CAP-CASCA

Joint Undergraduate Lecture Tour 2009

Higgs Physics and the Mystery of Mass

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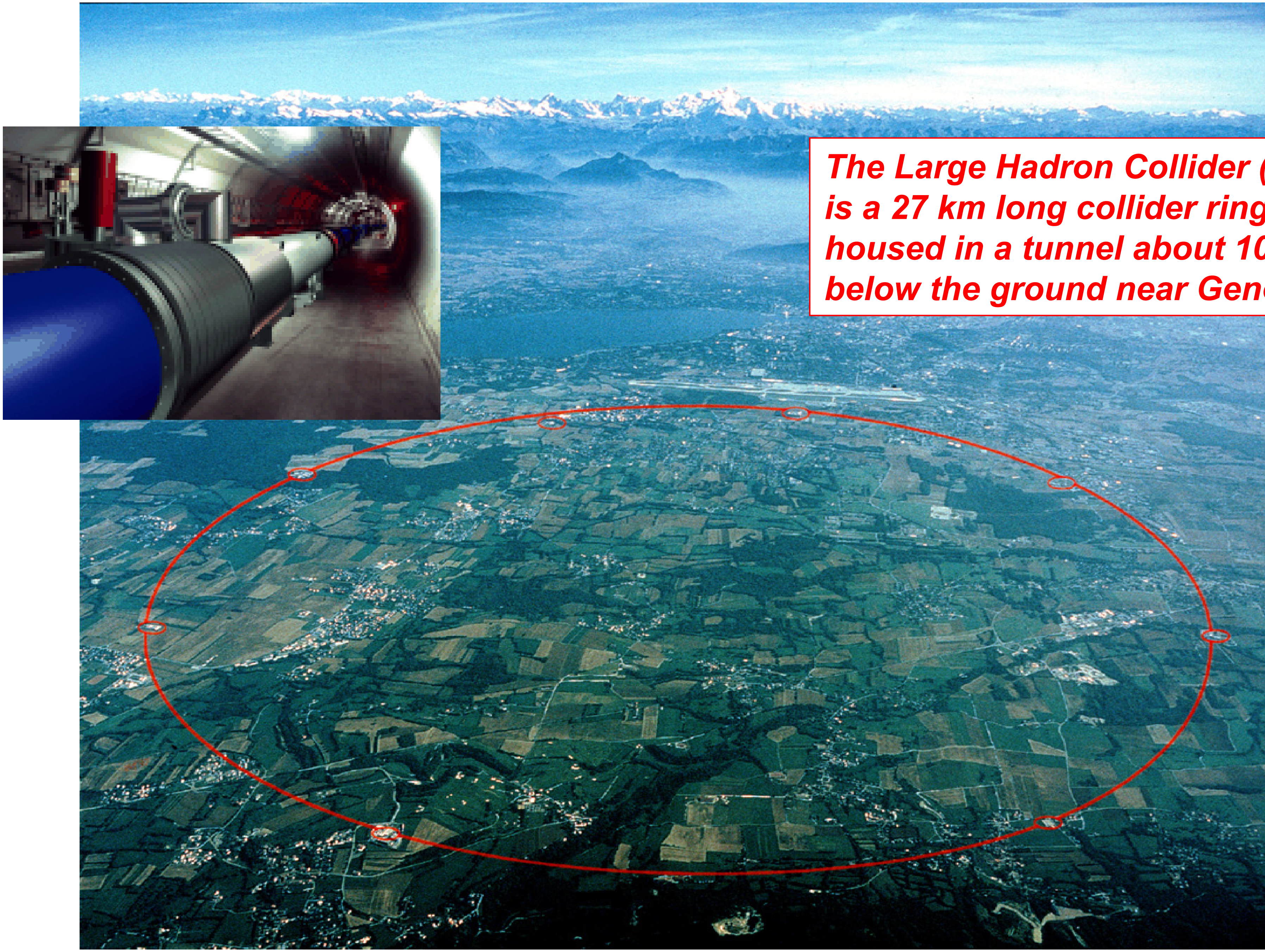
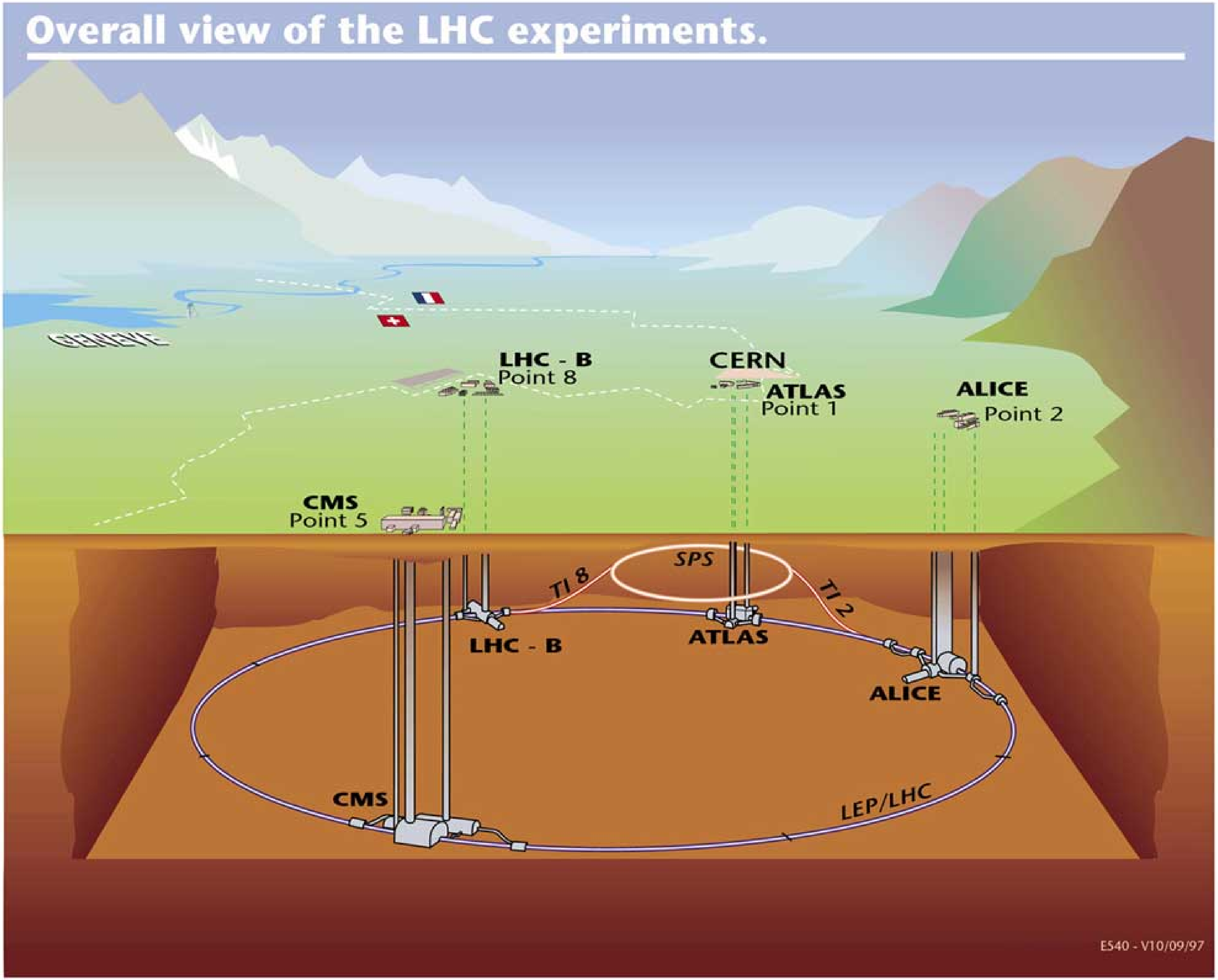
With thanks to
St. Mary's U., Acadia U., St. Francis Xavier U.,
Mount Allison U., & U. de Moncton



The Large Hadron Collider (LHC) is a 27 km long collider ring housed in a tunnel about 100 m below the ground near Geneva

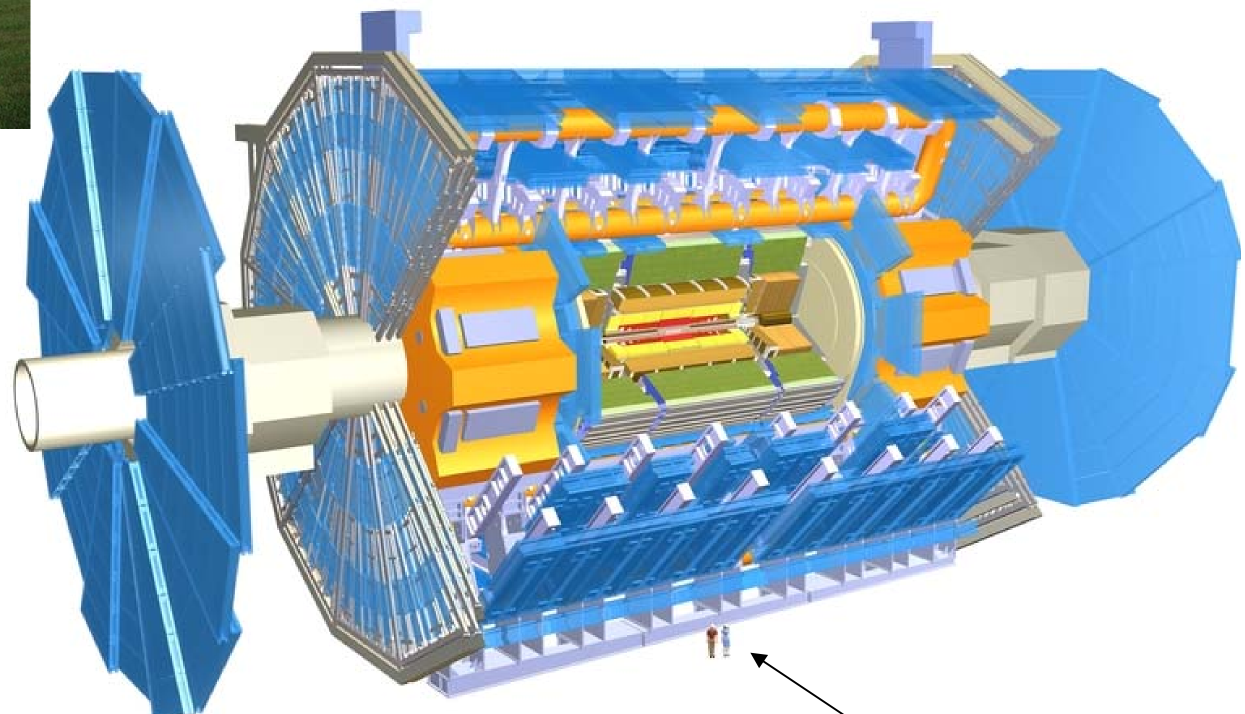
Last magnet installed April 2007



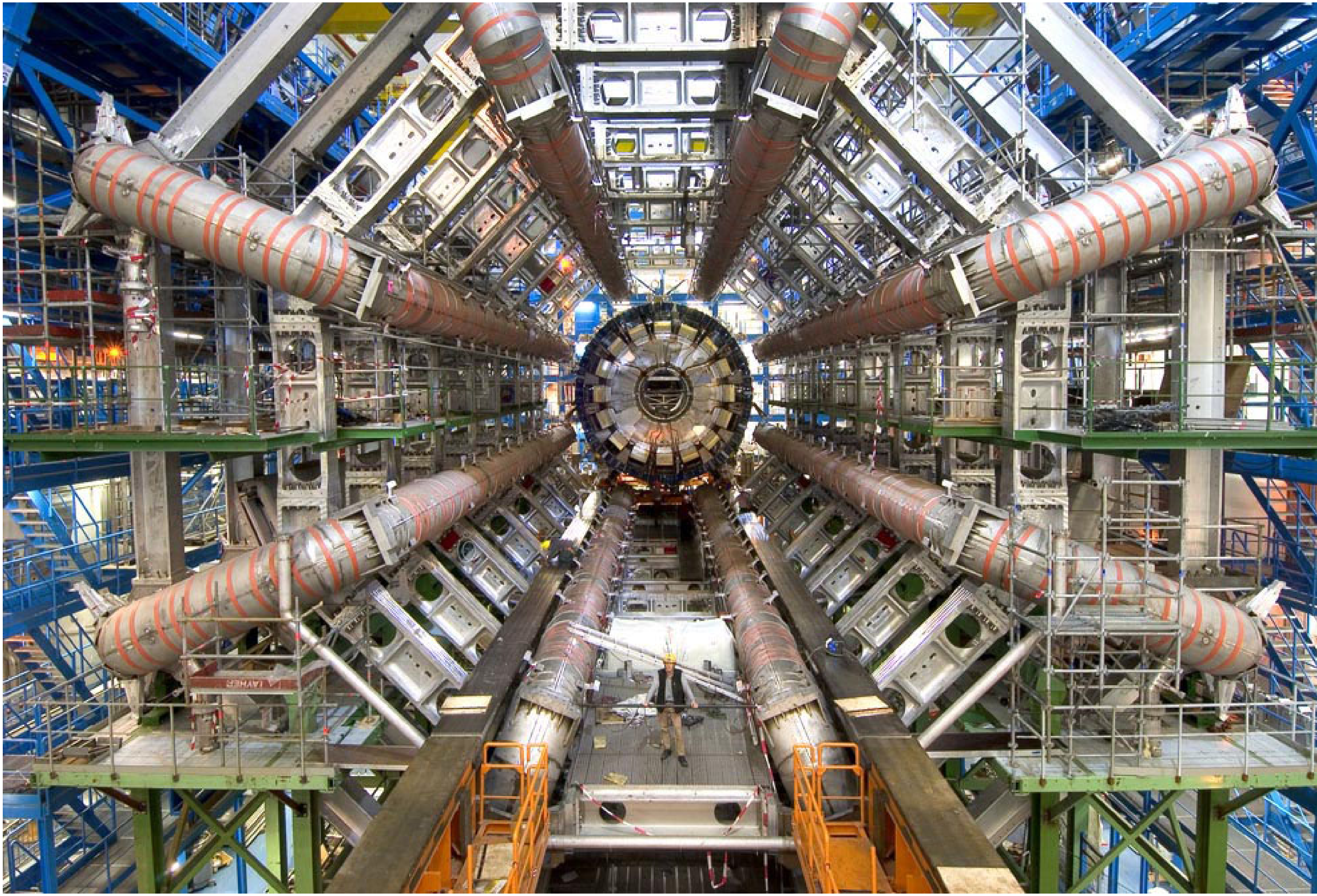
Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97

ATLAS superimposed to
the 5 floors of building 40

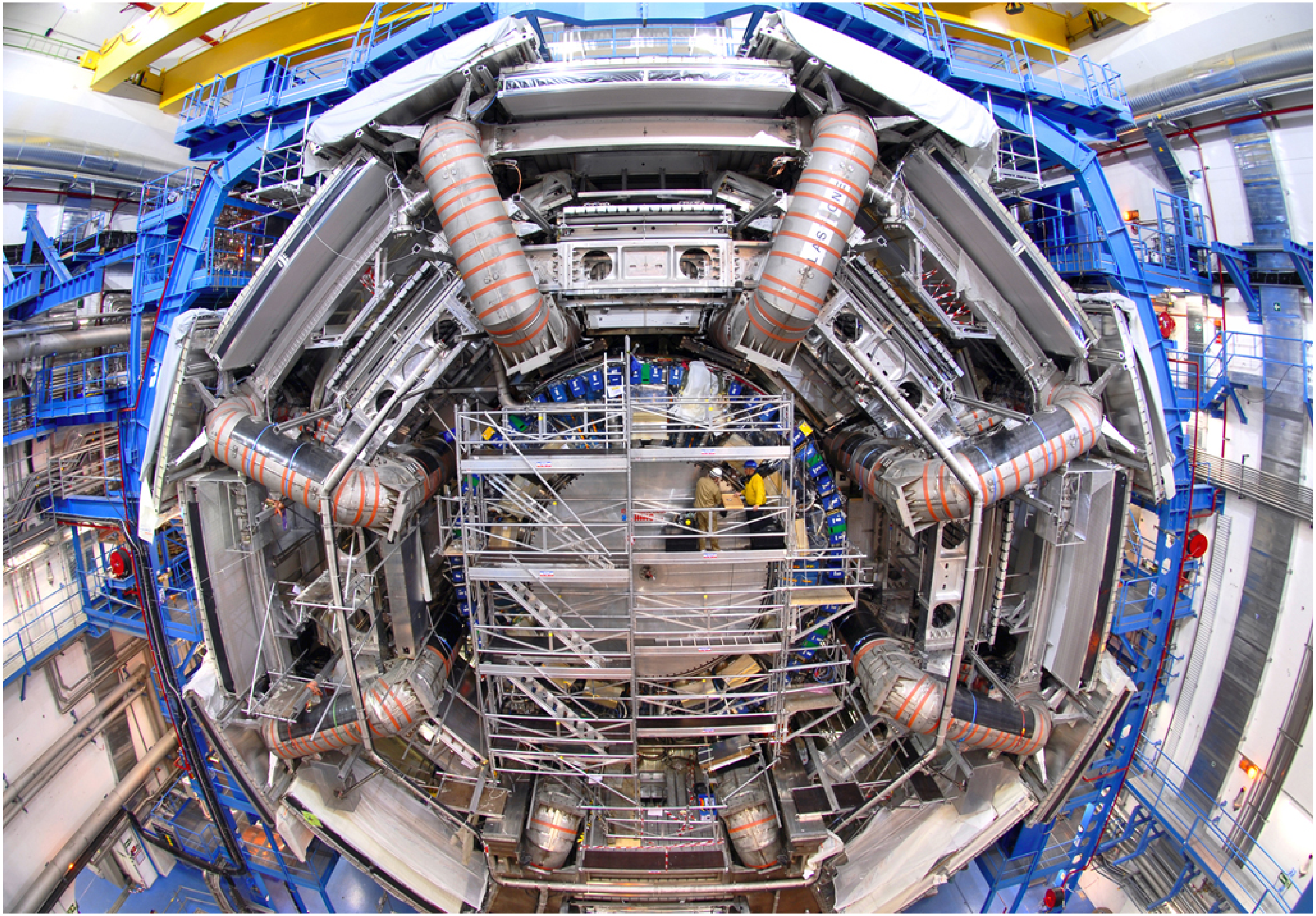
The ATLAS detector is being installed 100 m underground on the LHC ring.



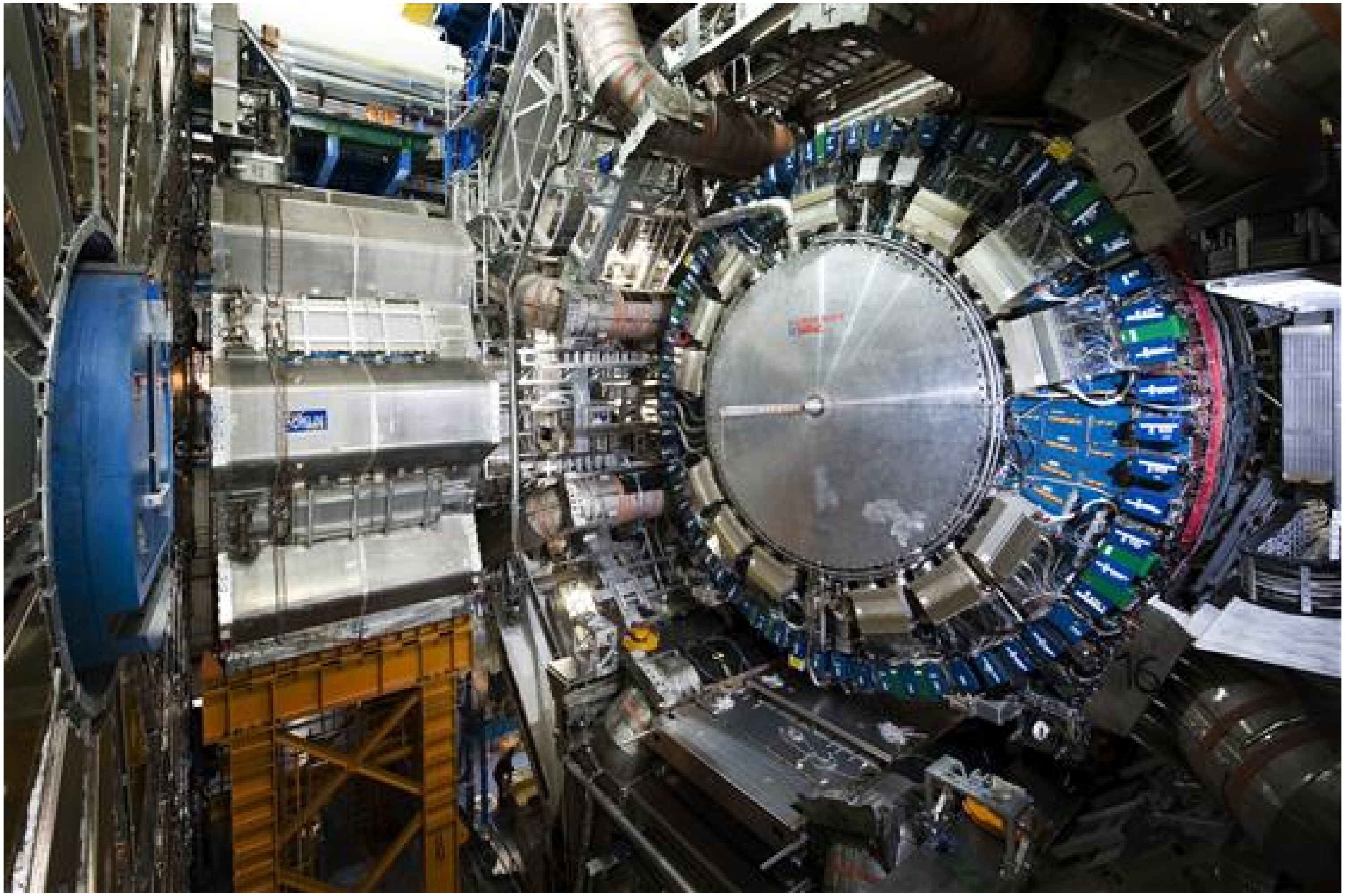
Diameter	*25 m*
Barrel toroid length	*26 m*
End-cap end-wall chamber span	*46 m*
Overall weight	*7000 Tons*



The ATLAS detector – October 2005



February 2007



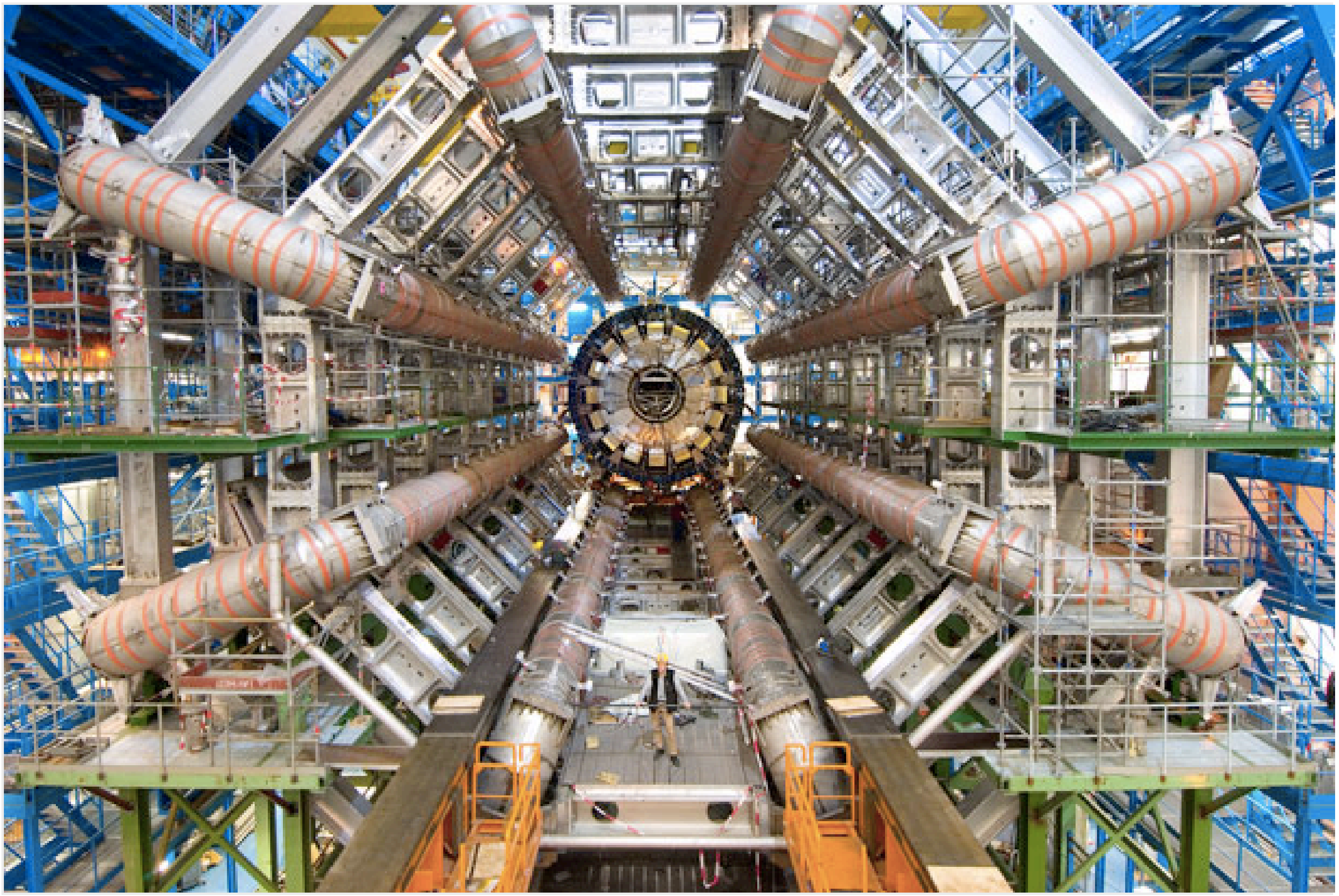
February 2008

~2,000 scientists and engineers on ATLAS
Another ~2,000 people on CMS

NATIONAL GEOGRAPHIC

The God Particle

Published: March 2008



At the Heart of All Matter

The hunt for the God particle

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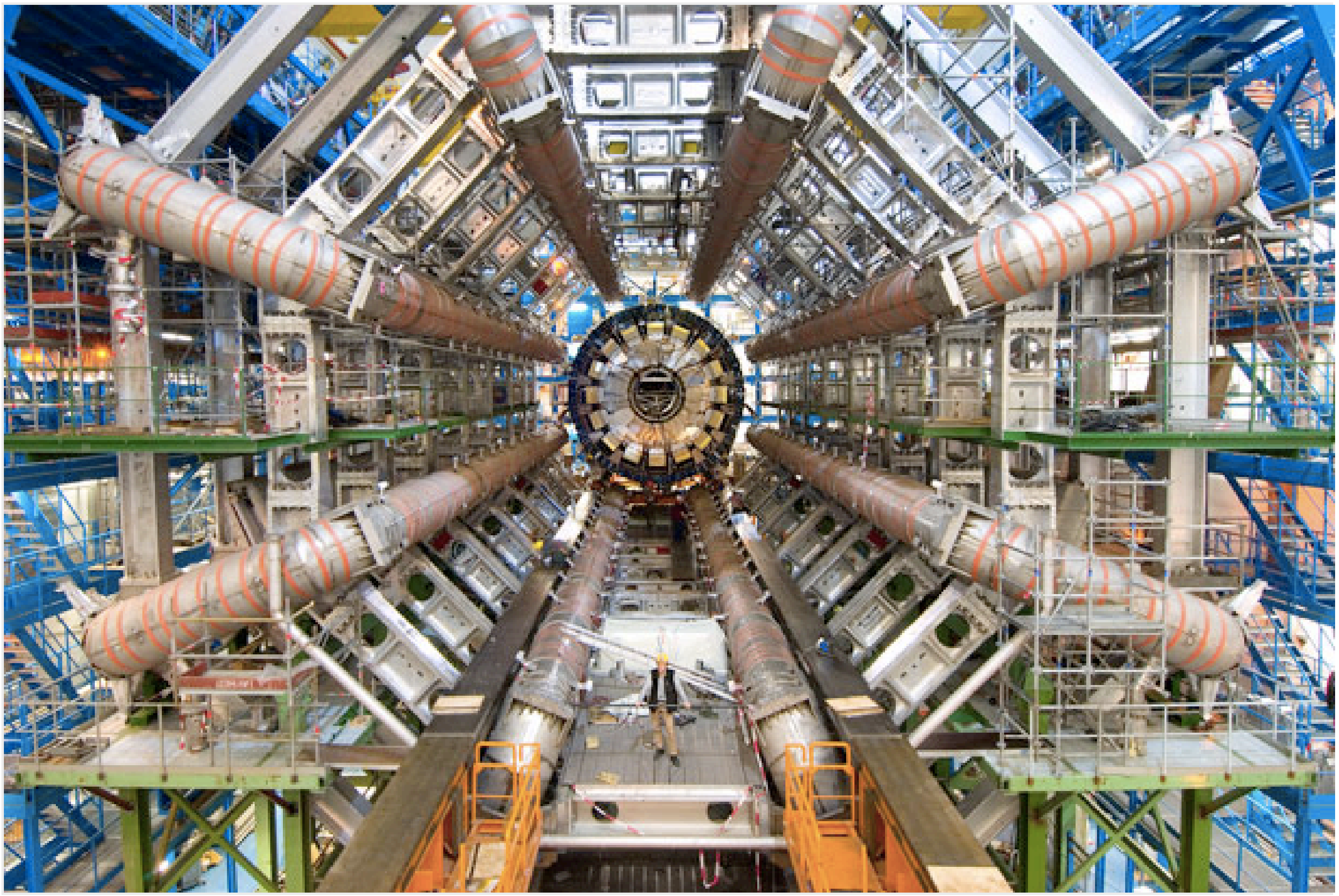

At the Heart of All Matter

The hunt for the God particle

"The God Particle" = media hyperbole for the Higgs boson

Outline

Back to basics: What is mass?

Mass in quantum mechanics

Gauge theories, weak interactions, and the problem with mass

The Higgs solution

Is it right? Testing the Higgs mechanism

Summary and outlook

What is mass?

How hard is it to lift?

Gravitational mass: Newton's law of gravity

$$\vec{F}_{\text{grav}} = -\frac{G_N \, M \, m}{r^2} \hat{r}$$

How hard is it to lift?

Gravitational mass: Newton's law of gravity

$$\vec{F}_{\text{grav}} = -\frac{G_N\,M\,m}{r^2}\widehat{r}$$

How hard is it to shift?

Kinematic mass: Newton's 2nd law

$$\vec{F} = m\,\vec{a}$$

How hard is it to lift?

Gravitational mass: Newton's law of gravity

$$\vec{F}_{\text{grav}} = -\frac{G_N \, M \, m}{r^2} \hat{r}$$

How hard is it to shift?

Kinematic mass: Newton's 2nd law

$$\vec{F} = m \, \vec{a}$$

Einstein: principle of equivalence

Gravitational mass = kinematic mass

Mass in quantum mechanics

Schrödinger equation:

$$\frac{-\hbar^2}{2m}\frac{\partial^2}{\partial x^2}\Psi(x,t) + V(x)\Psi(x,t) = i\hbar\frac{\partial}{\partial t}\Psi(x,t)$$

This "comes from" the energy conservation equation of classical mechanics:

$$\frac{p^2}{2m} + V(x) = E$$

by replacing

$$p \rightarrow \frac{\hbar}{i}\frac{\partial}{\partial x} \qquad \text{so} \qquad \frac{p^2}{2m} \rightarrow \frac{1}{2m}\left(\frac{\hbar}{i}\frac{\partial}{\partial x}\right)\left(\frac{\hbar}{i}\frac{\partial}{\partial x}\right) = \frac{-\hbar^2}{2m}\frac{\partial^2}{\partial x^2}$$

and

$$E \rightarrow i\hbar\frac{\partial}{\partial t}$$

Set $V(x) = 0$:
Plane wave solution of Schrödinger's equation:

$$\Psi(x,t) = A\, e^{i(kx-\omega t)}$$

This is a travelling wave for a quantum-mechanical particle moving in the $+x$ direction, with momentum $p = \hbar k$ and energy $E = \hbar\omega$.

Notice where the mass comes in:

$$E = \frac{p^2}{2m} \qquad \longrightarrow \qquad k = \sqrt{\frac{2mE}{\hbar^2}}, \quad \omega = E/\hbar$$

The mass shows up in the relation between k and ω.

What about relativity?

We used $E = p^2/2m$. Relativistic version is

$$E^2 = (pc)^2 + (mc^2)^2$$

Can get a new wave equation by using the same replacements:

$$p \to \frac{\hbar}{i}\frac{\partial}{\partial x}, \qquad E \to i\hbar\frac{\partial}{\partial t}$$

The result is,

$$-\hbar^2 \frac{\partial^2}{\partial t^2}\Psi(x,t) = -\hbar^2 c^2 \frac{\partial^2}{\partial x^2}\Psi(x,t) + m^2 c^4 \Psi(x,t)$$

or rearranging a little,

$$\left[\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right]\Psi - \frac{m^2 c^2}{\hbar^2}\Psi = 0$$

This is the relativistic wave equation for a particle with mass.

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Electromagnetism and the massless photon

The problem with mass shows up when we start to deal with interactions between particles.

Let's consider the simplest* force: electromagnetism.

We start with Maxwell's equations:

$$\vec{\nabla} \cdot \vec{E} = \frac{1}{\epsilon_0}\rho \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0 \qquad \vec{\nabla} \times \vec{B} - \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} = \mu_0 \vec{J}$$

$\vec{E}$ and $\vec{B}$ can be written in terms of the (scalar) electrostatic potential V and the vector potential $\vec{A}$:

$$\vec{B} = \vec{\nabla} \times \vec{A} \qquad \vec{E} = -\vec{\nabla} V - \frac{\partial \vec{A}}{\partial t}$$

*Gravity is much more complicated; think General Relativity.

$$\vec{B} = \vec{\nabla} \times \vec{A}$$
$$\vec{E} = -\vec{\nabla} V - \frac{\partial \vec{A}}{\partial t}$$

Two important features of the potential formulation:

1) Two of Maxwell's equations are automatically satisfied:

$$\vec{\nabla} \cdot \vec{B} = \vec{\nabla} \cdot (\vec{\nabla} \times \vec{A}) \equiv 0$$
$$\vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{E} + \frac{\partial \vec{A}}{\partial t} \right) = \vec{\nabla} \times \left(-\vec{\nabla} V \right) \equiv 0$$

2) V and $\vec{A}$ are not uniquely determined when you fix $\vec{E}$ and $\vec{B}$:

$$\vec{A}' = \vec{A} + \vec{\nabla}\lambda \qquad\qquad V' = V - \frac{\partial \lambda}{\partial t}$$

where λ is any arbitrary scalar function of $\vec{x}$ and t.

This is called a gauge transformation and is the heart of our modern understanding of *all* the forces (we even call them "gauge theories").

Invariance of Maxwell's equations under gauge transformations lets us choose whatever gauge is convenient.

Particularly nice is Lorenz gauge:

$$\vec{\nabla} \cdot \vec{A} = -\mu_0 \epsilon_0 \frac{\partial V}{\partial t}$$

Rewriting Maxwell's equations in terms of the potentials in this gauge gives:

$$\left[\nabla^2 - \mu_0 \epsilon_0 \frac{\partial^2}{\partial t^2}\right] \vec{A} = -\mu_0 \vec{J} \qquad \left[\nabla^2 - \mu_0 \epsilon_0 \frac{\partial^2}{\partial t^2}\right] V = -\frac{1}{\epsilon_0} \rho$$

Look familiar?

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Look familiar?

$$\left[\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right] \Psi - \frac{m^2 c^2}{\hbar^2}\Psi = 0$$

It's just the relativistic wave equation for $\vec{A}$ and V, with $m = 0$ and "sources" $\vec{J}$ and ρ included!

Relativistic: combine things into four-vectors:

$$A^{\mu} = (V/c, A_x, A_y, A_z) \qquad J^{\mu} = (c\rho, J_x, J_y, J_z)$$

$$\partial_{\mu}\partial^{\mu} \equiv \frac{\partial}{\partial x^{\mu}}\frac{\partial}{\partial x_{\mu}} = -\left[\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right]$$

The gauge transformation is

metric: $\mathrm{diag}(1, -1, -1, -1)$

$$A'^{\mu} = A^{\mu} + \partial^{\mu}\lambda \equiv A^{\mu} + \frac{\partial\lambda}{\partial x_{\mu}}$$

$$\vec{A}' = \vec{A} + \vec{\nabla}\lambda$$
$$V' = V - \frac{\partial\lambda}{\partial t}$$

Then we can write Maxwell's equations in Lorenz gauge in just one equation:

$$-\partial_{\mu}\partial^{\mu} A^{\nu} = -\mu_0 J^{\nu}$$

$$\left[\nabla^2 - \mu_0\epsilon_0\frac{\partial^2}{\partial t^2}\right]\vec{A} = -\mu_0\vec{J}$$
$$\left[\nabla^2 - \mu_0\epsilon_0\frac{\partial^2}{\partial t^2}\right]V = -\frac{1}{\epsilon_0}\rho$$

In fact we can do better and write Maxwell's equations in arbitrary gauge (in "T-shirt form"):

$$-\partial_\mu (\partial^\mu A^\nu - \partial^\nu A^\mu) \equiv -\partial_\mu F^{\mu\nu} = -\mu_0 J^\nu$$

where $F^{\mu\nu}$ is the (gauge invariant!) field strength tensor:

$$F^{\mu\nu} = \begin{pmatrix} 0 & E_x/c & E_y/c & E_z/c \\ -E_x/c & 0 & B_z & -B_y \\ -E_y/c & -B_z & 0 & B_x \\ -E_z/c & B_y & B_x & 0 \end{pmatrix}$$

Using the relations between fields and potentials,

$$\vec{B} = \vec{\nabla} \times \vec{A} \qquad \vec{E} = -\vec{\nabla} V - \frac{\partial \vec{A}}{\partial t}$$

you can show that this is identical to

$$F^{\mu\nu} = \frac{\partial A^\nu}{\partial x_\mu} - \frac{\partial A^\mu}{\partial x_\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

One more step to get the massless photon.

To give the photon a mass m we'd need to write its relativistic wave equation as:

$$-\partial_\mu F^{\mu\nu} - \frac{m^2c^2}{\hbar^2} A^\nu = 0$$

But this is not invariant under gauge transformations!

Plugging in $A^\nu = A'^\nu - \partial^\nu \lambda$ gives

$$-\partial_\mu F'^{\mu\nu} - \frac{m^2c^2}{\hbar^2} A'^\nu = -\frac{m^2c^2}{\hbar^2} \partial^\nu \lambda$$

(Not the same equation as before!)

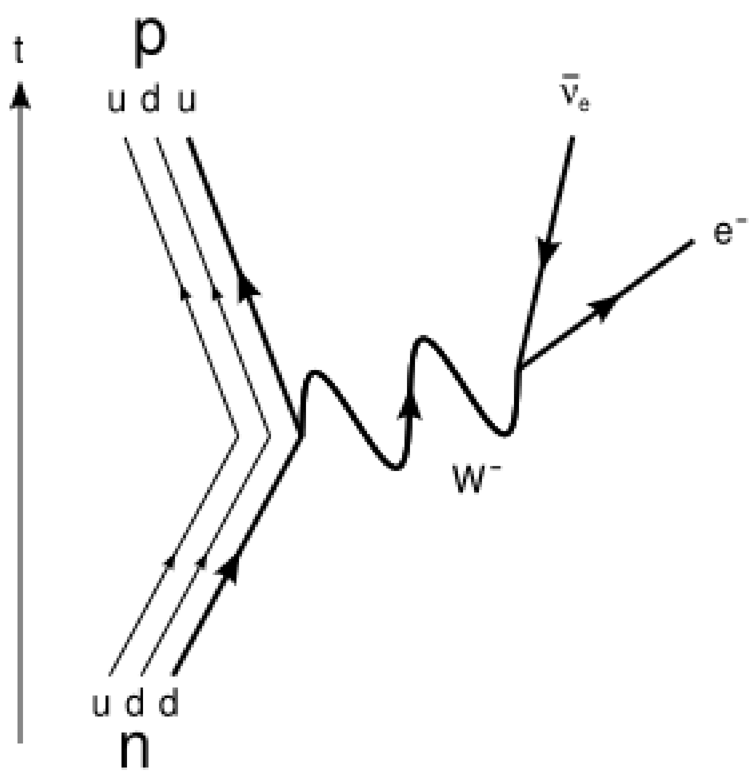
The problem is the mass term: it is not gauge invariant.

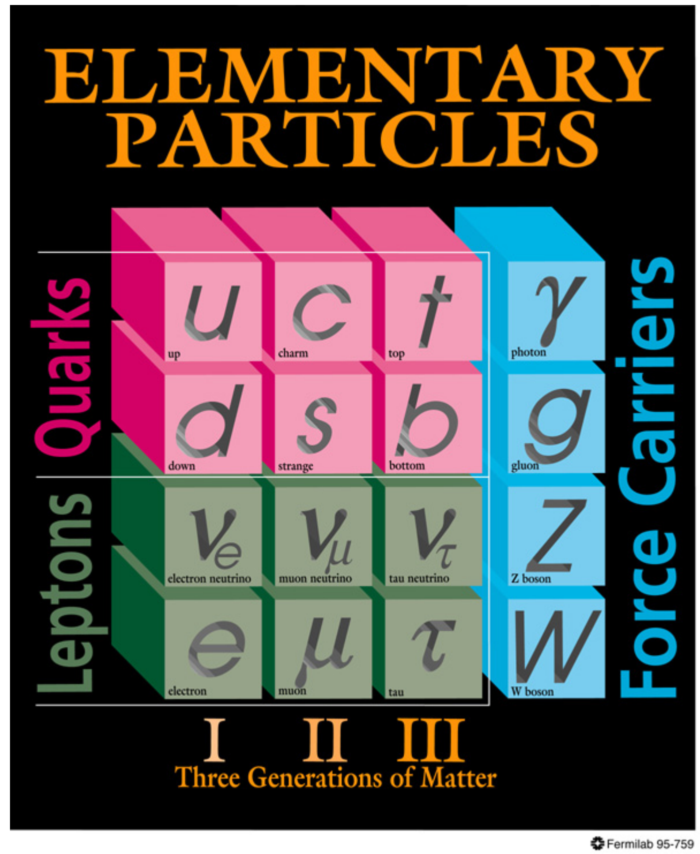
From the gauge theory point of view, this is why the photon is massless:

A nonzero photon mass is forbidden by gauge invariance.

Weak interactions and the problem with mass

Weak interactions are responsible, e.g., for nuclear beta decay.



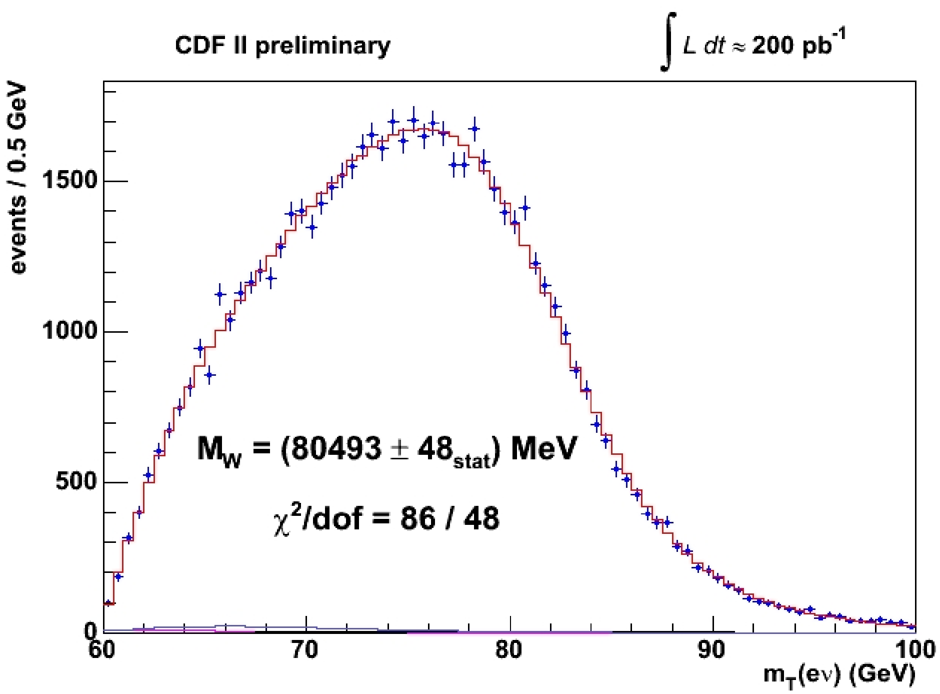


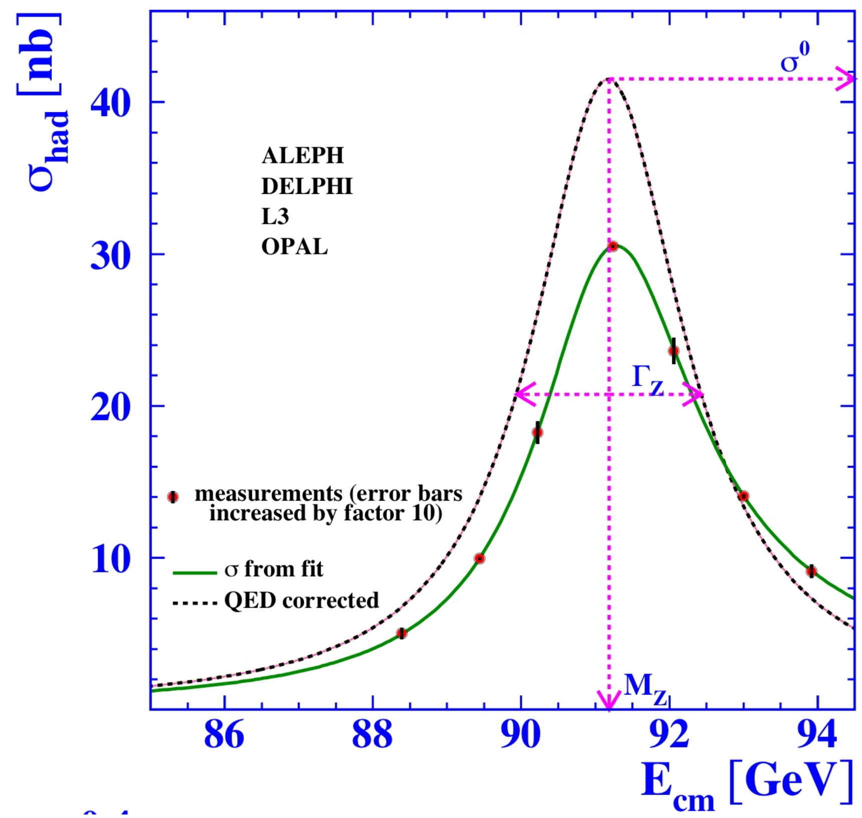
The force carriers are the charged W^+ and W^- bosons and the neutral Z boson.

Just like electromagnetism, the theory of weak interactions is a gauge theory.

But there's a snag: the W and Z bosons are not massless!

$m_W = 80.398 \pm 0.025\,\text{GeV}/c^2 \qquad m_Z = 91.1876 \pm 0.0021\,\text{GeV}/c^2$





Maybe weak interactions are not a gauge theory?

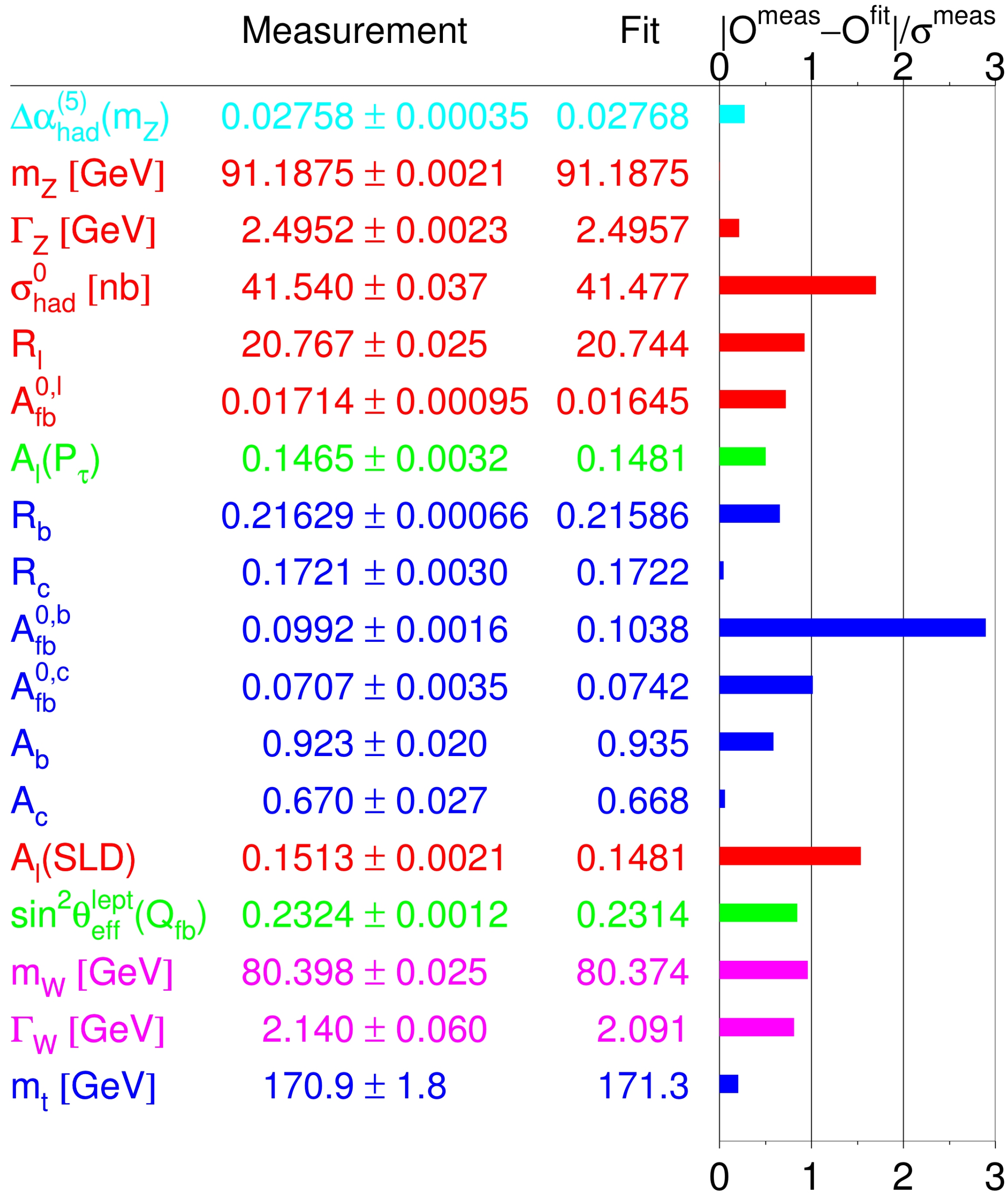
Requiring gauge invariance constrains the theory very tightly: stringent set of predictions, can be tested experimentally.

Maybe weak interactions are not a gauge theory?

Requiring gauge invariance constrains the theory very tightly: stringent set of predictions, can be tested experimentally.

Results:

All the measurements are in excellent agreement with standard gauge theory predictions!



Remember what happened when we tried to give a gauge boson a mass:

$$-\partial_\mu F^{\mu\nu} - \frac{m^2c^2}{\hbar^2} A^\nu = 0$$

Doing a gauge transformation, $A'^\nu = A^\nu + \partial^\nu \lambda$, gives

$$-\partial_\mu F'^{\mu\nu} - \frac{m^2c^2}{\hbar^2} A'^\nu = -\frac{m^2c^2}{\hbar^2} \partial^\nu \lambda$$

Compare to our original Maxwell's equation, including sources:

$$-\partial_\mu F^{\mu\nu} = -\mu_0 J^\nu$$

The new term that pops up on the right-hand side looks like some kind of weird current, which depends on the choice of gauge(!).

How can we understand this?

To go further, we need to write the equations of the gauge theory in a way where the gauge invariance is easier to deal with.

This can be done by taking a page from classical mechanics: the Lagrangian formalism, where all the symmetries are explicit.

Want to define some $\mathcal{L} = (\text{kinetic}) - (\text{potential})$ such that we get back Maxwell's equations when we run it through the Euler-Lagrange equation:

$$\partial_\mu \left[\frac{\partial \mathcal{L}}{\partial(\partial_\mu A)} \right] - \frac{\partial \mathcal{L}}{\partial A} = 0$$

This works if we define

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

To give the gauge boson a mass we'd need to add a new term:

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} m^2 A^\mu A_\mu$$

The $\frac{1}{2} m^2 A^\mu A_\mu$ term is not gauge invariant. That is the root of the problem.

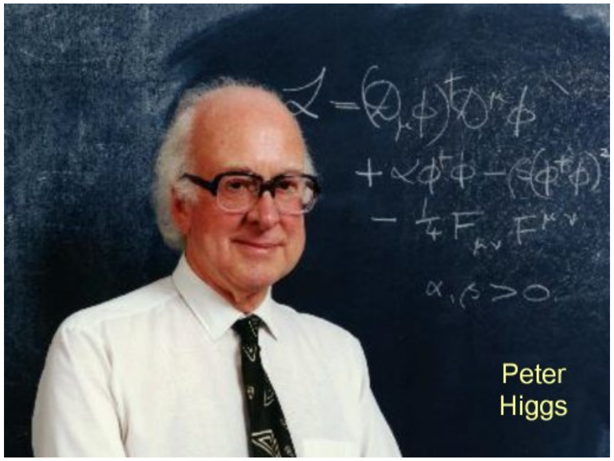
Outline

The Higgs solution: spontaneous breaking of gauge symmetry

Imagine we have a scalar (spin 0) field Φ (the so-called Higgs field).

It follows the same old relativistic wave equation:

$$\left[\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right]\Phi - \frac{m^2c^2}{\hbar^2}\Phi = 0$$



Let's put that into a Lagrangian, $\mathcal{L} =$ (kinetic) $-$ (potential):

$$\mathcal{L} = (\partial_\mu \Phi)^\dagger (\partial^\mu \Phi) - V$$

V is the potential. For the Higgs field, it has to have the general form (α and β are constants)

$$V = -\alpha\, \Phi^\dagger \Phi + \beta (\Phi^\dagger \Phi)^2$$

The minus sign in front of α will be important in a minute...

We also want Φ to interact with the weak gauge bosons. First add the gauge bosons to $\mathcal{L}$:

$$\mathcal{L} = (\partial_\mu \Phi)^\dagger (\partial^\mu \Phi) + \alpha\, \Phi^\dagger \Phi - \beta (\Phi^\dagger \Phi)^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

For Φ to interact with the gauge bosons, it has to participate in the gauge transformation (!)

$$A'^\nu = A^\nu + \partial^\nu \lambda \quad \text{while} \quad \Phi' = e^{i\lambda} \Phi$$

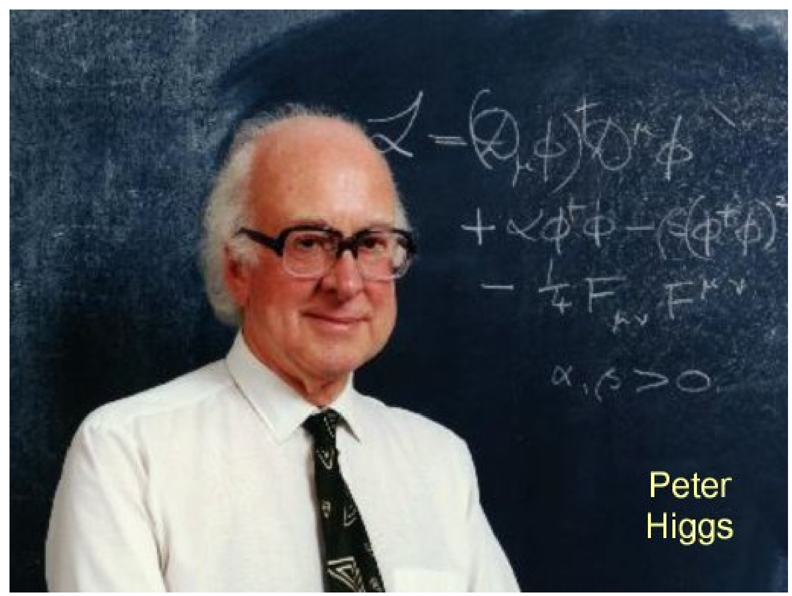
$\lambda \equiv \lambda(x)$: is affected by the ∂^μ acting on Φ. To keep $\mathcal{L}$ gauge invariant, must replace ∂^μ with the "covariant derivative"

$$\mathcal{D}^\mu = \partial^\mu - i A^\mu$$

Result:

$$\begin{aligned} \mathcal{L} \;=\; & (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) \\ & + \alpha\, \Phi^\dagger \Phi - \beta (\Phi^\dagger \Phi)^2 \\ & - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \end{aligned}$$

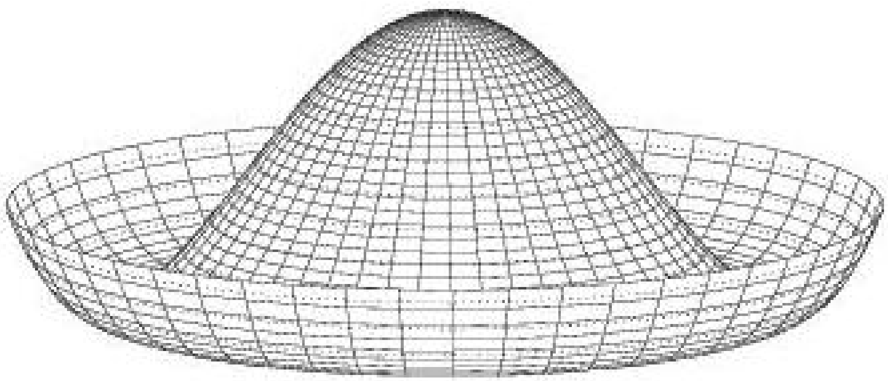
(Compare Prof. Higgs's chalkboard.)



Now the trick: look again at V

$$V = -\alpha\,\Phi^\dagger\Phi + \beta(\Phi^\dagger\Phi)^2$$

This is a quartic equation in Φ. It looks like this:



Rotational symmetry corresponds to the gauge symmetry: Φ is a kind of "vector" in the internal gauge symmetry space.

Important feature: the minimum of the potential is not at zero!

Universe must choose particular (non-symmetric) configuration: the ground state does not obey the (rotational) symmetry.

This is called spontaneous symmetry breaking.

Let's write Φ in terms of its value at the minimum of V:

$$\Phi(x^\mu) = v + h(x^\mu) \qquad \text{(schematically)} \quad \text{with} \quad v = \sqrt{\frac{\alpha}{2\beta}}$$

Now plug this back in to $\mathcal{L}$ and multiply out all the terms:

$$\begin{aligned} \mathcal{L} \;=\; & (\partial^\mu h)^2 - 4\beta v^2 h^2 \\ & -4\beta v h^3 - \beta h^4 + 2v A^\mu A_\mu h + A^\mu A_\mu h^2 \\ & -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + v^2 A^\mu A_\mu \end{aligned}$$

Line 1 gives the relativistic wave equation for h with mass $\sqrt{2\beta}v$.
Line 2 gives interactions between h's and between h and A^μ.
Line 3 gives the relativistic wave equation for A^μ with mass $\sqrt{2}v$.

came from A^2v^2 term in $|(\partial^\mu - iA^\mu)(v+h)|^2$

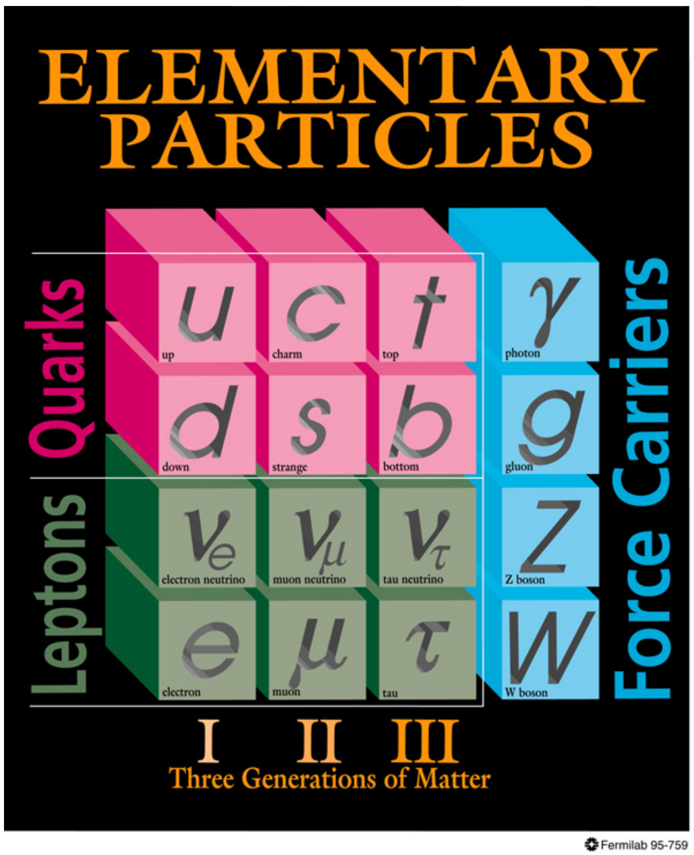
Spontaneous symmetry breaking gave us a massive gauge boson, just like we wanted!

We never put in any explicit breaking of gauge symmetry; our Lagrangian was always gauge invariant.

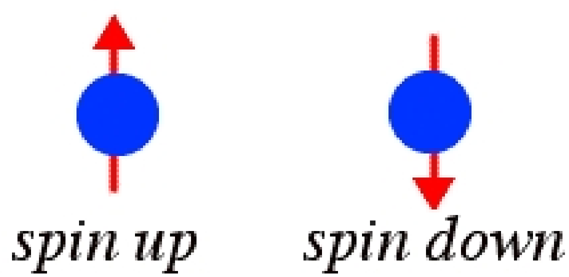
This is how the Standard Model works.

An extra bonus: masses for fermions

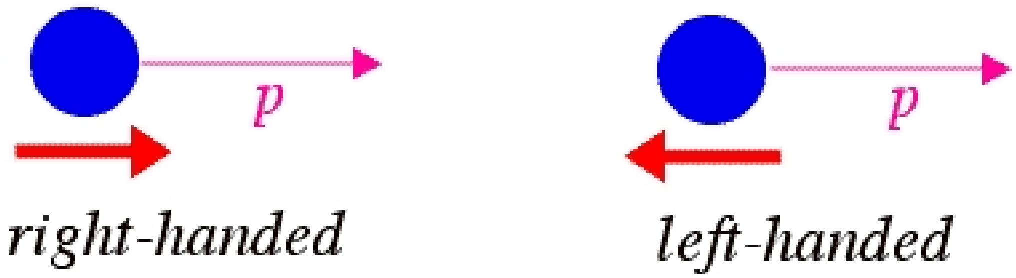
Not only does the Higgs mechanism solve the problem of massive W and Z bosons.
It also solves a problem with masses of ordinary elementary particles, like the electron and quarks.



Standard Model matter particles are fermions: spin-1/2.



For fast-moving particles, it's convenient to quantize spin along direction of motion: these are called helicity states.



Can transform a right-handed particle into a left-handed particle by Lorentz-boosting yourself past it:

This is only possible for particles with nonzero mass.

Massless particles move at the speed of light: can't boost past them, so the two helicity states are physically distinct.

If all we knew were electrodynamics and QCD (strong interactions), this would be fine: left-handed and right-handed particles have the same interactions.

But weak interactions distinguish between left-handed and right-handed particles!

- $W^\pm$ bosons couple only to left-handed fermions
- Z bosons couple with different strengths to left- and right-handed fermions

This "handedness" is called parity violation (discovered in the weak interactions in 1957).

Luckily for the Standard Model, the Higgs mechanism can provide fermion masses too!

To get the proper relativistic wave equation for a fermion (with mass m), the Lagrangian has to look like this:

$$\mathcal{L} = \bar{f}_L \gamma^\mu \partial_\mu f_L + \bar{f}_R \gamma^\mu \partial_\mu f_R - m \bar{f}_L f_R - m \bar{f}_R f_L$$

- f_L and f_R stand for the left- and right-handed helicity states
- the bar means antiparticle
- γ^μ is a technical detail for fermions

For a particle to interact with the gauge bosons, it has to participate in the gauge transformation:

$$A'^\nu = A^\nu + \partial^\nu \lambda \quad \text{while} \quad f'_L = e^{i\lambda} f_L, \; f'_R = f_R, \; \Phi' = e^{i\lambda} \Phi$$

f_L and Φ interact with W bosons but f_R doesn't.

The mass terms $-m\bar{f}_L f_R - m\bar{f}_R f_L$ are not gauge invariant!

But we can write a new gauge-invariant term:

$$\mathcal{L} = -y \bar{f}_L \Phi f_R - y \bar{f}_R \Phi^\dagger f_L + \cdots$$

The phases $e^{i\lambda}$ cancel between $\bar{f}_L$ and Φ: gauge invariant!

Gauge invariant Lagrangian for fermions:

$$\mathcal{L} = \bar{f}_L \gamma^\mu \mathcal{D}_\mu f_L + \bar{f}_R \gamma^\mu \mathcal{D}_\mu f_R - y \bar{f}_L \Phi f_R - y \bar{f}_R \Phi^\dagger f_L$$

Look what happens when we plug in $\Phi = v + h$:

$$\begin{aligned}\mathcal{L} &= \bar{f}_L \gamma^\mu \mathcal{D}_\mu f_L + \bar{f}_R \gamma^\mu \mathcal{D}_\mu f_R - yv \bar{f}_L f_R - yv \bar{f}_R f_L \\ &\quad - y\, h \bar{f}_L f_R - y\, h \bar{f}_R f_L\end{aligned}$$

Line 1 gives the relativistic wave equation for the fermion with mass yv.
Line 2 gives interactions between h and the fermion.

And everything is nicely gauge invariant!

The Higgs mechanism has solved the problem of mass.

Outline

Back to basics: What is mass? ✓

Mass in quantum mechanics ✓

Gauge theories, weak interactions, and the problem with mass ✓

The Higgs solution ✓

Is it right? Testing the Higgs mechanism

Summary and outlook

So how do we test it?

The Higgs mechanism makes two big predictions:
1) There's a particle h: the Higgs boson.
2) The same terms in $\mathcal{L}$ that gave masses to particles also gave them couplings to h proportional to that mass.

Fermions:

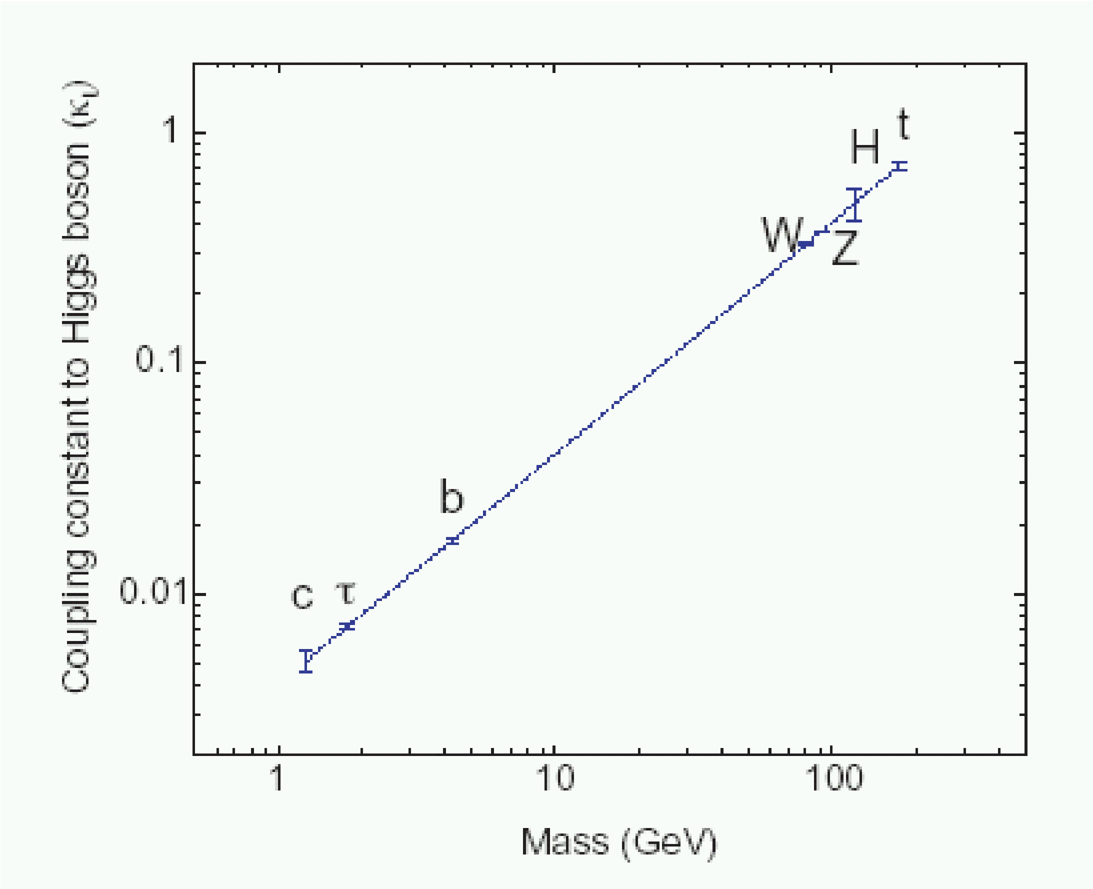
$$\begin{aligned} \mathcal{L} &\supset -y\bar{f}_L\Phi f_R - y\bar{f}_R\Phi^\dagger f_L \\ &= -yv\bar{f}_L f_R - yv\bar{f}_R f_L - y\,h\bar{f}_L f_R - y\,h\bar{f}_R f_L \end{aligned}$$

Gauge bosons:

$$\begin{aligned} \mathcal{L} &\supset (\mathcal{D}_\mu\Phi)^\dagger(\mathcal{D}^\mu\Phi) \\ &= |(\partial^\mu - iA^\mu)(v+h)|^2 \\ &\supset v^2A^\mu A_\mu + 2vA^\mu A_\mu h + A^\mu A_\mu h^2 \end{aligned}$$

So how do we test it?

The Higgs mechanism makes two big predictions:
1) There's a particle h: the Higgs boson.
2) The same terms in $\mathcal{L}$ that gave masses to particles also gave them couplings to h proportional to that mass.



Test the Higgs mechanism by:

1) discovering the Higgs

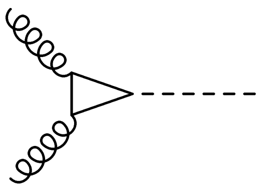
and

2) measuring its couplings to other particles.

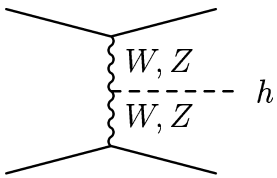
Here's where the LHC comes in!

Higgs production rates are controlled by Higgs couplings to Standard Model particles.

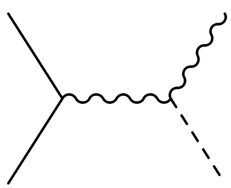
- Gluon fusion, $gg \to H$



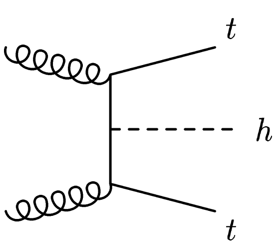
- Weak boson fusion, $qq \to Hqq$

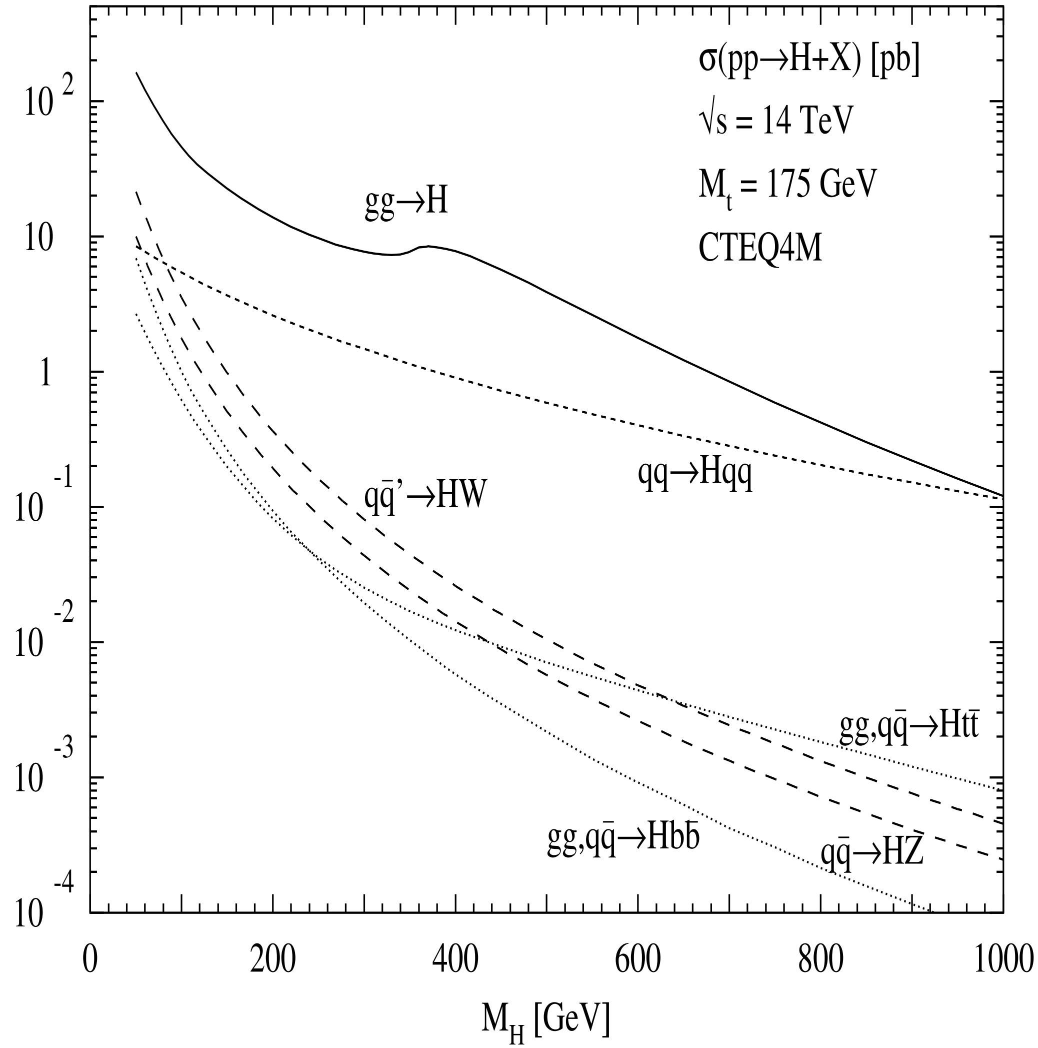


- WH, ZH associated production



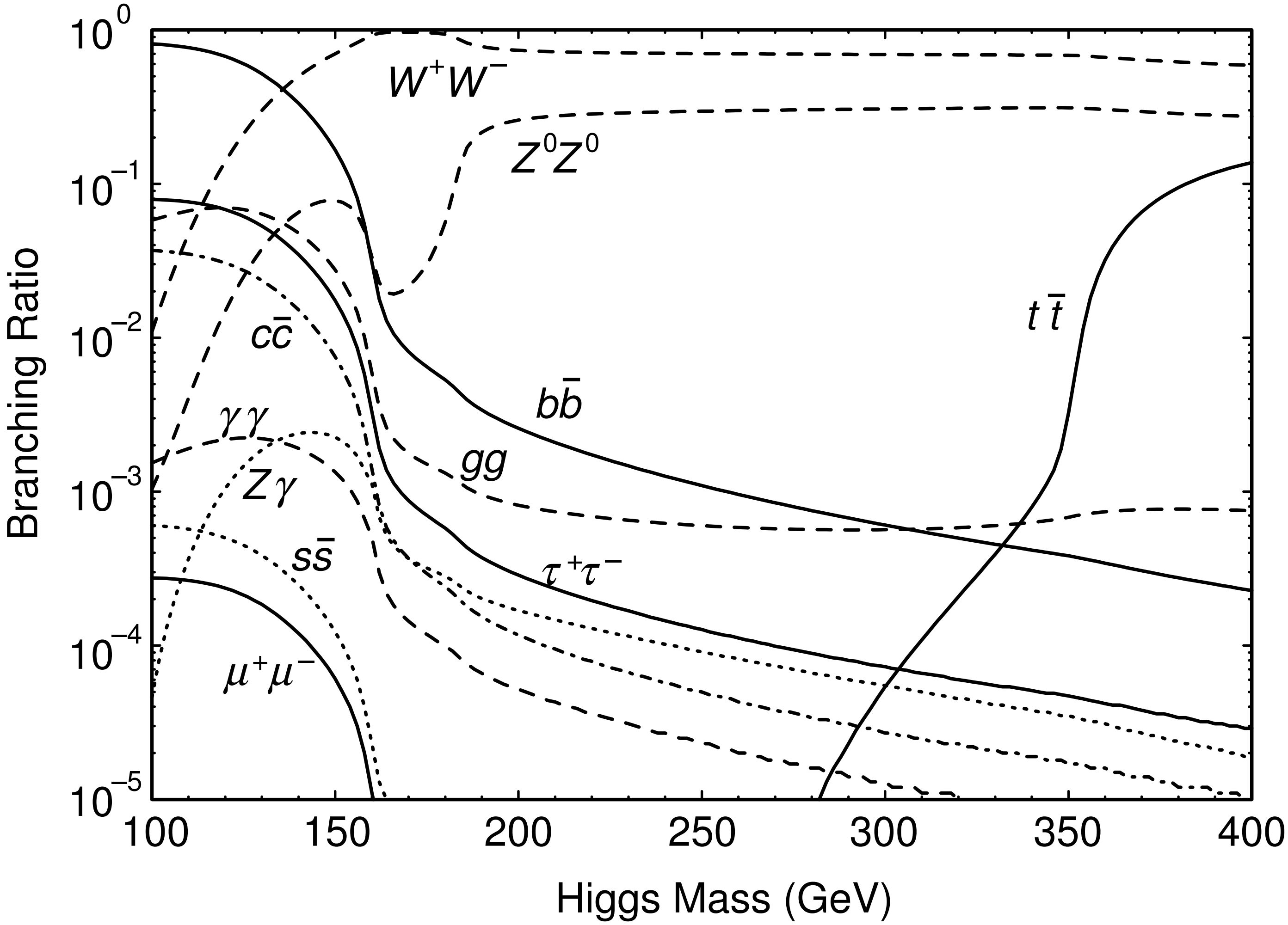
- ttH associated production





M. Spira, Fortsch. Phys. 46, 203 (1998)

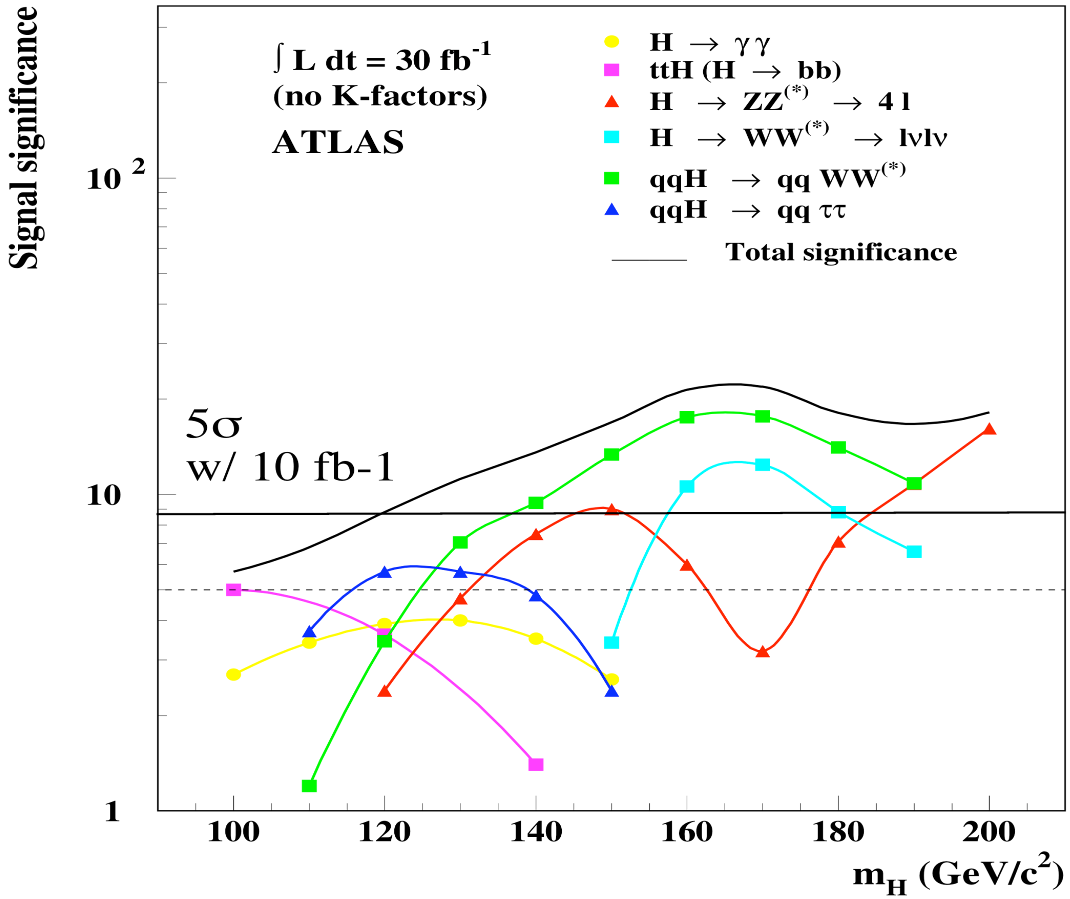
Higgs decay rates are controlled by Higgs couplings to Standard Model particles.



HDECAY

Decay modes depend on m_h.

Production rate $\times$ decay branching fraction $=$ signal rate.



Dashed line is 5-sigma discovery after first 3 years of LHC running.

Already know that $m_H > 114$ GeV.

S. Asai et al., Eur. Phys. J. C 32S2, 19 (2004)

LHC will discover the Higgs if its couplings are as predicted.
Measure signal rates $\rightarrow$ test the pattern of Higgs couplings.

Summary and outlook

Because of the weirdness of the weak interactions, we don't actually know why particles have mass.

The Higgs mechanism is our best guess: it fixes up the particle masses, but it is still not yet tested.

Thanks to the LHC, we won't have much longer to wait!