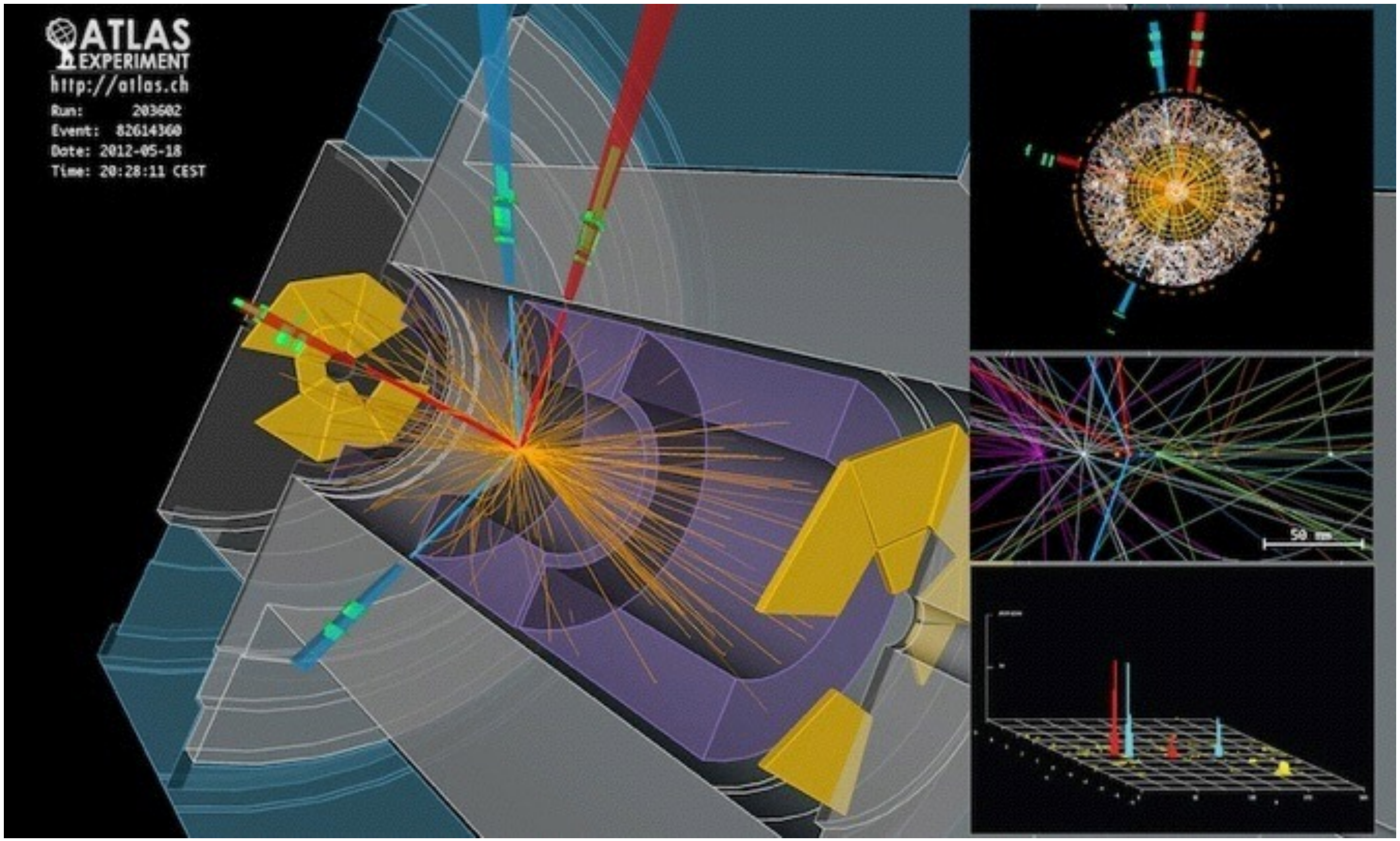
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



10. Higgs Discovery at the LHC

14.12.2015

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

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Dr. Frank Simon

Overview

- Discovering a New Boson
  - Recap: Status of Higgs search before LHC
  - Recap: Production and Decay
  - Discovery Channels & Discovery

- Properties of the New Boson
  - Branching fractions
  - Mass
  - Spin

Status of the Higgs Search w/o LHC Data

Precision measurements of electroweak observables, accounting for radiative corrections ($\propto \log m_H^2$):

$m_H = 94^{+29}_{-24}$ GeV (68% C.L.) and

$m_H < 171$ GeV (95% C.L.)

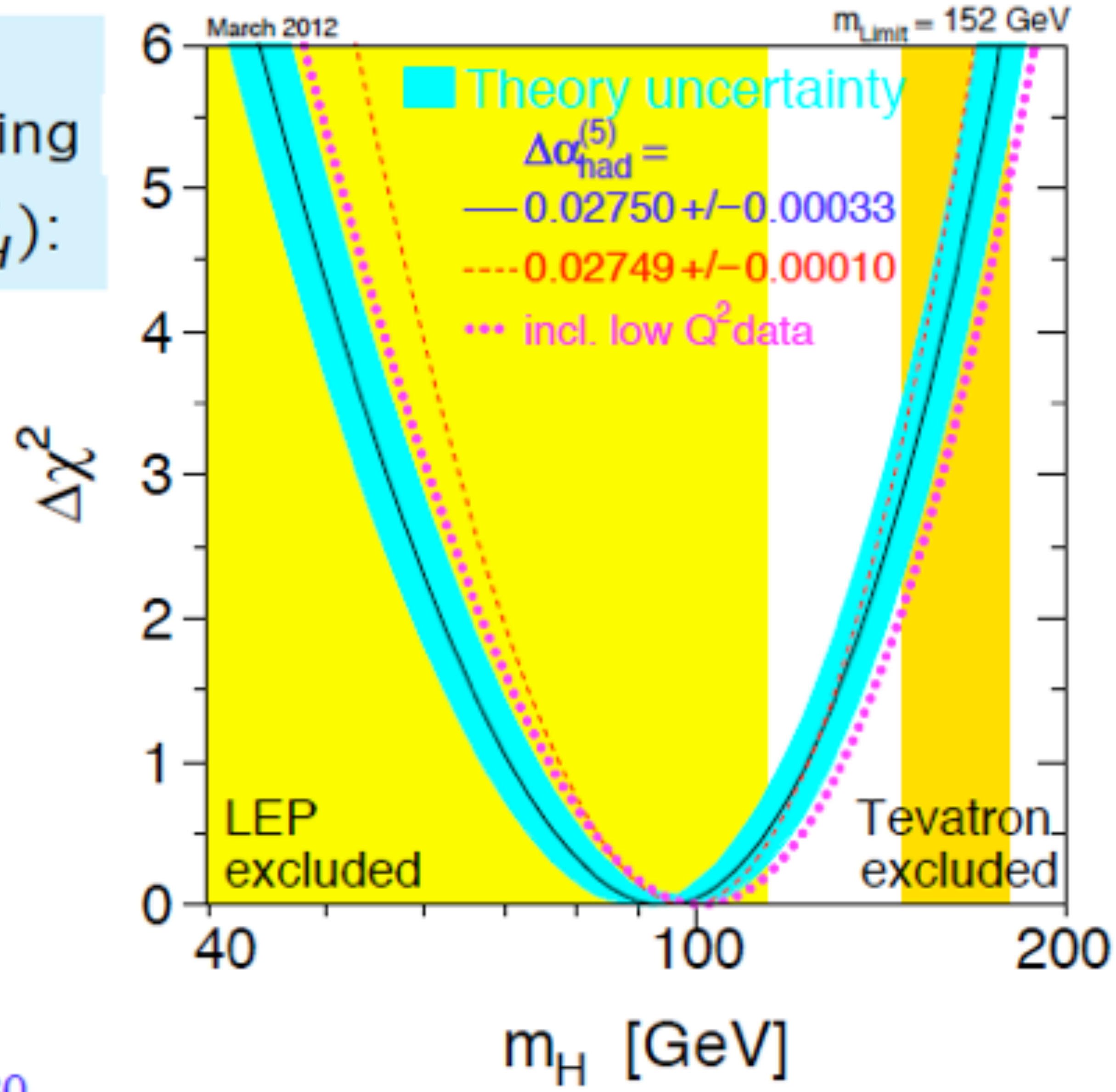
Direct searches at LEP:

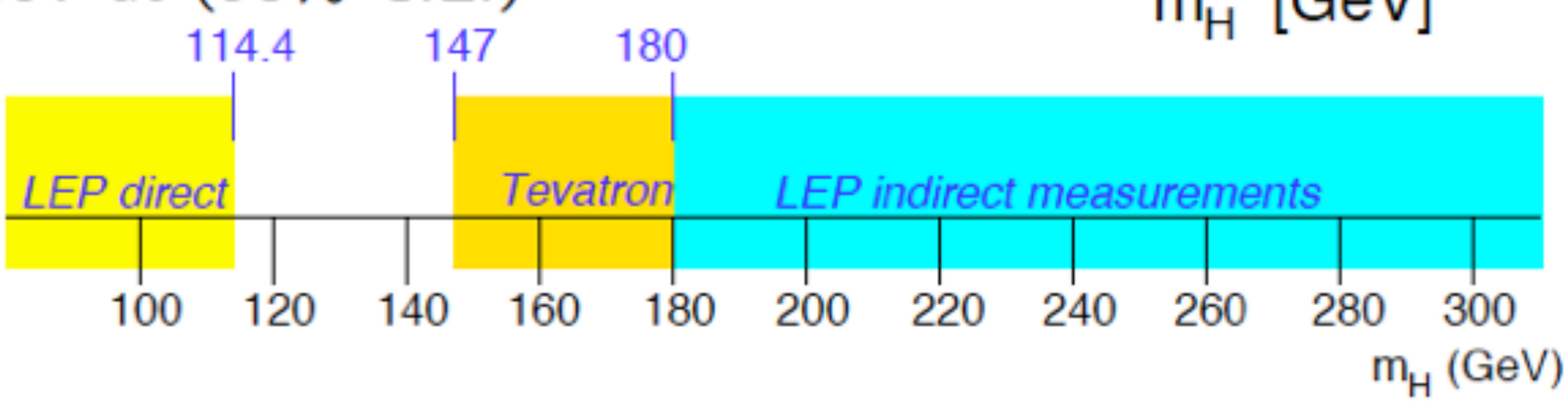
$m_H > 114.4$ GeV at (95% C.L.)

Direct searches at Tevatron:

$m_H < 147$ GeV at (95% C.L.) and

$m_H > 180$ GeV at (95% C.L.)

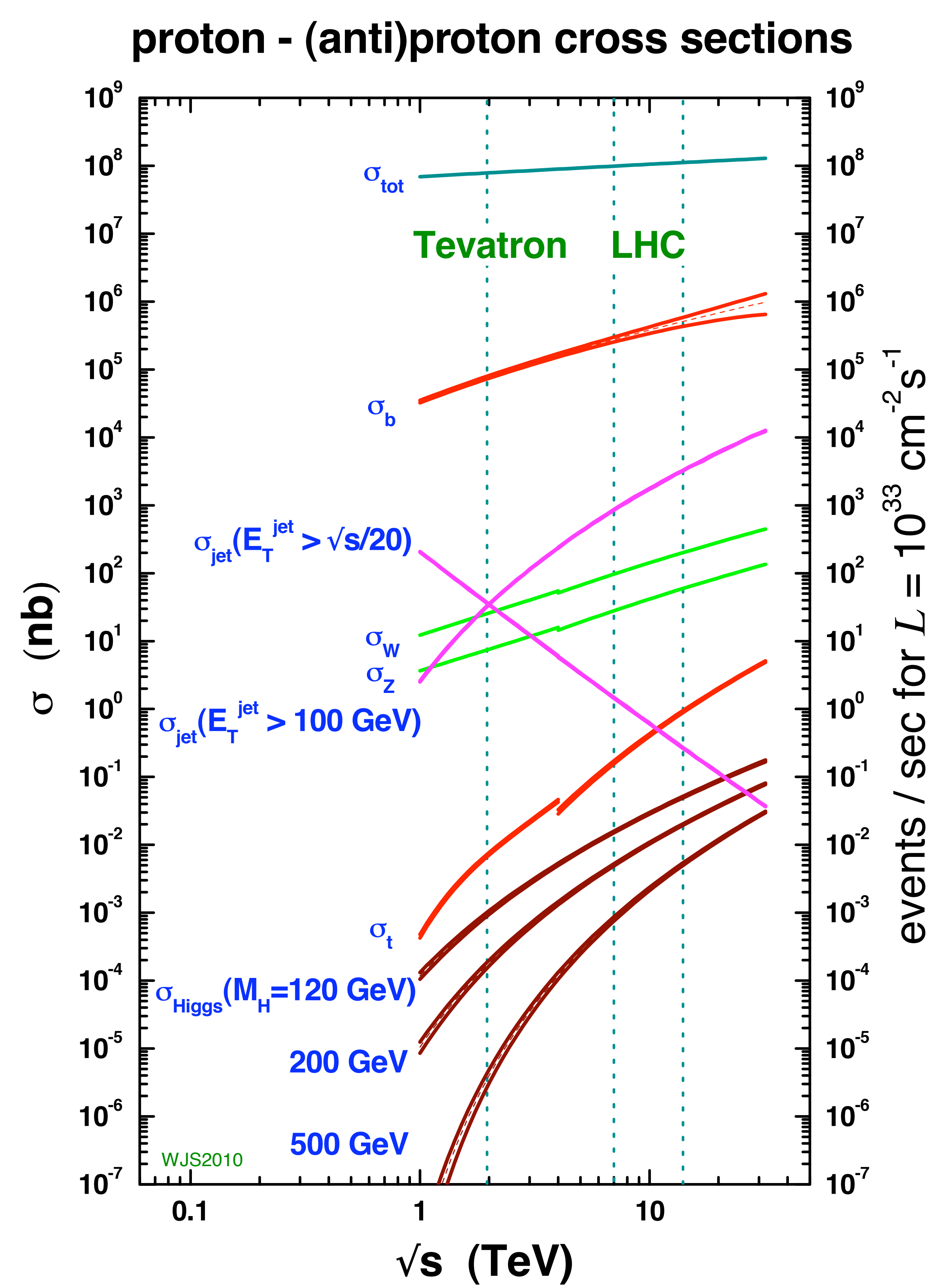




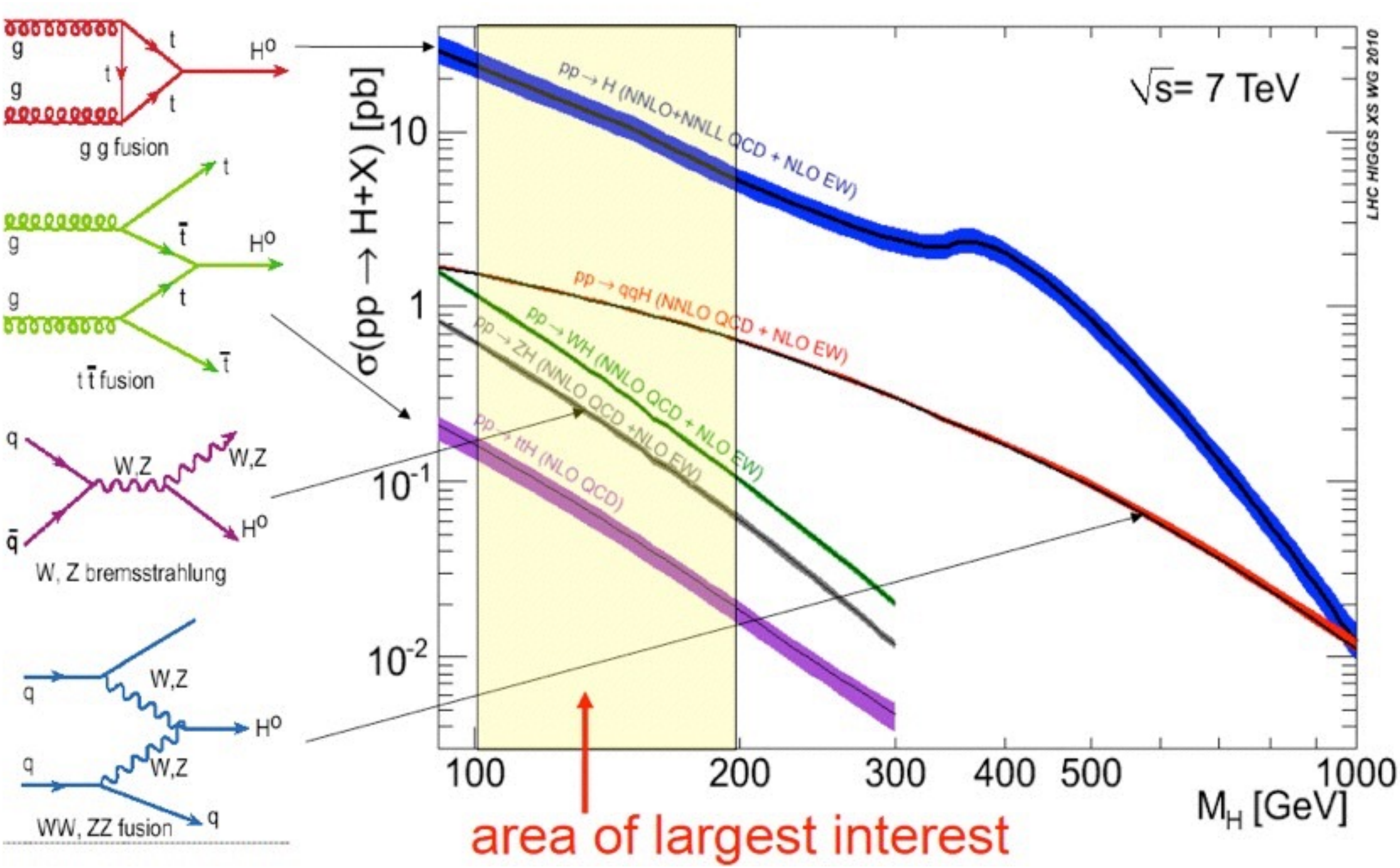
status: 2012

Higgs Production at LHC and Tevatron

- Cross section depends on Higgs mass and rises strongly with energy
    - no substantial “break” when going from proton-anti-proton to proton-proton

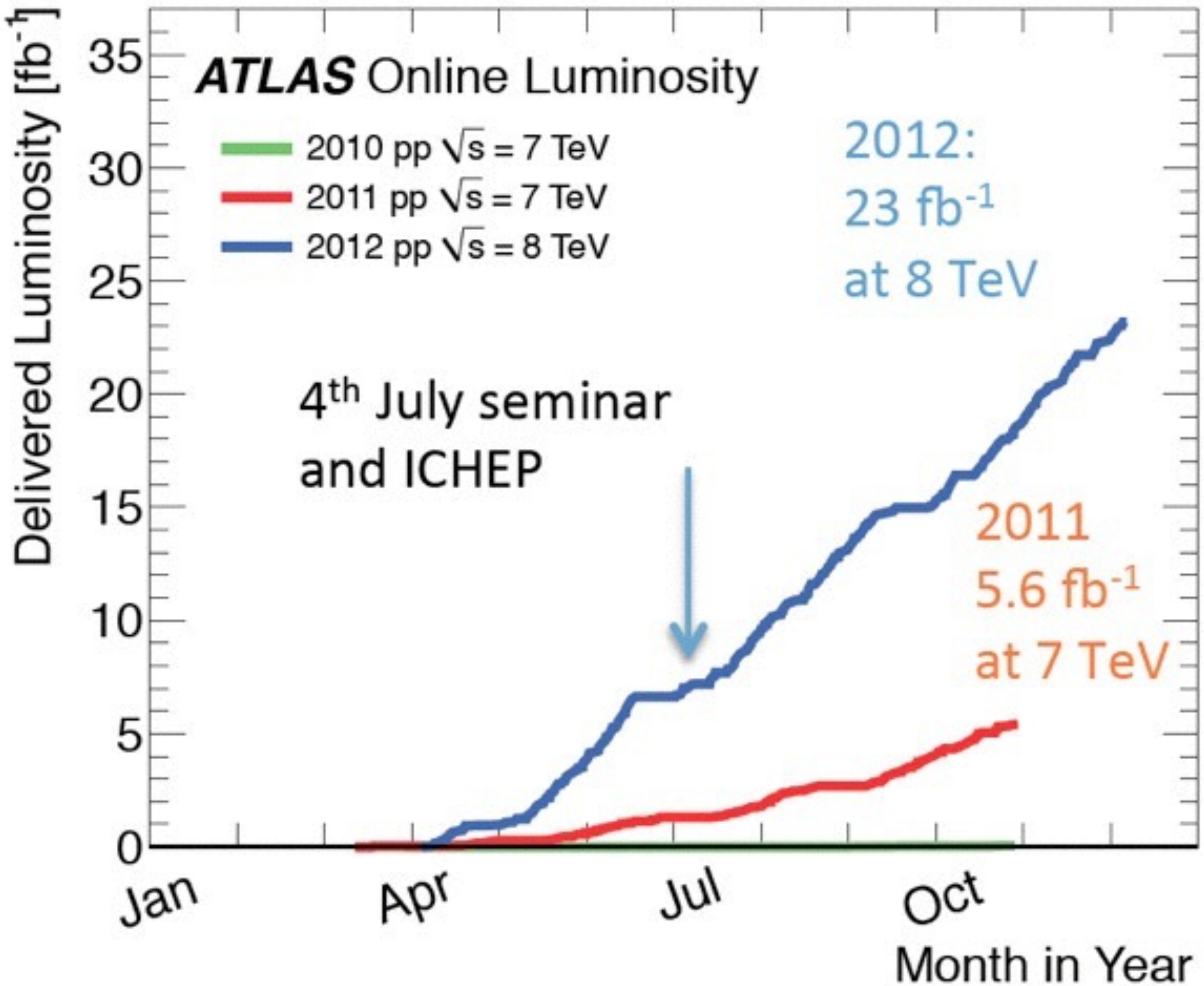


Higgs Production at the LHC



- Total H cross section ~ 17 pb @ 7 TeV, 21 pb @ 8 TeV for 125 GeV

LHC - What we have

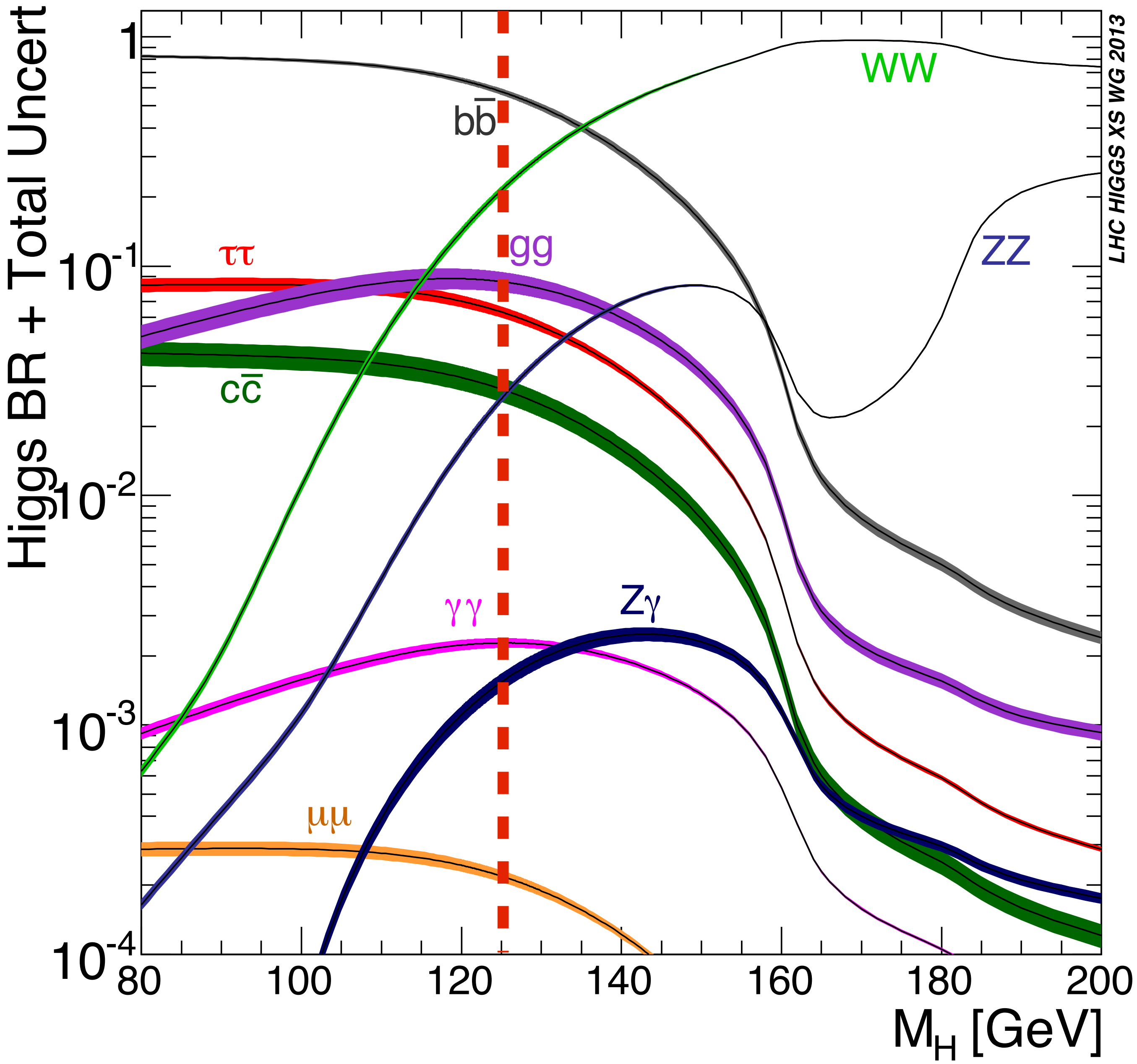


- In 2011: 5.6 fb^{-1} @ 7 TeV
  ~ 100k H produced
  (for a mass of 125 GeV)
- In 2012: 23 fb^{-1} @ 8 TeV
  ~ 500k H produced
  (for a mass of 125 GeV)

NB: No additional data in 2013 and 2014: LHC in shutdown
Since July 2015: 13 TeV,
up to now ~ 4.5 fb^{-1}

The challenge is to pick them out of an enormous background!

Higgs Decay I



- This defines the channels to look for:

bb - the most abundant
(but hopeless background - needs tricks!)

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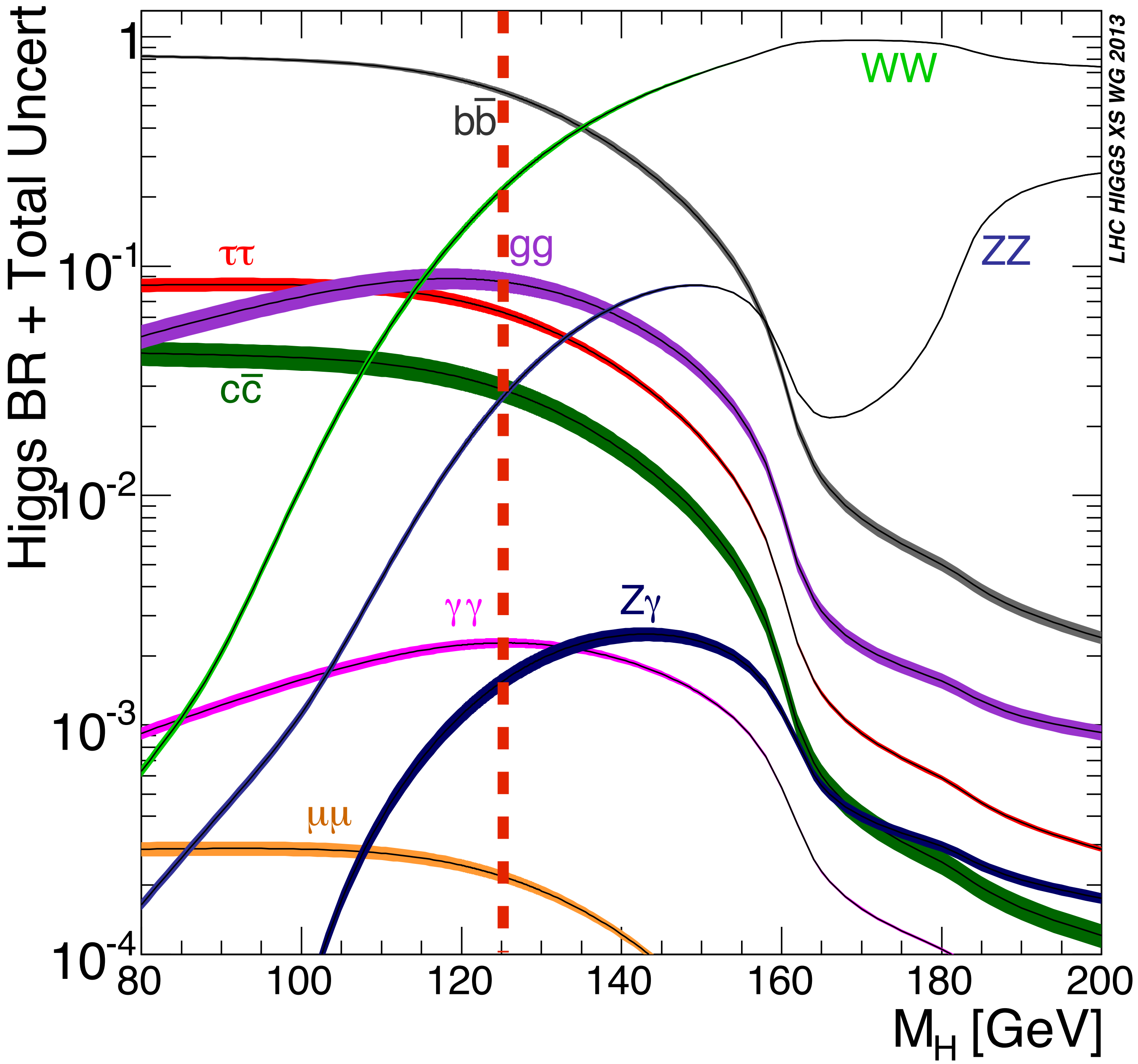

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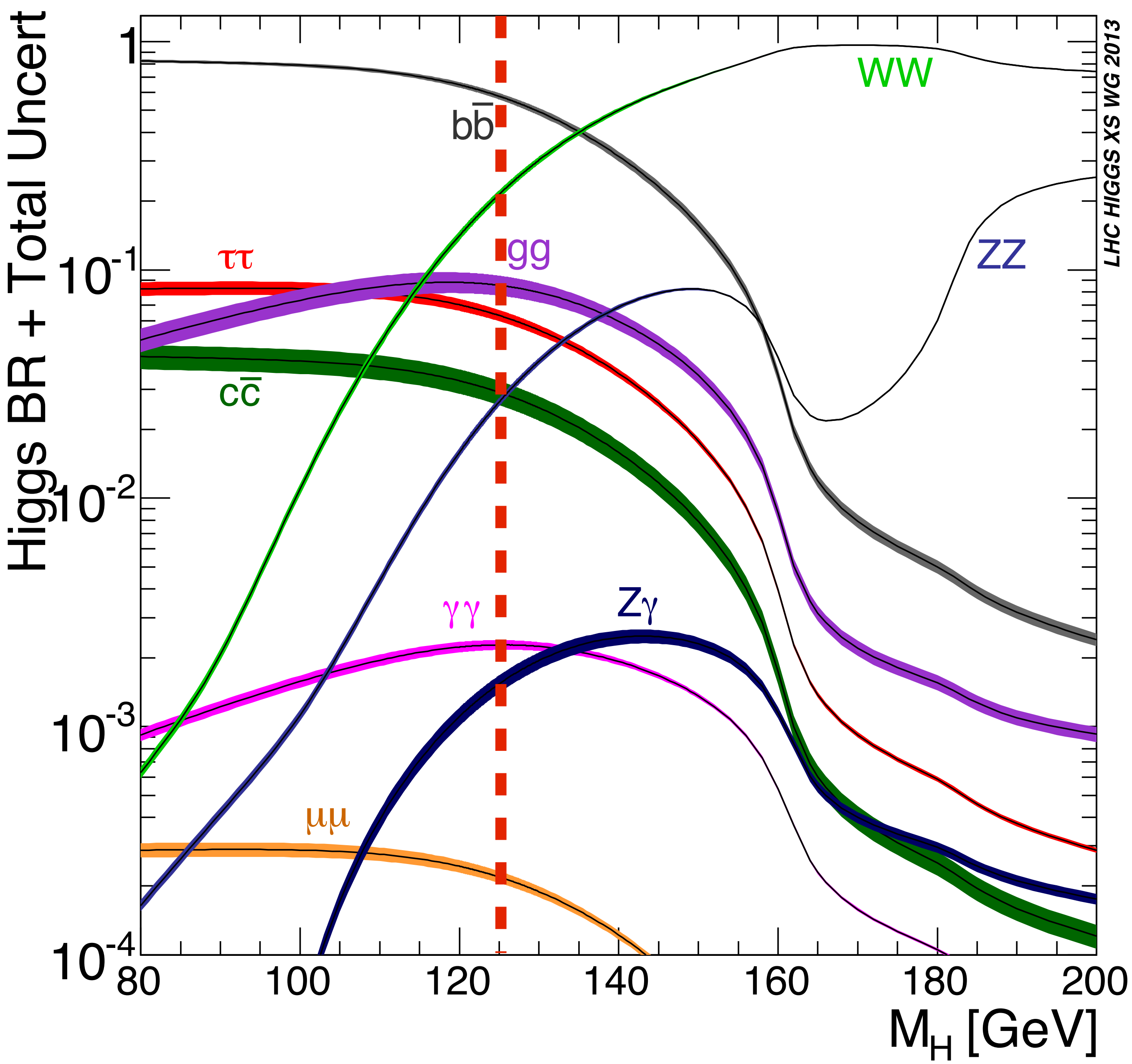
bb - the most abundant (but hopeless background - needs tricks!)
WW - Quite abundant, but: Background only manageable for leptonic W decays - Missing energy!

Higgs Decay I



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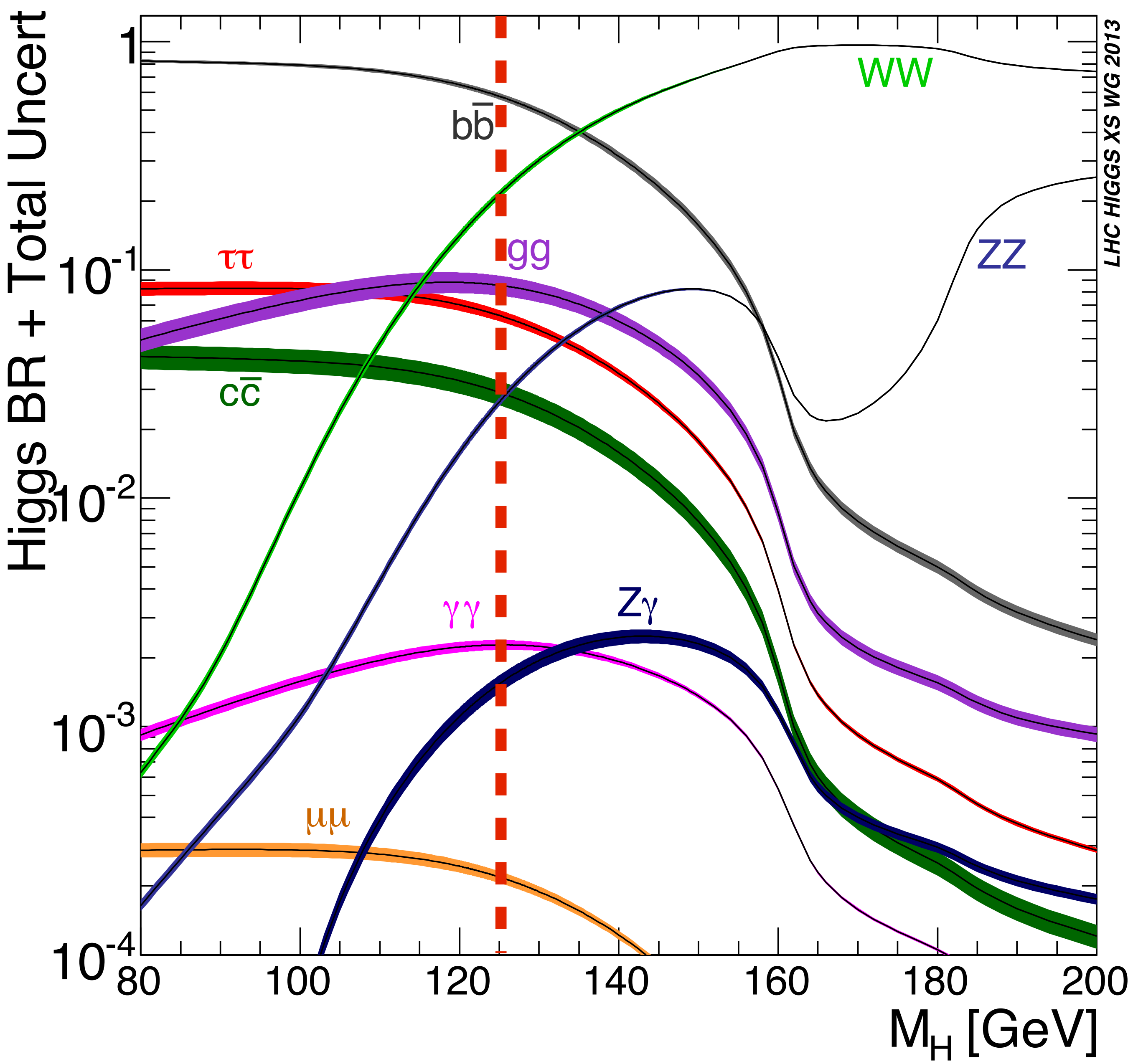

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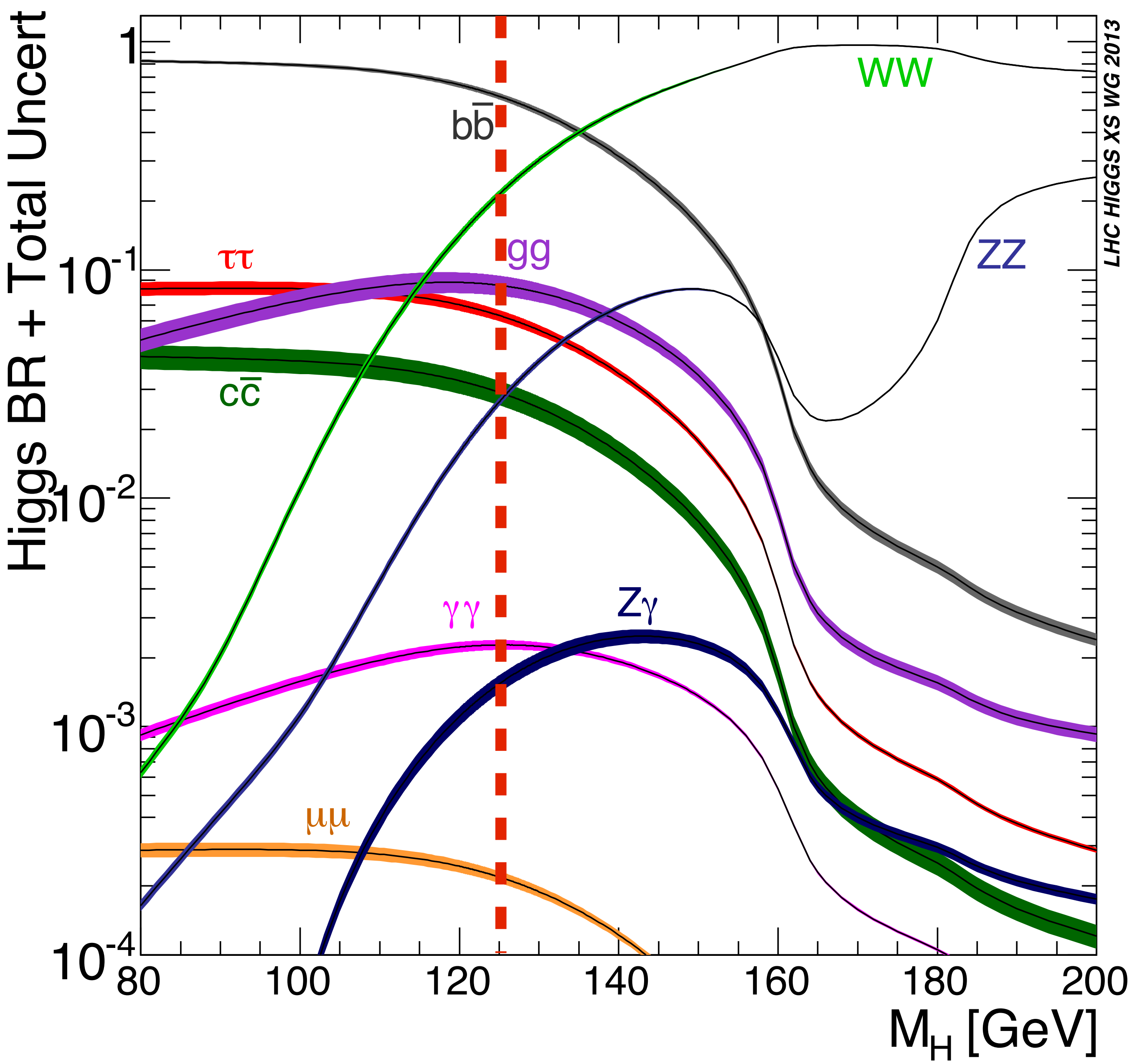
ττ - Taus are tough: Missing energy in leptonic decays, hard to identify in hadronic decays

Higgs Decay I



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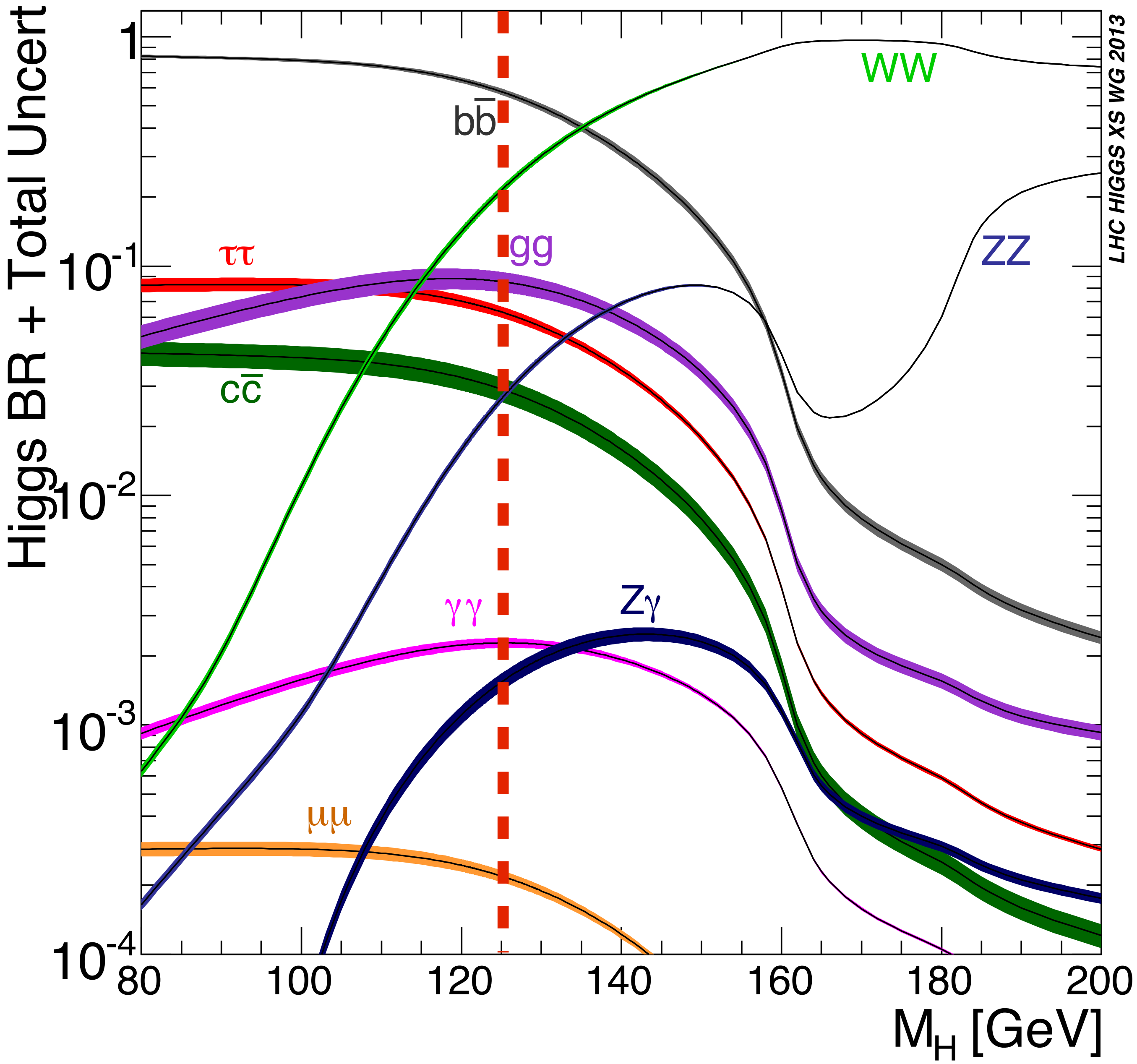

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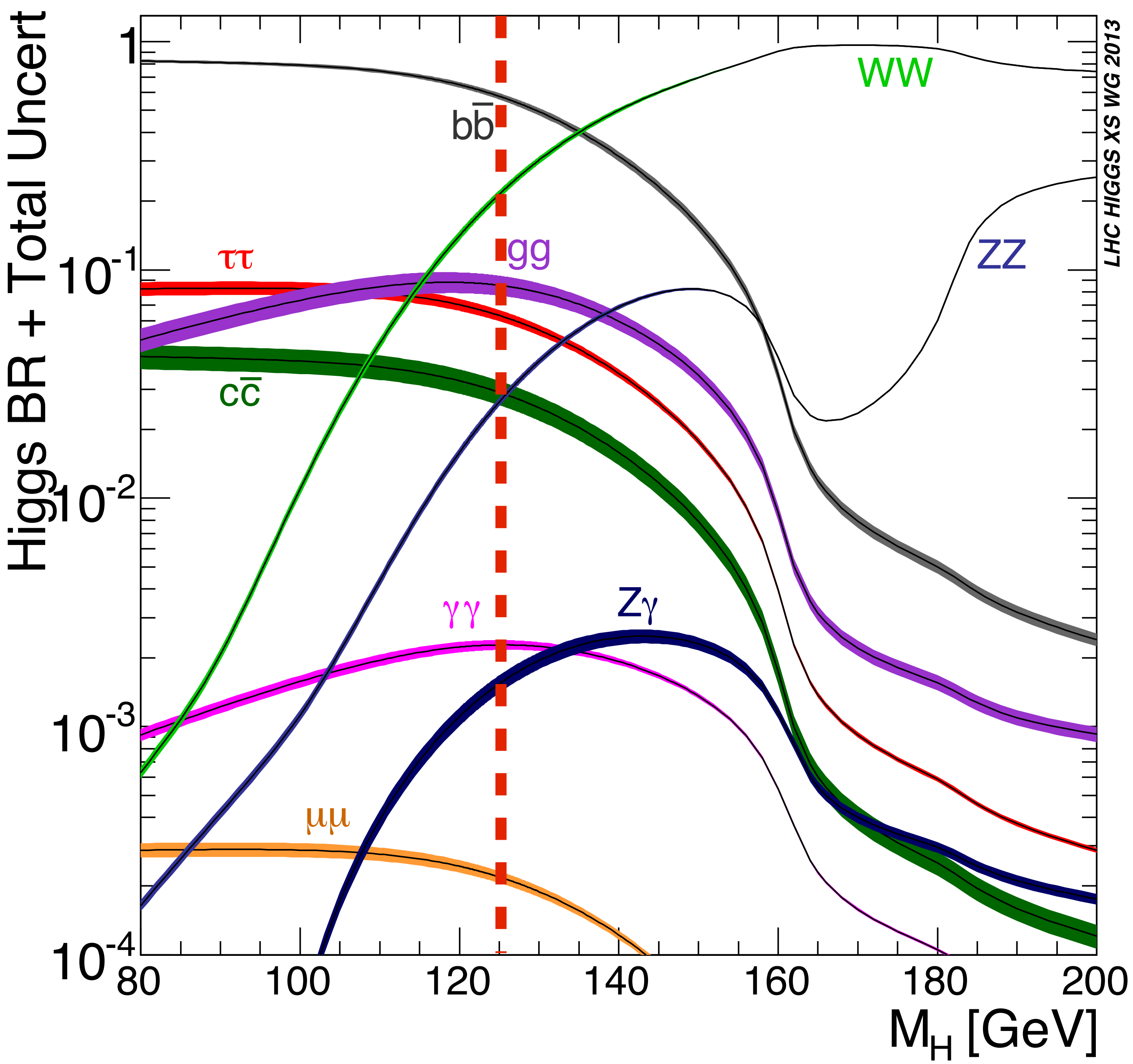
ZZ - Getting rare - but beautiful signature for leptonic Z decays!

γγ - Rare decay, but manageable background, good resolution

ττ - Taus are tough: Missing energy in leptonic decays, hard to identify in hadronic decays

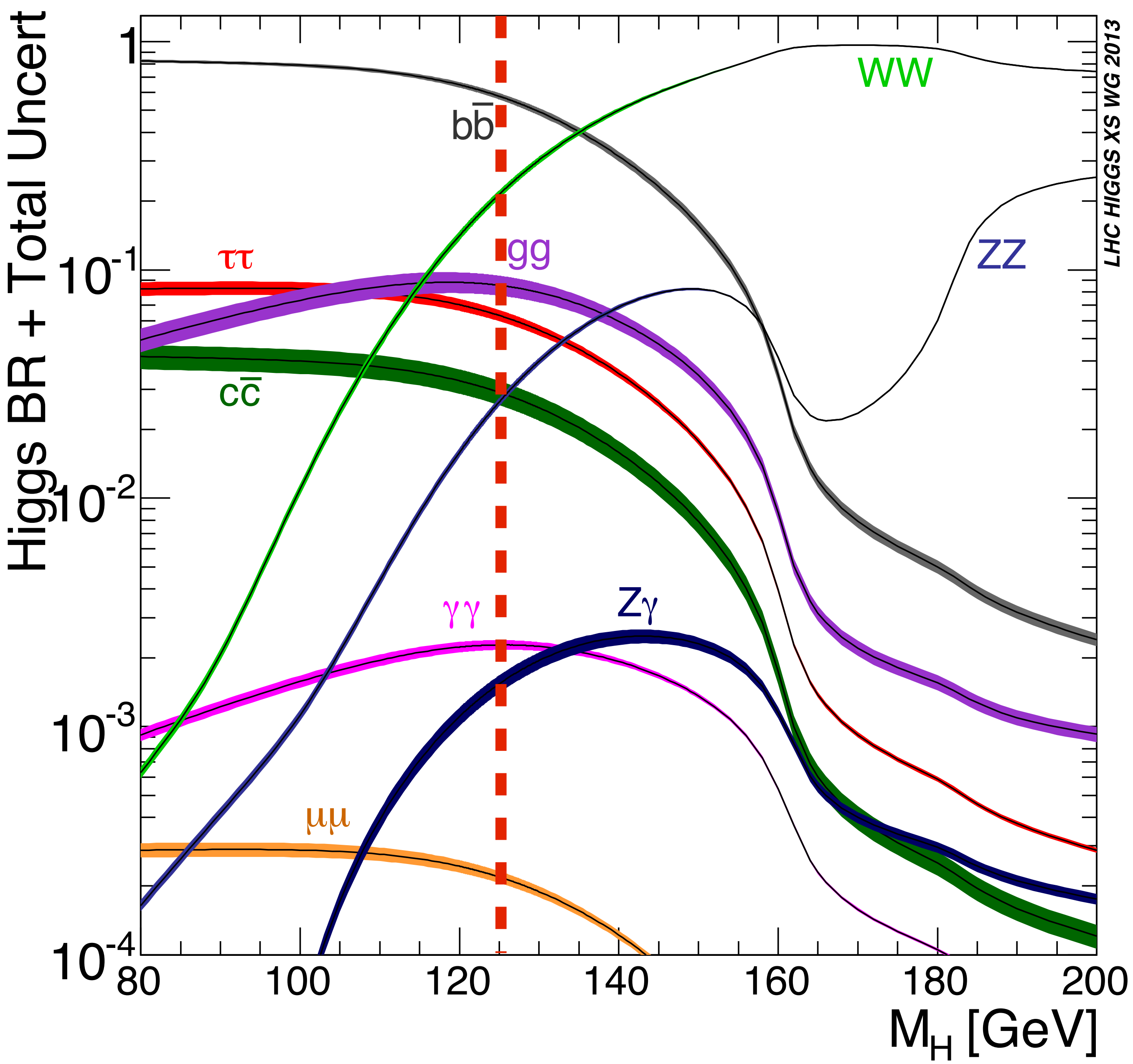
Higgs Decay II



- Additional decay channels:

cc - Two charm jets - quite rare, no chance at LHC

Higgs Decay II



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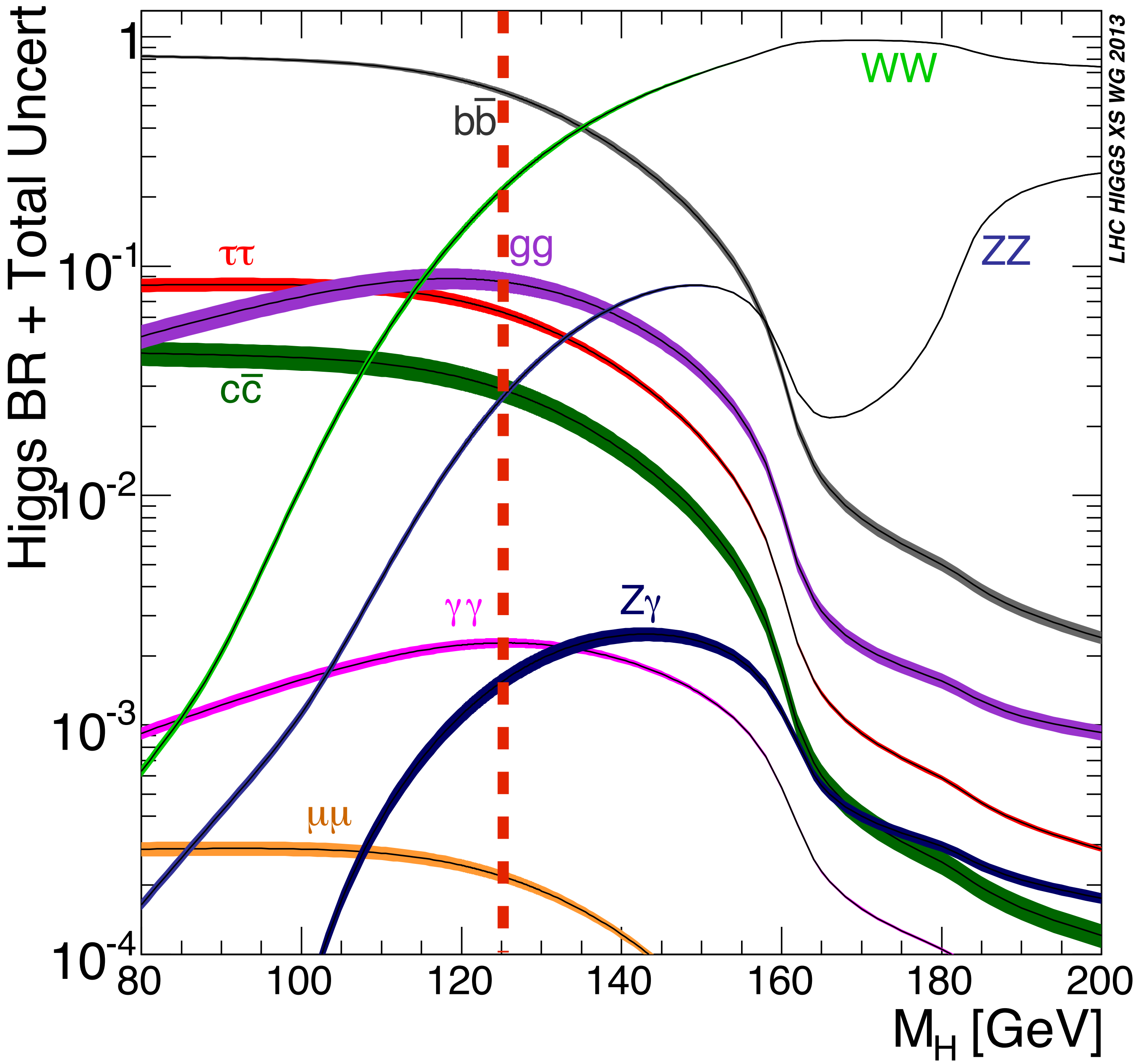
qq - Light quarks - two light jets: tiny branching fraction, no chance for measurement

Higgs Decay II



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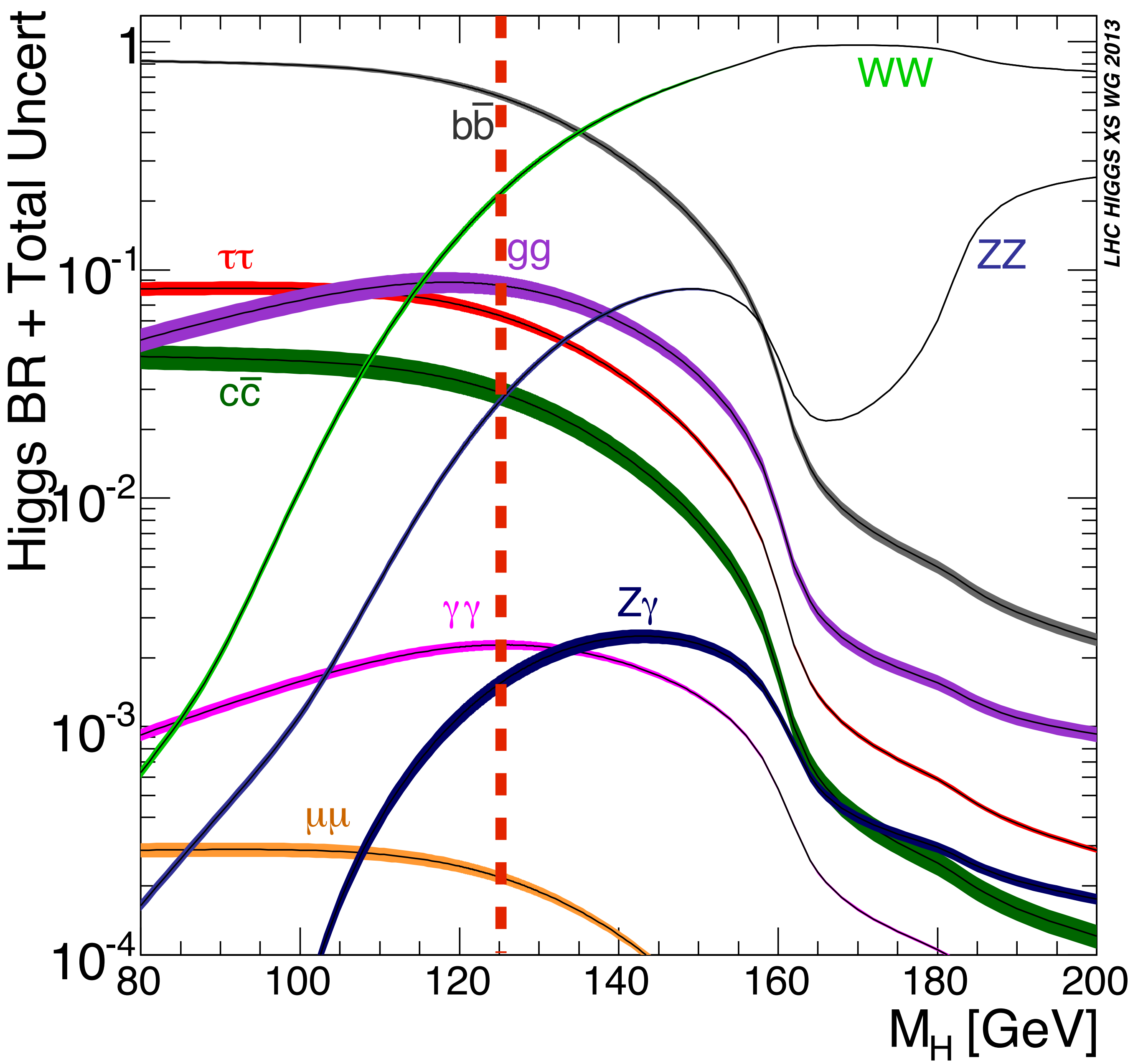


- Additional decay channels:

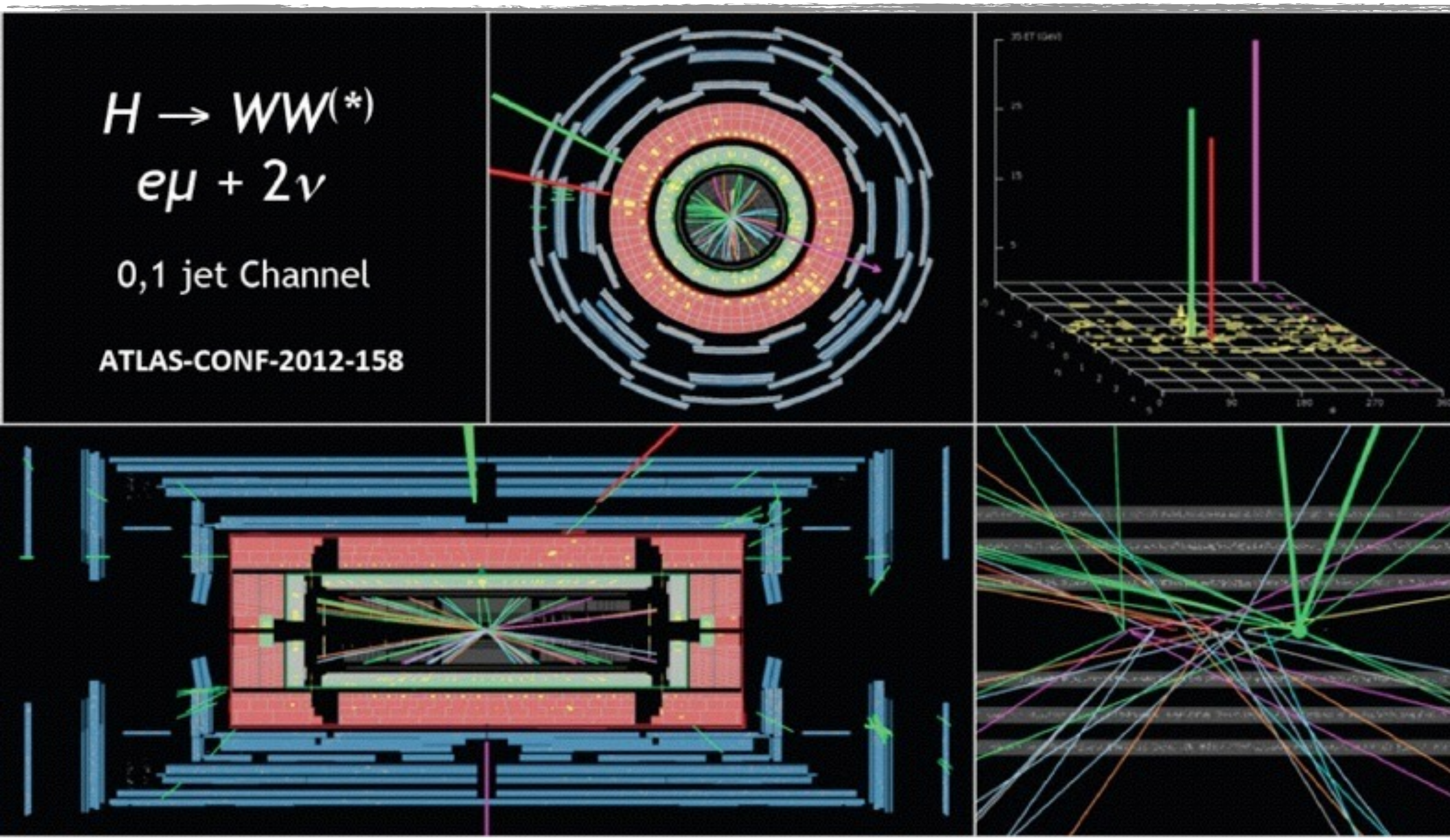
cc - Two charm jets - quite rare, no chance at LHC

qq - Light quarks - two light jets: tiny branching fraction, no chance for measurement

μμ - Excellent signature, very good mass measurement but tiny branching fraction: Needs high luminosity

ee - Excellent signature, negligible rate, no chance for measurement

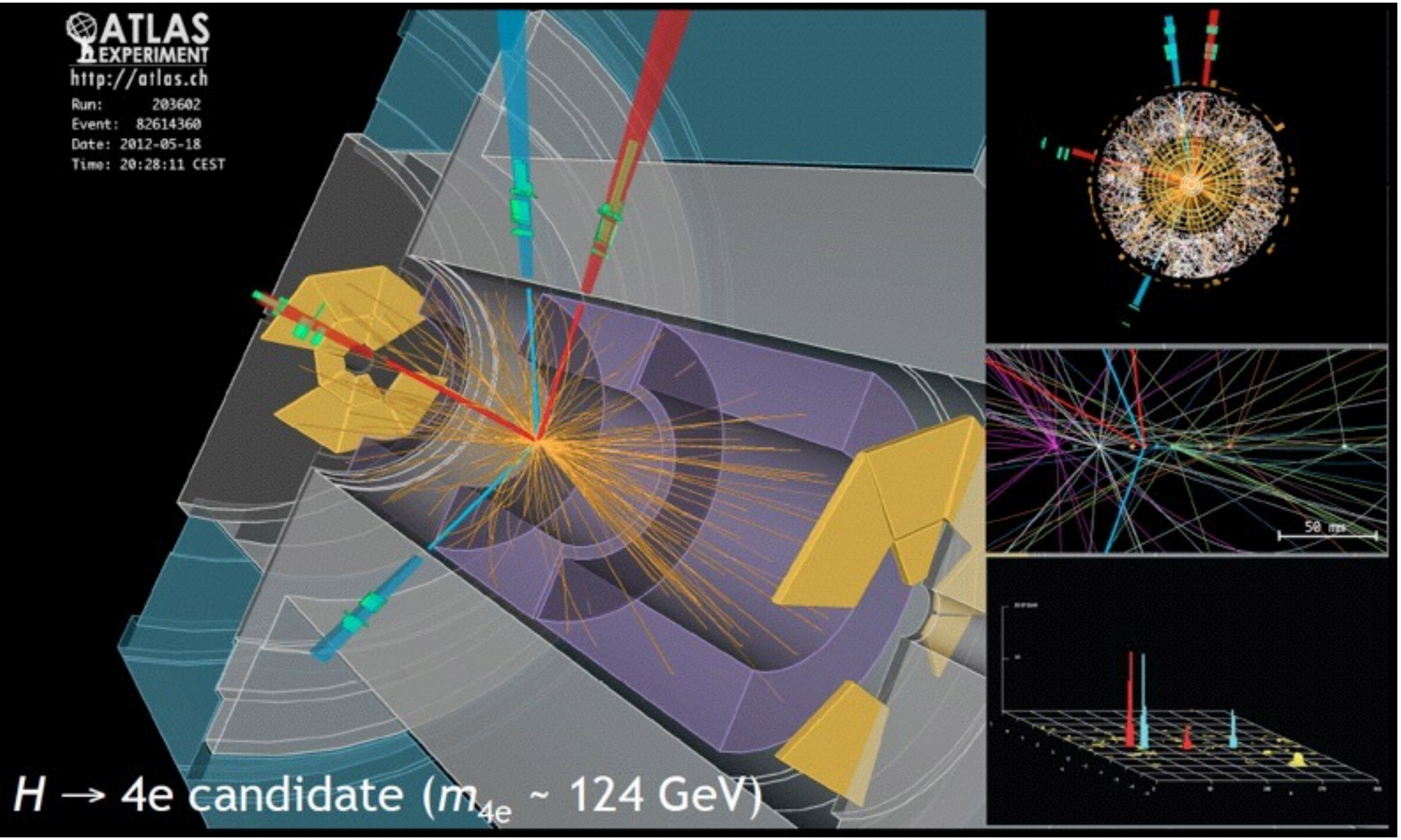
Discovery Channels - H -> WW



- High BR: 21.5%
- W decay into e, μ + neutrino: 2 x 10.8%
  - Total BR: 21.5% x $(21.6\%)^2$ = 1%

- The way to separate these events from background: Look for energetic leptons from the W decay -> Only leptonic decays of Ws
  - Poor mass resolution (two missing neutrinos)

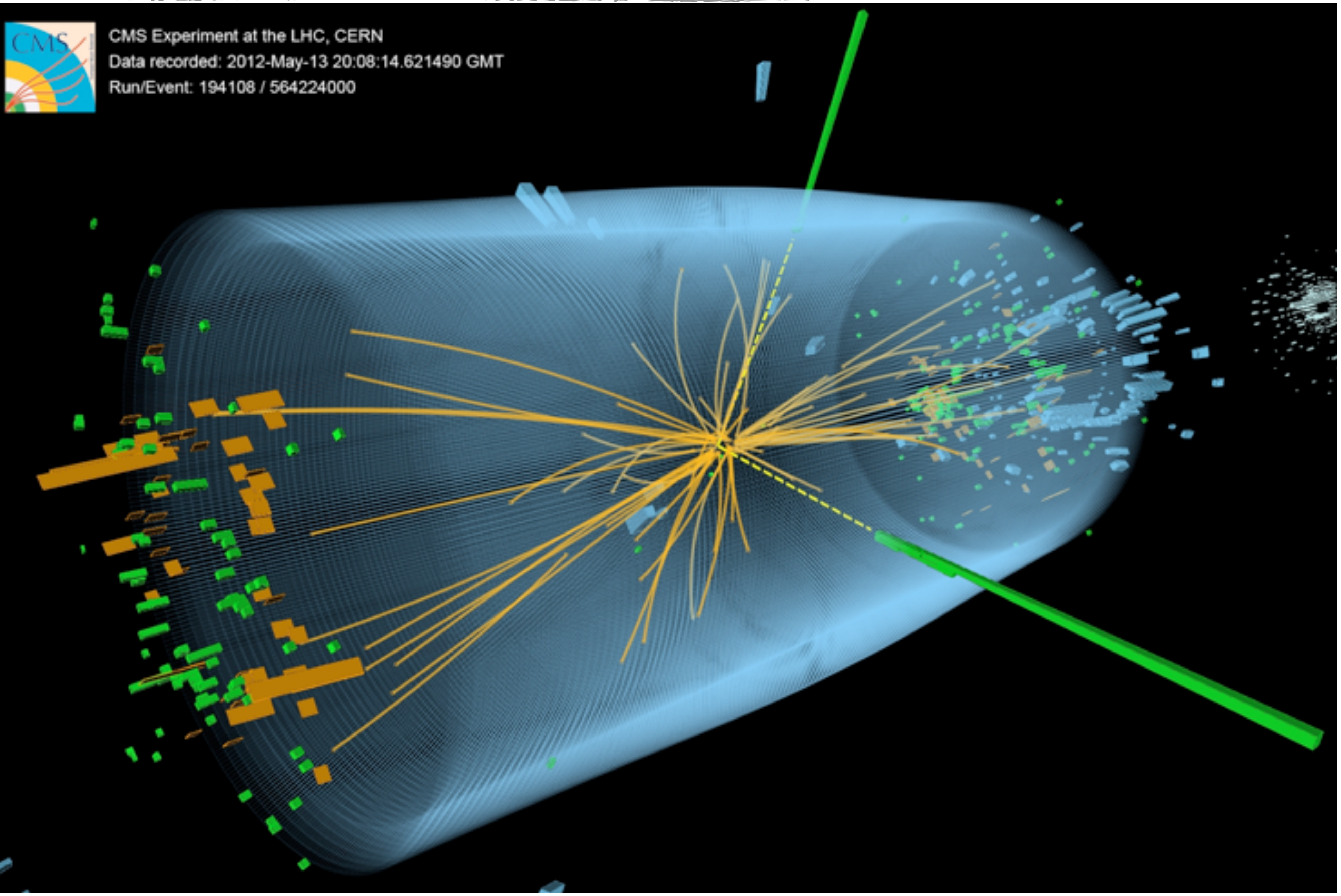
Discovery Channels - H -> ZZ



- Low BR: 2.6%
- Z decay into e, μ pairs: 2 x 3.4%
  - Total BR: 2.6% x $(6.8\%)^2$ = 1.2 x 10^{-4}

- The way to separate these events from background: Look for energetic leptons from the Z decay -> Only leptonic decays of Zs
  - Excellent mass resolution: ~ 1%, very good purity

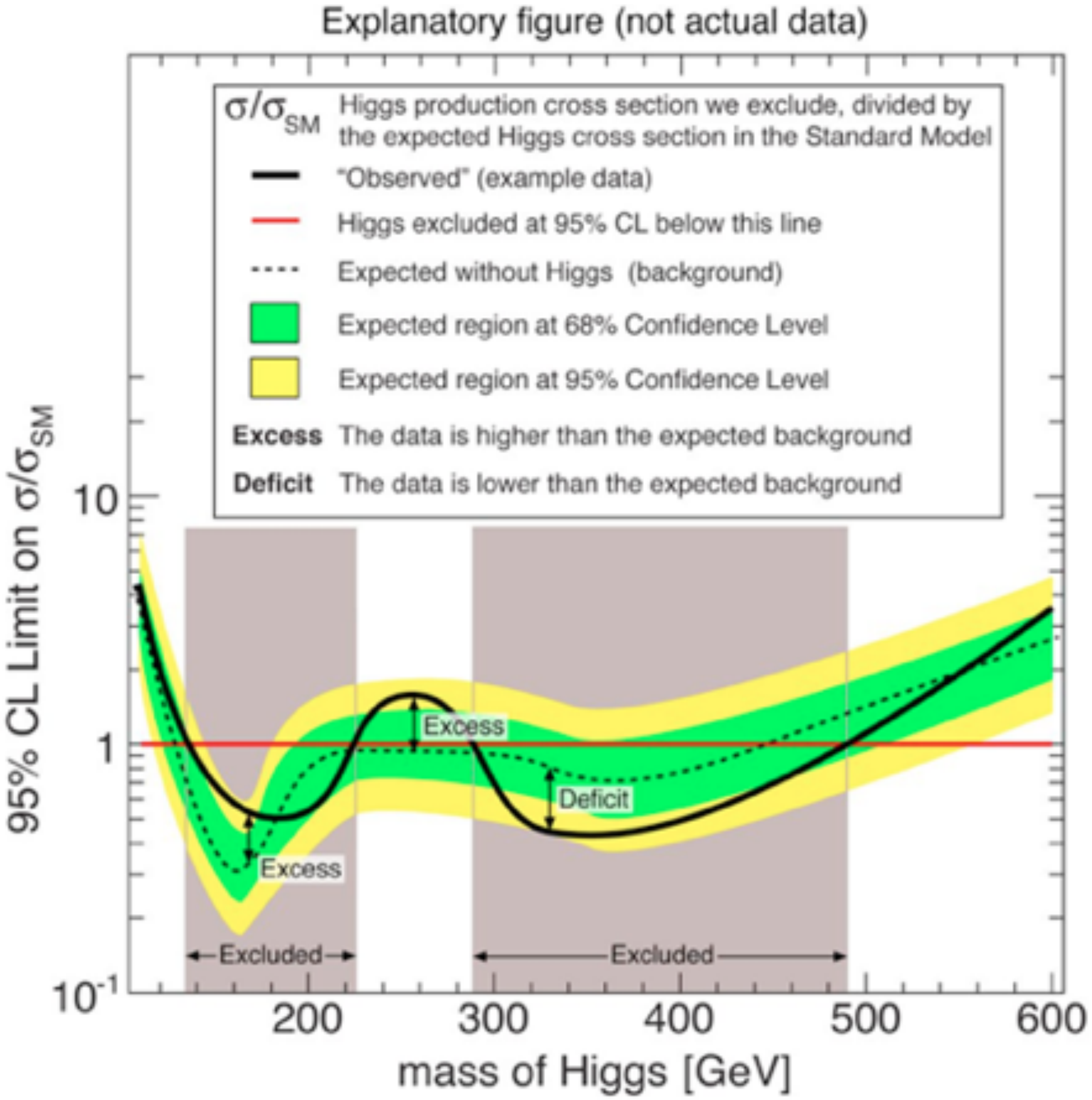
Discovery Channels - H -> $\gamma\gamma$



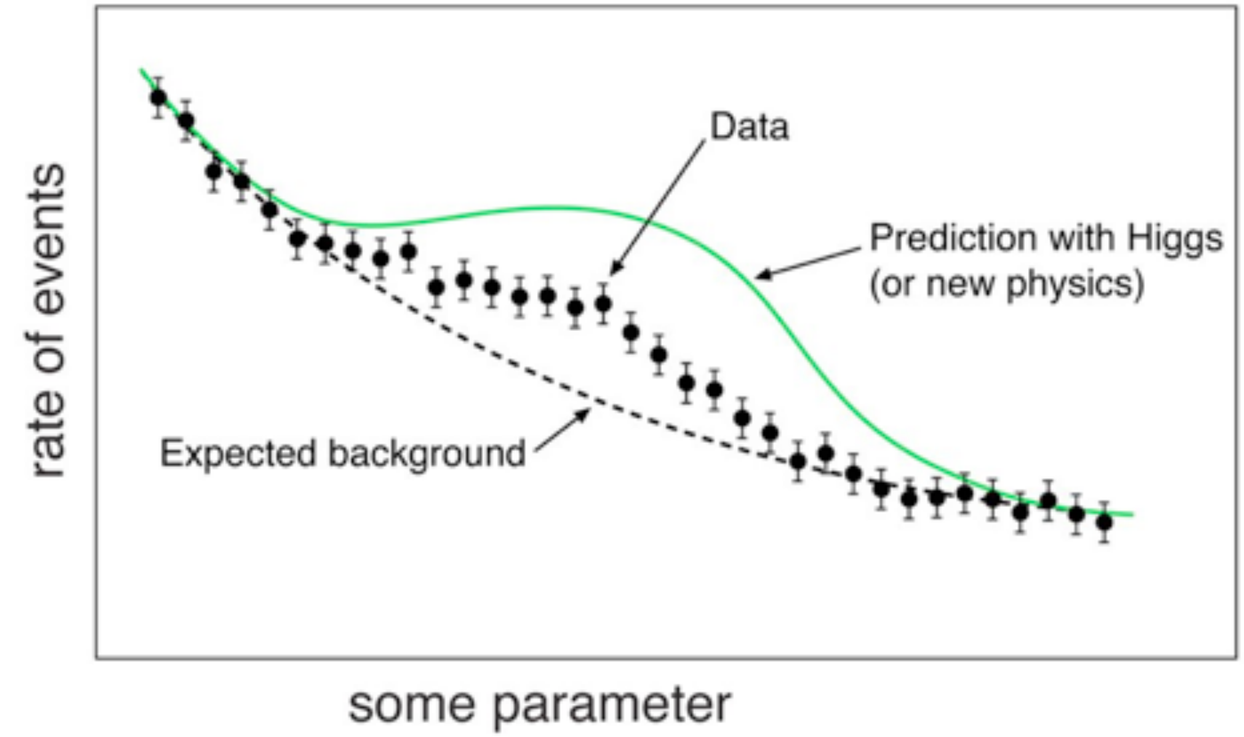
- Good mass resolution: ~ 1% level, given by photon energy resolution of ECAL
- Low branching fraction: 2.3×10^{-3}

- Moderate background level - Good mass resolution allows to identify signal on top of random photon pairs

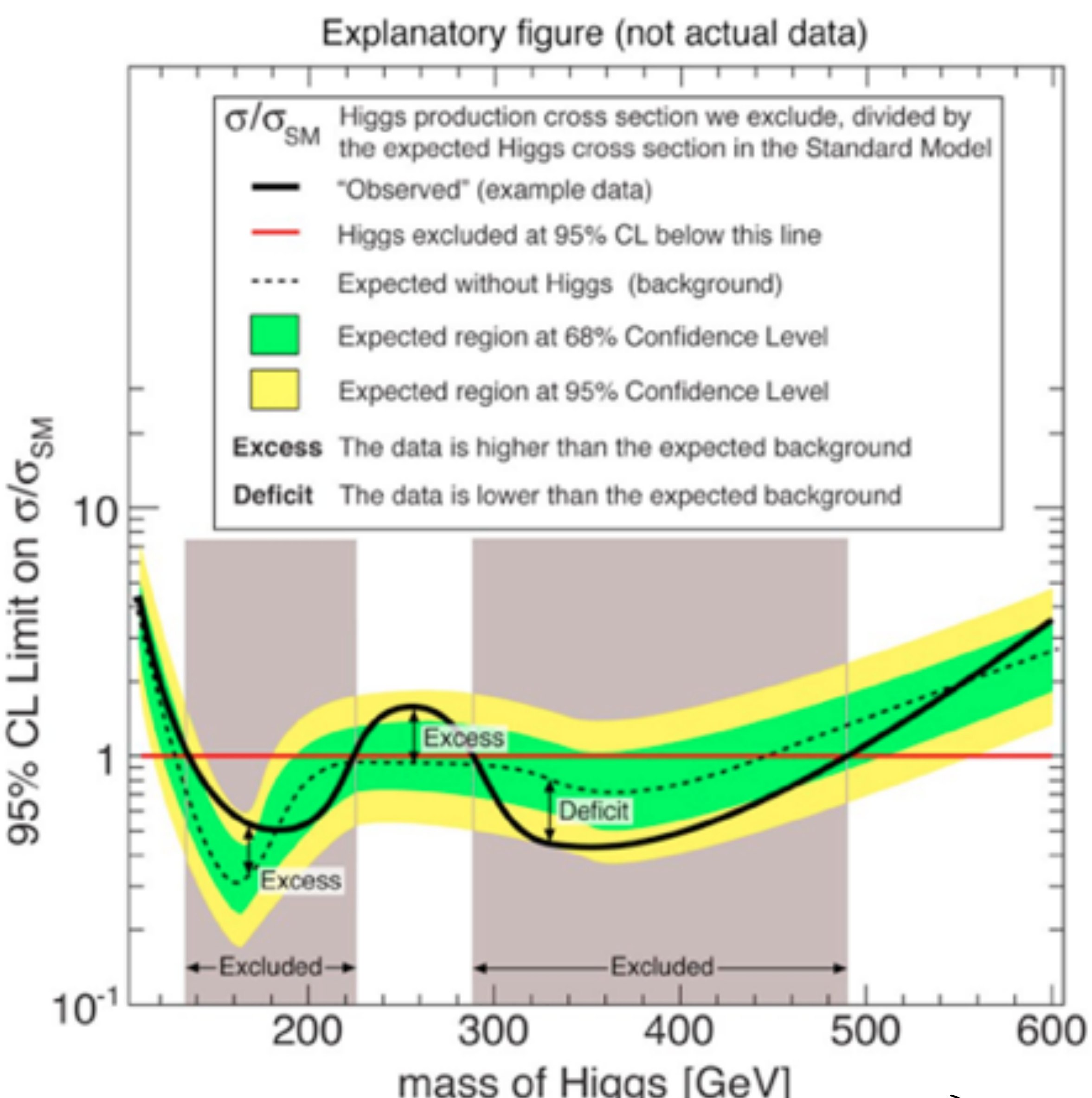
Understanding Higgs Exclusion Limits

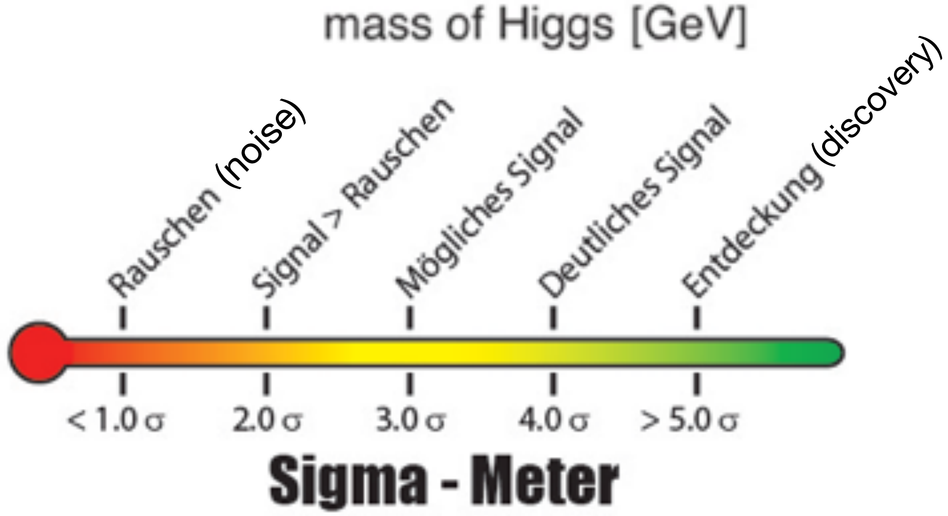


- Overall discovery strategy: Compare the observed event rates with calculated predictions for SM Higgs with different masses + background
  - Statistics give sensitivity compared to SM cross section
- Result: How much signal can there be, in units of SM x-section



Understanding Higgs Exclusion Limits





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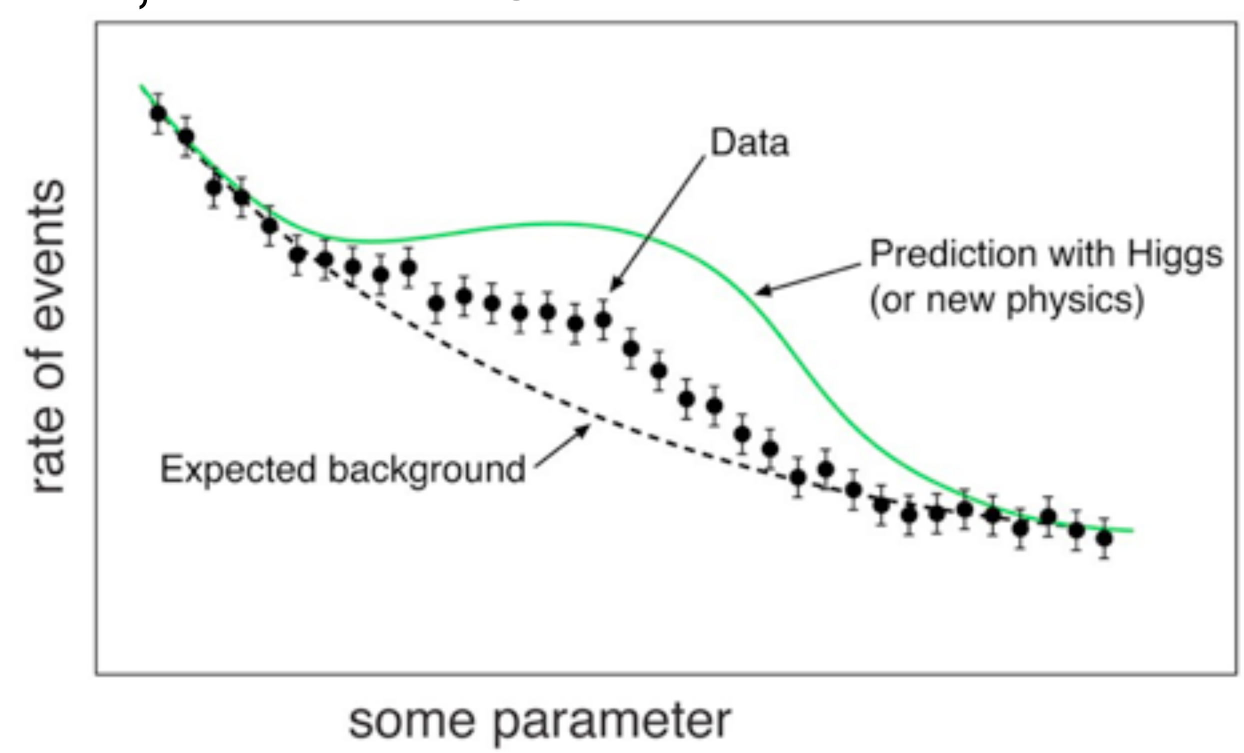
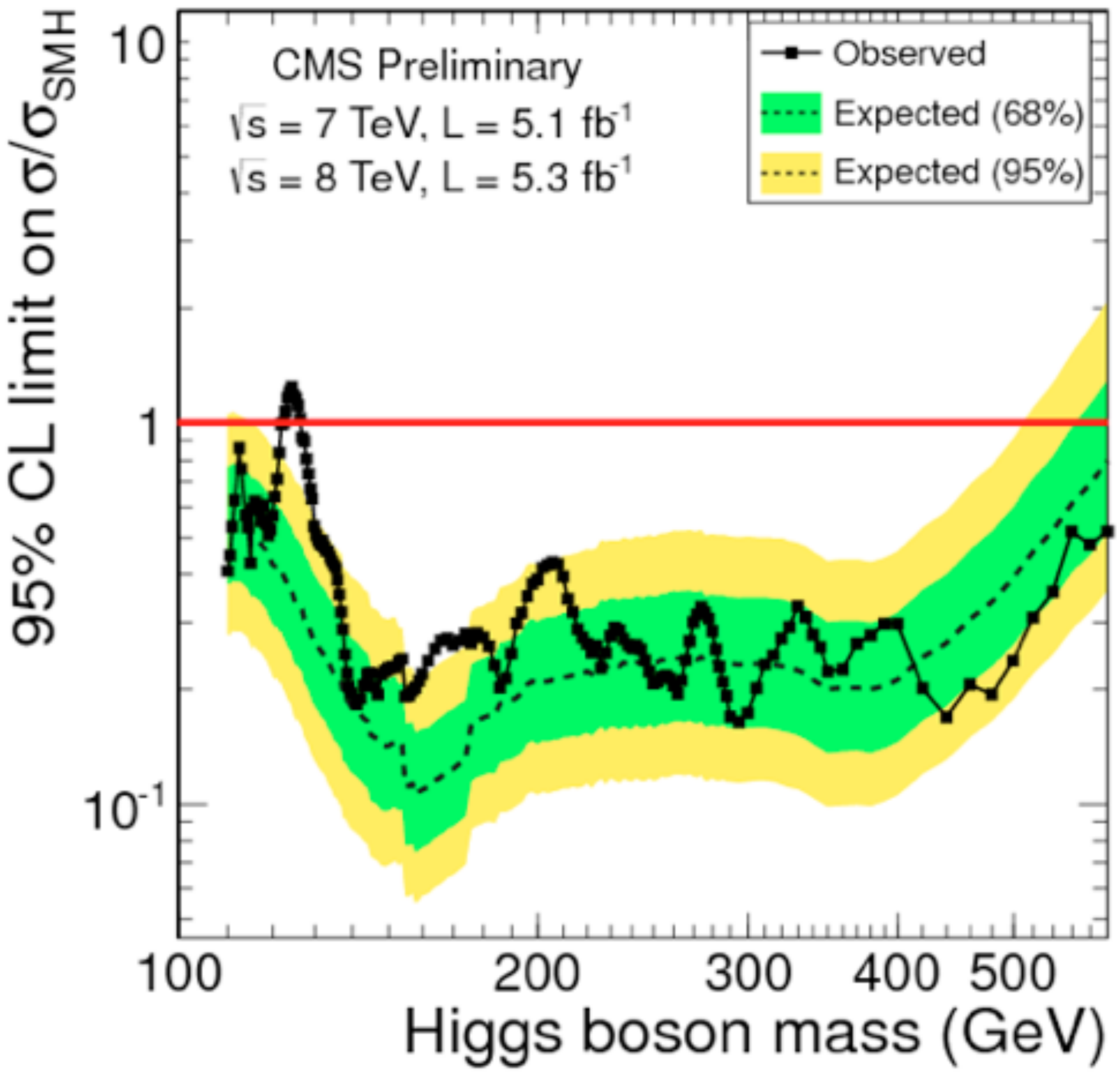
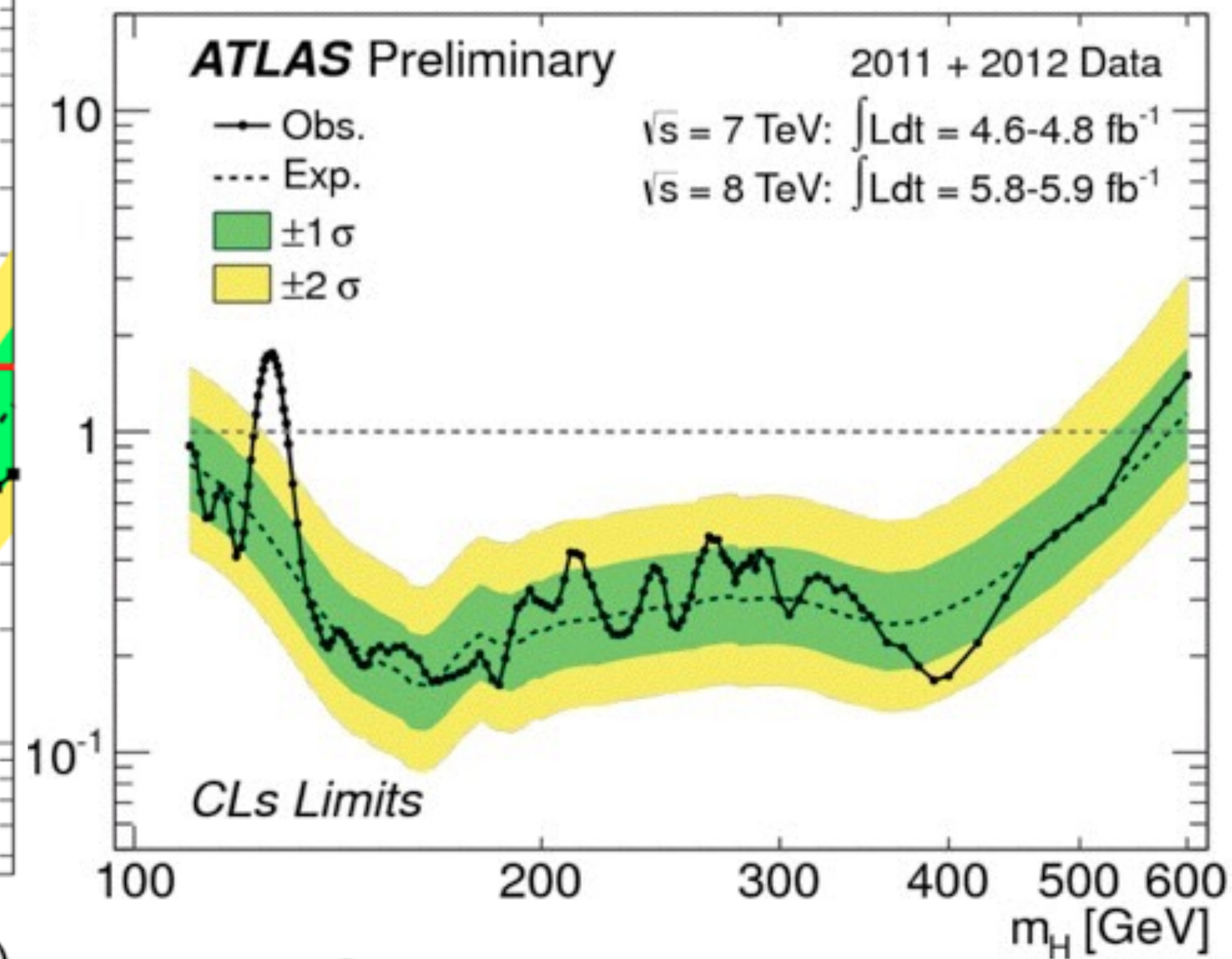


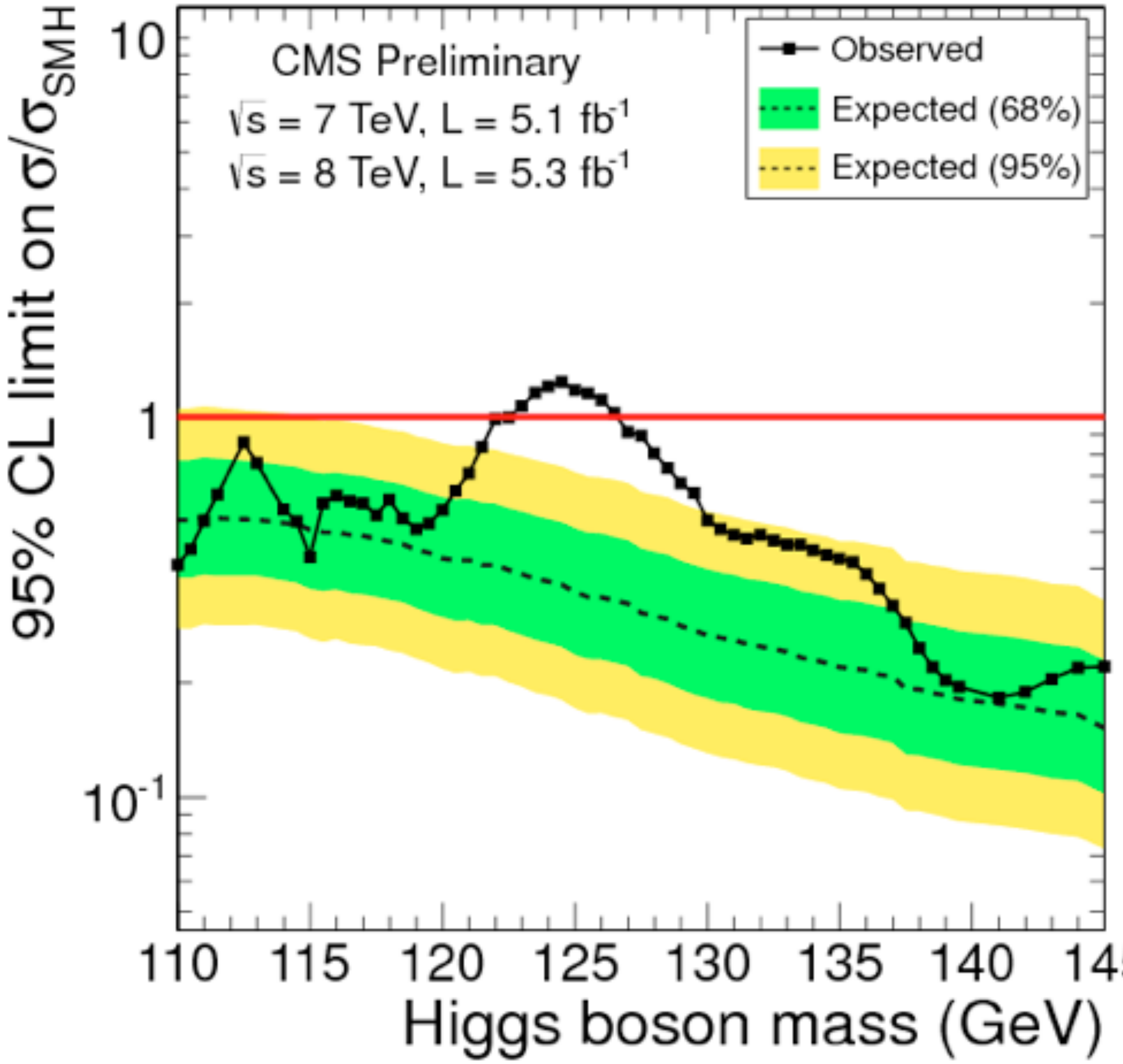
The Discovery - All Channels Combined

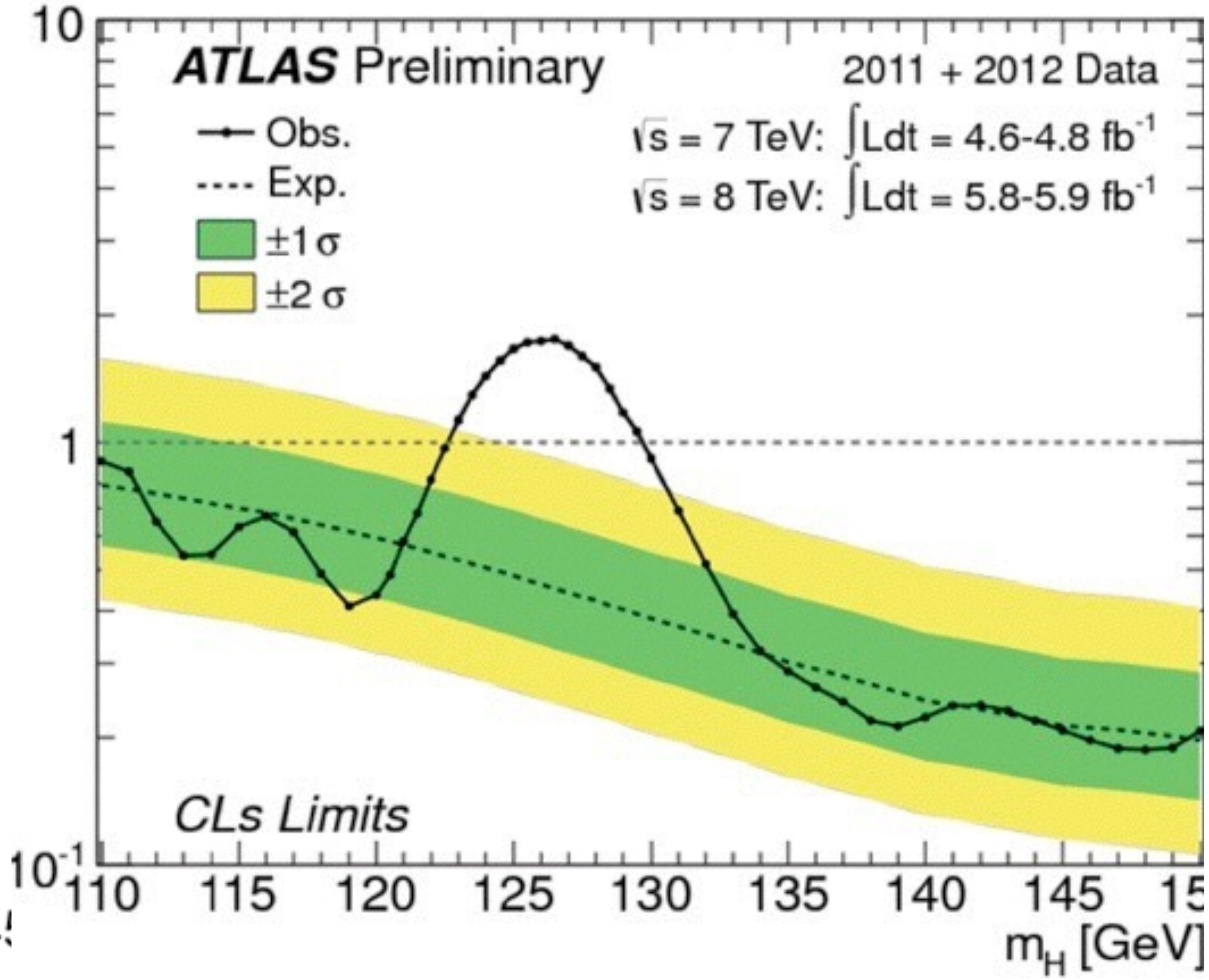




- The SM Higgs is excluded over the full range from 110 GeV to 600 GeV, with the exception of the region around 125 GeV
- Observed and expected limits match well within 1 - 2 σ

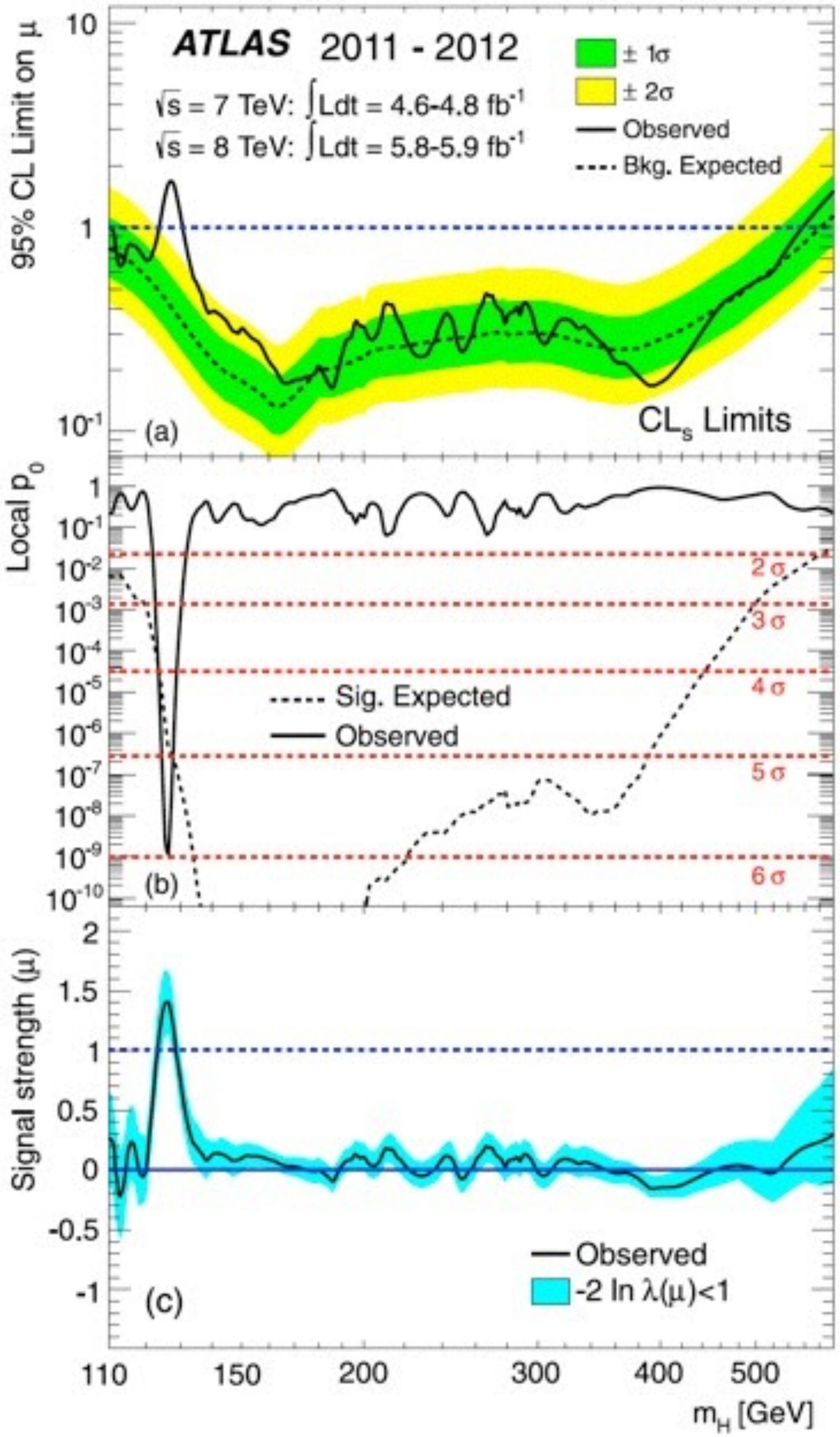
The Discovery - All Channels Combined



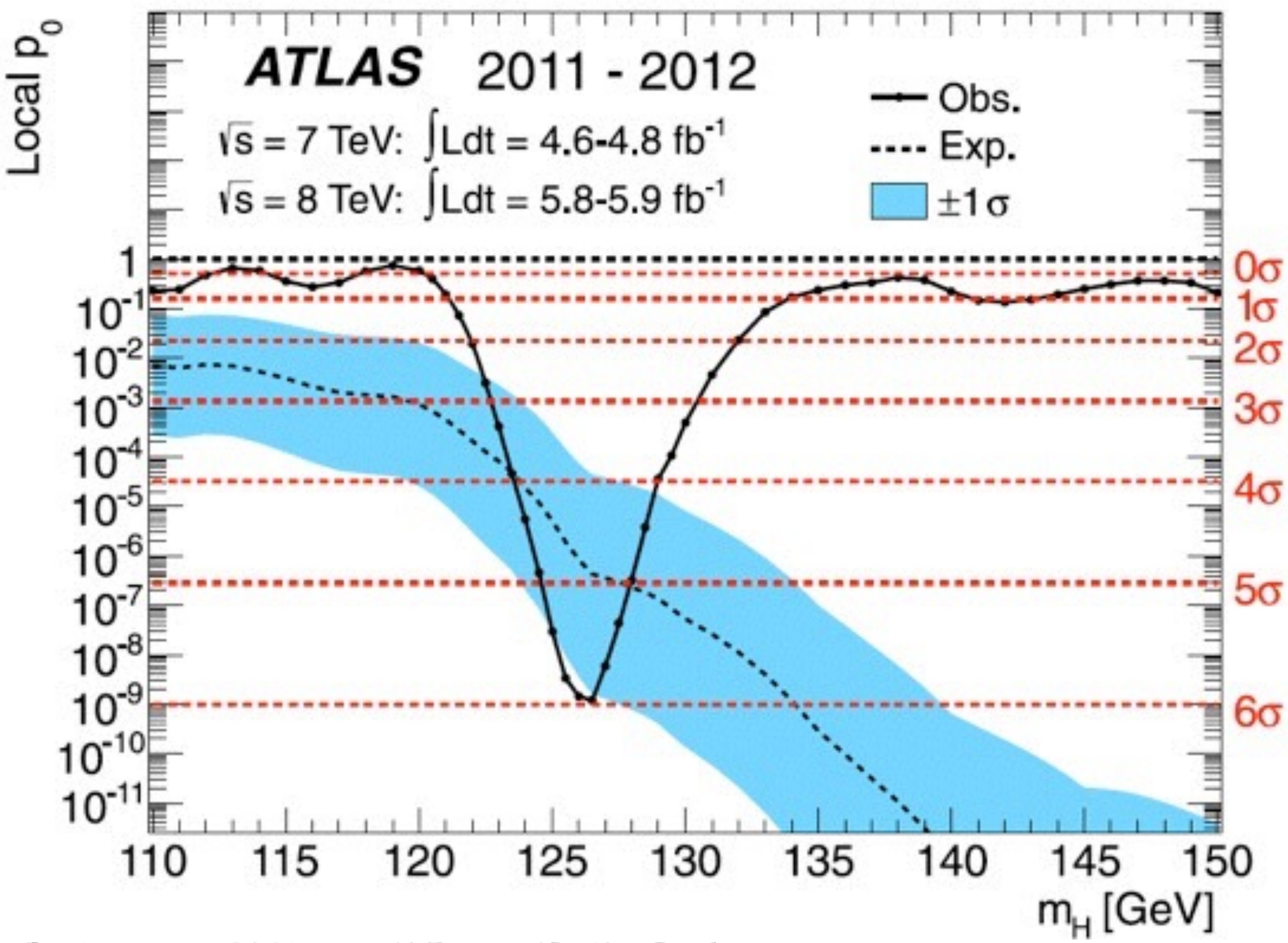


- Clear signal around 125 GeV, well in excess of the expected exclusion: A discovery!

The Discovery - A closer Look at ATLAS

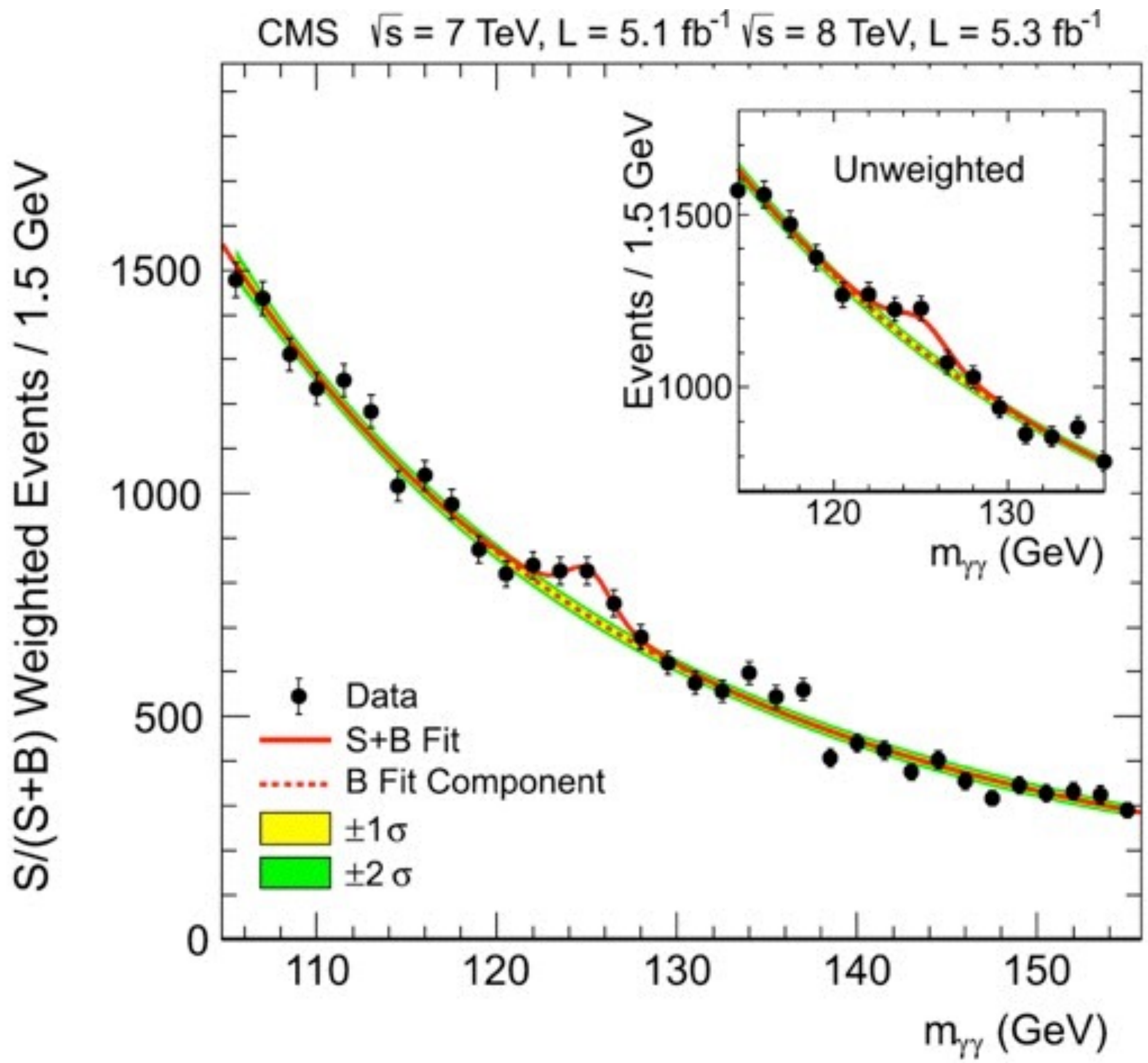


- Local significance (published!) ~ 6σ
  - Probability for a random fluctuation 10^{-9} (like tossing a coin and getting heads 30 times in a row)



Individual Channels

- The most significant: H -> γγ



CMS “discovery plot”

Individual Channels

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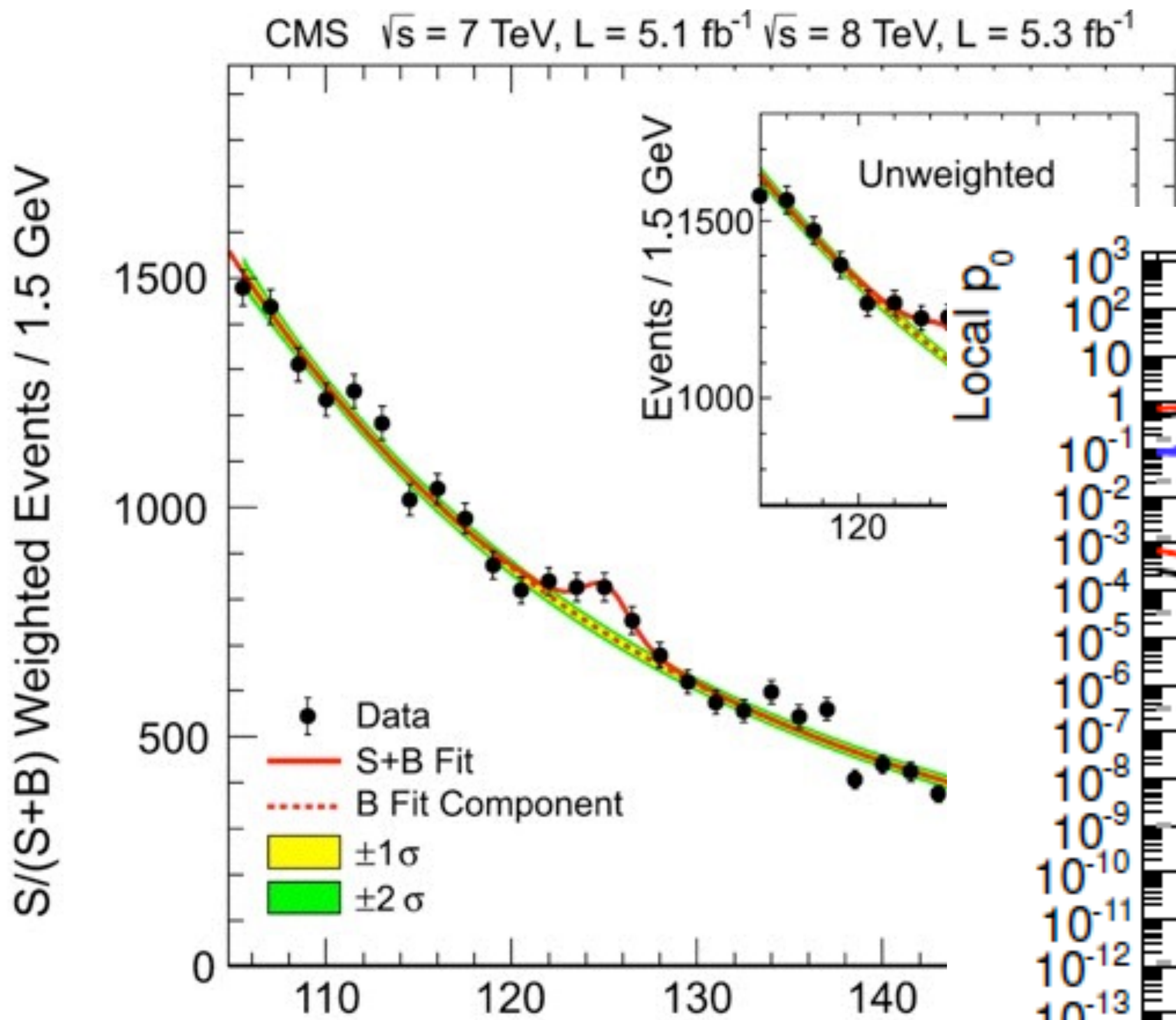
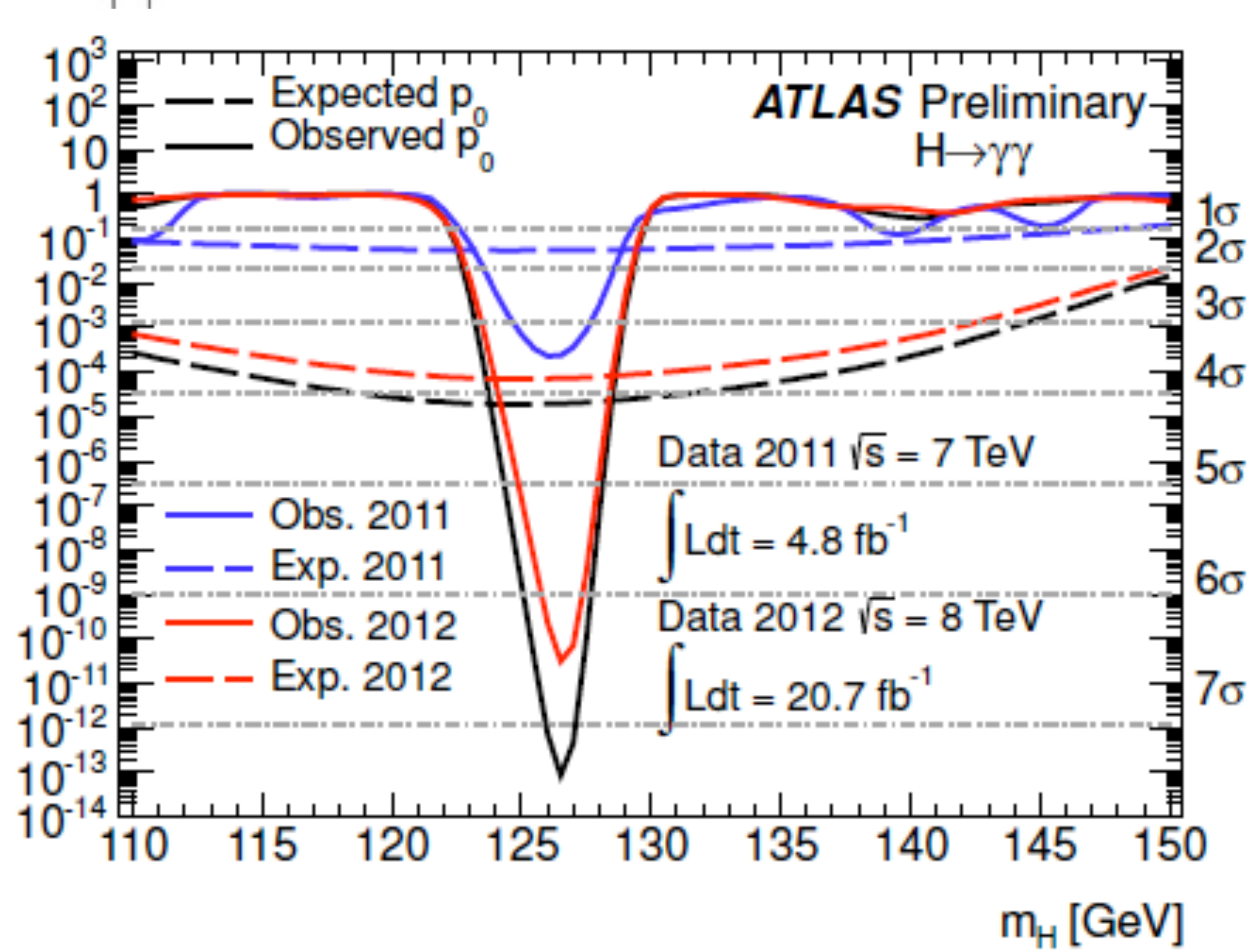


- With more data: Single channel discovery in ATLAS > 7 σ



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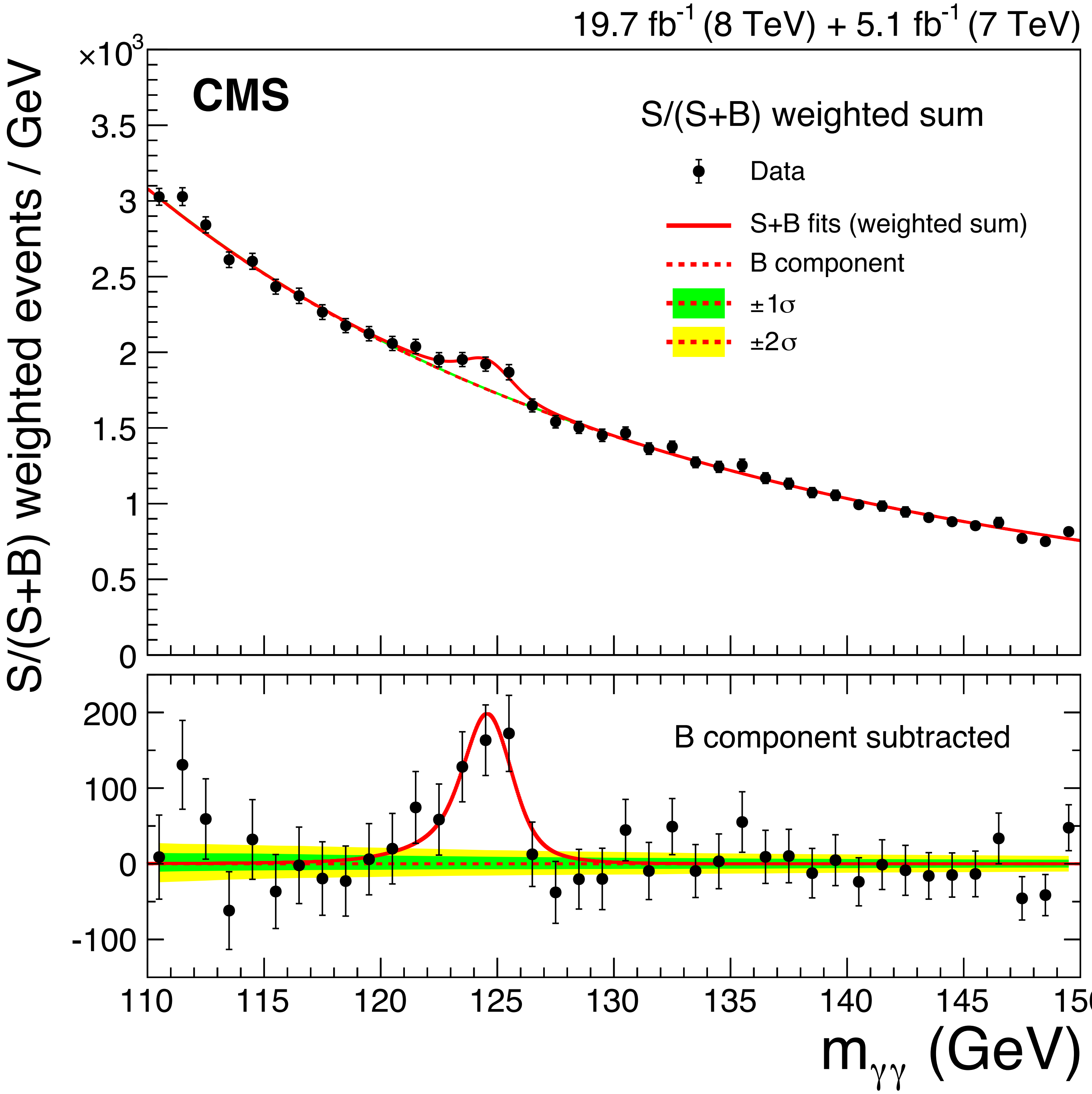

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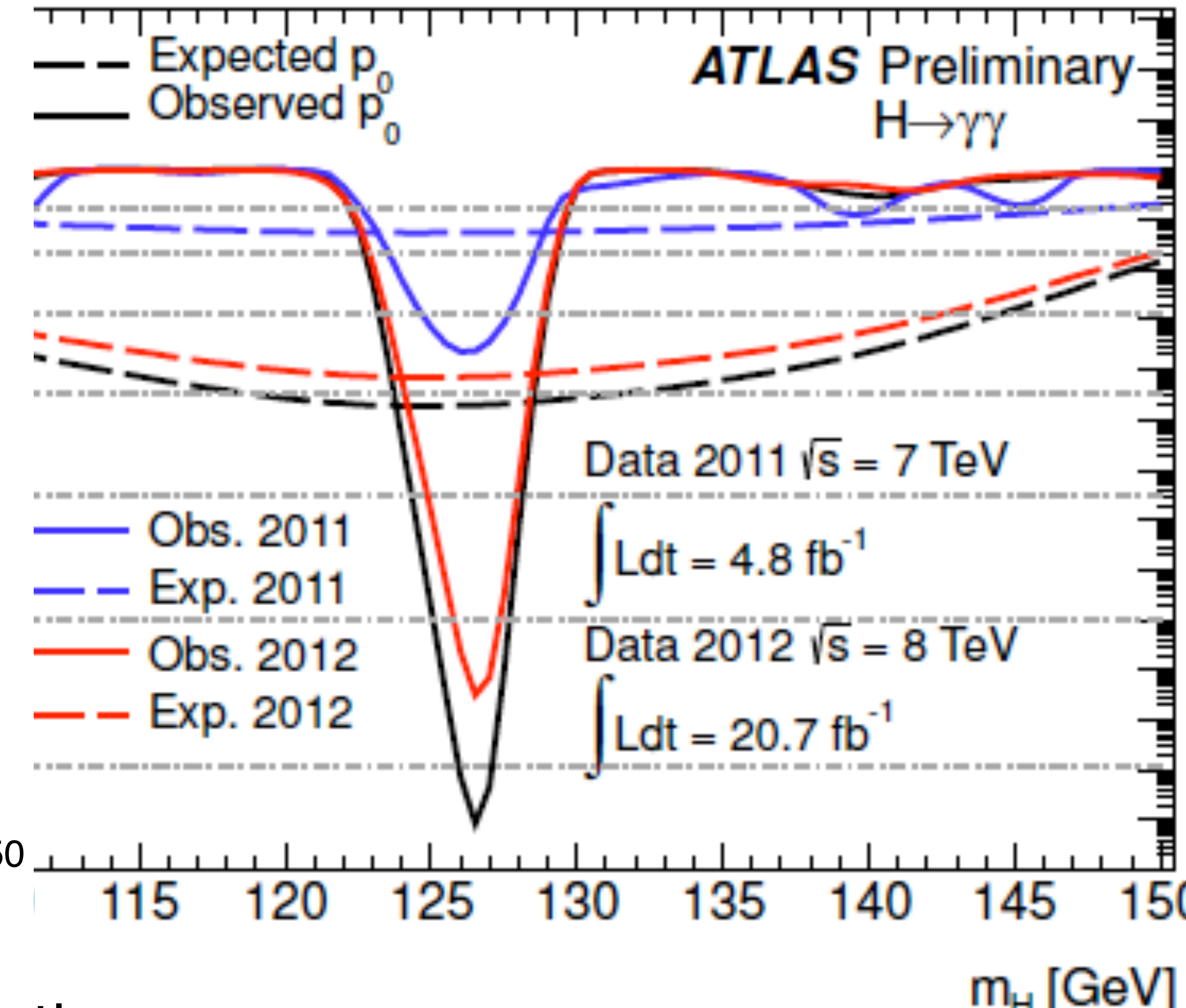
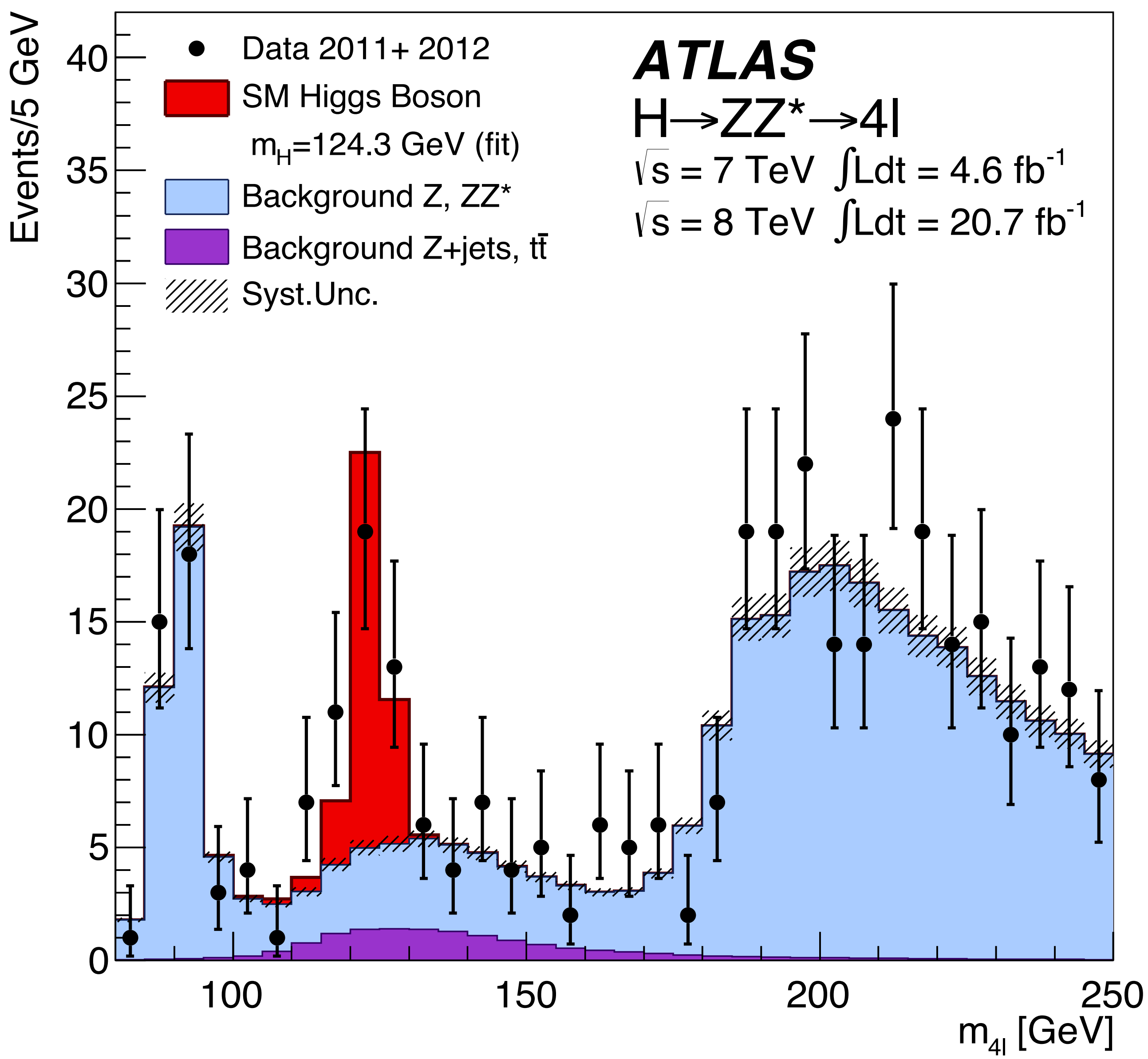
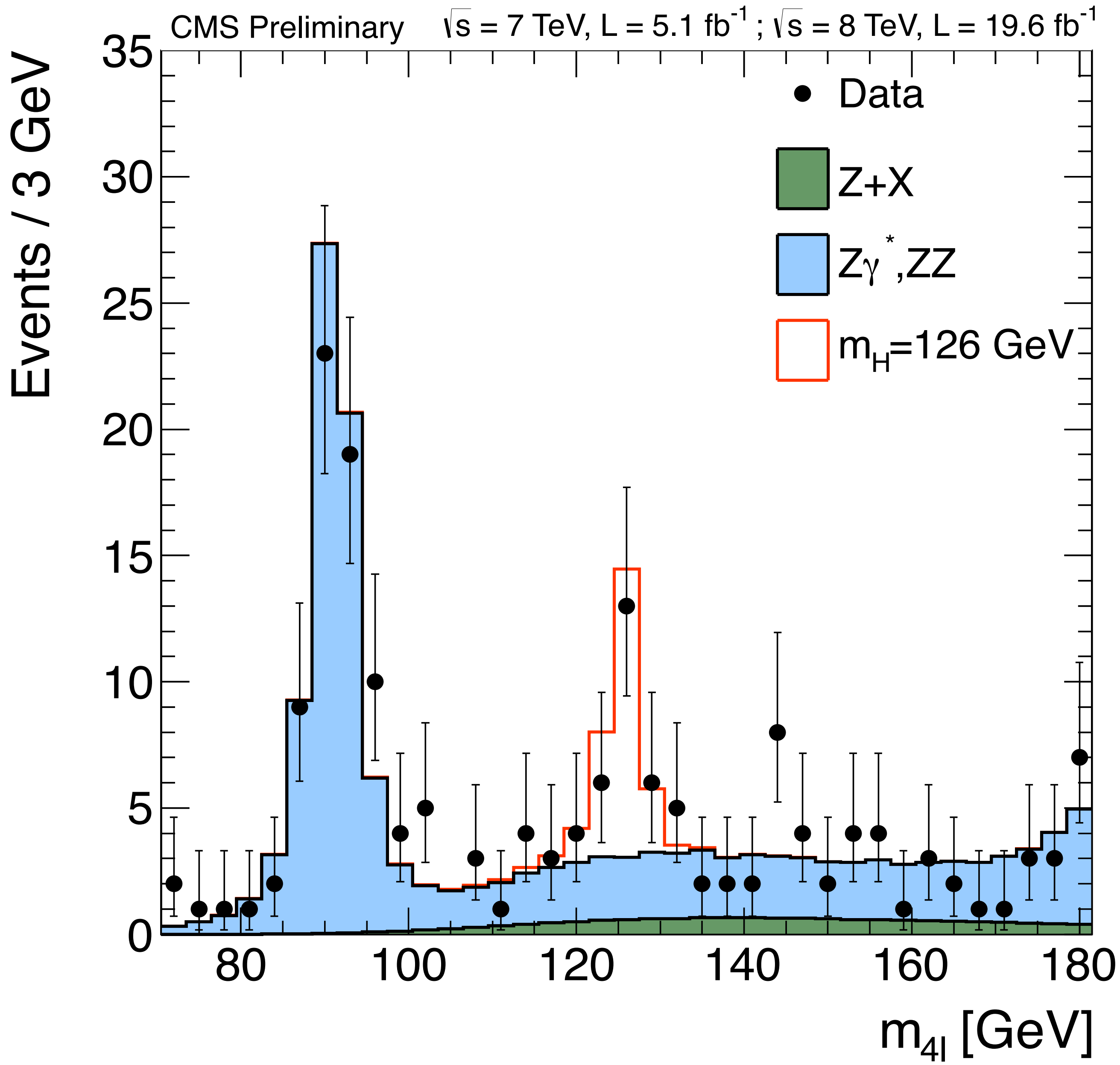


CMS “discovery plot” … and full statistics

Individual Channels

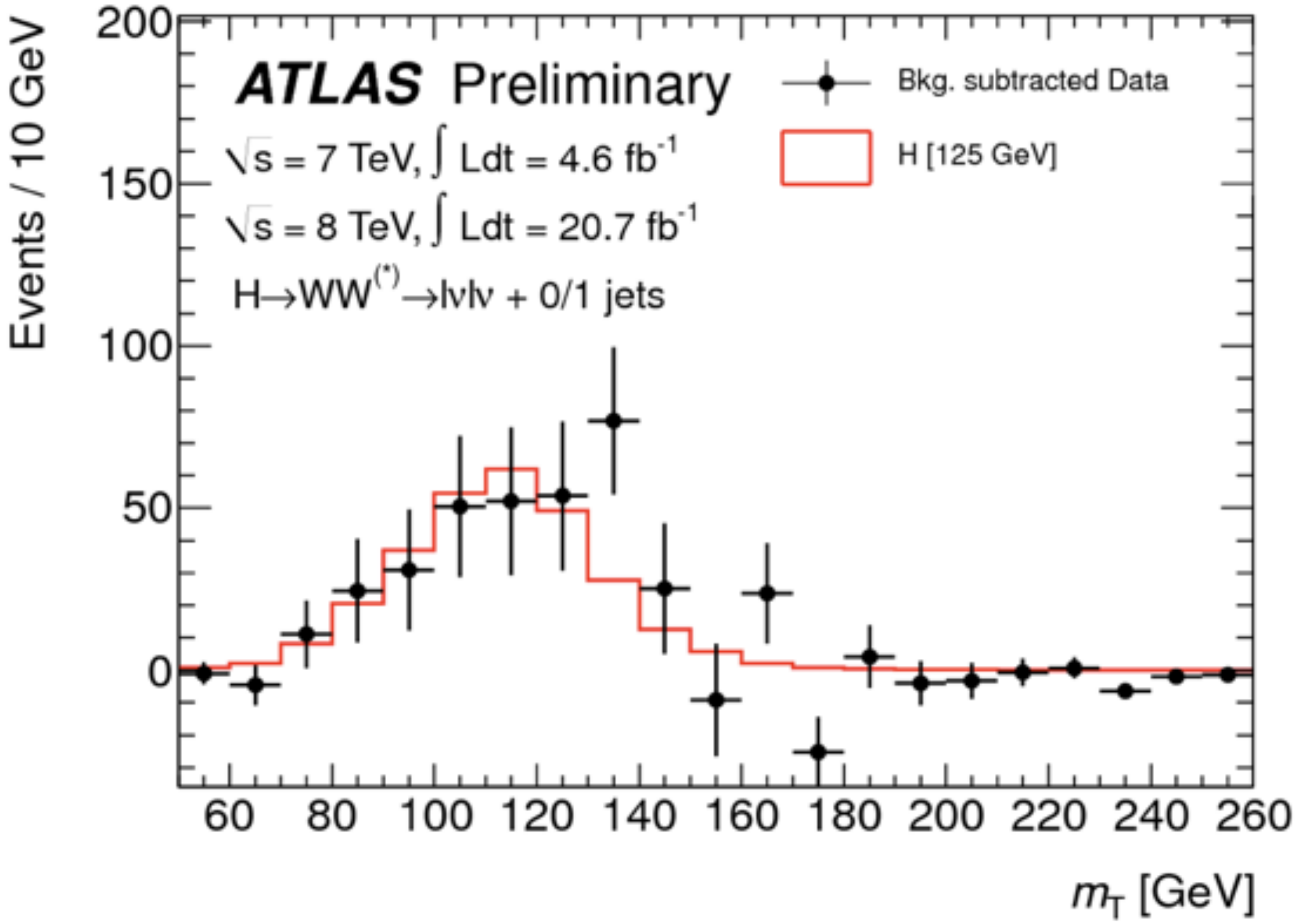
- The golden mode: H-> ZZ -> $l^+l^-l^+l^-$





Individual Channels

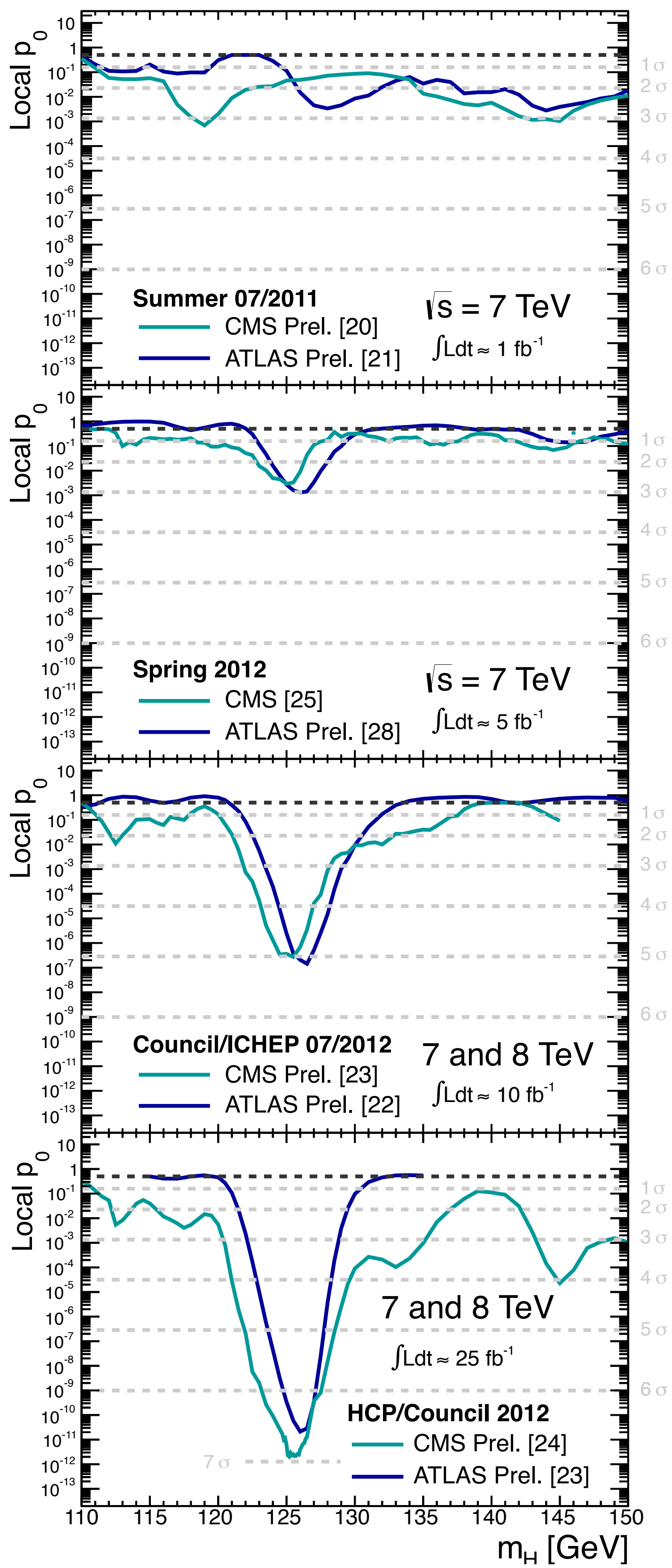
- The abundant: H->WW->lvlv



Significance: 3.8σ

- Limited mass resolution leads to a very broad peak: Background uncertainties accumulate, significance is reduced

The Discovery: Seeing it happen



- Summer 2011: First (and last) focus on limits from LHC
- December 2011: First hints of a signal presented to CERN council
- Summer 2012: Discovery
- December 2012: Well established signal - entering the era of detailed Higgs physics program

July 4, 2012 - The Big Day

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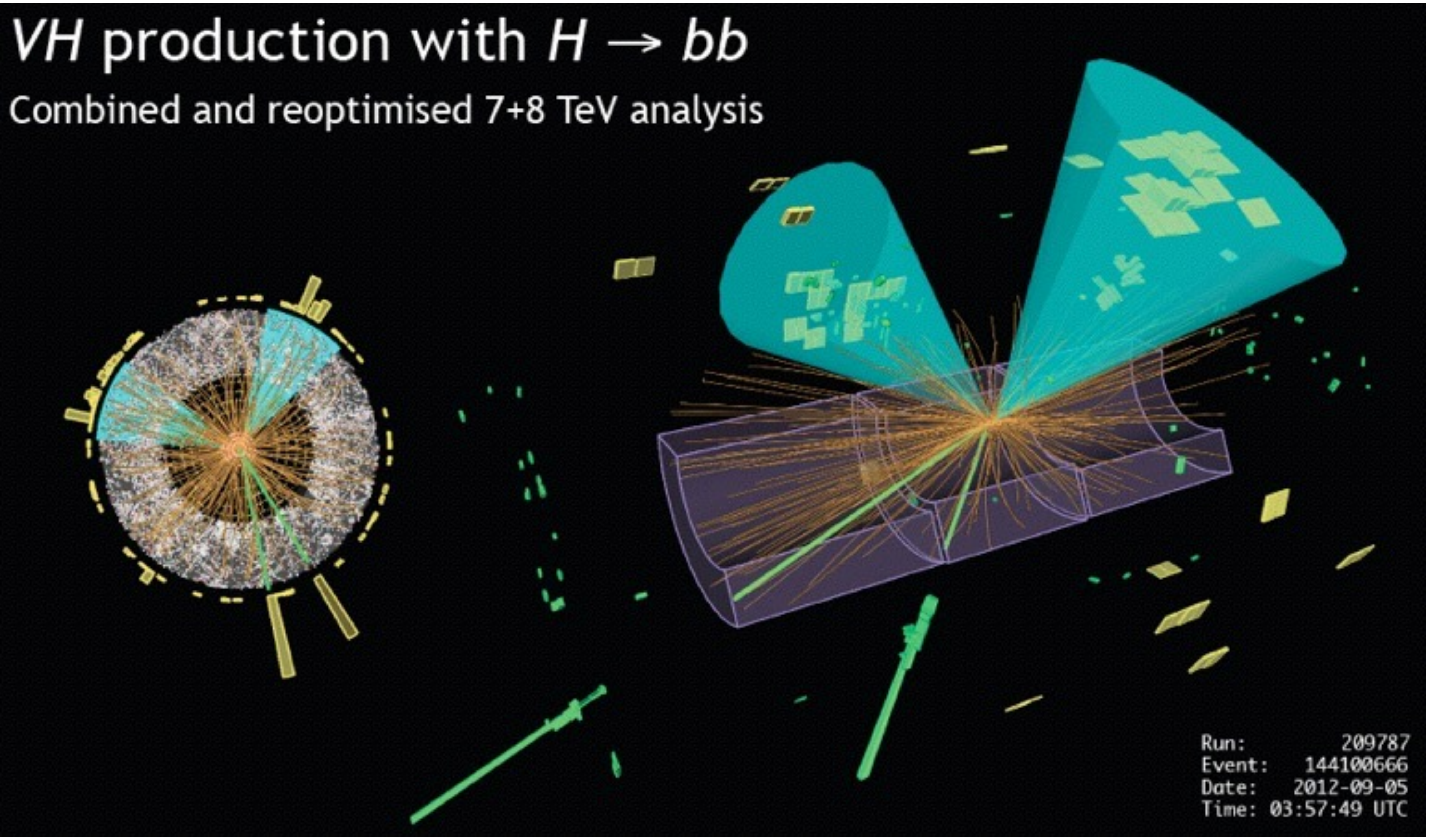
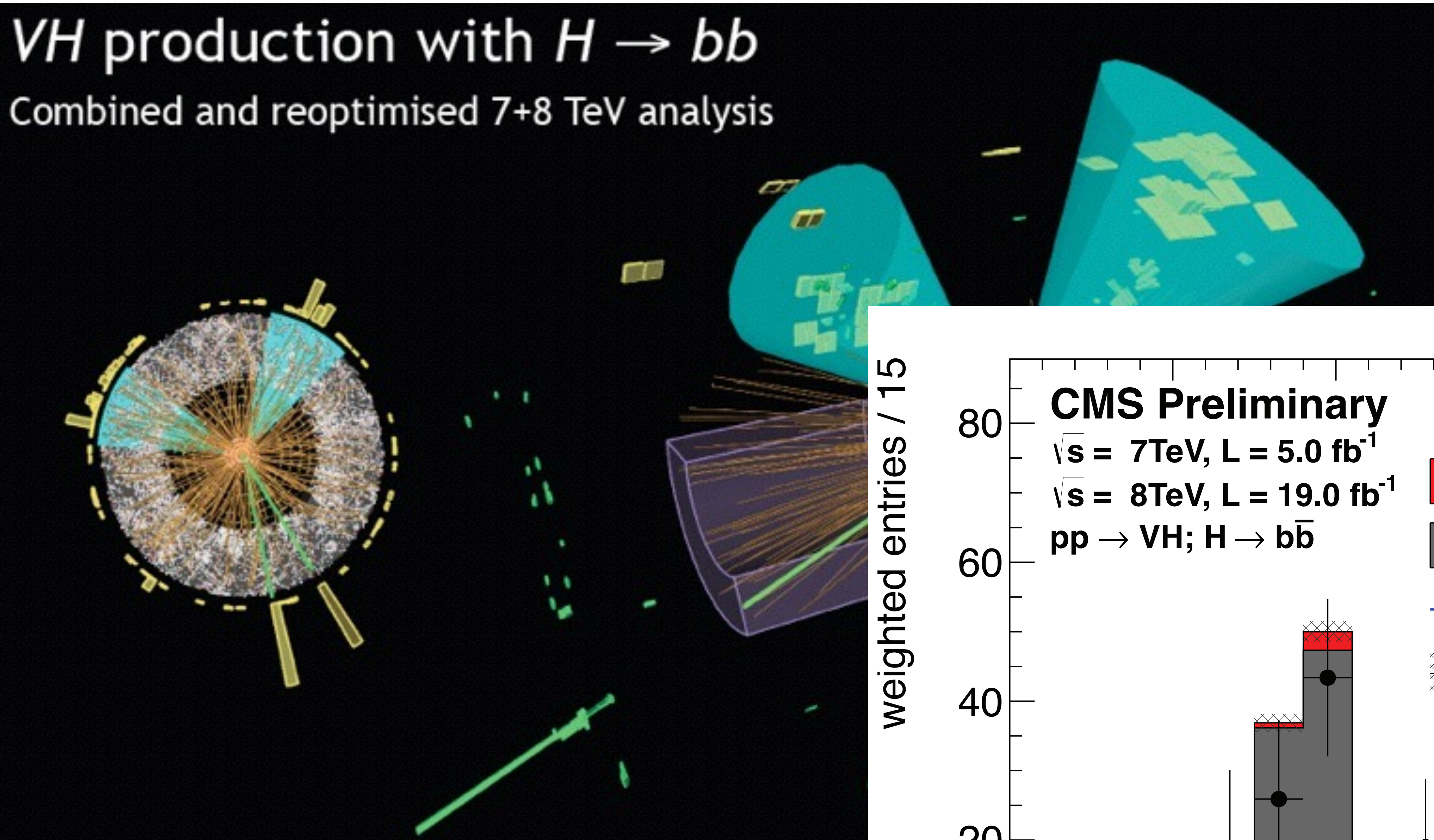
Beyond Discovery - Other Channels



- H->bb BR: 57%
- VH production: ~5% of all H production, only leptonic V decay: 0.7%
  - Combined: 0.2%
- Limited mass resolution: b-Jet reconstruction

- Enormous hadronic background, high branching fraction - best to reconstruct with additional particle to tag: Higgs production off vector bosons

Beyond Discovery - Other Channels



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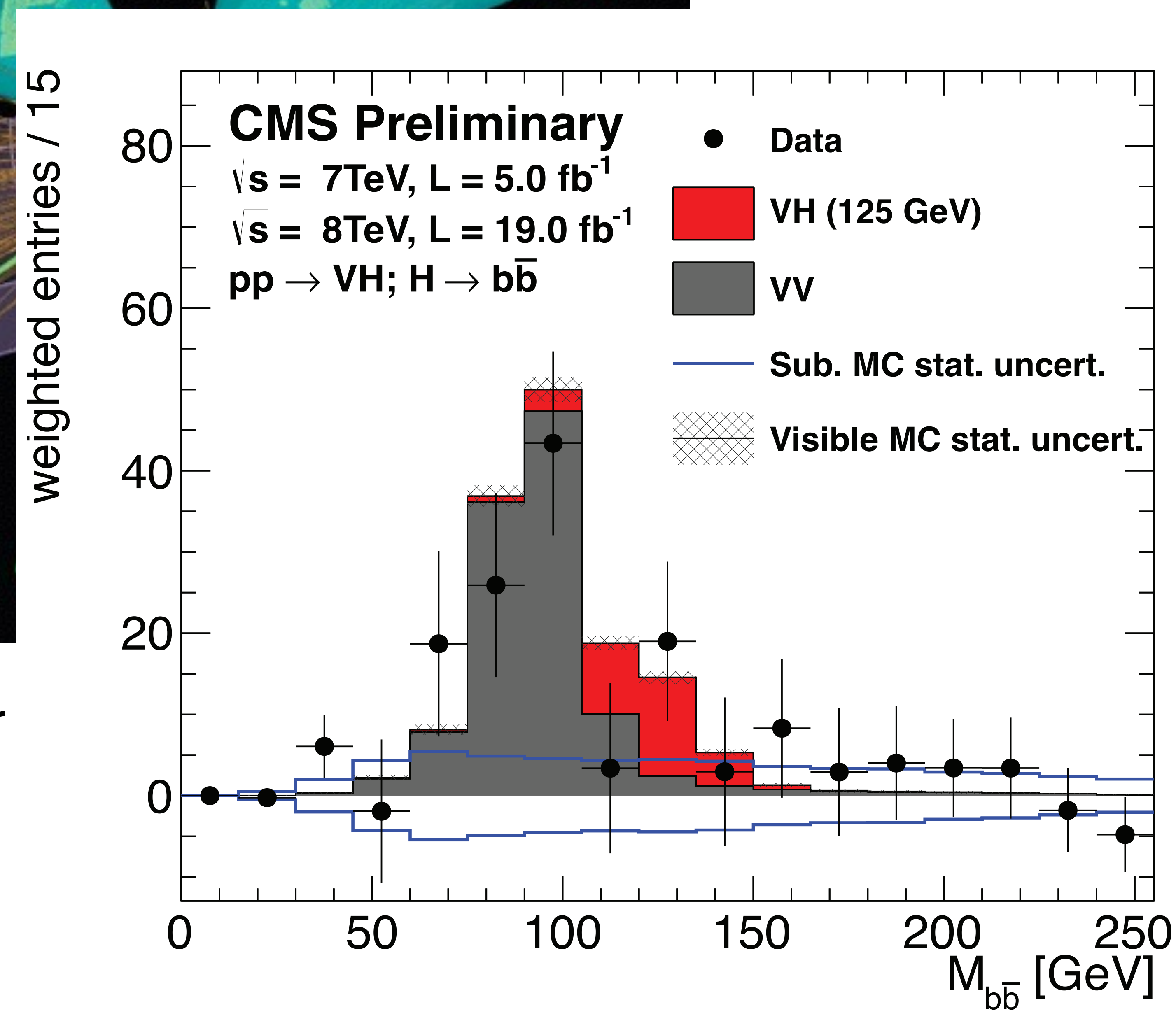
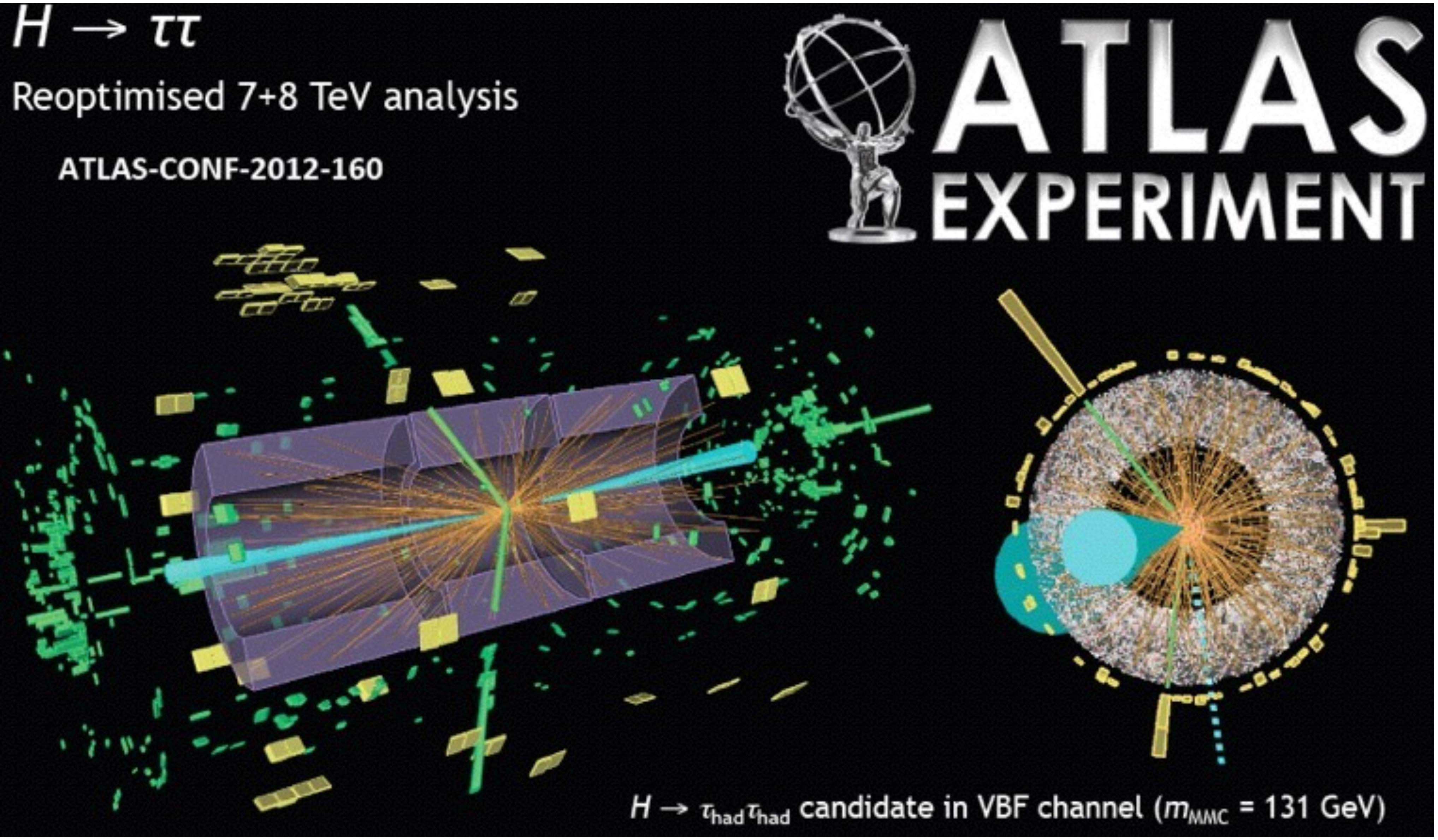


No observation yet: Event yield lower than expected

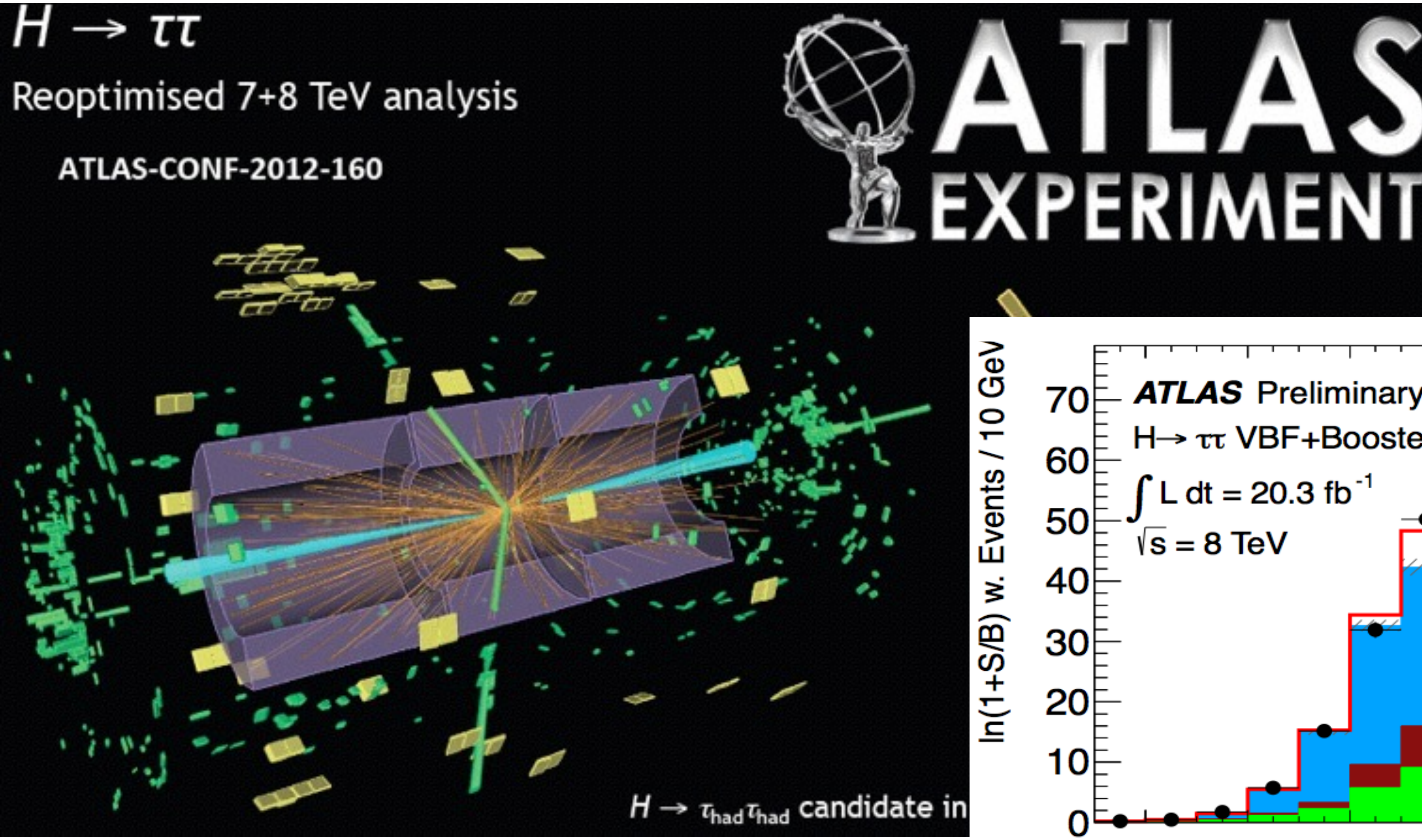
Combined Significance 2.6 σ (ATLAS + CMS)

Beyond Discovery - Other Channels



- Poor mass resolution: tau decays include at least one neutrinos
- BR: 6.3%
- All decays considered - none are easy to identify:
  - τ -> hadron(s) + ν
  - τ -> l + ν + ν

Beyond Discovery - Other Channels



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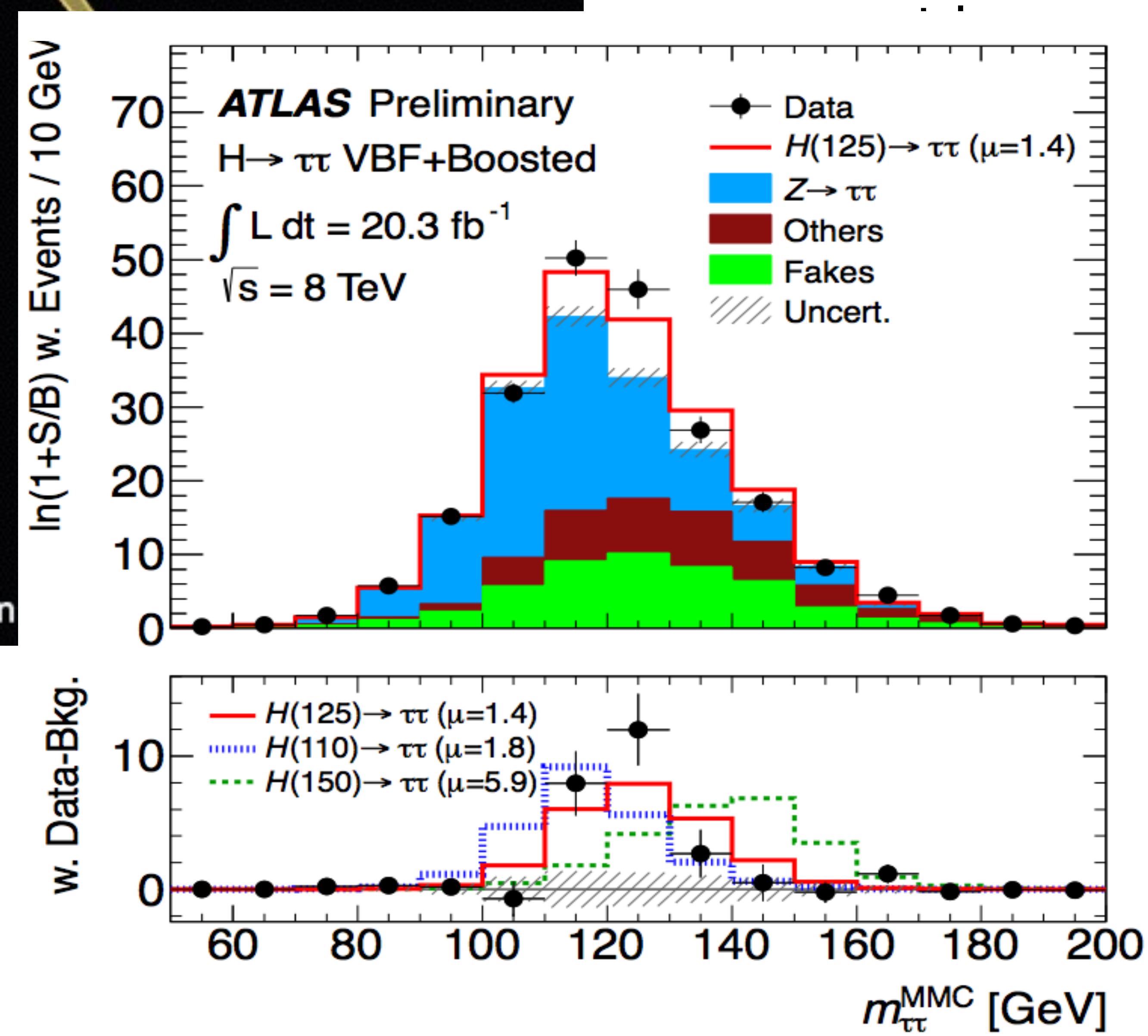


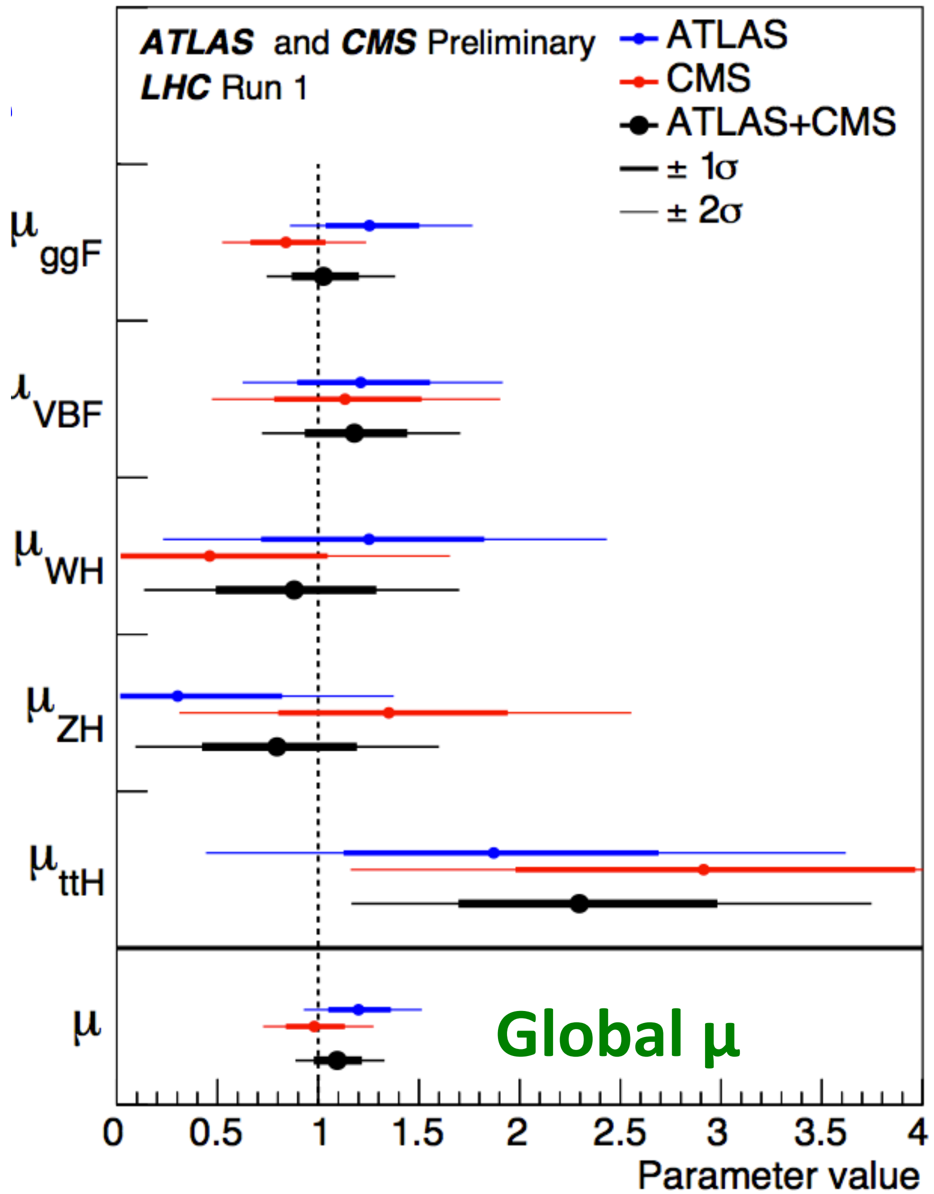
- Now established: Combined significance 5.5 σ

Higgs Properties

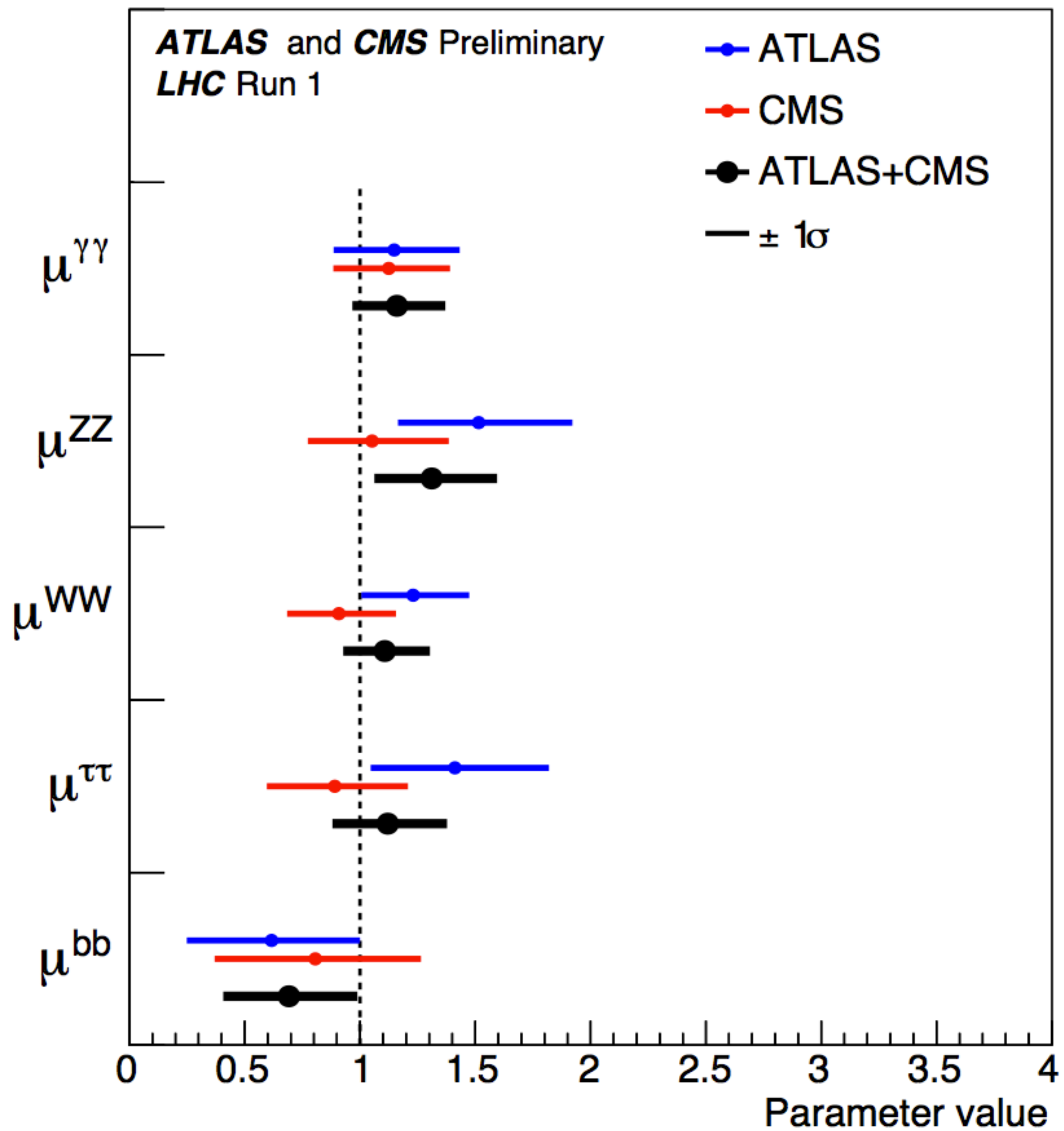
Branching Fractions & Signal Strength

- The key question: Does the new boson couple to mass as expected for the Higgs? -> Can be answered by measuring the ratios of different decay modes, compared to the SM expectation - now a Run 1 combination of ATLAS + CMS

SM BRs assumed



SM production σ assumed



μ: Signal strength, relative to SM expectation

μ = 1: SM Higgs;

μ = 0: No Higgs

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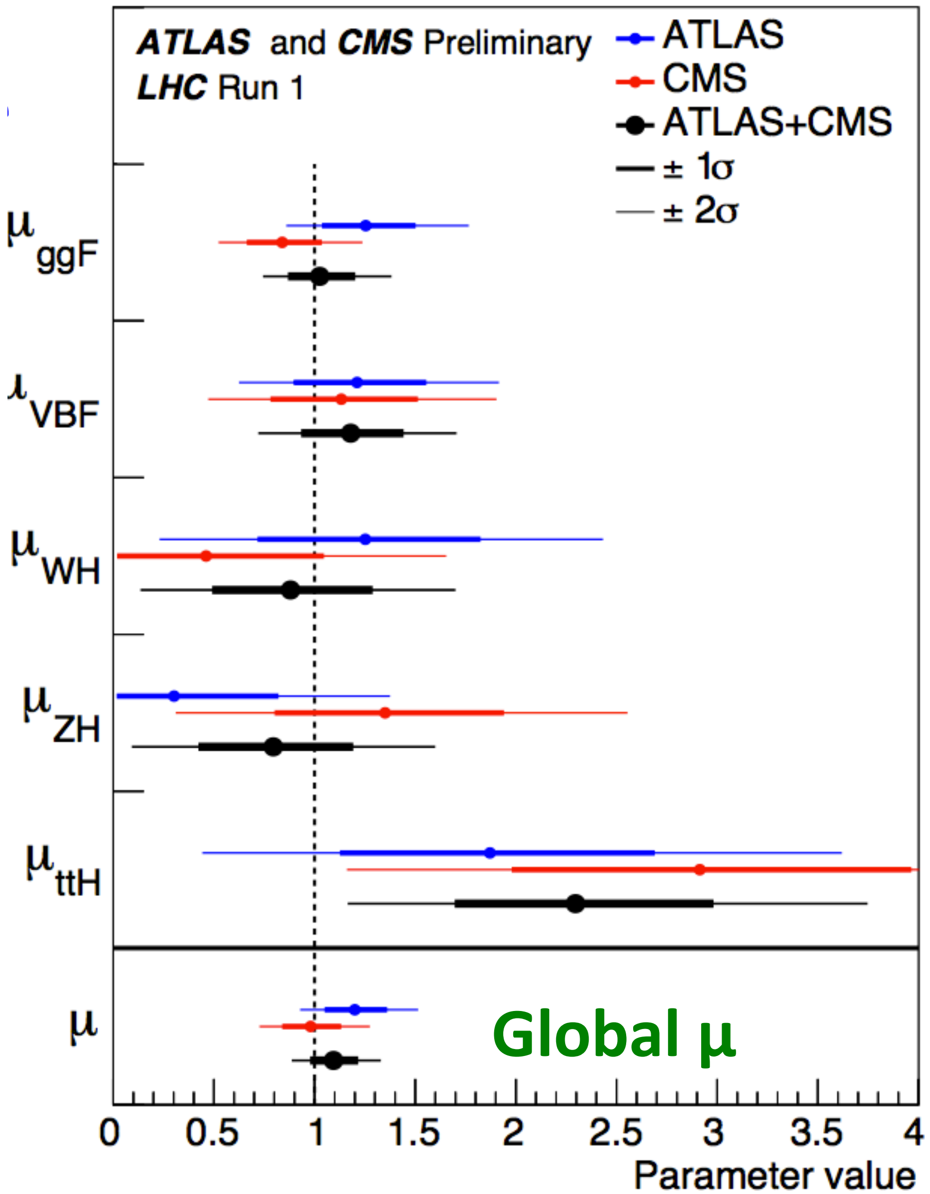

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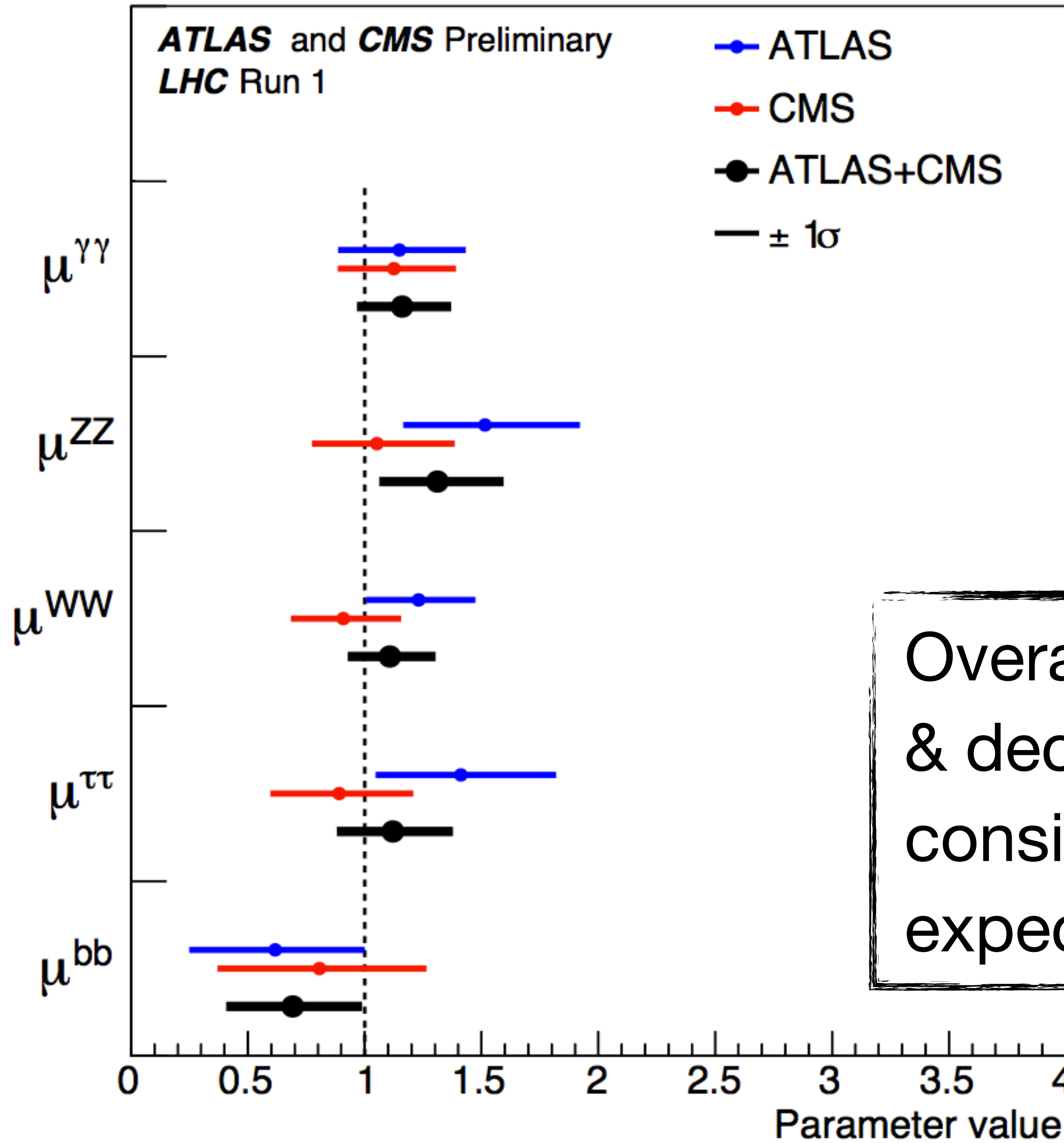
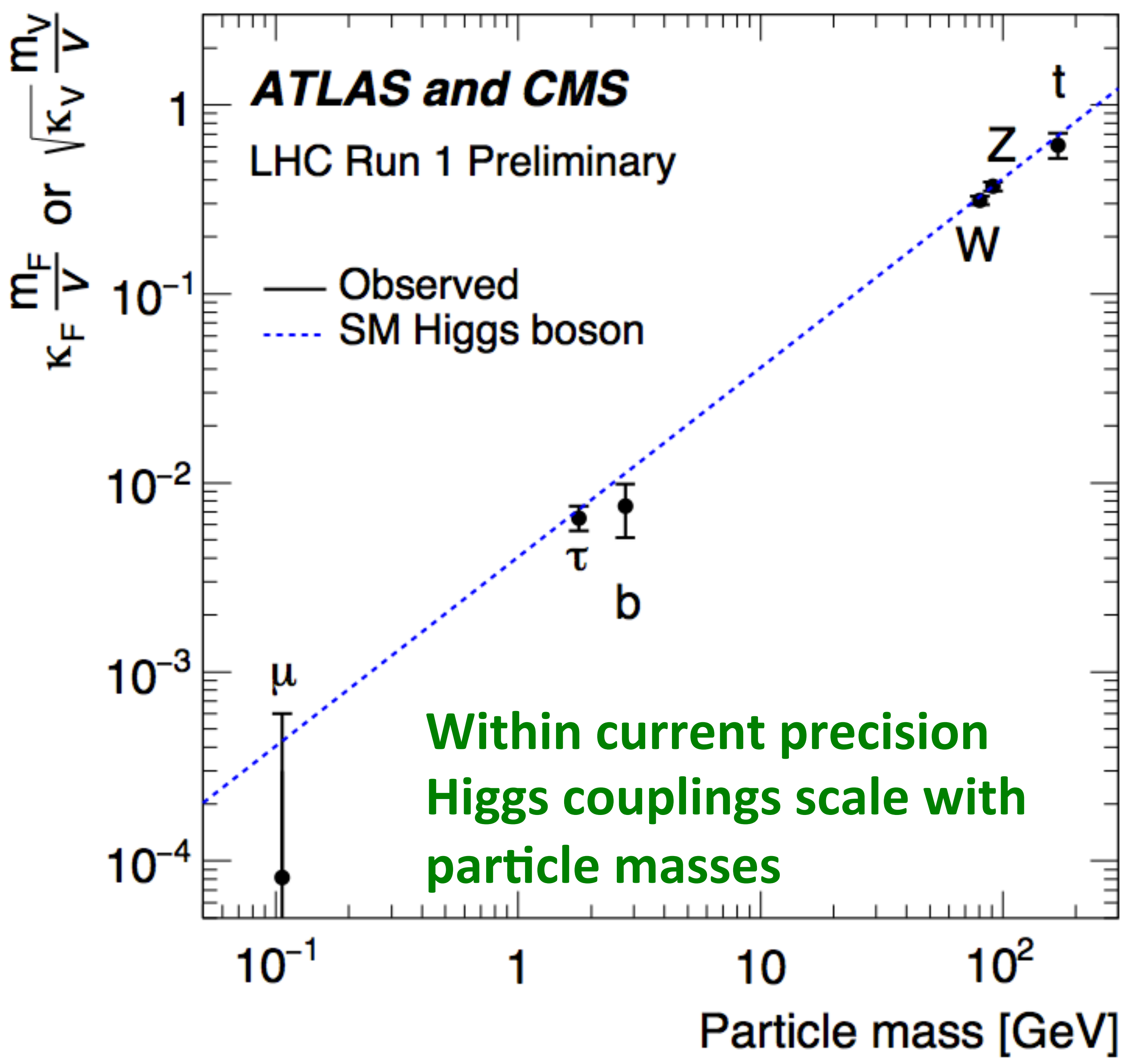


μ: Signal strength, relative to SM expectation
μ = 1: SM Higgs;
μ = 0: No Higgs

Overall: Production rate & decay patterns consistent with SM expectations!

Higgs Couplings



Within current precision Higgs couplings scale with particle masses

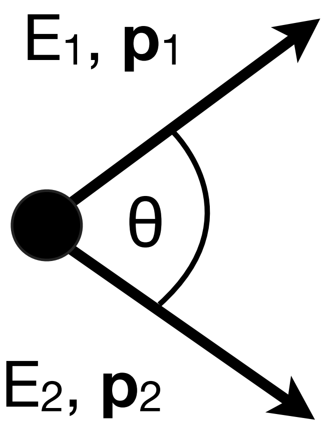
- From the measured signal strengths the couplings of the Higgs to various particles can be determined (with additional uncertainties)
- Clear evidence that couplings scale with particle mass (nothing like this has been observed for any other particle!):

It is a Higgs boson

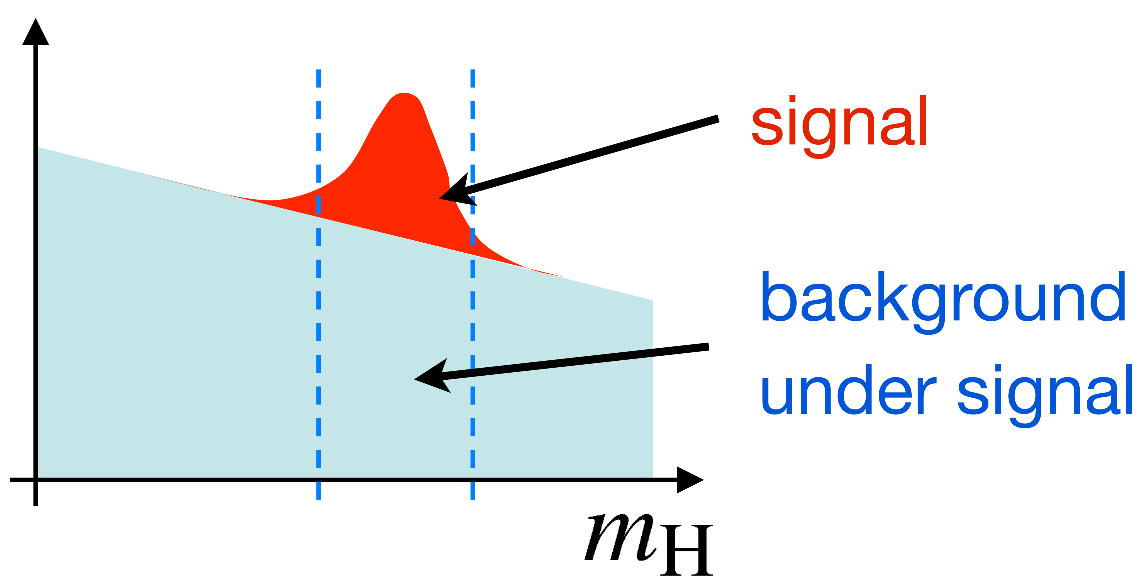
Mass

- The mass is a key parameter:
  - Important parameter in SM and BSM theories
  - Defines the SM expectations for the branching ratios

Determining mass: The invariant mass of observed decay products



$$m_{inv}^2 = (E_1 + E_2)^2 - (\mathbf{p_1} + \mathbf{p_2})^2$$
$$= m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2 cos\theta)$$

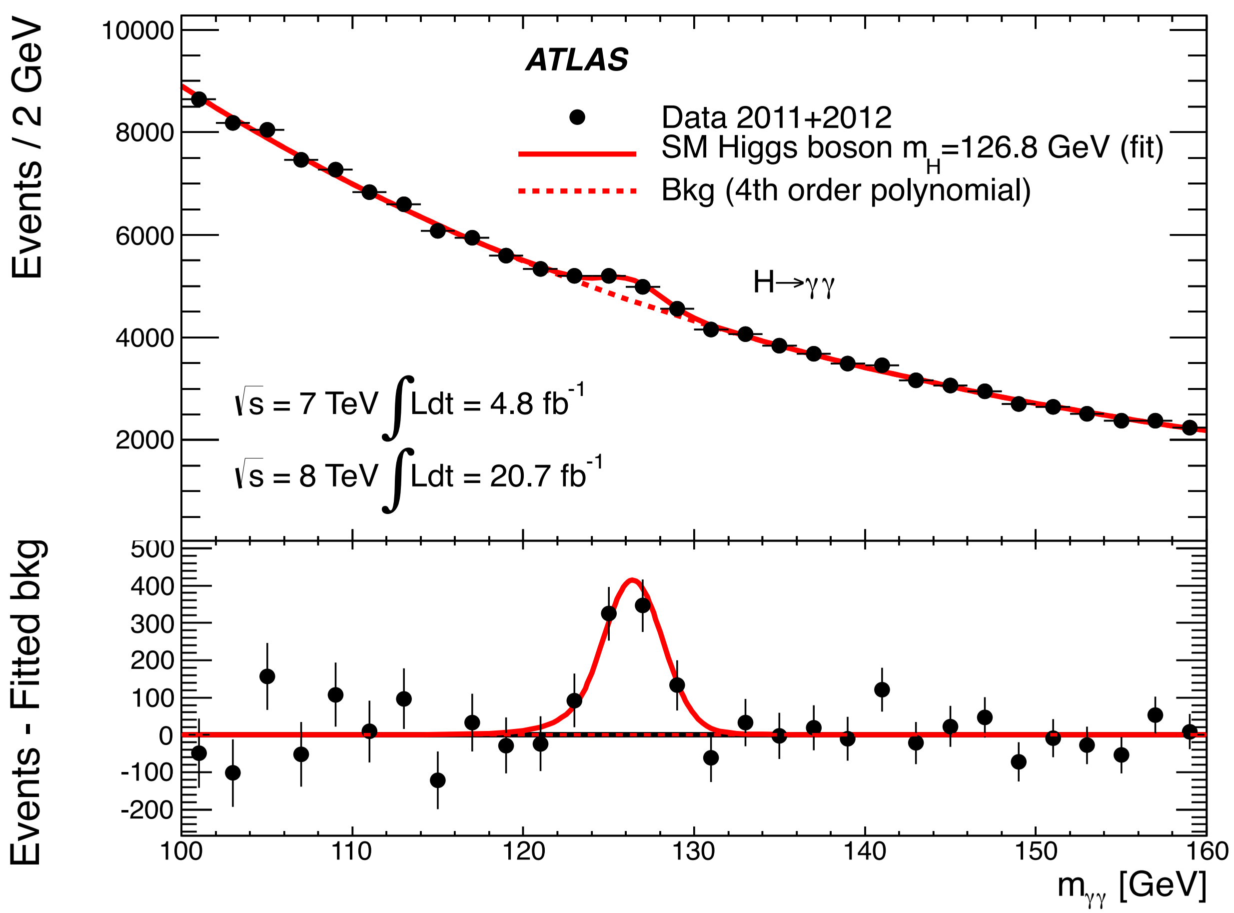


Significance: $\propto \frac{S}{\sqrt{B}} \quad \propto \frac{1}{\sqrt{\sigma(M)}}$

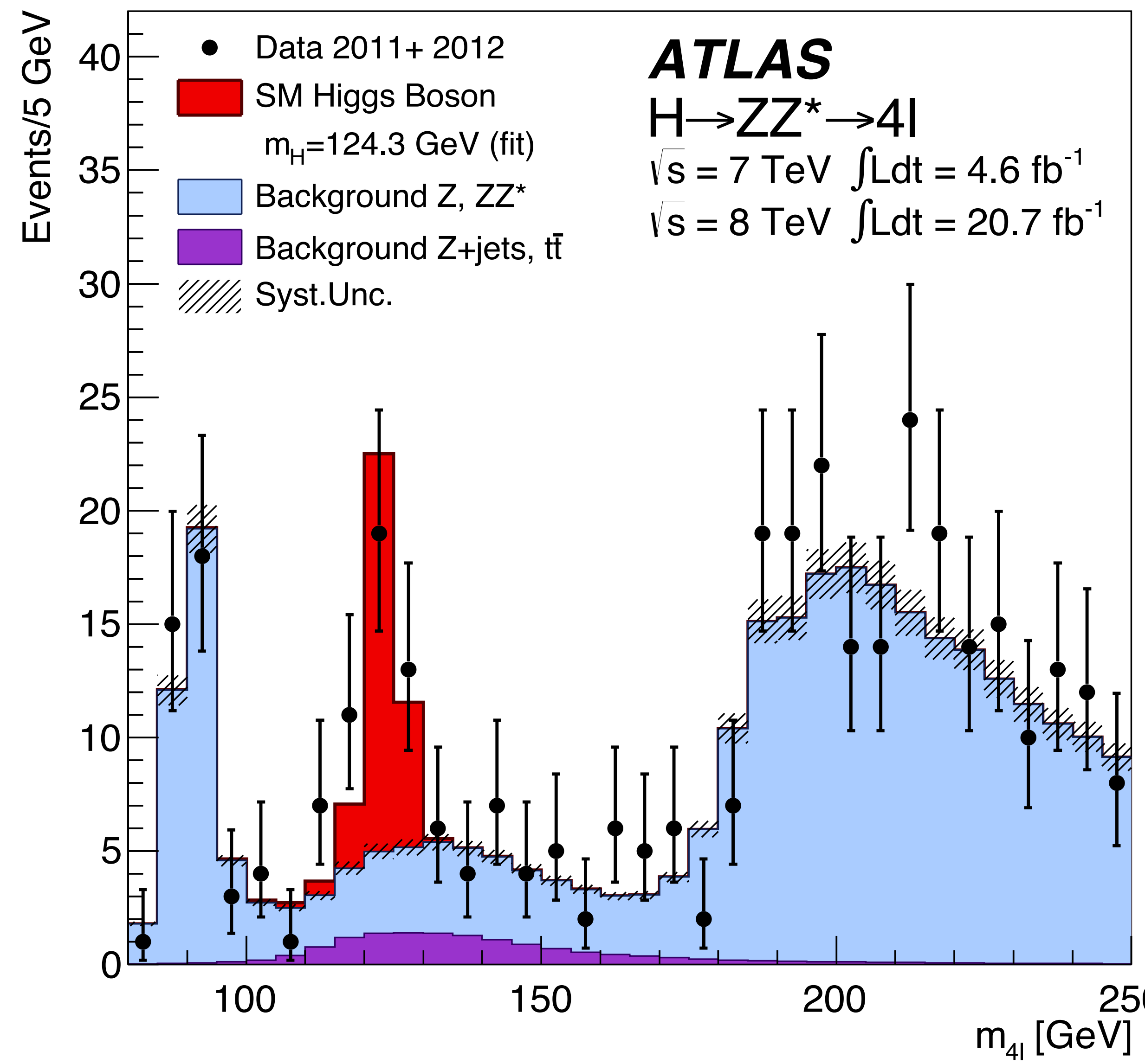
- Choose channels with good mass resolution -> Good energy and angular resolution for decay daughters

Mass: Measured in two Channels

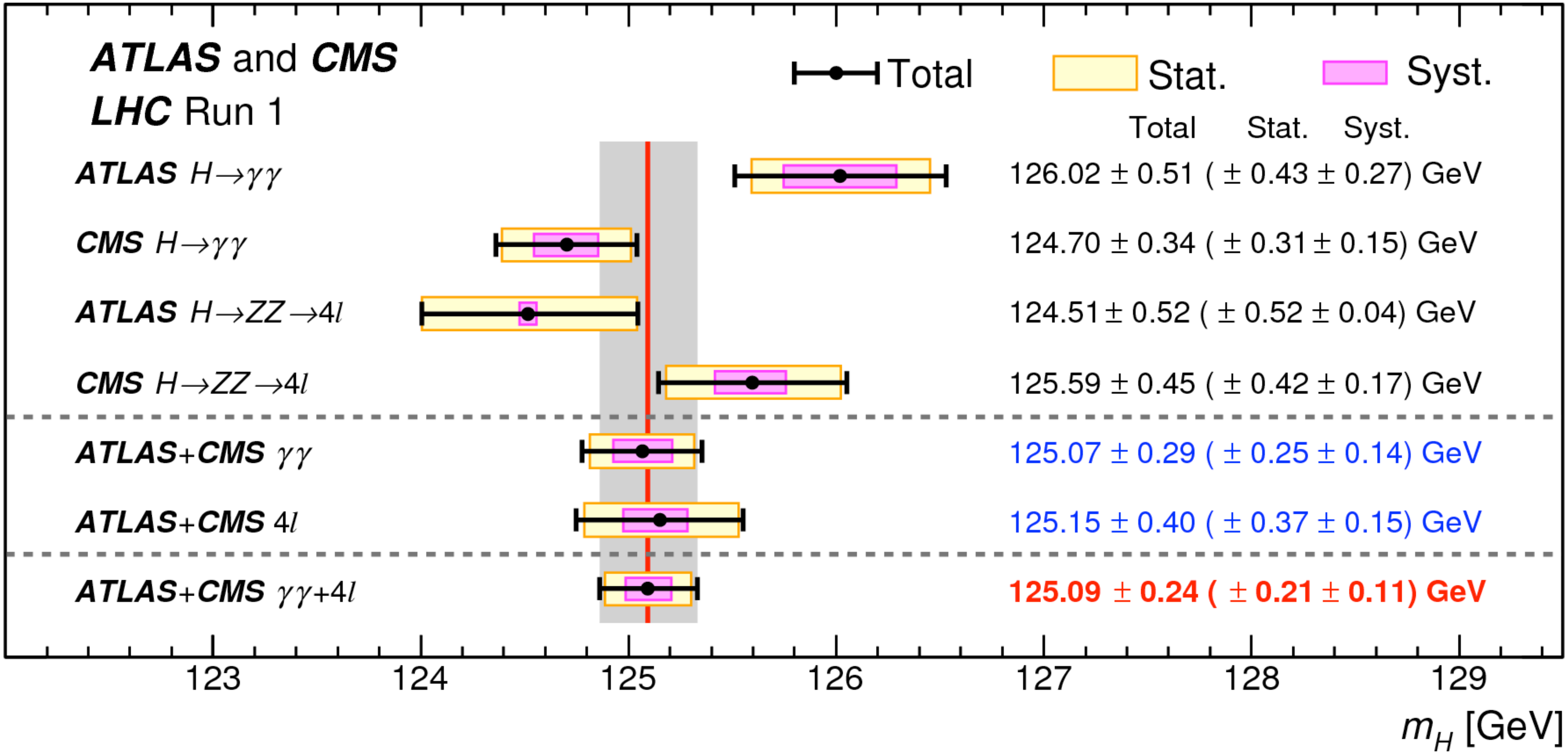
H -> γγ



H -> ZZ* -> 4l



Mass



In both experiments slightly different mass results for the two channels - but in opposite directions

The Spin of the New Boson

- We expect a scalar particle: Spin 0
- Naive first look - From observed decays (neglects possible angular momentum in final state - e.g. p-wave vs s-wave)

Decays	Observed?	Spin 0	Spin 1	Spin 2
H -> γγ	yes	yes	no	yes
H -> ZZ	yes	yes	yes	yes
H -> bb	not quite	yes	yes	(yes)
H -> ττ	yes	yes	yes	no
still allowed ?		yes	not really	no

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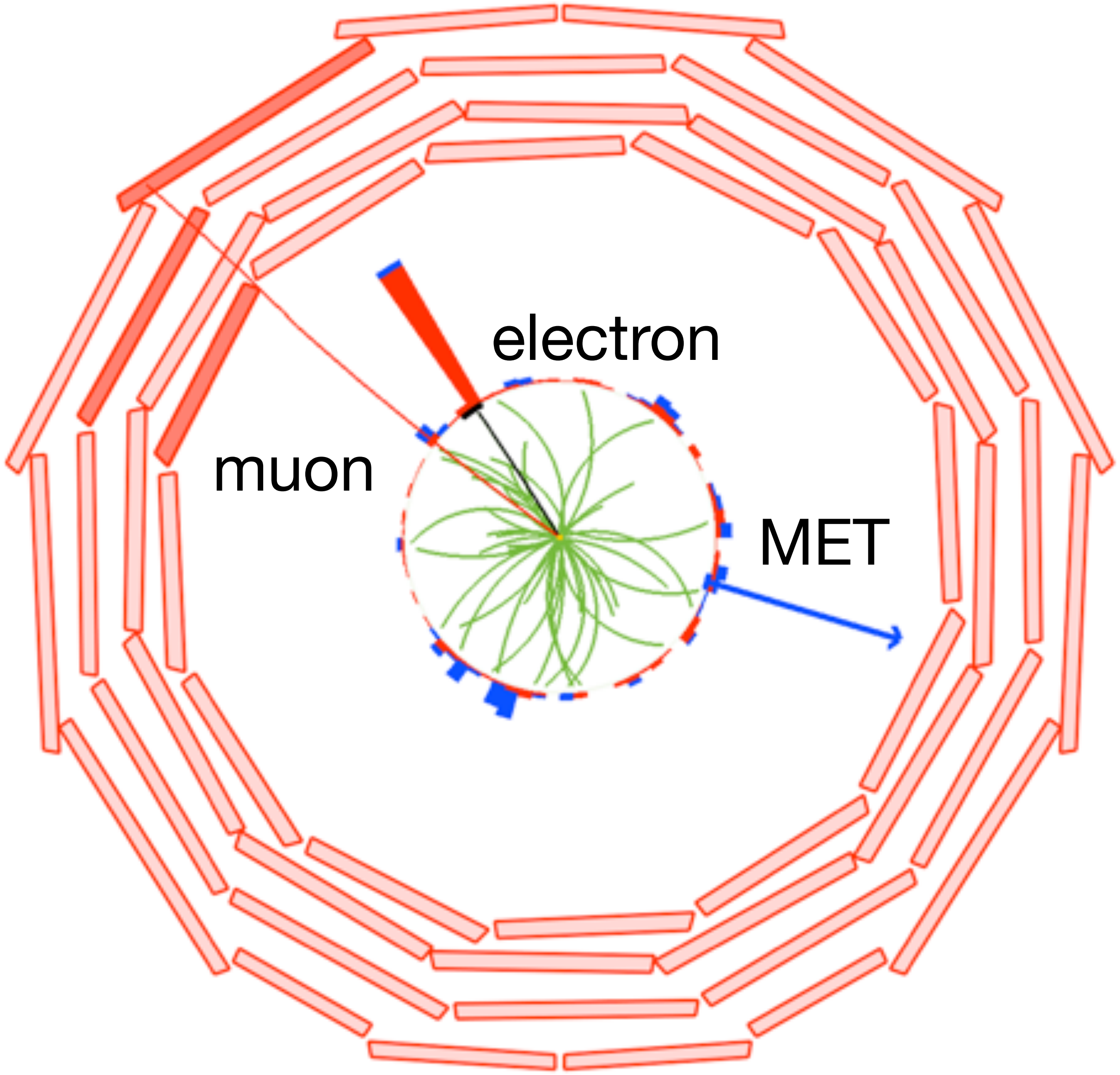
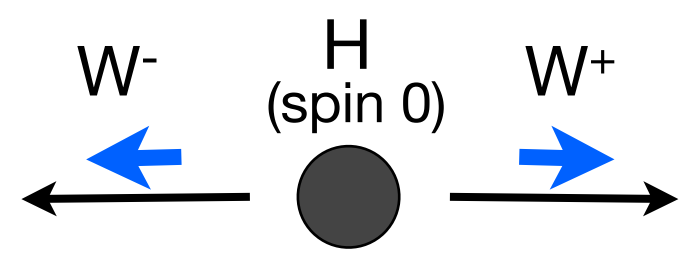
The question of spin is basically settled - not with decay mode observations alone, since there can be additional angular momentum in the two-particle final states...

The Spin of the New Boson

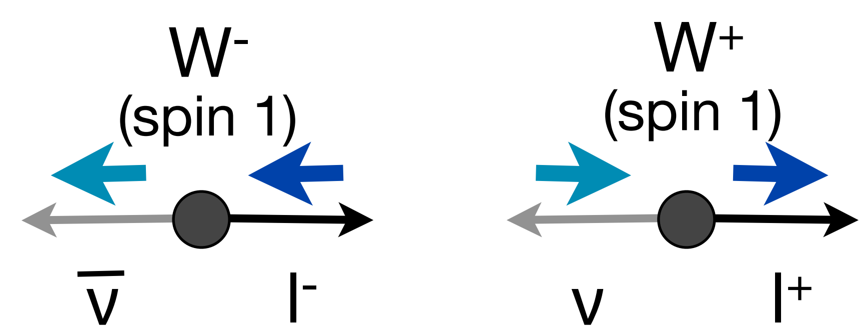


- The full answer will come from angular correlations!

One example: H->WW

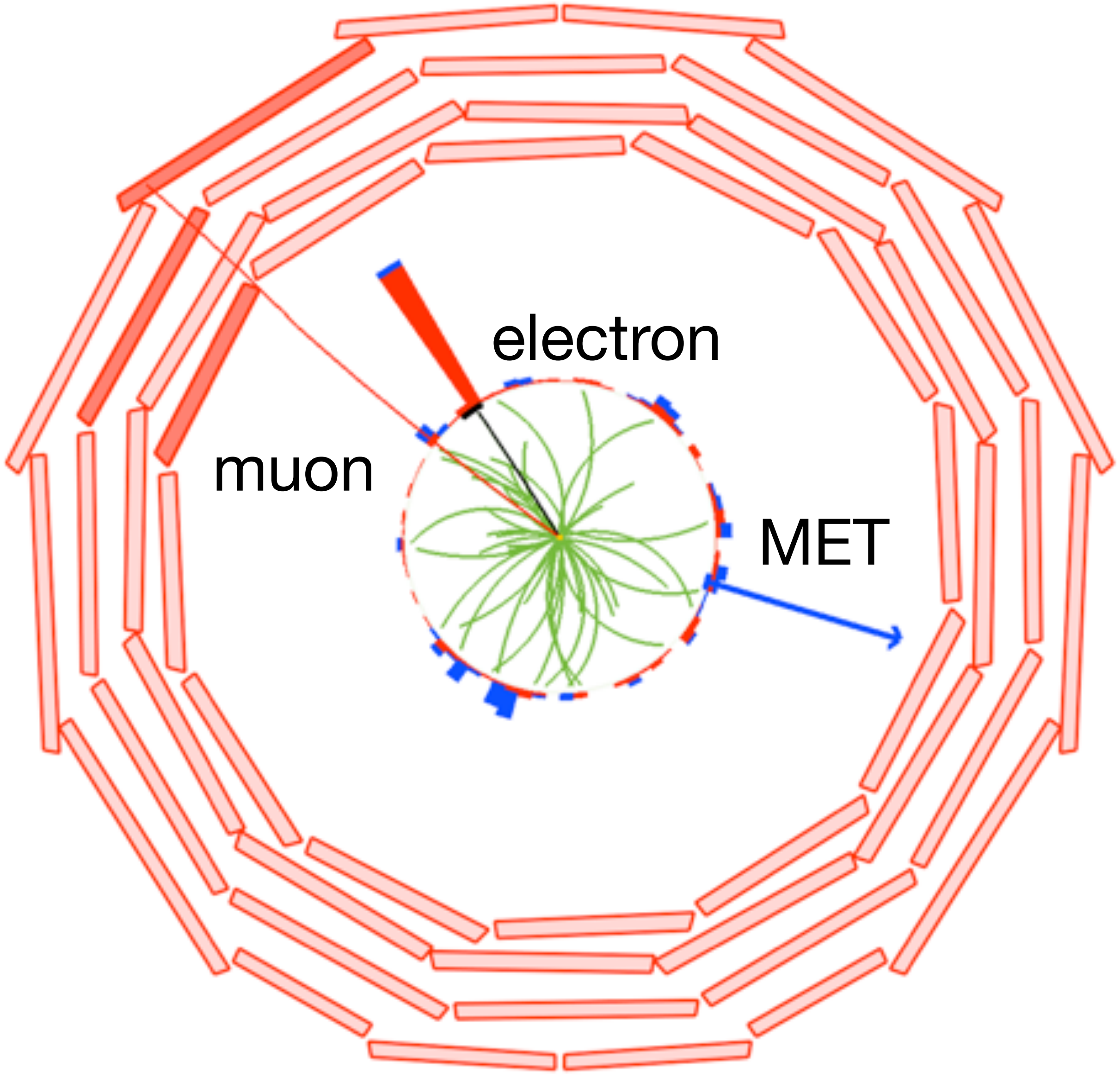


parity violation in weak interactions:



Charged leptons are close in angle!
(For spin 2, the W spins would be parallel, the charged leptons would be in opposite direction -> large angles!)

The Spin of the New Boson



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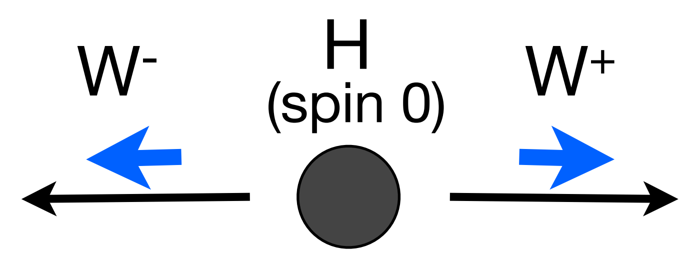

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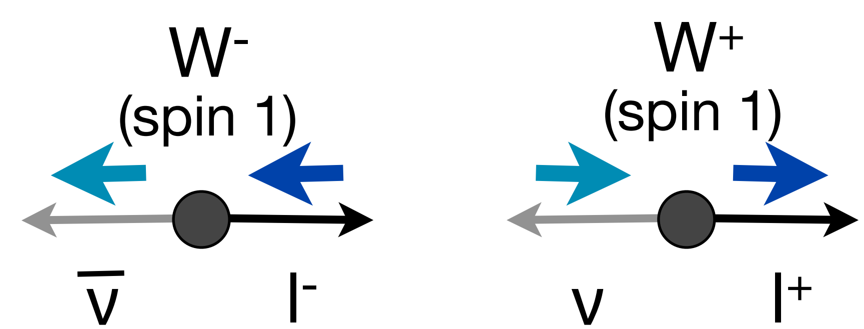
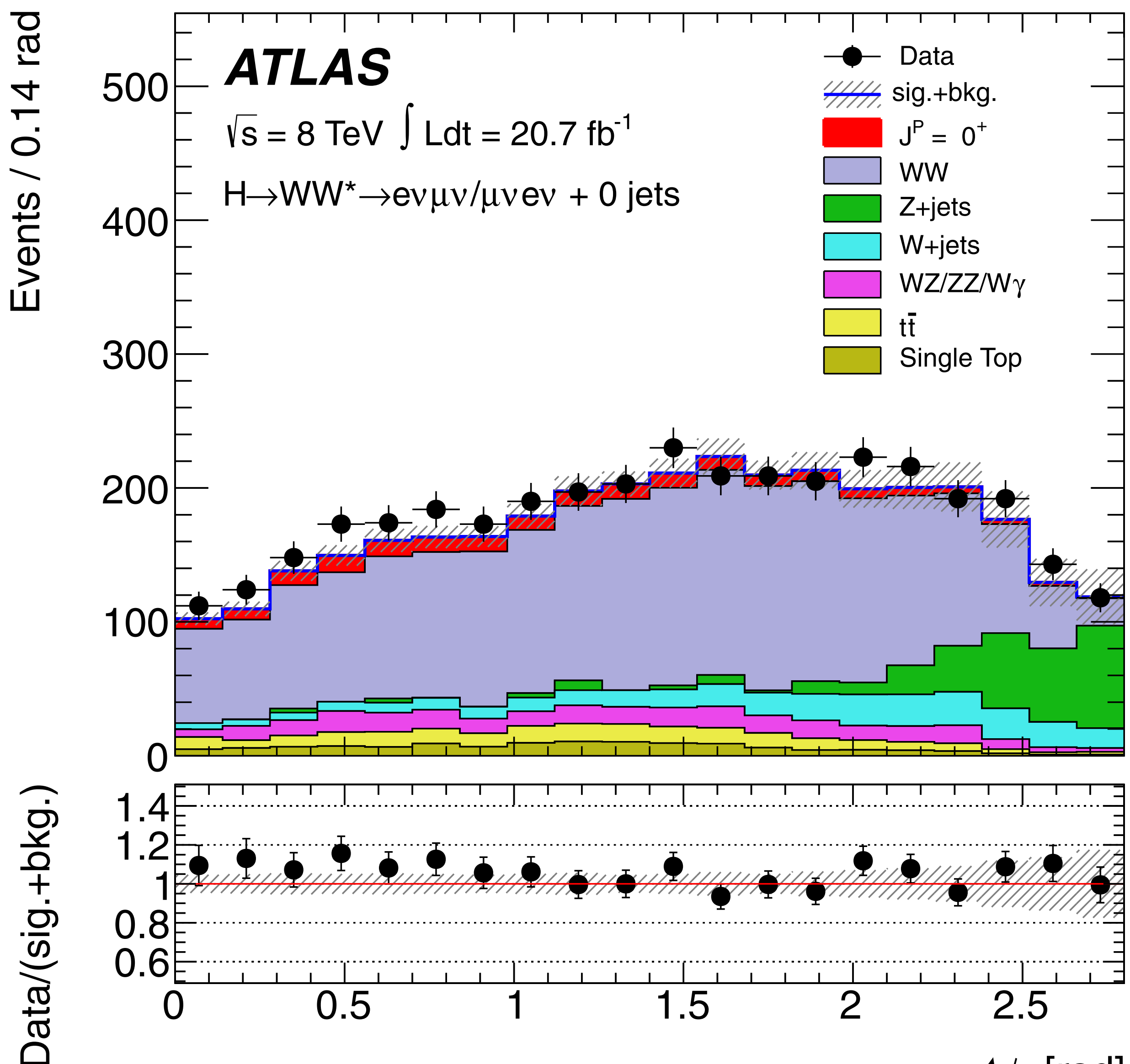
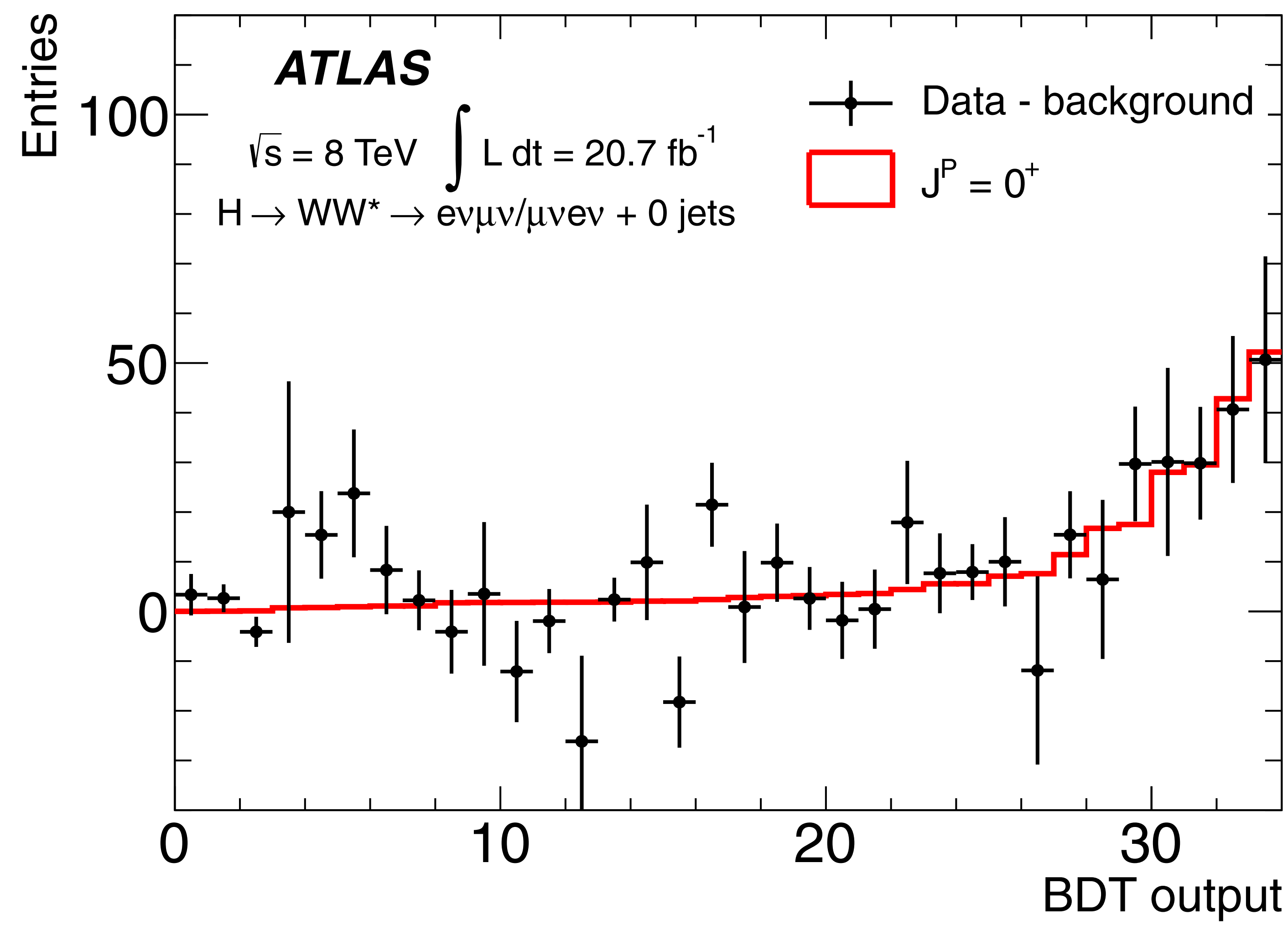


A word of caution: The requirements for large MET and also small opening angle between the leptons in the analysis disfavors event selection for spin ≠ 0

Charged leptons are close in angle! (For spin 2, the W spins would be parallel, the charged leptons would be in opposite direction -> large angles!)

The Spin in WW - ATLAS

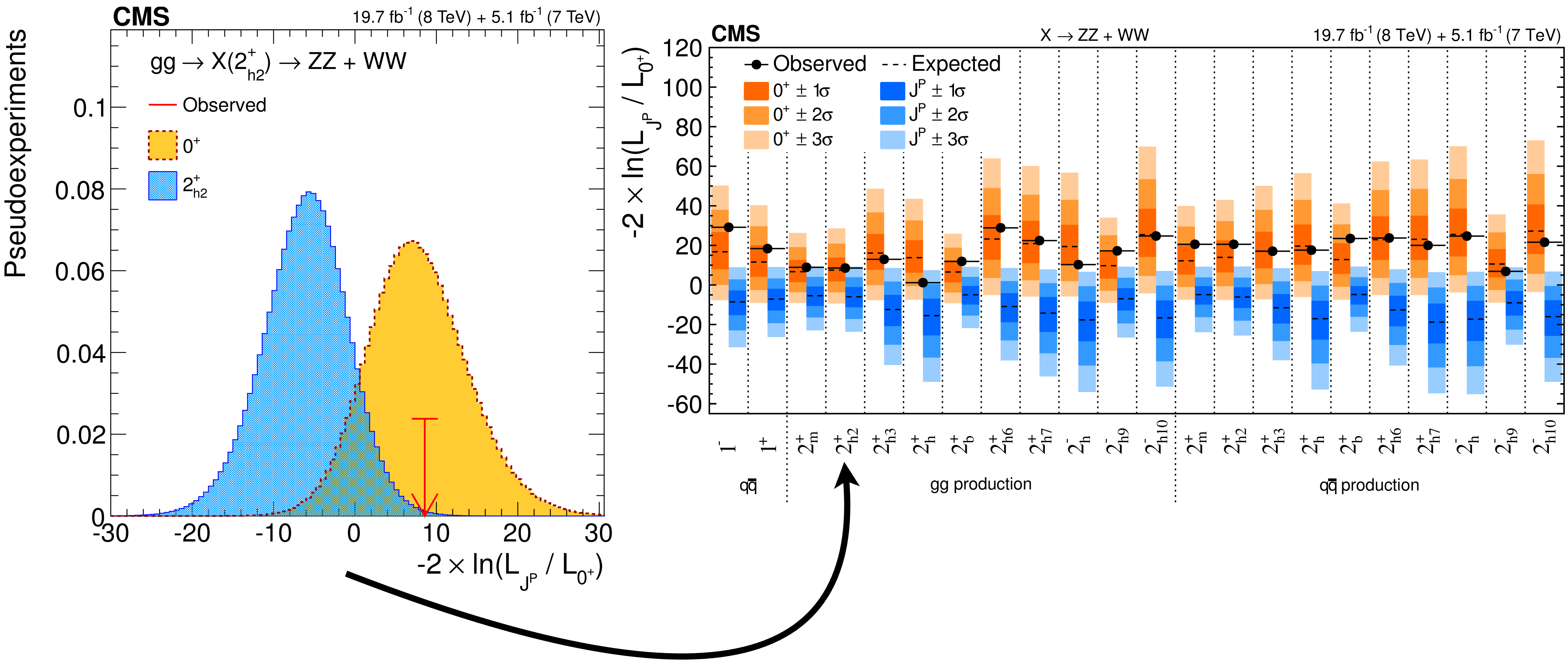




aziuthal angle between leptons

- Not an easy measurement: High background levels
  - 0^+ favored by data, but other hypotheses typically still allowed at the 5 - 10% probability level

The Spin and Parity of the New Boson



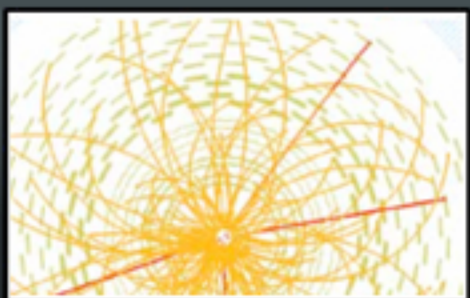
- CMS summary - alternative hypotheses tested compared to 0^+
- 0^+ strongly favored in every case - alternatives typically rejected at > 99% CL
    - only leaves room for small admixtures of other states for composite Higgs models

Summary - The Scientific Breakthrough of 2012

Breakthrough of the Year, 2012

Science

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.



FREE ACCESS

The Discovery of the Higgs Boson

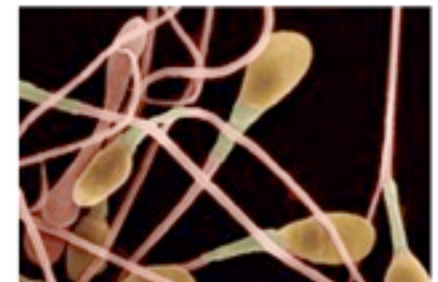
A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

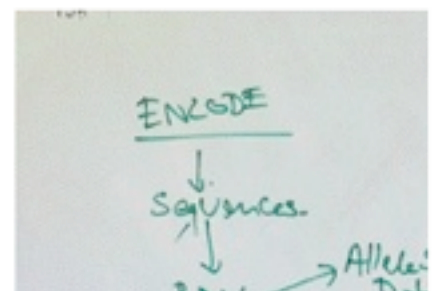
Read more about the Higgs boson from the research teams at CERN.

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

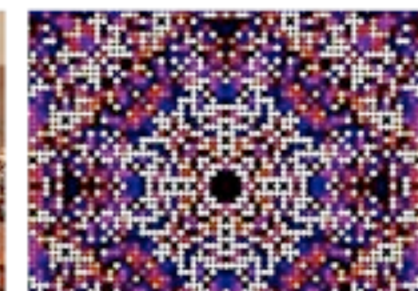

Denisovan Genome


Genome Engineering

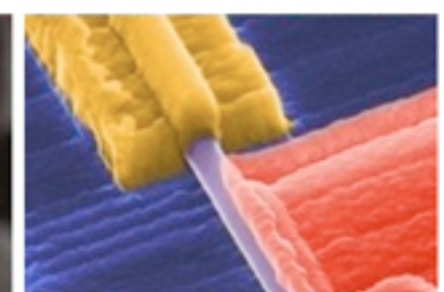

Neutrino Mixing Angle


ENCODE


Curiosity Landing


X-ray Laser Advances


Controlling Bionics


Majorana Fermions


Eggs from Stem Cells

Summary - The Scientific Breakthrough of 2012

Higgs-Boson

Teilchenphysikern gelingt Entdeckung des Jahres

Von Holger Dambeck

AP

So viel Aufregung um ein Partikel war selten: In diesem Jahr haben Forscher endlich das lange gesuchte Higgs-Boson aufgespürt. Die Entdeckung war mühsam und teuer - aber sie hat die Teilchenphysik ein großes Stück vorangebracht. Die Forscher planen bereits das nächste Milliardenexperiment.

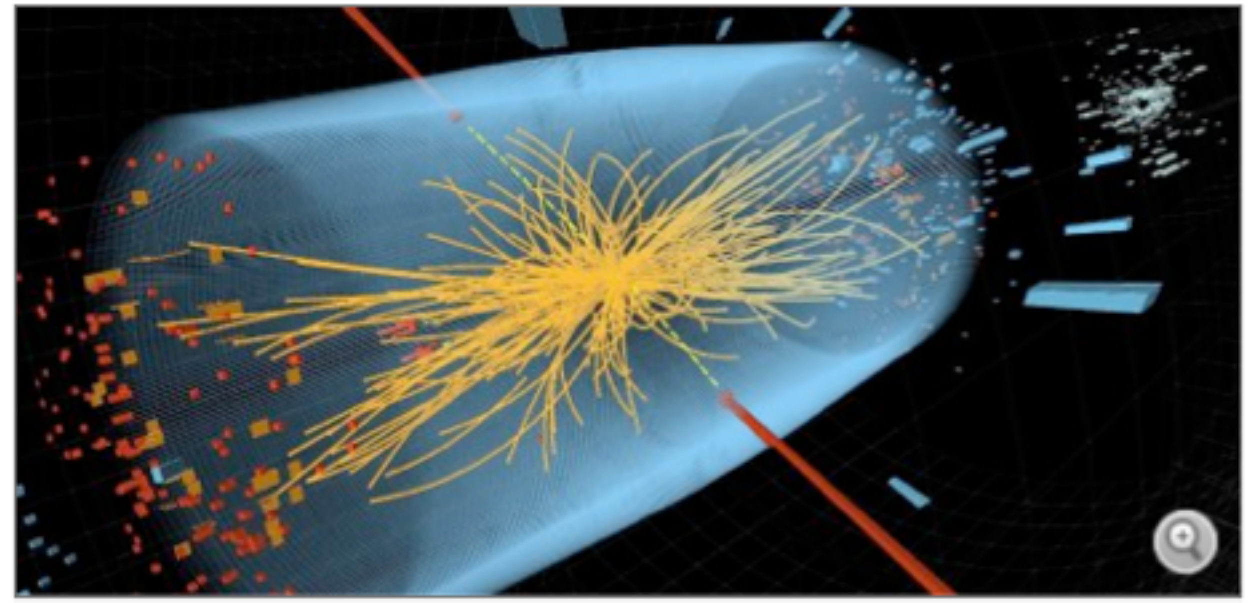
Twittern 1 Empfehlen 14 +1 0

Berlin - Die Protonen machen Winterpause am Kernforschungszentrum in Genf. Ende Dezember steht der weltgrößte Teilchenbeschleuniger LHC still. Wo in den vergangenen Jahren fast ununterbrochen Milliarden Protonen nahezu mit Lichtgeschwindigkeit aufeinander prallten, legen nun Mechaniker Hand an. Die größte Experimentiermaschine der Welt wird gewartet.

2012 war ohne Zweifel das erfolgreichste Jahr für die Teilchenphysiker am Cern. Sie haben gefunden, wonach sie schon lange suchen: das ominöse Teilchen, das sie Higgs-Boson nennen. Es gilt als Beweis für die Existenz des sogenannten Higgs-Felds, das Materie Masse verleiht. Das Wissenschaftsmagazin "Science" hat den Fund des neuen Partikels zum wissenschaftlichen Durchbruch des Jahres gekürt.

Wissenschaft 2012

Das Jahr des Gottesteilchens



EPA/CERN/DPA

Partikel-Kollision (Grafik): Die Suche nach dem Higgs-Boson war 2012 erfolgreich

Das Higgs-Boson ist entdeckt, der Rover "Curiosity" auf dem Mars gelandet, Bluttests erlauben Einblicke ins Erbgut von Embryos: Forscher haben 2012 beeindruckende Erfolge gefeiert. Allerdings gab es auch bedrohliche Entwicklungen - insbesondere aus Sicht von Erdbeben- und Klimaforschern.

Twittern 60 Empfehlen 39 +1 3

Selten herrschte in der Forschergemeinde eine so große Einigkeit über den Durchbruch des Jahres: Der Nachweis des Higgs-Bosons, landläufig auch Gottesteilchen genannt, überstrahlte 2012 alle anderen wissenschaftlichen Erfolge - zumindest in der Öffentlichkeit.

Spiegel Online

Summary

- A new boson has been discovered at the LHC by ATLAS and CMS
  - The significance of the observation is by now beyond 7σ in both experiments, the γγ channel has surpassed 7 σ in ATLAS - single channel discovery!
  - The mass of the new boson is ~125.1 GeV
  - Its properties are so far consistent with those for the SM Higgs boson:
    - Spin 0, even Parity favored
    - Production rate and observed decays match expectations

- The exploration of this fundamentally new sector of matter has only just begun:
  - Still large uncertainties on all measurements leave room for surprises
  - Many models of New Physics lead to modifications of expected Higgs properties
  - A lot still to come from LHC, and new colliders currently in planning (more in the last lecture in this series)

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Next Lecture: Supersymmetry, S. Bethke, 11.01.2016

Attention!

No lecture next week!

Zeitplan

1.	Introduction	12.10.
2.	Particle Detectors I	19.10.
3.	Particle Detectors II	26.10.
4.	Accelerators	02.11.
5.	Trigger, Data Acquisition, Computing	09.11.
6.	Monte Carlo Generators and Detector Simulation	16.11.
7.	Tests of the Standard Model	23.11.
8.	QCD, Jets, Proton Structure	30.12.
9.	Higgs Physics I	07.12.
10.	Higgs Physics II	14.12.
	----------- no lecture -------------	21.12.
	----------- Christmas ---------------------	
11.	Supersymmetry	11.01.
12.	Top Physics	18.01.
13.	Other models beyond the SM	25.01
14.	Future Collider Projects	01.02