Higgs Results from the LHC: In Search of Exotic Higgses

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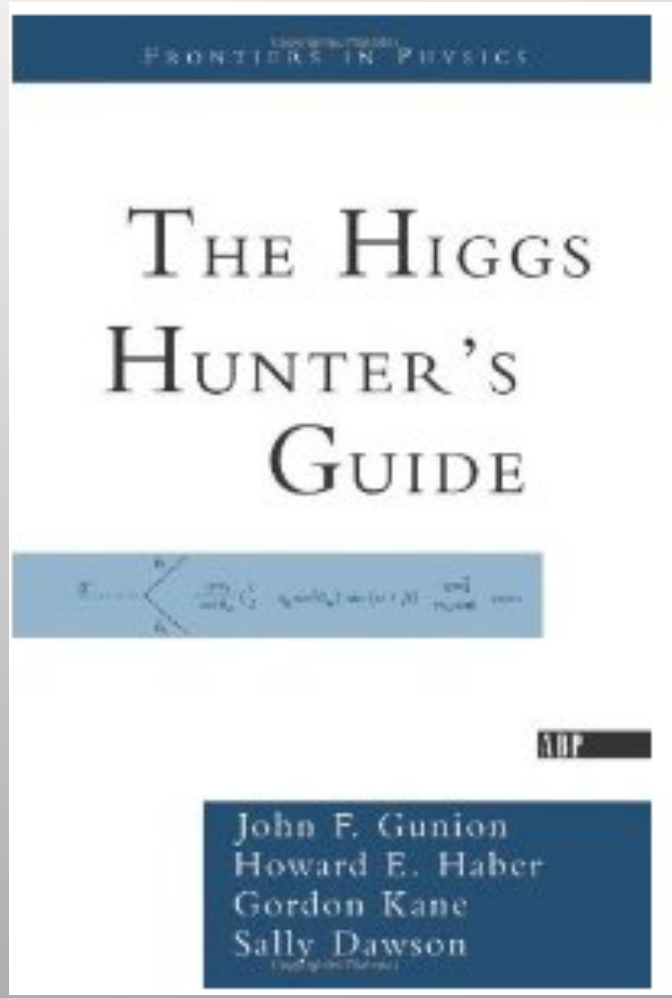
The Study of the Fundamental Scalar(*)

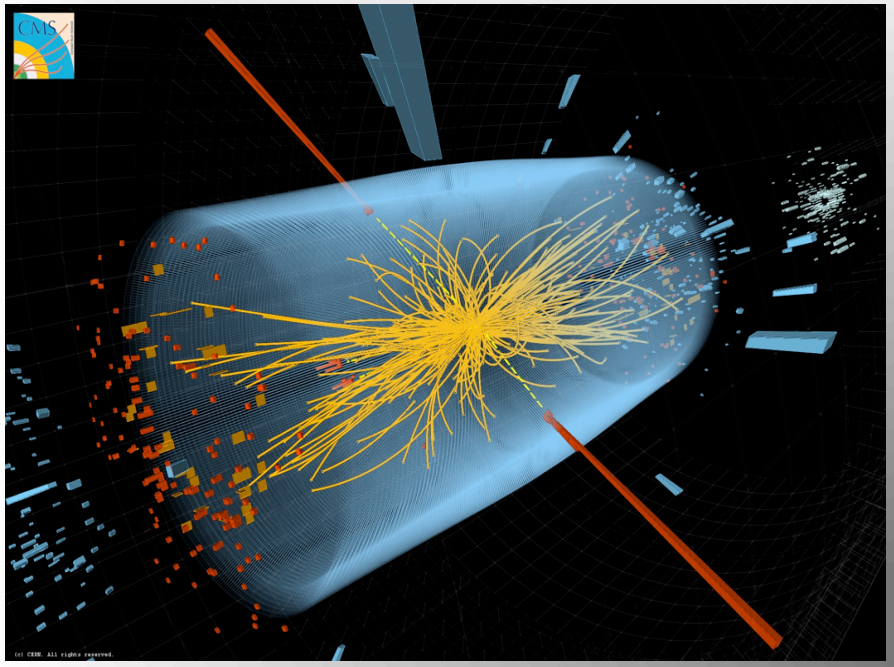
- A milestone book for young and fearless Higgs hunters in the 90's eg at LEP, Tevatron, LHC…
- My first "encounter" with Jack (since he is first author)
- A truly remarkable and useful guide for experimentalists and alike
- … and the ultimate answer is:

  125 GeV

  (not given in the book, however)

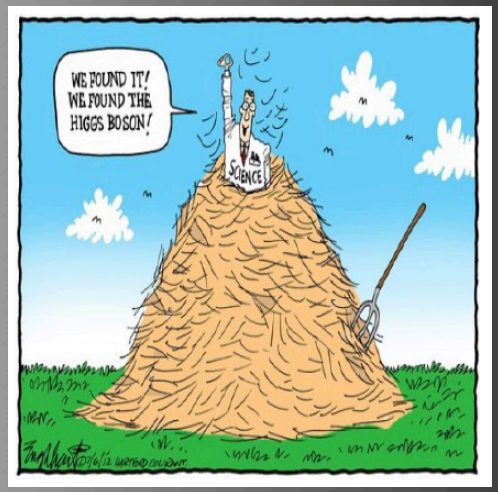


(*) To be compliant with the Belgian Laws for Scientific Funding
Hereafter we will however call it the HIGGS PARTICLE

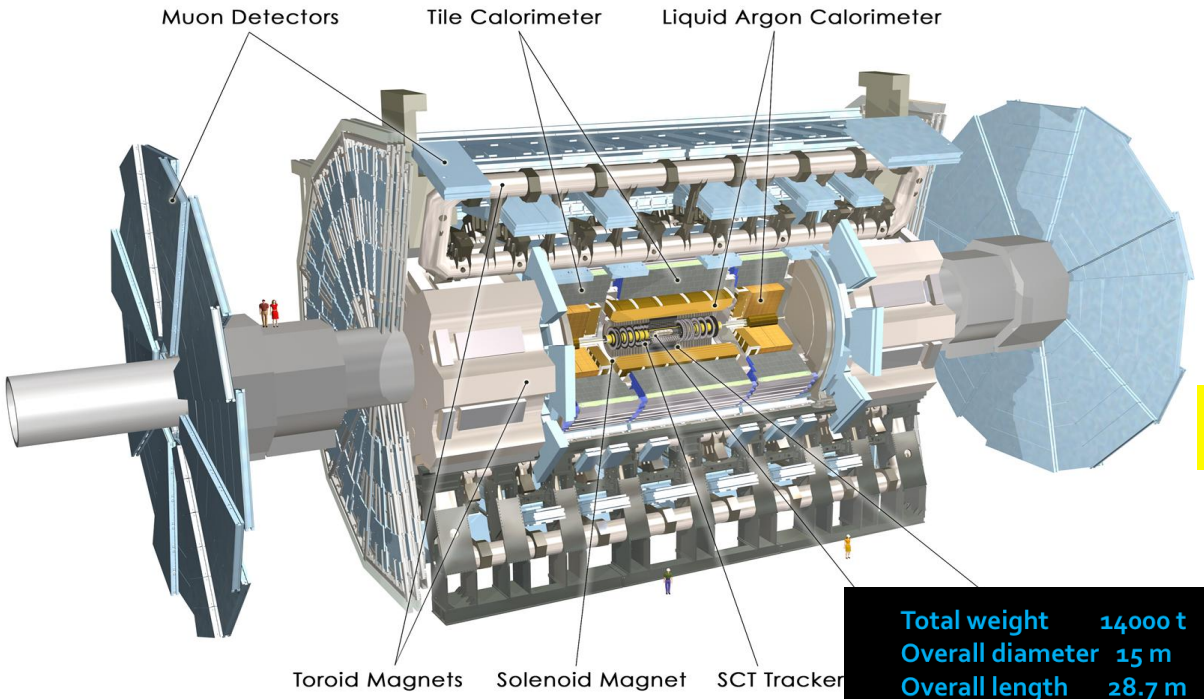


Outline

- Short introduction
- Standard Model Higgs channel studies overview
- Beyond the Standard Model
- Summary



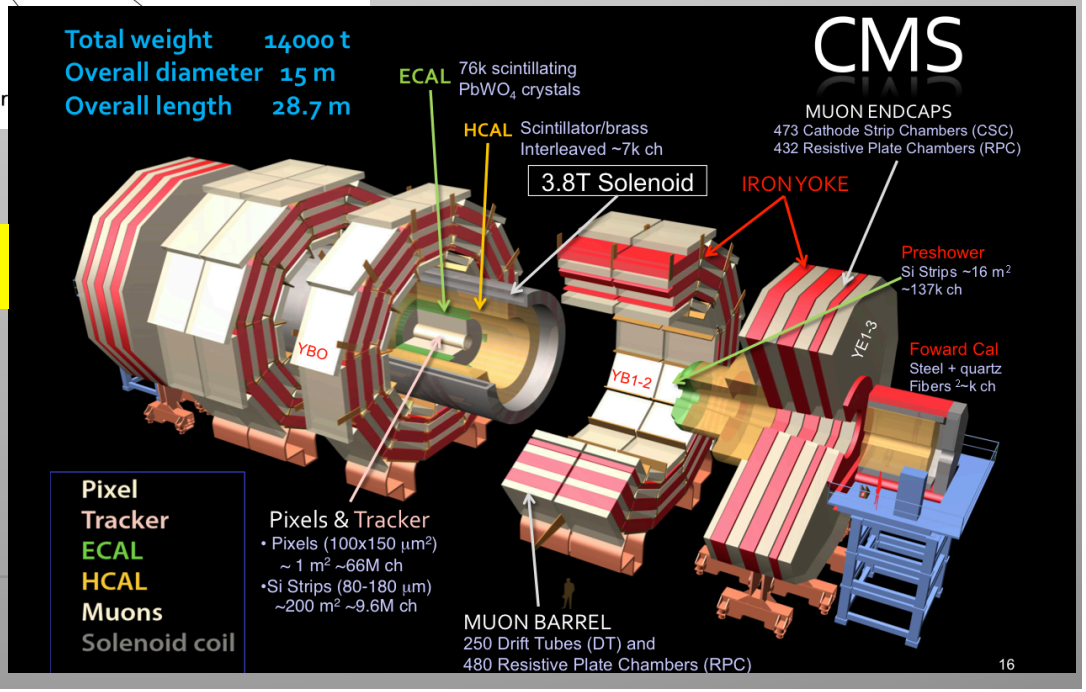
The Higgs Hunters @ the LHC



LHC: pp collisions
Luminosity:
5 fb^{-1} @ 7 TeV
20 fb^{-1} @ 8 TeV

The ATLAS experiment

The CMS experiment



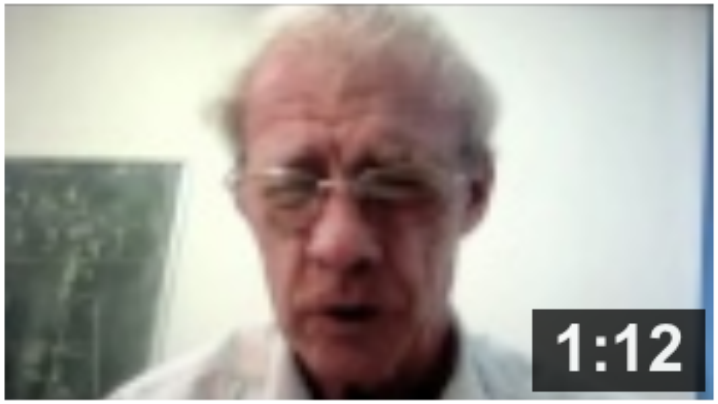
And LHCb…?

Is Jack in CMS?

- Sort of…
- Not a full member, ie not required (actually vetoed) for cabling up the detector, doing data taking shifts, or alike, but extremely good source of information and inspiration on (exotic) higgs matters
- Member of UC-Davis CMS group
- This has been very useful for CMS and led to some papers based on common work on Higgs and SUSY

Jack @ CMS
(at a time before selfies became popular)

Reporting from the LC front



Physics News from CERN

by **UCDavis**

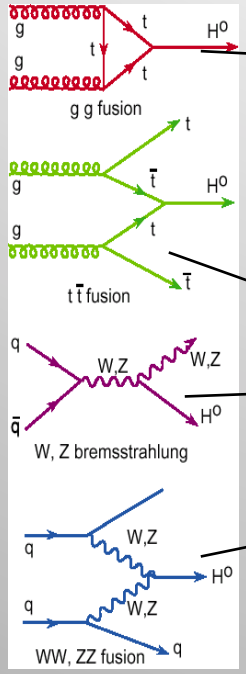
331 views

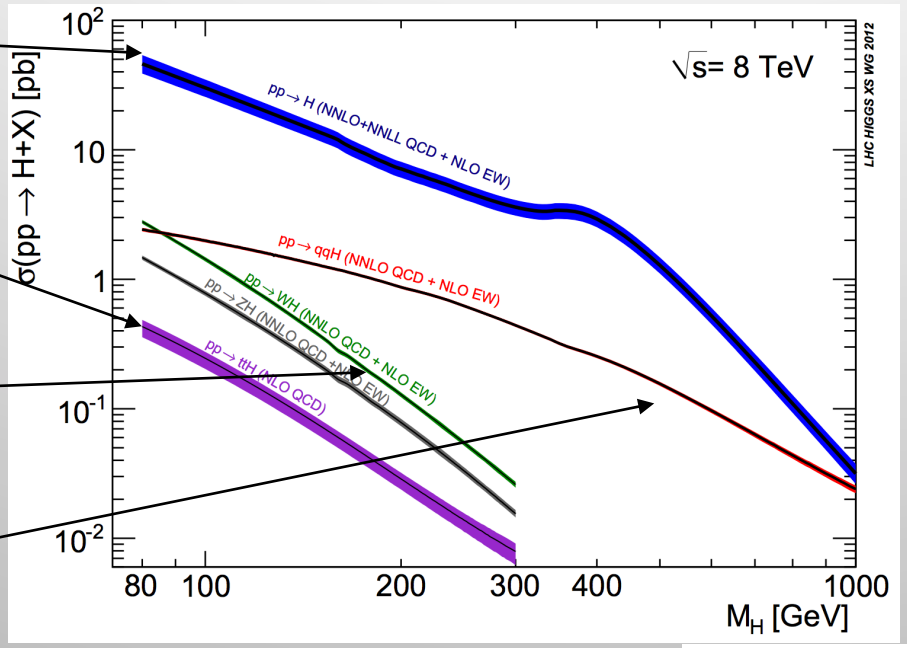
YouTube

CERN Large Hadron Collider (LHC)

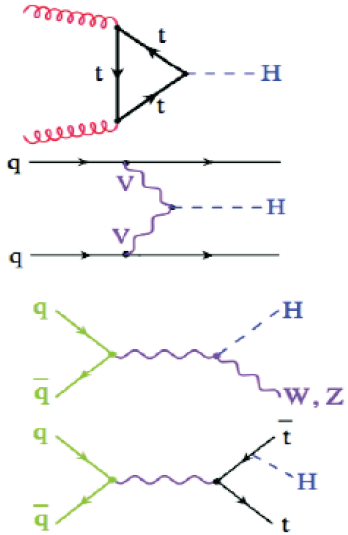
by **Lorenia de la Vega** • • 413,348 views

Higgs Production & Decay





- Gluon fusion
- VBF
- VH
- ttH

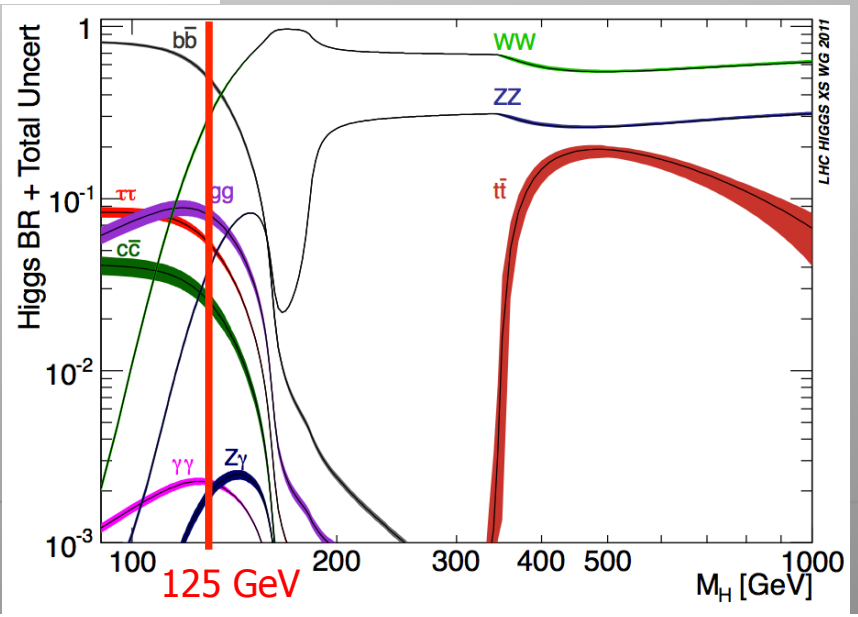


Numbers taken from the LHC Higgs Cross Section WG

YR1: Inclusive cross sections
arXiv:1101.0593

YR2: Differential cross sections
arXiv:1201.3084

YR3: Properties
arXiv:1307.1347



Higgs Studies

Higgs Hunting

Processes/decays studied:

Results released In progress

	untagged	VBF	VH	ttH
H-> gamgam				
H-> ZZ				
H->WW				
H-> bb				
H-> tau tau				
H-> Zgamma				
H-> mumu				
H-> invisible				

+ more exotic channels

Main decay channel characteristics:

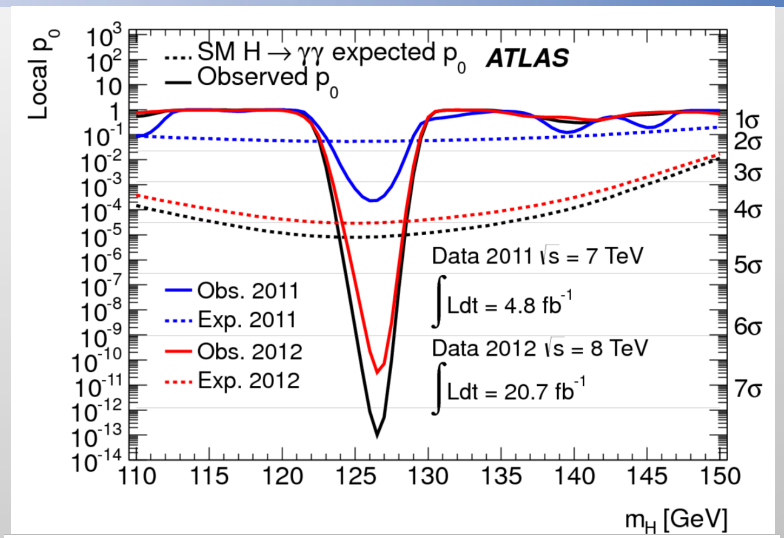
Channel	m_H range (GeV/c^2)	Data used 7+8 TeV (fb^{-1})	m_H resolution
H -> γγ	110-150	5.1+19.6	1-2%
H -> tautau	110-145	4.9+19.6	15%
H -> bb	110-135	5.0+19.0	10%
H -> WW -> lnulnu	110-1000	4.9+19.5	20%
H -> ZZ -> 4l	110-1000	5.1+19.6	1-2%

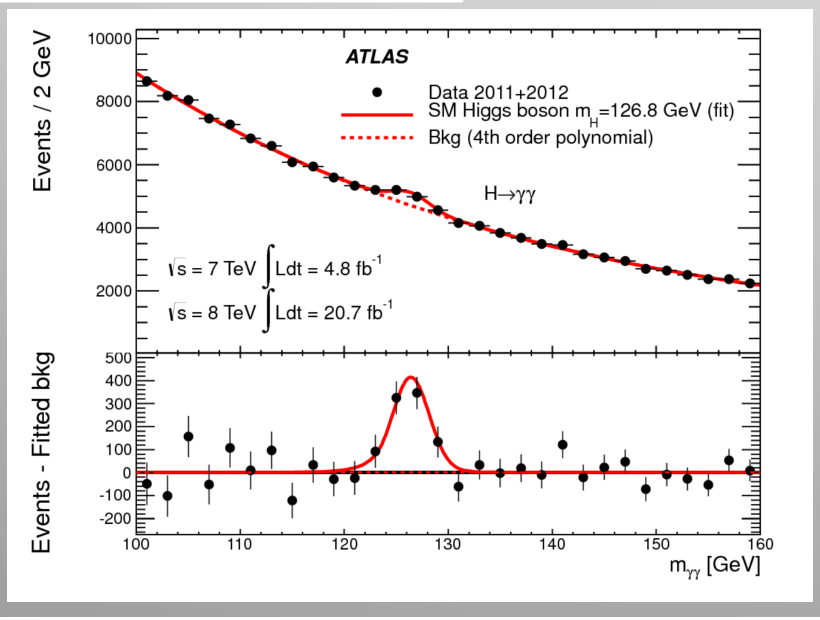
The Decay H→ γγ

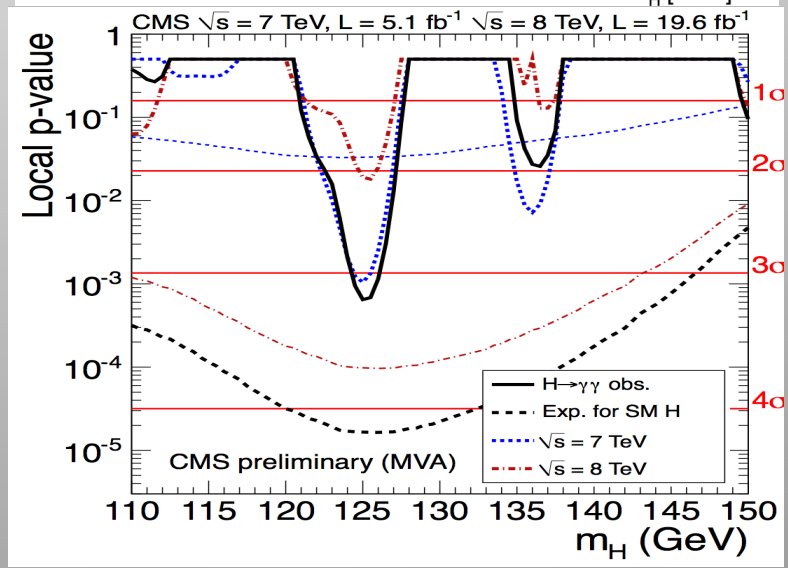
- Analysis optimized for S/B using categories to classify events
- Categories with VBF and VH tagging
- Background fitted from the side bands of the invariant mass spectrum

ATLAS: arXiv:1307.1427
CMS-PAS-HIG-13-001

$$\text{Signal strength } \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$







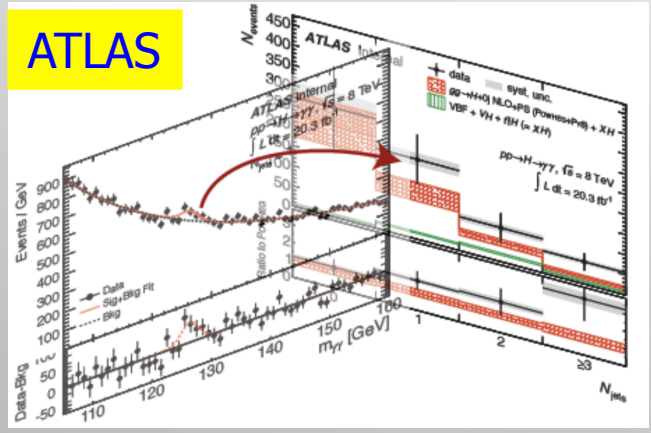
ATLAS: 7.4 sigma observed 4.3 sigma expected → $\mu = \sigma/\sigma_{SM} = 1.55^{+0.33}_{-0.28}$

CMS: 3.2 sigma observed 4.2 sigma expected → $\mu = \sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$

Differential Distributions in H→ γγ

First differential distributions in H→ γγ. Fits to $m_{\gamma\gamma}$ distributions in bins

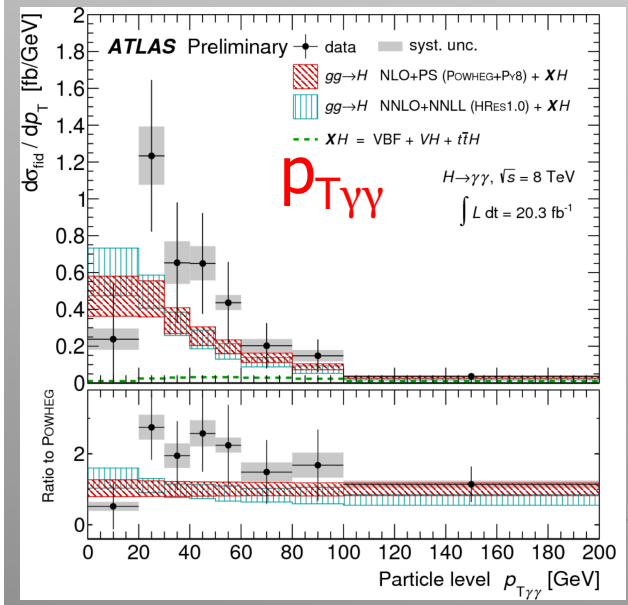
ATLAS-CONF-2013-072

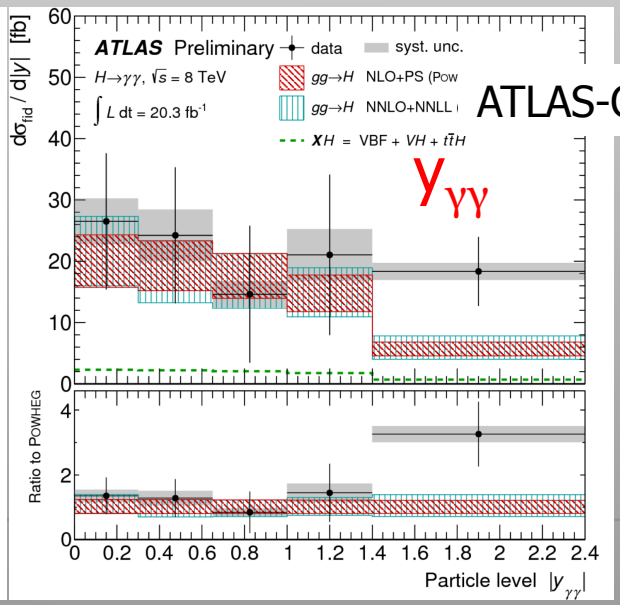


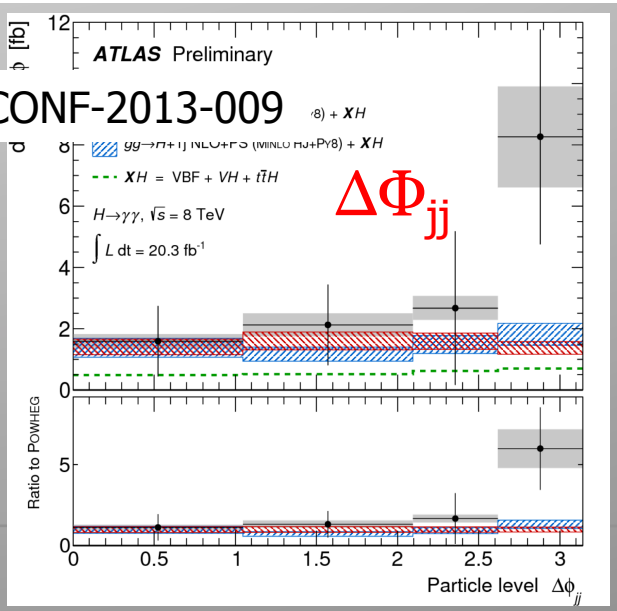
Inclusive	$p_T^{\gamma\gamma}$	Fundamental Kinematics + QCD Balance in $gg \to H$
	$\lvert y^{\gamma\gamma}\rvert$	Fundamental Kinematics + PDFs
	$\lvert\cos\theta^*\rvert$	Spin (Model Independent!)
	N_{jets}	Discriminate Prod. Modes, QCD
1-jet	leading jet p_T	Hardest parton emission and soft radiation
2-jet	$\Delta\phi_{jj}$	$gg \to H$: ME v. PS; VBF: Spin + CP
	p_T(H-jj)	Powerful VBF variable with large uncertainties

In general a fair agreement within errors but
-Somewhat harder p_T spectrum?
-Back to back dijets? (→POWHEG/PS!)

ATLAS-CONF-2013-009







Higgs Properties from H→γγ

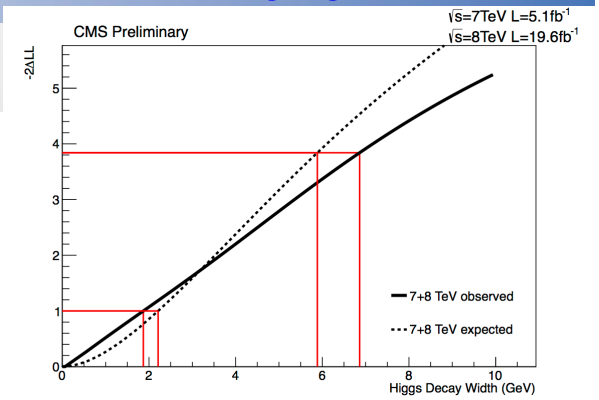
CMS-PAS-HIG-13-016

CMS

Upper limit on the Higgs width

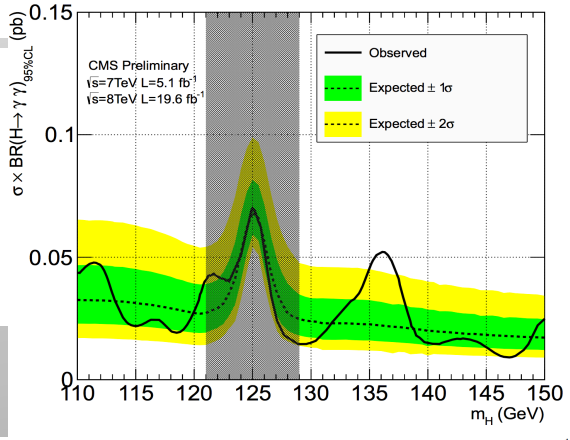
- Dominated by experimental resolution
- Breit-Wigner + Gaussian fit
- Observed (exp) upper limit = 6.9 (5.9) GeV 95% CL

Use interference? arXiv:1305.3854 & more



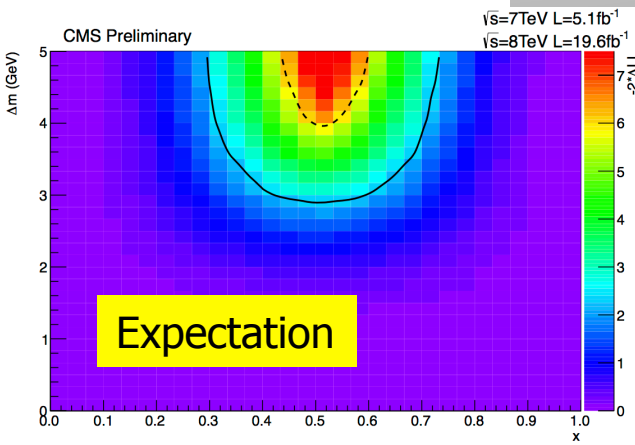
Additional Higgs-like states:

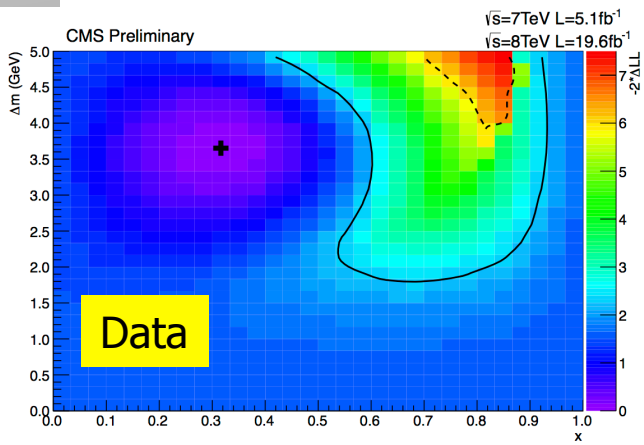
- Take SM 125 GeV as part of the background
- Search for additional Higgses
- Largest excess: 136.5 GeV with 2.9 σ (<2 σ after LEE)



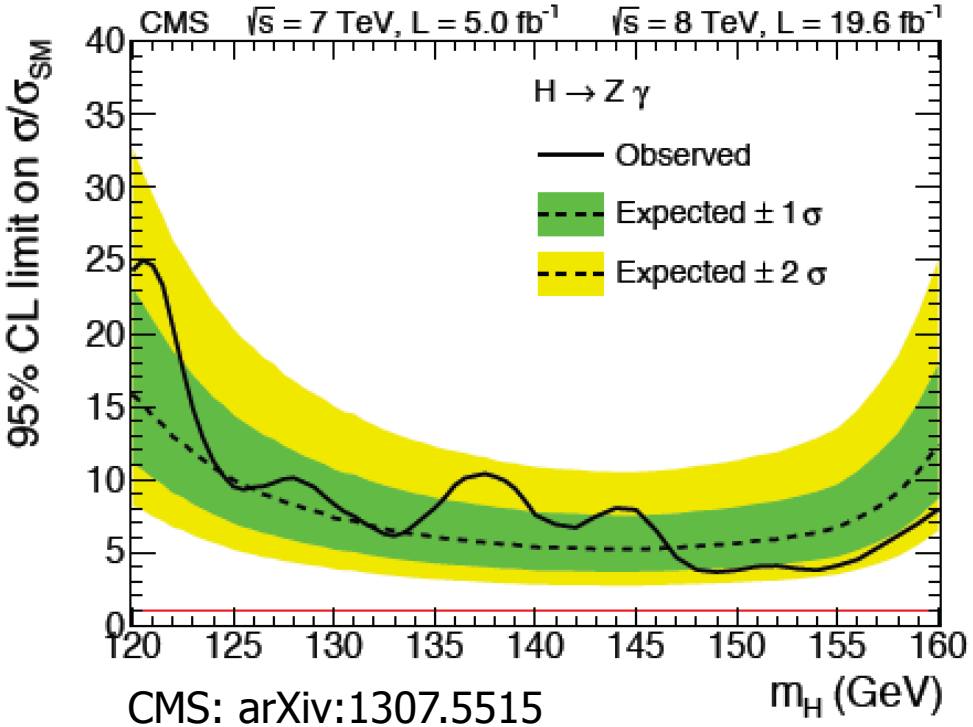
Search for near mass degenerate states

- Two signals with relative strength x mass difference Δm
- Perform a 2D scan
- No signal at 95% CL for Δm> 4 GeV

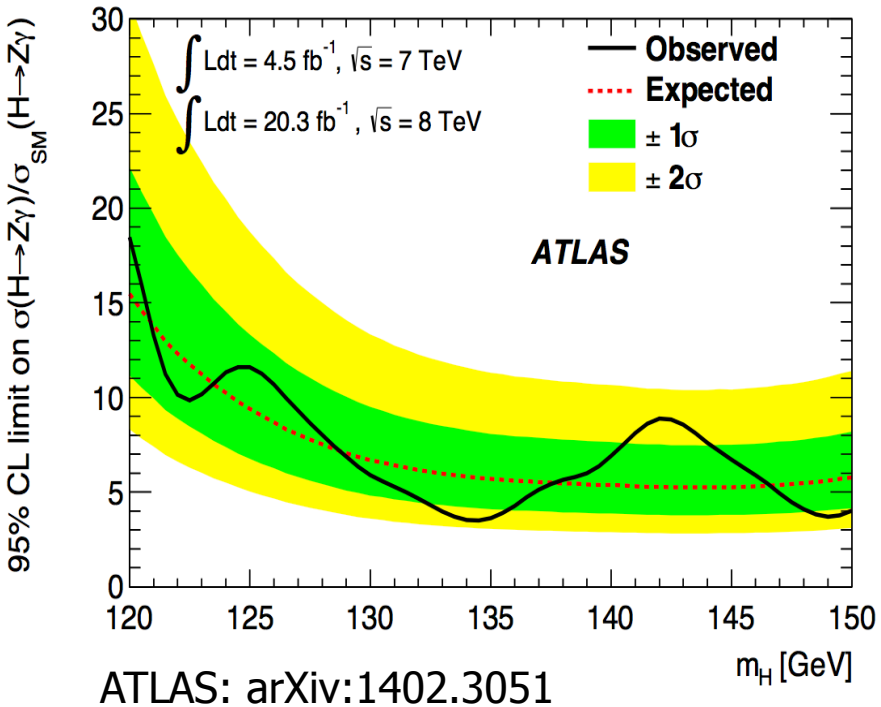




The Decay H→ Zγ



CMS: arXiv:1307.5515



ATLAS: arXiv:1402.3051

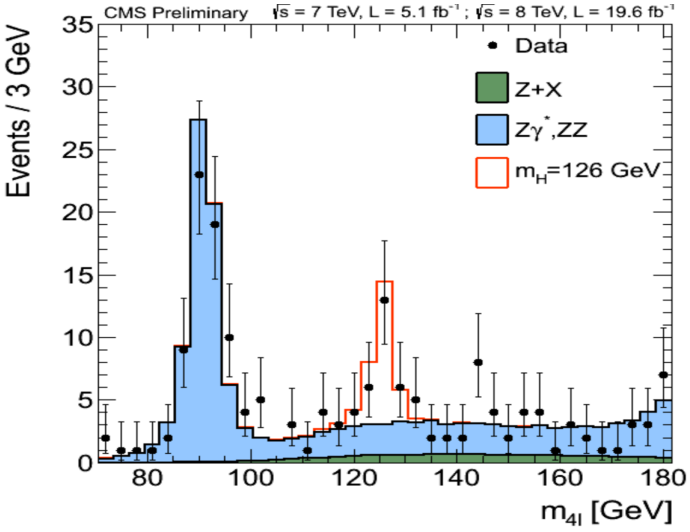
- Z decays into 2 charged leptons. The BR (H → Z γ) is comparable to BR(H → γγ) , but BR (Z → ll) reduces sensitivity (factor 15)
- Search for a narrow llγ peak on top of a falling background, as for H → γγ
- No significant excess seen over the entire search region

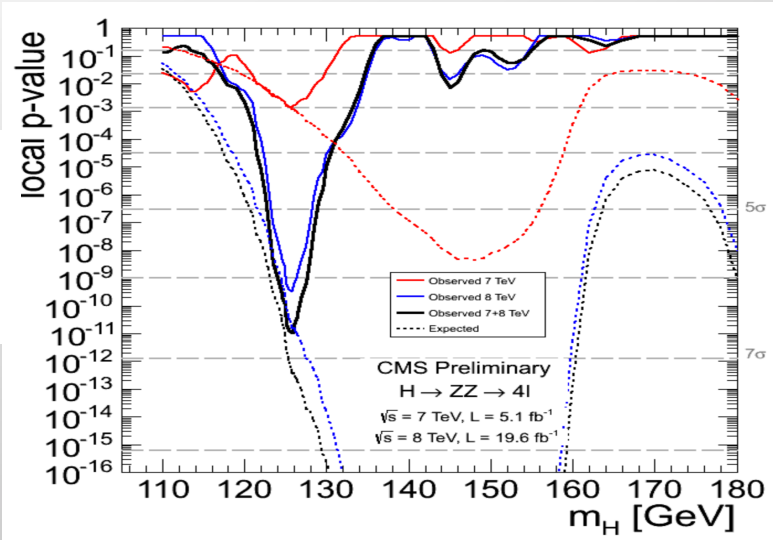
In certain models this channel could be largely enhanced via loops

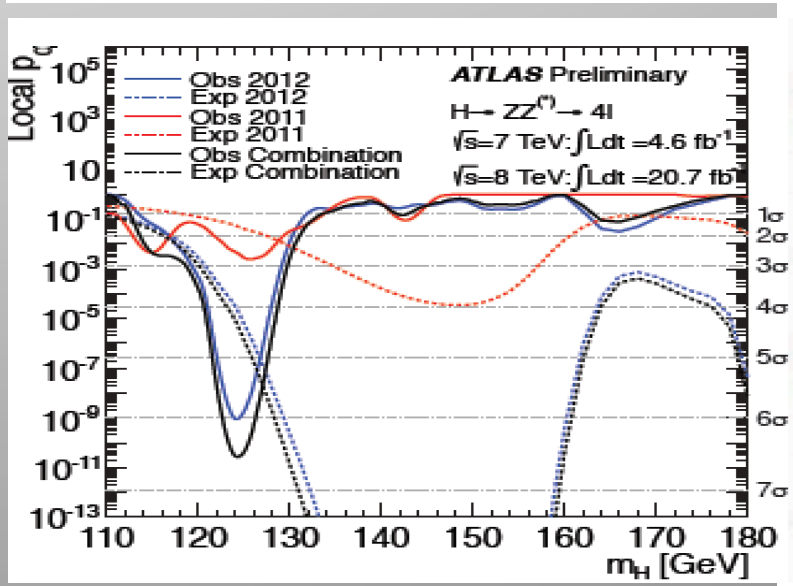
The Decay H → ZZ → 4l

ATLAS: arXiv:1307.1427
CMS: arXiv:1312.5353

- Search for a narrow peak in 4-lepton inv. Mass
- Low statistics & background channel
- Use kinematical discriminators and categories







ATLAS: Expected: 4.1σ Observed: 6.6σ
→ $\mu = 1.43^{+0.40}_{-0.35}$
CMS: Expected: 6.7σ Observed: 6.8σ
→ $\mu = 0.93^{+0.29}_{-0.24}$

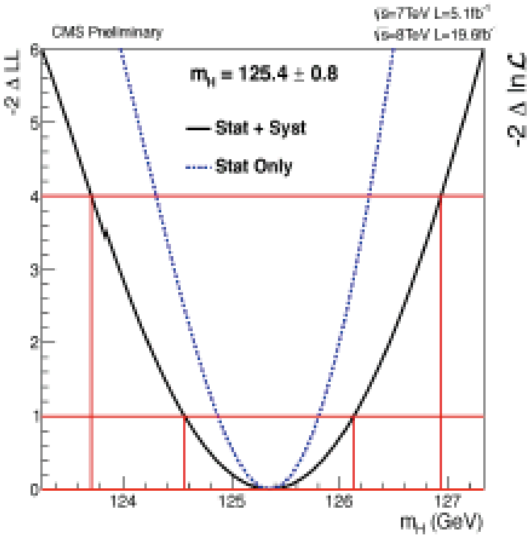
Significance is well over 6 standard deviations in this channel

The Mass of the New Particle

Determine the mass from ZZ and 2-photon channels which show a peak!

CMS H→γγ

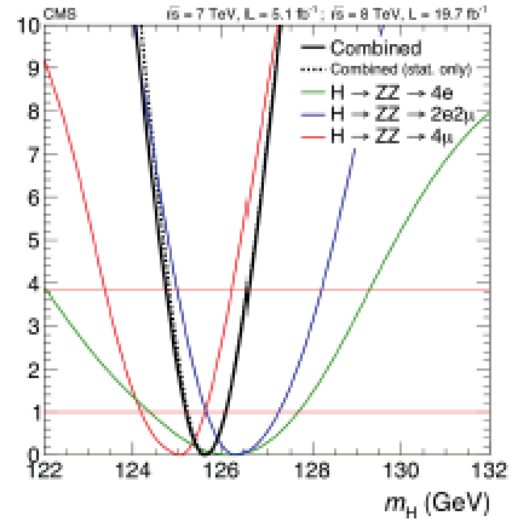
HIG-PAS-13/001



→ 125.4 ± 0.5 (stat)
± 0.6 (syst)
GeV

CMS H→ZZ→4l

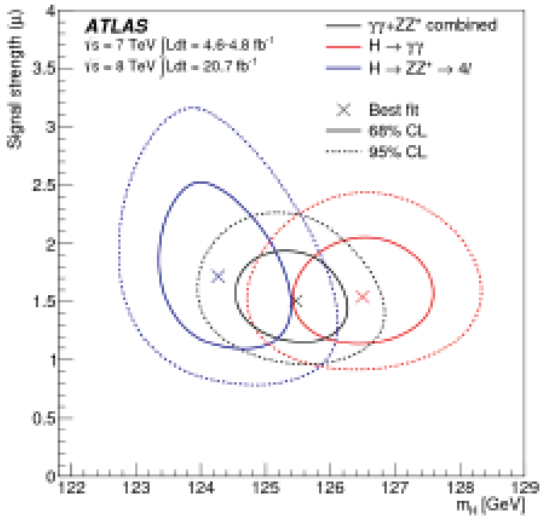
arXiv/1312.5353



→ 125.6 ± 0.4 (stat)
± 0.2 (syst)
GeV

ATLAS H→γγ & H→ZZ→4l

Phys. Lett. B 726 (2013) 88-119



ZZ: $126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{sys})$ GeV

γγ: $124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{sys})$ GeV

→ ATLAS ZZ+γγ combination:

$125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV.

→ CMS ZZ+γγ combination to be done …

→ "Overall agreement" on m_H

ATLAS and CMS observe the same particle!! ☺

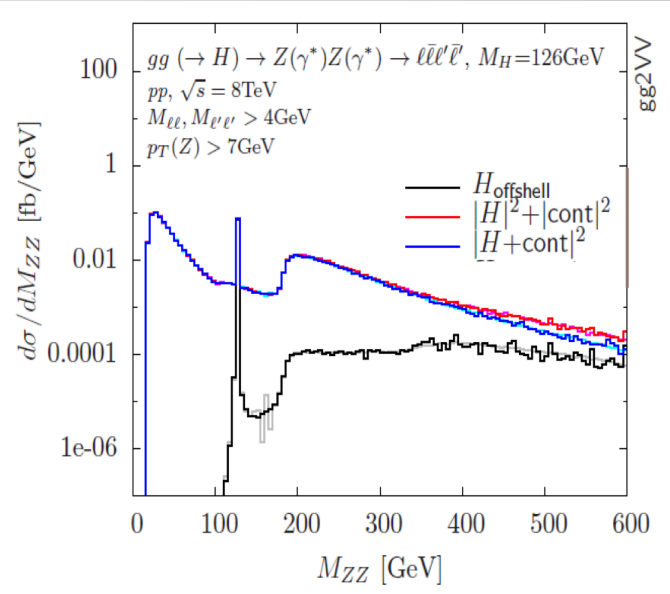
The Total Width of the Higgs?

Recent History

CMS-PAS-HIG-14-002

Direct width limits so far 3.4 GeV in ZZ and 6.9 GeV in two-photon decays (95% CL)
-> Dominated by experimental resolution

- **Until recently, seemed unlikely that LHC could contribute to knowledge of Γ_H. For this reason, coupling analyses use ratios of couplings (κ).**
- **In 2012, Kauer and Passarino (hep-ph 1206.4803) noted that despite the 4 MeV Γ_H in the SM, the zero-width approximation is not accurate for H->ZZ far from the H pole.**
- **In fact 7.6% of the cross-section is above ZZ threshold (180 GeV). This off-shell contribution is independent of Γ_H, so a ratio of on-shell and off-shell cross-sections can provide information on Γ_H.**
- **Li and Dixon analyzed the γγ case, while Caola and Melnikov (hep-ph 1307.4935) plus Campbell, Ellis, and Williams (hep-ph 1311.3589) analyzed the ZZ case.**



$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}.$$

$$r = \Gamma_H / \Gamma_H^{SM}$$

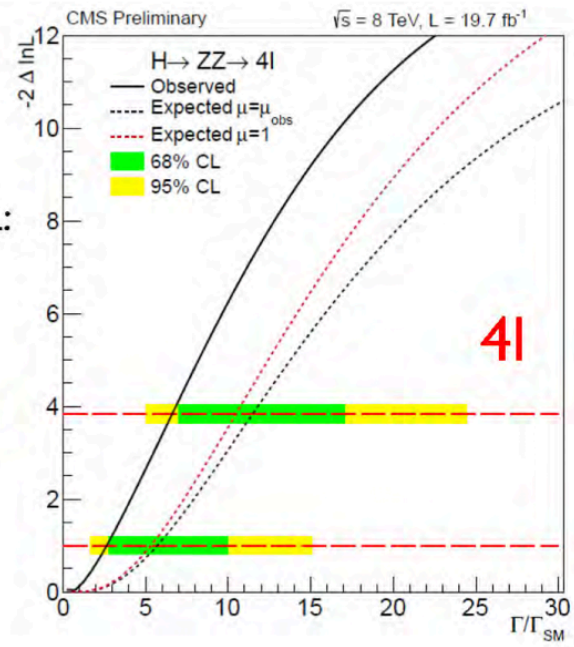
The Width of the Higgs

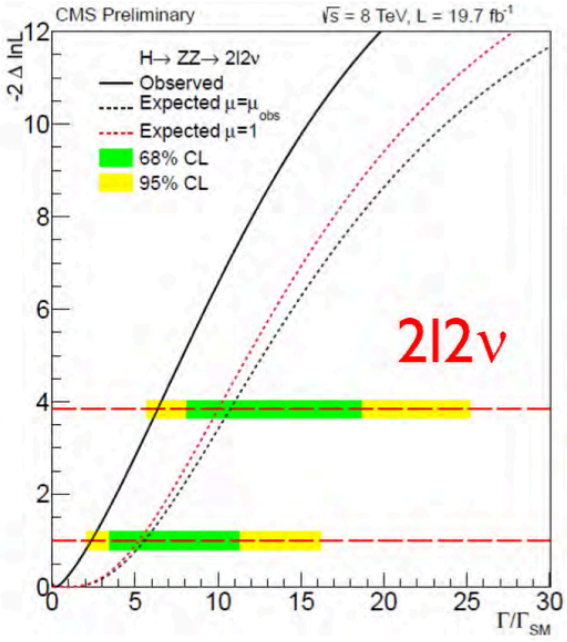
Moriond EWK 21st March

- **At Moriond, CMS released first measurement of $r=\Gamma/\Gamma_{SM}$, using H -> ZZ decaying into 4l and 2l2ν (PAS HIG-14-002)**
- **They use their published H -> ZZ on-shell cross-section value $\mu=0.93+0.26-0.24$, and also compare with $\mu=1.0$ for reference.**
- **They use a kinematic discriminant, similar to that of Campbell et al. to reduce the qq -> ZZ continuum relative to the gg signal.**

At 95% CL:

Expected
r < 11.5
Observed
r < 6.6





At 95% CL:

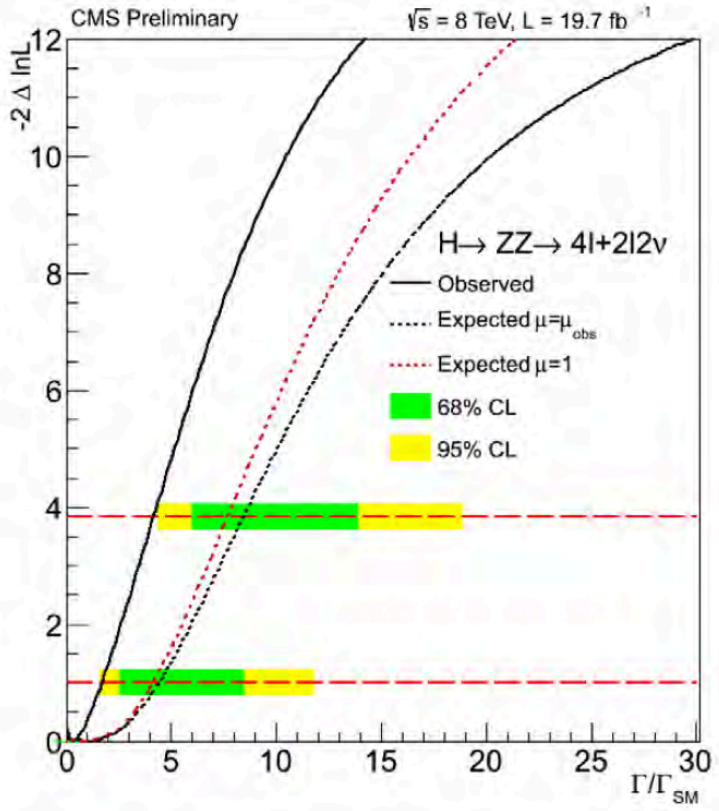
Expected
r < 10.7
Observed
r < 6.4

The Width of the Higgs

Moriond EWK 21st March

CMS-PAS-HIG-14-002

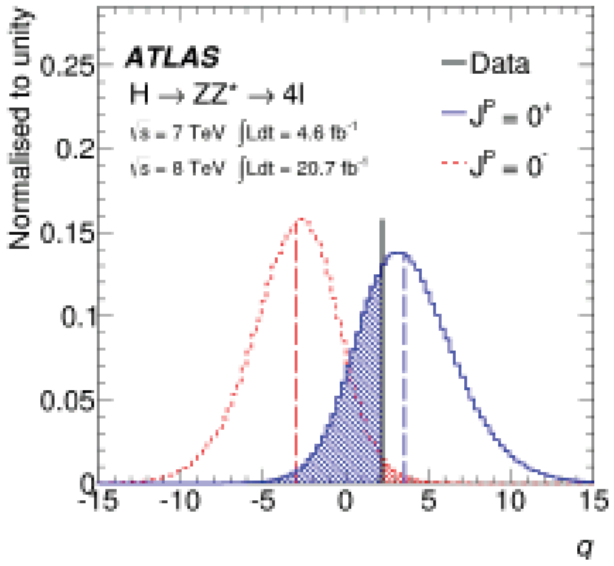
- **Combination of two channels gives:**

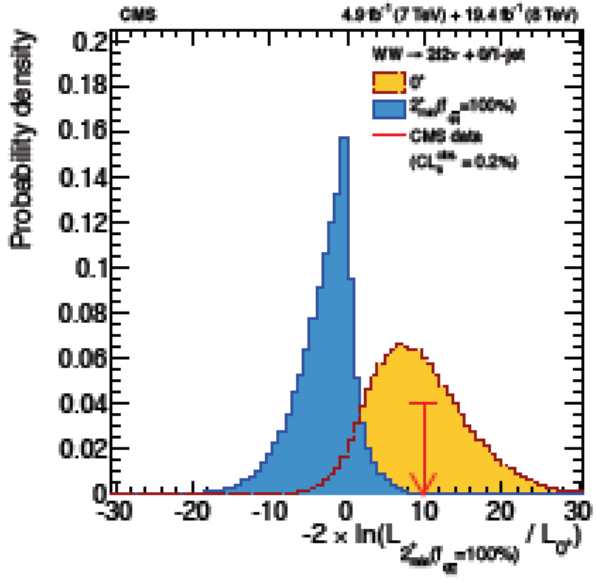


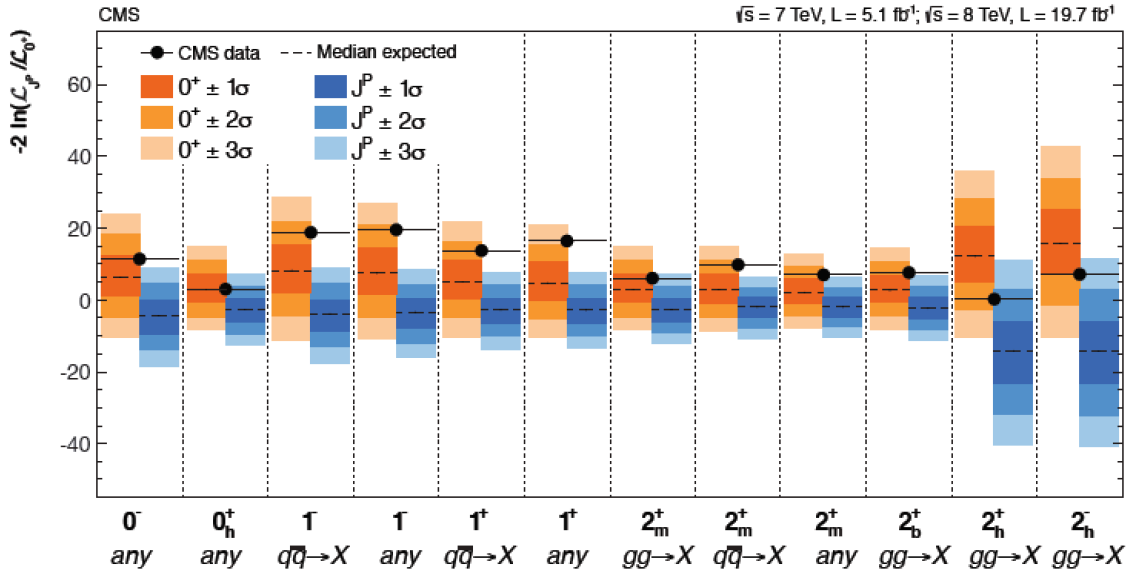
- Combined observed (expected) values
  - $r = \Gamma/\Gamma_{SM} < 4.2$ (8.5) @ 95% CL
    (p-value = 0.02)
  - $r = \Gamma/\Gamma_{SM} = 0.3^{+1.5}_{-0.3}$
- equivalent to:
  - $\Gamma < 17.4$ (35.3) MeV @ 95% CL

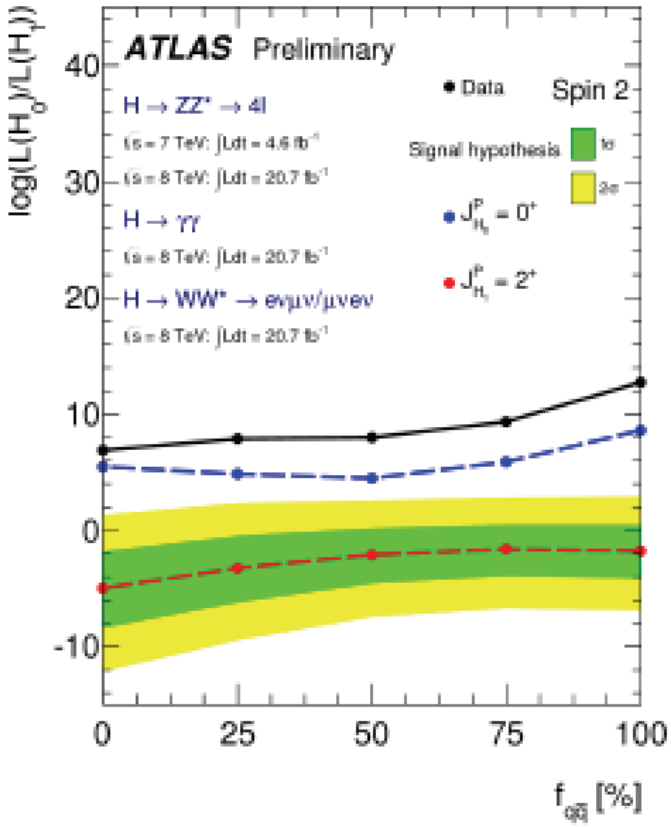
Very important result ! Observed limit is half of expected – data deficits in both channels ? Theory systs (LO+K_f) under control ?

Spin/Parity Studies







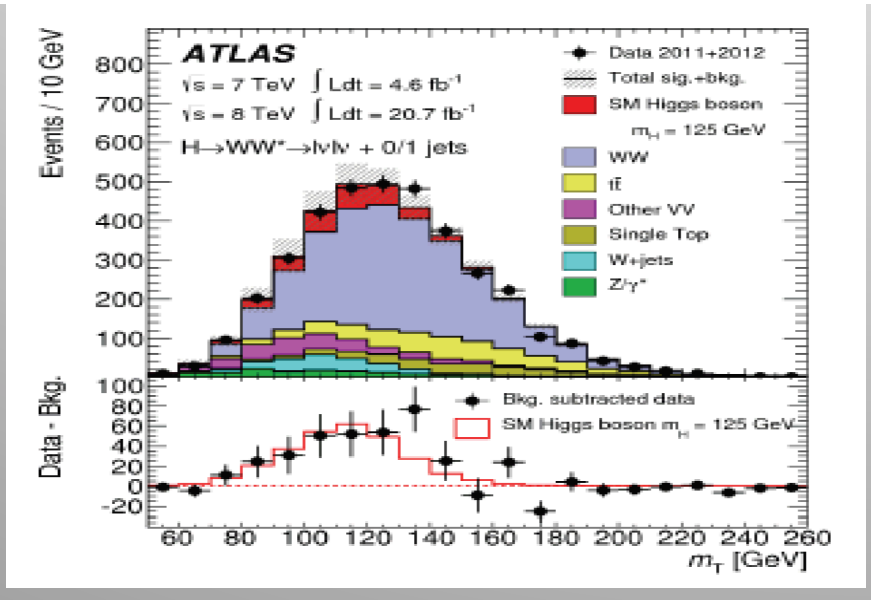


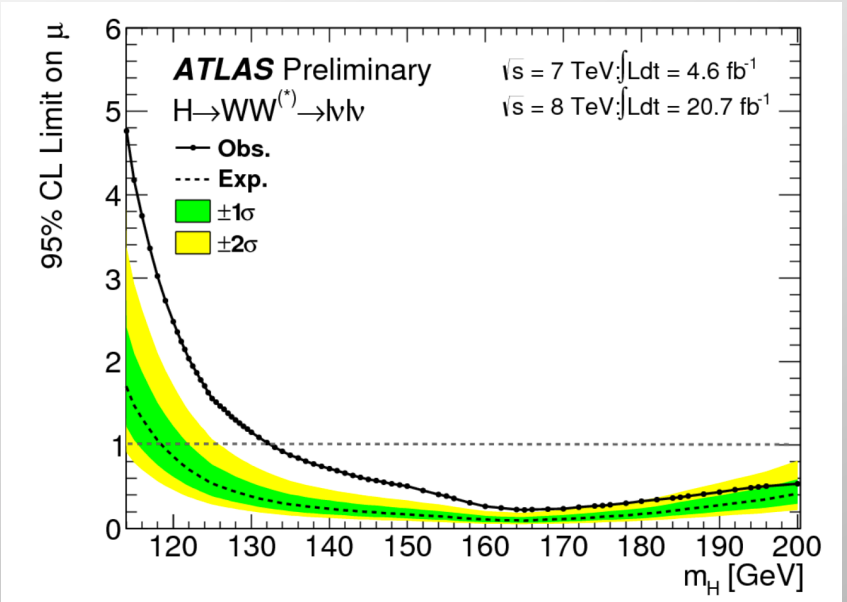
→ 0⁺ is always favored hypothesis against all tested 0⁻, 1± and 2± models

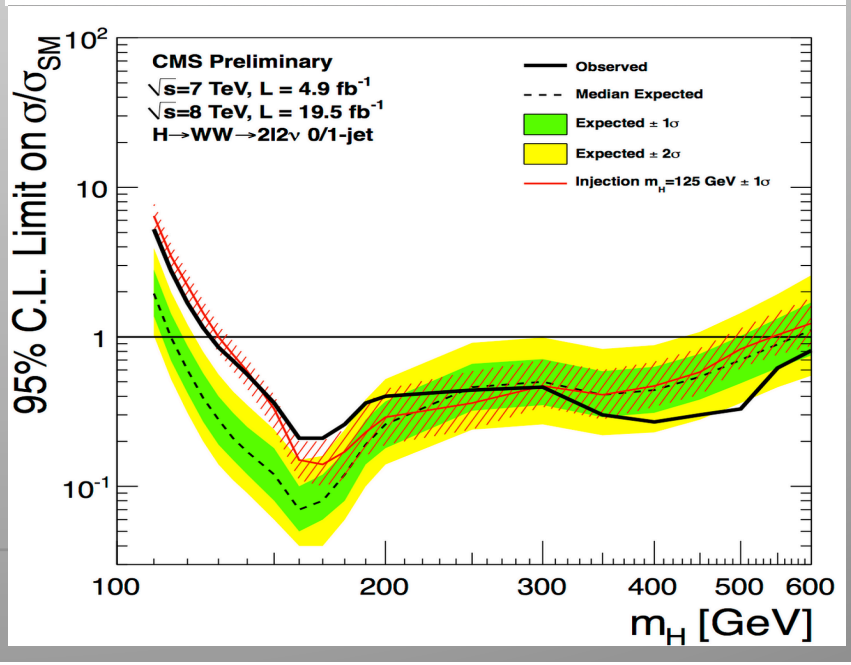
The Decay → WW → 2l 2ν

ATLAS: arXiv:1307.1427
CMS: arXiv:1312.1129

- Search for events with 2 leptons and missing transverse momentum
- Main backgrounds: WW,V+jets,DY,top…
- No mass peak-> broad excess







ATLAS @125 GeV: Expected: 3.8σ Obs: 3.8σ
→ $\mu = 0.99^{+0.31}_{-0.28}$
CMS @ 125 GeV: Expected: 5.8σ Obs: 4.3σ
→ $\mu = 0.72^{+0.20}_{-0.18}$

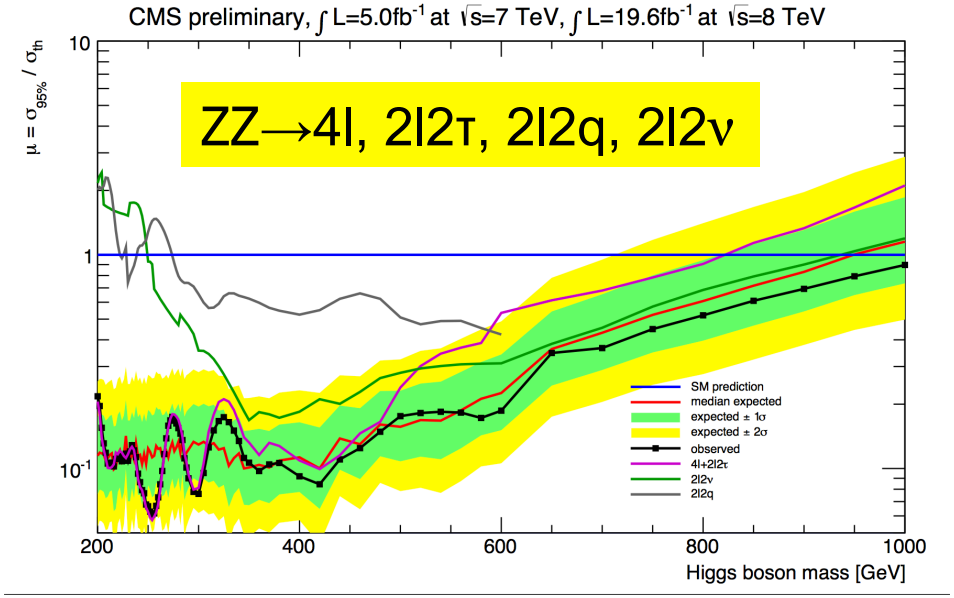
High Mass Higgs Searches

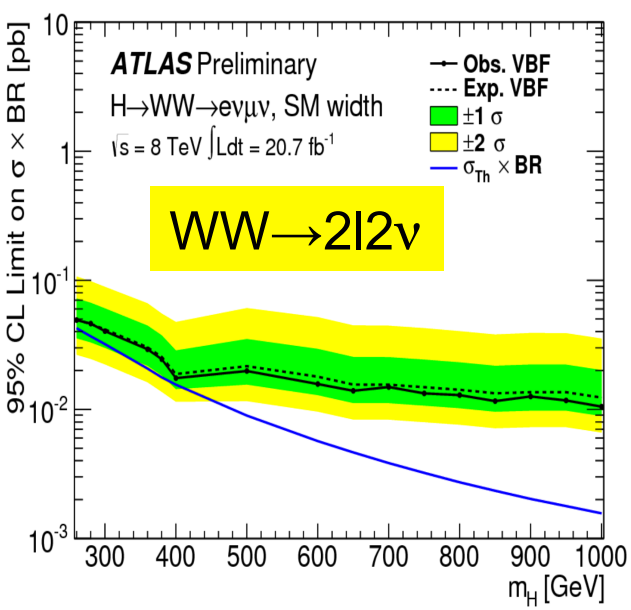
High mass Higgs searches with SM channels WW, ZZ updated with 2012 statistics

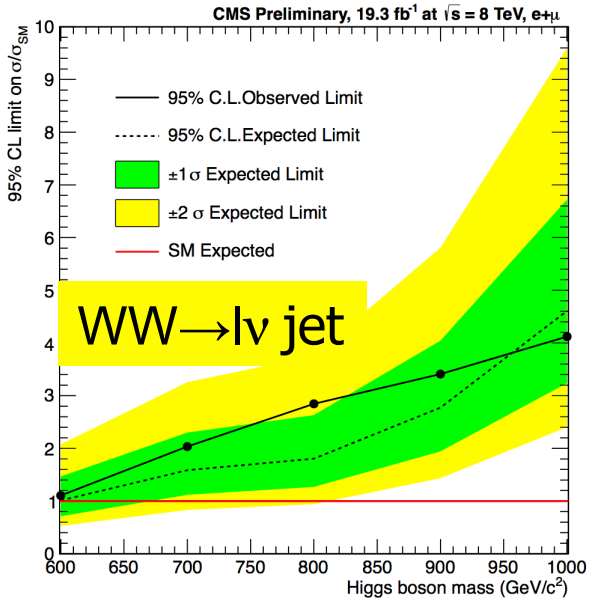
Sensitivity reaches now up to ~ 1 TeV

Interpretation of the data in eg EW-singlet models; Benchmark models proposed by the LHC XS WG

CMS-PAS-13-008
CMS-PAS-13-014
CMS-PAS-12-024
ATLAS-CONF-2013-067







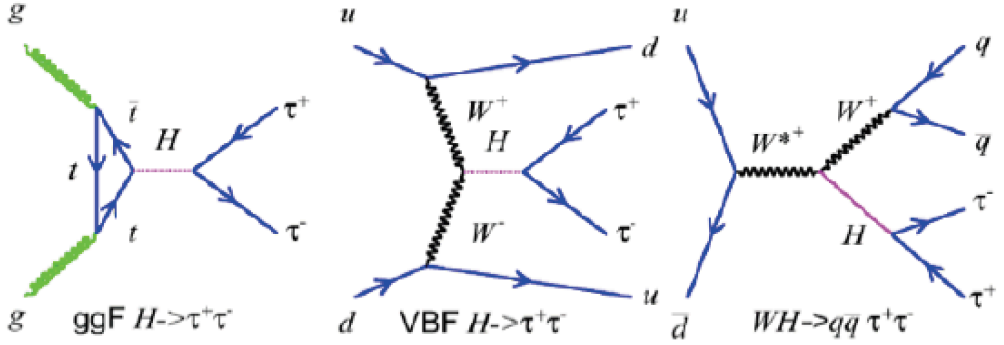
The Decay Higgs → tau tau

ATLAS-CONF-2013-108
CMS: arXiv:1401.5041

Analysis Overview

New: end of 2013

❑ **Search in ggH, VBF and VH production modes and five di-τ final states:**



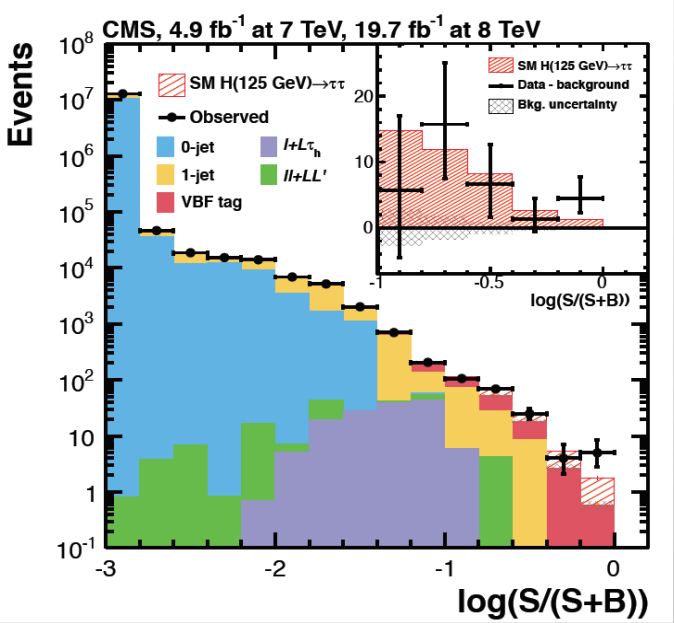
- H→ττ→μμ $(\tau_\mu \tau_\mu)$,
- H→ττ→eμ $(\tau_e \tau_\mu)$,
- H→ττ→μ+had. $(\tau_\mu \tau_h)$,
- H→ττ→e+had. $(\tau_e \tau_h)$,
- H→ττ→had.+had. $(\tau_h \tau_h)$.

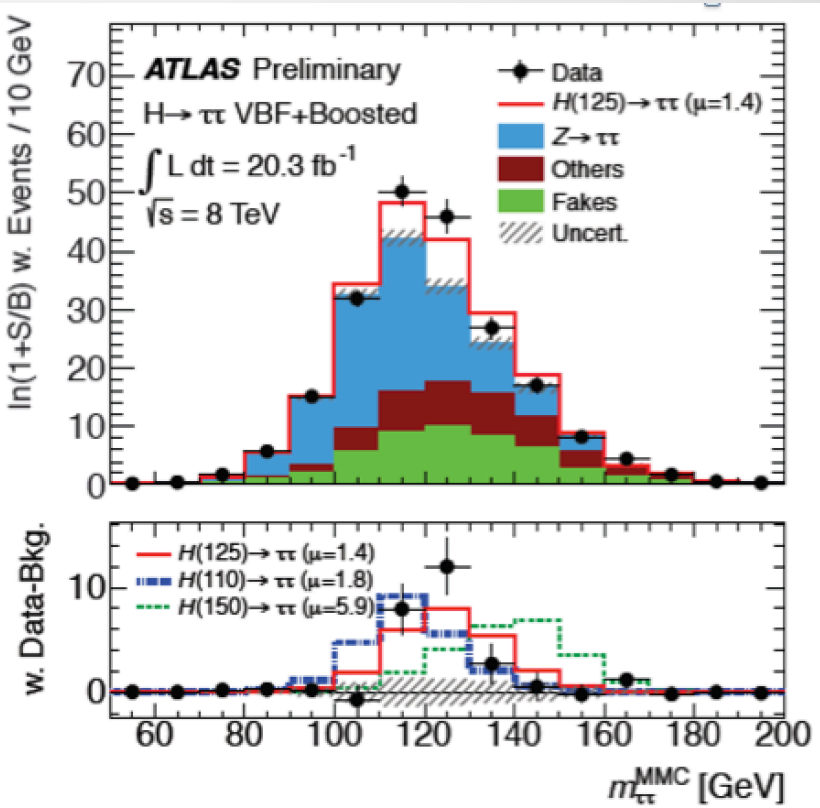
❑ **Separation in categories to enhance S/B (CMS example):**

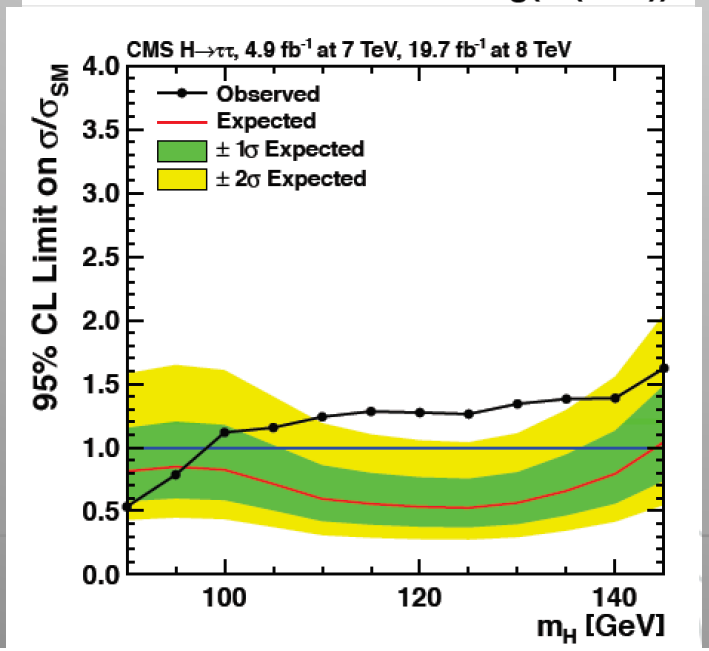
		0-jet		1-jet		2-jet	
				$p_T^{\tau\tau} > 100$ GeV	$m_{jj} > 500$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.5$	$p_T^{\tau\tau} > 100$ GeV $m_{jj} > 700$ GeV $\lvert\Delta\eta_{jj}\rvert > 4.0$	
$\mu\tau_h$	$p_T(\tau_h) > 45$ GeV	high $p_T(\tau_h)$	high $p_T(\tau_h)$	high $p_T(\tau_h)$ boost	loose VBF tag	tight VBF tag (2012 only)	
	baseline	low $p_T(\tau_h)$	low $p_T(\tau_h)$				

Use special reconstruction techniques to improve the Higgs mass resolution

The Decay Higgs → tau tau







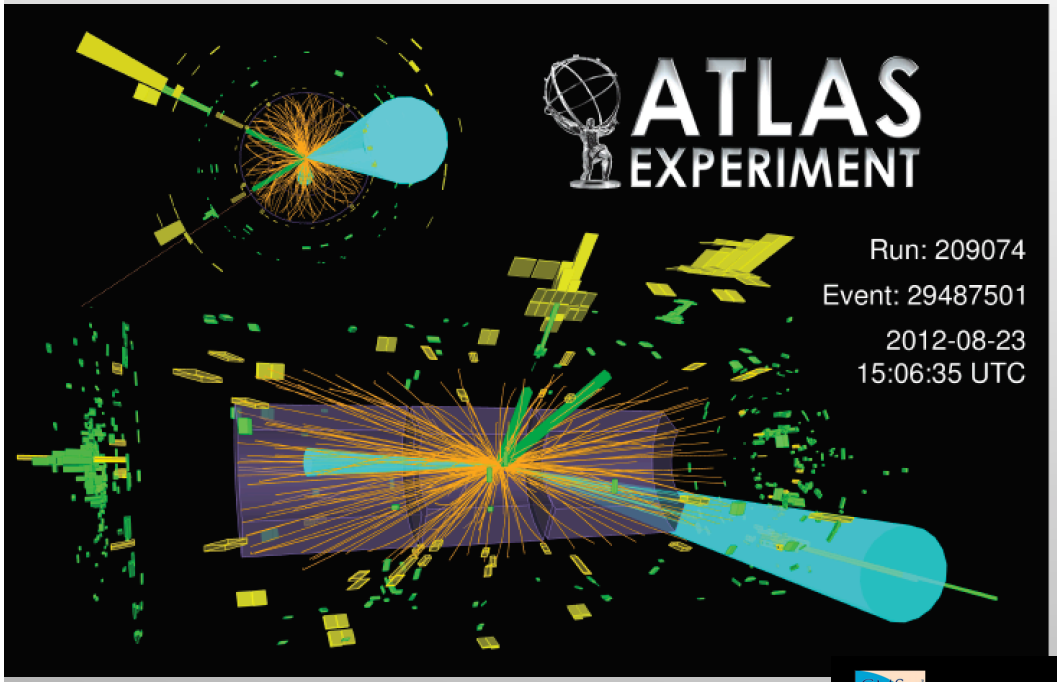
ATLAS @125 GeV: Expected: 3.2σ Obs: 4.1σ

→ $\mu = 1.5^{+0.5}_{-0.4}$

CMS @ 125 GeV: Expected: 3.7σ Obs: 3.2σ

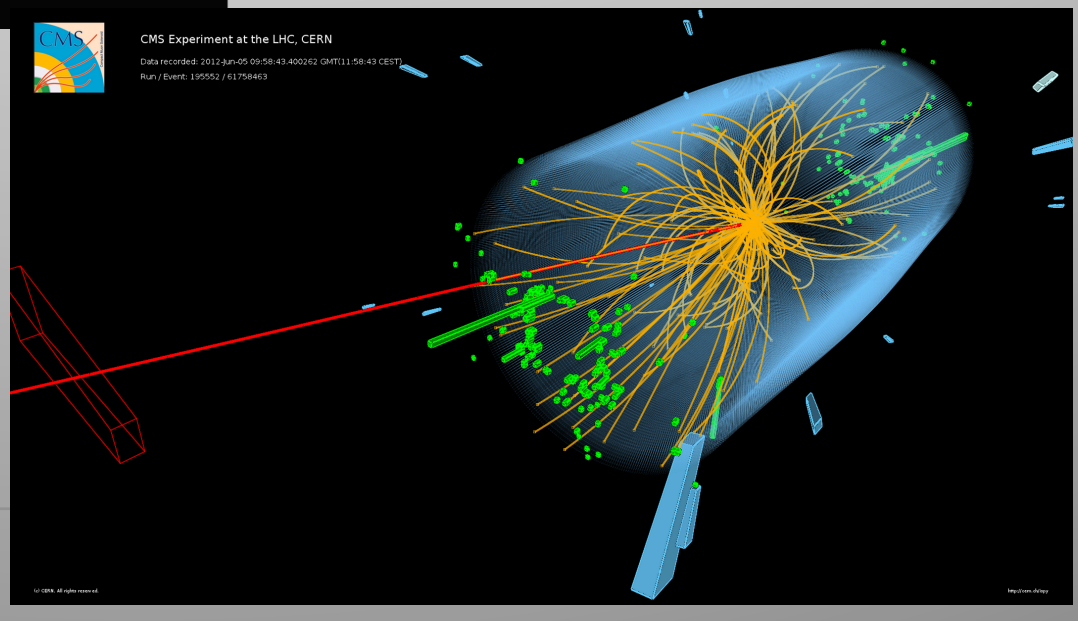
→ $\mu = 0.78^{+0.27}_{-0.27}$

Higgs → tau tau

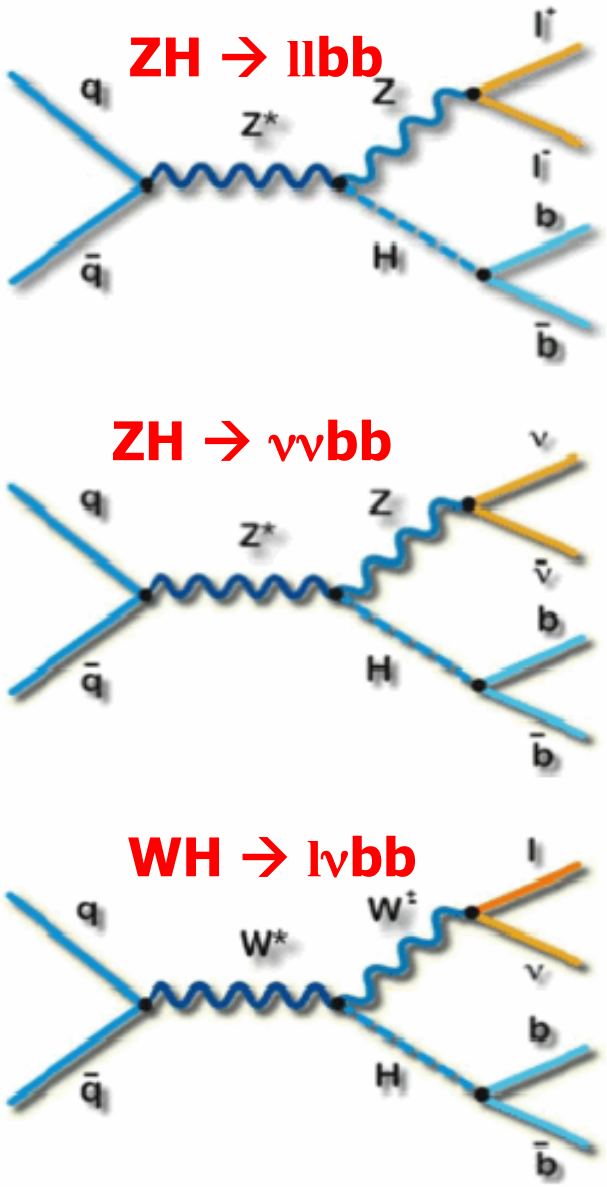


H→TauTau VBF event in the $\tau_{hadronic}\tau_{hadronic}$ channel.

H→TauTau VBF event in the $\mu\tau_{hadronic}$ channel.



The Decay Higgs→bb

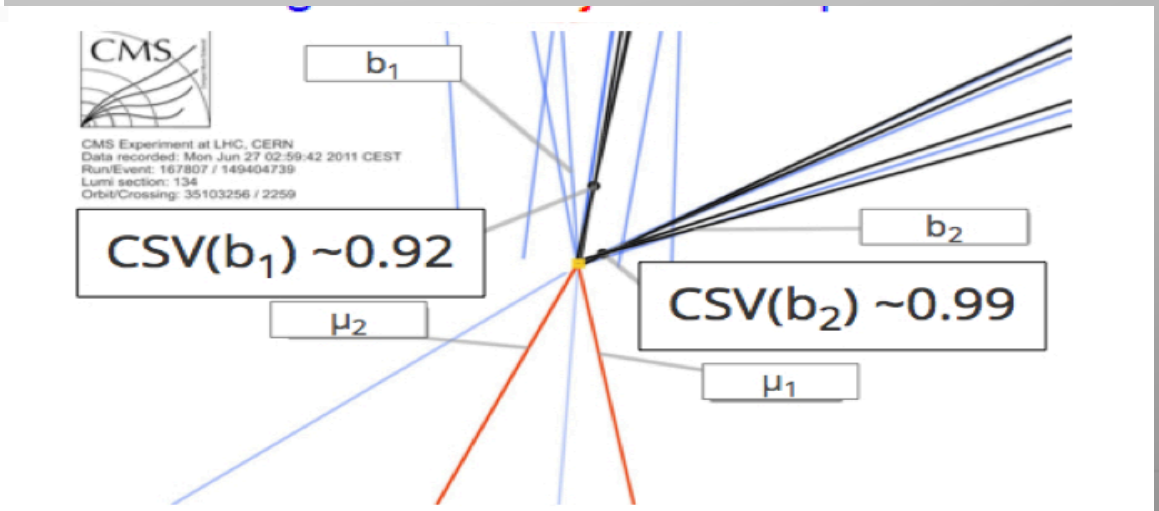


Analysis

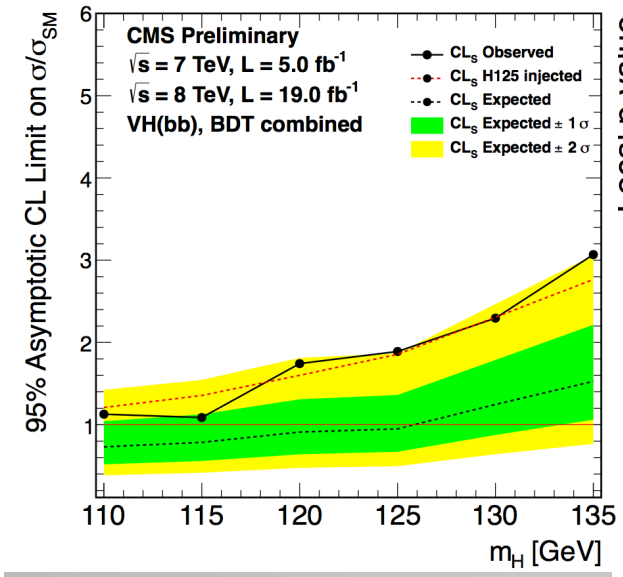
CMS:arXiv:1310.3687
ATLAS-CONF-2013-79

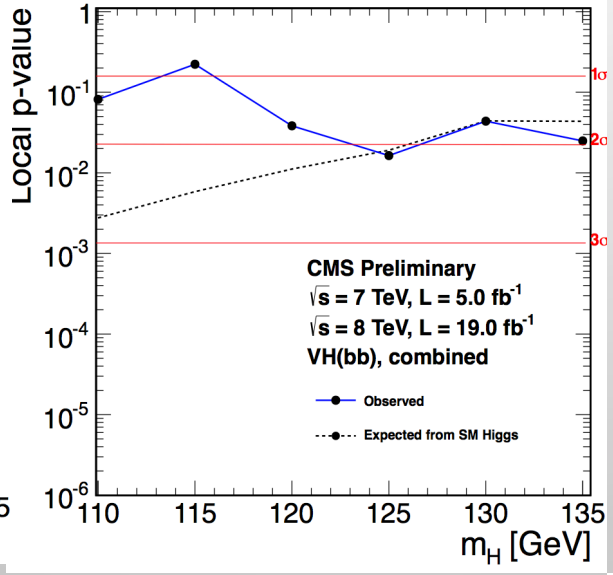
- By far largest number of Higgs decays but lots of QCD background (jets)
- Trigger based on leptons and missing E_T
- b-jets identified through displaced tracks
- Go to high p_T where Higgs is enhanced
- Main background W/Z+jets and top

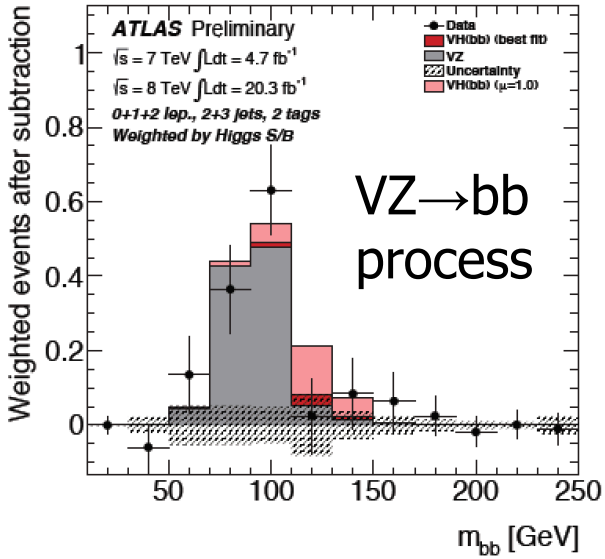
ATLAS: cut and count CMS: BDTs and shapes



The Decay Higgs→bb



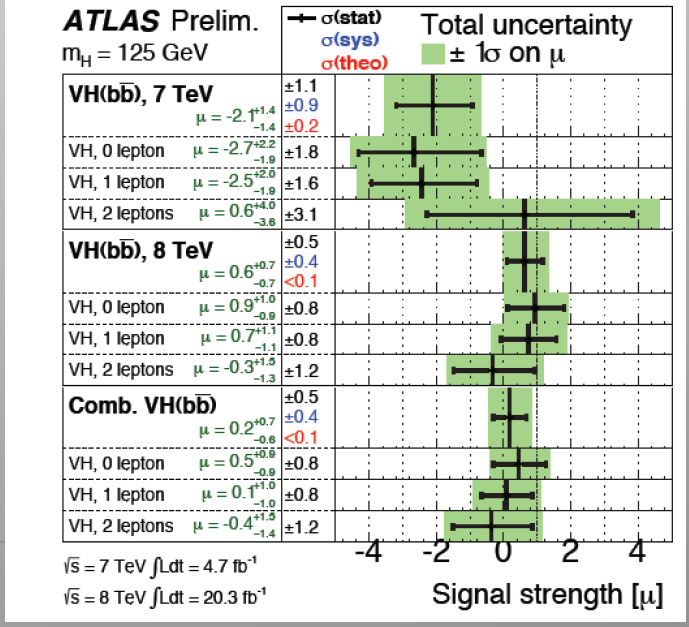




For 125 GeV:

- CMS → 2.1σ Observed (2.1σ Expected)
  μ = 1.0 ± 0.5
- ATLAS → $\mu = 0.2^{+0.7}_{-0.6}$

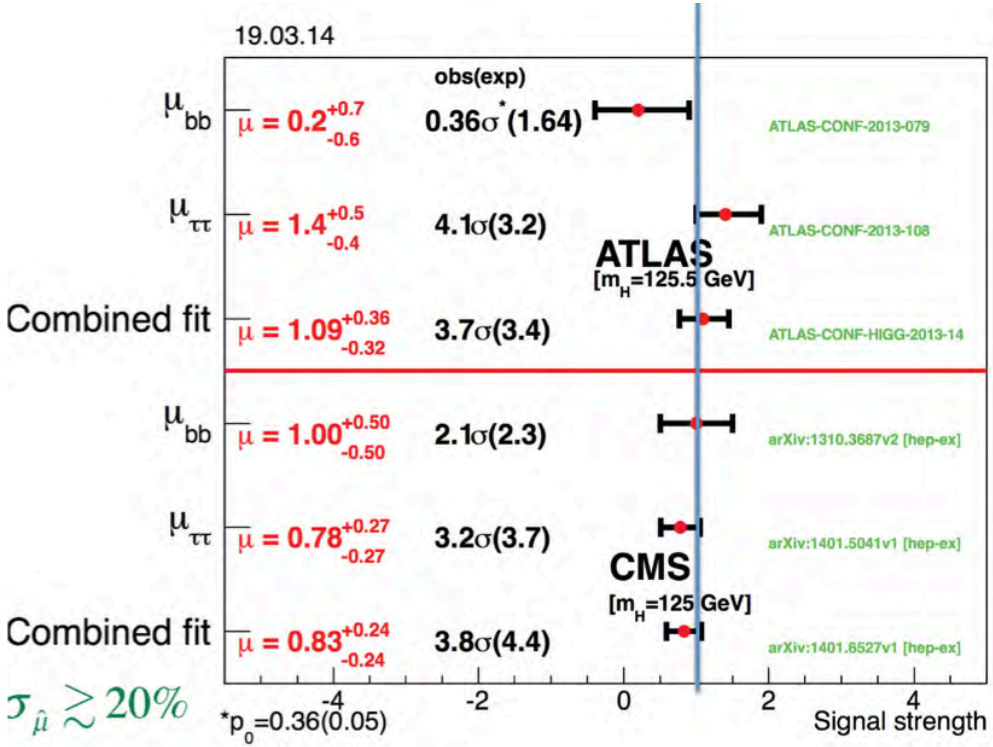
Mild excess observed in CMS data.



Couplings to Fermions (Decays)

Moriond EWK 21st March

- The combined H($\tau\tau$) and H(bb) result establishes a strong evidence for coupling of the Higgs boson to down-type third generation fermions
- Indirect and direct results on ttH coupling also evident for a coupling to up-type fermions

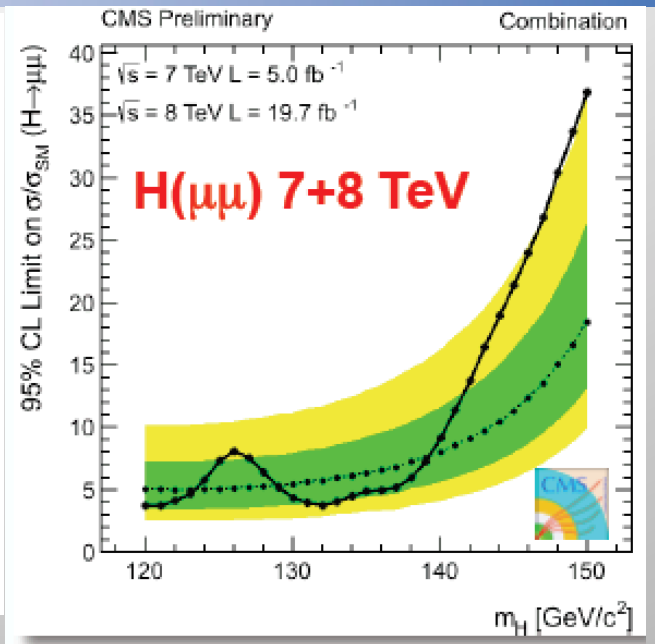


Very significant results for H->$\tau\tau$ (5σ combined ?)

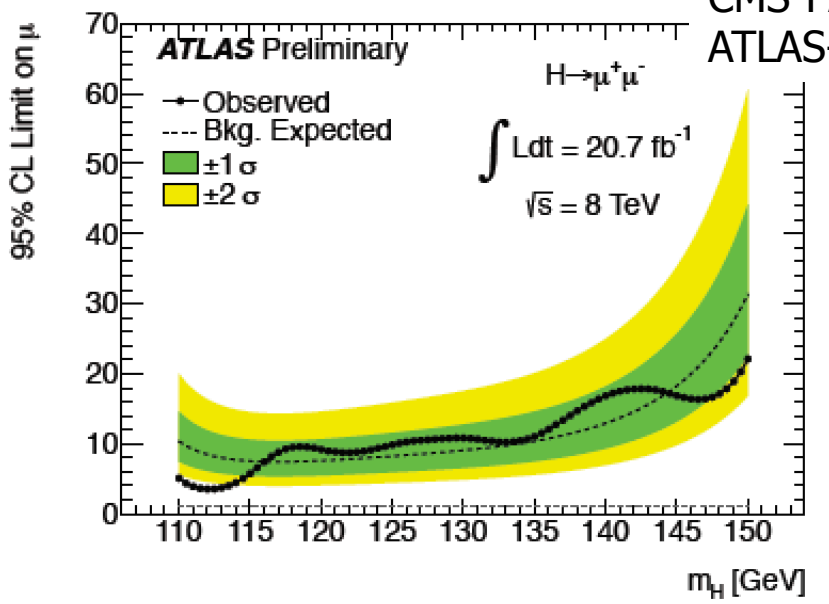
H->bb is more difficult, waiting for final ATLAS result (3σ combined ?)

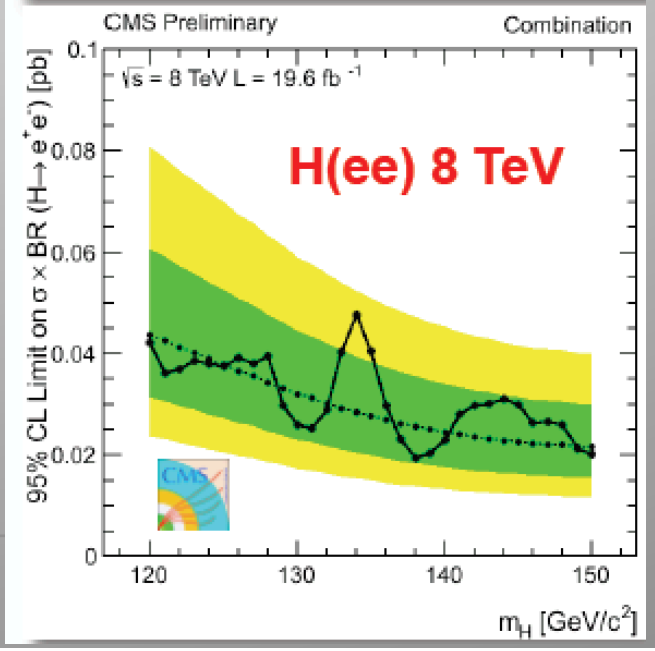
Higgs → μμ (ee)

- Observing H(μμ) decay may be the only way to show the non-flavor universal couplings
  - The coupling to charm will be hard to probe
- Requires very large statistics for an observation: a strong case for the High Luminosity-LHC: HE-LHC
- First searches have been already done
  - ATLAS: $\mu < 9.8$ (8.2 expected) @ 95% CL
  - CMS: $\mu < 7.4$ (5.1 expected) @ 95% CL
  - $BR(H \to ee) < 1.7 \times 10^{-3}$ @ 95% CL



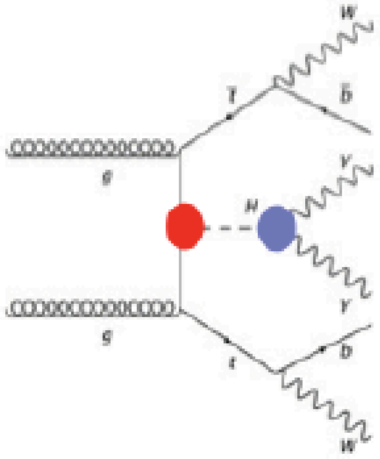
CMS-PAS-HIG-13-007
ATLAS-CONF-2013-010





Higgs-Top Associated Production

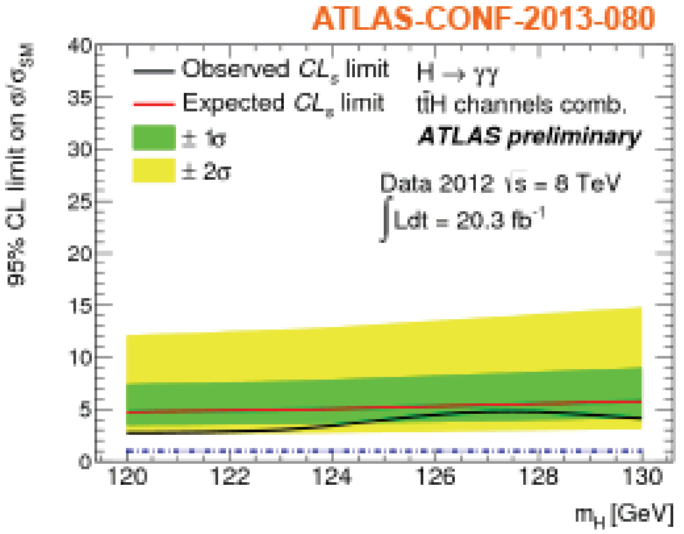
Various decay modes of the Higgs are considered

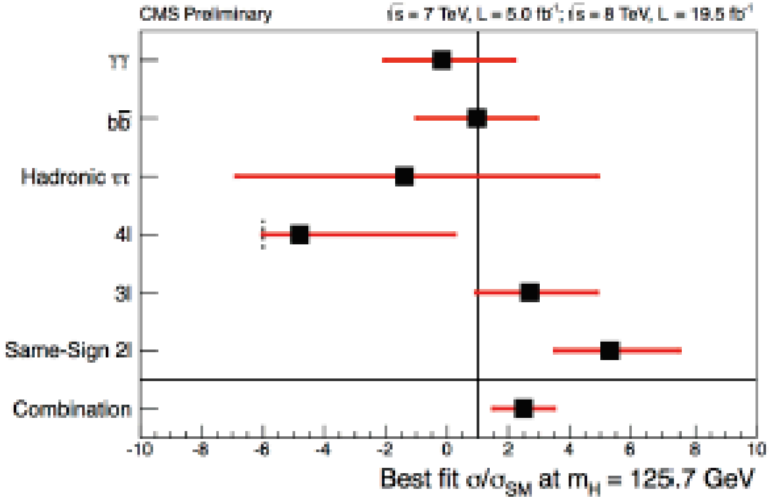


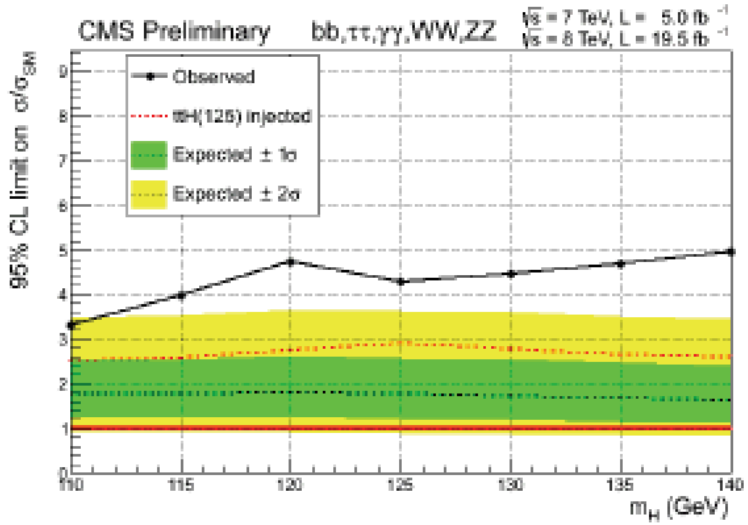
Probe of the H-top Yukawa coupling

CMS:

- H → γγ → HIG-13-015
- H → bb → HIG-13-019
- H → ττ → HIG-13-019
- H → ZZ → HIG-13-020
- H → WW → HIG-13-020







CMS: $\mu < 4.3$ (1.7 expected) @ 95% CL $\mu = 2.5\ ^{+1.1}_{-1.0}$

Higgs-Top Associated Production

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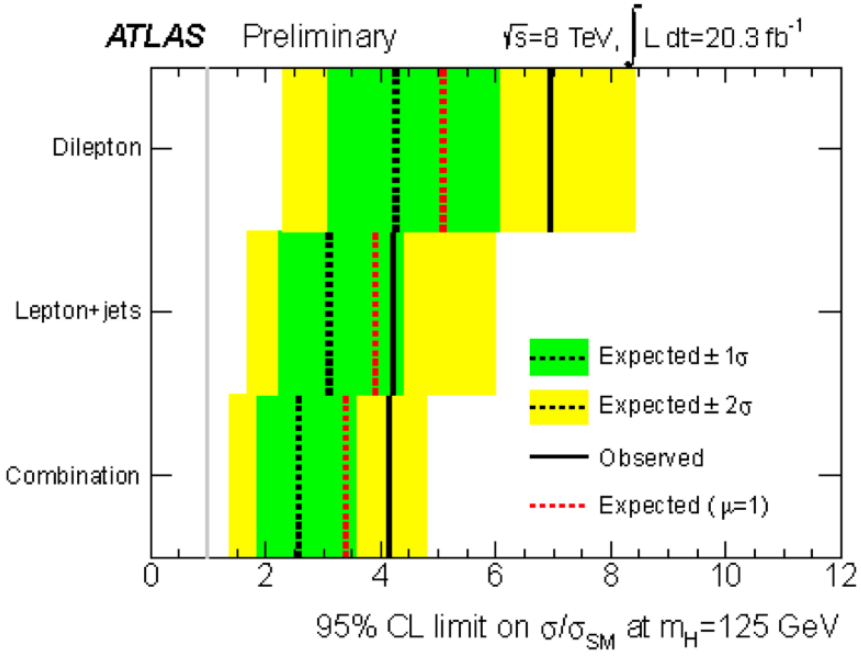
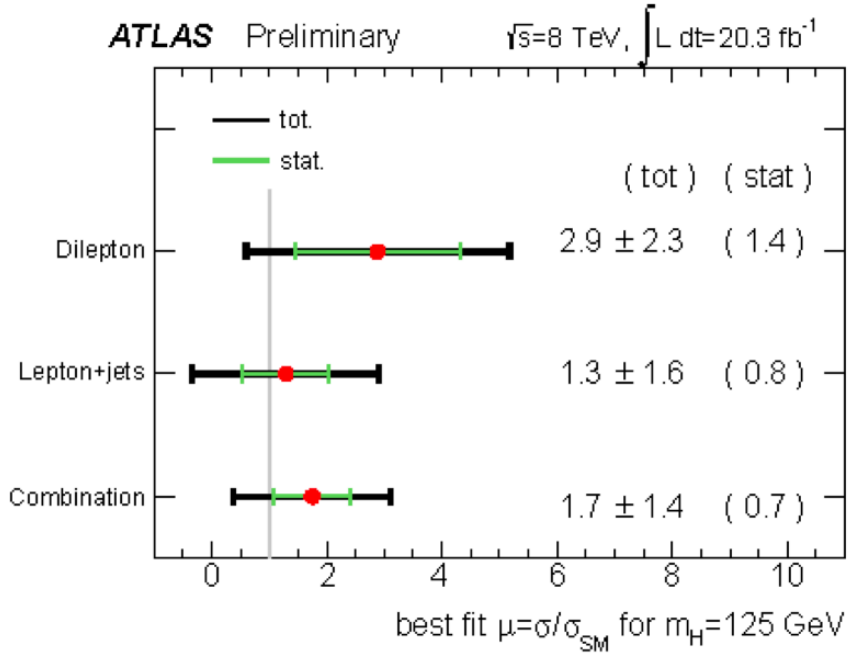
ATLAS-CONF-2014-01x

- **ATLAS has performed a search in ttbar+H; H -> γγ. Observed limit of μ = 4.7 (5.4 expected). Leptonic (2l, 3l, 4l, ττ) modes in progress**
- **New analysis in ttbar+H; H -> bb. Result is limit of μ = 4.1 (expected 2.6) 95% CL. Best fit value is μ = 1.7 +/- 1.4**





Single Top Production

- Direct coupling to the top quark -> C_t=-1 or large cancelations in the SM?
- Cross sections could be surprisingly large if there are deviations from SM
  Negative C_t gives 15x increased cross section plus 2x Higgs to 2 photons.
- Composite Higgs models heavy t' -> top + Higgs..

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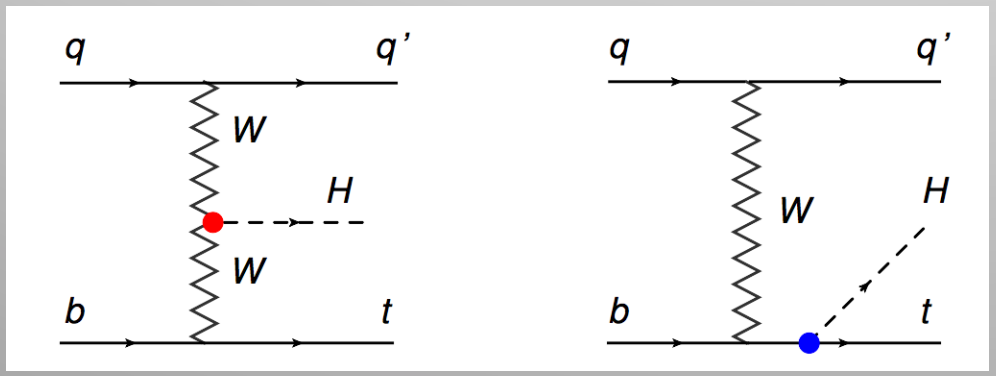
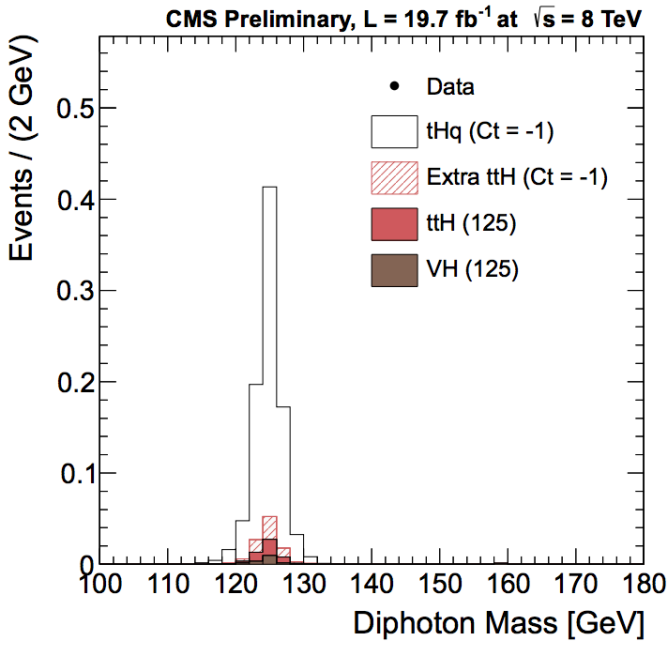
- Study the Higgs decay to two photon decay channel
  No events found top + two photon selection
  95% upper limit is 4.1 expected cross section for C_t=-1

CMS-PAS-HIG-14-001



$$\mathrm{tHq} \to (\mathrm{t} \to \mathrm{b}\ell\nu)(\mathrm{H} \to \gamma\gamma)q \quad \text{with } \ell = \mathrm{e}, \mu$$

Leading photon with $p_T > 50 \cdot m_{\gamma\gamma}/120$ GeV
Subleading photon with $p_T > 25$ GeV
Exactly one lepton (e/μ) with $p_T > 10$ GeV
At least one b-jet with $p_T > 20$ GeV
The hardest jet in the event which is not the b-Jet must have $p_T > 20$ GeV and $\lvert\eta\rvert > 1$
LD> 0.25



Higgs Boson Signal Strength

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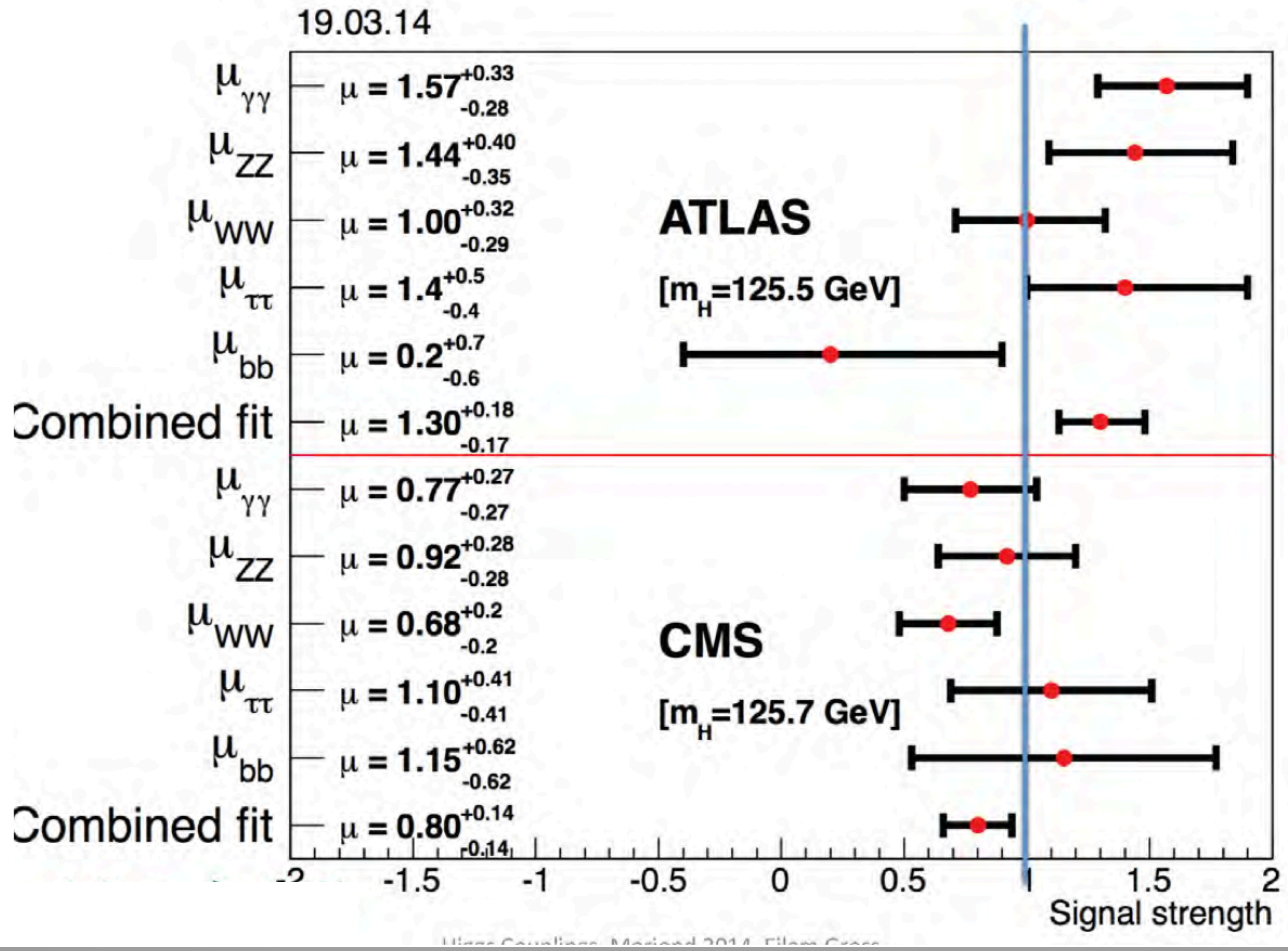
- **Overall comparison of all individual μ values:**

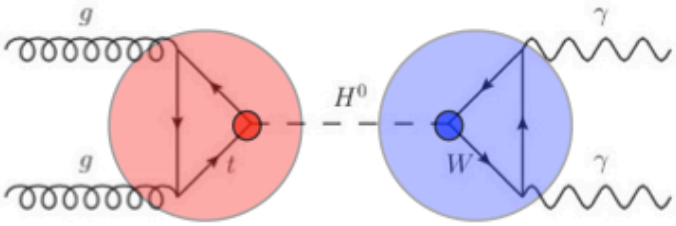


Coupling Measurements

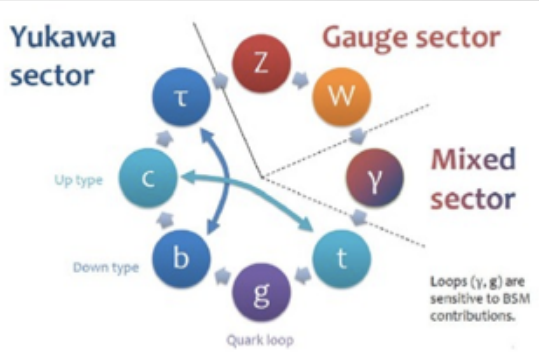
Assume the observed signal stems from one narrow resonance.

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

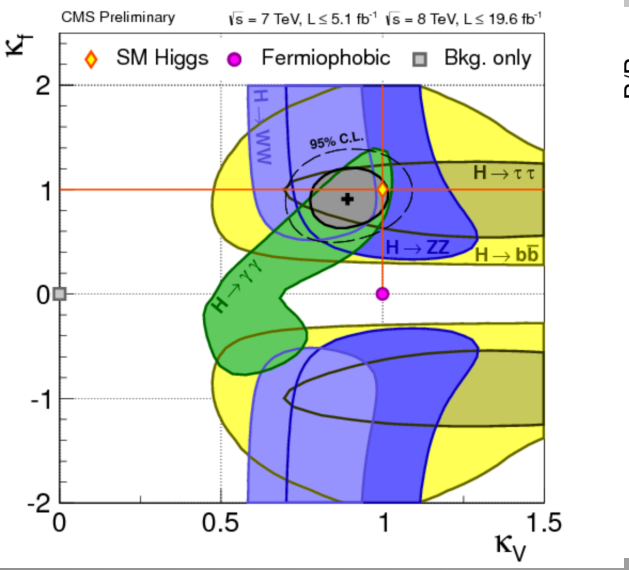
Parametrize deviations w.r.t. the SM in production and decay. This implies precise knowledge of the SM Higgs. Not considered are BSM acceptance effects.

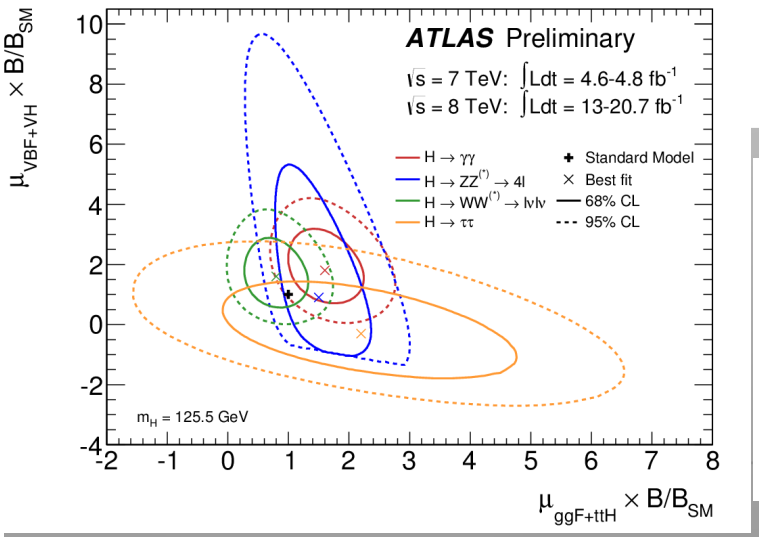


$$(\sigma \cdot \mathrm{BR})\,(gg \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \qquad \kappa_H^2 = \sum_X \kappa_X^2 \frac{\mathrm{BR}_{\mathrm{SM}}(H \to X)}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$



- one common scale factor
- scale vector and fermion coupling
- custodial symmetry
- new physics in loops
- BSM Higgs decays
- ...





ATLAS: arXiv:1307.1427
CMS-PAS-HIG-13-005

- No updates of overall combinations since summer 2013
- Expect new results in spring 2014

General Coupling Fit (6 parameters)

κ_g, κ_γ: loop diagrams → allow potential new physics

κ_V: assume custodial symmetry

κ_t, κ_b: up- and down-type quarks

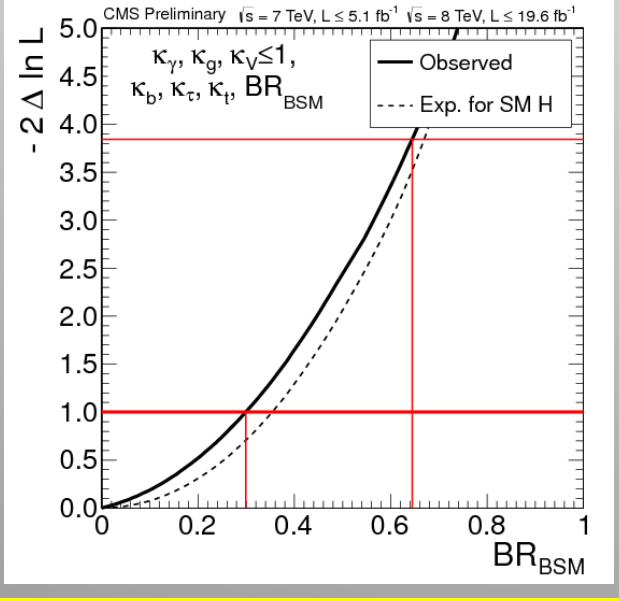
κ_τ: charged leptons

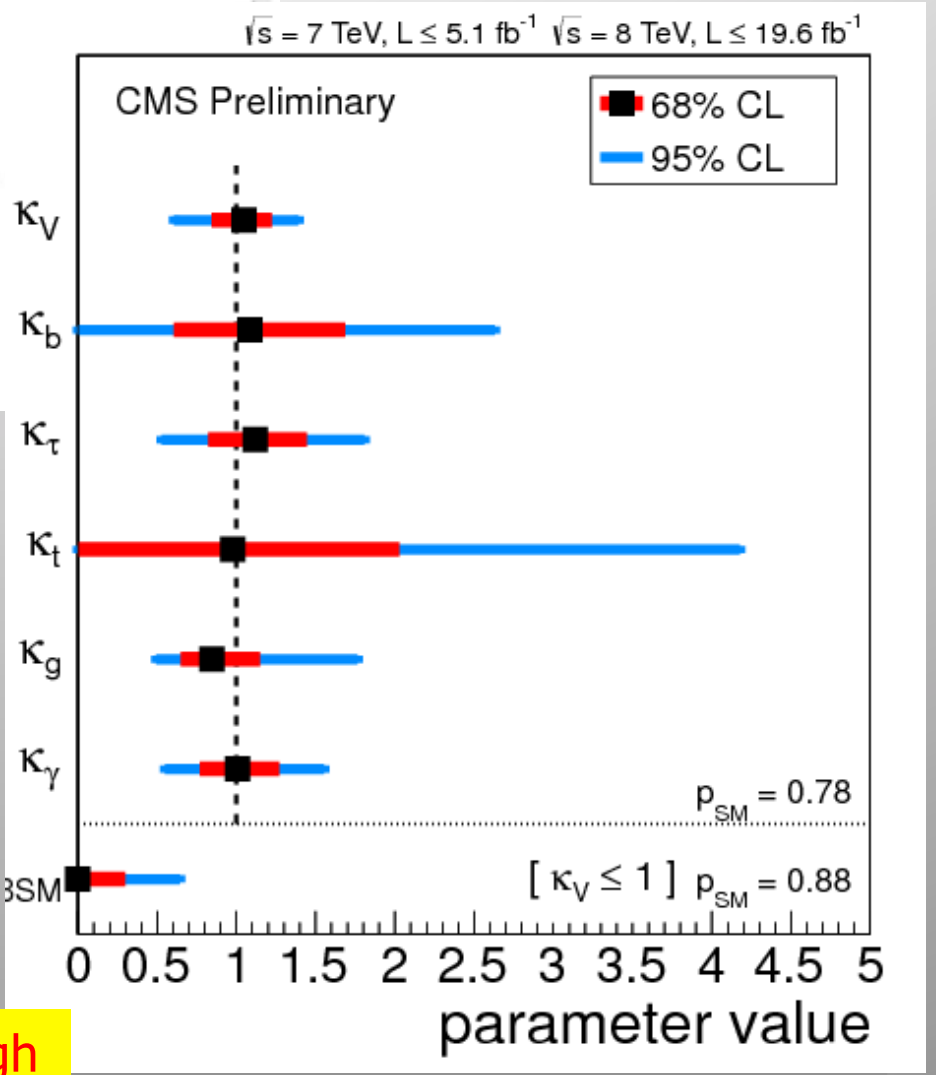
total width from sum of partial widths

alternatively:

$$\Gamma_{tot} = \sum \Gamma_{ii} + \Gamma_{BSM} \qquad BR_{BSM} = \Gamma_{BSM} / \Gamma_{tot}$$

assumption here κ_W, $\kappa_Z < 1$



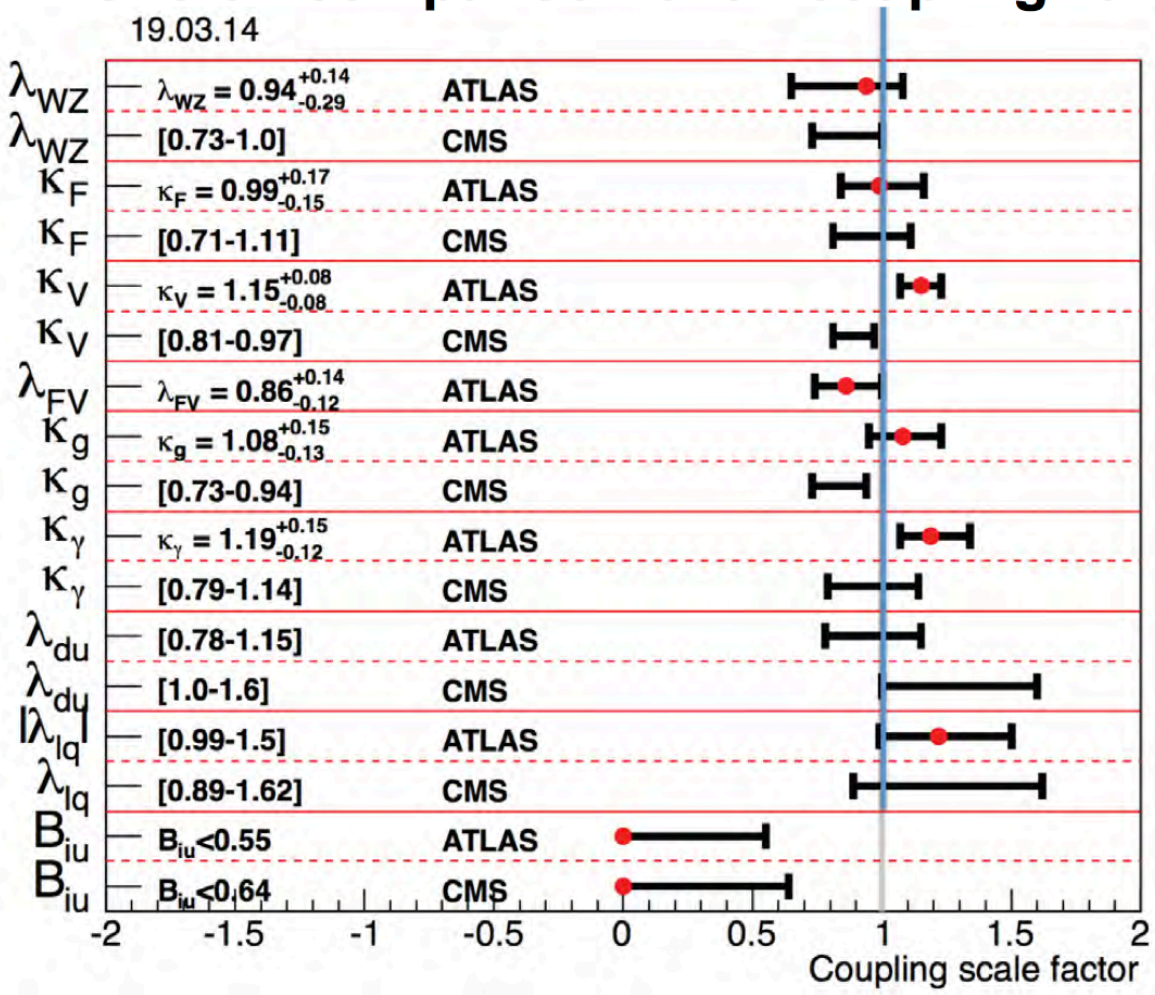


→ No deviation from SM observed but high precision needed to look for new physics

Comparison of the Coupling Values

Moriond EWK 21st March

- **Overall comparison of all coupling values:**

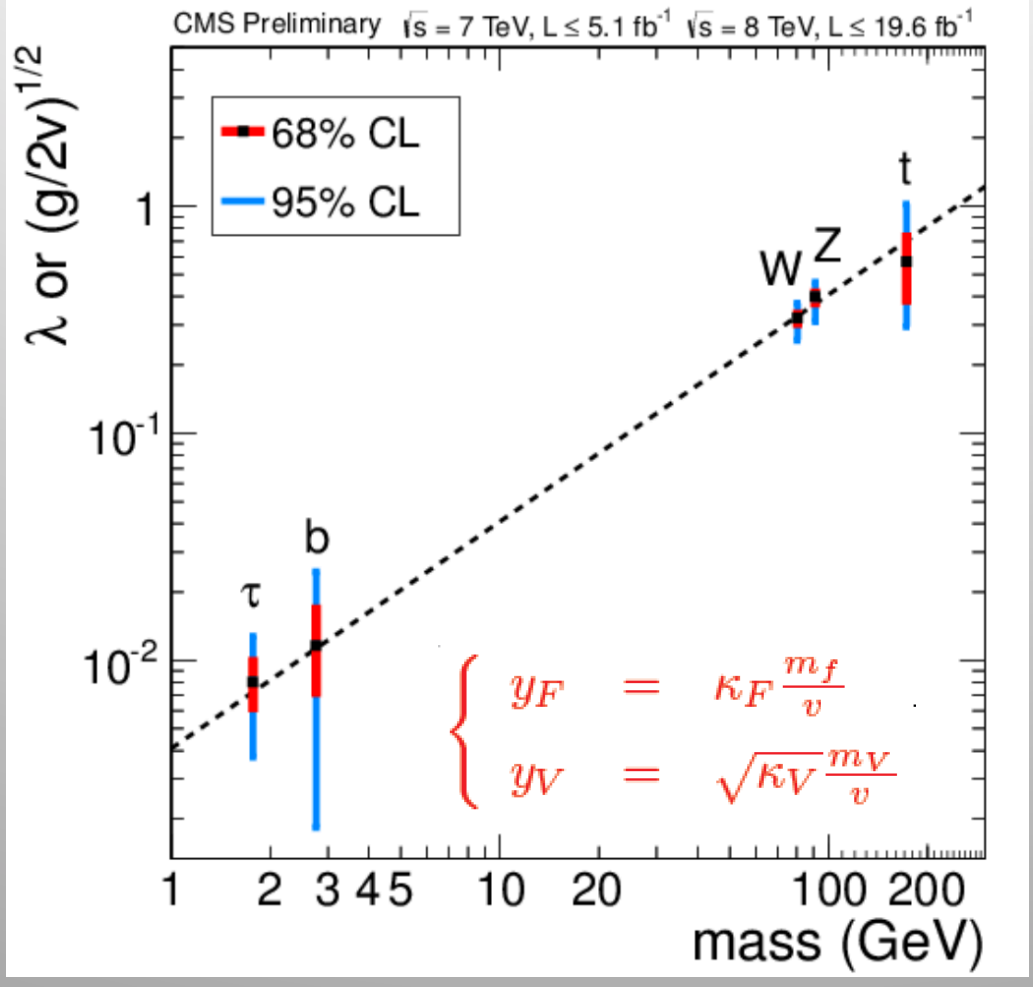


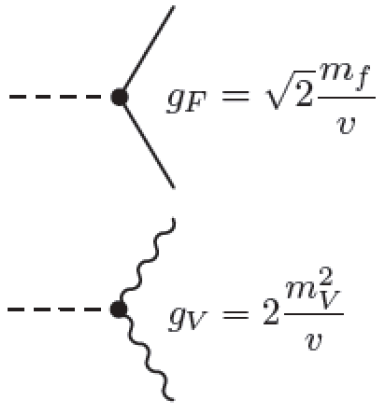
No sign of anything beyond the SM Higgs expectations !!!

Extraordinary amount of information extracted on the scalar boson from Run1 data !

Still more to come

Summary of the Couplings Test

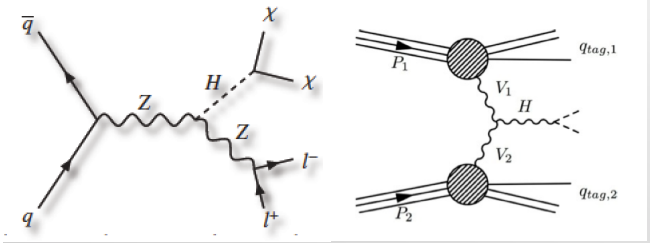




For the fermions, the values of the fitted yukawa couplings are shown, while for vector bosons the square-root of the coupling for the hVV vertex divided by twice the vacuum expectation value of the Higgs boson field.

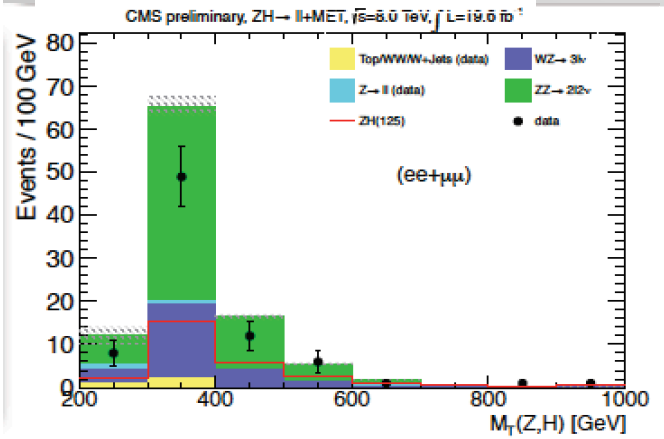
BSM Higgs Studies

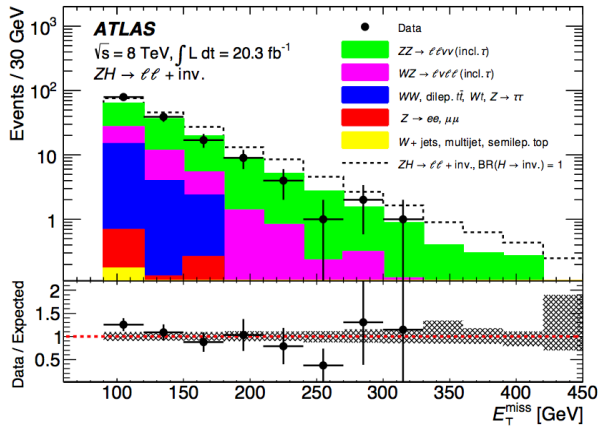
Invisible Higgs Decay Channel



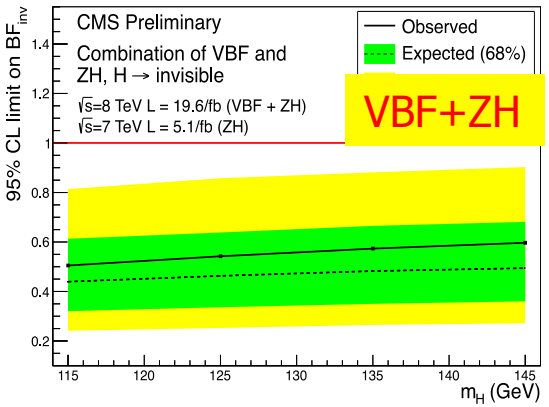
Search for invisible Higgs decays in the processes
Z+H → 2 leptons + missing E_T
VBF H → 2 jets + missing E_T
Possible decay in Dark Matter particles (if $M<M_H/2$)

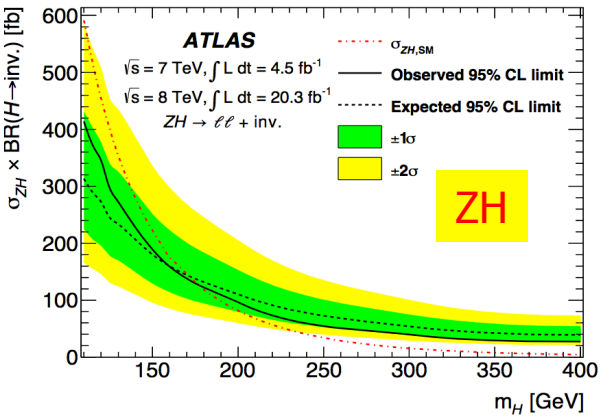
ATLAS :arXiv:1402.3244





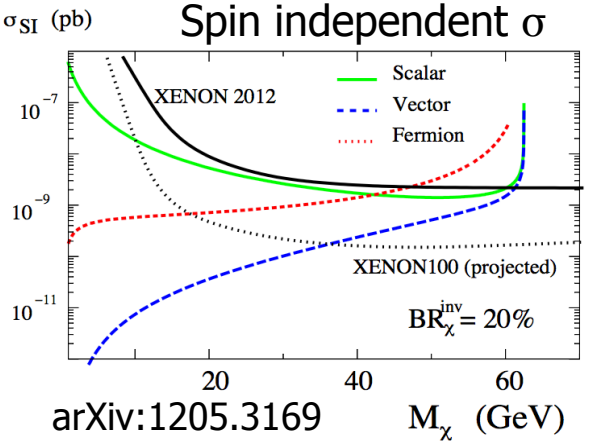
CMS-PAS-HIG-13-013/018





No evidence for invisible decays found so far

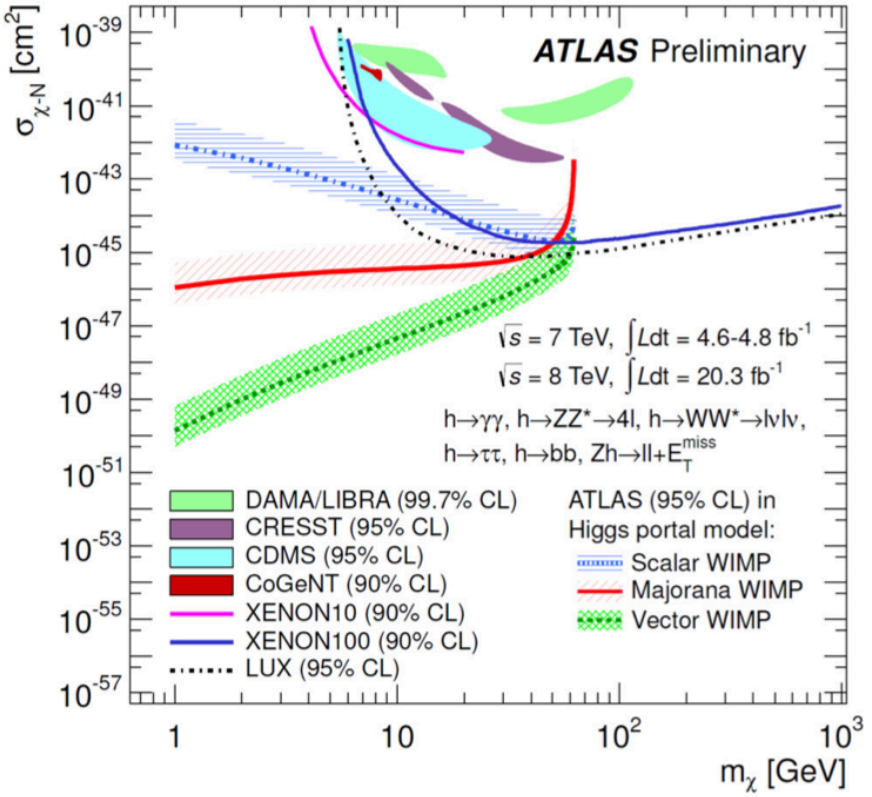
- ATLAS (4.7+13.0 fb^{-1}):
  - Br(H→χχ) <75%(62% exp) at 95% CL. m_H = 125 GeV
- CMS (5+20 fb^{-1}):
  - Br(H→χχ) <54%(46% exp) at 95% CL. m_H = 125 GeV

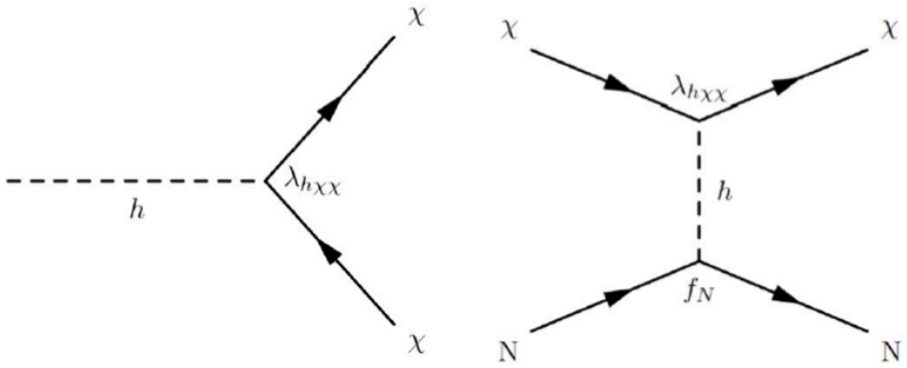


arXiv:1205.3169

Higgs Portal to Dark Matter

- "Higgs Portal" model extends SM to include weakly interacting massive particles (WIMPs) coupling to Higgs boson
- Dark matter-nucleon scattering as well as decay rate inferred from Higgs invisible decays
- Translate $BR_{i,u} < 0.37$ (0.39) obs. (exp.) at 95% CL (5-channel + Zh) into limits on DM rate (depends on WIMP spin)

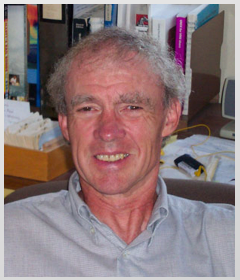




- Significantly more sensitive at low mass for vector WIMP than direct detection experiments *assuming Higgs Portal model*
- Sensitivity dominated by 5-channel coupling combination

MSSM Higgs?

•A lot of tribute to Jack here, discussed at this workshop Especially to the NMSSM



Minimal supersymmetric extension of SM there are 2 scalar doublets Φ_1, Φ_2

After EW symmetry breaking:

5 physical Higgs bosons
- **h, H (scalar, CP-even)**
- **A (pseudo-scalar, CP-odd)**
- **$H^{\pm}$ (charged)**

β (VEVs): $\tan\beta = v_2/v_1$ $[v_1^2+v_2^2 = v^2 = 2M_Z^2/(g_2^2+g_1^2) = (246\ \text{GeV})^2]$

- **MSSM Higgs sector @ tree level determined by: M_A & tanβ**

MSSM at large tanβ: enhanced Higgs couplings to b and τ

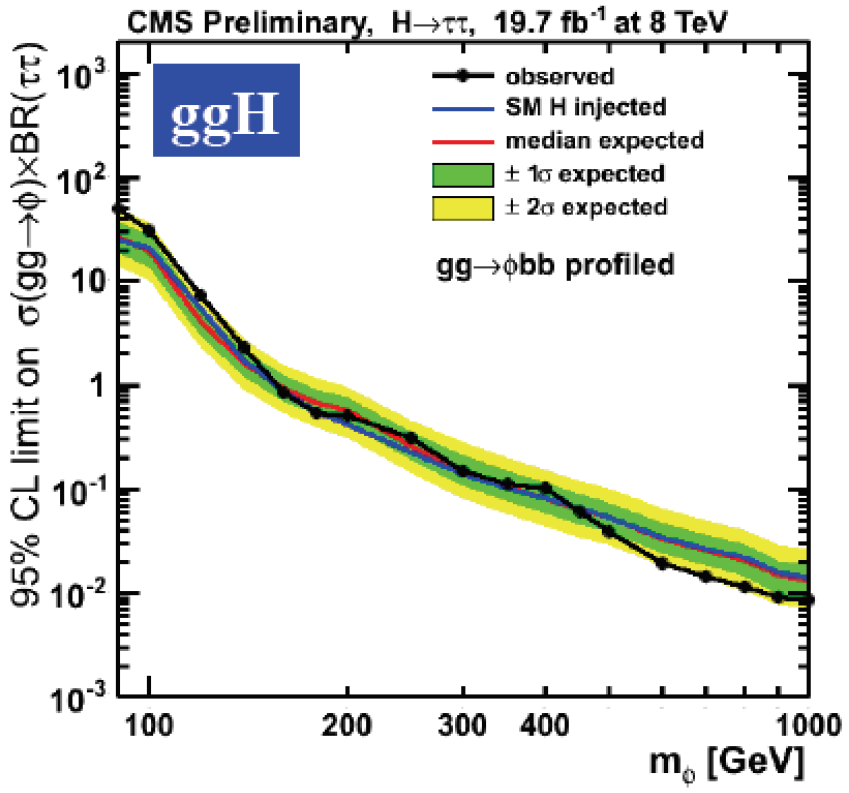
•The NMSSM provides a solution to the μ problem in MSSM introducing a new gauge singlet field in the Higgs sector of the superpotential
•A total of 7 Higgs bosons are now possible, 3 CP even, 2 CP-odd and 2 charged Higgs bosons

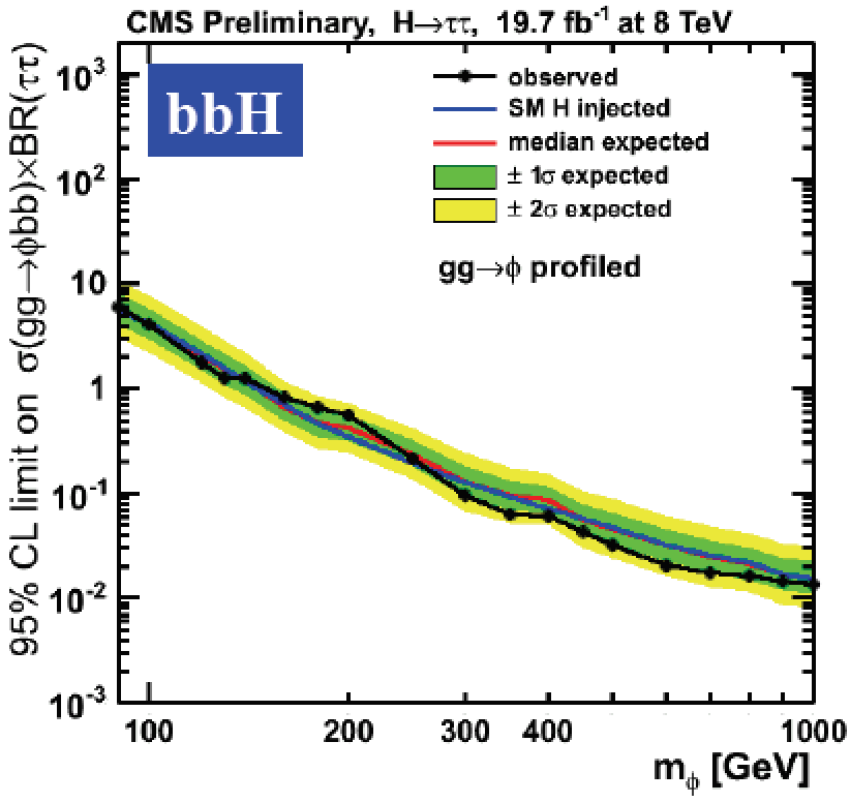
MSSM Neutral Higgs → tau tau

Study of the Neutral Higgs h/H/A to tau tau

Single resonance search: useful to probe different theoretical models!

Upper limits on ggH and bbH cross section times BR

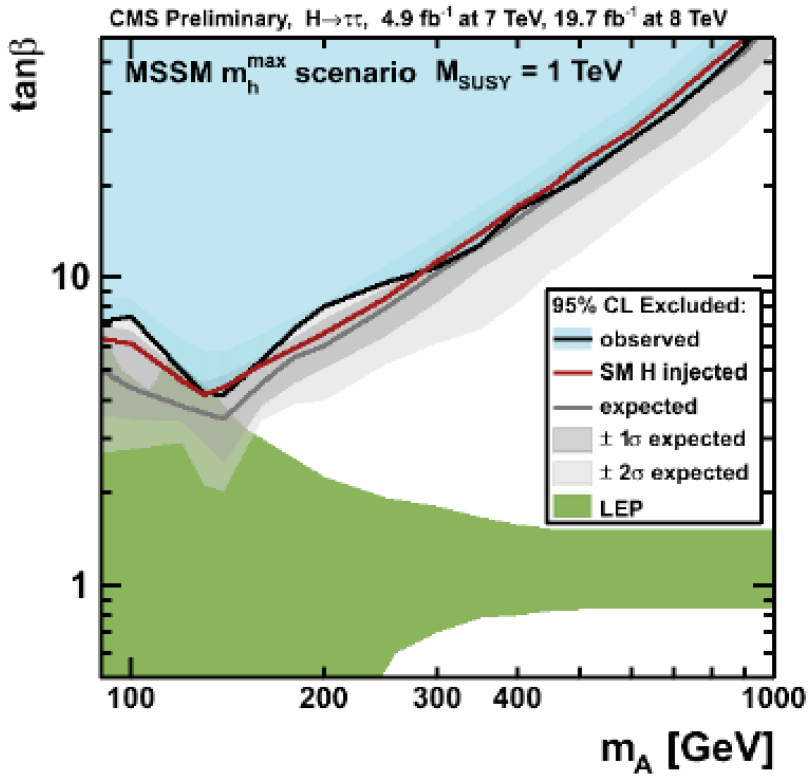


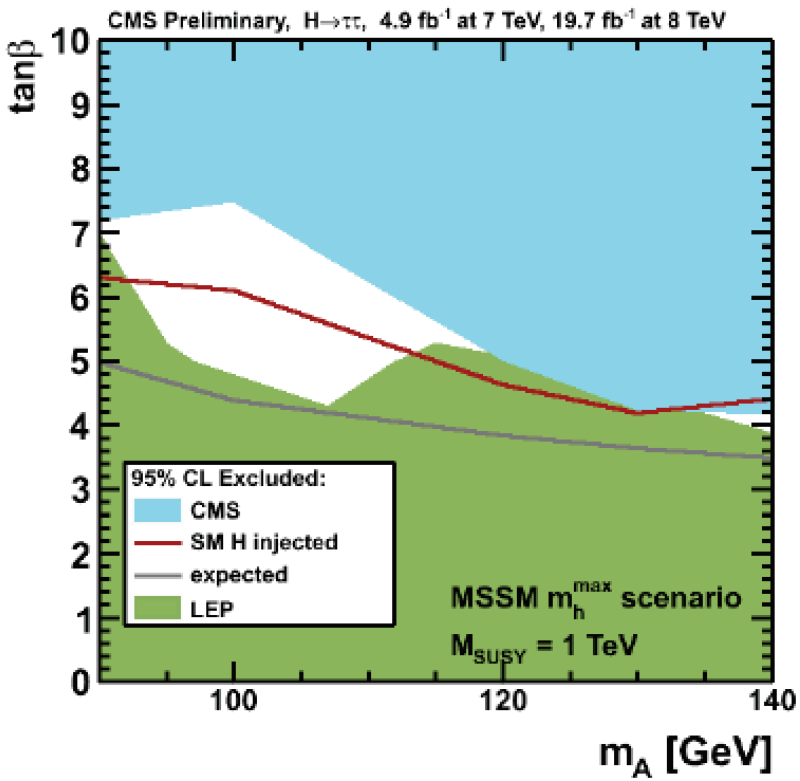


MSSM Neutral Higgs → tau tau

- Study of the Neutral Higgs h/H/A to tau tau
- Include channels with associated b-quark production
- No excess found so far -> exclusions (95%)

CMS-PAS-HIG-13-021



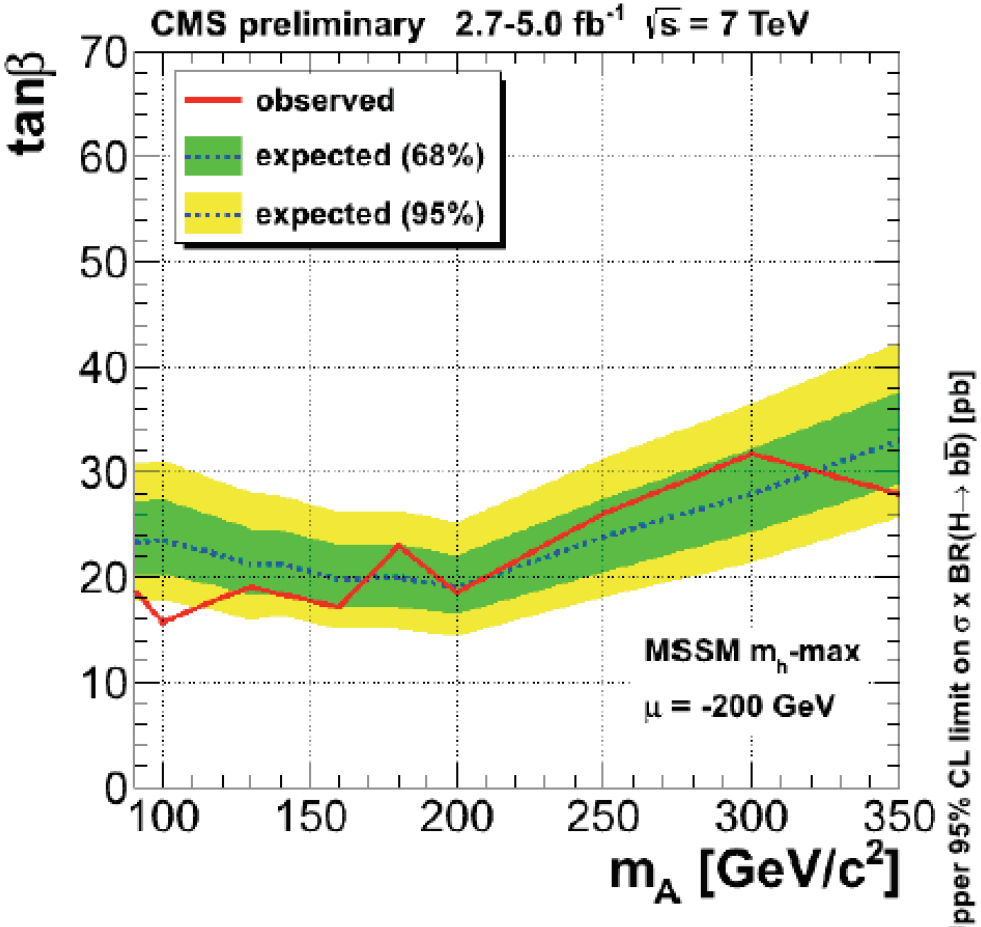


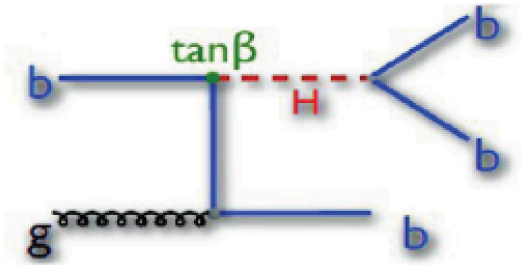
m_h^{max} scenario; other scenarios completed for the publication

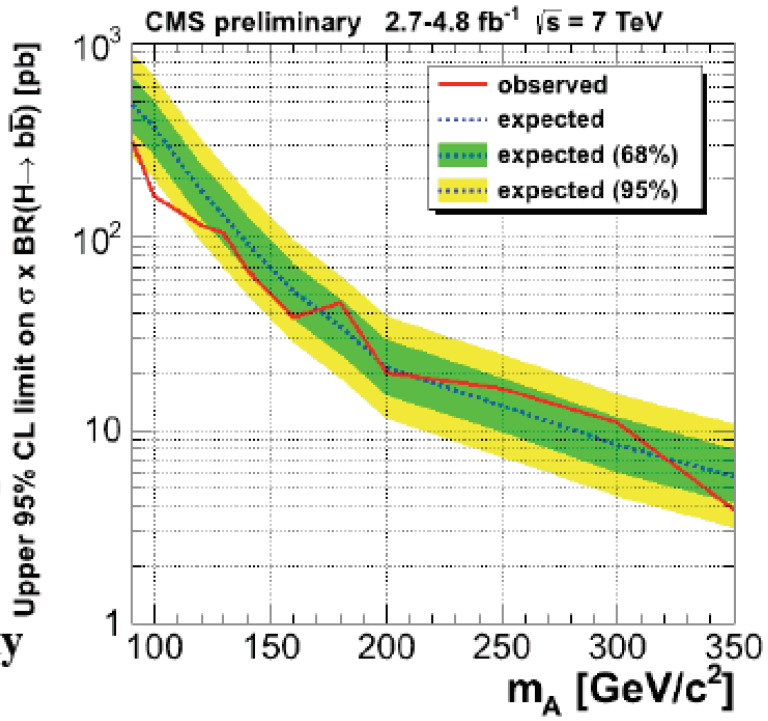
MSSM Neutral Higgs → bb

Study of the Neutral Higgs h/H/A to bb

arXiv:1302.2892

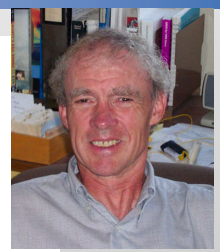






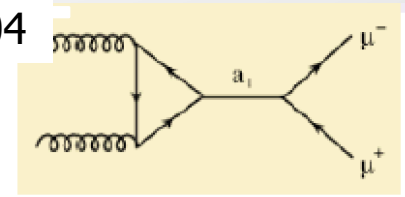
New analysis with 8 TeV data: increase sensitivity at large M_A

NMSSM: light pseudo-scalar search

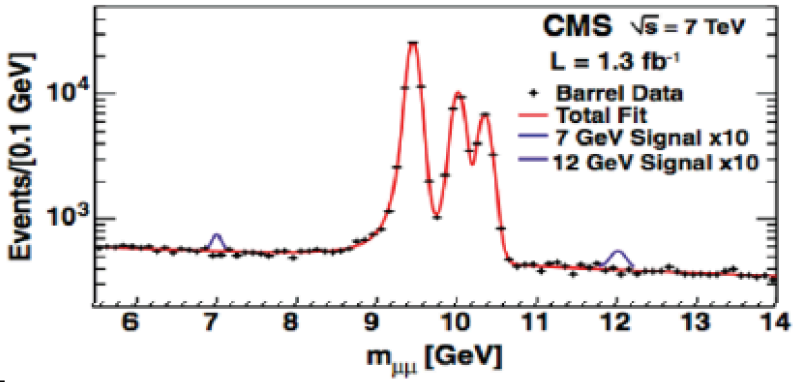


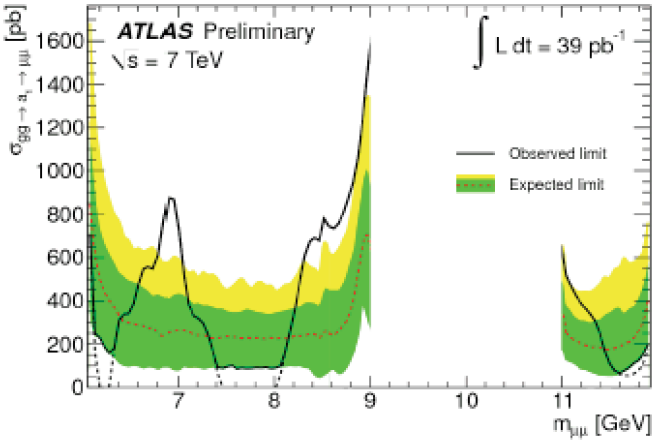
Add scalar singlet to MSSM CMS-PAS-HIG-12-004

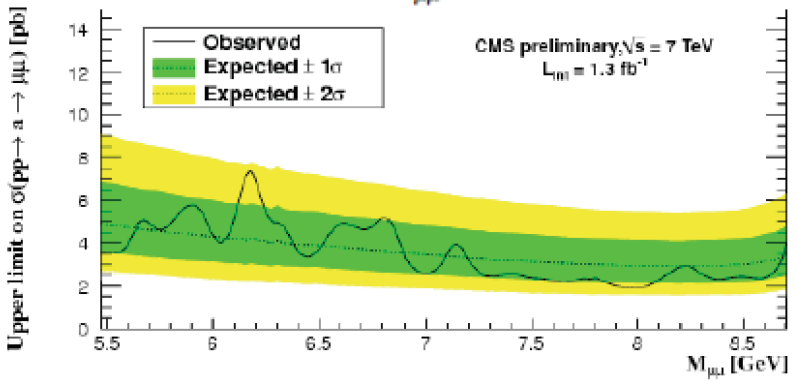
NMSSM: 3 CP-even scalars (h_1, h_2, h_3), 2 CP-odd (a_1, a_2), 2 charged ($H^{\pm}$)

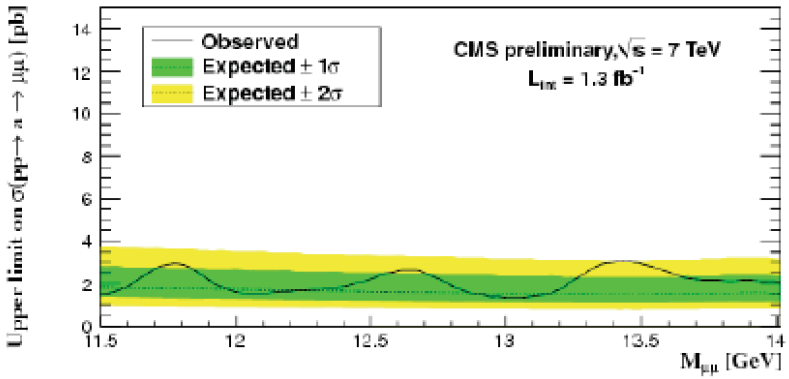


Search below & above the Υ resonance







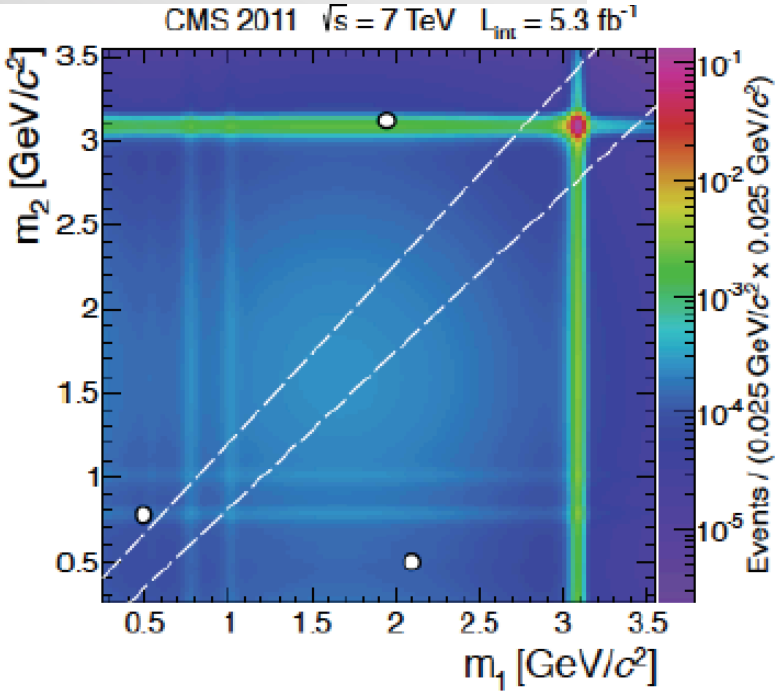


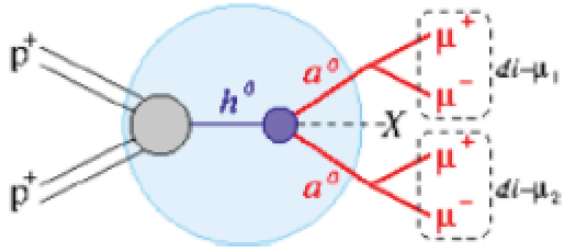
Analysis in CMS 'stimulated/driven' by Jack, with the Davis group…
New study under way for aa → μμττ

NMSSM: light pseudo-scalar search

H → aa → 4 muons

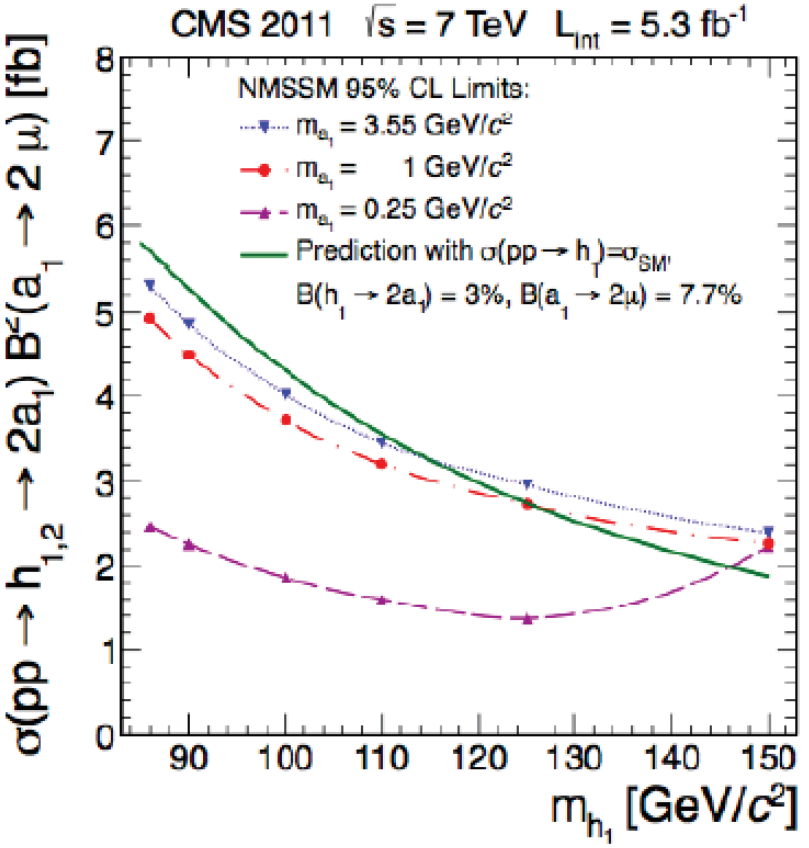
CMS-PAS-HIG-13-010





Observed 3 events in off-diagonal region, consistent with bkg expectations
Signal region: zero events (1.0±0.5 bkg)

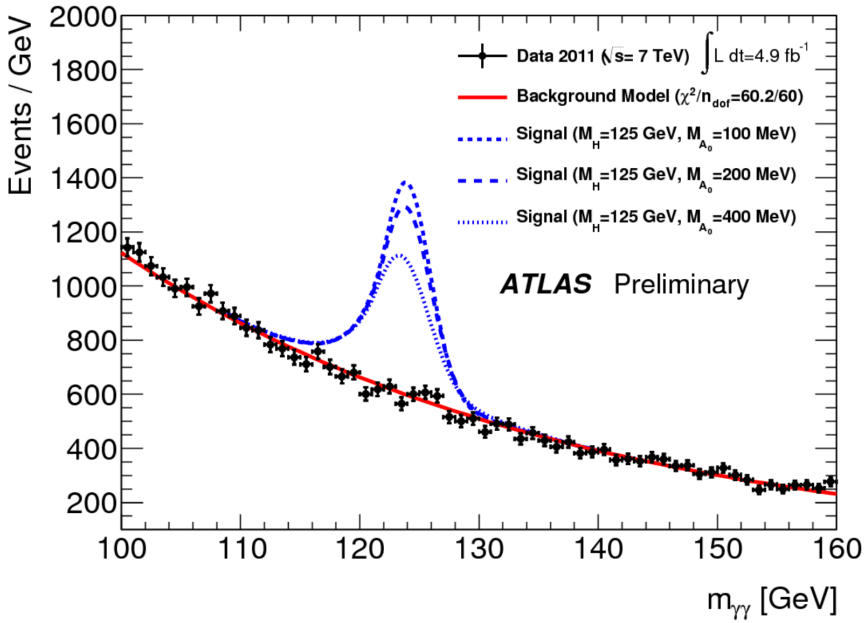
Model-independent upper limit of 0.78±0.05 fb on cross-section x BR x acceptance

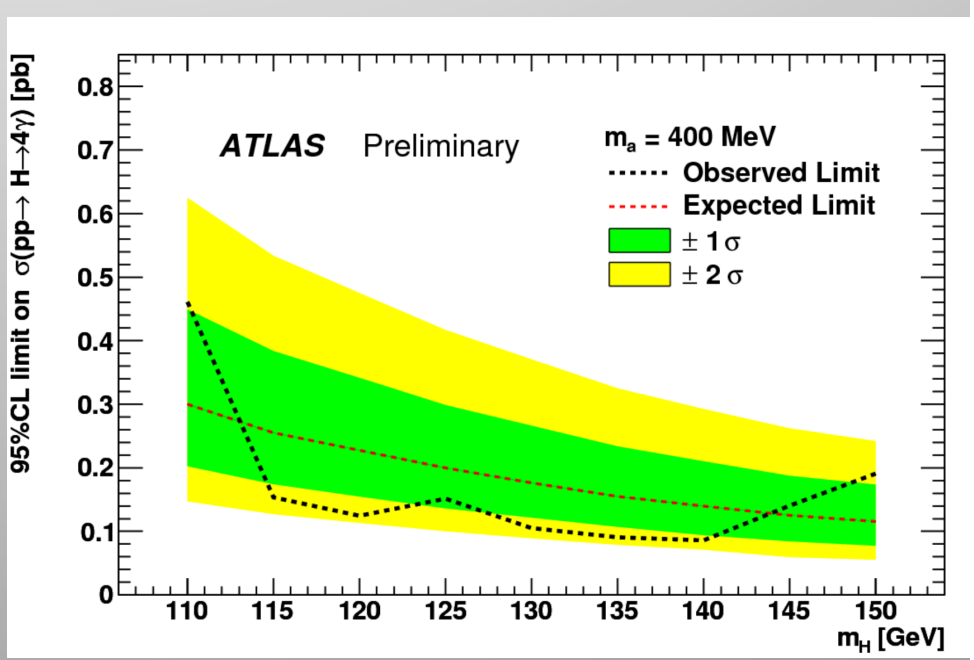


NMSSM: light pseudo-scalar search

Search for H→aa → 4 photons (2011 data)
For low mass pseudoscalars the 2 decay photons are observed as one clusters

ATLAS-CONF-2012-079



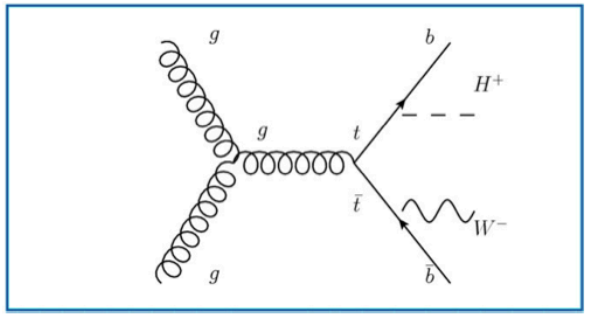


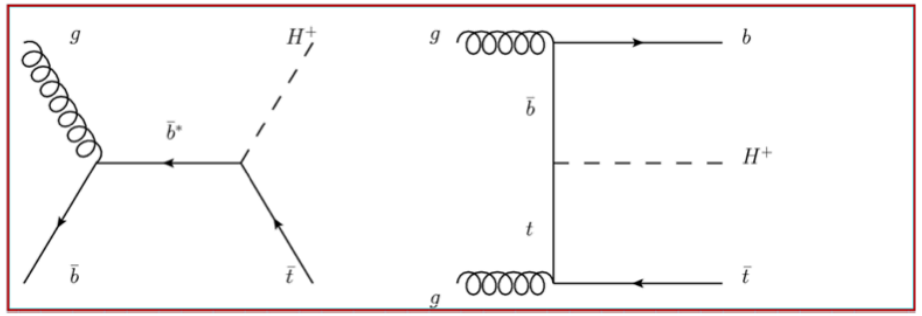
No signal observed with 5 fb^{-1}

Searches for Charged Higgs

- Search for H->τν , using assumption B(H->τν=1)
- Different channels dominate depending on m_H/m_t

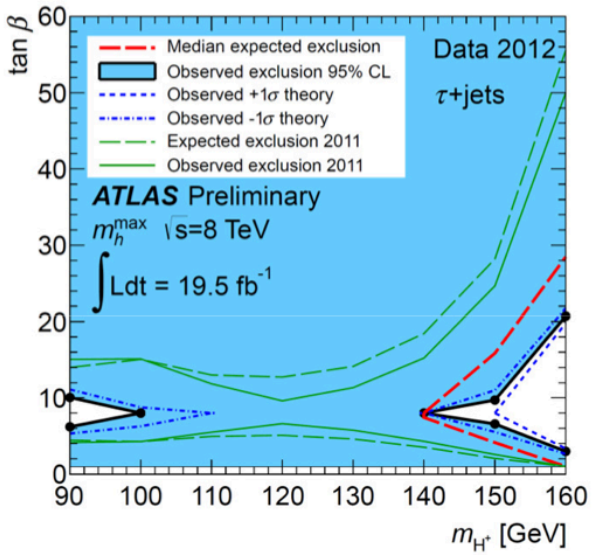
ATLAS-CONF-2013-09



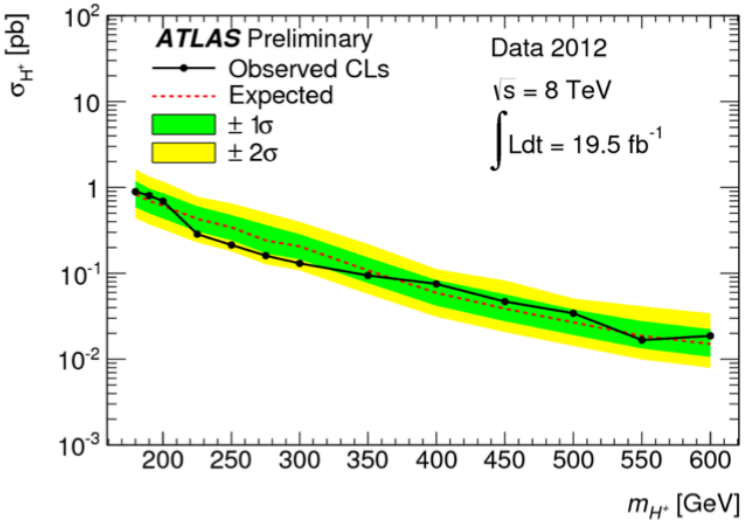


Light Higgs ($m_H<m_t$), tt->HbWb

Heavy Higgs ($m_H>m_t$)



Branching fraction B(t->Hb),0.24-2.1%

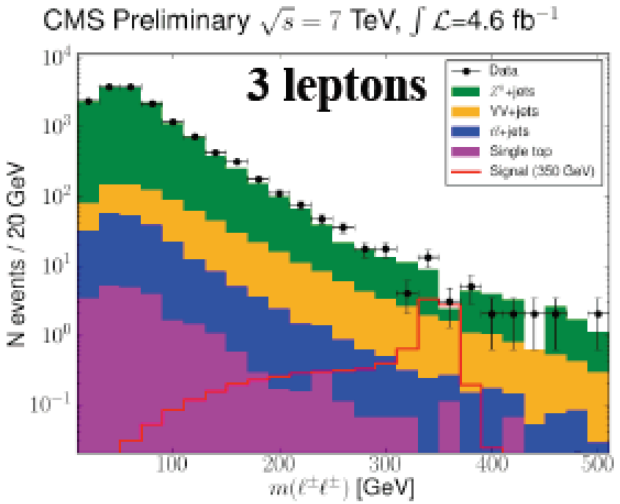


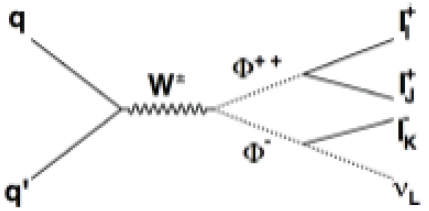
tH cross section limits:0.017-0.9pb

Double Charged Higgs

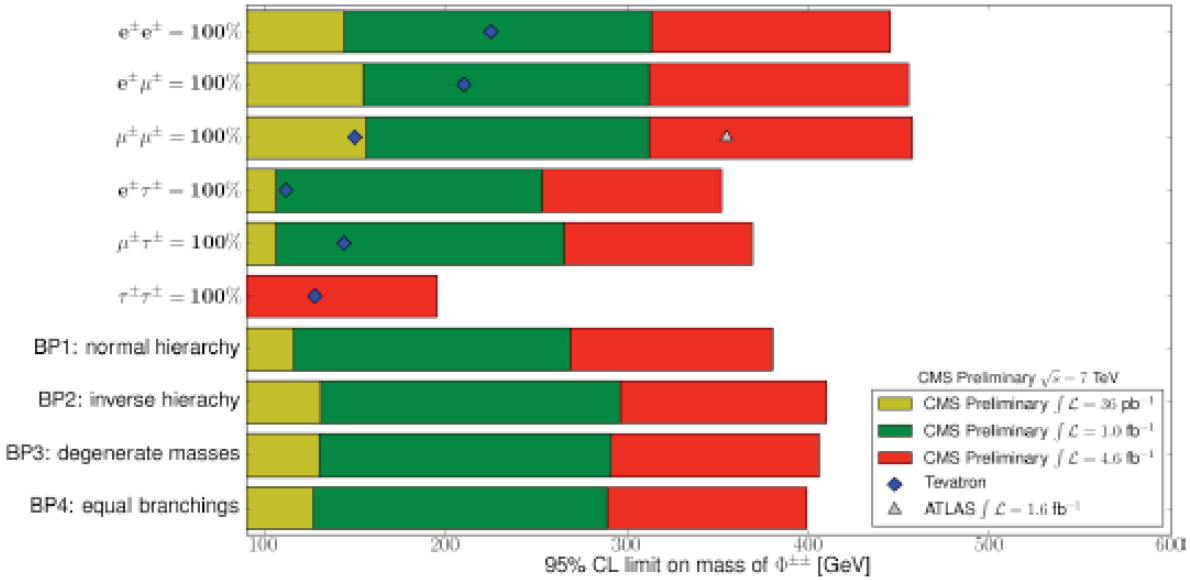
Model designed to explain neutrino masses through a scalar triplet (Φ^{++}, Φ^{+}, Φ^{o})
– Search for double and single charged Higgs

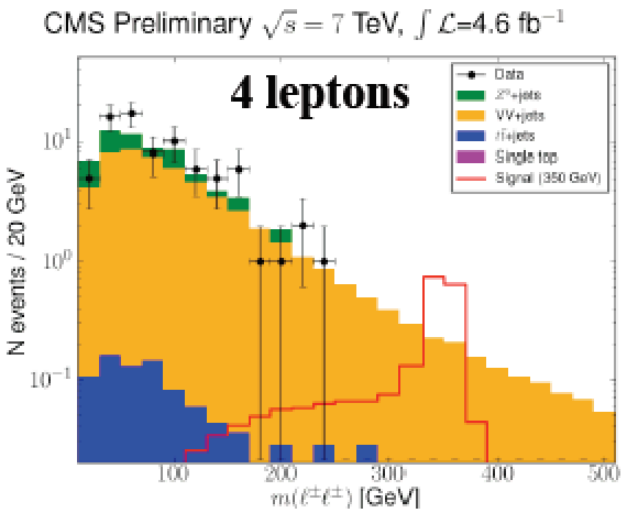
CMS-PAS-HIG-14-052

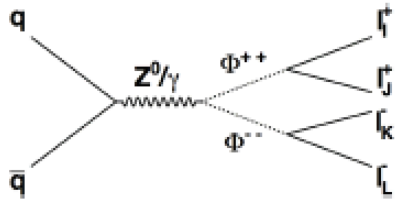




Exclusion up to ~ 450 GeV







Note yet redone for 8 TeV Data

FCNC: t → cH Decays

Moriond EWK 21st March

- Flavour Changing Neutral Current t->cH highly suppressed in SM due to Glashow-Iliopoulos-Maiani mechanism with branching ratio 10^{-13}-10^{-15}
- With large tt cross section and large t coupling to Higgs the LHC is ideally placed
- For t->cH possible new physics rate higher than SM by ~10^{10}-10^{12}

- Study multilepton (CMS-PAS-SUS-13-002) and diphoton (CMS-PAS-HIG-13-025) final states
- H->WW->lνlν, H->ττ, H->ZZ->jjll,ννll,llll, and H->γγ

CMS-PAS-HIG-13-034

NEW

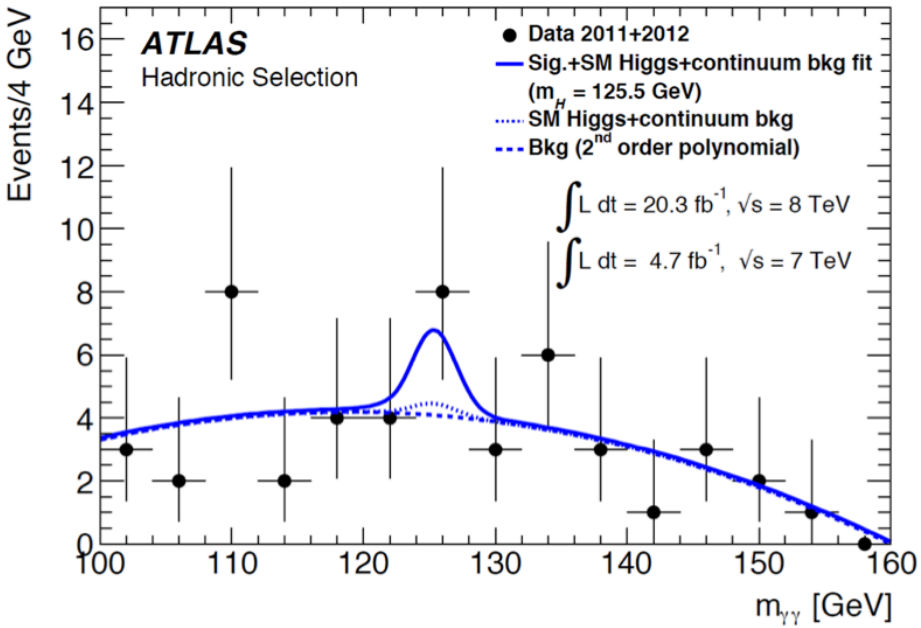
- Limits yielded $\mathcal{B}$(t->cH) < 0.56 (0.65) % for observed (expected)
- Can be used to place limit on coupling λ_{tc}^{H} < 0.14 (observed)

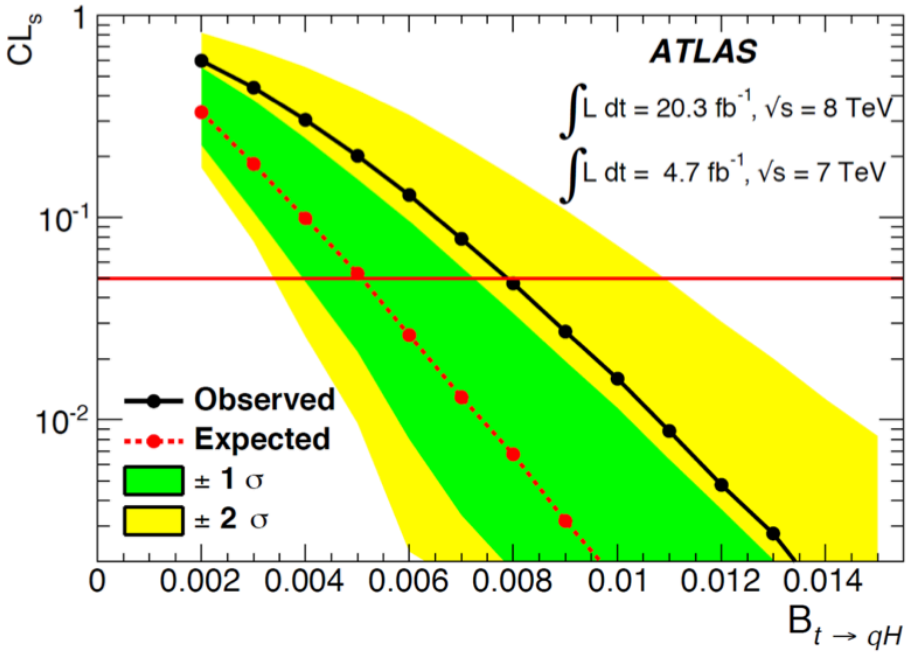
Higgs Decay Mode	observed	expected	1σ range
$H \to WW^*$ ($\mathcal{B} = 23.1\,\%$)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$ ($\mathcal{B} = 6.15\,\%$)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$ ($\mathcal{B} = 2.89\,\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons (WW^*, $\tau\tau$, ZZ^*)	1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$ ($\mathcal{B} = 0.23\,\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

FCNC: t → cH Decays

- Flavour Changing Neutral Current t->qH, where H->γγ
- Other t->bW, both leptonic and hadronic W decays used
- Full 7 TeV and 8 TeV data sample

ATLAS final result submitted to JHEP





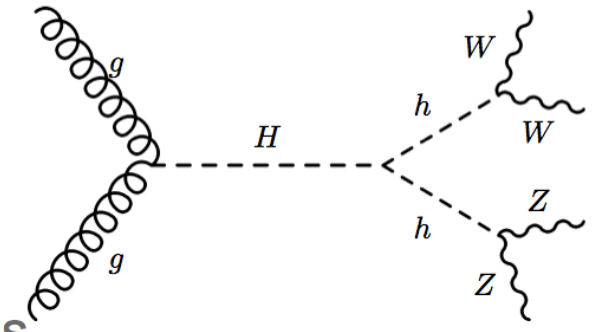
- Limit on branching ratio *B*(t->cH) < 0.83(0.53)% at 95% CL converted to limit on Higgs Yukawa coupling t->cH < 0.17(0.14) observed(exp.)
- Analysis equally sensitive to t->cH and t->uH, so limit can be expressed as

$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$$

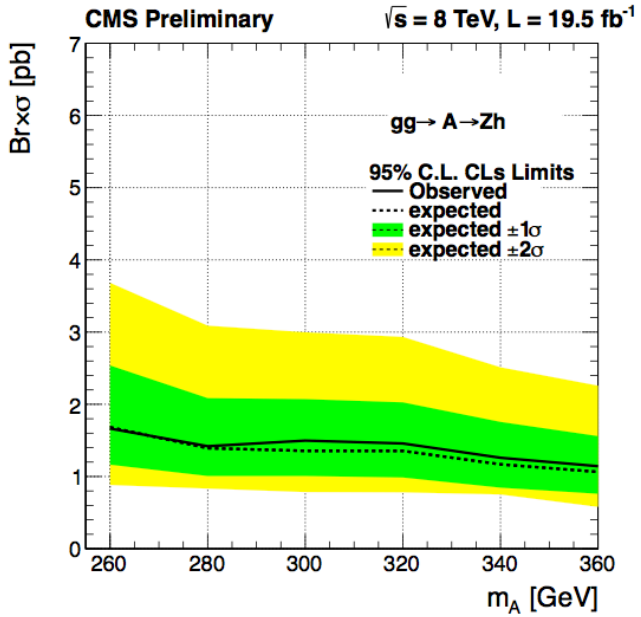
Search for H→hh and A→Zh

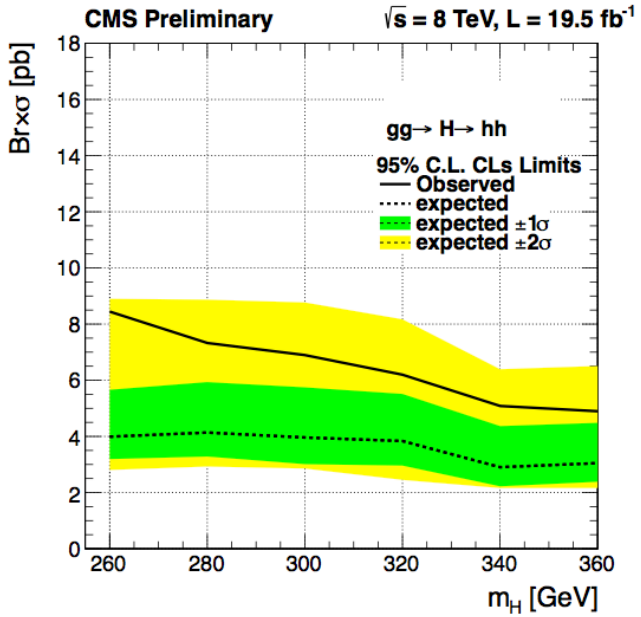
- Search for decays of heavy scalar H→hh and pseudo-scalar Higgs boson A→Zh
  - h is a SM-like Higgs boson
  - h is assumed to have SM branching fractions

CMS-HIG-13-025



- Use multileptons and γγ+leptons channels



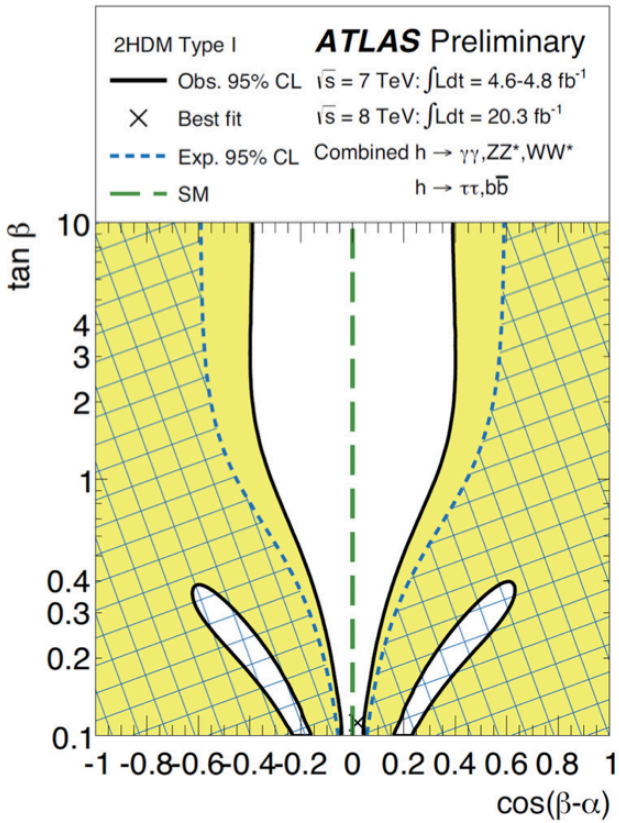


- 2HDM – specific limits and further details to follow soon

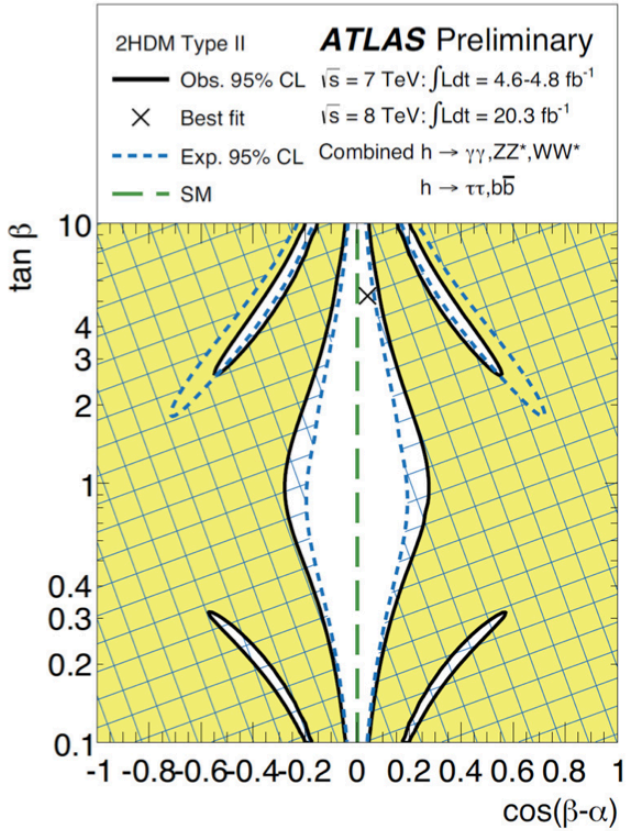
2 Higgs Doublet Models Searches

ATLAS-CONF-2013-027

Type I: "fermiophobic"



Type II: "MSSM-like"



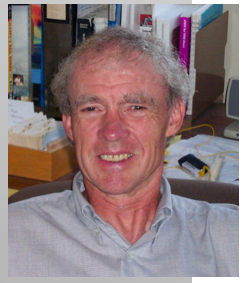
- Observed exclusion limit (95% CL) for four types of 2HDM models in (cos(β–α) , tan β) plane
- Compared with expected exclusion limits for SM Higgs Boson
- Data are consistent with SM alignment limit cos (β-α)=0 to within 1-2 σ for all models

February 2012: Talk to CMS

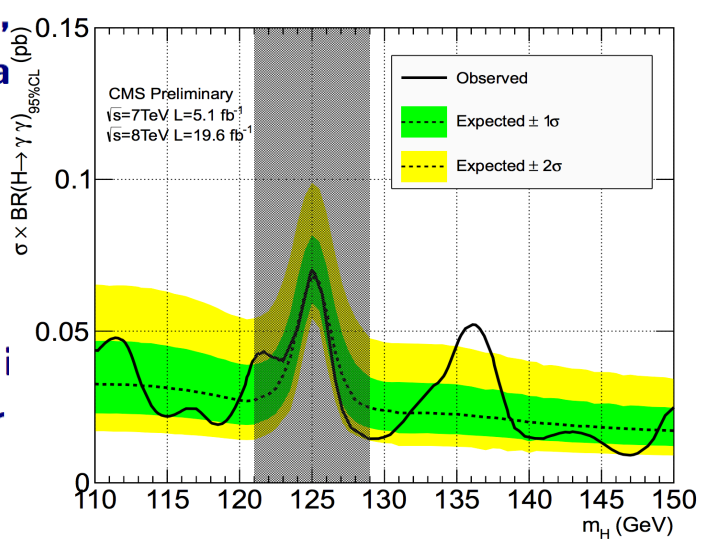
- Given that the mass(es) is(are) of order 125 GeV, more attractive NMSSM extension thereof is a na

  After all, SUSY solves the hierarchy problem, unification at the GUT scale and so forth.

  However:



  - A SM-like Higgs with mass as large as 125 GeV i in the NMSSM 125 GeV is "on the edge" for GUT boundary conditions (and not possible for
  - This is aggravated if the signal is $>$ SM.
  - And, even more problematically, there may be more than one 'excess' in the data (cf. CMS data).



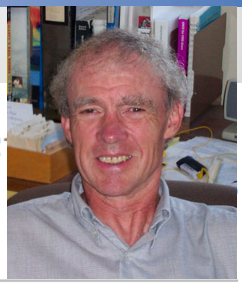
- The only other really attractive alternate solution to the hierarchy problem that provides a self-contained ultraviolet complete framework is to allow extra dimensions.

  One particular implementation is the Randall Sundrum model in which there is a warped 5th dimension.

Radion-Higgs mixing? Two resonances?

Watch that space…

Never enough information!



John Gunion

November 2

To: Béranger Dumont <beranger@gmail.com> , Sabine Kraml , Genevieve Belanger and 3 more…

Re: HCP Higgs results

this note concerns only the cms h to tau tau. As I have noted, my cmstautau_table1_jfg.nb mathematica file reproduces beranger's fractional compositions nicely. However, I am quite confused about the following.

Dear all:

Let me continue to focus on table 1 of the CMS search for higgs to tau tau PAS. As part of the fractional contribution calculation I did (that agrees with Belanger), one computes an effective total cross section for the higgs in the mu-tau_h category using the efficiencies quoted in table 1. For example, for 1-jet the cross section I obtain is 0.11 pb (see the attached printout of the mathematica.nb file). If I multiply by the integrated luminosity of about 17 fb-1, this gives 1883 events, i.e. far bigger than the expected number of events in their table of 112. Of course, Beranger computes the mu value for the 1j category quoted in his email using the expected number of higgs events in the 1j category (112) as quoted in table 1 divided by the excess of events (using table 1) above the background (31) and obtains mu_1j\sim 0.277. My effective mu_1j would be MUCH smaller. So, how can I understand the difference between the 1883 events I obtain using the efficiencies vs. the 112 quoted by CMS? I believe that something else must be going on. Perhaps the efficiencies in the table are not the whole story and there are additional acceptance, ... whatever efficiencies that they have not told us about. These could of course be process dependent, in which case our fractional compositions would not necessarily be relevant. Perhaps our failure to obtain their net \mu is because of some missing ingredient(s) that are associated with my problem.

Please help!

Jack

But we (experimentalists) always aim to please... ☺

Publications

Jack and I have 25 'common' publications, mostly workshop reports.
In fact, Jack and I co-authored a paper which has so far 2345 citations!!

HEP **475** records found 1 - 25 ▶ ▶▶ jump to record: 1

1. **Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC**
(2345) CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012. 42 pp.
Published in **Phys.Lett. B716 (2012) 30-61**
CMS-HIG-12-028, CERN-PH-EP-2012-220
DOI: 10.1016/j.physletb.2012.08.021
e-Print: **arXiv:1207.7235 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Link to PRESSRELEASE; Interactions.org article
Detailed record - Cited by 2345 records 1000+

...and an additional 3245 authors....

Jack & CMS

1. **A New Boson with a Mass of 125 GeV Observed with the CMS Experiment at the Large Hadron Collider**
   CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). 2012. 7 16 pp.
   Published in **Science 338 (2012) 1569-1575**
   DOI: 10.1126/science.1230816
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server ; ADS Abstract Service; Link to Preprint
   Detailed record - Cited by 21 records

2. **Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC**
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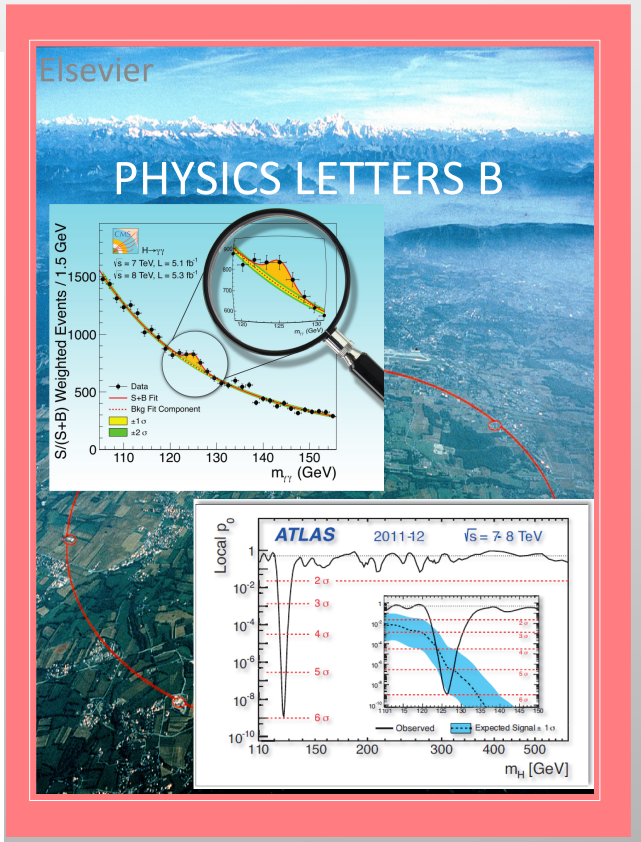

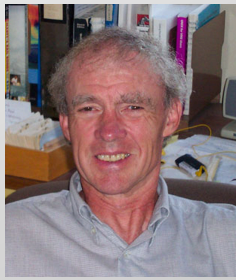

..recognizing his work in the preparatory studies of CMS..

Analysis	Approved Plots	CDS Entry	Luminosity	Comment
Phenomenological MSSM interpretation of the CMS results at sqrt(s)= 7 TeV	SUS12030	PAS-SUS-12-030	4.98/fb	

and

Phenomenological MSSM Interpretation of the 7 and 8 TeV results	SUS13020	PAS-SUS-13-020 (coming soon)	19.5/fb	NEW

Summary

- Jack Gunion has spend a lot of his scientific career on the theoretical study of the Higgs particle, in the standard model and beyond, especially the NMSSM extension
- He is a close contact to the CMS experiment through the UC-Davis connection. He is a source of inspiration for our BSM searches
- The Higgs Boson was finally discovered in 2012
- The spin/parity is compatible with a 0^+ state and not with (simple) 0^- or spin 2 states. The mass has a value ~125.6 GeV with a precision of order ~0.5%.
- Hunt for 'unexpected' decays & processes is going on…
- We wish to have Jack with us still for a long time on this adventure @ the LHC… There is a lot to do.