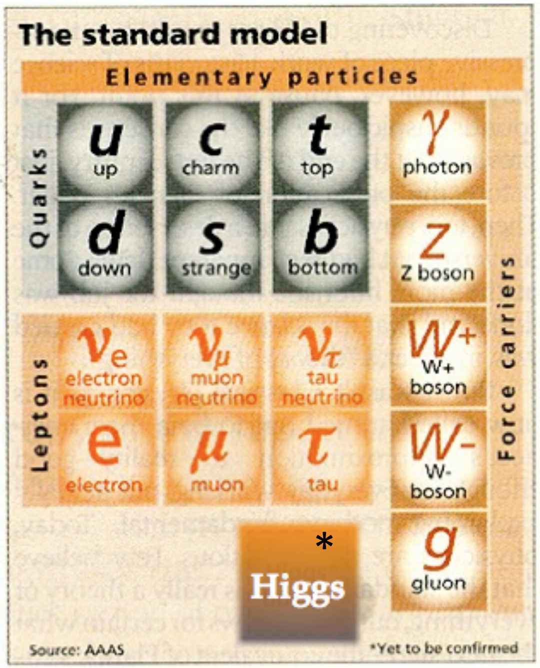
$$M \propto <\mu^+\mu^- | H_I | \gamma >^\alpha < \gamma | H_I | e^+e^- >_\alpha$$

$$<\gamma | H_I | e^+e^- >^\alpha \propto e\,(0,1,i,0)$$

$$<\mu^+\mu^- | H_I | \gamma >^\alpha \propto e\,(0,\cos\theta,i,\sin\theta)$$

$$M(RL \to RL) = \quad e^2(1+\cos\theta)$$

The Standard Model



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Higgs Boson looks special but more generally
Mass is a special charge!...
can you give a reason why?

Mass and the elementary particles

i) There is no anti-charge for mass!
But here we completely neglect gravity which is unimportant for elementary particle processes and we dont have a quantum theory of gravity…theres plenty to do!

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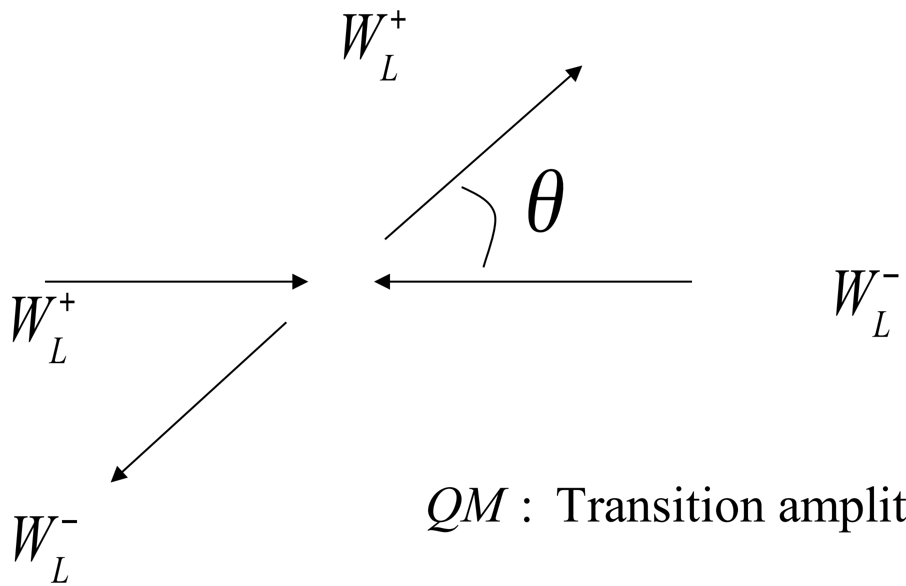
ii) There is another peculiar feature of mass in a quantum theory :
Scattering of massive spin one-states:

Do you remember any spin-1 states (Lorentz vector) from classical or quantum physics?
How many *degrees of freedom?*
How many *physical* degrees of freedom does a massless spin-1 field have?
How about a massive spin-1 vector. Can you explain why?

Scattering of massive W-bosons



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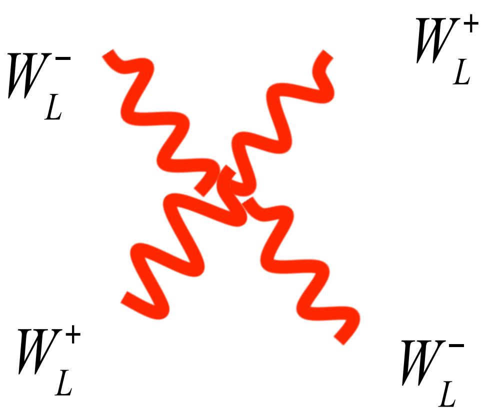
Feynman diagram

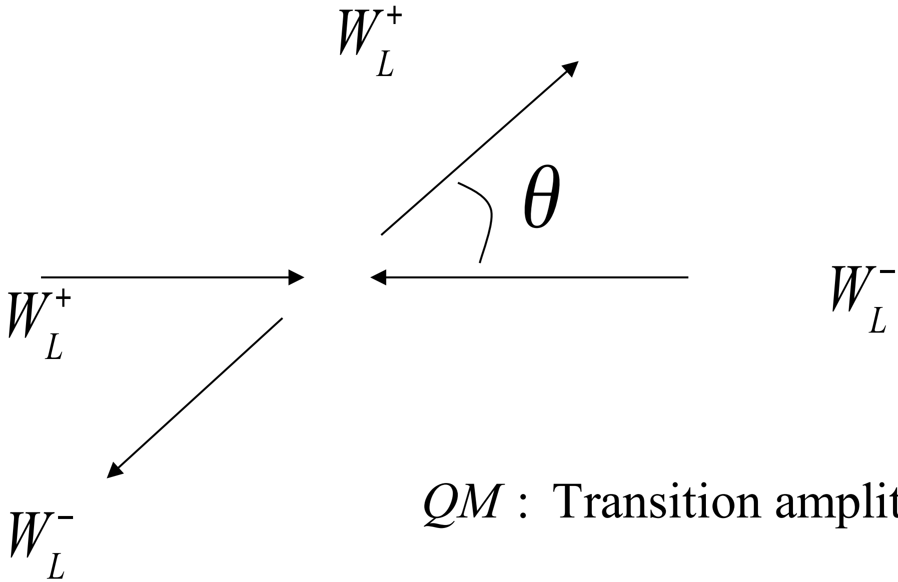


$$M \propto \langle W^+W^- | H_I | W^+W^- \rangle$$

$$M(W_L^+W_L^- \rightarrow W_L^+W_L) \sim \quad E^2 / m_W^2 \,!$$

Where E is the energy…what does this imply for
High energy scatterings such as at LHC?

Scattering of massive W-bosons



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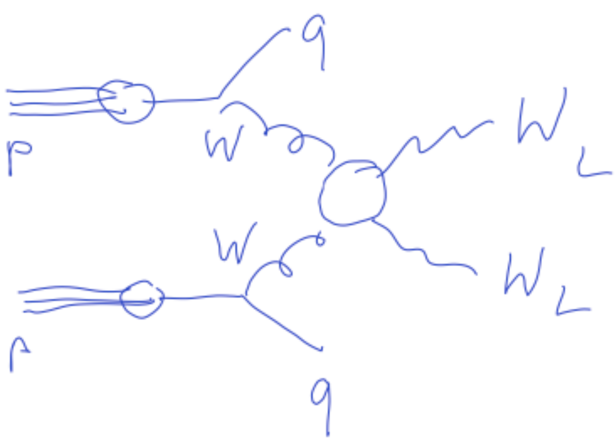

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Either QM breaks down or we discover something new at LHC…seems that we already are starting to see it

The Higgs mechanism

Gauge theories do not suffer from the *unitarity* problem, spin-1 gauge fields are massless

In fact we take *gauge symmetry* as a fundamental symmetry of the SM.
However, the W/Z *Bosons are still observed to be massive*

The way out is to invoke the Higgs-mechanism and mass as an emergent phenomenon via *Spontaneous symmetry breaking*

We will (hopefully) see towards the end how the Higgs boson can unitarize WW scattering

The Higgs mechanism - teaser

Consider a theory with a real scalar field ϕ(x,t) (you can think of it just as a classical particle Next lecture will introduce Quantum Field Theory)

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

What *symmetry*, i.e. a non-trivial transformation of ϕ(x,t) leaves the potential invariant?:

$$P : \phi \to \phi' \ ; \quad V(\phi) = V(\phi')$$

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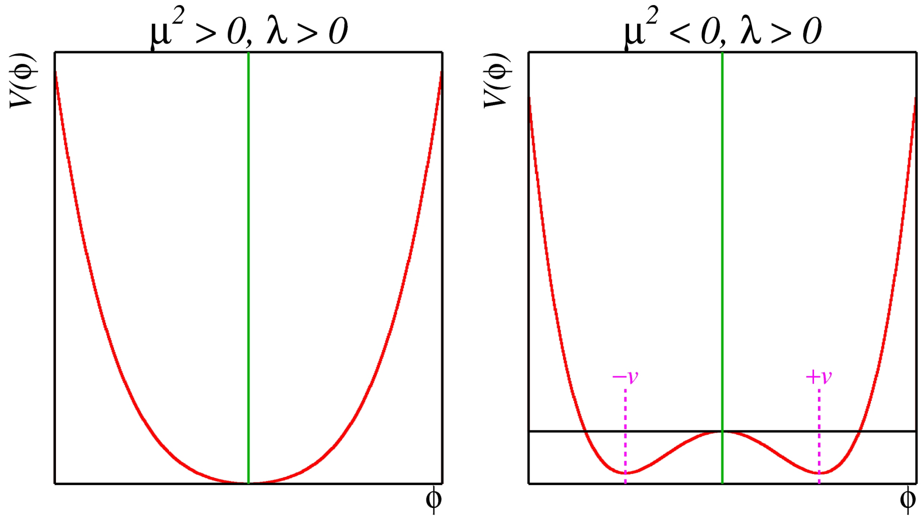

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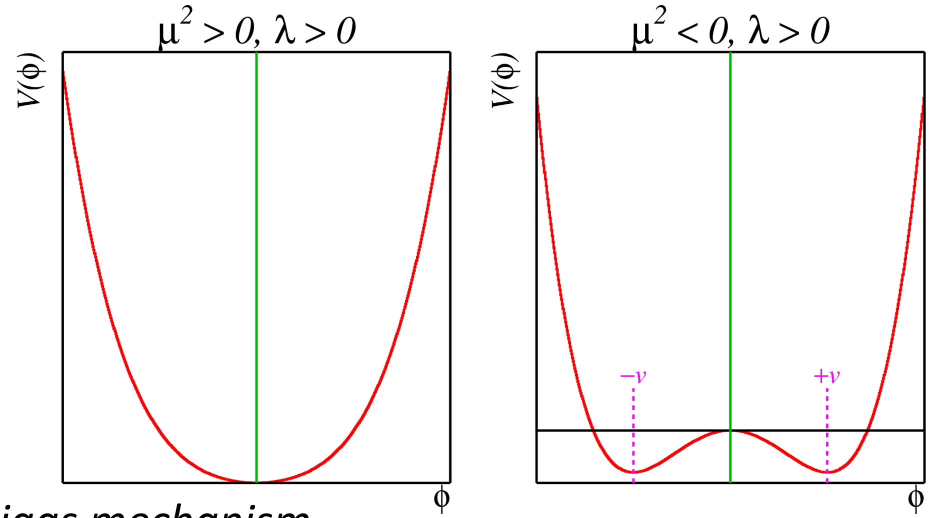

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This is our first example of
Spontaneous symmetry breaking or the Higgs mechanism

The Higgs mechanism - teaser

Now consider the same theory coupled to another field ψ via

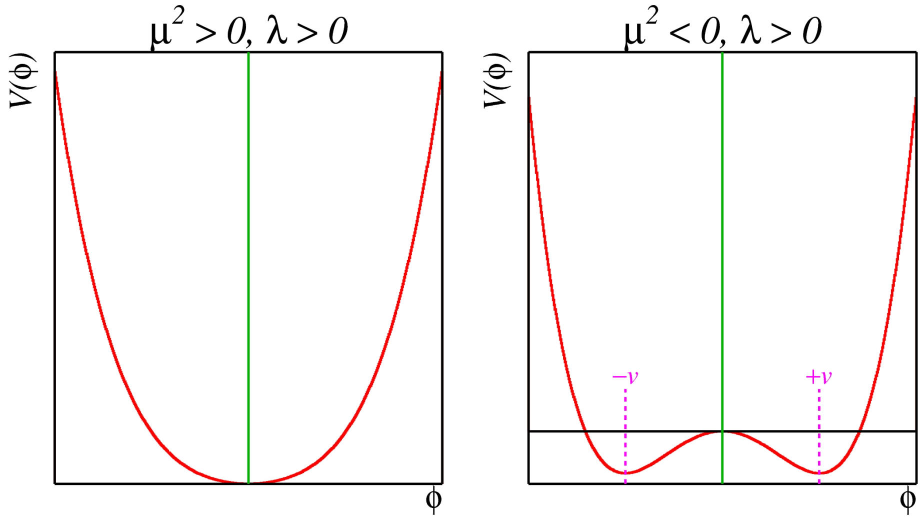
$$V(\phi) = \mu^2\phi^2 + \frac{1}{2}\lambda^2\phi^4 + \frac{1}{2}\psi^2\phi$$

To do perturbation theory in the broken phase we expand $\phi = v + \delta\phi$

$$V(\phi) \to \frac{1}{2}\psi^2 v + \ldots$$

The field ψ has acquired a mass!

This is our first example of
Spontaneous symmetry breaking
and *the Higgs mechanism*



v is a 'preferred direction' in field space – compare alignment of magnets, Hansson's lecture

Goldstone Theorem

It turns out that there is one essential feature need for the SM Higgs mechanism that our toy model does not capture – *Goldstone bosons*

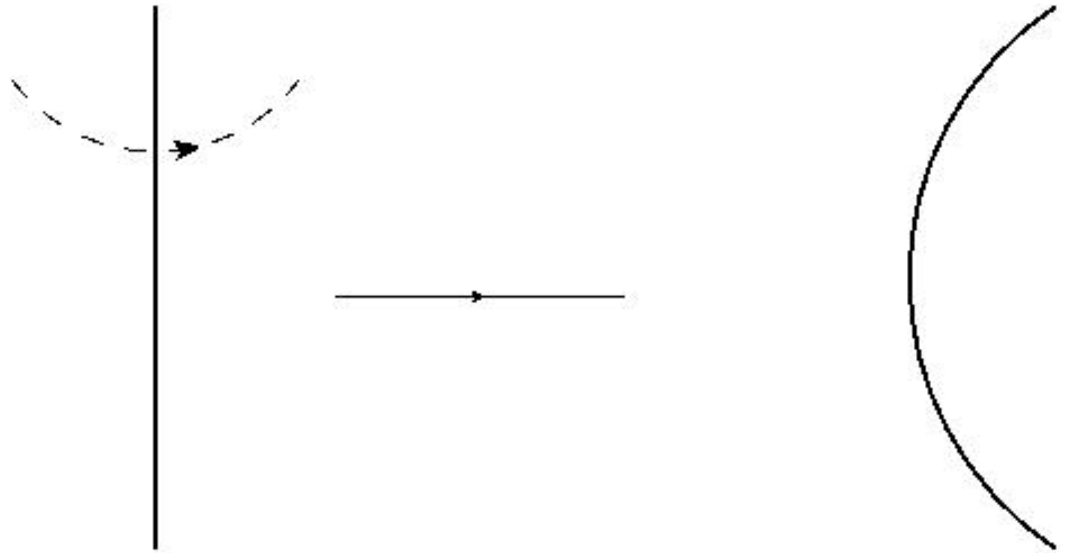
Our example was of spontaneous breaking of a *discrete symme*try we need to consider Spontaneous breaking of a *continuous symmetry*

Goldstones Theorem:

For every *spontaneously broken global continuous* symmetry
there will be an associated *massless* particle

Goldstone Theorem - examples

This is simpler than it might sound!
What are the symmetries before and after we bend a (nearly) rigid rod attached at both ends?



Can you identify a ‘massless excitation’ existing after but not before symmetry breaking?

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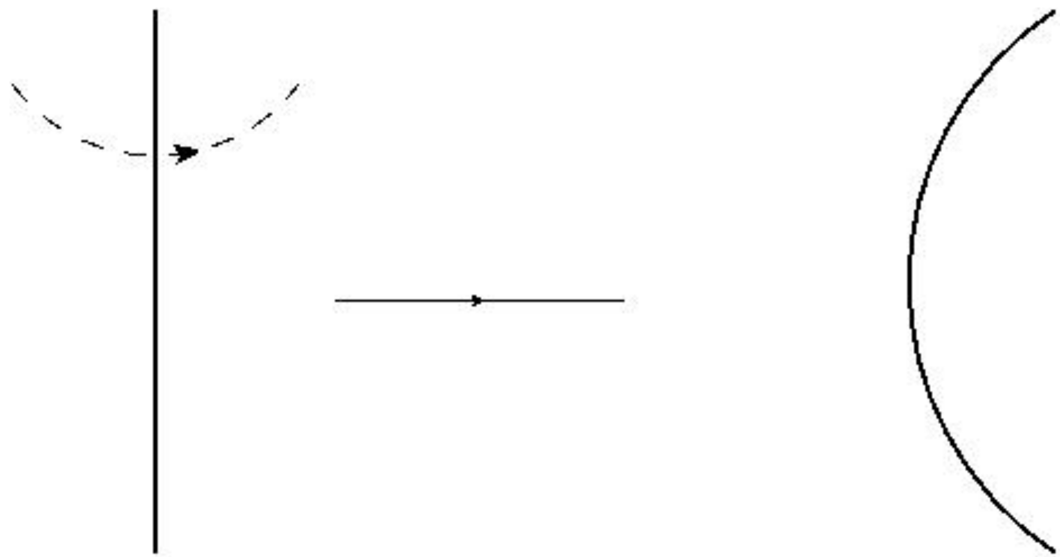

Can you identify a ‘massless excitation’ existing after but not before symmetry breaking?

What about water freezing to ice, can you identify a ‘massless excitation’ there?

Generally related to phase transitions as in Hansson’s lectures –
What drives the Higgs mechanism? -> Beyond the Standard Model!

Goldstone Theorem

Goldstones Theorem:

For every *spontaneously broken* *global continuous* symmetry there will be an associated *massless* particle

The Higgs Mechanism:

If the spontaneously broken global symmetries are *gauged* the corresponding gauge fields will acquire mass.

In fact the longitudinal mode of those gauge fields 'are' the Goldstone bosons which are *eaten*

All of these statements and toy examples are what we now aim to concretize in the SM Quantum Field Theory and beyond!