The Hunt for the Higgs Boson

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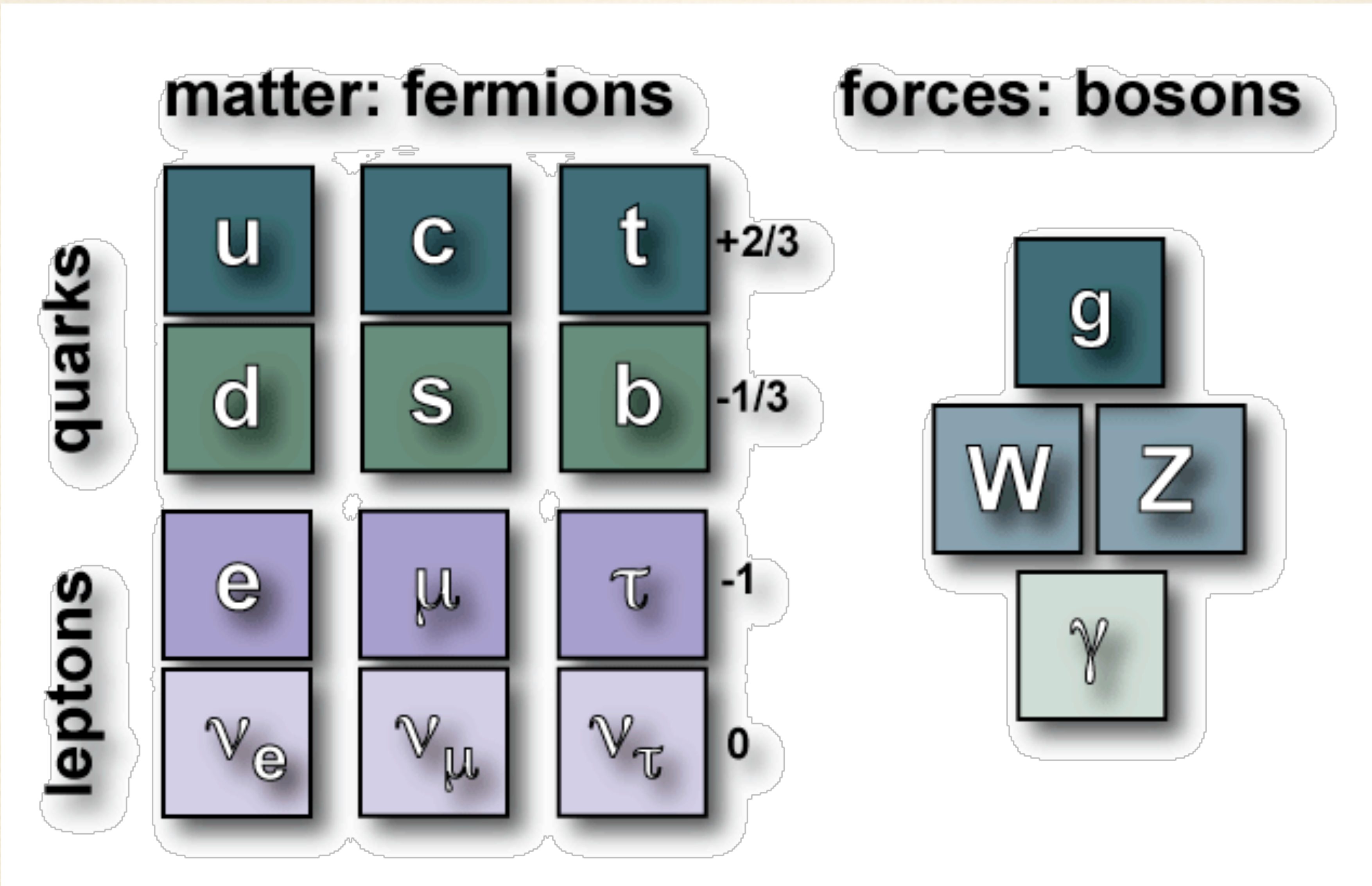
Univ. of California, Davis

Haber-Dine Symposium

January 4, 2013

The Quarry

After the revolution of the '70s and '80s, we have a wonderfully simple table of the fundamental particles...



...but a rather complicated description:

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f(i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f\bar{\Psi}_f\gamma^\mu\Psi_f A_\mu) +$$

$$+\frac{g}{\sqrt{2}}\sum_i(\bar{a}^i_L\gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L\gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w}\sum_f \bar{\Psi}_f\gamma^\mu(I^3_f - 2s^2_w Q_f - I^3_f\gamma_5)\Psi_f Z_\mu +$$

$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w(W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

$$-\frac{1}{2}M^2_\eta\eta^2 - \frac{gM^2_\eta}{8M_W}\eta^3 - \frac{g'^2 M^2_\eta}{32M_W}\eta^4 + |M_W W^+_\mu + \frac{g}{2}\eta W^+_\mu|^2 +$$

$$+\frac{1}{2}|\partial_\mu\eta + iM_Z Z_\mu + \frac{ig}{2c_w}\eta Z_\mu|^2 - \sum_f \frac{g}{2}\frac{m_f}{M_W}\bar{\Psi}_f\Psi_f\eta$$

(Ignore the missing parenthesis...sorry.)

...but a rather complicated description:

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f(i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f\bar{\Psi}_f\gamma^\mu\Psi_f A_\mu) +$$

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$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w(W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

$$-\frac{1}{2}M^2_\eta \eta^2 - \frac{gM^2_\eta}{8M_W}\eta^3 - \frac{g'^2 M^2_\eta}{32M_W}\eta^4 + |M_W W^+_\mu + \frac{g}{2}\eta W^+_\mu|^2 +$$

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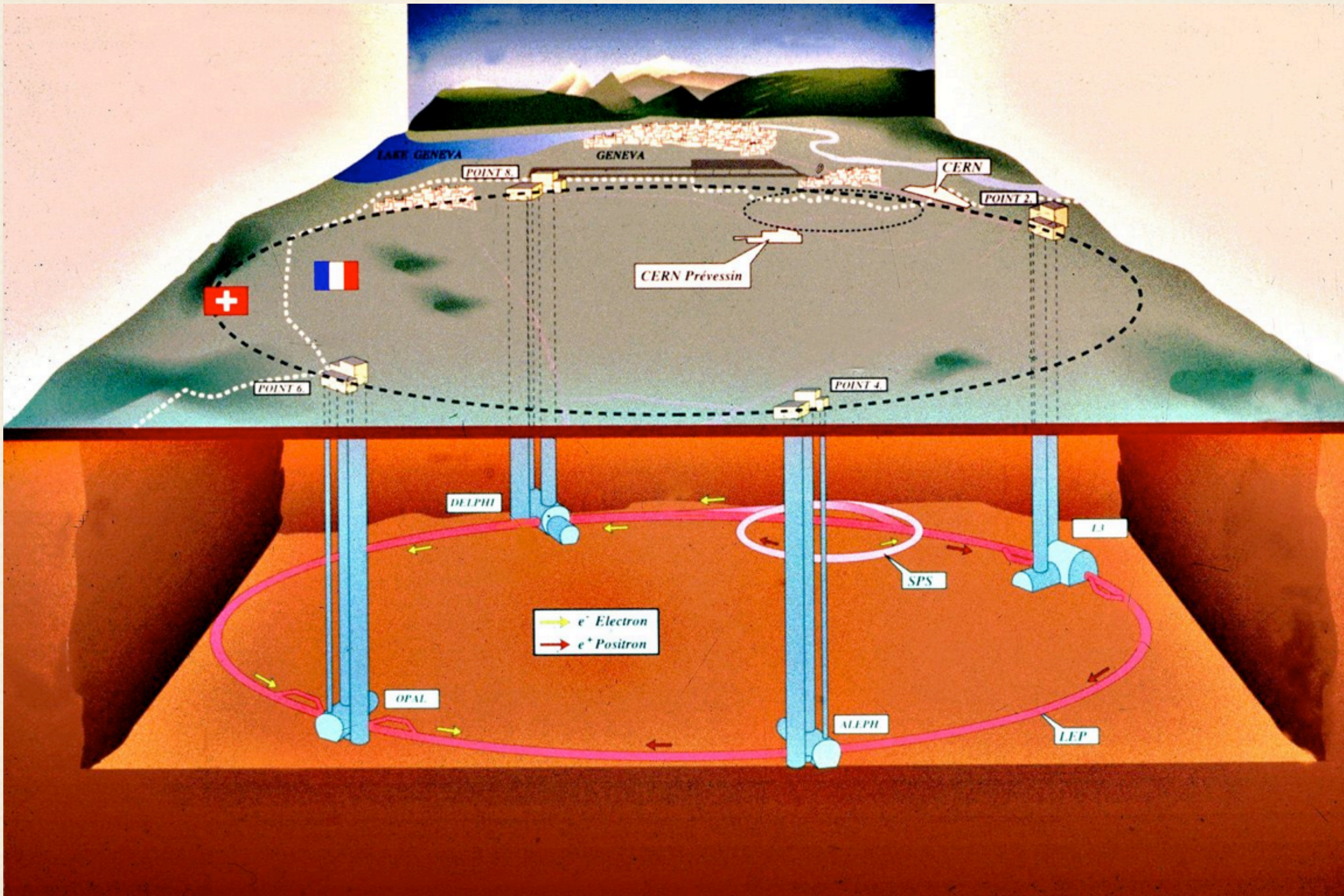
The Hunt Begins!

The hunt began at LEP in 1989

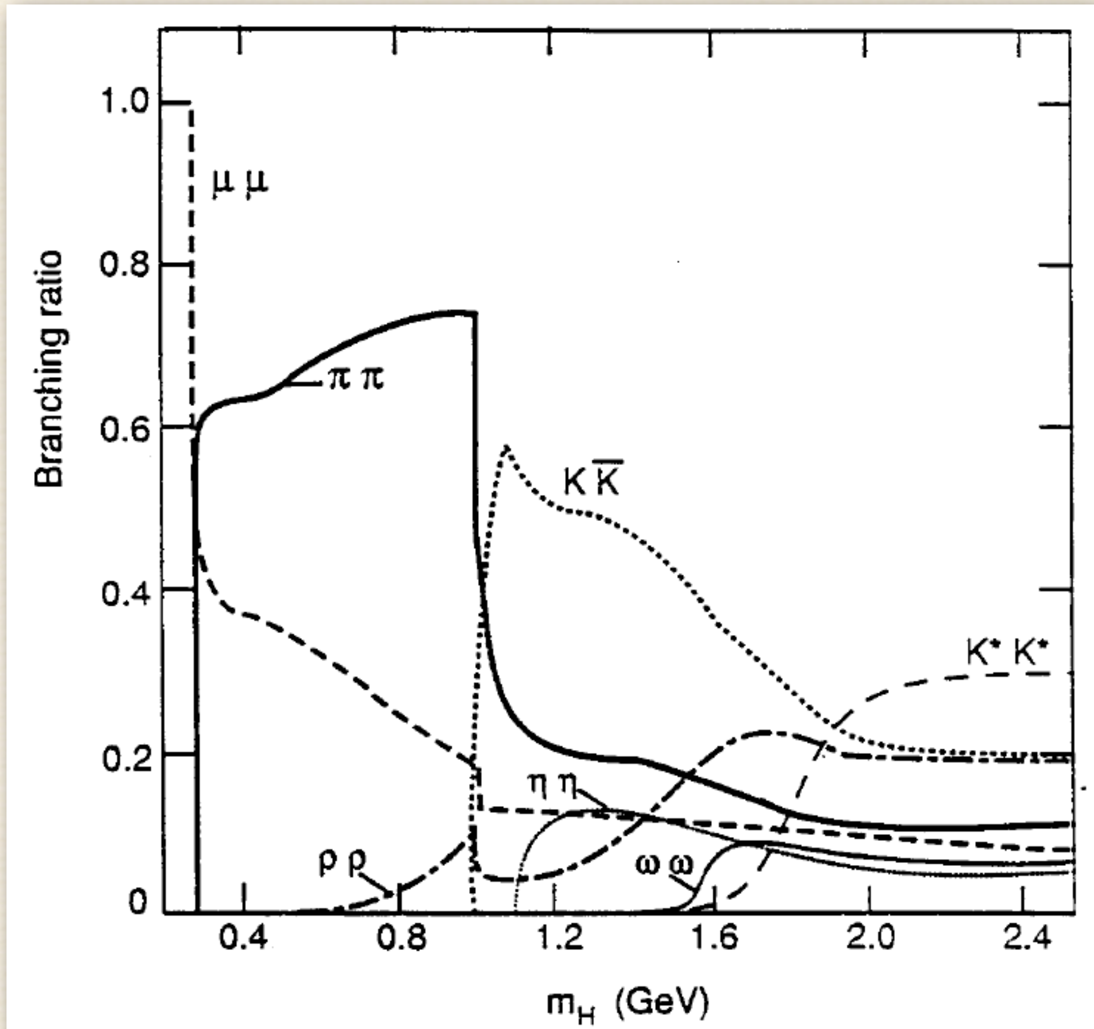


ALEPH - Dec. 1989

Search for Higgs boson using first 11k Z

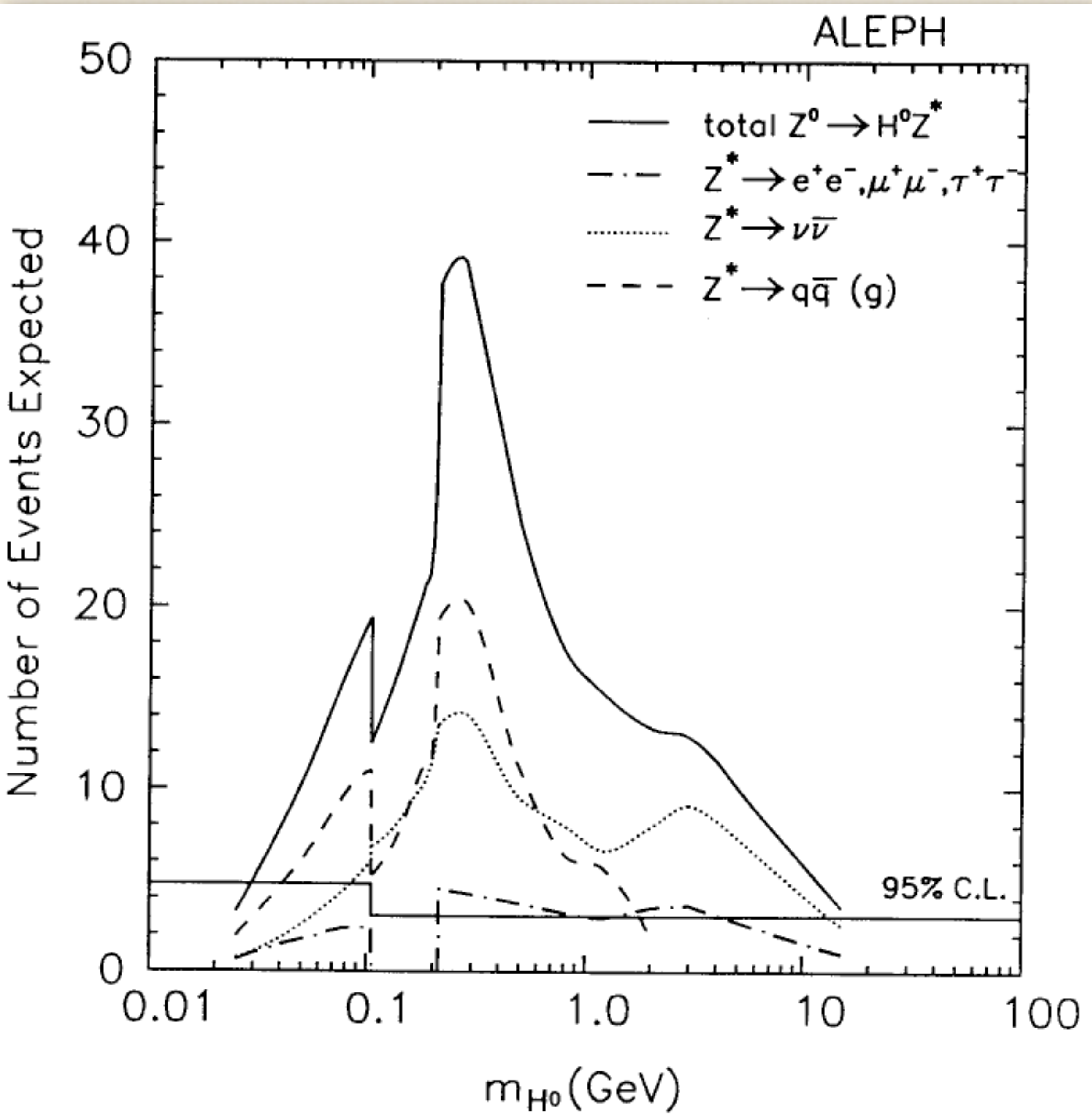
Covered the mass range 32 MeV - 15 GeV

H → e^+e^- at lowest masses; H can be long-lived (~nsec)



Rely on Higgsstrahlung: Z → ℓℓ, νν, $\cancel{qq}$

Link to ALEPH paper http://cds.cern.ch/record/203199/files/199001194.pdf



Result: SM Higgs boson excluded at 95% CL in range

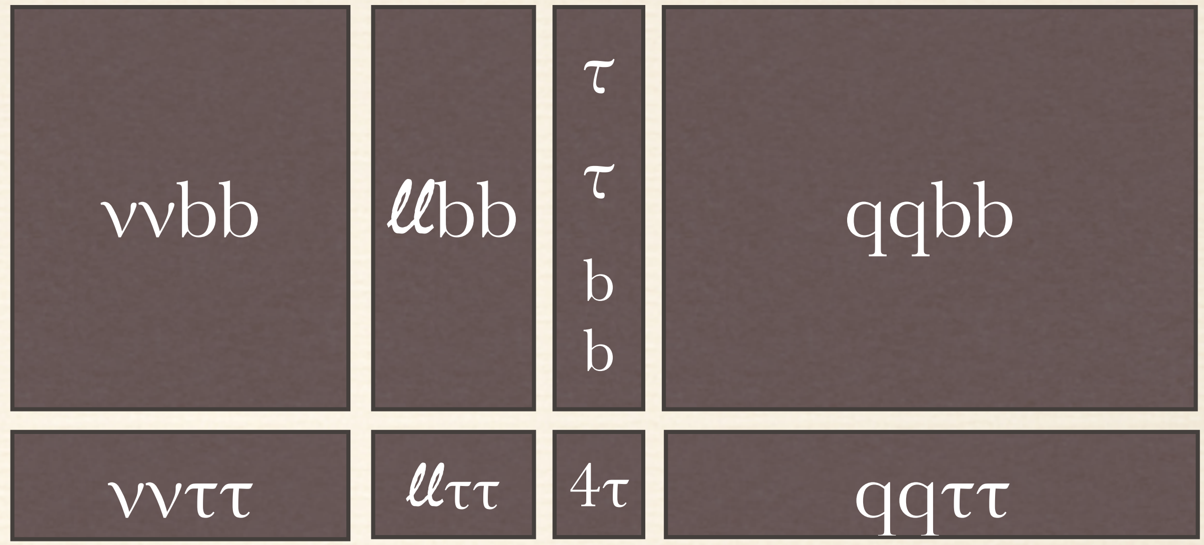
32 MeV - 15 GeV

I believe this was the first search sensitive to the SM Higgs boson

LEP 1 search for SM Higgs

$m_H \sim 15 - 60$ GeV

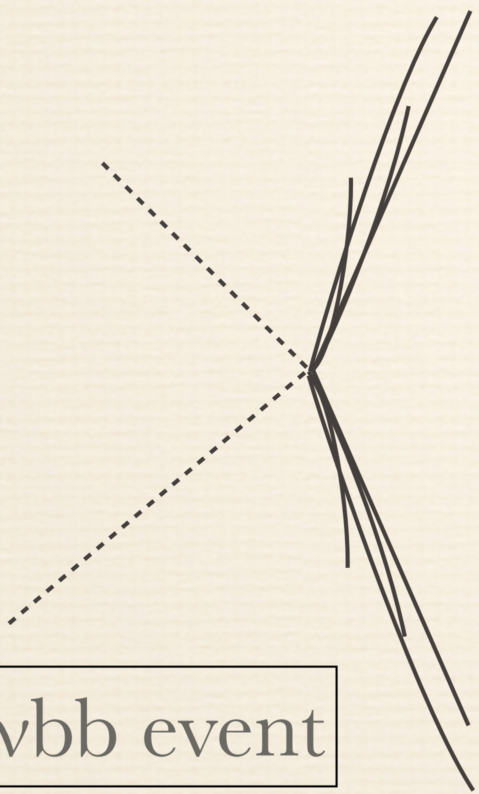
$Z \rightarrow Z^*H$



Above not to scale...

Most sensitive channel: ννbb

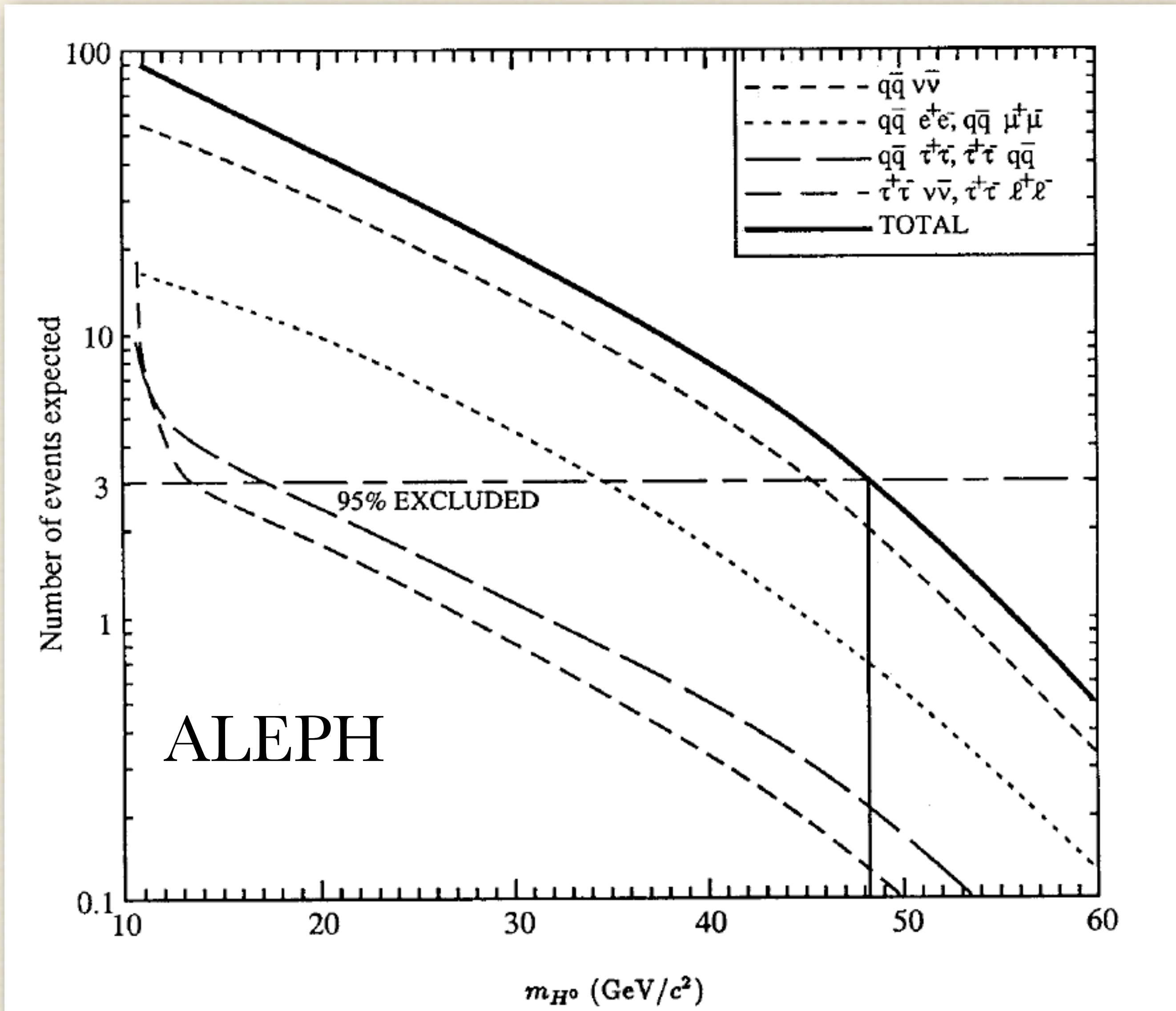
Completely statistics-limited!



ννbb event

By late 1990, with 185k Z had excluded a large new range:

LEP Yellow Report (1986) predicted LEP 1 could perhaps reach 40 GeV sensitivity.



$m_H > 48$ GeV at 95% CL

http://cds.cern.ch/record/216735/files/cer-000129110.pdf

To Higher Ground

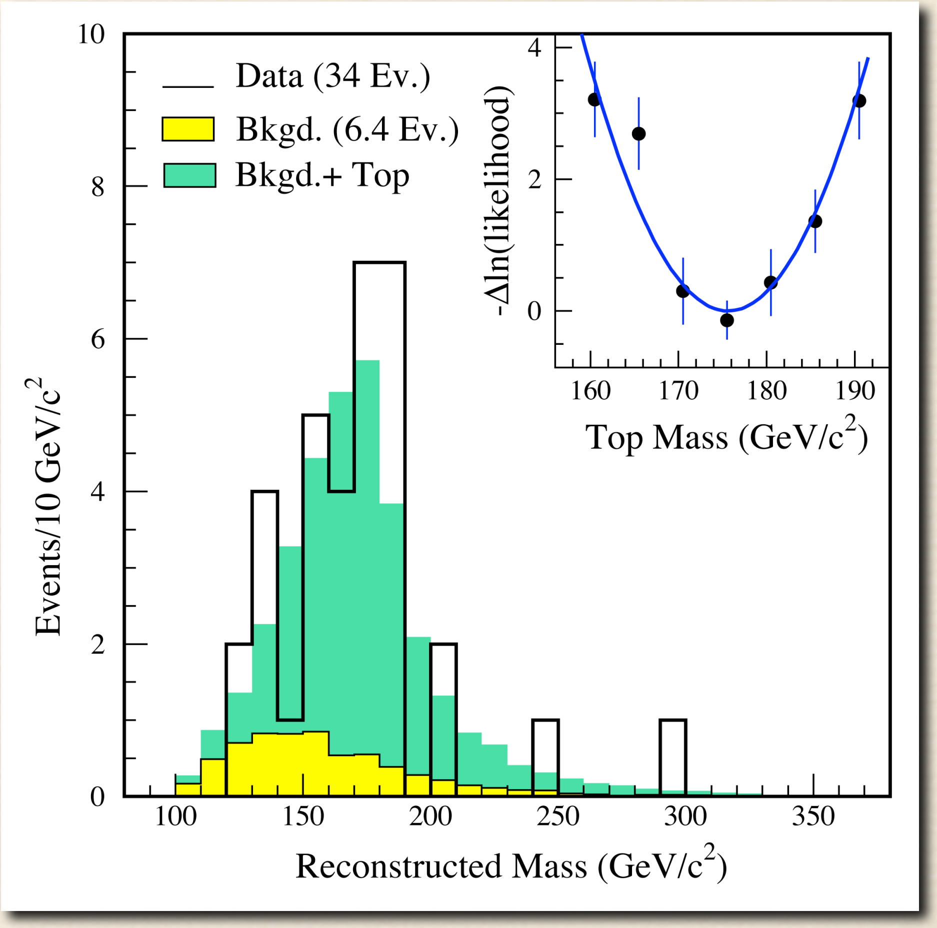
- By the early 1990's it became clear that the hunt needed to head to higher ground - more energy
- Three possibilities:
  - LEP 2 - install as much SC RF as possible, push to highest energy... 200 GeV?
  - SSC - by 1993 nearly 15 miles had been bored, and $2G spent on the 40 TeV pp collider, which would begin operating in 1999
  - LHC - 14 TeV demands 8-Tesla magnets...

SSC magnet string test

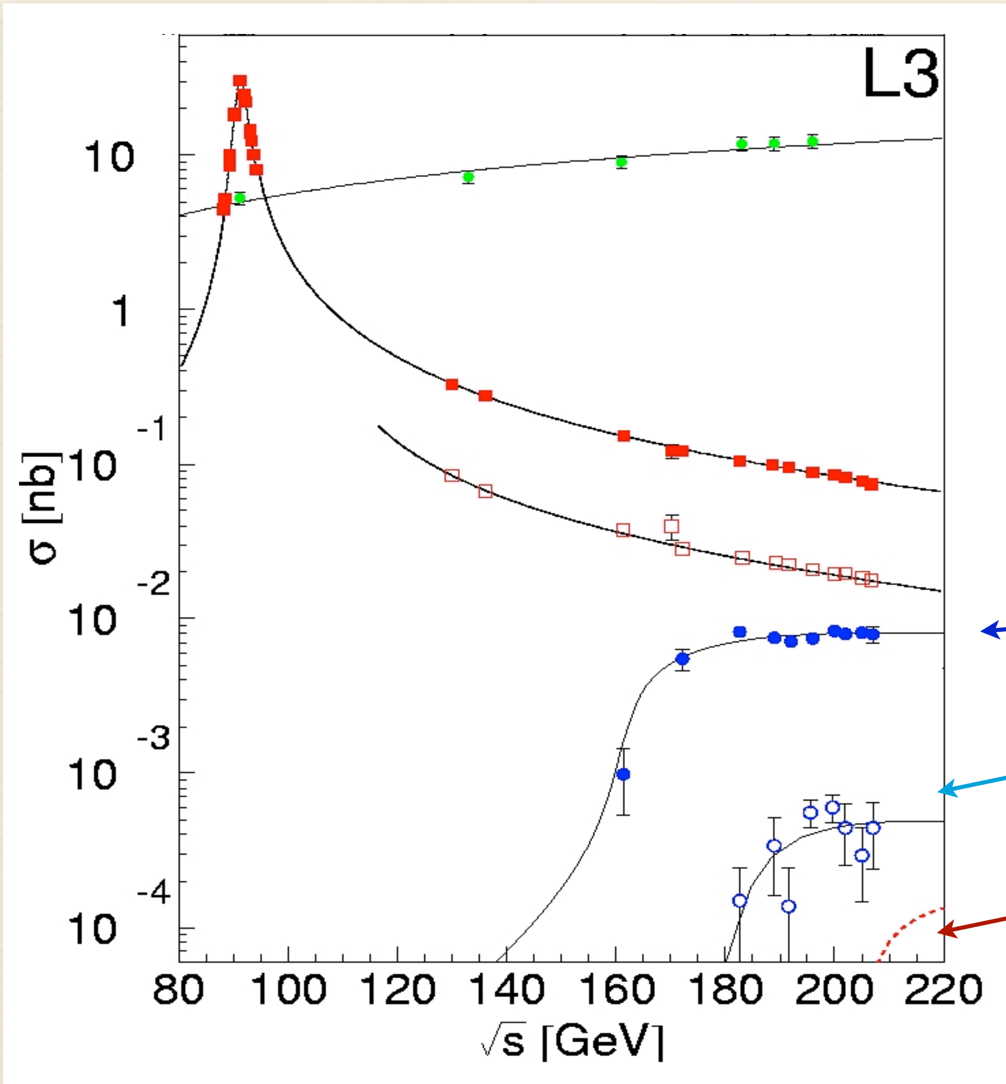
SSC tunnel construction

- In October 1993, the SSC was cancelled
- This gave strong impetus for CERN to go forward with the LHC
- Superconducting RF for LEP 2 was coming on line
- The Tevatron had finally begun collecting significant samples of pbar-p collision data...and now planning for Run 2 began

- In early 1995 CDF and D0 announced the discovery of the top quark
- The top mass was surprisingly heavy at 175 GeV
- What did this mean for the SM Higgs?
- Immediately exploited discovery to search for charged Higgs at the Tevatron...



❖ Challenge of LEP 2



In the mid- to late 90's LEP continued to push upward in energy, ultimately to 206 GeV

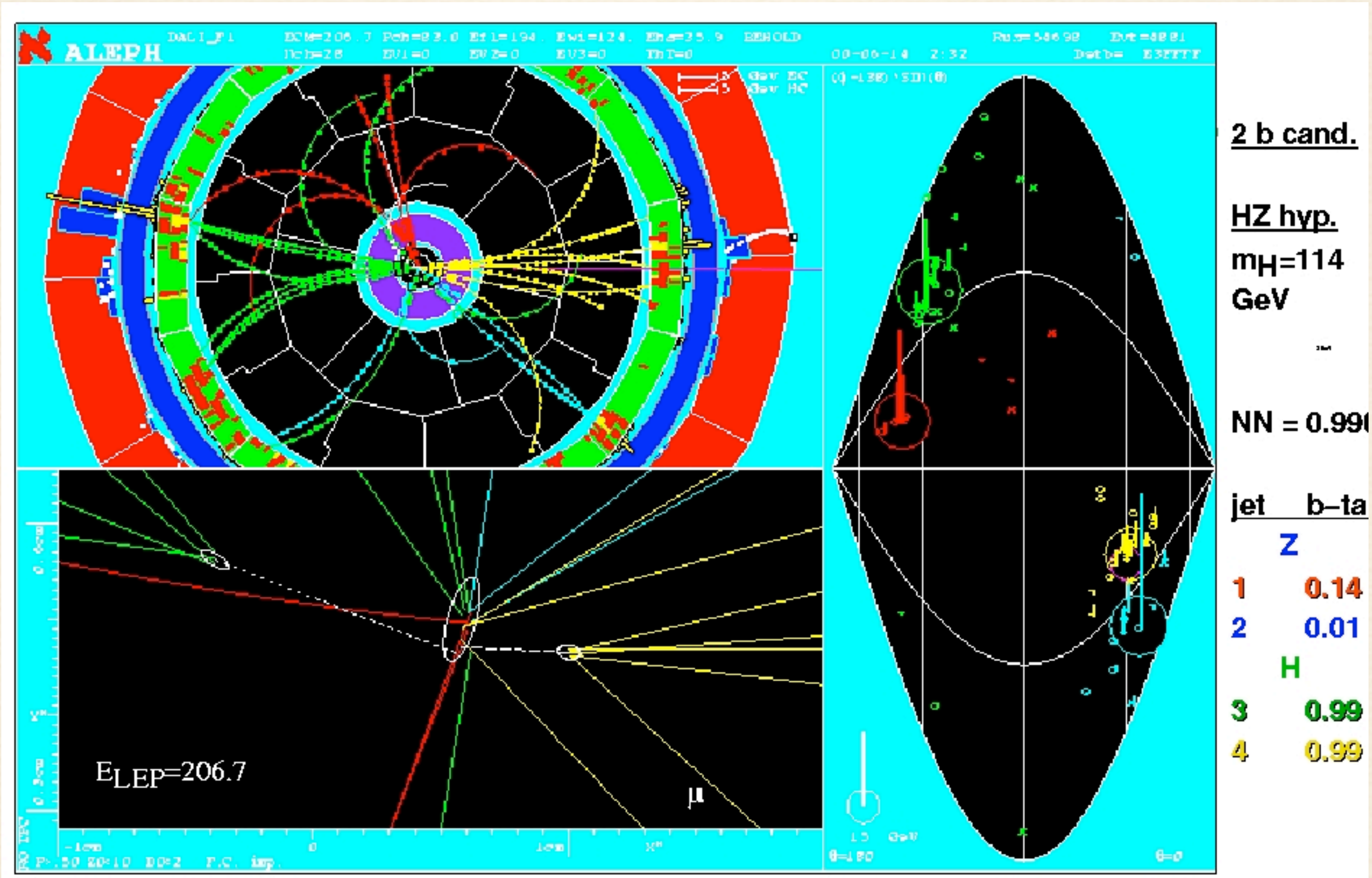
WW

ZZ

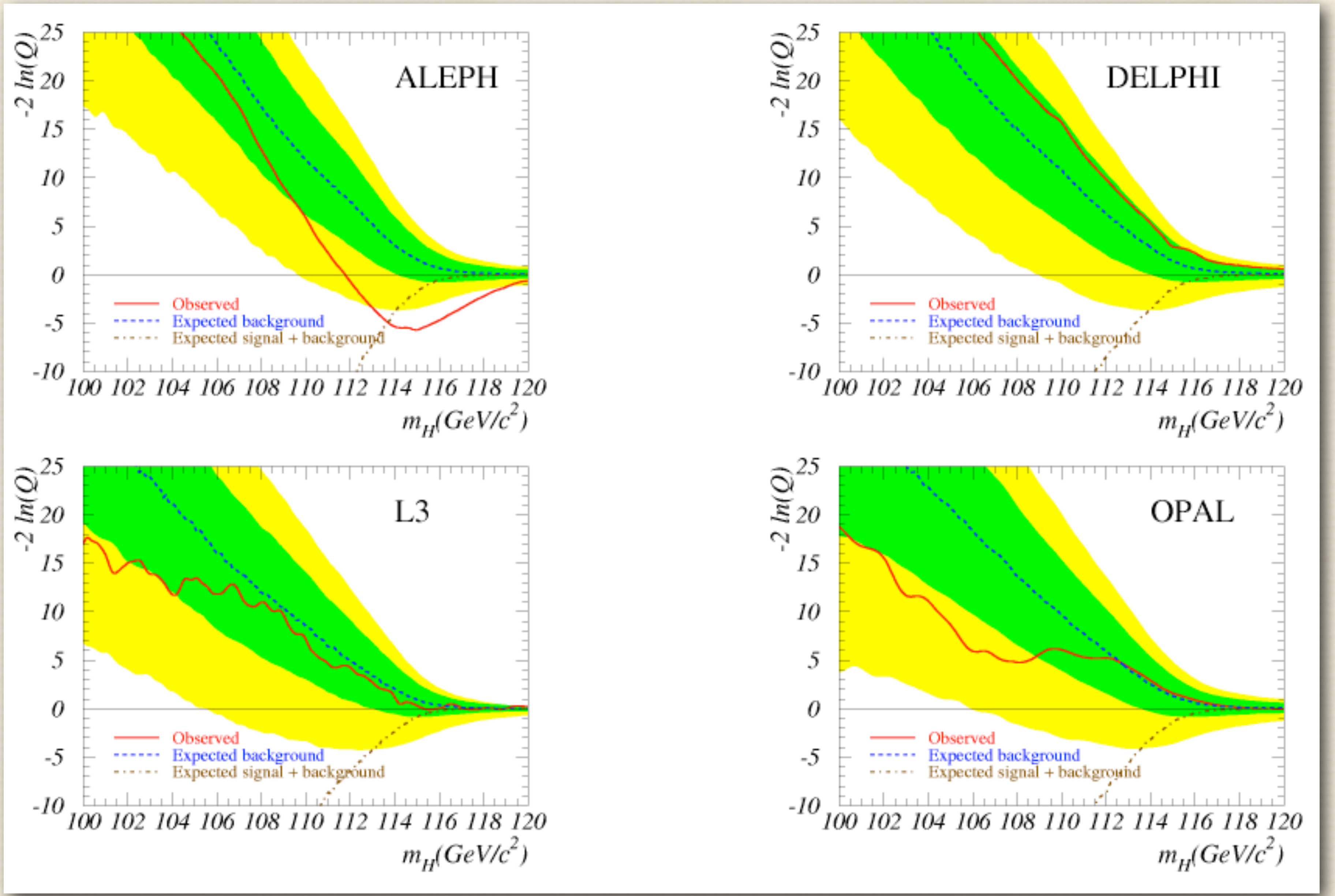
$Z^* \rightarrow ZH$

($m_H = 115$ GeV)

- Ultimately, by 2000, LEP 2 reached 206 GeV energy; had sensitivity to m_H ~115 GeV...and tantalizing hints from ALEPH:

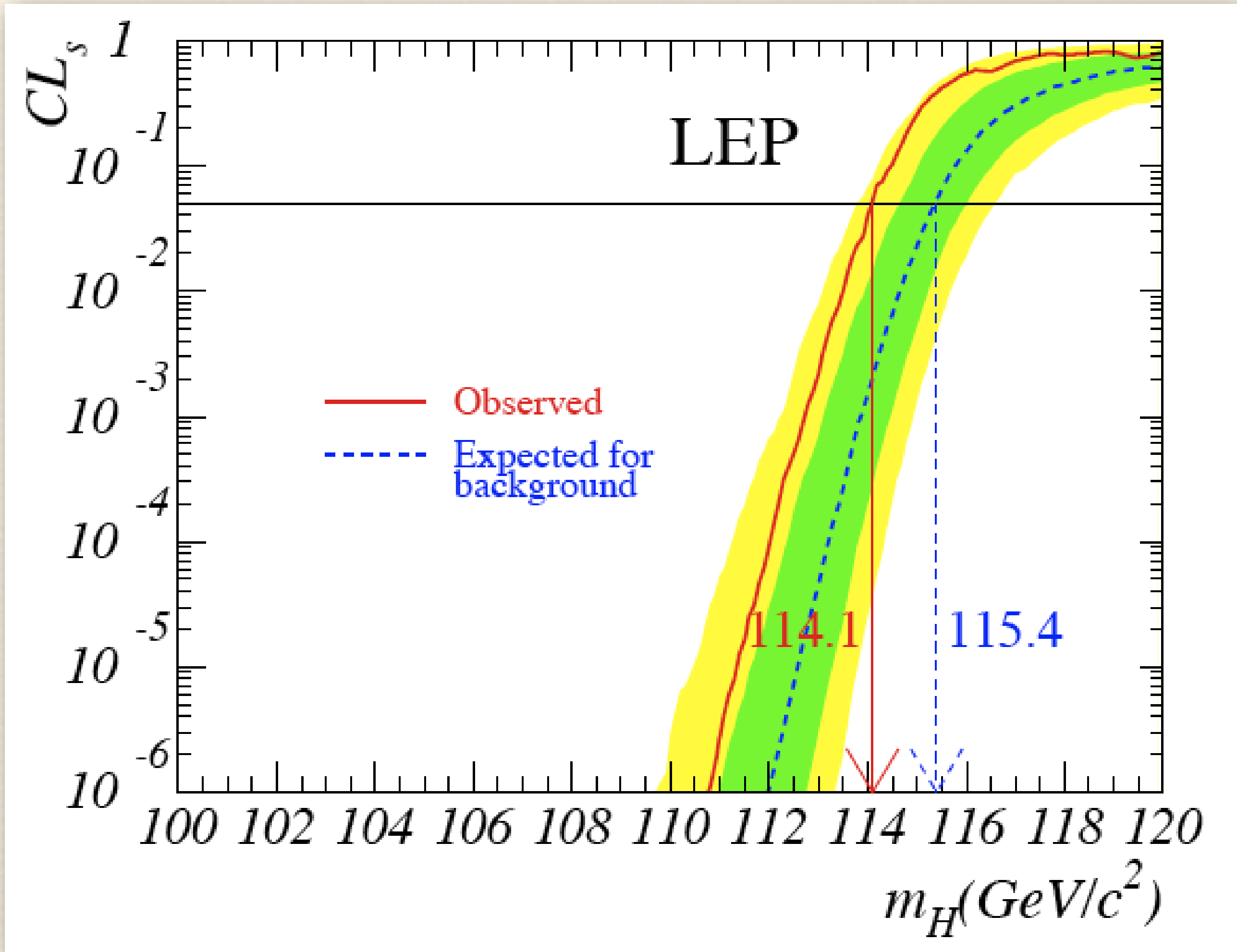


- but only ALEPH had a hint of a signal:

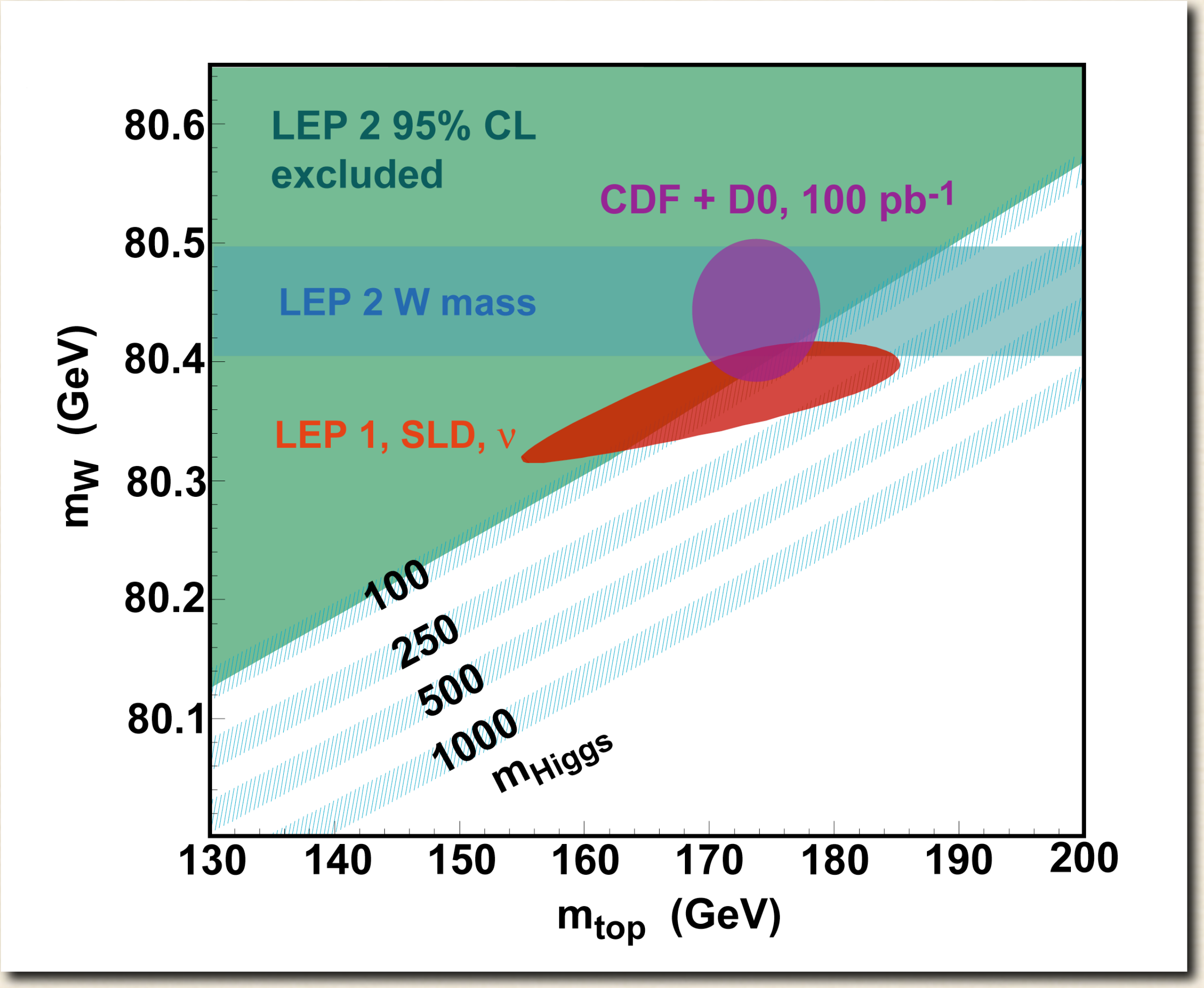


- LEP 2 ended with a limit at 114.1 GeV

- In late 2000 LEP ended to make way for the LHC



The Billion Dollar Plot, ca. 2000



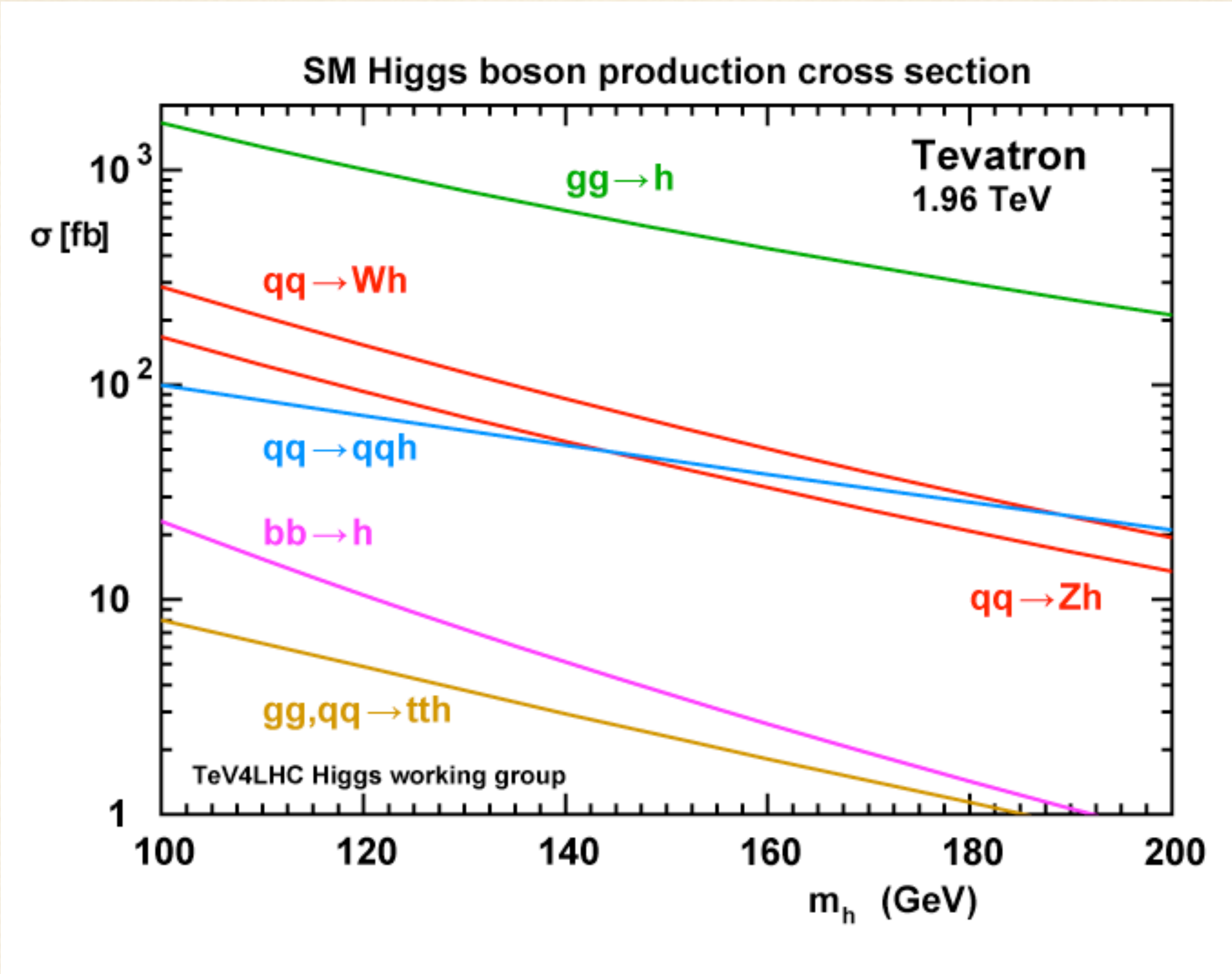
Was the Higgs light? Could the Tevatron see it before LHC could turn on?

Planning the Next Foray

- Tevatron Run 1 ended in 1996; Run 2 (at 2 TeV) foreseen to begin in 2000
- Major shut down for upgrades to detectors and accelerator complex (Main Injector, Recycler)
- anticipated at least 10 fb^{-1} per experiment; more?
- Tevatron Run 2 SUSY/Higgs Workshop in 1998:
    - evaluate reach of Tevatron for discovery in pre-LHC era (until 2005)
    - bring together D0, CDF, theory communities

- Howie and Marcela, John Hobbs and I led the SHW Higgs Working Group
- Worked on two fronts:
  - document theoretical state of affairs
  - perform experimental reach studies
- Lacked full simulations of CDF/D0 in early ’98 so we created the simulation called “SHW” which later became the PGS package

- SM Higgs at the Tevatron



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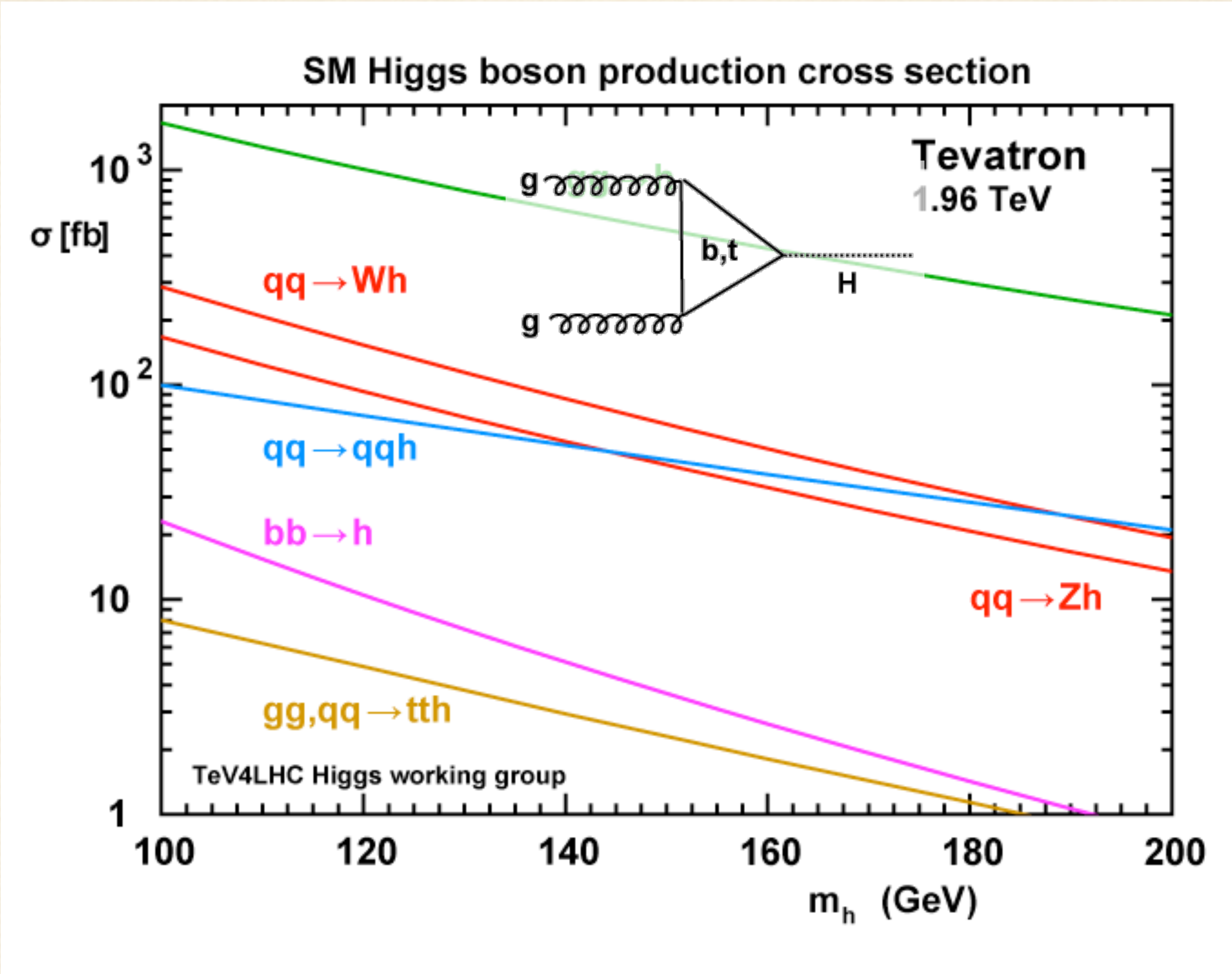

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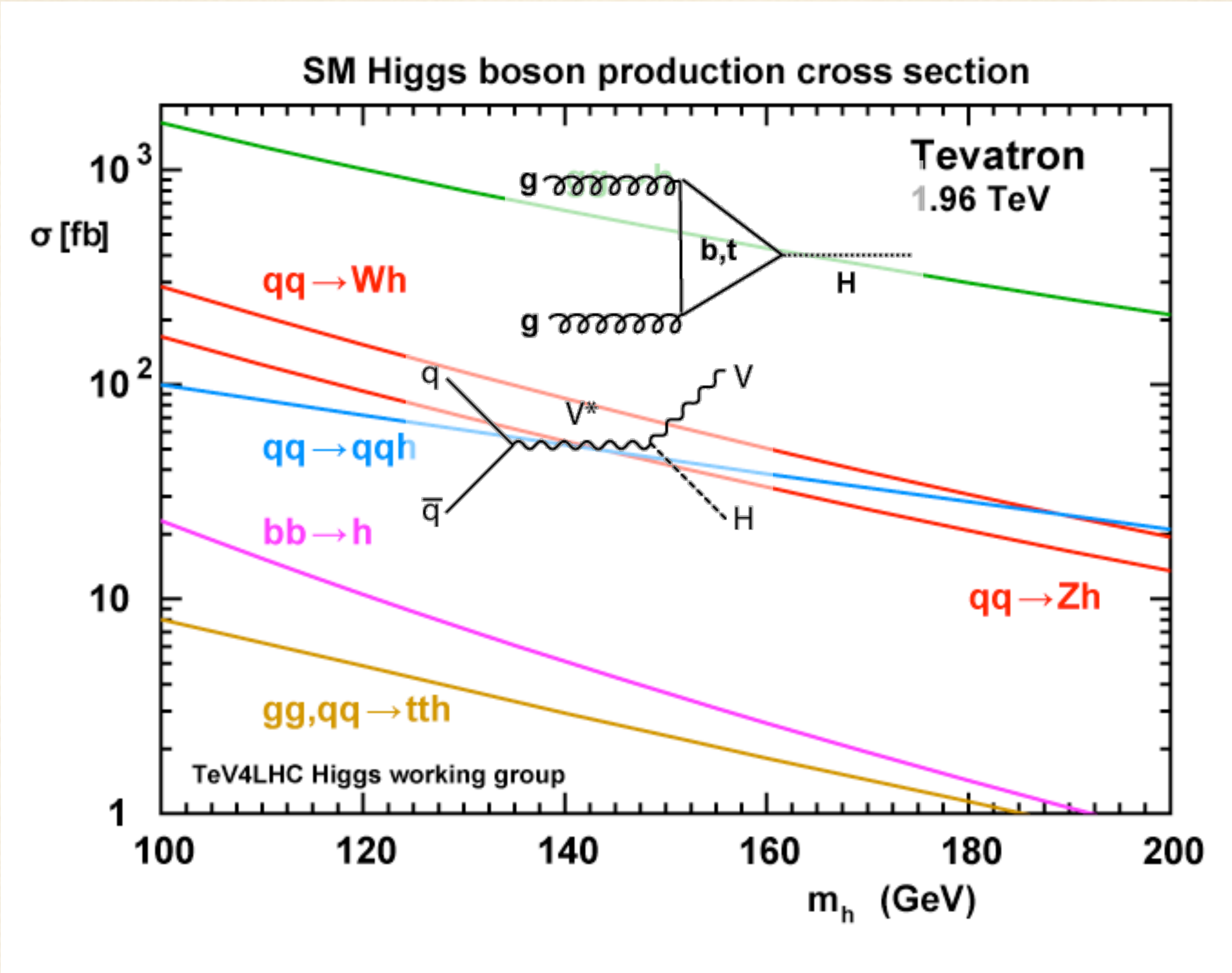
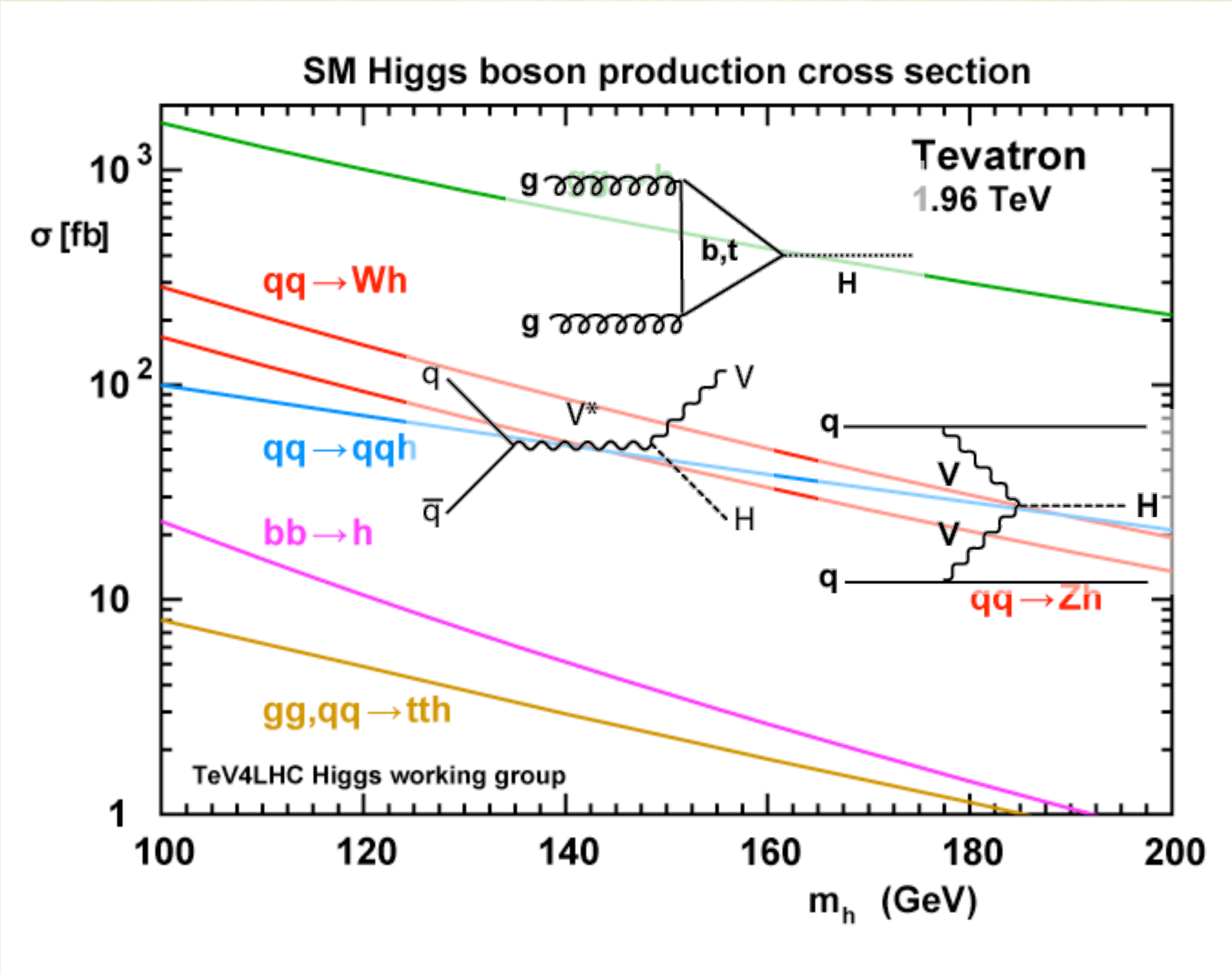
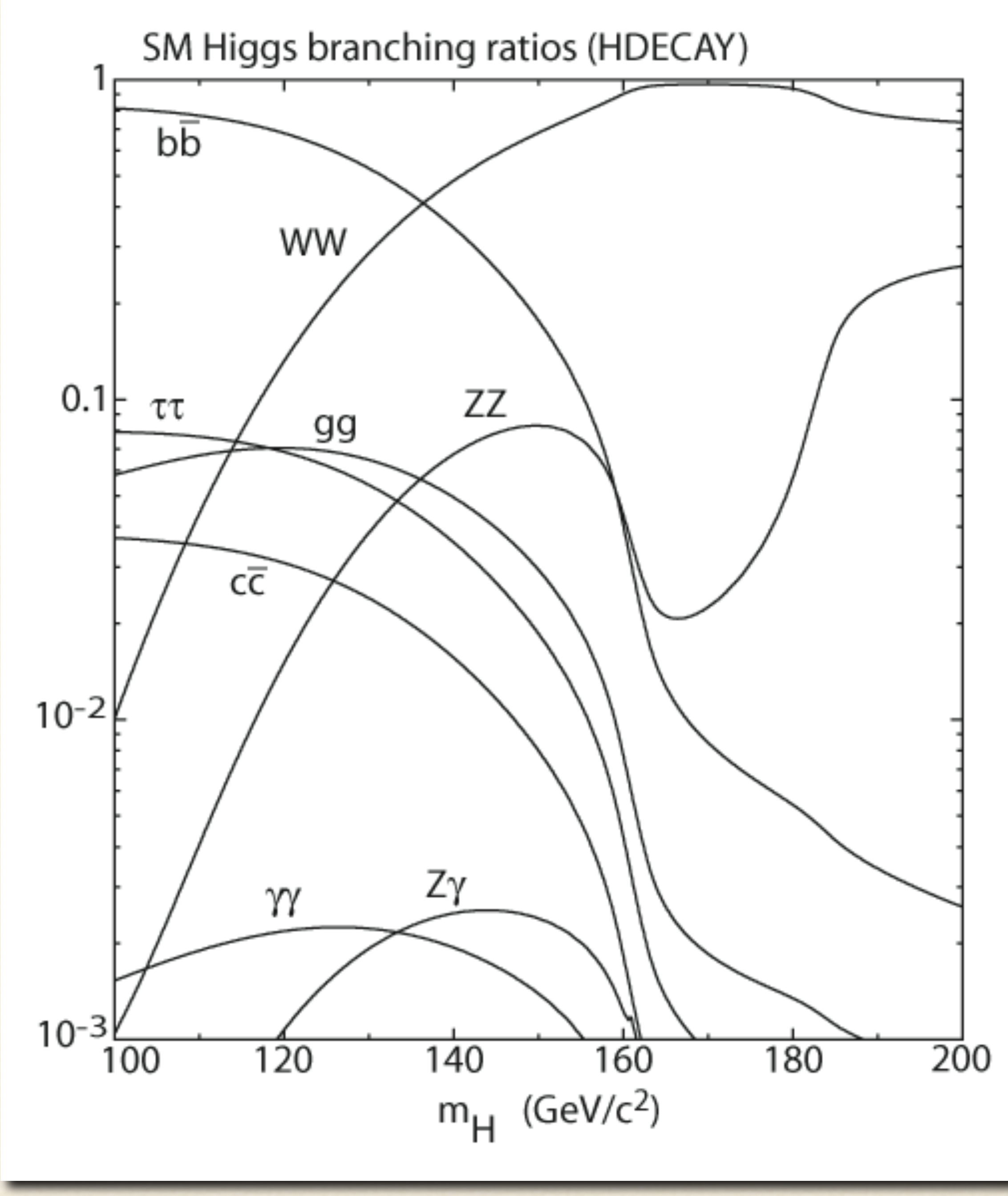


SM Higgs at the Tevatron



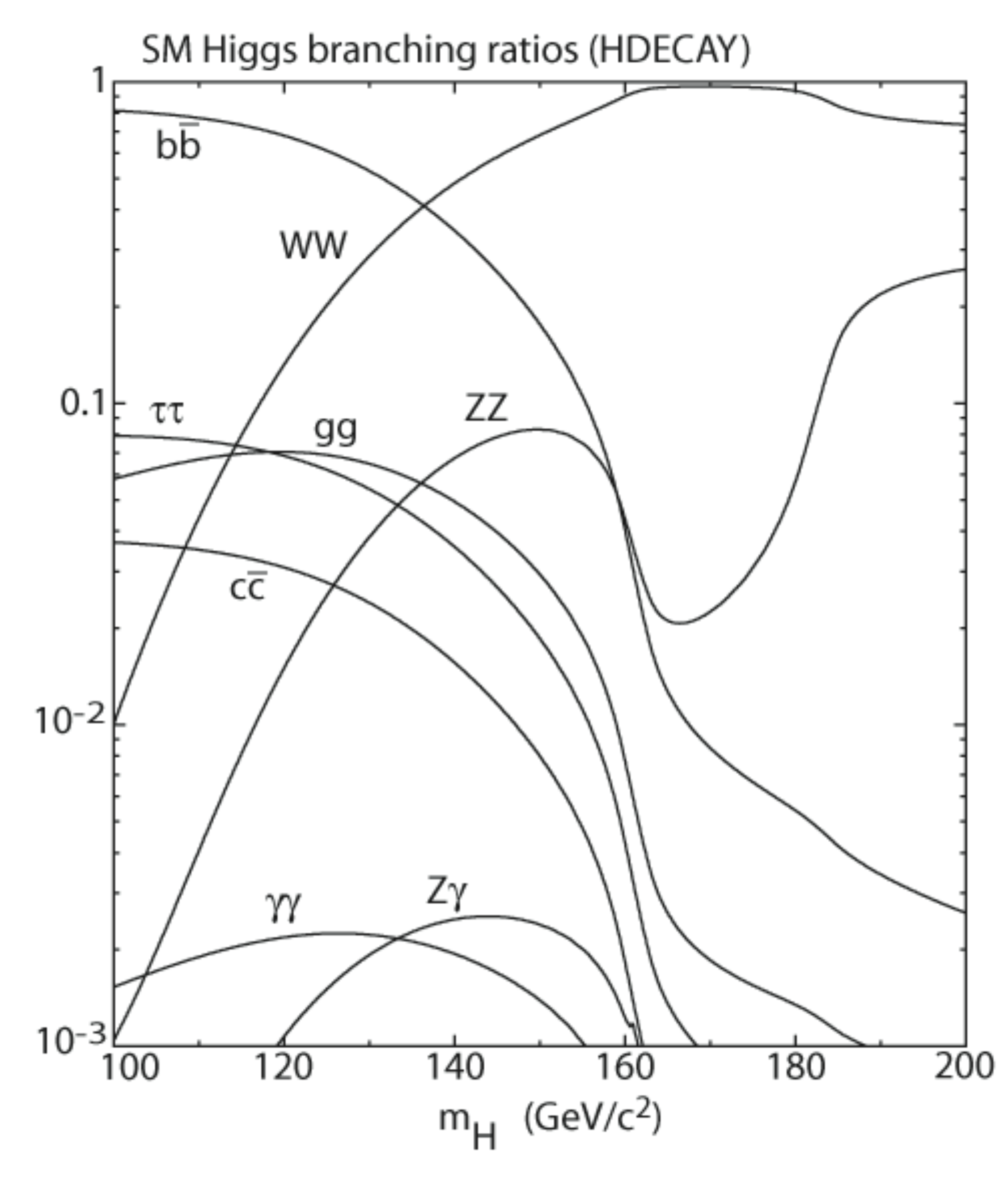

SM Higgs branching ratios (HDECAY)
1
0.1
10^{-2}
10^{-3}
$b\bar{b}$
WW
$\tau\tau$
gg
ZZ
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$
100
120
140
160
180
200
m_H (GeV/c^2)

light SM Higgs boson

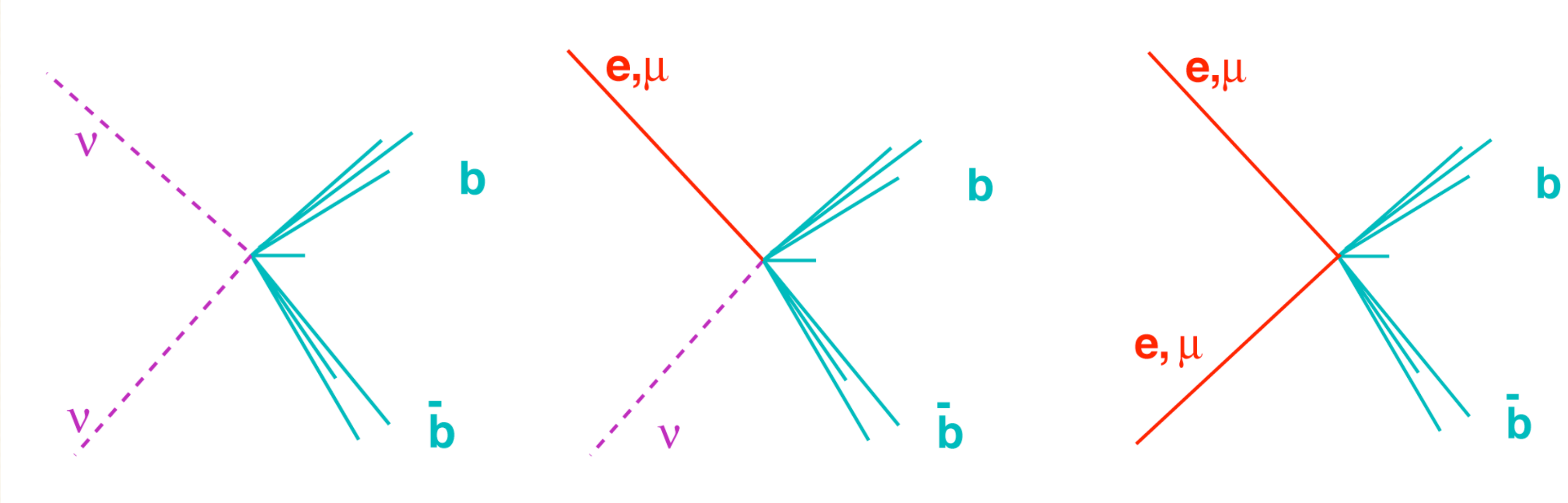
bb decay dominates
ττ plays a role

heavy SM Higgs boson

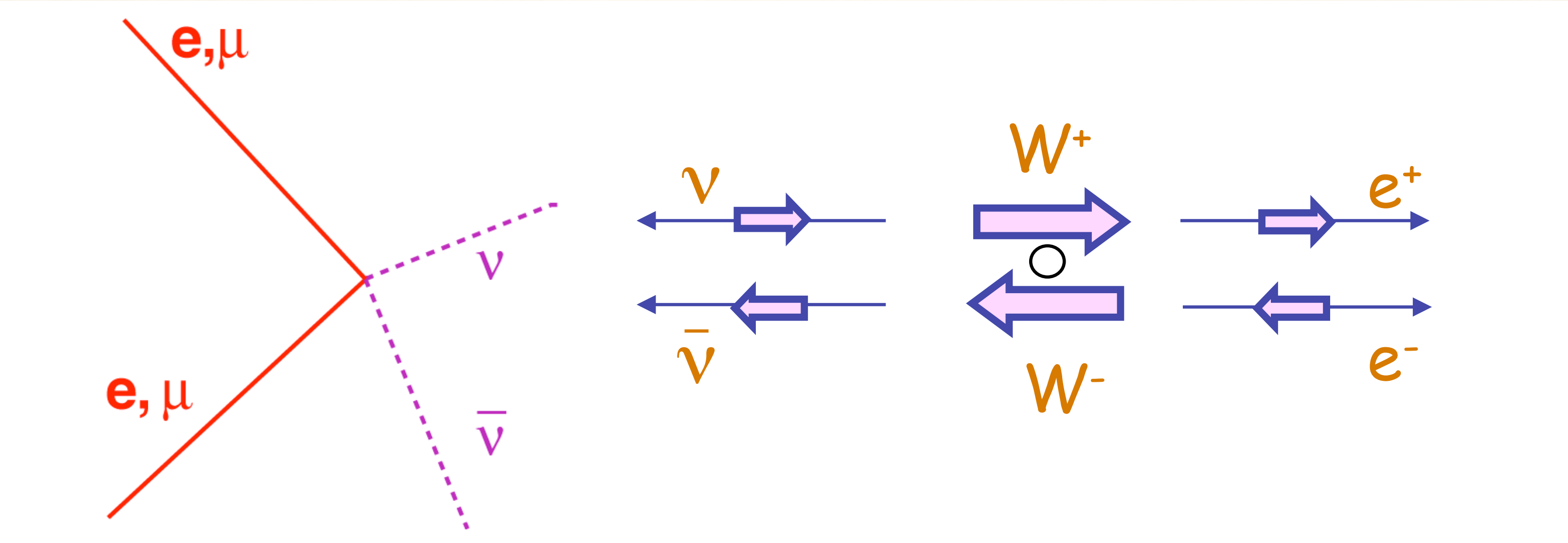
WW decay dominates
ZZ: ℓℓ BR too small



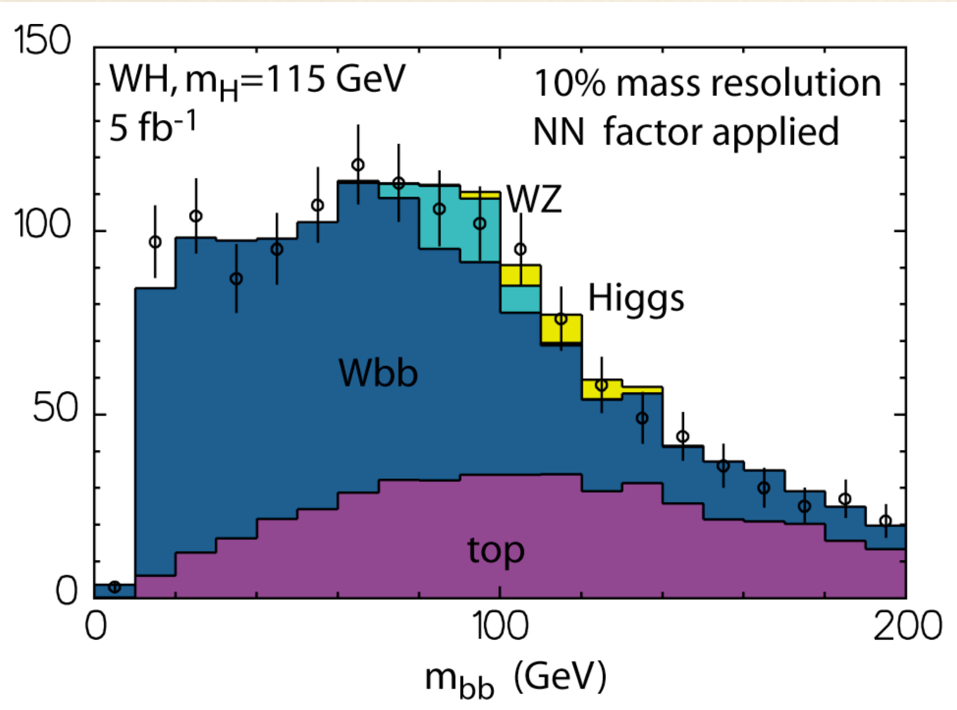
- low mass channels (WH and ZH)

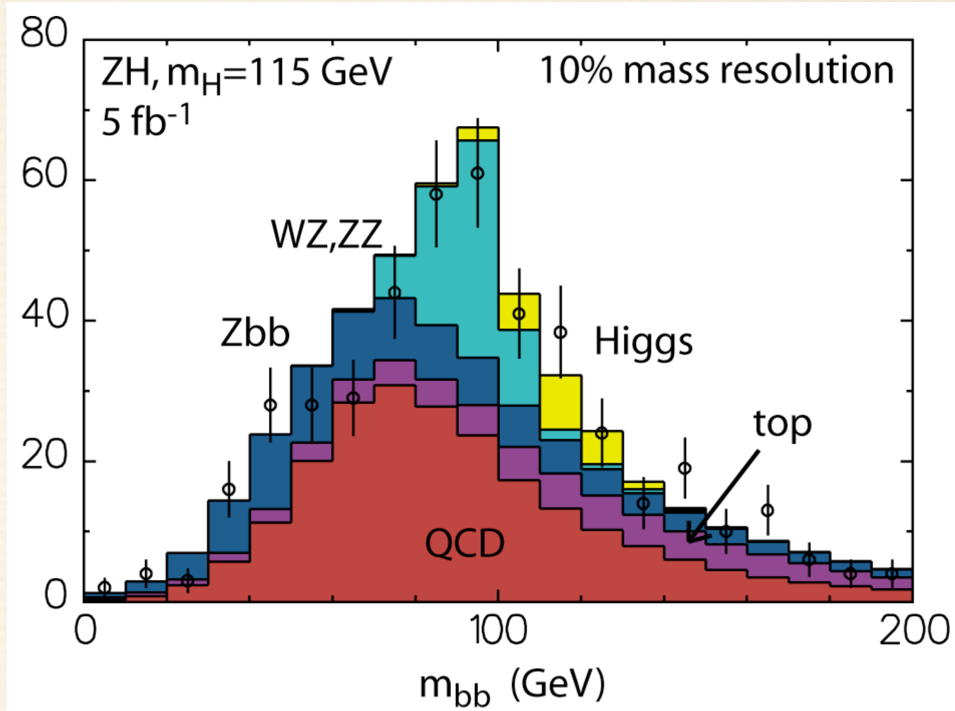


- high mass channels (WW, WWW/WWZ):

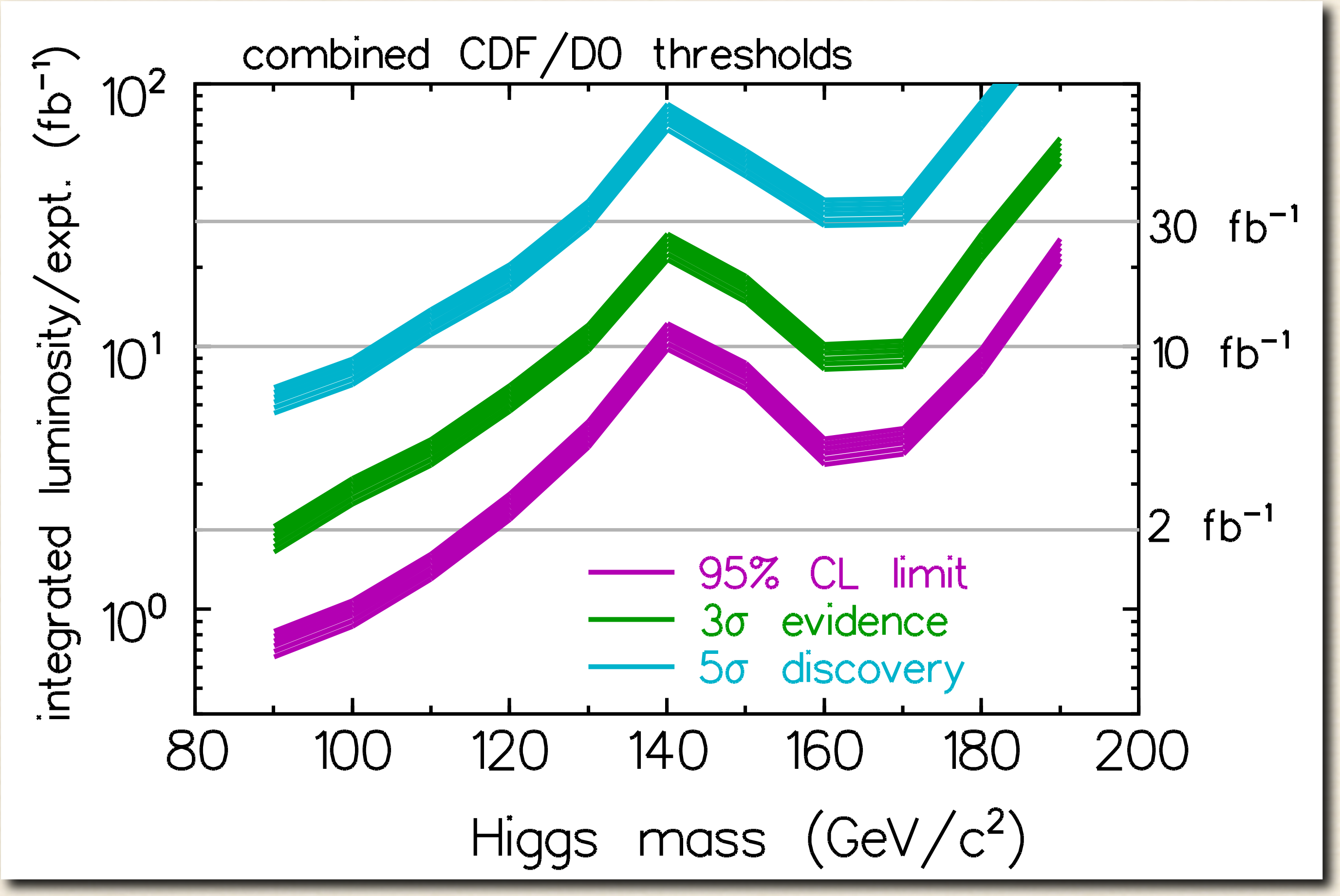


- It never looked like it would be easy...





- We made a reasonably optimistic projection of integrated luminosity required for exclusion/observation/discovery:



The Race

Run 2 started slowly due to Tevatron issues

In 2003 the silicon upgrades to CDF and D0 were cancelled

Key sub-atomic particle slips away again

10:00 30 June 03

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The most elusive particle in physics has skipped even furt
Pinning down the Higgs boson, or proving that it does not
huge step towards understanding why our Universe has

But fresh predictions from Fermilab, home to the world's
particle accelerator, have dashed hopes of achieving th
the next six years.

Current understanding of the Universe is summarised
standard model, but this lacks any explanation for wh
The popular Higgs theory says that a gooey "Higgs f
Universe and endows matter with mass through the

So finding the Higgs has become a matter of urgen
confirm the theory, while disproving its existence w
new theory, such as a slew of higher dimensions.

"It is one of the most important discoveries in sci
former spokesman for one of the collaborations '
Tevatron accelerator in Batavia, Illinois.

Below-par performance hampers Fermilab quest for Higgs boson

Geoff Brumfiel, Washington

Physicists at the Tevatron particle accelerator near Chicago are steeling themselves for failure in their ambitious bid to detect the elusive Higgs boson.

Researchers working on the machine, at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, are searching for signs of the particle, thought to give other particles their mass, in the debris of high-energy particle collisions.

But they have now cut their estimate of the number of proton–antiproton collisions they expect to see by 2008 by 60–80%. As many collisions have to be studied to detect the Higgs boson, this is a serious blow to the lab's hopes of observing the particle.

The figures appear in a document prepared for Fermilab's sponsor, the US Department of Energy, and released on 15 June. Stephen Holmes, associate director for accelerators at the lab, says that problems have arisen with the equipment used to accelerate the protons and antiprotons. The Tevatron is 20 years old and its accelerators have been plagued by trouble during 'Run II', an upgraded second phase of operation that began in 2001.

The news is forcing Michael Witherell, Fermilab's director, to reconsider funding for Run II, which consumes nearly two-thirds of the lab's $300-million annual budget. "We have to make some tough choices," he says.

Poor results mean that Fermilab may not splash out on new silicon wafers for its particle detectors.

Witherell says he may have to withhold $25 million needed to replace the detectors' silicon wafers, which create electrical signals when hit by particles. Researchers warn that this could severely impair the detectors' performance.

Many observers doubt whether the Tevatron will be able to find the Higgs boson before the rival Large Hadron Collider comes online in 2007 at CERN, the European particle-physics lab near Geneva. Witherell puts the chance of spotting the Higgs at "something like 50%". Others disagree: "I don't think there's any chance they will find it," says CERN physicist Daniel Froidevaux.

Many Fermilab researchers admit that they placed too much emphasis on finding the Higgs. Now, they say, they need to draw attention to their other research, such as studies of the top quark, a subatomic particle that was discovered at the lab in 1995. "I think we need to get some buttons out there that say: 'Run II, it ain't just the Higgs'," says Holmes.

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Below-par performance hampers Fermilab quest for ... boson

Of course, it's not all about the SM Higgs!

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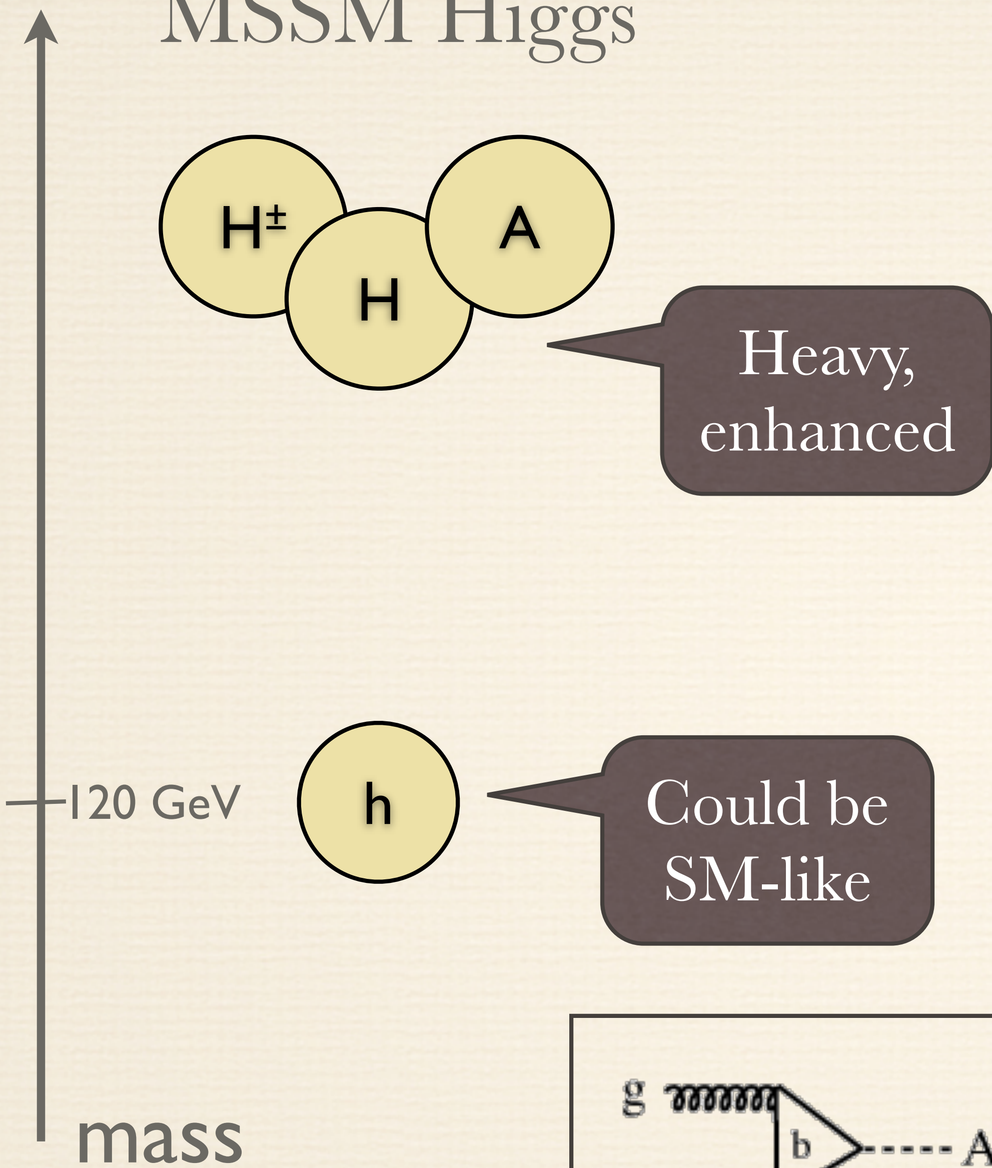
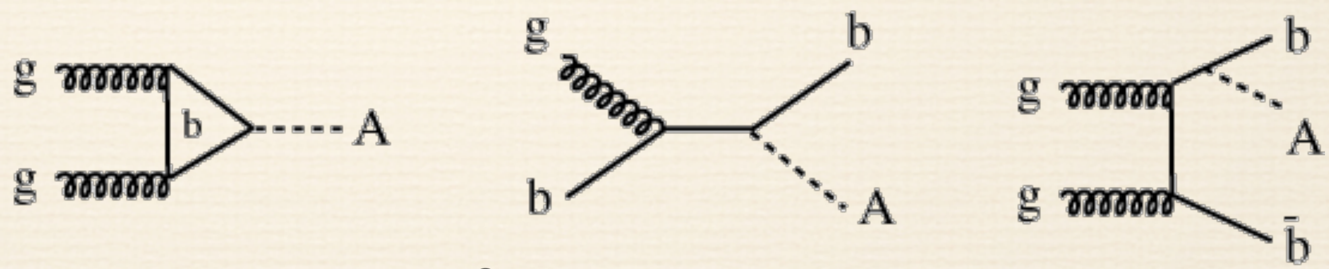
MSSM Higgs



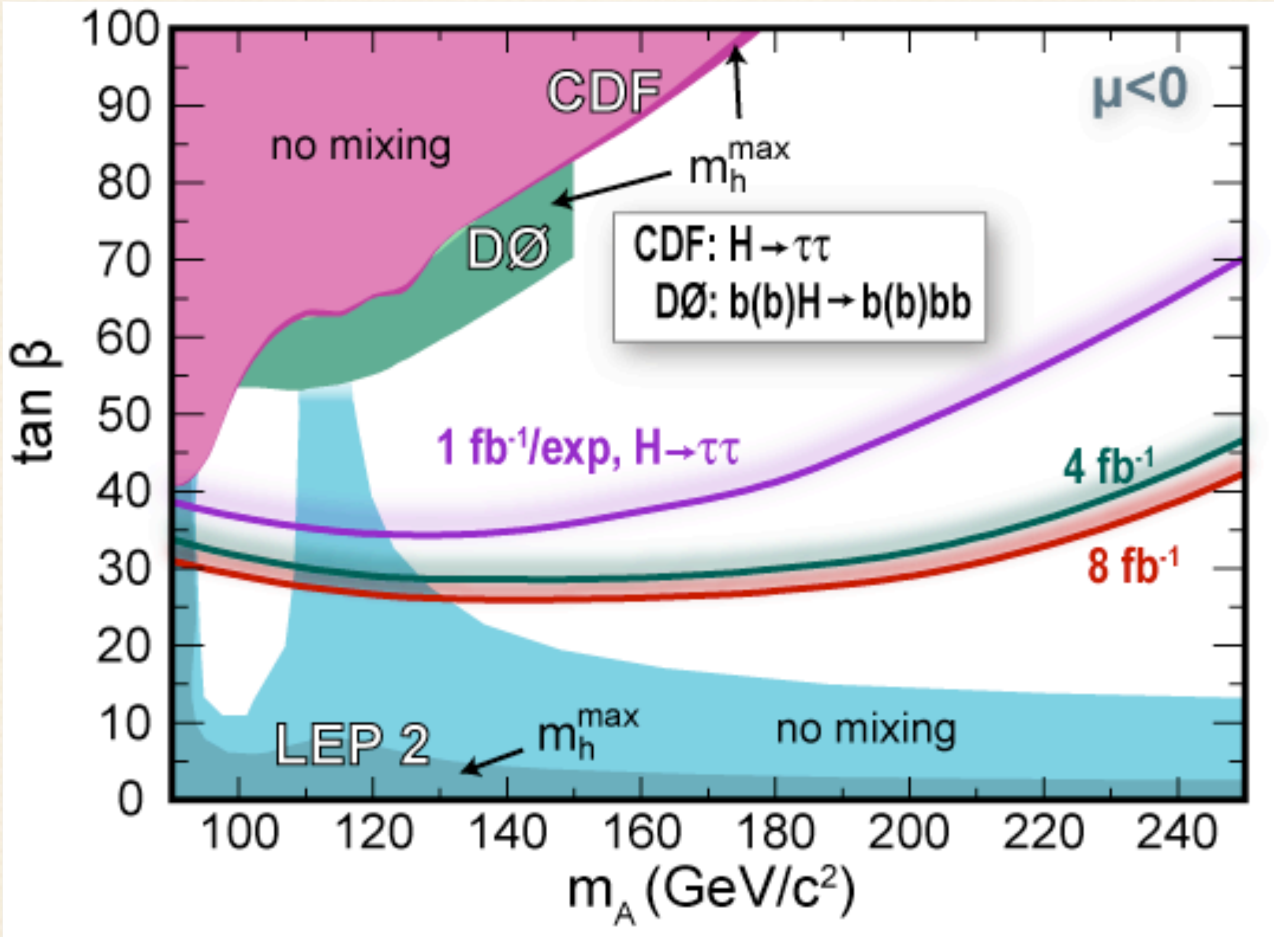
If there was a race is was for non-SM Higgs!

SUSY: five higgs states, potentially with enhanced production rates



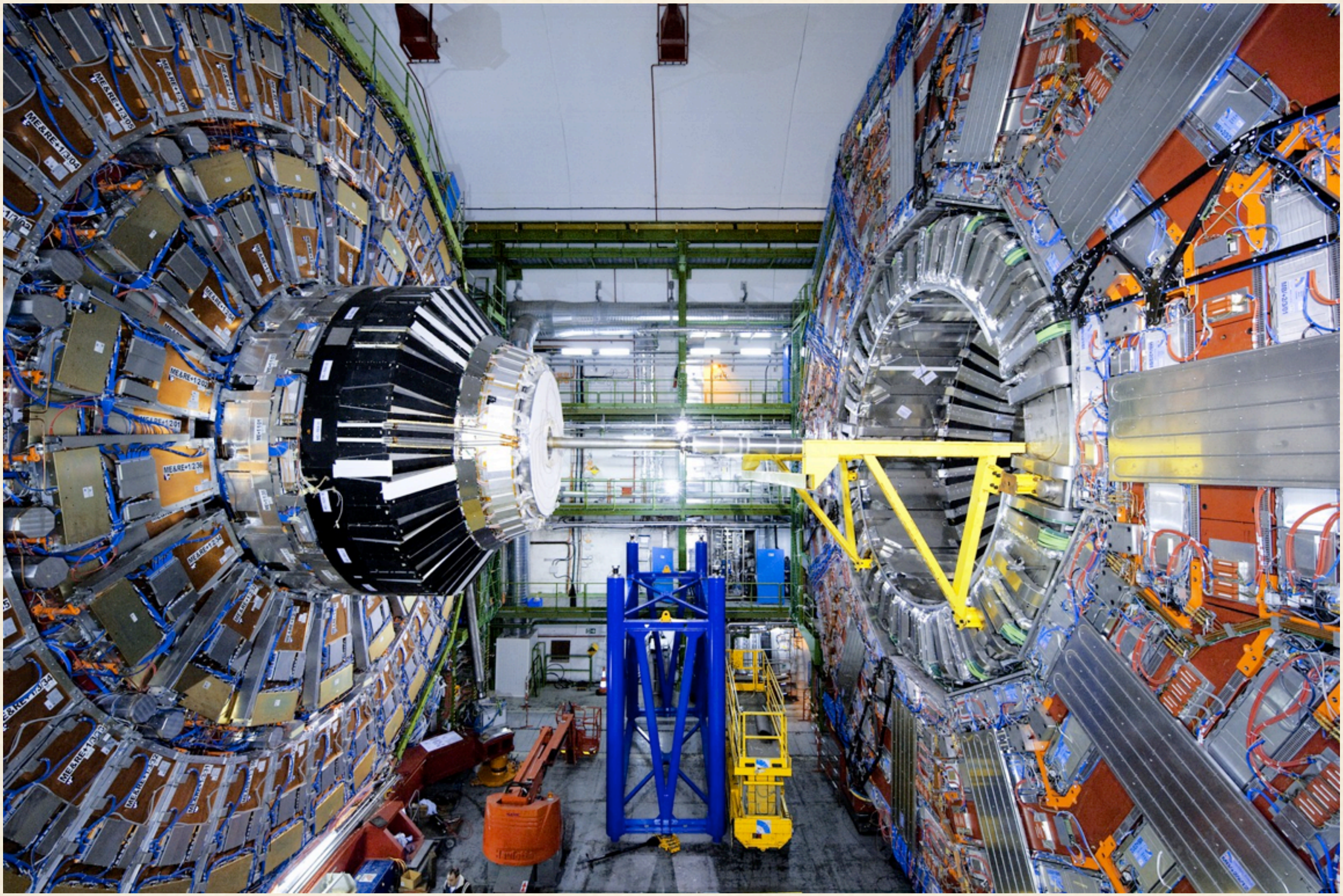
$\propto \tan^2\beta$

With the very first Run 2 data, 0.3 fb-1, CDF and D0 began searching for MSSM Higgs bosons:



The MSSM Higgs search is, was, and always will be statistics-limited...could the Tevatron get lucky?

In mid 2008 the LHC and detectors were finally ready



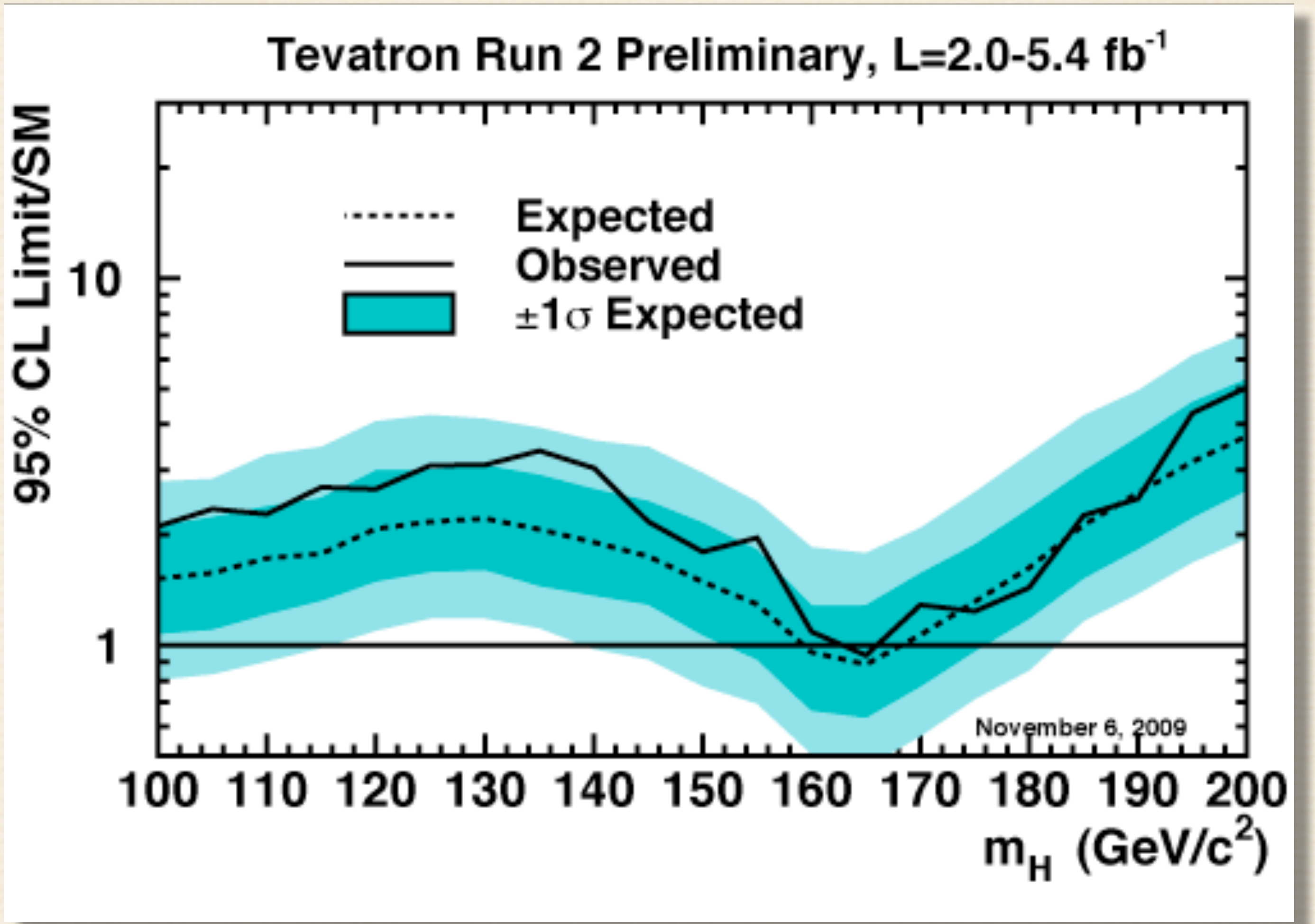
September 2008...beam at last! Party at Swissnex in SF

September 2008...beam at last! Party at Swissnex in SF

But after a week of commissioning, an electrical fault triggered a catastrophic series of events in the LHC:

By mid-2005 the Tevatron had delivered the first fb^{-1}.

It took 5 fb^{-1} to finally set SM bounds, in 2009!



Tevatron run extended until Sept. 2011

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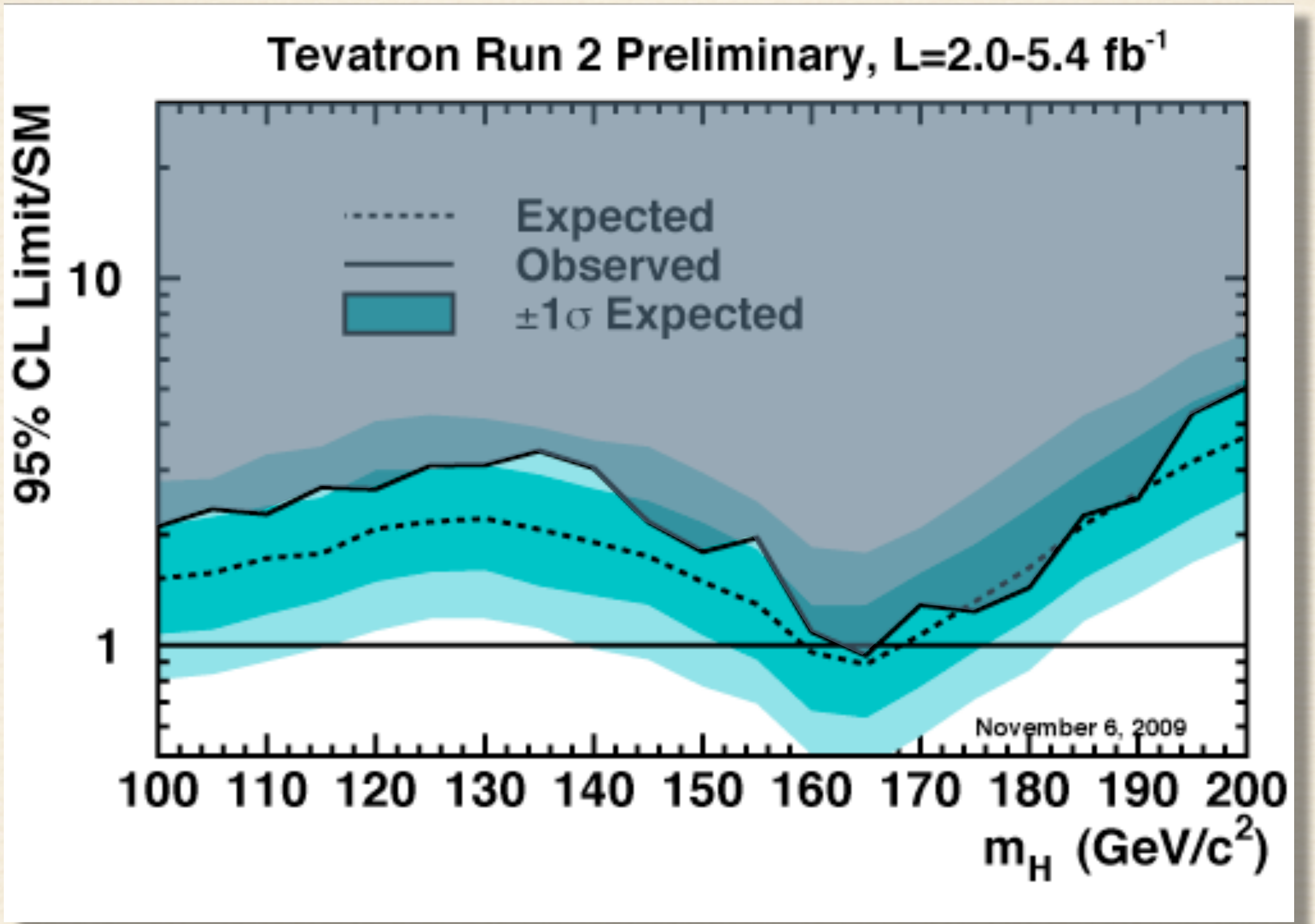

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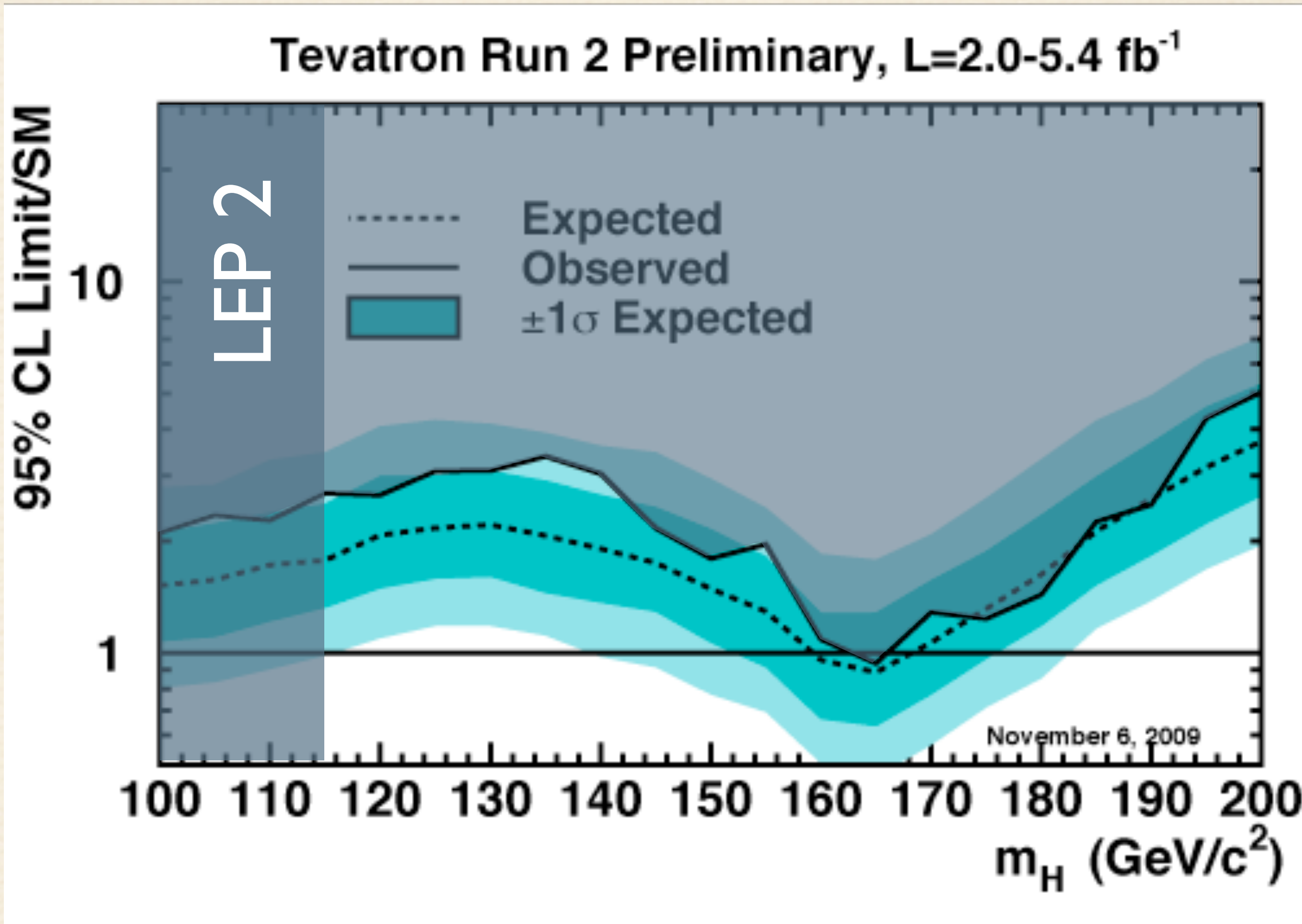

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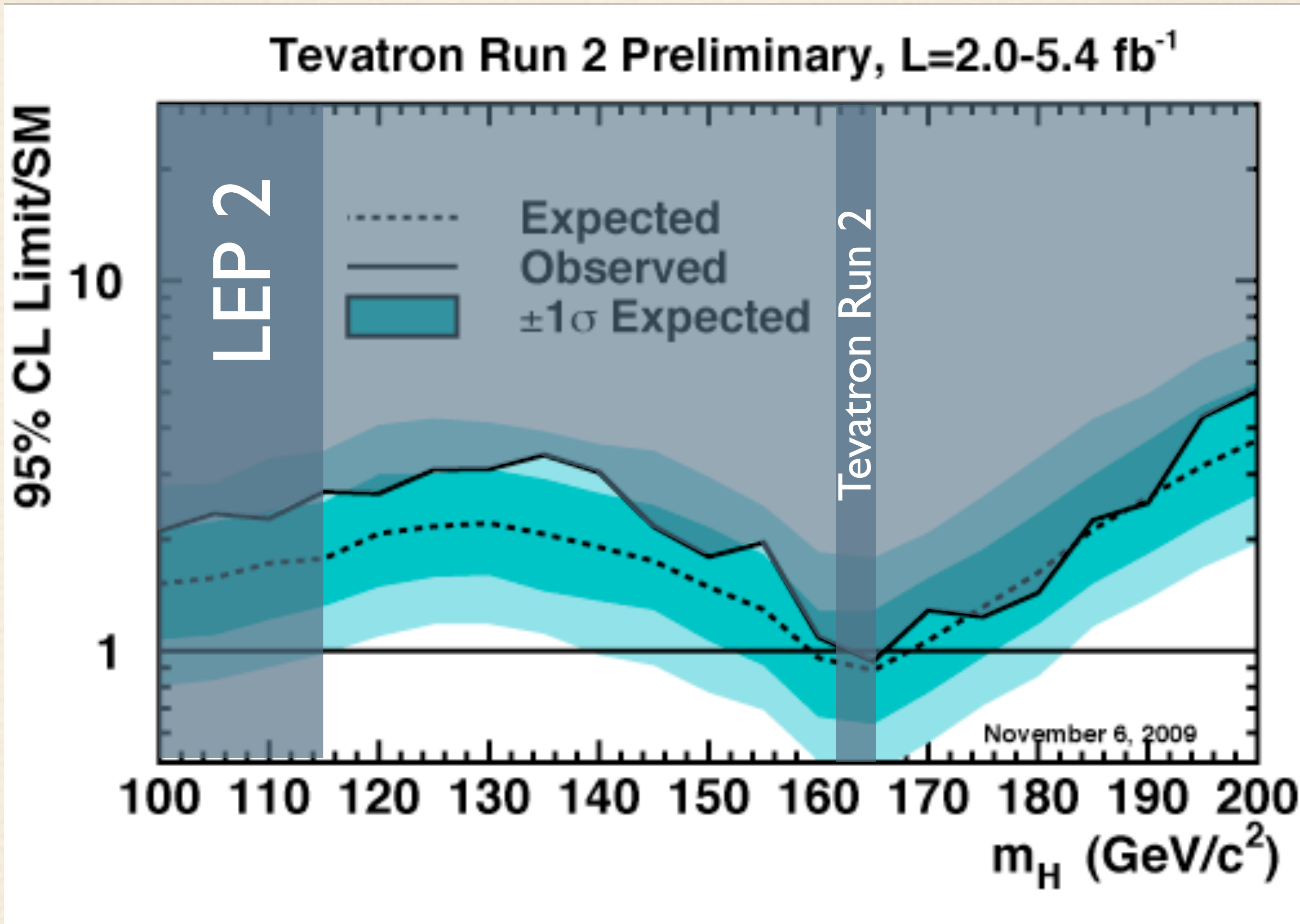
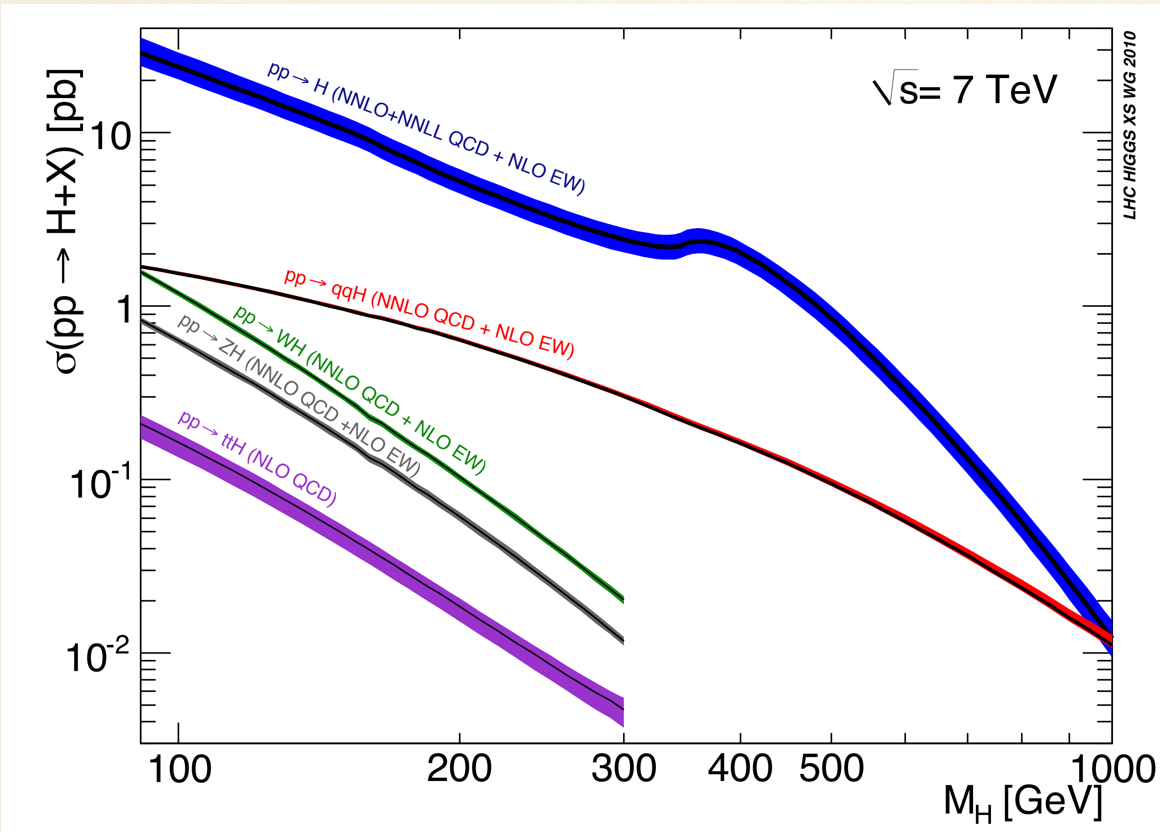


Tevatron run extended until Sept. 2011

No Escape

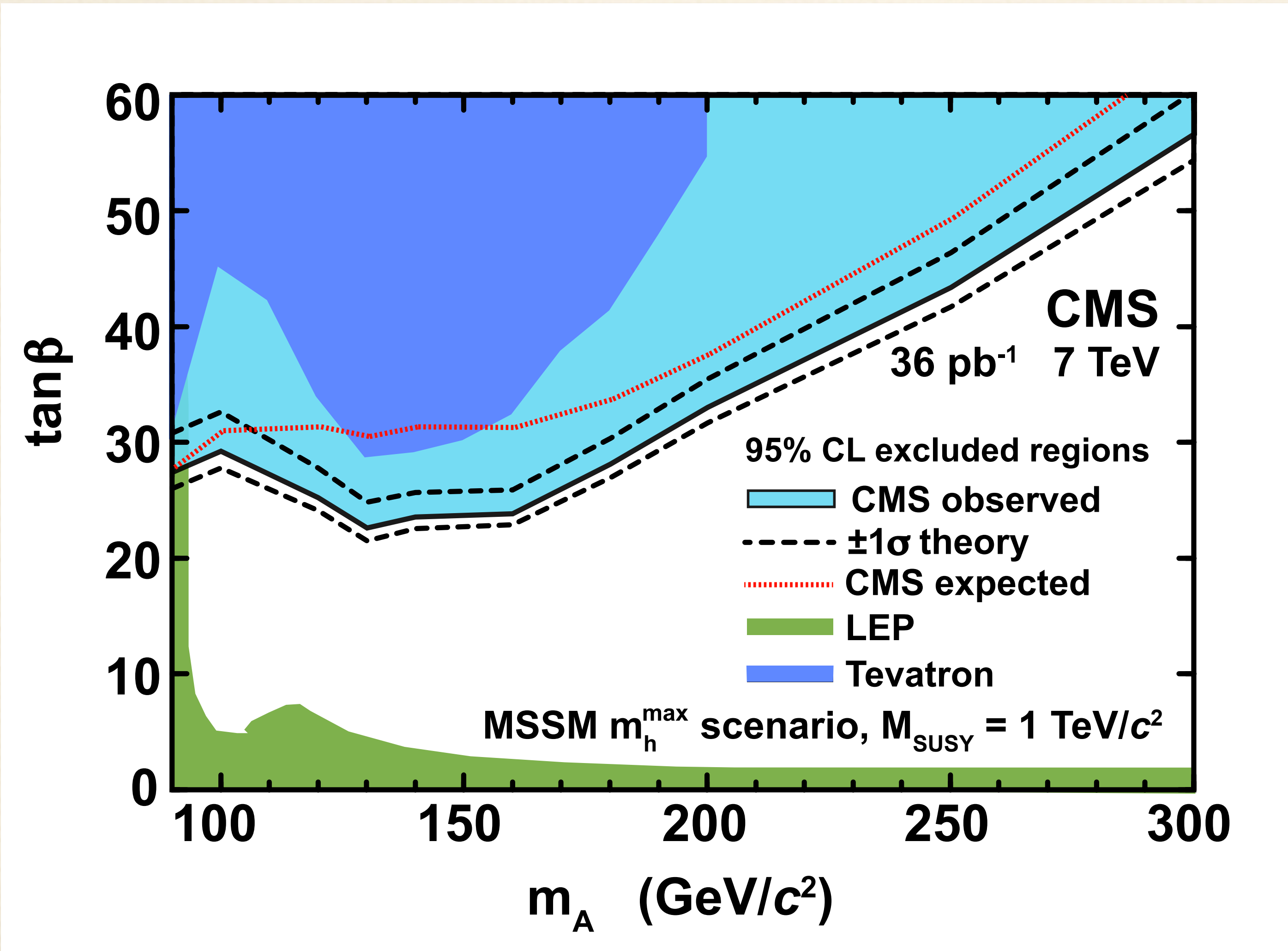
LHC spent 2009 retrofitting and repairing, and began colliding at high energy in early 2010, at 7 TeV

Commissioning of the detectors was rapid, though in 2010 only 36 pb^{-1} were delivered/recorded



Fewer than 1000 Higgs boson events in 2010

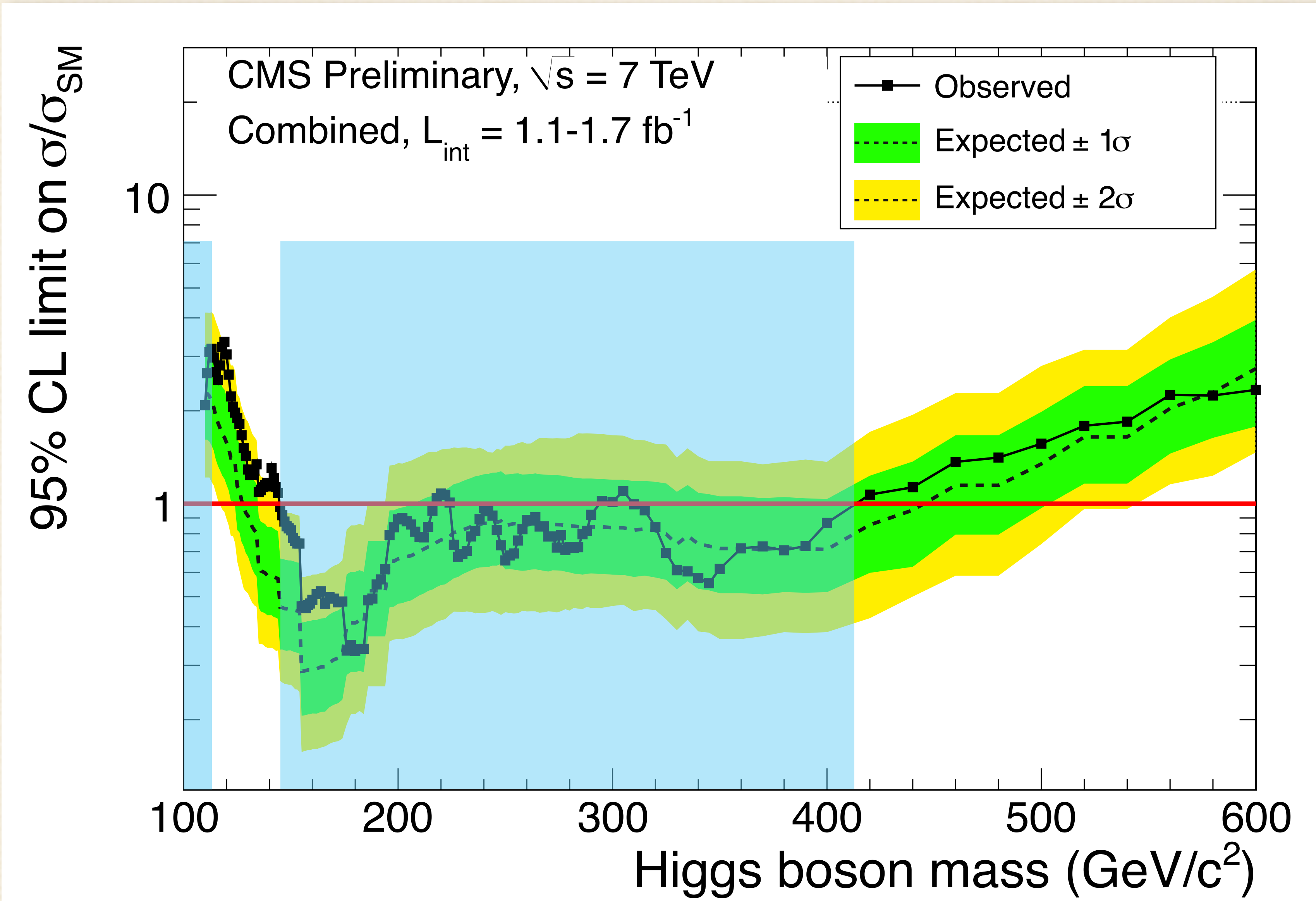
With only 36 pb^{-1} the MSSM search completely eclipsed that of the Tevatron:



CMS search for MSSM

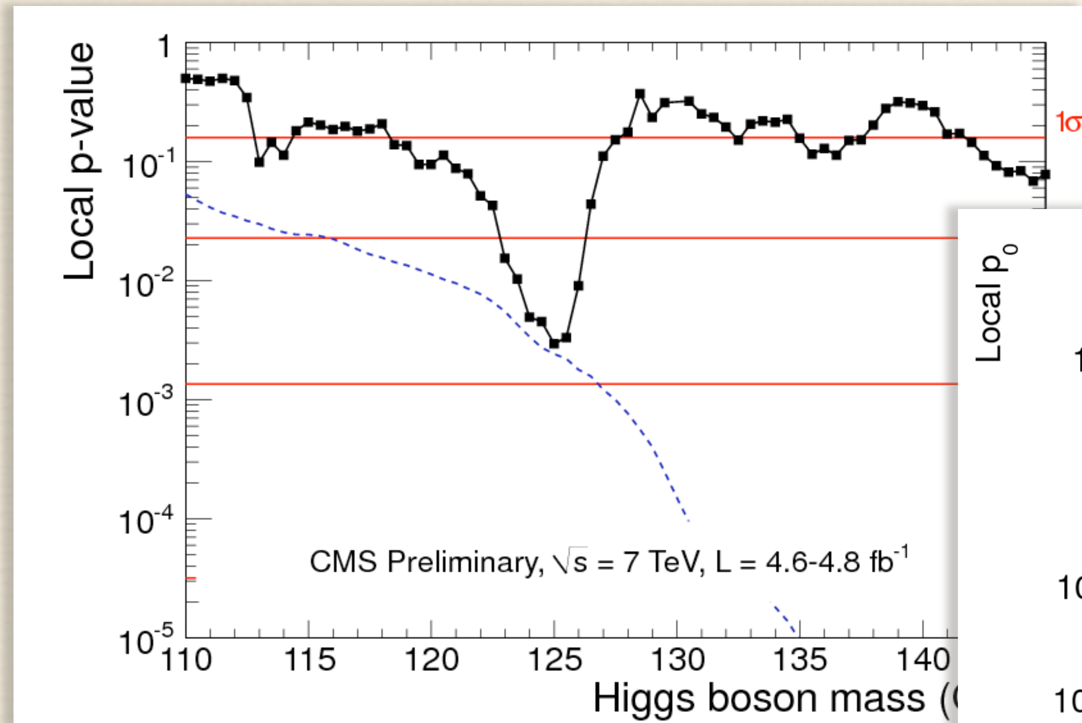
h/A/H→ττ

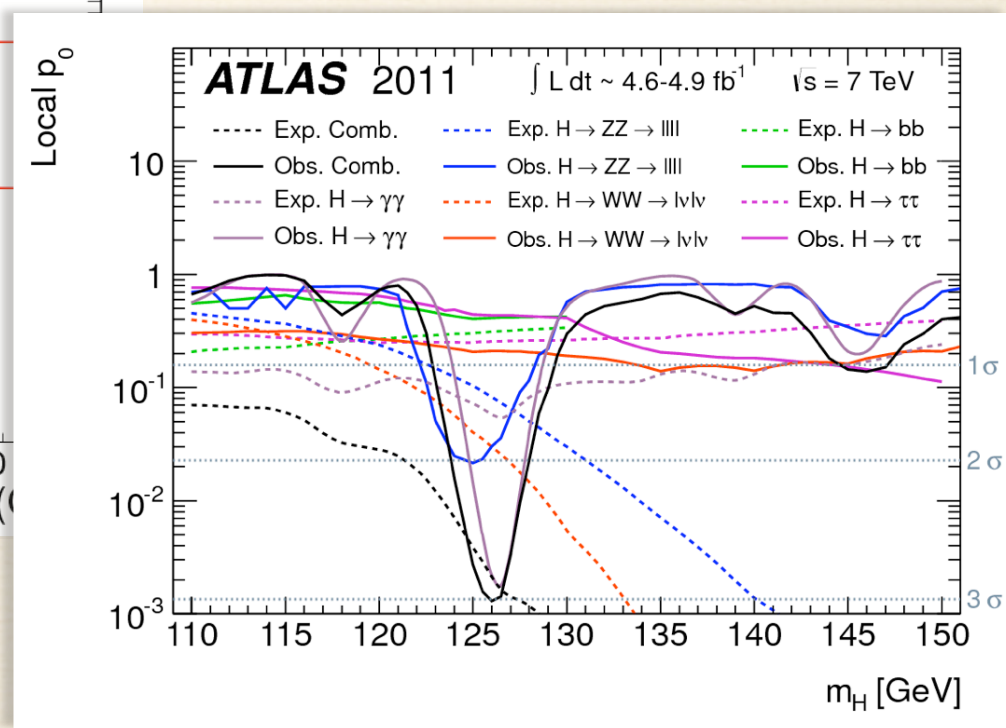
2011: LHC delivers 1 fb^{-1} by summer, and suddenly the landscape changed dramatically:



2011: Delivered 5 fb^{-1} by the end of the year - 150x the 2010 sample!

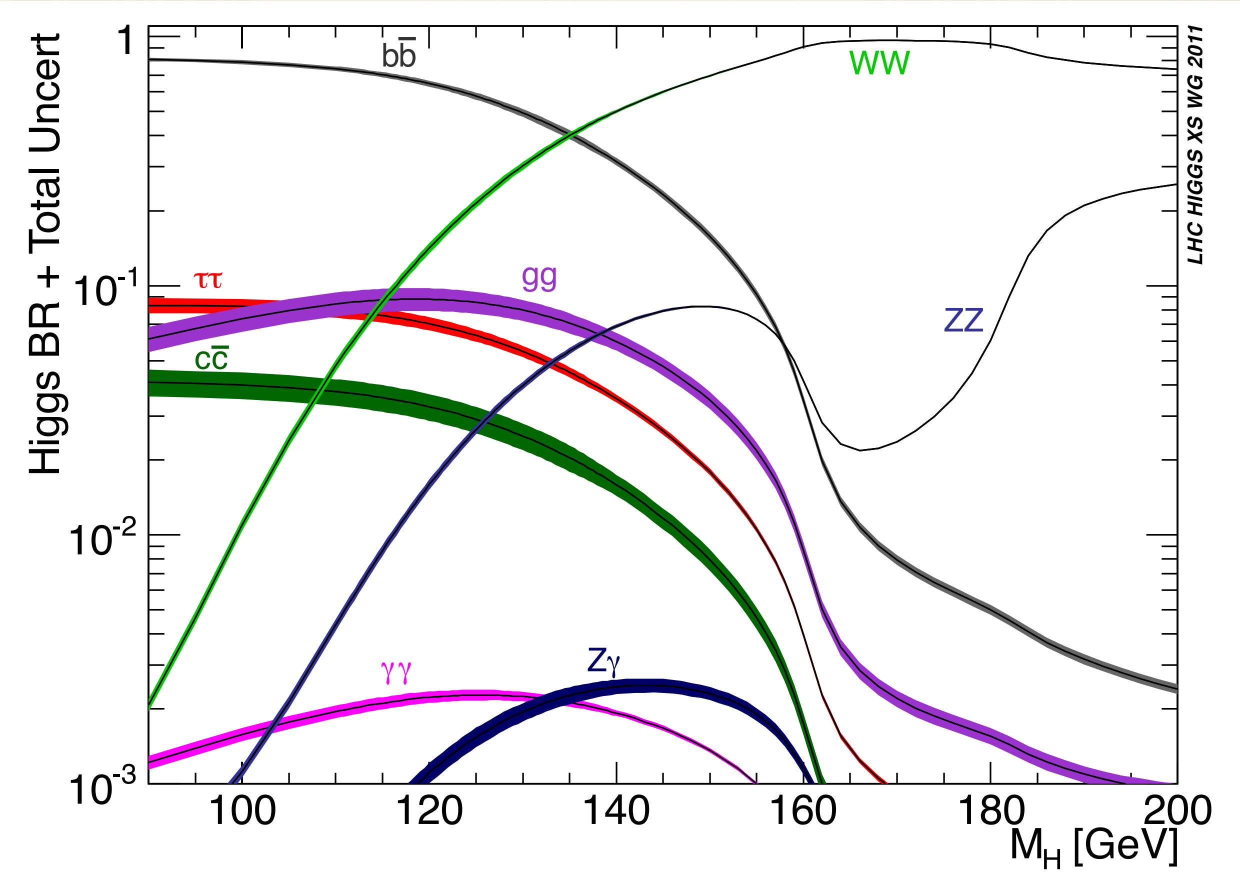
CMS and ATLAS showed hints of a signal near 125 GeV!



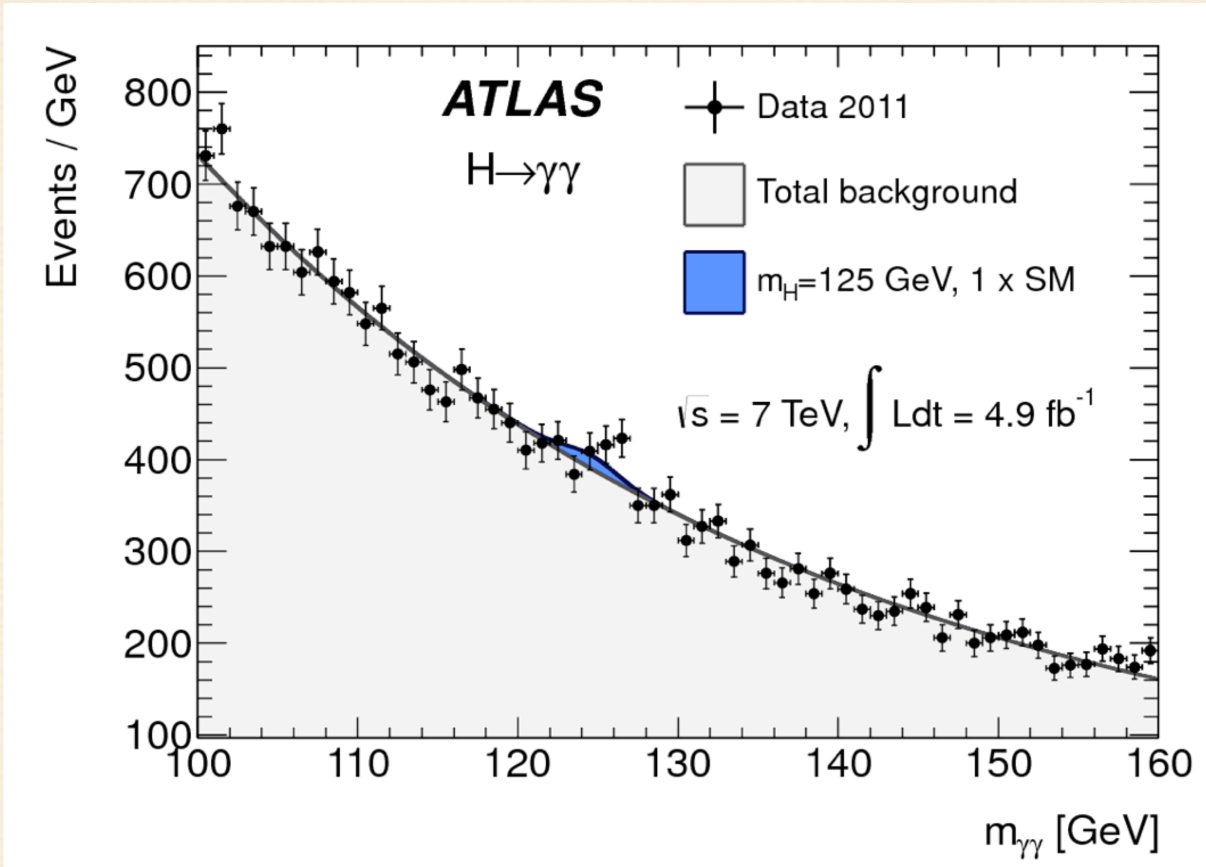


At ~125 GeV, the main Higgs discovery modes are

γγ - sharp resolution, large background
ZZ - sharp resolution, statistics limited
WW - poor resolution, good sensitivity



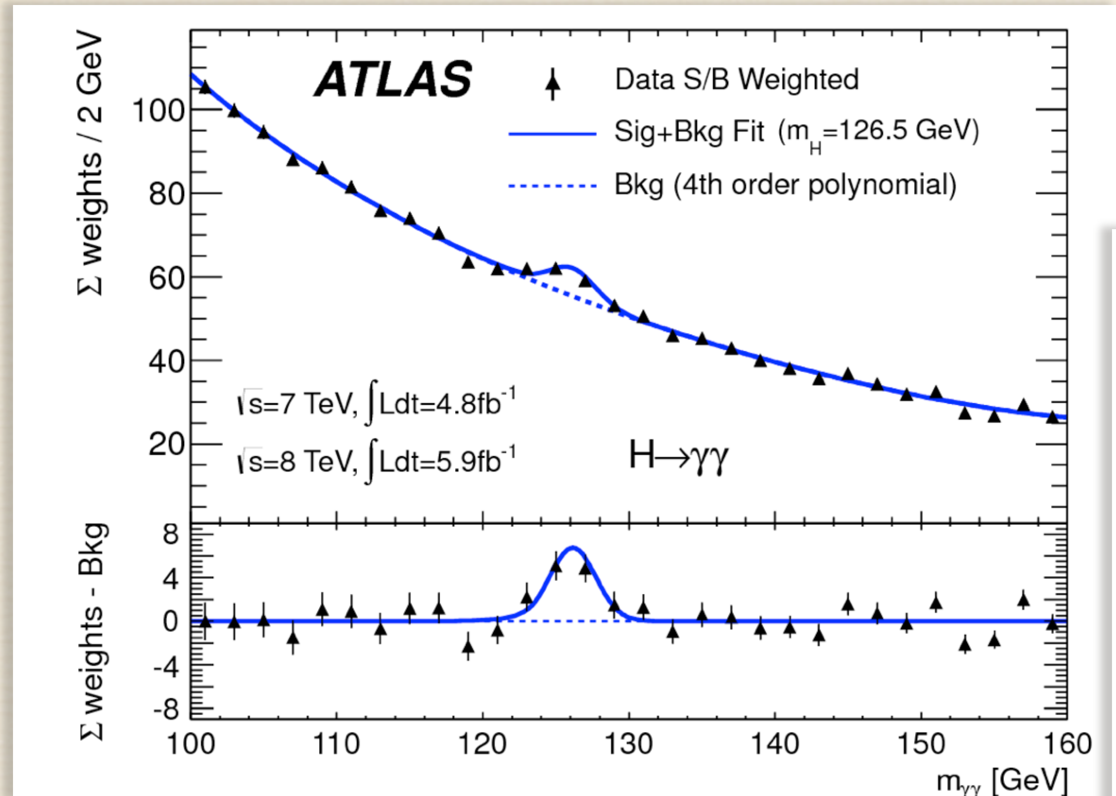
ATLAS had a nice bump-let at the favored mass:

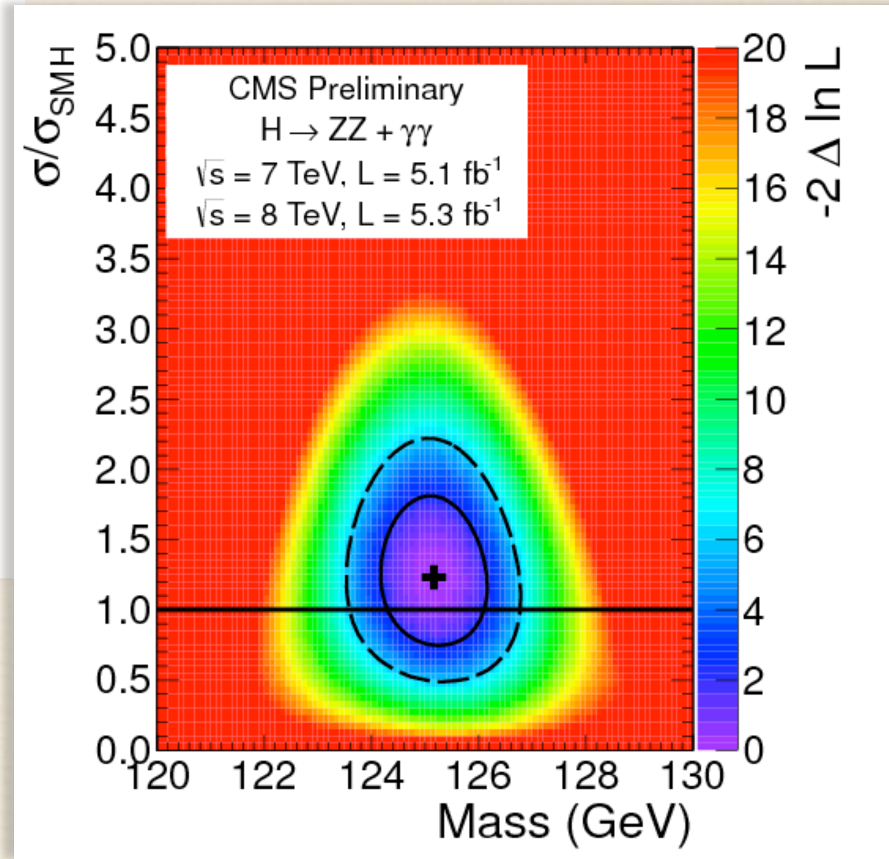


Rather less compelling for CMS at that point...

Captured!

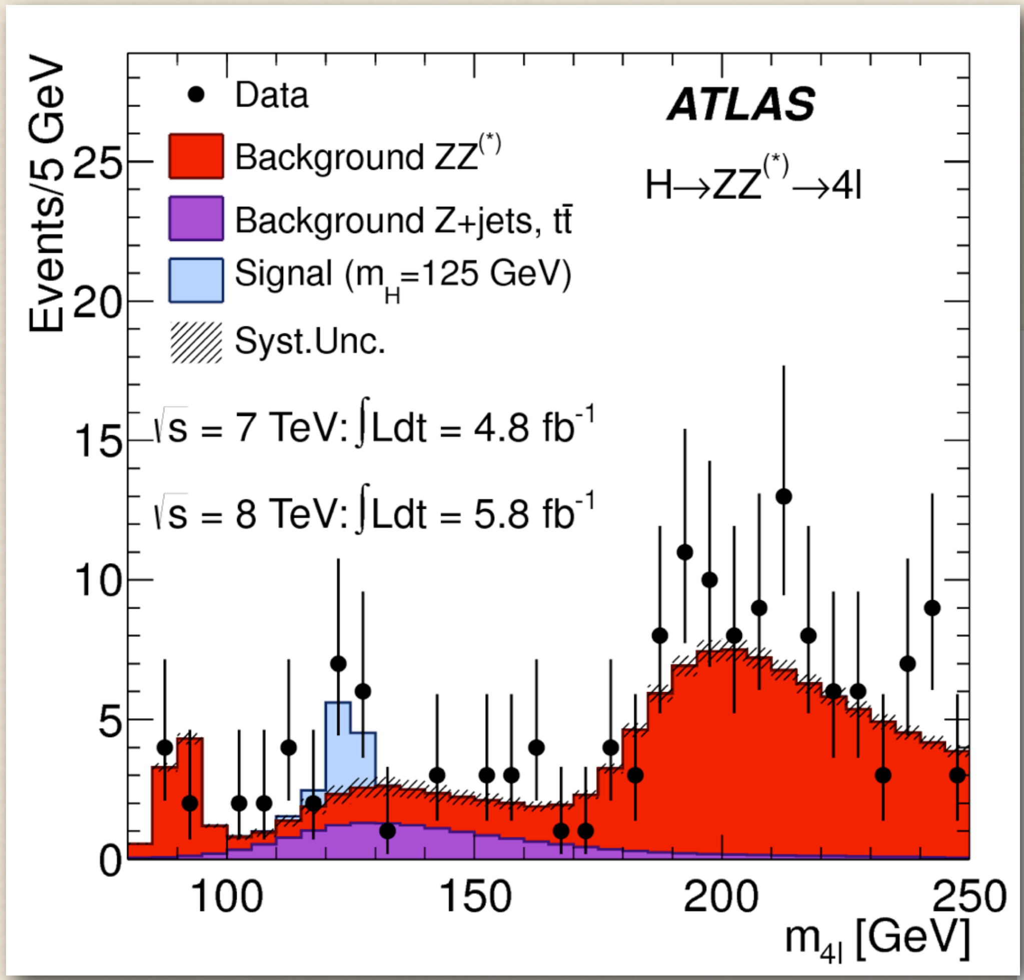
In 2012 the LHC increased to 8 TeV and increased the luminosity...by summer we had 5 fb^{-1} more

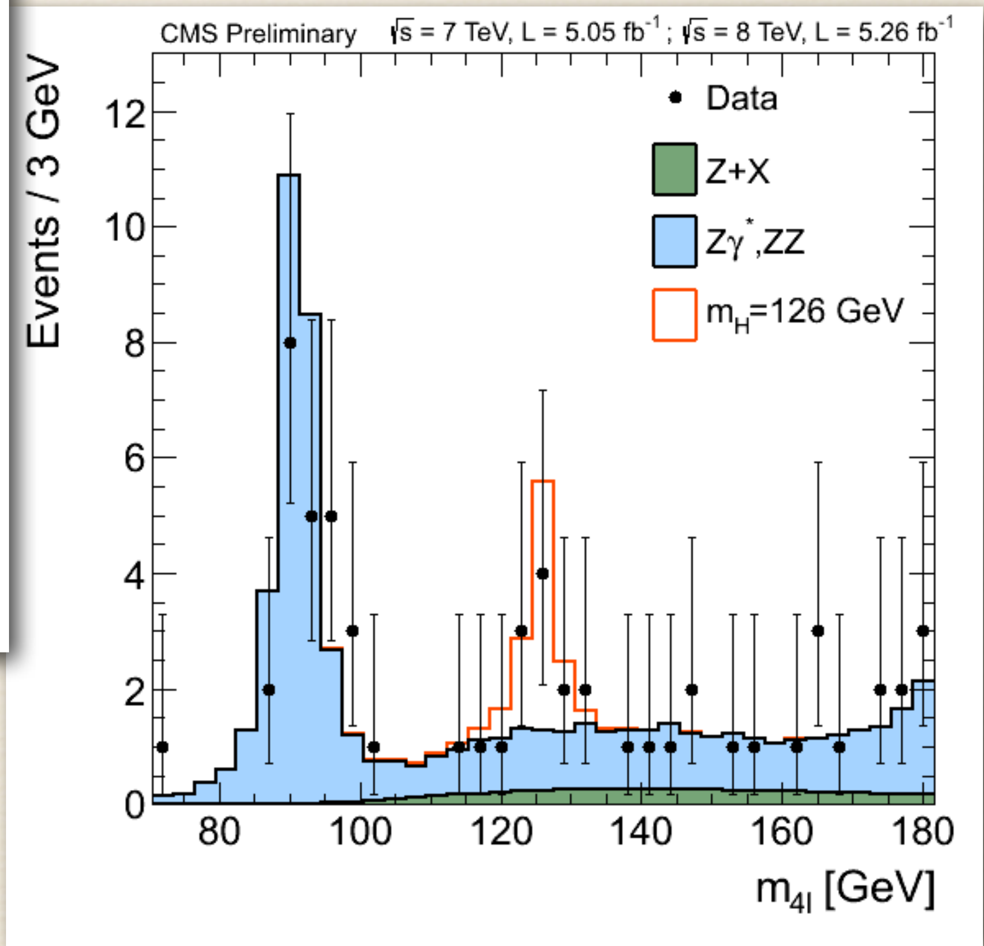


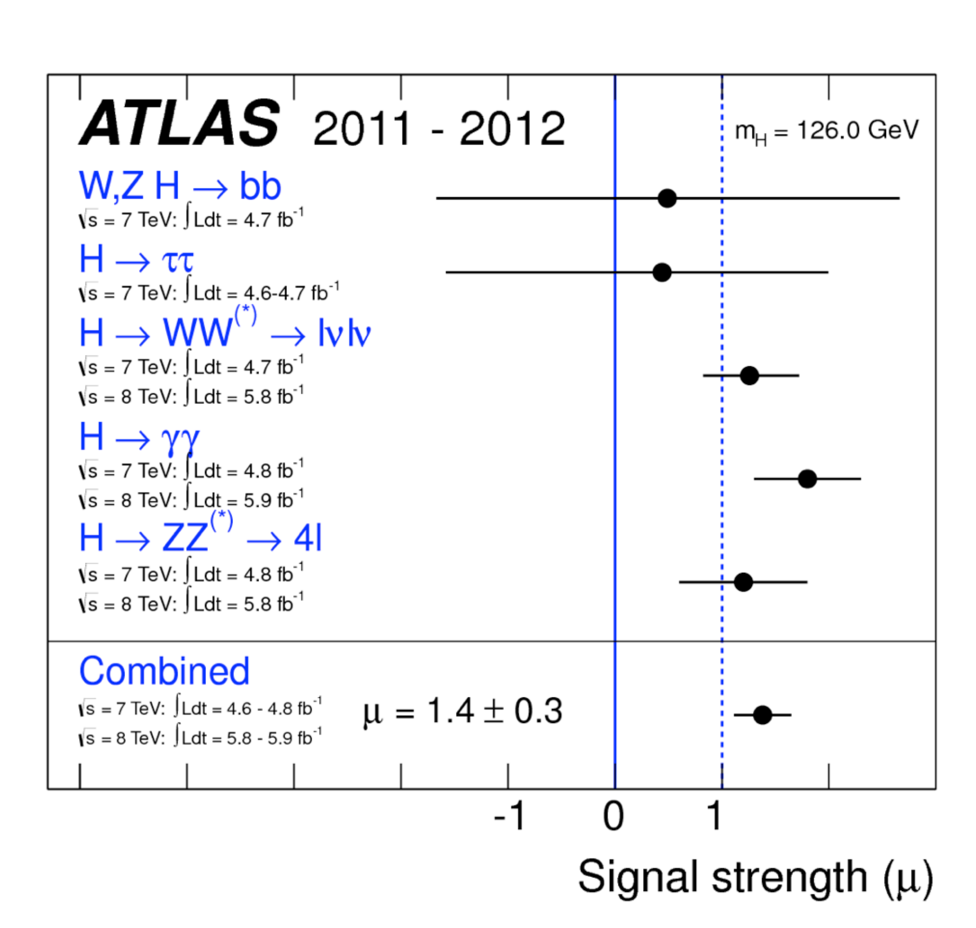


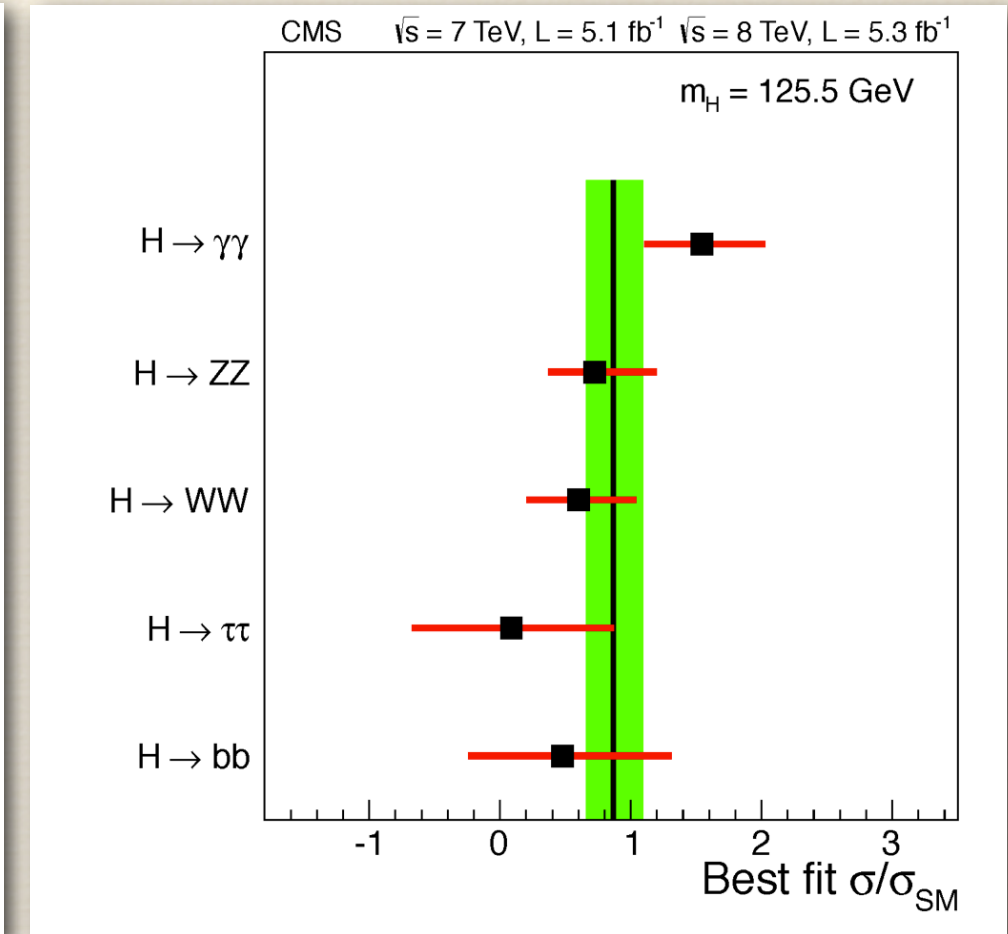
On July 4 both experiments reported 5σ discoveries

ATLAS and CMS had nice signals in $ZZ \to 4\ell$



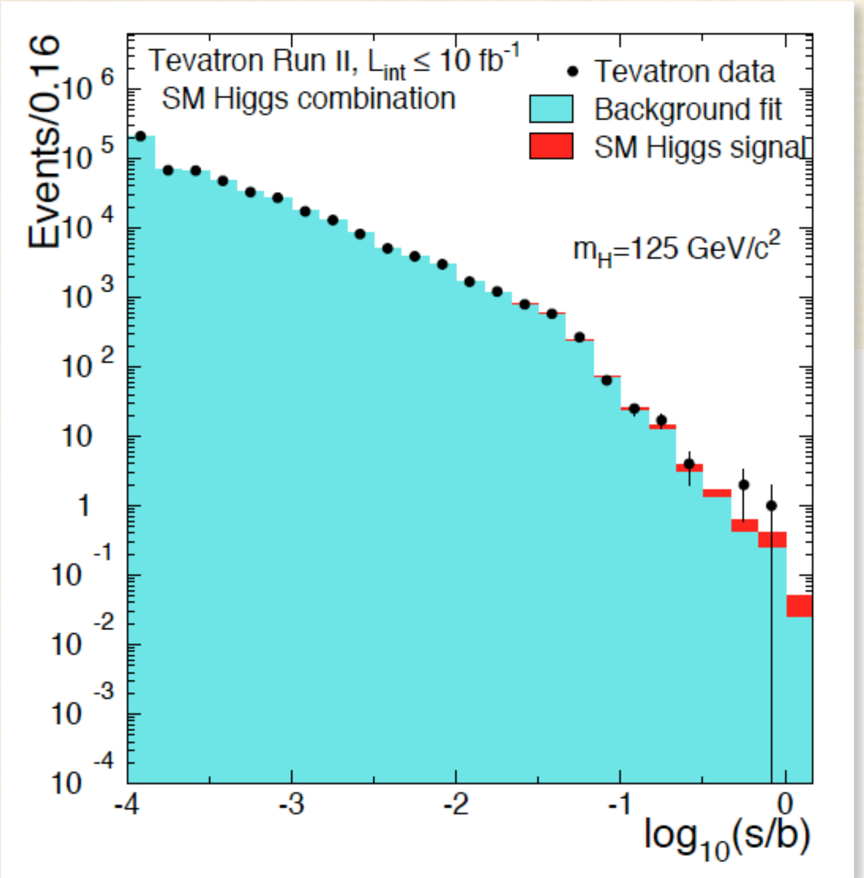


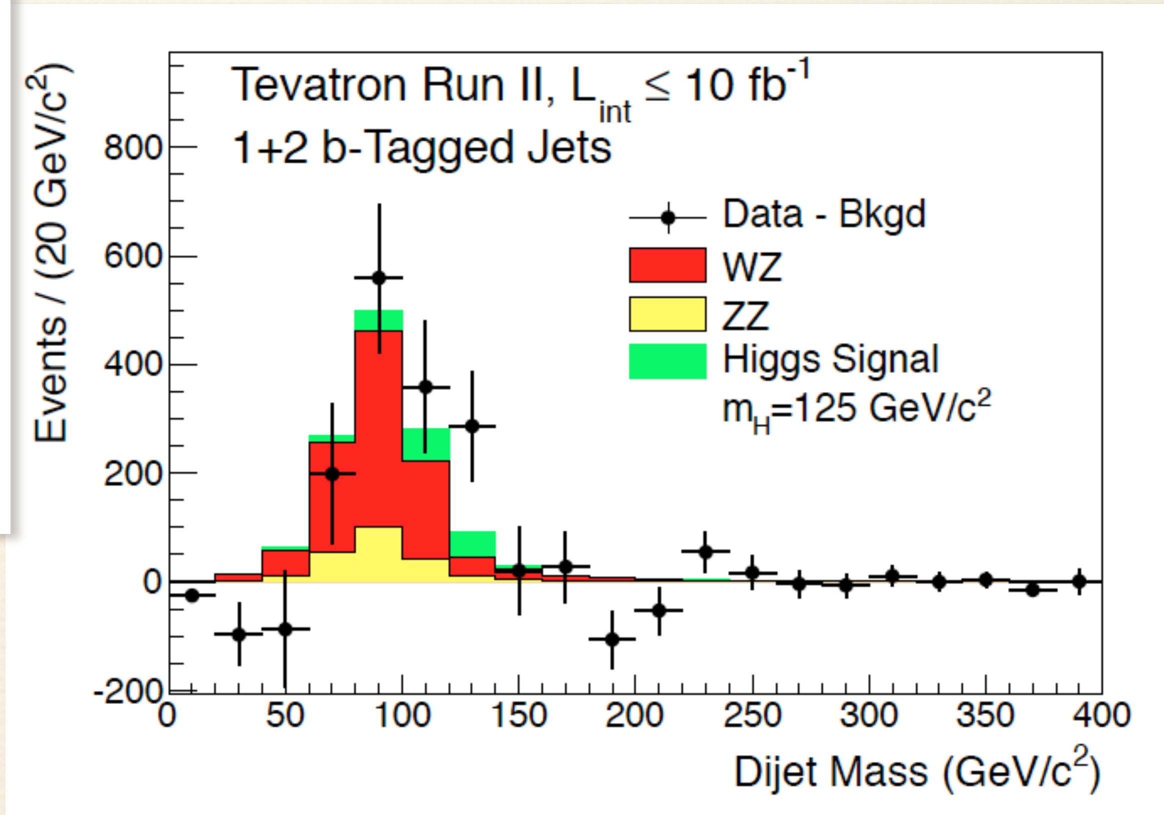




Broken into Higgs decay modes, discovery data lead to the next question: does the new boson decay to fermion pairs? Much more data needed...

The Tevatron ended on an up-note: 3σ excess, dominated by the bb mode!





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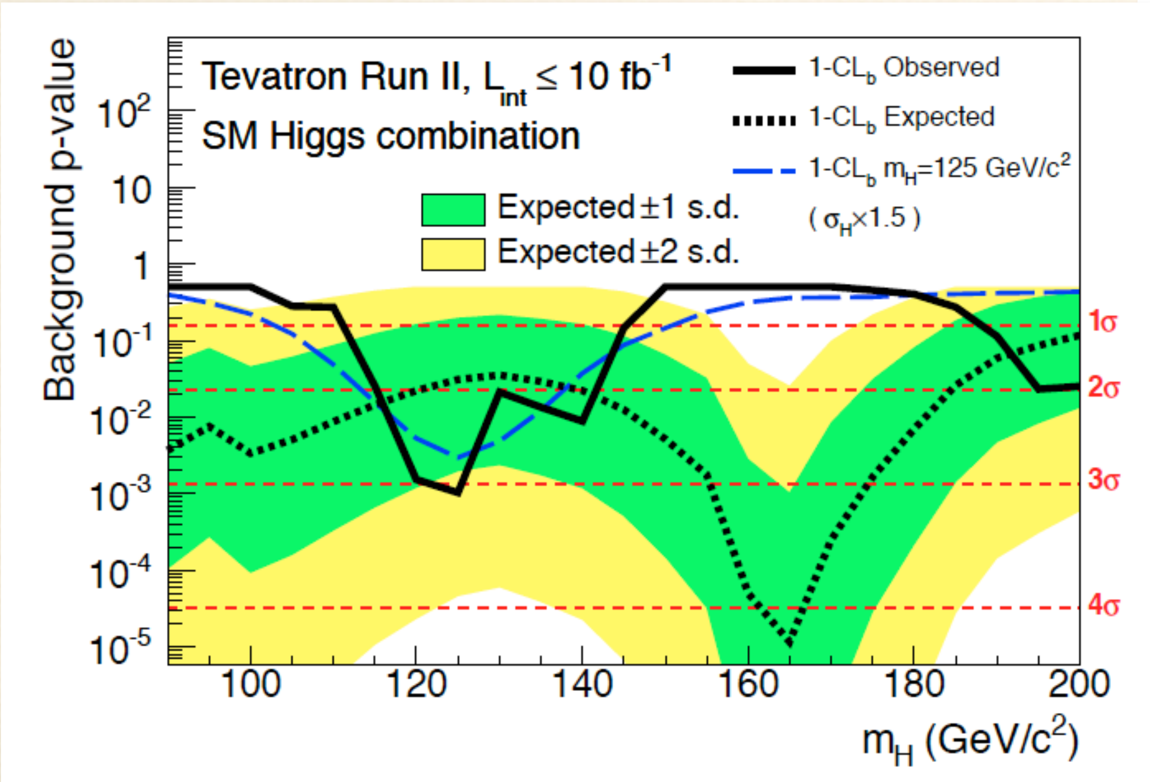
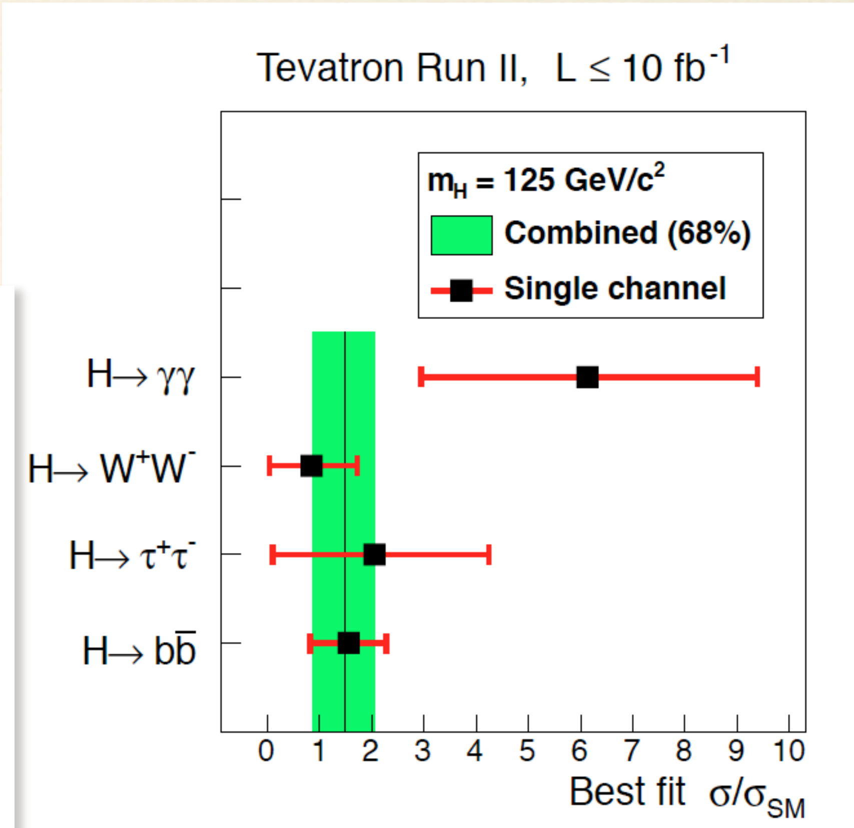




The most recent Higgs results from ATLAS and CMS were presented at HCP in Kyoto in November, based on 17 fb^{-1} (5 fb^{-1} at 7 TeV, 12 fb^{-1} at 8 TeV)

Time to analyze new data at higher luminosity was short, the analyses were in certain cases improved, and not all channels made it to HCP in either experiment...

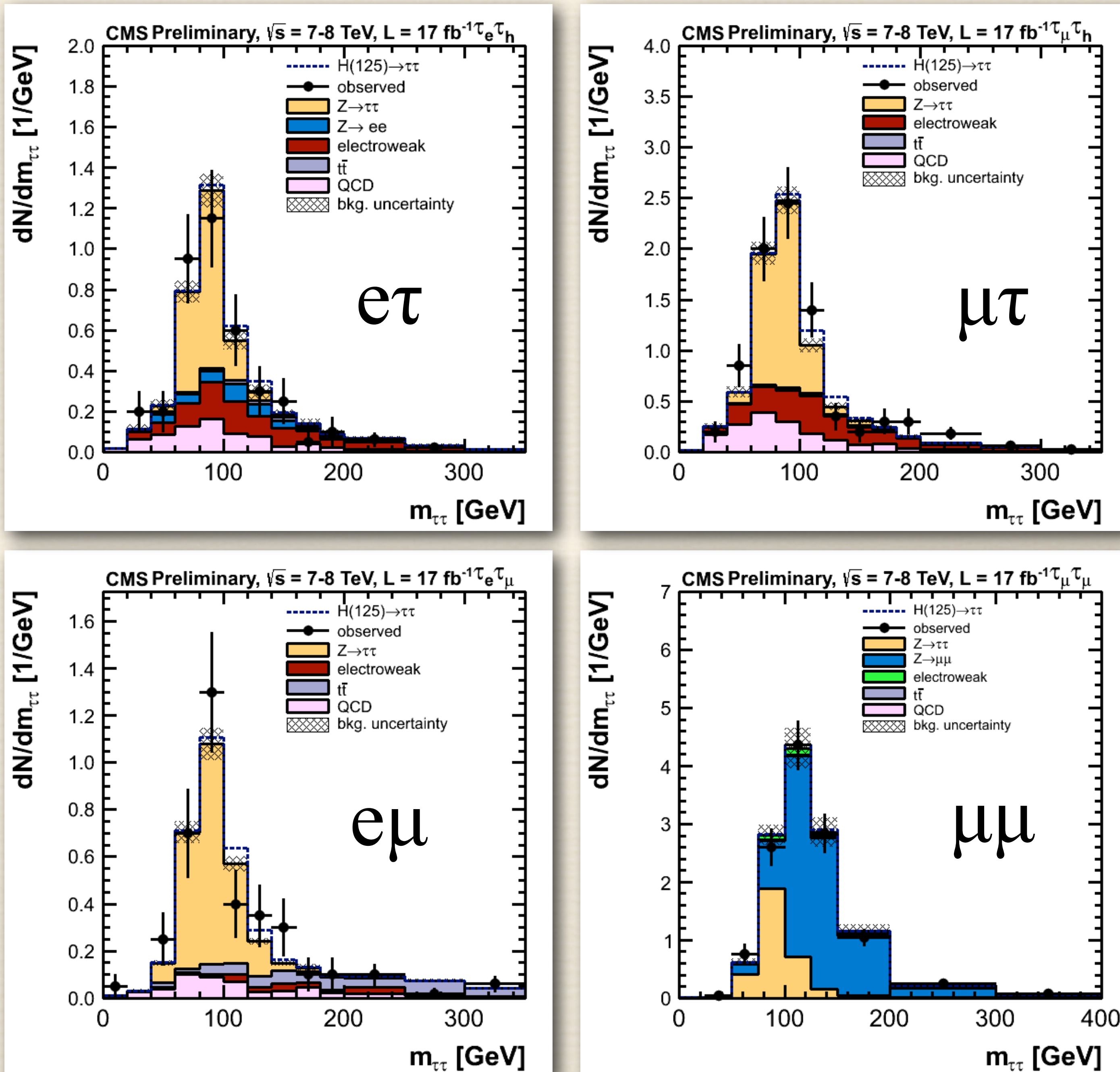
In particular, the $\gamma\gamma$ results from both CMS required more scrutiny; ATLAS released new $\gamma\gamma$ for the CERN council meeting in December.

Nevertheless...after the hunt...

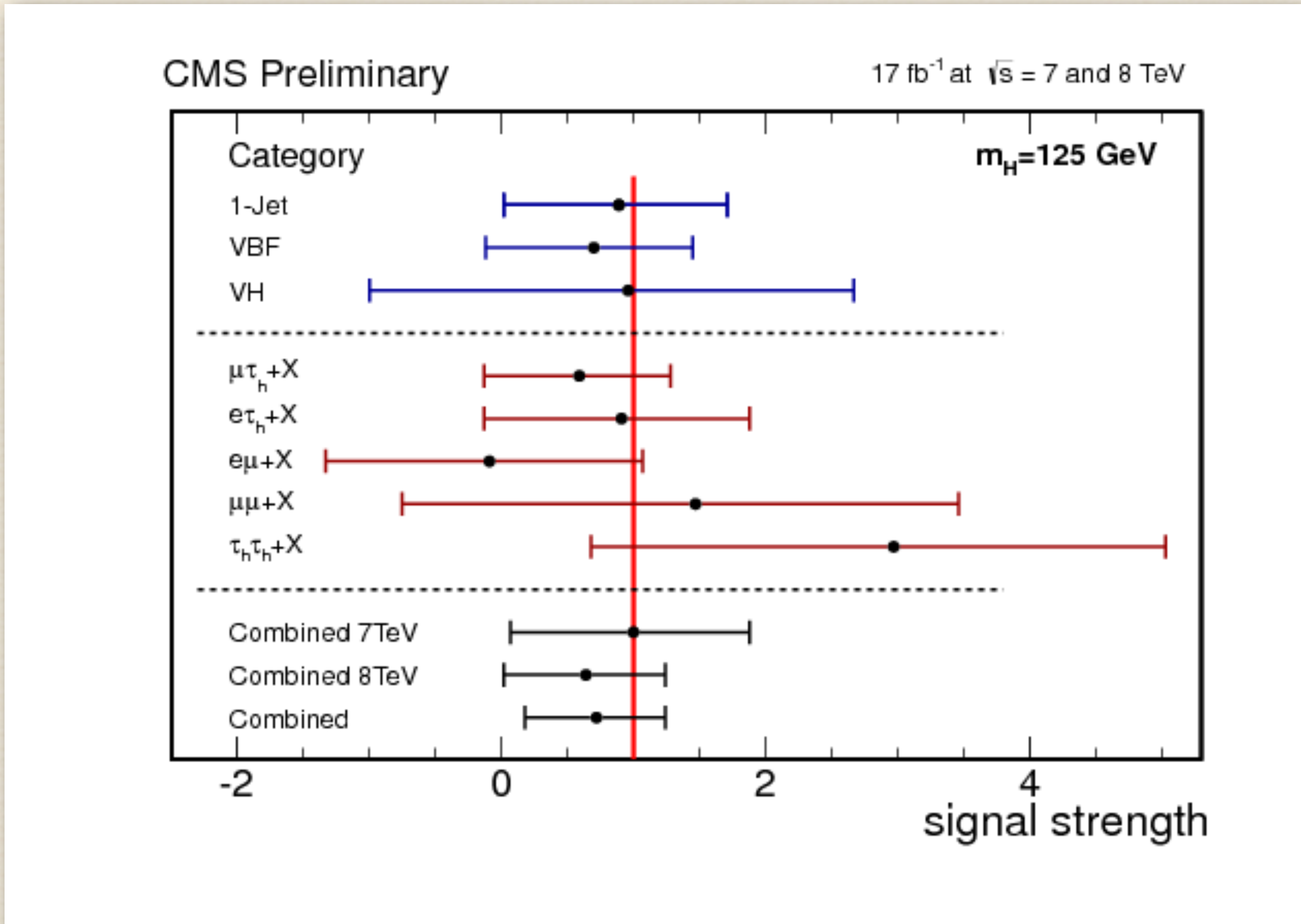
The Feast Begins!

New results on H → ττ from CMS

VBF channel



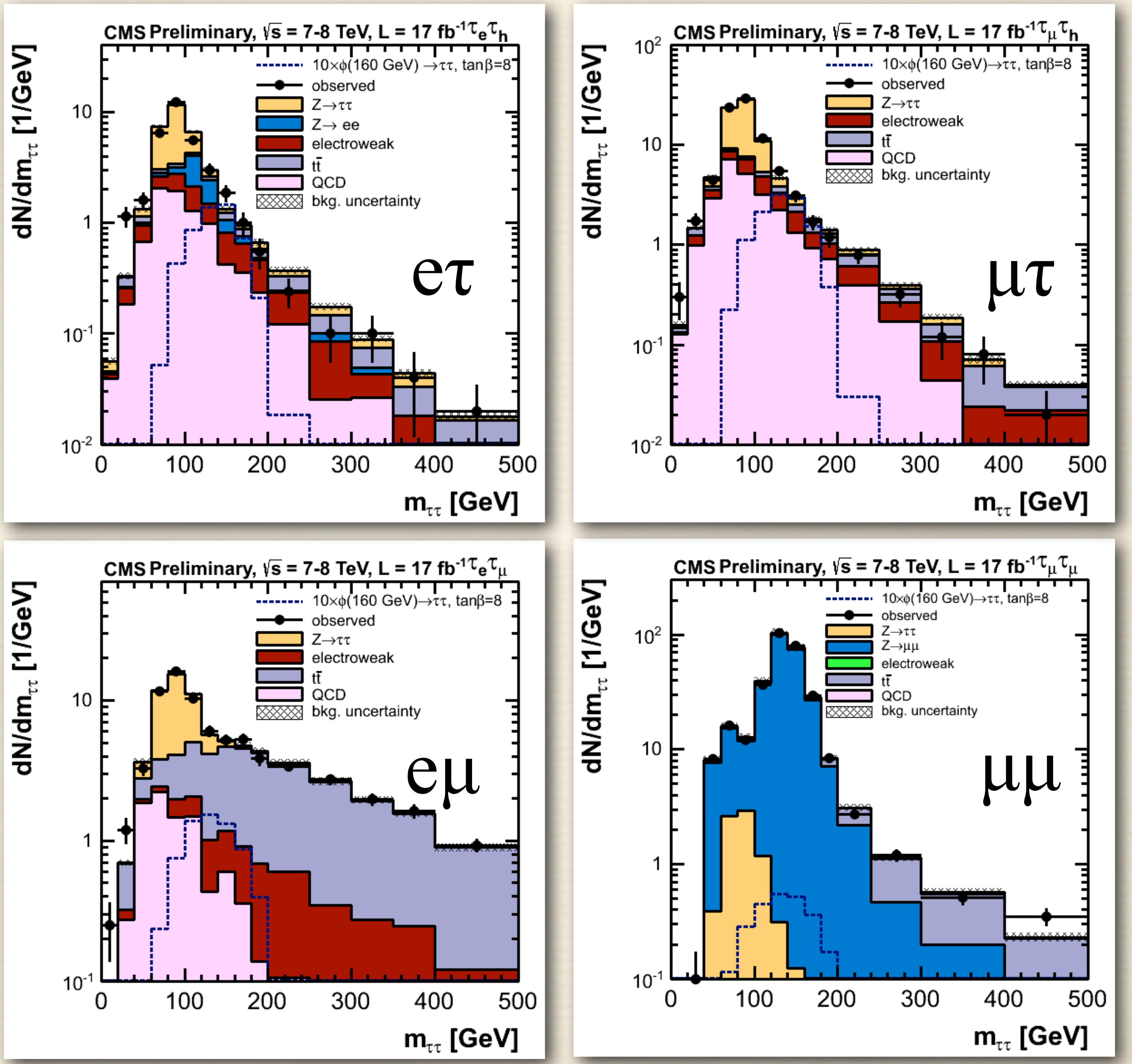
New results on $H \to \tau\tau$ from CMS



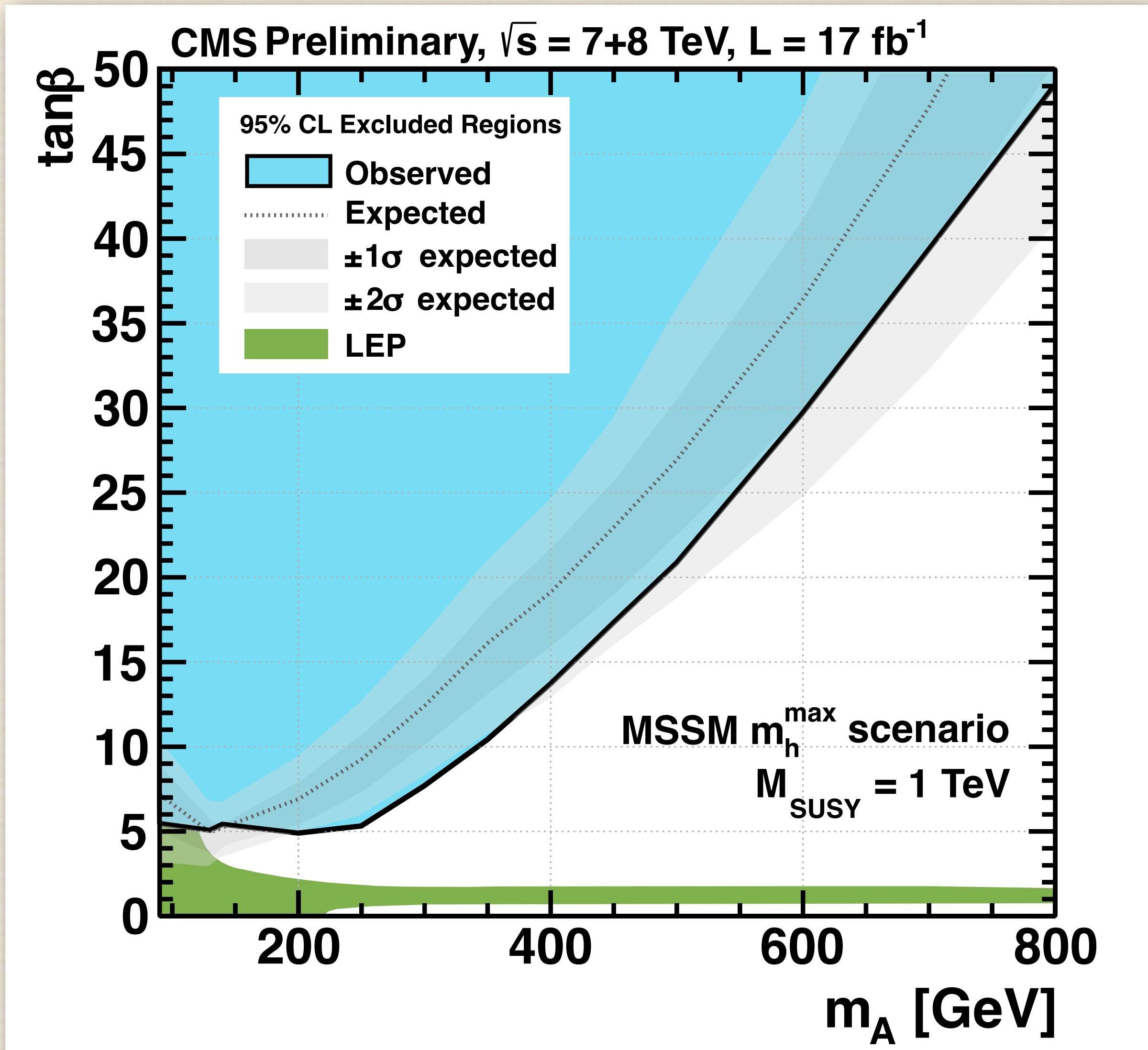
Combined: $\mu = 0.7 \pm 0.5$

New results on MSSM h/A/H → ττ from CMS

b tag channel

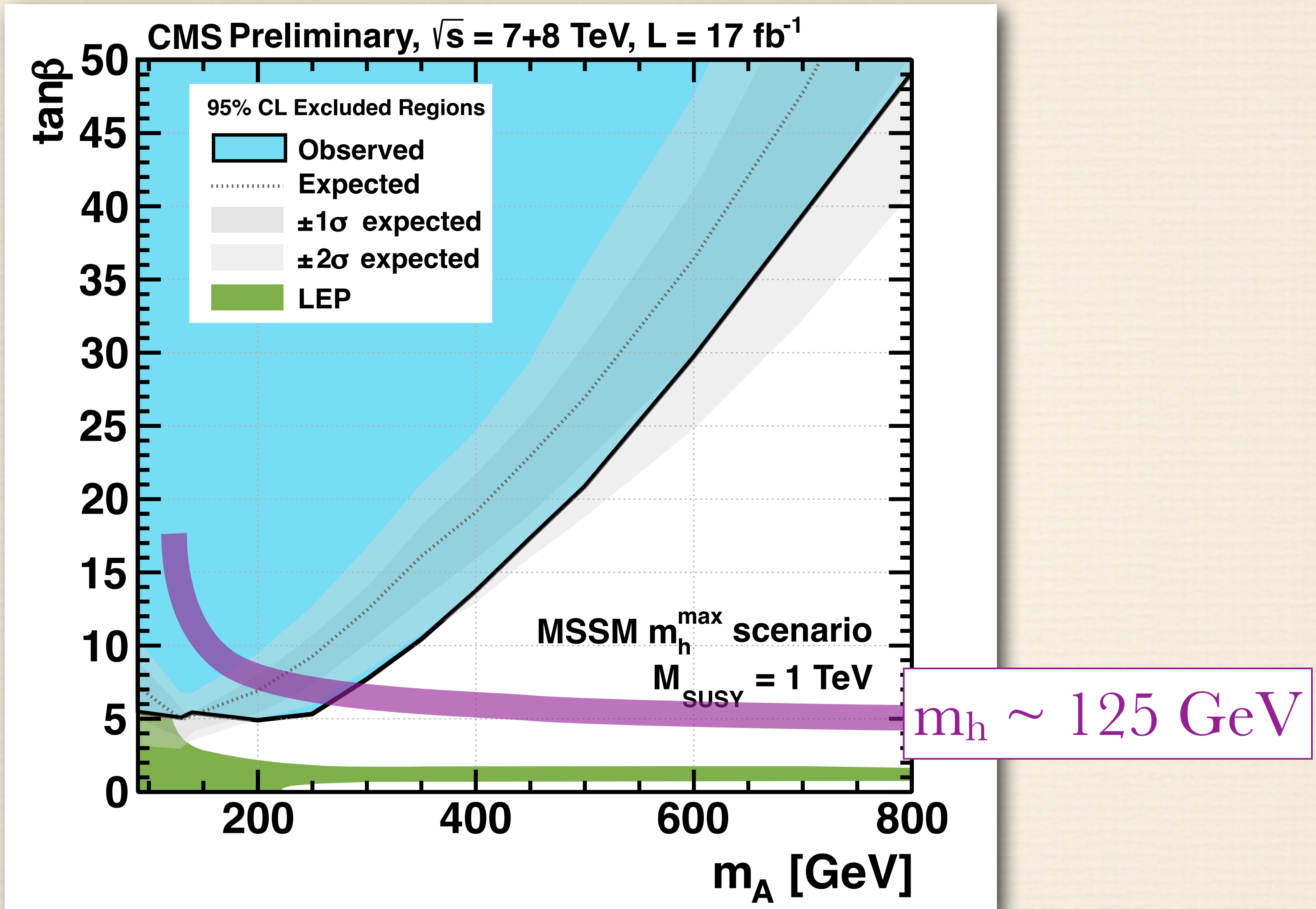


New results on MSSM h/A/H → ττ from CMS



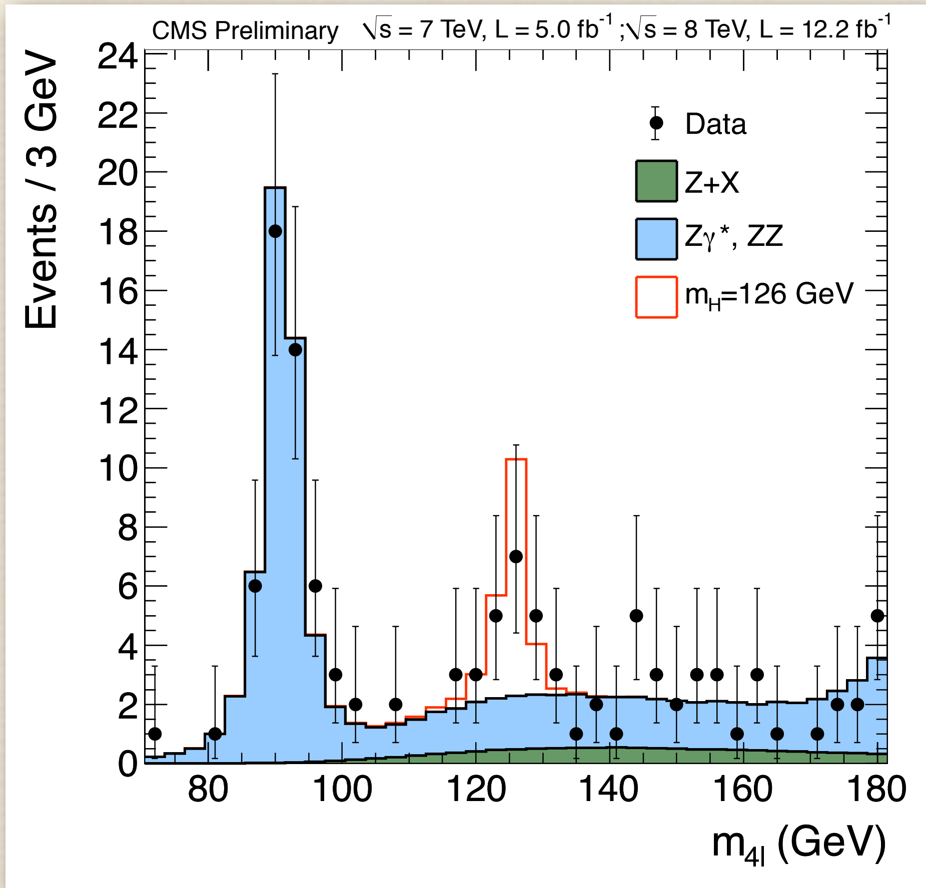
No sign of excess anywhere - still statistics limited!

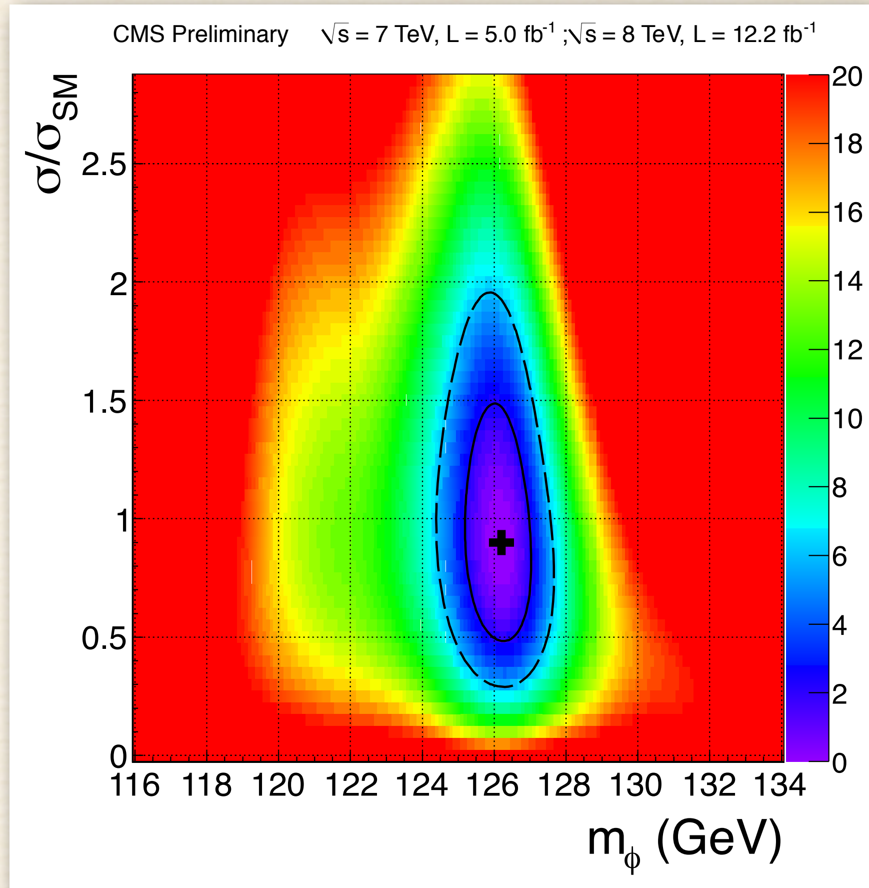
New results on MSSM h/A/H → ττ from CMS



No sign of excess anywhere - still statistics limited!

Updated results on ZZ → 4ℓ: CMS

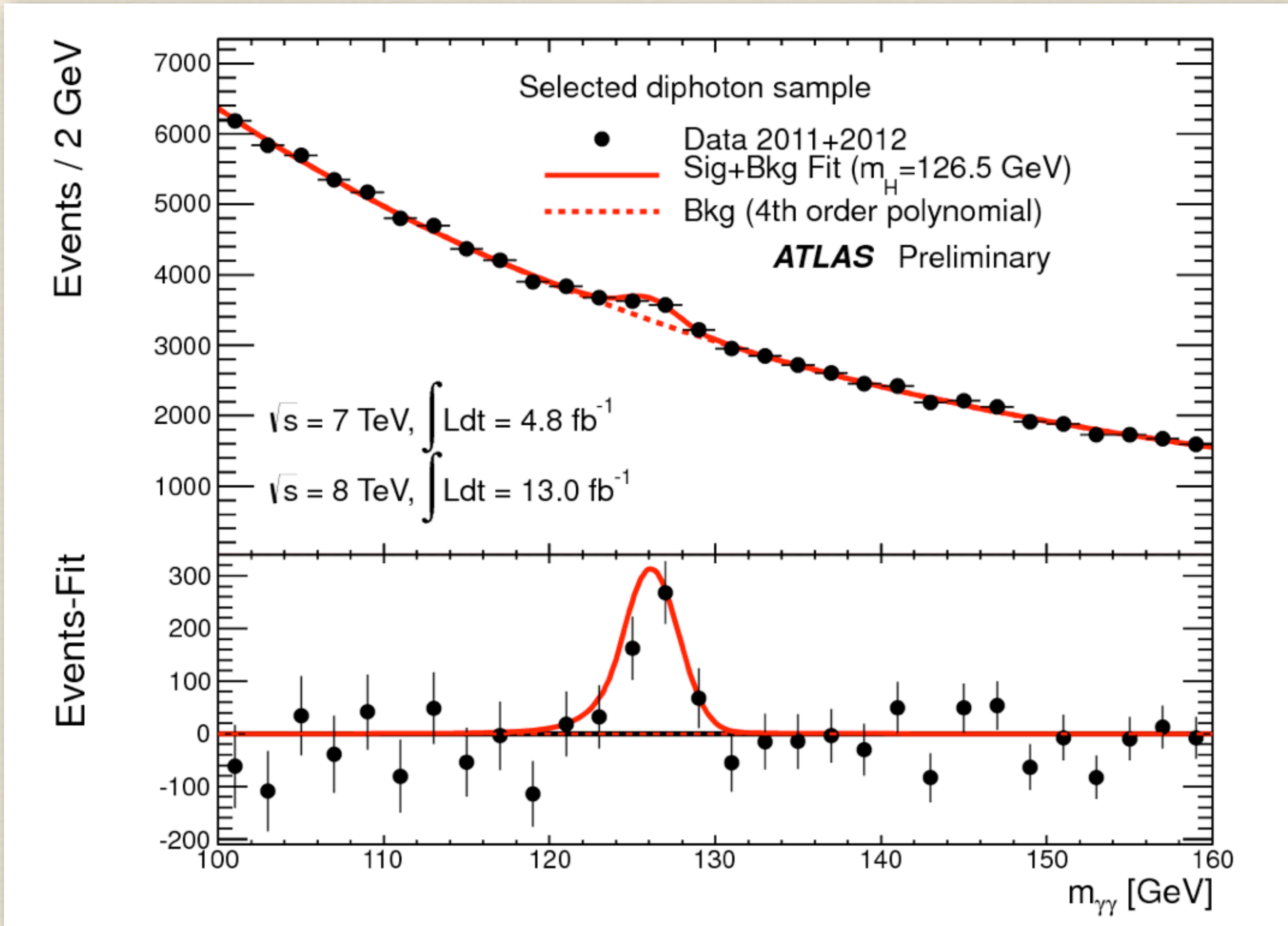




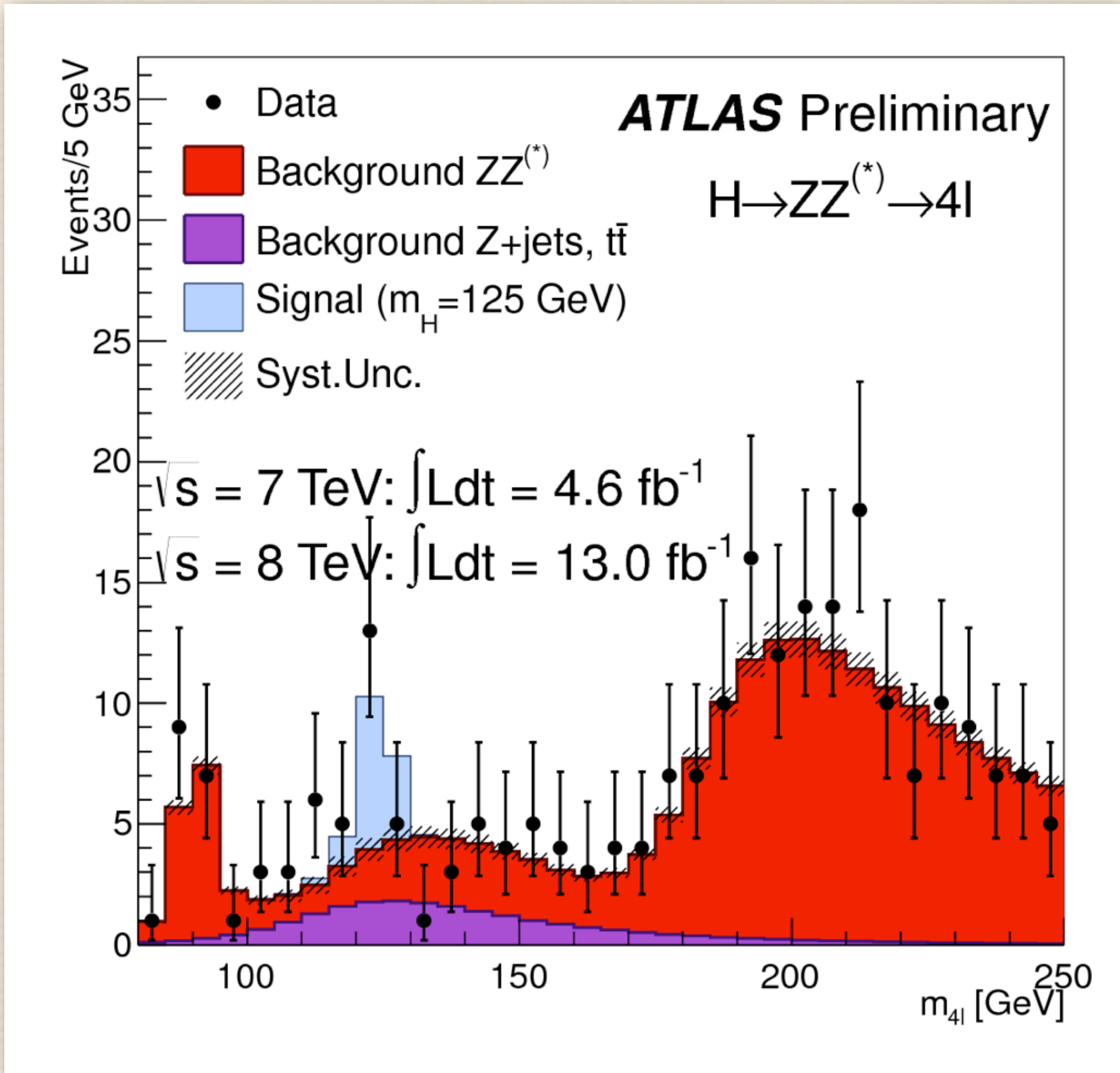
Peak nicely growing - mass result 126.2±0.6±0.2 GeV

(CMS γγ/ZZ combined mass: 125.8±0.4±0.4 GeV)

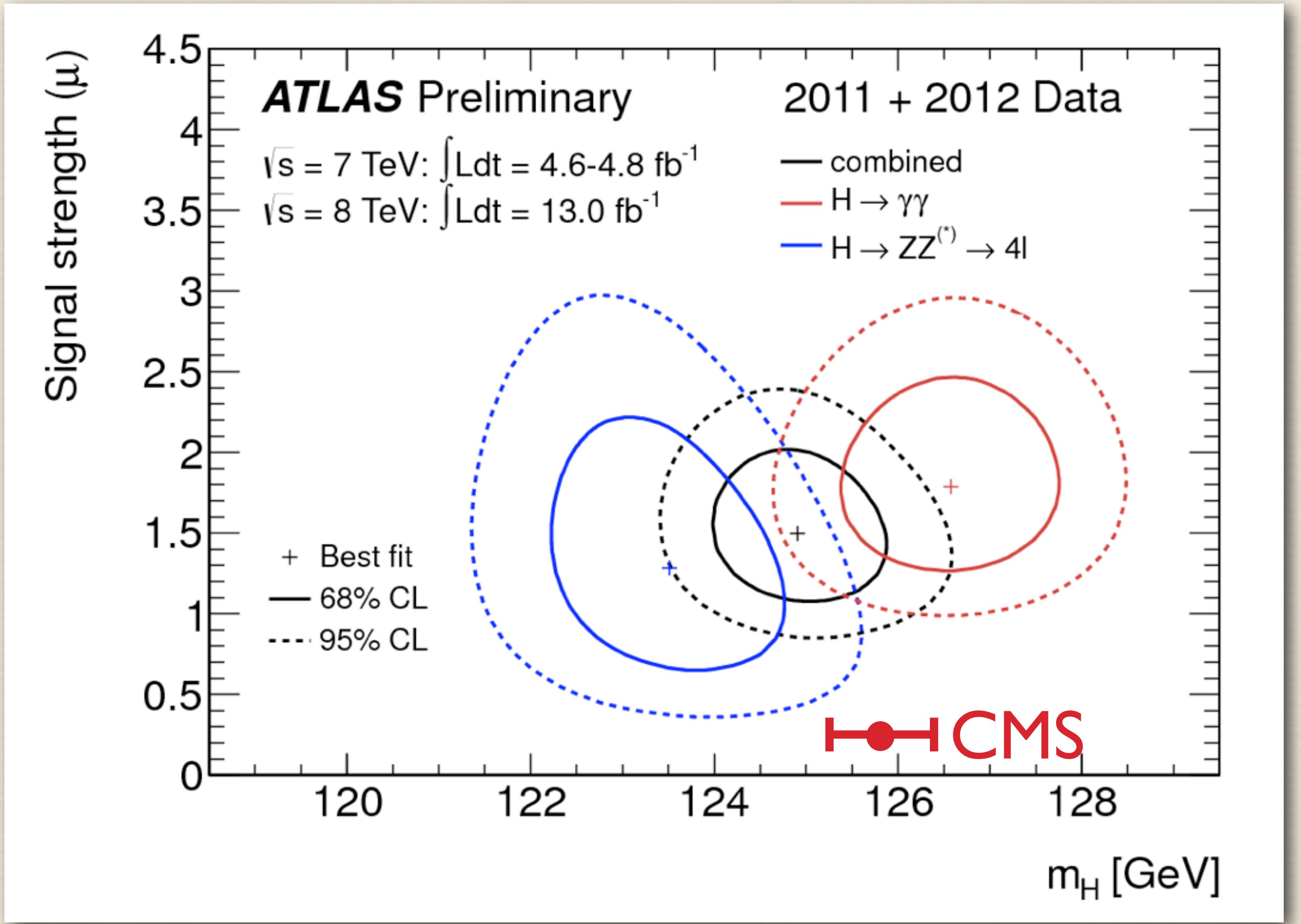
Updated results on γγ: ATLAS



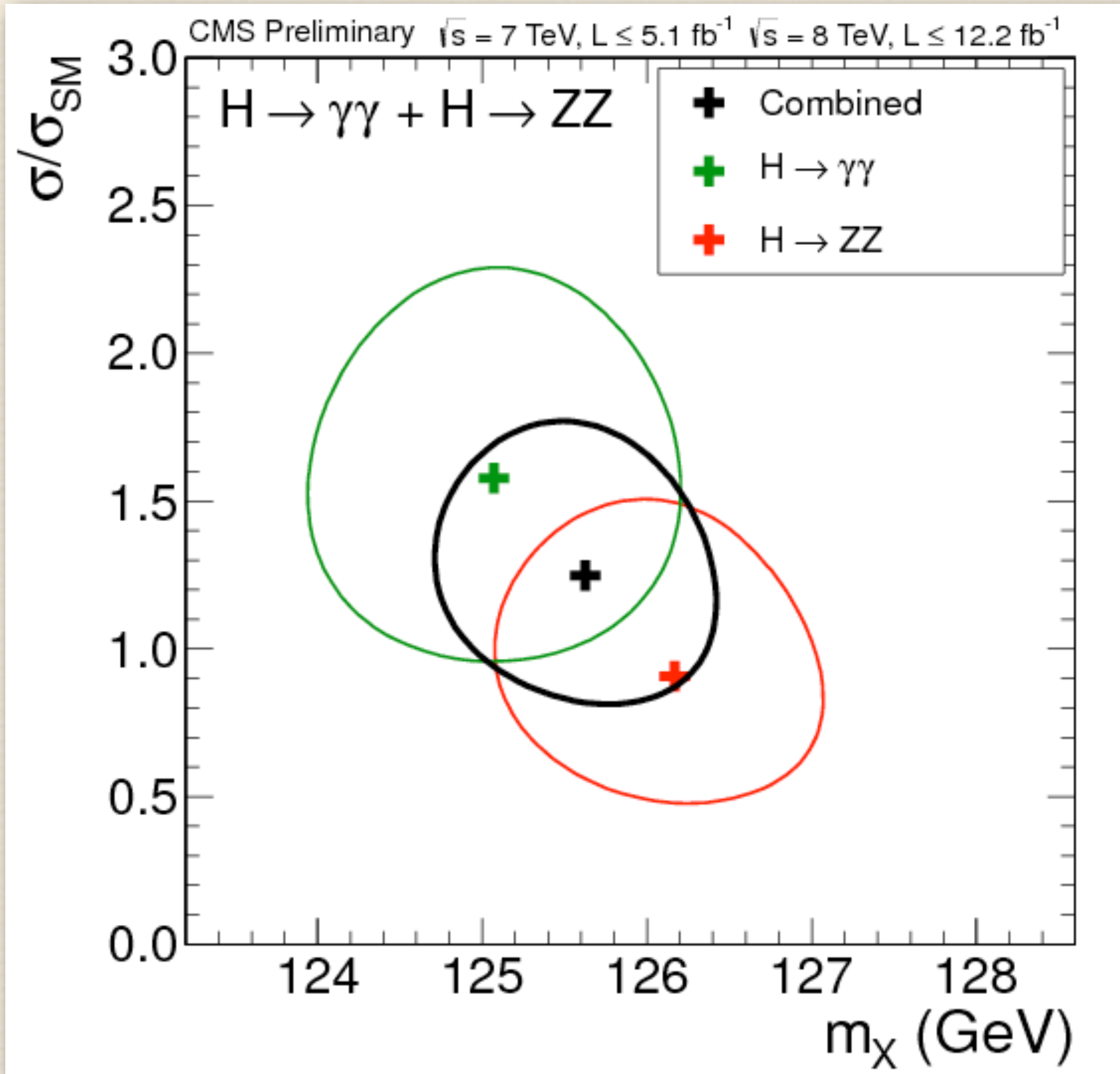
Updated results on $ZZ \to 4\ell$: ATLAS



Updated results on ZZ → 4ℓ and γγ: ATLAS



Mass/mu results on ZZ → 4ℓ and γγ: CMS



Less splitting, opposite sense!

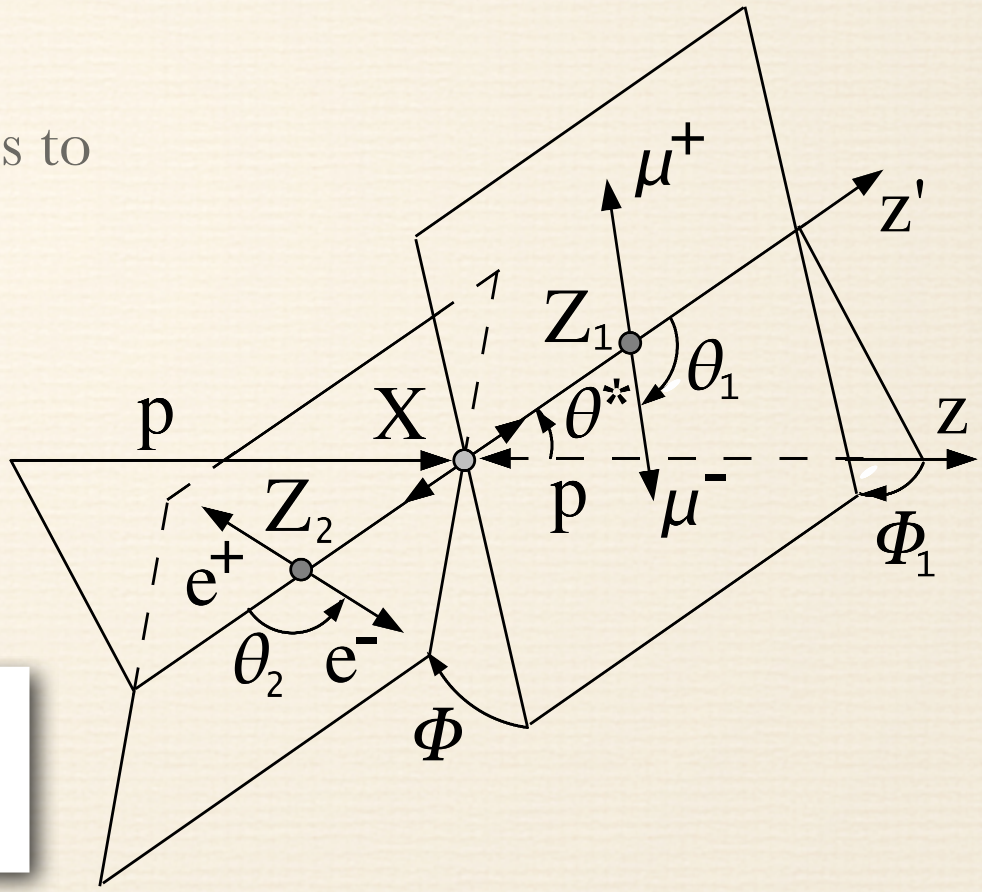
Higgs spin/parity determination from ZZ→4ℓ

One of the two golden modes for discovery and Higgs mass measurement

Can use the angular correlations to distinguish Higgs from continuum ZZ background

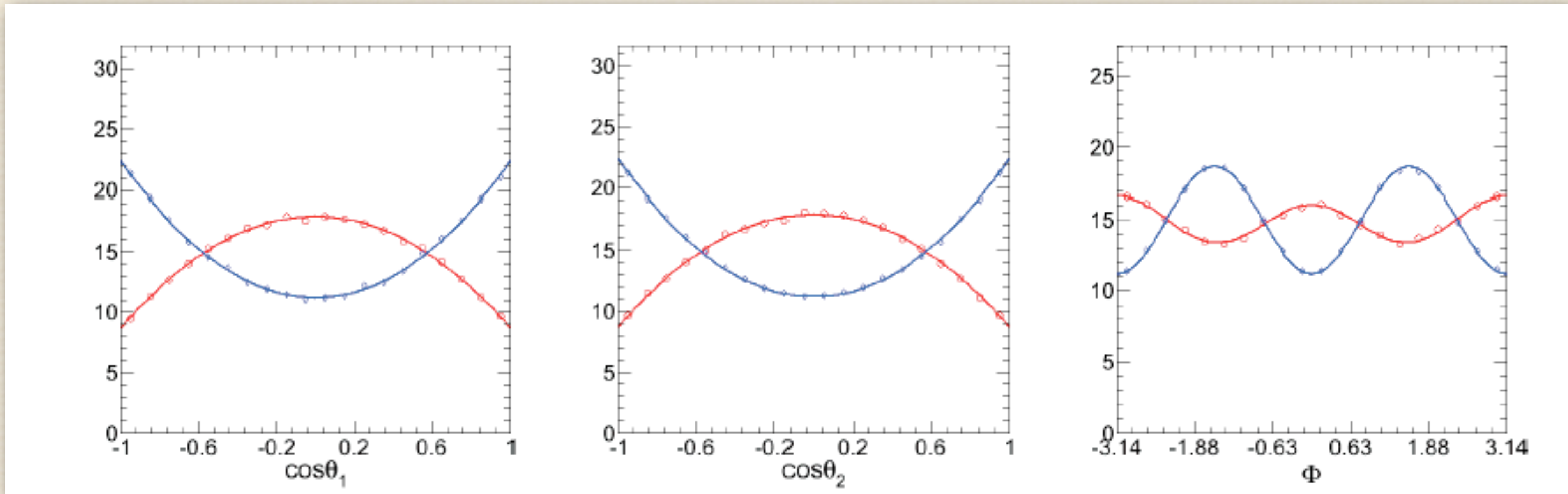
Can also use angular correlations to distinguish spin/parity states

Use “MELA” technique:
Matrix Element
Likelihood Analysis



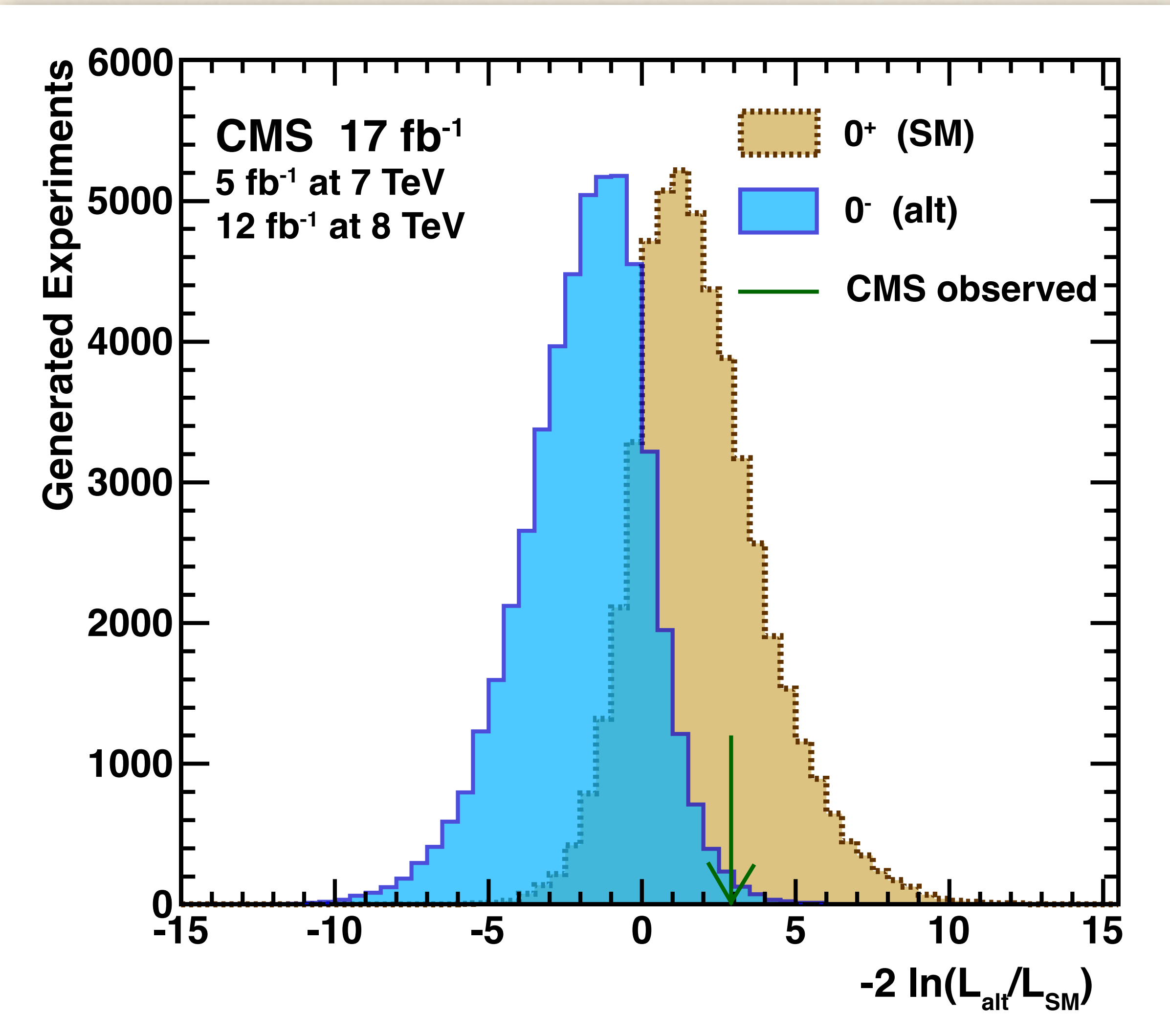
$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

Example: scalar (0^+) versus pseudoscalar (0^-)



- we first perform fit in sig/bkg MELA to "rediscover" the boson and measure mass etc.
- then we perform fits in 2D: sig/bkg MELA versus scalar/pseudoscalar MELA

Data strongly disfavor the pure pseudoscalar case:



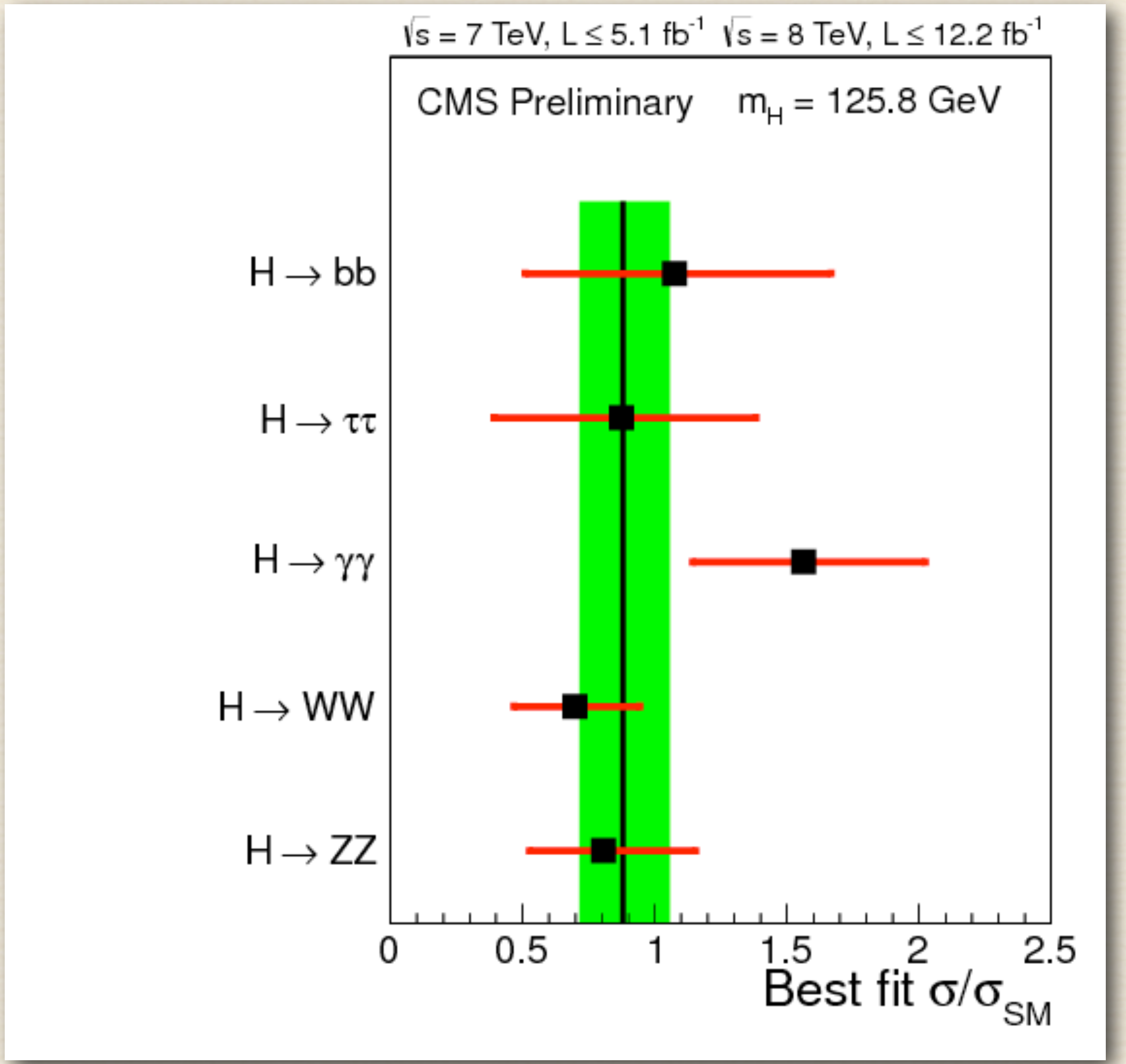
p-value for 0^- 0.00648

p-value for 0^+ 0.28

CLs = 2.4%

Submitted to PRL: http://arxiv.org/abs/1212.6639

Latest CMS signal strength results



Happy 60th, Howie and Michael!

Vanilla Higgs, anyone?

What's next?

Many tasks lie ahead:

- complete analysis of full 8 TeV data
- retrofit LHC for 13 TeV running
- make precise measurements of mass and couplings, particularly to fermion pairs
- search for BSM Higgs bosons!