Higgs Physics – Lecture 1

Higgs Physics at the LHC – Introduction

Ricardo Gonçalo – LIP

IDPASC Course on Physics at the LHC – LIP, 2 April 2018

Cofinanciado por:

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

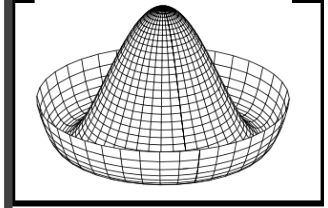
Models, properties, and interpretation.
Case-study of the coupling strengths.
Case-study of the hypothesis test for different spin-parity assignments.

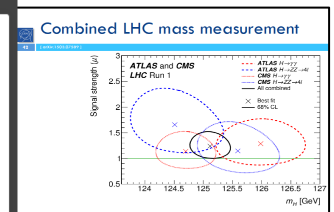
Speaker: Pedro Vieira De Castro Ferreira Da Silva (CERN)

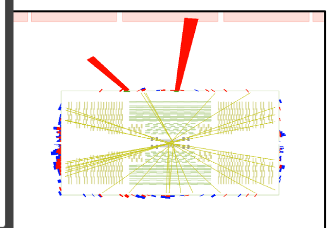
Wednesday, 11 April

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.

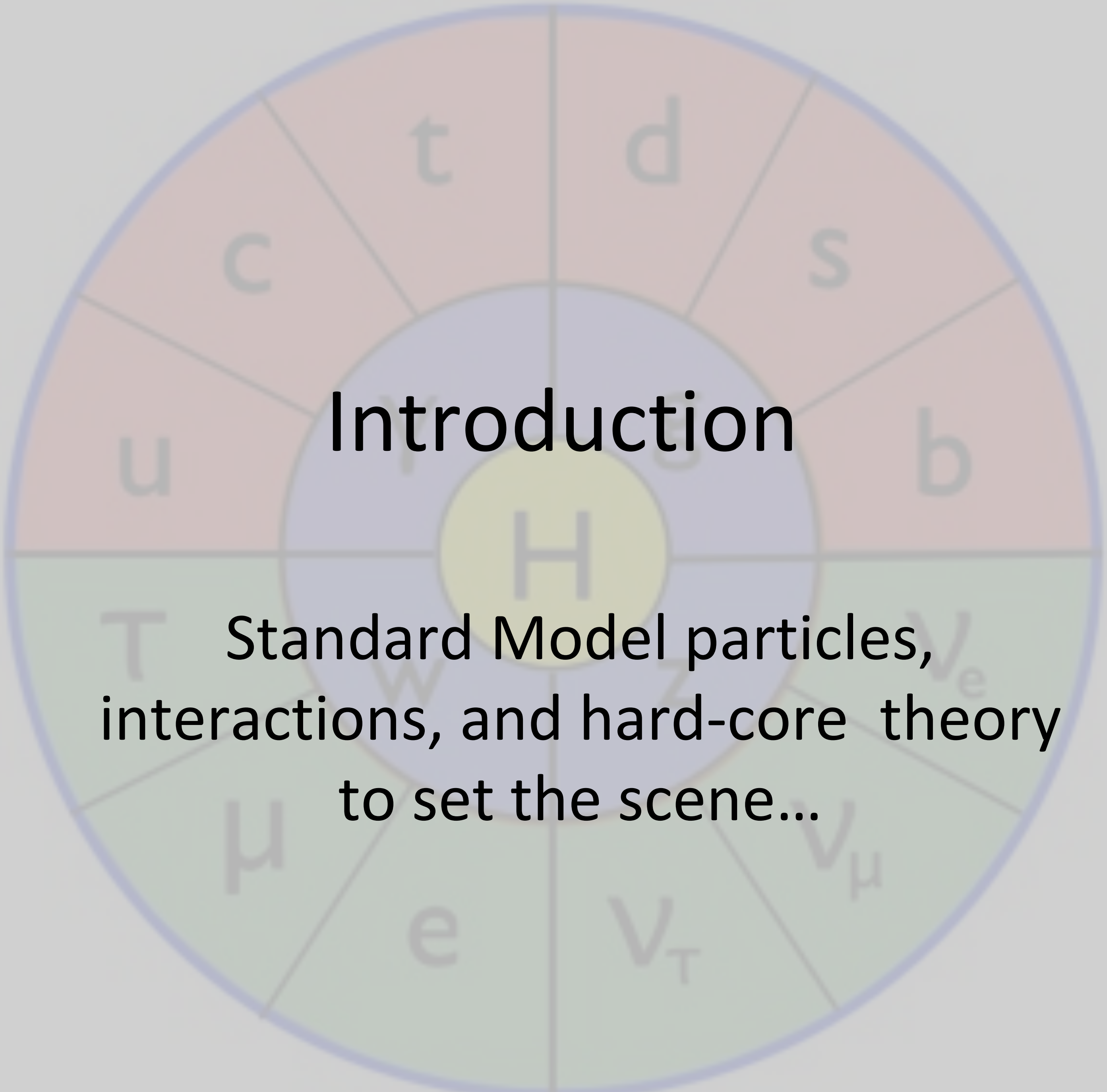






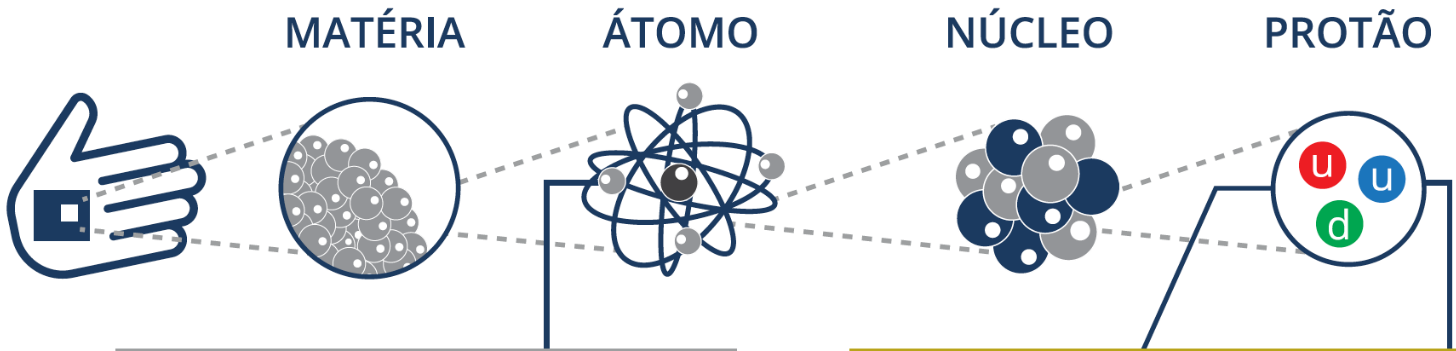
Outlook

- 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

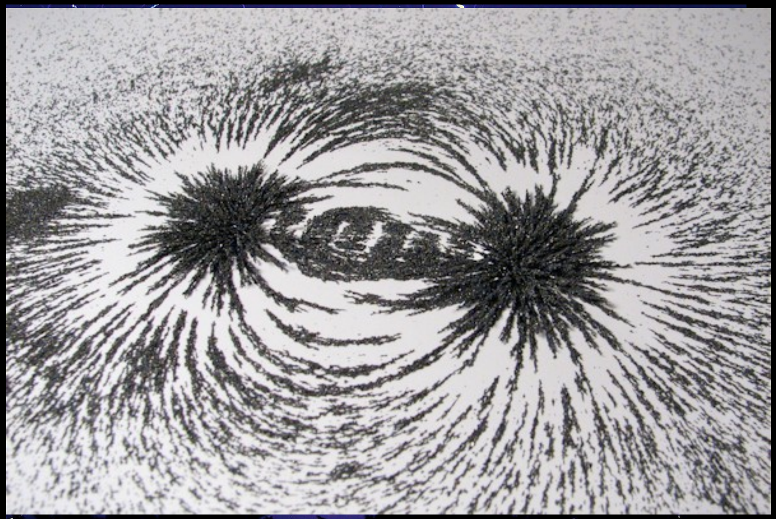


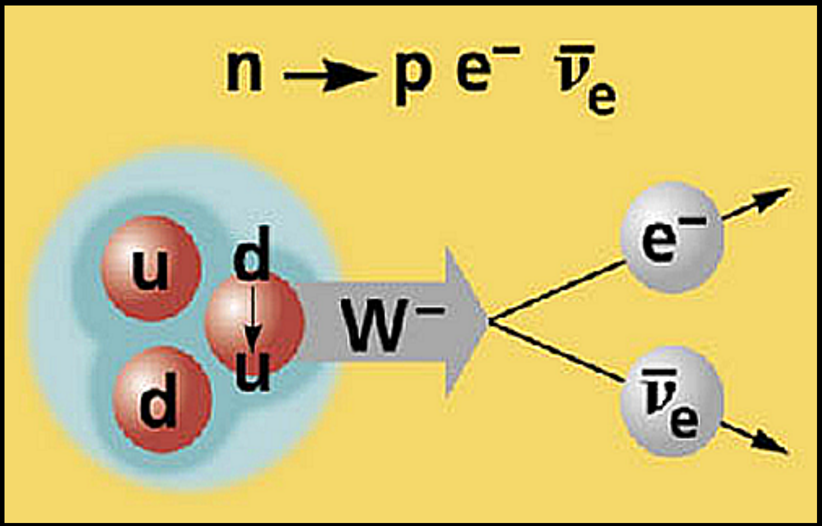
Introduction

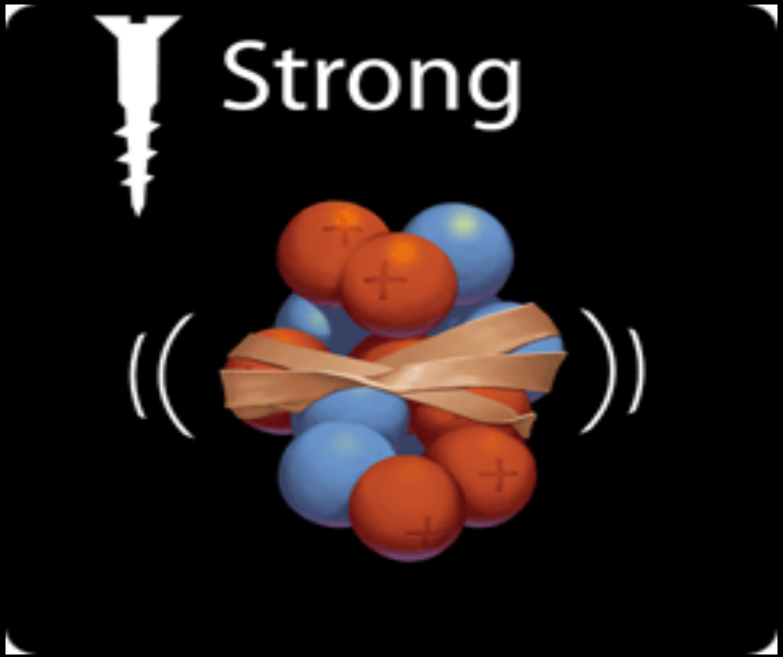
Standard Model particles, interactions, and hard-core theory to set the scene…

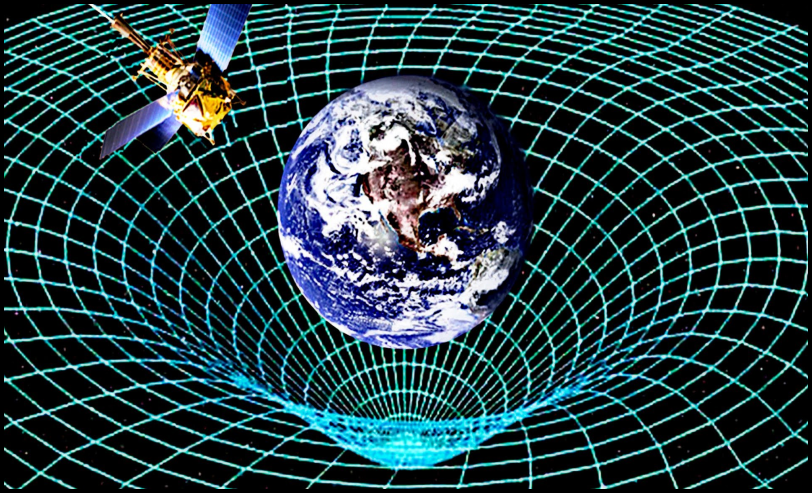


LEPTÕES		QUARKS	
ν_e NEUTRINO DO ELETRÃO 0 ½	e ELETRÃO -1 ½	u UP ⅔ ½	d DOWN -⅓ ½
ν_μ NEUTRINO DO MUÃO 0 ½	μ MUÃO -1 ½	c CHARM ⅔ ½	s STRANGE -⅓ ½
ν_τ NEUTRINO DO TAU 0 ½	τ TAU -1 ½	t TOP ⅔ ½	b BOTTOM -⅓ ½




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

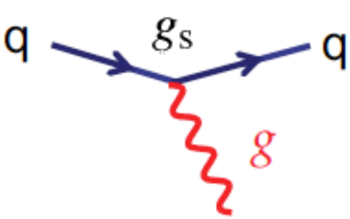

Strong



Standard model interactions

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

STRONG



Only quarks

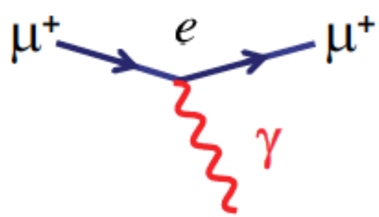
Never changes flavour

$\alpha_S \sim 1$

Gluons

massless

EM



All charged fermions

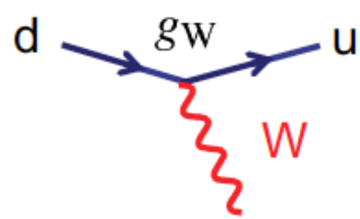
Never changes flavour

$\alpha \simeq 1/137$

Photon

massless

WEAK CC



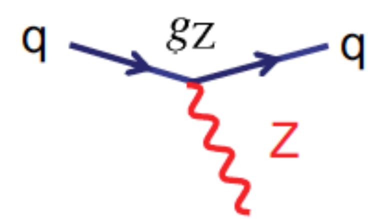
All fermions

<u>Always</u> changes flavour

W+, W-

very massive

WEAK NC



All fermions

Never changes flavour

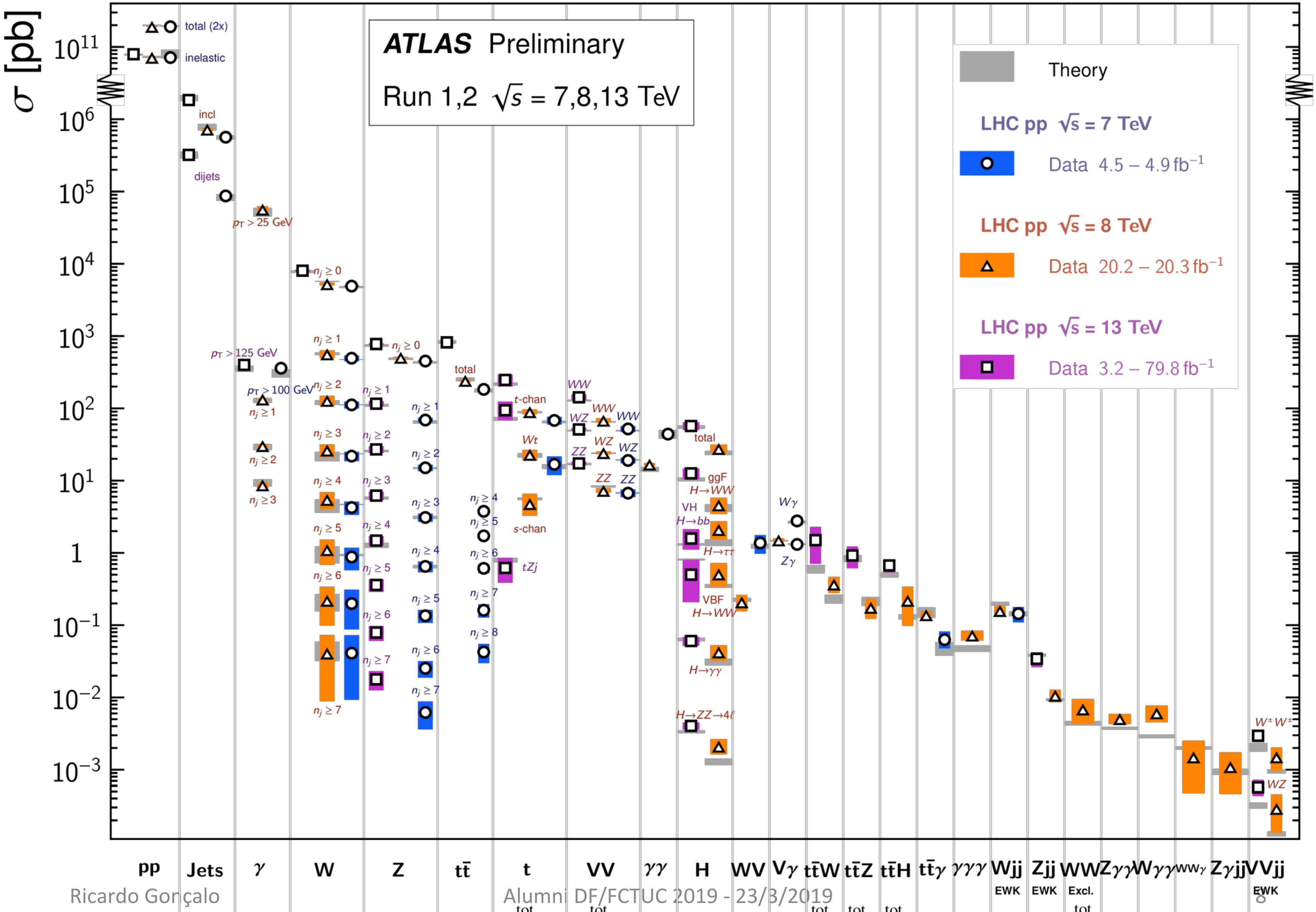
$\alpha_{W/Z} \sim 1/40$

Z^0

very massive

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

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

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**

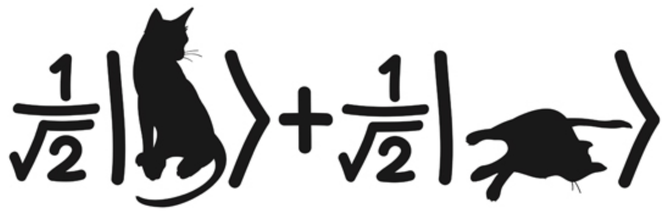
$$L(r,\phi,\dot{r},\dot{\phi}) = T - V = \frac{1}{2}m\dot{r}^2 + \frac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

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...



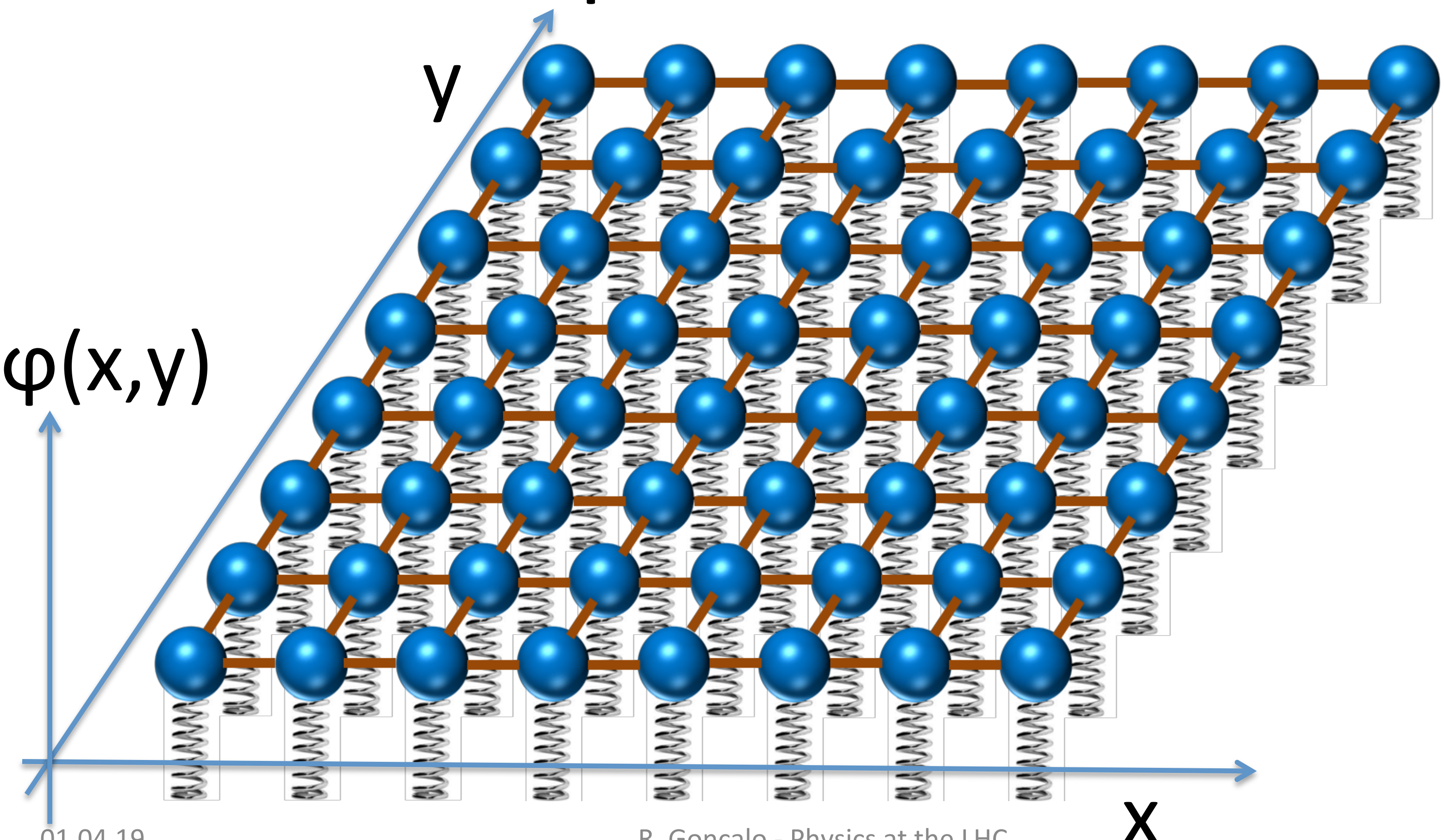
Richard Feynman
(1918 - 1988)

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:

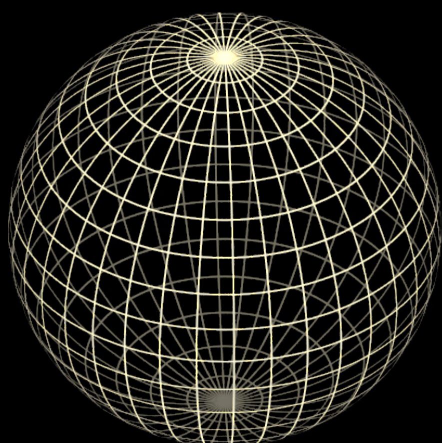
$$\psi(x) \rightarrow \psi'(x) = e^{iq\chi}\psi(x)$$

Where **χ** is a constant

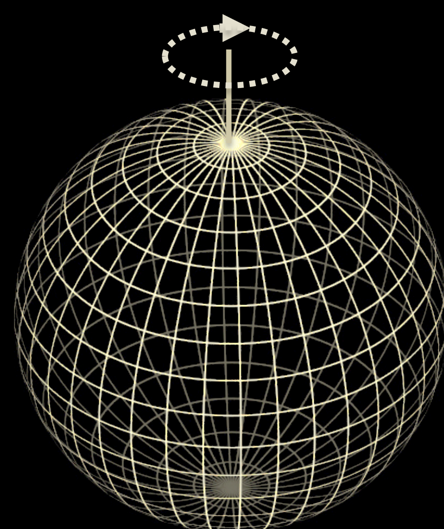
$$\mathcal{L}' = e^{-iq\chi}e^{iq\chi}(i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi) = \mathcal{L}$$

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

Original sphere

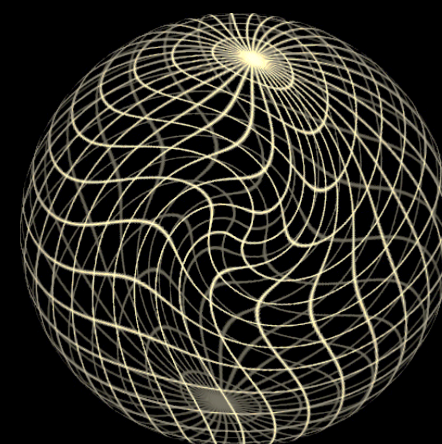


Global transformation



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…

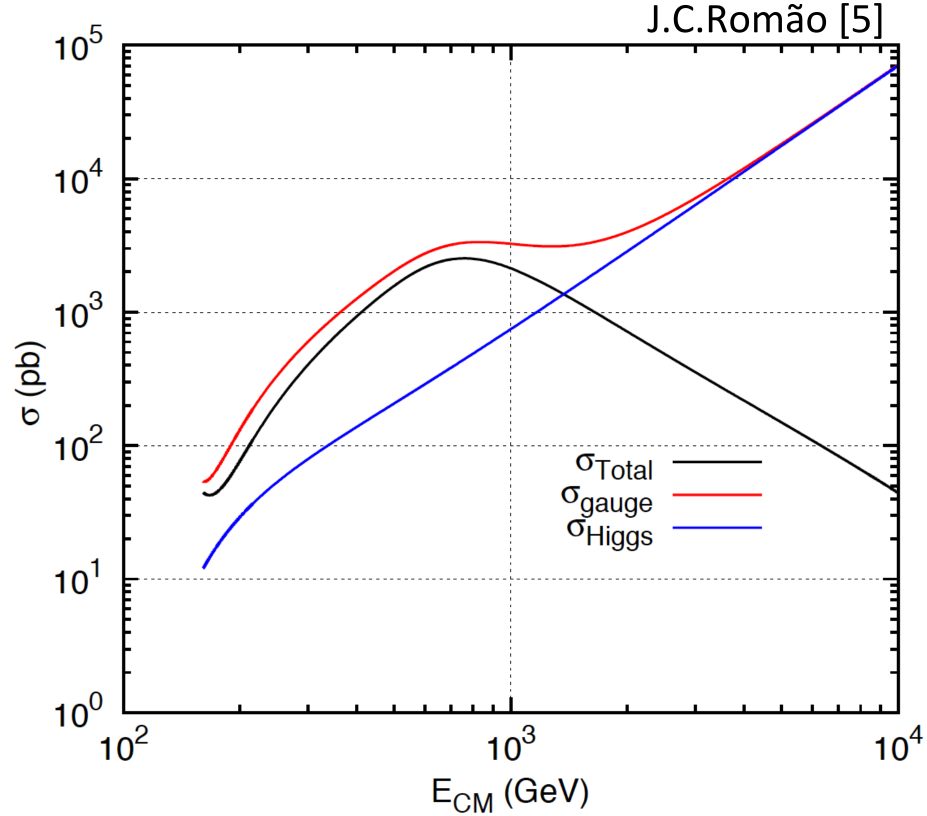
Now for the problems...

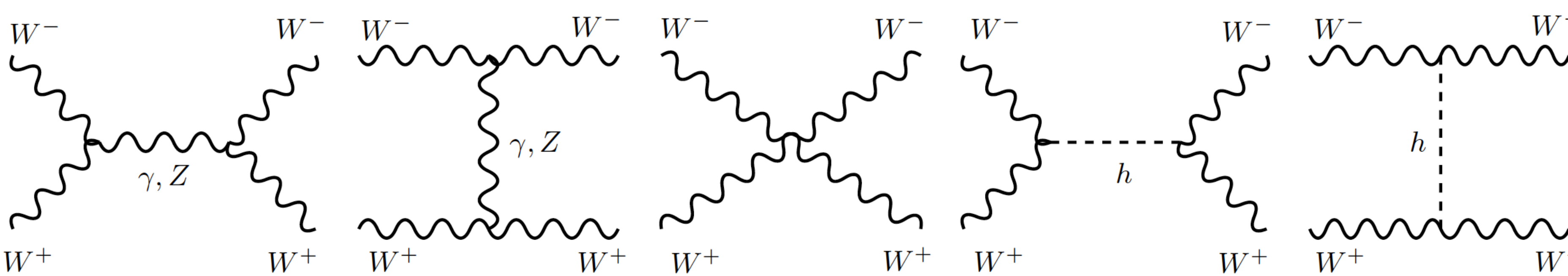
1: Longitudinal gauge-boson scattering

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:

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

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!

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

The Higgs Mechanism

- 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

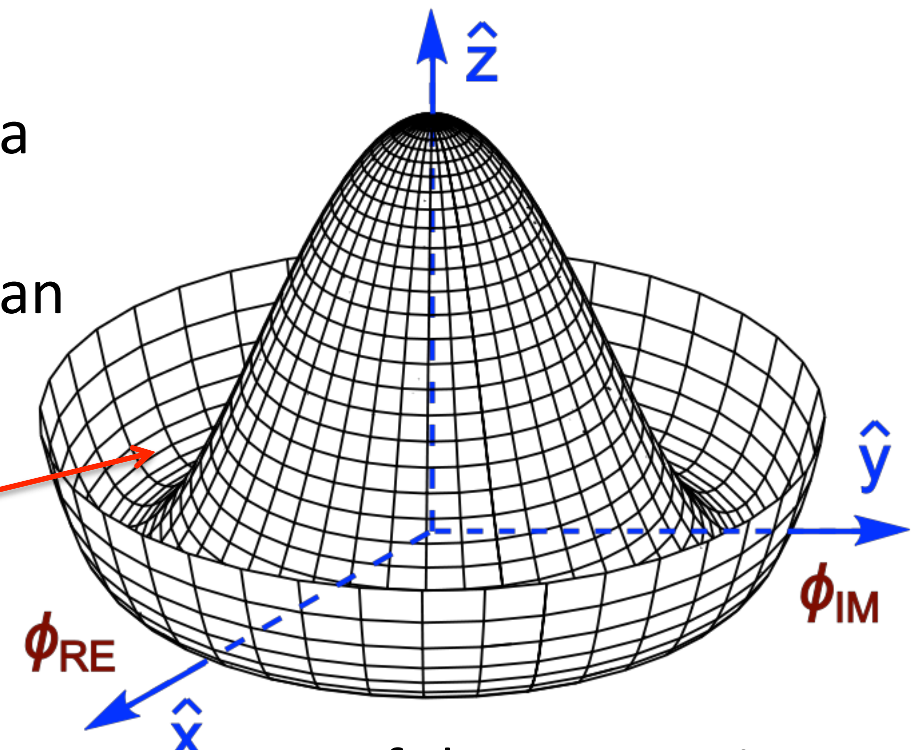
$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

- With a potential

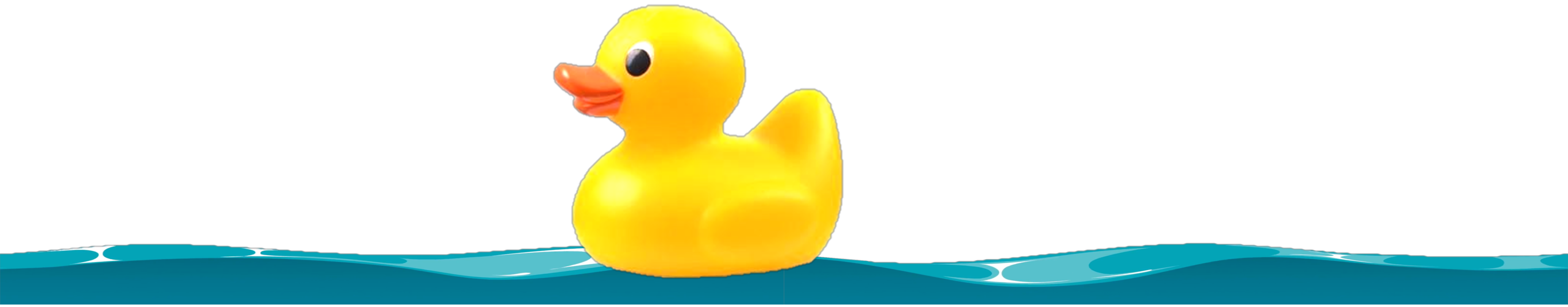
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

- 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:

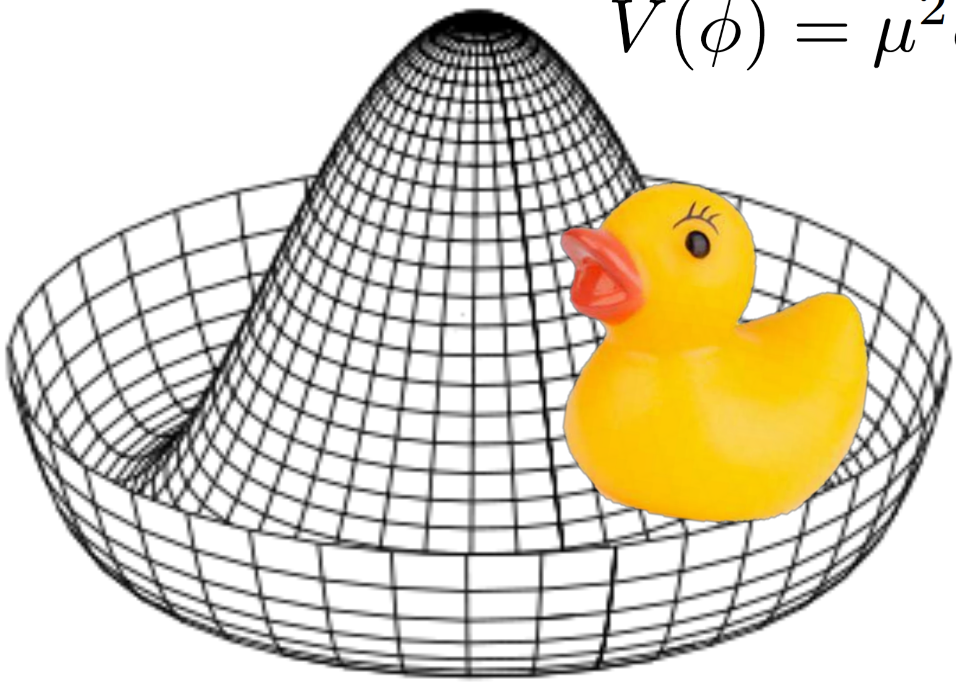
$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$



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



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

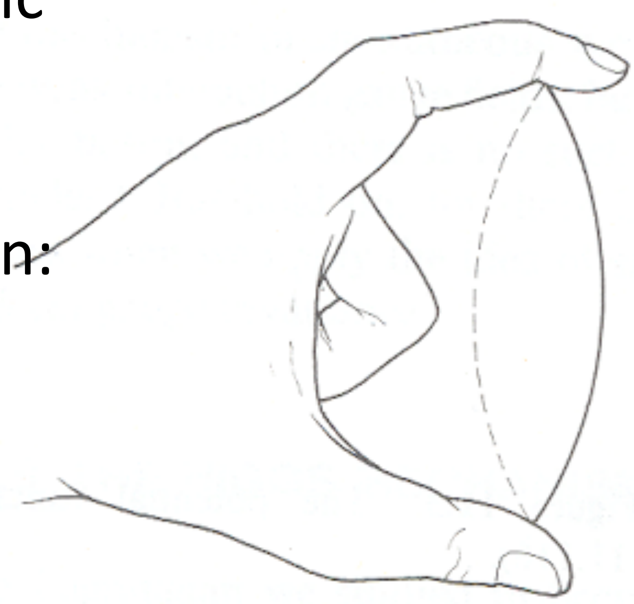


Electroweak symmetry breaking

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

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

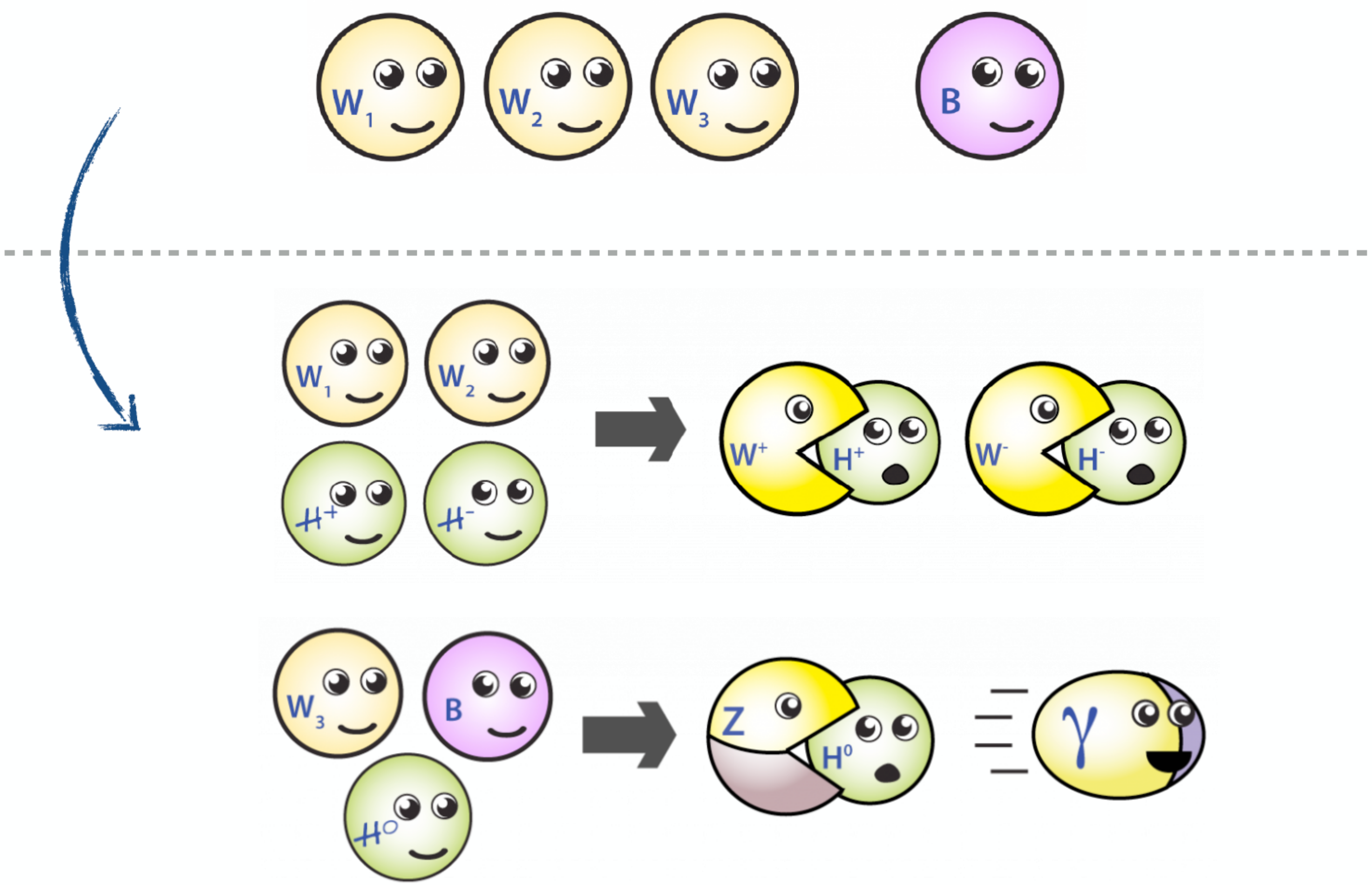
- Higgs mechanism: mass of W and Z results from the Higgs mechanism
- Masses of fermions come from a direct interaction with the Higgs field



see J.Varela's lecture


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
WWW.PHDCOMICS.COM

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)

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

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

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

with g, g_W the couplings of electromagnetic and weak forces

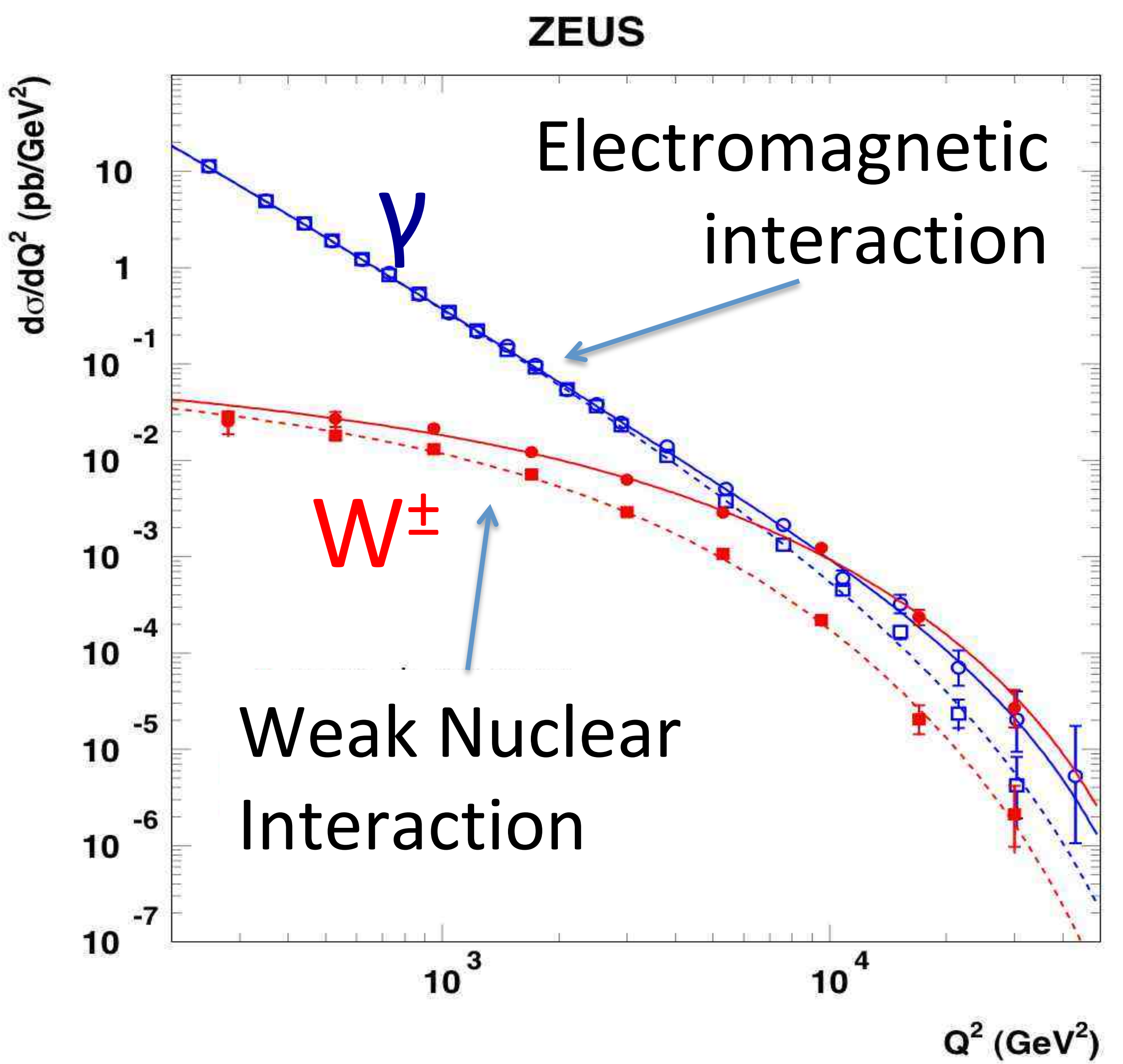
- Defining the Weinberg angle as

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

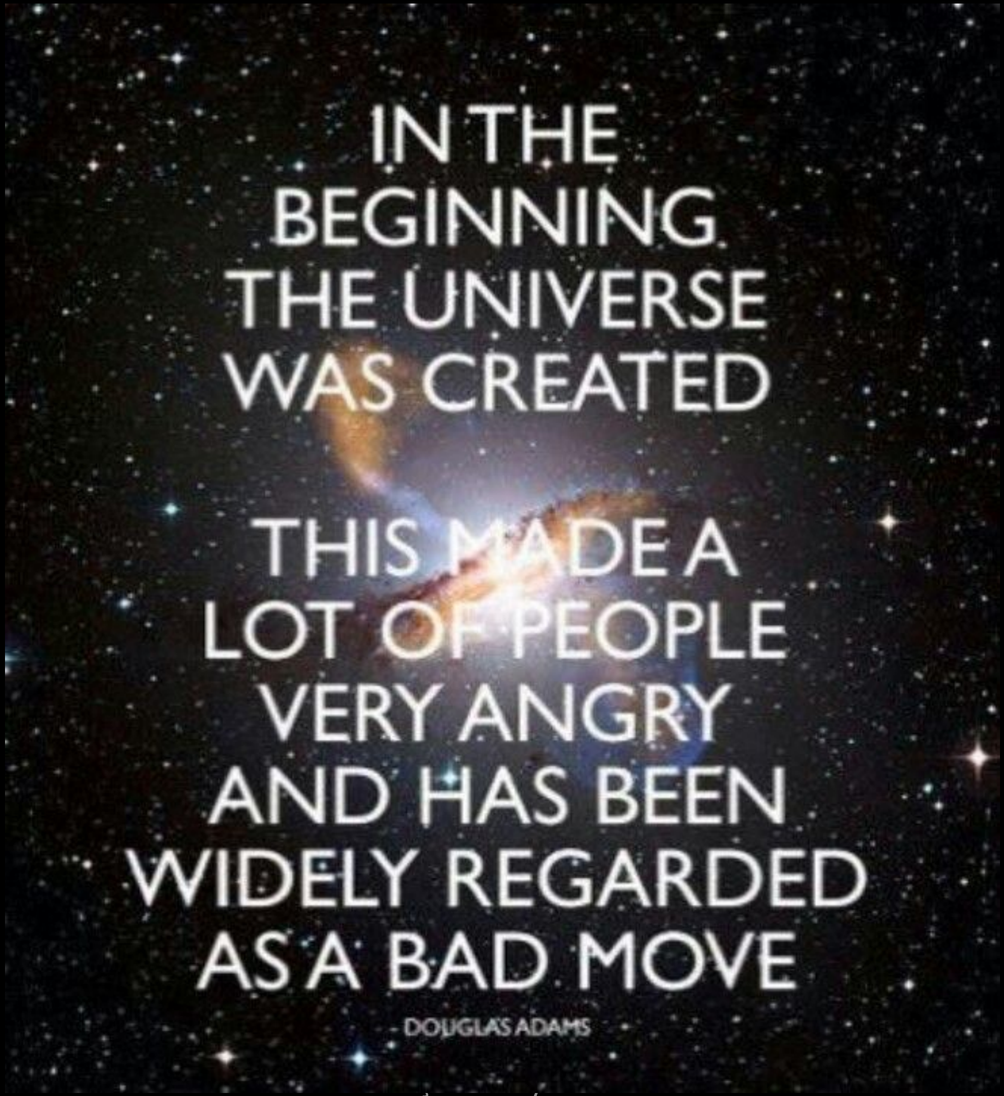
we also get the relation between the masses of W and Z

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

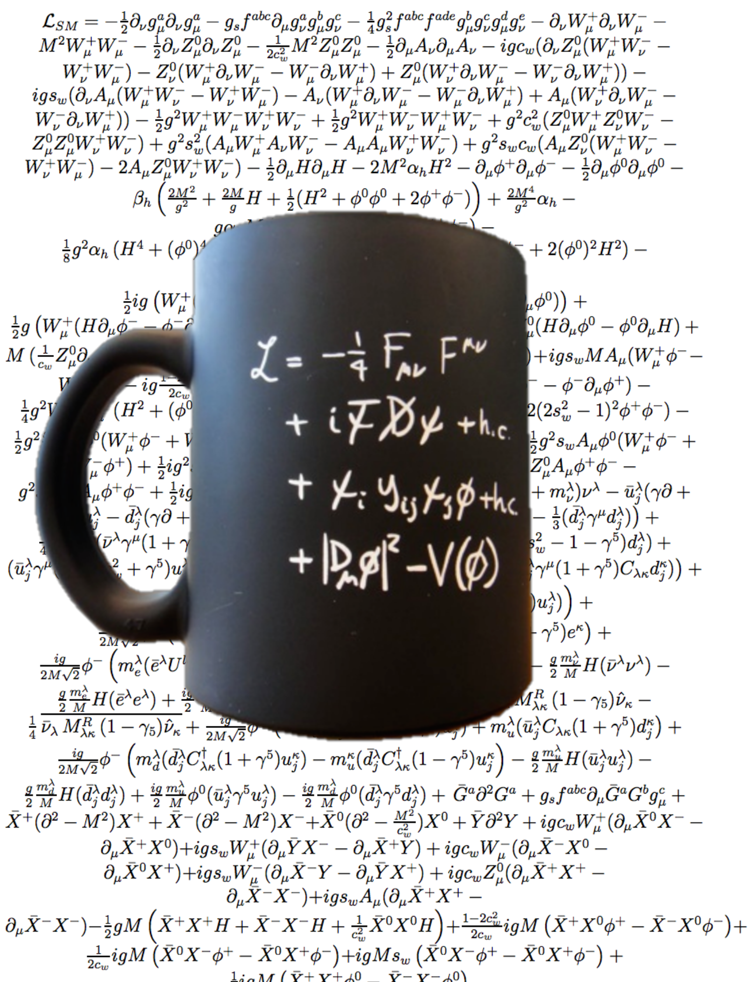
- Fermions get their masses from interaction terms with the Higgs field (Yukawa coupling)

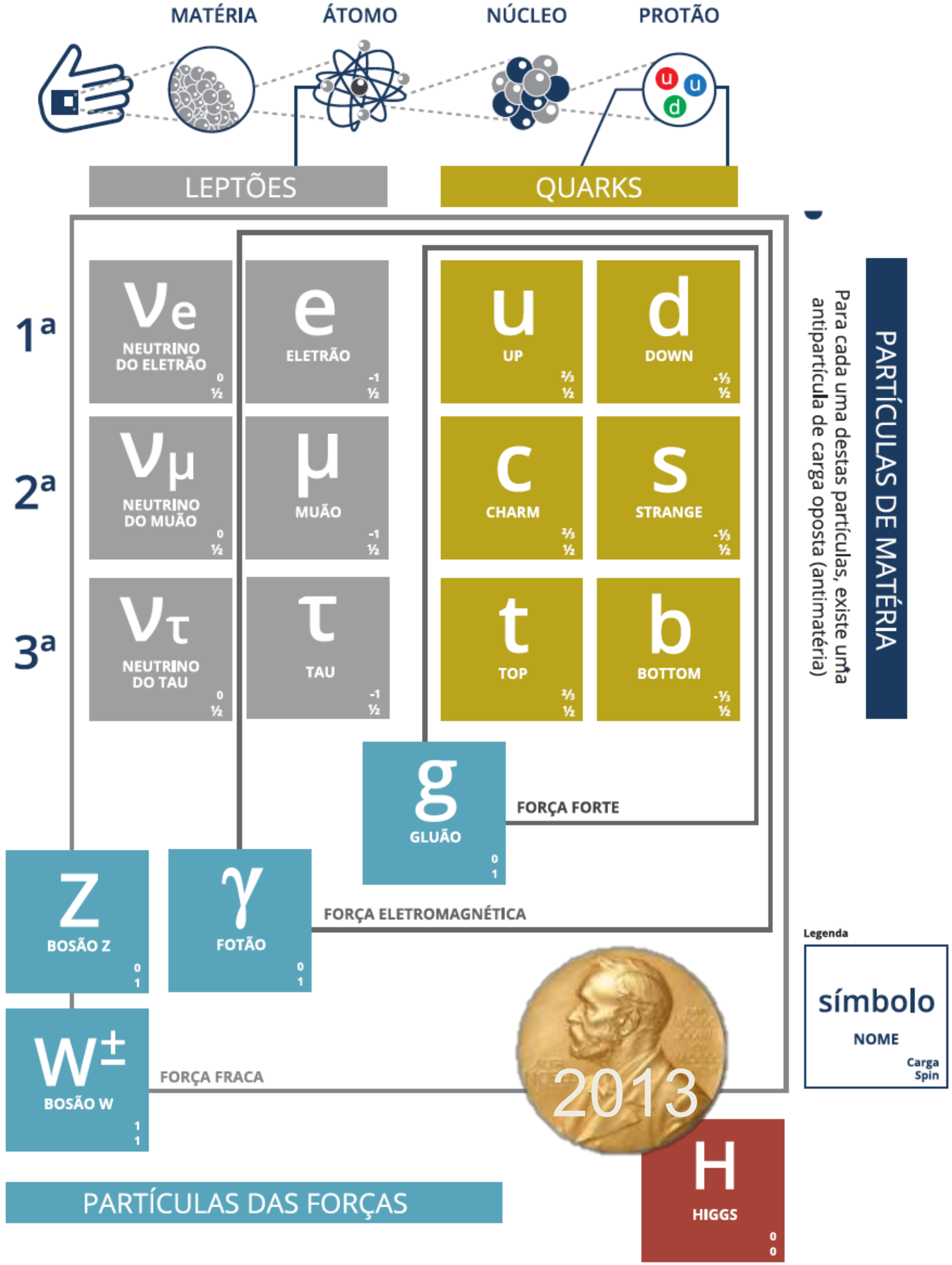

ZEUS
dσ/dQ² (pb/GeV²)
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10³
10⁴
Q² (GeV²)
Electromagnetic
interaction
γ
W±
Weak Nuclear
Interaction

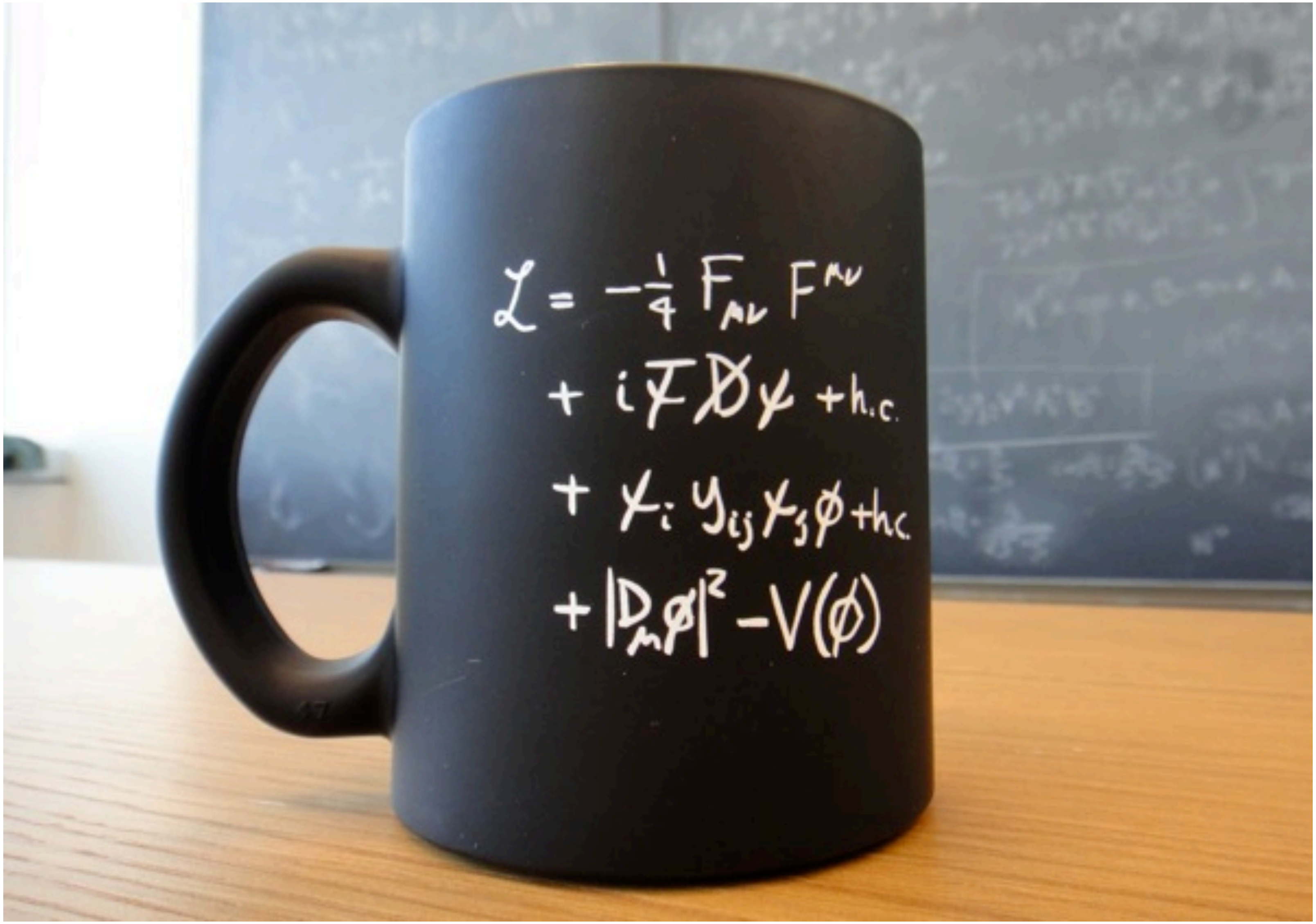
The Story So Far...



The Standard Model of particle physics






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

What we think we know:

- Higgs mass (was) the only unknown parameter

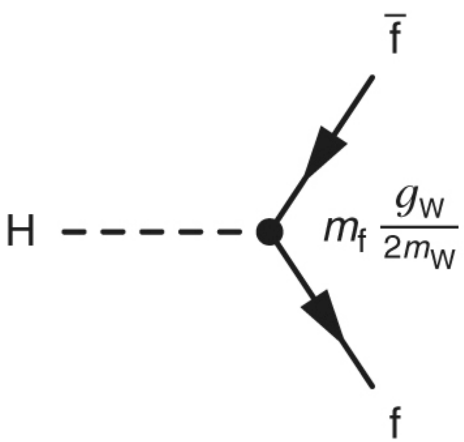
$$m_h = \sqrt{2\lambda}v$$

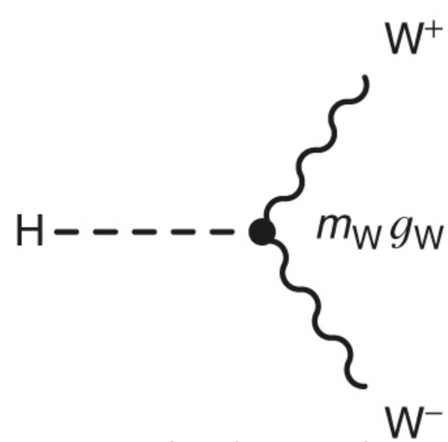
- We can give mass to $W^{\pm}$ and Z while keeping the photon massless
- Relation between masses of W and Z

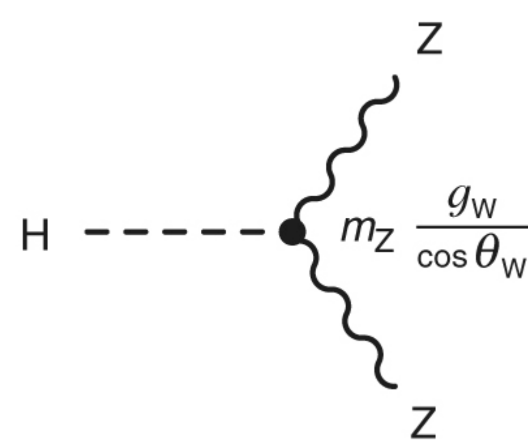
$$\frac{m_W}{m_Z} = \cos\theta_W$$

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

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



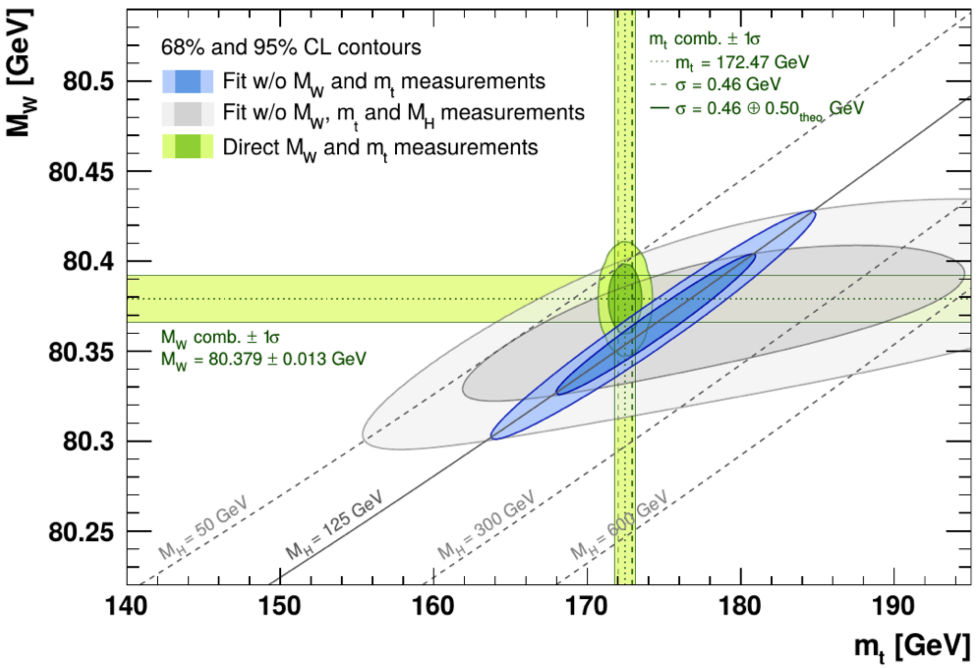


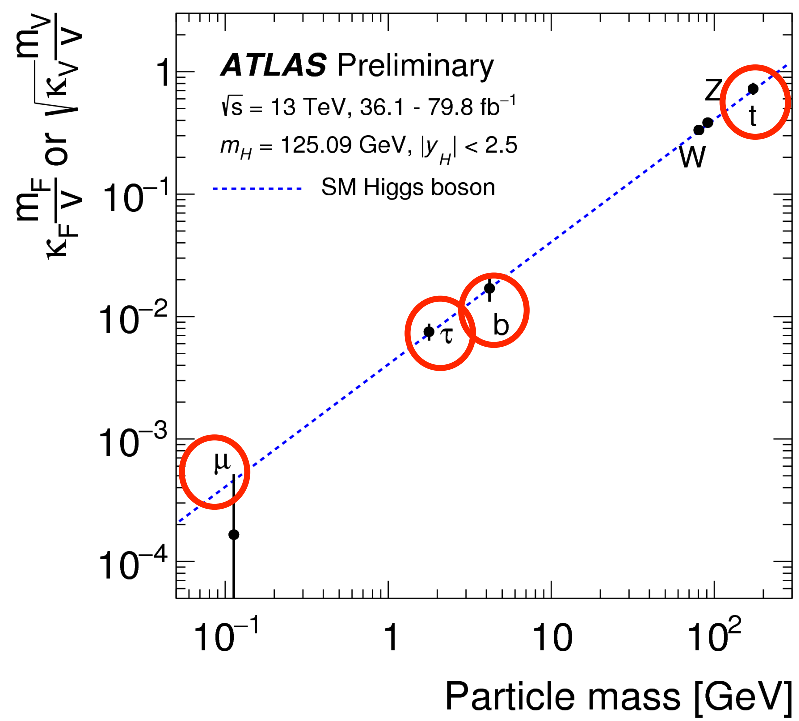


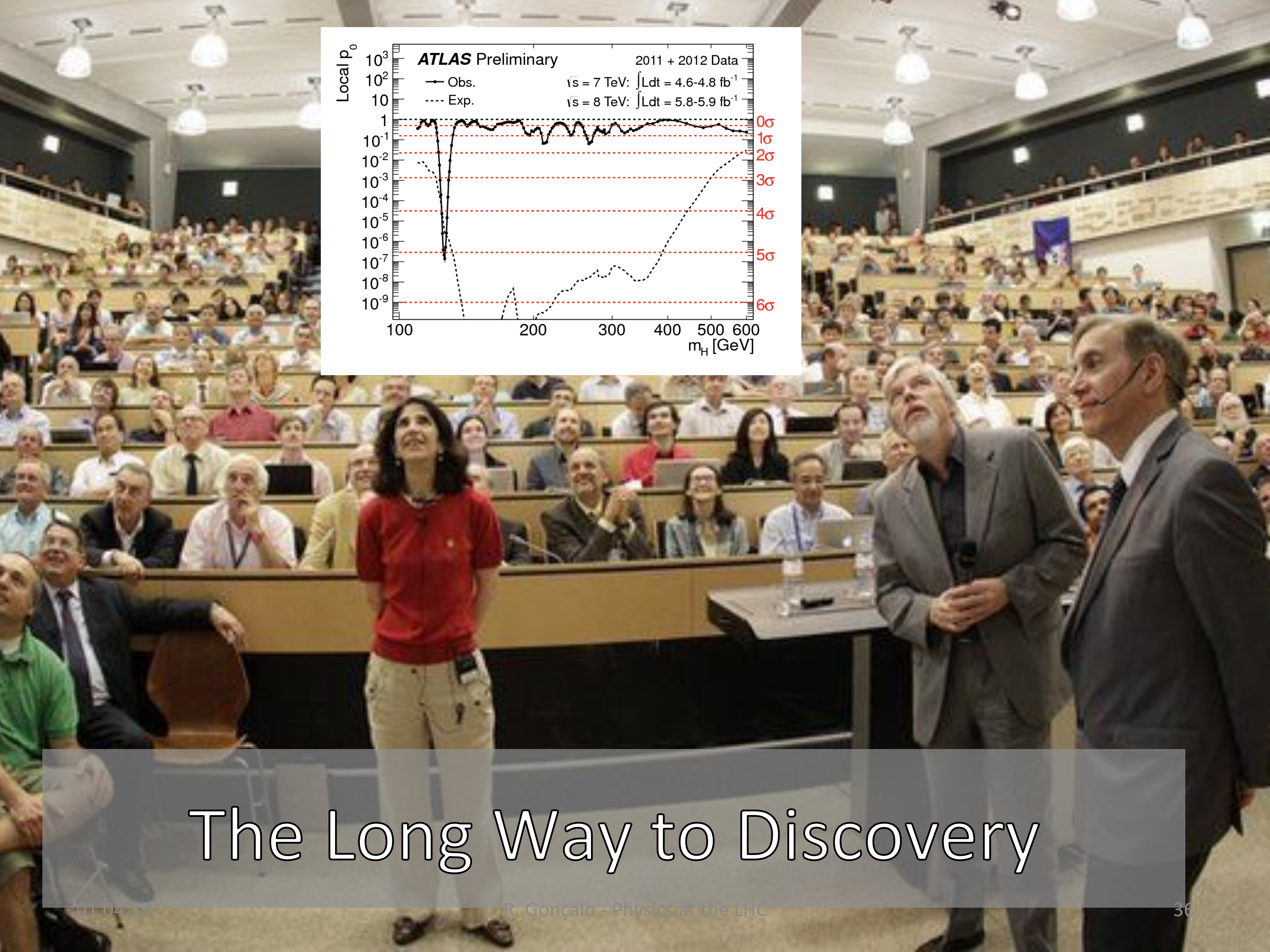
Exploring the electroweak scale

- 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







The Long Way to Discovery

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

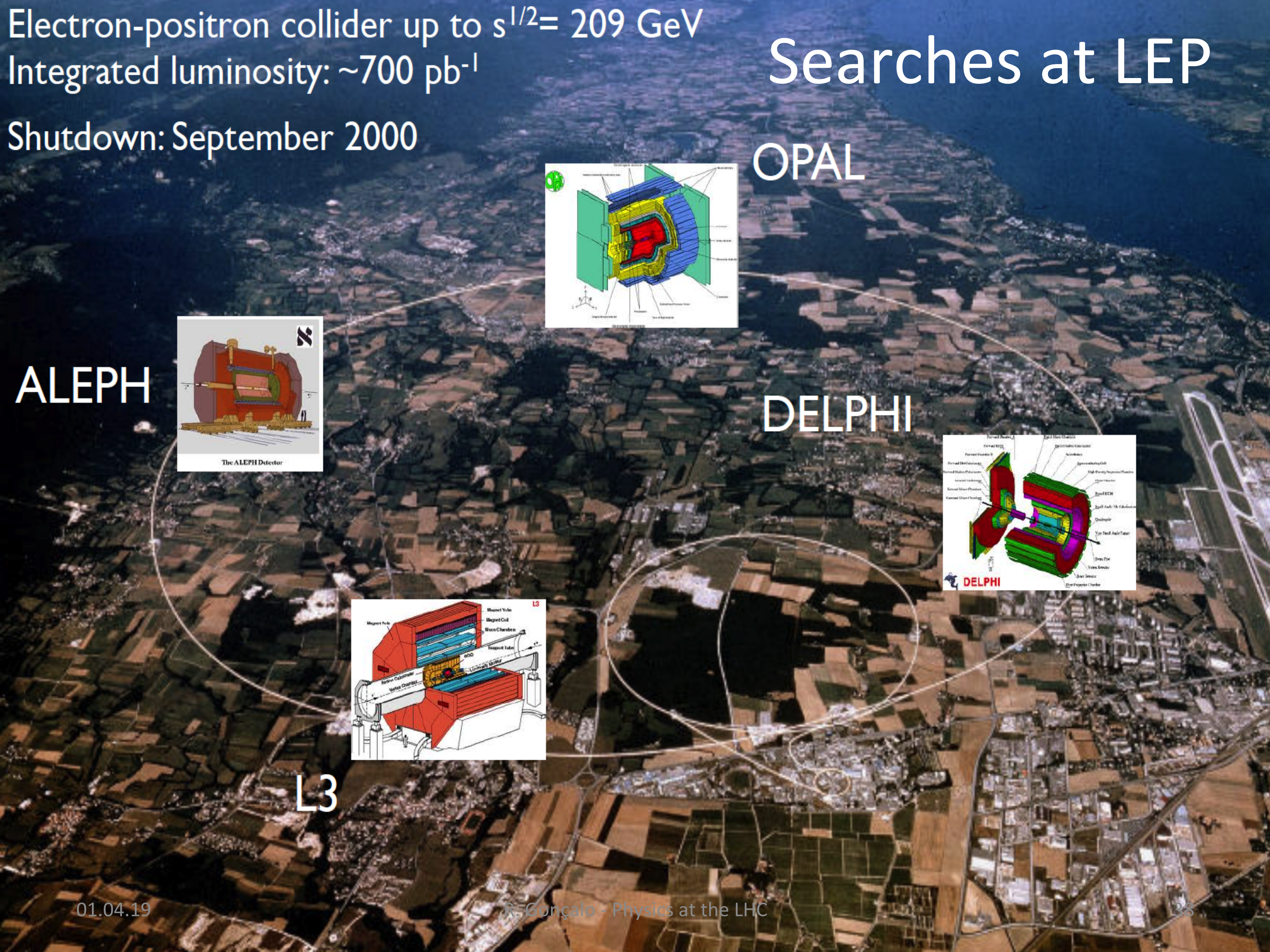
Received 7 November 1975

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}

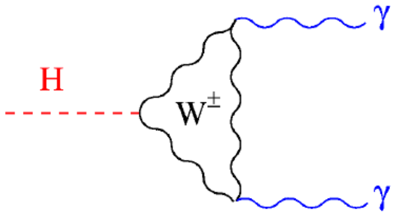
Shutdown: September 2000



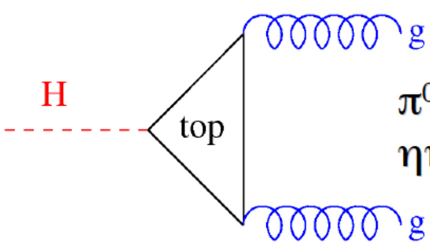
Low-mass searches at LEP

The decay branching ratios depend only on m_H:

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



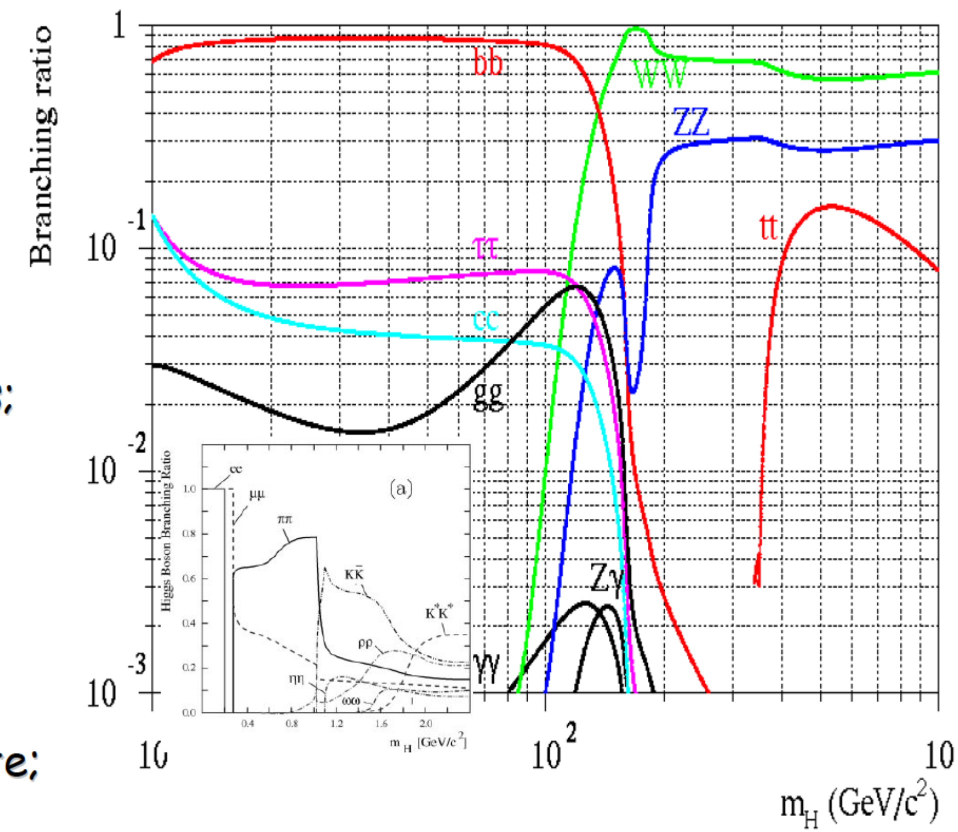
- ❑ $m_H < 2m_\mu$: $H \to e^+e^-$ dominates;
- ❑ $m_H < 2m_\pi$: $H \to \mu^+\mu^-$ dominates;
- ❑ $m_H <$ 3 - 4 GeV: $H \to gg$ dominates;



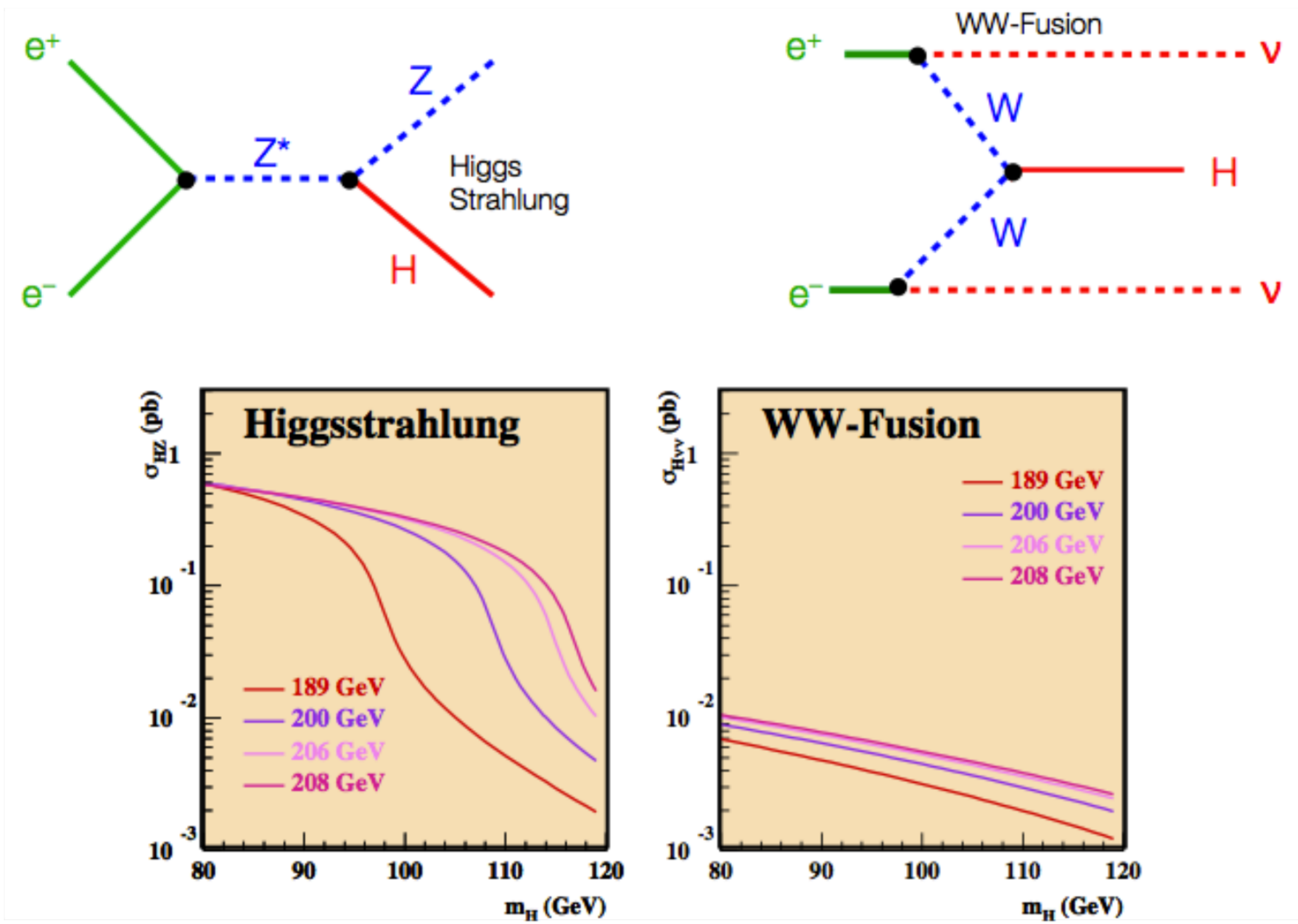
$\pi^0\pi^0$, $\pi^+\pi^-$, KK, $\eta\eta$, ... etc

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

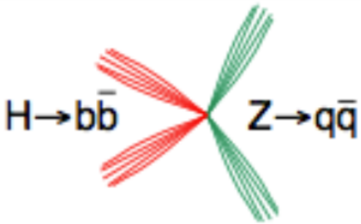
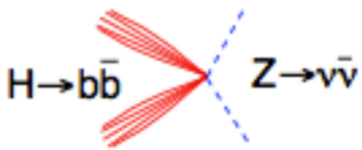
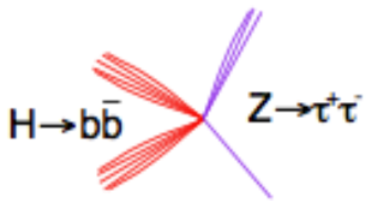
- ❑ $m_H > 2m_b$ up to 1000 GeV/c²:



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%	$WW \to qqqq$ $ZZ \to qqqq$ QCD 4-jets
 $H \to b\bar{b}$, $Z \to \nu\bar{\nu}$	missing energy	15%	$WW \to ql\nu$ $ZZ \to bb\nu\nu$
 $H \to b\bar{b}$, $Z \to \tau^+\tau^-$	τ-channel	2.4%	$WW \to qq\tau\nu$ $ZZ \to bb\tau\tau$ $ZZ \to qq\tau\tau$ 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%	$ZZ \to bbee$ $ZZ \to bb\mu\mu$

Summary of all Higgs candidates found at LEP

Invariant mass of all candidates

In total 17 candidates selected

- 15.8 background events expected

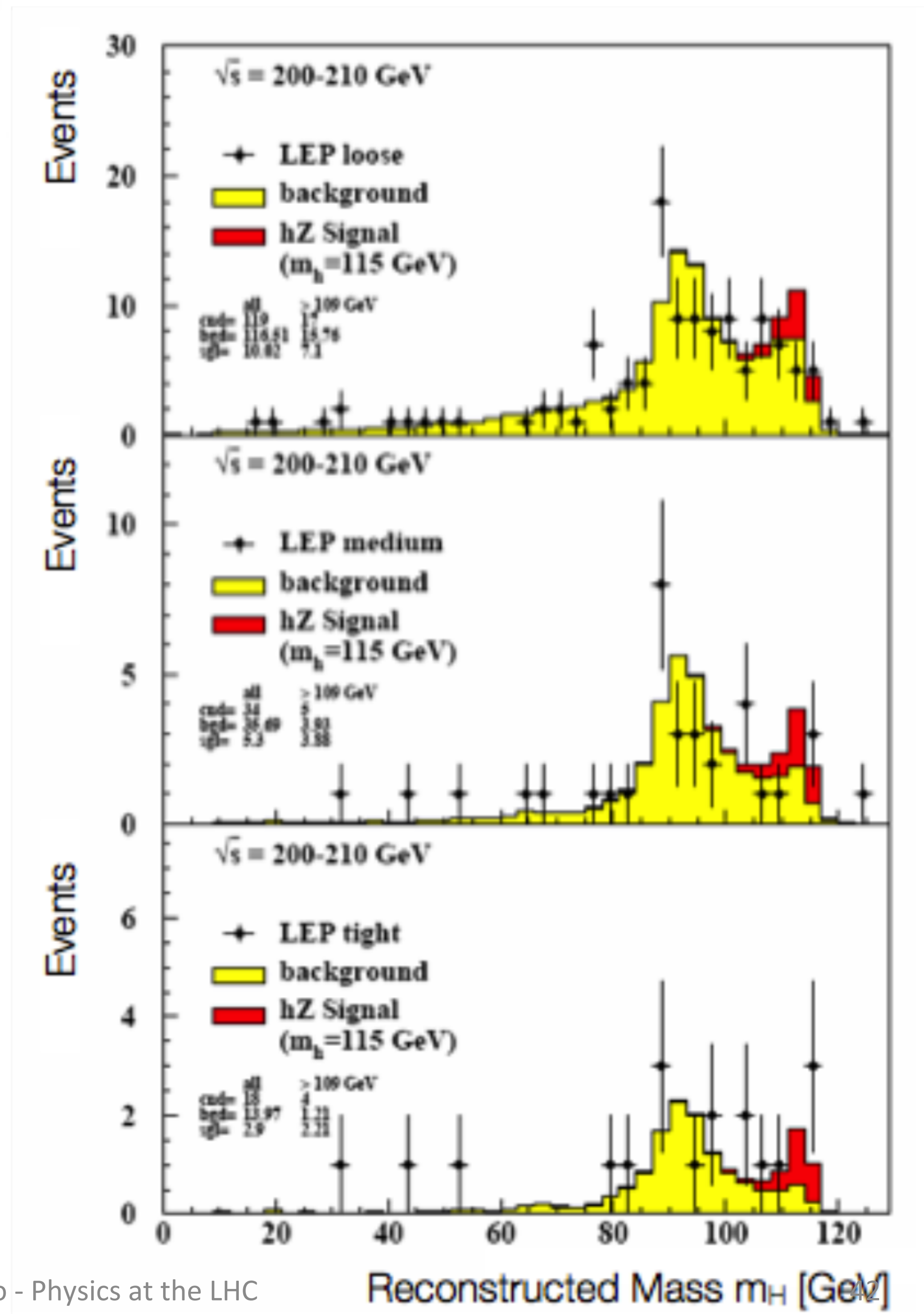
Expectation for m_H=115 GeV

- 8.4 events

Corresponding excess was not observed

Final verdict from LEP

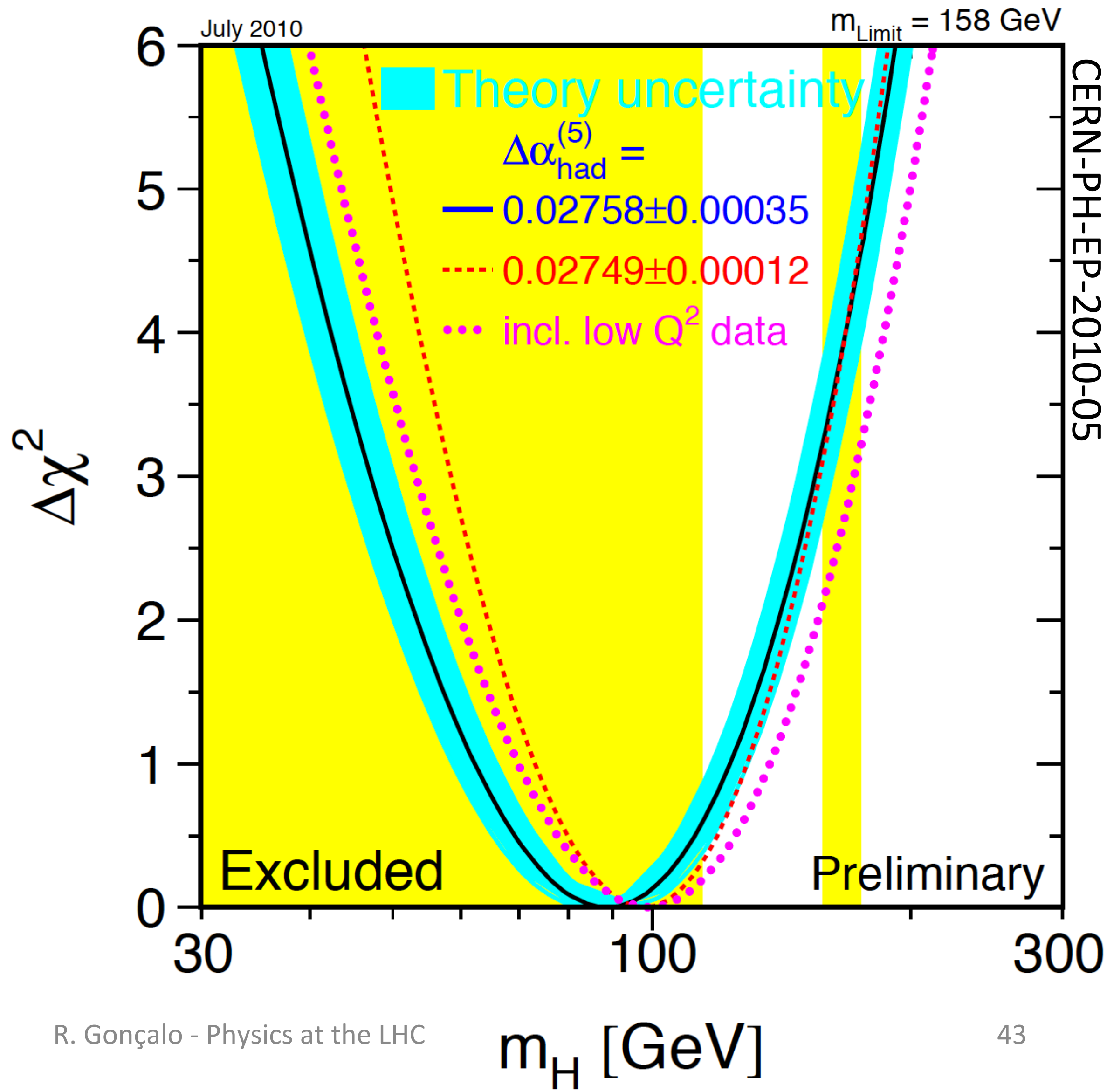
m_H>114.4 GeV @ 95% CL



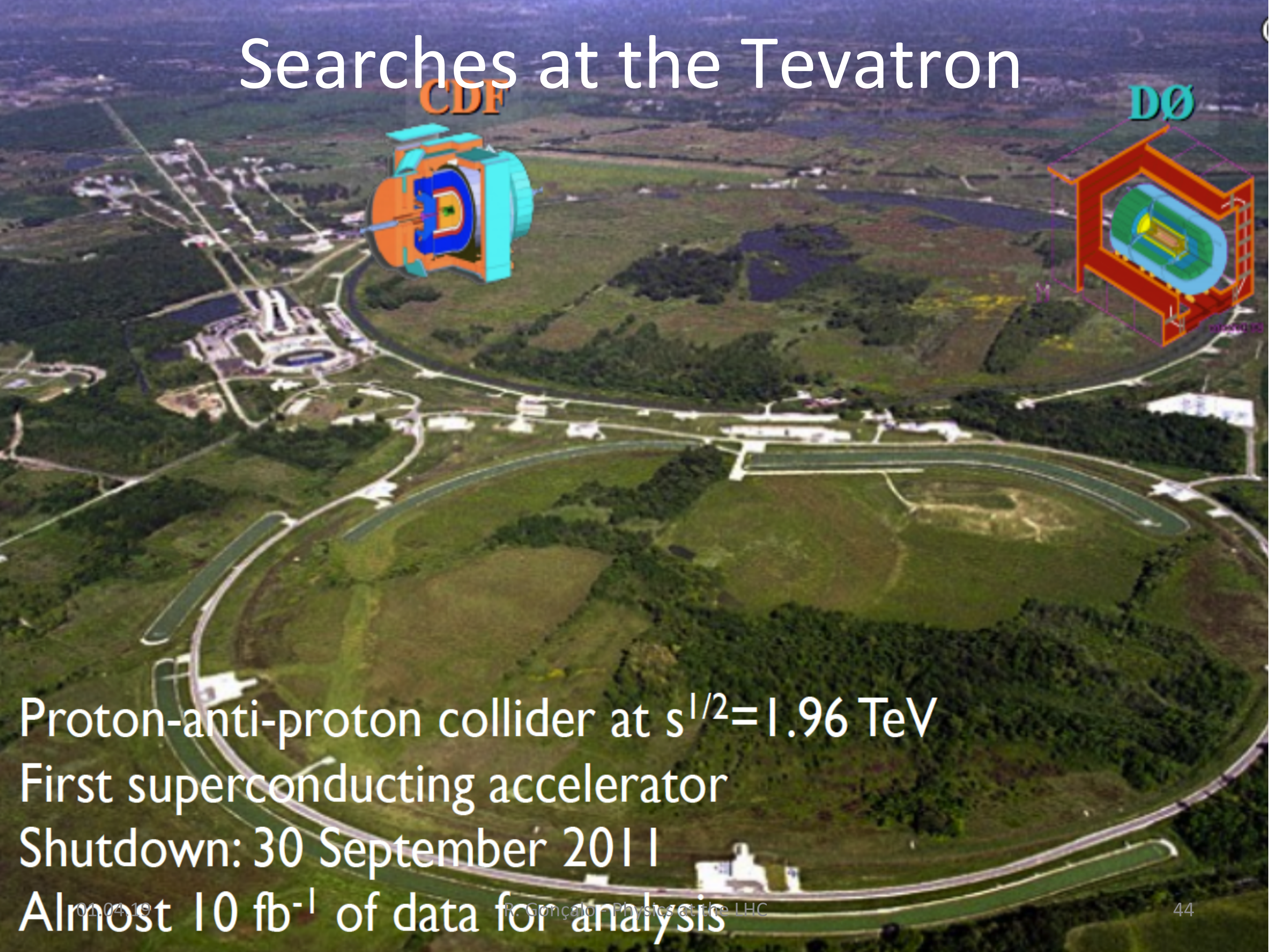
LEP's Final Legacy: the Blue Band Plot

- 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

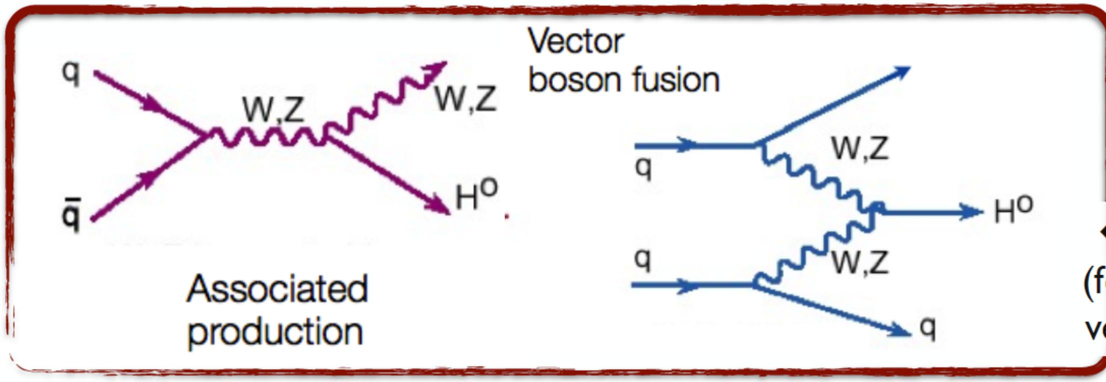


Searches at the Tevatron

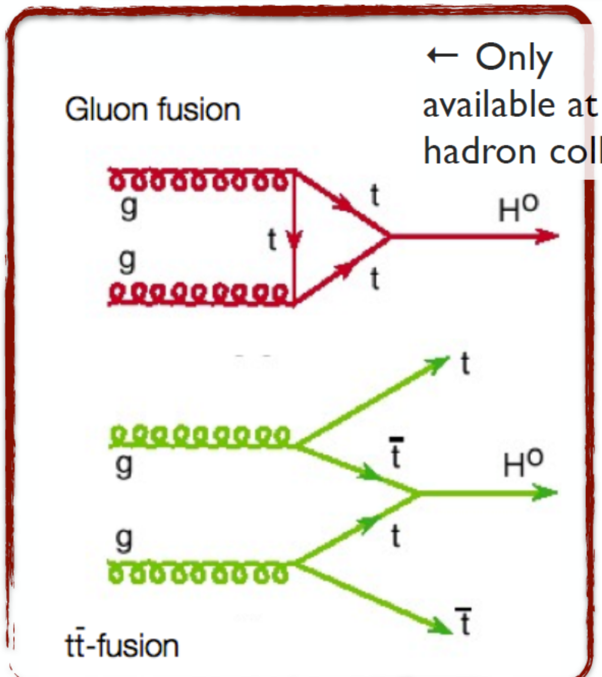


Proton-anti-proton collider at $s^{1/2}$=1.96 TeV
First superconducting accelerator
Shutdown: 30 September 2011
Almost 10 fb^{-1} of data for analysis

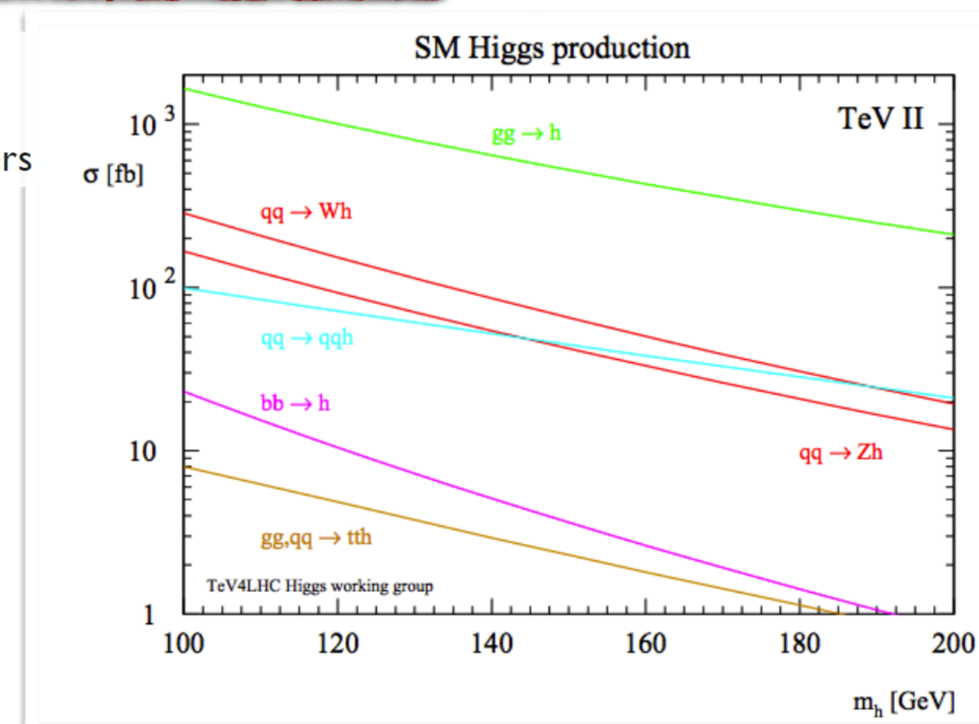
Higgs production at the Tevatron



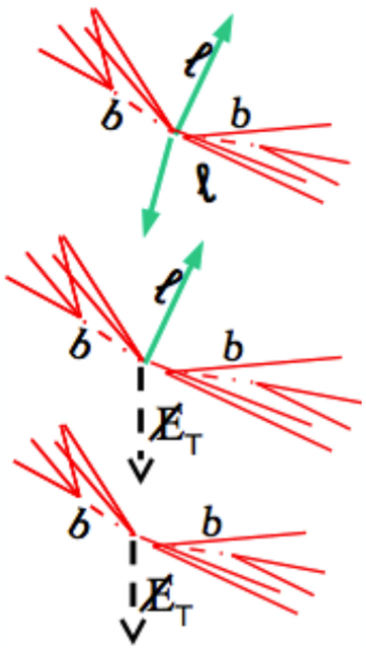
← (fermion annihilation and vector boson scattering)

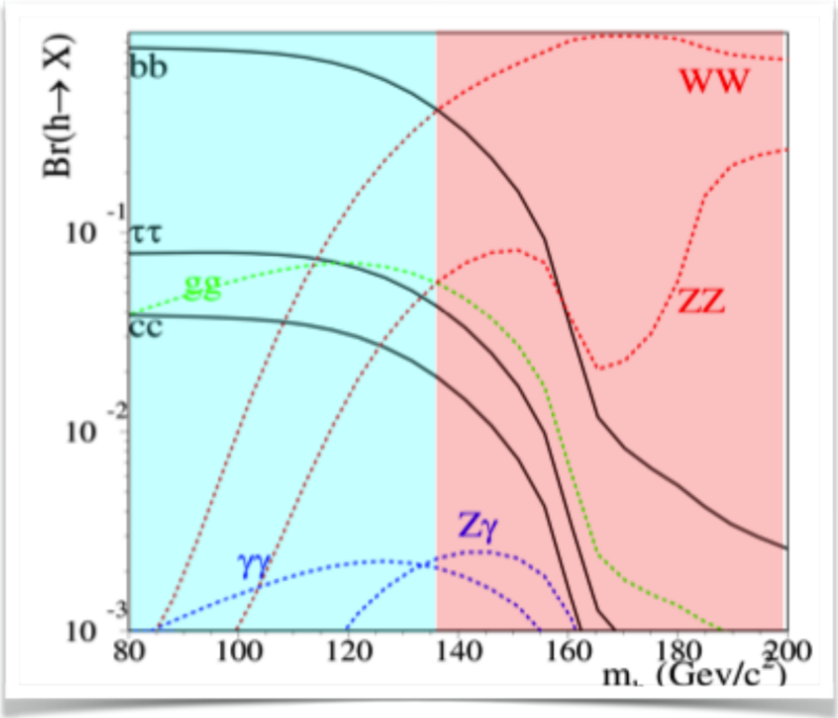


← Only available at hadron colliders



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

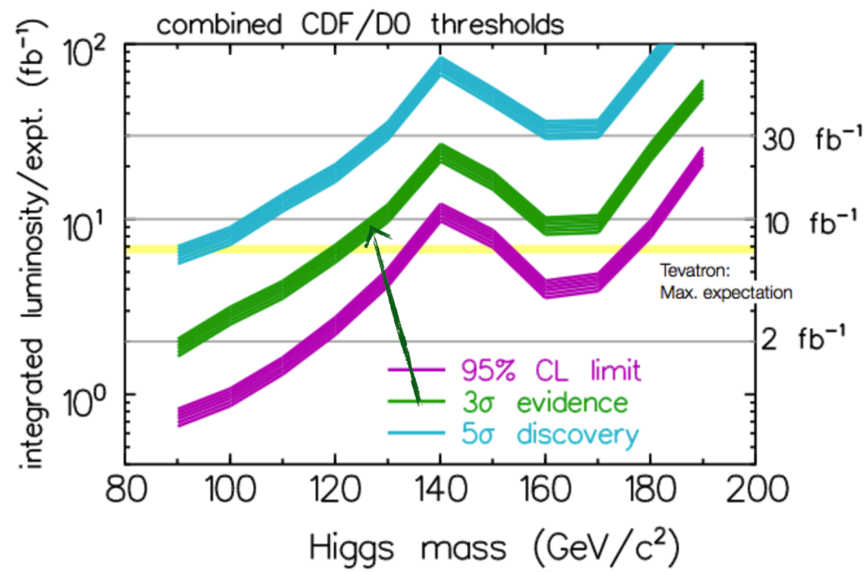
The final stand of the Tevatron

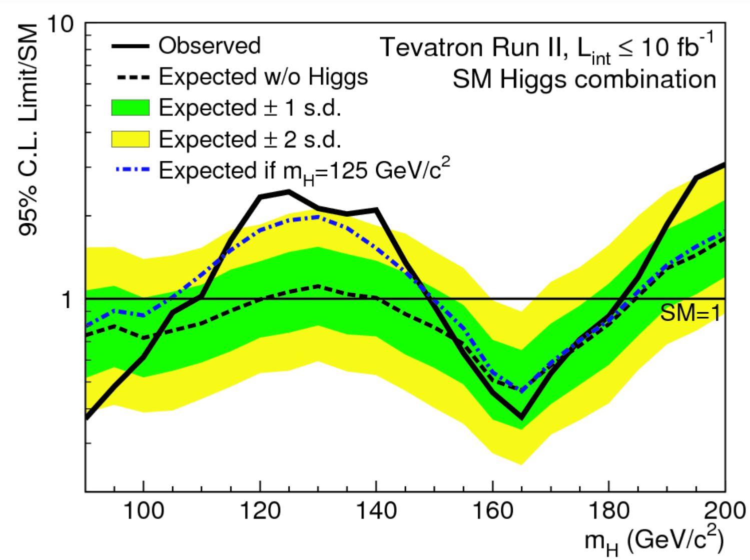
- By the end of its lifetime, the Tevatron had very sophisticated analyses of a huge number of channels

- By that time the LHC was collecting data and analysing it very fast

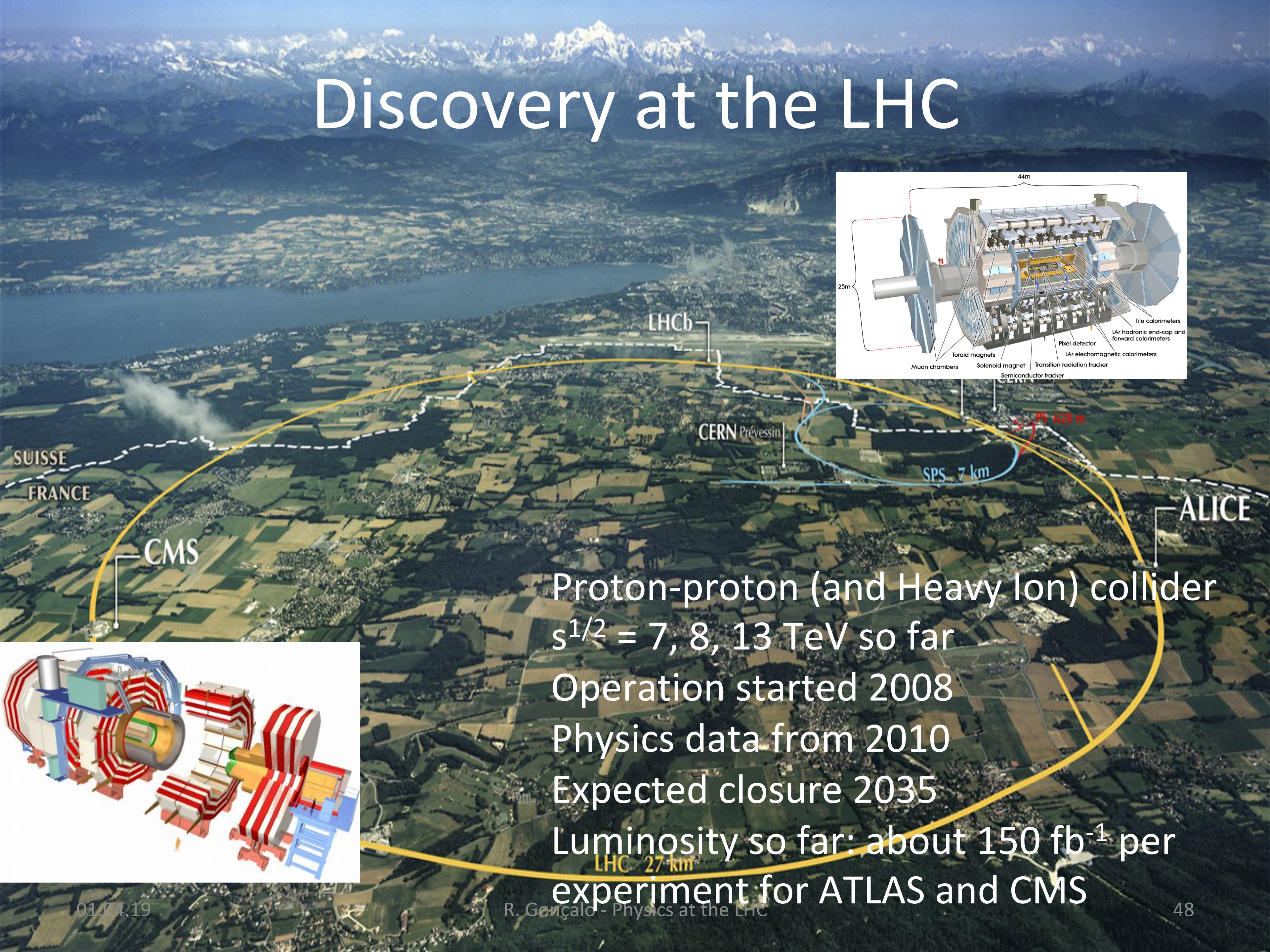
- The CDF and D0 experiments obtained a significant excess of around 3 standard deviations in the mass range $115<M_H<140$ GeV

- Not enough to claim discovery, but consistent with the LHC results



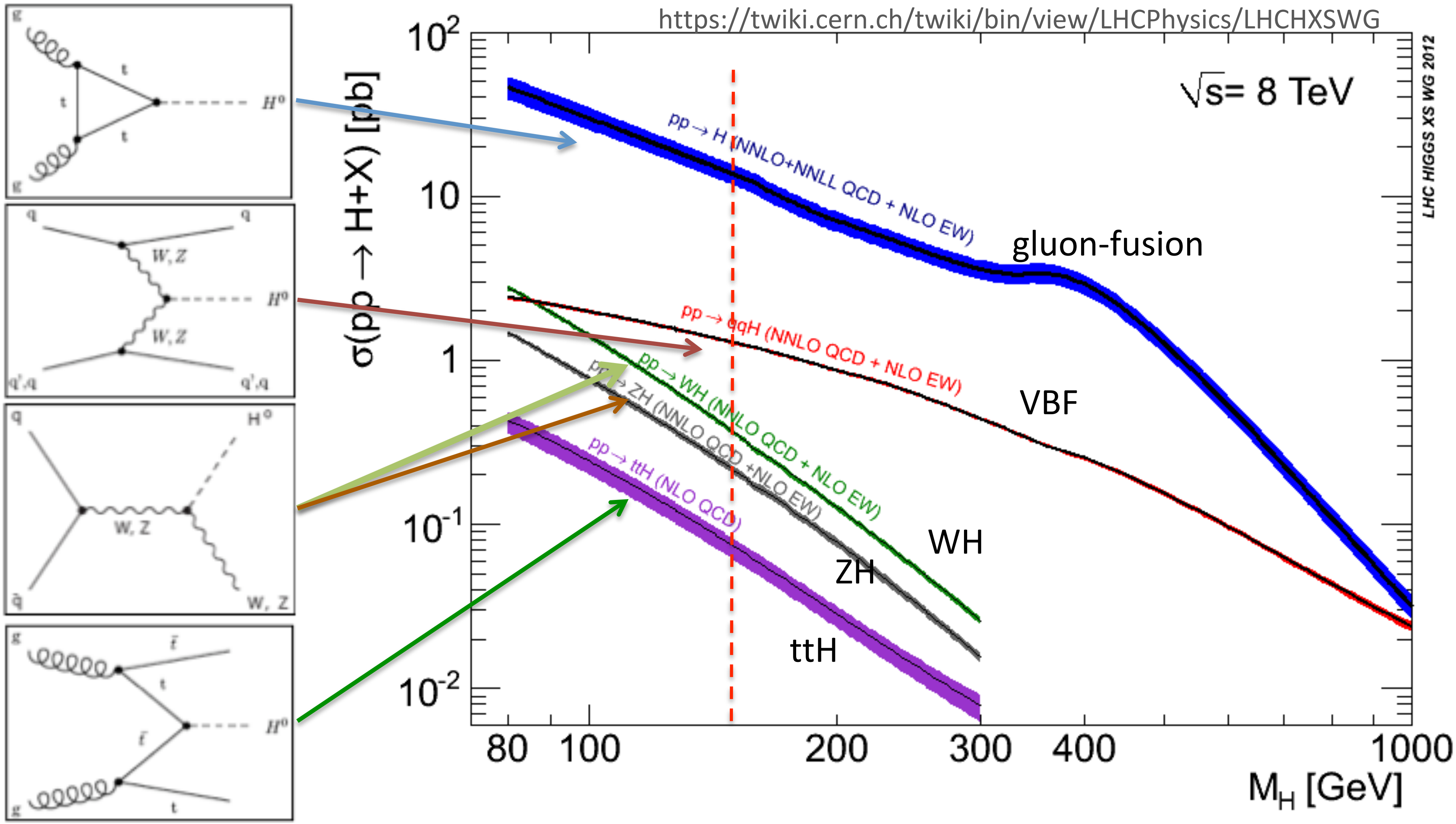


Discovery at the LHC

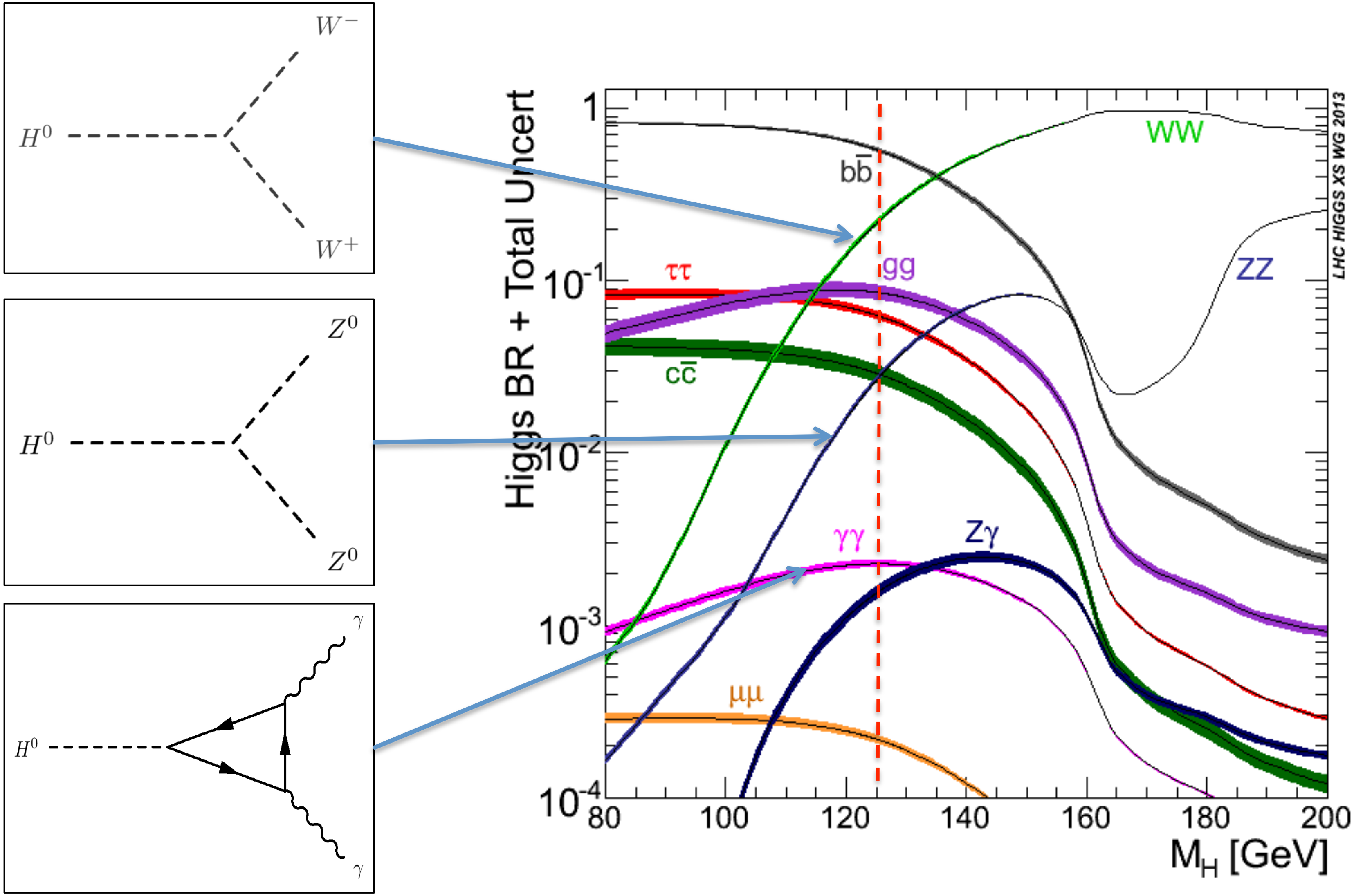


- Proton-proton (and Heavy Ion) collider
- $s^{1/2}$ = 7, 8, 13 TeV so far
- Operation started 2008
- Physics data from 2010
- Expected closure 2035
- Luminosity so far: about 150 fb^{-1} per experiment for ATLAS and CMS

At the LHC

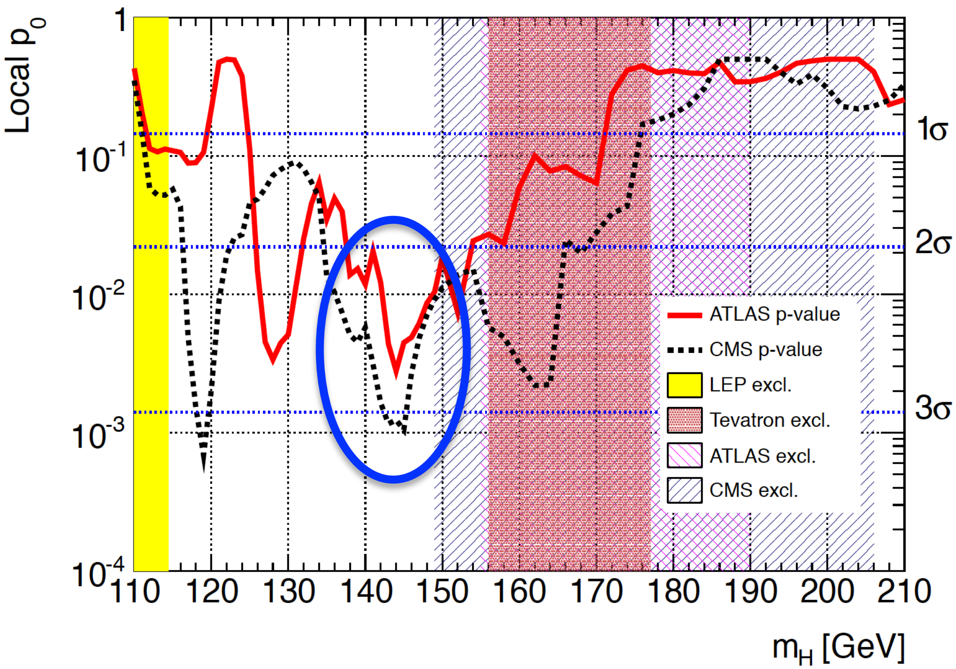


https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG
√s= 8 TeV
LHC HIGGS XS WG 2012
σ(pp → H+X) [pb]
M_H [GeV]
pp → H (NNLO+NNLL QCD + NLO EW)
gluon-fusion
pp → qqH (NNLO QCD + NLO EW)
VBF
pp → WH (NNLO QCD + NLO EW)
WH
pp → ZH (NNLO QCD +NLO EW)
ZH
pp → ttH (NLO QCD)
ttH


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

It takes time to get it right

EPS-HEP 2011 conference [6]

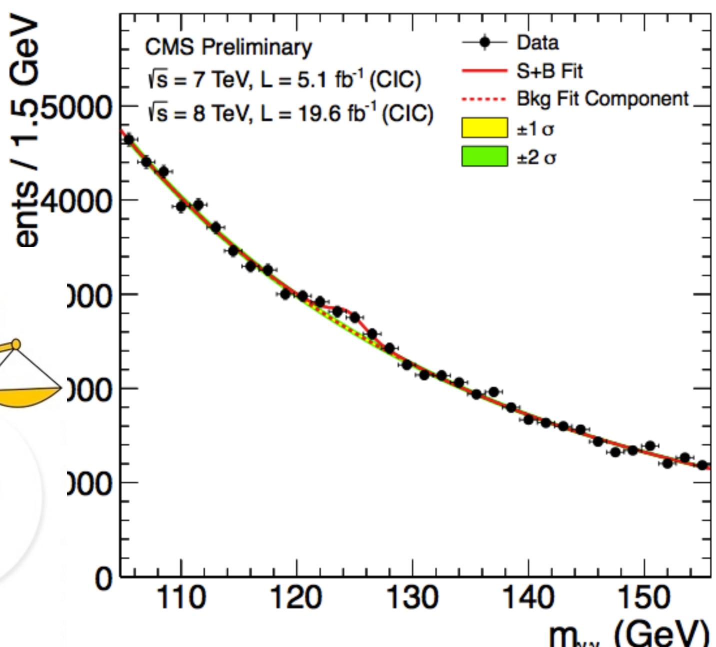


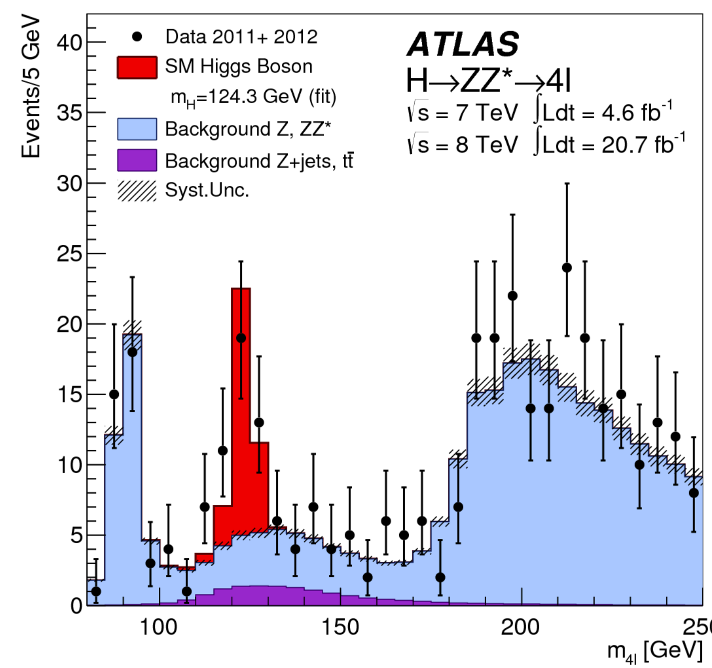
Discovery channels

- 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

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

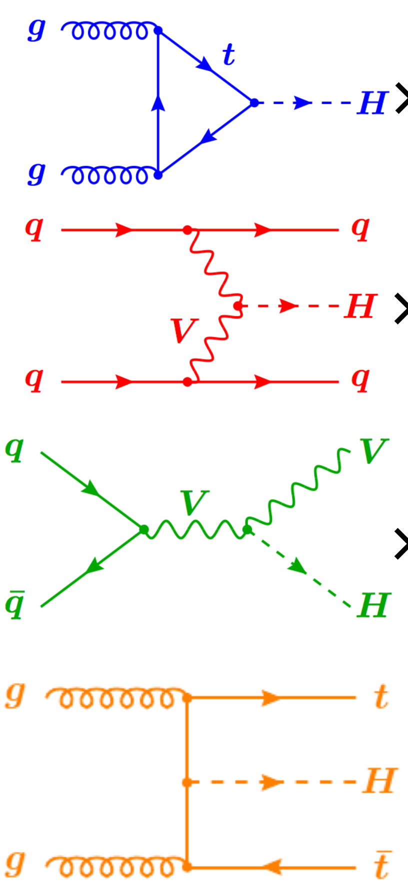
- This means about 400 000 Higgs bosons produced in about 8 000 000 000 000 000 ($8\text{x}10^{15}$) proton collisions
  - Only about 4000 events with Higgs bosons contributed to the discovery





Combining Higgs Channels

Production



$\times\kappa_g^2$

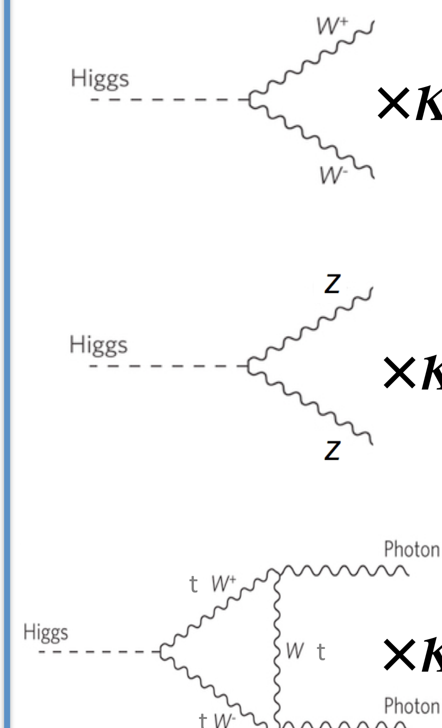
$\times\kappa_{W/Z}^2$

$\times\kappa_{W/Z}^2$

$\times\kappa_t^2$

$\times$

Decay



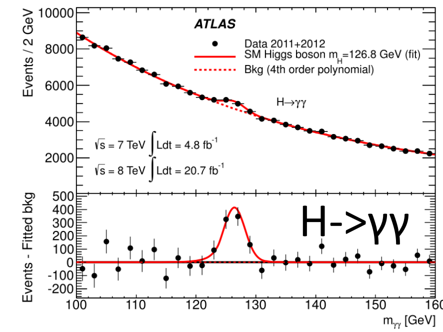
$\times\kappa_W^2$

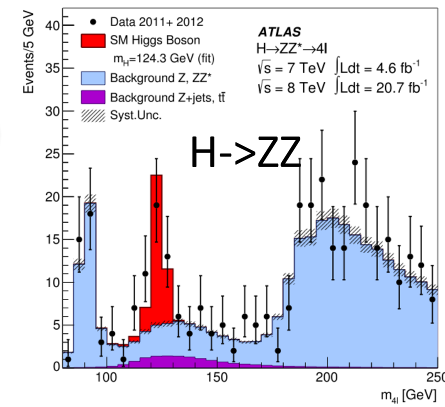
$\times\kappa_Z^2$

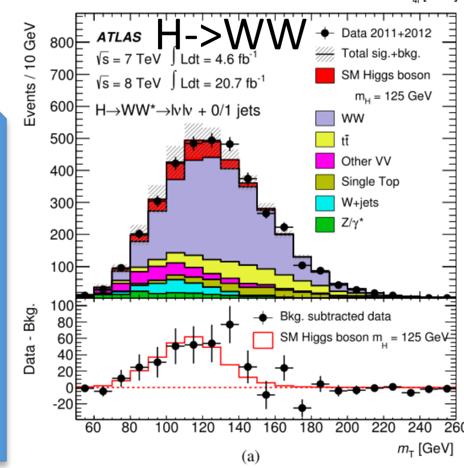
$\times\kappa_\gamma^2$

FIT

Backgrounds +

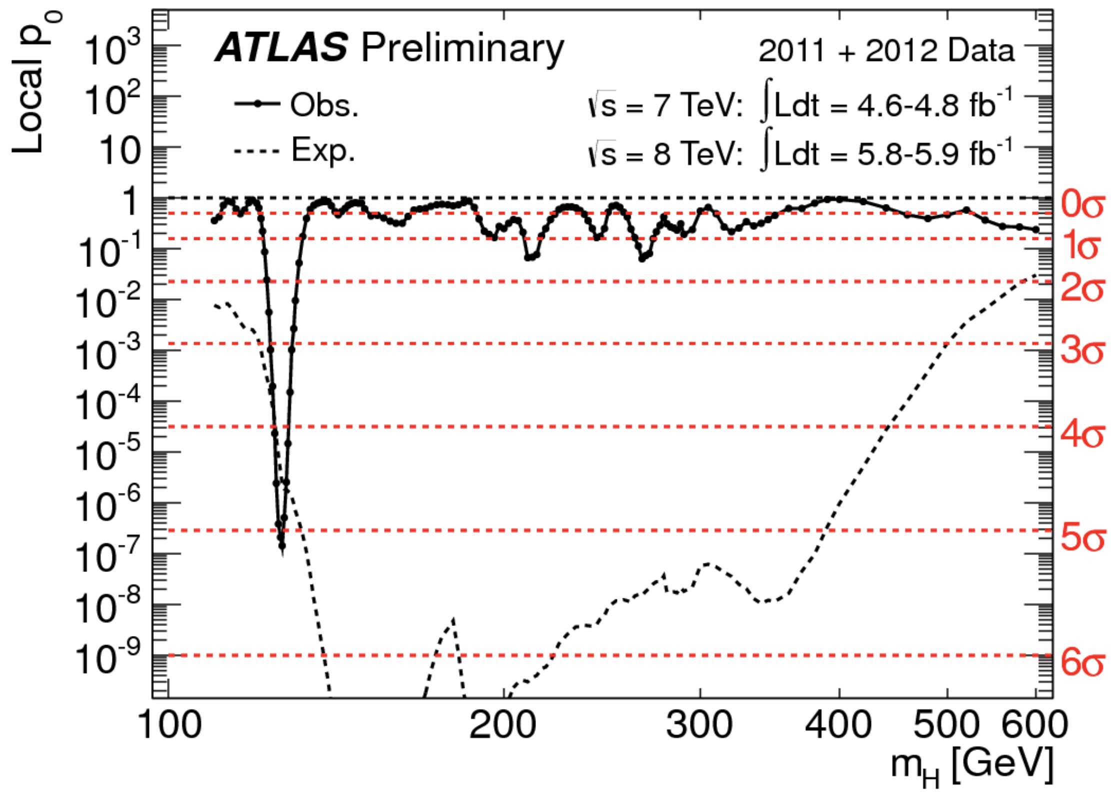






The p_0 Discovery Plot

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

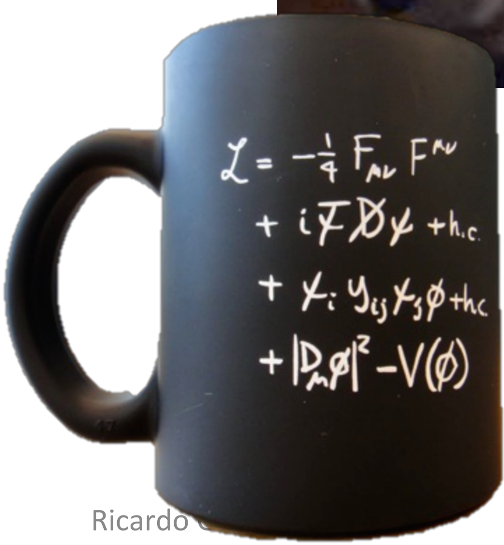


- This corresponds to a probability of **1 in 3.5 million** that this was a false positive from fluctuating backgrounds

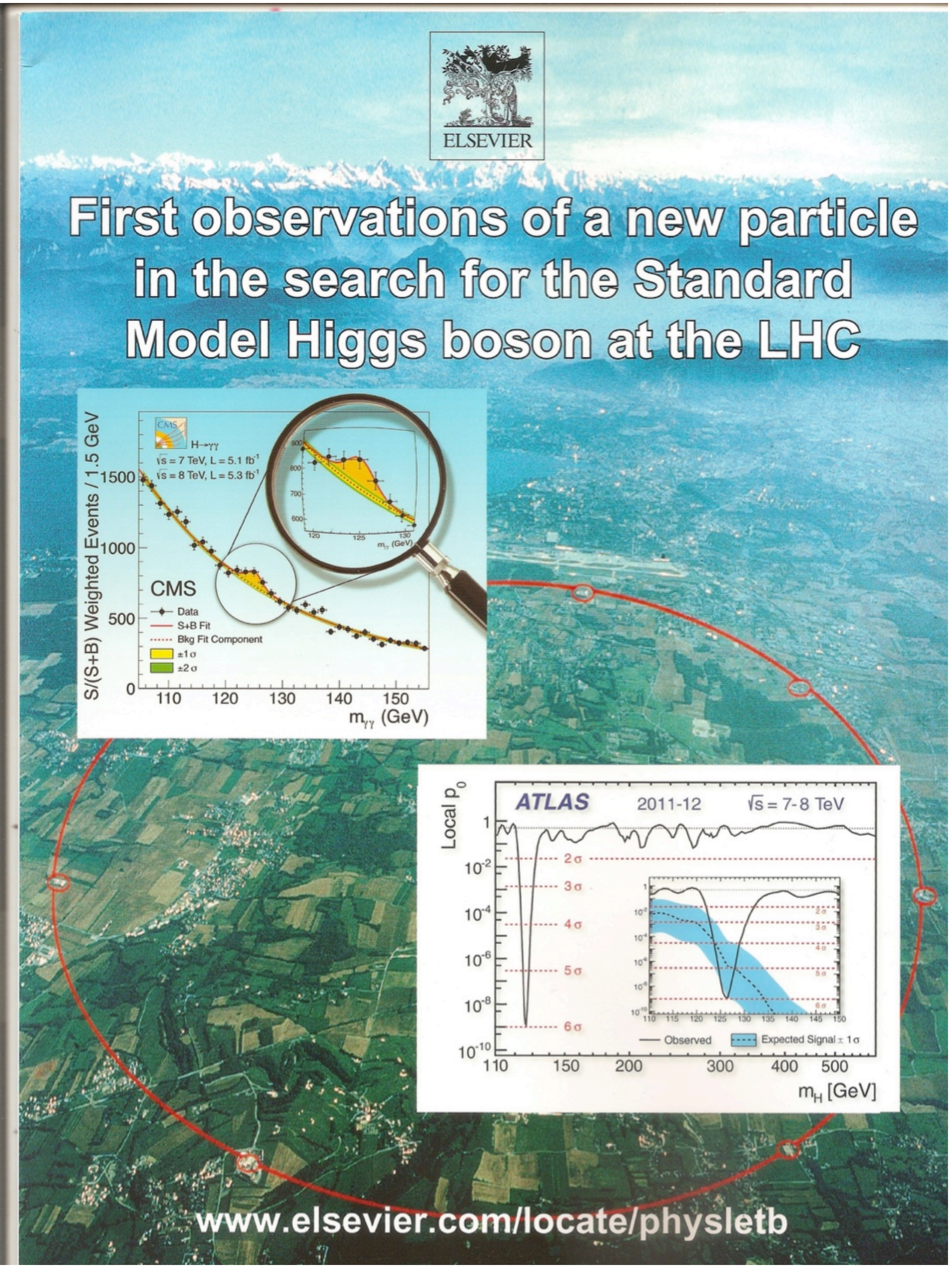
2013 Physics Nobel Prize Higgs for the Higgs Boson Discovery

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**"*



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

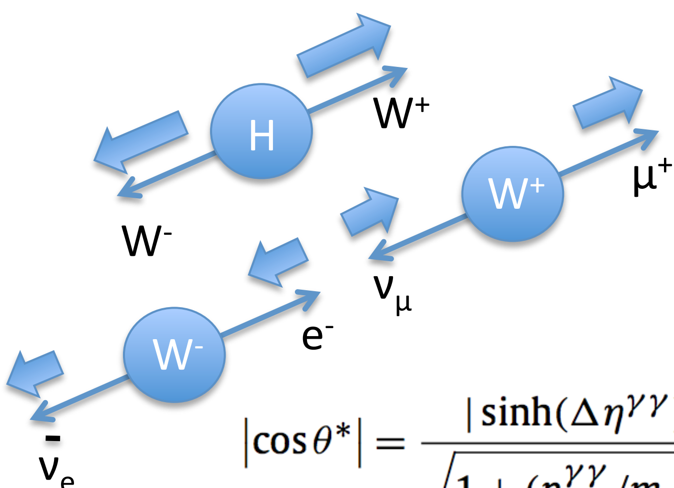
Best wishes!
Peter Higgs

What we have found out since

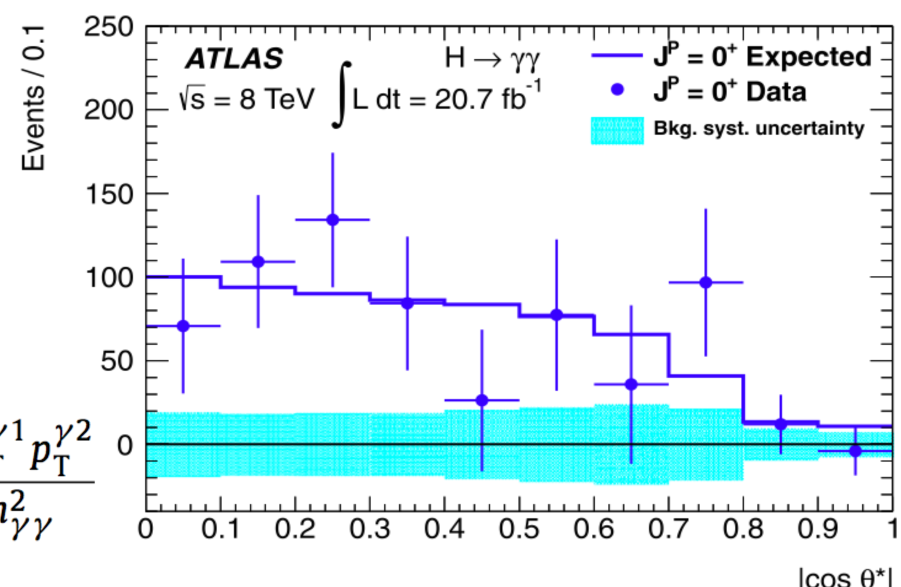
A (quick) foretaste of the next few lectures

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)



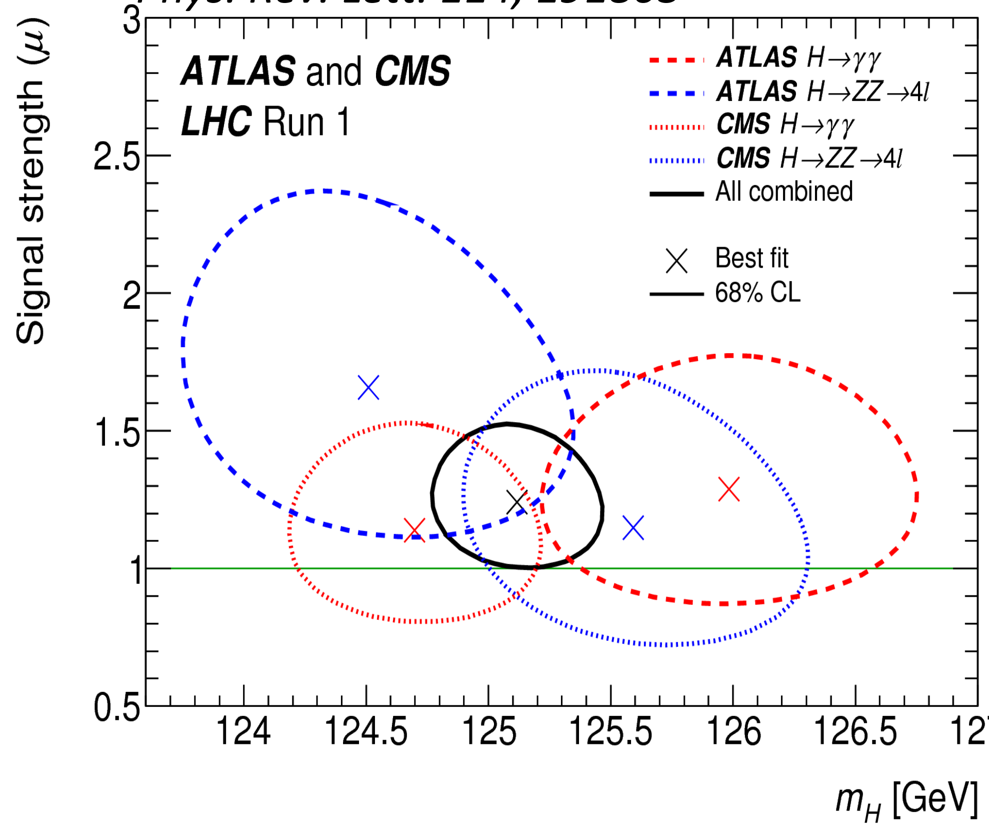
$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}}\frac{2p_T^{\gamma 1}p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$



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!

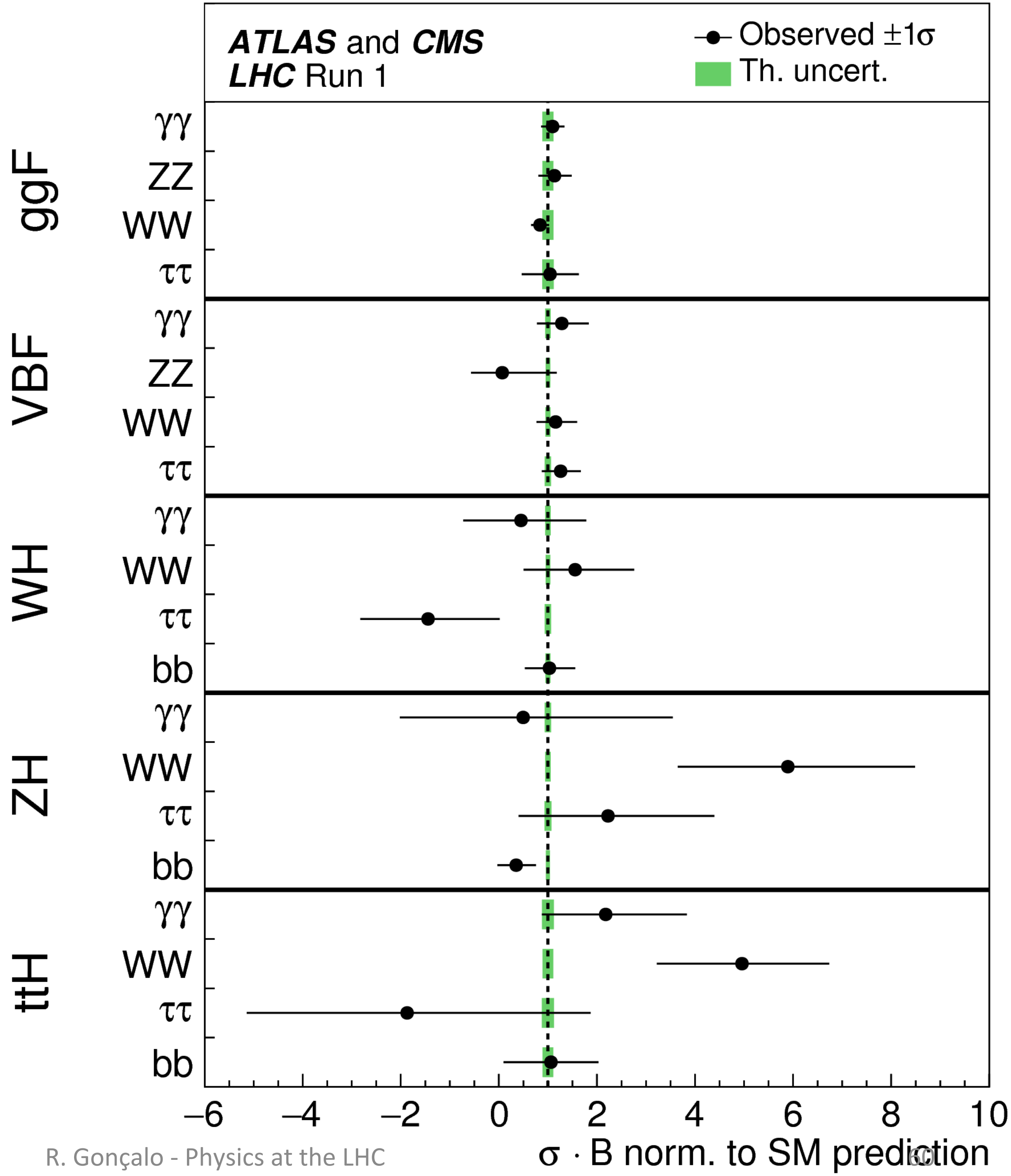
Phys. Rev. Lett. 114, 191803



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

Cross section compared to SM expectation

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



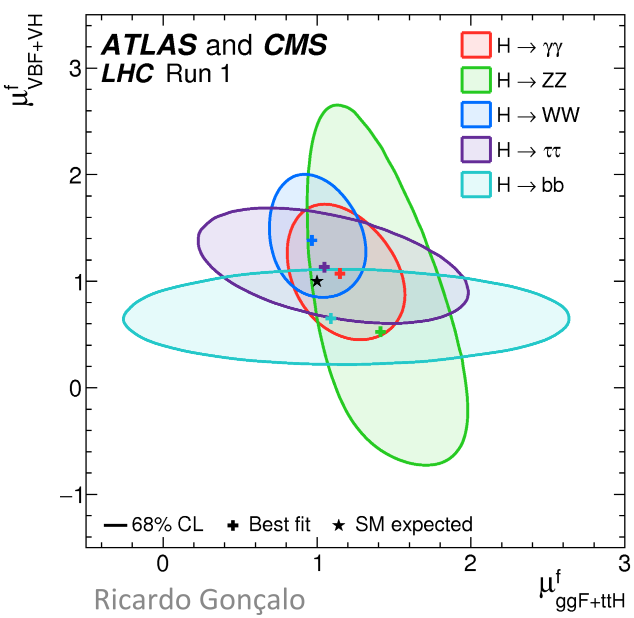
Probing the 125 GeV Higgs

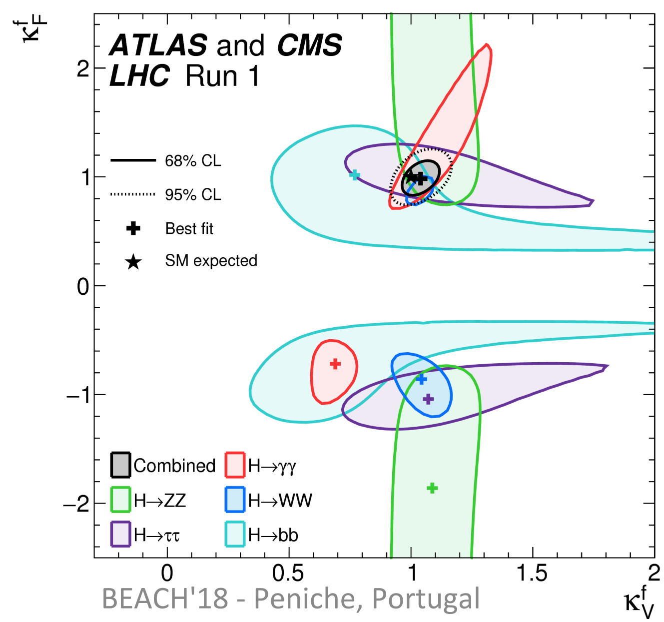
Phys. Rev. Lett. 114 (2015) 191803
JHEP 08 (2016) 045

The Run 1 legacy

- Mass – Higgs mass measured with 0.4% accuracy:
  - **m_H = 125.09 ± 0.21 (stat.) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV**
- Couplings:
  - ggF with H → ZZ,γγ,WW **observed** by individual experiments
  - VBF and H → ττ observed with **>5σ** significance by ATLAS+CMS combination
  - ttH, VH production and H → bb **not observed** during Run1
- Couplings **compatible with SM**:
  - Signal strength: $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.06^{+0.35}_{-0.27}$
  - Coupling modifiers broadly consistent with SM but still large uncertainty

$\mu = (\sigma \times BR)_{Obs} / (\sigma \times BR)_{SM}$



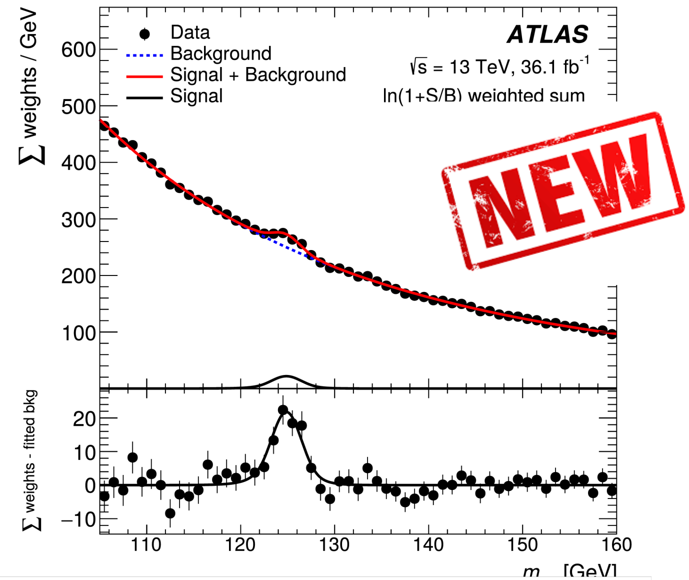


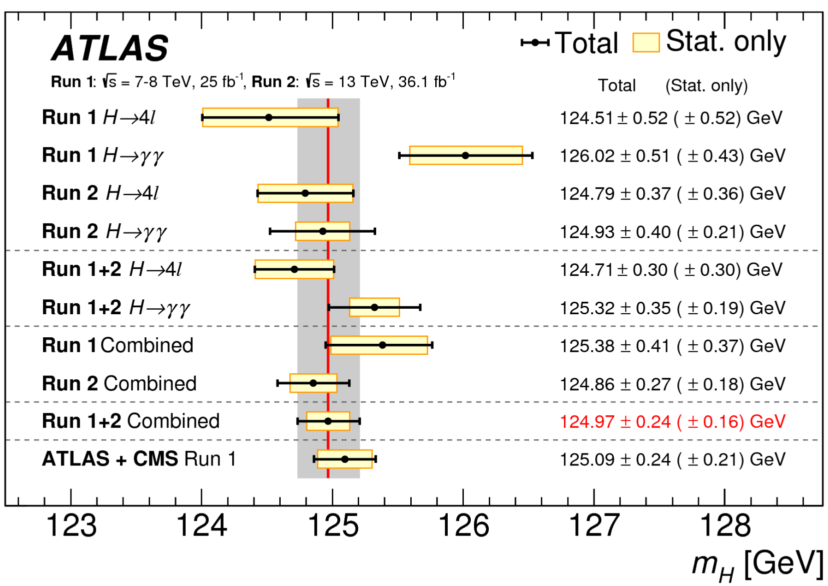
Significance (σ)		
Prod.	Obs.	Expect.
VBF	5.4	4.7
VH	3.5	4.2
ttH	4.4	2.0
Decay	Obs.	Expect.
H→ττ	5.5	5.0
H→bb	2.6	3.7

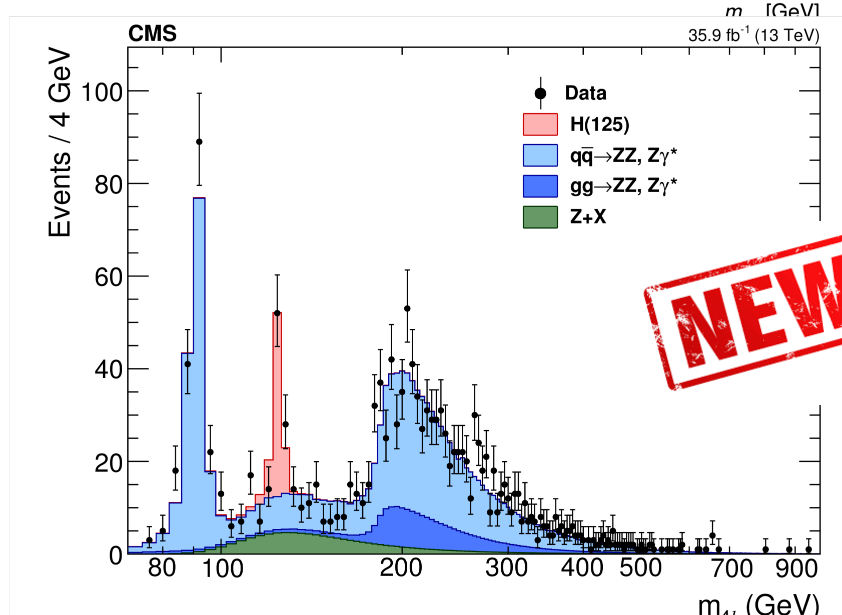
arXiv:1804.02716 [hep-ex]; arXiv:1706.09936 [hep-ex]; arXiv:1806.00242 [hep-ex]

Run 2: Higgs boson mass

- Mass measurement from CMS $H \rightarrow ZZ^* \rightarrow 4l$:
  $m_H^{ZZ^*} = 125.26 \pm 0.20\ (\text{stat}) \pm 0.08\ (\text{syst})$ GeV
- New Measurements from ATLAS
  $H \rightarrow \gamma\gamma$: $m_H^{\gamma\gamma} = 124.93 \pm 0.40$ GeV
  $H \rightarrow ZZ^* \rightarrow 4l$: $m_H^{ZZ^*} = 124.79 \pm 0.37$ GeV
- Run 1+2 combination from ATLAS:
  $m_H = 124.97 \pm 0.19\ (\text{stat}) \pm 0.13\ (\text{syst.})$ GeV







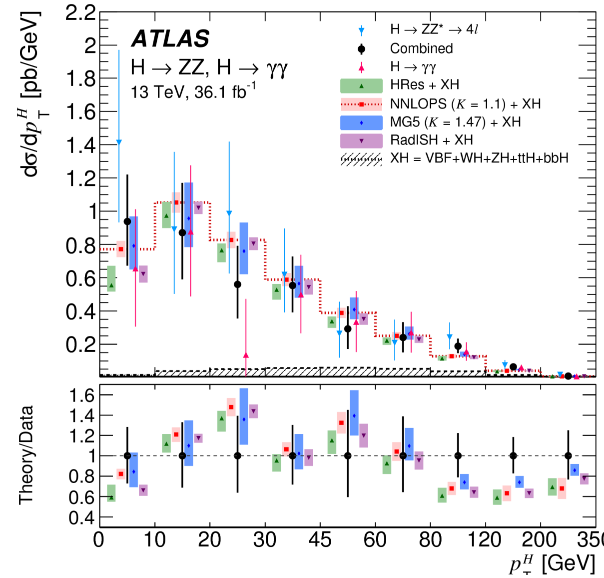
JHEP 11 (2017) 047; CMS-HIG-17-015; ATLAS-CONF-2018-002; ATLAS-CONF-2018-018

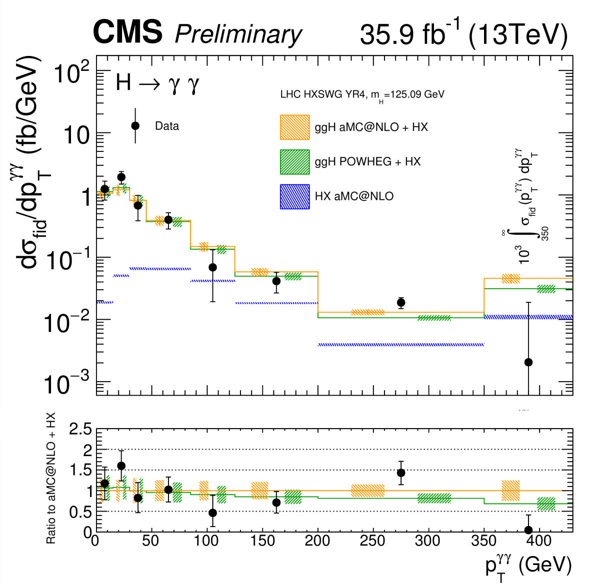
Differential Higgs boson cross sections

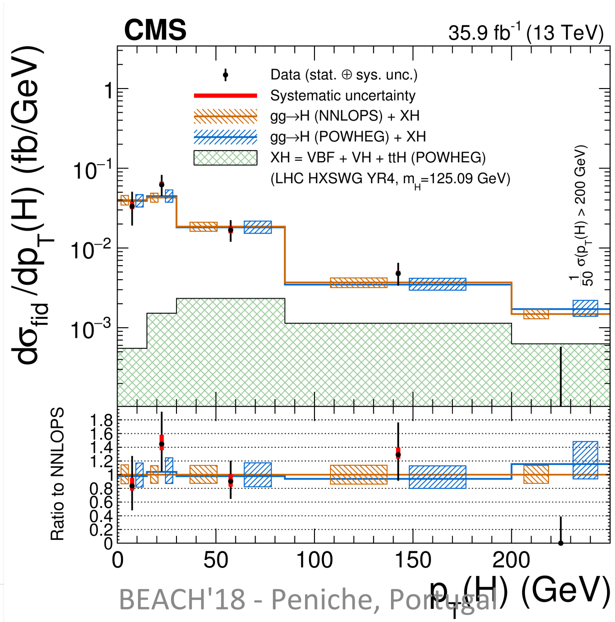
- Reached a new phase in the exploration of the Higgs sector!

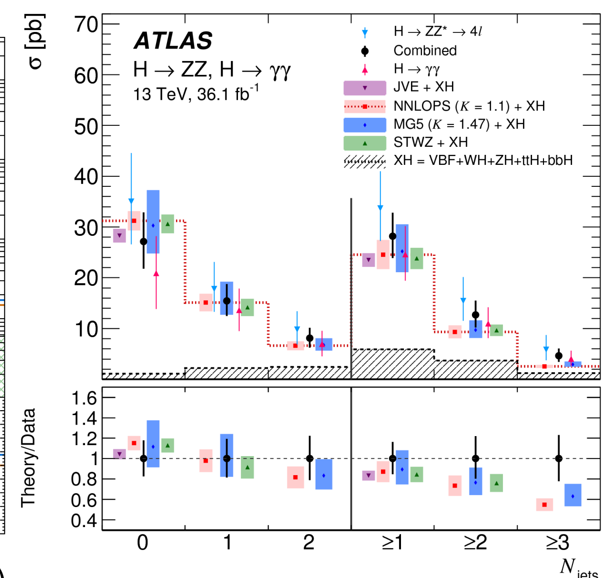
NEW

- Differential cross sections:
  - Higgs p_T sensitive to new physics in gluon-fusion loop
  - Number of jets sensitive to modeling of radiation and different production modes









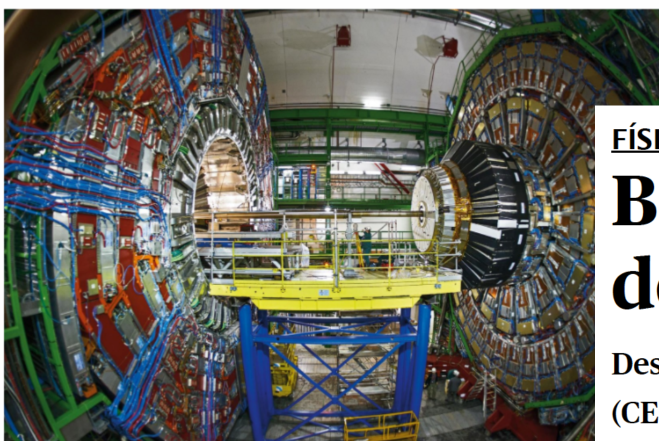
Últimas novidades!!

FÍSICA DE PARTÍCULAS

Bosão de Higgs revela que relação mantém com o quark *top*

Investigadores portugueses participaram na descoberta.

PÚBLICO • 4 de Junho de 2018, 19:42



O detector CMS no grande acelerador de partículas LHC, em Genebr

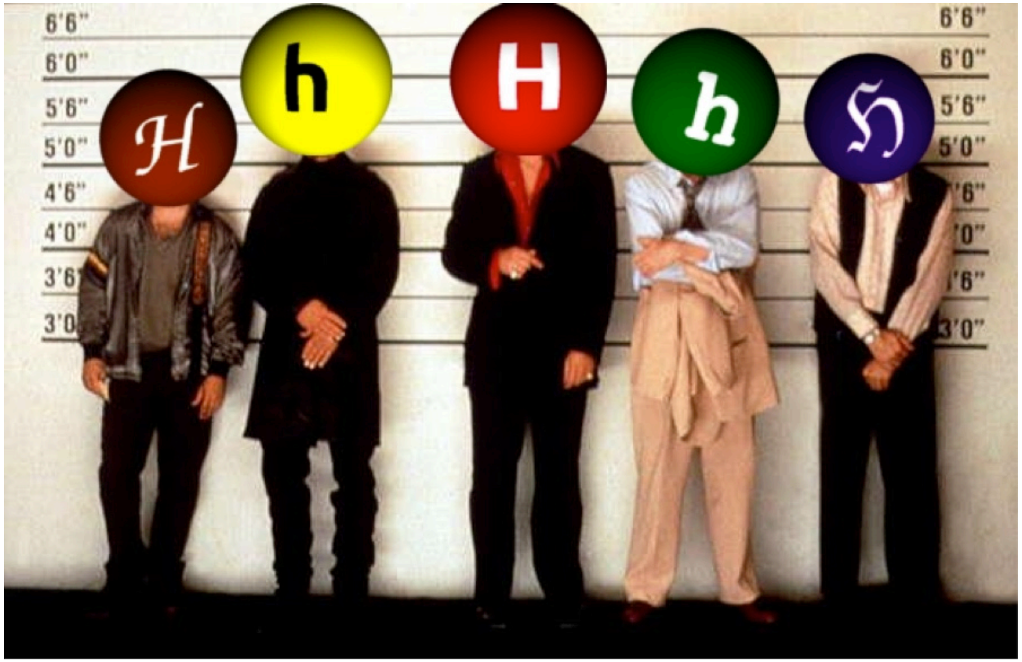
FÍSICA DE PARTÍCULAS

Bosão de Higgs visto (finalmente) a desintegrar-se em quarks *bottom*

Descoberta anunciada no Laboratório Europeu de Física de Partículas (CERN) é um passo fundamental para perceber como o bosão de Higgs faz com que as partículas fundamentais adquiram massa.

PÚBLICO • 28 de Agosto de 2018, 17:47

Casting a wider net



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?

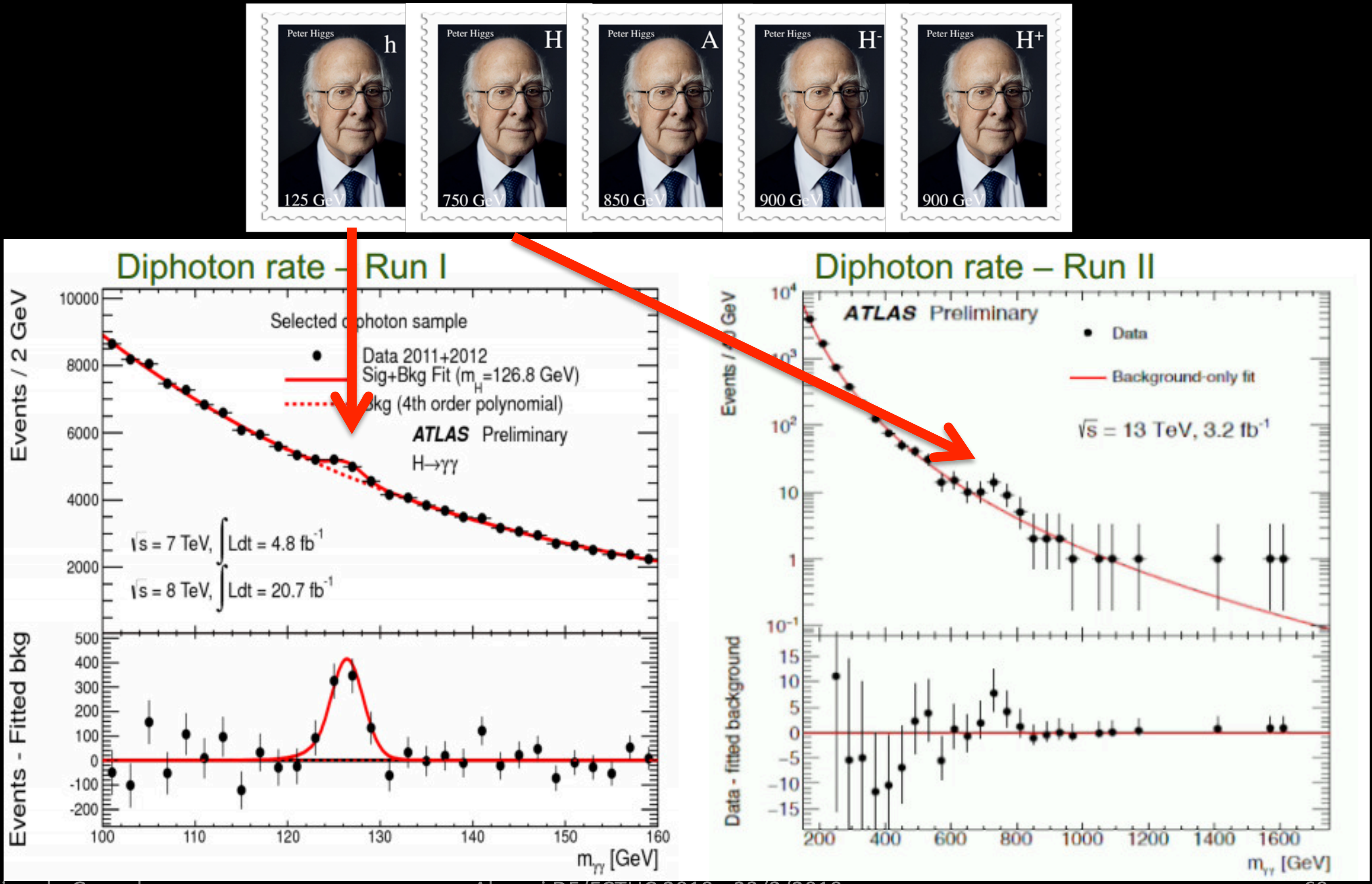
Many possible theories

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

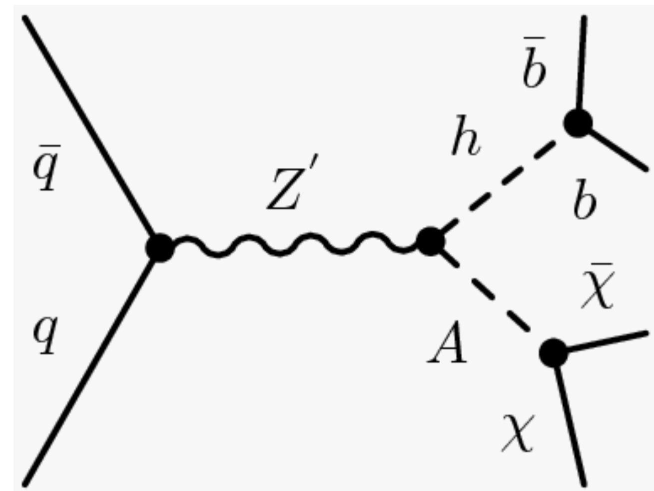
Additional Higgs bosons?

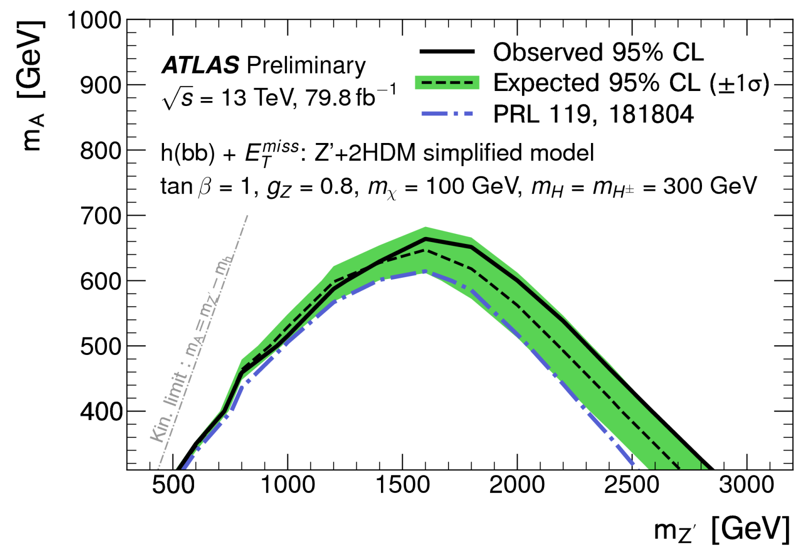


NEW
25 July 2018

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





NEW
10 Aug 2018

arXiv:1808.03599

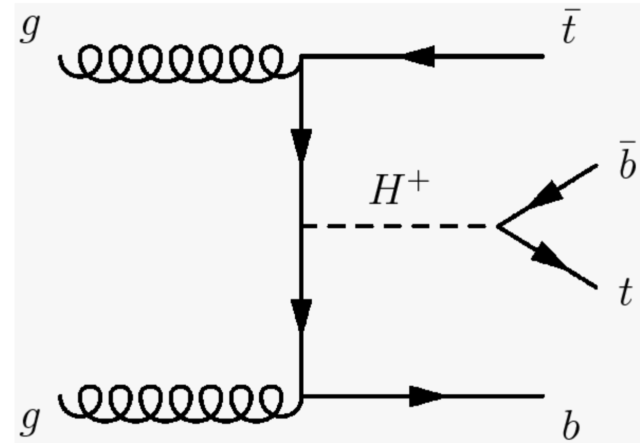
Charged Higgs: $H^+ \rightarrow tb$

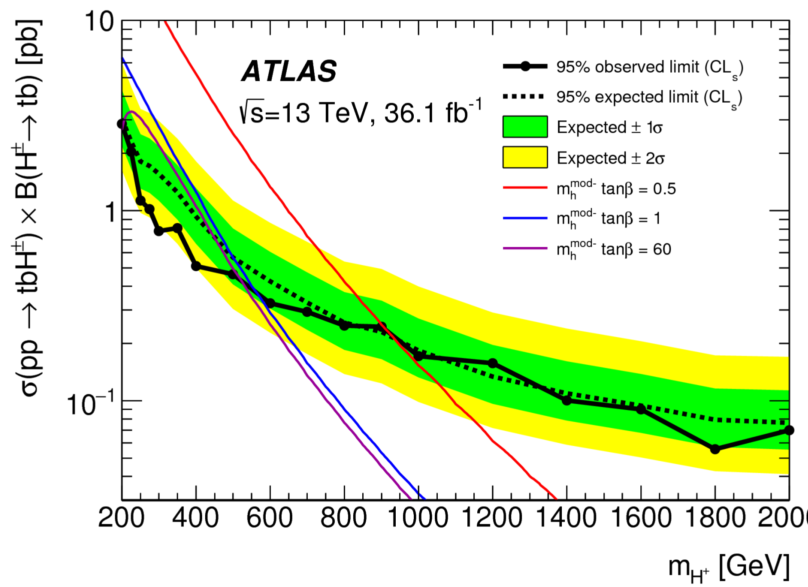
- Explored single-lepton and dilepton tt final states
  - In range m_{H+}: 200 – 2000 GeV
- 36.1 fb^{-1} of 13 TeV data

- Events categories: N_{jets} and $N_{b\text{-}tags}$
  - Allow to constrain backgrounds in simultaneous fit

- BDTs trained in signal regions
  - Separate signal and background for 18 mass points
  - Matrix method used in single-lepton channel

- Extracted limits on σ x BR and on m_{H+} - tan β plane for two MSSM scenarios





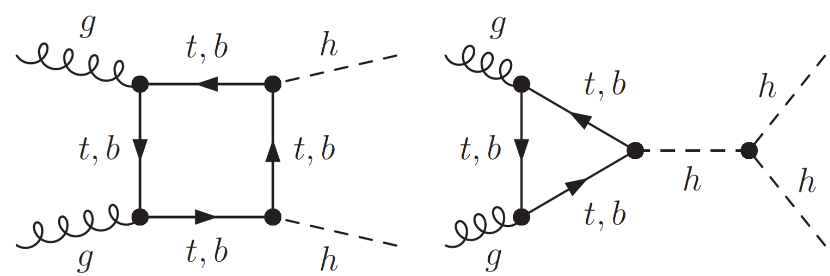
arXiv:1808.00336 [hep-ex]; ATLAS-CONF-2018-043

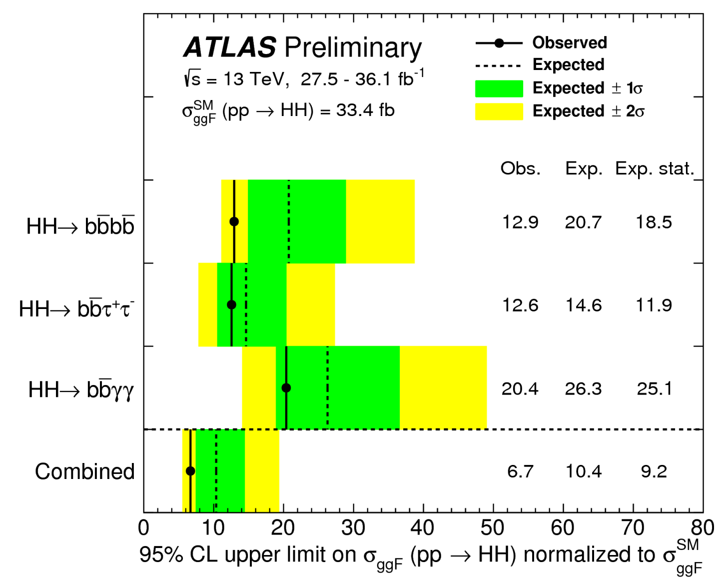
7 July 2018
4 Sep 2018

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

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



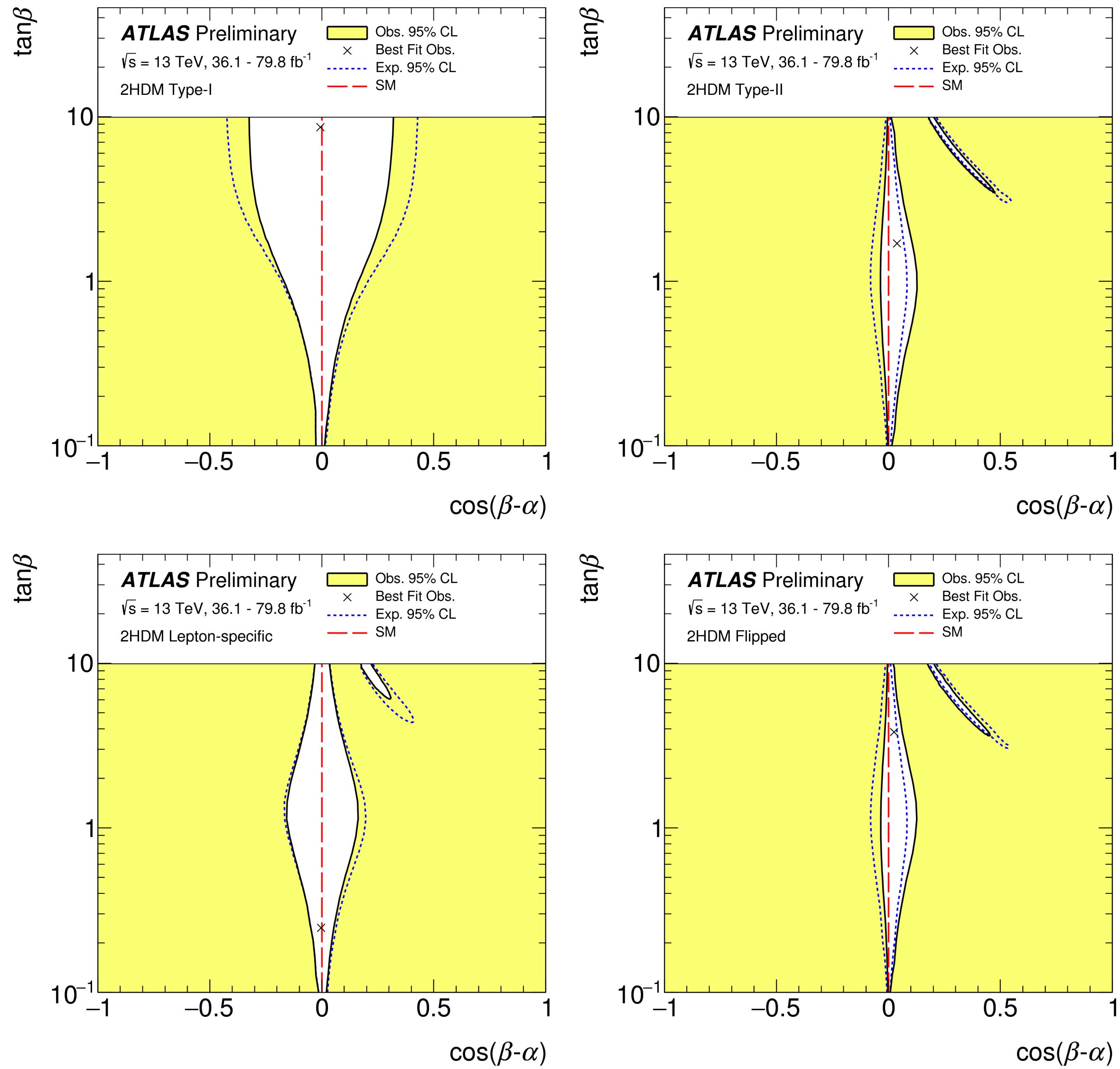


Di-Higgs combination plot [here]

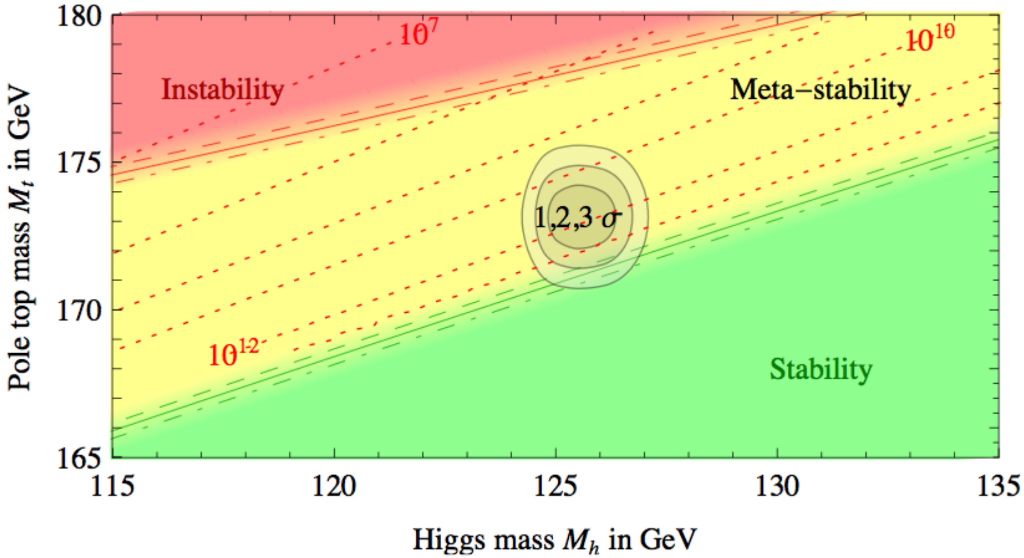
Implications for 2HDM

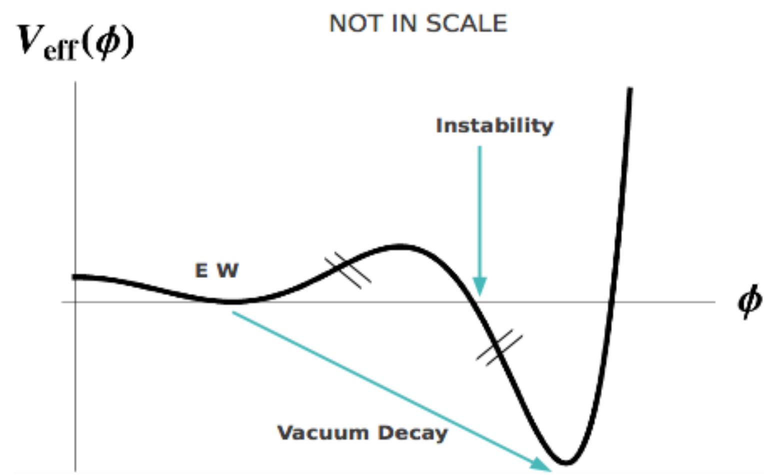
- H(125) assumed to be light CP-even neutral scalar *h* in 2HDM

- *h* production and decay same as for SM 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

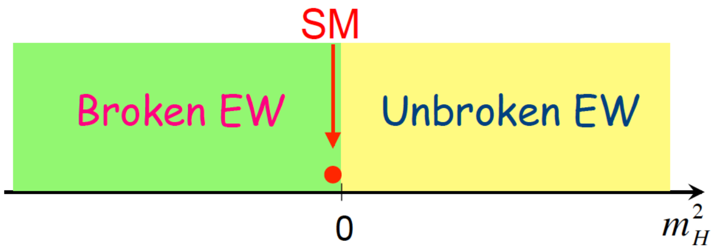
The universe seems to live near a critical condition

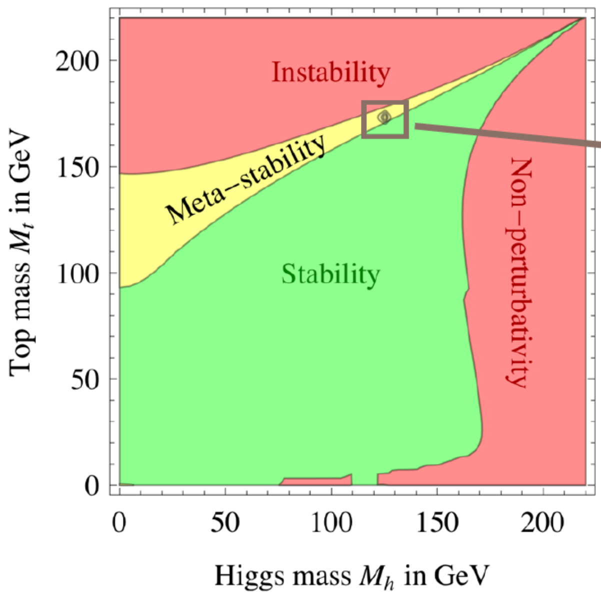
JHEP 1208 (2012) 098

Why?!

Explained by underlying theory?

Anthropic principle?





Questions?

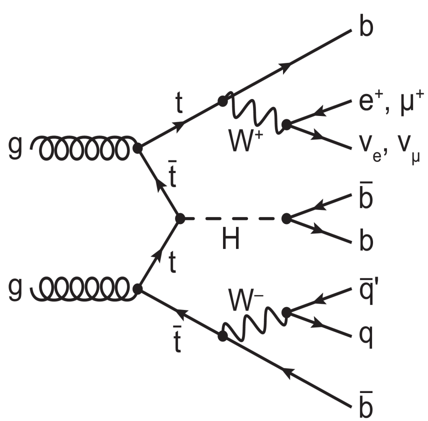
Thank you for your interest!

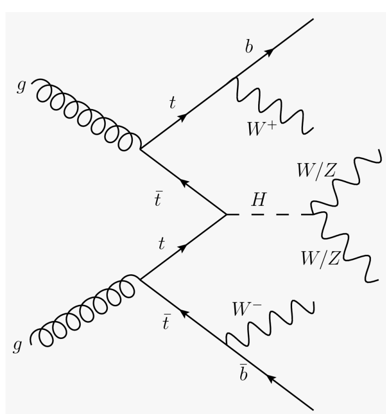
jgoncalo@lip.pt

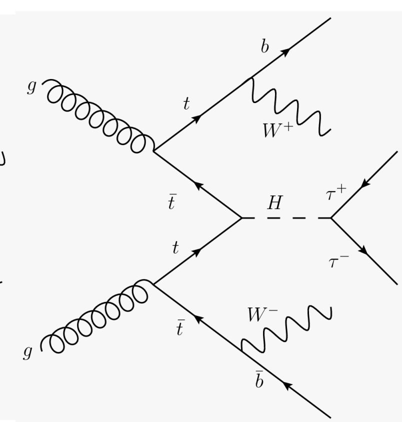
arXiv:1806.00425 [hep-ex];

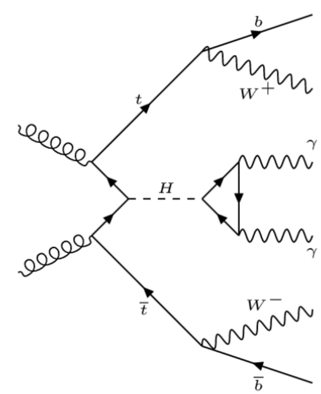
Observation of ttH production

- **Direct** access to top Yukawa coupling
- Experimental tour-de-force!
  - Complex final states
  - Large irreducible backgrounds
  - Small cross sections: O(0.5)pb @ 13 TeV
- Use all available final states:
  - **H→bb**: high stats but low purity BR≈58%, S/B≈1-6%
  - **Multileptons:** H→$\tau\tau$, H→WW*, H→ZZ* BR = 30%, S/B=4-34%
  - **H→$\gamma\gamma$**: clean but low stats BR = 0.23%, S/B=5-200%
  - **H→ZZ*→4lep**: clean but very low stats BR = 0.01%, S/B=50-500%









ttH observation: bb and Multileptons

ttH(H→leptons)

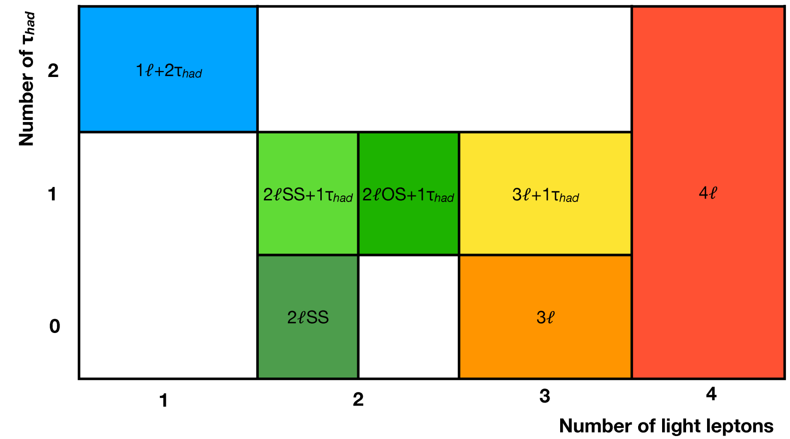
- Sensitive to: H→$\tau\tau$, H→WW* and H→ZZ*
- Backgrounds: ttW/ttZ, non-prompt leptons and jets faking taus
- Main uncertainties: signal modelling, jet energy scale and non-prompt lepton estimate
- 4.1σ observed; 2.8σ expected

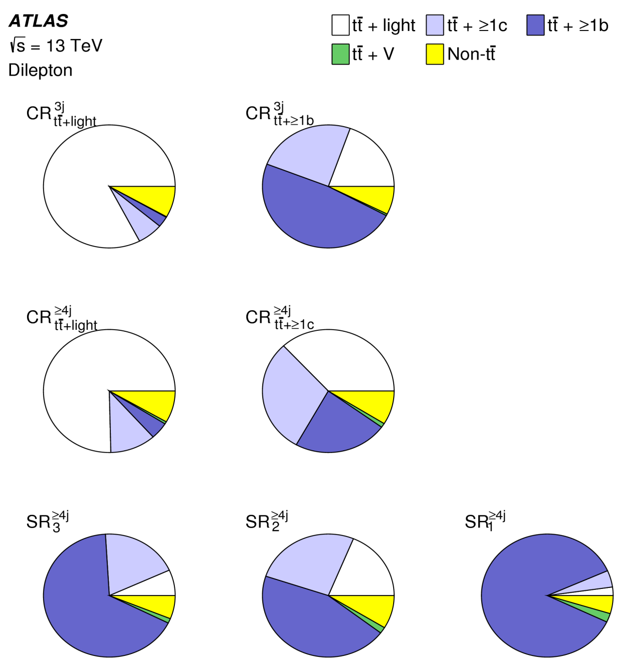
ttH(H→bb):

- Profit from large H→bb branching ratio (58.4%)
- But challenging final state: large ttbb irreducible background, theory uncertainties, combinatorics...
- Main uncertainties: tt+heavy flavours, b tagging, jet calibration
- ATLAS: 1.2σ observed; 1.6σ expected

For **both** channels:

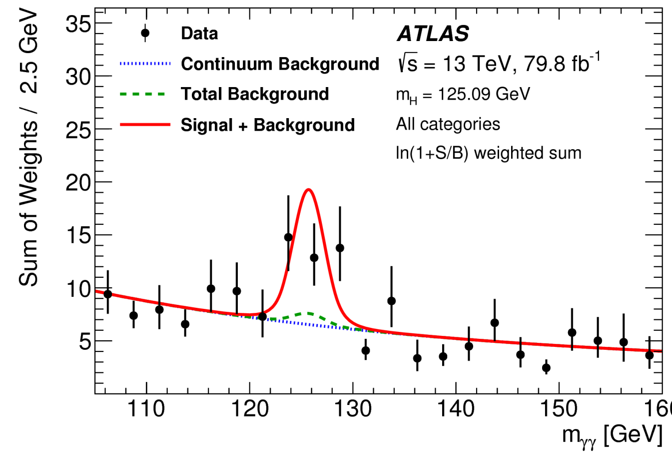
- Intensive use of dedicated machine learning (NN, BDT) and matrix element methods: suppress fake leptons, reconstruct events, flavour tagging, and enhance S/B





ttH(H→γγ) and Combination

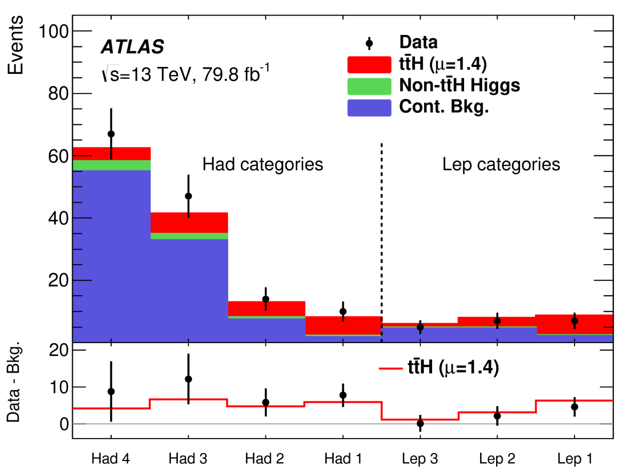
- ttH(H→$\gamma\gamma$):
  - New signal categories from BDT discriminant
  - **Sensitivity increased by 50%**

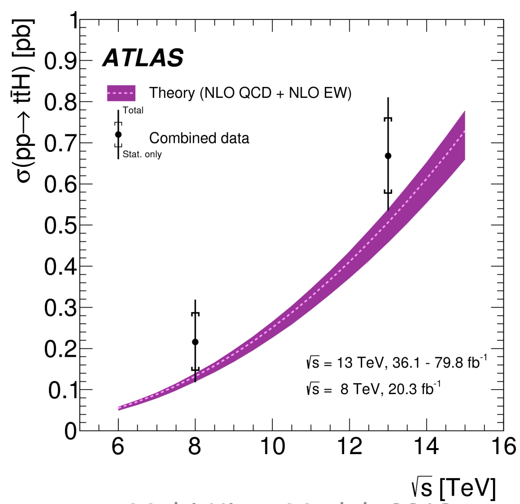


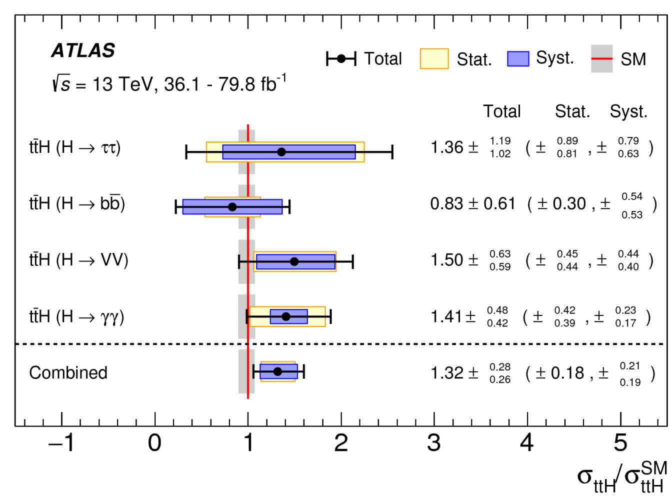
ttH combination: ttH(H→leptons + H→bb + H→γγ)

- Run 2 data from 2015+2016+2017 ($\gamma\gamma$/ZZ): 79.8 fb^{-1}
  - 5.2 σ observed, 4.9 σ expected
- Adding Run 1: 6.3 σ observed, 5.1 σ expected
- Measured production cross section at 13 TeV:

  670 ± 90 (stat.) +110−100 (syst.) fb



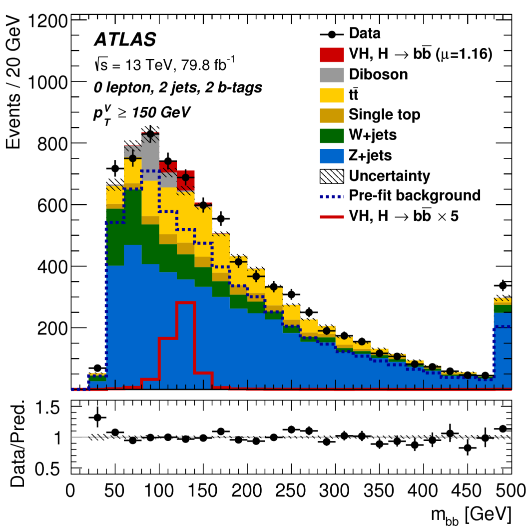


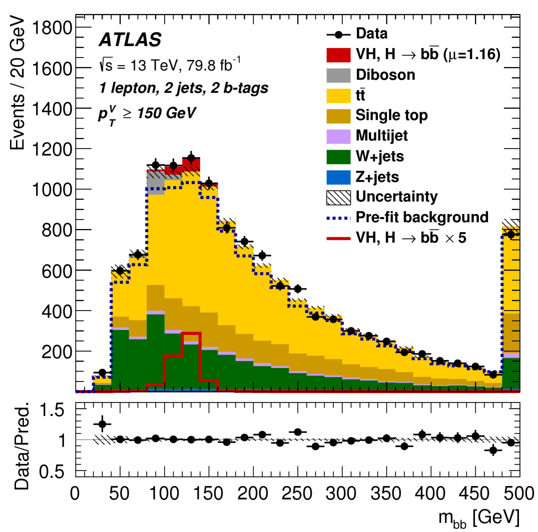


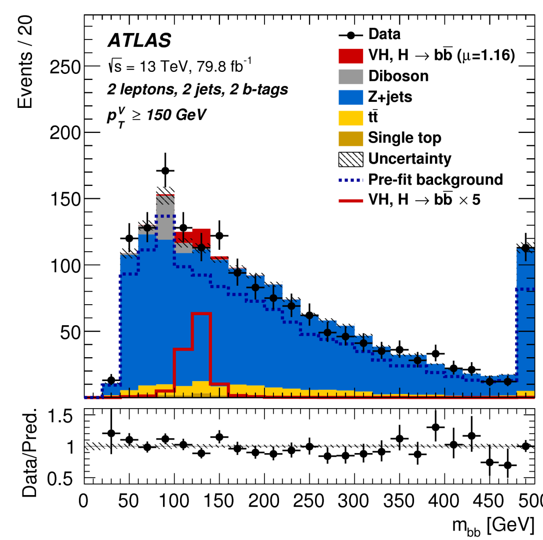
Observation of H→bb

- See **CERN seminar last week**! (https://indico.cern.ch/event/750541/)
- Largest branching fraction (58.4%) but huge background from heavy flavour production
- Must use associated production: WH/ZH
  - Require 2 b jets + 0 (Z→$\nu\nu$), 1 (W→$\ell\nu$) or 2 (Z→$\ell\ell$) leptons
- Largest backgrounds:
  - Z+heavy flavour (0- and 2-lepton) and tt (1-lepton)
  - Irreducible background from VZ with Z→bb

9 July 2018

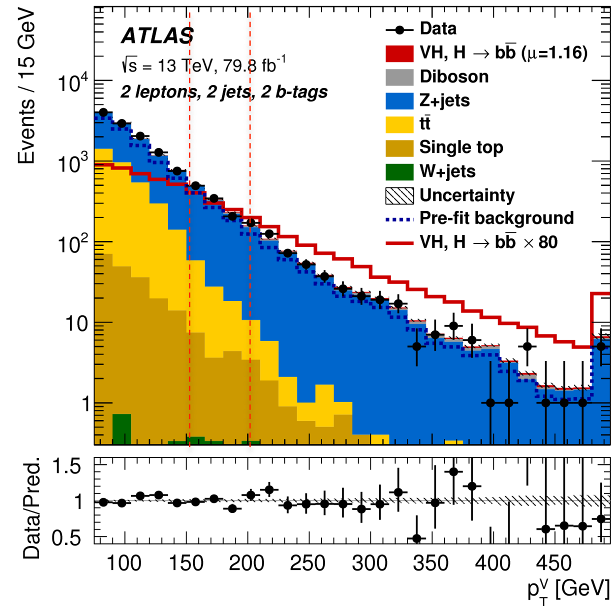




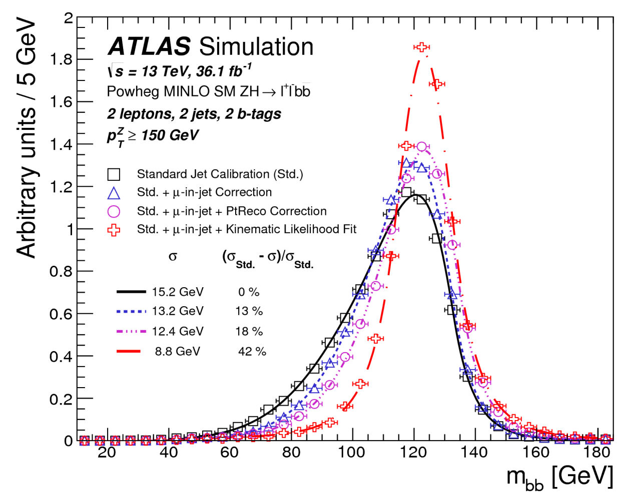


Observation of H→bb

- Harder p_T spectrum for signal than backgrounds
  - Go to high p_T to improve S/B
- Use for event categories:
  - $75 < p_T^V < 150$ GeV (2ℓ only)
  - $150 < p_T^V < 200$ GeV
  - $p_T^V > 200$ GeV

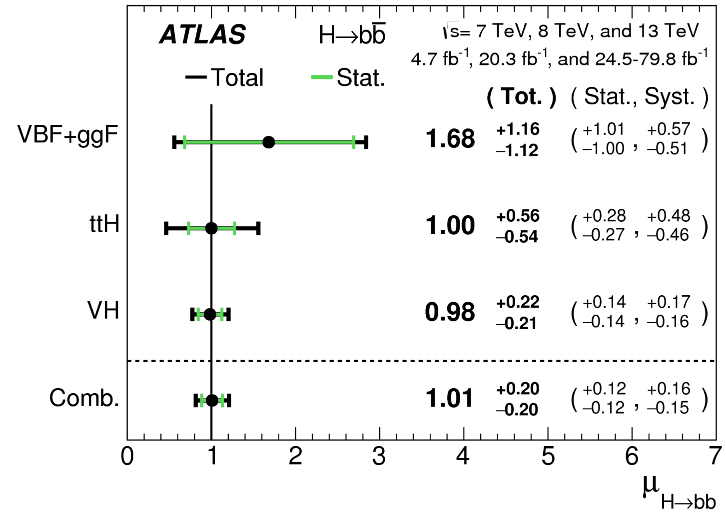


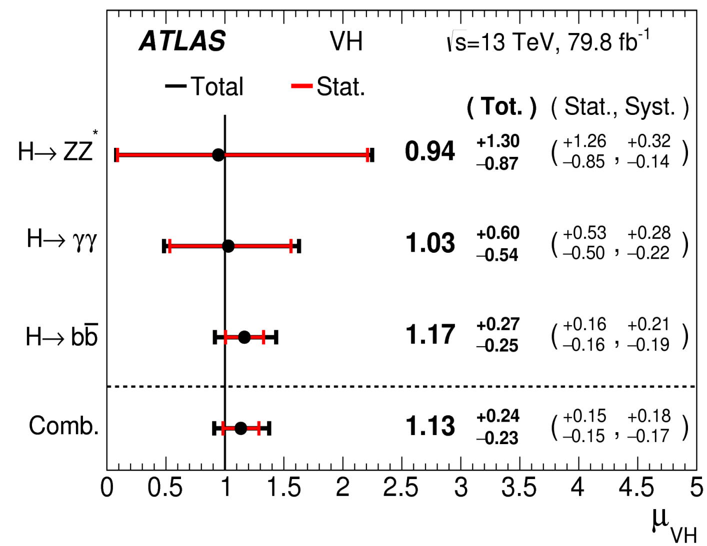
- Main discriminant variables m_{bb}, p_T^V and ΔR_{bb}
  - m_{bb} resolution extremely important!



Observation of H→bb

- Run 2:
  - Observed (expected) of 4.9σ (4.3σ)
- Adding Run 1:
  - Observed (expected) of 4.9σ (5.1σ)
- Adding ttH and VBF:
  - Observed (expected) of 5.4σ (5.5σ)
  - **Observation of H→bb decays**
- Adding H→ZZ and H→γγ:
  - Observed (expected) of 5.3σ (4.8σ)
  - **Observation of VH production**

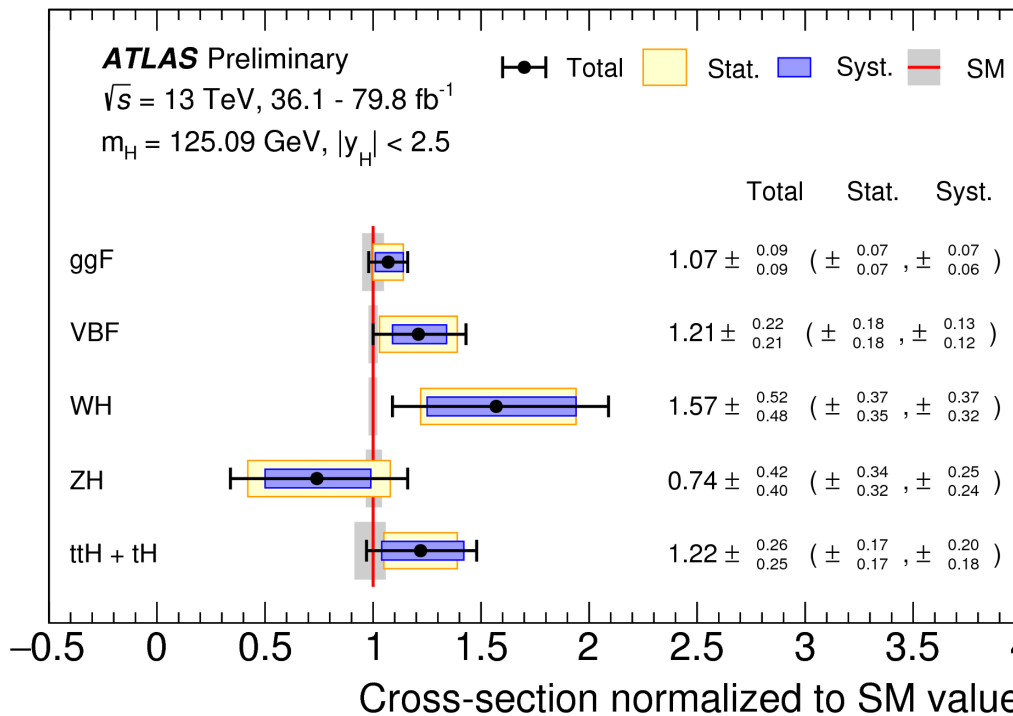




Combination

- Combined γγ, ZZ, WW,ττ, μμ and bb (incl. ttH+tH modes)
  - Up to 79.8 fb^{-1} of √s = 13 TeV data
- Combination yields VBF significance 6.5σ (5.3σ expected) **from ATLAS alone**
- Main production modes (ggF, VBF, VH, ttH) have all been observed!!
- Good agreement with SM predictions
- Overall signal strength:

  $\mu = 1.13^{+0.09}_{-0.08}$
- Quantified space for undetectable decays or modified BR (e.g. BSM H→cc)
  - $B_{BSM} < 0.13$ at 95% CL.(*)



(*) In determination of κ_g and κ_γ - assumption dependent


Route A. EINSTEIN
11

Feixes de protões