Higgs Physics at the LHC Experimental Review

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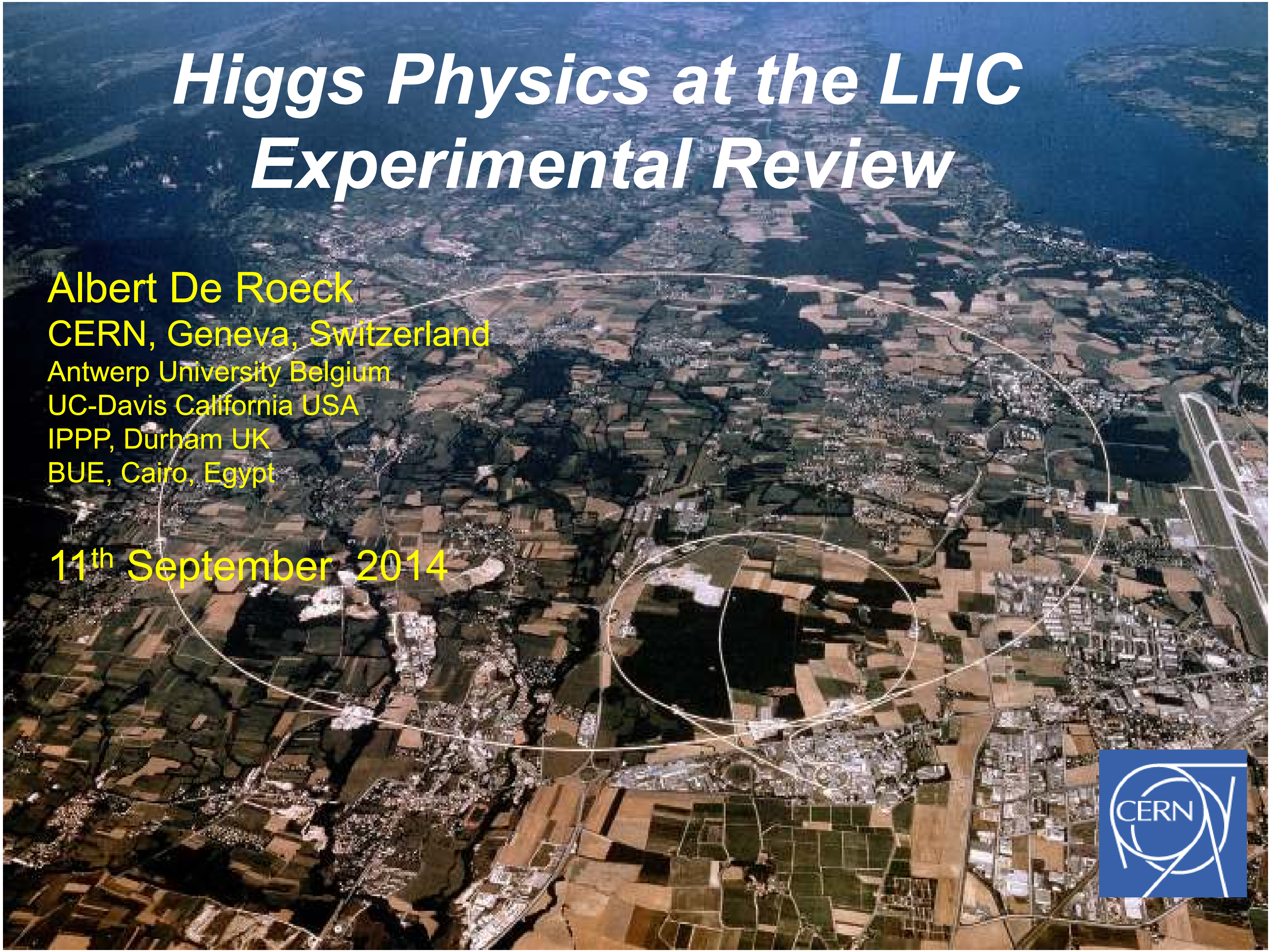
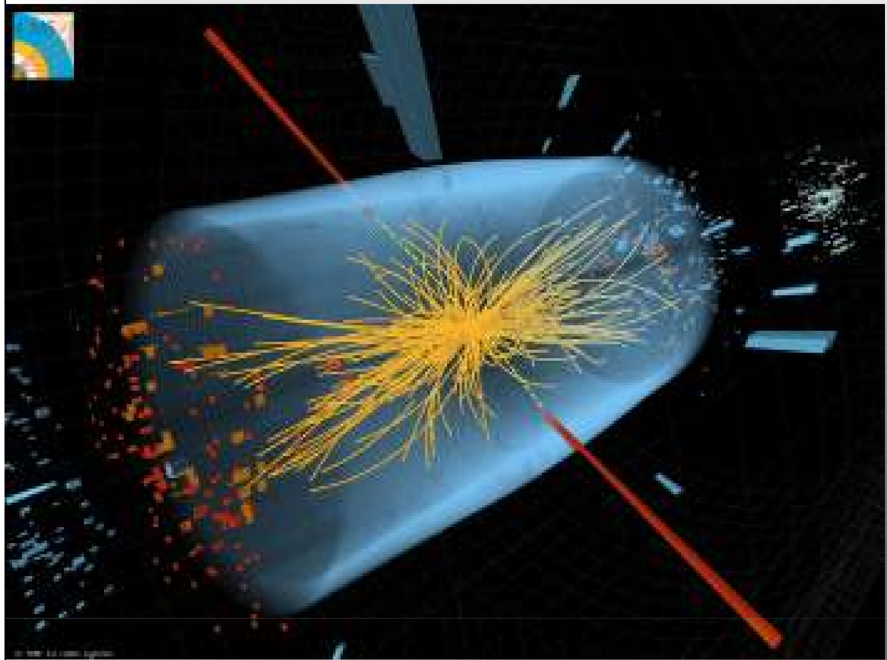
11th September 2014

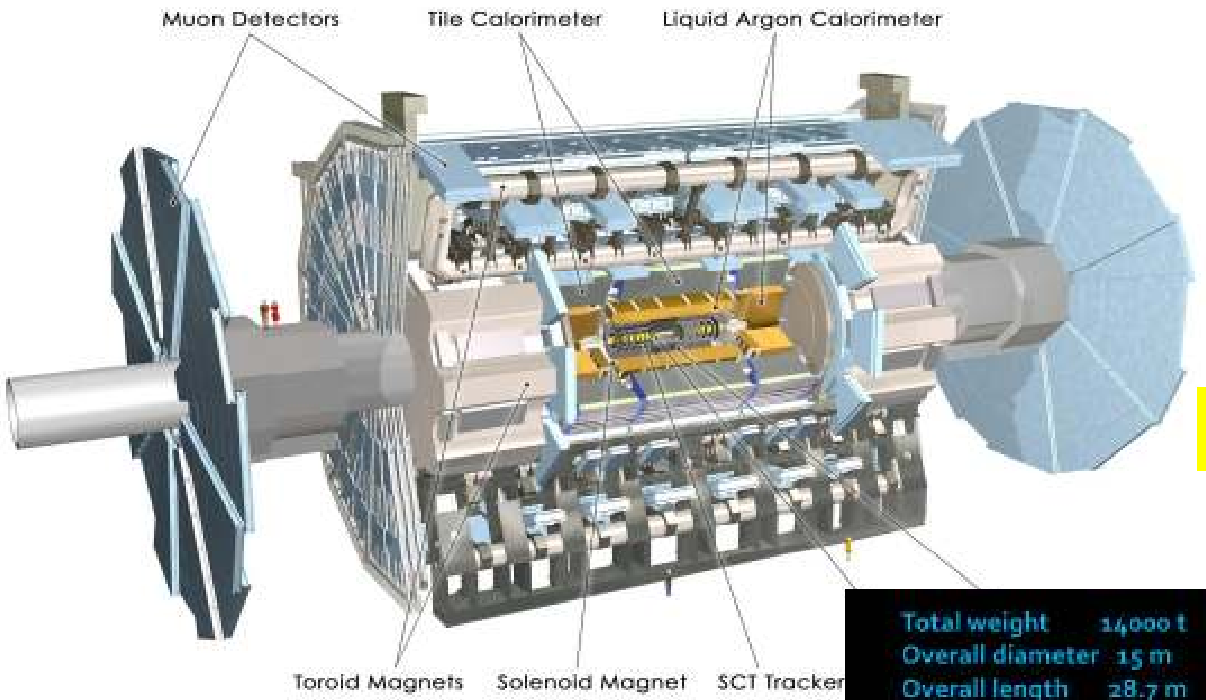




Outline

- Short introduction
- Standard Model Higgs channel studies overview
- Studies of Higgs properties
- Beyond the SM?
- Summary

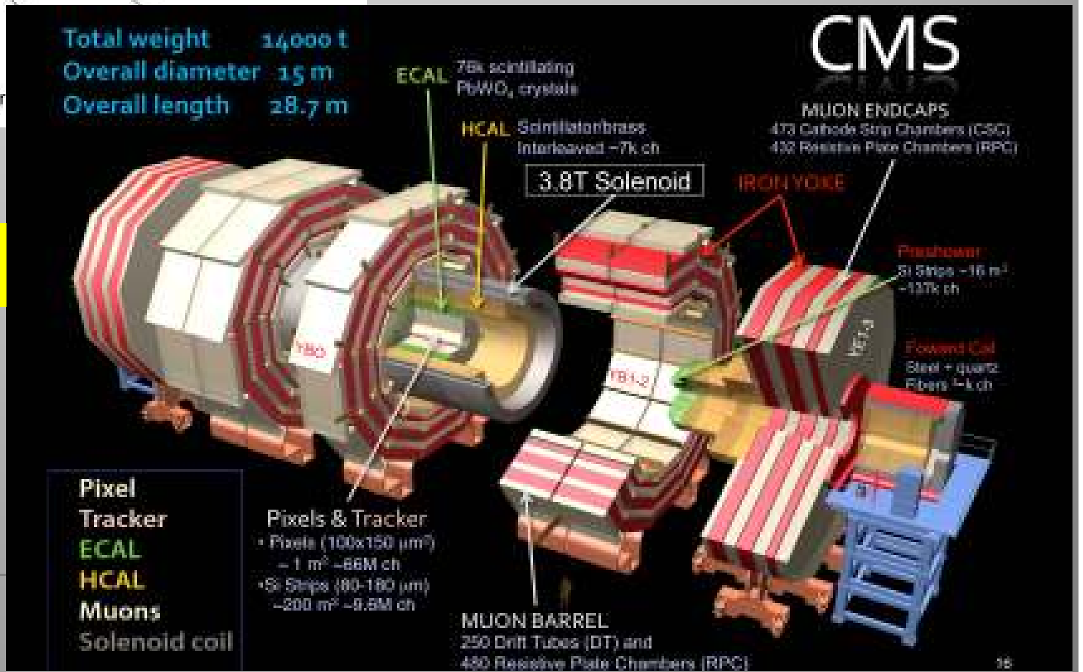
The Higgs Hunters @ the LHC



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

The ATLAS experiment

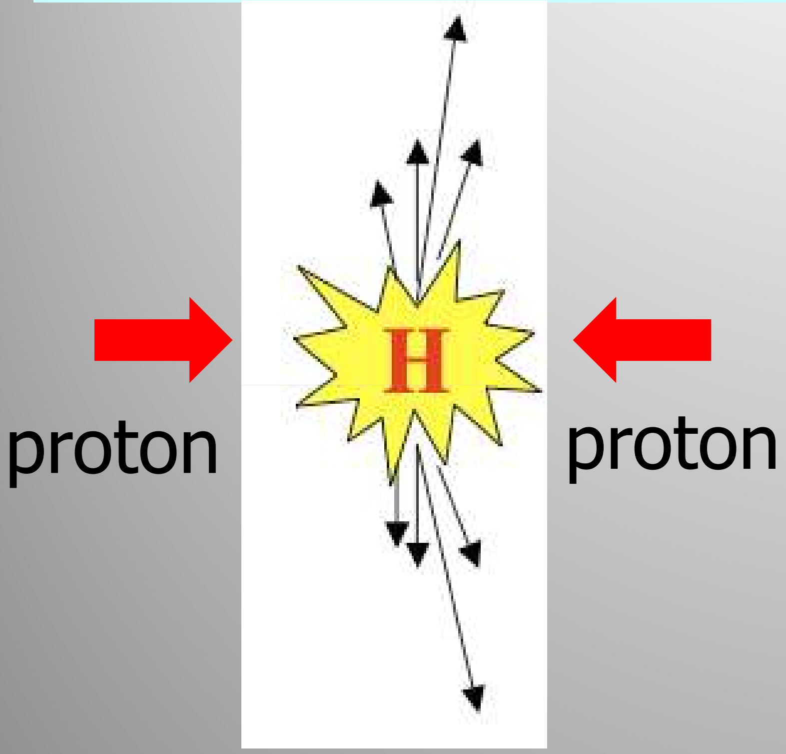
The CMS experiment

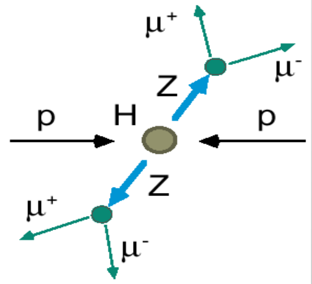


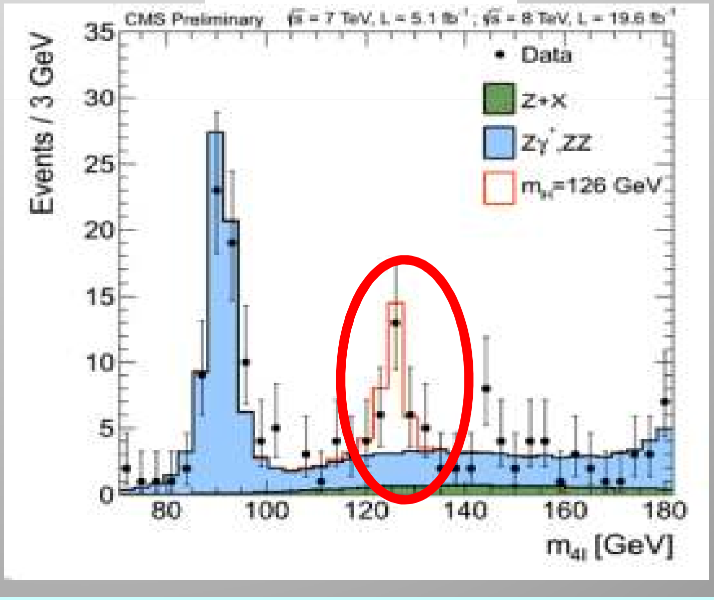
And LHCb...?

2012: A Milestone in Particle Physics

Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it





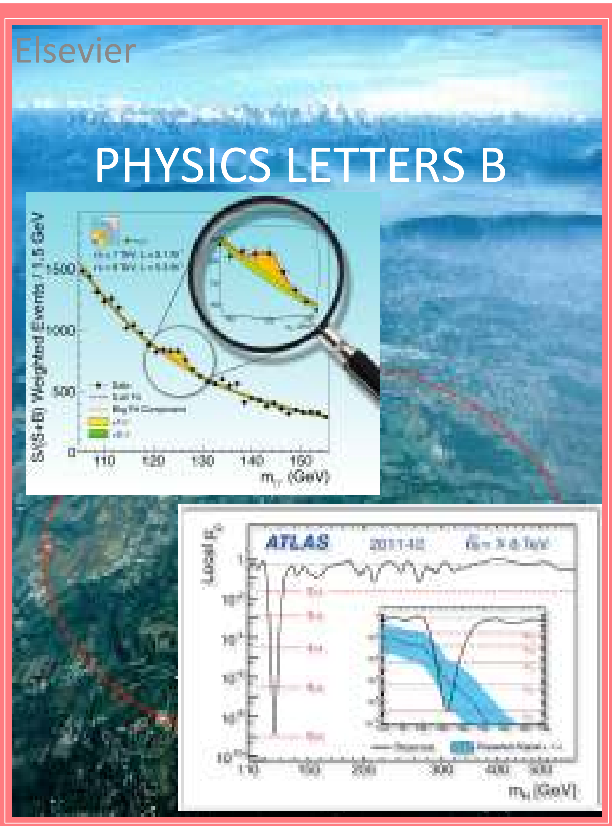


2013

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

Most cited LHC papers so far...

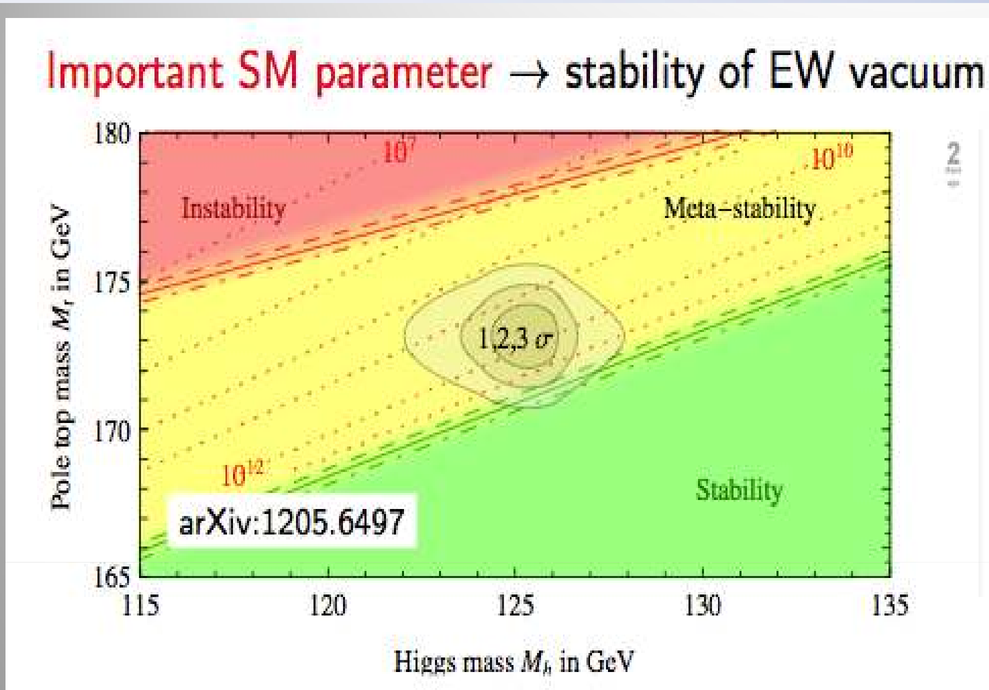
Special Physics Letters B edition with the ATLAS and CMS CMS papers on the Higgs Discovery



More than 3000 times cited so far…

Also…

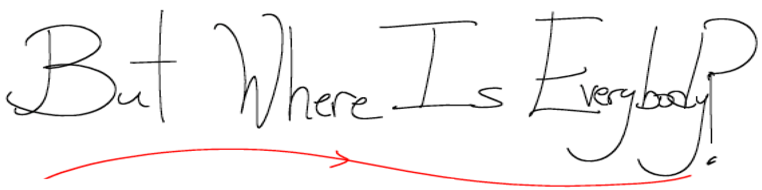
Consequences for our Universe?



Precise measurements of the top quark and first measurements of the Higgs mass:

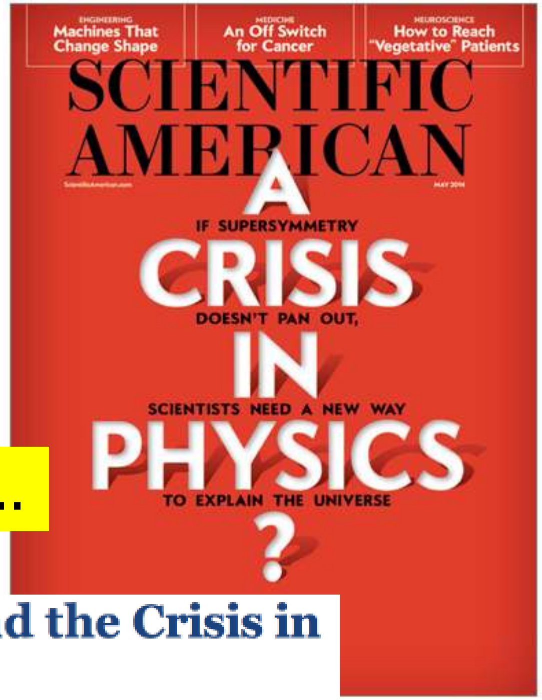
Our Universe meta-stable ? Will the Universe disappear in a Big Slurp? (NBCNEWS.com)

New Physics inevitable? But at which scale/energy?



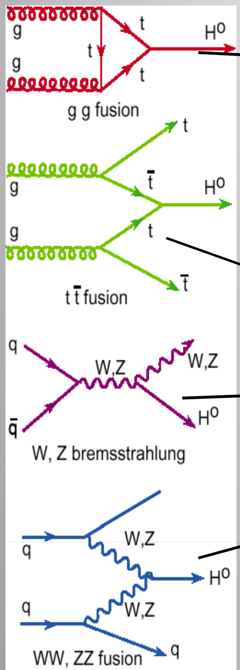
N. Arkani-Hamed

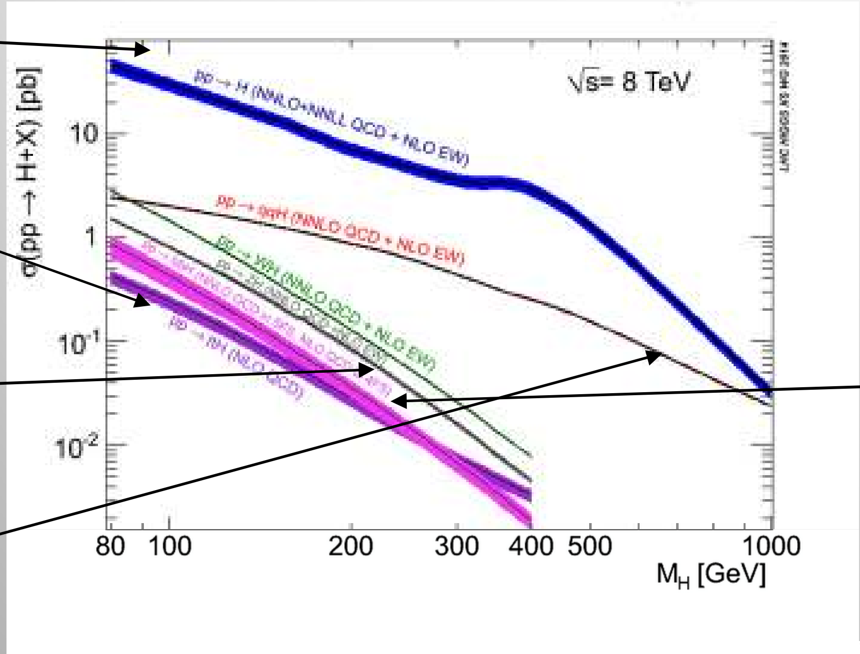
...The May Issue...



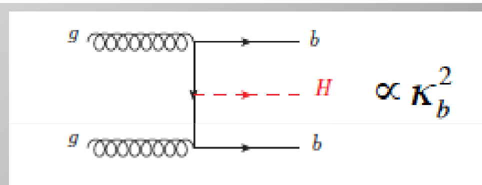
Supersymmetry and the Crisis in Physics

Higgs Production & Decay



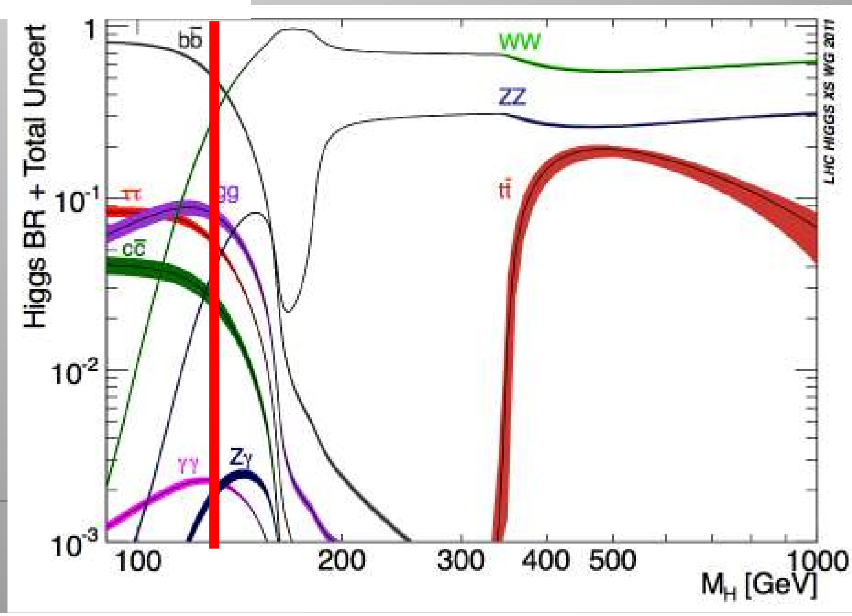


Processes
- Gluon fusion
- Vector Boson Fusion
- W/Z associated prod.
- Top associated prod
- B-quark associated prod?



Numbers taken from the LHC Higgs Cross Section WG

See yellow reports:
YR1: Inclusive cross sections
YR2: Differential cross sections
YR3: Properties (to appear)



Higgs Hunting: Channel Overview

Processes/decays studied:

Results released   In progress

	untagged	VBF	VH	ttH	bbH?
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 -> $\gamma\gamma$	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%

Higgs Analyses

•In summer 2012 we called it a “Higgs-like” particle
•In spring 2013 (with 3x more data) we called it a Higgs particle
Spin/parity 0^+ favored, couplings roughly as in SM for Bosons
What happened Next?

- More detailed analyses of the 125 GeV particle, in particular the search for direct decays into fermions, ttH channel,...
- More precise measurements of the “signal strength σ/σ_{SM}“ and of the mass of the particle, and the spin, couplings
- Searches for Higgs like particles at higher masses
- Searches for exotic, non-SM decays (none found so far)
- Searches for di-Higgs events (in BSM scenarios, none found so far)
- Differential distributions + fiducial volume cross sections

→The Experiments have published Run-I legacy papers

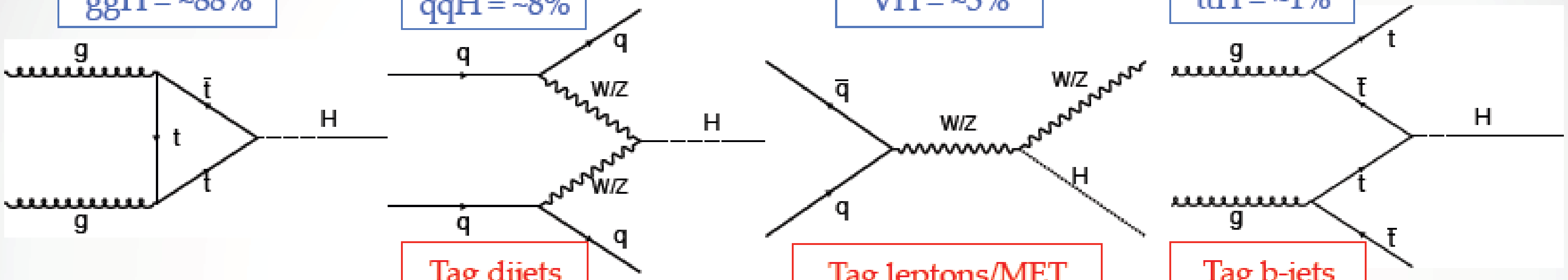
The Higgs is the new playground: Room for new experimental/theoretical ideas!!
Remember: we have already ~1 Million Higgses produced at the LHC

Higgs Decaying into Bosons

Higgs → γγ

- Small peaking signal on large QCD falling background
  - Signal:

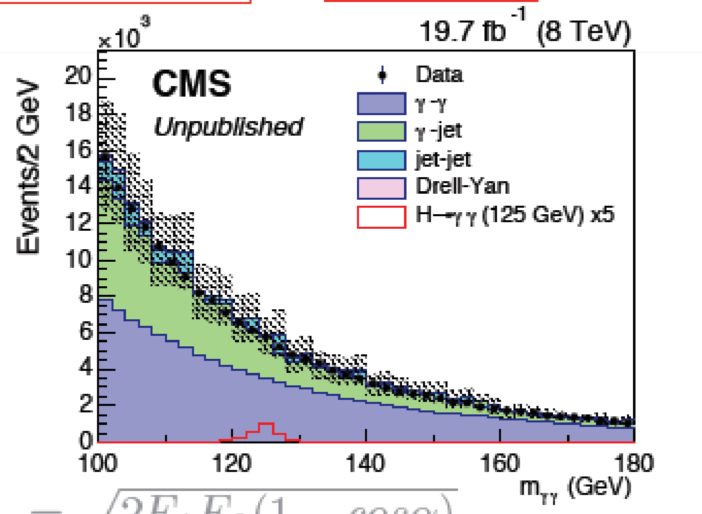
ggH = ~88% | qqH = ~8% | VH = ~3% | ttH = ~1%



Tag dijets | Tag leptons/MET | Tag b-jets

  - Background:

γγ = ~70% | γ+jet = ~30% | jet-jet = <1%



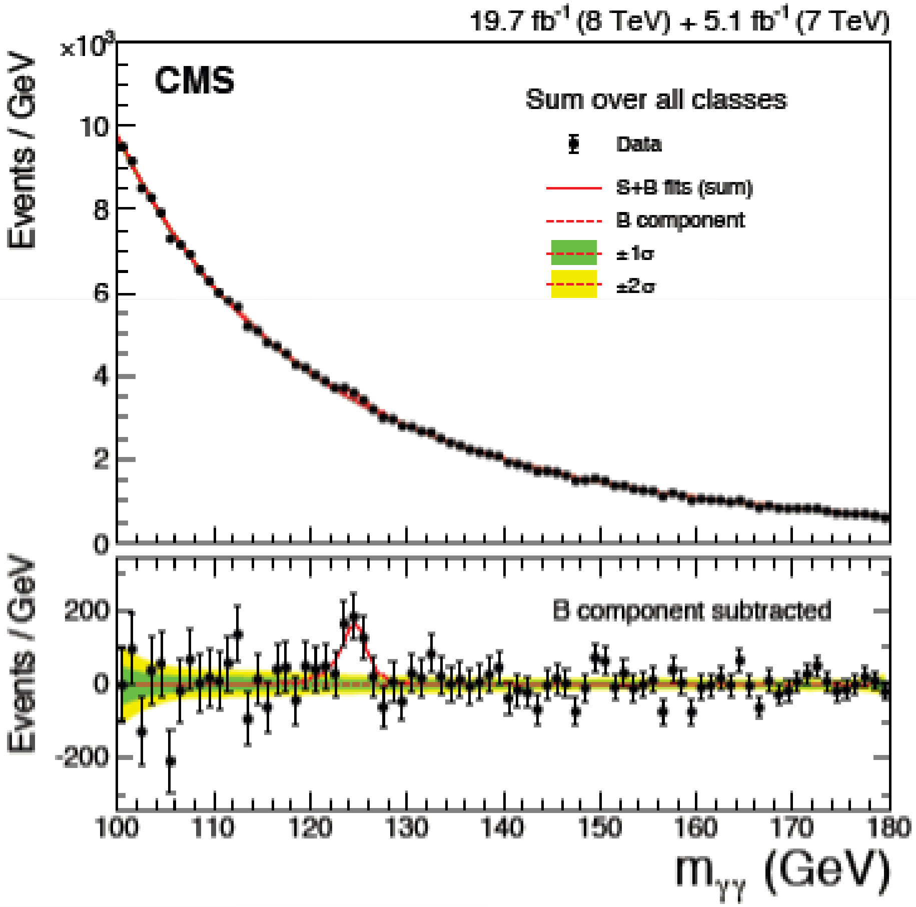
- Low BR ~0.2%
  - With $5.1 fb^{-1}$ at 7 TeV, $19.7 fb^{-1}$ at 8 TeV
  - For SM Higgs at m_H=125 GeV
  - CMS can expect around ½ million Higgs'
  - Of which ~1000 decay into two photons ($\alpha\varepsilon$=0.5)
- Clean final state
- Can reconstruct mass with good precision: $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-cos\alpha)}$

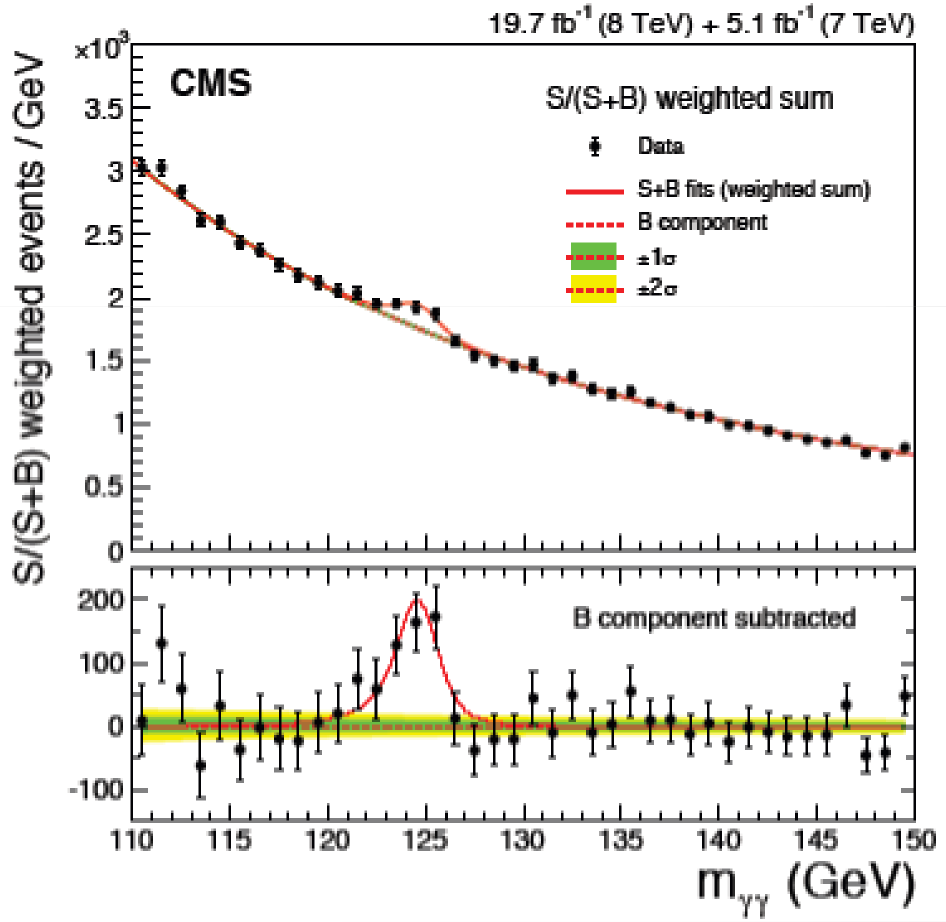
•New –ultimate- calibration of the Electromagnetic Calorimeter,...
•Improved analysis techniques! Unify 7 TeV and 8 TeV analysis

CMS: Higgs → γγ

Inclusive sum of all events chosen

Sum weighted by sensitivity





arXiv:1407.0558

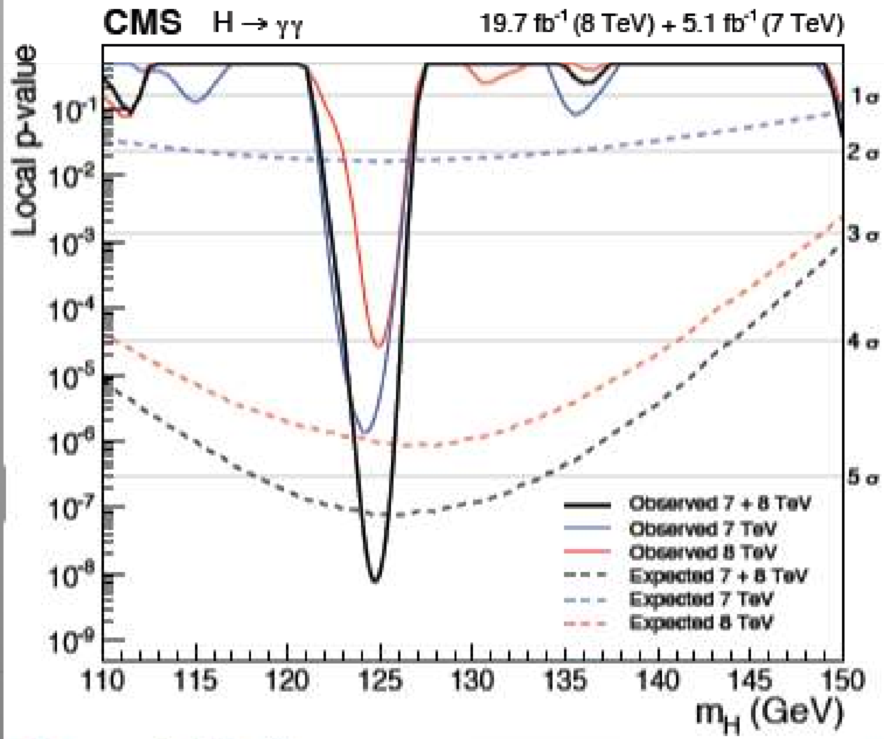
CMS: Higgs → γγ

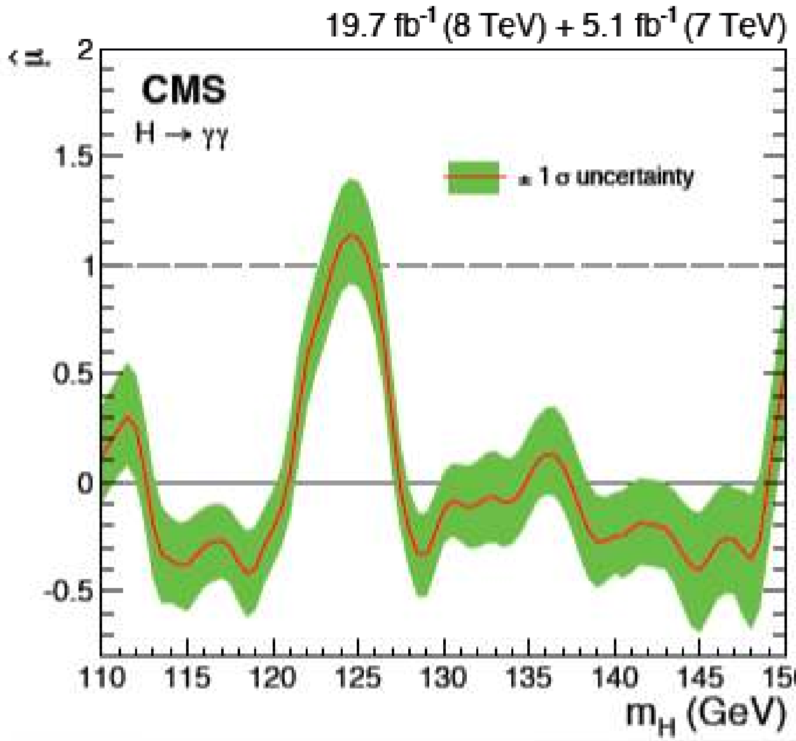
Signal Strength:

arXiv:1407.0558

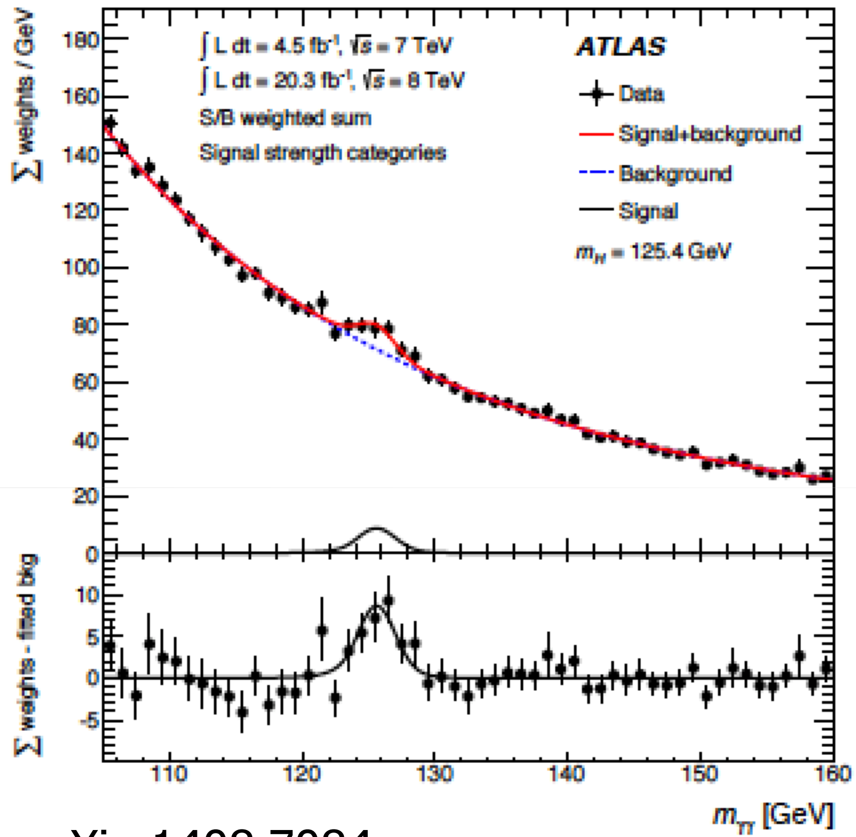
Dataset	Significance (obs)	σ/σ_{SM}	m_H (GeV)
7 TeV	4.7σ	$2.22^{+0.62}_{-0.55}$	124.2
8 TeV	4.0σ	$0.90^{+0.26}_{-0.23}$	124.9
7 + 8 TeV	**5.7σ**	$\mathbf{1.14^{+0.26}_{-0.23}}$	**124.7**

$$\sigma/\sigma_{SM} = 1.14^{+0.26}_{-0.23}\left[{}^{+0.21}_{-0.21}(\text{stat.}){}^{+0.09}_{-0.05}(\text{syst.}){}^{+0.13}_{-0.09}(\text{th.})\right]$$

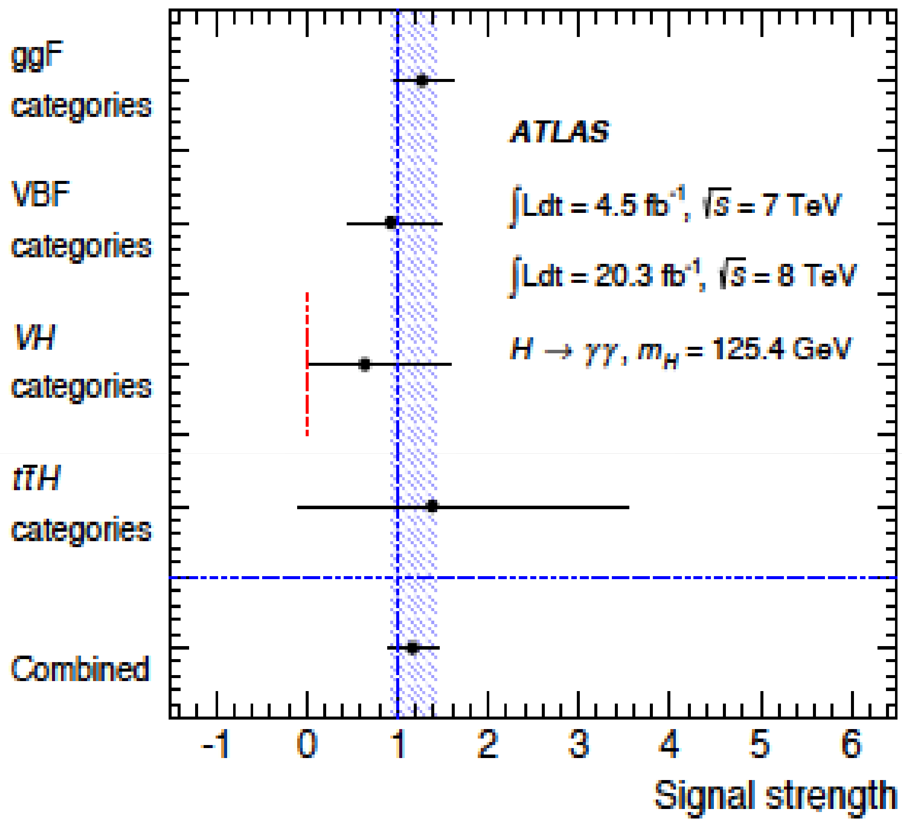




ATLAS: Higgs → γγ



arXiv:1408.7084



$\mu = 1.17 \pm 0.27$

For M_H=125.4 GeV

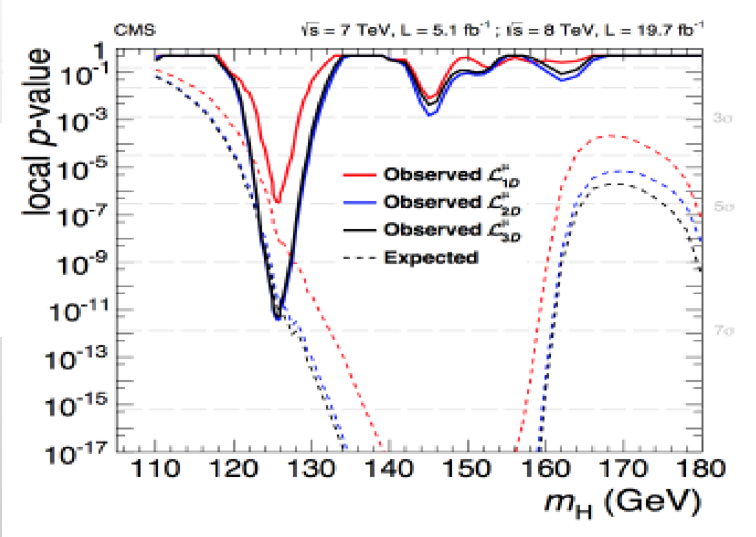
Signal strength $\mu = \dfrac{\sigma_{measured}}{\sigma_{SM}}$

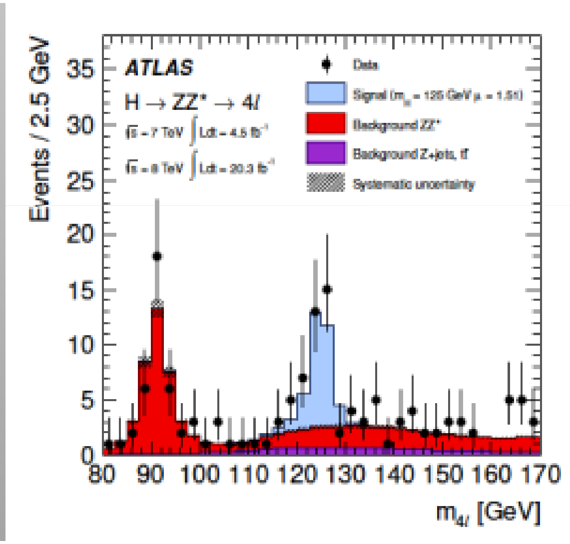
Especially new calibrations for electromagnetic showers…

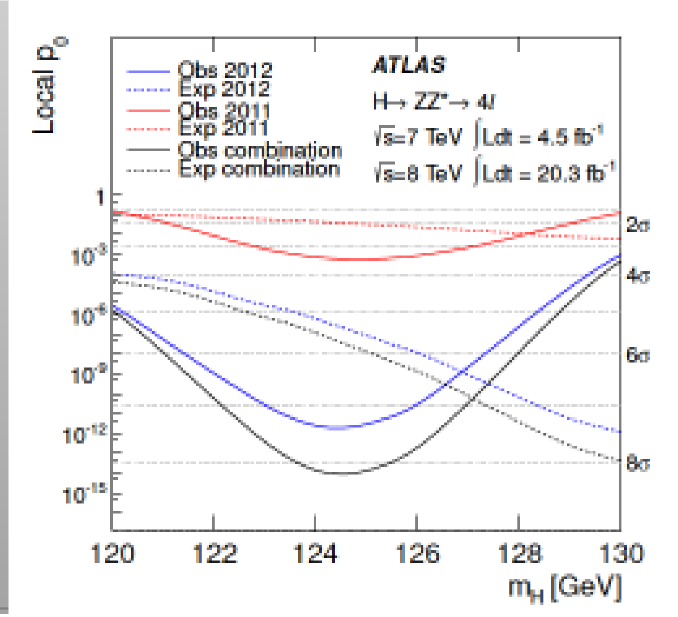
The Decay H → ZZ → 4l

ATLAS: arXiv:1408.5191
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: 6σ Observed: 8.1σ
→ $\mu = 1.44^{+0.40}_{-0.33}$
CMS: Expected: 6.7σ Observed: 6.8σ
→ $\mu = 0.93^{+0.29}_{-0.24}$

Significance is well over 6 standard deviations in this channel

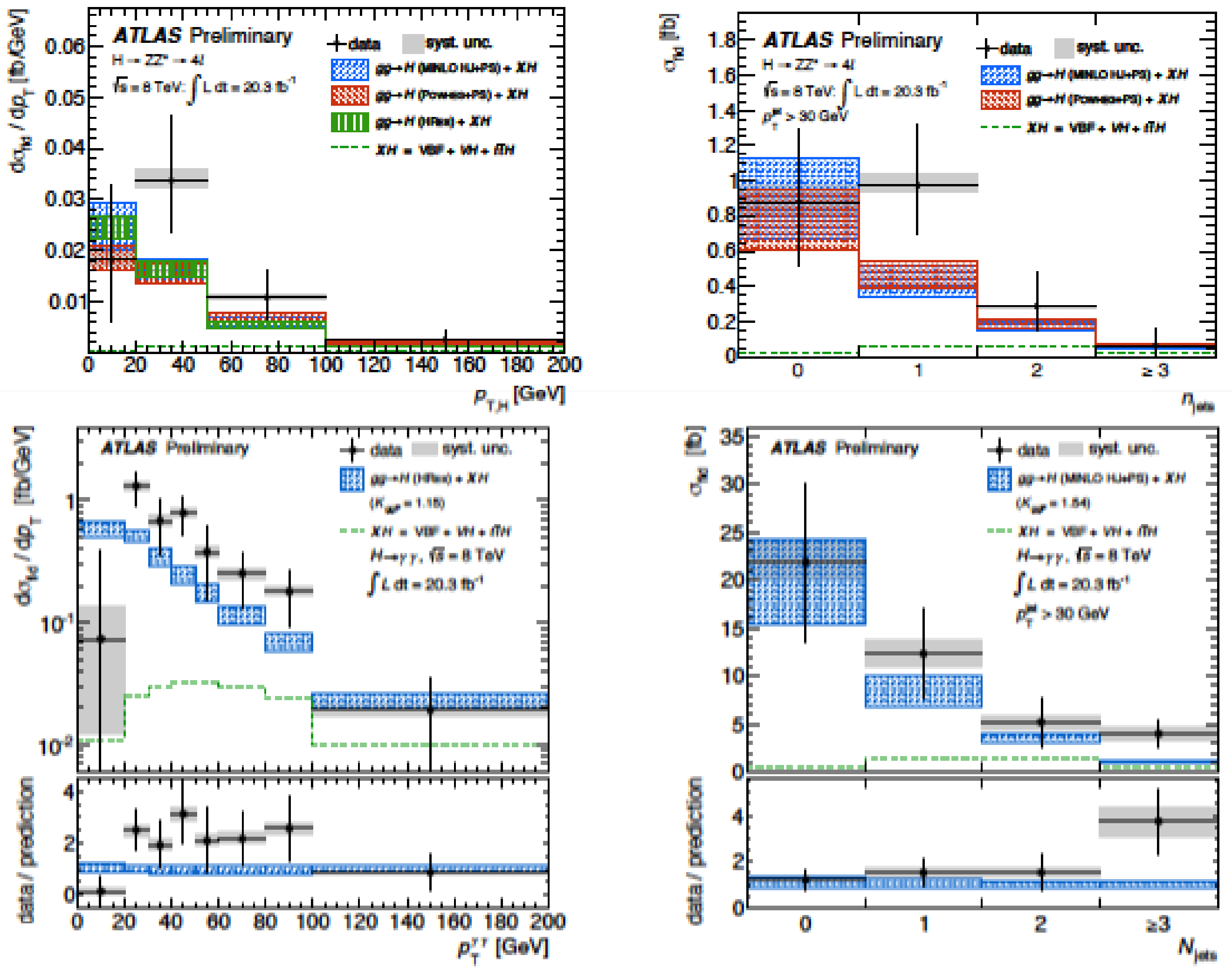
ATLAS: Higgs → ZZ and γγ

Differential distributions (& fiducial cross sections)

H→ ZZ

arXiv:1408.3226
arXiv:1407.4222

H→ γγ

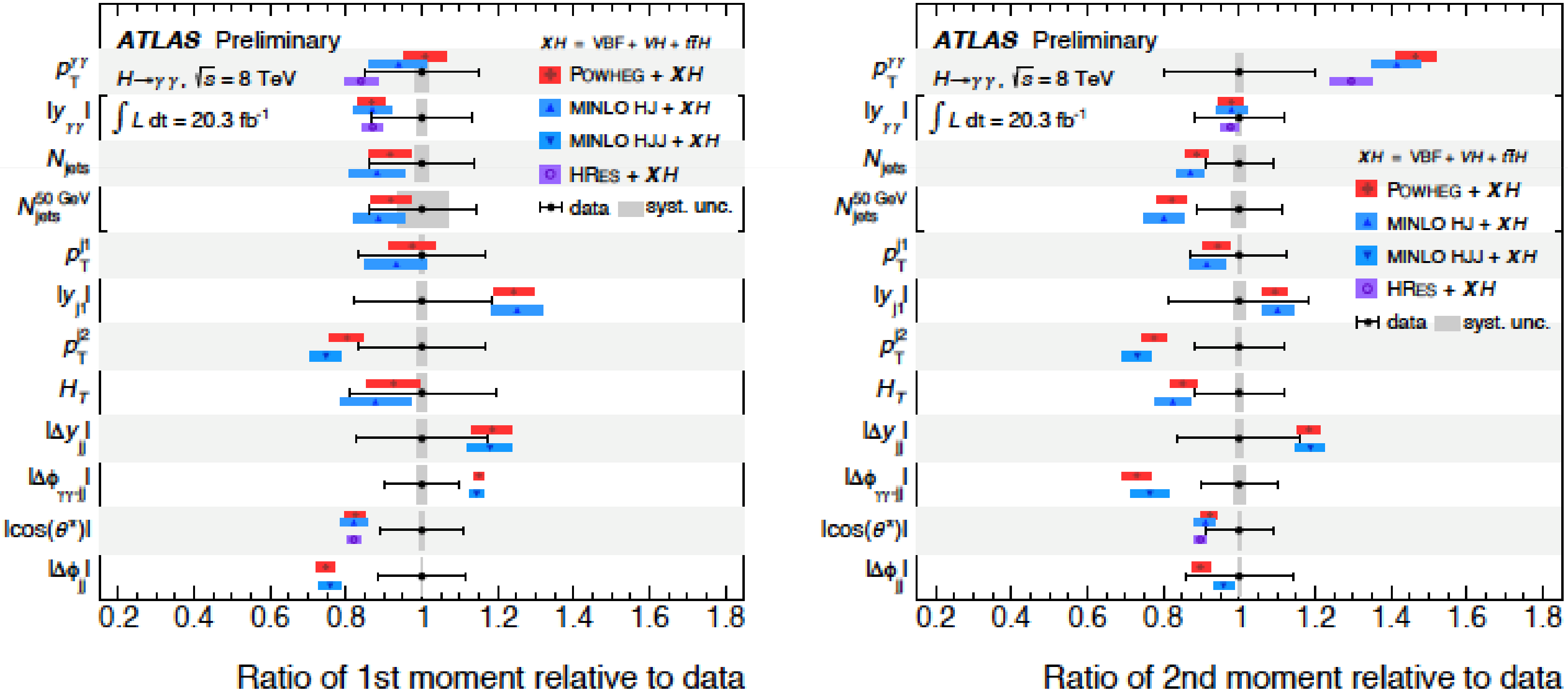


Still limited sensitivity
but shows the potential

ATLAS: Higgs → ZZ and γγ

- Large number of observable tested
- Summary in terms of:
  - 1st moment of the distributions (Mean)
  - 2nd moment of the distributions (RMS)

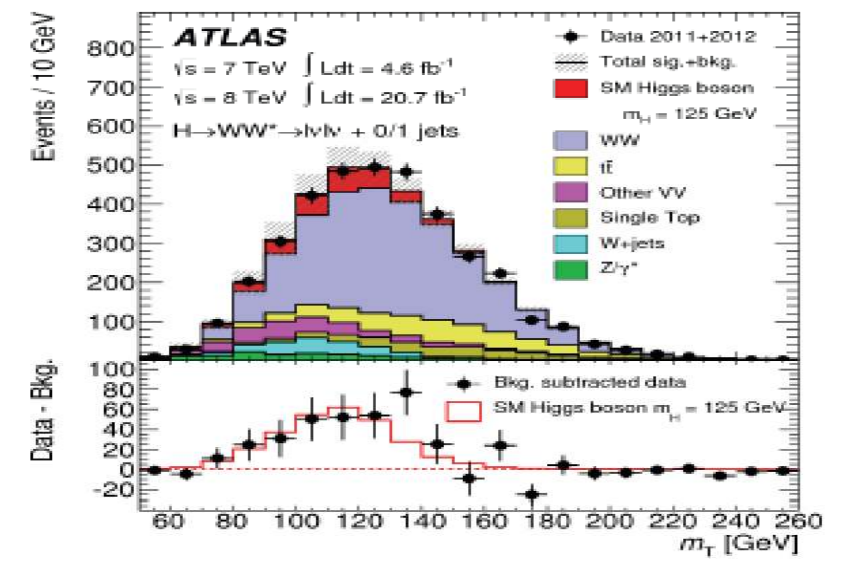
$$H \rightarrow \gamma\gamma$$

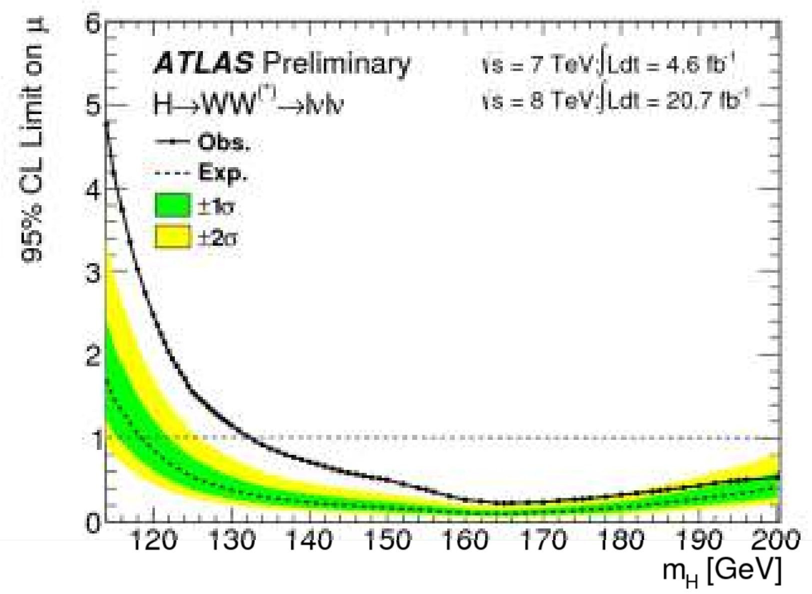


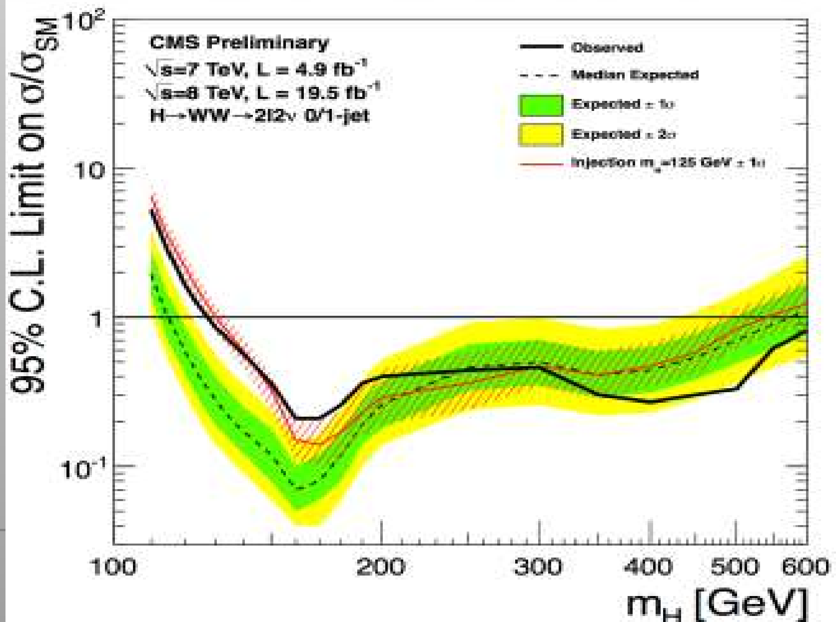
The Decay → WW → 2l 2ν

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





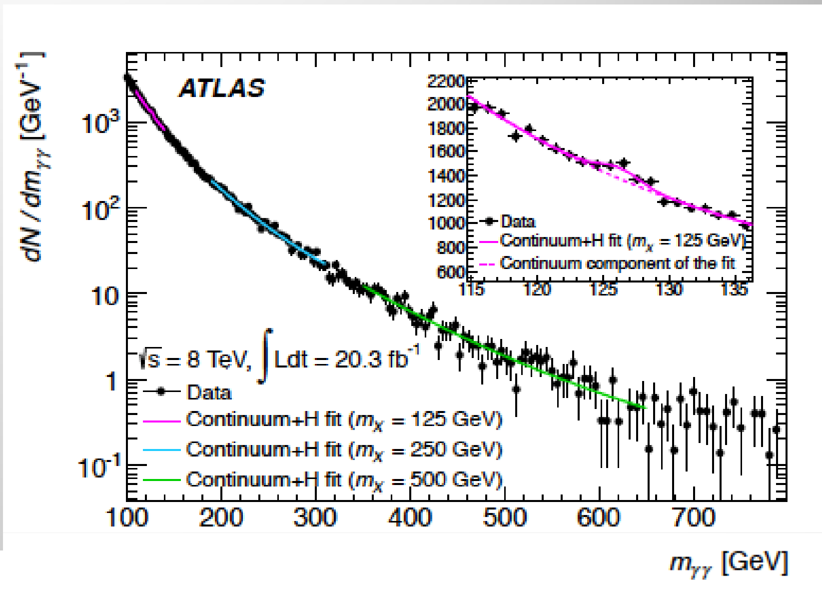


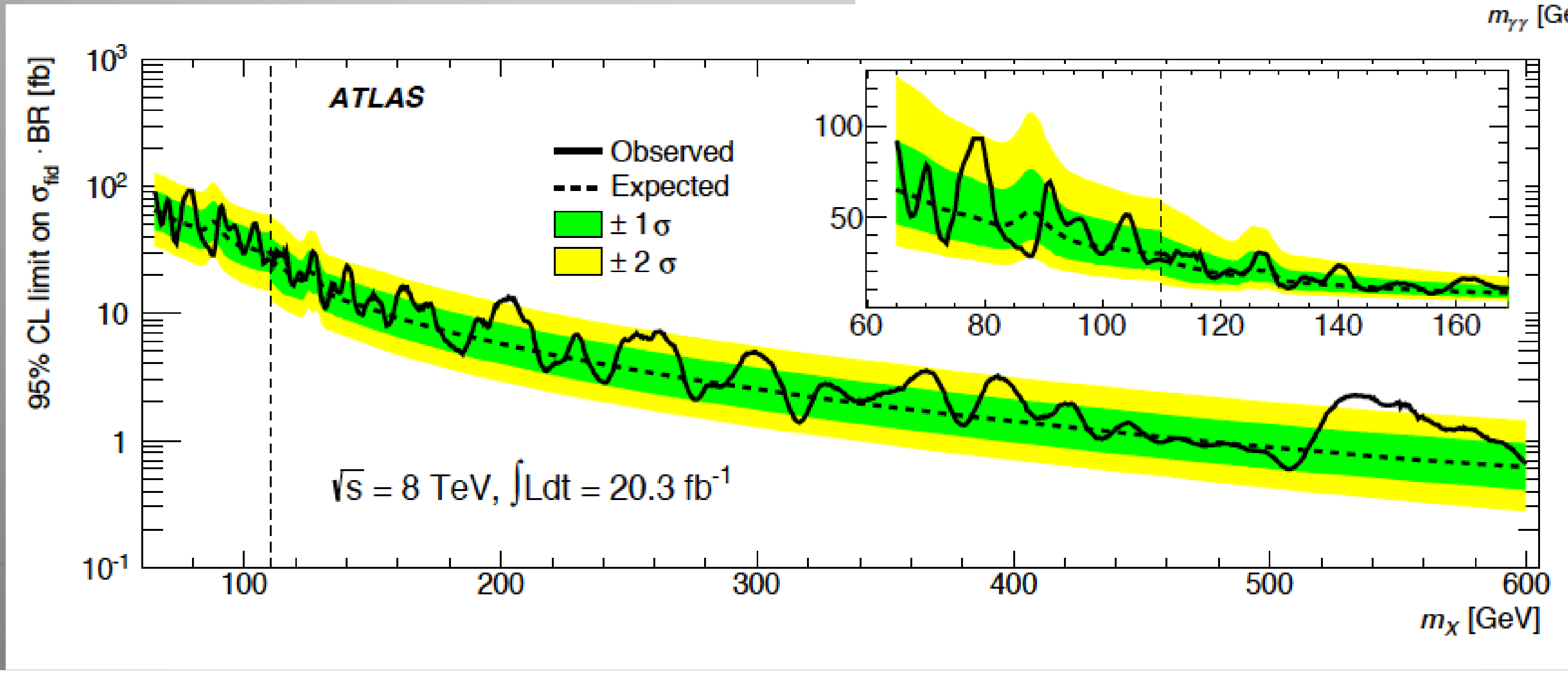
ATLAS @125 GeV: Expected: 3.8σ Obs: 3.8σ
→ $\mu = 0.99^{+0.31}_{-0.28}$
CMS @ 125 GeV: Expected: 5.8σ Obs: 4.3σ
→ $\mu = 0.72^{+0.20}_{-0.18}$

High Mass Search: Higgs → γγ

arXiv:1407.6583

No (additional) excess found in the region from 65 to 600 GeV





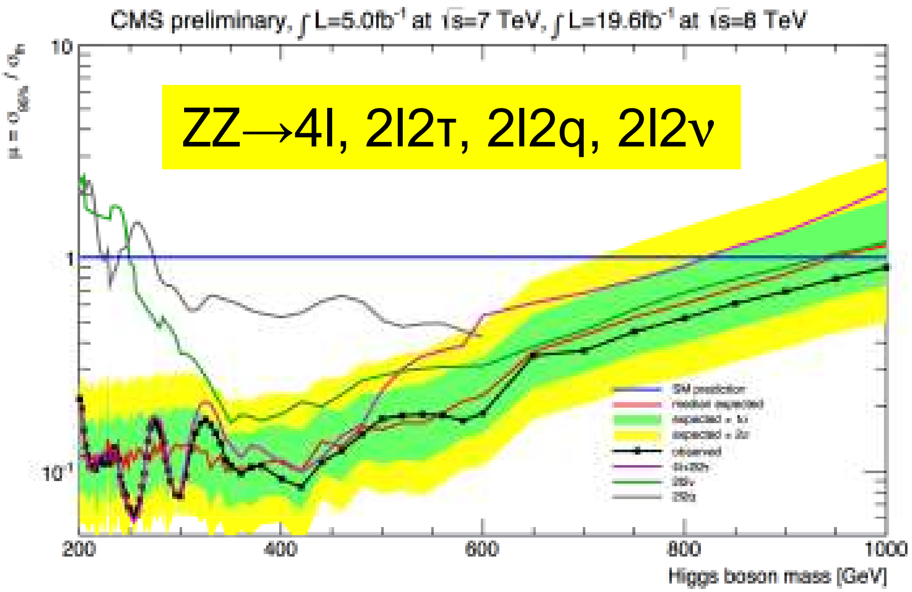
High Mass Search: Higgs → ZZ,WW

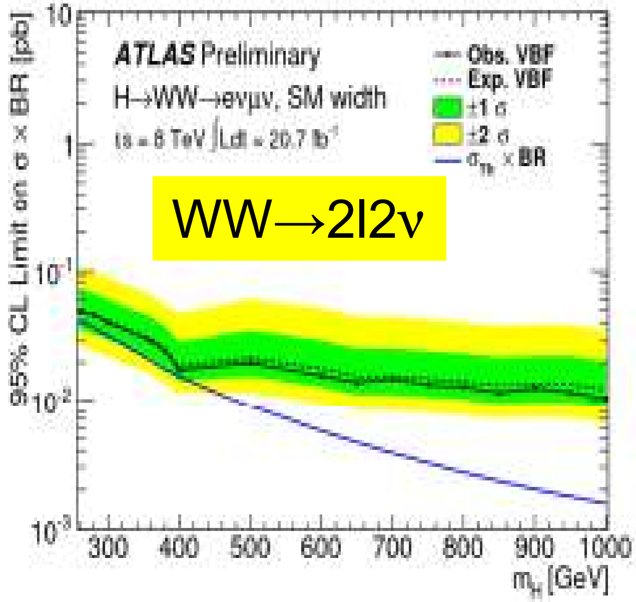
High mass Higgs searches with SM channels WW, ZZ updated with 2012 statistics

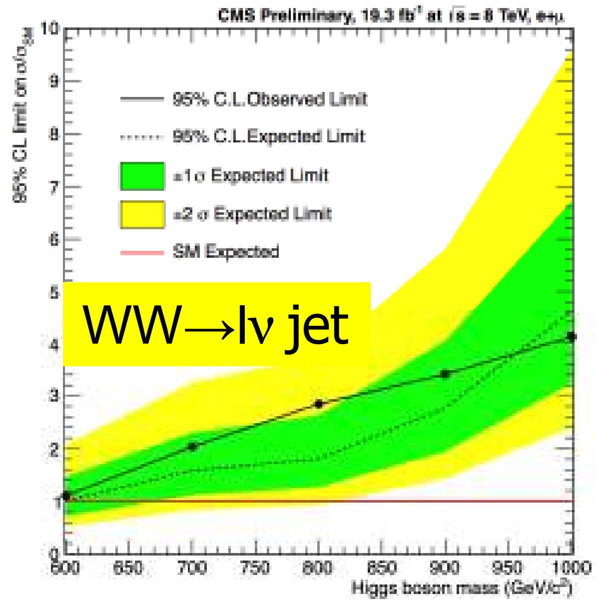
Sensitivity reaches now up to ~ 1 TeV

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

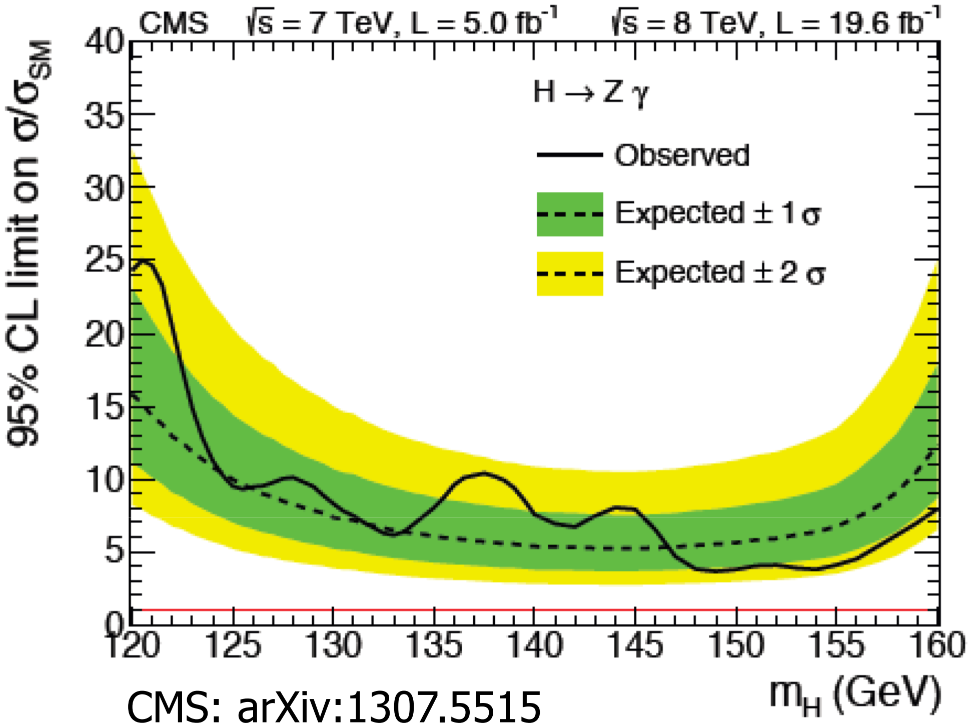
CMS-PAS-13-008
CMS-PAS-13-014
CMS-PAS-12-024
ATLAS-CONF-2013-067



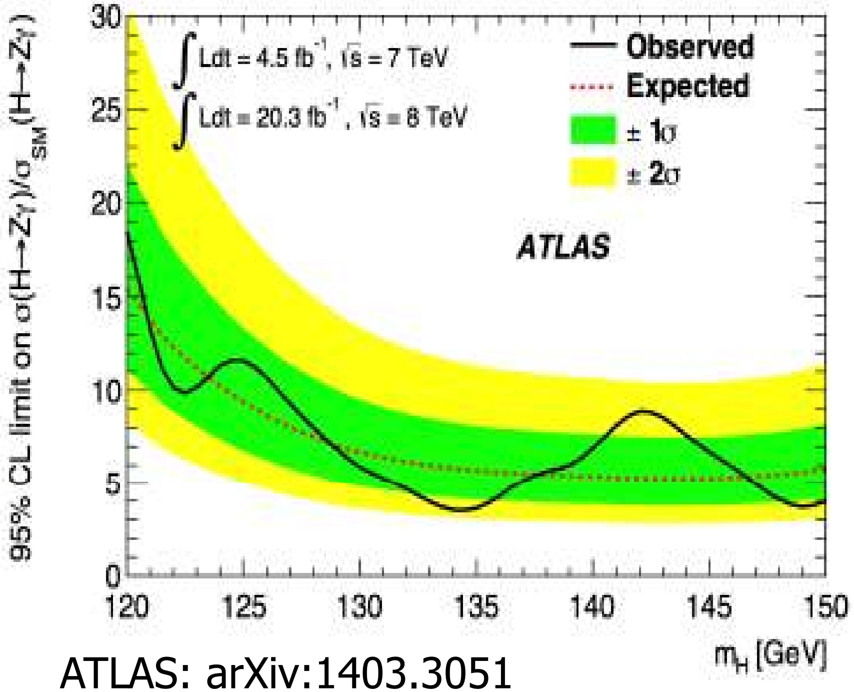




The Decay $H \to Z\gamma$



CMS: arXiv:1307.5515



ATLAS: arXiv:1403.3051

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

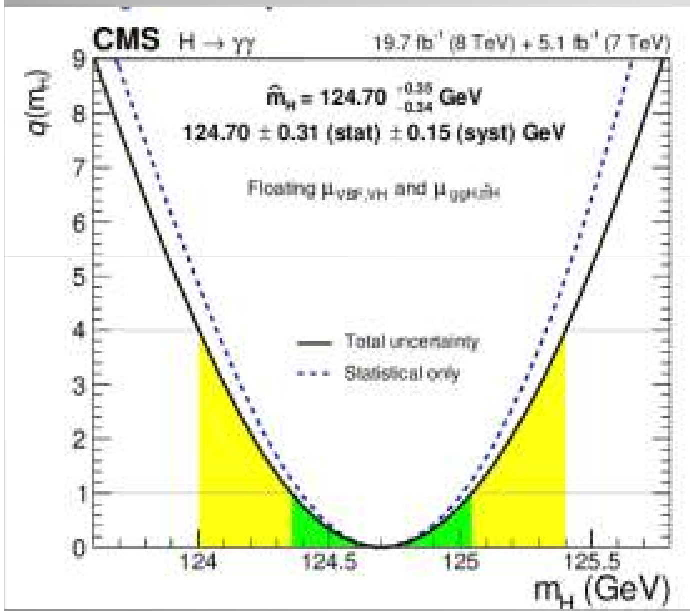
In certain models this channel could be largely enhanced via loops

The Mass of the New Particle

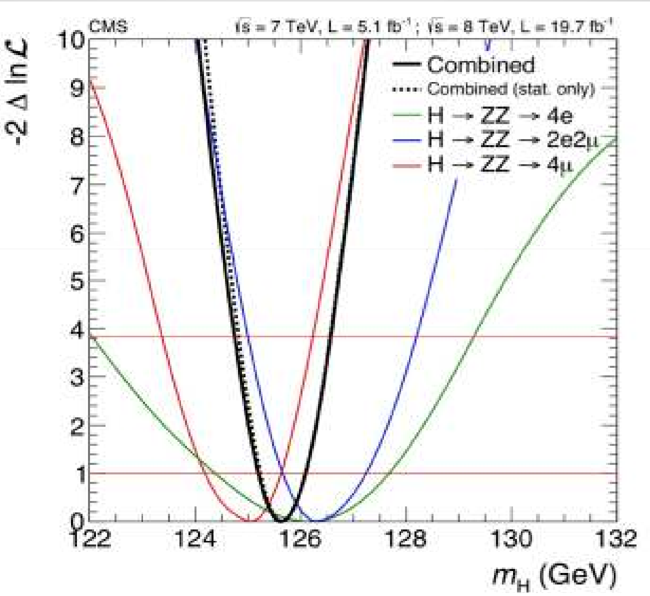
Determine the mass from ZZ and 2-photon channels which show a peak!

New calibration & strong effort on systematics

CMS



$m_H = 124.70 \pm 0.31\,(stat) \pm 0.15\,(syst)\,GeV$



$m_H = 125.6 \pm 0.4\,(stat) \pm 0.2\,(syst)\,GeV$

Two-photon and two Z channel mass estimates agree (within 1.6σ)

Mass value is about 125.0 GeV with 0.3 GeV uncertainty

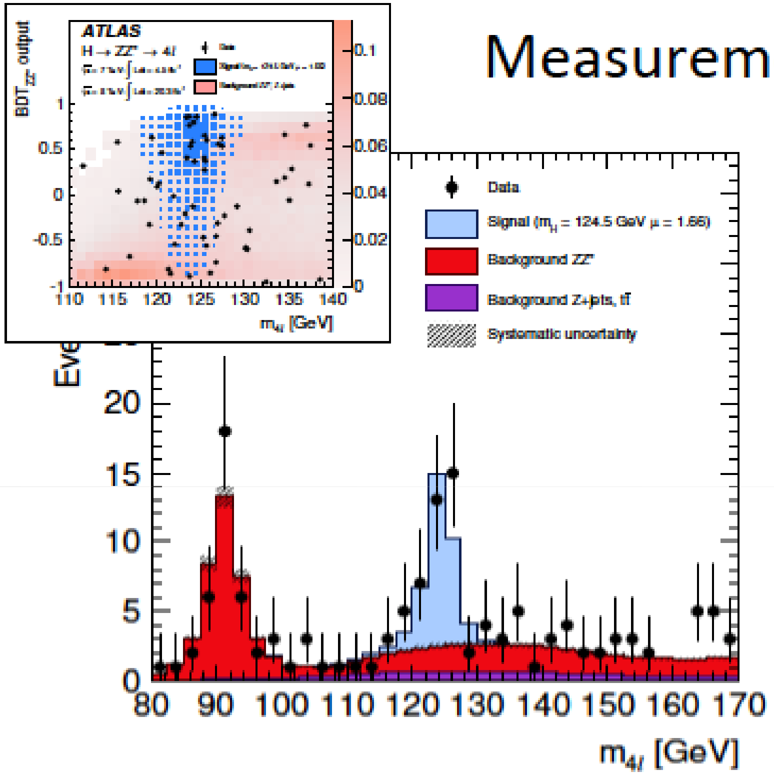
$$m_H = 125.03\,^{+0.26}_{-0.27}\,(stat)\,^{+0.13}_{-0.15}\,(syst) = 125.03\,^{+0.29}_{-0.31}\,(tot)\,GeV$$

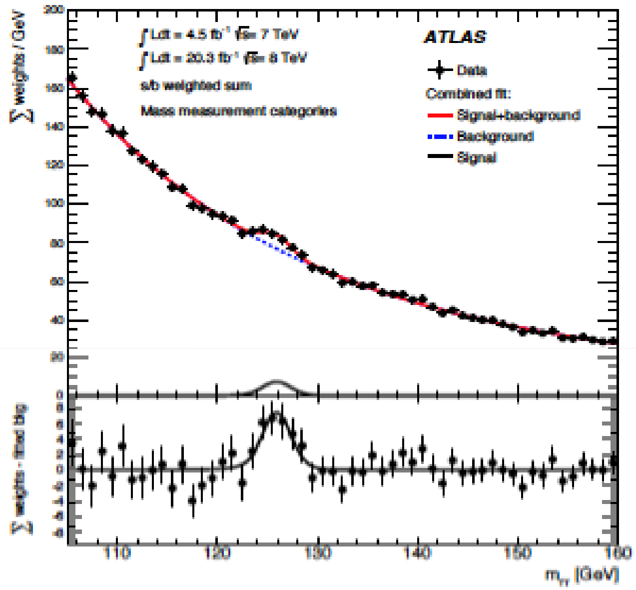
Old value: 125.5 GeV

ATLAS: Higgs Mass

Measurement of the Higgs boson mass

Use of BDT ZZ





Old

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

$$124.51\ \pm 0.37\ \text{(stat)}\ \pm 0.06\ \text{(syst)}\ \text{GeV}$$

- Analyses improvements
  - Categories for mass in the diphoton
  - BDT-ZZ, far FSR corrections

Old

$$126.8\ \pm 0.2\ \text{(stat)}\ \pm 0.7\ \text{(syst)}\ \text{GeV}$$

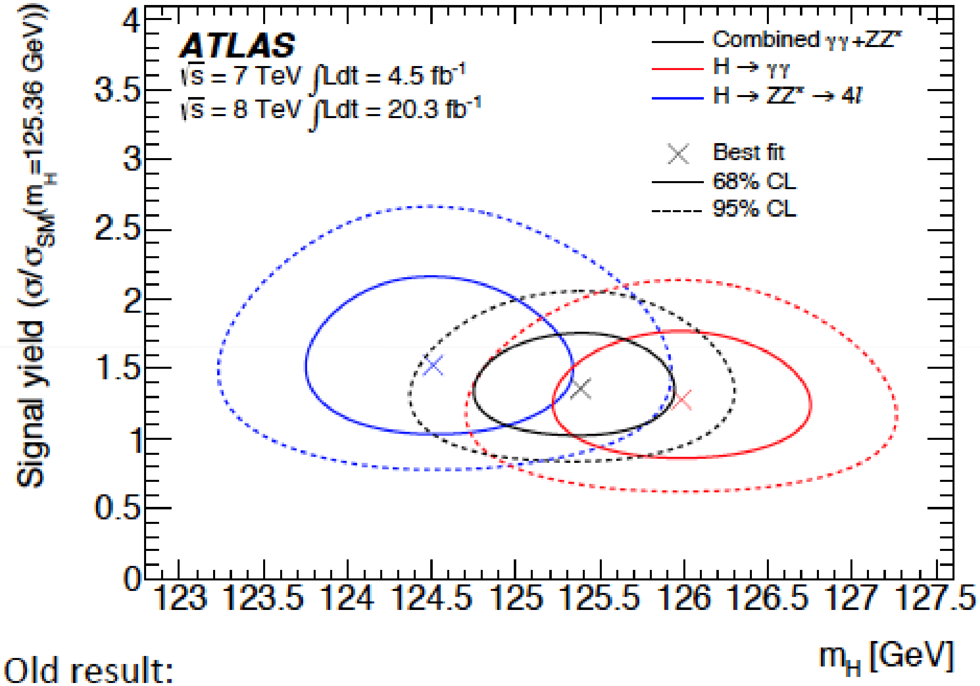
Expected mass shift -450 +/- 350 MeV

$$125.98\ \pm 0.42\ \text{(stat)}\ \pm 0.28\ \text{(syst)}\ \text{GeV}$$

- Large improvement on systematics
- Increase in stat uncertainty in diphoton:
  - Lower signal rate
  - Fluctuation of the error (exp. 0.35 GeV)

ATLAS: Higgs Mass

Measurement of the Higgs boson mass
(and signal strengths)



Note measure channels signal strength

$$\mu^{\gamma\gamma}_{(m_H=125.98\,GeV)} = 1.29 \pm 0.30$$

$$\mu^{ZZ}_{(m_H=124.51\,GeV)} = 1.66\,^{+0.45}_{-0.38}$$

Old result:

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

New:

$$\boxed{125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})\ \text{GeV}}$$

0.3% Precision measurement (statistical uncertainty dominant)

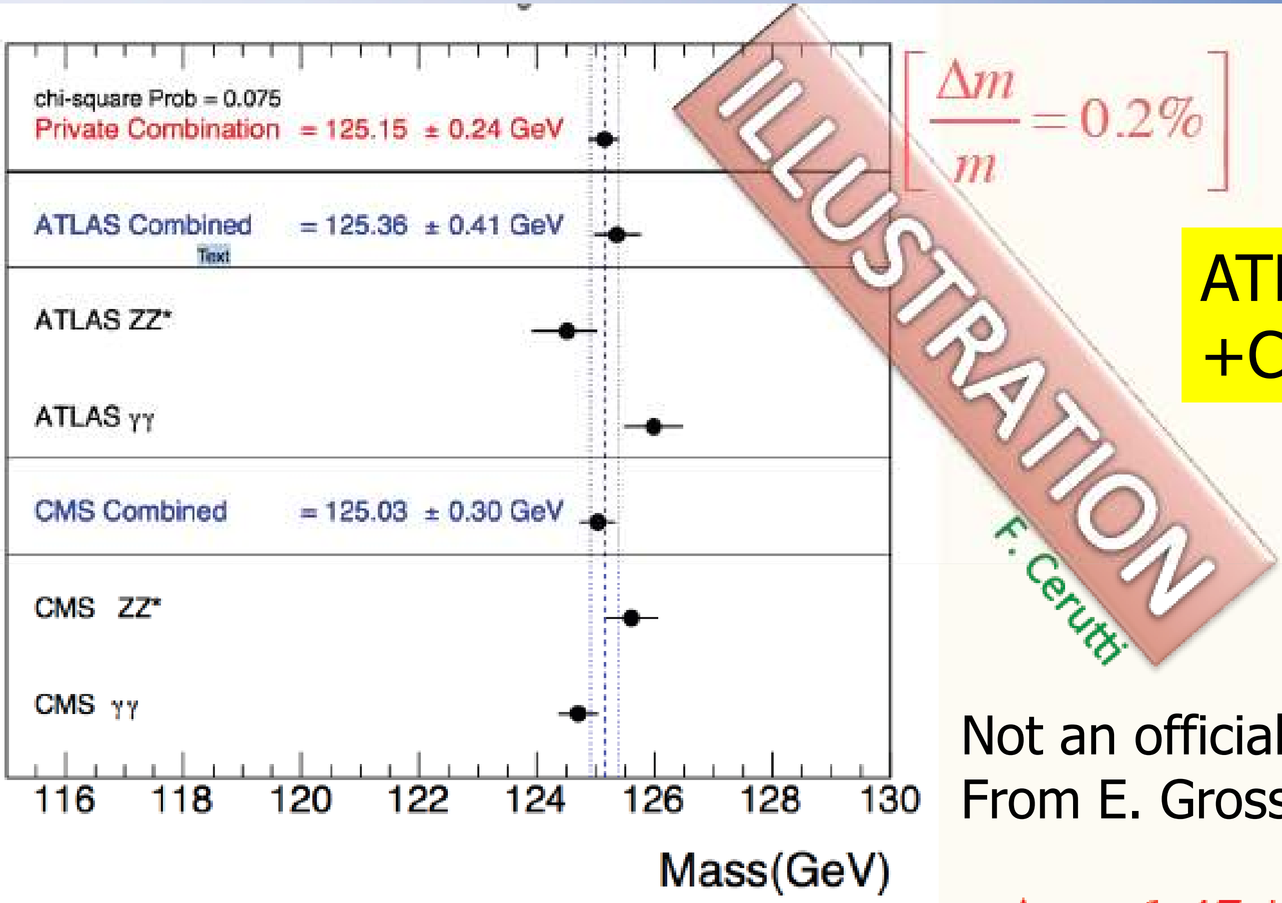
ZZ and γγ compatibity

Old $\begin{cases} \Delta m = 2.3 \pm 0.9 \\ \text{Compatibility } 2.4\sigma \end{cases}$

$$\Delta m = 1.47 \pm 0.72$$

Compatibility 1.97σ

Higgs Mass (not official!!)



$$\left[\frac{\Delta m}{m} = 0.2\%\right]$$

ATLAS +CMS

Not an official result!
From E. Gross (7/14)

ATLAS

$$m_H = 125.36 \ \pm 0.37 \text{ (stat) } \pm 0.18 \text{ (syst) GeV}$$

$$\Delta m = 1.47 \pm 0.72$$

Compatibility 1.97σ

CMS

$$m_H = 125.03 \ ^{+0.26}_{-0.27} \text{ (stat) } ^{+0.13}_{-0.15} \text{ (syst) GeV}$$

$$\Delta m = -0.87^{+0.54}_{-0.59}$$

Compatibility 1.6σ

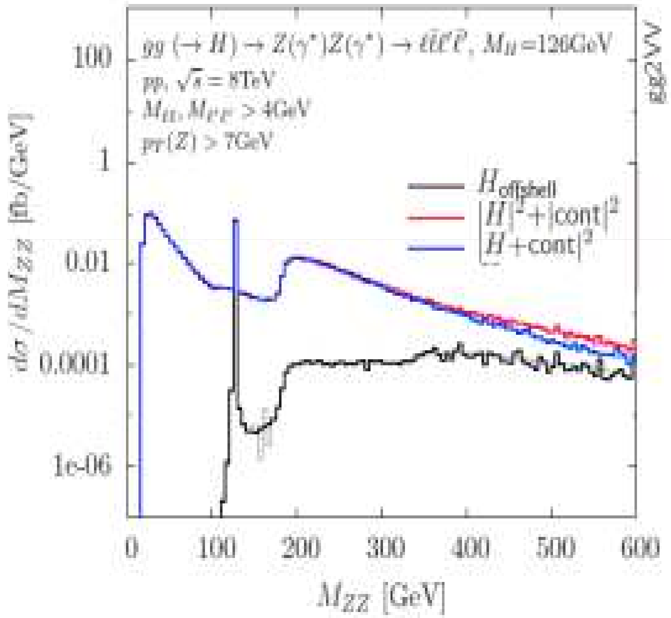
The Total Width of the Higgs

Recent History

arXiv:1405.3455

Direct width limits so far 3.4 GeV in ZZ and 6.9 GeV in two-photon decays (95% CL) from the resonance peak measurement
→Dominated by experimental resolution

- Until recently it seemed unlikely the LHC could measure the total Higgs width (~4.2 MeV in SM)
- In 2012 it was noted that 7.6% of the Higgs to ZZ cross section is above 180 GeV arXiv:1206.4803
- The off-shell contribution is independent of the total width!
- The ratio of on-shell to off-shell can thus provide information on the width
- Interference of the signal with ZZ continuum is important and must be taken into account



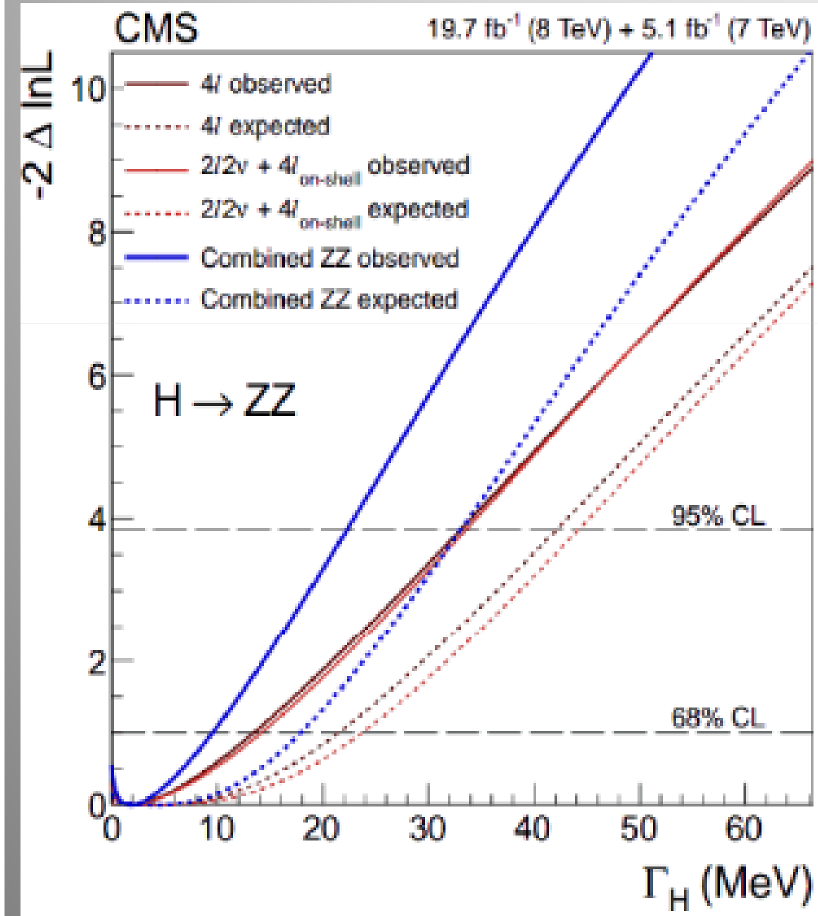
2012/13: Kauer, Passarino; Caola, Melnikov; Campbell, Ellis, Williams …

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

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

The Total Width of the Higgs

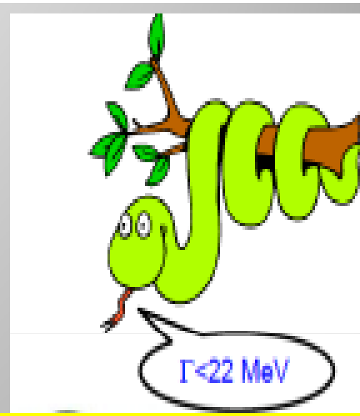
- Study Higgs → ZZ in the 4 charged lepton and 2 charged lepton + 2ν decay
- Determine the total Higgs width in the two channels separately
- Use a kinematic discriminant and m_T distributions to reduce ZZ continuum



- **Reminder : SM predicts :**
  - $\Gamma_H = 4.2$MeV
- **95% C.L. Limits on Γ_H :**
  - Expected : 33MeV
  - Observed : 22MeV

$= 5.4 \bullet \Gamma^{SM}$

- **Combination** improves the individual limits by ~20%
- Compatibility between the observed results and the SM hypothesis lead to a **p-value of 0.24**



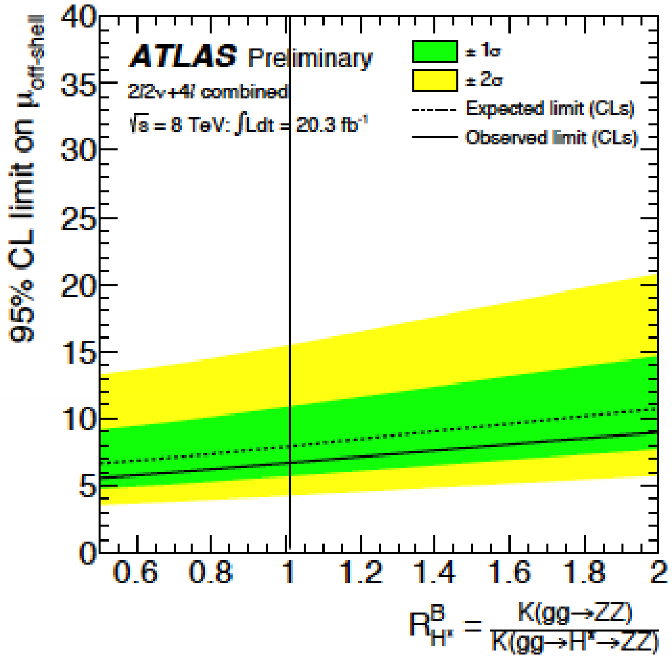
ICHEP: ATLAS!
ATLAS-CONF-2014-042

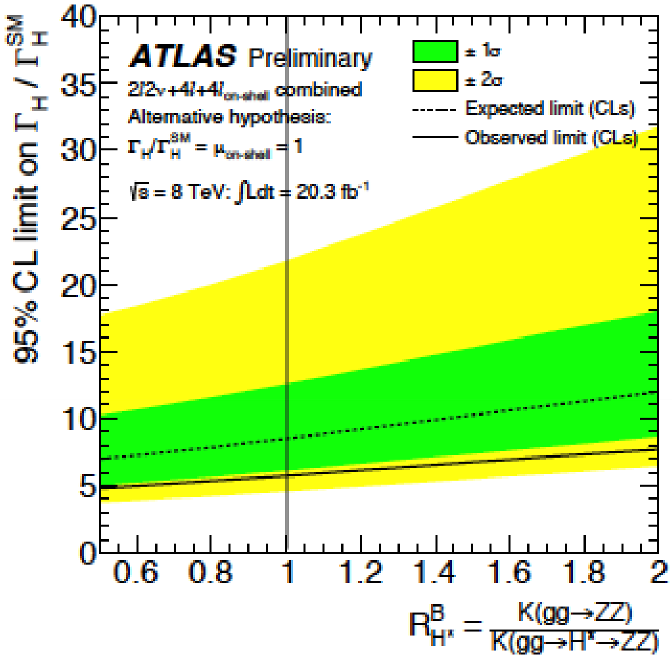
Γ_H/Γ_{SM}	Observed	Expected μ =1
R_H^B=0.5	4.8	7.0
R_H^B=1	5.7	8.5
R_H^B=2	7.7	12.0

Issue with the Theory??

The Total Width of the Higgs

CLs limits on Off-Shell signal strength





Agnostic to k-factor!

R=1 (Verified in the soft colinear approximation)
(G. Passarino)

95% CL limit obs. (exp.)
$\mu_{OffShell} < 6.7$ (7.9)

...and on the total width

$$\mu_{OnShell} \equiv \frac{\kappa_t^2 \kappa_V^2}{\Gamma_H / \Gamma_H^{SM}}$$

Assuming $\mu_{OffShell} = \mu_{OnShell}$

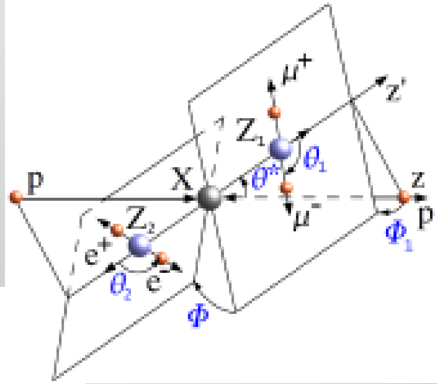
95% CL limit obs. (exp.)
$\Gamma_H / \Gamma_H^{SM} < 5.7$ (8.5)

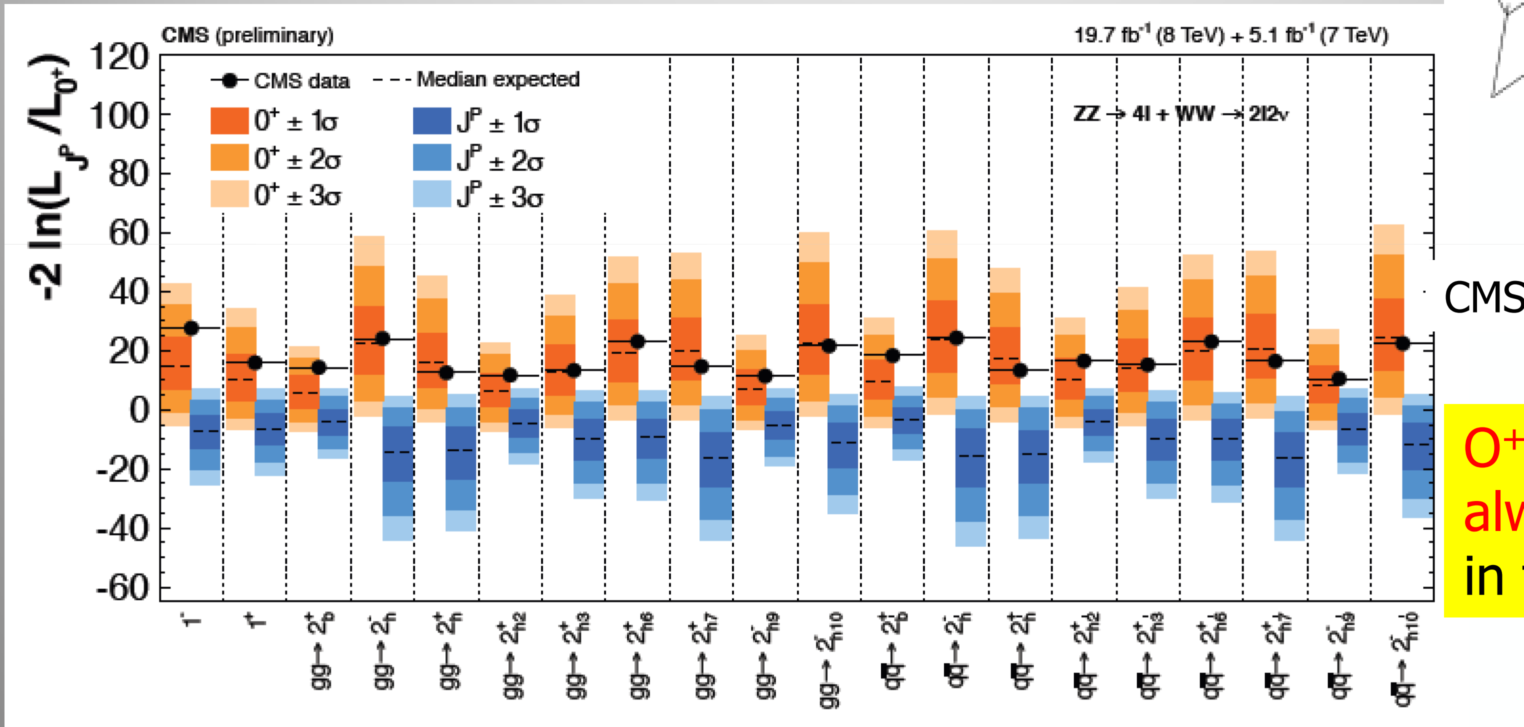
ATLAS-CONF-2014-042

Spin/Parity Studies

Combined study of H→ZZ and H→WW

- Tested using all diboson channels
- Hypotheses comparison O⁺/other states





CMS-PAS-HIG-14-014

O⁺ hypothesis is always favoured in the comparison

All "exotic" scenarios excluded scenarios excluded with 99.9% CL

Also CP studies of J=0 state → Results consistent with SM

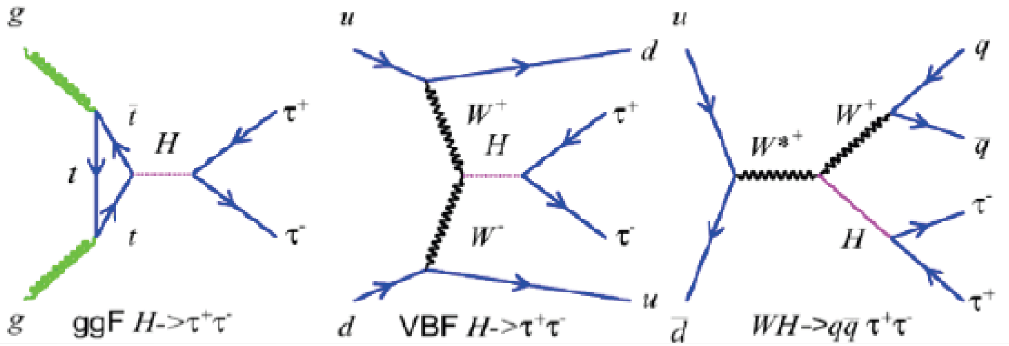
Higgs Decaying into Fermions

The Decay Higgs → tau tau

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

Analysis Overview

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



- $H \to \tau\tau \to \mu\mu$ $(\tau_\mu \tau_\mu)$,
- $H \to \tau\tau \to e\mu$ $(\tau_e \tau_\mu)$,
- $H \to \tau\tau \to \mu$+had. $(\tau_\mu \tau_h)$,
- $H \to \tau\tau \to e$+had. $(\tau_e \tau_h)$,
- $H \to \tau\tau \to$ had.+had. $(\tau_h \tau_h)$.

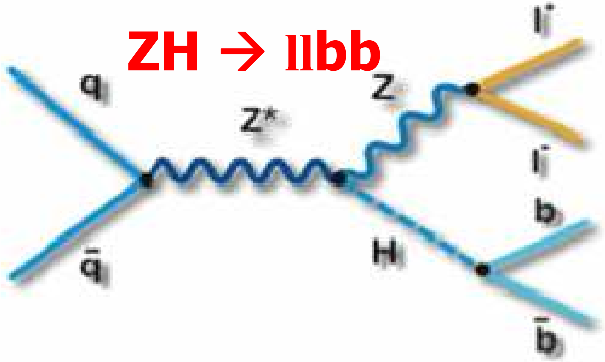
- Separation in categories to enhance S/B (CMS example):

		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 $p_T(\tau_h)$			

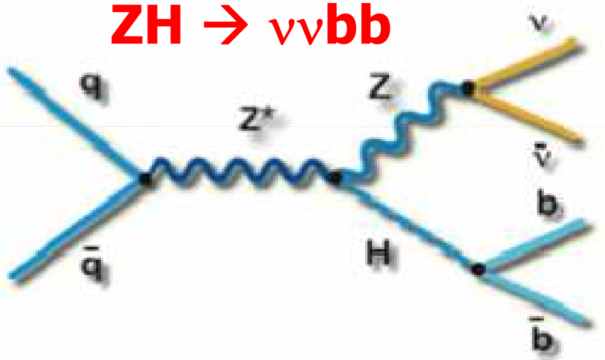
Use special reconstruction techniques to improve the Higgs mass resolution

The Decay Higgs→bb

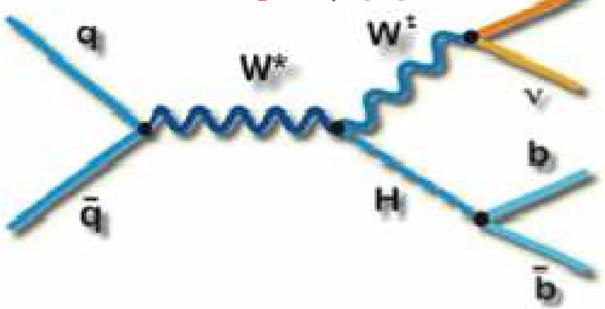
ZH → llbb



ZH → ννbb



WH → lνbb

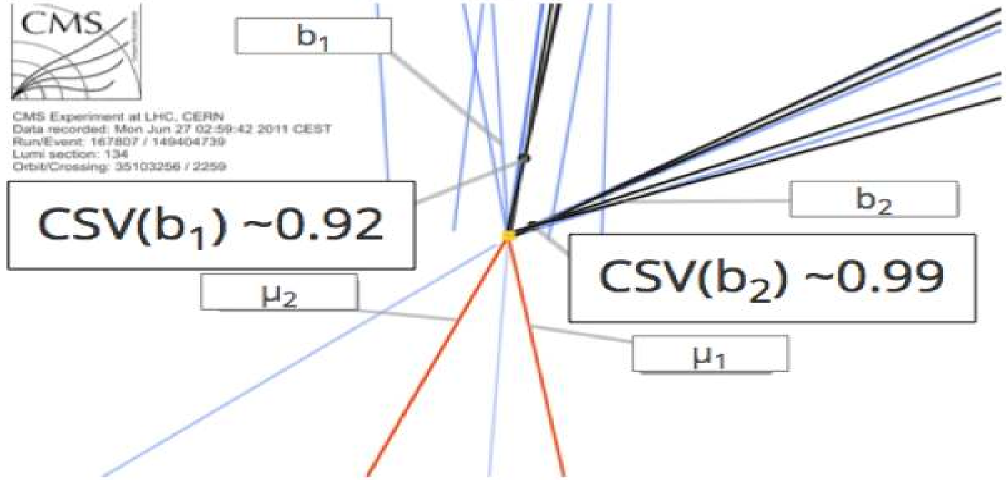


Analysis

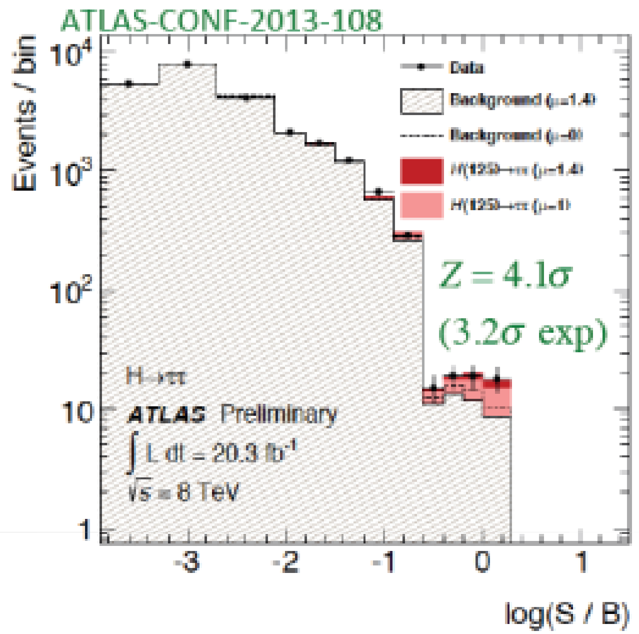
CMS:arXiv:1310.3687
ATLAS-CONF-2013-79

- 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

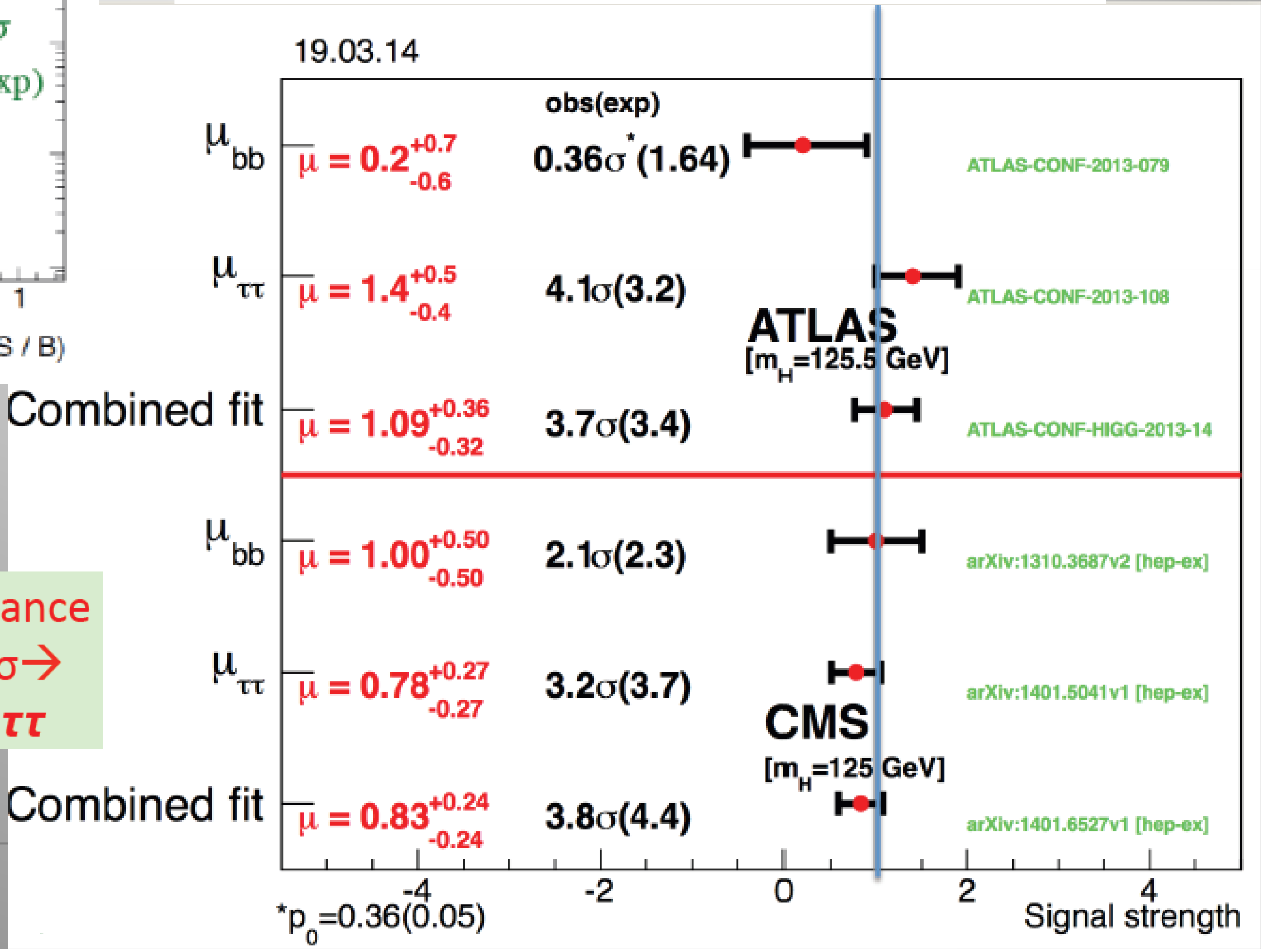


Higgs Decaying to Fermions



Higgs → tau tau and Higgs → bb

- No narrow mass peak:
- Escaping neutrinos (taus) and jets (b)
- Large backgrounds



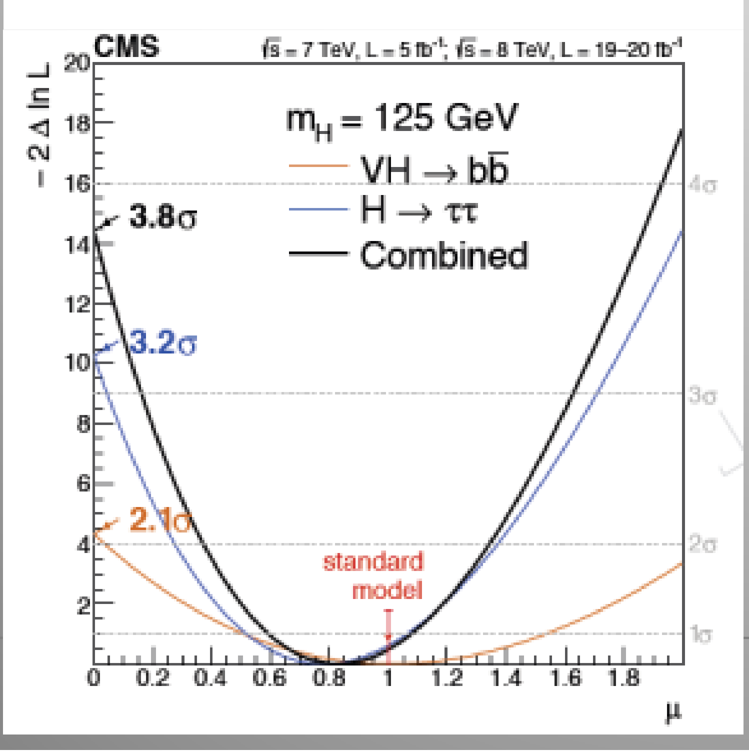
When combined the significance observation goes beyond 5σ→ ATLAS+CMS discovered H→***ττ***

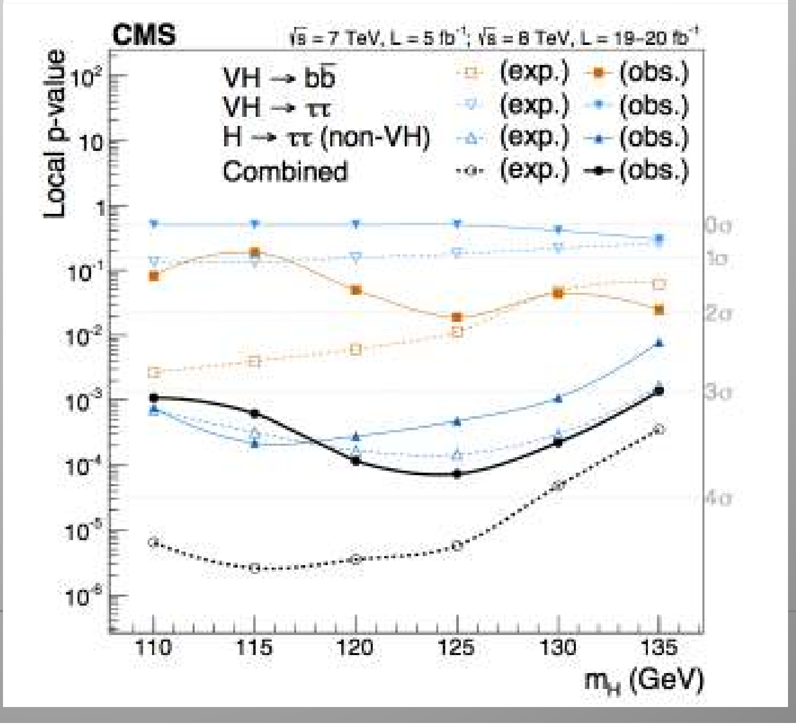
Higgs → Fermions Combination

- The combined H(ττ) 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

arXiv:1401.6527 and
Nature Physics 10 (2014)

Channel ($m_H = 125$ GeV)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
$VH \to b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24





Higgs → μμ (ee)

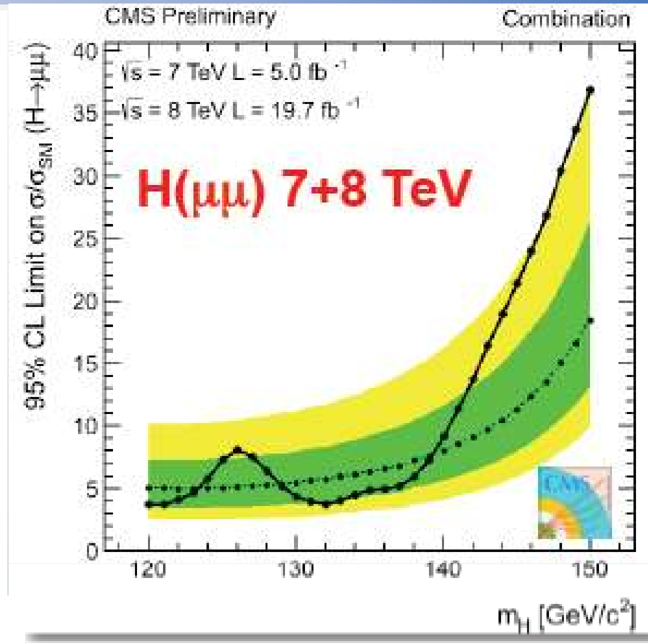
- Observing H(μμ) decay may be the only way to show the non-flavor universal couplings

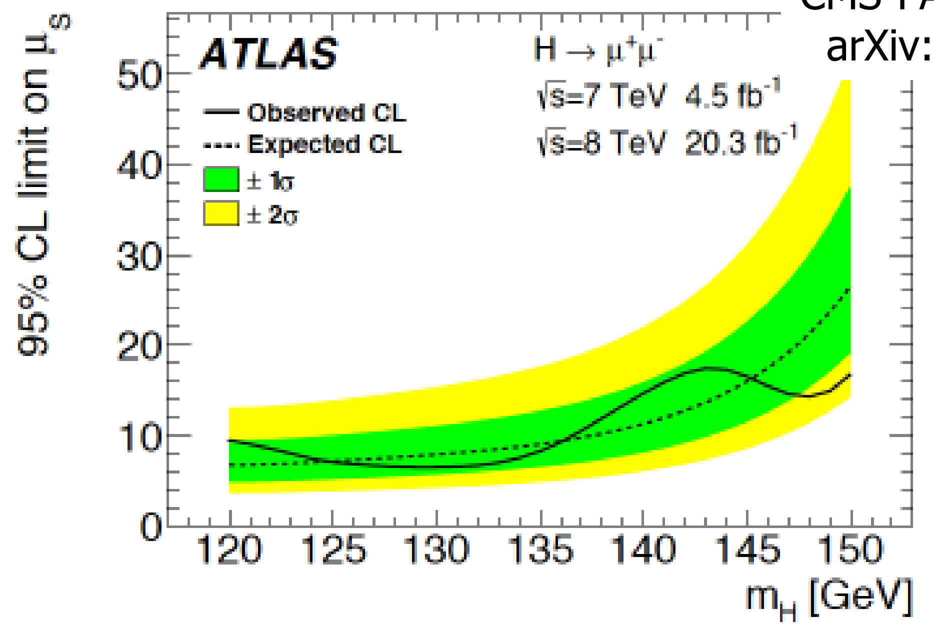
  The coupling to charm will be hard to probe
- Requires very large statistics for an observation: a strong case for the High Luminosity-LHC: HE-LHC
- First searches have been already done

  ATLAS: $\mu < 7.0$ (7.2 expected) @ 95% CL

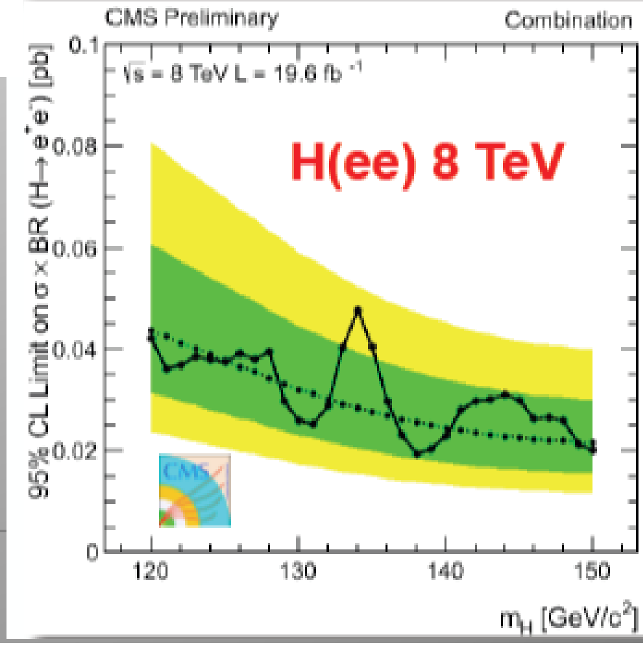
  CMS: $\mu < 7.4$ (5.1 expected) @ 95% CL

  $BR(H \rightarrow ee) < 1.7 \times 10^{-3}$ @ 95% CL



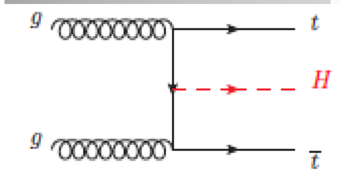


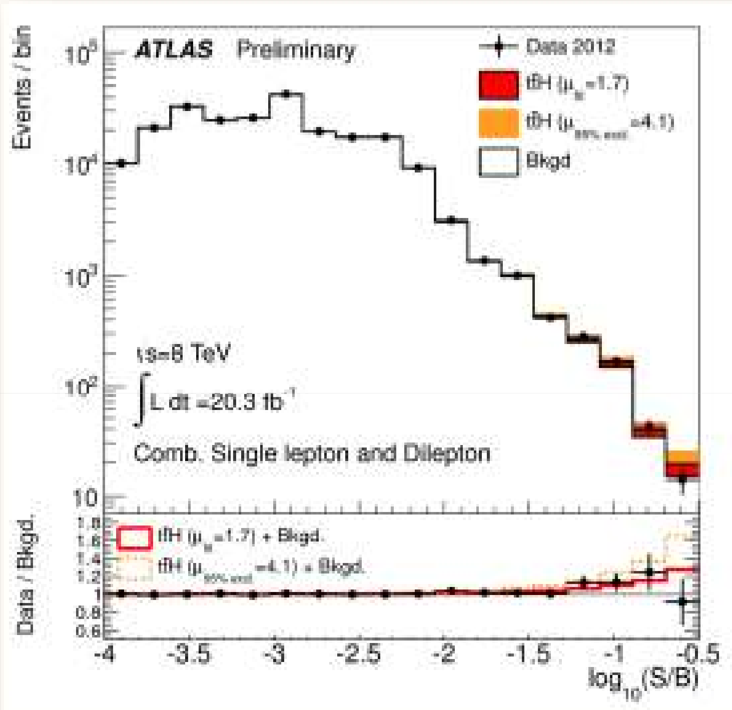
CMS-PAS-HIG-13-007
arXiv:1406.7663

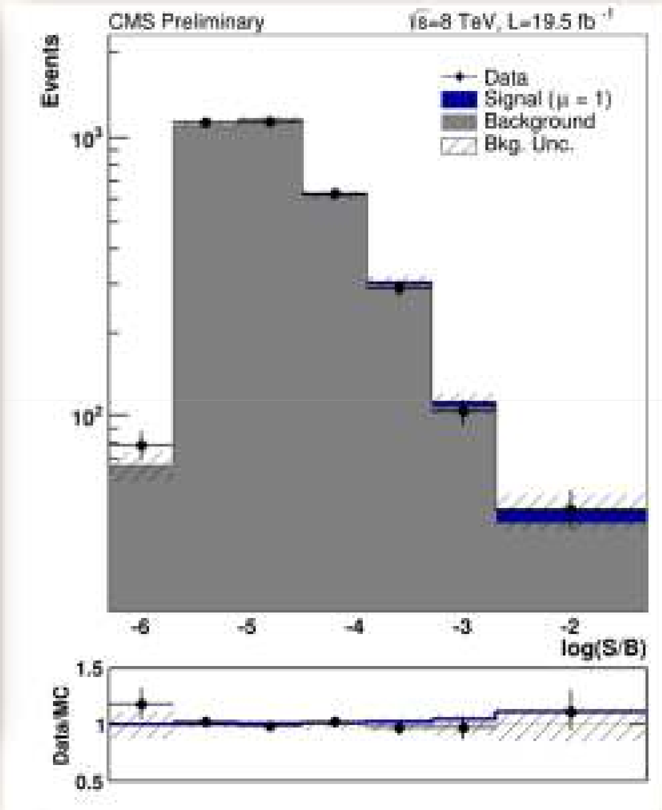


Higgs-Top Associated Production

ttH, H→ bb: Select events with top candidates and extra b-quark jets







$ttH, H \rightarrow bb$

CMS using ME $\mu < 2.9$ $(exp\ 3.3)$ $\mu = 0.67^{+1.35}_{-1.33}$

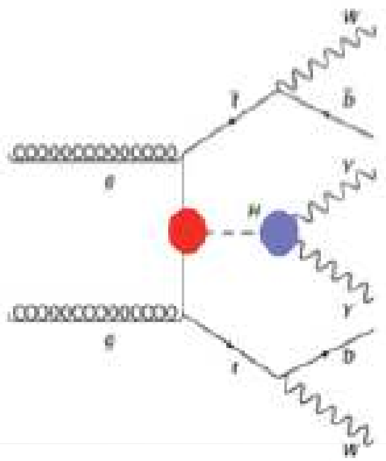
ATLAS $\mu < 4.1$ $(exp\ 2.6)$ $\mu = 1.7 \pm 1.4$

So far no signal
Seen yet, but close?
For the 2015+ run…

Higgs-Top Associated Production

Various decay modes of the Higgs are considered

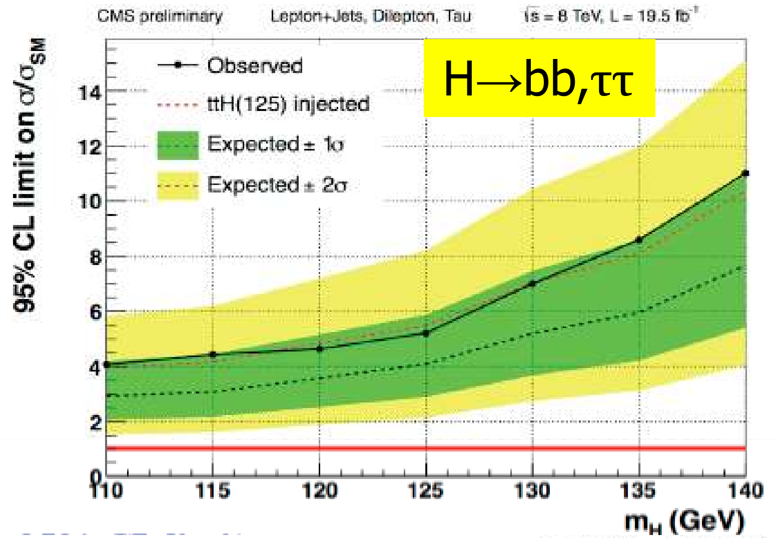
arXiv:1408.1682

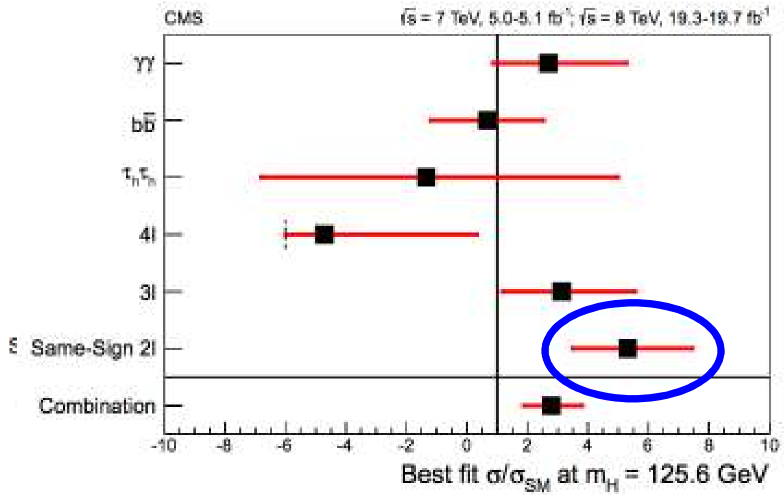


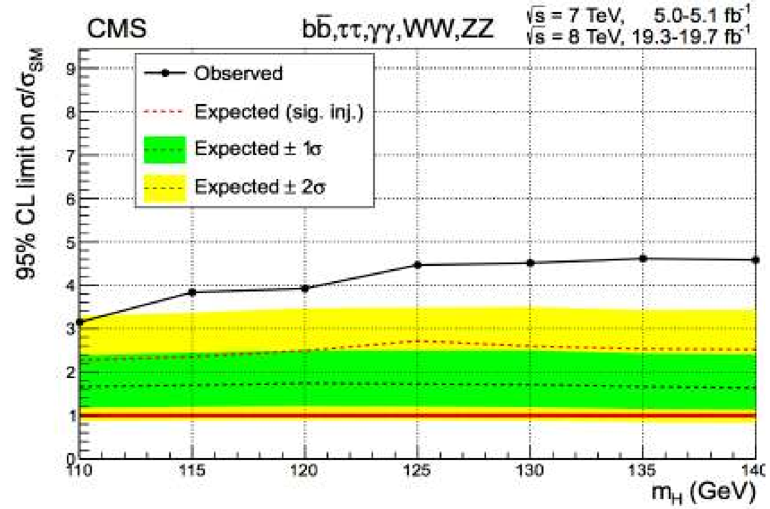
Probe of the H-top Yukawa coupling

CMS:

- $H \to \gamma\gamma$ → HIG-13-015
- $H \to bb$ → HIG-13-019
- $H \to \tau\tau$ → HIG-13-019
- $H \to ZZ$ → HIG-13-020
- $H \to WW$ → HIG-13-020







CMS: $\mu < 4.5$ (1.7 expected) @ 95% CL

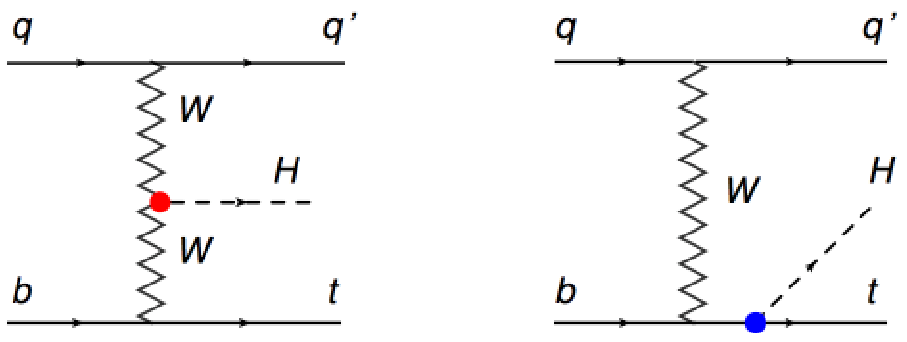
$\mu = 2.8 \pm 1.0$

Single Top + Higgs 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.
- Composite Higgs models heavy t' -> top + Higgs..

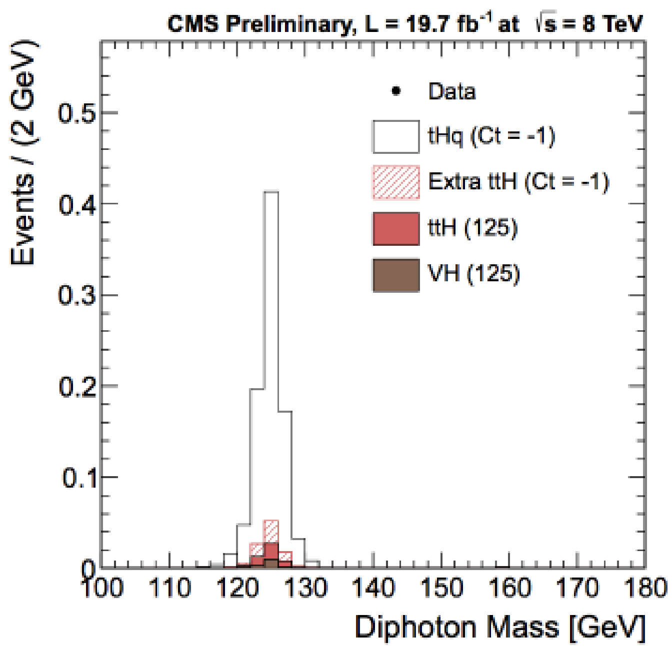
- Study the Higgs decay to two photon decay channel
  No events found top + two photon selection
  95% upper limit is 4.1 times the expected cross section for C_t=-1

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 $|\eta| > 1$
LD> 0.25



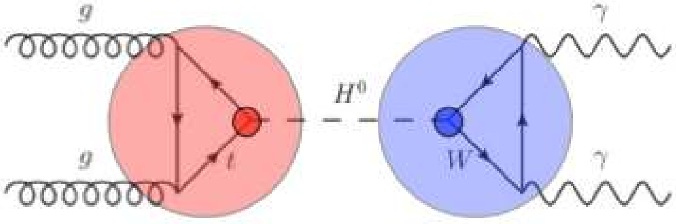
Higgs Combined analysis

Coupling Measurements

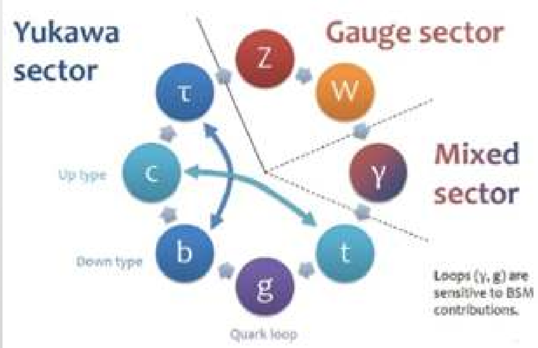
Assume the observed signal stems from one narrow resonance.

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

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.



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



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

Decay tag	incl.(ggH)	VBF tag	VH tag	ttH tag
H→ZZ	✔	✔		
H→γγ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
H→ττ	✔	✔	✔	✔
H→bb		✓	✔	✔
H→Zγ	✓	✓		
H→μμ	✓	✓		
H→inv.		✓	✓	

✔ Used in the NEW combination

CMS-PAS-HIG-14-009

- New update of overall combination since spring 2013

All Channels in Overview (CMS)

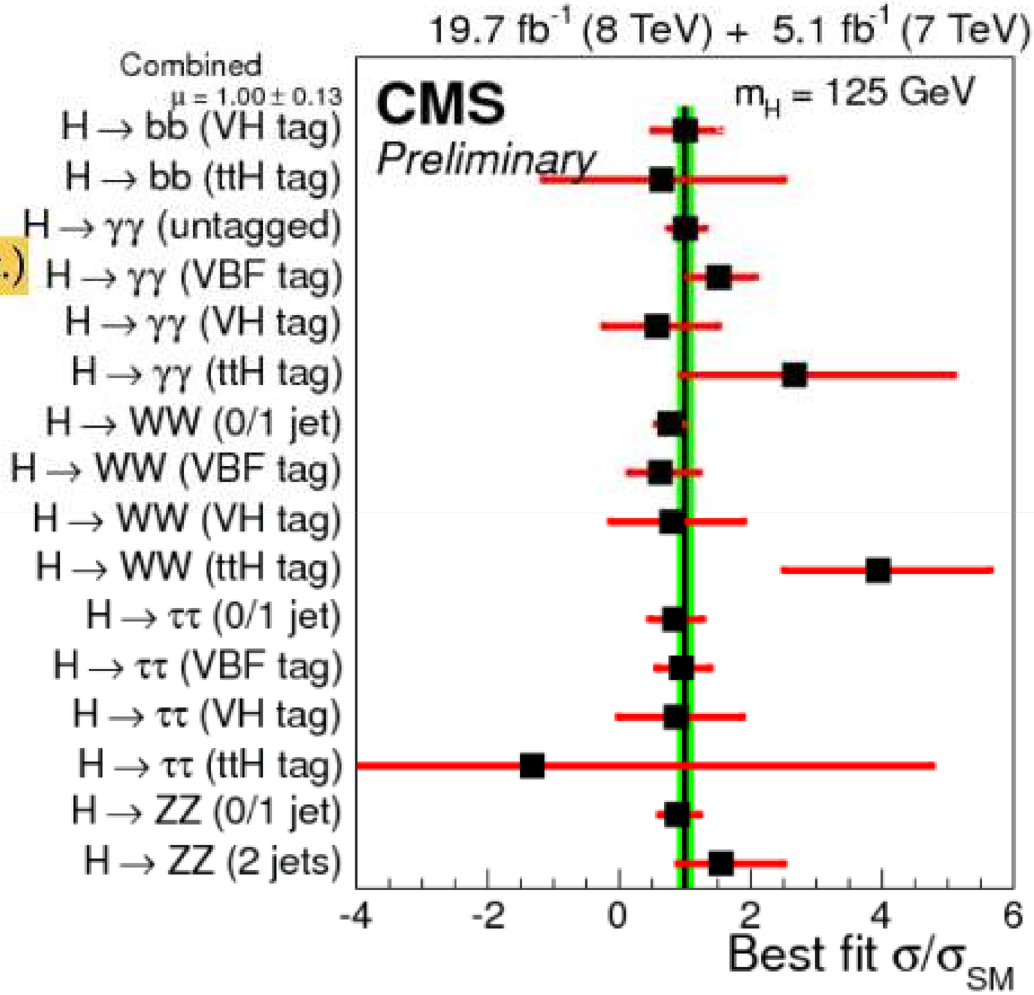
- Overall signal strength

  1.00 ± 0.13

  $1.00 \pm 0.09\,(\text{stat.})\ ^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$

  - "theo." includes QCD scales, PDF+α_s, UEPS, and BR

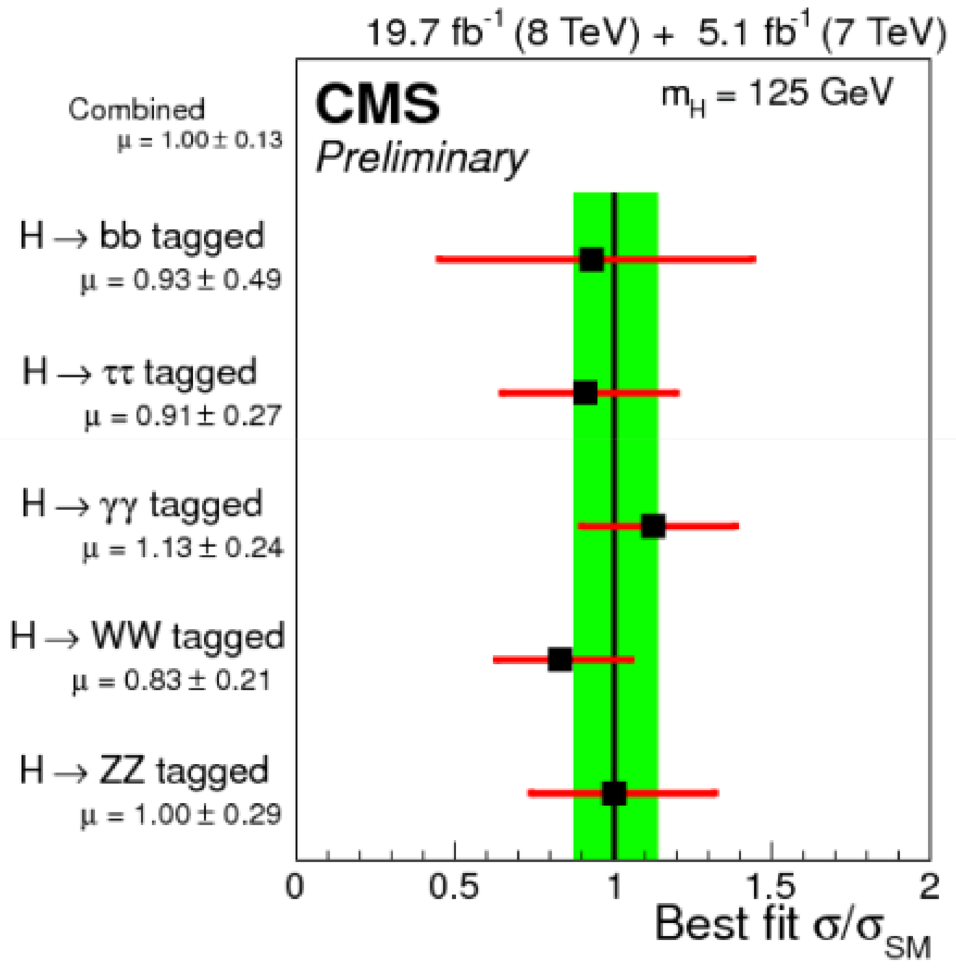
- Per production and decay tag:
  - χ^2/dof = 10.5/16
  - p-value = 0.84 (asymptotic)



Overall strength was 0.82 ± 0.15 before ICHEP14 (spring 2013)

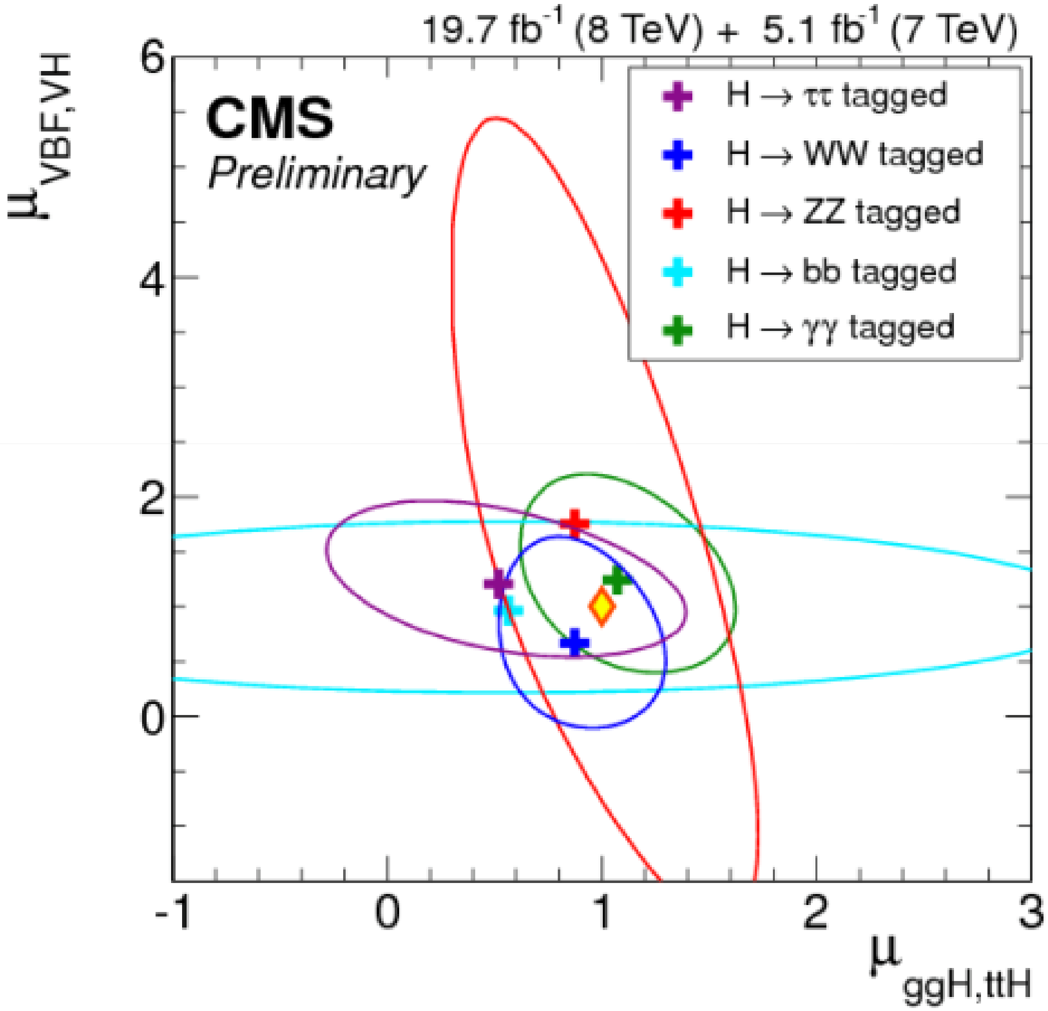
Signal Strength per Decay Channel

- Per decay tag:
  - $\chi^2/\mathrm{dof} = 0.9/5$
  - p-value = 0.97 (asymptotic)



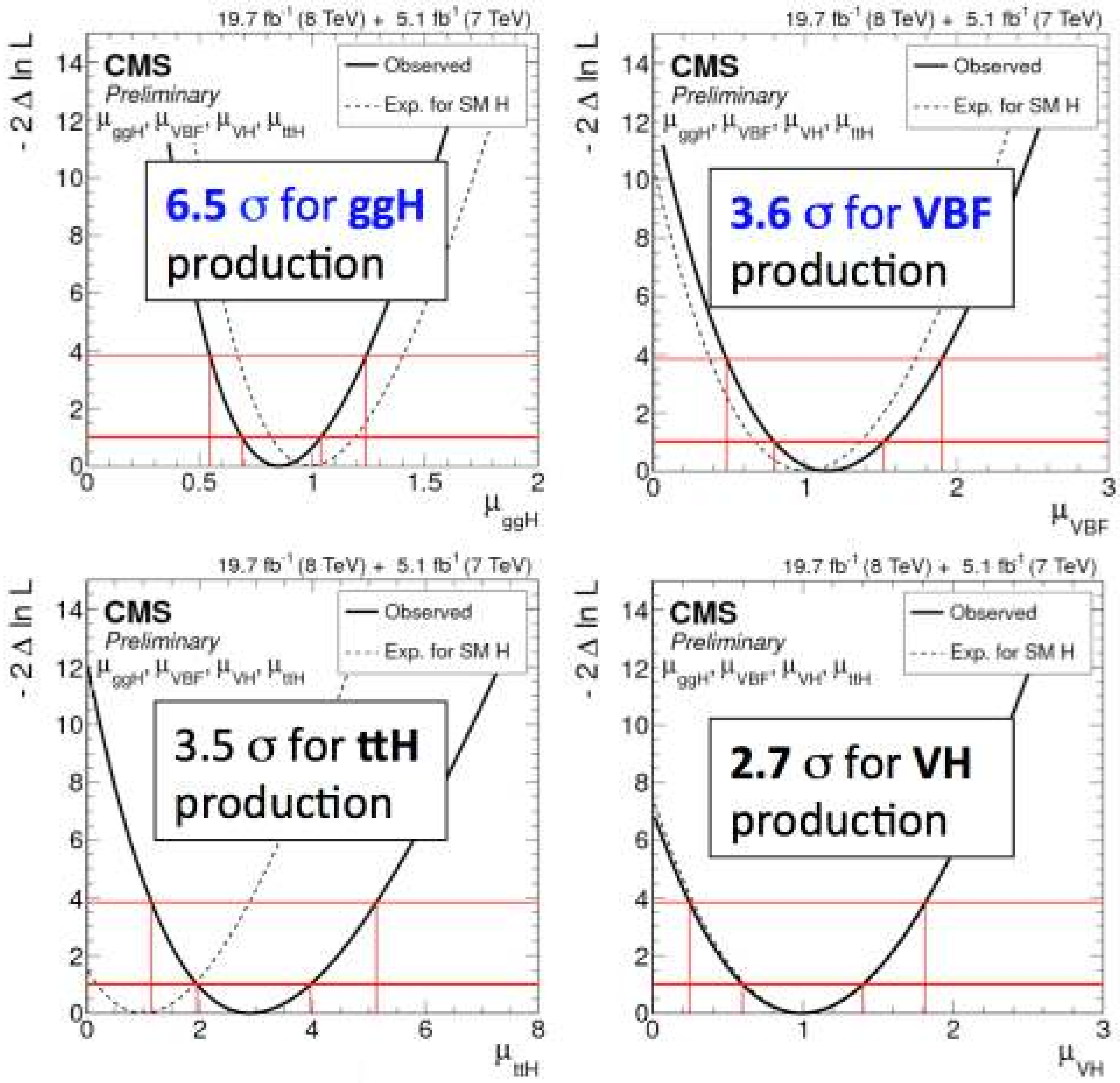
Fermion/Boson μ-Values

- Group **fermion-related** and **vector-boson-related** production processes
- Properly accounts for composition in the tagged categories and its uncertainty



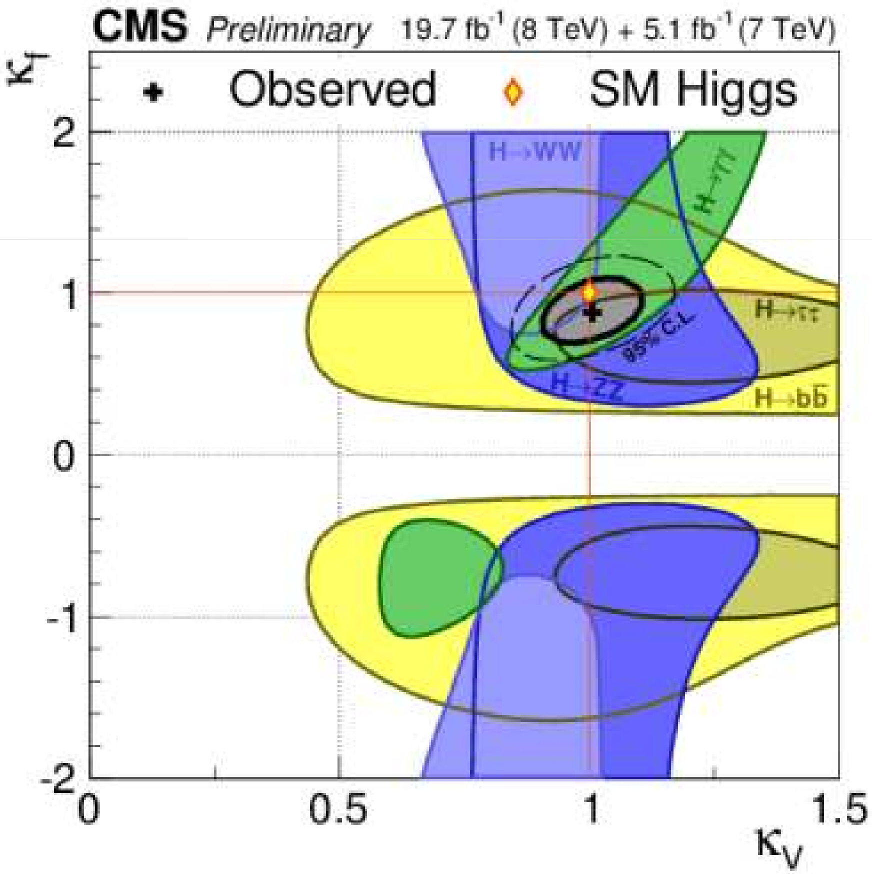
Significance of the 4 Prod. Channels

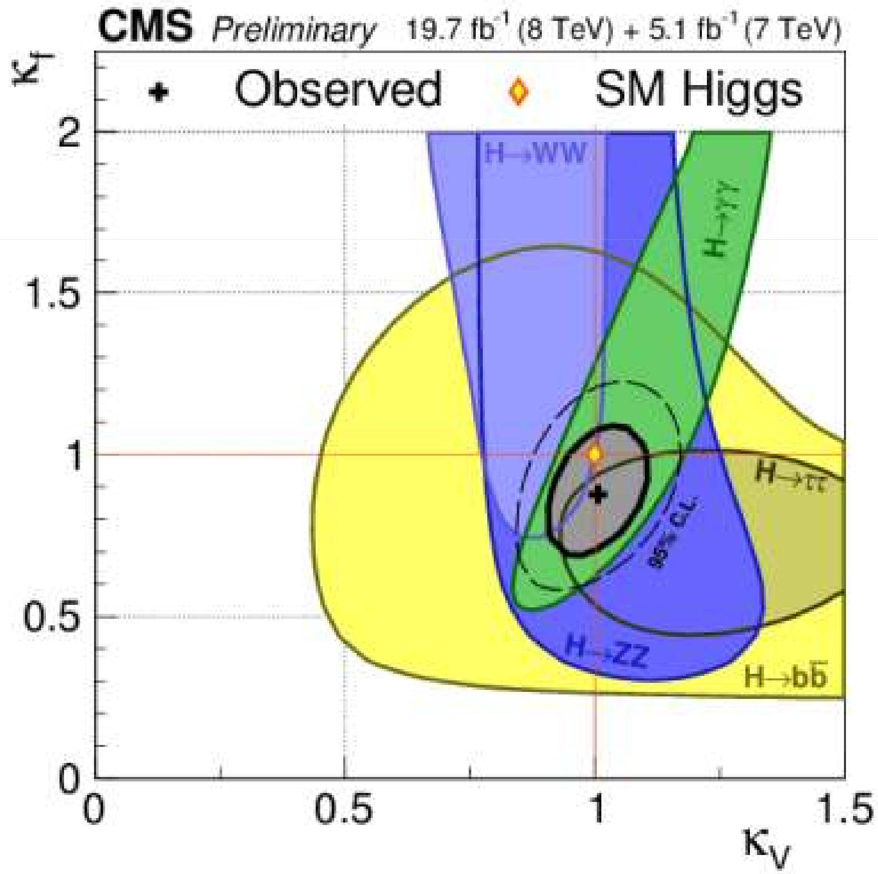
- Simultaneous fit for 4 production cross sections, normalized to SM
- Decay BR's assumed to be the SM ones.



Coupling Modifiers

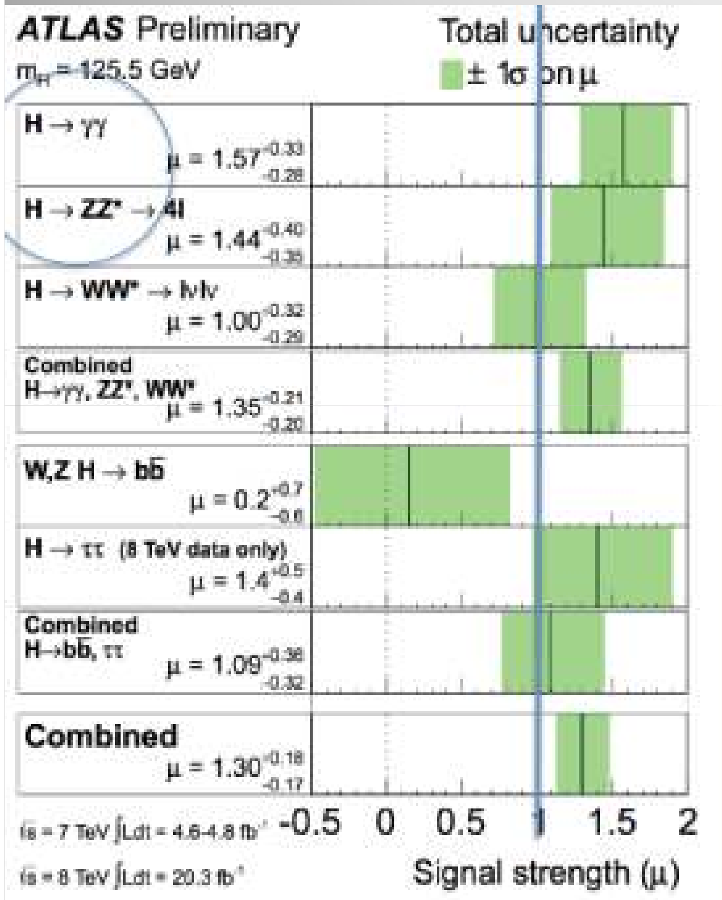
- Map vector-boson and fermionic couplings into κ_V and κ_f
- two-quadrant ⬋ and **one-quadrant** ⬊

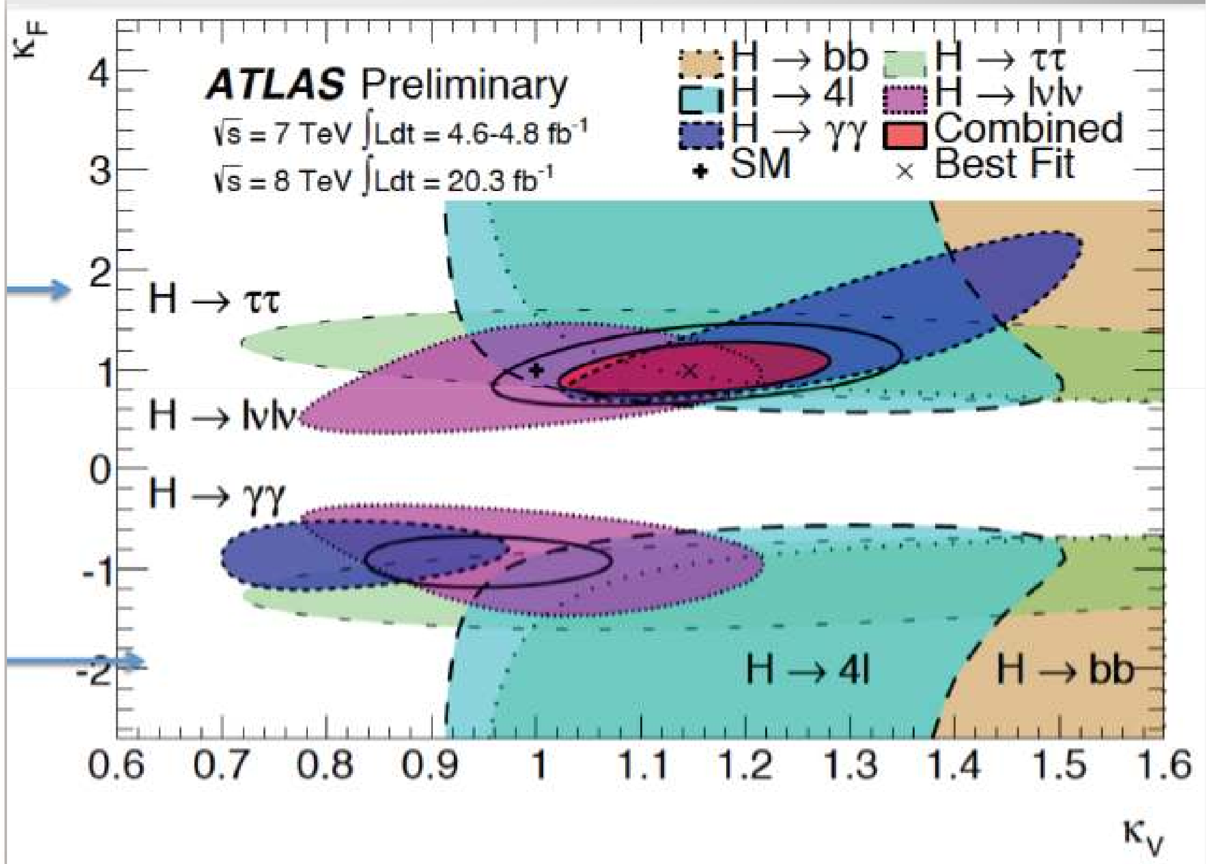




ATLAS: Strength and Couplings

$$\mu = 1.30 \pm 0.12\ (\text{stat})\ \pm 0.10\ (\text{th})\ \pm 0.09\ (\text{syst})$$

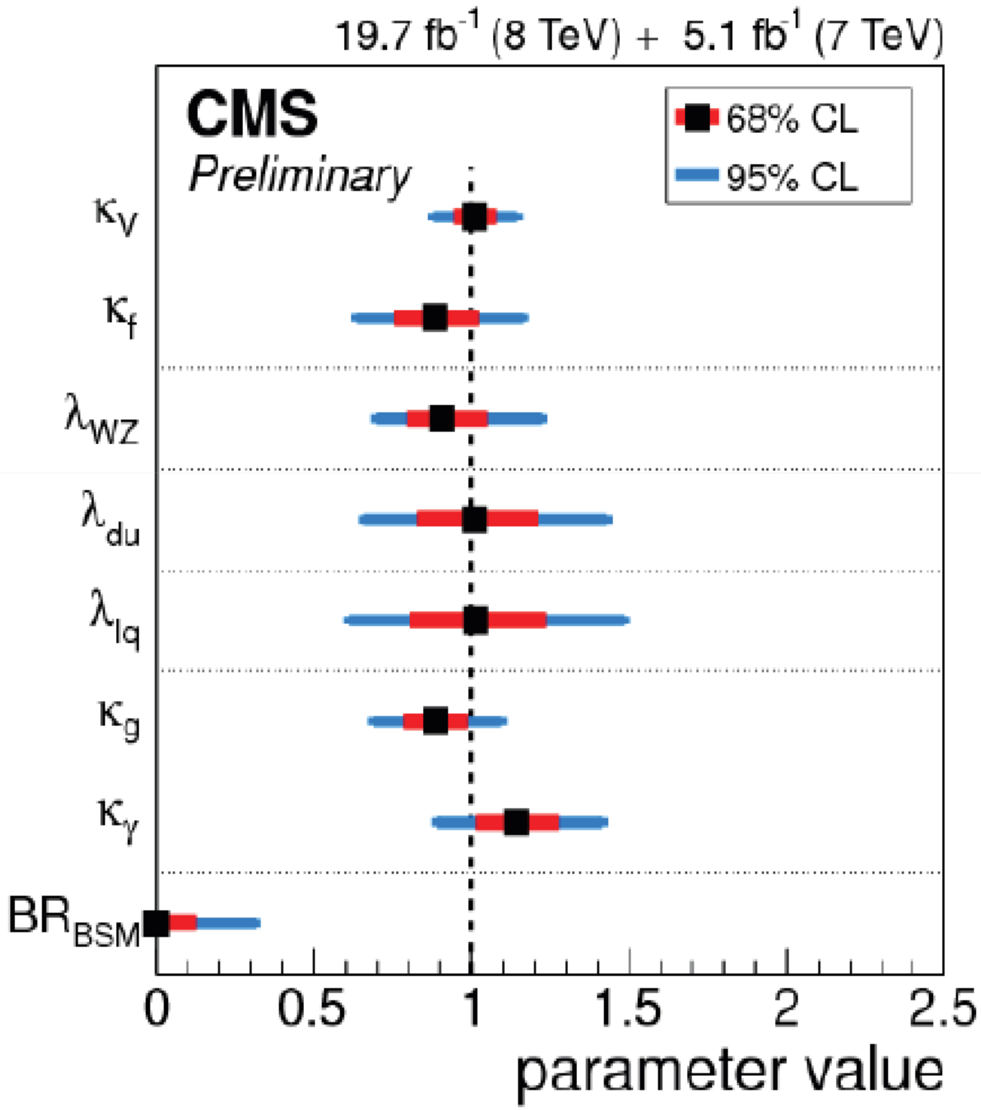




New results in preparation… (M. Kado ICHEP 2014)

Generic Model Tests

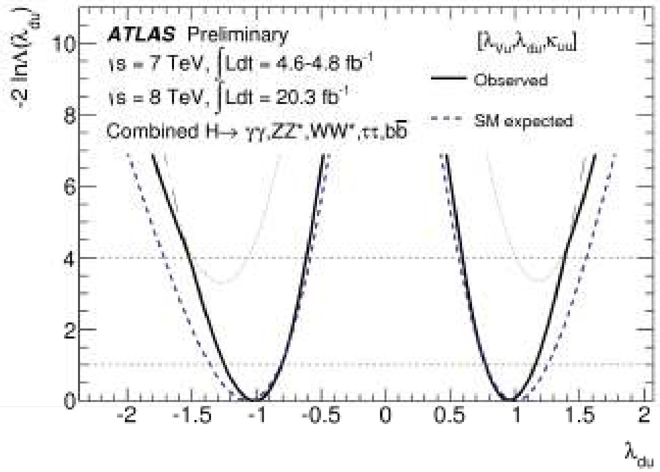
- Summary of the fits of **six benchmarks models** probing:
  - Fermions and vector bosons.
  - Custodial symmetry.
  - Up/down fermion coupling ratio.
  - Lepton/quark coupling ratio.
  - BSM in loops: gluons and photons.
  - Extra width: BR_{BSM}.
- **No significance deviations from SM.**

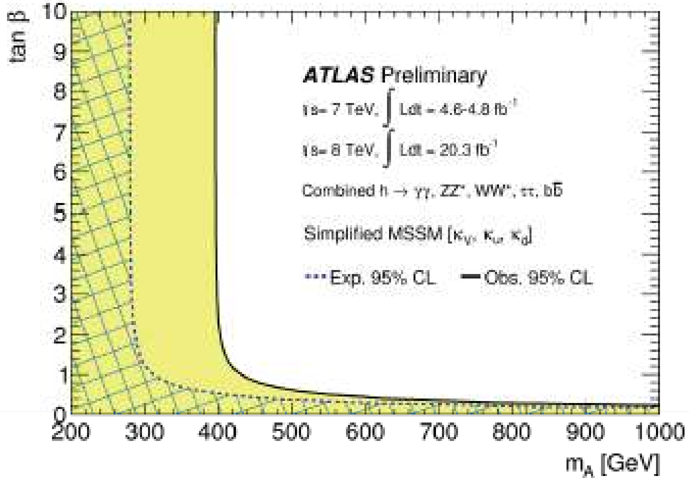


$\lambda_{xy} = \kappa_x / \kappa_y$

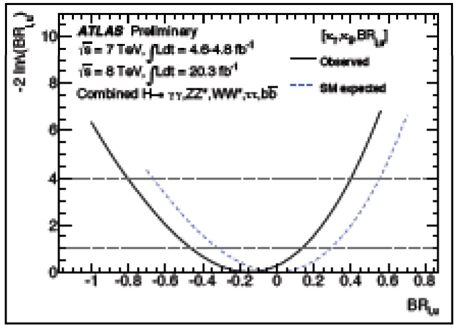
ATLAS: Coupling Tests

- Assuming no BSM in the production and decay
- Testing the couplings to up and down type fermions





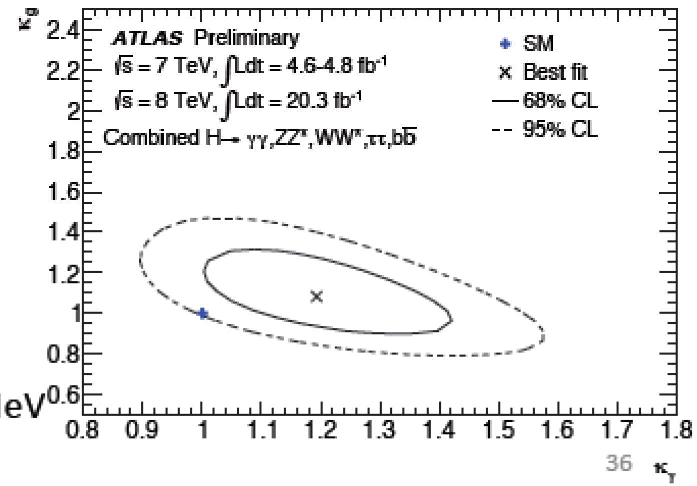
- Assuming SM couplings to SM fields
- Testing the loops!
- ...and testing the invisible width



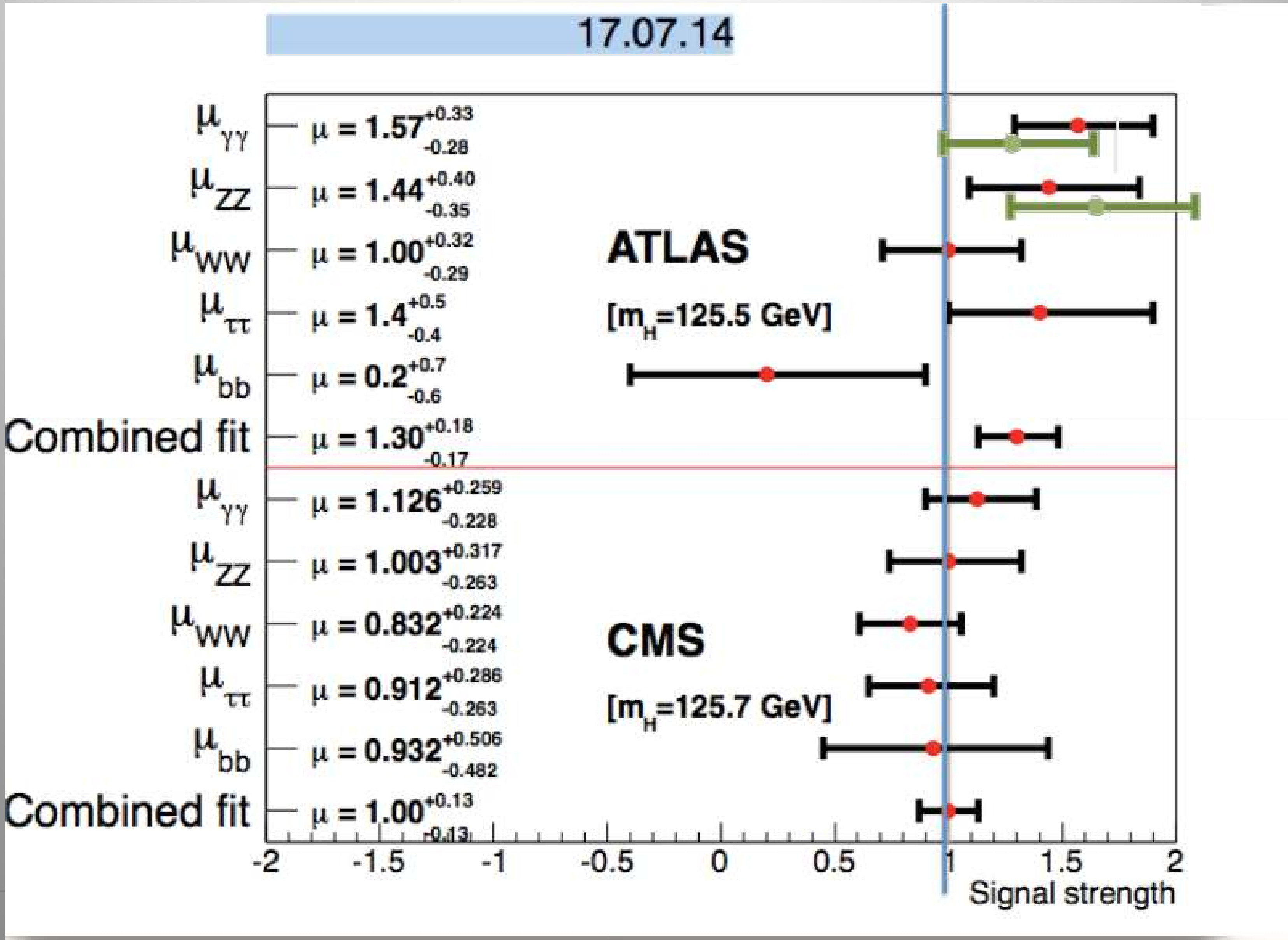
$Br_{inv,und}$ < 41 (55)%

Equivalent limit on total width:

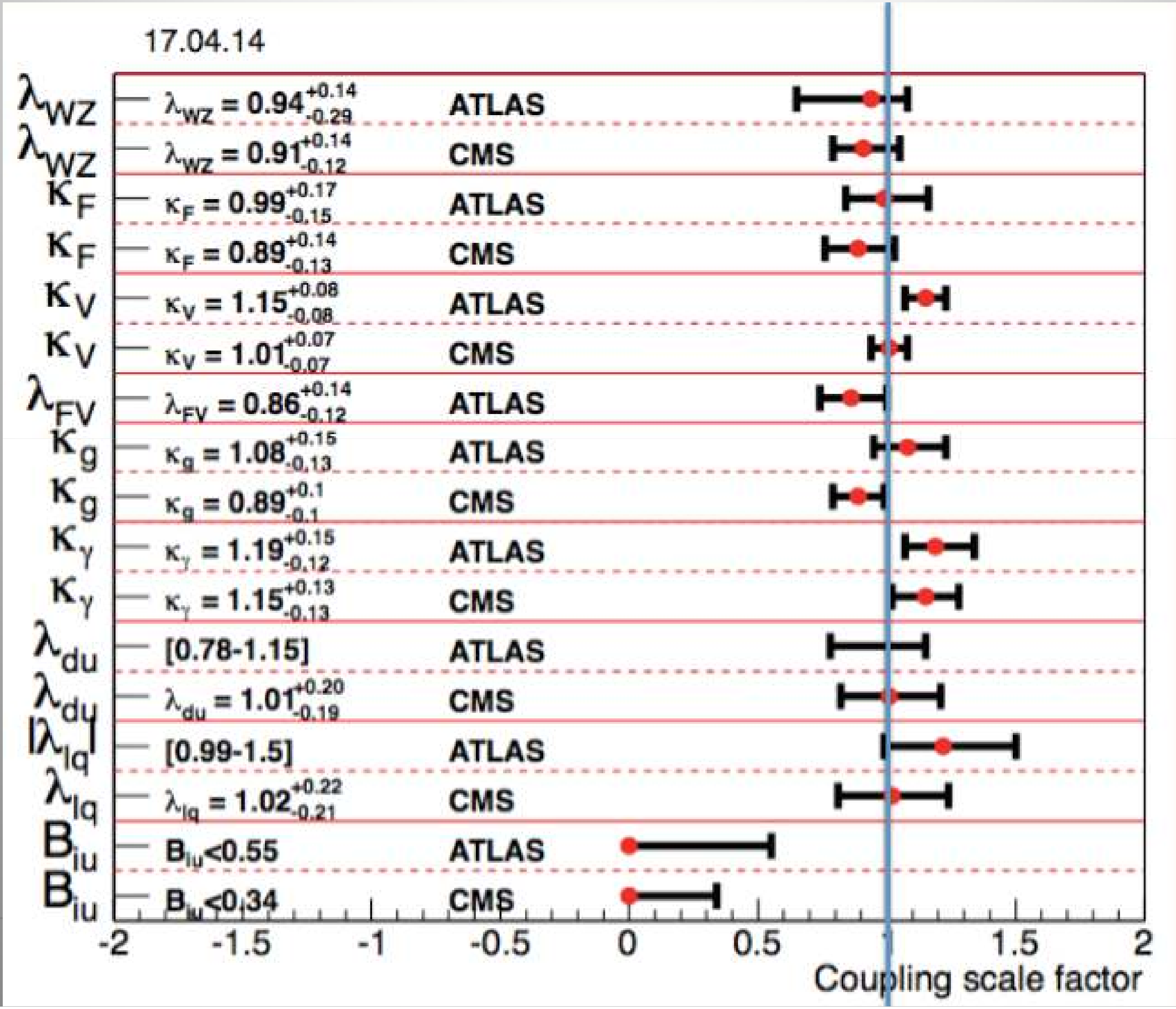
$\Gamma_{inv,und}$ < 7.1 (9.3) MeV



Overall ATLAS and CMS Results



Overall ATLAS and CMS Results



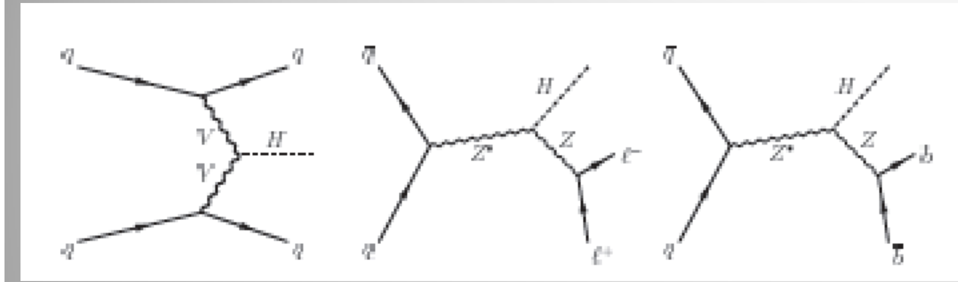
Exotic Higgs?

Searches for BSM Higgs

- MSSM neutral Higgs searches
- Charged Higgses (single, double…)
- Associated production
- Double Higgs production
- 2HDM searches
- FCNC tests
- Unusual decays (LFV, others…)

- No signal reported so far.

Invisible Higgs Decay Channel

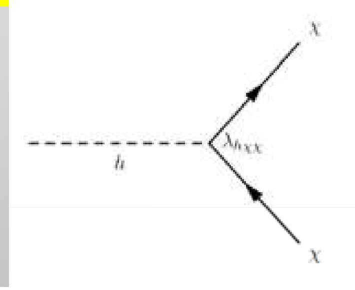


Search for invisible Higgs decays using

$Z+H \rightarrow$ 2 leptons + missing E_T

VBF $H \rightarrow$ 2 jets + missing E_T

Possible decay in Dark Matter particles (if $M<M_H/2$): Higgs Portal Models

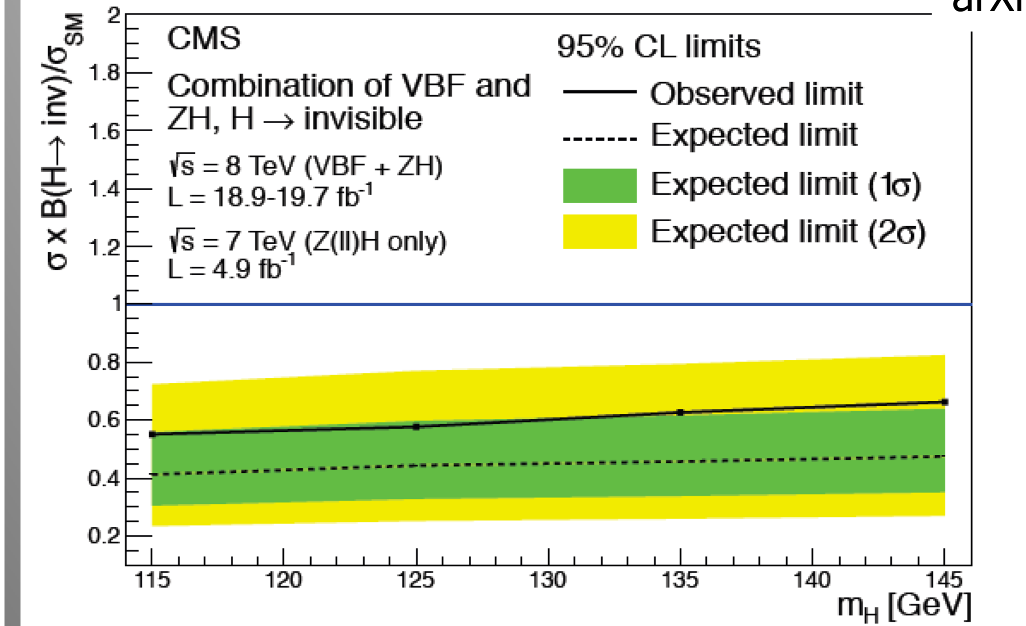


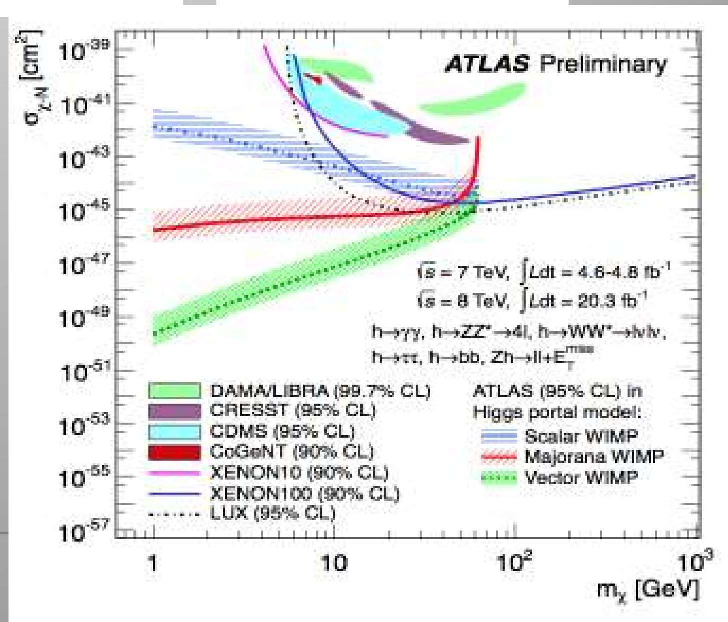
Combined result from the three channels

BR($H\rightarrow$invisible)<58%(44% exp) at 95% CL.

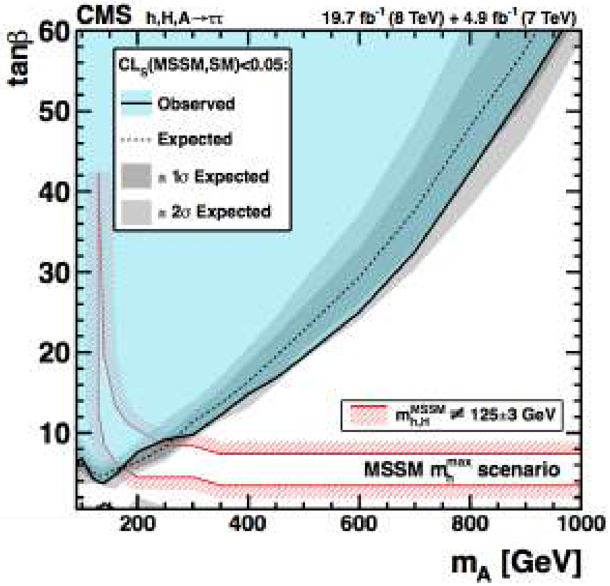
for a Higgs with a mass of 125 GeV

arXiv:1404.1344
arXiv:1402.3244





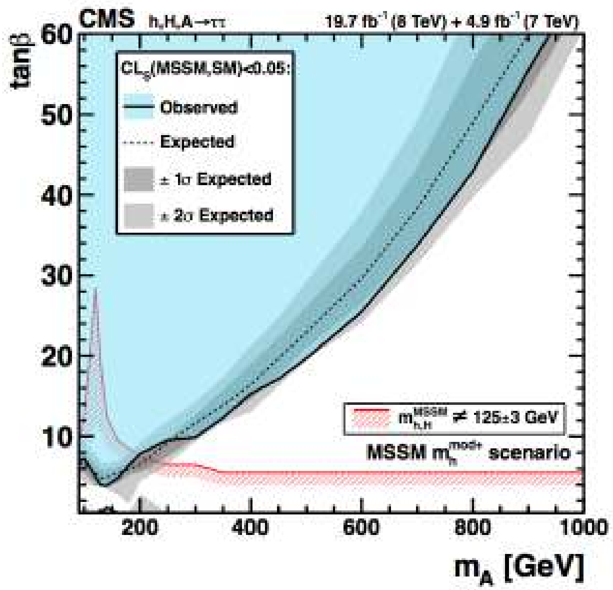
MSSM Neutral Higgs $\rightarrow$ tau tau

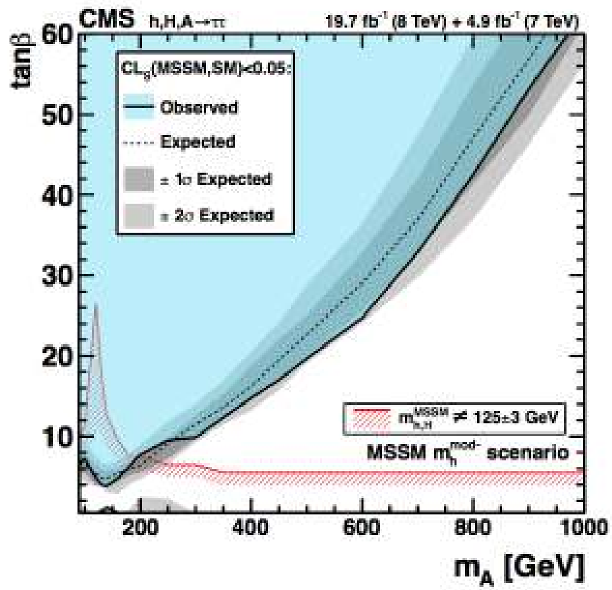


arXiv:1408.3316

- 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% CL)

m_h^{max} scenario;
m_h^{mod+} and m_h^{mod+} scenarios
with modified stop mixing





MSSM Scenarios

Proposed by Carena et al., Eur.Phys.J.C73, 2552 (2013)

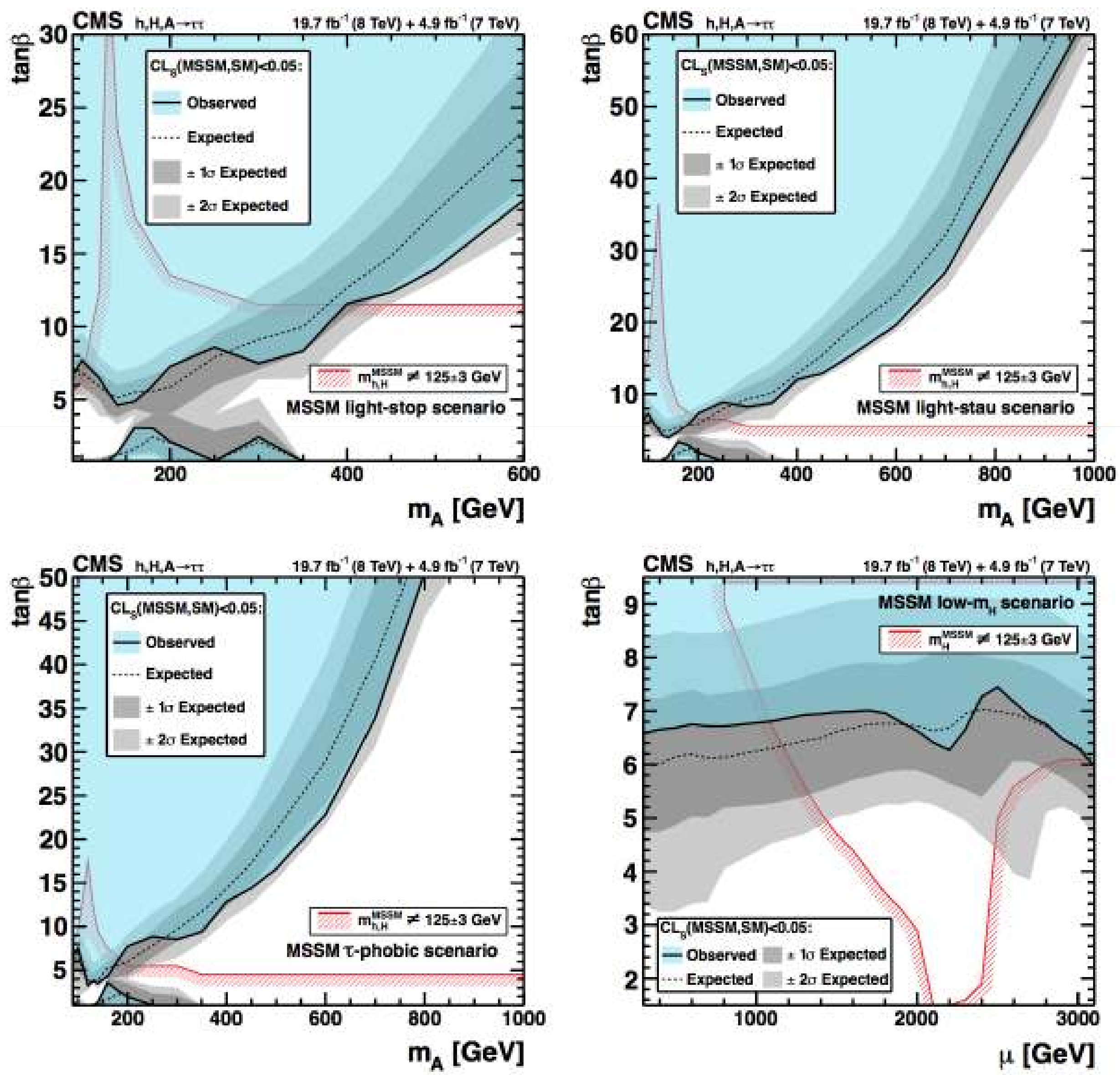
Light or heavy scalar Higgs: h or H
compatible with Higgs-like particle discovered at 125 ± 3 GeV
theoretical uncertainty

scenario	Mass (GeV)	Higgs sector phenomenology
m_h^{max}	$M_h \sim 135$	stop mixing parameter: $X_t = 2$ TeV
m_h^{mod+}	$M_h \sim 125$	m_h^{max} except $X_t = 1.5$ TeV compatible w. μ g-2
m_h^{mod-}	$M_h \sim 125$	m_h^{max} except $X_t = -1.9$ TeV compatible w. $B(b \to s\gamma)$
light-stop	$M_h \sim 125$	$M_{stop,1} \sim 340$ GeV & suppressed decay mode stop $\to$ top + χ^0 $\to$ reduced ggH rate
light-stau	$M_h \sim 125$	$M_{stau} \sim 245$ GeV $\to$ enhanced $H \to \gamma\gamma$ rate
tauphobic	$M_h \sim 125$	Reduced coupling to down-type fermions
low-m_H	$M_H \sim 125$	$M_A = 110$ GeV Variation in $\tan\beta - \mu$ (Higgsino mass parameter)

MSSM Neutral Higgs → tau tau

arXiv:1408.3316

No excess found so far
–> exclusions (95% CL)

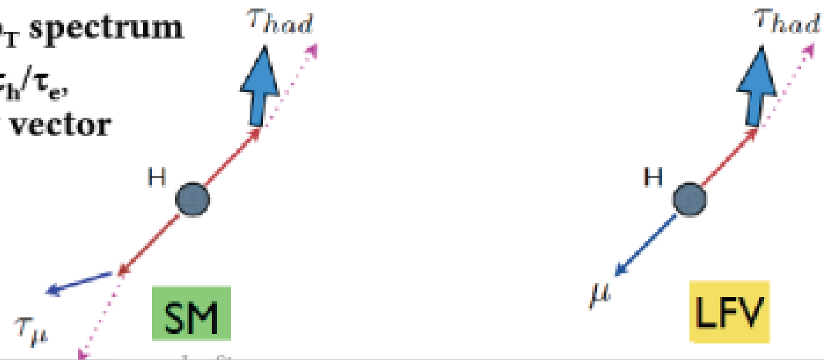


More scenarios:
see M. Carena et al.
Eur. Phys.J.C73, 2552 (2013)

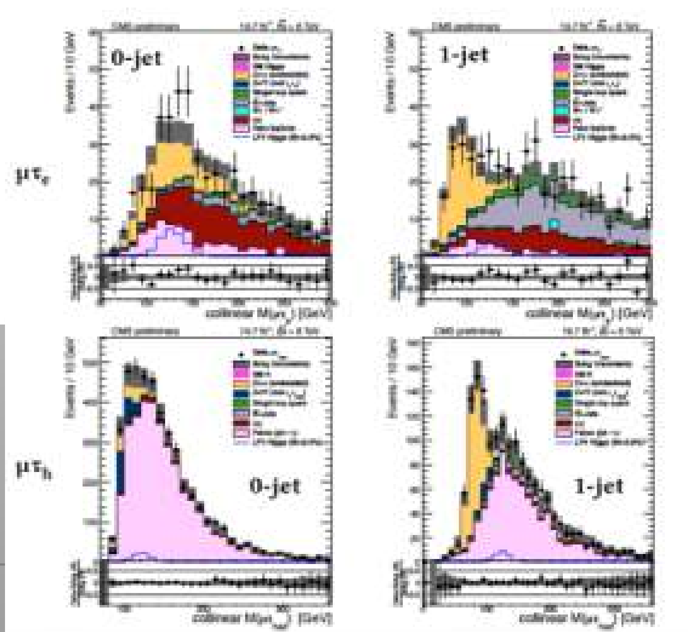
Search for LFV Decays: H →μτ

CMS-PAS-HIG-14-005

- Previous best limits on B(H→μτ) <~ 10% from reinterpretation of LHC H→ττ searches and from τ→μγ arXiv:1209.1397
  - **Can do better with first dedicated search**
- Consider hadronic (τ_h) and electron (τ_e) tau decays
- Same basic event selection and jet categories as SM H→ττ analysis (0-jet, 1-jet, VBF-tag)
- Differences in kinematics
  - **Harder muon p_T spectrum**
  - **Δφ between μ, τ_h/τ_e, missing energy vector**

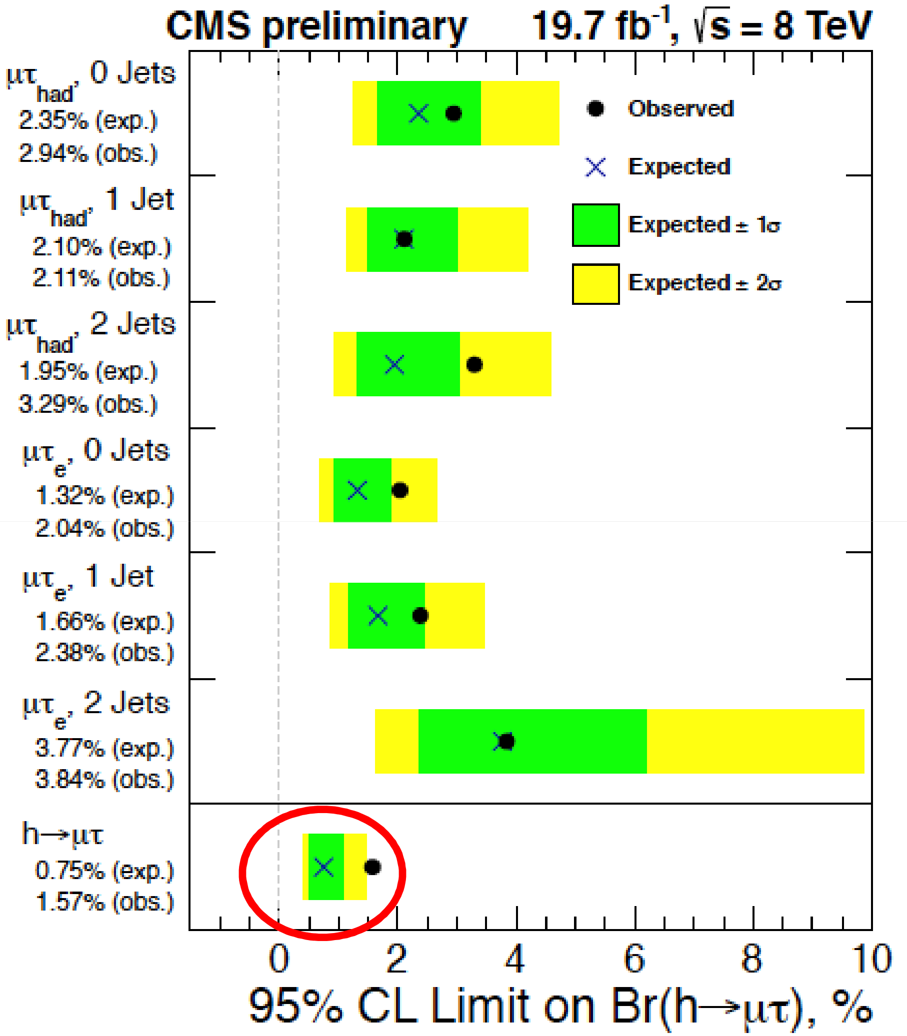


On public demand from our theory friends ☺



Search for LFV Decays: H $\rightarrow \mu\tau$

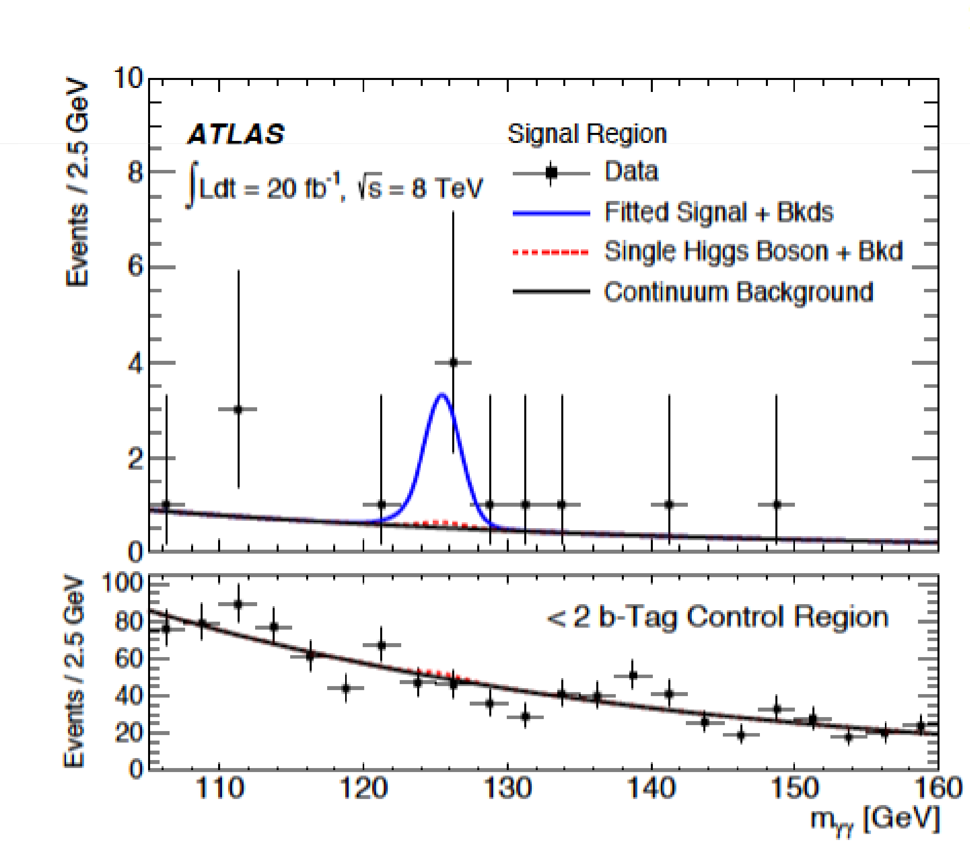
- Comparable sensitivity from all channels
- Observed limit 1.57% (exp. 0.75%)
- **Large improvement of previous limits**
- **Background-only p-value of 0.007 (2.46σ)**
  - Best-fit $B(H\rightarrow\mu\tau) = 0.89^{+0.40}_{-0.37}\%$



Mild excess giving a 2.5σ effect… To be watched!!!

ATLAS: hh → γγbb

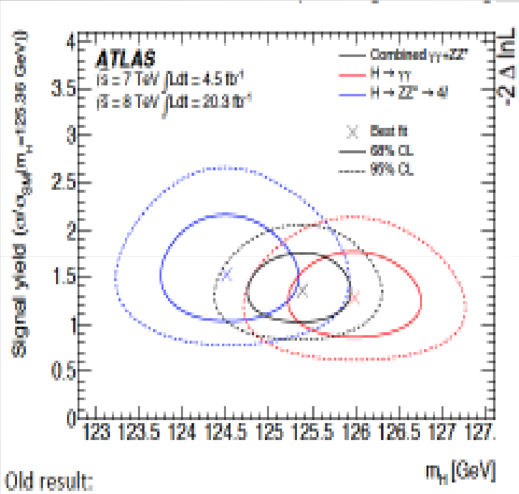
- No signal expected with the present collected luminosity for this channel
- Select events with 2 b jets and 2 photons. (non-resonant channel)
- 5 events within bin of $M\gamma\gamma \pm 2\sigma_{M\gamma\gamma}$ and 1.5 expected which is about 2.4σ significance…

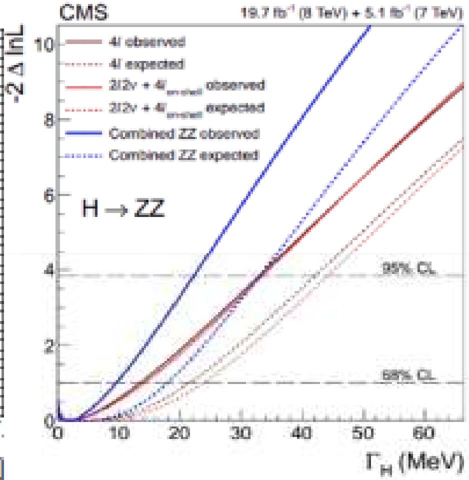


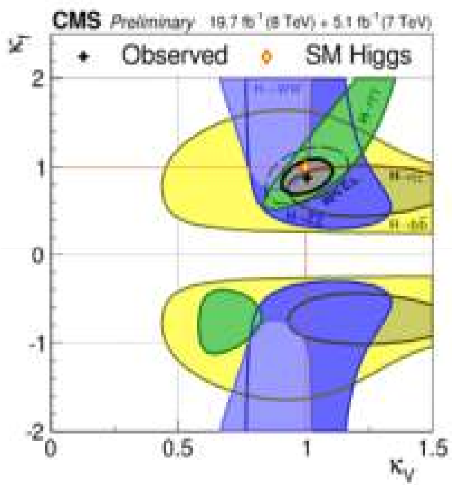
arXiv:1406.5053

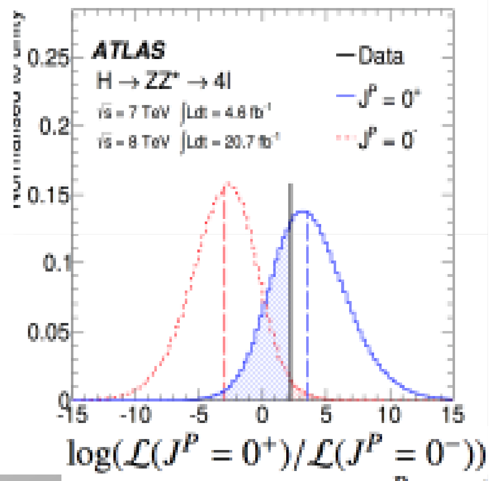
Brief Higgs Summary

We know already a lot on this Brand New Higgs Particle!!









Mass =
A: 125.4 ±0.4 GeV
C: 125.0 ±0.3 GeV

Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

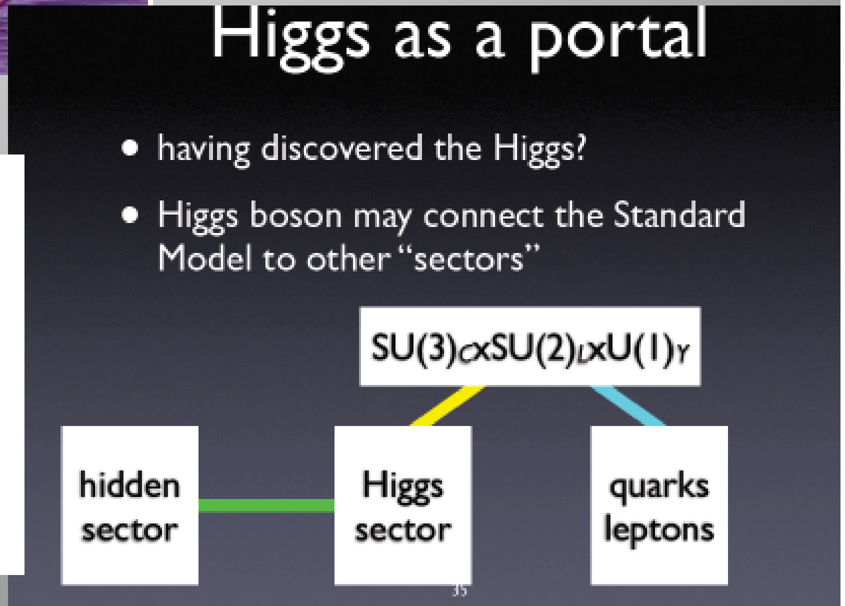
Couplings are within 20% of the SM values

Spin =
0^+ preferred over 0^-,1,2

SM-like behaviour for most properties, but we look of course for anomalies, i.e. unexpected decay modes or couplings, multi-higgs production…

The Future: Studying the Higgs…

Higher Energy in 2015!
LHC lumi upgrade !
Experiment upgrades!!
(Other/new machines?)

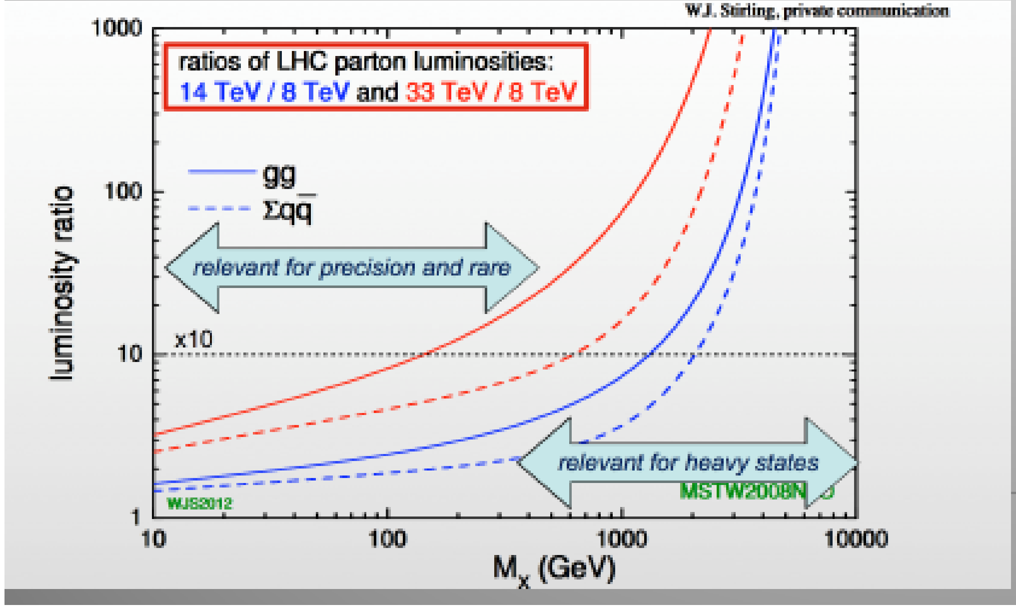


Many questions are still unanswered:

- What explain a Higgs mass ~ 126 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤

Future Colliders Physics Program?

- Properties of the new Higgs boson, precise determination of its characteristics
- High mass reach for new particles and interactions
- Precision measurements
- Rare processes



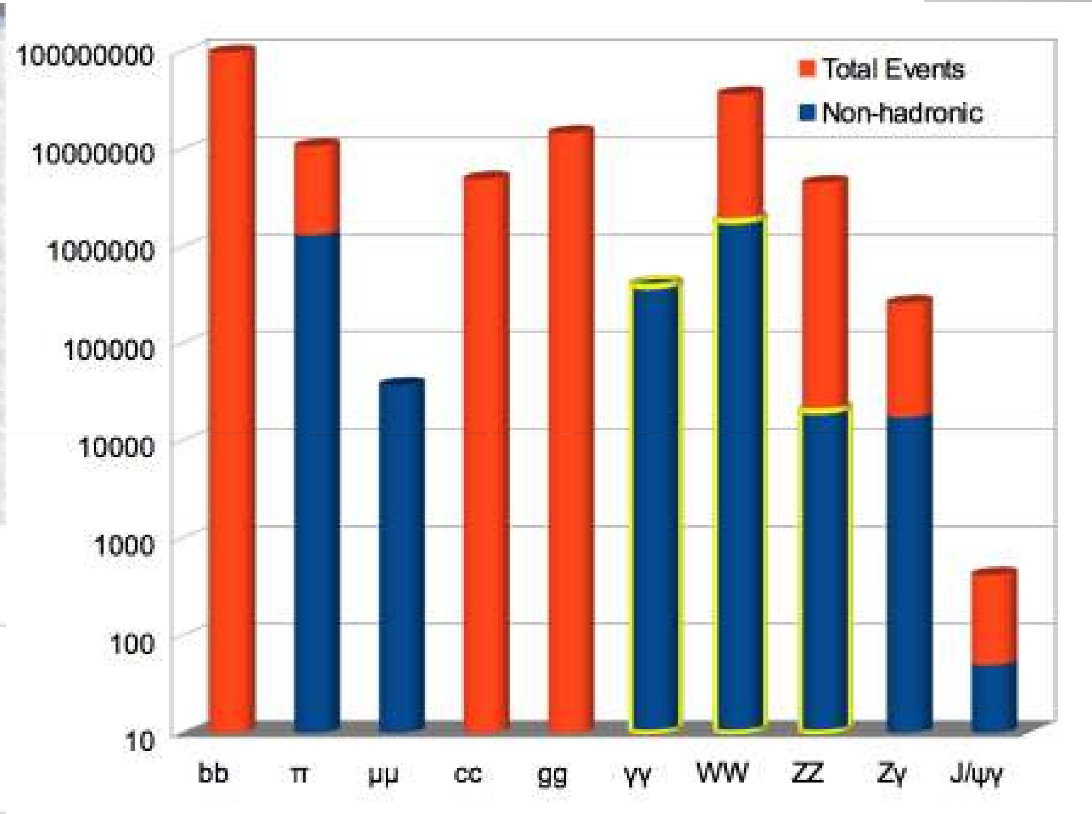
- Higgs mass precisions ~ 100-200 MeV enough?
- Higgs self-coupling precision Better than 20% needed?
- Higgs couplings? Few %? Better?

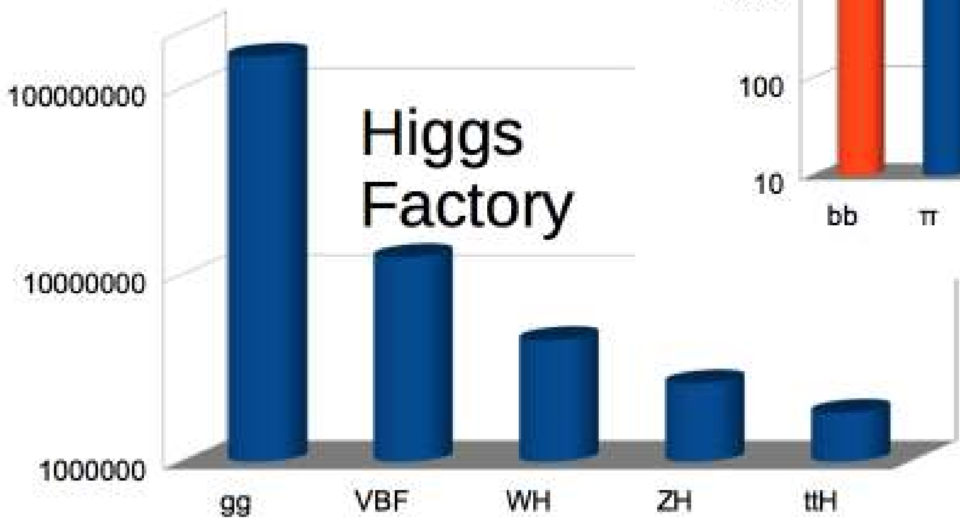
(J. Wells et al., arXiv:1305.6397)

High Luminosity LHC?

Number of Higgs Bosons produced with 3000 fb^{-1}

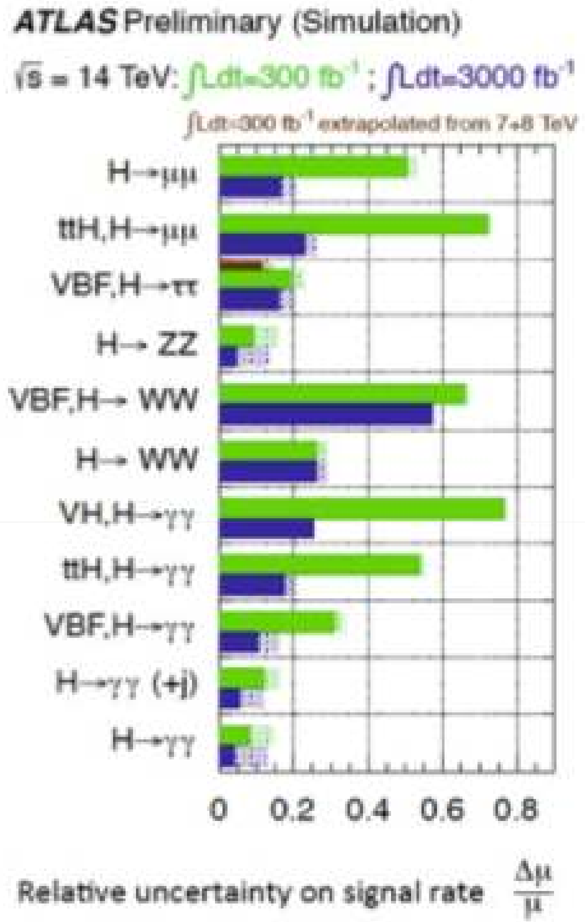
- Over 100M Higgs bosons
- 20K H→ZZ→llll
- 400K γγ
- 50 H→J/ψγ



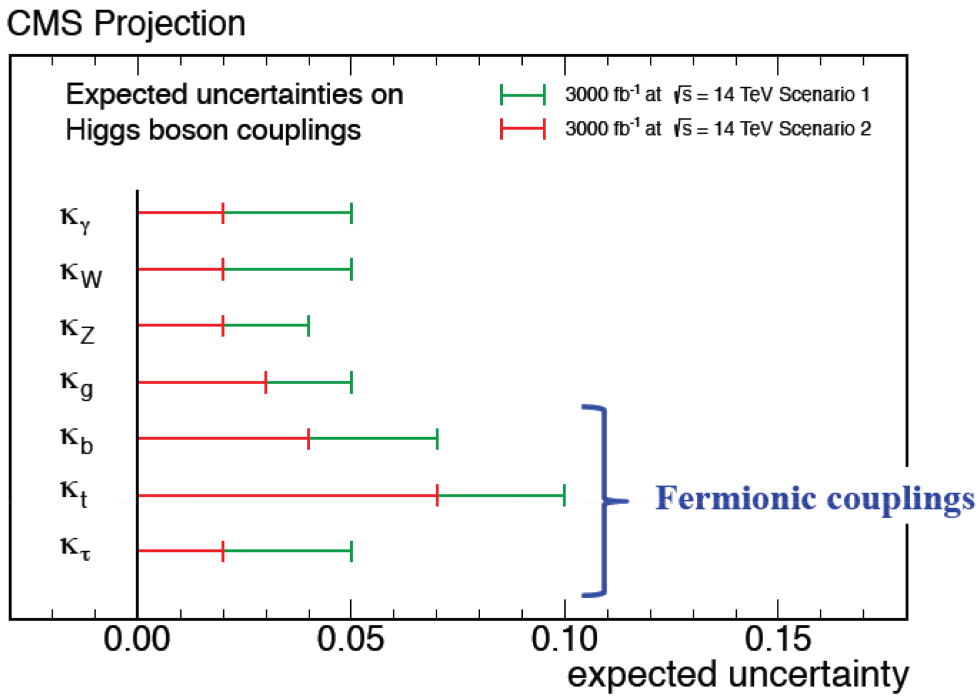


- Over 1M in all major production modes

High Luminosity LHC Precision



Based on parametric simulation

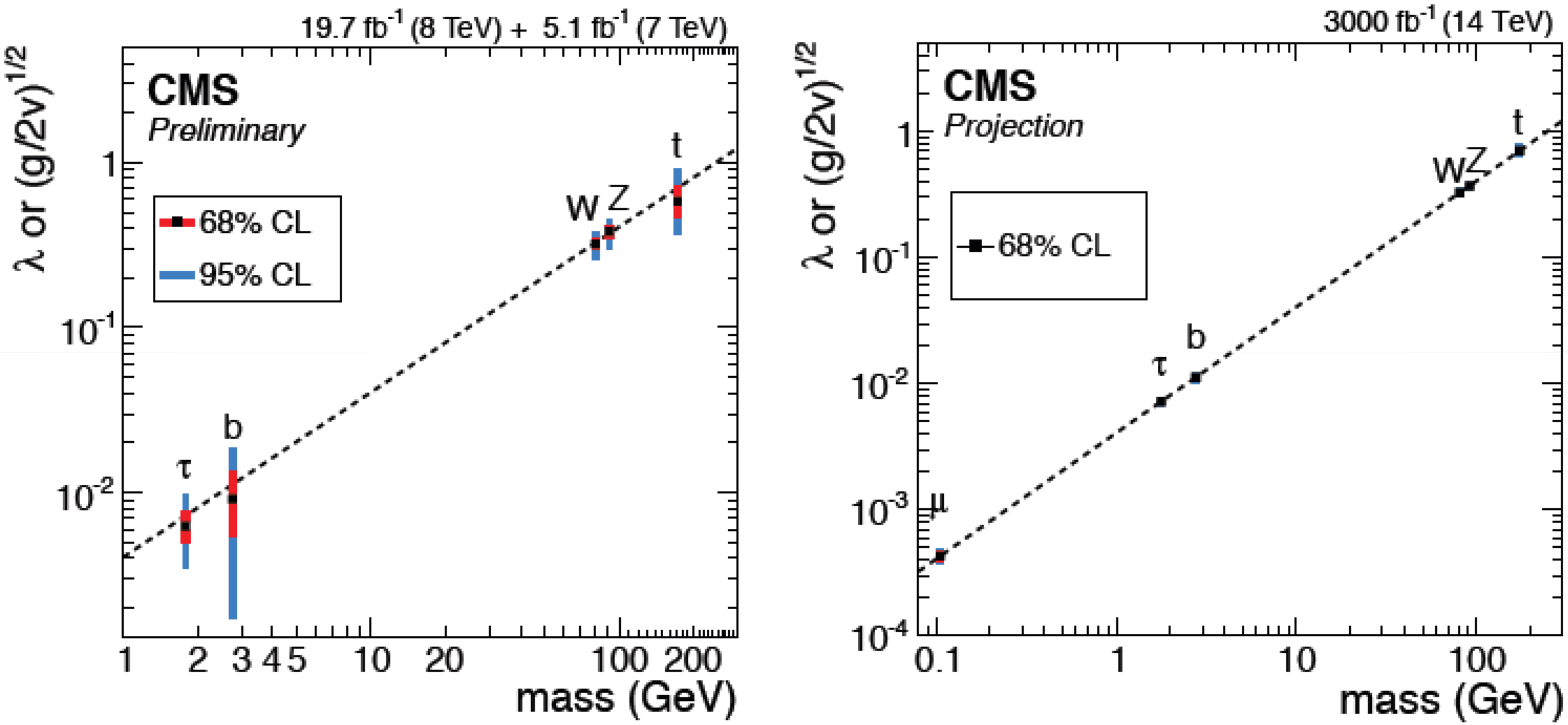


Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ $1/\sqrt{L}$

Extrapolated from 2011/12 results

Determine the Higgs couplings to a few % precision…

High Luminosity LHC Precision



Determine the Higgs couplings to a few % precision…

Summary

- The discovery has been confirmed with more collisions. Now: measuring properties, search for other Higgses…
- Rare processes now studied: $H\rightarrow Z\gamma$, ttH, ($H\rightarrow\mu\mu$)…
- The spin/parity is compatible with a 0^+ state and not with (simple) 0^- or spin 2 states. General fits ongoing…
- The mass is ~125 GeV with a precision of order ~0.3%.
- Recent: new results on the fermion decay channels. The significance of the τ and combined τ+b channels is $>3\sigma$
- The couplings to bosons and fermions are consistent with SM predictions, but these are tested so far up to ~20-30% precision only; Surprises still possible!!
- Hunt for 'unexpected' decays & processes is going on…
  - But it just takes ONE deviation to show us the way