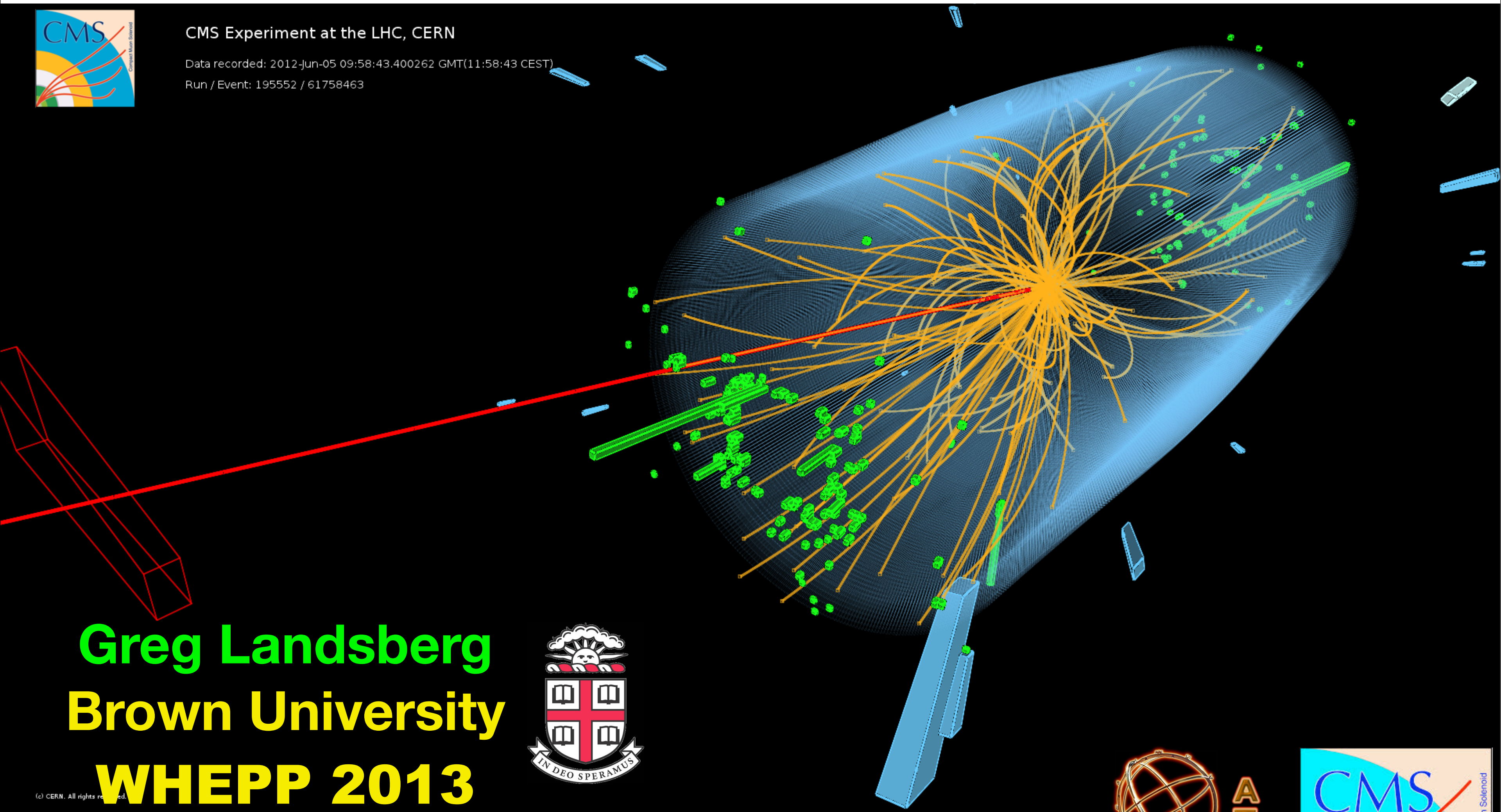
STATUS OF THE HIGGS BOSON SEARCHES AT THE LHC



Greg Landsberg
Brown University

WHEPP 2013

Puri

December 17, 2013

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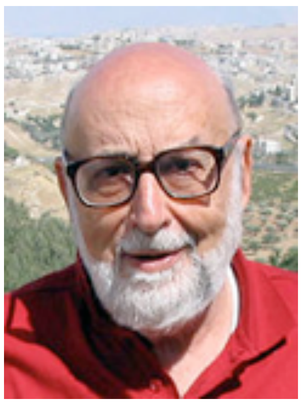
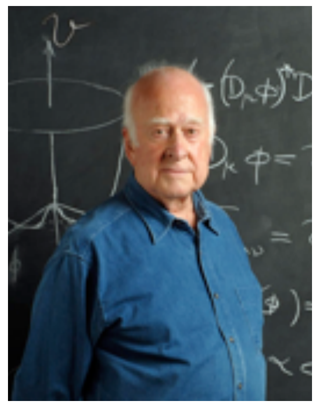
Dedication

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

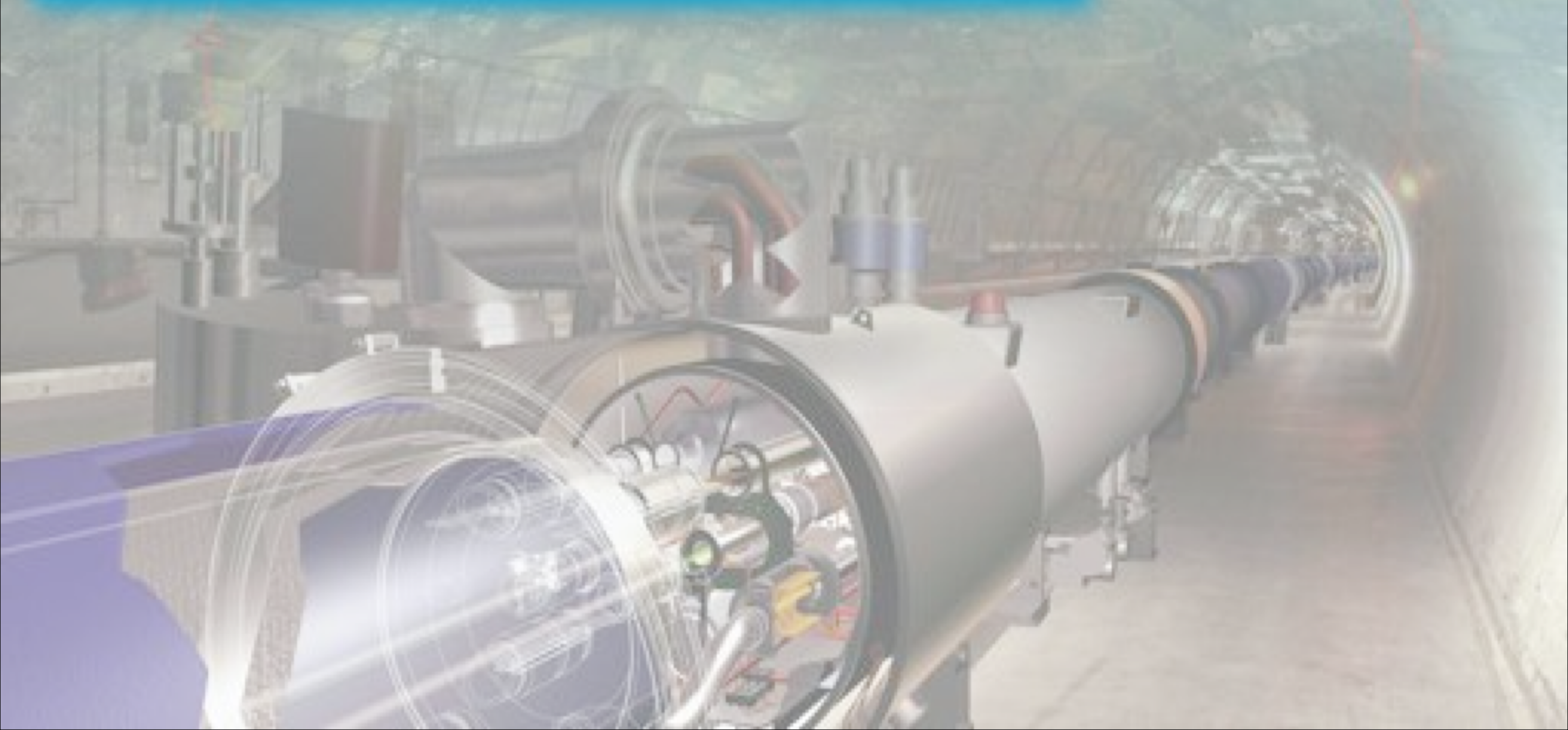
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

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

Outline

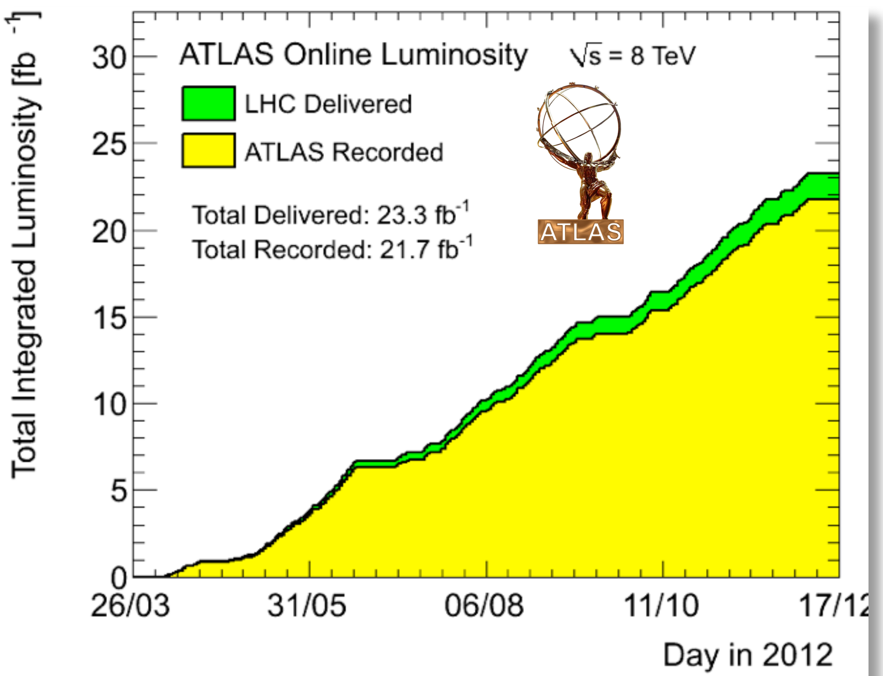
- The Higgs boson playground
- Happy birthday, Mr. Higgs!
- Higgs boson production and decay
- Experimental results:
  - Lucid Higgs boson
  - Visible Higgs boson
  - Not-yet-visible Higgs boson
  - Invisible Higgs boson
  - Invincible Higgs boson
  - Lesson from the Higgs boson discovery
- Conclusions

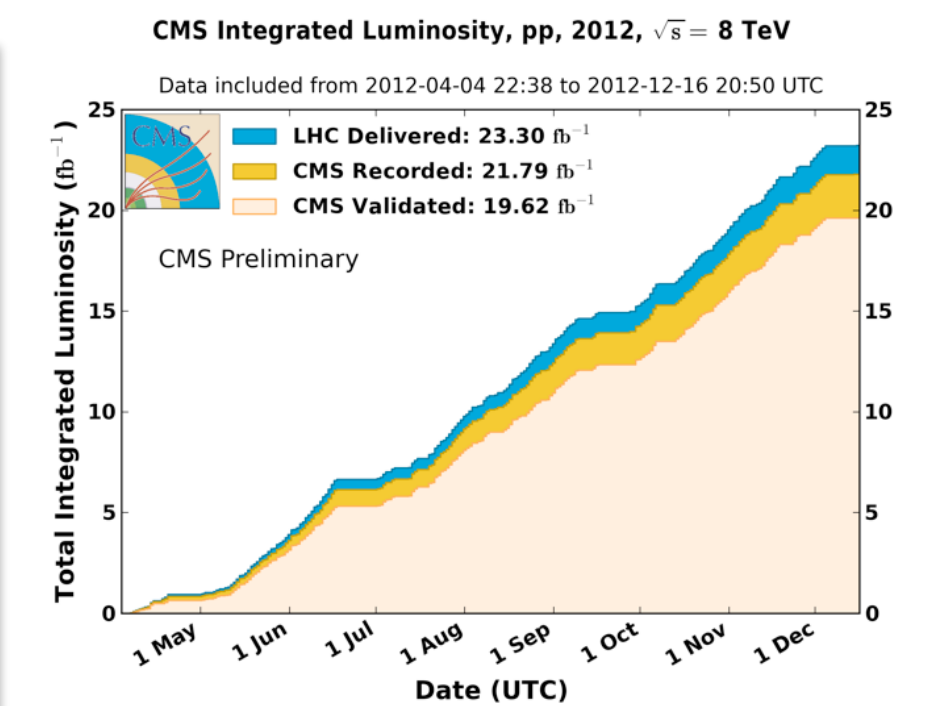
The Higgs Playground



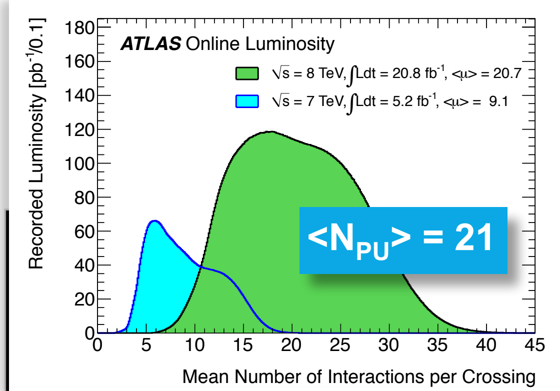
High-Quality, Plentiful Data

- 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!

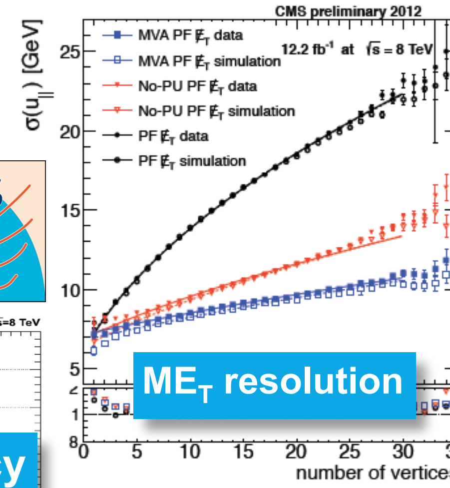


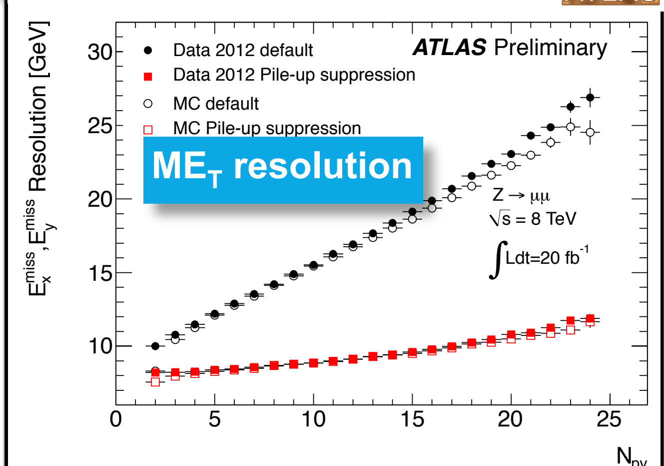


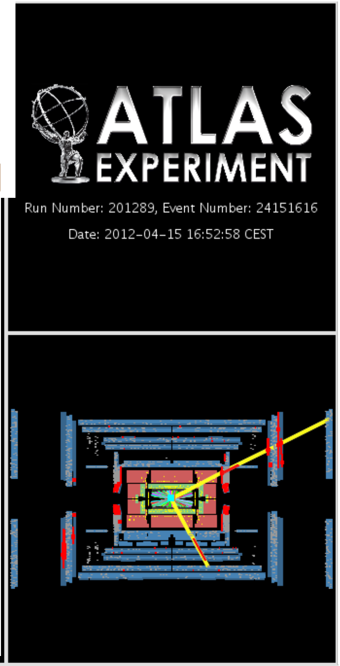
Successful Pileup Mitigation

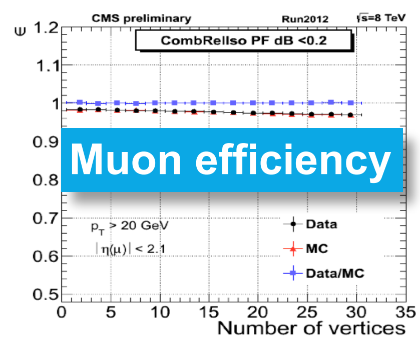


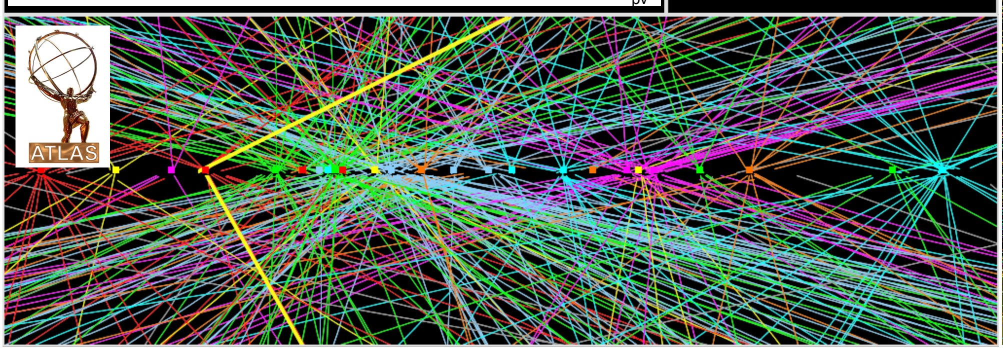
LHC already reached nominal pileup rate; experiments cope well!

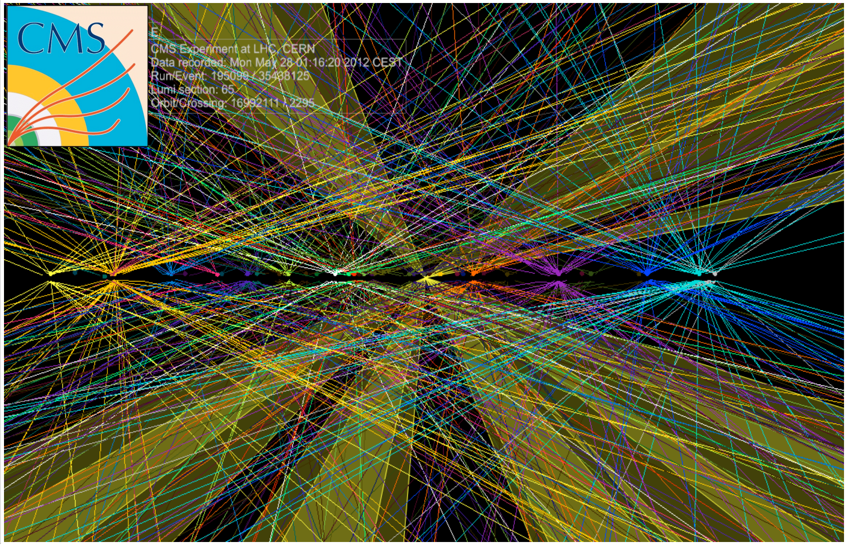








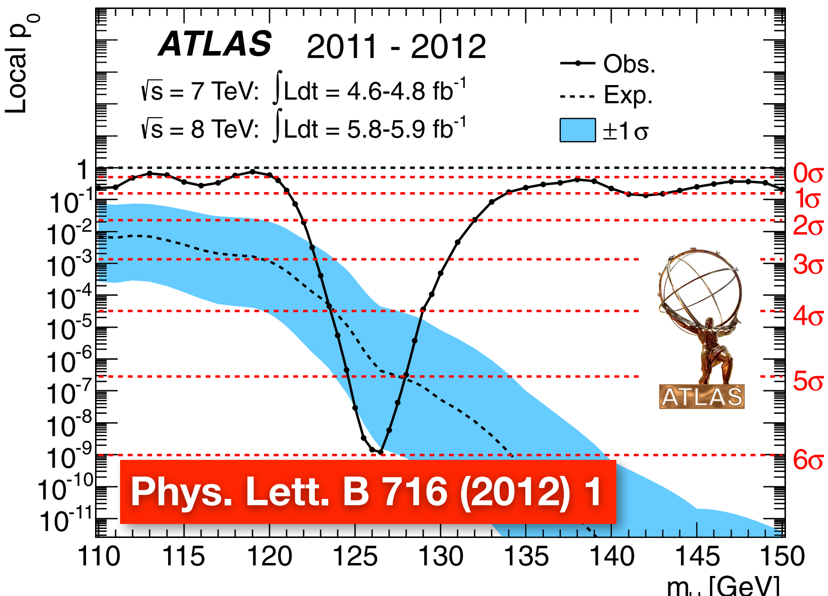




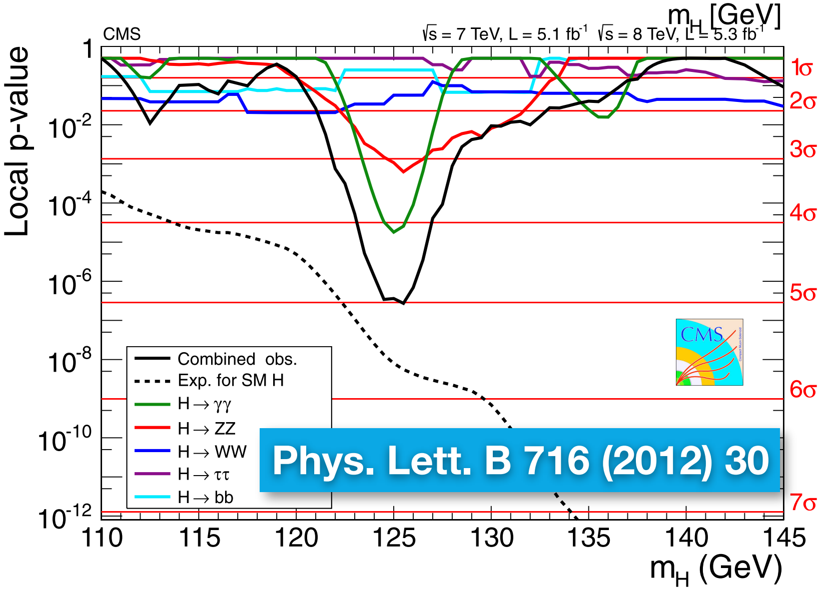
The Higgs Story

4th of July Fireworks

A New Boson Discovery



Phys. Lett. B 716 (2012) 1



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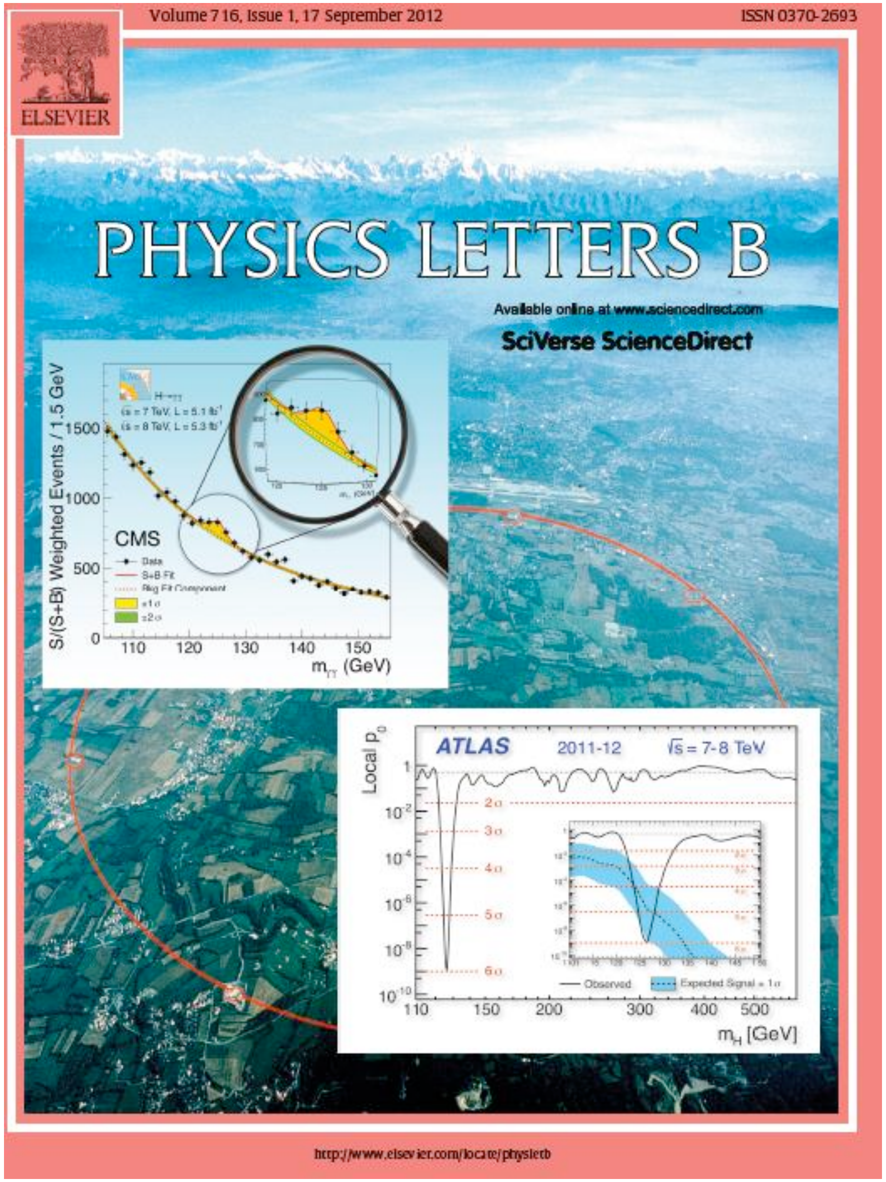

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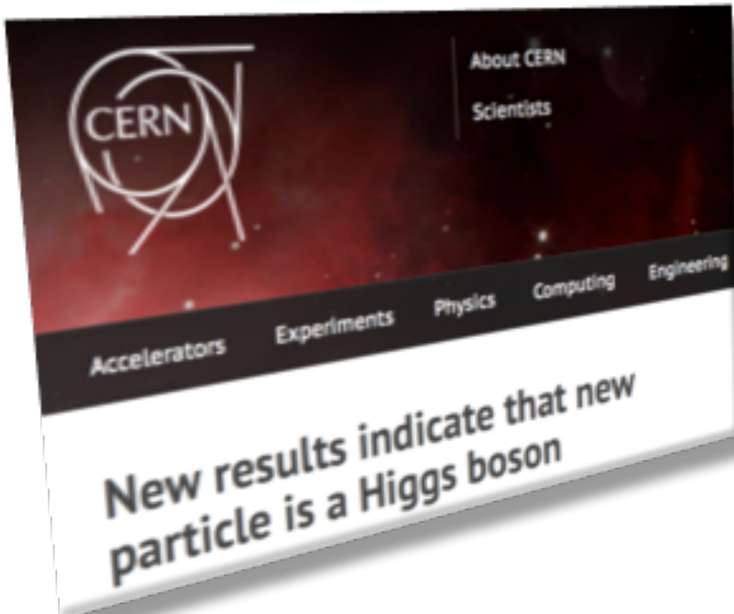
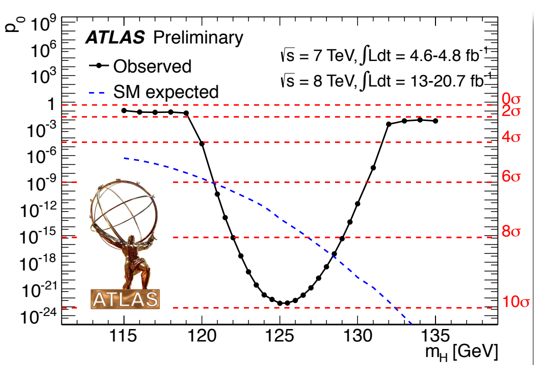
Moriond 2013 - What a Week!



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 $\tau\tau$)

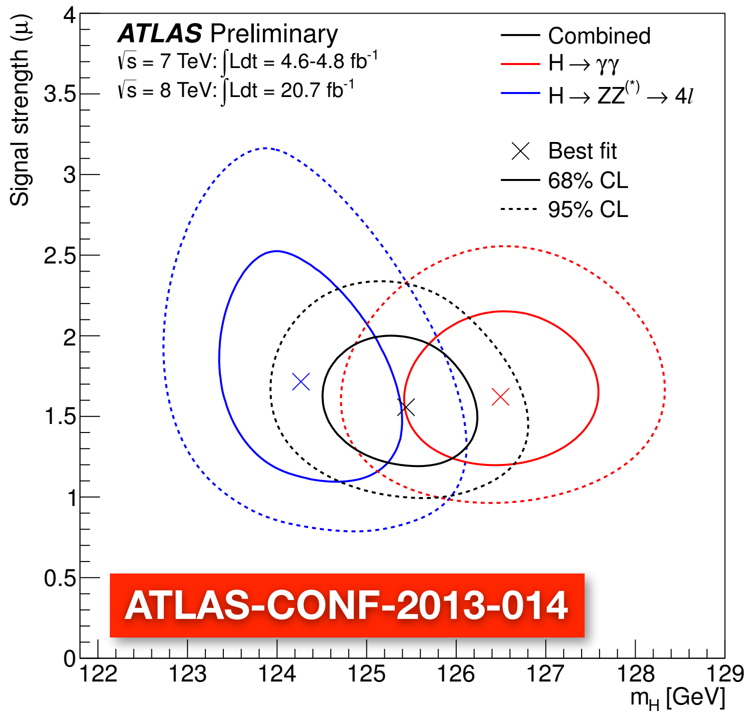


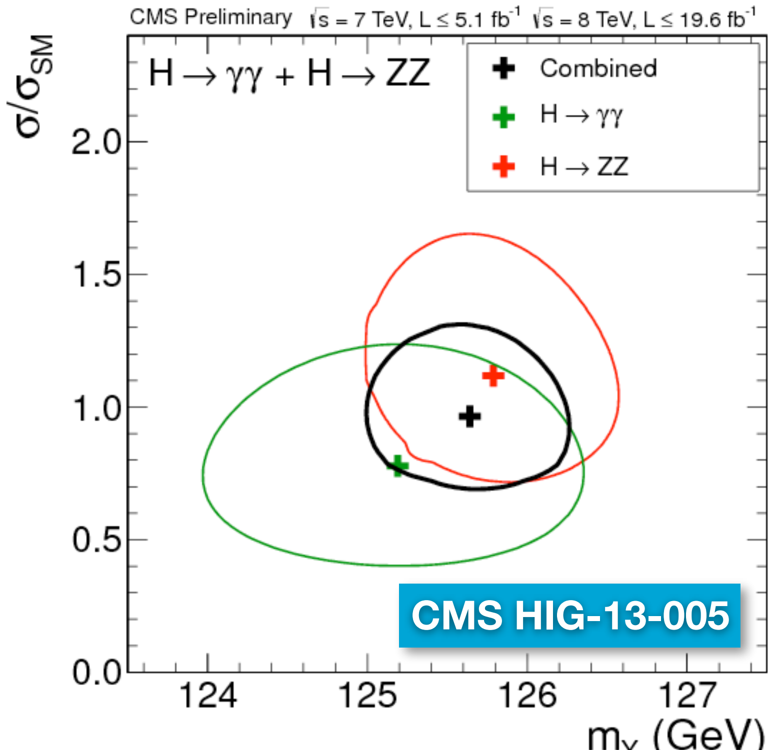
CMS PAS HIG-13-005

	Significance (m_H = 125.7 GeV)		
Combination	**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 Boson Mass

- Higgs boson mass:
  - ATLAS: $M_H = 125.5 \pm 0.2\ ^{+0.5}_{-0.6}$ GeV (0.43% precision)
  - CMS: $M_H = 125.7 \pm 0.3 \pm 0.3$ GeV (0.34% precision)
- The Higgs boson mass has been already measured to a better precision than the top (or any other quark!) mass (0.50%)

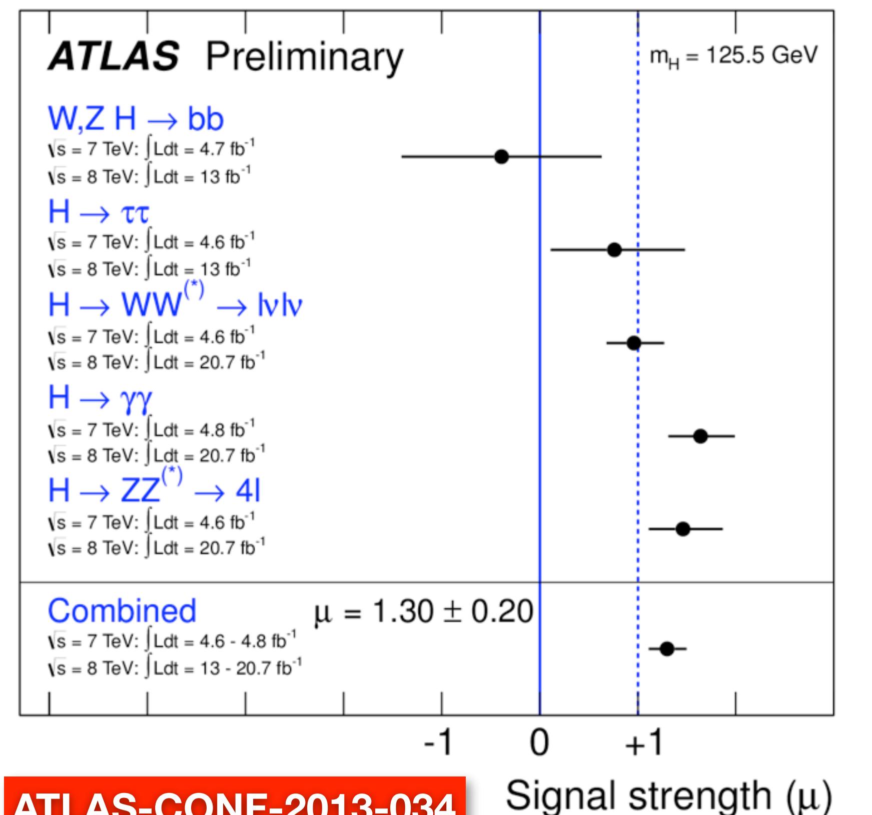




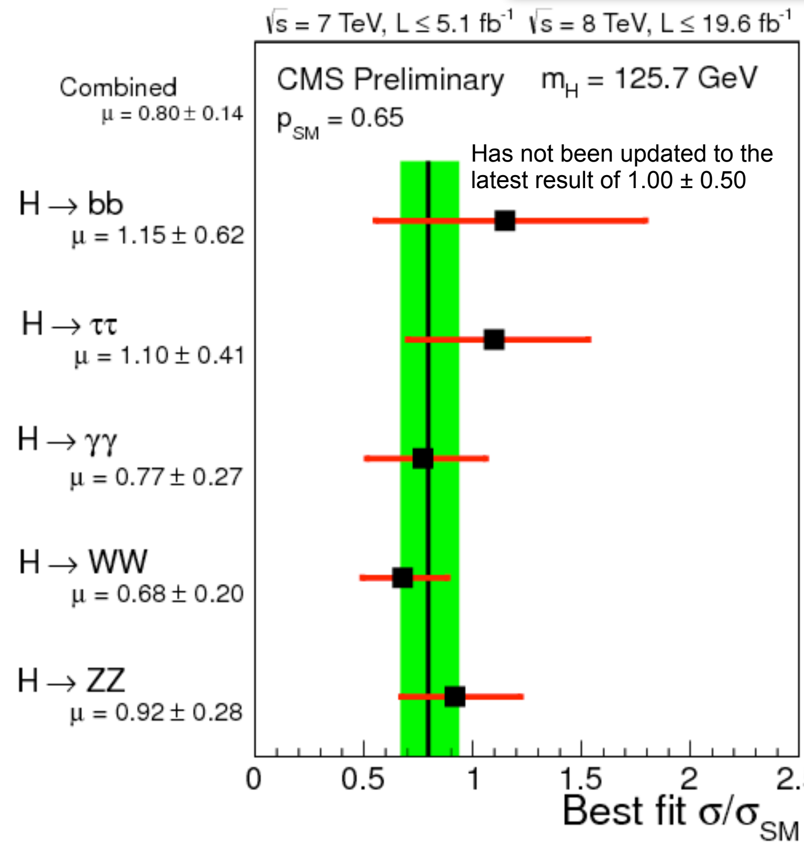
Higgs Boson Signal Strength

- Consistency with the SM Higgs boson:
  - ATLAS: $\mu = 1.30 \pm 0.20$ @ 125.5 GeV
  - CMS: $\mu = 0.80 \pm 0.14$ @ 125.7 GeV

CMS HIG-13-005



ATLAS-CONF-2013-034



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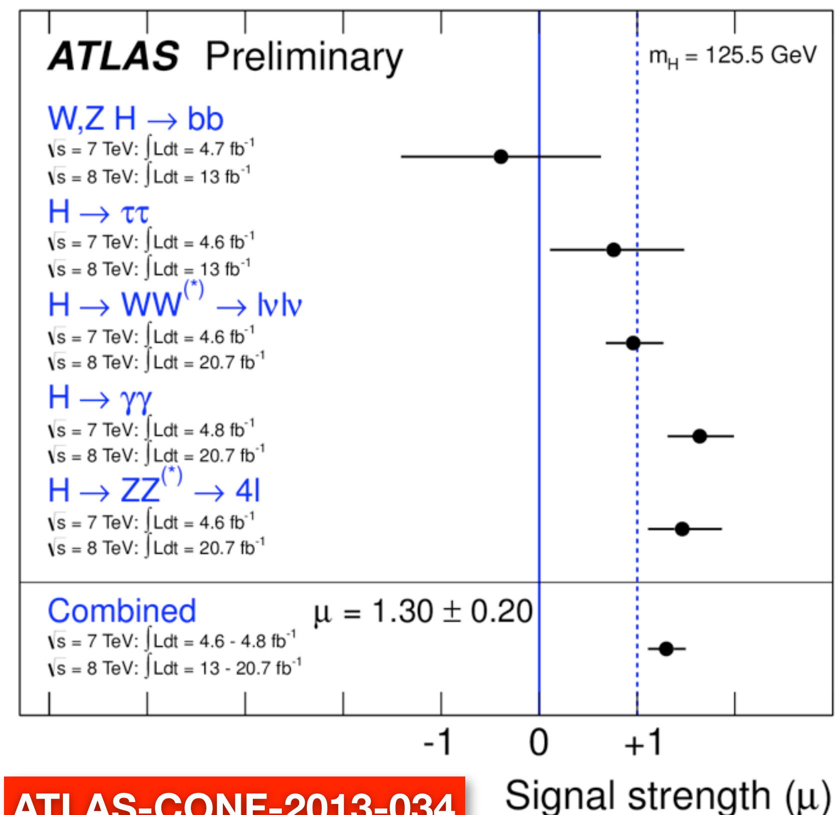
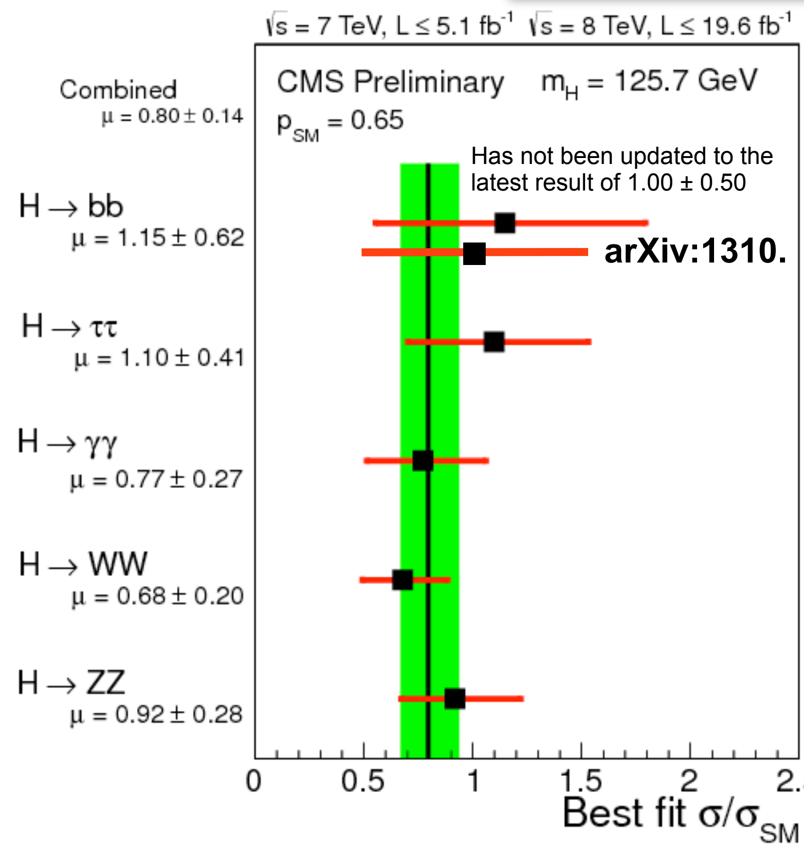
CMS HIG-13-005



ATLAS-CONF-2013-034



Higgs Boson Spin

- Both ATLAS and CMS strongly prefer $J^{PC} = 0^{++}$ over the alternatives
  - Pseudoscalar 0^{-+} and tensor 2^{++} hypotheses have been excluded at ~3σ level by each experiment

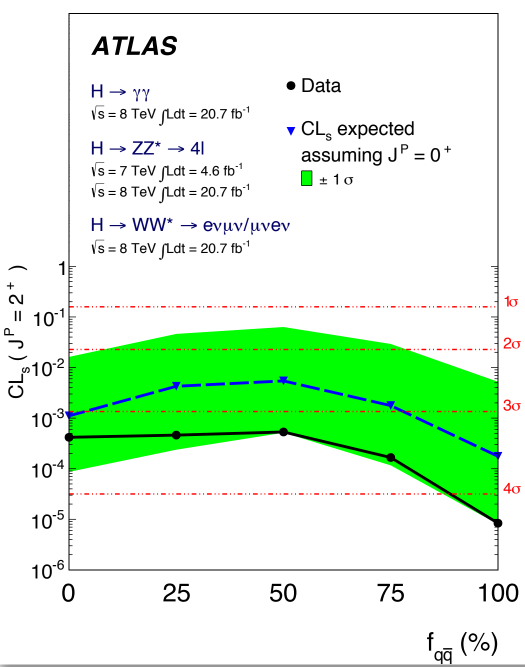
CMS HIG-13-002

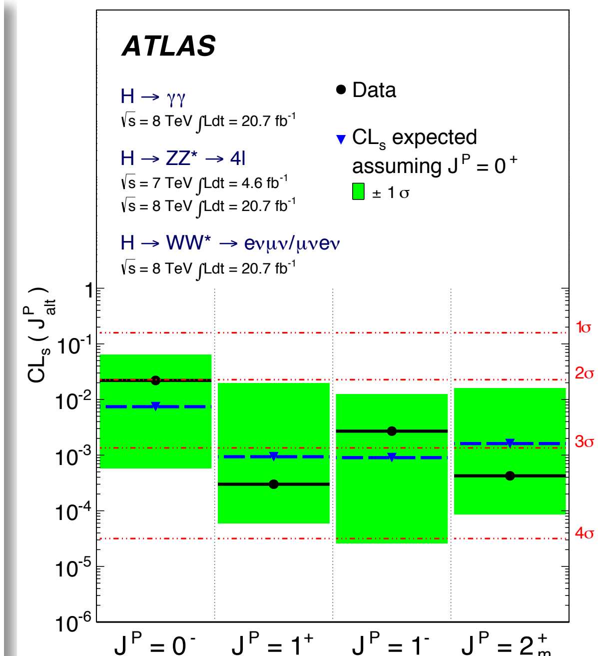
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%

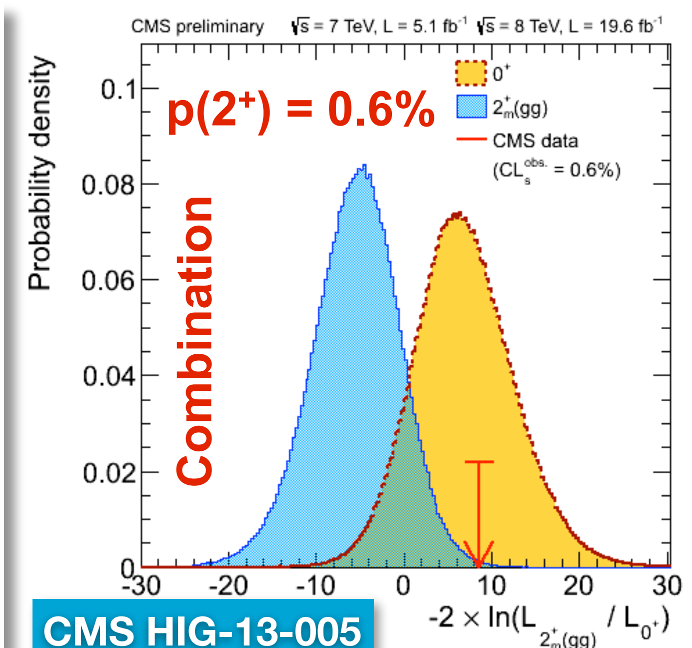
ATLAS Collaboration arXiv:1307.1432

0^- is excluded at 97.8% CL
1^+ is excluded at 99.97% CL
1^- is excluded at 99.7% CL
2^+ is excluded at >99.9% CL

H(ZZ) alone



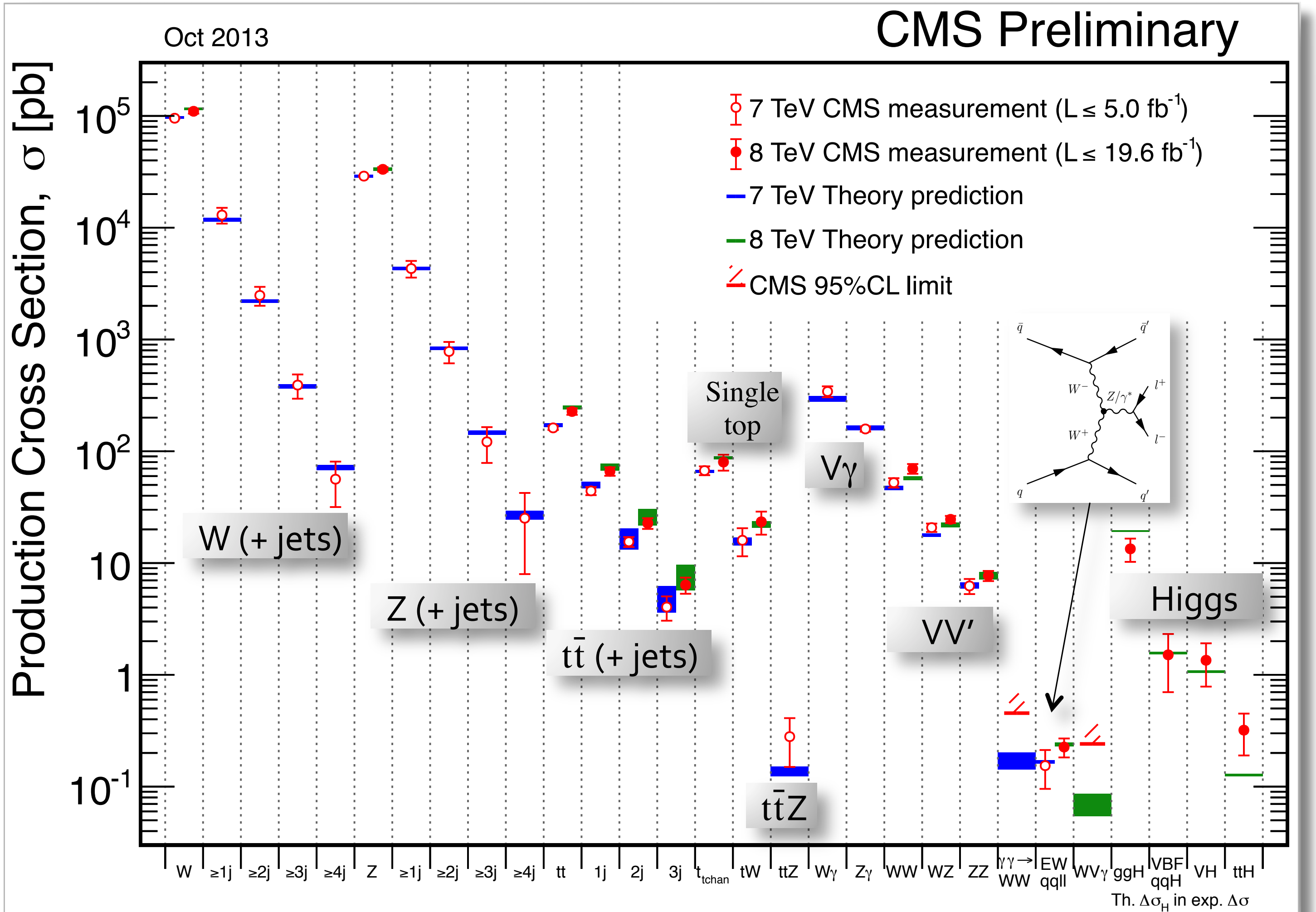




CMS HIG-13-005

The Road to the Holy Grail

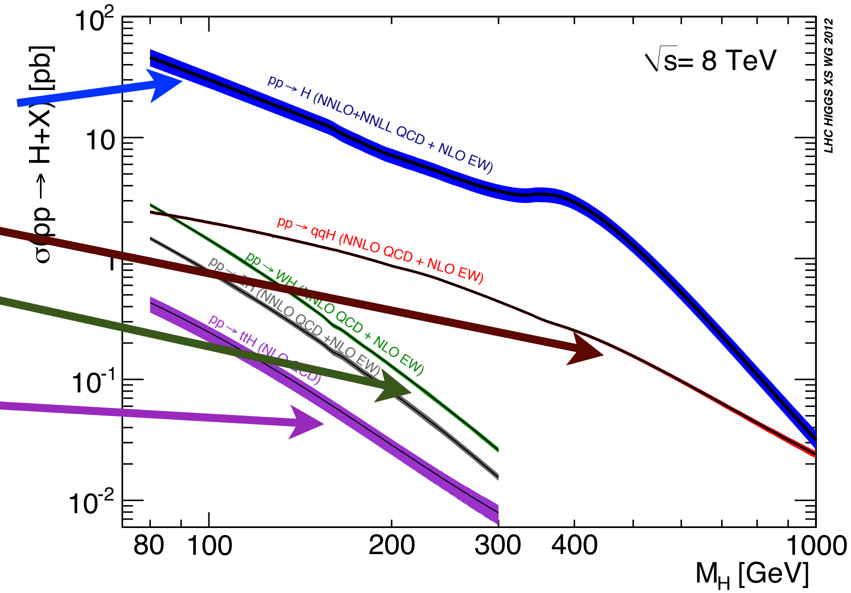
- Impressive host of SM measurement leading to the Higgs boson discovery and measurement of its properties

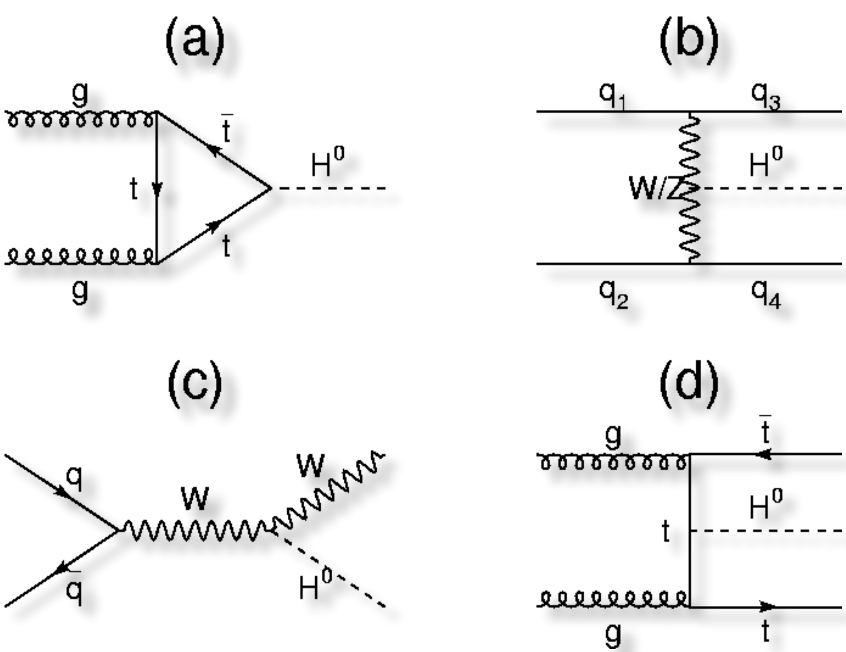


Higgs: Production and Decay

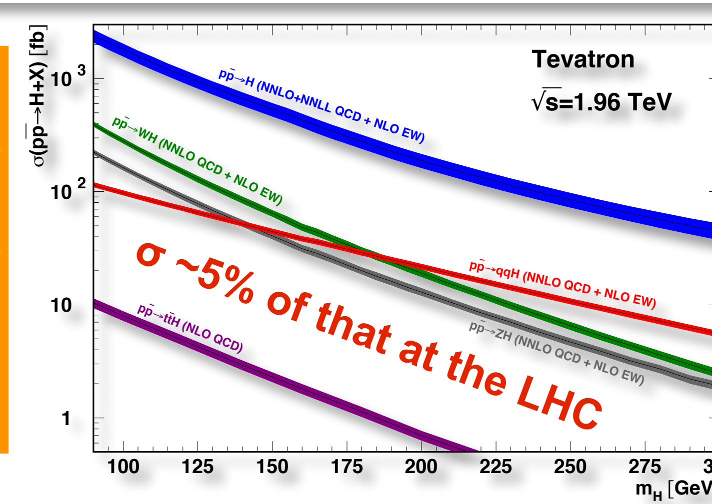
Higgs Boson Production

- 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



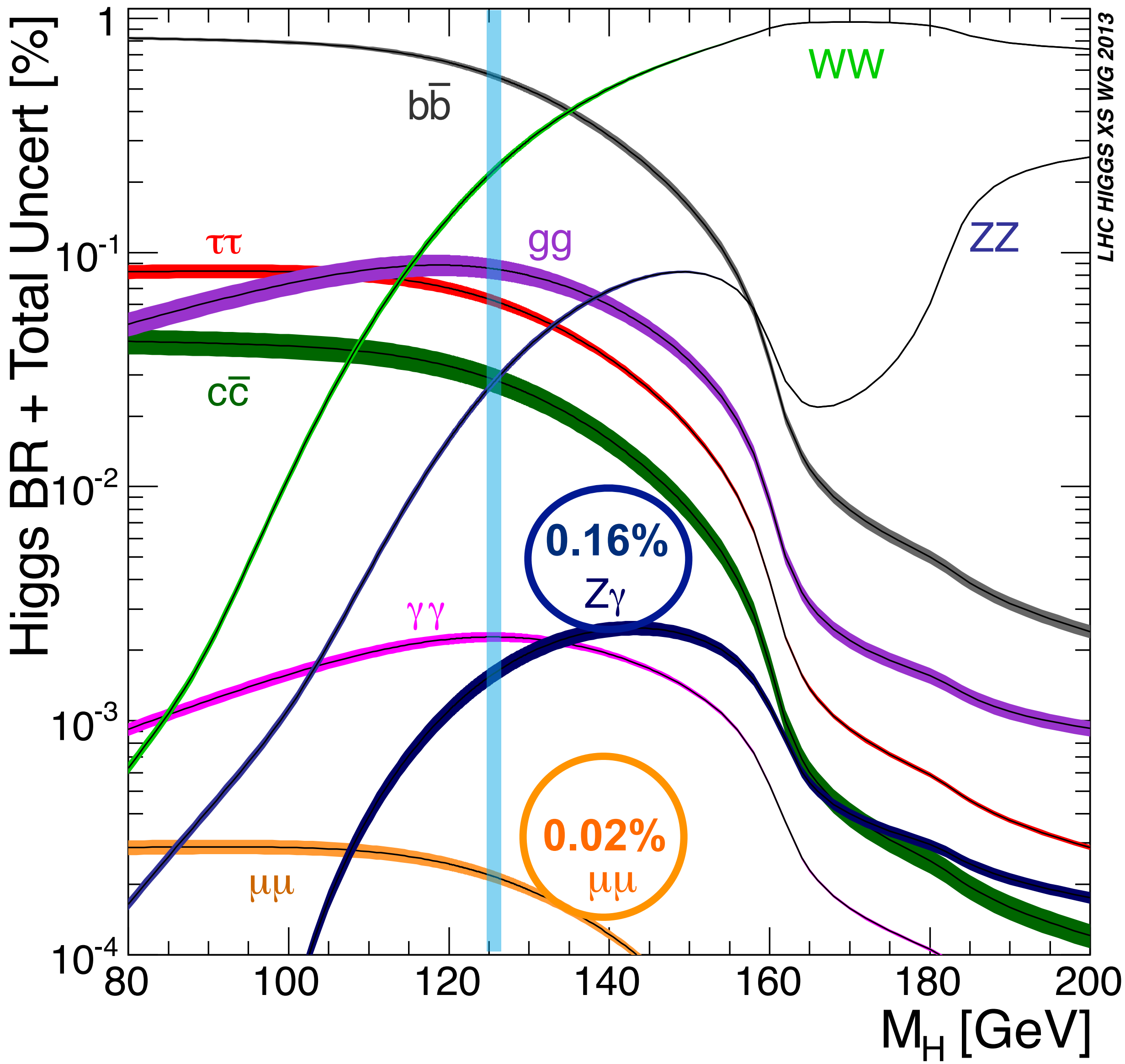


Baglio, Djouadi JHEP 10 (2010) 064



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%



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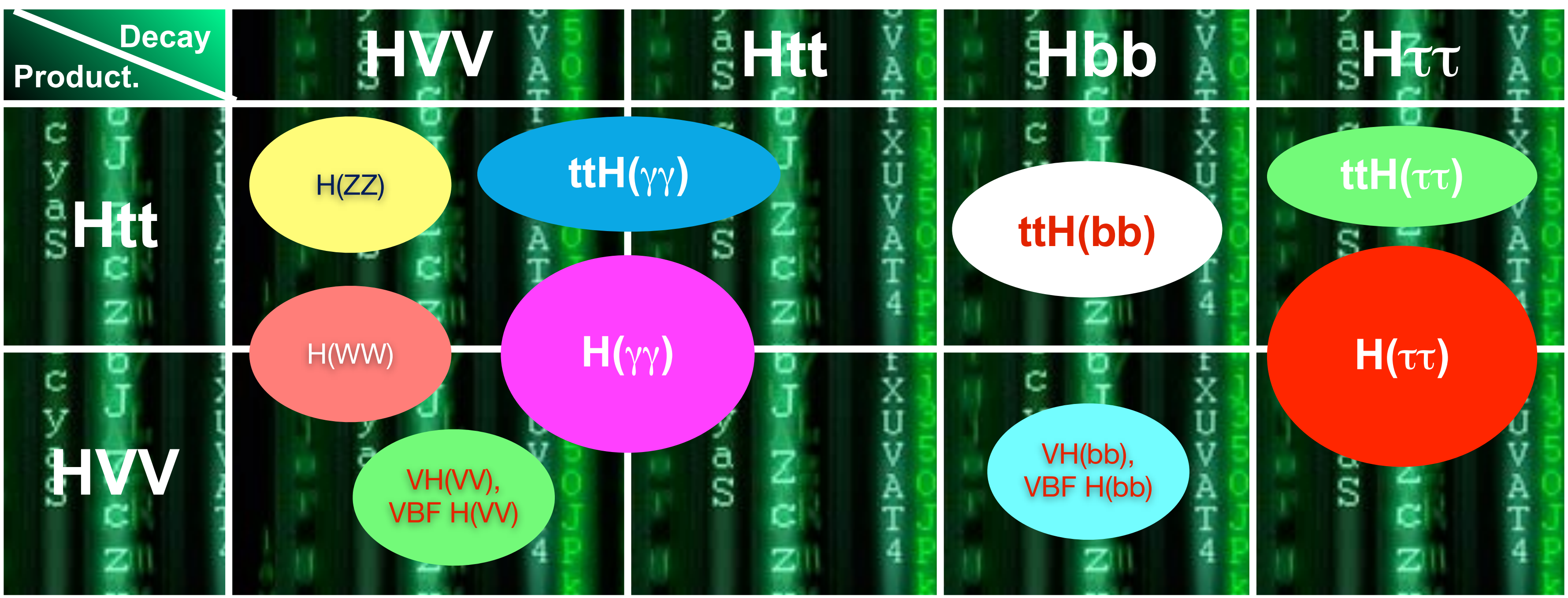
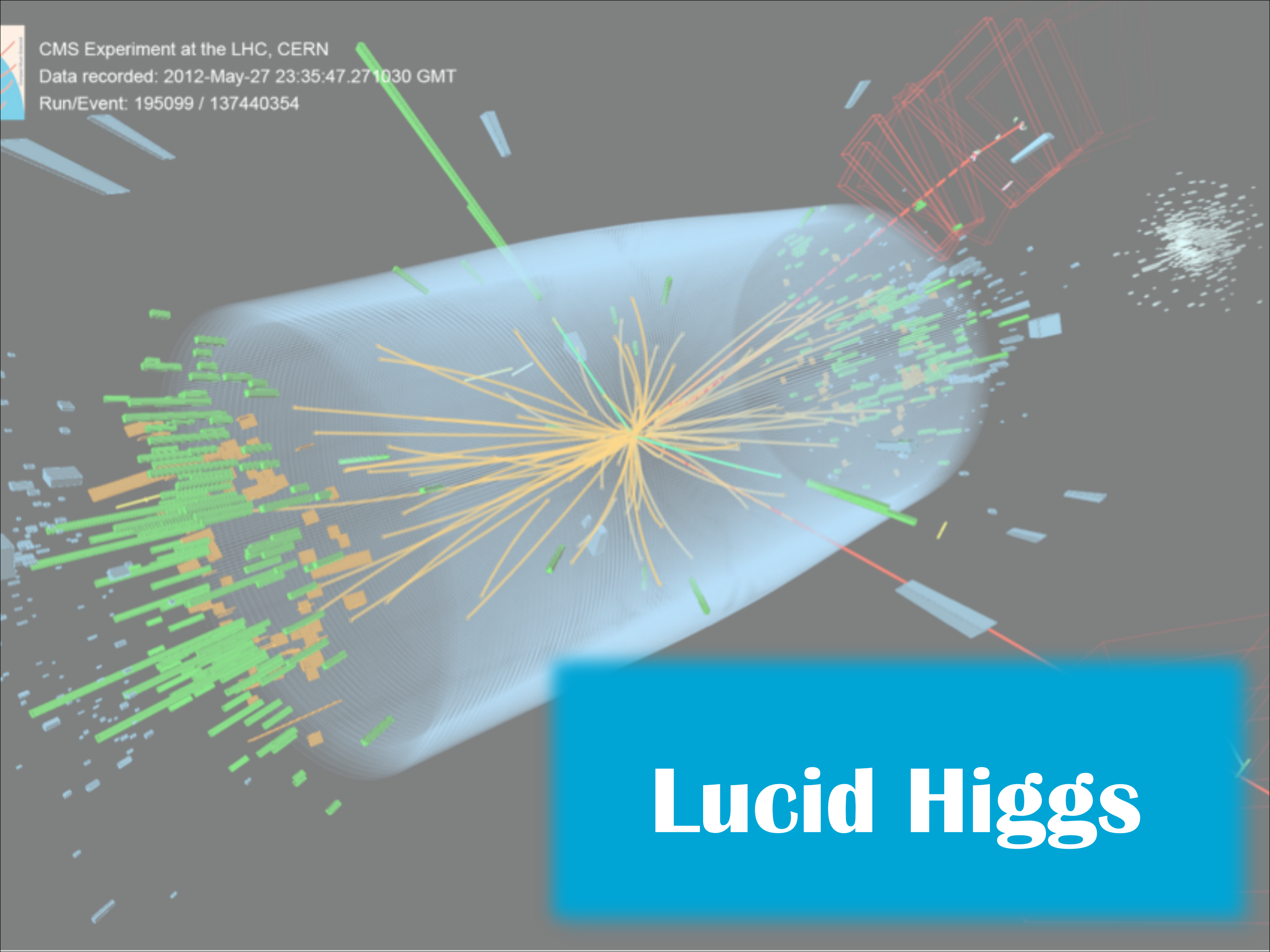
The Matrix

- Production ⊕ decay are always sensitive to a linear combination of products of two couplings:
  - Simple example: $\sigma(gg \to H(ZZ \to 4l)) \sim |\kappa_{tt}\, \kappa_{ZZ}|^2 = \kappa_{tt}^2 \kappa_{ZZ}^2$
  - More complex: $\sigma(ttH \to H(\gamma\gamma)) \sim |\kappa_{tt}(\kappa_{tt} - \alpha\kappa_{WW})|^2 = \kappa_{tt}^4 + \alpha^2\kappa_{tt}^2\kappa_{WW}^2 - \alpha\kappa_{tt}\kappa_{WW}$
- Not easy to disentangle couplings; requires model assumptions
  - Practically, only the H(γγ) channels offer direct sensitivity to the sign of the couplings (VBF and gg fusion have very little interference), unless we succeed with qb → q′tH



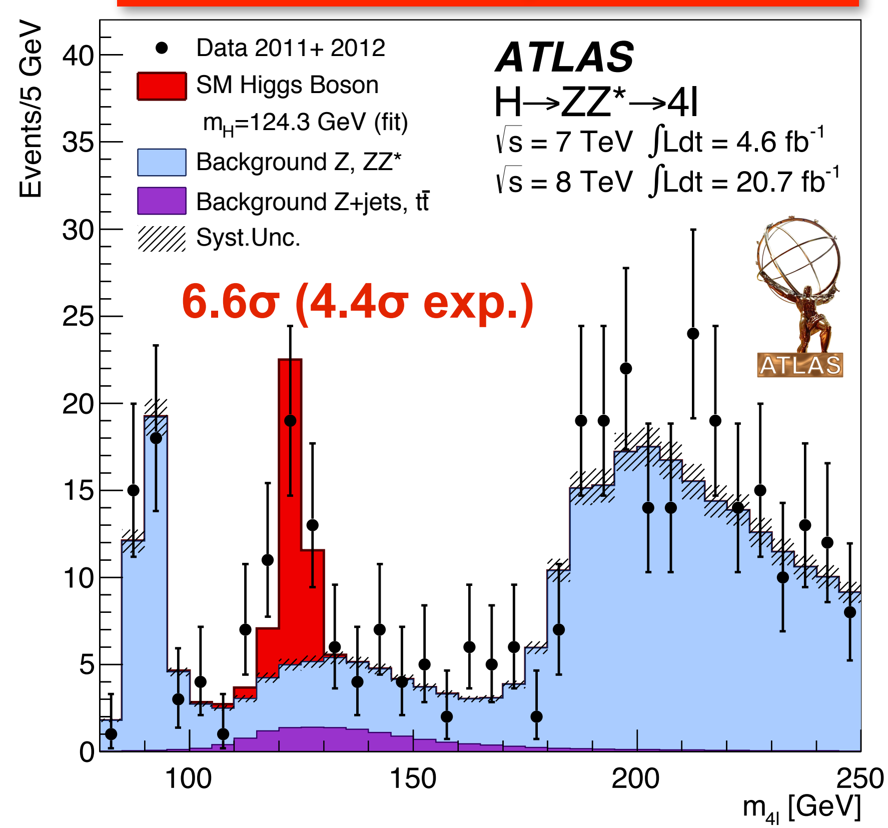

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

Lucid Higgs

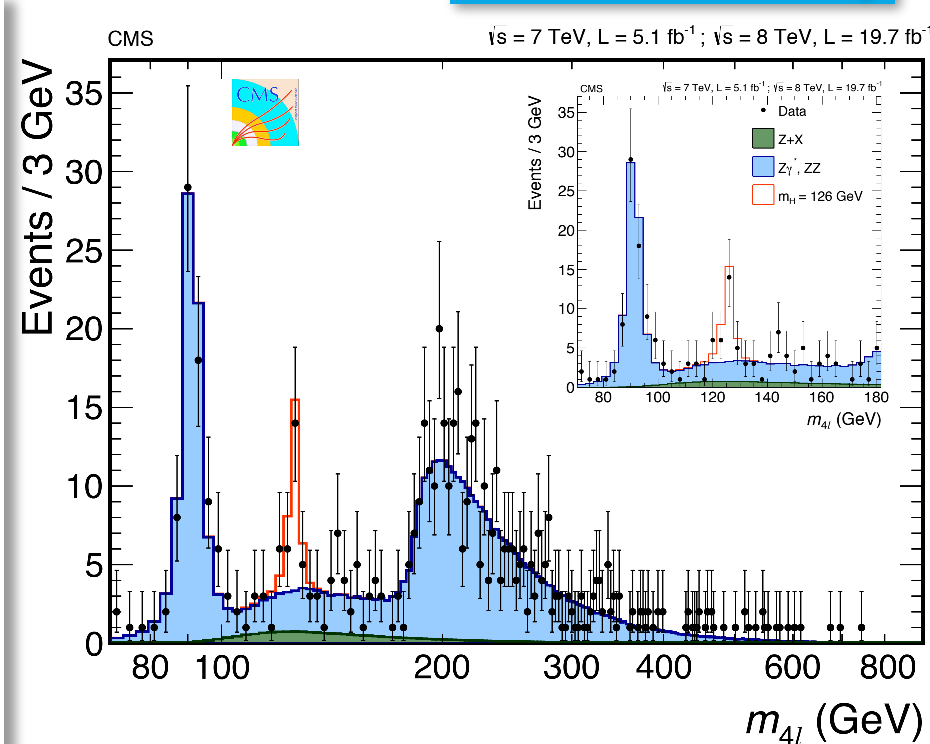
H(ZZ→4l)

- ✦ 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 to be submitted today

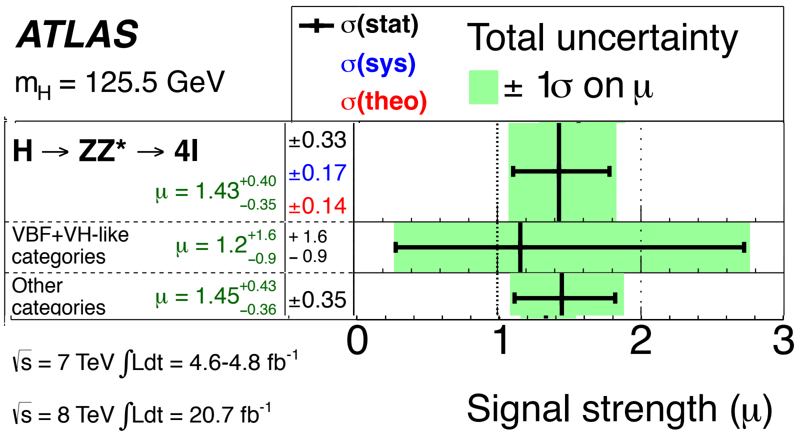


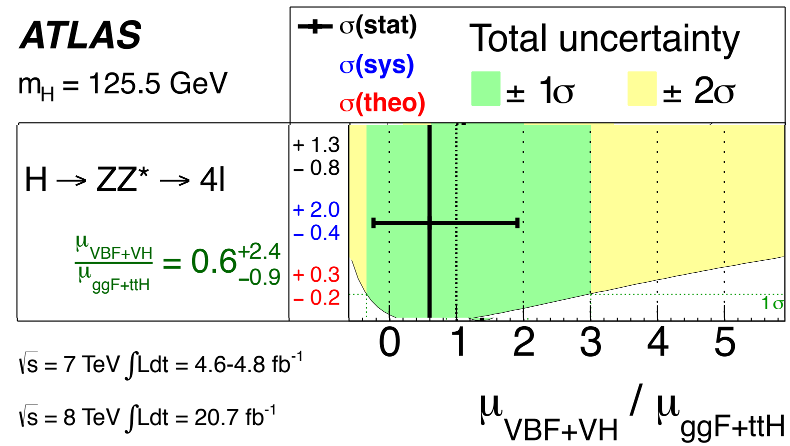
6.8σ (6.7σ exp.) @ 125.7 GeV

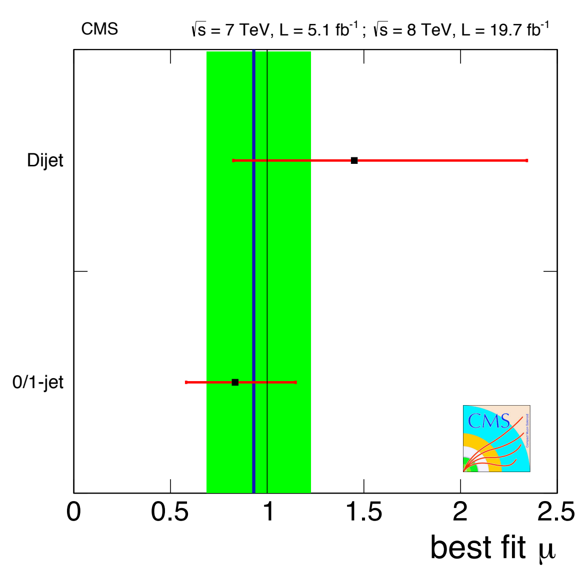
H(ZZ→4l) Results

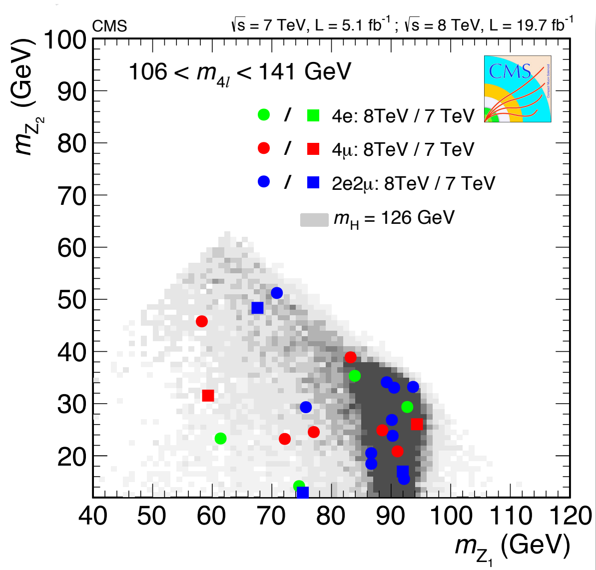
ATLAS Collaboration, arXiv:1307.1427

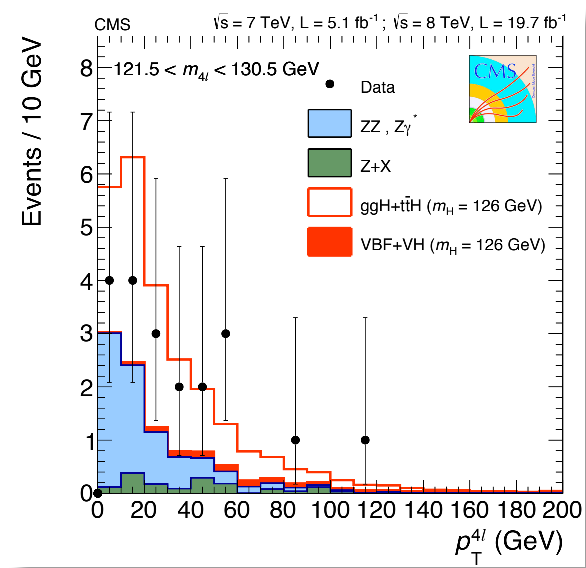
$m_H = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV











$\mu = 0.93^{+0.26}_{-0.23}{}^{+0.13}_{-0.09}$

CMS PAS HIG-13-002

$m_H = 125.6 \pm 0.4 \pm 0.2$ GeV

Seeing Light Higgs w/ Light

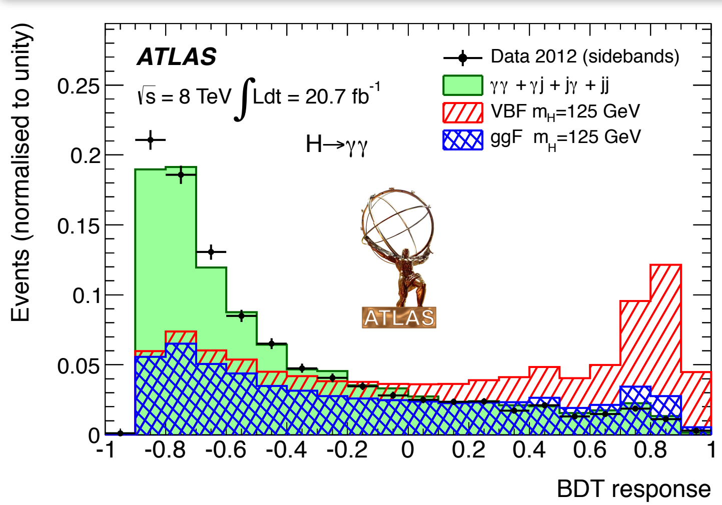
- One of the most challenging and sensitive channels:
  - Small branching fraction (0.23%), compensated by large cross section
  - Large QCD background from direct diphotons, and direct photons with j → γ
    - Thorough optimization; background estimated from sidebands
  - Ambiguity with primary vertex 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!)

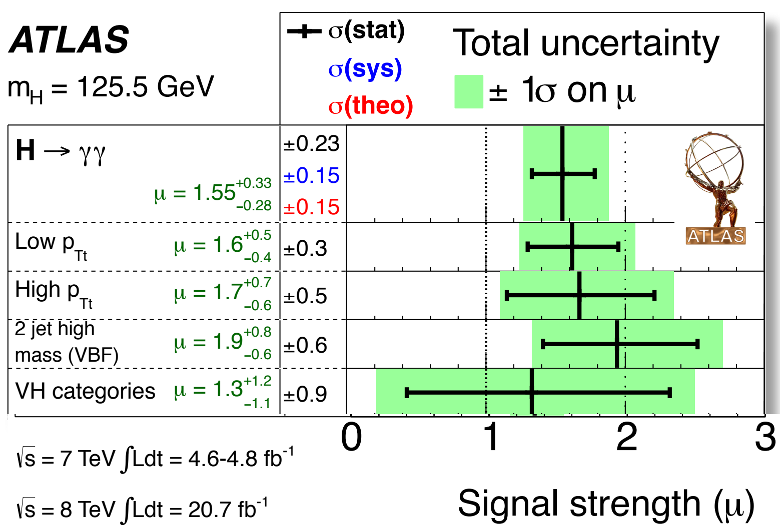
ATLAS H(γγ) Results

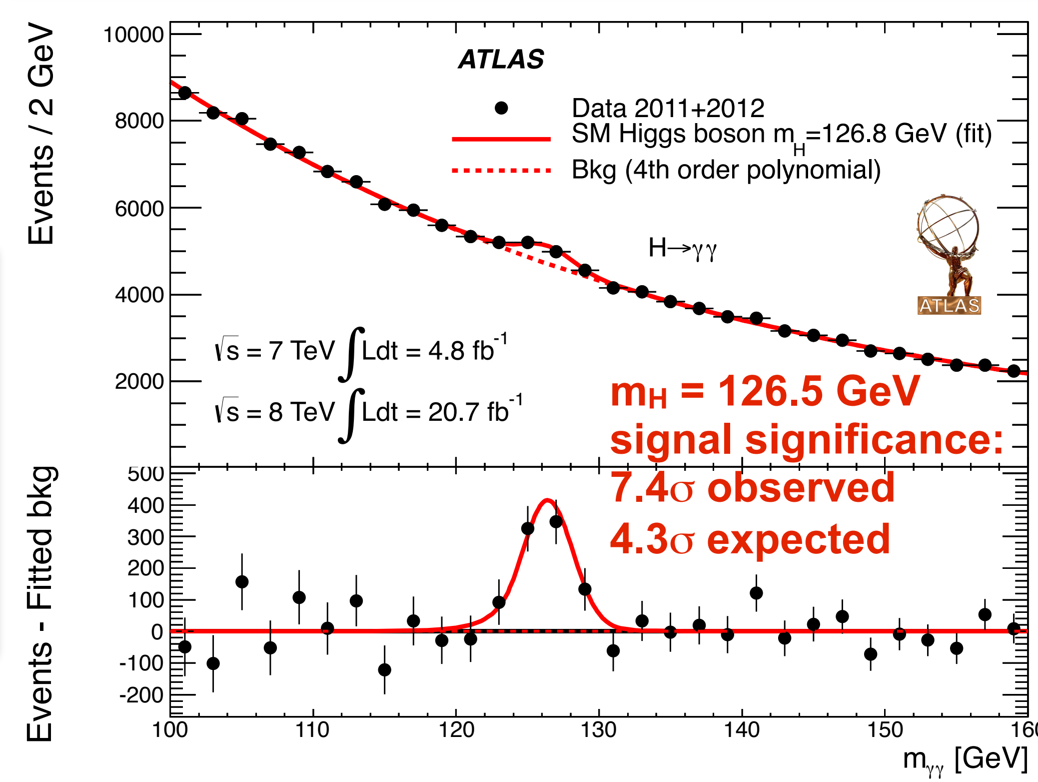
ATLAS Collaboration, arXiv:1307.1427

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





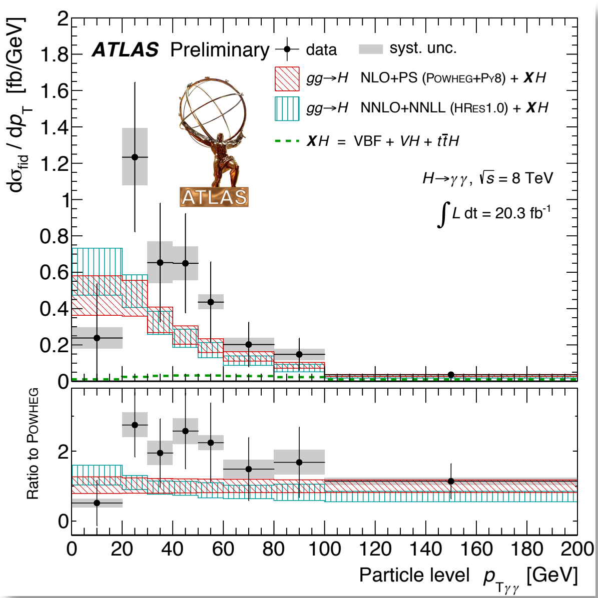


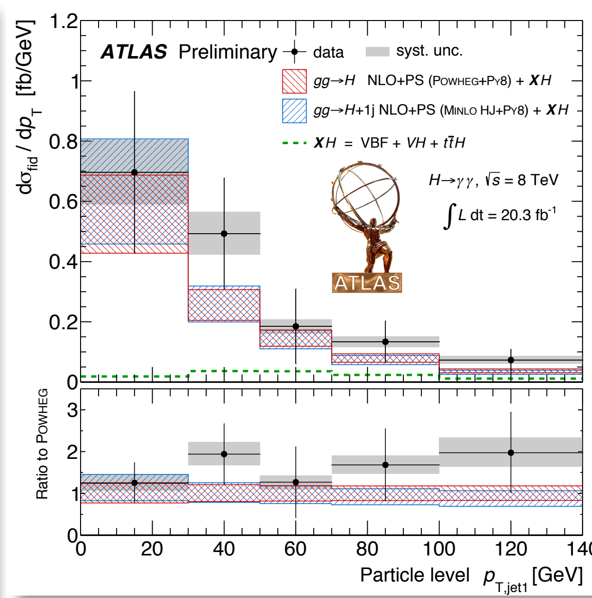
m_H = 126.5 GeV
signal significance:
7.4σ observed
4.3σ expected

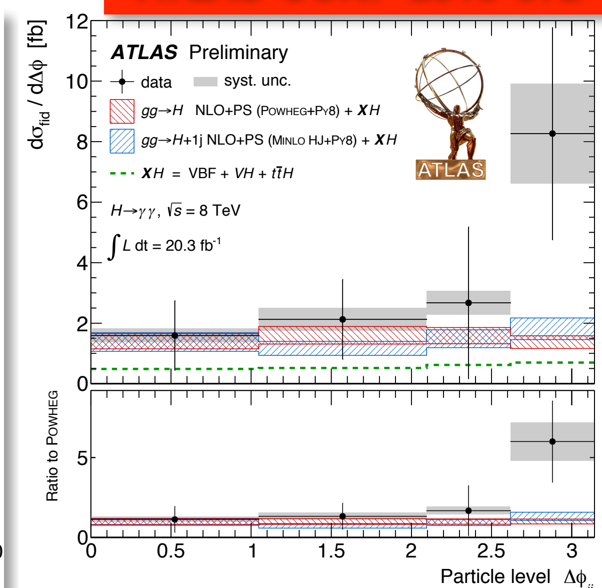
Differential Measurements

- "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





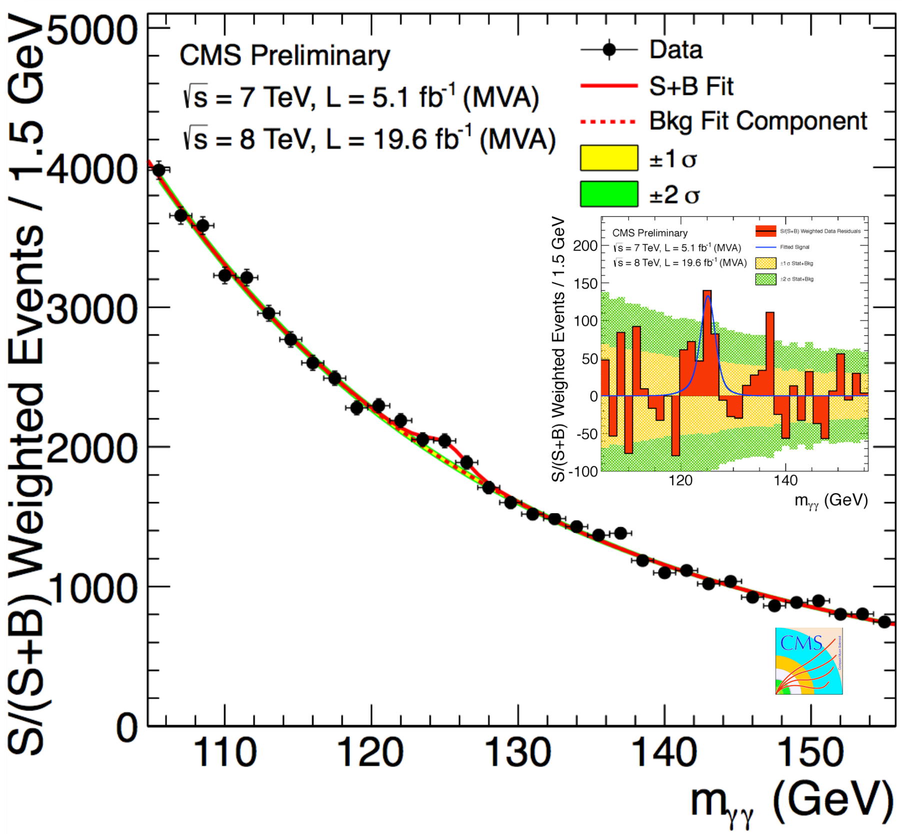


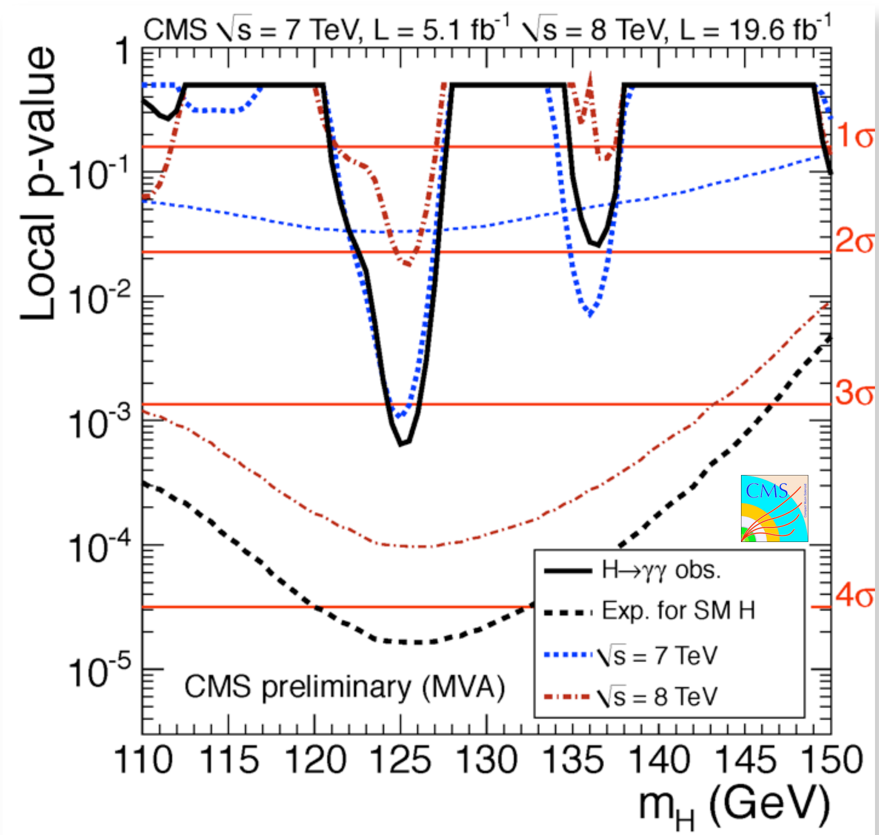
CMS H(γγ) Results

- 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	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$





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	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
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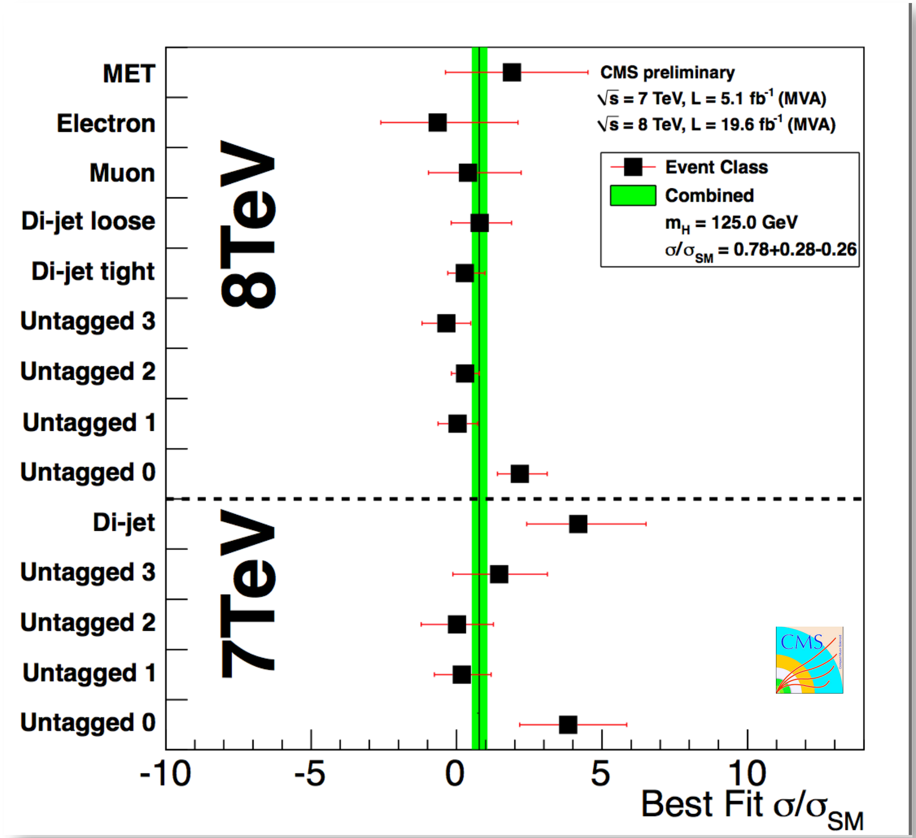
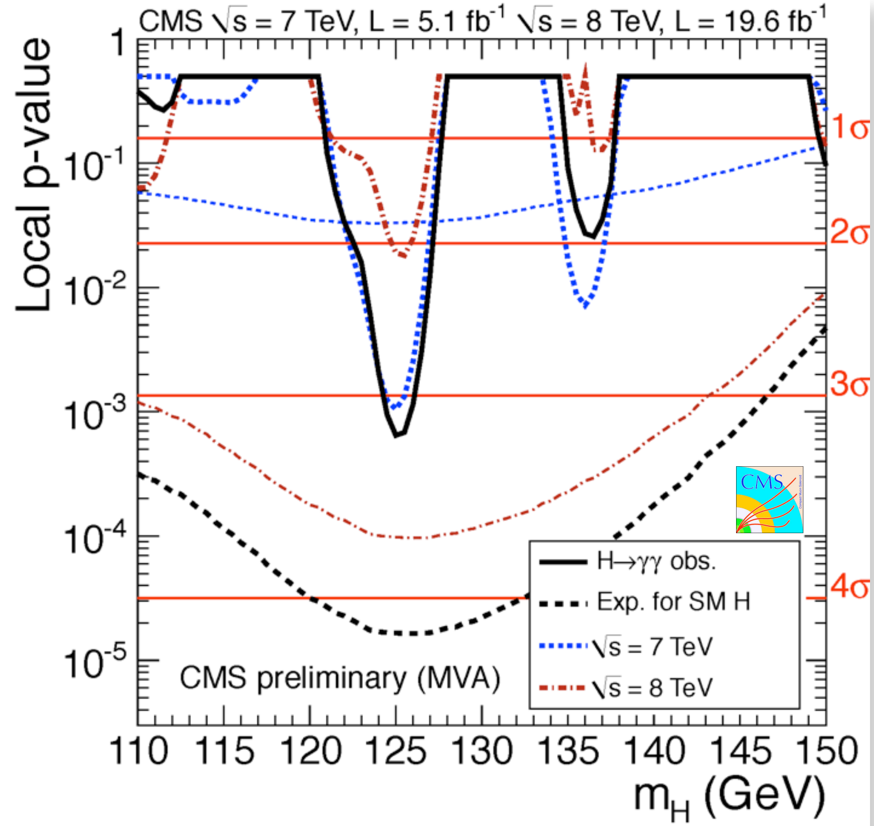
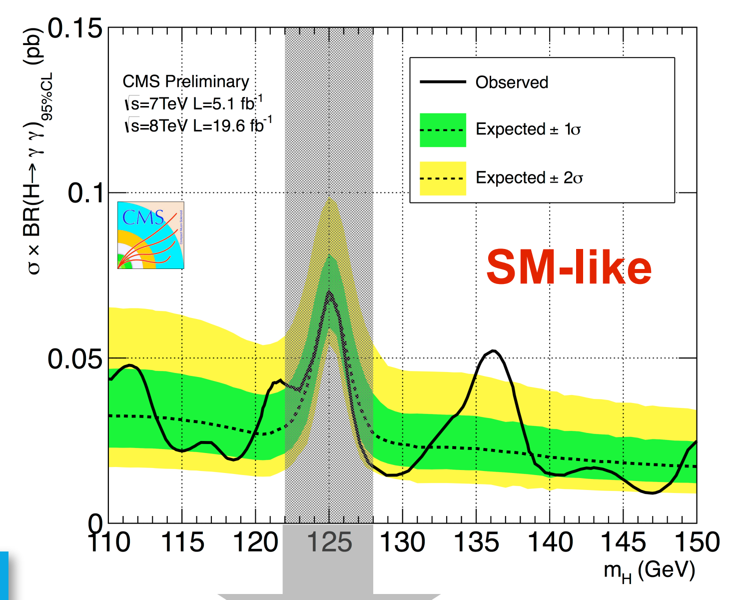




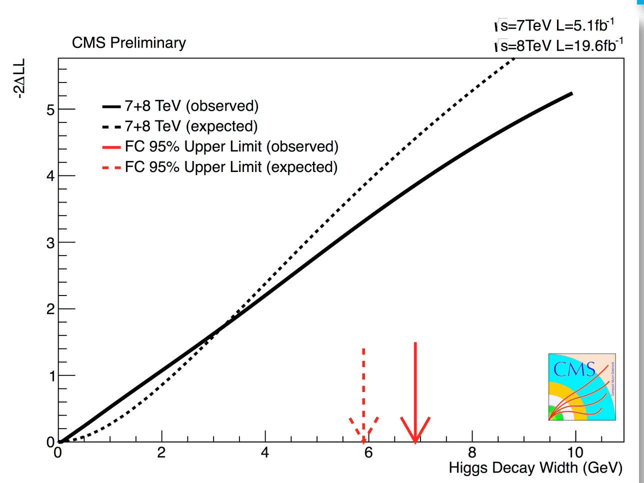
Angular/Width Analysis

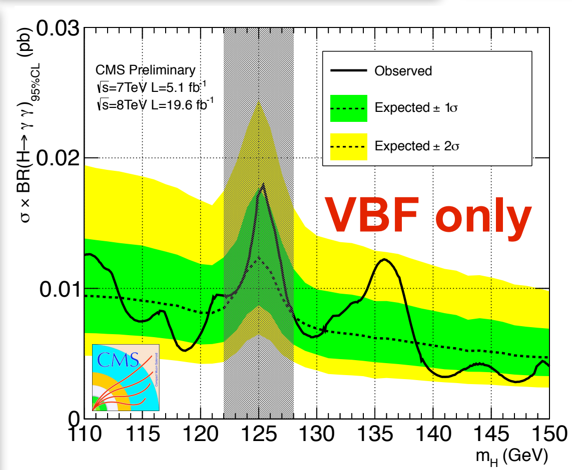
- Use CiC/MVA H(γγ) analyses to:
  - Look for additional Higgs bosons (with SM-like couplings; in gg fusion only; and VBF only)
  - Look for nearly mass-degenerate additional Higgs bosons
  - Set a limit on the Higgs boson width
  - Study the Higgs boson spin-parity
- $\Gamma_H < 6.9$ (5.9 exp.) GeV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

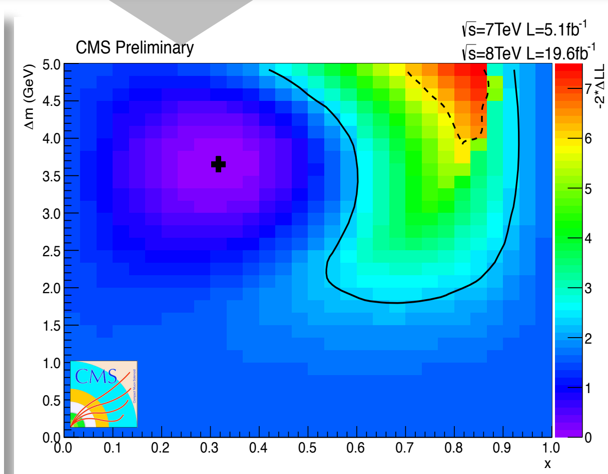
$(\sigma \times Br)_{SM}$ = 0.044 pb @ 8 TeV



CMS PAS HIG-13-016

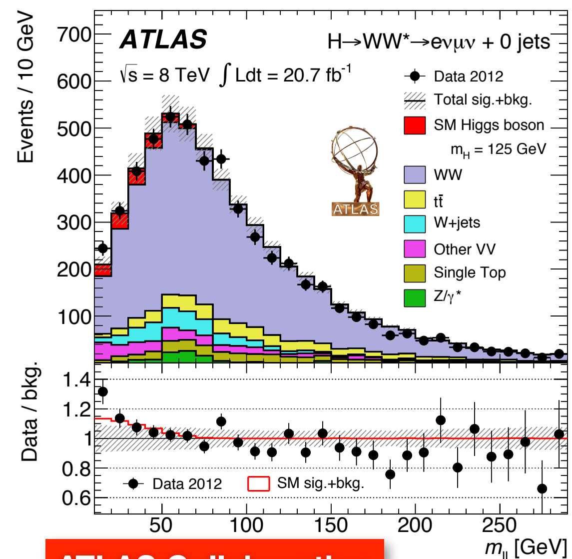




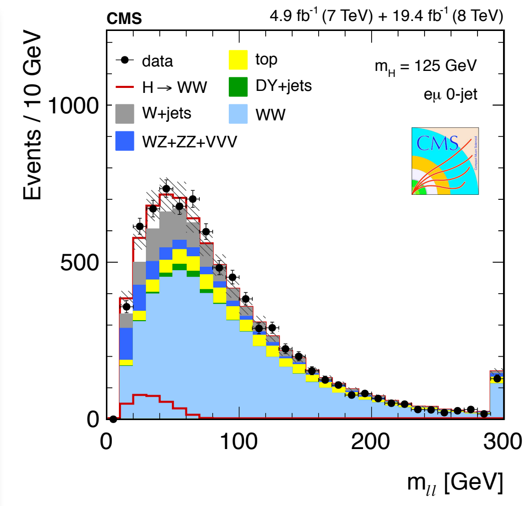


H(WW→lνlν)

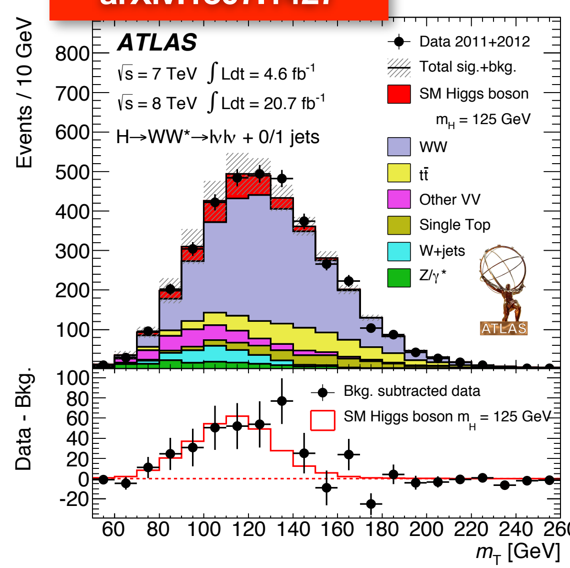
- High-yield, low-resolution channel
  - Most discriminating variables: M_{ll} and M_T (dilepton transverse mass)
  - Search done in 0-, 1-, and 2-jet categories; in the ee, eμ, and μμ channels
- ATLAS: fit to the M_T distribution
- CMS: 2D analysis in M_{ll} vs. M_T for the eμ channel and cut-based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

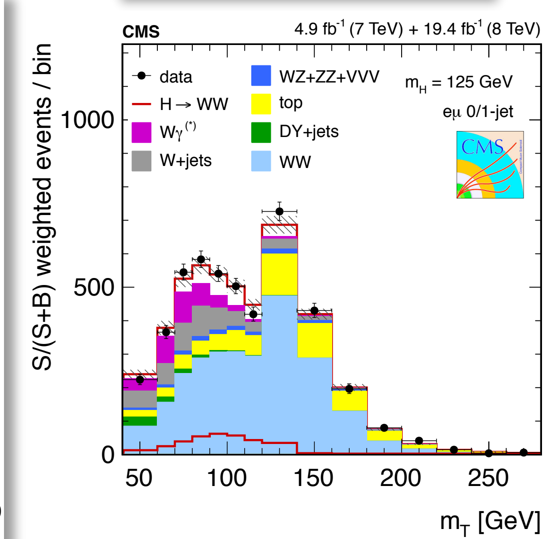


ATLAS Collaboration
arXiv:1307.1427



CMS Collaboration
arXiv:1312.1129

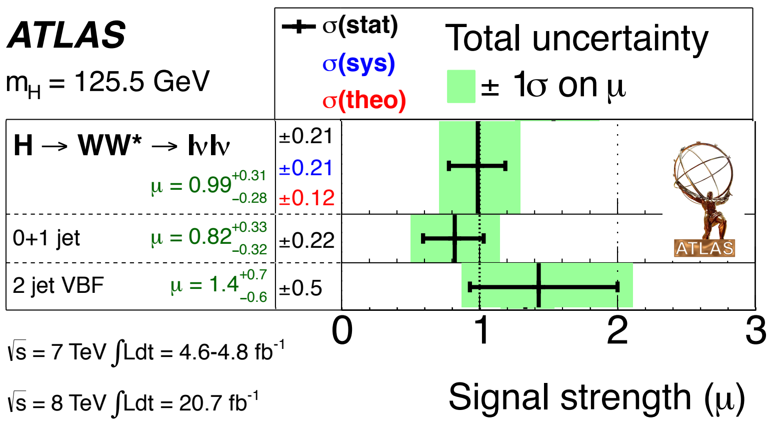




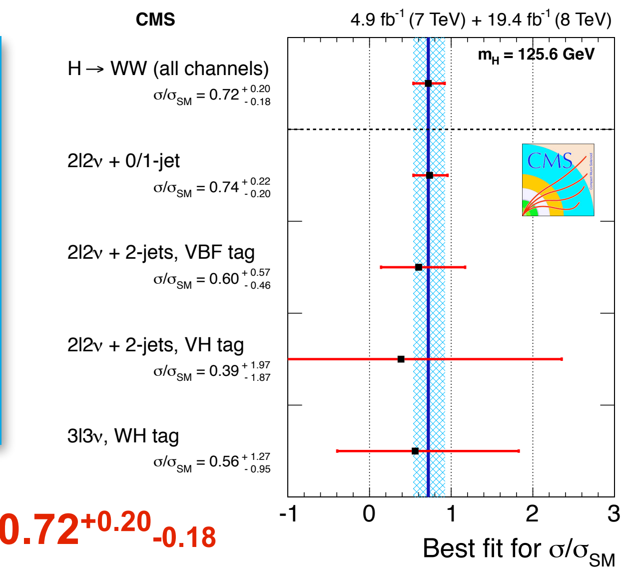
H(WW→lνlν) Results

- Significant excess is observed:

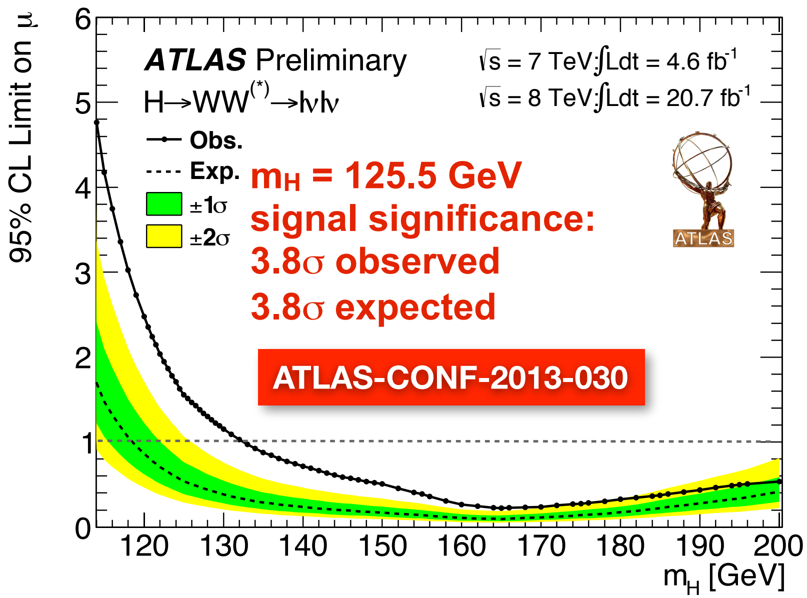
ATLAS Collaboration arXiv:1307.1427

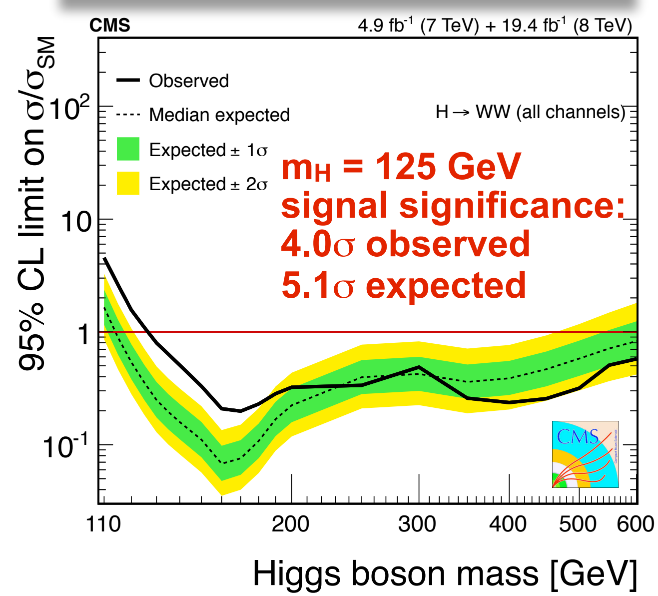


CMS Collaboration arXiv:1312.1129



$\mu = 0.72^{+0.20}_{-0.18}$

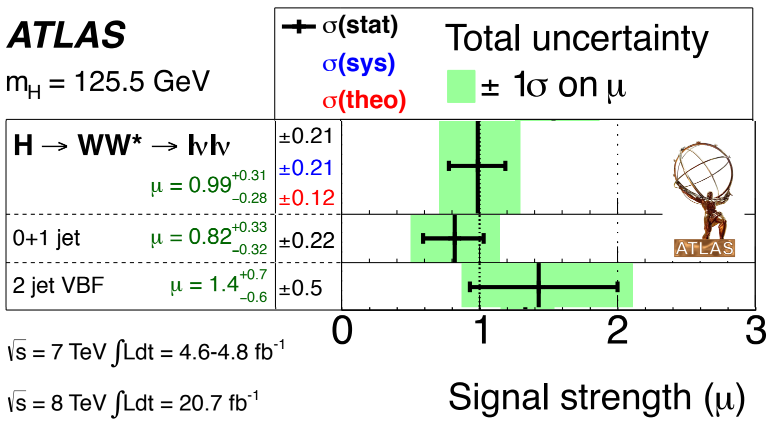




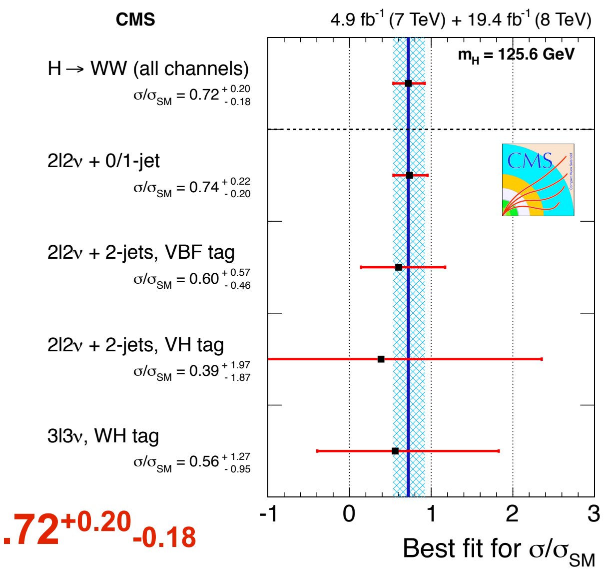
H(WW→lνlν) Results

- Significant excess is observed:

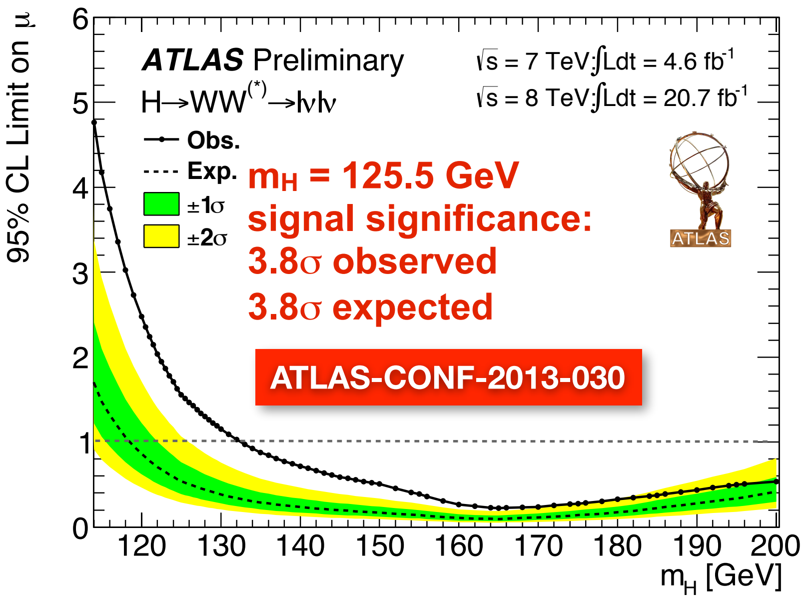
ATLAS Collaboration arXiv:1307.1427



CMS Collaboration arXiv:1312.1129

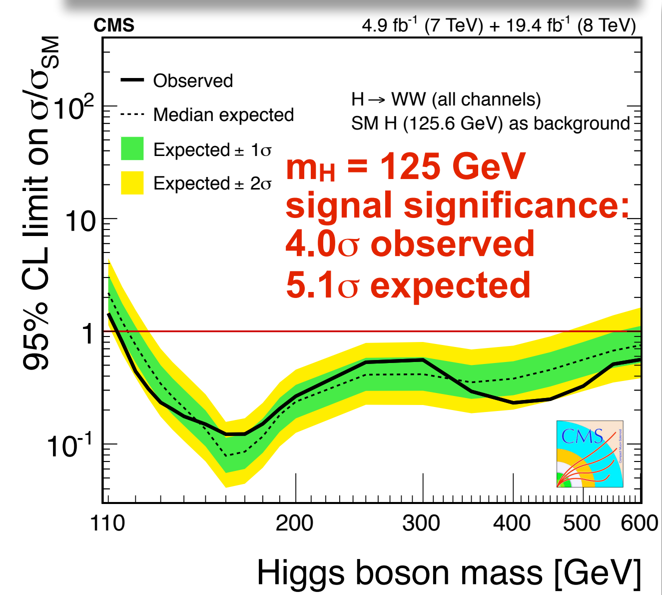


$\mu = 0.72^{+0.20}_{-0.18}$



m_H = 125.5 GeV
signal significance:
3.8σ observed
3.8σ expected

ATLAS-CONF-2013-030

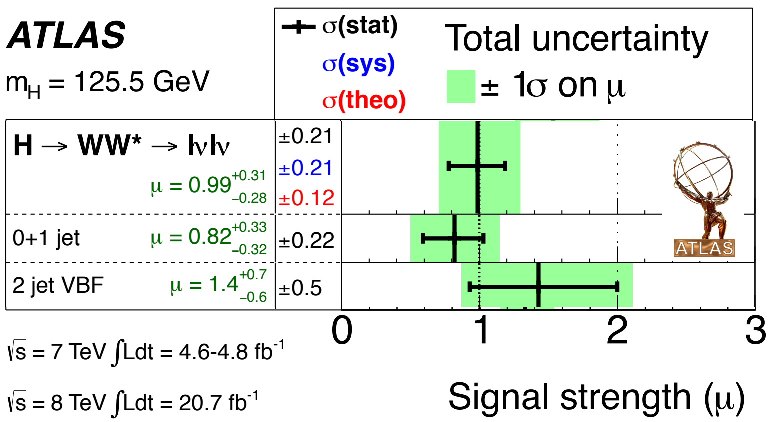


m_H = 125 GeV
signal significance:
4.0σ observed
5.1σ expected

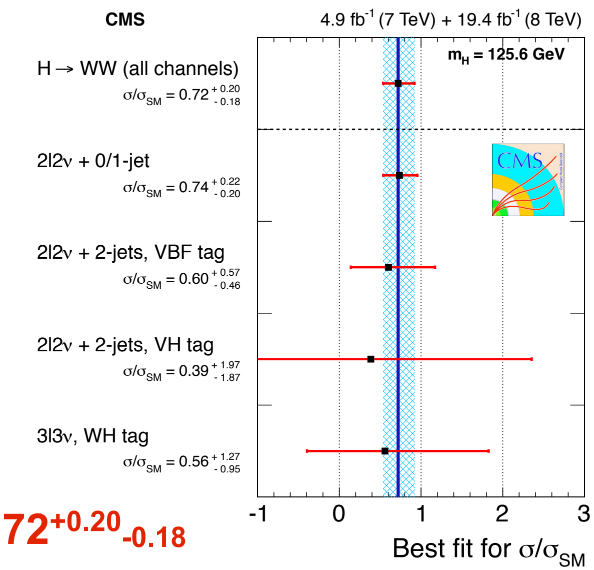
H(WW→lνlν) Results

- Significant excess is observed:

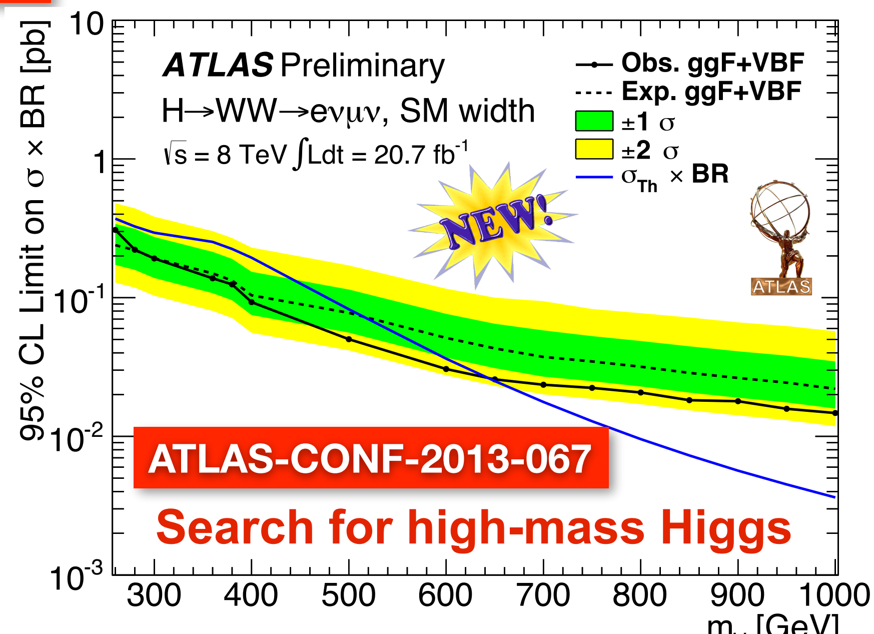
ATLAS Collaboration arXiv:1307.1427



CMS Collaboration arXiv:1312.1129

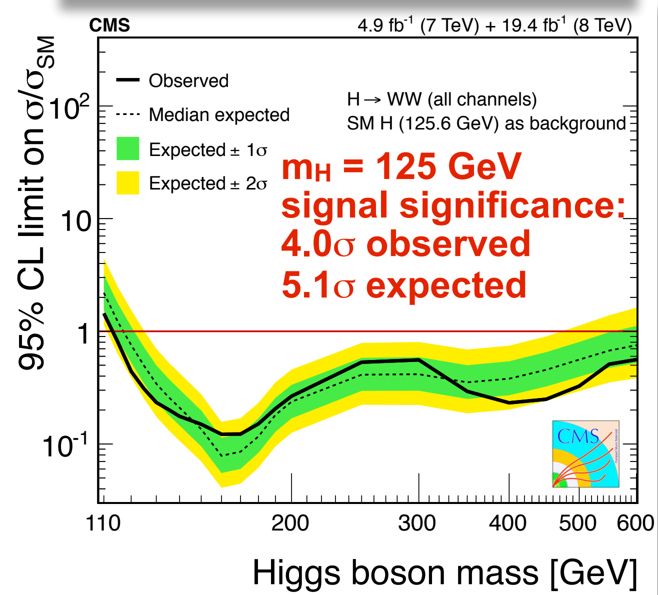


$\mu = 0.72^{+0.20}_{-0.18}$



ATLAS-CONF-2013-067

Search for high-mass Higgs

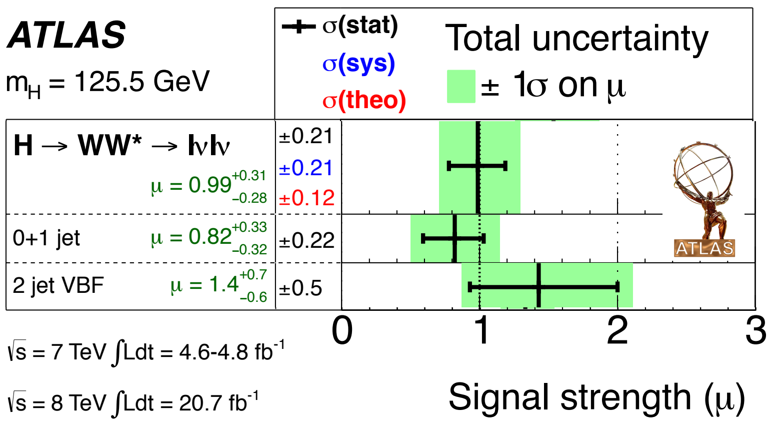


m_H = 125 GeV signal significance: 4.0σ observed 5.1σ expected

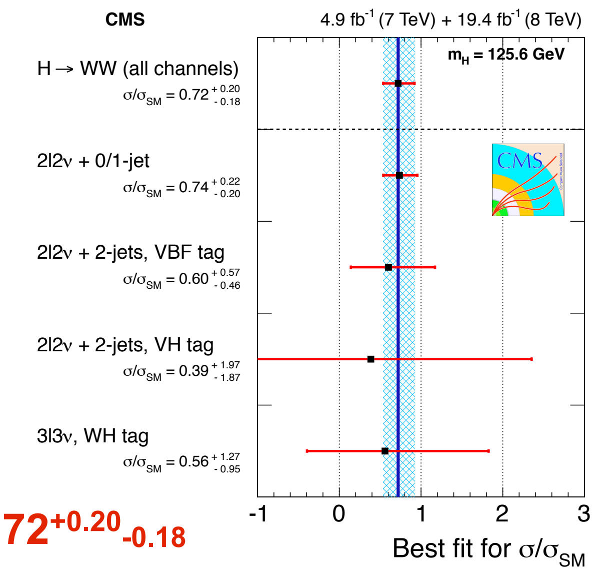
H(WW→lνlν) Results

- Significant excess is observed:

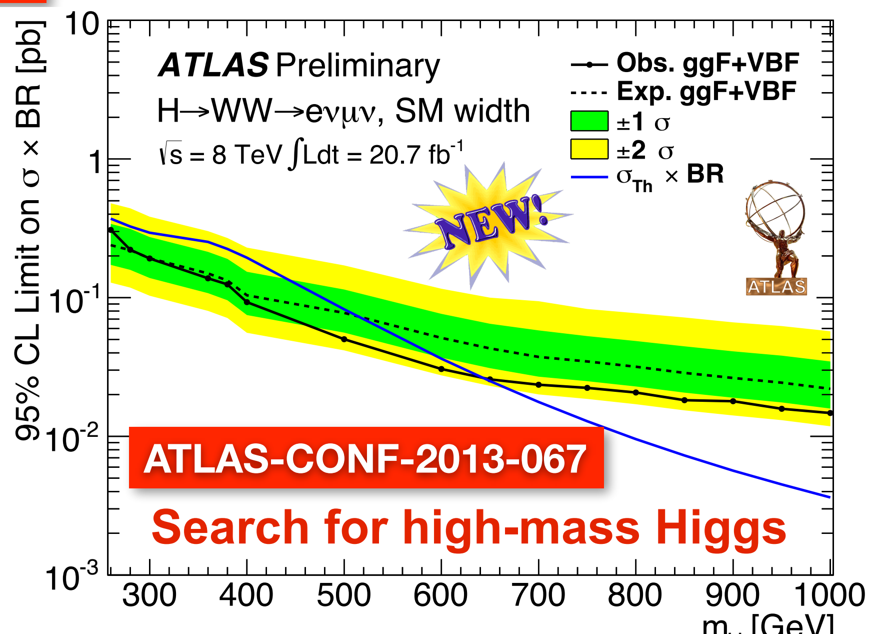
ATLAS Collaboration arXiv:1307.1427



CMS Collaboration arXiv:1312.1129

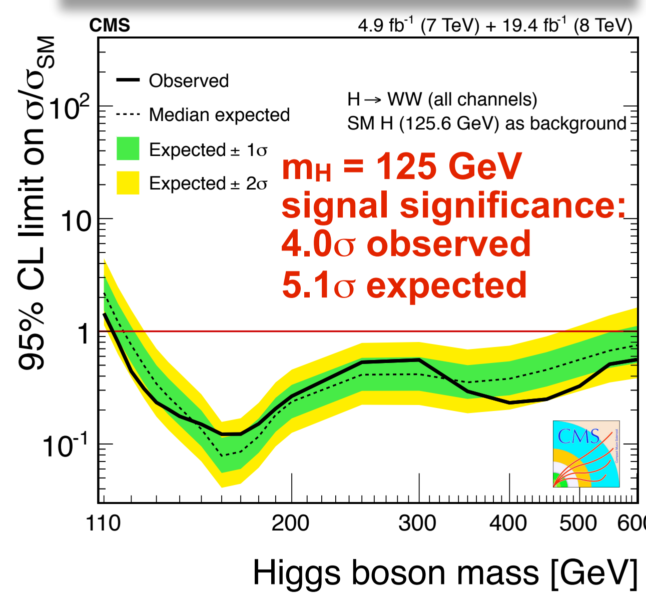


$\mu = 0.72^{+0.20}_{-0.18}$



ATLAS-CONF-2013-067

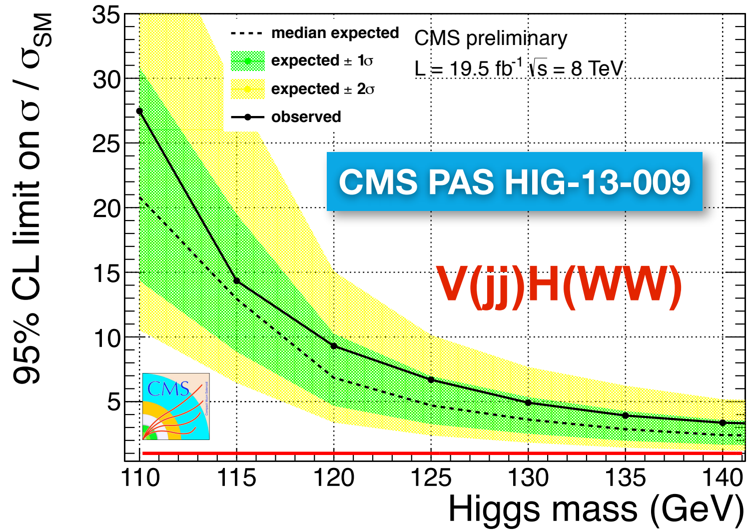
Search for high-mass Higgs



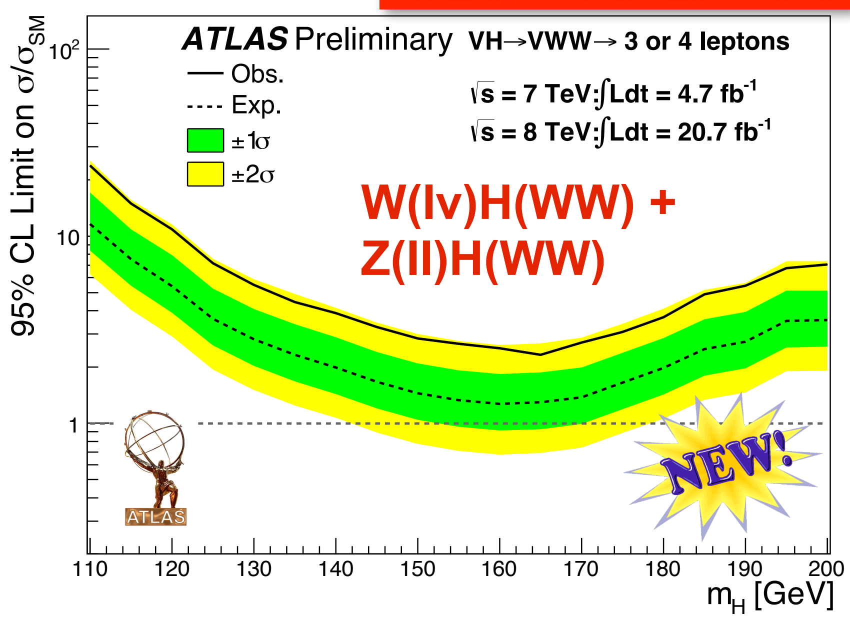
m_H = 125 GeV signal significance: 4.0σ observed 5.1σ expected

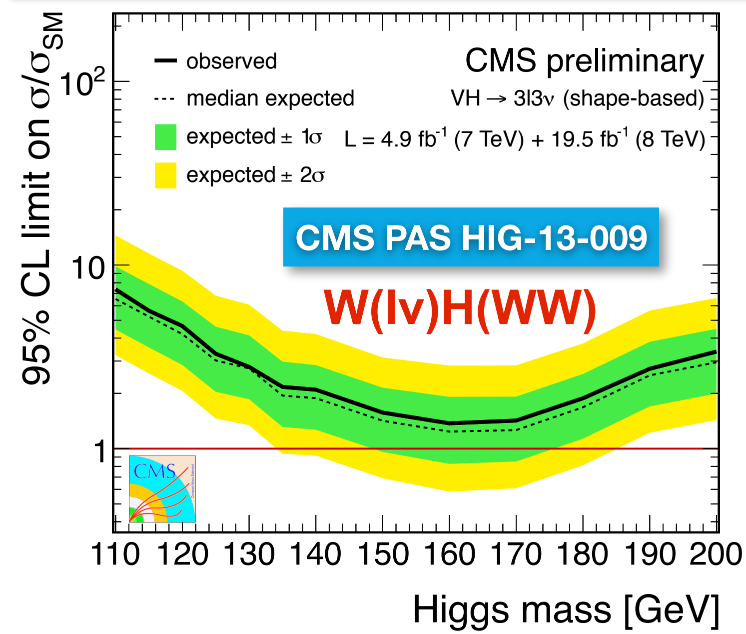
Adding VH(WW)

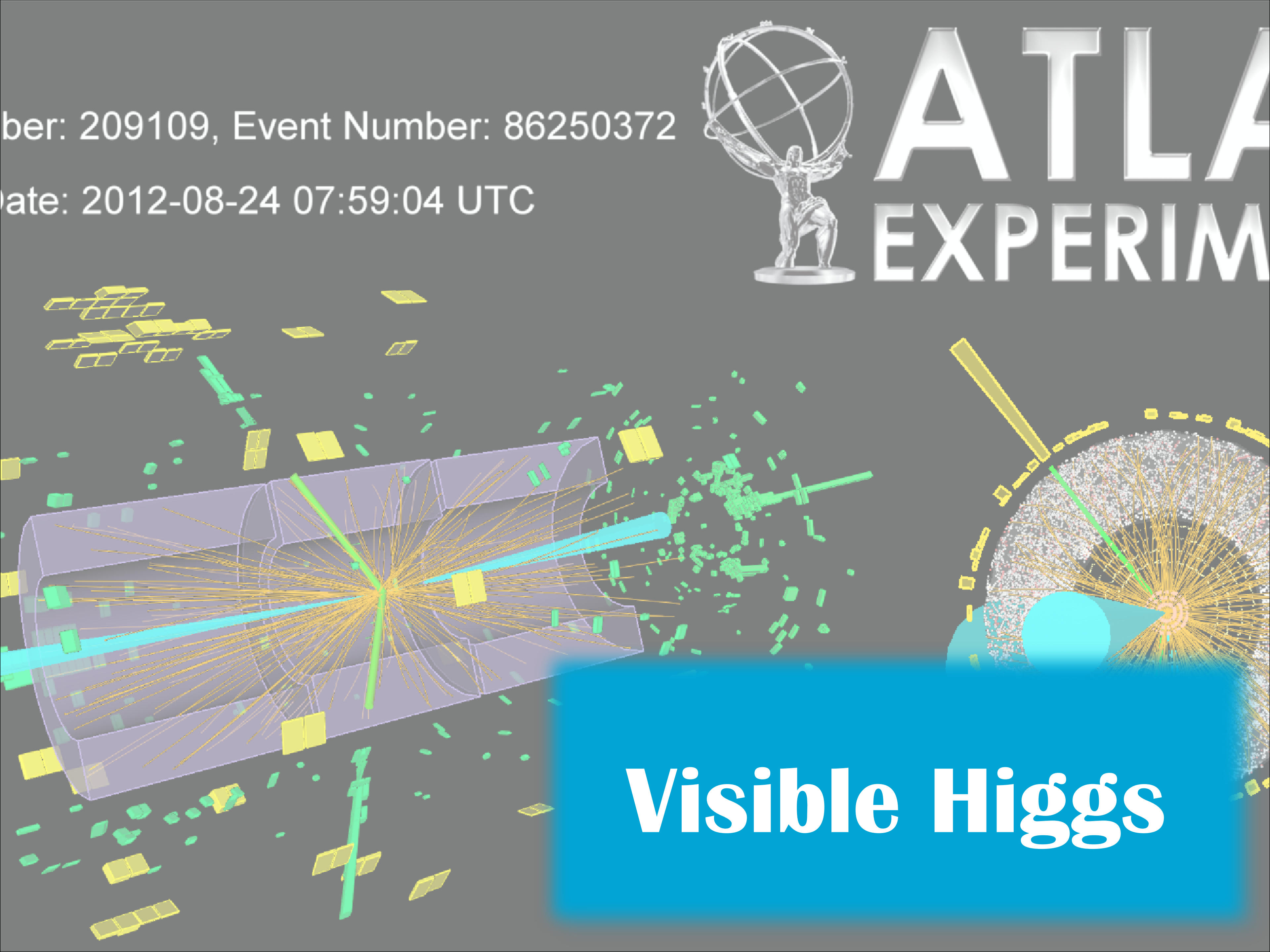
- A bit extra help from the VH(WW) in 3-lepton (ATLAS+CMS), 4-lepton (ATLAS), and lljj (CMS) final states
- ATLAS: combination with the H(WW) analysis:
  - **4.0σ (3.8σ exp.)** significance at m_H = 125 GeV



ATLAS-CONF-2013-075



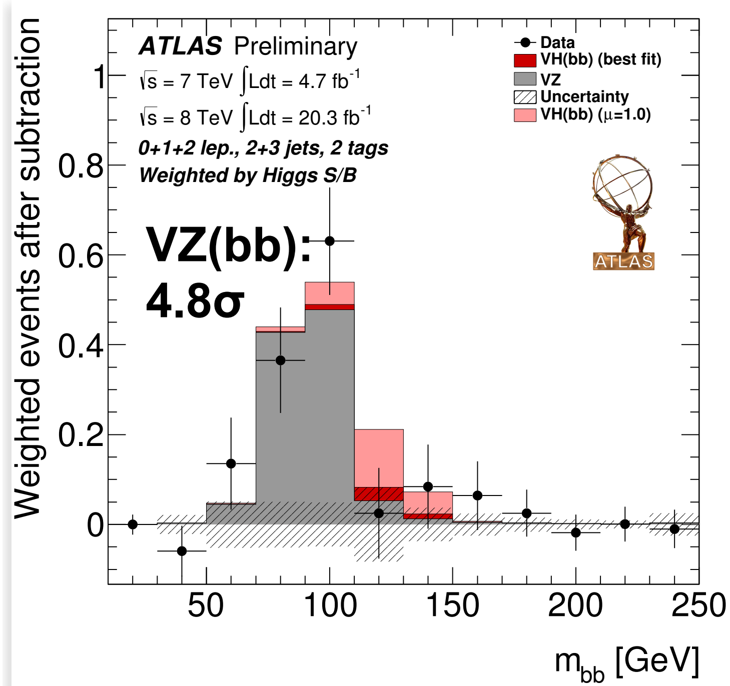


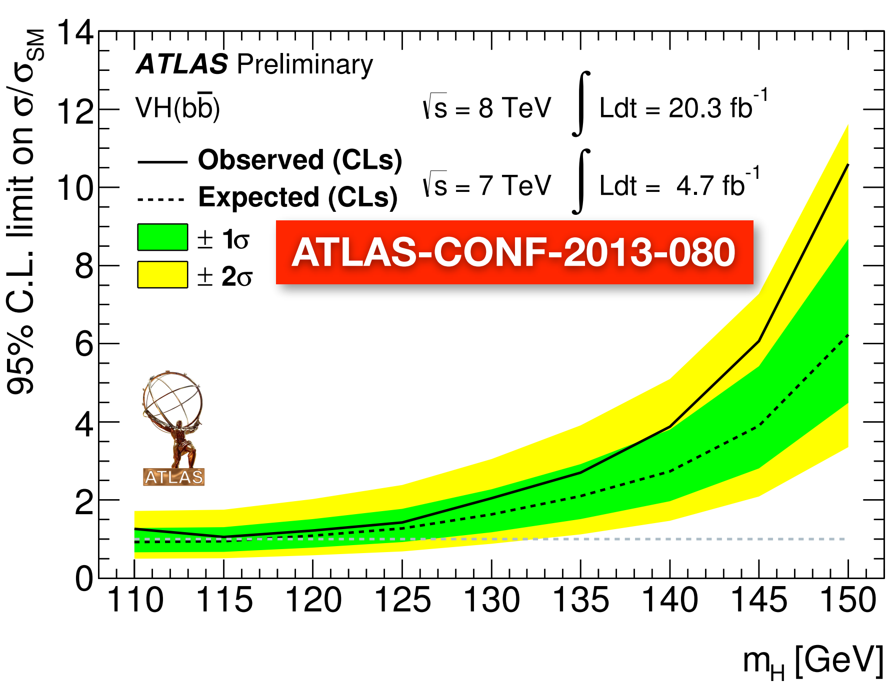


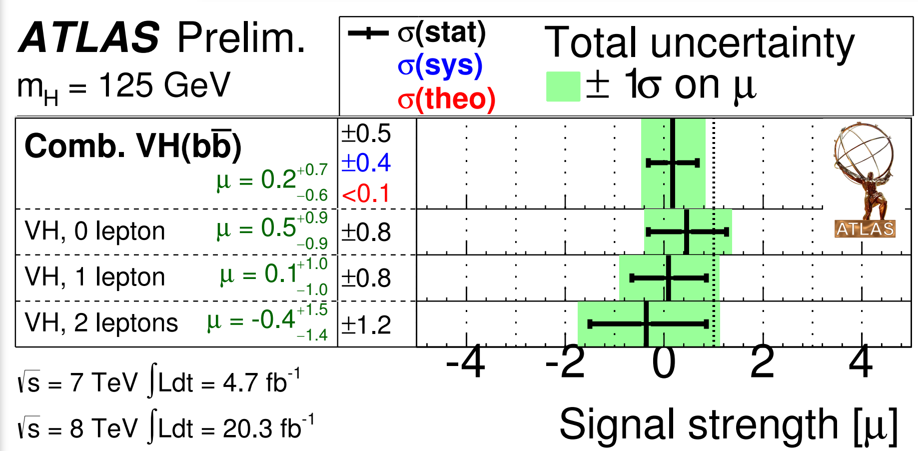
Visible Higgs

VH(bb) in ATLAS

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

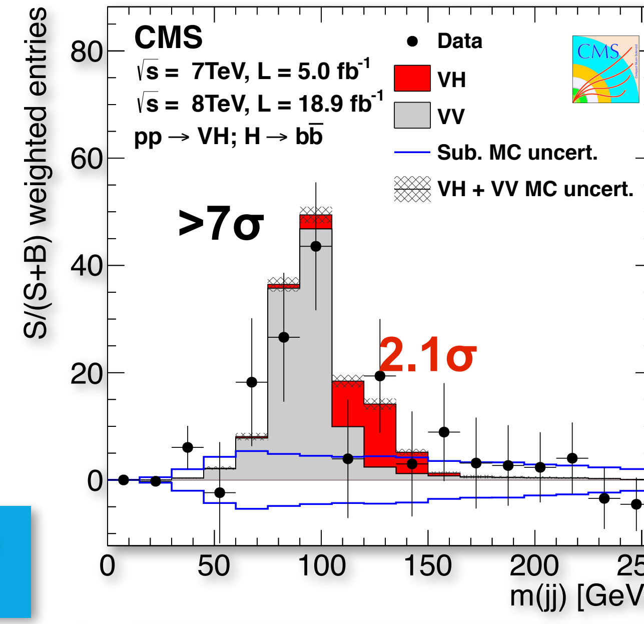




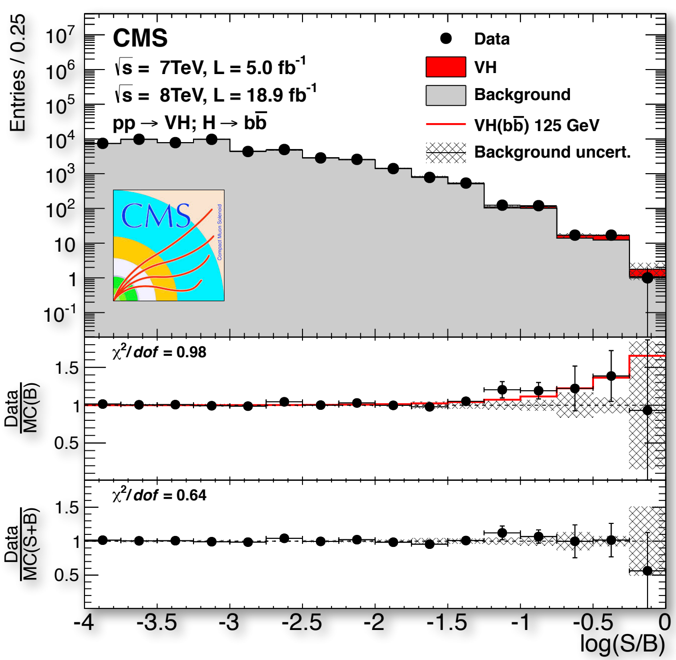


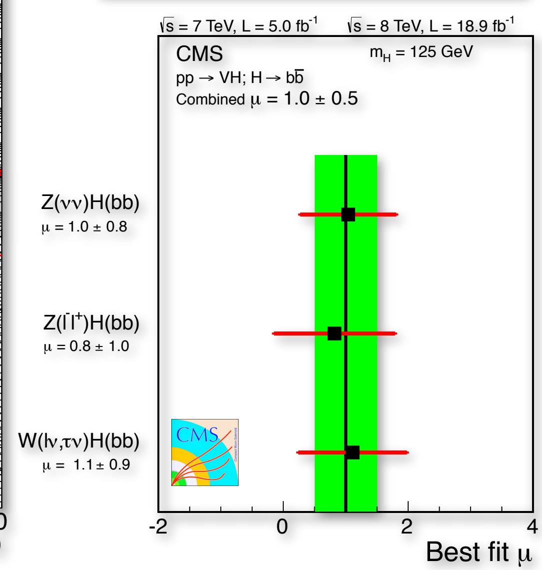
VH(bb) in CMS

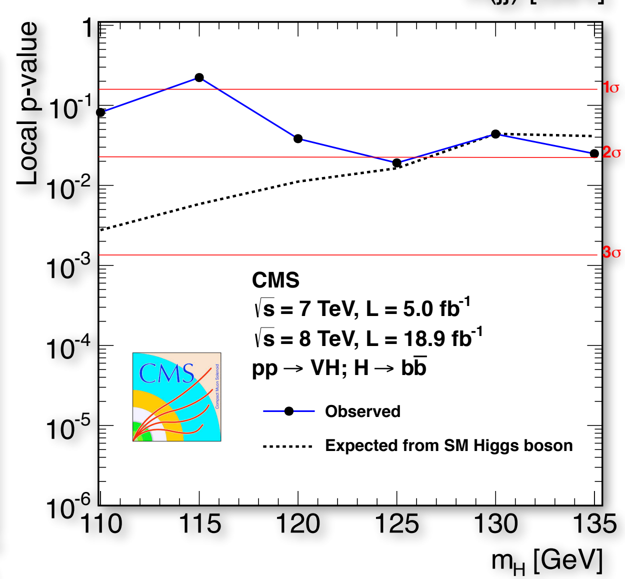
- Combines the W(lν) (including τ), Z(ee,μμ,νν) channels; BDT is used in most
- M_{bb} resolution ~10%, after regression
- Observed a **2.1σ excess (2.1σ expected)**
  - Over 7σ significance for the VZ(bb) signal
- Corresponding signal strength:
  - **μ = 1.0 ± 0.5 at M_H = 125 GeV**



CMS Collaboration arXiv:1310.3687





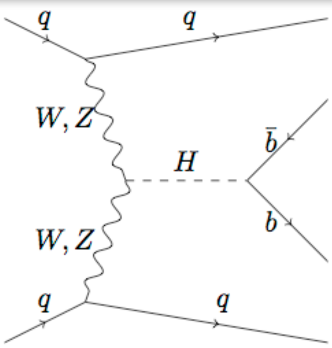


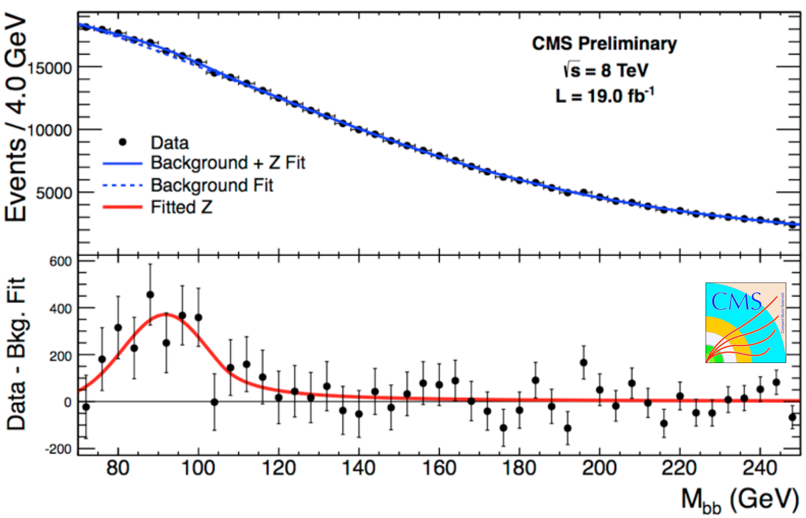
Greg Landsberg - Higgs Bosons Searches at the LHC - WHEPP 2013

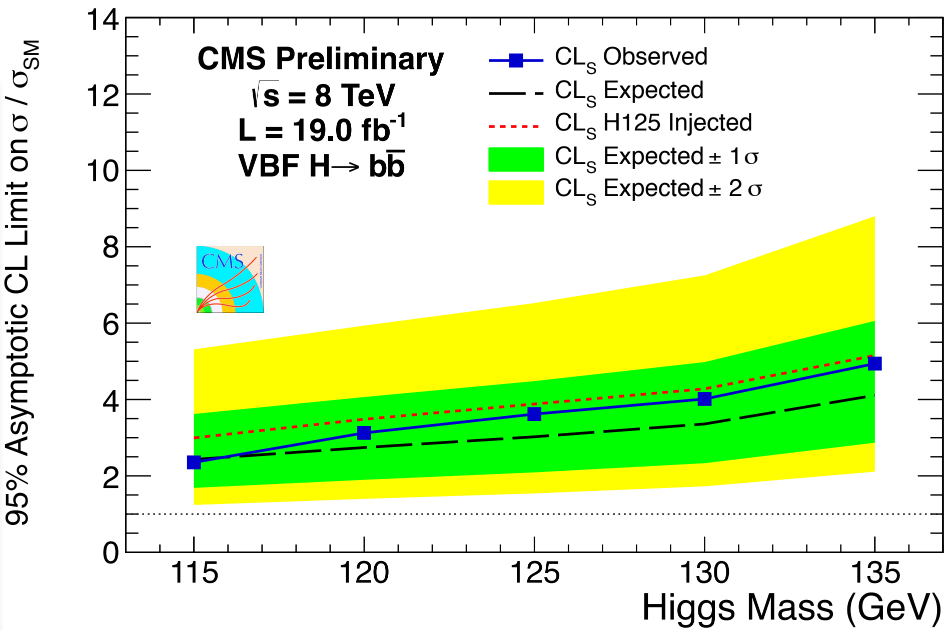
CMS: VBF H(bb)

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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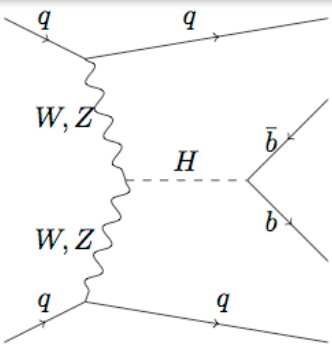
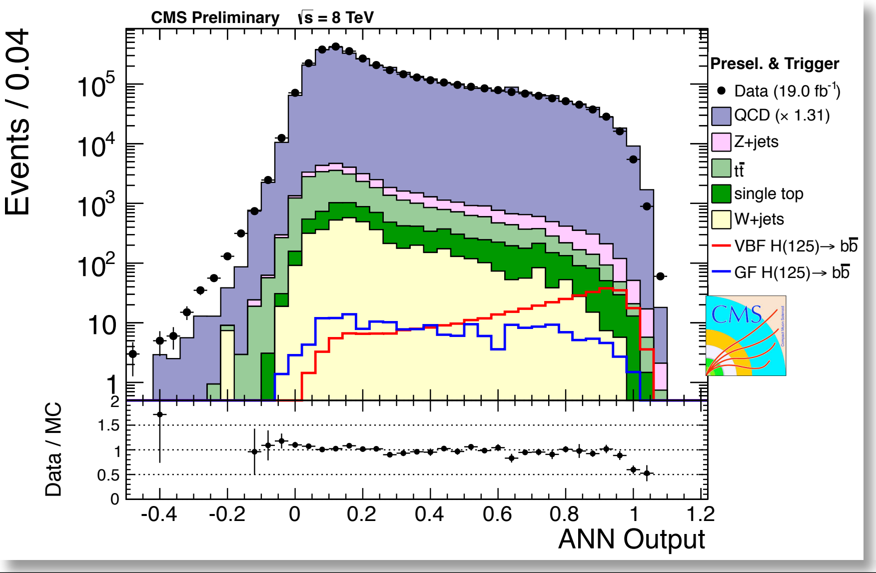
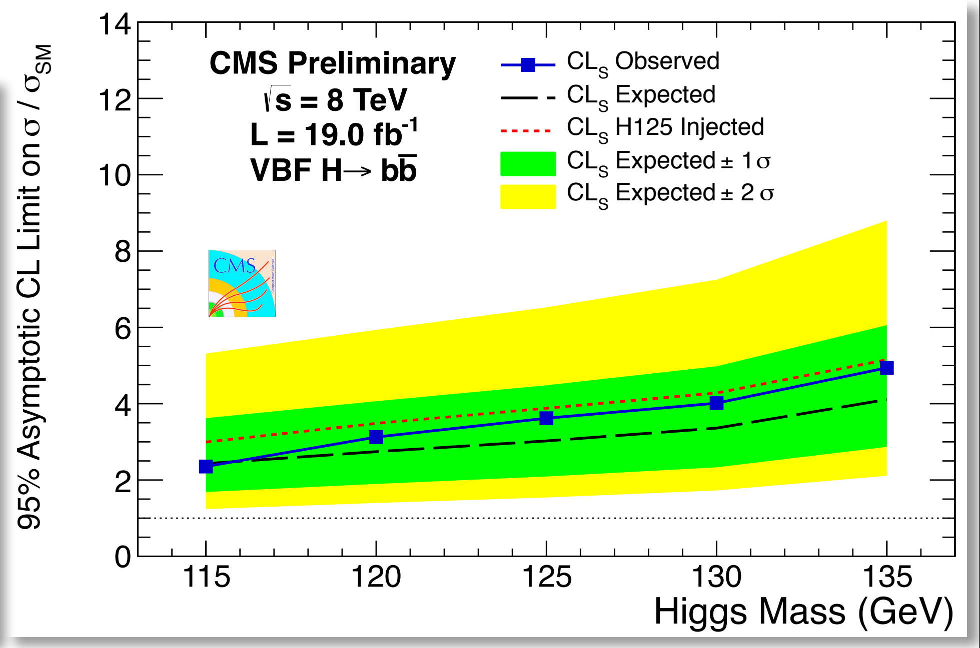




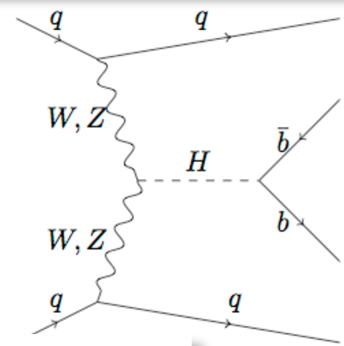


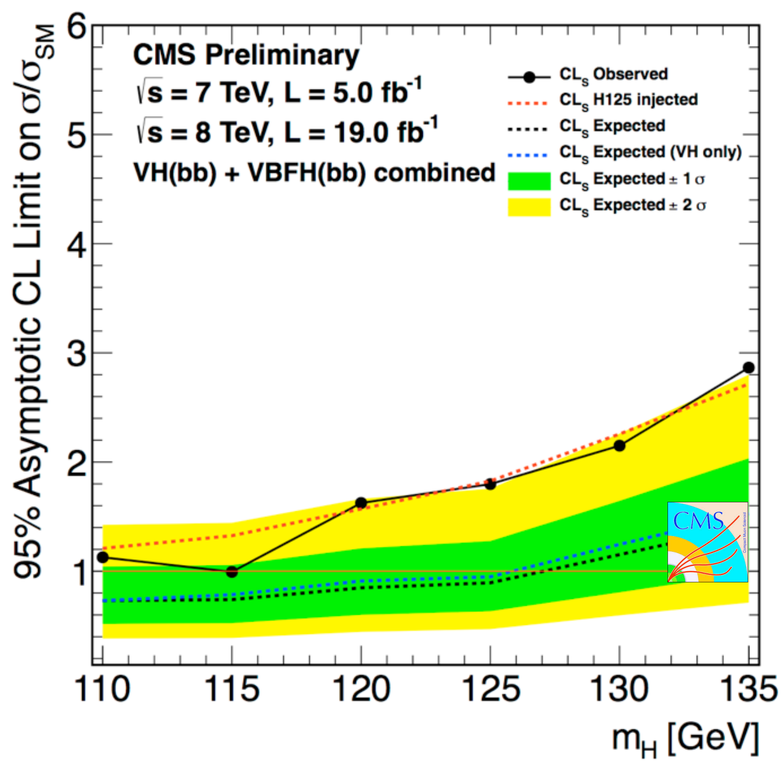
BROWN

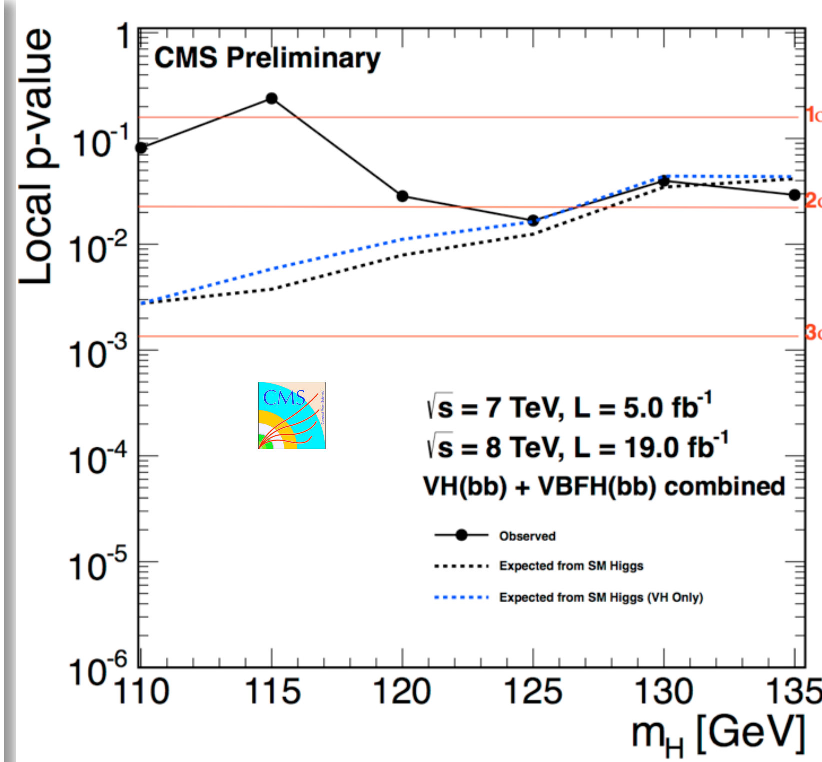
CMS: VBF H(bb)

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

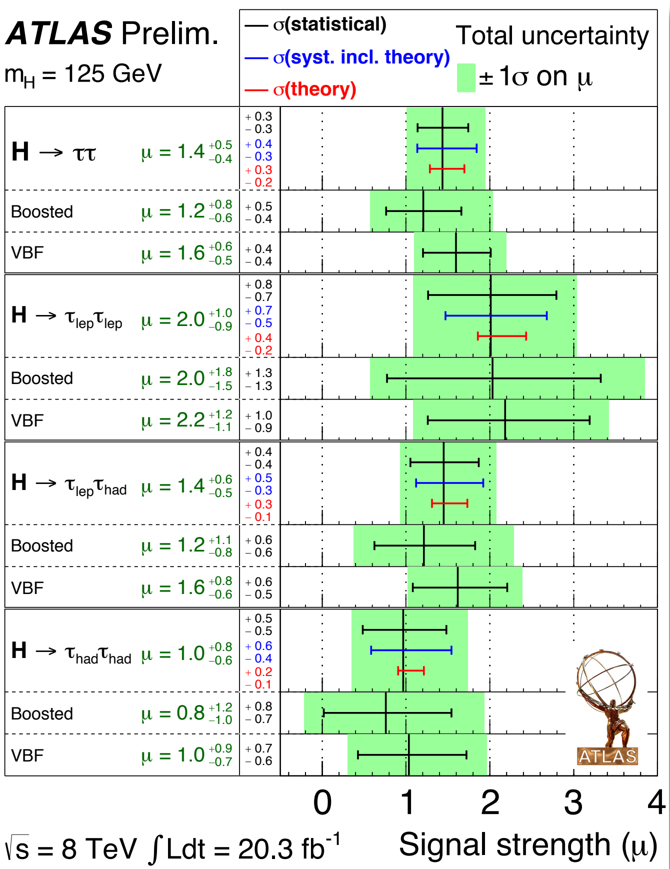




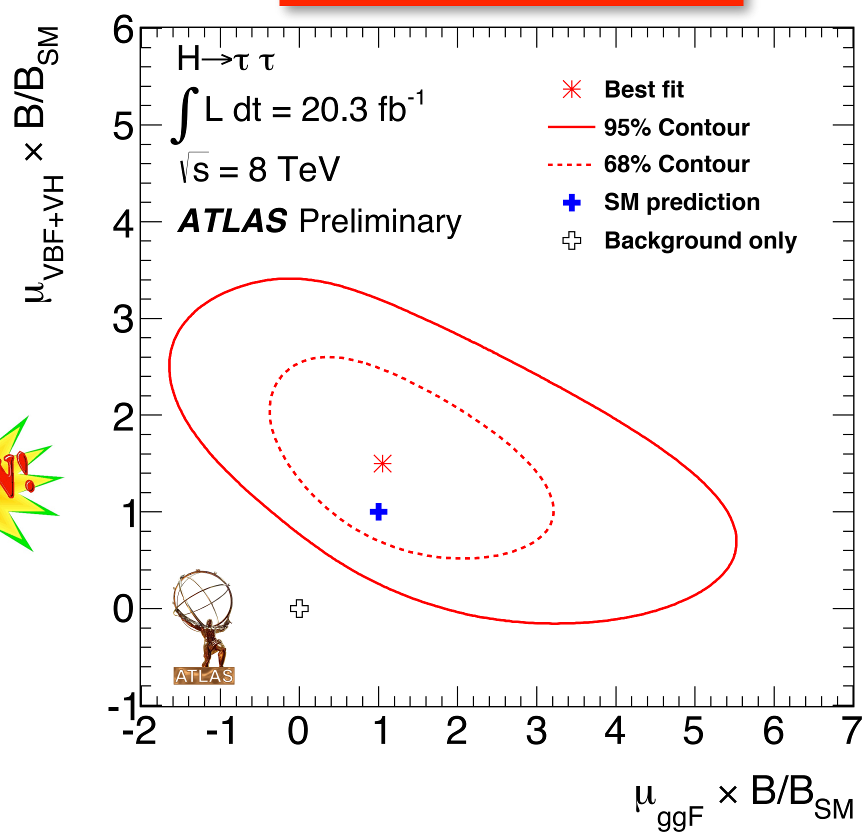


H(ττ) in ATLAS

- Analysis has just been updated to full 8 TeV statistics
  - 7 TeV has not been reanalyzed yet since ATLAS-CONF-2012-102
- Uses multivariate technique with $m_{\tau\tau}$ as one of the most discriminating variables
- **$\mu = 1.4^{+0.5}_{-0.4}$**; significance **4.1σ (3.2σ exp.)** - strong evidence for H(ττ) coupling



ATLAS-CONF-2013-108

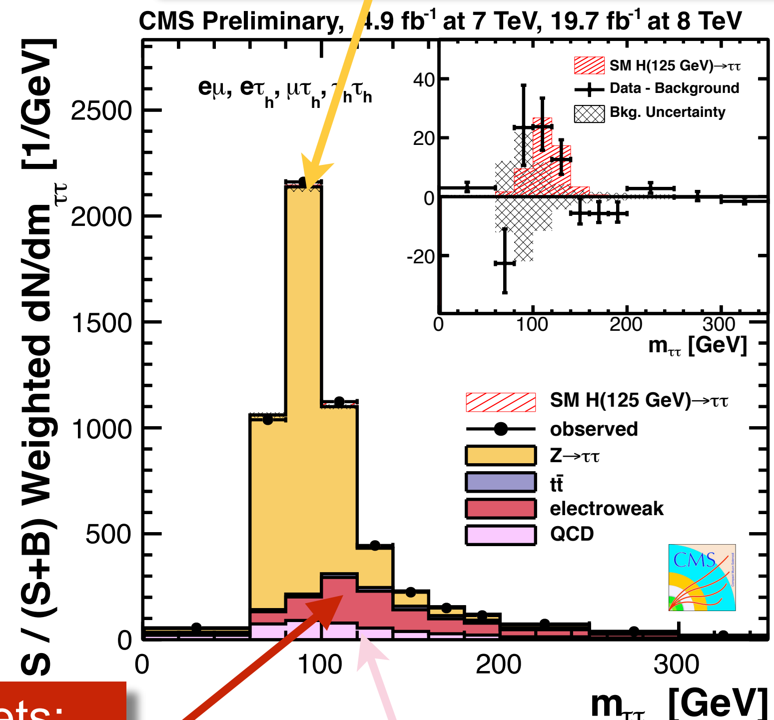


BROWN

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

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.)

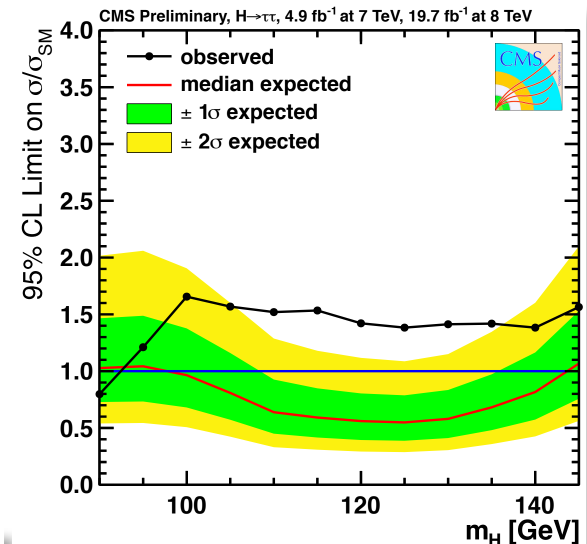
QCD: from SS sample (10% syst.)

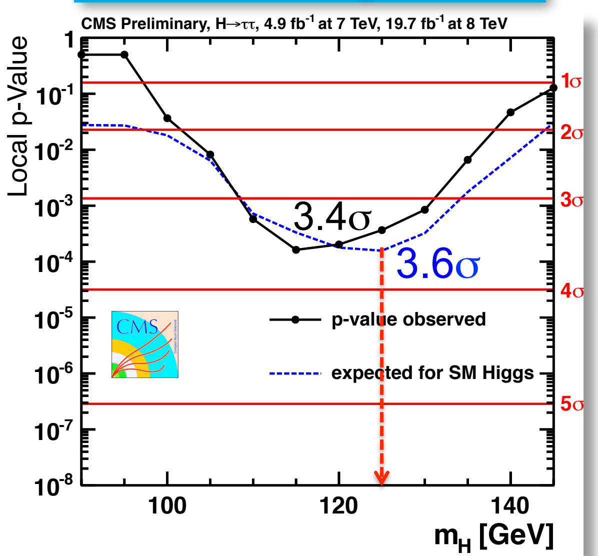
CMS Twiki HIG-13-004
Dec 2013 update

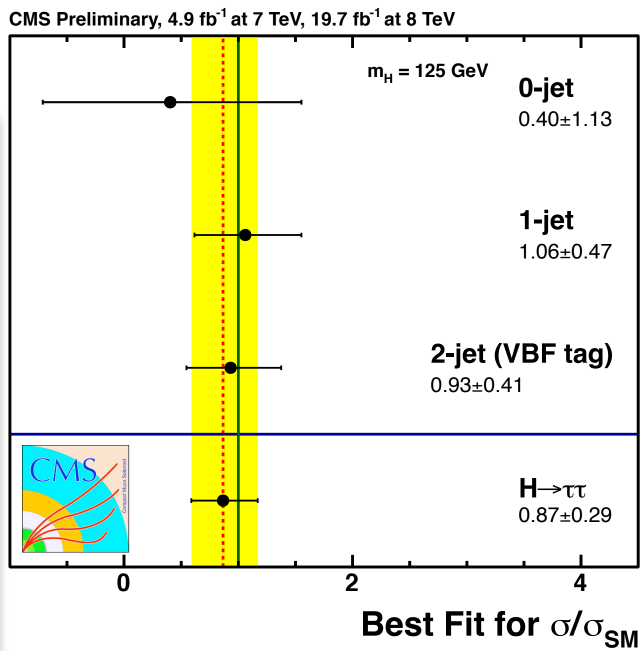
CMS: H(ττ) Results

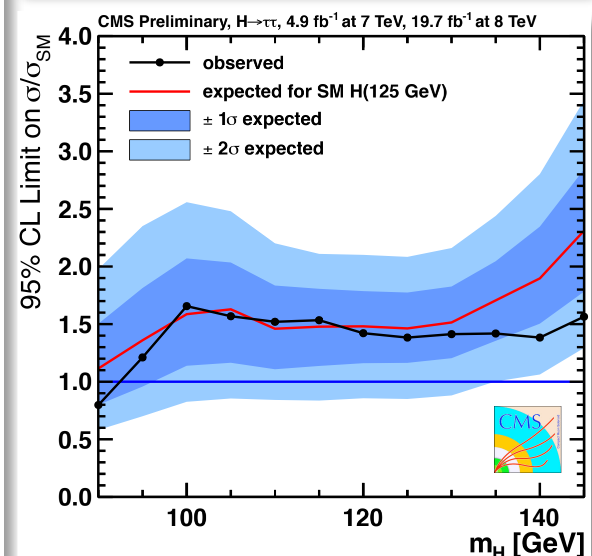
- **Observed 3.4σ (3.6σ exp.)** for m_H = 125 GeV
- Strong *evidence* for the Hff coupling to the 3rd-generation *down-type* fermion
- First mass measurement in this channel:
  - **$m_H = 115^{+8}_{-2}$ GeV**

CMS Twiki HIG-13-004
Dec 2013 update







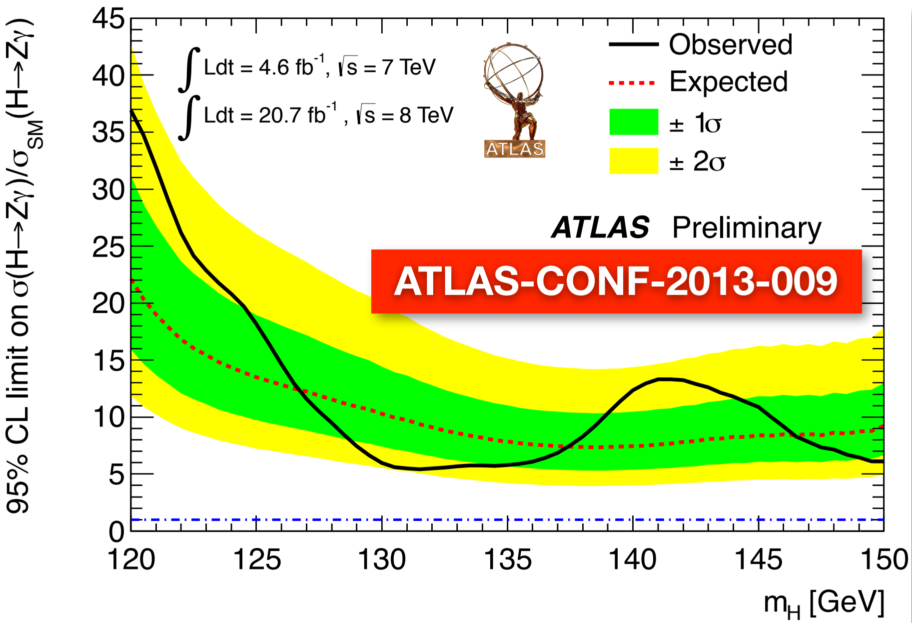


Not-yet-Visible Higgs

H(Zγ) Results

- Similar branching fraction to H(γγ) (0.16%), 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 exp.)**
  - CMS: **μ < 10 @ 95% CL (10 exp.)**

CMS Collaboration arXiv:1307.5515



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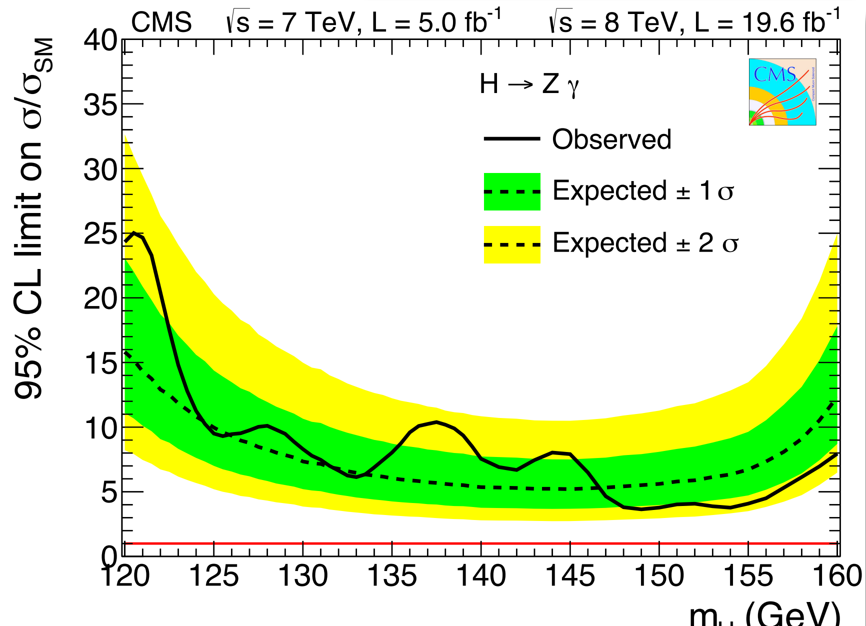
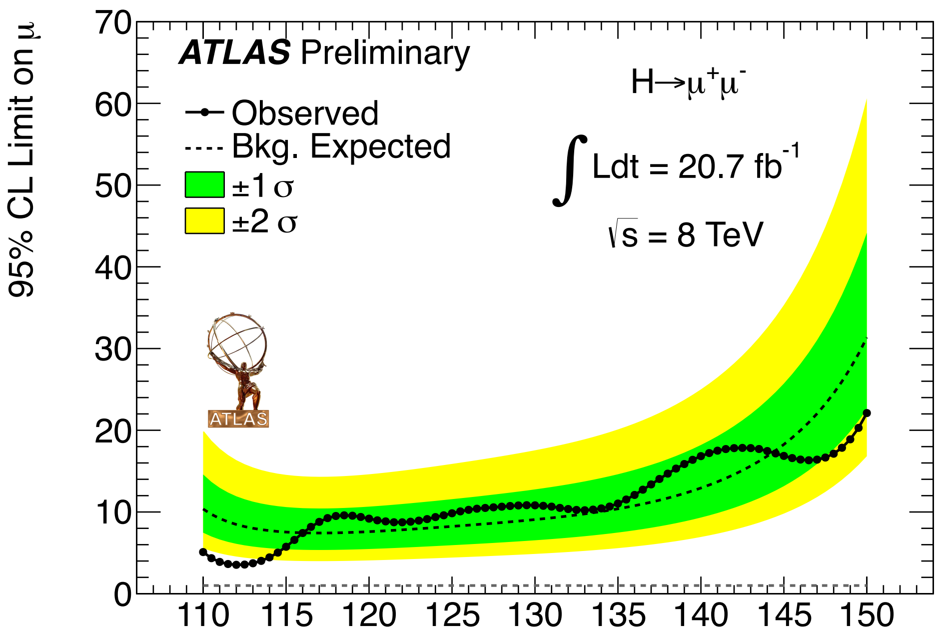


H(μμ/ee) Results

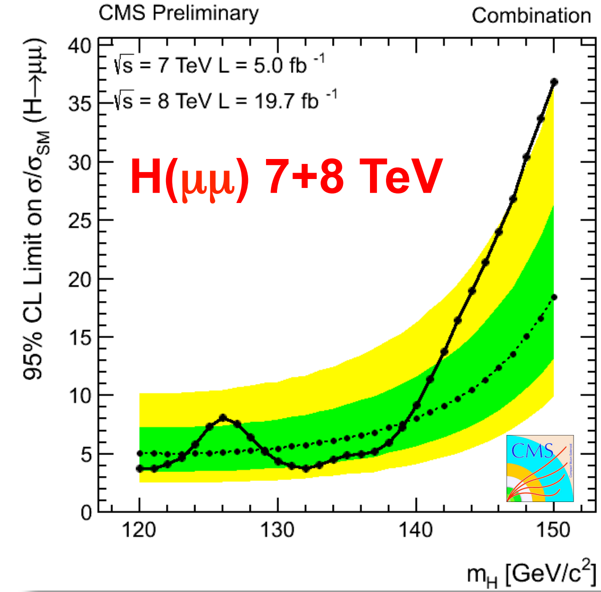
- Observing H(μμ) decay may be the only way to prove non-flavor-universal couplings of the Higgs boson
  - N.B. Coupling to charm is very hard to probe
- Requires very large statistics for observation: a strong case for HL-LHC
- First searches have been done already:
  - ATLAS: **μ < 9.8 (8.2 expected) @ 95% CL**
  - CMS: **μ < 7.4 (5.1 expected) @ 95% CL; Br(H→ee) < 1.7 x 10^{-3} @ 95% CL**

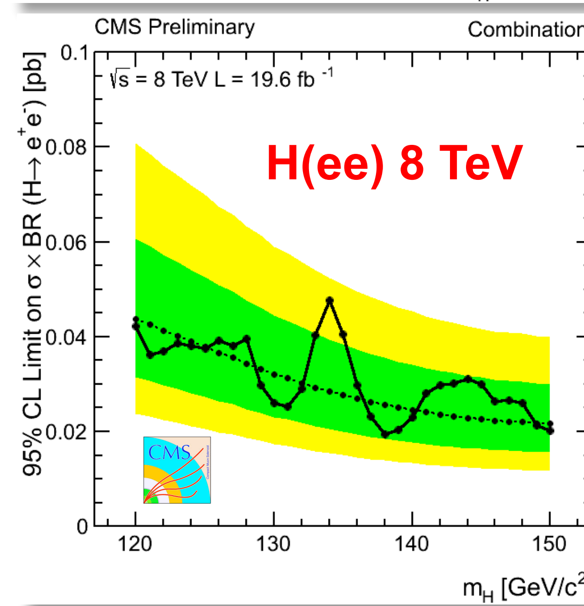
ATLAS-CONF-2013-010



SM: Br(H → μμ) = 2×10^{-4}

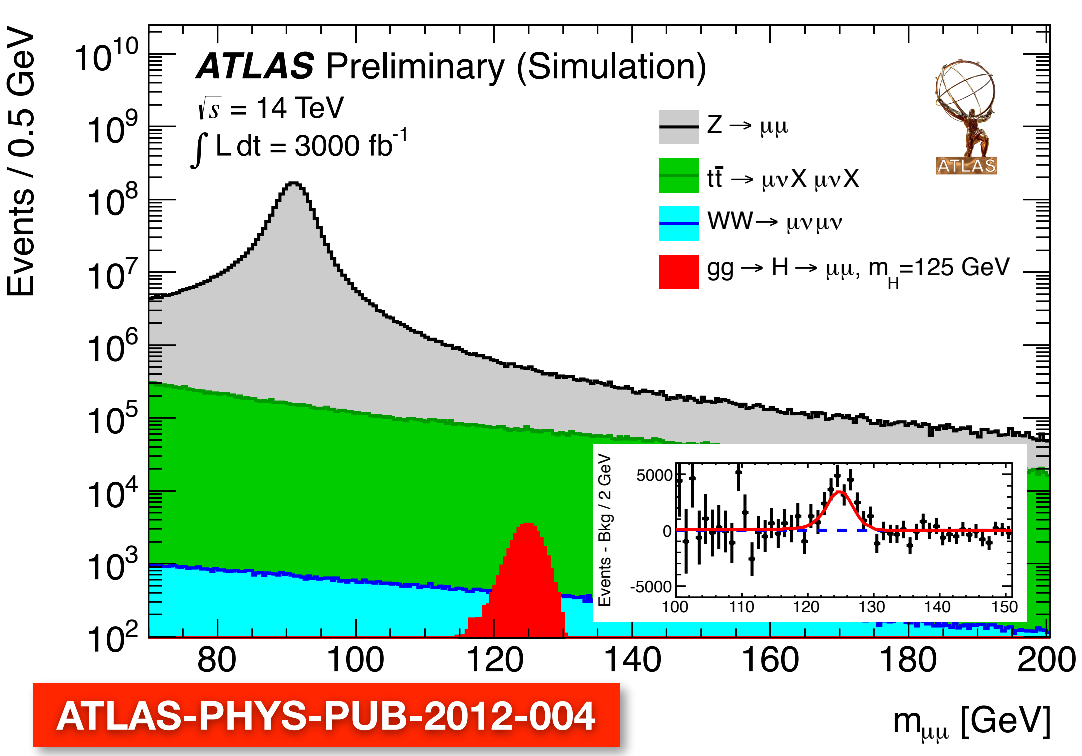
CMS PAS HIG-13-007





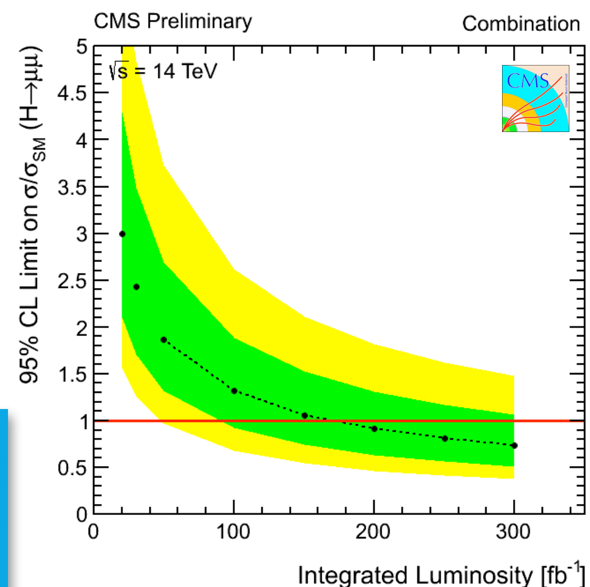
H(μμ) Projections

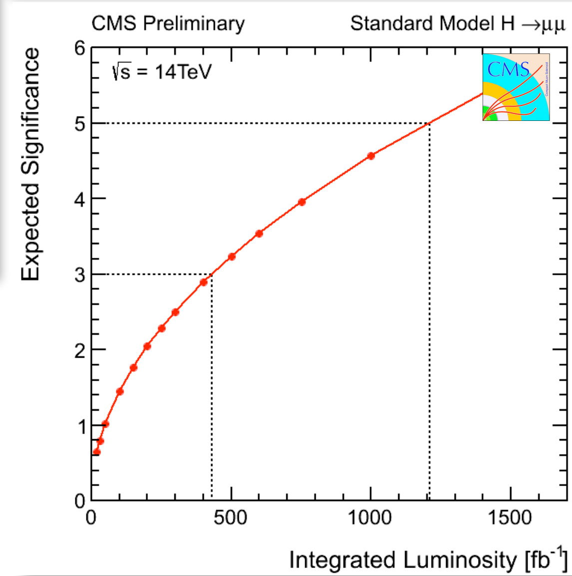
- CMS: 5σ discovery w/ ~1.2 ab^{-1} @ 14 TeV
  - Measure muon coupling with 8% precision with ~3 ab^{-1} @14 TeV
  - Reach SM branching fraction sensitivity already in Run 2, with ~150 fb^{-1}
- ATLAS: ~6σ discovery with ~3 ab^{-1}



ATLAS-PHYS-PUB-2012-004

CMS Twiki HIG-13-007





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ttH - the New Player

VOLUME 86, NUMBER 9 PHYSICAL REVIEW LETTERS 26 FEBRUARY 2001

$p\bar{p} \rightarrow t\bar{t}H$: 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 $H \rightarrow b\bar{b}$ decays yields a significant number of events and that this mode is competitive with and complementary to the searches using $p\bar{p} \rightarrow WH, ZH$ associated production. For higher mass Higgs bosons the $H \rightarrow W^+W^-$ 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!

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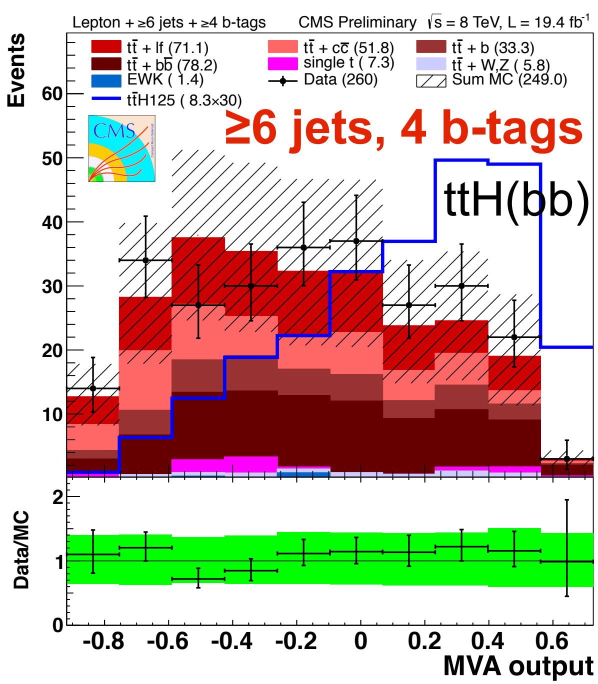
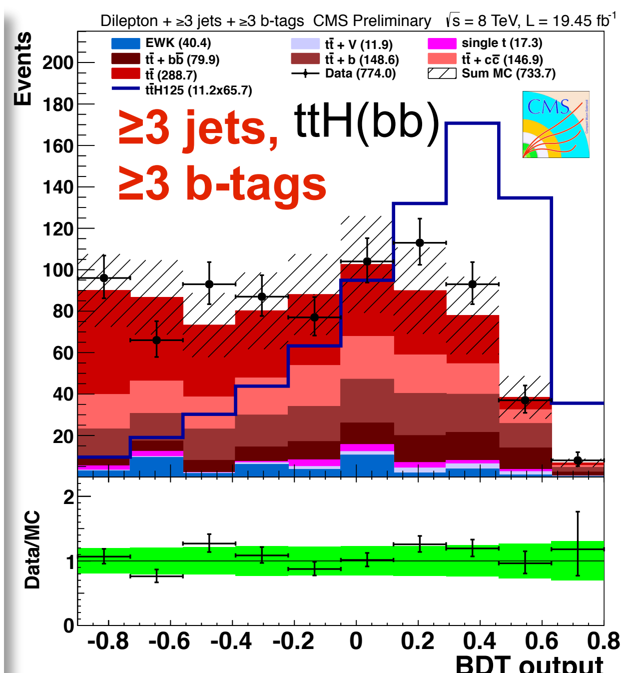
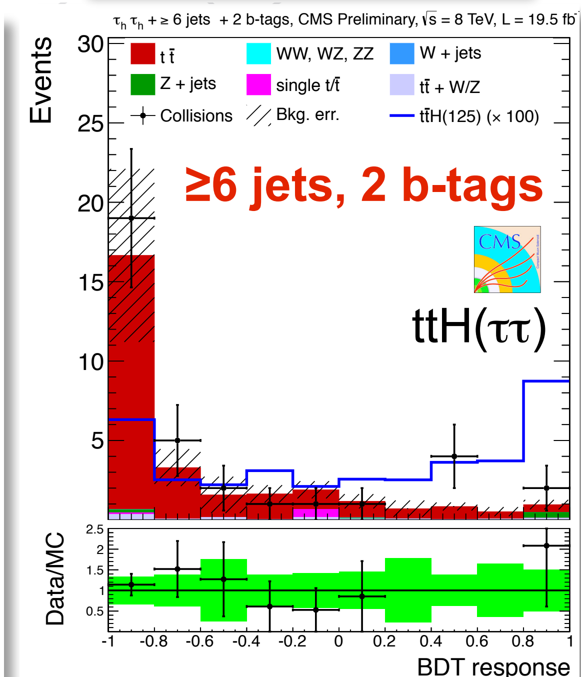
CMS Search in ttH(bb+ττ)

- 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







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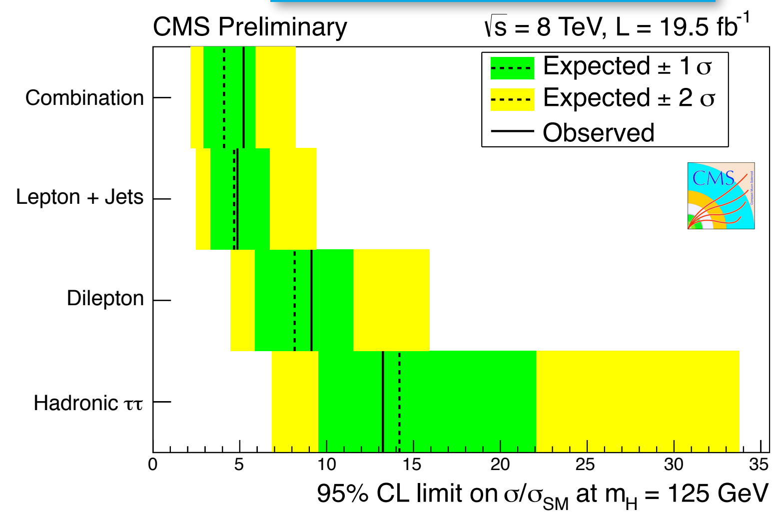
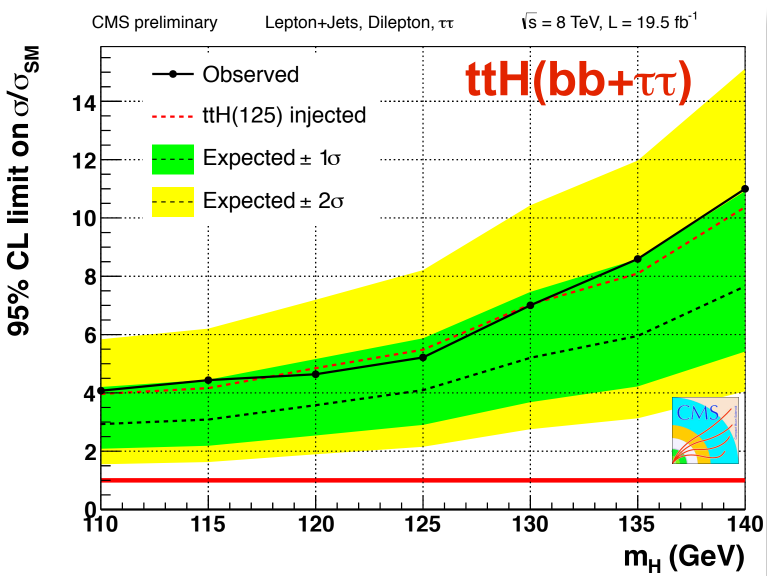
ttH Results

- ttH(bb+ττ) results:
  - CMS: **μ < 5.2 (4.1 exp.)** @ 95% CL
- Also recent results 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
  - CMS: **μ < 5.4 (5.3 exp.)** @ 95% CL,
  - ATLAS: **μ < 5.3 (6.4 exp.)** @ 95% CL

CMS PAS HIG-13-015



CMS PAS HIG-13-019



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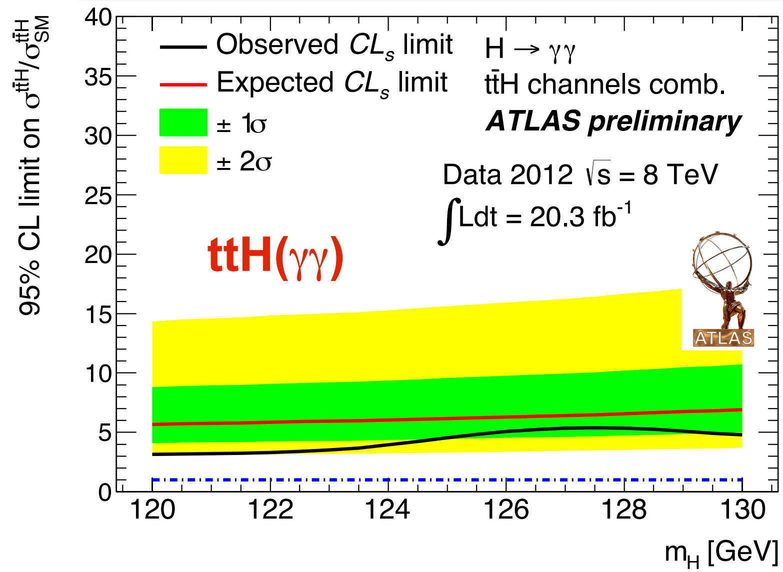
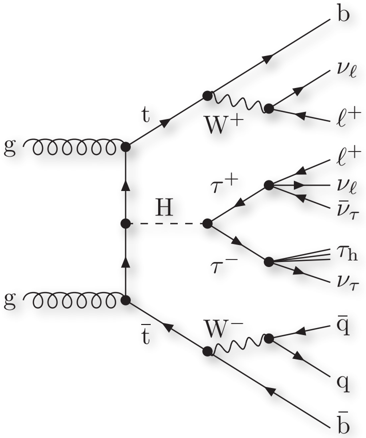
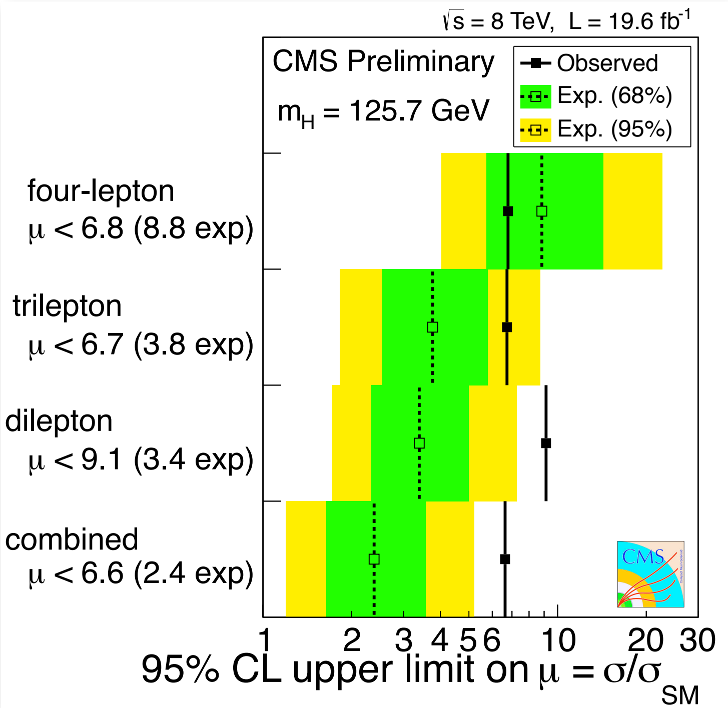


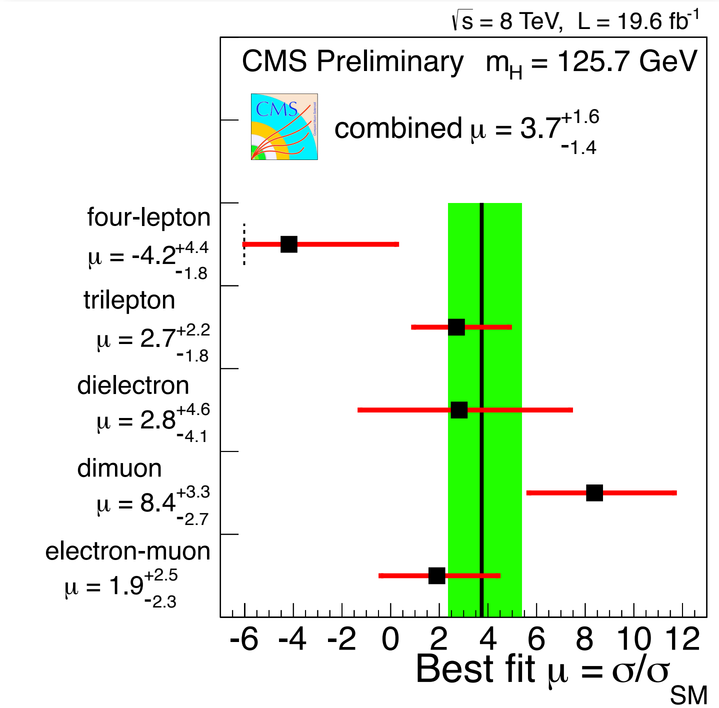
ttH in Multileptons

- New analysis exploring various top and Higgs decays resulting in like-sign dilepton, trilepton, and quadlepton final states
- An excess (~2.5σ) seen in likesign dimuons has been extensively scrutinized and demonstrated to have all the features of a statistical fluctuation
  - Overall consistency with the SM: 3%



CMS PAS HIG-13-020

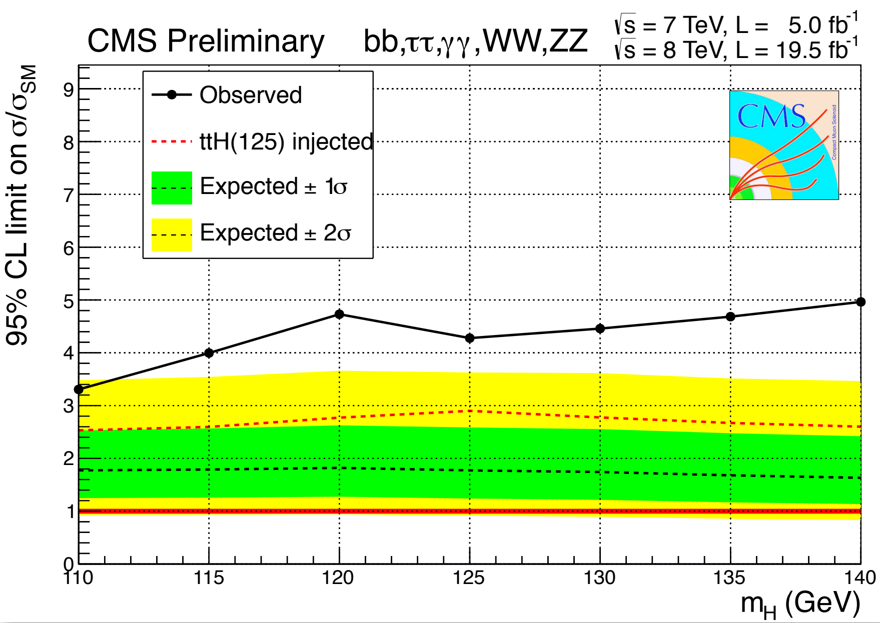


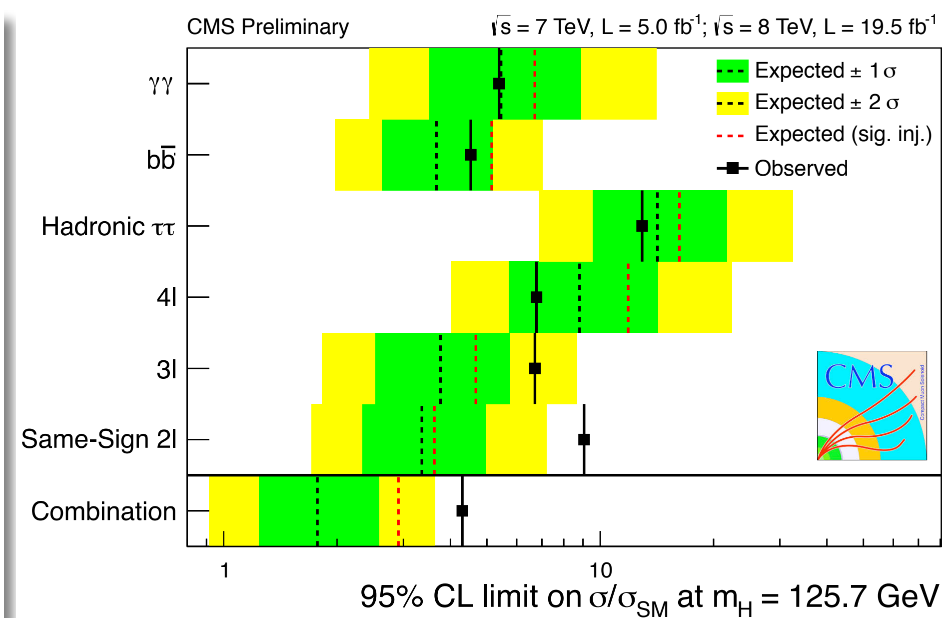


CMS ttH Combination

CMS PAS HIG-13-015
CMS PAS HIG-13-019
CMS PAS HIG-3-020
and arXiv:1303.0763

- CMS combined results:
  - **$\mu < 4.3$ (1.7 expected)**
  - **$\mu = 2.5^{+1.1}_{-1.0}$; 2.5σ evidence for ttH production**
- 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!

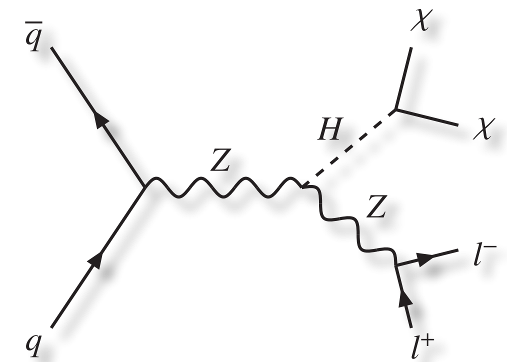




Invisible Higgs

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→χχ) < 65%** (84% exp.) @ 95% CL, m_H = 125 GeV
- CMS (5+20 fb^{-1}):
  - **Br(H→χχ) < 75%** (91% exp.) @ 95% CL, m_H = 125 GeV



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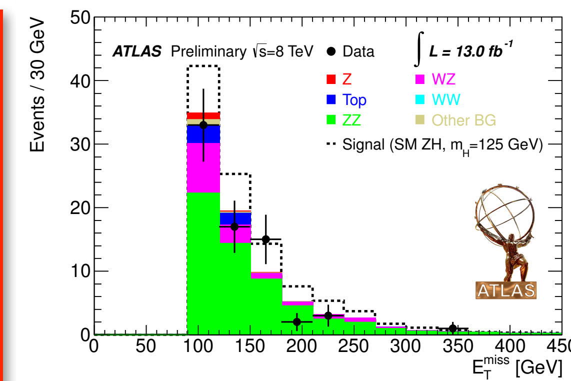
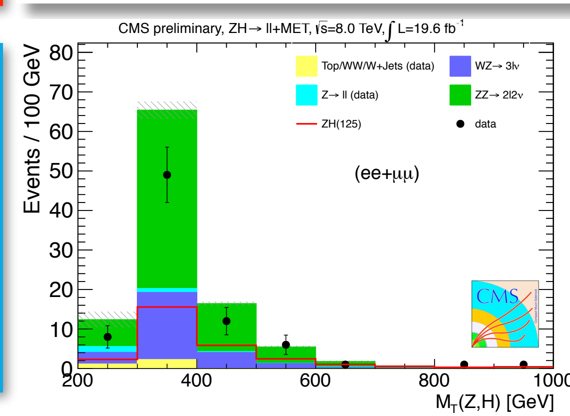
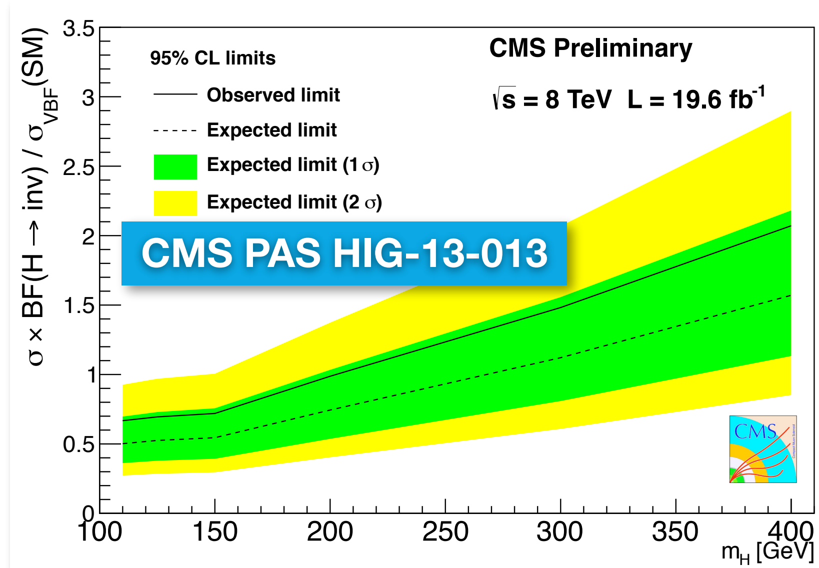


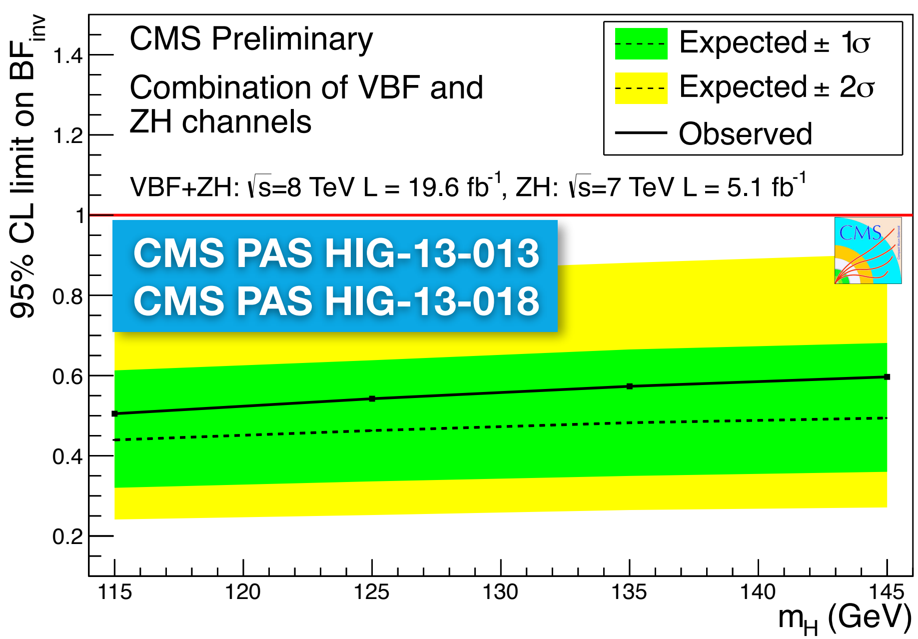
CMS PAS HIG-13-018



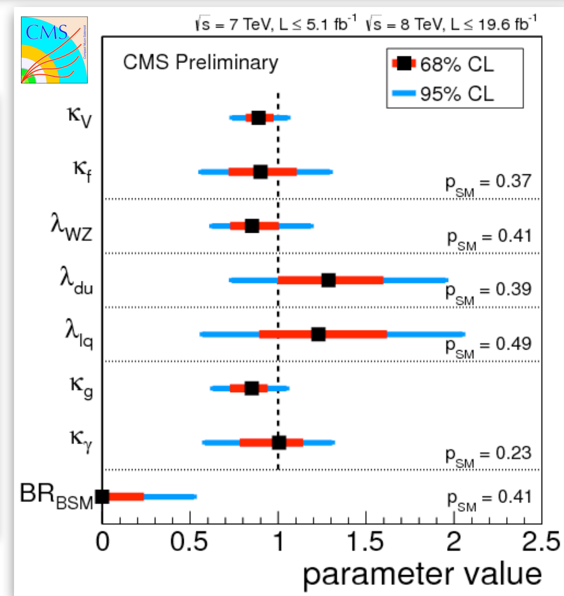
More on Invisible Higgs

- CMS also studied a VBF production of invisibly decaying Higgs boson:
  - **Br(H→inv.) < 69%** (55% exp.) @ 95% CL
- Also in HZ(bb):
  - **Br(H→inv.) < 182%** (199% exp.) @ 95% CL
- Two most sensitive direct searches have been combined
- Further improvement could come from combination with the similar indirect limit B < 0.52 @ 95% CL





CMS PAS HIG-13-005



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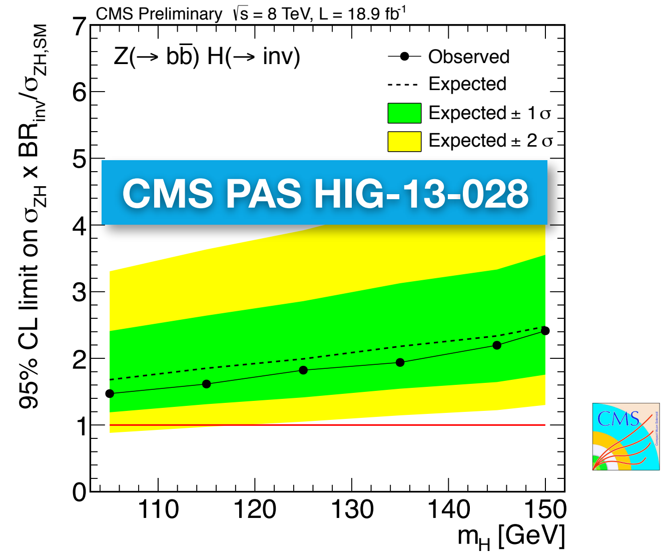
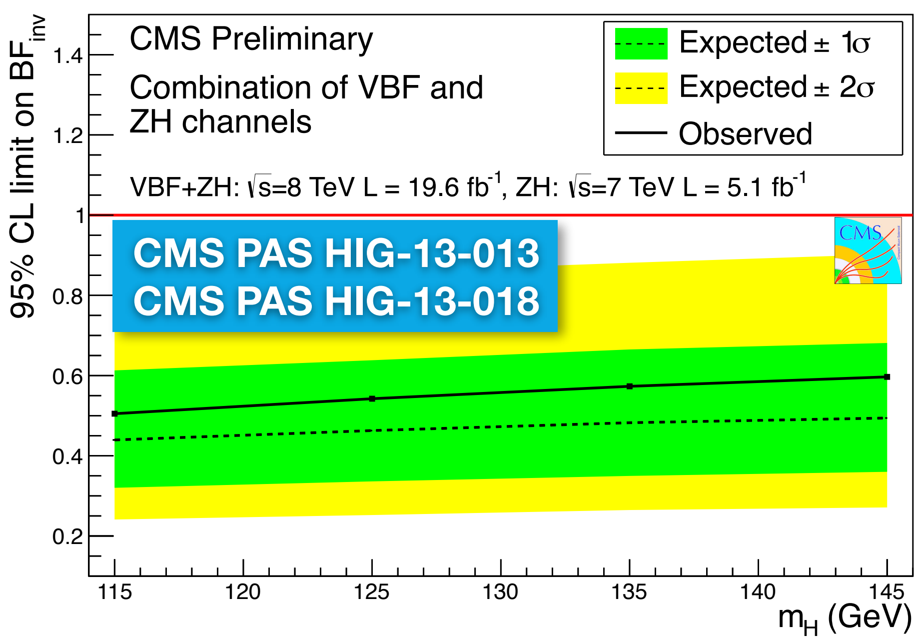
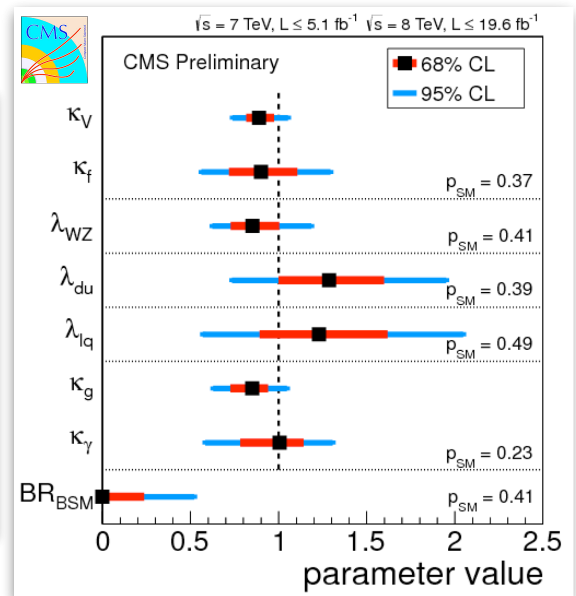




CMS PAS HIG-13-005



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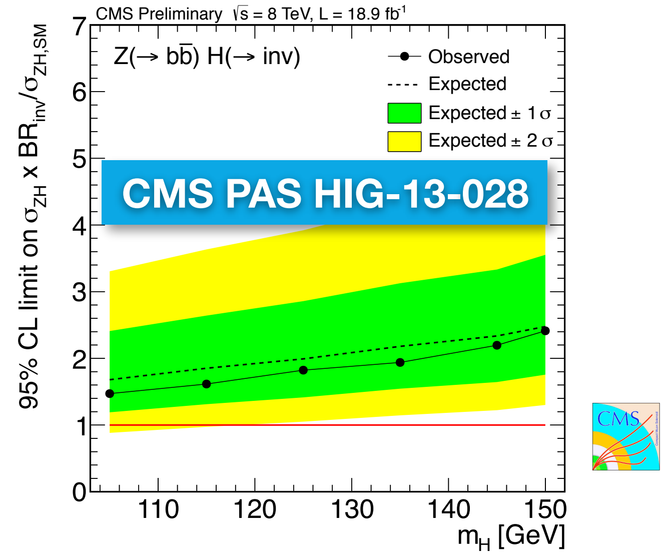

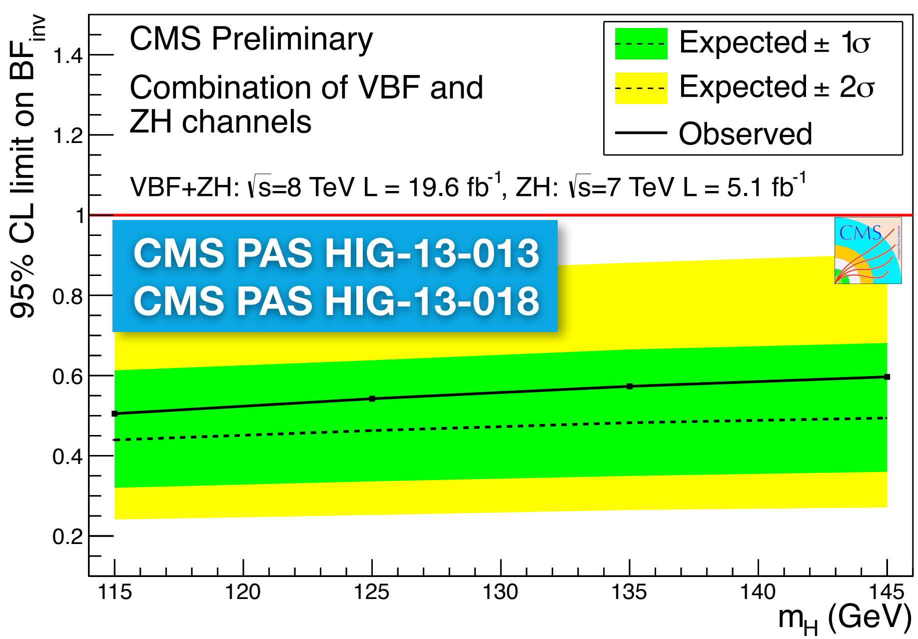

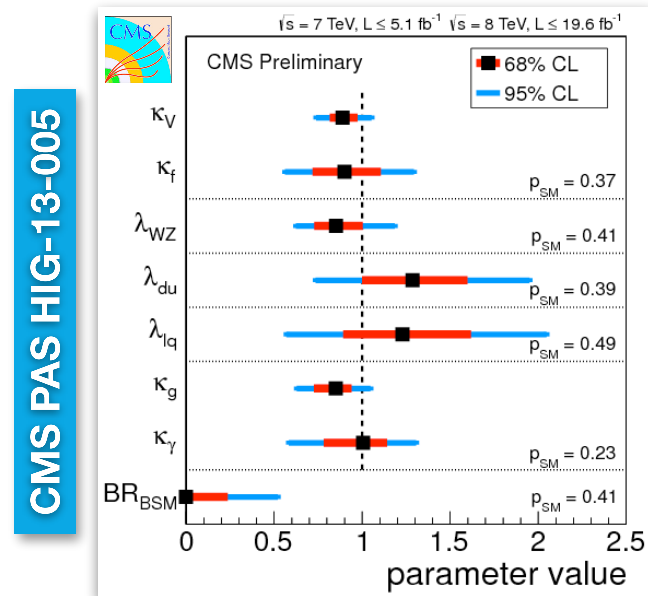


Invincible Higgs

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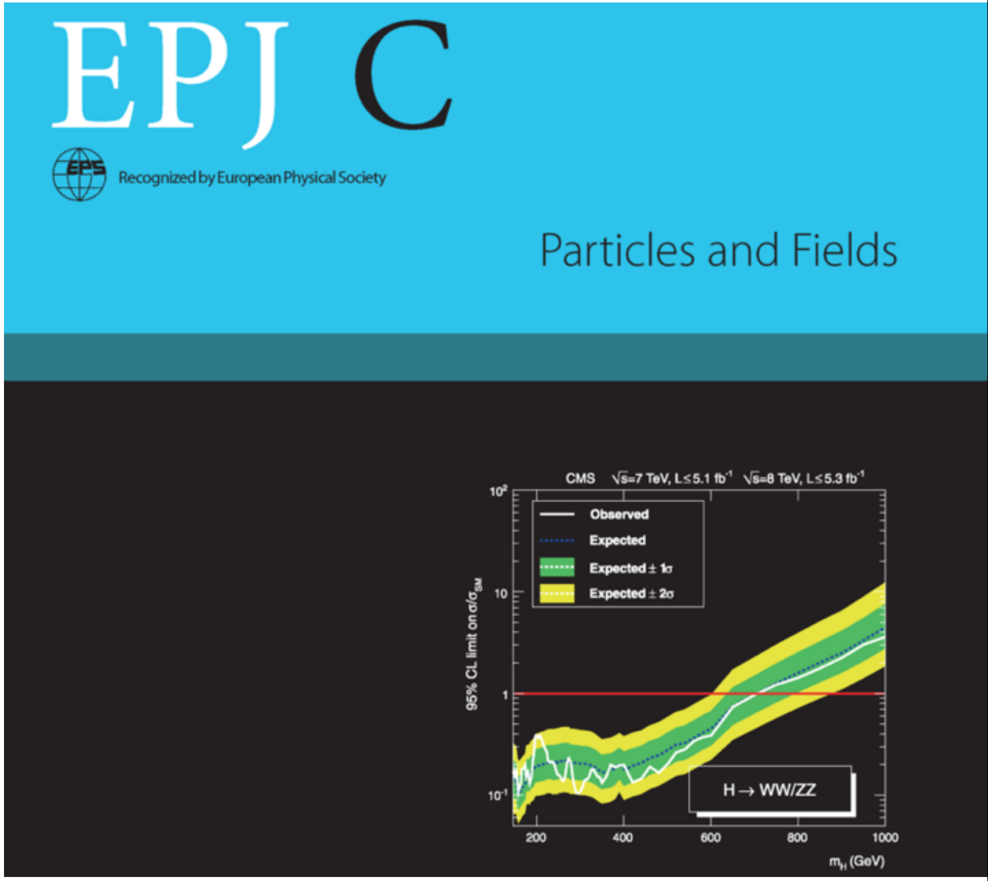
In 2HDM Speramus!

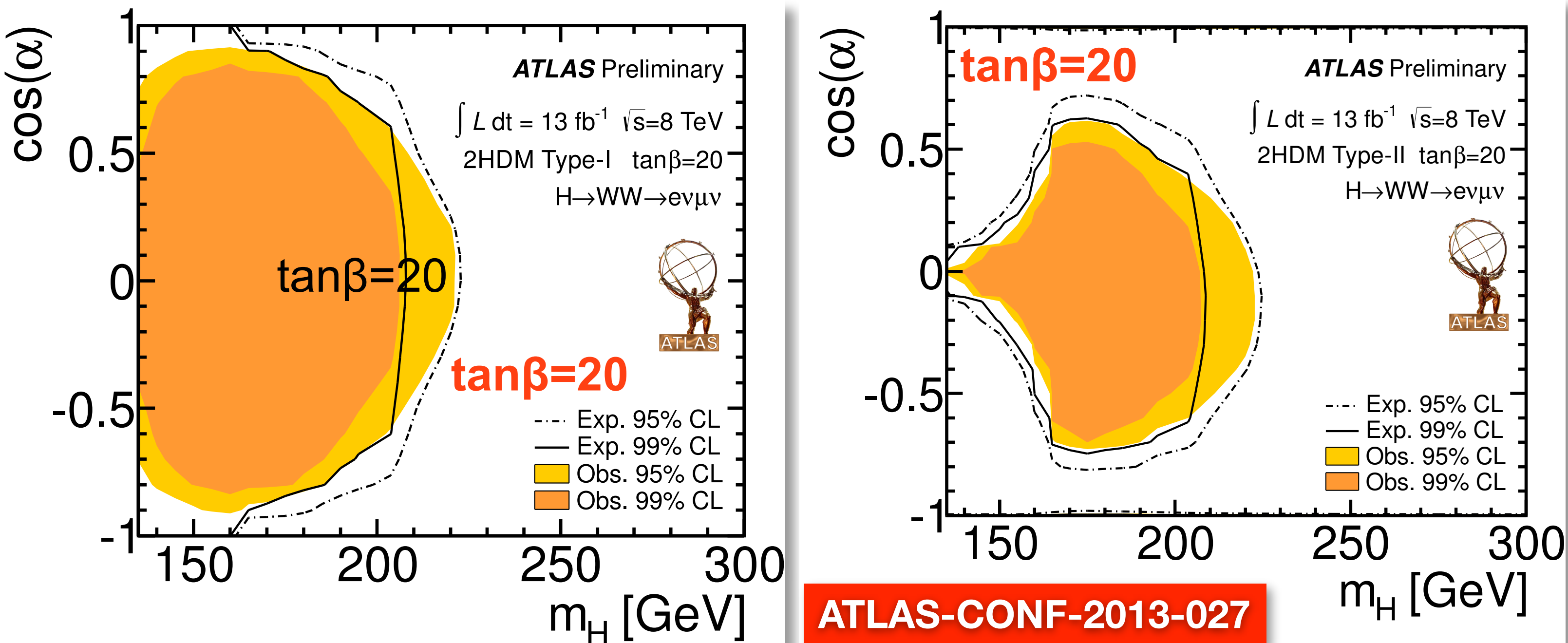
- Many extensions of the SM predict more than one Higgs doublet
- A classic realization of 2HDM (two-Higgs-doublet model) is SUSY, or its constrained version, MSSM
  - Additional heavy CP-even neutral Higgs boson H, CP-odd neutral A, and $H^{\pm}$



- 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)

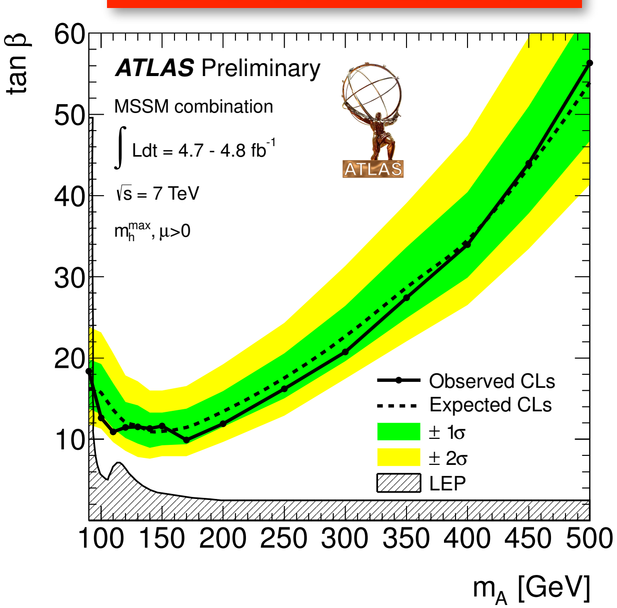


ATLAS-CONF-2013-027

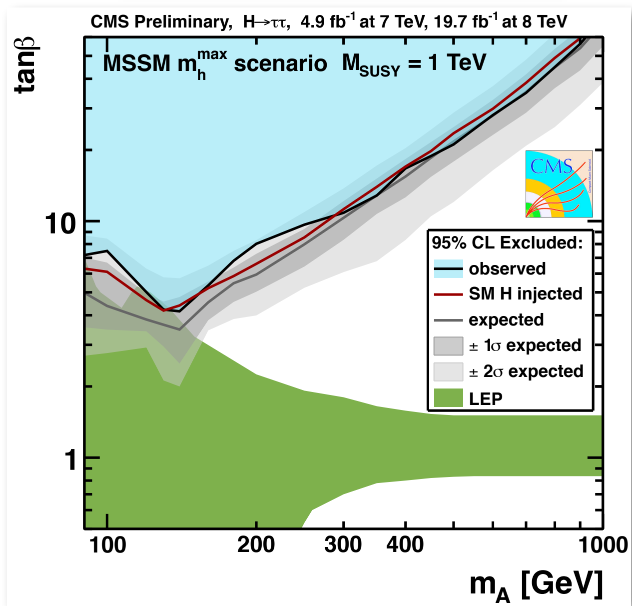
MSSM Higgs Searches

- Most recent results on the H/A(ττ), including the new LHCb search exploiting τ's in the forward region
- Also, limits on charged Higgs from top decays in τν (ATLAS+CMS) and cs (ATLAS) channels and search for NMSSM h → a^0a^0 → 4μ (CMS, D0), 4γ (ATLAS) and a_1 → 2μ (ATLAS & CMS), as well as ϒ(1S,2S) → a^0γ → ττγ, μμγ (BaBar, Belle); and ggγ, and ssγ (BaBar)

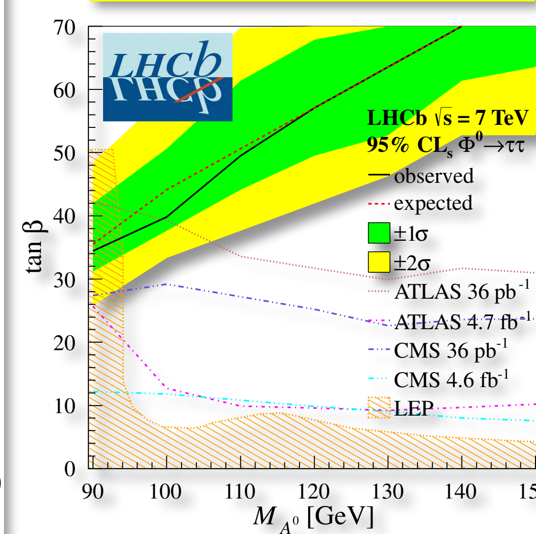
ATLAS-CONF-2012-094



CMS PAS HIG-13-021



LHCb Collaboration arXiv:1304.2591



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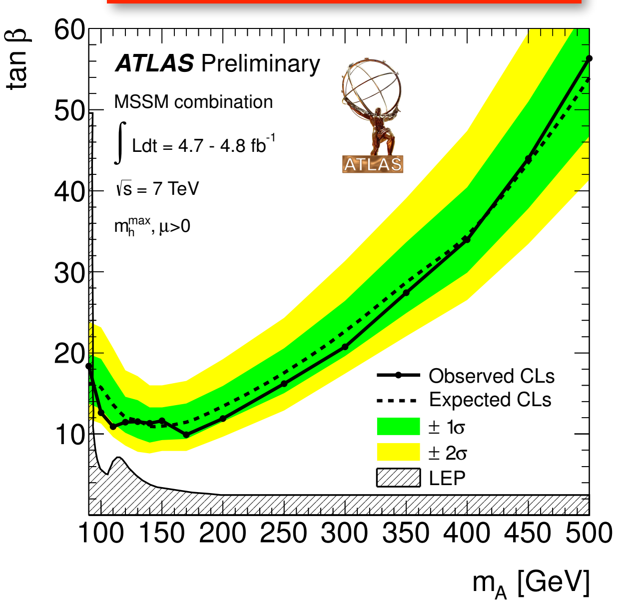
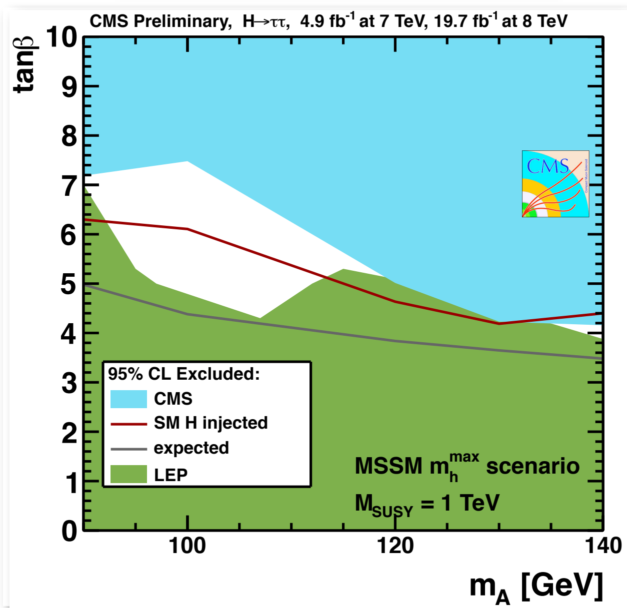
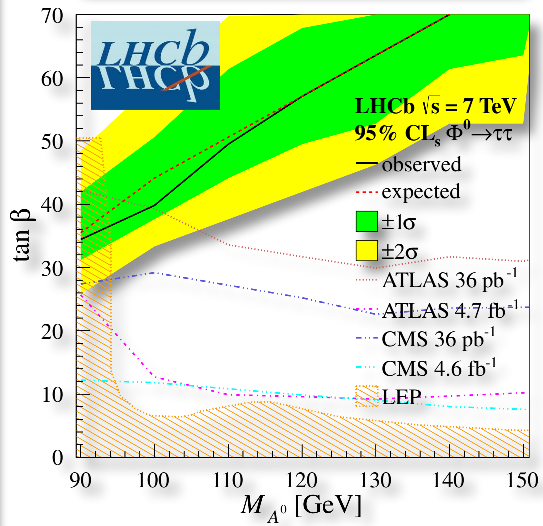
ATLAS-CONF-2012-094



CMS PAS HIG-13-021



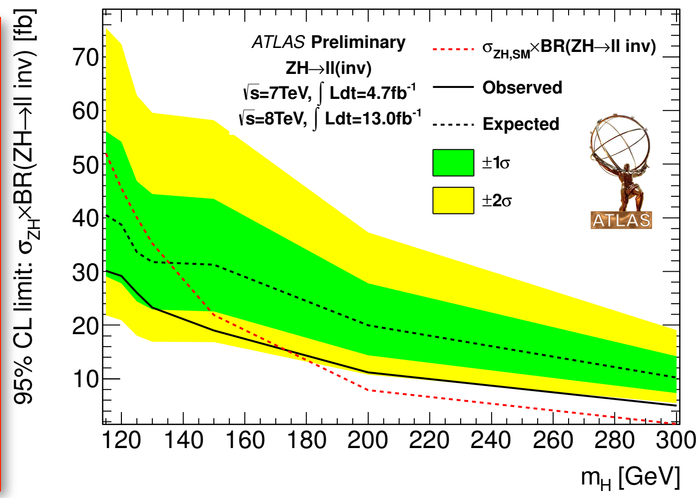
LHCb Collaboration arXiv:1304.2591



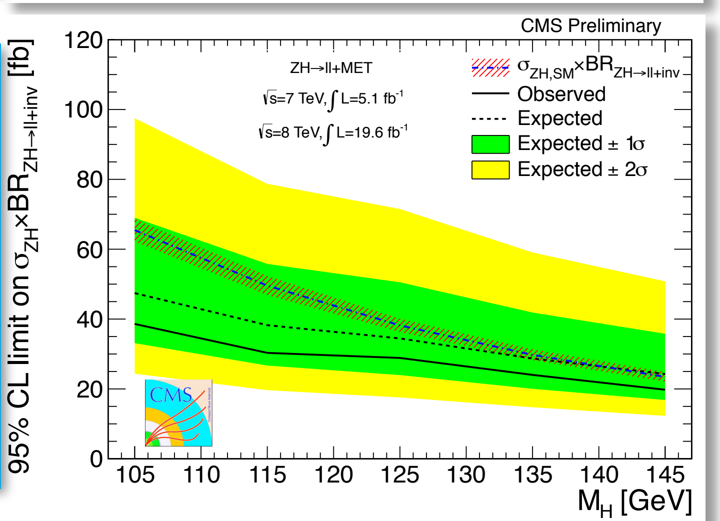
Additional Higgs Searches

- ✦ γγ/WW channels (shown earlier in the talk)
- ✦ Invisible channel:
- ✦ Heavy Higgs decaying into ZZ(llνν) or ZZ(lljj)

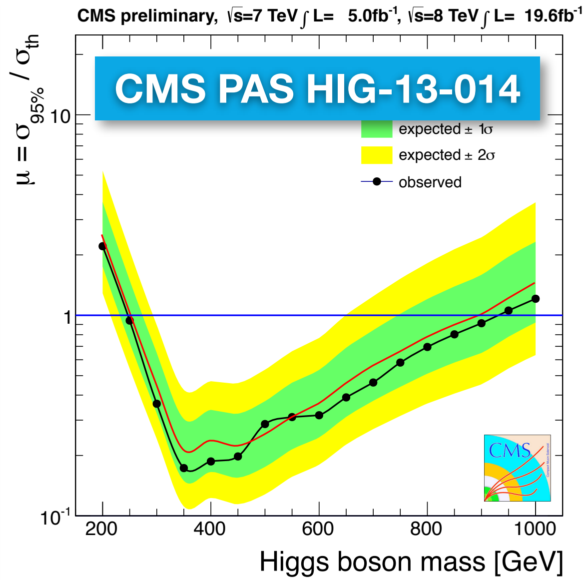
ATLAS-CONF-2013-011



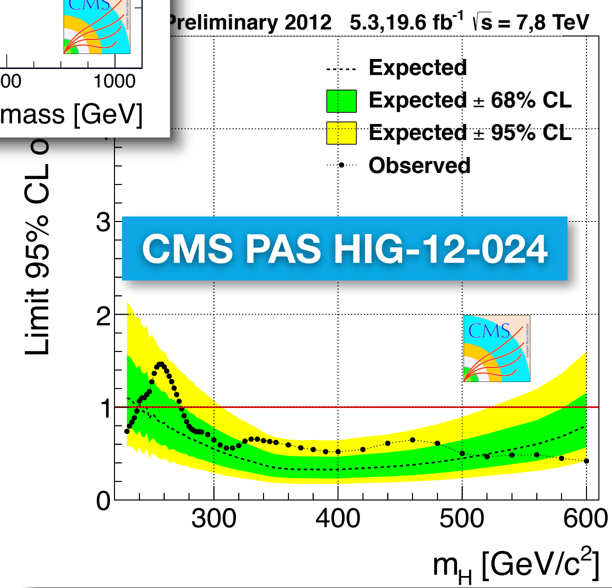
CMS PAS HIG-13-018



CMS PAS HIG-13-014



CMS PAS HIG-12-024



High-Mass Higgs Boson

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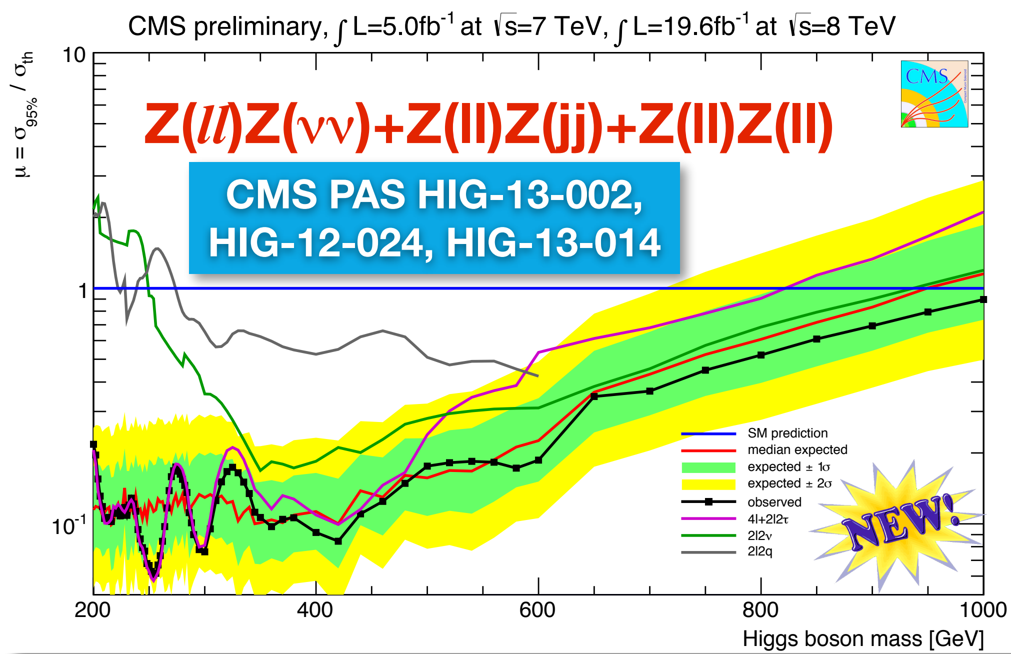
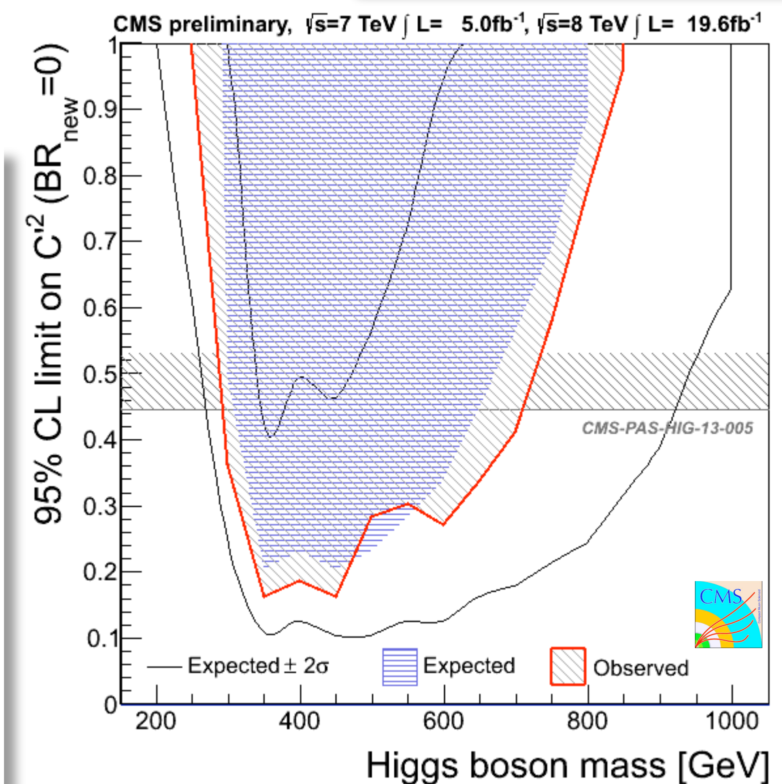
- A combined high-mass ZZ search to full statistics
  - Probes SM-like heavy Higgs up to ~900 GeV
  - Also explore modified couplings and reduced (by C'^2) width of an additional Higgs boson
    - $C^2 + C'^2 = 1$

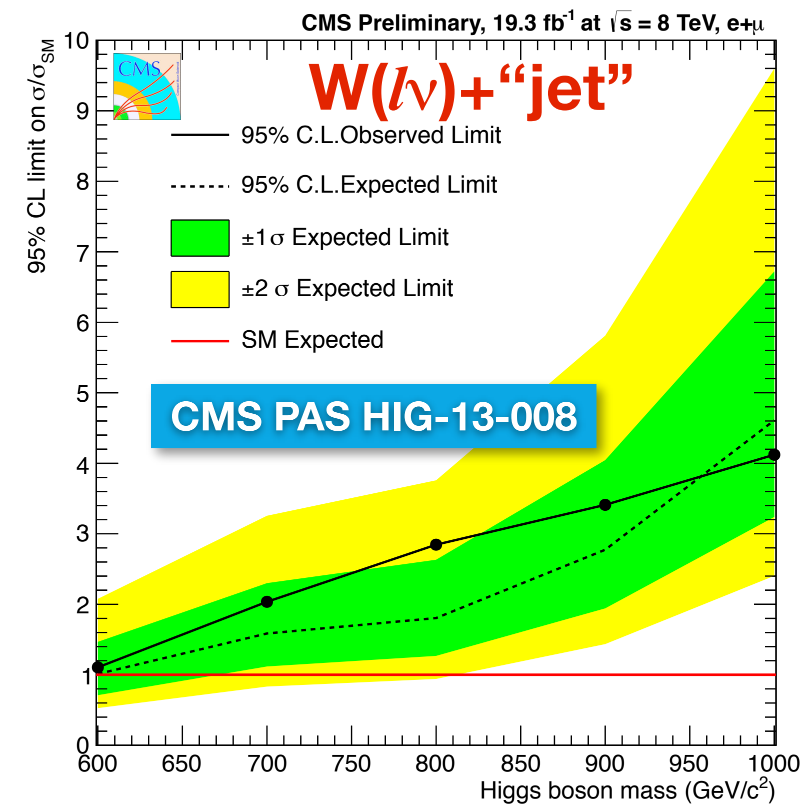
CMS PAS HIG-13-014

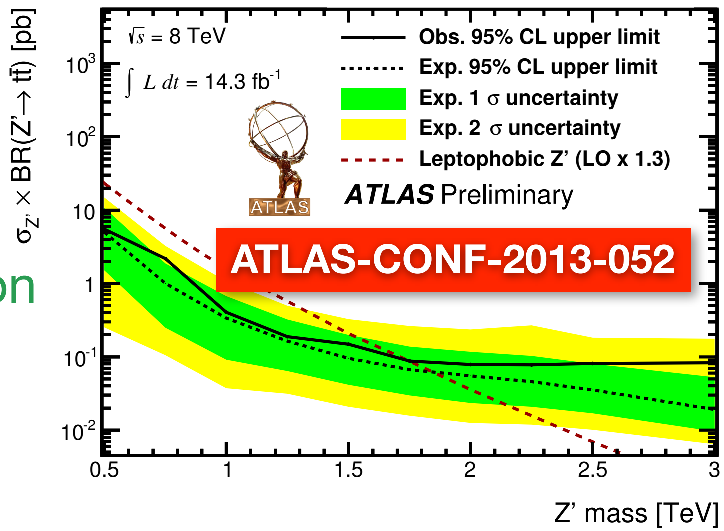


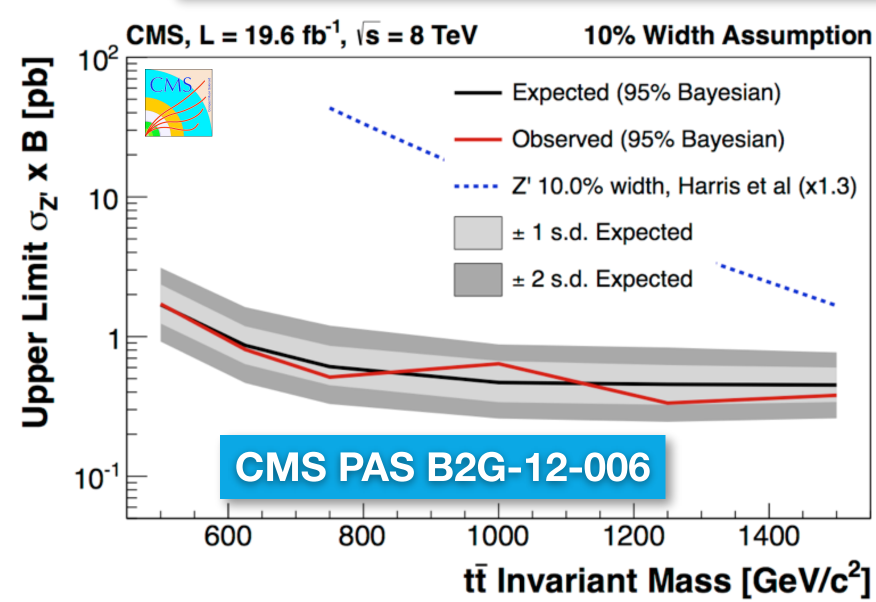


Higgs: Boosted Topology

- 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



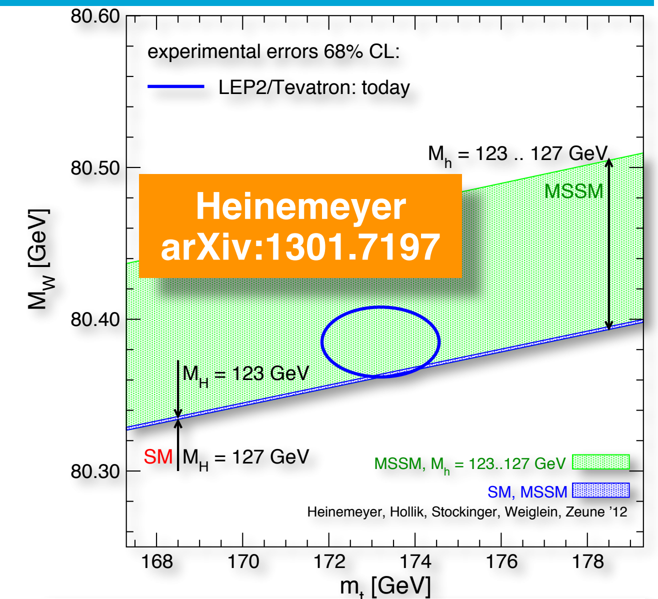


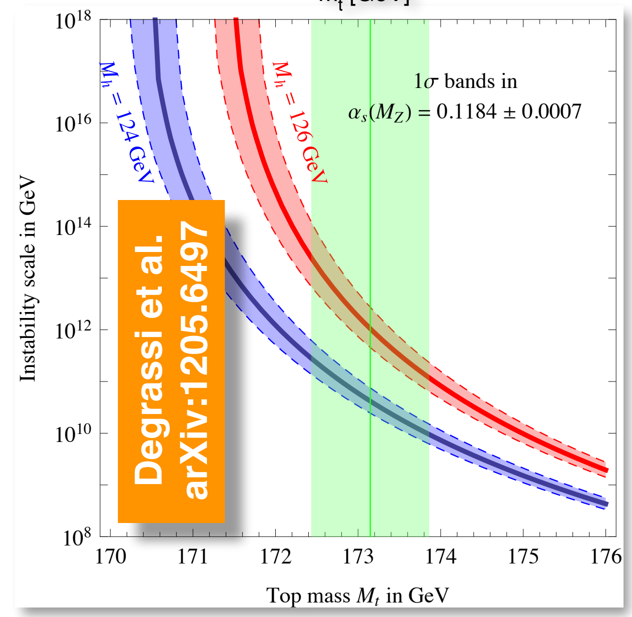


Learning from the Higgs Discovery

Higgs Discovery Implications

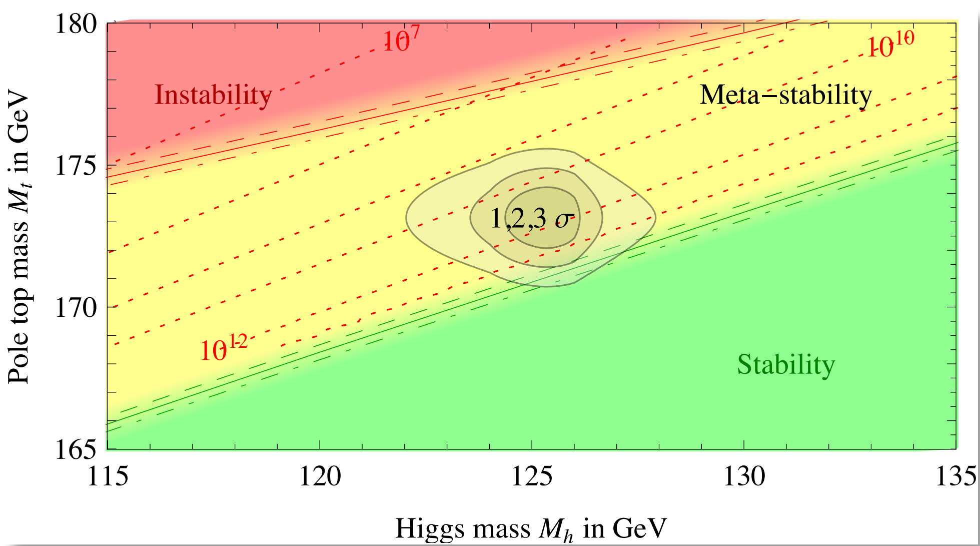
- Light Higgs boson discovery implies that the SM can not be a complete theory up to the Planck scale
- It's light enough to be a MSSM Higgs, but yet too heavy to obviously prefer MSSM vs. SM!
    - Had it been just 10% heavier we would probably stop talking about low-scale SUSY!
- If we found the SM Higgs boson, we now need to explain the EWSB mechanism, i.e. what makes the Higgs potential what it is (explain the origin of the λ term in the Lagrangian)
    - It looks more and more like the SM Higgs boson, but there is still room for surprises!
- Vacuum stability arguments require new physics to come at a scale ~10 GeV or less
    - Curiously points to a similar scale as suggested by the neutrino mass hierarchy via see-saw mechanism
- Nevertheless, a metastable vacuum could survive w/o new physics
- In a sense, a 125 GeV Higgs boson is maximally challenging and rich experimentally, but also inflicts "maximum pain" theoretically, as it is not so easy to accommodate

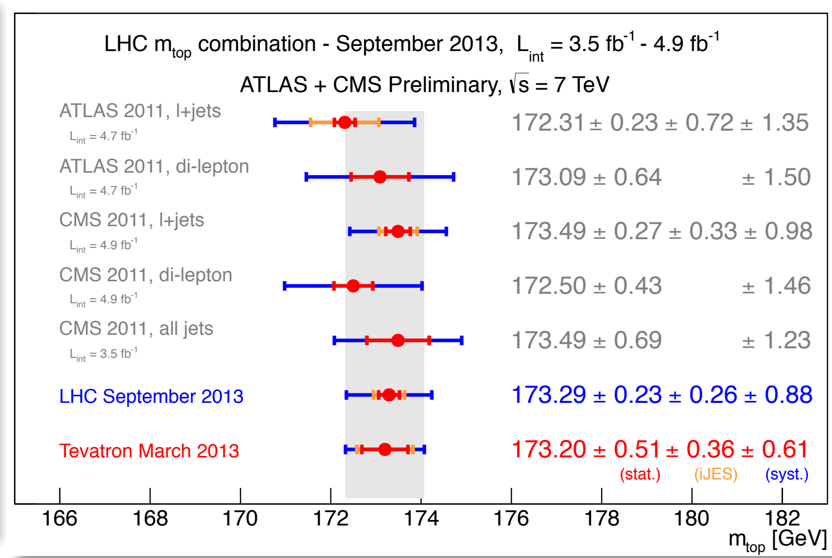




Just-So Higgs?

- The simultaneous measurement of the Higgs boson and top quark masses allowed for the first time to infer properties of the very vacuum we leave in!
  - We are in a highly fine-tuned situation: the vacuum is at the verge of being either stable or metastable!
  - ~1 GeV in either the top-quark or the Higgs boson mass is all it takes to tip the scales!
- Perhaps Nature is trying to tell us something here?
  - Very important to improve on the precision of top quark mass measurements, including various complementary methods and reduction of theoretical uncertainties
  - Tevatron is still leading with the new combined M_t result, but LHC is catching up quickly!



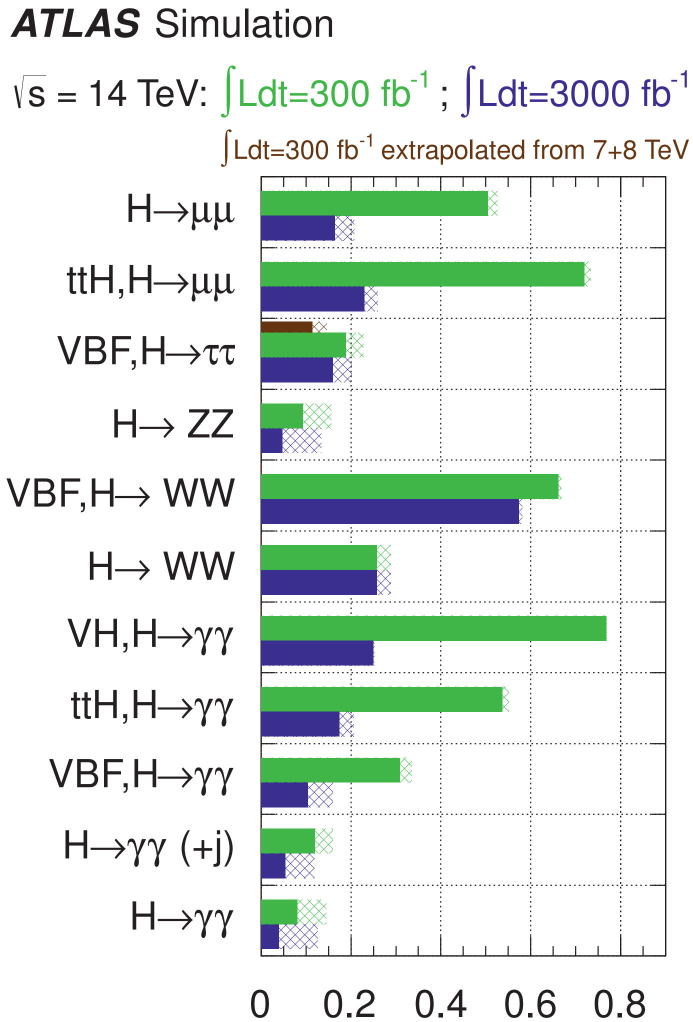


Degrassi et al, arXiv:1205.6497

Future of Higgs Studies

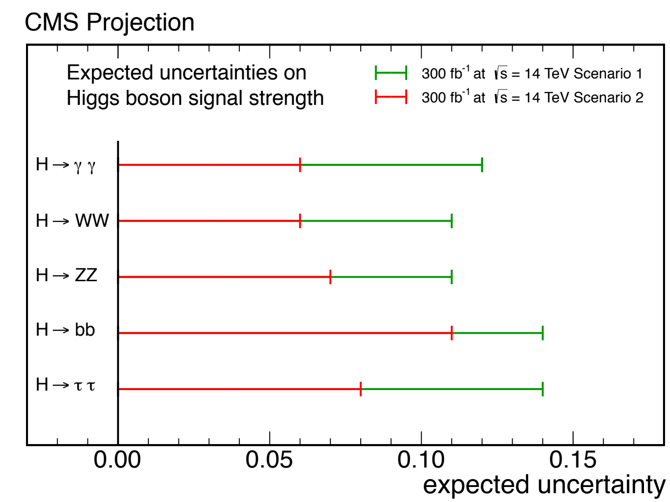
- Number of dedicated studies from ATLAS and CMS
  - ESPG submissions, Nov 2012
    - ATLAS-PUB-2013-004
    - CMS Note 2012/006
  - Snowmass contributions, July 2013
    - ATLAS: arXiv:1307.7292
    - CMS: arXiv:1307.7135
  - ECFA submission, October 2013
- CMS: two scenarios
  - Scenario 1: all systematics are unchanged
  - Scenario 2: experimental systematics scale as $1/\sqrt{\int L dt}$; theory uncertainties are halved

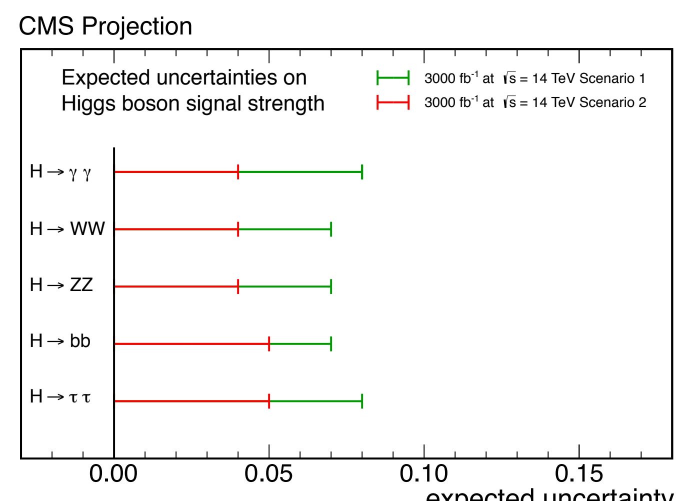
Higgs: Signal Strength



ATLAS Collaboration arXiv:1307.7292

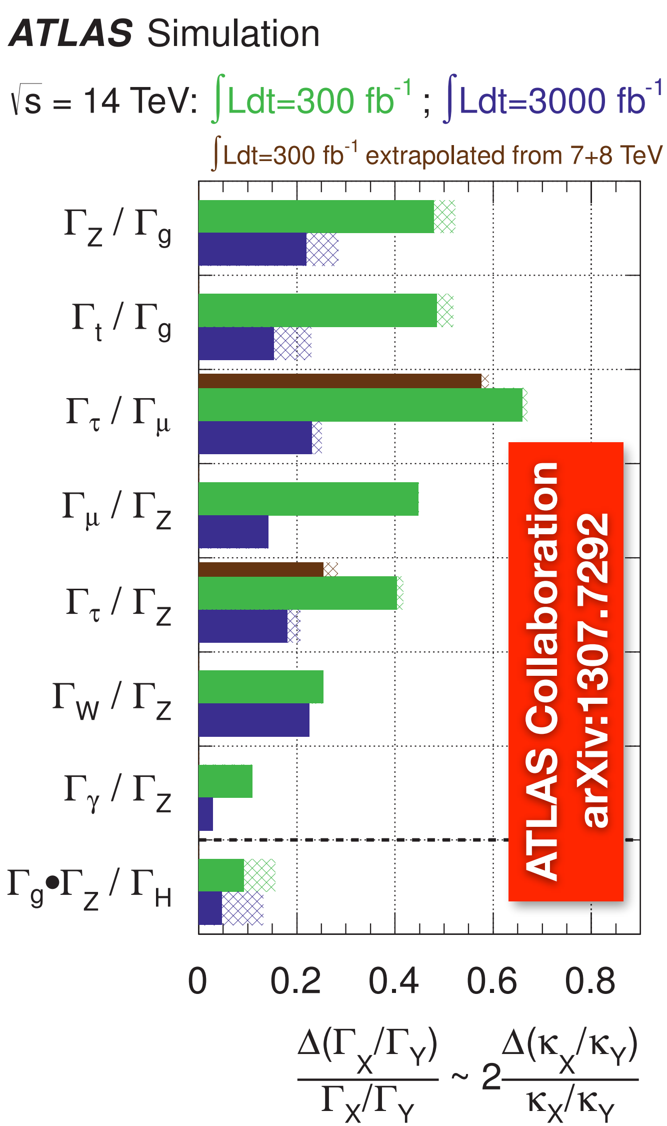
L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]



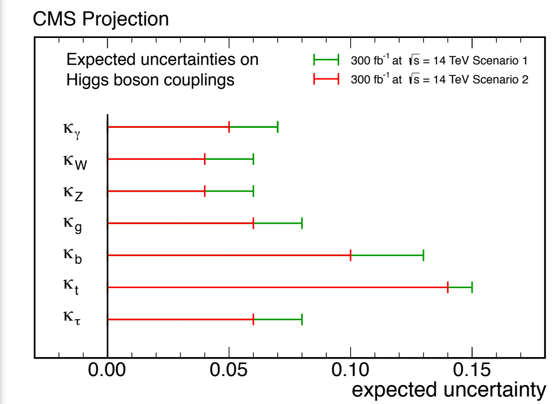


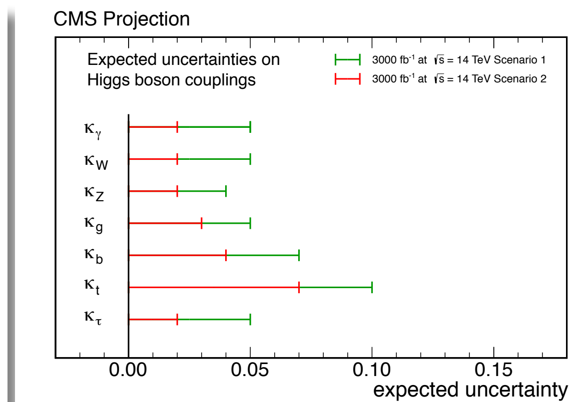
CMS Collaboration arXiv:1307.7135

Coupling Determination



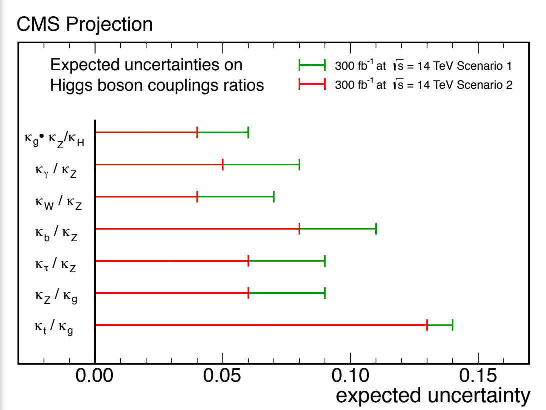
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]

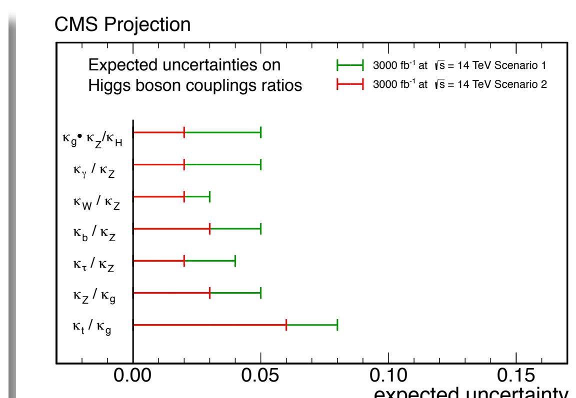




CMS Collaboration, arXiv:1307.7135

L (fb^{-1})	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ / κ_Z	κ_W / κ_Z	κ_b / κ_Z	κ_τ / κ_Z	κ_Z / κ_g	κ_t / κ_g	κ_μ / κ_Z	$\kappa_{Z\gamma} / \kappa_Z$
300	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

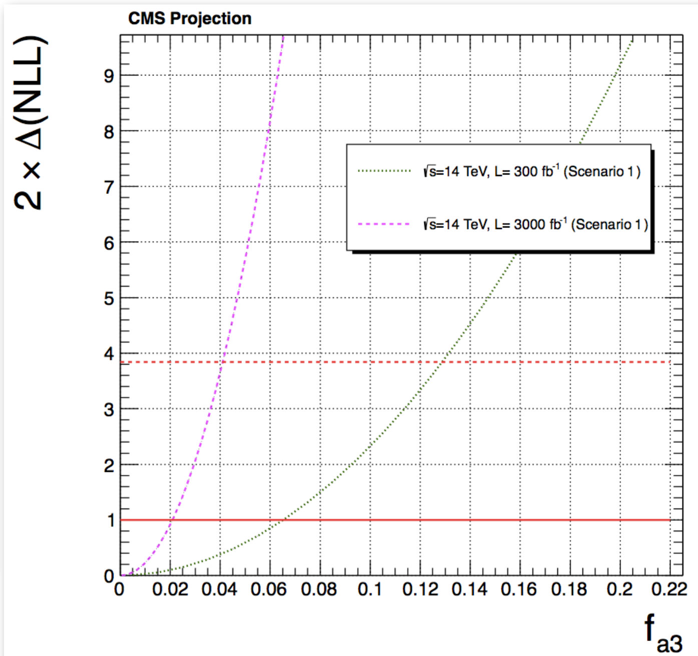


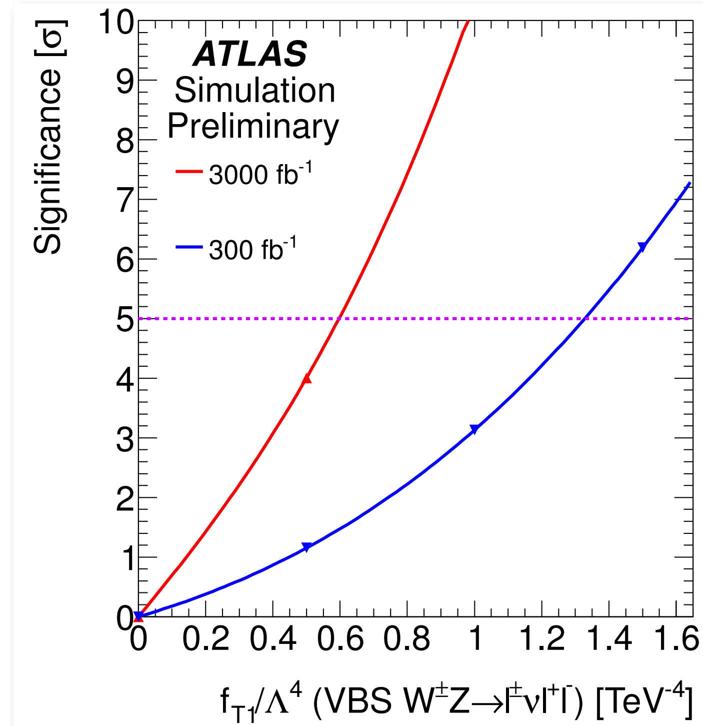


Spin and VV Scattering

✦ Pseudoscalar admixture:

CMS Collaboration
arXiv:1307.7135





ATLAS PUB-2013-006

✦ VV scattering and aQGC

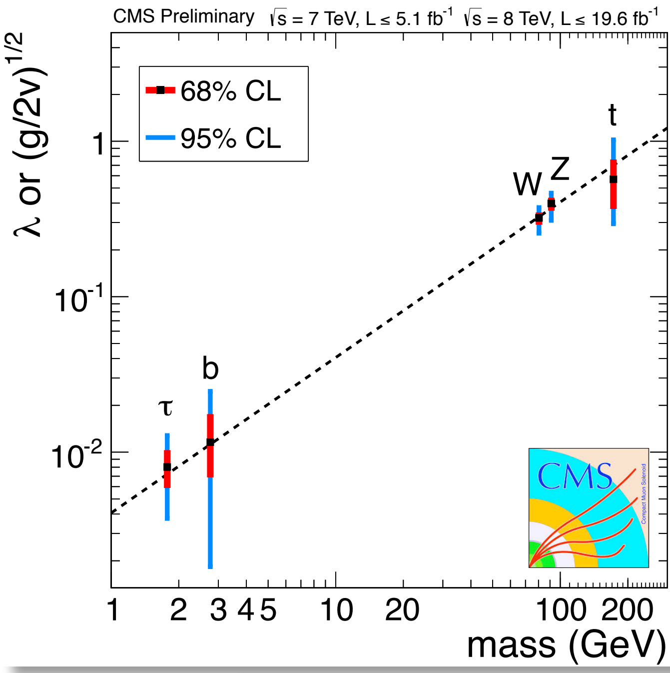
CMS PAS FTR-13-006

Significance	3σ	5σ
SM EWK Scattering Discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
f_{T1}/Λ^4 at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

	300 fb^{-1}	3000 fb^{-1}
f_{T1}/Λ^4	1.3 TeV^{-4}	0.6 TeV^{-4}

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 indirectly via gluon fusion production mechanism



CMS PAS HIG-13-005

- Couplings to the down-type third-generation fermions are established directly at ~4σ level
- The spin and the mass of a new state have been determined
- 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

Thank You!