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

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- 2007: first collisions at LHC

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- Noether's theorem implies conserved charge

the higgs boson – from symmetries to interactions 2/3

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

$$D_\mu \equiv \partial_\mu - igV_\mu, \tag{5}$$

with vector (gauge) field V_μ that transorms as

$$V_\mu \longrightarrow V_\mu + \frac{1}{g}\partial_\mu\alpha. \tag{6}$$

the higgs boson – from symmetries to interactions 3/3

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

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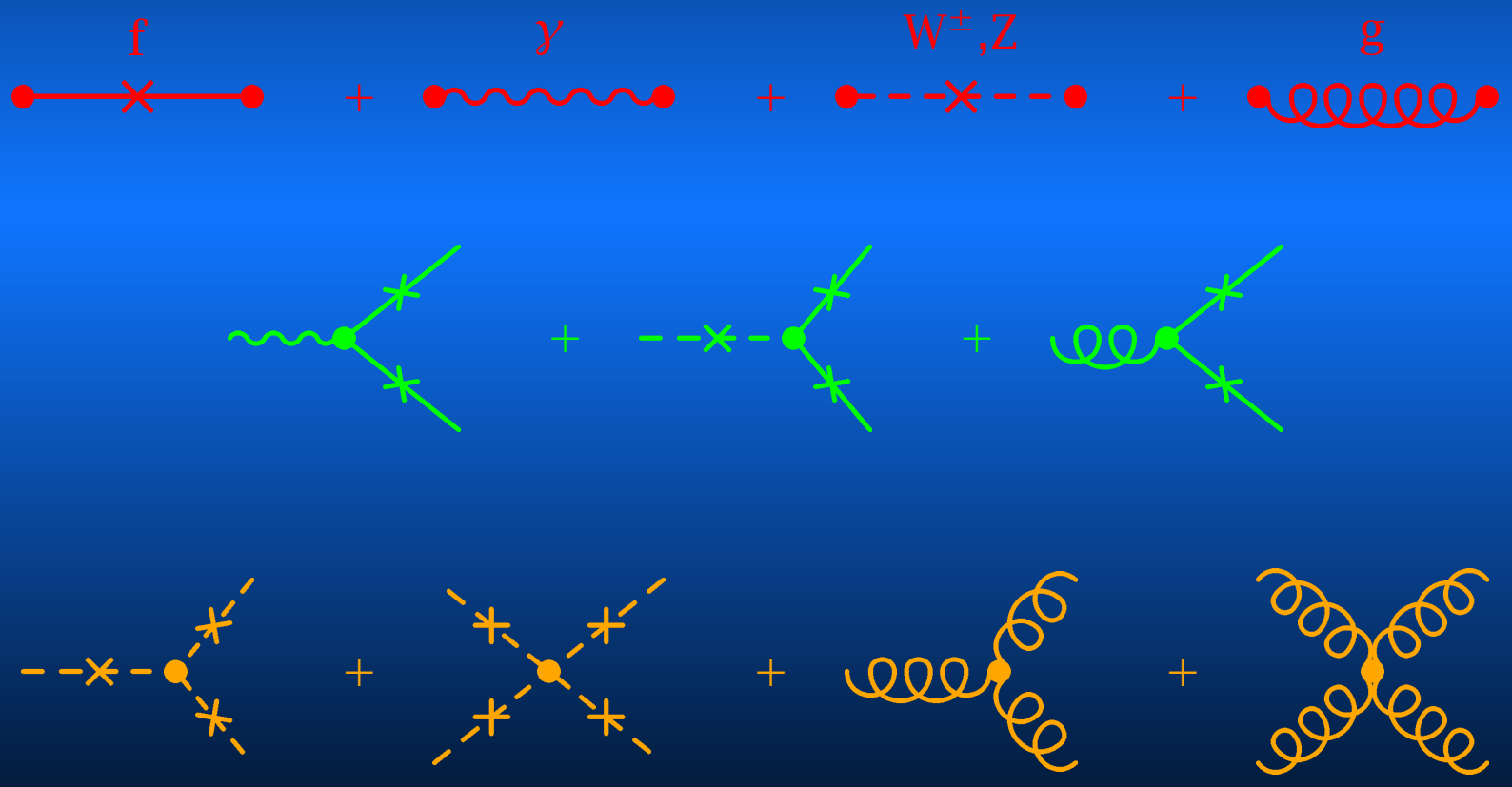
There is no $\frac{1}{2}m^2 V_\mu V^\mu$ since it is prohibited by gauge invariance. The gauge particle (in QED example the photon) is massless.

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 higgs boson – the world we live in 2/3

First line of 1 symbolically corresponds to kinetic energies of fermions, photons, bosons and gluons (in that order), where crosses on fermion and boson line simply point out that fermions and bosons have mass.

The second line corresponds to (massive) fermion interactions with photon, boson and gluon respectively, and the last line is showing us third and quartic order self–interaction of (massive) bosons and (massless) gluons.

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Any possible electroweak and color interactions found in nature can be written down using just these “building blocks”.

the higgs boson – the world we live in 3/3

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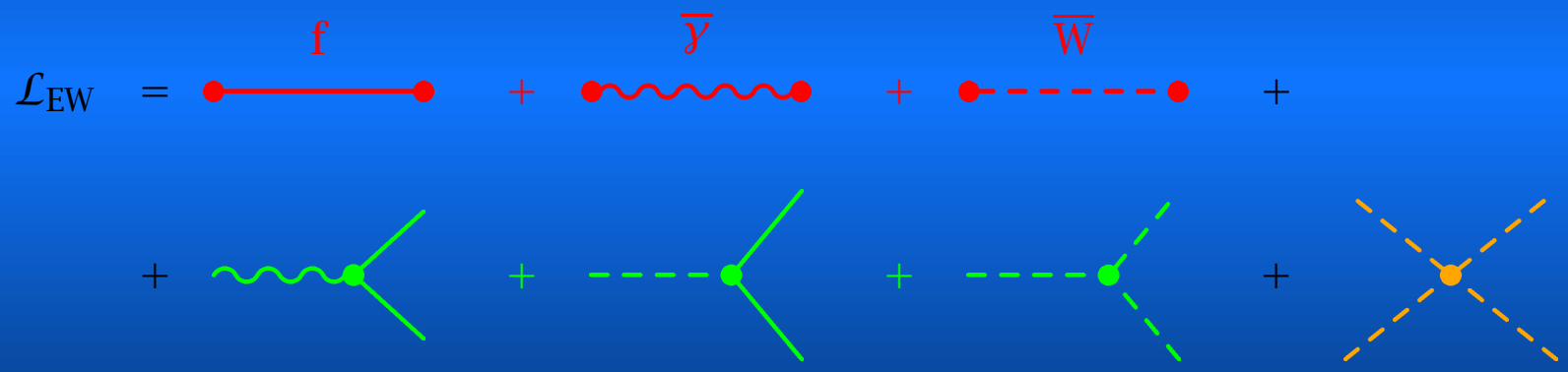

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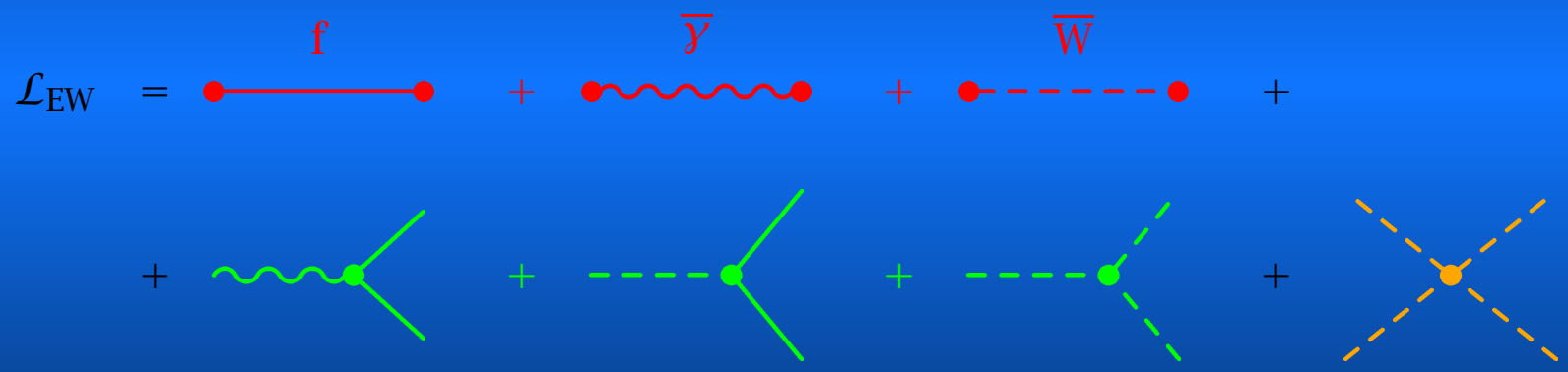

So we have massless fermions and bosons?

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the higgs boson – spontaneous symmetry–breaking 2/6

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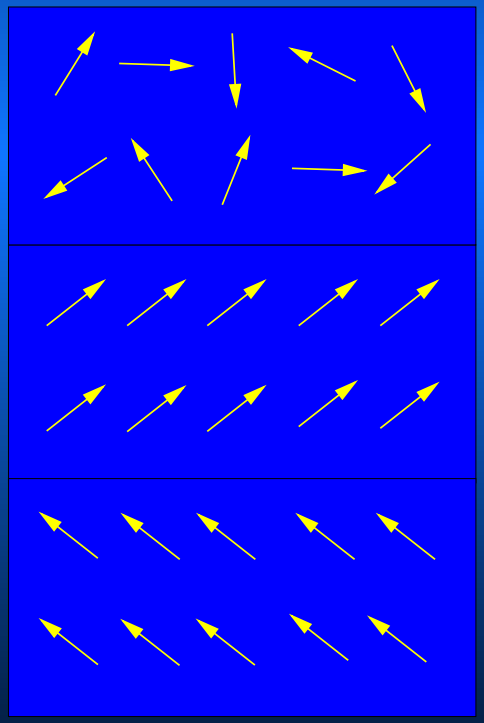

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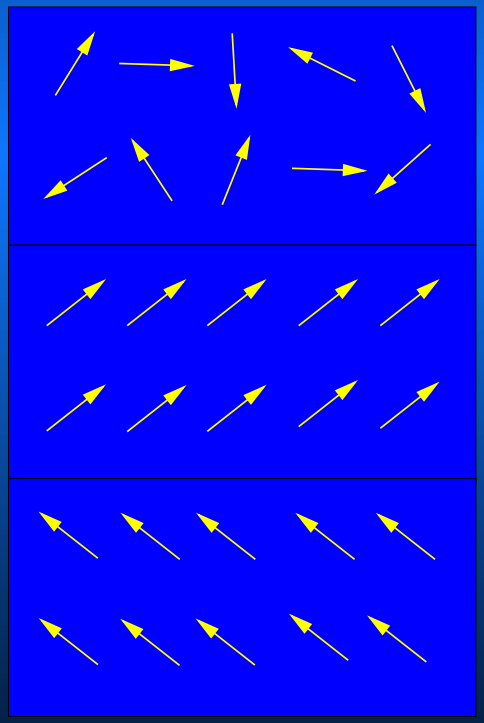

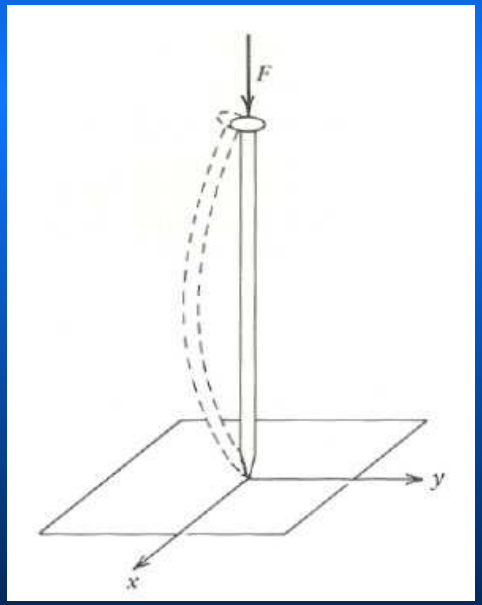

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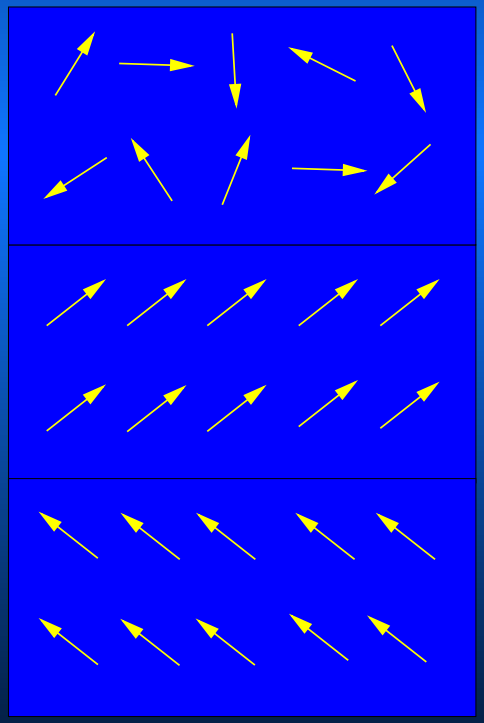

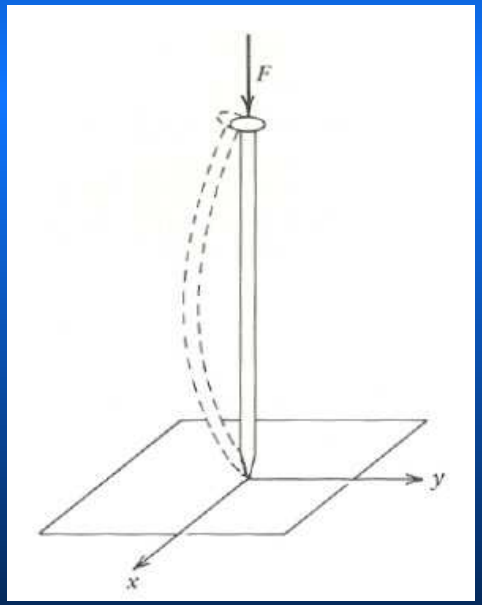

the higgs boson – spontaneous symmetry–breaking 3/6

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.

the higgs boson – spontaneous symmetry–breaking 3/6

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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 $\mu^2 < 0$.

the higgs boson – spontaneous symmetry–breaking 4/6

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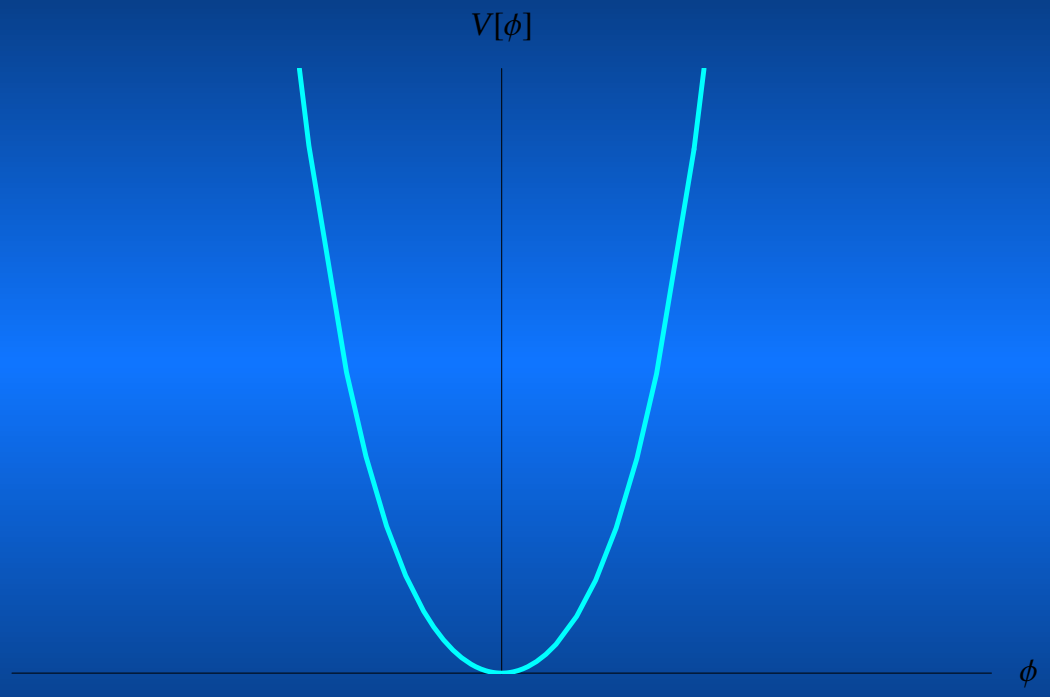

Figure 3: Plot of the potential V as a function of ϕ for $\mu^2 > 0$.

the higgs boson – spontaneous symmetry–breaking 5/6

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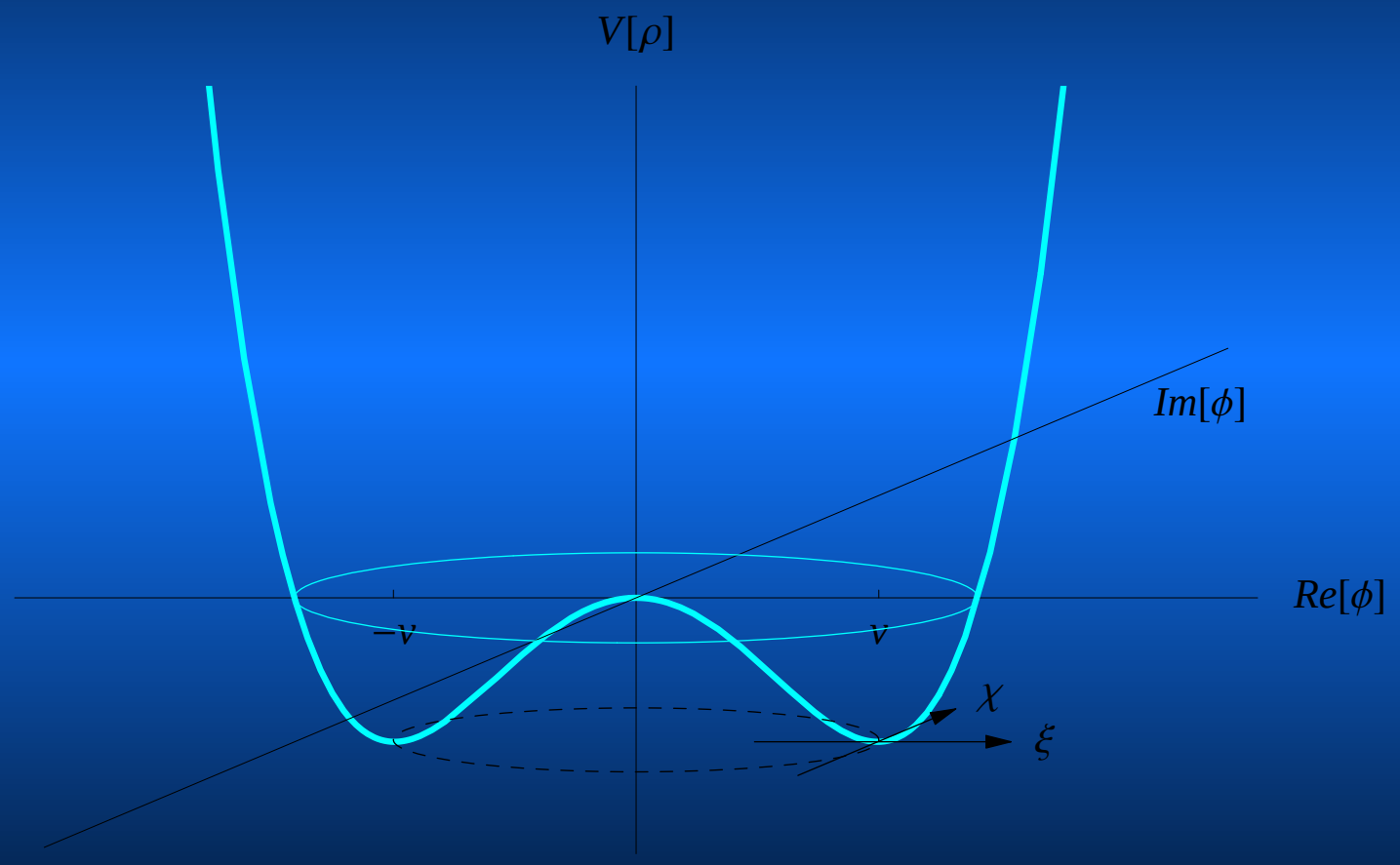

Figure 4: Plot of the potential V as a function of $\phi\phi^*$ for $\mu^2 < 0$.

the higgs boson – spontaneous symmetry–breaking 6/6

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the higgs boson – spontaneous symmetry–breaking 6/6

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We choose

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

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Substituting into 8 one has

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

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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

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

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

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

where $h(x)$ is real.

Now we can finally write our Lagrangian

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- its mass depends on v (determined by gauge boson mass) and λ (parameter);

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

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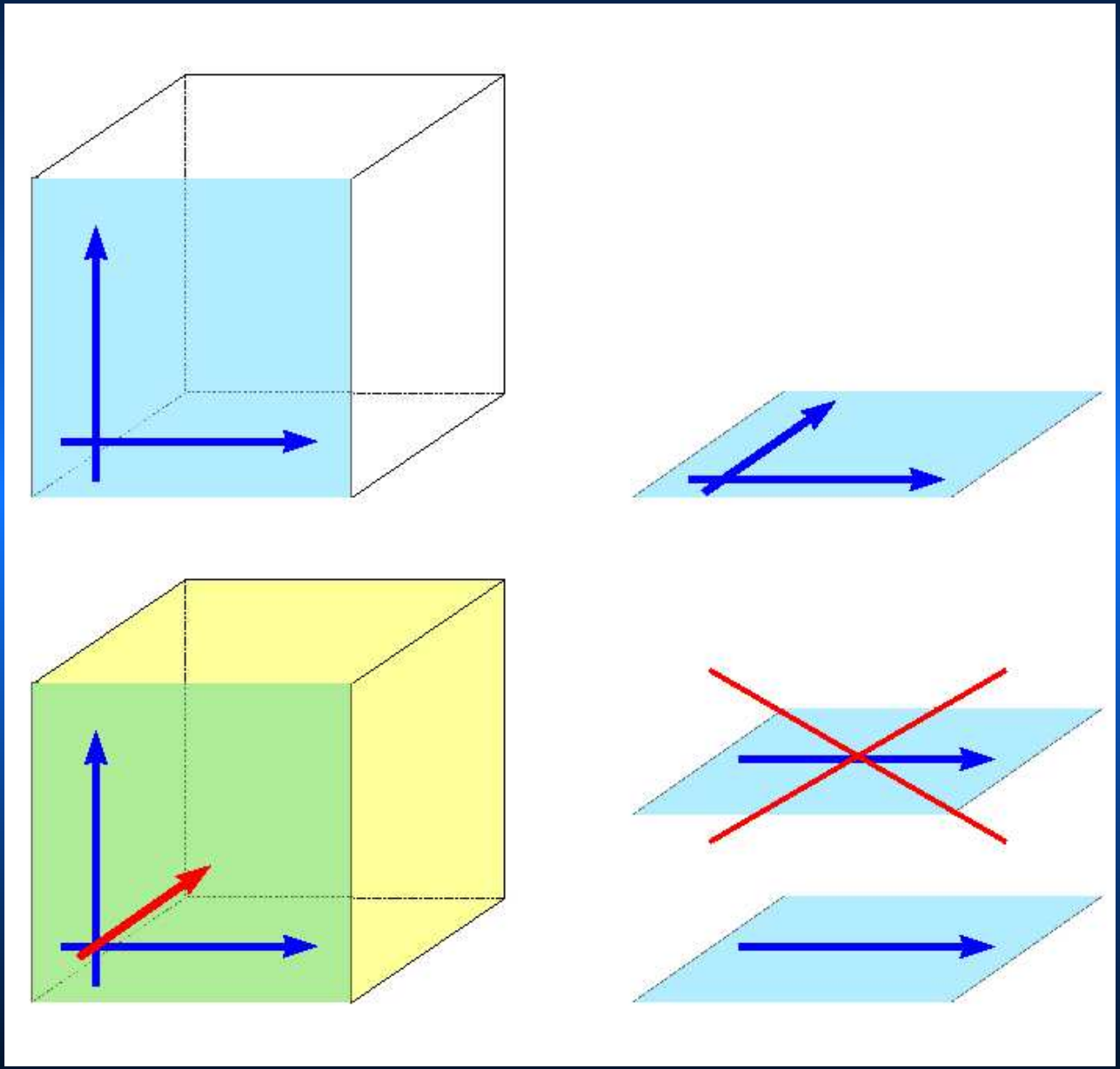

the higgs boson – the higgs mechanism 4/4

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

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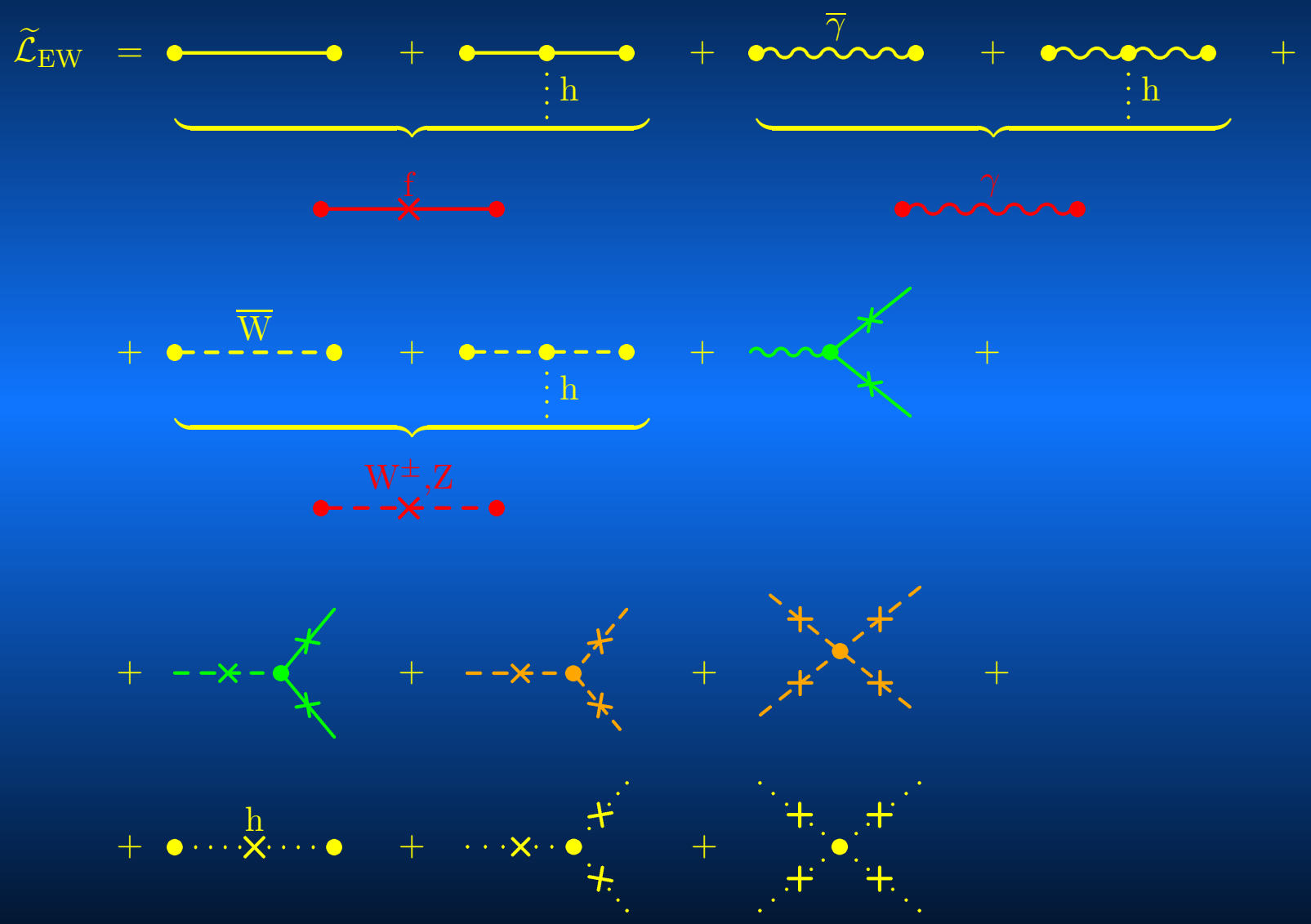

7 – The Higgs boson mass

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 $M_{\mathrm{W}} = 80.4\ \mathrm{GeV}$.

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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

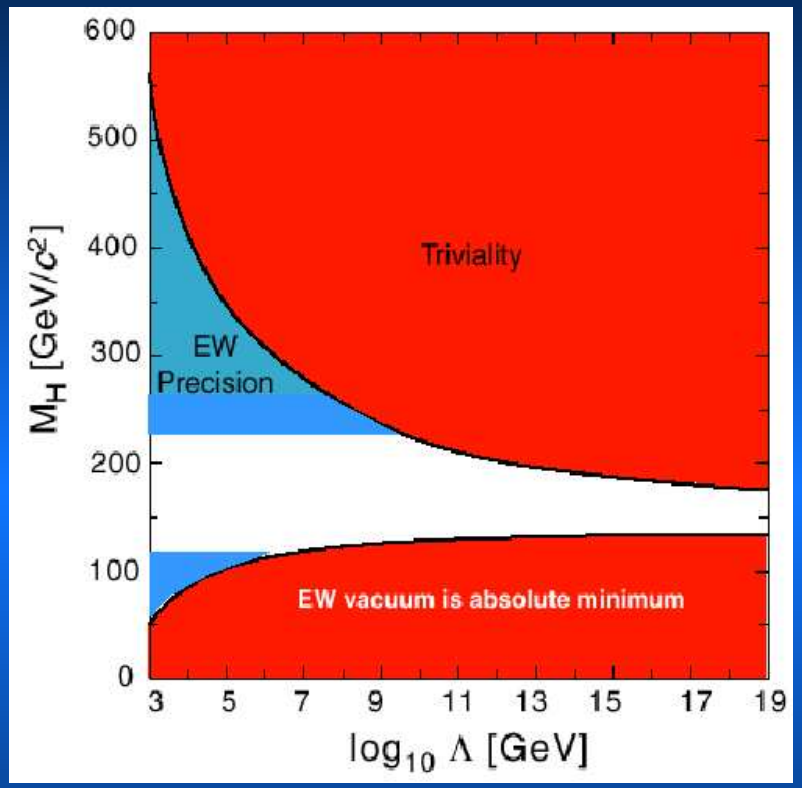

Figure 5: Higgs mass constraints from vacuum stability and Higgs self–coupling.

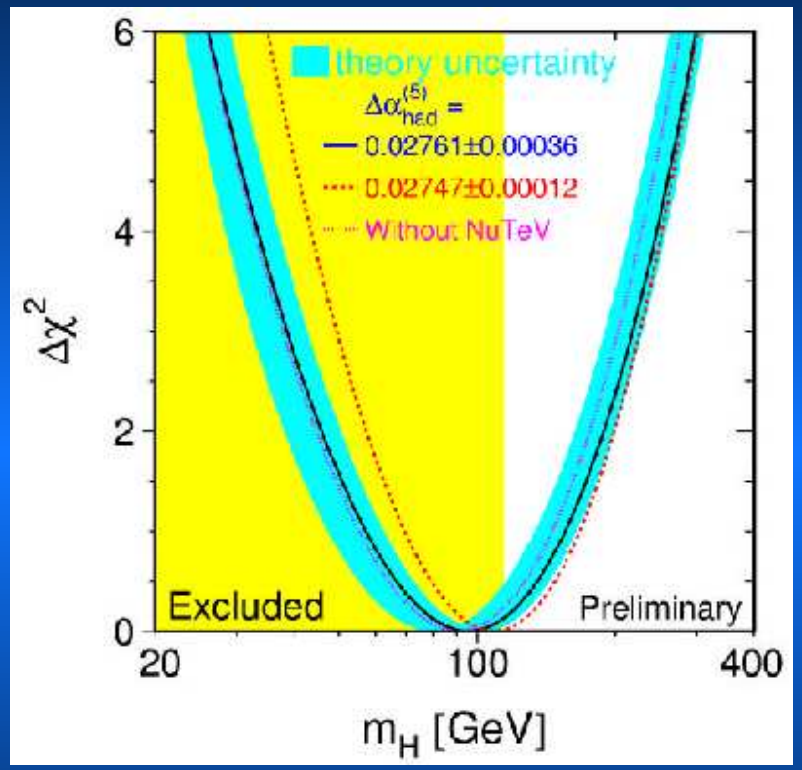

Figure 6: Higgs mass bounds from LEP.

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.

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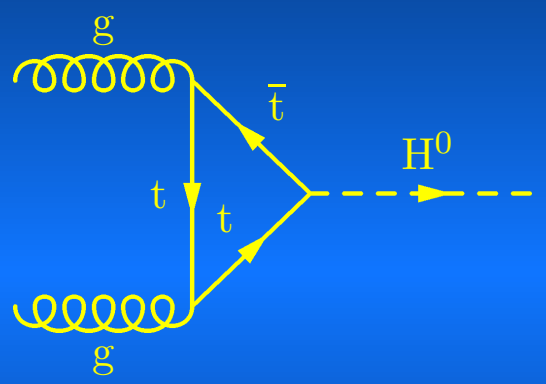

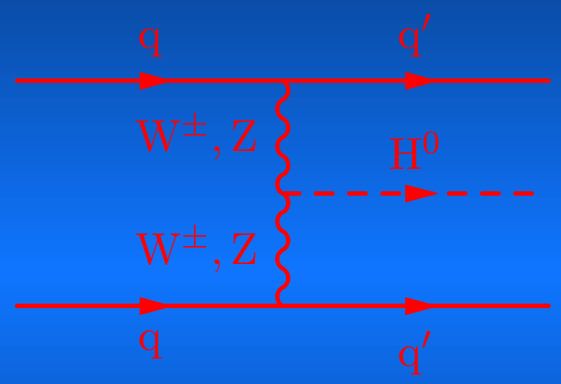

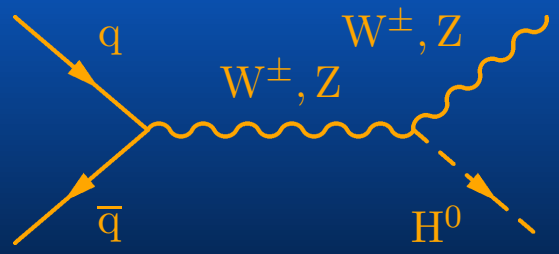

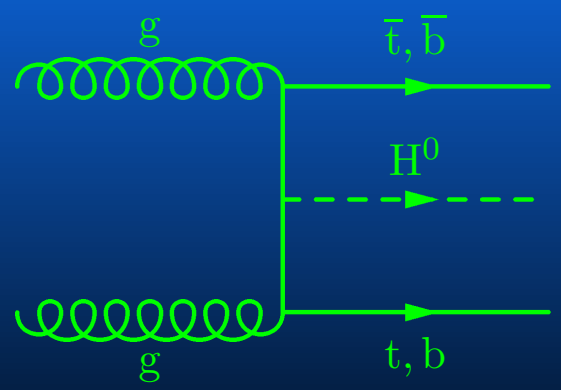

the higgs boson – higgs production and decay at lhc 2/3

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

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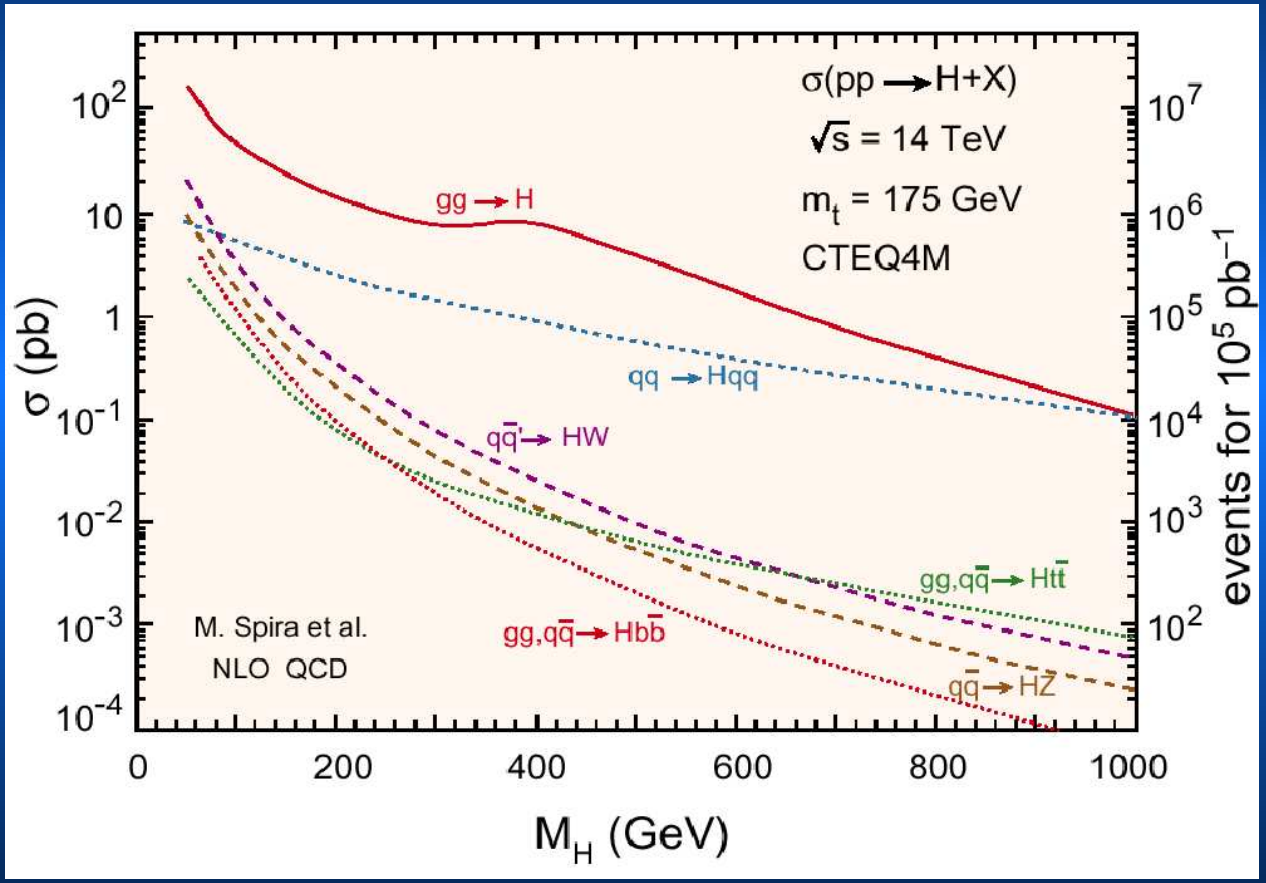

the higgs boson – higgs production and decay at lhc 3/3

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

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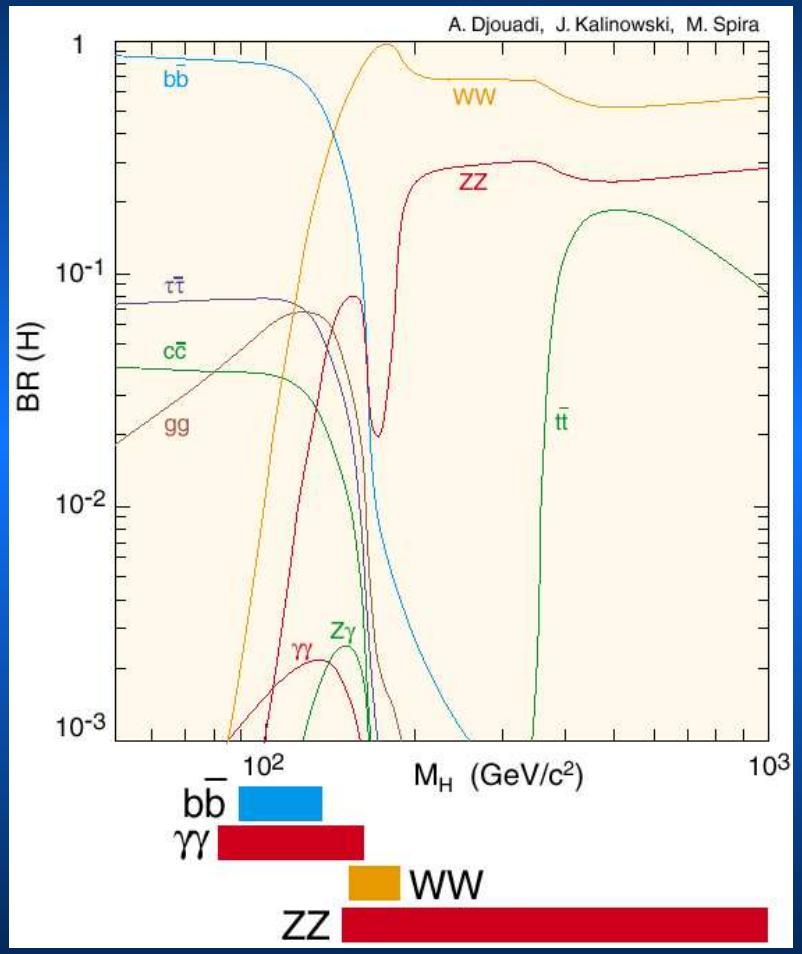

the higgs boson – conclusions

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

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