[u c s b] *High Energy Physics*

Results on the Search for the Higgs Boson

The Higgs boson, aka "the God particle", is the Holy Grail of particle physics. The most recent results from the Large Hadron Collider at CERN are getting us closer and closer to finding it....or not. Come hear what the hype is all about.

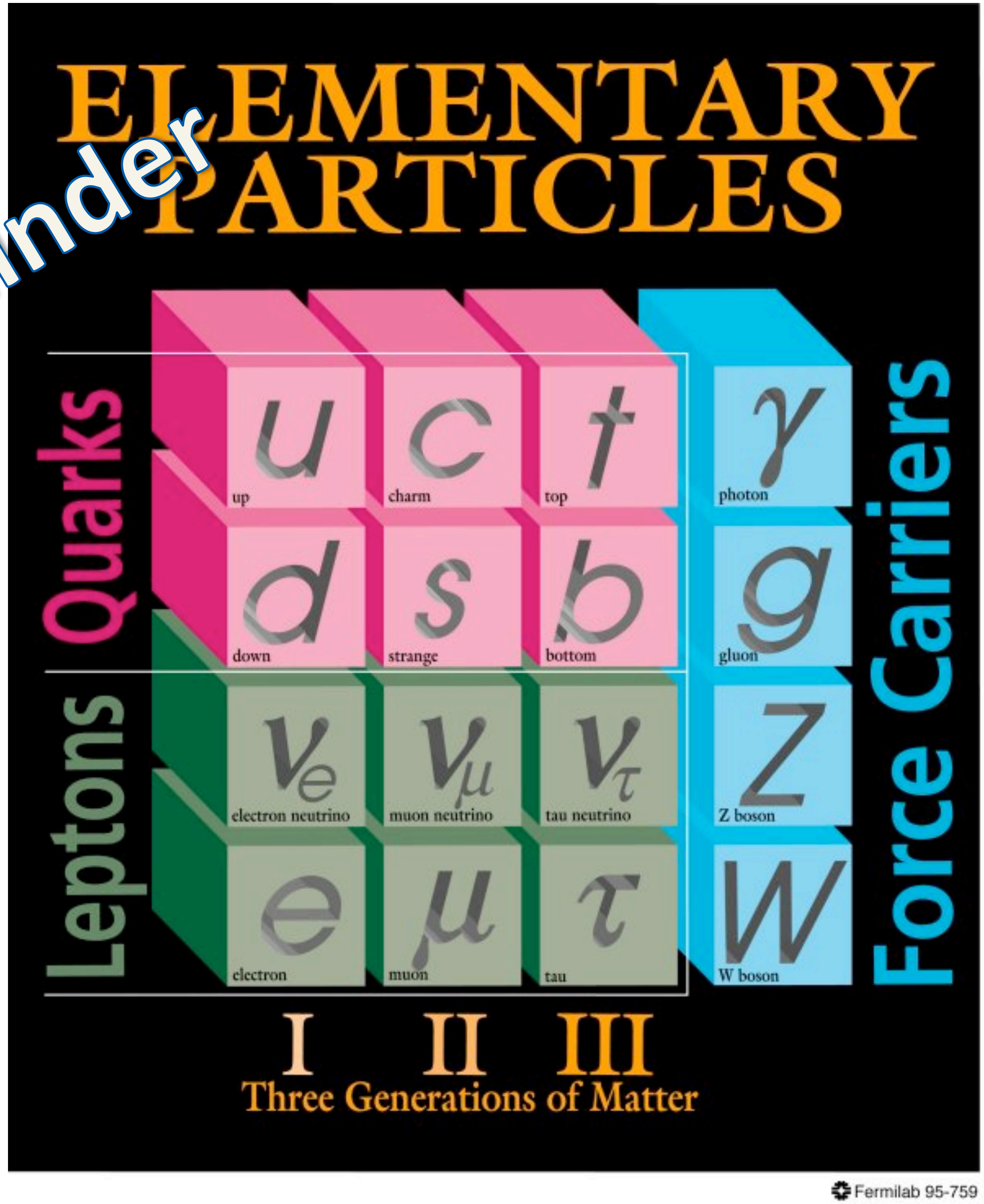
Claudio Campagnari UCSB
10 January 2012

Outline

- What is the Higgs boson
- What did we know about the Higgs boson one year ago?
- What do we know now?
  – "So, have you found it or not?"
- Conclusions

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

Reminder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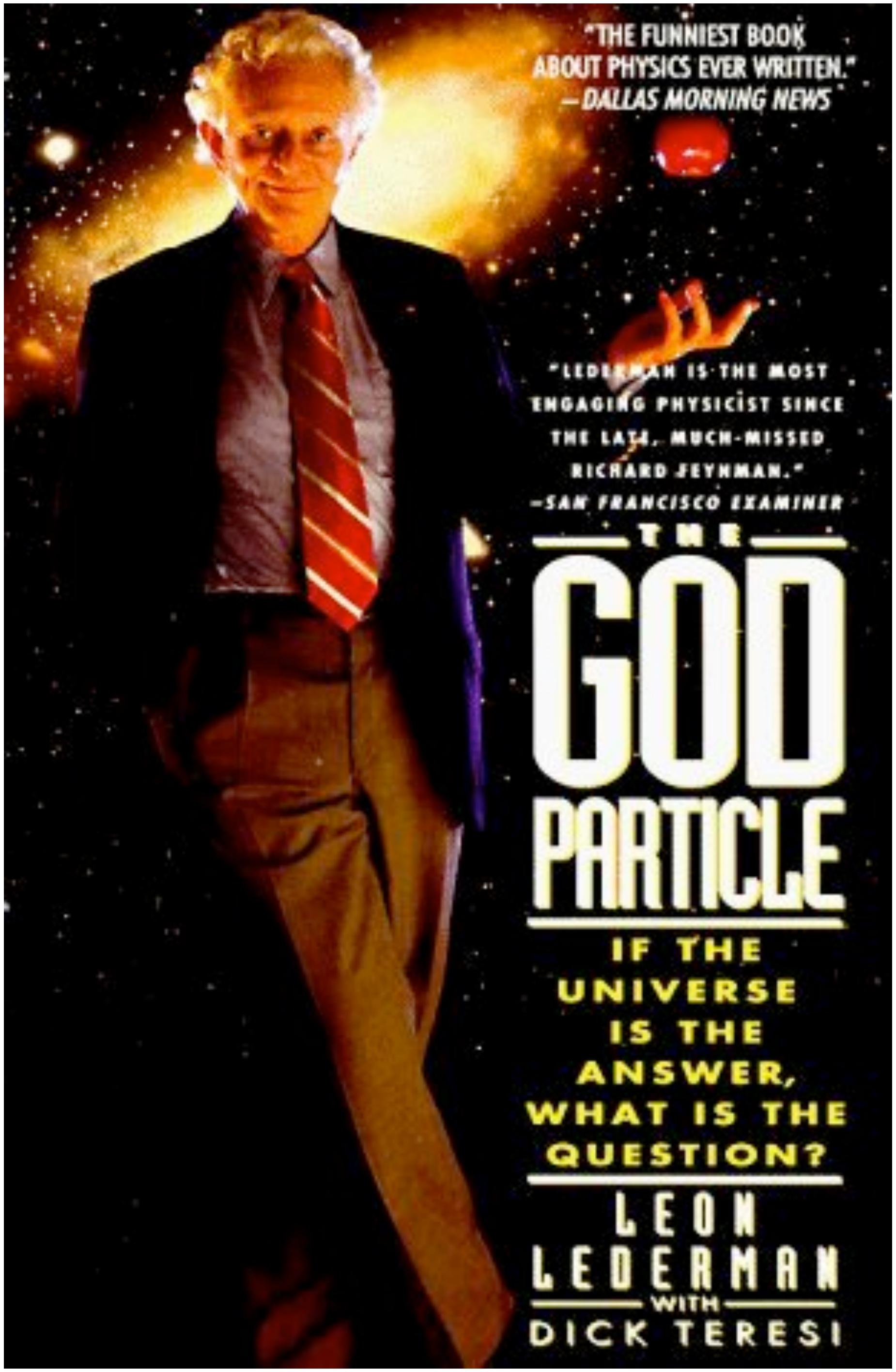
W boson
I II III
Three Generations of Matter
Fermilab 95-759

What is the Higgs Boson?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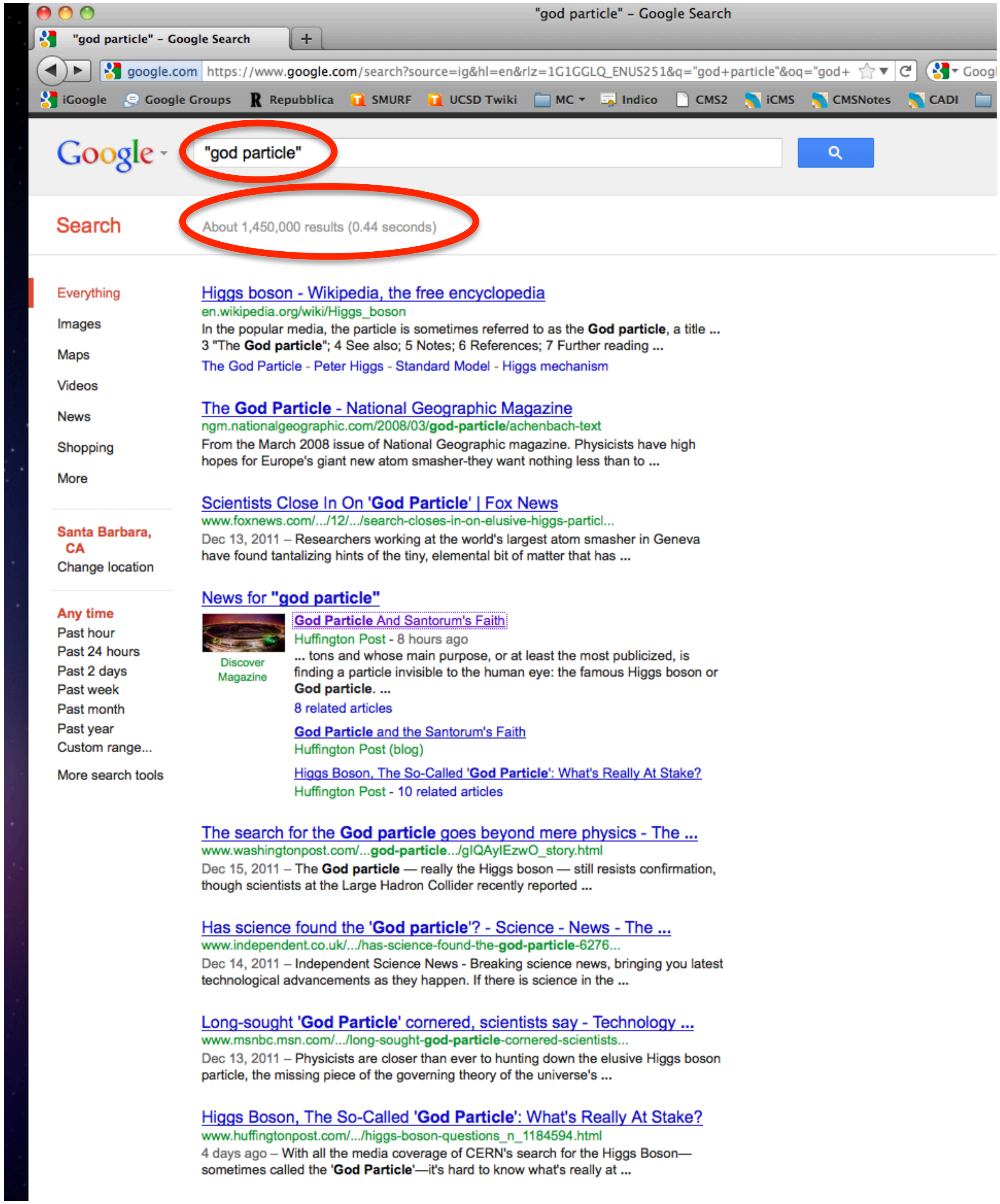
THE
GOD
PARTICLE
IF THE UNIVERSE IS THE ANSWER, WHAT IS THE QUESTION?
LEON LEDERMAN
WITH
DICK TERESI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In the popular media, the particle is sometimes referred to as the God particle, a title ...
3 "The God particle"; 4 See also; 5 Notes; 6 References; 7 Further reading ...
The God Particle - Peter Higgs - Standard Model - Higgs mechanism
The God Particle - National Geographic Magazine
ngm.nationalgeographic.com/2008/03/god-particle/achenbach-text
From the March 2008 issue of National Geographic magazine. Physicists have high hopes for Europe's giant new atom smasher-they want nothing less than to ...
Scientists Close In On 'God Particle' | Fox News
www.foxnews.com/.../12/.../search-closes-in-on-elusive-higgs-particl...
Dec 13, 2011 – Researchers working at the world's largest atom smasher in Geneva have found tantalizing hints of the tiny, elemental bit of matter that has ...
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Dec 15, 2011 – The God particle — really the Higgs boson — still resists confirmation, though scientists at the Large Hadron Collider recently reported ...
Has science found the 'God particle'? - Science - News - The ...
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Dec 14, 2011 – Independent Science News - Breaking science news, bringing you latest technological advancements as they happen. If there is science in the ...
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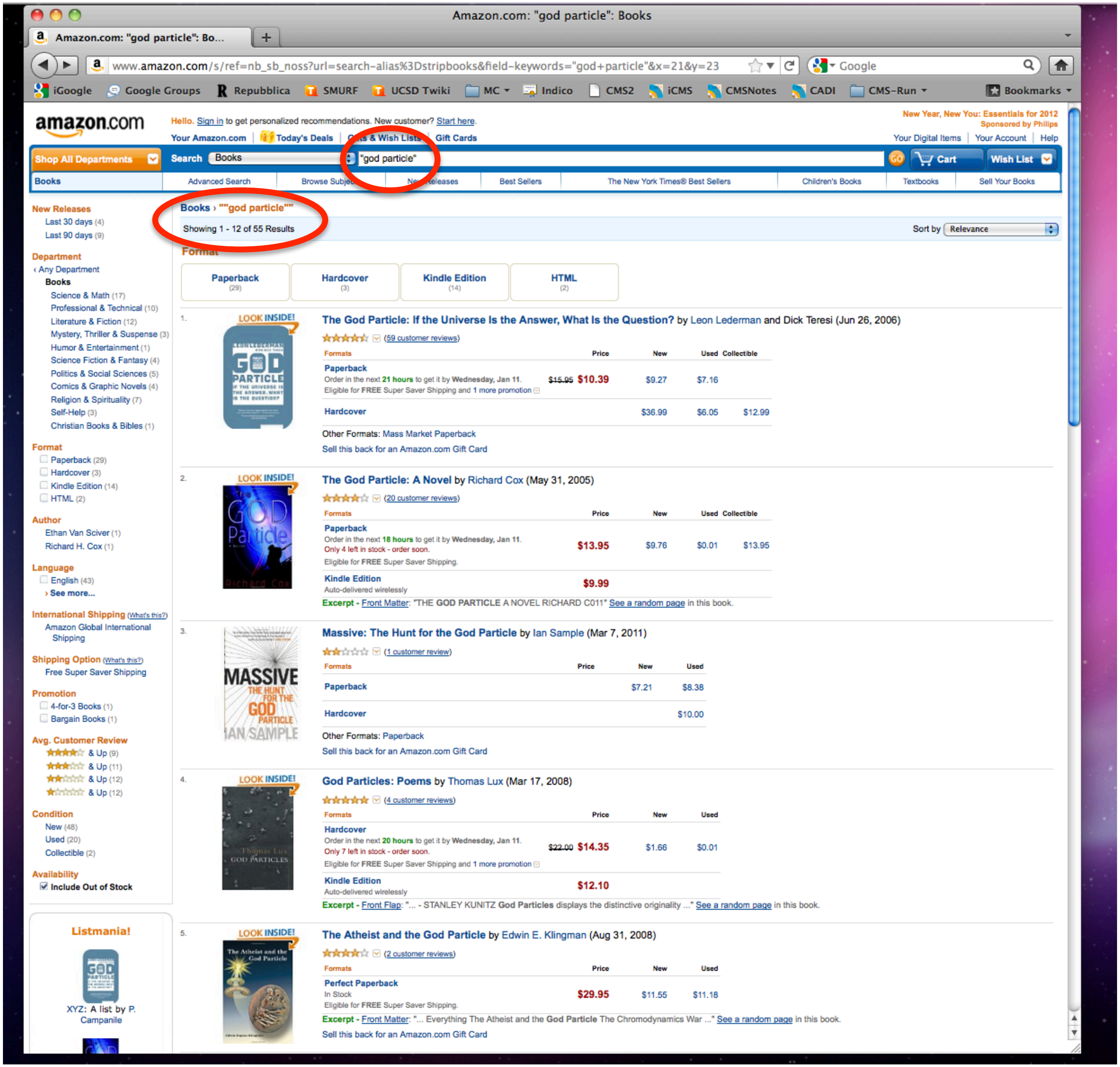
4 days ago – With all the media coverage of CERN's search for the Higgs Boson—sometimes called the 'God Particle'—it's hard to know what's really at ...



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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 Telegraph

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

By Iain Hollingshead
7:48PM GMT 13 Dec 2011

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

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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:

<u>The Higgs boson likes to decay to the heaviest particles that it can</u>

Are we sure that this is right?

- **No**
- 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 bosons. (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)
- Bottom Line:
  - It is not a sure bet that it exists
  - Excluding its existence would be even more exciting than finding it
  - If we do find it: we need to study its properties and see whether they agree with expectations from the SM

What did we know about the Higgs boson ~ 1 year 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 ~ 116 GeV
    - I can show you some plots from this hint at the end if time permits
- The Fermilab ppbar experiments at a center-of-mass-energy of 2 TeV excluded 156 < M_H < 173 GeV

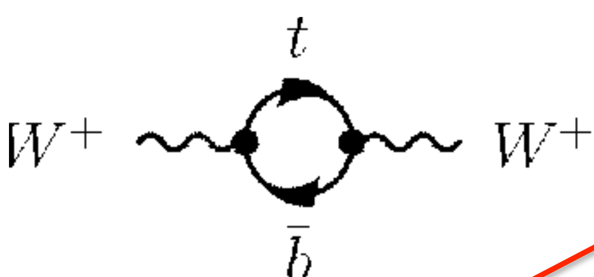
Indirect Constraints, an example

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

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

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

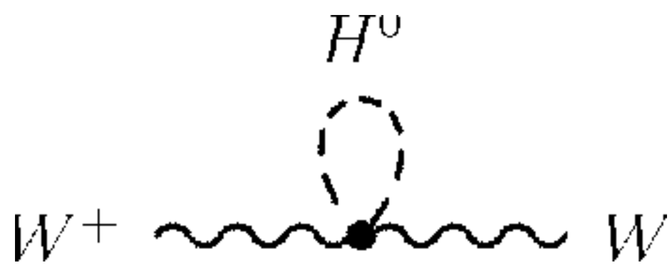
Higher order terms



Mass of the top
known to ~ 1%

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

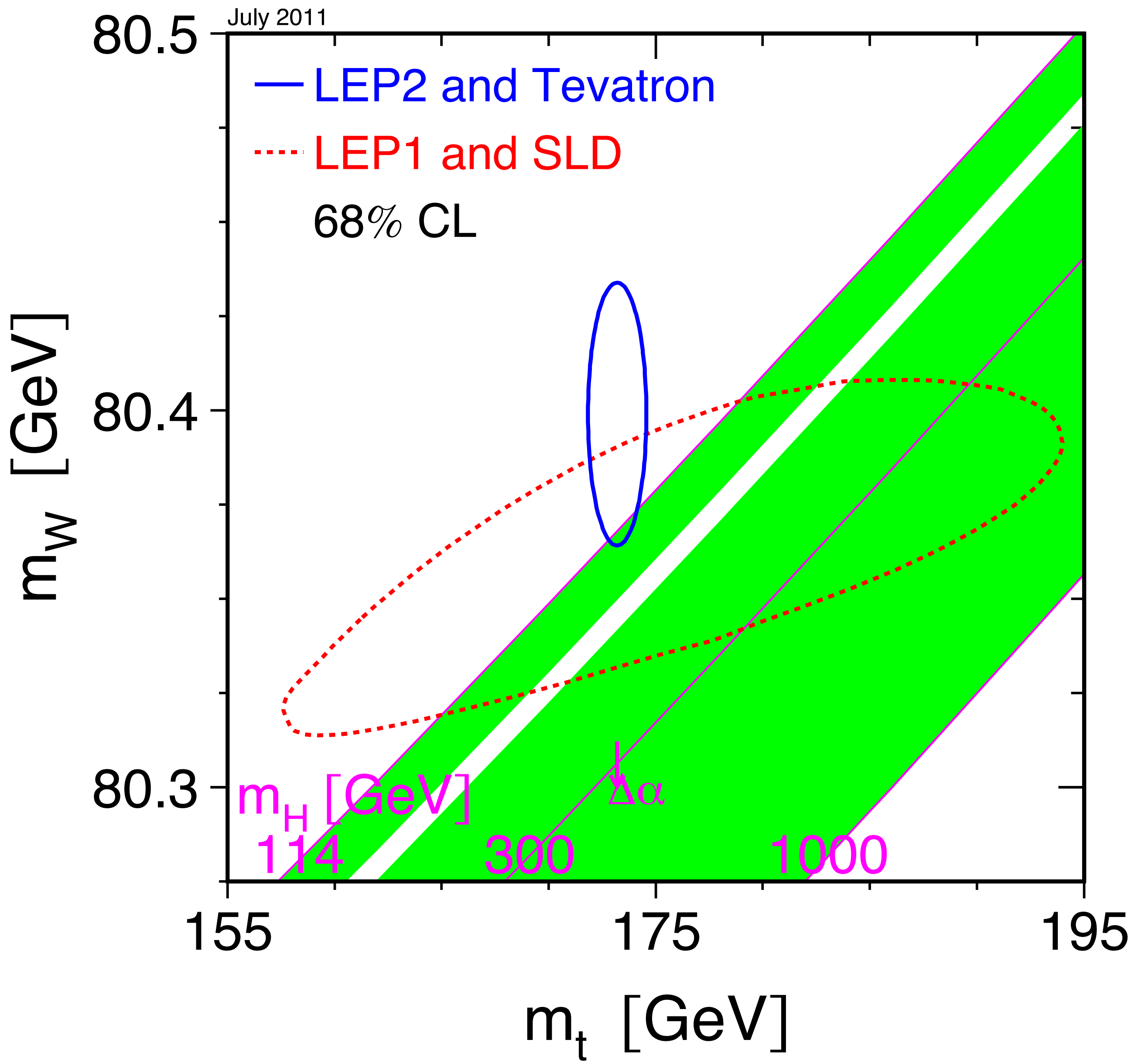
quadratic dependence
on top mass



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

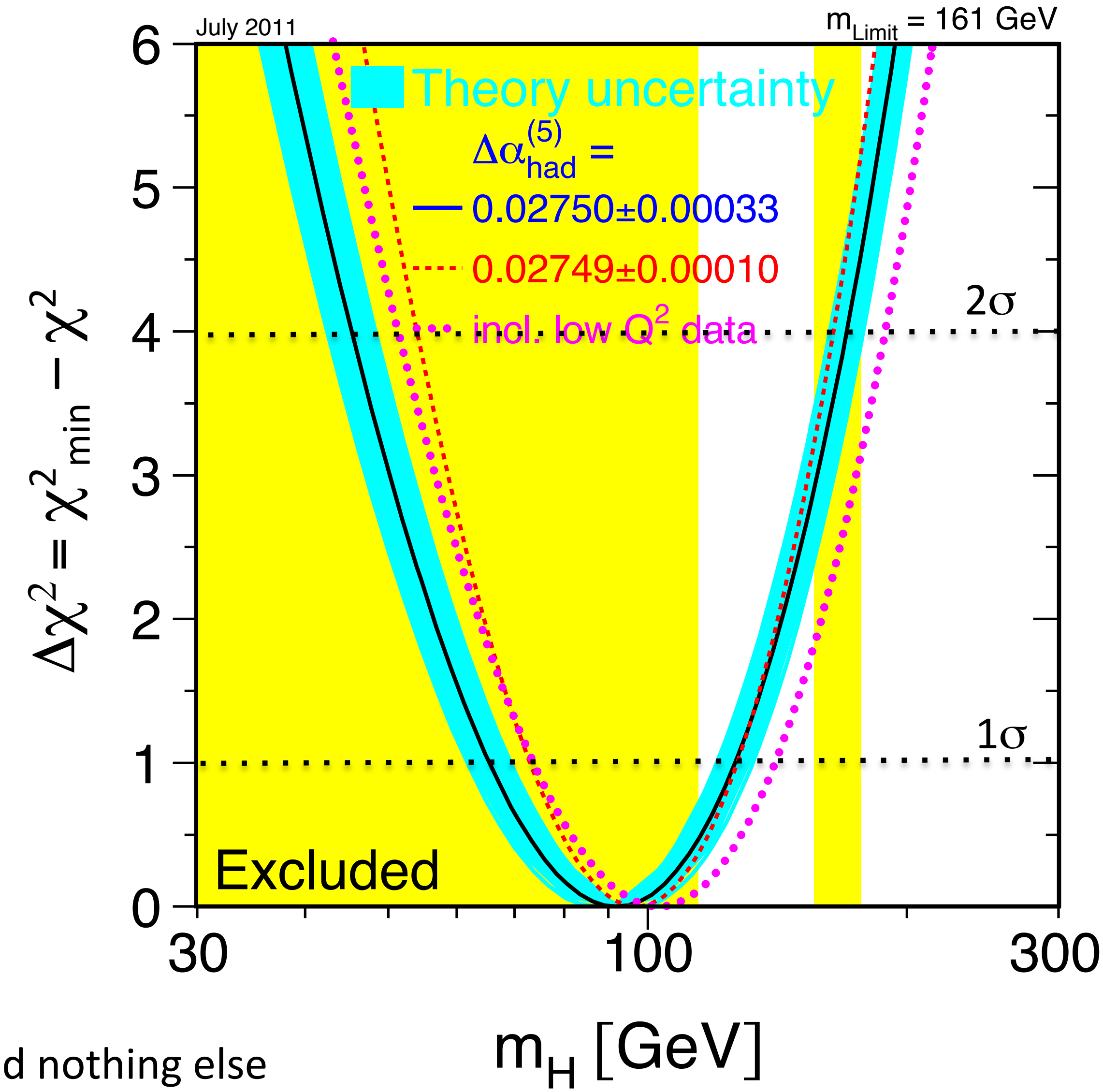
logarithmic dependence
on Higgs mass

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 year ago

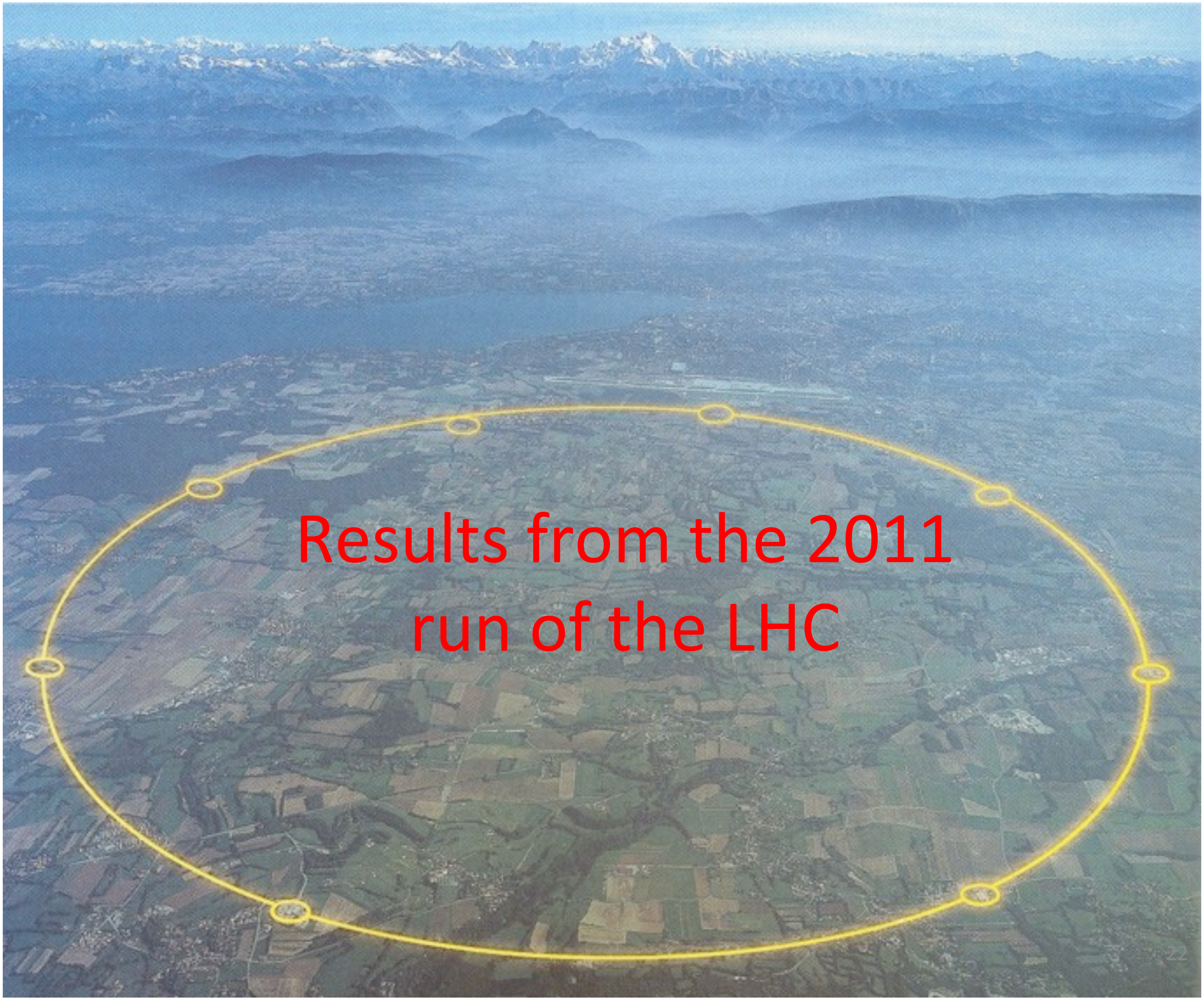
- The SM tells us everything about the Higgs except for its mass.
  - If it exists.

- 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

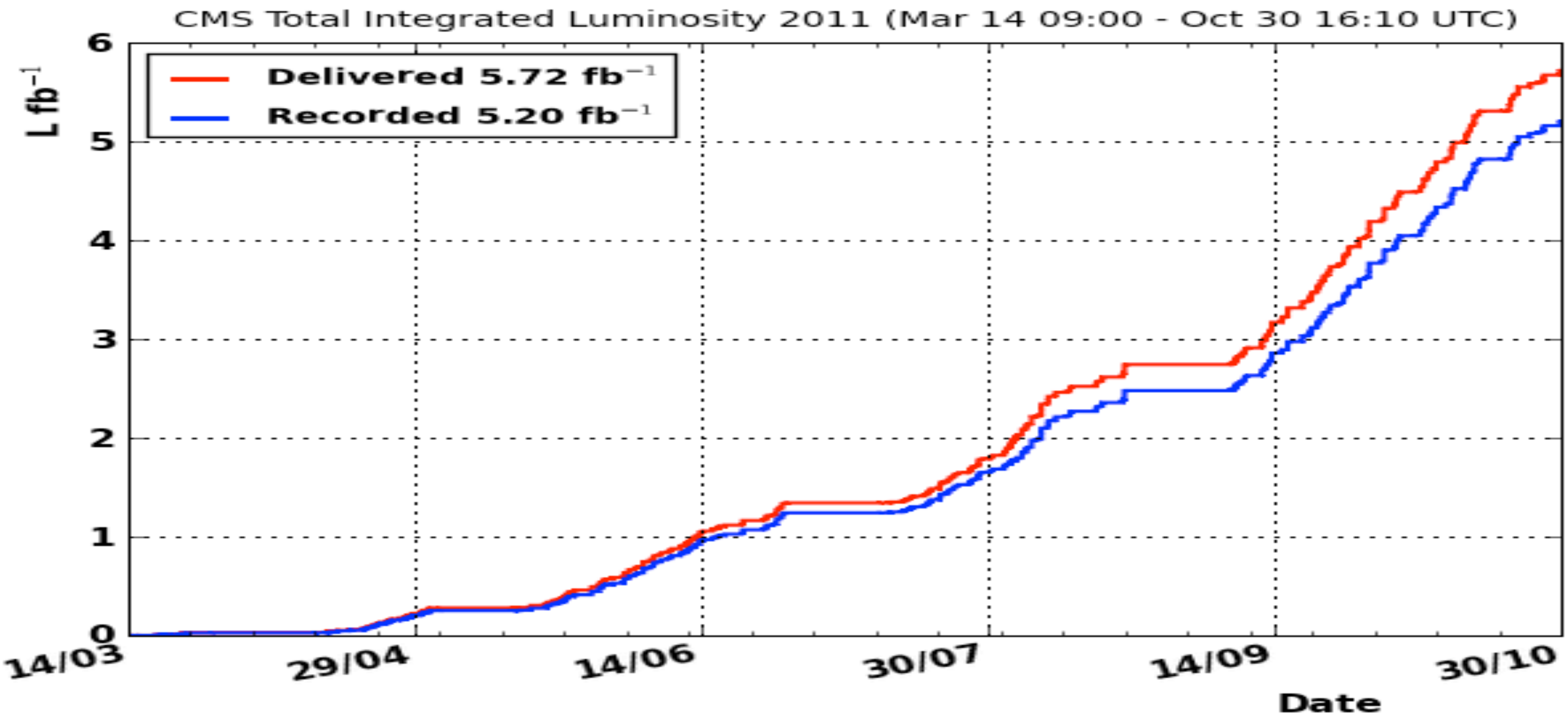
- Indirect evidence points to a light SM Higgs

Results from the 2011 run of the LHC



About the Results That I Present Today

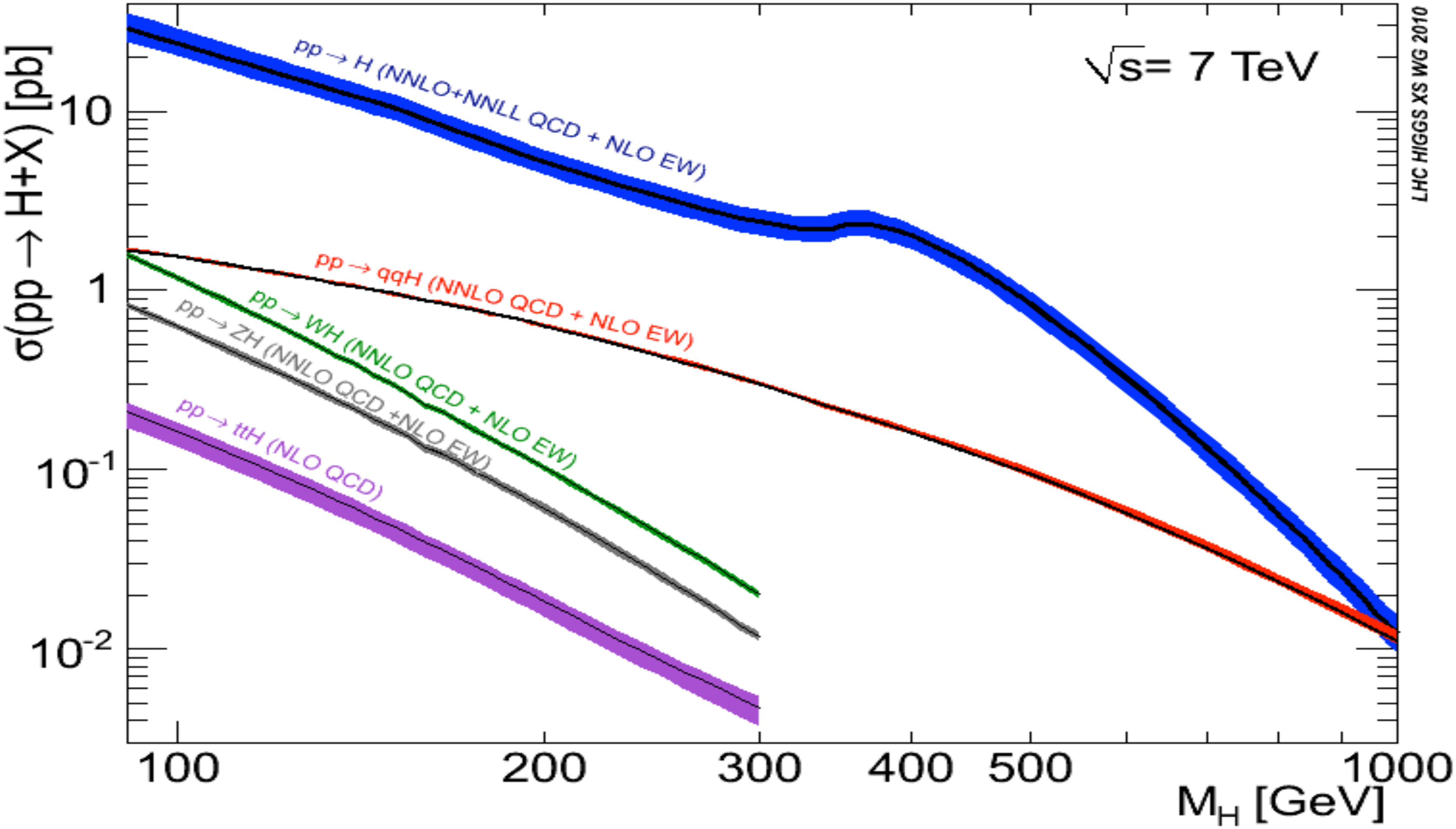
- There are two “big” detectors at the LHC, Atlas and CSM
- For simplicity, I only show CMS results
  - Because I am on CMS
- Results from Atlas are comparable
- At the end, for the “money plots”, I will show Atlas as well



- Data were collected between March 14 and Oct 30, 2011
- The analyses were completed ~ 1 month later
- The *integrated luminosity* was ~ 5 fb^{-1}. This is x150 more data than in 2010.
- It corresponds to ~ 5 10^{14} proton-proton interactions

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

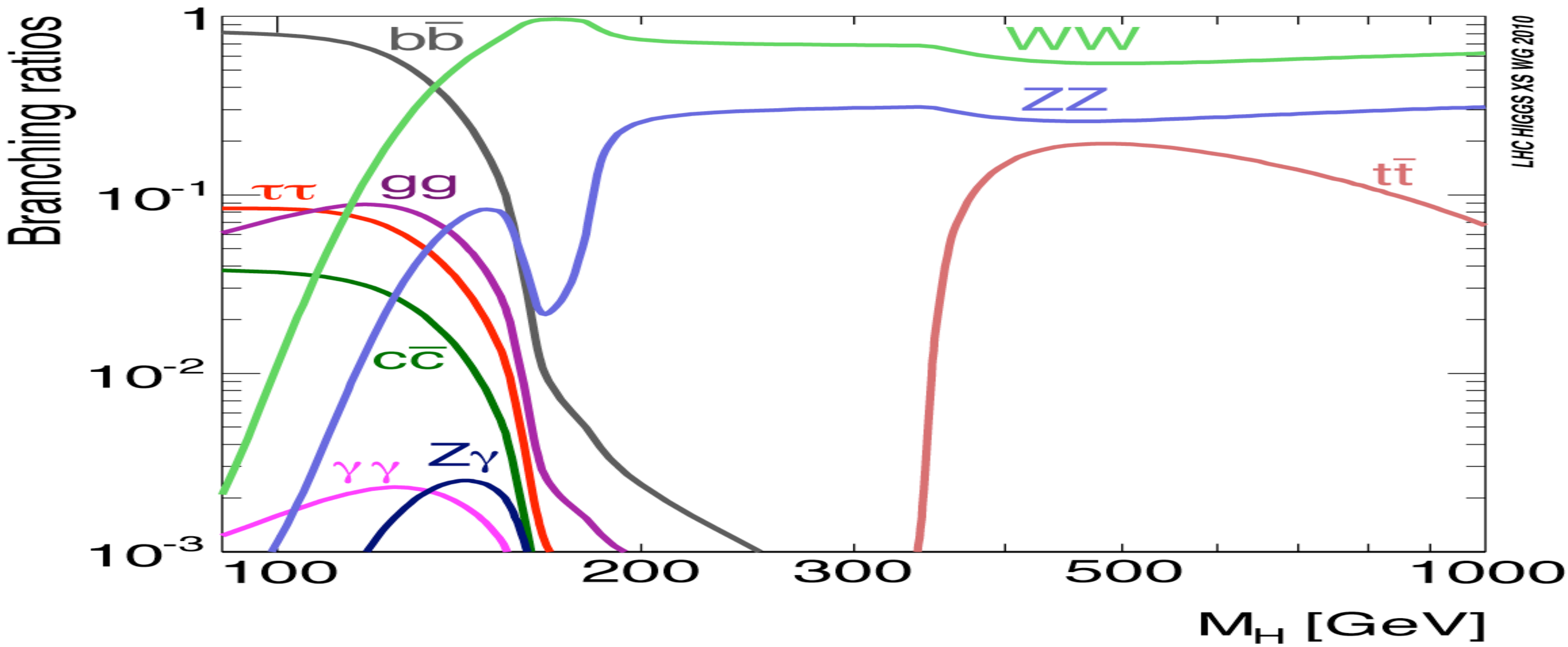
1. Produced in pp interactions, look for its decay signature



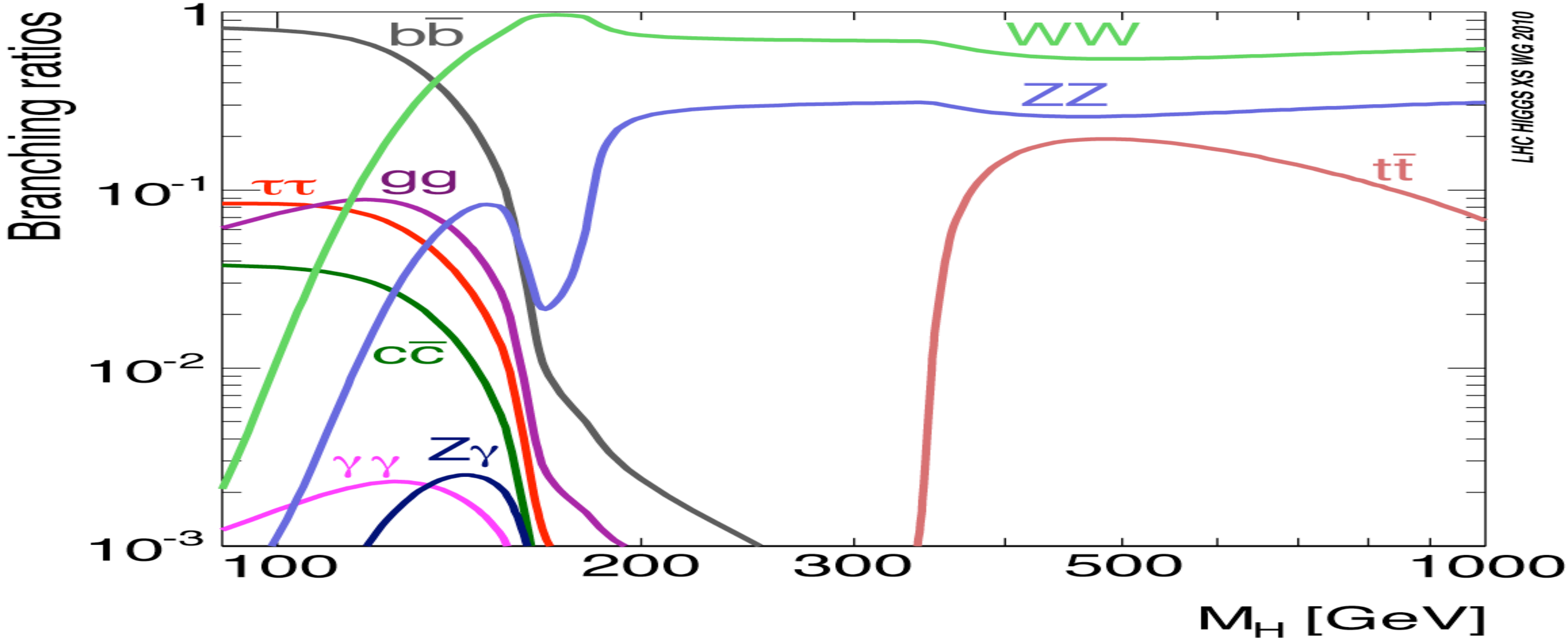
- There are a few different production mechanisms
- As M_H increases, the cross-section decreases
- It is a rare process
- In ~ 5 10^{14} pp collision, ~ 85 K (4 K) higgses were produced for M_H=120 (500) GeV

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 (perhaps!) 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
  - 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 intermediate and high mass (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 $H \rightarrow \gamma\gamma$ 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 ~ 1 GeV or so)

- OTOH: in $H \rightarrow WW \rightarrow e\nu\mu\nu$ 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

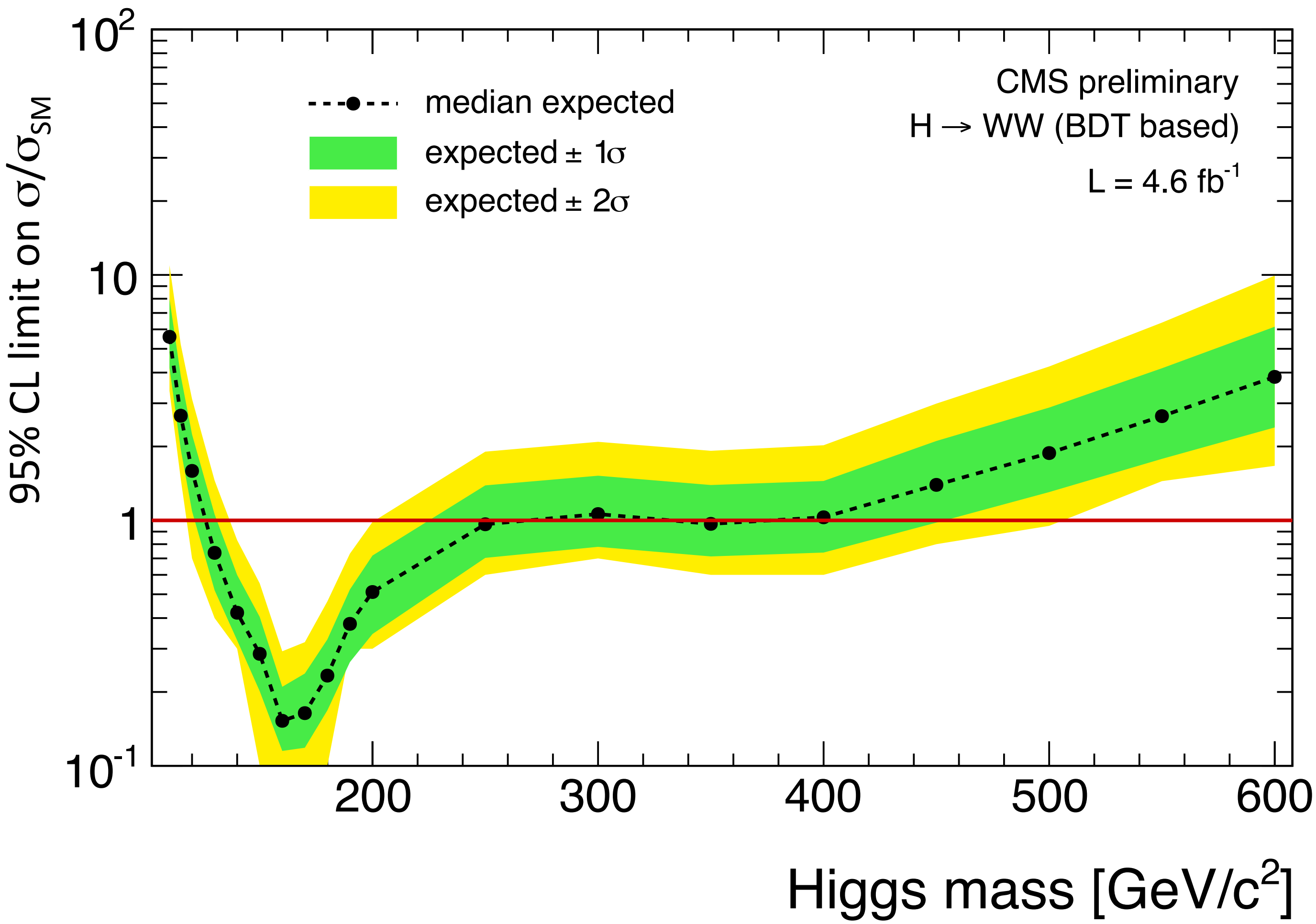
- Since we know from theory what σ and BR should be as a function of M_H, we can exclude any M_H that results in σ*BR > xx

(Is this obvious?)

There are three kinds of lies:
lies, damned lies, and statistics

Mark Twain (?)
Benjamin Disraeli (?)

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

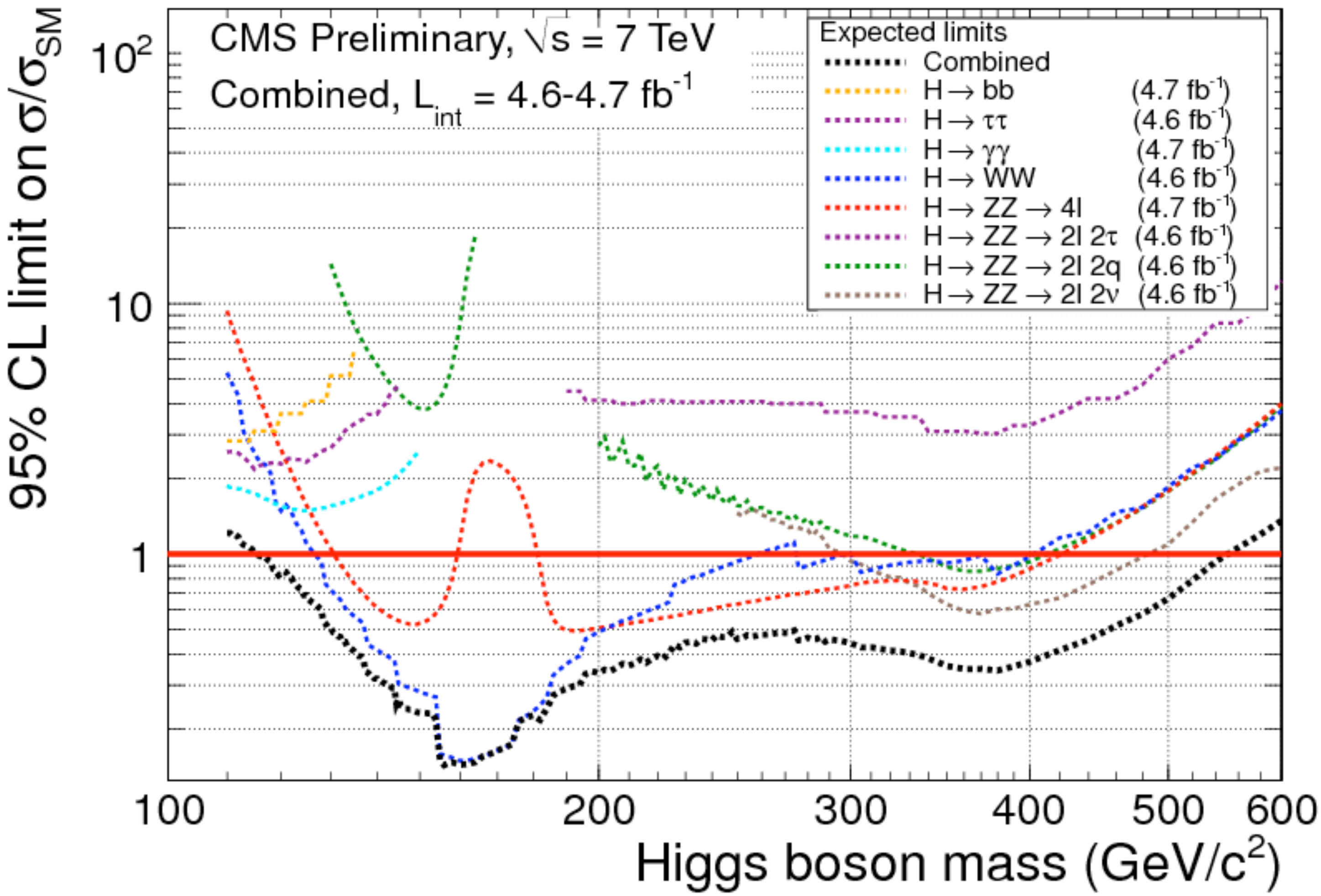
  Or

  - 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 ~ $(2/n)\sigma$ worse-than-expected

Expected limits



Results

Will look at the results for (l=e or μ):

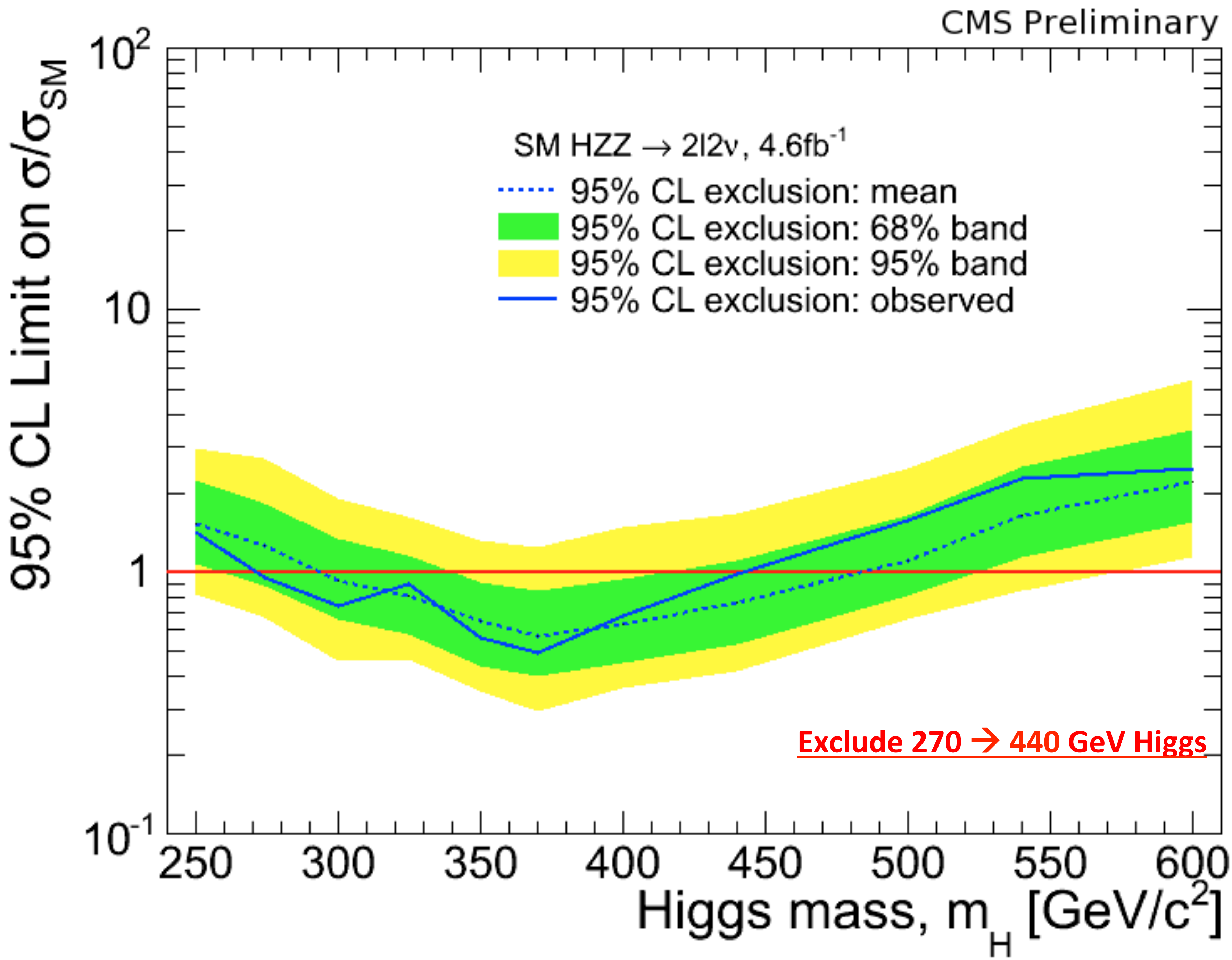
1. $H \rightarrow ZZ \rightarrow ll\nu\nu$
2. $H \rightarrow WW \rightarrow l\nu l\nu$
3. $H \rightarrow \gamma\gamma$
4. $H \rightarrow ZZ \rightarrow llll$
5. Everything together

H→ZZ→llνν

- Mode without a mass peak
- Select events with Z→ll and missing energy that could be signature of Z→νν.
  - Different selections for different M_H hypoteses
- Count number of events, compare with expectations with and without SM Higgs contribution

m_H (GeV/c^2)	ZZ	WZ	Top/WW/ W+jets/Z→ $\tau\tau$	Z+Jets	Total	Signal	Data
250	$36 \pm 0.2 \pm 2.6$	$24 \pm 0.31 \pm 2$	$65 \pm 3.8 \pm 5.8$	15 ± 15	$140 \pm 3.8 \pm 16$	22 ± 2.1	142
300	$23 \pm 0.17 \pm 1.7$	$13 \pm 0.23 \pm 1.1$	$18 \pm 1.1 \pm 3$	6.3 ± 6.3	$60 \pm 1.1 \pm 7.3$	21 ± 2	64
350	$16 \pm 0.14 \pm 1.1$	$7 \pm 0.17 \pm 0.6$	$2 \pm 0.12 \pm 1$	4.1 ± 4.1	$29 \pm 0.25 \pm 4.4$	21 ± 2.3	26
400	$12 \pm 0.13 \pm 0.87$	$4.6 \pm 0.14 \pm 0.39$	0	2.7 ± 2.7	$19 \pm 0.19 \pm 2.9$	17 ± 1.6	18
500	$7.5 \pm 0.1 \pm 0.54$	$2 \pm 0.092 \pm 0.17$	0	1.4 ± 1.4	$11 \pm 0.14 \pm 1.5$	7.4 ± 0.76	14
600	$3.9 \pm 0.075 \pm 0.28$	$0.82 \pm 0.058 \pm 0.07$	0	0.64 ± 0.64	$5.3 \pm 0.095 \pm 0.7$	2.9 ± 0.31	5

- No excess of events over BG prediction
- Clearly sensitive for SM Higgs at high mass. It is not there.



CMS Preliminary
95% CL Limit on σ/σ_SM
SM HZZ → 2l2ν, 4.6fb^-1
95% CL exclusion: mean
95% CL exclusion: 68% band
95% CL exclusion: 95% band
95% CL exclusion: observed
Exclude 270 → 440 GeV Higgs
Higgs mass, m_H [GeV/c^2]
10^2
10
1
10^-1
250
300
350
400
450
500
550
600

$H \rightarrow WW \rightarrow l\nu l\nu$

- Also a mode without a mass peak
- Select events with 2 leptons and missing energy, compare with expectation with and without SM Higgs
- Two-step analysis
  1. Just event counts after tight cuts
  2. Construct multivariate discriminator (Boosted Decision Tree) trained to tell apart signal from background after looser cuts
     - More sensitive than "cut-and-count"

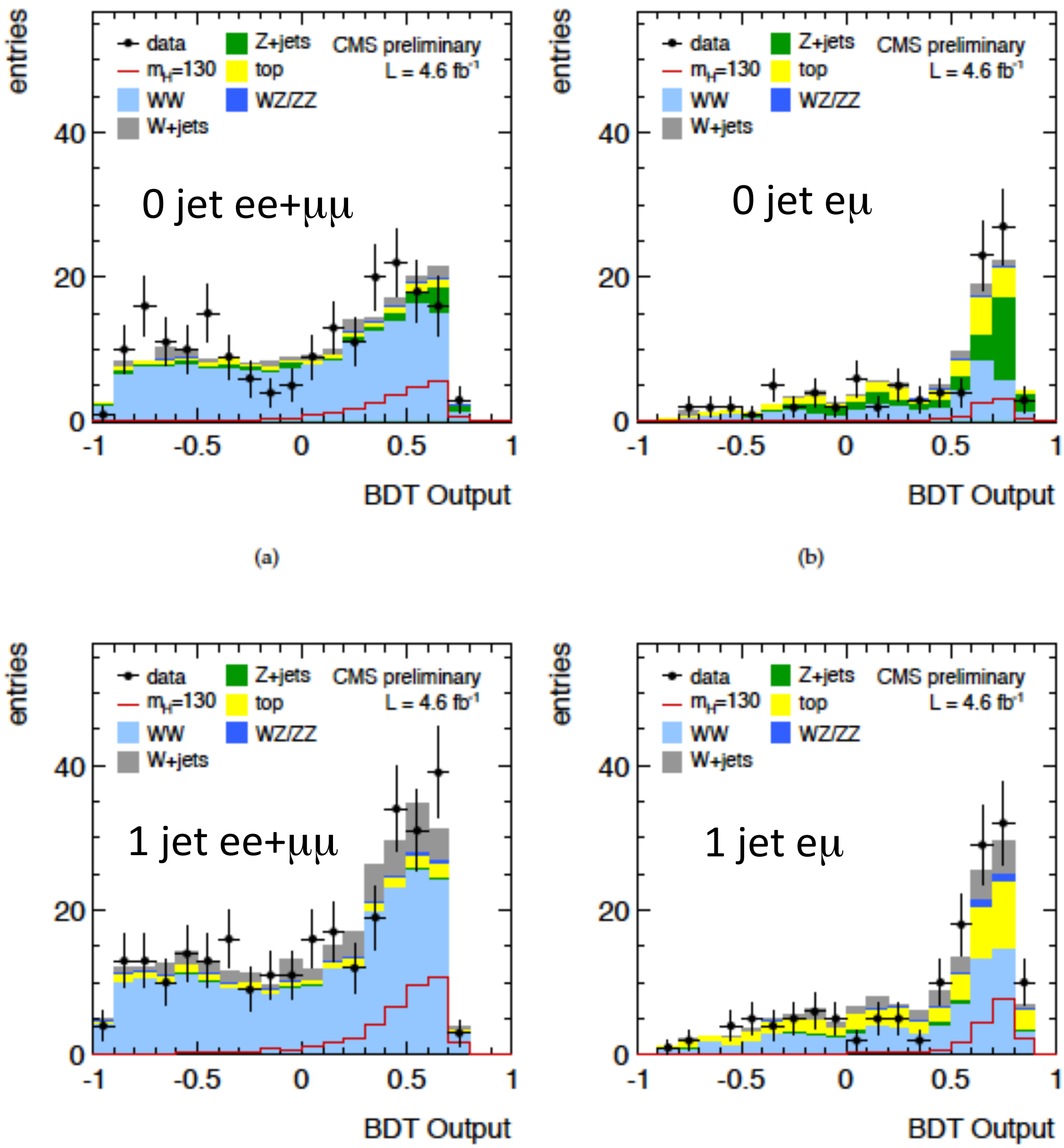
- **cut based approach in the 0-jet category**:

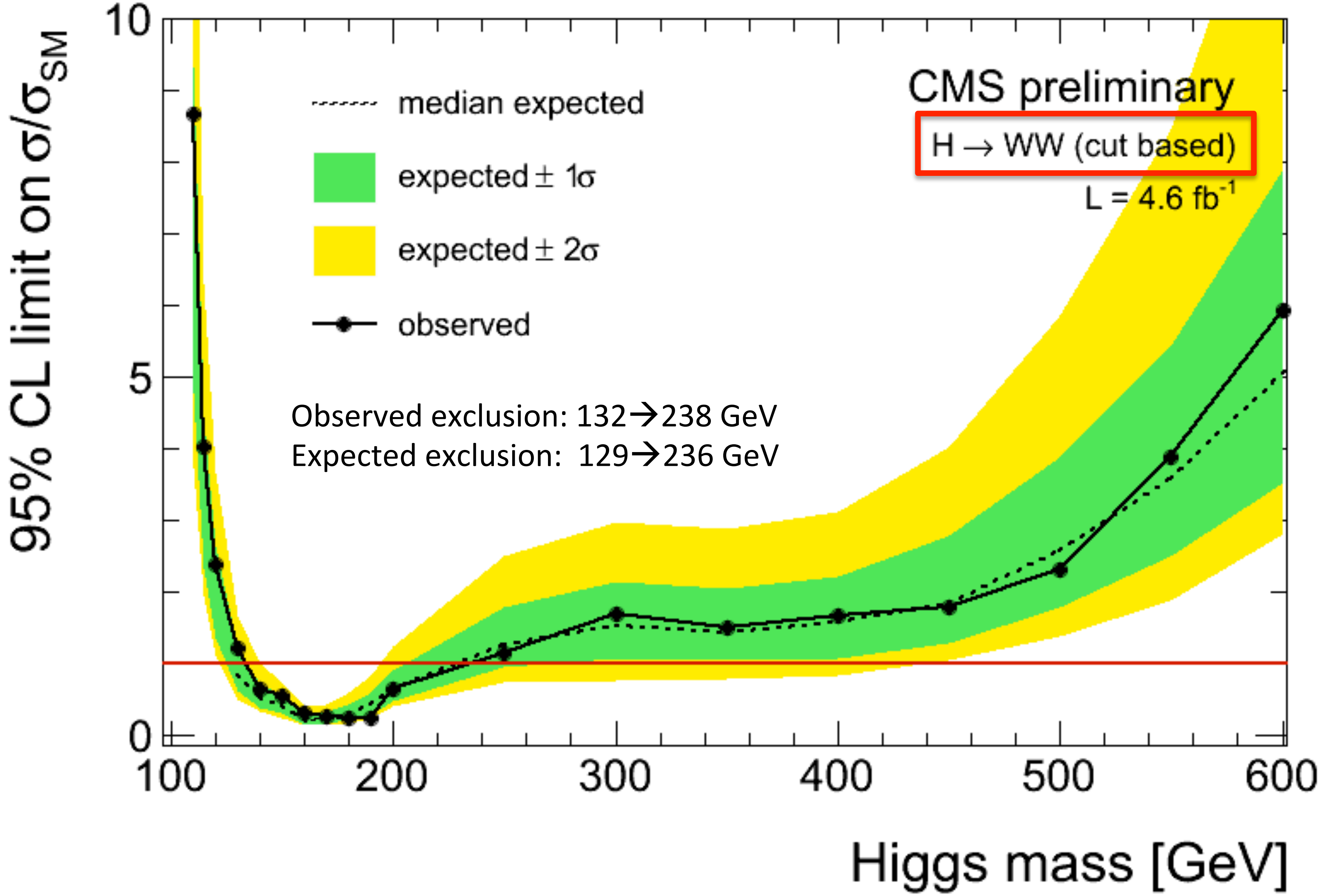
mH	DY→ll	ttbar+tW	W+jets	WZ+ZZ+Wγ	WW	all bkg.	H→WW	data
120	8.8 ± 9.2	6.7 ± 1.0	14.7 ± 4.7	6.1 ± 1.5	100.3 ± 7.2	136.7 ± 12.7	15.7 ± 0.8	136
130	13.7 ± 7.8	10.6 ± 1.6	17.6 ± 5.5	7.4 ± 1.6	142.2 ± 10.0	191.5 ± 14.0	45.2 ± 2.1	193
160	3.4 ± 3.4	10.5 ± 1.4	3.0 ± 1.5	2.2 ± 0.4	82.6 ± 5.4	101.7 ± 6.8	122.9 ± 5.6	111
200	2.7 ± 3.7	23.3 ± 3.1	3.4 ± 1.5	3.2 ± 0.3	108.2 ± 4.5	140.8 ± 6.8	48.8 ± 2.2	159
250	0.3 ± 0.6	36.2 ± 4.8	6.7 ± 2.1	5.7 ± 0.7	101.8 ± 4.5	150.8 ± 6.9	23.5 ± 1.1	152
300	0.7 ± 1.9	41.6 ± 5.4	6.5 ± 2.1	7.0 ± 0.7	87.5 ± 3.9	143.3 ± 7.2	20.2 ± 0.9	147
400	0.2 ± 0.2	35.9 ± 4.7	5.5 ± 1.8	9.3 ± 1.1	59.8 ± 2.7	110.8 ± 5.8	17.5 ± 0.8	109

- **cut based approach in the 1-jet category**:

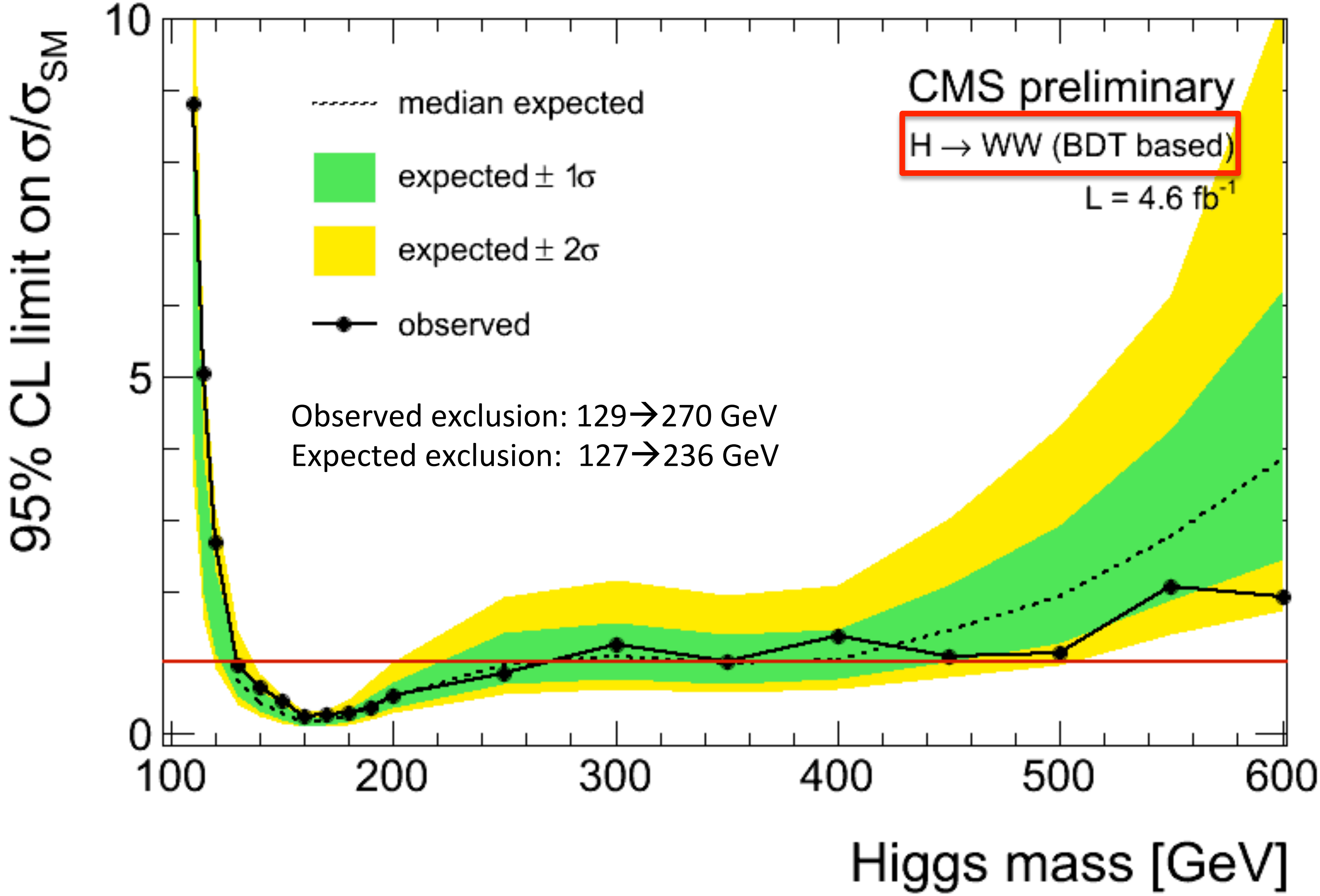
mH	DY→ll	ttbar+tW	W+jets	WZ+ZZ+Wγ	WW	all bkg.	H→WW	data
120	6.6 ± 2.3	17.2 ± 1.0	5.4 ± 2.4	3.2 ± 0.6	27.0 ± 4.7	59.5 ± 5.9	6.5 ± 0.3	72
130	5.3 ± 2.5	25.6 ± 1.4	6.5 ± 2.5	4.0 ± 0.6	38.5 ± 6.6	79.9 ± 7.7	17.6 ± 0.8	105
160	4.2 ± 1.4	27.9 ± 1.4	3.2 ± 1.4	1.9 ± 0.3	33.7 ± 5.5	70.8 ± 6.0	60.2 ± 2.6	86
200	14.6 ± 5.3	59.4 ± 2.8	5.2 ± 1.8	2.2 ± 0.1	49.3 ± 2.2	130.8 ± 6.7	25.8 ± 1.1	111
250	12.9 ± 6.8	83.8 ± 3.9	5.9 ± 2.1	3.3 ± 0.2	60.3 ± 2.8	166.2 ± 8.6	14.8 ± 0.6	158
300	12.8 ± 4.8	83.6 ± 3.9	6.2 ± 2.2	3.8 ± 0.4	57.5 ± 2.7	163.9 ± 7.1	13.7 ± 0.6	168
400	8.3 ± 3.2	60.6 ± 2.9	6.2 ± 2.1	3.9 ± 0.5	44.6 ± 2.2	123.6 ± 5.3	12.2 ± 0.5	128

BDT output for M_H = 130 GeV hypothesis, a mass at the edge of the SM sensitivity

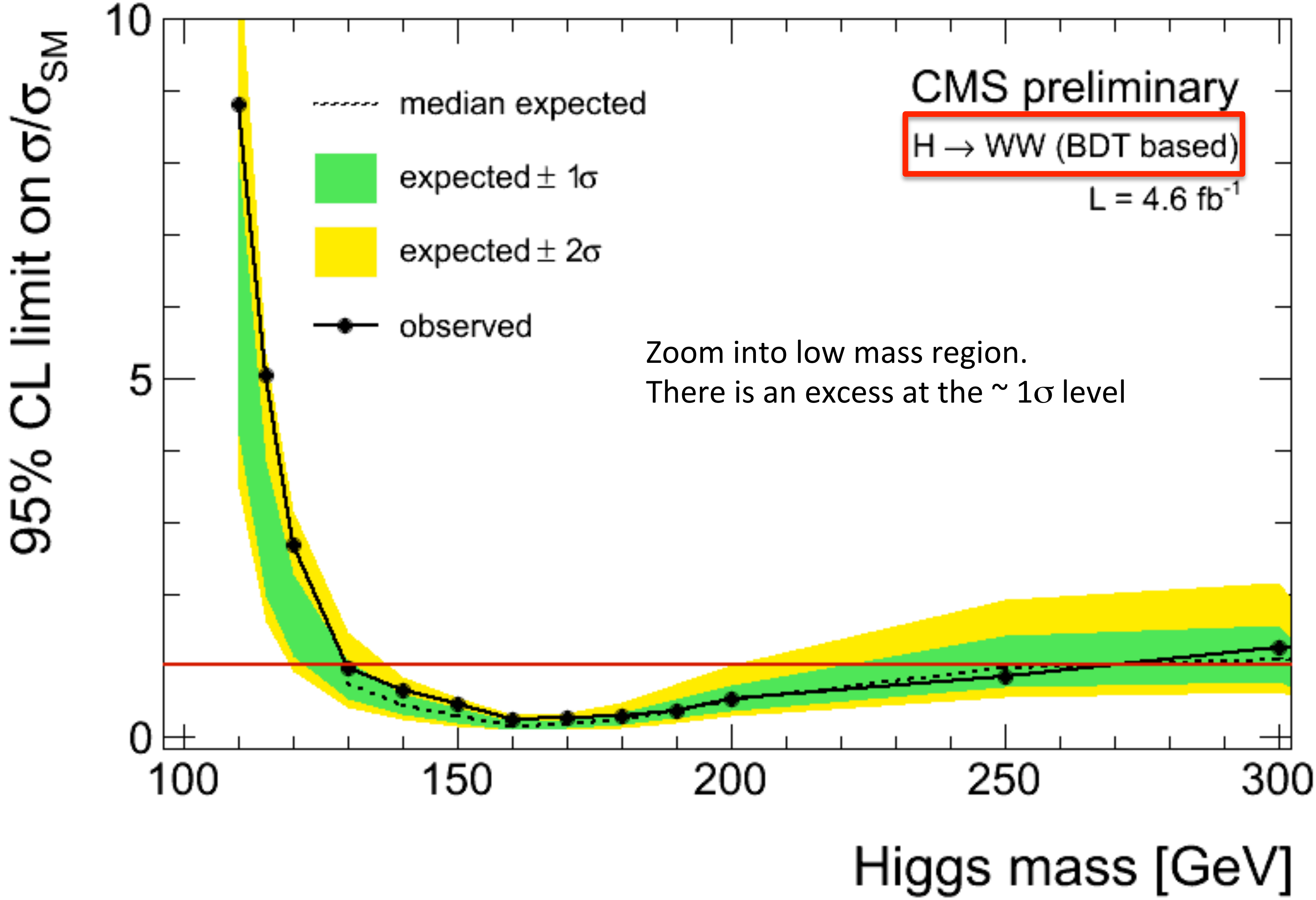




95% CL limit on σ/σ_SM
10
5
0
100
200
300
400
500
600
Higgs mass [GeV]
median expected
expected ± 1σ
expected ± 2σ
observed
CMS preliminary
H → WW (cut based)
L = 4.6 fb-1
Observed exclusion: 132→238 GeV
Expected exclusion: 129→236 GeV



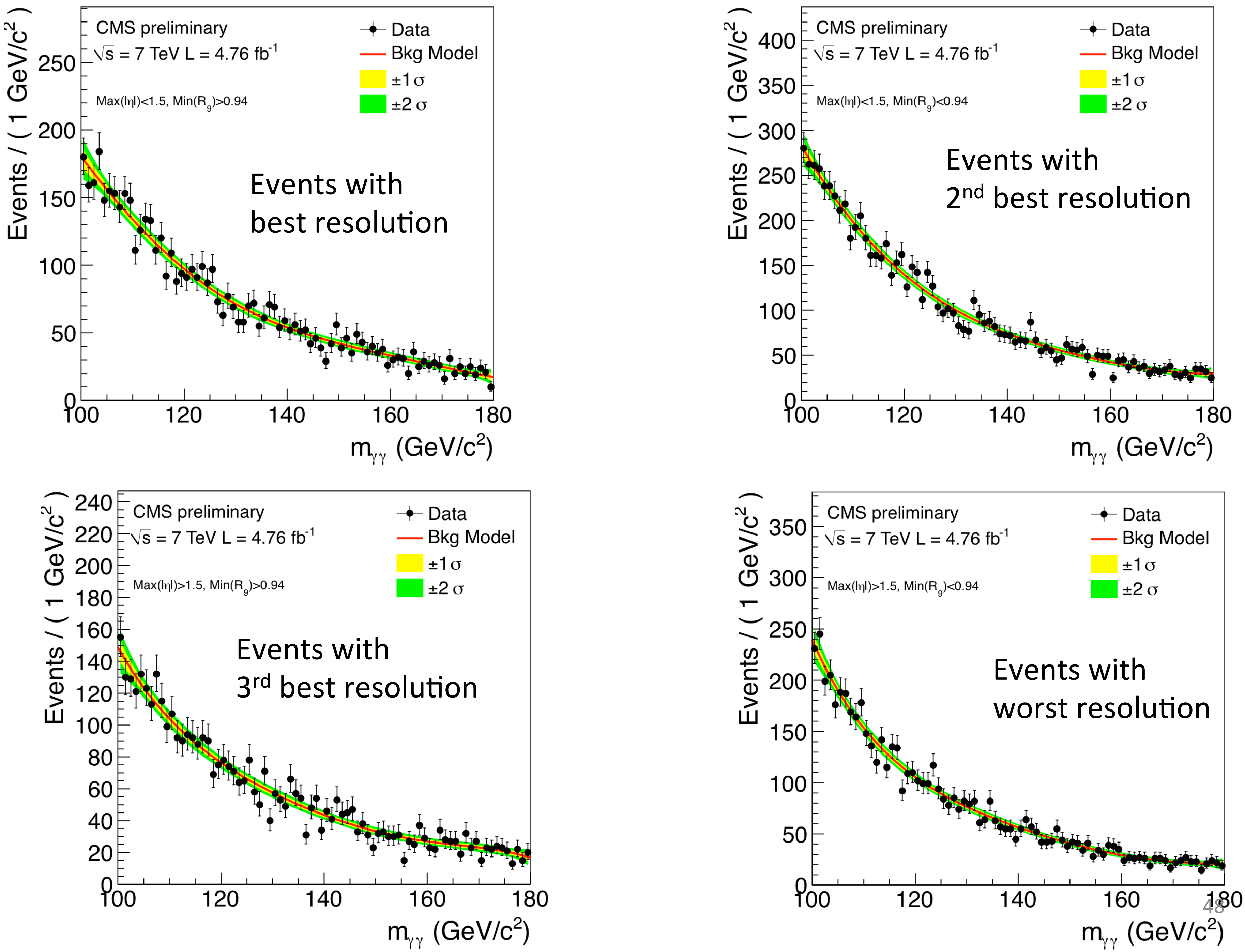
95% CL limit on σ/σ_SM
10
5
0
100
200
300
400
500
600
Higgs mass [GeV]
median expected
expected ± 1σ
expected ± 2σ
observed
CMS preliminary
H → WW (BDT based)
L = 4.6 fb-1
Observed exclusion: 129→270 GeV
Expected exclusion: 127→236 GeV

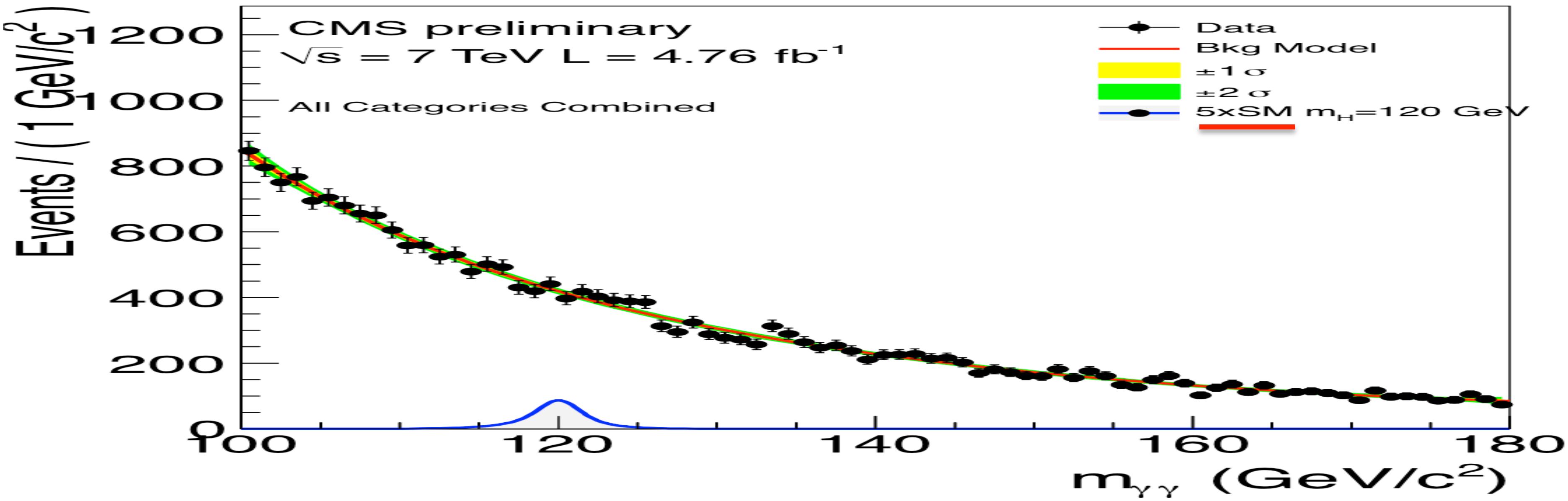


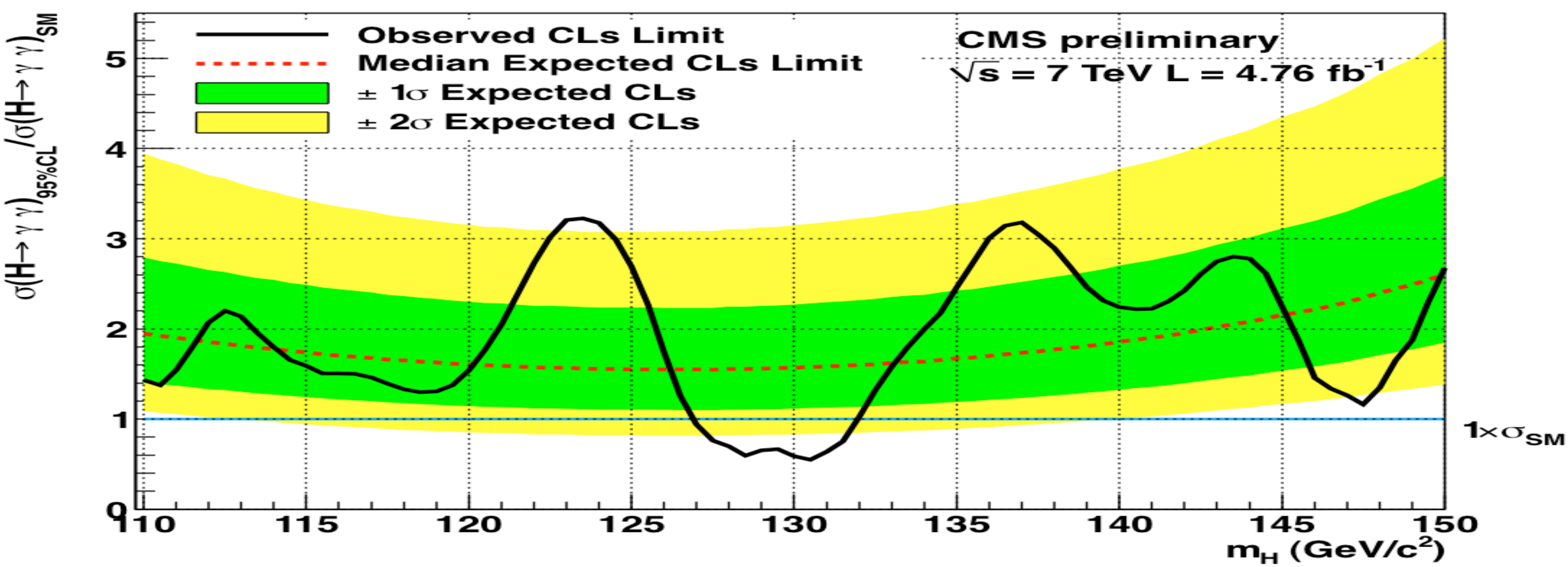
Zoom into low mass region.
There is an excess at the ~ 1σ level

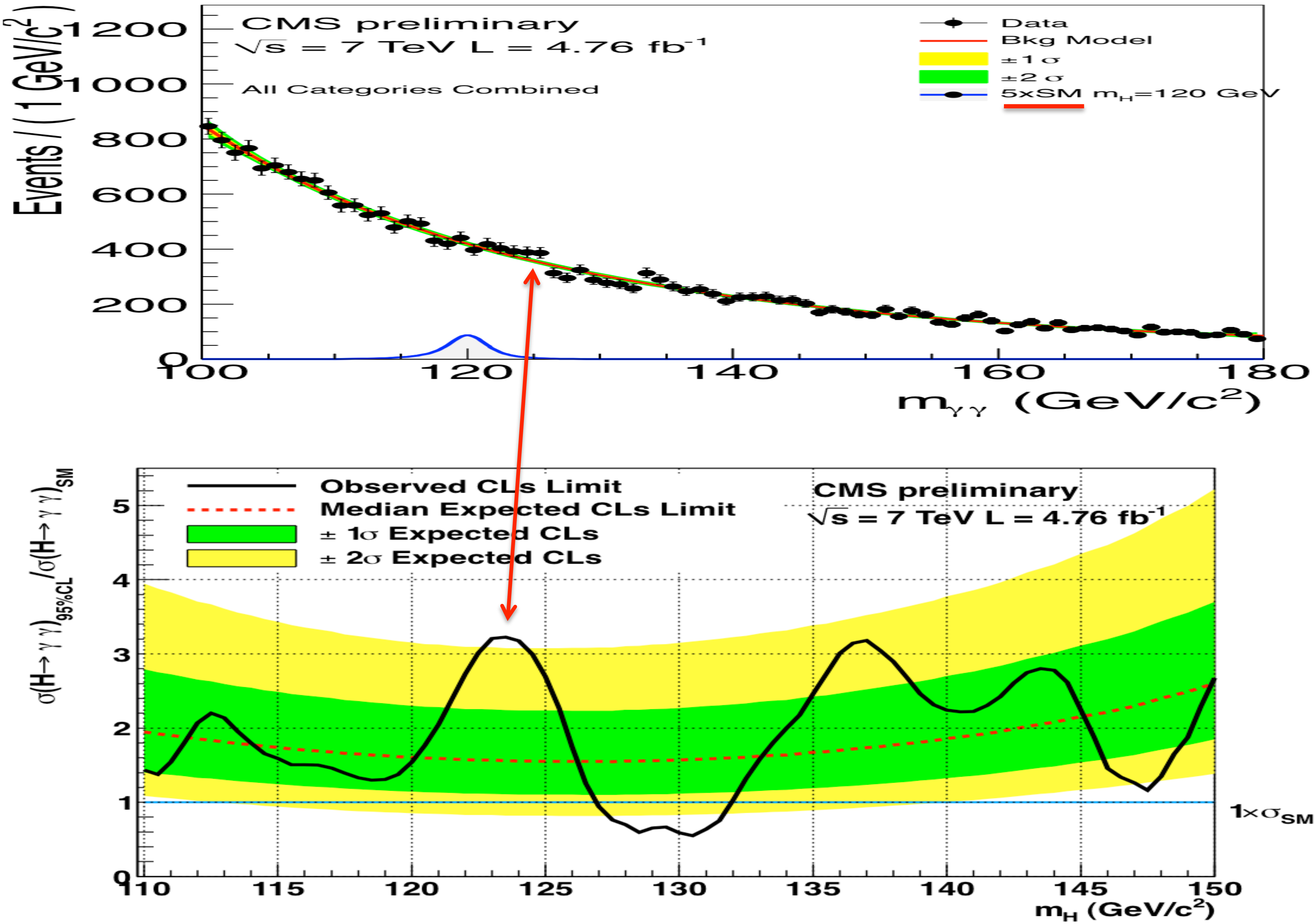
H→γγ

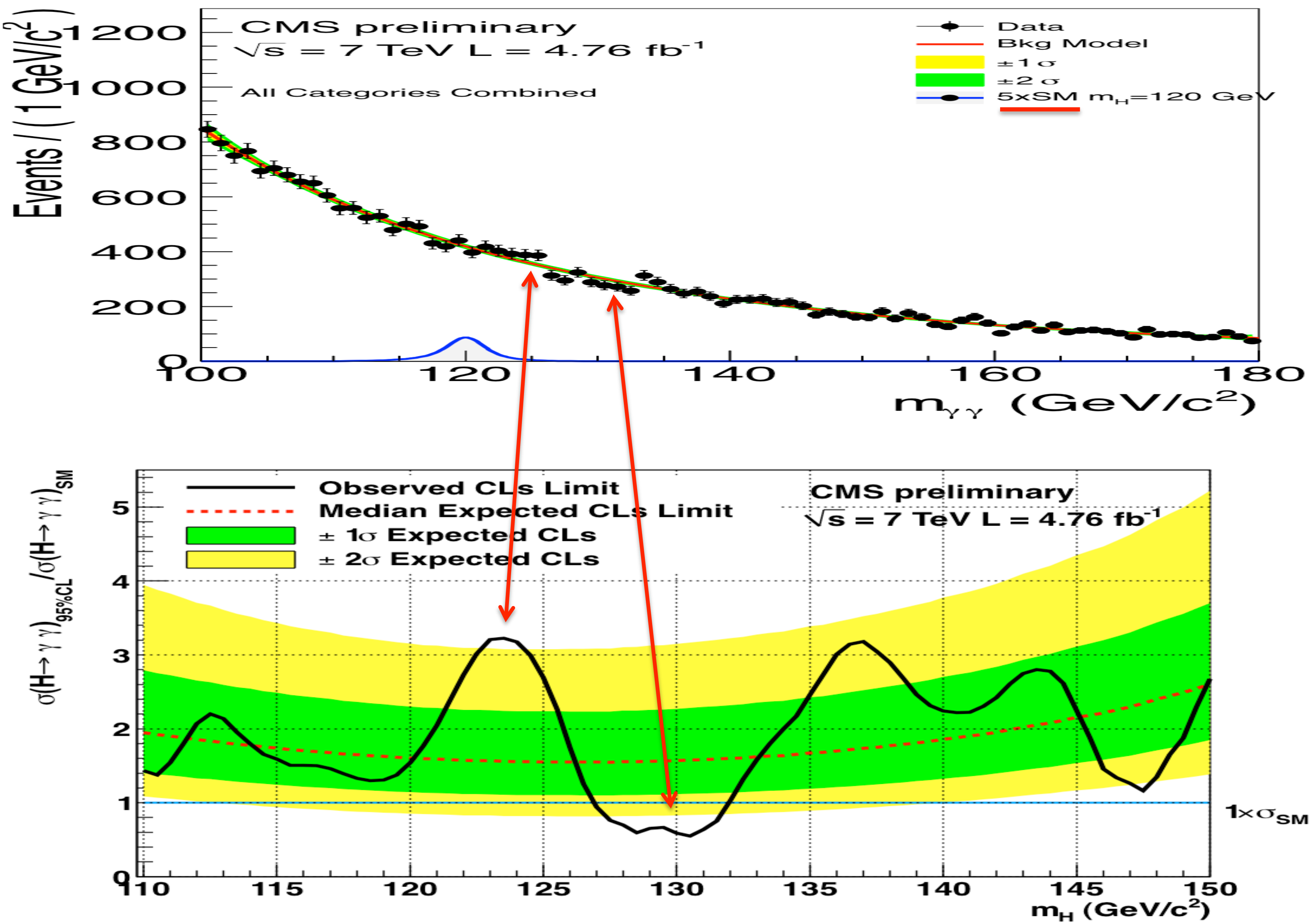
- This is a channel which should give a mass peak
- Useful only for M_H < 140 GeV
- There are backgrounds from pp→γγ not associated with Higgs.
- The BG is a smooth distribution parametrized by a continuous function
- Mass resolution is at a premium

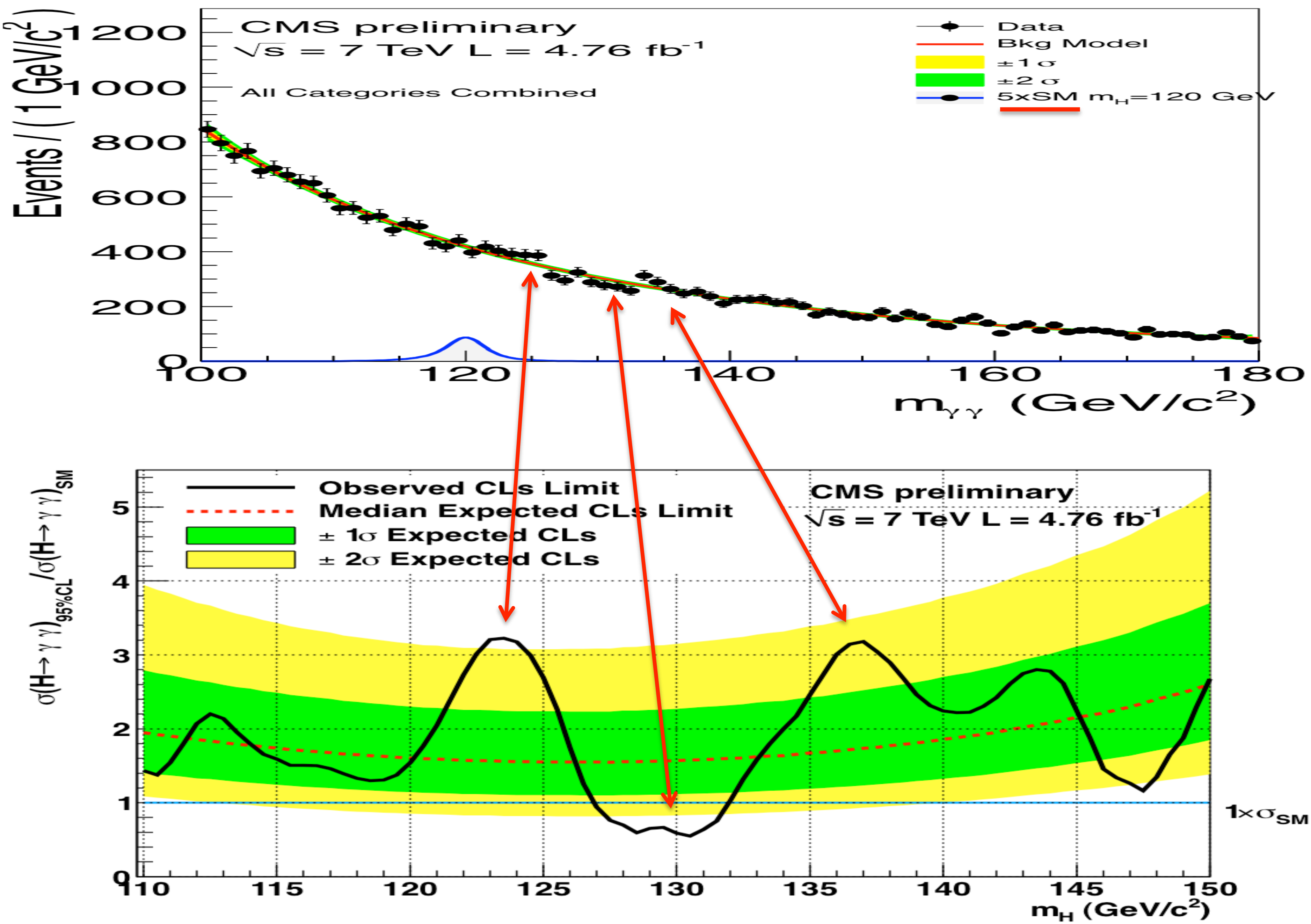

CMS preliminary
√s = 7 TeV L = 4.76 fb-1
Max(|η|)<1.5, Min(R9)>0.94
Data
Bkg Model
±1 σ
±2 σ
Events with
best resolution
Events / (1 GeV/c2)
mγγ (GeV/c2)
CMS preliminary
√s = 7 TeV L = 4.76 fb-1
Max(|η|)<1.5, Min(R9)<0.94
Data
Bkg Model
±1 σ
±2 σ
Events with
2nd best resolution
Events / (1 GeV/c2)
mγγ (GeV/c2)
CMS preliminary
√s = 7 TeV L = 4.76 fb-1
Max(|η|)>1.5, Min(R9)>0.94
Data
Bkg Model
±1 σ
±2 σ
Events with
3rd best resolution
Events / (1 GeV/c2)
mγγ (GeV/c2)
CMS preliminary
√s = 7 TeV L = 4.76 fb-1
Max(|η|)>1.5, Min(R9)<0.94
Data
Bkg Model
±1 σ
±2 σ
Events with
worst resolution
Events / (1 GeV/c2)
mγγ (GeV/c2)


CMS preliminary
√s = 7 TeV L = 4.76 fb-1
All Categories Combined
Data
Bkg Model
±1 σ
±2 σ
5xSM mH=120 GeV
Events / (1 GeV/c2)
0
200
400
600
800
1000
1200
100
120
140
160
180
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
σ(H→γγ)95%CL/σ(H→γγ)SM
0
1
2
3
4
5
110
115
120
125
130
135
140
145
150
mH (GeV/c2)
1×σSM


CMS preliminary
√s = 7 TeV L = 4.76 fb-1
All Categories Combined
Data
Bkg Model
±1 σ
±2 σ
5xSM mH=120 GeV
Events / (1 GeV/c2)
1200
1000
800
600
400
200
0
100
120
140
160
180
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
σ(H→γγ)95%CL/σ(H→γγ)SM
5
4
3
2
1
0
1×σSM
110
115
120
125
130
135
140
145
150
mH (GeV/c2)


CMS preliminary
√s = 7 TeV L = 4.76 fb-1
All Categories Combined
Data
Bkg Model
±1 σ
±2 σ
5xSM mH=120 GeV
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
√s = 7 TeV L = 4.76 fb-1
All Categories Combined
Data
Bkg Model
±1 σ
±2 σ
5xSM mH=120 GeV
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
σ(H→γγ)95%CL/σ(H→γγ)SM
1×σSM
mH (GeV/c2)

The Look Elsewhere Effect (LEE)

- There is a 2.3σ excess at M_H ~ 123 GeV
  - On the face of it: ~ 1% probability of BG only

- But hold on. There is nothing special about 123 GeV

- The probability of having such an excess anywhere in the mass range is ~ 21% (0.8σ)

- You can see that this is not at all unlikely since there is also a deficit of about the same size at M_H ~ 130 GeV.

Eur. Phys. J. C (2010) 70: 525–530
DOI 10.1140/epjc/s10052-010-1470-8

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

Trial factors for the look elsewhere effect in high energy physics

Eilam Gross, Ofer Vitells[a]

Weizmann Institute of Science, Rehovot 76100, Israel

On hypothesis testing, trials factor, hypertests and the BUMPHUNTER

Georgios Choudalakis *
University of Chicago, Enrico Fermi Institute

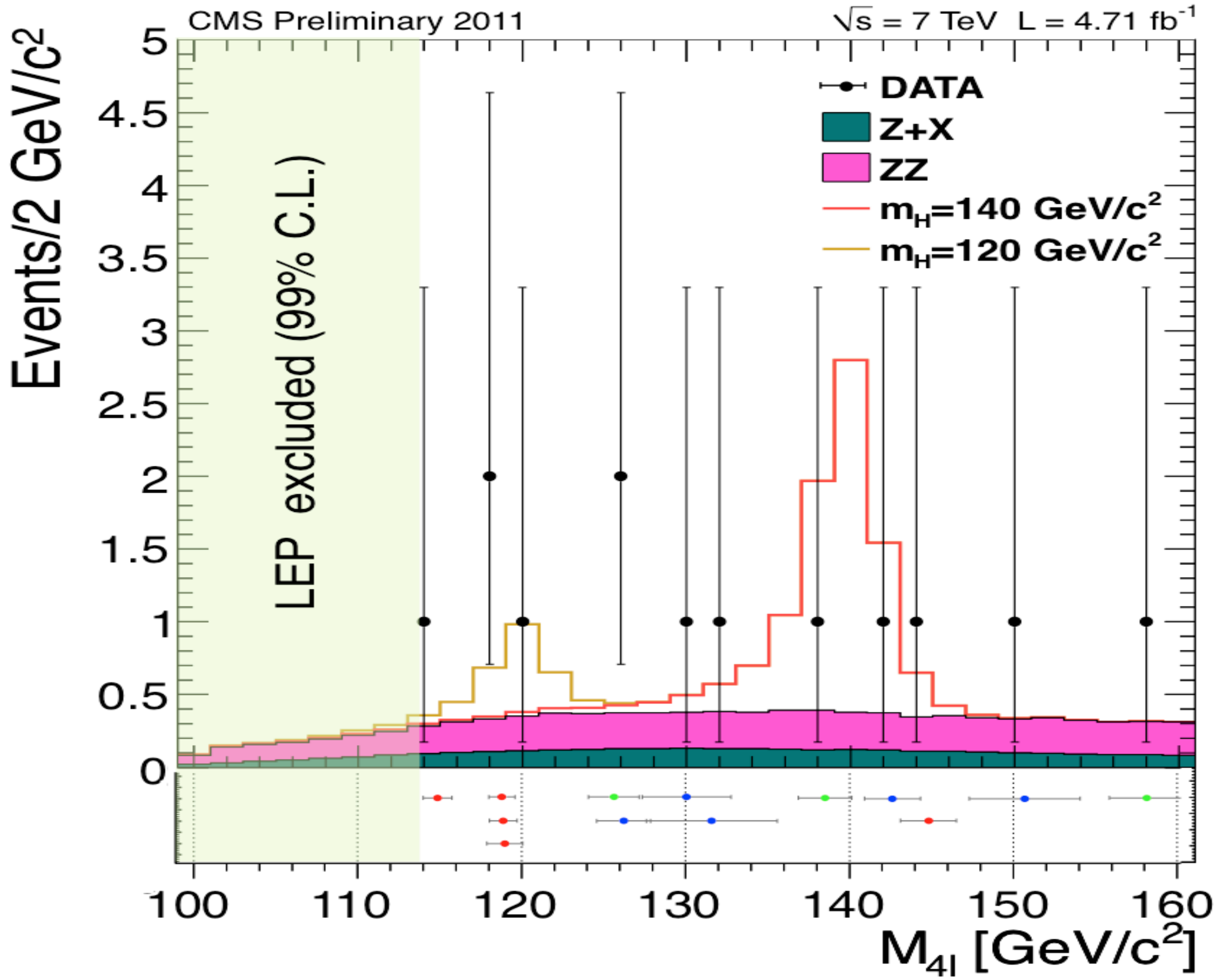
January 10, 2011

Abstract

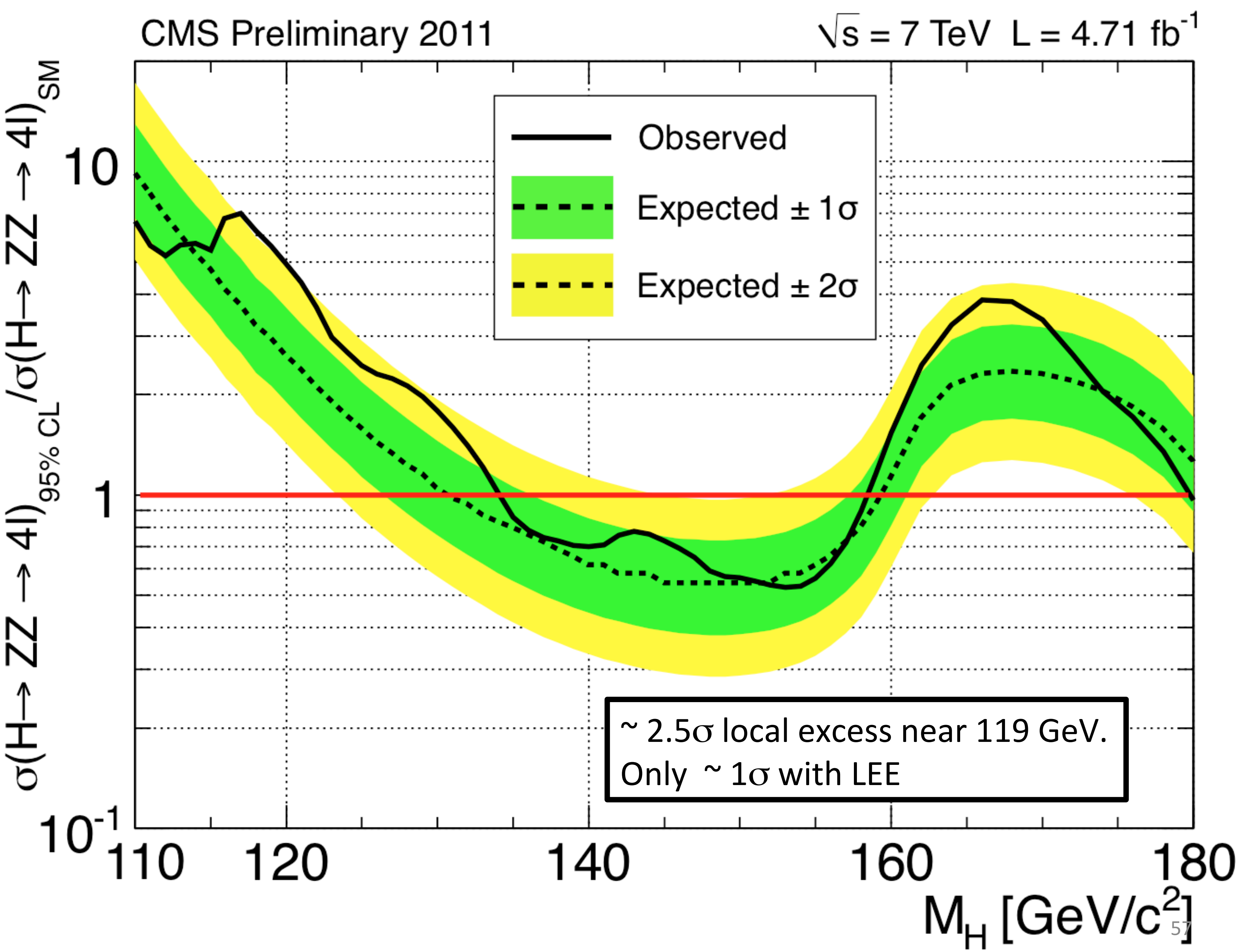
A detailed presentation of hypothesis testing is given. The "look elsewhere" effect is illustrated, and a treatment of the trials factor is proposed with the introduction of hypothesis hypertests. An example of such a hypertest is presented, named BUMPHUNTER, which is used in ATLAS [1], and in an earlier version also in CDF [2], to search for exotic phenomena in high energy physics. As a demonstration, the BUMPHUNTER is used to address Problem 1 of the Banff Challenge [3].

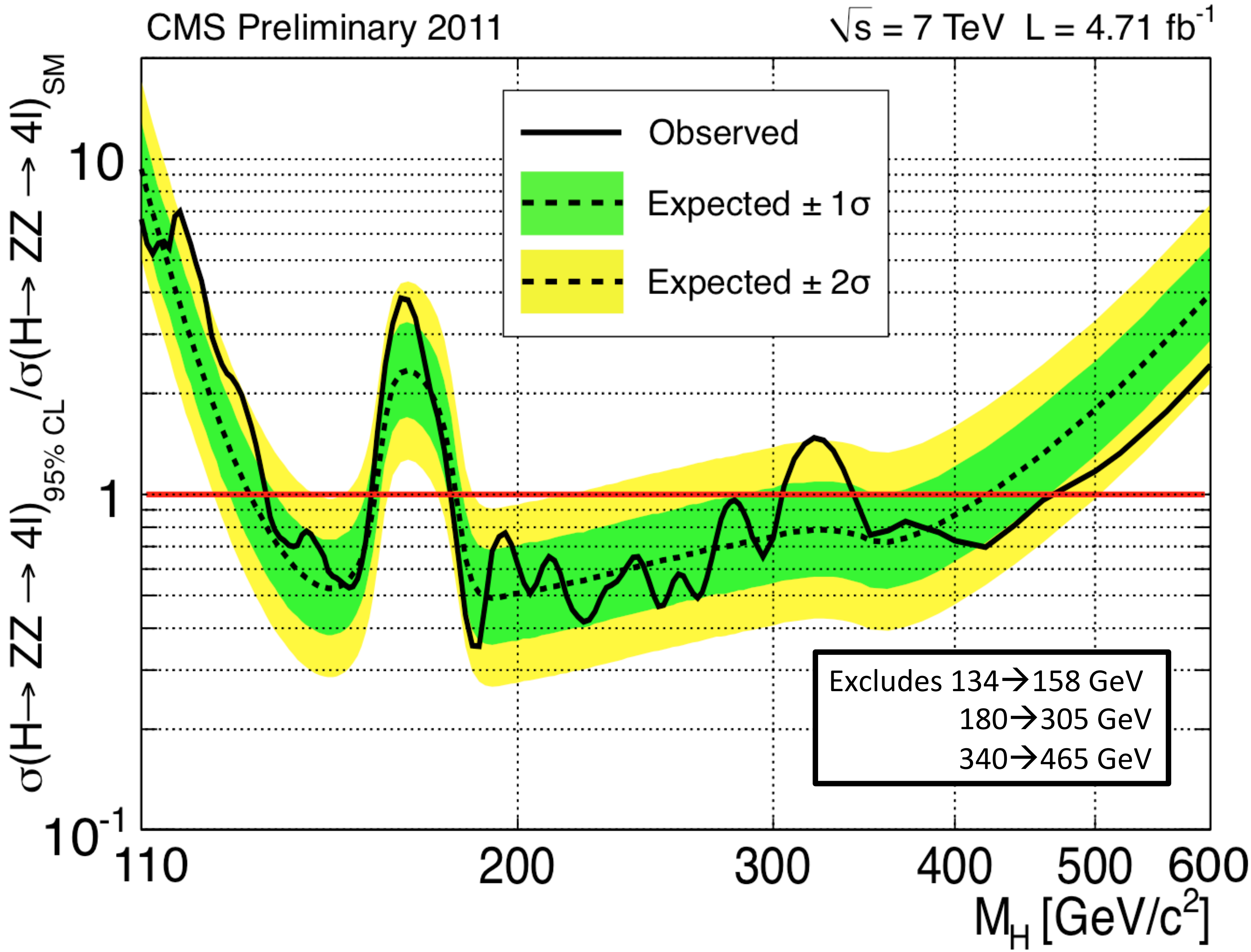
H→ZZ→4leptons

- A channel with good mass resolution
- With not a lot of background
- But not a lot of signal either



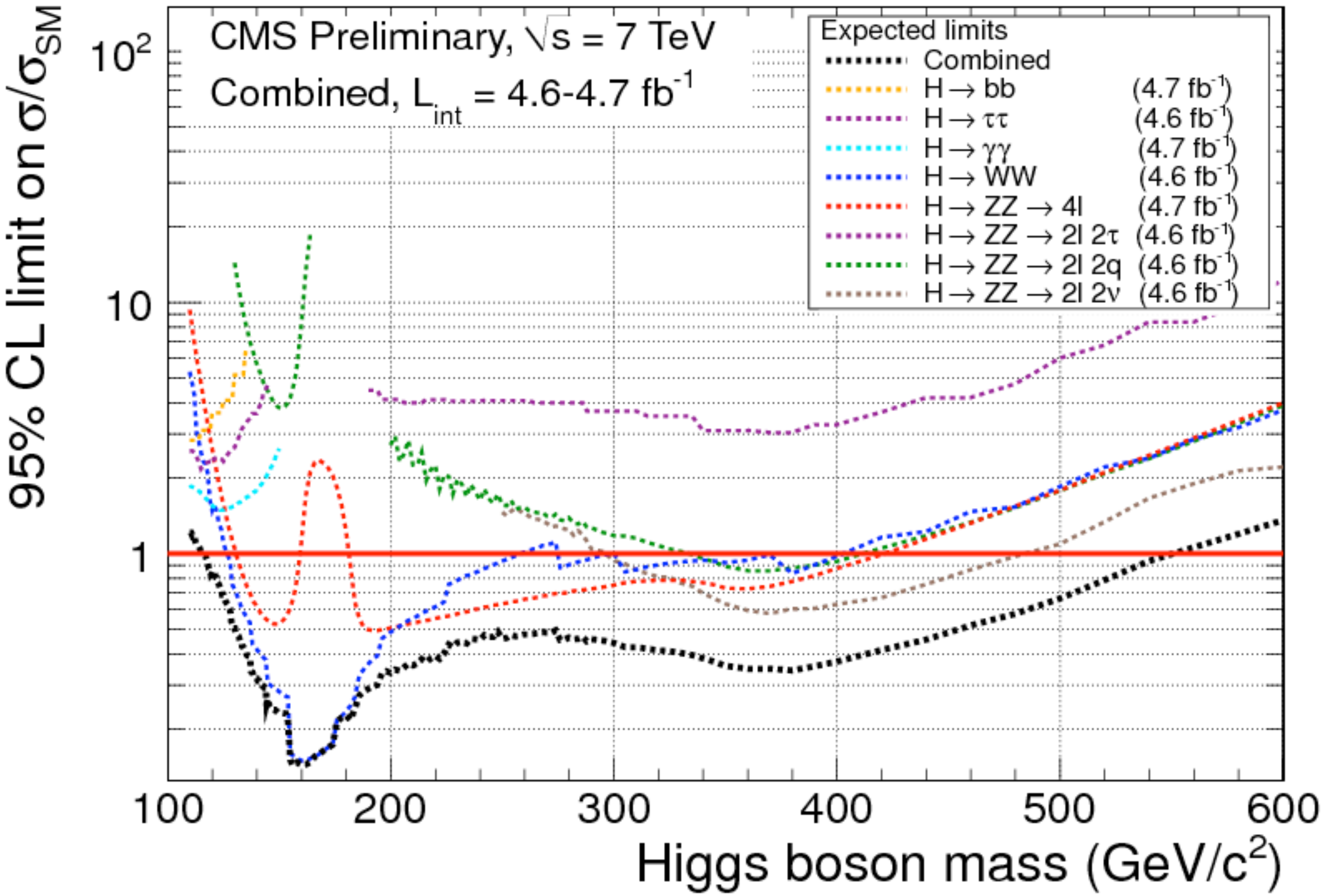
- 13 events observed with $M_{4l} < 160$ GeV.
- 9.5 ± 1.3 expected from BG
- Small cluster near 119 GeV

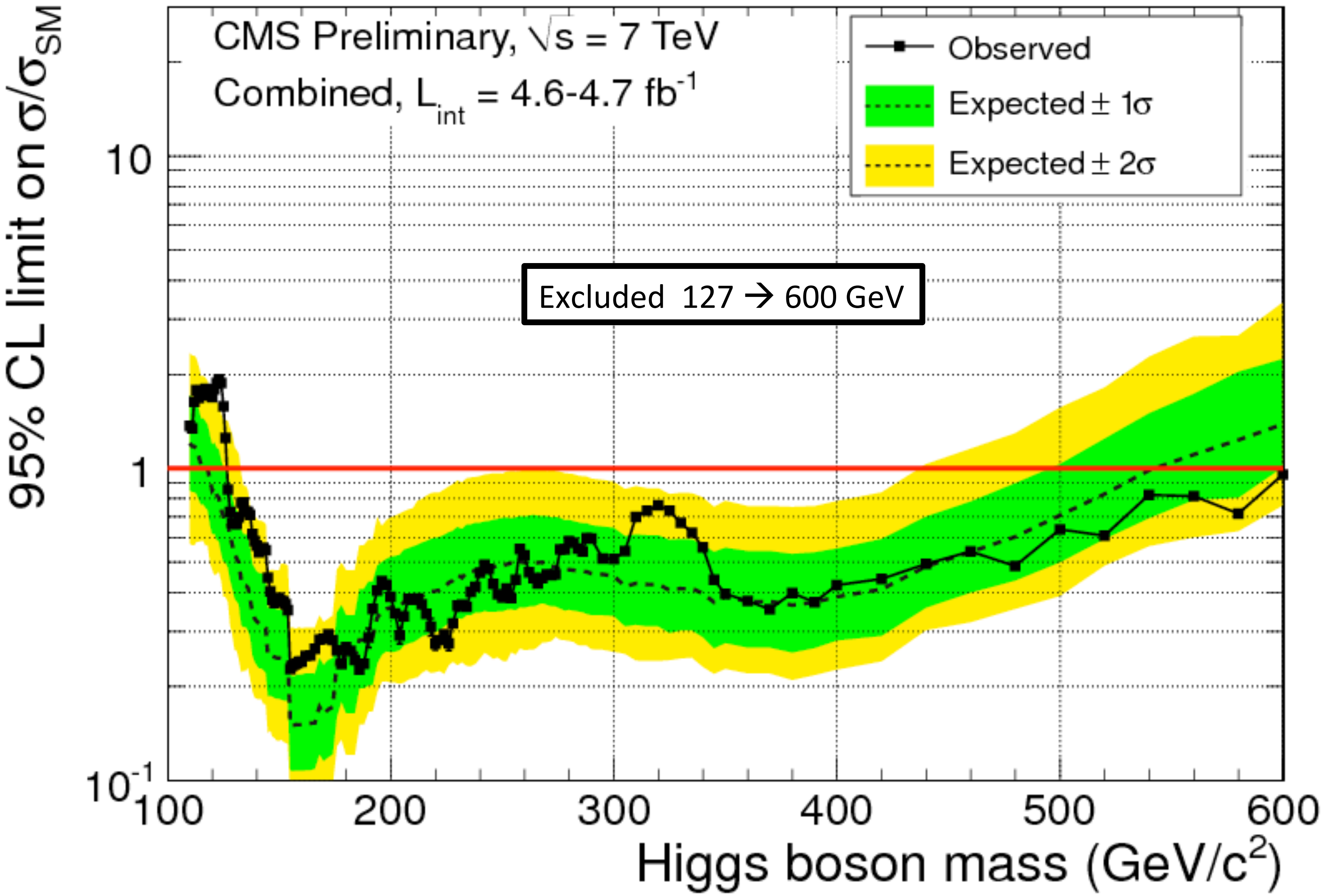

CMS Preliminary 2011
√s = 7 TeV L = 4.71 fb⁻¹
Observed
Expected ± 1σ
Expected ± 2σ
σ(H→ ZZ → 4l)95% CL/σ(H→ ZZ → 4l)SM
10
1
10⁻¹
110
120
140
160
180
MH [GeV/c²]
~ 2.5σ local excess near 119 GeV.
Only ~ 1σ with LEE


CMS Preliminary 2011
√s = 7 TeV L = 4.71 fb-1
Observed
Expected ± 1σ
Expected ± 2σ
Excludes 134→158 GeV
180→305 GeV
340→465 GeV
σ(H→ ZZ → 4l)95% CL/σ(H→ ZZ → 4l)SM
10
1
10-1
110
200
300
400
500
600
MH [GeV/c2]

Putting it all together

All the drops go in the bucket.....





CMS Preliminary, √s = 7 TeV
Combined, L_int = 4.6-4.7 fb^-1
Observed
Expected ± 1σ
Expected ± 2σ
Excluded 127 → 600 GeV
95% CL limit on σ/σ_SM
10
1
10^-1
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)

Summary of CMS results

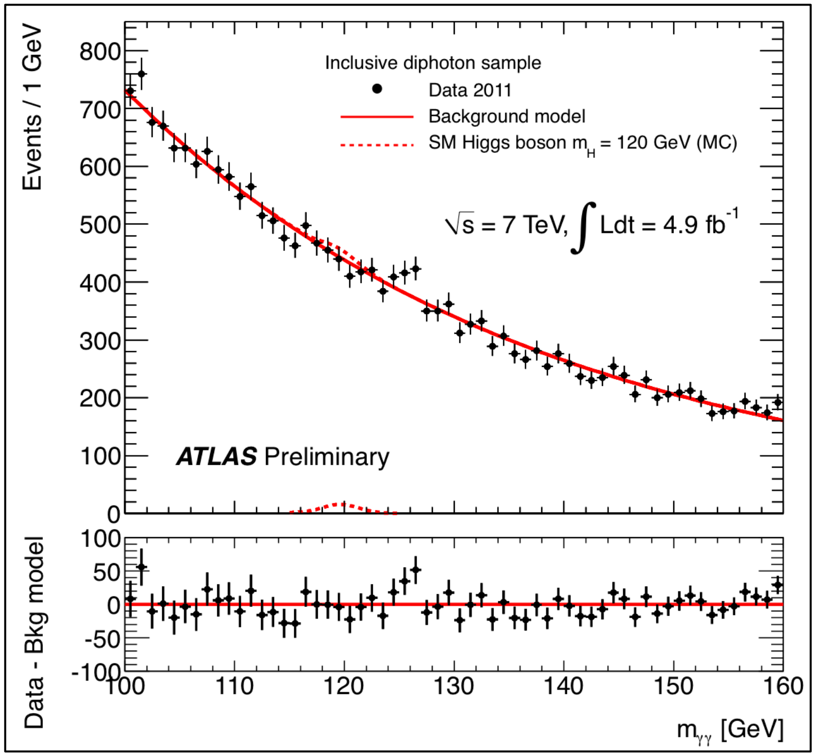
- We have excluded the existence of the Standard Model Higgs in the mass range 127→600 GeV at 95% Confidence Level.
- There is an excess of events in the low mass region
- To ascertain the origin of this excess, more data are required

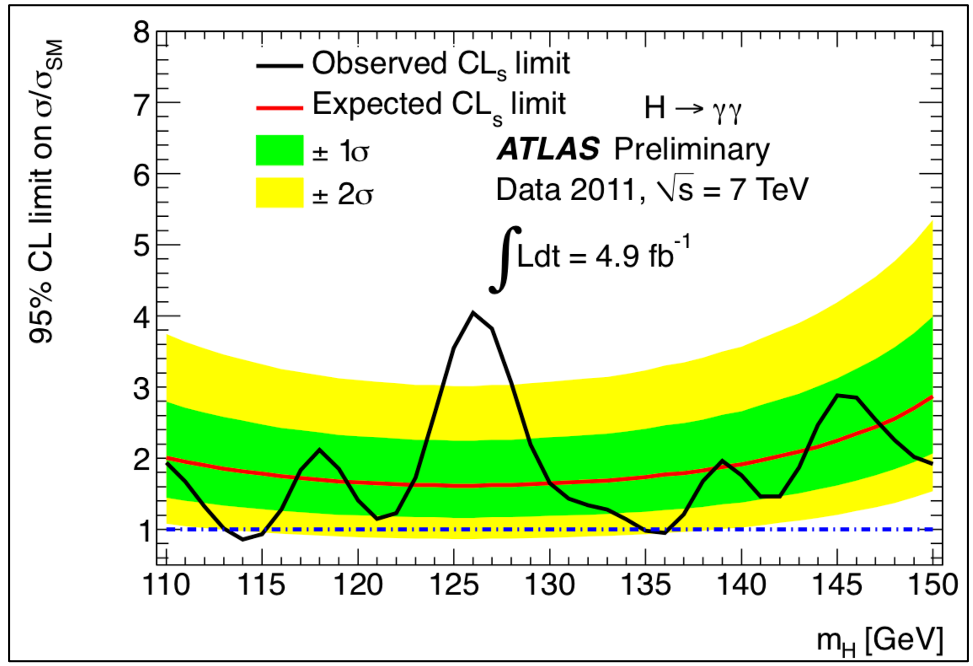
What about Atlas?

Atlas (as of Dec 13)

- They analyzed the full data set only in the $H \rightarrow \gamma\gamma$ and $H \rightarrow 4$leptons mode.
- For the other modes they used only between 20 and 40% of the data

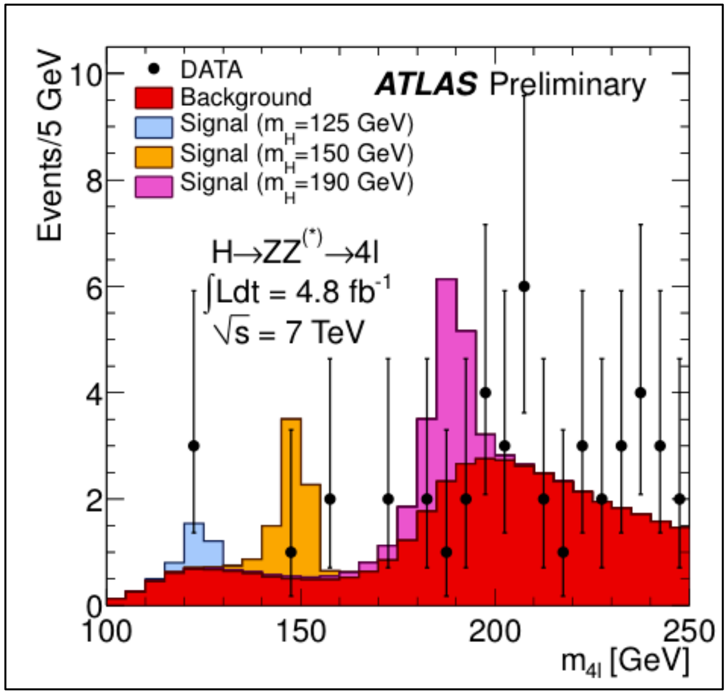
Atlas H→γγ

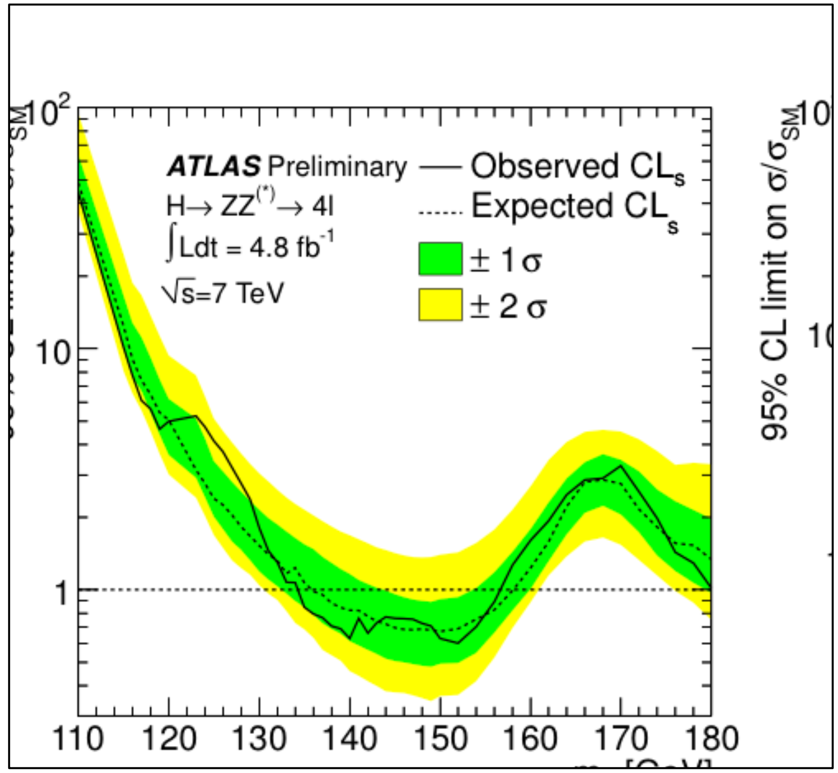




- A 2.8σ local excess at M_H ~ 126 GeV
- Reduced to ~ 1.5σ with LEE

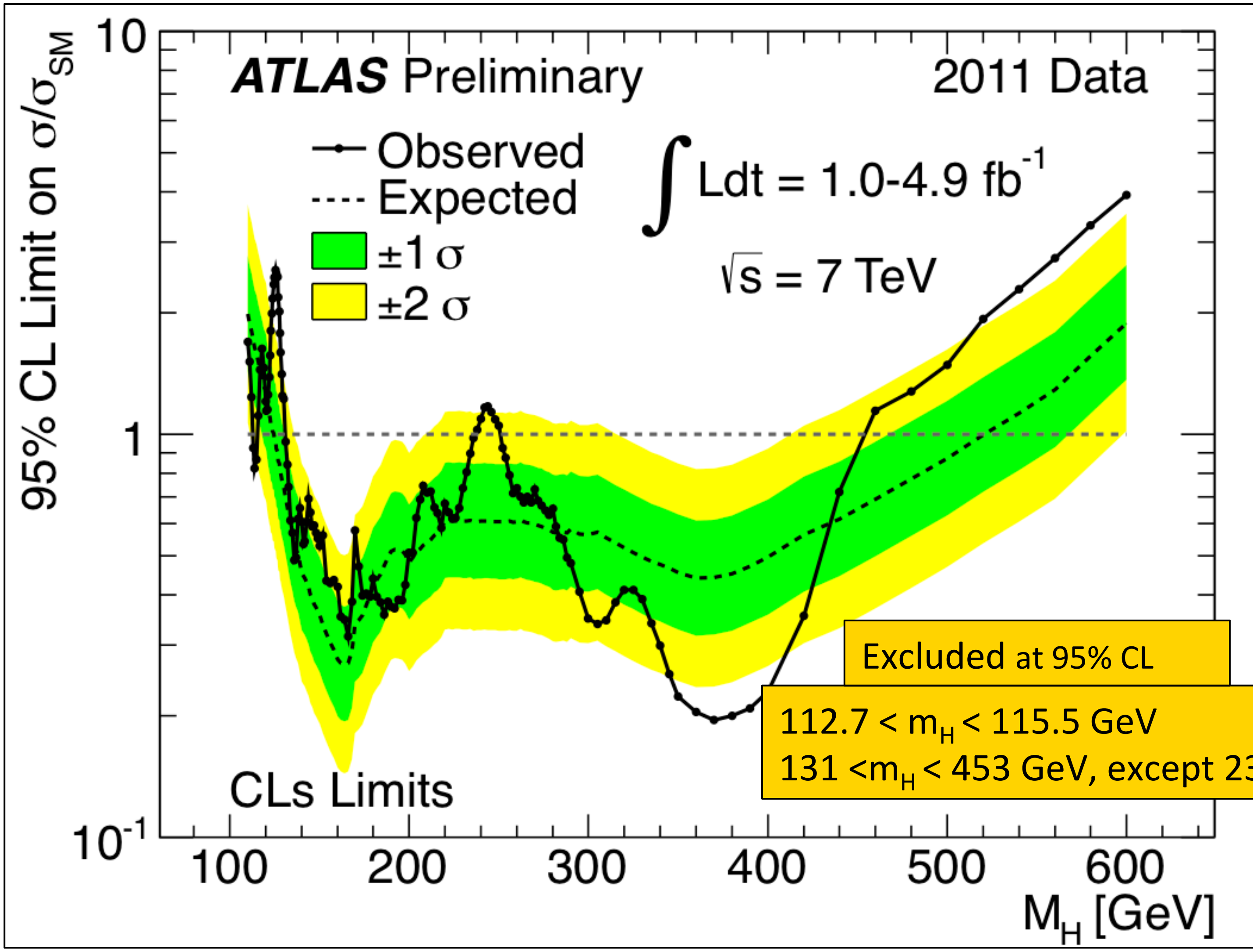
Atlas Z→4leptons





- A 2.1σ local excess at MH ~ 124 GeV
- Expected excess for SM Higgs: ~ 1.4σ

Atlas, combination



Excluded at 95% CL

$112.7 < m_H < 115.5$ GeV

$131 < m_H < 453$ GeV, except 237-251 GeV

Atlas statements about their excesses at low mass

Maximum deviation from background-only expectation observed for m_H~126 GeV

Local p_0-value: 1.9 10^{-4}
→ local significance of the excess: 3.6σ
~ 2.8σ H→ γγ, 2.1σ H→ 4l, 1.4σ H→ lνlν

Expected from SM Higgs: ~2.4σ local (~1.4σ per channel)

Global p_0-value : 0.6% →2.5σ LEE over 110-146 GeV
Global p_0-value : 1.4% →2.2σ LEE over 110-600 GeV

Conclusion: So, did we find the Higgs?

- **No**
- The great scientific result of the 2011 LHC data is that we now know that the possible SM Higgs mass range has been narrowed to ~ 115→127 GeV
- This is the range favored by global fits to precision electroweak measurements
- It is the toughest mass range experimentally
- There are some excesses in this range but they are not significant enough
- It may be fun to speculate about 125 GeV, but it is not very useful. We'll know more a year from now

UCSB and the Higgs Search at CMS

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

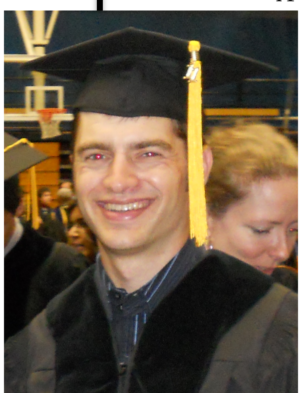
Doctor of Philosophy

in

Physics

by

Jacob Thomas Ribnik



Committee in Charge:

Professor Claudio Campagnari, Chair

Professor Jeffrey D. Richman

Professor Mark Srednicki

June 2011

The core of the CMS H→WW “A team”
“α team” not shown

Measurement of σ(pp→WW) with 2010 CMS data, laying the foundation for the H→WW search

The End

Search for the Standard Model Higgs Boson at LEP

ALEPH, DELPHI, L3 and OPAL Collaborations

The LEP Working Group for Higgs Boson Searches

Abstract

The four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, have collected 2461 pb^{-1} of e^+e^- collision data at centre-of-mass energies between 189 and 209 GeV, of which 536 pb^{-1} have energies above 206 GeV. The data have been used to search for the Standard Model Higgs boson. The search results of the four collaborations are combined and examined for their consistency with two hypotheses: (a) the Standard Model background hypothesis and (b) the signal plus background hypothesis. The confidence levels for the two hypotheses have been computed in a likelihood analysis as a function of the hypothetical Higgs boson mass. The evolution of the likelihood as a function of the test-mass shows a slight preference for the signal plus background hypothesis for a Higgs boson mass in the vicinity of 116 GeV, where the confidence level for the signal plus background hypothesis is 37% while that for the background hypothesis is about 8%. A lower bound of 114.4 GeV has been established, at the 95% confidence level, for the mass of the Standard Model Higgs boson.

The results presented in this note are preliminary

Contributed paper for ICHEP'02 (Amsterdam, July 2002)

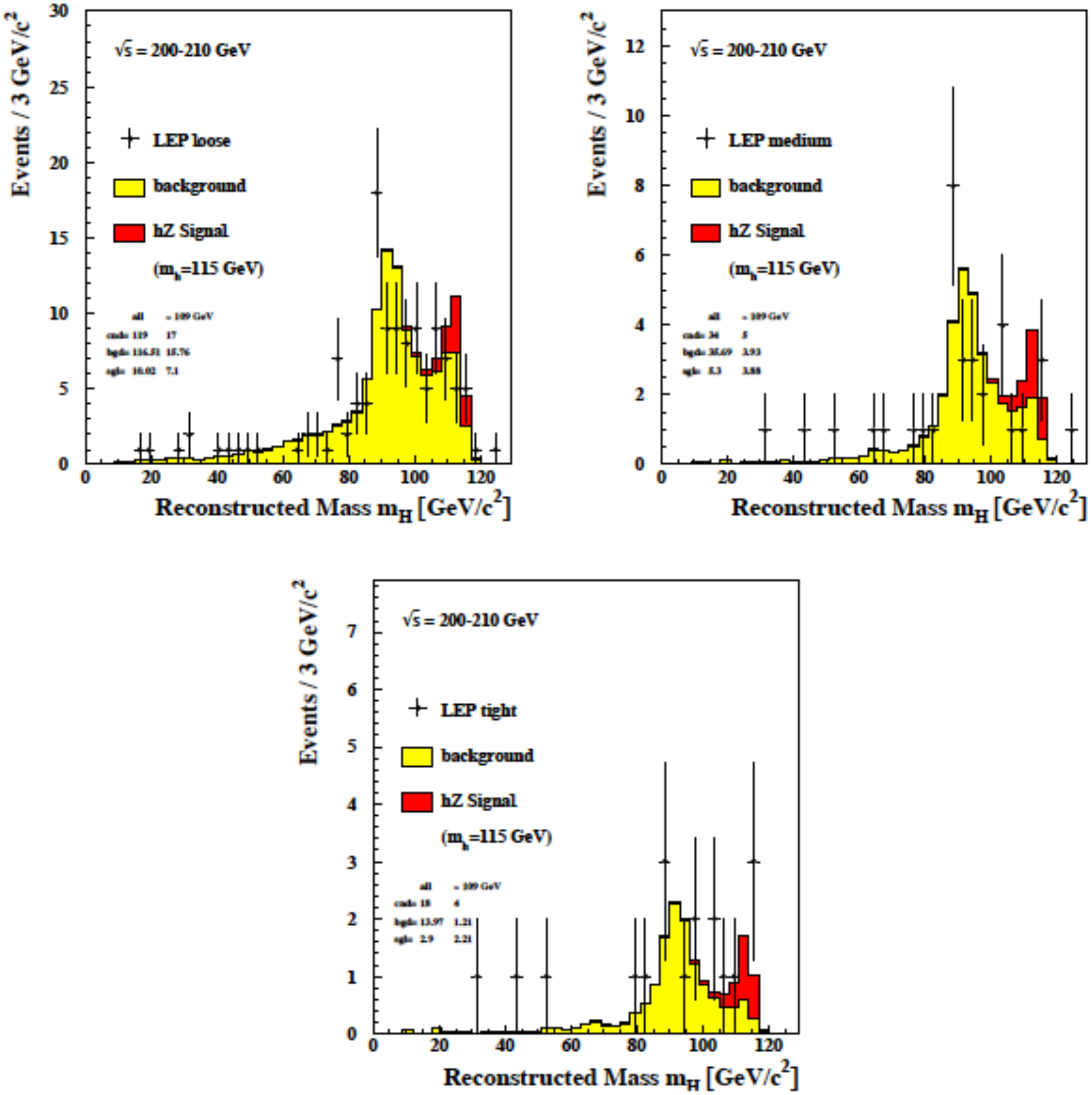


Figure 6: Distributions of the reconstructed Higgs mass, m_{H}^{rec}, obtained from three special, non-biasing, selections with increasing signal purity. In the loose/medium/tight selections the cuts are adjusted in such a way as to obtain, for a Higgs boson of 115 GeV mass, approximately 0.5/1/2 times as many expected signal as background events in the region $m_{\mathrm{H}}^{rec} > 109$ GeV.

Higgs Decay Feynman Diagrams

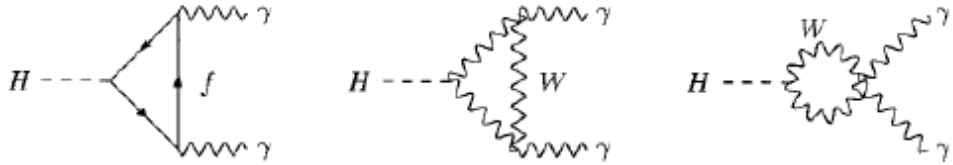


Figure 11: Typical diagrams contributing to $H \to \gamma\gamma$ at lowest order.

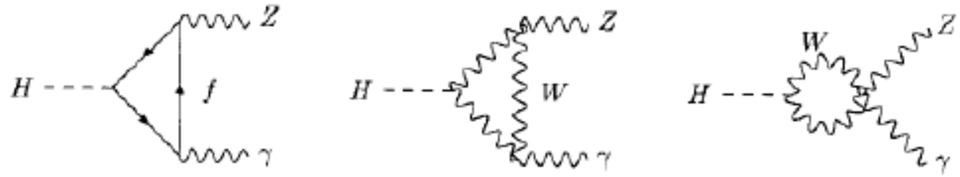


Figure 14: Typical diagrams contributing to $H \to Z\gamma$ at lowest order.

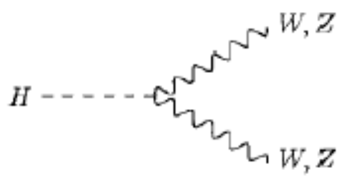


Figure 16: Diagram contributing to $H \to VV$ $[V = W, Z]$.

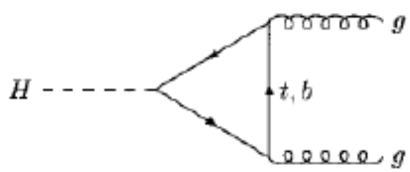
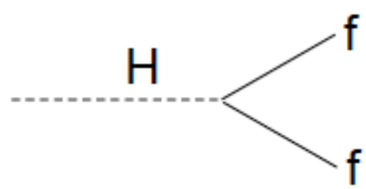
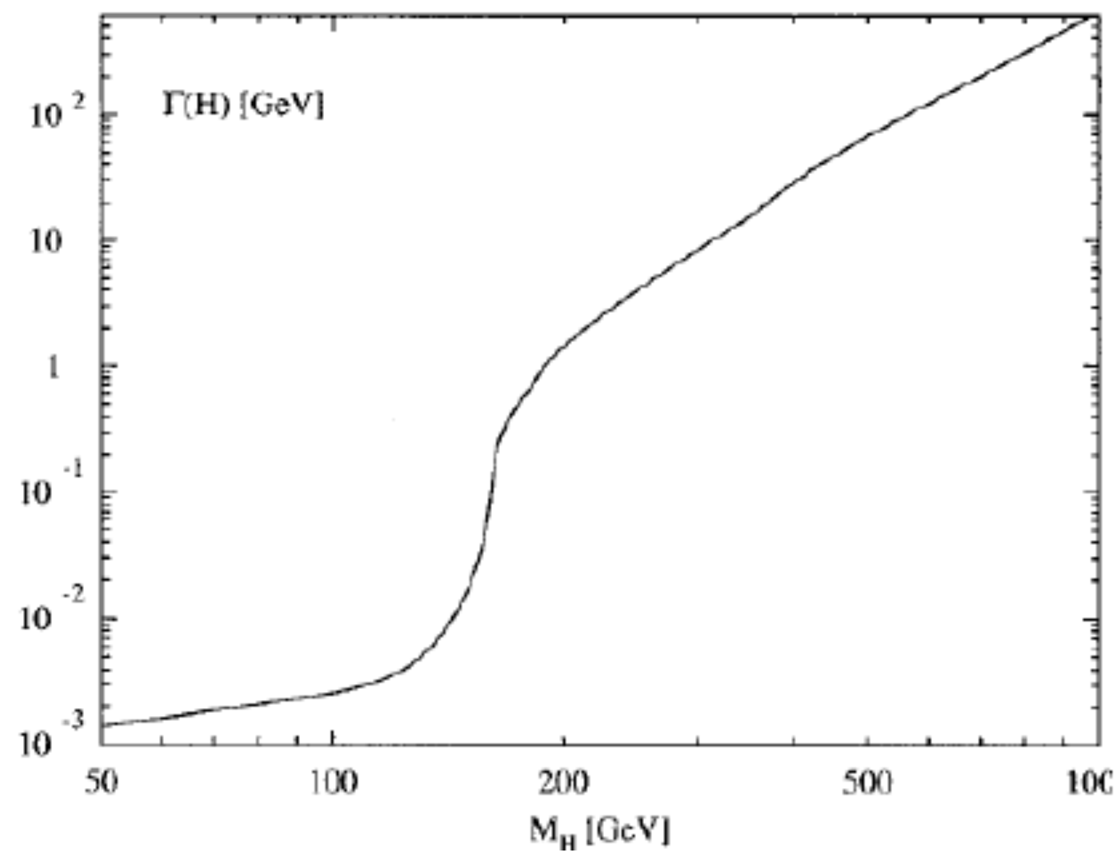


Figure 5: Diagrams contributing to $H \to gg$ at lowest order.

and of course H → ff:

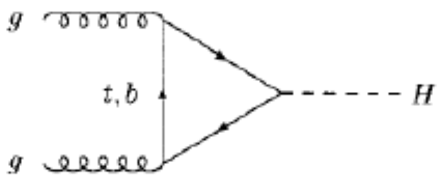


From Spira, Fortsch.Phys.46:203-284,1998 or hep-ph/9705337



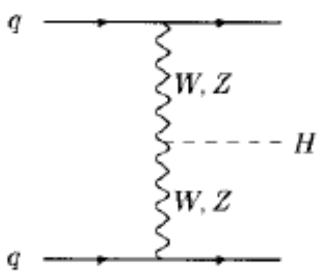
1

Higgs Production at LHC



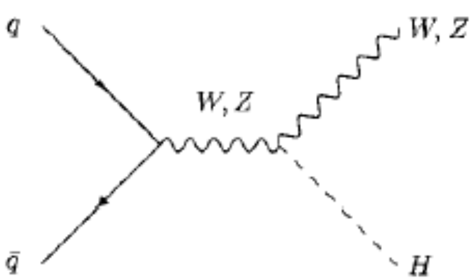
gluon fusion

Figure 18: Diagrams contributing to $gg \to H$ at lowest order.



vector boson fusion

Figure 26: Diagram contributing to $qq \to qqV^*V^* \to qqH$ at lowest order.



WH, ZH (Higgs-strahlung)

Figure 28: Diagram contributing to $q\bar{q} \to V^* \to VH$ at lowest order.

Higgs production at LHC

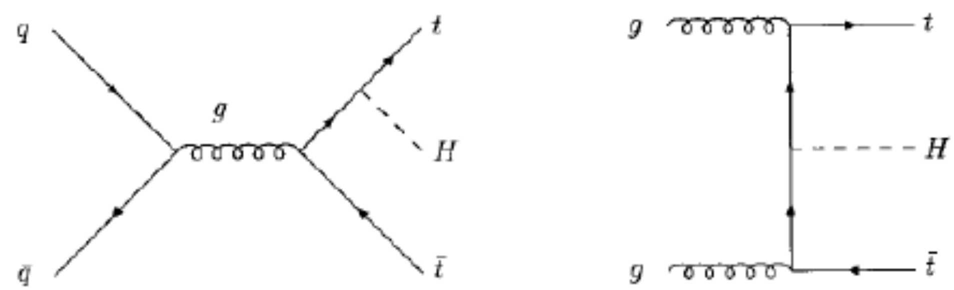
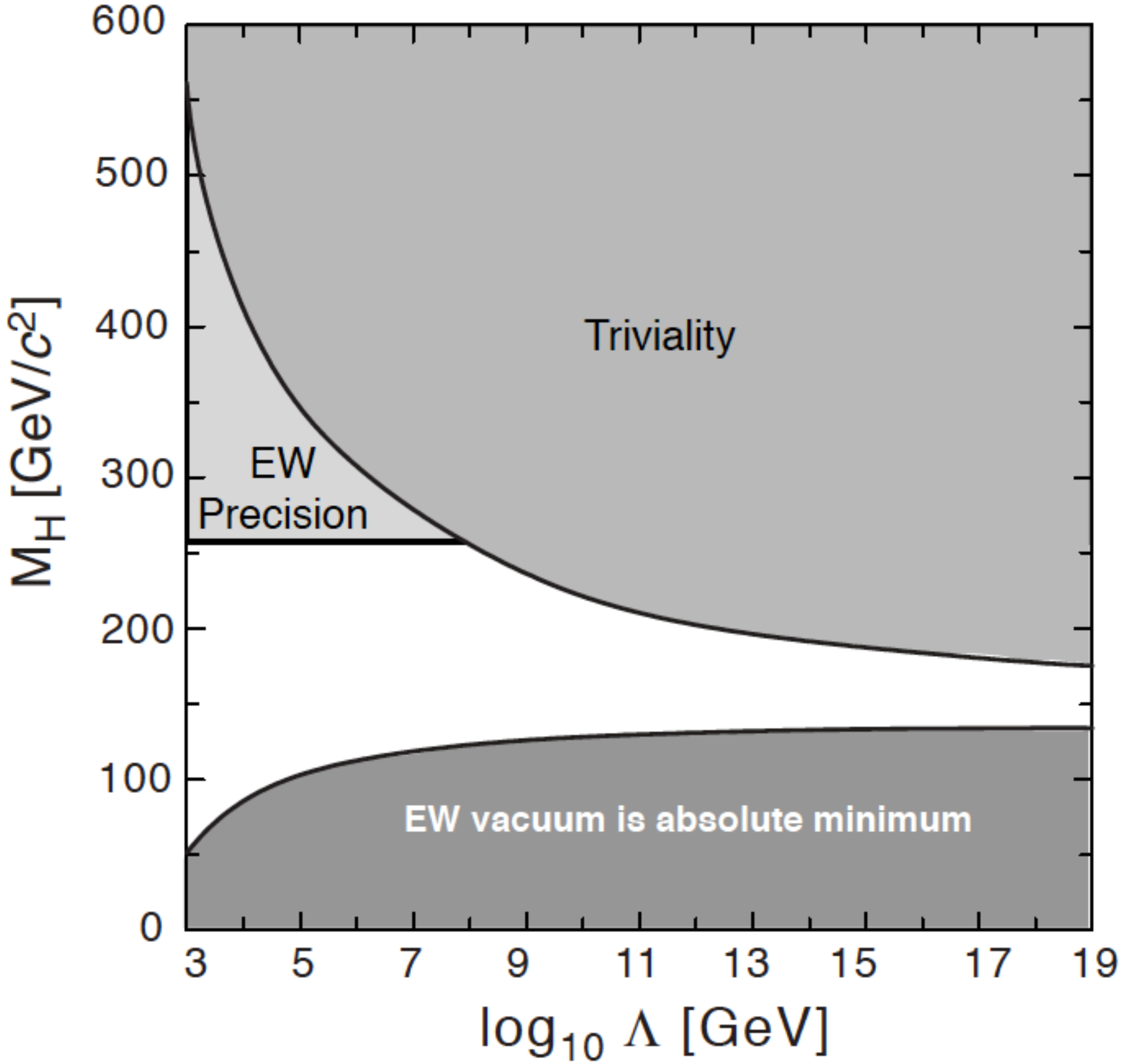
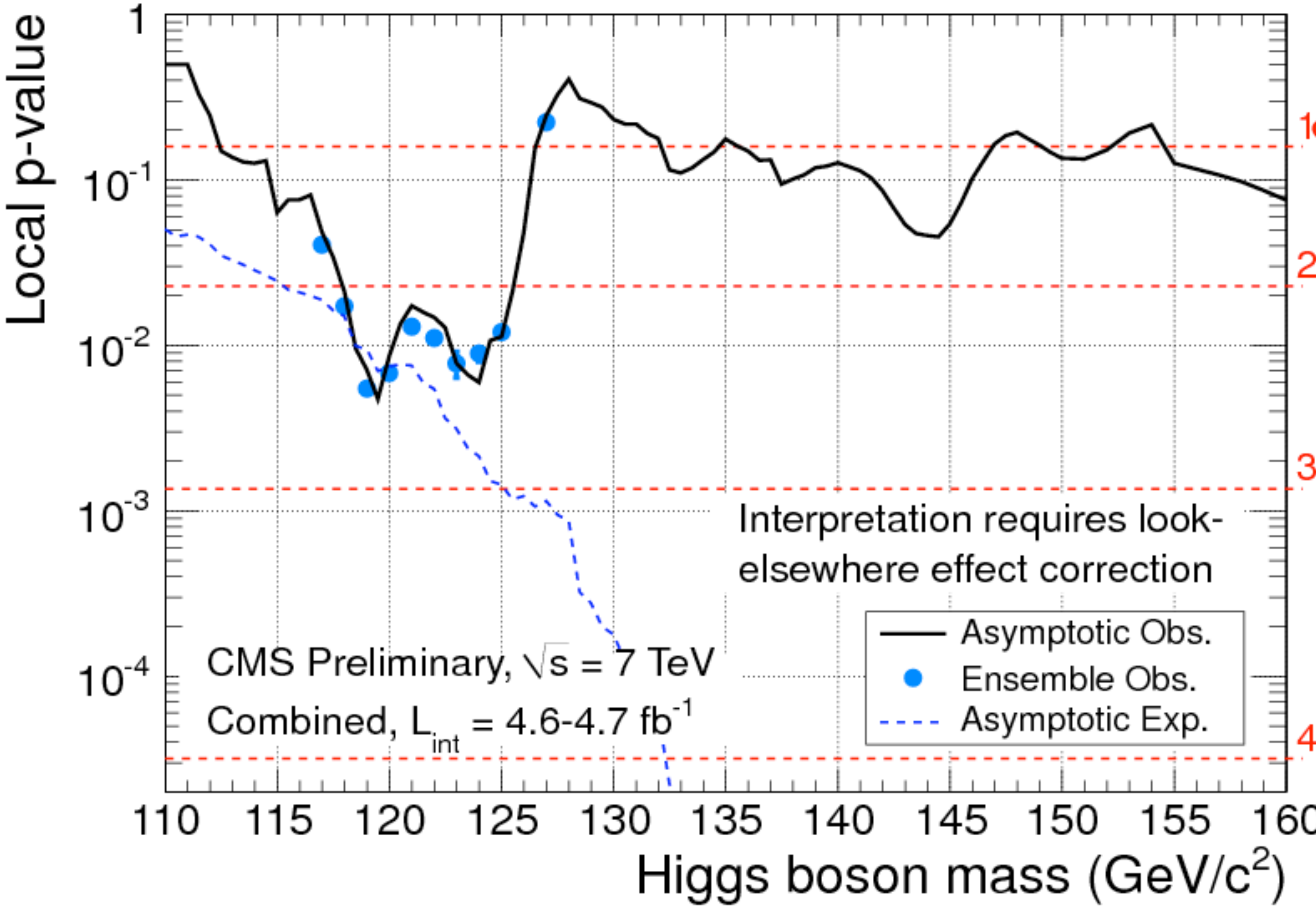


Figure 30: Typical diagrams contributing to $q\bar{q}/gg \to Ht\bar{t}$ at lowest order.

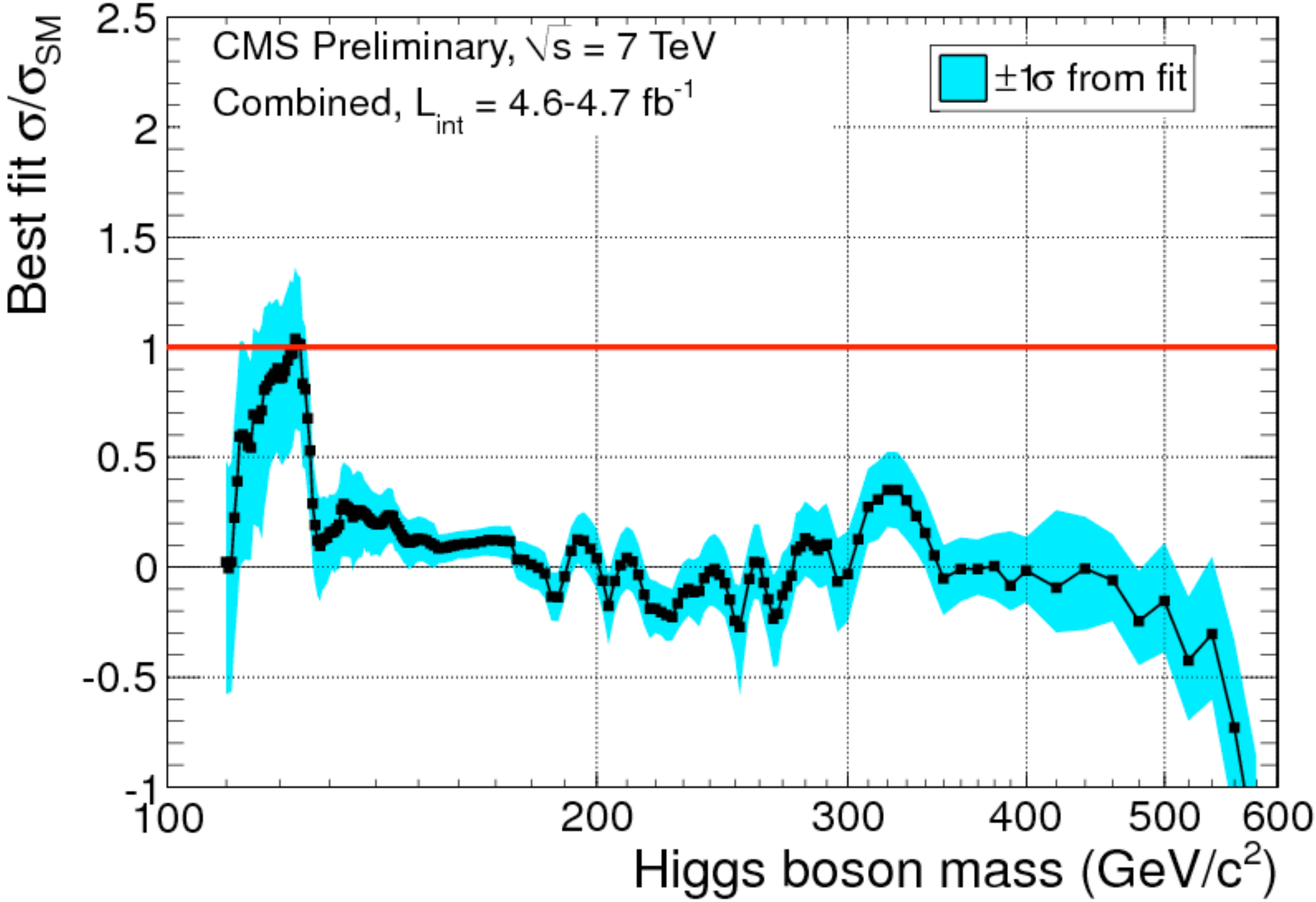
tt-Higgs (also bbH)

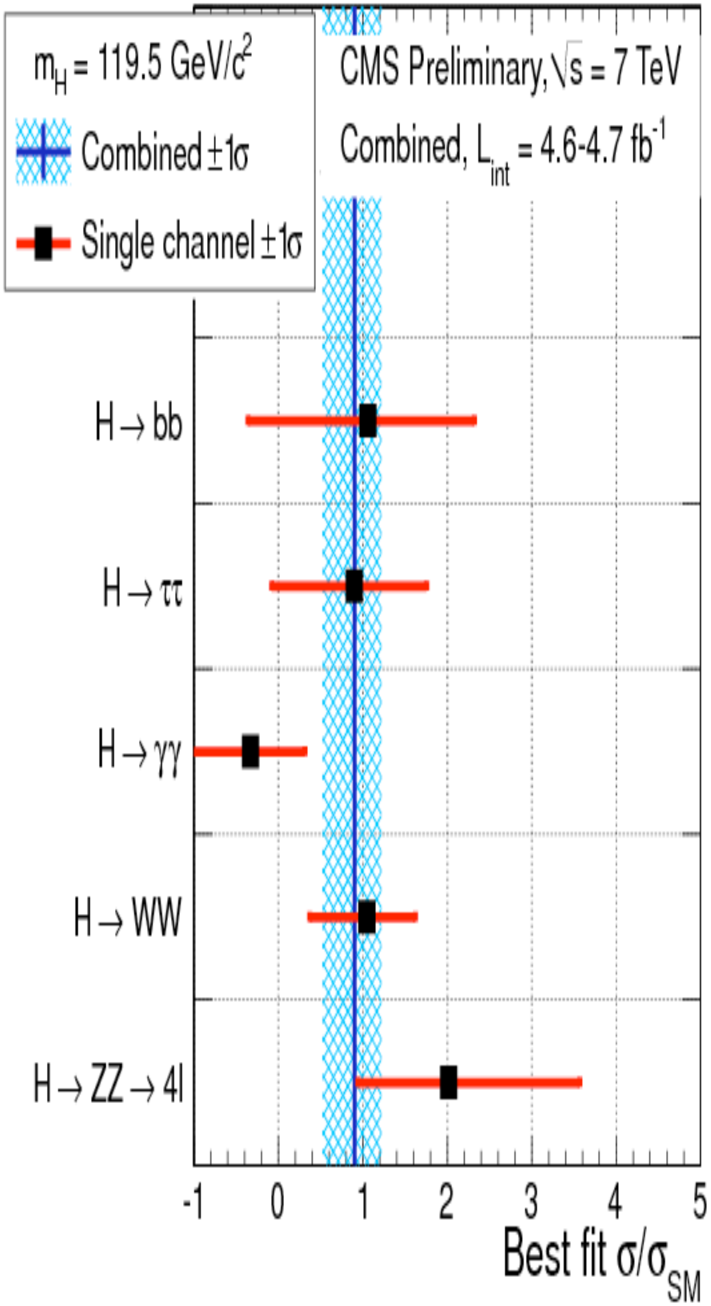


600
500
400
300
200
100
0
3
5
7
9
11
13
15
17
19
M_H [GeV/c^2]
$\log_{10} \Lambda$ [GeV]
Triviality
EW
Precision
EW vacuum is absolute minimum

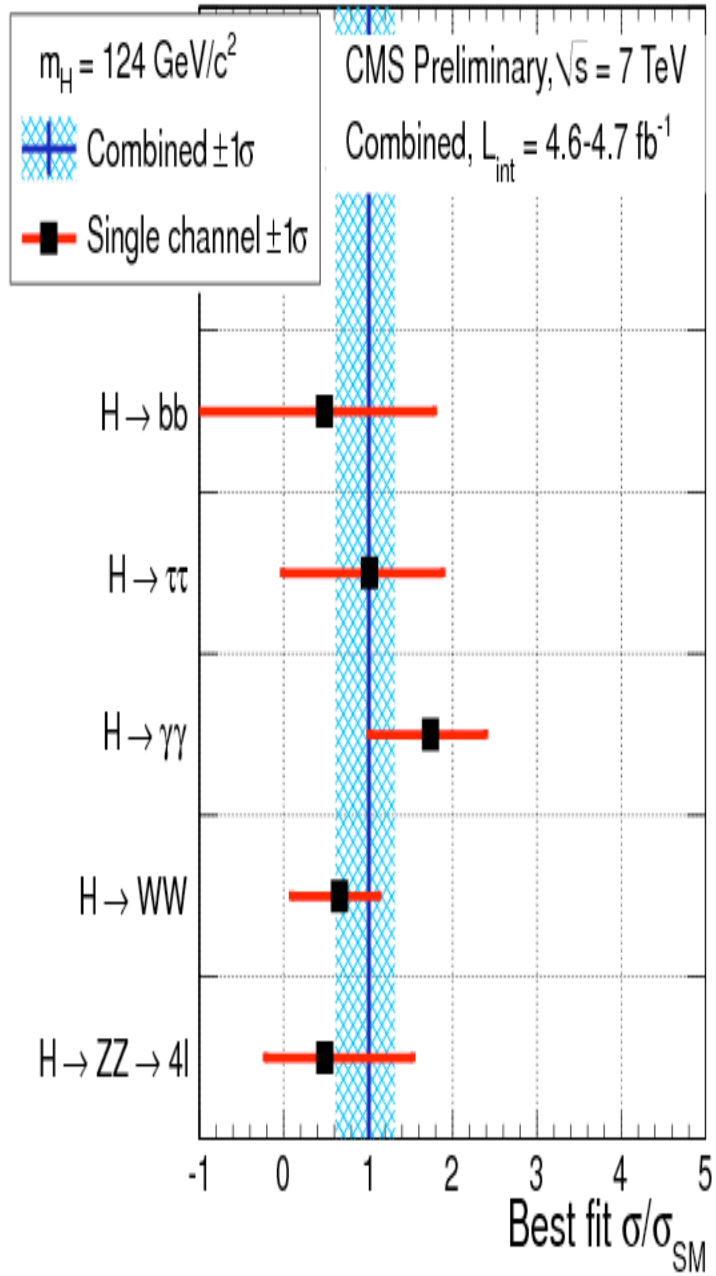


Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1σ
2σ
3σ
4σ
Interpretation requires look-elsewhere effect correction
CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
Asymptotic Obs.
Ensemble Obs.
Asymptotic Exp.
110 115 120 125 130 135 140 145 150 155 160
Higgs boson mass (GeV/c^2)

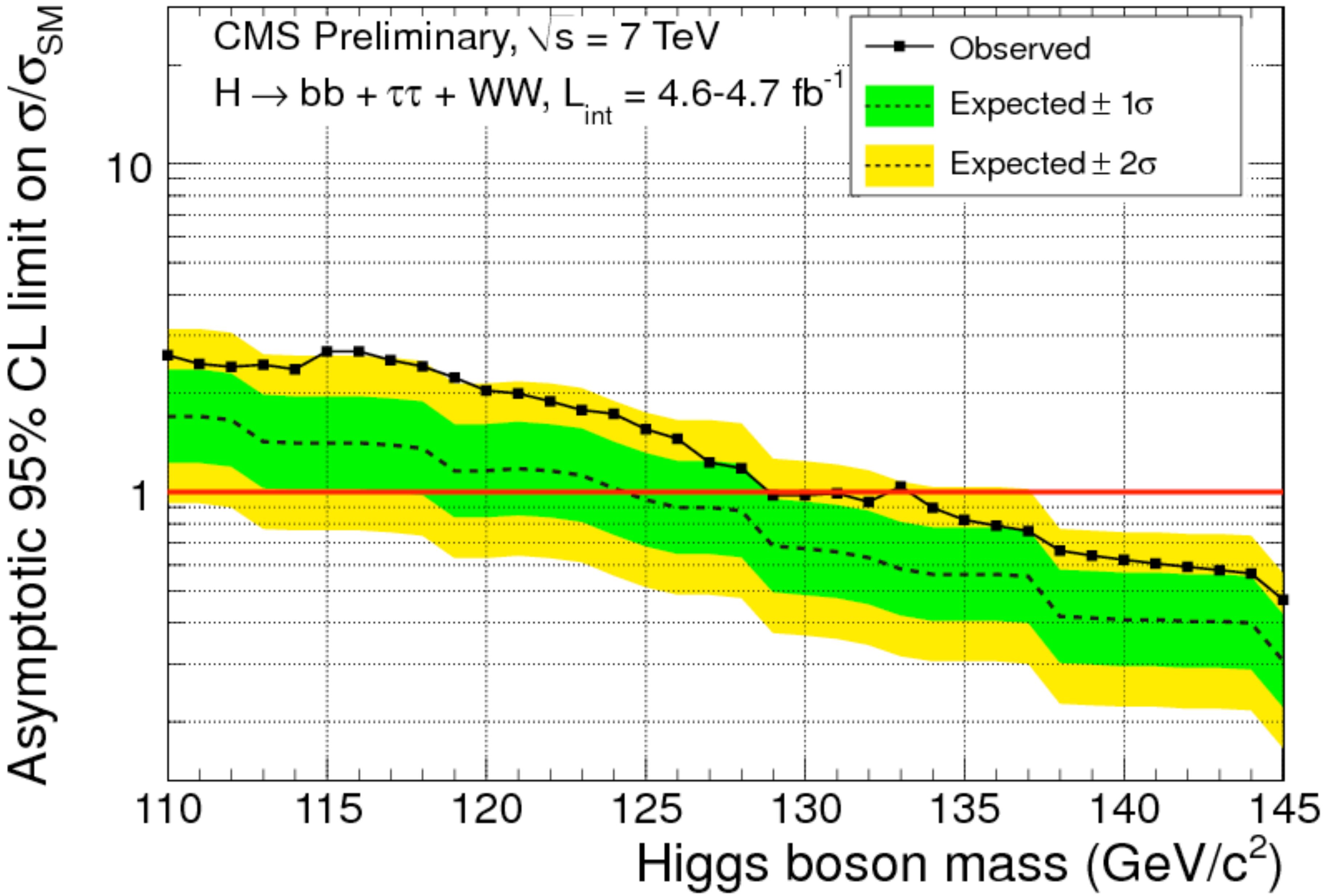

CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
±1σ from fit
Best fit σ/σ_{SM}
Higgs boson mass (GeV/c^2)
2.5
2
1.5
1
0.5
0
-0.5
-1
100
200
300
400
500
600



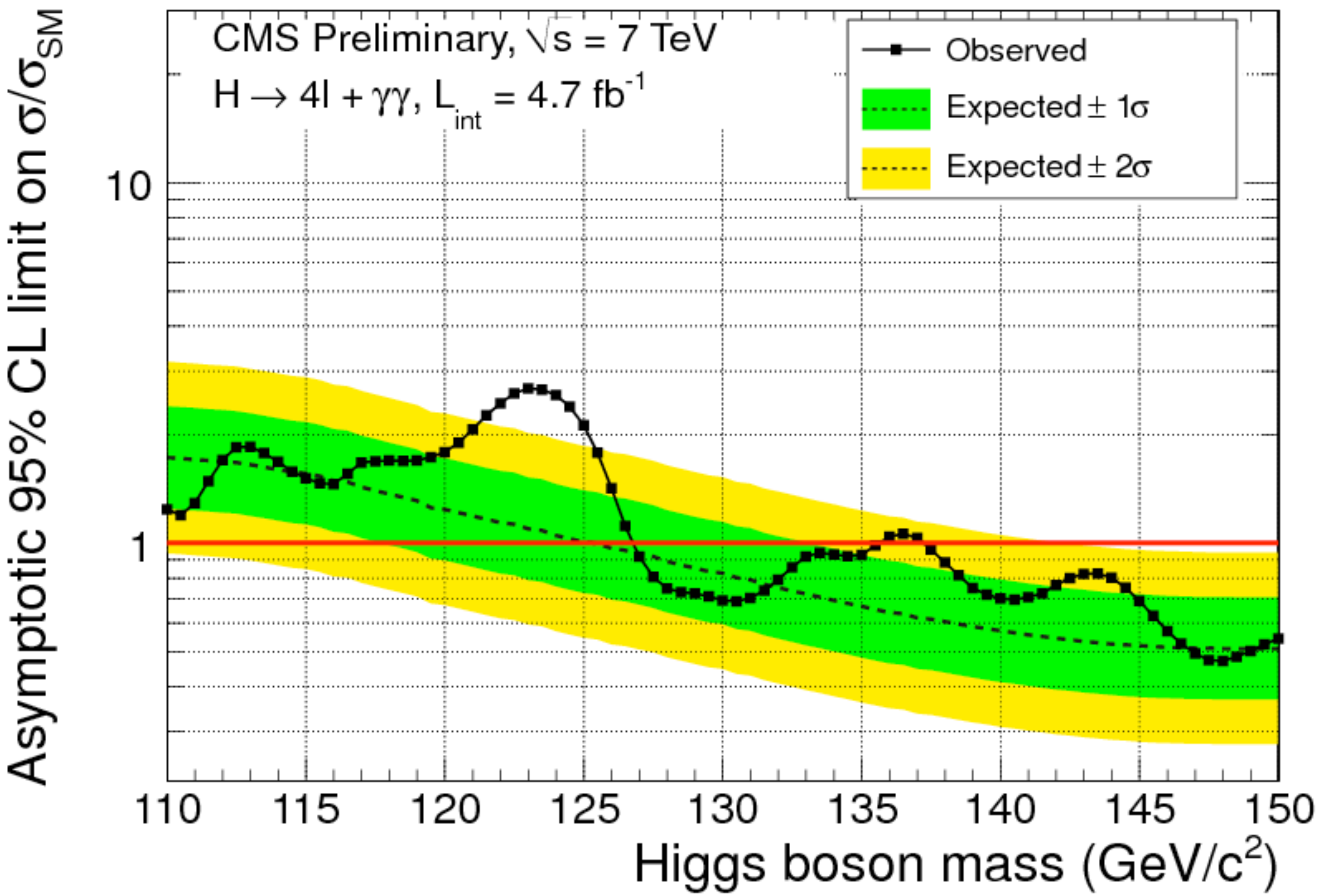
m_H = 119.5 GeV/c^2
Combined ±1σ
Single channel ±1σ
CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
H→bb
H→ττ
H→γγ
H→WW
H→ZZ→4l
-1
0
1
2
3
4
5
Best fit σ/σ_{SM}

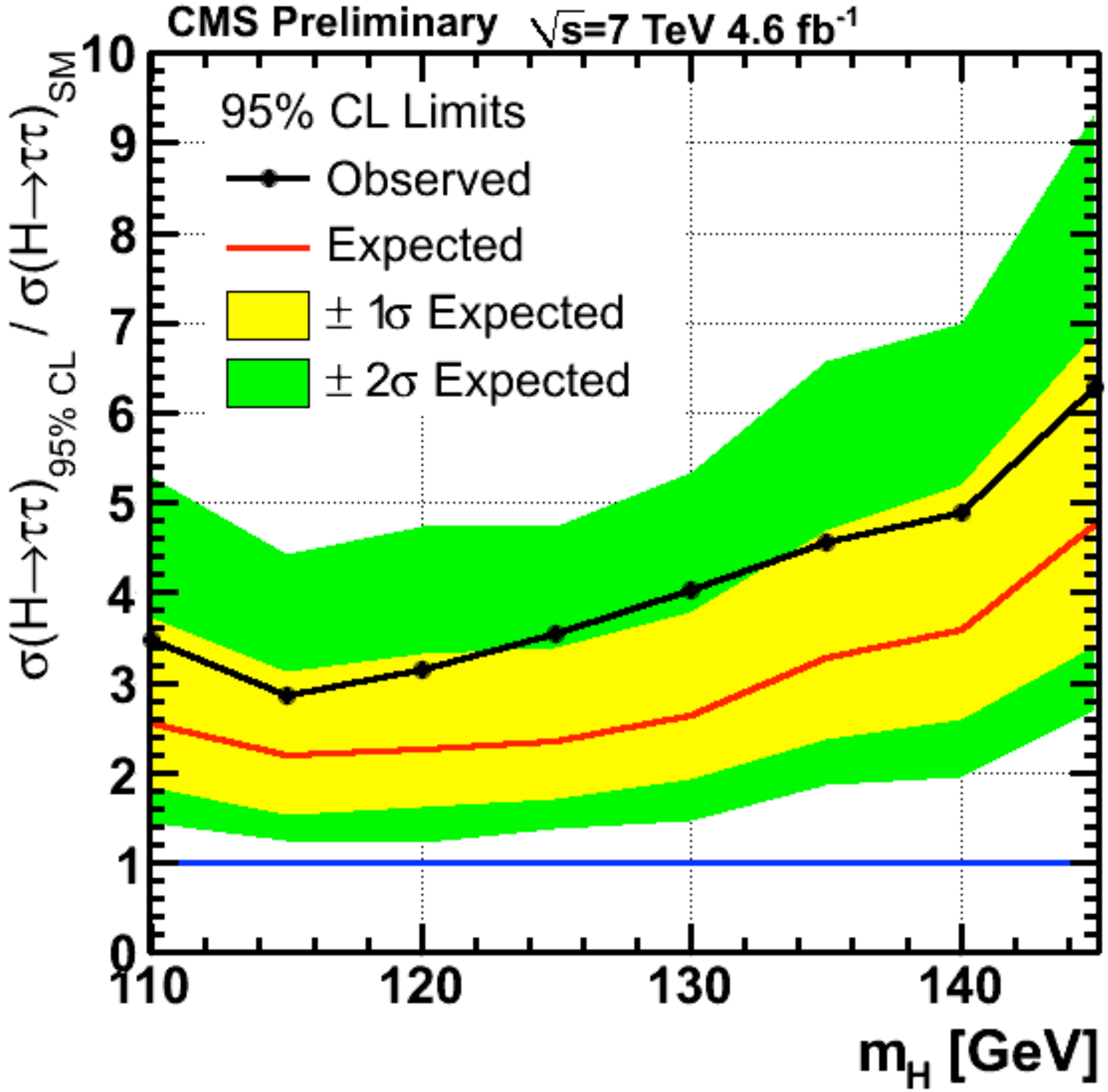


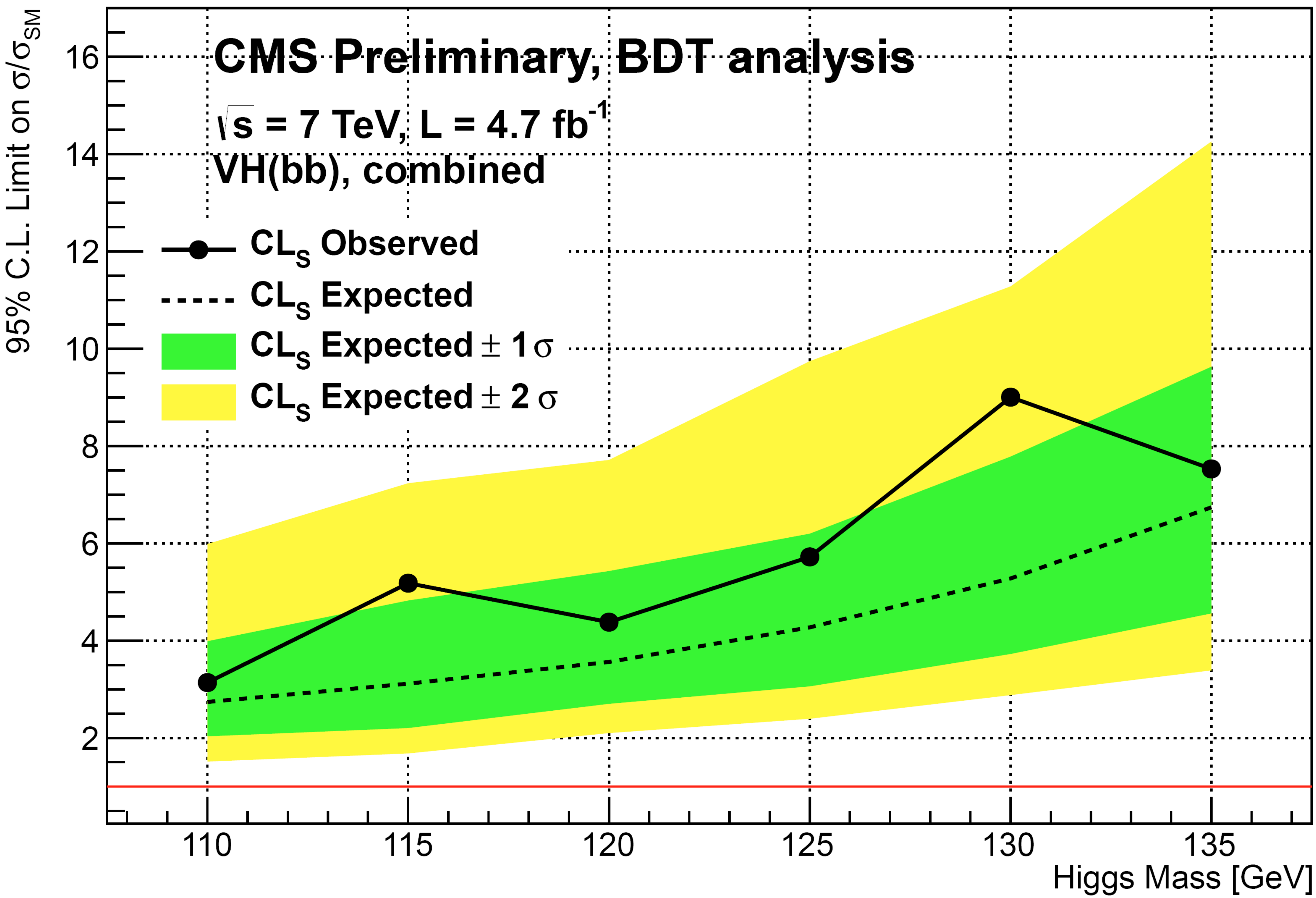
m_H = 124 GeV/c^2
Combined ±1σ
Single channel ±1σ
CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
H→bb
H→ττ
H→γγ
H→WW
H→ZZ→4l
-1
0
1
2
3
4
5
Best fit σ/σ_{SM}



CMS Preliminary, $\sqrt{s}$ = 7 TeV
$H \rightarrow bb + \tau\tau + WW$, L_{int} = 4.6-4.7 fb^{-1}
Observed
Expected ± 1σ
Expected ± 2σ
Asymptotic 95% CL limit on σ/σ_{SM}
10
1
110
115
120
125
130
135
140
145
Higgs boson mass (GeV/c^2)


CMS Preliminary, √s = 7 TeV
H → 4l + γγ, L_int = 4.7 fb^-1
Observed
Expected ± 1σ
Expected ± 2σ
Asymptotic 95% CL limit on σ/σ_SM
10
1
110
115
120
125
130
135
140
145
150
Higgs boson mass (GeV/c^2)


CMS Preliminary $\sqrt{s}$=7 TeV 4.6 fb^{-1}
95% CL Limits
Observed
Expected
± 1σ Expected
± 2σ Expected
$\sigma(H\rightarrow\tau\tau)_{95\% CL} / \sigma(H\rightarrow\tau\tau)_{SM}$
m_H [GeV]
0
1
2
3
4
5
6
7
8
9
10
110
120
130
140


CMS Preliminary, BDT analysis
√s = 7 TeV, L = 4.7 fb-1
VH(bb), combined
CLs Observed
CLs Expected
CLs Expected ± 1 σ
CLs Expected ± 2 σ
95% C.L. Limit on σ/σSM
Higgs Mass [GeV]
2
4
6
8
10
12
14
16
110
115
120
125
130
135