The Higgs Boson

Seminar

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1 – Outline

- Historical Introduction
- From Symmetries to Interactions
- The World we live in and problems with its description
- Spontaneous Symmetry Breaking
- The Higgs Mechanism
- The Higgs boson mass
- Production and Decay of a Higgs particle at LHC

2 – Historical Introduction

- ☞ 1964: Peter W. Higgs formulates the Higgs Mechanism
- ☞ 1967: Glashow, Salam and Weinberg unify electroweak interactions
- ☞ 1973: discovery of neutral currents
- ☞ 1983: weak bosons W and Z are discovered
- ☞ 1989: electron–positron collisions at LEP and SLC start
- ☞ 1995: discovery of top quark at Fermilab
- ☞ 2007: first collisions at LHC

3 – From Symmetries to Interactions

Invariance under transformation leads us to conservation laws (Noether's theorem):

- translations $\longrightarrow$ conservation of momentum;
- time displacements $\longrightarrow$ energy conservation;
- rotations $\longrightarrow$ angular momentum.

Lagrange equation $(L(q_i, \dot{q}_i, t) \longrightarrow \mathcal{L}(\phi, \frac{\partial \phi}{\partial x_\mu}, x_\mu))$:

$$\frac{\partial}{\partial x_\mu}\left(\frac{\partial \mathcal{L}}{\partial(\partial \phi / \partial x_\mu)}\right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0 \tag{1}$$

An electron, described by the Dirac equation is invariant under phase transformation

$$\psi(x) \longrightarrow e^{i\alpha}\psi(x). \tag{2}$$

The family of such phase transformations forms a unitary Abelian group known as $U(1)$.

- Noether's theorem implies conserved charge

the higgs boson – from symmetries to interactions 2/3

Invariance of type 2 implies that phase α is unmeasurable: it can be chosen arbitrarily.

$\Downarrow$

global gauge

More general case is when $\alpha = \alpha(x)$. We shall call this type of gauge local gauge.

Lagrangian of an electron, described by the Dirac equation

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi. \qquad (3)$$

It is invariant under a global phase transformation, but not under local

$$\psi(x) \longrightarrow e^{i\alpha(x}\psi(x) \qquad (4)$$

since the $\partial_{\mu}\alpha(x)$ term breaks the invariance. We define modified derivative

$$D_{\mu} \equiv \partial_{\mu} - igV_{\mu}, \qquad (5)$$

with vector (gauge) field V_{μ} that transorms as

$$V_{\mu} \longrightarrow V_{\mu} + \frac{1}{g}\partial_{\mu}\alpha. \qquad (6)$$

Local gauge invariant Lagraingian for electron that corresponds to the Dirac equation:

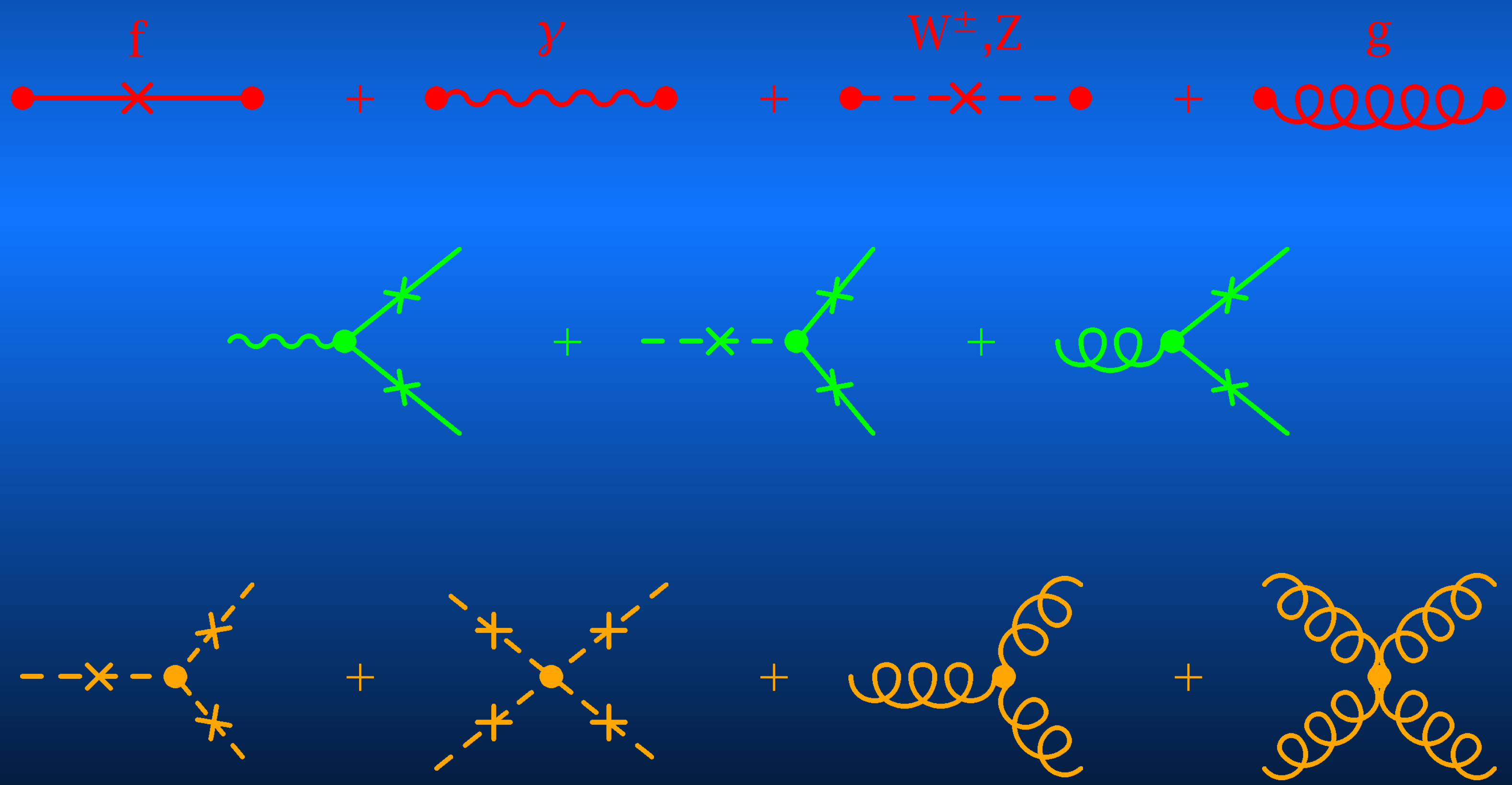
$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi + g\bar{\psi}\gamma^{\mu}\psi V_{\mu} + \ldots \tag{7}$$

There is no $\frac{1}{2}m^2 V_{\mu}V^{\mu}$ since it is prohibited by gauge invariance. The gauge particle (in QED example the photon) is massless.

4 – The World we live in

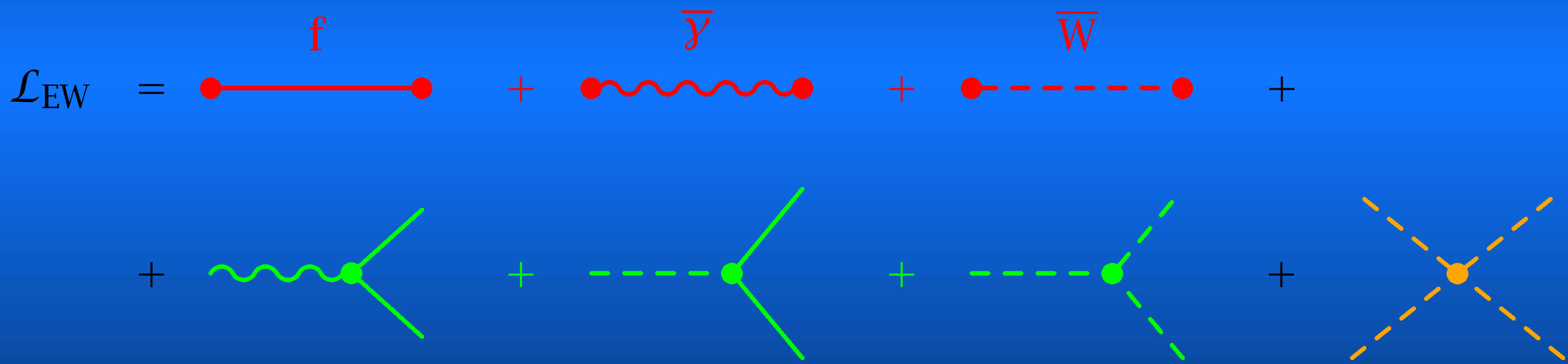
A Lagrangian corresponding to the observed interactions is presented in 1. This is the world we live in or better the part we know how to describe.

Figure 1:



The electroweak theory, developed by Glashow, Weinberg and Salam in 1967 describes just a part of the Lagrangian, depictated in 1. The electroweak $(SU(2)_L \times U(1)_Y)$ Lagrangian consists of:

Figure 2:



the higgs boson – the world we live in 2/2

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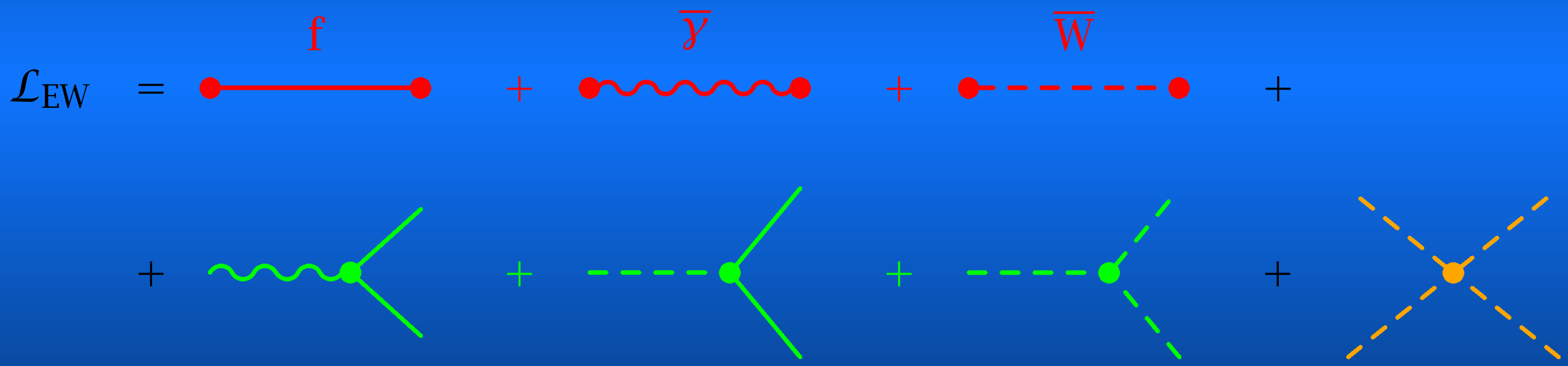

So we have massless fermions and bosons?

5 – Spontaneous symmetry–breaking

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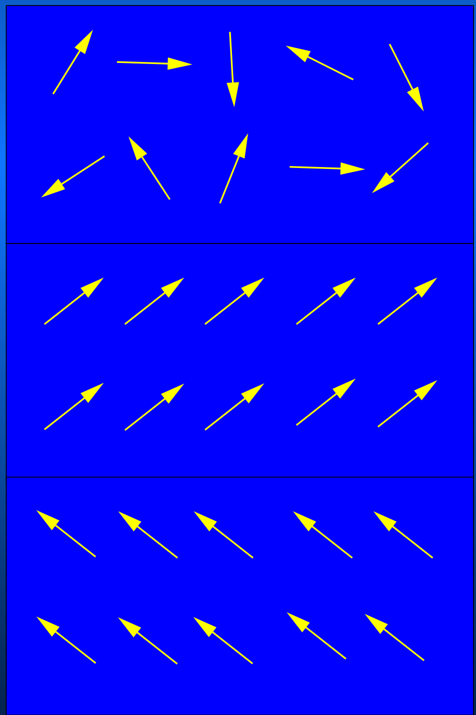
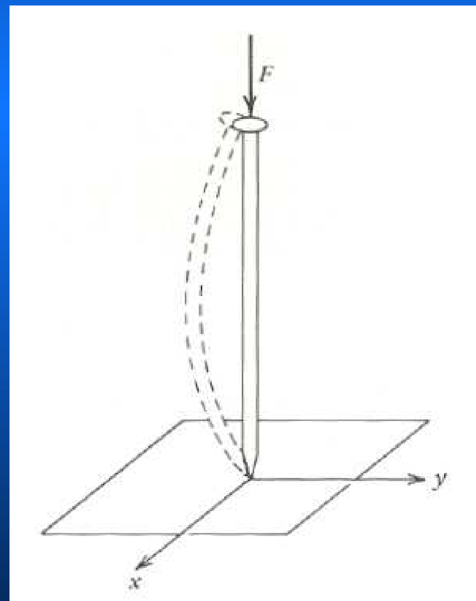
We have many (more) examples of such mechanism in nature itself.

- ferromagnet;
- bending of a rod;
- . . .





Illustrative presentation of spontaneous symmetry–breaking on “toy model” using one complex scalar field ϕ and $U(1)$ symmetry instead of two complex scalar fields and $SU(2)_L \times U(1)_Y$ symmetry. Lagrangian is of the form

$$\mathcal{L} = (\partial_\mu \phi)(\partial^\mu \phi^*) - \mu^2 \phi\phi^* - \lambda(\phi\phi^*)^2. \tag{8}$$

We obtain ground state from minimum of the potential

$$V(\phi) \equiv \mu^2 \rho + \lambda \rho^2, \tag{9}$$

where $\rho \equiv \phi\phi^*$. For potential to have minimum $\lambda > 0$ must hold. In that case we have two options: $\mu^2 > 0$ and $\mu^2 < 0$.

In case of a massive particle, that is if $\mu^2 > 0$, V is minimal when $\rho = 0$, i.e. $\phi = 0$.

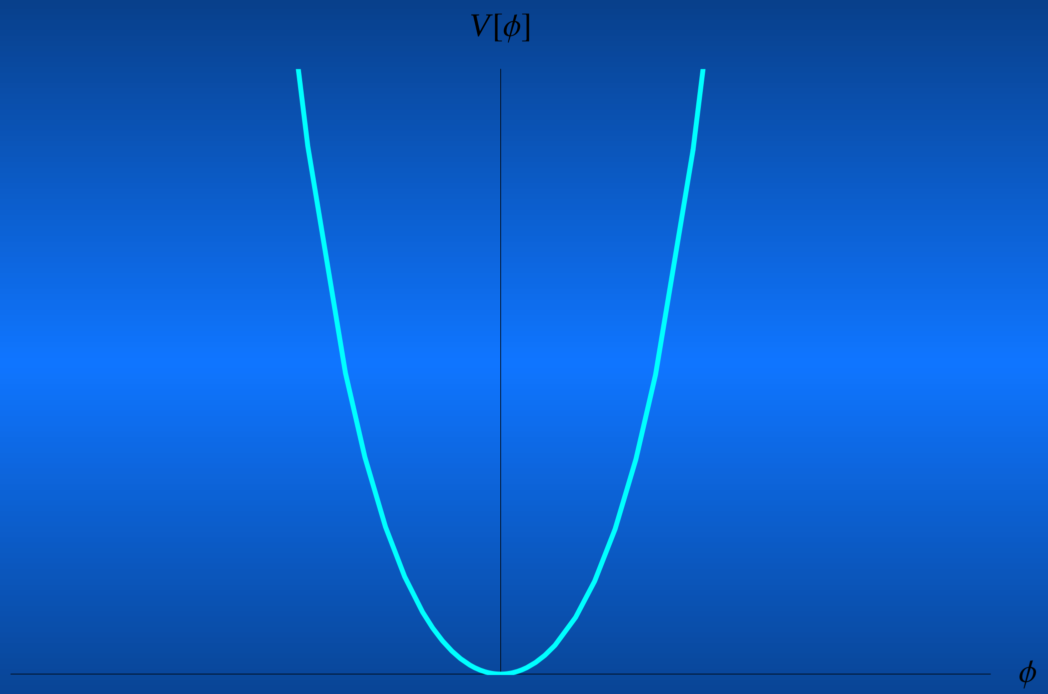


Figure 3: Plot of the potential V as a function of ϕ for $\mu^2 > 0$.

Consequently the option where $\mu^2 < 0$ is the choice we really wish to explore. Minimum now lies at $\rho = -\frac{\mu^2}{2\lambda}$ which means that there is a whole ring of radius $|\phi| = \frac{v}{\sqrt{2}} \equiv \sqrt{\frac{-\mu^2}{2\lambda}}$ in the complex ϕ plane at each of whose points V is at its minimum value, as shown in 4.

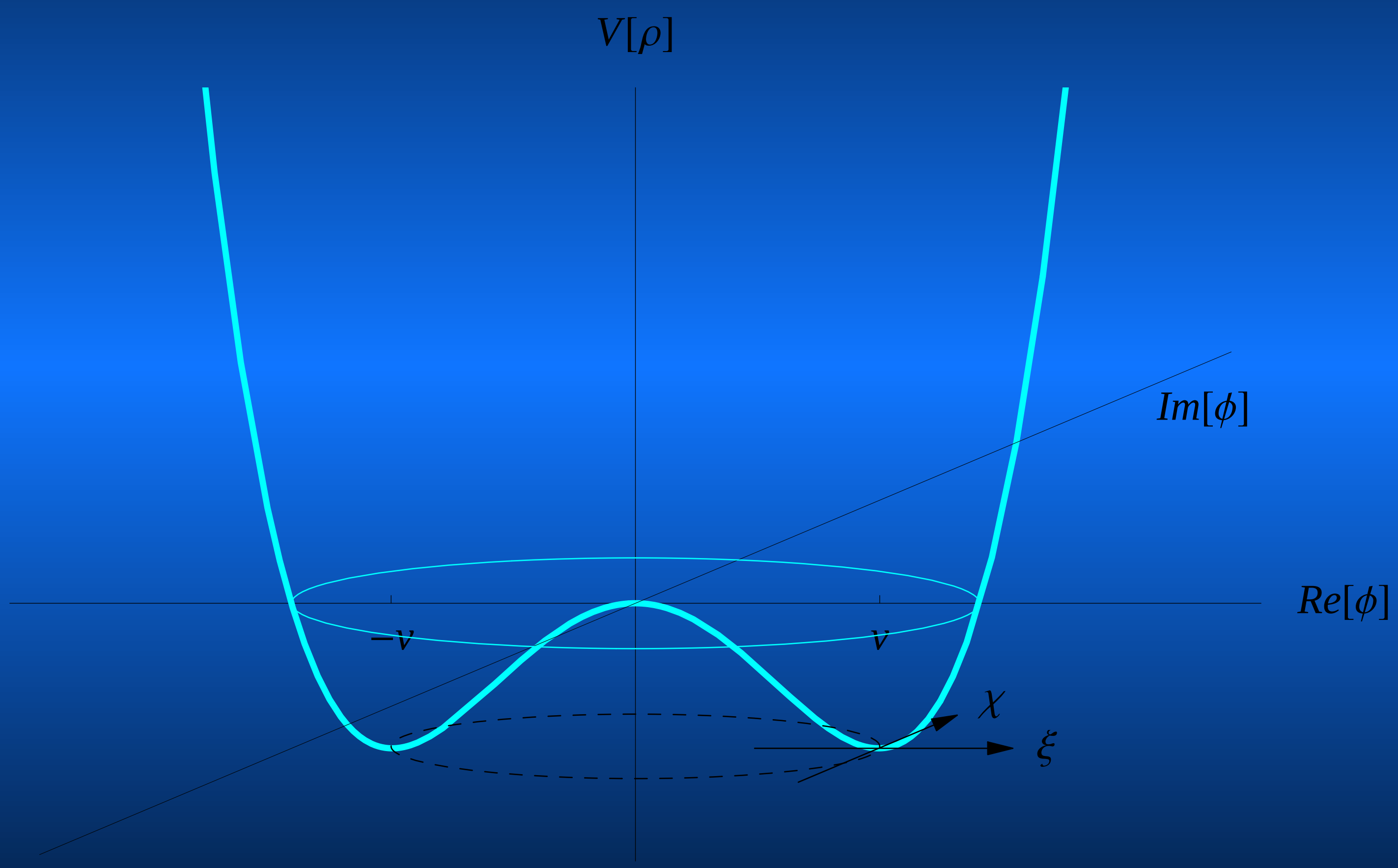


Figure 4: Plot of the potential V as a function of $\phi\phi^*$ for $\mu^2 < 0$.

Let's evaluate small perturbation about the energy minimum.

We choose

$$\phi(x) = \sqrt{\frac{1}{2}}\left(v + \xi(x) + i\chi(x)\right), \tag{10}$$

with ξ, χ real and $\xi = \chi = 0$ in the ground state.

Substituting into 8 one has

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \xi\right)^2 + \frac{1}{2}\left(\partial_\mu \chi\right)^2 - \lambda v^2 \xi^2 - \lambda v \xi \left(\xi^2 + \chi^2\right) - \frac{1}{4}\left(\xi^2 + \chi^2\right)^2. \tag{11}$$

Lagrangian $\mathcal{L}$ contains no mass term for the χ field but a normal mass term for the ξ field with

$$m_\xi^2 = 2\lambda v^2. \tag{12}$$

Spontaneous symmetry–breaking introduces its own massless bosons: Goldstone bosons.

6 – The Higgs Mechanism

As a further step we impose the local $U(1)$ gauge invariance on previous Lagrangian, Eq. 11. Lagrangian becomes

$$\mathcal{L} = \left[\left(\partial_\mu + igV_\mu \right) \phi^* \right] \left[\left(\partial_\mu - igV_\mu \right) \phi \right] - \mu^2 \phi \phi^* - \lambda \left(\phi \phi^* \right)^2 . \qquad (13)$$

Proceeding as before (evaluating small perturbations around chosen ground state) we find:

$$\mathcal{L} = \frac{1}{2} g^2 v^2 V_\mu V^\mu + \frac{1}{2} \left(\partial_\mu \xi \right)^2 + \frac{1}{2} \left(\partial_\mu \chi \right)^2 - \lambda v^2 \xi^2 - ev V_\mu \partial^\mu \chi . \qquad (14)$$

Gauge field V_μ has acquired mass!

Choosing a particular gauge in which χ simply does not appear we rewrite our expansion of ϕ around the minima

$$\phi(x) = \sqrt{\frac{1}{2}} \left(v + h(x) \right) , \qquad (15)$$

where $h(x)$ is real.

Now we can finally write our Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4 + v e^2 V_\mu^2 h + \frac{1}{2} e^2 v^2 V_\mu^2 + \frac{1}{2} e^2 V_\mu^2 h^2. \quad (16)$$

It describes the interaction of the massive vector boson V_μ with the massive, real, scalar field h – the Higgs boson.

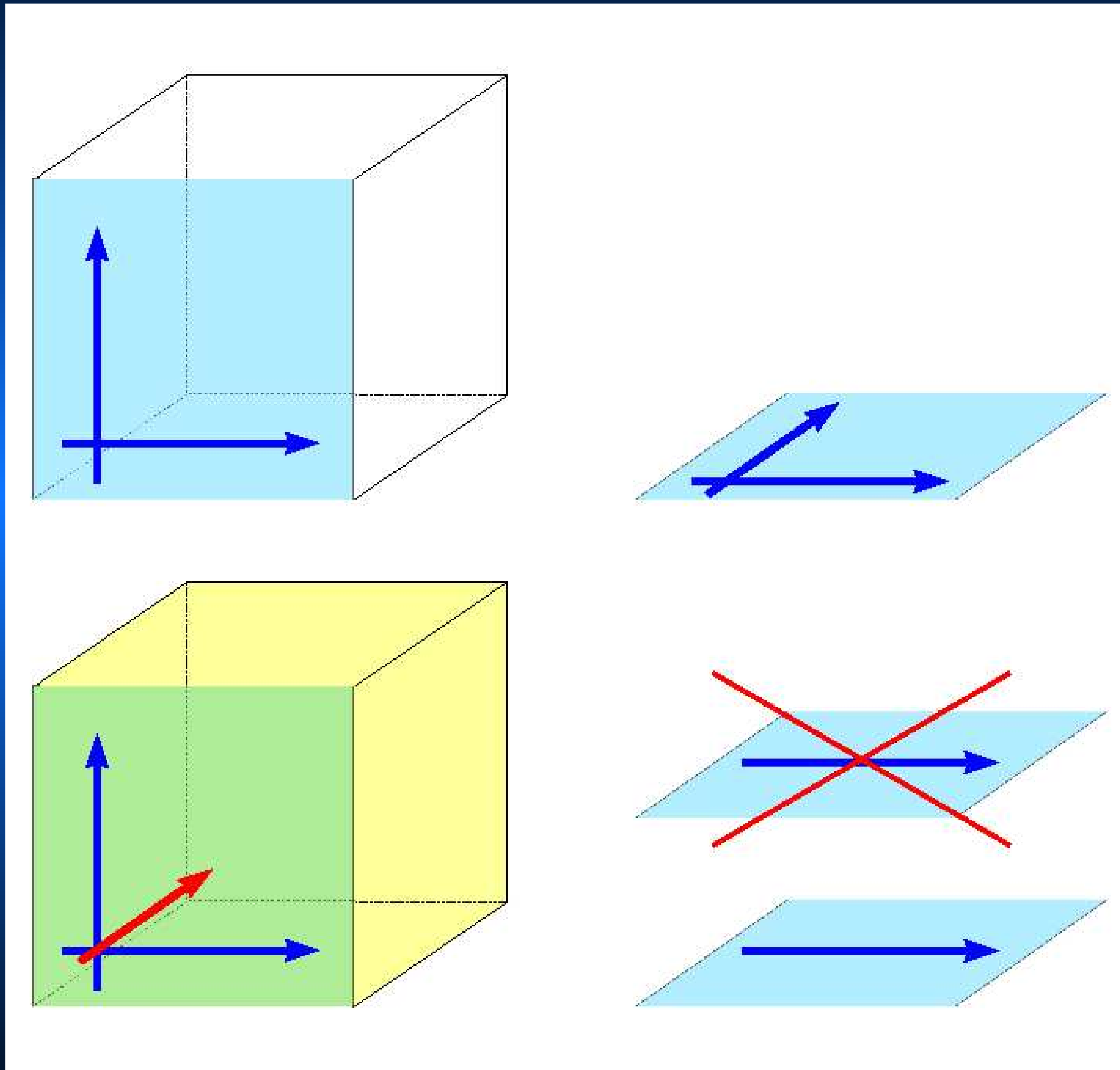
The Higgs boson mass is given by

$$2\lambda v^2 = -2\mu^2 \quad (17)$$

Three things should be emphasized:

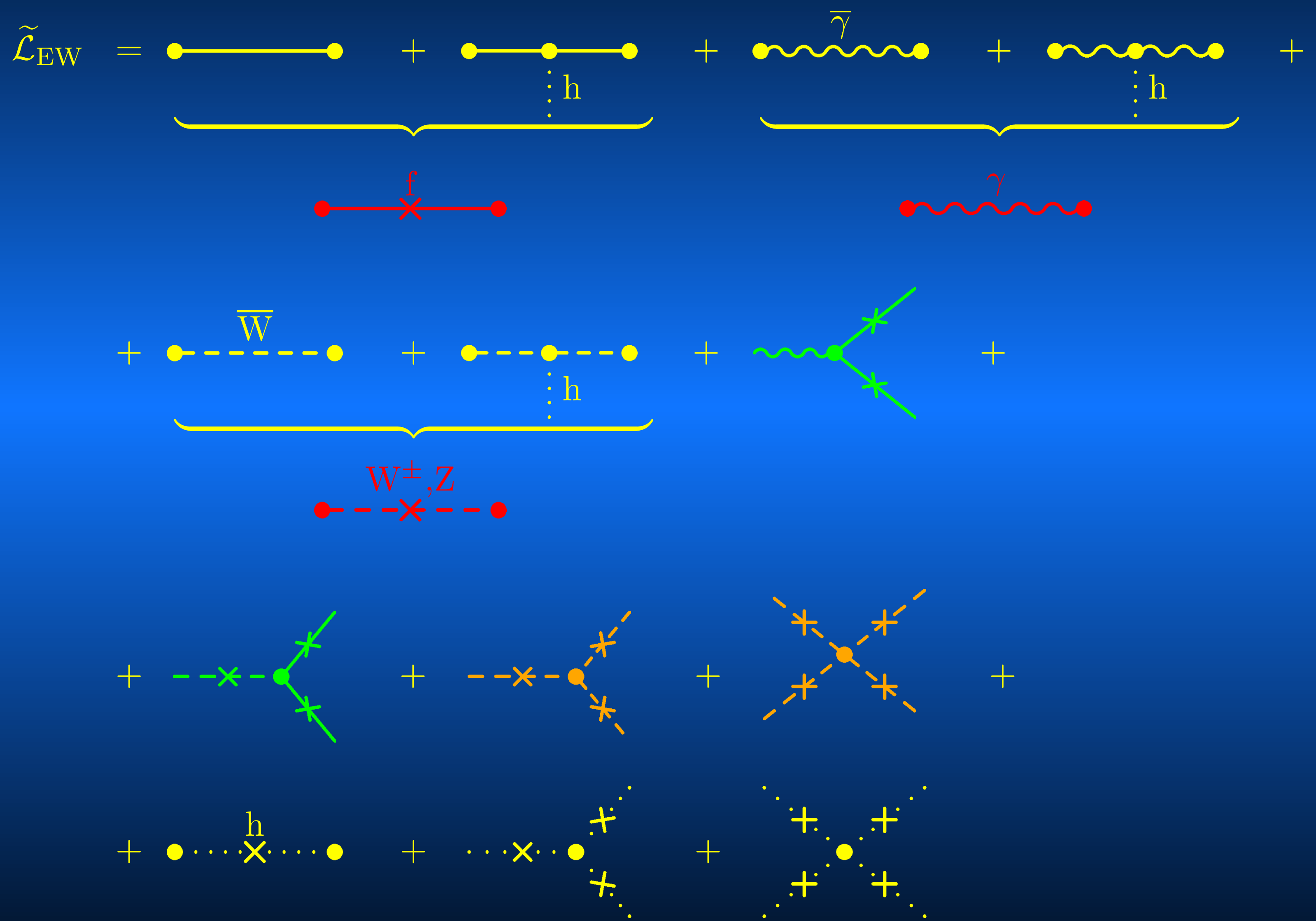
- we have real scalar boson, h;
- its mass depends on v (determined by gauge boson mass) and λ (parameter);
- interaction terms determine the production and decay mechanisms of the Higgs boson.

Counting degrees of freedom



the higgs boson – the higgs mechanism 4/4

Diagrammatic form of electroweak Lagrangian after symmetry–breaking and Higgs mechanism (using $SU(2)_L \times U(1)_Y$ symmetry).



7 – The Higgs boson mass

From the final Lagrangian 16 we can write for the weak boson $\mathrm{W}^{\pm}$ mass

$$M_{\mathrm{W}} = \frac{1}{2} g v \tag{18}$$

which gives us $v = 246\ \mathrm{GeV}$ at $M_{\mathrm{W}} = 80.4\ \mathrm{GeV}$.

Consequently, v is fixed while λ remains uncertain $\longrightarrow$ we cannot predict Higgs mass.

Current bounds on Higgs mass at 95% confidence level today are

$$114.4\ \mathrm{GeV} < M_{\mathrm{H}} < 211\ \mathrm{GeV}, \tag{19}$$

where the lower mass bound is defined by LEP measurements and upper limit by calculations from higher order corrections.

the higgs boson – the higgs boson mass 2/2

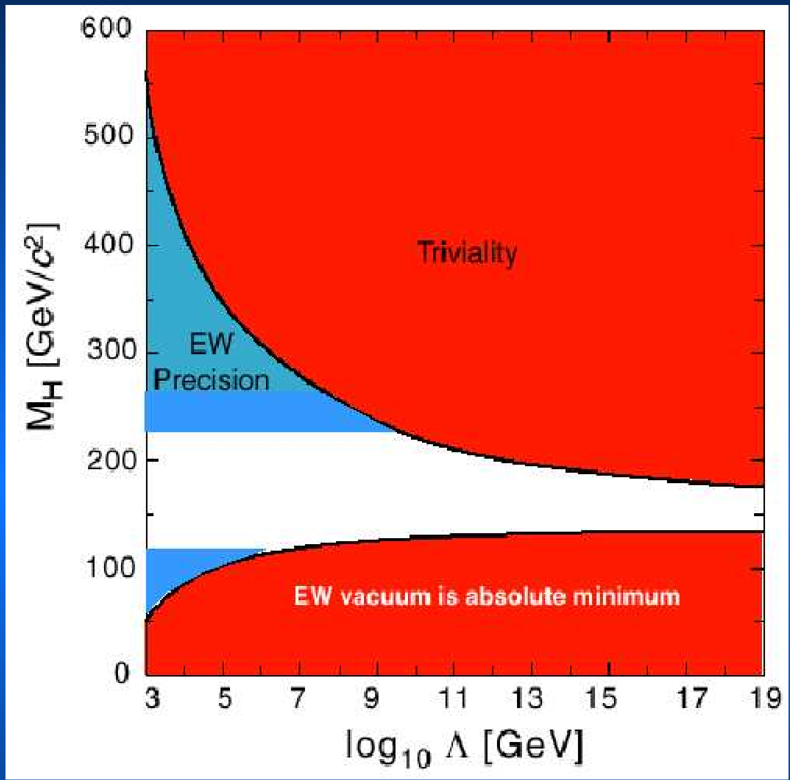


Figure 5: Higgs mass constraints from vacuum stability and Higgs self–coupling.

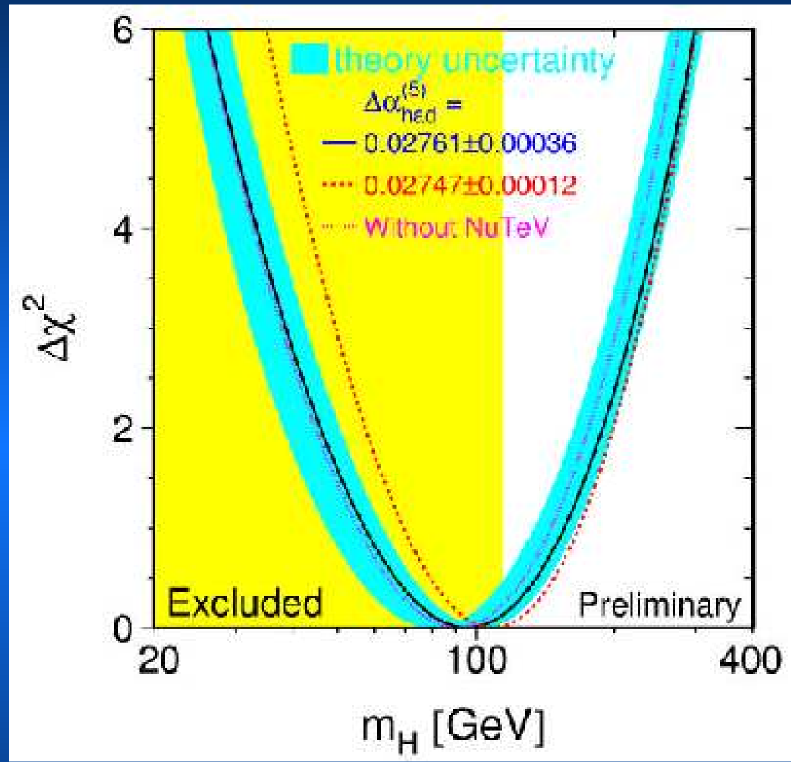
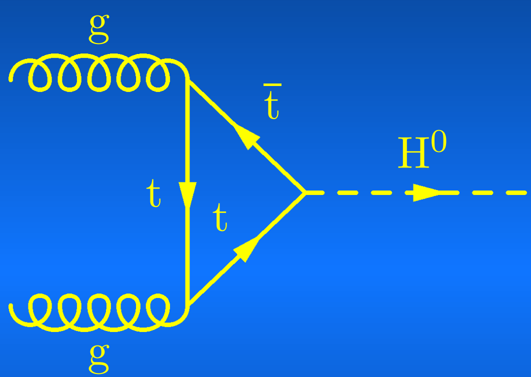
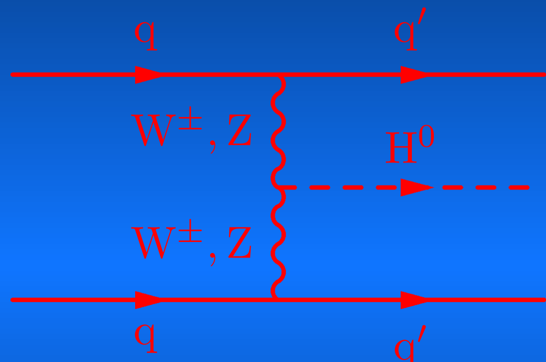


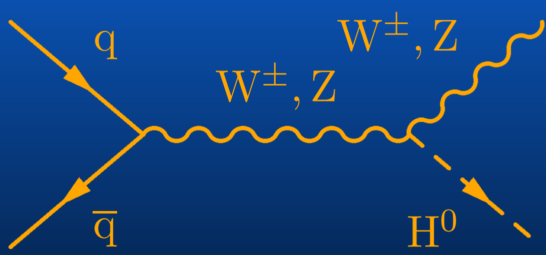
Figure 6: Higgs mass bounds from LEP.

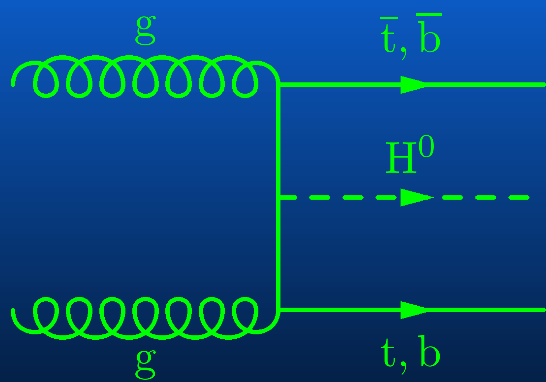
8 – Production and Decay of a Higgs particle at LHC

Most important processes for Higgs production at hadron colliders. Gluon fusion, vector boson fusion, associated production with weak bosons and an example of the diagram having associated production with a t or b pair.



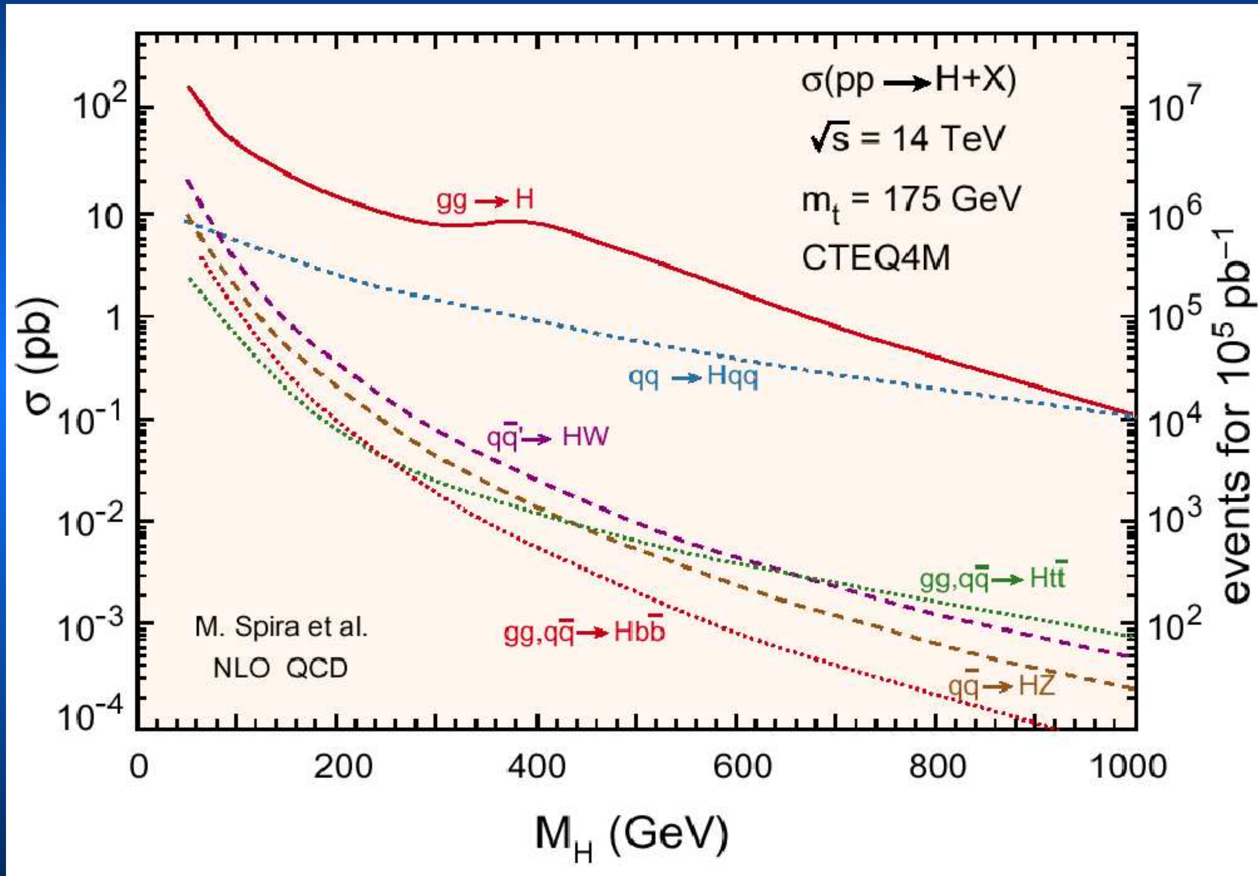




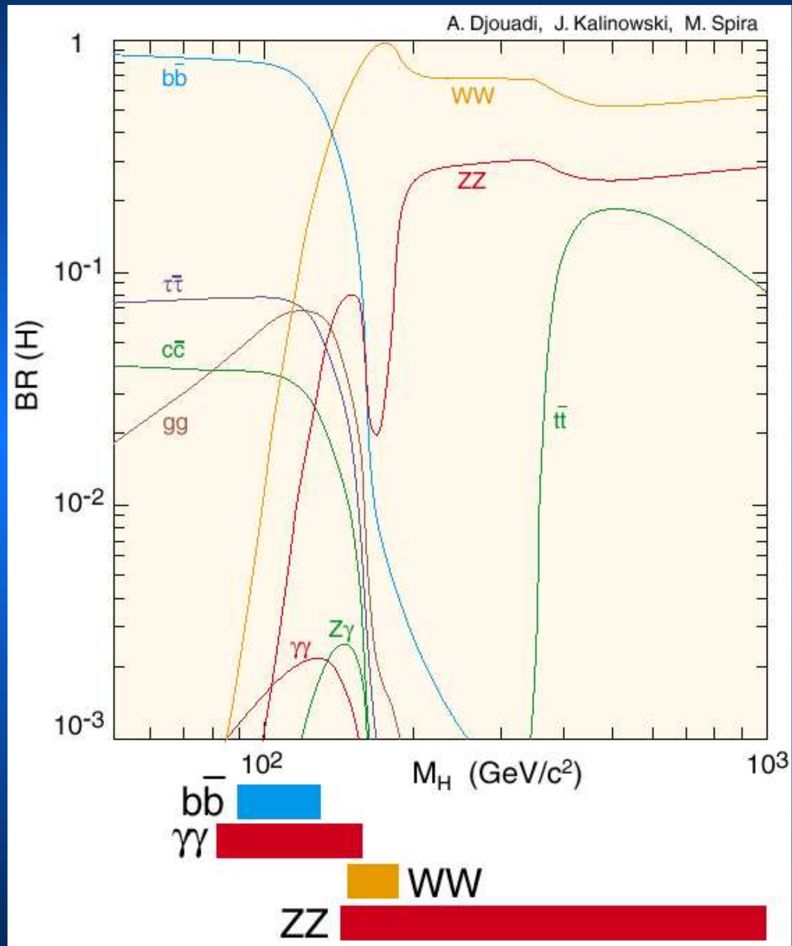


the higgs boson – higgs production and decay at lhc 2/3

Dominant Higgs production mechanism at the LHC for all possible Higgs masses will be the gluon fussion process.



Branching ratios of the dominant decay modes of the standard model Higgs particle.



the higgs boson – conclusions

What will the new experiments show nobody knows. But one thing for shure: if not Higgs, then some other physics will be employed at energies of LHC. And physicists quest for The Theory will continue.

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And the Lord looked upon Her world, and She marveled at its beauty - for so much beauty there was that She wept. It was a world of one kind of particle and one force carried by one messenger who was, with divine simplicity, also the one particle.

- The Very New Testament 2:1