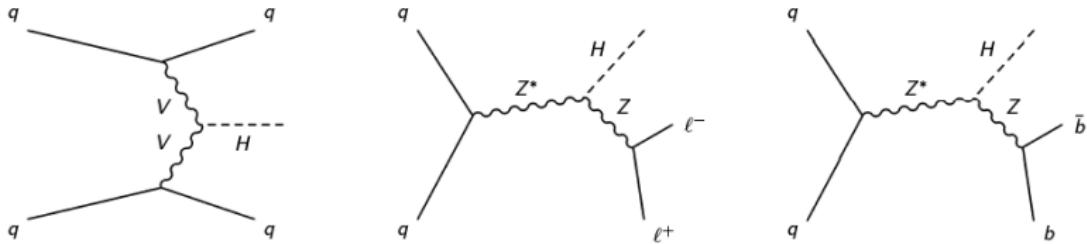


Searching for the Higgs boson at the LHC

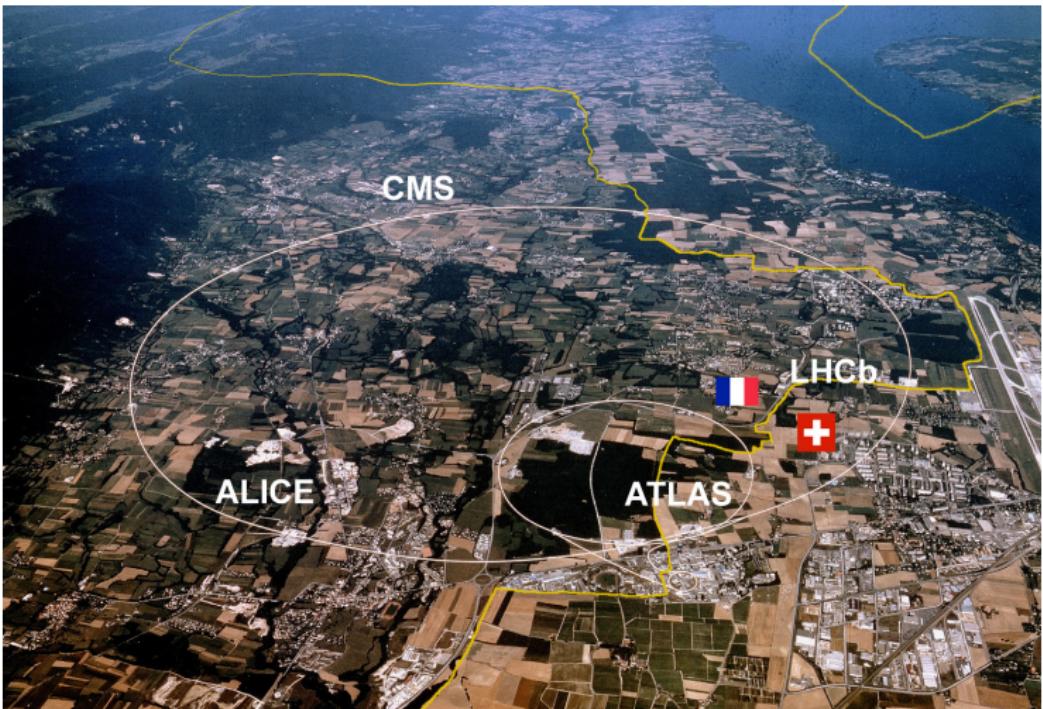
P. Dunne - Imperial College London



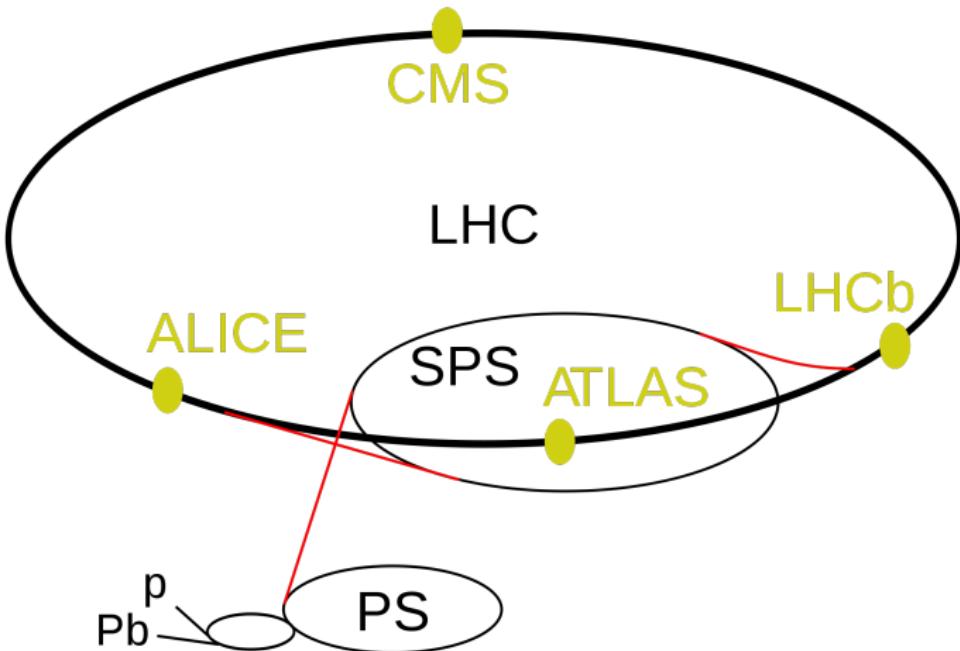
Introduction

- ▶ What is the LHC?
- ▶ What is the Higgs boson?
- ▶ How do we search for it?
- ▶ What do we see?

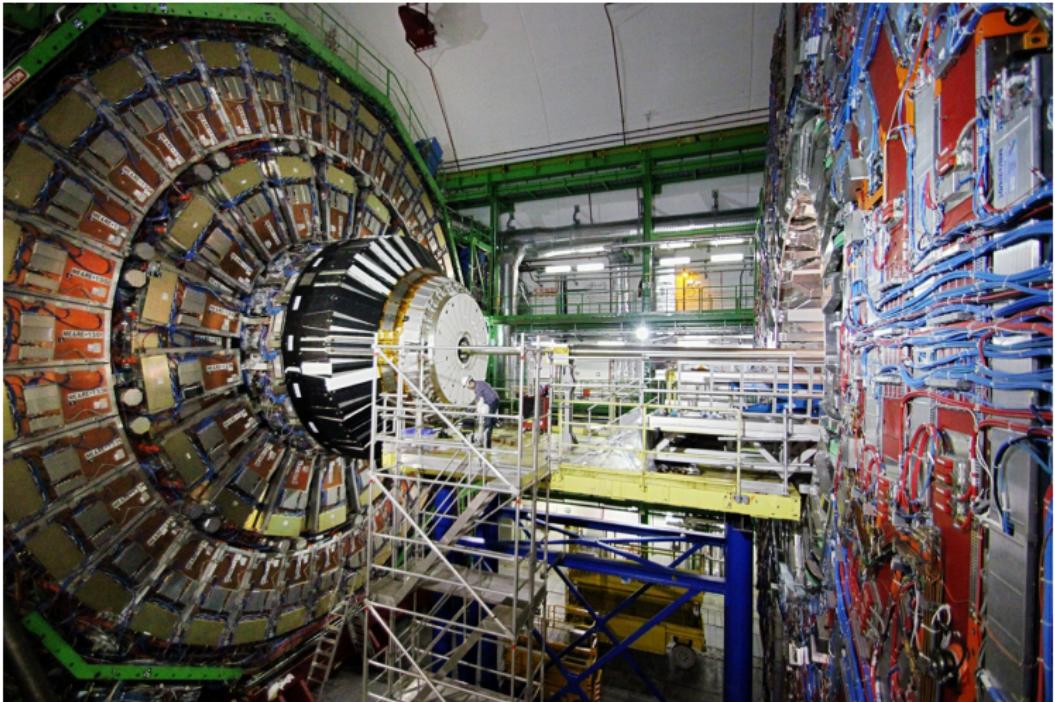
CMS and the LHC



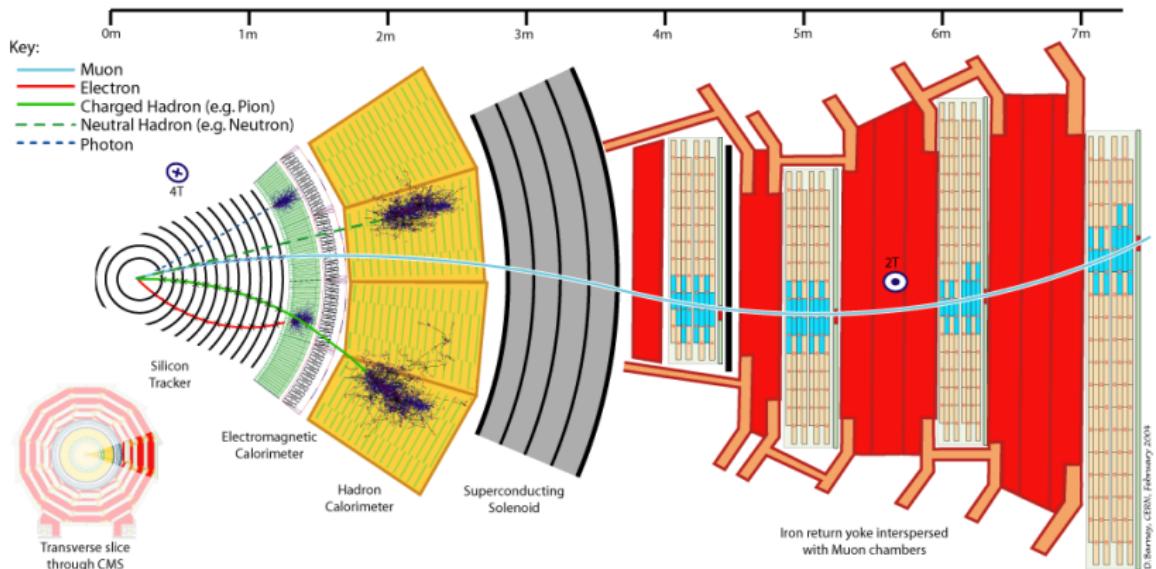
CMS and the LHC



CMS



CMS



D. Berney, CERN, February 2004

Symmetry and the Standard Model (SM)

1) The universe has symmetries:

- ▶ Results of experiments are the same if the apparatus is in London or Lisbon

Symmetry and the Standard Model (SM)

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 - ▶ Everything that can happen will so if the universe never breaks a symmetry it's a good hint of a fundamental property

Symmetry and the Standard Model (SM)

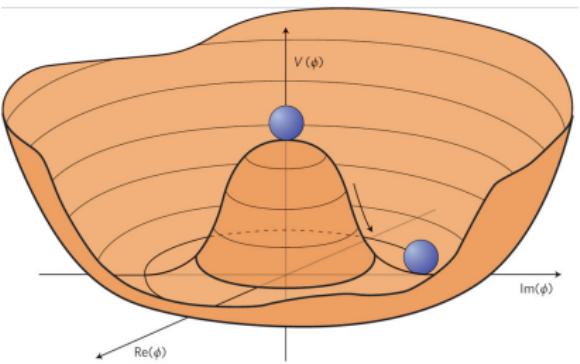
- 1) The universe has symmetries:
 - ▶ Results of experiments are the same if the apparatus is in London or Lisbon
- 2) The equations that govern the universe must also have these symmetries:
 - ▶ Everything that can happen will so if the universe never breaks a symmetry it's a good hint of a fundamental property
- 3) Start by writing down the most general formula that satisfies the symmetries:
 - ▶ Need to know what particles you're trying to describe

SM Particles

Three Generations of Matter (Fermions)				
	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	
name→	u up	c charm	t top	
Quarks	4.8 MeV - $\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV - $\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV - $\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 γ photon
				0 0 1 g gluon
Leptons	<2.2 eV 0 $\frac{1}{2}$ νe electron neutrino	<0.17 MeV 0 $\frac{1}{2}$ νμ muon neutrino	<15.5 MeV 0 $\frac{1}{2}$ ντ tau neutrino	91.2 GeV 0 0 1 Z weak force
Bosons (Forces)	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	80.4 GeV ± 1 1 W weak force

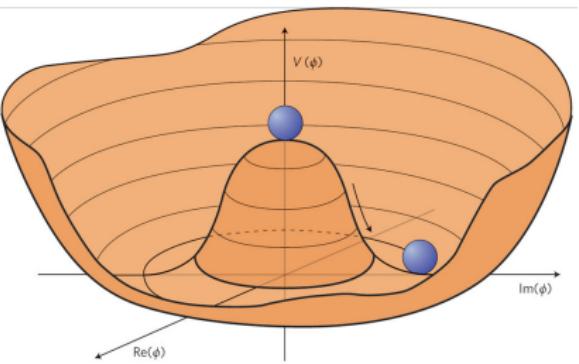
The Higgs boson

- Things have mass



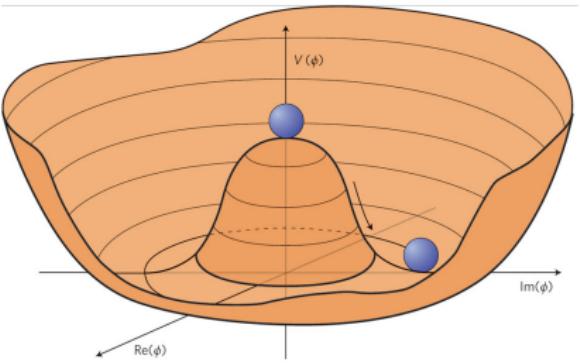
The Higgs boson

- ▶ Things have mass
- ▶ Mass terms for particles/forces we know about break symmetries



The Higgs boson

- ▶ Things have mass
- ▶ Mass terms for particles/forces we know about break symmetries
- ▶ There must be another particle/force with exactly the properties to give things mass



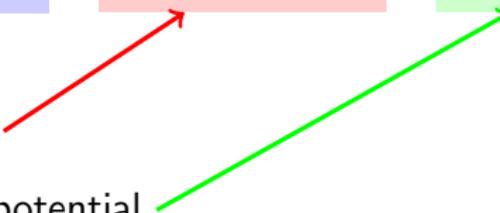
Symmetry and the SM

- ▶ Forces: EM, strong, weak



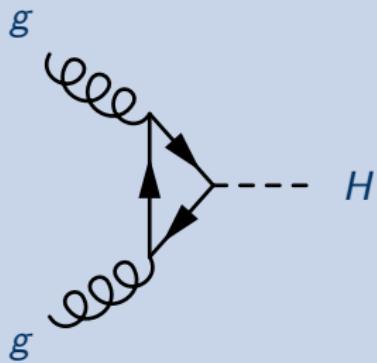
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

- ▶ Quark and lepton Masses
- ▶ Boson masses and Higgs potential

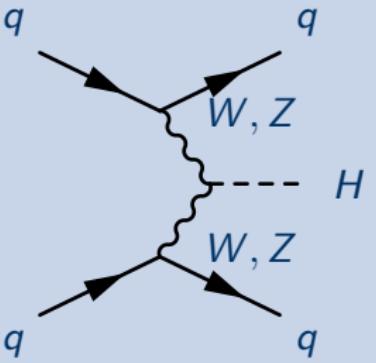


How is the Higgs made at the LHC?

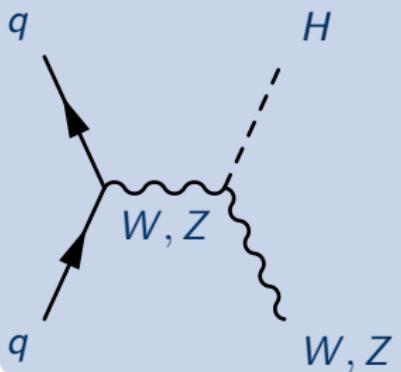
ggH



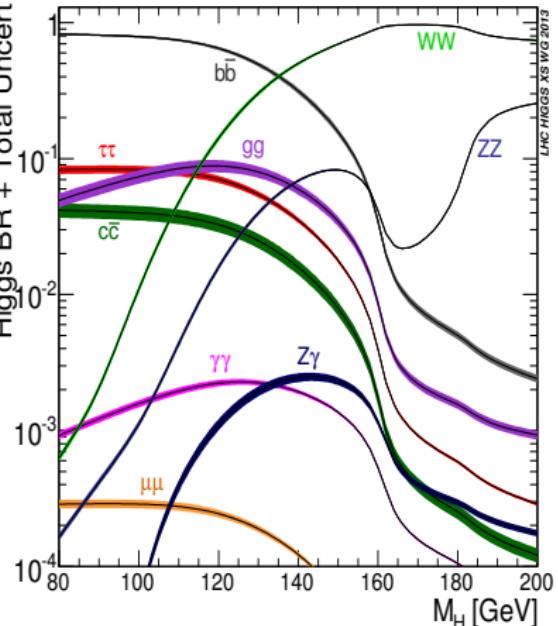
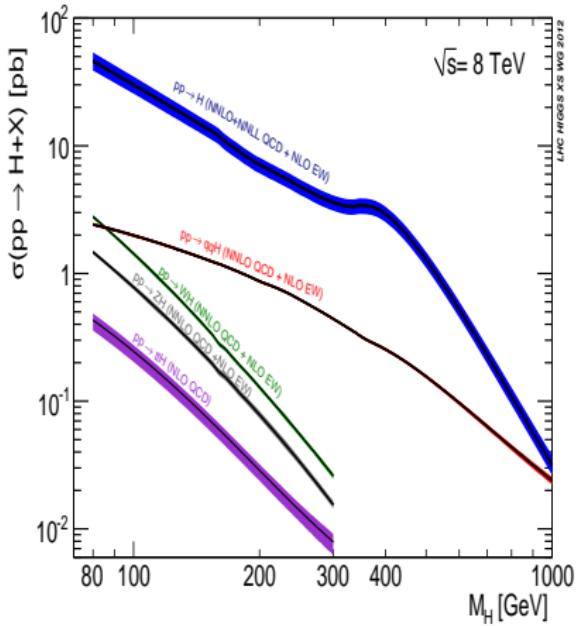
VBF



Z/WH

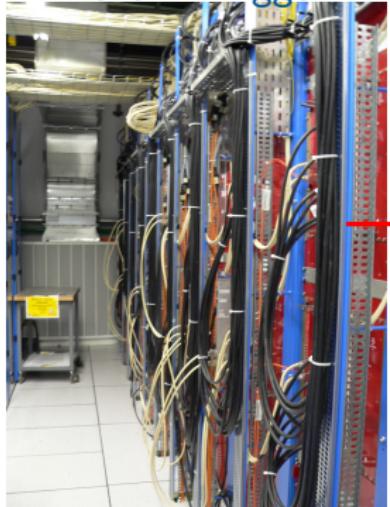


What does the Higgs boson look like at the LHC?



Getting the data

Level 1 Trigger



$40\text{MHz} \rightarrow 100\text{kHz}$

High Level Trigger



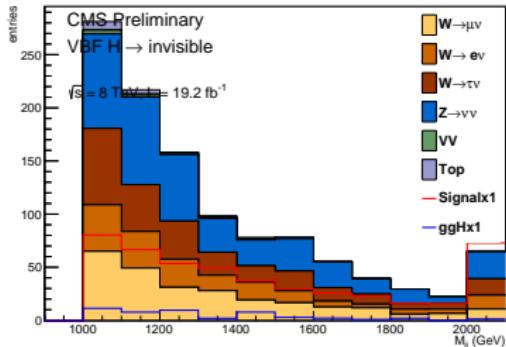
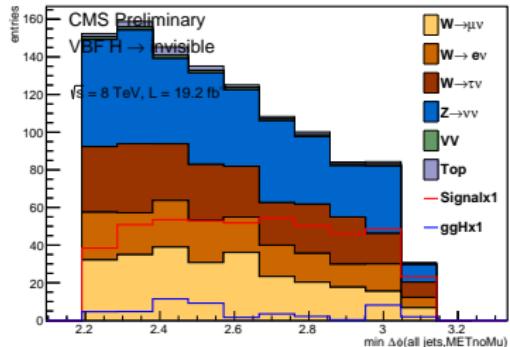
$100\text{kHz} \rightarrow 1\text{kHz}$

Analysis



How do we search for it?

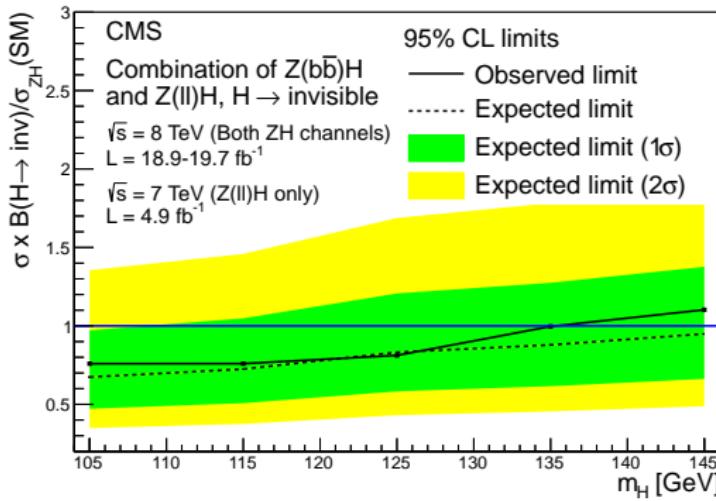
- Pick a region with lots of signal and not much background



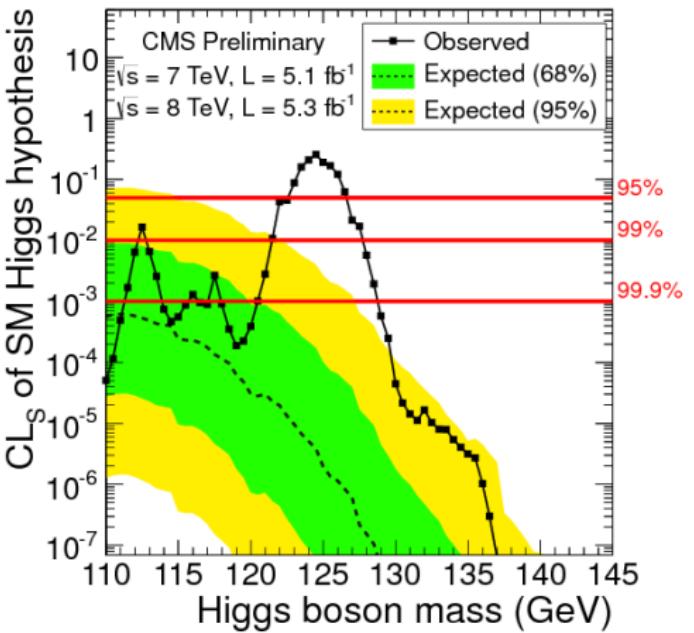
- Predict what you expect to see:
 - Background only and signal + background

How do we search for it?

- ▶ Compare prediction with data
- ▶ Use statistics to decide if the result is more like signal or background

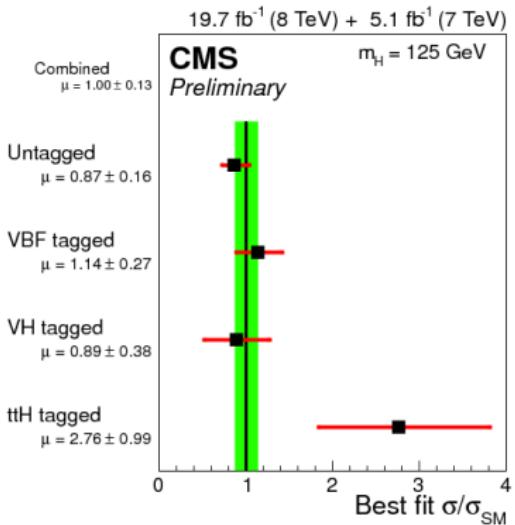
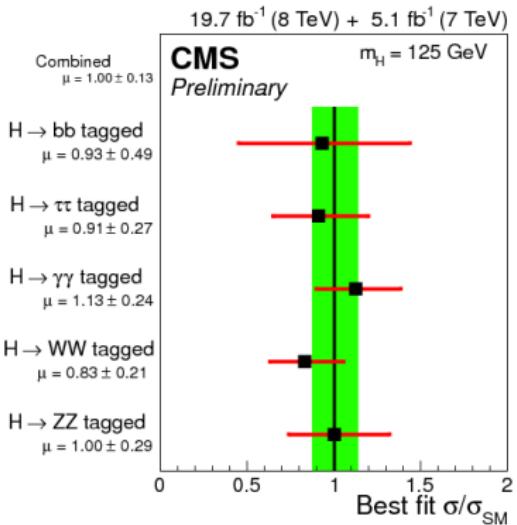


What did we find?

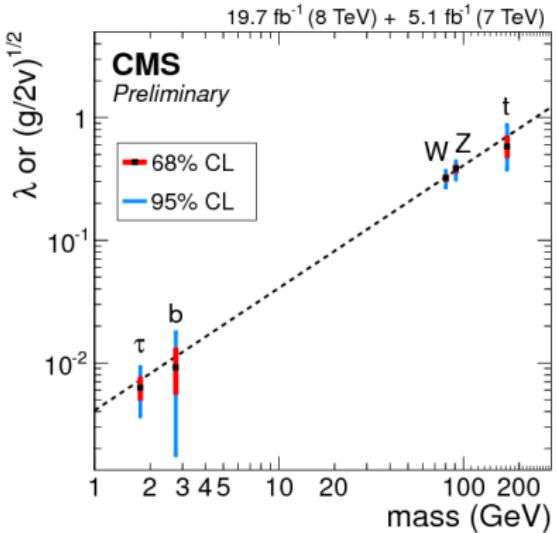


Is it a Higgs boson?

- ▶ Not enough to find a new particle:
 - ▶ Higgs boson has very well predicted properties



Does it couple to mass?

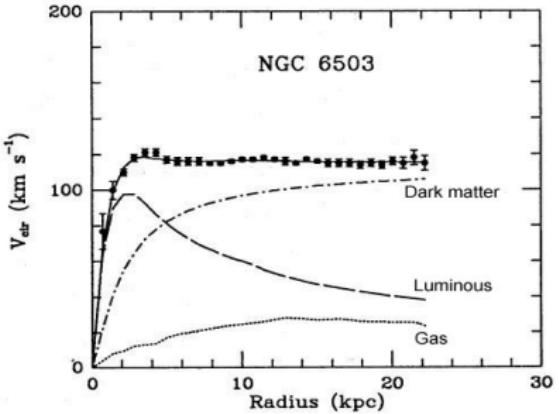
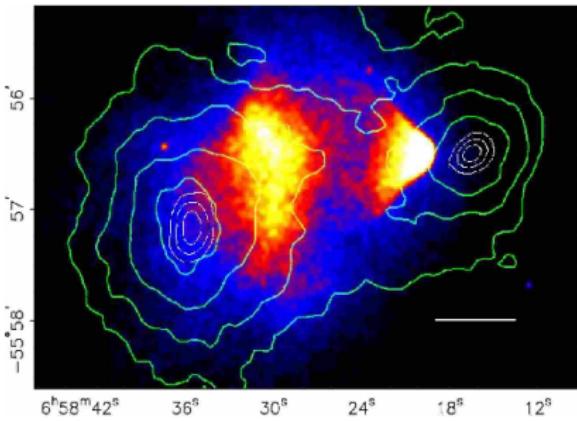


What do we do now?

- ▶ What we see looks very like a Higgs boson:
 - ▶ uncertainties are still large
- ▶ The SM has problems:
 - ▶ dark matter, fine tuning, matter anti-matter difference, gravity
- ▶ Many theories try to fix these problems:
 - ▶ these theories often have differently behaving Higgs bosons
- ▶ Studying the Higgs boson in more detail can confirm/exclude theories

What I do: dark matter

- ▶ What is dark matter?
 - ▶ Invisible, cold, massive



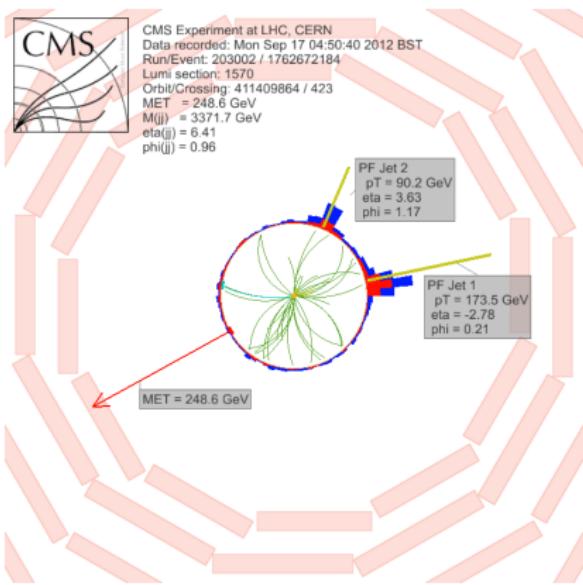
Why is the Higgs boson a good place to look for dark matter

- ▶ If dark matter has mass it should couple to the Higgs
- ▶ If it's light enough the Higgs will decay to it
- ▶ Look for invisibly decaying Higgs...



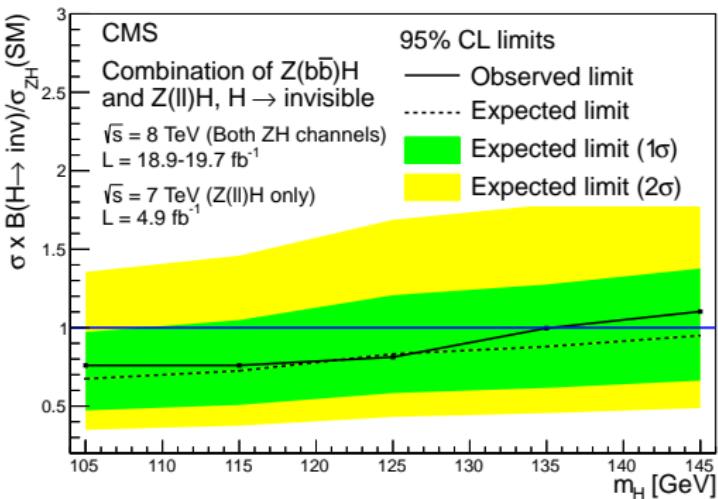
Finding something invisible

- ▶ Higgs must be created with something else
 - ▶ VBF, ZH



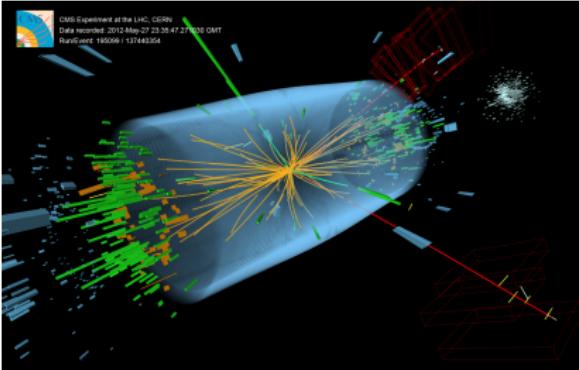
What do we see?

- ▶ Invisible decays very rare in SM
 - ▶ if we see anything it's very likely to be dark matter



Summary

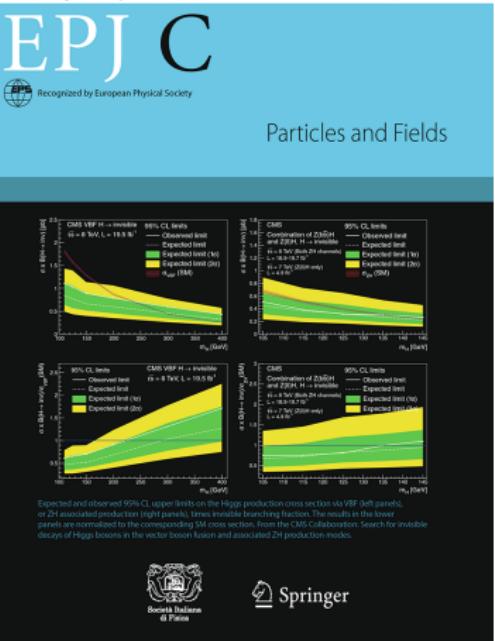
- ▶ The Higgs boson gives mass to all the particles we know about
- ▶ We found something which looks very like it at the LHC
- ▶ Discovery is only the beginning
 - ▶ the Higgs boson might tell us how to fix the SM
 - ▶ some theories predict 5 Higgs bosons!



The Higgs Boson

What do I do?

The European Physical Journal volume 74 · number 8 · august · 2014

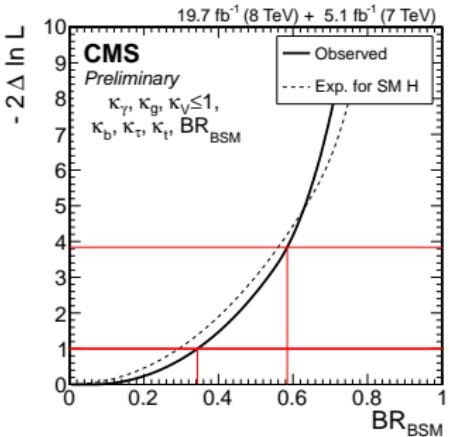


Springer

Why Higgs to Invisible?

Experimental motivation

- ▶ Current measurements of the 125 GeV Higgs boson are compatible with Standard Model (SM) expectations
 - large uncertainties can still accommodate significant beyond the SM (BSM) properties
- ▶ Additional Higgs bosons with exotic decays are not excluded



Theoretical motivation

- ▶ Many BSM theories predict Higgs boson decays to invisible final states:
 - e.g. SUSY, extra dimensions, fourth-generation neutrinos
- ▶ These final state particles are often dark matter candidates

CMS-PAS-HIG-14-009