u c s b High Energy Physics

The discovery of the Higgs Boson

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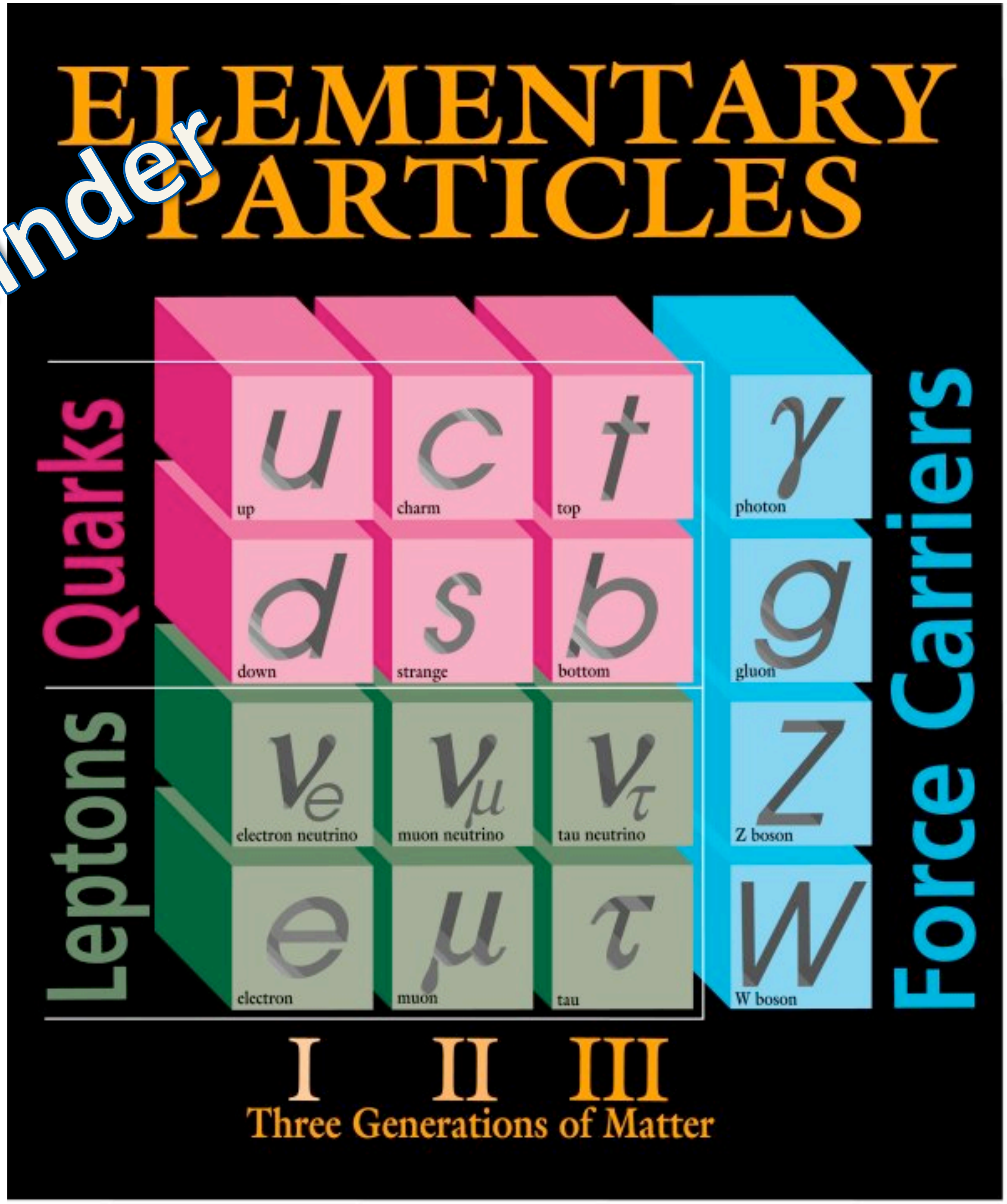
2 October 2012

Outline

- What is the Higgs boson
- What did we know about the Higgs boson 2 years ago?
- What did we know last Christmas?
- It has now been found!
- Conclusions and prospects

Technical Details kept to a minimum…this is not a talk for experts in particle physics

Reminder



Fermilab 95-759

What is the Higgs Boson?

The Higgs Boson and Particle Physics

- We have a beautiful theory of the strong and electromagnetic interaction based on "gauge" interactions. The Standard Model (SM).
- It works great. But it breaks down miserably if we put the masses of lepton, quarks, force carriers, into the theory by hand
- The Higgs mechanism is a way around this
- It predicts the existence of a neutral, spin=0, fundamental particle: the Higgs Boson

Higgs boson: what Margaret Thatcher and the 'God Particle' have in common

The former prime minister Margaret Thatcher is playing an intriguing role in helping to understand the great scientific mystery of the Higgs boson.

The Ion Lady: Mrs Thatcher's momentum was hard to stop Photo: JULIAN SIMMONDS

By Iain Hollingshead

7:48PM GMT 13 Dec 2011

Historians – or at least those, like me, who spent three happy years

Large
Science »
Margaret Tha
Iain Hollingshea

IN LARGE HADRON COLLIDER

Large Hadron Collider experiment explained

Cern. Yesterday, it was reported that researchers in Geneva may have glimpsed the Higgs boson, some sort of subatomic particle proton thingy which has something to do with mass (or is it density…?).

You see the problem? Perhaps you're a physics genius who bandies around phrases such as "Standard Model theory" and "Compact Muon Solenoid" at drinks parties. But what about the rest of us who gave up

I have more joy with Roger Highfield, Telegraph columnist and former editor of New Scientist. In 1993, he points out, William Waldegrave, then science minister, challenged physicists to produce a one-page answer to the question: "What is the Higgs boson, and why do we want to find it?" The winning entry, which Highfield says the director-general of Cern still uses, compared the universe to a cocktail party of political workers attended by **Margaret Thatcher**. Her popularity (among Tories in 1993) means that as she moves around the room she has more mass than everyone else; once she is moving, she is hard to stop, and once she has stopped she is hard to get moving again. That, in essence, is the Higgs mechanism. Now imagine a political rumour passing through the same room. It would travel in clusters, giving those carrying the rumour extra mass in a similar way to the former PM's. That, in essence, is the Higgs boson.

- Elementary particles acquire mass through their interactions with Higgs field
- The stronger the interaction, the larger the mass of the particle

- This has an important consequence:

The Higgs boson likes to decay to the heaviest particles that it can

The Higgs Boson and the Standard Model

- It is the least tested feature of the SM
- The implementation of the Higgs Mechanism in the SM is the most “economical”, but it could be more complicated, eg “two Higgs Doublet Models” (2HDM) result in 5 physical particles. (SUSY is a 2HDM)
- There are higgs-less alternatives (technicolor, etc)
- There are issues with fundamental scalars (S=0) in the theory (the “fine tuning” issue – SUSY fixes that, sort of)

What did we know about the Higgs boson ~ 1.5 years ago

Where does our knowledge come from

1. Theory
   - In the SM the couplings are fully specified
     - We know how it decays ("branching fractions") and how it can be produced ("cross-sections")
     - This is extremely important in a search
   - **But the mass is a free parameter**
2. Experiment
   - We have been searching for the Higgs boson. We have not found it. *This results in ruling out certain mass ranges*
3. Experiment + Theory
   - The mass of the Higgs enters in SM calculations of higher order corrections to quantities that we can measure.
   - Results in *indirect* constraints on the Higgs mass

Experimental Searches

- LEP was a CERN e^+e^- collider that run until ~ 2002 at a center-of-mass energy up to ~ 210 GeV
  - **Established a limit $M_H > 114$ GeV**
  - It saw a hint of a signal at $M_H \sim 116$ GeV

- The Fermilab ppbar experiments at a center-of-mass-energy of 2 TeV excluded $156 < M_H < 173$ GeV

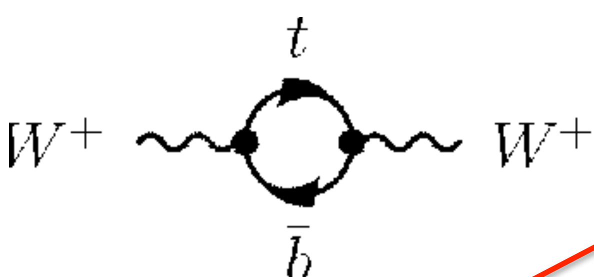
Indirect Constraints, an example

$$M_W^2 = \frac{\pi\alpha}{\sqrt{2}} \frac{1}{G_F s_W^2}(1+\Delta r)$$

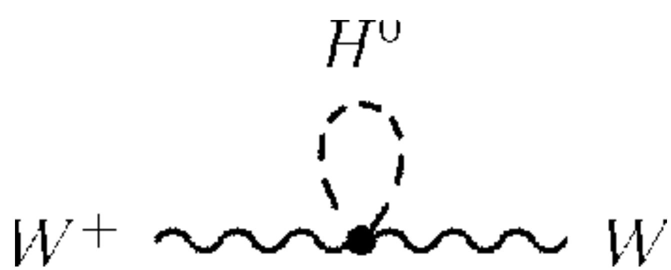
Mass of the W
known at the 3 10^{-4} level

Fermi Constant
known at the 10^{-5} level

Higher order terms



Mass of the top
known to ~ 1%



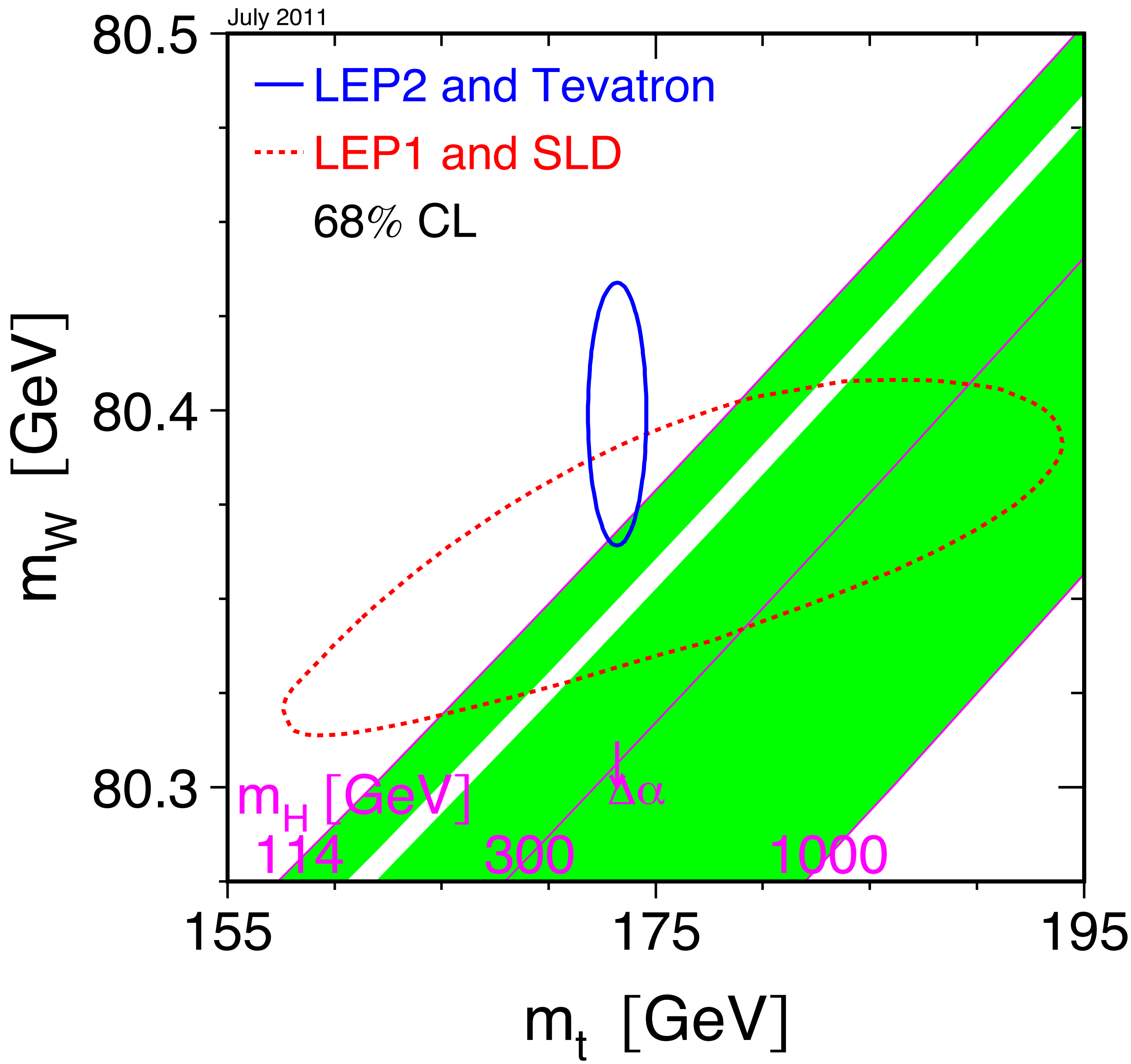
$$\Delta r_{top} \approx 0.03 \cdot (\frac{M_{top}}{175\ \mathrm{GeV}})^2$$

quadratic dependence
on top mass

$$\Delta r_H \approx 0.003 \cdot (\log \frac{M_H^2}{c_W^2 M_Z^2} - \frac{5}{6})$$

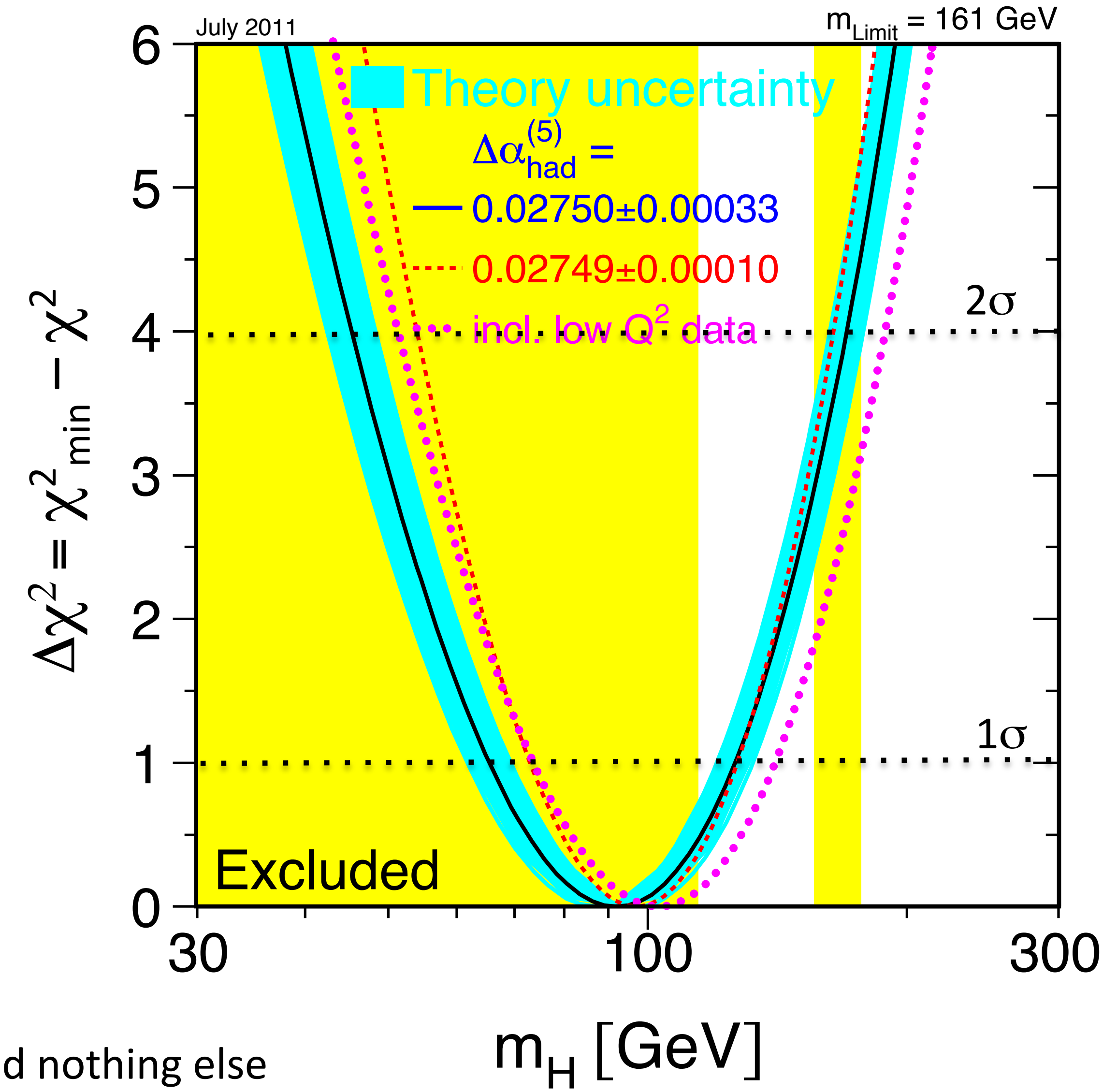
logarithmic dependence
on Higgs mass

Relationship between W, top, Higgs masses



All “precision” measurements are thrown into a a big statistical fit.

$$M_H = 89^{+35}_{-26}\ \mathrm{GeV}$$

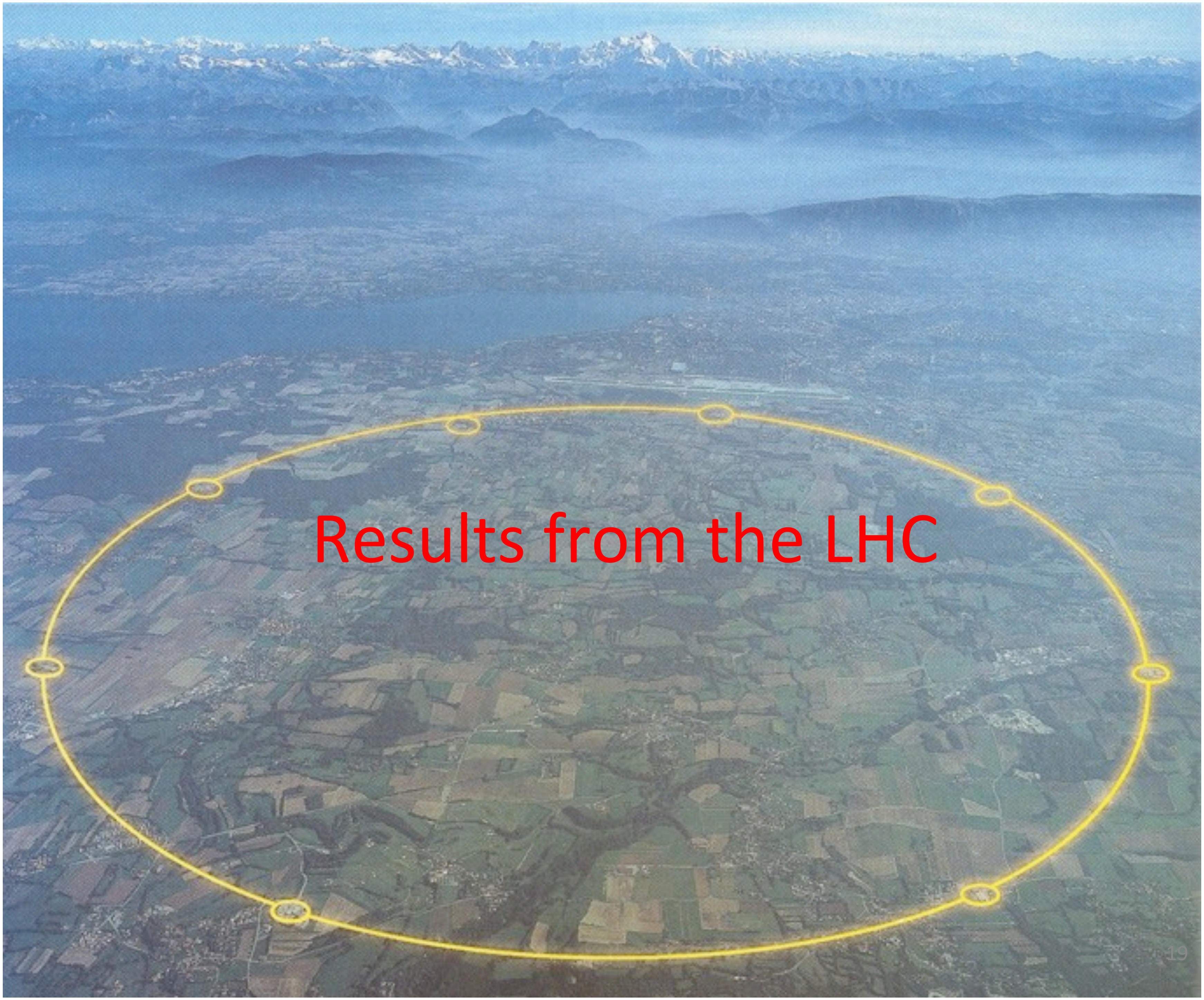


Assumes SM and nothing else

Executive Summary, as of ~ 1.5 year ago

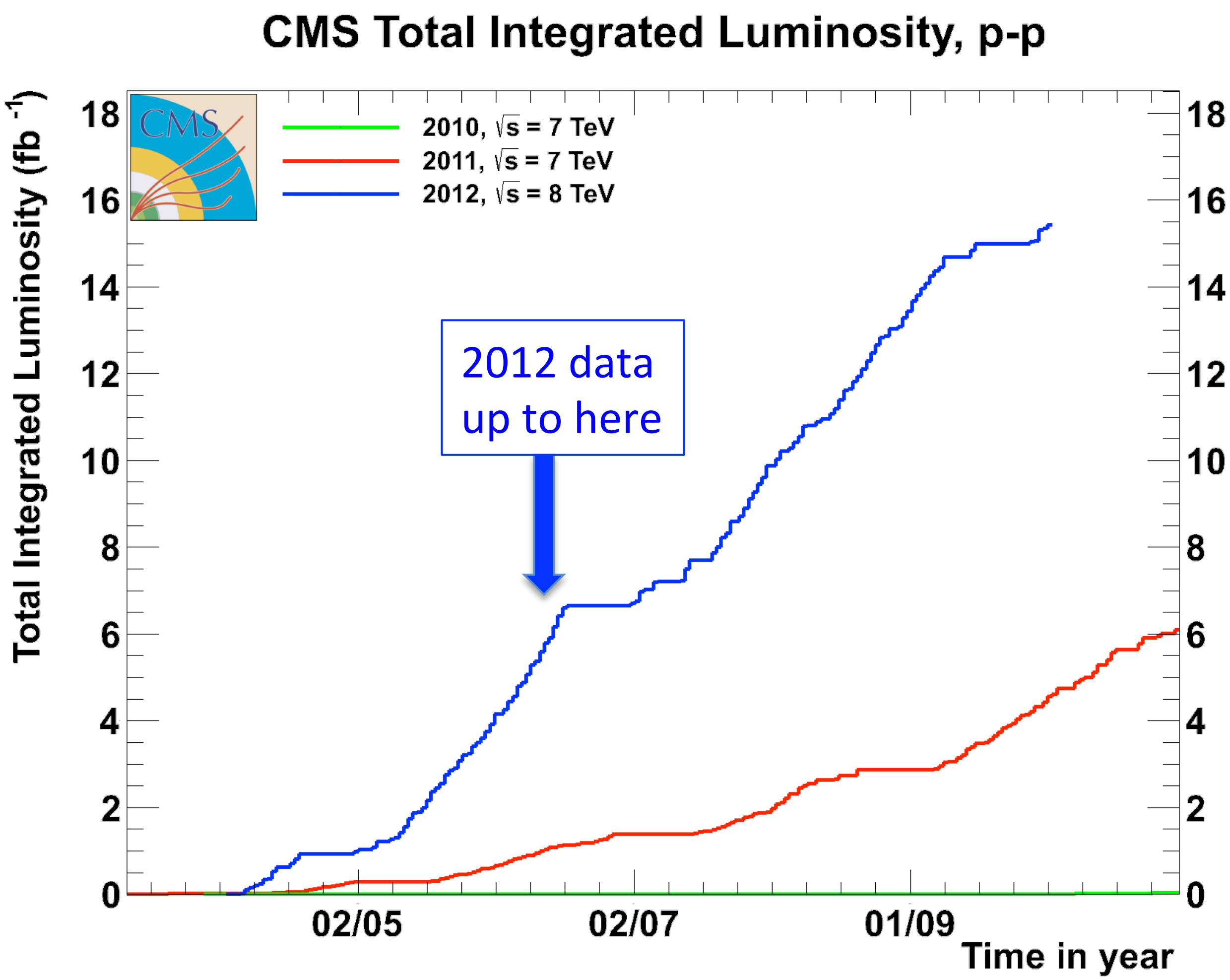
- The SM tells us everything about the Higgs except for its mass.
- Direct searches excluded M_H<114 GeV (LEP) and a small interval around 160 GeV (Tevatron)
- There was a hint of a signal near 116 GeV at LEP
- Indirect evidence points to a light SM Higgs

Results from the LHC



About the Results That I Present Today

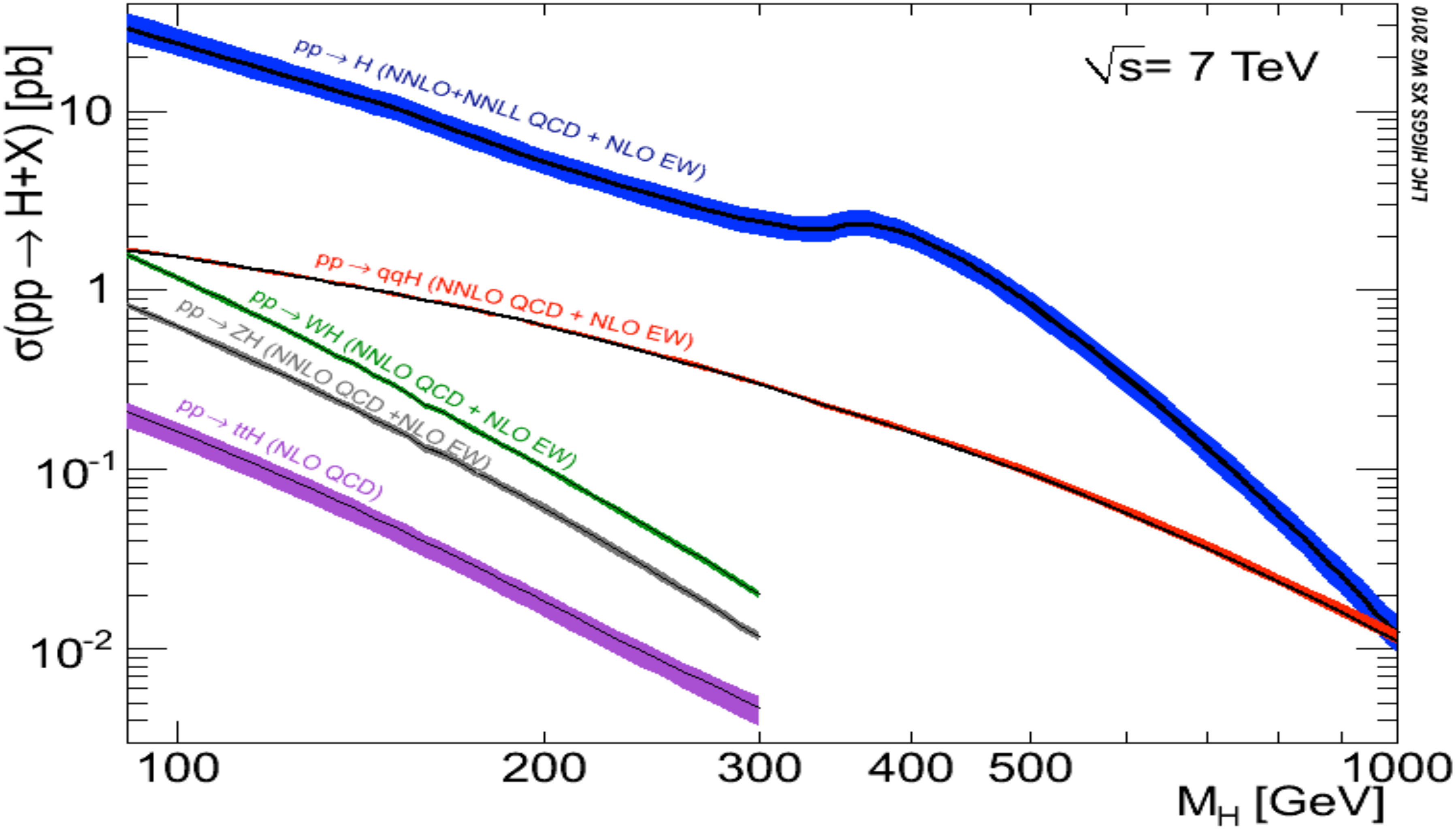
- There are two “big” detectors at the LHC, Atlas and CMS
- For simplicity, I (mostly) show CMS results
  – Because I am on CMS
- Results from Atlas are comparable



- Results are based on data collected in 2011 and until end of June 2012
- The *integrated luminosity* was ~ 5 fb^{-1} for each run period
- It corresponds to ~ 10^{15} proton-proton interactions

General considerations: how can you find (or exclude) the Higgs?

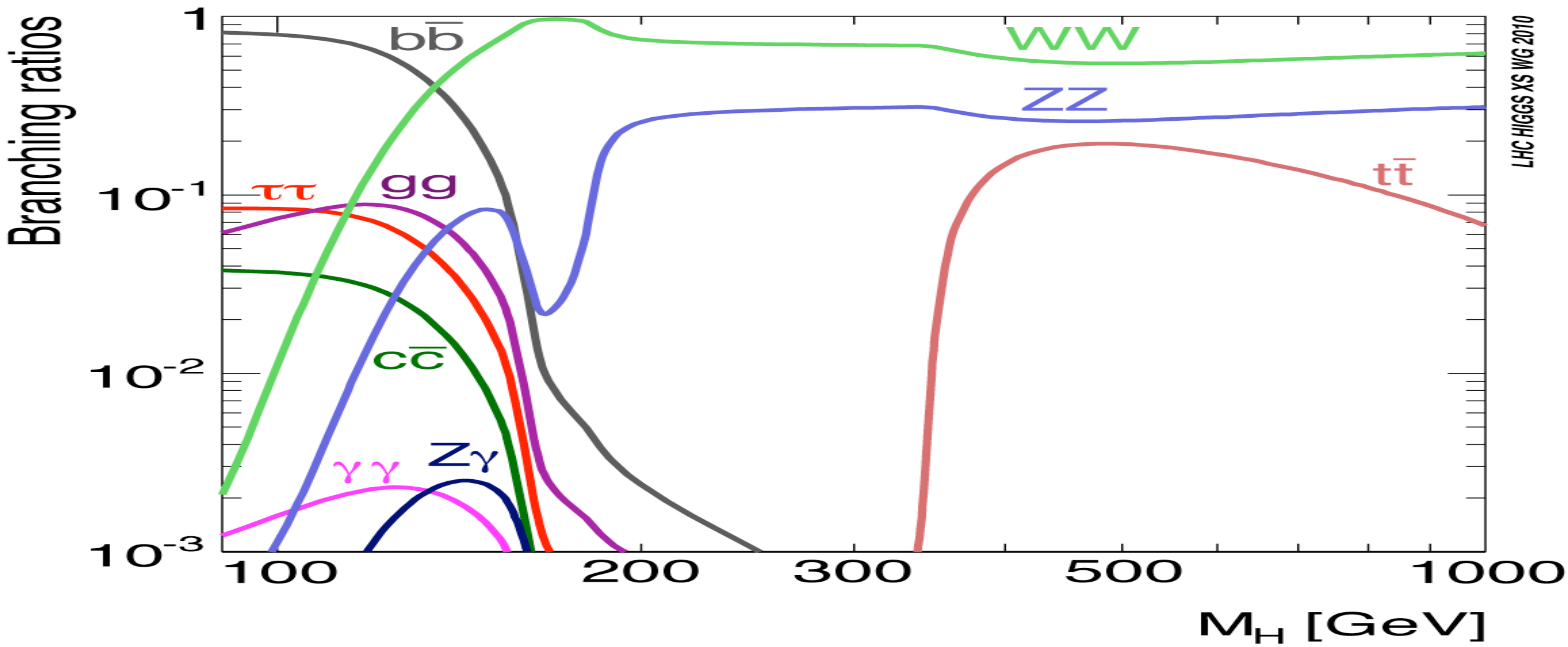
1. Produced in pp interactions, look for its decay signature



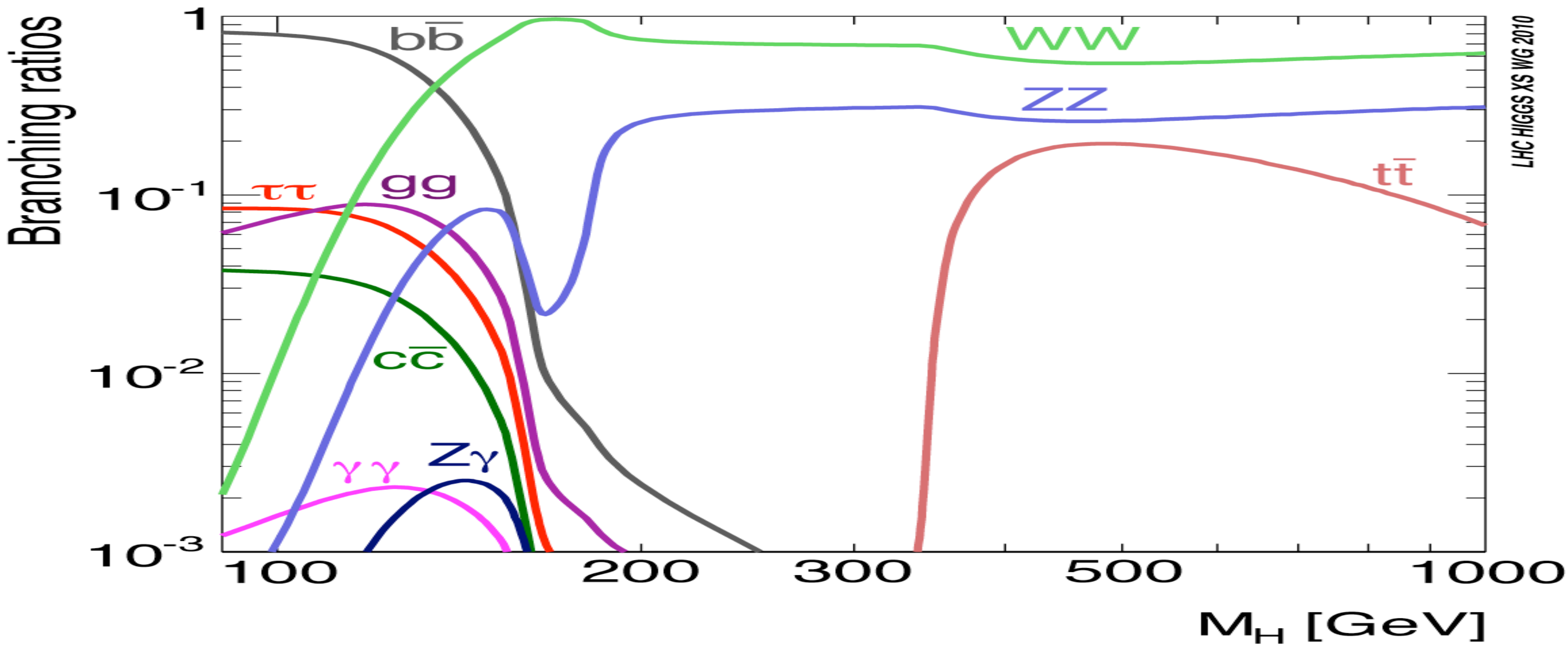
- There are a few different production mechanisms
- As M_H increases, the cross-section decreases
- It is a rare process
- In ~ 10^{15} pp collision, ~ 180 K (9 K) higgses were produced for M_H=120 (500) GeV

General considerations: how can you find (or exclude) the Higgs?

1. Produced in pp interactions, look for its decay signature
2. Concentrate on different decay modes depending on M_H. For a given decay mode often perform several searches fine tuned for different M_H



- Not all decay modes are accessible because of backgrounds
  - For example: H→gg is hopeless
  - H→bbar can only be seen if the Higgs is produced in association with a W or Z.
    - This looses a factor of O(100) in rate
- Many of the final state particles also decay
  - Some of their decay modes are also swamped by backgrounds.
  - For example H→WW final state must require both W decay as W→eν or W→μν.
    - Lose factor of ~ 20 in rate



Bottom line decay modes

- Many decay modes are looked at
  - The "drops in the bucket approach"
- The most important ones are
  - pp → H → γγ at low mass (BR ~ 10^{-3})
  - pp → H → WW → eν eν/μν μν/eν μν at intermediate mass (BR ~ 5%)
  - pp → H → ZZ → ee νν/μμ νν at high mass (BR ~ 6%)
  - pp → H → ZZ → ee ee/μμ μμ/ee μμ at all masses (BR ~ 0.5%)

General considerations: how can you find (or exclude) the Higgs?

1. Produced in pp interactions, look for its decay signature
2. Concentrate on different decay modes depending on M_H. For a given decay mode often perform several searches fine tuned for different M_H
3. Fundamental difference between decay modes with and without neutrinos

Modes with and without neutrinos

- For example: in H→$\gamma\gamma$ measure energy and direction of the two photons.
  - Can reconstruct invariant mass of $\gamma\gamma$ pair.
  - Signal is clear: a peak in mass($\gamma\gamma$)
  - You can measure M_H precisely (to better than 1 GeV)

- OTOH: in H→WW→$e\nu\mu\nu$ cannot measure momentum of the two neutrinos
  - Cannot reconstruct invariant mass of WW pair
  - Signal is an excess of "eμ + missing momentum" events with characteristics consistent with Higgs on top of all possible contributions from other sources
  - You can get only coarse information on M_H (to ~ 20 GeV or so)

General considerations: how can you find (or exclude) the Higgs?

1. Produced in pp interactions, look for its decay signature
2. Concentrate on different decay modes depending on M_H. For a given decay mode often perform several searches fine-tuned for different M_H
3. Fundamental difference between decay modes with and without neutrinos
4. If you do not see a signal, how can you exclude a mass range?

Excluding a mass range

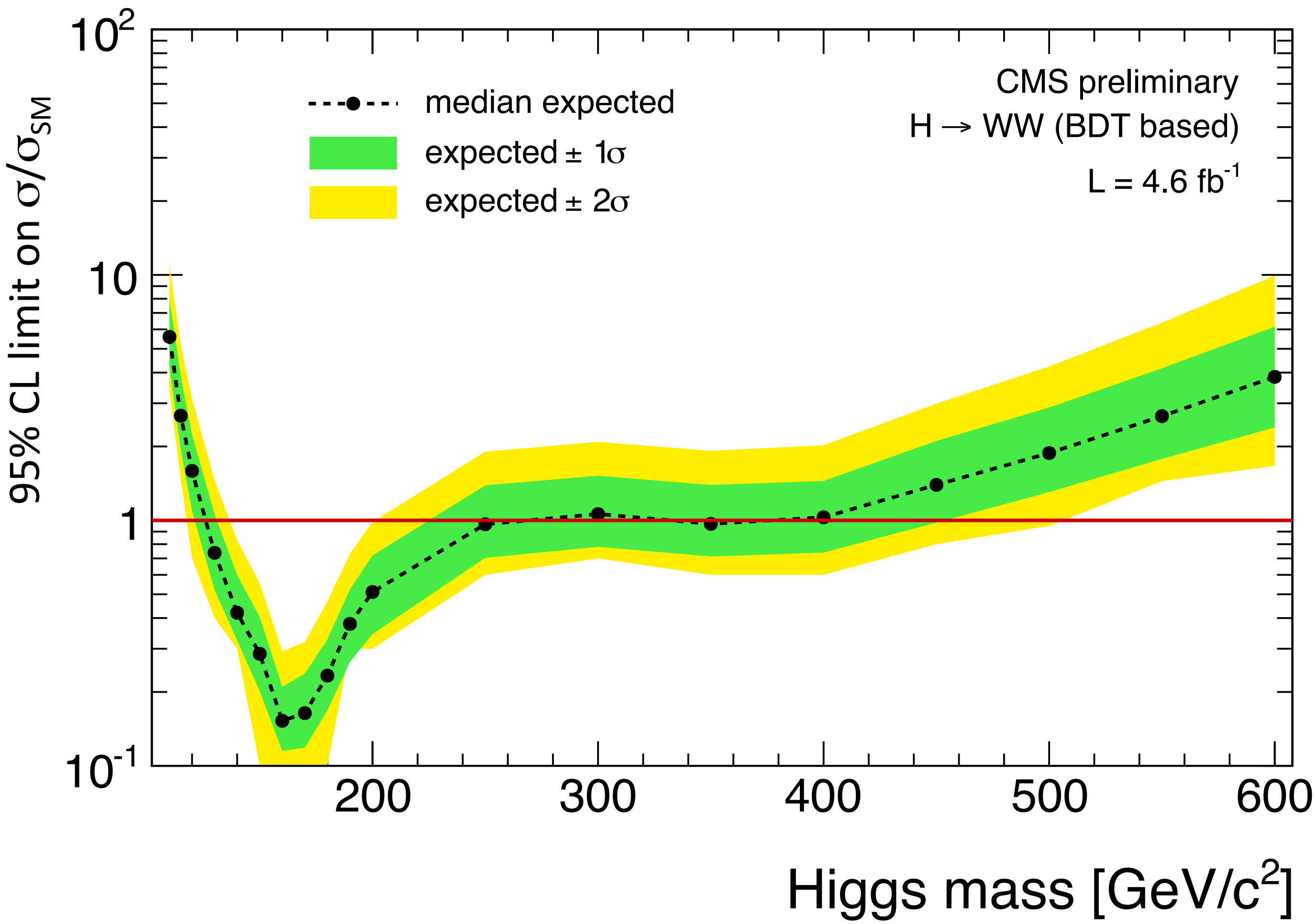
- If you do not see a signal in a given mode, your result is

  $\sigma(pp \rightarrow H)$*BR(your mode) < xx at 95% CL

- Since we know from theory what σ and BR should be as a function of M_H, we can exclude any M_H that results in σ*BR > xx

(Is this obvious?)

The “brazilian flag plot”



- If the observed limit is above (ie: worse) than the expected limit it means that there is an excess over what you expect from background-only
  - Statistical fluctuation of background

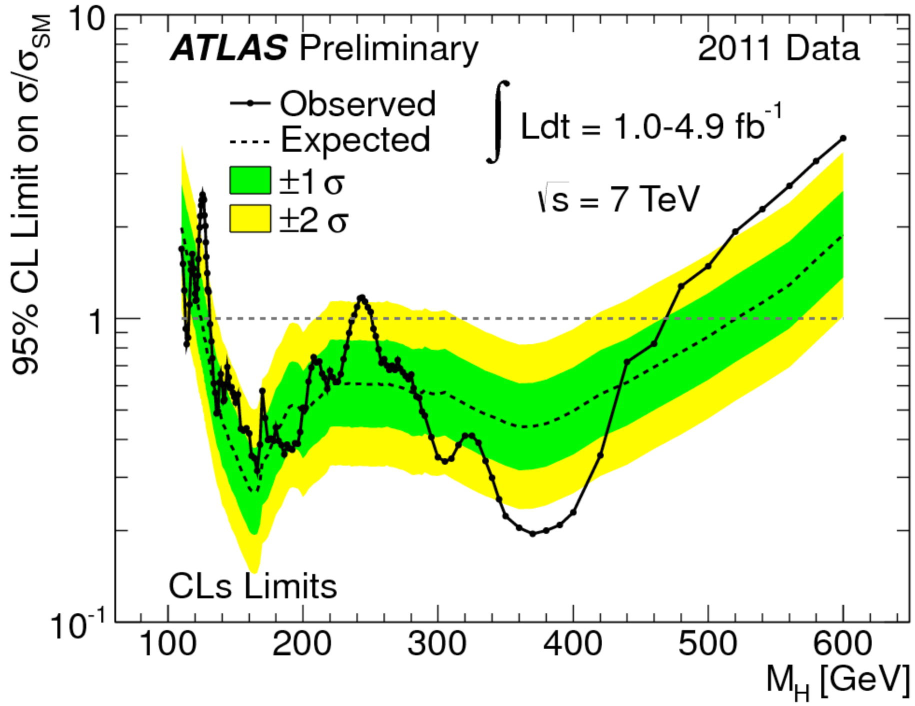
  Or

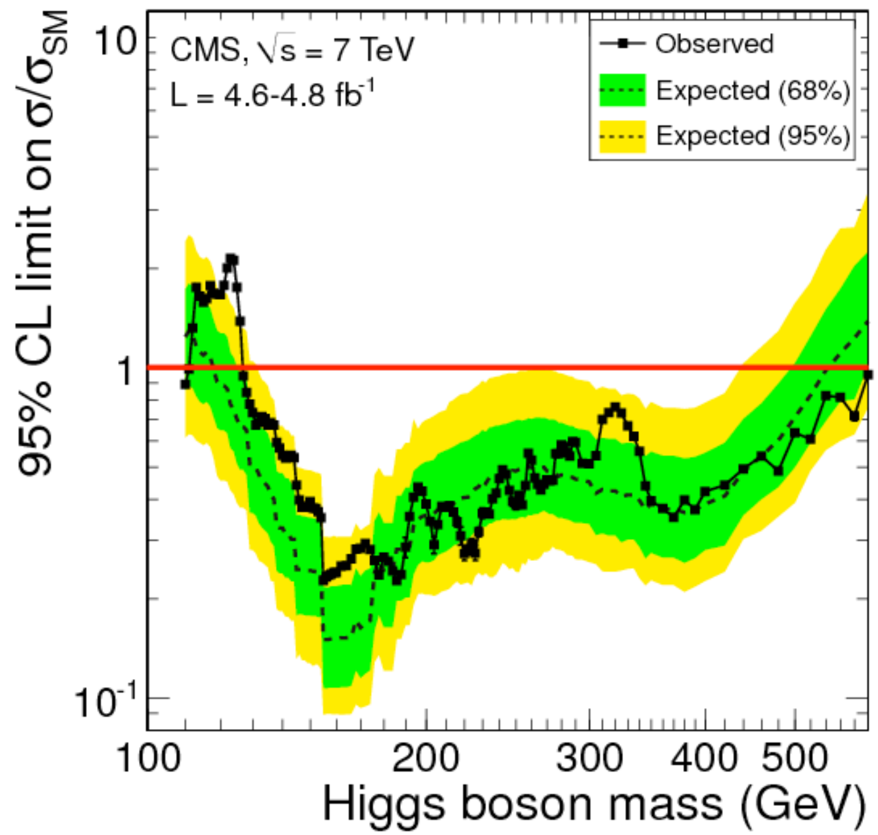
  - You are starting to see a signal

  Or

  - You messed up your background analysis
- A 1σ (2σ) excess of events results in limit 1σ (2σ) worse-than-expected limit
- If the expected limit is n-times the SM cross-section, then a SM Higgs, if it exist will lead, on average, to a limit ~ (2/n)σ worse-than-expected

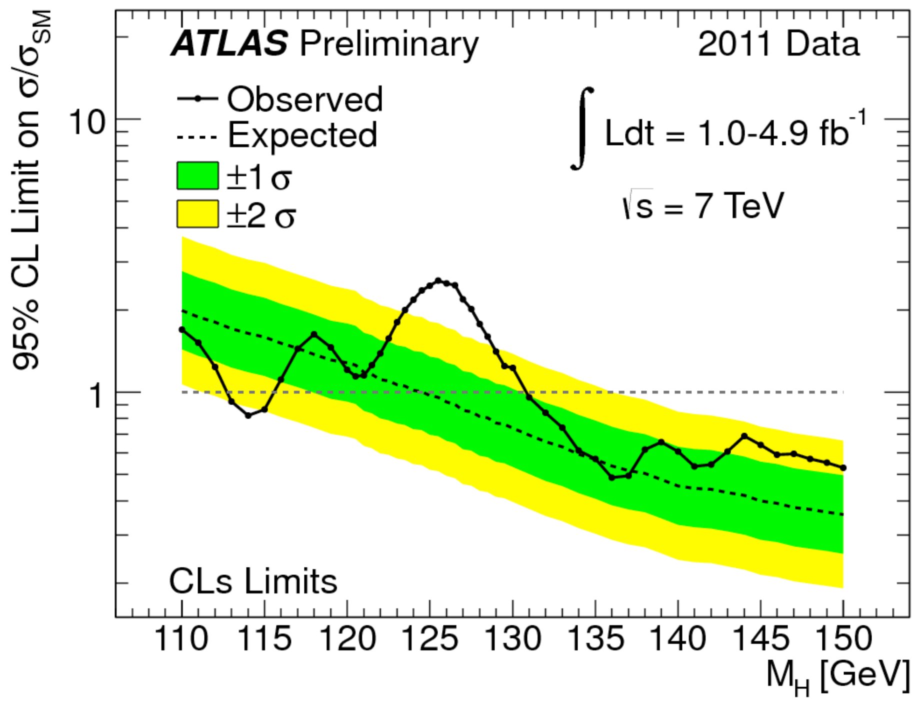
The 2011 results

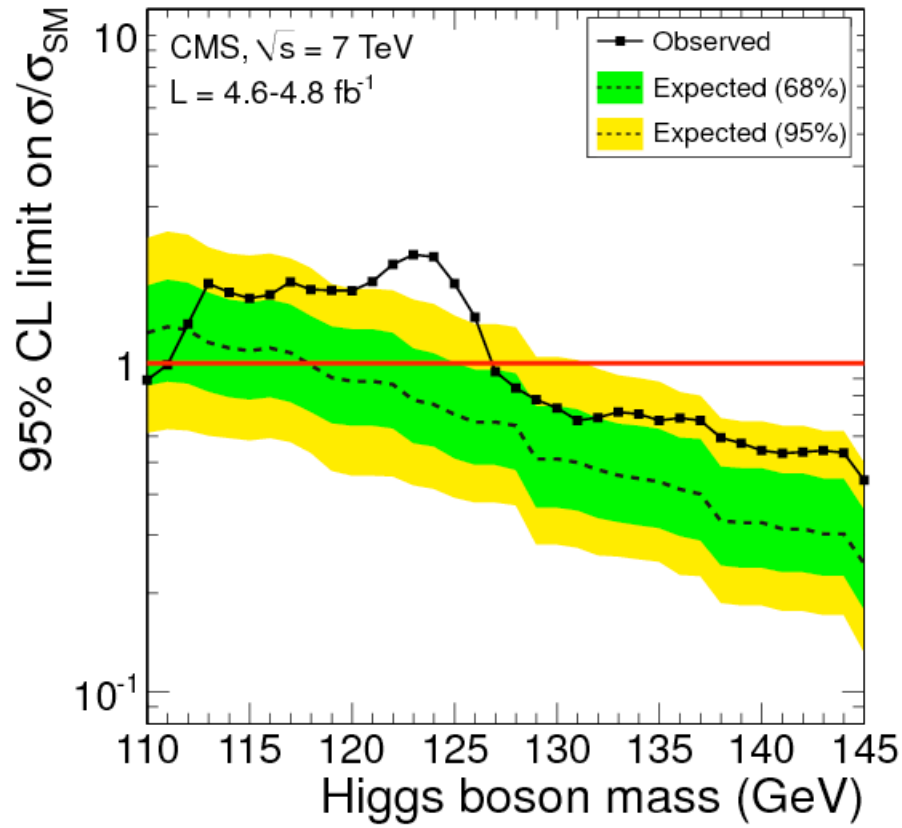




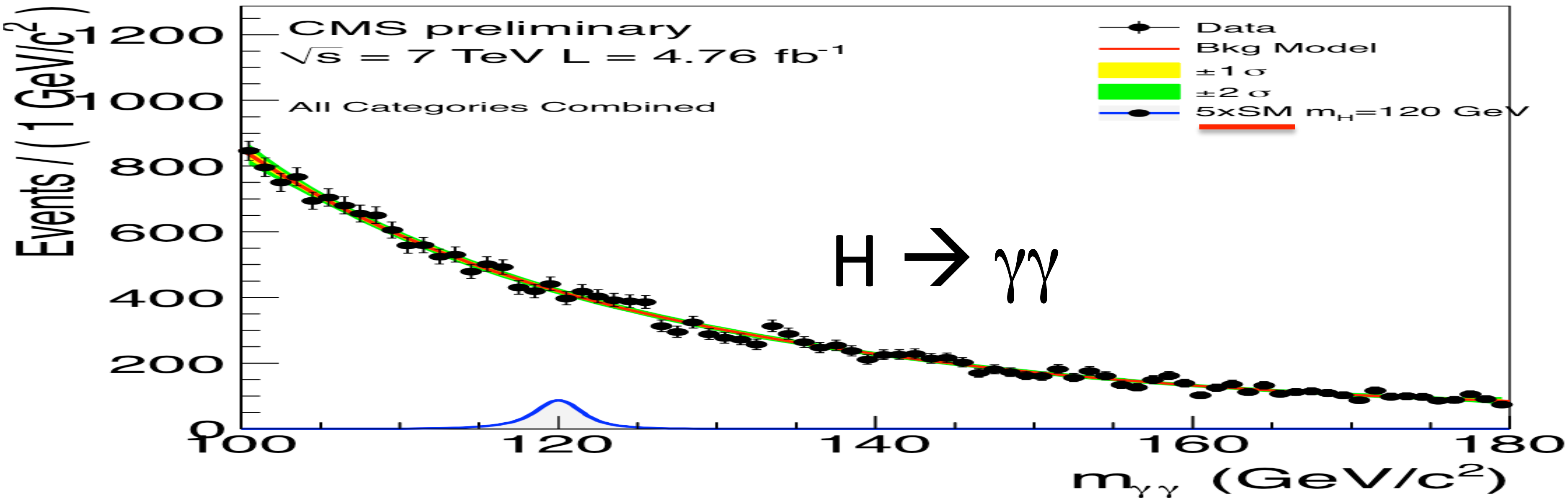
Excluded almost the full mass range…except at the low end

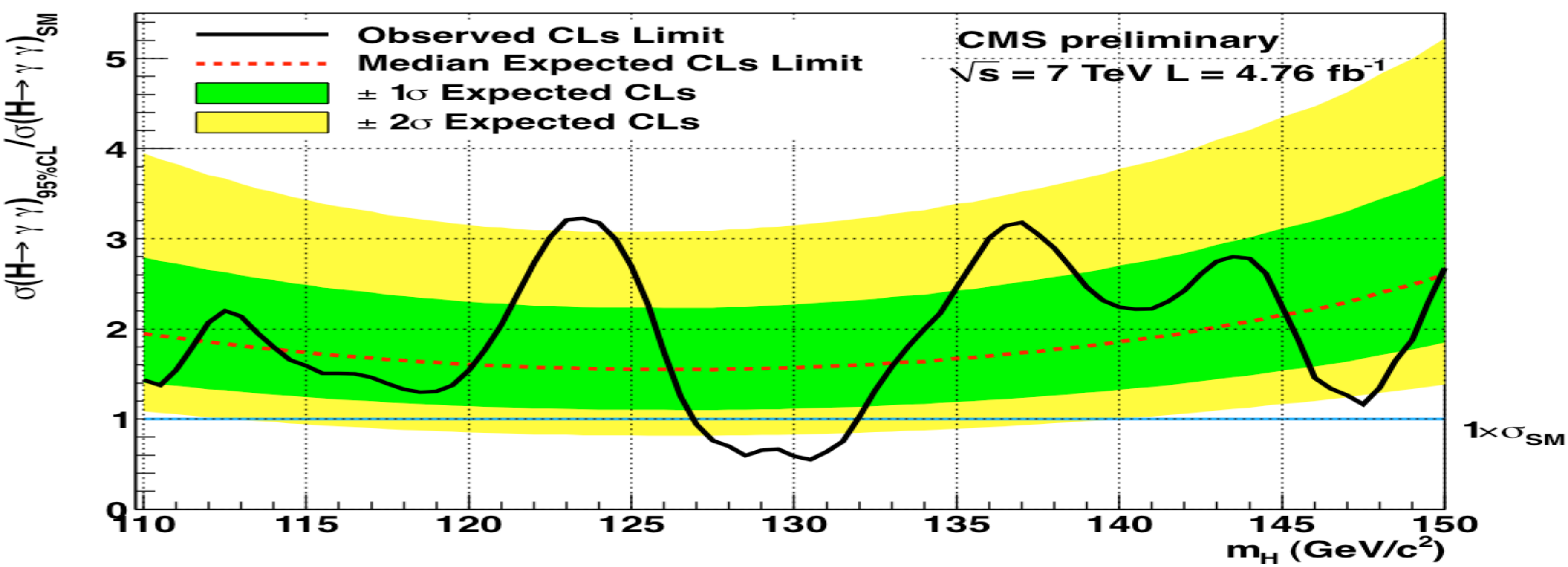
Zoom in

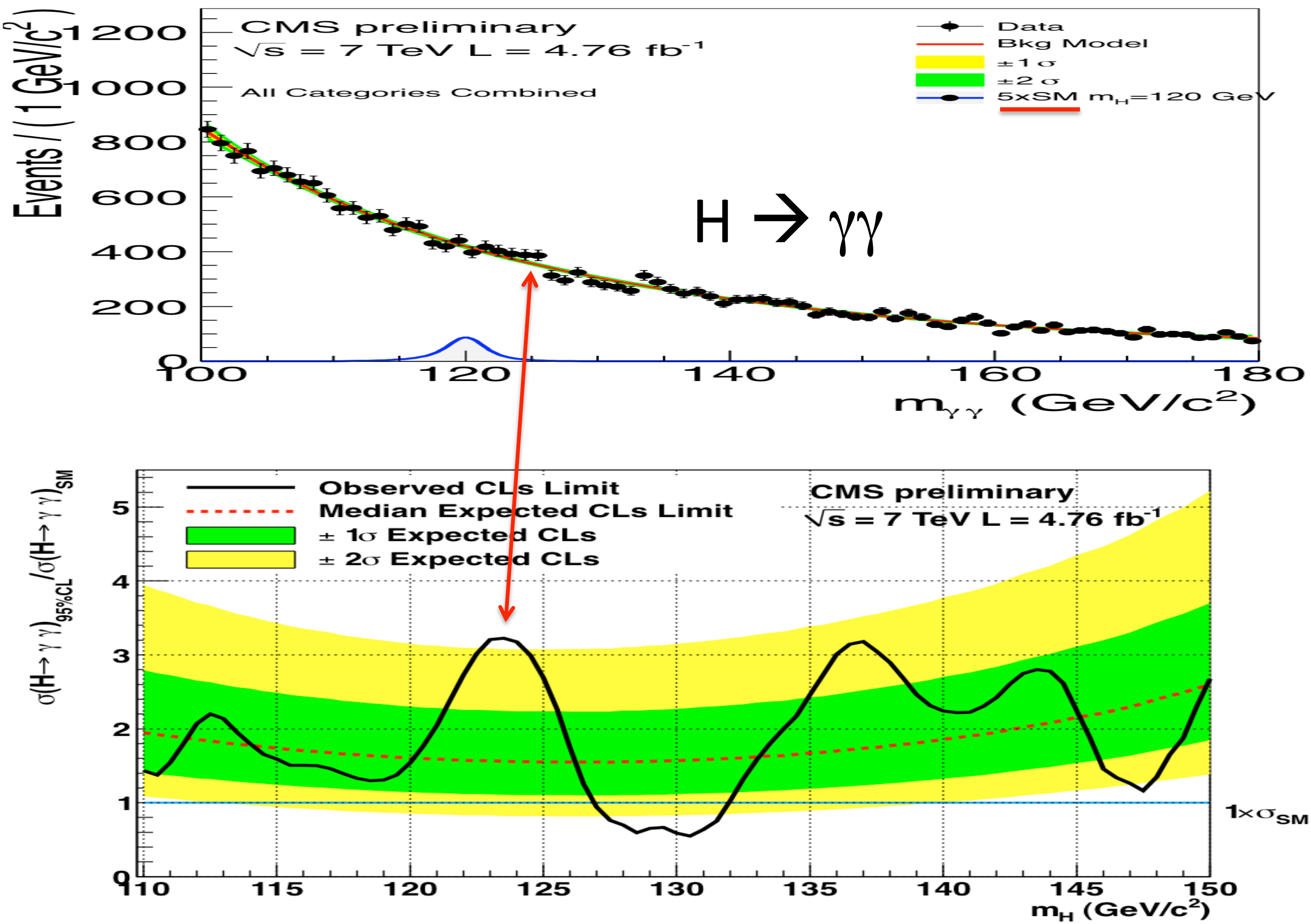




Both experiments had a 2-3σ excess near 125 GeV


CMS preliminary
√s = 7 TeV L = 4.76 fb-1
All Categories Combined
Data
Bkg Model
±1 σ
±2 σ
5xSM mH=120 GeV
H → γγ
Events / (1 GeV/c2)
mγγ (GeV/c2)


Observed CLs Limit
Median Expected CLs Limit
± 1σ Expected CLs
± 2σ Expected CLs
CMS preliminary
√s = 7 TeV L = 4.76 fb-1
1×σSM
σ(H→γγ)95%CL/σ(H→γγ)SM
mH (GeV/c2)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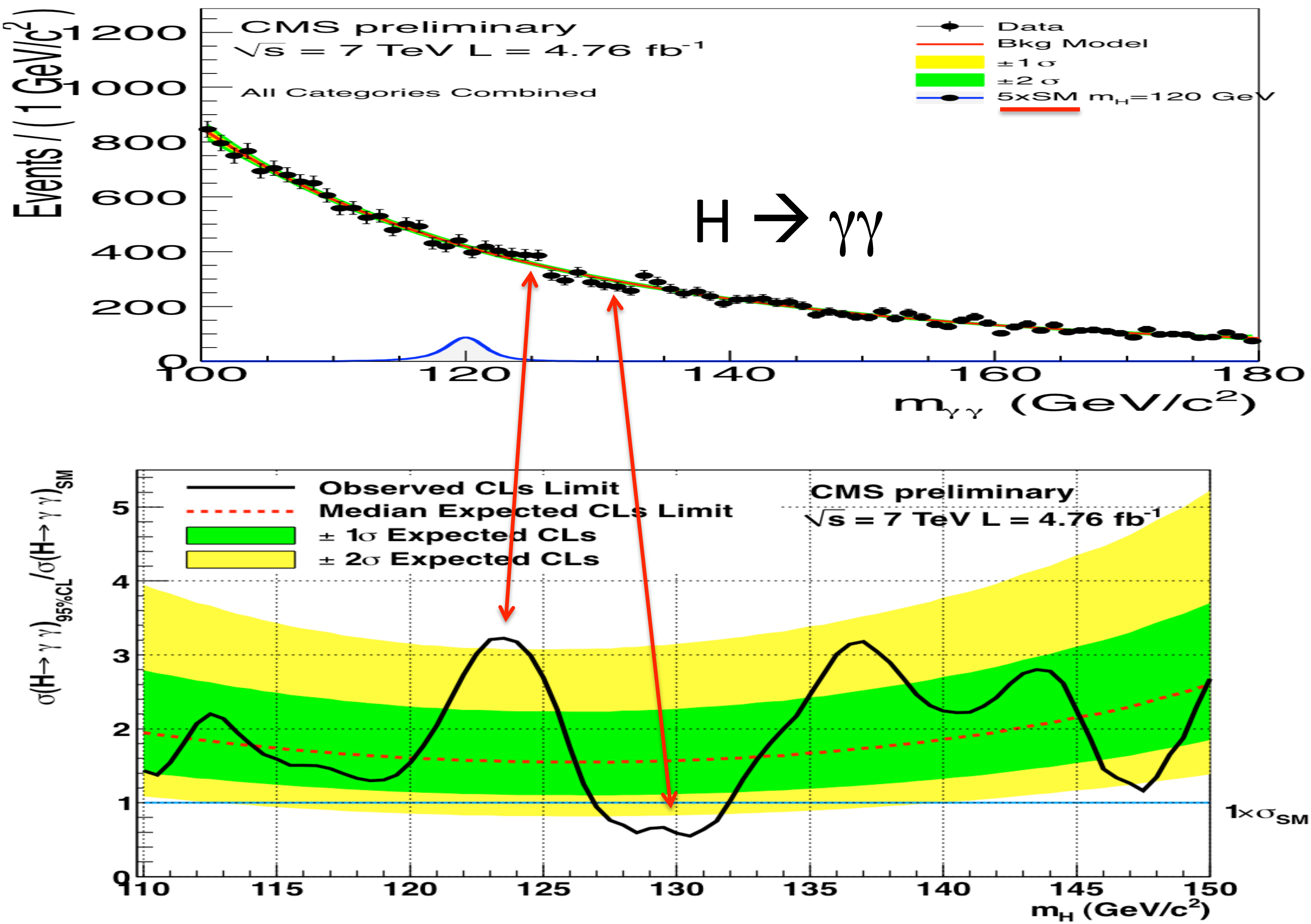
H → γγ
Events / (1 GeV/c2)
mγγ (GeV/c2)
Observed CLs Limit
Median Expected CLs Limit
± 1σ Expected CLs
± 2σ Expected CLs
CMS preliminary
√s = 7 TeV L = 4.76 fb-1
1×σSM
σ(H→γγ)95%CL/σ(H→γγ)SM
mH (GeV/c2)


CMS preliminary
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All Categories Combined
Data
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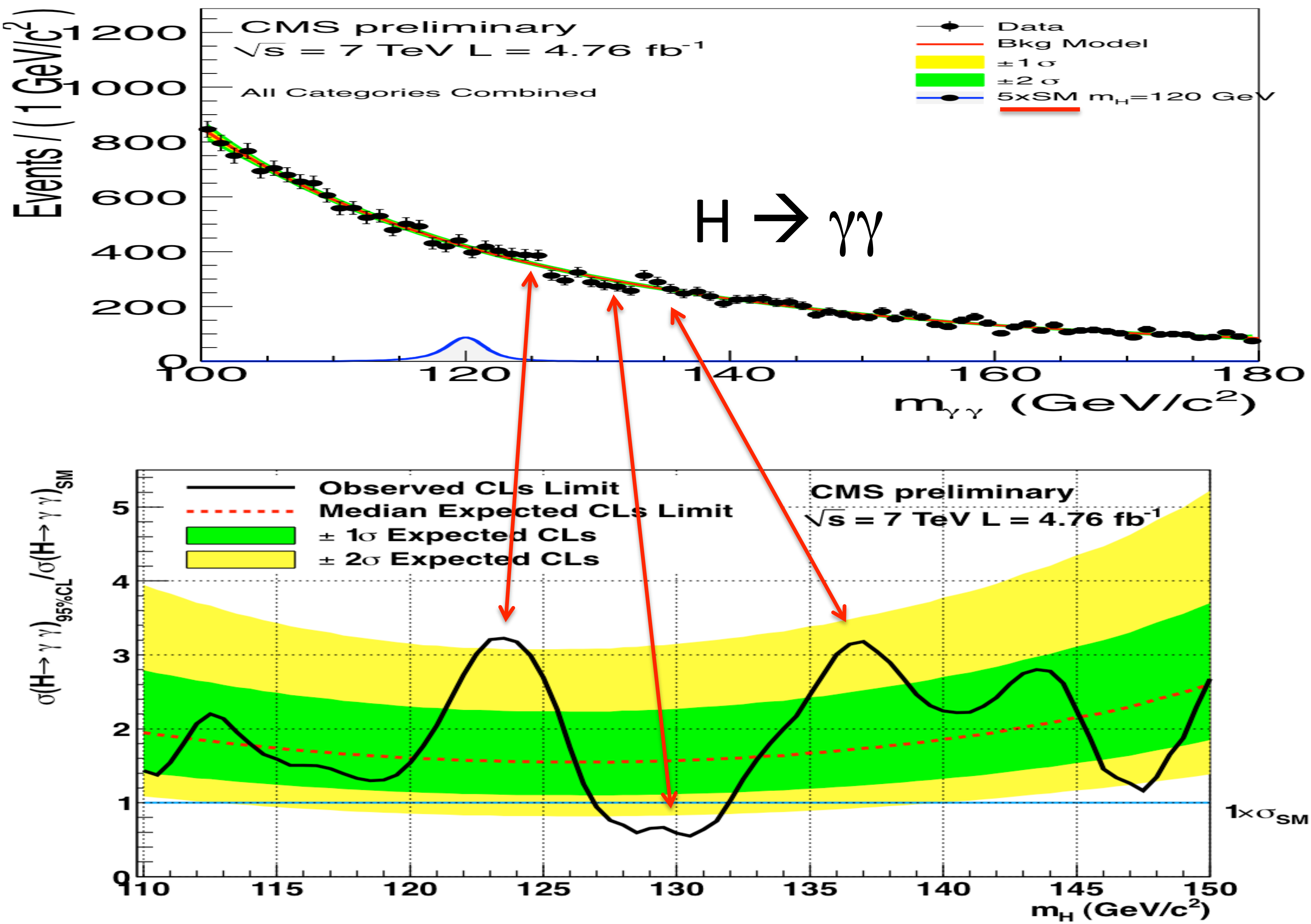
H → γγ
Events / (1 GeV/c^2)
$m_{\gamma\gamma}$ (GeV/c^2)
Observed CLs Limit
Median Expected CLs Limit
± 1σ Expected CLs
± 2σ Expected CLs
CMS preliminary
$\sqrt{s}$ = 7 TeV L = 4.76 fb^{-1}
$1\times\sigma_{SM}$
$\sigma(H\to\gamma\gamma)_{95\%CL}/\sigma(H\to\gamma\gamma)_{SM}$
m_H (GeV/c^2)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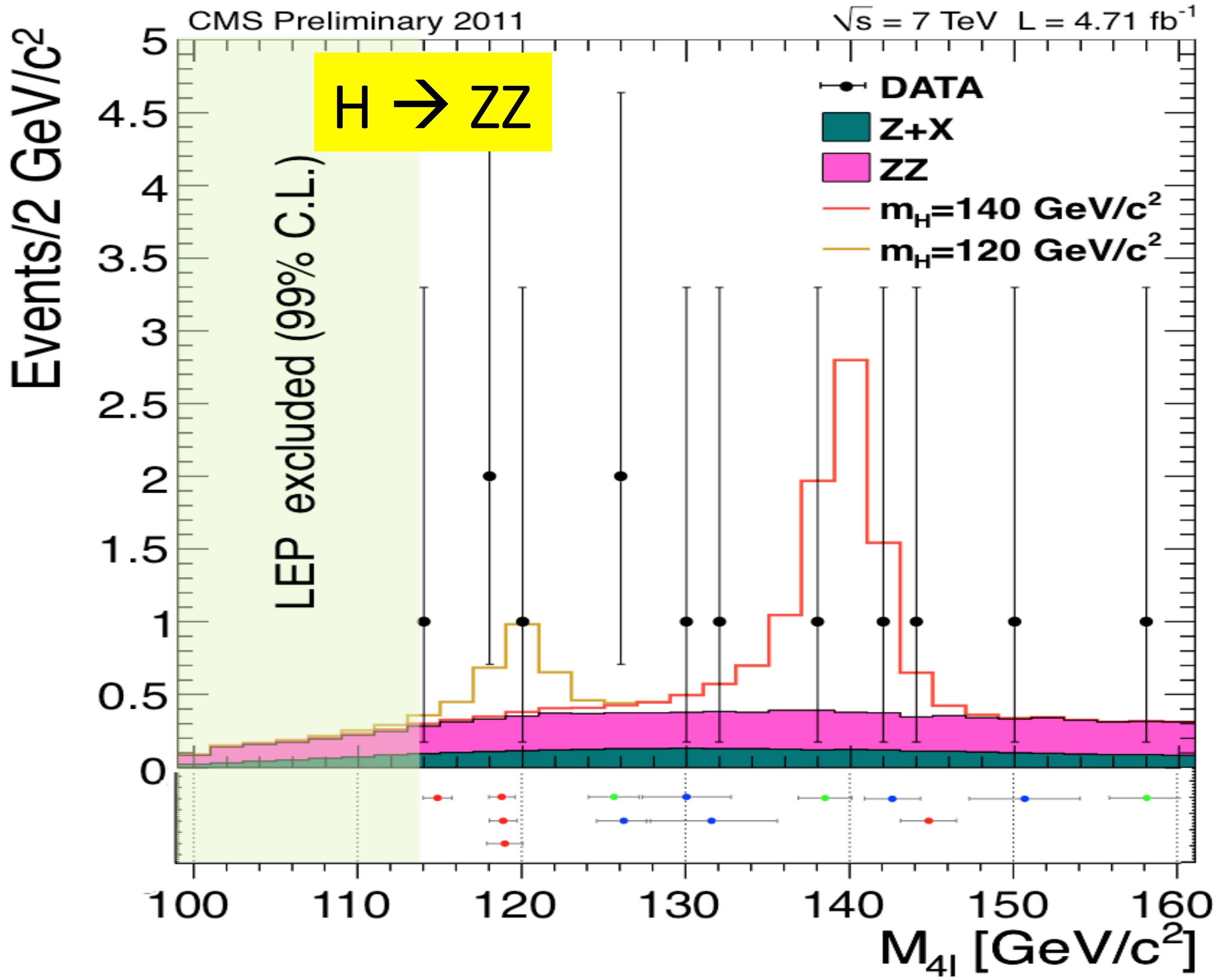
√s = 7 TeV L = 4.76 fb-1
1×σSM
σ(H→γγ)95%CL/σ(H→γγ)SM
mH (GeV/c2)



- 13 events observed with M_{4l} < 160 GeV.
- 9.5 ± 1.3 expected from BG
- Small cluster near 119 GeV

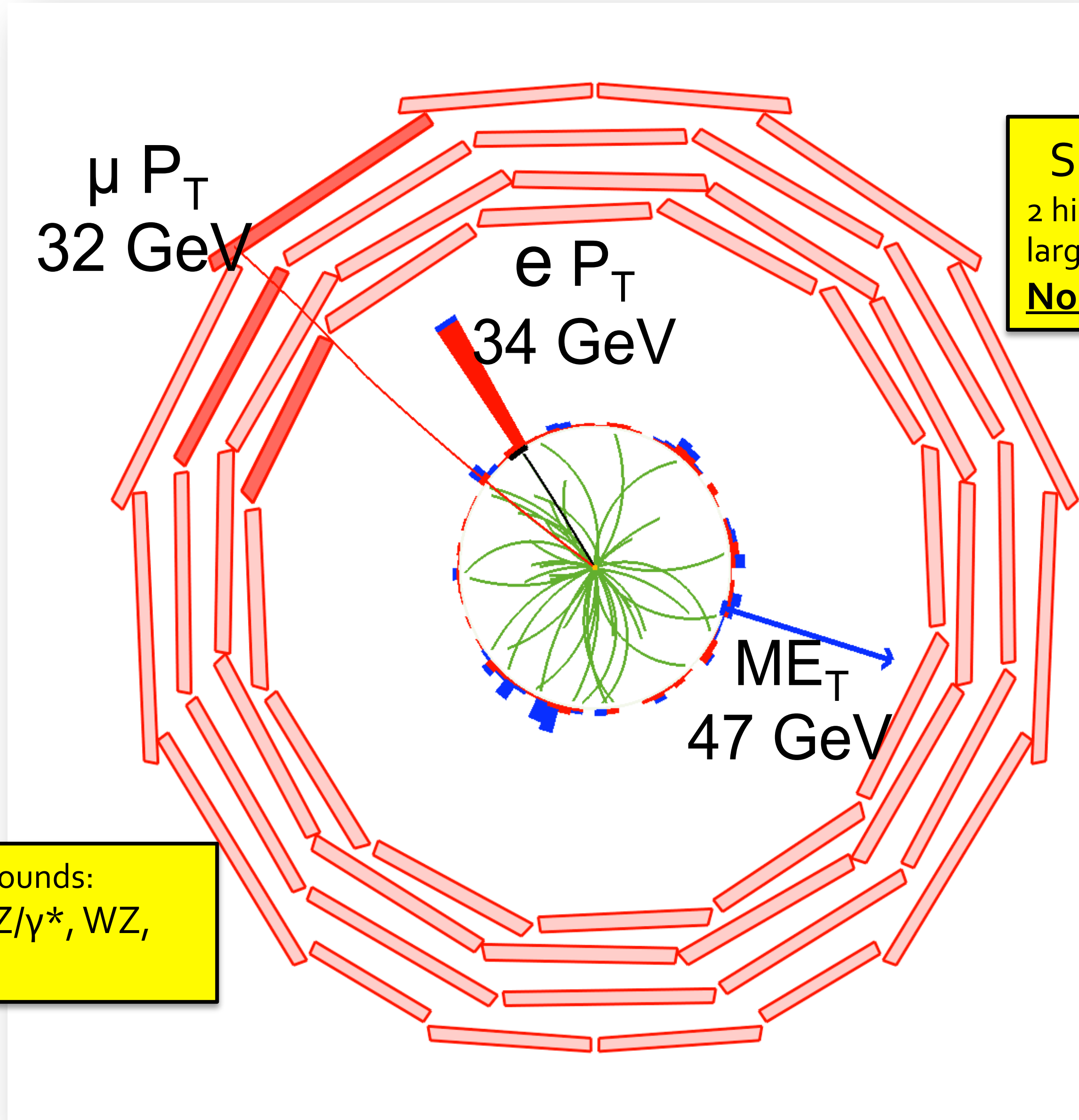
First 2012 results

unveiled in CERN seminars on July 4th

2012 (July 4th) vs 2011

- Double the luminosity by adding 2012 data to 2011 data
- 8 TeV (2012) vs. 7 TeV (2011) → gain ~ 30% in Higgs production cross-section
- Many little analysis improvements that add up
- Have to fight harsher ambient background conditions: ~ 16 pp interactions per beam crossing in 2012 vs. ~ 7 in 2011

H→WW→lνlν Signature

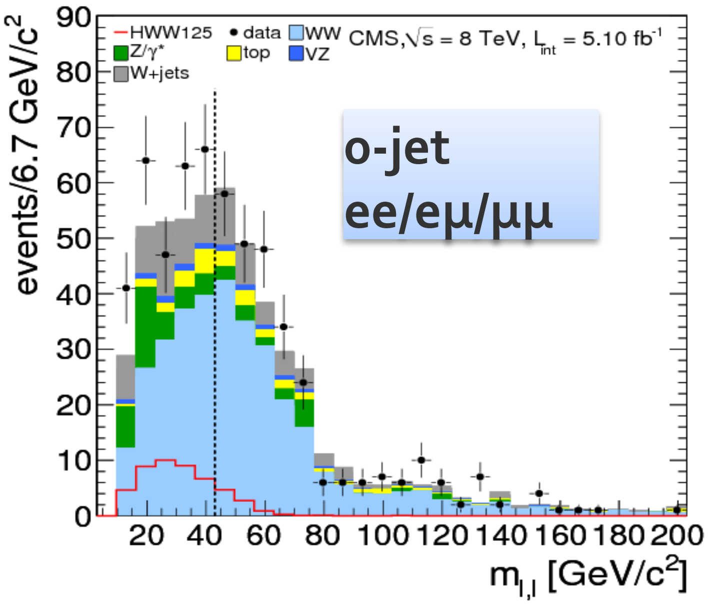


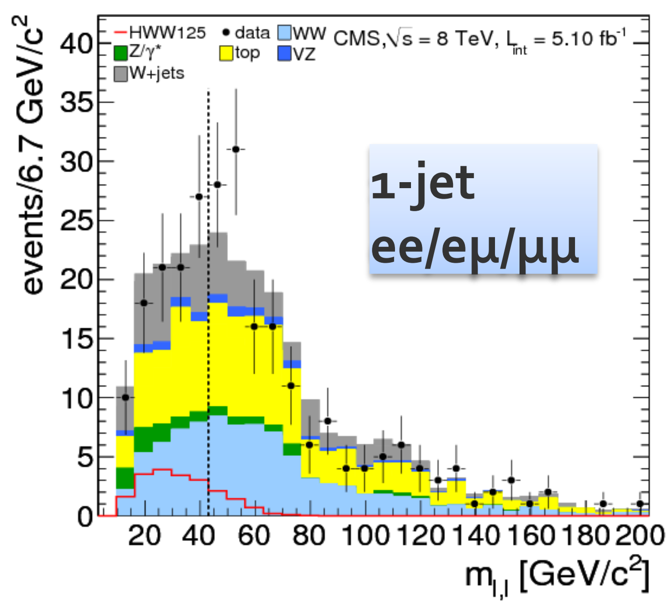
Signature:
2 high p_T leptons
large missing E_T
No mass peak

Many backgrounds:
WW, top, W+jet, Z/γ*, WZ, ZZ, Wγ

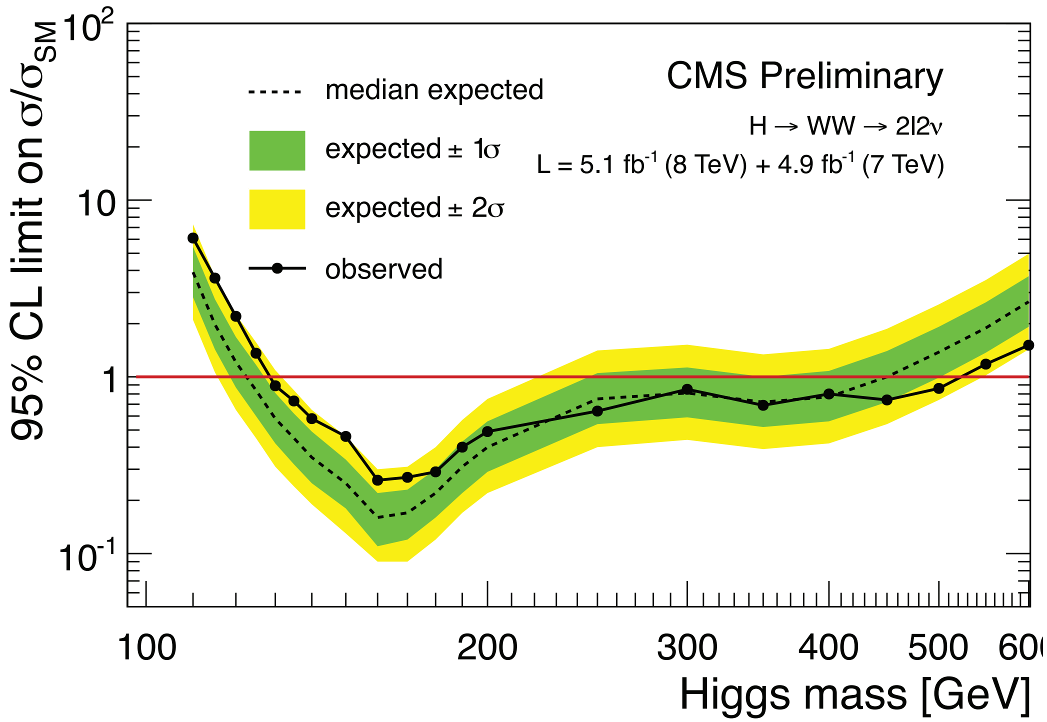
H→WW→lνlν

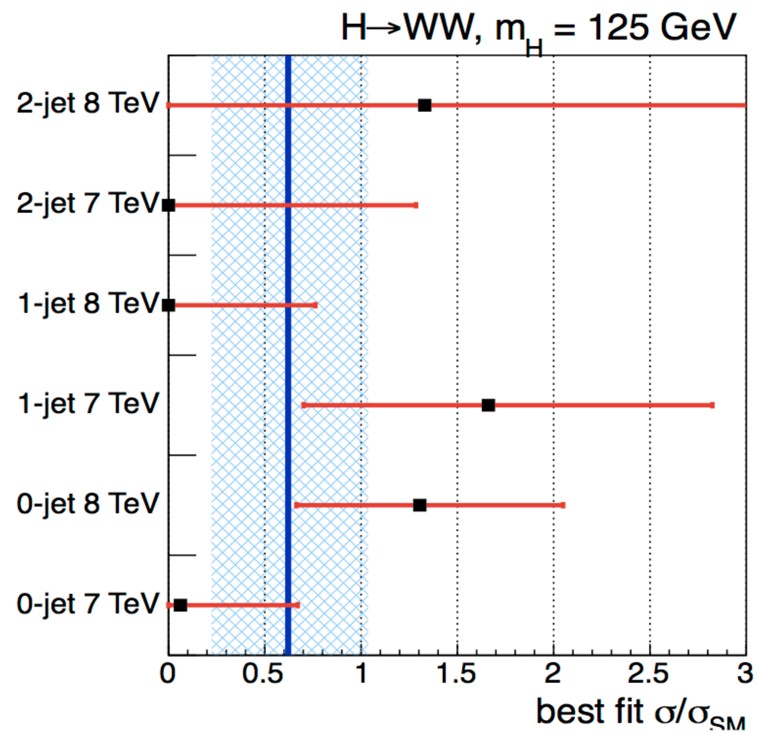
- Exploit kinematical differences between signal and background
- Need to painstakingly understand all sources of dileptons and missing energy (from neutrinos)





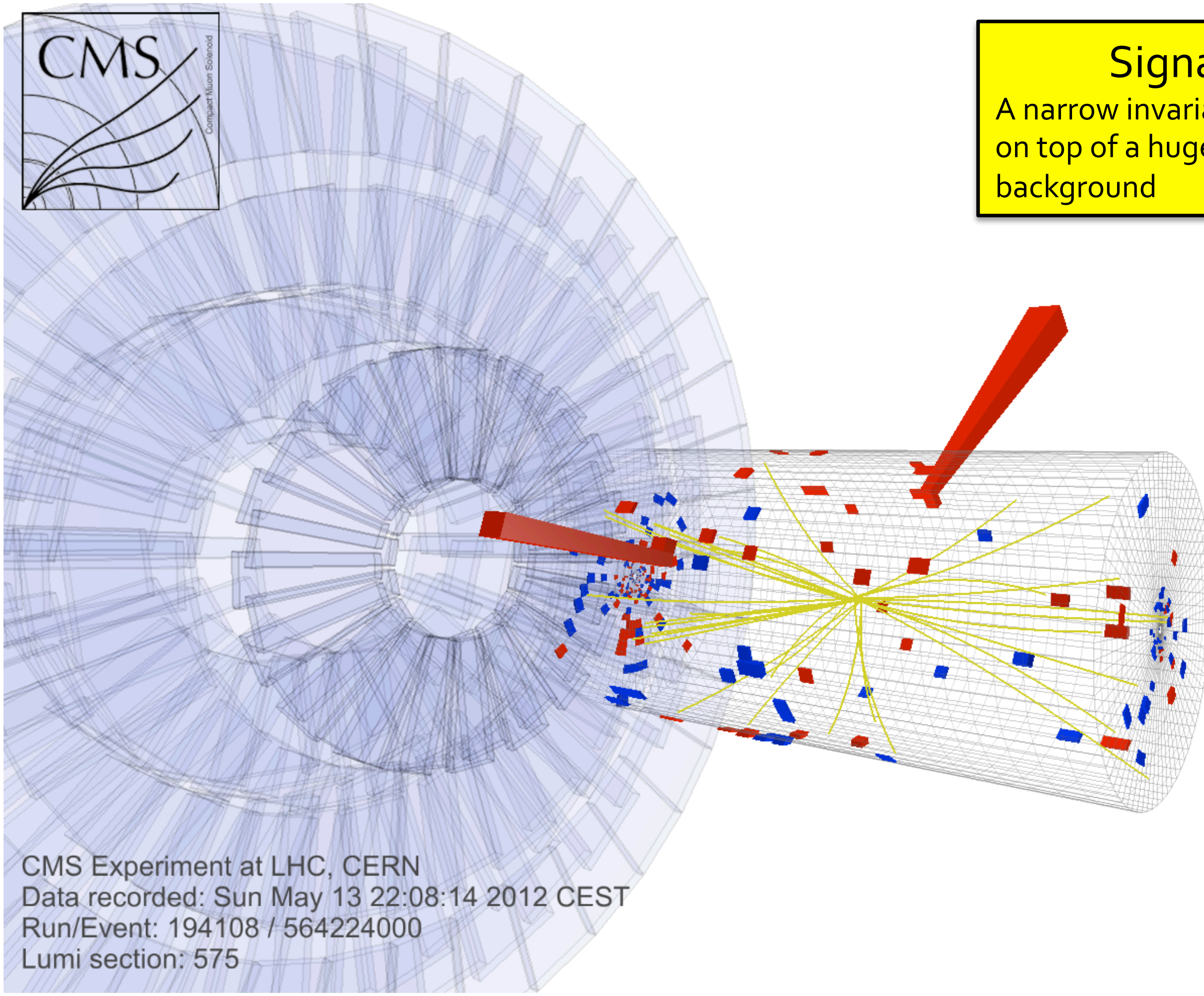
$H \to WW \to l\nu l\nu$





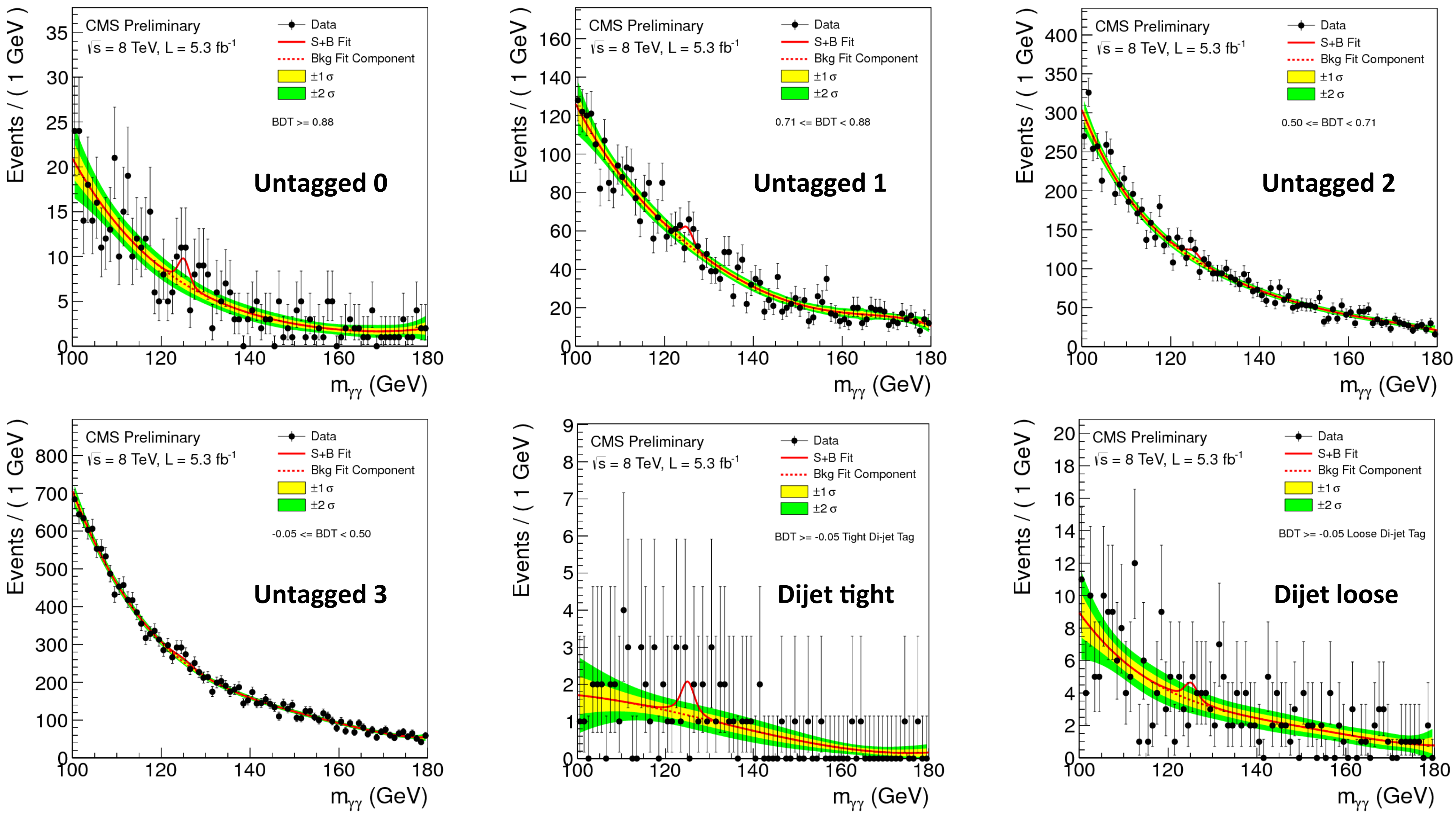
There is an overall excess of events at the level of ~ 1.5-2σ in the low mass region.
The excess is consistent with Higgs expectations

H→γγ



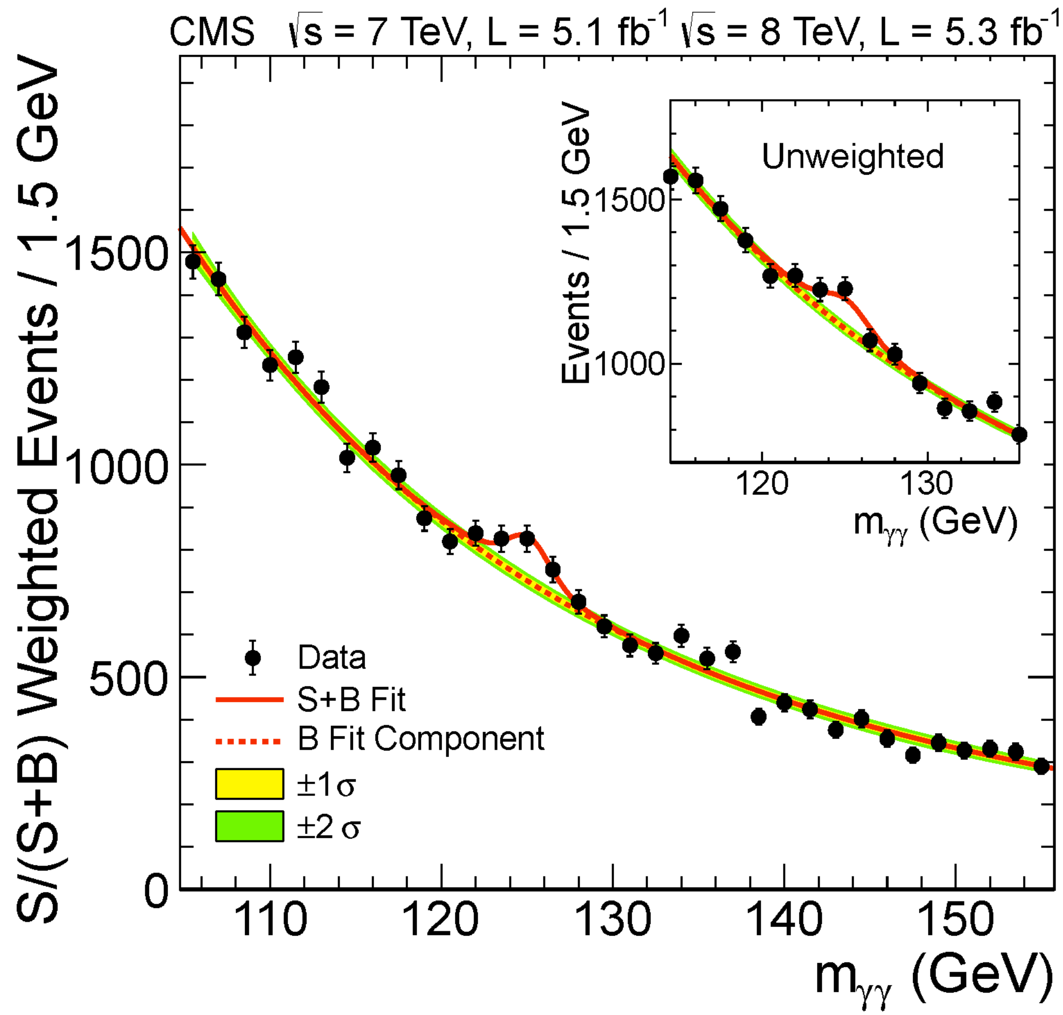
Signature:
A narrow invariant mass peak on top of a huge continuum background

$H \rightarrow \gamma\gamma$



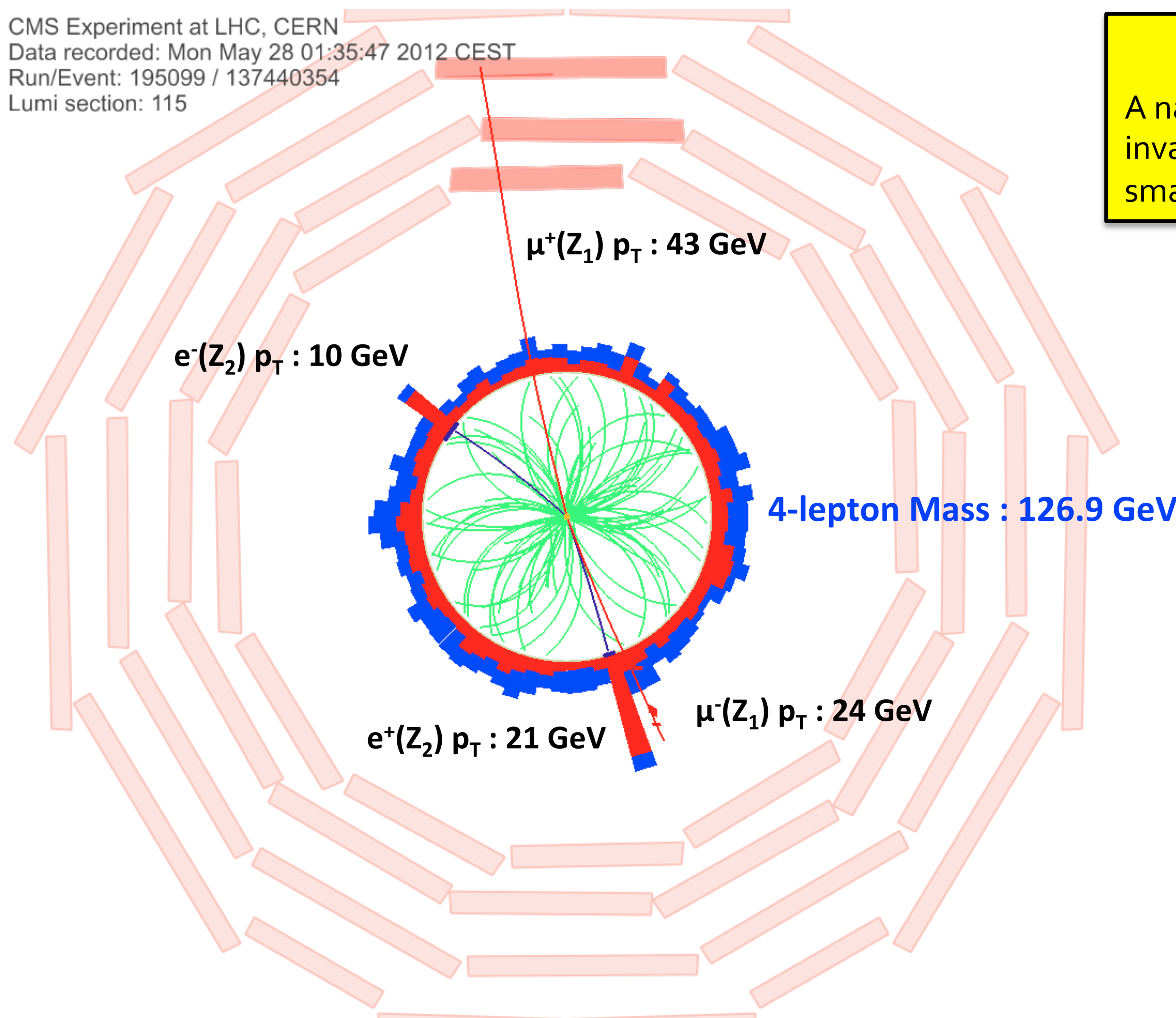
To gain statistical power, define 6 different categories with different signal-to-background

H→γγ: weighted mass distribution



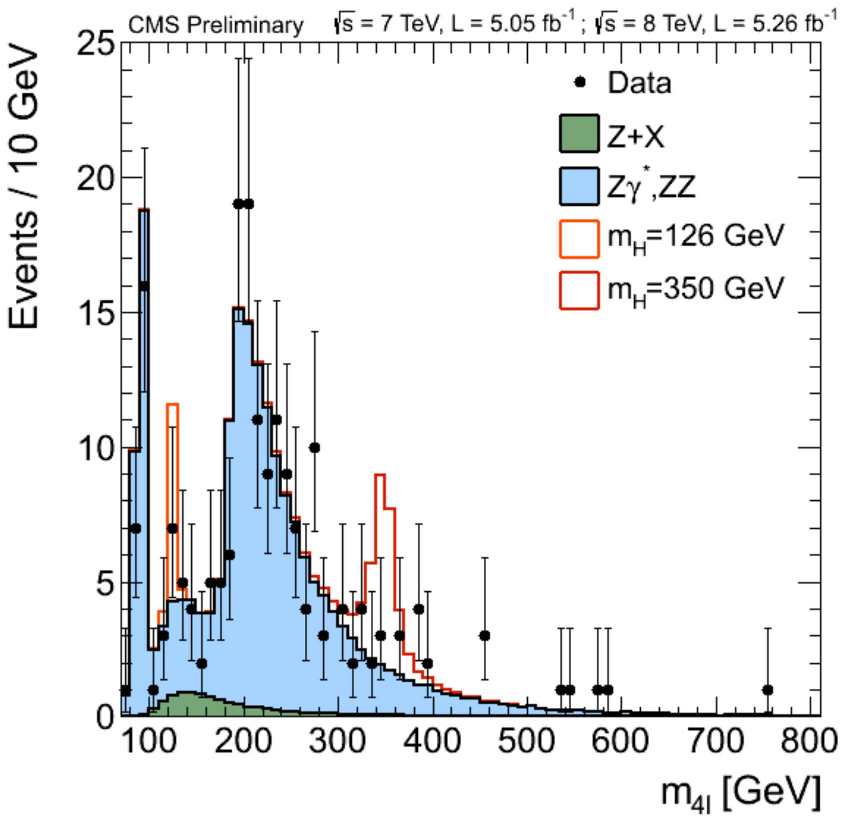
The bump at 125 GeV has a (local) stat significance of 4.1σ

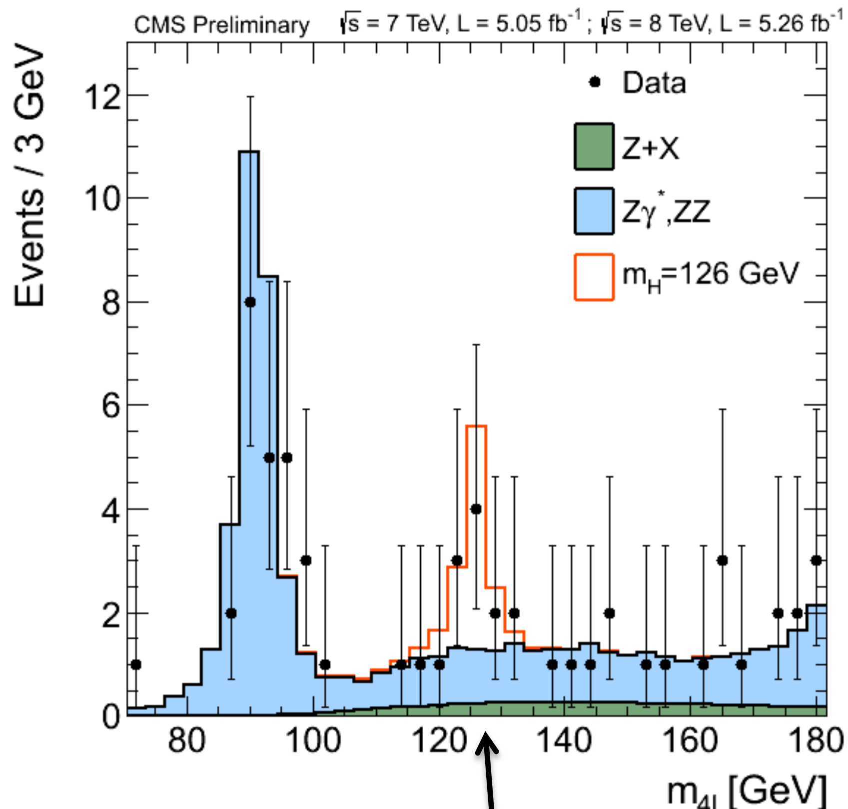
H→ZZ*→4 leptons



Signature:
A narrow, low statistics, invariant mass peak on top of a small continuum background

H→ZZ*→4 leptons, mass spectrum

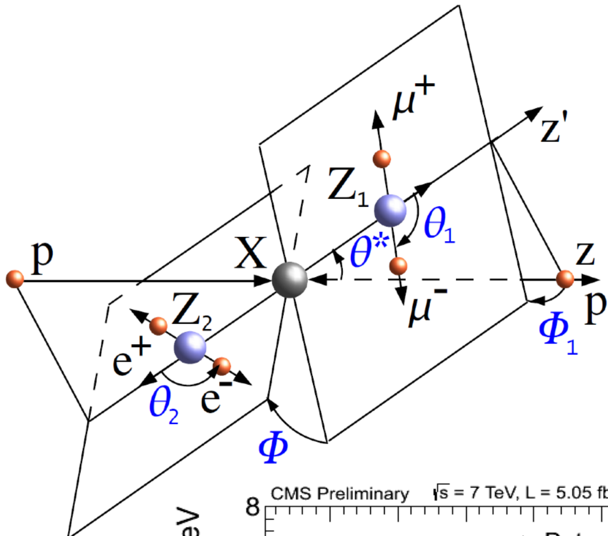




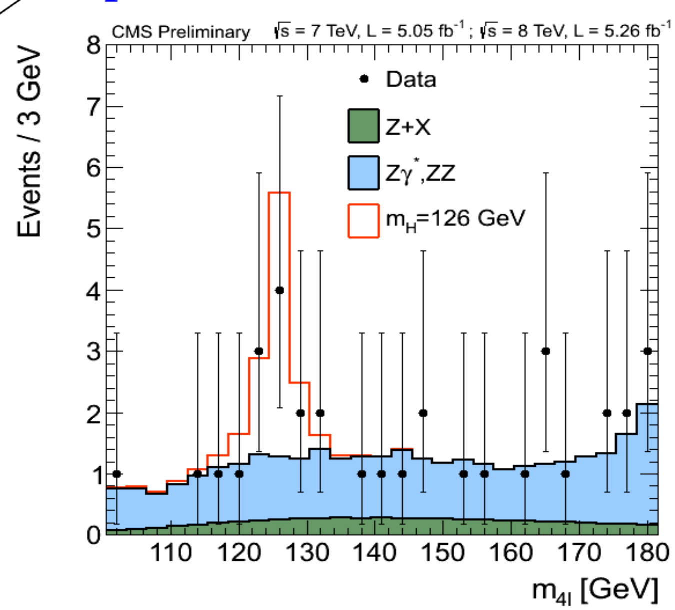
Some accumulation of events here

H→ZZ*→4 leptons, beyond the mass spectrum

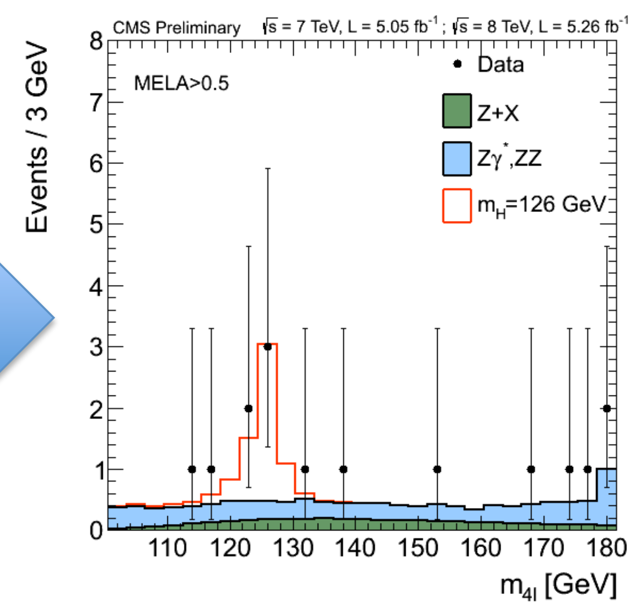
Leptons from H→ZZ* have distinct angular decay distributions



$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

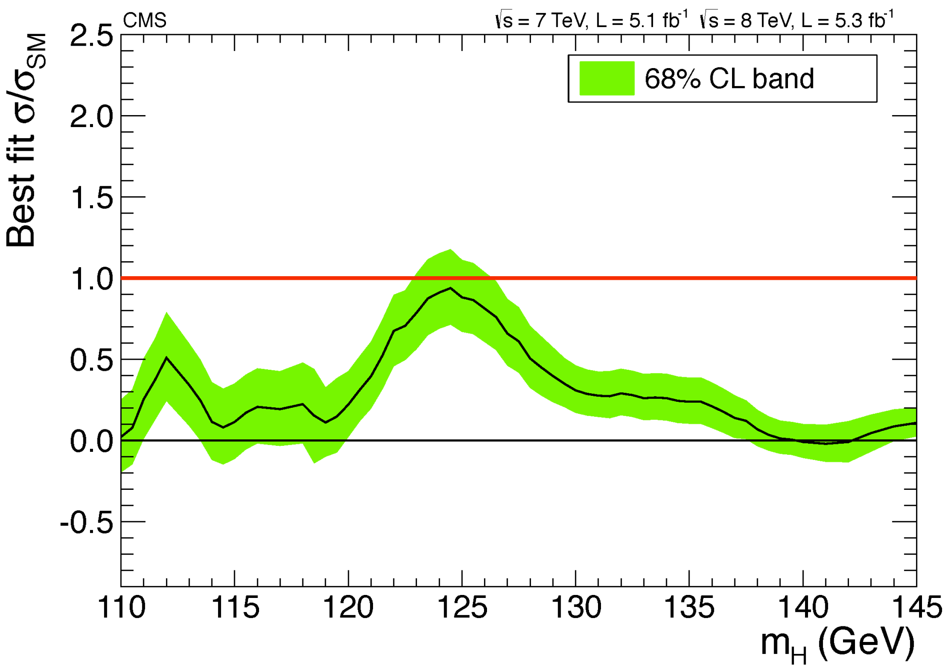


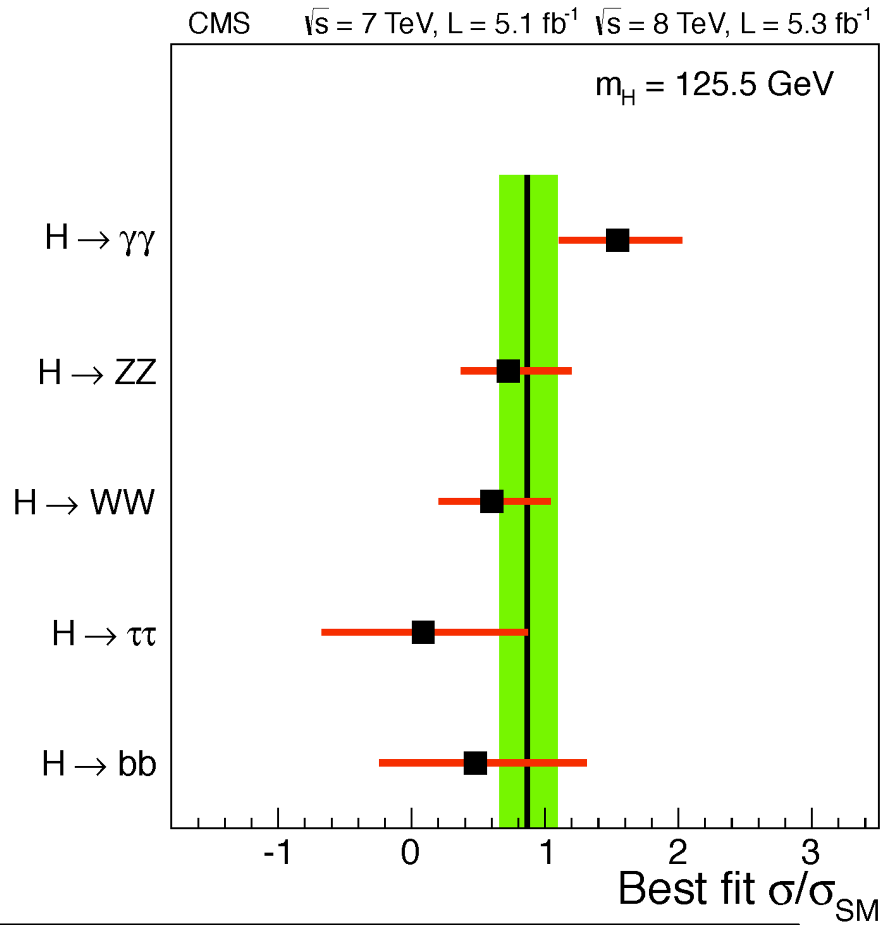
MELA > 0.5



The cluster of events has Higgs-like kinematical properties. Stat significance 3.2σ

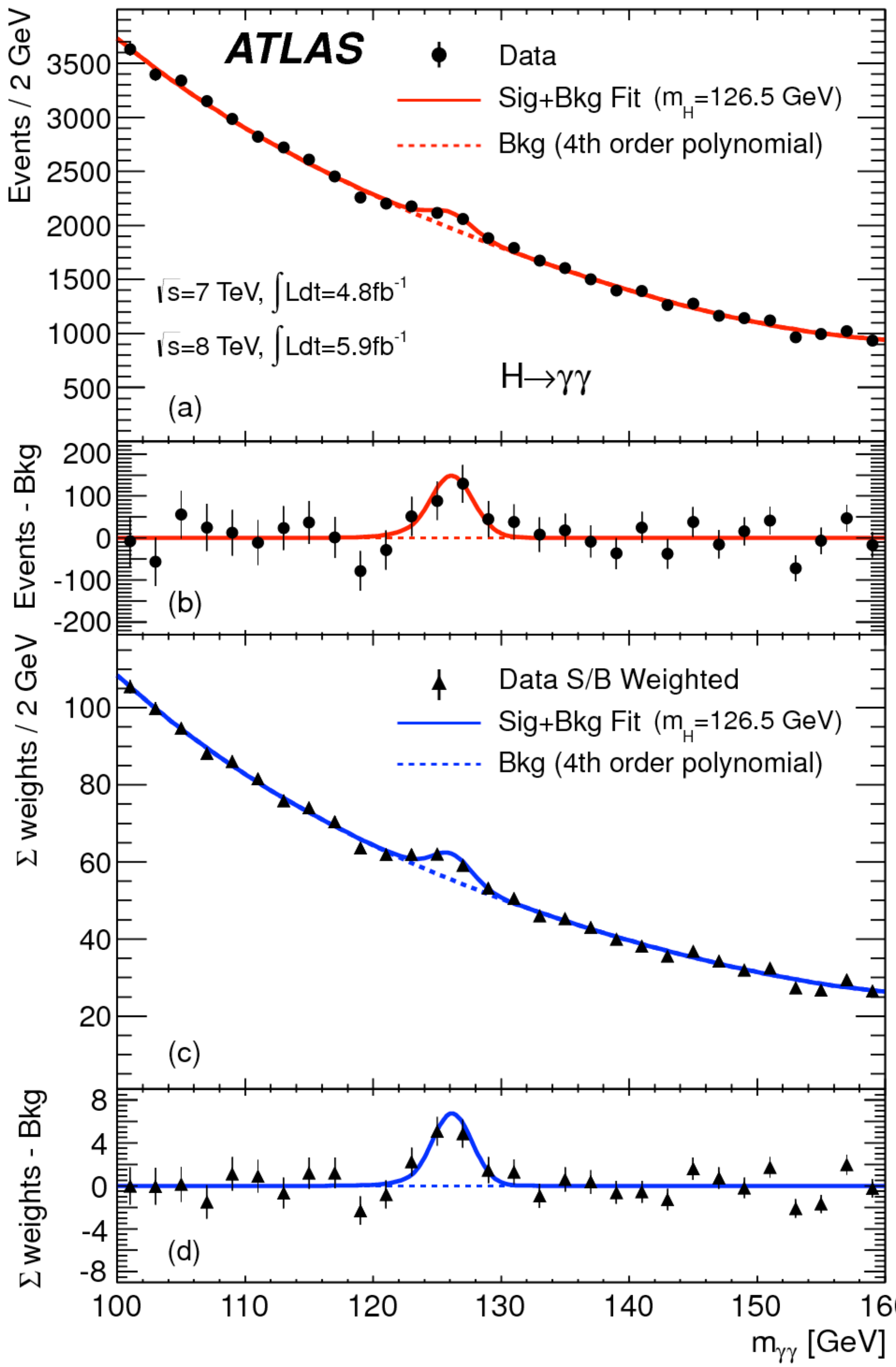
Putting it all together (CMS)

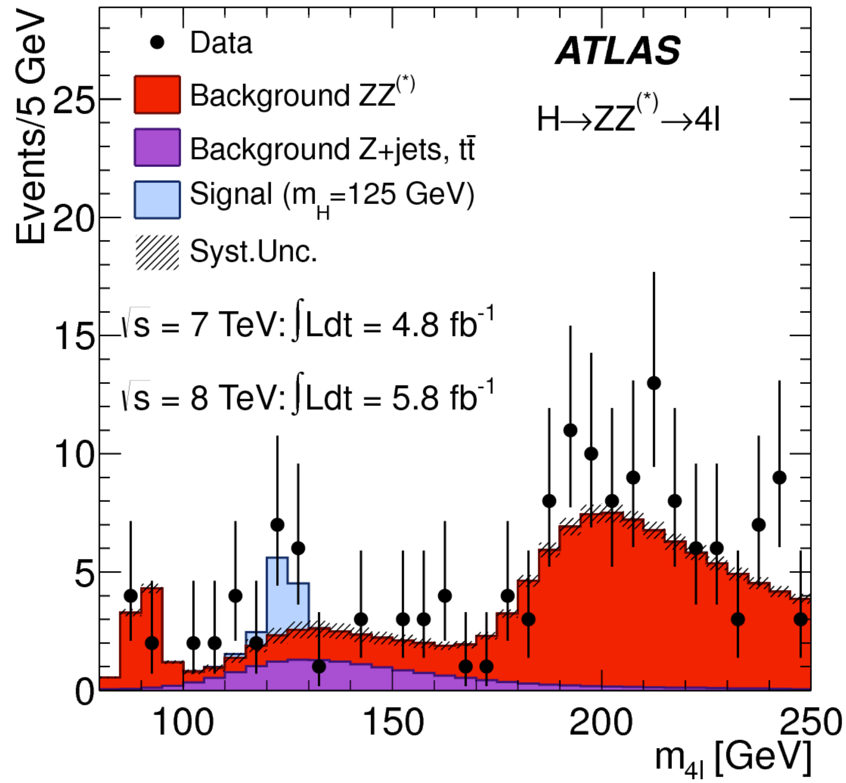


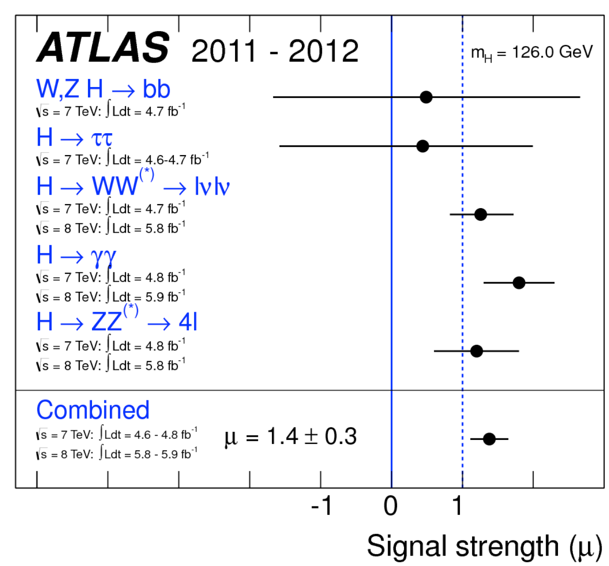


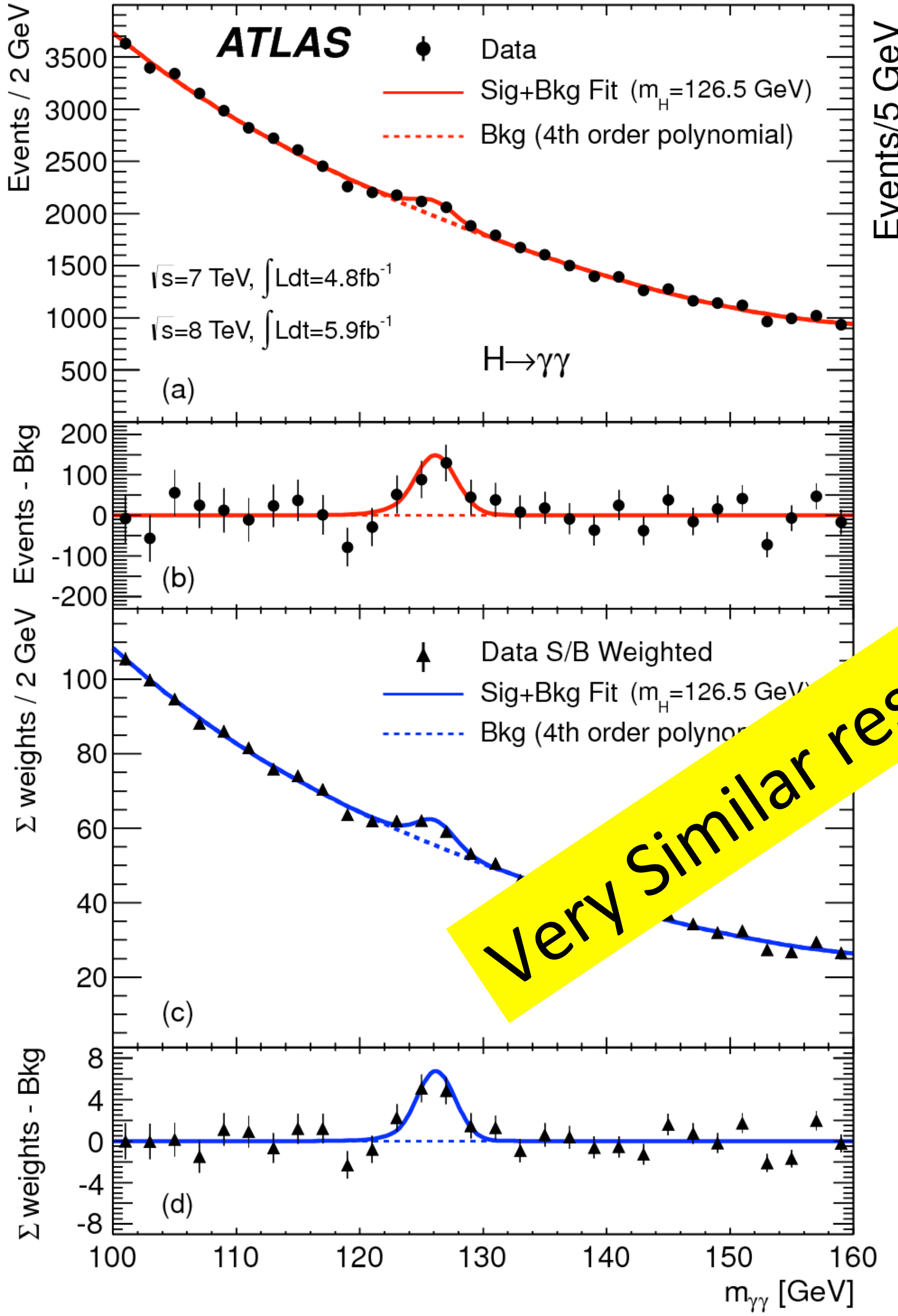
- A combined local significance of 5σ
- Cross-sections and branching ratios in agreement with SM (but low stats)
- Mass = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV

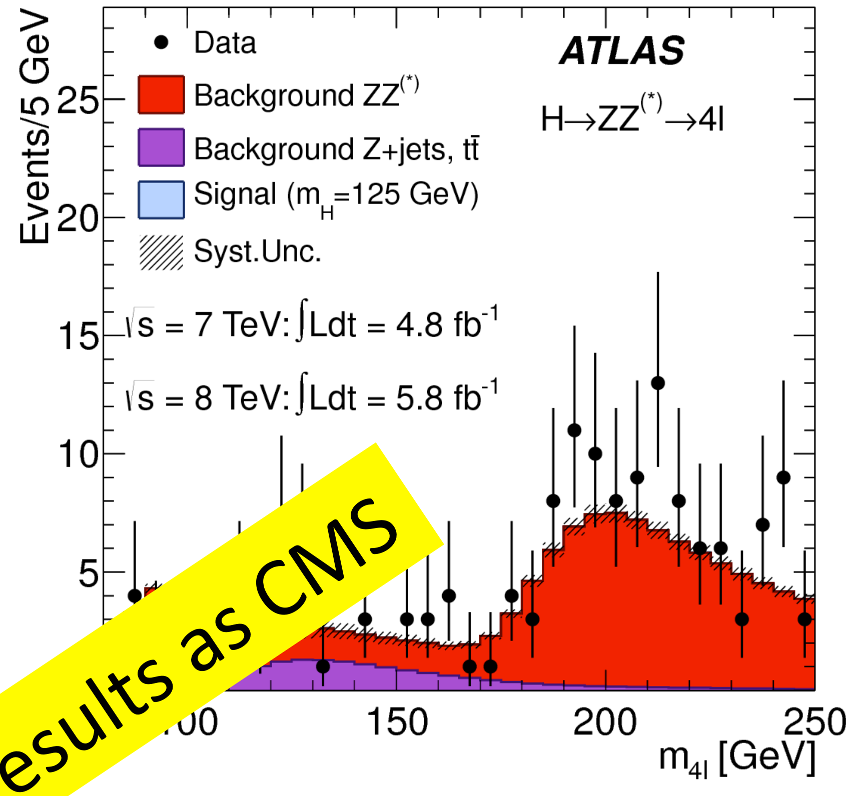
What about Atlas?


ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb-1
√s=8 TeV, ∫Ldt=5.9fb-1
H→γγ
(a)
(b)
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
(c)
(d)
Events / 2 GeV
Events - Bkg
Σ weights / 2 GeV
Σ weights - Bkg
m_γγ [GeV]

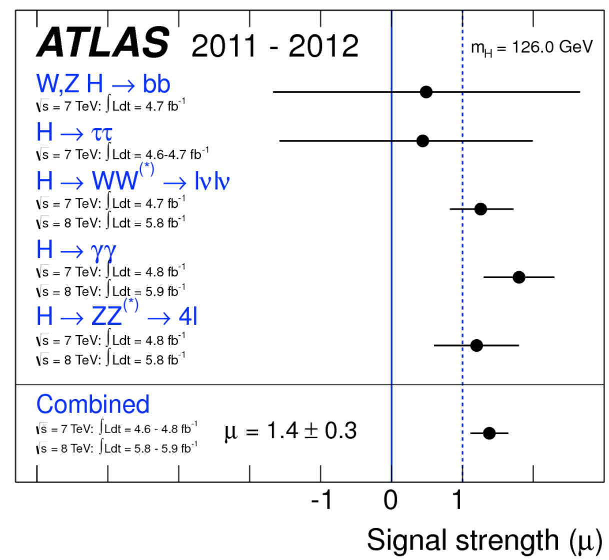

Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Syst.Unc.
ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
m_4l [GeV]


ATLAS 2011 - 2012
m_H = 126.0 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb-1
H → ττ
√s = 7 TeV: ∫Ldt = 4.6-4.7 fb-1
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.7 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.9 fb-1
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Combined
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 - 5.9 fb-1
μ = 1.4 ± 0.3
Signal strength (μ)





Very Similar results as CMS



Physics Letters B 716 (2012) 1–29

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Physics Letters B

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Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 8 August 2012
Accepted 11 August 2012
Available online 14 August 2012
Editor: W.-D. Schlatter

ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW$
published results of searches for $H \to ZZ$
improved analyses of the $H \to ZZ^{(*)} \to 4$
the production of a neutral boson with a m
This observation, which has a significanc
fluctuation probability of 1.7×10^{-9}, is co
Higgs boson.

Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

ARTICLE INFO

Article history:
Received 31 July 2012
Received in revised form 9 August 2012
Accepted 11 August 2012
Available online 18 August 2012
Editor: W.-D. Schlatter

Keywords:
CMS
Physics
Higgs

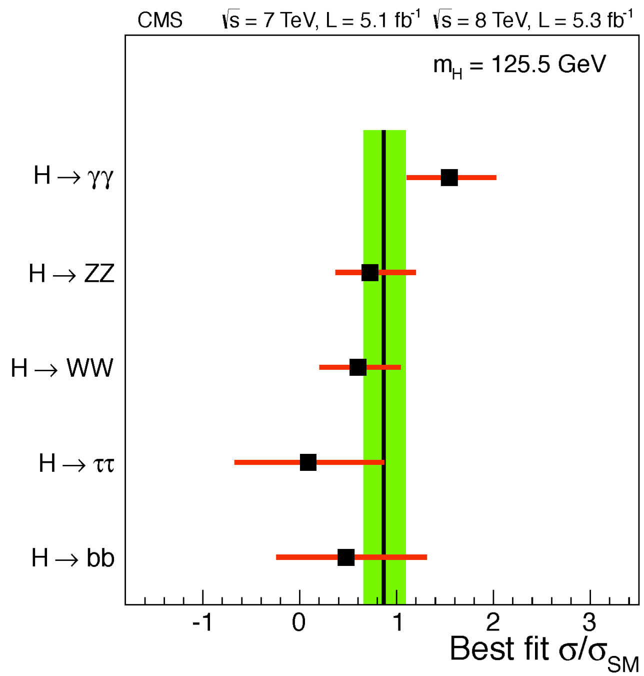
ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

What's next for the Higgs?

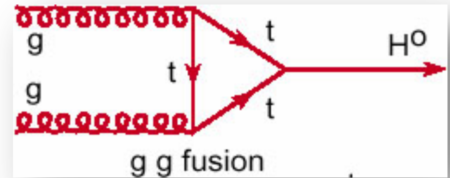
- Only 2012 data until end of June fully analyzed (~ 5 fb^{-1})
- By end of the year we will have 25-30 fb^{-1}
- The key question now: is this **the** SM Higgs Boson?

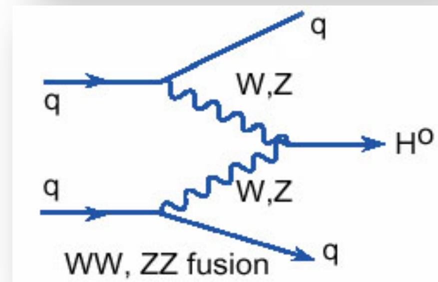
Improve branching ratio measurements

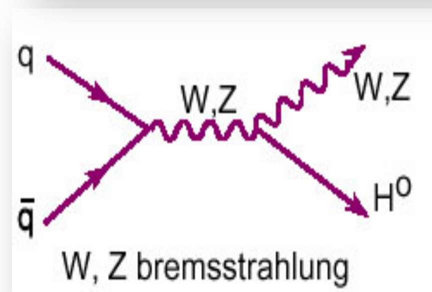


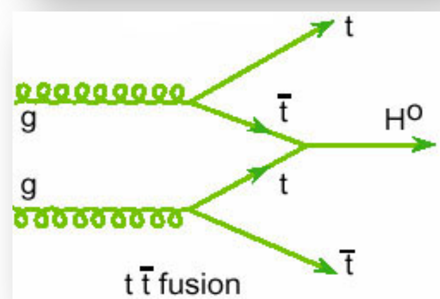
Is the spin 0 or 2?
What is the parity?
Are there other Higgses?

Begin to separate production mechanisms









UCSB and the Higgs Search

UNIVERSITY OF CALIFORNIA
Santa Barbara

Measurement of the production cross-section of two W bosons from seven-trillion-electronvolt center-of-mass-energy proton-proton collisions

A Dissertation submitted in partial satisfaction of the requirements for the degree of

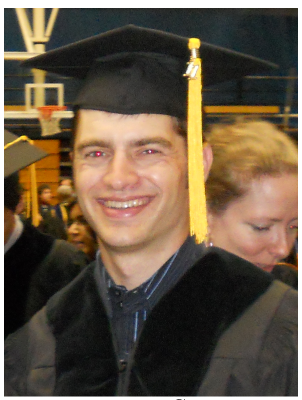
Doctor of Philosophy

in

Physics

by

Jacob Thomas Ribnik



Committee in Charge:

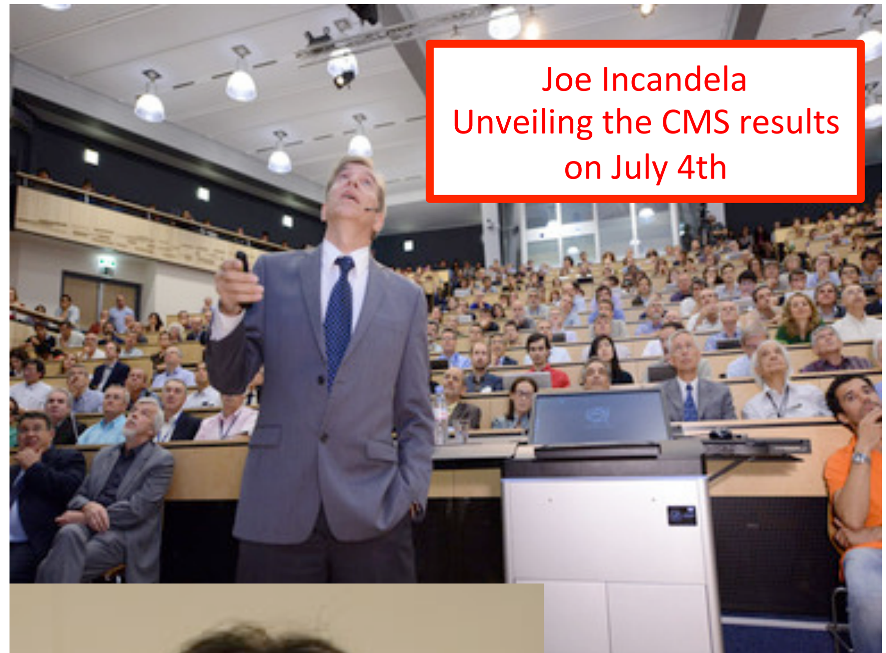
Professor Claudio Campagnari, Chair

Professor Jeffrey D. Richman

Professor Mark Srednicki

June 2011

Jake Ribnik, UCSB grad student
Measurement of pp→WW with 201 data,
laying the foundation for the H→WW search



Joe Incandela
Unveiling the CMS results
on July 4th

Dima Kovalskyi
UCSB Postdoc
Co-leader of the
H→WW analysis team

The End