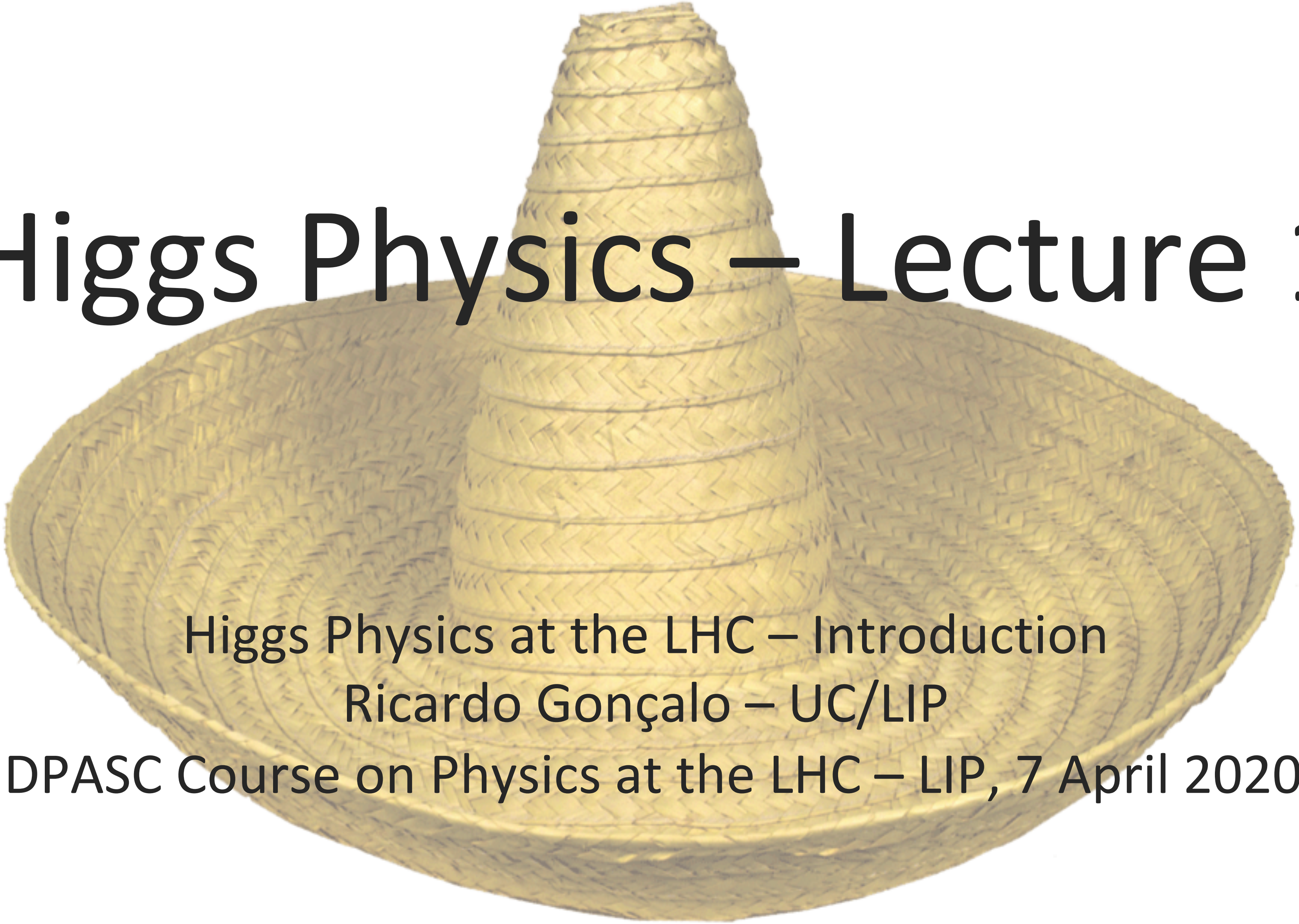

Higgs Physics – Lecture 1

Higgs Physics at the LHC – Introduction

Ricardo Gonçalo – UC/LIP

IDPASC Course on Physics at the LHC – LIP, 7 April 2020

Cofinanciado por:
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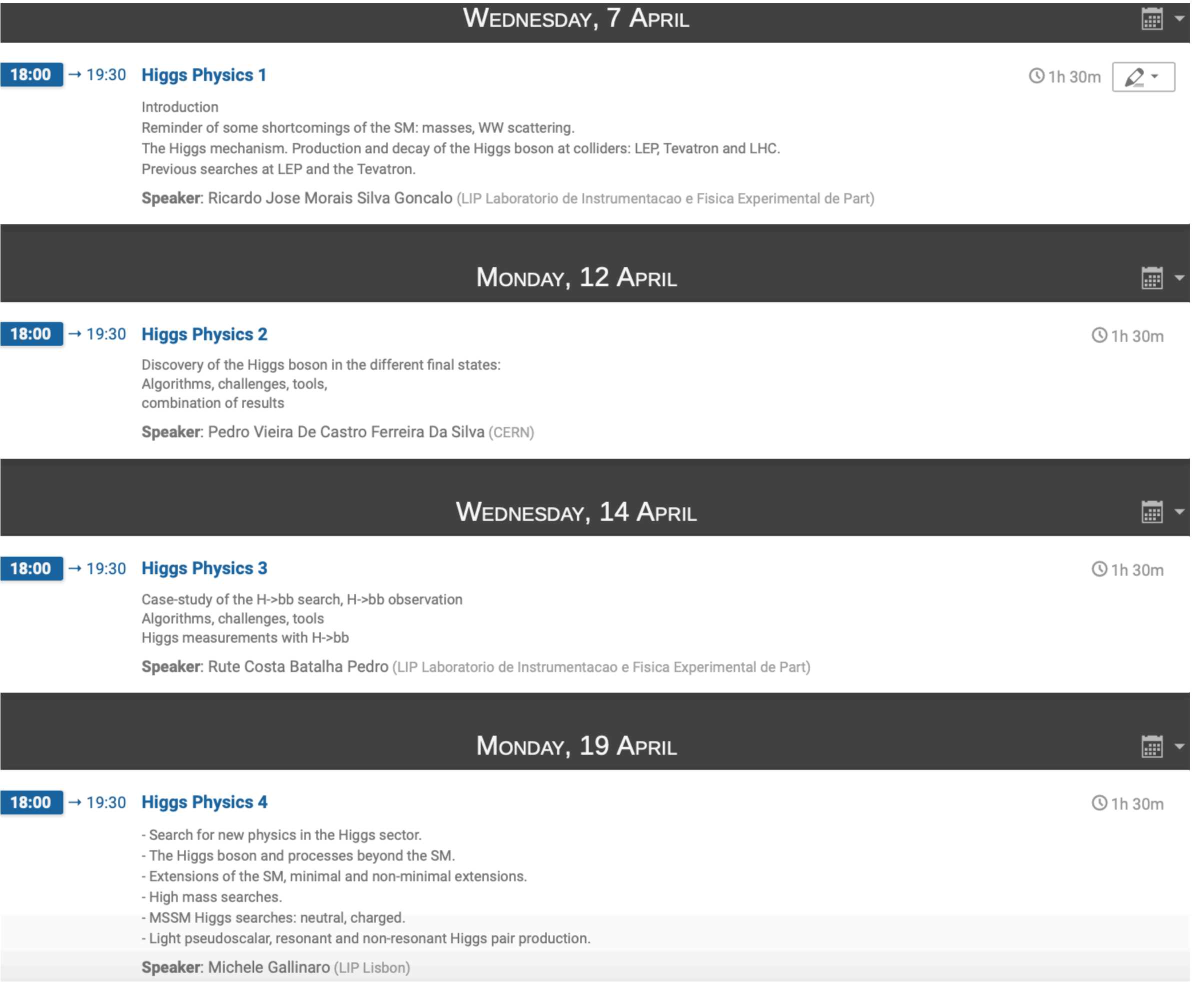
Fundos Europeus Estruturais e de Investimento

Higgs Lectures



Wednesday, 7 April

18:00 → 19:30 **Higgs Physics 1** 1h 30m

Introduction
Reminder of some shortcomings of the SM: masses, WW scattering.
The Higgs mechanism. Production and decay of the Higgs boson at colliders: LEP, Tevatron and LHC.
Previous searches at LEP and the Tevatron.

Speaker: Ricardo Jose Morais Silva Goncalo (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

Monday, 12 April

18:00 → 19:30 **Higgs Physics 2** 1h 30m

Discovery of the Higgs boson in the different final states:
Algorithms, challenges, tools,
combination of results

Speaker: Pedro Vieira De Castro Ferreira Da Silva (CERN)

Wednesday, 14 April

18:00 → 19:30 **Higgs Physics 3** 1h 30m

Case-study of the H->bb search, H->bb observation
Algorithms, challenges, tools
Higgs measurements with H->bb

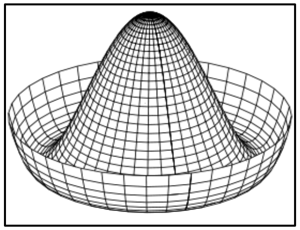
Speaker: Rute Costa Batalha Pedro (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

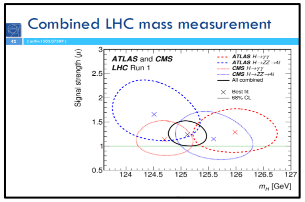
Monday, 19 April

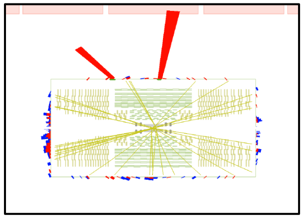
18:00 → 19:30 **Higgs Physics 4** 1h 30m

- Search for new physics in the Higgs sector.
- The Higgs boson and processes beyond the SM.
- Extensions of the SM, minimal and non-minimal extensions.
- High mass searches.
- MSSM Higgs searches: neutral, charged.
- Light pseudoscalar, resonant and non-resonant Higgs pair production.

Speaker: Michele Gallinaro (LIP Lisbon)




Combined LHC mass measurement

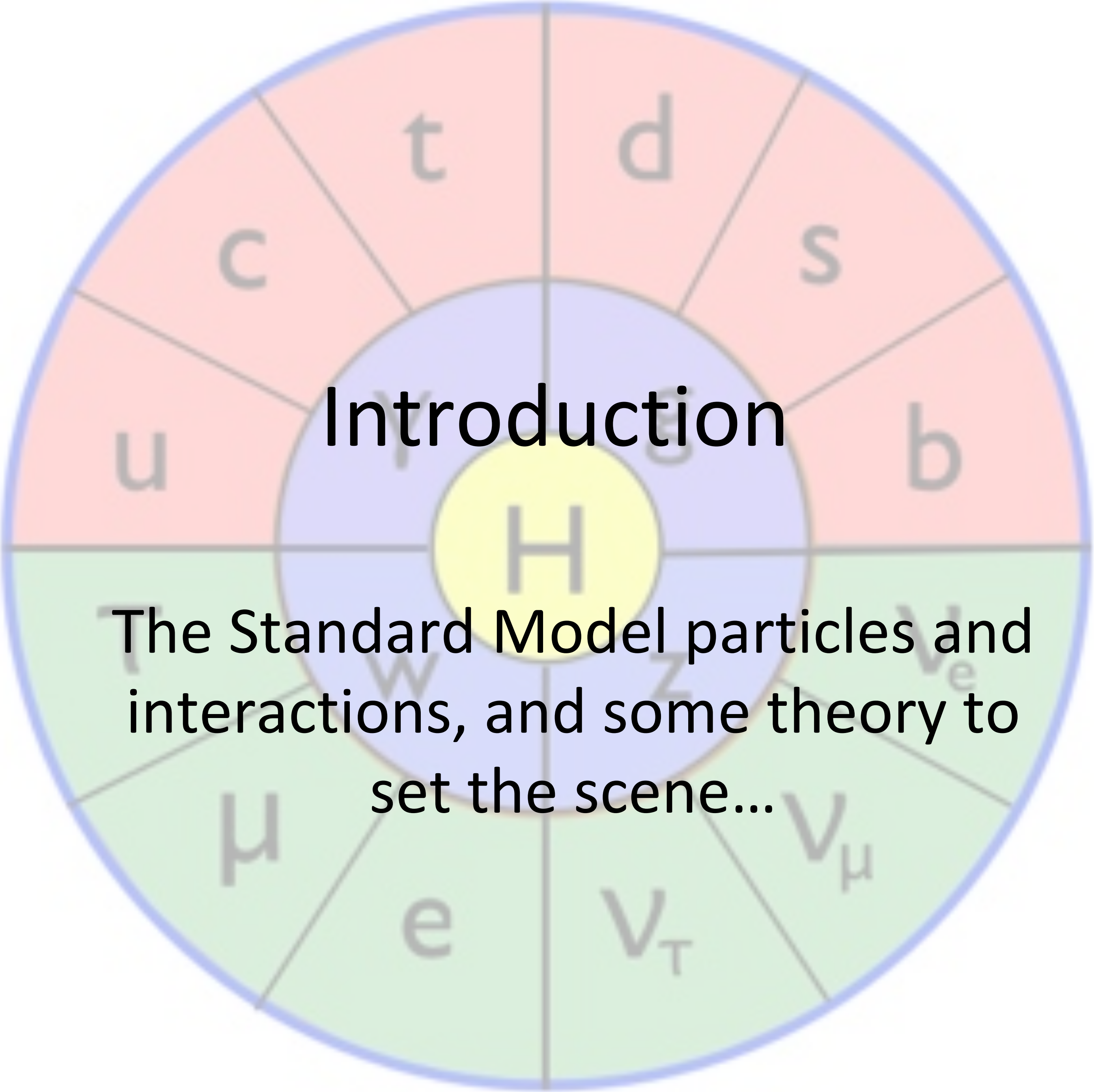


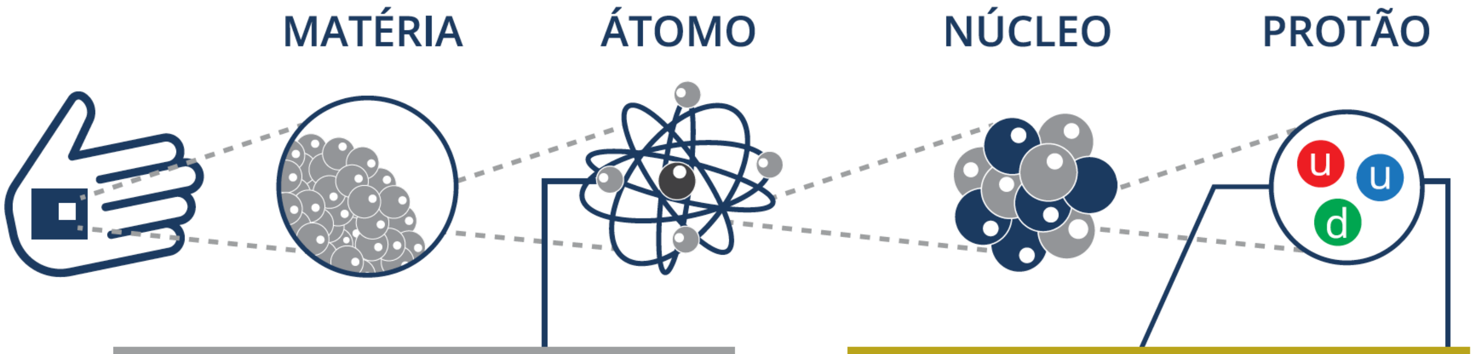
Outlook

- Introduction
- Some theory
- Problems with the Standard Model
- The Higgs mechanism
- The long way to discovery
  - LEP experiments
  - Tevatron experiments
  - Search and Discovery at the LHC
- Higgs boson properties
- Open questions

Introduction

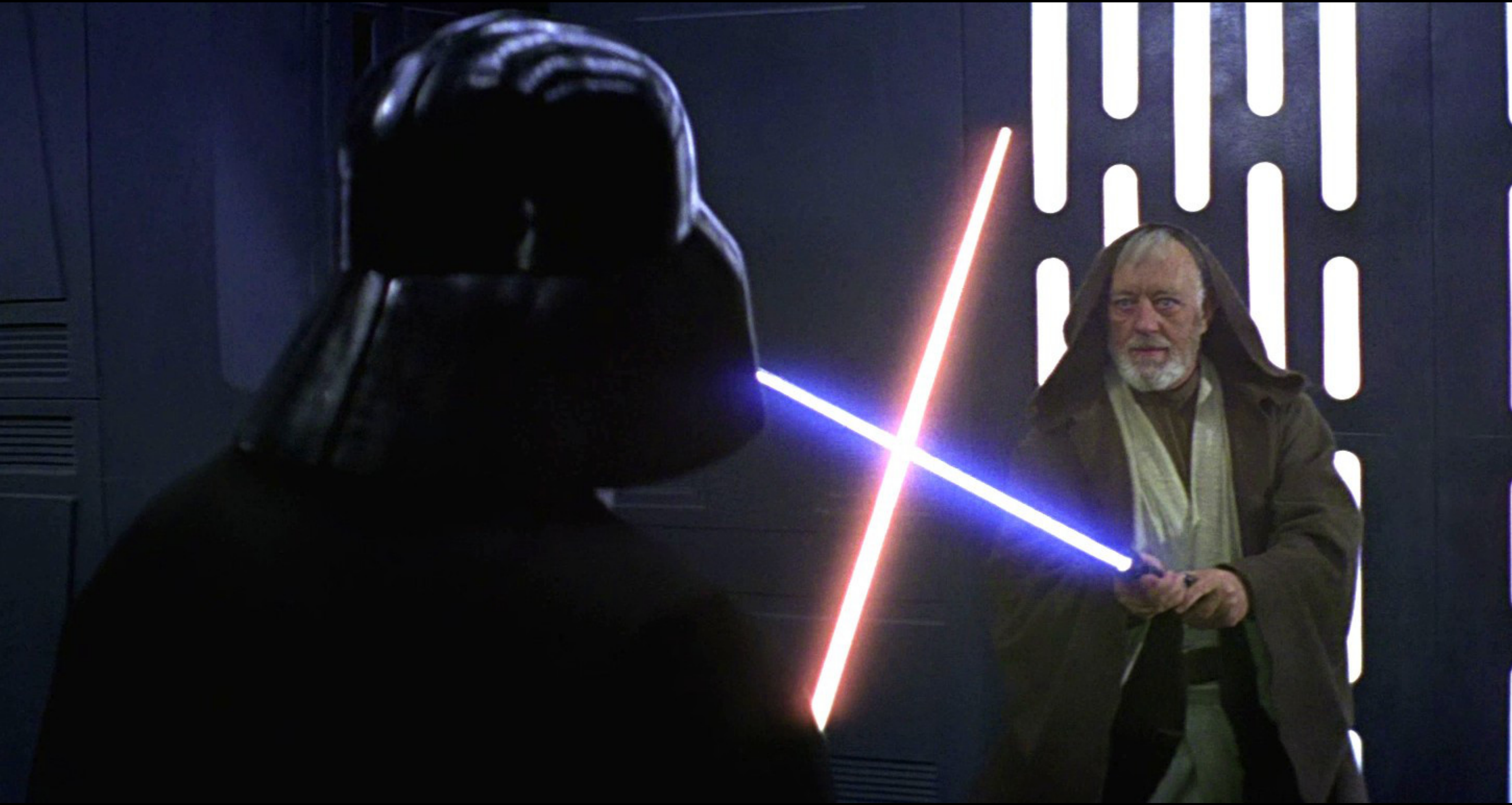
The Standard Model particles and interactions, and some theory to set the scene…





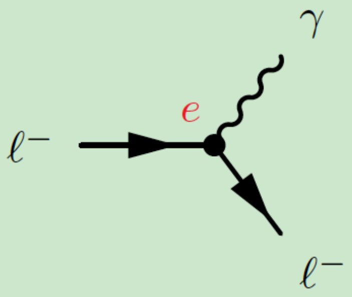
LEPTÕES		QUARKS	
ν_e **NEUTRINO DO ELETRÃO** 0 ½	e **ELETRÃO** -1 ½	u **UP** ⅔ ½	d **DOWN** -⅓ ½
ν_μ **NEUTRINO DO MUÃO** 0 ½	μ **MUÃO** -1 ½	c **CHARM** ⅔ ½	s **STRANGE** -⅓ ½
ν_τ **NEUTRINO DO TAU** 0 ½	τ **TAU** -1 ½	t **TOP** ⅔ ½	b **BOTTOM** -⅓ ½

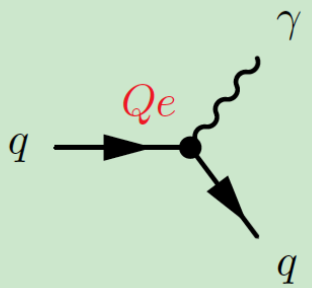
E as forças fundamentais?



Summary of Standard Model matter vertices

Electromagnetic (QED)



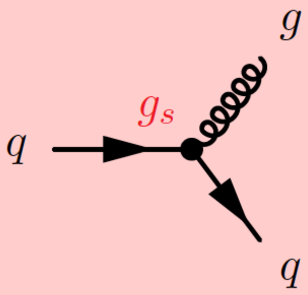


$$\alpha = \frac{e^2}{4\pi}$$

$q = u, d, s, c, b, t$

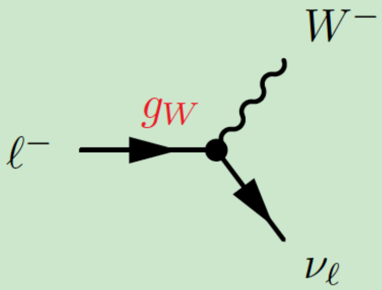
$+$ antiparticles

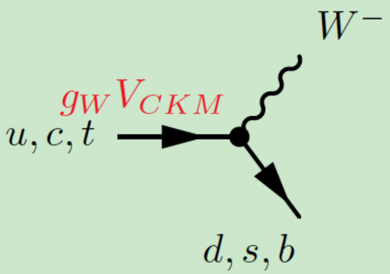
Strong (QCD)



$$\alpha_s = \frac{g_s^2}{4\pi}$$

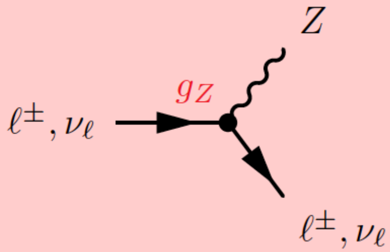
Weak CC

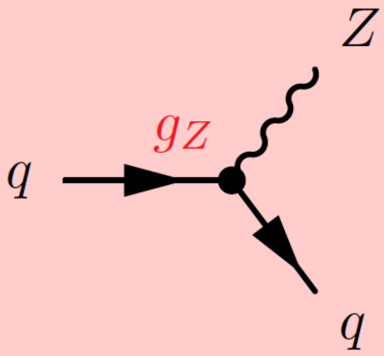




$$\alpha_W = \frac{g_W^2}{4\pi}$$

Weak NC



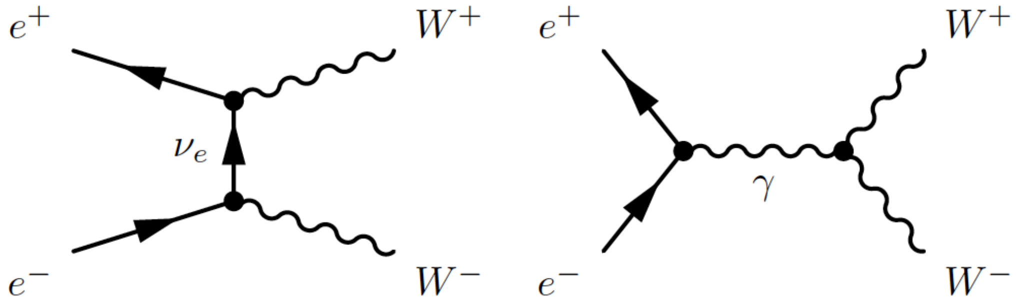


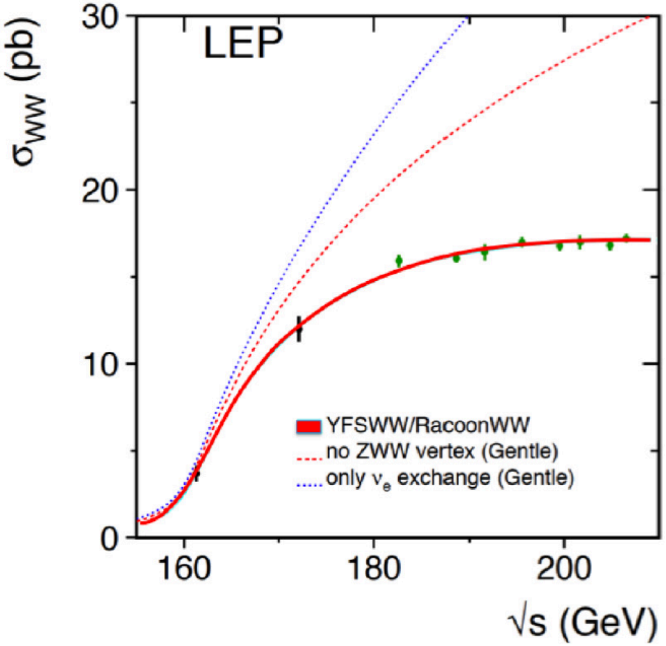
$$g_Z = \frac{g_W}{\cos\theta_W}$$

Electroweak Unification

- Weak CC interactions explained by $W^\pm$ boson exchange
- $W^\pm$ bosons are charged, thus they couple to the γ

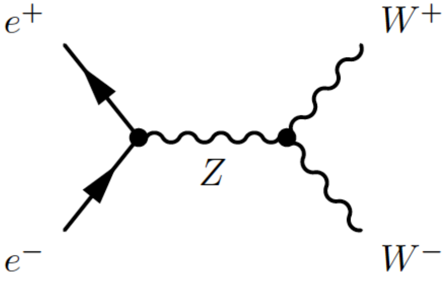
Consider $e^- e^+ \to W^+ W^-$: 2 diagrams (+interference)





- Cross-section diverges at high energy
- Divergence cured by introducing Z boson
- Extra diagram for $e^- e^+ \to W^+ W^-$
- Idea only works if γ, $W^\pm$, Z couplings are related

$\Rightarrow$ **Electroweak Unification**



Electroweak Gauge Theory

- Postulate invariance under a gauge transformation like:

  $$\psi \rightarrow \psi' = e^{ig\vec{\sigma}.\vec{\Lambda}(\vec{r},t)}\psi$$

  an "SU(2)" transformation (σ are 2x2 matrices).
- Operates on the state of "weak isospin" – a "rotation" of the isospin state.
- Invariance under SU(2) transformations $\Rightarrow$ three massless gauge bosons (W_1, W_2, W_3) whose couplings are well specified.
- They also have self-couplings.

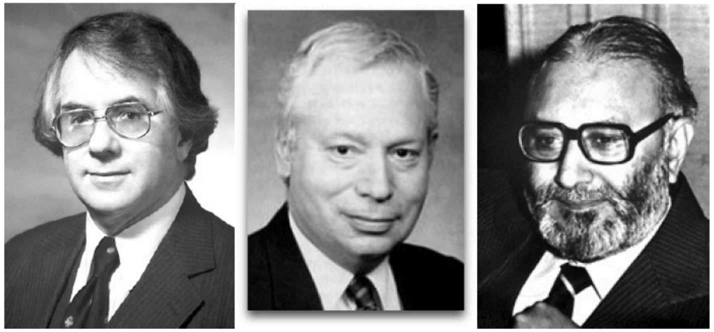
But this doesn't quite work...
Predicts W and Z have the same couplings – not seen experimentally!

Electroweak Gauge Theory

The solution…

- Unify QED and the weak force ⇒ electroweak model
- "SU(2)xU(1)" transformation
  U(1) operates on the "weak hypercharge" $Y = 2(Q - I_3)$
  SU(2) operates on the state of "weak isospin, I"
- Invariance under SU(2)xU(1) transformations ⇒ four massless gauge bosons W^+, W^-, W_3, B
- The two neutral bosons W_3 and B then **mix** to produce the physical bosons Z and γ
- Photon properties must be the same as QED ⇒ predictions of the couplings of the Z in terms of those of the W and γ
- Still need to account for the masses of the W and Z. This is the job of the Higgs mechanism (later).

The GWS Model



The Glashow, Weinberg and Salam model treats EM and weak interactions as different manifestations of a single unified electroweak force (Nobel Prize 1979)

Start with 4 massless bosons W^+, W_3, W^- and B. The neutral bosons mix to give physical bosons (the particles we see), i.e. the $W^\pm$, Z, and γ.

$$\begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix} ; \quad B \quad \rightarrow \quad \begin{pmatrix} W^+ \\ Z \\ W^- \end{pmatrix} ; \quad \gamma$$

Physical fields: W^+, Z, W^- and A (photon).

$$Z = W_3 \cos\theta_W - B \sin\theta_W$$

$$A = W_3 \sin\theta_W + B \cos\theta_W$$

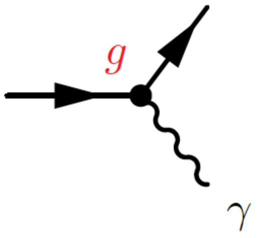
θ_W Weak Mixing Angle

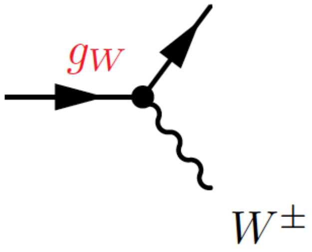
$W^\pm$, Z “acquire” mass via the Higgs mechanism.

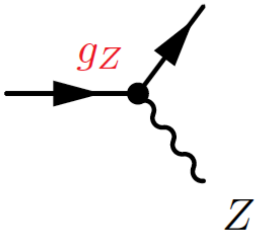
The GWS Model

The beauty of the GWS model is that it makes exact predictions of the $W^\pm$ and Z masses and of their couplings with only 3 free parameters.

Couplings given by α_{EM} and θ_W







$$\alpha_{EM} = \frac{e^2}{4\pi} \quad g \sim e \qquad g_W = \frac{e}{\sin\theta_W} \qquad g_Z = \frac{e}{\sin\theta_W \cos\theta_W} = \frac{g_W}{\cos\theta_W}$$

Masses also given by G_F and θ_W

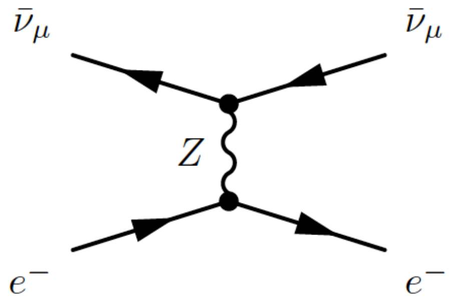
From Fermi theory

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2} = \frac{e^2}{8m_W^2\sin^2\theta_W} \qquad m_{W^\pm} = \left(\frac{\sqrt{2}e^2}{8G_F\sin^2\theta_W}\right)^{1/2} \qquad m_Z = \frac{m_W}{\cos\theta_W}$$

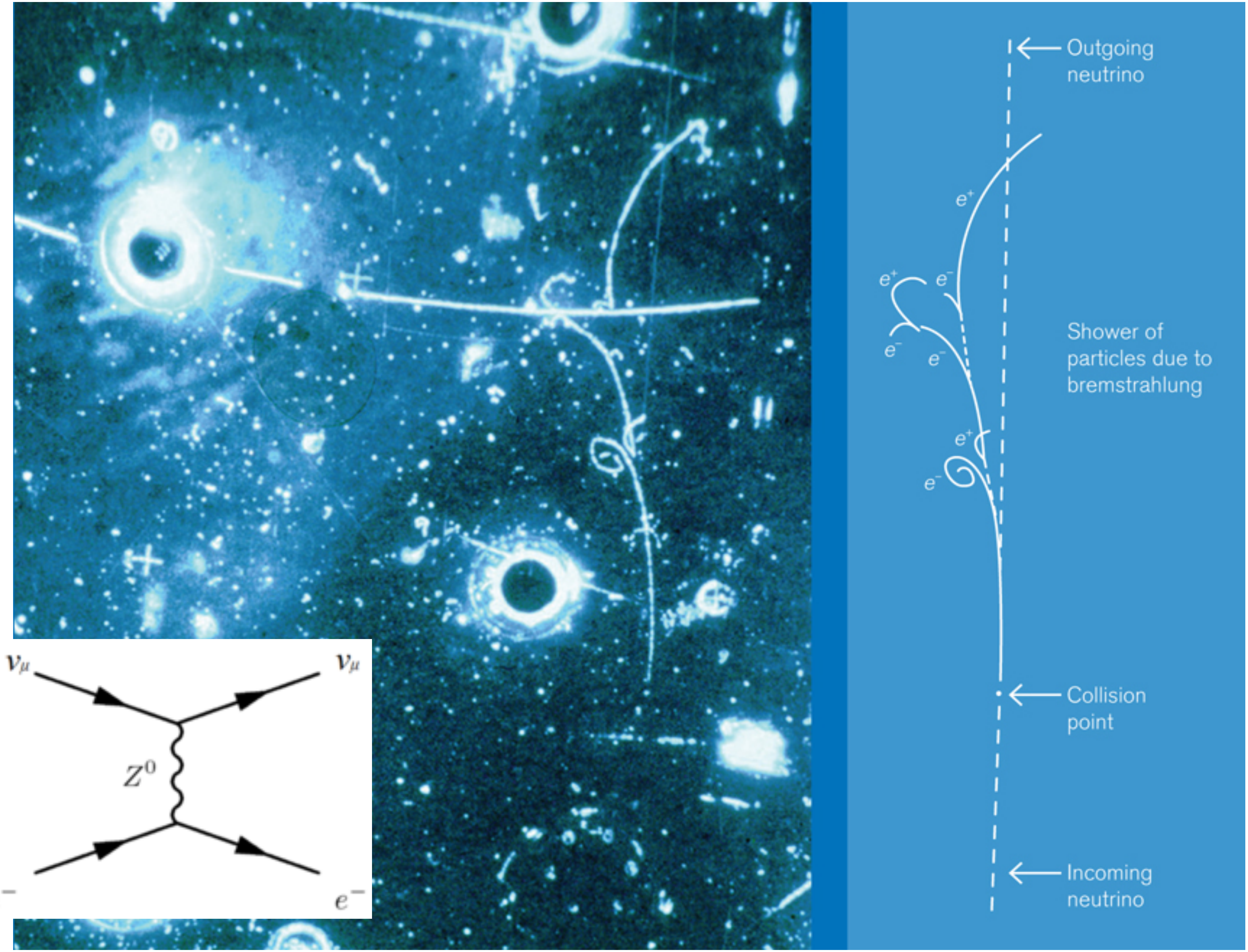
If we know α_{EM}, G_F, $\sin\theta_W$ (from experiment), everything else is defined.

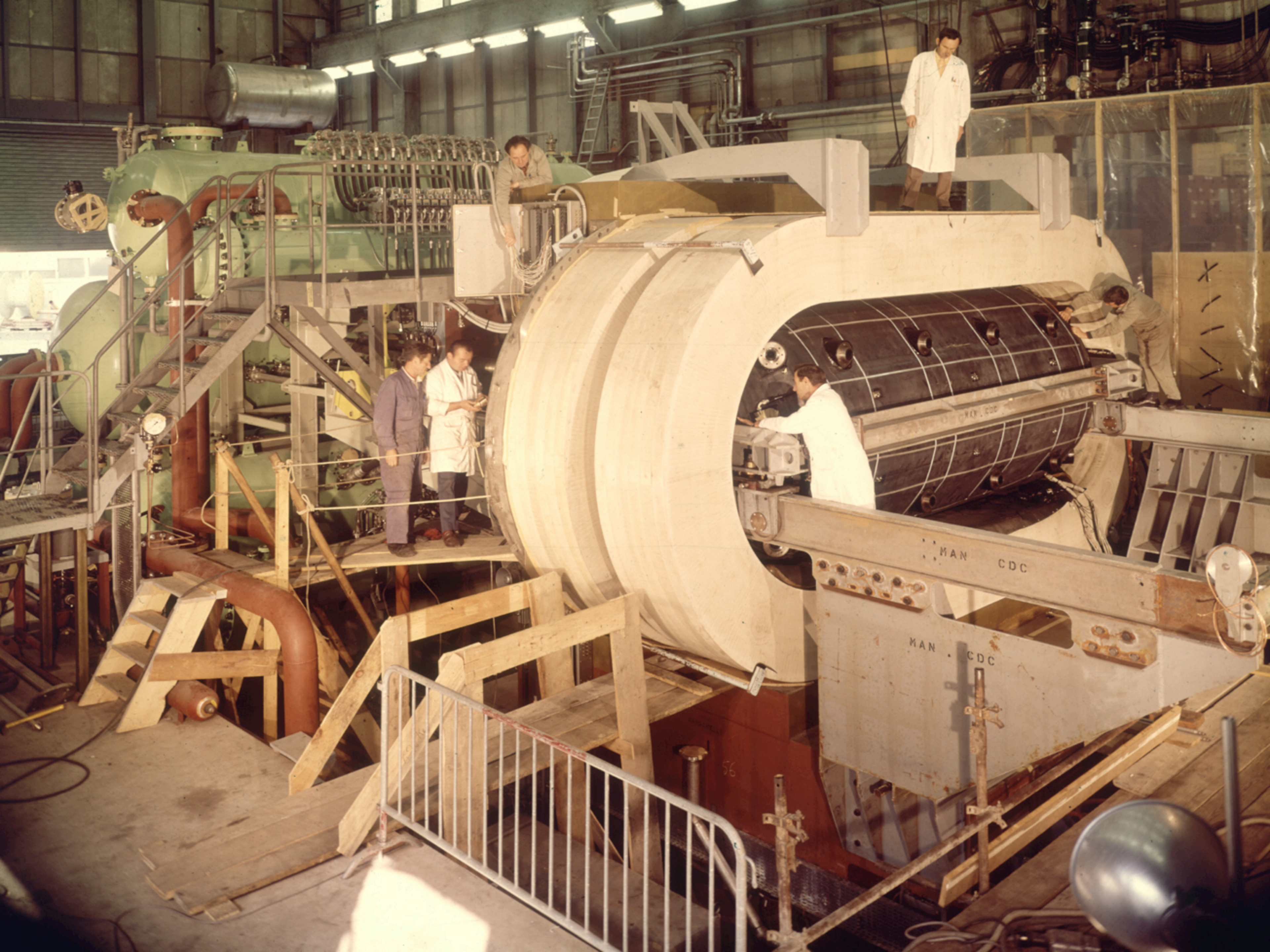
Evidence for the GWS model

- **Discovery of Neutral Currents (1973)**
  The process $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$ was observed.
  Only possible Feynman diagram (no $W^\pm$ diagram).
  Indirect evidence for Z.



Gargamelle Bubble
Chamber at CERN


ν_μ
ν_μ
Z^0
e^-
e^-
Outgoing neutrino
e^+
e^+
e^-
e^-
e^-
e^+
e^-
Shower of particles due to bremstrahlung
Collision point
Incoming neutrino


MAN CDC
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56

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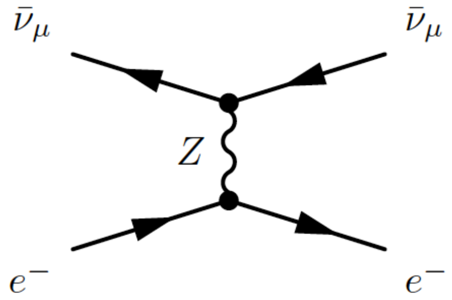
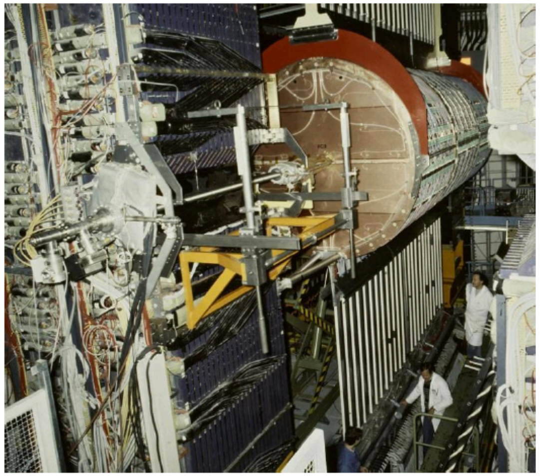
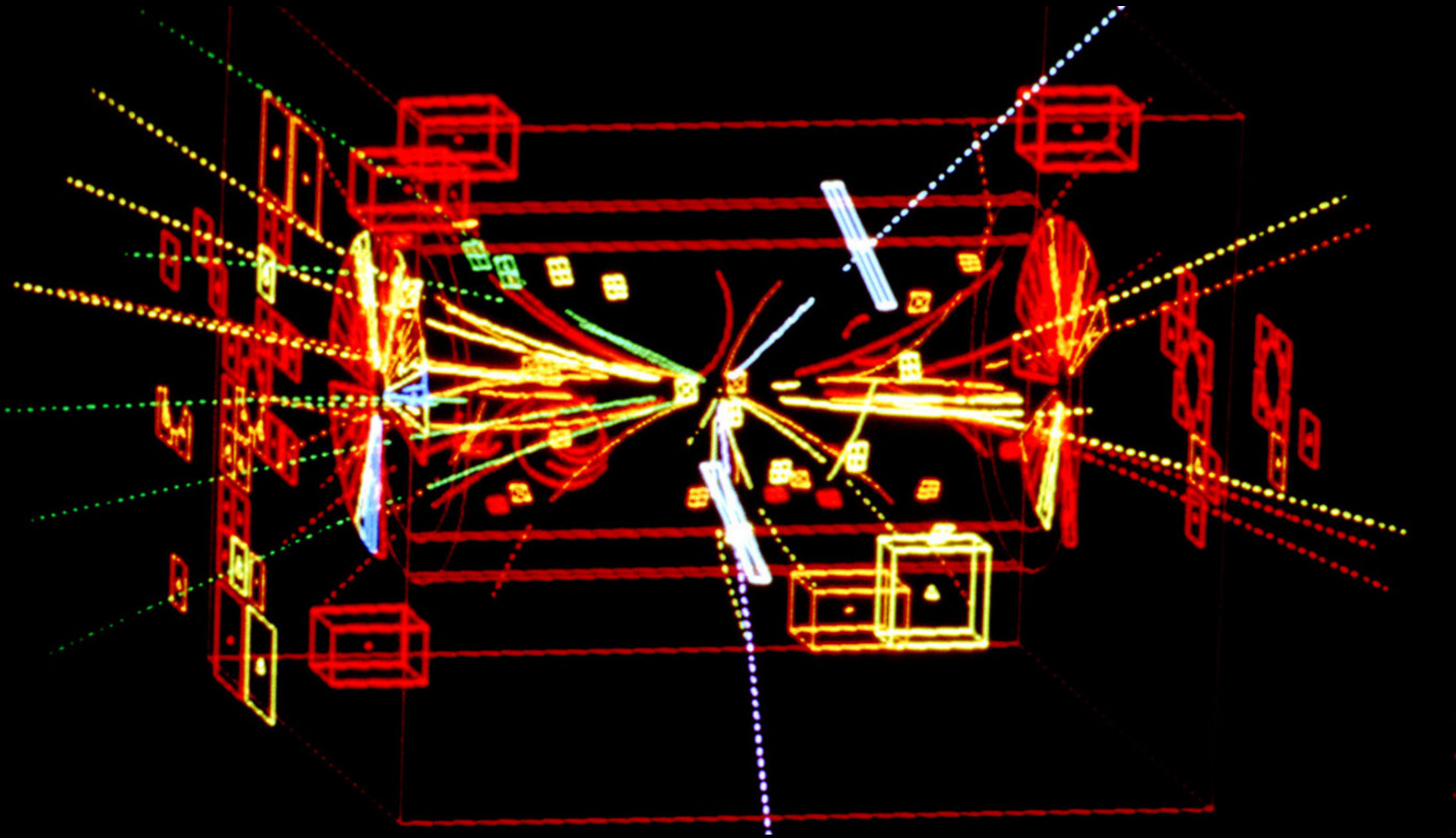


- **Direct Observation of $W^\pm$ and Z (1983)**
  First direct observation in $p\bar{p}$ collisions at $\sqrt{s} = 540\ \mathrm{GeV}$ via decays into leptons

$$p\bar{p} \to W^\pm + X \quad \hookrightarrow e^\pm \nu_e, \mu^\pm \nu_\mu \qquad p\bar{p} \to Z + X \quad \hookrightarrow e^+ e^-, \mu^+ \mu^-$$

UA1 Experiment at CERN
Used Super Proton Synchrotron
(now part of LHC!)





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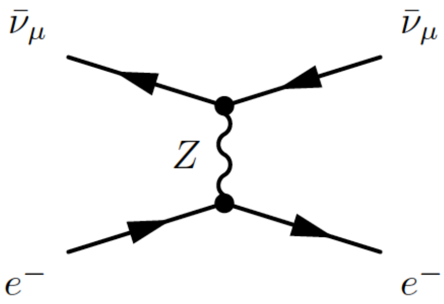

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$$p\bar{p} \rightarrow W^\pm + X \qquad\qquad p\bar{p} \rightarrow Z + X$$

$$\hookrightarrow e^\pm\nu_e, \mu^\pm\nu_\mu \qquad\qquad \hookrightarrow e^+e^-, \mu^+\mu^-$$

- **Precision Measurements of the Standard Model (1989-2000)**

  LEP e^+e^- collider provided many precision measurements of the Standard Model.

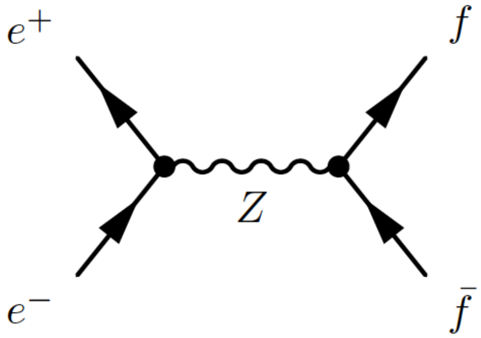
- Wide variety of different processes consistent with GWS model predictions and measure same value of

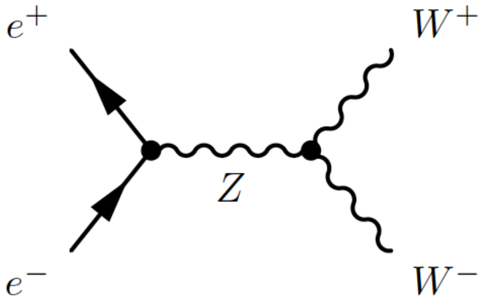
$$\sin^2\theta_W = 0.23113 \pm 0.00015 \qquad\qquad \theta_W \sim 29^\circ$$

Experimental tests of the Electroweak model at LEP

The Large Electron Positron (LEP) collider at CERN provided high precision measurements of the Standard Model (1989-2000).

Designed as a Z and $W^{\pm}$ boson factory





Precise measurements of the properties of Z and $W^{\pm}$ bosons provide the most stringent test of our current understanding of particle physics.

- LEP is the highest energy e^+e^- collider ever built $\sqrt{s} = 90 - 209\ \mathrm{GeV}$
- Large circumference, 27 km
- 4 experiments combined saw 16×10^6 Z events, 30×10^3 $W^{\pm}$ events

Summary of Electroweak tests

Now have 5 precise measurements of fundamental parameters of the Standard Model

$$\alpha_{EM} = 1/(137.03599976 \pm 0.00000050) \qquad (\text{at } q^2 = 0\ )$$

$$G_F = (1.16632 \pm 0.00002) \times 10^5\ \mathrm{GeV}^{-2}$$

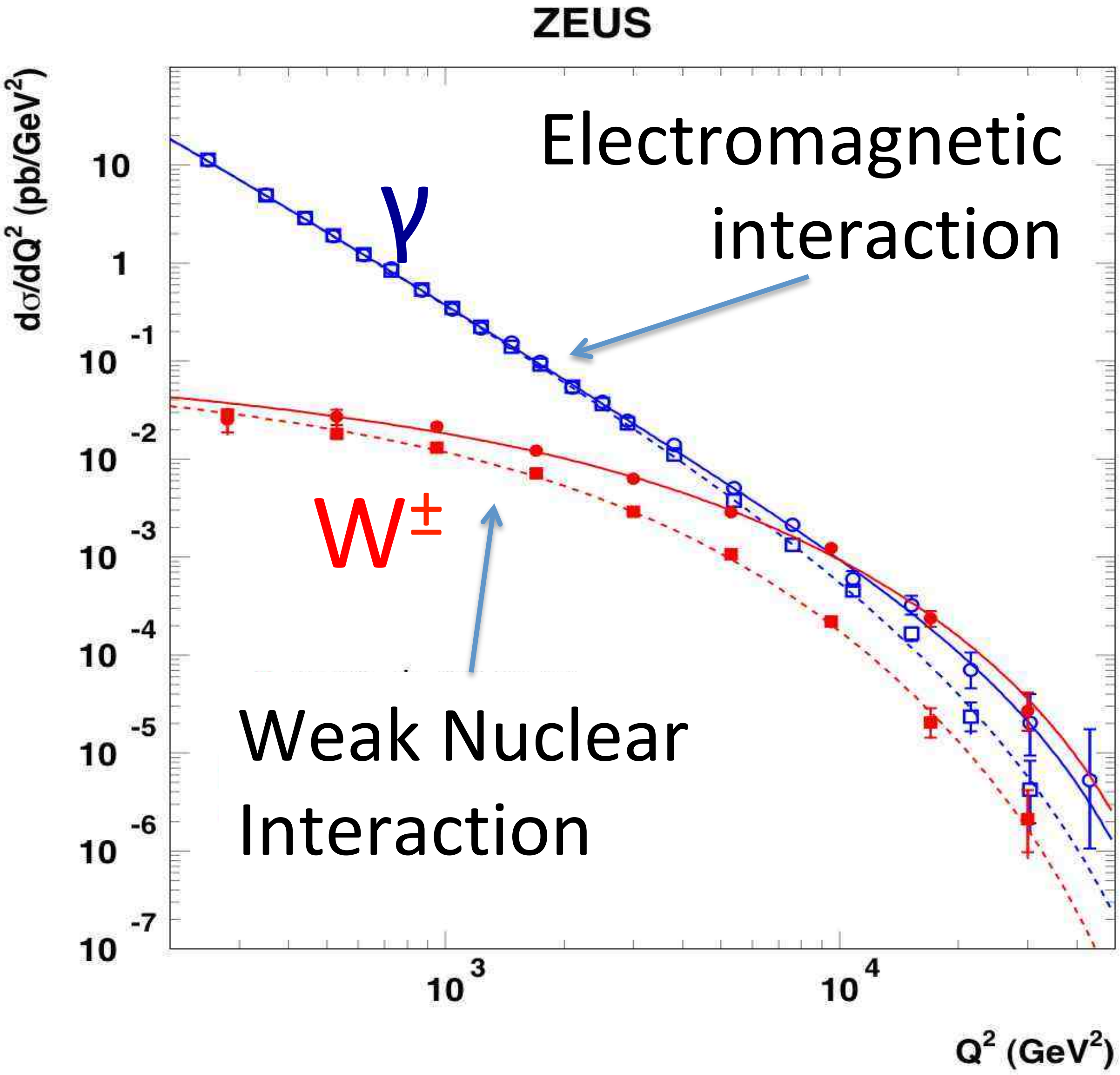
$$m_W = 80.385 \pm 0.015\ \mathrm{GeV}$$

$$m_Z = 91.1875 \pm 0.0021\ \mathrm{GeV}$$

$$\sin^2\theta_W = 0.23143 \pm 0.00015$$

In the Standard Model, only 3 are independent.

The measurements are consistent, which is an incredibly powerful test of the Standard Model of Electroweak Interactions.

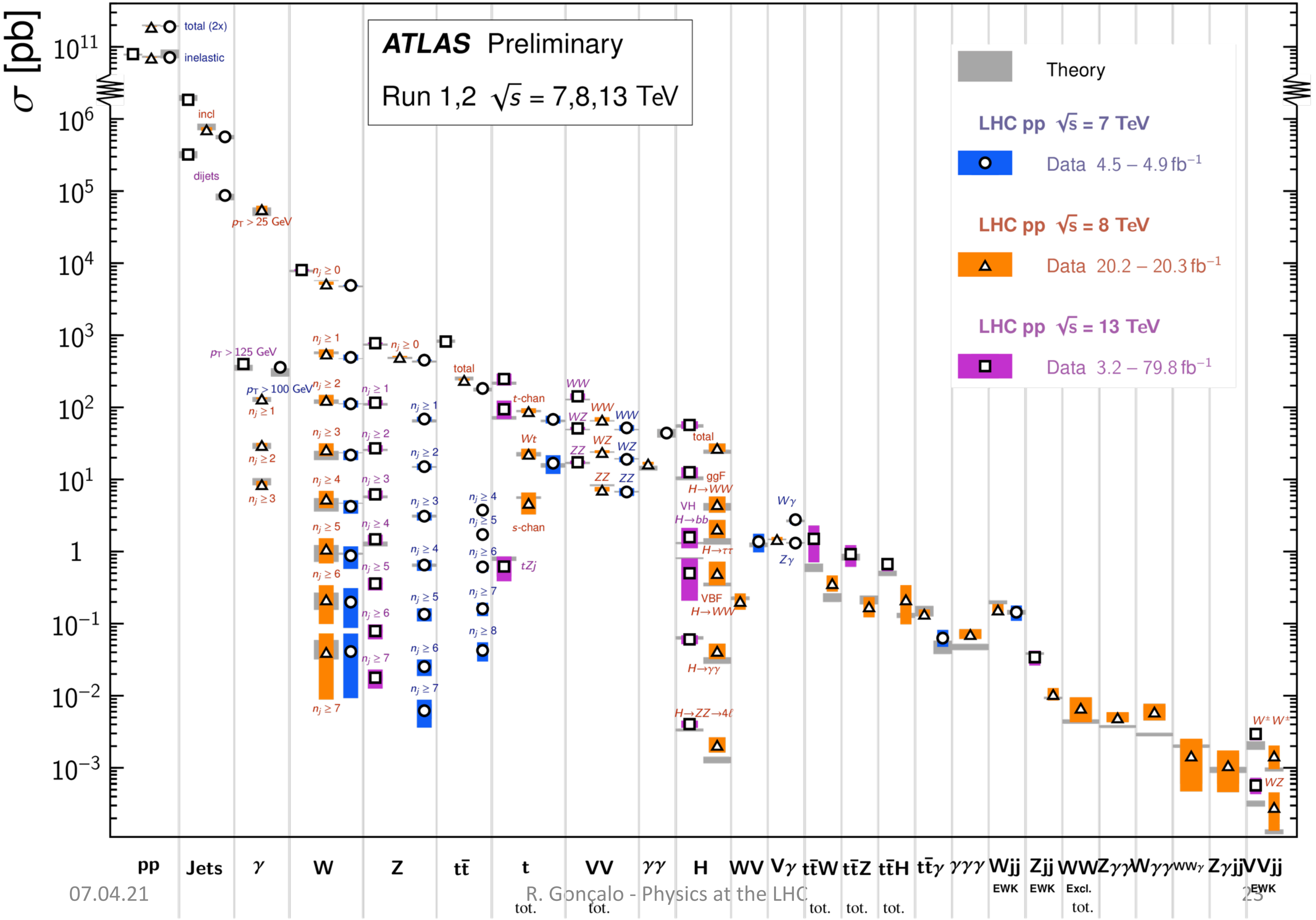


Electromagnetic interaction

Weak Nuclear Interaction

Standard Model Production Cross Section Measurements

Status: July 2018



Lagrangians, symmetries and all that

Emmy Noether (1882 – 1935)

Leonhard Euler(1707–1783)

Joseph-Louis Lagrange (1736–1813)

Reminder: Lagrangians in classical mechanics

The equations of motion of a system are derived from a scalar **Lagrangian** function of **generalized coordinates** and **velocities** (time derivatives of the coordinates)

$$L(q, \dot{q}) = T - V$$

and from the **Euler-Lagrange equations**:

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} = 0$$

Example

Particle in a conservative potential V. The Lagrangian

$$L = \tfrac{1}{2}m(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) - V(x, y, z)$$

has derivatives (e.g. for *x*)

$$\frac{\partial L}{\partial x} = -\frac{\partial V}{\partial x}, \frac{\partial L}{\partial \dot{x}} = m\dot{x}, \tfrac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = m\ddot{x}$$

and Euler-Lagrange's equations

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} = 0$$

finally give us Newton's familiar 2nd law!

$$m\ddot{x} = -\frac{\partial V}{\partial x}, m\ddot{y} = -\frac{\partial V}{\partial y}, m\ddot{z} = -\frac{\partial V}{\partial z} \Leftrightarrow m\vec{a} = \vec{F}$$

Symmetries and conservation laws

Noether's theorem:

If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

Simplest case: Coordinates not explicitly appearing in the Lagrangian

$\Rightarrow$ Lagrangian invariant over a continuous transformation of the coordinates

Example: mass **m** orbiting in the field of a fixed mass **M**

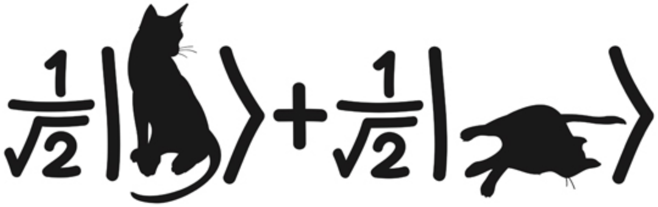
$$L(r,\phi,\dot{r},\dot{\phi}) = T - V = \tfrac{1}{2}m\dot{r}^2 + \tfrac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

Since the lagrangian doesn't depend explicitly on **ϕ** (symmetry with respect to rotations in space), the Euler-Lagrange equation gives

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) = 0 \Leftrightarrow \frac{\partial L}{\partial \dot{\phi}} = mr^2\dot{\phi} = J$$

Where the **angular momentum J** is a constant of motion!

Let’s go to quantum fields...



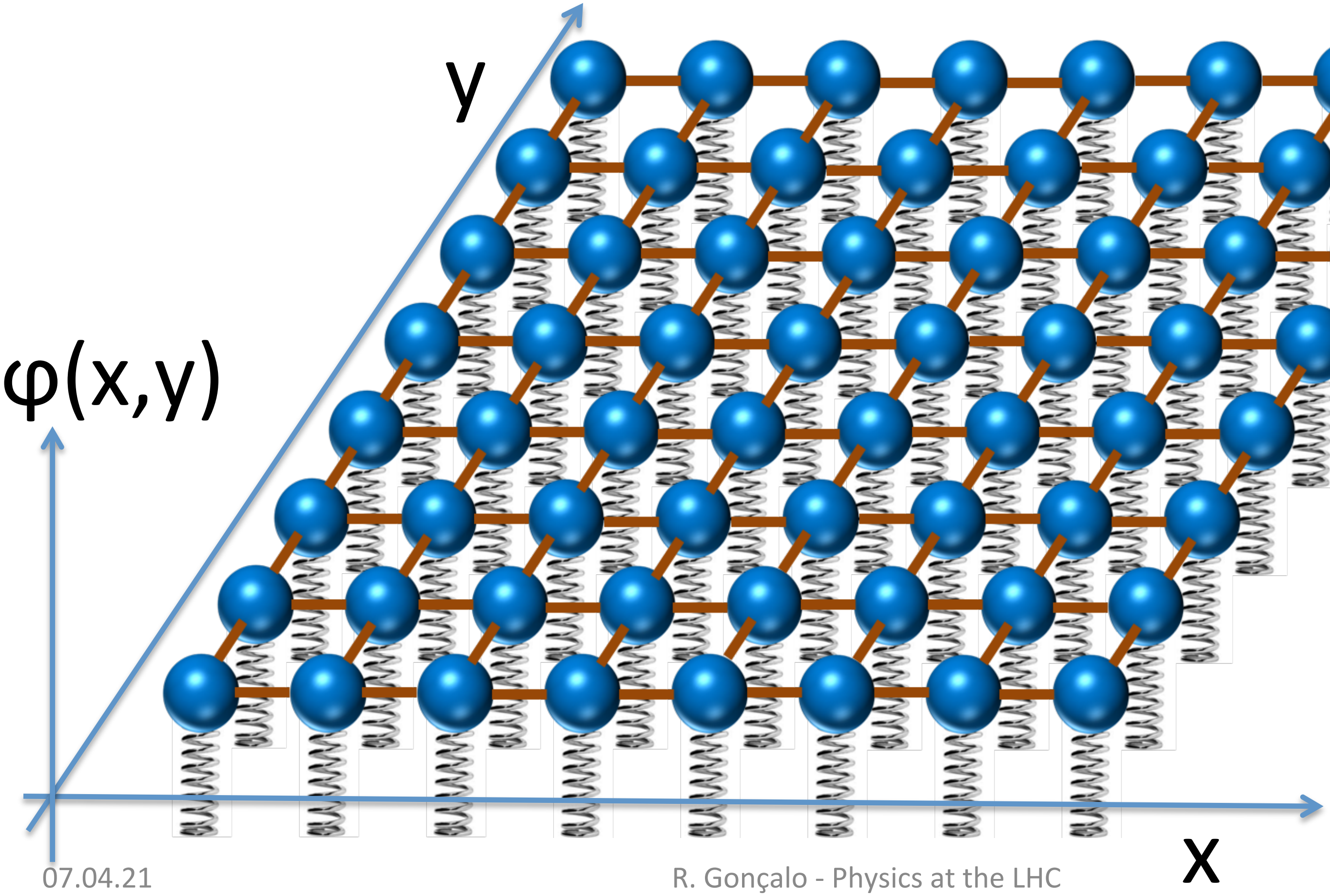

Richard Feynman
(1918 - 1988)


Schrödinger’s cat (?-?)


Erwin
Schrödinger
(1887 - 1961)

Now in quantum field theory…

Imagine space as an infinite continuum of balls and springs, where each ball is connected to its neighbours by elastic bands. **Particles are perturbations of this field**



Generalized coordinates are now **fields** (dislocation of each spring)

$$q_i \rightarrow \phi_i(x^\mu)$$

In a relativistic theory we must treat space and time coordinates on an equal footing, so the derivatives in the classical equations are now

$$\frac{d}{dt}, \nabla \rightarrow \partial_\mu = (\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$$

In place of a Lagrangian we have a **Lagrangian density** (we call it Lagrangian anyway, just to be confusing)

$L(q_i, \frac{dq_i}{dt}) \rightarrow \mathcal{L}(\phi_i, \partial_\mu \phi_i)$ with: $L = \int \mathcal{L} d^3\boldsymbol{x}$

The new Euler-Lagrange equation now becomes

$$\partial_\mu(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0$$

Gauge invariance

Take the Dirac Lagrangian for a spinor field ψ representing a spin-½ particle, for example an electron:

$$\mathcal{L} = i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$$

It is invariant under a global U(1) phase transformation like:

$$\psi(x) \to \psi'(x) = e^{iq\chi}\psi(x)$$

Where **χ** is a constant

$$\mathcal{L}' = e^{-iq\chi}e^{iq\chi}(i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi) = \mathcal{L}$$

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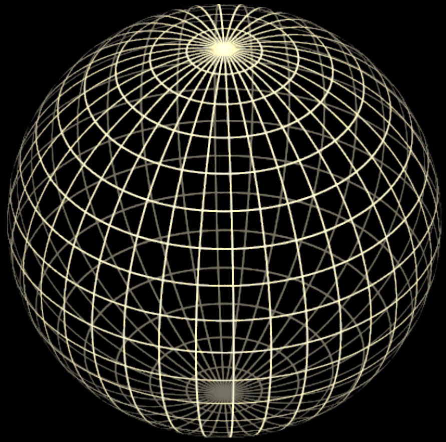
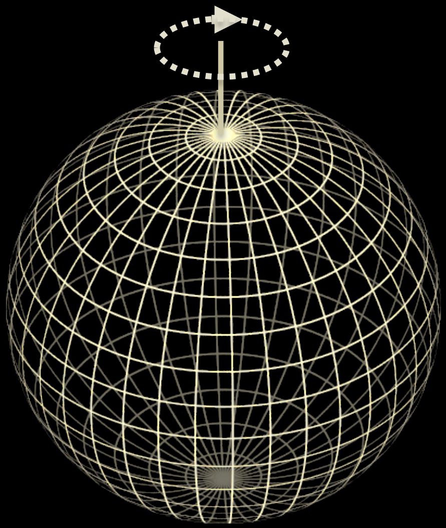
Original sphere

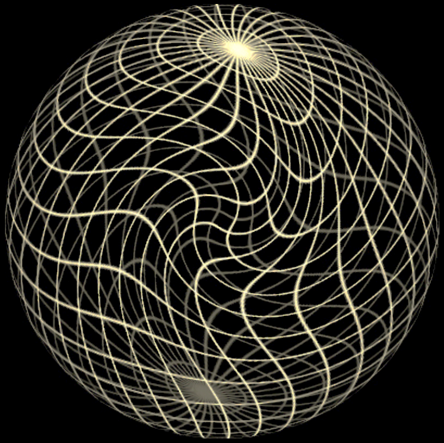


Global transformation



χ = constant

Local transformação



χ = χ (*x*)

Now for the problems...

Local gauge invariance and interactions

If **χ** = **χ** (*x*) then we get extra terms in the Lagrangian:

$$\begin{aligned} \mathcal{L}' &= ie^{-iq\chi}\bar{\psi}\gamma^{\mu}[e^{iq\chi}\partial_{\mu}\psi + iq(\partial_{\mu}\chi)e^{iq\chi}\psi] - me^{-iq\chi}e^{iq\chi}\bar{\psi}\psi \\ &= \mathcal{L}' - q\bar{\psi}\gamma^{\mu}(\partial_{\mu}\chi)\psi \end{aligned}$$

But we can now make the Lagrangian invariant by adding an ***interaction term*** with a new **gauge** field $\boldsymbol{A_\mu}$ which transforms as:

$$A_{\mu} \to A'_{\mu} = A_{\mu} - \partial_{\mu}\chi$$

We get:

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

A few things to note:

1. Gauge theories are renormalizable, i.e. calculable without infinities popping up everywhere (Nobel prize of t'Hooft and Veltman)
2. The new gauge field $\boldsymbol{A_\mu}$ is the photon in QED
3. The mass of the fermion is the coefficient of the term on $\boldsymbol{\psi\bar{\psi}}$
4. There is no term in $\boldsymbol{A_\mu A^\mu}$ (the photon has zero mass) → this is the beginning of the Higgs story…

Problem 1: Mass of elementary particles and gauge bosons

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu\partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma A_\mu A^\mu$$

To keep the Lagrangian gauge invariant (against a U(1) local phase transformation) the photon field transforms as:

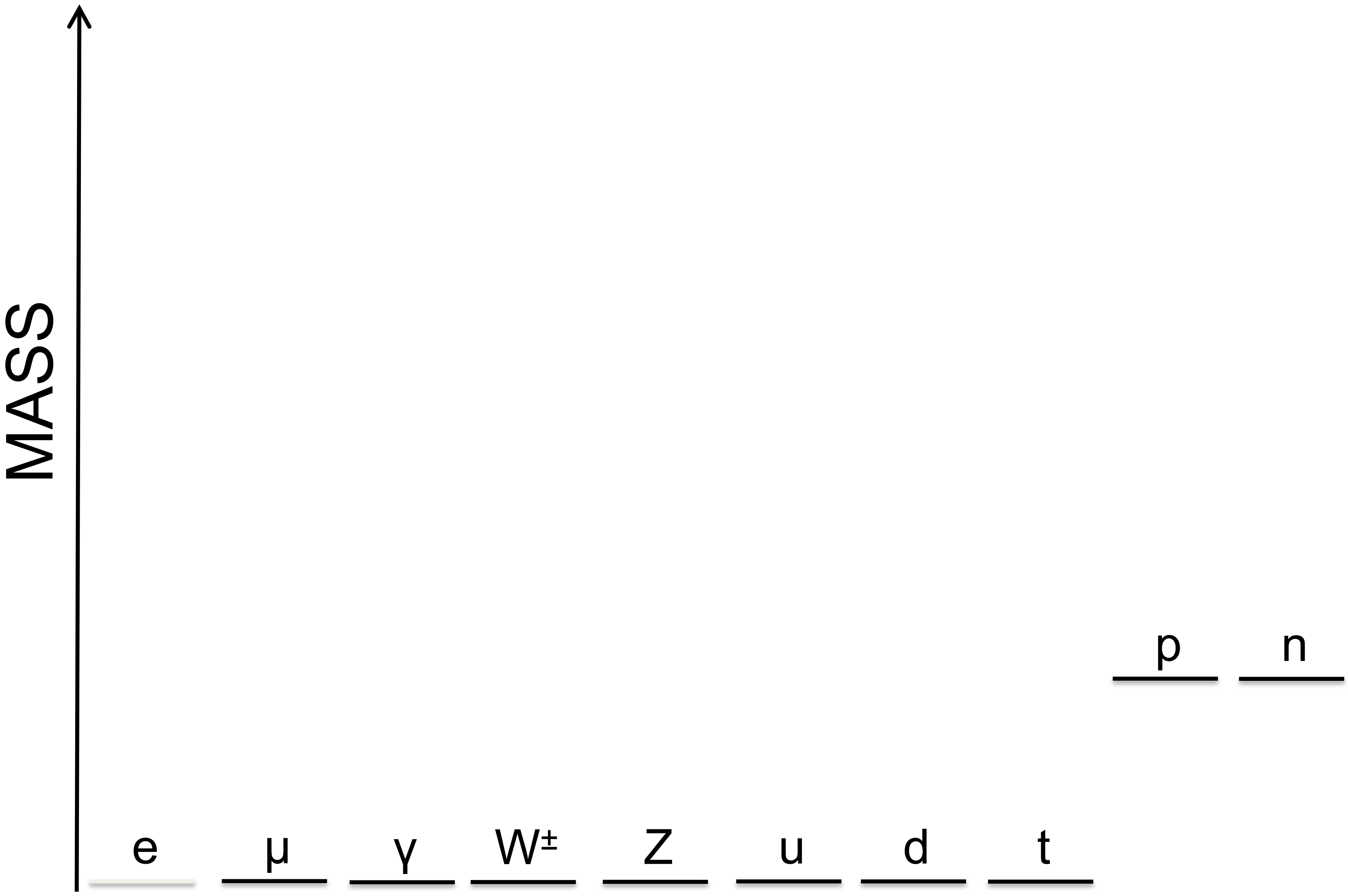
$$A_\mu \to A'_\mu = A_\mu - \partial_\mu\chi$$

But the $\boldsymbol{A^\mu}$ mass term breaks the invariance of the Lagrangian:

$$\frac{1}{2}m_\gamma A_\mu A^\mu \to \frac{1}{2}m_\gamma(A_\mu - \partial_\mu)(A^\mu - \partial^\mu\chi) \neq \frac{1}{2}m_\gamma A_\mu A^\mu$$

For the $SU(2)_L$ gauge symmetry transformations of the **weak interaction** the fermion mass term $\mathbf{m_e\bar{\psi}\psi}$ also breaks invariance!

It should not work…



MASS

p n

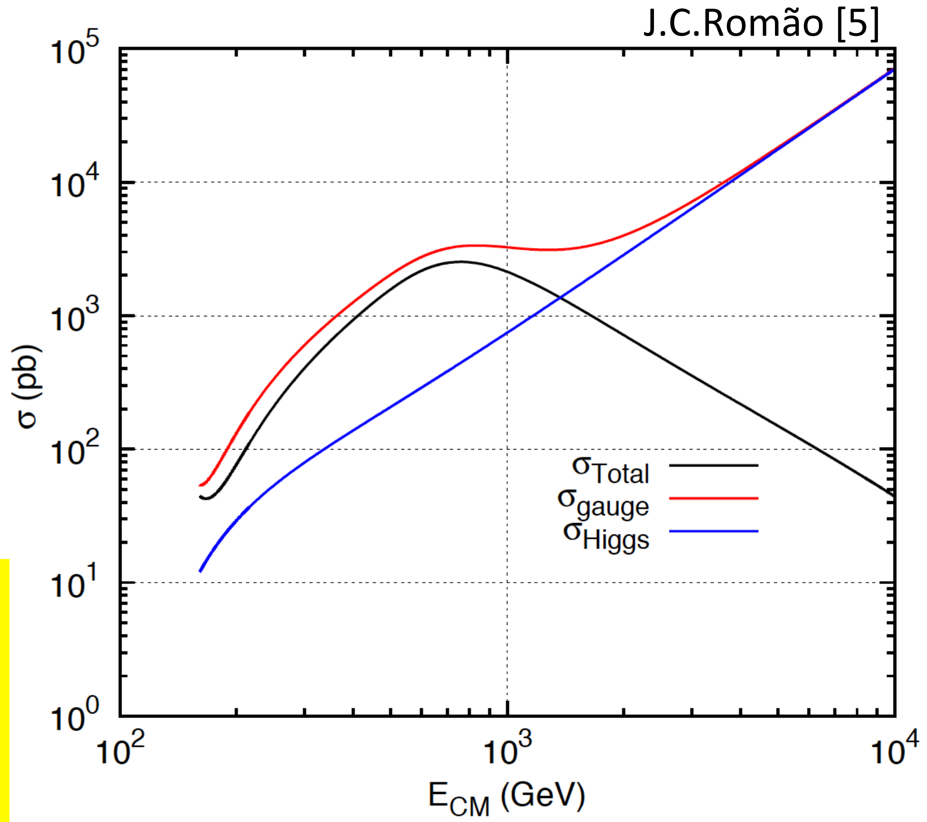
e μ γ W± Z u d t

Problem 2:

Longitudinal gauge-boson scattering

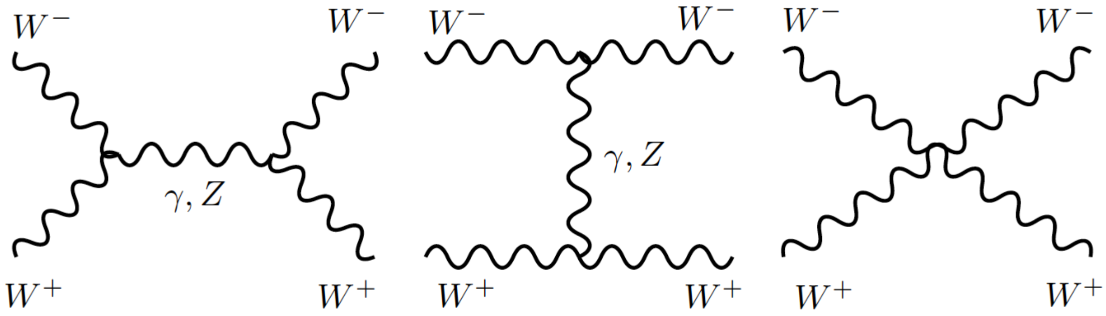
In the absence of the Higgs, some processes have cross sections that grow with the centre of mass energy of the collision… i.e. breaks unitarity!

The Higgs regulates the cross section through negative interference



J.C.Romão [5]

Bottom line: **the SM (without the Higgs mechanism) results in wrong calculations and breaks down for massive particles**



Feynman diagrams contributing to longitudinal WW scattering

The Higgs Mechanism

Robert Brout (1928 – 2011)

Peter Higgs (b. 1929)

François Englert
(b. 1932)


THE HIGGS IS SIGNIFICANT BECAUSE IT EXPLAINS WHY STUFF HAS MASS.
FOR ME IT'S THE RAMEN DIET.
WAIT, WE DON'T KNOW WHY STUFF HAS MASS??
WHAT IS MASS?
YOU JUST BLEW MY MIND.
I KNOW.
JORGE CHAM © 2008
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- Introduce a SU(2) doublet of spin-0 complex fields

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi 4 \end{pmatrix}$$

- The Lagrangian is

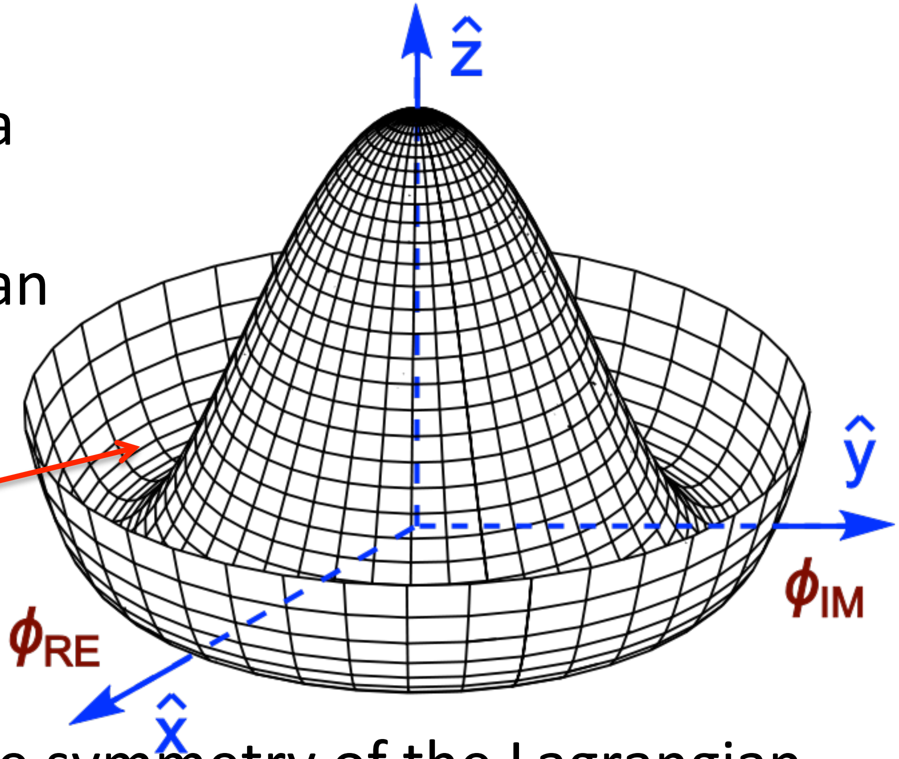
$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

- With a potential

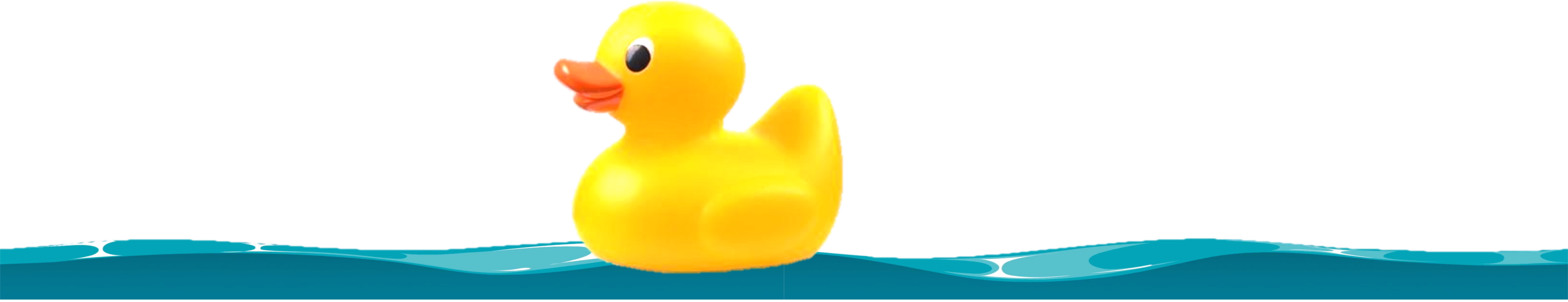
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

- For λ>0, $\mu^2<0$ the potential has a minimum at the origin
- For λ>0, $\mu^2<0$ the potential has an infinite number of minima at:

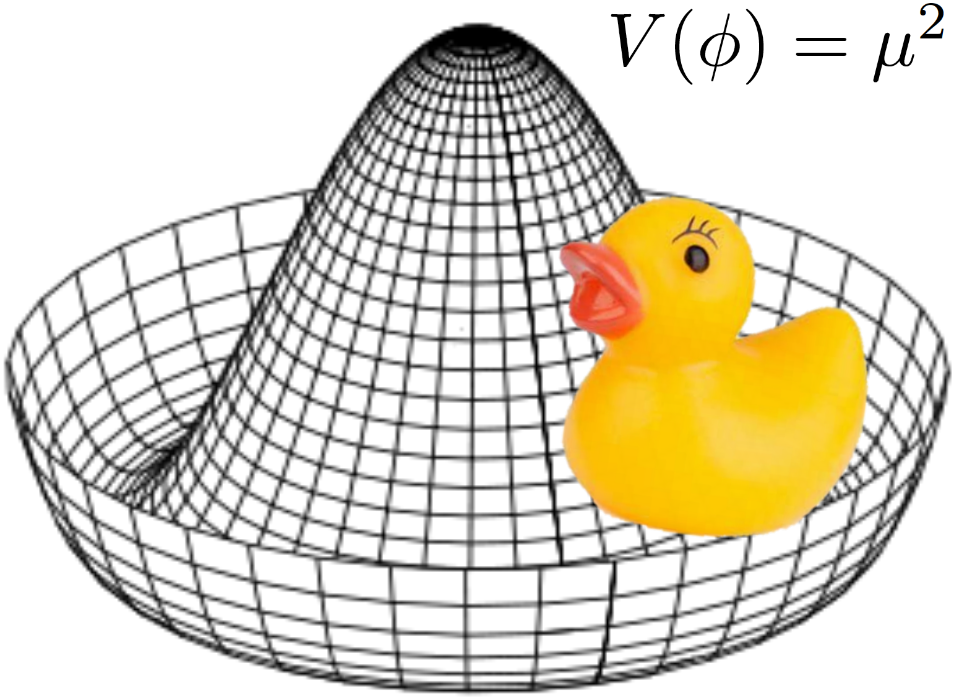
$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$



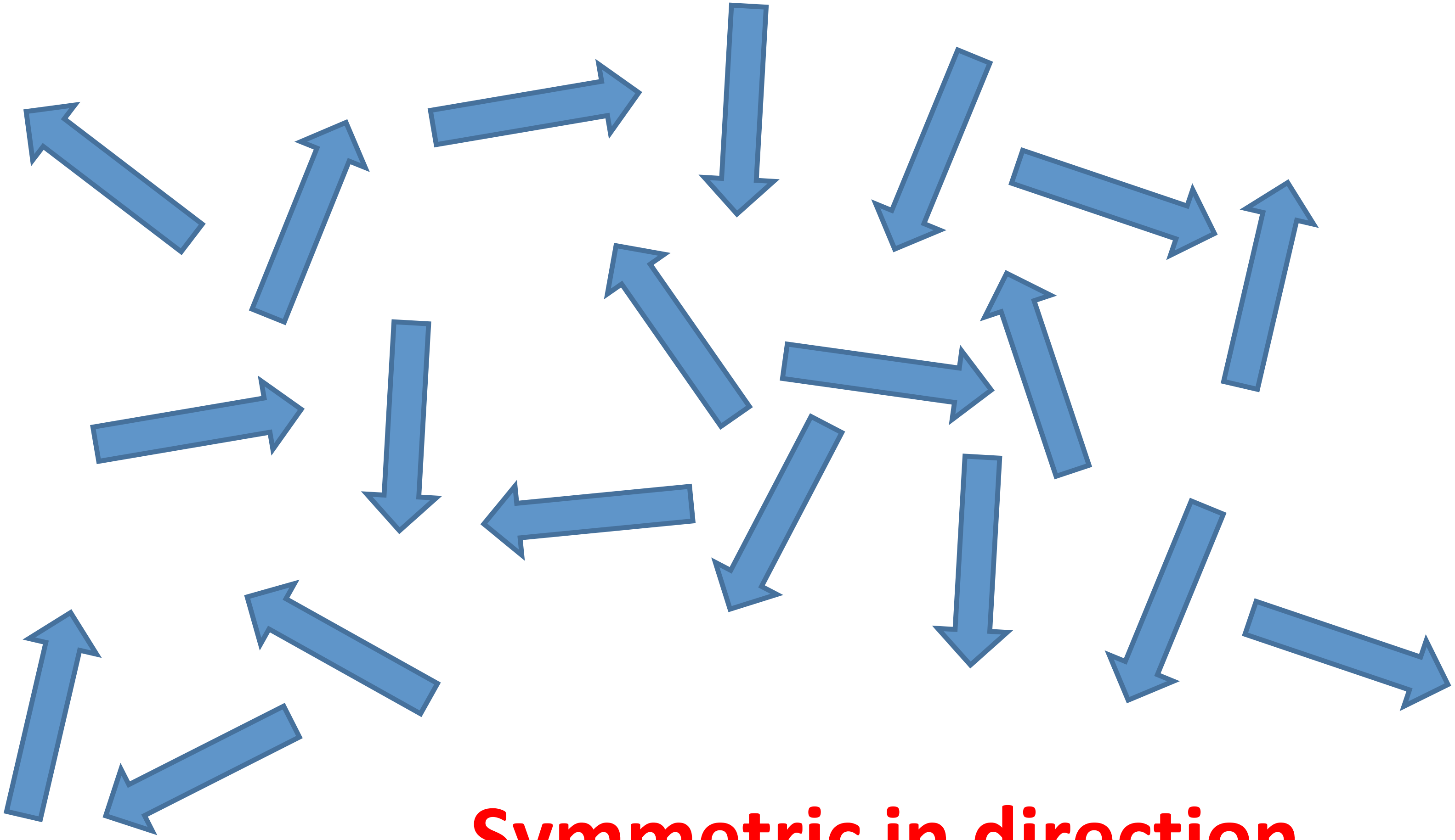
The choice of vacuum (lowest energy state of the field) breaks the symmetry of the Lagrangian



$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

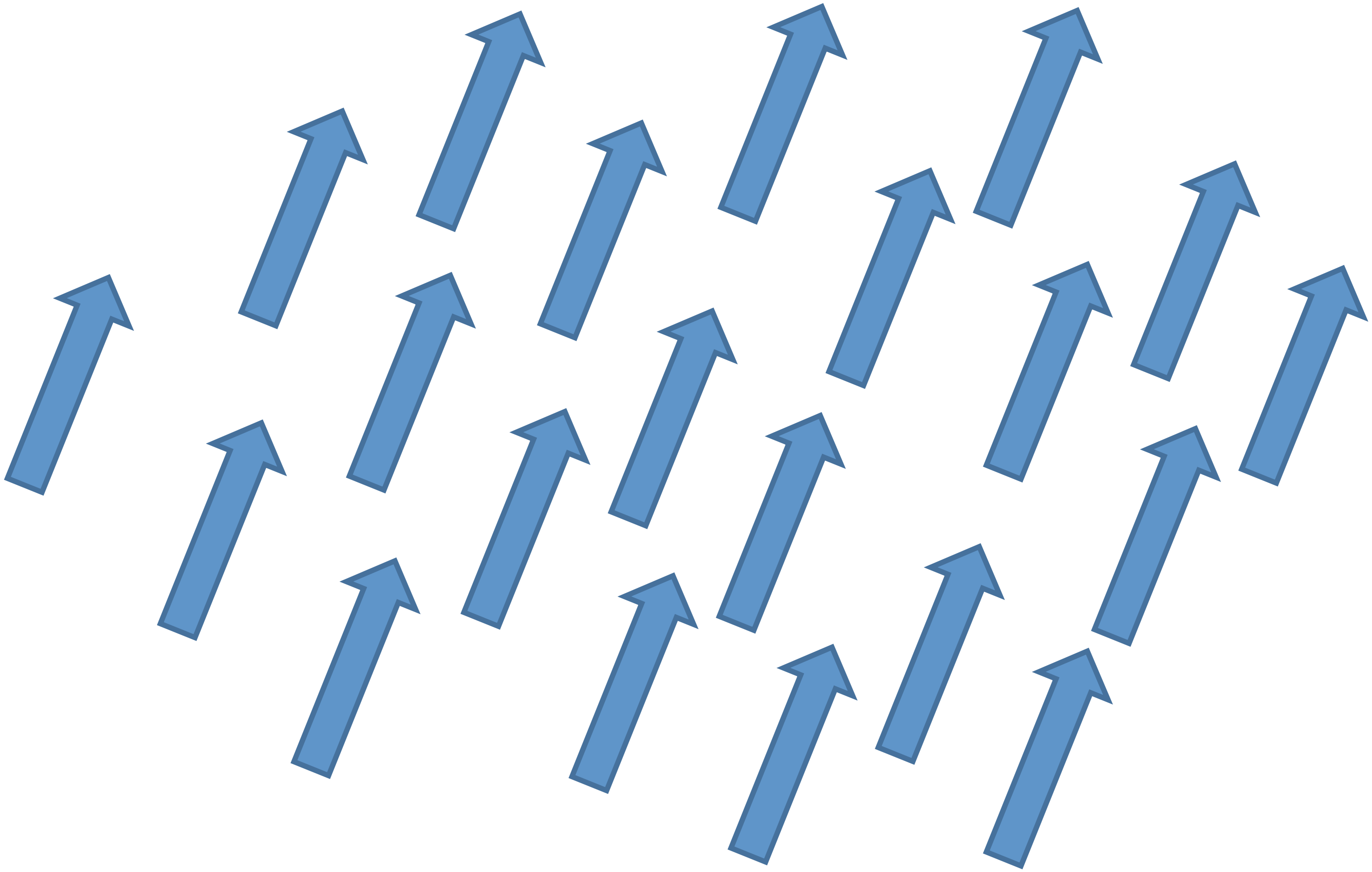


Magnetic material at **high temperatures**



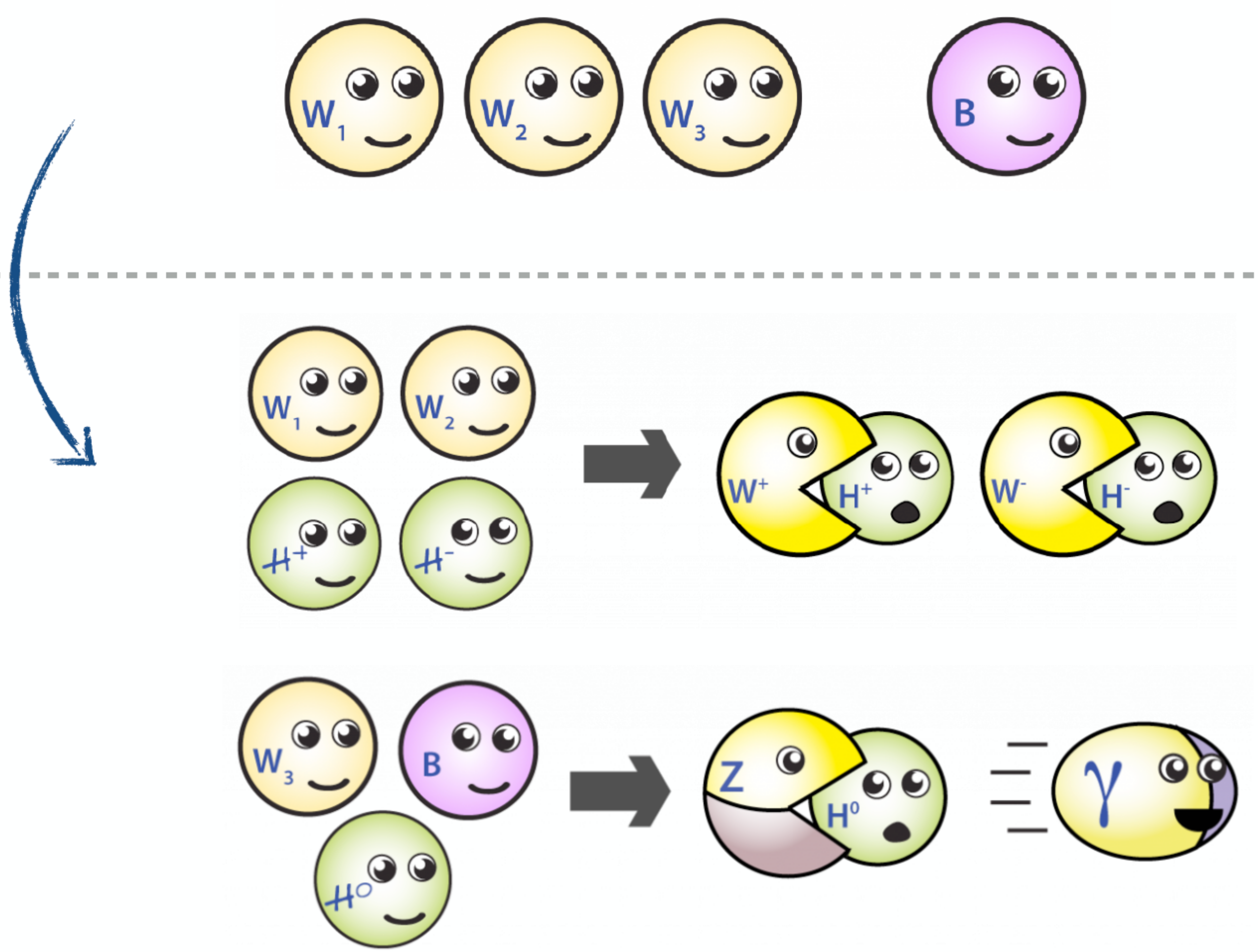
Symmetric in direction

Magnetic material at **low temperature**

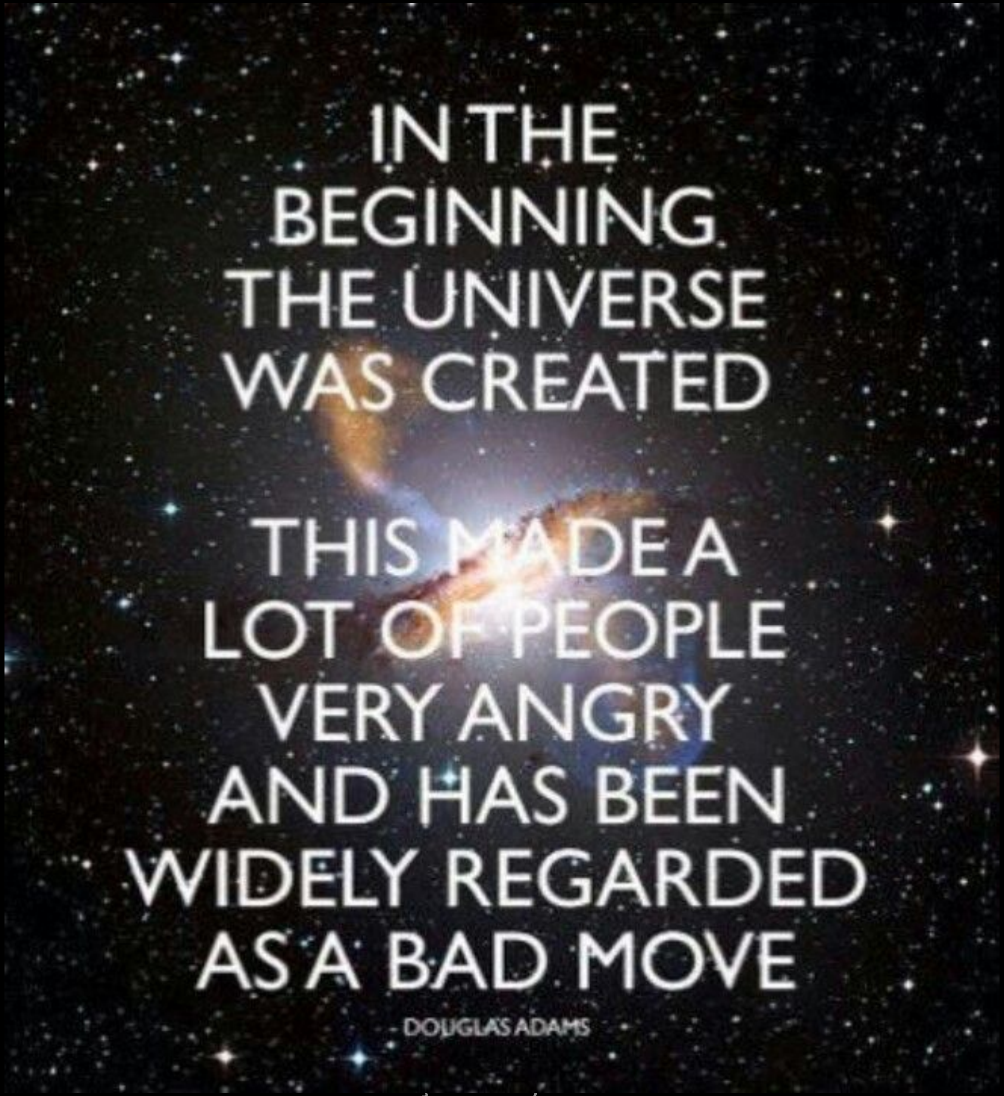


Symmetry broken – special direction

EWK Symmetry Breaking in Pictures



The Story So Far...



IN THE
BEGINNING
THE UNIVERSE
WAS CREATED

THIS MADE A
LOT OF PEOPLE
VERY ANGRY
AND HAS BEEN
WIDELY REGARDED
AS A BAD MOVE

- DOUGLAS ADAMS

The Standard Model of particle physics

$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) -$$
$$igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu -$$
$$Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 -$$
$$\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h -$$

$g\alpha$ [illegible] $) -$

$\tfrac{1}{8}g^2\alpha_h(H^4 + (\phi^0)^4$ [illegible] $+ 2(\phi^0)^2H^2) -$

$\tfrac{1}{2}ig\left(W^+_\mu\right.$ [illegible] $\left._\mu\phi^0)\right) +$

$\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial\right.$ [illegible] $\left.^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H)\right) +$

$M\left(\tfrac{1}{c_w}Z^0_\mu\partial\right.$ [illegible] $) + igs_w M A_\mu(W^+_\mu\phi^- -$

W [illegible] $- ig\tfrac{1-}{2c_w}$ [illegible] $- \phi^-\partial_\mu\phi^+) -$

$\tfrac{1}{4}g^2 W$ [illegible] $(H^2 + (\phi^0$ [illegible] $2(2s_w^2 - 1)^2\phi^+\phi^-) -$

$\tfrac{1}{2}g^2$ [illegible] $^0(W^+_\mu\phi^- + W$ [illegible] $\tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- +$

[illegible] $_\mu\phi^+) + \tfrac{1}{2}ig^2$ [illegible] $Z^0_\mu A_\mu\phi^+\phi^- -$

g^2 [illegible] $A_\mu\phi^+\phi^- + \tfrac{1}{2}ig$ [illegible] $+ m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial +$

[illegible] $u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial +$ [illegible] $- \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)) +$

$\tfrac{}{4}$ [illegible] $(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma$ [illegible] $s_w^2 - 1 - \gamma^5)d^\lambda_j) +$

$(\bar{u}^\lambda_j\gamma^\mu$ [illegible] $^2 + \gamma^5)u^\lambda$ [illegible] $\gamma^\mu(1 + \gamma^5)C_{\lambda\kappa}d^\kappa_j)) +$

[illegible] $u^\lambda_j)) +$

[illegible] $\gamma^5)e^\kappa) +$

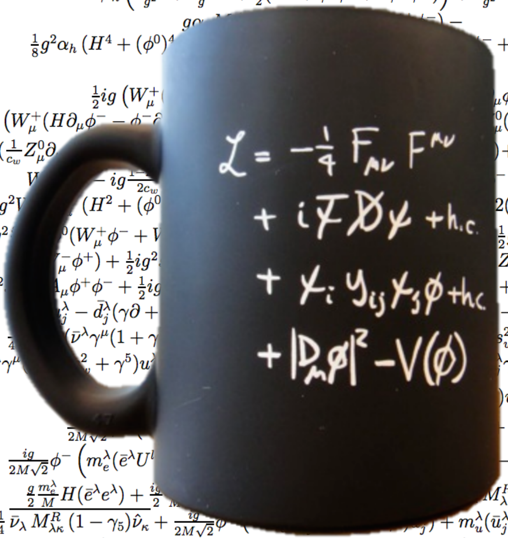
$\tfrac{}{2M\sqrt{2}}$ [illegible]

$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^l\right.$ [illegible] $- \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) -$

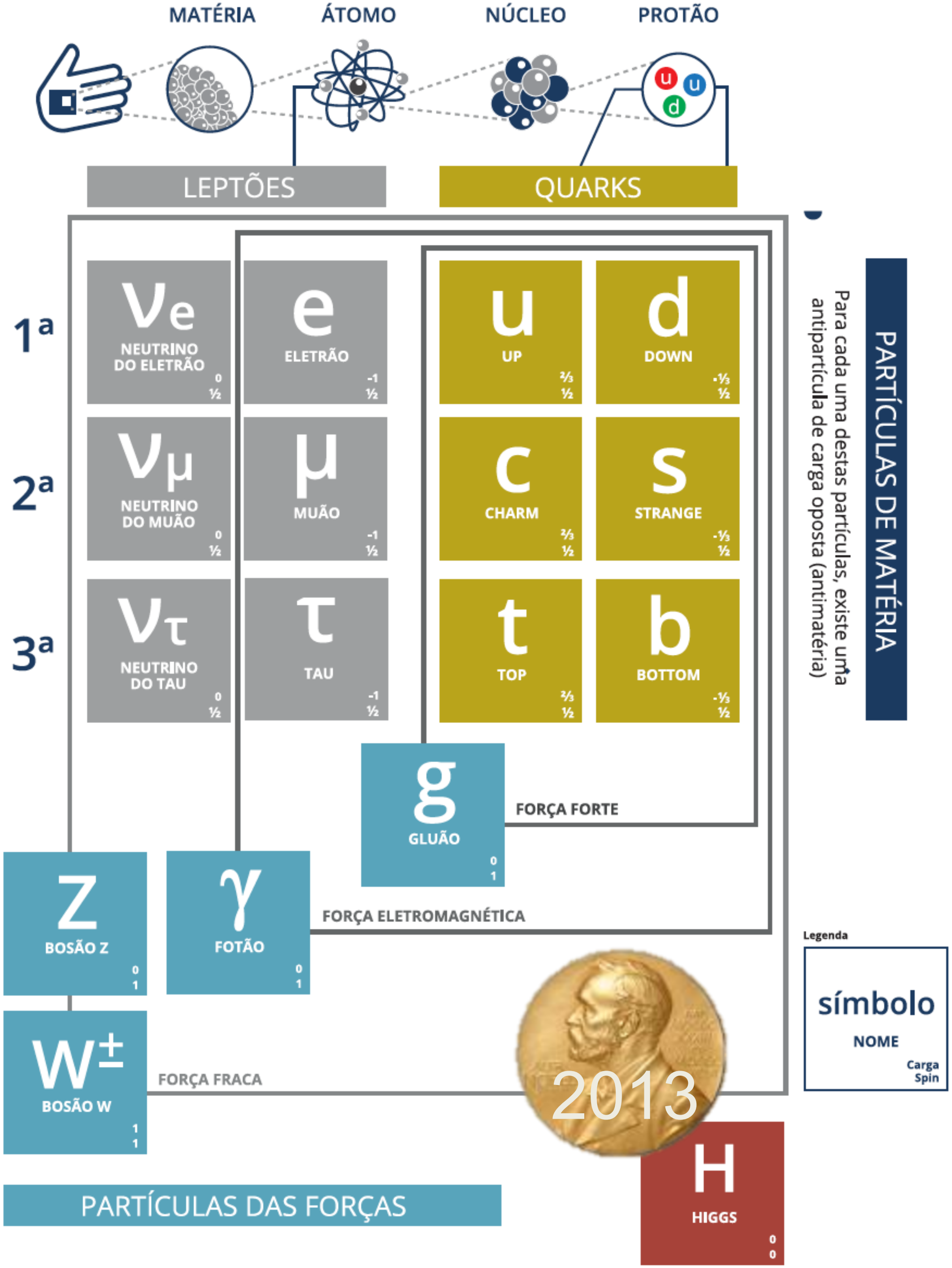
$\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{}{M}$ [illegible] $M^R_{\lambda\kappa}(1 - \gamma_5)\hat{\nu}_\kappa -$

$\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1 - \gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi$ [illegible] $+ m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1 + \gamma^5)d^\kappa_j) +$

$$\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) -$$
$$\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- -$$
$$\partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 -$$
$$\partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ -$$
$$\partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ -$$
$$\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) +$$
$$\tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) +$$
$$\tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).$$



$$\mathcal{L} = -\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$



PARTÍCULAS DE MATÉRIA

Para cada uma destas partículas, existe uma antipartícula de carga oposta (antimatéria)

	LEPTÕES		QUARKS	
1ª	νe NEUTRINO DO ELETRÃO 0 ½	e ELETRÃO -1 ½	u UP ⅔ ½	d DOWN -⅓ ½
2ª	νμ NEUTRINO DO MUÃO 0 ½	μ MUÃO -1 ½	c CHARM ⅔ ½	s STRANGE -⅓ ½
3ª	ντ NEUTRINO DO TAU 0 ½	τ TAU -1 ½	t TOP ⅔ ½	b BOTTOM -⅓ ½

g GLUÃO 0 1 — FORÇA FORTE

Z BOSÃO Z 0 1

γ FOTÃO 0 1 — FORÇA ELETROMAGNÉTICA

W± BOSÃO W 1 1 — FORÇA FRACA

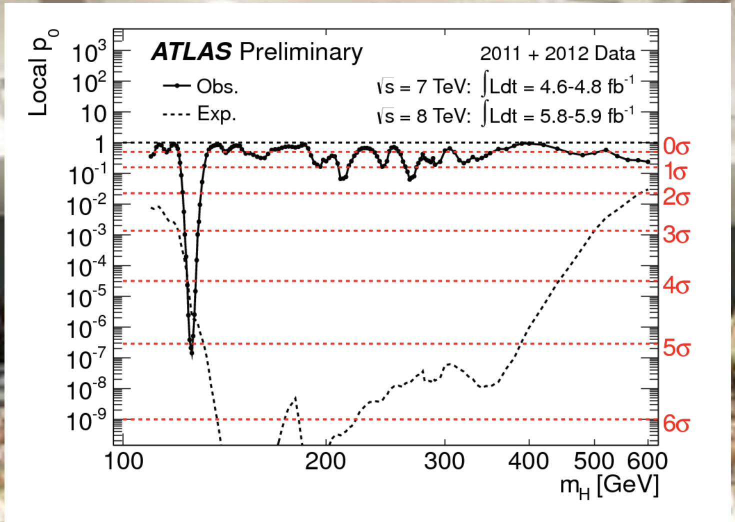
PARTÍCULAS DAS FORÇAS

H HIGGS 0 0

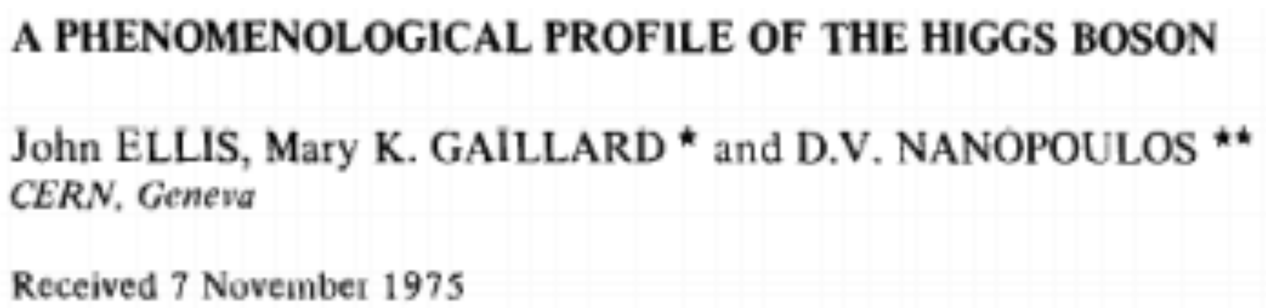
2013

Legenda

símbolo
NOME
Carga
Spin



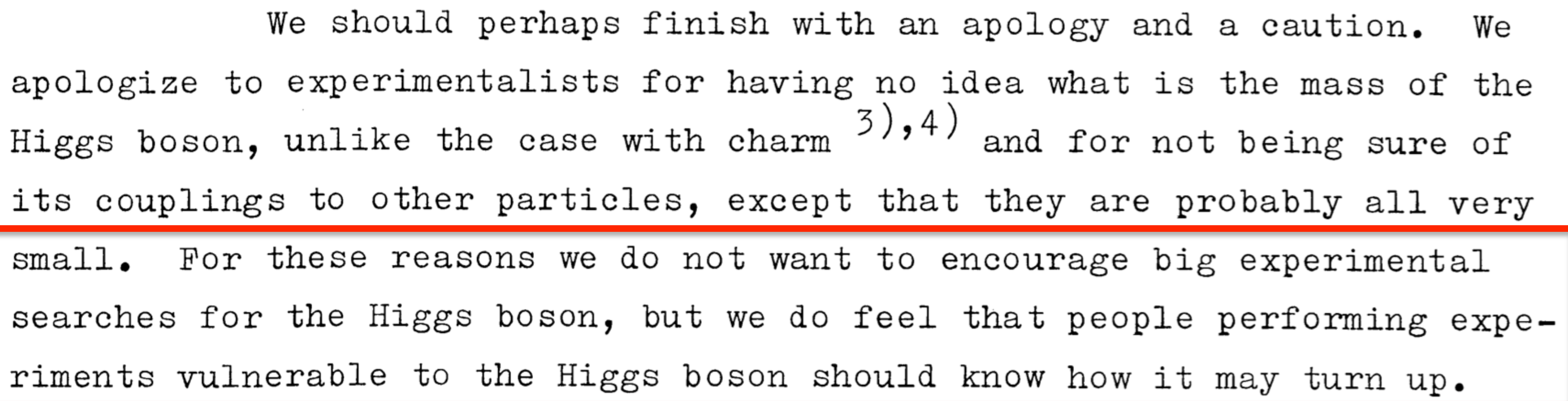
The Long Way to Discovery



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

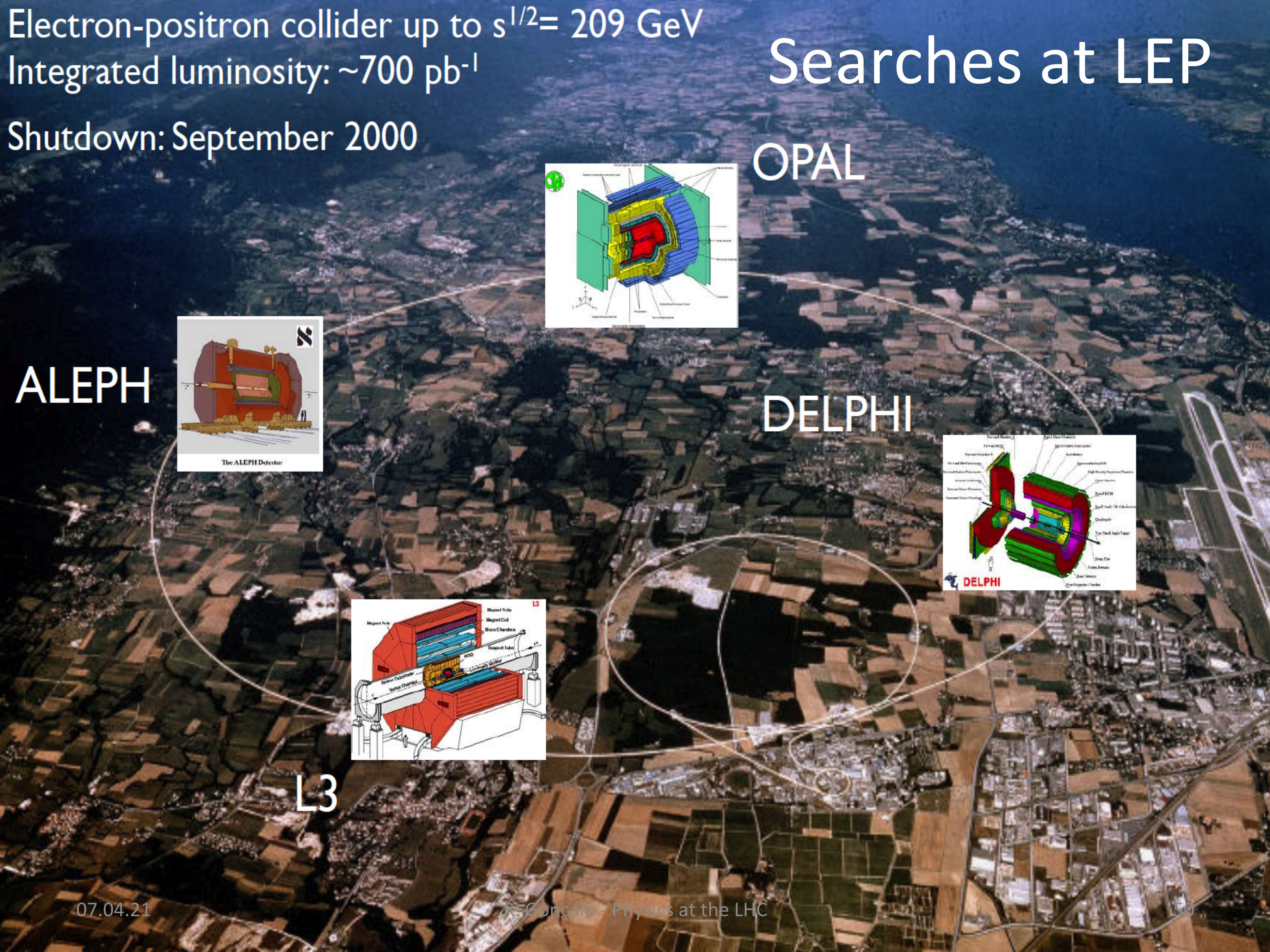


We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm 3),4) and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Searches at LEP

Electron-positron collider up to $s^{1/2}$= 209 GeV
Integrated luminosity: ~700 pb^{-1}

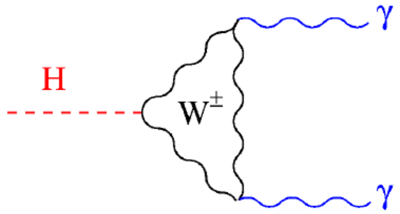
Shutdown: September 2000



Low-mass searches at LEP

The decay branching ratios depend only on m_H:

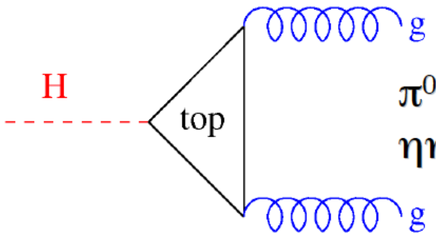
☐ $m_H < 2m_e$: $H \to \gamma\gamma$ + large lifetime;



☐ $m_H < 2m_\mu$: $H \to e^+e^-$ dominates;

☐ $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates;

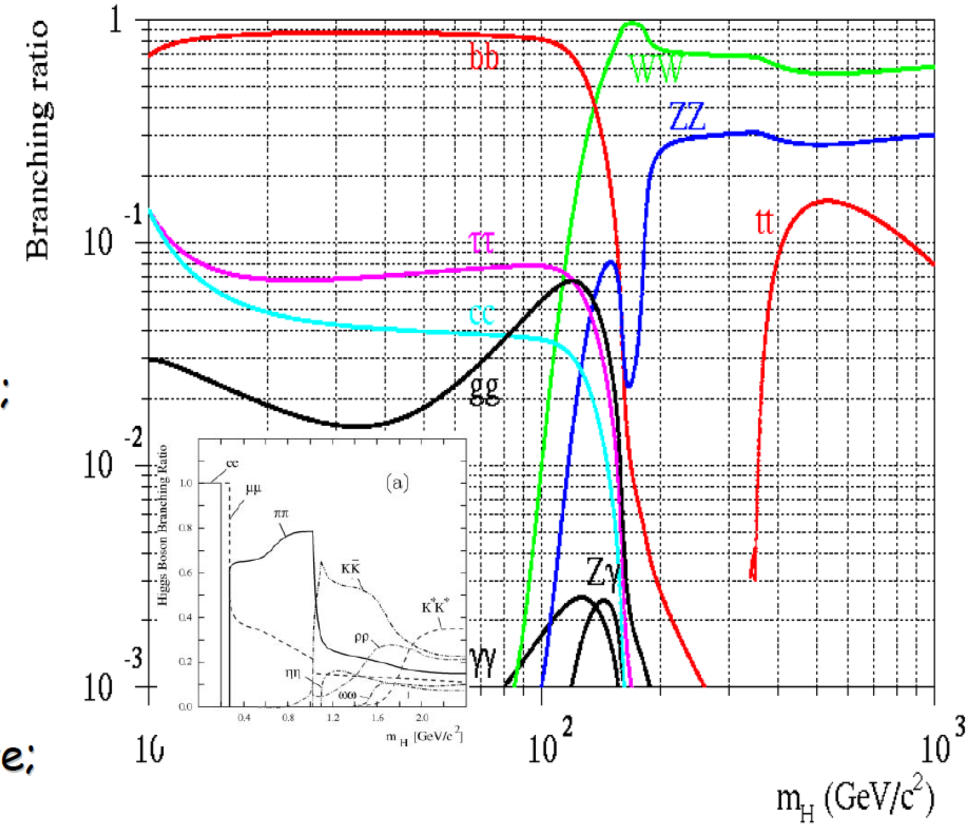
☐ $m_H <$ 3 - 4 GeV: $H \to gg$ dominates;



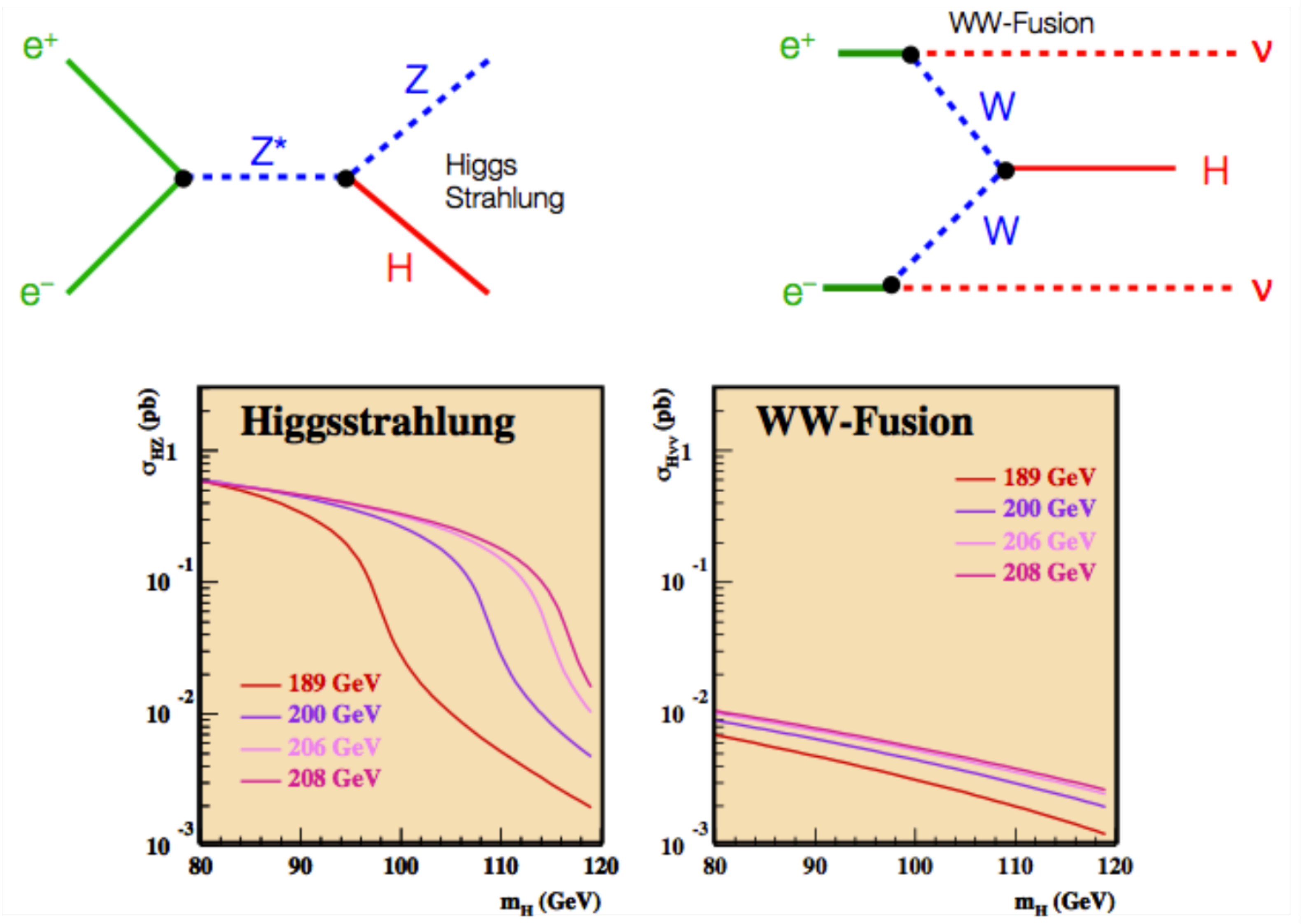
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, … etc

☐ $m_H < 2m_b$: $H \to \tau^+\tau^-$ and $c\bar{c}$ dominate;

☐ $m_H > 2m_b$ up to 1000 GeV/c^2:



Higher-mass Higgs production at LEP



Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

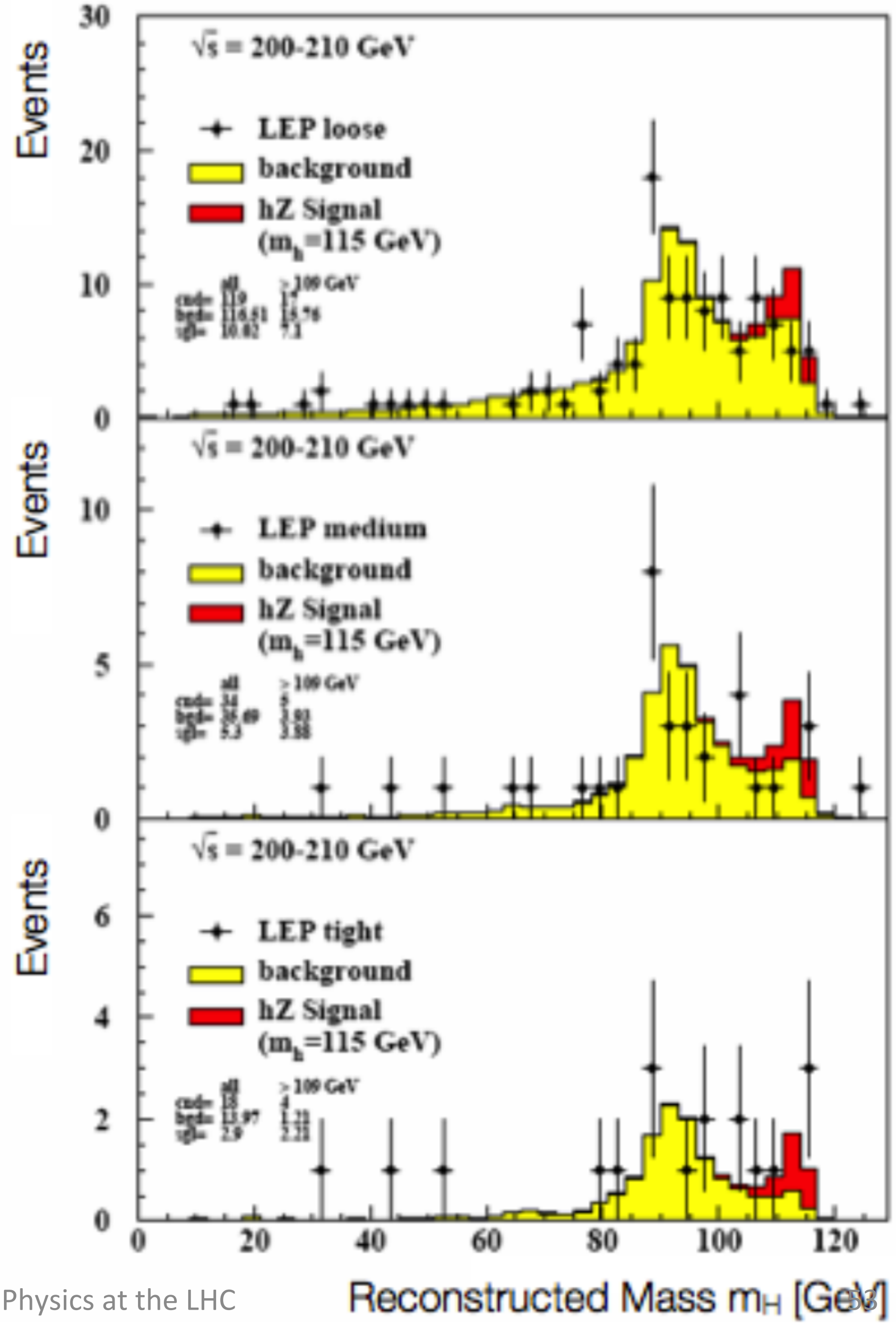
Expectation for m_H=115 GeV

- 8.4 events

Corresponding excess was not observed

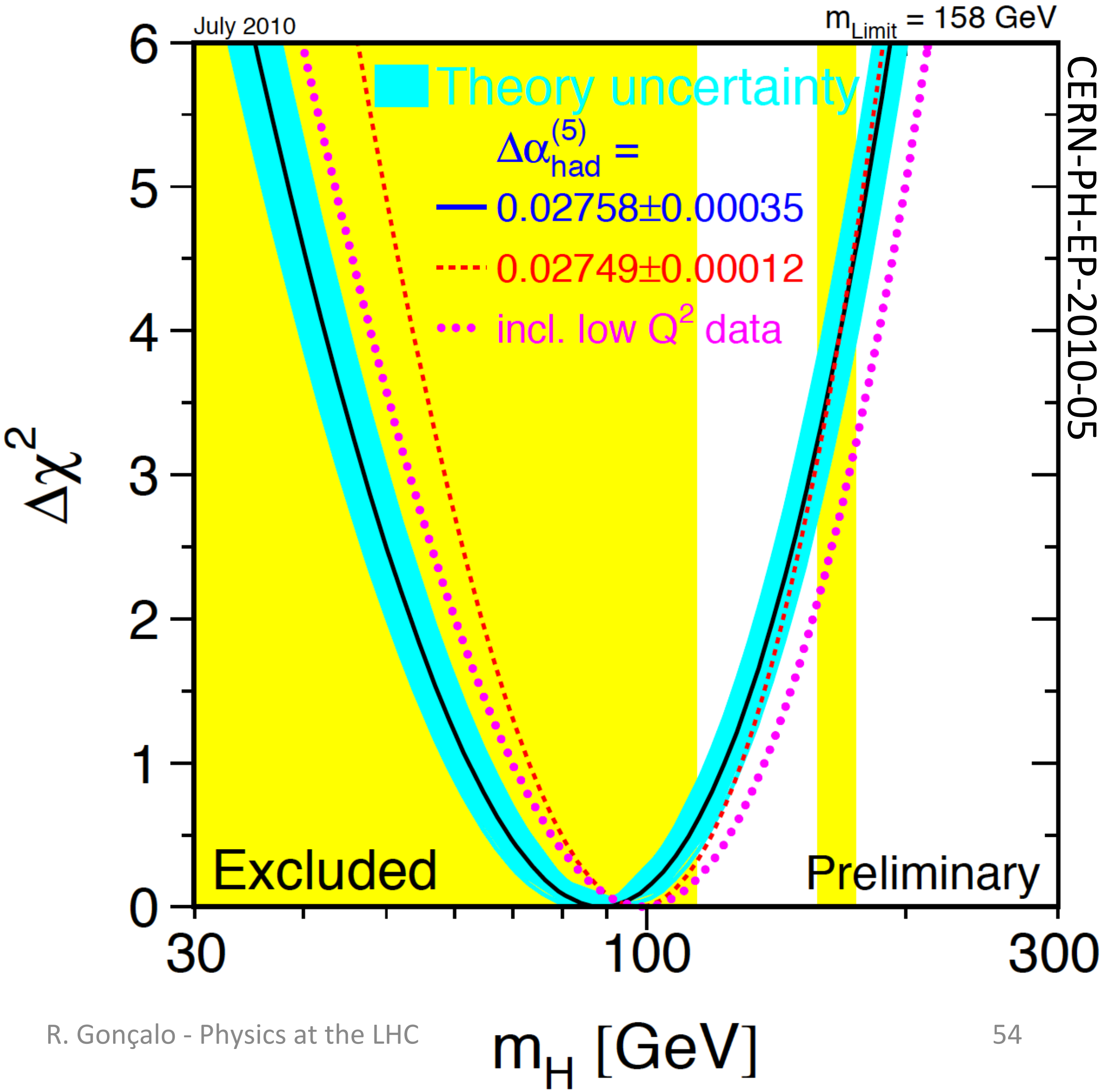
Final verdict from LEP

m_H>114.4 GeV @ 95% CL

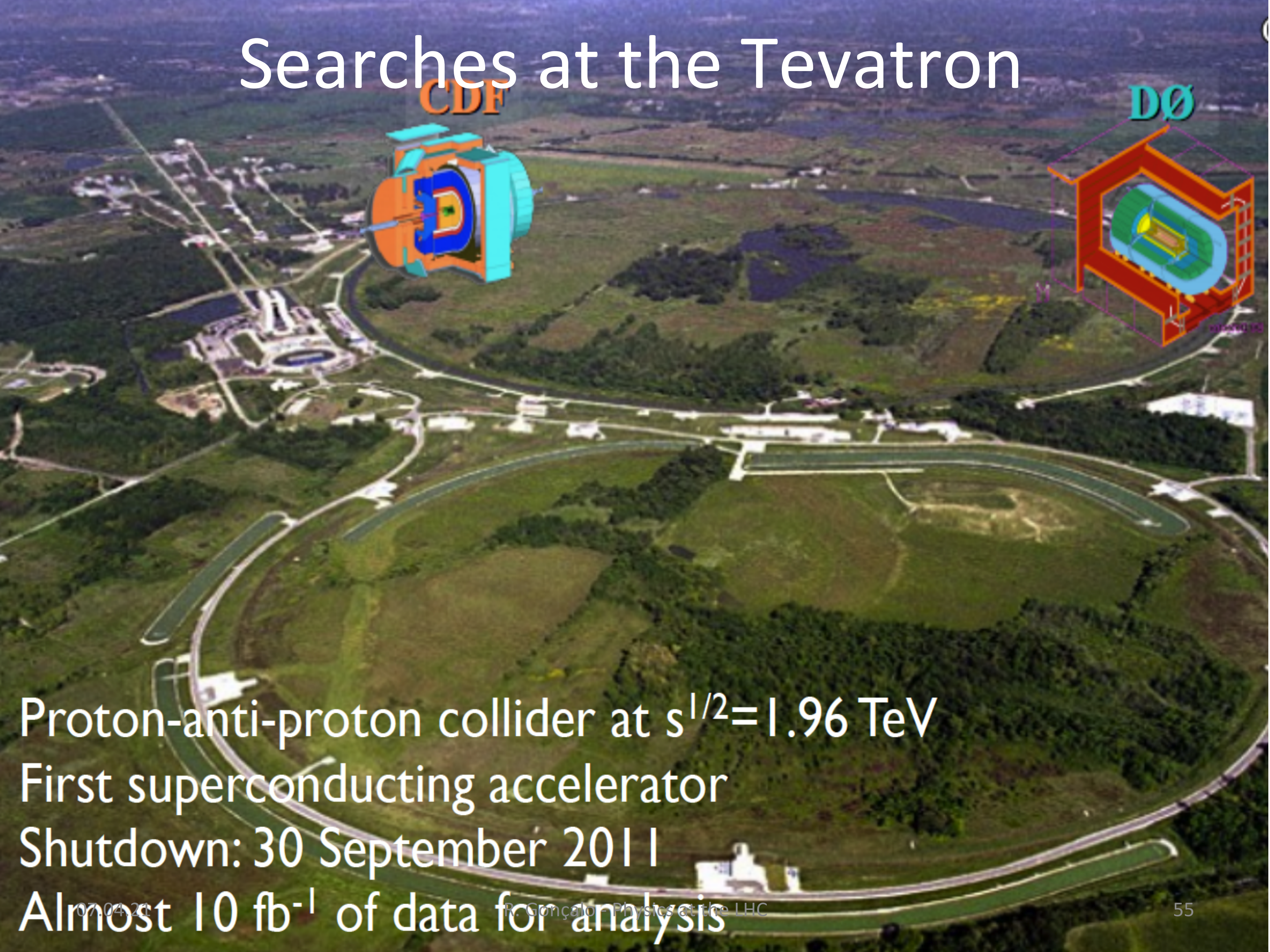


LEP’s Final Legacy: the Blue Band Plot

- Decades of searches in many experiments...
- By July 2010:
  - LEP+Tevatron+SLD limits
  - Higgs excluded m_h<114.4 GeV at 95% CL
  - Plus between 158 and 175 GeV

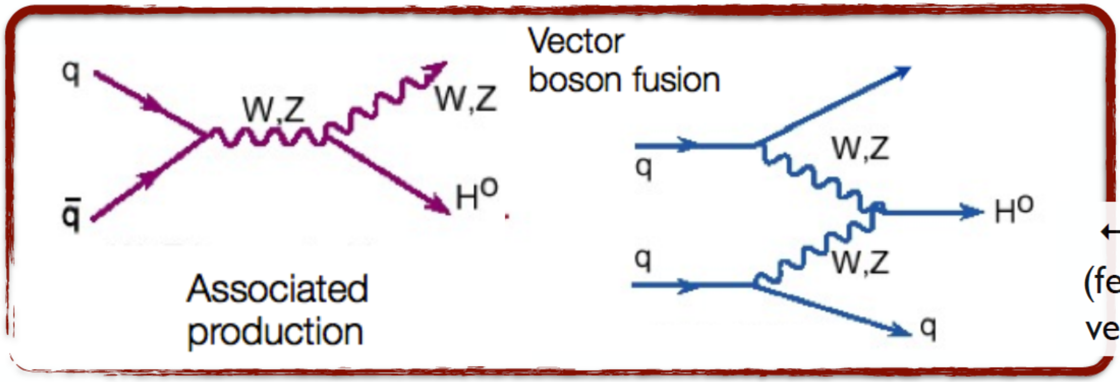


Searches at the Tevatron



Proton-anti-proton collider at $s^{1/2}=1.96$ TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb^{-1} of data for analysis

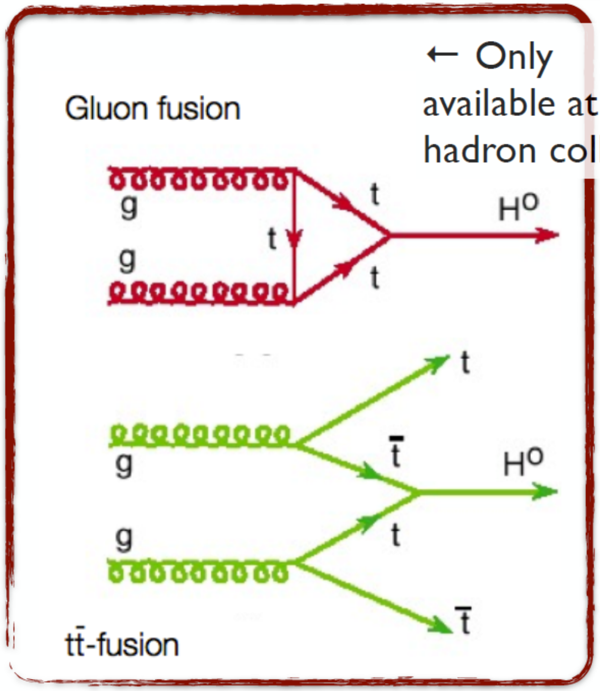
Higgs production at the Tevatron



Associated production

Vector boson fusion

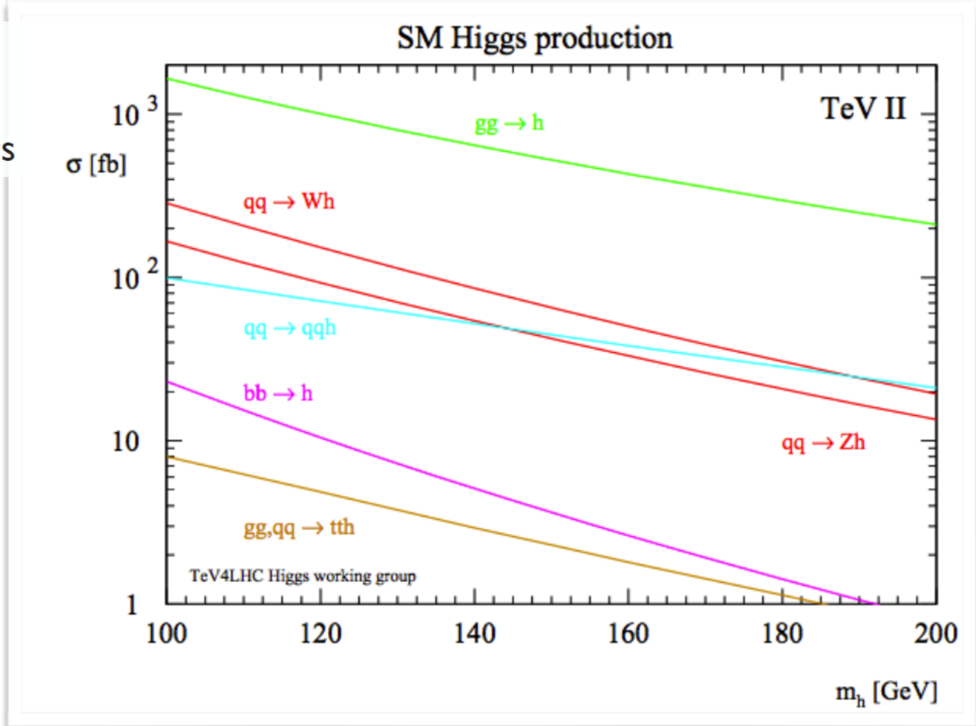
← (fermion annihilation and vector boson scattering)



Gluon fusion

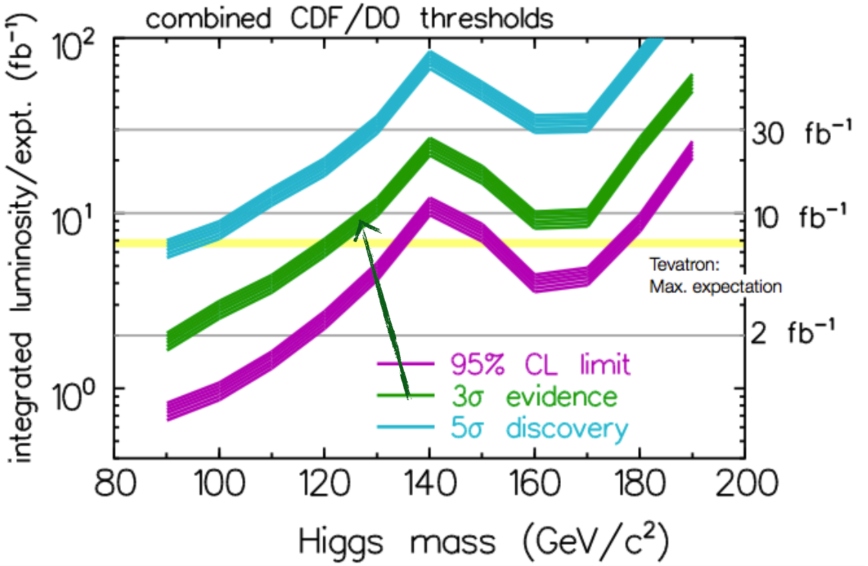
← Only available at hadron colliders

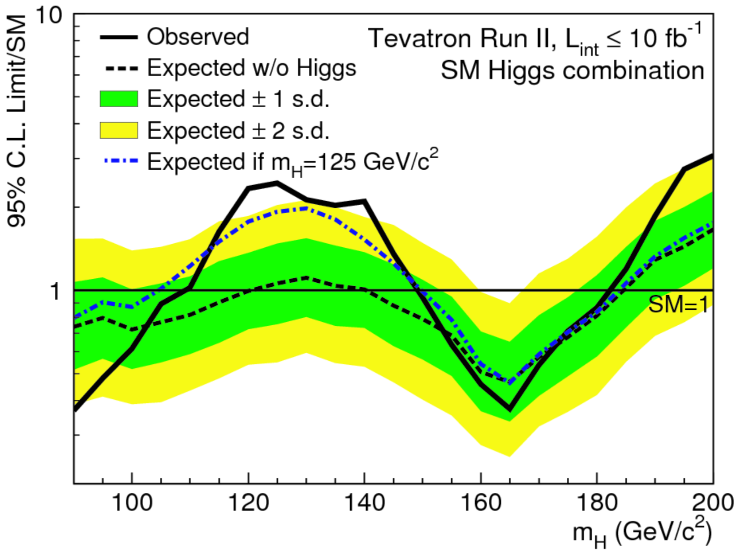
tt̄-fusion



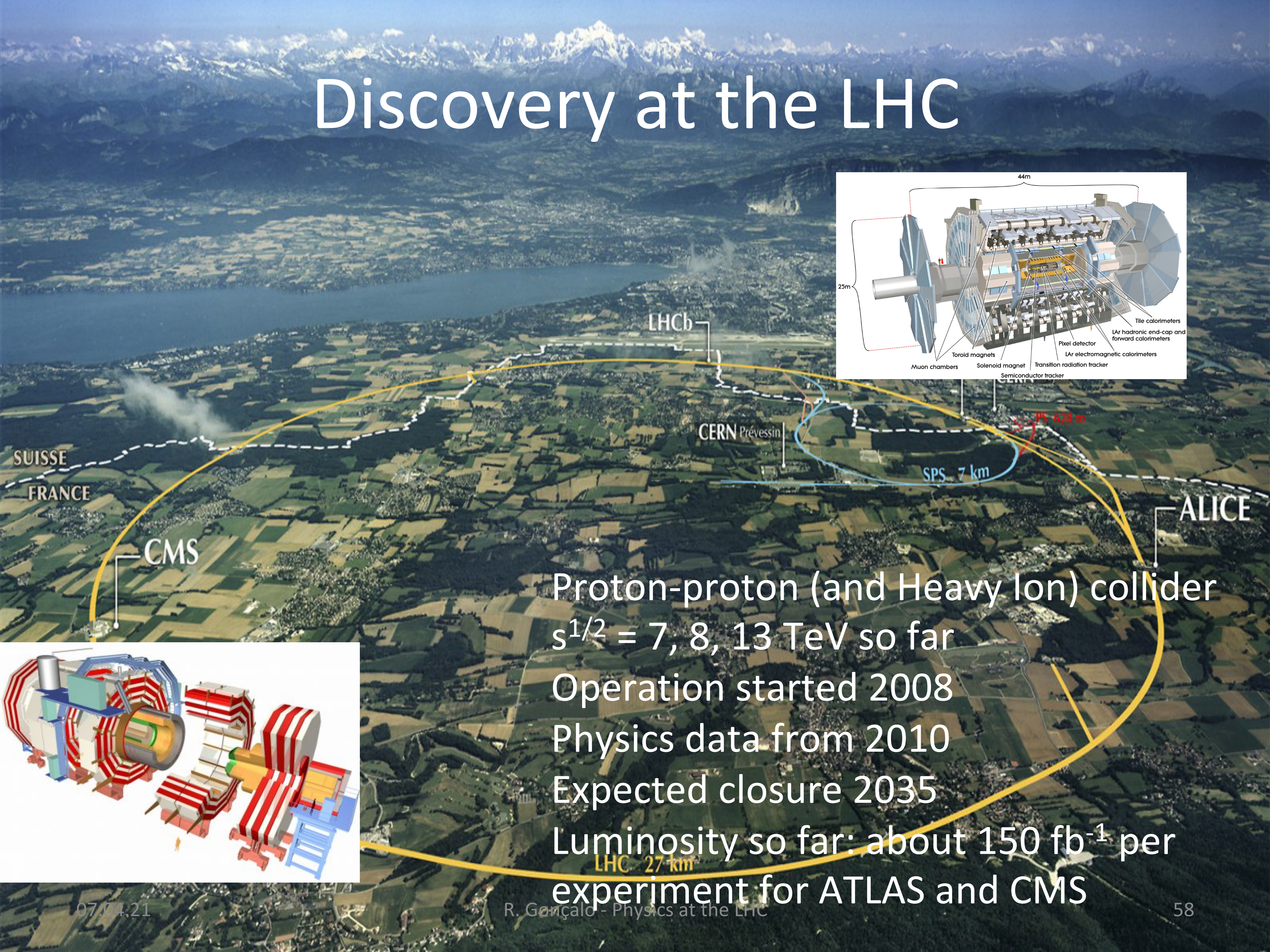
The final stand of the Tevatron

- By the end of its lifetime, the Tevatron had very sophisticated analyses of a huge number of channels
- By that time the LHC was collecting data and analysing it very fast
- The CDF and D0 experiments obtained a significant excess of around 3 standard deviations in the mass range $115<M_H<140$ GeV
- Not enough to claim discovery, but consistent with the LHC results





Discovery at the LHC



Proton-proton (and Heavy Ion) collider

$s^{1/2}$ = 7, 8, 13 TeV so far

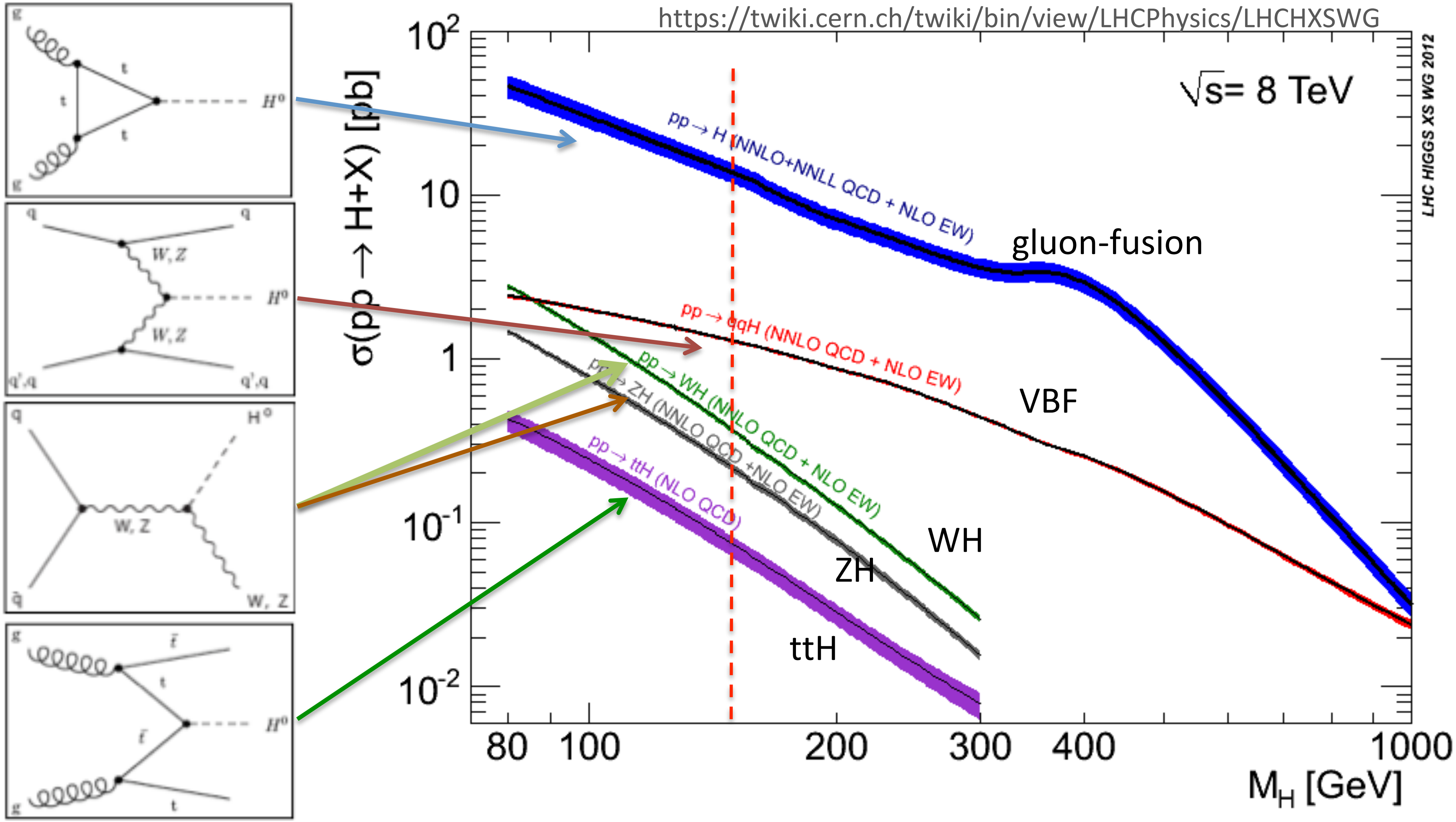
Operation started 2008

Physics data from 2010

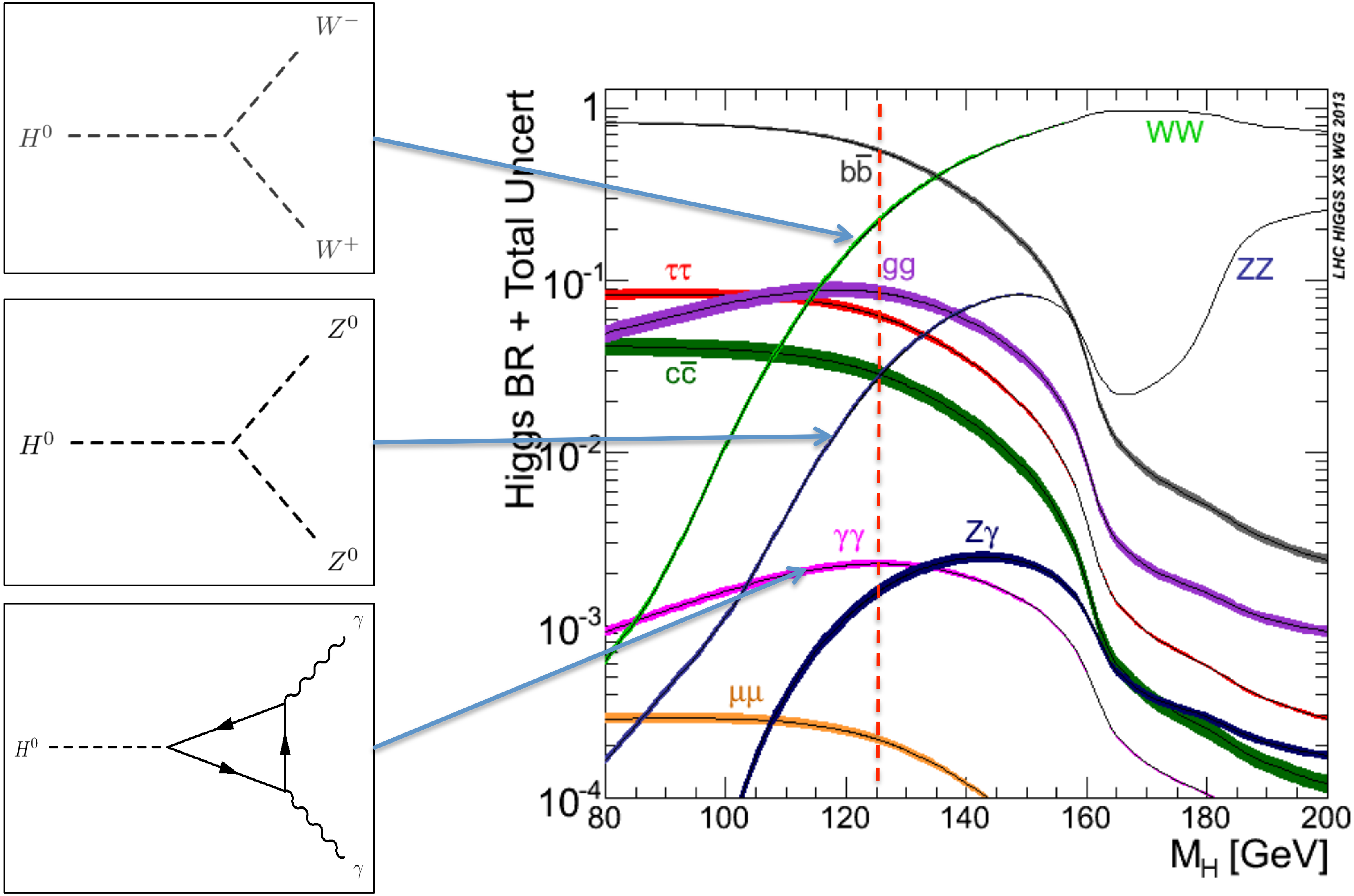
Expected closure 2035

Luminosity so far: about 150 fb^{-1} per experiment for ATLAS and CMS

At the LHC

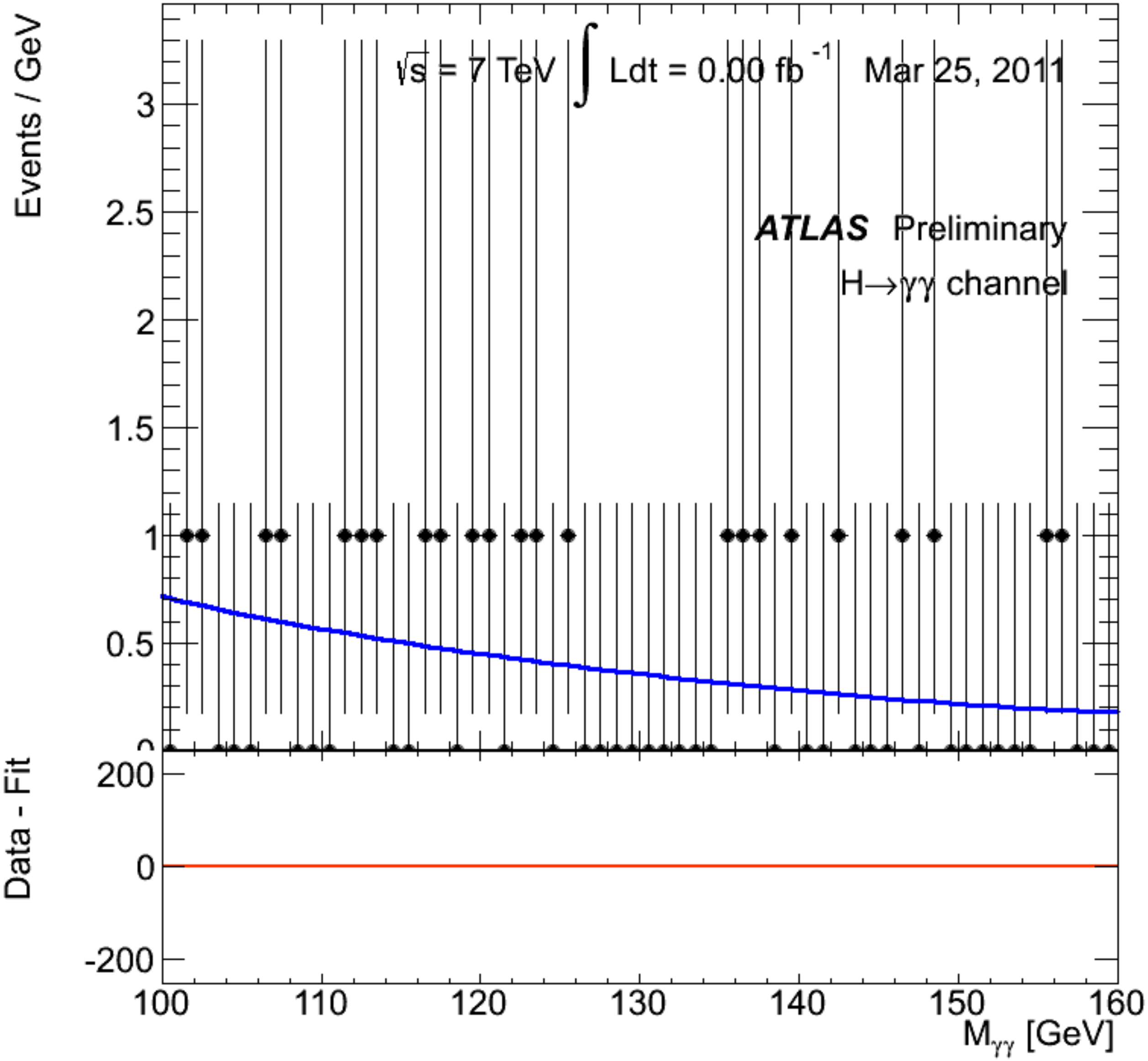


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG



H^0
W^−
W^+
H^0
Z^0
Z^0
H^0
γ
γ
Higgs BR + Total Uncert
1
10^-1
10^-2
10^-3
10^-4
80
100
120
140
160
180
200
M_H [GeV]
LHC HIGGS XS WG 2013
bb̄
WW
ττ
gg
ZZ
cc̄
γγ
Zγ
μμ

2012: Descoberta do bosão de Higgs: H->$\gamma\gamma$

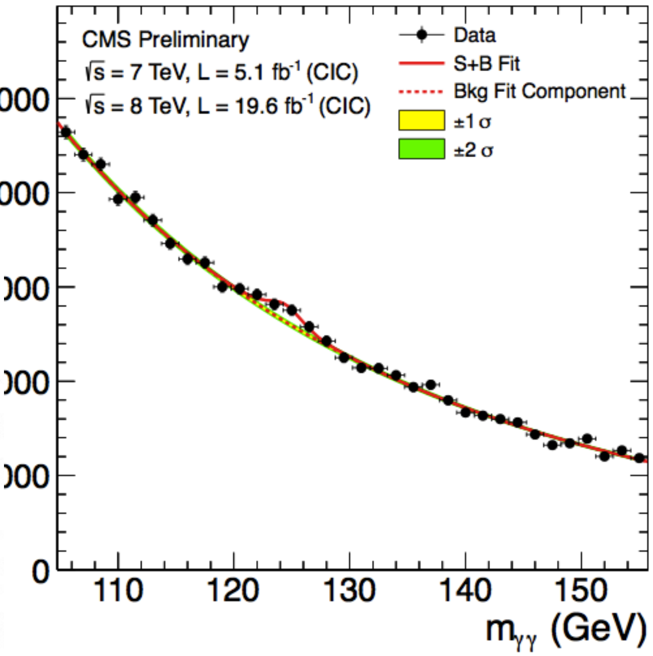


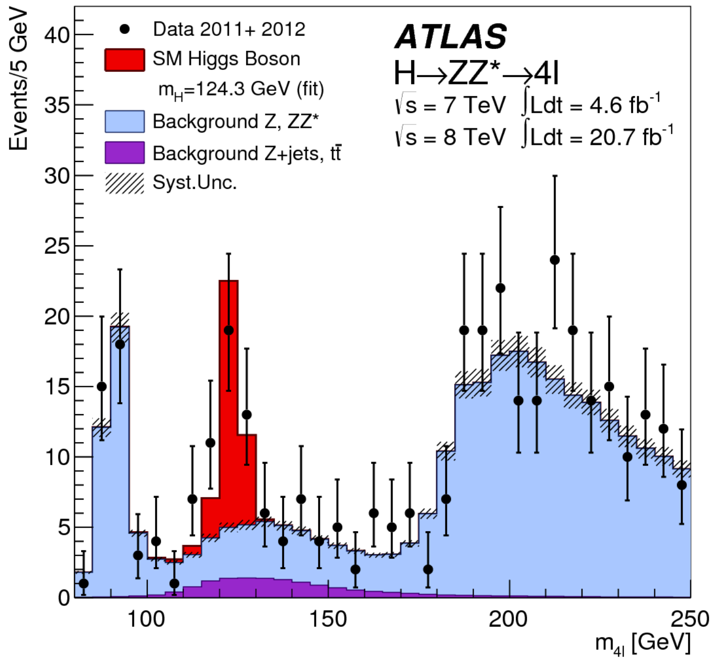
Discovery channels

- Discovery was made in ATLAS and CMS with about 5 fb^{-1} of 7 TeV data and 20 fb^{-1} of 8 TeV data per experiment; several channels combined

$$h \to \gamma\gamma; h \to ZZ^* \to 4\ell; h \to WW^*; h \to \tau^+\tau^-; h \to b\bar{b}$$

- This means about 400 000 Higgs bosons produced in about 8 000 000 000 000 000 (8x10^{15}) proton collisions
  - Only about 4000 events with Higgs bosons contributed to the discovery

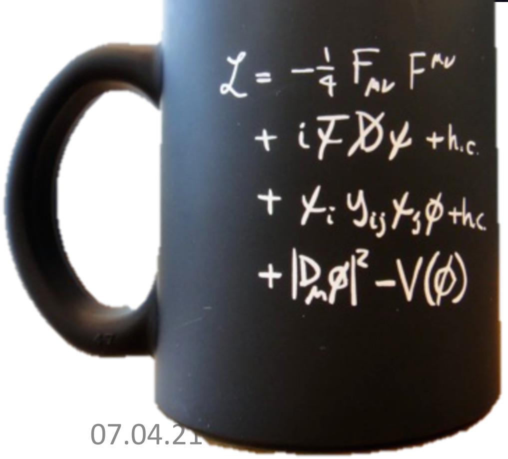




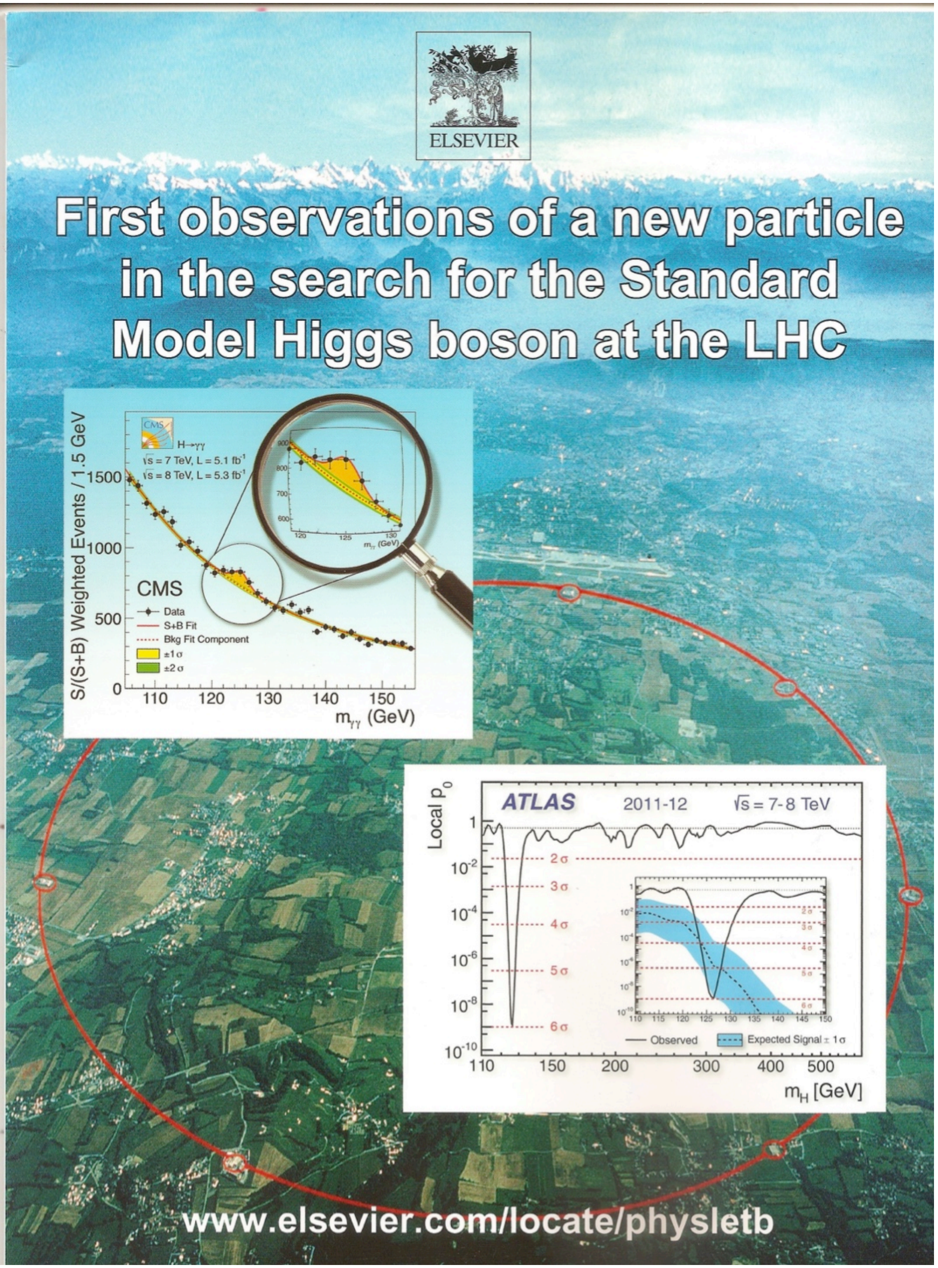
2013 Physics Nobel Prize Higgs for the Higgs Boson Discovery

François Englert, Belga, born 1932, U. Libre de Bruxelles

Peter Higgs, English, born 1929, Univ. of Edimburgh



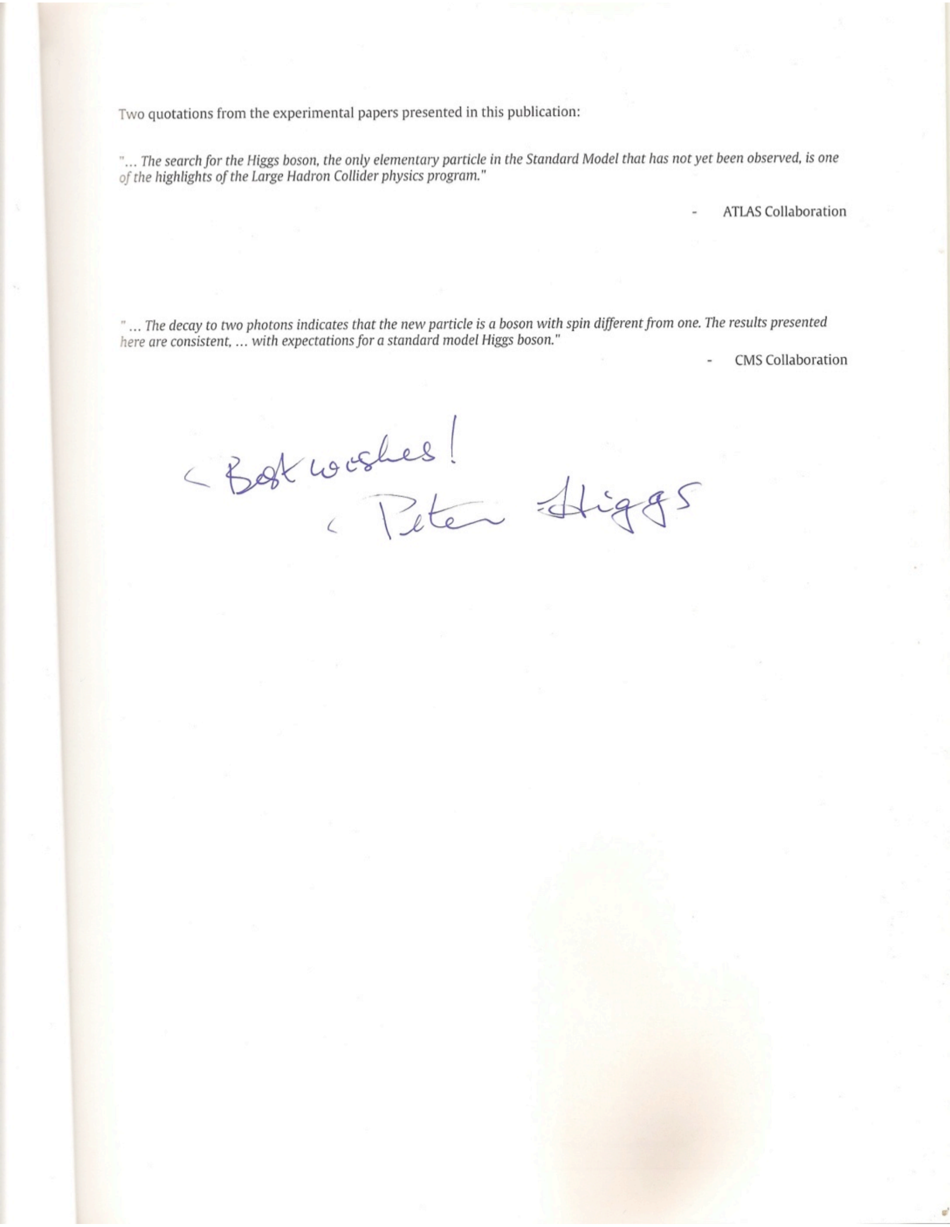
*"for the **theoretical discovery** of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the **discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider**"*



ELSEVIER

First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

www.elsevier.com/locate/physletb



Two quotations from the experimental papers presented in this publication:

> *"... The search for the Higgs boson, the only elementary particle in the Standard Model that has not yet been observed, is one of the highlights of the Large Hadron Collider physics program."*
>
> \- ATLAS Collaboration

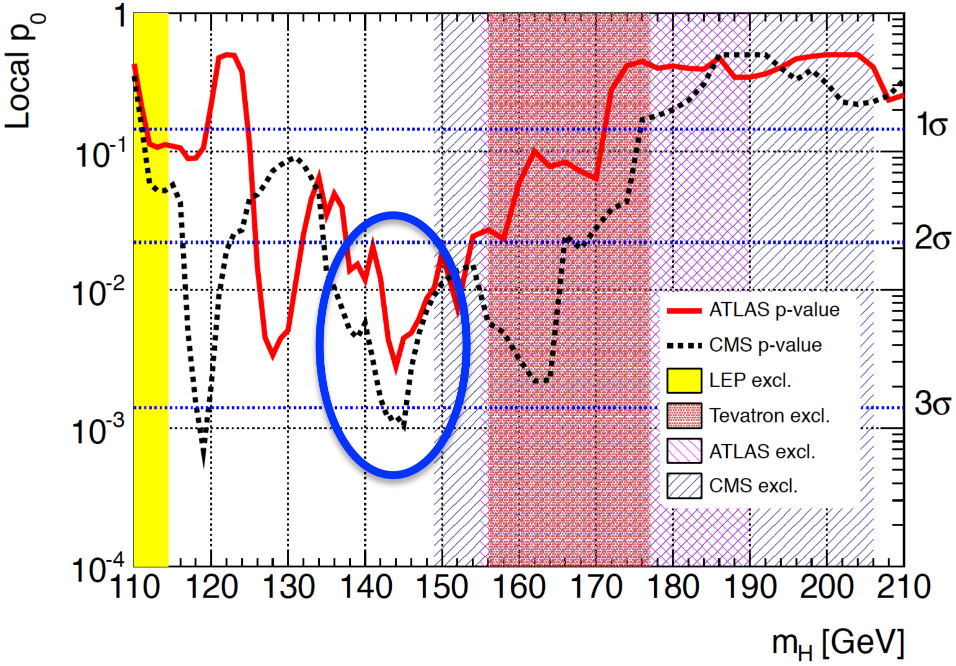
> *" ... The decay to two photons indicates that the new particle is a boson with spin different from one. The results presented here are consistent, ... with expectations for a standard model Higgs boson."*
>
> \- CMS Collaboration

Best wishes!

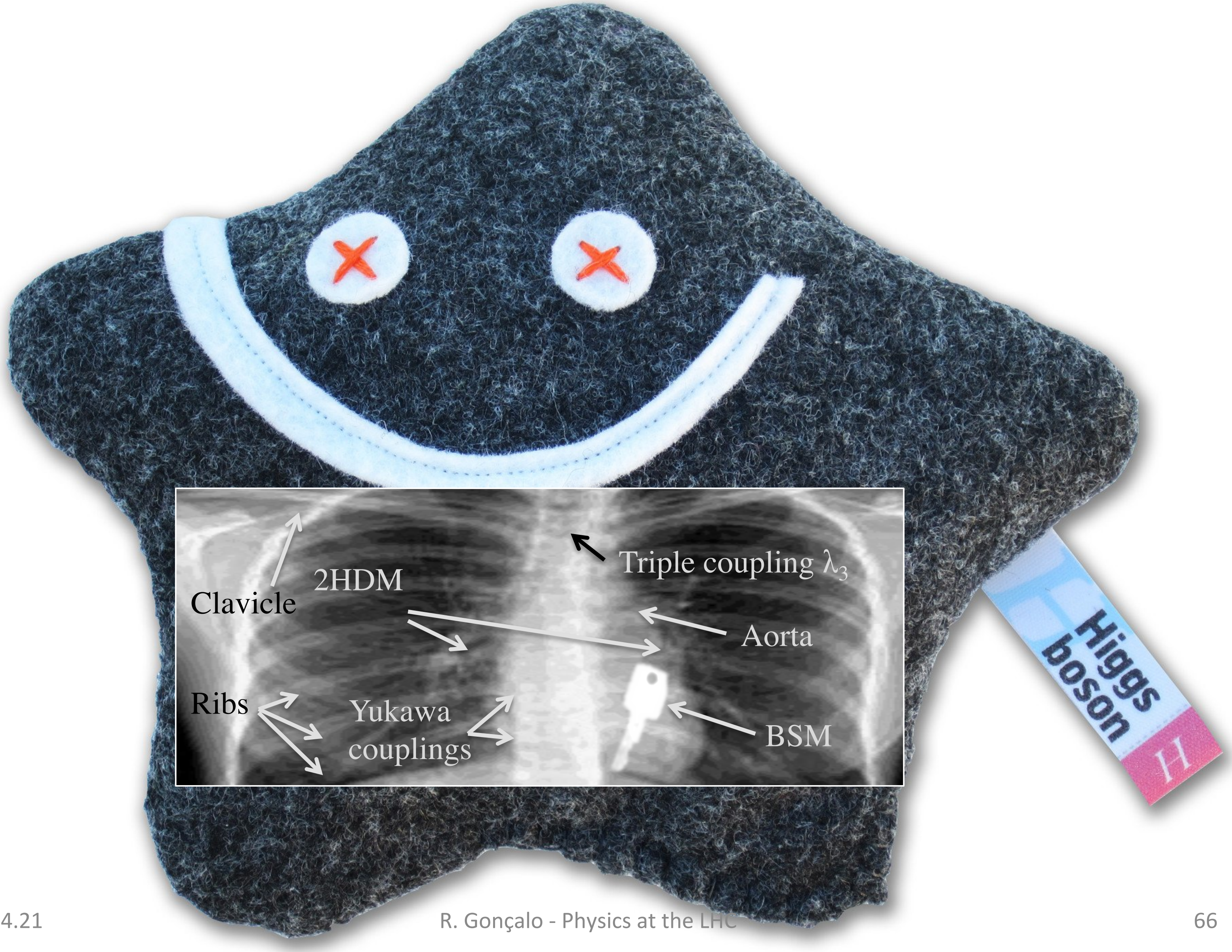
Peter Higgs

It takes time to get it right

EPS-HEP 2011 conference [6]



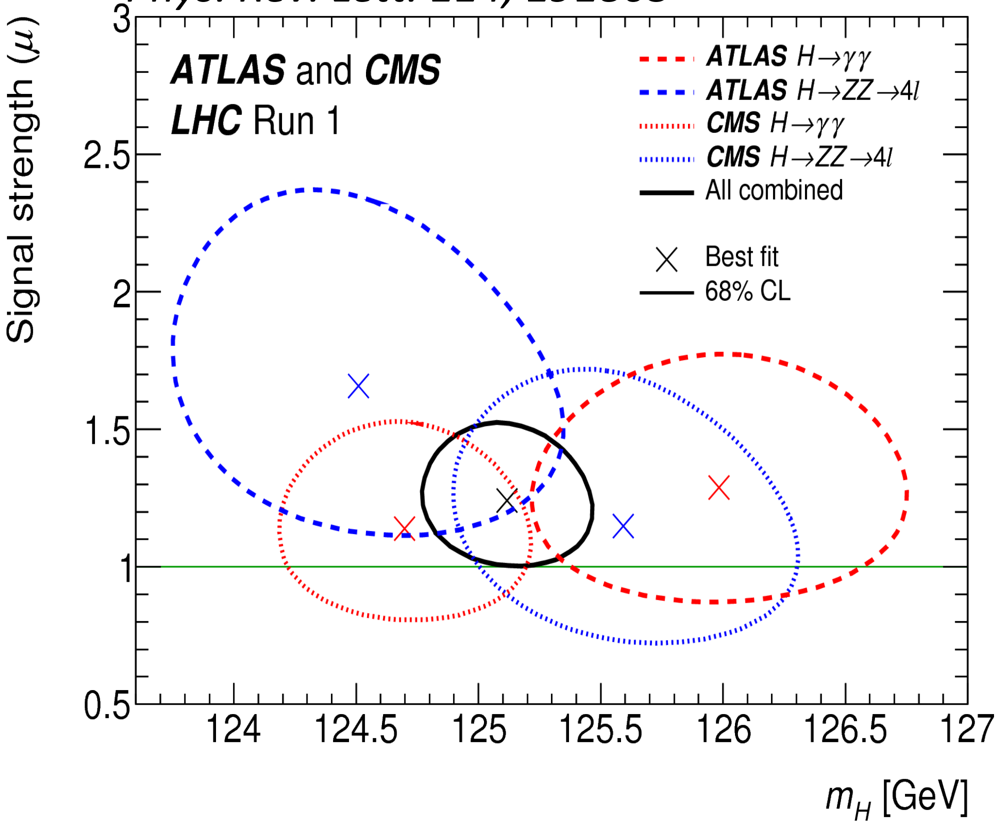
Probing the 125 GeV Higgs - Examples



Higgs boson mass

- **Mass:** around 125GeV
  Was the only unknown
  SM parameter ☺
- For a while, different mass values were being measured in ATLAS and CMS, and in different channels
- Numbers evolved with accumulated statistics
- Current most precise value from ATLAS+CMS has 0.2% precision!

Phys. Rev. Lett. 114, 191803

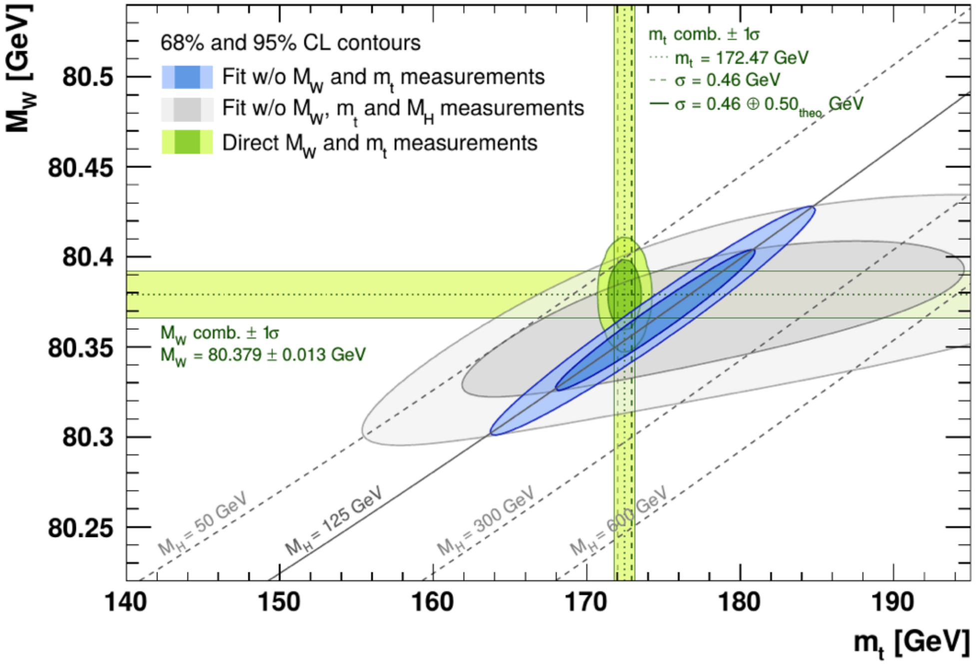


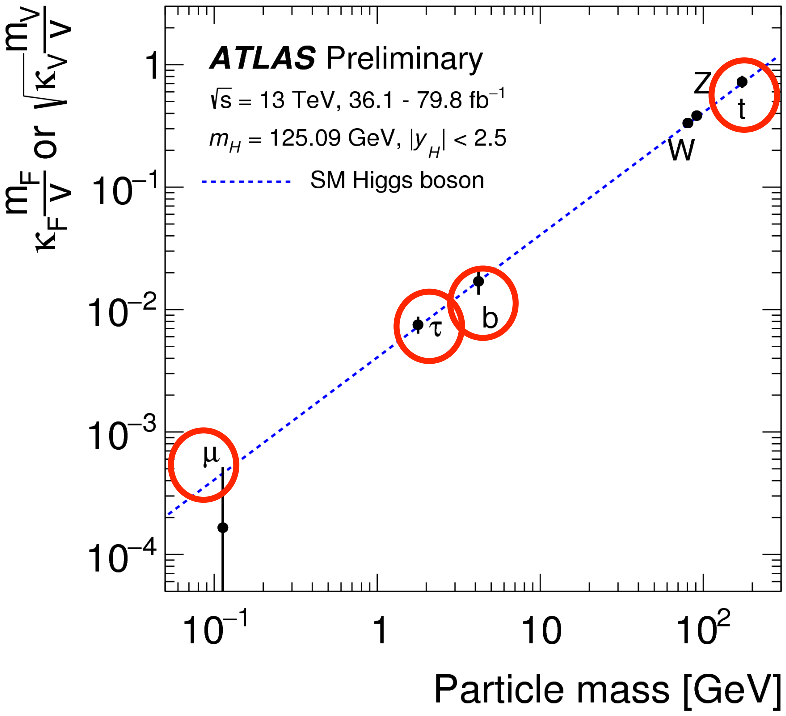
m_H=125.09±0.21 (stat)±0.11 (syst) GeV

Exploring the electroweak scale

- Precision measurements of m_W, m_t, m_H are stringent tests of the SM at the EW scale
  - E.g. excluding measured m_H, global EW fit gives $m_H = 90 \pm 21$ GeV (1.7 σ tension) driven in part by m_{top}

arXiv:1803.01853





arXiv:1804.02716 [hep-ex]; arXiv:1706.09936 [hep-ex]; arXiv:1806.00242 [hep-ex]

Run 2: Higgs boson mass

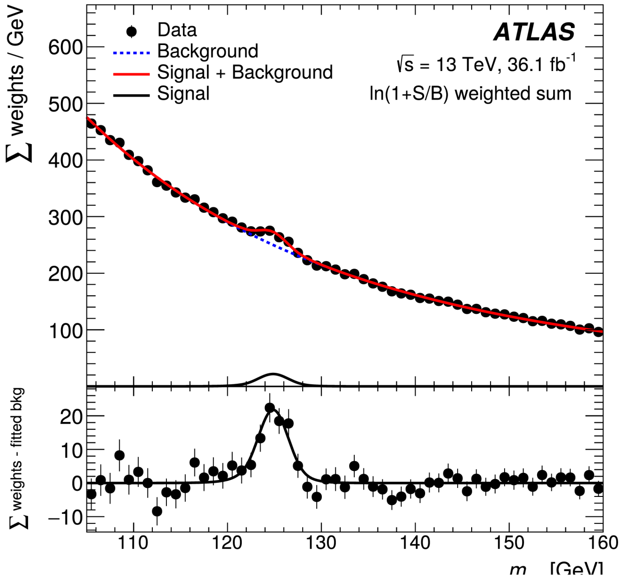
- Mass measurement from CMS H→ZZ*→4l:

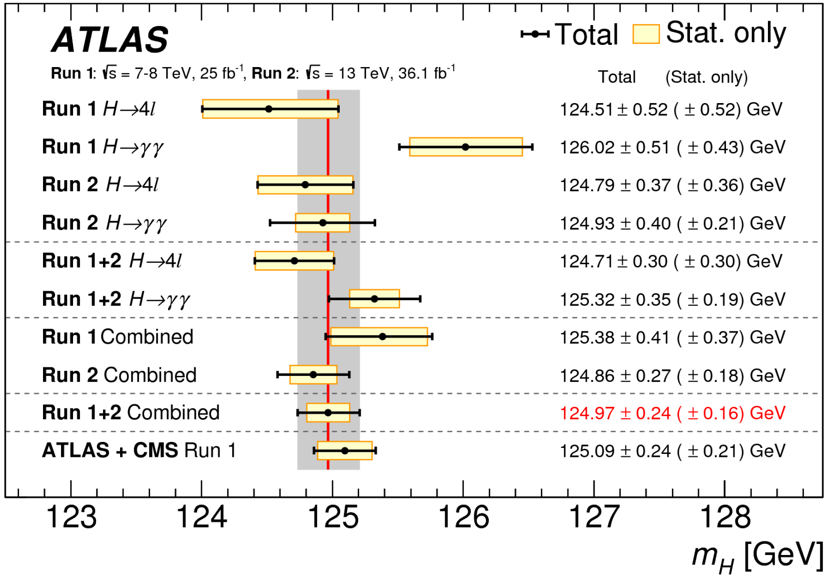
  $m_H^{ZZ^*}$ = 125.26 ± 0.20 (stat) ± 0.08 (syst) GeV
- New Measurements from ATLAS

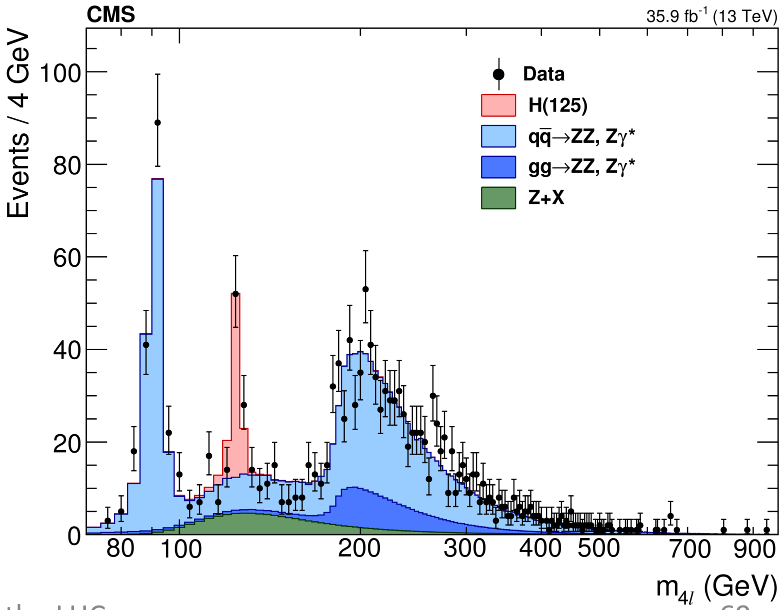
  H→ γγ: $m_H^{\gamma\gamma}$ = 124.93 ± 0.40 GeV

  H→ZZ*→4l: $m_H^{ZZ^*}$ = 124.79 ± 0.37 GeV
- Run 1+2 combination from ATLAS:

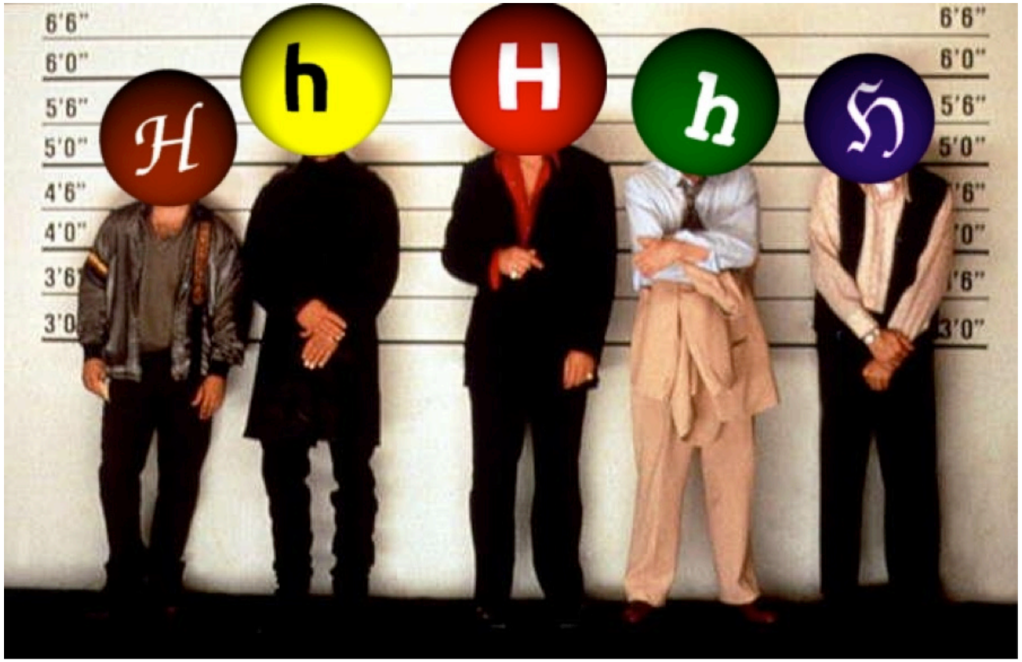
  m_H = 124.97 ± 0.19 (stat) ± 0.13 (syst.) GeV



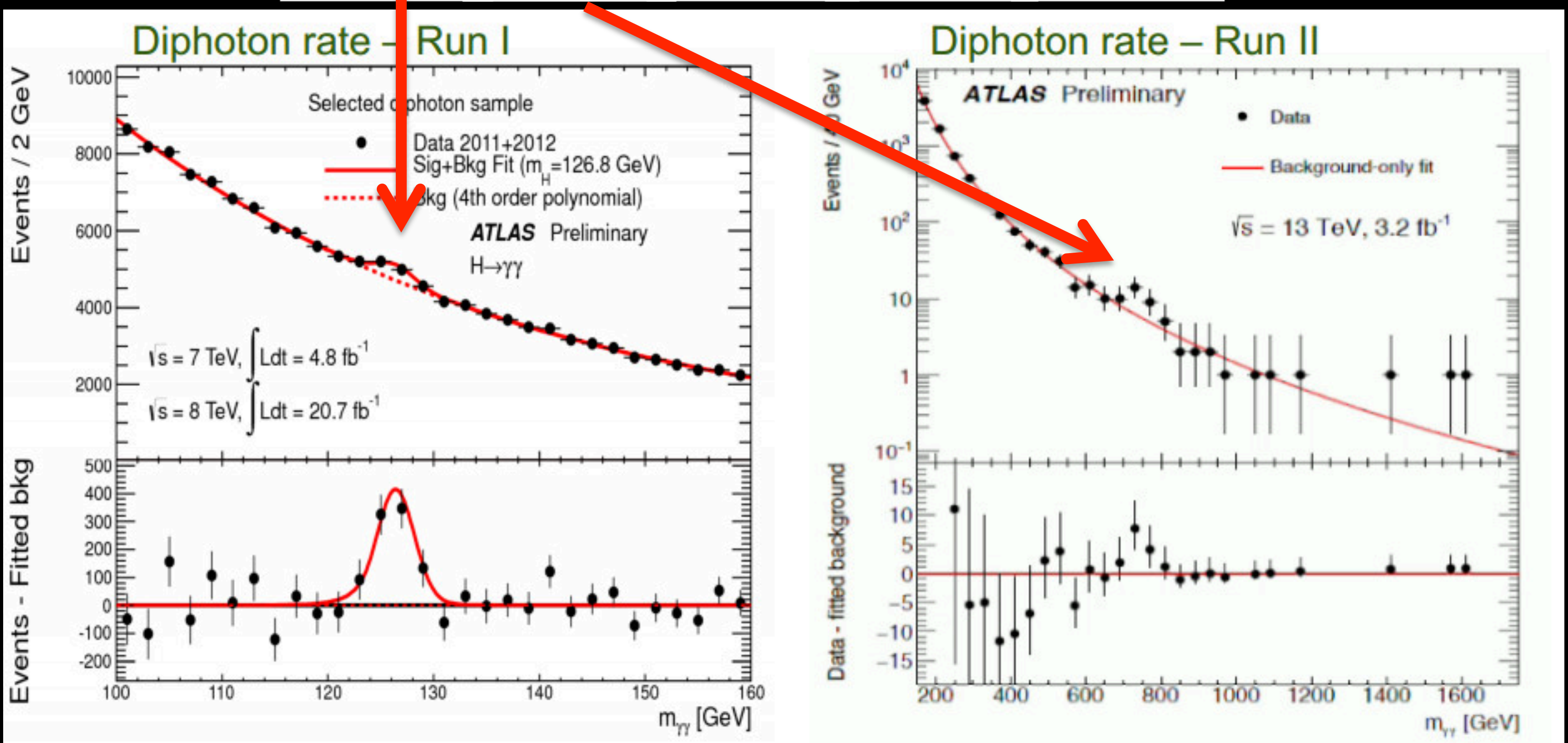




Casting a wider net



Additional Higgs bosons?

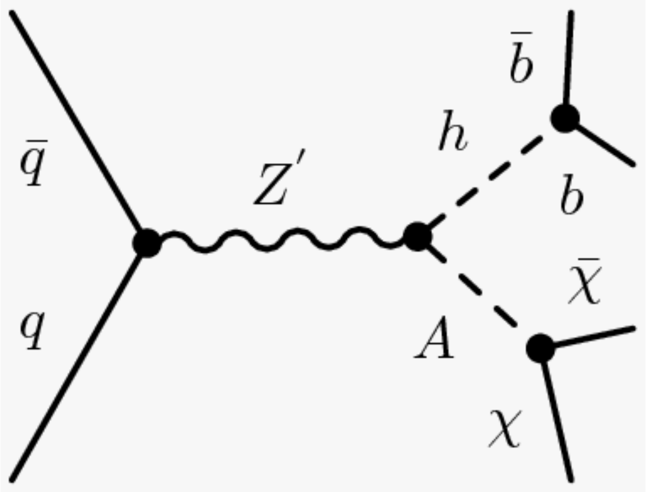

Diphoton rate – Run I

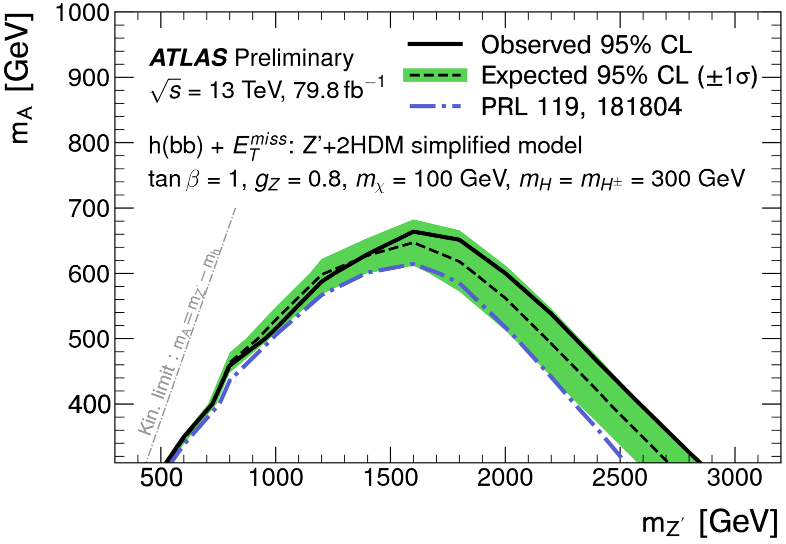
Diphoton rate – Run II

ATLAS-CONF-2018-039

Higgs + Dark Matter

- Used 79.8 fb^{-1} of 13 TeV data
    - High E_T^{miss} (>150GeV) and b-tagging to suppress backgrounds
    - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets
- Signal benchmark: Type-II 2HDM + $U(1)_{Z'}$ symmetry (Z'-2HDM)
- Main backgrounds: tt, W/Z+jets
- Excluded region in $m_A - m_{Z'}$ plane





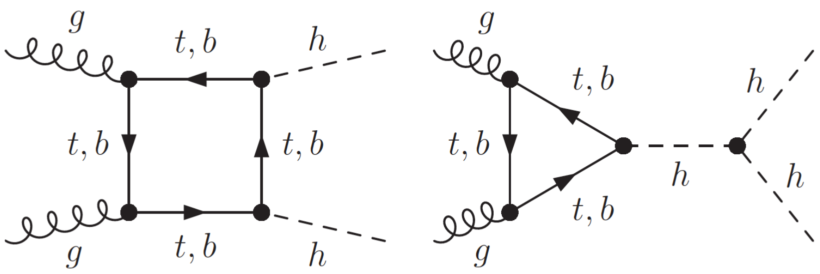
arXiv:1808.00336 [hep-ex]; ATLAS-CONF-2018-043

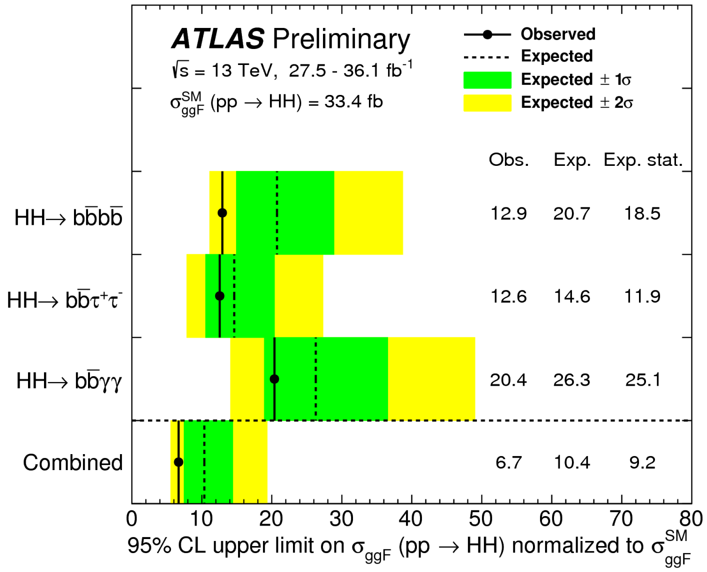
Triple Higgs coupling

- The triple Higgs coupling λ_{HHH} can be probed through di-Higgs production
- Very suppressed in SM!
  - Negative interference between LO diagrams
  - Cross section 1500x less than ggF
- Wide range of decay BR and channel purity
- bbττ analysis:
  - Used 36 fb^{-1} of 13 TeV data
  - Final state BR(bbττ)=7%
  - Non-Resonant 95% CL limit:

    μ < 12.7 observed (14.8 expexcted)
- Combination: at ≈10 x SM sensitivity – with 3% of the HL-LHC luminosity analyzed

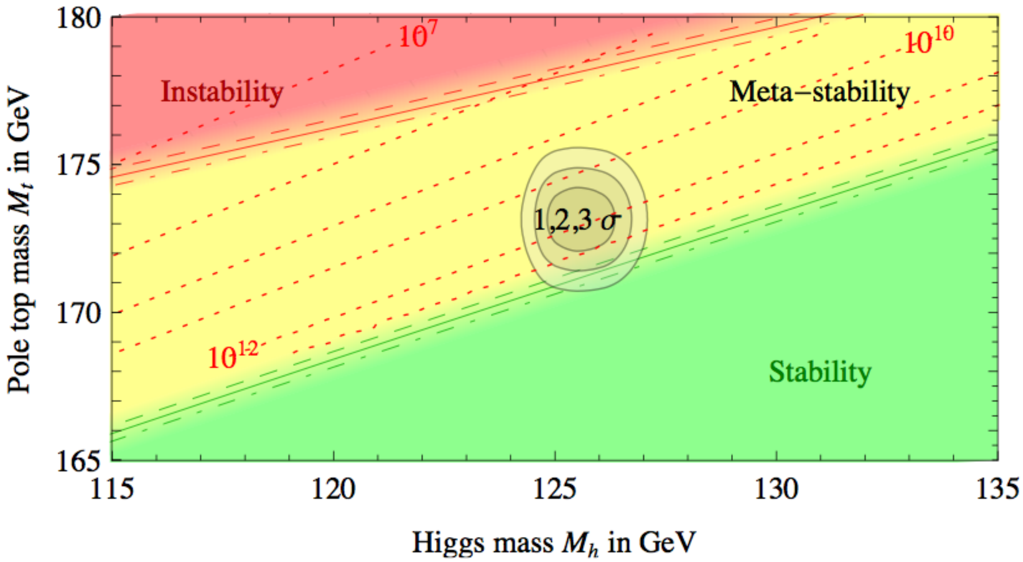
$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

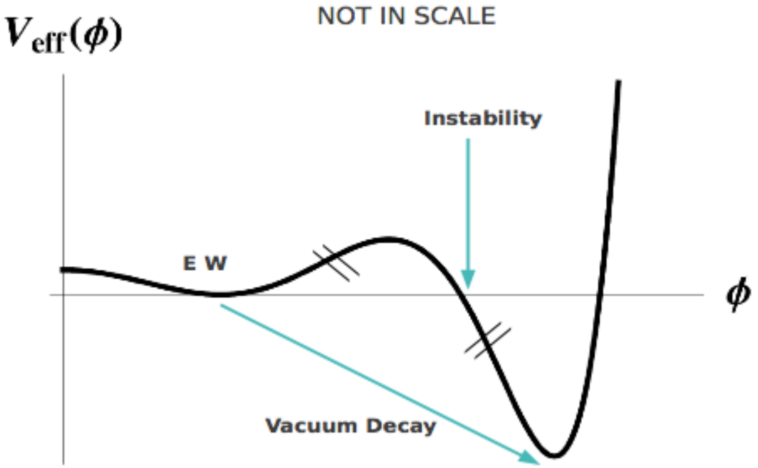




Di-Higgs combination plot here

A bit of fun…





RG-improved potential

- What if…
  - At higher orders, Higgs potential doesn't have to be stable
  - Depending on m_t and m_H second minimum can be lower than EW minimum ⇒ tunneling between EW vacuum and true vacuum?!
- "For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Higgs potential develops a shallow local minimum at energies of about 10^{16} GeV, where primordial inflation could have started in a cold metastable state", I. Masina, arXiv:1403.5244 [astro-ph.CO]
  - See also: V. Brachina, Moriond 2014 (Phys.Rev.Lett.111, 241801 (2013)), G. Degrassi et al, arXiv:1205.6497v2; R.Contino, Workshop sulla fisica p-p a LHC, 2013

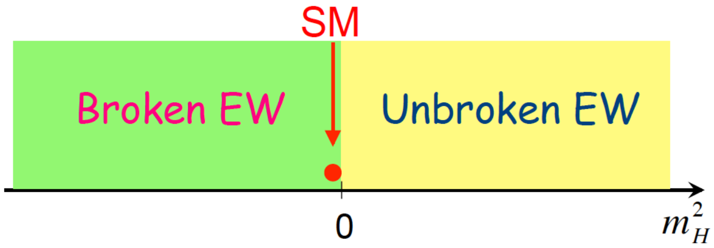
The universe seems to live near a critical condition

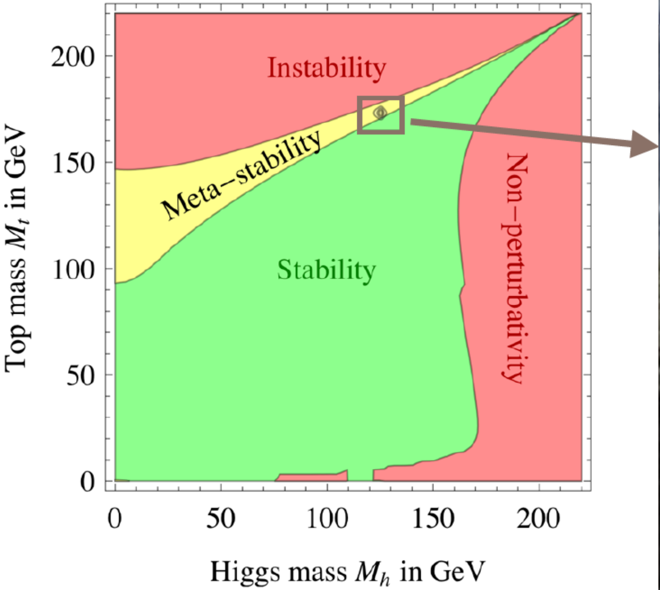
JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?





Questions?

Thank you for your interest!

jgoncalo@lip.pt