HIGGS BOSONS IN THE STANDARD MODEL AND BEYOND

Greg Landsberg
Brown University

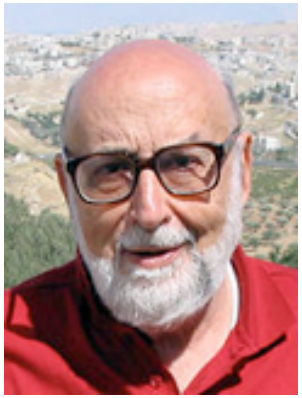
EPS-HEP 2013

Stockholm

July 22, 2013

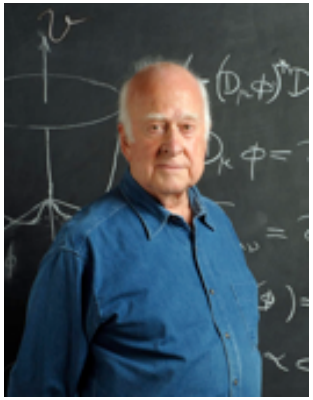
Dedication

To the great minds who made a theoretical breakthrough half-a-century ago, which took so long to confirm experimentally, and Ad Memoriam Robert Brout (1928-2011)



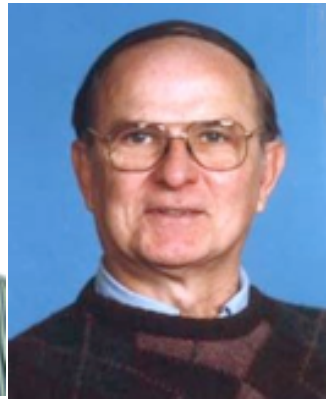
François Englert

Robert Brout



Peter Higgs

Gerald Guralnik



Carl Hagen

Tom Kibble

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

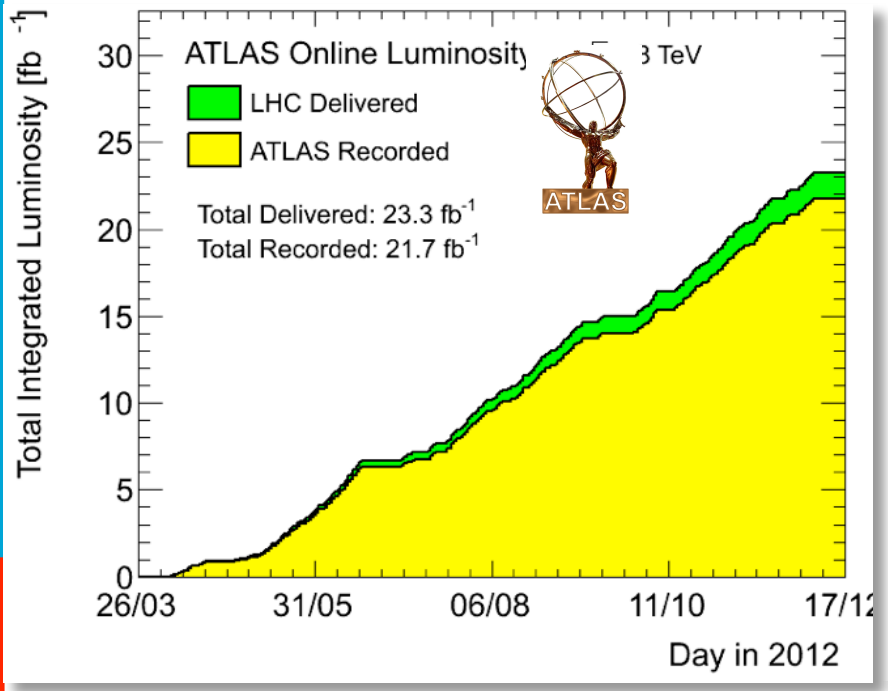
Outline

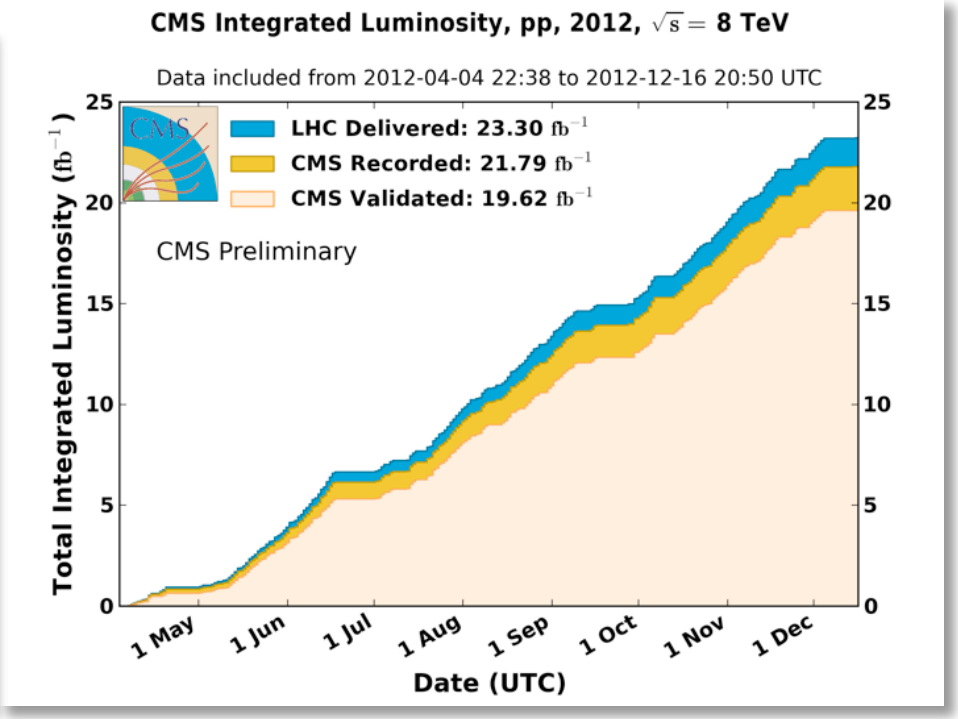
- The Higgs boson playground
- Happy birthday, Mr. Higgs!
- Higgs boson production and decay
- Experimental results:
  - Lucid Higgs boson
  - Visible Higgs boson
  - Not-yet-visible Higgs boson
  - Invisible Higgs boson
  - Invincible Higgs boson
- Conclusions

The Higgs Playground

High-Quality, Plentiful Data

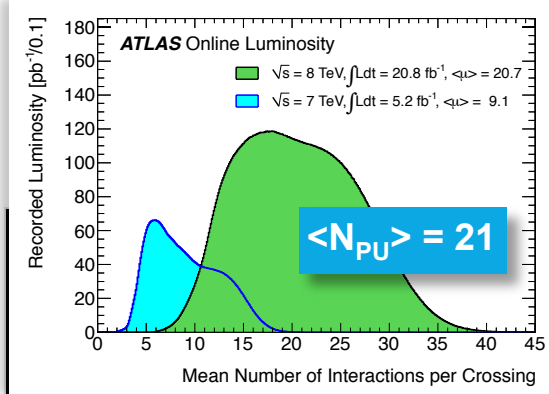
- Excellent machine and detector performance resulted in large amount of data with very high quality: ~95% of delivered data are recorded, and ~90% of those are certified and used in physics publications!
  - We publish based on ~85% of all the bunch collisions that took place at the LHC!

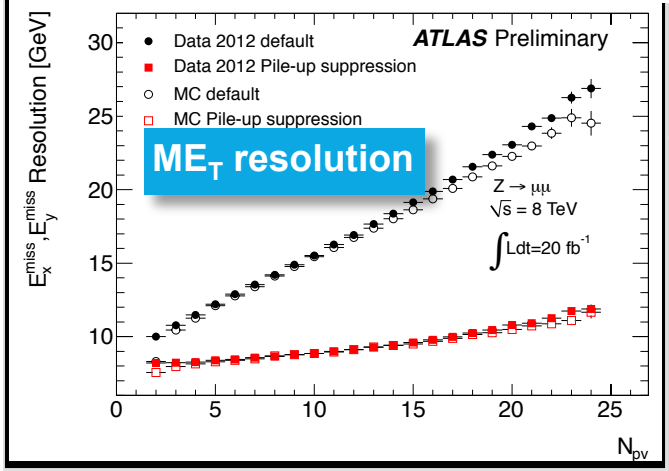


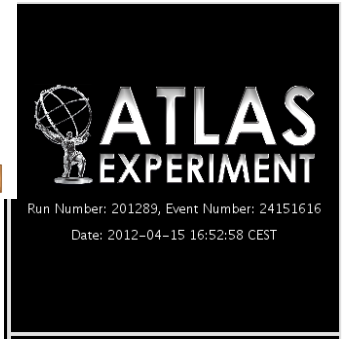


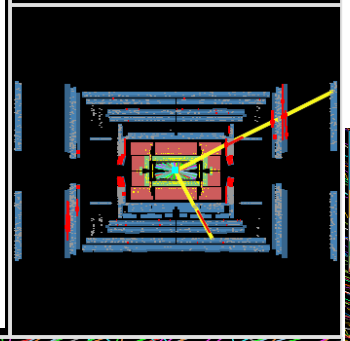
Successful Pileup Mitigation

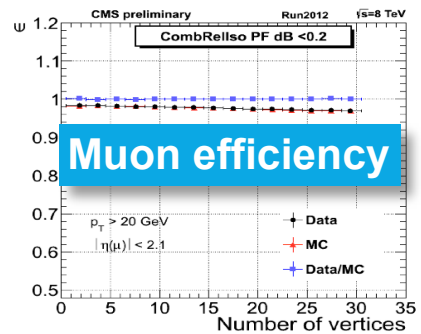
LHC already reached nominal pileup rate; experiments cope well!

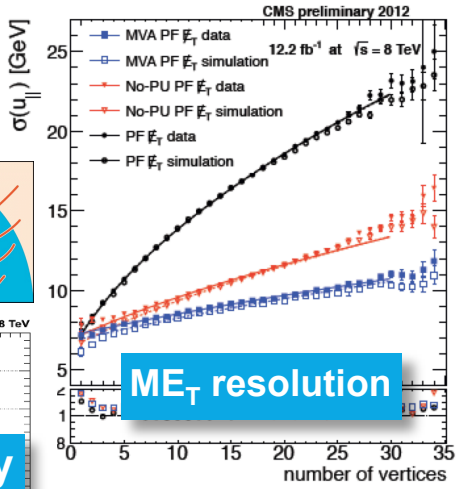


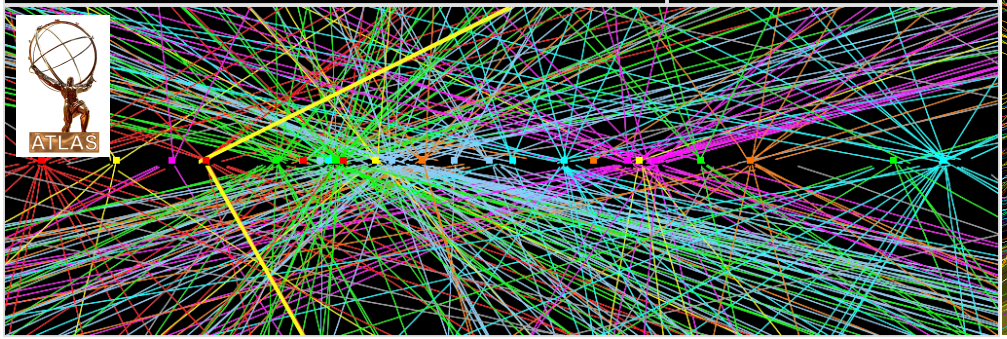


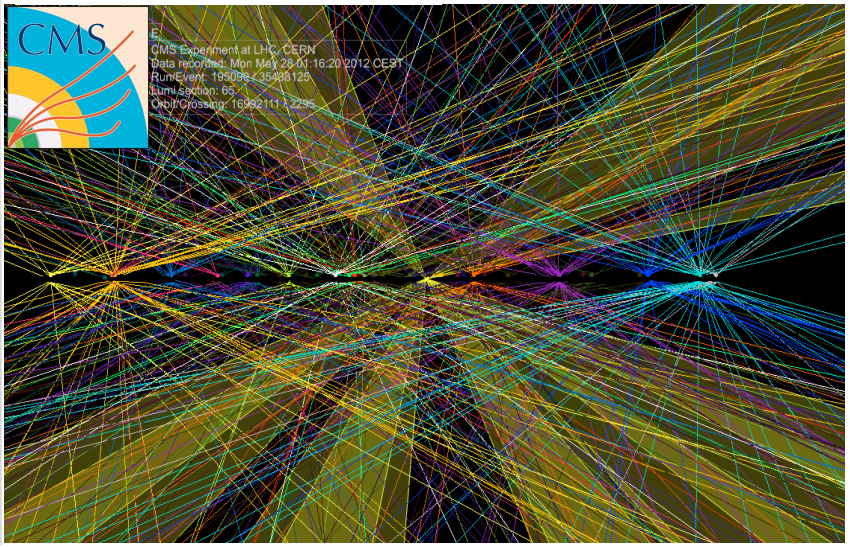








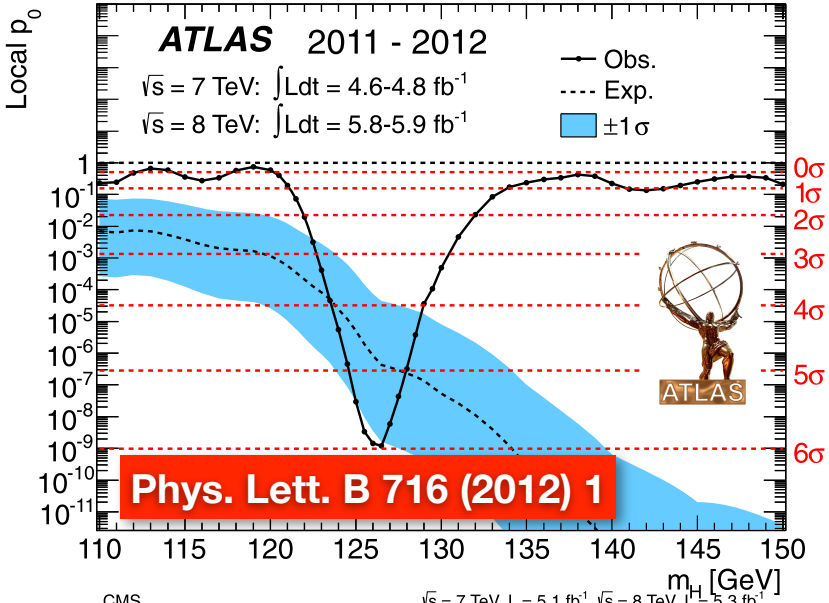


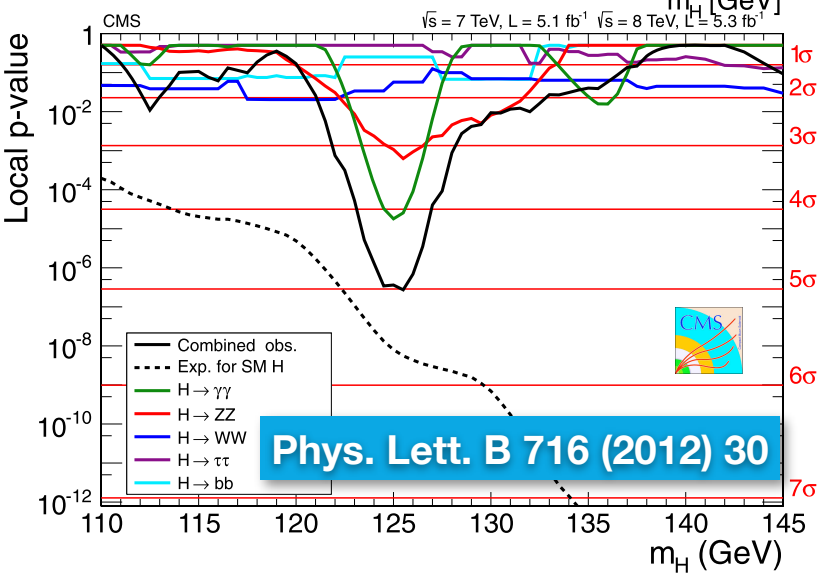


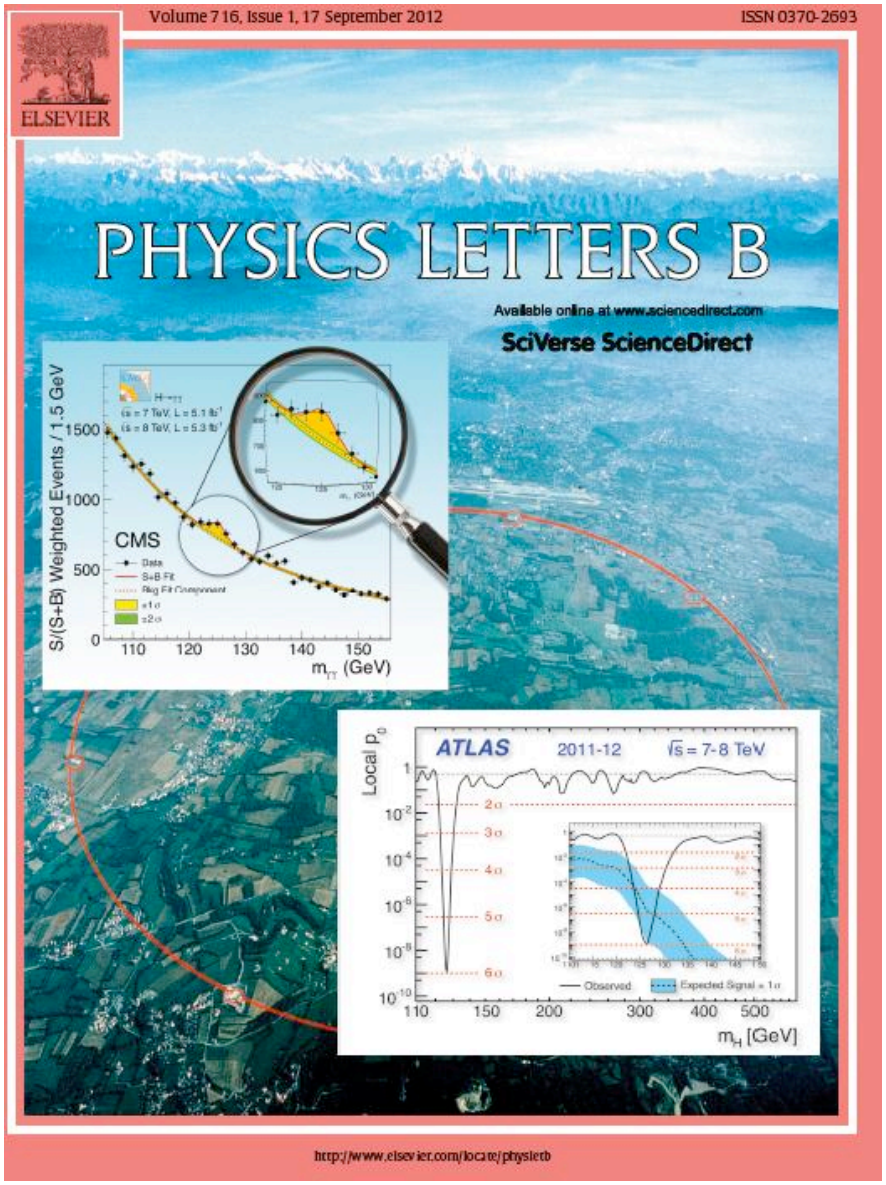
The Higgs Story

4th of July Fireworks

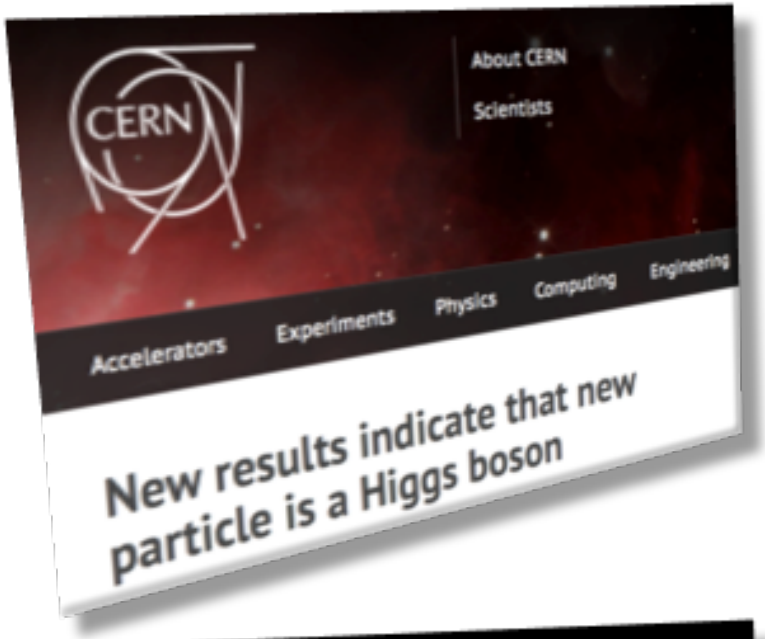
A New Boson Discovery





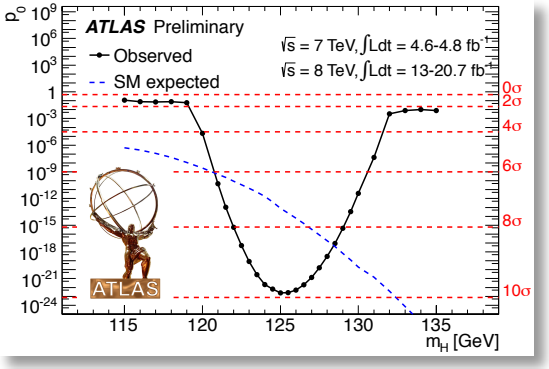


Moriond 2013 - What a Week!



Happy Birthday, Mr. Higgs

- It's been a great year for the Higgses (both Peter and the Boson)!
- Long journey in one year:
  - Established the existence of new particle beyond any doubts (LHC+Tevatron)
  - Mass measured to 0.50% precision, i.e. better than top (or any other) quark mass! (ATLAS+CMS)
  - It is a 0^{++} boson responsible for EWSB, as evident from its relative couplings to W/Z vs. γ (ATLAS+CMS)
  - Established couplings to the third-generation fermions (CMS+Tevatron)
  - Nearly excluded negative couplings to fermions (CMS)
  - Big 5 → big 6: thanks to ttH (bb, $\gamma\gamma$, and $\tau\tau$)
- See more in Fabio Cerutti's talk (next)



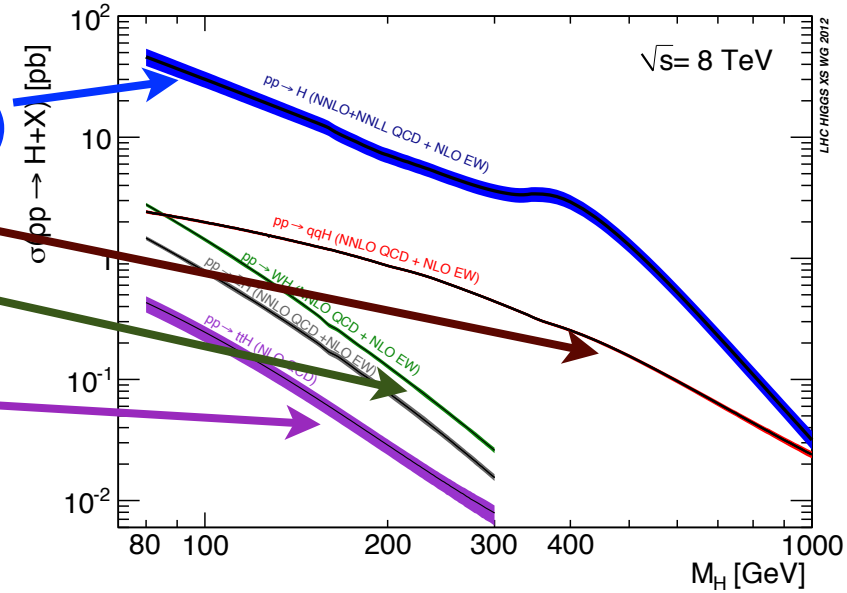
CMS PAS HIG-13-005

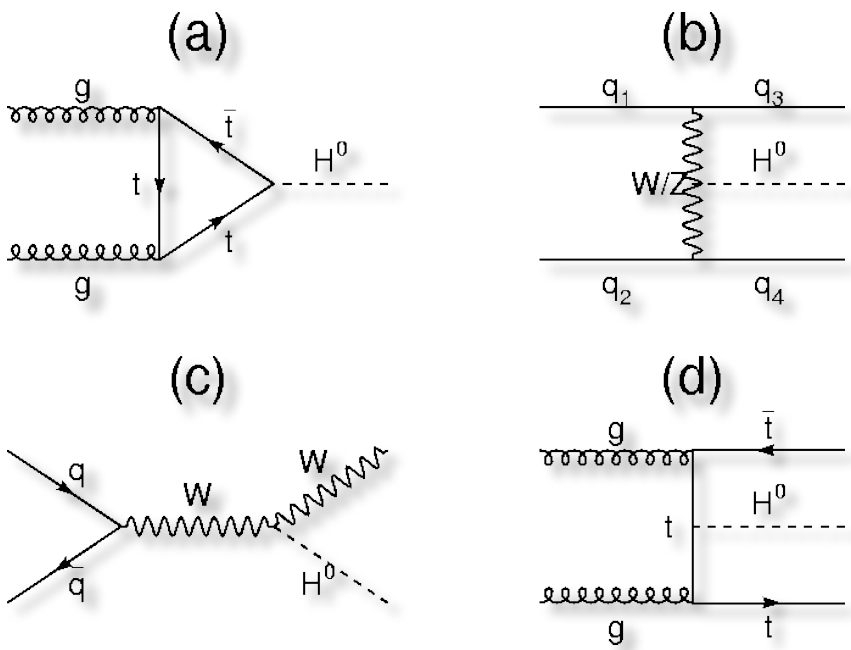
Combination	Significance (m_H = 125.7 GeV) Expected (pre-fit)	Expected (post-fit)	Observed
H→ZZ	7.1 σ	7.1 σ	6.7 σ
H→γγ	4.2 σ	3.9 σ	3.2 σ
H→WW	5.6 σ	5.3 σ	3.9 σ
H→bb	2.1 σ	2.2 σ	2.0 σ
H→ττ	2.7 σ	2.6 σ	2.8 σ
H→ττ and H→bb	3.5 σ	3.4 σ	3.4 σ

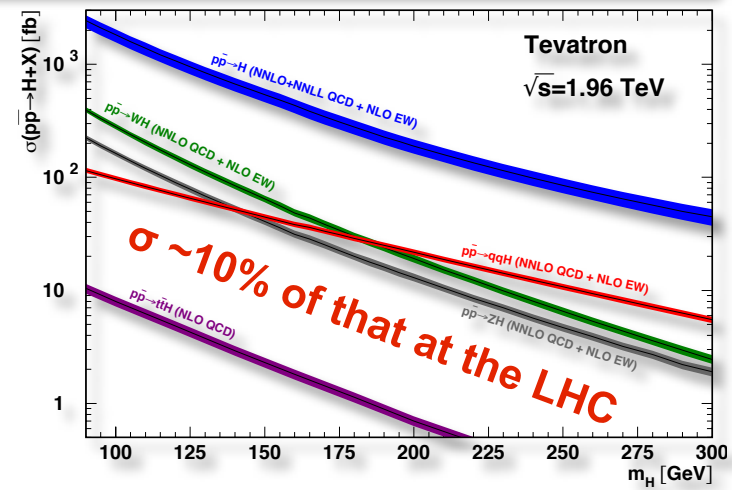
Higgs: Production and Decay

Higgs Boson Production

- The following four mechanisms can be tested at the LHC and the Tevatron:
  - (a) gluon fusion (19 pb @ 8 TeV)
  - (b) VBF (WW or ZZ fusion)
  - (c) Associated production (VH)
  - (d) ttH production



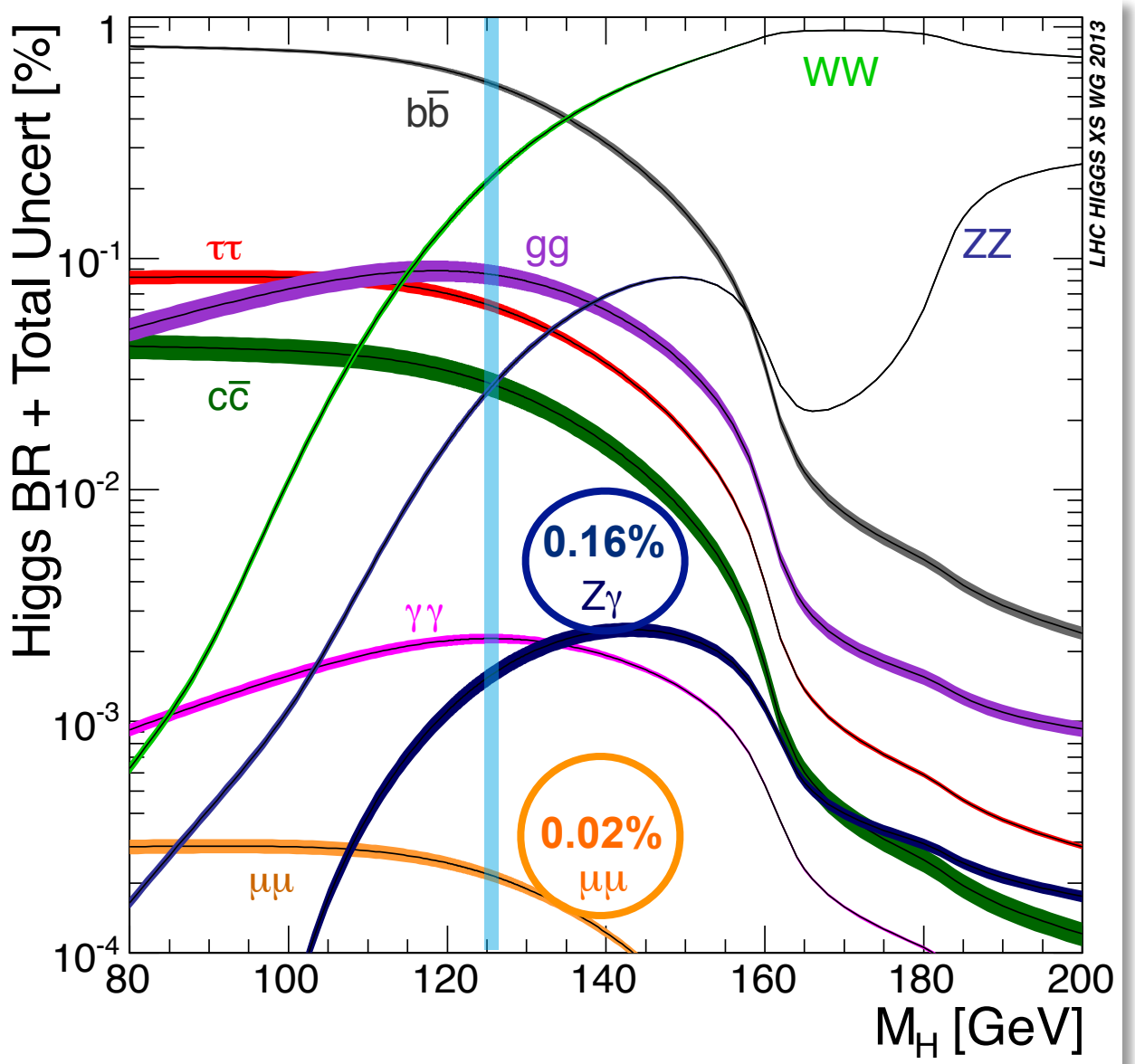


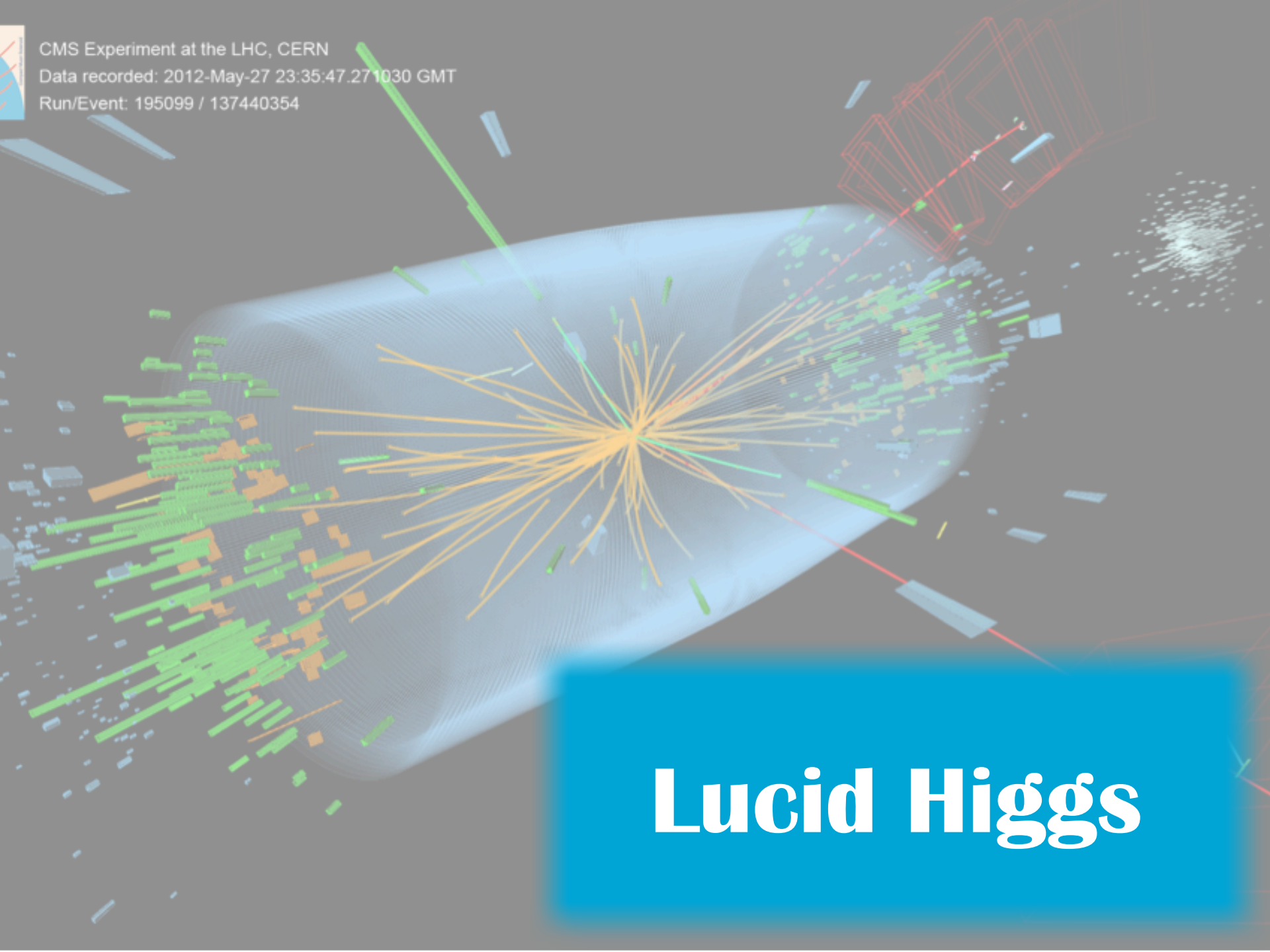


Baglio, Djouadi
JHEP 10 (2010) 064

Higgs Boson Decays

- The Nature has chosen the Higgs boson mass (~125.5 GeV) maximally rich, but quite challenging experimentally
- The "big five":
  - H(bb) - 57%
  - H(WW) - 22%
  - H(ττ) - 6.2%
  - H(ZZ) - 2.8%
  - H(γγ) - 0.23%



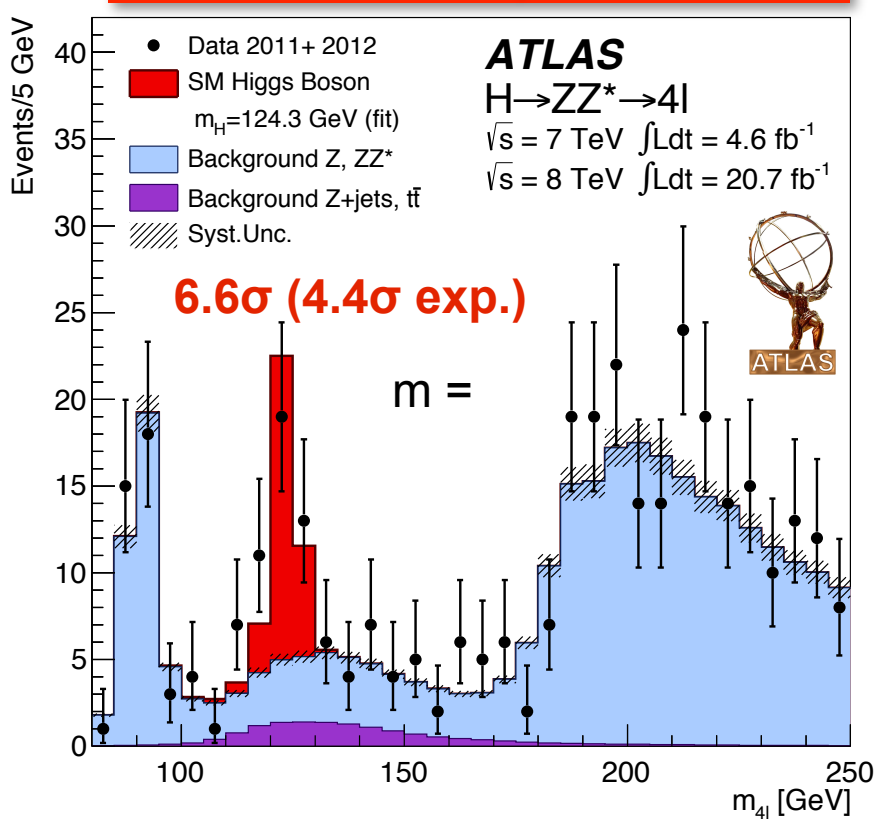

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

Lucid Higgs

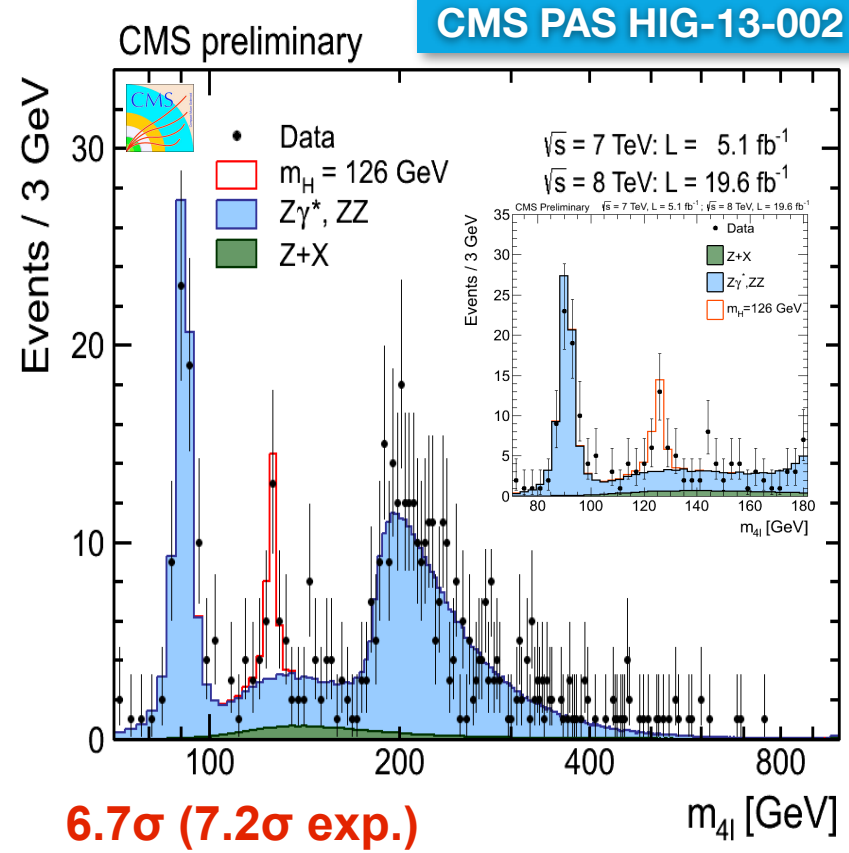
H(ZZ→4l)

- Most sensitive, high-resolution channel for a 125 GeV Higgs!
  - ATLAS: Cut-in-categories, FSR accounting, untagged + VBF+ VH
  - CMS: MELA (angular analysis), FSR recovery, untagged + VBF

ATLAS Collaboration, arXiv:1307.1427



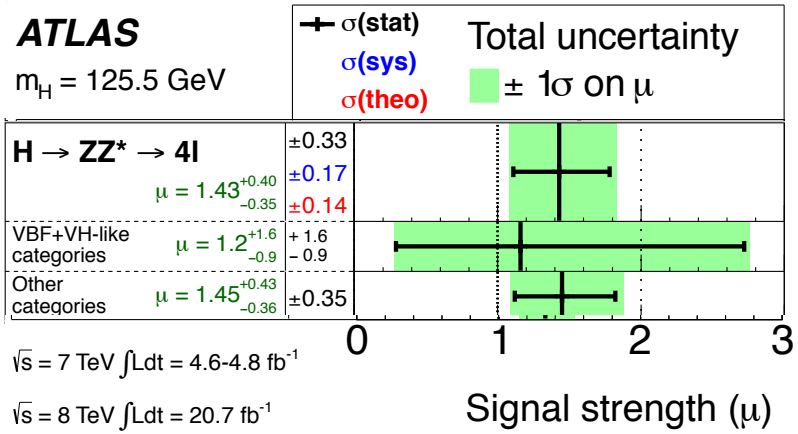
CMS PAS HIG-13-002



H(ZZ→4l) Results

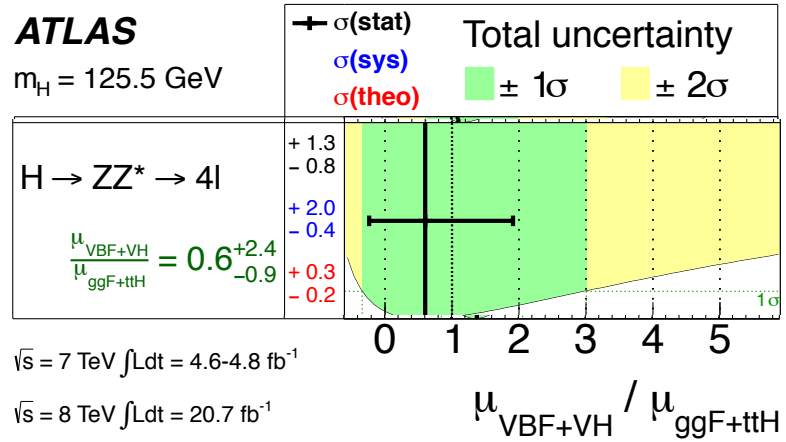
ATLAS Collaboration, arXiv:1307.1427

$m_H = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV



$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6-4.8 fb^{-1}

$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}



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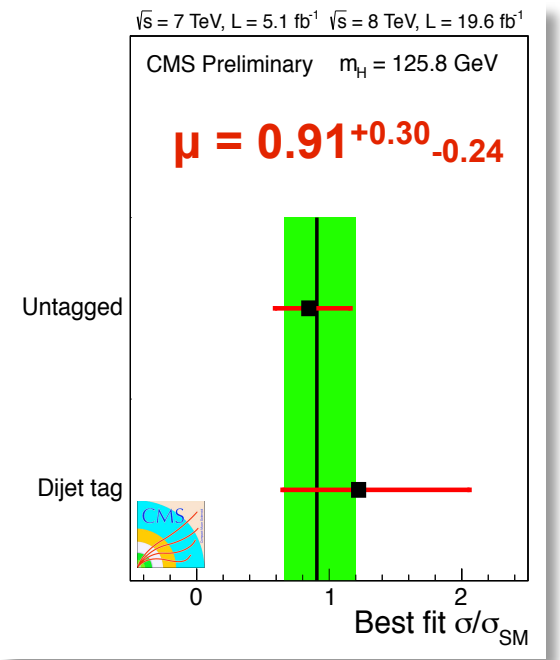
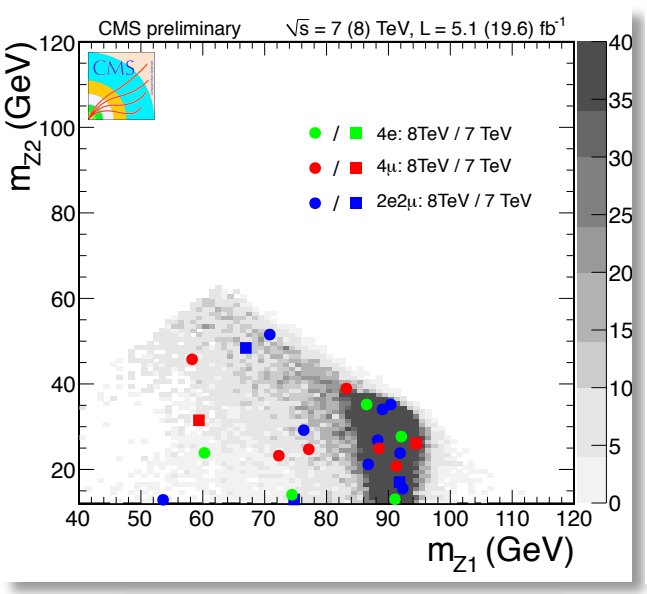
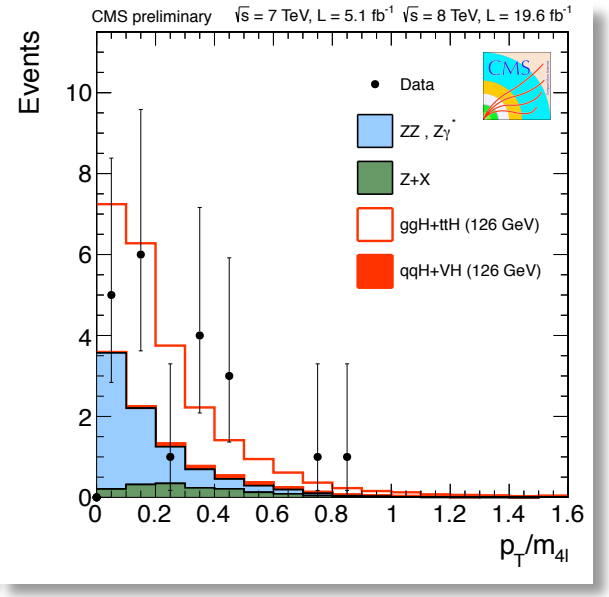






CMS PAS HIG-13-002

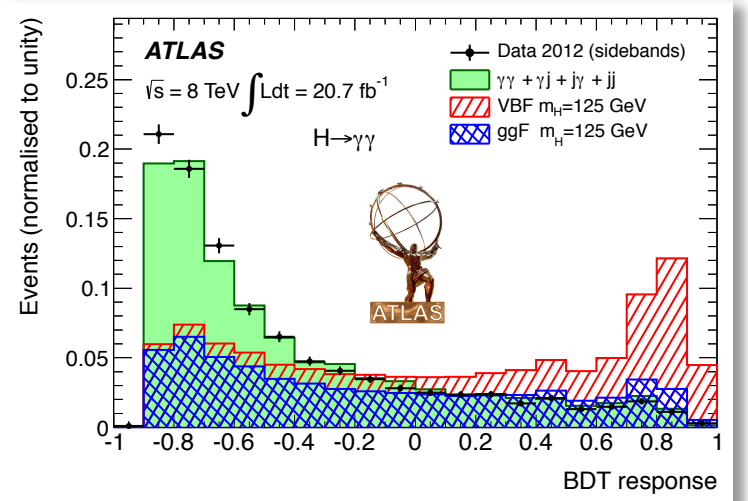
$m_H = 125.8 \pm 0.5 \pm 0.2$ GeV

Seeing Light Higgs w/ Light

- One of the most challenging and sensitive channels:
  - Small branching fraction (0.23%), compensated by large cross section
  - Large QCD background from direct diphotons, and direct photons with $j \rightarrow \gamma$
    - Thorough optimization; background estimated from sidebands
  - Ambiguity with primary vertex selection
    - ATLAS - photon pointing
    - CMS - dedicated MVA technique
  - Analysis is done in categories:
    - ATLAS: untagged (9 sub-categories), lepton-tag (WH/ZH), ME_T tag ($Z(\nu\nu)H$, 8 TeV only), VBF (1 or 2 categories)
    - CMS: untagged (4 sub-categories), lepton-tag, ME_T tag, VBF (1 or 2 categories); also a cut-in-categories cross-check analysis
  - Takes advantage of higher boost of the Higgs boson with respect to background (gluons radiate more than quarks!)

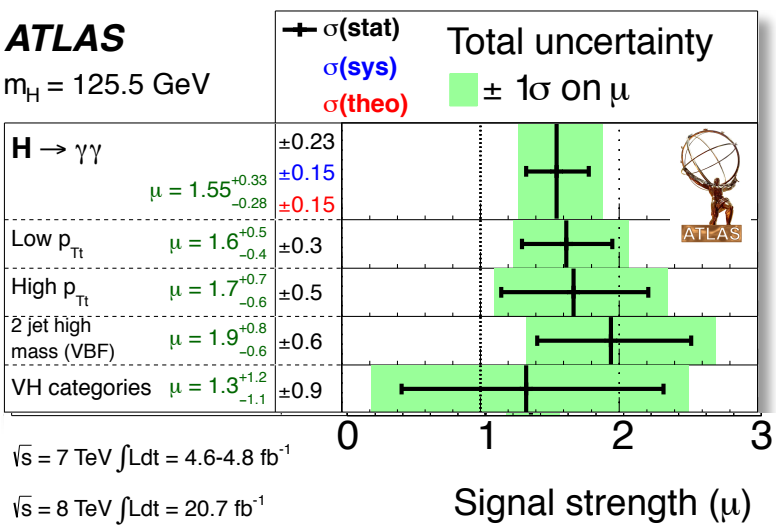
ATLAS H(γγ) Results

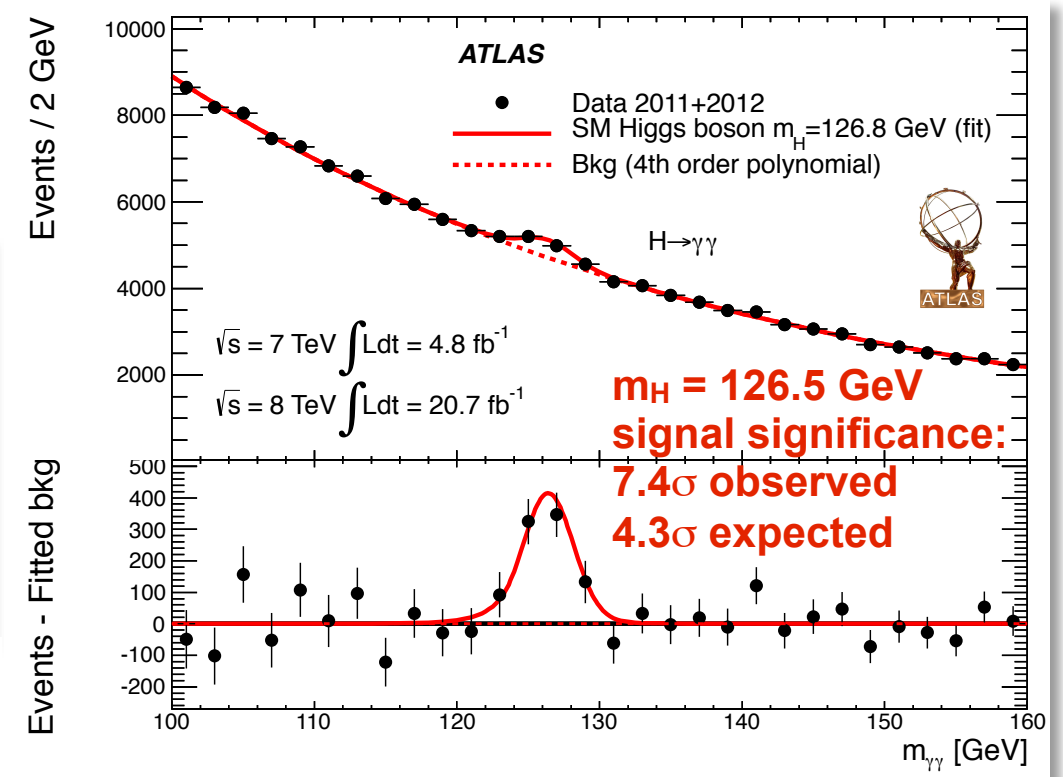
ATLAS Collaboration, arXiv:1307.1427



m_H = 126.8 ± 0.2 ± 0.7 GeV

Category	N_D	N_B	N_S	ggF	VBF	WH	ZH	ttH
Untagged	14248	13582	350	320	19	7.0	4.2	1.0
Loose high-mass two-jet	41	28	5.0	2.3	2.7	< 0.1	< 0.1	< 0.1
Tight high-mass two-jet	23	13	7.7	1.8	5.9	< 0.1	< 0.1	< 0.1
Low-mass two-jet	19	21	3.1	1.5	< 0.1	0.92	0.54	< 0.1
E_T^{miss} significance	8	4	1.2	< 0.1	< 0.1	0.43	0.57	0.14
Lepton	20	12	2.7	< 0.1	< 0.1	1.7	0.41	0.50
All categories (inclusive)	13931	13205	370	330	27	10	5.8	1.7

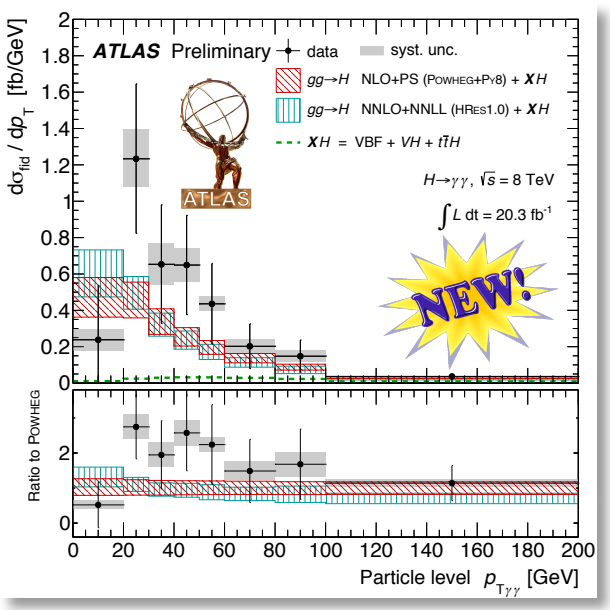


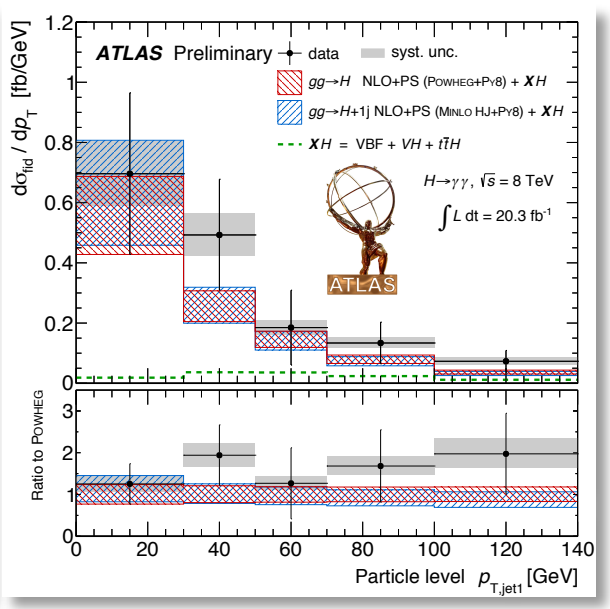


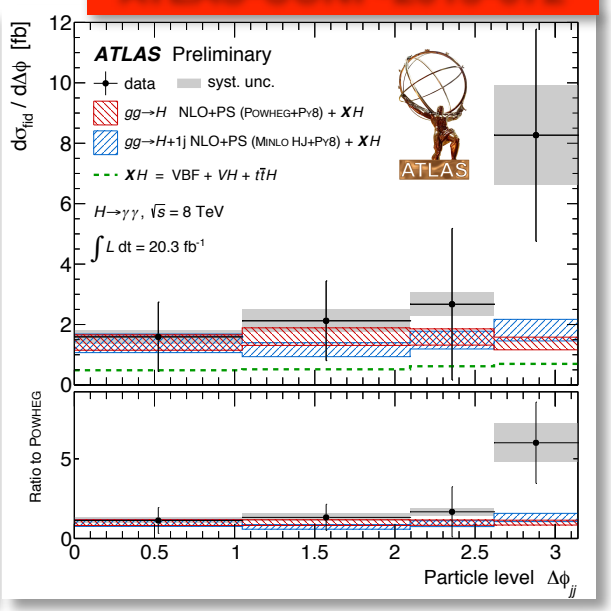
Differential Measurements

- "One event - discovery; two events - differential cross sections; three events - partial-wave analysis"
- Given a strong signal, ATLAS proceeded with determining differential distributions for H(γγ)
  - Similar selection, detector unfolding
  - Observed somewhat harder p_T spectrum than predicted at NLO (POWHEG, MINLO) or NNLO +NNLL (HRes)
  - No deviations seen in the leading jet spectrum, but a slight excess in the back-to-back dijets is seen
- N.B.: important to understand whether effect is real: we assume SM production in the search and if the p_T spectrum is harder, the results may be biased

ATLAS-CONF-2013-072





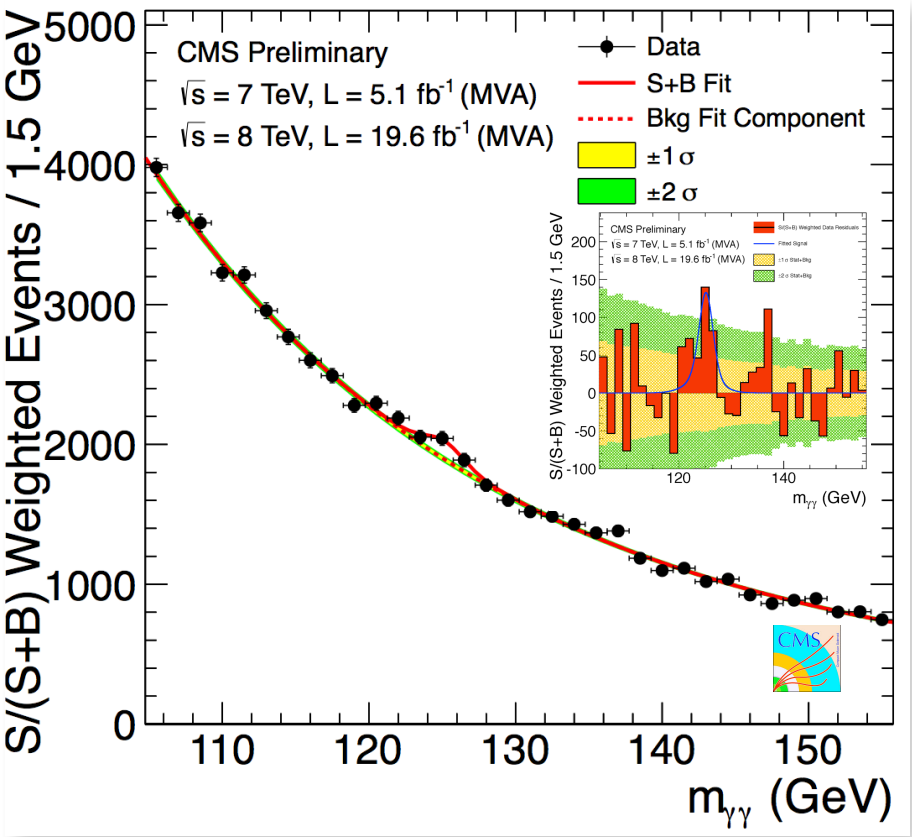


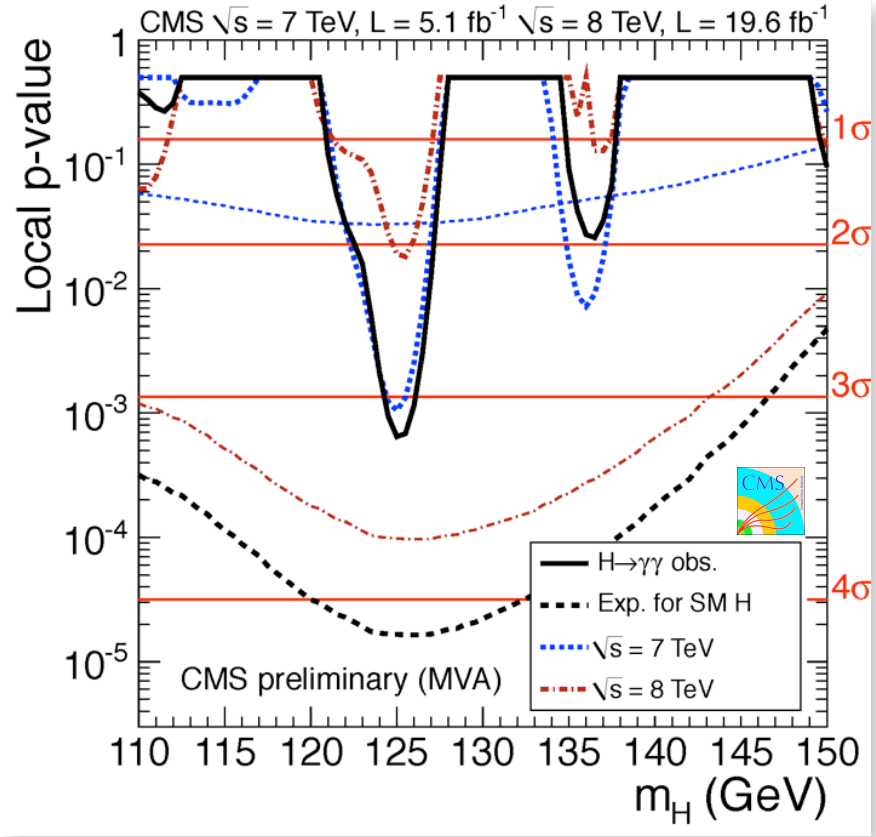
CMS H(γγ) Results

- Main analysis: MVA; cross-check: cut-in-categories (CiC)
  - Significances:
    - MVA: 3.2σ (4.2σ expected)
    - CiC: 3.9σ (3.5σ expected)
  - Mass: **125.4 ± 0.8 GeV**

μ-values:

	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$





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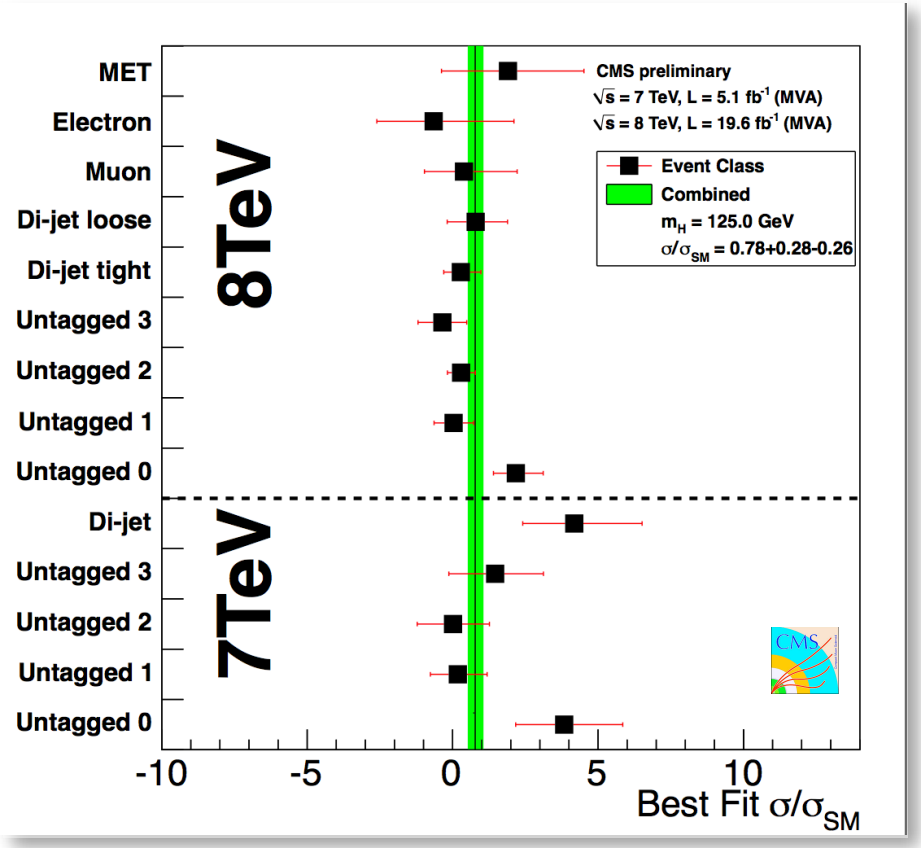
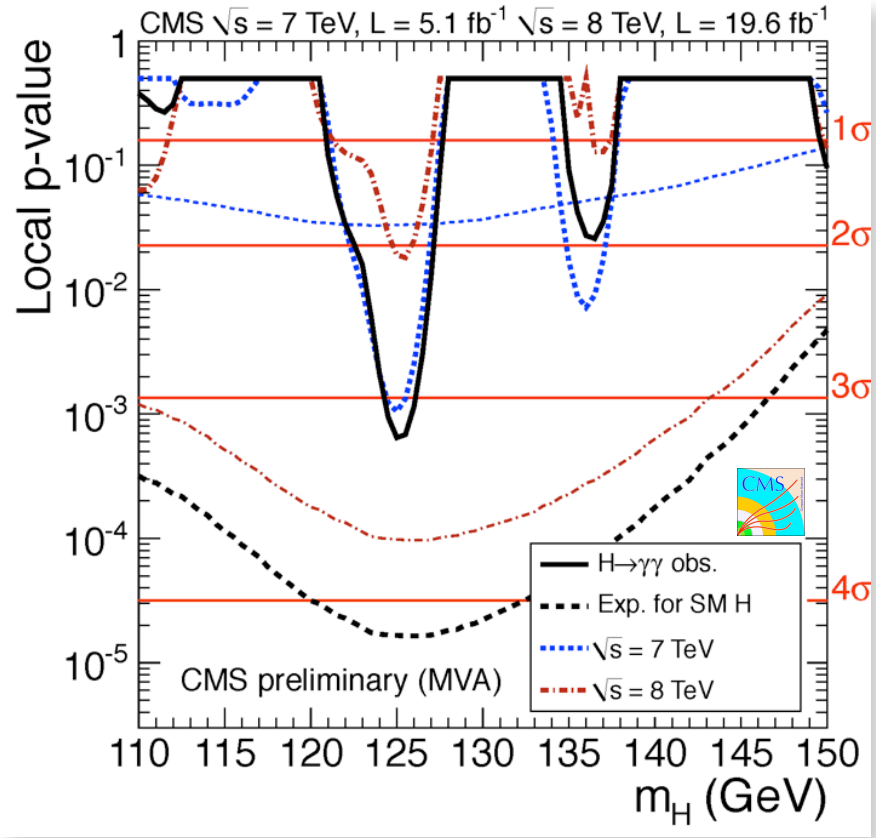
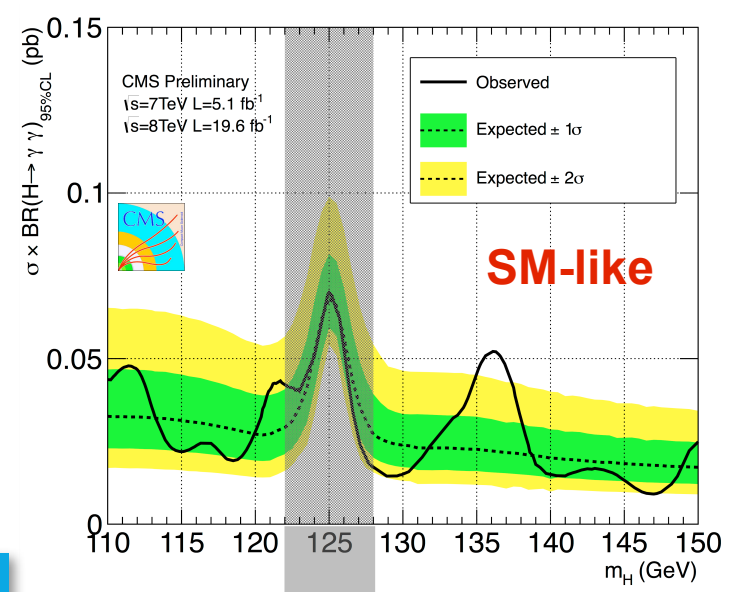




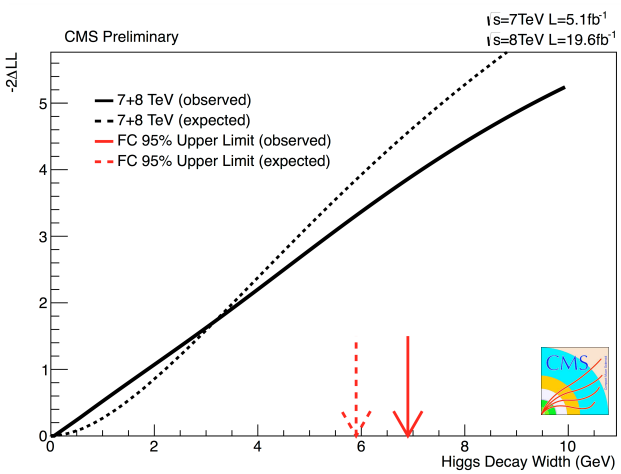
Angular/Width Analysis

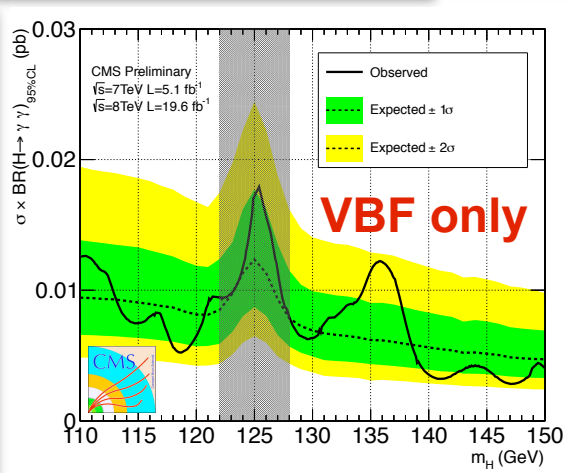
- Use CiC/MVA H(γγ) analyses to:
  - Look for additional Higgs bosons (with SM-like couplings; in gg fusion only; and VBF only)
  - Look for nearly mass-degenerate additional Higgs bosons
  - Set a limit on the Higgs boson width
  - Study the Higgs boson spin-parity (see Fabio's talk)
- $\Gamma_H < 6.9$ (5.9 exp.) GeV - first direct limit on the width

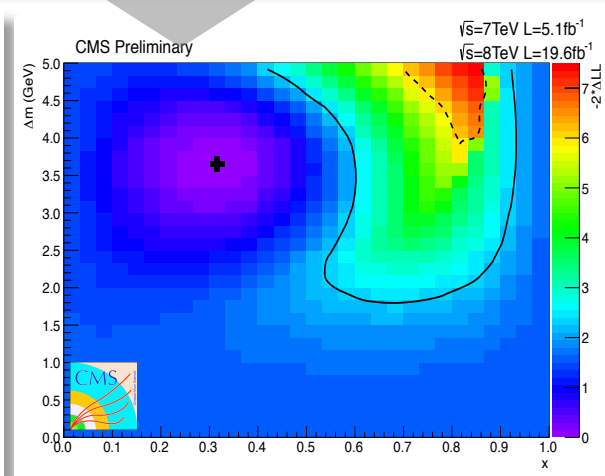
$(\sigma \times Br)_{SM}$ = 0.044 pb @ 8 TeV



CMS PAS HIG-13-016

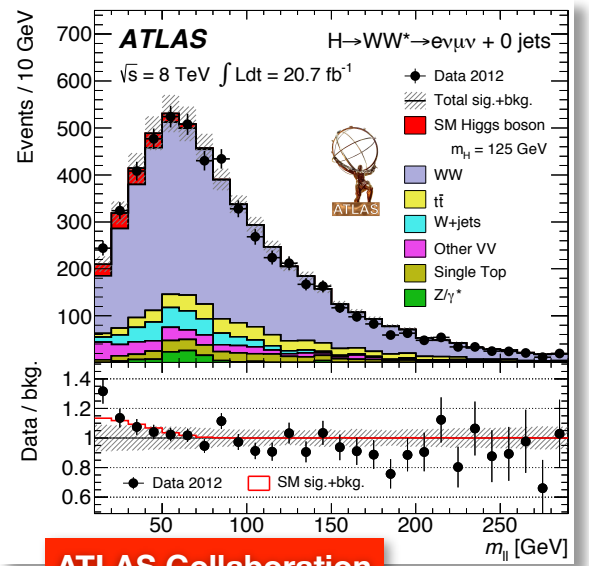




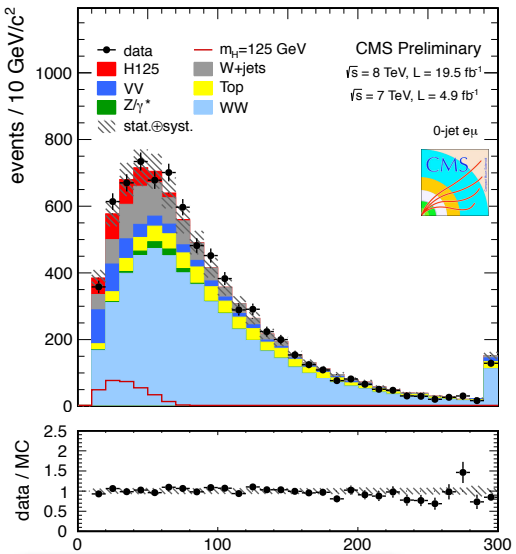


H(WW→lνlν)

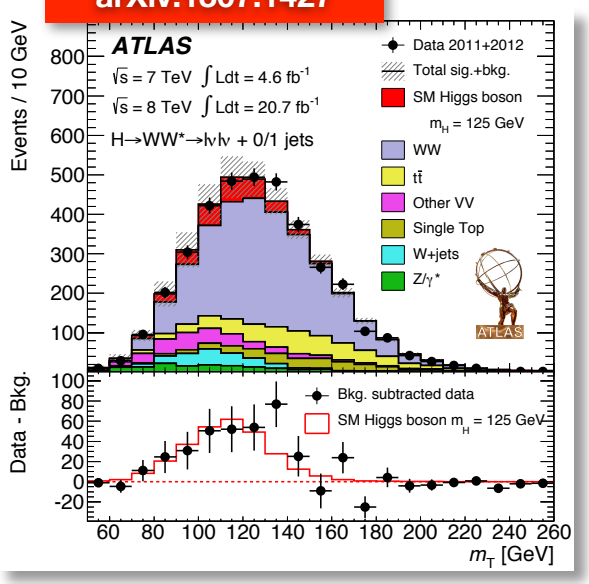
- High-yield, low-resolution channel
  - Most discriminating variables: M_{ll} and M_T (dilepton transverse mass)
  - Search done in 0-, 1-, and 2-jet categories; in the ee, eμ, and μμ channels
- ATLAS: fit to the M_T distribution
- CMS: 2D analysis in M_{ll} vs. M_T for the eμ channel and cut-based analysis for the same-flavor channels (also as a cross-check in eμ)

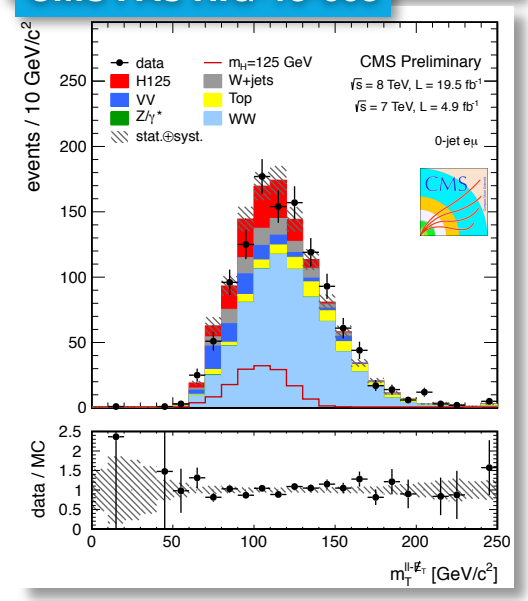


ATLAS Collaboration arXiv:1307.1427



CMS PAS HIG-13-003

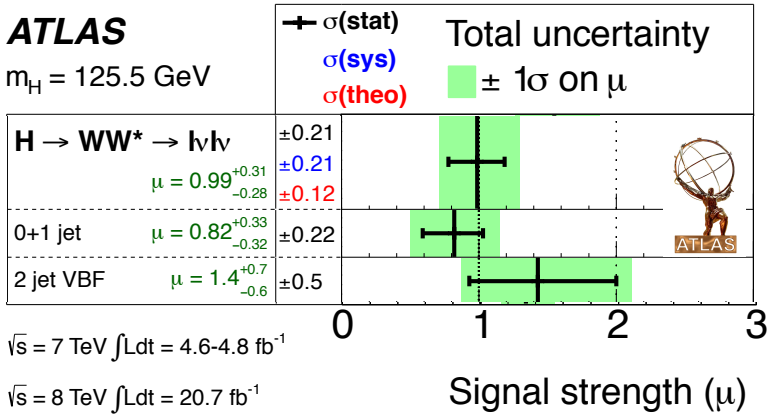


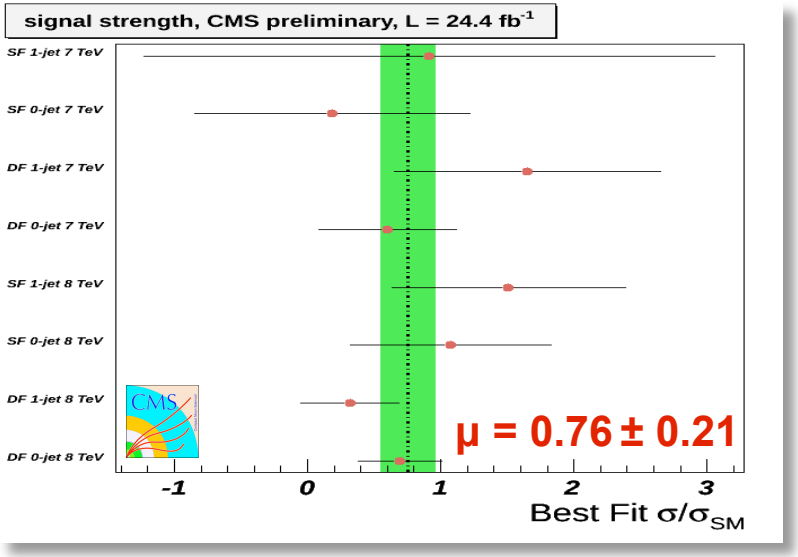


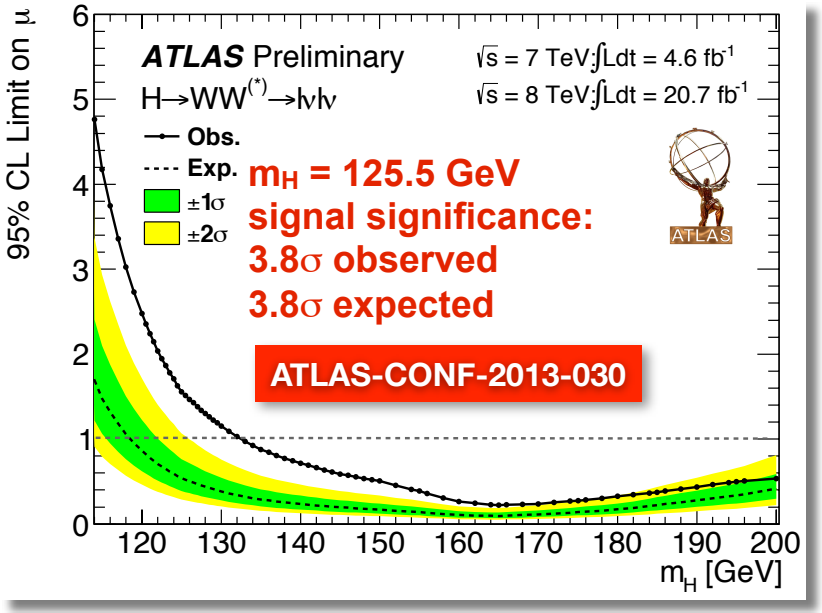
H(WW→lνlν) Results

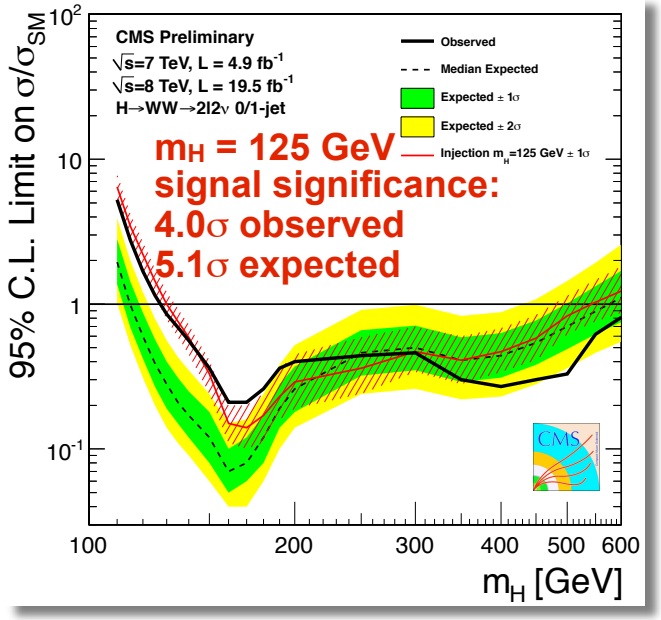
- Significant excess is observed:

ATLAS Collaboration arXiv:1307.1427







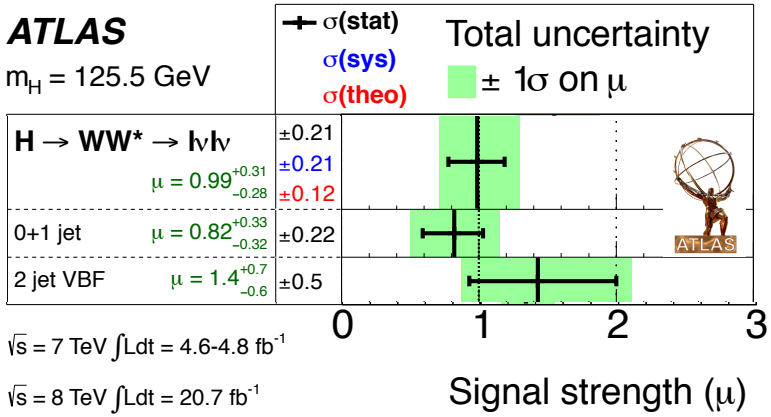


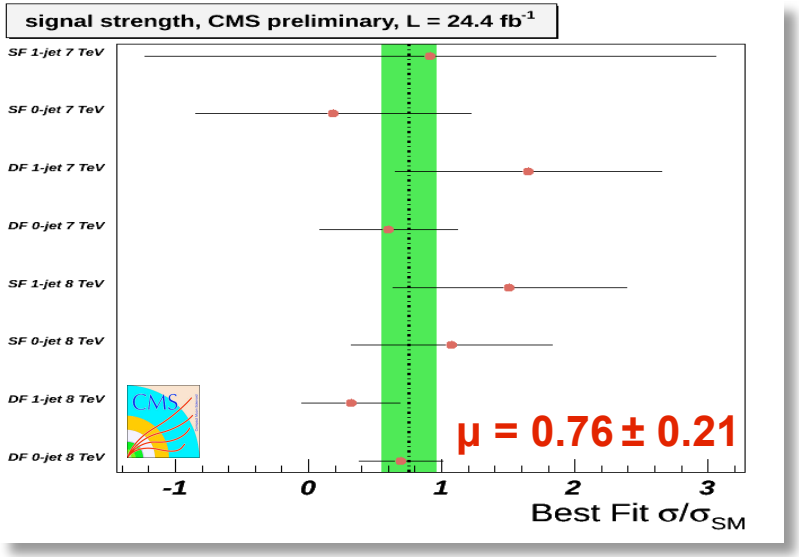
CMS PAS HIG-13-003

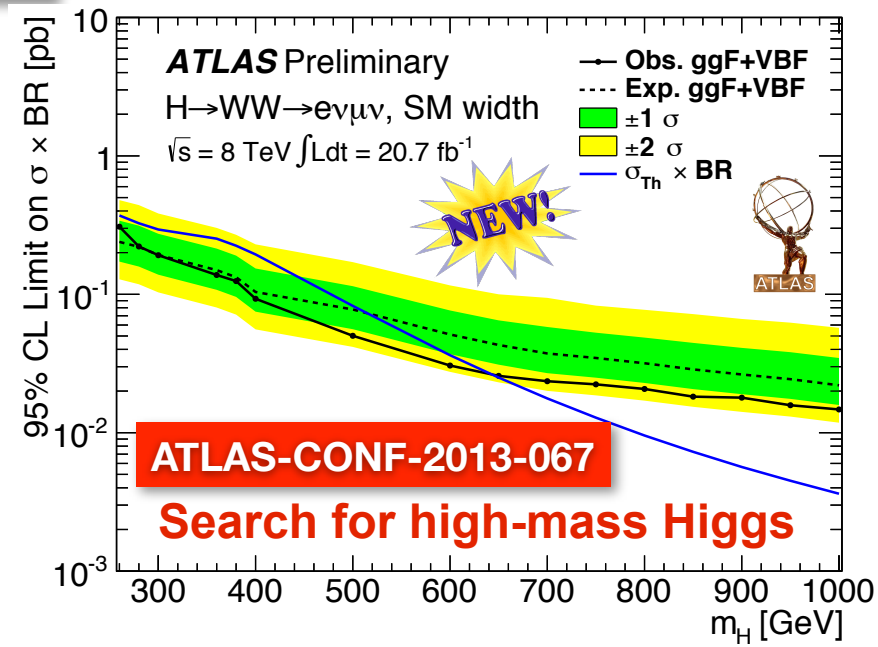
H(WW→lνlν) Results

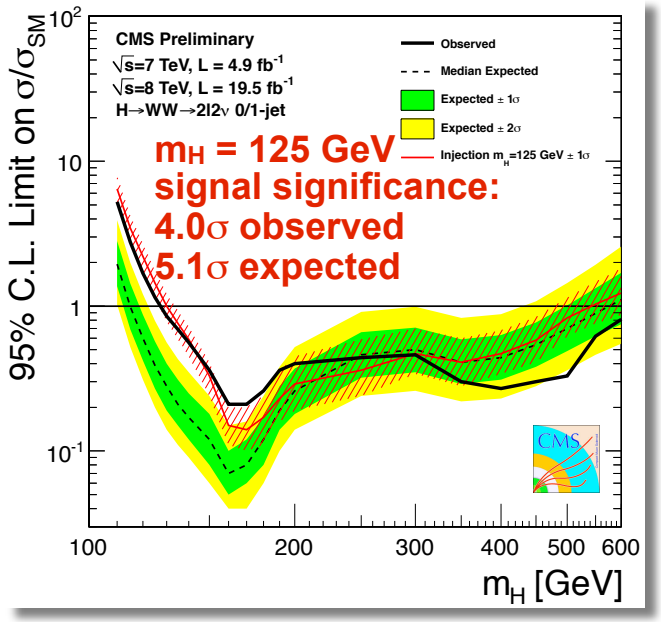
- Significant excess is observed:

ATLAS Collaboration arXiv:1307.1427





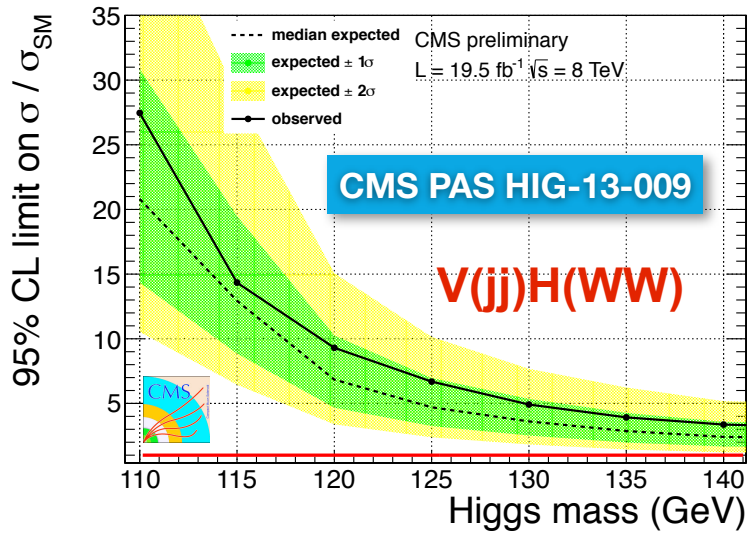




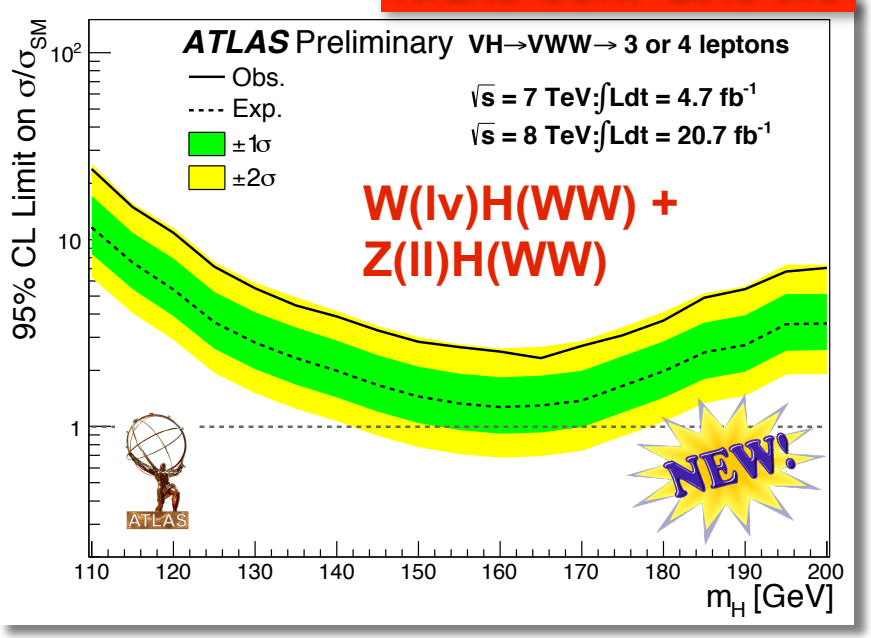
CMS PAS HIG-13-003

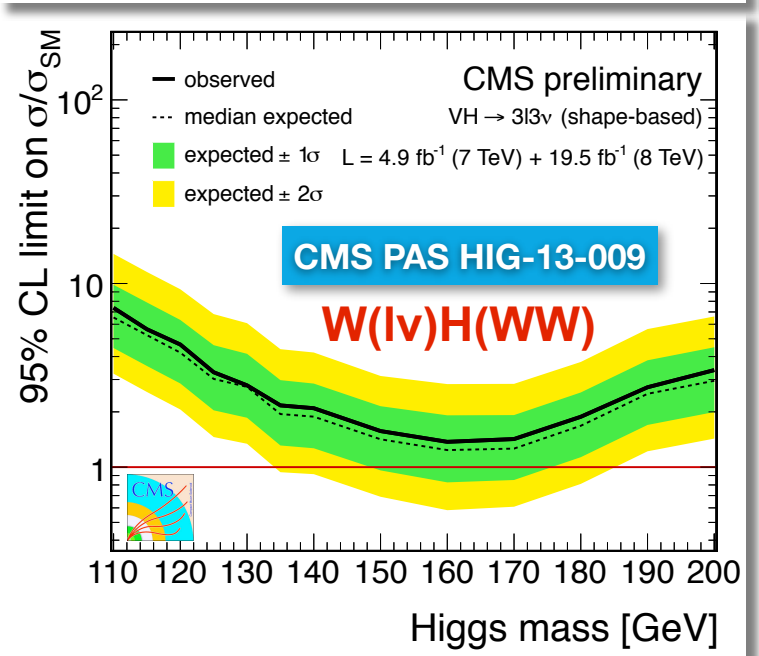
Adding VH(WW)

- A bit extra help from the VH(WW) in 3-lepton (ATLAS+CMS), 4-lepton (ATLAS), and lljj (CMS) final states
- ATLAS: combination with the H(WW) analysis:
  - **4.0σ (3.8σ exp.)** significance at m_H = 125 GeV



ATLAS-CONF-2013-075



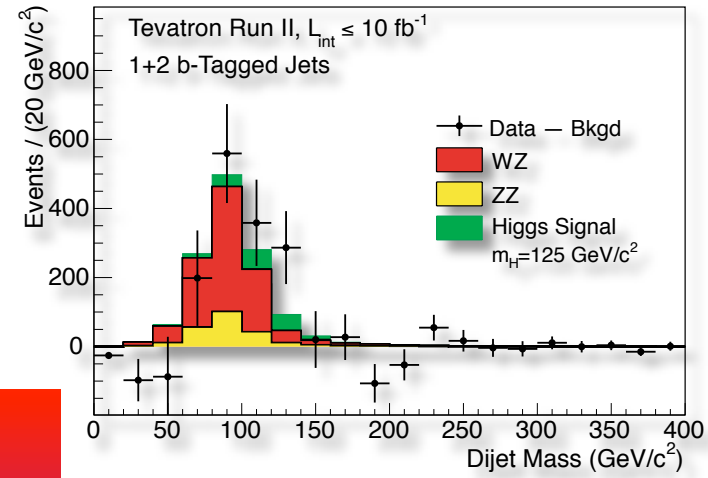


Visible Higgs

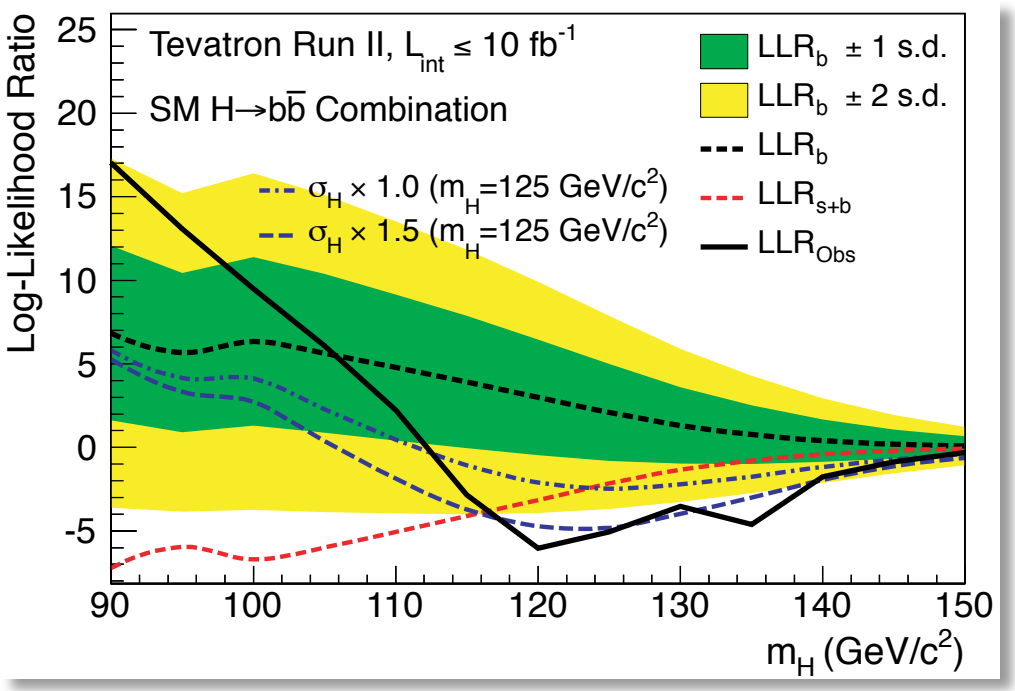
VH(bb) at the Tevatron

- Sensitivity is dominated by the VH(bb) channel
- Evidence for VZ(bb) production consistent with $\sigma_{SM} = 4.4 \pm 0.3$ pb
- Spin-parity is being investigated as well (see Fabio's talk)

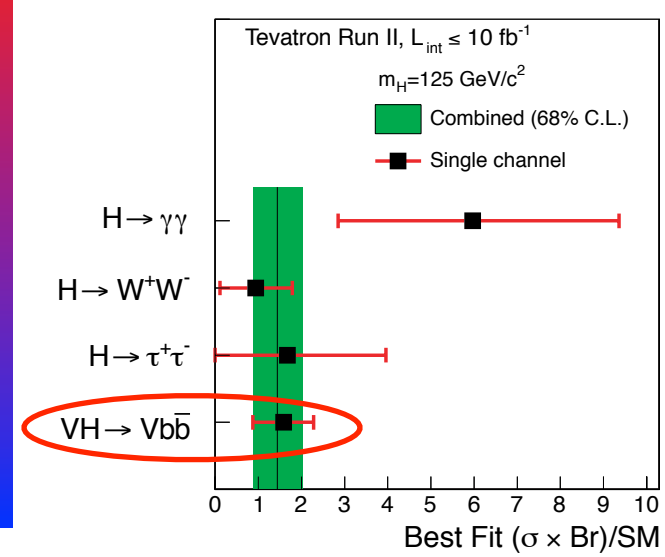
$\sigma_{VZ} = 3.0 \pm 0.6 \pm 0.7$ pb
~3σ significance



~3σ significance @ m_H = 125 GeV



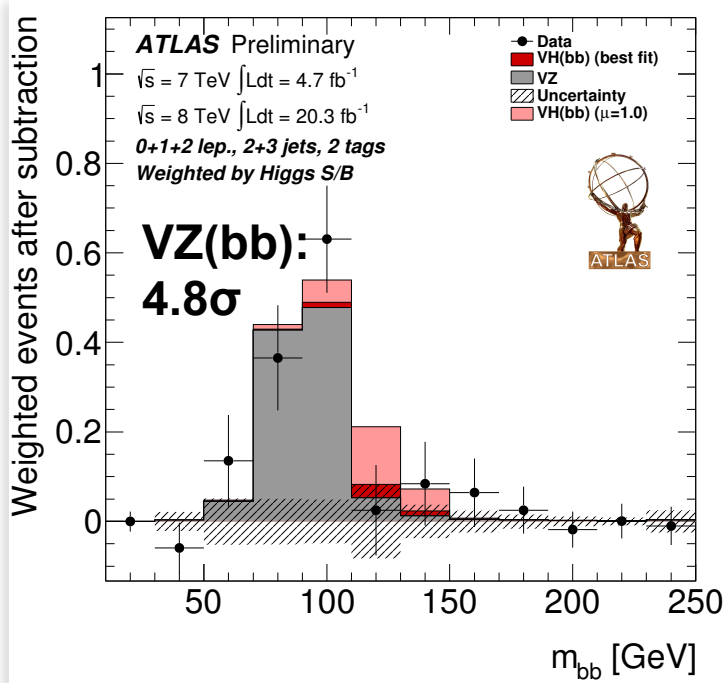
CDF & D0 Collaborations arXiv:1303.6346

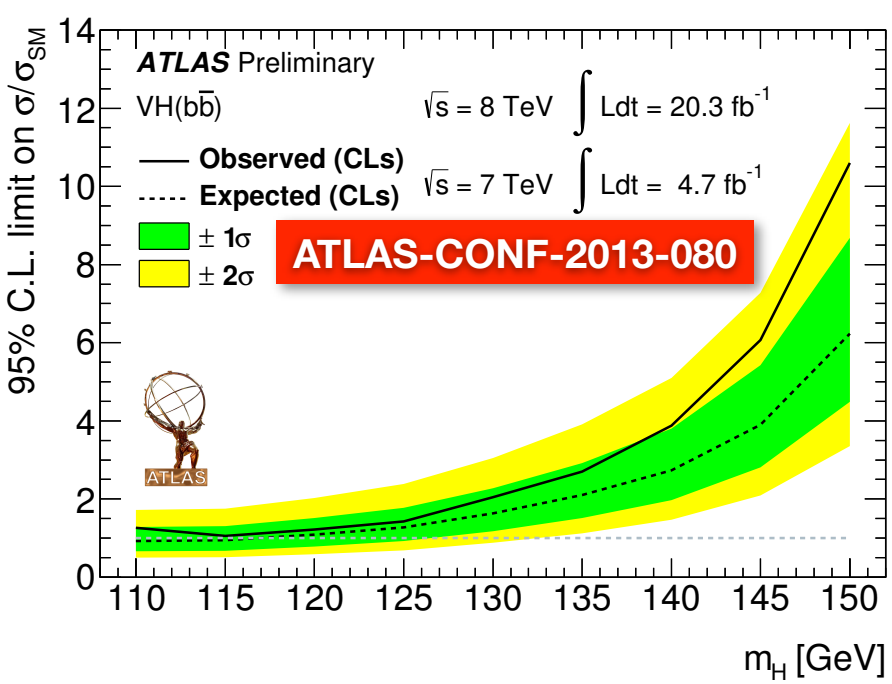


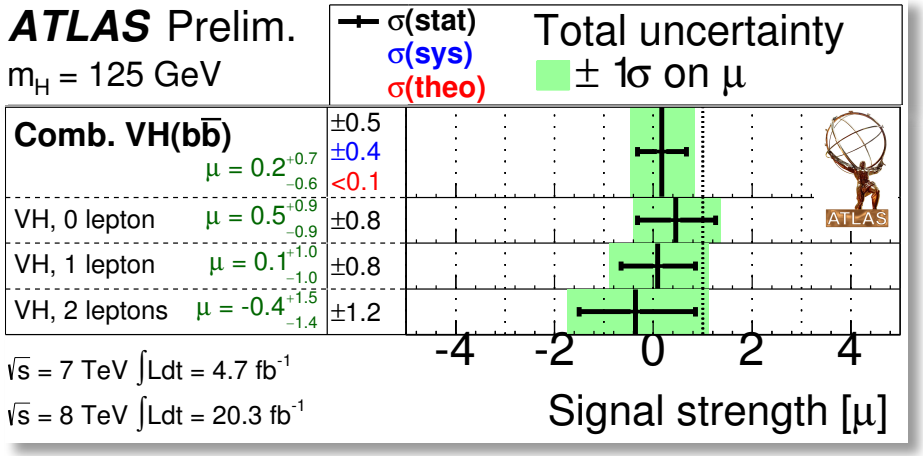
VH(bb) in ATLAS

- Search done in 0-, 1-, and 2-lepton categories, further split in bins of $p_T(V)$
  - $\mu = 0.2^{+0.7}_{-0.6}$
  - Limit: $\mu < 1.4$ (1.3 exp.) at $m_H = 125$ GeV

NEW!

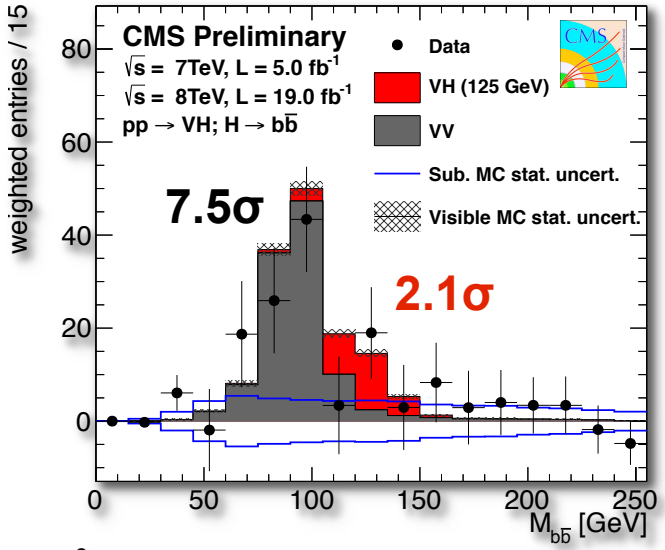


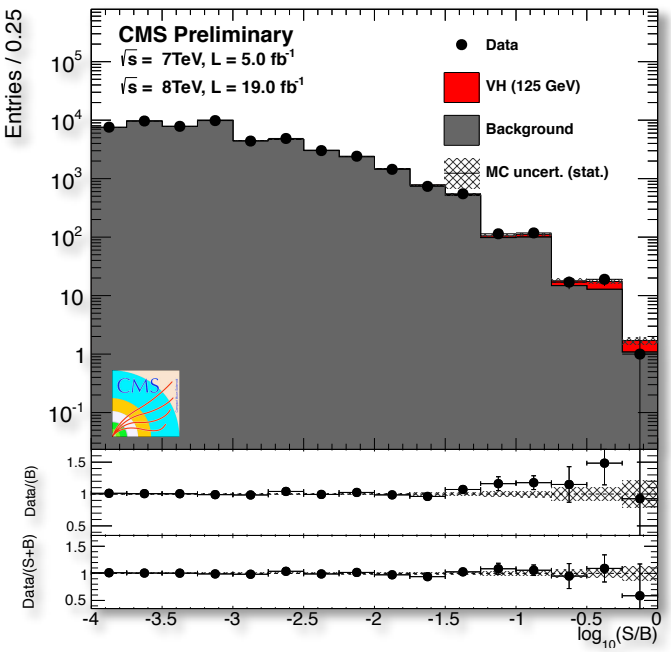




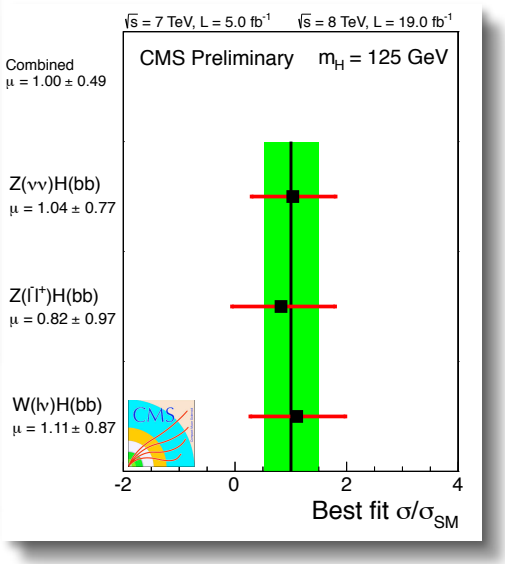
VH(bb) in CMS

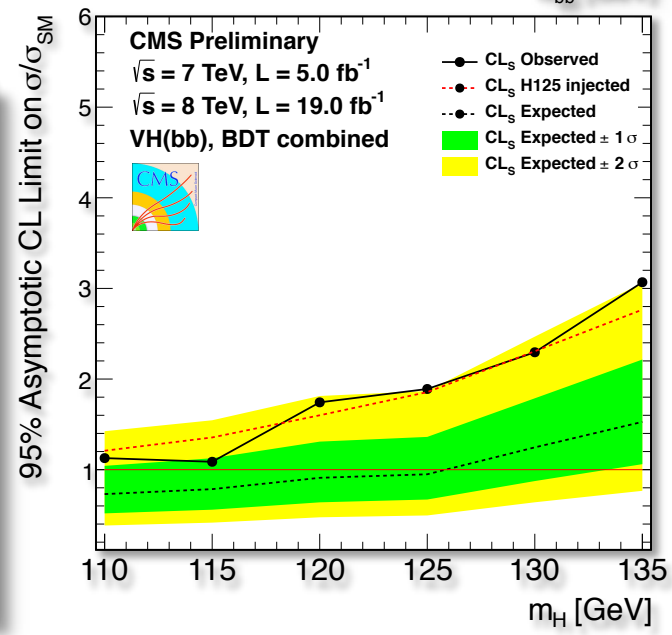
- Combines the W(lν) (including τ), Z(ee,μμ,νν) channels; BDT is used in most
- M_{bb} resolution ~10%, after regression
- Observed a **2.1σ excess (2.1σ expected)**
  - Over 7σ significance for the VZ(bb) signal
- Corresponding signal strength:
  - **$\mu = 1.00 \pm 0.49$ at $M_H = 125$ GeV**





CMS PAS HIG-13-012

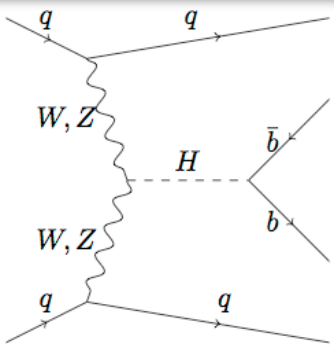


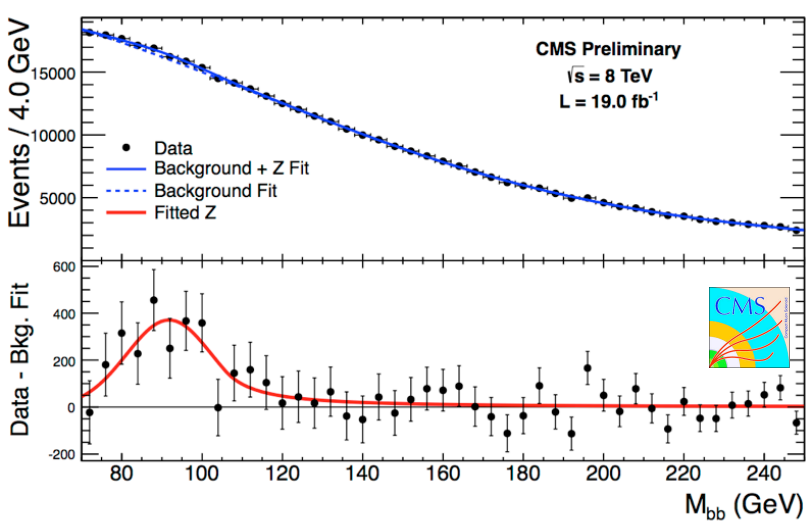


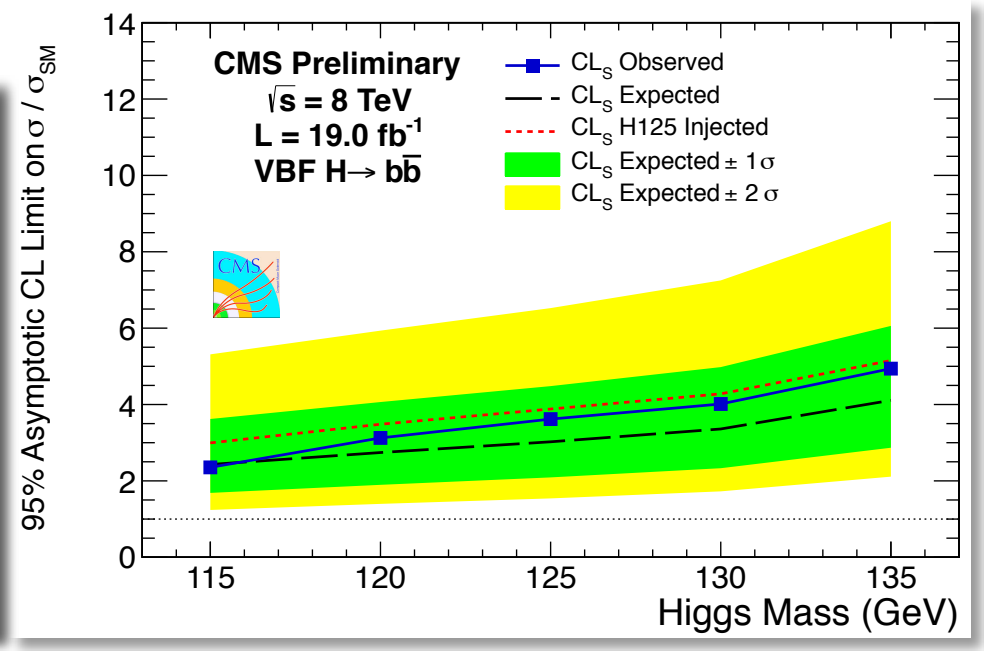
CMS: VBF H(bb)

CMS PAS HIG-13-011

- Interesting channel, directly comparable with VH(bb)
- New analysis from CMS @ 8 TeV
- Based on an ANN, with input variables describing properties of the two b-jets in the event and two VBF tagged jets
  - See a clear Z(bb) peak after preselection
- Combination done with the VH(bb) results







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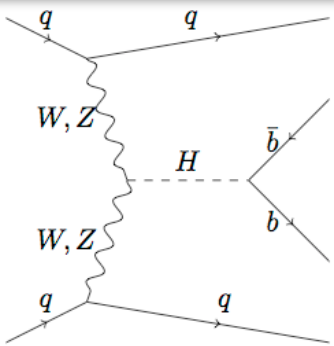

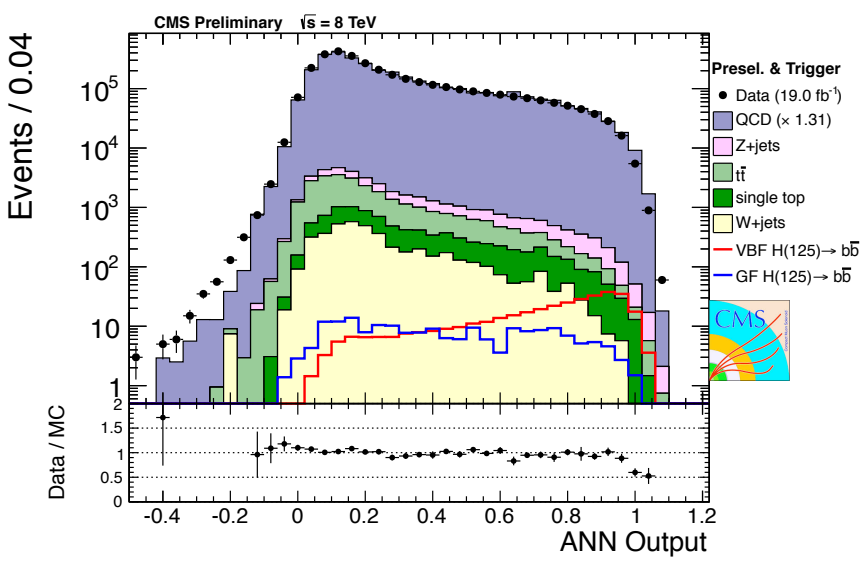

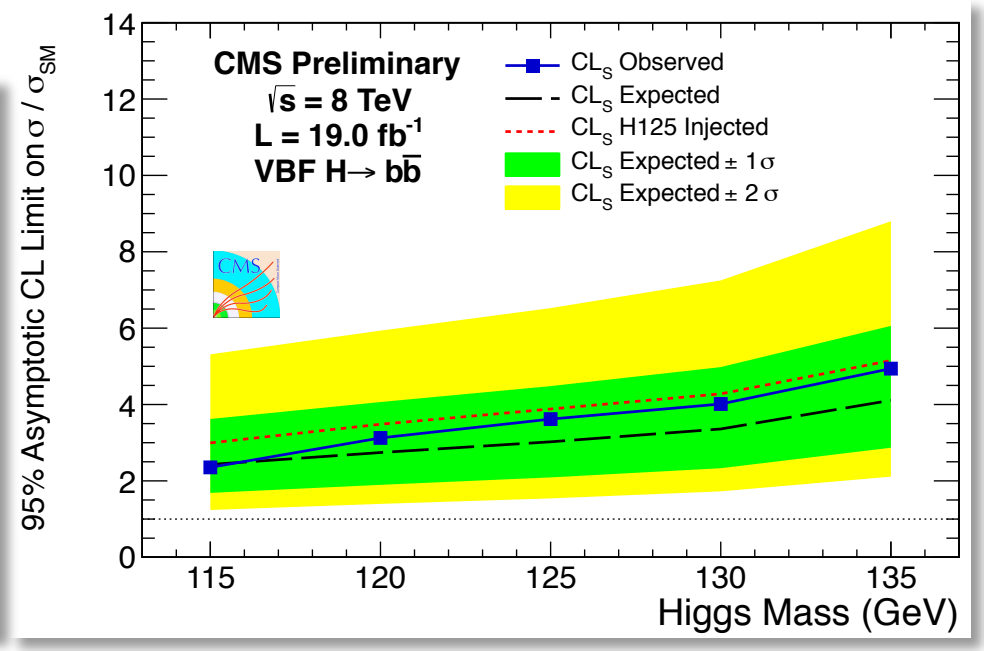

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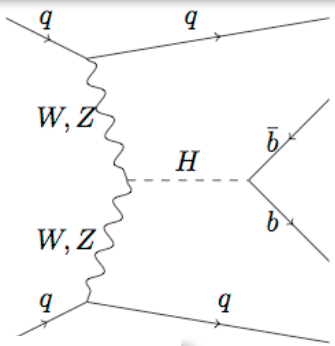
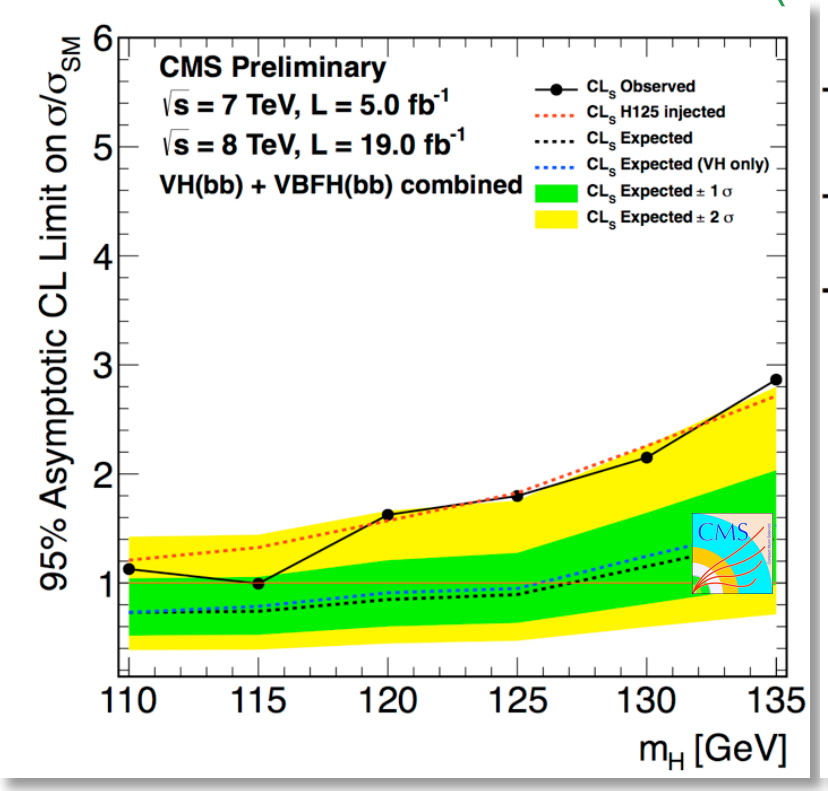
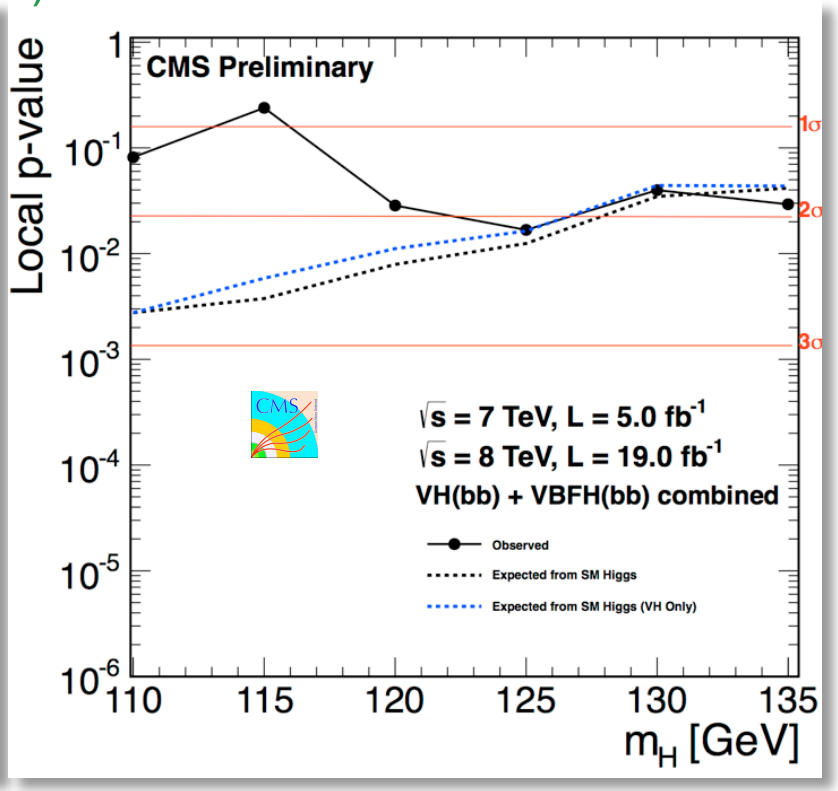




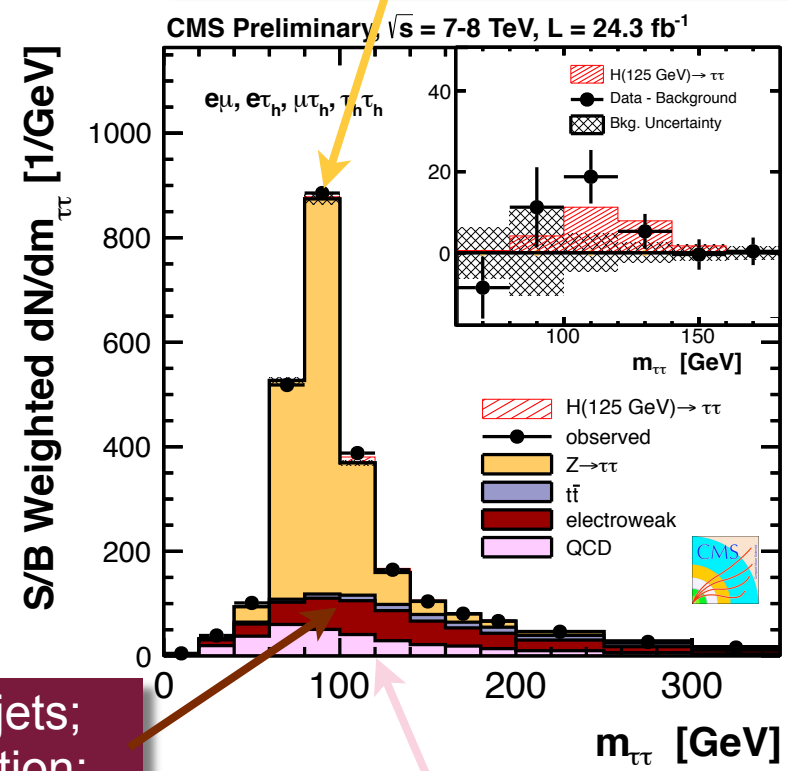


H(ττ) in CMS

- Updated to full statistics; based on eμ, μμ, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$ channels
- Analysis is done separately in 0-, 1-, and 2-jet (VBF) categories
  - 0- and 1-jet categories are each split in two, depending on the p_T of the τ-decay products
  - $\tau_h\tau_h$ doesn't use 0-jet category and the 1- and 2-jet categories are not split
- Also include VH(ττ) channels
- Optimized ττ mass reconstruction (SVFIT) with ~20% resolution
- Benefits significantly from particle-flow reconstruction

CMS PAS HIG-13-004

Embedding (replace μ with simulated τ in Z(μμ) sample); normalization from Z(μμ) (5% syst.)



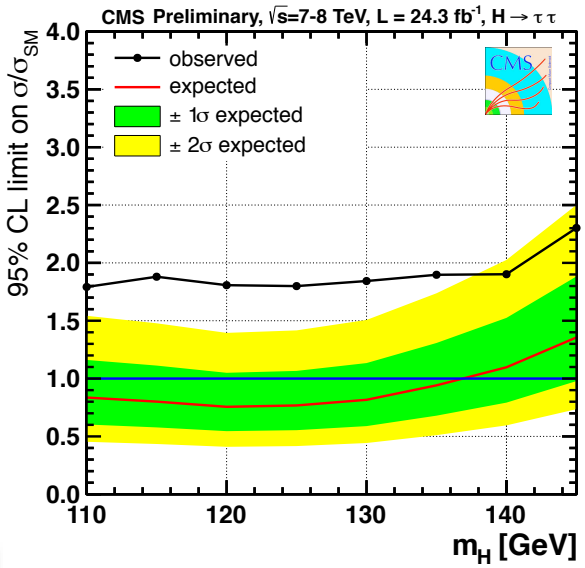
Dominated by W+jets; shape from simulation; normalization from control regions (10-20% syst.)

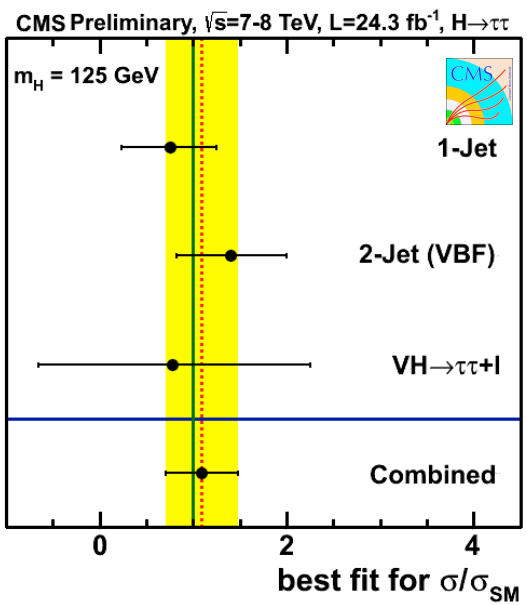
QCD: from SS sample (10% syst.)

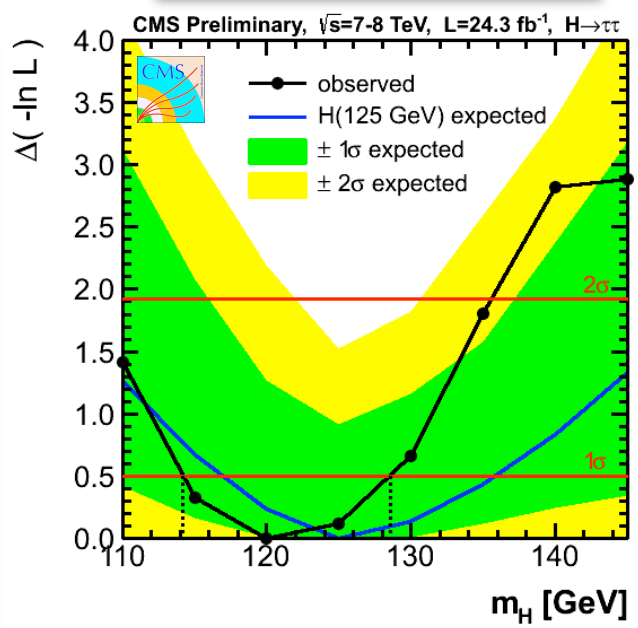
CMS: H(ττ) Results

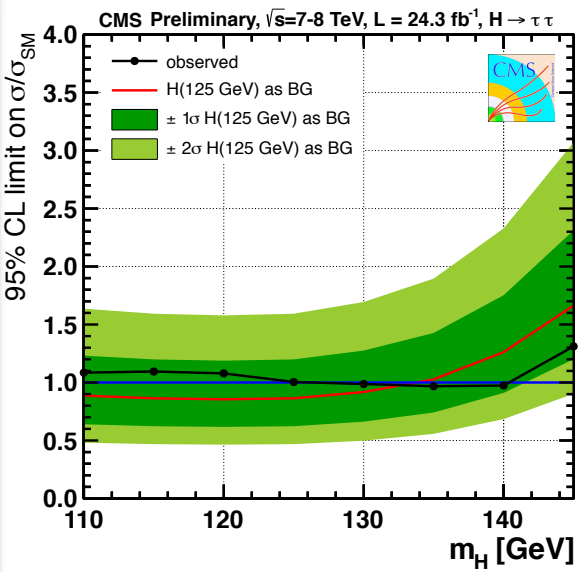
- **Observed 2.9σ (2.6σ exp.)** for m_H = 125 GeV
- Combined with VH(bb), CMS sees an *evidence* for the Hff coupling to the 3rd-generation *down-type* fermions at **3.4σ (3.4σ exp.)**
- First mass measurement in this channel:
  - **$m_H = 120^{+9}_{-7}$ GeV**

CMS PAS HIG-13-004



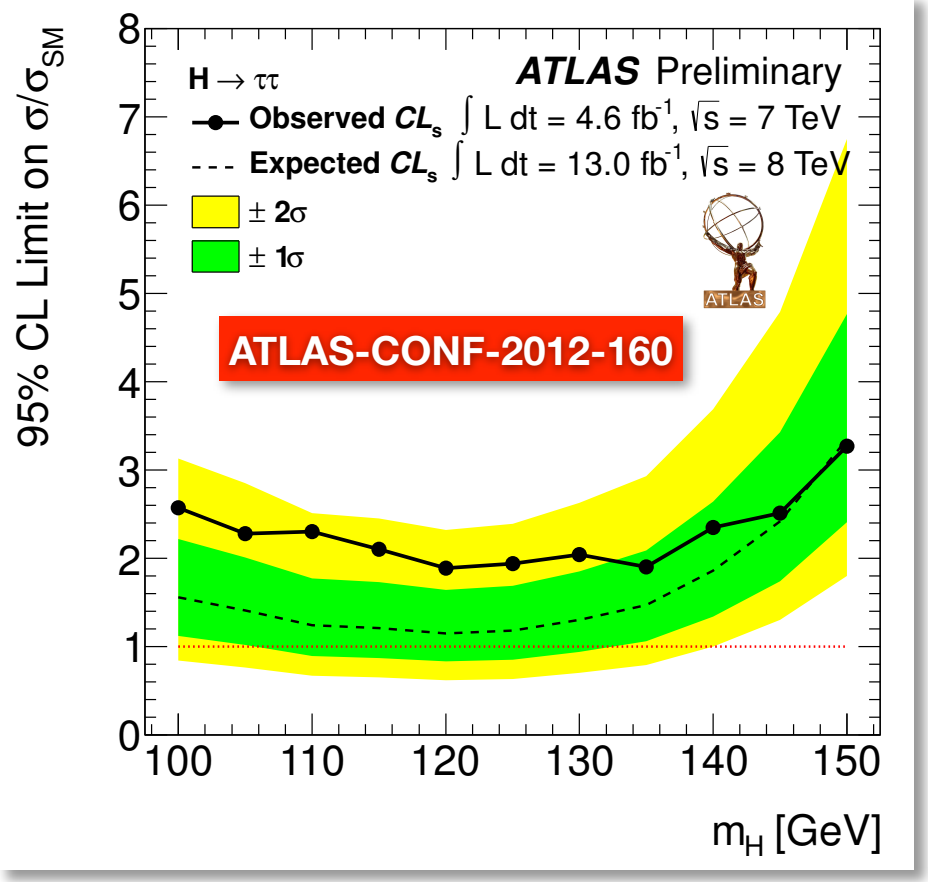


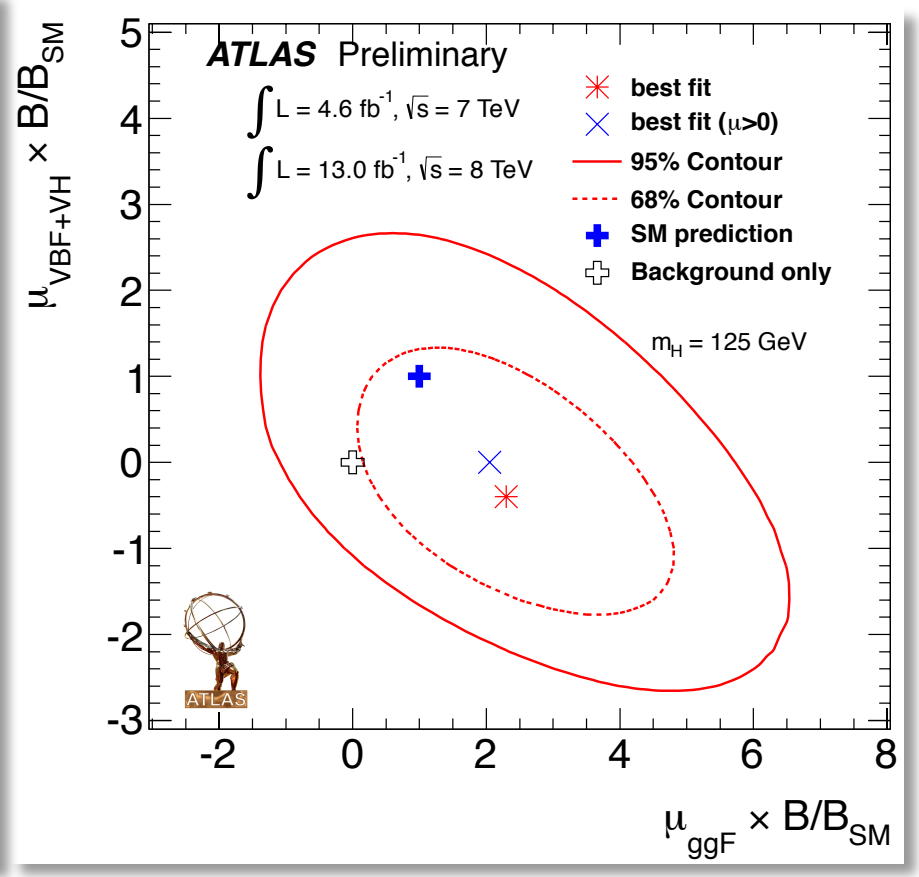




H(ττ) in ATLAS

- Analysis hasn't been updated to full statistics yet
- Uses similar techniques as the CMS analysis
- **μ = 0.7 ± 0.7**; significance **1.1σ (1.7σ exp.)**



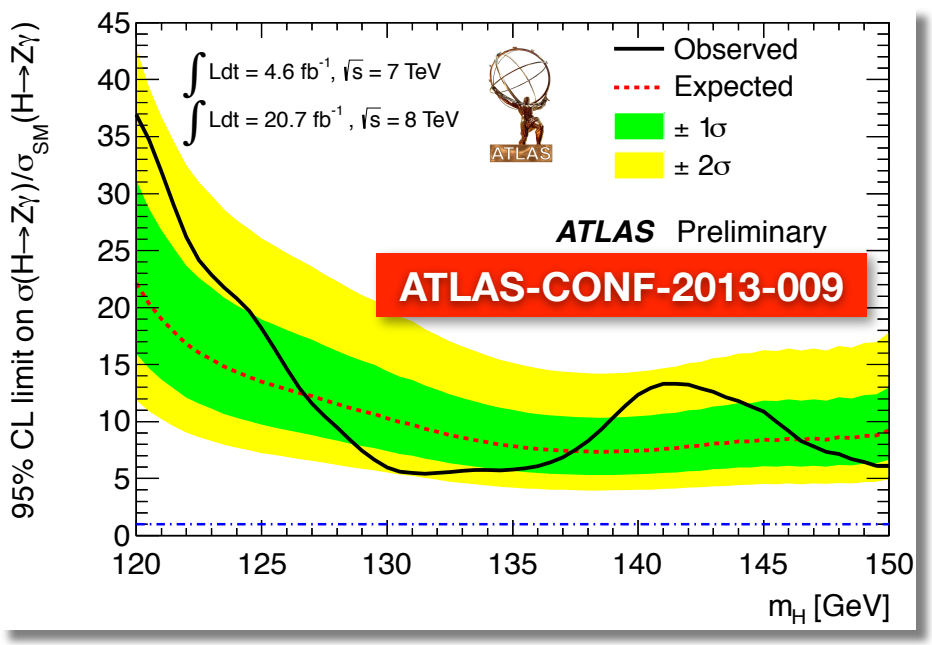


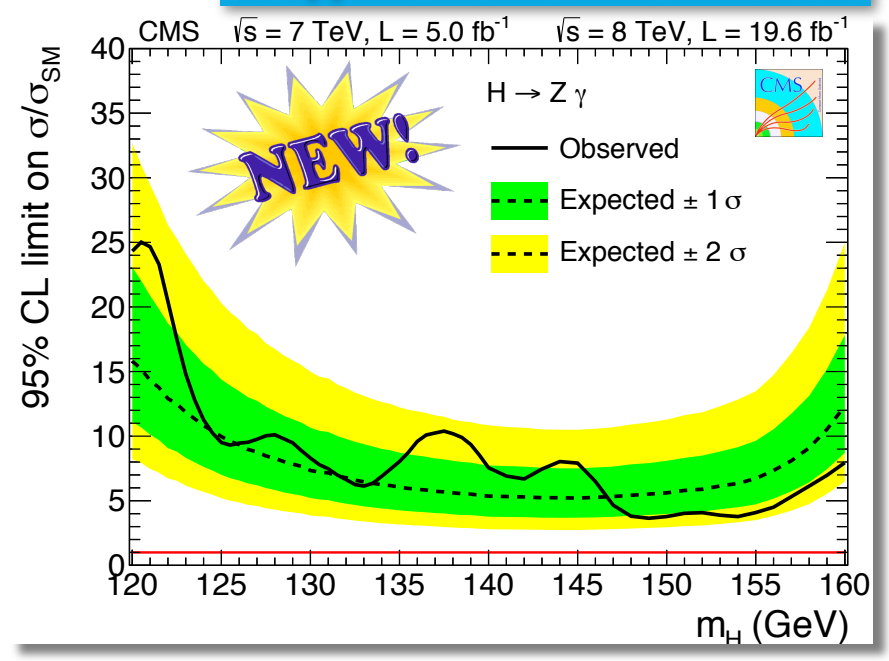
Not-yet-Visible Higgs

H(Zγ) Results

- Similar branching fraction to H(γγ), but an additional price to pay for the leptonic branching fraction of the Z
- Decay can be enhanced/suppressed independently of H(γγ)
  - Sensitive to new physics via loops
- Not sensitive to the SM Higgs boson (yet), set the following limits:
  - ATLAS: μ < 18.2 @ 95% CL (13.5 expected)
  - CMS: μ < 10 @ 95% CL (10 expected)

CMS Collaboration
CERN-PH-EP-2013-113
to appear on the arXiv tomorrow

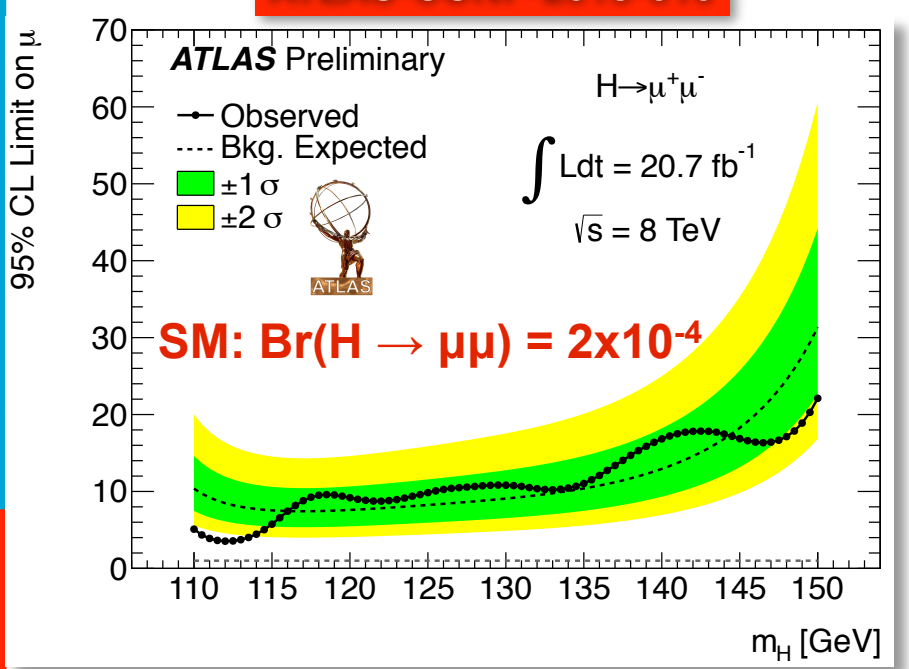




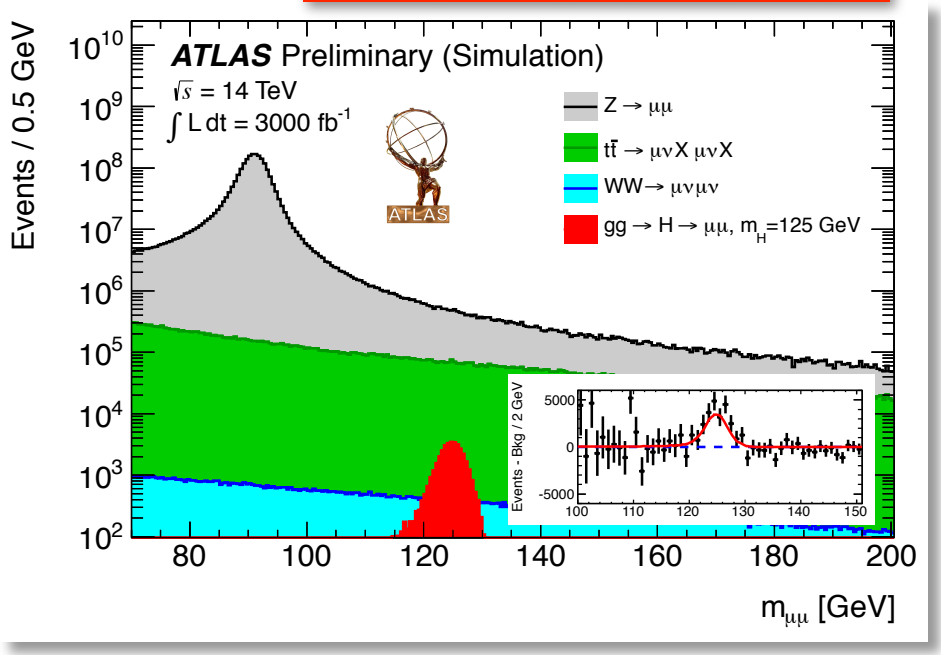
H(μμ) Results

- Observing H(μμ) decay may be the only way to prove non-flavor-universal couplings of the Higgs boson
  - N.B. Coupling to charm is very hard to probe
- Requires very large statistics for observation: a strong case for HL-LHC
- First search has been done already by ATLAS
  - Sets limit μ < 9.8 (8.2 expected) @ 95% CL

ATLAS-CONF-2013-010



ATLAS-PHYS-PUB-2012-004



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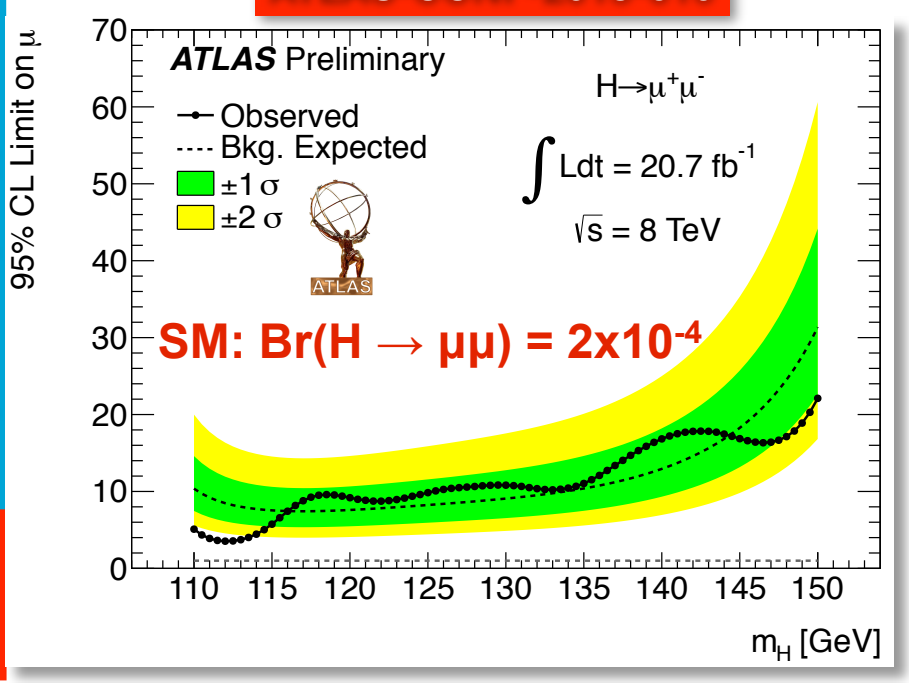
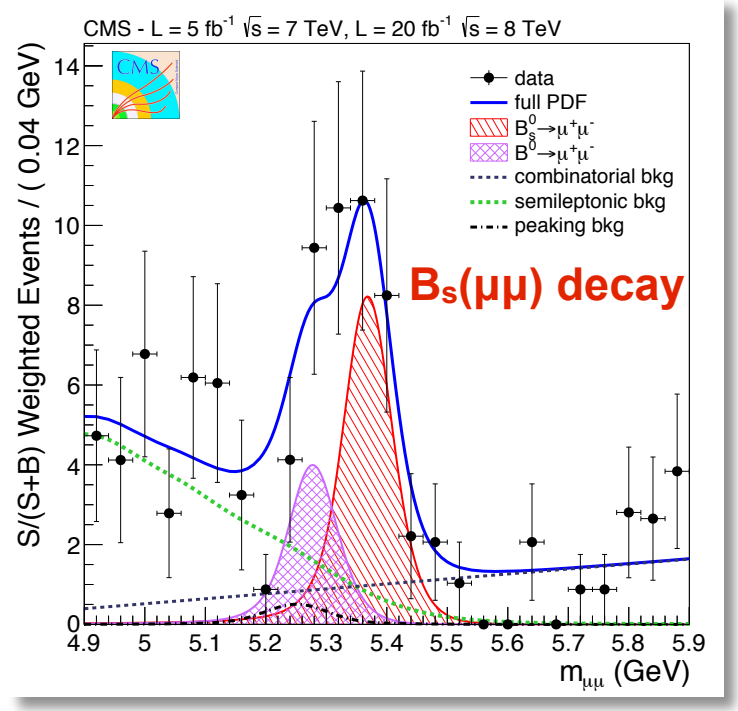
Br = $3.0^{+1.0}_{-0.9} \times 10^{-9}$

ATLAS-CONF-2013-010





CMS Collaboration arXiv:1307.5025

ttH - the New Player

VOLUME 86, NUMBER 9 PHYSICAL REVIEW LETTERS 26 FEBRUARY 2001

$p\bar{p} \to t\bar{t}H$: A Discovery Mode for the Higgs Boson at the Fermilab Tevatron

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(Received 28 June 2000)

The production of a standard model Higgs boson in association with a top quark pair at the upcoming high luminosity run (15 fb^{-1} integrated luminosity) of the Fermilab Tevatron ($\sqrt{s} = 2.0$ TeV) is revisited. For Higgs masses below 140 GeV we demonstrate that the production cross section times branching ratio for $H \to b\bar{b}$ decays yields a significant number of events and that this mode is competitive with and complementary to the searches using $p\bar{p} \to WH, ZH$ associated production. For higher mass Higgs bosons the $H \to W^+W^-$ decays are more difficult but have the potential to provide a few spectacular events.

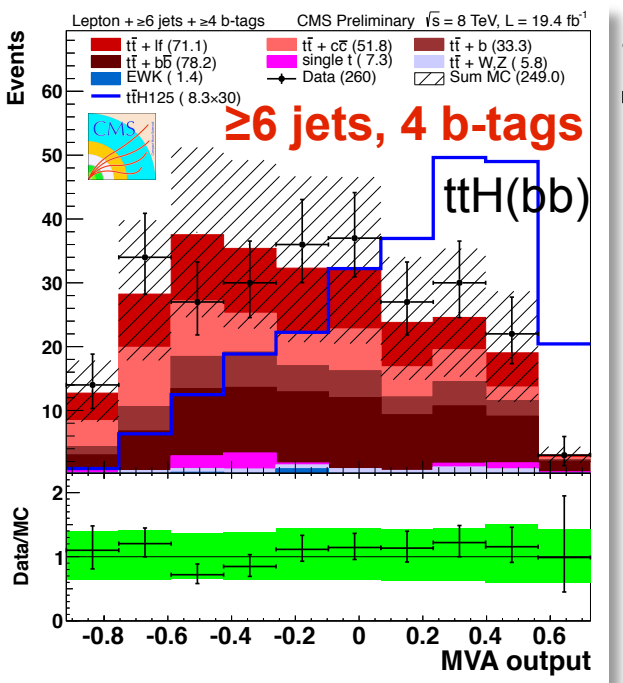
- Very challenging mode, requires tour-de-force analysis
- Important backgrounds from tt+X, typically poorly known theoretically and experimentally
- The only channel that offers direct probe of the Htt coupling at tree level
- Long history: from the first paper suggesting this as a promising channel at the Tevatron (2001), to “oscillations” on whether it is feasible at the LHC, to first successful analysis a decade later
  - First search: CDF, PRL 109 (2012) 181802 (August 2012)
  - First LHC search: CMS, JHEP 05 (2013) 145 (March 2013)
- Today, we are close to an answer to the feasibility question!

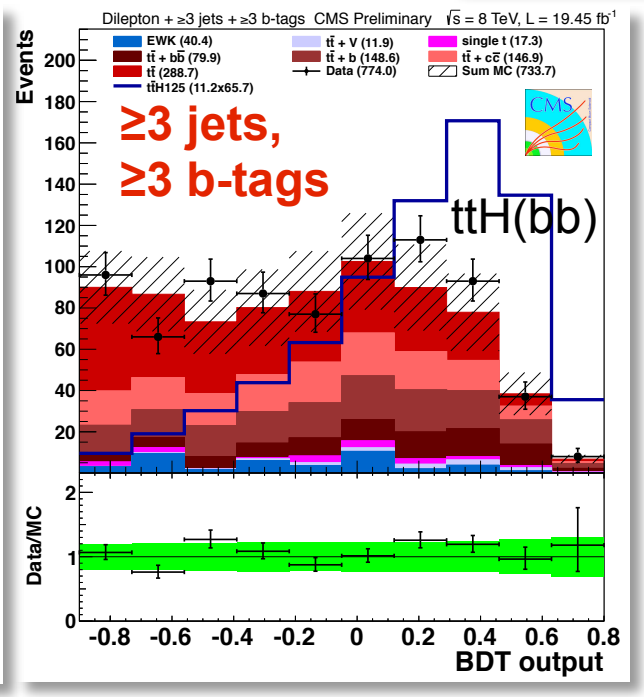
CMS Search in ttH(bb+ττ)

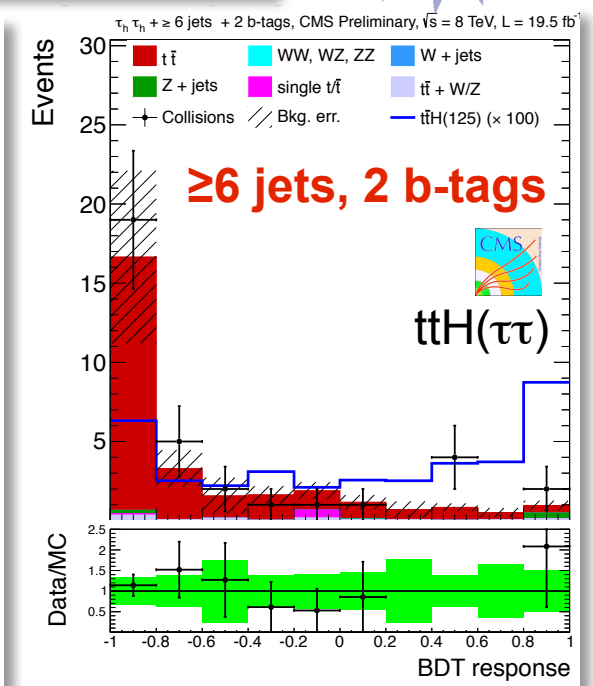
- New analysis; supersedes recent publication arXiv:1303.0763 based on 5+5 fb^{-1}
  - Updated to the full 2012 statistics (7 TeV not reanalyzed) and added the ττ decay channel (8 TeV only)
  - tt decays are reconstructed in the lepton+jets and dilepton channel; 2 or more b-tagged jets required for the ttH(bb) search
  - H(ττ) decays are looked for in $\tau_h\tau_h$ channel, with tt decaying in lepton+jets, with 1 or 2 b-tagged jets
  - Signal extraction via BDTs; separate BDTs for each jet and b-tagged jet multiplicity

CMS PAS HIG-13-019

NEW!



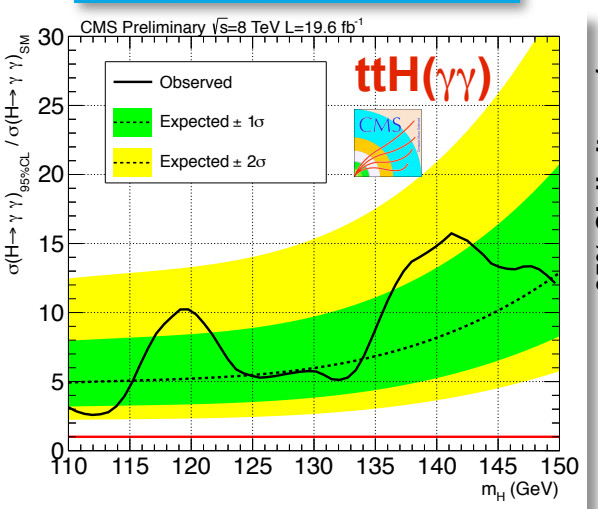




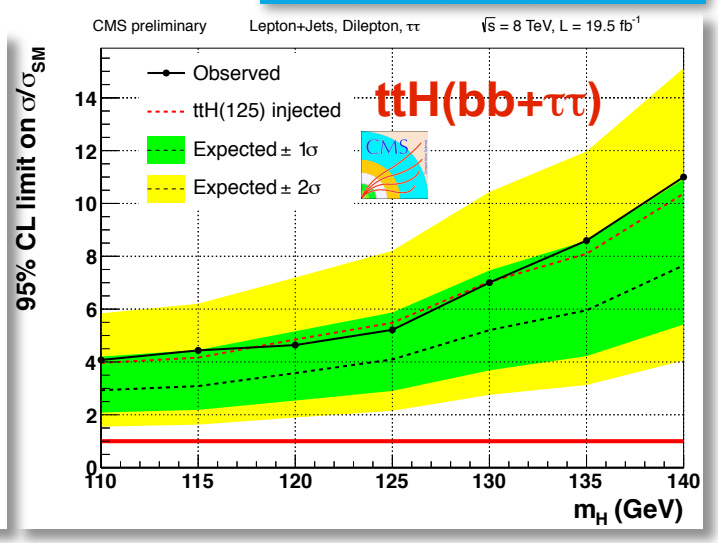
ttH Results

- ttH(bb+ττ) results:
  - **μ < 5.2 (4.1 exp.)** @ 95% CL, m_H = 125 GeV
- Also a recent result in ttH(γγ) channel
  - All-hadronic and semileptonic tt decays with loose selection and at least one b-tagged jet
  - Analysis of the diphoton mass spectrum similar to that in the H(γγ) analysis
  - **μ < 5.4 (5.3 exp.)** @ 95% CL, m_H = 125 GeV

CMS PAS HIG-13-015



CMS PAS HIG-13-019



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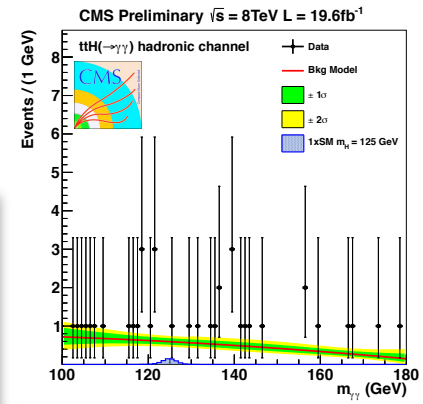
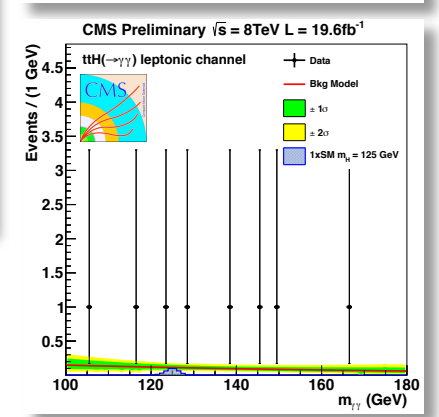
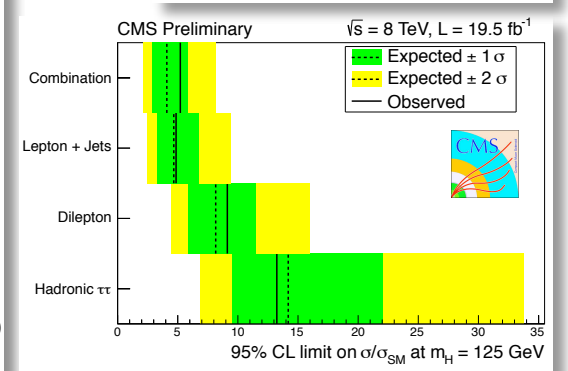
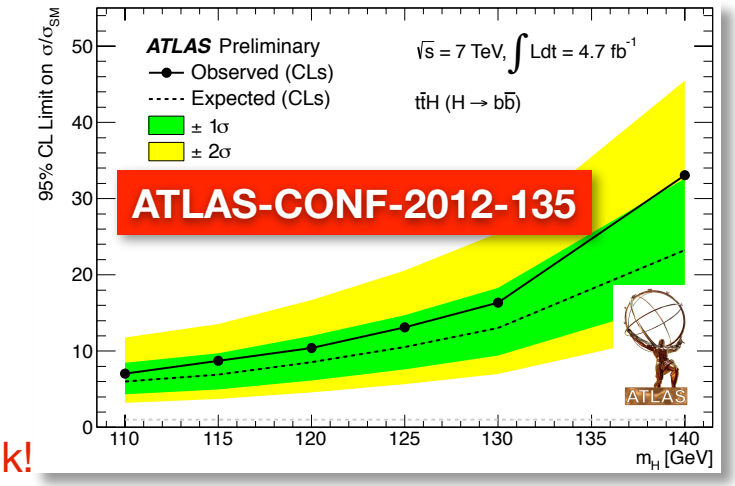


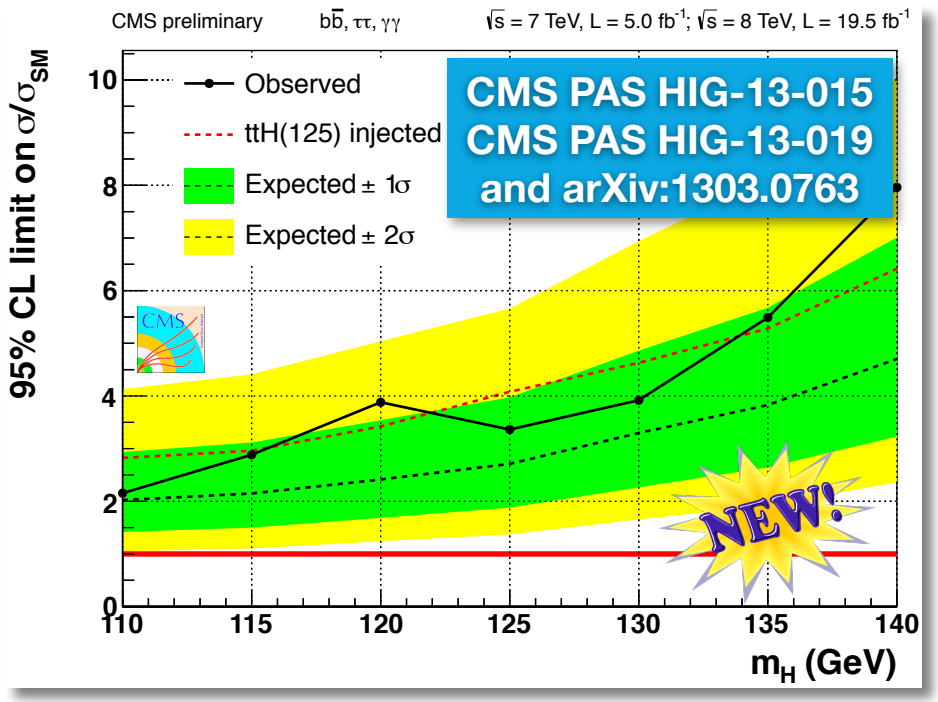


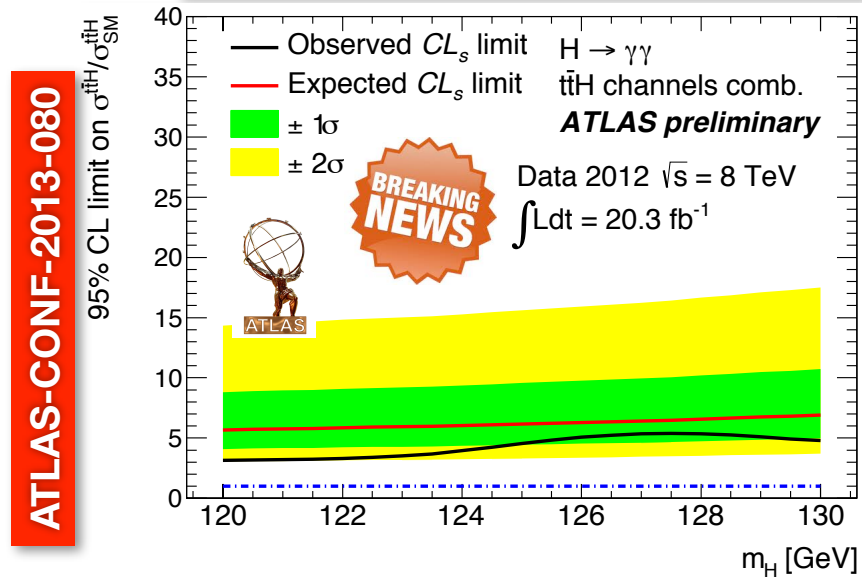


ttH Combination

- CMS combined results:
  - **μ < 3.4 (2.7 expected)**
- Would improve even more when additional channels are added and combined with ATLAS (once the analysis is updated)
- Closing on the SM Higgs boson sensitivity!
  - Soon to become the 6th of the "big" channels and can be moved into "visible" category of my talk!





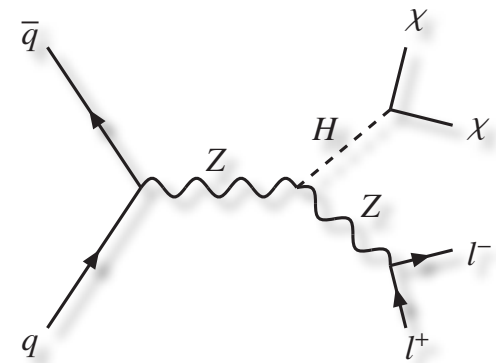


Breaking news - brand new ATLAS ttH(γγ) 8 TeV result: **μ < 5.3 (6.4 exp.)**

Invisible Higgs

Invisible Higgs Decays

- Given the accuracy of present measurement of Higgs branching fractions, there is a lot of room for non-SM decays, e.g. decays into invisible particles
- Many theoretical models predict such decays, e.g.:
  - Higgs coupled to light dark matter
  - Hidden valley models
  - Right-handed neutrino models
- Search is done in associated production with the Z boson decaying leptonically
  - Discriminating variables: ME_T (ATLAS), M_T (CMS)
- ATLAS (4.7+13.0 fb^{-1}):
  - **$Br(H\rightarrow\chi\chi) < 65\%$** (84% exp.) @ 95% CL, m_H = 125 GeV
- CMS (5+20 fb^{-1}):
  - **$Br(H\rightarrow\chi\chi) < 75\%$** (91% exp.) @ 95% CL, m_H = 125 GeV



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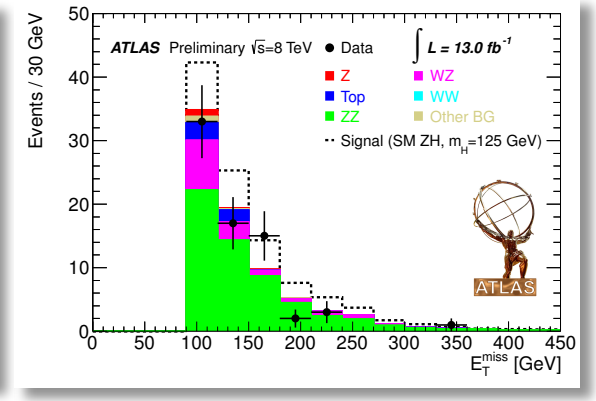
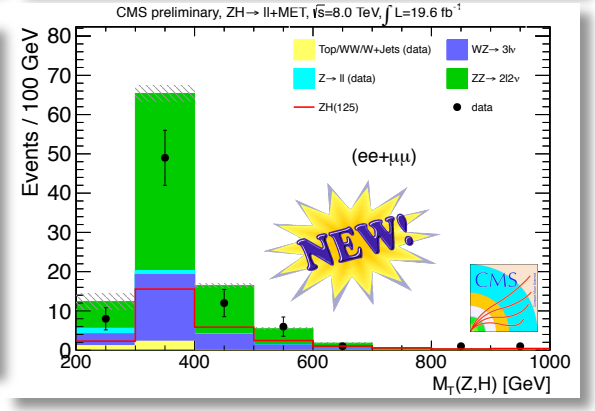


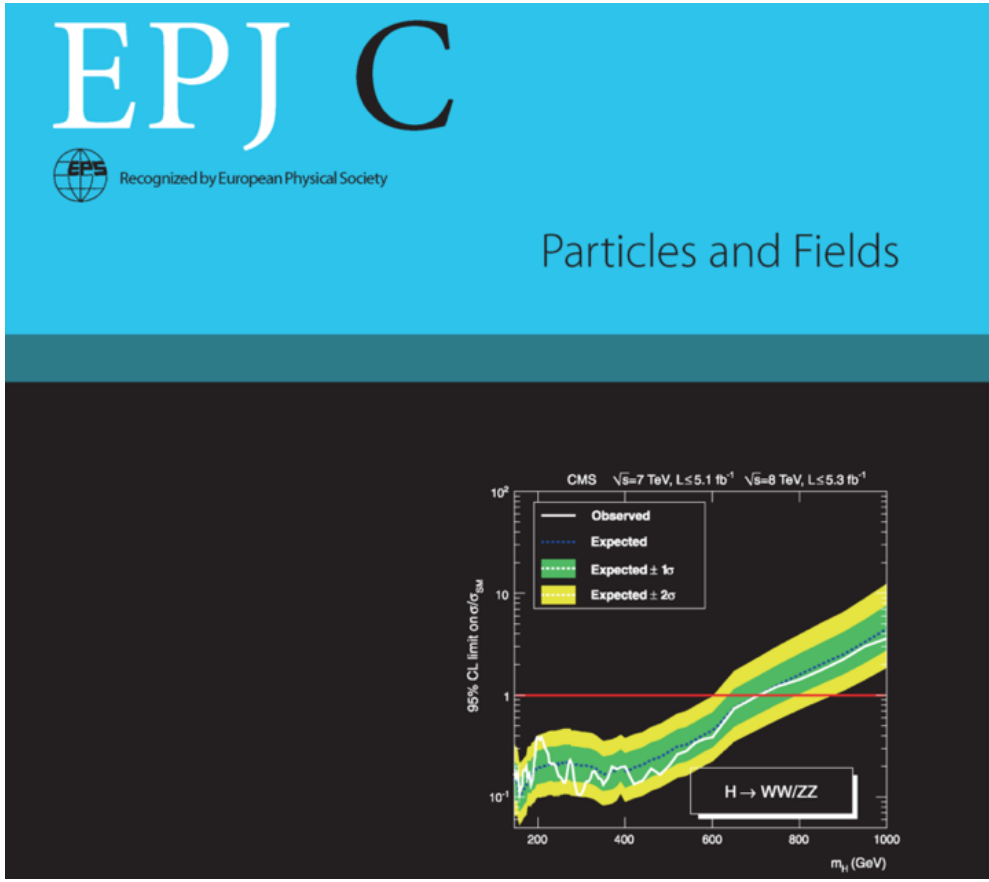
CMS PAS HIG-13-018




Invincible Higgs

In 2HDM Speramus!

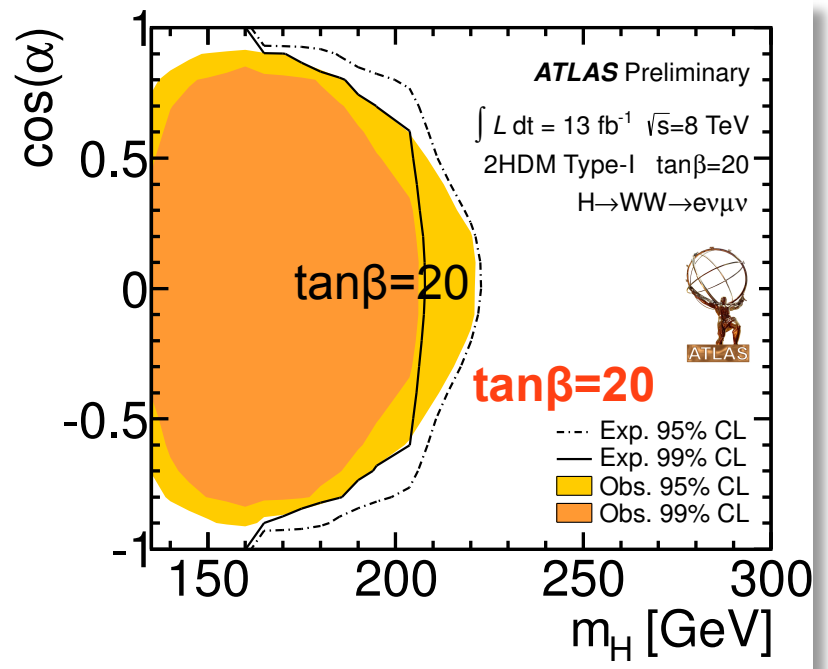
- Many extensions of the SM predict more than one Higgs doublet
- A classic realization of 2HDM (two-Higgs-doublet model) is SUSY, or its constrained version, MSSM
  - Additional heavy CP-even neutral Higgs boson H, CP-odd neutral A, and $H^{\pm}$

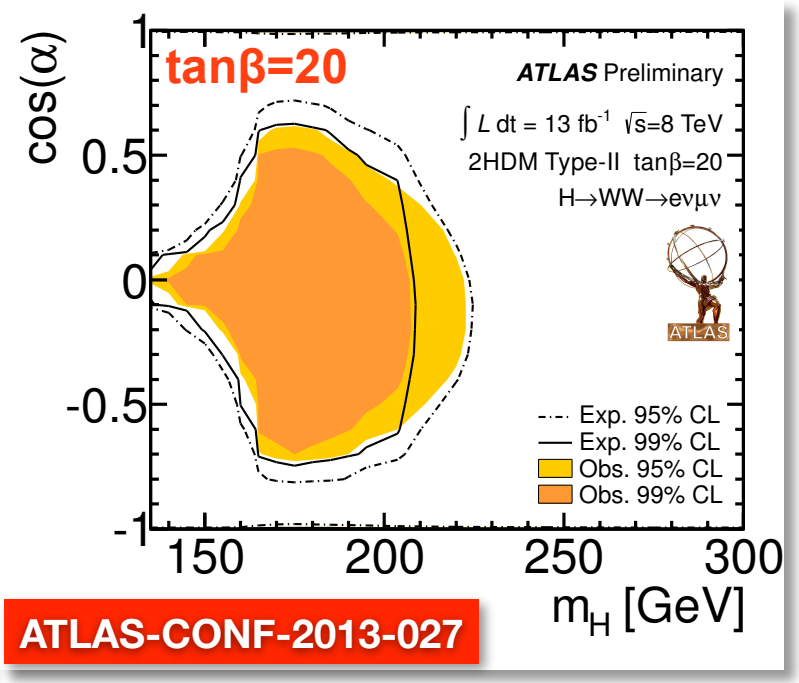


- Thus, it's very important to continue searches for additional Higgs bosons at high and low masses, in both SM and exotic decay channels
- This has been by now realized even by the journal editors!

2HDM Search for H(WW)

- Look for heavy CP-conserving Higgs boson H(WW) decays
- Consider separately VBF and gluon fusion production
- Probe two type of 2HDM:
  - Type I - all quarks couple only to one doublet
  - Type II - all up-type right-handed quarks couple to one doublet, and down-type to the other
- Ratio of VBF and gluon fusion production is modified
- Important parameters: tanβ - the ratio of two vevs, and cosα, which determines coupling of H to fermions (~sinα/sinβ in Type I or to up quarks in Type II)





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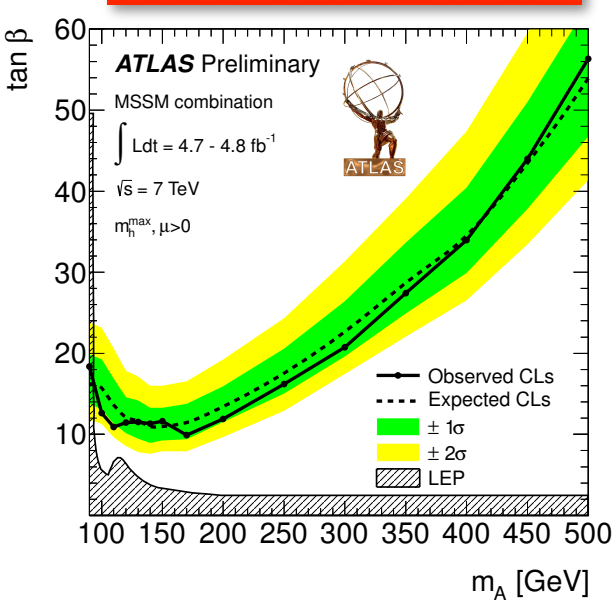
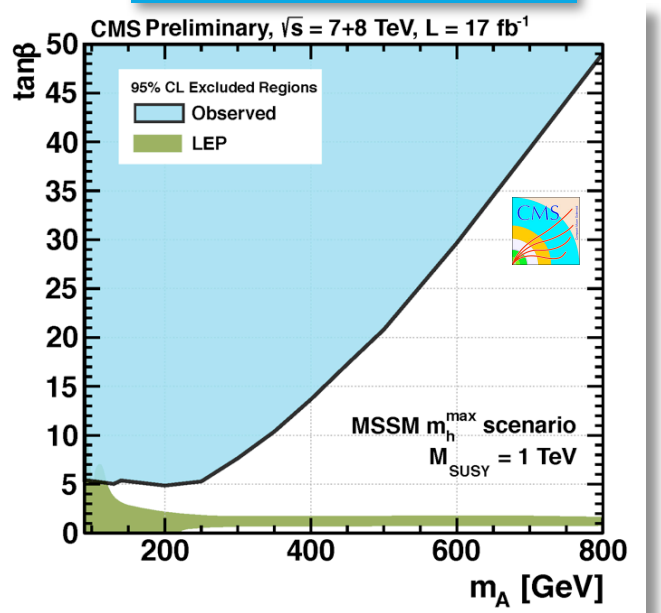
MSSM Higgs Searches

- Most recent results on the H/A($\tau\tau$), including the new LHCb search exploiting τ's in the forward region
- Also, limits on charged Higgs from top decays in $\tau\nu$ (ATLAS+CMS) and cs (ATLAS) channels and search for NMSSM $h \rightarrow a^0a^0 \rightarrow 4\mu$ (CMS, D0), 4γ (ATLAS) and $a_1 \rightarrow 2\mu$ (ATLAS & CMS), as well as Υ(1S,2S) $\rightarrow a^0\gamma \rightarrow \tau\tau\gamma$, $\mu\mu\gamma$ (BaBar, Belle); and $gg\gamma$, and $ss\gamma$ (BaBar)

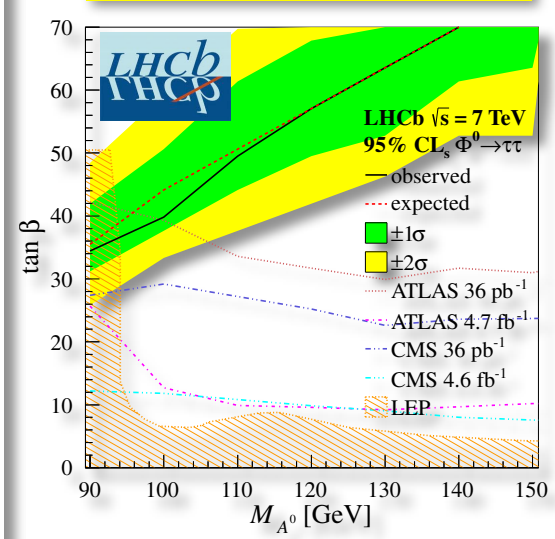
ATLAS-CONF-2012-094



CMS PAS HIG-12-050



LHCb Collaboration arXiv:1304.2591



Additional Higgs Searches

- $\gamma\gamma$/WW channels (shown earlier in the talk)
- Invisible channel:
- Heavy Higgs decaying into ZZ(llvv) or ZZ(lljj)

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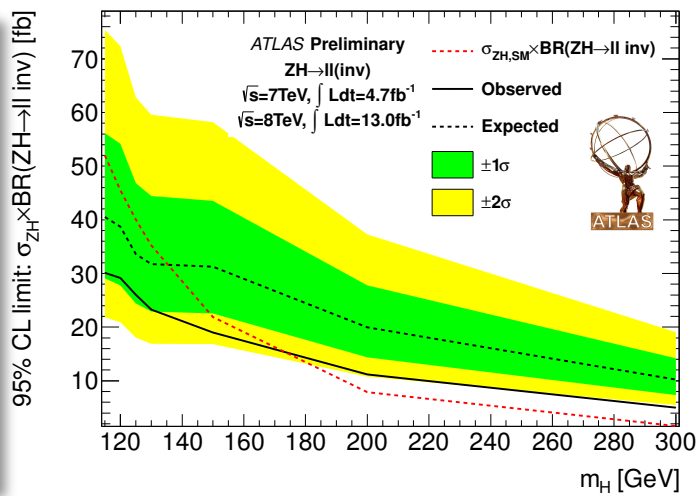
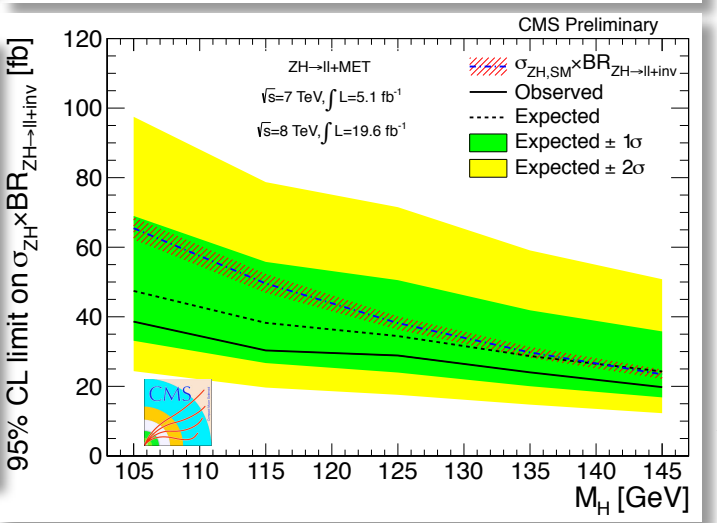
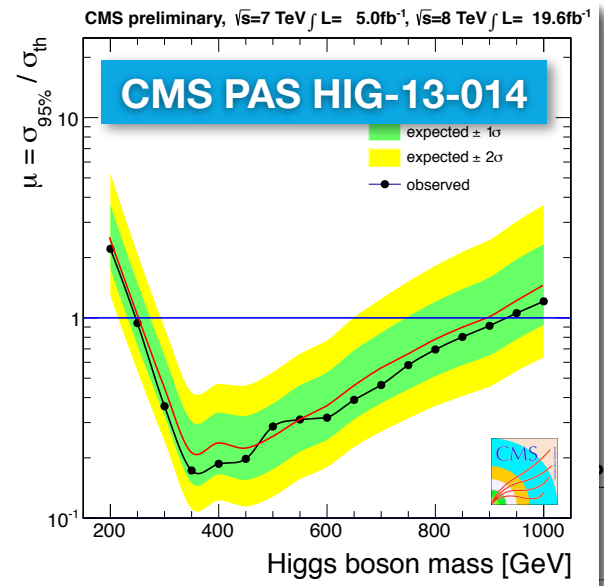
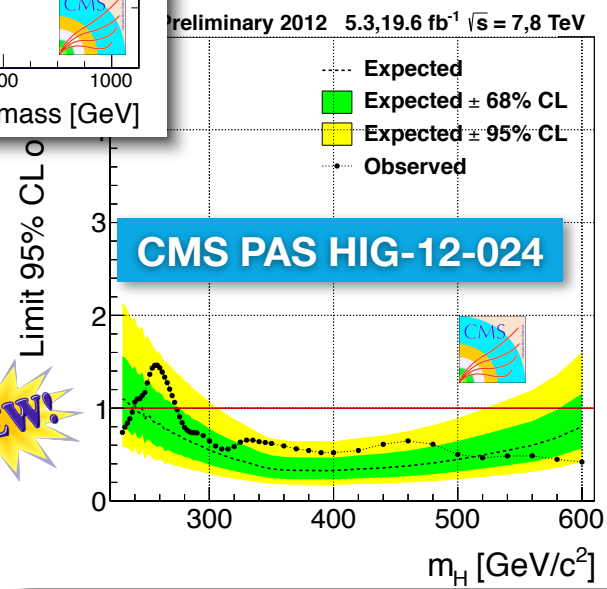


CMS PAS HIG-13-014





NEW!

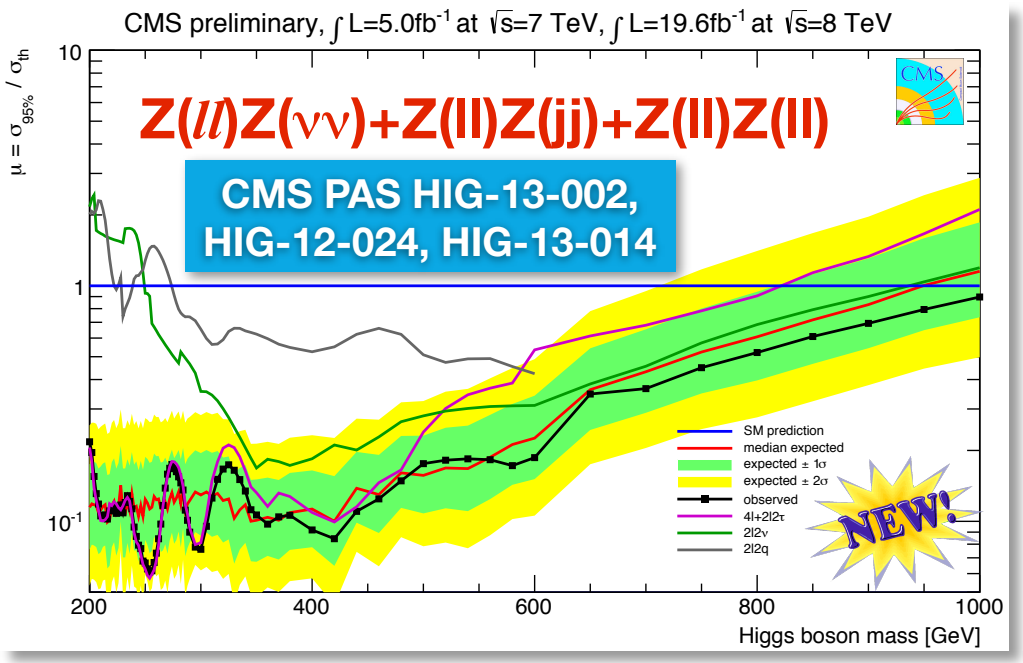


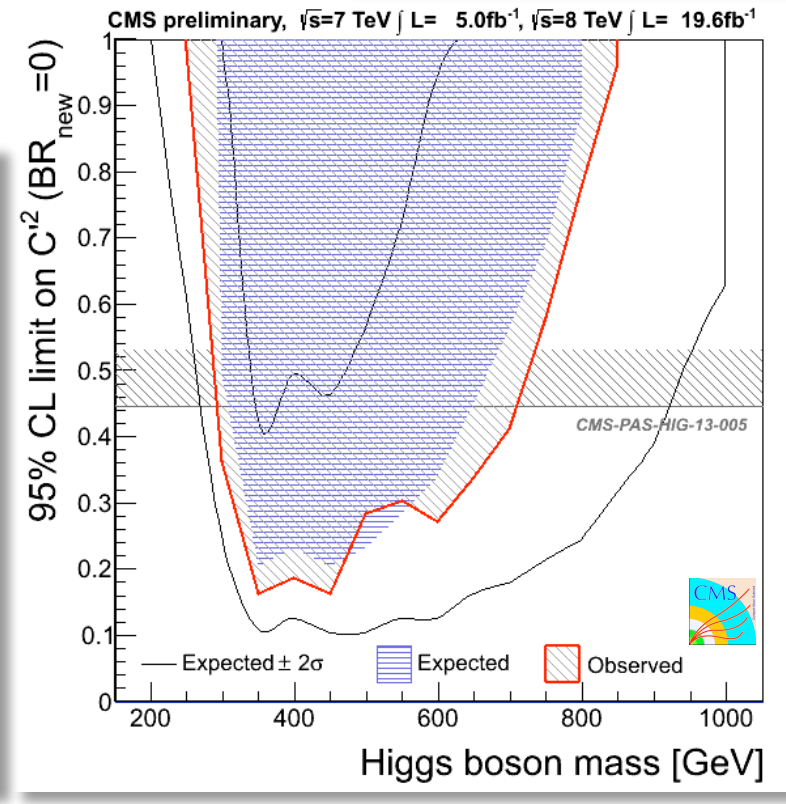
NEW!

High-Mass Higgs Boson

- A combined high-mass ZZ search to full statistics
  - Probes SM-like heavy Higgs up to ~900 GeV
  - Also explore modified couplings and reduced (by C'^2) width of an additional Higgs boson
    - $C^2 + C'^2 = 1$

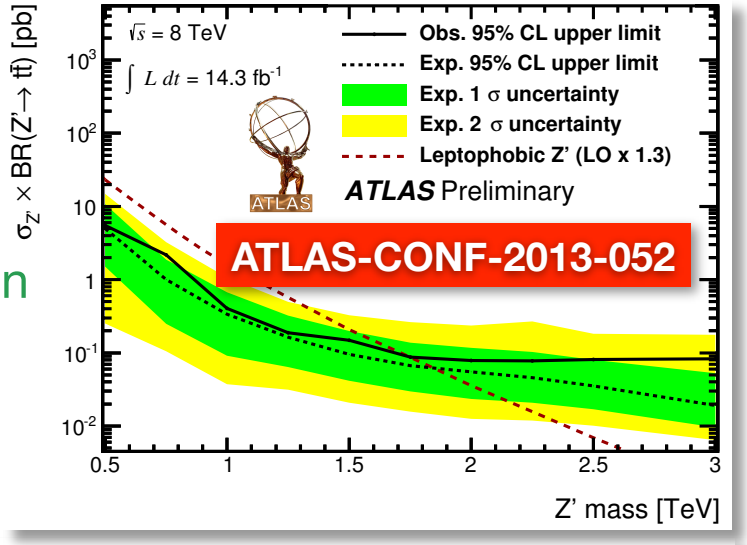
CMS PAS HIG-13-014

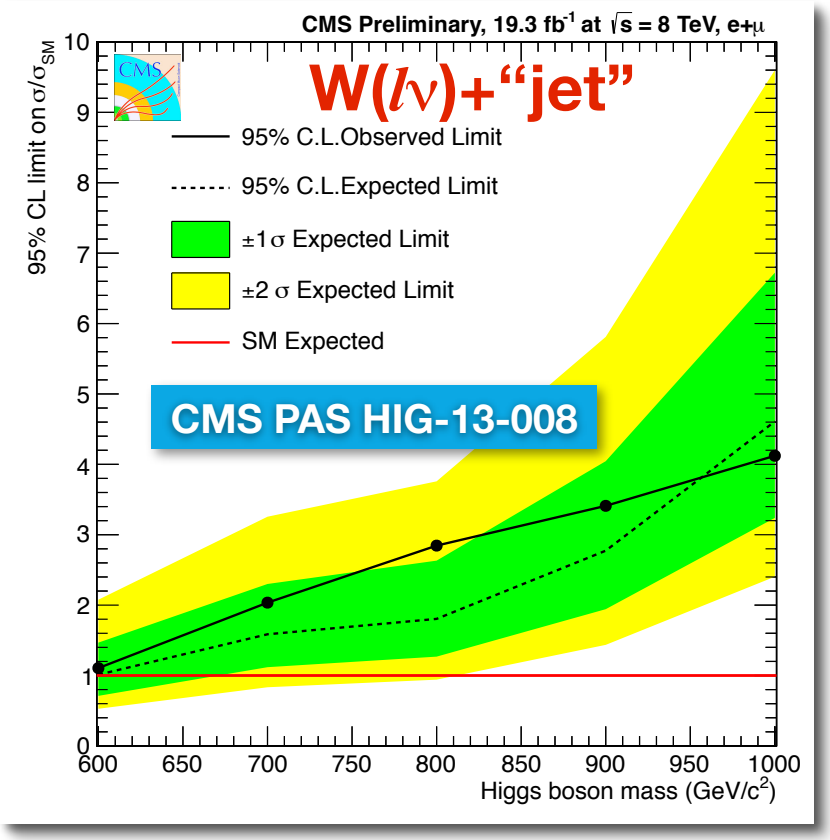


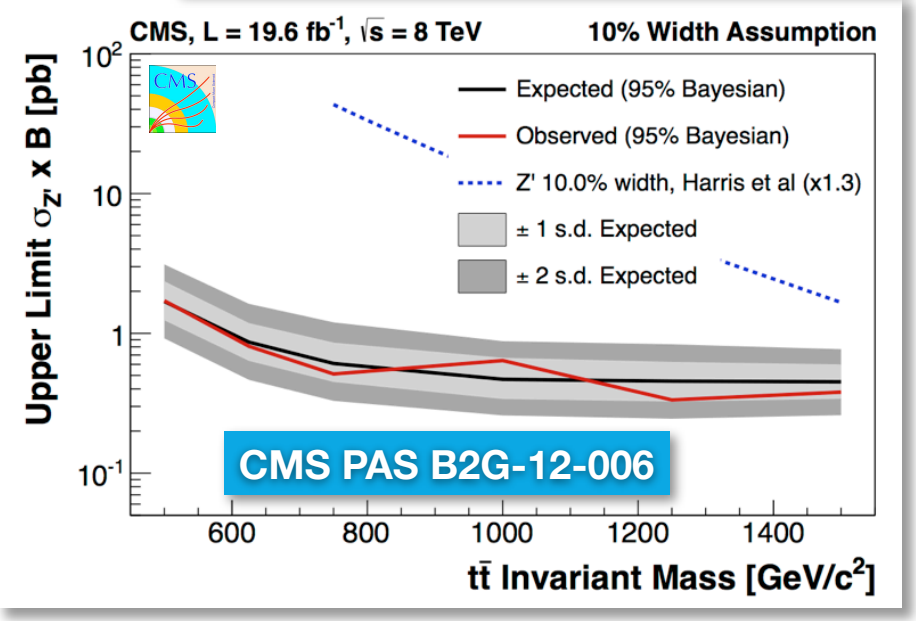


Higgs: Boosted Topology

- New search in the W(lν)W("j") channel in a boosted regime
  - Sensitive to Higgs masses above ~600 GeV
- Also tt resonance searches can be reinterpreted as limits on a heavy Higgs boson

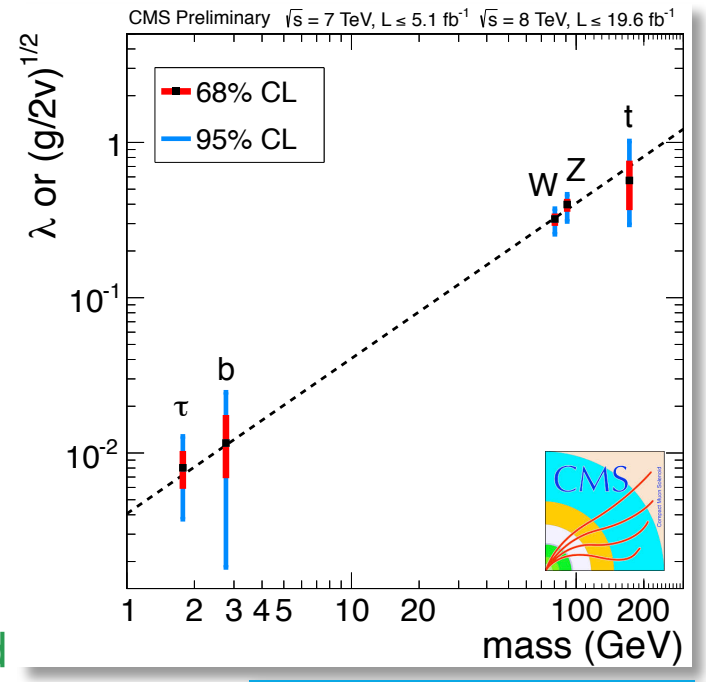






Conclusions

- Higgs physics remains the apex of the LHC program
- Amazing progress since the discovery of a Higgs boson just a year ago:
  - Seen beyond any doubts in three bosonic channels
  - Looks more and more like the SM Higgs boson
  - No evidence for non-SM decays yet
  - No evidence for additional Higgs bosons at higher or lower mass so far
- Coupling to the top quarks has been established via gluon fusion production mechanism
- Couplings to the down-type third-generation fermions are established at >3 sigma level, thanks to the Tevatron and the LHC efforts
- The spin and the mass of a new state have been determined (see next talk)
- Many new directions of studies, with an exciting LHC program that will last some two decades
  - Cf. nearly 20 years of beautiful top physics since its discovery in 1995
- The goal is to shrink the error bars to dots on the "Regge plot" above and fill it in



CMS PAS HIG-13-005

Thank You!