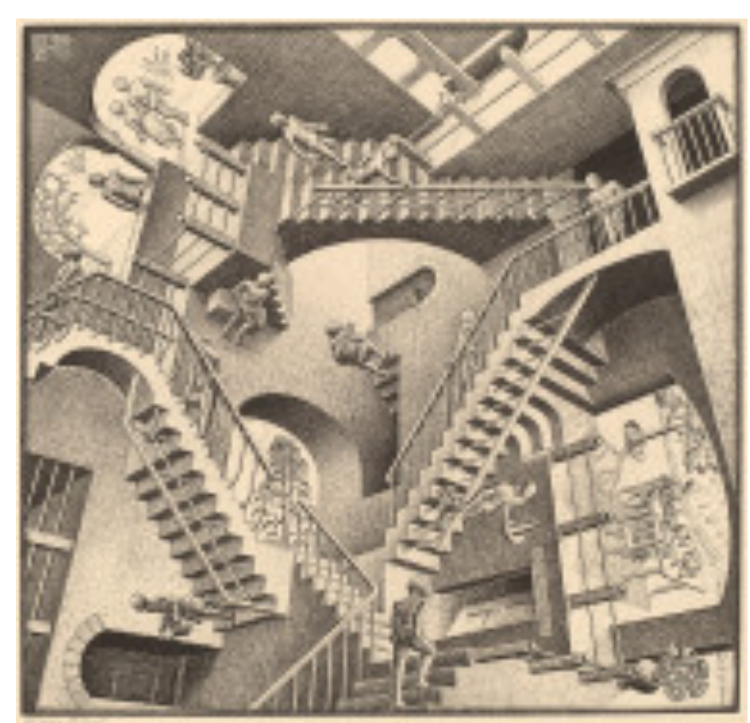
The Art of the Impossible

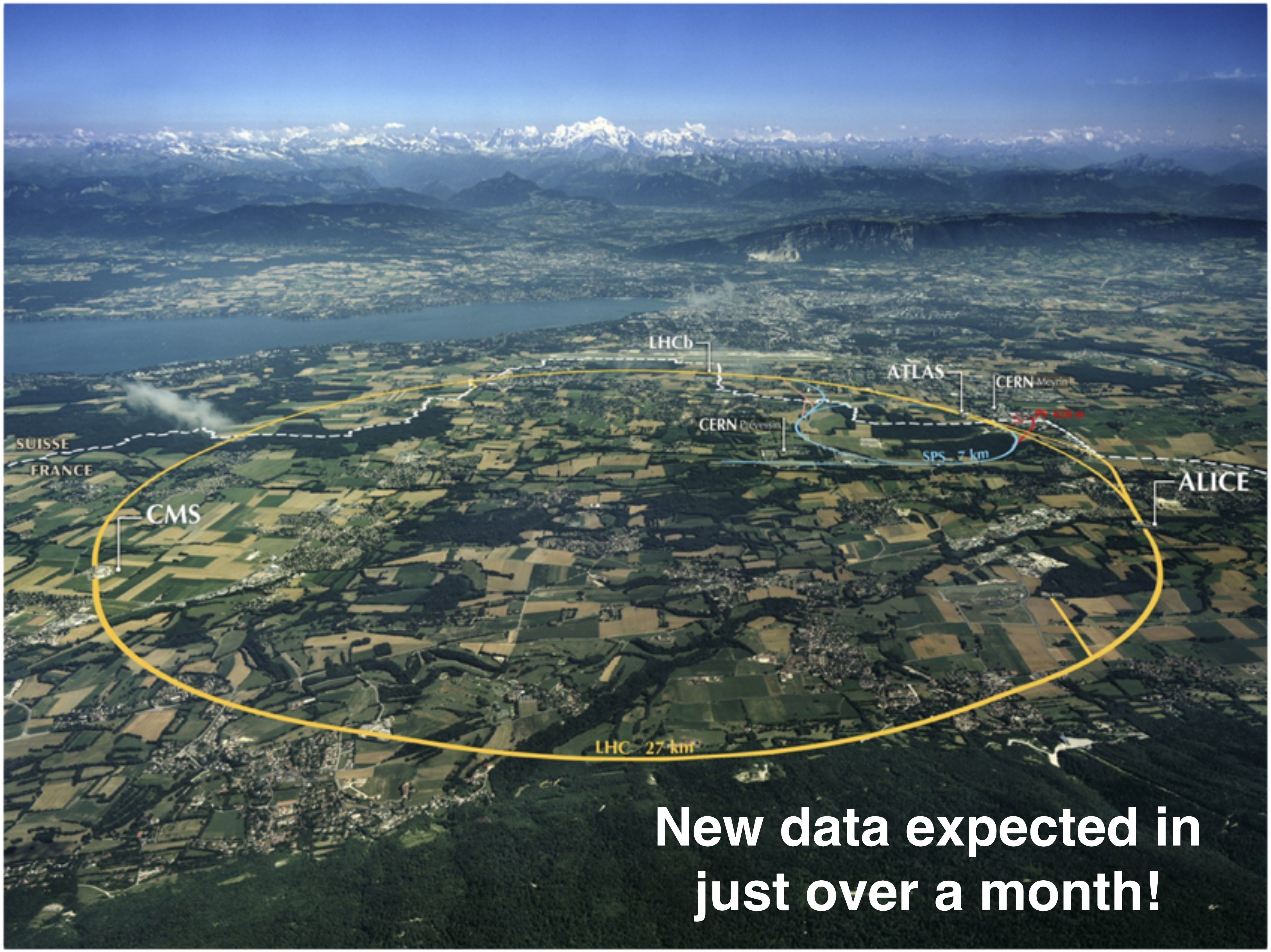
Probing Challenging Higgs Channels at the LHC

Heather M. Gray, CERN



The discovery of the Higgs at the LHC

The Large Hadron Collider (LHC)



New data expected in just over a month!

4 July 2012: Higgs (In)dependence Day

LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

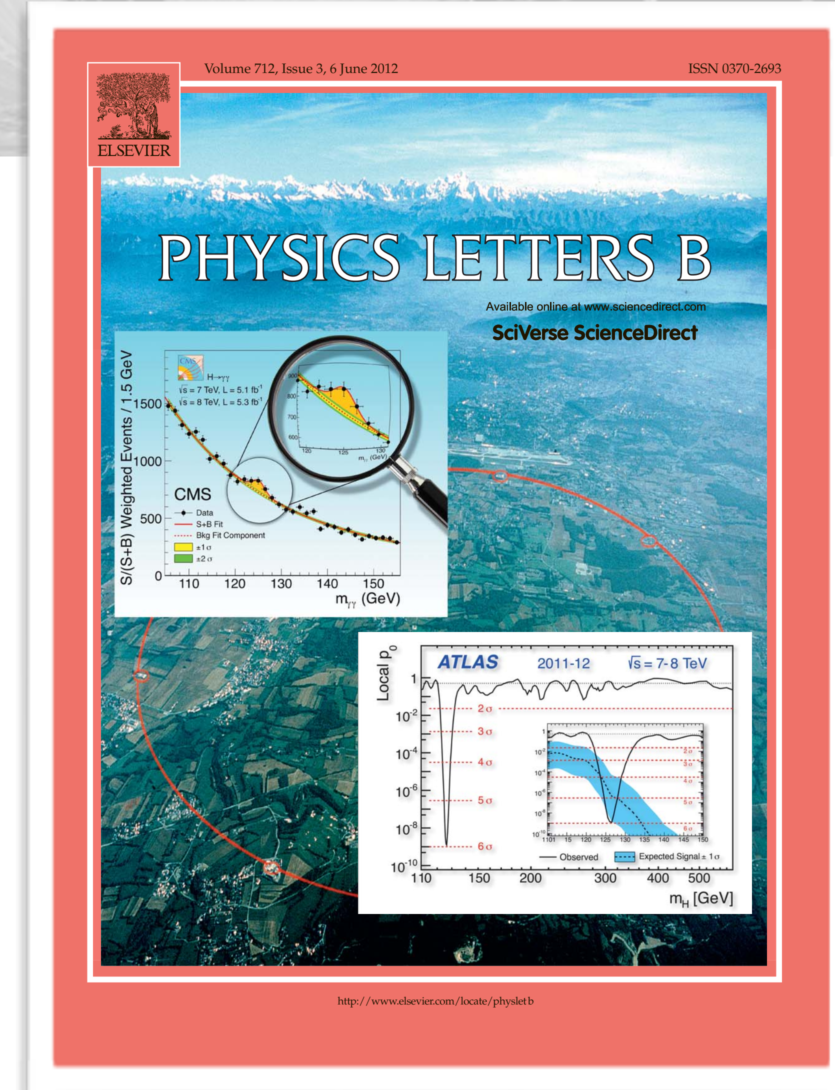
This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

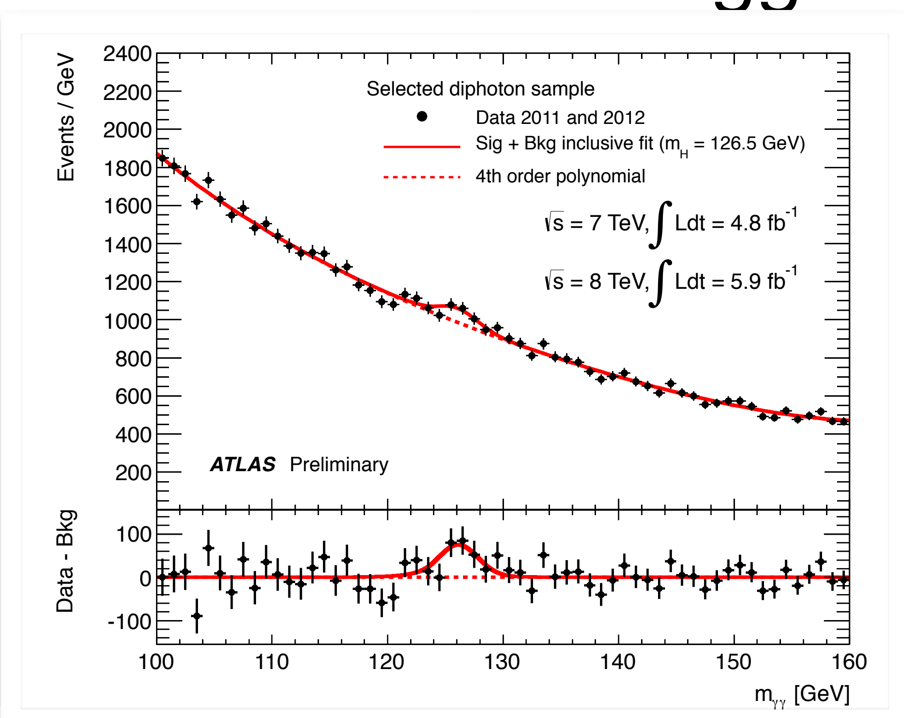
We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

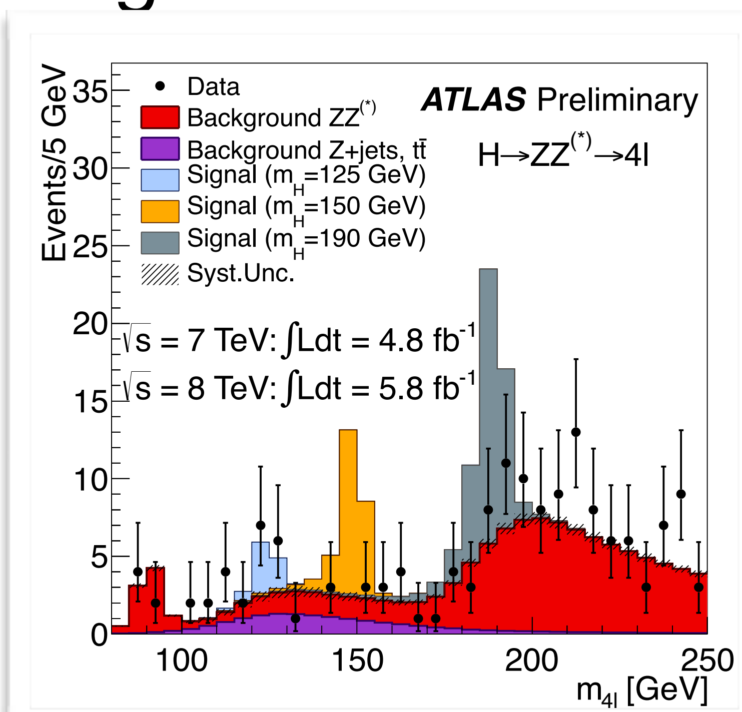
Duration of projects /planning stability:
First LHC workshop 1984 !

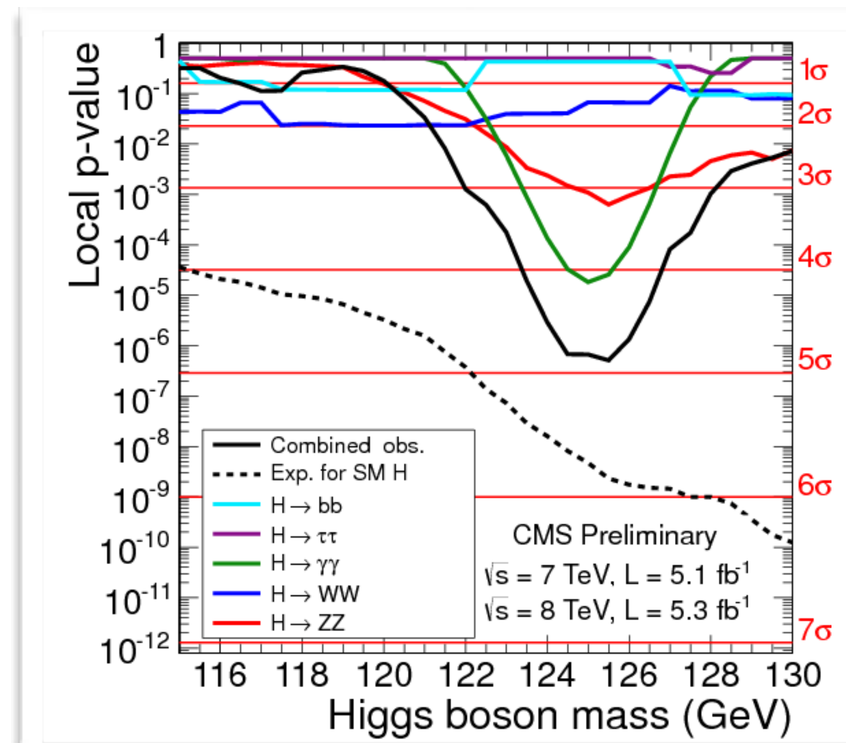
Discovery in One Slide

- 5+5 fb^{-1}: ~5σ observation
- CMS: five decay modes; $\gamma\gamma$, ZZ, WW, bb, $\tau\tau$
- ATLAS: Only $\gamma\gamma$ and ZZ, but slightly greater sensitivity
  - Key contributions from members of the Tokyo group
- Published in Phys. Lett. B
- Nobel Prize for Higgs and Englert in 2013









From Discovery to Measurement

- Since the 2012 **discovery**, we have moved on to measuring the **properties** of the Higgs
- **Key properties include**
  - Mass
  - Width
  - Couplings to fermions and gauge bosons

$$\frac{\Gamma(H \to b\bar{b})}{\Gamma(H \to \tau^+\tau^-)} \approx 3\frac{m_b^2}{m_\tau^2}$$

  - Spin/parity

$$J^{PC} = 0^{++}$$

  - Self-interaction

$$V = \frac{M_H^2}{2}H + \frac{m_H^2}{2\nu}H^3\frac{M_H^2}{8\nu^2}H^4$$

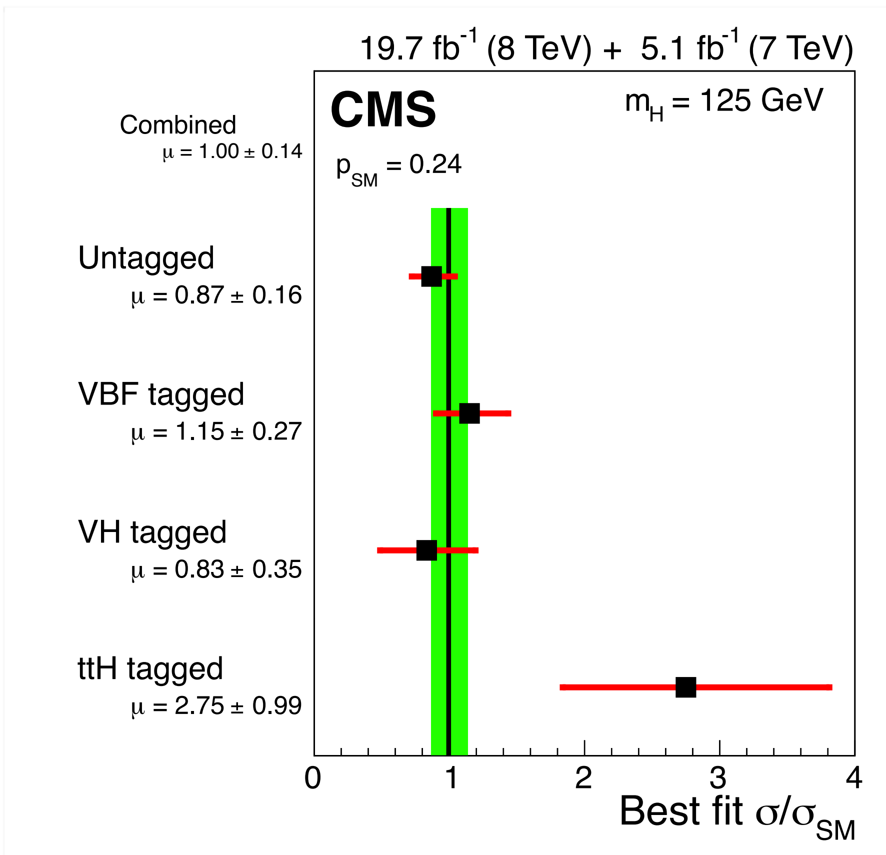
H^0 $J = 0$

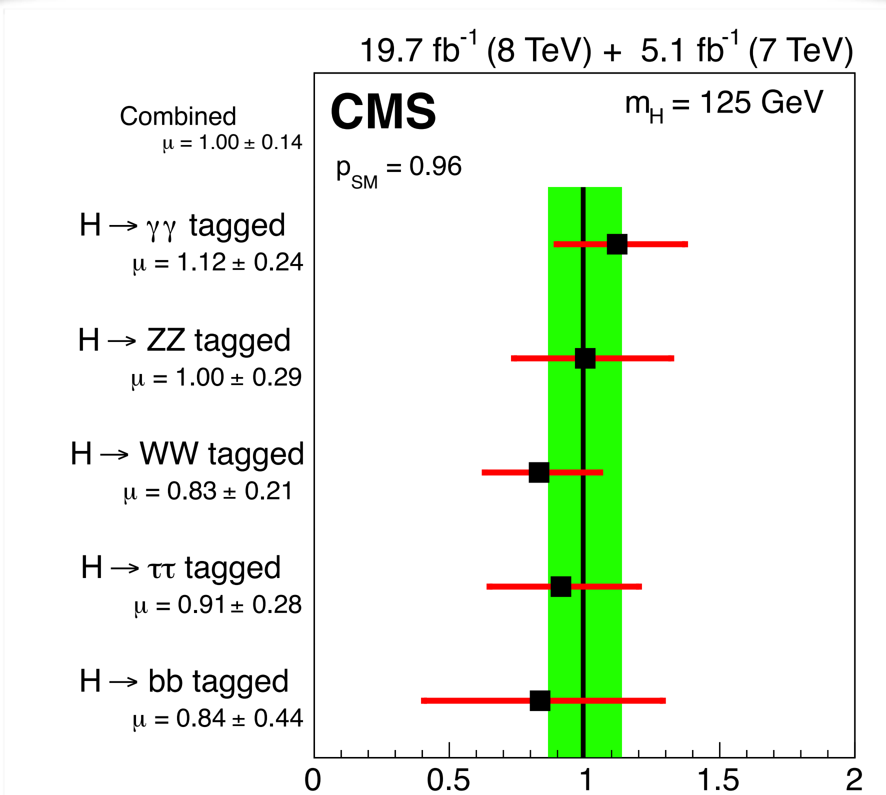
Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$W W^* = 0.87^{+0.24}_{-0.22}$
$Z Z^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$
$b\bar{b} = 1.1 \pm 0.5$
$\tau^+\tau^- = 0.4 \pm 0.6$
$Z\gamma <$ 9.5, CL = 95%

(Almost) Final Run-1 Coupling Results

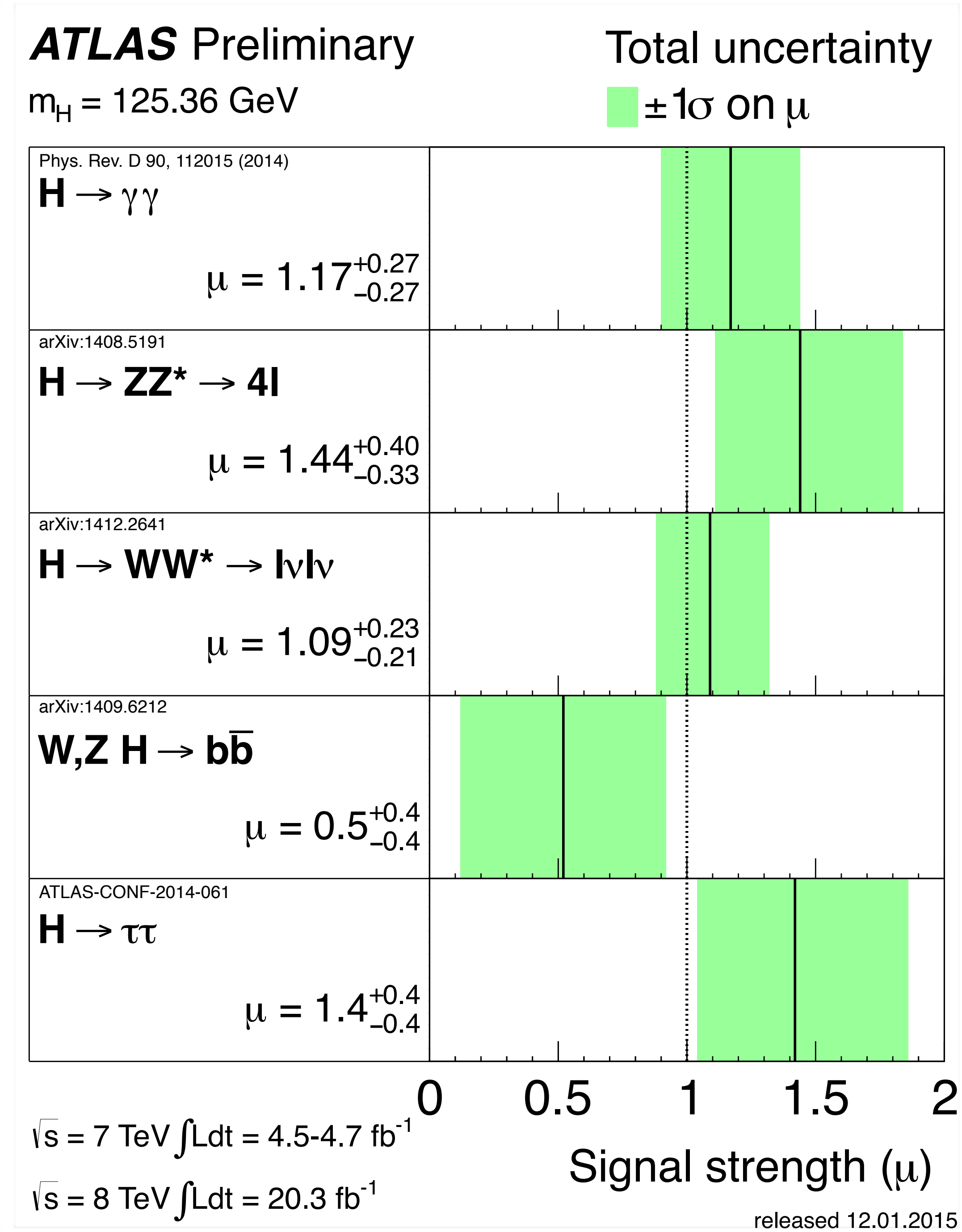




arXiv:1412.8662

Measure coupling strength of each channel

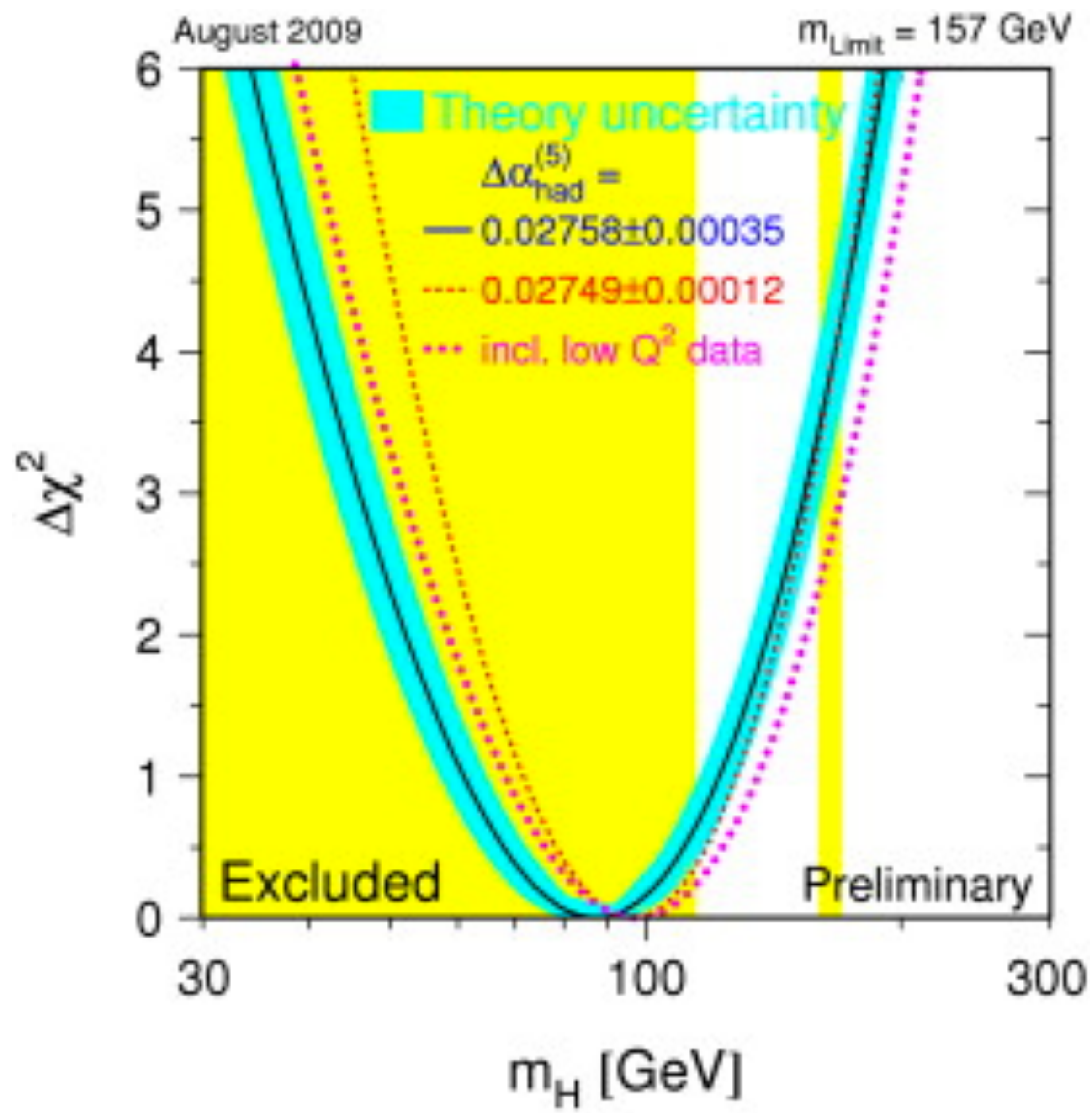
$$\mu_i = \frac{\sigma_i}{\sigma_{SM}}$$



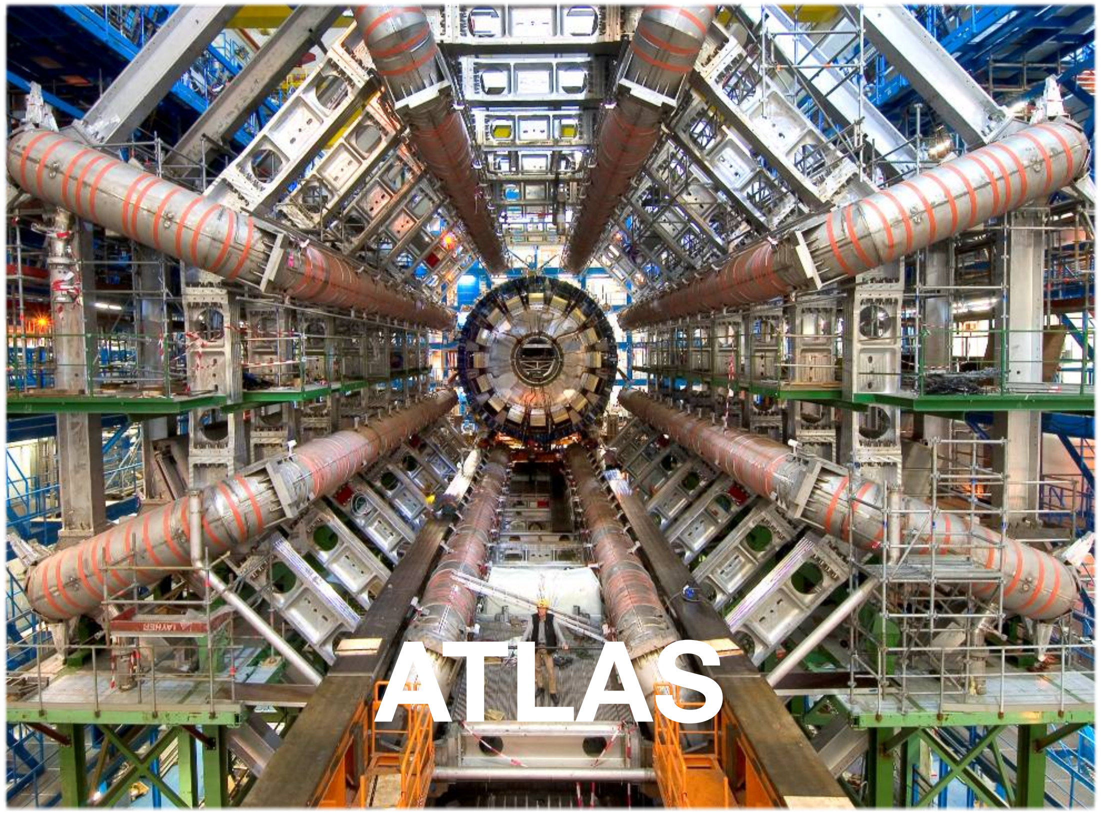
Designing for Discovery

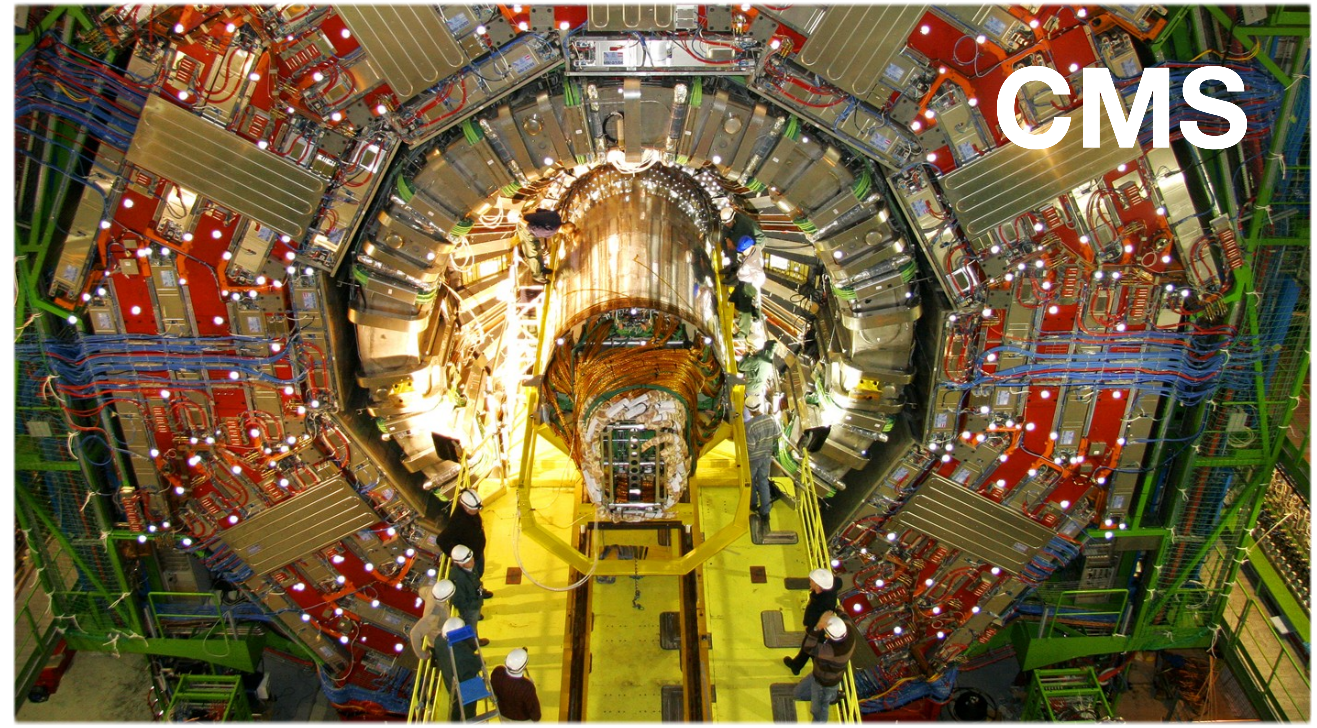
Expected discovery? No lose theorem

- **Discoveries** are never really expected
- For the LHC, we were very lucky in that we had very **strong arguments** that we would have to see something
- **Experiment**
  - Higgs mass between 114 and 200 GeV from LEP, Tevatron and EW constraints
- **Theory**
  - Some mechanism needed to give **mass** to the W,Z bosons
  - **Unitarity violated** if nothing found < 1 TeV



Designing for Discovery





- γγ and ZZ(4l) analyses played a key role in driving the design requirements for ATLAS and CMS, e.g.
  - good diphoton and dimuon mass resolution: <1% at 100GeV
  - wide geometric coverage: |η|<2.5

CMS TDR

> The $H \rightarrow \gamma\gamma$ analysis covers one of the most promising channels for a low mass Higgs discovery and for precision Higgs mass measurement at the LHC. This channel has been an important motivation for the design of the electromagnetic calorimeter (ECAL) of CMS. It is

The Unexpected

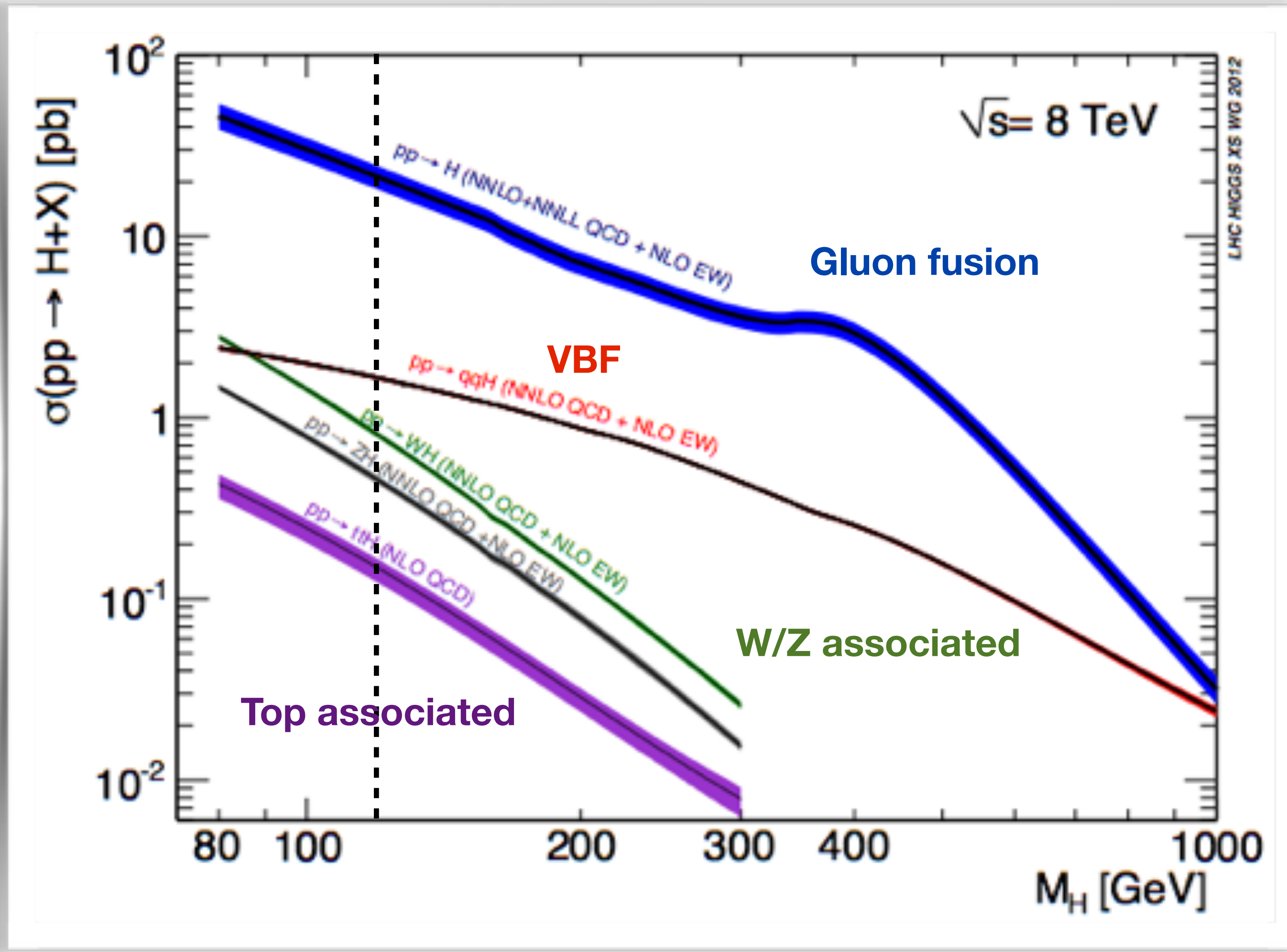
- The **discovery of the Higgs boson** has been by far the crowning achievement of the LHC
  - ATLAS and CMS were designed to and did discover the Higgs boson
- But for the rest of this talk, I'd like to focus on something a little different
- I'd like to talk about what was **not predicted, not expected**
- And some things that were even thought to **be impossible** at the LHC
- Goal: Try to briefly explain what happened to make the **impossible possible**

Higgs Production and Decay at the LHC

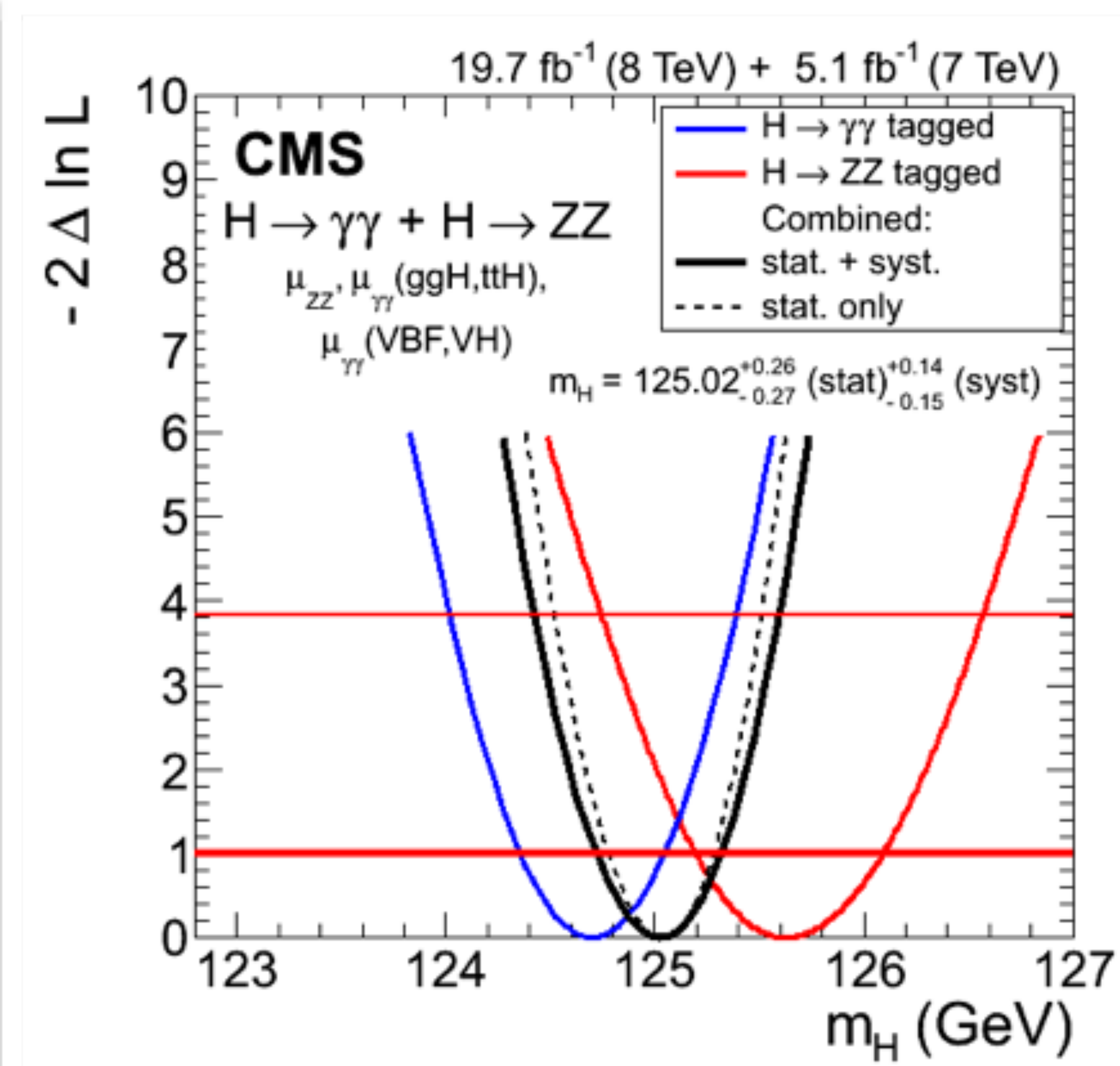
Reminder: Higgs Production at the LHC

Standard Model is a very predictive theory for the Higgs boson
only unknown parameter is the **Higgs mass**

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections



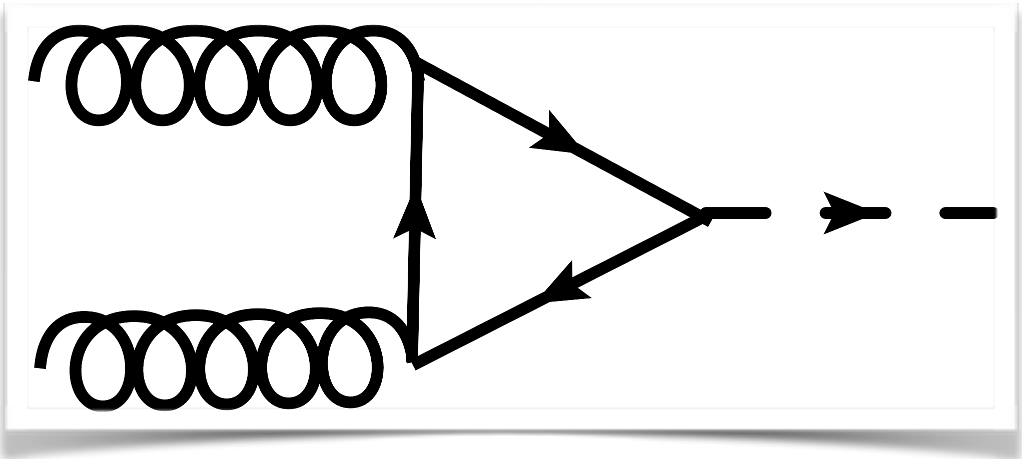
Production rates known to ~10%



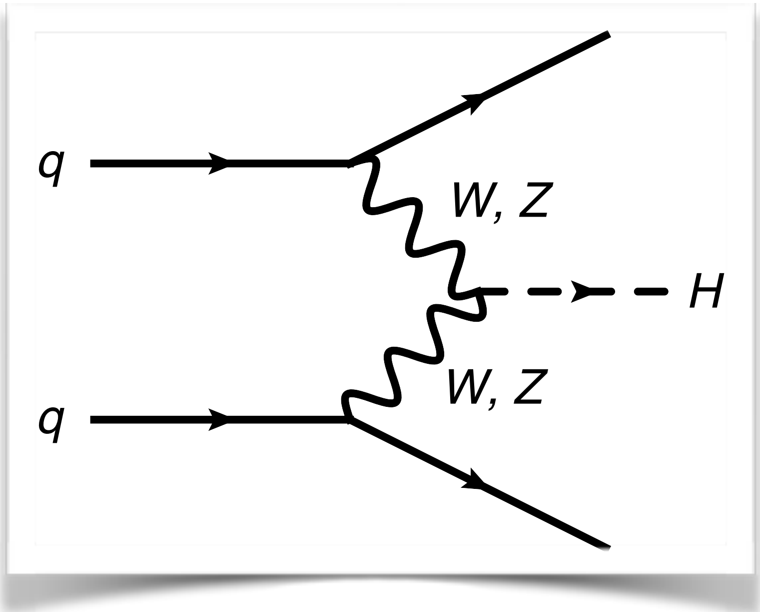
arXiv:1412.8662

Higgs Production Mechanisms

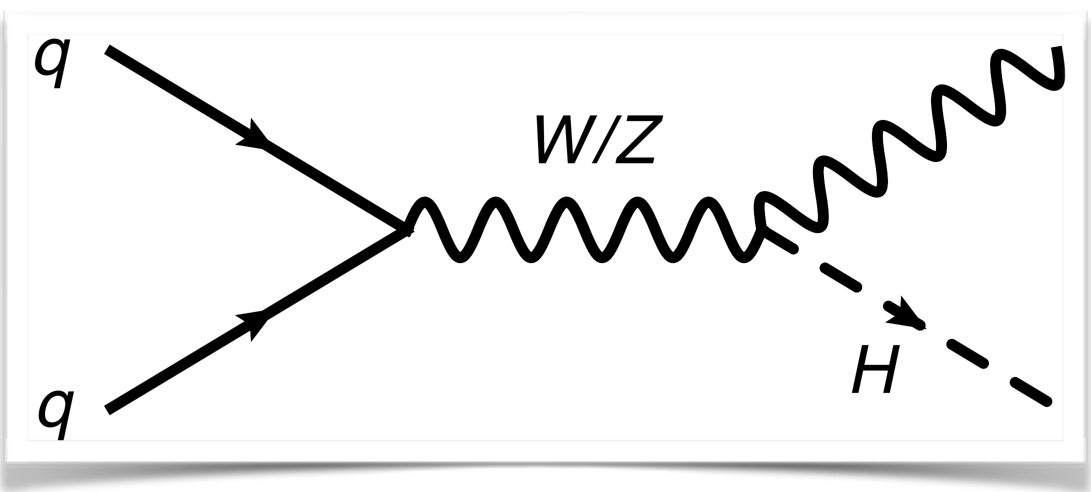
Gluon fusion
Dominant process 20 pb



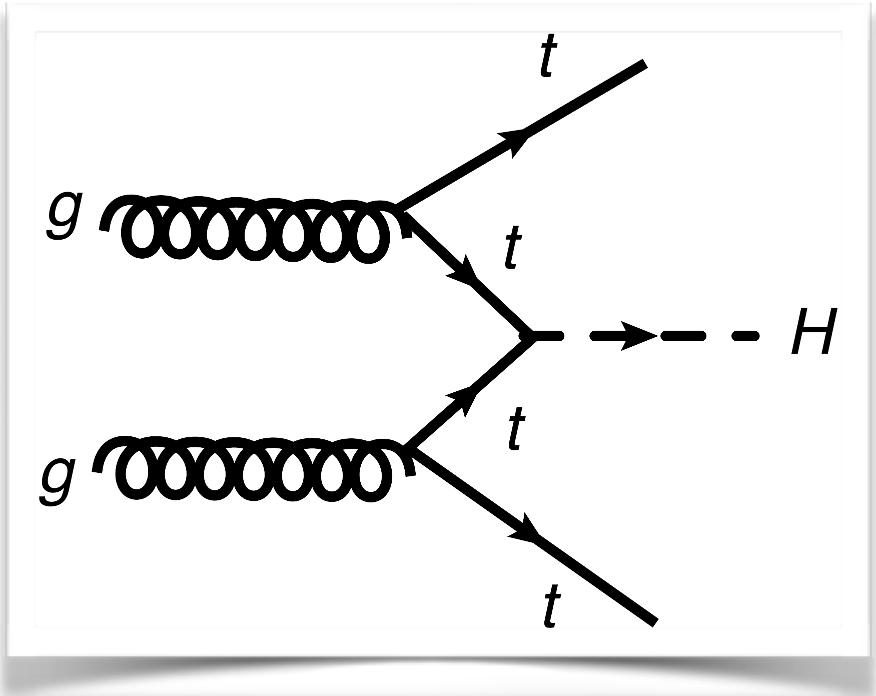
Vector Boson Fusion (VBF) 1.6 pb
Two forward jets and a rapidity gap



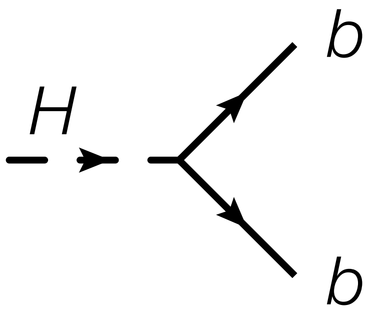
Associated production with W/Z boson
Z or W decays leptonically 1 pb



Associated production with a top pair
2 b-jets 0.1 pb



Higgs decay



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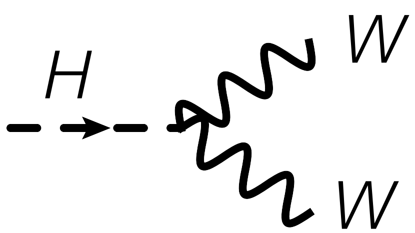

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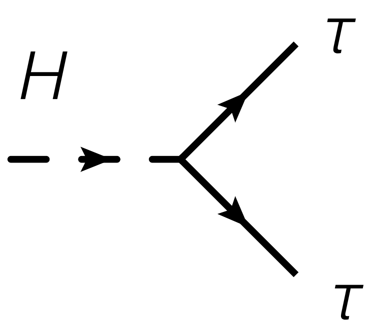

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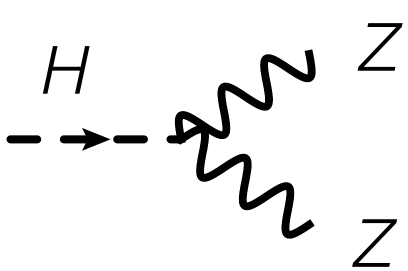

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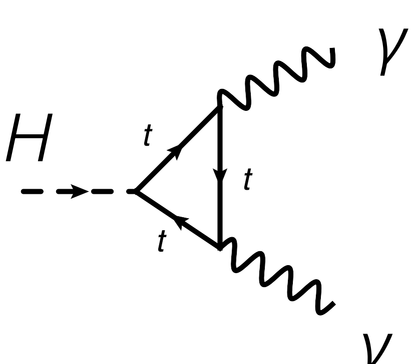

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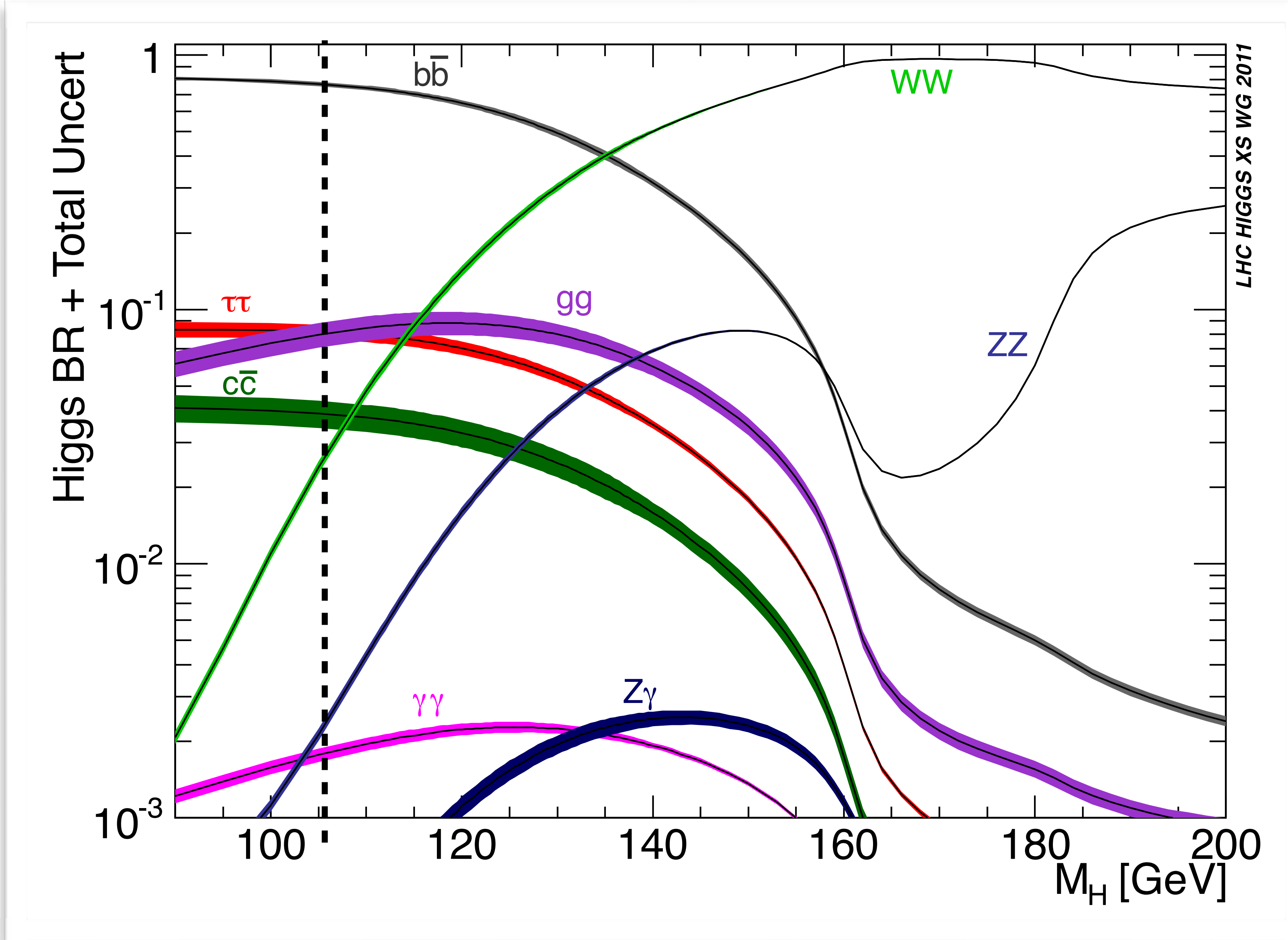
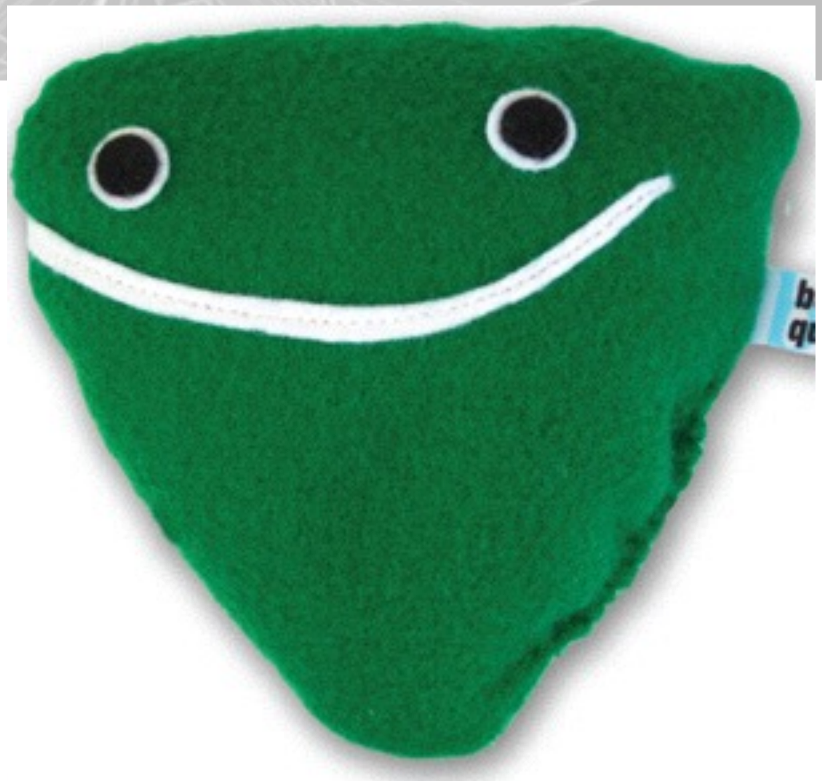


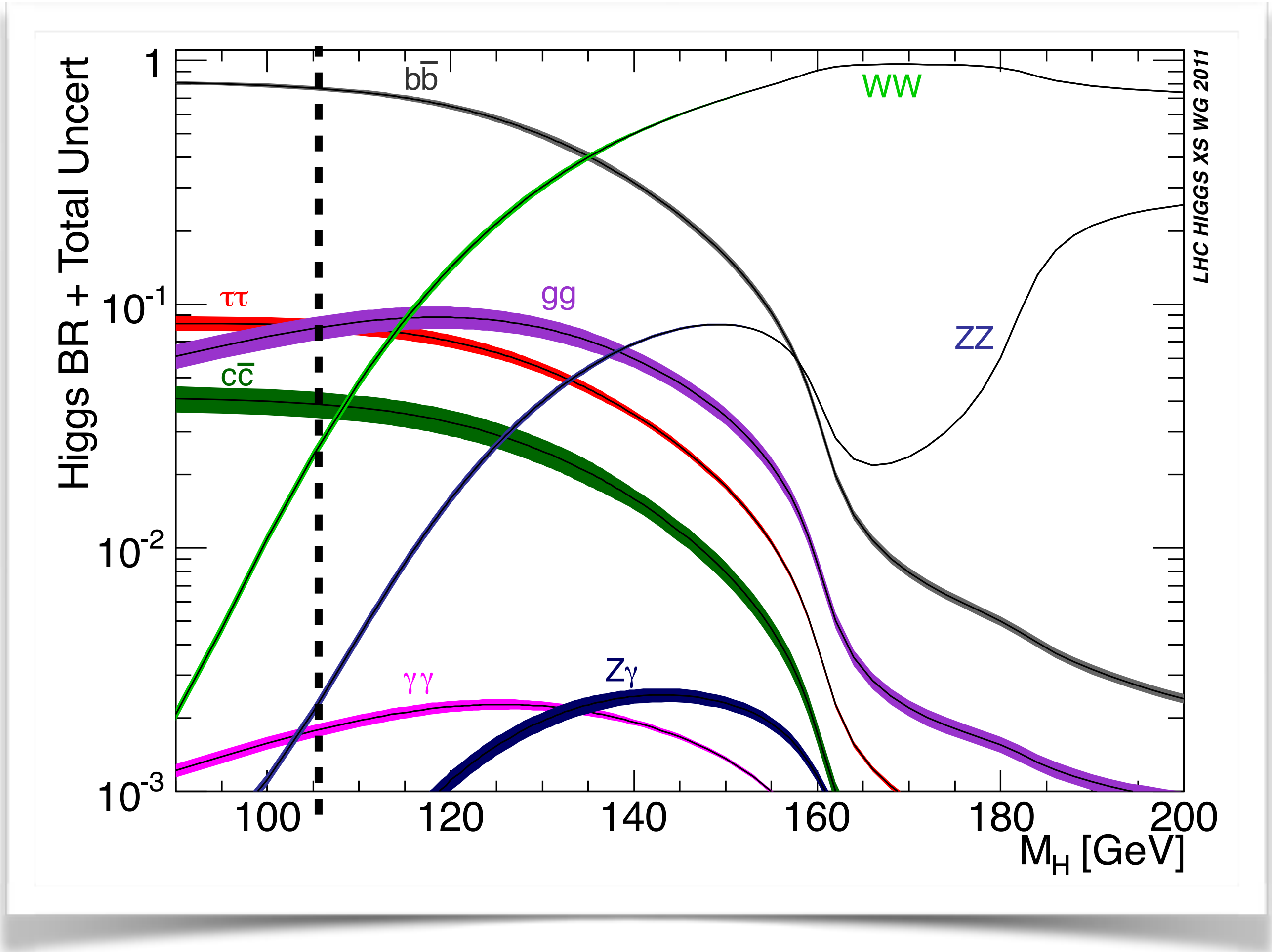
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Coupling to b-quarks



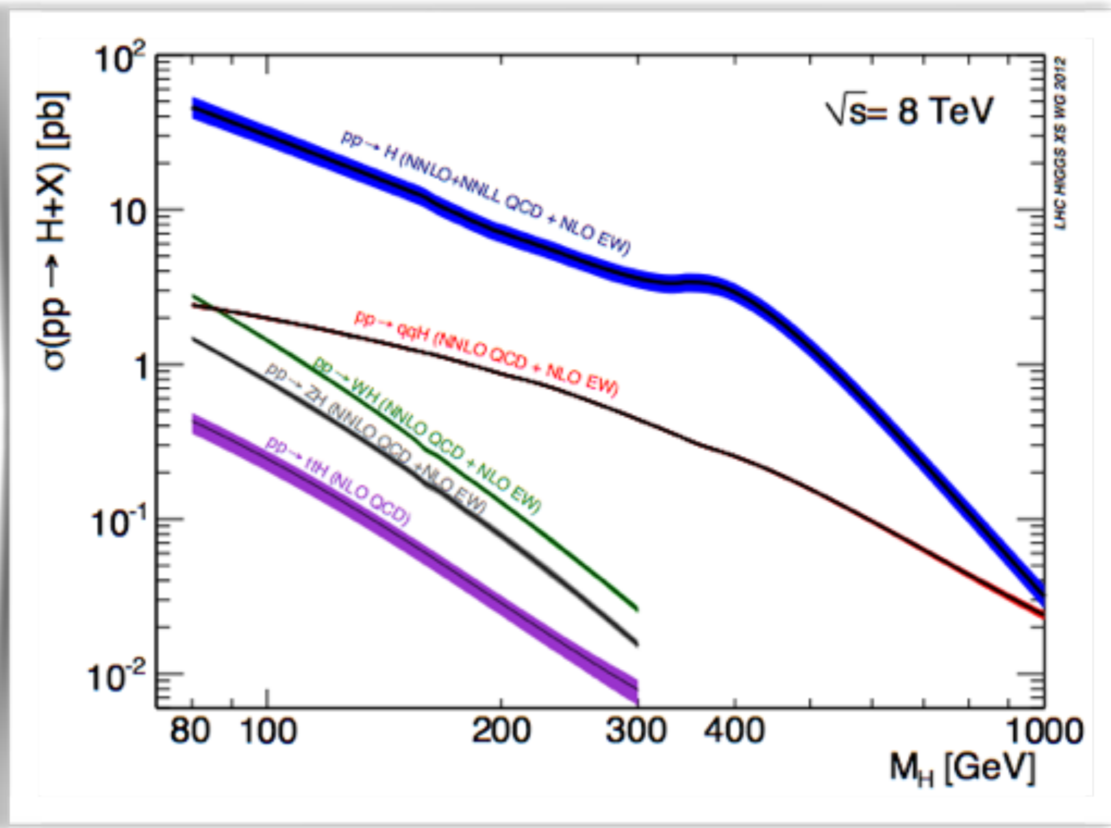
Coupling to b-quarks

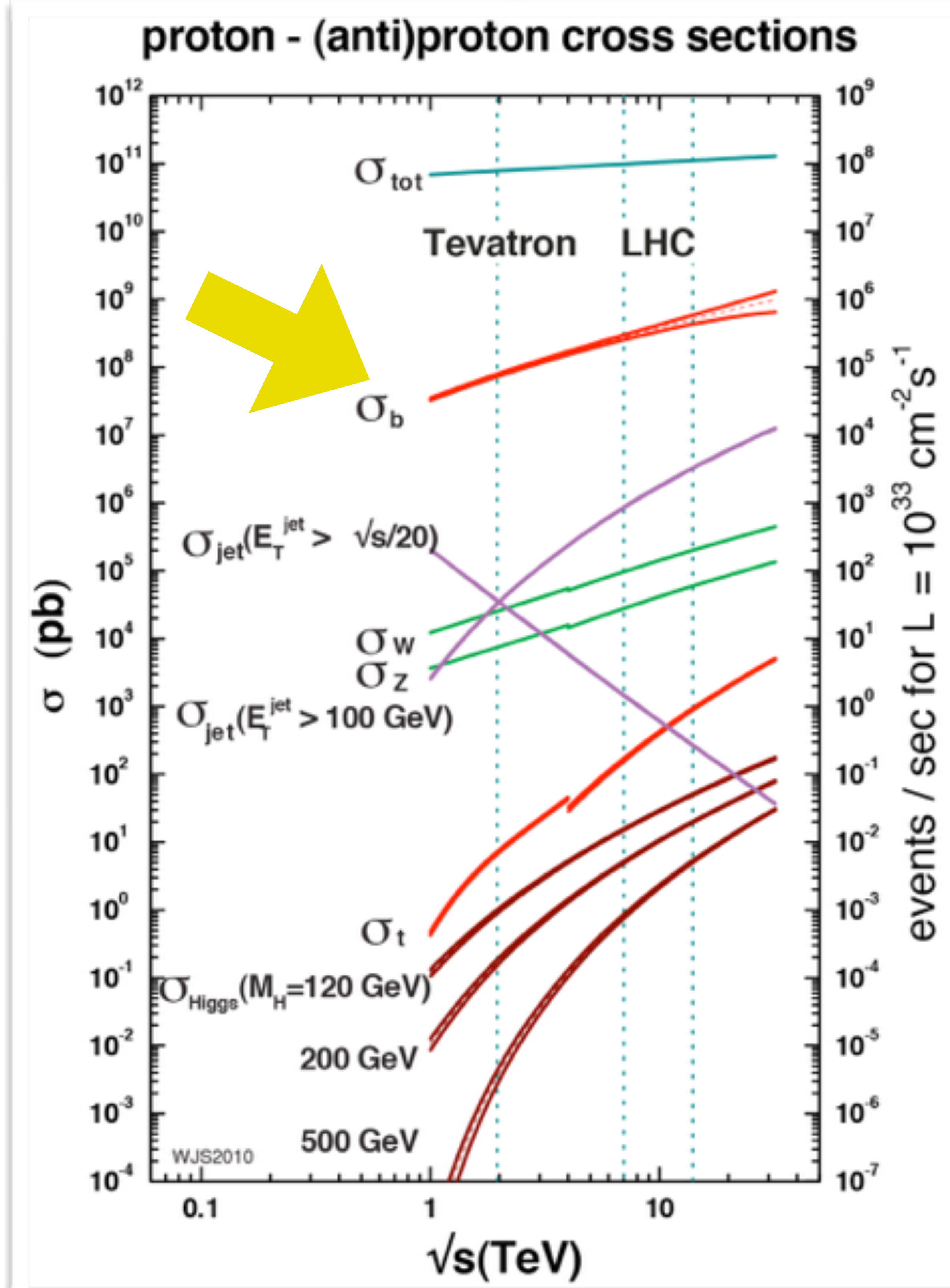
- The Higgs decays most often to a pair of b-quarks (~58% BR)
- Obviously an important property to measure
- Also provides key input for measurements of
  - total width: largest BR
  - coupling to fermions: bosonic channels only for the discovery



Not an easy measurement

- Measuring the b-coupling ggF is basically hopeless
  - bb dijet production cross-section is many orders of magnitude larger
  - no clear trigger
- Focus on associated production





WH(bb) in the ATLAS TDR

- One trigger lepton with p_T > 20 GeV (electron) and p_T > 6 GeV (muon)
  - No additional lepton with p_T > 6 GeV
- Two jets with p_T > 15 GeV and $|\eta|$ < 2.5
  - No additional jets with p_T > 15 GeV and $|\eta|$ < 5.0
- 60% b-tagging efficiency

ATLAS detector and physics performance Technical Design Report

Volume II
25 May 1999

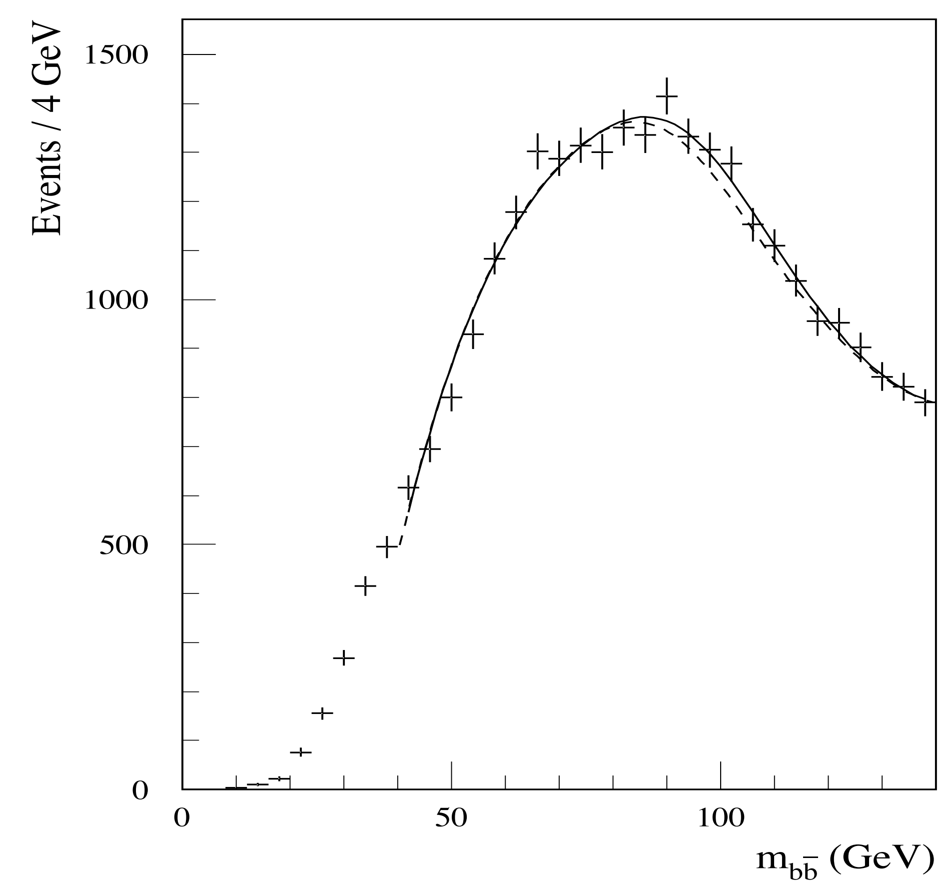


Figure 19-7 Expected *WH* signal with $H \to b\bar{b}$ above the summed background for m_H = 100 GeV and for an integrated luminosity of 30 fb^{-1}. The dashed line represents the shape of the background.

Conclusion: WH(bb) will be very difficult

As shown in Table 19-6, a *WH* signal might be extracted if one assumes that the various background distributions are all perfectly known. Even in this optimistic scenario, the signal significance is at best 4.7σ for $m_H = 80$ GeV and is below 3σ for values of m_H above the ultimate sensitivity expected for LEP2. These numbers correspond to an integrated luminosity of 30 fb^{-1} expected to be reached over three years of initial operation at low luminosity. It is not clear in all cases how to achieve an accurate knowledge of the various backgrounds from the data.

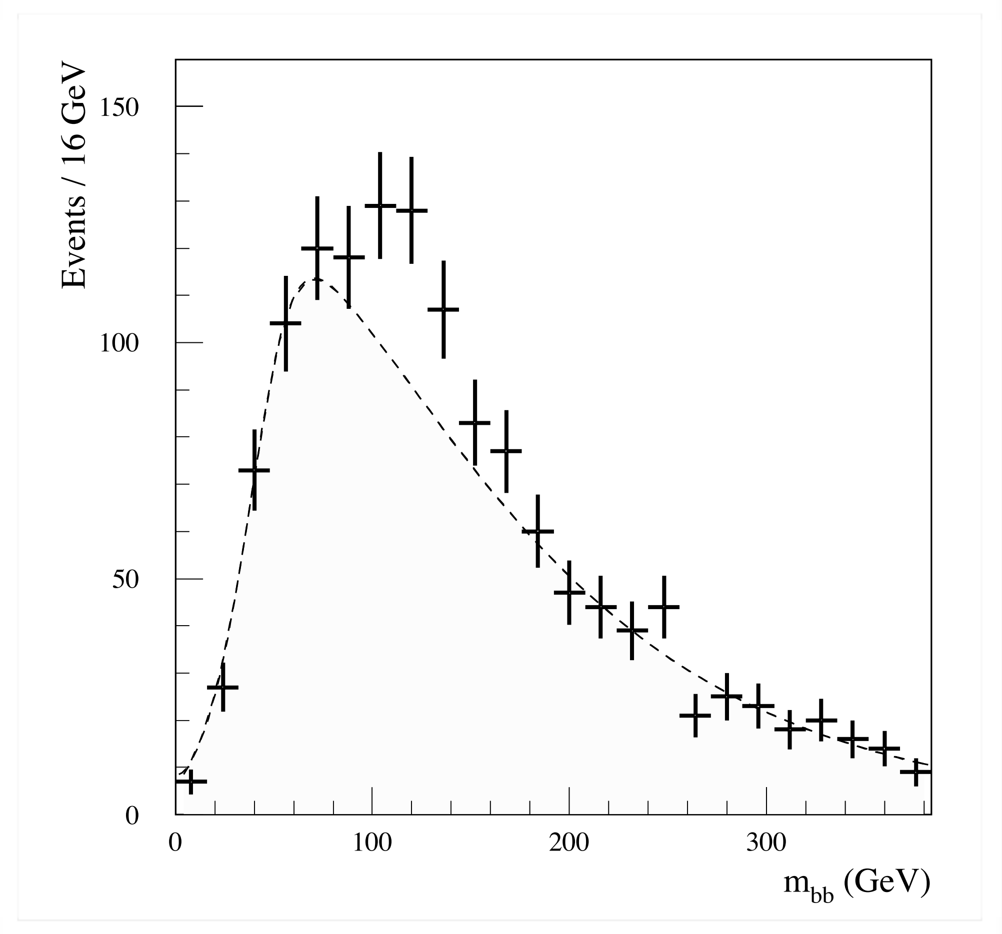
In conclusion, the extraction of a signal from $H \to b\bar{b}$ decays in the *WH* channel will be very difficult at the LHC, even under the most optimistic assumptions for the *b*-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself.

ttH(bb) instead?

In conclusion, the extraction of a Higgs-boson signal in the $t\bar{t}H$, $H \to b\bar{b}$ channel appears to be feasible over a wide range in the low Higgs-boson mass region, provided that the two top-quark decays are reconstructed completely with a reasonably high efficiency. This calls for excellent b-tagging capabilities of the detector. Another crucial item is the knowledge of the shape of the main residual background from $t\bar{t}jj$ production. If the shape can be accurately determined

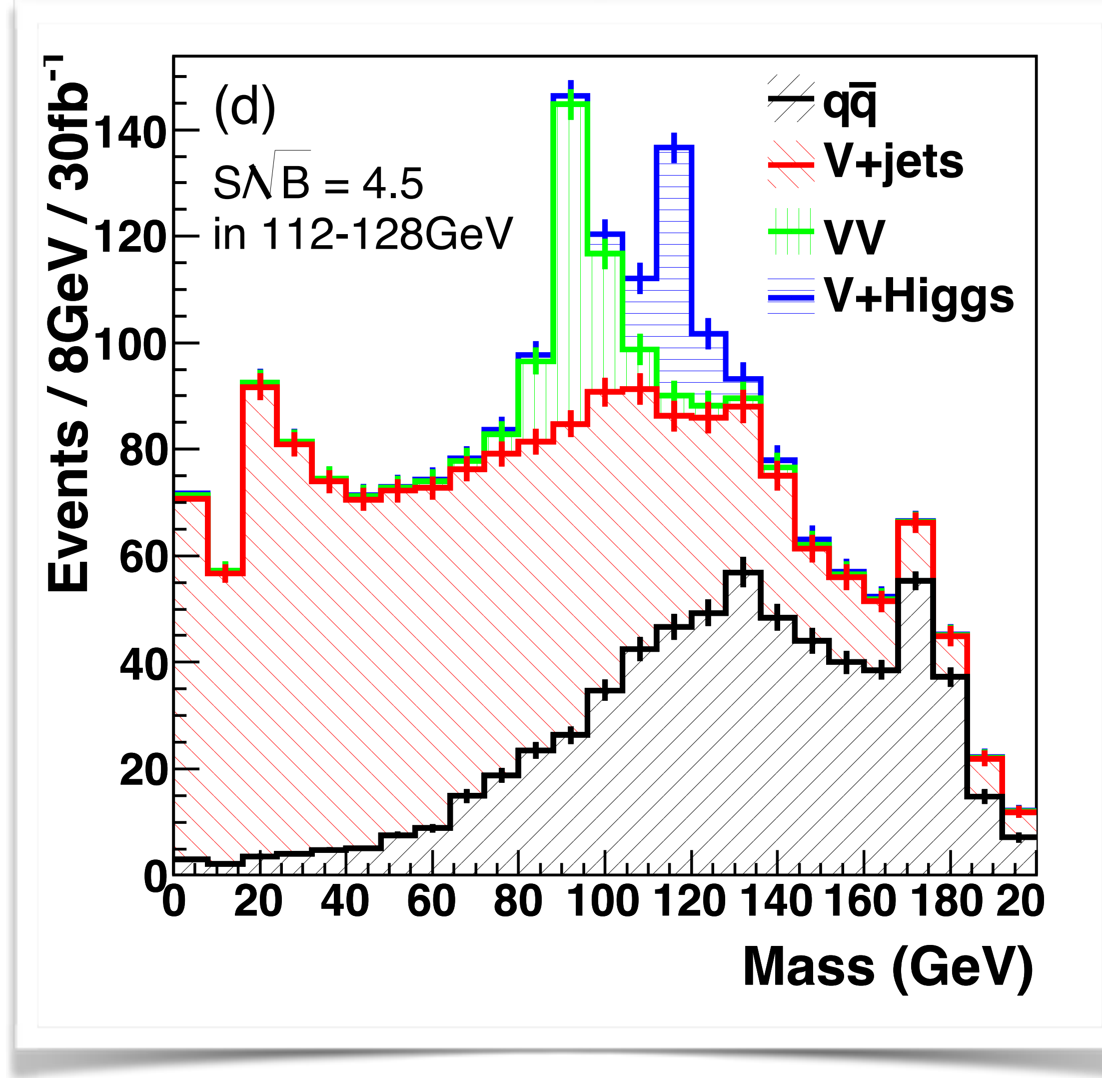
using real data from $t\bar{t}$ production, a Higgs-boson signal could be extracted with a significance of more than 5σ in the mass range from 80 to 130 GeV, assuming an integrated luminosity of 300 fb^{-1}. For an uncertainty of ±5% on the absolute normalisation of the background shape, the discovery window would be reduced to the range between 80 and 125 GeV.

- So dire, were the prospects of VH(bb) considered to be that ttH(bb) was thought to be the more promising channel

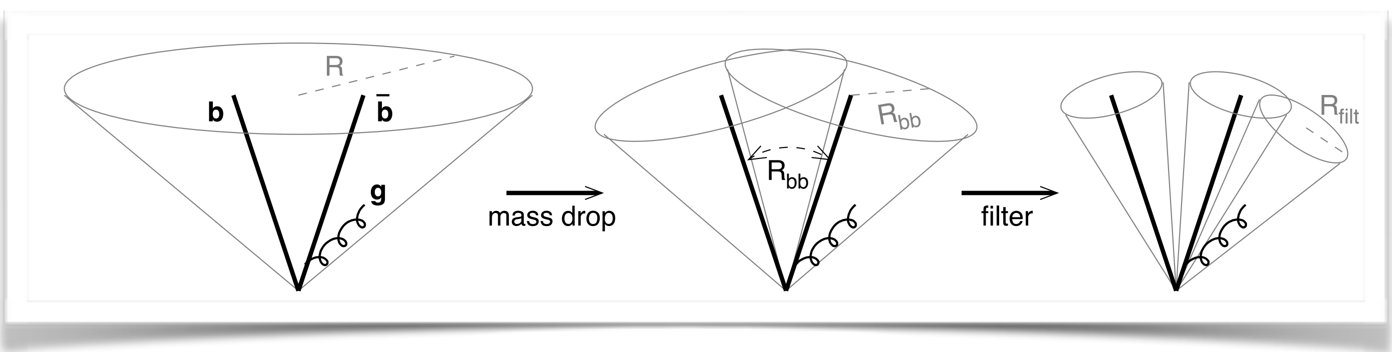


Jet substructure

- In 2008, paper from Butterworth et al.
  - large improvement in significance from focussing on the high p_T Higgs region and using jet substructure techniques



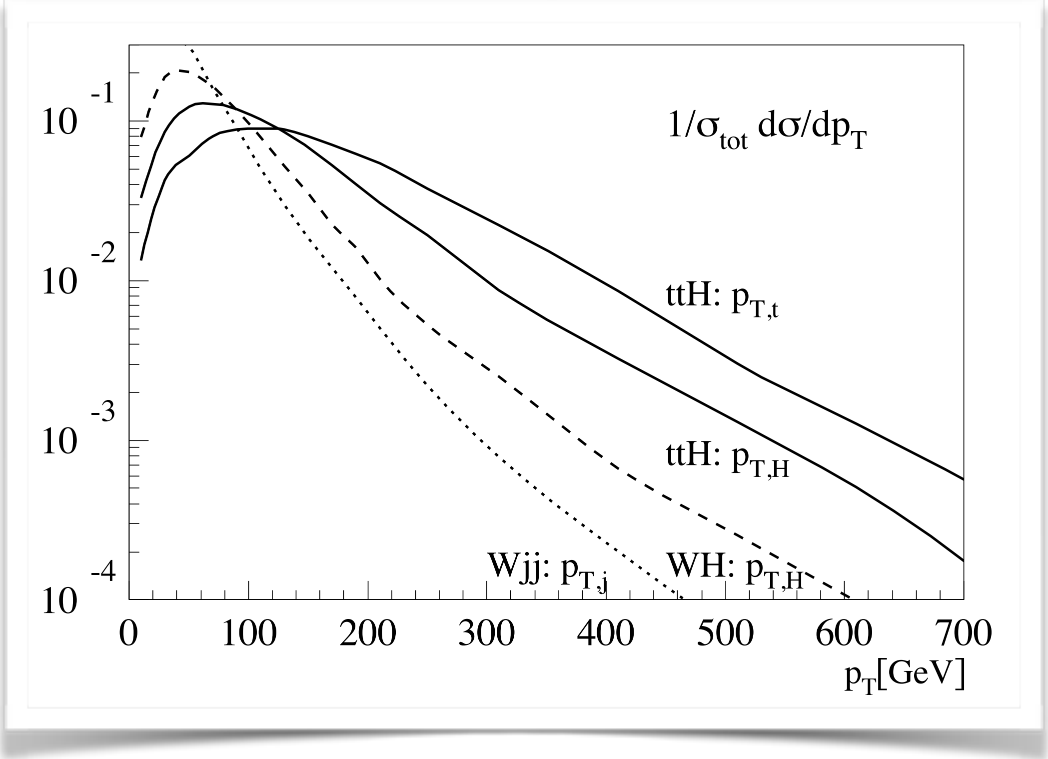
Phys.Rev.Lett.100:242001,2008



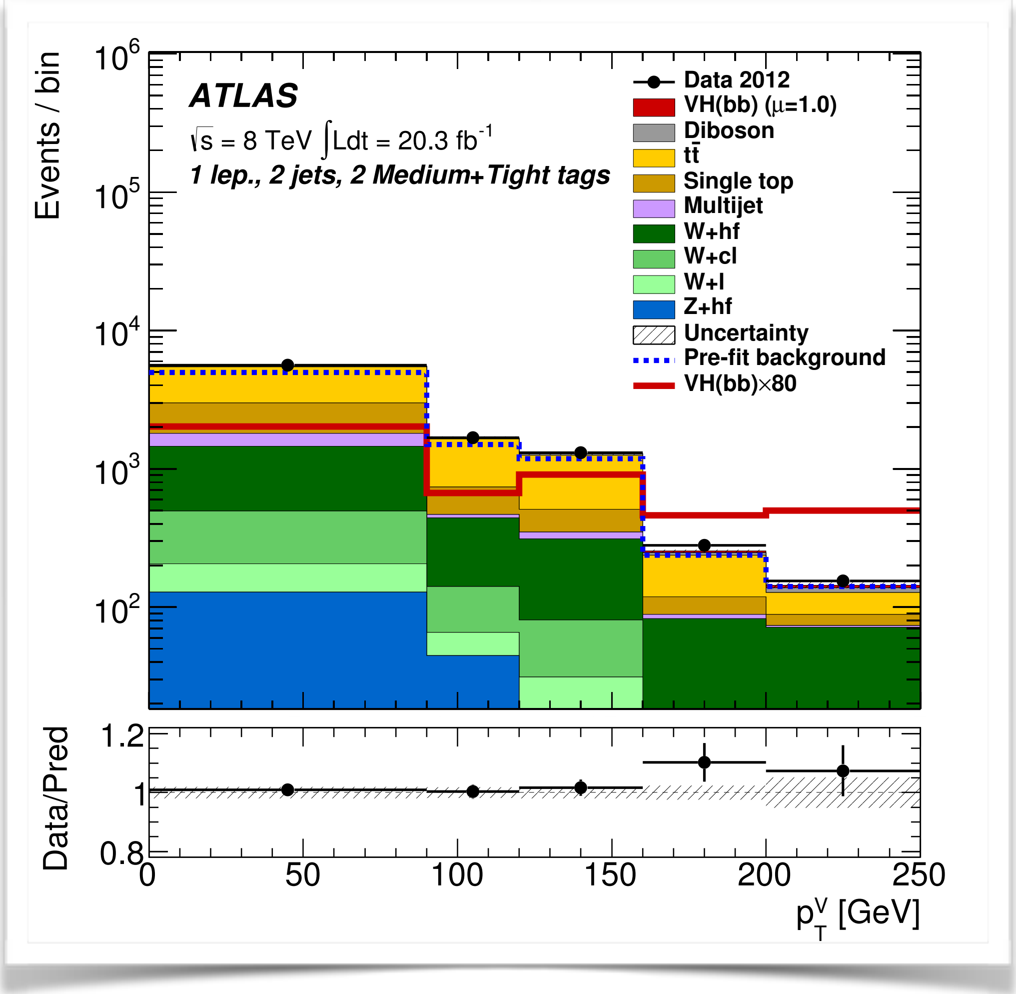
It is widely considered that, for Higgs boson searches at the Large Hadron Collider, WH and ZH production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.

Boost not substructure

- Key observation is that the signal p_T spectrum of the signal is much harder than the background
  - Applying the p_T cut necessary for substructure techniques dramatically improved S/B
  - Exploited in the current ATLAS/CMS analyses by explicit p_T categories and as input variables to BDTs
  - No gain from substructure at 8 TeV



http://arxiv.org/pdf/0910.5472v2.pdf



JHEP01(2015)069

Z(νν)H(bb)

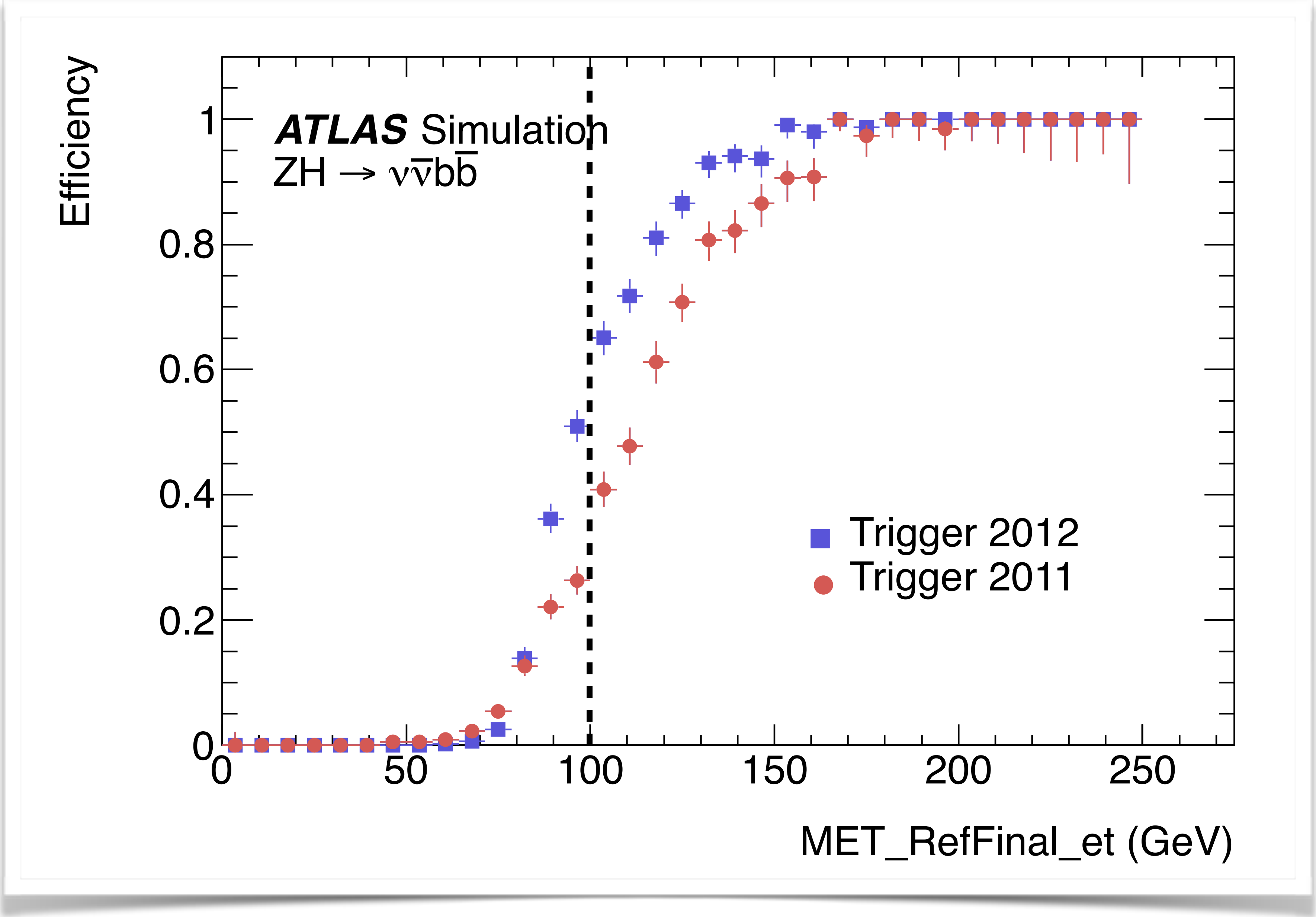
ATLAS TDR

ZH production with $Z \rightarrow \nu\nu$: it would be difficult to trigger efficiently on such final states. In addition, this channel suffers from potentially very large experimental backgrounds, given the rather low E_T^{miss} expected for the signal.

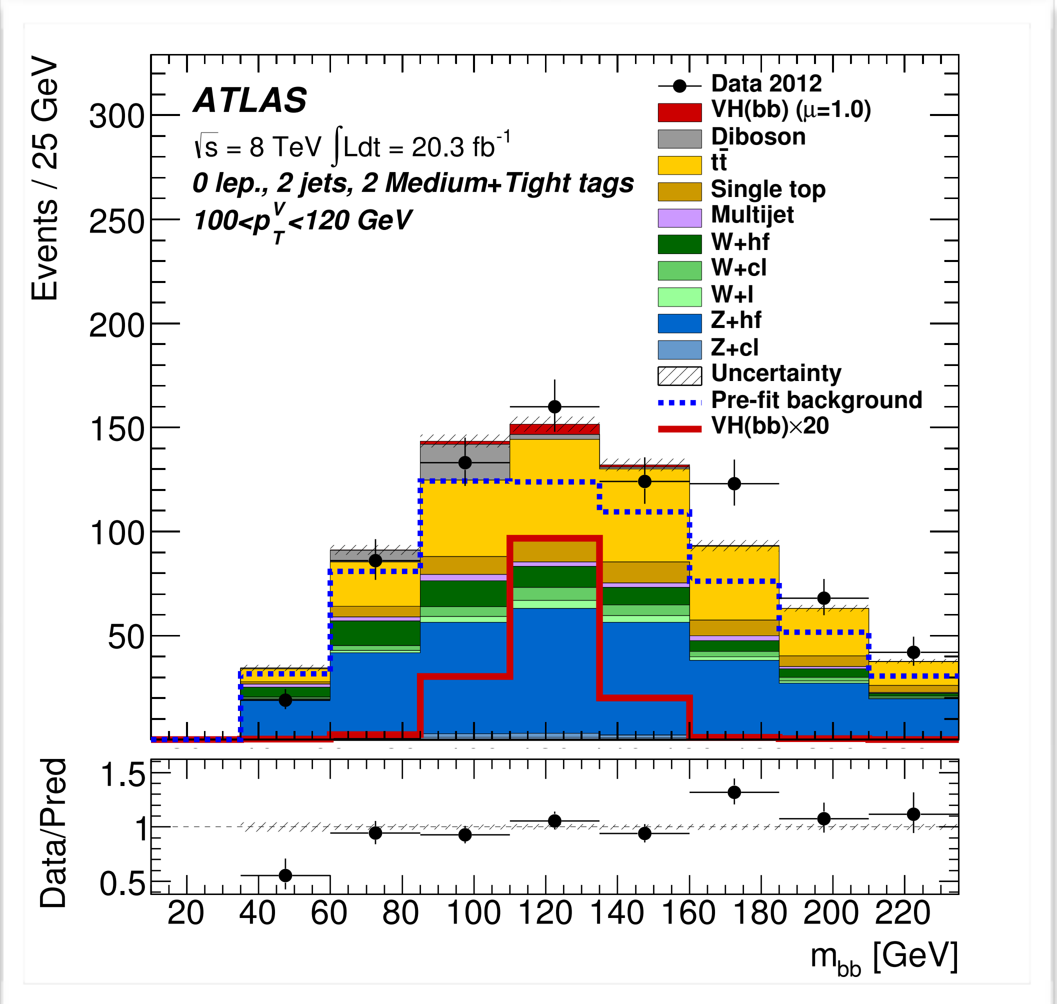
Final state contains two b-jets and MET

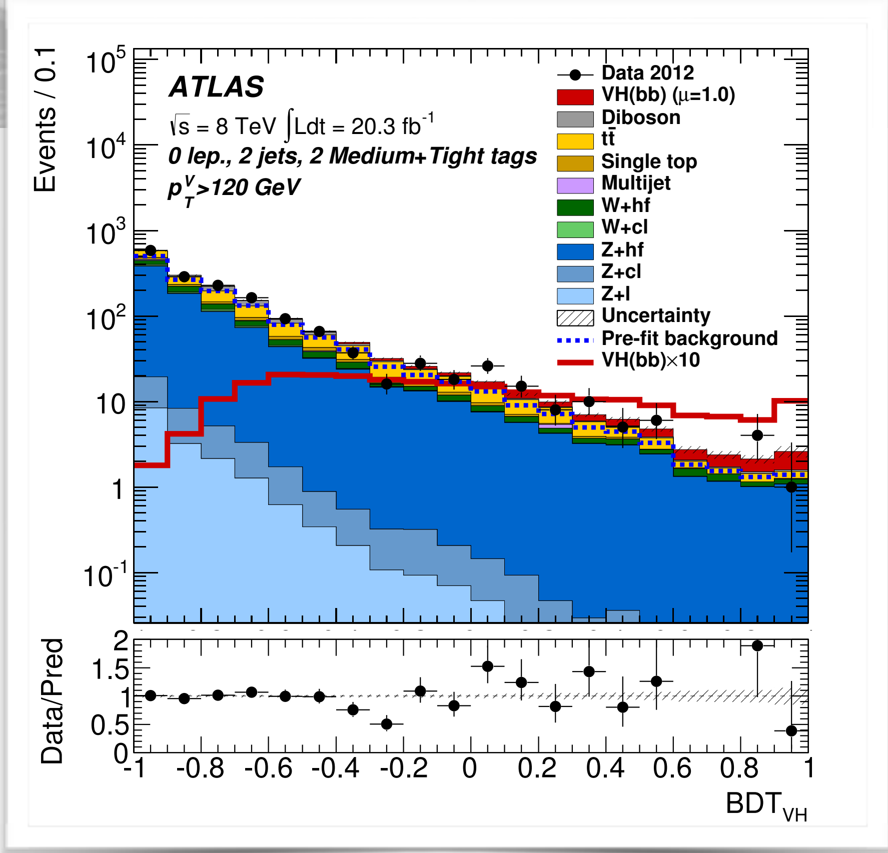
Triggering on MET

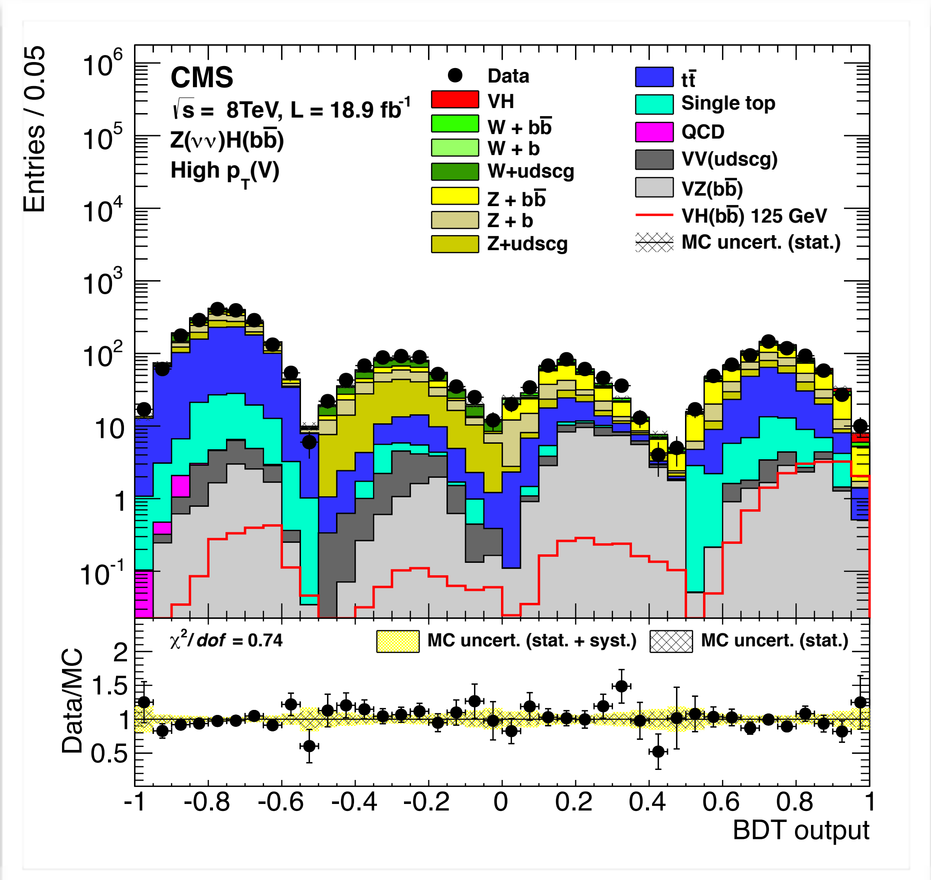
- Significant effort to develop an efficient MET trigger
- Accurate measurements of the modelling of the turn-on region allowed the ATLAS analysis to extend to 100 GeV (5% uncertainty)



Z(vv)H(bb)





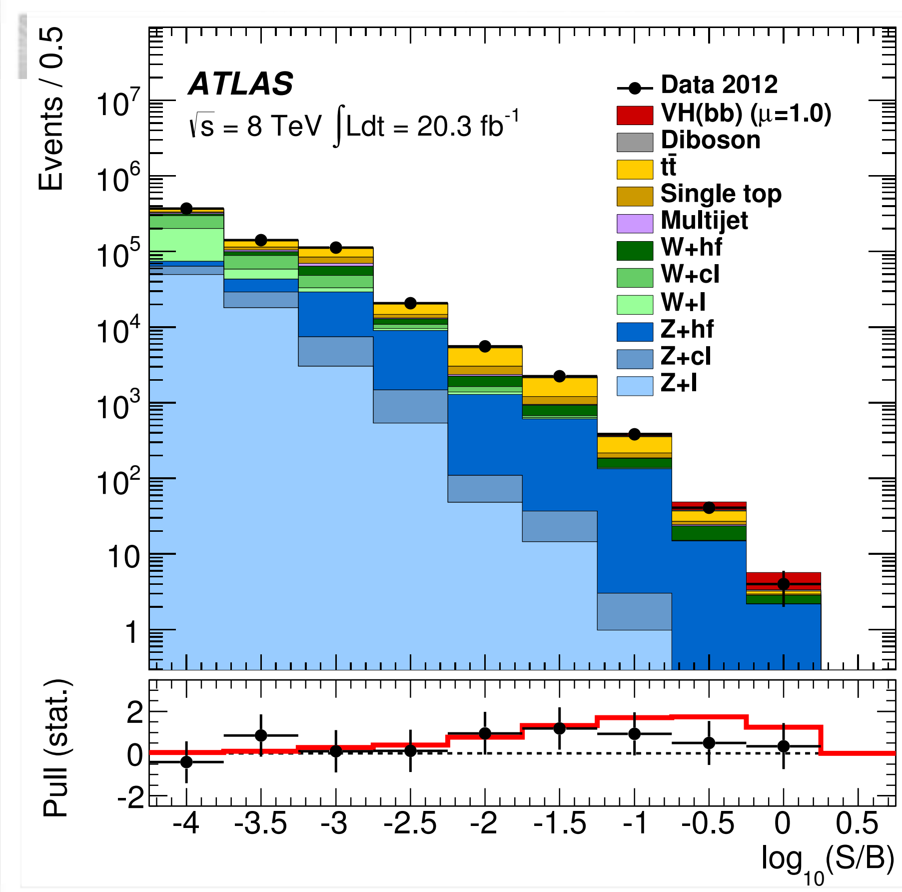


- Topological cuts to reduce backgrounds
- Control regions to normalise backgrounds
  - ATLAS: signal region of other VH(bb) channels

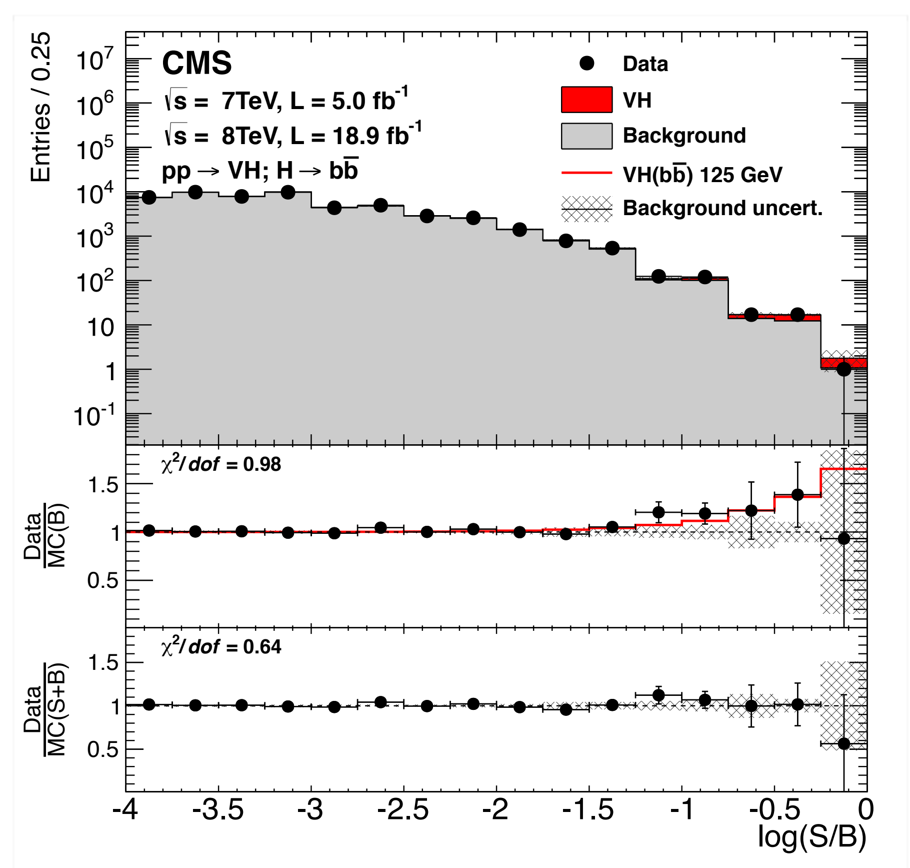
Most powerful channel!

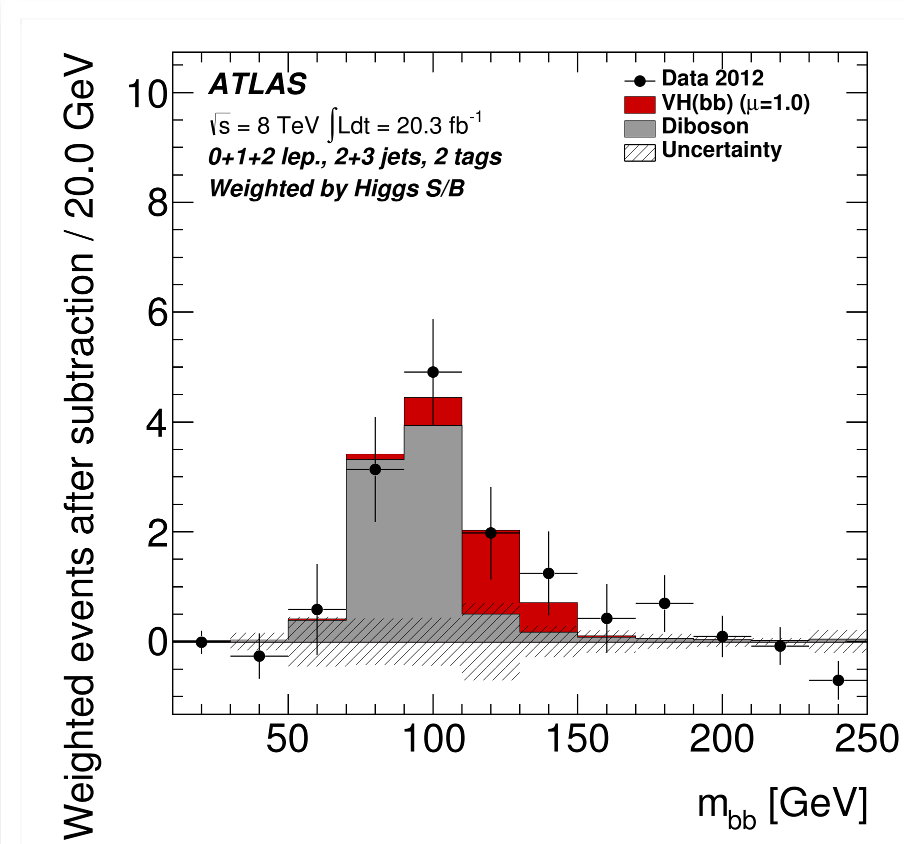
Final VH(bb) distributions

- Complex analyses using sophisticated multivariate techniques and advanced fit models
- Detailed studies of background modelling
  - Fit model designed to normalise backgrounds

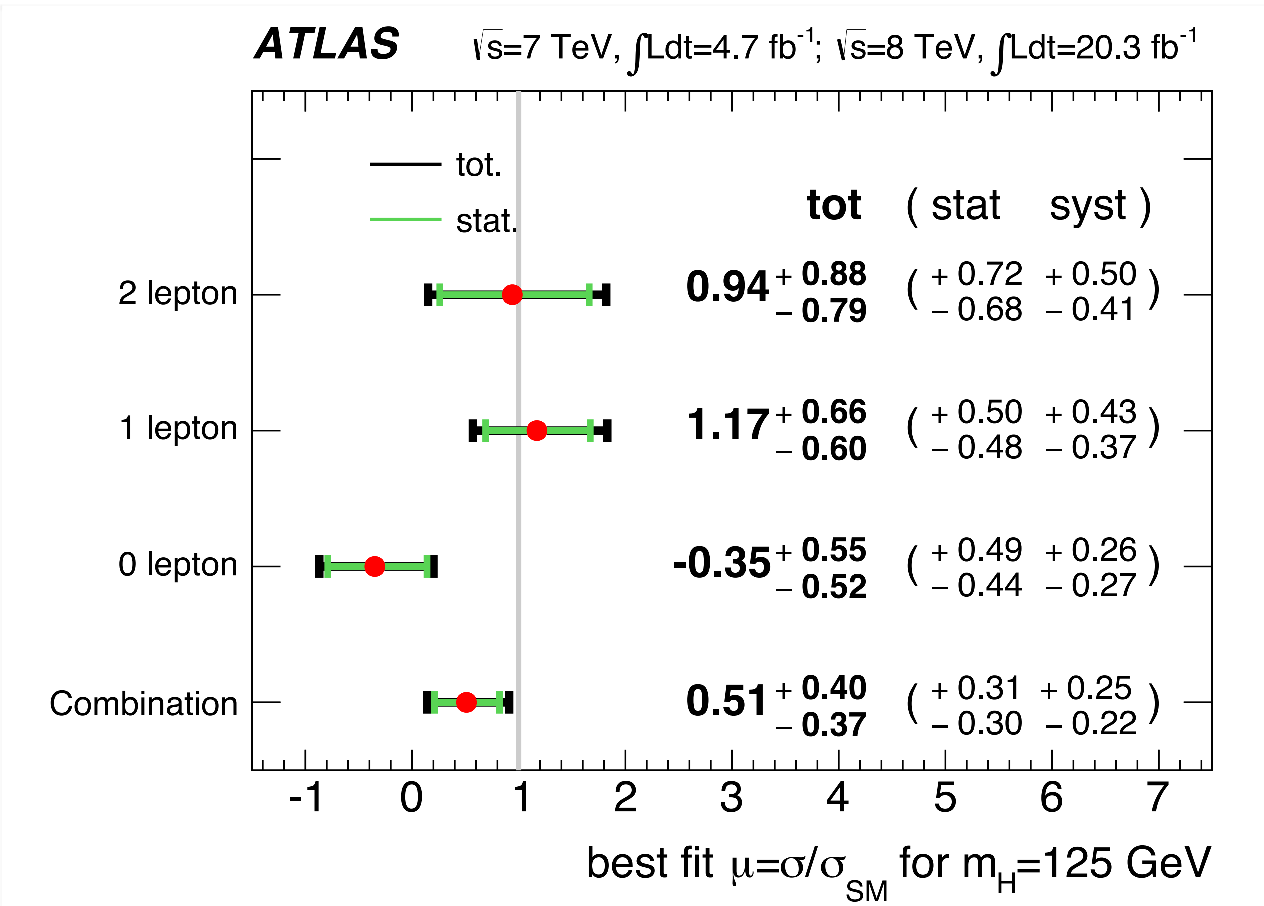


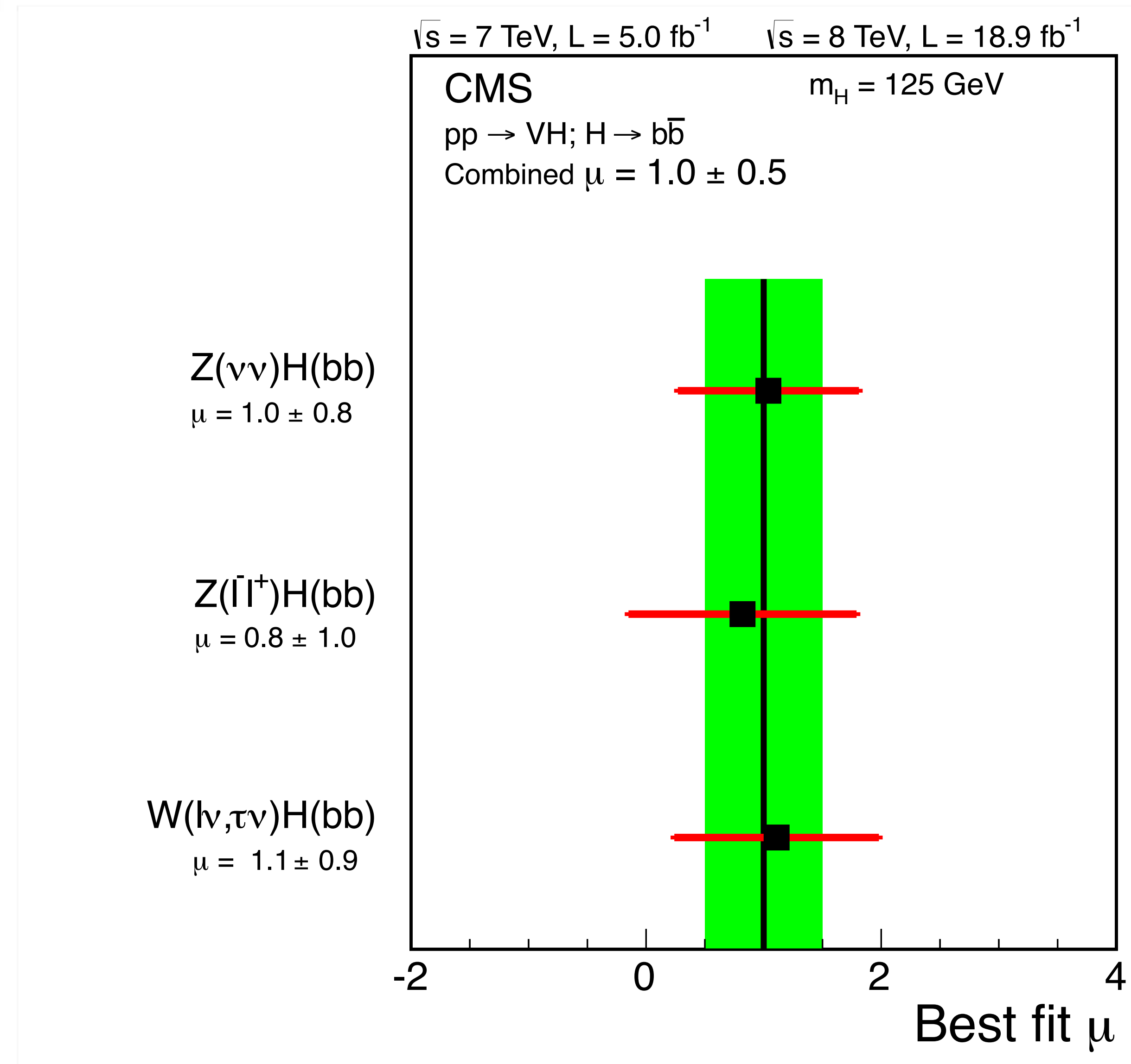
arXiv:1310.3687





VH(bb) Results





	Expected	Observed
ATLAS	2.6σ	1.4σ
CMS	2.1σ	2.1σ

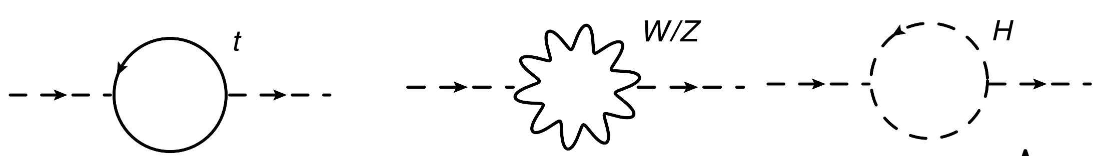
Coupling to Top Quarks

H→tt coupling

- Top quark **couples** very **strongly** to the Higgs boson
- For m_t = 173 GeV

$$\lambda_t = \frac{\sqrt{2} m_t}{v} = 0.996 \pm 0.005$$

- The **top quark**
  - Only quark with a ‘natural mass’
  - Main culprit in the instability of the Higgs mass

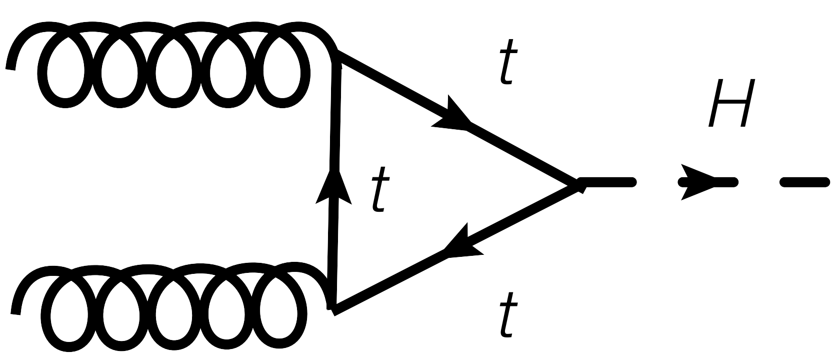


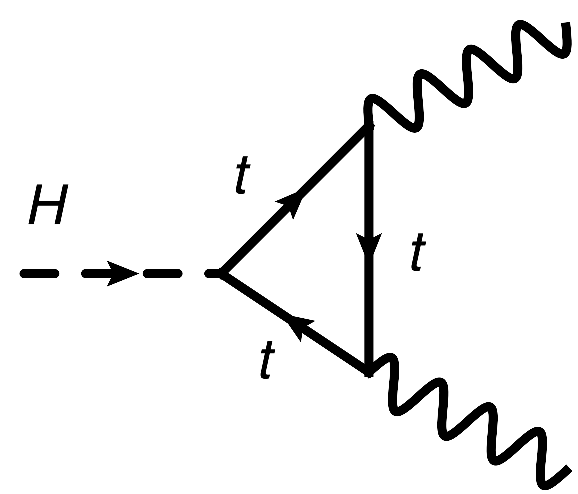
$$(125\ \mathrm{GeV})^2 = m_{H_0}^2 + (-2000^2 + 700^2 + 500^2)(\frac{\Lambda}{10})^2\ [\mathrm{TeV}^2]$$

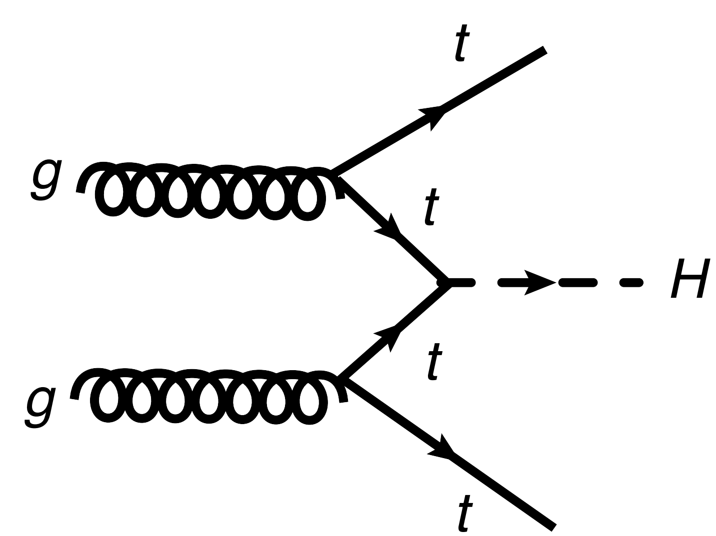
  - Could play a key role in EWSB or as a window to new physics
- Need accurate measurement of the top Yukawa coupling

ttH Motivation

- **Indirect constraints** on top-Higgs Yukawa coupling can be extracted from channels using **ggH** and **γγH** vertices
    - Assumption: **No new particles**
- ttH production can measure the top-Higgs Yukawa coupling directly
    - Probes **NP contributions** in the ggH and γγH vertices
- **Small production** cross-section at the LHC
    - Need to consider all channels to boost sensitivity



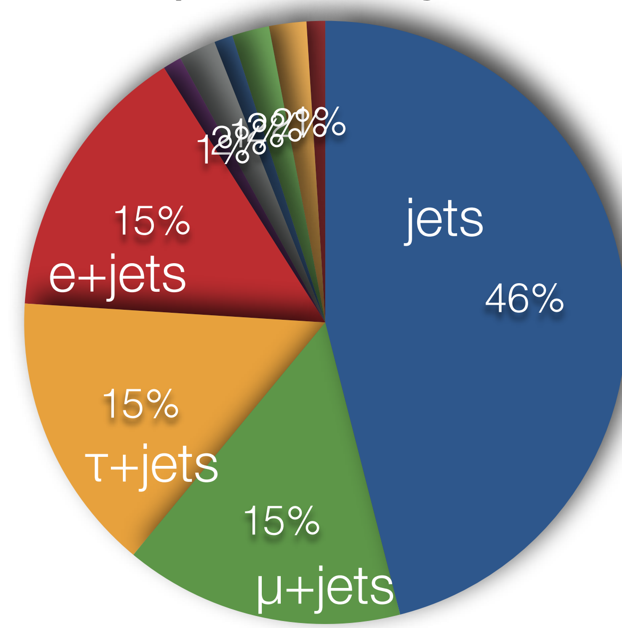




Potential searches for ttH at the LHC

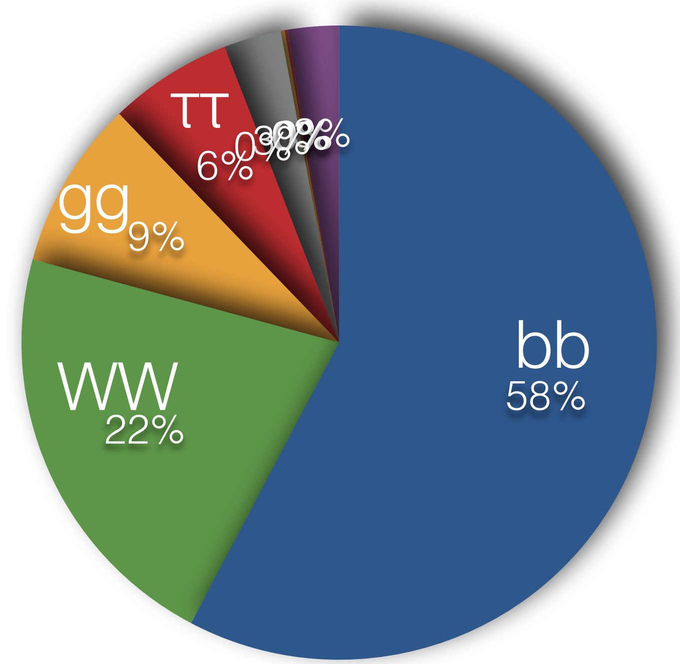
- **H→hadrons** (bb, ττ)
  - Large signal rates
  - Large combinatorial and physics backgrounds
  - Large systematic uncertainties
- **H→leptons** (WW, ZZ, ττ)
  - Smaller backgrounds
  - Smaller signal rate
- **H→γγ**
  - No combinatorics
  - Small signal rate

Top Decays



jets
leptons
lepton+jets

$\otimes$



hadrons
leptons
photons

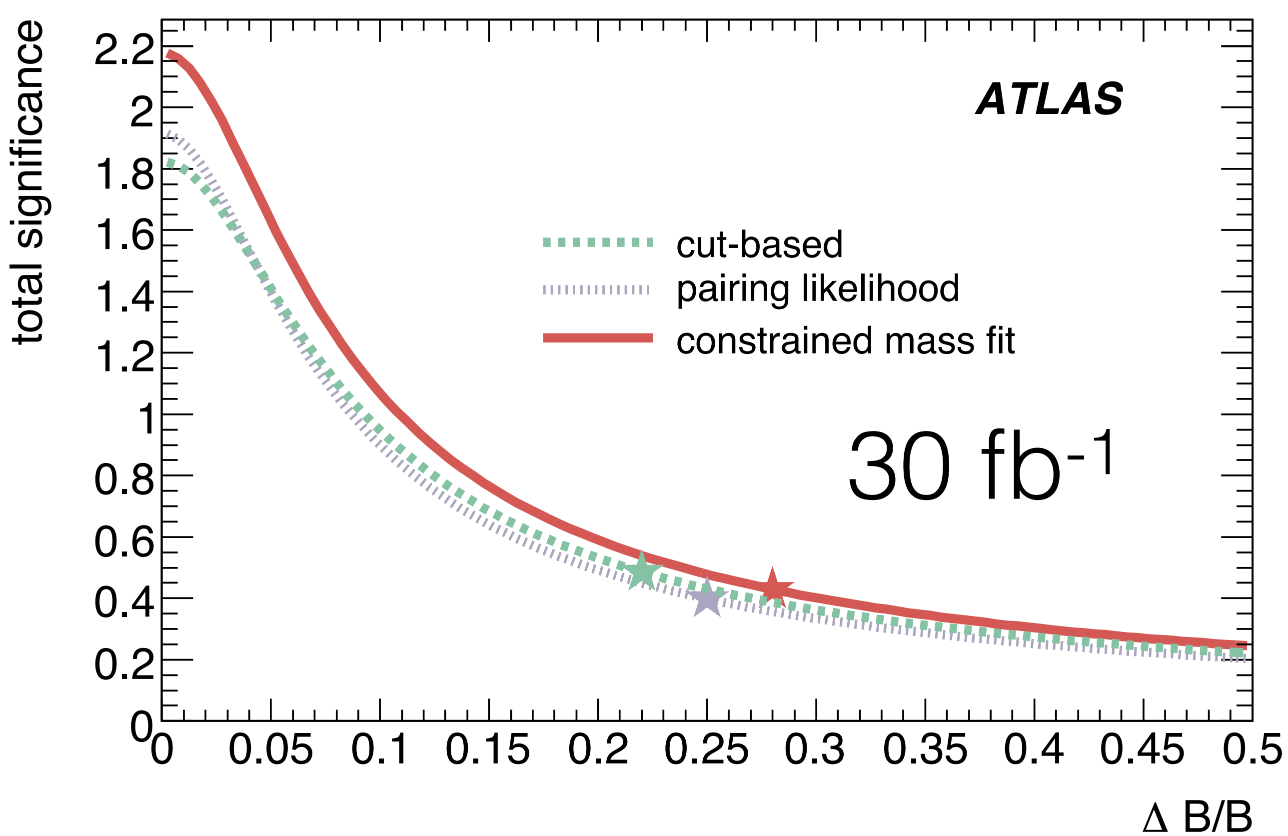
Higgs Decays

ttH Predictions

ttH(leptons) Projection

The $t\bar{t}H, H \rightarrow WW^{(*)}$ and $WH, H \rightarrow WW^{(*)}$ processes have been studied using two- and three-lepton final states. The signal and main backgrounds have been estimated using a full GEANT based simulation of the detector. The estimated accepted cross-sections in fb of signal and background for these processes are 1.9:10 ($t\bar{t}H$ 2L), 0.8:3.4 ($t\bar{t}H$ 3L) and 0.3:0.4 (WH 3L) respectively. The signal is small and clear distinguishing features such as resonance peaks have not been established. The backgrounds are larger and their uncertainties have not been fully controlled. The analysis is therefore very challenging.

ttH(bb) Projection



For ttH(bb), the main problem is achieving sufficient control over the background uncertainty

bitrarily chosen reference. It is interesting to note that it does not quite yield a substantial significance, even though background uncertainties of 1% and 4% for $t\bar{t}$Nj and $t\bar{t}b\bar{b}$ are probably substantially better than what will be accessible in reality. This highlights the challenge that is faced in observing $t\bar{t}$H.

ttH(bb)

ttH(bb) Systematic Uncertainties

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Systematic uncertainty	Type	Components
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
b-tagging efficiency	SN	6
c-tagging efficiency	SN	6
Light jet-tagging efficiency	SN	12
Background Model		
$t\bar{t}$ cross section	N	1
$t\bar{t}$ modelling: p_T reweighting	SN	9
$t\bar{t}$ modelling: parton shower	SN	2
$t\bar{t}$+heavy-flavour: normalisation	N	2
$t\bar{t}$+heavy-flavour: HF reweighting	SN	2
$t\bar{t}$+heavy-flavour: generator	SN	5
W+jets normalisation	N	3
W p_T reweighting	SN	1
Z+jets normalisation	N	2
Z p_T reweighting	SN	1
Multijet normalisation	N	3
Multijet shape dilepton	S	1
Single top cross section	N	1
Dibosons cross section	N	1
$t\bar{t}V$ cross section	N	1
Signal Model		
$t\bar{t}H$ modelling	SN	2

	$\geq$ 6 j, $\geq$ 4 b							
	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$
Luminosity	±2.8	±2.8	±2.8	±2.8	±2.6	±2.6	±2.6	±2.6
Lepton efficiencies	±1.4	±1.4	±1.4	±1.5	±1.3	±1.3	±1.3	±1.3
Jet energy scale	±6.5	±14	±10	±8.2	±2.6	±5.9	±4.2	±3.5
Jet efficiencies	±1.6	±5.4	±2.5	±2.4	±0.7	±2.3	±1.1	±1.1
Jet energy resolution	±0.1	±8.5	±4.1	±4.3	±0.1	±5.6	±3.7	±3.9
b-tagging efficiency	±9.0	±5.8	±5.1	±9.2	±6.4	±4.2	±3.7	±6.5
c-tagging efficiency	±1.9	±7.3	±14	±2.8	±0.8	±4.0	±7.8	±1.6
Light jet-tagging efficiency	±1.0	±17	±4.4	±1.5	±0.8	±14	±3.7	±1.2
$t\bar{t}$ modelling: reweighting	–	±11	±13	±13	–	±5.3	±6.0	±6.4
$t\bar{t}$ modelling: parton shower	–	±7.5	±1.8	±10	–	±2.3	±0.7	±4.0
$t\bar{t}$ heavy-flavour: normalisation	–	–	±50	±50	–	–	±29	±15
$t\bar{t}$ heavy-flavour: reweighting	–	–	±11	±12	–	–	±6.3	±6.8
$t\bar{t}$ heavy-flavour: generator	–	–	±2.2	±2.9	–	–	±2.2	±2.8
Theoretical cross sections	–	±6.2	±6.3	±6.3	–	±4.3	±4.3	±4.3
$t\bar{t}H$ modelling	±1.9	–	–	–	±1.9	–	–	–
Total	±12	±30	±57	±56	±7.2	±14	±25	±14

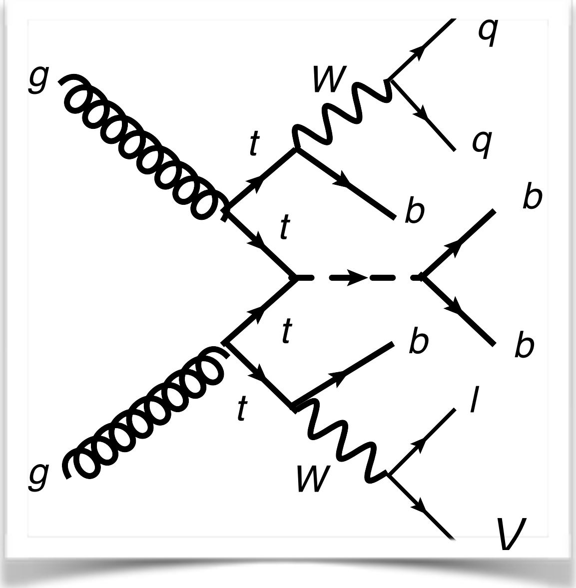
Many systematic uncertainties: both theoretical and experimental

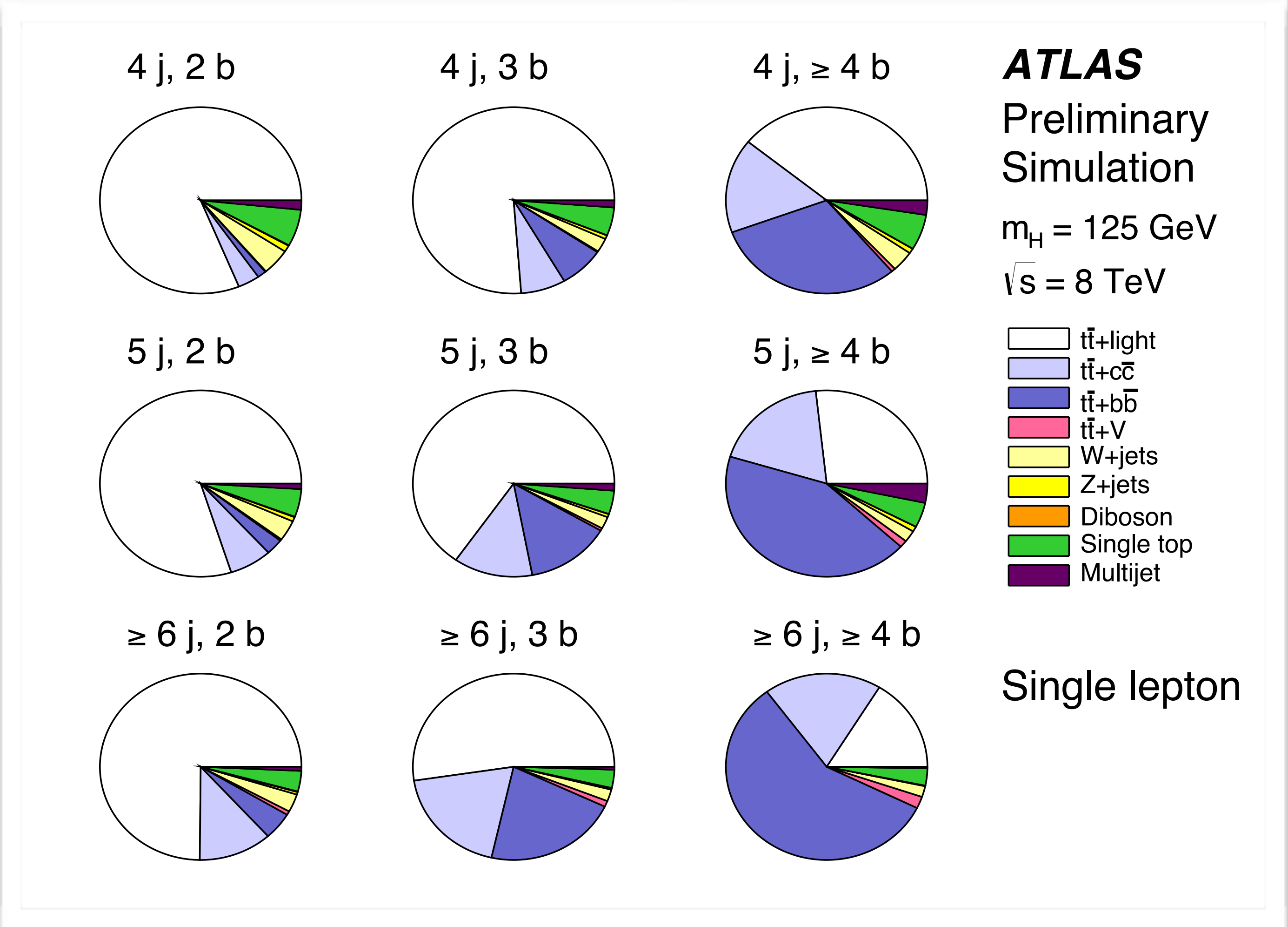
Background systematics are **larger** than expected **signal yield (64)**

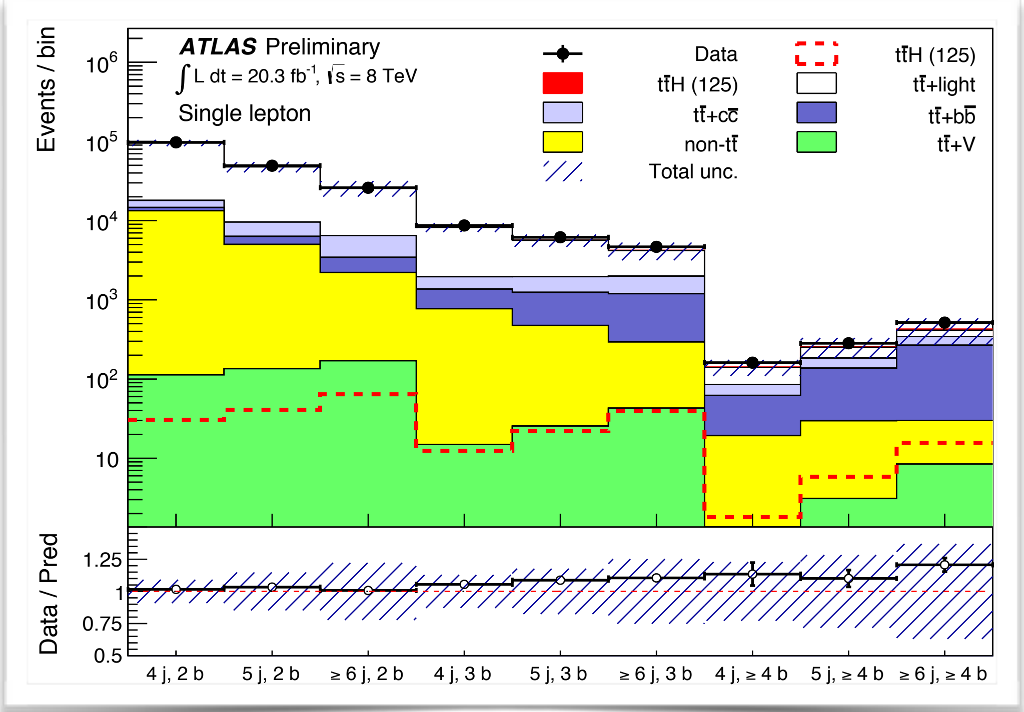
Background uncertainty: ~37%
Expected S/B: ~3.8%

ttH(bb) Analysis Model

- Select **tt-enriched** samples
  - Lepton+jets or dilepton
- Categorise events by **jet** and **b-tag** multiplicity
  - Separate **high** and **low** S/√B channels
  - **Constrain systematic uncertainties** from signal depleted categories using profile likelihood fit

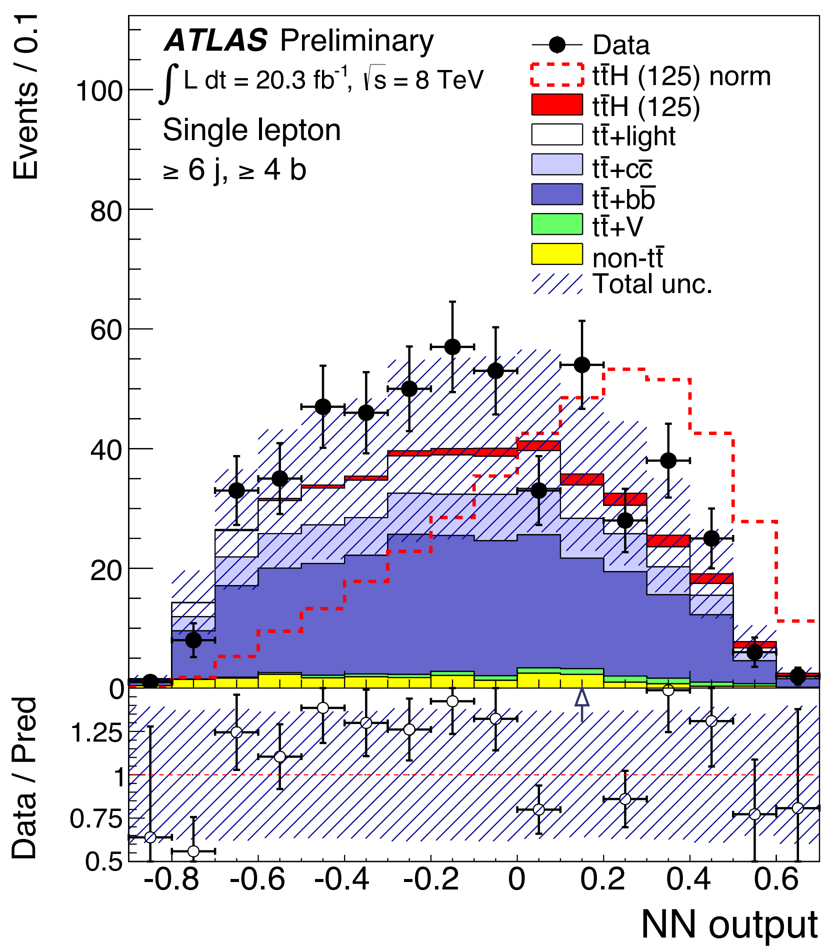




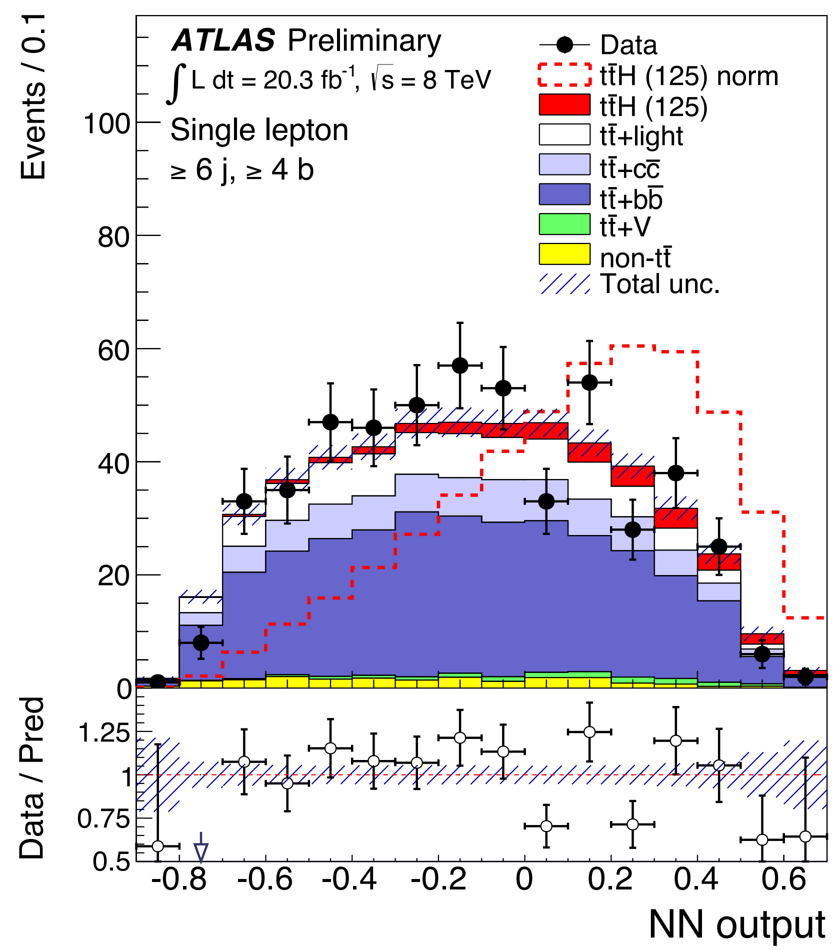


Profiling Example

- Profile likelihood fits treat systematic uncertainties as nuisance parameters that can be constrained from data
- Constraints from **high-statistics control samples**
- **Caution**: Sufficiently sophisticated treatment needed to avoid overconstraints



Background uncertainty: ~37%



Background uncertainty: ~5%

Similar for CMS: ~37% → ~7 %

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ttH(bb) Ranking Plot

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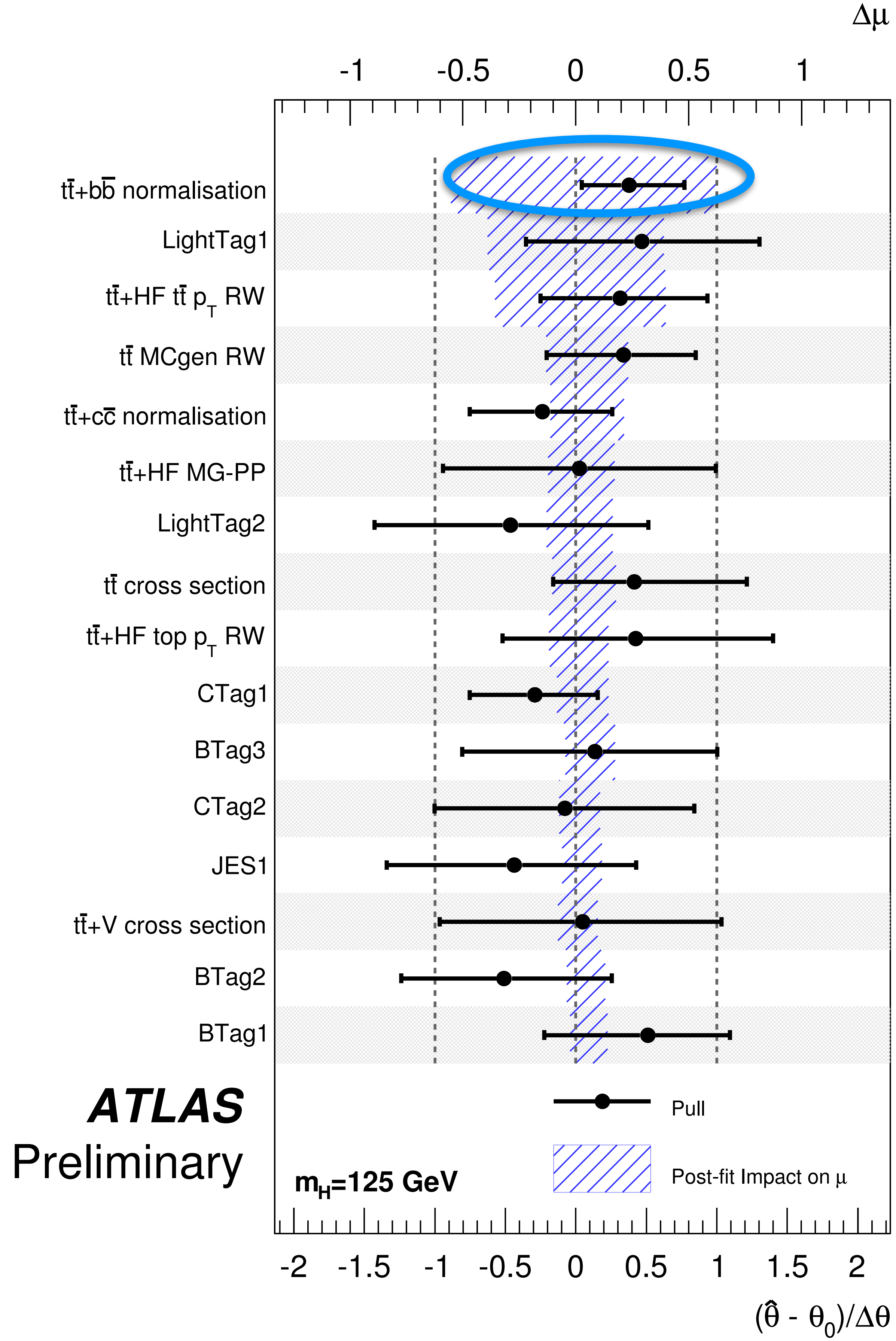
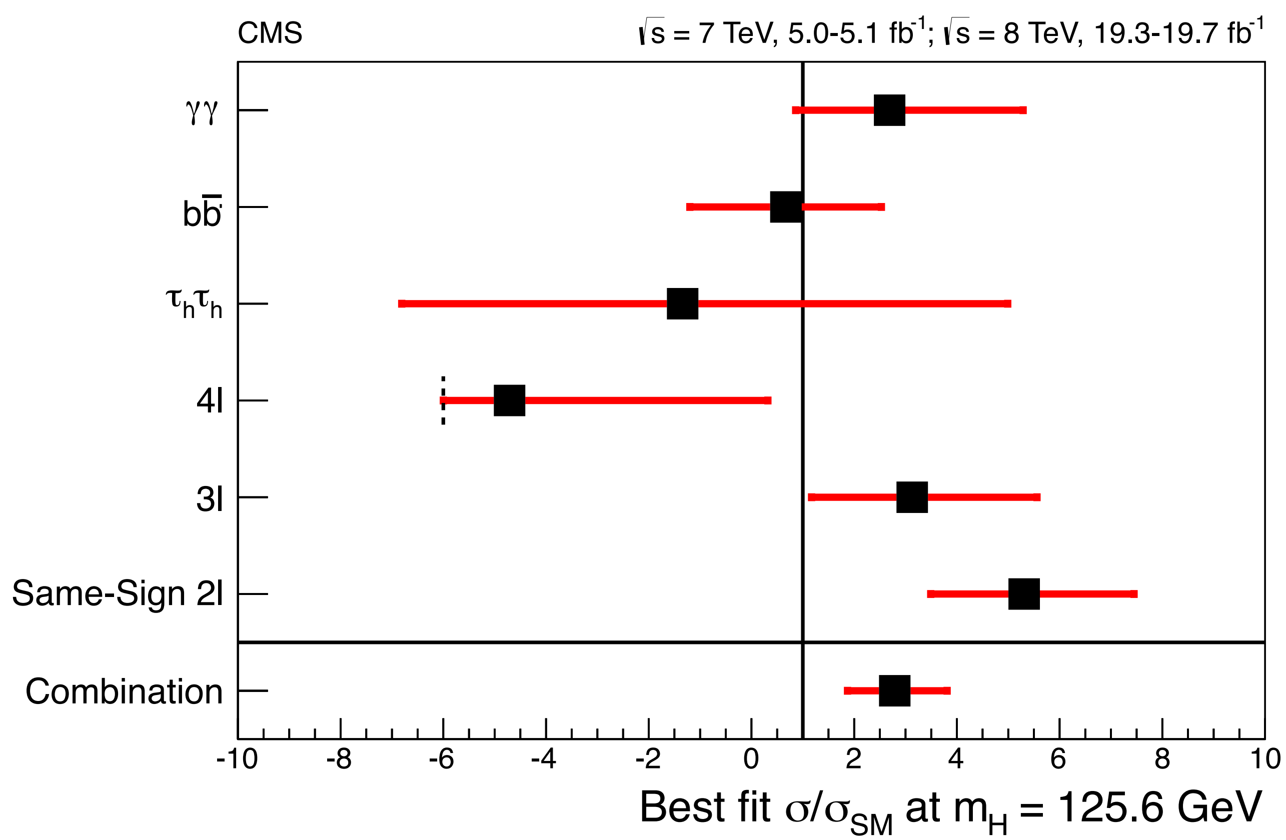
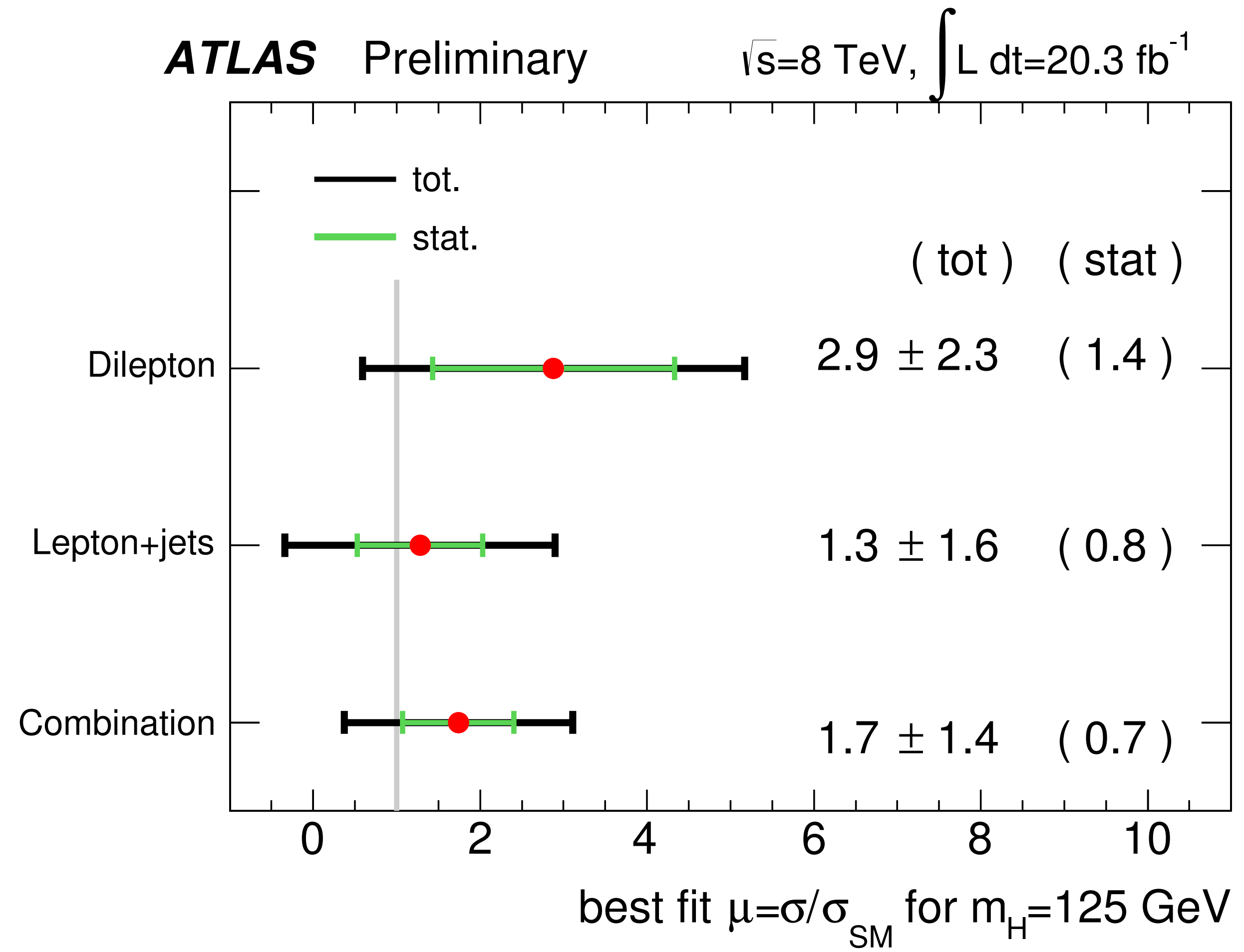


H->bb Results





- CMS: Observed (expected) limit @ 125 GeV
  - **4.1 x SM** (3.5 x SM)
- ATLAS: Observed (expected) limit @ M_H=125 GeV
  - **4.1xSM** (2.6xSM)

ATLAS-CONF-2014-011

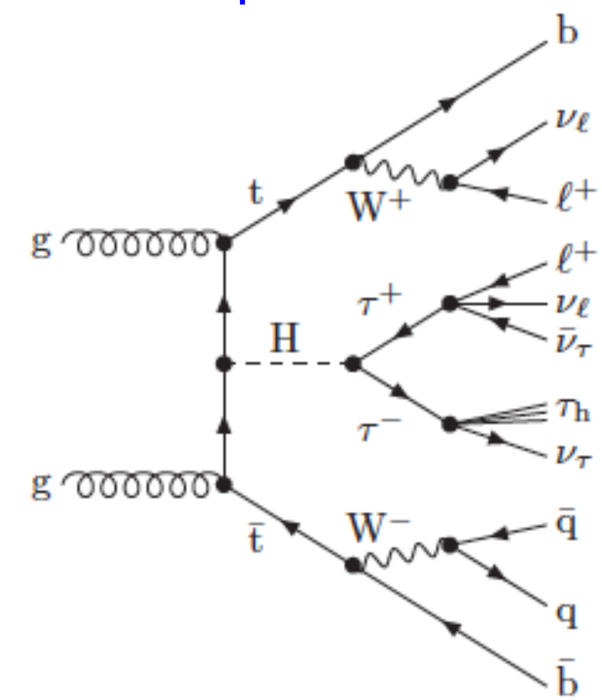
CMS-PAS-HIG-14-009

The forgotten leptons

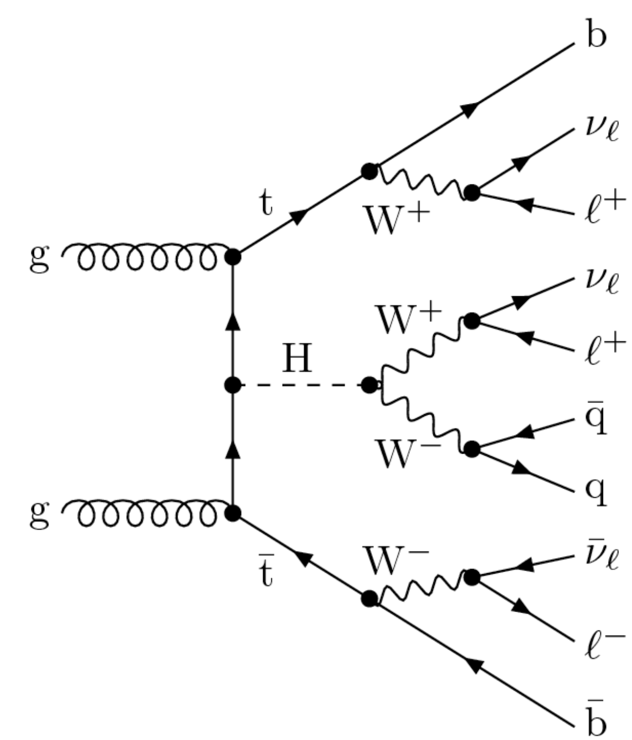
ttH Multileptons

- Despite being studied in projections by ATLAS, there were initially no analyses looking for ttH in the multilepton channels
- During 2013, it was realised that these channels would actually already be quite sensitive
  - Multilepton analyses began to be developed

SS 2-leptons channel



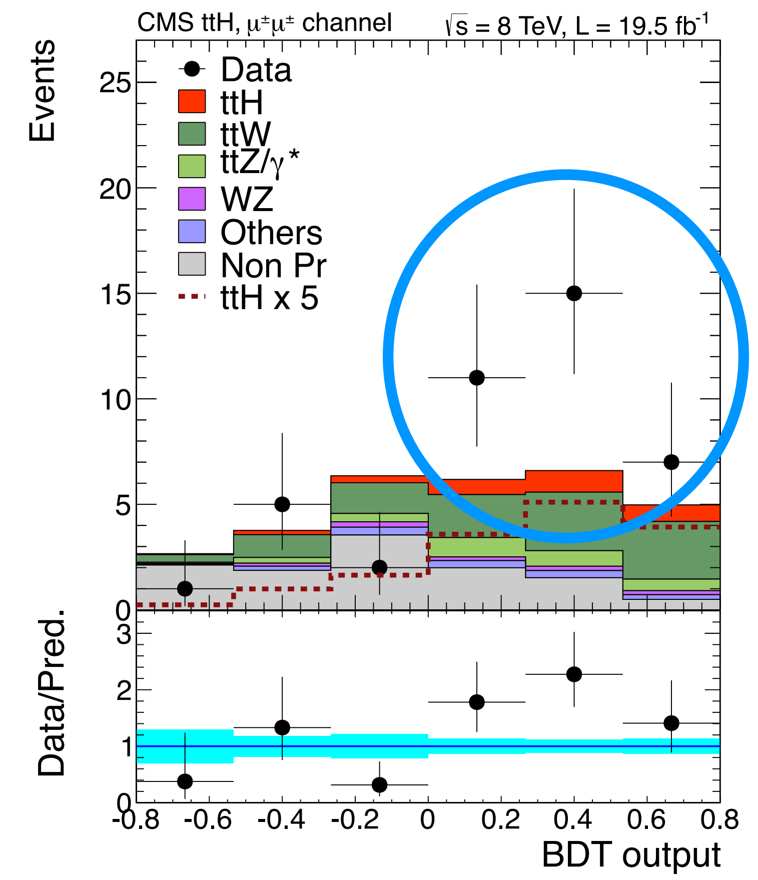
3-leptons channel

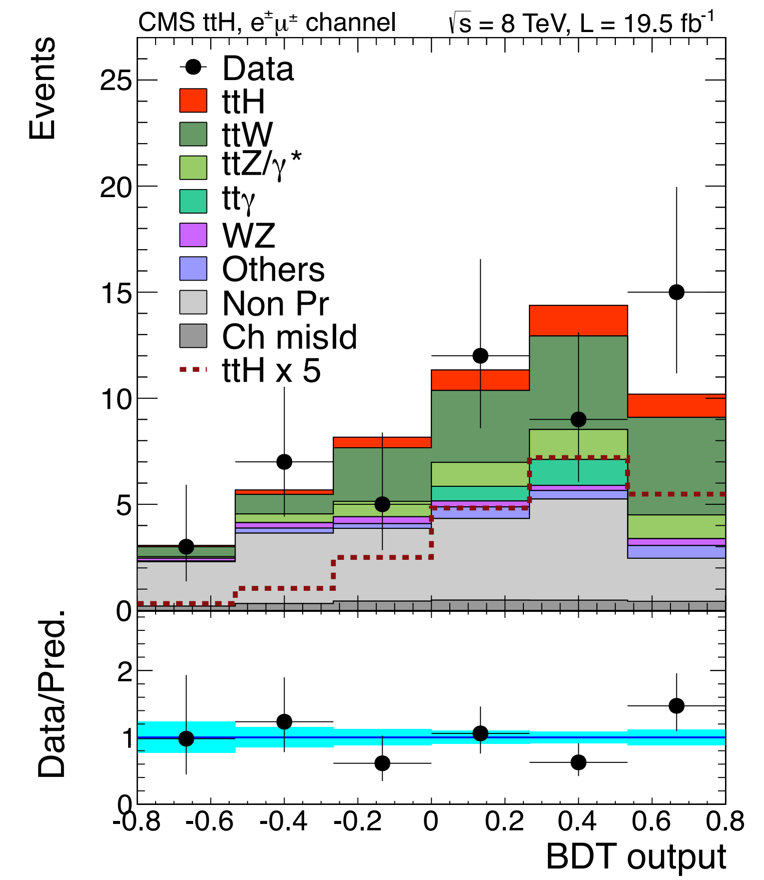


> The $t\bar{t}H, H \to WW^{(*)}$ and $WH, H \to WW^{(*)}$ processes have been studied using two- and three-lepton final states. The signal and main backgrounds have been estimated using a full GEANT based simulation of the detector. The estimated accepted cross-sections in fb of signal and background for these processes are 1.9:10 ($t\bar{t}H$ 2L), 0.8:3.4 ($t\bar{t}H$ 3L) and 0.3:0.4 (WH 3L) respectively. The signal is small and clear distinguishing features such as resonance peaks have not been established. The backgrounds are larger and their uncertainties have not been fully controlled. The analysis is therefore very challenging.

ttH Multileptons Strategy

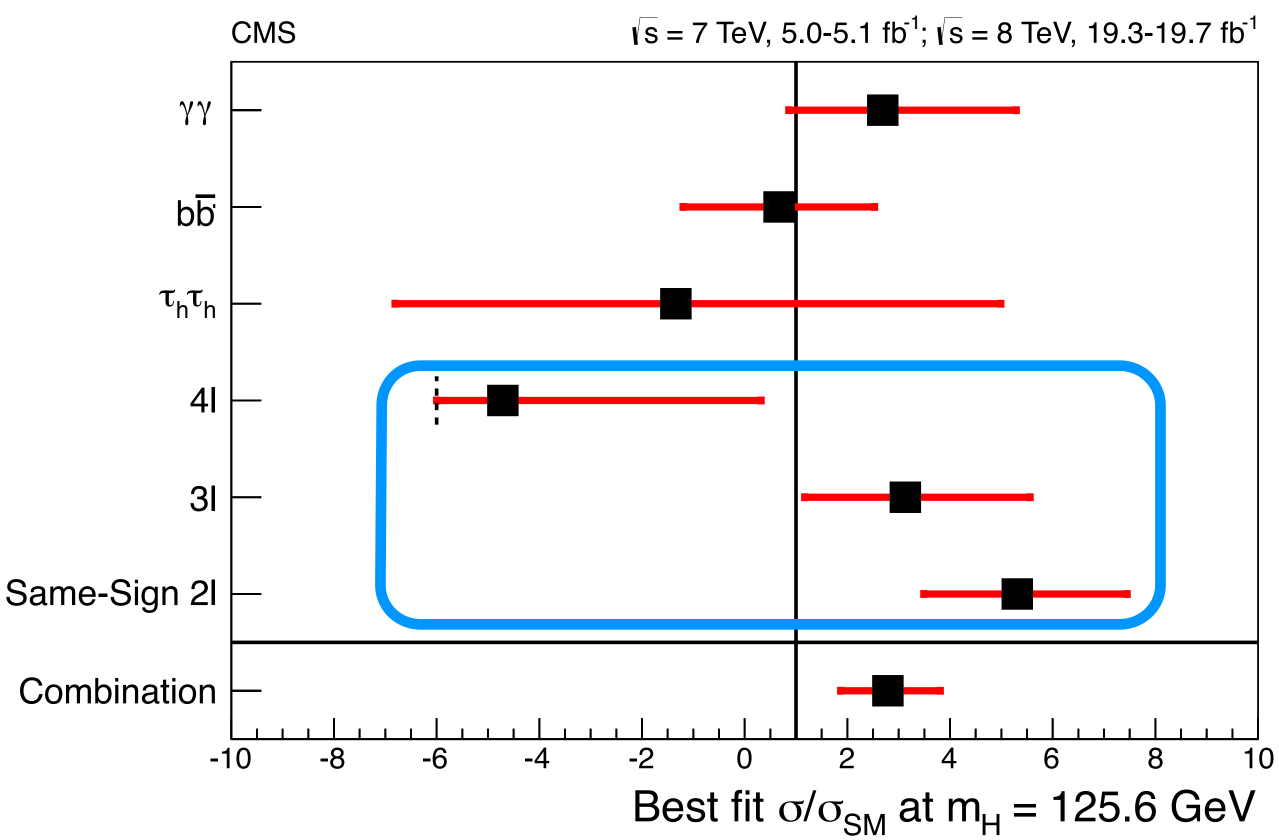
- Channels defined by **number of leptons**
  - **SS 2-leptons**, 6 jets, 2 b-jets
  - **3-leptons**, 4 jets, 2 b-jets
  - **4-leptons**, 2 jets, 2 b-jets
- Main target is **H→WW**, but also contributions from H→ττ and H→ZZ
- Low signal rate, but low background
- Main background is **ttW/Z/γ***; also diboson (WZ and ZZ), ttbar (2/3-leptons)
- **Multivariate discriminants** to separate signal and background
- Only **CMS** result is currently public

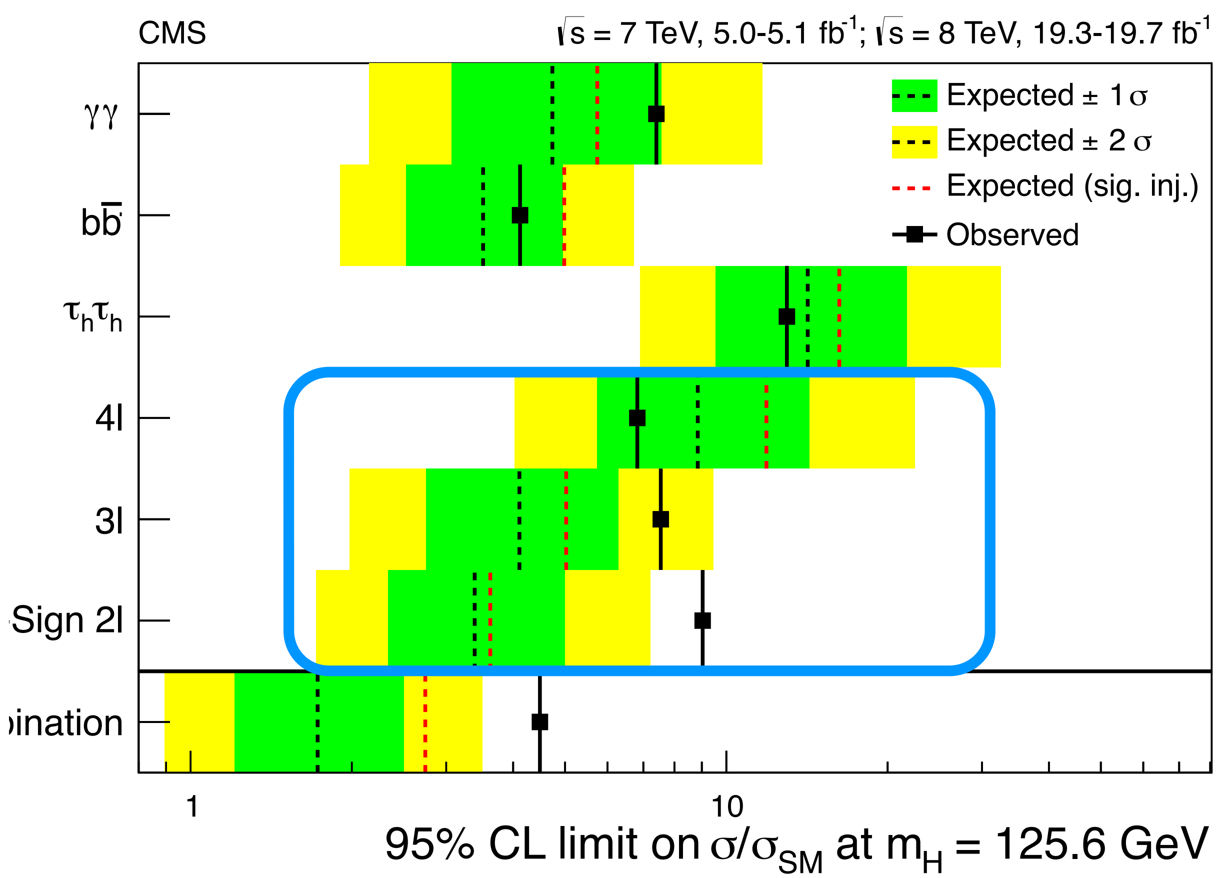




CMS Multilepton Results

CMS-PAS-HIG-14-009

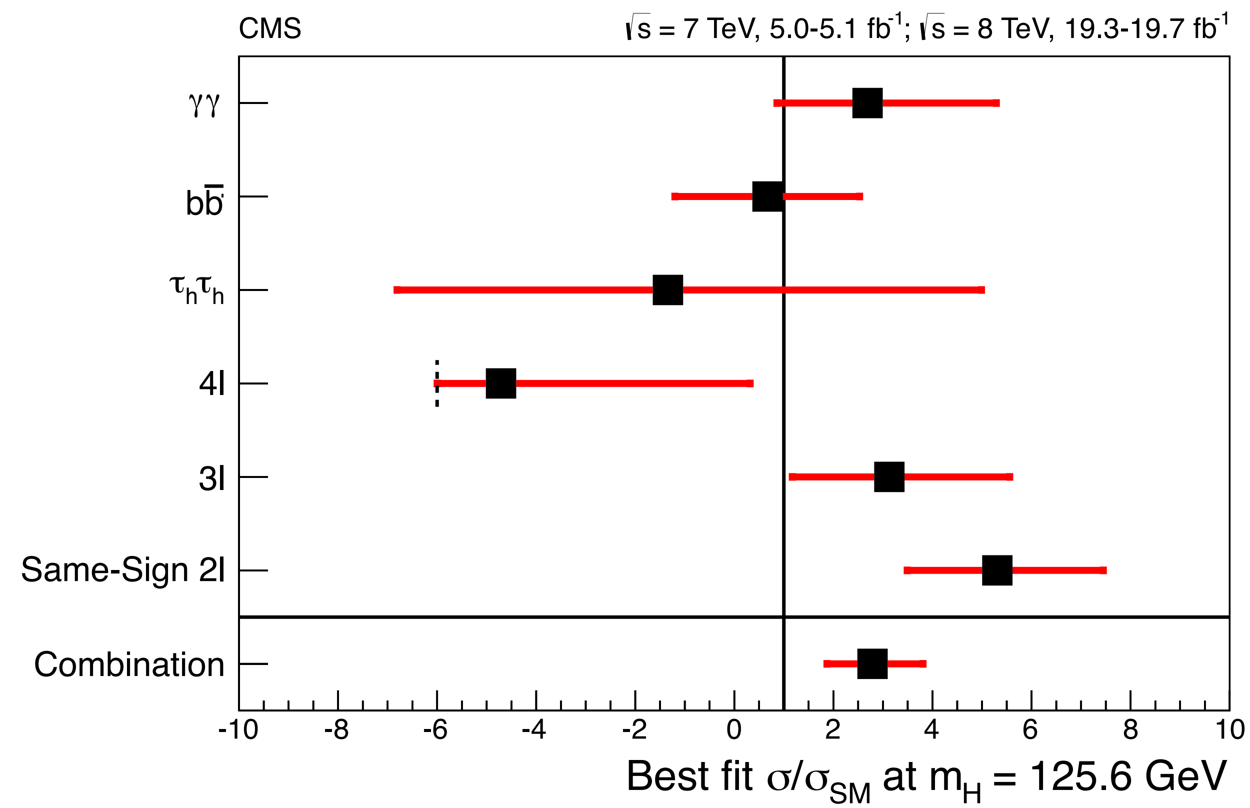


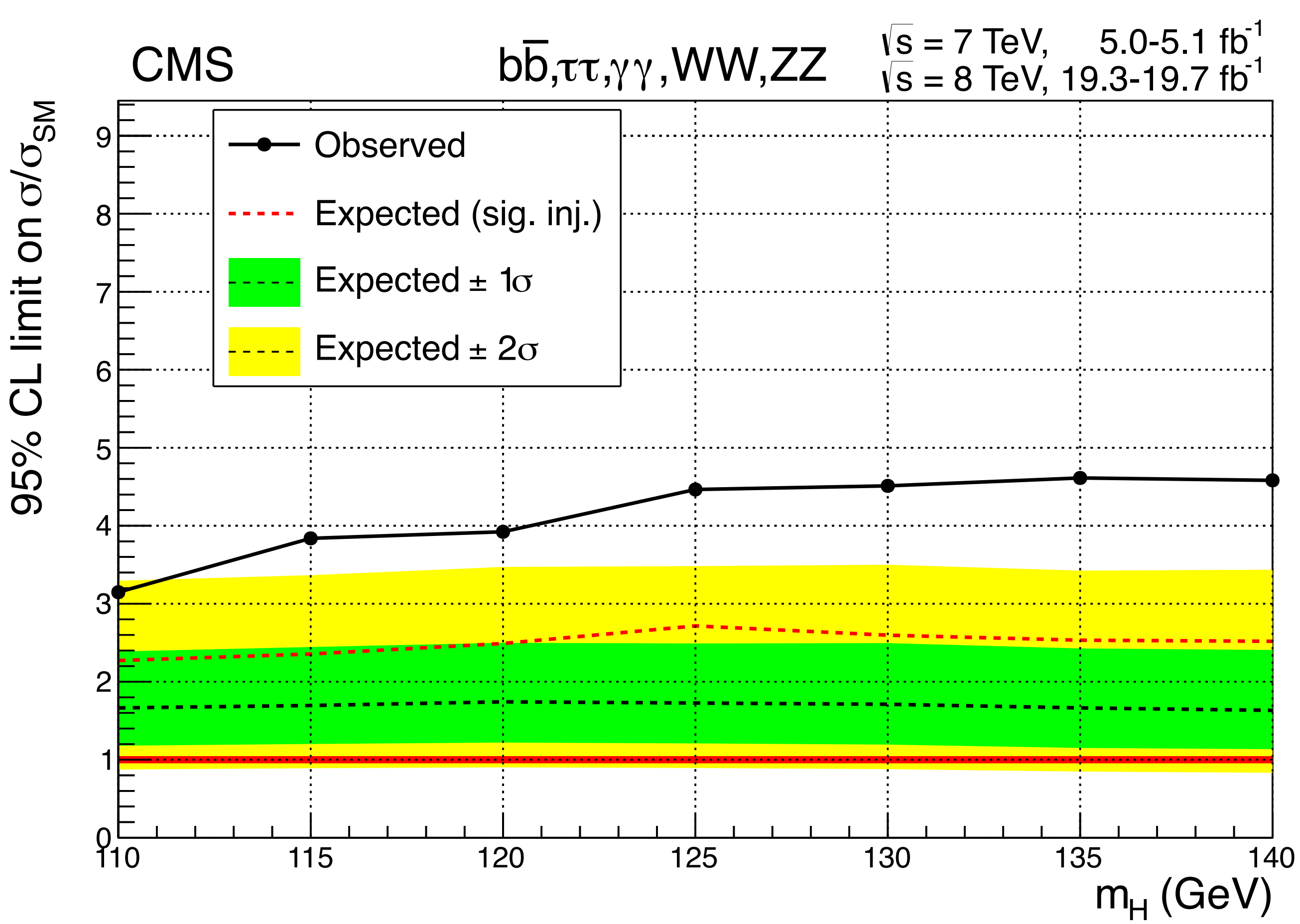


- Despite low statistics, the analyses are already powerful
- Observed (expected) limit @ 125 GeV
  - 9.0 x SM (3.4 x SM) for **SS 2-lepton**
  - 7.5 x SM (4.1 x SM) for **3-lepton**
  - 6.8 x SM (8.8 x SM) for **4-lepton**
- Combined multi lepton sensitivity is ~6.6xSM (2.4xSM) (PAS)

CMS ttH Final Results

- Combination of all CMS ttH Results
- Observed (expected) limit @ 125 GeV
  - 4.5 x SM (1.7 x SM)
- Largely driven by excess in Same-Sign 2l channel

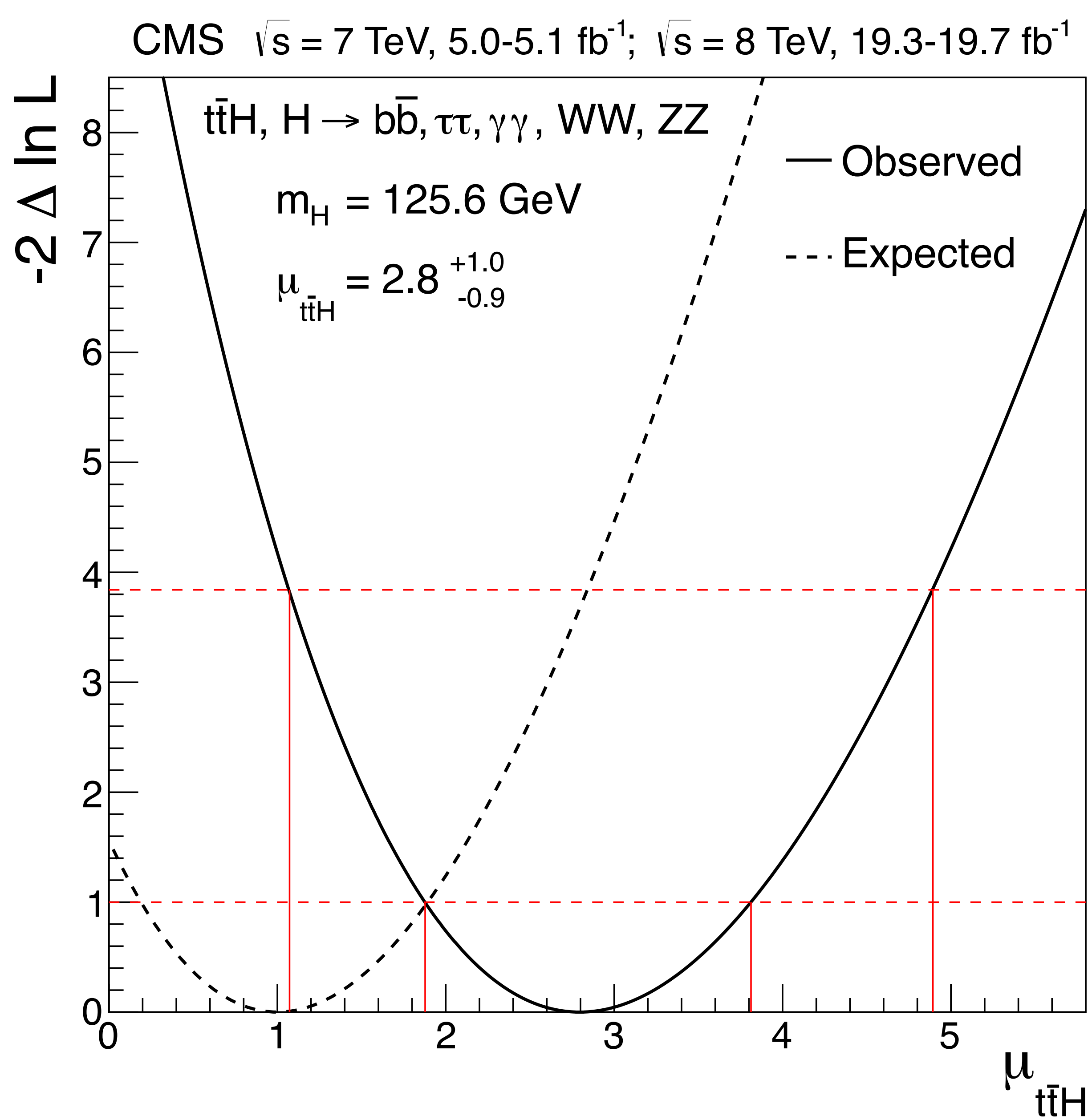


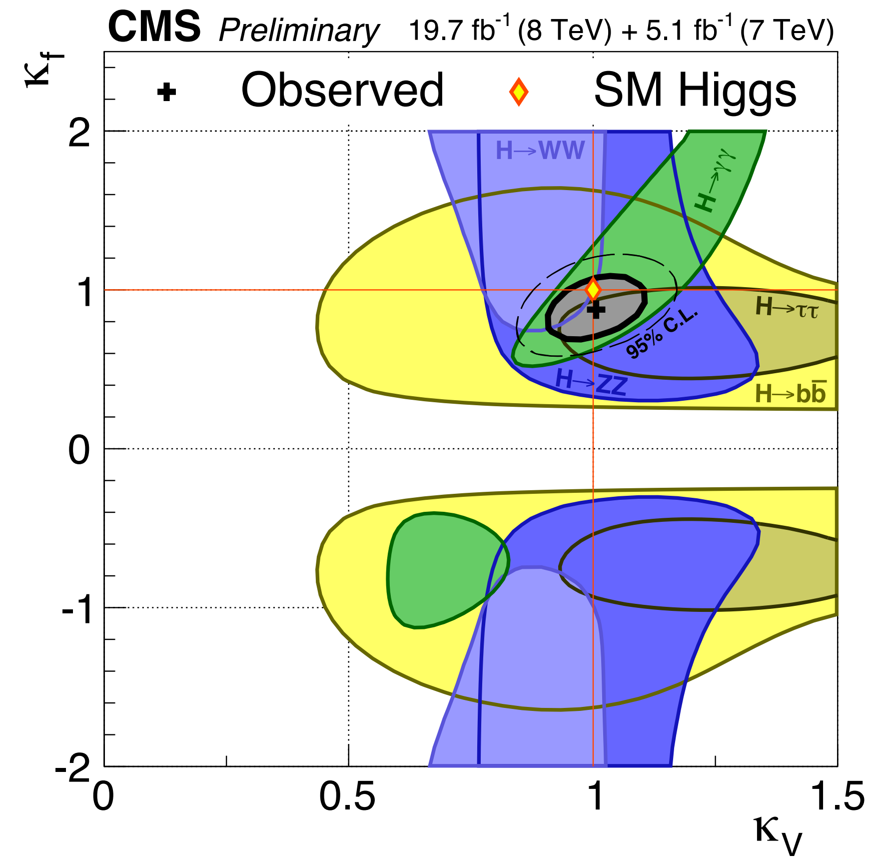


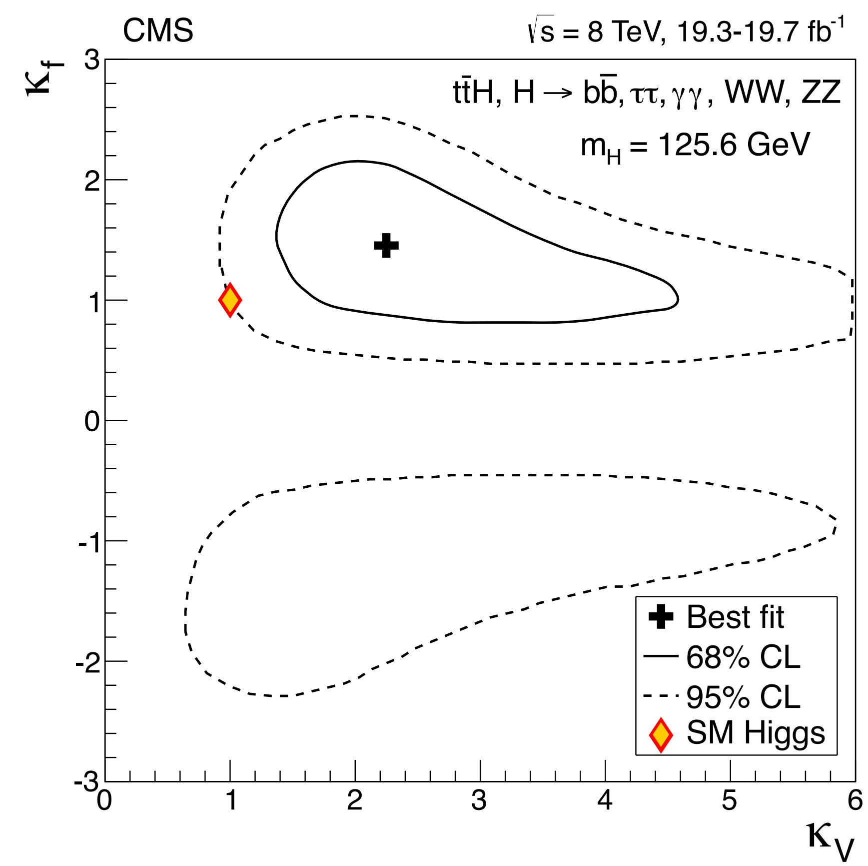
$t\bar{t}$H channel	Best-fit μ	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.6$ GeV)				
			Expected			
	Observed	Observed	Median signal-injected	Median	68% CL range	95% CL range
$\gamma\gamma$	$+2.7^{+2.6}_{-1.8}$	7.4	5.7	4.7	[3.1, 7.6]	[2.2, 11.7]
$b\bar{b}$	$+0.7^{+1.9}_{-1.9}$	4.1	5.0	3.5	[2.5, 5.0]	[1.9, 6.7]
$\tau_h\tau_h$	$-1.3^{+6.3}_{-5.5}$	13.0	16.2	14.2	[9.5, 21.7]	[6.9, 32.5]
4l	$-4.7^{+5.0}_{-1.3}$	6.8	11.9	8.8	[5.7, 14.3]	[4.0, 22.5]
3l	$+3.1^{+2.4}_{-2.0}$	7.5	5.0	4.1	[2.8, 6.3]	[2.0, 9.5]
Same-sign 2l	$+5.3^{+2.1}_{-1.8}$	9.0	3.6	3.4	[2.3, 5.0]	[1.7, 7.2]
Combined	$+2.8^{+1.0}_{-0.9}$	4.5	2.7	1.7	[1.2, 2.5]	[0.9, 3.5]

CMS-PAS-HIG-14-009

Combination Interpretation





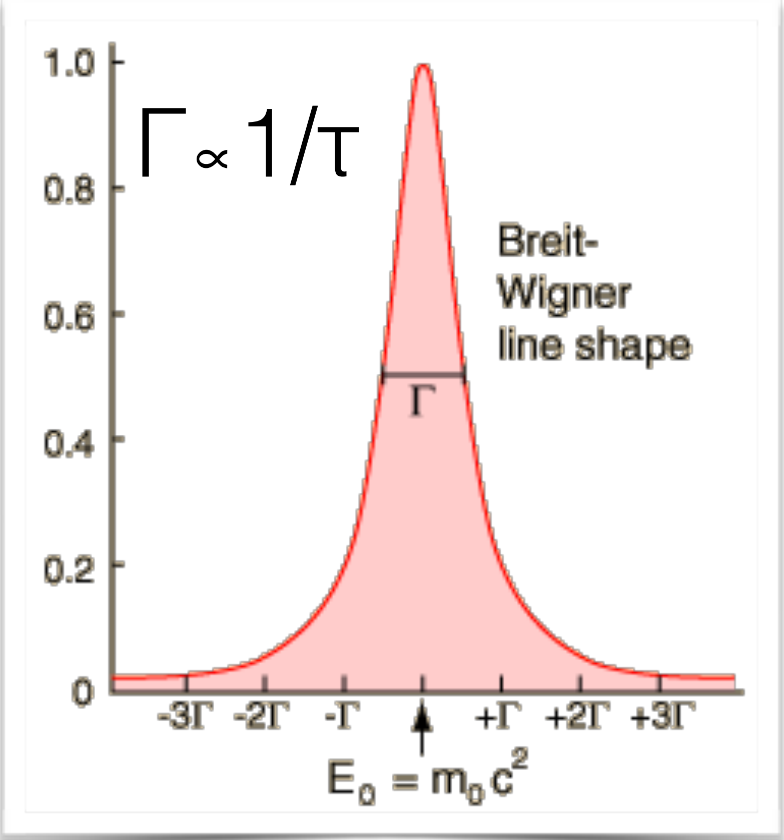


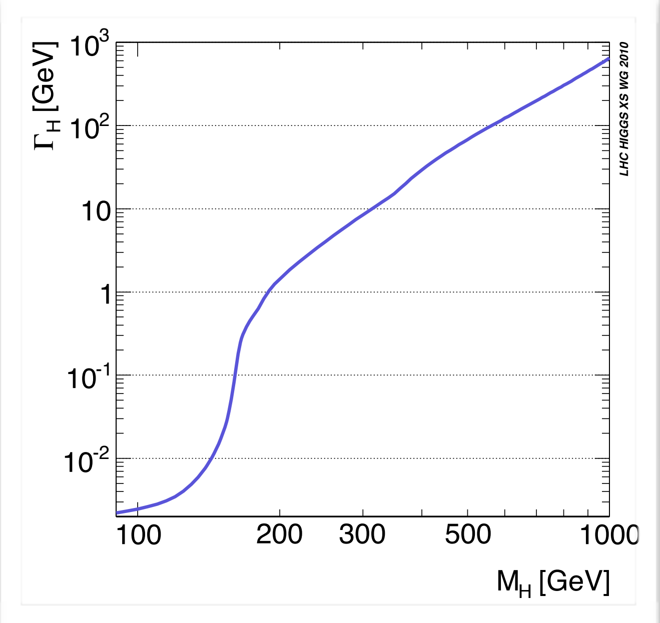
CMS-PAS-HIG-14-009

Width

Width

- As an highly unstable elementary particle, the lifetime of the Higgs is very short
- For m_H = 125 GeV
  - Γ=4.07 x 10^{-3} MeV
- Direct experimental measurements probe widths **3 orders of magnitude larger** ~1.6 GeV (ATLAS, ZZ)
- Thought to be impossible to measure the width at a hadron collider





Expectations for width measurements

A measurement of the width is possible only for Higgs boson masses above $\gtrsim 2m_Z$ where at the same time the Higgs natural width is becoming large and the detector resolution is improving. A Gaussian width with central values of about 2.3 GeV/c^2 for $m_H = 200$ GeV/c^2 and 4.2 GeV/c^2 for $m_H = 300$ GeV/c^2 is obtained from the fit, but with a rather large uncertainty of about 50%.

The CMS TDR plot showing the expected precision on the width doesn't even extend below a Higgs mass of 200 GeV …

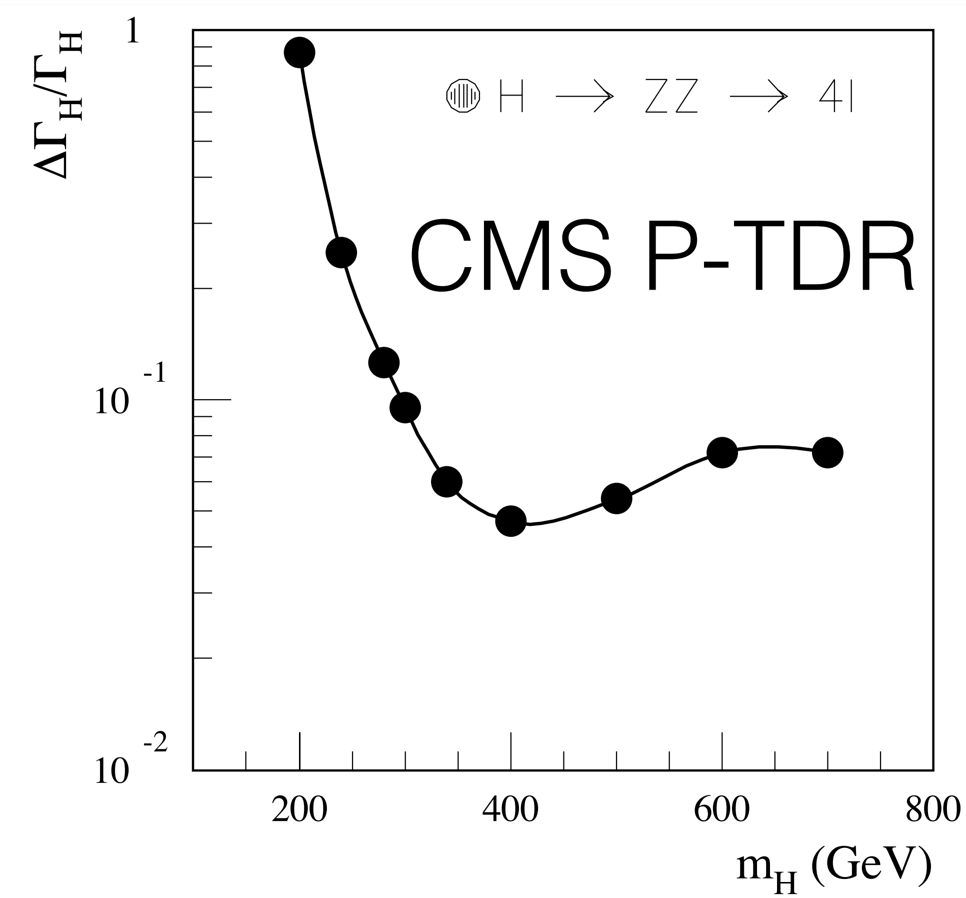


Figure 19-46 Relative precision $\Delta\Gamma_H/\Gamma_H$ on the measured Higgs-boson width as a function of m_H, assuming an integrated luminosity of 300 fb^{-1}.

Off-shell Higgs Production

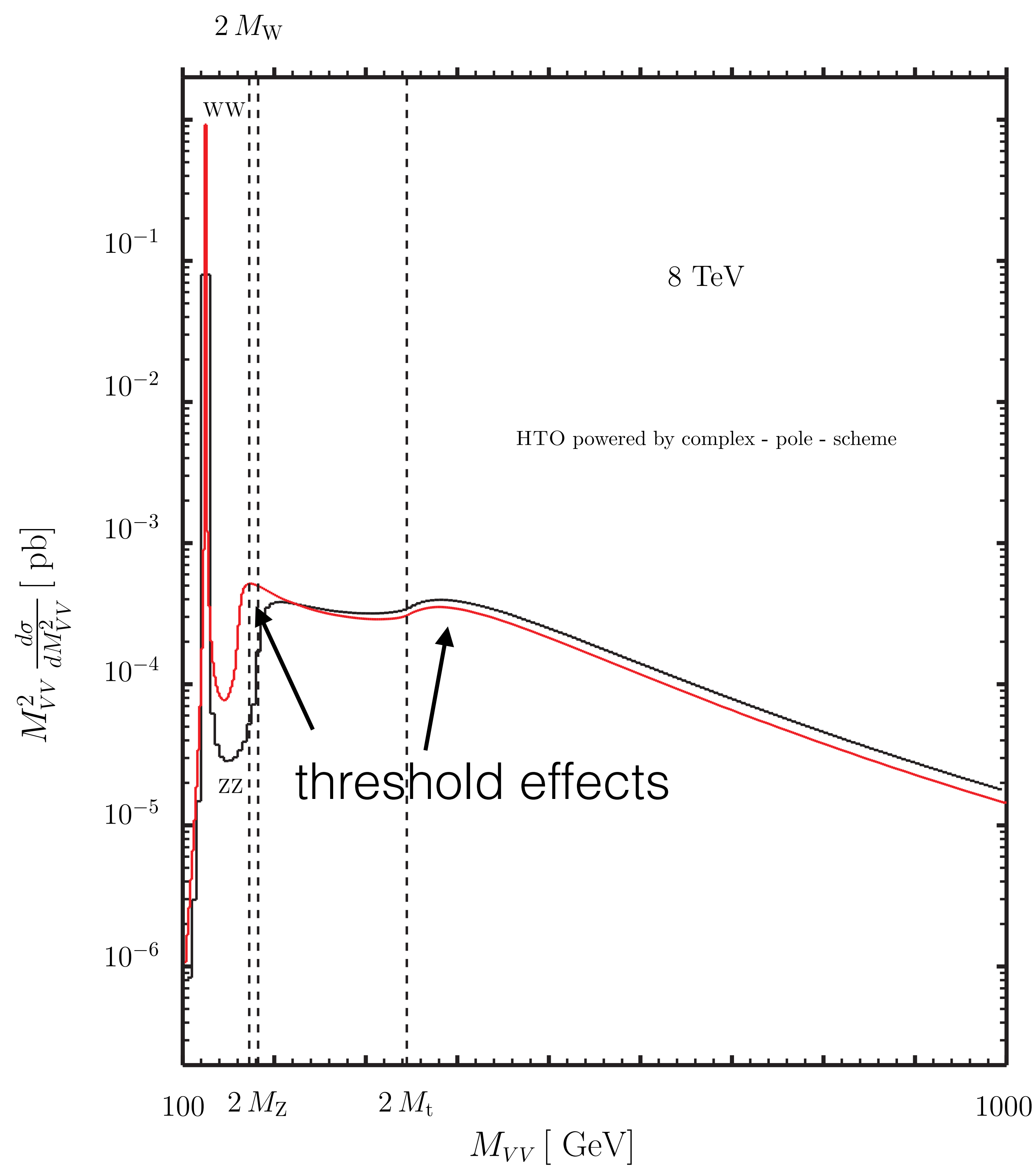
- A paper from Kauer and Passerino in 2012 pointed out a peculiar cancellation between the Breit-Wigner trend and the width as a function of m_{VV} enhances the cross-section at high mass

$$\left(\frac{d\sigma}{dM_{VV}}\right)_{\rm ZWA} = \sigma_{H,\rm ZWA}\,\frac{M_H\Gamma_H}{\pi}\,\frac{2M_{VV}}{\left(M_{VV}^2 - M_H^2\right)^2 + (M_H\Gamma_H)^2}\,.$$

- For ZZ, ~7.6% of the total cross-section is at high mass

	Tot[pb]	$M_{ZZ} > 2\,M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

N. Kauer and G. Passarino, JHEP 08 (2012) 116



Measuring the Width

F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024)
J. Campbell et al. (arXiv:1311.3589)

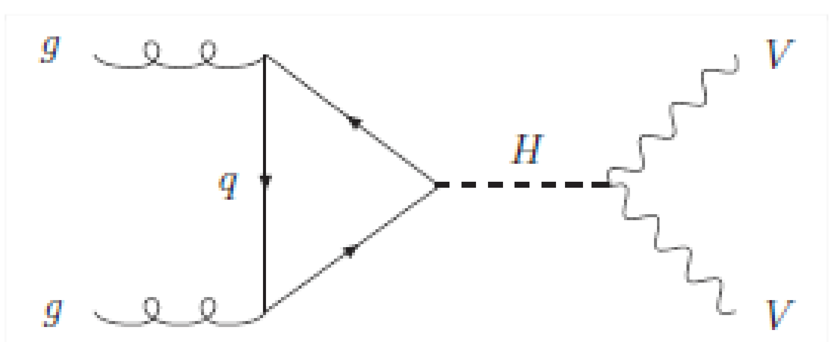
- Can be used to set a constraint on the Higgs width as follows

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2\kappa_Z^2}{r}(\sigma\cdot \text{BR})_{\text{SM}} \equiv \mu(\sigma\cdot\text{BR})_{\text{SM}}$$

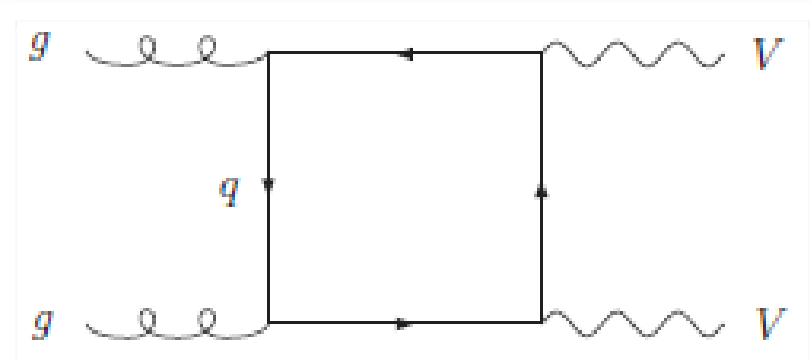
$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2 \frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

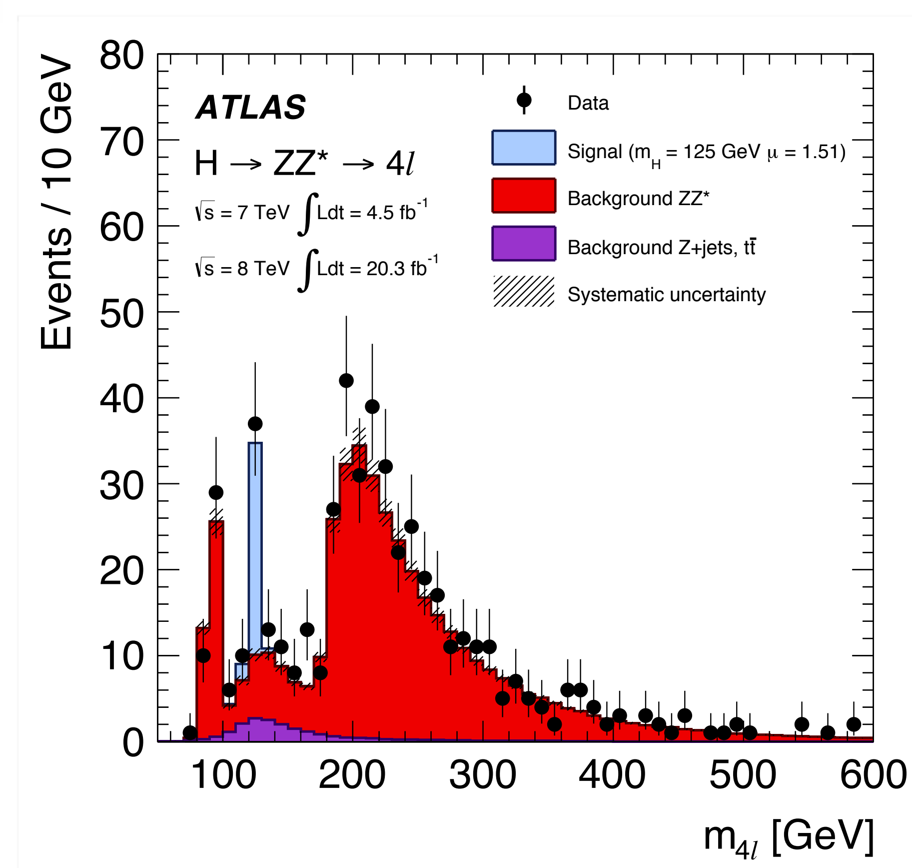
$$\kappa_g = g_{ggH}/g^{\text{SM}}_{ggH}$$
$$\kappa_Z = g_{HZZ}/g^{\text{SM}}_{HZZ},$$
$$r = \Gamma_H/\Gamma_H^{\text{SM}}$$

- Determine r by measuring ratio of off-peak to on-peak cross-section



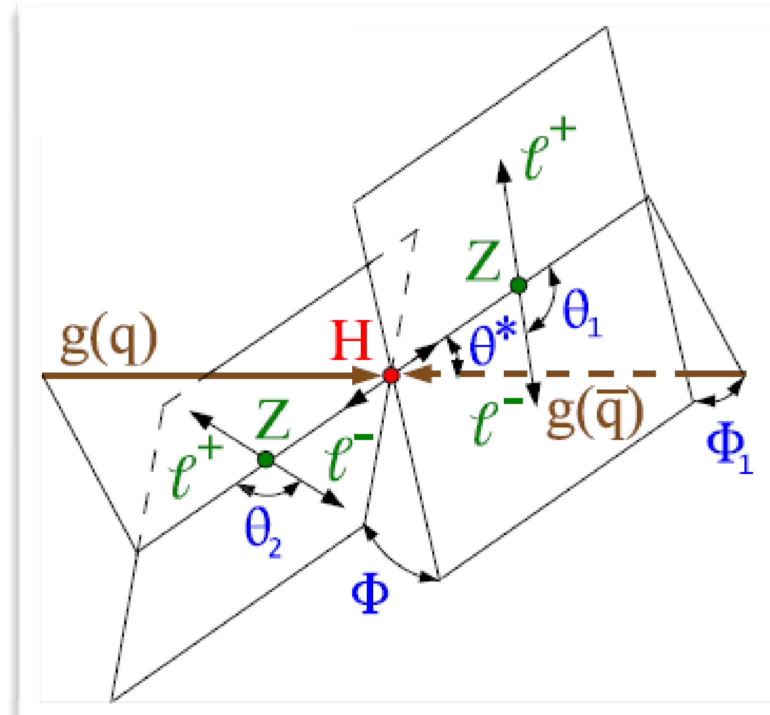
Significant interference with the SM VV background at high mass

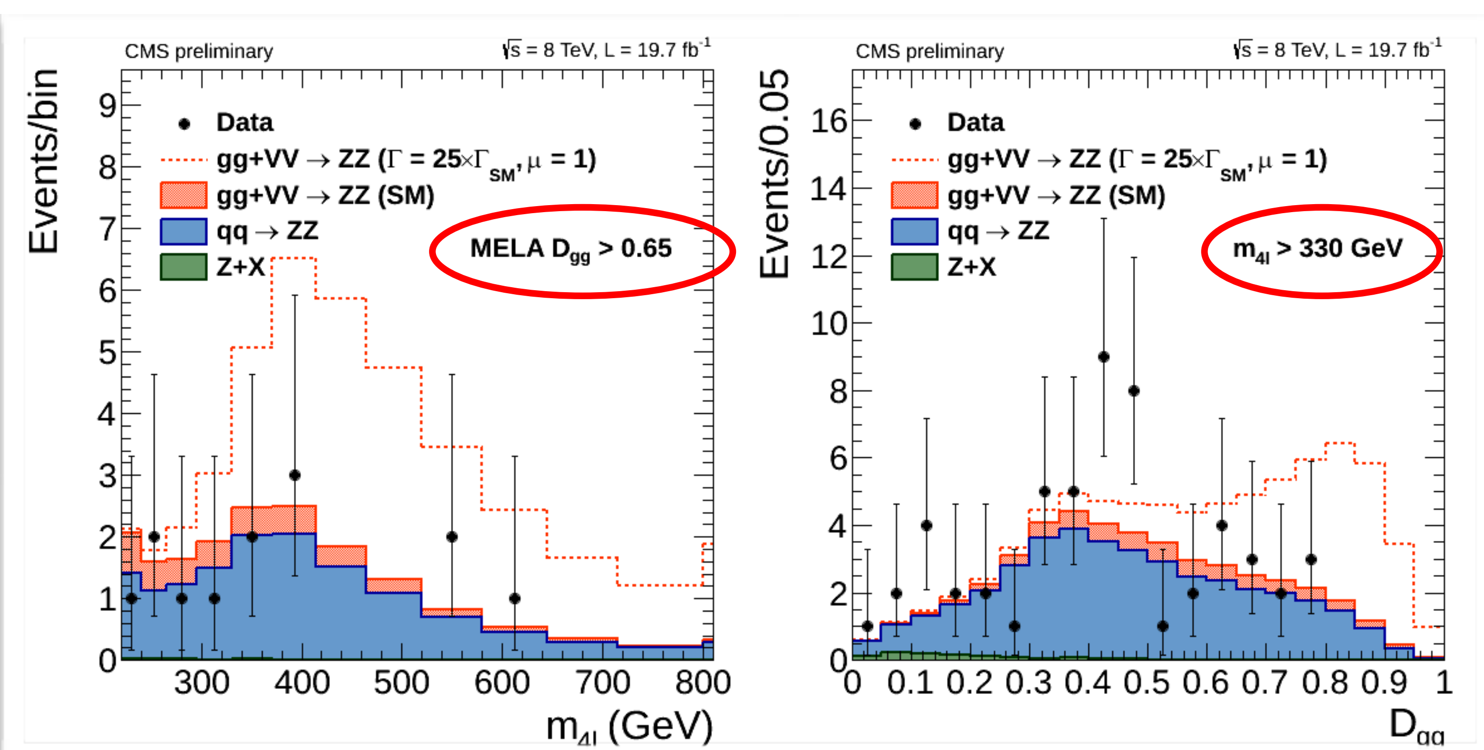


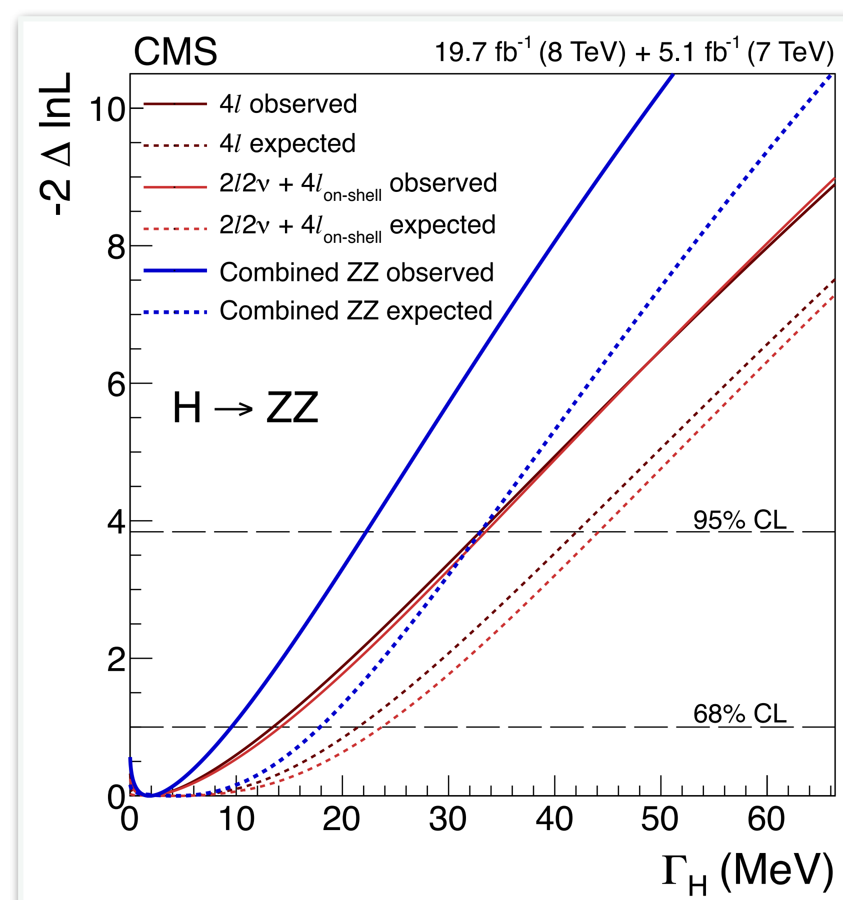


CMS measurement of the width

- First measured by CMS (Moriond 2014) using the 4l and 2l2v using a matrix element likelihood approach (MELA)
- Combined observed (expected) values
  - r < 4.2 (8.5) @ 96% CL
  - Γ < 17.4 (35.3) MeV)
- Two orders of magnitude better than direct measurements



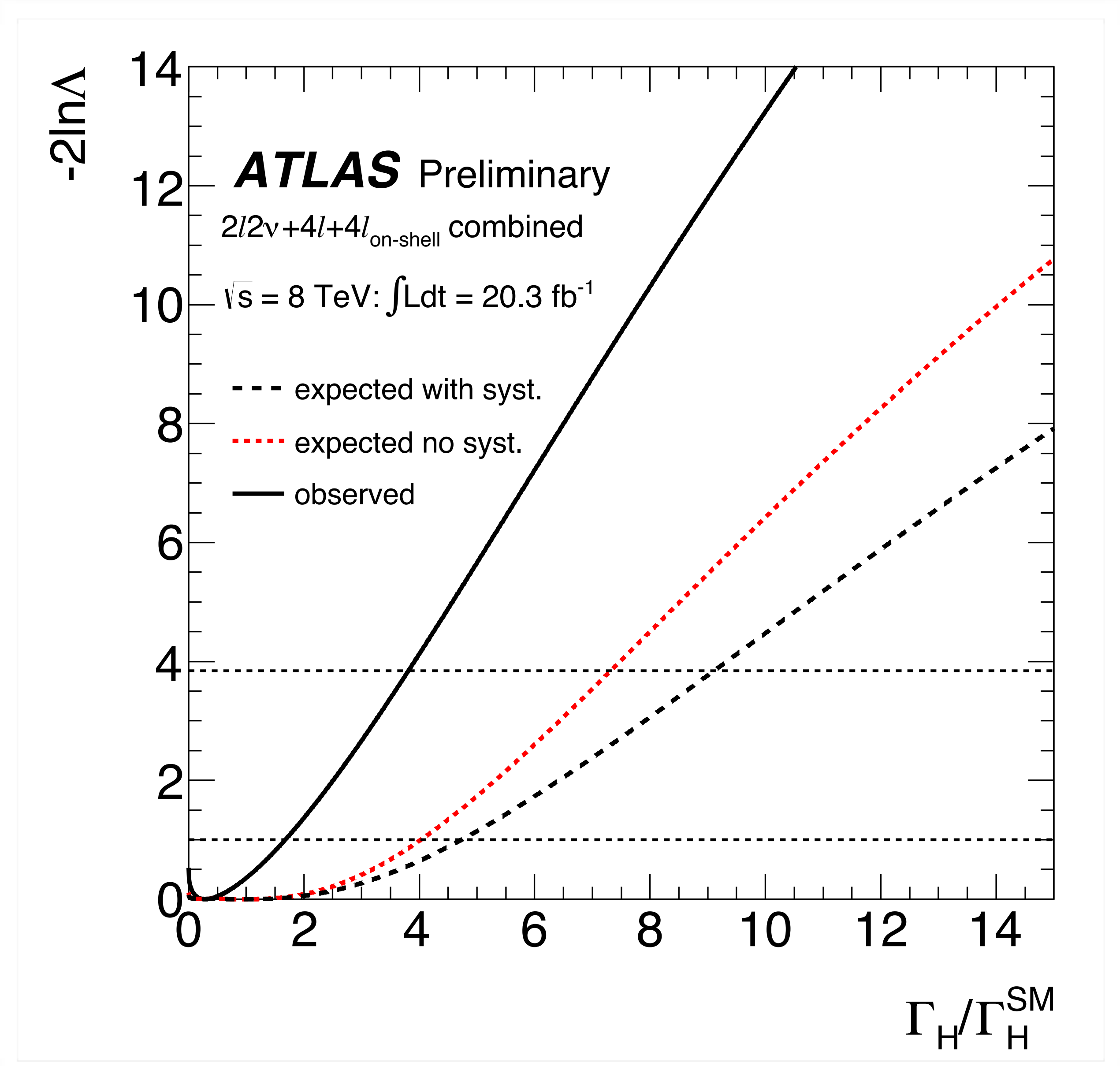


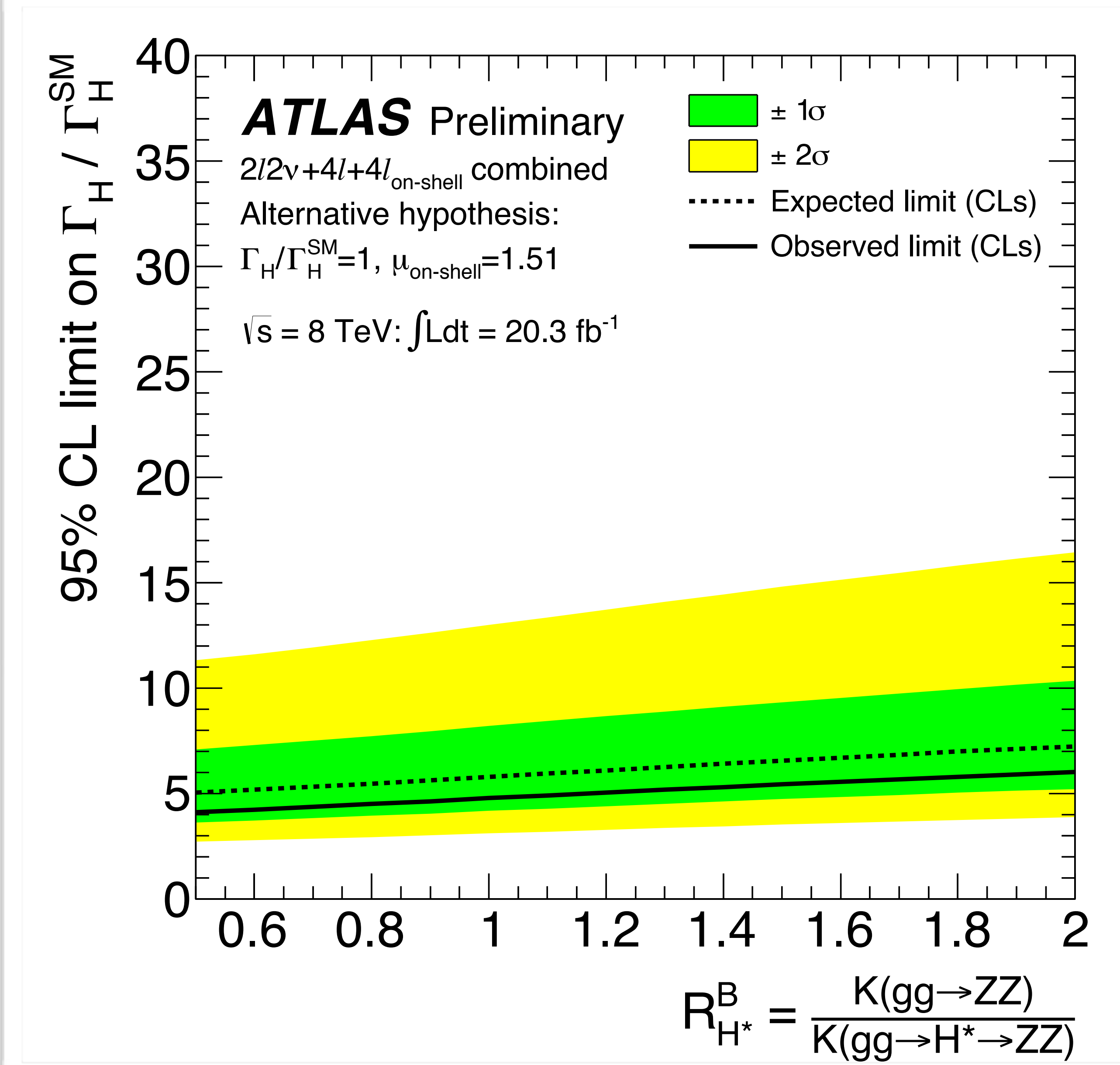


ATLAS width result

ATLAS-CONF-2014-042

- Similar result from ATLAS during 2014
- Additionally, showed the dependence on the k-factor for the ZZ background
  - No strong dependence observed





Conclusion

- The first run of the LHC has been a **fascinating** and **exciting** time
  - Privileged enough to participate in the discovery of a **new elementary particle**
- Extensive measurement program is currently ongoing to measure its properties
- The channels used for the discovery were anticipated
  - **Benchmark** channels for detector design
- This talk has focussed on some results that were **not anticipated**
  - **bb, ttH, width**
- Some of these were even **thought to be impossible**
- Small message for the future: **always learn from the past, but don't let the past constrain you**
- Clever ideas and innovation can make the **impossible possible**