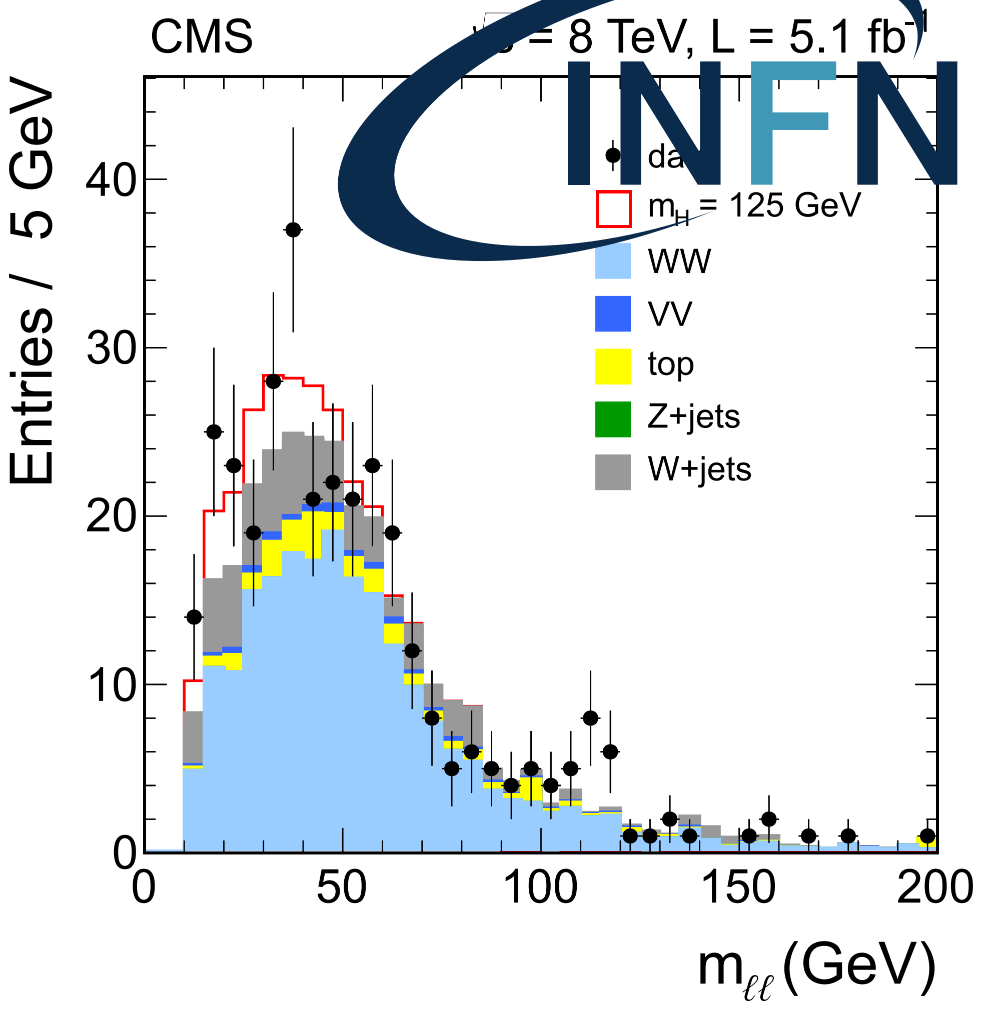
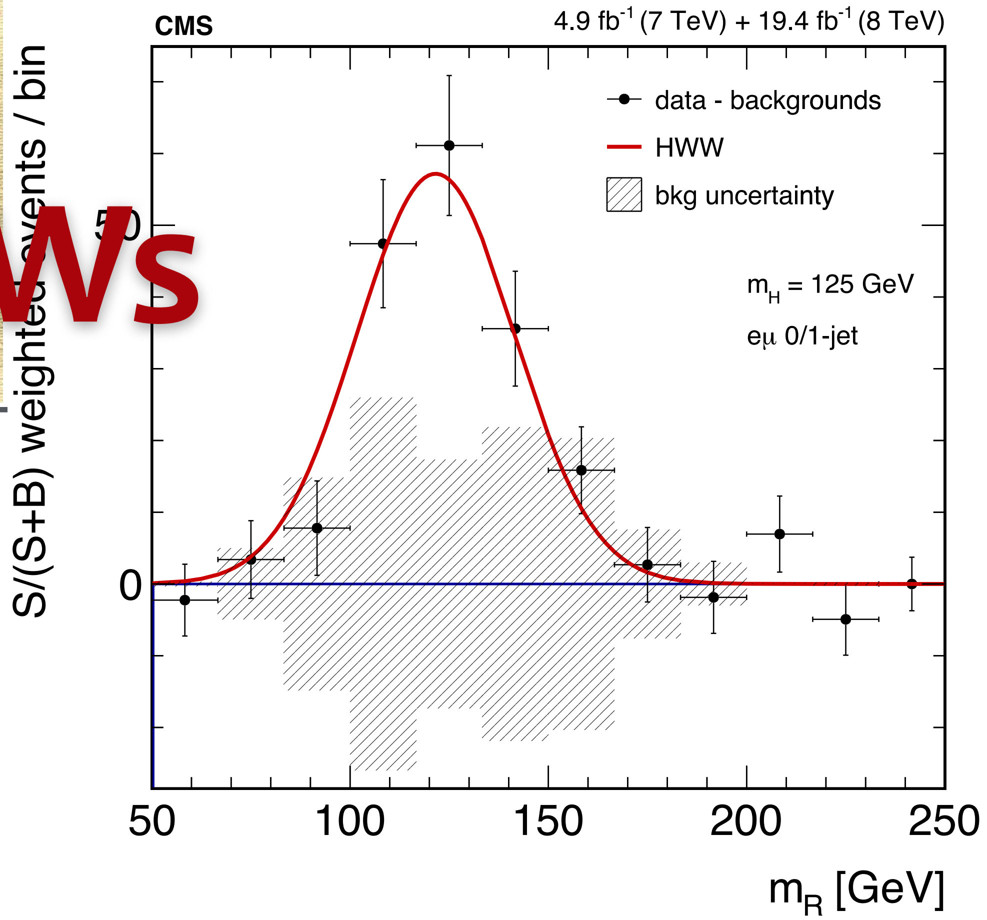
Higgs decays to two Ws





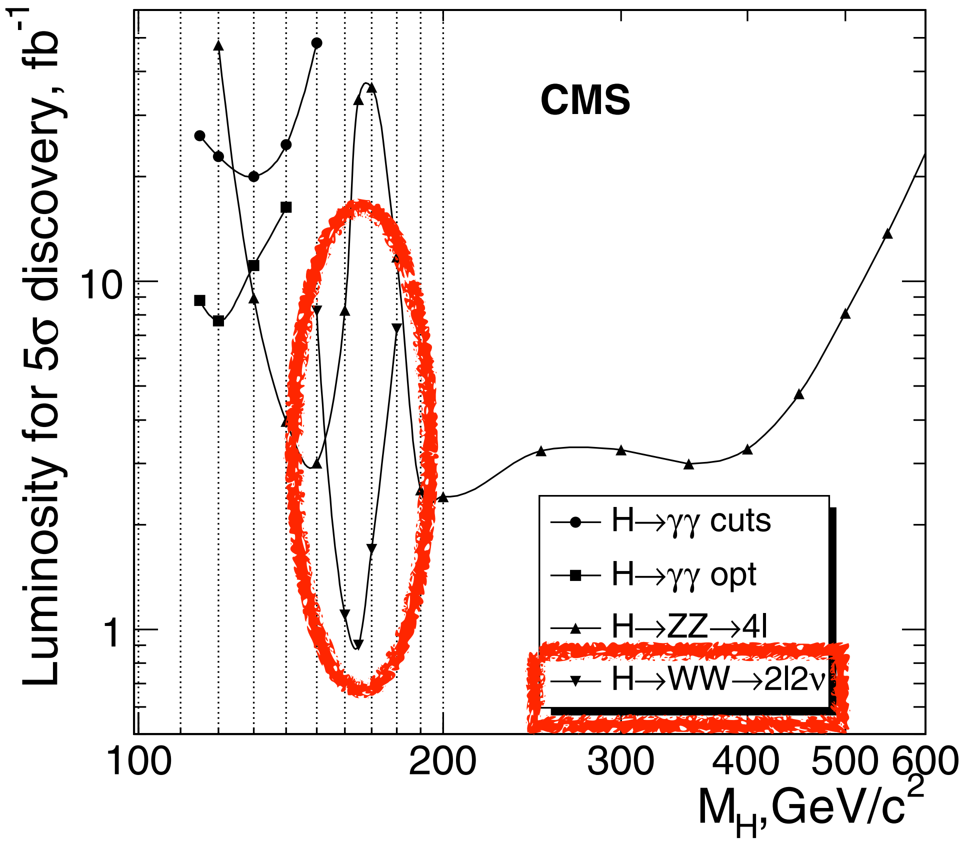
E. Di Marco(INFN Roma)

Higgs Discovery@10 (Birmingham)

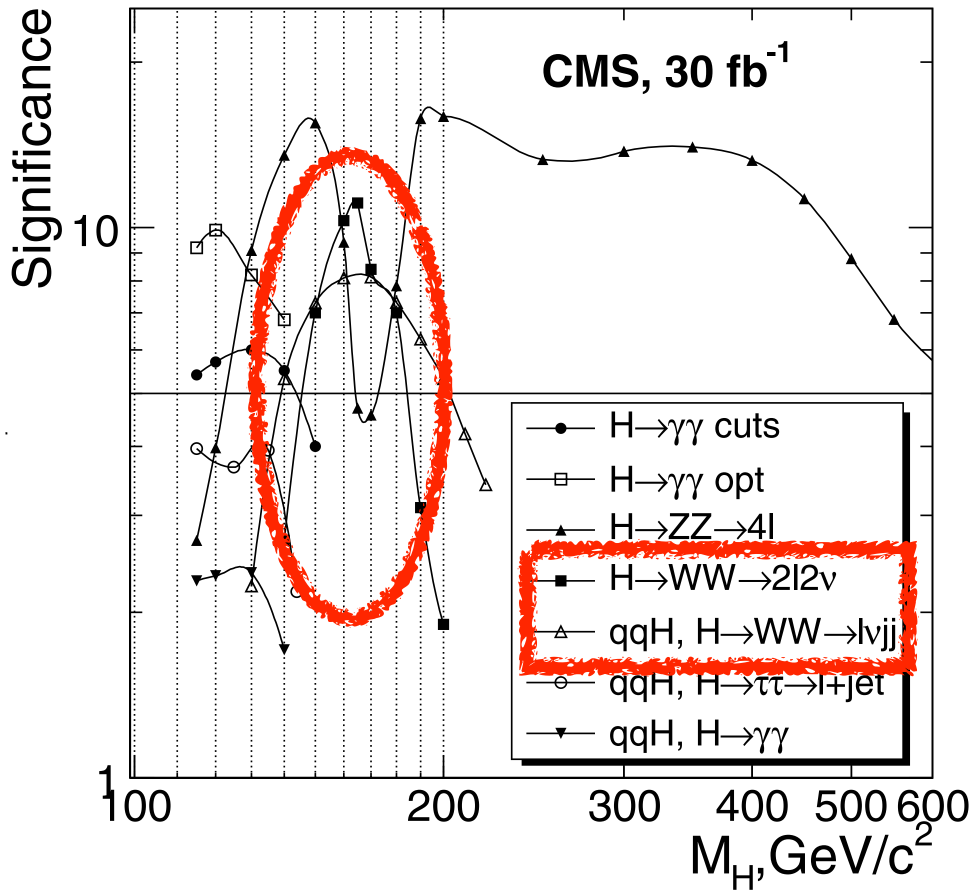
30 / 6 / 2022

LHC expectations at startup

- The LHC started collisions in 2007 with a precise program of Higgs search in the mass range allowed by LEP e^+e^- collider: $\mathrm{M_H} > 114\ \mathrm{GeV/c^2}$
  - At $\sqrt{s} = 14\ \mathrm{TeV}$ and inst. luminosity of $10^{34}\ \mathrm{cm^{-2}s^{-1}}$, LHC could produce a Higgs boson with a mass up to $\approx 800\ \mathrm{GeV}$ and CMS and ATLAS discover it



CMS TDR
2007

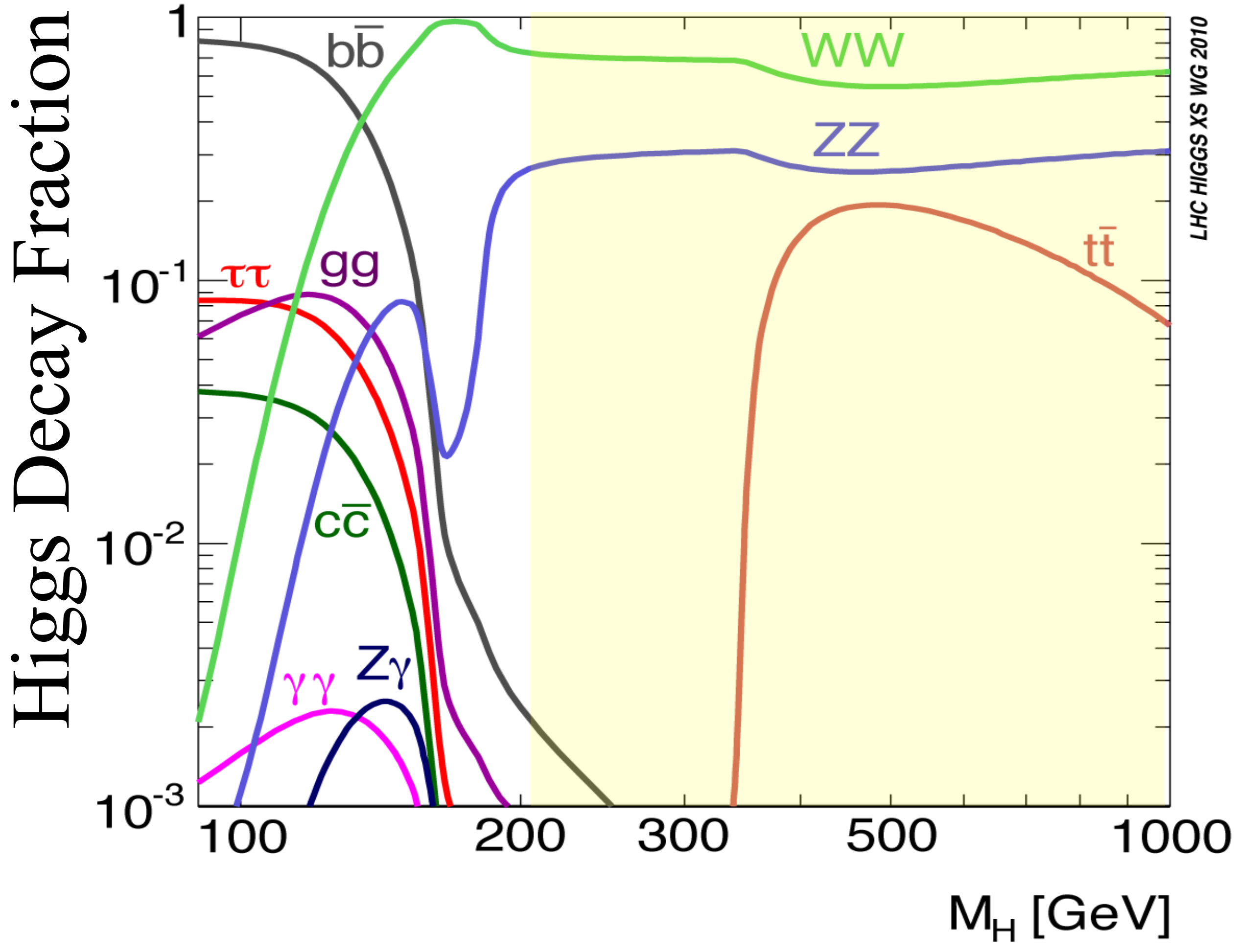


- And if they didn't, then signs of new underlying strong dynamics in the TeV range should show up! **The no-lose theorem**
- $H \to WW$ is the first channel to be explore for $M_H \approx 2M_W \approx 160\ \mathrm{GeV}$.
  - directly competing with Tevatron existing exclusion: high initial pressure

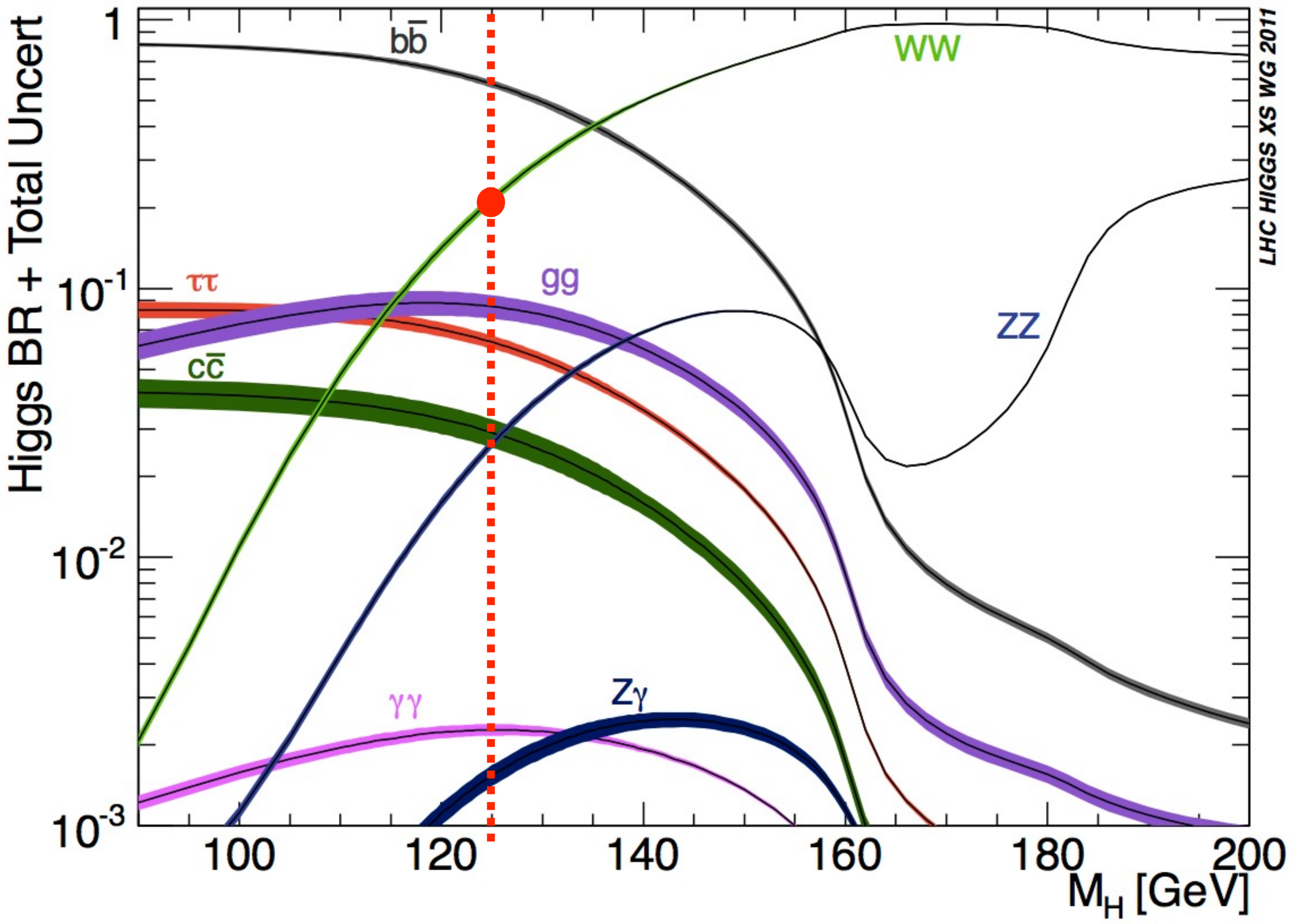
$H \rightarrow WW$ the workhorse at startup

- The Higgs boson decays mostly in the heaviest particle kinematically allowed

At high M_H WW & ZZ dominate



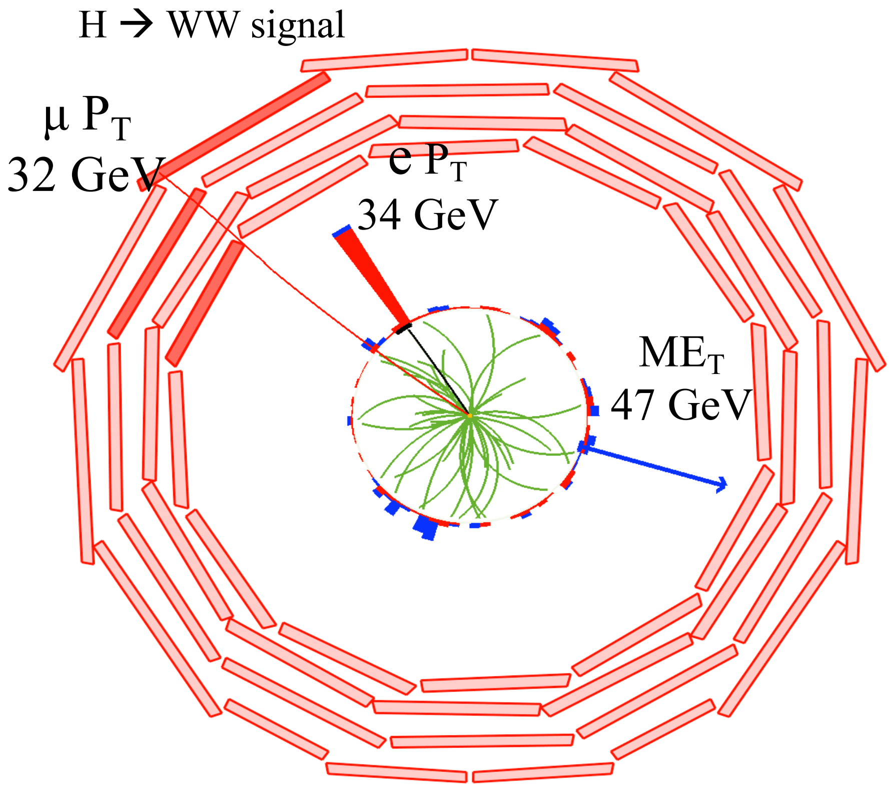
At low M_H variety of final states in play, excellent for measuring Higgs couplings

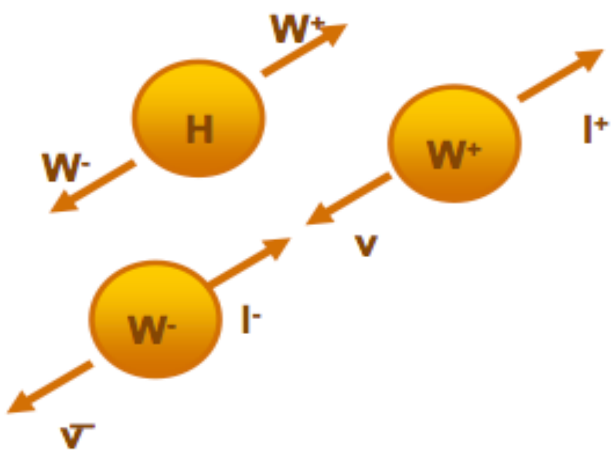


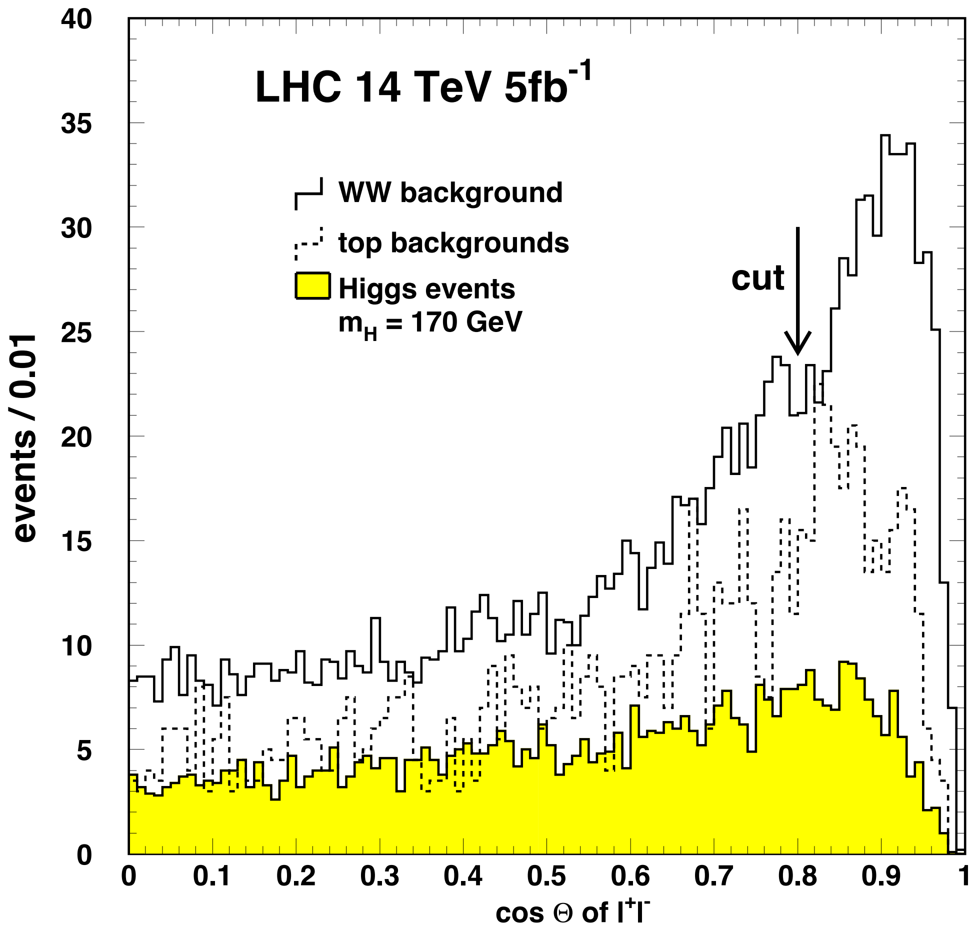
Even if initially not foreseen for $M_H \ll 2M_W$, when the stakes became hot, WW was extremely optimised to make use of the largest BR at $\mathrm{M_H} = 125\ \mathrm{GeV}$ experimentally accessible (fully leptonic mode: $2\ell 2\nu$)

Seminal ideas

- First MC studies were seminal: main kinematical variables, triggers and main backgrounds were individuated
  - Look for events with two energetic & isolated leptons and missing energy (due to neutrinos)
  - Large $t\bar{t}$ background → jet veto
  - Higgs boson has spin = 0 => leptons are spatially aligned
  - Nevertheless, below $\mathrm{M_H} = 155\ \mathrm{GeV}$ it was not even considered a possibility







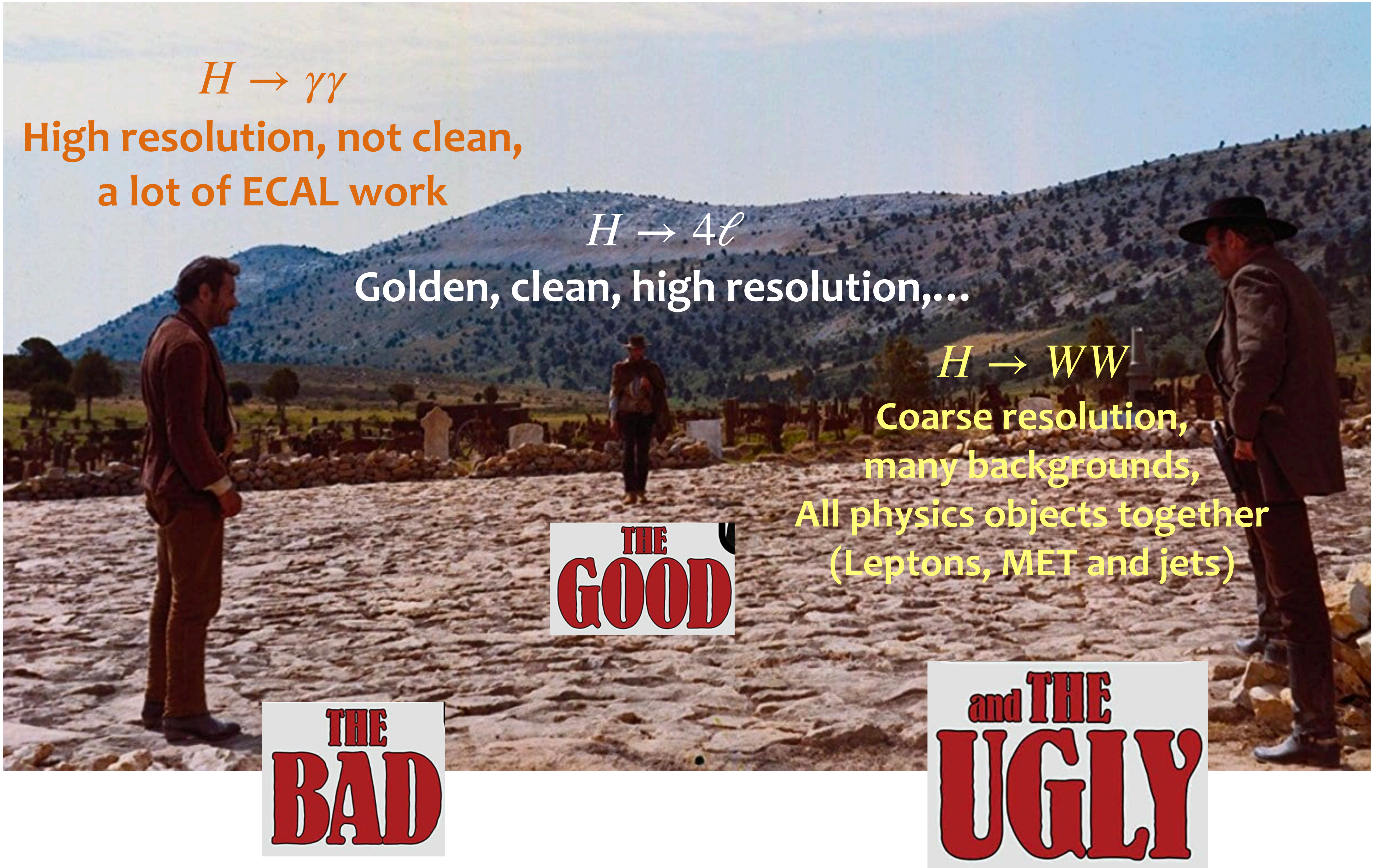
How to find a Higgs Boson with a Mass between 155–180 GeV at the LHC

arXiv:hep-ph/9608317v1 14 Aug 1996

M. Dittmar[1], H. Dreiner[2]

A difficult channel for LHC startup

- Between the two shiny golden brothers (high mass resolution)



$H \to \gamma\gamma$

High resolution, not clean,
a lot of ECAL work

$H \to 4\ell$

Golden, clean, high resolution,…

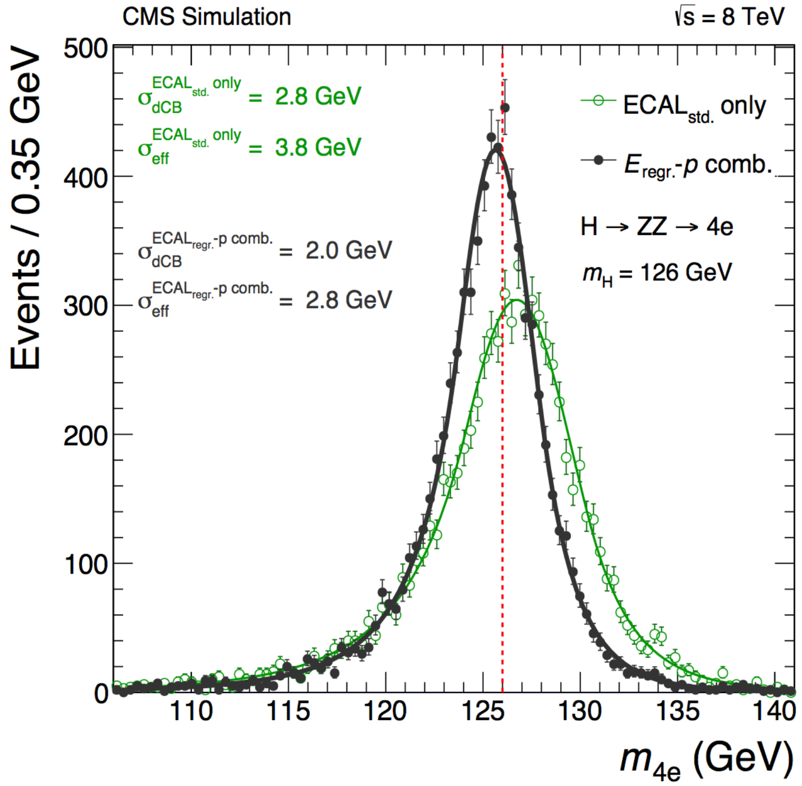
$H \to WW$

Coarse resolution,
many backgrounds,
All physics objects together
(Leptons, MET and jets)

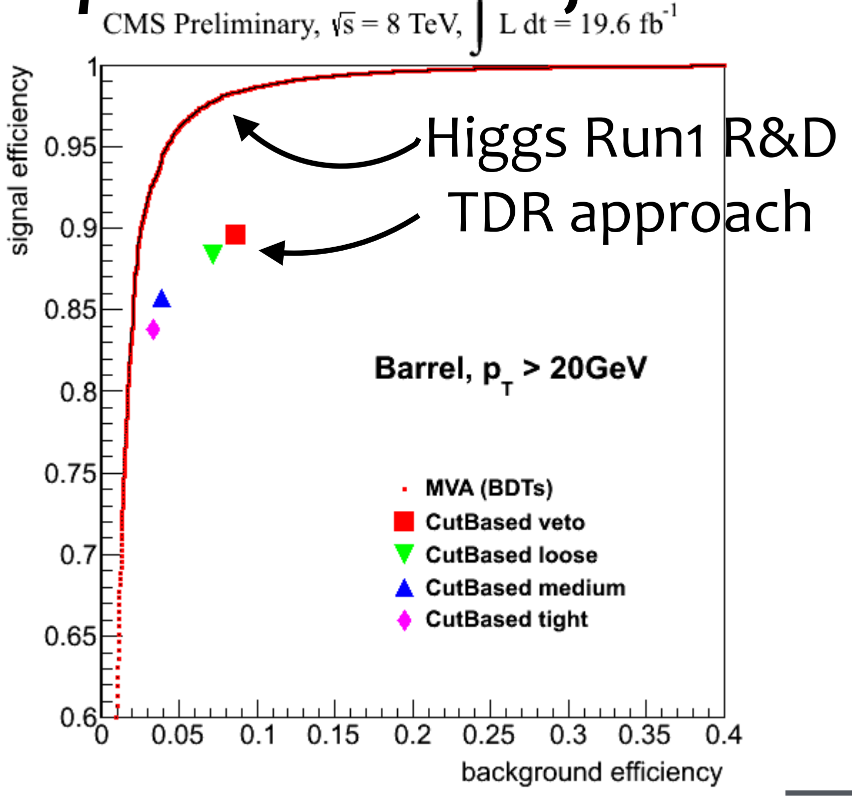
The two leptonic brothers

- The $H \to WW$ and $H \to ZZ$ fully leptonic channels drove the R&D of the lepton identification as they are (still) now at the dawn of Run-3:
  - High efficiency down to a p_T of few GeVs: 4th lepton of $H \to 4\ell$ (~5 GeV) and need of high fake-lepton rejection from W+jets in $\mathrm{H} \to \mathrm{WW}$
    - especially challenging for electrons
- The definition of tight (WW: $\epsilon \approx 80\,\%$) and loose (ZZ: $\epsilon \approx 90\,\%$) leptons came from here
  - Furious development of MVA identification: the raise of Machine Learning applied at CMS started here
- Another first ML application now widespread at LHC:
  - Energy corrections for electrons (and photons) using MVA regression

Energy MVA regression



Lepton MVA identification



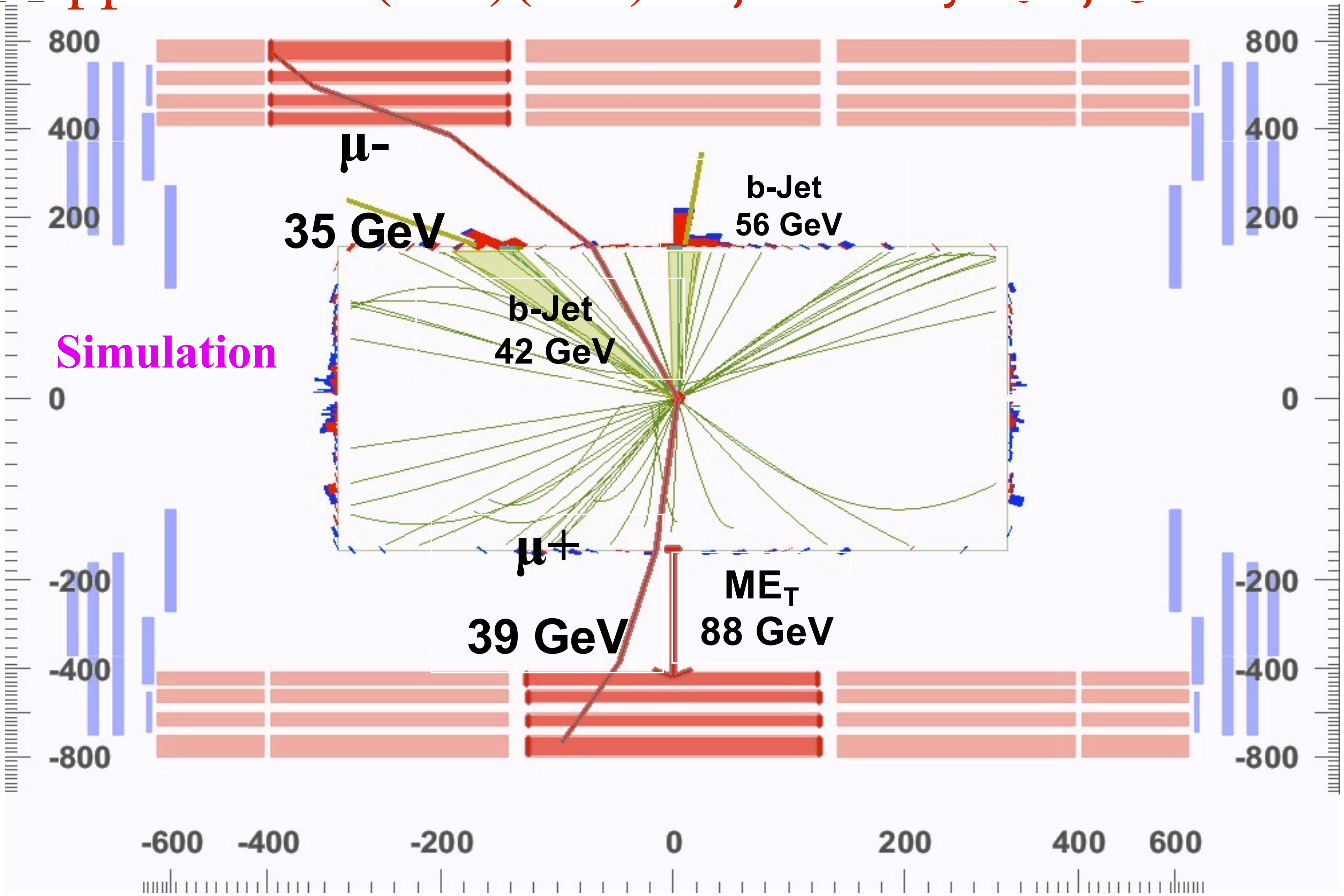
Higgs Run1 R&D

TDR approach

And we used jets...

- Initially we used the good, old, the jet-veto:

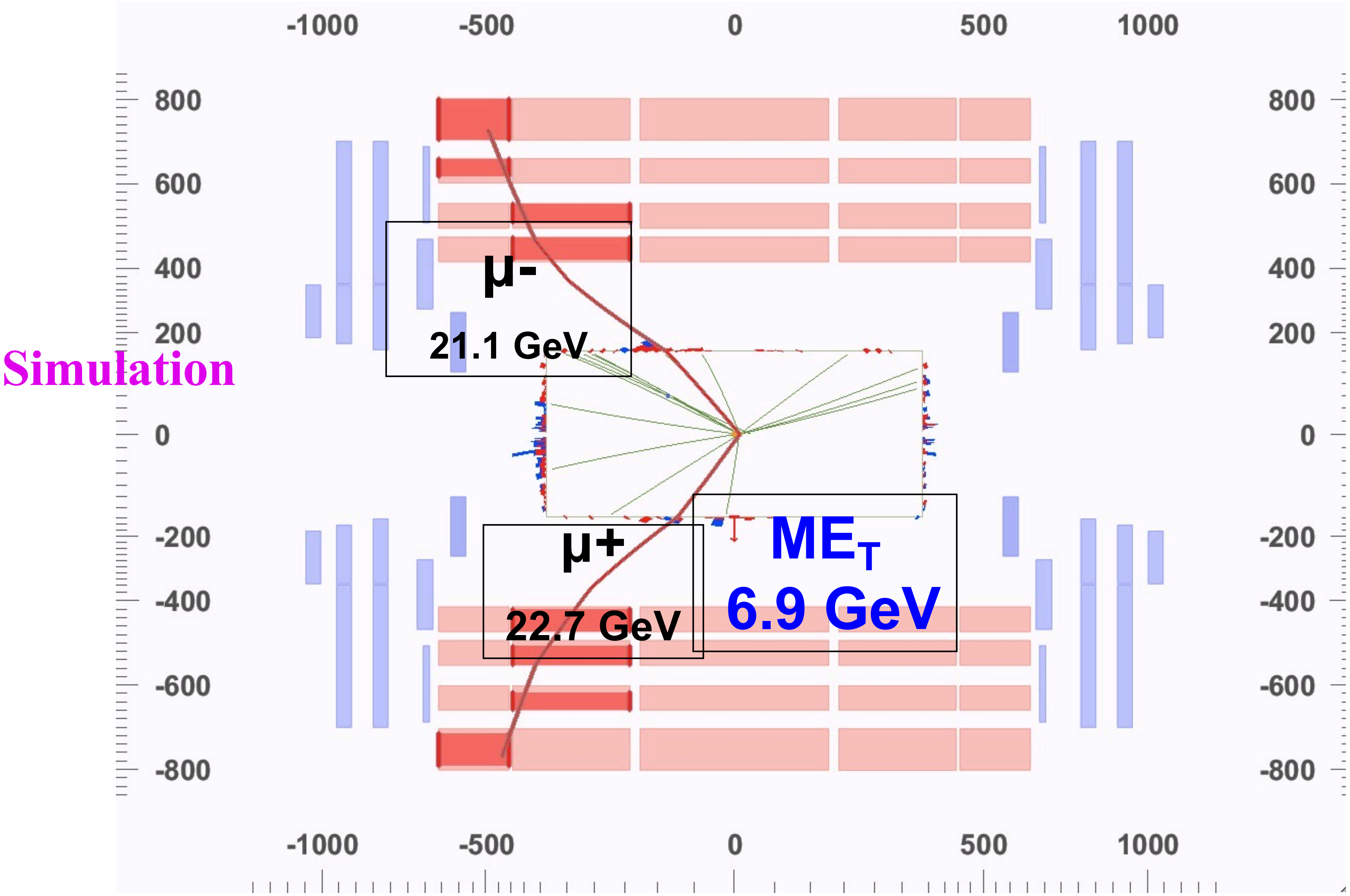
$pp \to t\bar{t} \to (bW)(bW)$: rejected by the jet veto



- But then we started to categorize events (0-jet, 1-jet, 2-jets) to gain sensitivity.
  - In 2011 analysis first attempt to get in the VBF production

And we used MET...

- Large DrellYan $\rightarrow 2\ell$ bkg can be suppressed by requiring large $|\overrightarrow{p_T^{miss}}|$
- But the HWW expected MET is not large: $\mathcal{O}$(40 GeV) => not far from the bulk of no-MET events, given its resolution



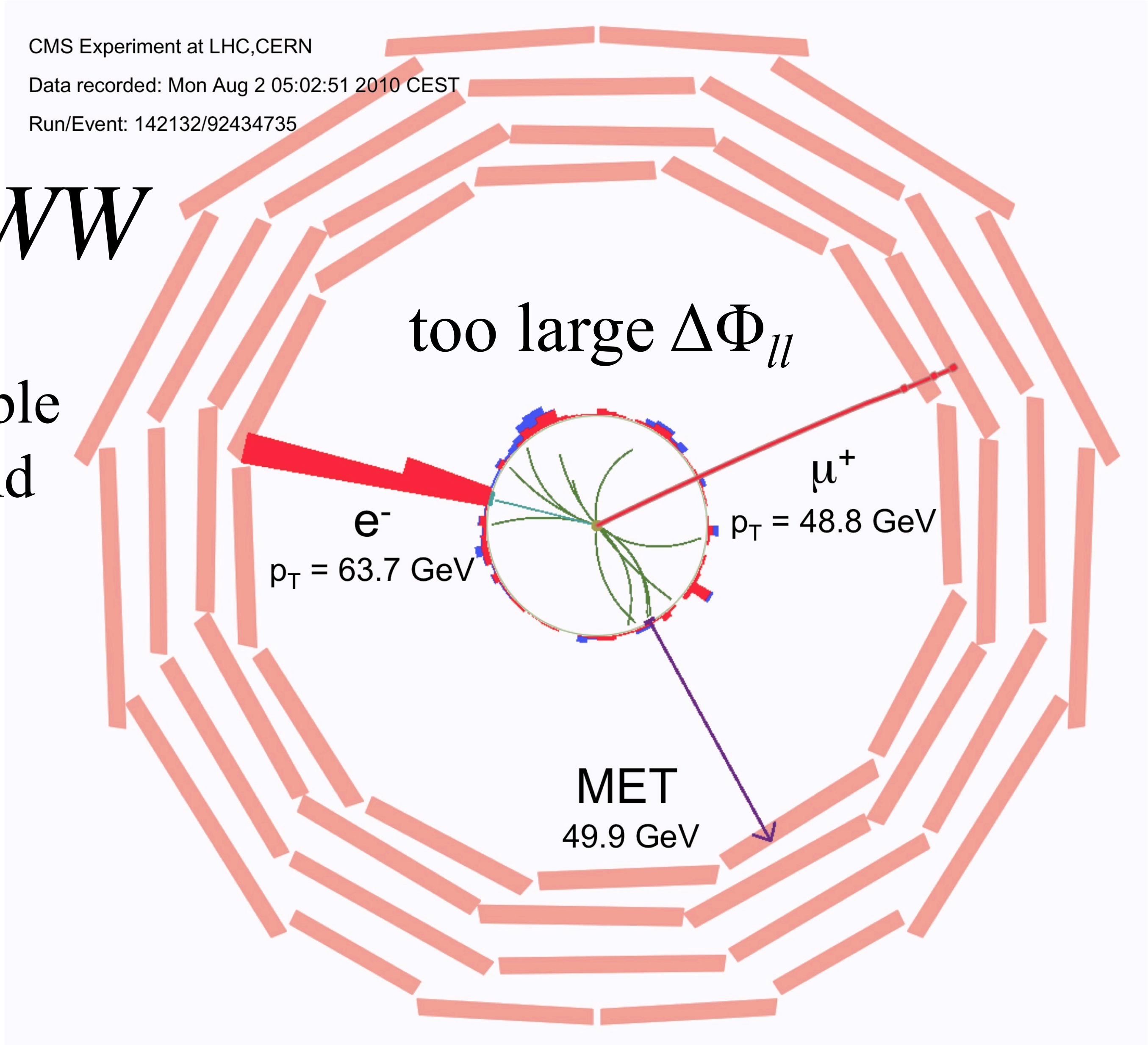
pp $\rightarrow$ Z + jets event “killed” by MET requirement

And we used spin-0 expectations

- The main physics motivated quantity to reduce the pp→WW irreducible background

$$pp \rightarrow WW$$

An irreducible background



too large $\Delta\Phi_{ll}$

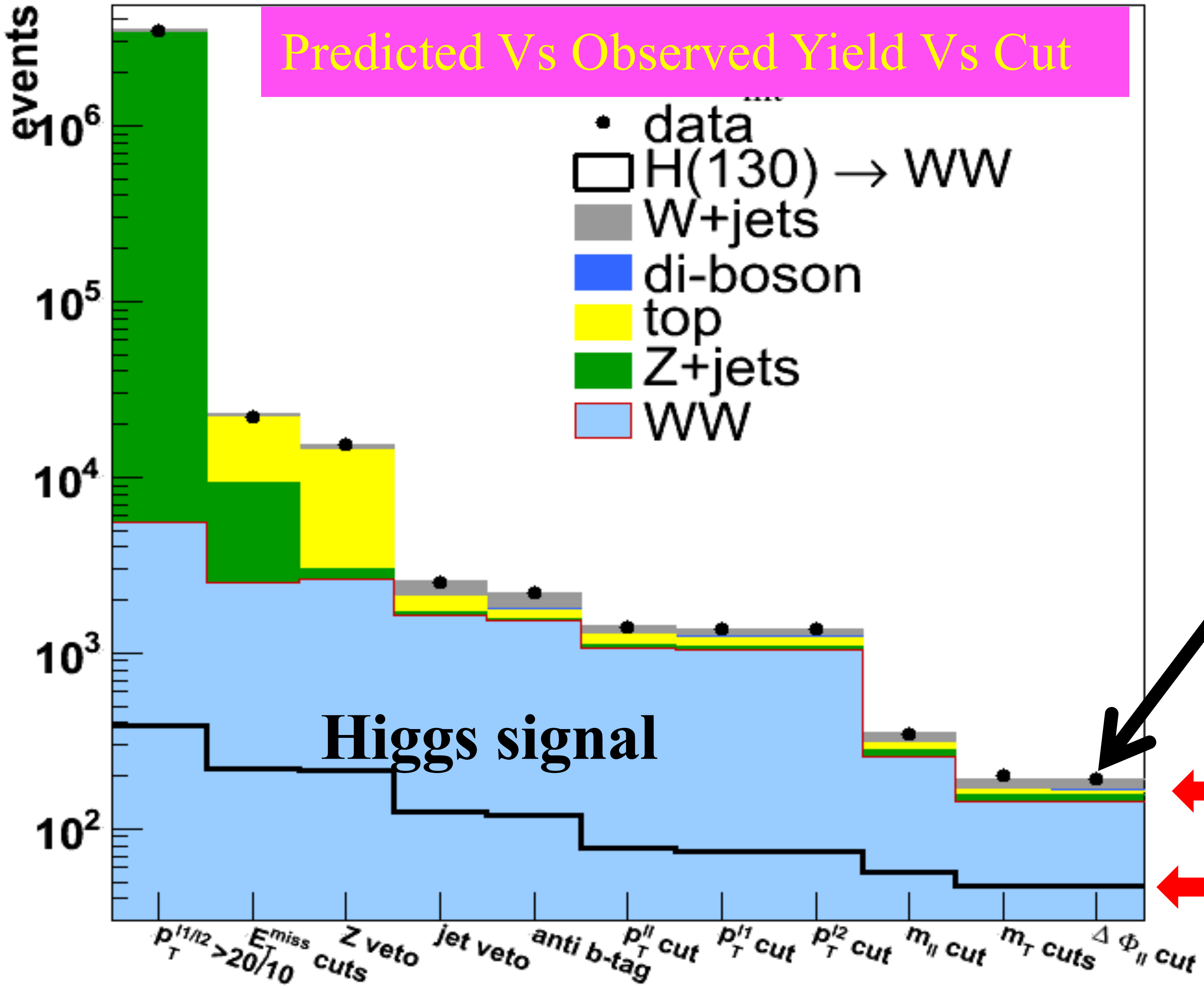
- Like a SUSY analysis, but with small lepton pTs, small MET, and the bulk of SM backgrounds (DrellYan, W+jets, $t\bar{t}$) there
  - And all these backgrounds deserved a control samples: many techniques, e.g. fake-lepton background (W+jets) estimate started here

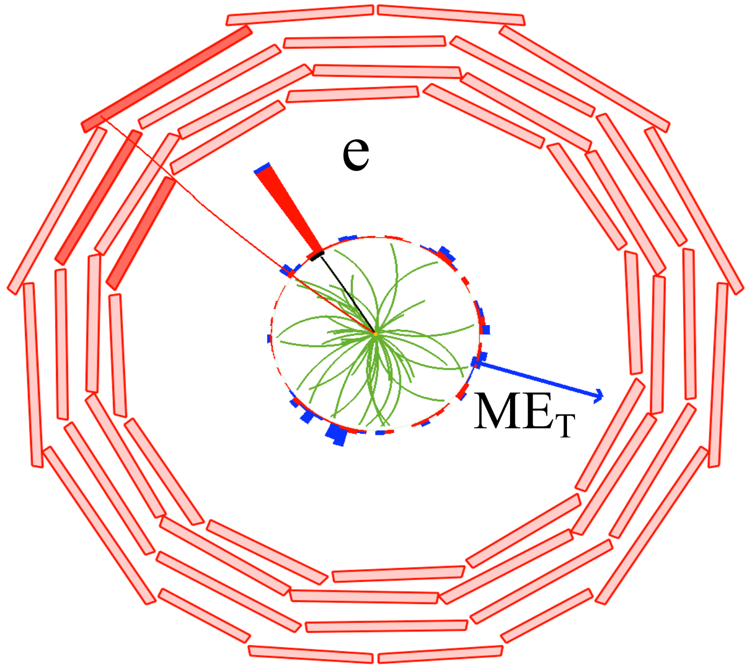
Sensitivity is all in bkg control

Large backgrounds and no mass peak implies that one needs to control backgrounds very well.

=> Here the nightmares started:

excess or BAD background estimate?





Data

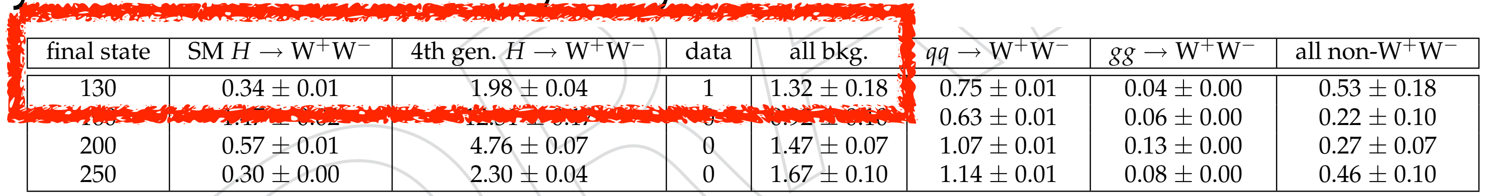
~200 background events

expect~40 Higgs events if M_H=130 GeV

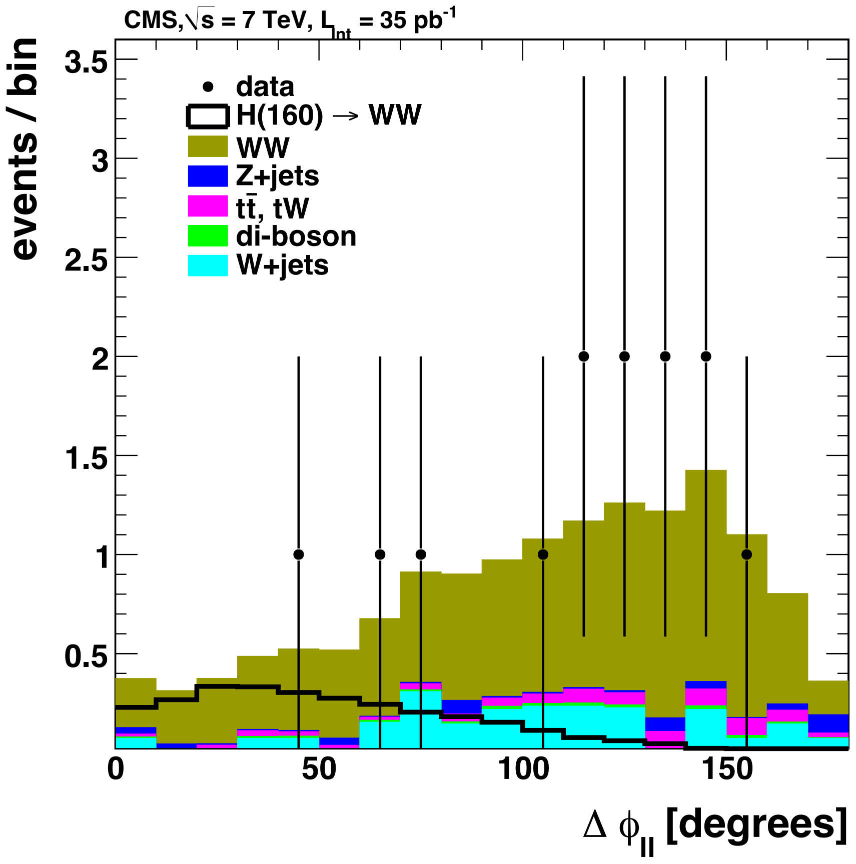
26

2010: lot of developments, small data

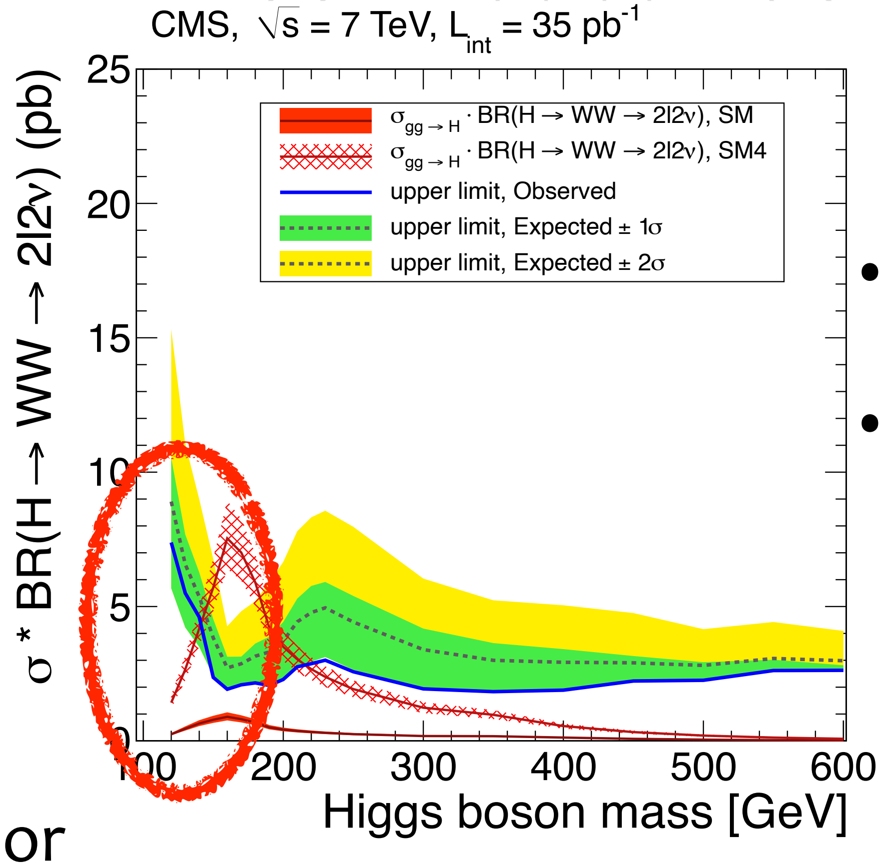
- First 35 pb^{-1} of data has shown the hunger of Higgs first analyzers:
  - The first 13 WW pre-selected events were used at maximum:
    1. The must-do “cut-based” analysis was performed, of course
    2. But already at that time, alternative analysis with BDT (one per M_H) was done: first in the LHC Higgs era.
    3. At $M_H \approx 2M_W$, sensitivity was not bad: already only 2 x SM



final state	SM $H \rightarrow W^+W^-$	4th gen. $H \rightarrow W^+W^-$	data	all bkg.	$qq \rightarrow W^+W^-$	$gg \rightarrow W^+W^-$	all non-W^+W^-
130	0.34 ± 0.01	1.98 ± 0.04	1	1.32 ± 0.18	0.75 ± 0.01	0.04 ± 0.00	0.53 ± 0.18
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.63 ± 0.01	0.06 ± 0.00	0.22 ± 0.10
200	0.57 ± 0.01	4.76 ± 0.07	0	1.47 ± 0.07	1.07 ± 0.01	0.13 ± 0.00	0.27 ± 0.07
250	0.30 ± 0.00	2.30 ± 0.04	0	1.67 ± 0.10	1.14 ± 0.01	0.08 ± 0.00	0.46 ± 0.10



$\Delta\phi_{ll}$: the spin-0 discriminator

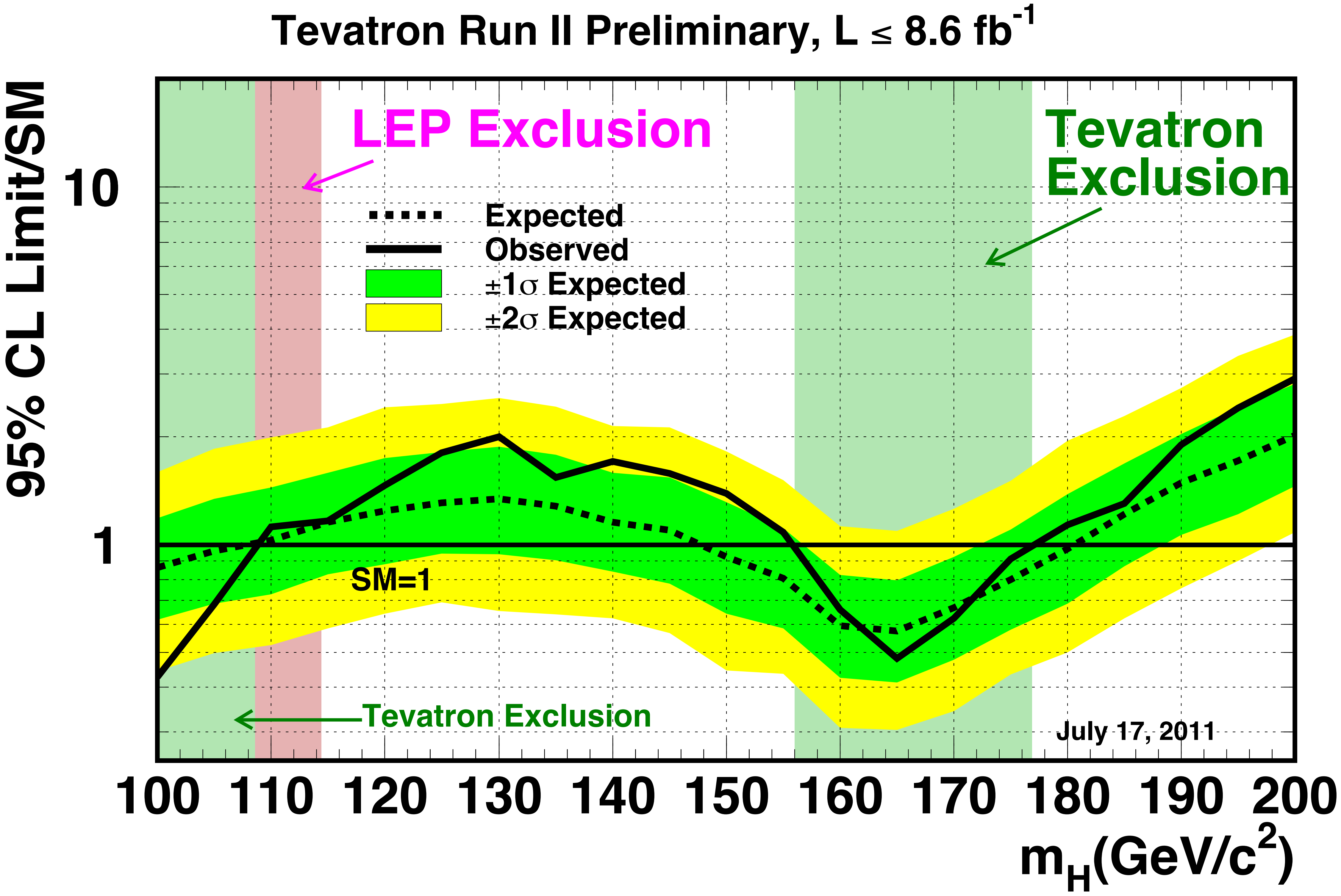


Already in 2010:

- The analysis was optimized down to $M_H = 130$ GeV
- The only excess is from 1 data point surviving the BDT analysis for $M_H = 130$ GeV
  - Of course nobody gave it a chance as signal event

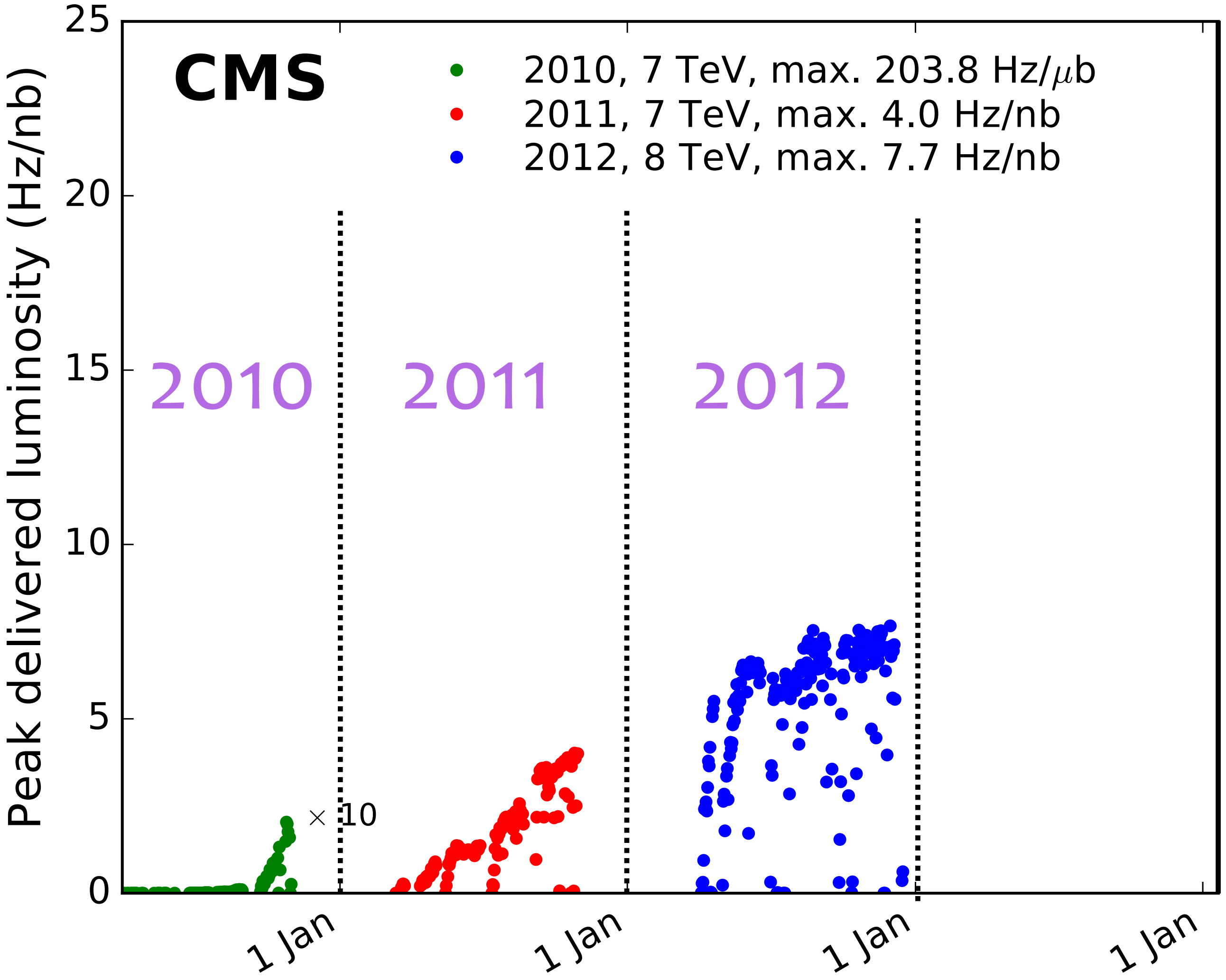
Under pressure across Atlantic

- Meanwhile Tevatron was an existential threat (above all for the initial HWW targets of a 160 GeV Higgs)



Rise of The Machine

- After the short 35 pb-1 run, LHC luminosity increased steadily in 2011 and 2012



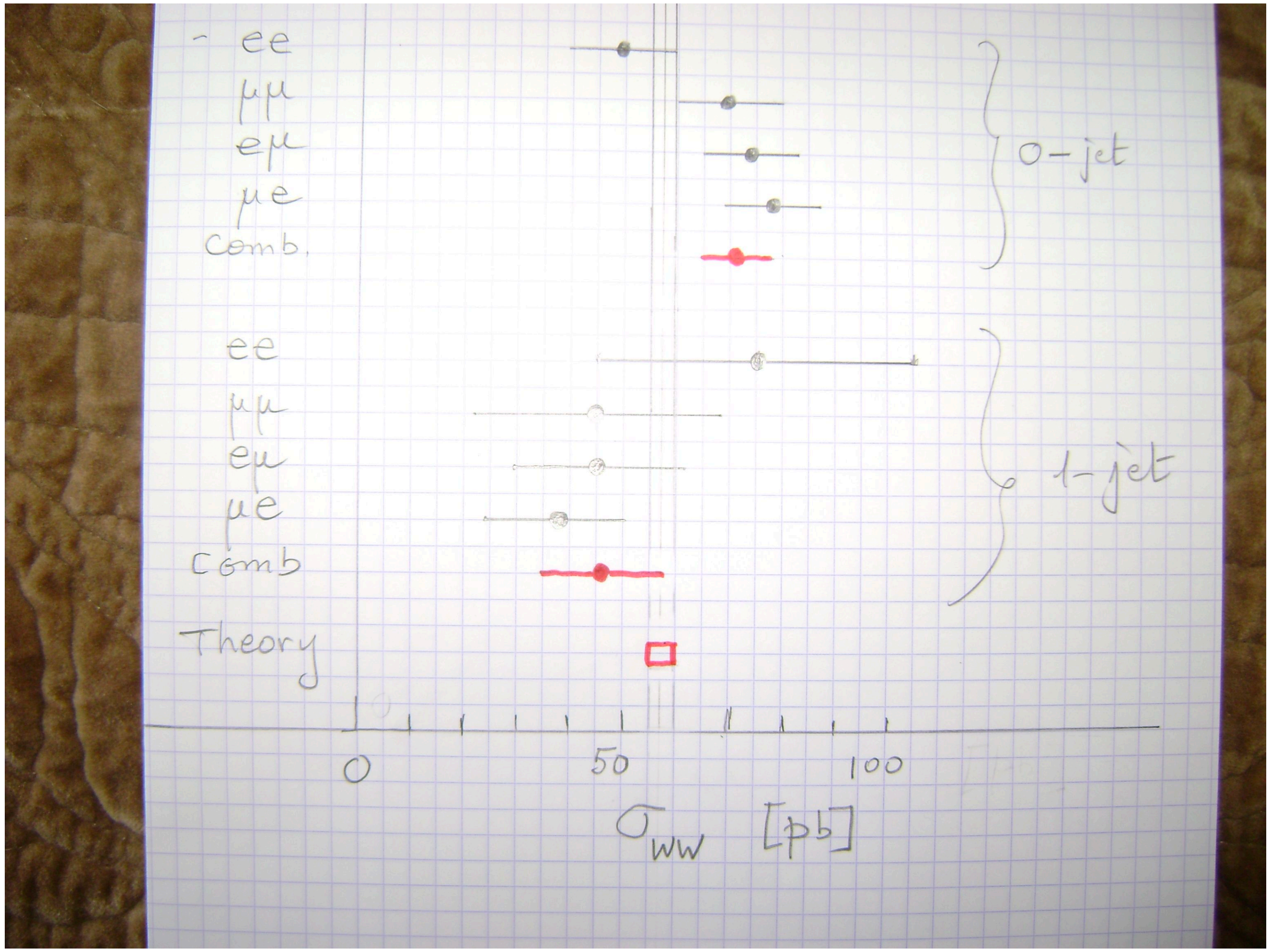
- So increased the pressure to include the latest bits of data
  - We did an update from EPS 2011 to Lepton-Photon 2011 including few pb^{-1} more taken between the two conferences
- At the same time, CMS did multiple re-reconstructions of small runs to recover any drop of data to be included in the analyses - offline & computing felt the pressure as well

The role of CERN building 32

- Great developments came also from an internal competition at fast pace
  - Continuous exchange of ideas boosted the analysis beyond the expectations
  - Along the whole Run1, two skilled groups lead the effort with undiscussed dedication
- Examples of different expertise (and opposite views on the importance of the other approach)
  - robust cut-based analyses, expertise on pp-collider background estimates, first usage of MVAs
  - shape fitting, inclusion of multiple categories, development of innovative statistical tools (Higgs combination dawn, BTW)
- Produced *more than 30 internal analysis notes* on this analysis in 2010/2011/2012
- Most of them were written during long nights at **CERN, building 32**
- Any big update (EPS11, LeptonPhoton, CERN seminar, ICHEP 2012) was preceded by weeks of **daily meetings (at CERN B32 as well)**

No analysis without good review

- The first HWW analysis with data (and until the discovery) was assigned to a review committee of excellent physicists



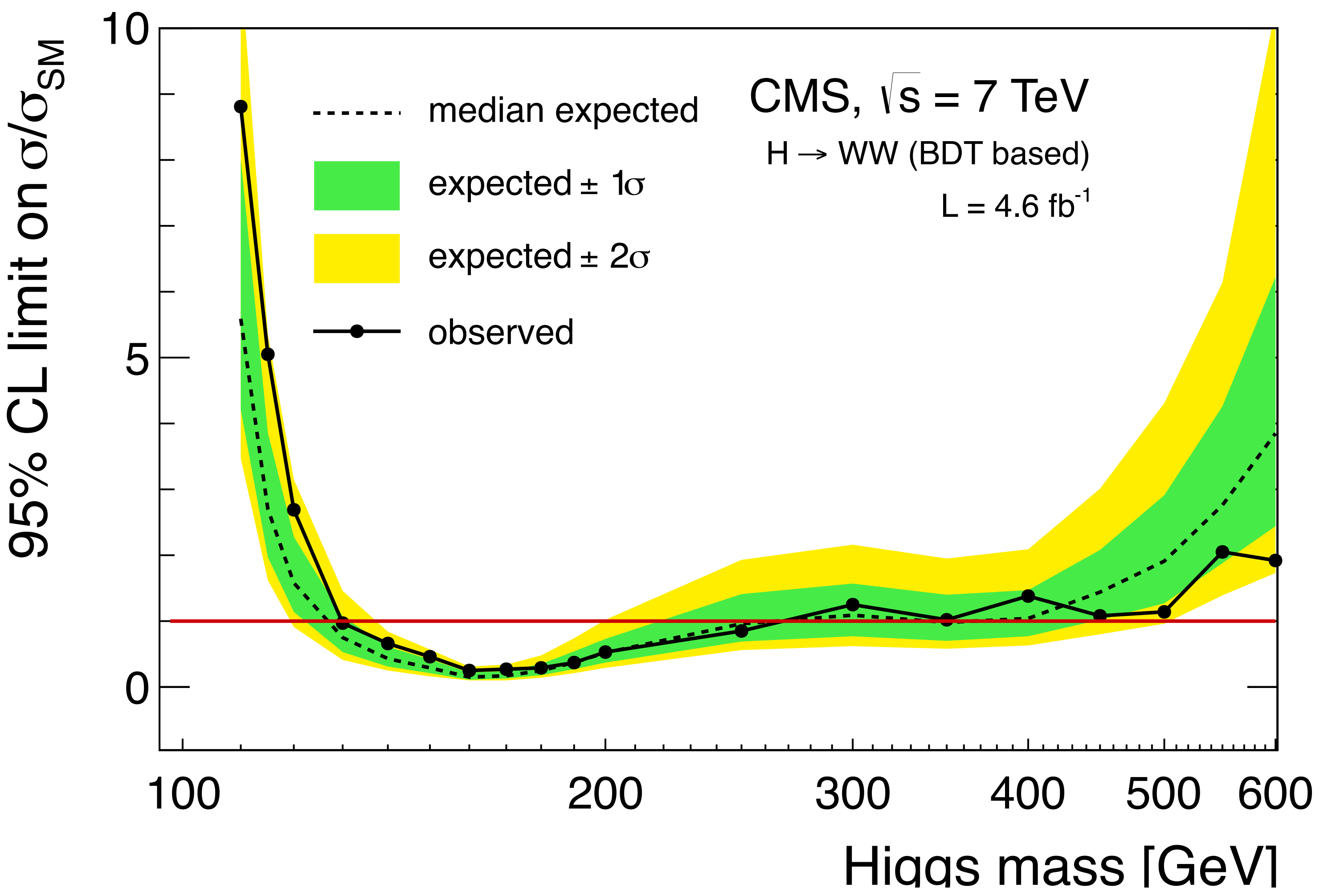
Example of good-old-style checks:
2011 analysis review

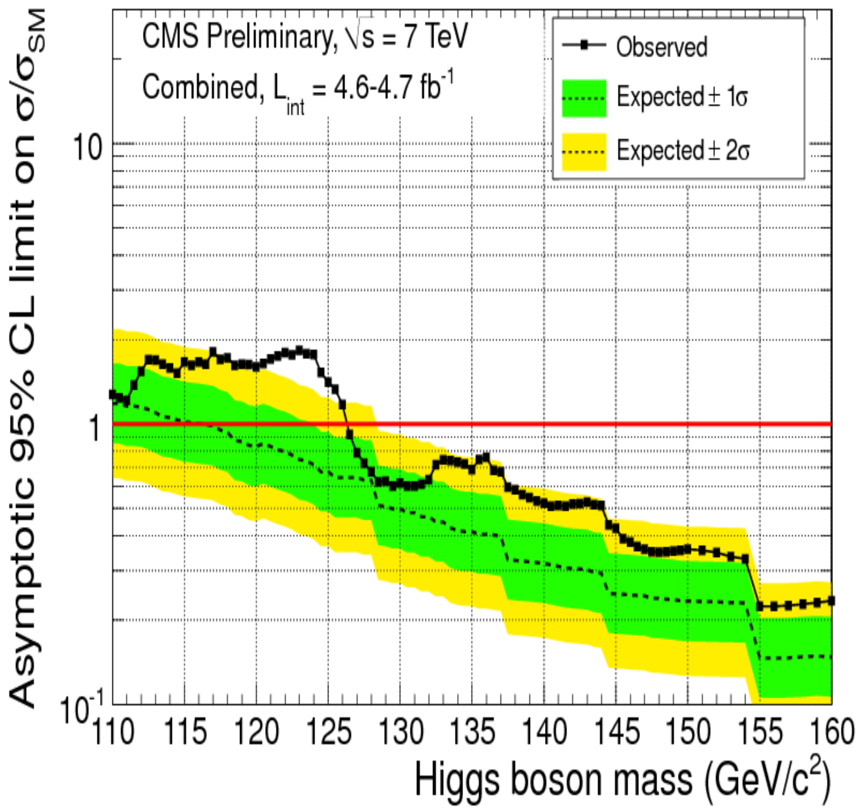
Example of worries from the emerging signal, but on a channel w/o mass peak:

“Congratulations for the green light. I would like to share with you the following worry: There is a 2 sigma discrepancy between observed and expected limit in the mass range [130, 170]. The question will come: Is it a statistical fluctuation or an underestimation of the errors? The systematic error on the shape needs to be properly addressed.”

Results at the end of 2011

- By the end of 2011, LHC delivered $\approx 5\ \mathrm{fb}^{-1}$ per experiment.
  - $H \rightarrow WW$ alone ruled out a SM Higgs boson with a mass [129 - 270] GeV at 95% CL
  - Together with the other channels, and putting together ATLAS+CMS, Higgs boson was restricted in a rather narrow range.
    - And the small excess was spread in WW up to $M_H \approx$ 130 GeV

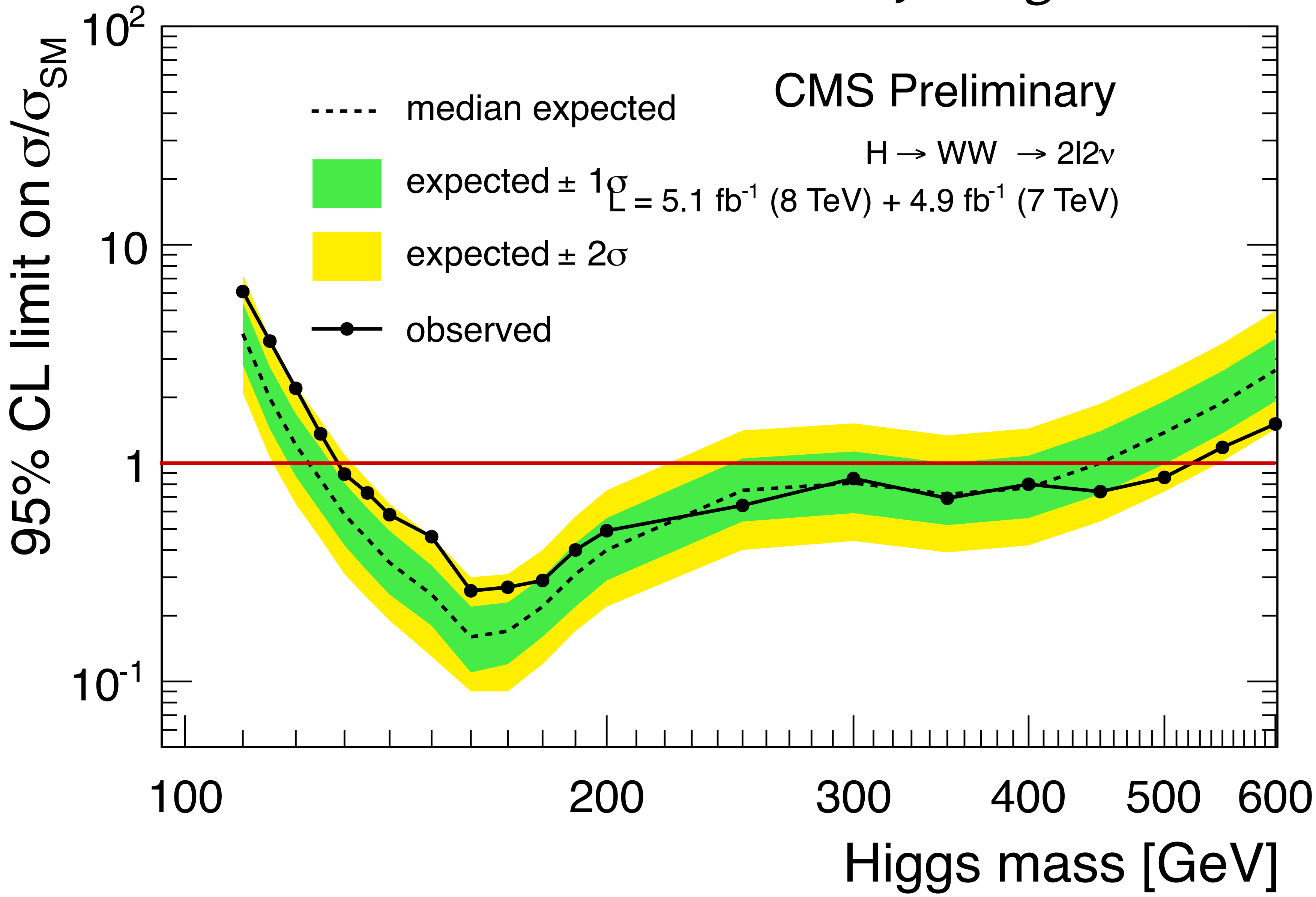


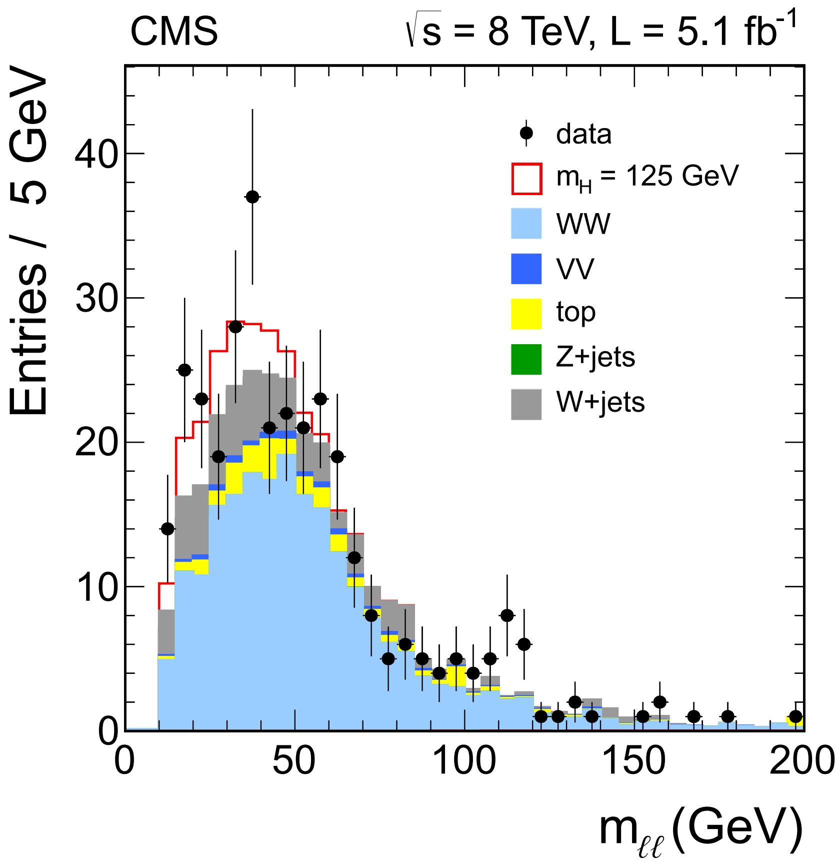


$H \rightarrow WW$, end of 2011

Discovery data: $H \to WW$ limits

Unblinding night in 2012: *took from midnight to 6 am to convince ourselves that everything was ok*



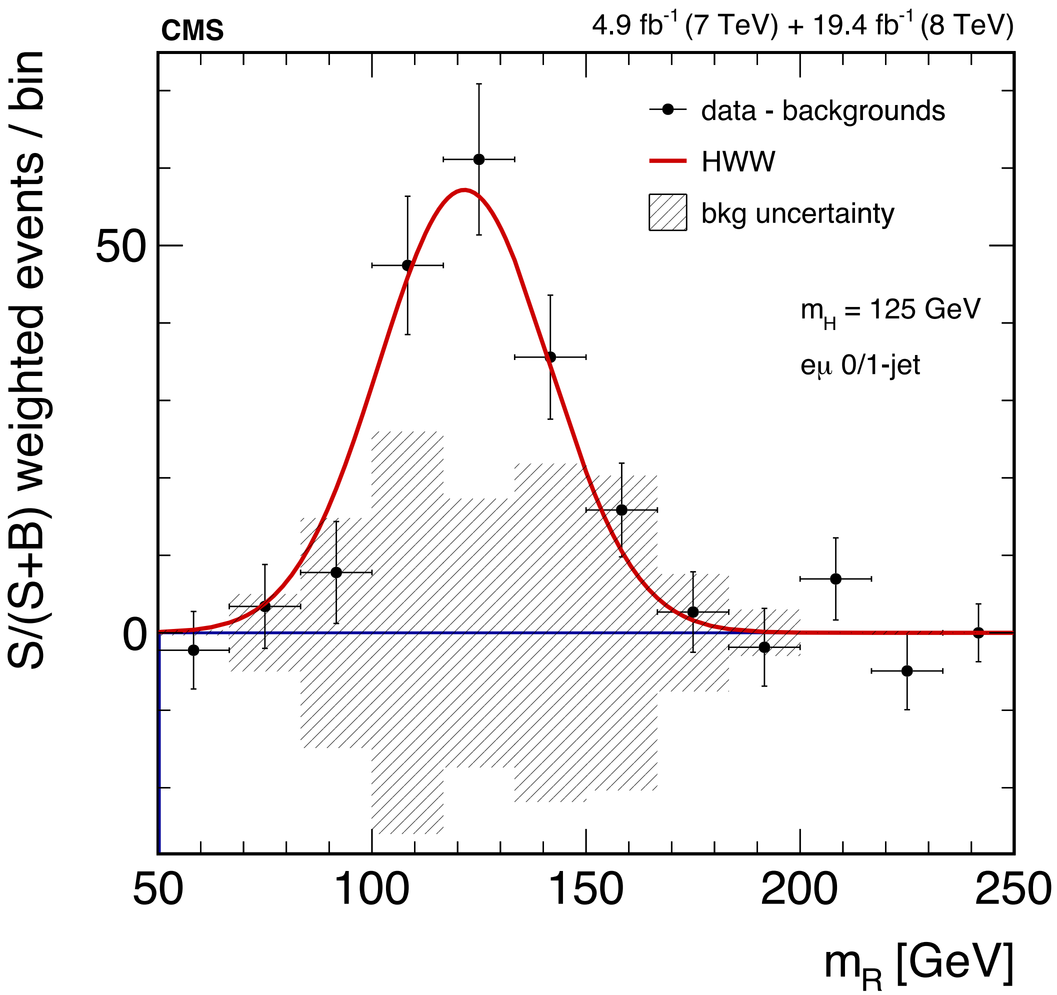


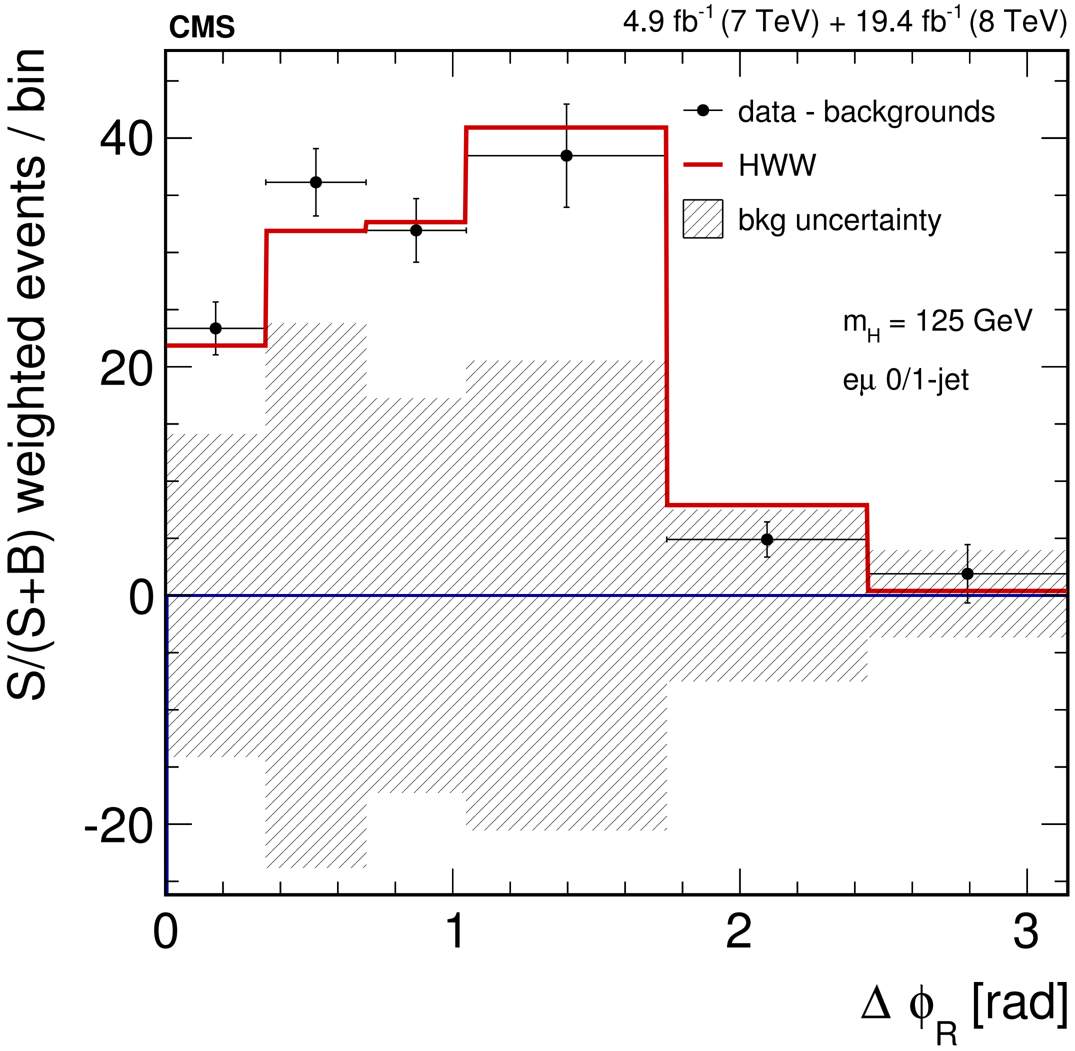
Observed Exclusion at 95% CL: $129 < M_H < 520$ GeV.

A small excess at low masses

And with full Run1 data

- A "mass peak" done with a kinematic variable initially developed for SUSY decay chains with multiple invisible particles (here the 2 neutrinos)





$$m_{\mathrm{R}} = \sqrt{\frac{1}{2}\left[m_{\ell\ell}^2 - \vec{E}_{\mathrm{T}}^{\mathrm{miss}} \cdot \vec{p}_{\mathrm{T}}^{\ell\ell} + \sqrt{(m_{\ell\ell}^2 + (p_{\mathrm{T}}^{\ell\ell})^2)(m_{\ell\ell}^2 + (E_T^{\mathrm{miss}})^2)}\right]}$$

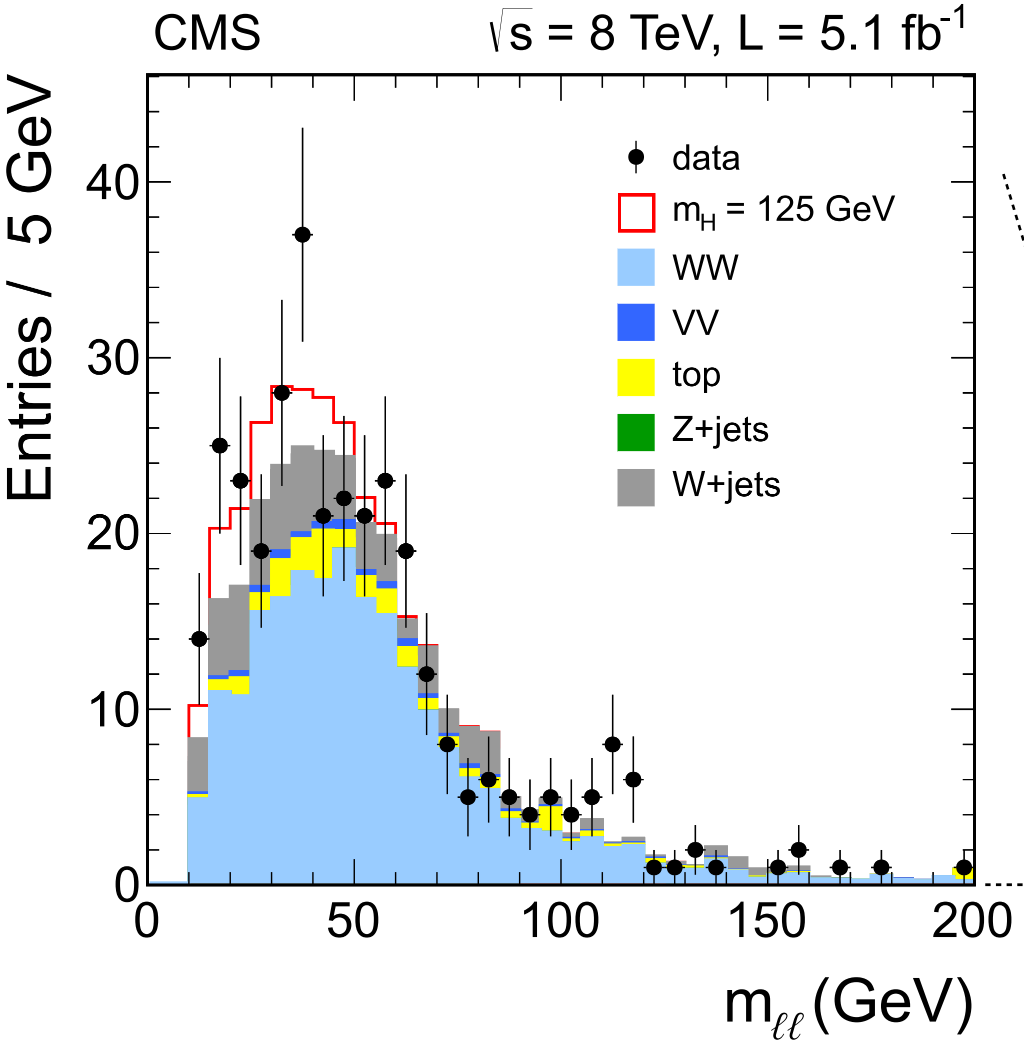
Make clear HWW

≈20 GeV mass resolution…

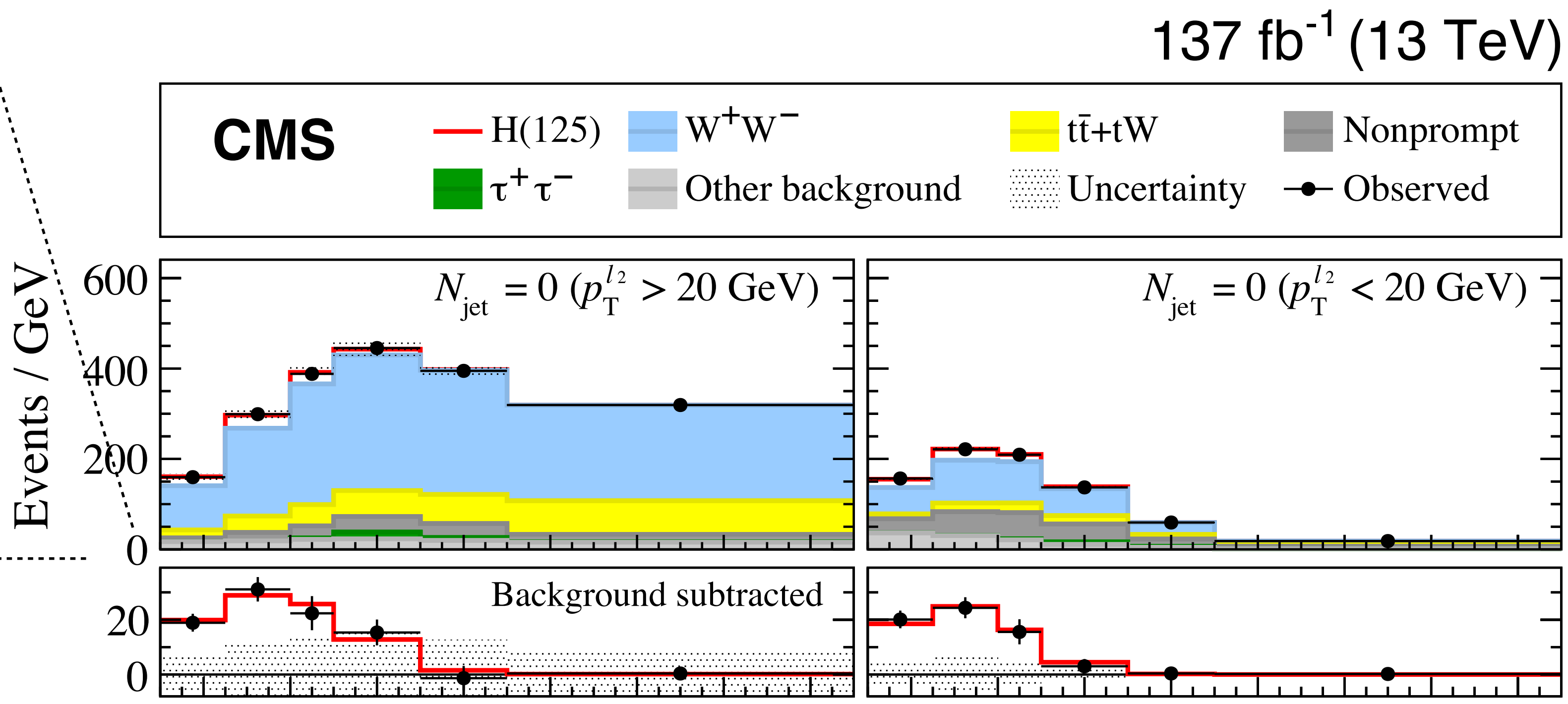
and matches the expectation of a small lepton $\Delta\phi$ for a spin-0 particle decaying to 2 vector bosons

$H \rightarrow WW^*$: discovery and today

Higgs boson discovery: end of Run-1



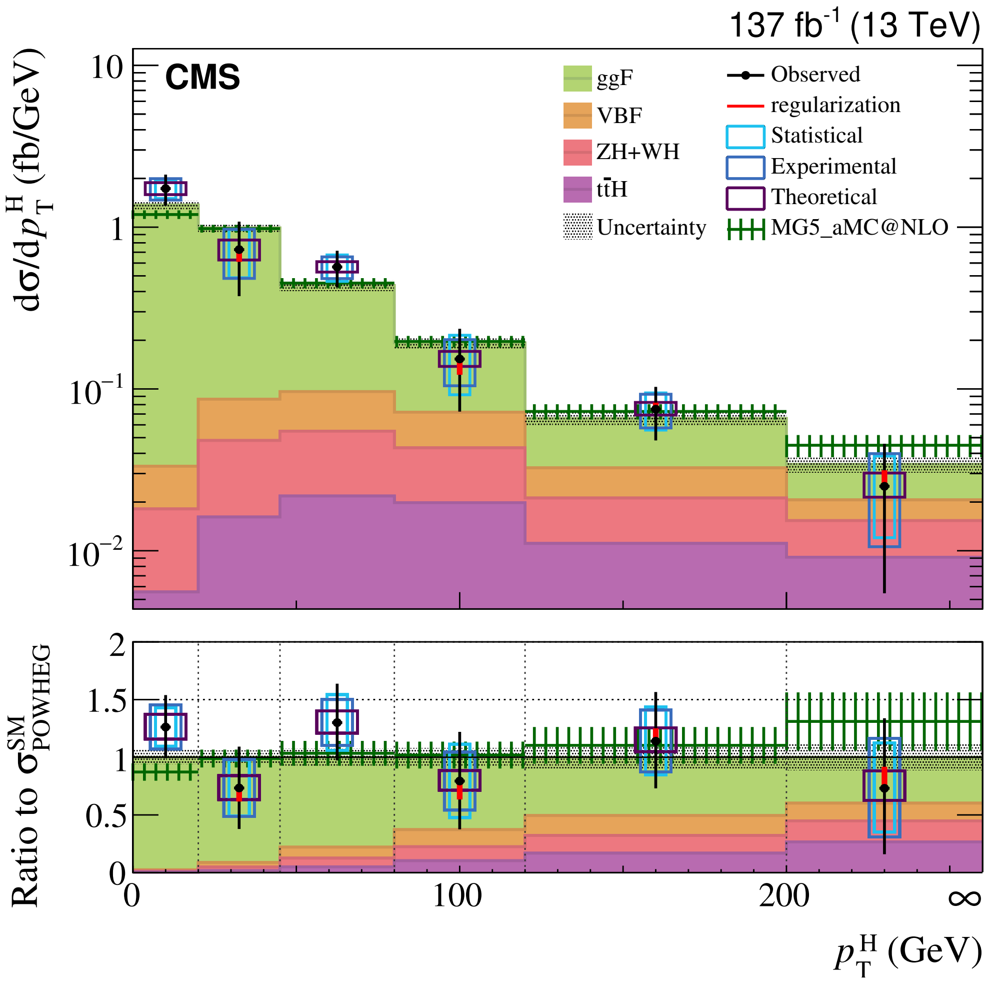
End of Run-2



Not a high resolution channel due to neutrinos in the final state, but the workhorse of the decay rate, due to the high BR

And at the dawn of Run3

- It remains a challenging channel: all the physics object need tuning with higher pileup, irradiation, etc.



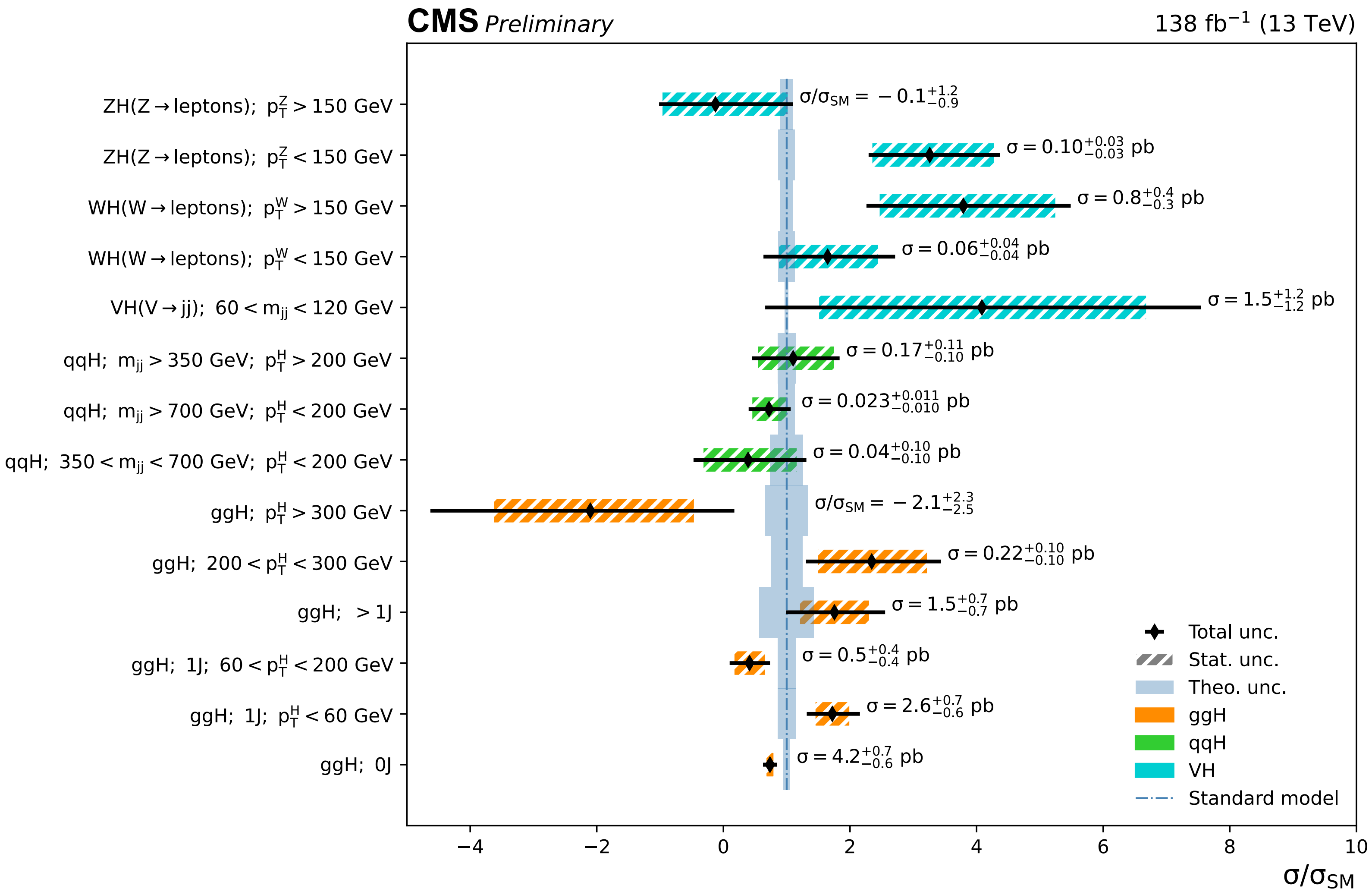
Differential x-sections

Cross Sections, eg.

Simplified Template X-Sections

for ggH, qqH, VH

(And ttH in a dedicated analysis)

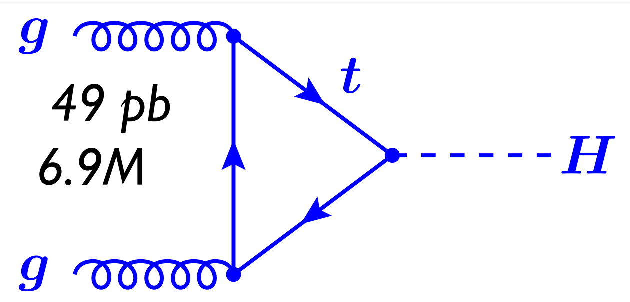


Summary

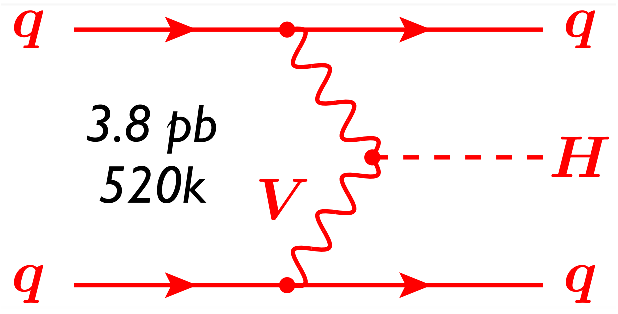
- The $\mathrm{H} \rightarrow \mathrm{WW}$ channel has been the first one with the responsibility to be carried on
  - Initially thought only for a restricted mass range around $2M_W$, has been instead one of the three big $H \rightarrow VV$ brothers to contribute to the discovery of H(125)
  - The $2\ell 2\nu$ final state has been such to need to drive the optimisation of many physics objects in CMS: leptons, but also MET, jets
    - And also many analysis techniques, from bkg estimates to statistic tools
    - on these grounding is still part of the CMS success today
- Nowadays and in the future:
  - It remains the same challenging, dirty workhorse of 10 years ago: increased PU, detector varying conditions makes any result update a difficult job
  - Despite no mass peak, it remains one of the driving channels for the x-section related measurements
    - Differential cross sections, STXS, rarer associated production (eg. $t\bar{t}H$)
- Last, but not least, it is where young physicists can learn pp phenomenology at 360° while studying this 10 years old new particle

extras

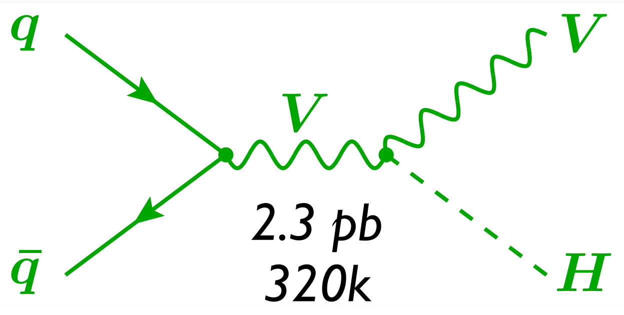
The LHC Higgs factory



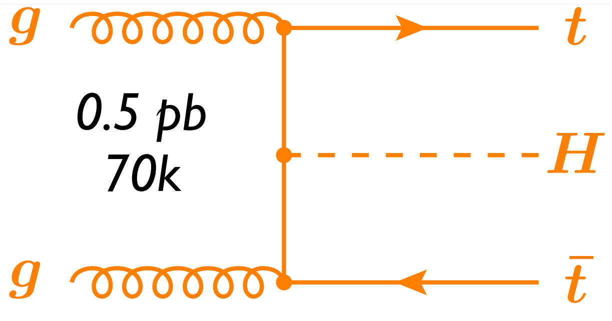
gluon fusion



vector boson fusion (VBF)



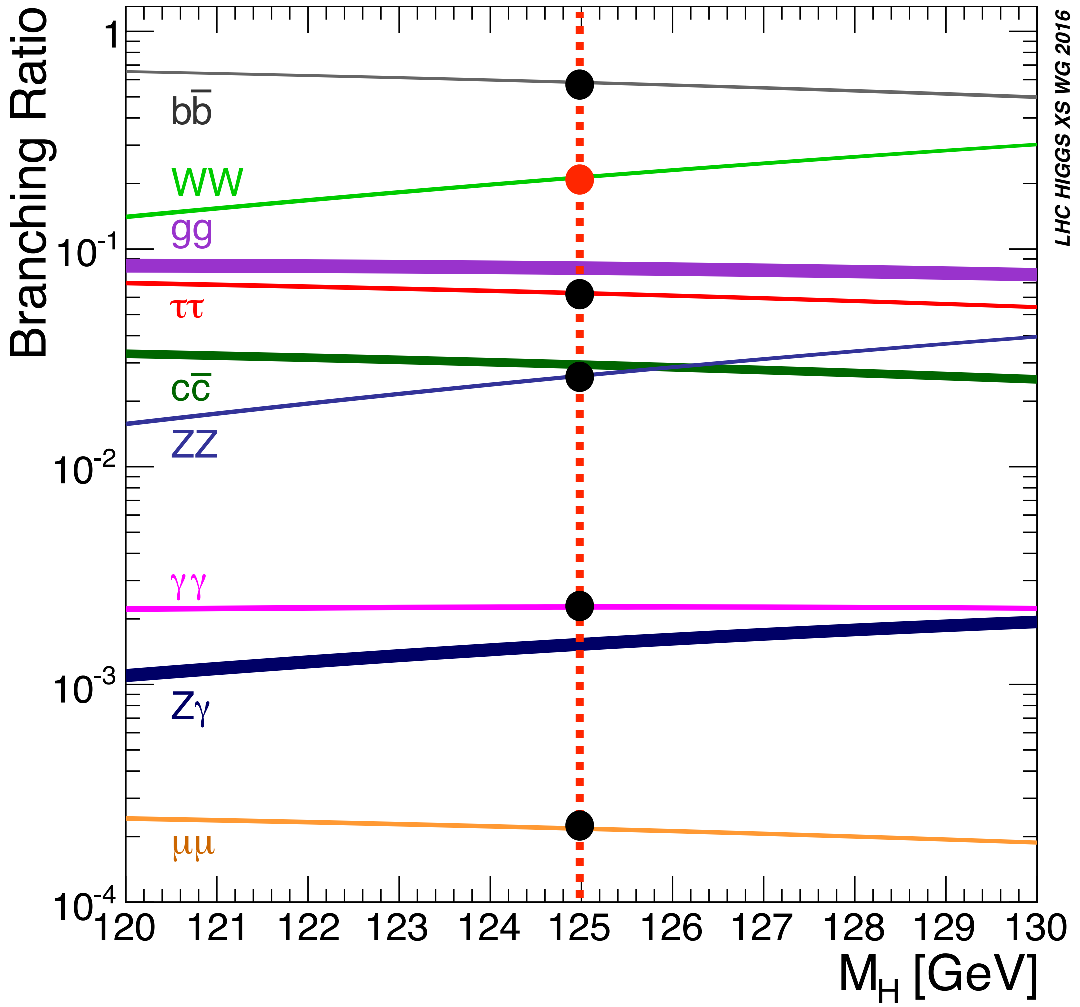
W,Z associated production



$t\bar{t}H$ associated production

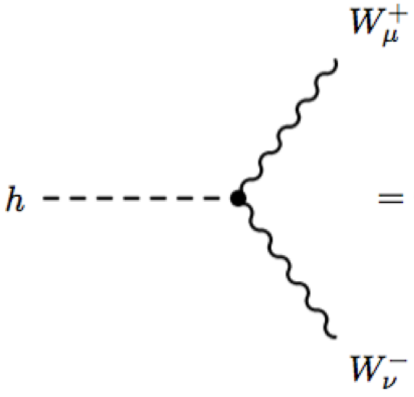
σ [pb]
#Higgs produced during Run-2

- For $m_H \sim 125\ \mathrm{GeV}$ a wide range of production and decay modes accessible
- $H \to b\bar{b}$ not viable at startup: WW was the workhorse at startup !

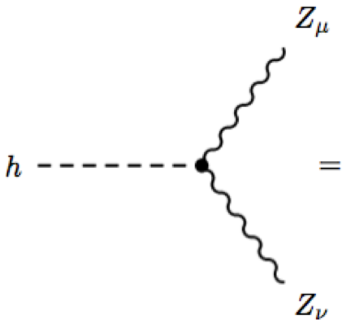


Higgs couplings to gauge bosons

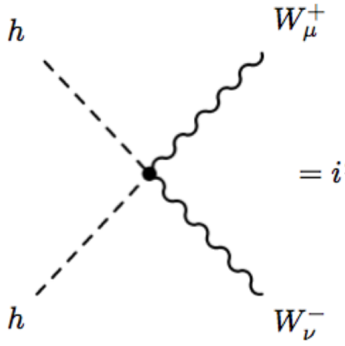
$$\mathscr{L}_{H-W/Z} = \frac{1}{2}(v+\Phi)^2\left[\frac{g_2^2}{2}W_\mu^+W^{-\mu} + \frac{g_2^2+g_1^2}{4}Z_\mu Z^\mu\right]$$



$$= i\frac{g^2 v}{2}g_{\mu\nu} = 2i\frac{M_W^2}{v}g_{\mu\nu}$$



$$= i\frac{(g^2+g'^2)v}{4}\cdot 2g_{\mu\nu} = 2i\frac{M_Z^2}{v}g_{\mu\nu}$$

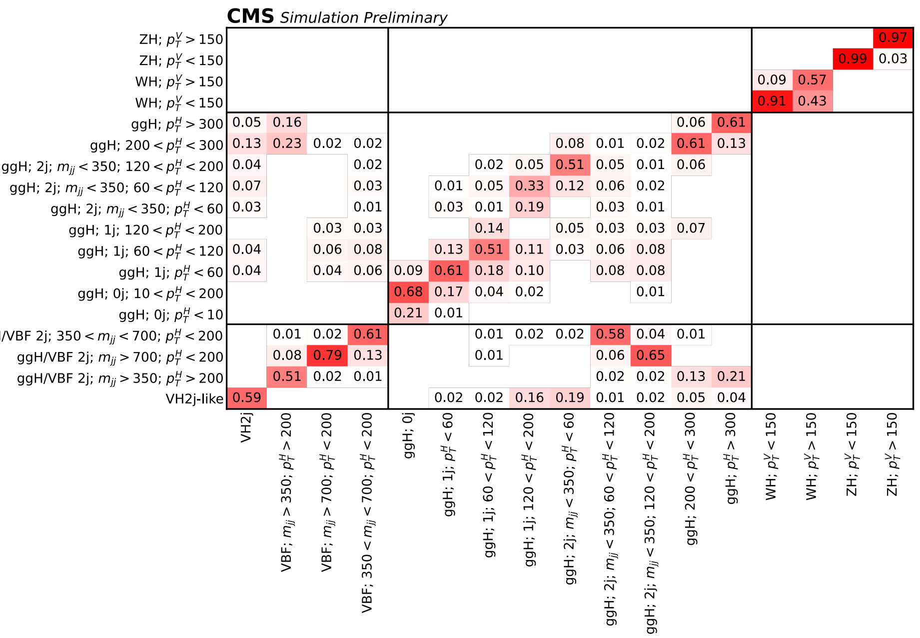


$$= i\frac{g^2}{4}\cdot 2g_{\mu\nu} = 2i\frac{M_W^2}{v^2}g_{\mu\nu}$$

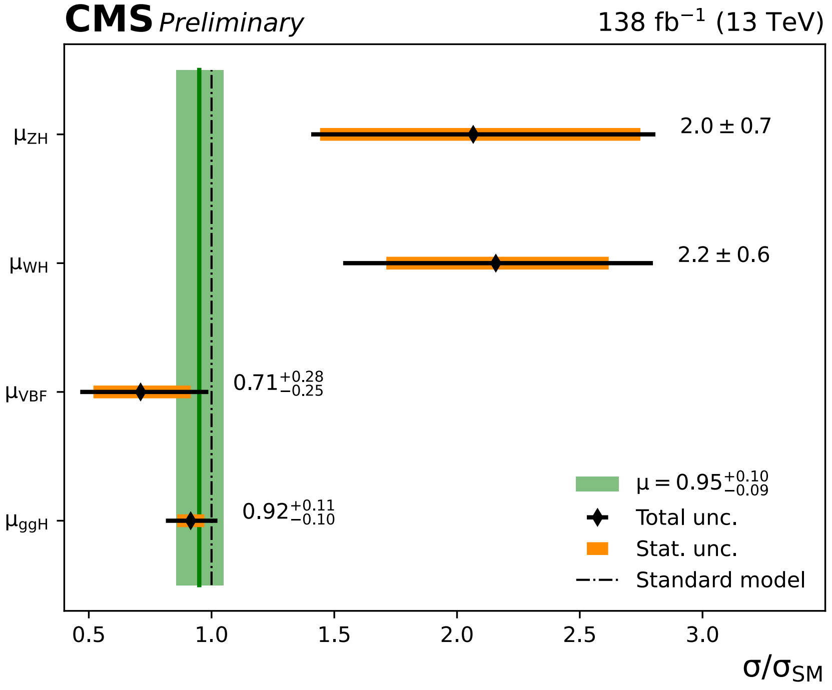
- Tree level couplings proportional to masses
- The couplings govern the (single and double) Higgs boson production and the branching ratios
  - at the LHC the large datasets of Run1 - Run2 and just started Run3 provides evidence of their realization in nature
- One of the primary goals of the LHC program is to look for deviations from these SM couplings and thus the precise determination of the shape of the Higgs potential

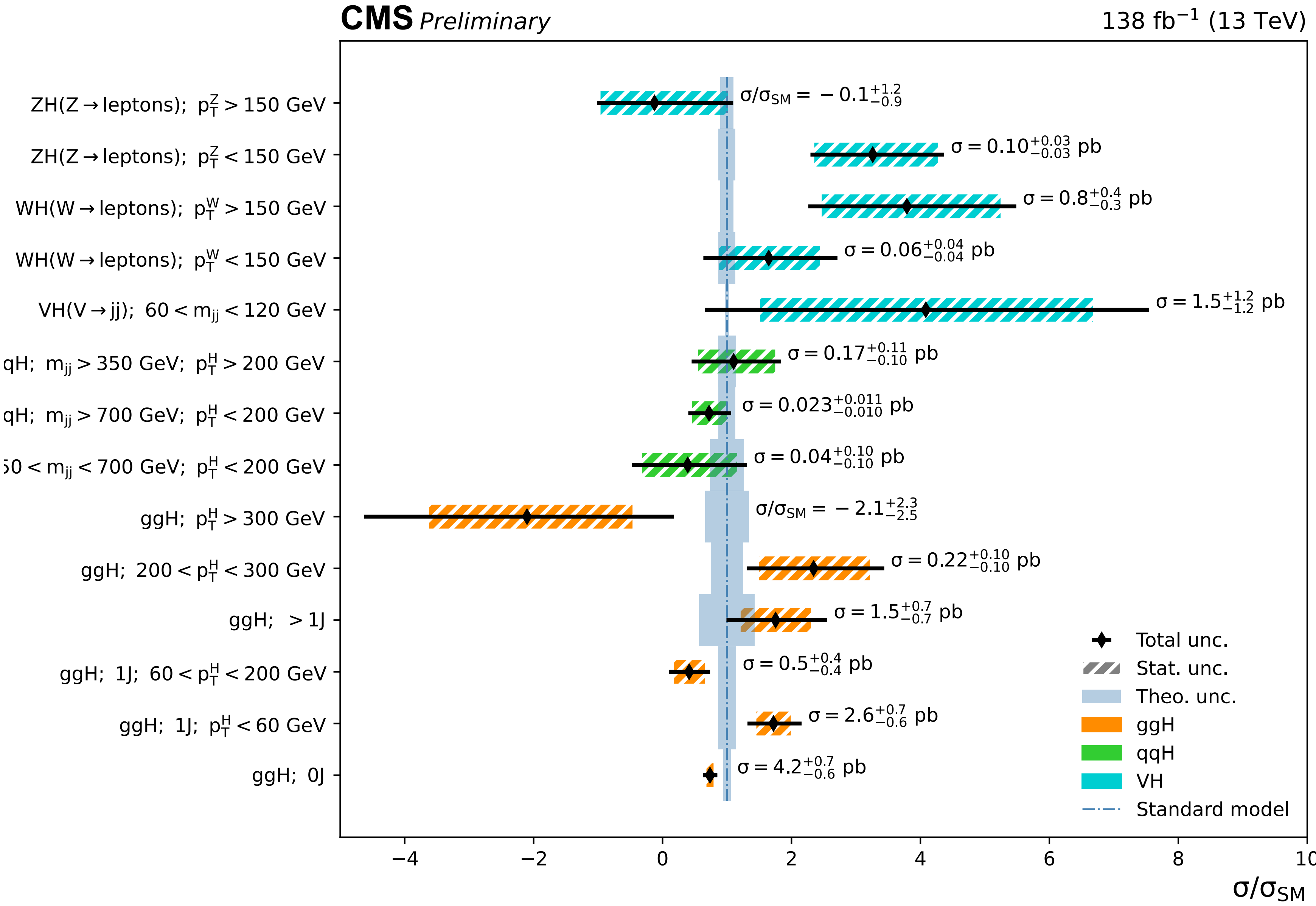
STXS, $H \to WW^*$

- Limited by signal uncertainty and background estimate



μ per production mode

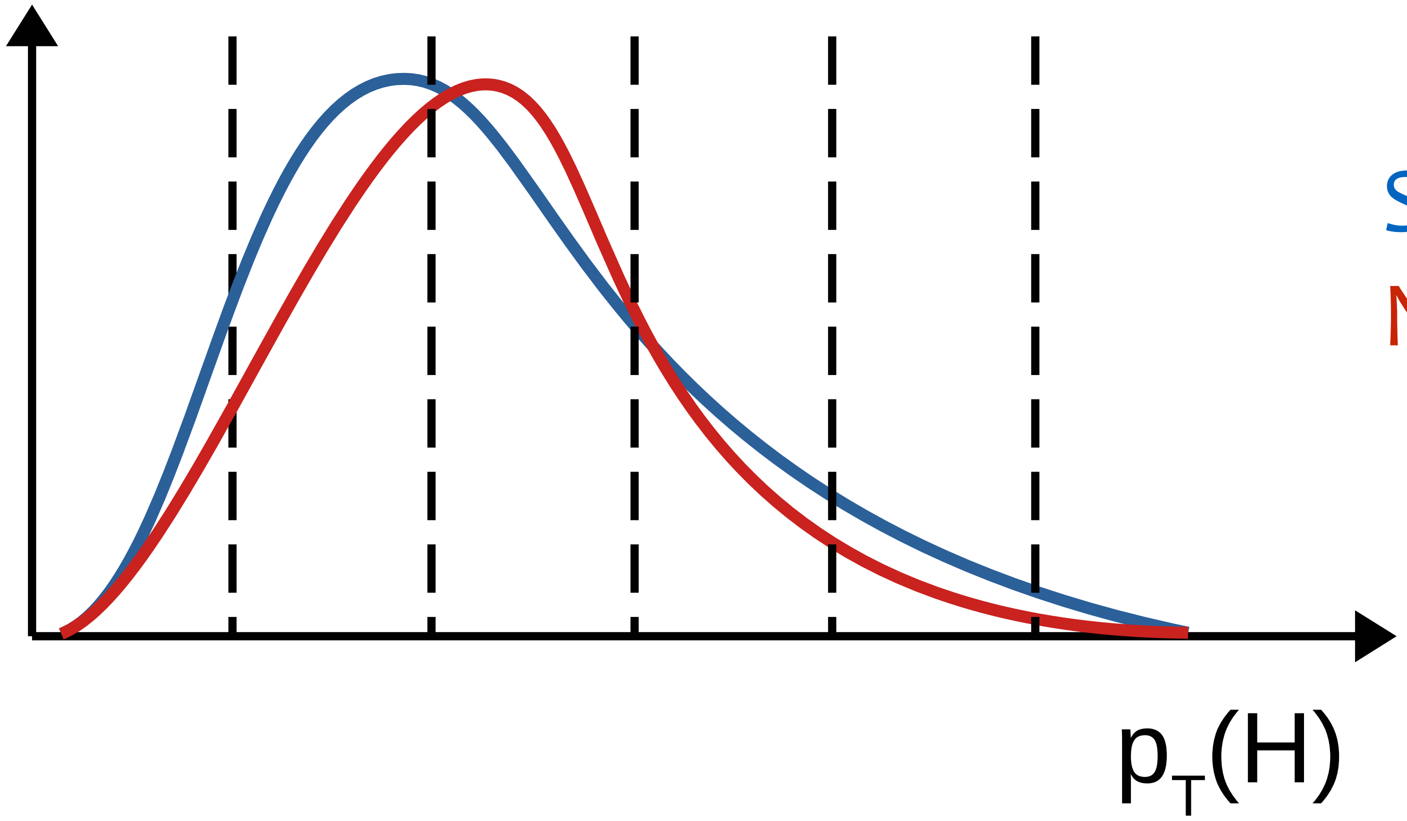




STXS results

Differential cross sections

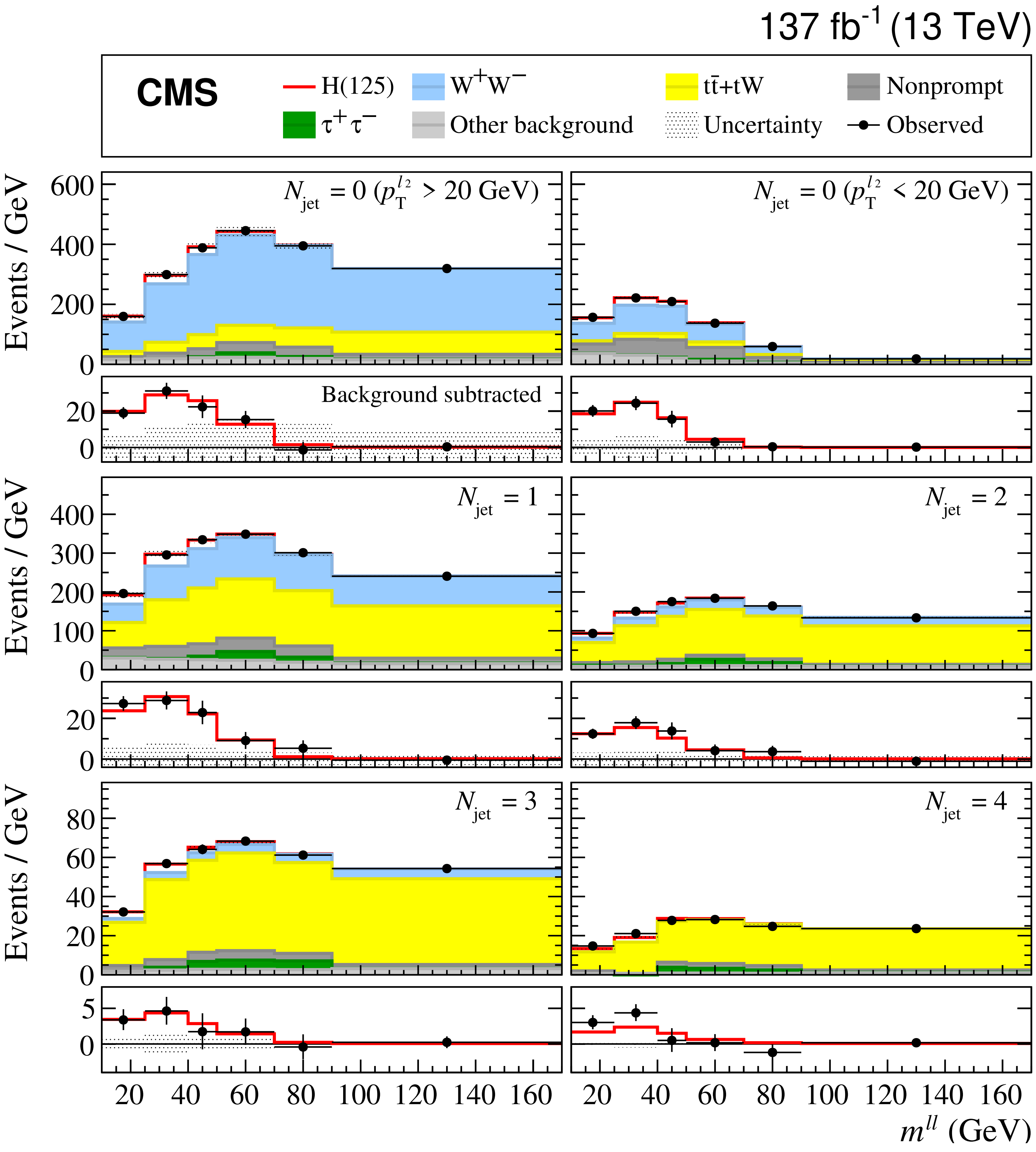
- A more classical approach is measuring differential cross sections in many variables
  - with increasing precision, the shape of kinematic variables are sensitive to new physics



- Typical obs tics of associated jets, etc.

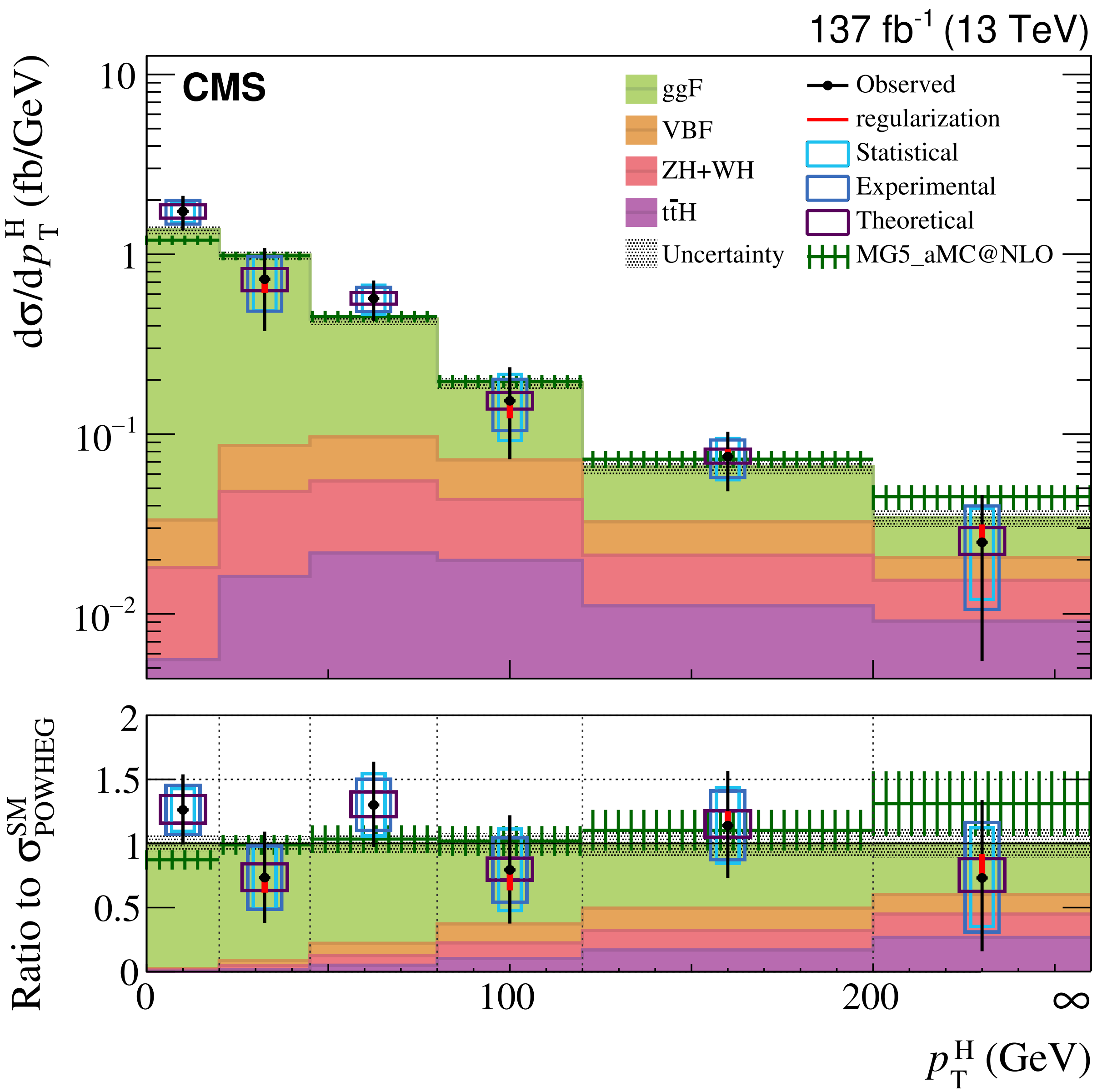
$H \rightarrow WW^*$

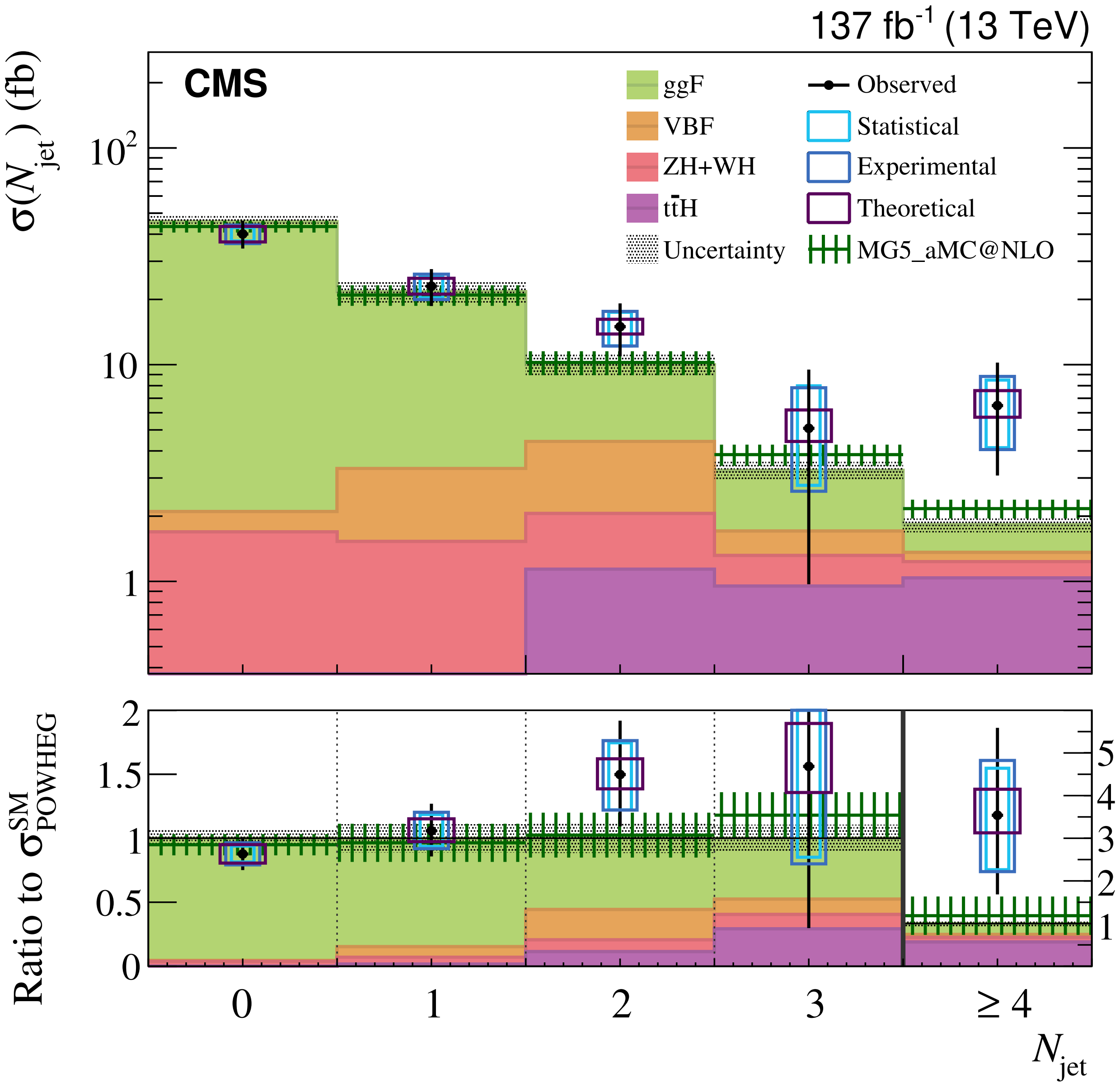
- The viable final state is $H \rightarrow 2\ell 2\nu$: the two undetected neutrinos make it a challenging channel
  - need control of large top and fake lepton background
  - large sensitivity to cross section due to large BR compared to 4l or $\gamma\gamma$



$H \to WW^*$: differential

- Large BR allows measuring precisely high pT(H) and n(jets)>2
  - uncertainty 85% in the last p_T^H bin





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$$\mu_{\text{fid}} = 1.05 \pm 0.12 \;\; \left(\pm 0.05 \;(\text{stat}) \pm 0.07 \;(\text{exp}) \pm 0.01 \;(\text{signal}) \pm 0.07 \;(\text{bkg}) \pm 0.03 \;(\text{lumi})\right)$$

VH, H → WW*

- Measured of VH,H→WW with V going to leptons
  - Observed (expected) signal significance: 4.7 σ (2.8)
  - cross section is extracted as a function of the vector boson p_T

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1-jet bin