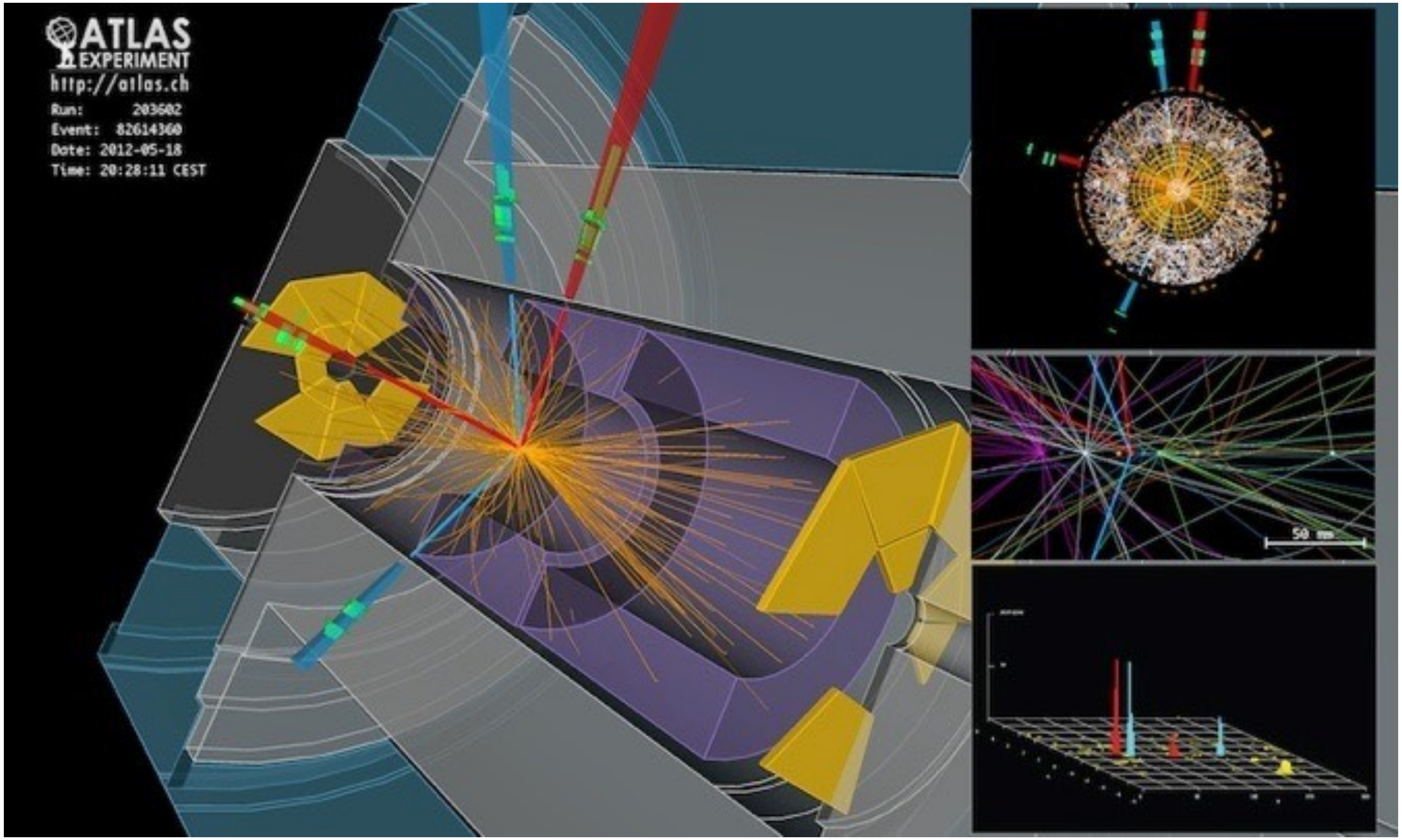
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



12. Higgs Discovery at the LHC

22.01.2018

… and the theoretical foundations

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

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

Overview

- Theoretical foundations: What you missed last week, courtesy of Deutsche Bahn

- 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

The SM Higgs Boson - Theoretical Basis

- gauge field theory with ***gauge symmetry*** in weak isospin/hyper charge [SU(2) x U(1)] to describe electromagnetic and weak interactions of quarks and leptons:

  includes ***massless*** gauge bosons (γ, Z0, W+, W–) and fermions
- any attempt to include ***mass terms*** breaks gauge symmetry and ***destroys renormalizabilty*** of the theories

The SM Higgs Boson - Theoretical Basis

- The solution:
  Englert, Brout and Higgs (1964): ***spontaneous symmetry breaking***
  (generates mass, keeps renormalizabilty):
  - introduction of complex SU(2) doublets of scalar fields with a potential of V(ϕ) = λ (ϕ+ϕ)2 - μ2 ϕ+ϕ ; with λ, μ2 > 0 ;

$$\phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

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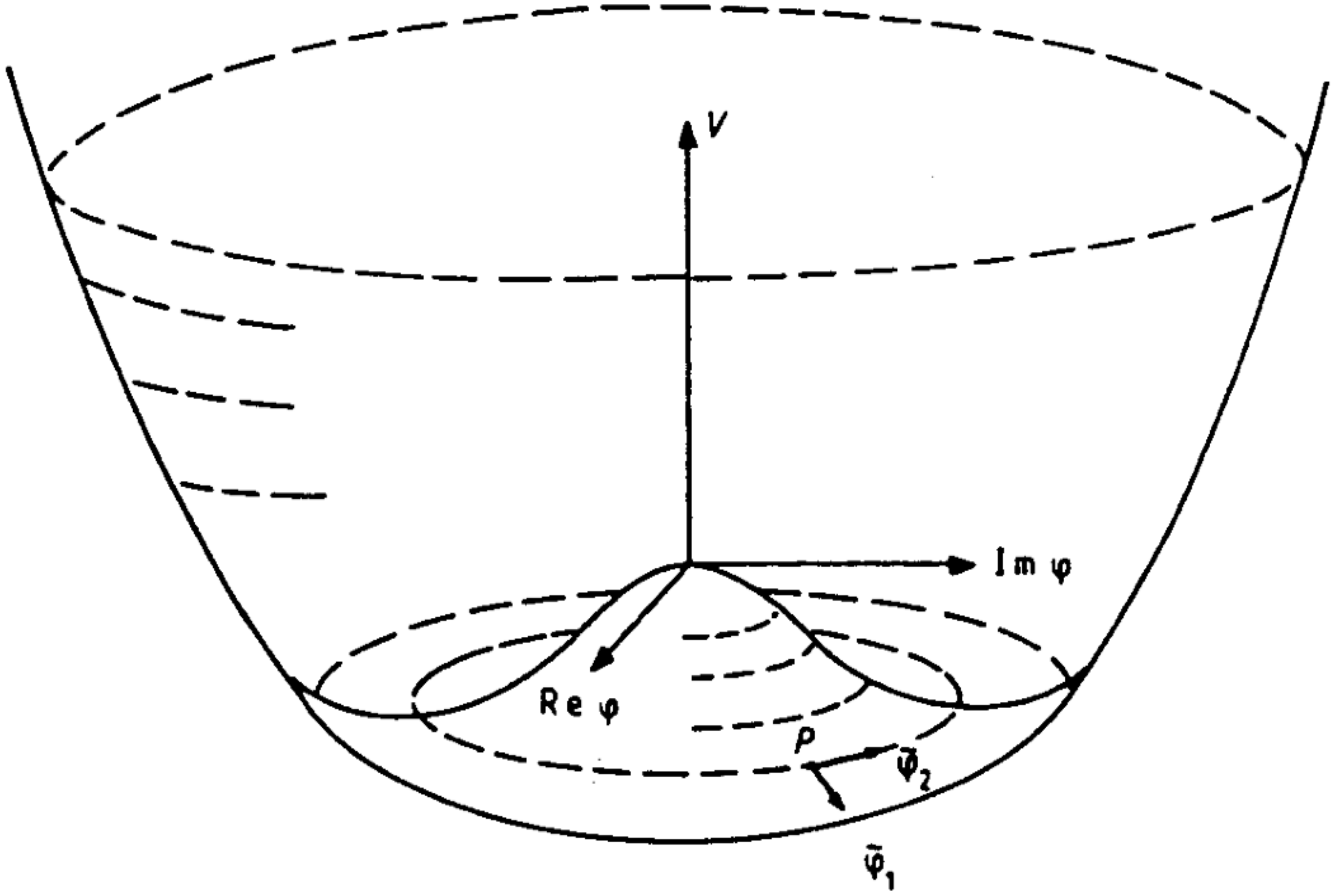

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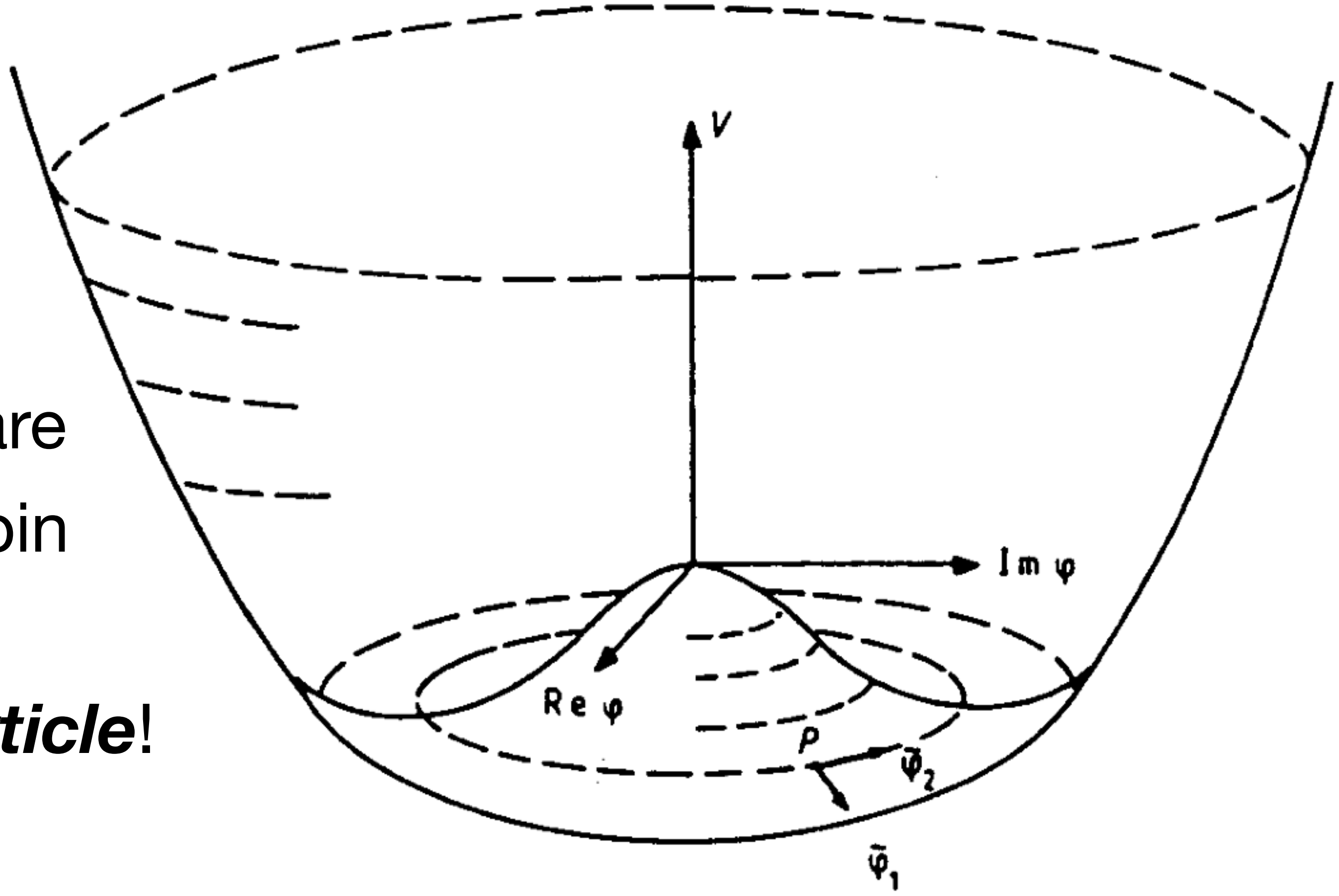
  - 3 of the 4 real degrees of freedom are used to generate the longitudinal spin d.o.f. of Z^0 and $W^\pm$
    The 4. d.o.f. –> ***physical Higgs particle***!



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Frank Simon (fsimon@mpp.mpg.de)

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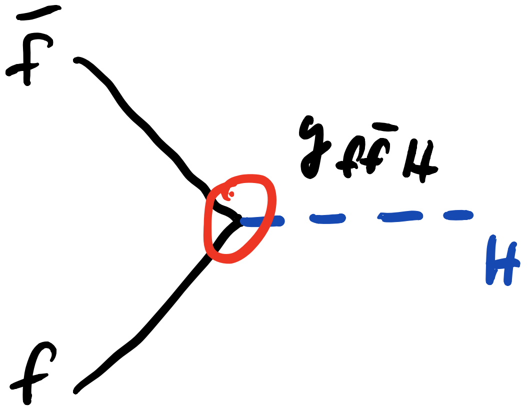
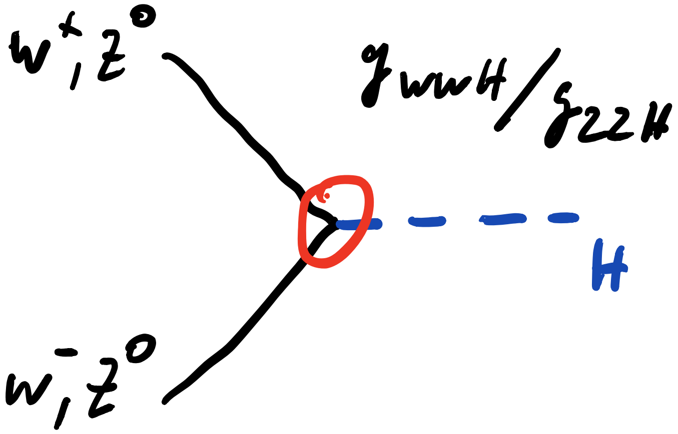
- fundamental coupling of the Higgs to fermions and bosons:



$$g_{f\bar{f}H} = \frac{e\, m_f}{2M_W \sin\theta_w}$$



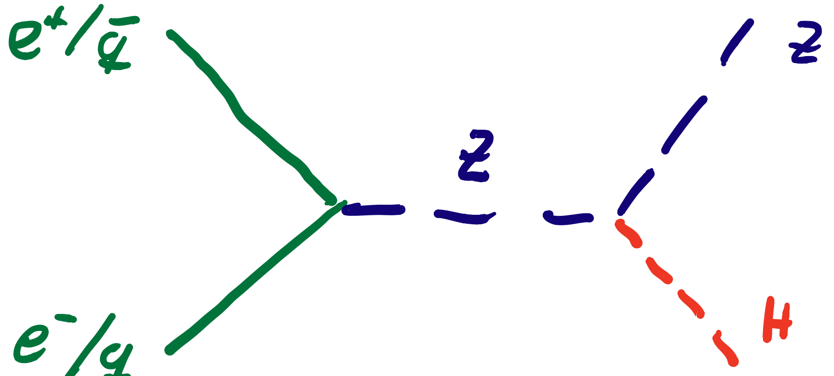
$$g_{WWH} = \frac{e\, M_W}{\sin\theta_w}$$

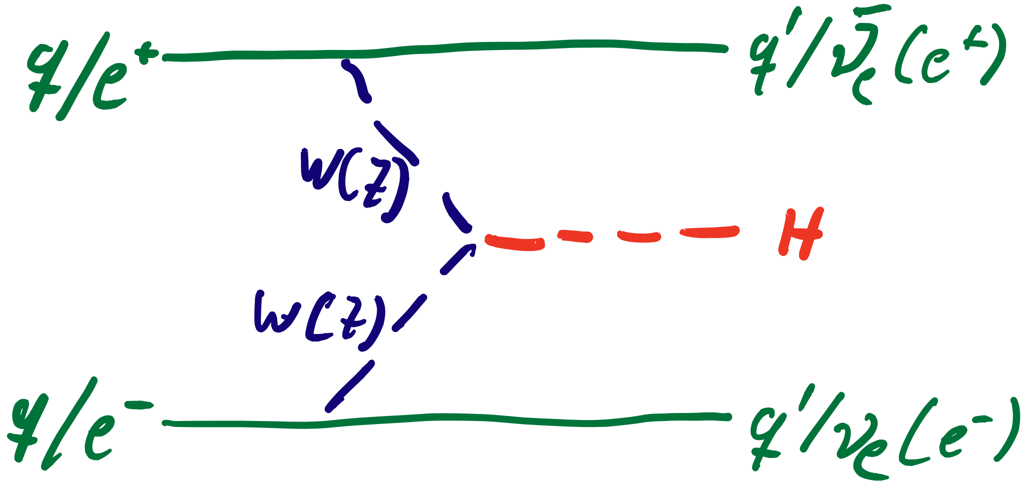
$$g_{ZZH} = \frac{e\, M_Z}{\sin\theta_w \cos\theta_w}$$

The SM Higgs Boson: Production

- Production and decay options given by the couplings

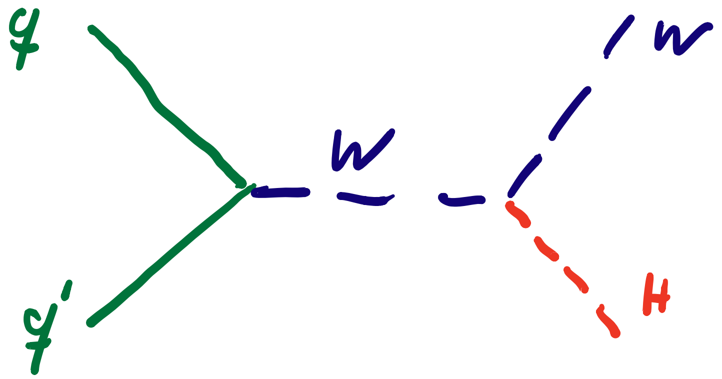
  Leading production processes:

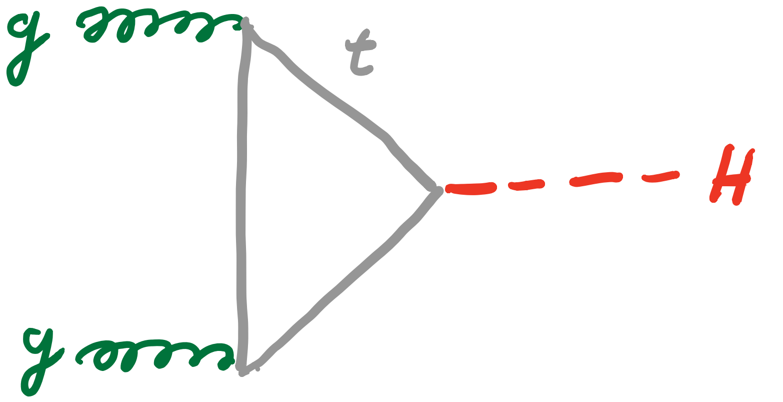




Higgsstrahlung / associated production

Vector Boson Fusion (VBF)



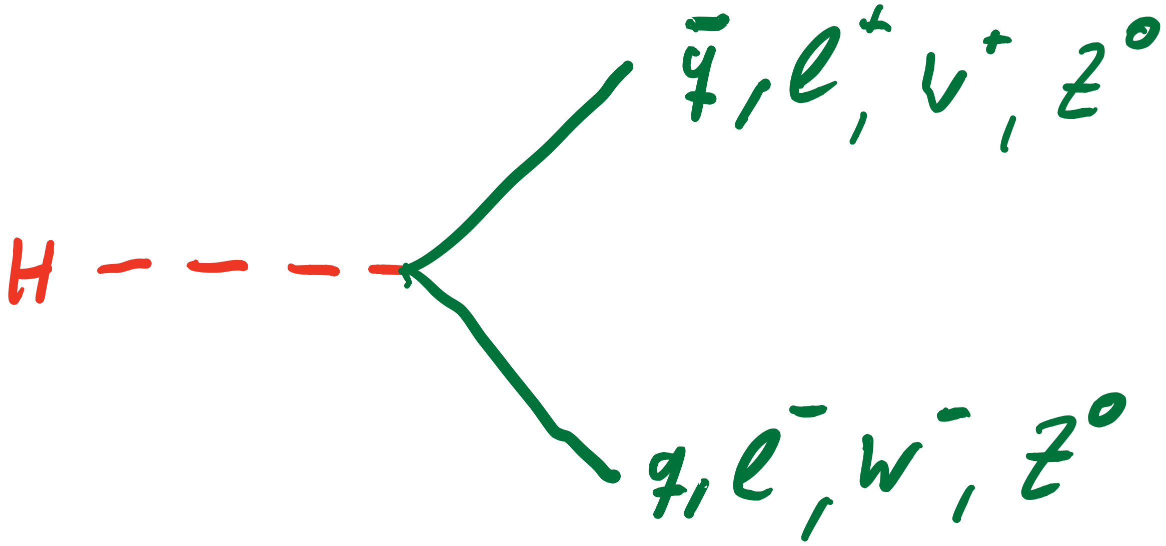


Gluon Fusion

The SM Higgs Boson: Decay

- Production and decay options given by the couplings

Tree-level processes:

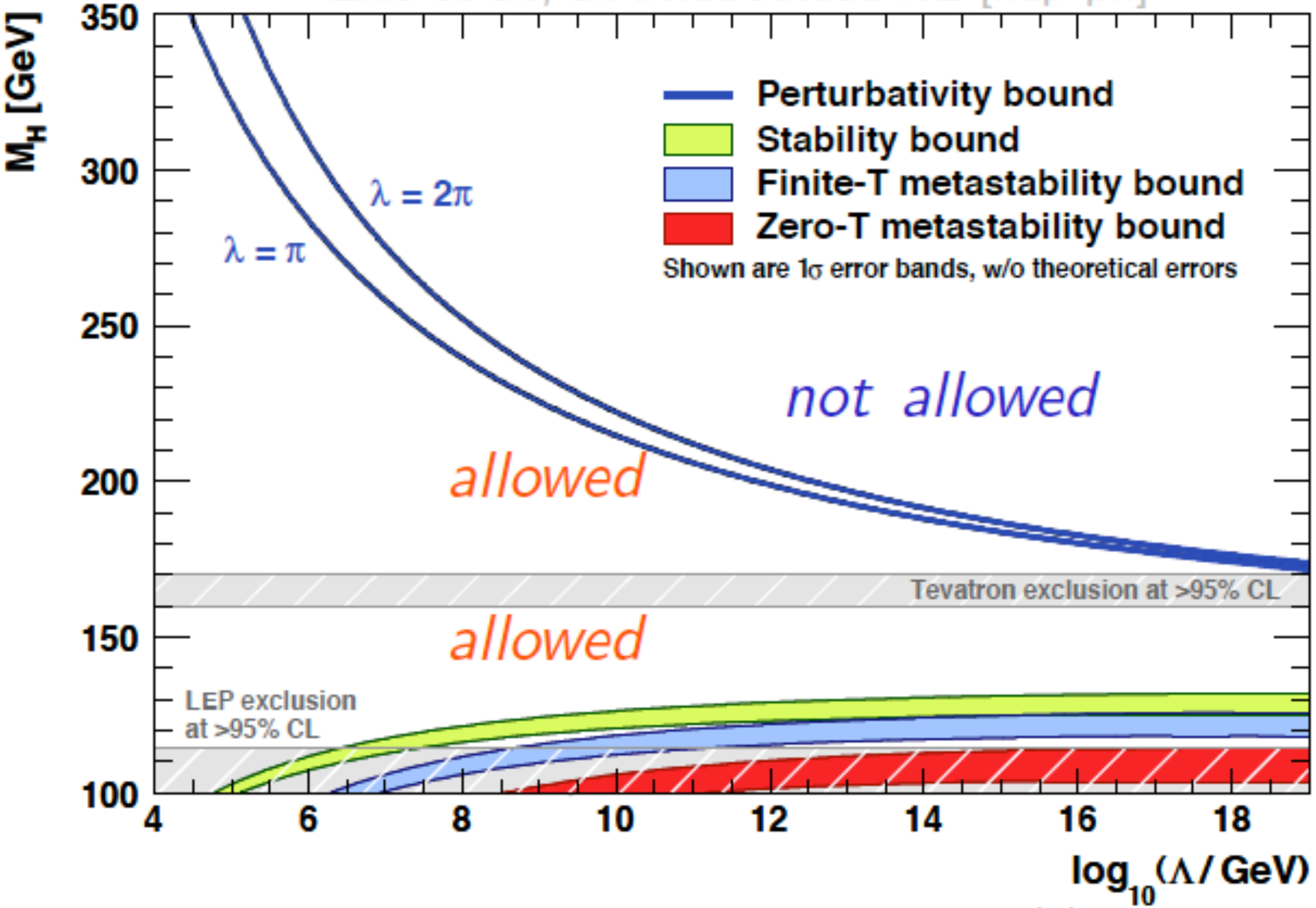


predominantly into the heaviest kinematically accessible pair of fermions or bosons

The only Unknown: The Mass of the Higgs Boson

- theoretical bounds for MH from self-consistency arguments of the Standard-Model:
- upper bound: perturbativity
- lower bound: vacuum stability

Ellis et al., arXiv:0906.0954v2 [hep-ph]



validity scale of the Standard Model (Λ)

Λ: energy scale up to which SM is valid

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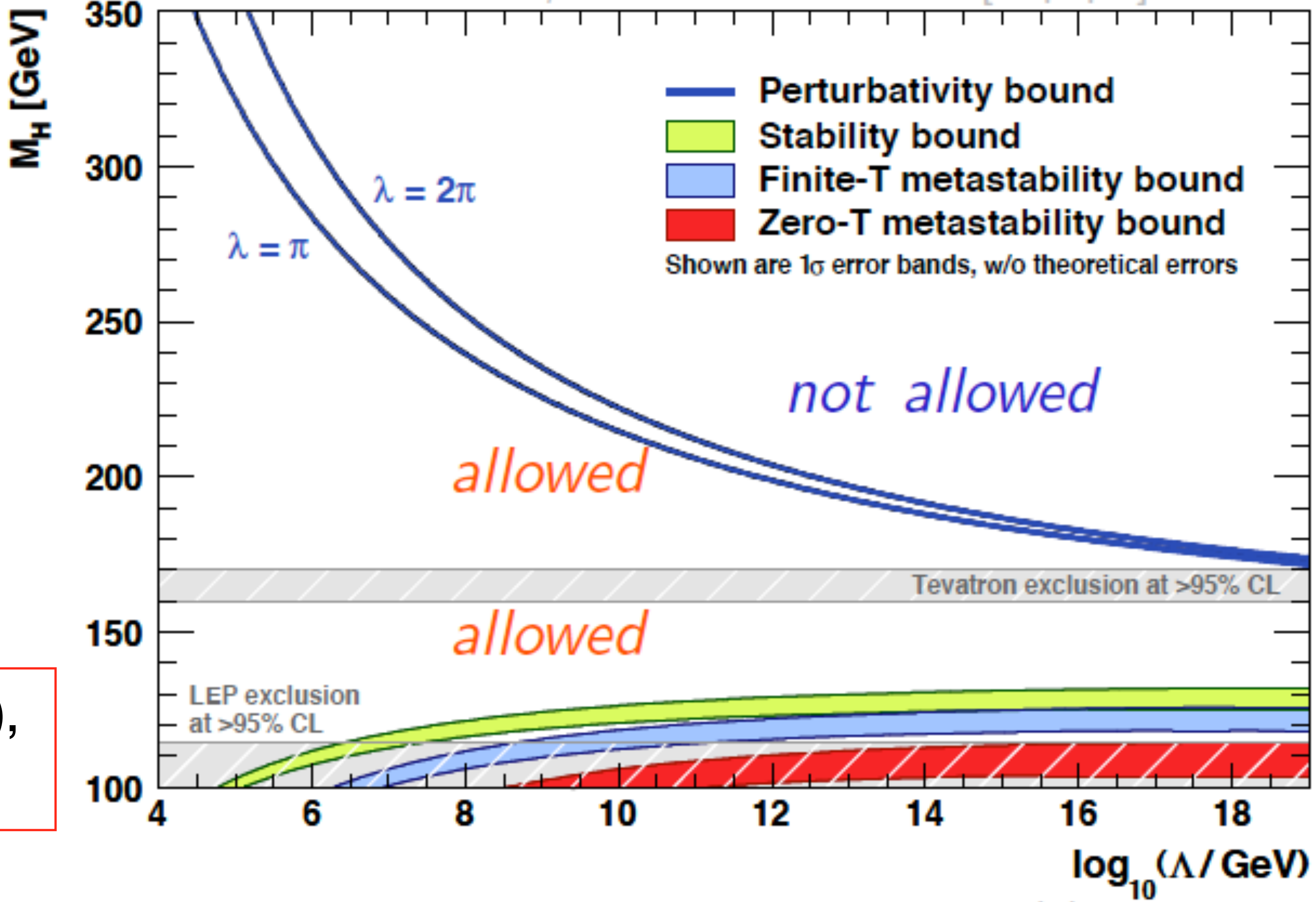

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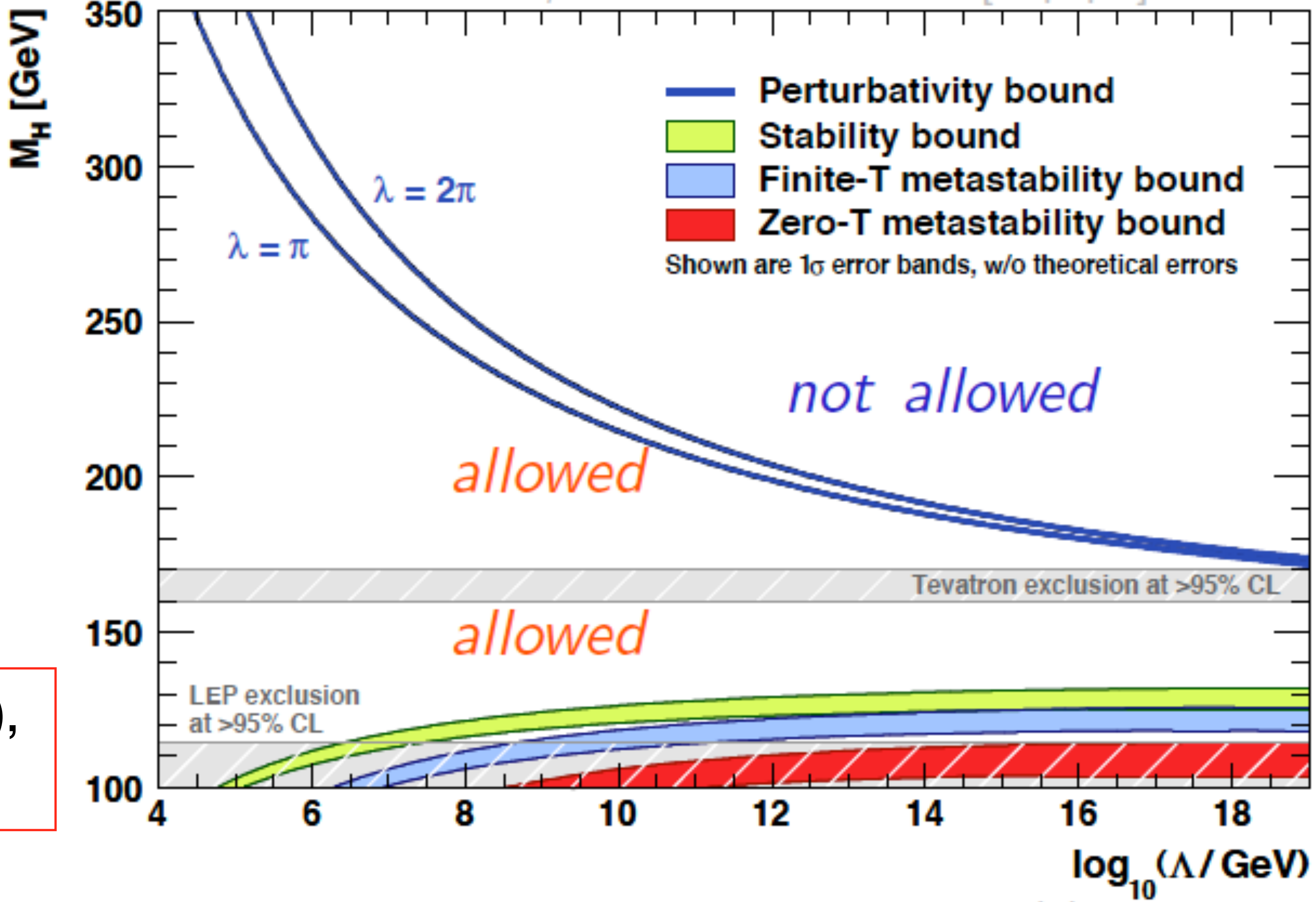


validity scale of the Standard Model (Λ)

If SM is valid only up to Λ = O(1 TeV), then M_H = 50 ... 1000 GeV

If SM is valid up to Λ = O(M_{Planck}) then M_H ~ 125 ... 180 GeV

Λ: energy scale up to which SM is valid

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.)

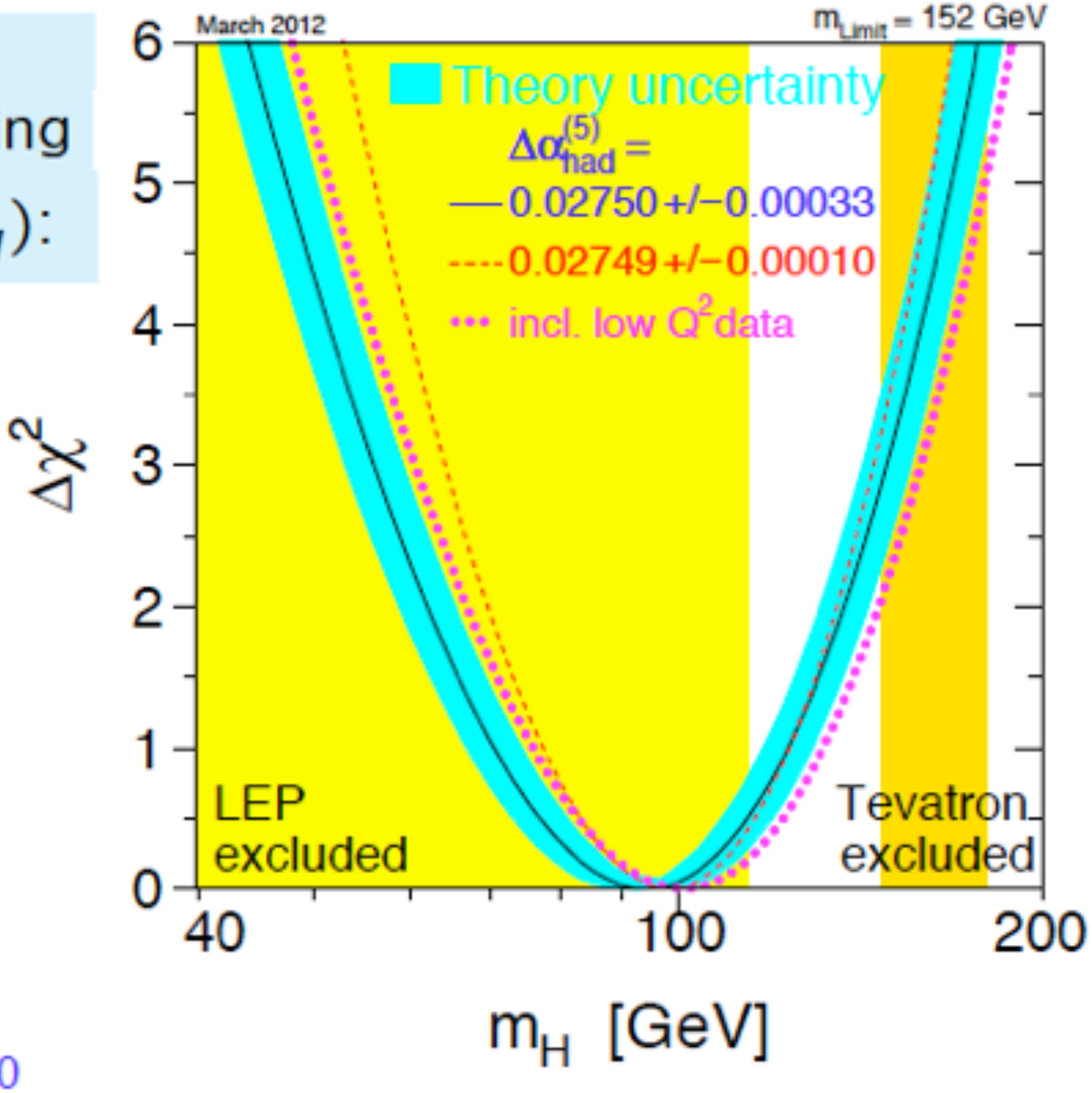
Direct searches at LEP:

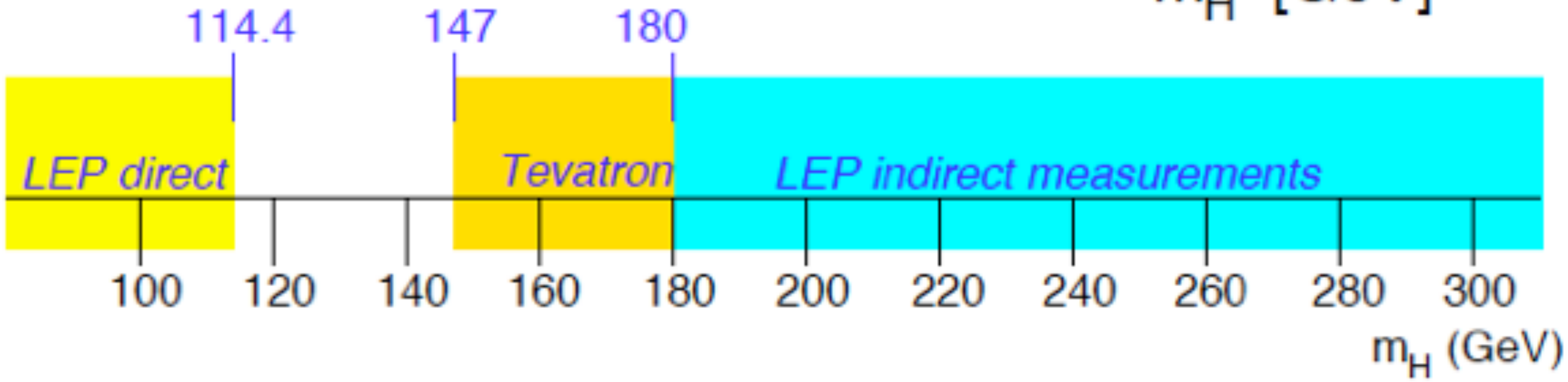
$m_H > 114.4$ GeV at (95% C.L.)

Direct searches at Tevatron:

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

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

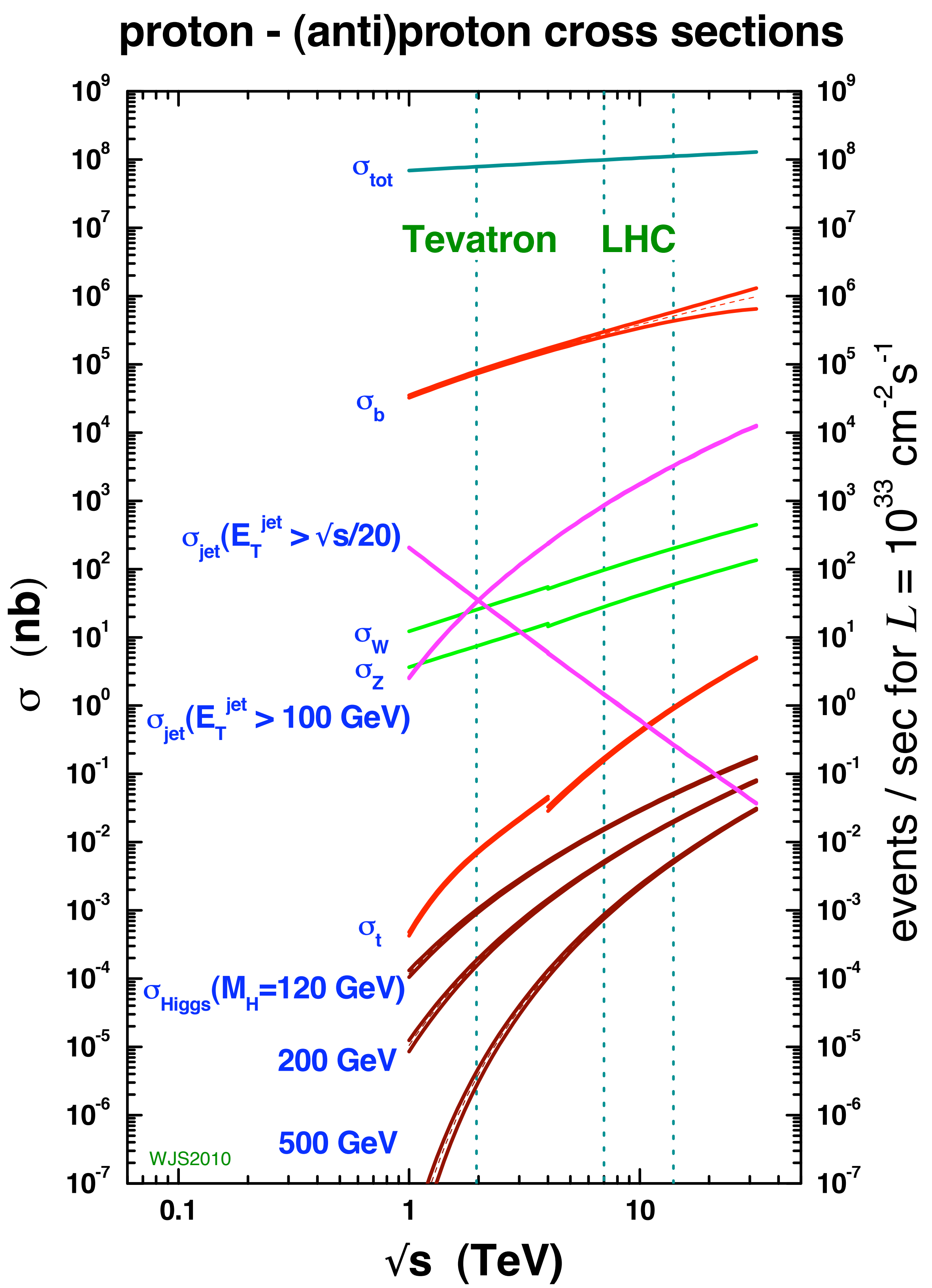




status: 2012

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



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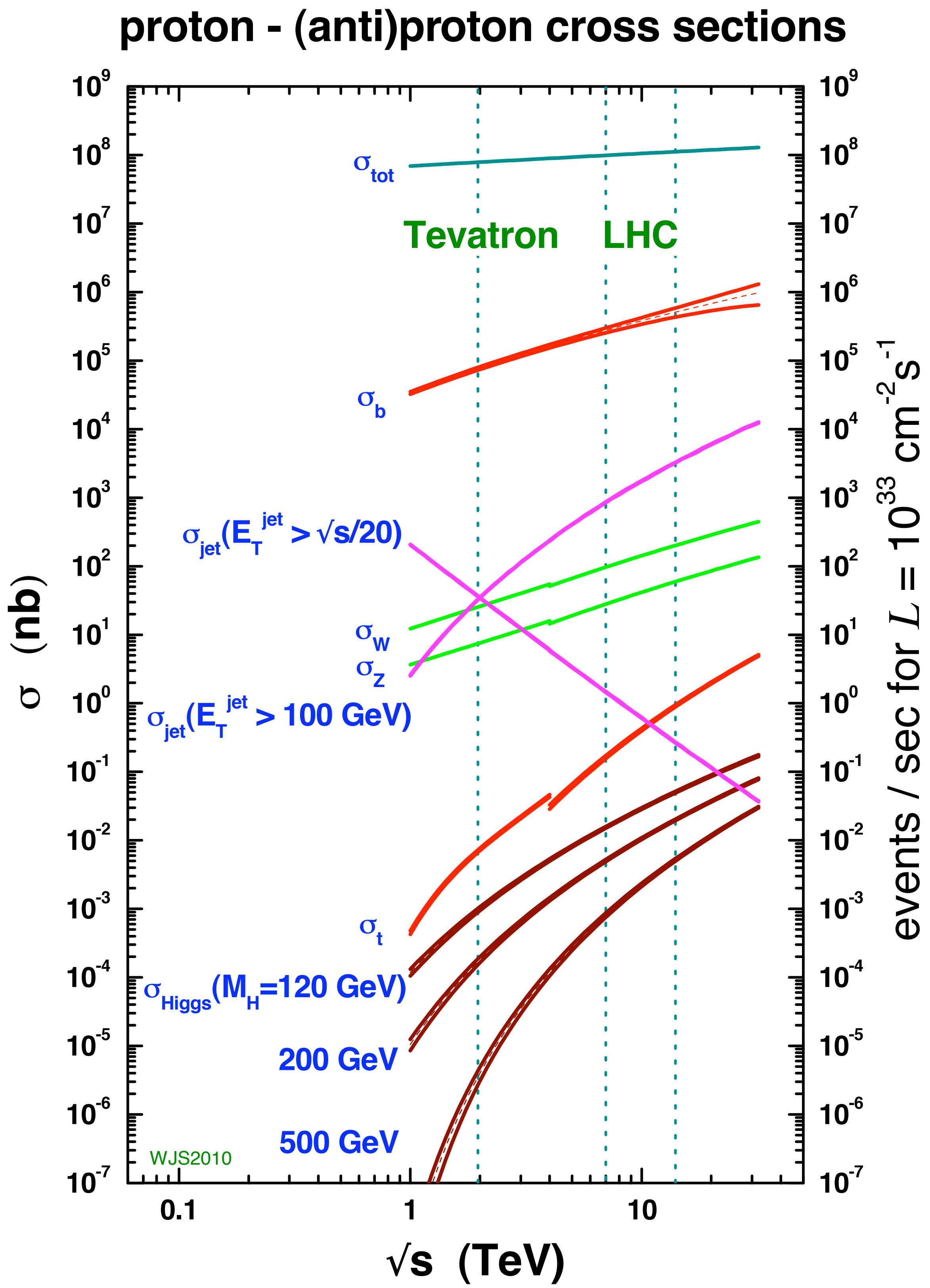
=> Production dominated by gluons!



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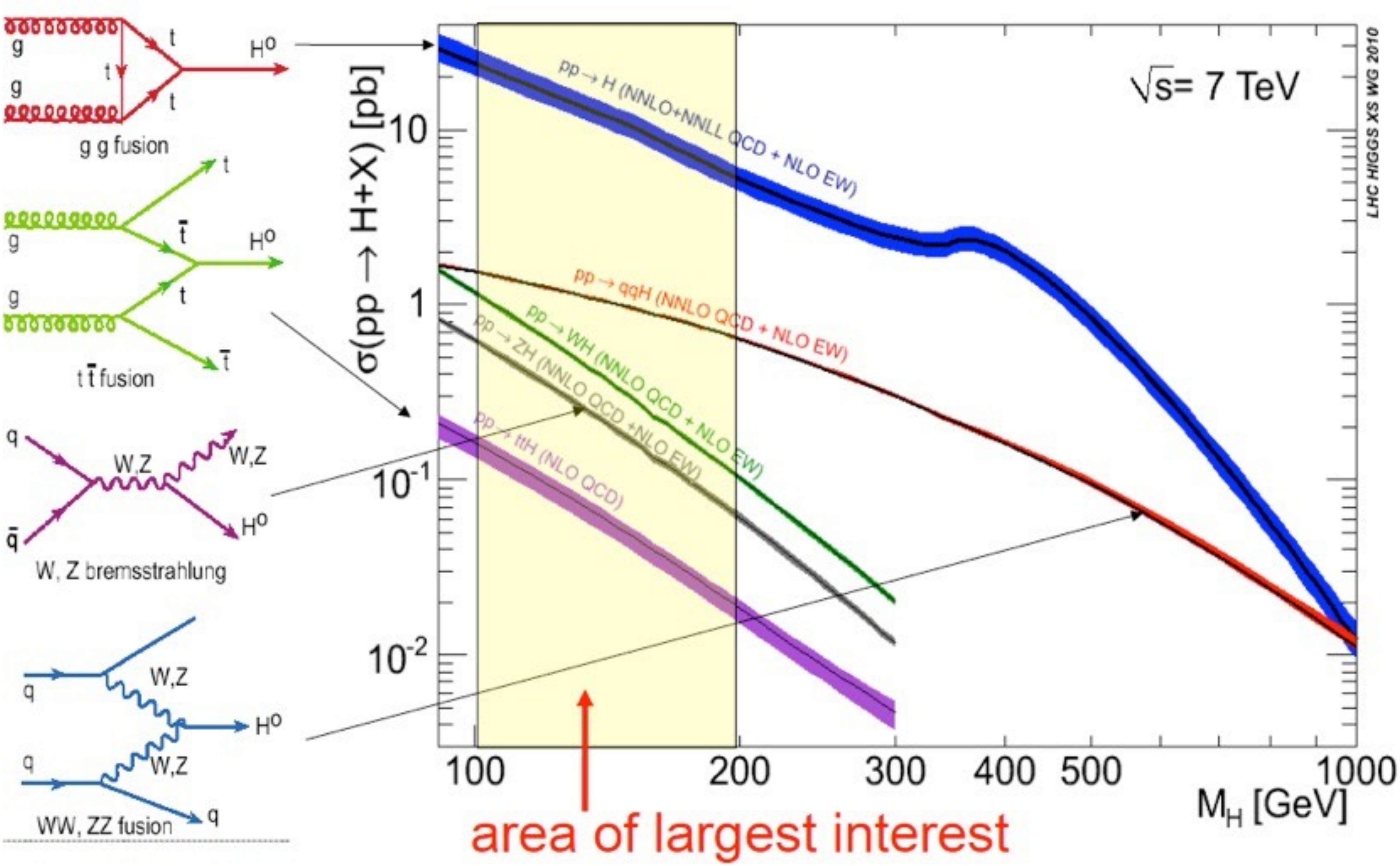
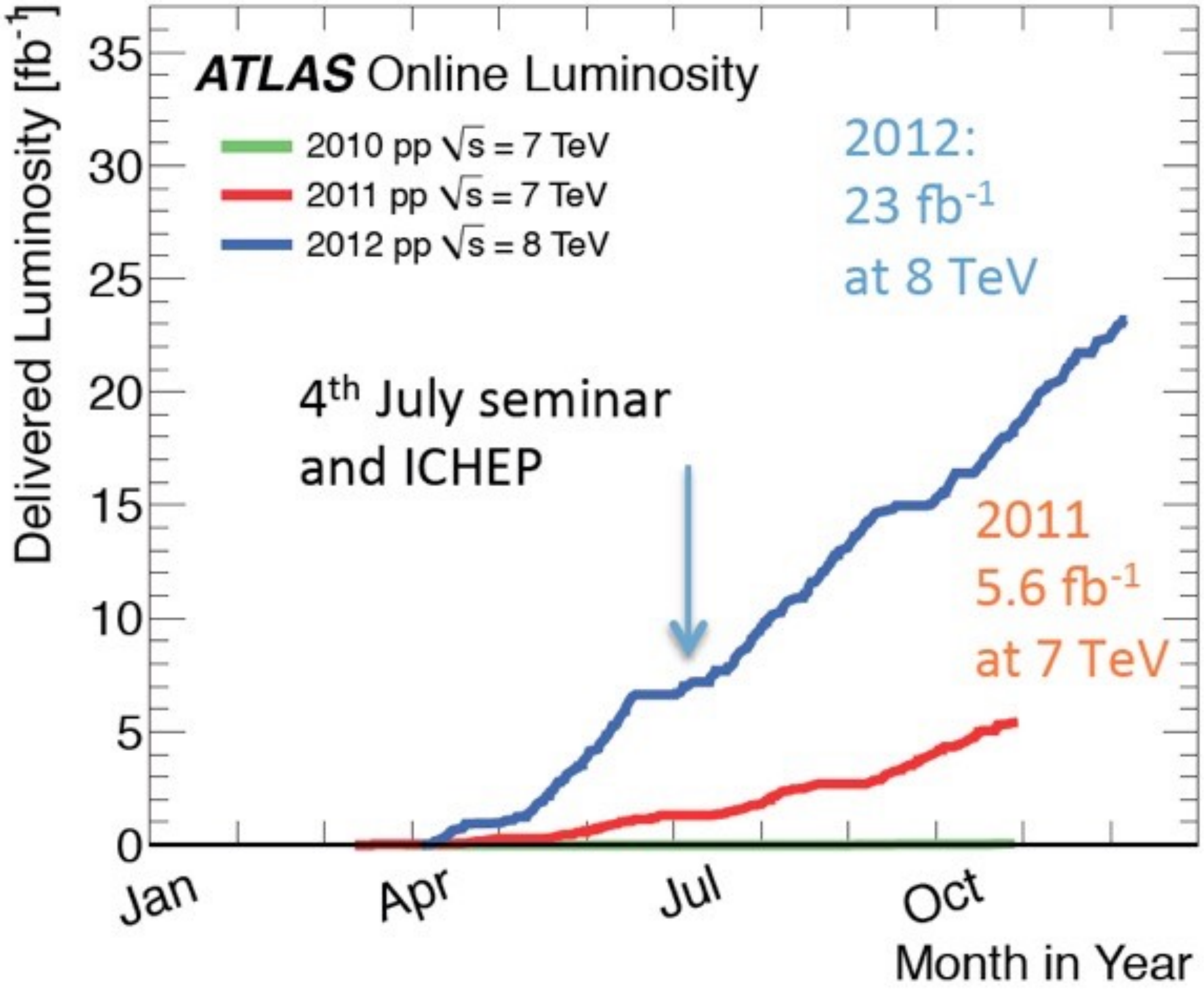


area of largest interest

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

LHC - What we had for the Discovery

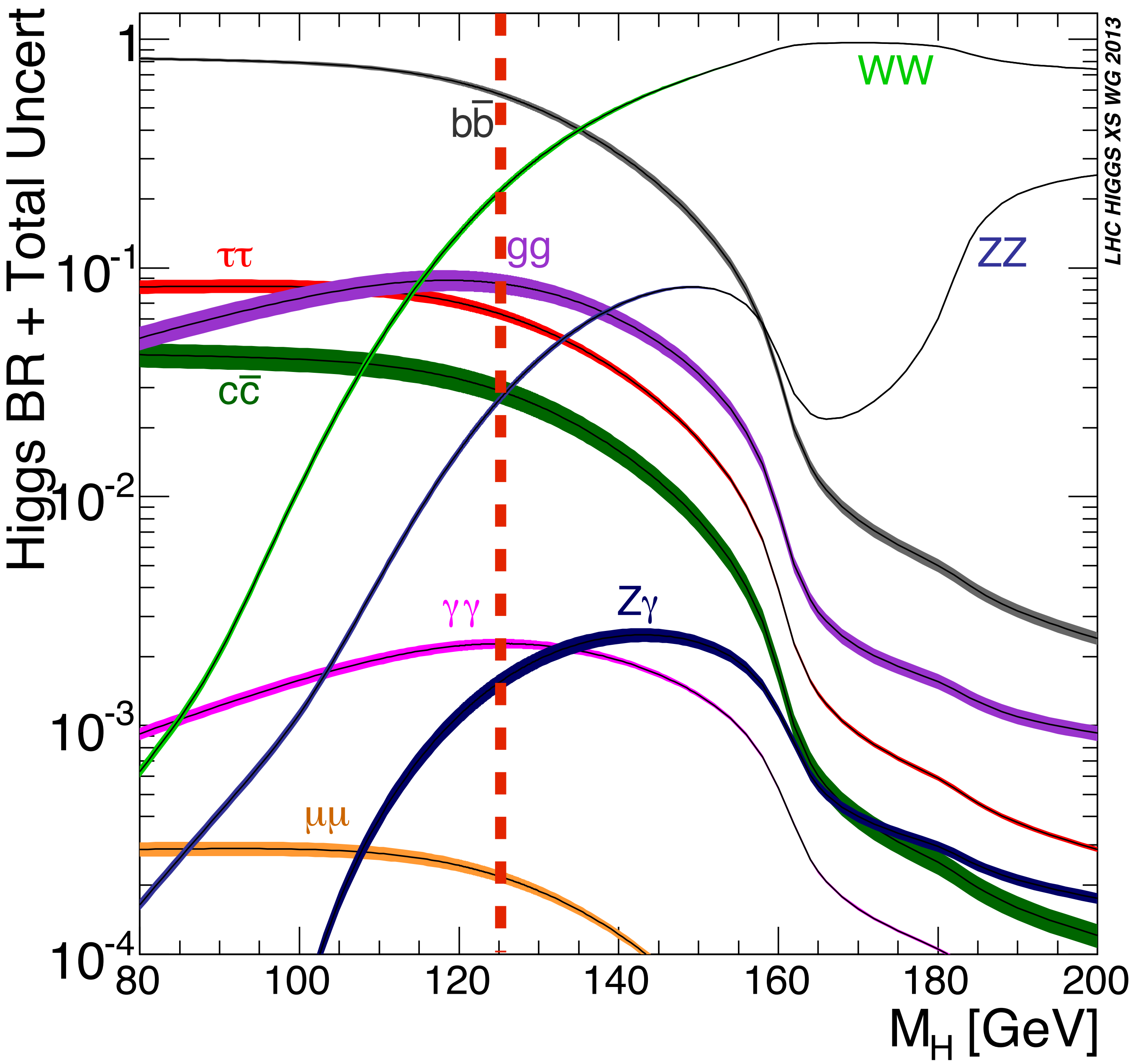


- In 2011: 5.6 fb^{-1} @ 7 TeV
  ~ 100k H produced
  (for a mass of 125 GeV)
- In 2012: 23 fb^{-1} @ 8 TeV
  ~ 500k H produced
  (for a mass of 125 GeV)

NB: No additional data in 2013 and 2014: LHC in shutdown
Since July 2015: 13 TeV,
up to now ~ 90 fb^{-1}

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

Higgs Decay I



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

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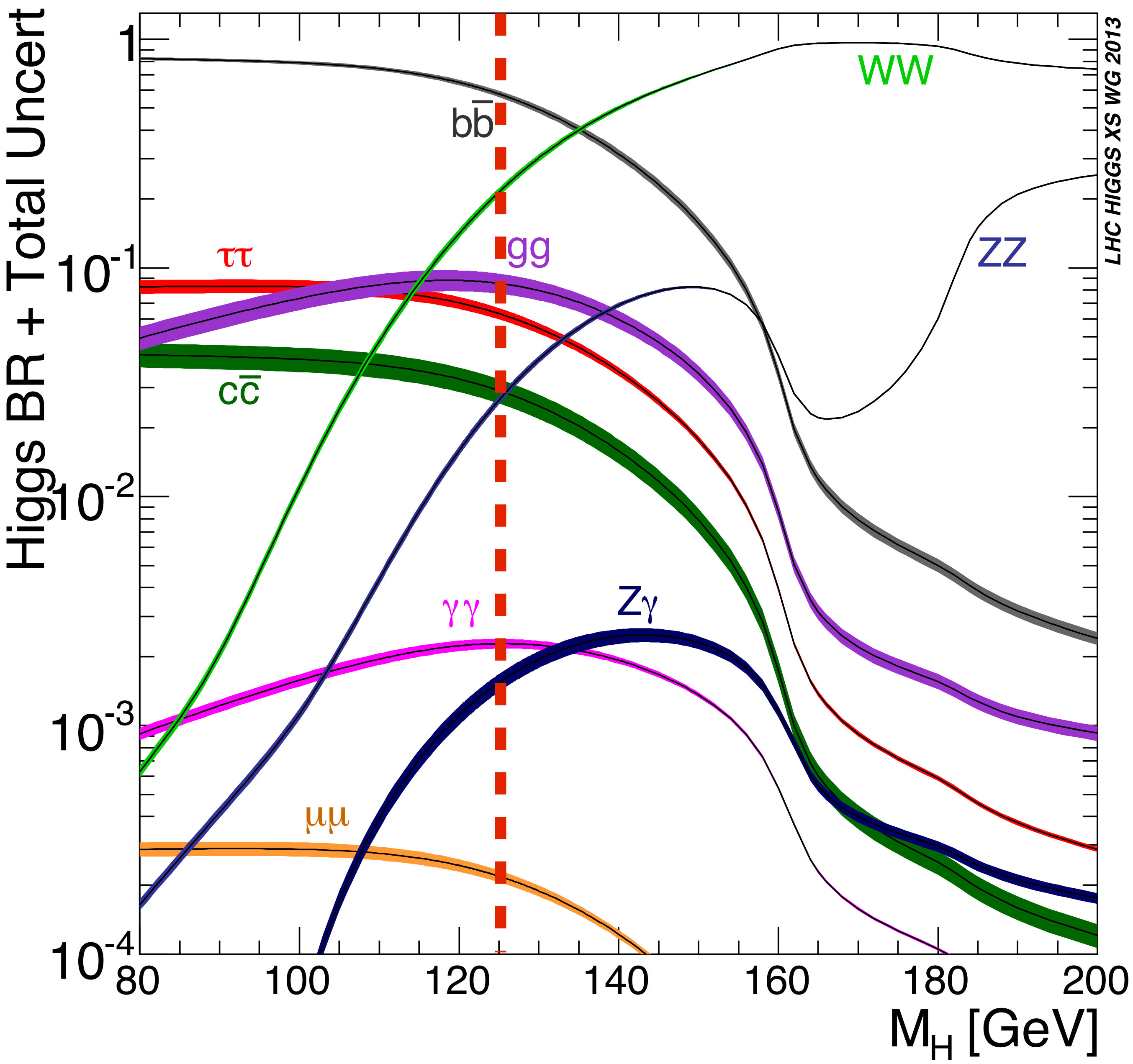

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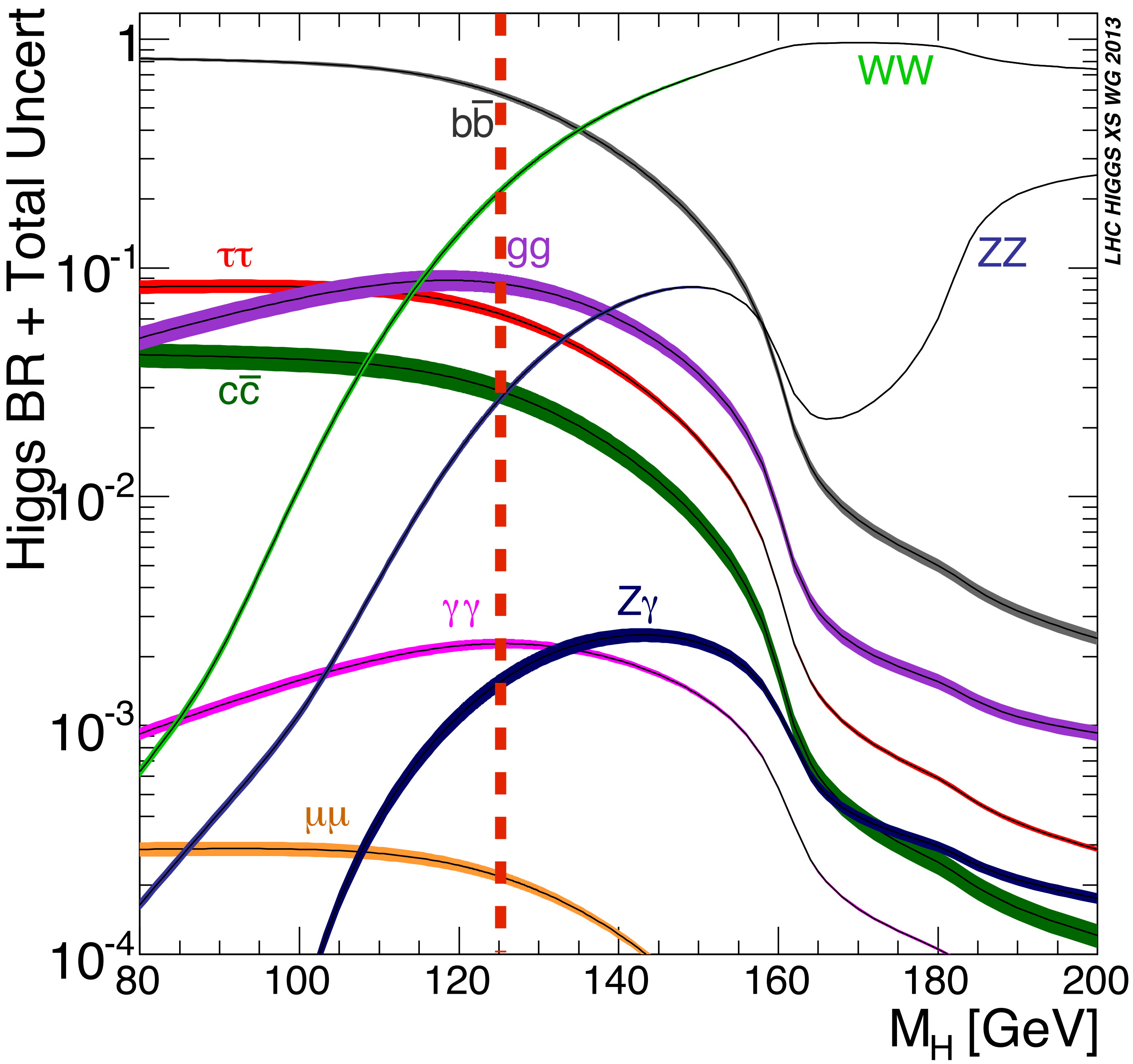

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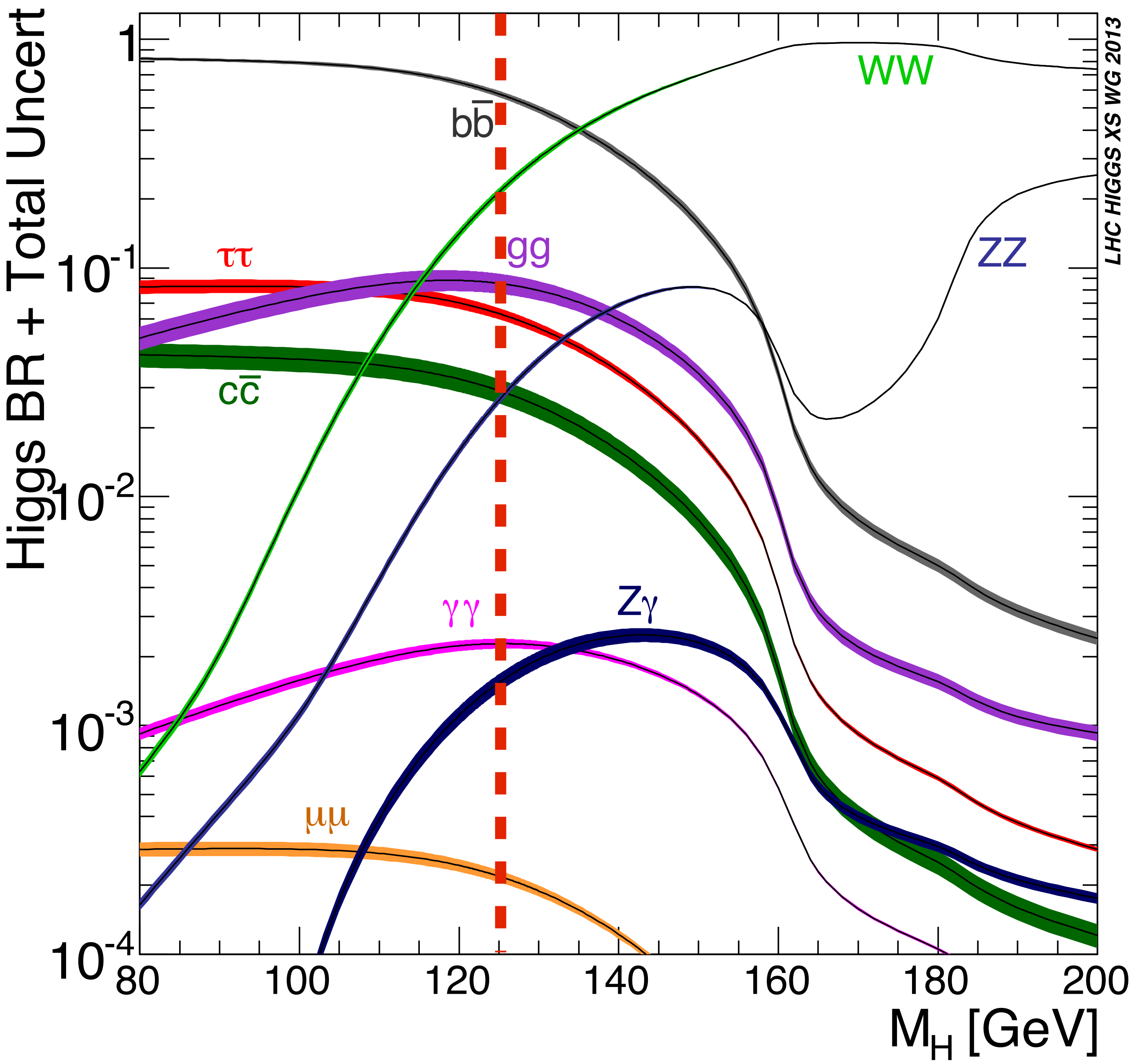

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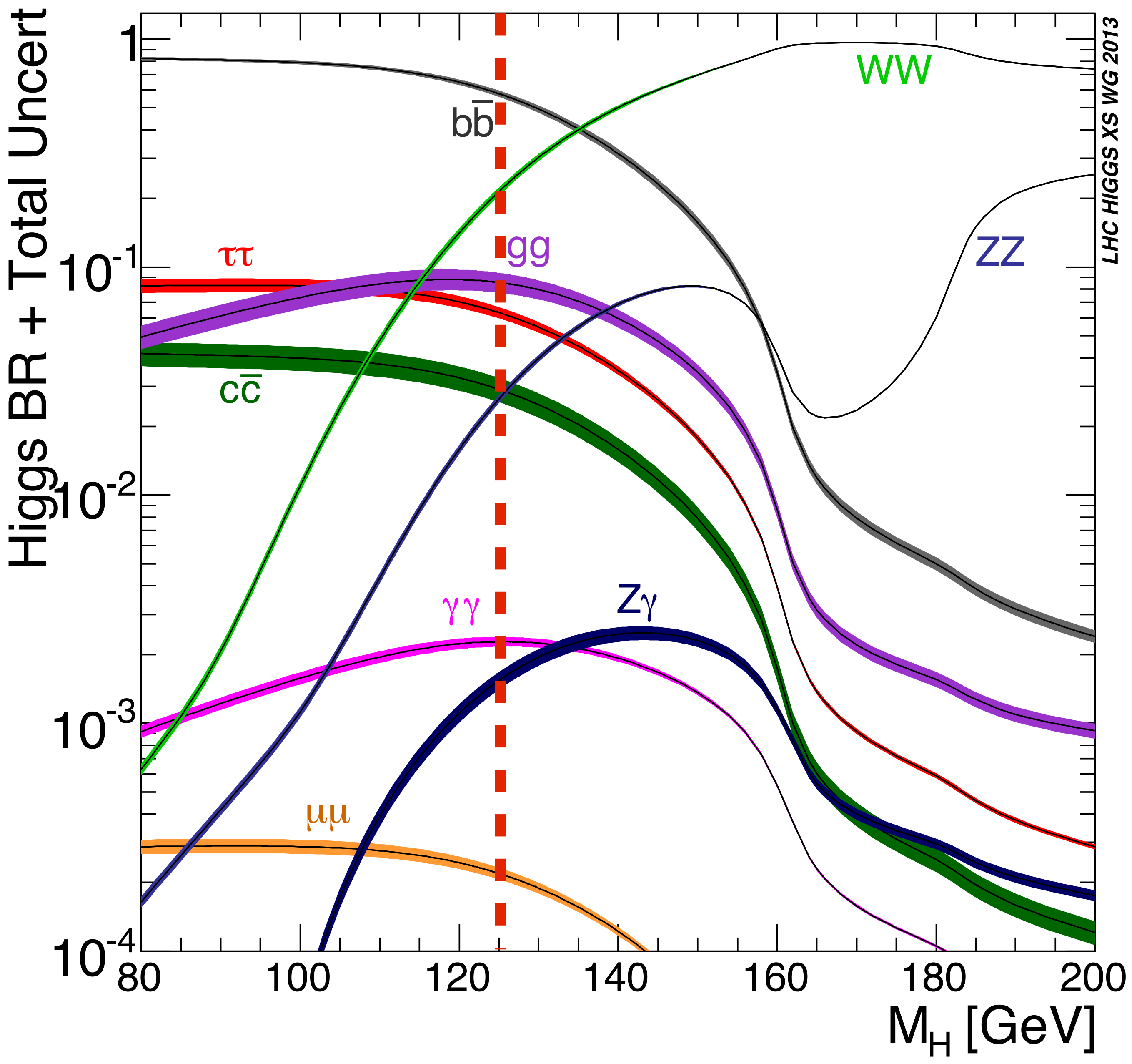

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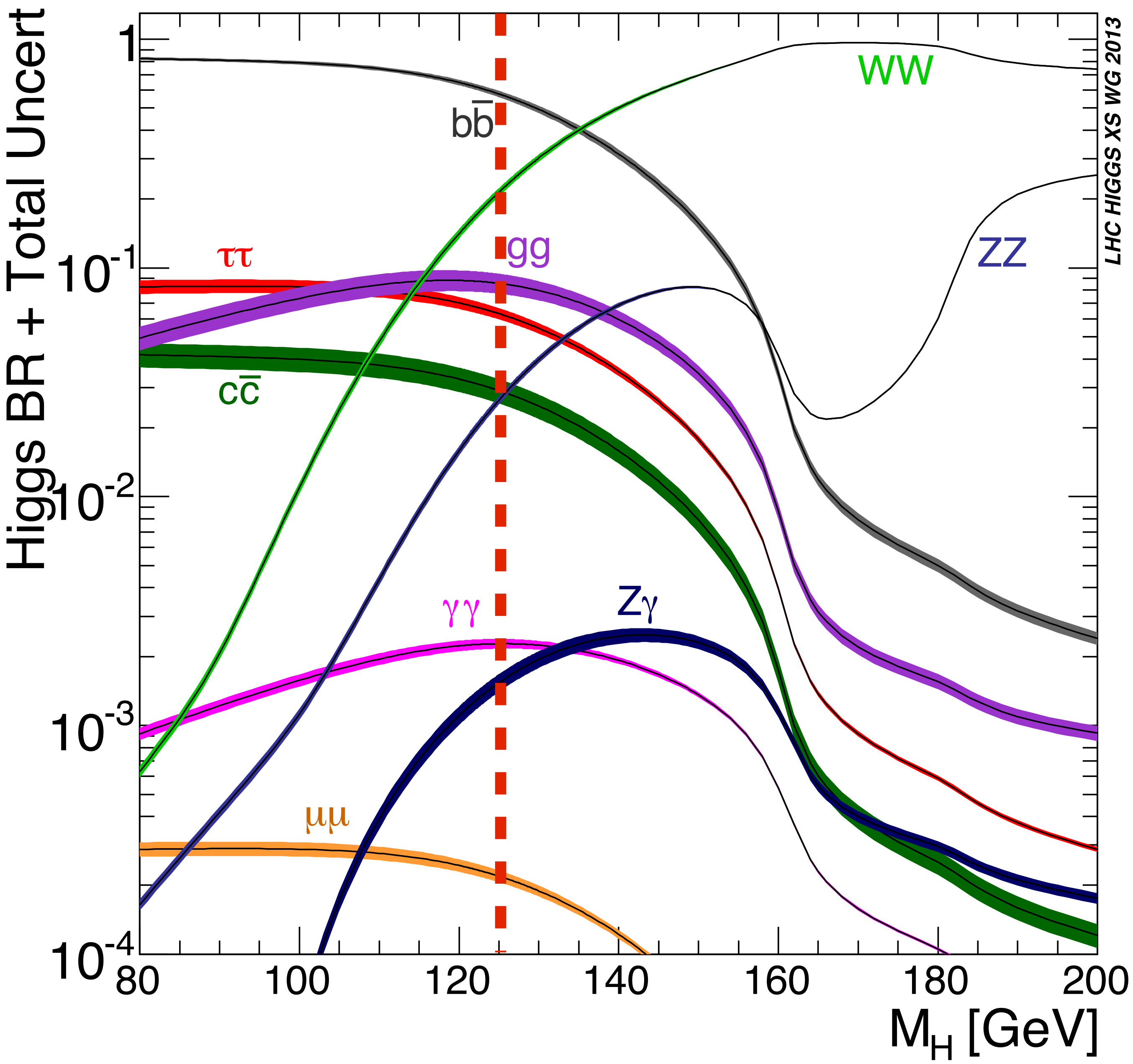

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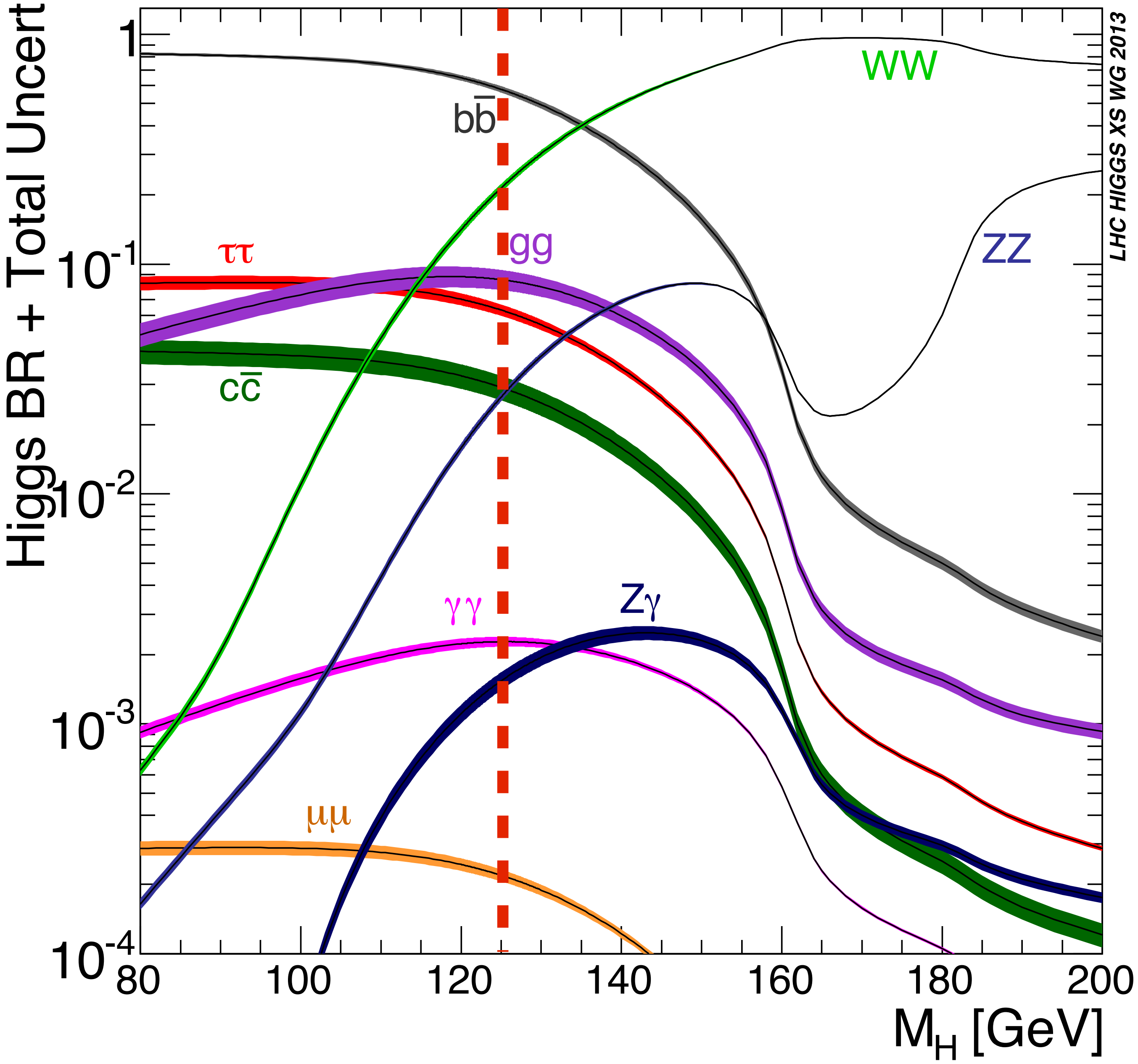
γγ - Rare decay, but manageable background, good resolution

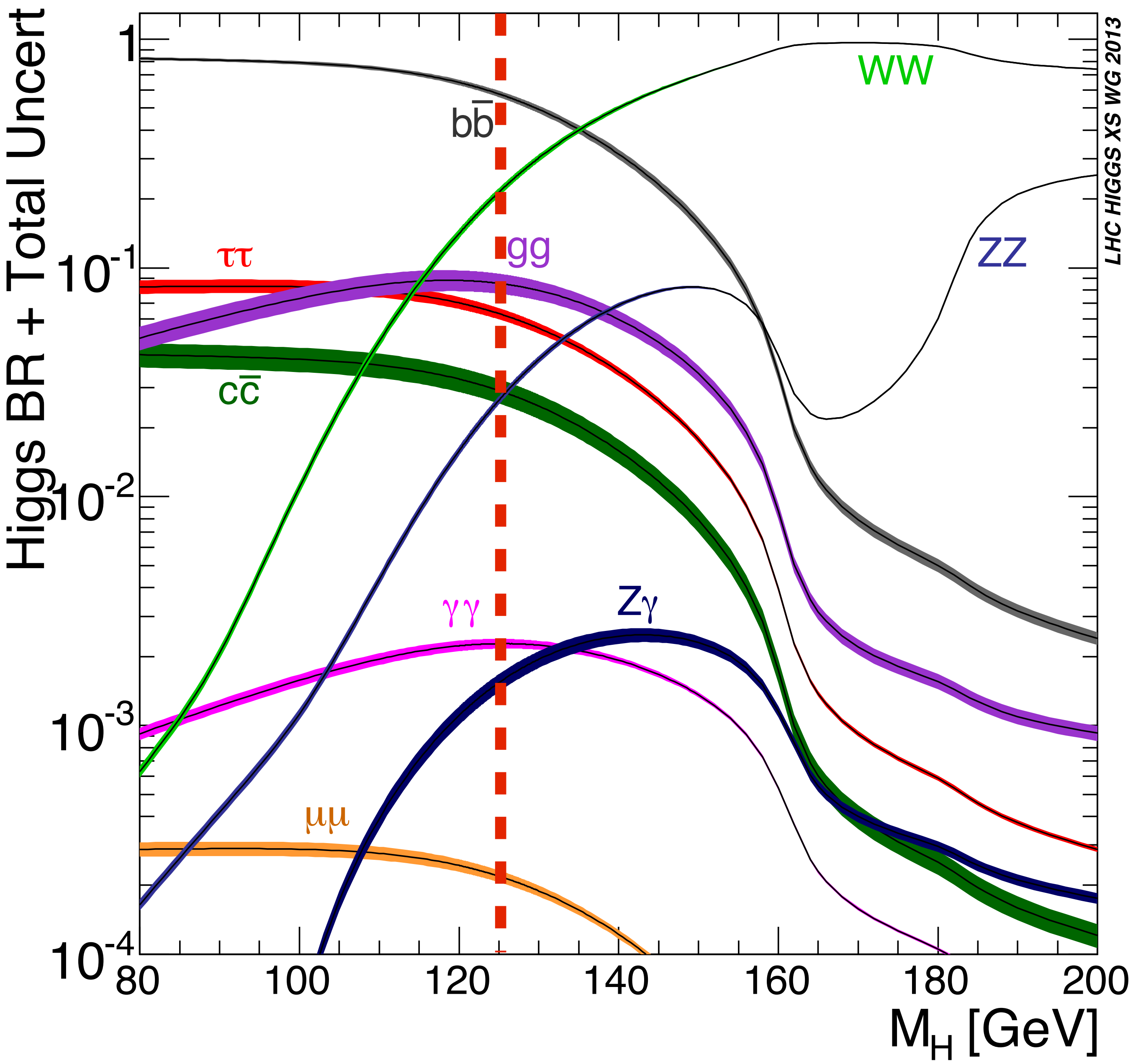
Higgs Decay II



- Additional decay channels:

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

Higgs Decay II



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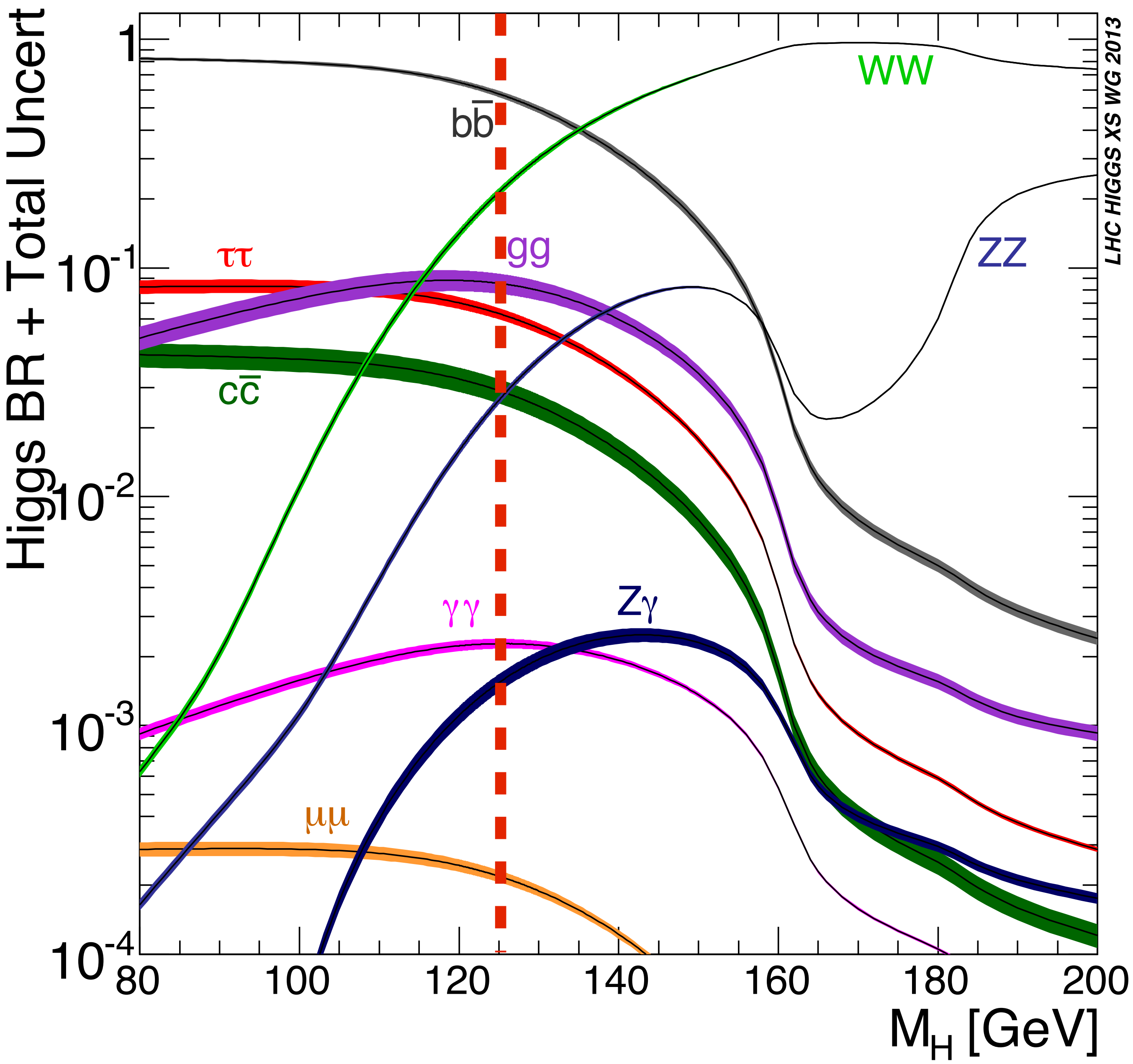

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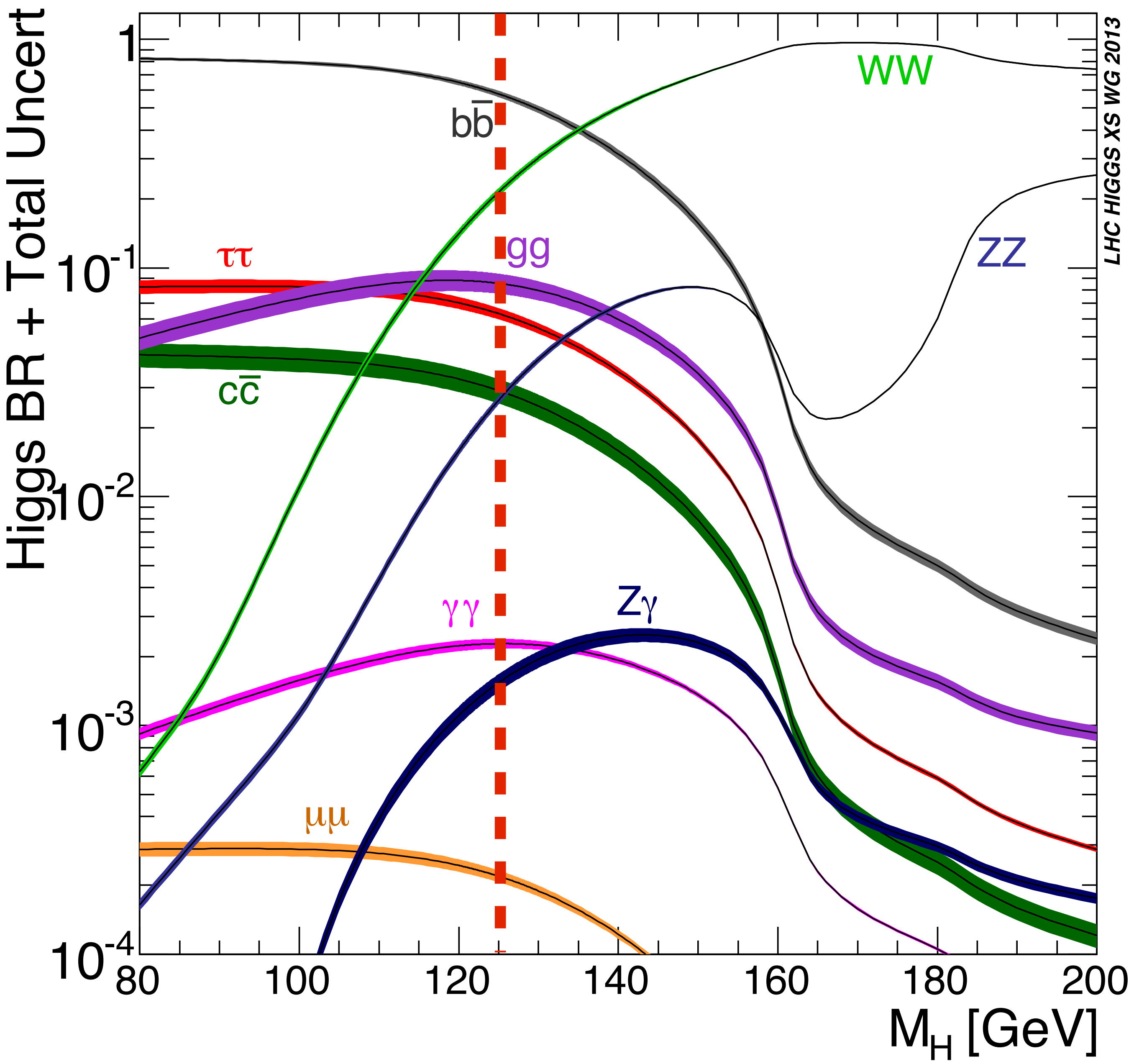

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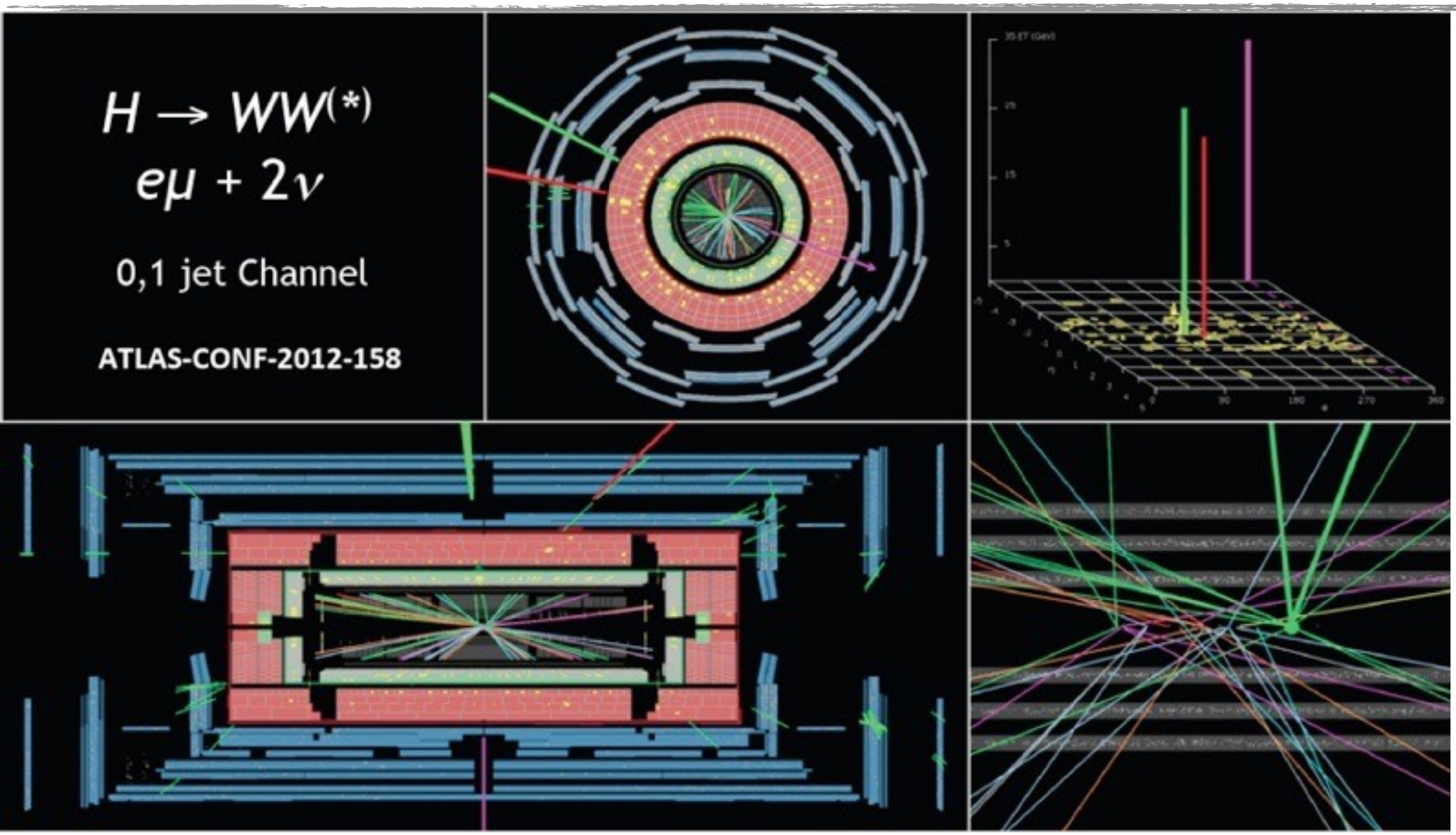
cc - Two charm jets - quite rare, no chance at LHC

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

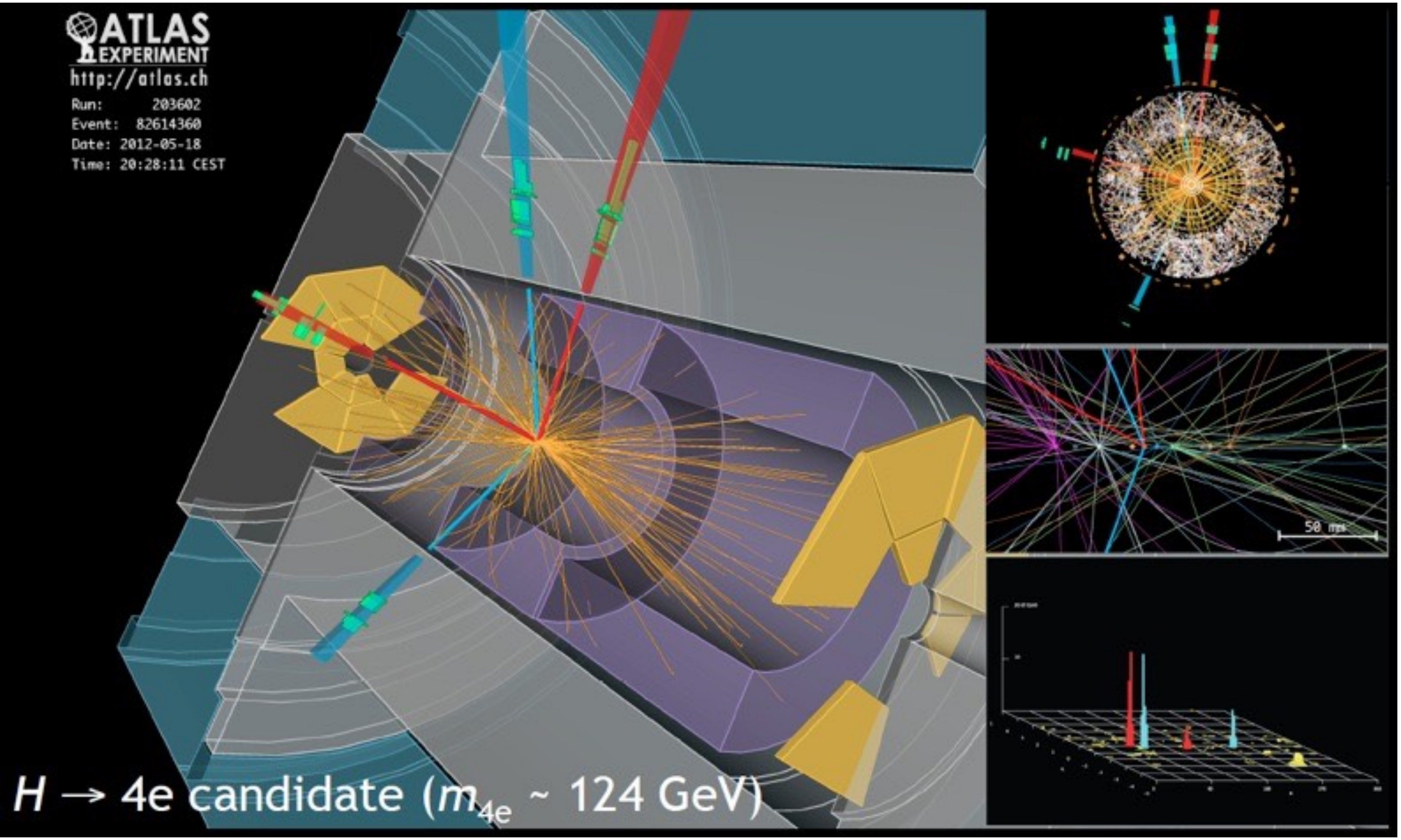
Discovery Channels - H -> WW



- 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)

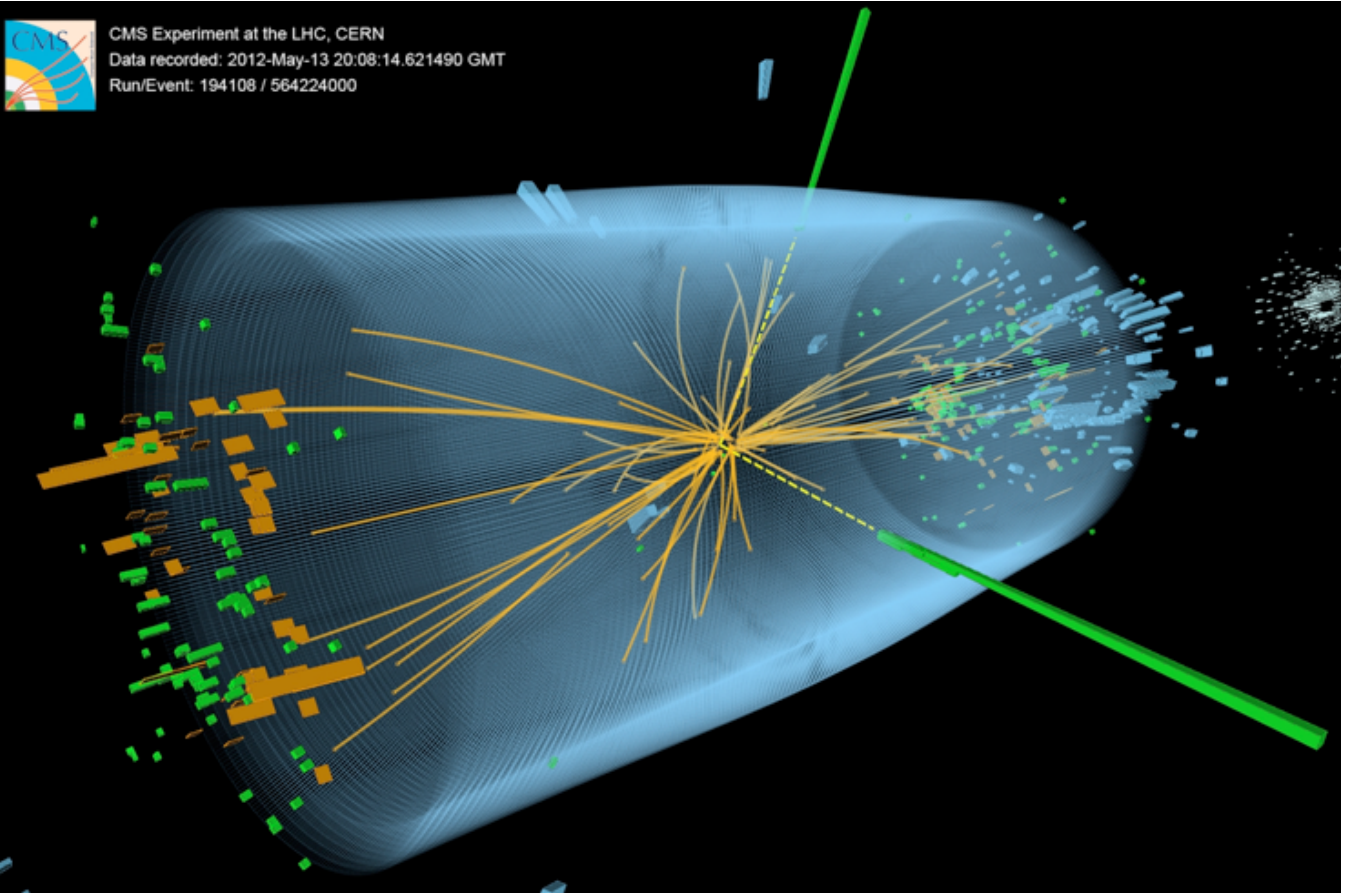
Discovery Channels - H -> ZZ



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

- 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

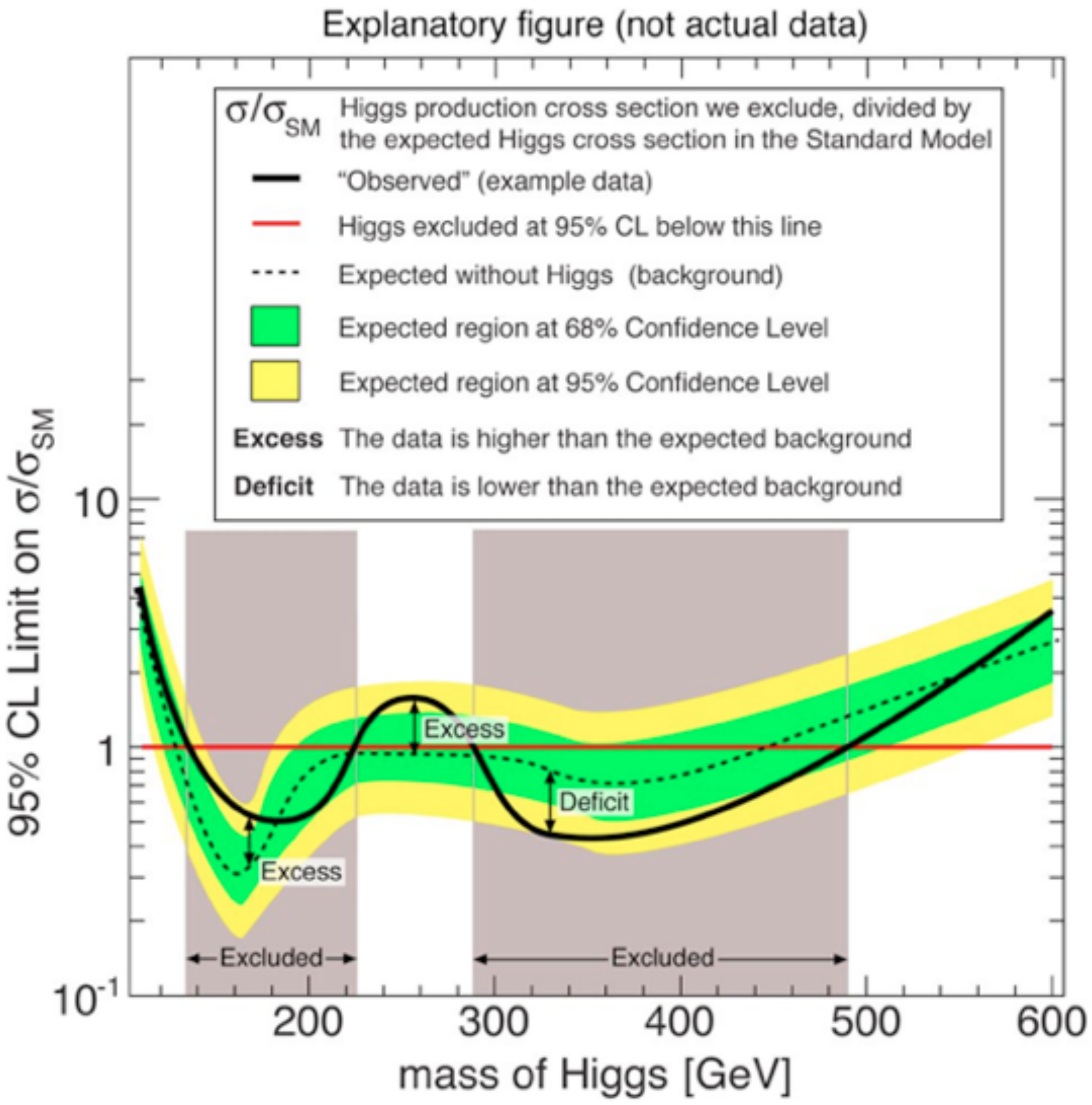
Discovery Channels - H -> γγ



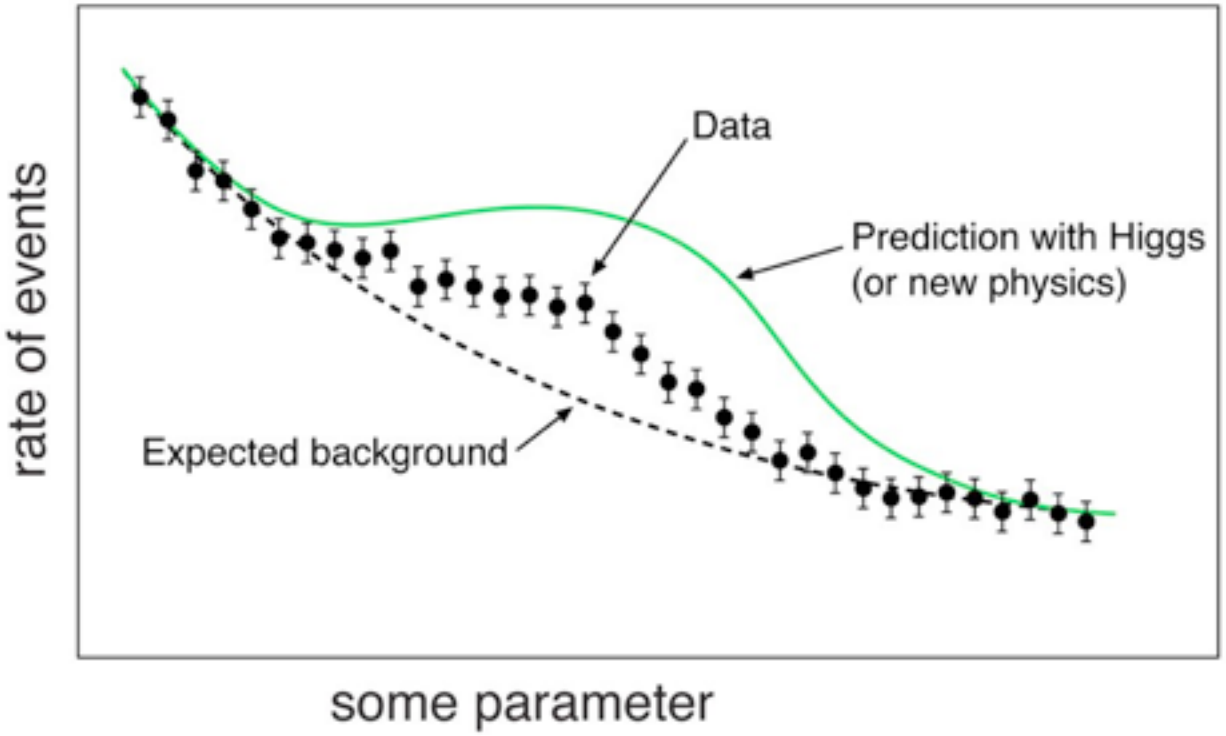
- Good mass resolution: ~ 1% level, given by photon energy resolution of ECAL
- Low branching fraction: $\boxed{2.3 \times 10^{-3}}$

- 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



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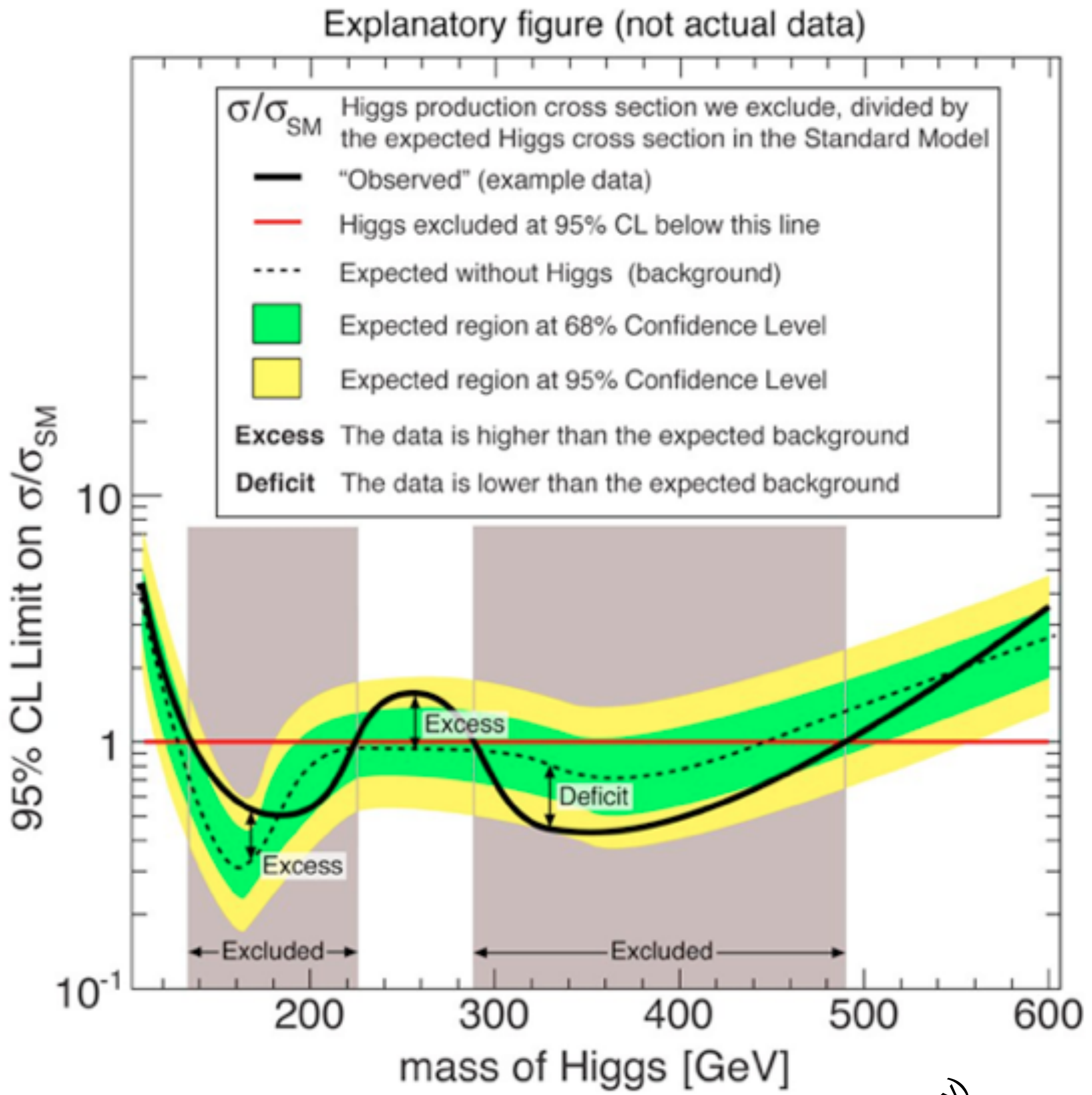

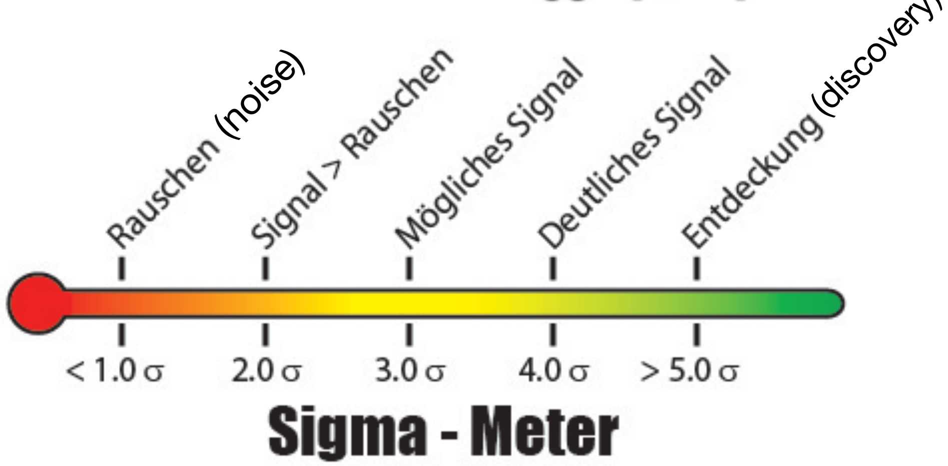

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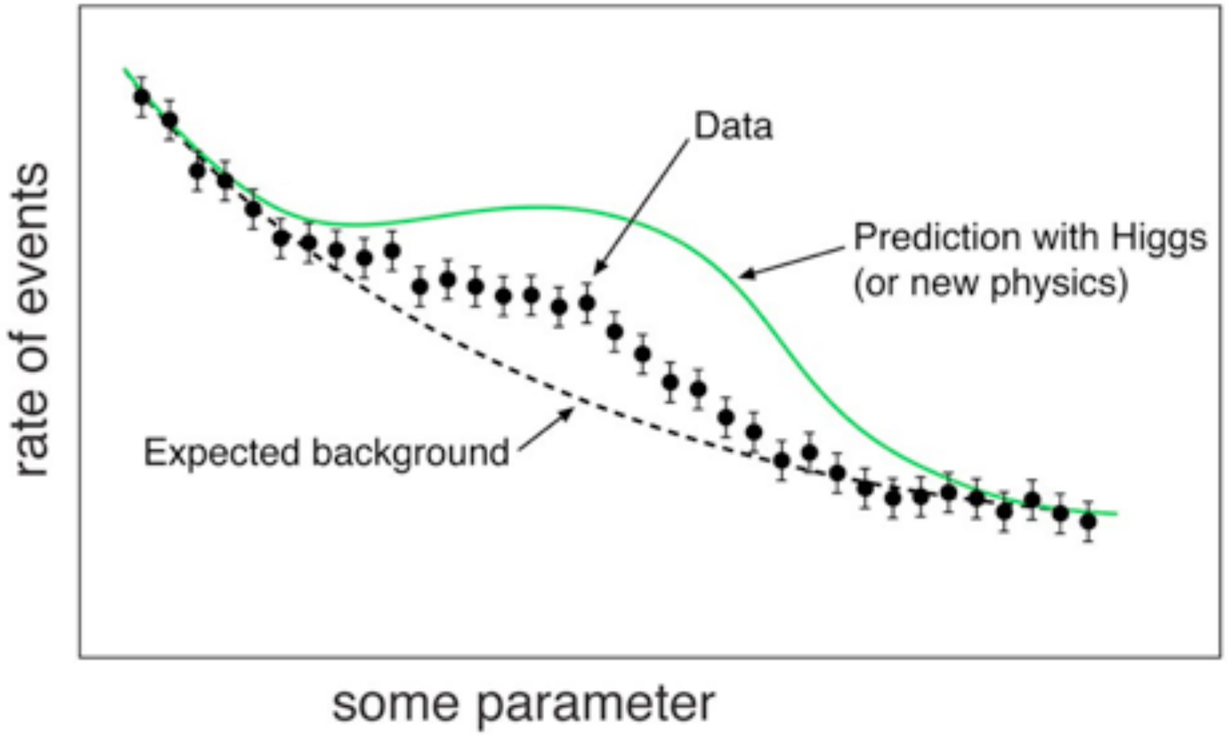
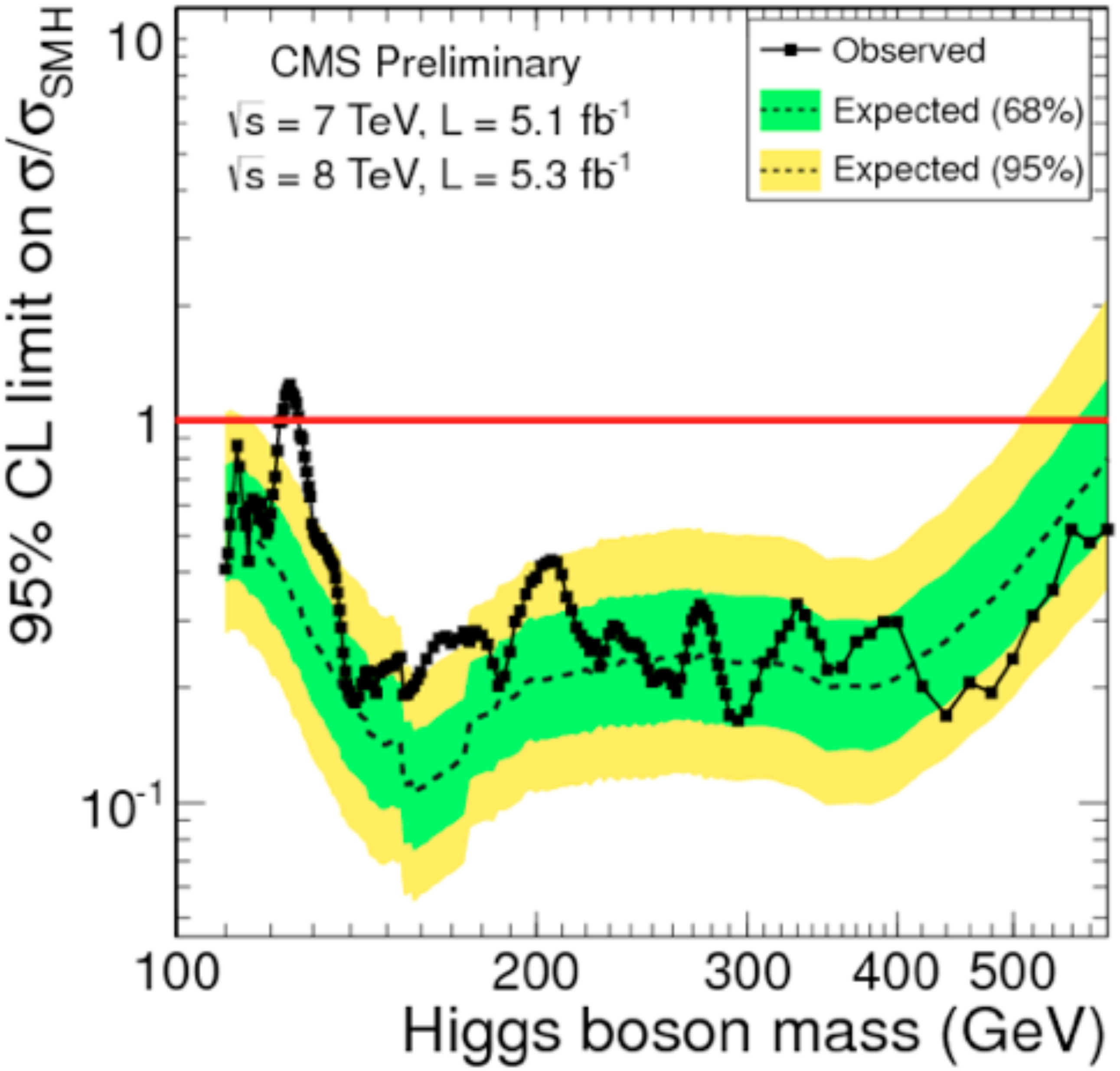
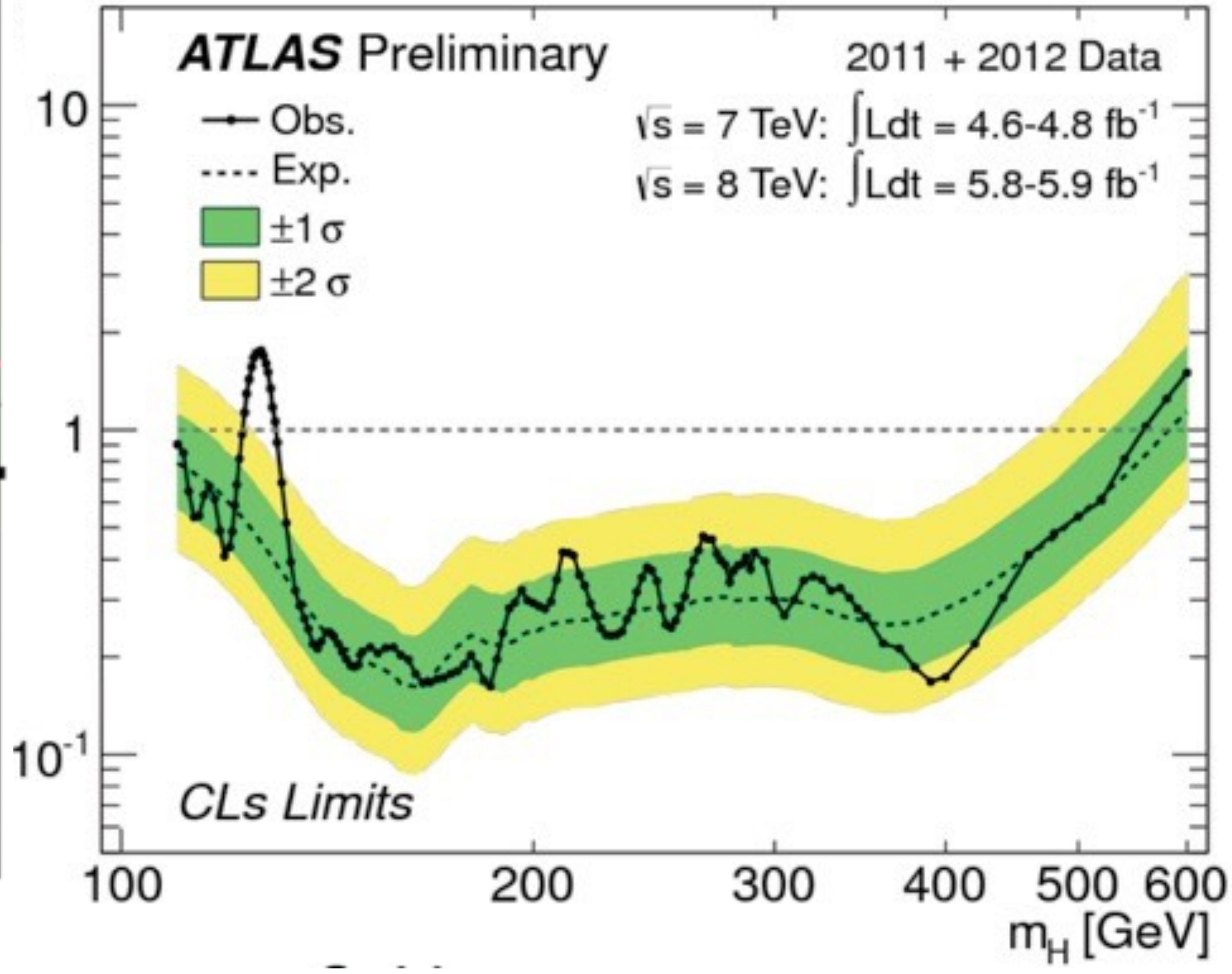


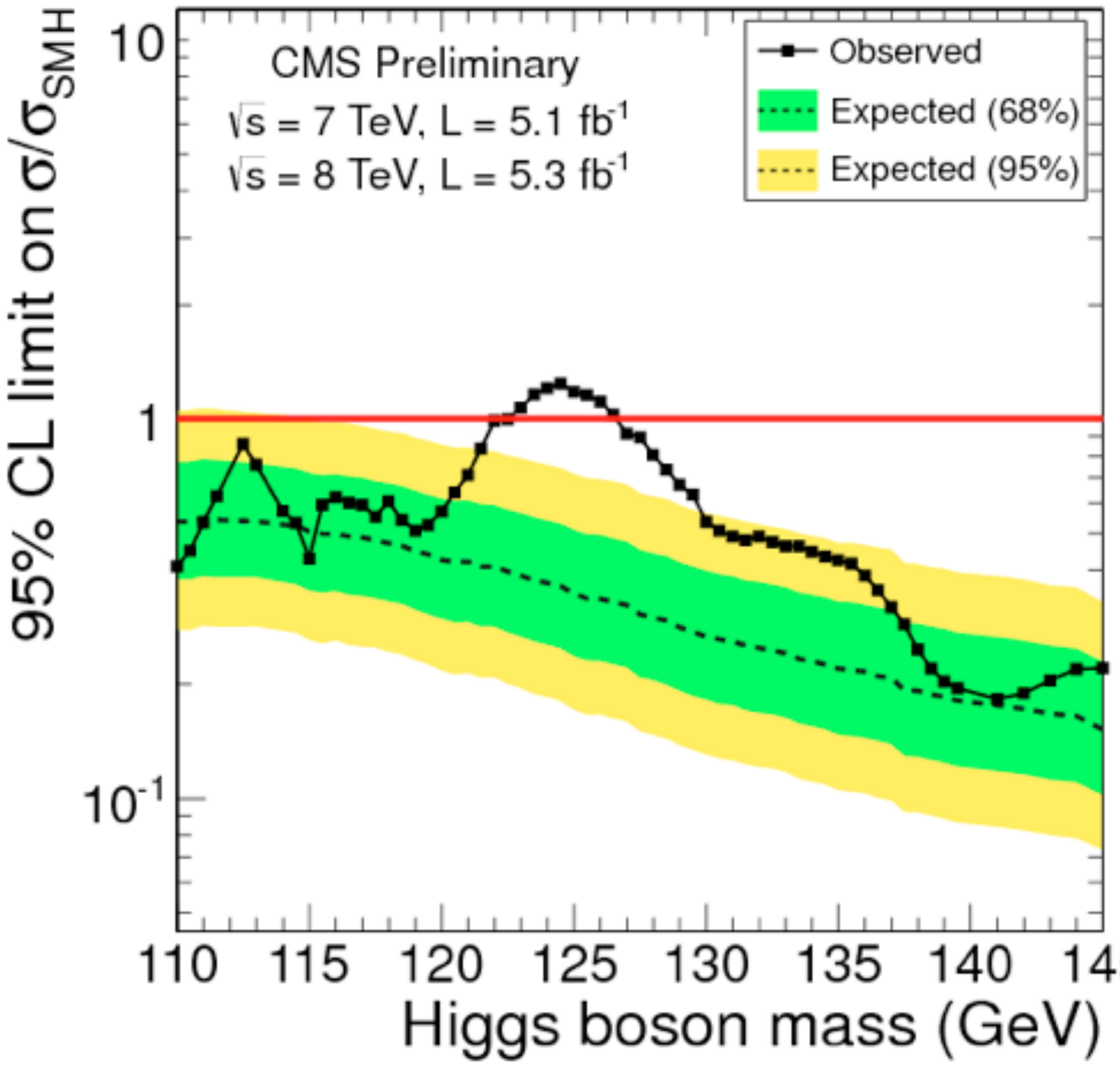
The Discovery - All Channels Combined

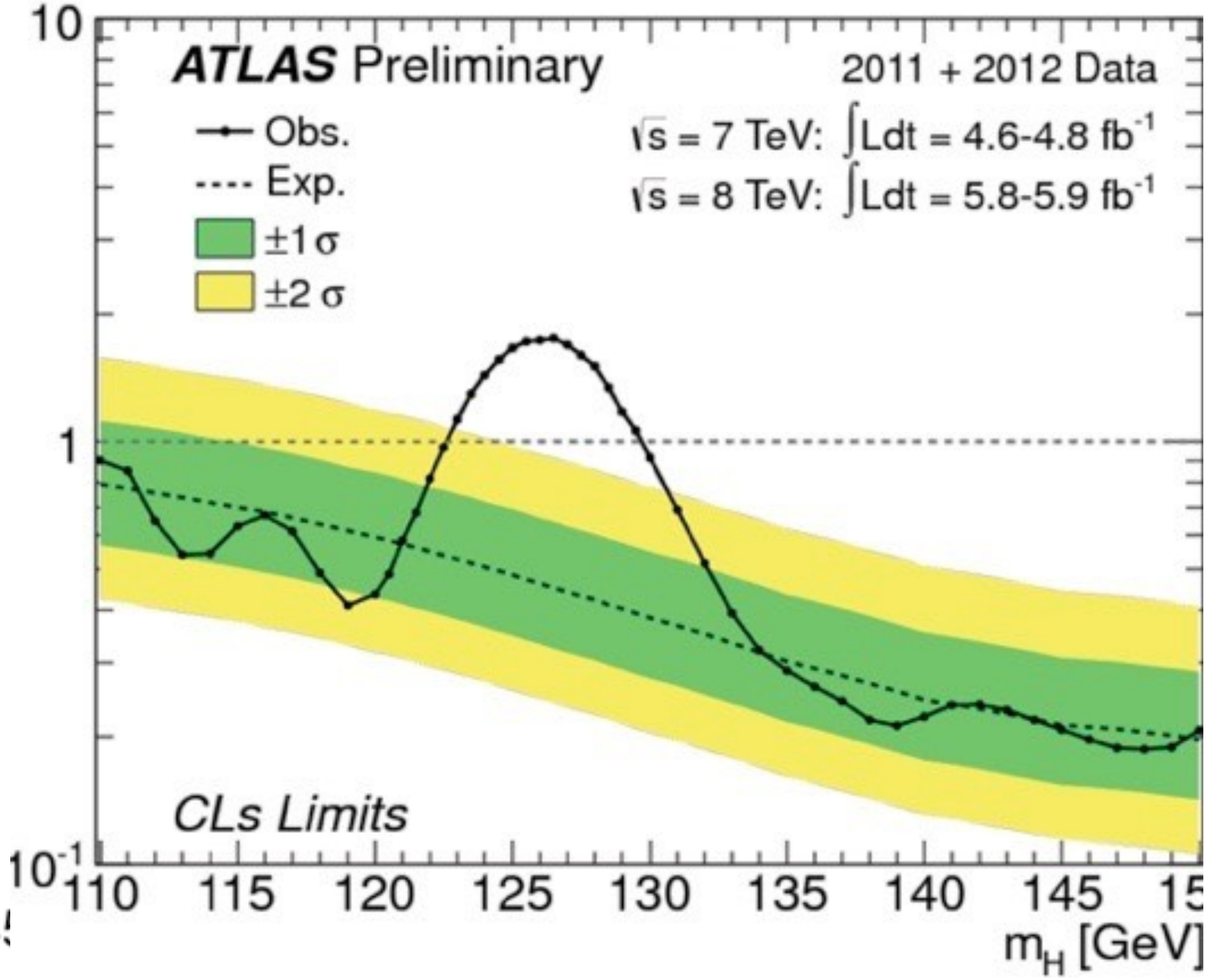




- The SM Higgs is excluded over the full range from 110 GeV to 600 GeV, with the exception of the region around 125 GeV
- Observed and expected limits match well within 1 - 2 σ

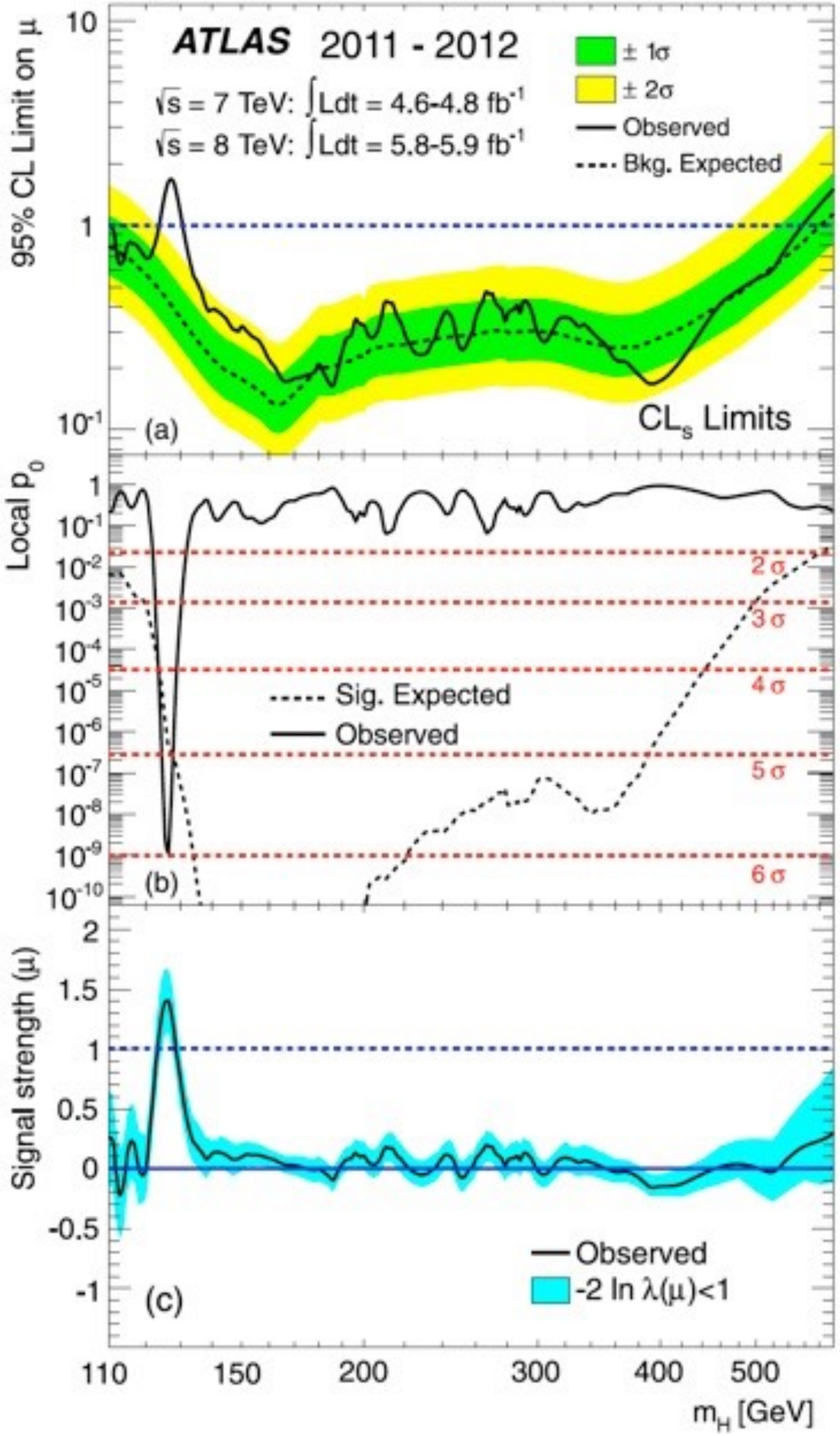
The Discovery - All Channels Combined



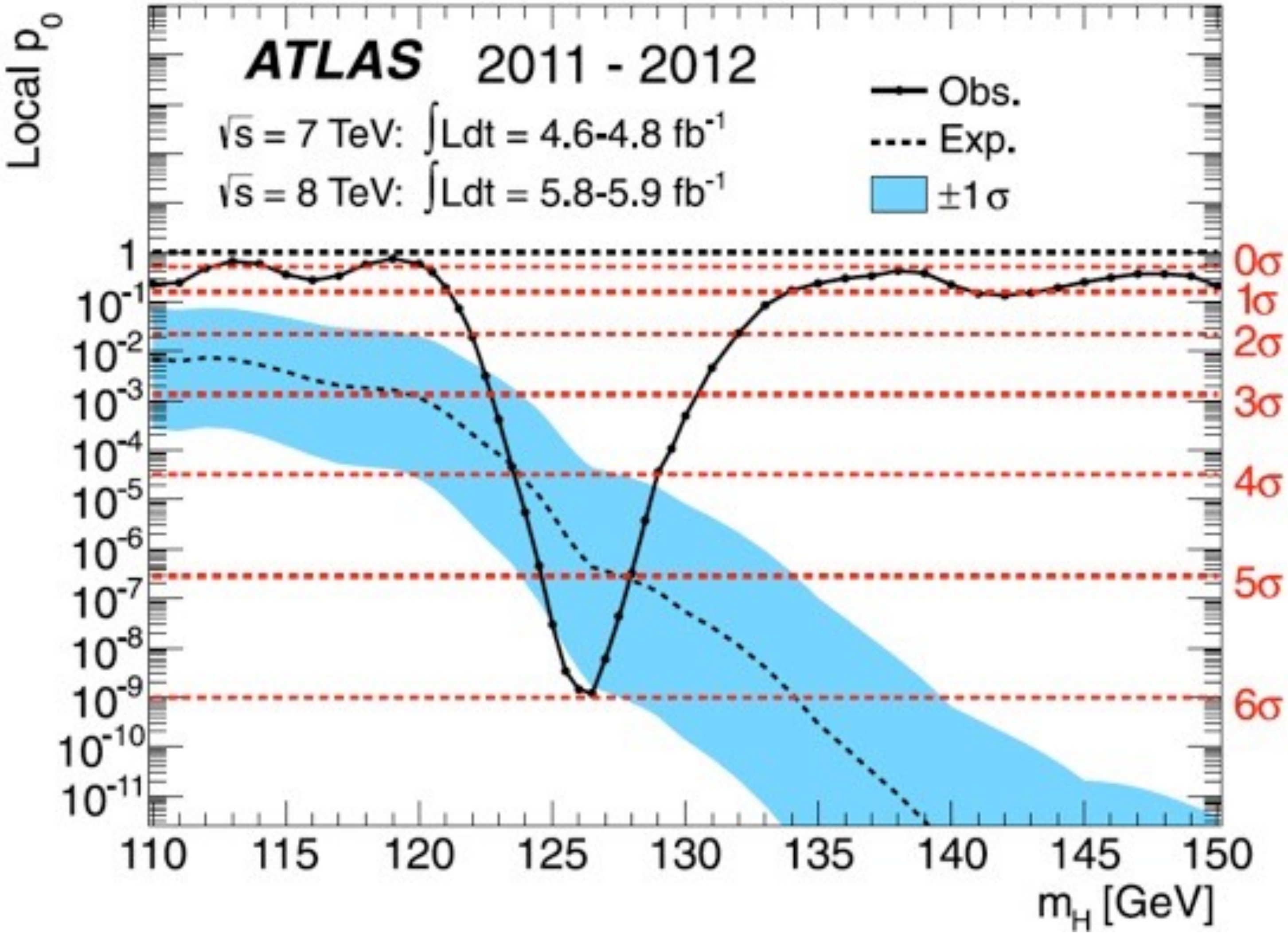


- Clear signal around 125 GeV, well in excess of the expected exclusion: A discovery!

The Discovery - A closer Look at ATLAS

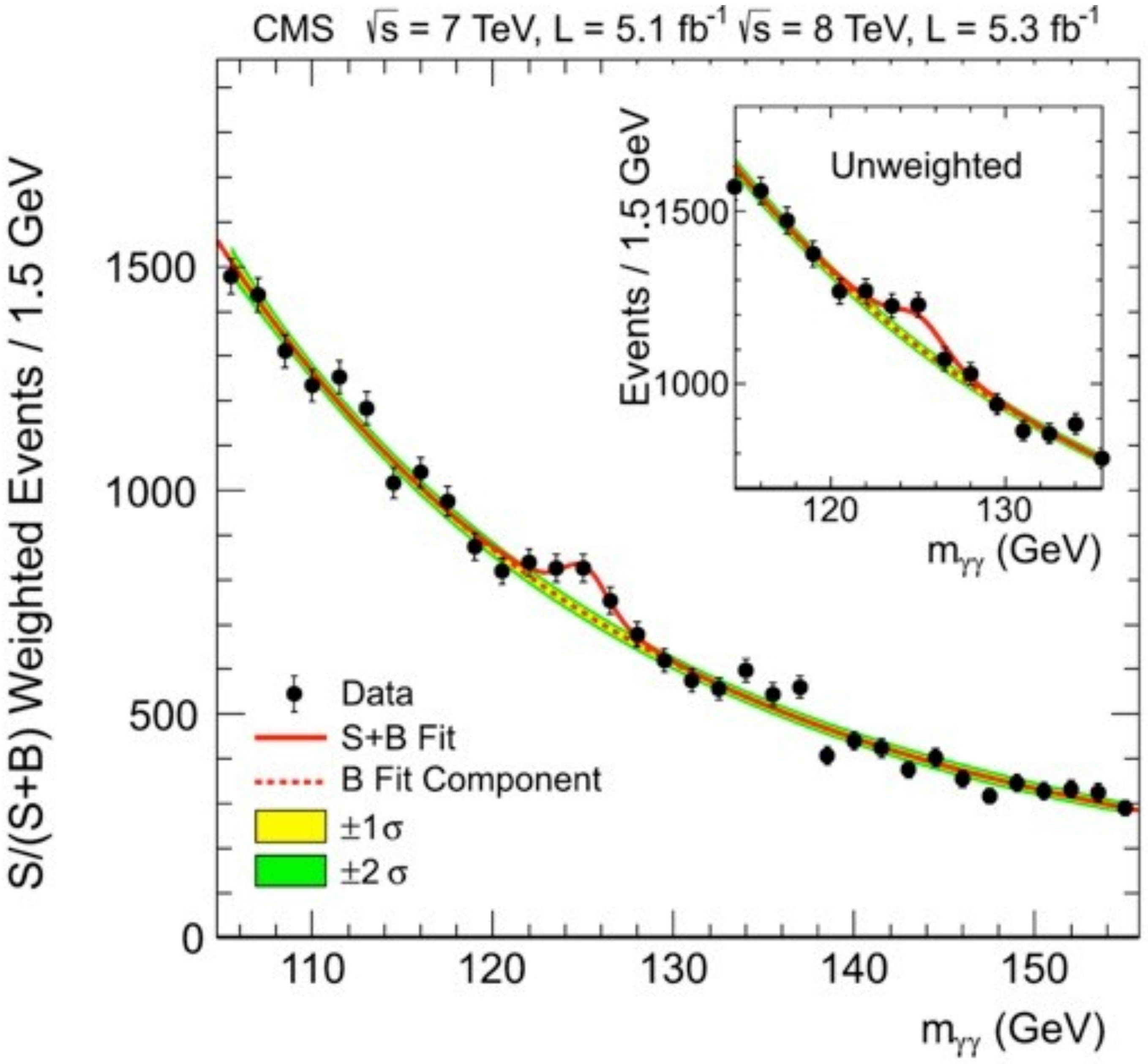


- Local significance (published!) ~ 6σ
  - Probability for a random fluctuation 10^{-9} (like tossing a coin and getting heads 30 times in a row)



Individual Channels

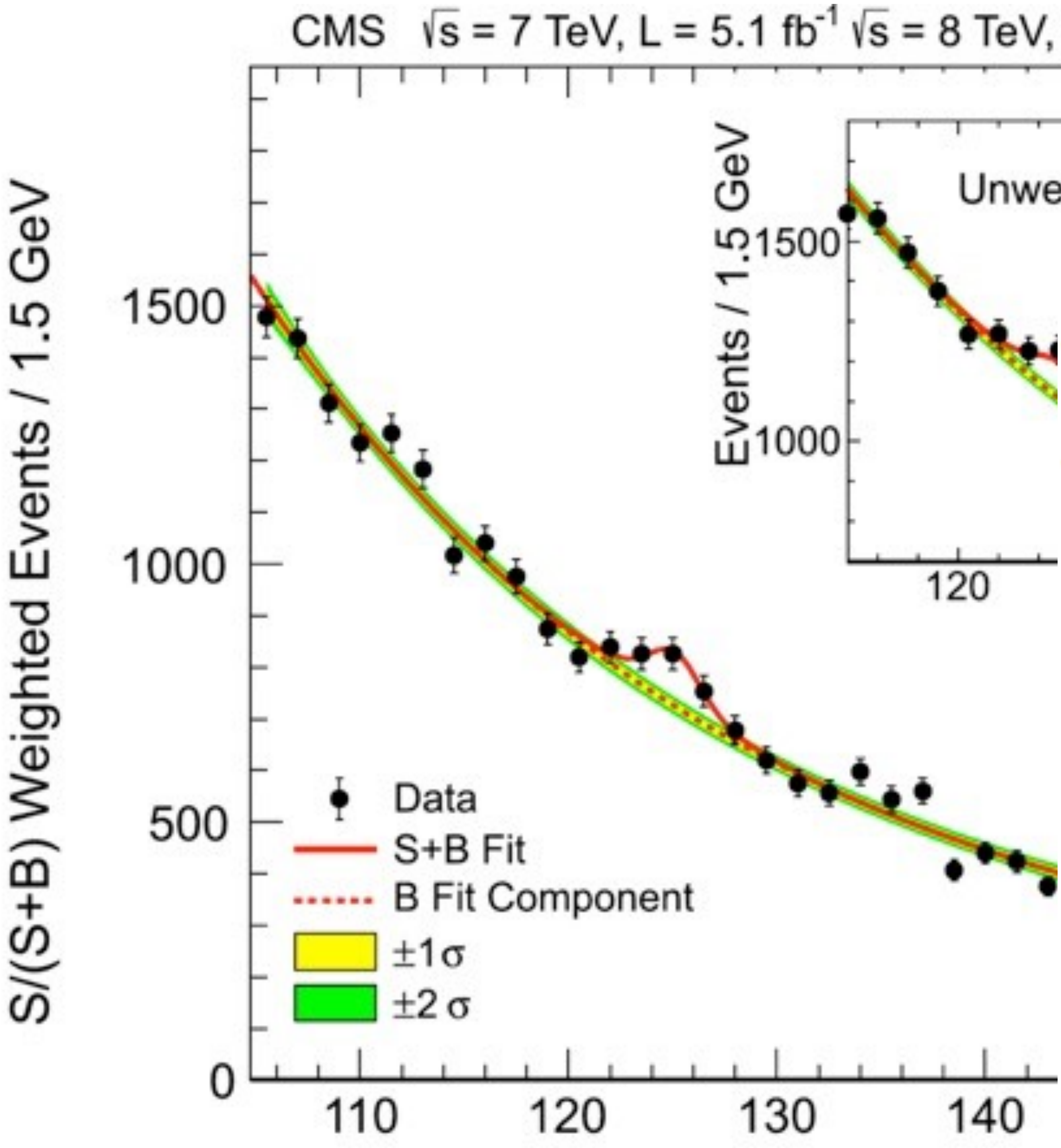
- The most significant: H -> γγ



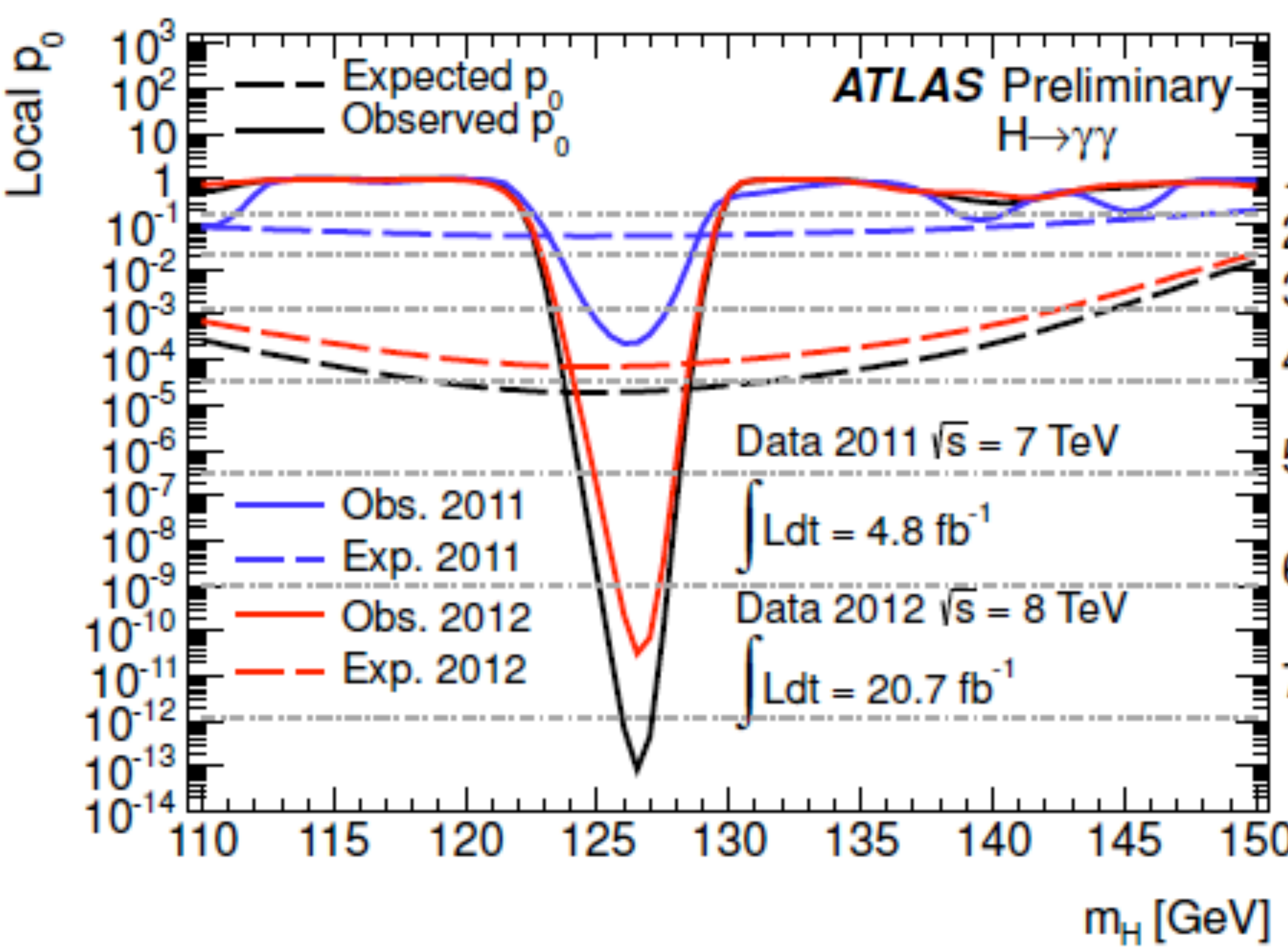
CMS “discovery plot”

Individual Channels

- The most significant: H -> γγ



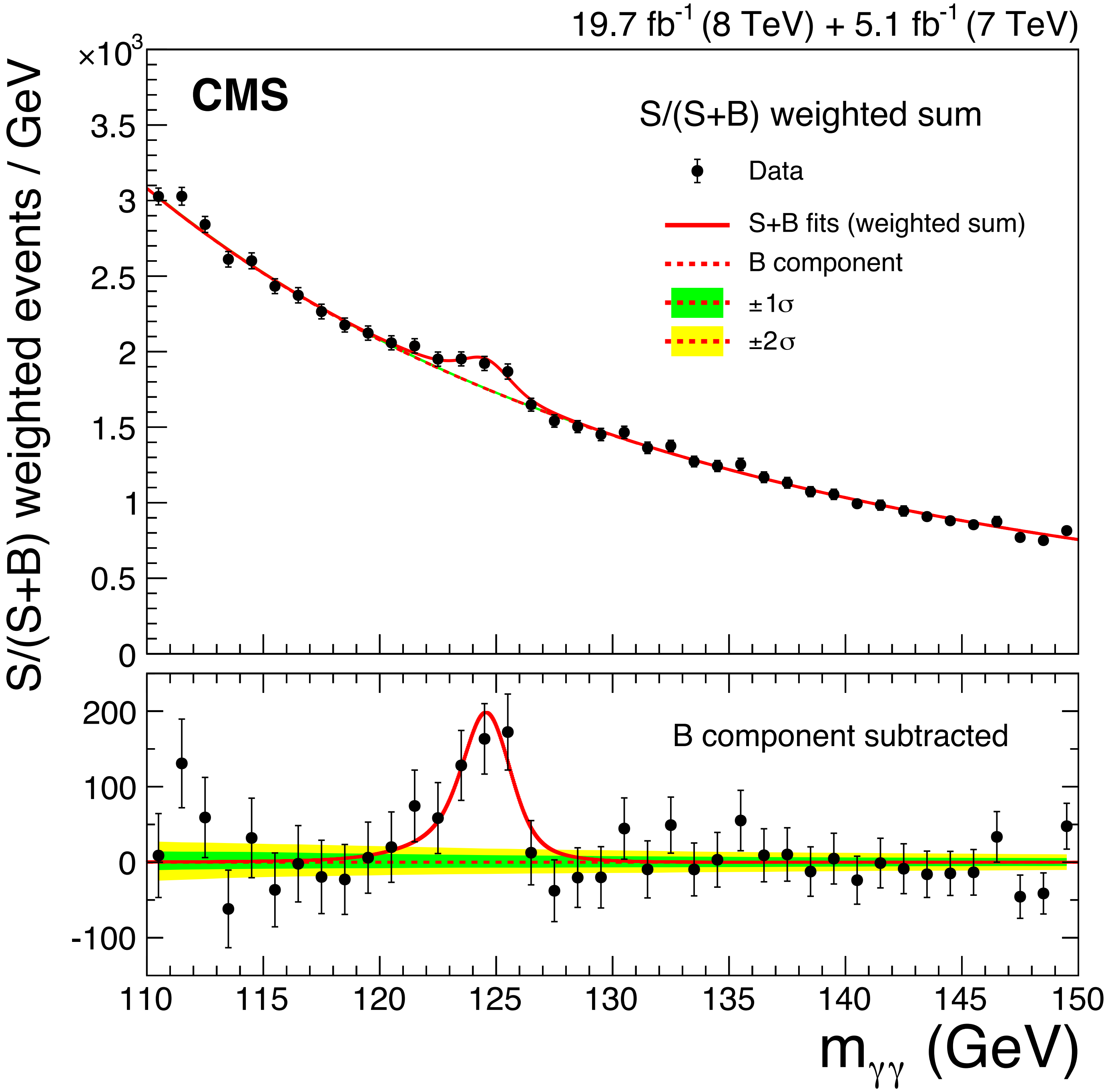
- With more data: Single channel discovery in ATLAS > 7 σ



CMS “discovery plot”

Individual Channels

- The most significant: H -> γγ



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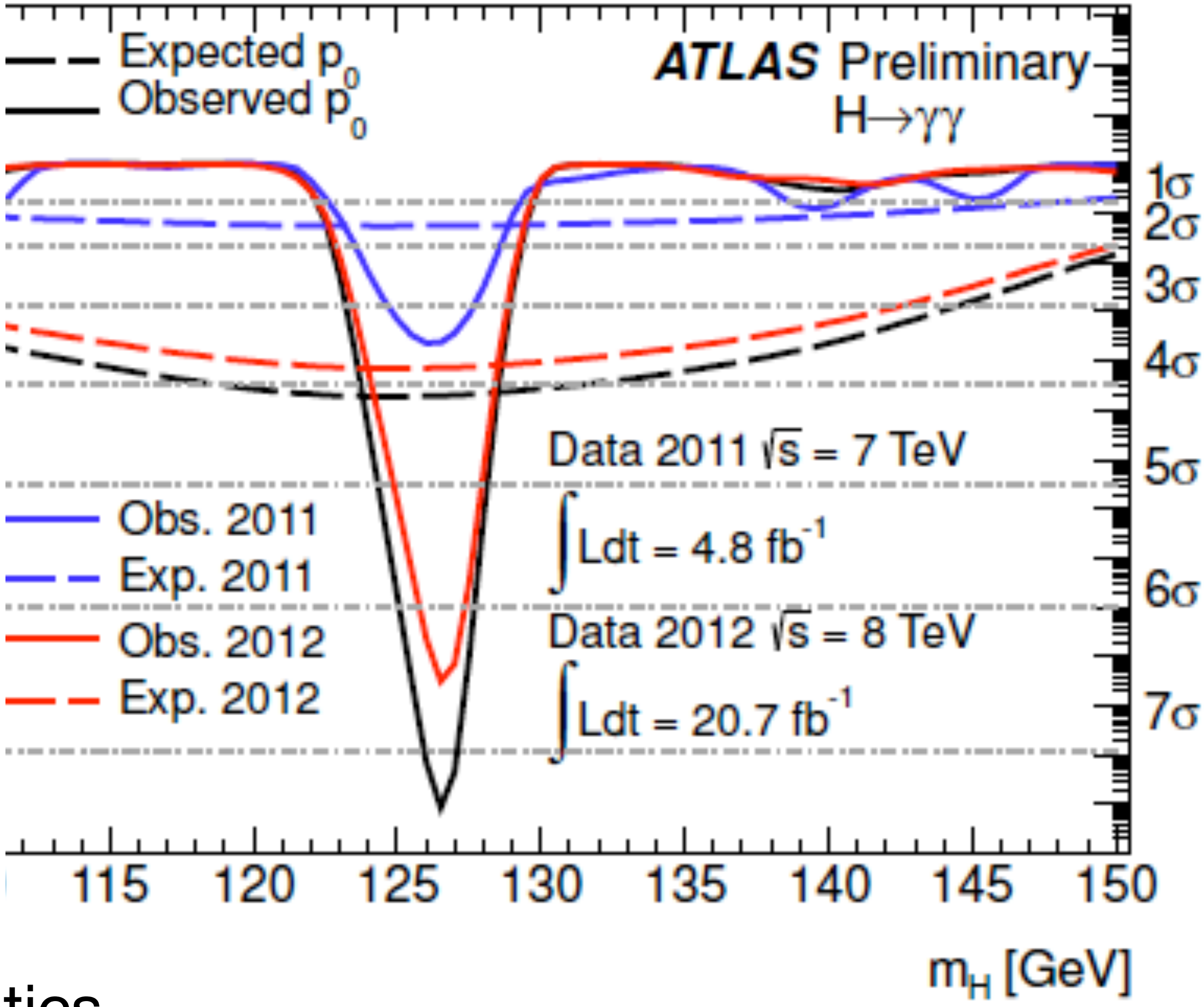
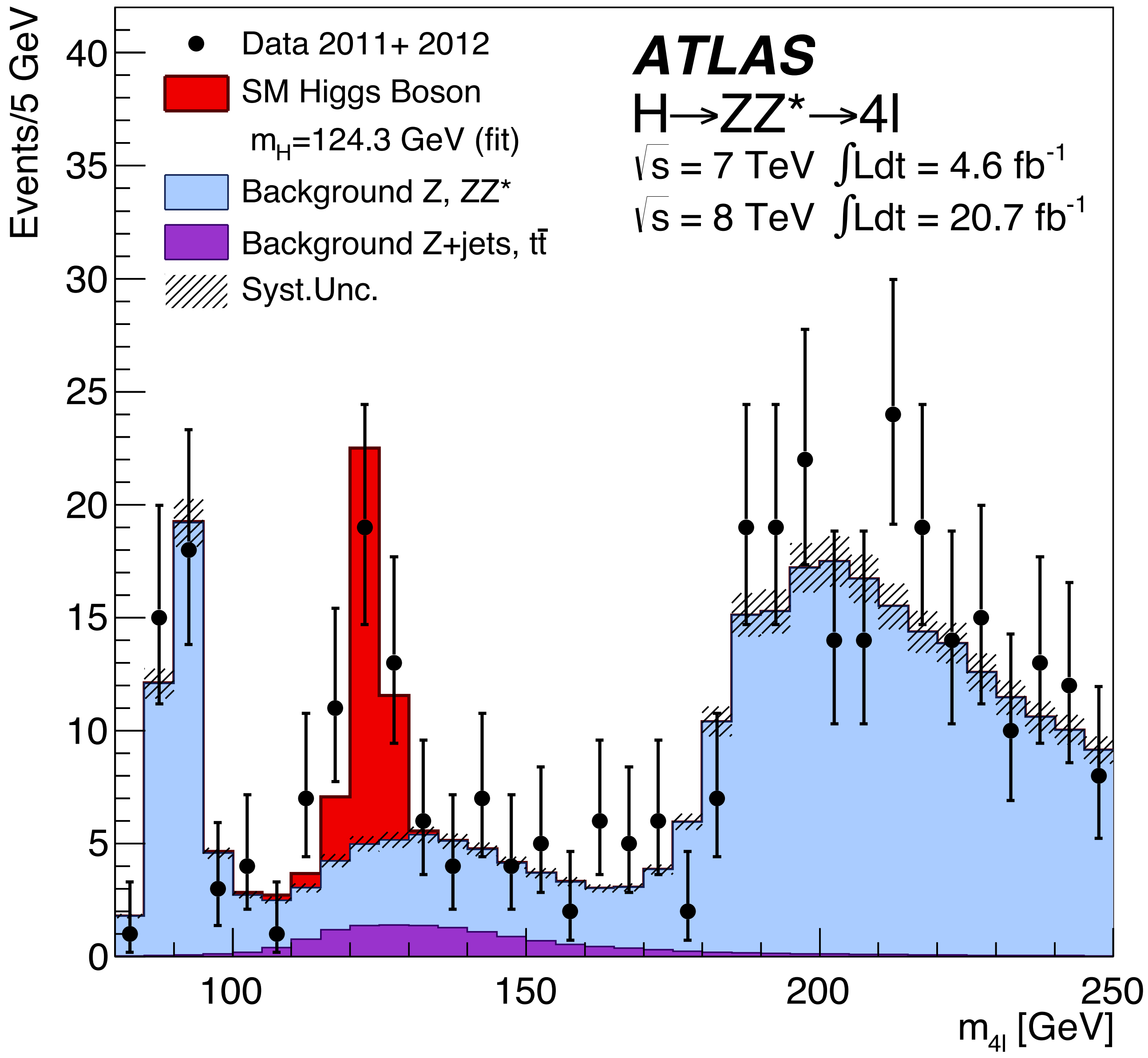
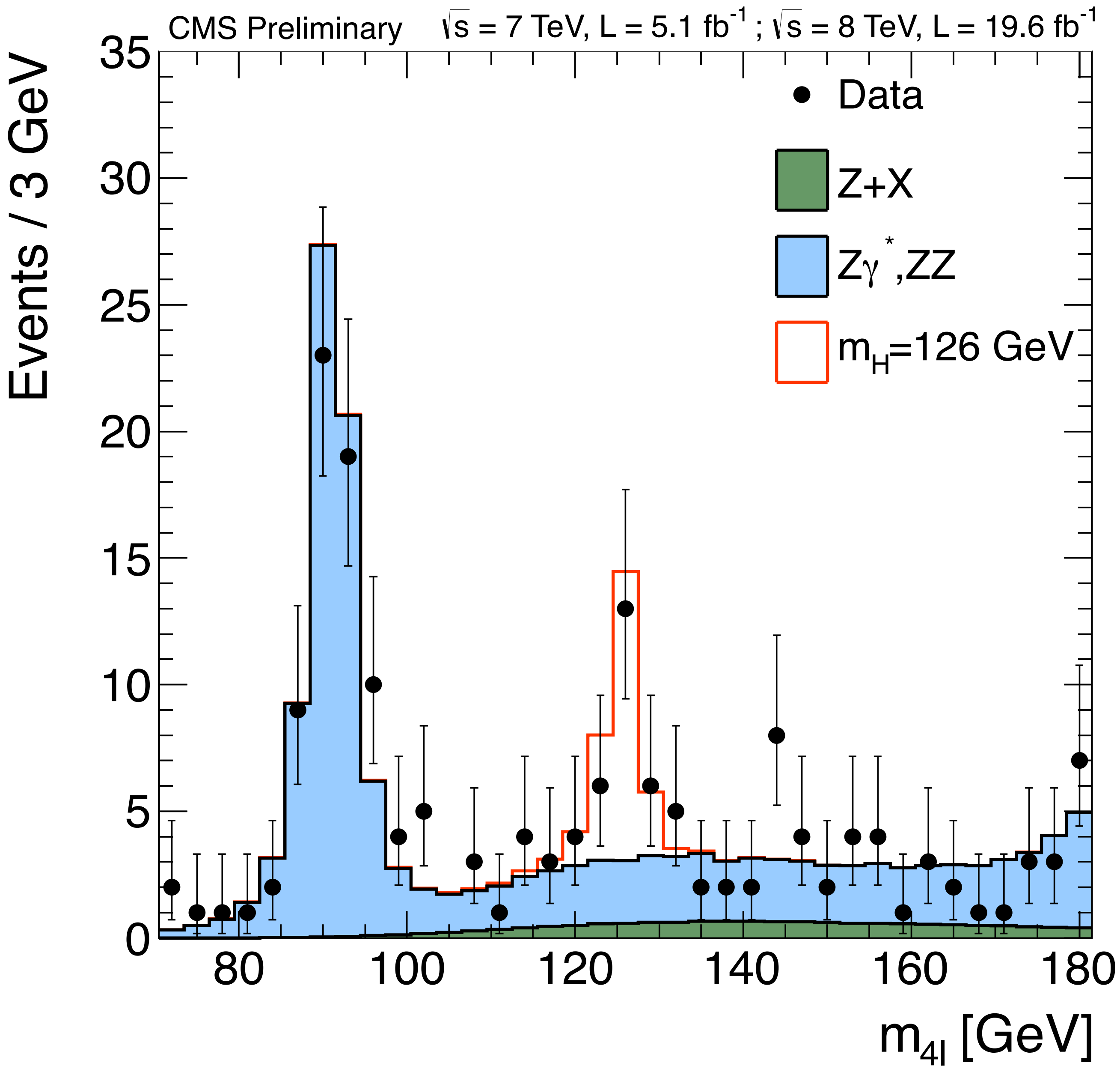


CMS "discovery plot" … and full statistics

Individual Channels

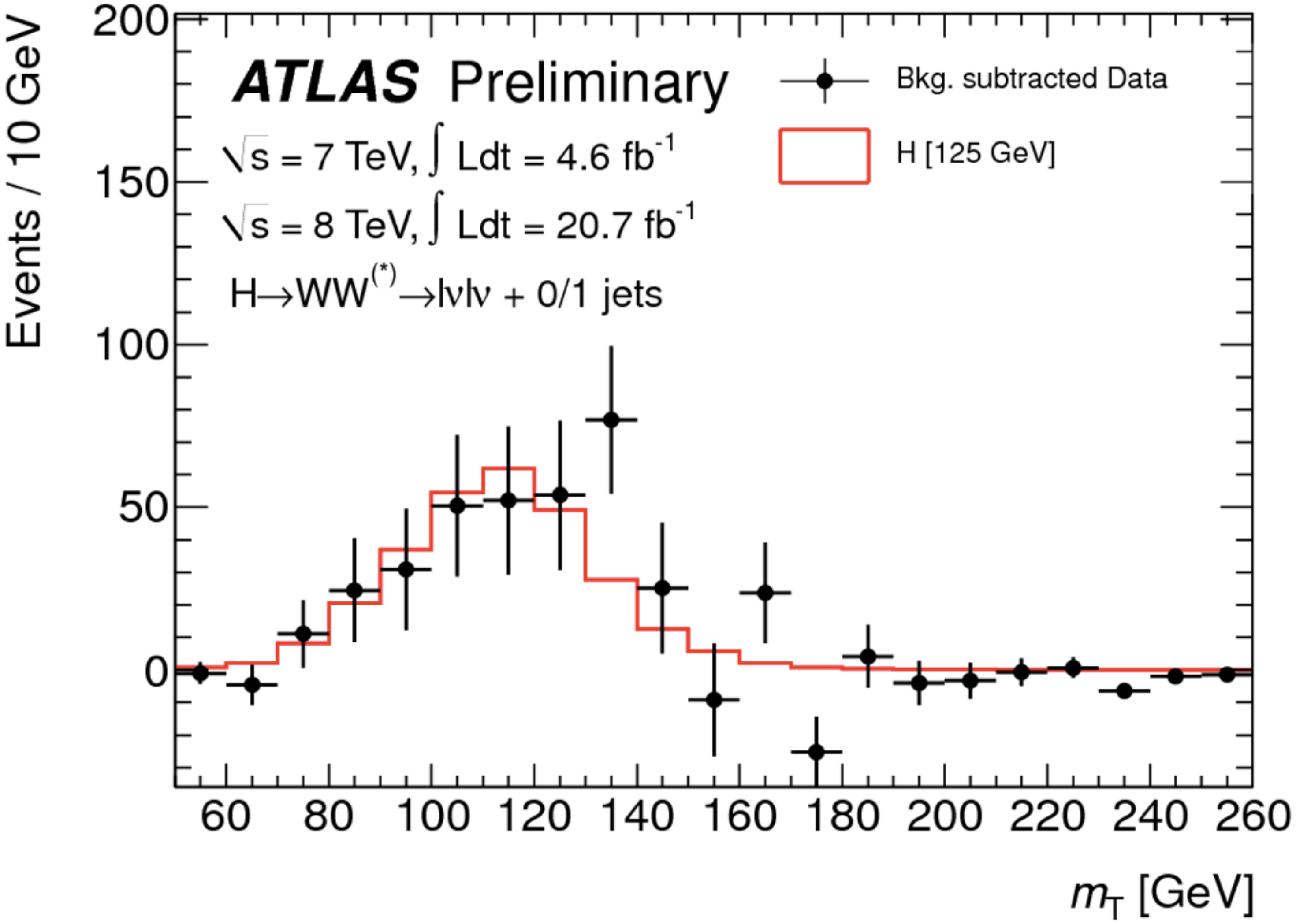
- The golden mode: H-> ZZ -> $l^+l^-l^+l^-$





Individual Channels

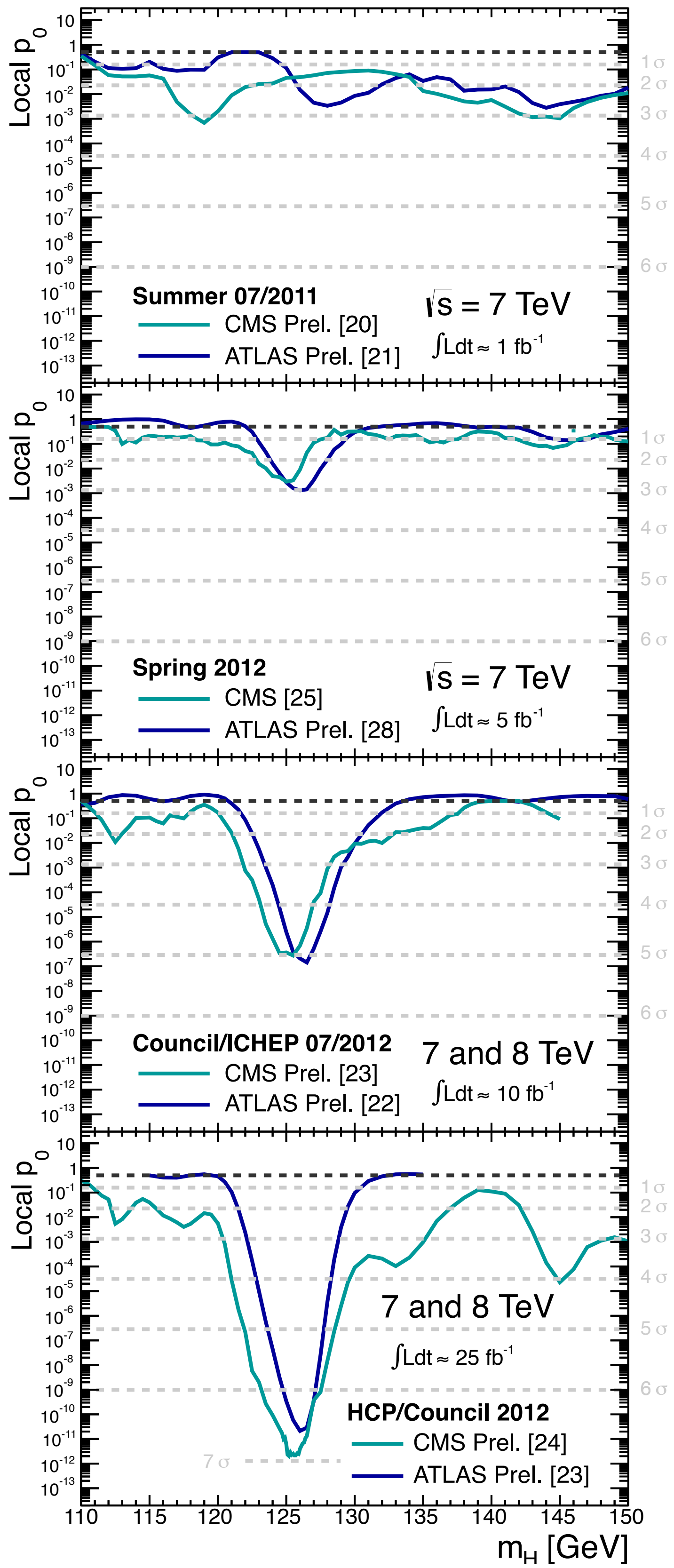
- The abundant: H->WW->lνlν



Significance: 3.8σ

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

The Discovery: Seeing it happen



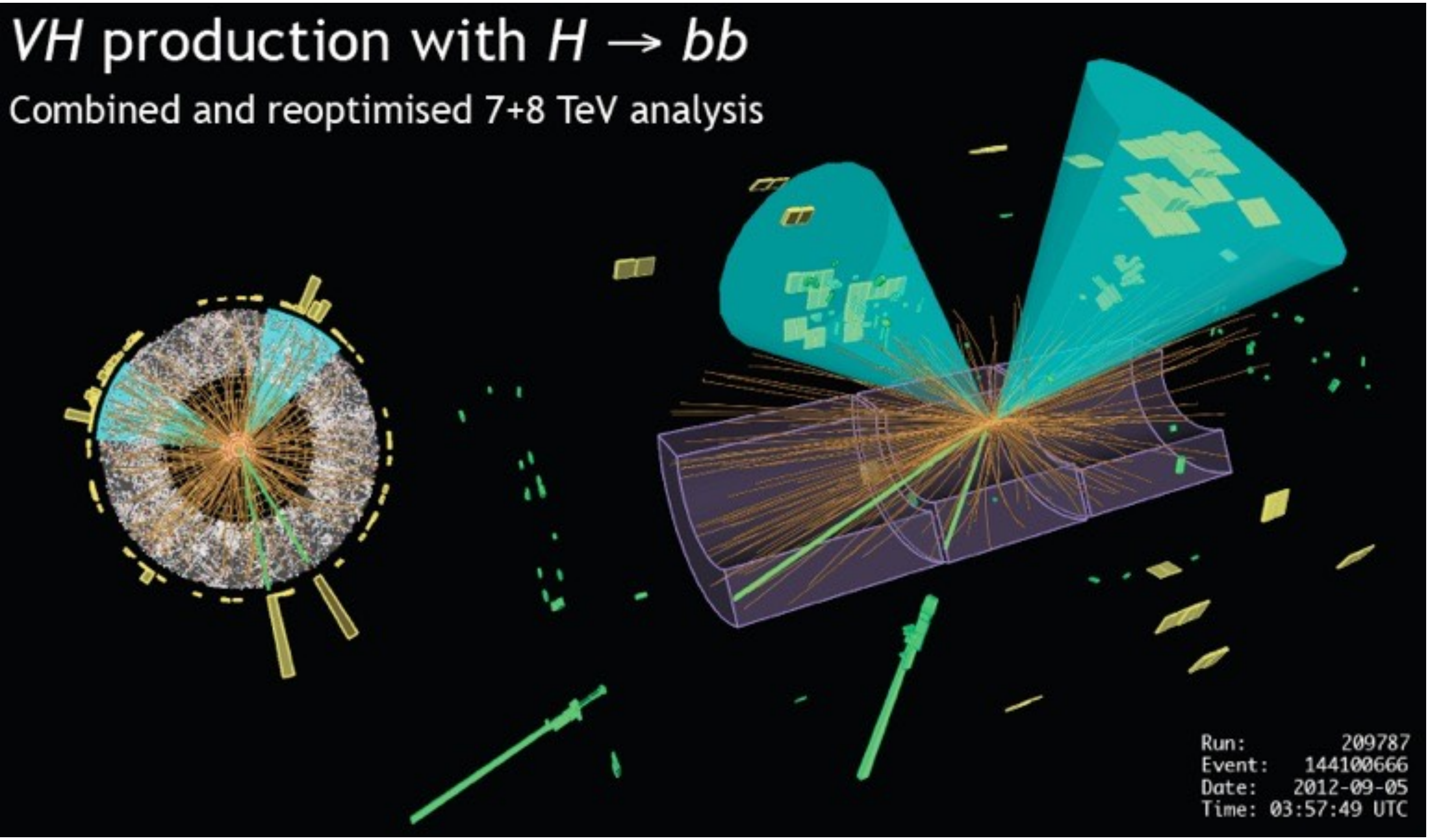
- Summer 2011: First (and last) focus on limits from LHC
- December 2011: First hints of a signal presented to CERN council
- Summer 2012: Discovery
- December 2012: Well established signal - entering the era of detailed Higgs physics program

July 4, 2012 - The Big Day

July 4, 2012 - The Big Day

July 4, 2012 - The Big Day

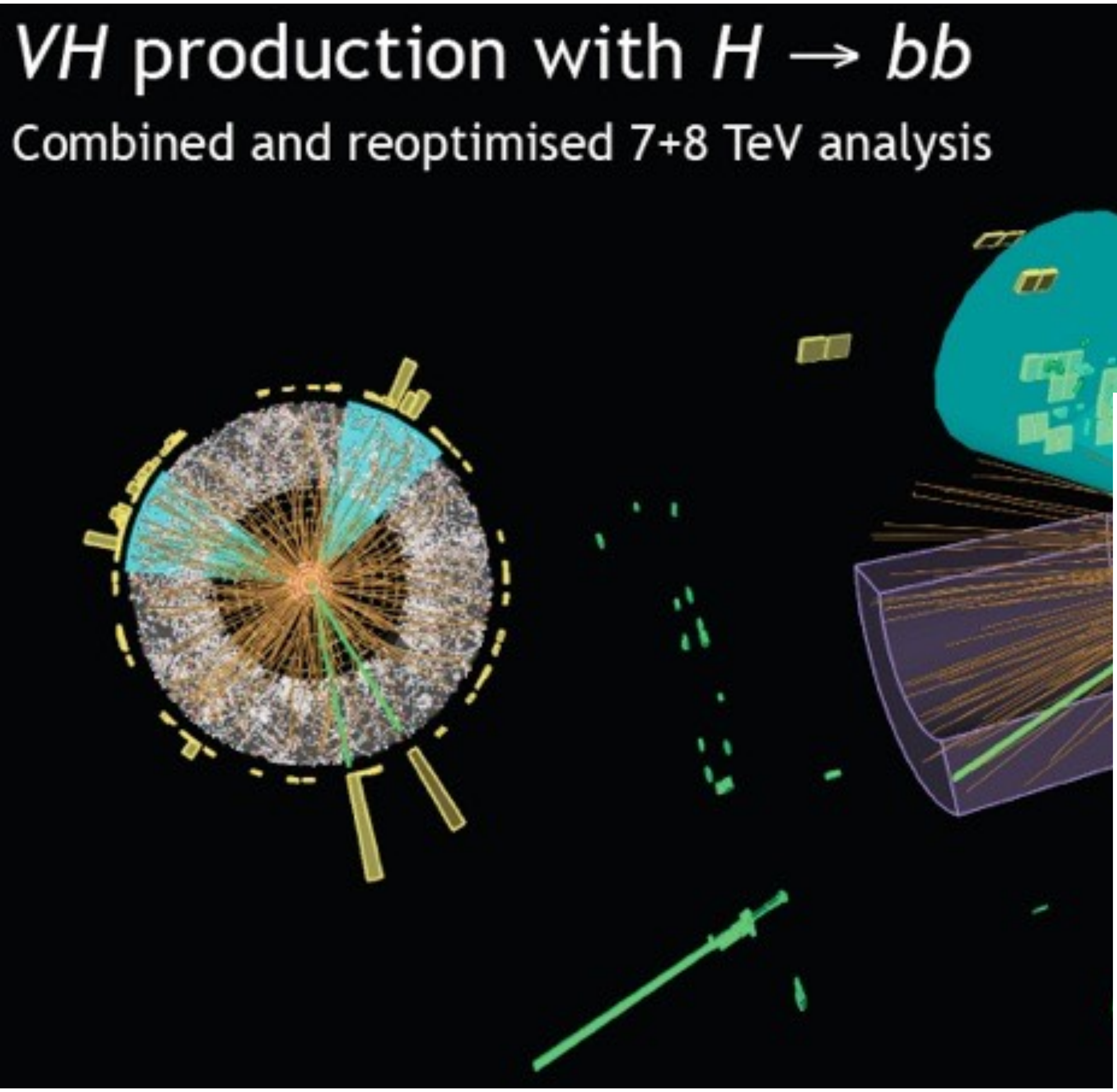
Beyond Discovery - Other Channels



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

- 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

Beyond Discovery - Other Channels



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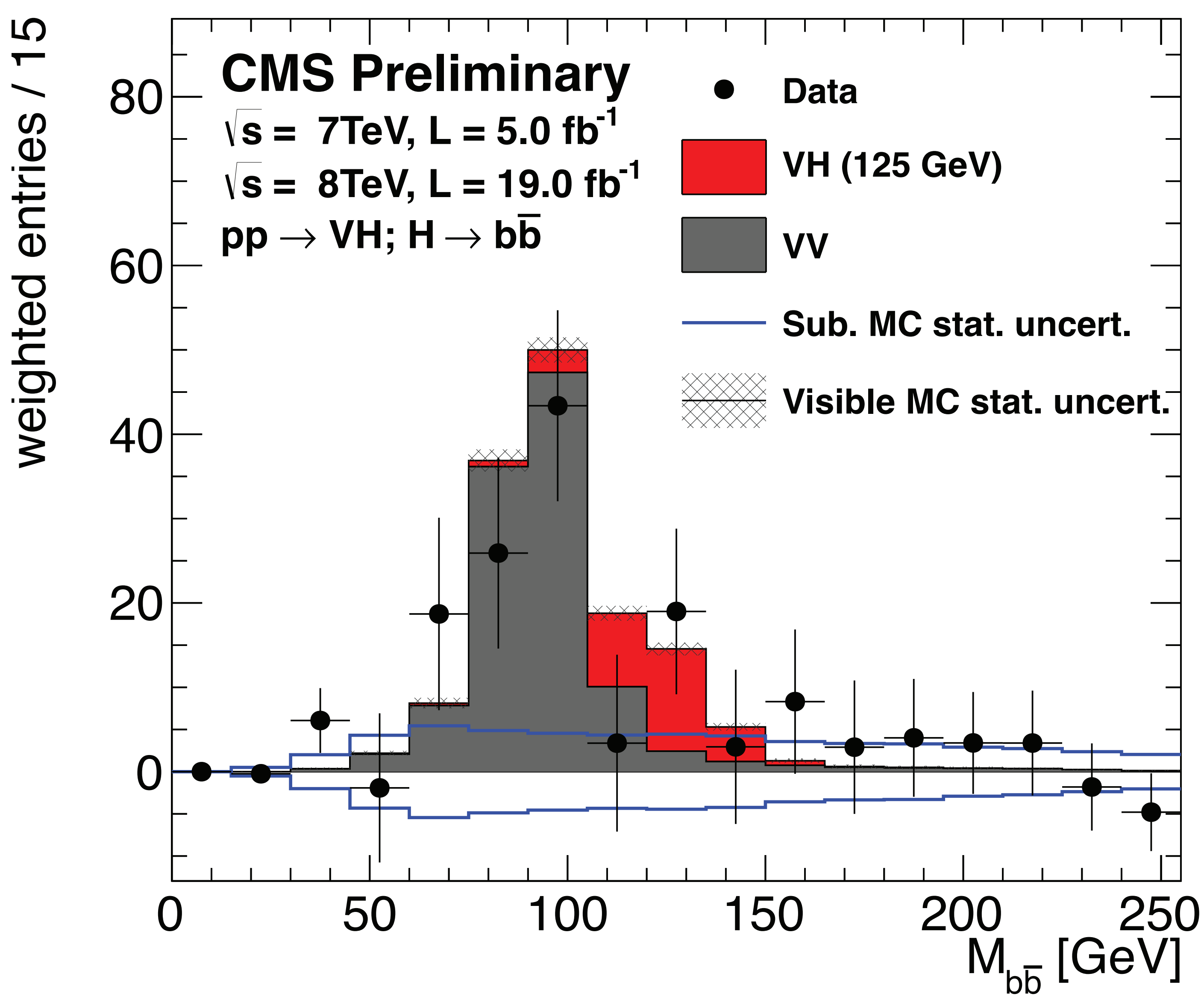
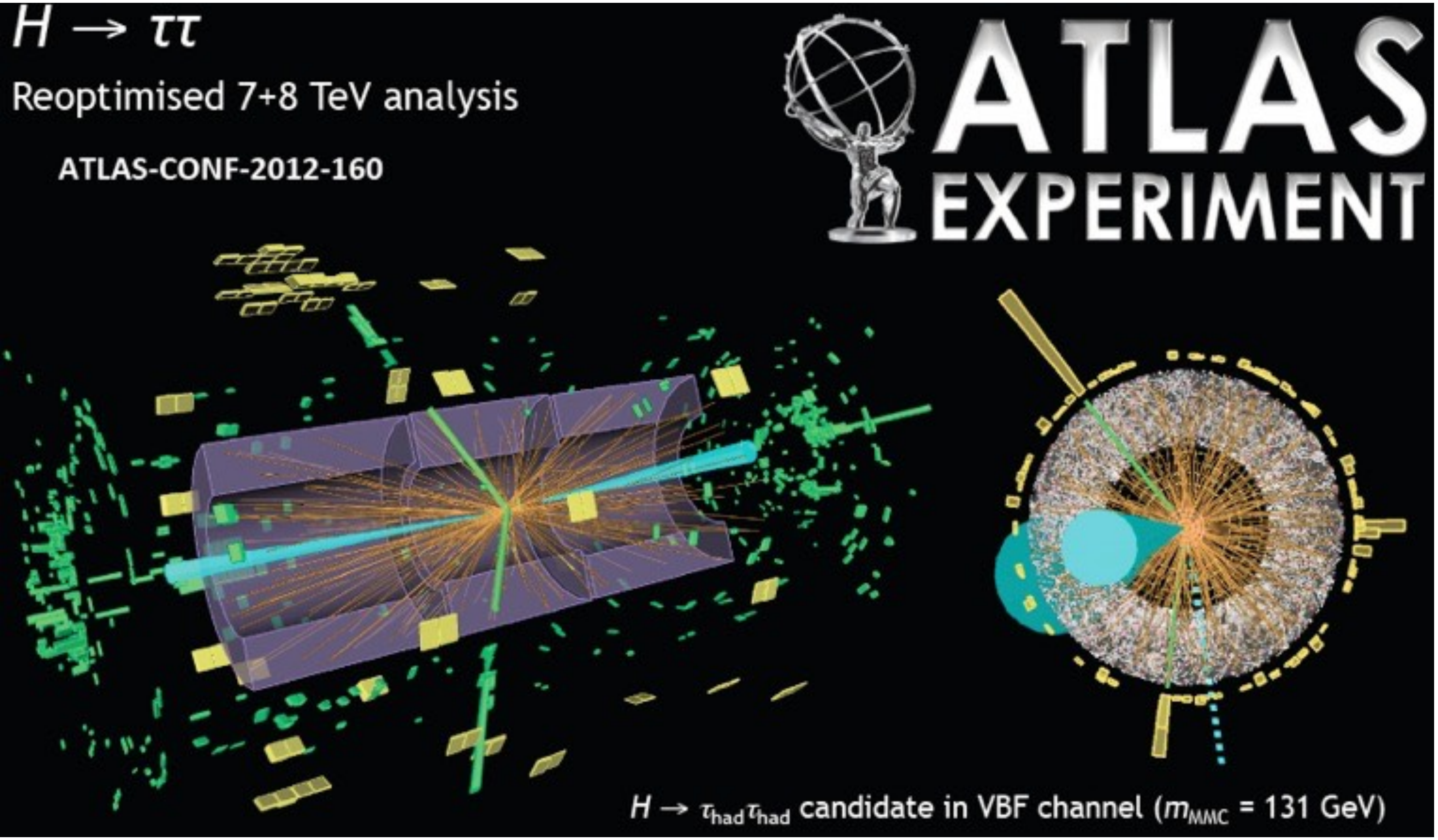


No observation yet: Event yield lower than expected

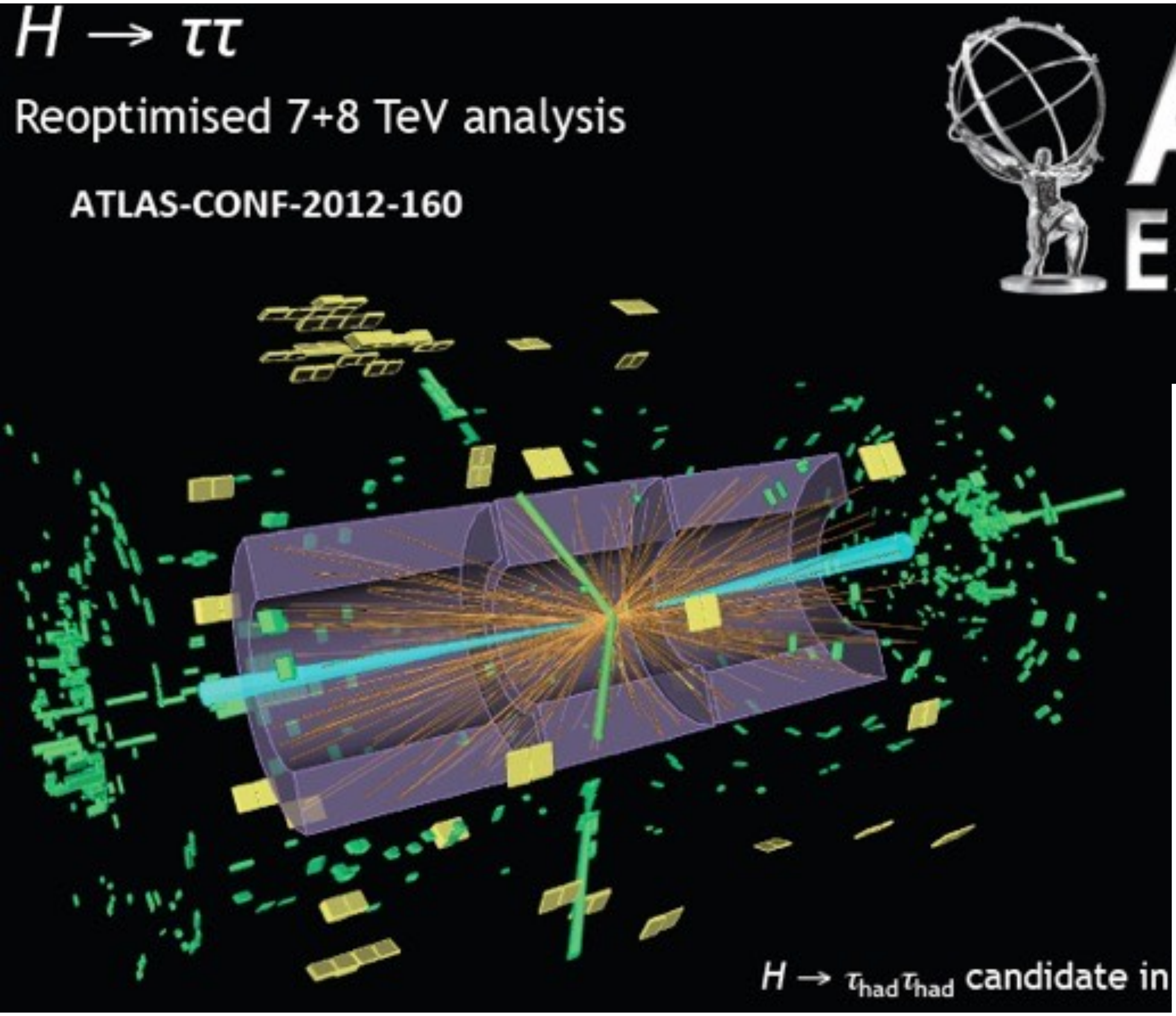
Combined Significance 2.6 σ (ATLAS + CMS)

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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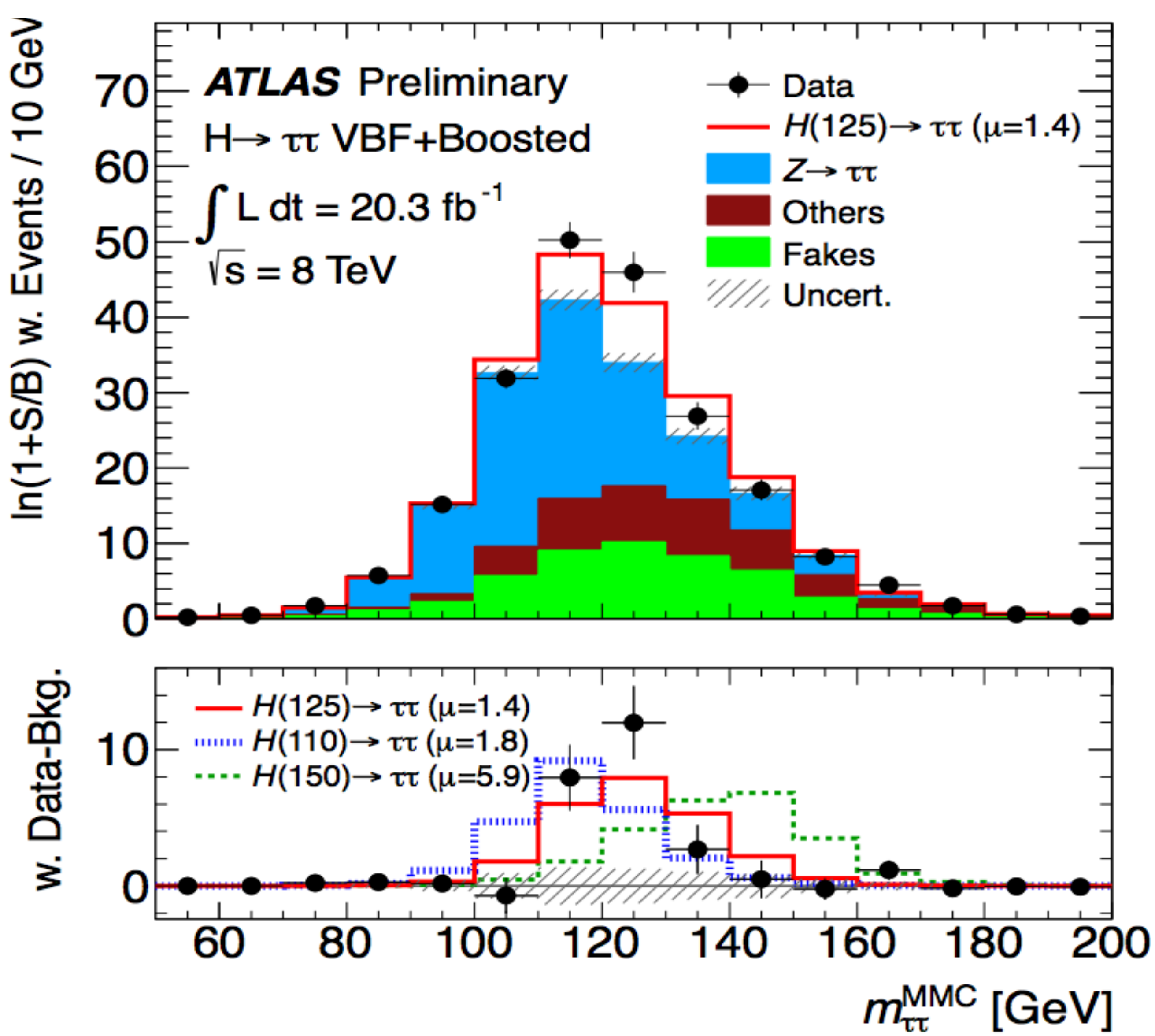
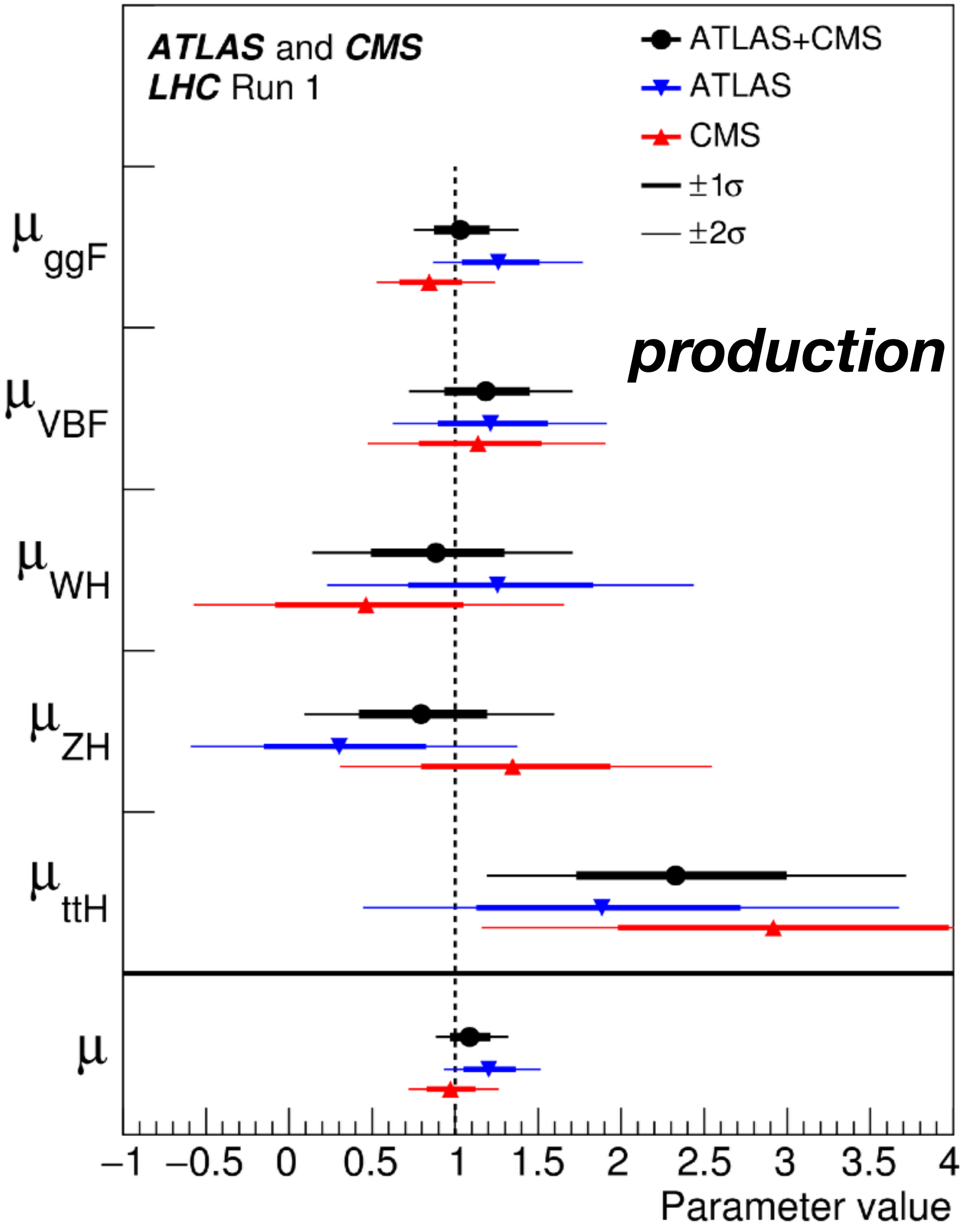


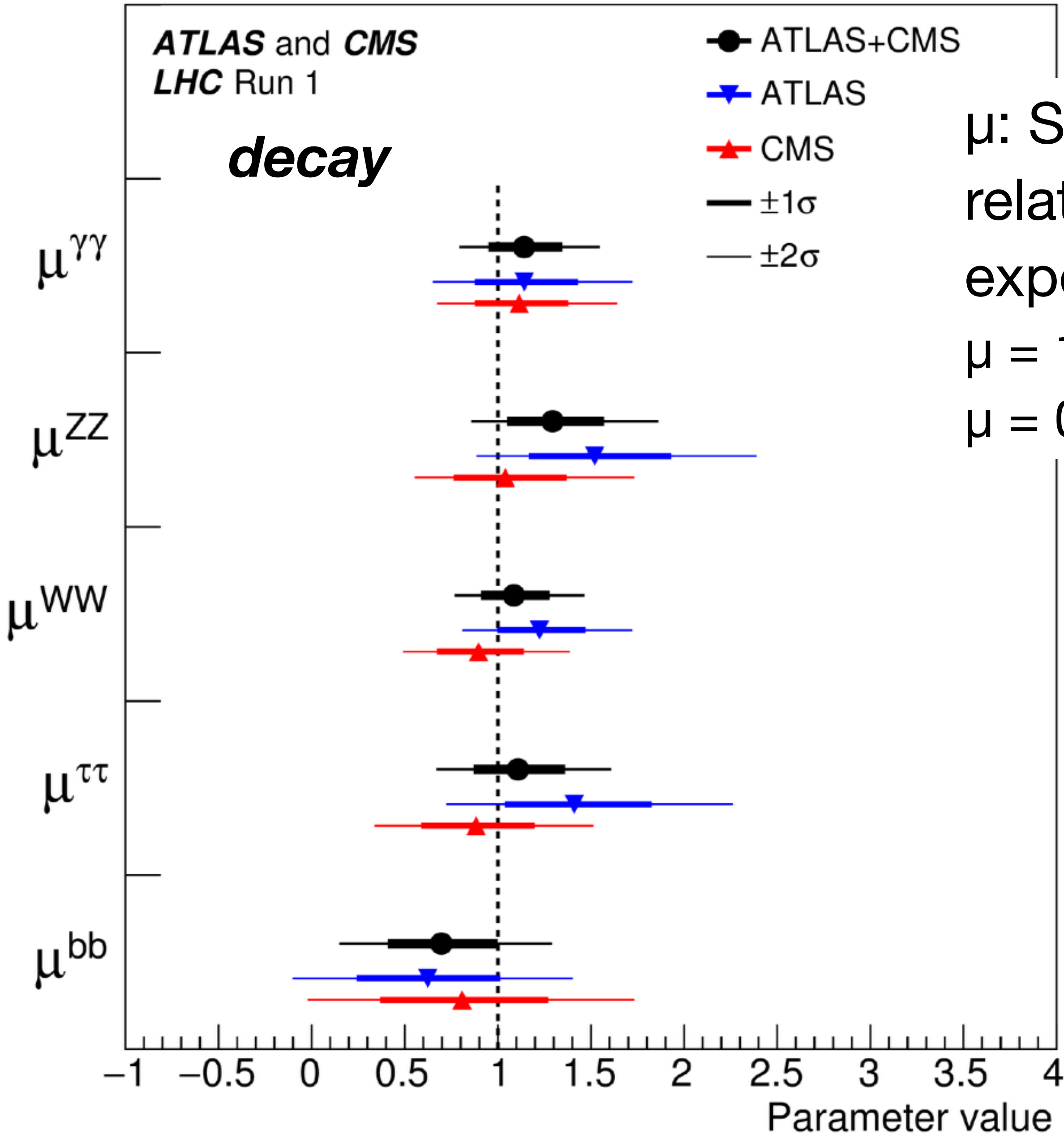
- Now established: Combined significance 5.5 σ

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





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

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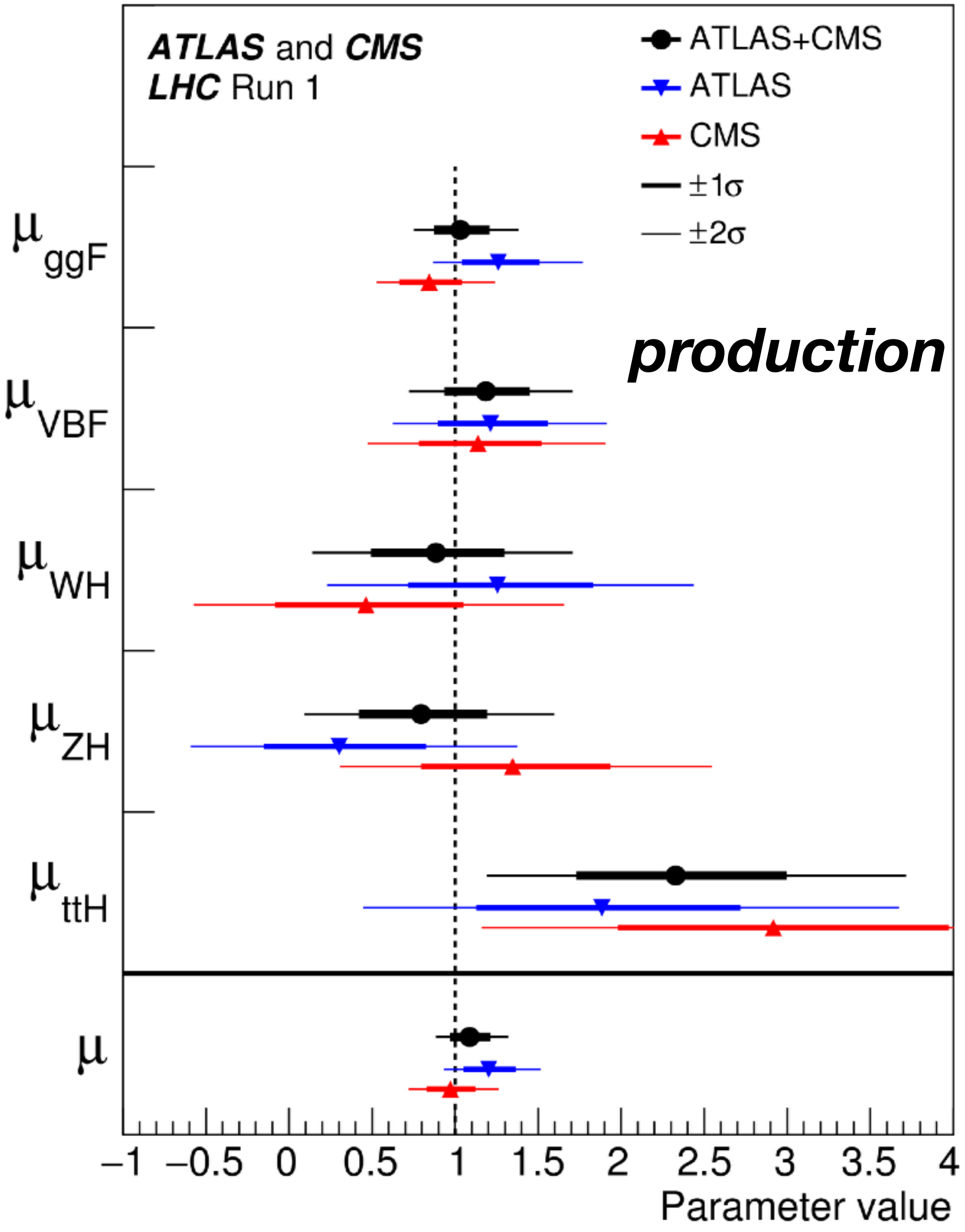
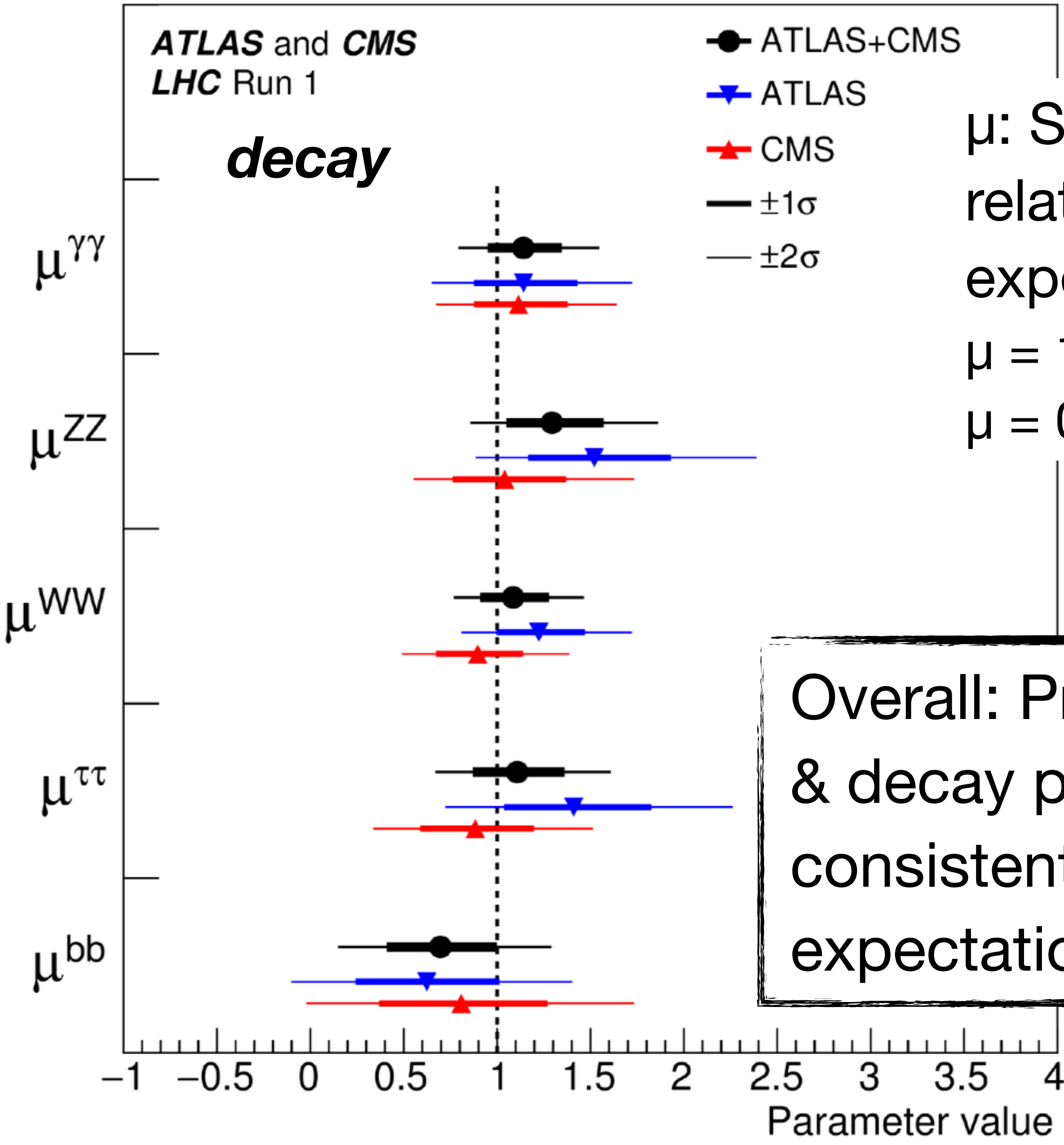
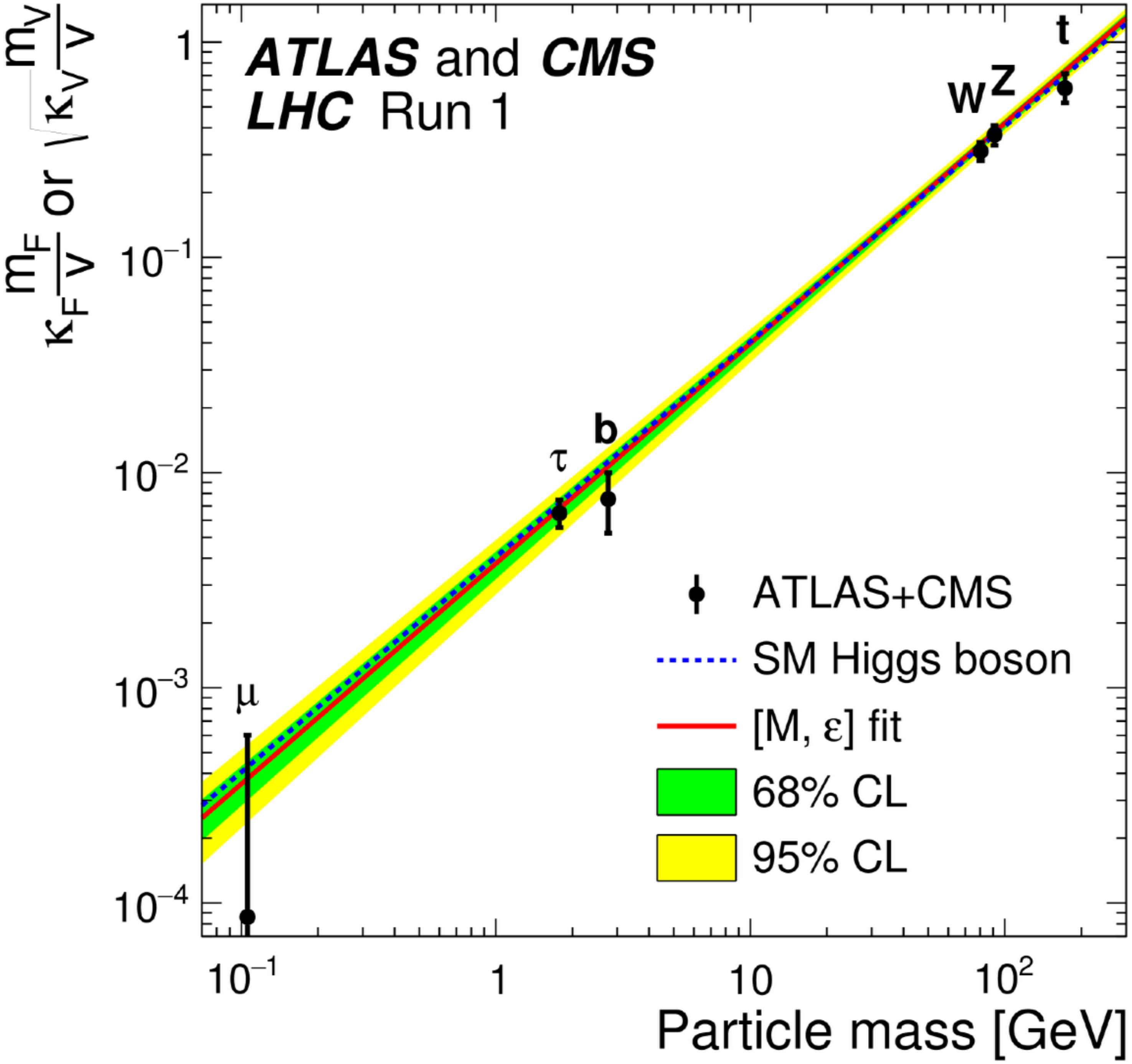




μ: Signal strength, relative to SM expectation
μ = 1: SM Higgs;
μ = 0: No Higgs

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

Higgs Couplings



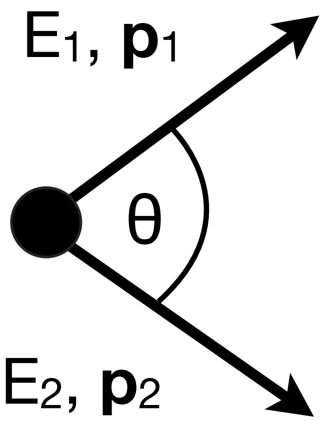
- From the measured signal strengths the couplings of the Higgs to various particles can be determined (with additional uncertainties)
- Clear evidence that couplings scale with particle mass (nothing like this has been observed for any other particle!):

It is a Higgs boson

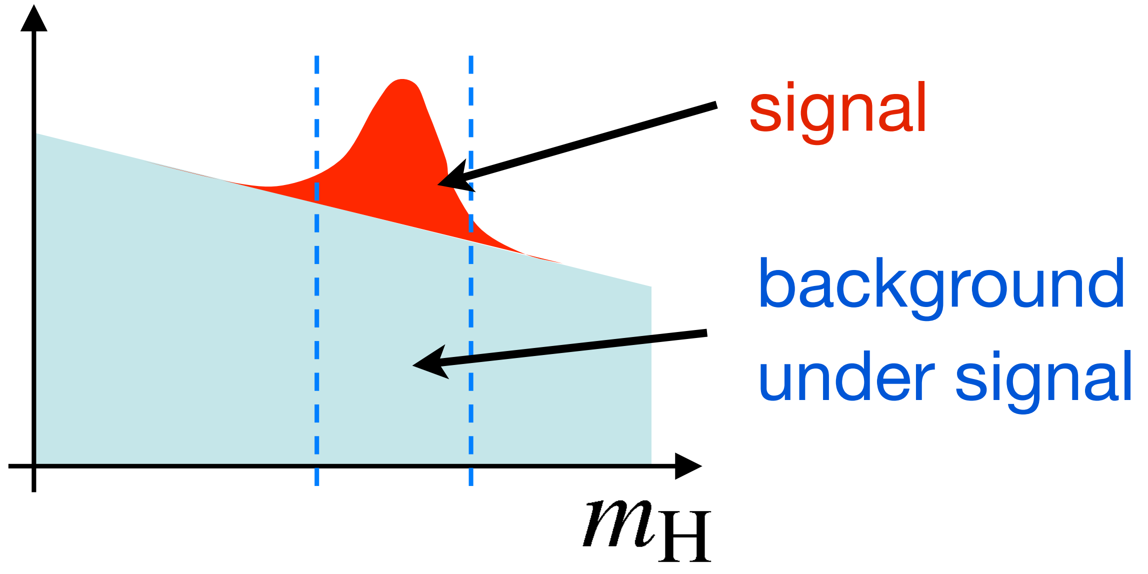
Mass

- 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



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

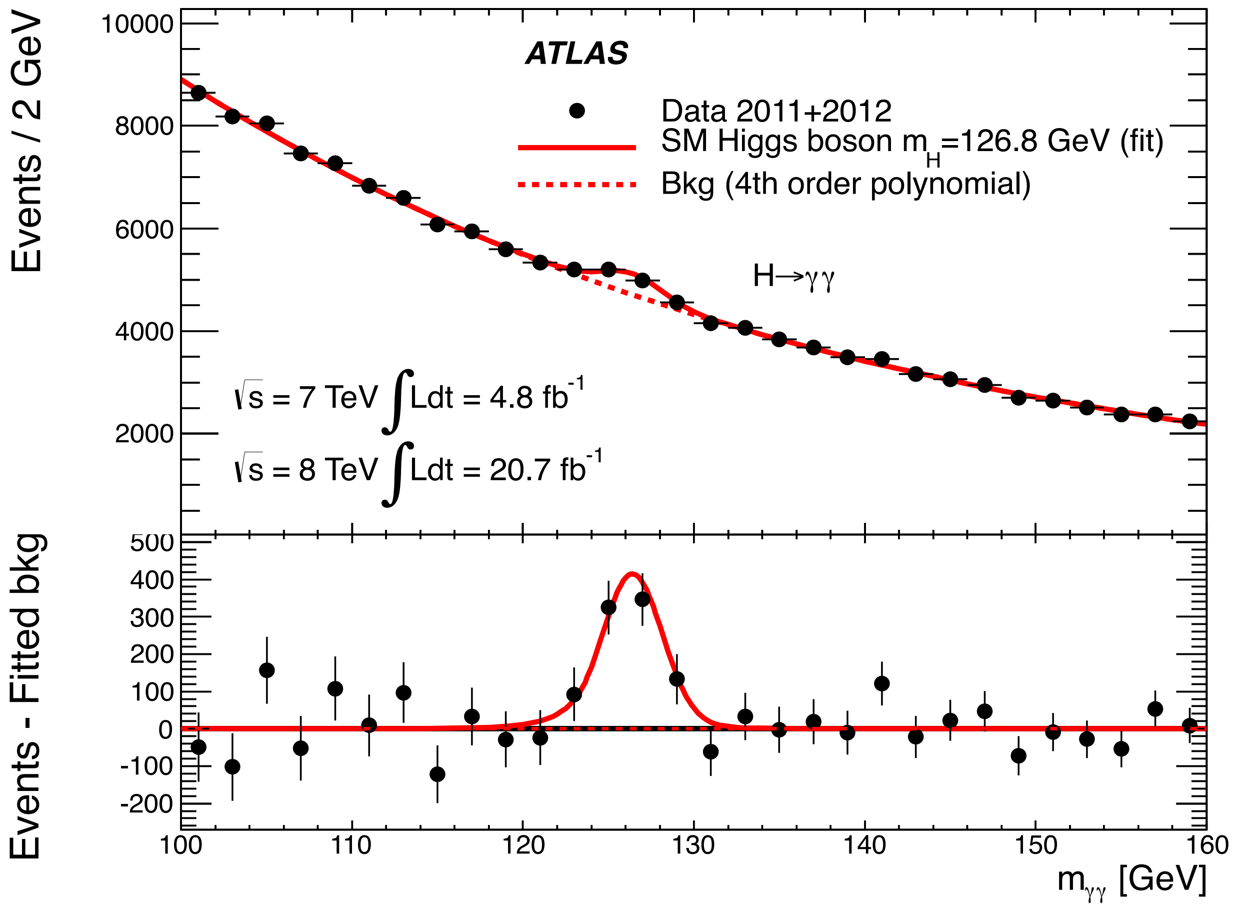


Significance: $\propto \frac{S}{\sqrt{B}} \propto \frac{1}{\sqrt{\sigma(M)}}$

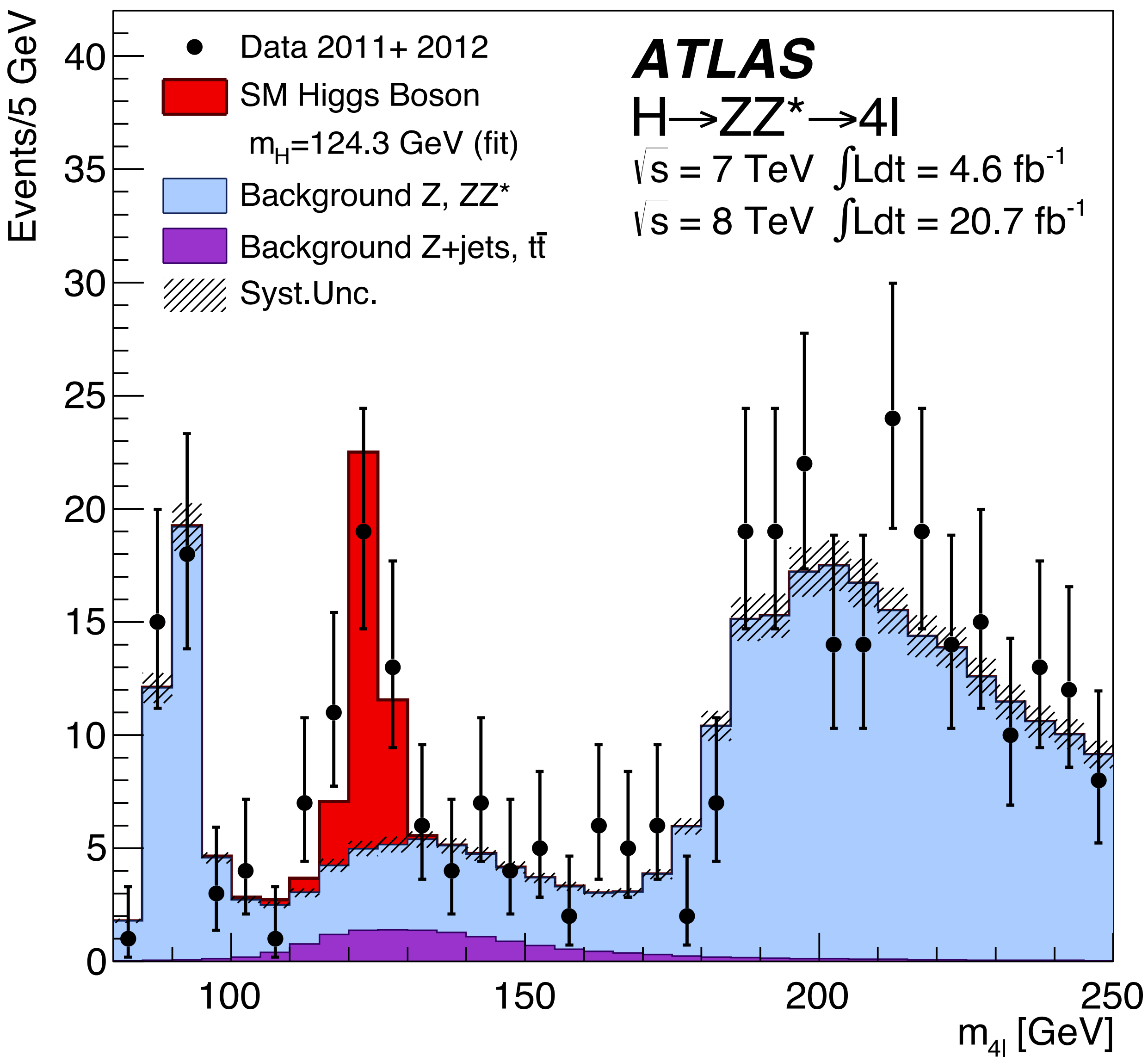
- Choose channels with good mass resolution -> Good energy and angular resolution for decay daughters

Mass: Measured in two Channels

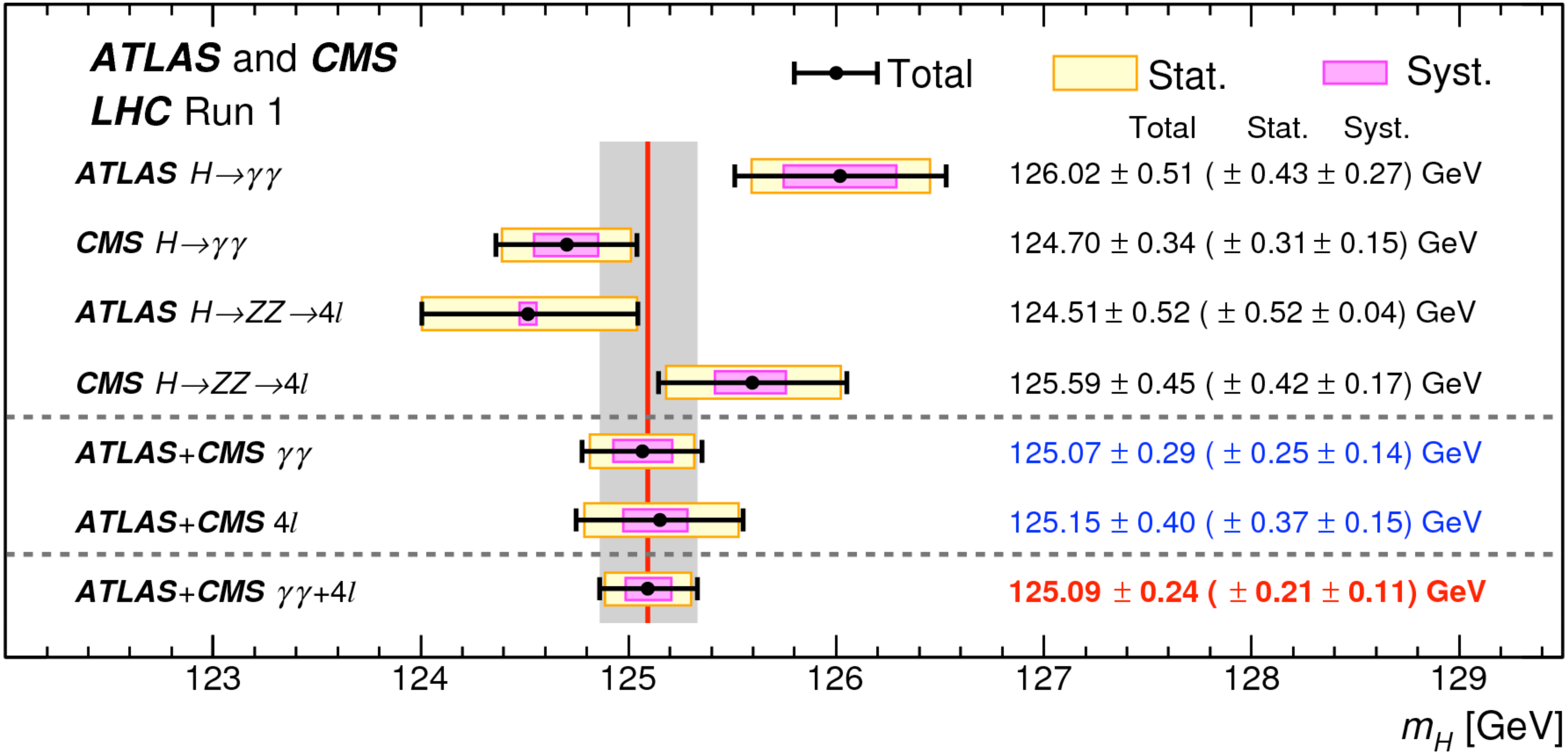
H -> γγ



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	**(yes)**	**yes**	**yes**	**(yes)**
H -> ττ	**yes**	**yes**	**yes**	**no**
still allowed ?		**yes**	**not really**	**no**

Frank Simon (fsimon@mpp.mpg.de)

The Spin of the New Boson

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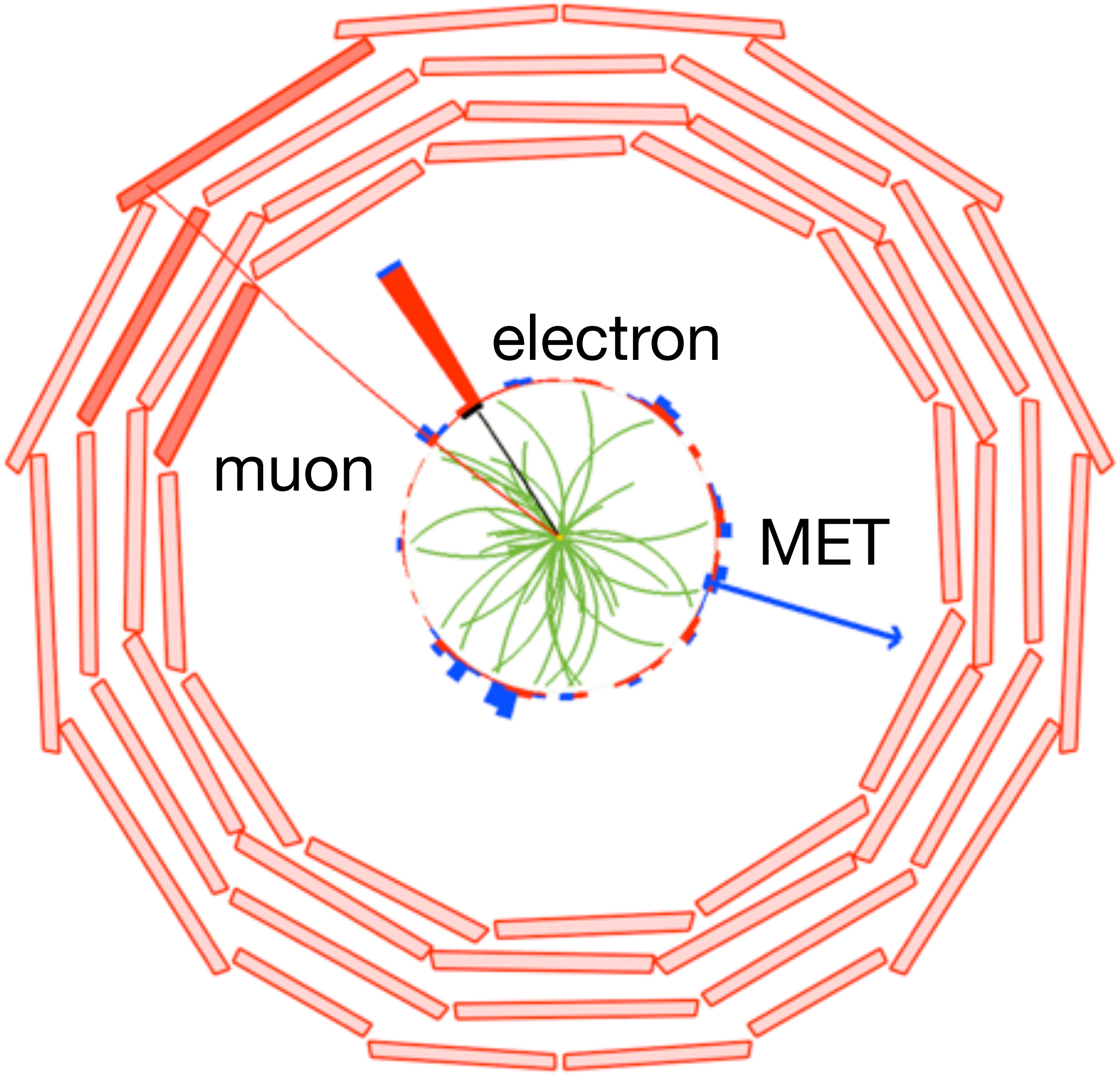
H -> bb	**(yes)**	**yes**	**yes**	**(yes)**
H -> ττ	**yes**	**yes**	**yes**	**no**
still allowed ?		**yes**	**not really**	**no**

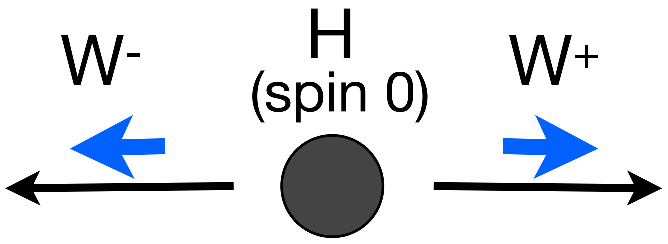
The question of spin is basically settled - not with decay mode observations alone, since there can be additional angular momentum in the two-particle final states...

The Spin of the New Boson

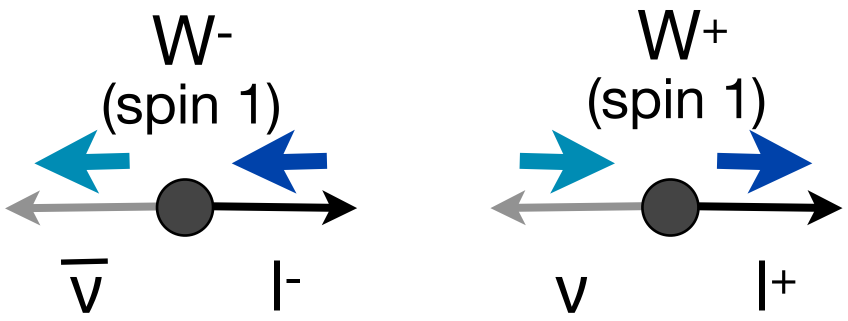


- The full answer will come from angular correlations!

One example: H->WW

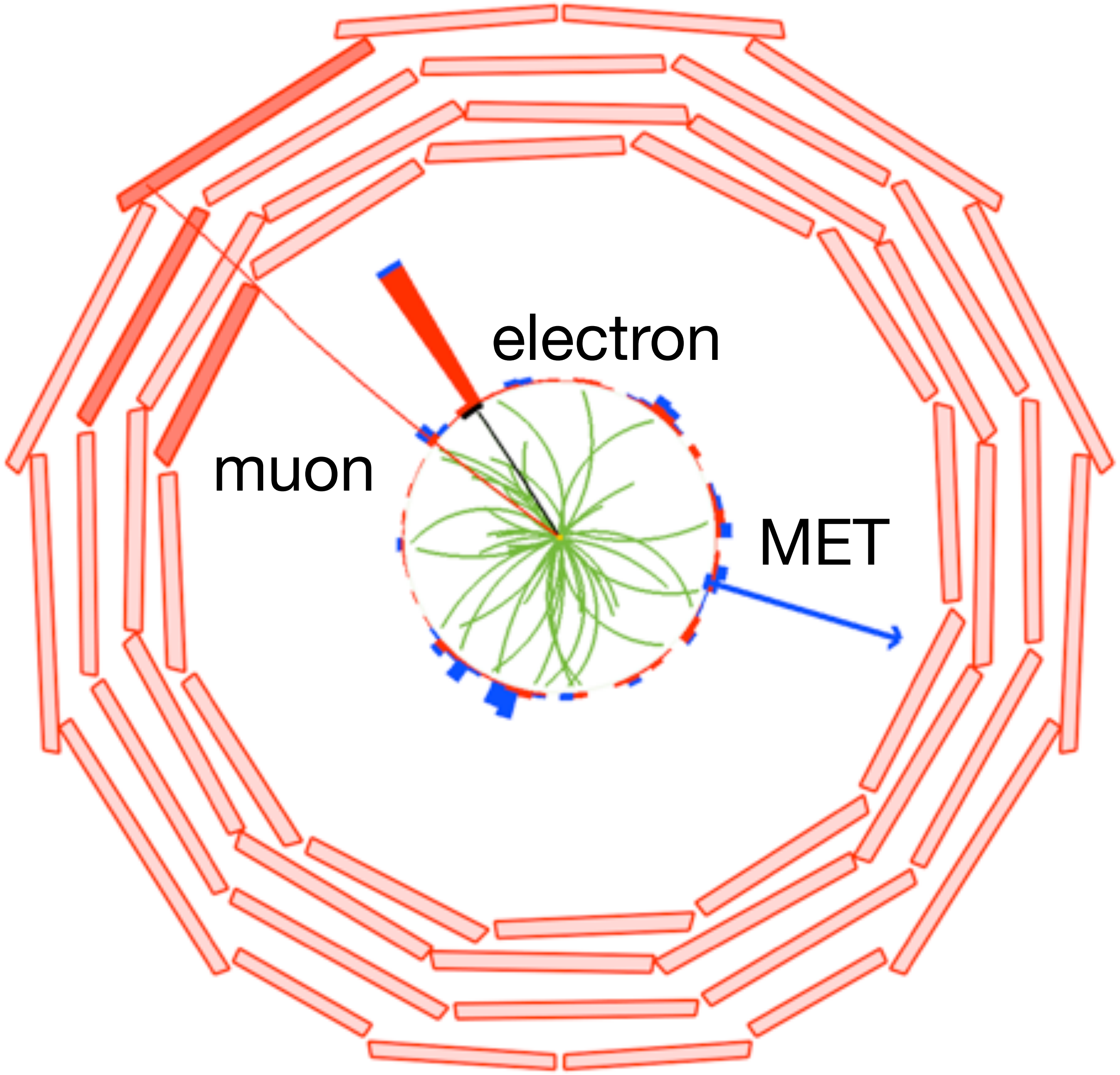


parity violation in weak interactions:



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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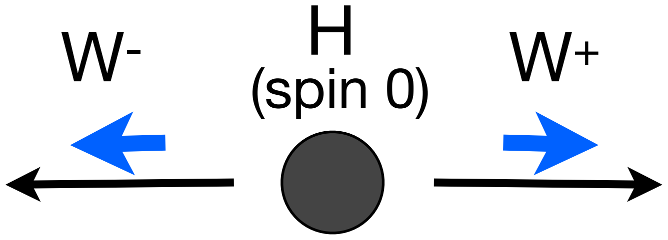

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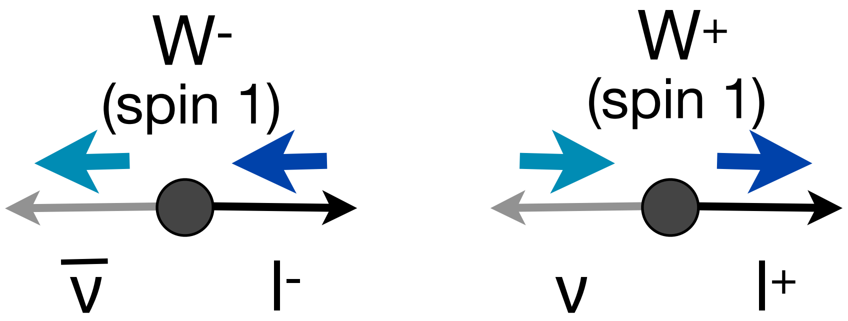
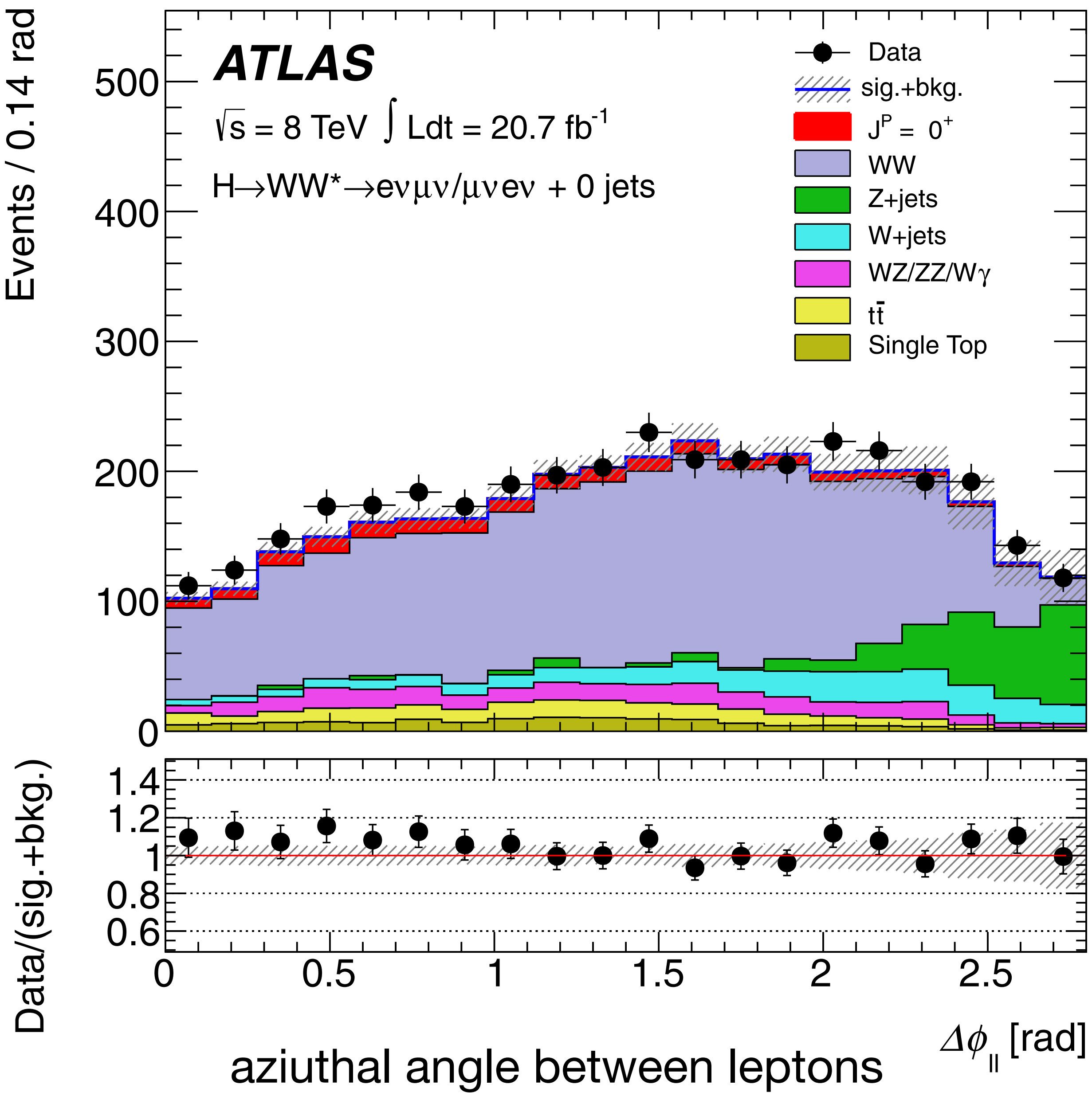


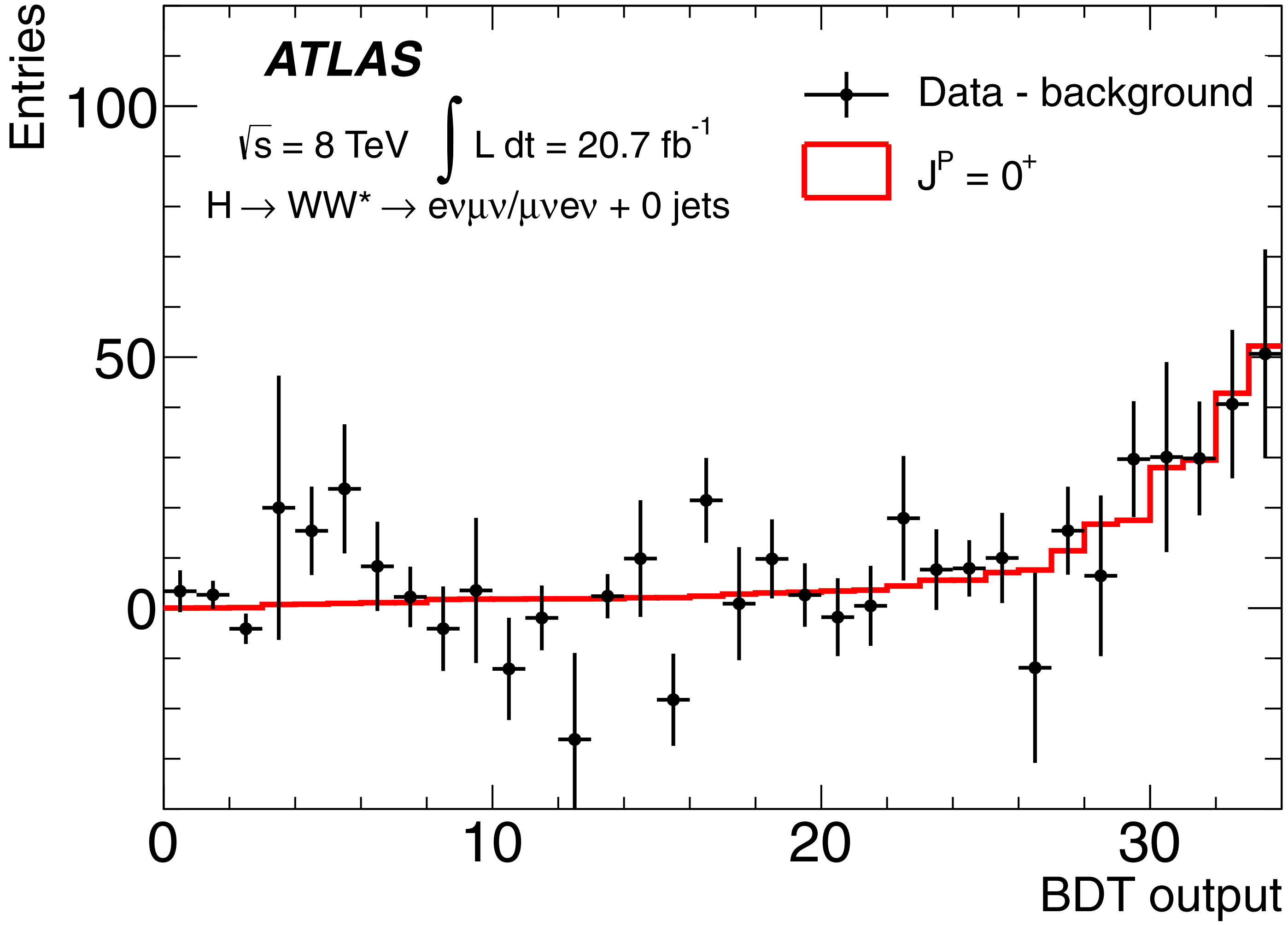
A word of caution: The requirements for large MET and also small opening angle between the leptons in the analysis disfavors event selection for spin ≠ 0

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

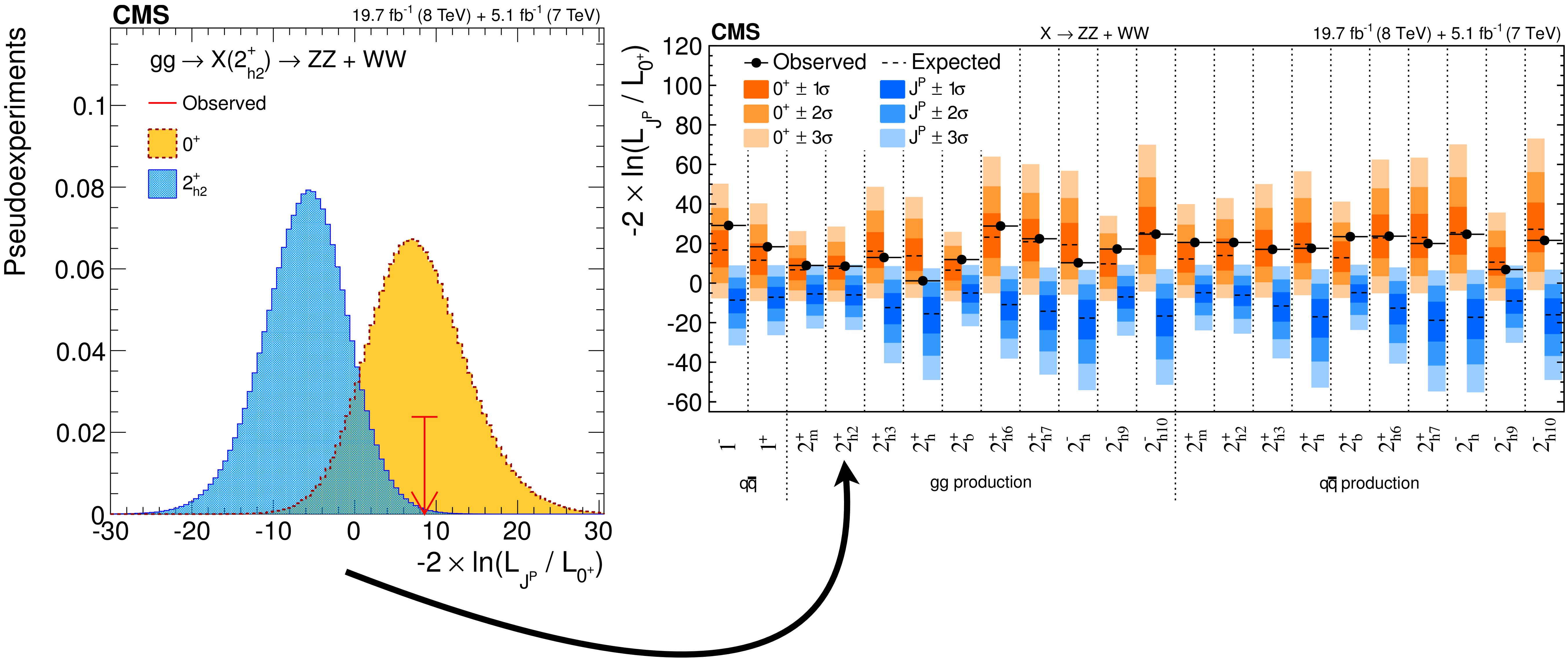


aziuthal angle between leptons



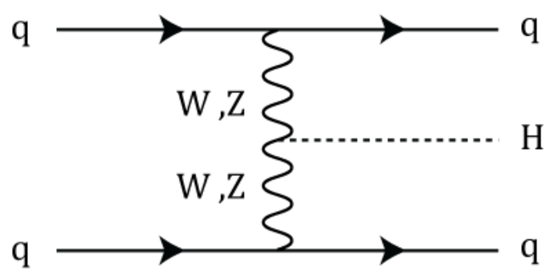
- Not an easy measurement: High background levels
  - 0^+ favored by data, but other hypotheses typically still allowed at the 5 - 10% probability level

The Spin and Parity of the New Boson

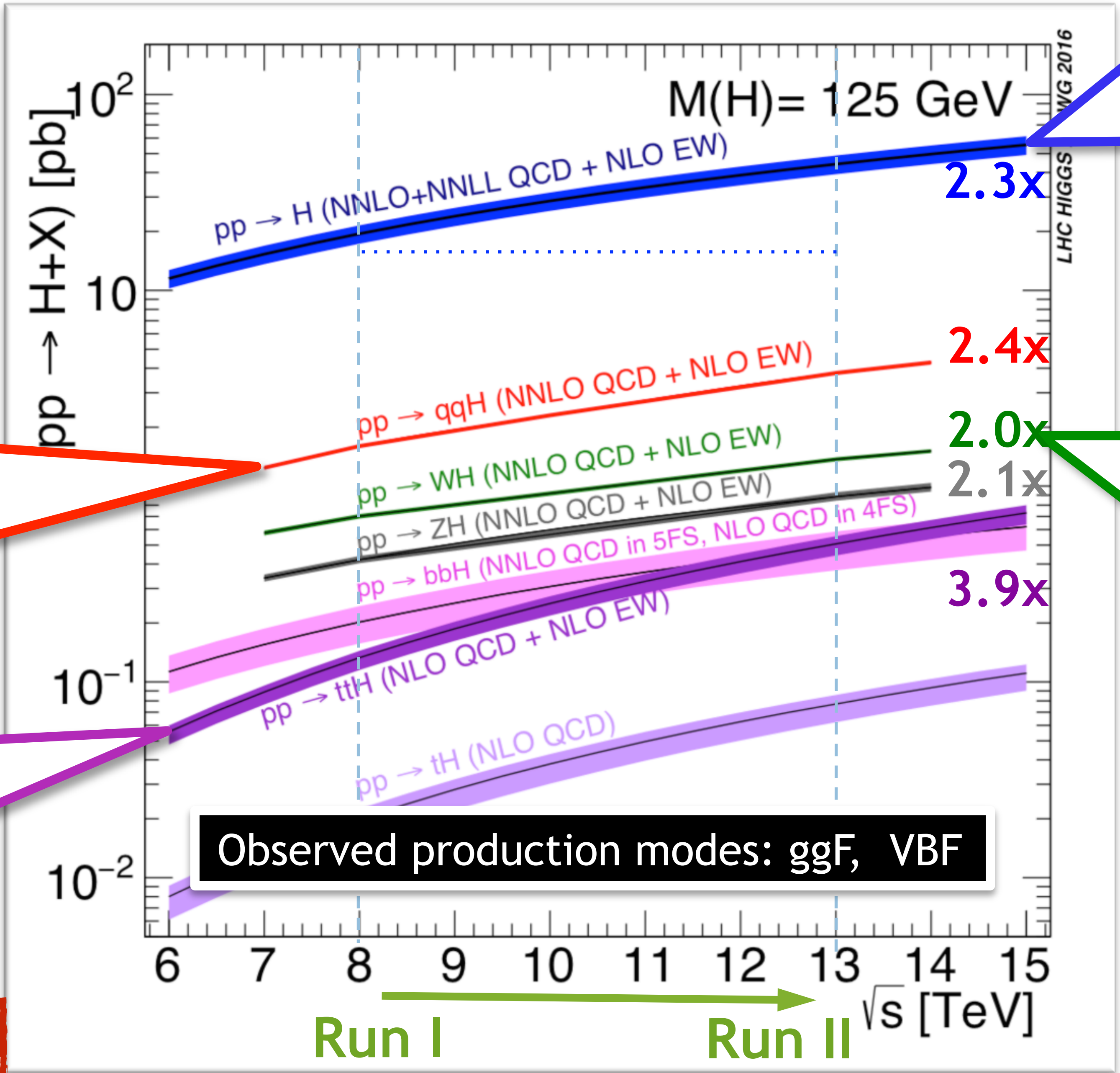


- CMS summary - alternative hypotheses tested compared to 0^+
- 0^+ strongly favored in every case - alternatives typically rejected at > 99% CL
  - only leaves room for small admixtures of other states for composite Higgs models

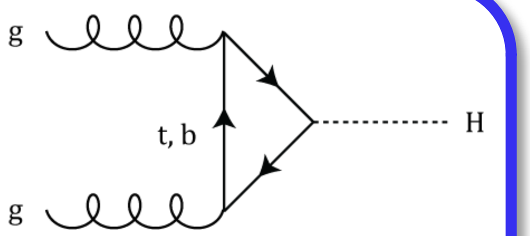
Newest Results: Higgs @ 13 TeV



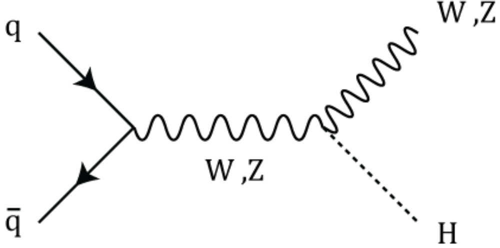
VBF (7.1%)
Vector boson fusion



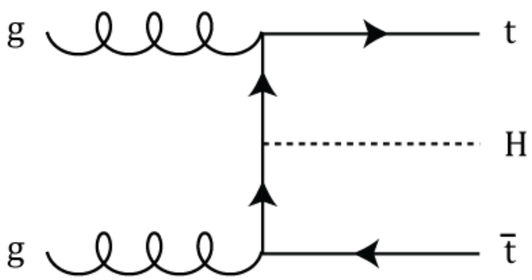
Observed production modes: ggF, VBF



ggH (87.4%)
Gluon fusion



VH (4.9%)



ttH (0.6%)

This year: Have seen evidence for ttH production!

7/8 TeV (2011/2012) **13 TeV (>2015)**

… already ~ 4 x more data than run 1, and higher cross section: many more Higgses!

Summary - The Scientific Breakthrough of 2012

Science

Breakthrough of the Year, 2012

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.

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.

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 $\gamma\gamma$ channel has surpassed $7\ \sigma$ 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:
  - Mostly still large uncertainties on 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: Heavy Quarks, S. Bethke, 29.01.2018

Schedule

1.	Introduction	16.10.
2.	Accelerators	23.10.
3.	Particle Detectors I	30.10.
	----------- no lecture -------------	**06.11.**
4.	Particle Detectors II	13.11.
5.	Monte Carlo Generators and Detector Simulation	20.11.
6.	Trigger, Data Acquisition, Computing	27.11.
7.	QCD, Jets, Proton Structure	04.12.
8.	Top Physics	11.12
9.	Tests of the Standard Model	18.12.
	----------- Christmas ---------------------	
10.	Physics beyond the SM	08.01.
11.	Higgs Physics I	15.01.
12.	Higgs Physics II	22.01.
13.	Heavy Quarks	29.01.
14.	LHC Outlook & Future Collider Projects	05.02.