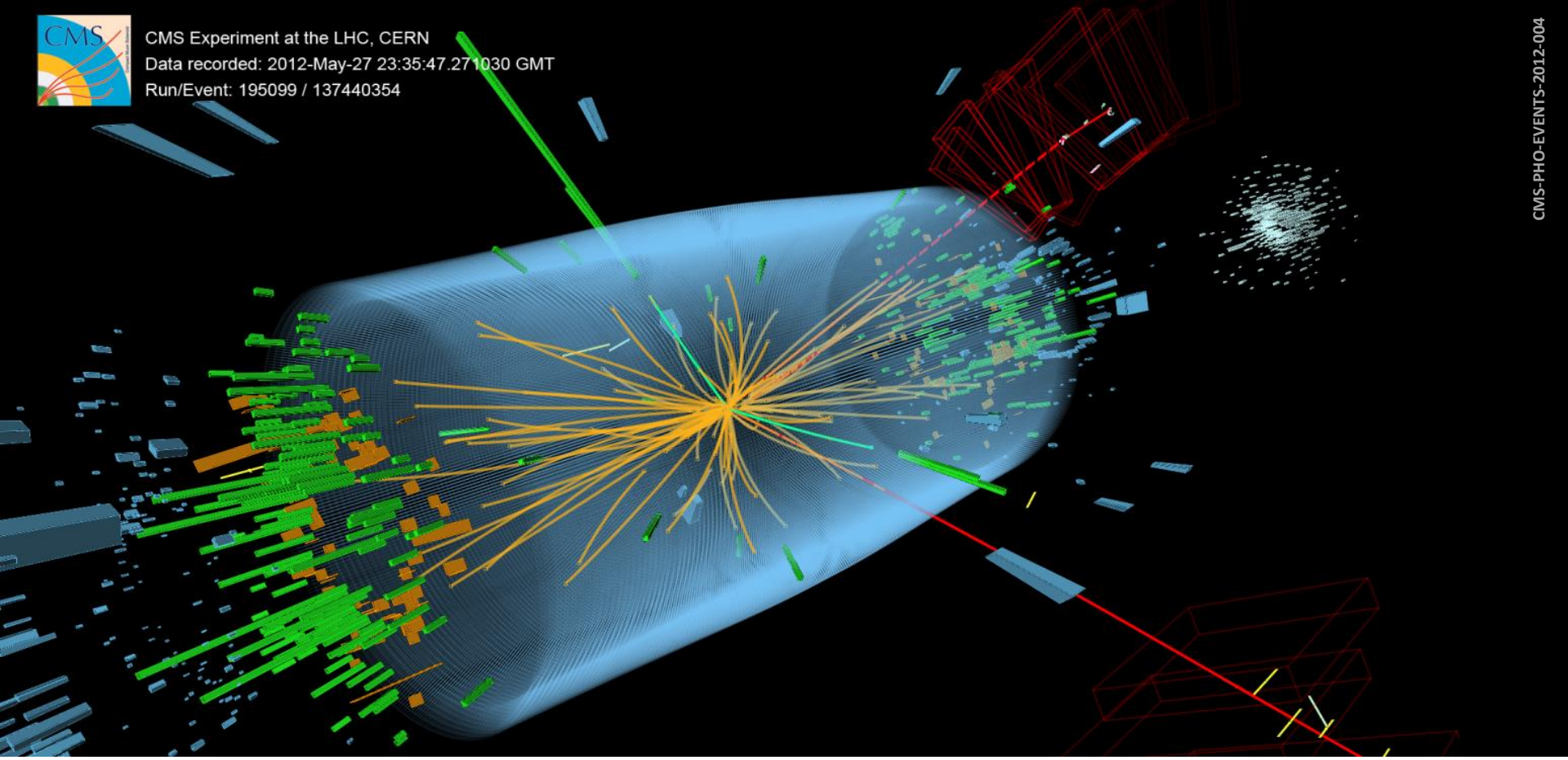


The observation of H→ZZ→4l in CMS

Nicola Amapane (Università di Torino and INFN, Torino, Italy)

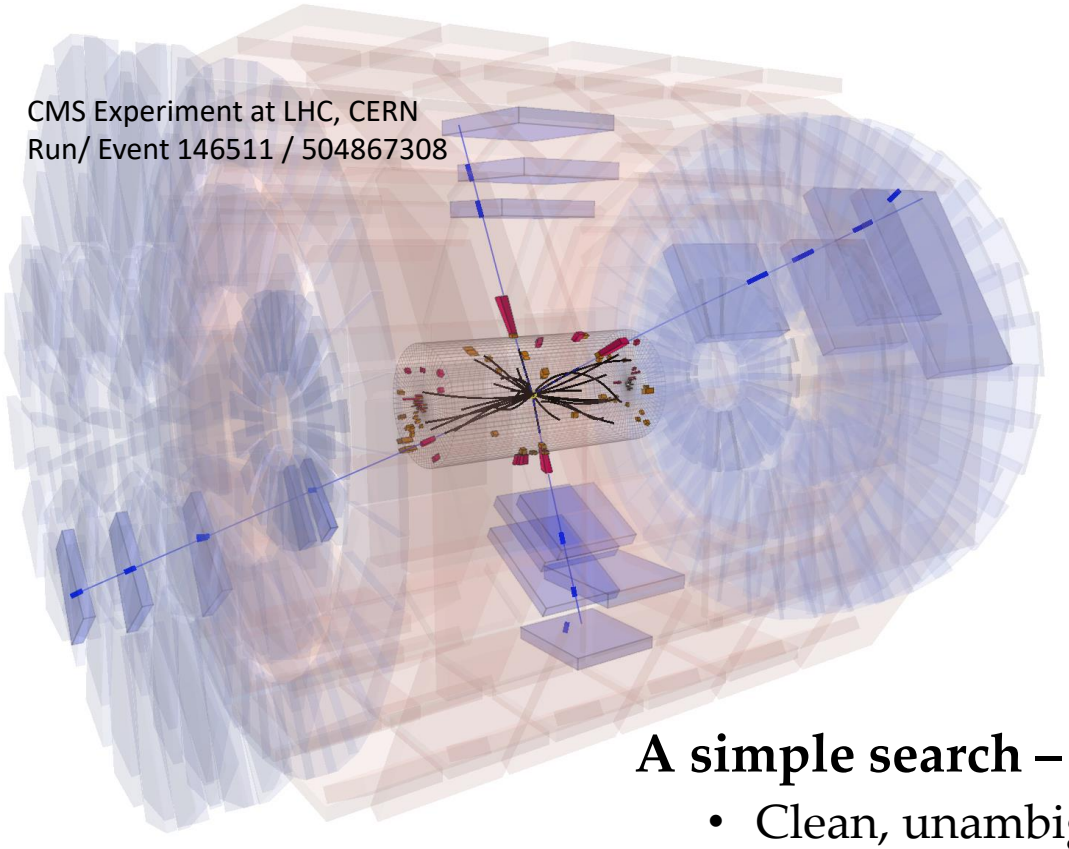
HiggsDiscovery@10

Birmingham, June 30, 2022

Istituto Nazionale di Fisica Nucleare

A Beautiful Detector to Start With

The H→ZZ→4l channel

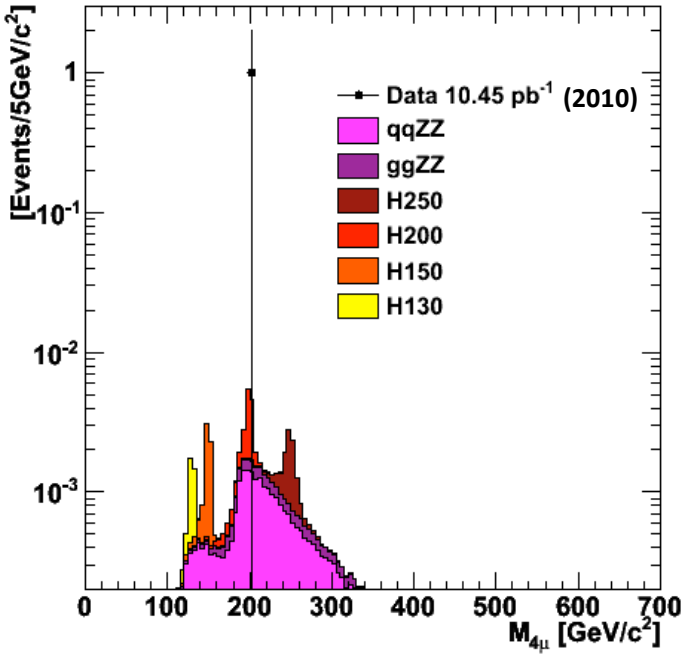


A simple search – *in principle*

- Clean, unambiguous signature
- Accurate reconstruction of lepton kinematics
- ZZ continuum can be modelled with MC
- Very small instrumental background

Expect a **narrow peak** over a **smooth background**

In real life…



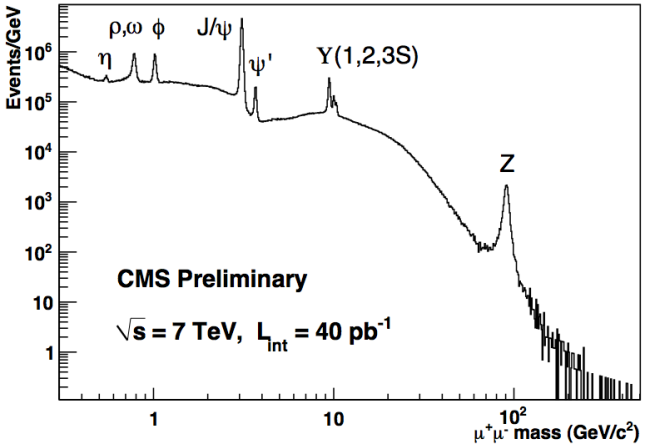
Looking for **very rare events** while the **detector is being understood**

- A 4l signal can be easily washed out by flaws in reconstruction (efficiency or resolution)
- Even a tiny unexpected instrumental background may produce a very significant excess

Not many handles, as initially ~zero signal over ~zero background events are expected…

Building **confidence in our understanding of instrumental details** with the early 2010/2011 data took an impressive amount of ingenuity and effort

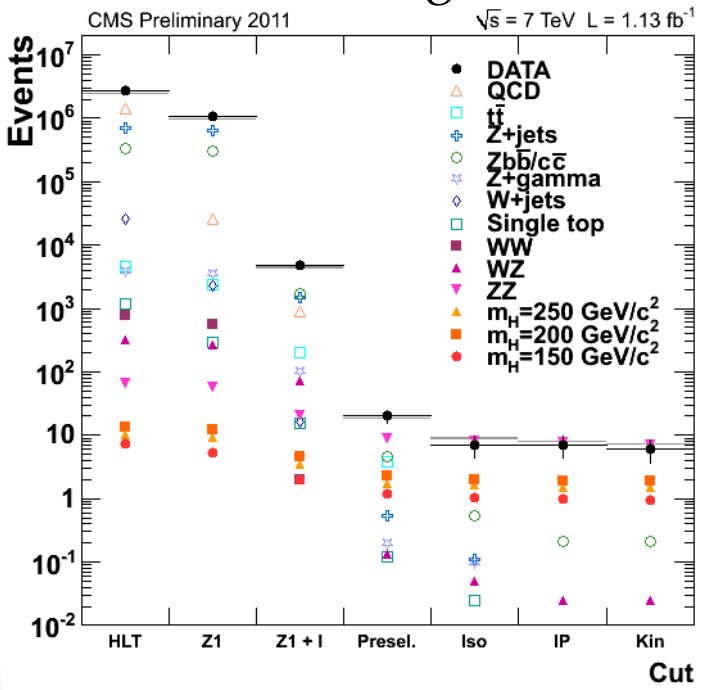
- Trigger, reconstruction and identification efficiencies with Tag-and-Probe methods
- Momentum scale, stability over time
- PU-dependent effects
- Data control regions to study/estimate reducible backgrounds



The H→4l search with 2011 data

We were paranoid about possible unexpected instrumental backgrounds

- Analysis flow designed to include several "**checkpoints**" to look at background
- Data inspected in frequent "reloads" immediately after certification
- Candidates dissected individually
  - For a long time, we gave a label to each one



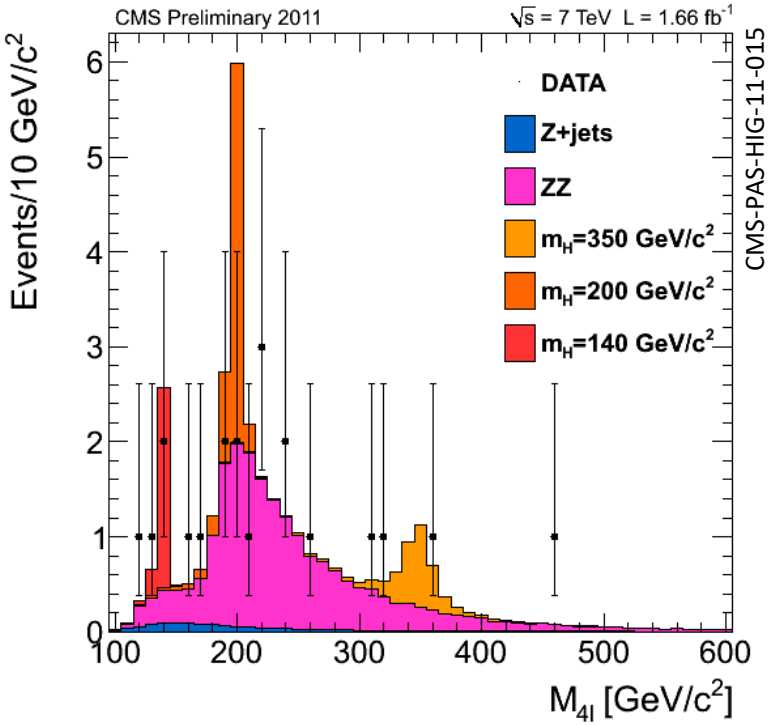
CMS-PAS-HIG-11-004

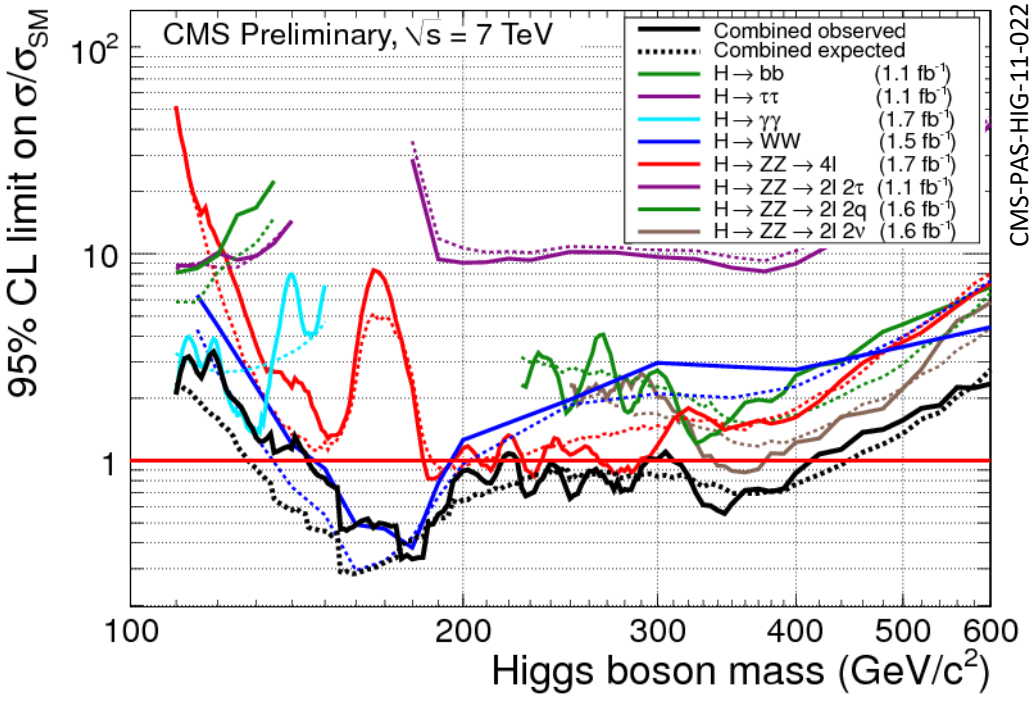
CMS-PAS-HIG-11-015

Event	Run #	Event #	Channel	m_{Z_1}	m_{Z_2} (GeV/c^2)	$m_{4\ell}$	$p_{T,4\ell}$ (GeV/c)	$y_{4\ell}$
A	146511	504867308	4μ	91.4	92.6	201.2	2.9	0.18
B	147926	368148849	4μ	101.5	40.0	167.8	43.7	1.45
C	163334	286336207	2e2μ	94.5	65.1	162.9	10.4	-0.53
D	163659	344708580	4e	93.3	28.8	139.3	24.9	0.39
E	163795	30998576	2e2μ	91.9	82.3	207.1	5.0	1.84
F	163817	155679852	4μ	91.3	34.8	144.9	24.1	-0.36
G	165633	394010457	2e2μ	91.2	92.8	243.7	11.6	-0.48
H	166408	917379387	2e2μ	88.8	105.3	257.9	29.3	-1.21
I	166438	78213037	4e	94.5	44.6	216.7	22.9	0.04
J	166512	337493970	4μ	91.0	93.2	238.5	22.0	0.26
K	166950	1491724484	2e2μ	92.4	93.9	194.6	14.2	0.82
L	167281	480301165	4μ	90.4	54.8	222.3	42.3	-0.64
M	167284	1038911933	4μ	77.8	29.7	119.0	43.9	0.58
N	167675	876658967	4e	92.6	27.1	125.7	15.3	0.07
O	167807	966824024	2e2μ	90.2	93.4	323.0	40.9	-0.43
		141954801	4e	91.0	91.5	190.2	7.5	-0.33
				90.2	88.3	218.9	9.8	-0.78
							8.7	1.2

2011: First results

- First public results at EPS and LP 2011
  - Complete analysis, including shape analysis for statistical interpretation and integrated in CMS combination
    - CMS combined @LP11: SM H excluded by CMS in [144-440] GeV





Sociology of an Early Search

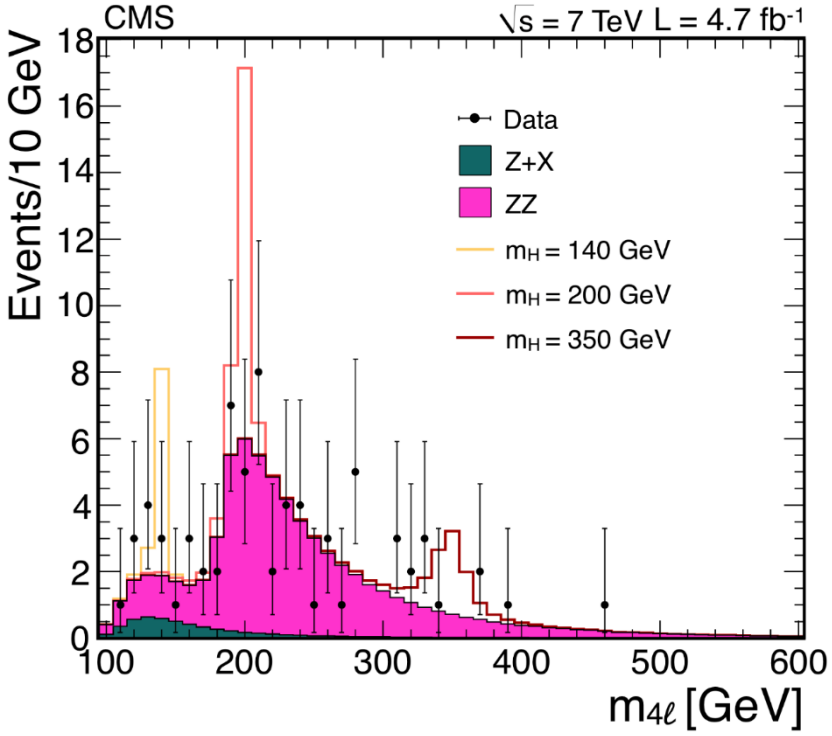
Several teams collaborating – and competing

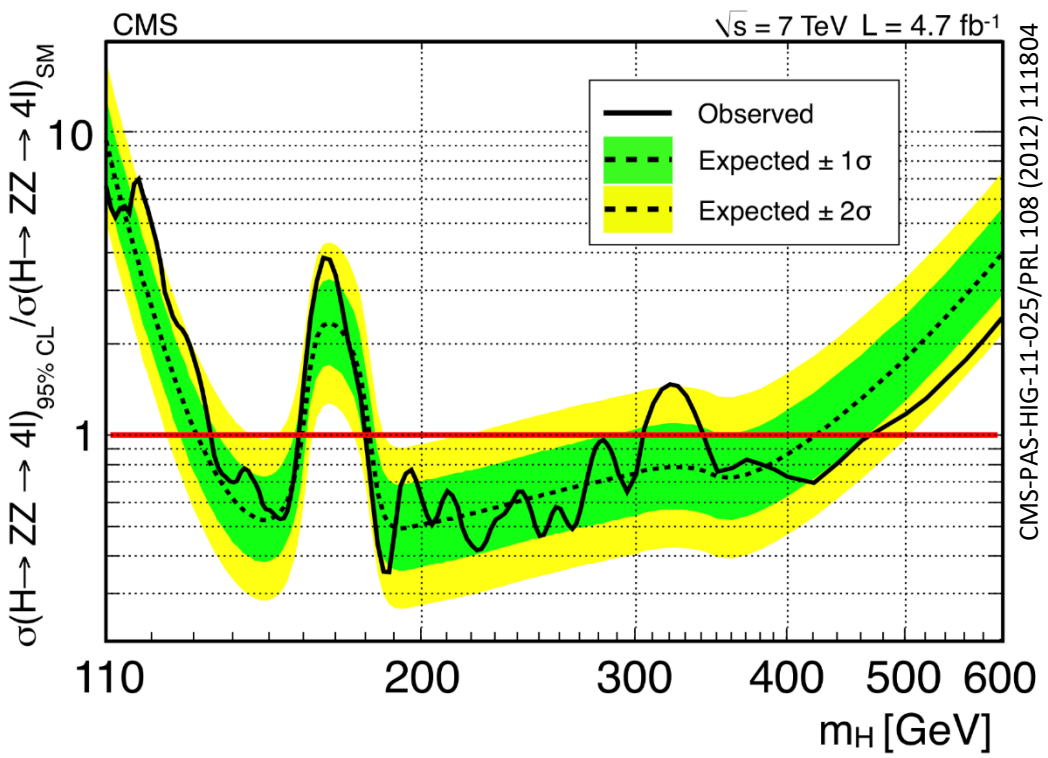
- New ideas and proposals coming up regularly
  - Different lepton identification criteria, selection strategy, analysis flow, background estimation techniques, improvements extend acceptance at low mass…
  - needed to **balance improvements with stability and consistency**
- An "**improvementy policy**" was established in the ZZ subgroup
  - **Benchmark analysis** recipe maintained as a common starting point and reference for improvements
  - Synchronization exercises on MC among different groups
    - Effort to understand differences at the event level (not just statistical)

Turned out to be a very successful *modus operandi*

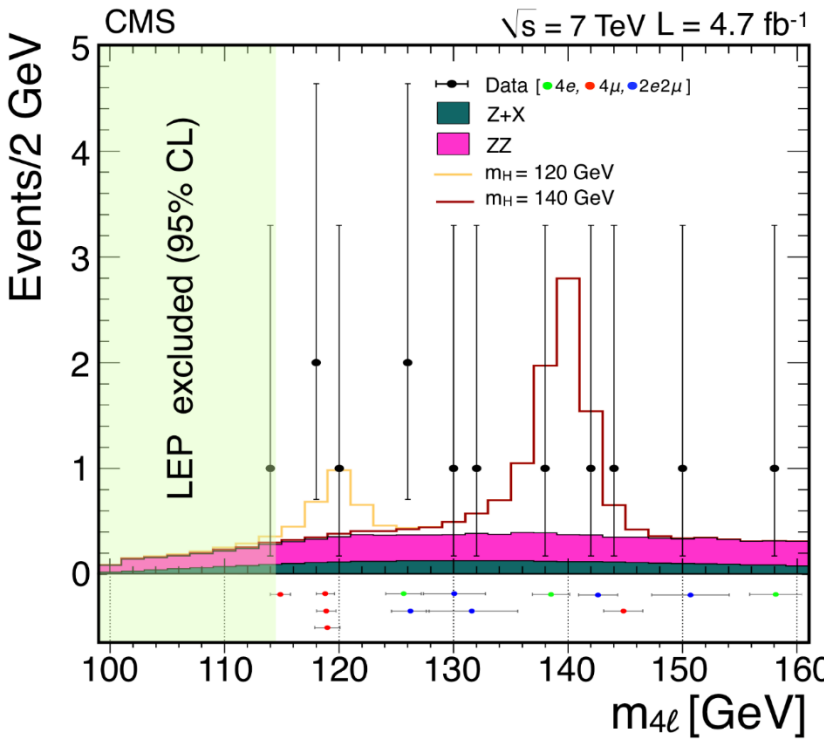
December 2011: 4.7 fb^{-1}

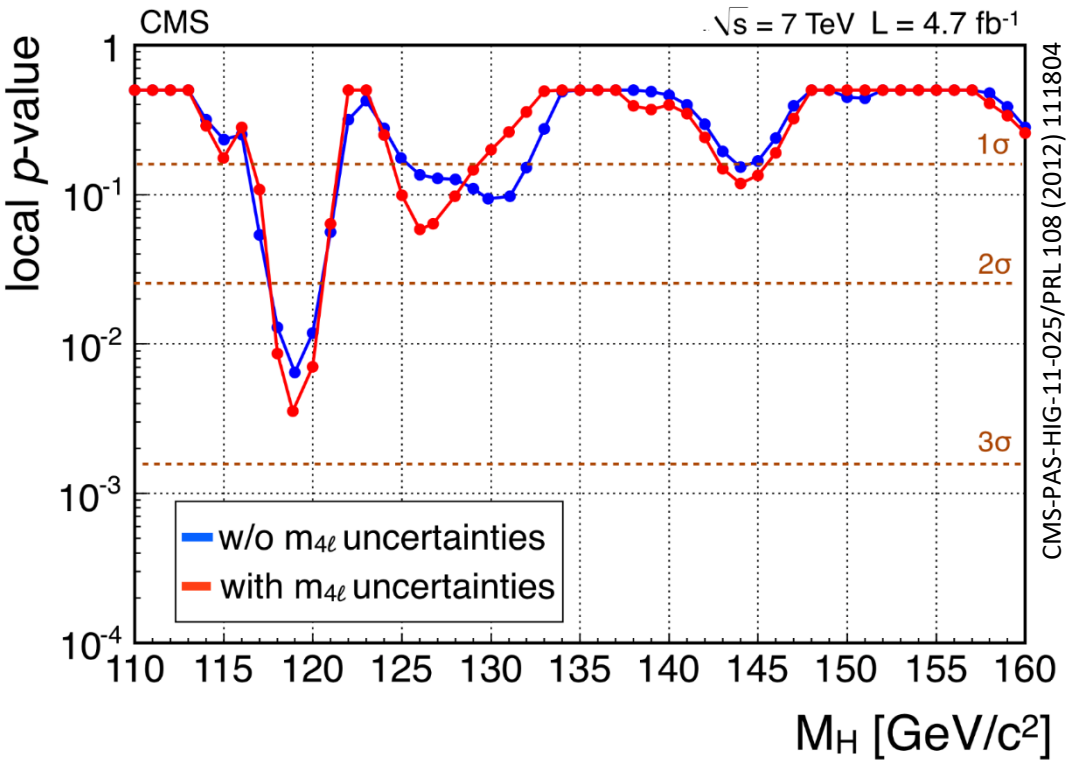
With the full 7 TeV dataset, we excluded [134-158],[180-305],[340-460] GeV with H→4l alone…





December 2011



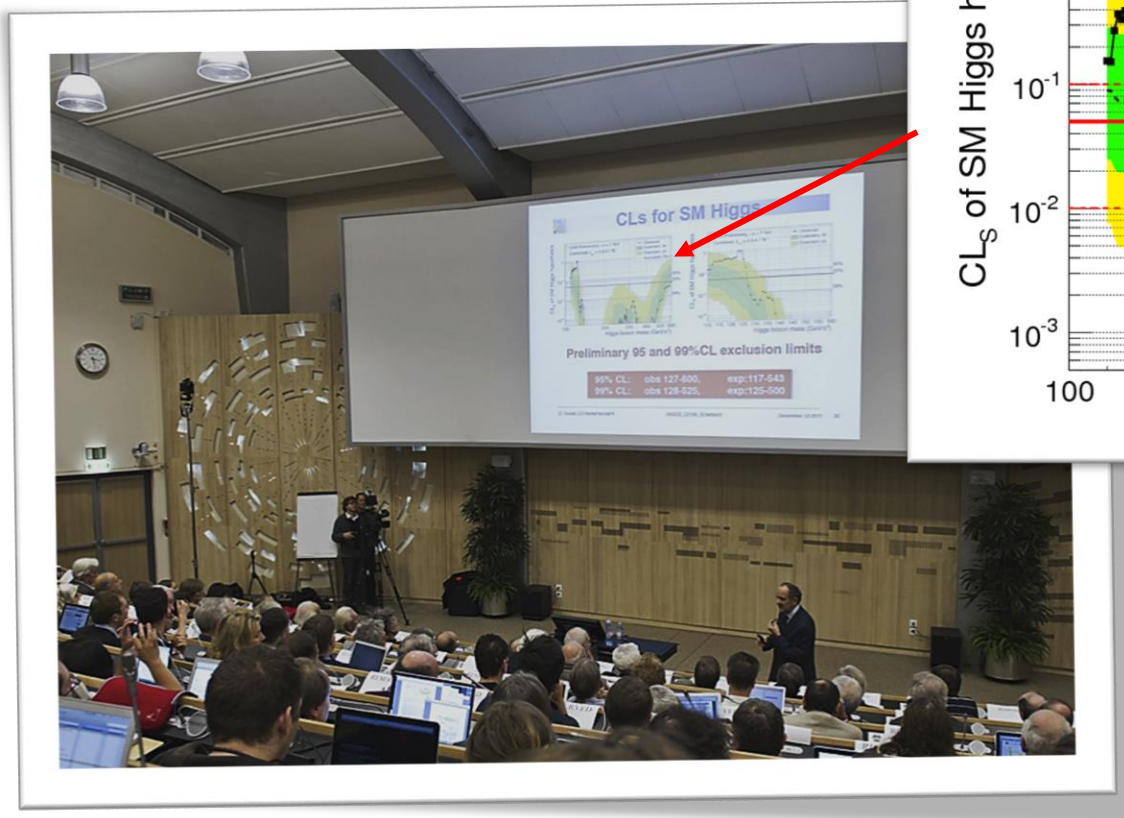


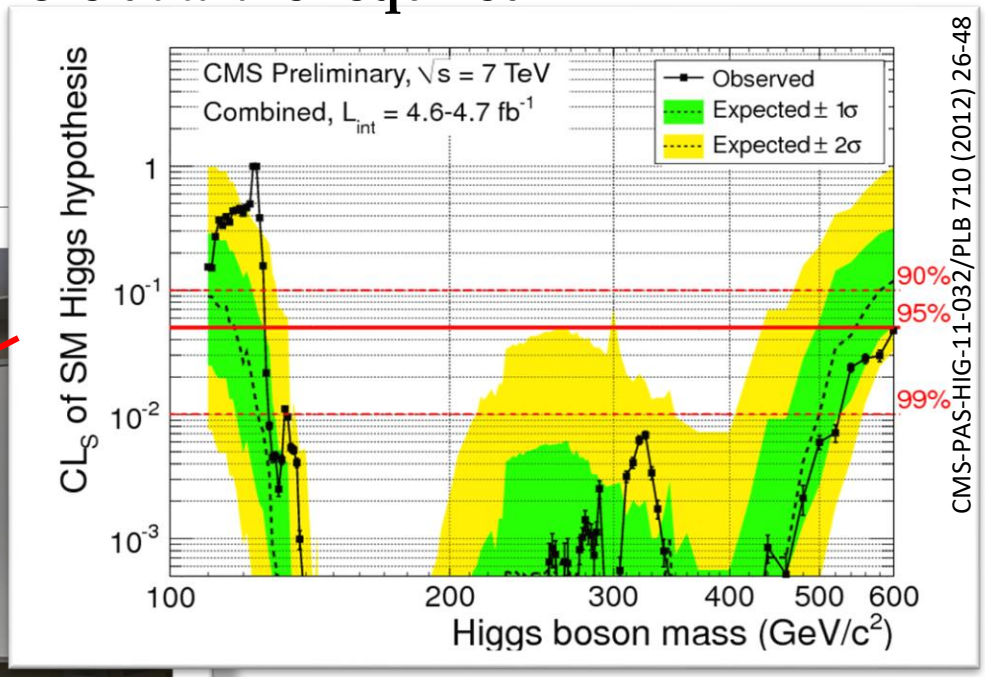
- 2D statistical analysis with mass shape and m_{4l} uncertainty
- The 7 TeV run left us with some suspense

December 2011: ATLAS/CMS Jamboree

The combination of all CMS analyses excluded the range [127-600]

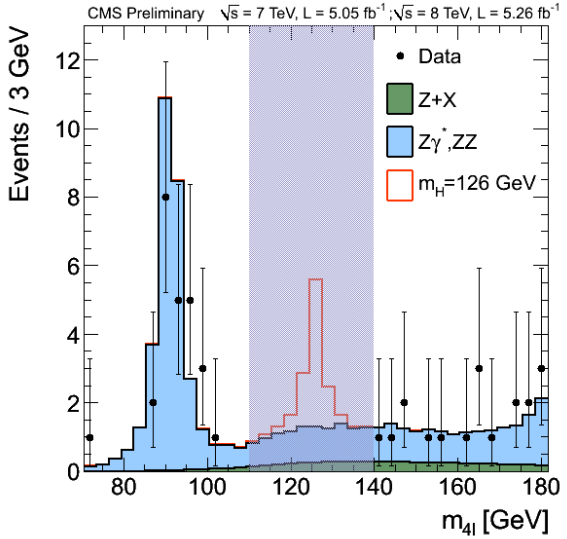
"…excess […] makes observed limits weaker than the expected ones. To ascertain the origin of the excess, more data are required"

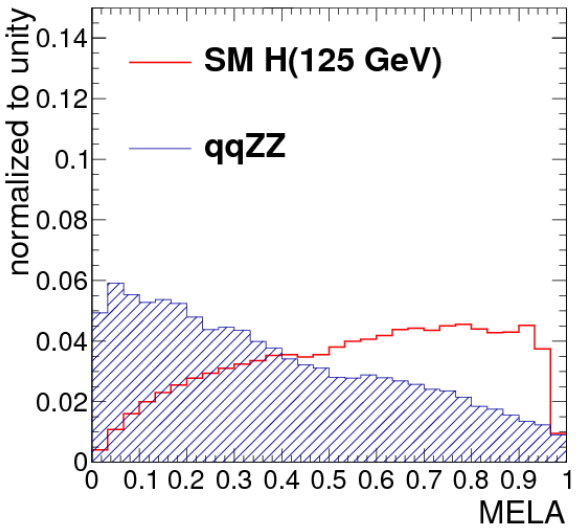


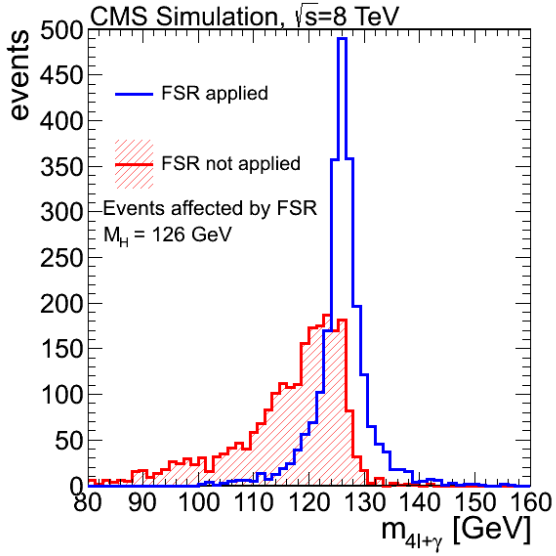


2012: A fresh start for 8 TeV

- At the beginning of 2012 it was evident that H, if existing, was to be discovered within few months, with 4l and γγ in a privileged position
- Aggressive approach: **invest in re-visiting both the basic objects and the statistical approach** while analysis remained **blinded**
  - Improve lepton ID including MVA techniques
  - Improve sensitivity for low m_{4l}
  - More sophisticated data-driven methods for bkg
  - **Kinematic discriminants**
  - **FSR recollection**







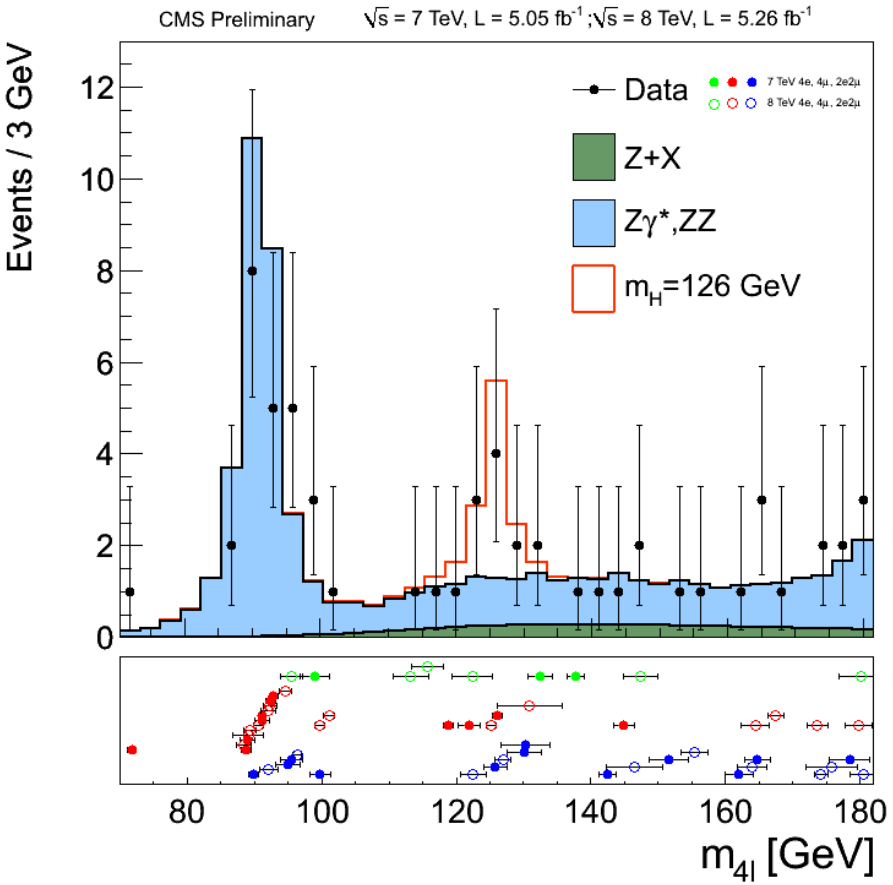
Bracing for a discovery

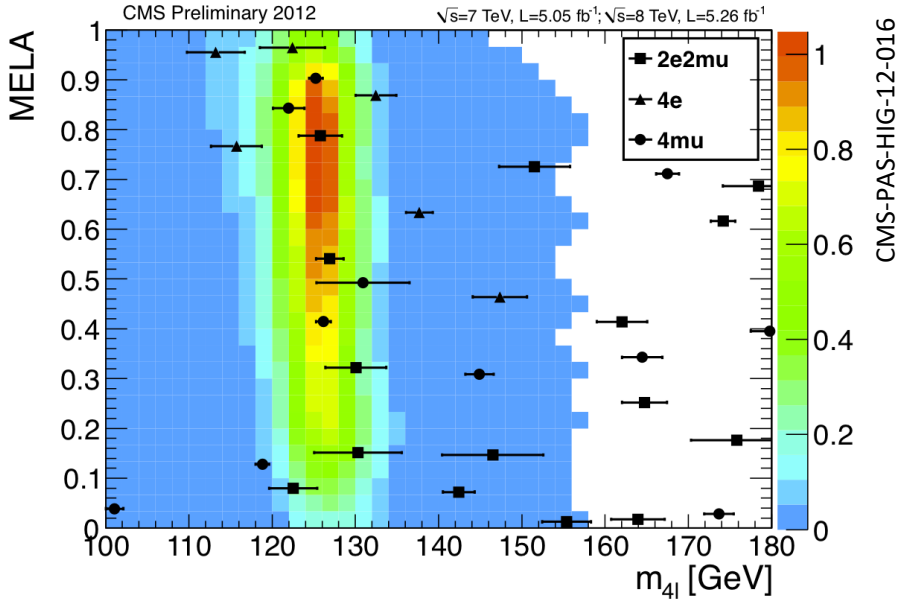
- **Unblinding** was planned meticulously for June 13
  - Hour-by-hour schedule for the short time between the ARC green light on June 13, and the report to the Collaboration to be given the following day
  - Plan for all possible if's and then's

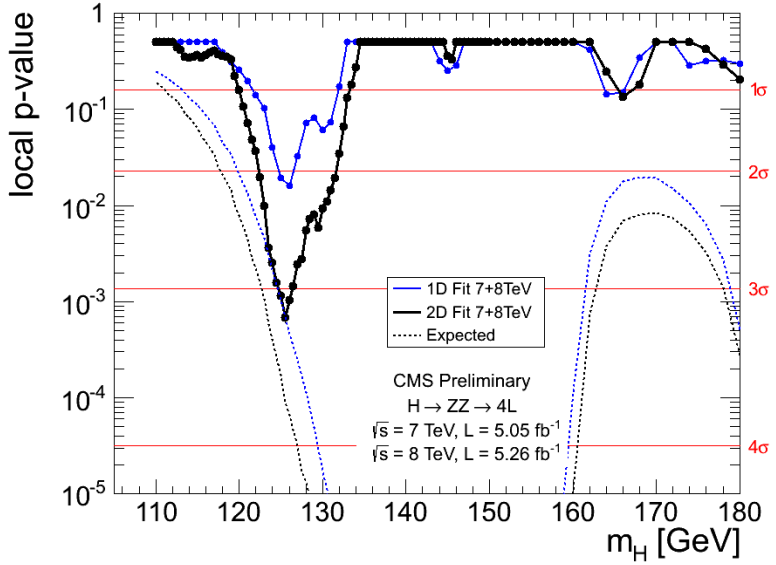
- The actual unblinding happened in a **closed meeting** in the evening
  - That was the most exciting event in my career as a physicist

The only record of that meeting is this disappointing picture
(caveat: only a few contributors fitted in the frame…)

July 4, 2012



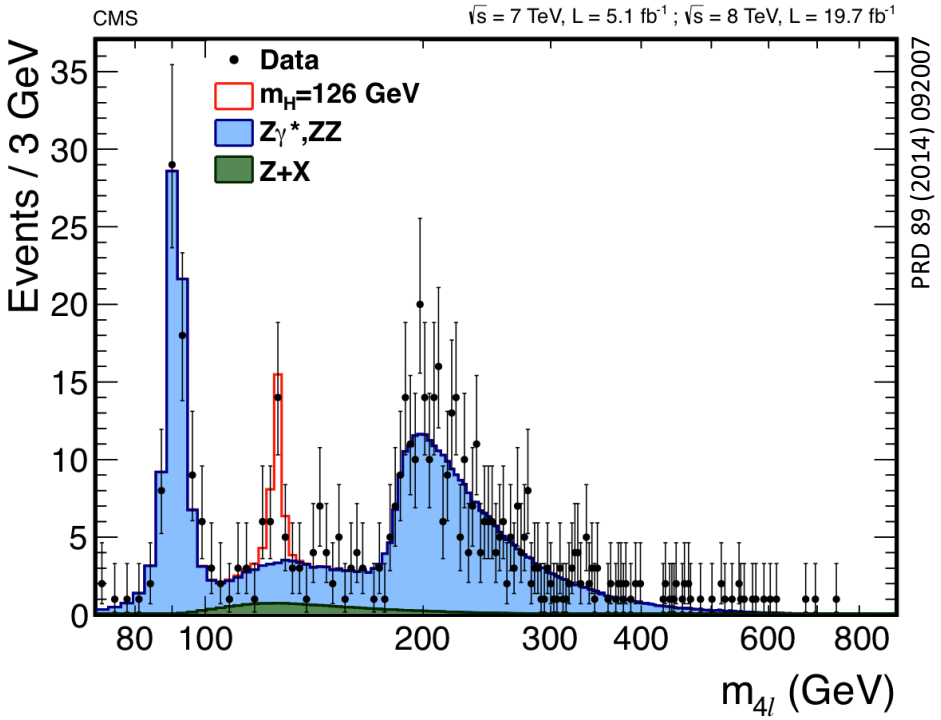




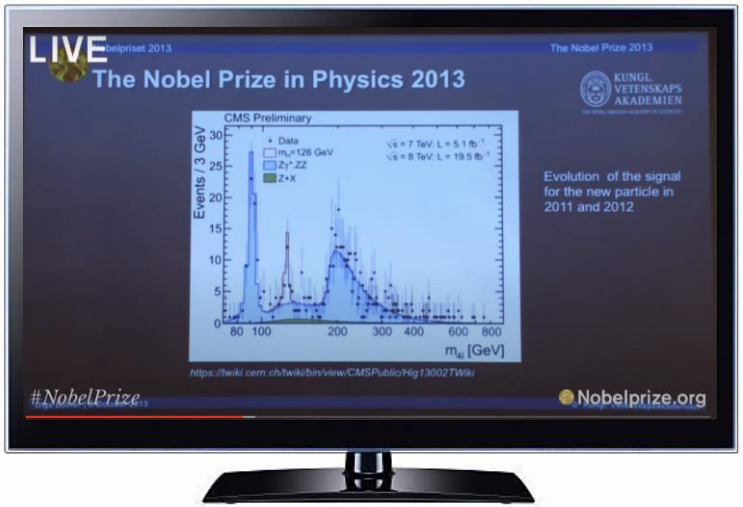
Evidence by 4l alone

The Nobel Prize in Physics 2013

By then, the 4l analysis had been extended to mass measurement,
categorization to target VBF production,
exclusion of alternative spin/CP using kinematics



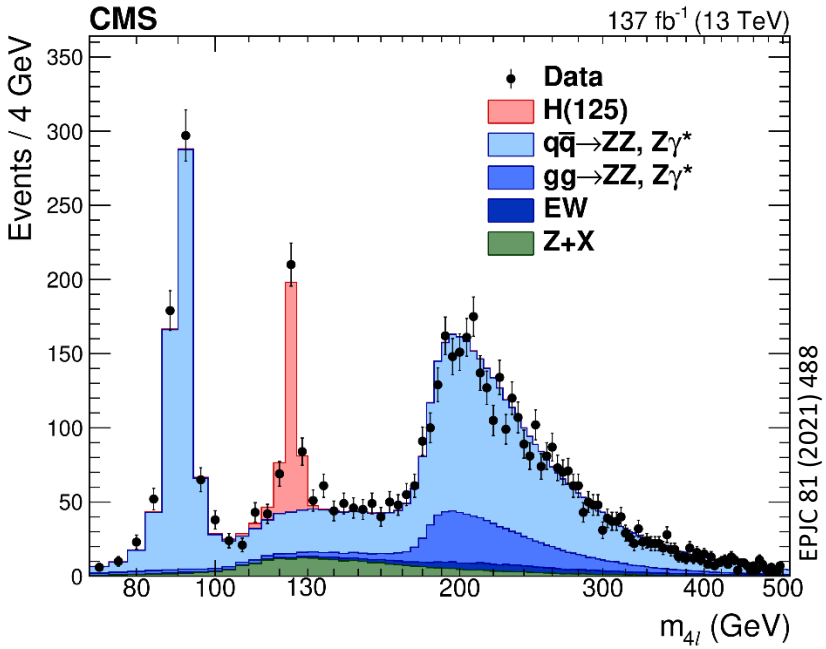
We copied the idea of animated GIF from ATLAS…



https://youtu.be/8MRqQQuvGzs?t=830

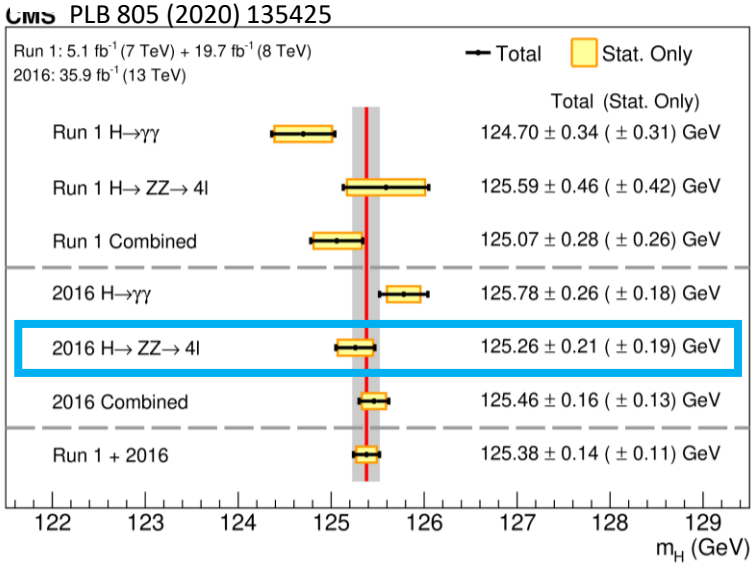
…it was featured in the Nobel Prize Announcement

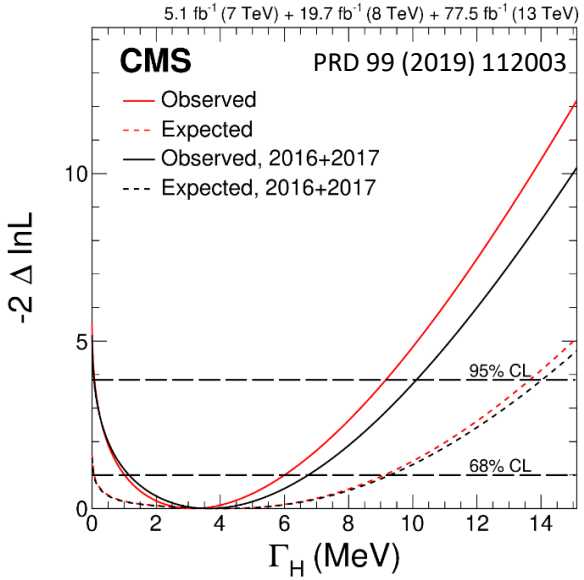
H→4l after the discovery

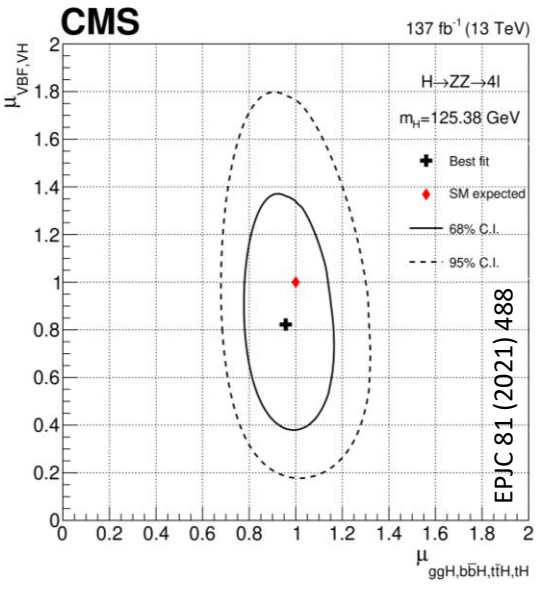


A gold mine in the investigation of Higgs properties

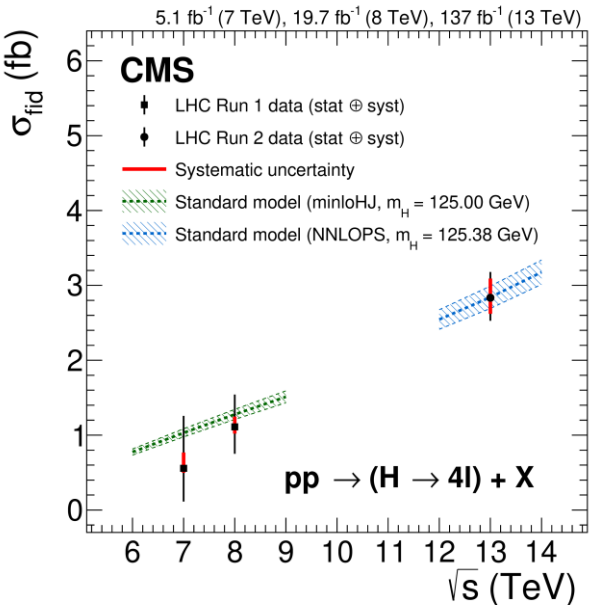
- Mass
- Width from offshell/onshell
- Probe production mechanisms with categorization…

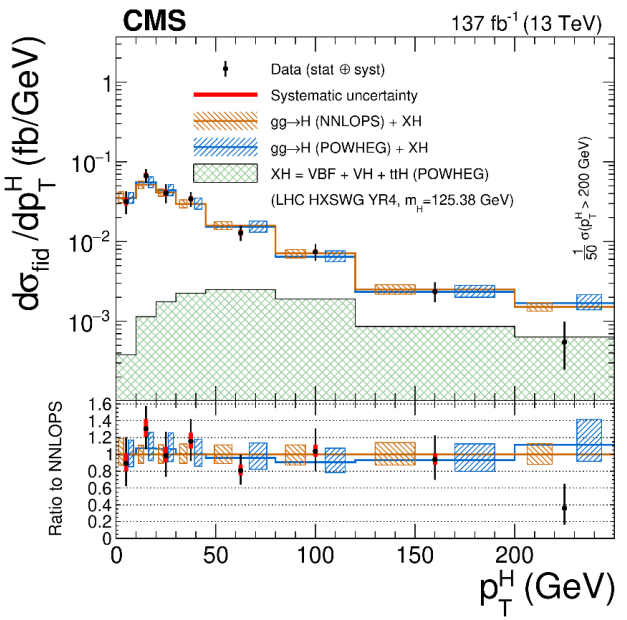






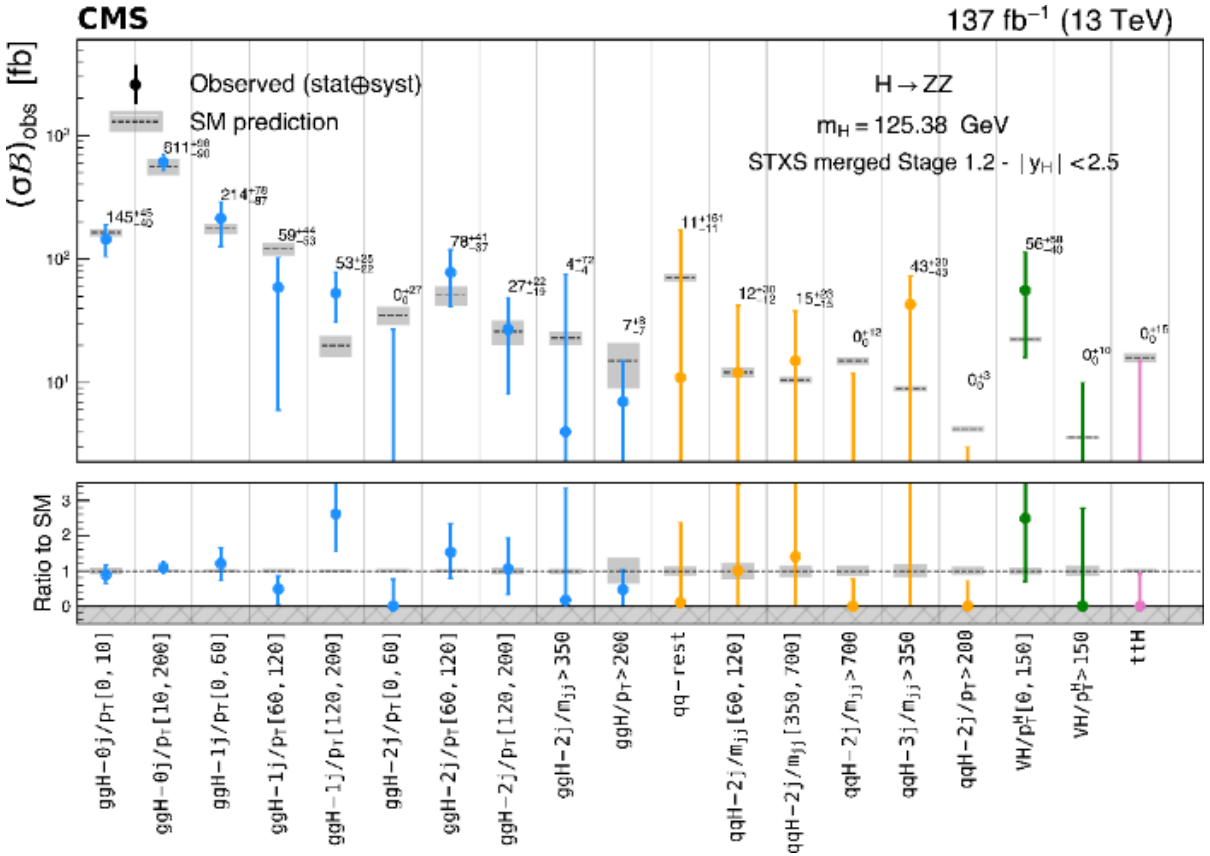
H→4l after the discovery





- Fiducial and differential cross sections
- STXS
- Spin/CP, anomalous couplings, from kinematics

…



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Conclusions

- A fantastic collaborative achievement
- Extremely demanding for analyzers, but also extremely rewarding
- Setting the internal collaboration right was a key for success
- What started as a search analysis then turned into a precision measurement channel
- More results and more fun to come!