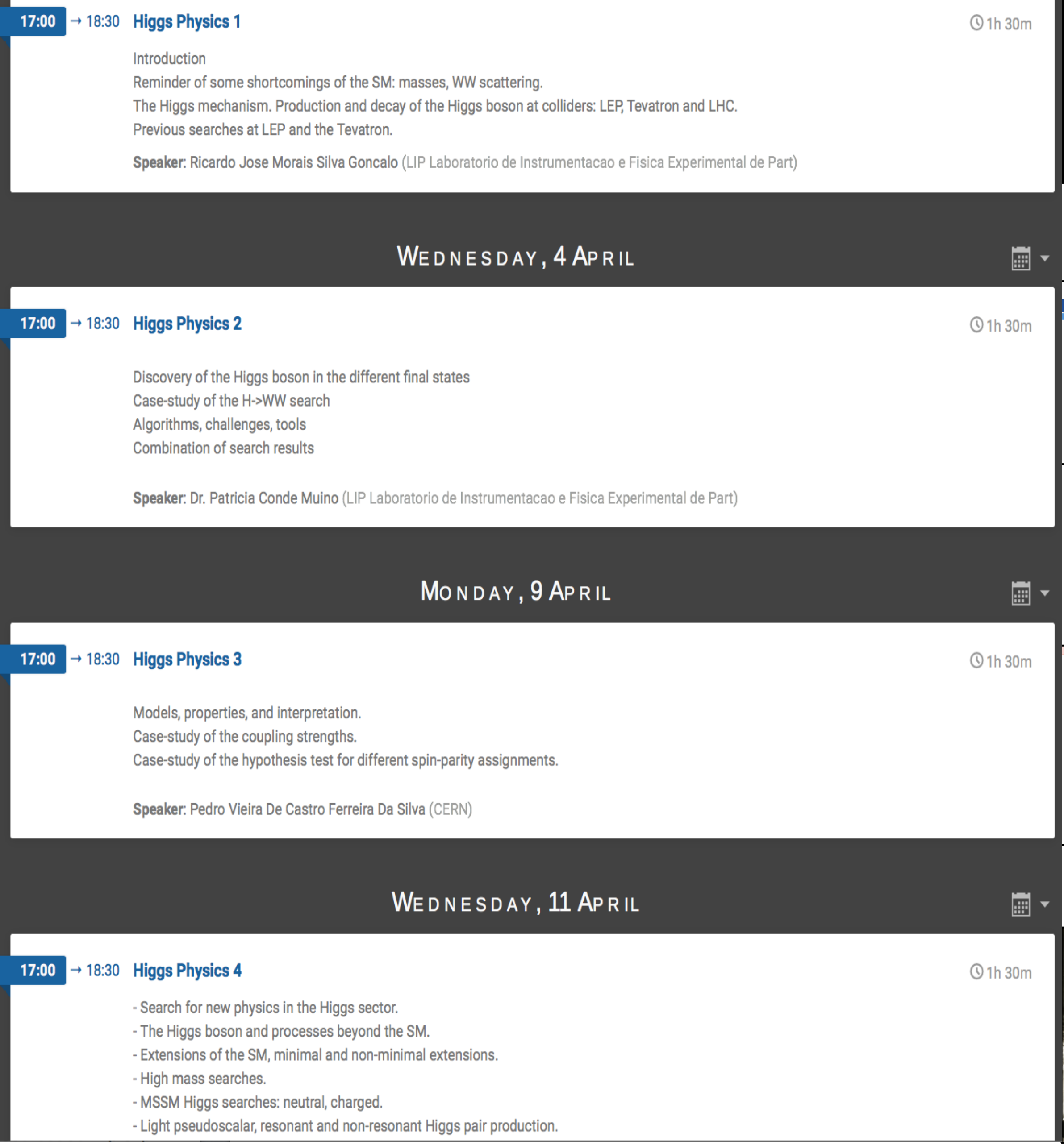
Higgs Physics – Lecture 1

Higgs Physics at the LHC – Introduction
Ricardo Gonçalo – LIP
IDPASC Course on Physics at the LHC – LIP, 2 April 2018

INVESTIGADOR FCT
Cofinanciado por:
UNIÃO EUROPEIA
Fundos Europeus Estruturais e de Investimento

Higgs Lectures



17:00 → 18:30 **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)

WEDNESDAY, 4 APRIL

17:00 → 18:30 **Higgs Physics 2** 1h 30m

Discovery of the Higgs boson in the different final states
Case-study of the H->WW search
Algorithms, challenges, tools
Combination of search results

Speaker: Dr. Patricia Conde Muino (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

MONDAY, 9 APRIL

17:00 → 18:30 **Higgs Physics 3** 1h 30m

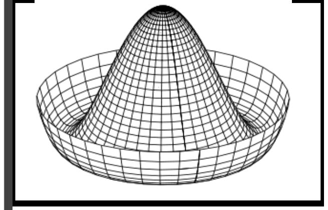
Models, properties, and interpretation.
Case-study of the coupling strengths.
Case-study of the hypothesis test for different spin-parity assignments.

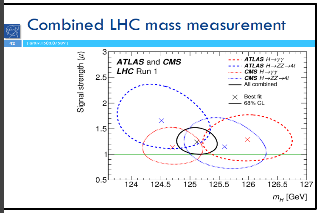
Speaker: Pedro Vieira De Castro Ferreira Da Silva (CERN)

WEDNESDAY, 11 APRIL

17:00 → 18:30 **Higgs Physics 4** 1h 30m

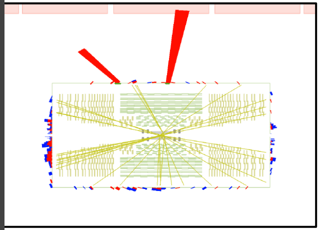
- Search for new physics in the Higgs sector.
- The Higgs boson and processes beyond the SM.
- Extensions of the SM, minimal and non-minimal extensions.
- High mass searches.
- MSSM Higgs searches: neutral, charged.
- Light pseudoscalar, resonant and non-resonant Higgs pair production.





Combined LHC mass measurement

42 [arXiv:1503.07589]

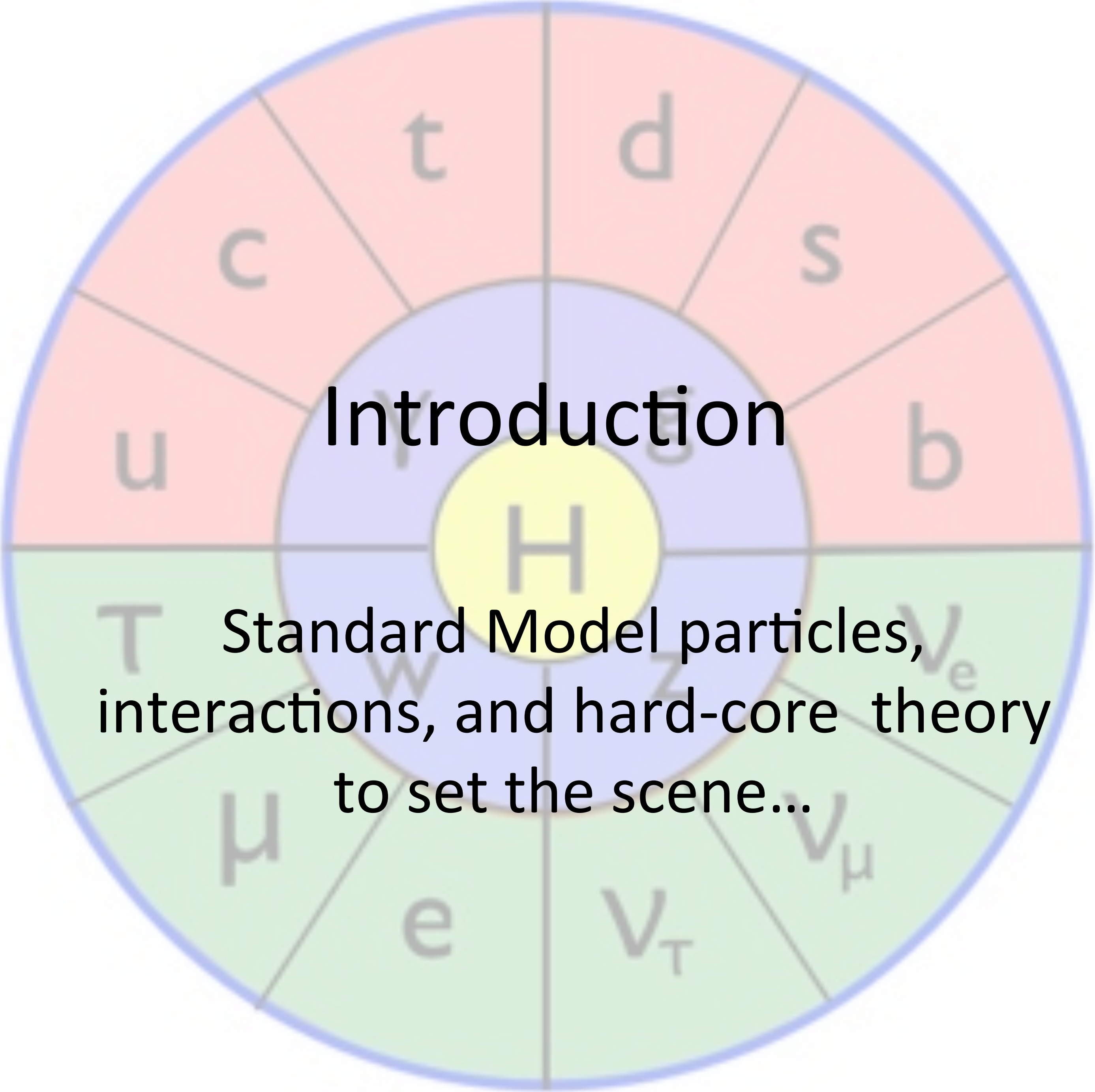


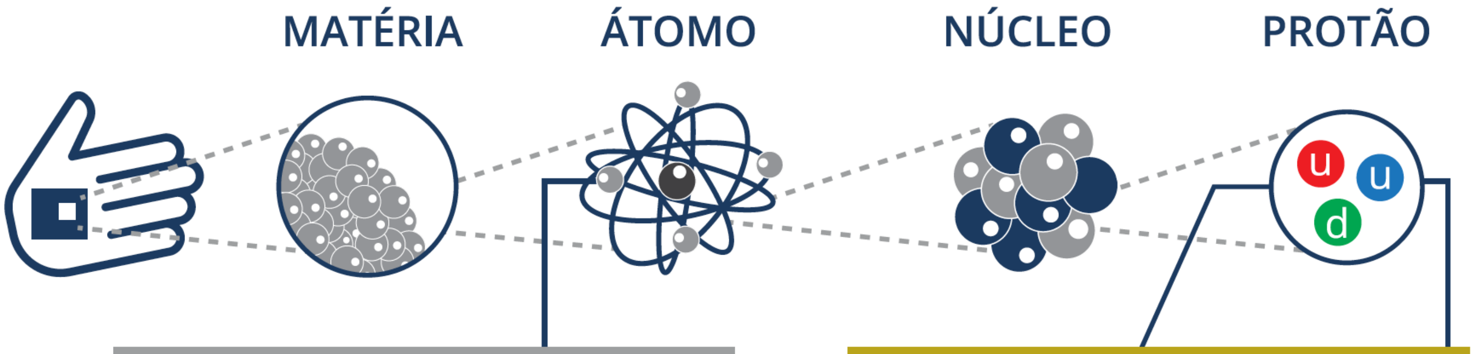
Outlook

- Introduction
- Hard-core theory
  - Lagrangians and symmetries
  - Quantum fields
  - 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

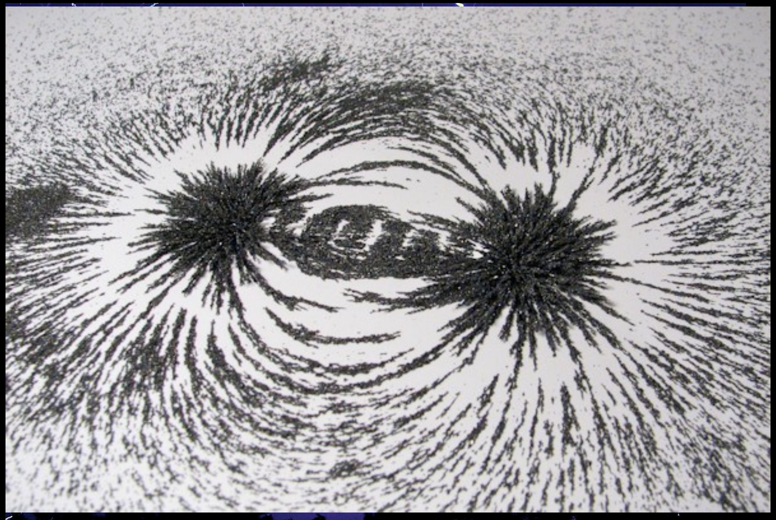
Introduction

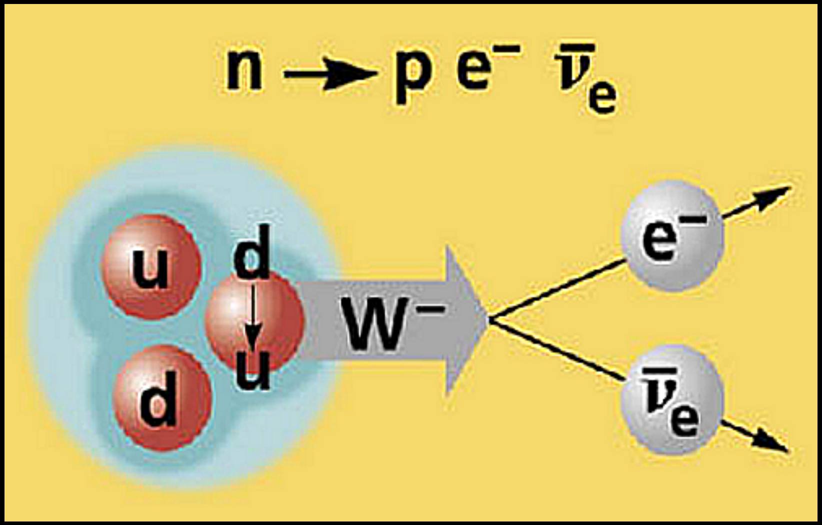
Standard Model particles, interactions, and hard-core theory to set the scene…

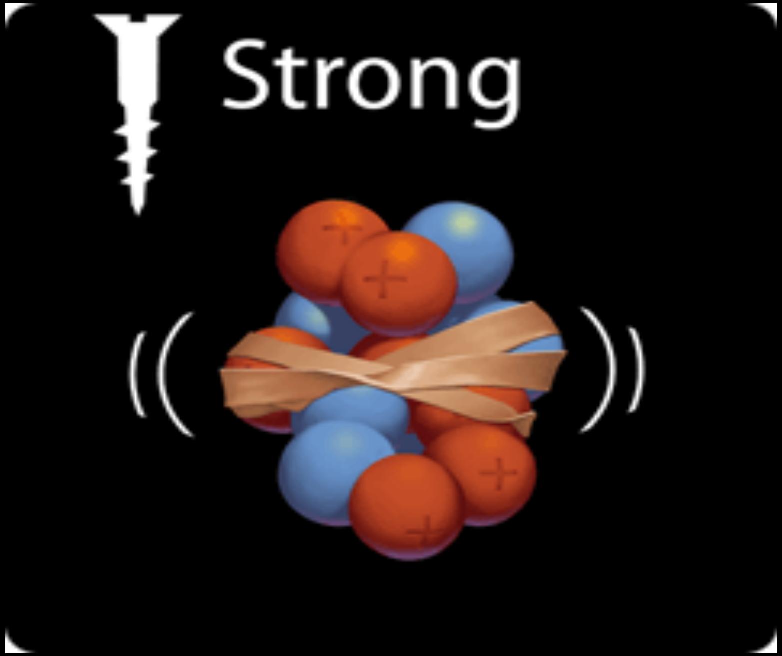


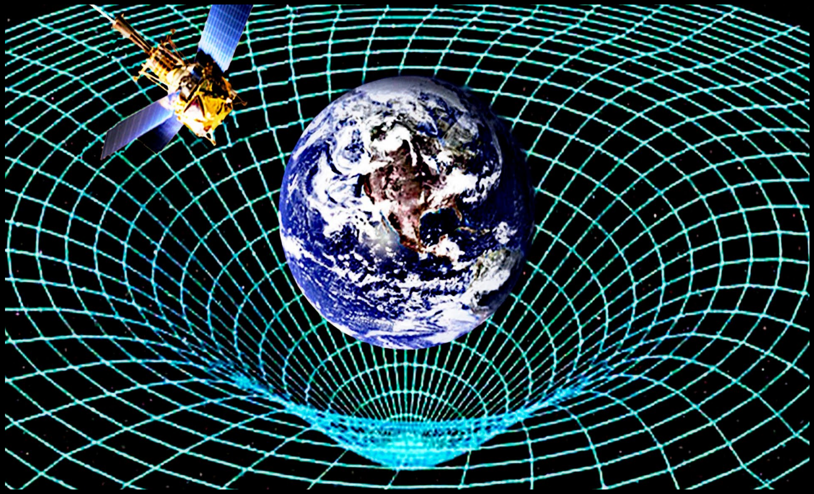


LEPTÕES		QUARKS	
ν_e NEUTRINO DO ELETRÃO 0 ½	e ELETRÃO -1 ½	u UP ⅔ ½	d DOWN -⅓ ½
ν_μ NEUTRINO DO MUÃO 0 ½	μ MUÃO -1 ½	c CHARM ⅔ ½	s STRANGE -⅓ ½
ν_τ NEUTRINO DO TAU 0 ½	τ TAU -1 ½	t TOP ⅔ ½	b BOTTOM -⅓ ½



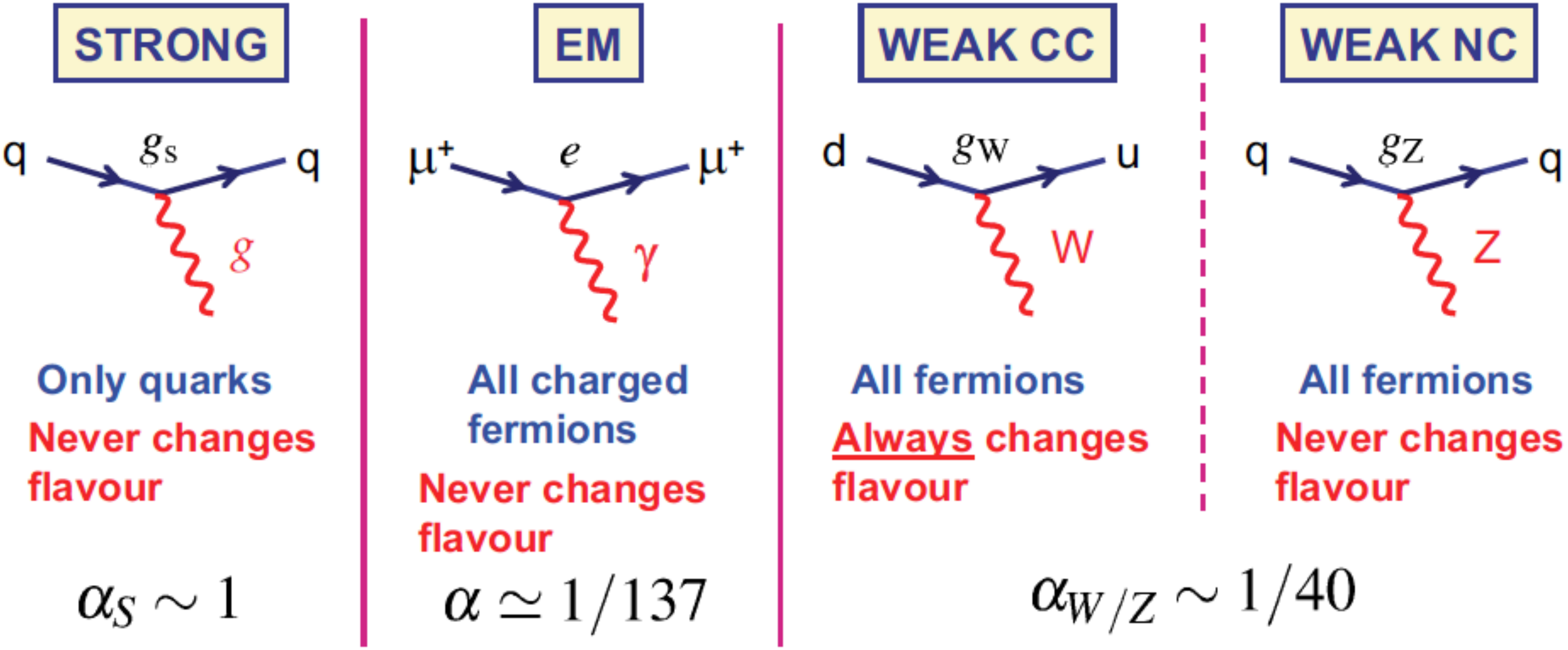

$n \rightarrow p\, e^- \,\bar{\nu}_e$
u
d
d
u
W^-
e^-
$\bar{\nu}_e$


Strong
+



Standard model interactions

The interaction of gauge bosons with fermions is (very) well described by the Standard Model



STRONG

Only quarks

Never changes flavour

$\alpha_S \sim 1$

EM

All charged fermions

Never changes flavour

$\alpha \simeq 1/137$

WEAK CC

All fermions

Always changes flavour

WEAK NC

All fermions

Never changes flavour

$\alpha_{W/Z} \sim 1/40$

Gluons
massless

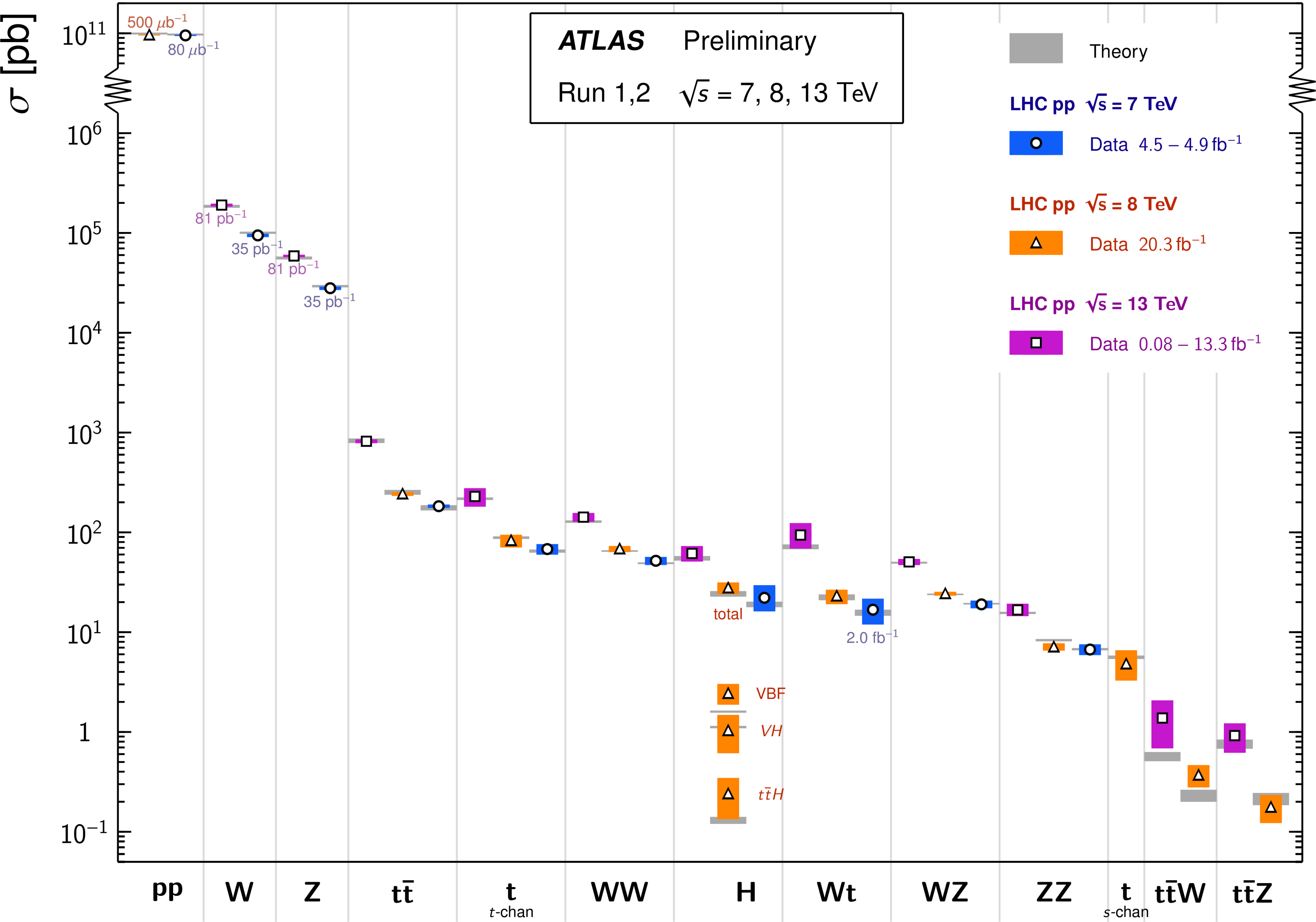
Photon
massless

W+, W-
very massive

Z^0
very massive

Standard Model Total Production Cross Section Measurements

Status: August 2016



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*)

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

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**

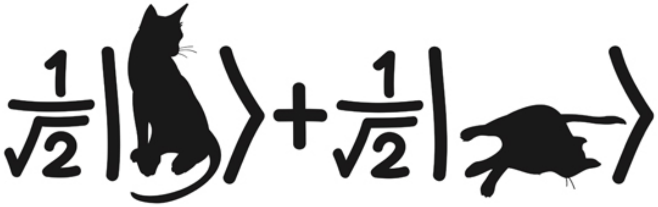
$$L(r,\phi,\dot{r},\dot{\phi}) = T - V = \tfrac{1}{2}m\dot{r}^2 + \tfrac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

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...



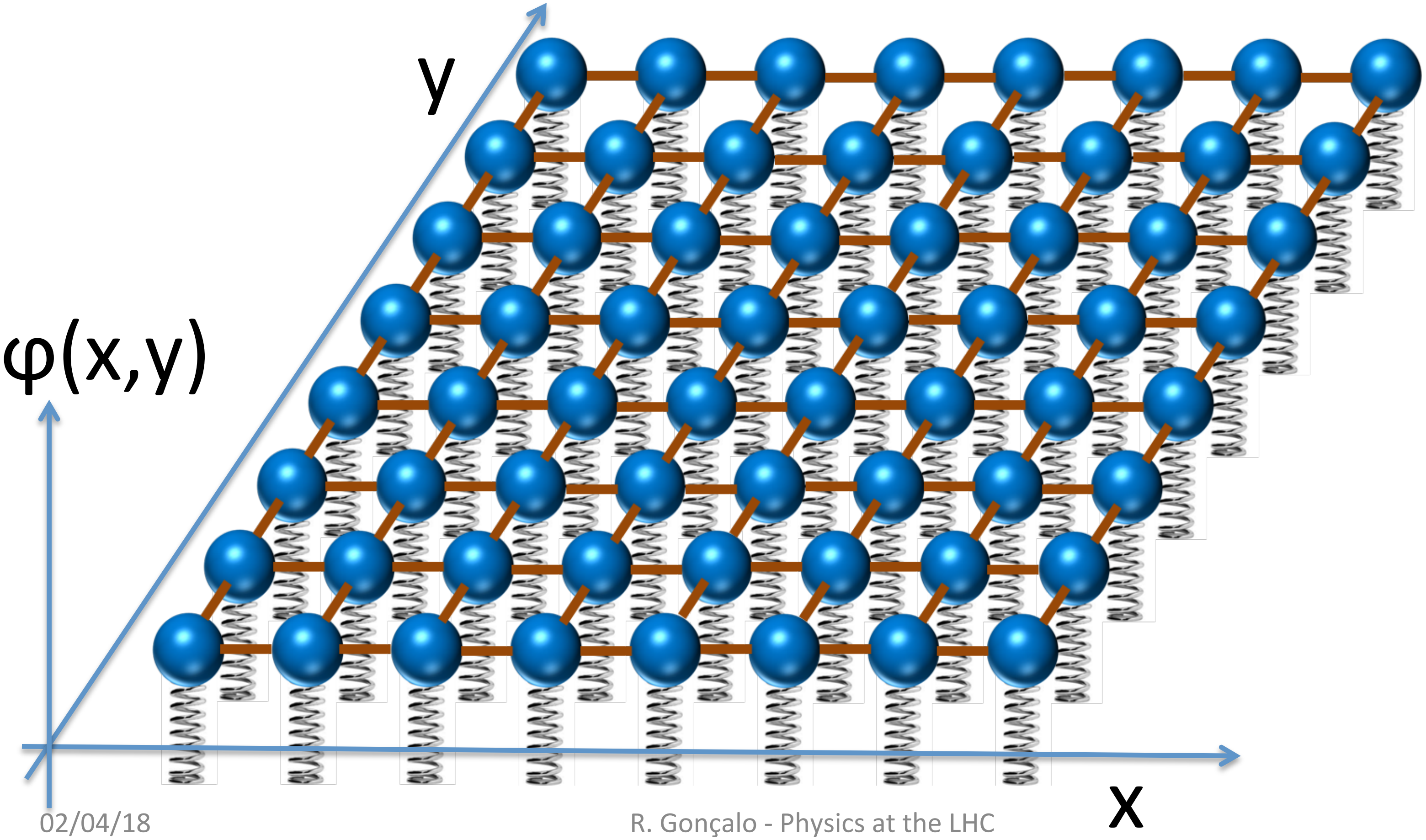
Richard Feynman
(1918 - 1988)

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:

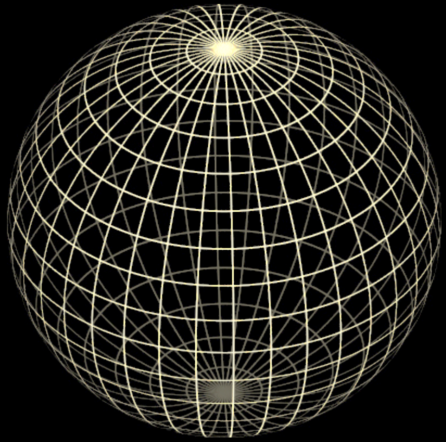
$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi}\psi(x)$$

Where **χ** is a constant

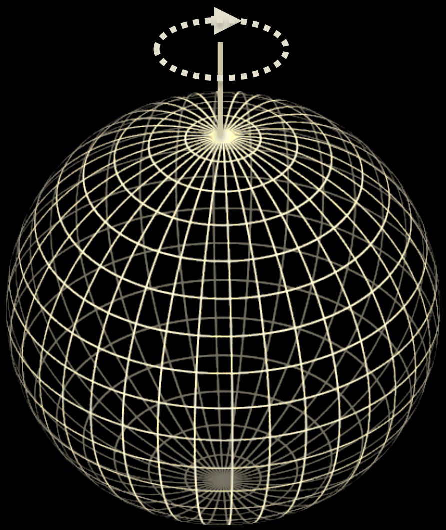
$$\mathcal{L}' = e^{-iq\chi}e^{iq\chi}(i\hbar\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi) = \mathcal{L}$$

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

Original sphere

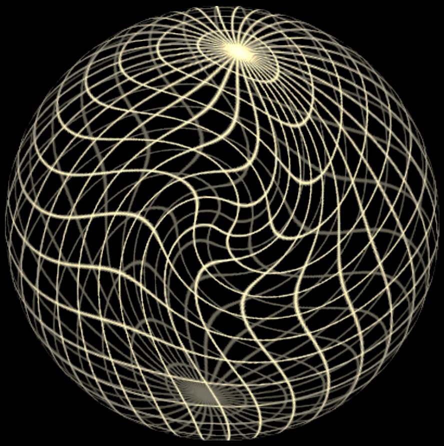


Global transformation



χ = constant

Local transformação



$\chi = \chi(x)$

Local gauge invariance and interactions

If **$\chi = \chi$** (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:

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

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…

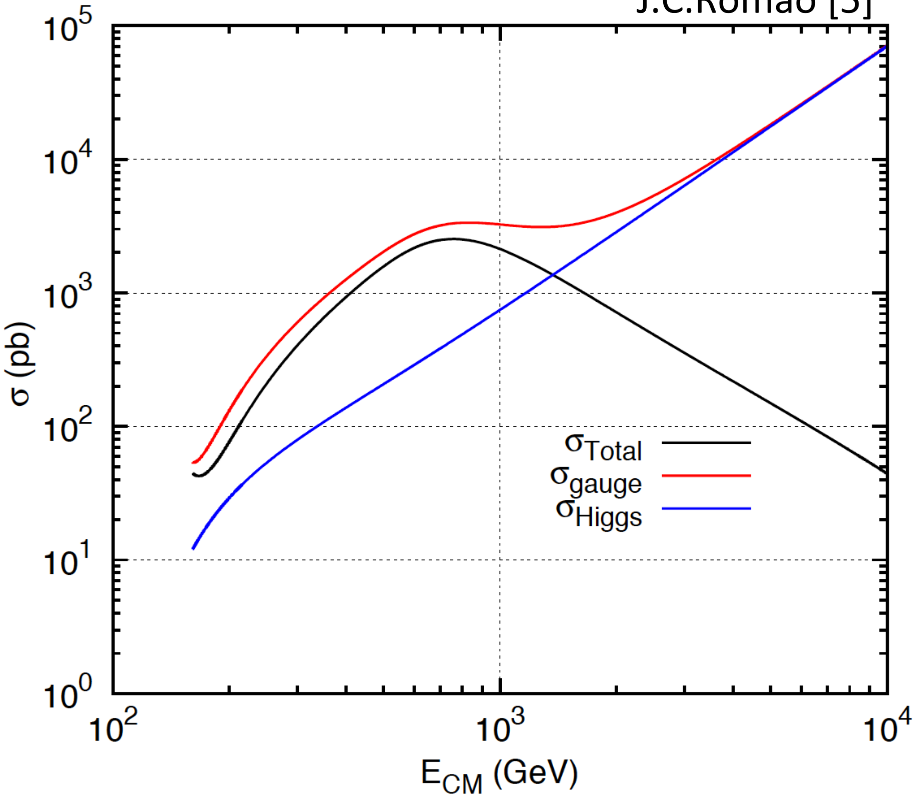
Now for the problems...

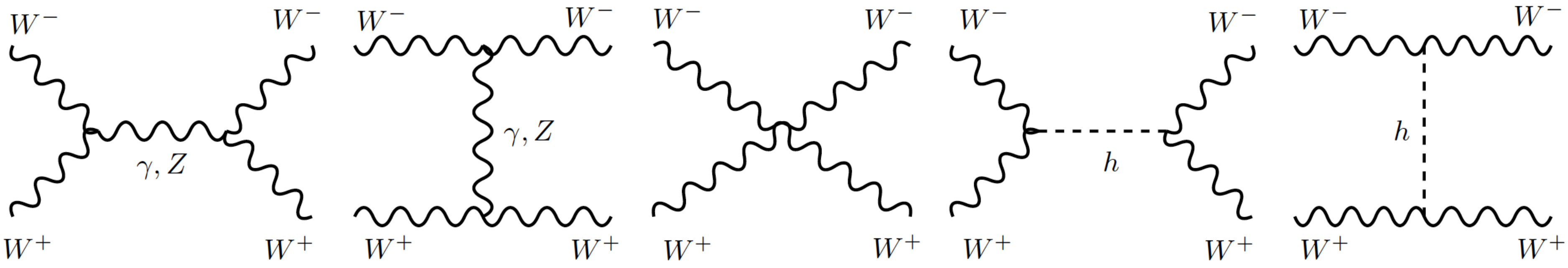
1: Longitudinal gauge-boson scattering

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]





Feynman diagrams contributing to longitudinal WW scattering

2: 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:

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

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

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

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

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

The Higgs Mechanism

Robert Brout (1928 – 2011

Peter Higgs (b. 1929)

François Englert
(b. 1932)

- 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

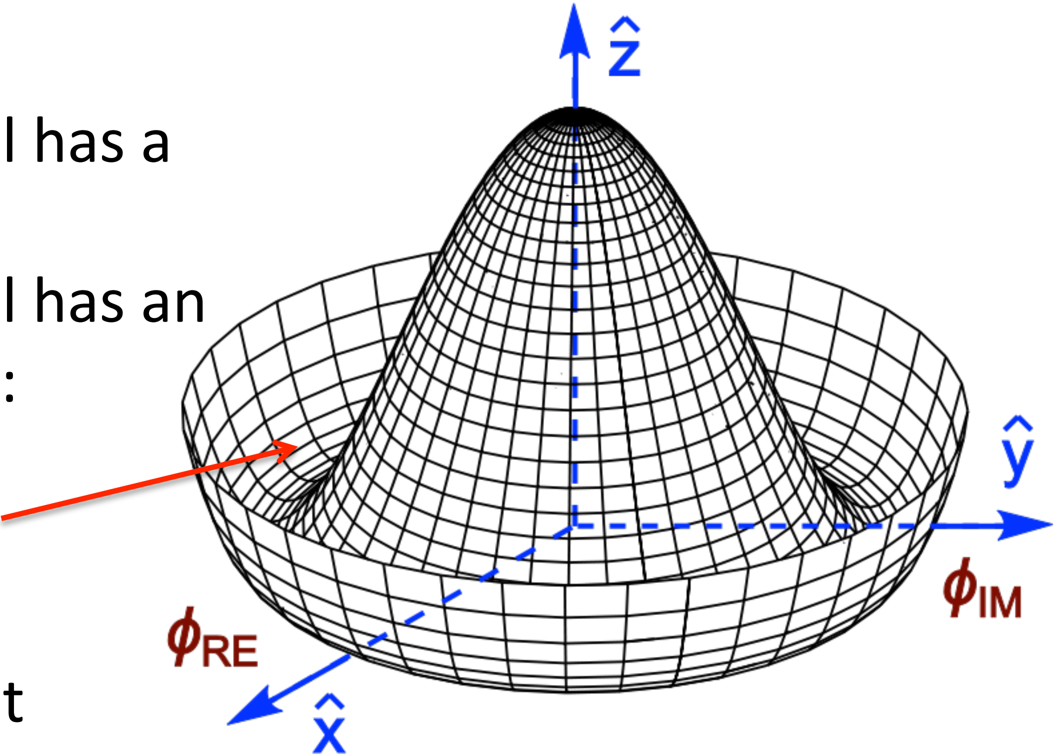
$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

- With a potential

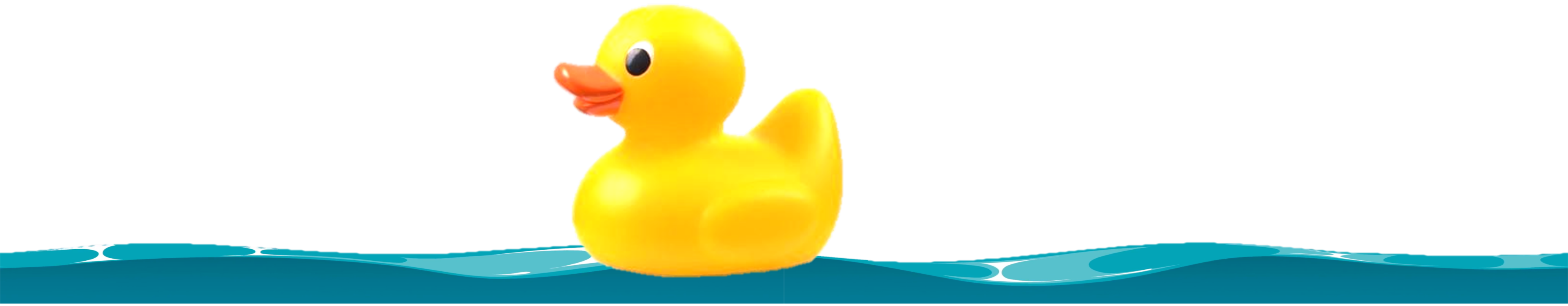
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

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

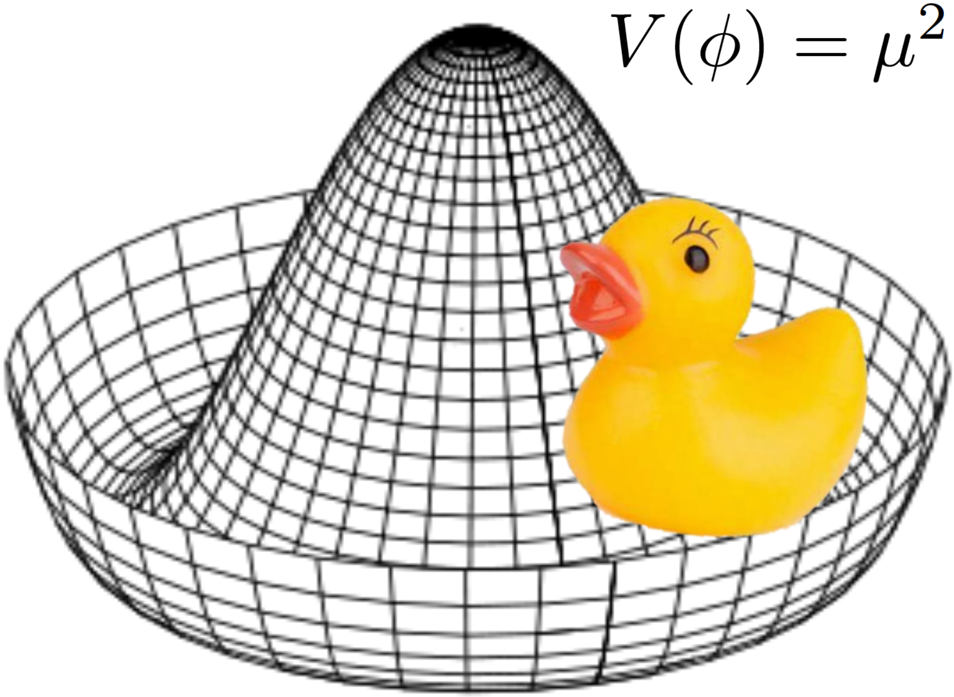
$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$



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



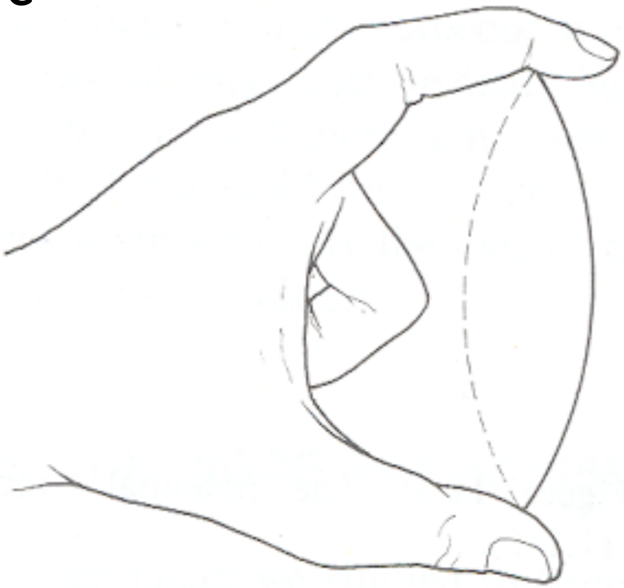
$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$



Electroweak symmetry breaking

- In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass

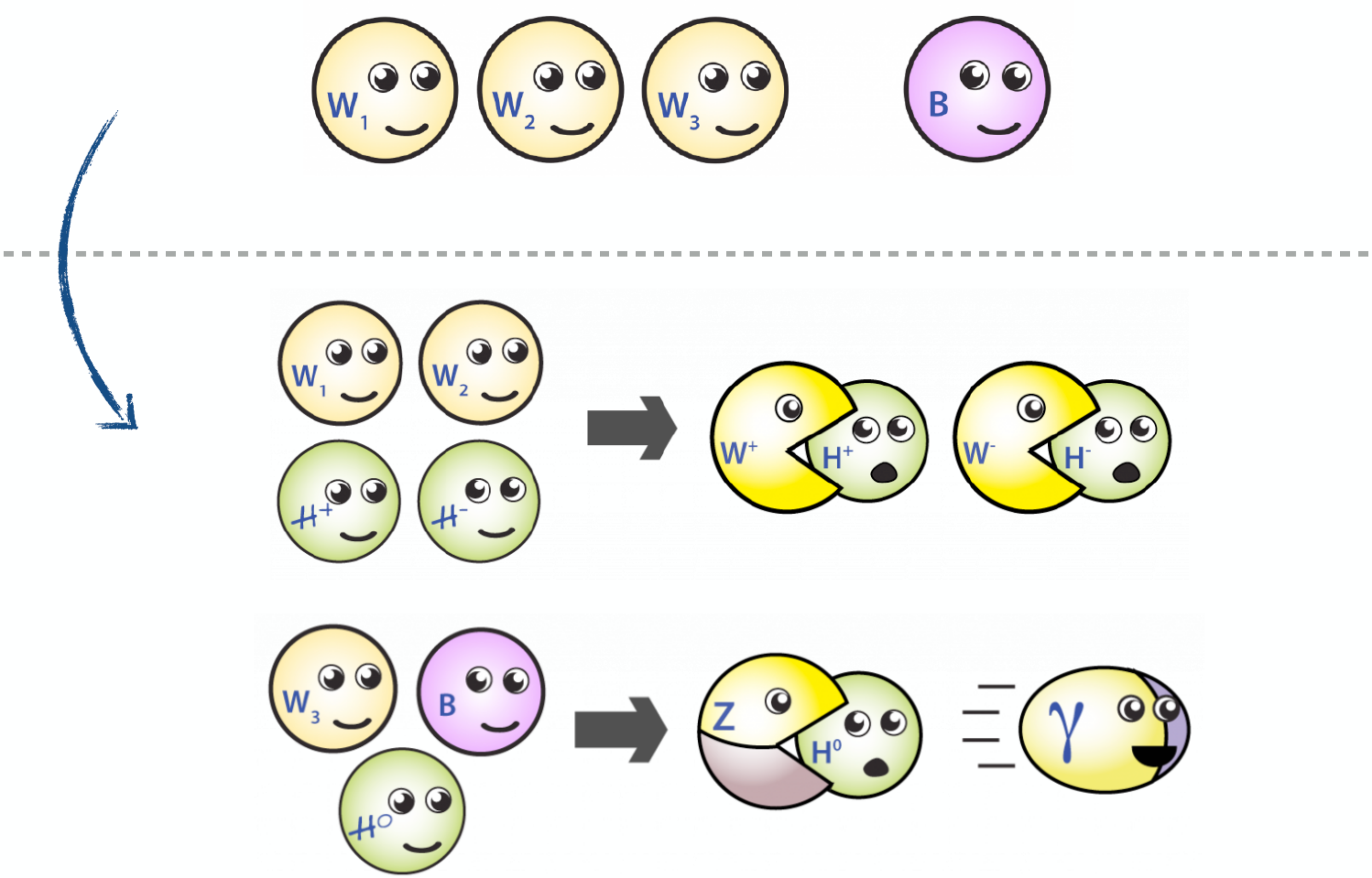
- Electroweak symmetry is broken:
  - Photon does not have mass
  - W, Z have a large mass



- Higgs mechanism: mass of W and Z results from the Higgs mechanism
- Masses of fermions come from a direct interaction with the Higgs field

see J.Varela's lecture

EWK Symmetry Breaking in Pictures



- We have at this point a massive scalar field with vacuum expectation value ***v*** and mass

$$m_h = \sqrt{2\lambda} v$$

- 4 gauge fields: $W^{(1)}$, $W^{(2)}$, $W^{(3)}$, and $B^{(1)}$ which transform to give the massive W^+, W^- and Z, and massless A (the photon)

$$m_W = \tfrac{1}{2} g_W v$$

$$m_A = 0 \qquad\qquad \Leftrightarrow v = 246\mathrm{GeV}$$

$$m_Z = \tfrac{1}{2} v \sqrt{g_W^2 + g^2}$$

with g, g_W the couplings of electromagnetic and weak forces

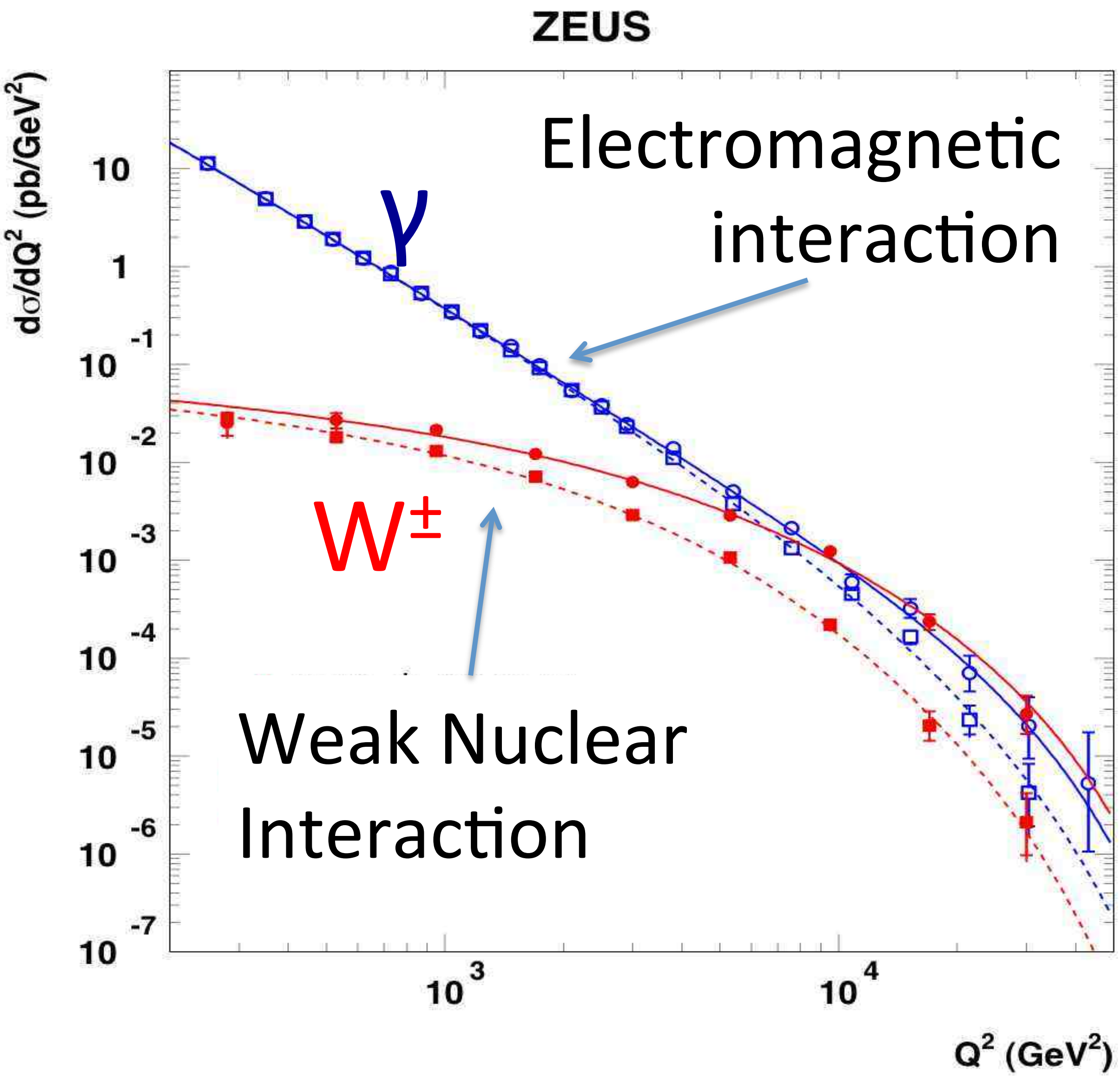
- Defining the Weinberg angle as

$$\frac{g}{g_W} = \tan\theta_W$$

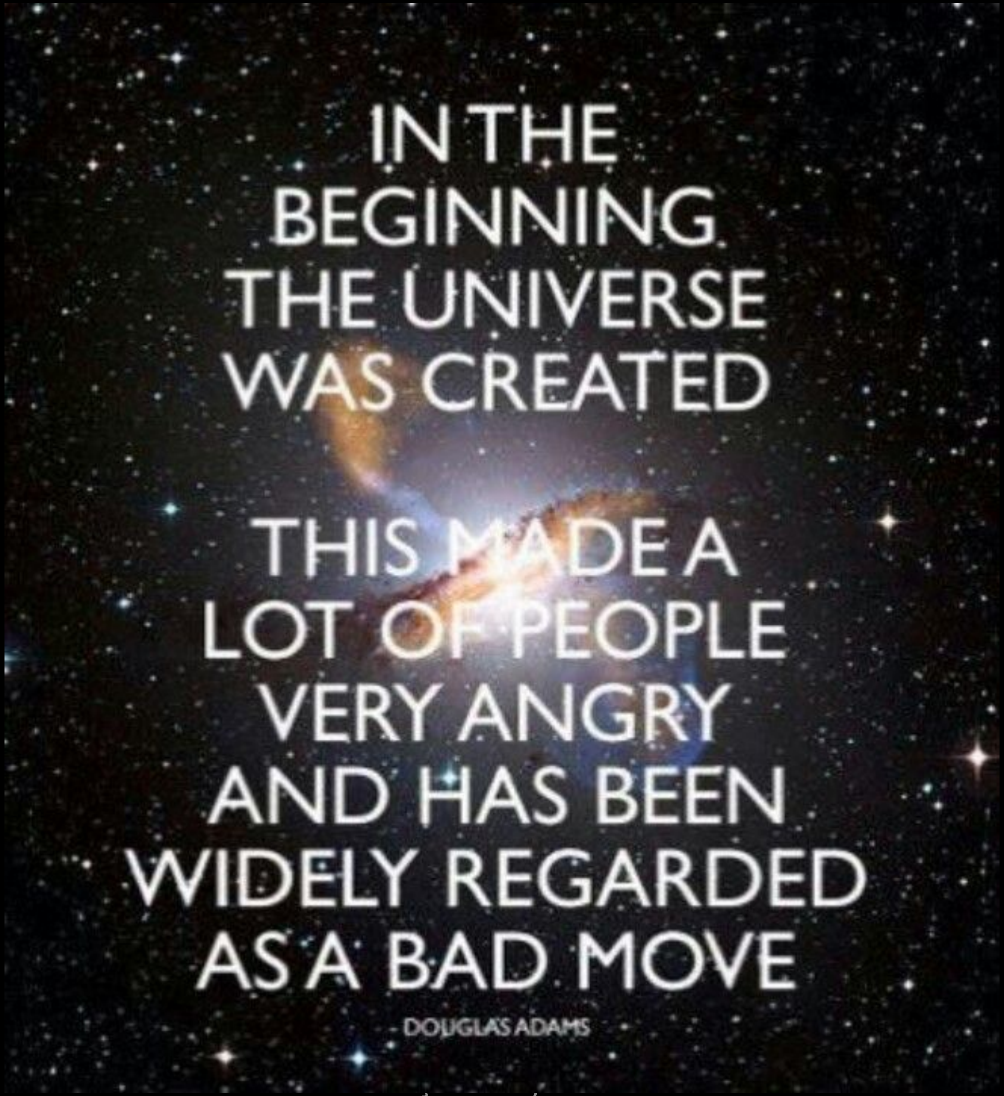
we also get the relation between the masses of W and Z

$$\frac{m_W}{m_Z} = \cos\theta_W$$

- Fermions get their masses from interaction terms with the Higgs field (Yukawa coupling)


ZEUS
dσ/dQ² (pb/GeV²)
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10³
10⁴
Q² (GeV²)
γ
W±
Electromagnetic interaction
Weak Nuclear Interaction

The Story So Far...

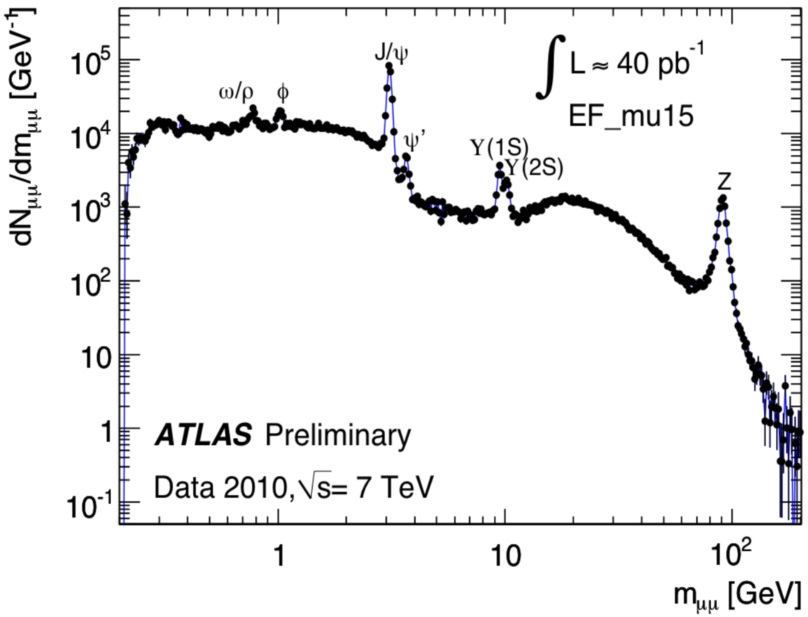


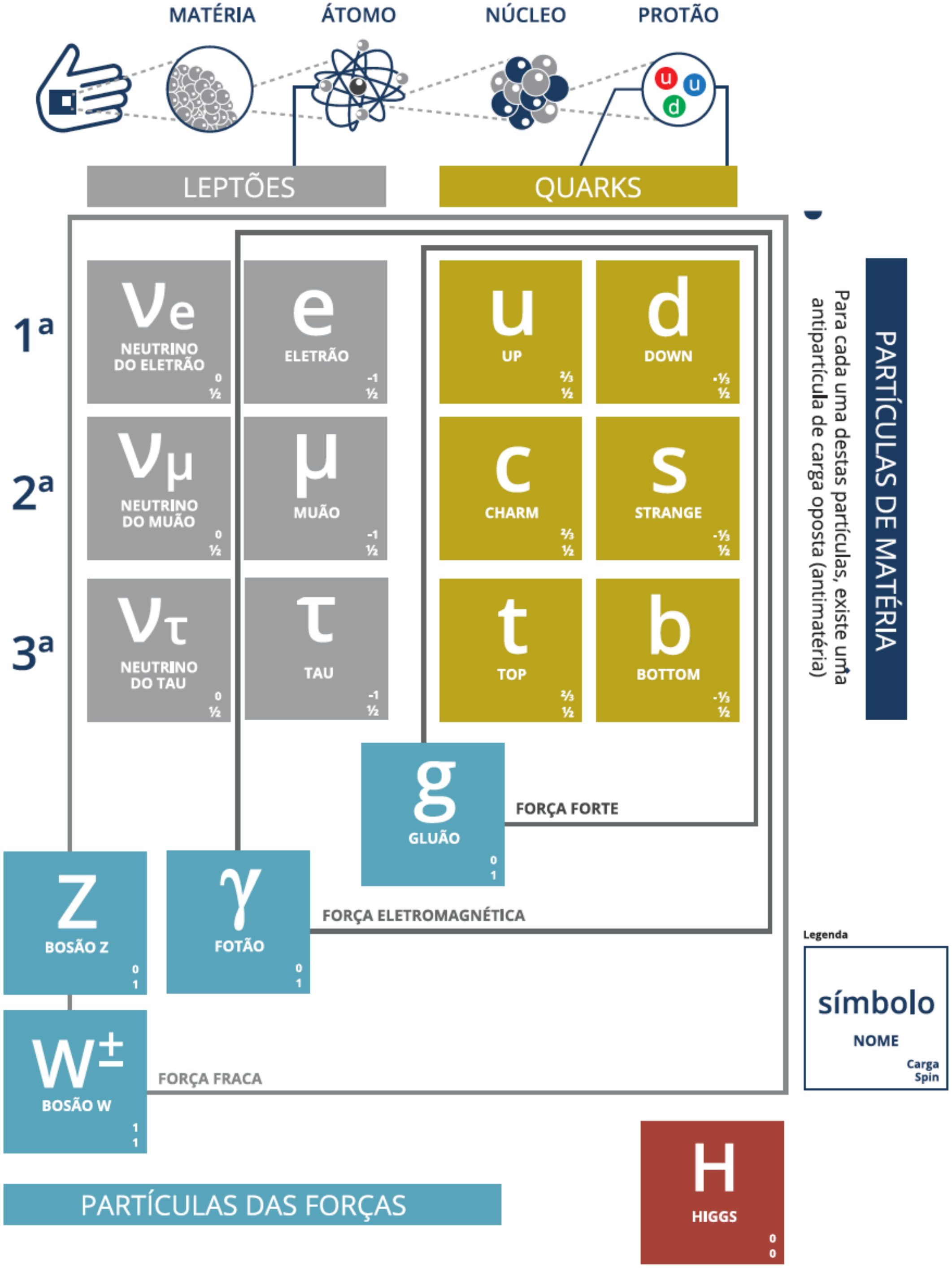
IN THE
BEGINNING
THE UNIVERSE
WAS CREATED

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





LEPTÕES

QUARKS

1ª
2ª
3ª

νe NEUTRINO DO ELETRÃO 0 ½

e ELETRÃO -1 ½

u UP ⅔ ½

d DOWN -⅓ ½

νμ NEUTRINO DO MUÃO 0 ½

μ MUÃO -1 ½

c CHARM ⅔ ½

s STRANGE -⅓ ½

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

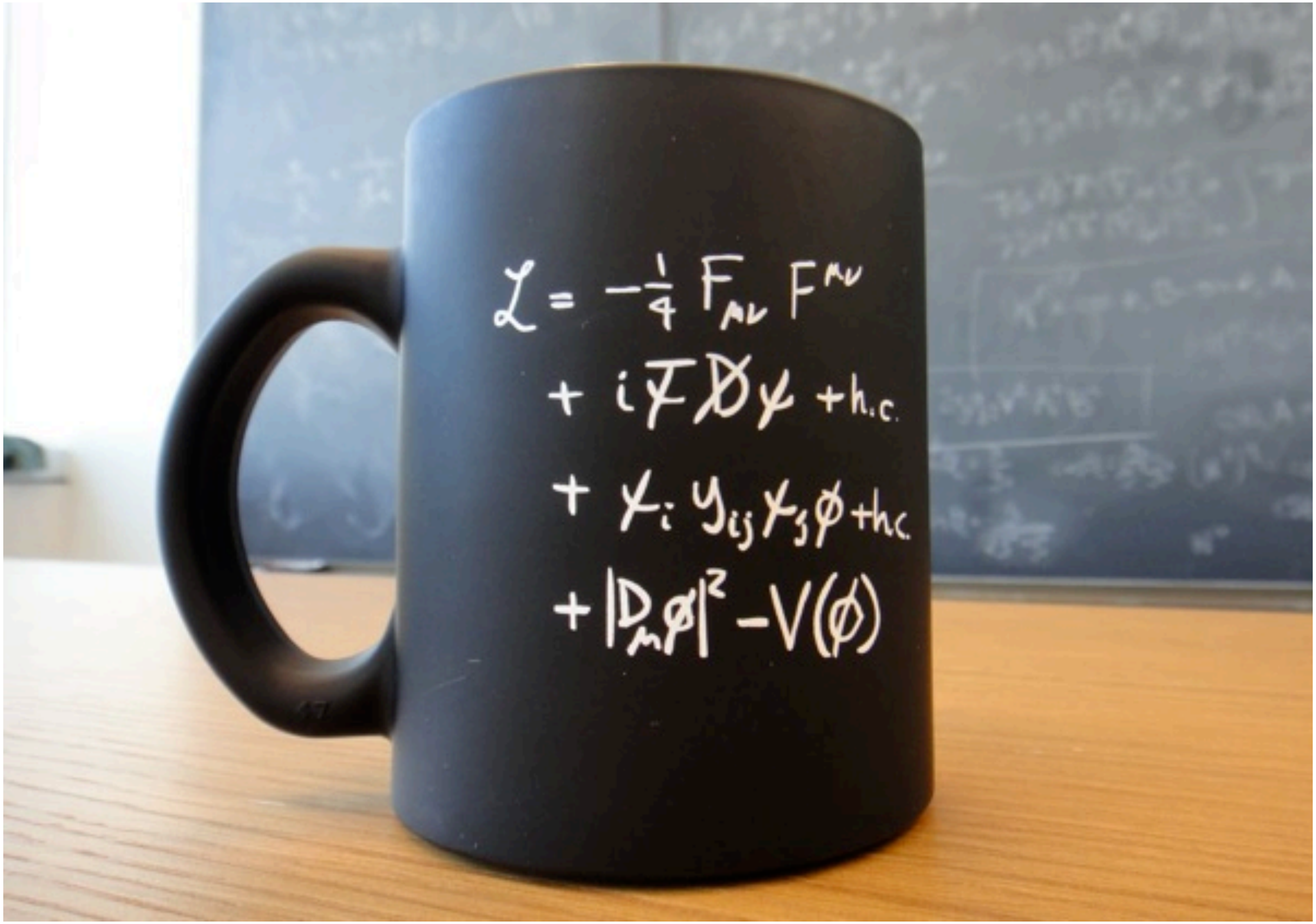
H HIGGS 0 0

PARTÍCULAS DE MATÉRIA

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

Legenda

símbolo
NOME
Carga
Spin


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

What we think we know:

- Higgs mass (was) the only unknown parameter

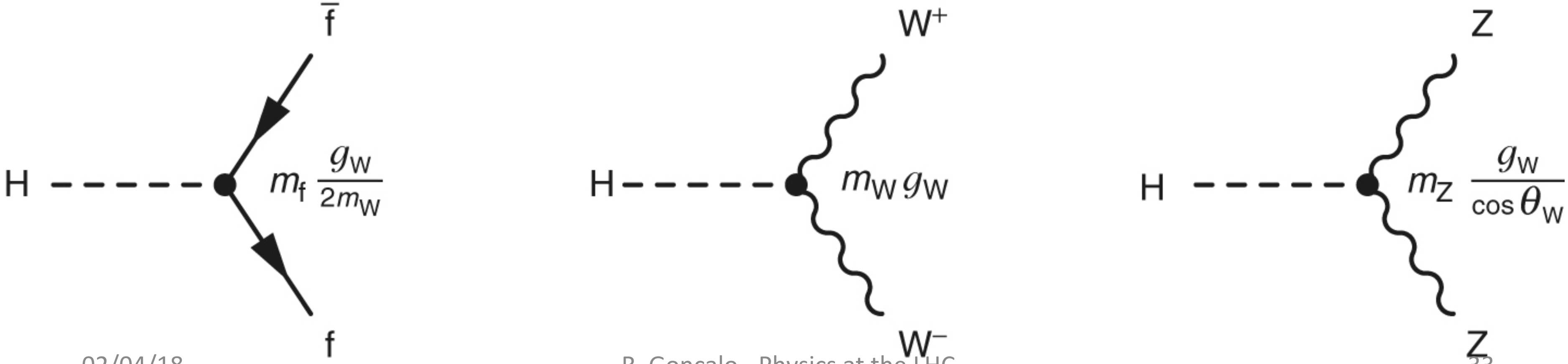
$$m_h = \sqrt{2\lambda}v$$

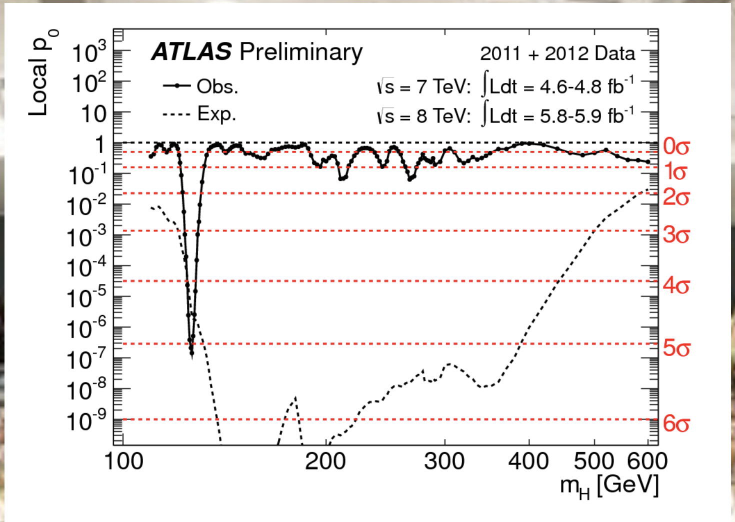
- We can give mass to W± and Z while keeping the photon massless
- Relation between masses of W and Z

$$\frac{m_W}{m_Z} = \cos\theta_W$$

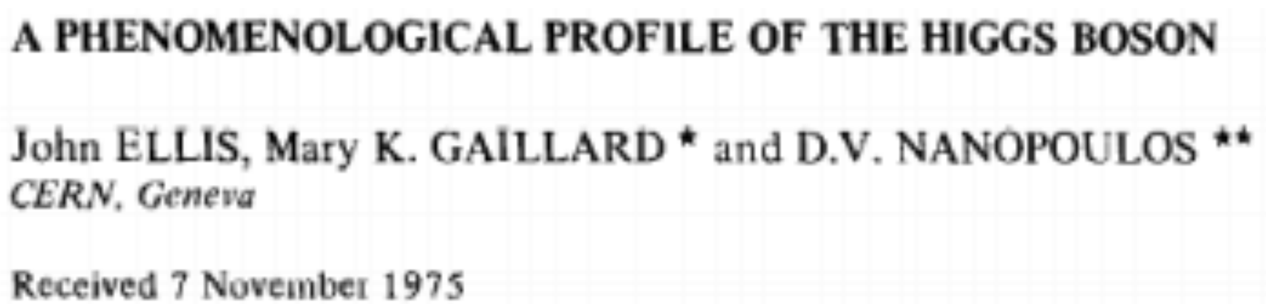
- Higgs couples to W and Z with strengths proportional to their masses
- Higgs couples to all fermions with a strength proportional to their mass

$$g_f = \sqrt{2}\frac{m_f}{v}$$





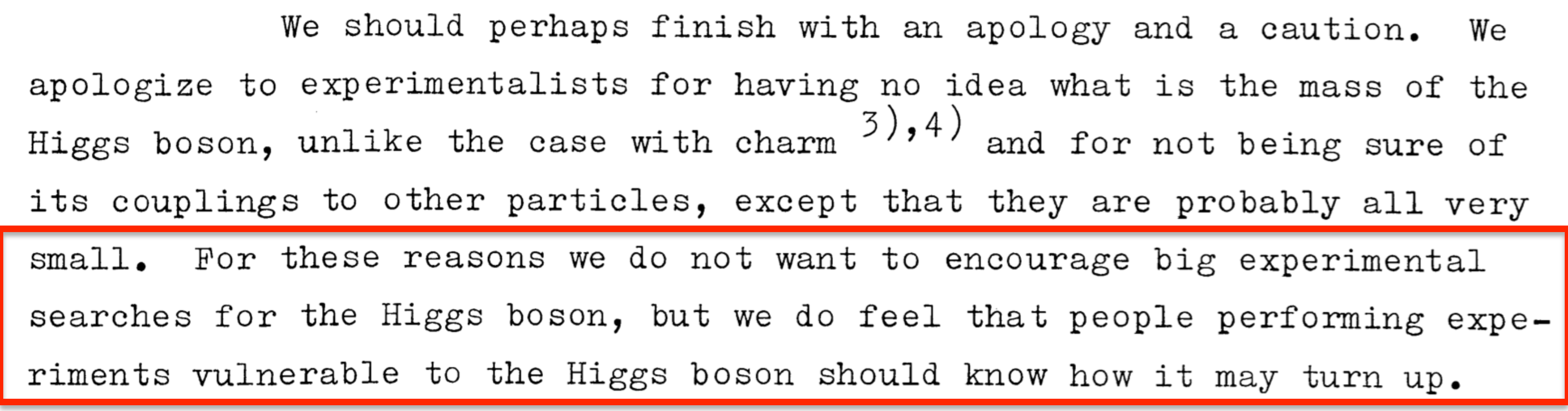
The Long Way to Discovery



A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

Received 7 November 1975



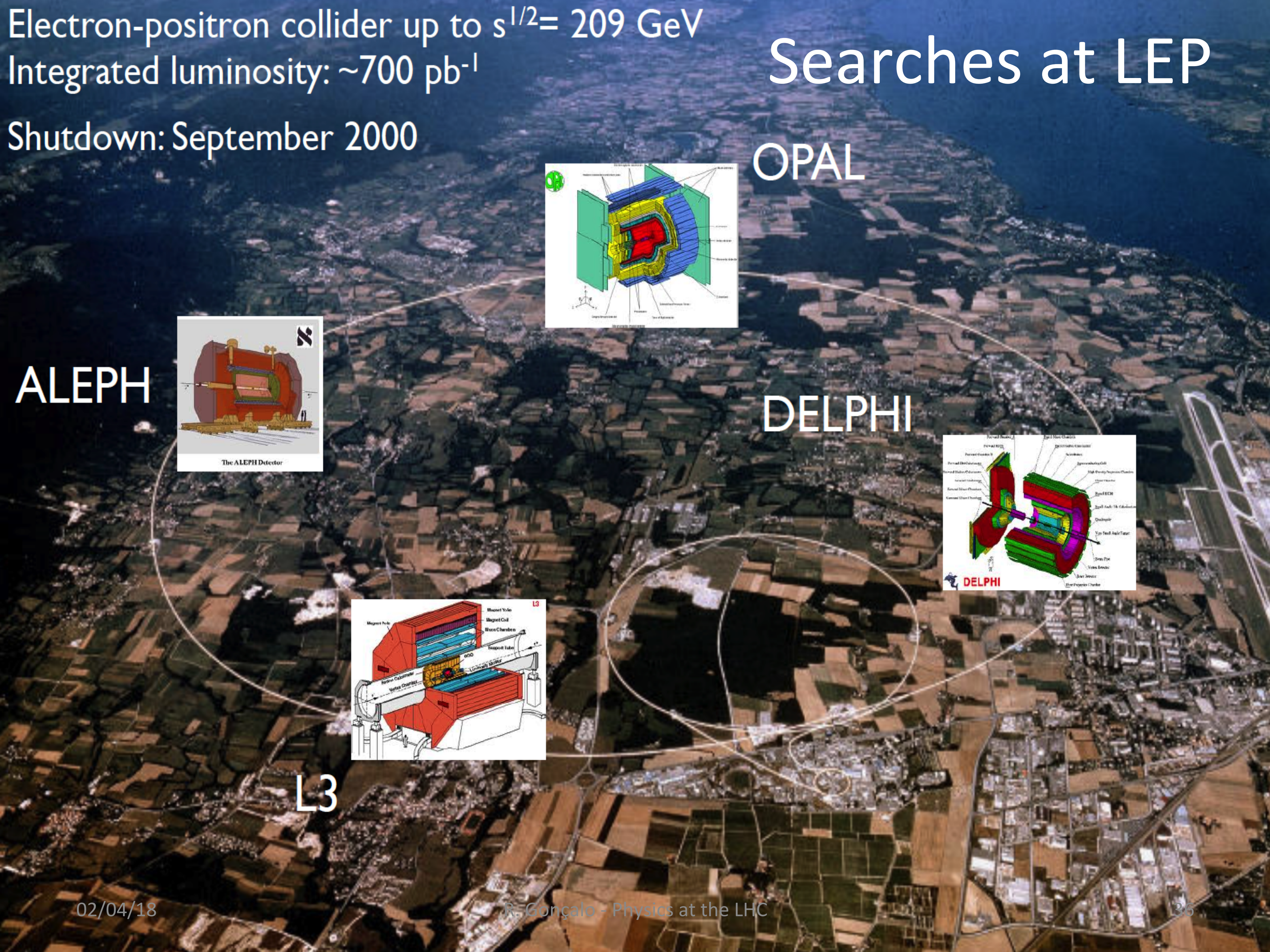
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm 3),4) and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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}

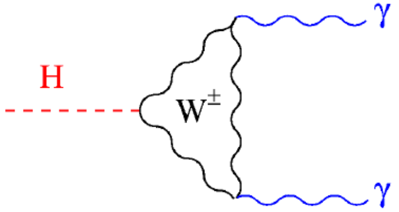
Shutdown: September 2000



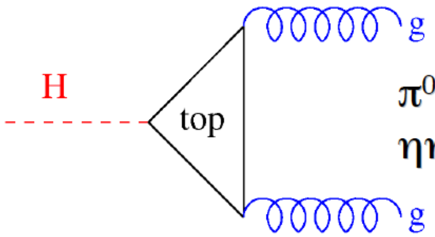
Low-mass searches at LEP

The decay branching ratios depend only on m_H:

- $m_H < 2m_e$: $H \rightarrow \gamma\gamma$ + large lifetime;



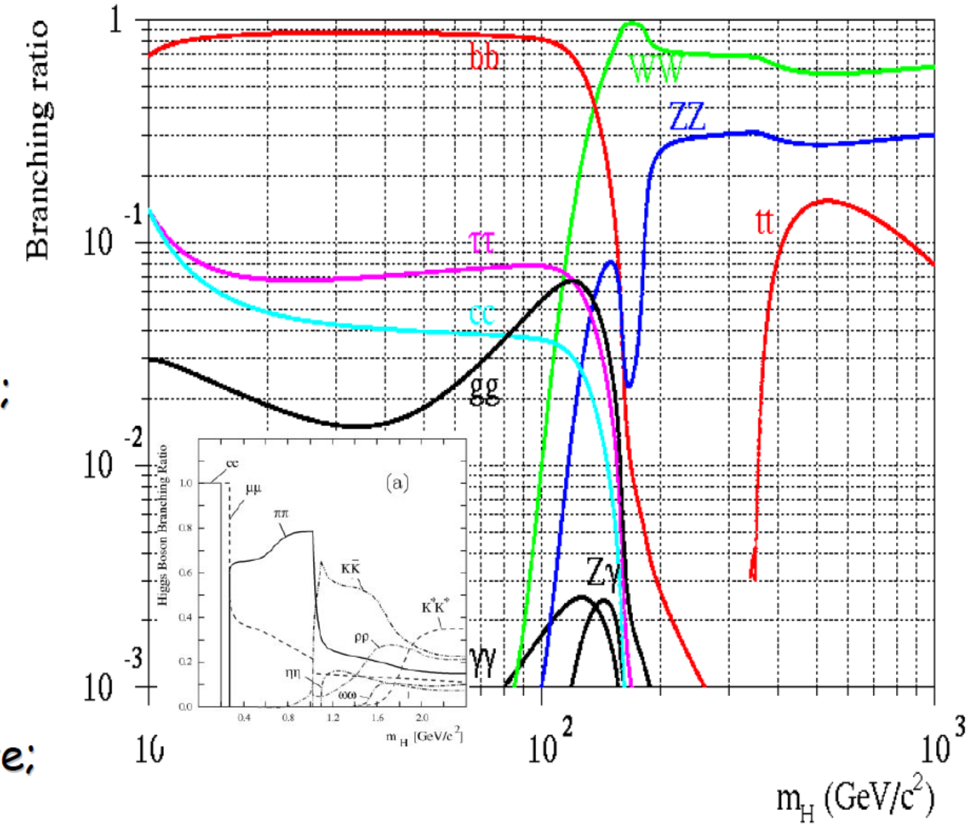
- $m_H < 2m_\mu$: $H \rightarrow e^+e^-$ dominates;
- $m_H < 2m_\pi$: $H \rightarrow \mu^+\mu^-$ dominates;
- $m_H < 3 - 4$ GeV: $H \rightarrow gg$ dominates;



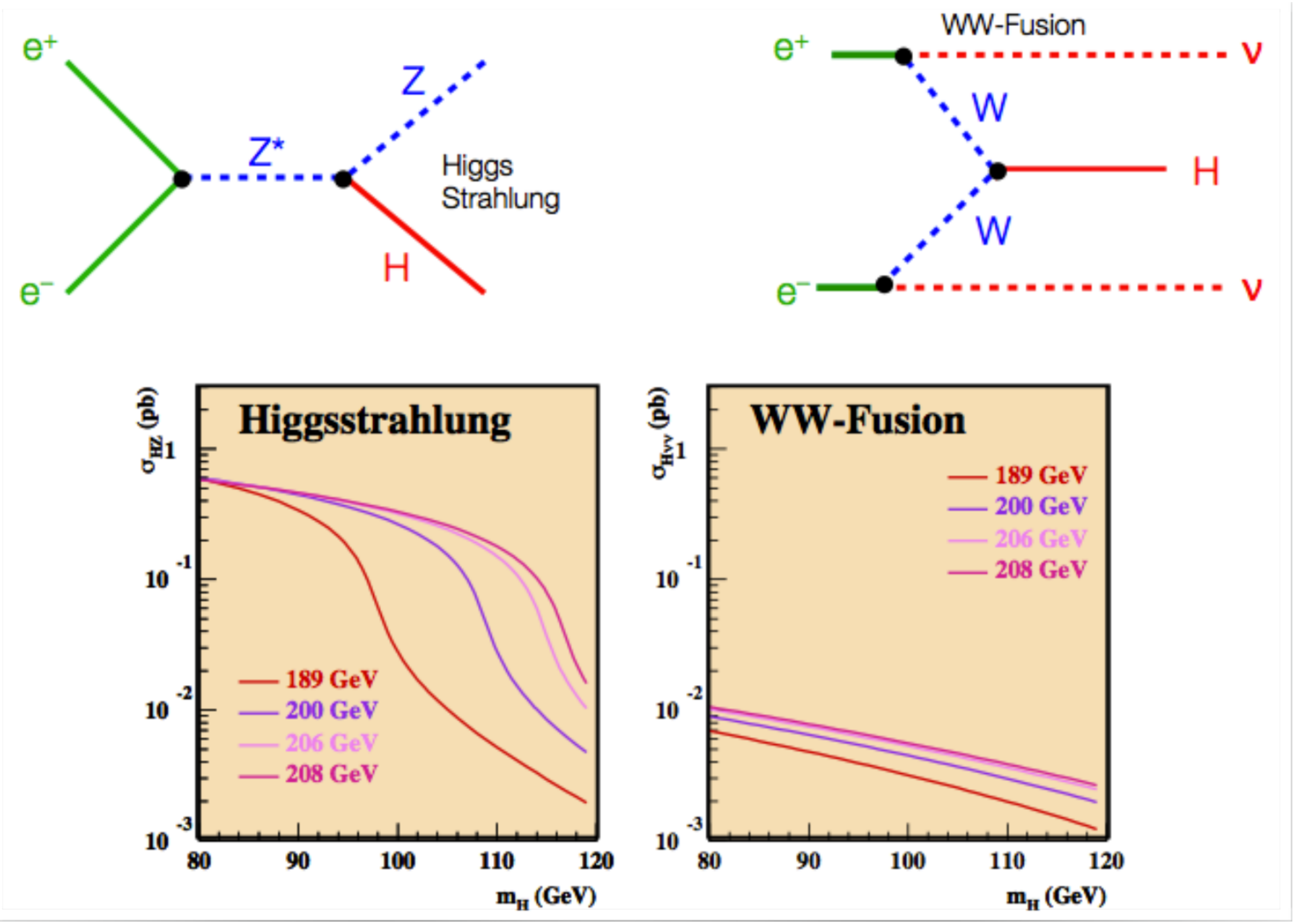
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, … etc

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

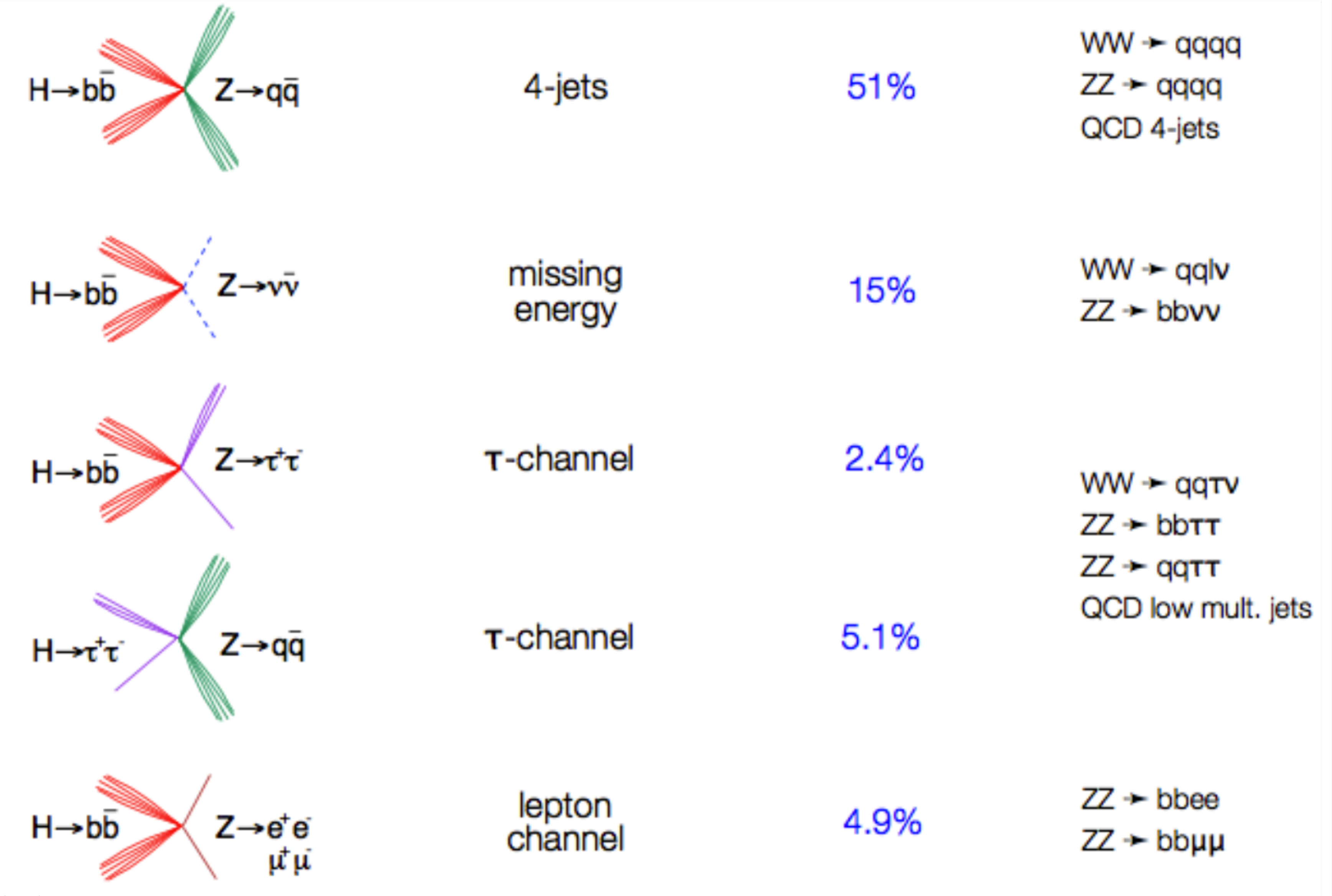
- $m_H > 2m_b$ up to 1000 GeV/c^2:



Higher-mass Higgs production at LEP



Higgs decays: focus on 3rd generation



$H \to b\bar{b}$ $Z \to q\bar{q}$	4-jets	51%	WW → qqqq ZZ → qqqq QCD 4-jets
$H \to b\bar{b}$ $Z \to \nu\bar{\nu}$	missing energy	15%	WW → qqlν ZZ → bbνν
$H \to b\bar{b}$ $Z \to \tau^+\tau^-$	τ-channel	2.4%	WW → qqτν ZZ → bbττ ZZ → qqττ QCD low mult. jets
$H \to \tau^+\tau^-$ $Z \to q\bar{q}$	τ-channel	5.1%	
$H \to b\bar{b}$ $Z \to e^+e^-$ $\mu^+\mu^-$	lepton channel	4.9%	ZZ → bbee ZZ → bbμμ

Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

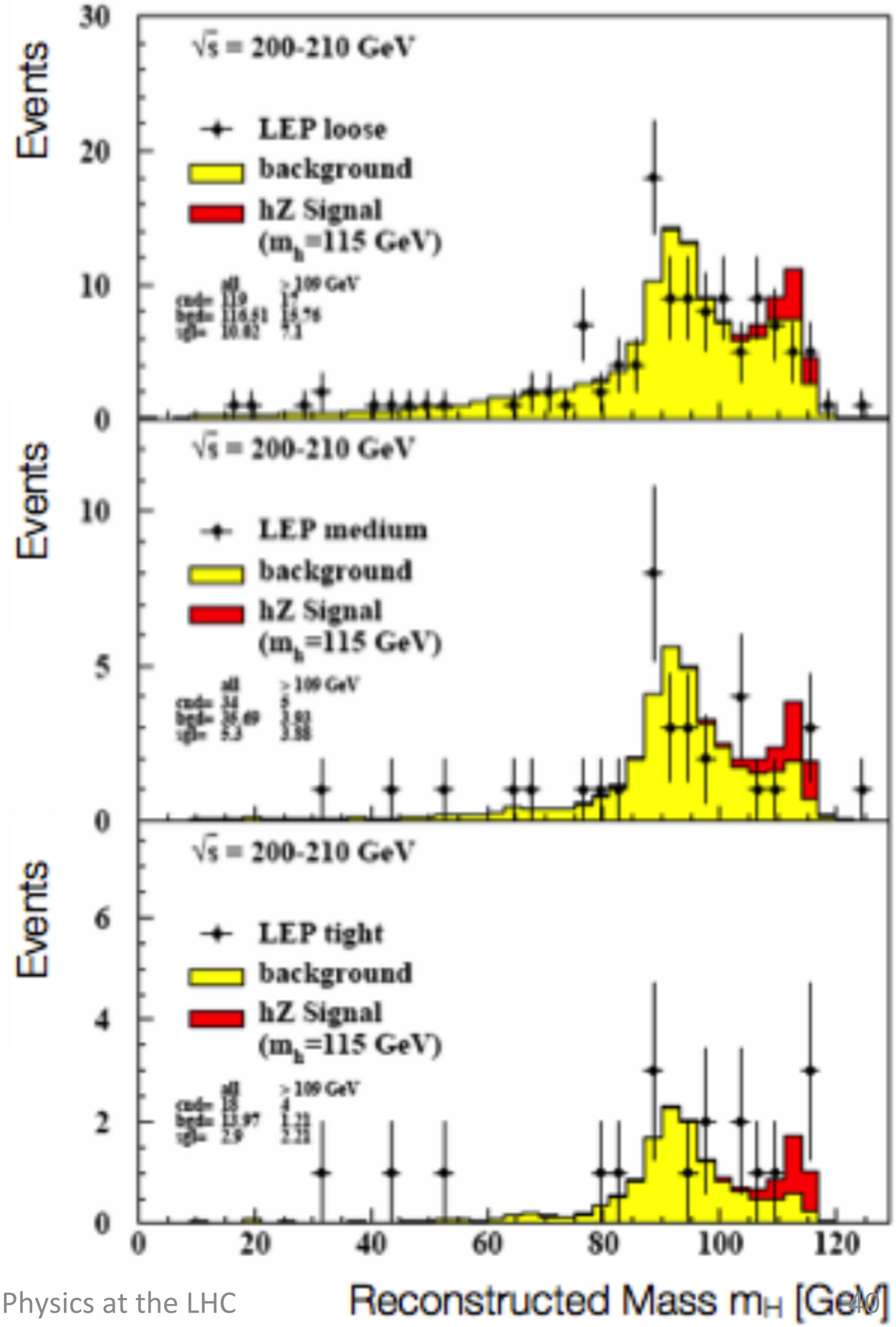
Expectation for m_H=115 GeV

- 8.4 events

Corresponding excess was not observed

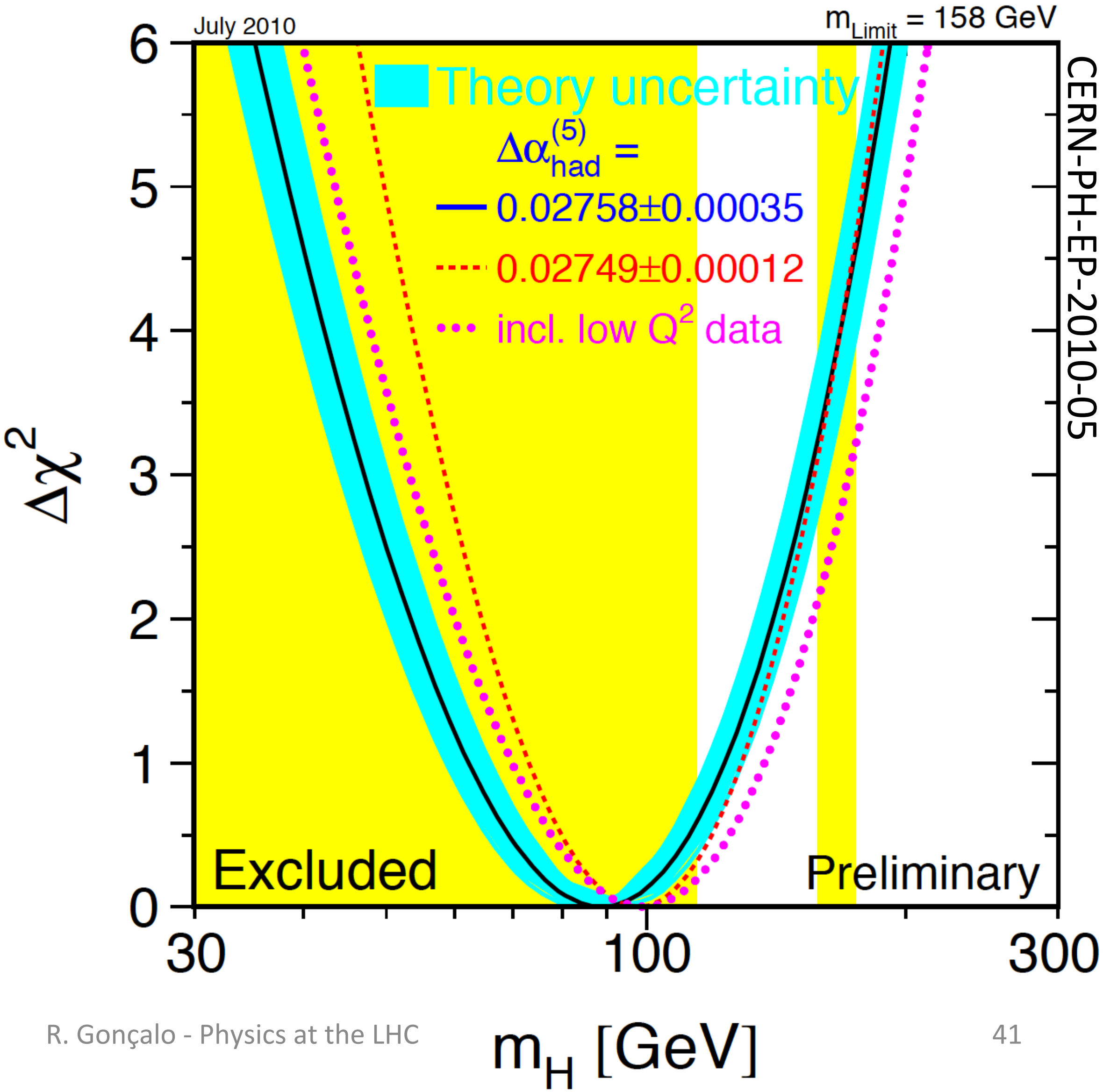
Final verdict from LEP

m_H>114.4 GeV @ 95% CL

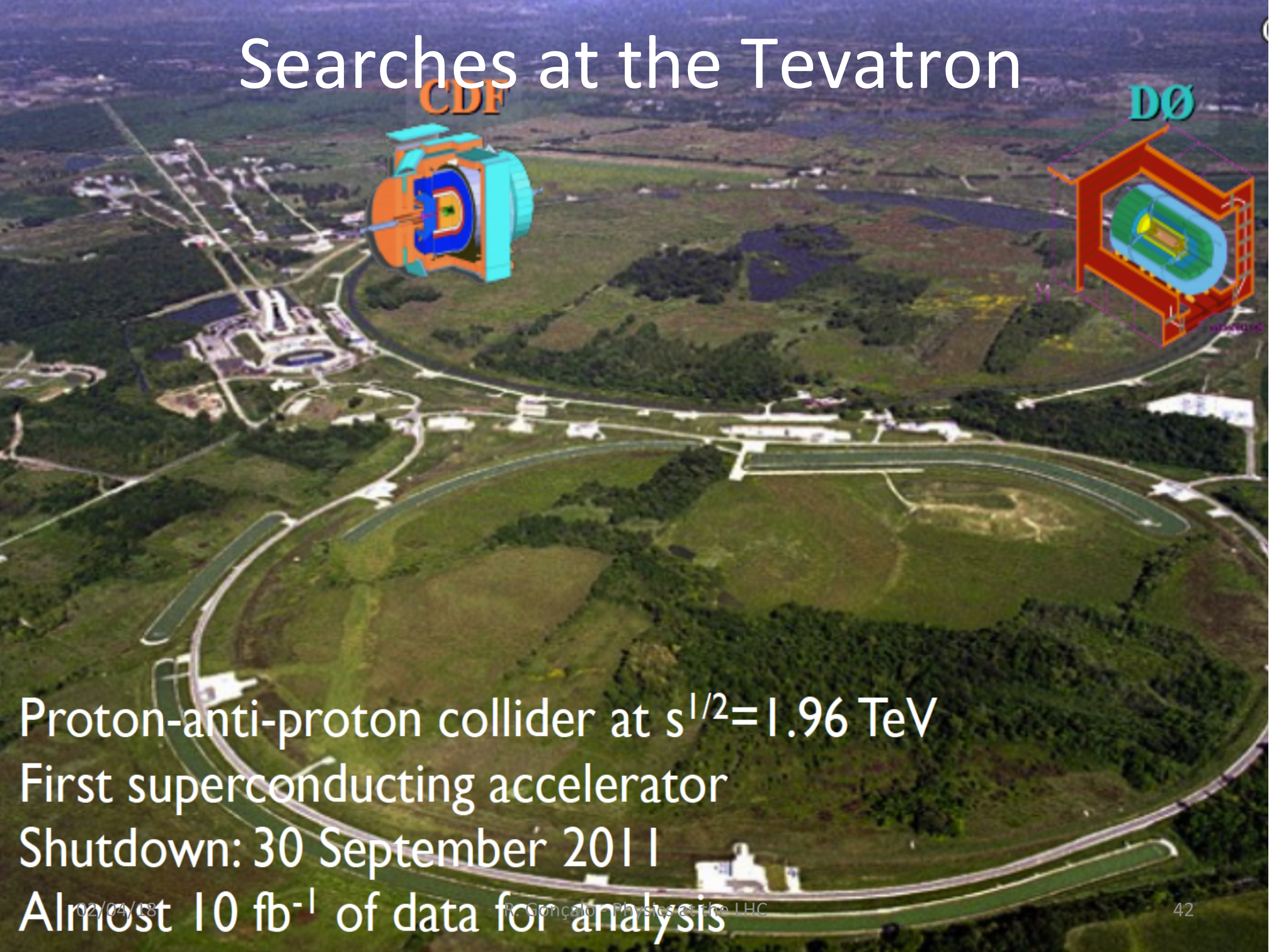


LEP’s Final Legacy: the Blue Band Plot

- 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



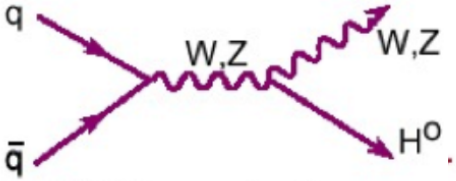
Proton-anti-proton collider at $s^{1/2}$=1.96 TeV

First superconducting accelerator

Shutdown: 30 September 2011

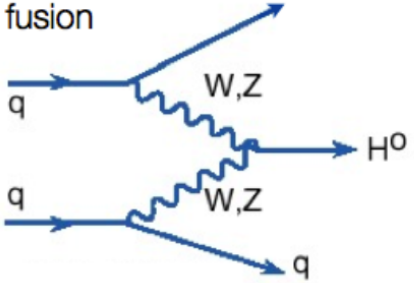
Almost 10 fb^{-1} of data for analysis

Higgs production at the Tevatron



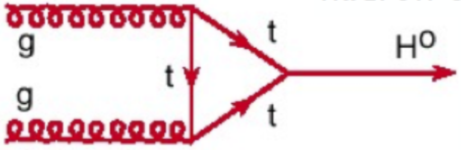
Associated production

Vector boson fusion

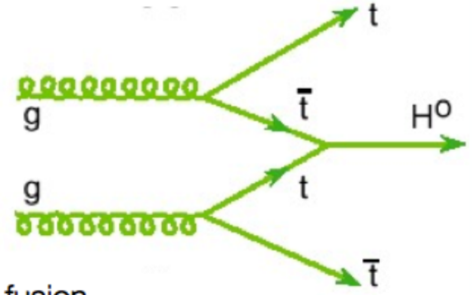


← (fermion annihilation and vector boson scattering)

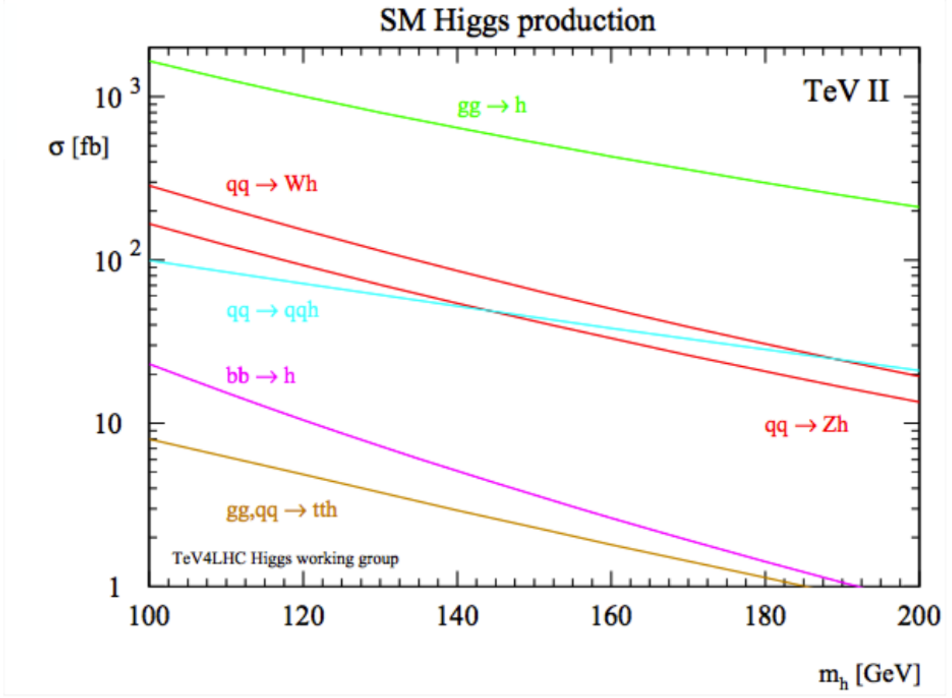
Gluon fusion



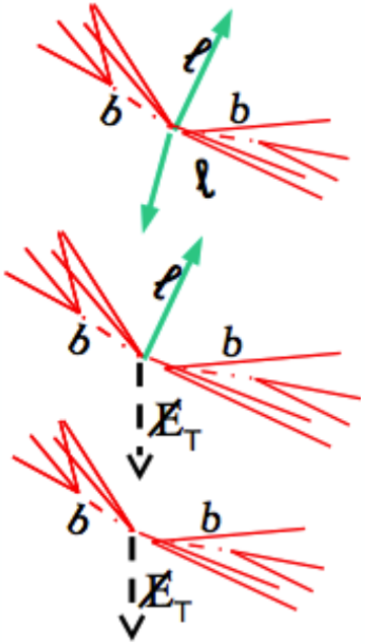
← Only available at hadron colliders

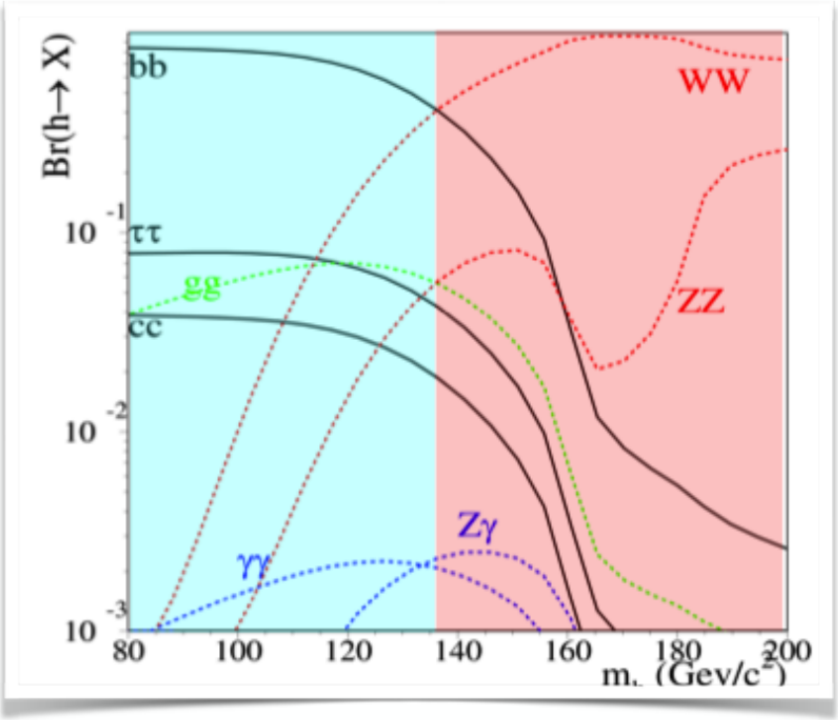


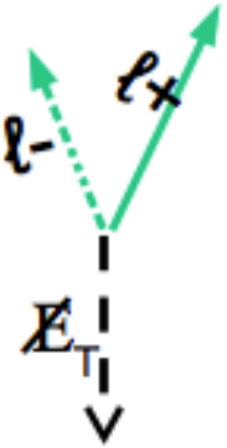
$t\bar{t}$-fusion



Most sensitive searches





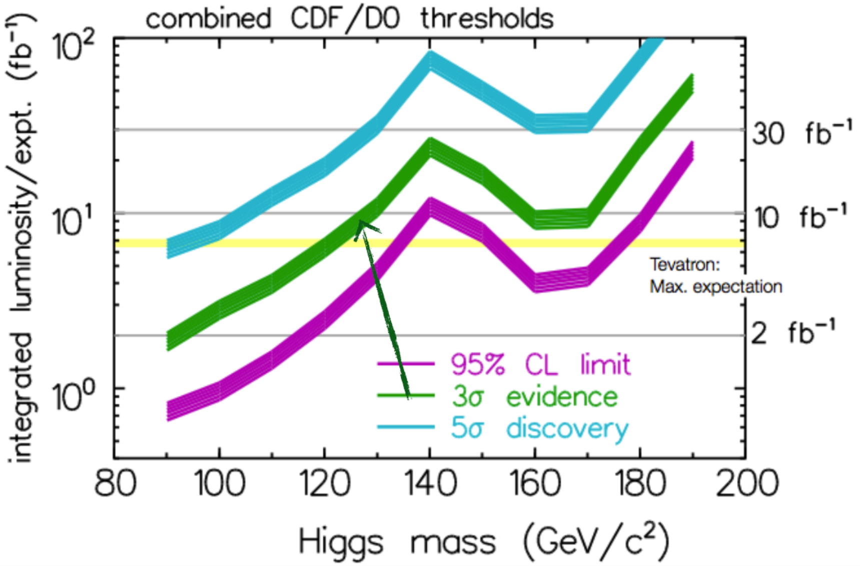


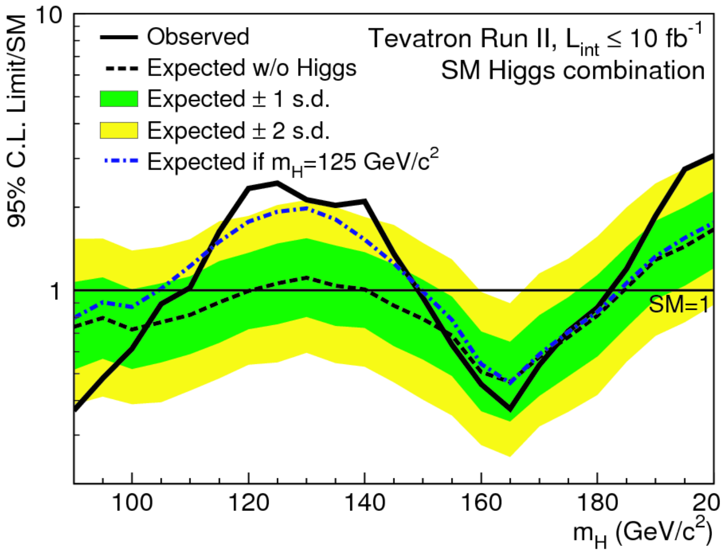
- At **low mass use h→bb final states**
  - associated production with W or Z
  - challenging: b-tagging, jet resolution
  - backgrounds: top, W/Z+heavy flavour di-bosons

- At **high mass use H→WW final states**
  - benefit from high gluon-gluon cross section
  - challenging: lepton acceptance, missing energy
  - backgrounds: top, di-bosons

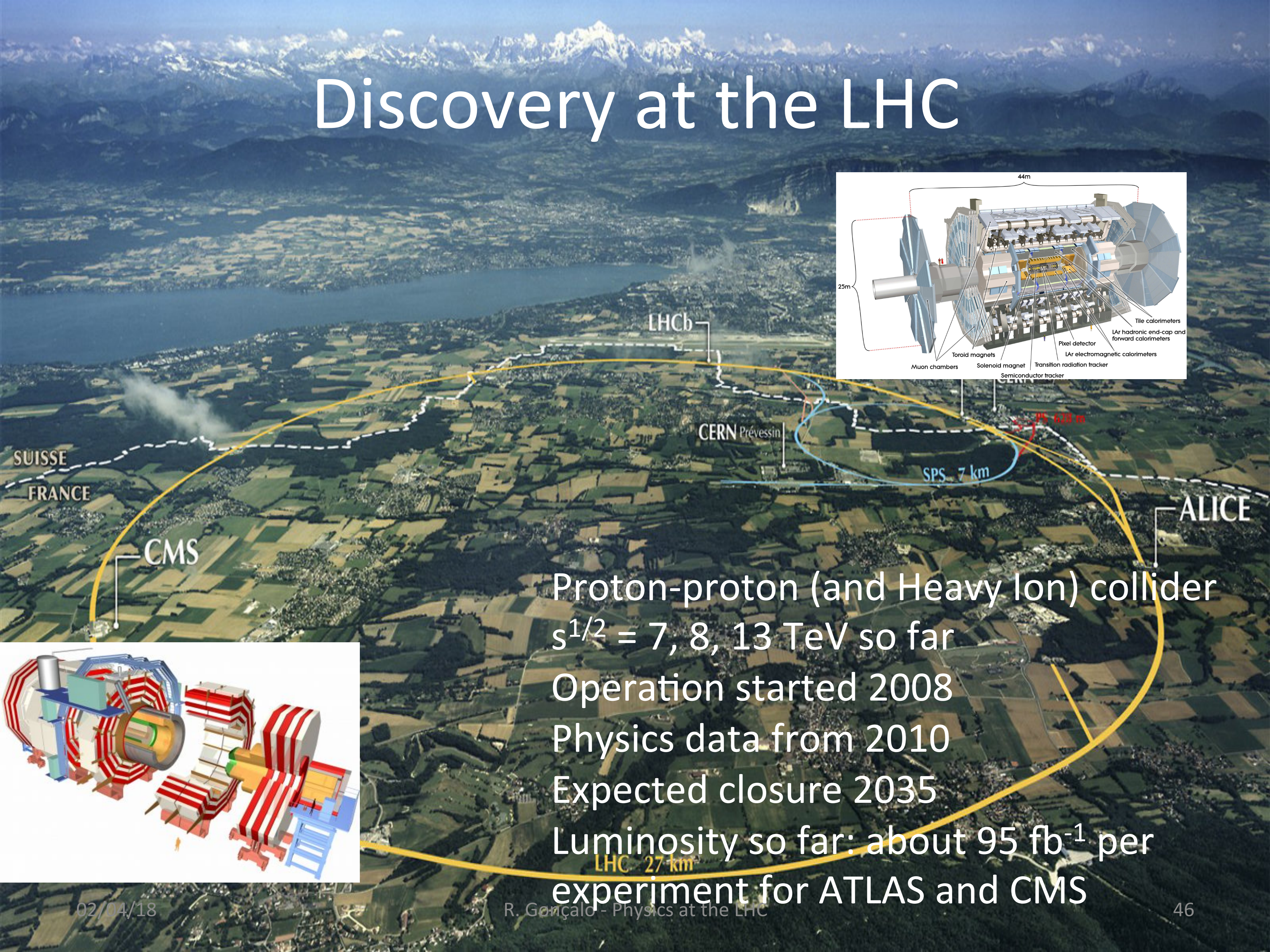
The final stand of the Tevatron

- 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

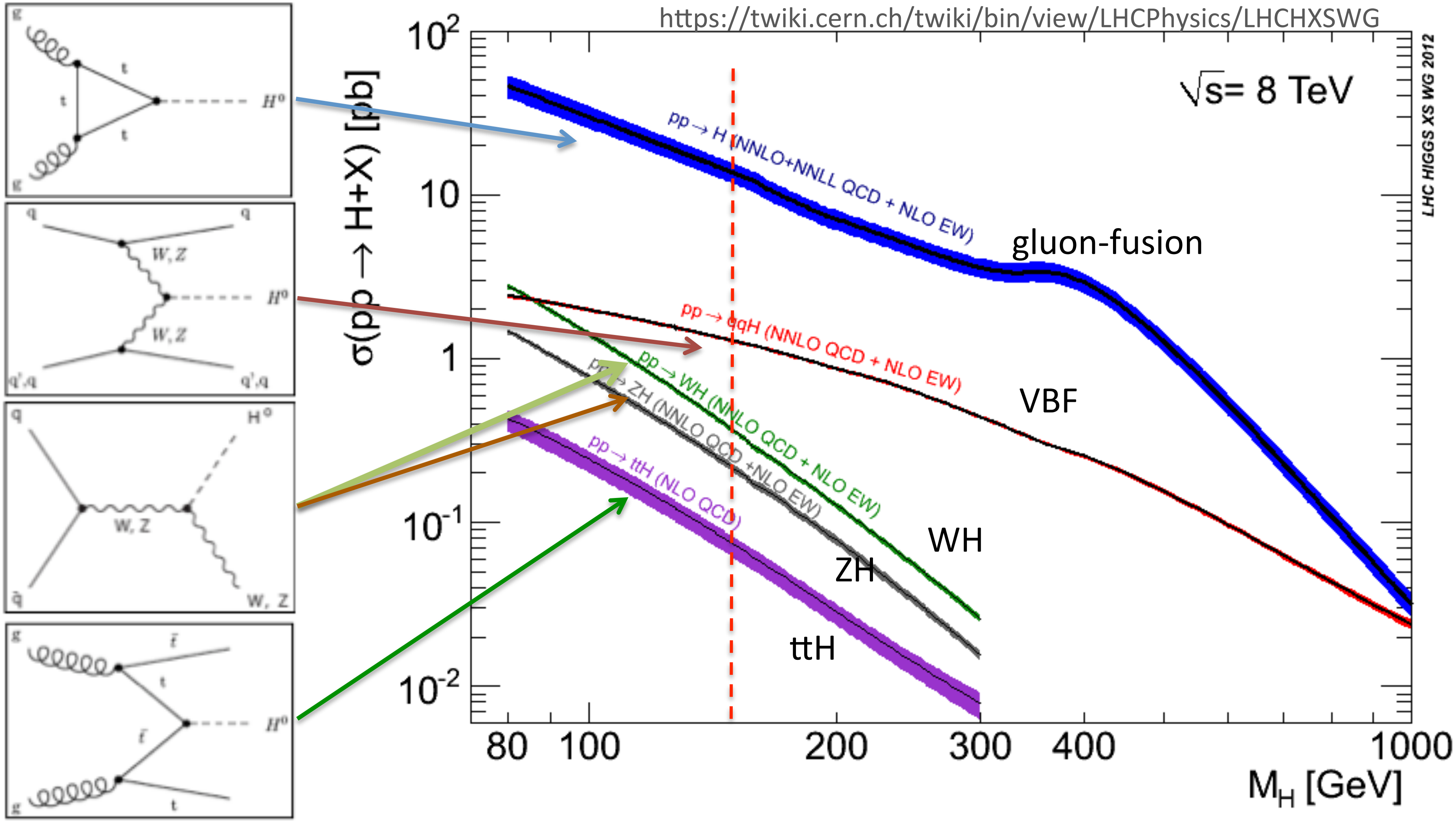
Operation started 2008

Physics data from 2010

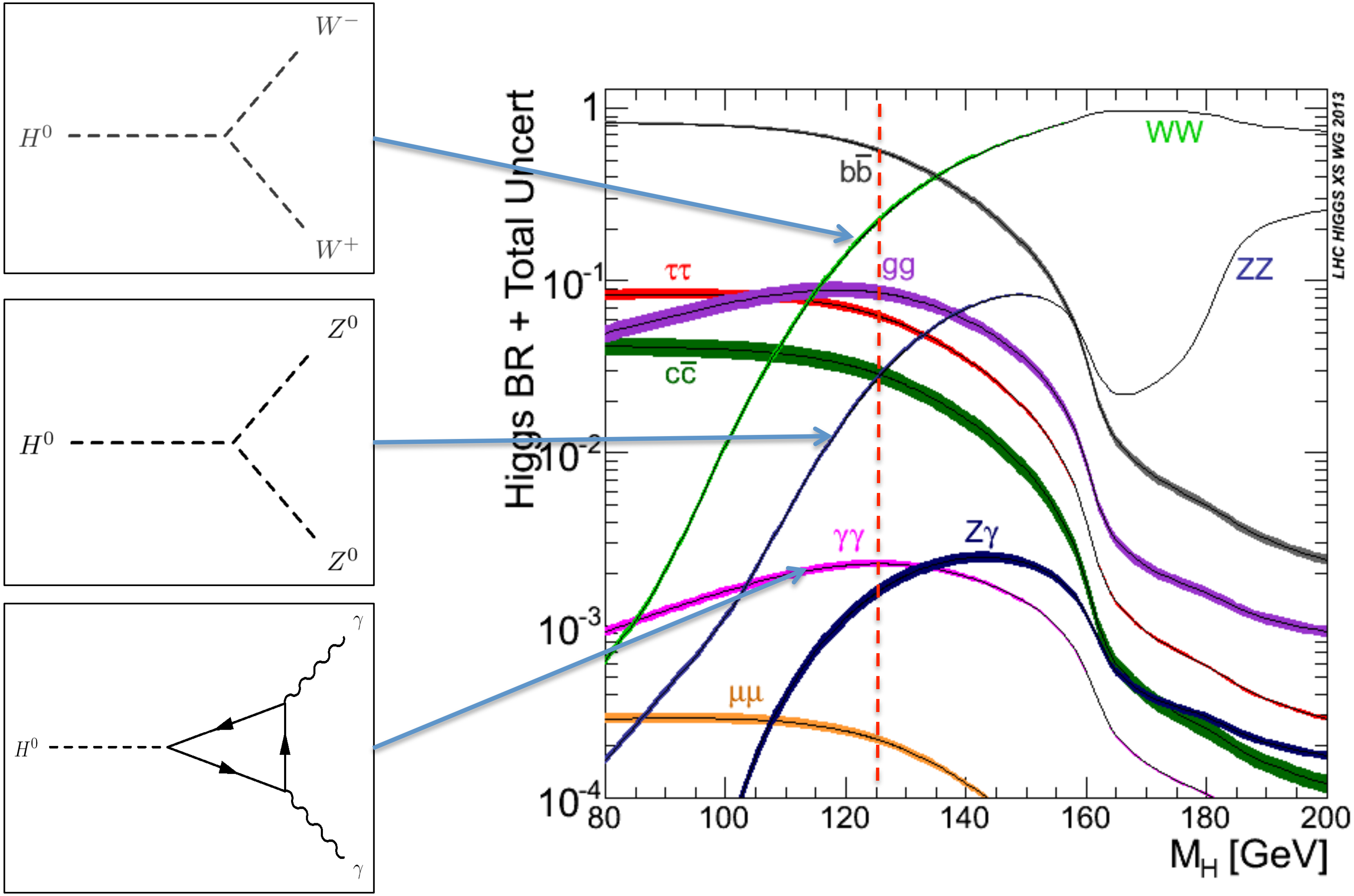
Expected closure 2035

Luminosity so far: about 95 fb^{-1} per experiment for ATLAS and CMS

At the LHC

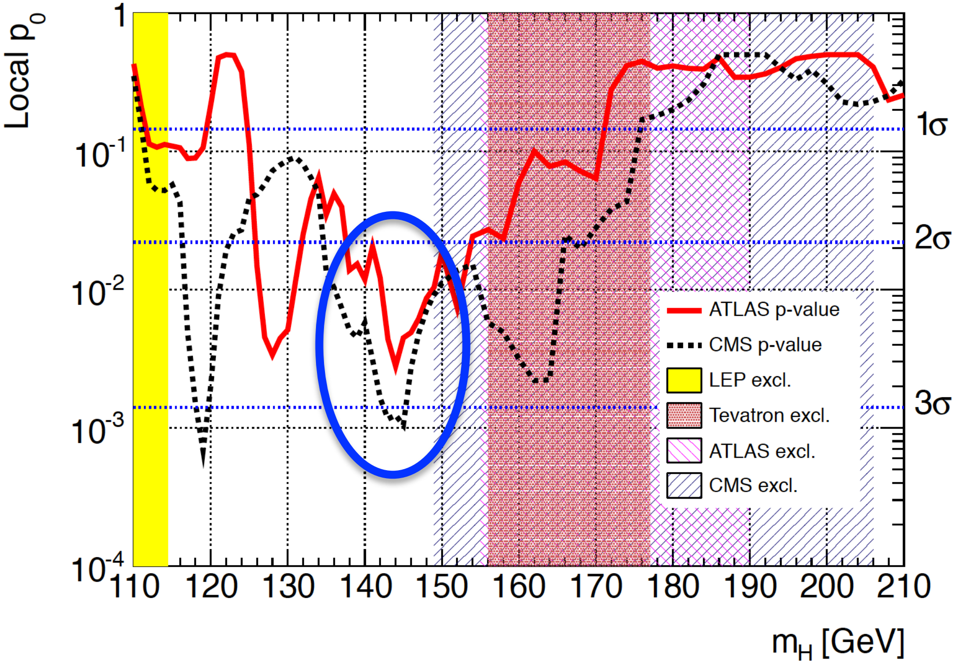


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG


W^-
H^0
W^+
Z^0
H^0
Z^0
γ
H^0
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
$b\bar{b}$
WW
ZZ
ττ
gg
$c\bar{c}$
γγ
Zγ
μμ

It takes time to get it right

EPS-HEP 2011 conference [6]

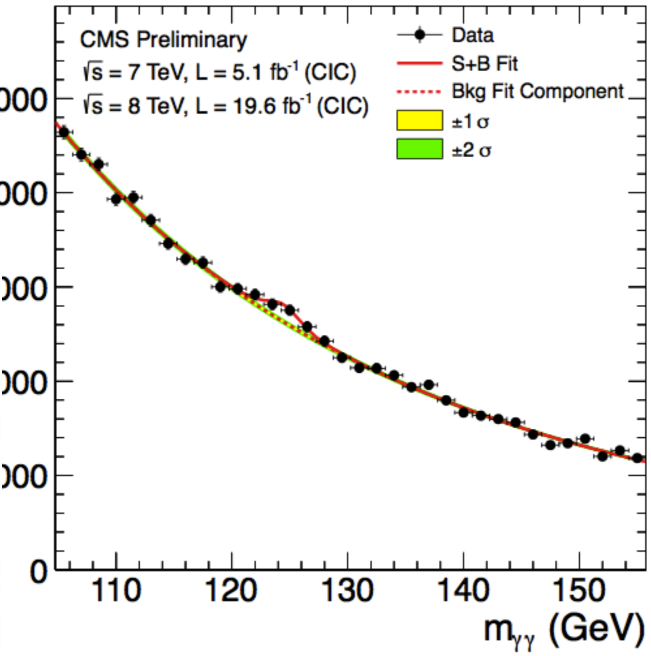


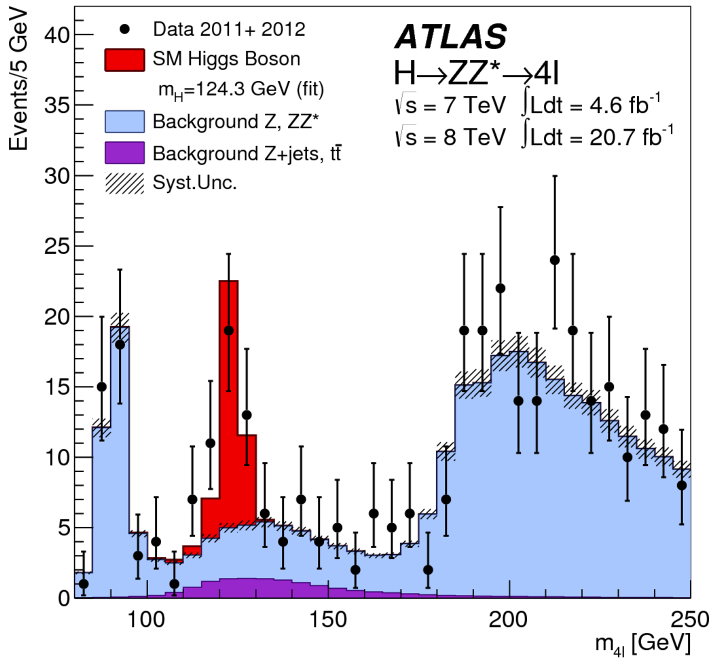
Discovery channels

- 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

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

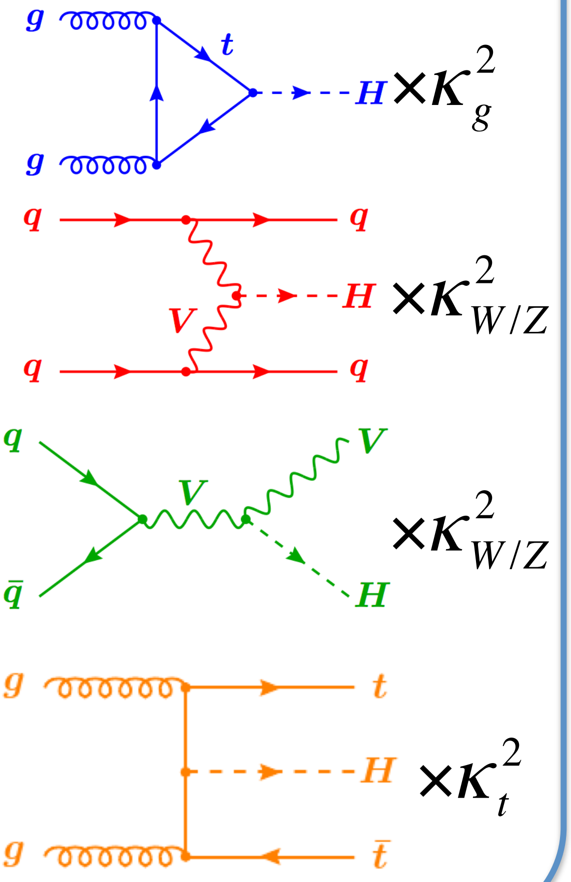
- This means about 400 000 Higgs bosons produced in about 8 000 000 000 000 000 (8x10^{15}) proton collisions
  - Only about 4000 events with Higgs bosons contributed to the discovery





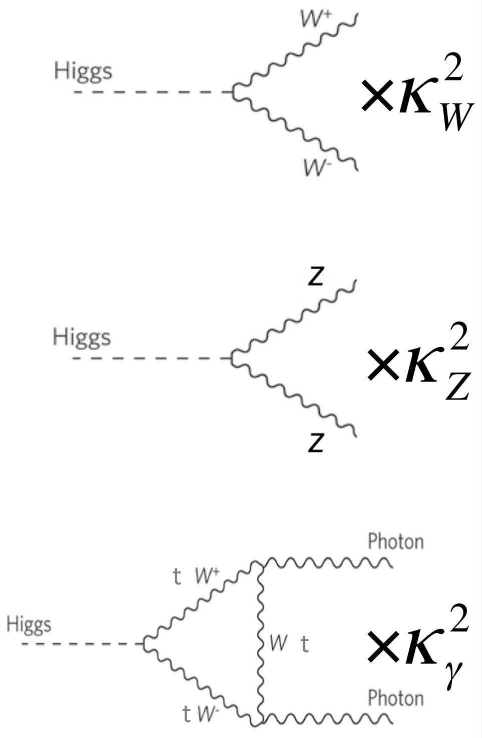
Combining Higgs Channels

Production



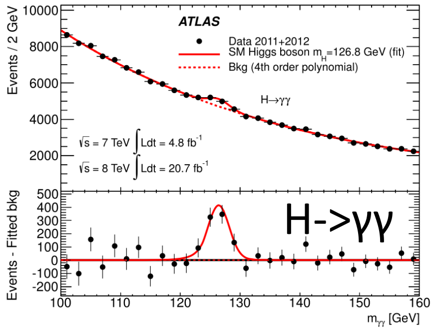
×

Decay

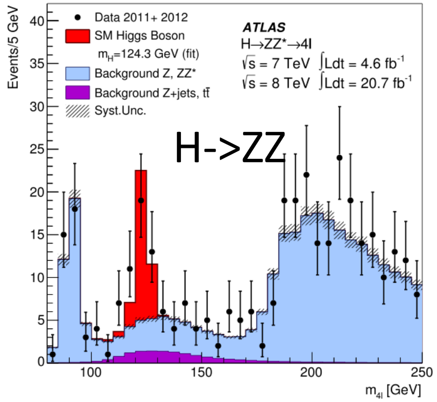


FIT

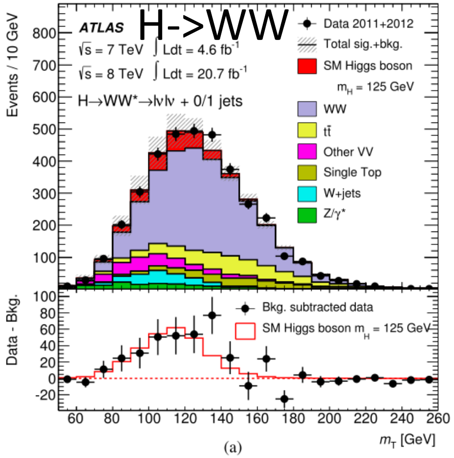
Backgrounds +



H->γγ



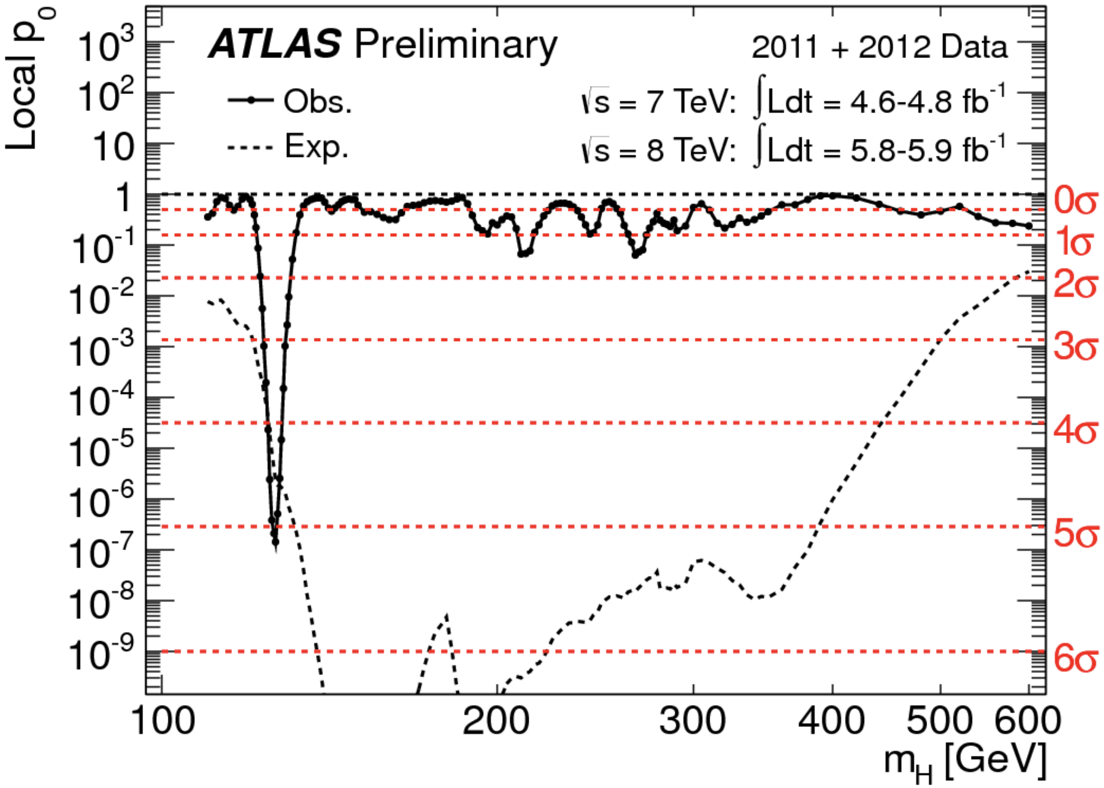
H->ZZ



H->WW

The p_0 Discovery Plot

- **p_0** is the combined probability that the background fluctuates to look like signal
- Translated into the one-sided Gaussian probability



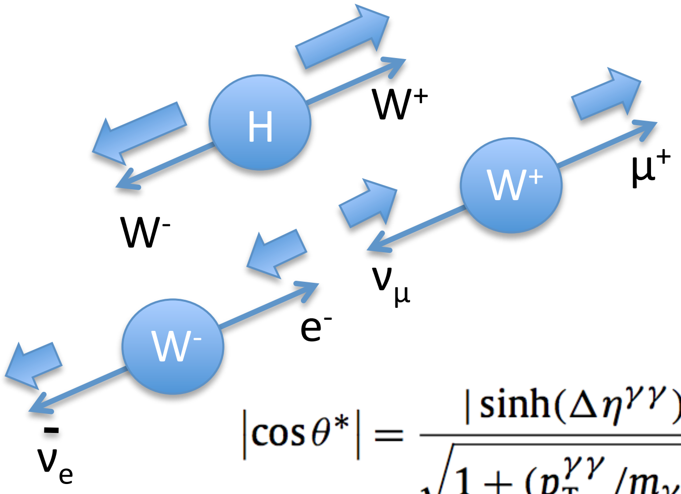
- This corresponds to a probability of **1 in 3.5 million** that this was a false positive from fluctuating backgrounds

What we have found out since

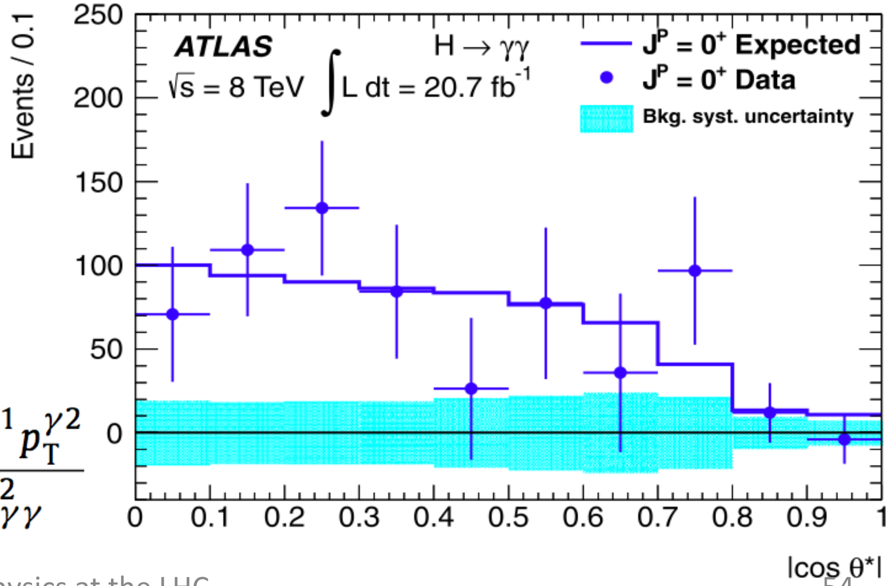
A (quick) foretaste of the next few lectures

Spin and Parity

- First concern after observation!
- Some observable quantities sensitive to J^P: for example angle between leptons from W decay in H->WW
- Pure $J^P = 0^-, 1^+, 1^-$, and 2^+ excluded with 97.8, 99.97, 99.7, and 99.9% Confidence Level (ATLAS arXiv 1307.1432; CMS Phys. Rev. D 92, 012004)



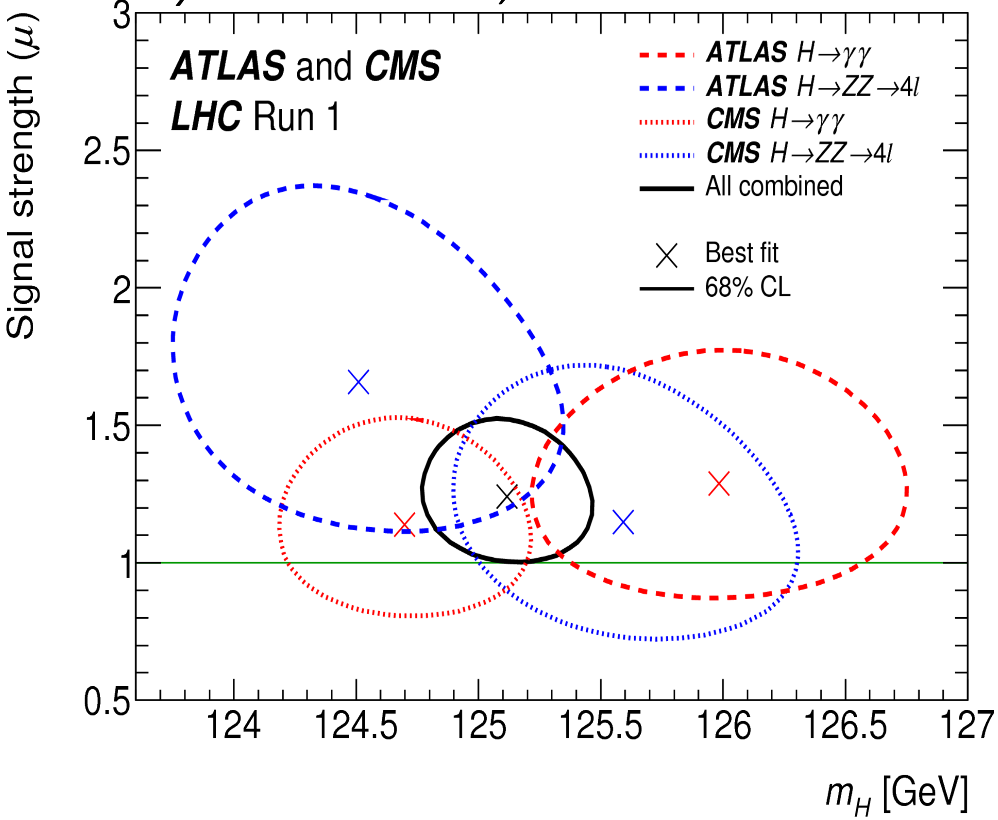
$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_{\mathrm{T}}^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_{\mathrm{T}}^{\gamma 1} p_{\mathrm{T}}^{\gamma 2}}{m_{\gamma\gamma}^2}$$



Higgs boson mass

- **Mass:** around 125GeV
  Used to be the only unknown SM-Higgs parameter, remember? ☺
- 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!

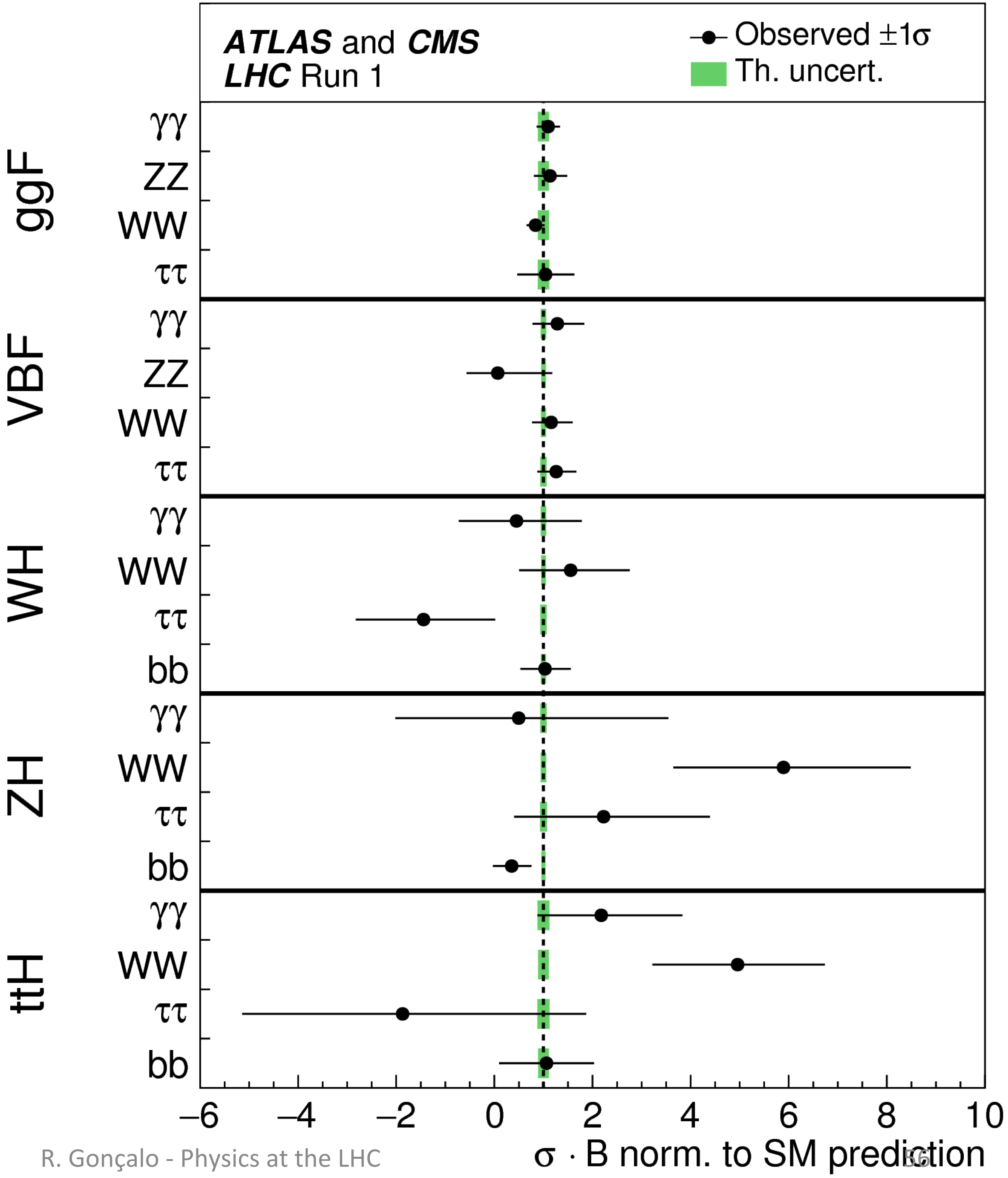
Phys. Rev. Lett. 114, 191803



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

Cross section compared to SM expectation

$$\frac{\sigma_{meas}.BR}{\sigma_{SM}.BR}$$



Going beyond the standard model

But the Standard Model is not complete; there are still many unanswered questions.

Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?

What is this "dark matter" that we can't see but has visible gravitational effects in the cosmos?

Are quarks and leptons actually fundamental, or made up of even more fundamental particles?

Why are there exactly three generations of quarks and leptons? What is the explanation for the observed pattern for particle masses?

How does gravity fit into all of this?

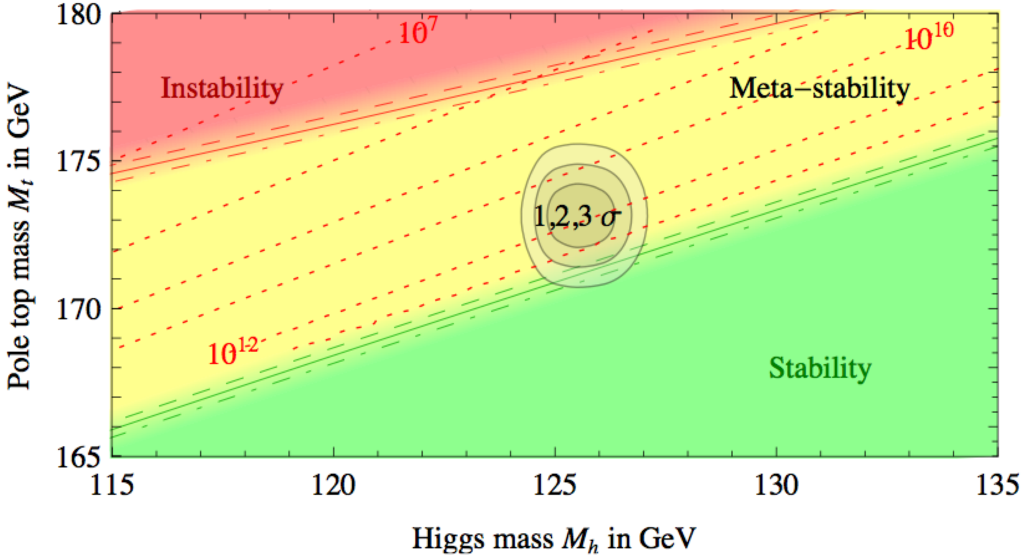
Many possible theories

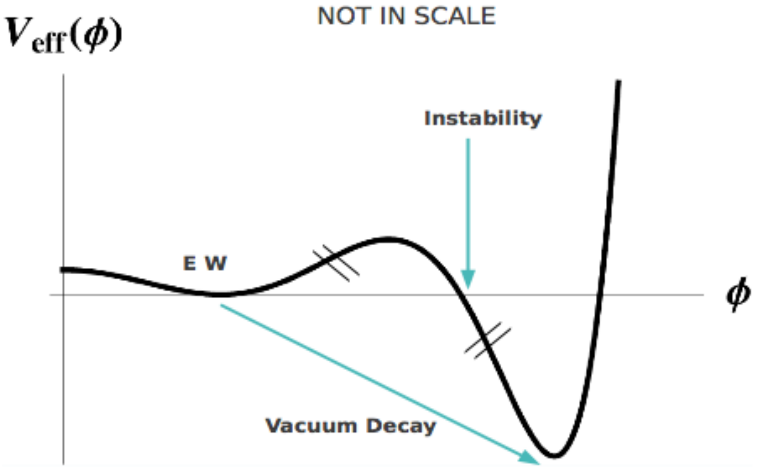
There are a large number of models which predict new physics at the TeV scale accessible at the LHC:

- Supersymmetry (SUSY)
- Extra dimensions
- Extended Higgs Sector e.g. in SUSY Models
- Grand Unified Theories (SU(5), O(10), E6, …)
- Leptoquarks
- New Heavy Gauge Bosons
- Technicolour
- Compositeness

Any of this could still be found at the LHC and most have a connection to the Higgs boson

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

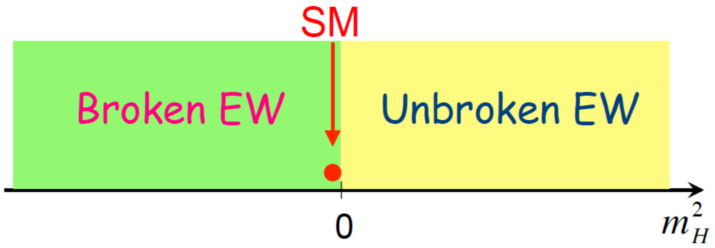
The universe seems to live near a critical condition

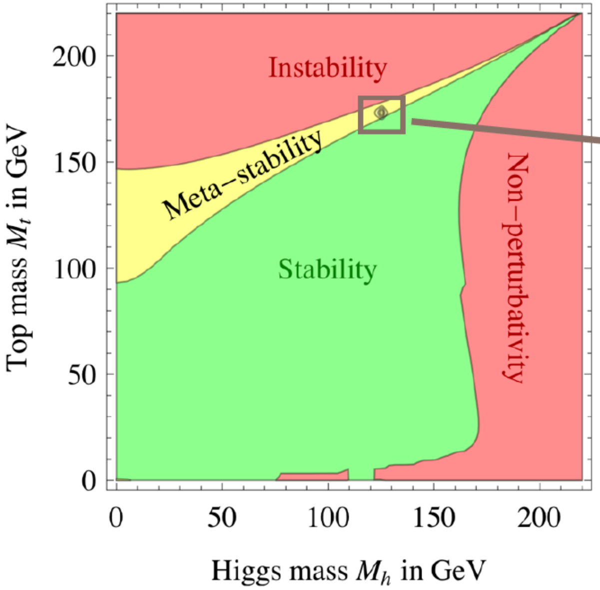
JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?





Where we stand now?

- The Higgs may very well be a window into the new physics which we know must exist
- We now have very precise results from the Higgs sector
- And no surprises (yet?)

- **But the truth is out there! Must keep looking!**

The End

1. Goldstein, 'Classical Mechanics', Addison-Wesley Publishing Company (1980)
2. D. Griffiths, 'Introduction to Elementary Particles ', John Wiley and Sons (1987)
3. Exposição "Partículas – do Bosão de Higgs à Matéria Escura": http://www.lip.pt/particulas/
4. Wikipedia: https://en.wikipedia.org/
5. M. Thompson, Modern Particle Physics, Cambridge University Press, 2013
6. J. Butterworth, Smashing Physics – inside the world's biggest experiment, Headline Publishing Group, 2014
7. J.C. Romão, The need for the Higgs boson in the Standard Model, private note, http://porthos.ist.utl.pt/CTQFT/
8. W.Murray on behalf of the ATLAS and CMS Collaborations, proceedings of the 2011 Europhysics Conference on High Energy Physics, EPS-HEP 2011, July 21-27, 2011 Grenoble, Rhône-Alpes, France, PoS (EPS-HEP2011) 031
9. LEP Electroweak Working Group, Precision Electroweak Measurements and Constraints on the Standard Model, CERN-PH-EP-2010-095, July 2010
10. LHC Higgs Cross Section Working Group: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG
11. CMS Collaboration, Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV, Phys. Rev. D 92, 012004, 2015
12. ATLAS and CMS Collaborations, Combined Measurement of the Higgs Boson Mass in pp Collisions at s√=7 and 8 TeV with the ATLAS and CMS Experiments, Phys. Rev. Lett. 114, 191803
13. I. Masina, arXiv:1403.5244 [astro-ph.CO], 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