The Higgs Discovery

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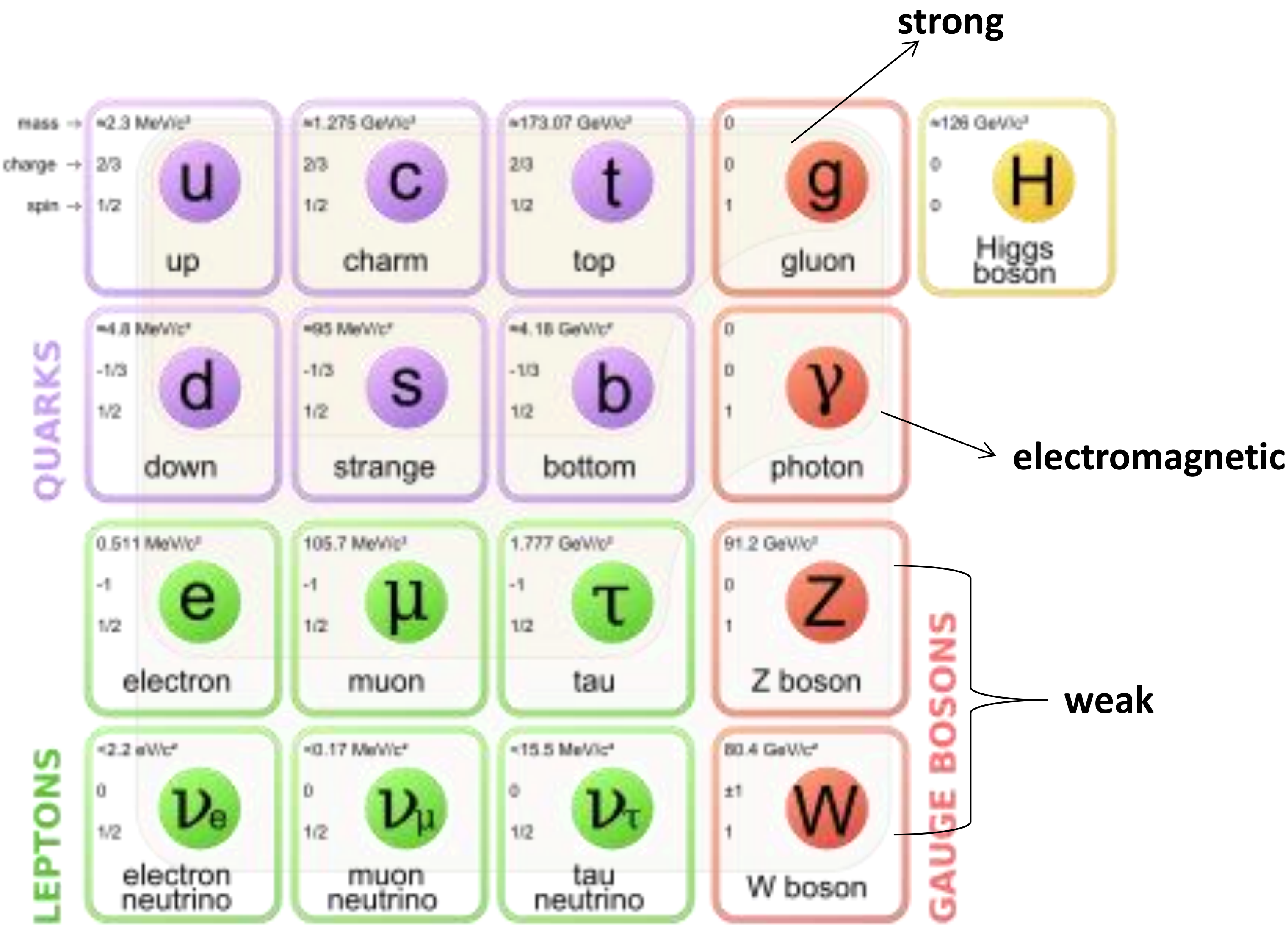
IAPS Visit

24.04.14

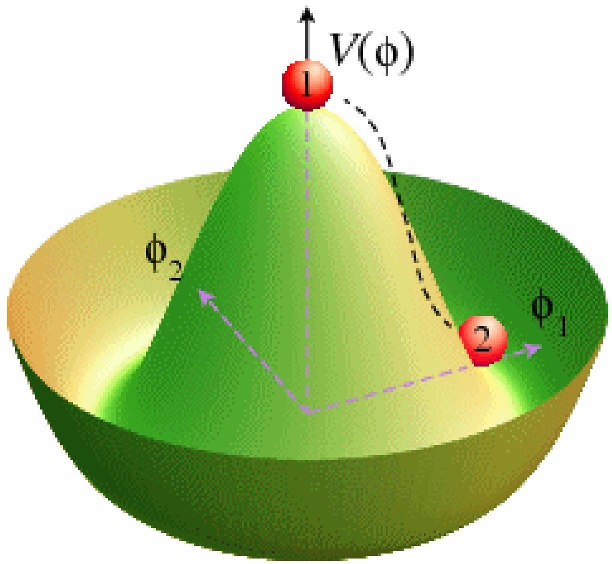
The Standard Model

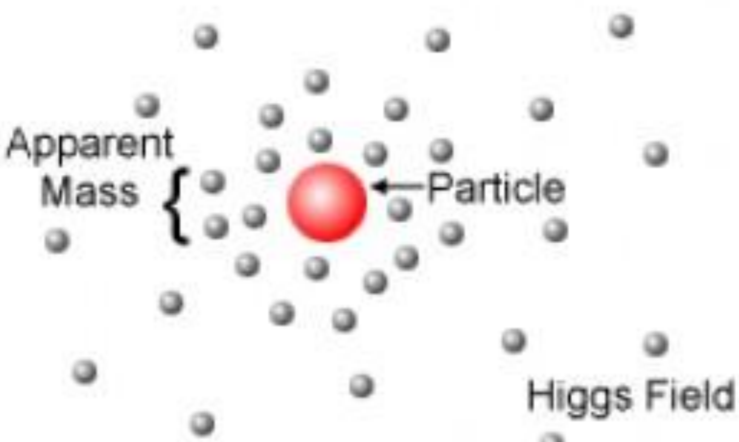


*no gravity

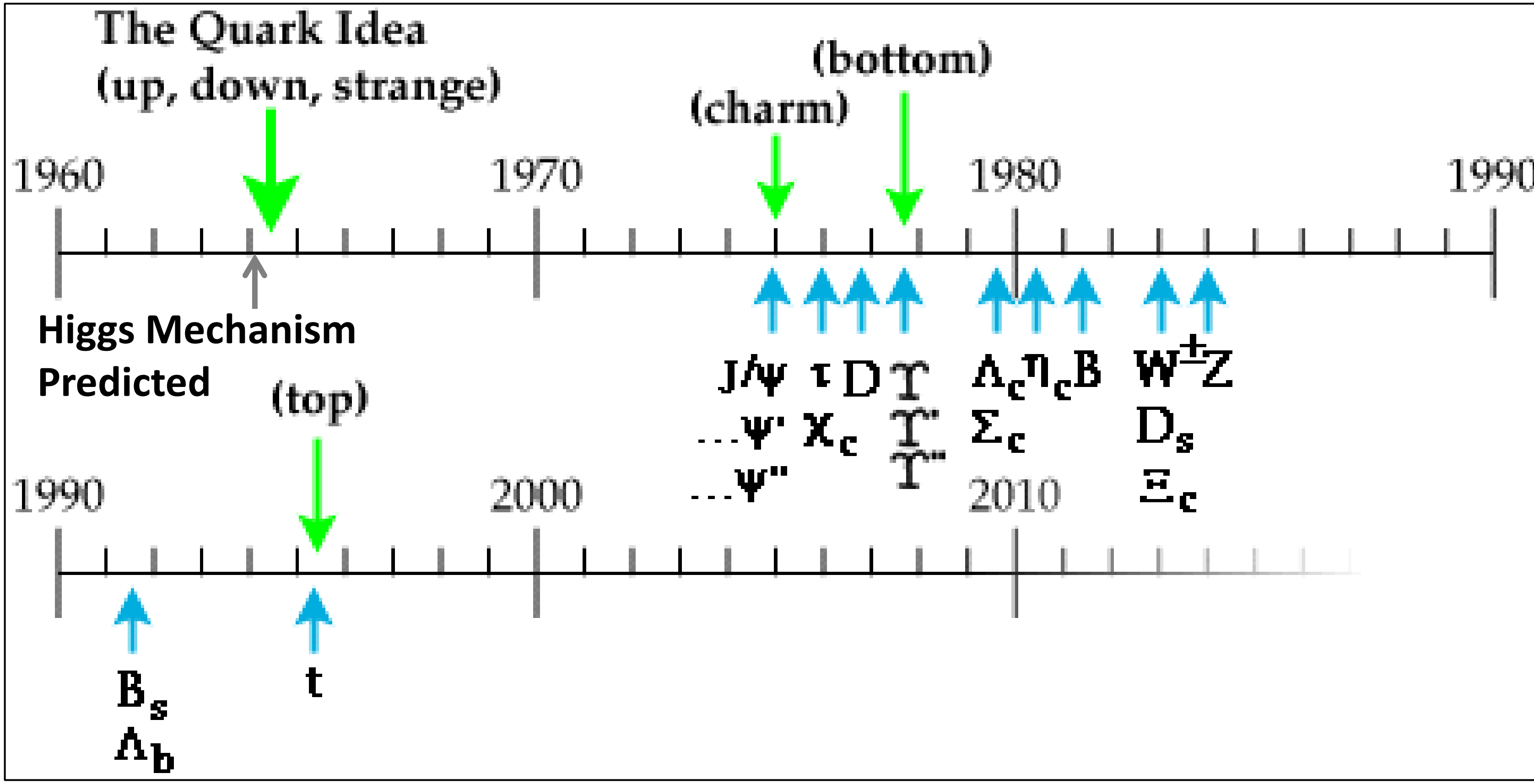
The Higgs Mechanism

- **Breaks electroweak symmetry**
  - Unified electroweak force manifests as separate electromagnetic and weak forces at low energies
- Allows fundamental particles to have mass
  - Interaction strength between Higgs boson and SM particle proportional to mass of particle

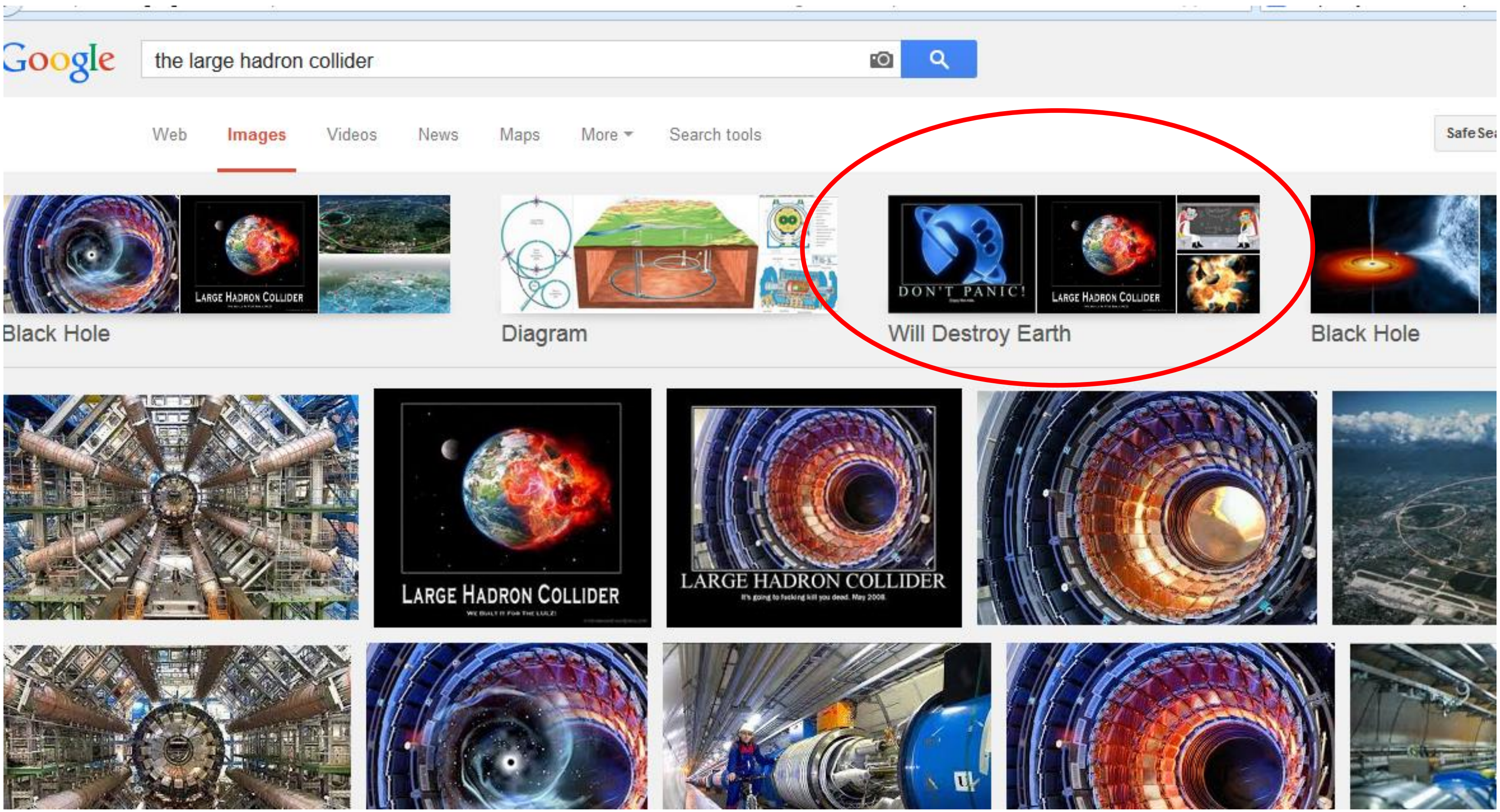




Particle Discovery Timeline



The Large Hadron Collider

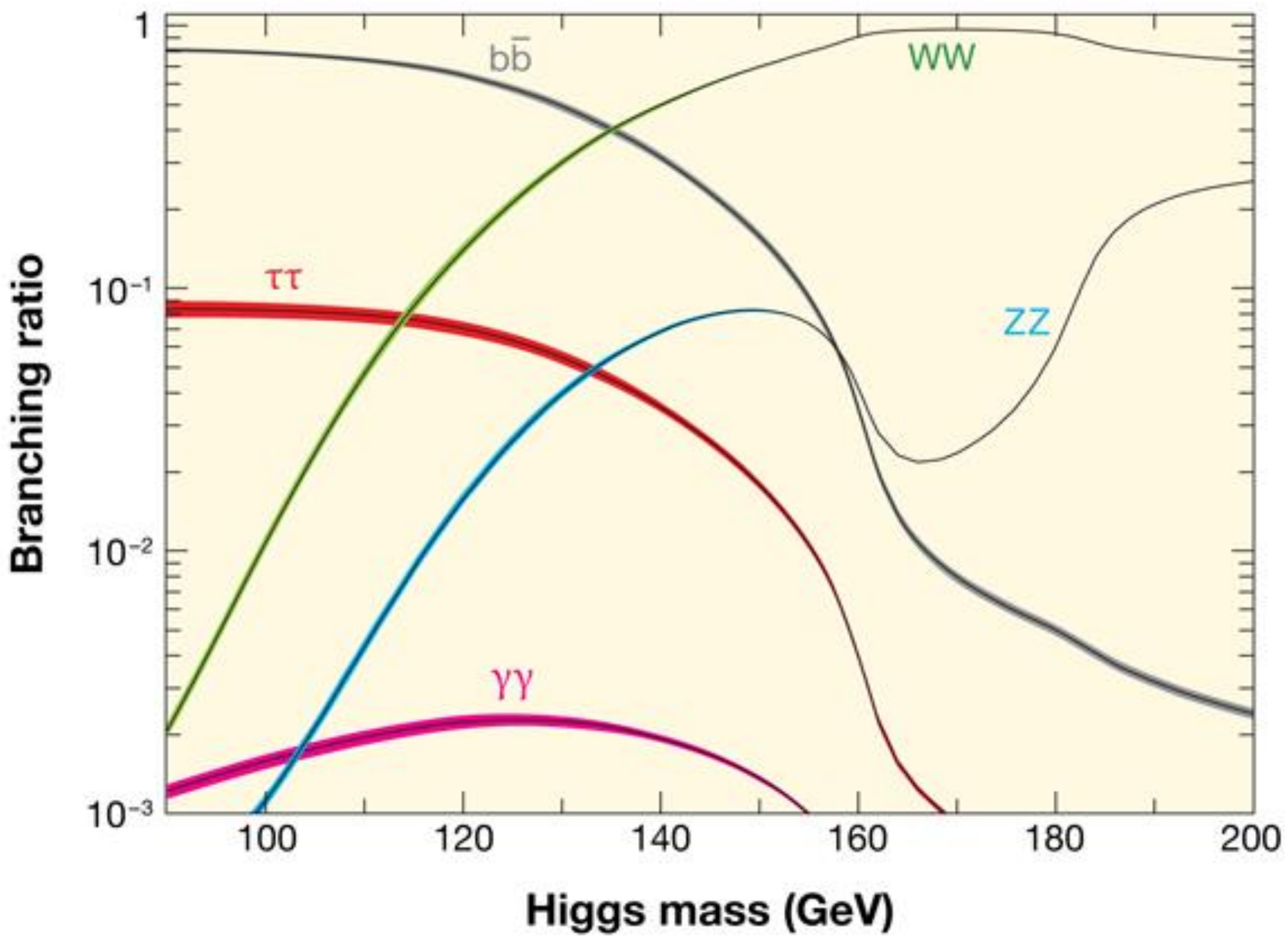


The Large Hadron Collider

- Has not destroyed the Earth (yet)
- pp collider
  - 27 km circumference rings
  - Design centre-of-mass energy (c.o.m.) 14 TeV
    - 7 TeV for each beam
  - Design luminosity 10^{34} $cm^{-2}s^{-1}$

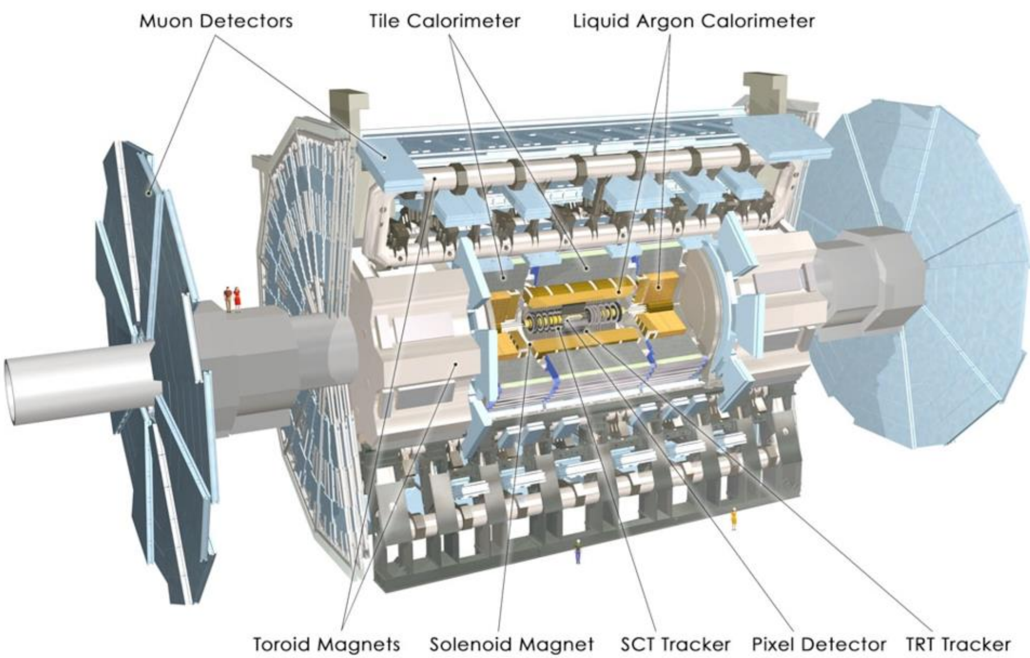
How do you look for a particle that you can't see?

Look for its decay products

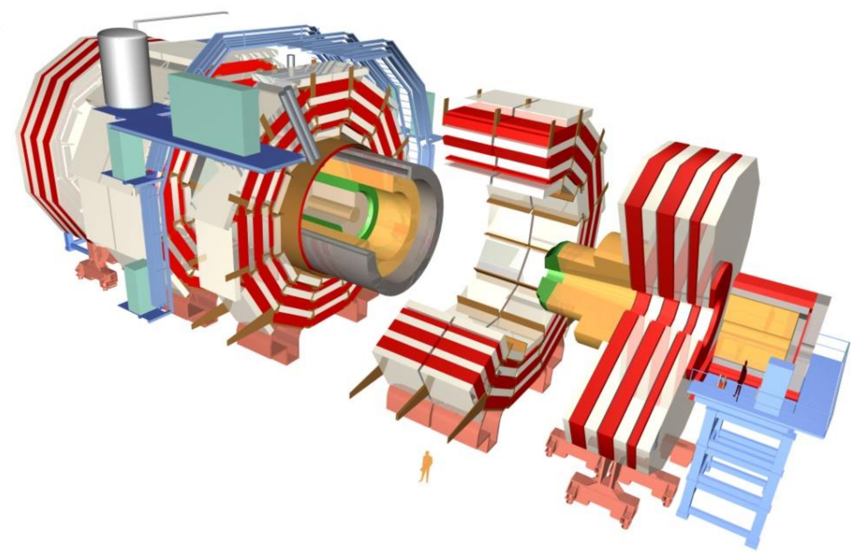


How do you look for decay products that you can’t see?

ATLAS

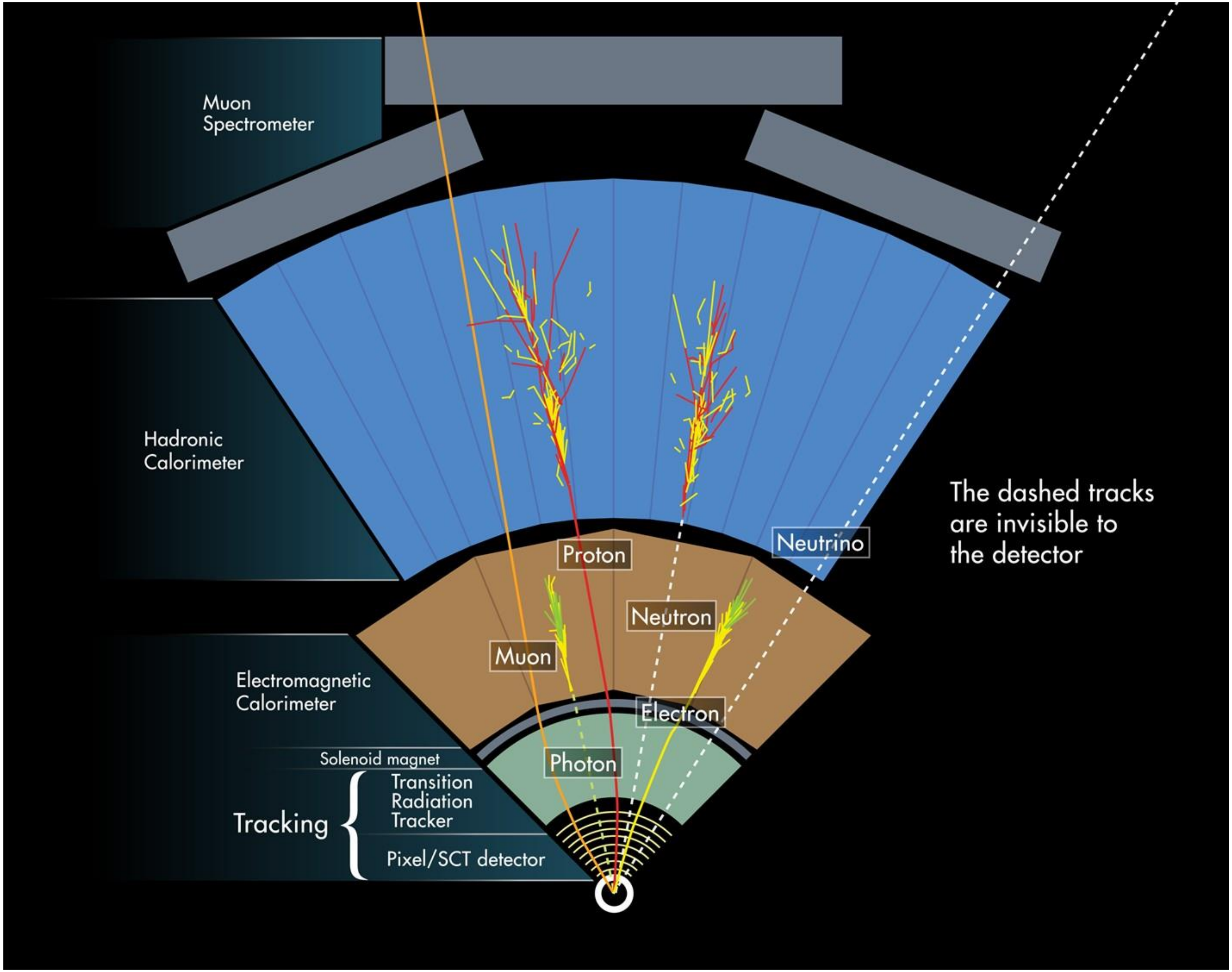


CMS



- They leave their marks in your detectors

Different particles in the Detector



The Cleanest Decay Channels

- H -> γγ
  - Two high energy photons in the detector
  - One of the cleanest channels (low background) in hadron colliders
  - Low probability of production
- H-> ZZ -> 4 leptons
  - 2 pairs of leptons with same flavours and opposite charges
  - At least one or both pairs must be consistent with the decay of a Z boson
  - Very clean
  - Low production probability for low-mass Higgs
- In both cases, the Higgs should produce a resonant peak in the invariant mass spectrum of the final state particles

How do you know if you really know?

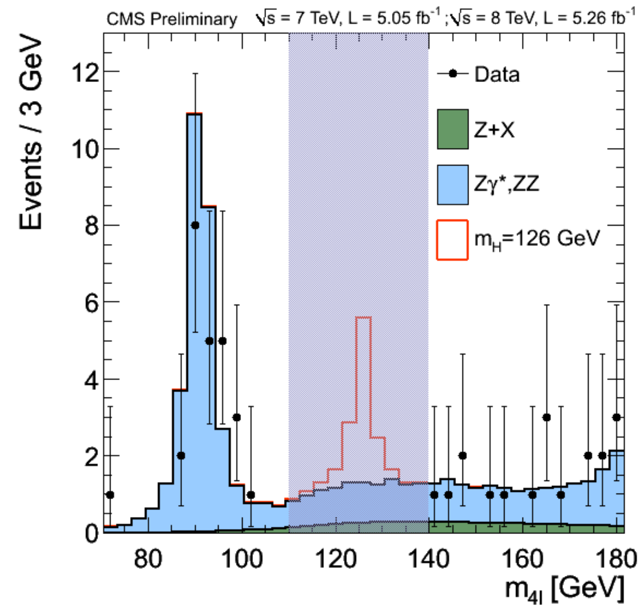
- Hypothesis testing
  - Null hypothesis H_0
  - Alternate hypothesis H_a
  - Make measurements in data and construct a test statistic T
  - $P(T = T_{meas} \mid H_0) < \alpha \Rightarrow H_0$ is unlikely
    - Hold H_a to be true at confidence level of $1 - \alpha$
  - **p-value** = $P(T = T_{meas} \mid H_0)$
    - The smaller the measured p-value, the more H_a likely to be true
- Conventional p-value threshold to claim a new discovery in particle physics is $\mathbf{5.7 \times 10^{-7}}$
  - Corresponds to a statistical significance of **5σ**
- Beware the systematics
  - Underestimating the uncertainty sources can lead to overstated confidence limits

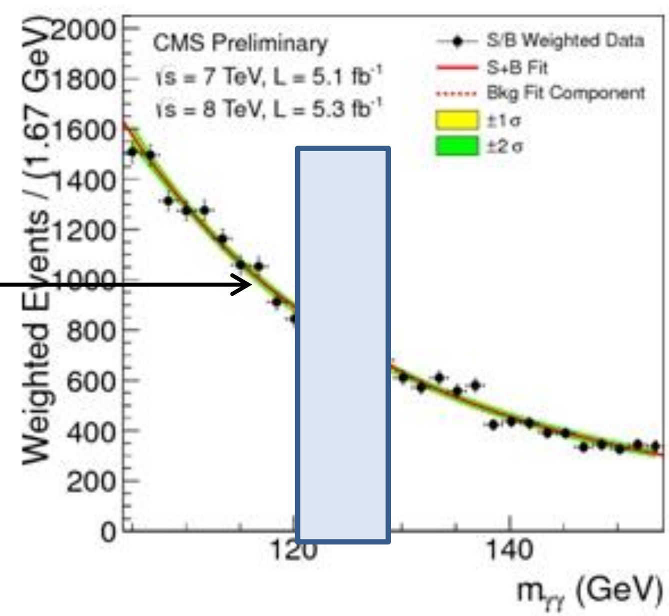
Steps in a Search

- Define signature of signal
  - e.g. H->γγ => two good photons in detector
- Identify sources of backgrounds
  - Optimise selections to eliminate as many backgrounds as possible
- Identify sources of systematic uncertainties
  - Uncertainties from detector modelling
  - Selection biases
  - Uncertainties from theory
- Construct statistical test of signal and background hypotheses
- Run test on measured data
- Quantify statistical significance of result

To peek or not to peek – Blind analyses

- Protect against bias
  - Quantify background expectations and uncertainties before looking at data
- In practice, background modellings and uncertainty measurements often taken from data
  - Define control regions where backgrounds will be measured and validated
  - Signal region defined by selection cuts and kept blinded

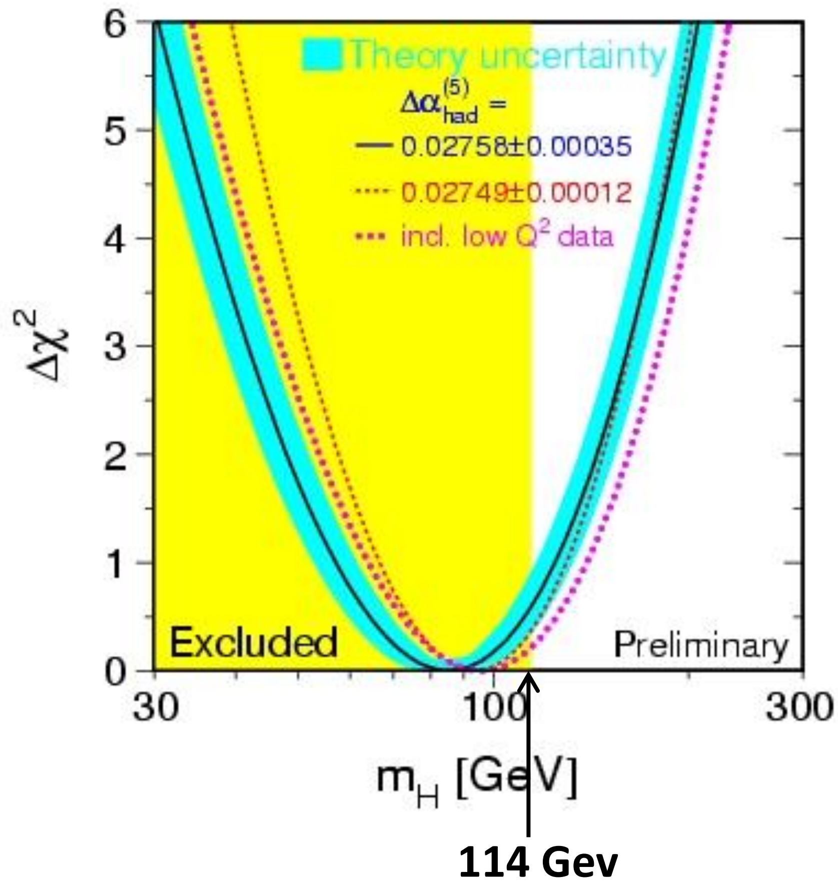




Smoothly falling background spectrum

Legacy from LEP

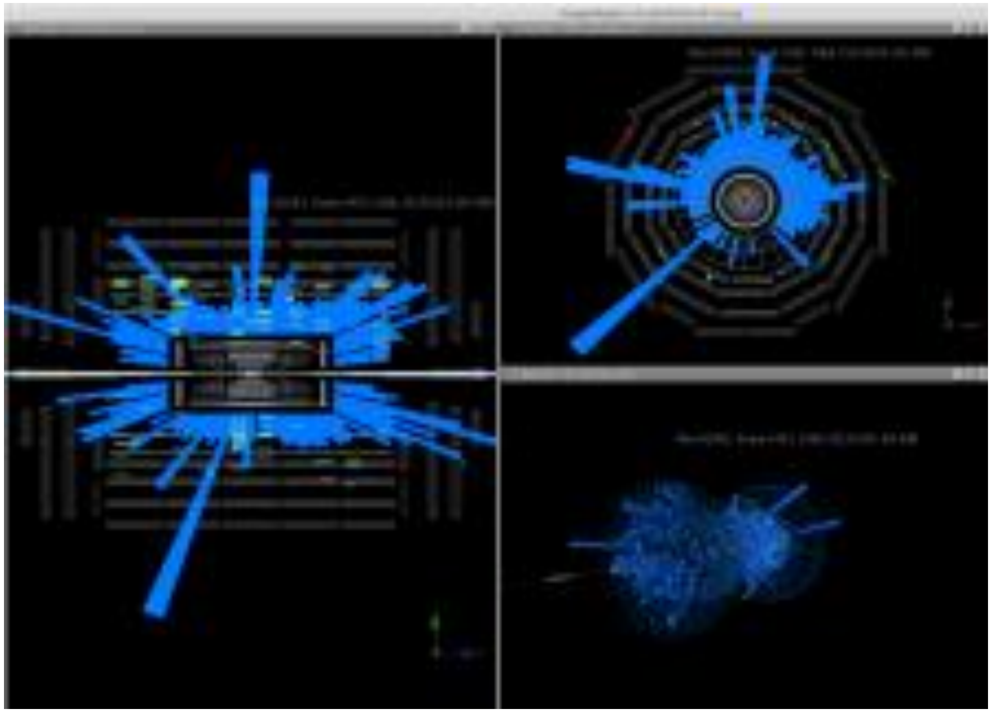
- e^-e^+ collider
- 2.461 fb-1 at 189-209 GeV c.o.m. energy
- Hints of a Higgs excess
    - 1.7σ at m_H = 115 GeV



A Brief History of (LHC) Time

First Beam

10th September 2008



First beam activity in CMS

ATLAS Control Room

Setback and Comeback

17th September 2008

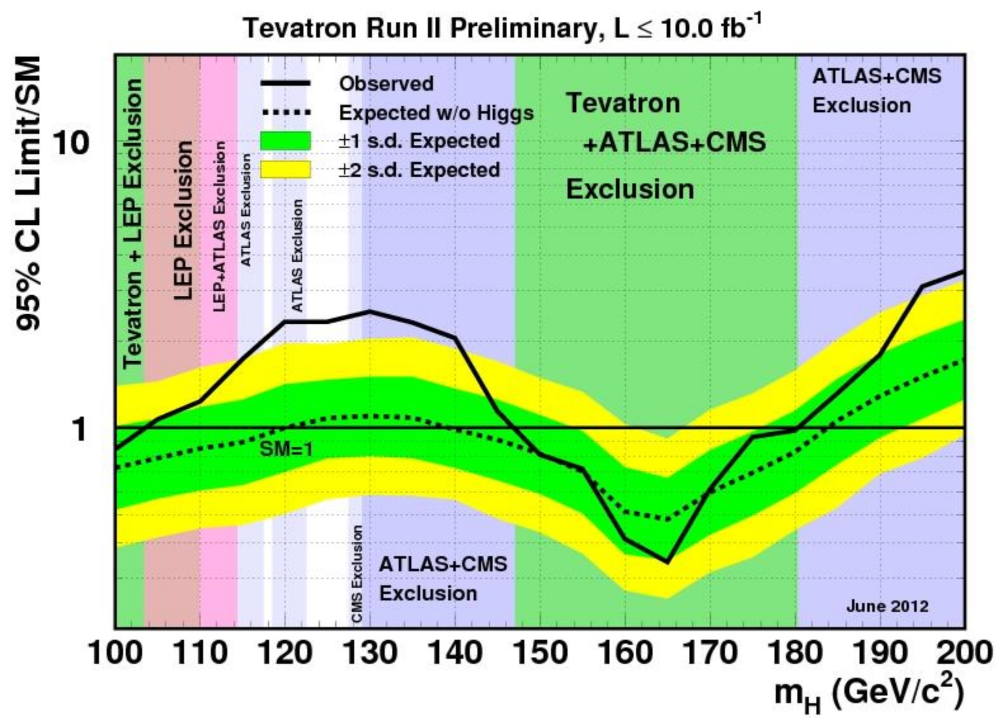
- Cautious work plan
    - Beam energy reduced to 3.5 TeV for entire 2010 + 2011 run
    - Increased to 4 TeV in 2012

23rd November 2009*

*** We are an optimistic bunch**

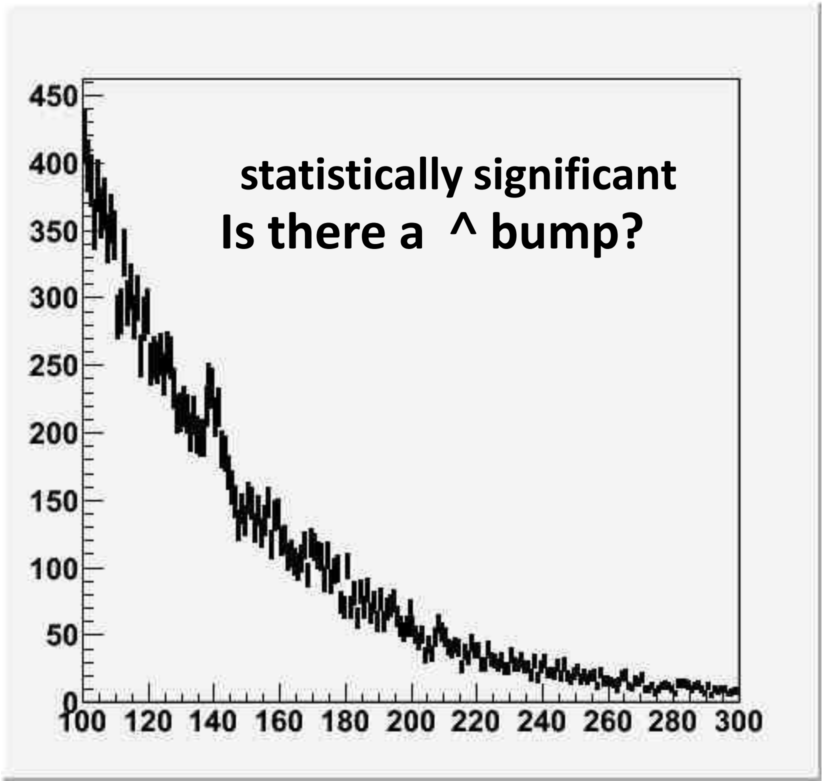
Across the Pond

- The Tevatron at Fermilab
  - p^+p^- collider (1983-2011)
- 10 fb^{-1} collected at 1.96 TeV
- Higgs exclusion
  - m_H in 147-180 GeV
- 2.5σ excess for m_H in 115-135 GeV

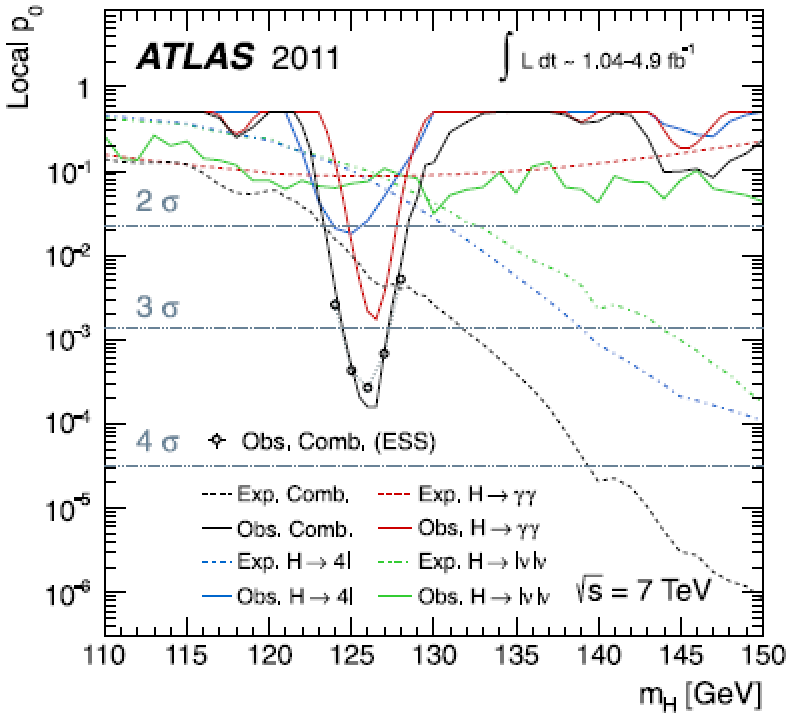


The Look-elsewhere Effect

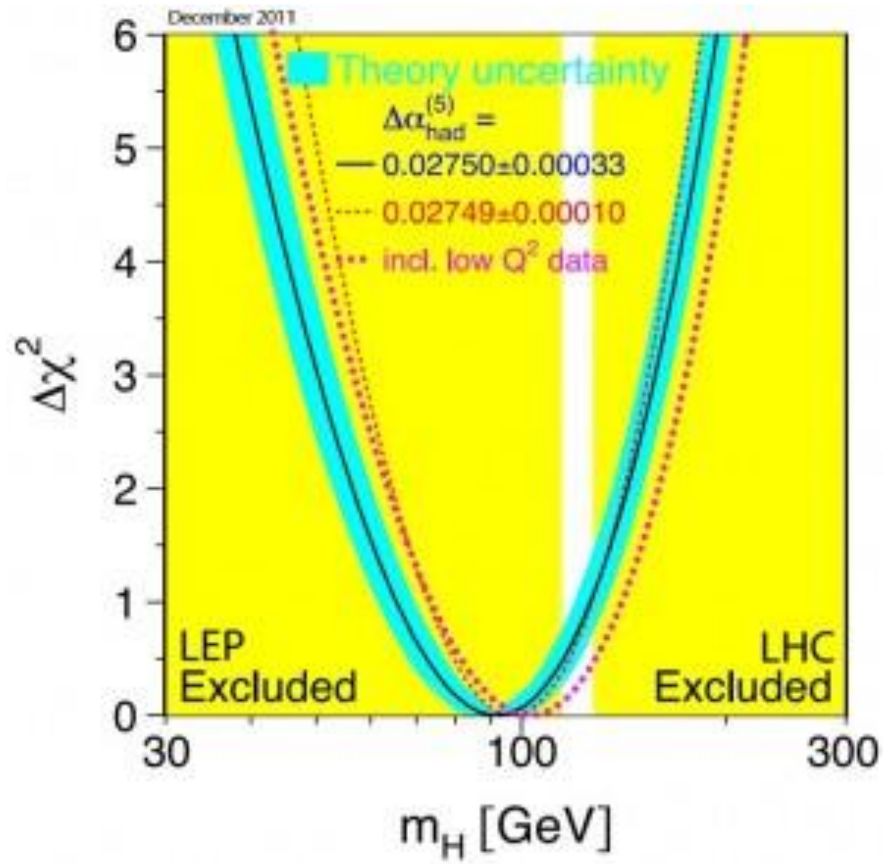
- Random fluctuations can produce false signal-like phenomena in the data
- Probability of local fluctuations increases as the search space is widened
- One needs to consider the **global** p-value
  - What is the probability that such a background fluctuation could have occurred anywhere in my search space?



First Hints at LHC



Global significance 2.5 σ



LEP + LHC combination 2011

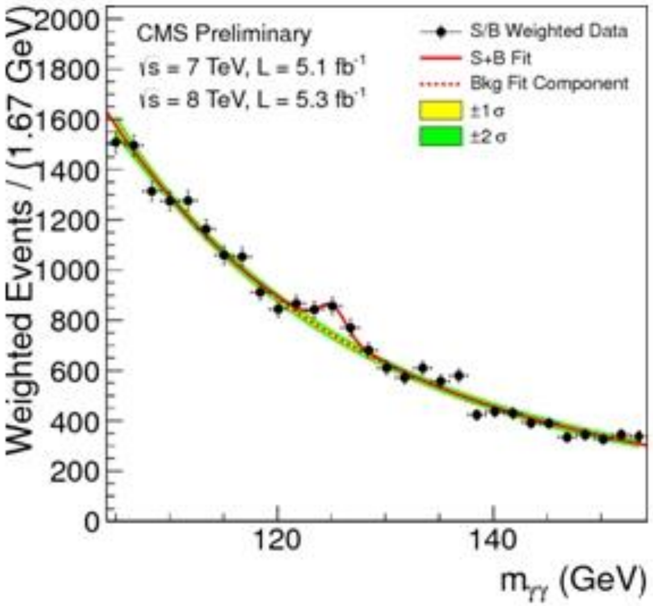
D-Day at CERN

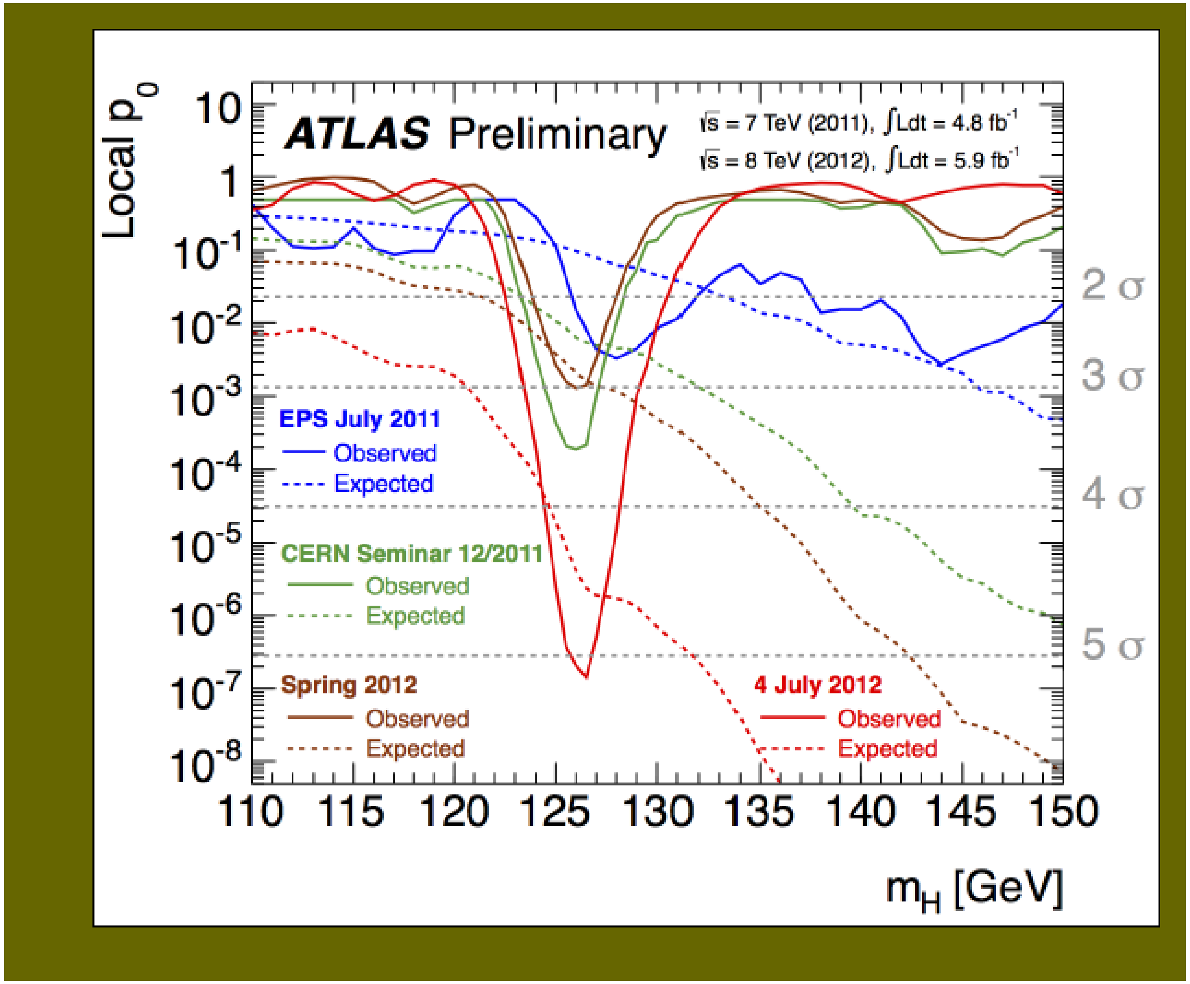
4th July 2012

The Long Wait*

*** We are a patient bunch**

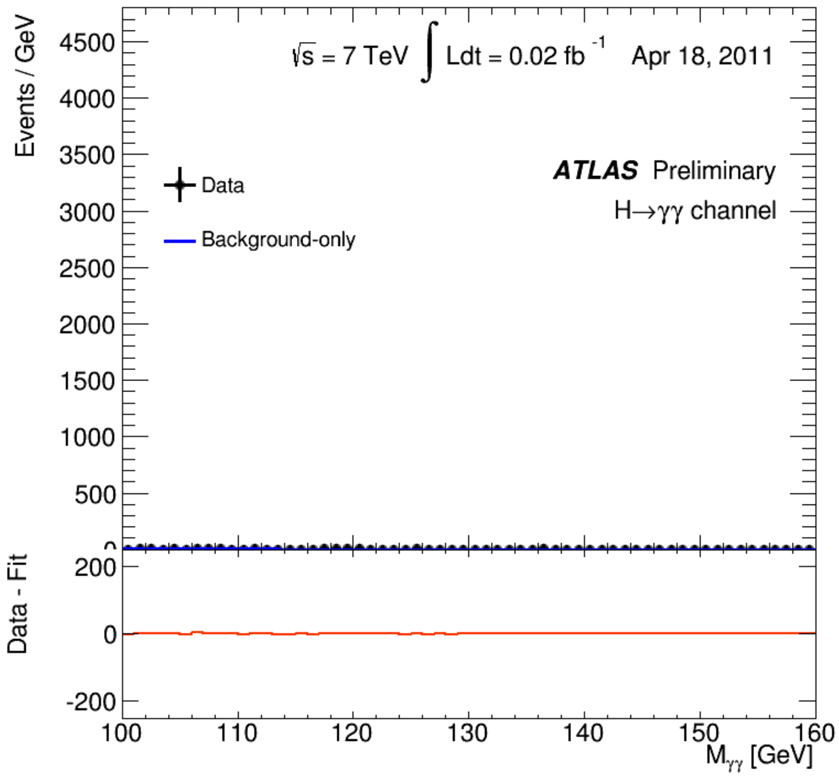
And we have it!

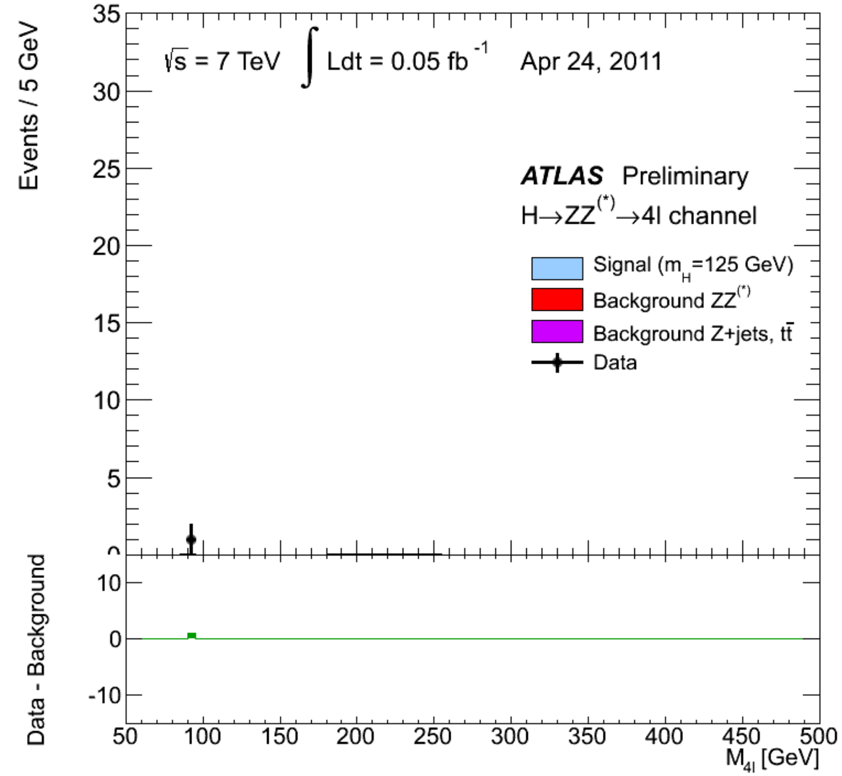




And we have it!

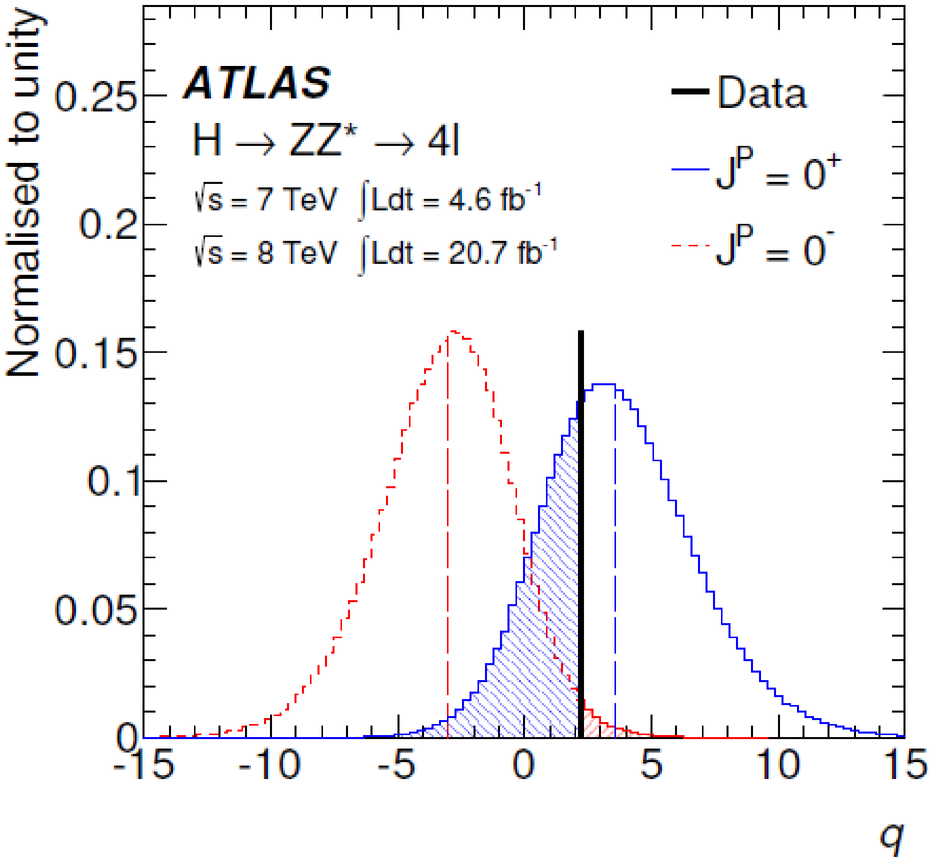
The Long Haul



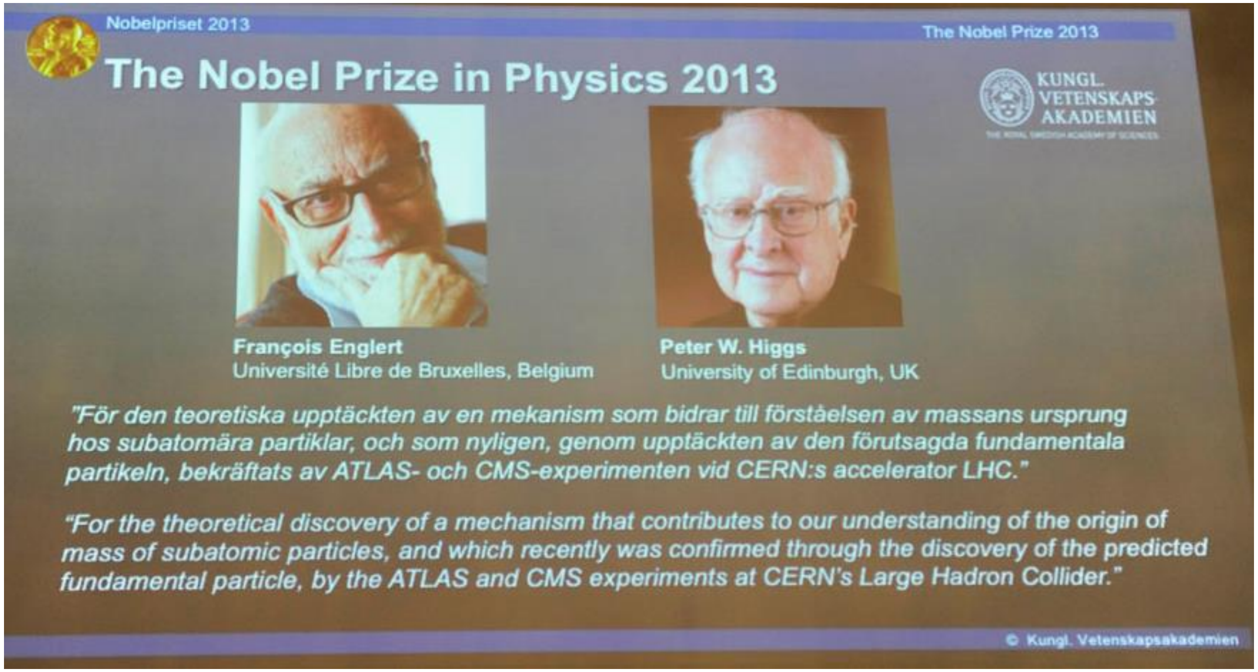


Moriond 2013: The Higgs-like boson is a Higgs boson

- Spin and parity measured from several angular observables
  - e.g. polar angle difference between photons in H->γγ events
- Data consistent with spin-0 and positive parity



2013 Nobel Prize



Celebrations at CERN*

*** We are a jubilant bunch**

Is this the End?

Is this the End?

NO

Higgs Measurements

- Observed particle is very consistent with SM Higgs, but:
  - Many production and decay modes remain to be observed
    - $H \to b\bar{b}$: very challenging due to large backgrounds from other SM processes; look for production in association with W/Z/ top quark pair
    - Associated production of Higgs with top quark pair
      - Top is heaviest fundamental particle – strongest coupling to Higgs boson
      - Direct measurement of this coupling strength
  - Measurements of mass, charge, spin properties of Higgs
    - Test of SM predictions and window into new physics

Beyond the Standard Model (BSM)

- Missing pieces in the Standard Model
  - Gravity
  - Dark matter & dark energy
  - Why three generations?
  - Origin of mass and interaction strength hierarchies in Standard Model
  - Matter-antimatter asymmetry
  - The naturalness problem
- Many BSM theories predict extensions to the Higgs sector
  - Supersymmetry
  - Composit Higgs Models
  - Two-Higgs Doublet Models

Summary and Outlook

- The Higgs discovery was a dramatic culmintation of **decades** of work by theorists and experimentalists
- A great validation for the Standard Model
- A huge boost to the particle physics community
  - Great publicity!
  - Hopefully convinces people that science is a worthy investment
- But the universe is full of mysteries
  - Many more riddles to be solved