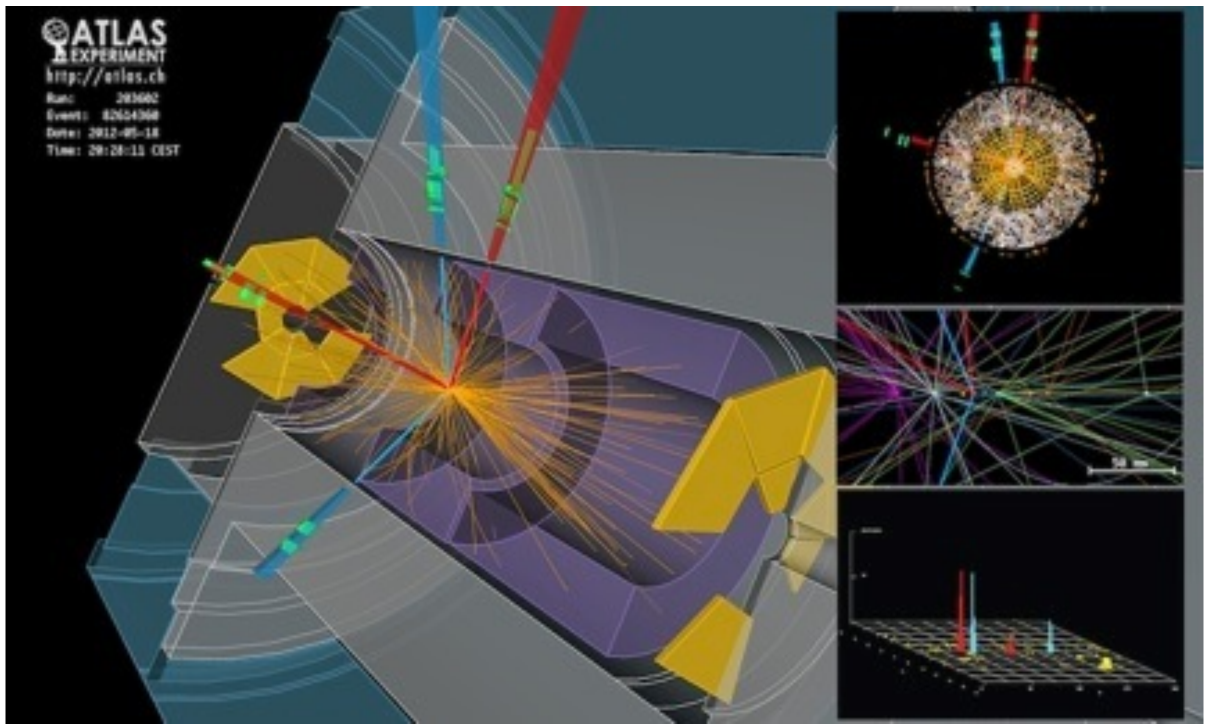
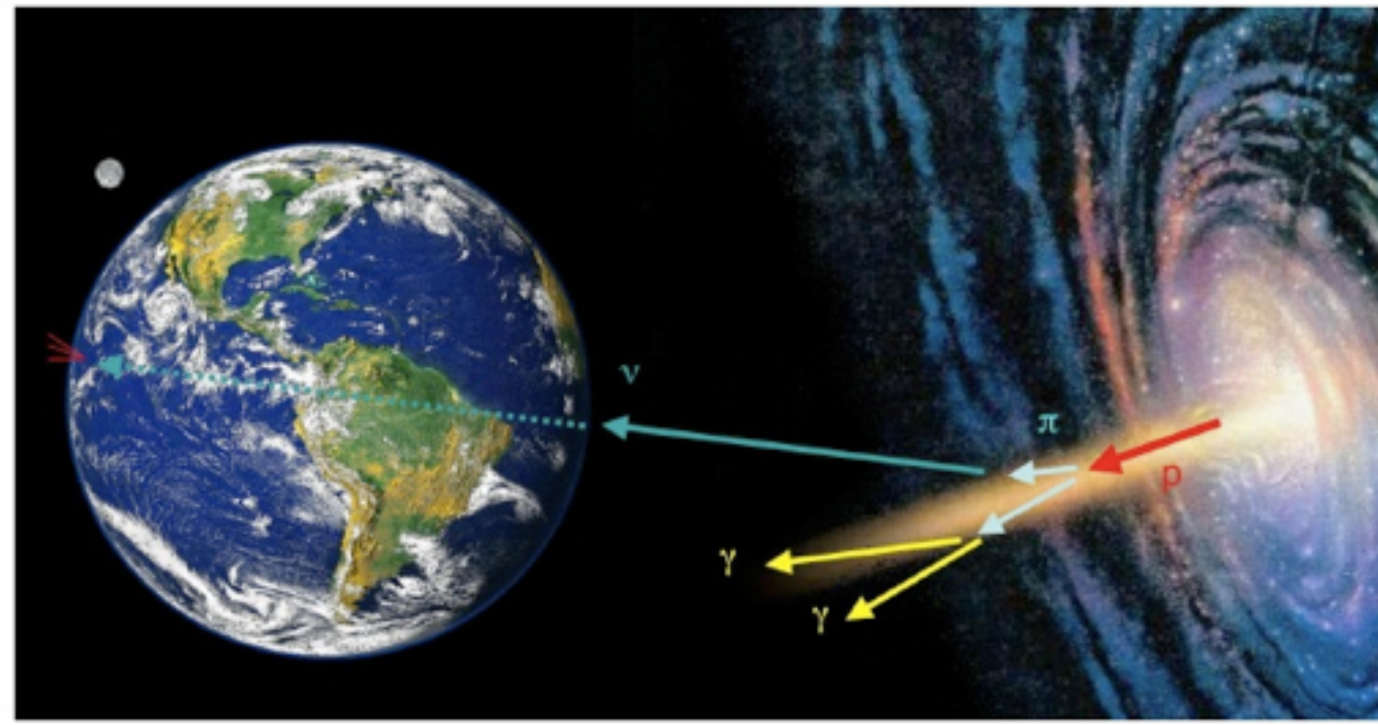
Particle Physics at Colliders and in the High Energy Universe





5. The Higgs Boson

12.11.2018

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

Dr. Frank Simon
Dr. Bela Majorovits

Outline

- Theoretical Foundations: The Higgs Mechanism & the Higgs Boson
- Discovering a New Boson
  - 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, Z^0, 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 $V(\phi) = \lambda (\phi^\dagger\phi)^2 - \mu^2 \phi^\dagger\phi$; with $\lambda, \mu^2 > 0$;

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

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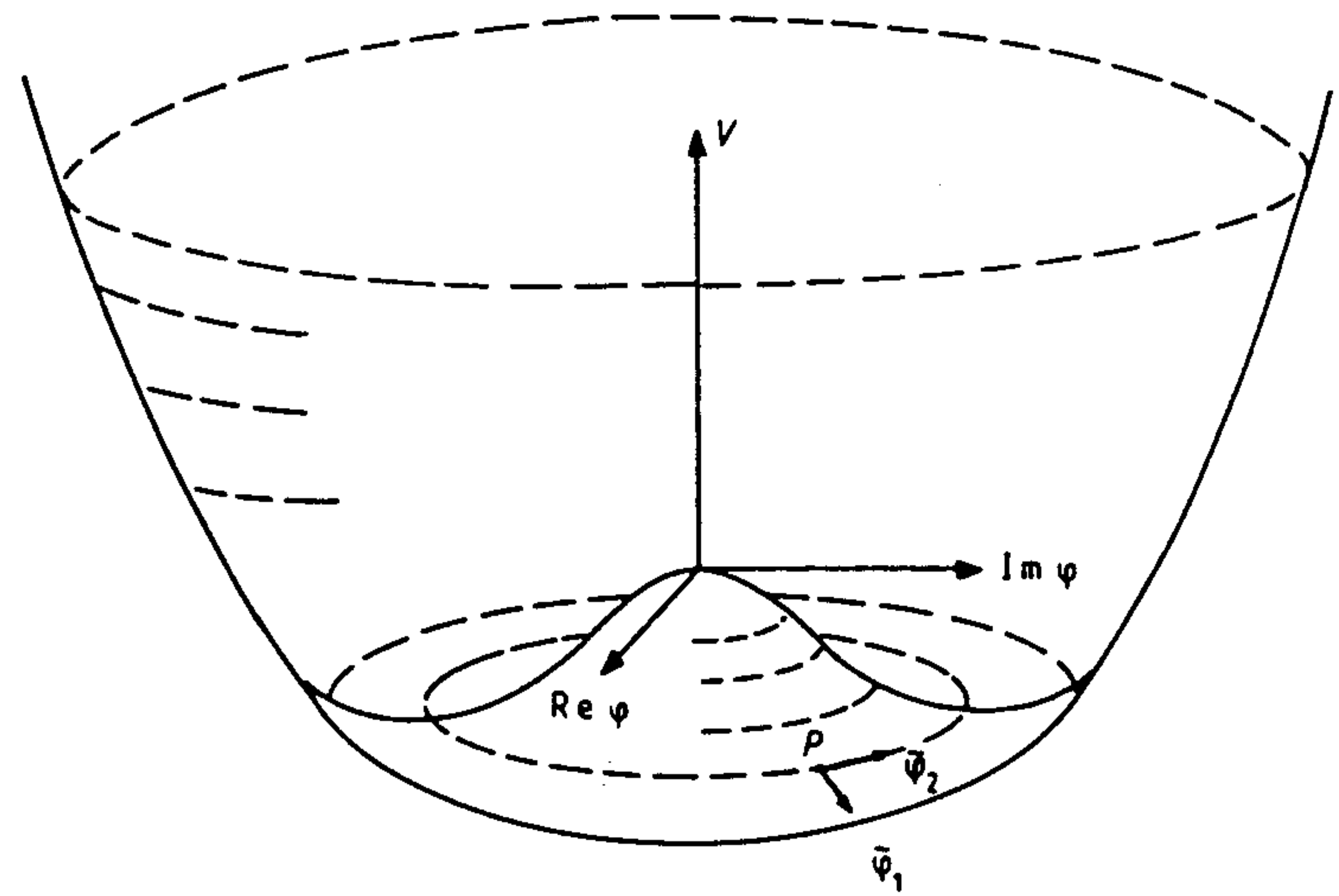

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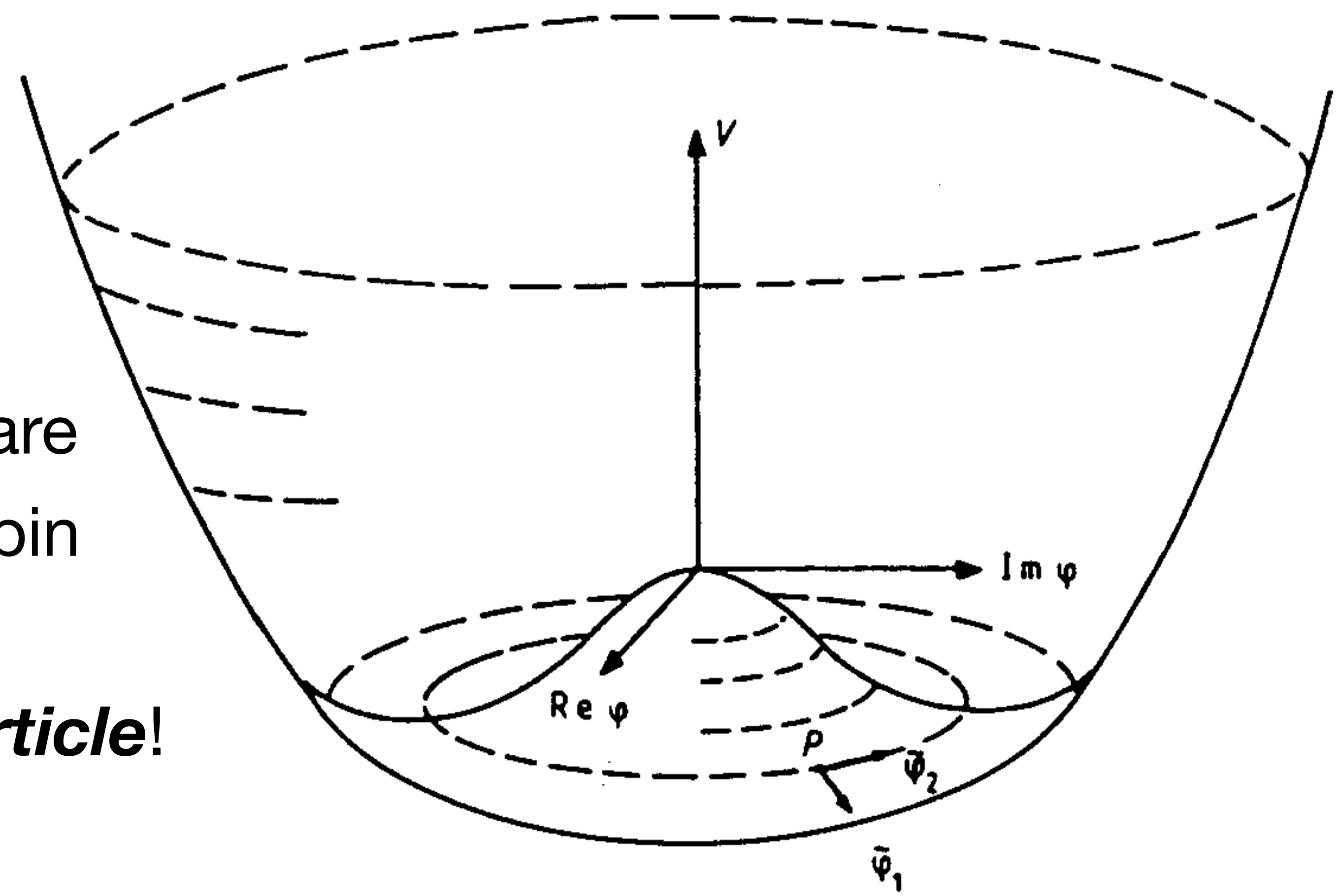

  - 3 of the 4 real degrees of freedom are used to generate the longitudinal spin d.o.f. of Z^0 and $W^\pm$
    The 4. d.o.f. –> ***physical Higgs particle***!

The SM Higgs Boson: Theoretical Basis

- inserting ϕ in Lagrange function results in 3 massive vector fields, 1 massless vector-field, plus one massive scalar field with

$$M_W = \frac{1}{2} g v \quad \Rightarrow \quad v = 246 \text{ GeV}$$

$$M_Z = M_W / \cos\theta_w \qquad (g = e/\sin\theta_w)$$

$$M_\gamma = 0$$

$$M_H = 2\mu^2 = 2\lambda v^2$$

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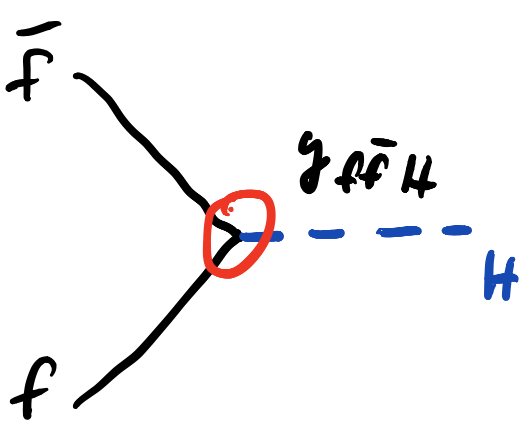
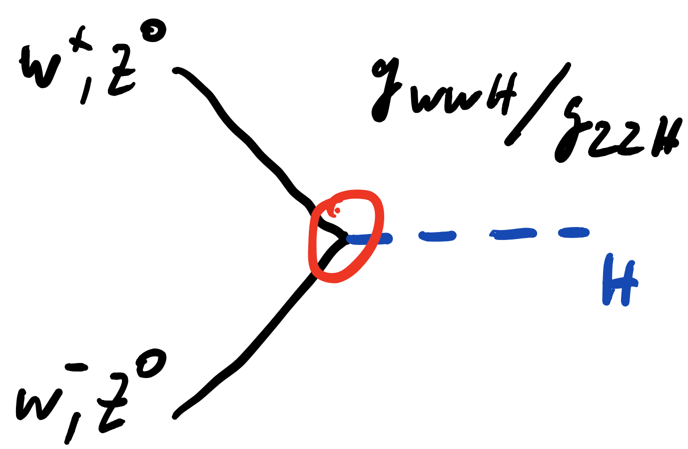
- fundamental coupling of the Higgs to fermions and bosons:



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



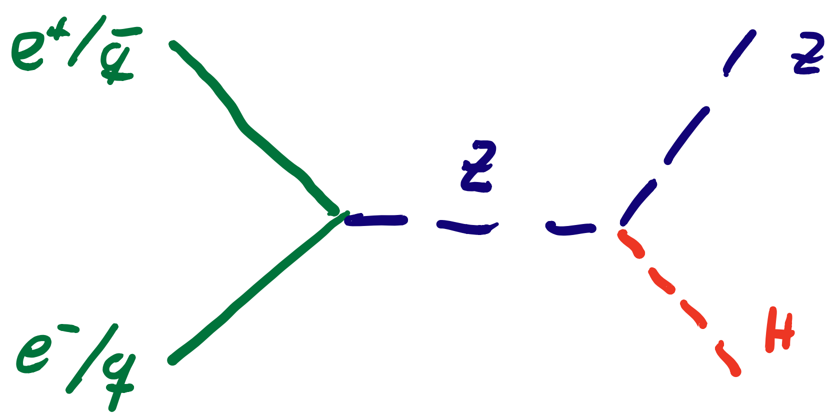
$$g_{WWH} = \frac{e\, M_W}{\sin\theta_W}$$

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

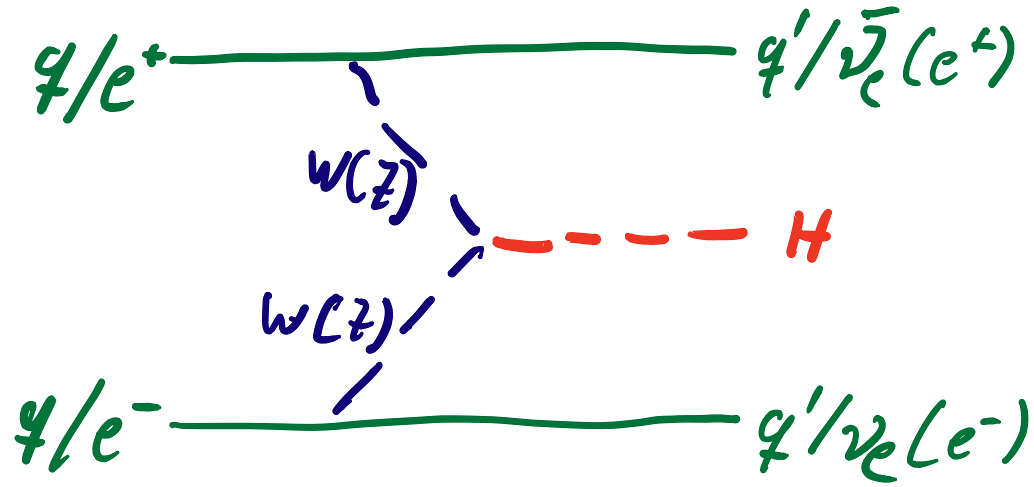
The SM Higgs Boson: Production

- Production and decay options given by the couplings

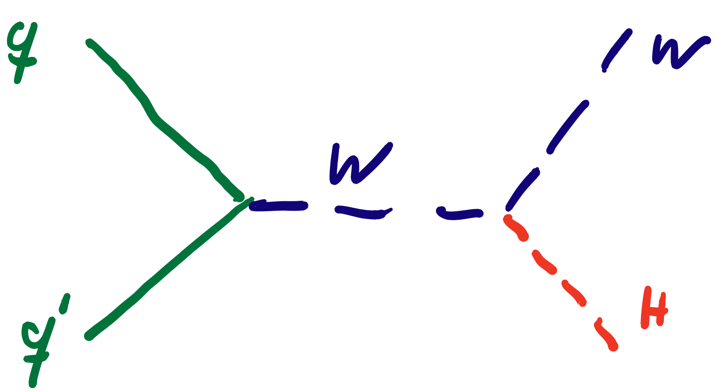
Leading production processes:

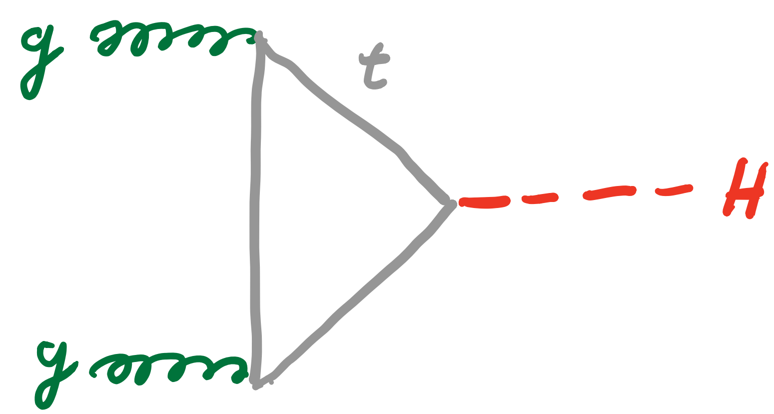


Higgsstrahlung / associated production



Vector Boson Fusion (VBF)



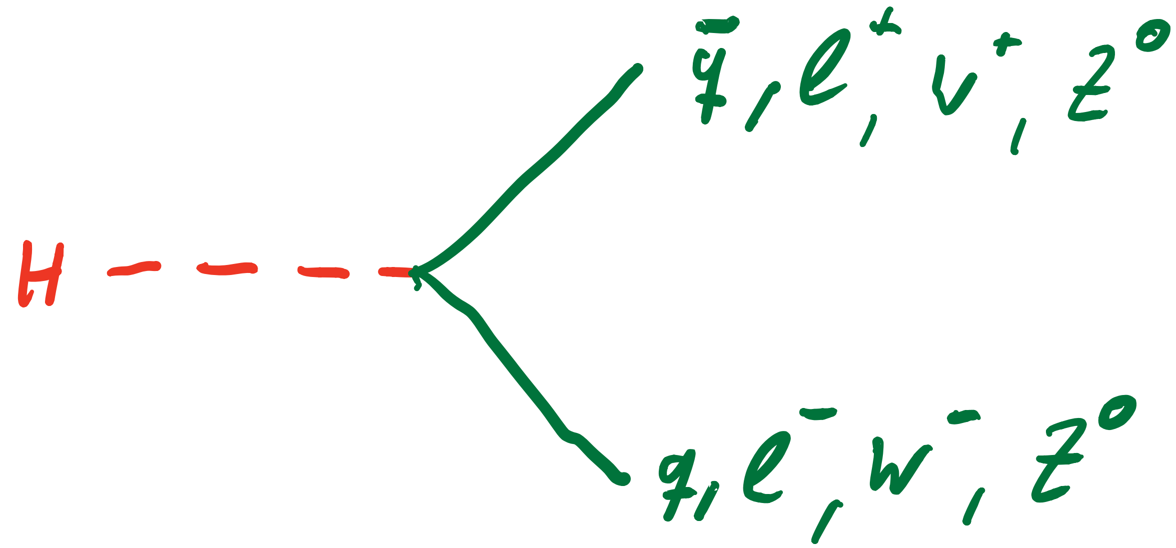


Gluon Fusion

The SM Higgs Boson: Decay

- Production and decay options given by the couplings

Tree-level processes:



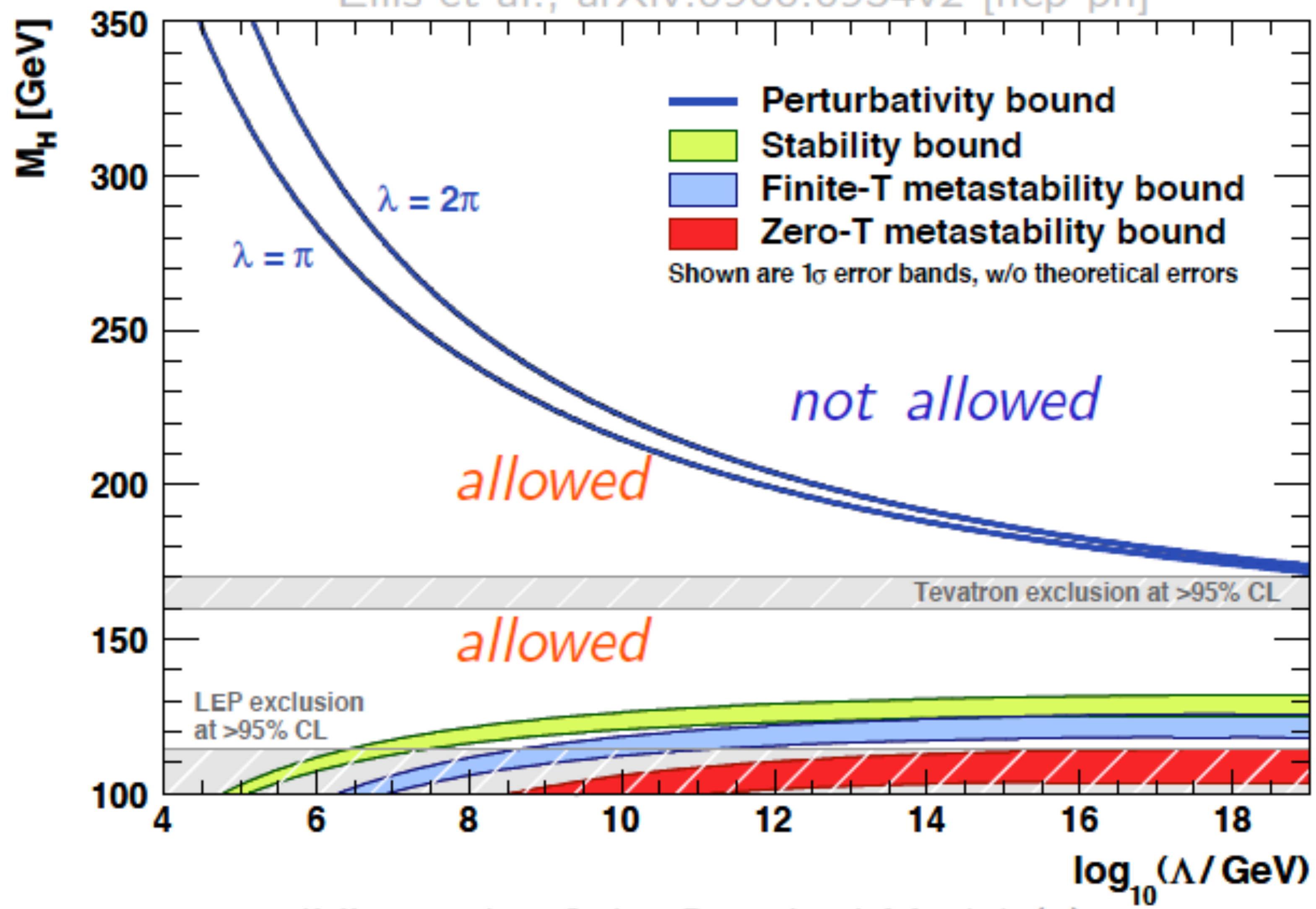
+ loop-induced decays to photons, gluons

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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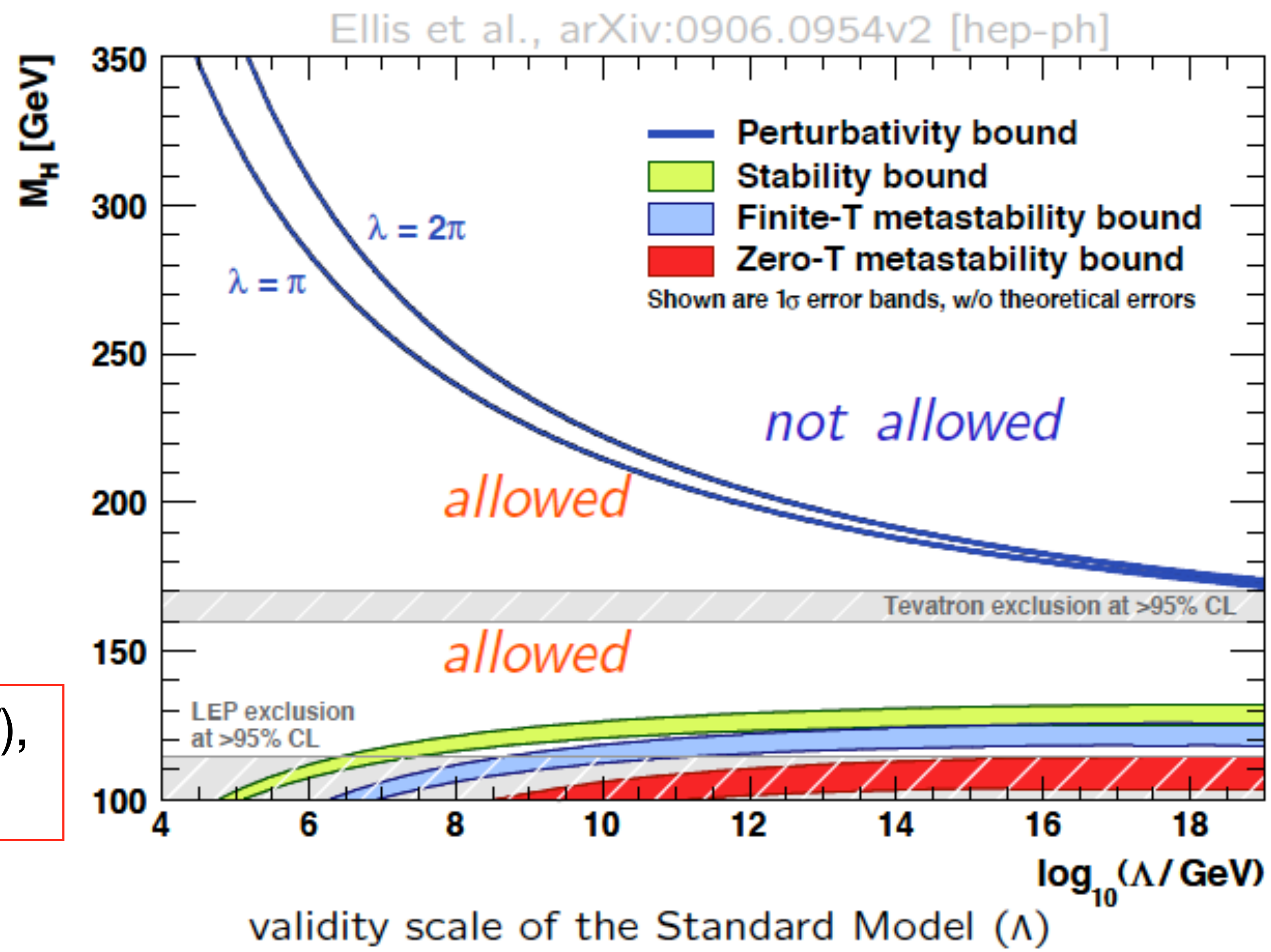

If SM is valid only up to Λ = O(1 TeV), then M_H = 50 ... 1000 GeV

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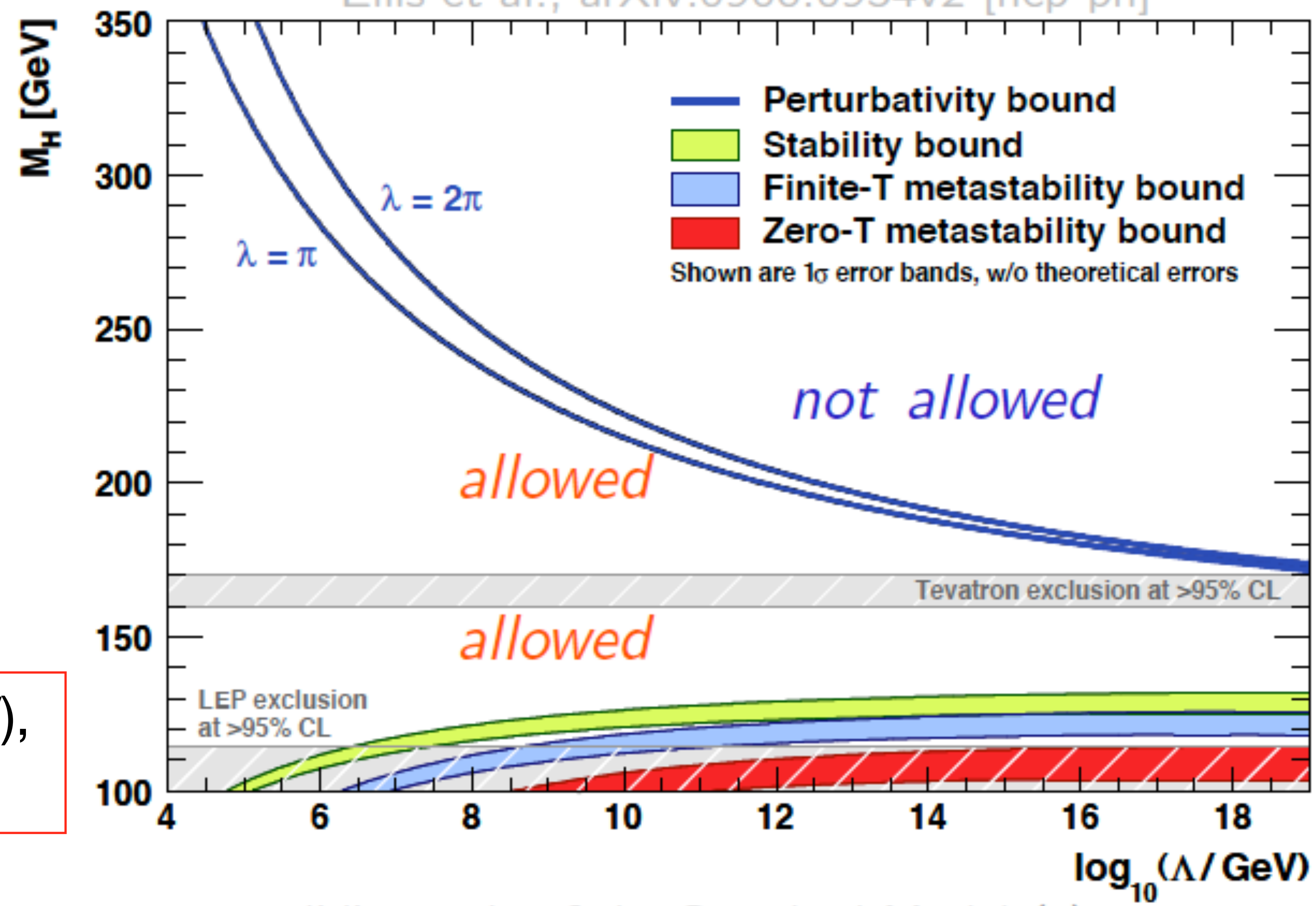


validity scale of the Standard Model (Λ)

If SM is valid only up to $\Lambda = O(1\ \text{TeV})$,
then M_H = 50 ... 1000 GeV

If SM is valid up to $\Lambda = O(M_{Planck})$
then $M_H \sim$ 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.)

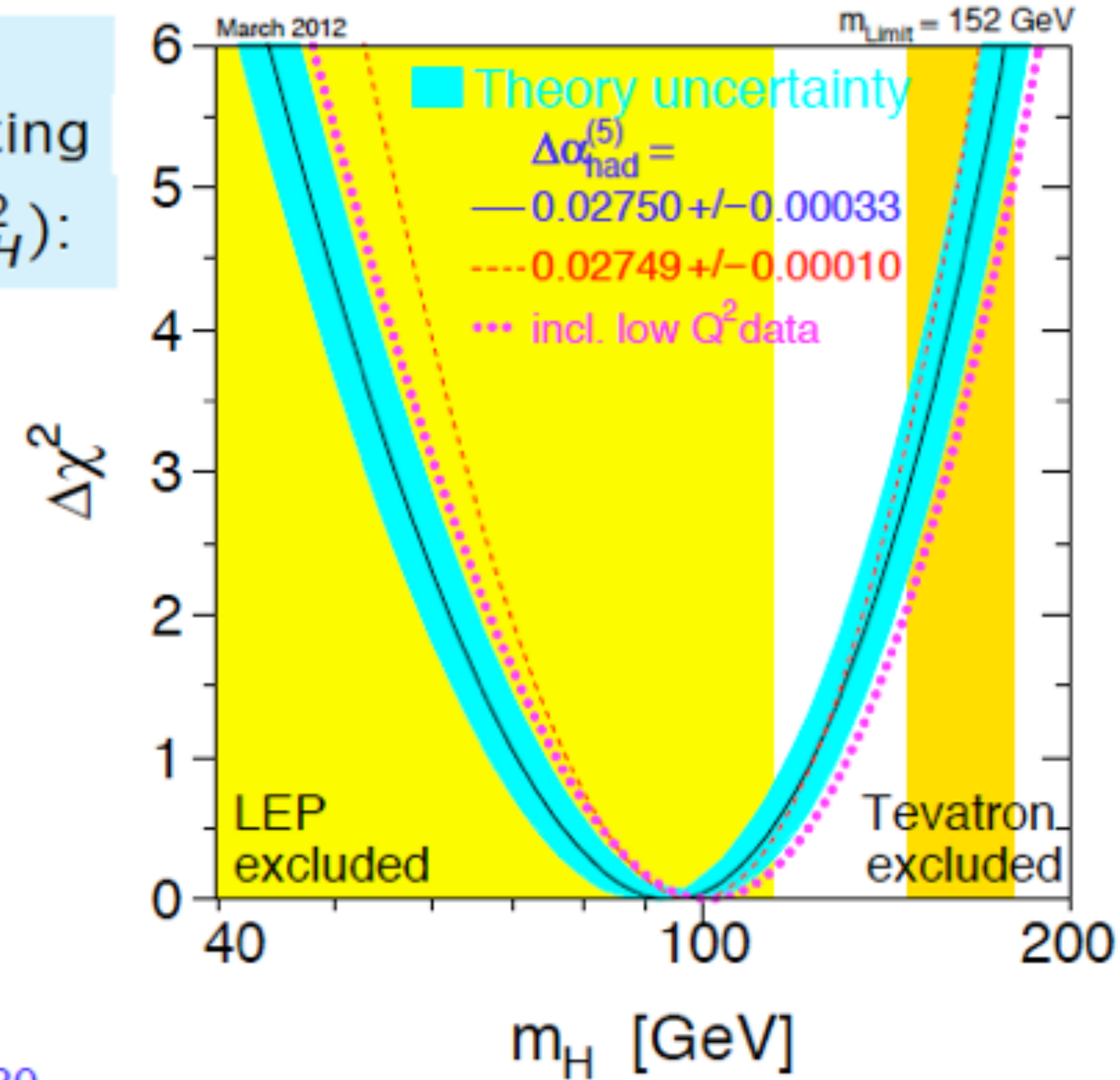
Direct searches at LEP:

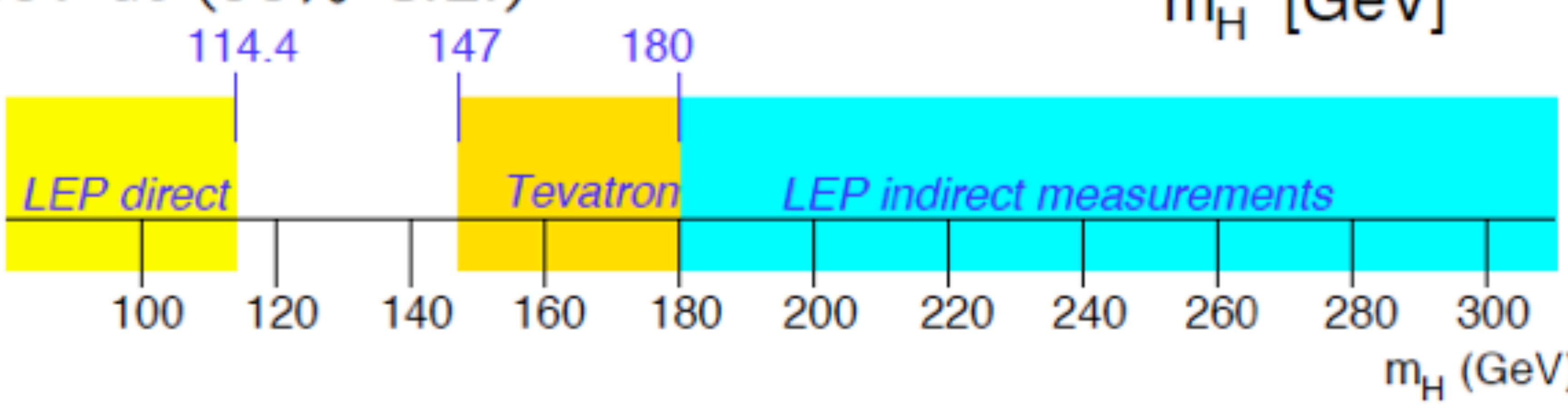
$m_H >$114.4 GeV at (95% C.L.)

Direct searches at Tevatron:

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

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

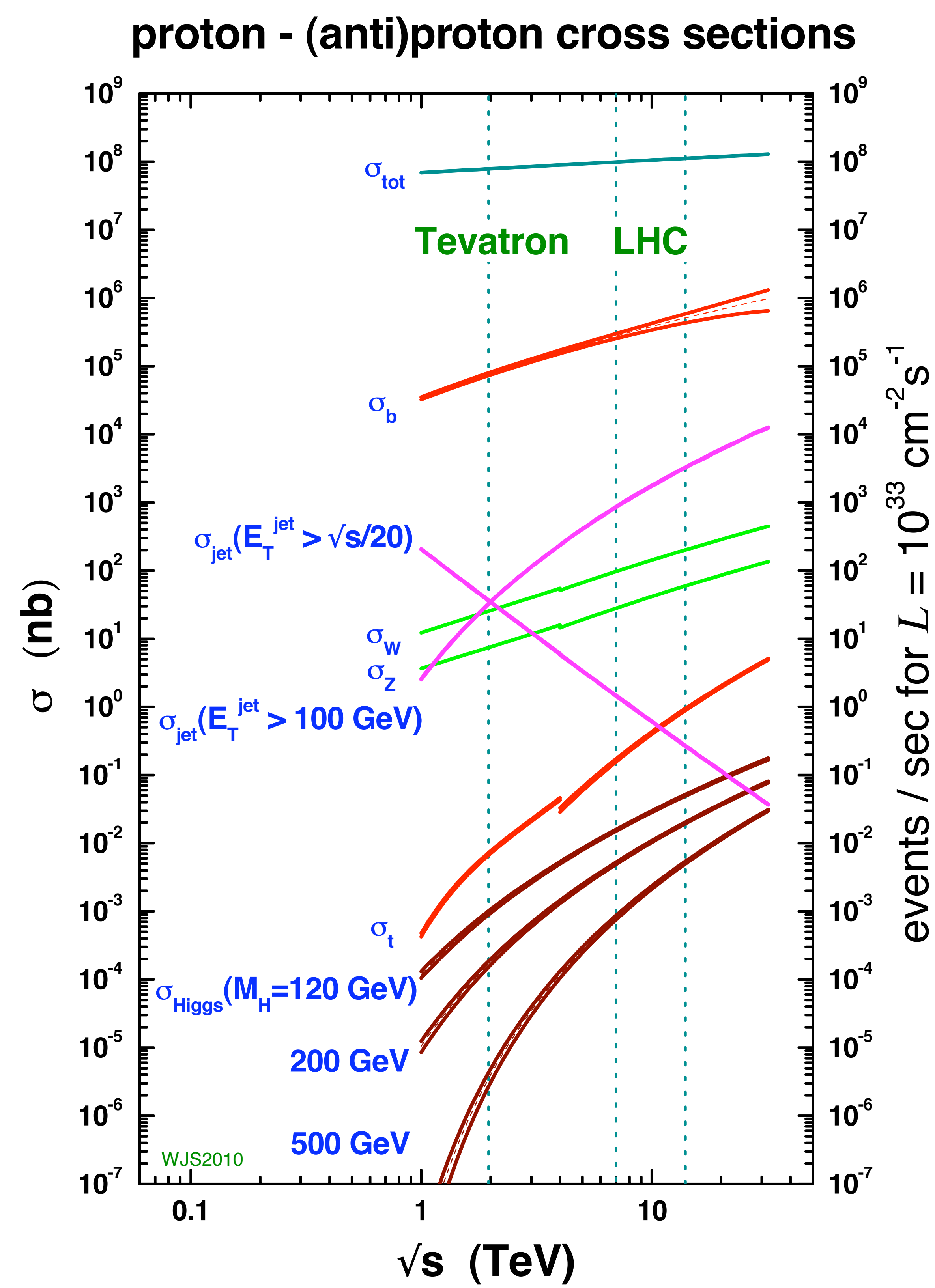




status: 2012

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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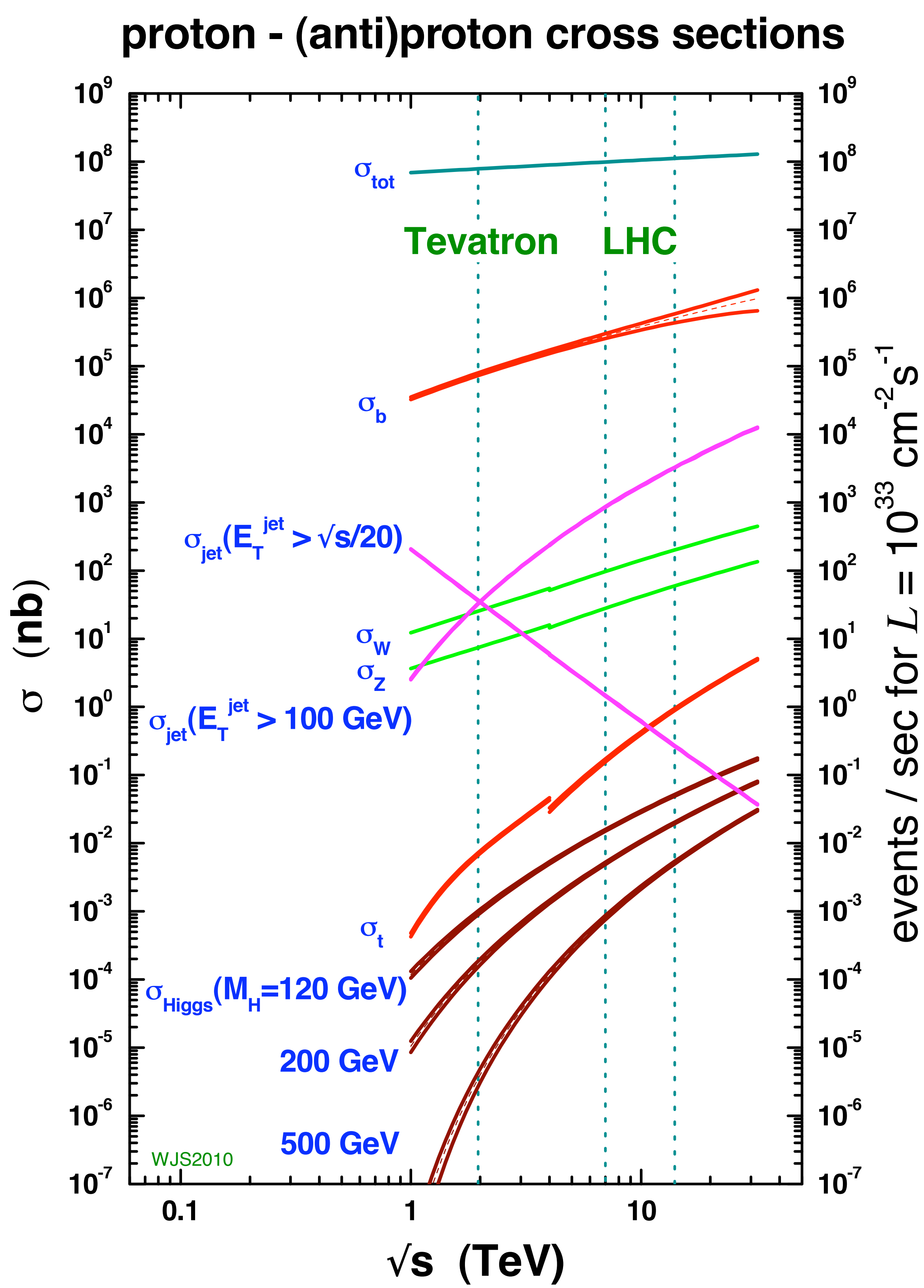
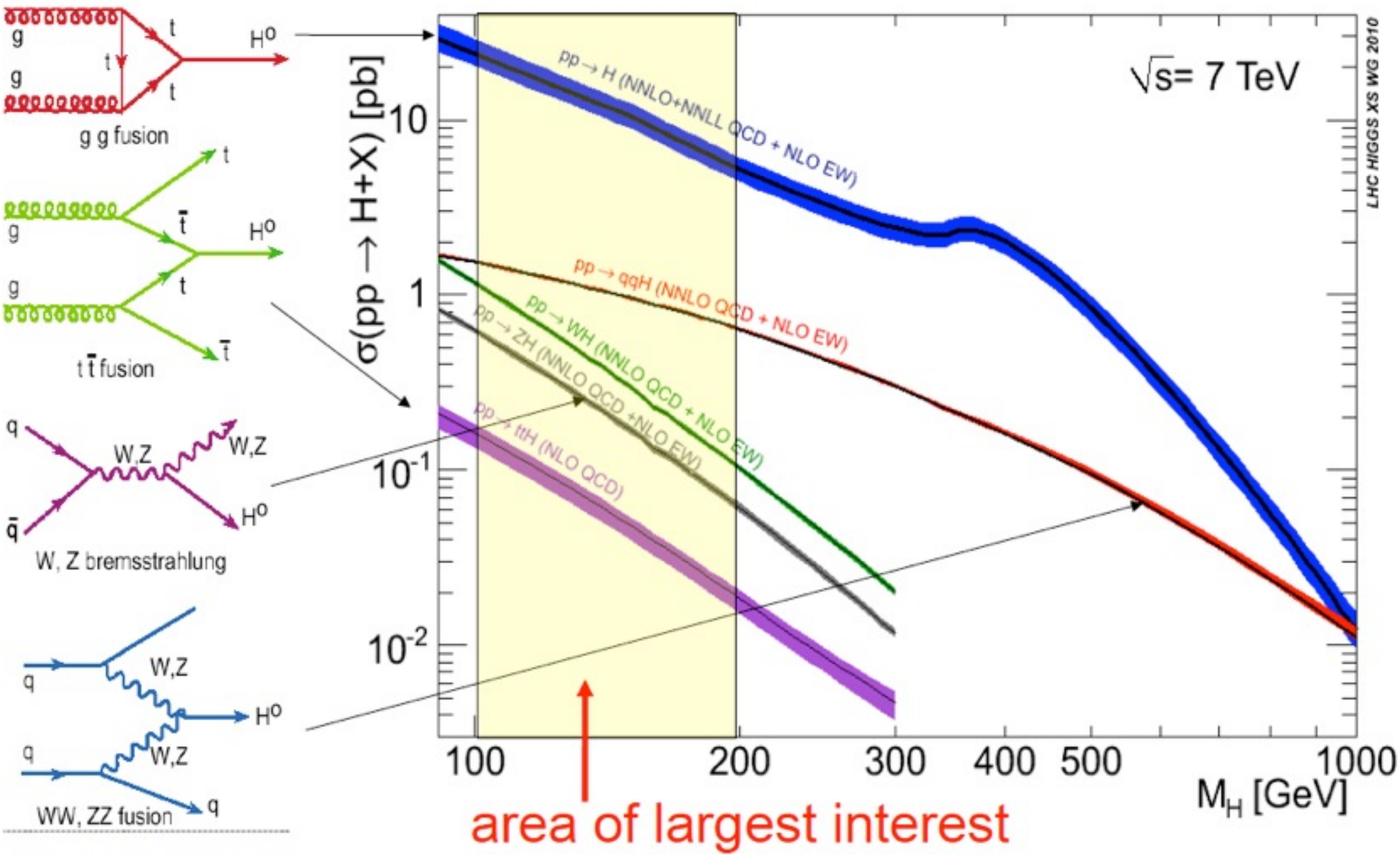
=> Production dominated by gluons!

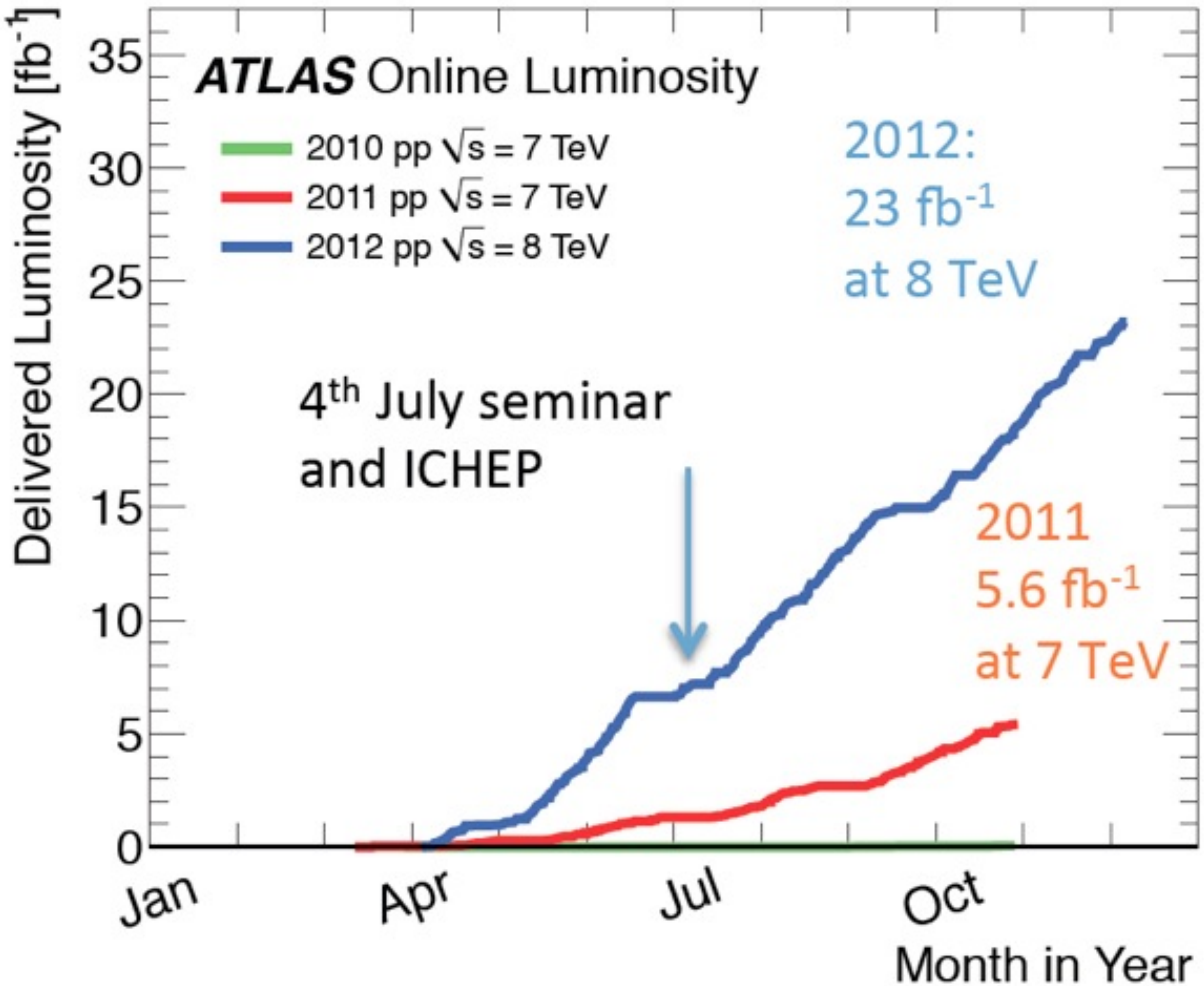


Higgs Production at the LHC



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

The LHC Dataset for the Discovery

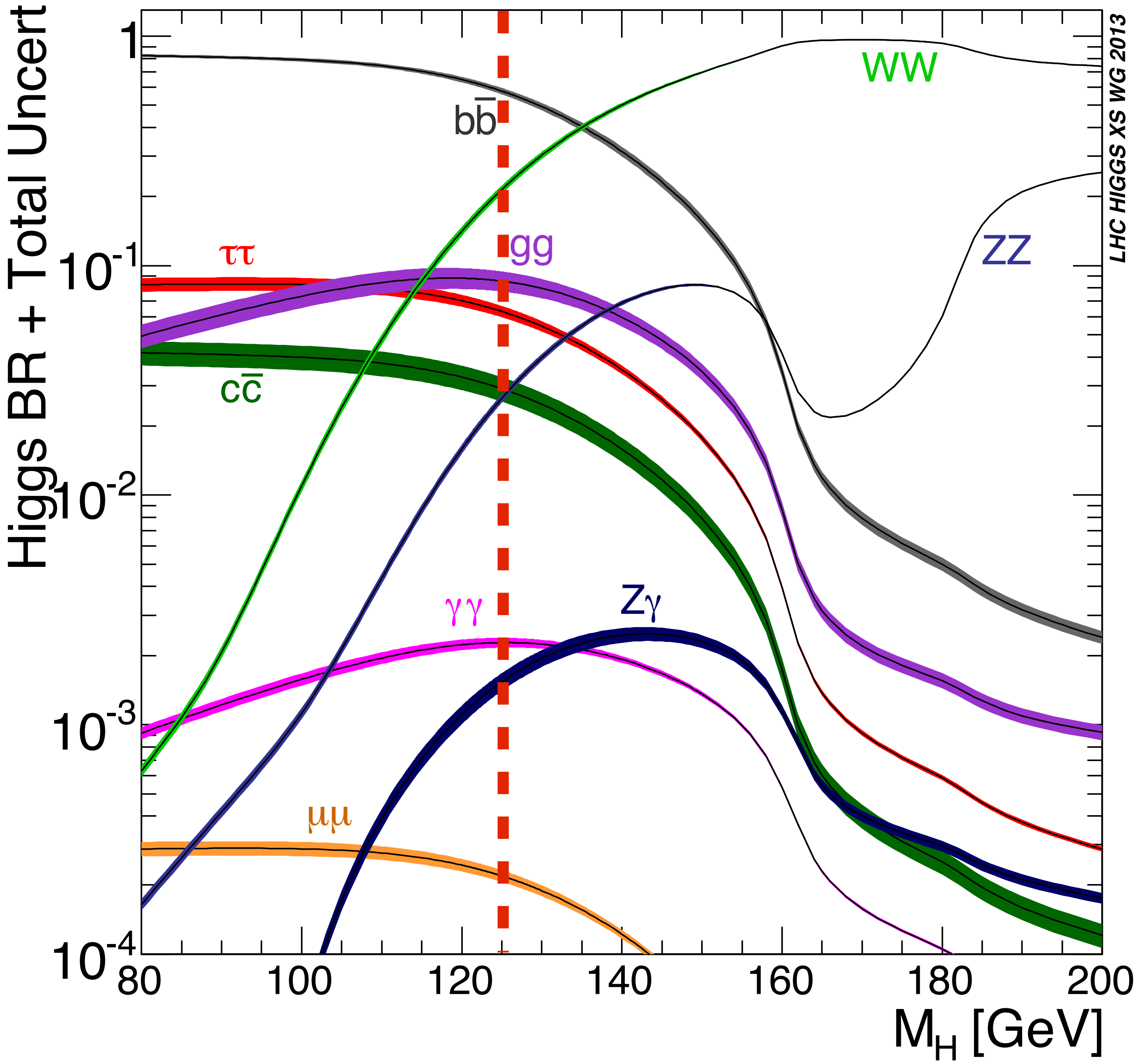


- In 2011: 5.6 fb^{-1} @ 7 TeV
  ~ 100k H produced
  (for a mass of 125 GeV)
- In 2012: 23 fb^{-1} @ 8 TeV
  ~ 500k H produced
  (for a mass of 125 GeV)

NB: No additional data in 2013 and 2014: LHC in shutdown
Since July 2015: 13 TeV,
up to now ~ xxx 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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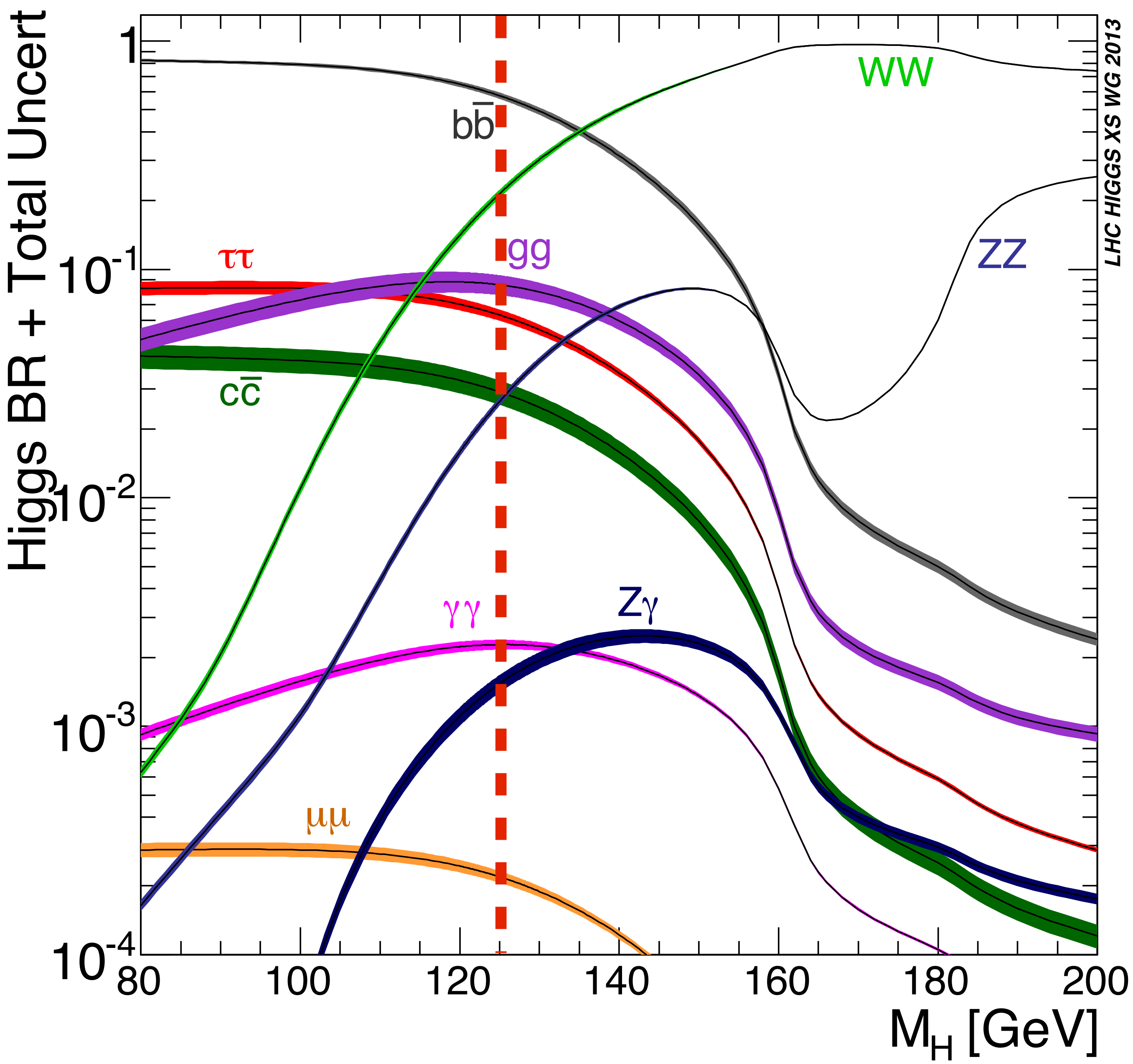

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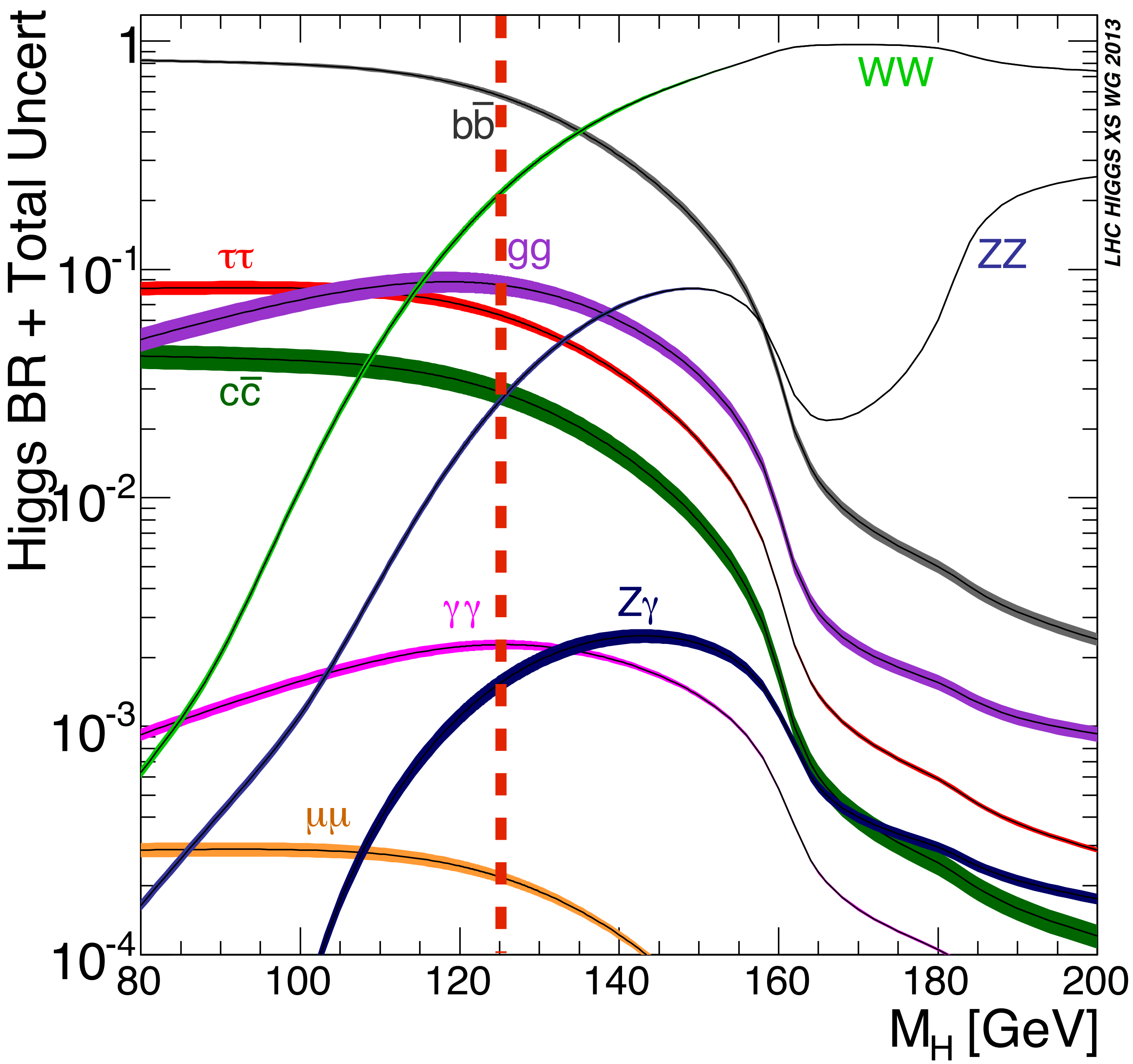

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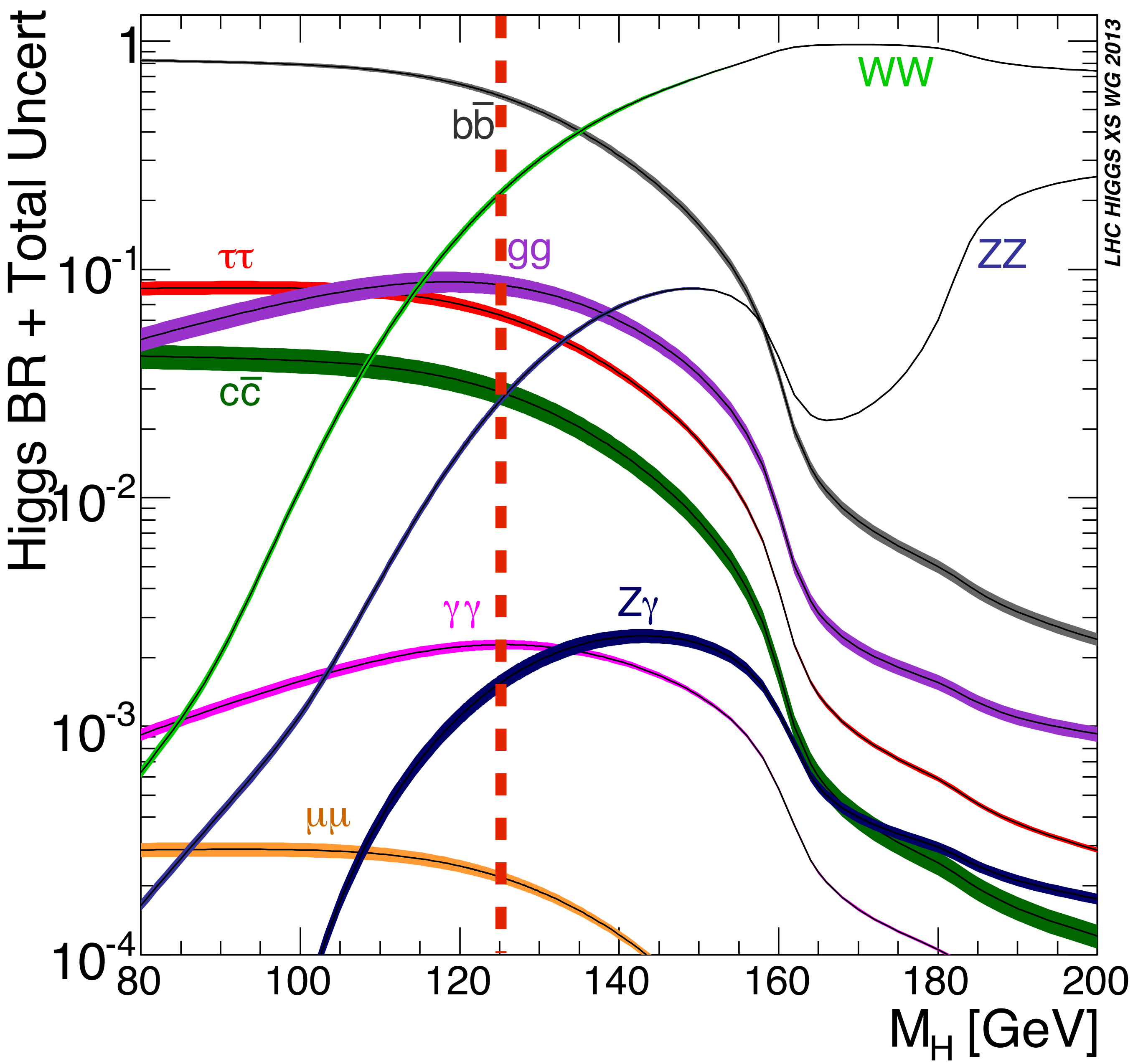

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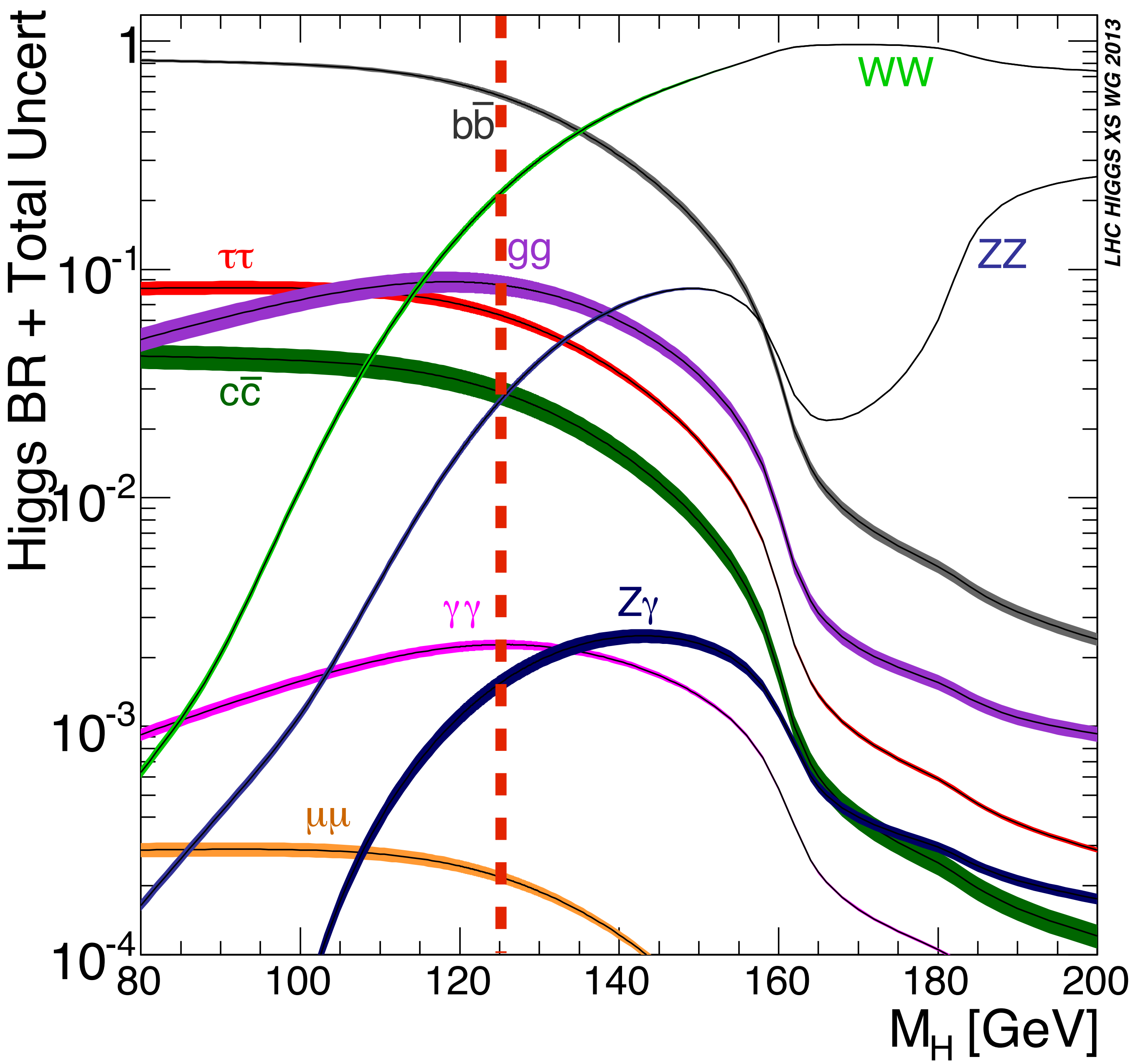

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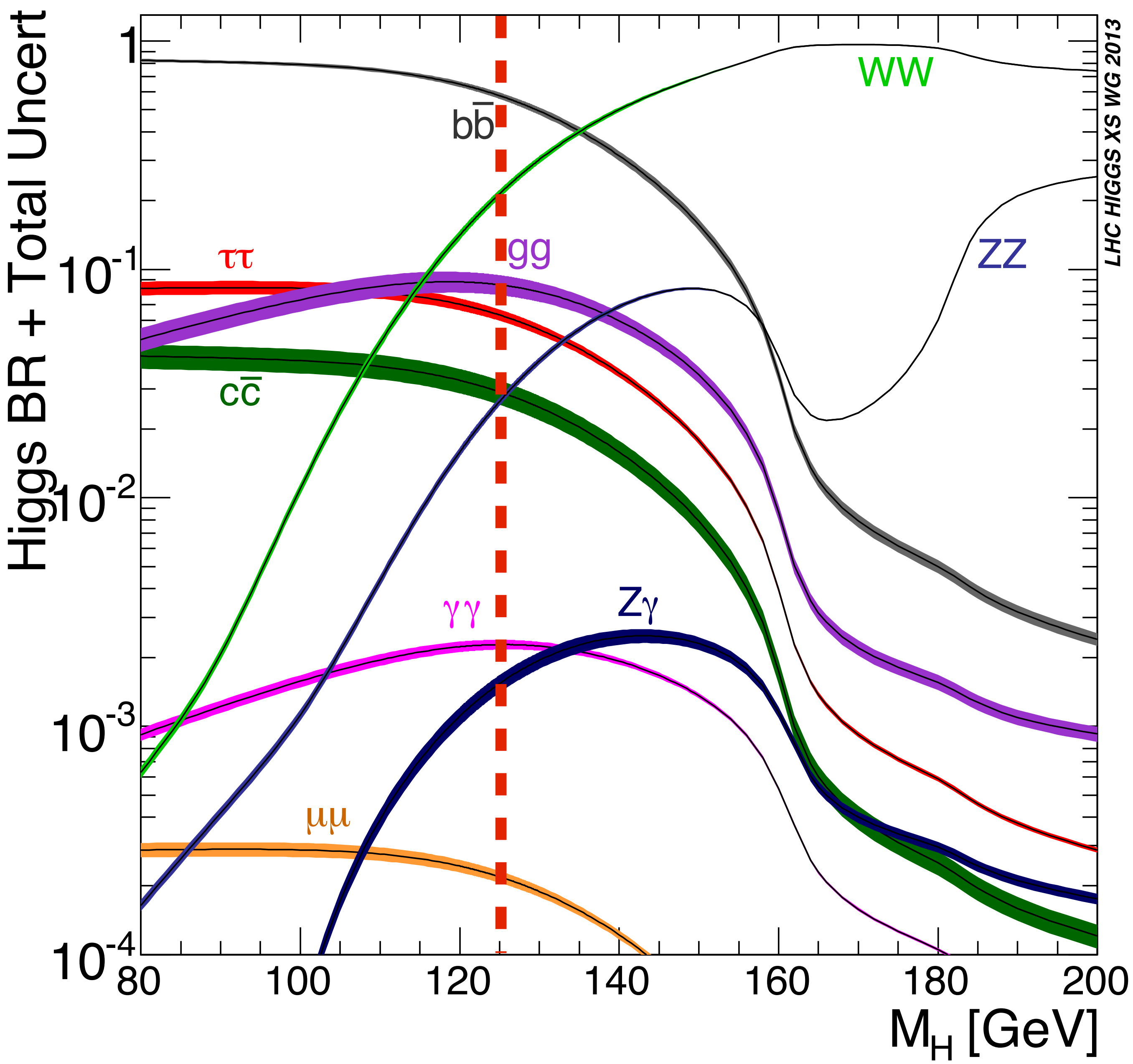

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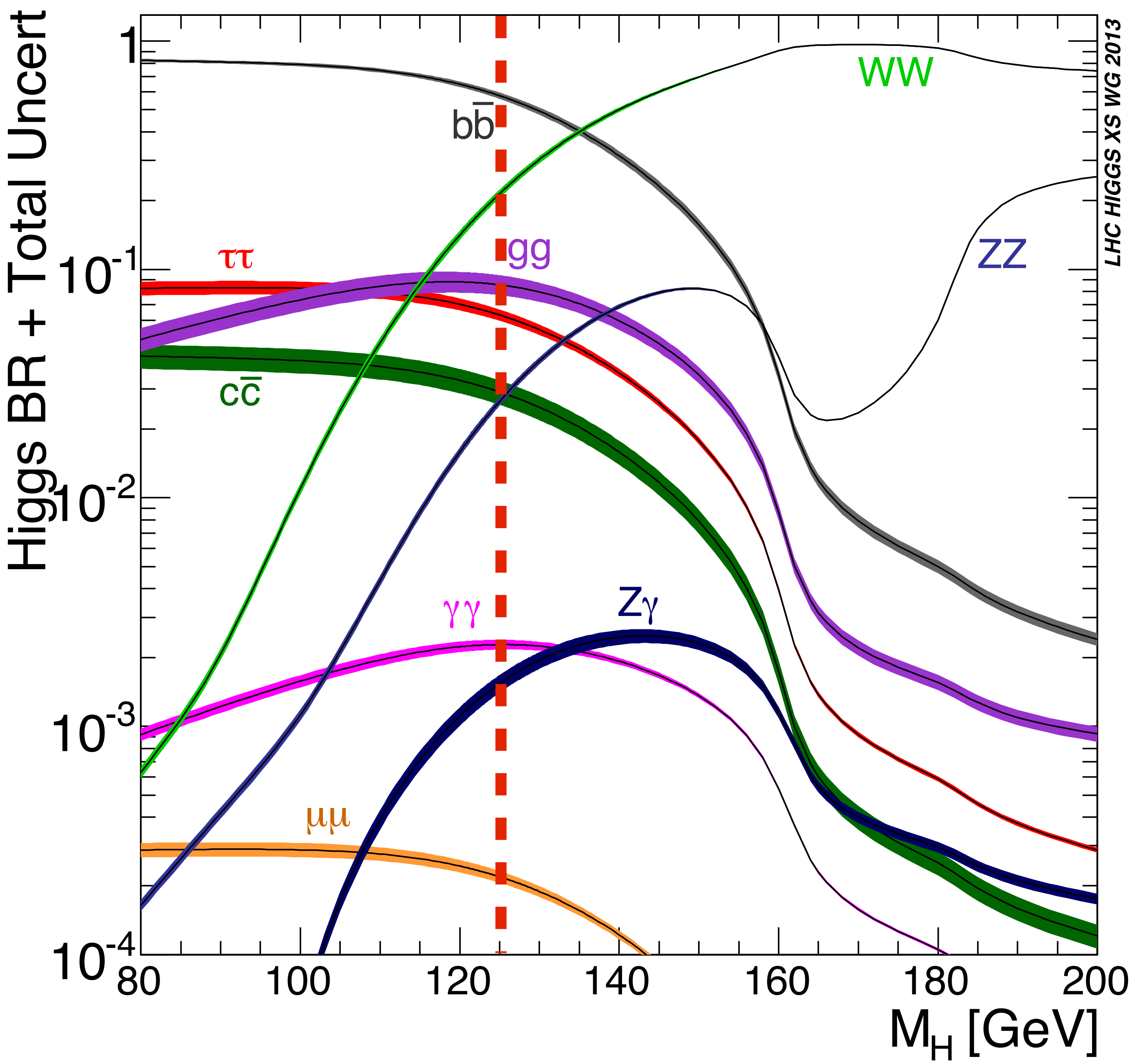
γγ - Rare decay, but manageable background, good resolution

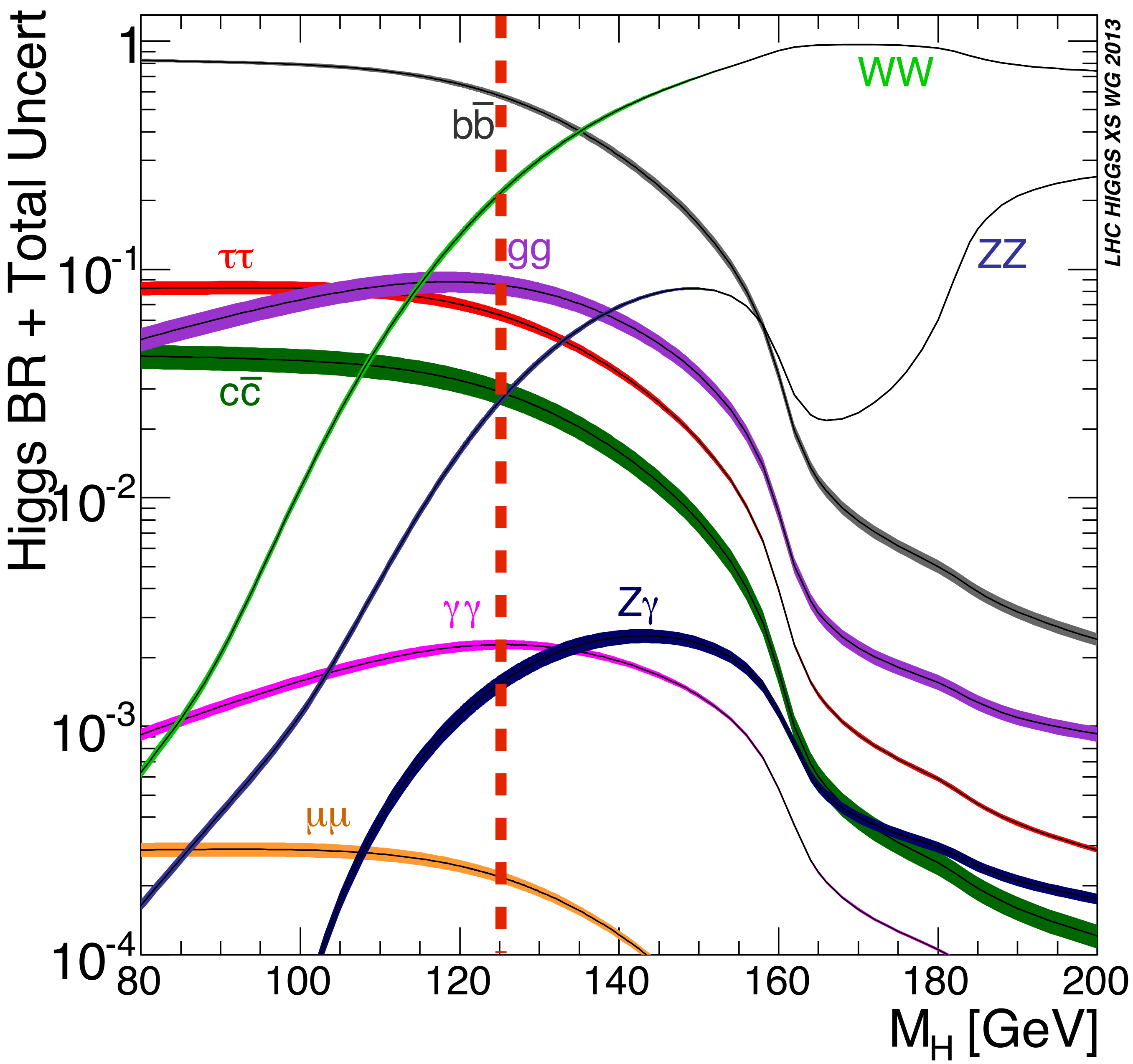
Higgs Decay II



- Additional decay channels:

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

Higgs Decay II



- Additional decay channels:

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

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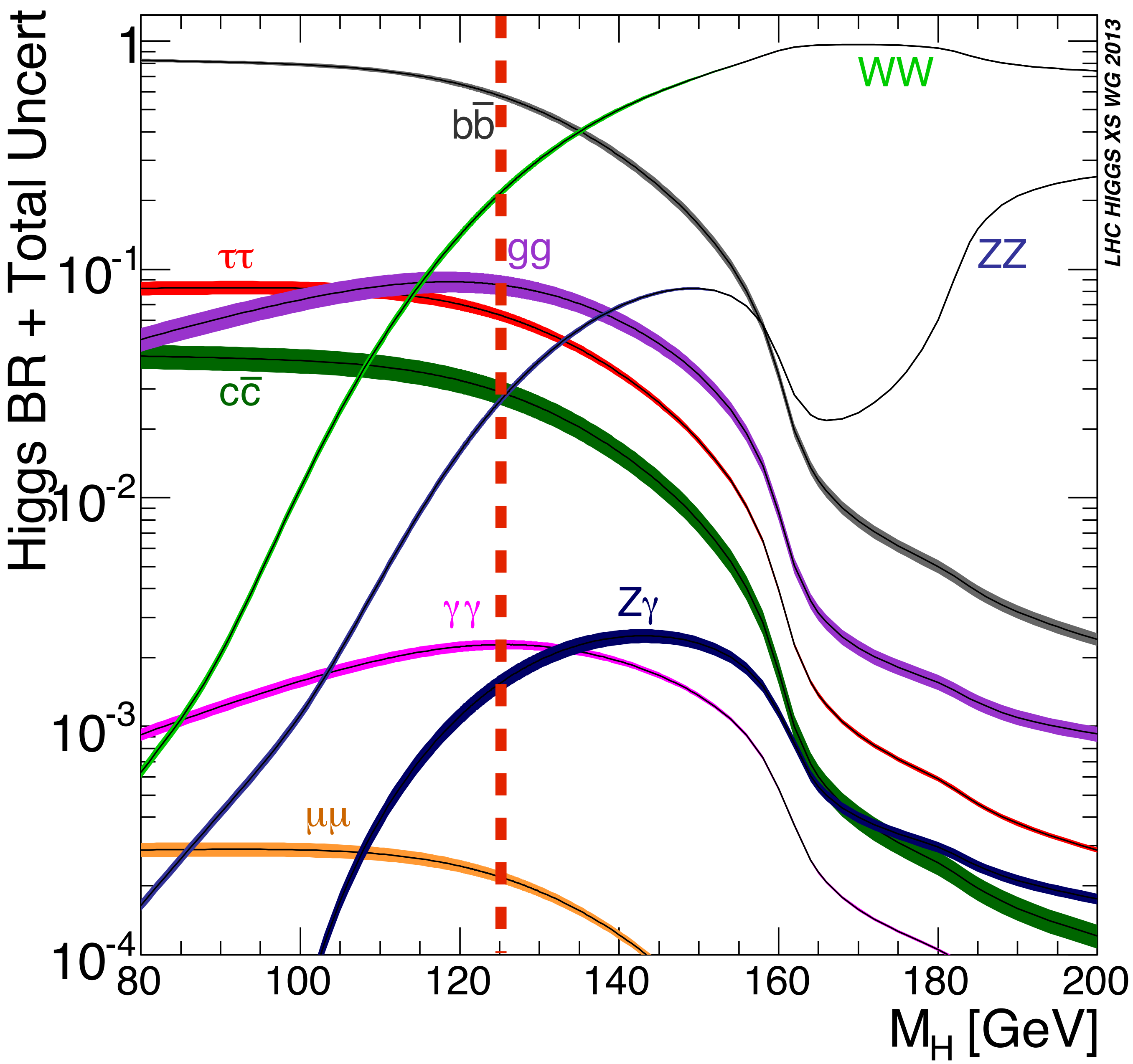

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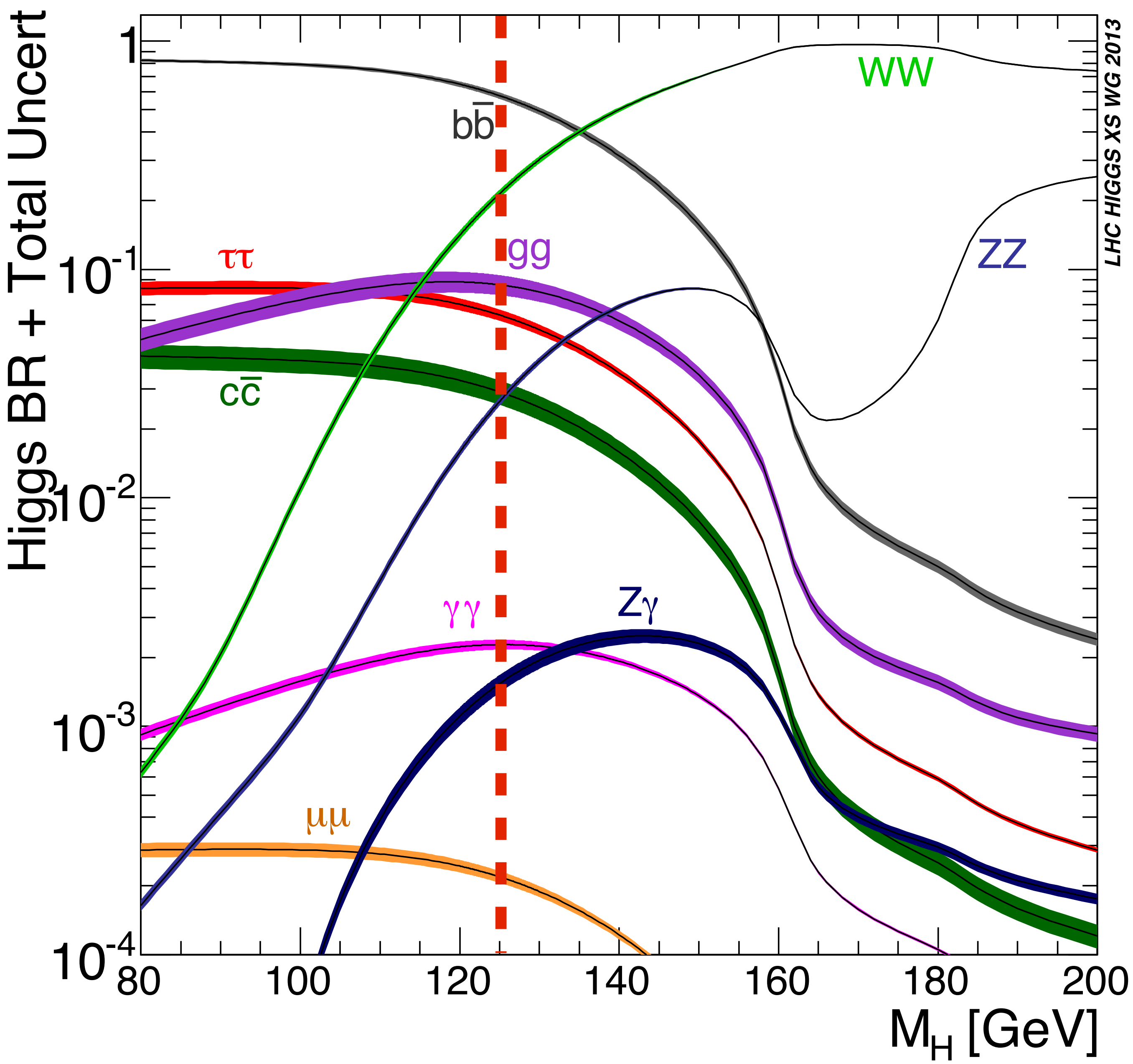


- Additional decay channels:

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

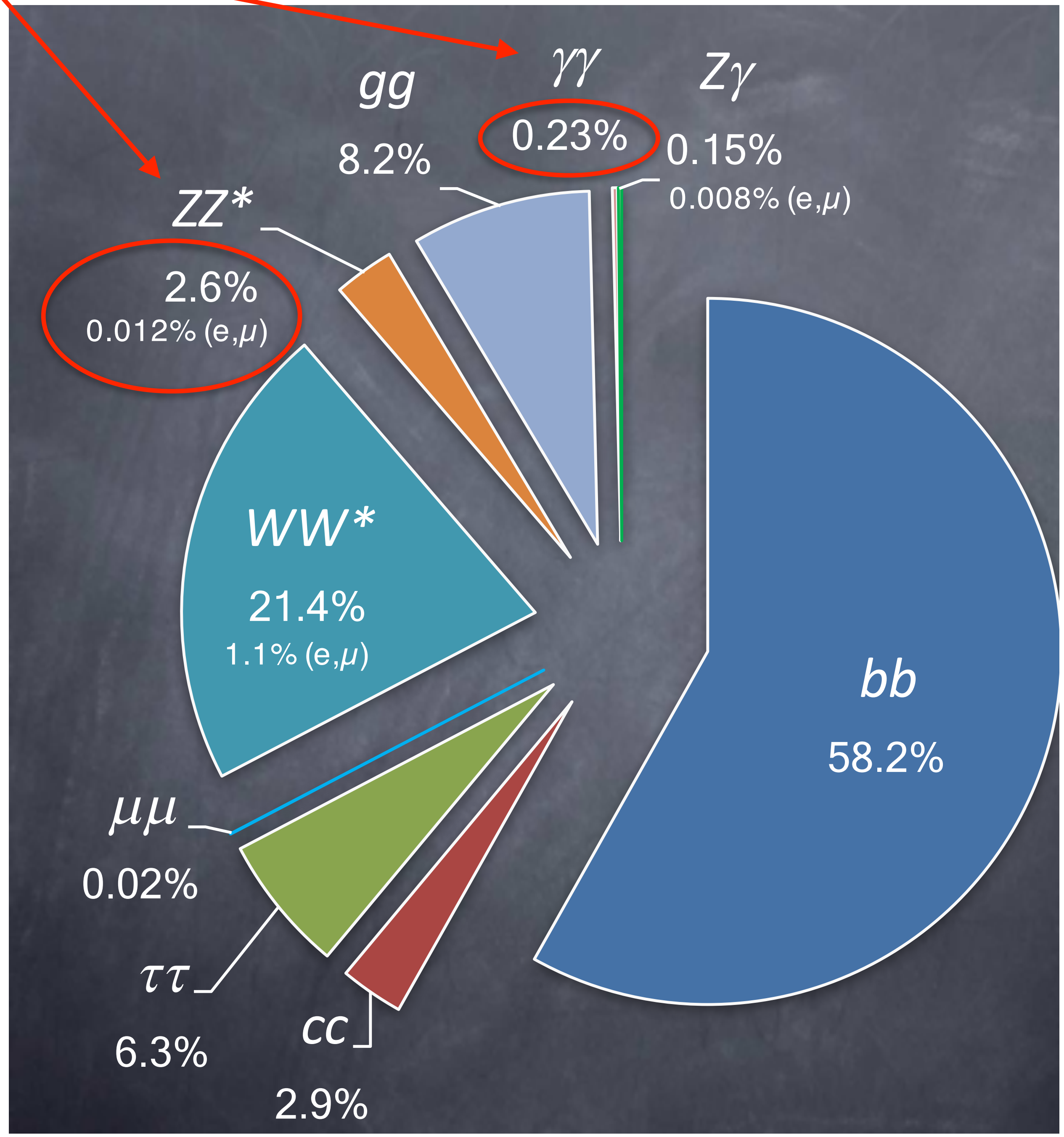
ee - Excellent signature, negligible rate, no chance for measurement

Higgs Decay: All together

ZZ, **γγ**: high mass resolution channels mass and precise differential measurements

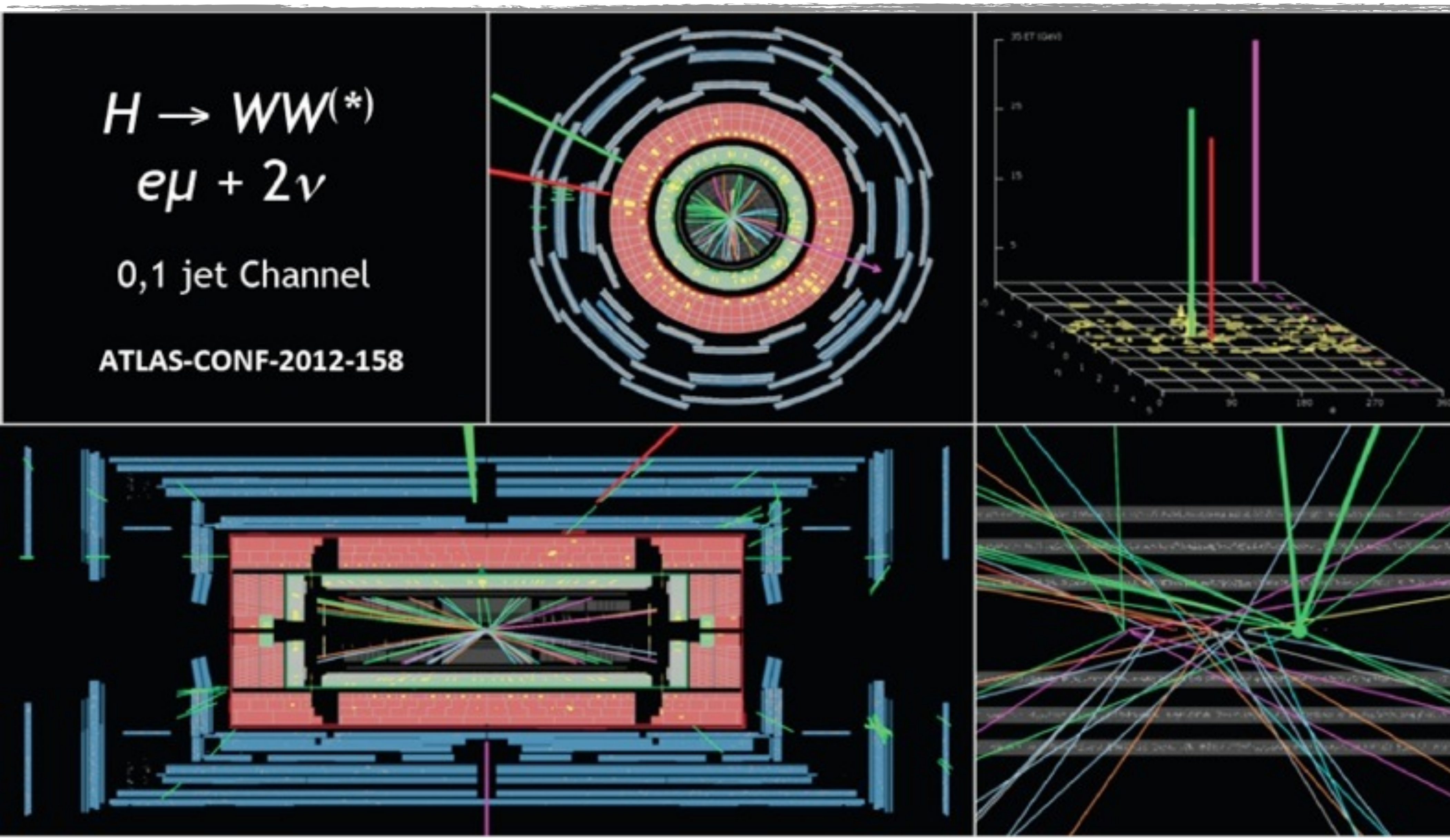
WW: High BR, but low mass resolution

μμ: very small BR, but access to coupling to 2nd generation fermions



bb, **ττ**: high BR, but low S/B, important to directly probe Higgs boson coupling to fermions

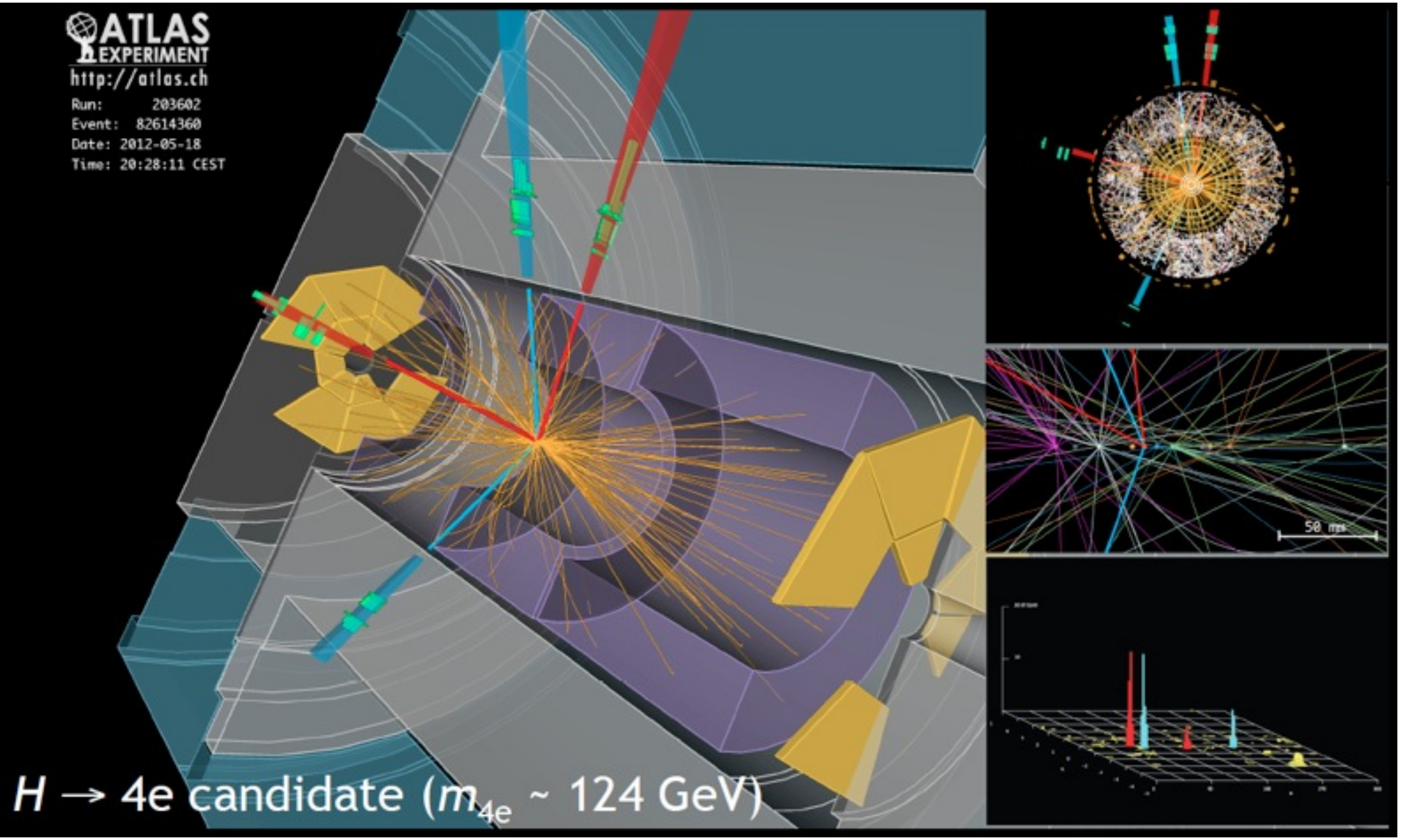
Discovery Channels - H -> WW



- 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)

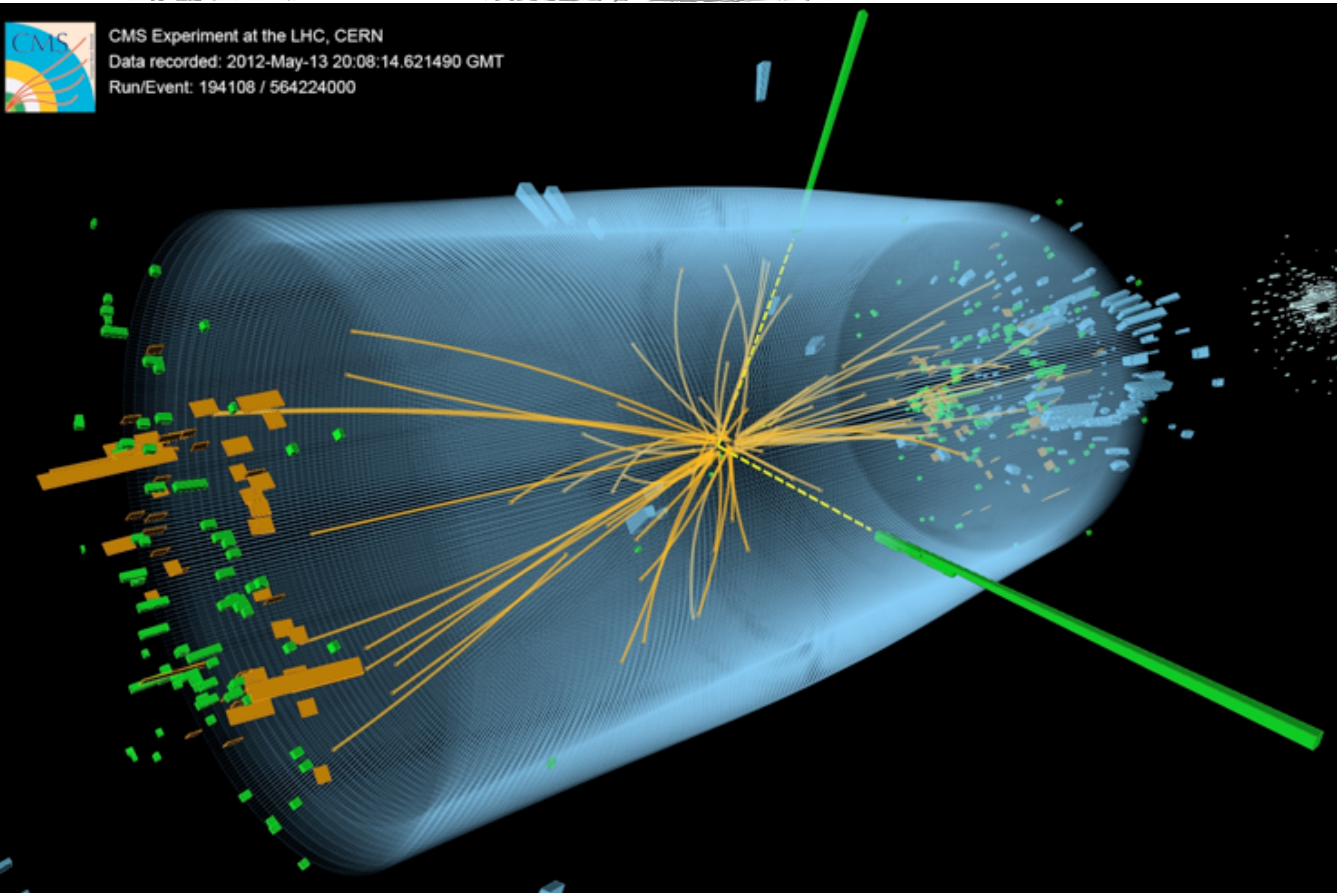
Discovery Channels - H -> ZZ



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

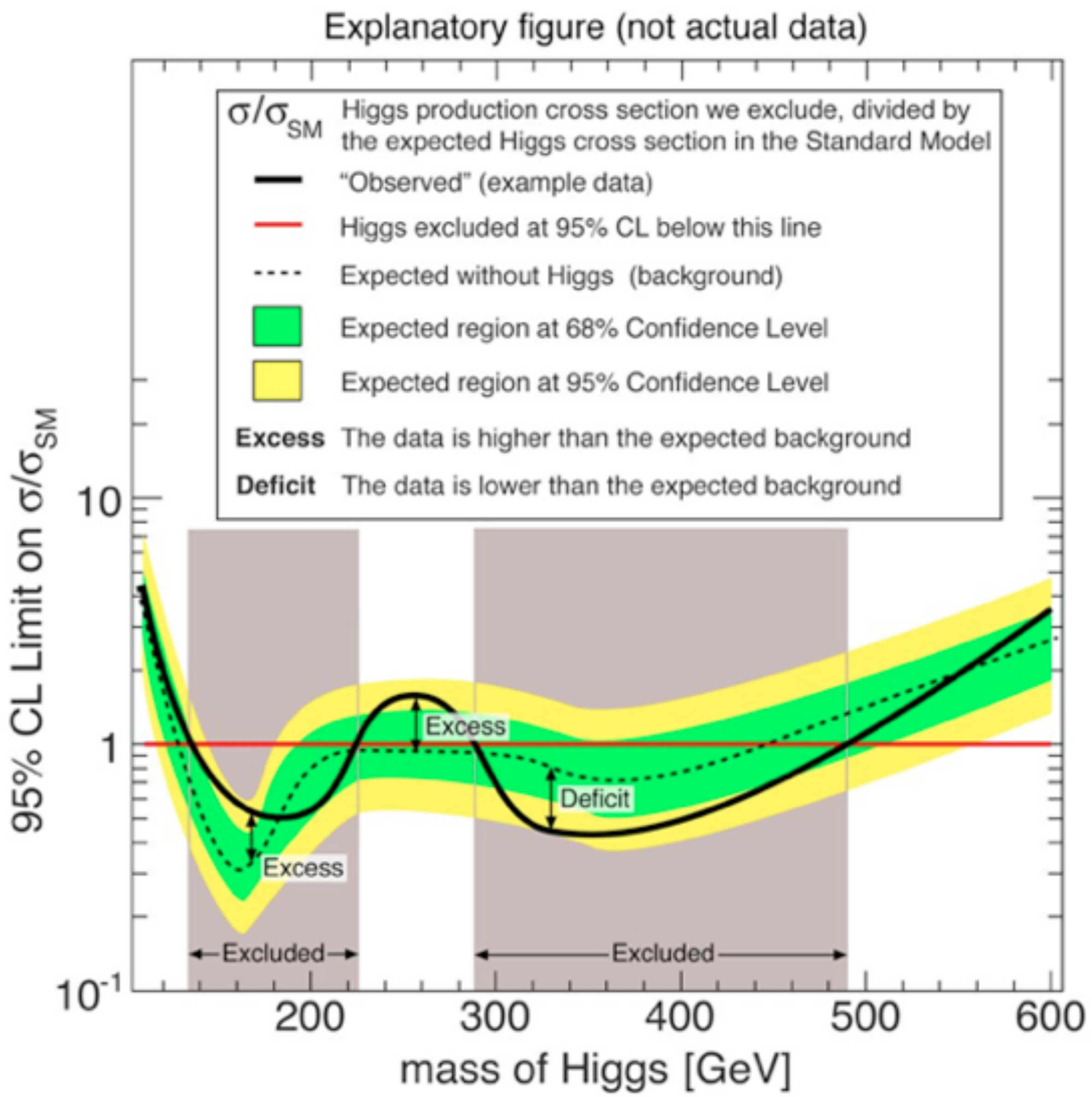
Discovery Channels - H -> γγ



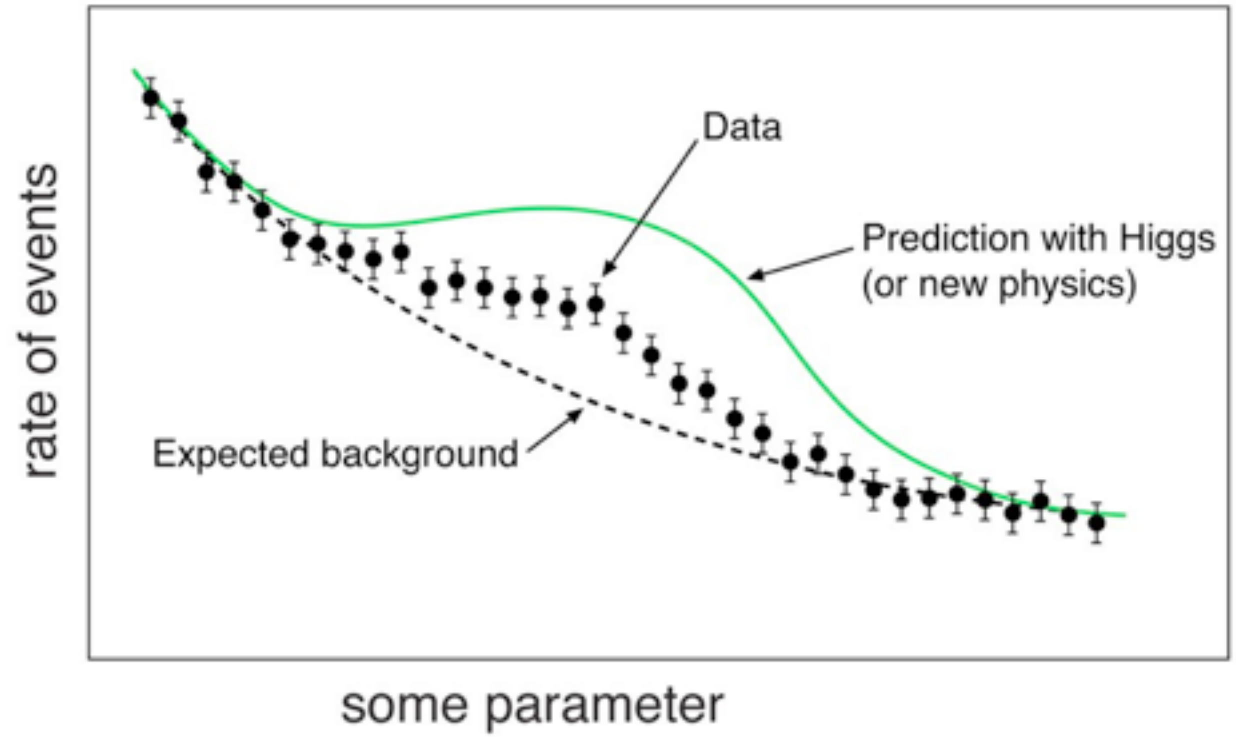
- Good mass resolution: ~ 1% level, given by photon energy resolution of ECAL
- Low branching fraction: 2.3×10^{-3}

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

Discovery and Exclusions: Understanding 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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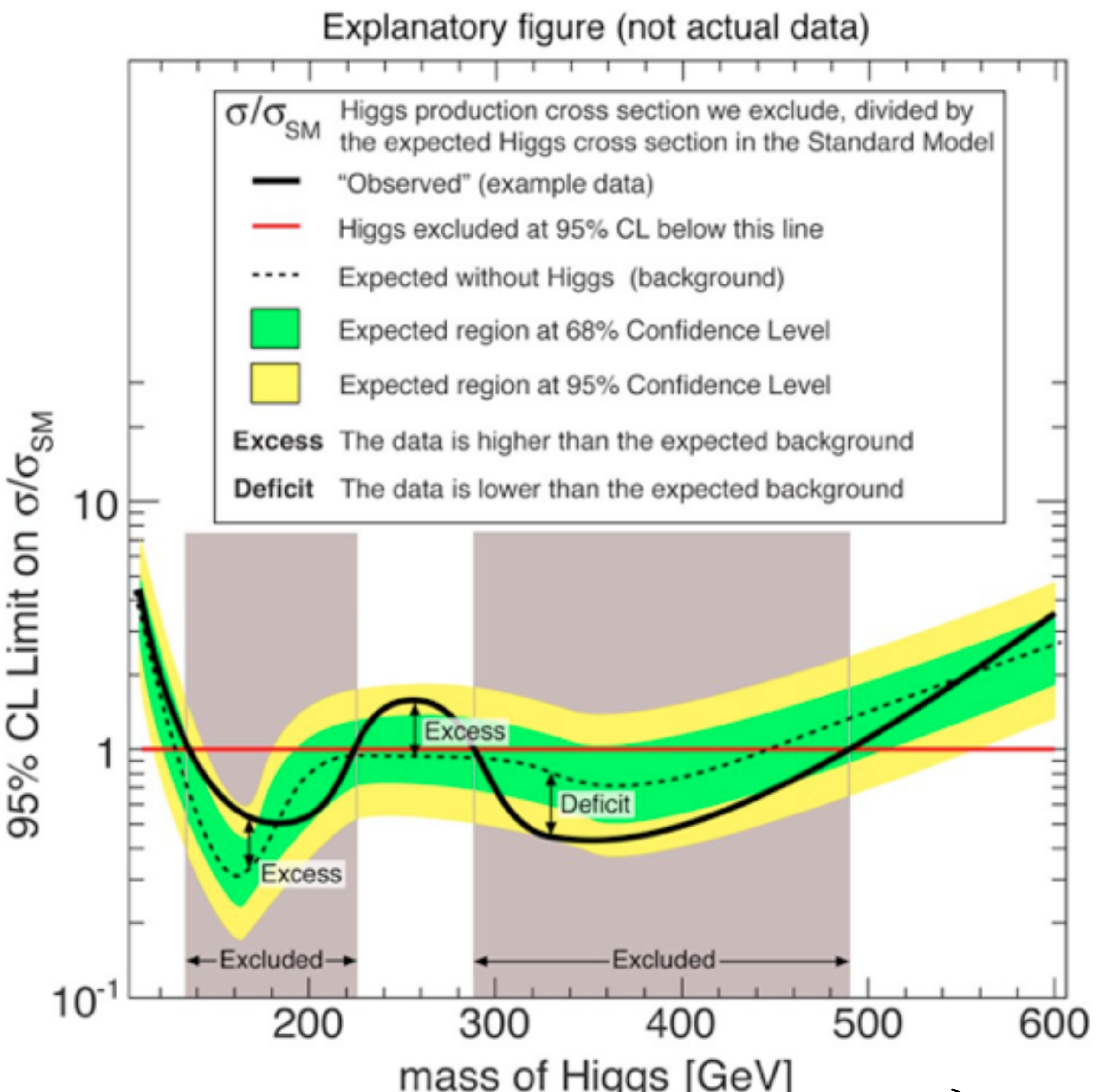

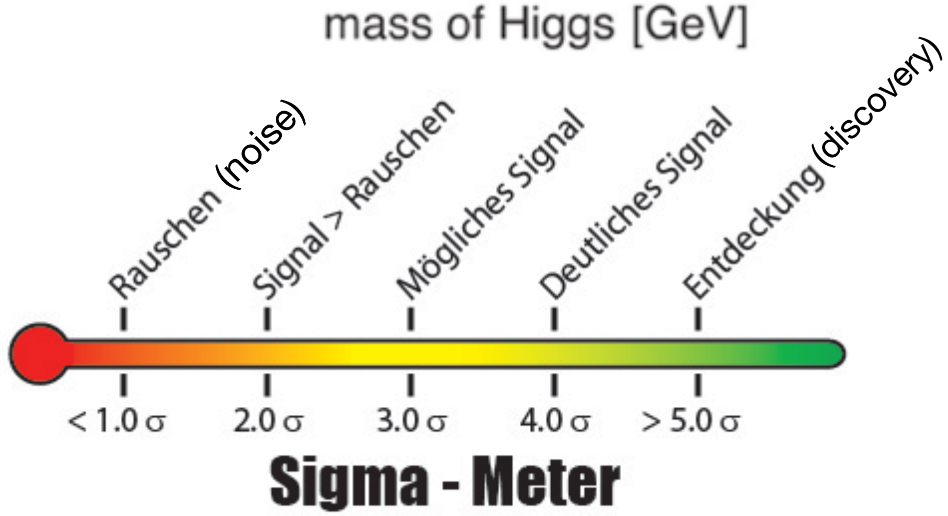

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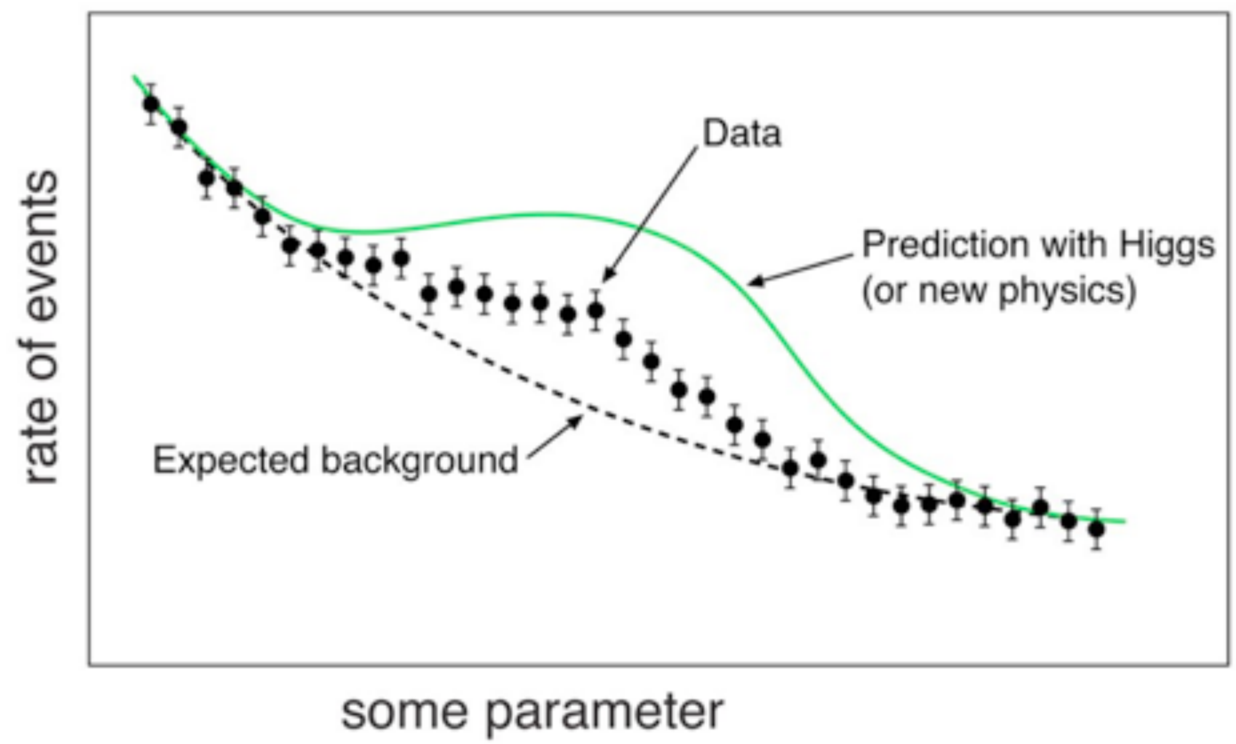
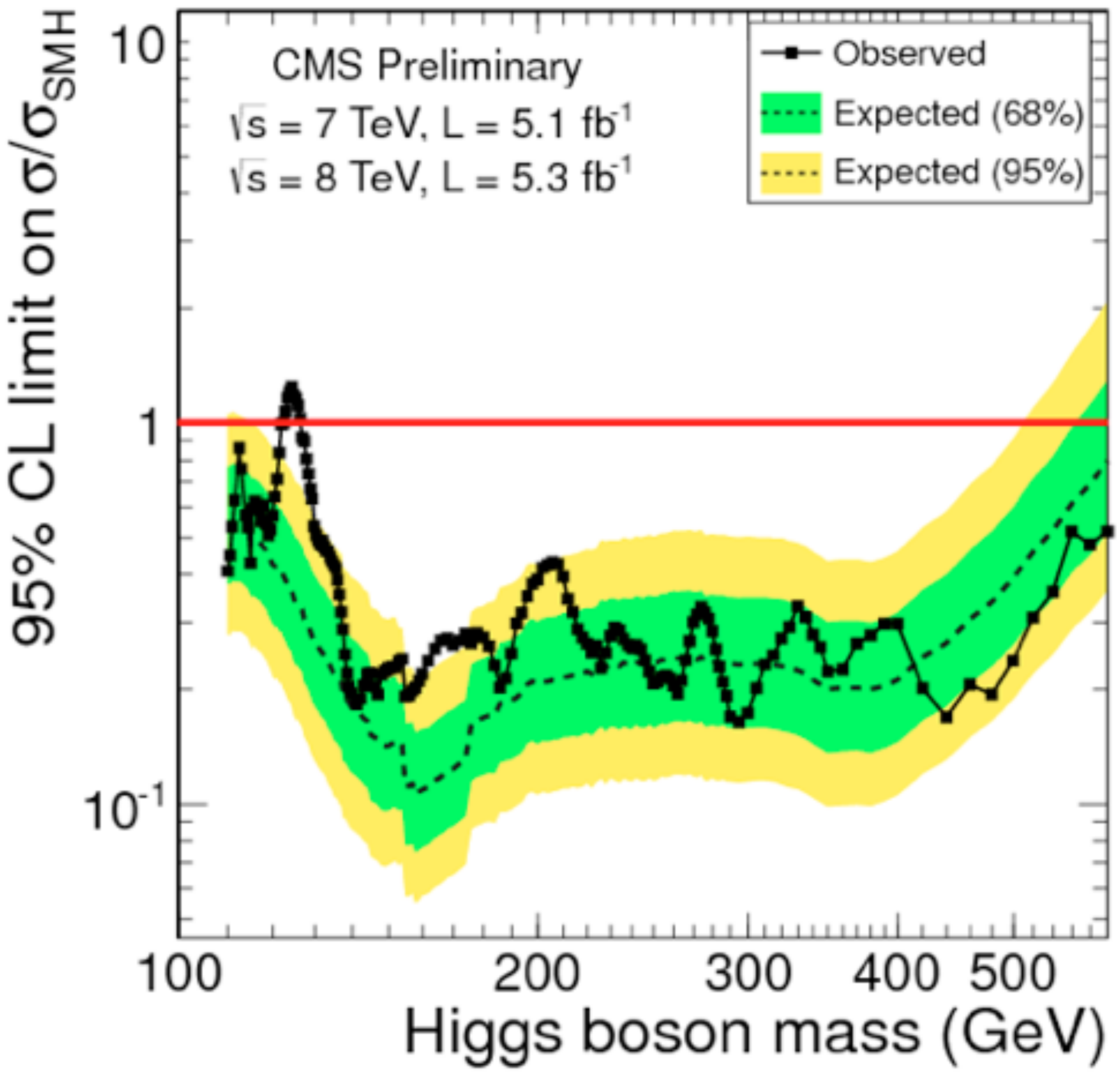
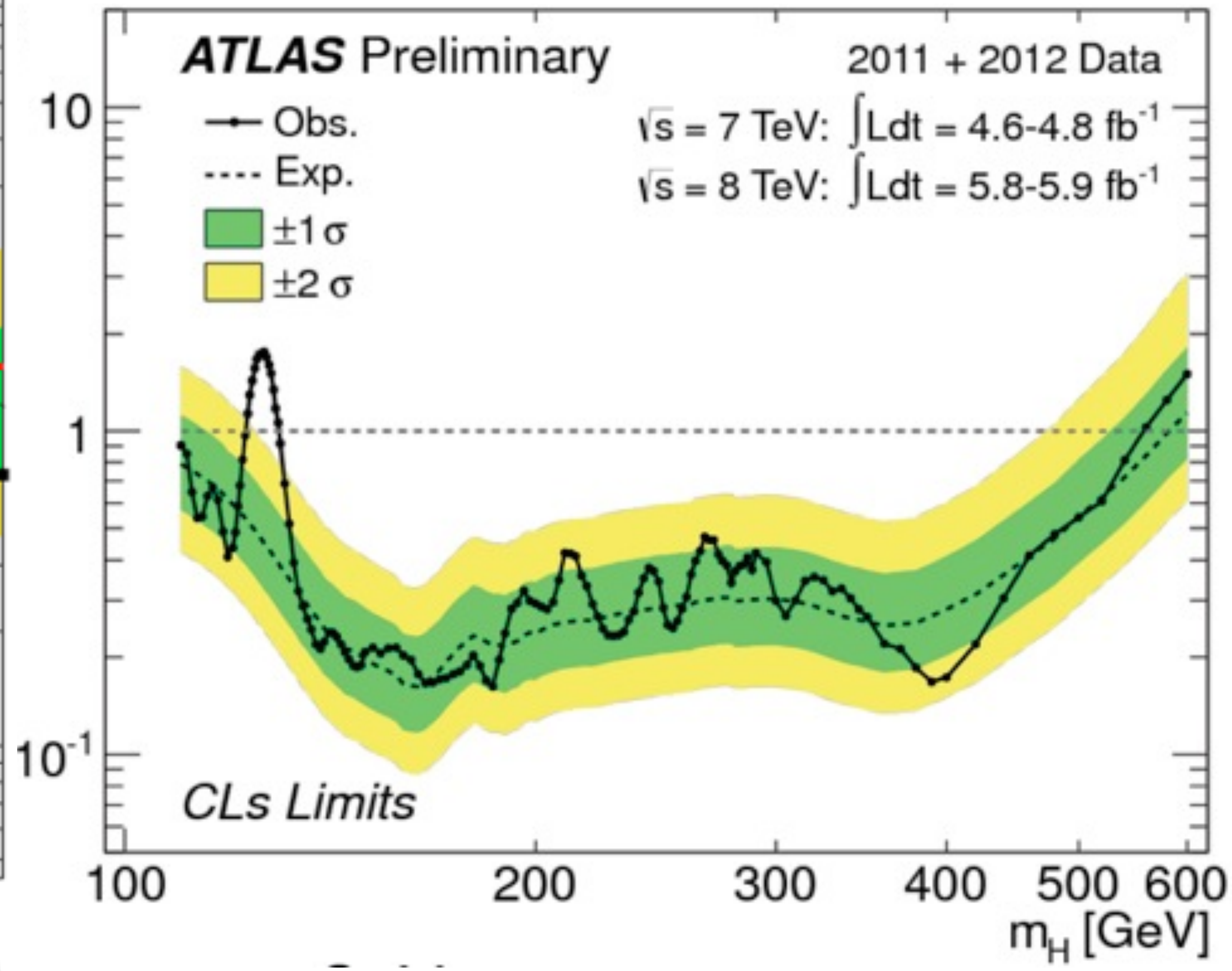


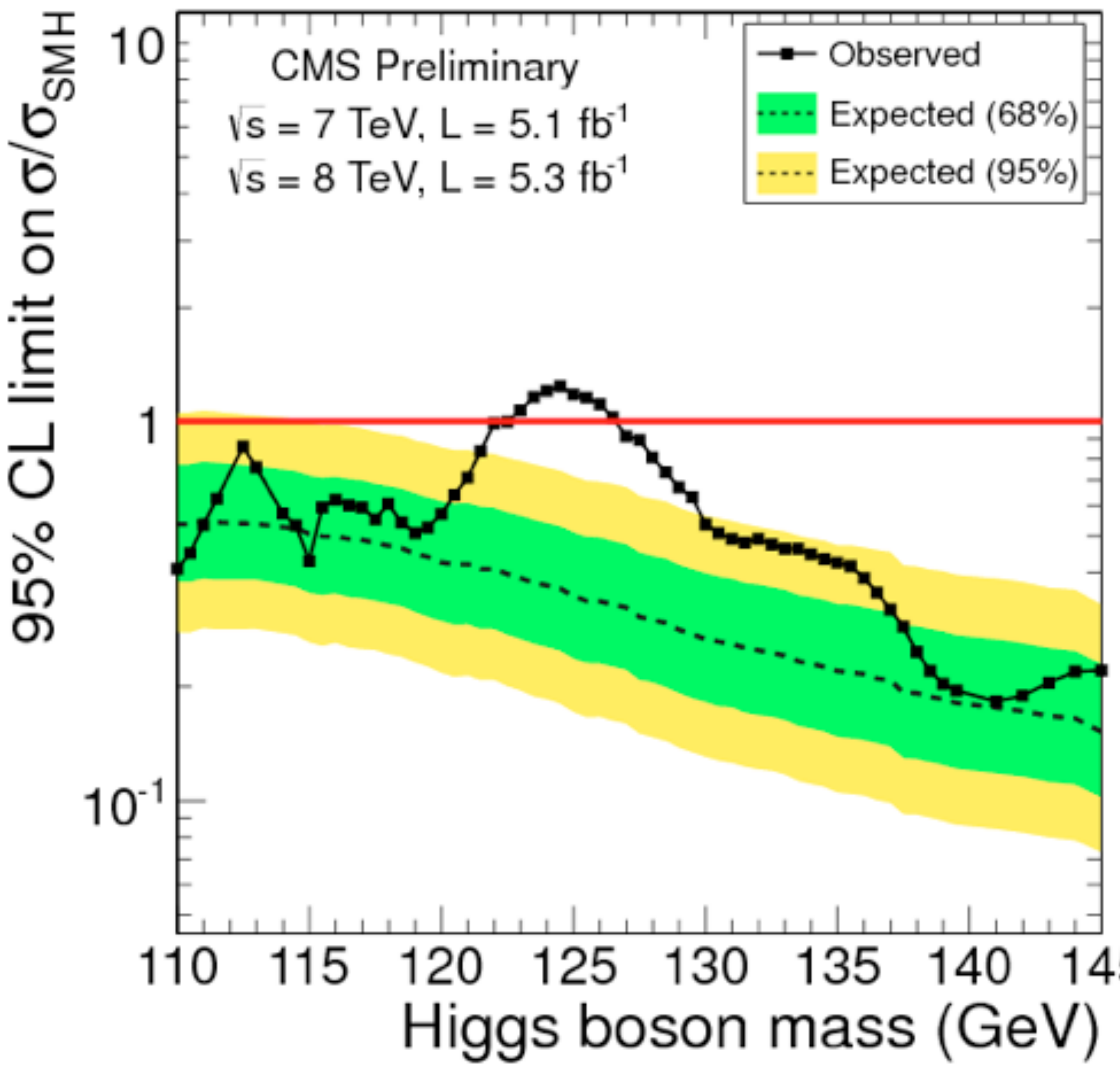
Higgs Discovery: All Channels Combined

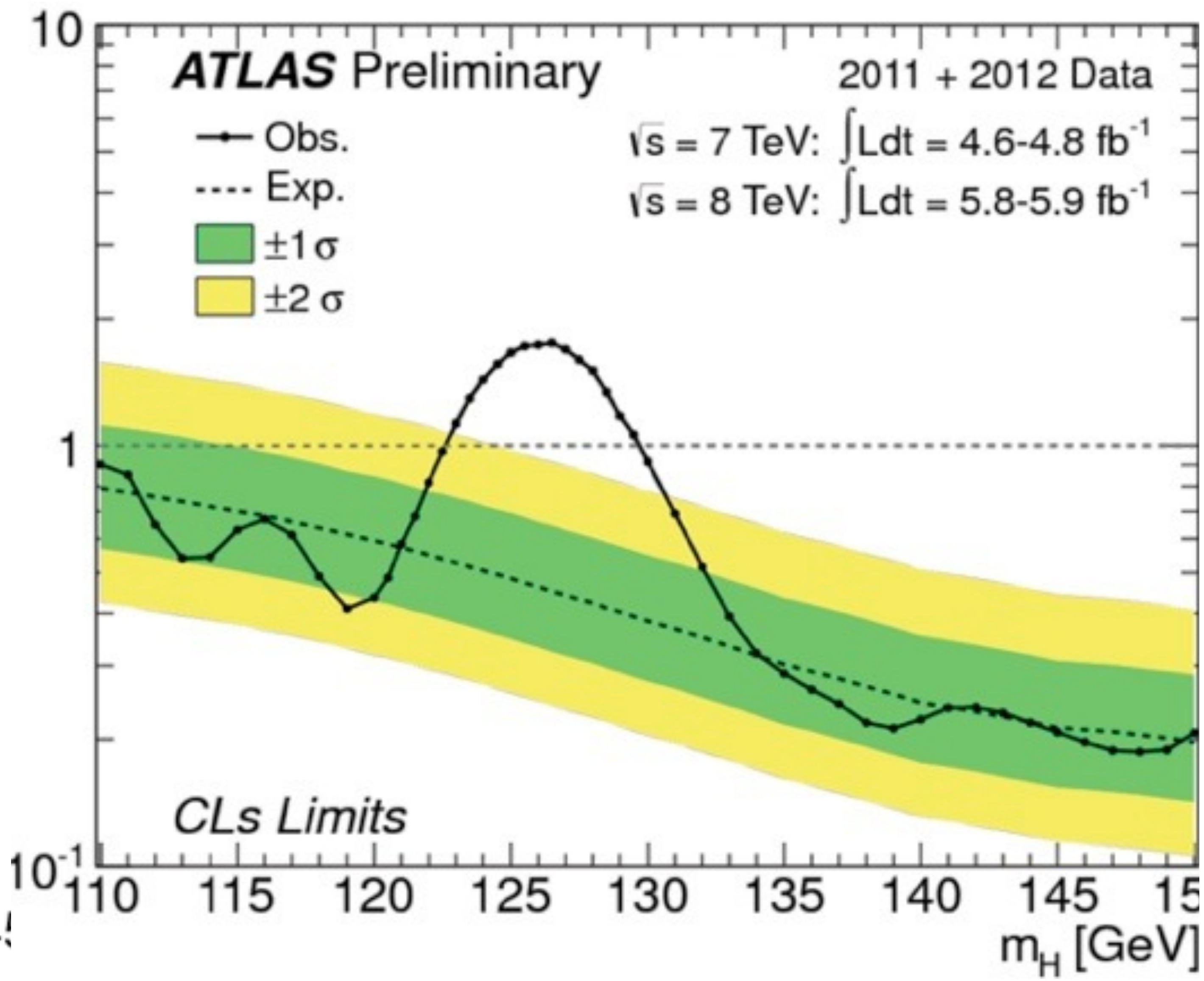




- The SM Higgs is excluded over the full range from 110 GeV to 600 GeV, with the exception of the region around 125 GeV
- Observed and expected limits match well within 1 - 2 σ

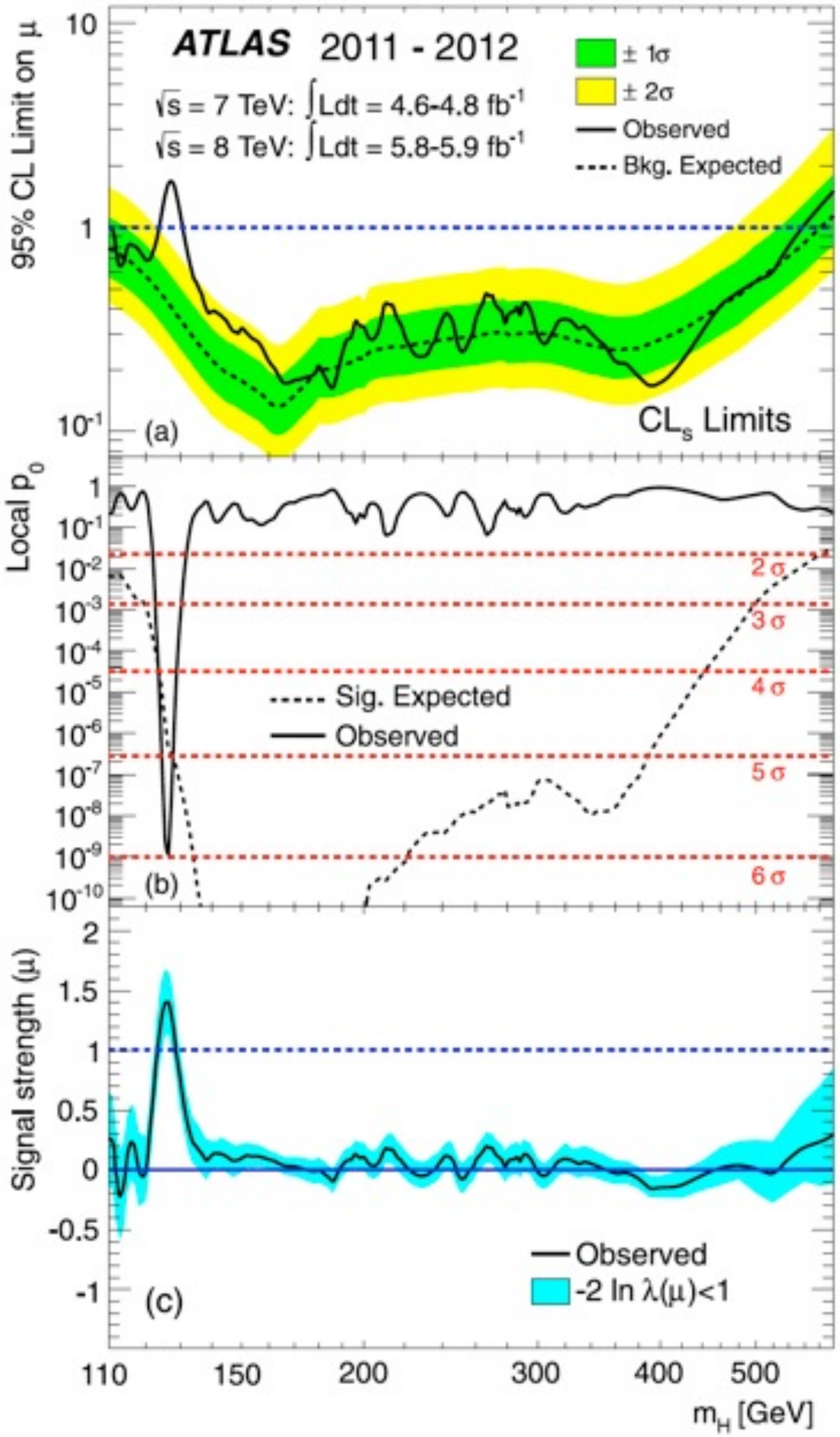
Higgs Discovery: All Channels Combined



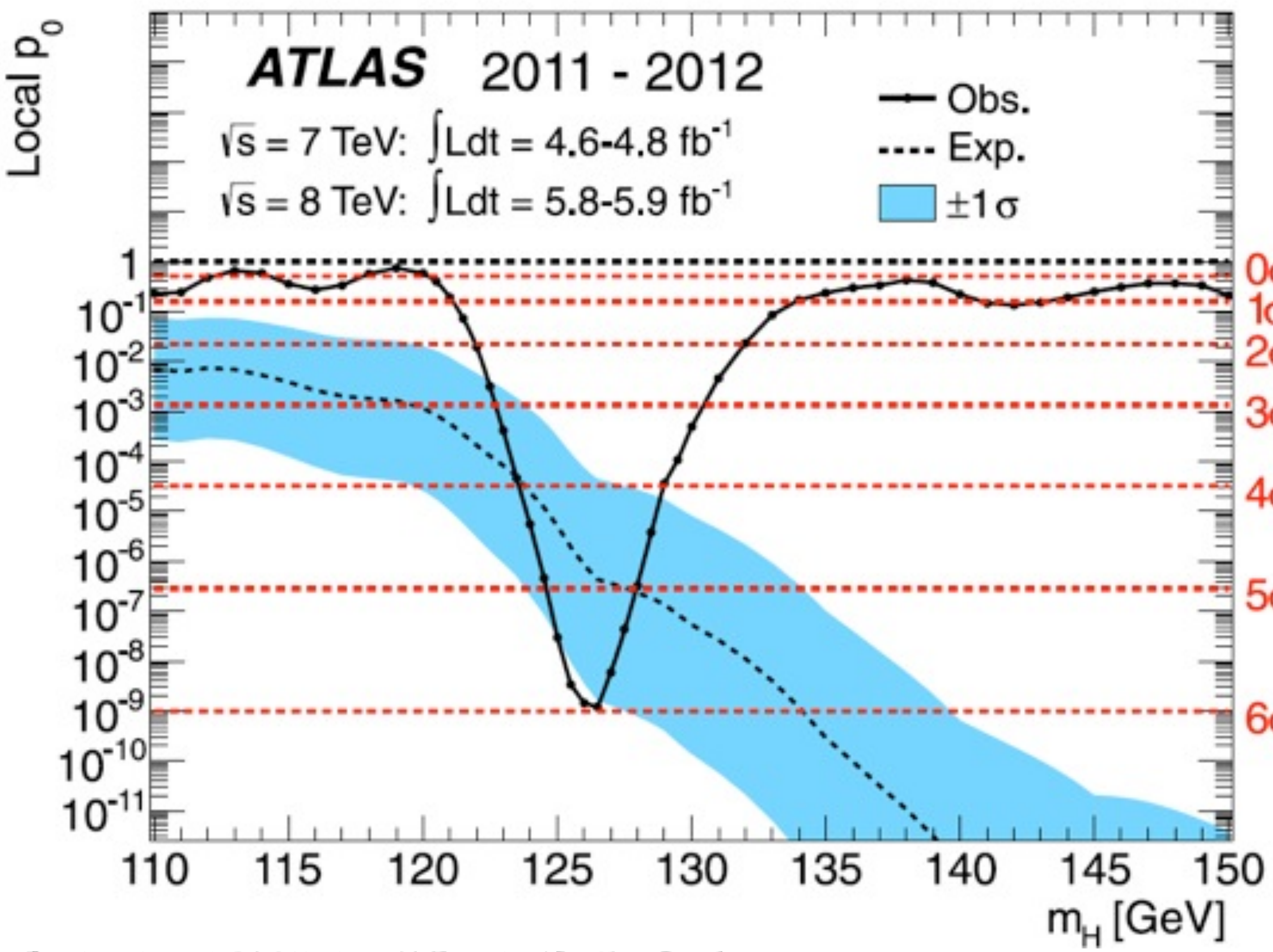


- Clear signal around 125 GeV, well in excess of the expected exclusion:
  A discovery!

Higgs Discovery: A Closer Look at ATLAS

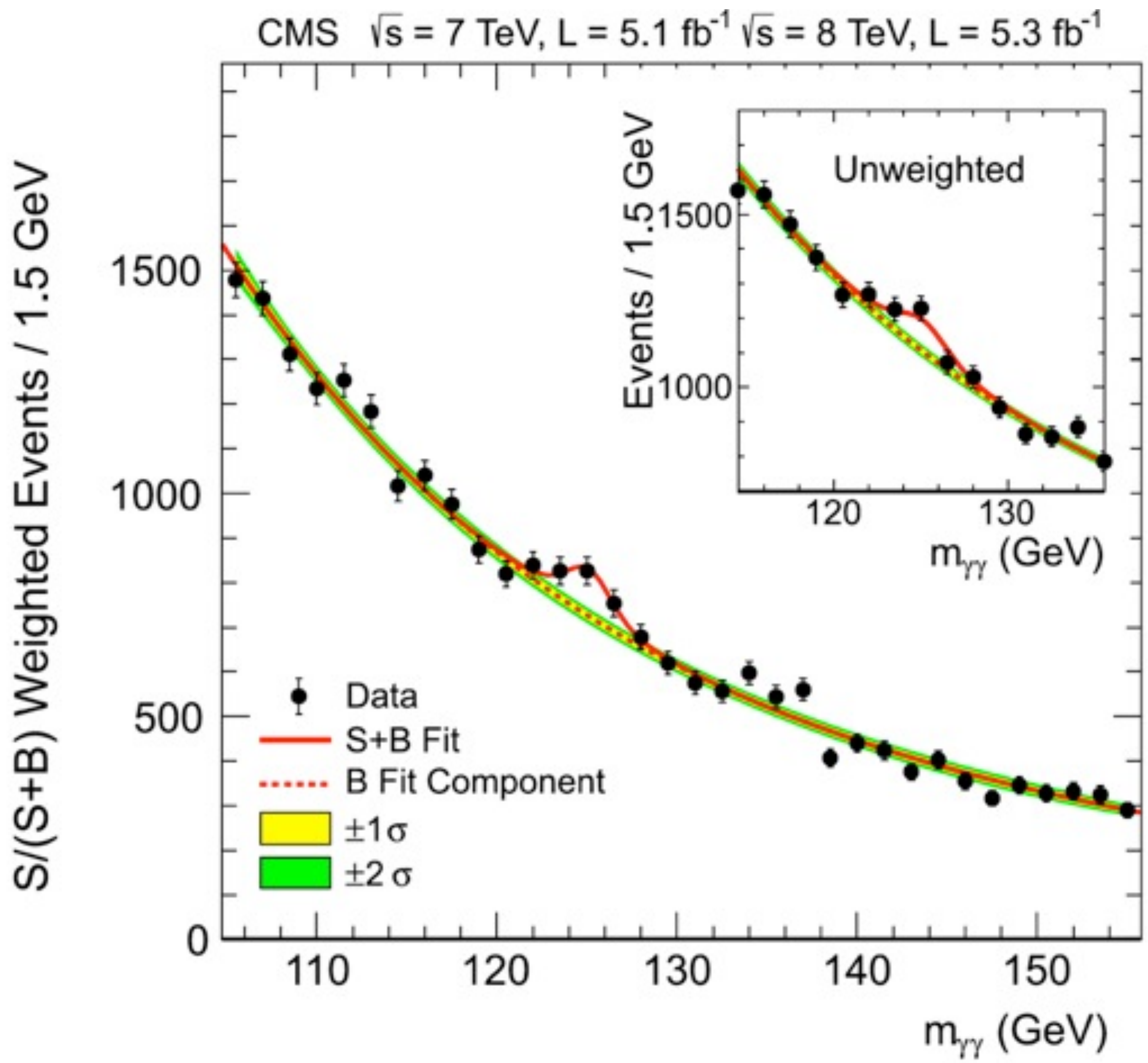


- Local significance (published!) ~ 6σ
  - Probability for a random fluctuation 10^{-9} (like tossing a coin and getting heads 30 times in a row)



Individual Channels

- The most significant: H -> γγ



CMS “discovery plot”

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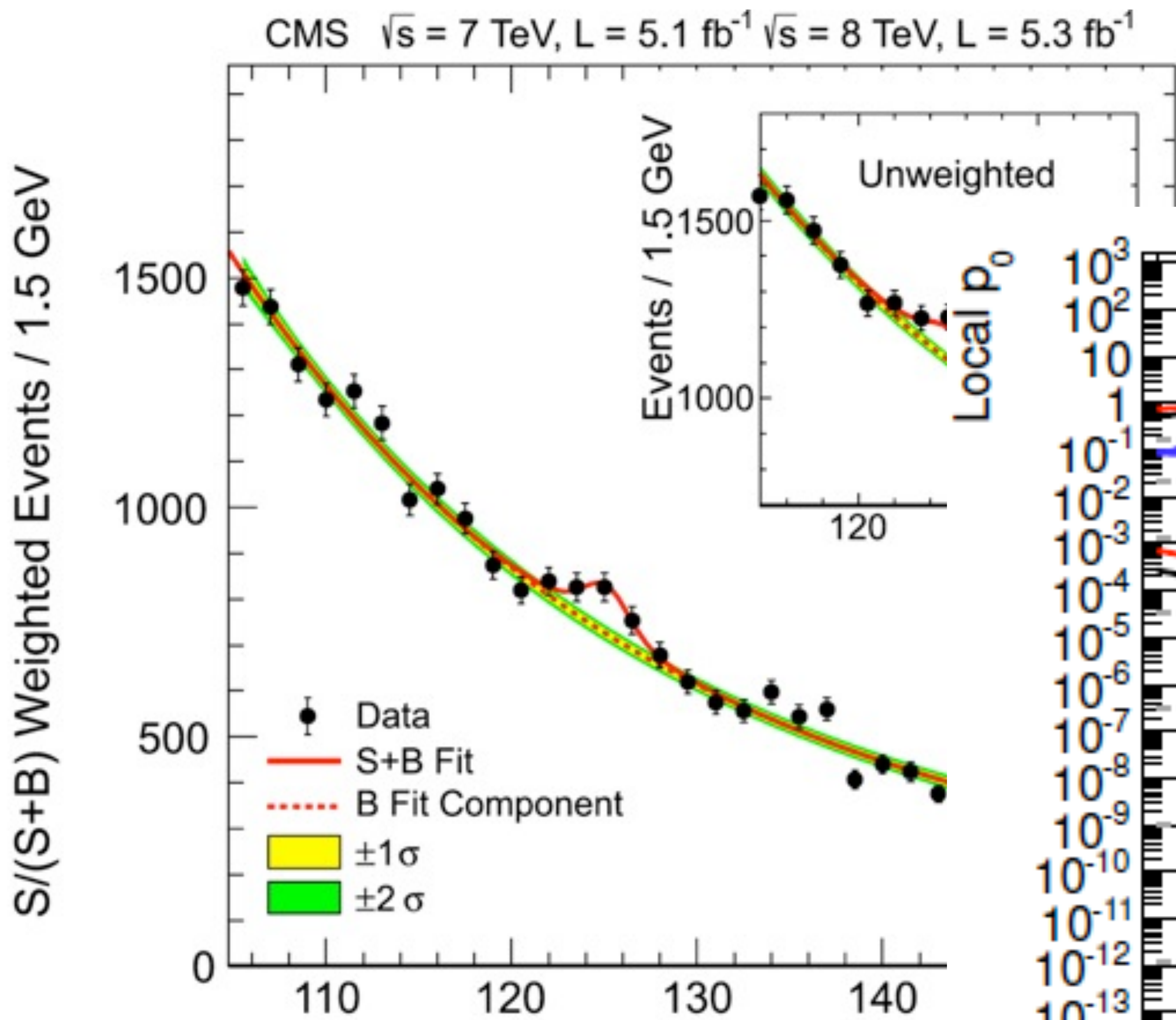
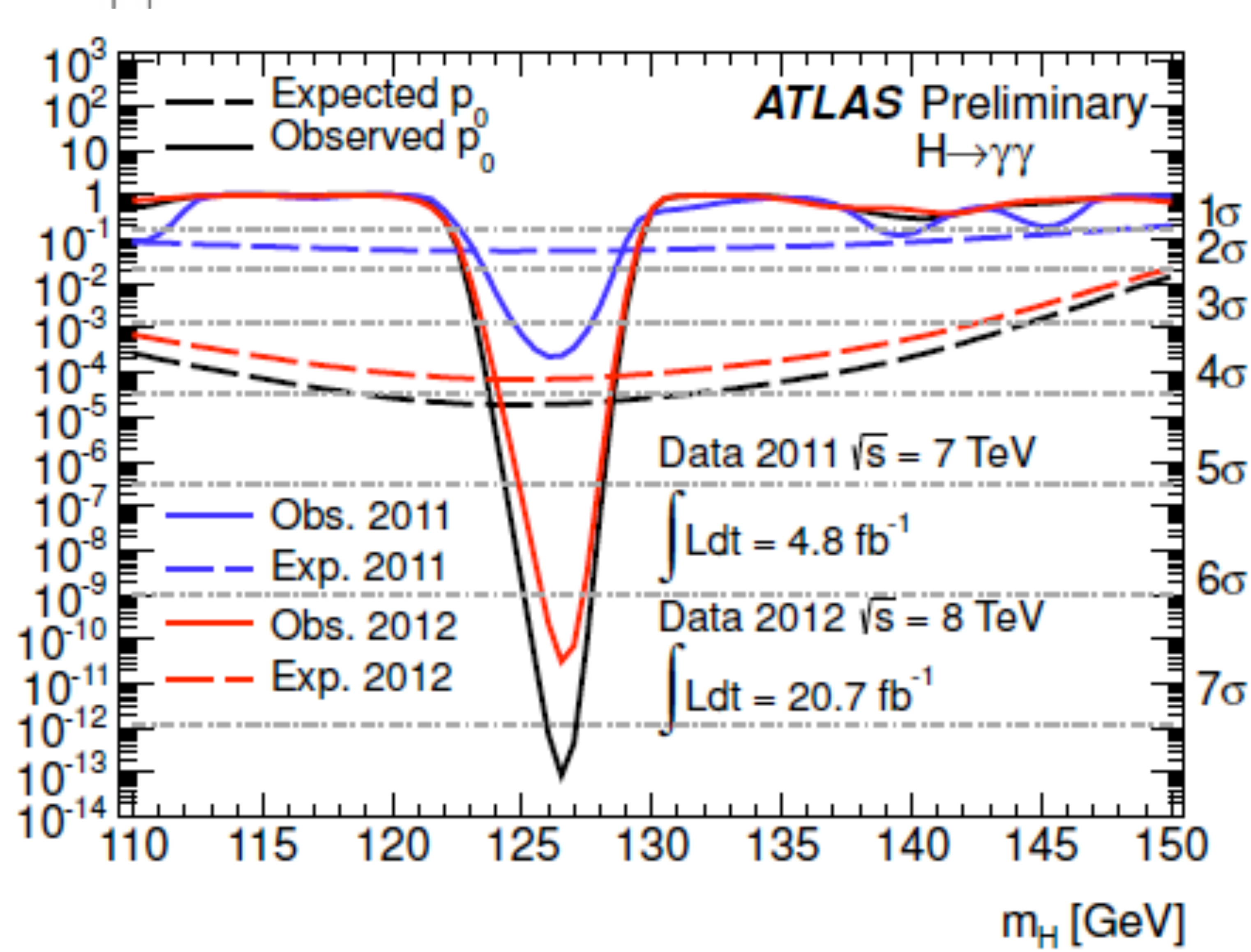


- With more data: Single channel discovery in ATLAS > 7 σ



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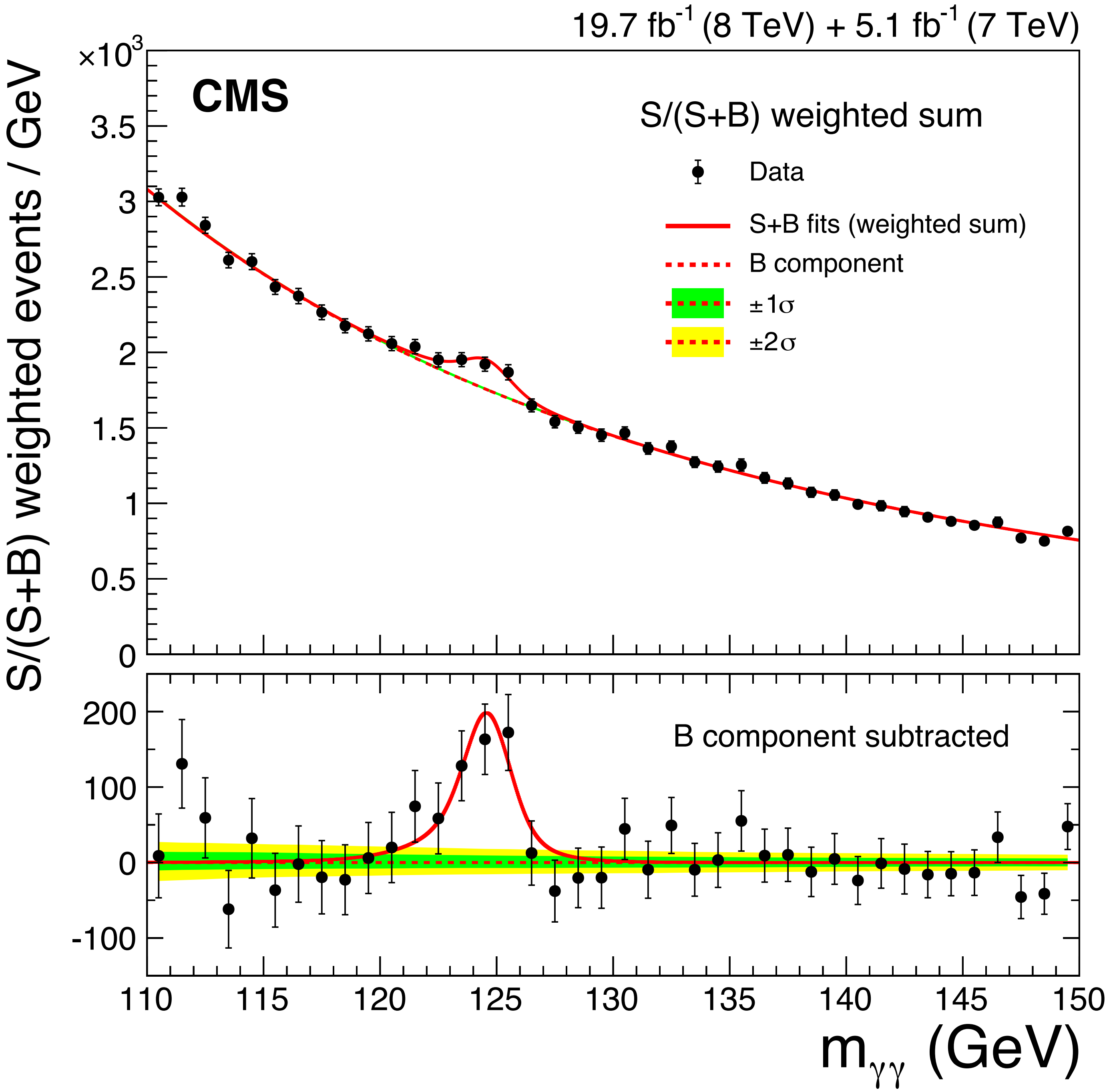

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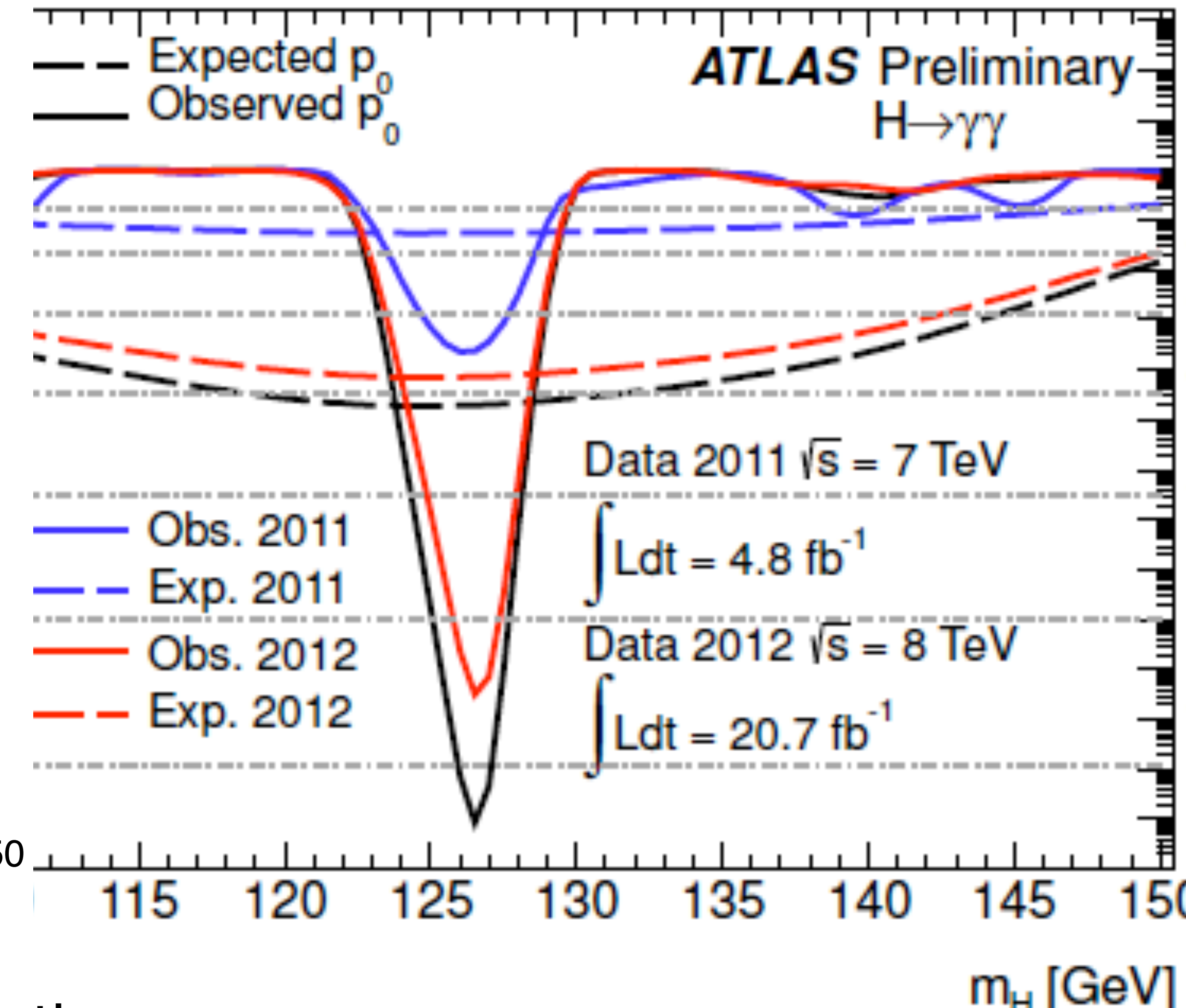
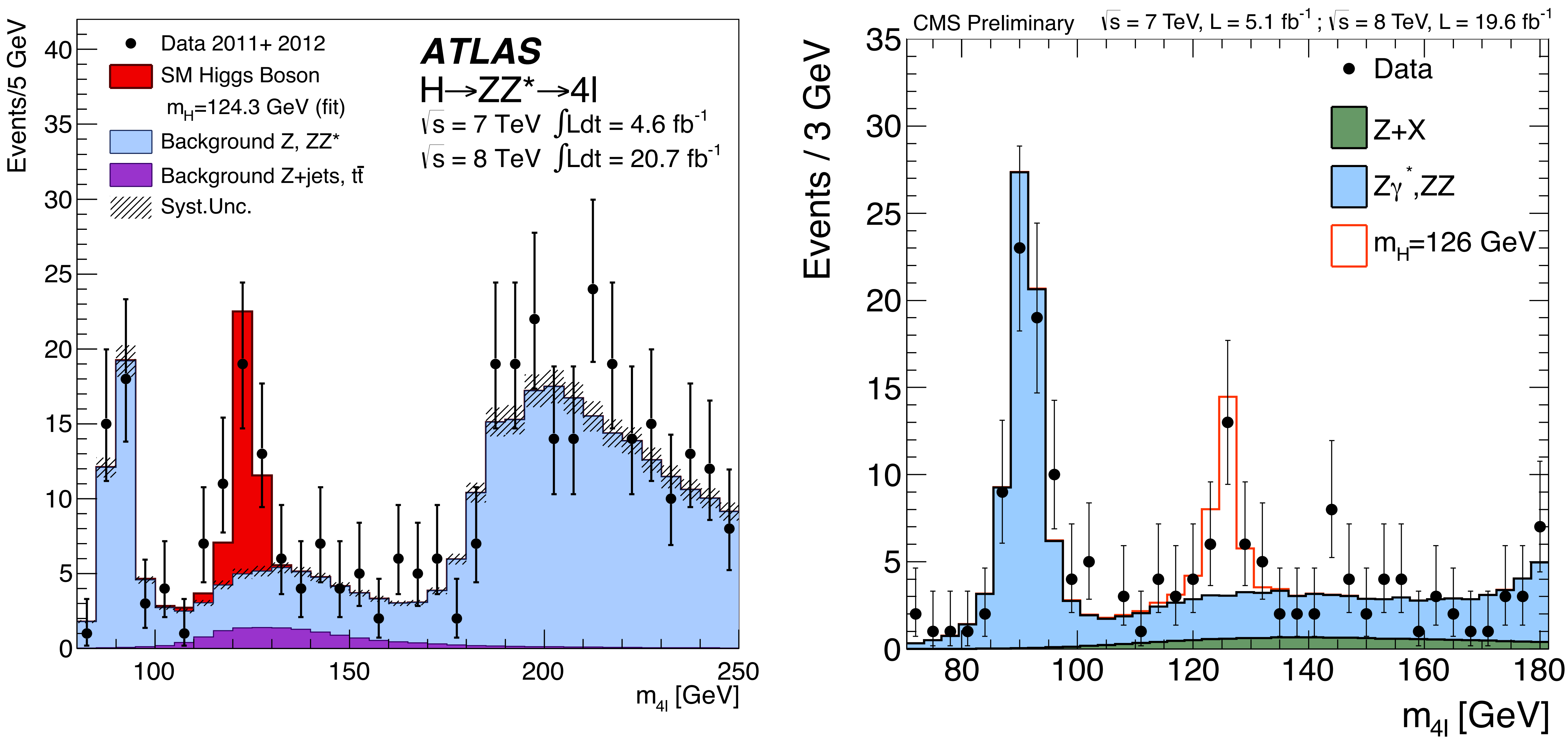


CMS “discovery plot” … and full statistics

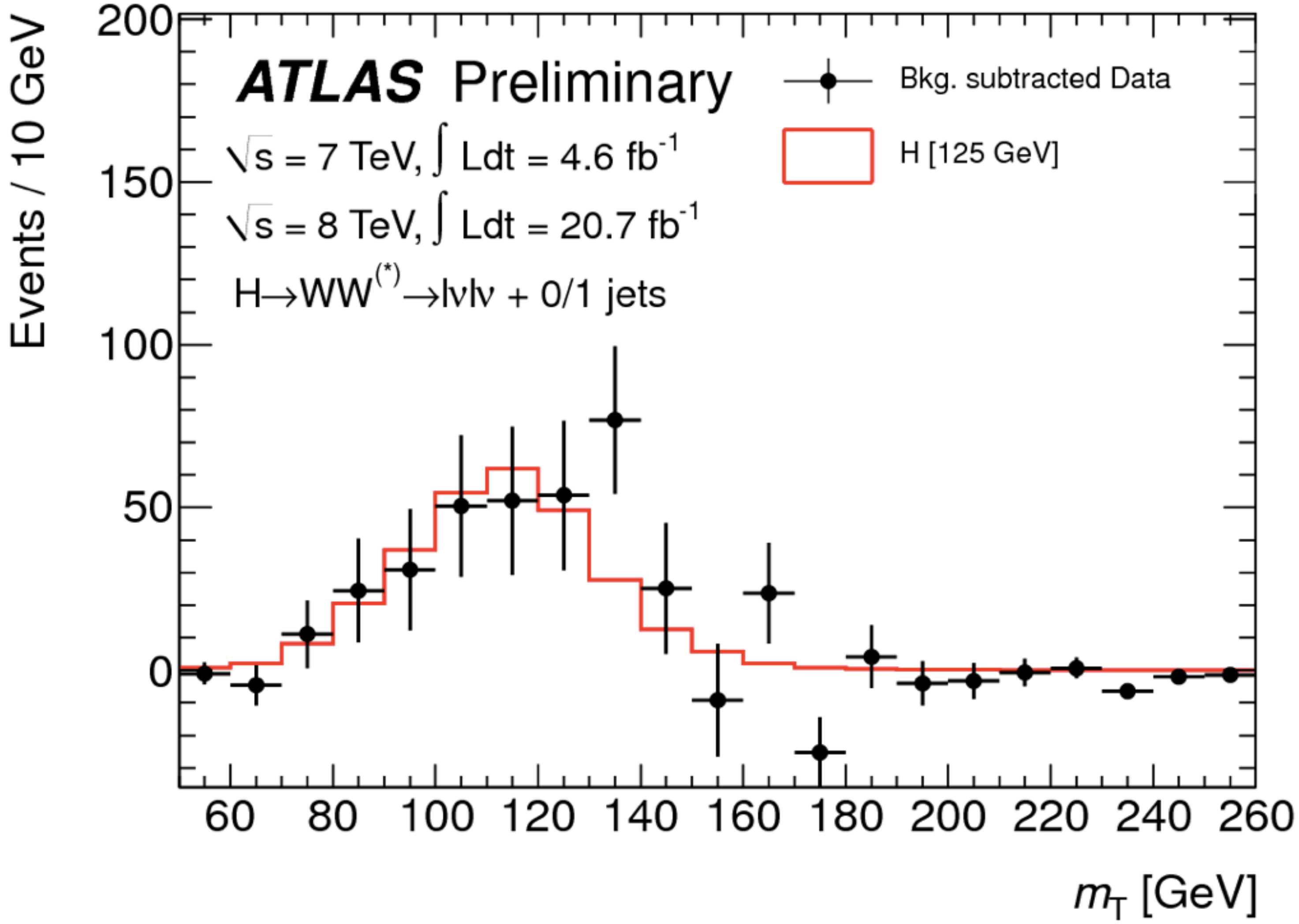
Individual Channels

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



Individual Channels

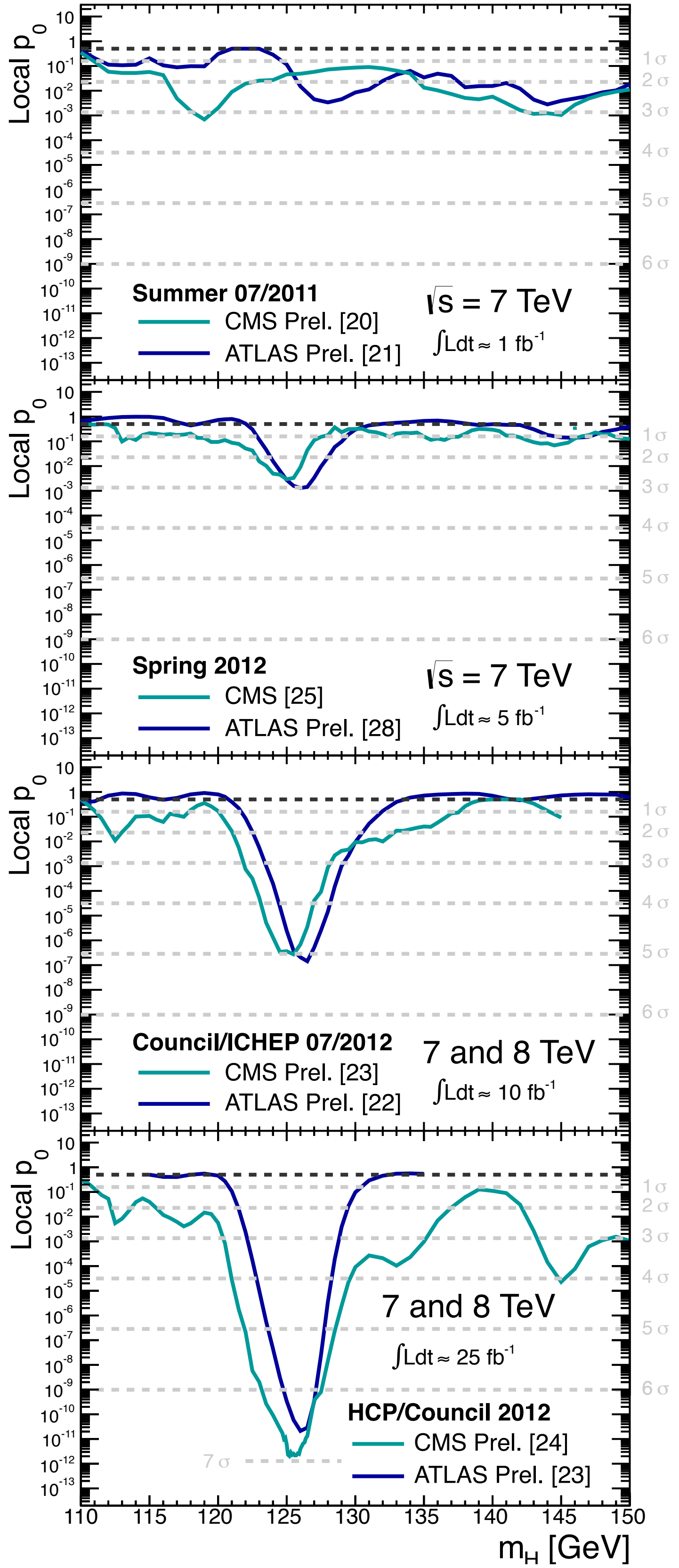
- The abundant: H->WW->lνlν



Significance: 3.8σ

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

The Discovery: Seeing it happen



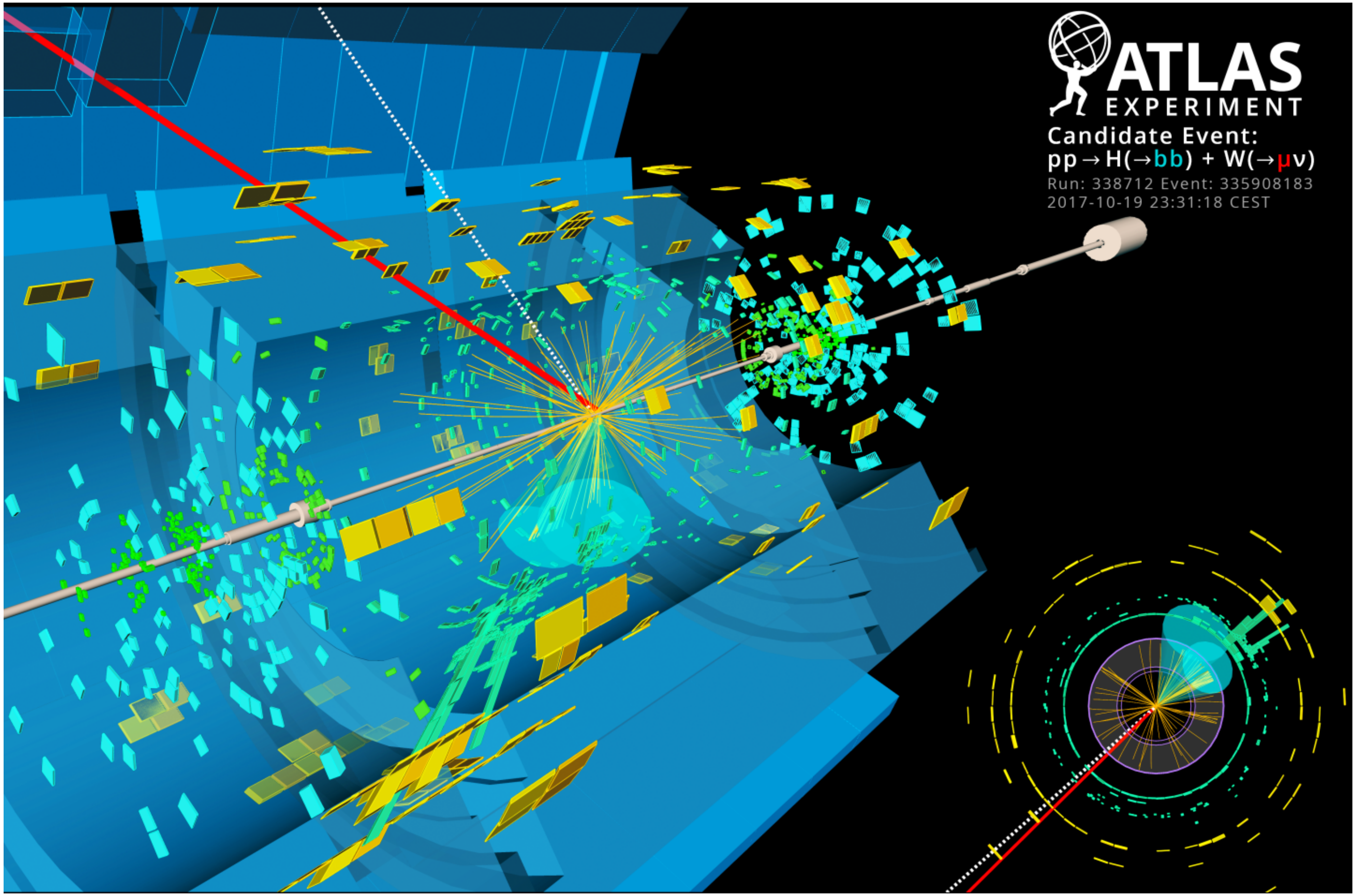
- Summer 2011: First (and last) focus on limits from LHC
- December 2011: First hints of a signal presented to CERN council
- Summer 2012: Discovery
- December 2012: Well established signal - entering the era of detailed Higgs physics program

July 4, 2012 - The Big Day

July 4, 2012 - The Big Day

July 4, 2012 - The Big Day

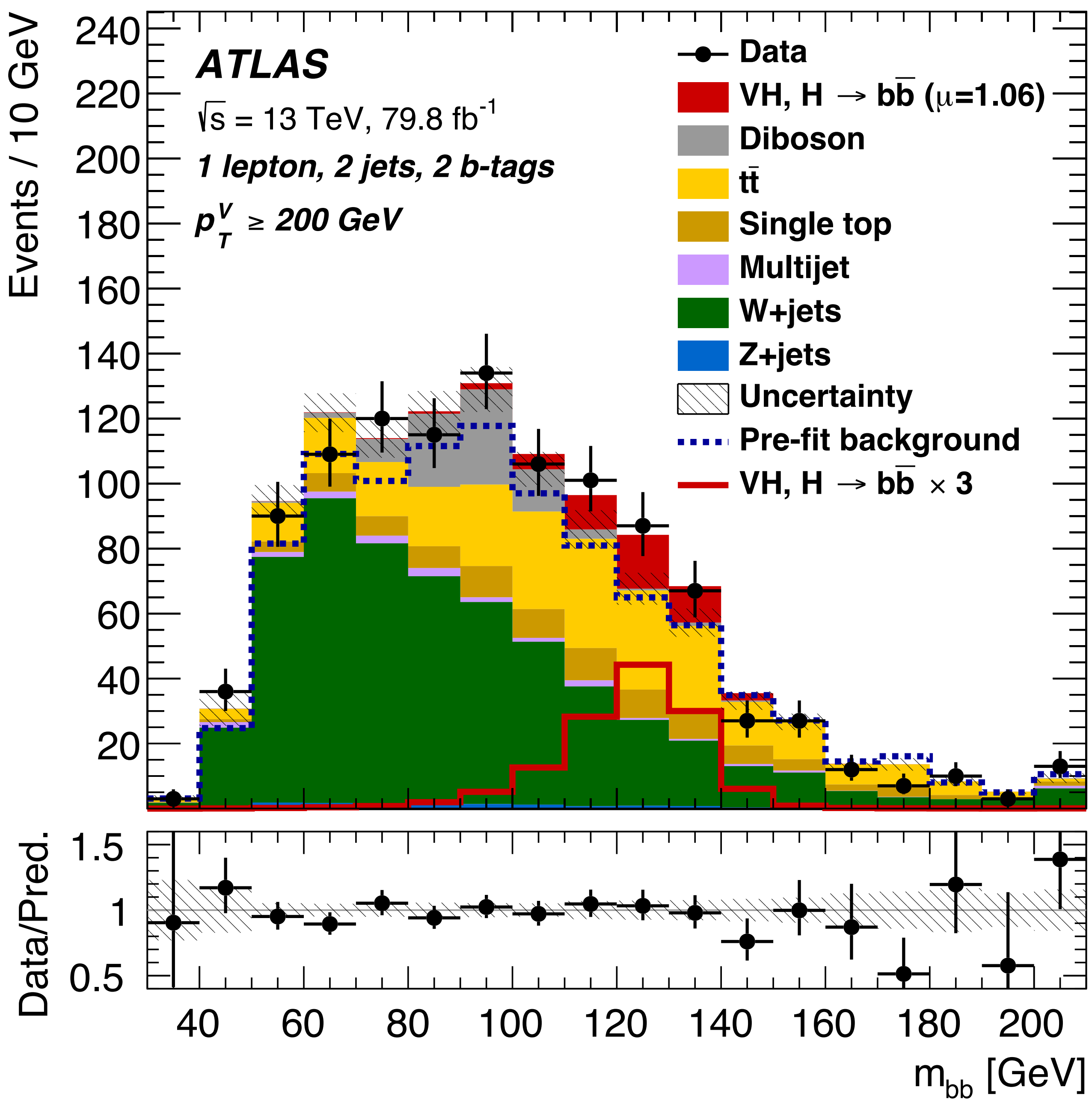
Beyond Discovery: Other Channels - H->bb



- H->bb BR: 57%
- VH production: ~5% of all H production, only leptonic V decay: 0.7%
  - Combined: 0.4%
- 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 - H->bb



definitive observation of process in 2018 - consistent with SM expectation

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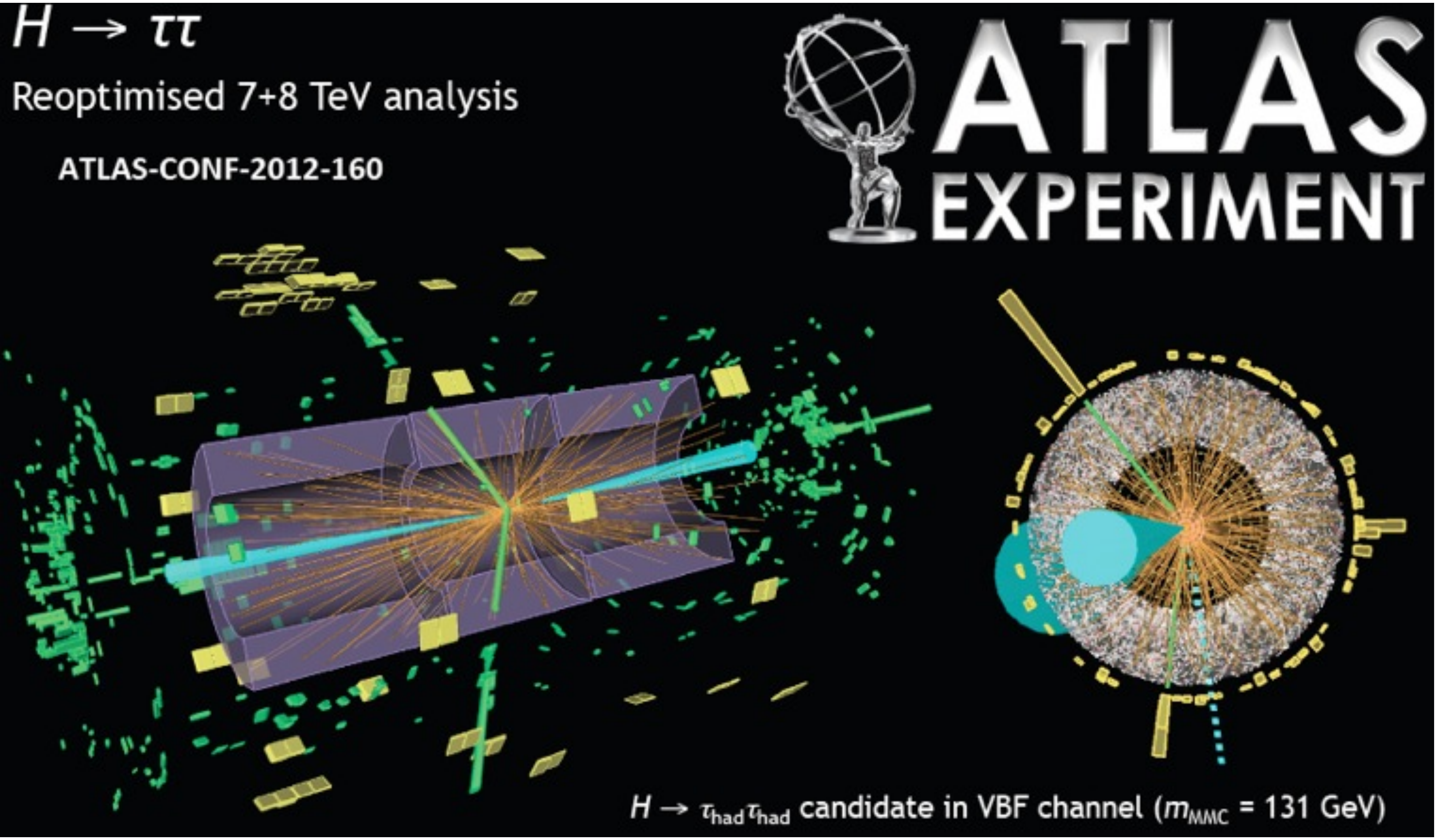
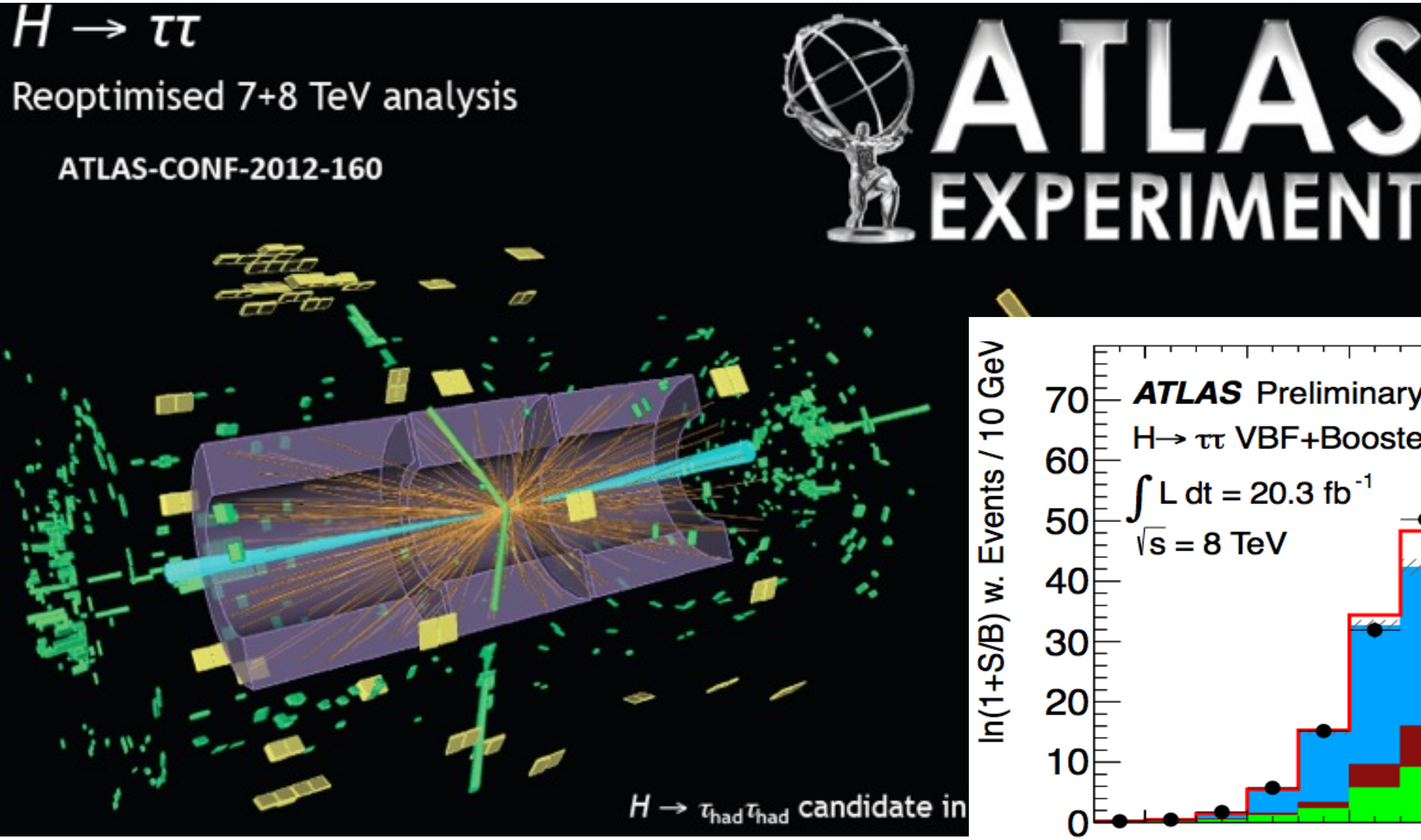
Beyond Discovery: Other Channels



- 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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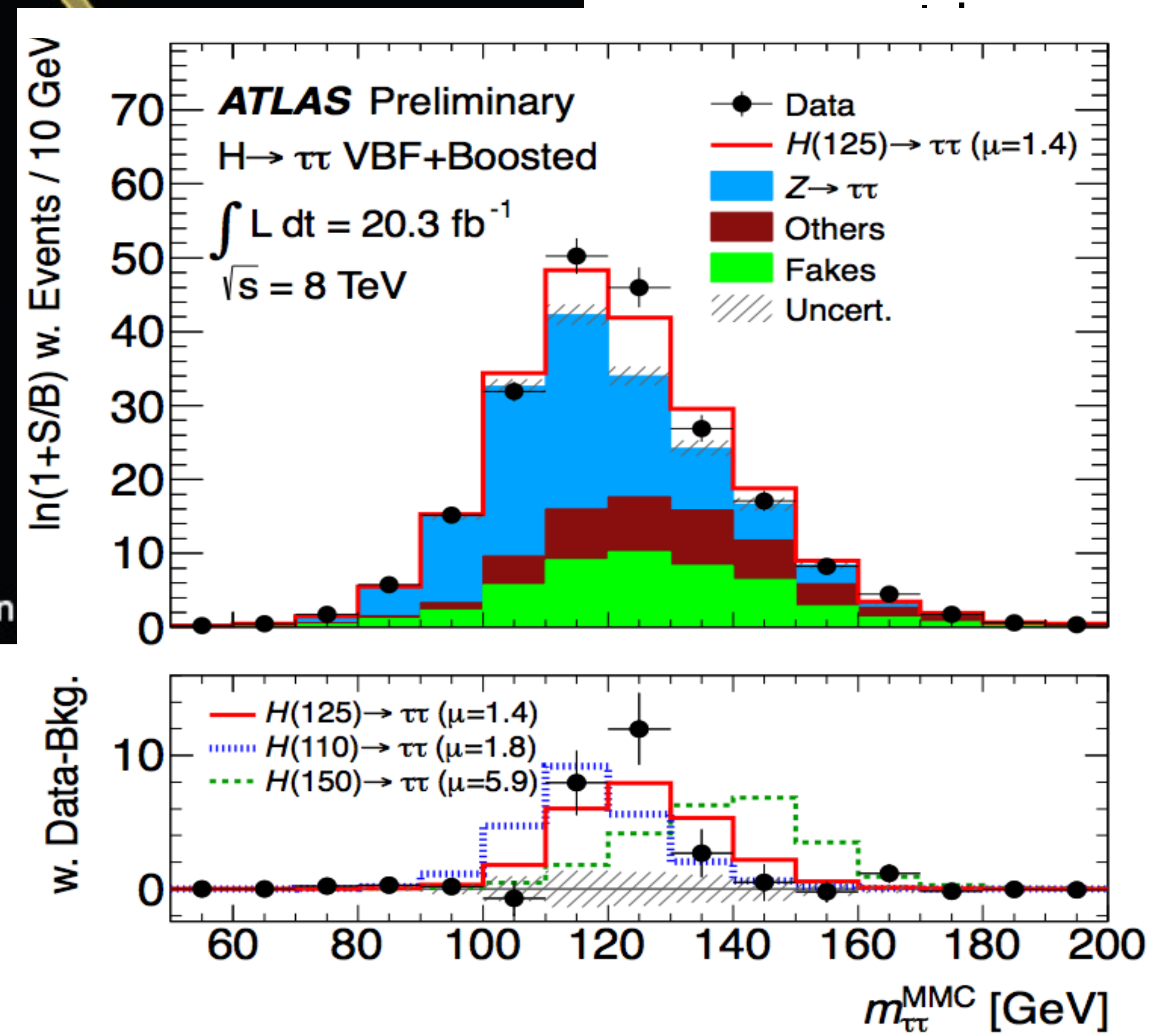
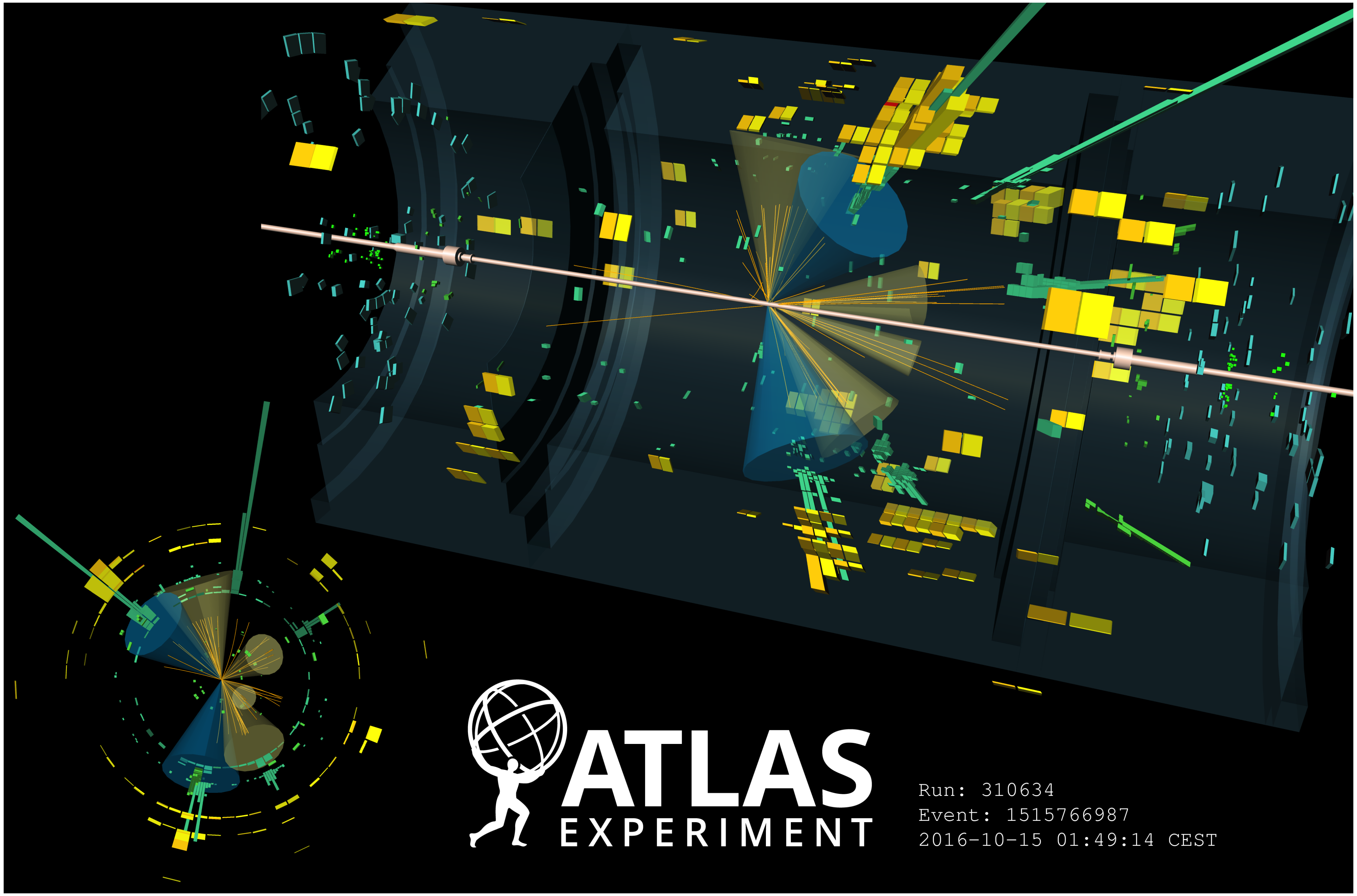


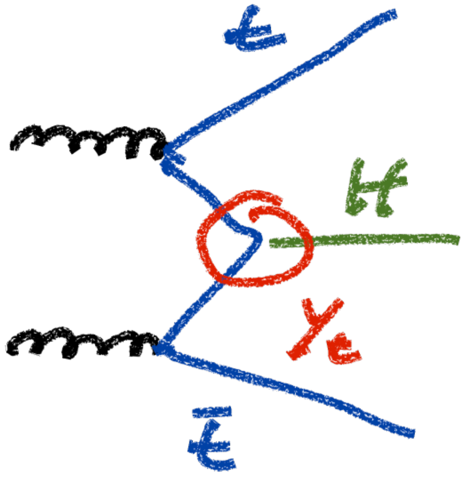
- Established already with full Run 1 dataset

Beyond Discovery: Coupling to the Top Quark



- A key measurement: Directly observing the strongest Yukawa coupling

definitive observation of process in 2018 - consistent with SM expectation

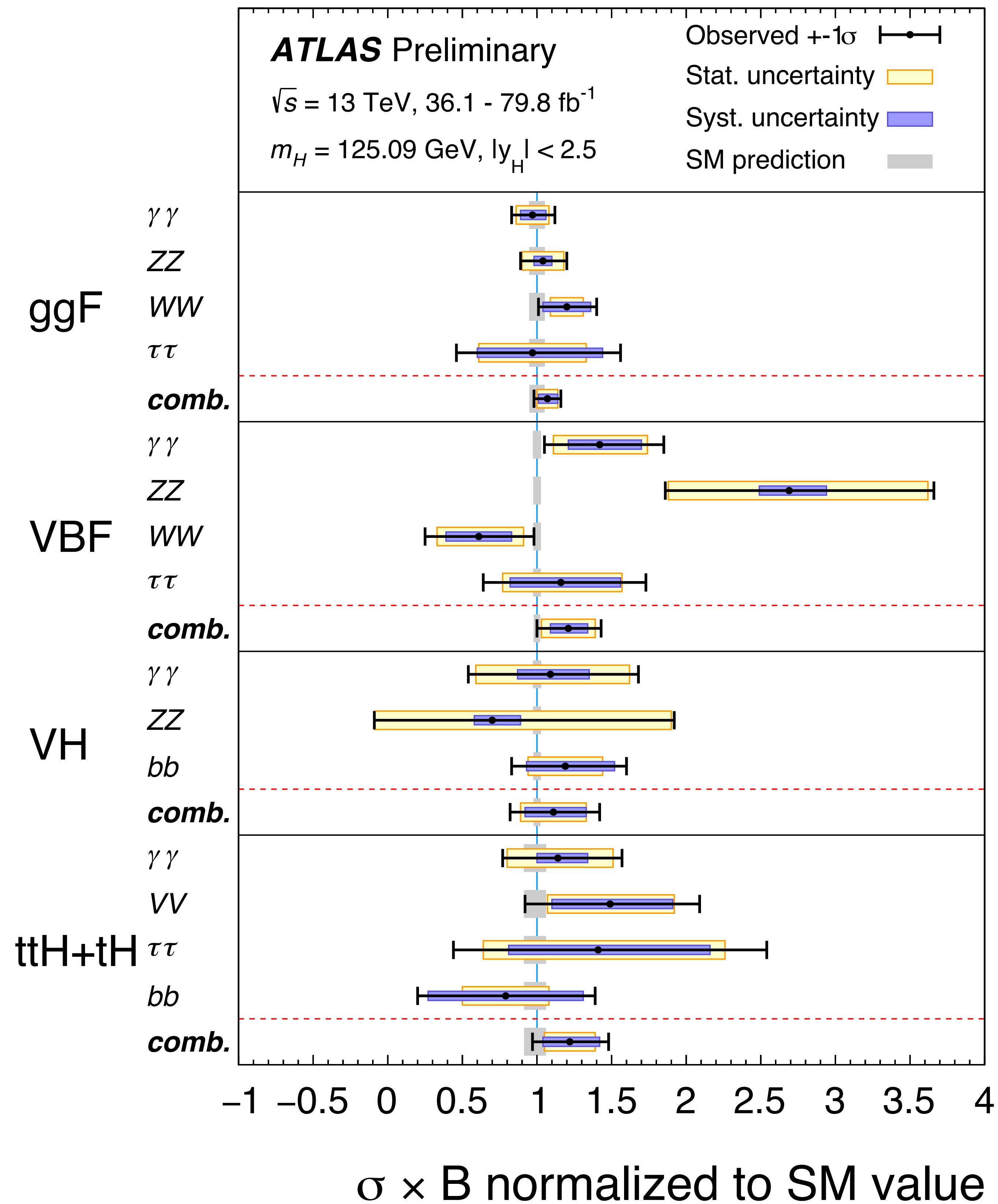


- A difficult measurement: Lower cross section, highly complicated final state: ttH

Higgs Properties

The Coupling of the Boson: Is it a Higgs?

- The key question: Does the new boson couple to mass as expected for the Higgs? -> Can be answered by measuring the cross sections and decay branching ratios for different production and decay modes



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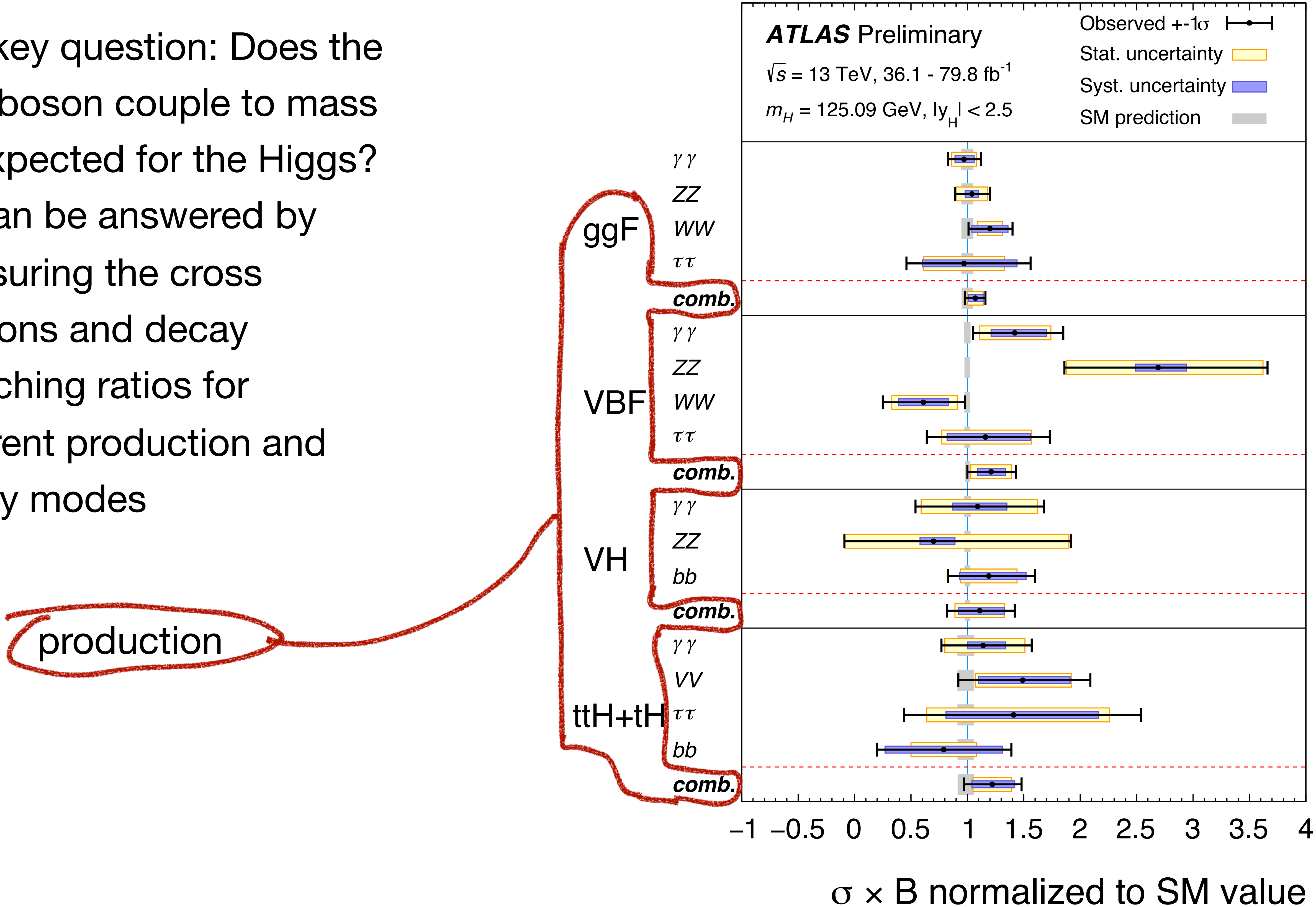

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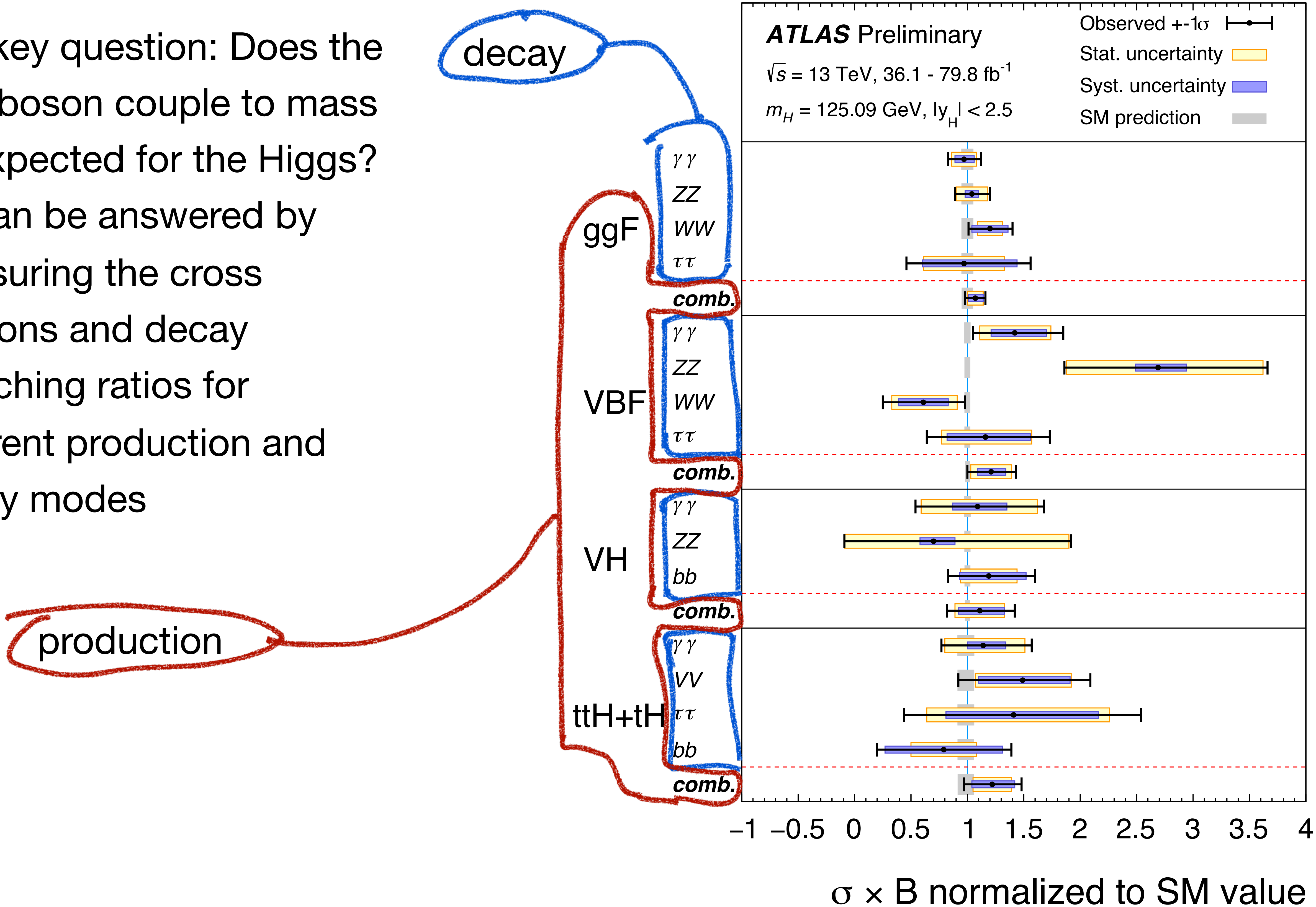

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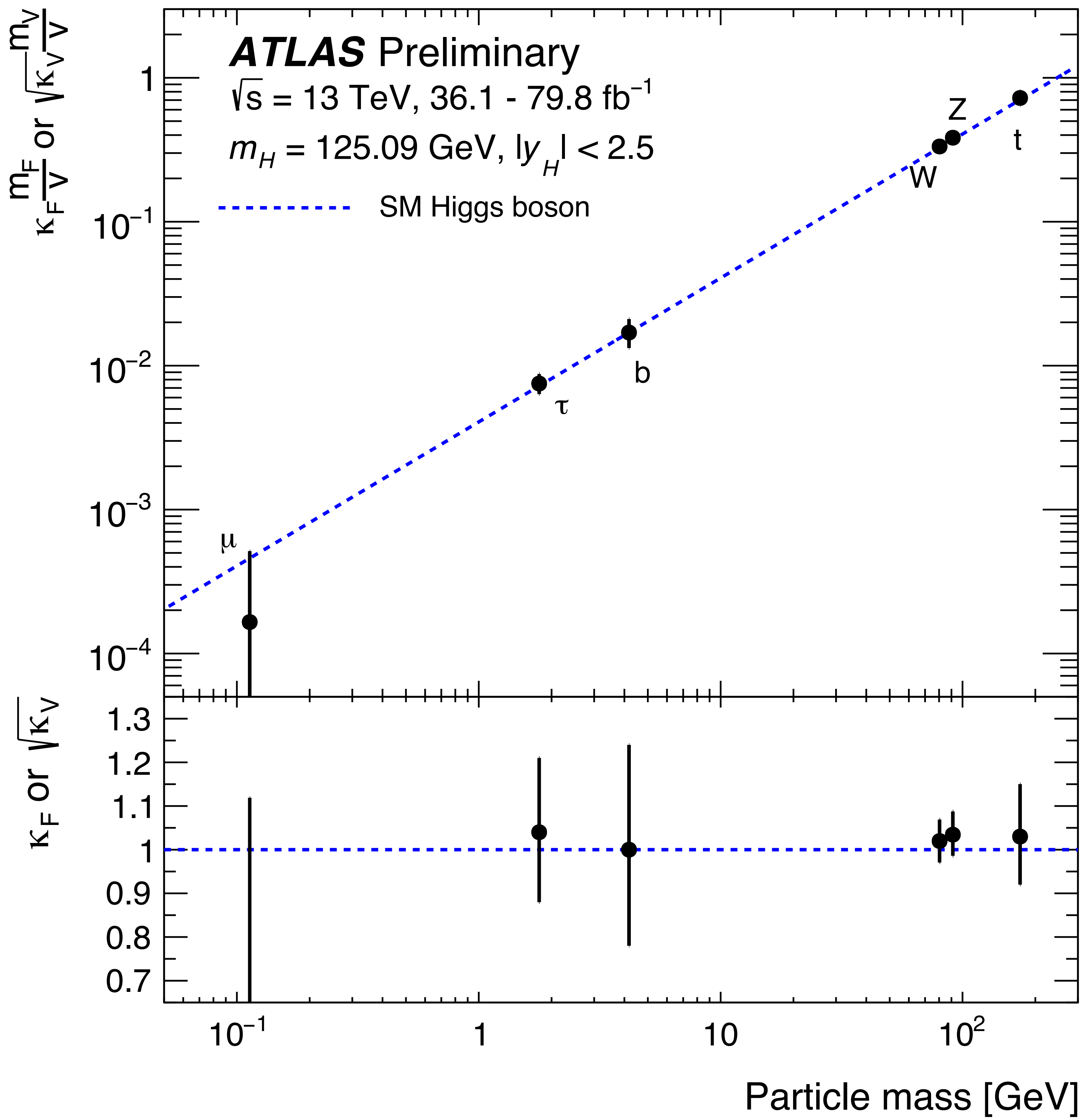


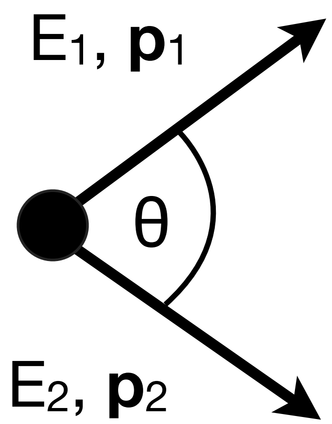
- From the measured signal strengths the couplings of the Higgs to various particles can be determined (with additional uncertainties)
- Clear evidence that couplings scale with particle mass (nothing like this has been observed for any other particle!):

It is a Higgs boson

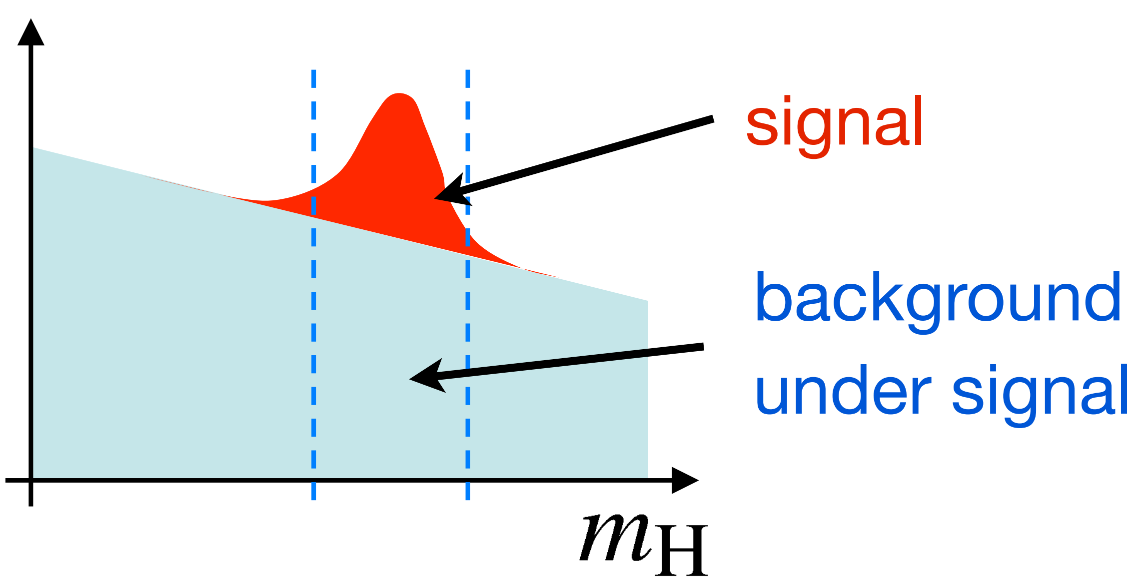
The Mass

- 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



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

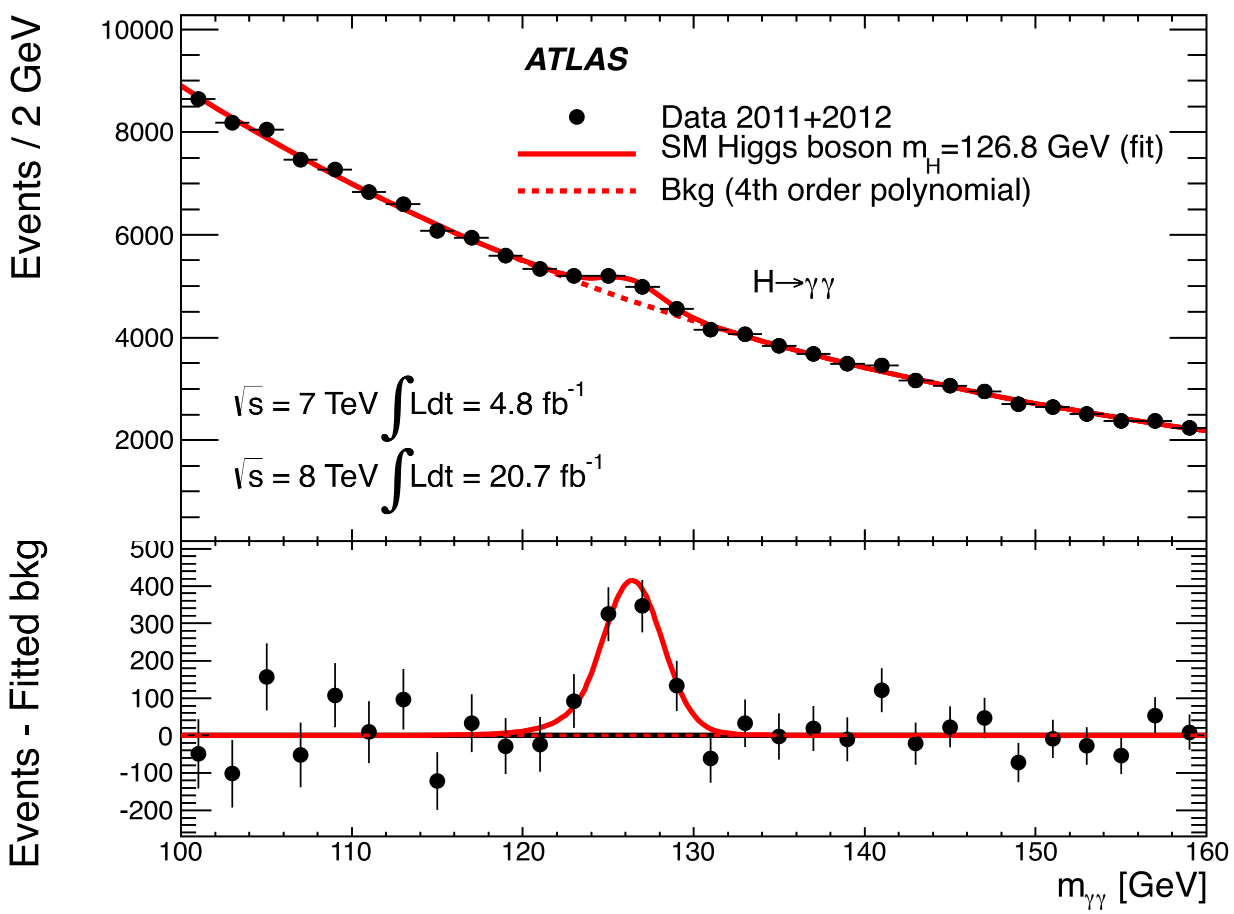


Significance: $\propto \frac{S}{\sqrt{B}} \propto \frac{1}{\sqrt{\sigma(M)}}$

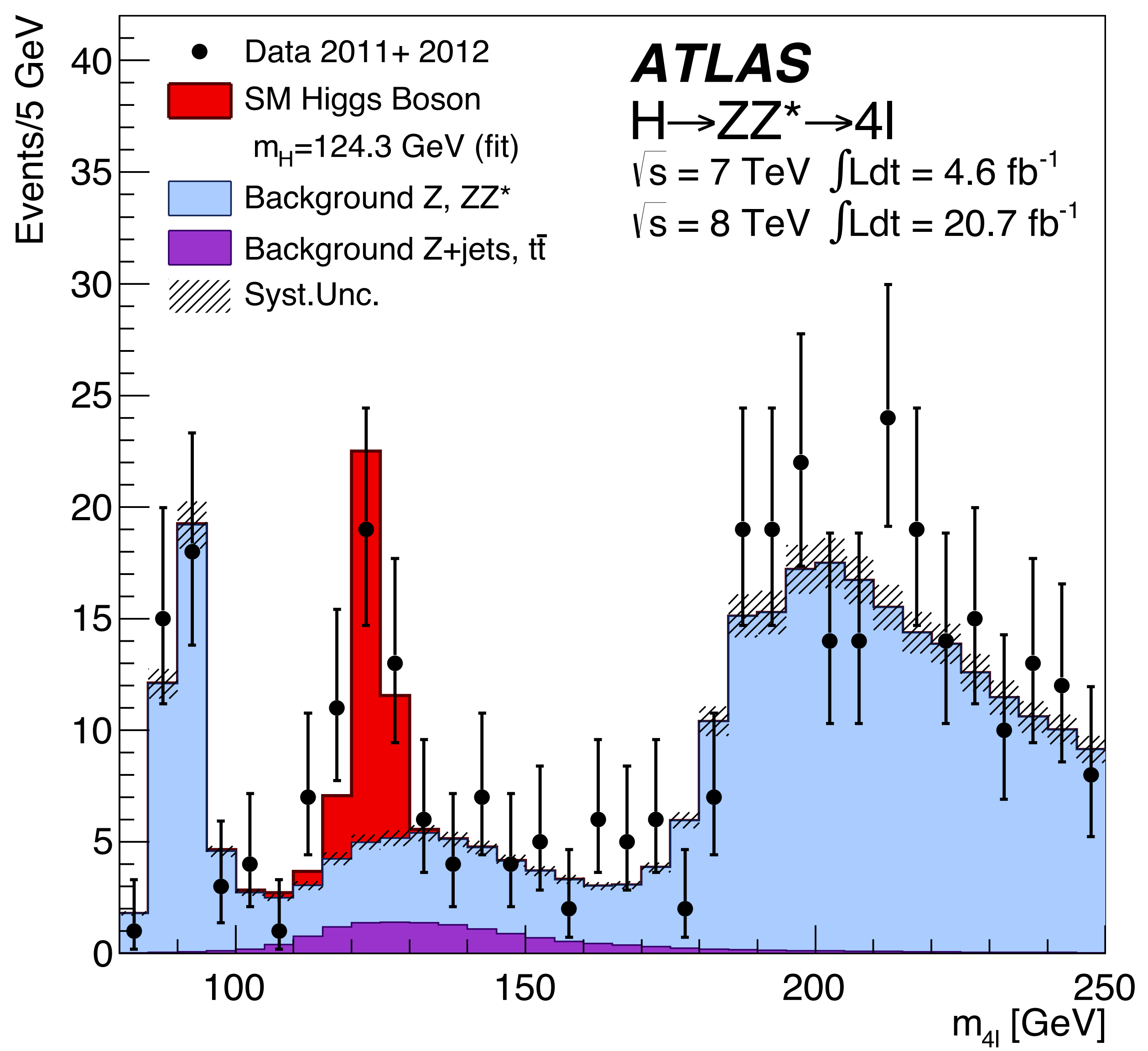
- Choose channels with good mass resolution -> Good energy and angular resolution for decay daughters

The Mass: Measured in Two Channel

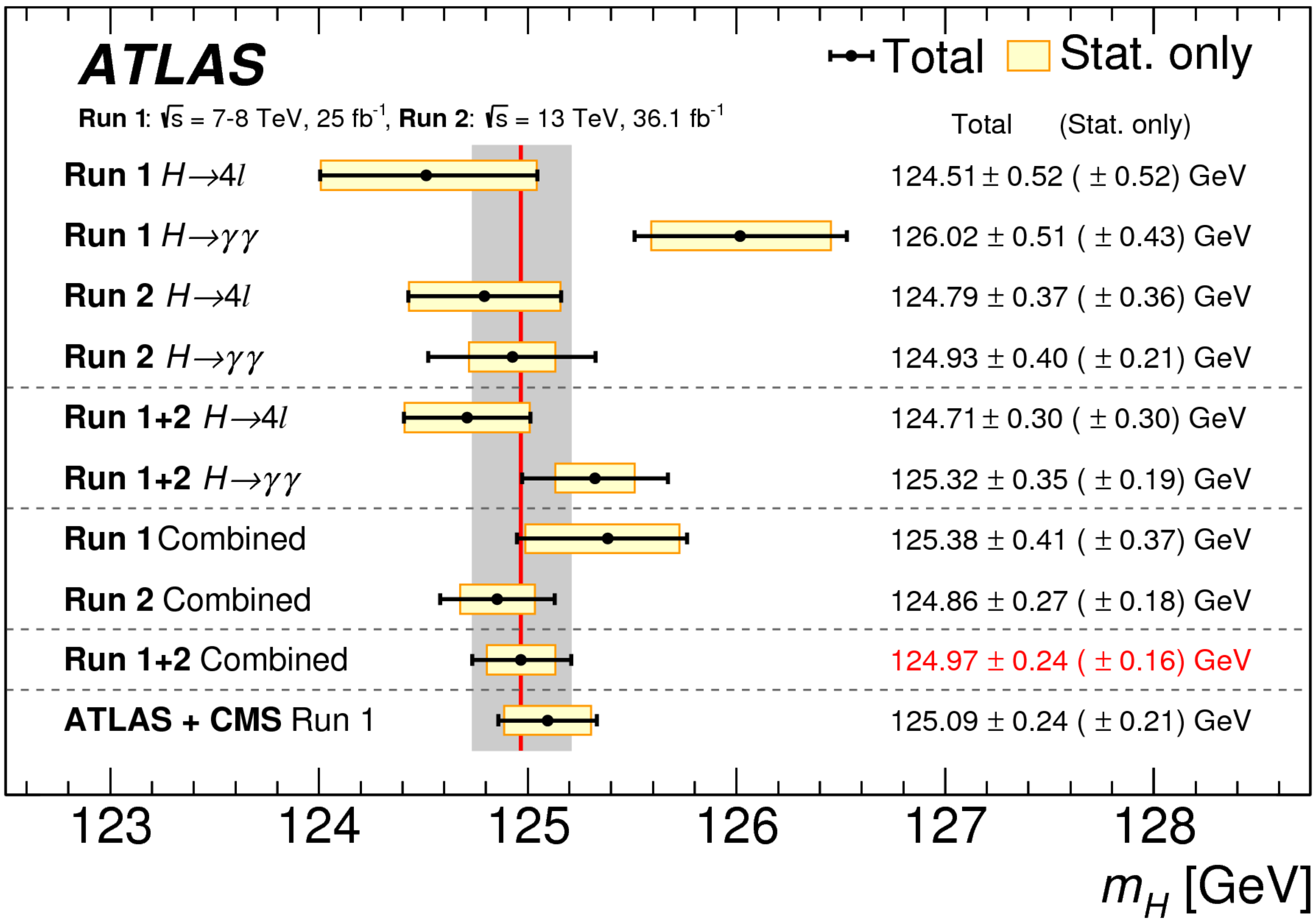
H -> γγ



H -> ZZ* -> 4l



The Mass: Current Status from ATLAS



- In Run 2: Consistent mass measurements for both channels
  - discrepancies seen in Run 1, also for CMS (but there: opposite pattern)

The Spin of the 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	no	no

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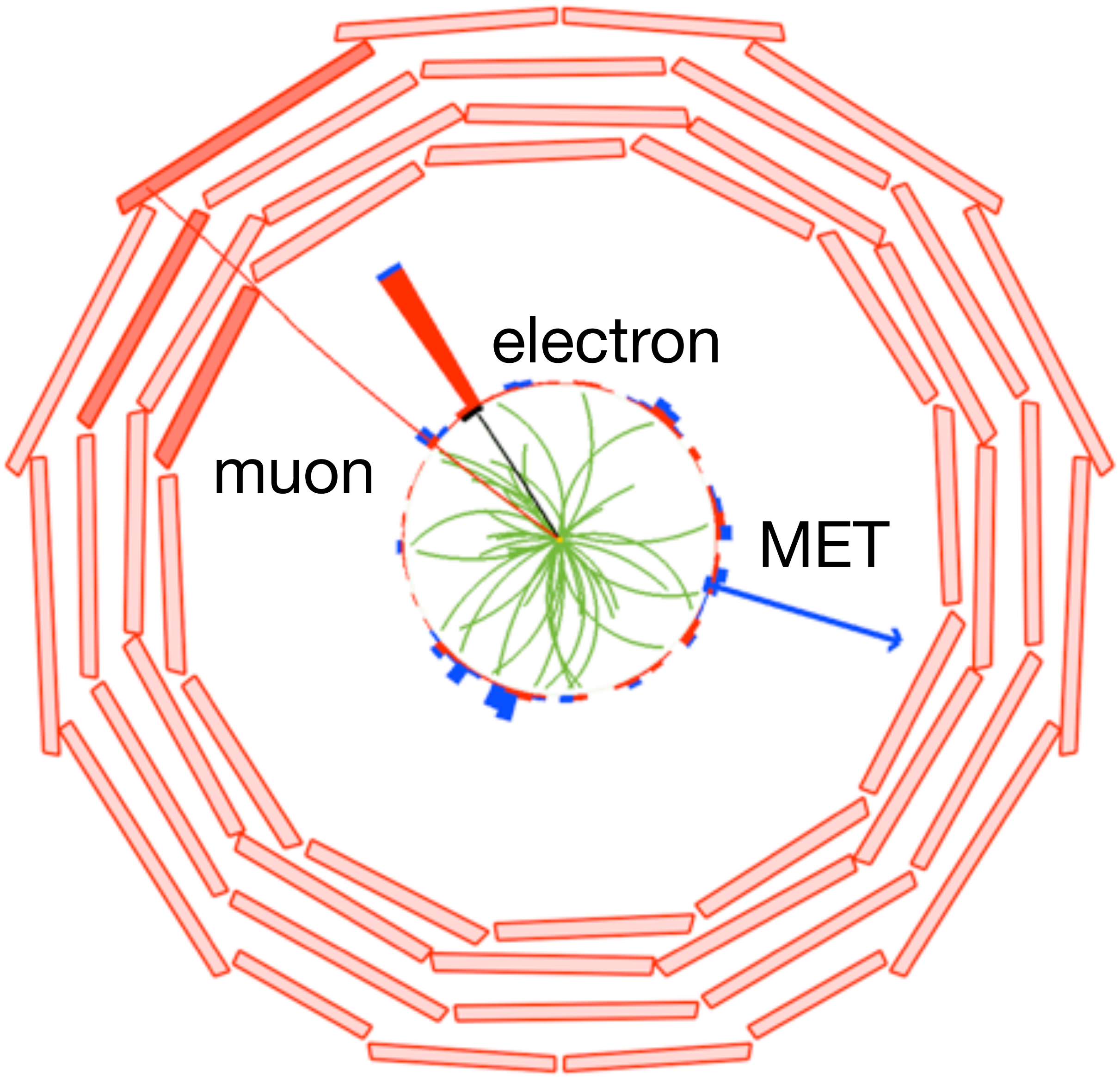
- We expect a scalar particle: Spin 0
- Naive first look - From observed decays (neglects possible angular momentum in final state - e.g. p-wave vs s-wave)

Decays	Observed?	Spin 0	Spin 1	Spin 2
H -> $\gamma\gamma$	**yes**	**yes**	**no**	**yes**
H -> ZZ	**yes**	**yes**	**yes**	**yes**
H -> bb	**yes**	**yes**	**yes**	**(yes)**
H -> $\tau\tau$	**yes**	**yes**	**yes**	**no**
still allowed ?		**yes**	**no**	**no**

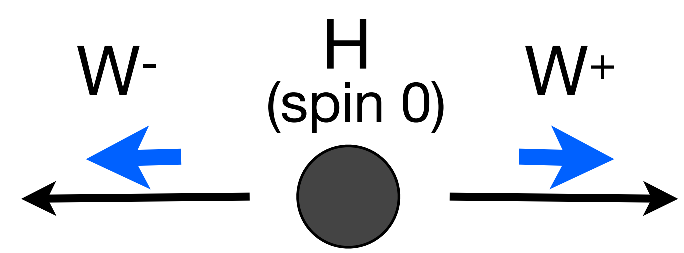
The question of spin is basically settled - not with decay mode observations alone, since there can be additional angular momentum in the two-particle final states...

The Spin of the Boson

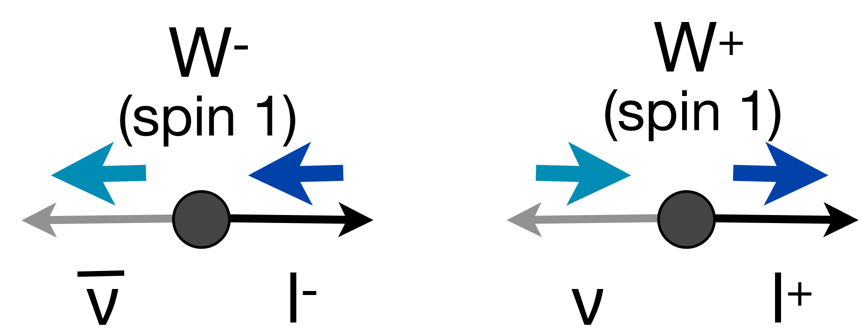


- The full answer will come from angular correlations!

One example: H->WW

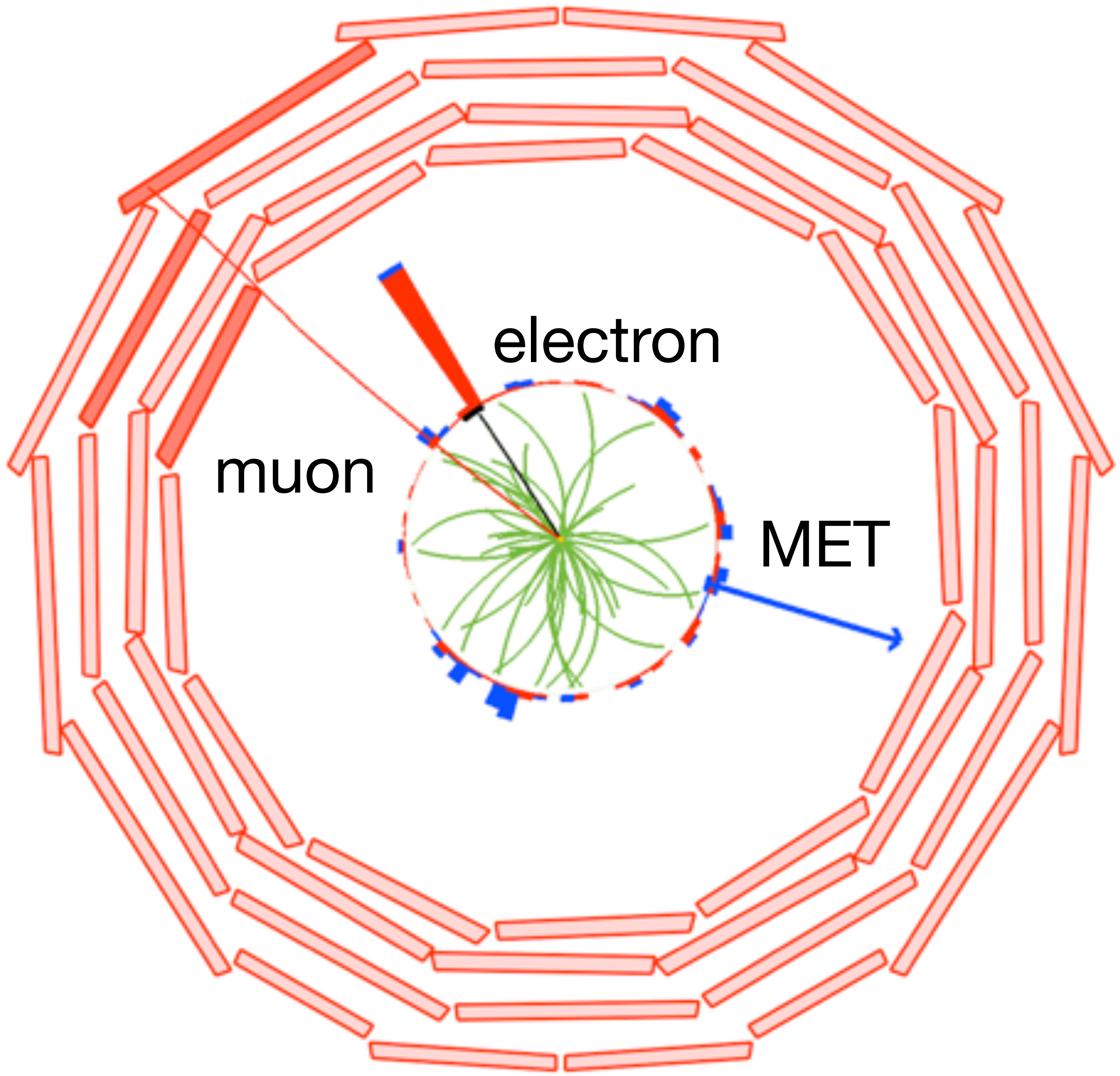


parity violation in weak interactions:



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 Boson



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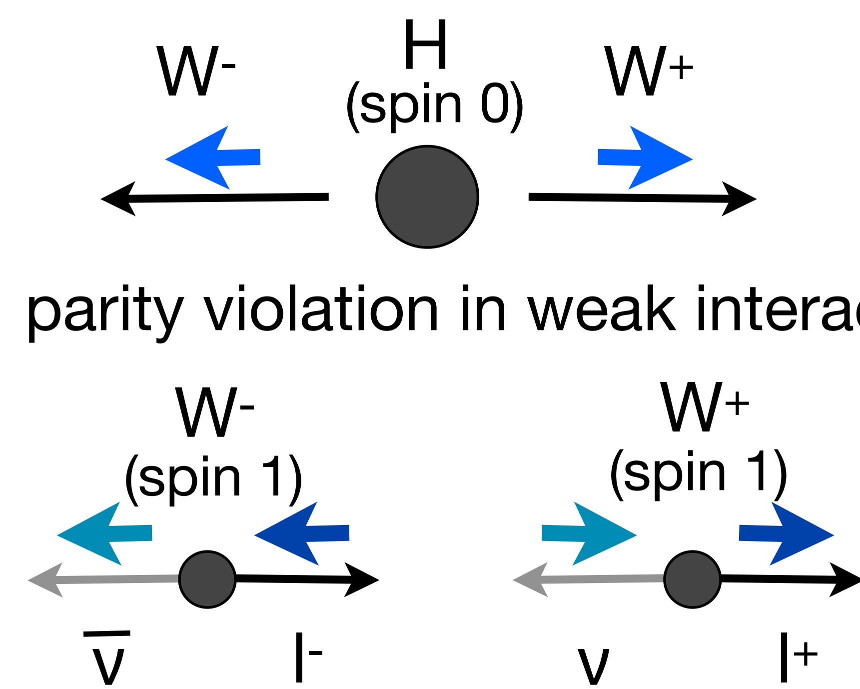
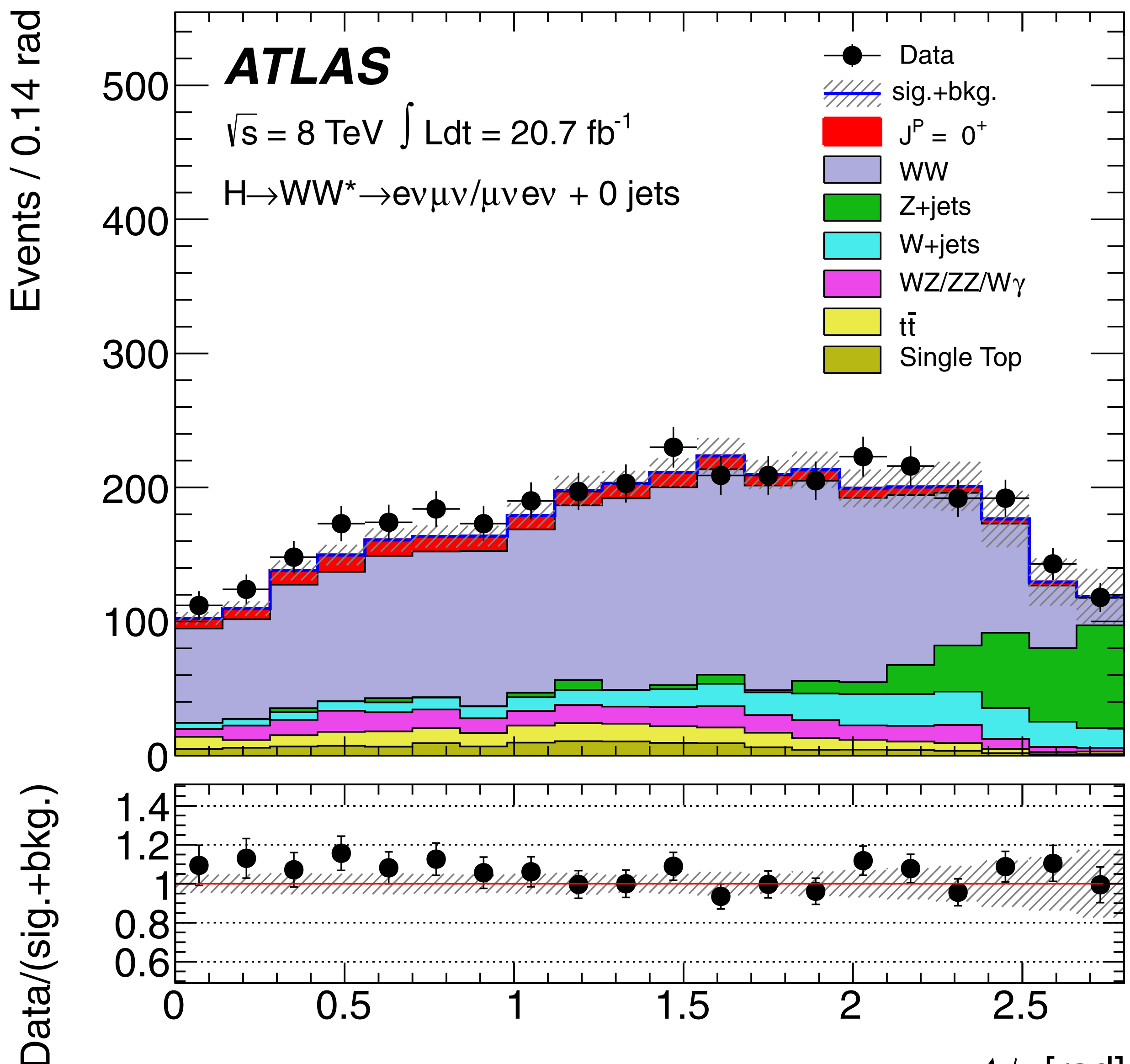


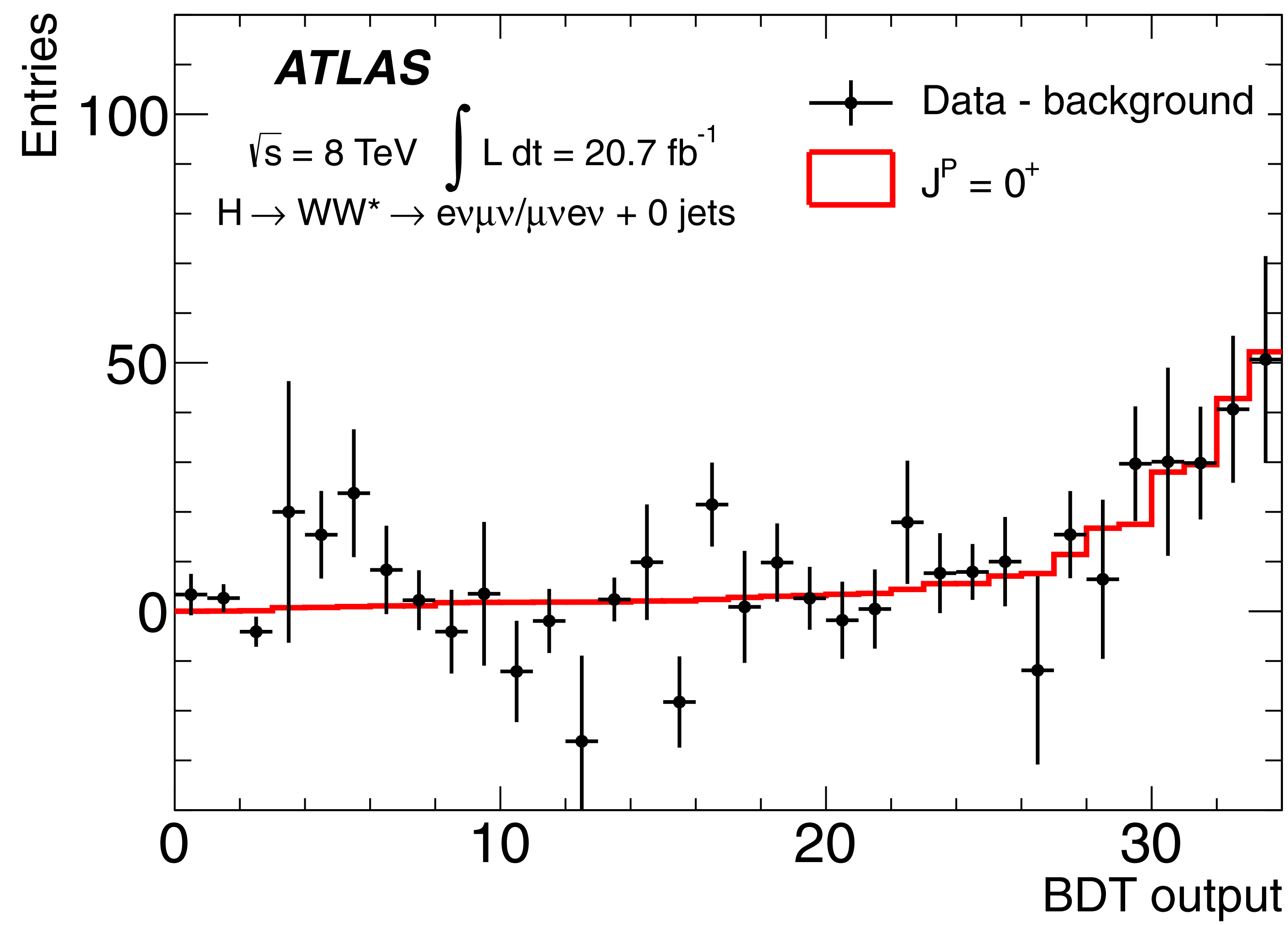
A word of caution: The requirements for large MET and also small opening angle between the leptons in the analysis disfavors event selection for spin ≠ 0

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 from Run 1 WW in 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

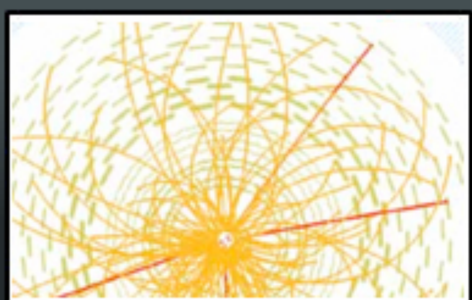
When taking all information together (CMS, other channels): 0^+, only small admixtures of other states allowed

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

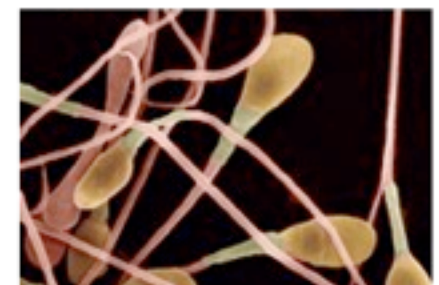
A. Cho

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.

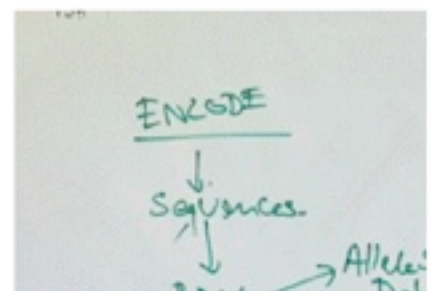
Read more about the Higgs boson from the research teams at CERN.

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

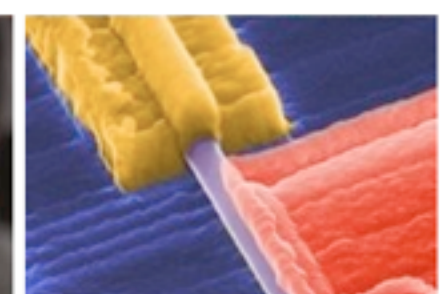

Neutrino Mixing Angle


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

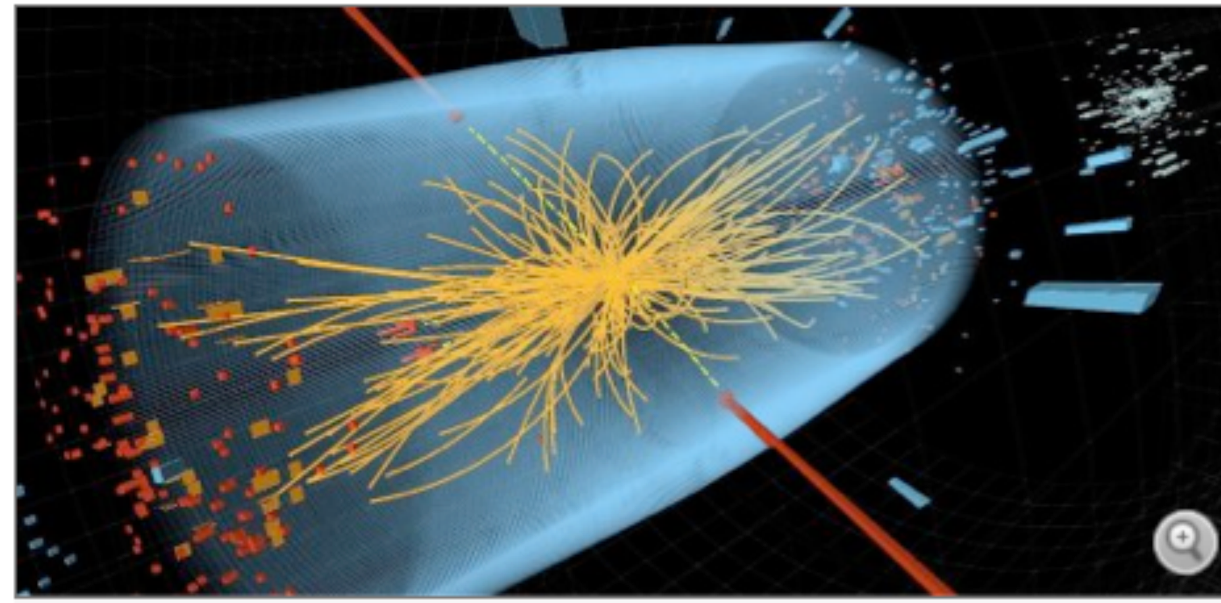
So viel Aufregung um ein Partikel war selten: In diesem Jahr haben Forscher endlich das lange gesuchte Higgs-Boson aufgespürt. Die Entdeckung war mühsam und teuer - aber sie hat die Teilchenphysik ein großes Stück vorangebracht. Die Forscher planen bereits das nächste Milliardenexperiment.

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 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:
      Couplings proportional to mass - unique in particle physics!

- 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

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Next Lecture: The Early Universe: Thermal Freeze-out of Particles,
B. Majorovits, 19.11.2018

Lecture Overview

15.10.	Introduction, Particle Physics Refresher	*F. Simon*
22.10.	Introduction to Cosmology I	*B. Majorovits*
29.10.	Introduction to Cosmology II	*B. Majorovits*
05.11.	Particle Collisions at High Energy	*F. Simon*
12.11.	The Higgs Boson	*F. Simon*
19.11.	The Early Universe: Thermal Freeze-out of Particles	*B. Majorovits*
26.11.	The Universe as a High Energy Laboratory: BBN	*B. Majorovits*
03.12.	The Universe as a High Energy Laboratory: CMB	*B. Majorovits*
10.12.	Particle Colliders	*F. Simon*
17.12.	Detectors for Particle Colliders I	*F. Simon*
	Christmas Break	
07.01.	Detectors for Particle Colliders II	*F. Simon*
14.01.	Cosmic Rays: Acceleration Mechanisms and Possible Sources	*B. Majorovits*
21.01.	Supernovae Accelerators for Charged Particles and Neutrinos	*B. Majorovits*
28.01.	Searching for New Physics at the Energy Frontier	*F. Simon*
04.02.	Baryogenesis via Leptogenesis	*B. Majorovits*