Experimental Particle Physics at the LHC: The Higgs Boson

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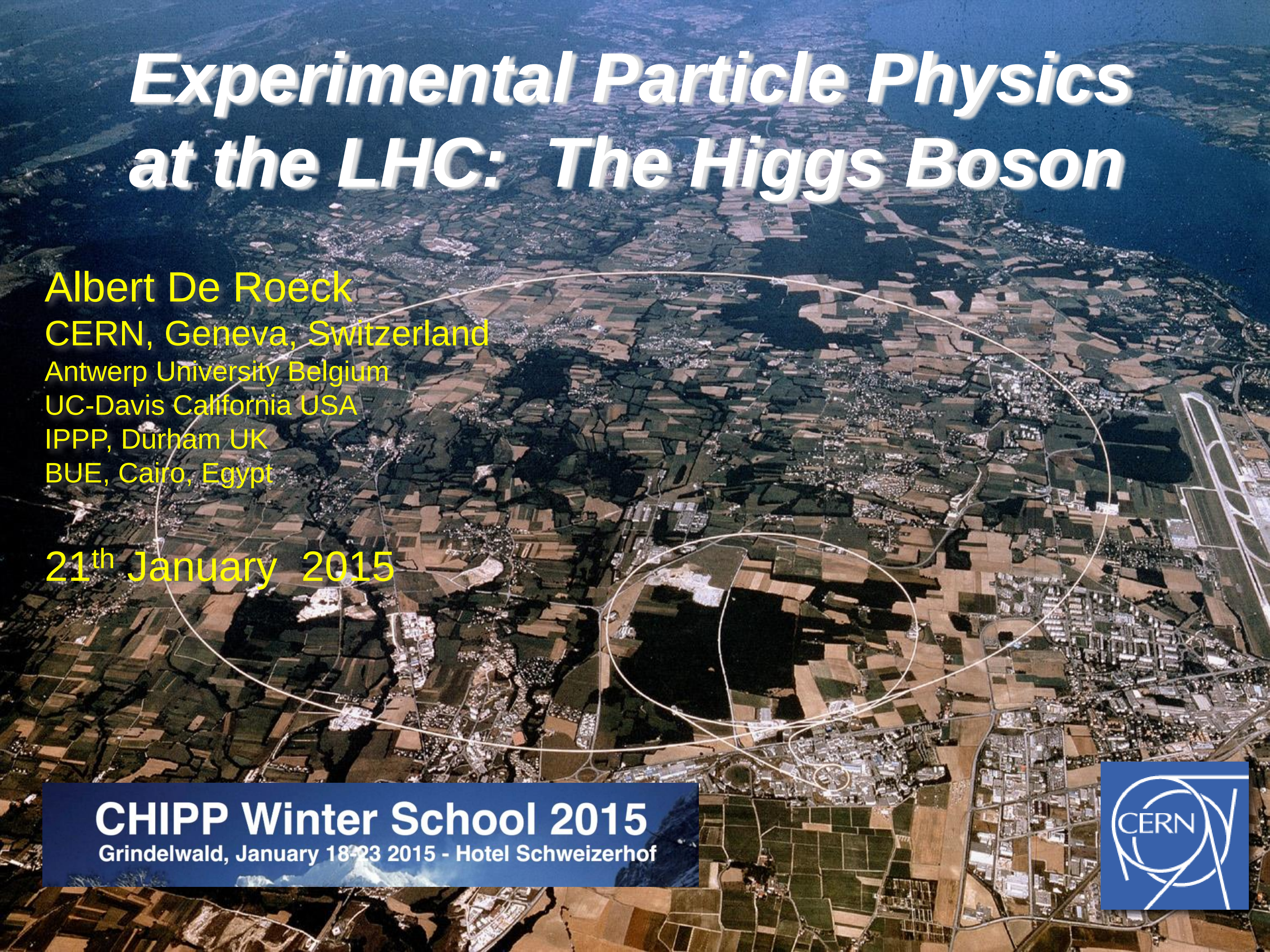
21[th] January 2015



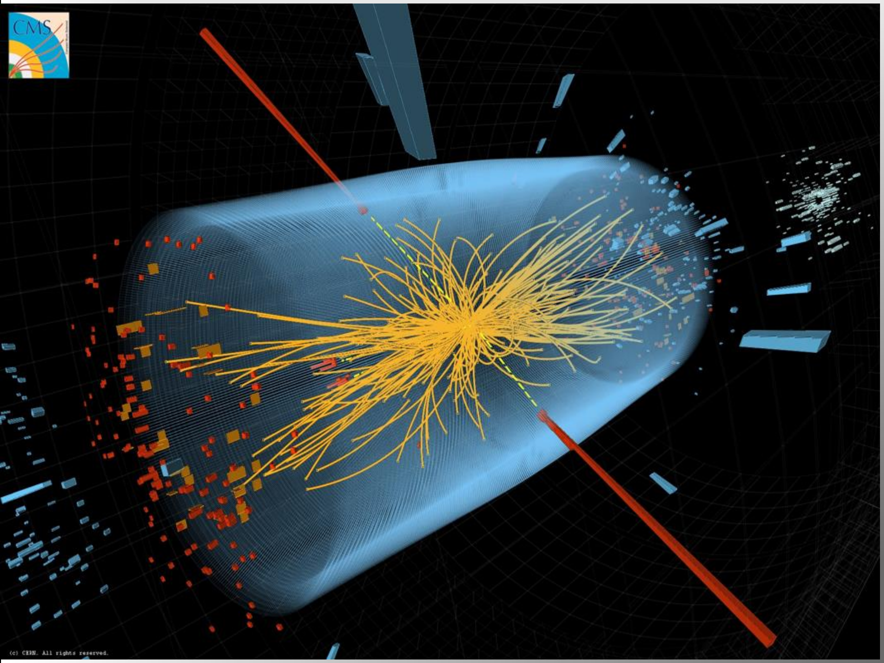
CHIPP Winter School 2015

Grindelwald, January 18-23 2015 - Hotel Schweizerhof

Lecture Plan

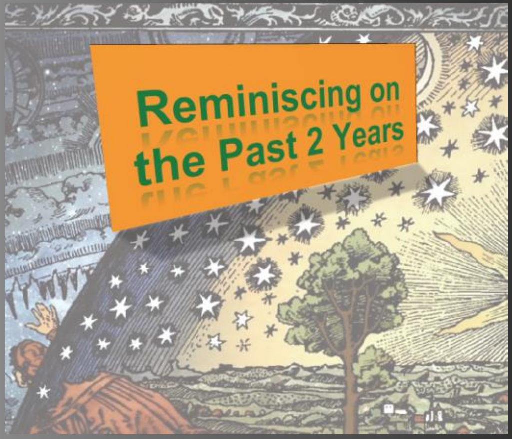
Overview of the 4 lectures in the next days

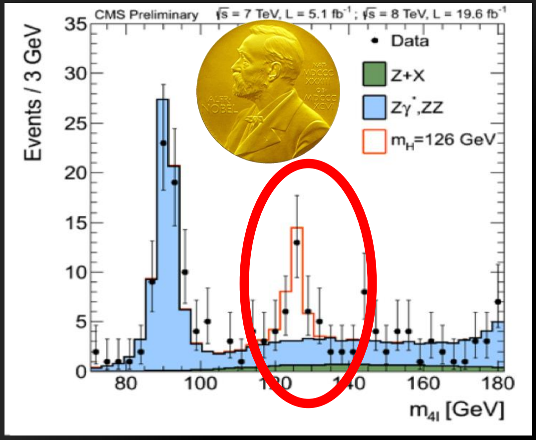
- Lecture 1: Introduction to Experimental Particle Physics at the LHC
- Lecture 2: Measurements and test of the Standard Model
- Lecture 3: The Higgs Boson
- Lecture 4: Searches beyond the Standard Model at the LHC



Outline Lecture III

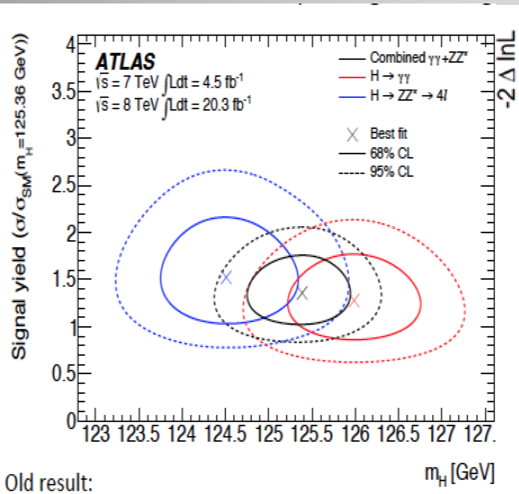
- Short introduction
- Standard Model Higgs channel studies overview
- Studies of Higgs properties
- Beyond the SM?
- Summary and Outlook

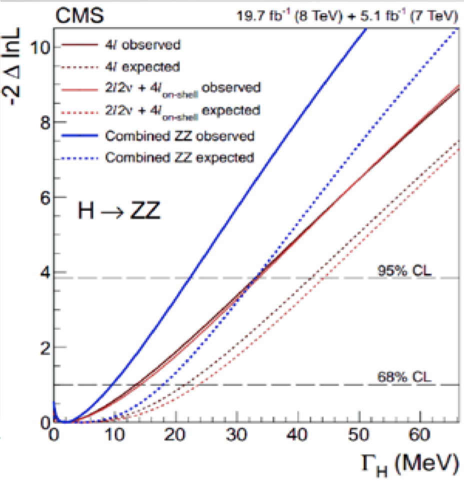


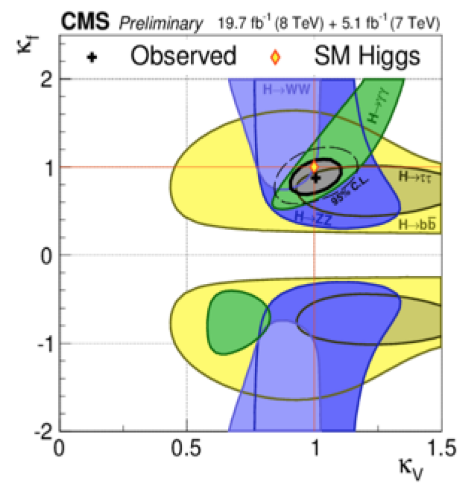


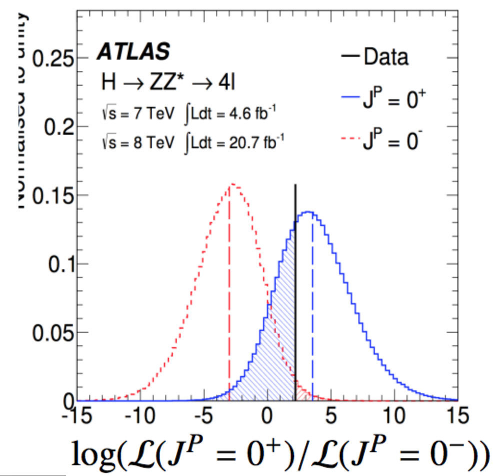
Brief Higgs Summary

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









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

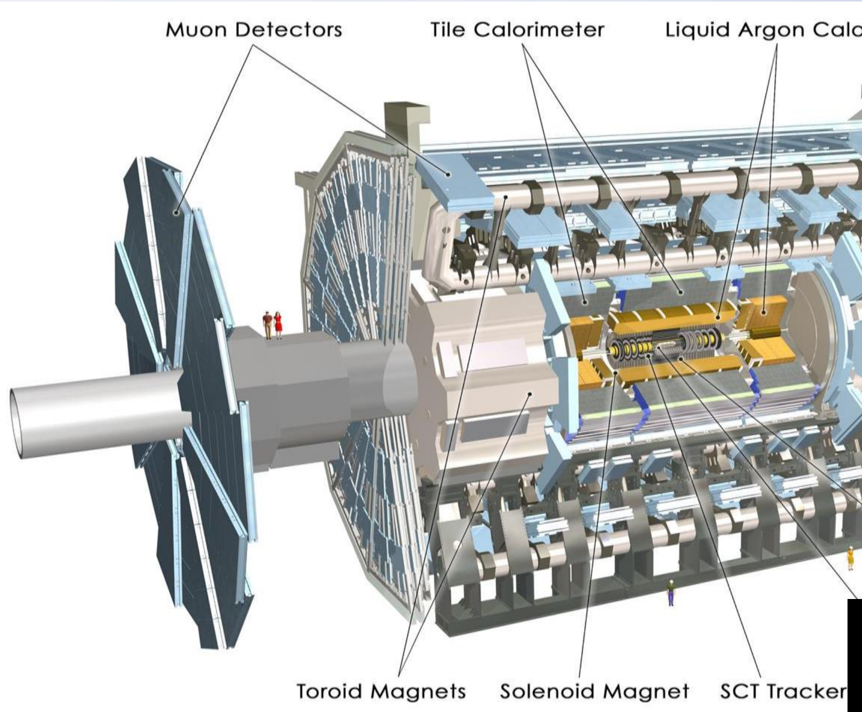
Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

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 Higgs Hunters @ the LHC

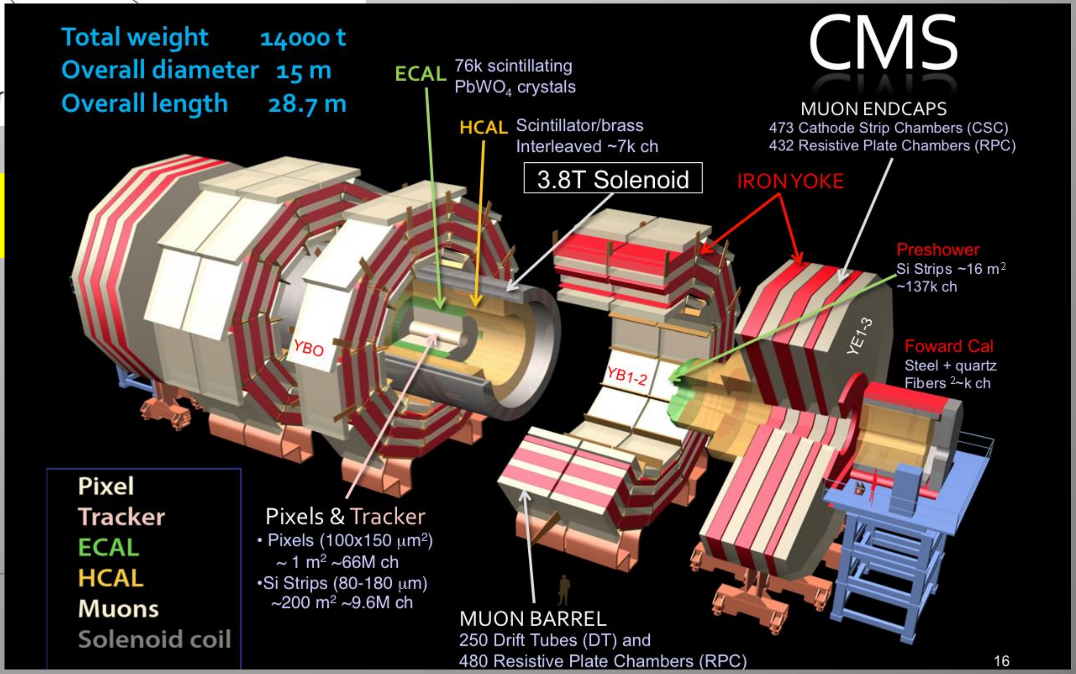


LHC: pp collisions
Luminosity:
5 fb^{-1} @ 7 TeV
20 fb^{-1} @ 8 TeV

The ATLAS experiment

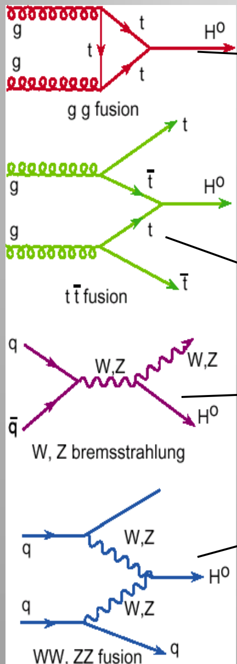
The CMS experiment

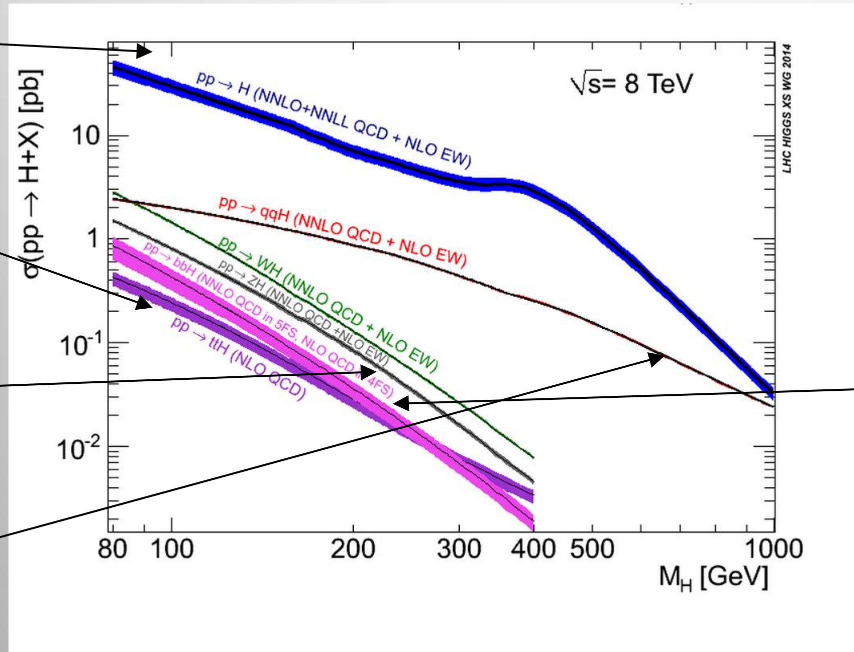
Excellent 4π-acceptance detectors that performed extremely well in 2010-2013!



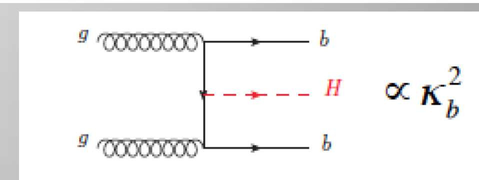
And LHCb…?

Higgs Production & Decay



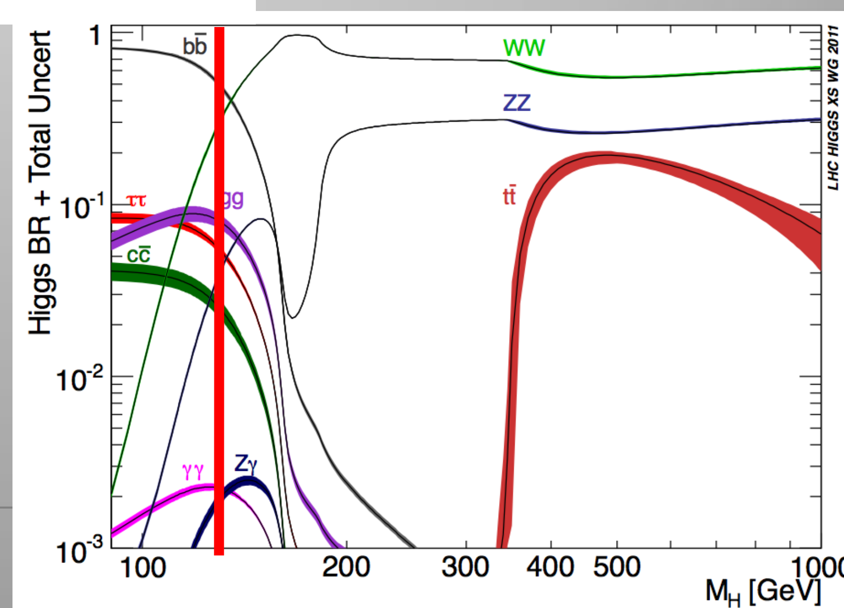


Processes
- •Gluon fusion
- •Vector Boson Fusion
- •W/Z associated prod.
- •Top associated prod
- •B-quark associated prod?



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 - 110-1000 lnu	110-600	4.9+19.5	20%
H -> ZZ -> 4l	110-1000	5.1+19.6	1-2%

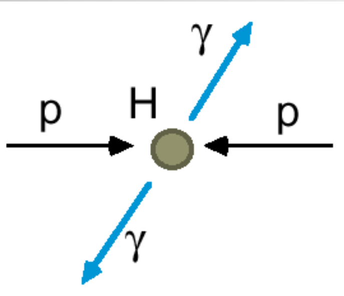
Higgs Boson Searches (simulation)

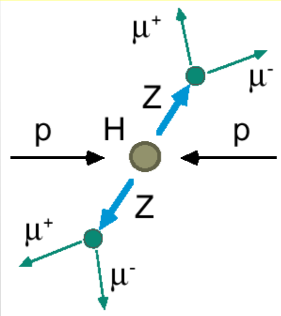
Low M_H < 140 GeV/c²

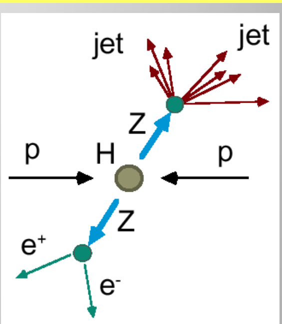
Medium 130<M_H<500 GeV/c²

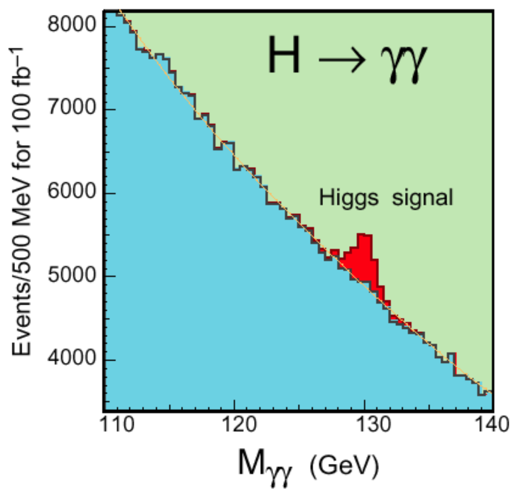
High M_H > 500 GeV/c²

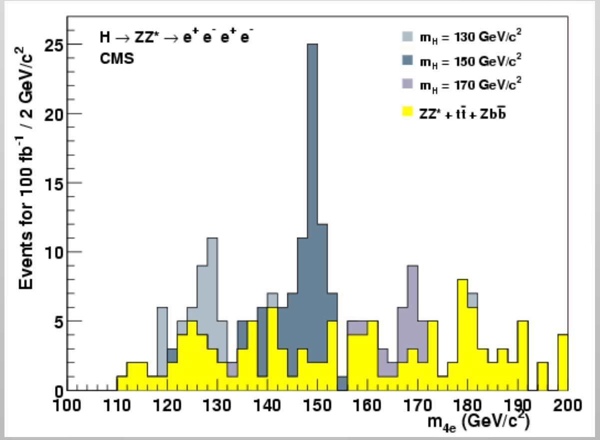
simulation

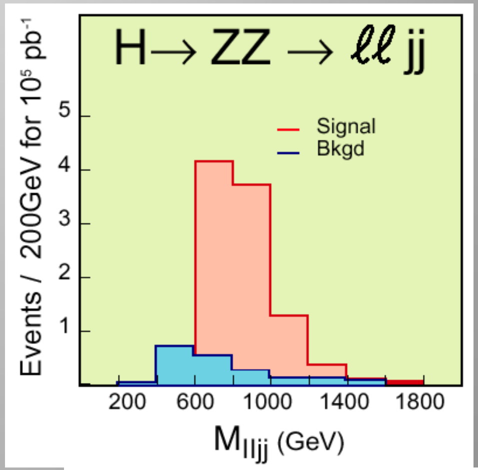


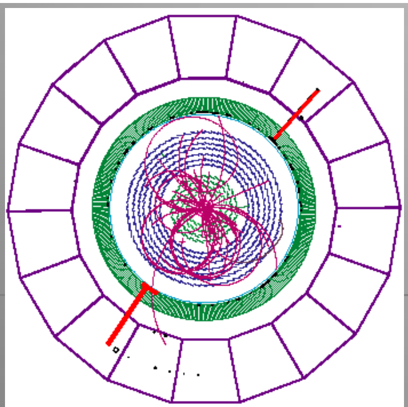


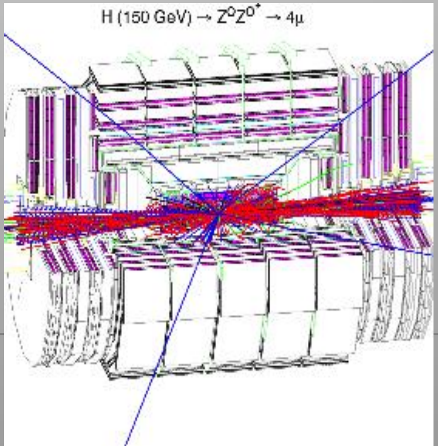


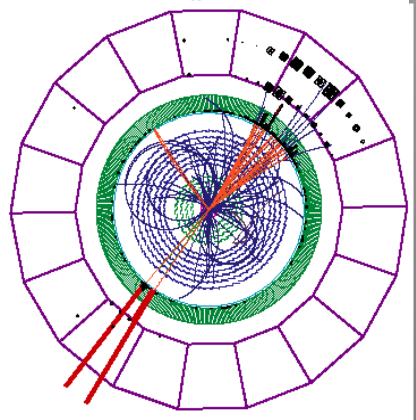




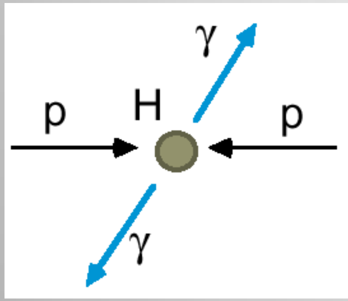




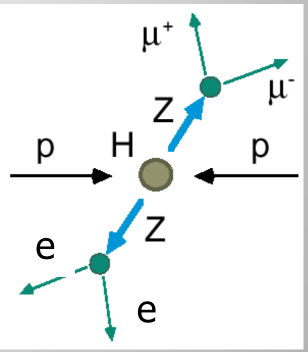


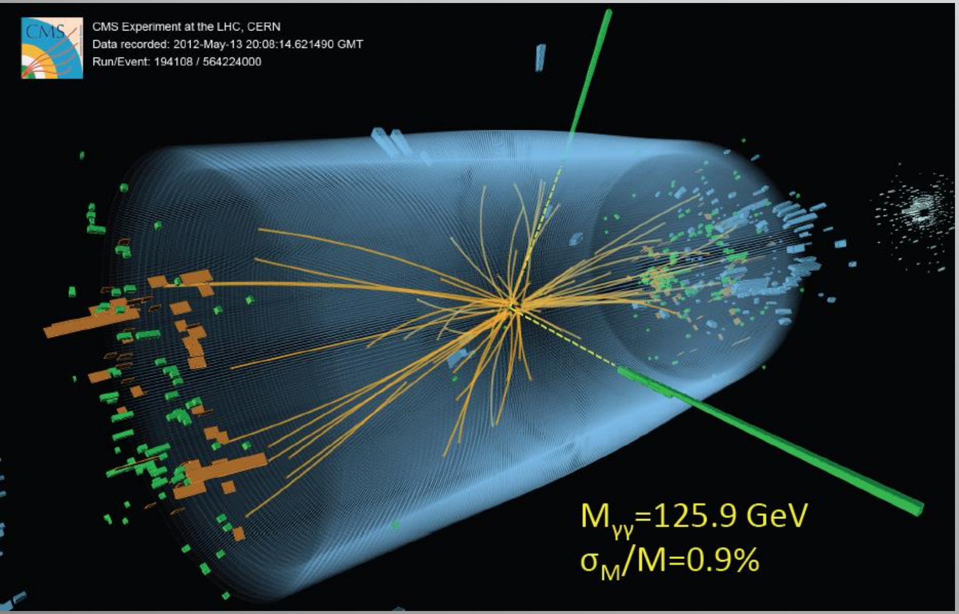


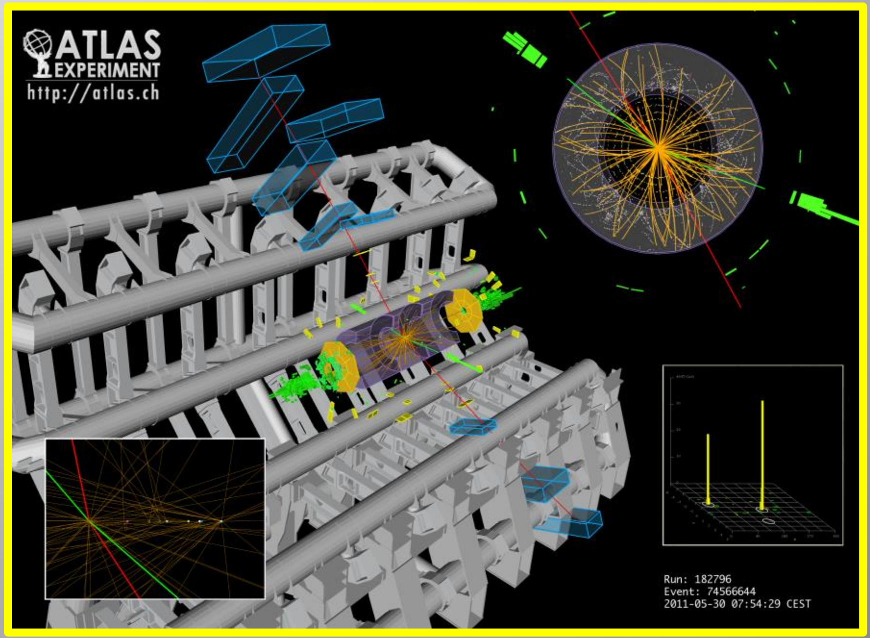
Collisions with a Higgs Candidate



A Higgs or
a ‘background’
process without
a Higgs?

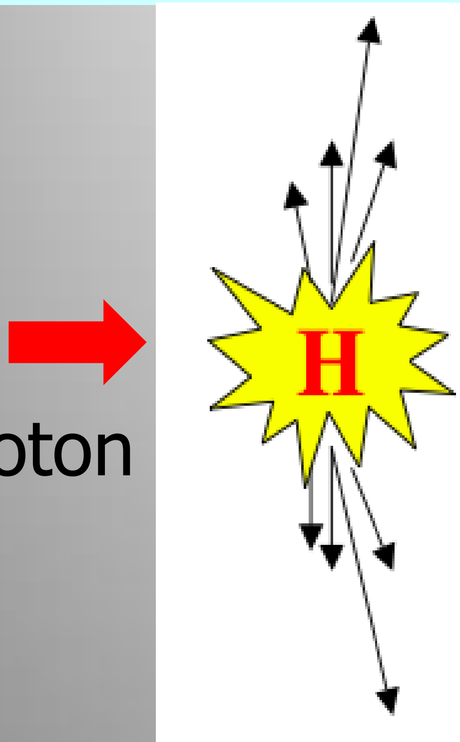


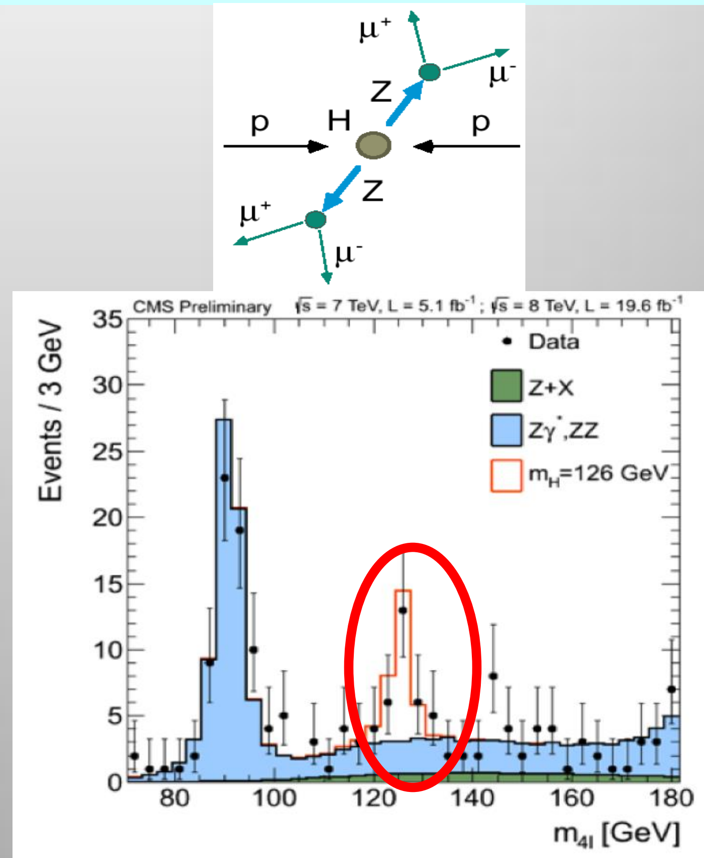




2012: A Milestone in Particle Physics

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



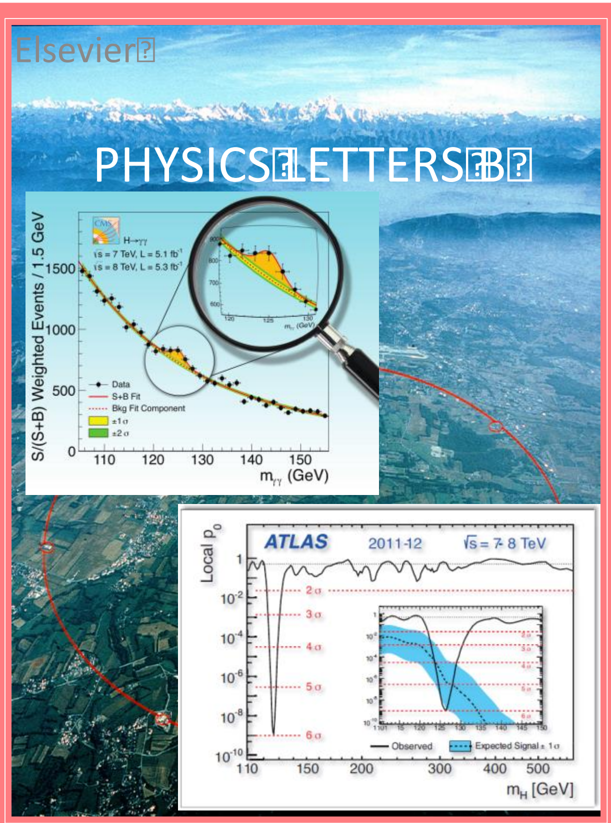


2013

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 paper so far...

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



More than 3800 times cited so far…

Also…

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 (0++), 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

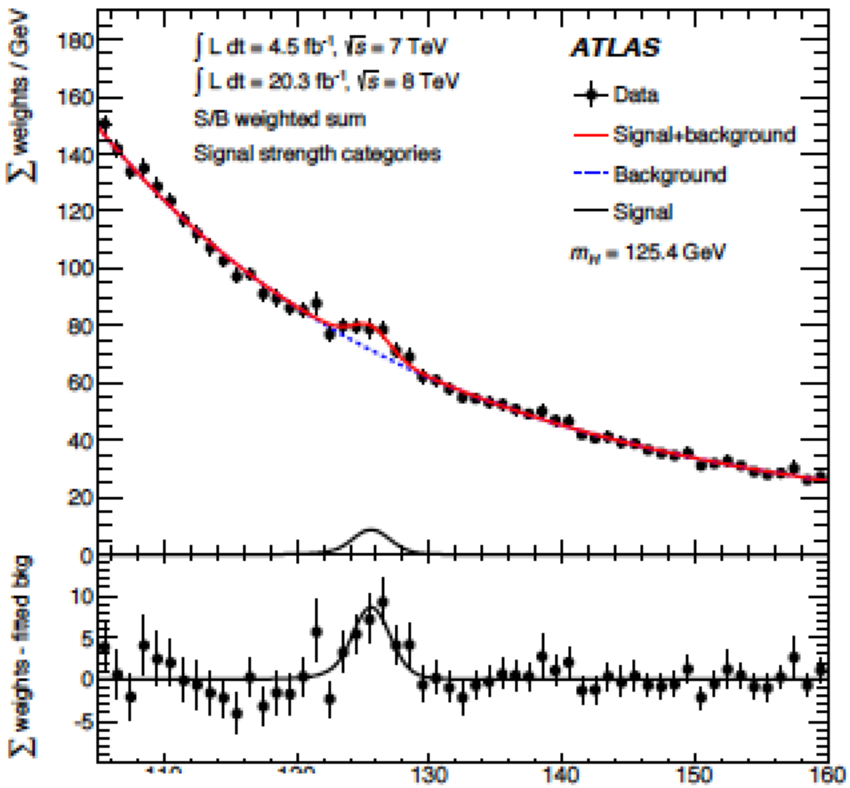
The Higgs is the new playground: Room for new experimental/theoretical ideas!!
Remember: we have already ~1 Million Higgses produced at the LHC

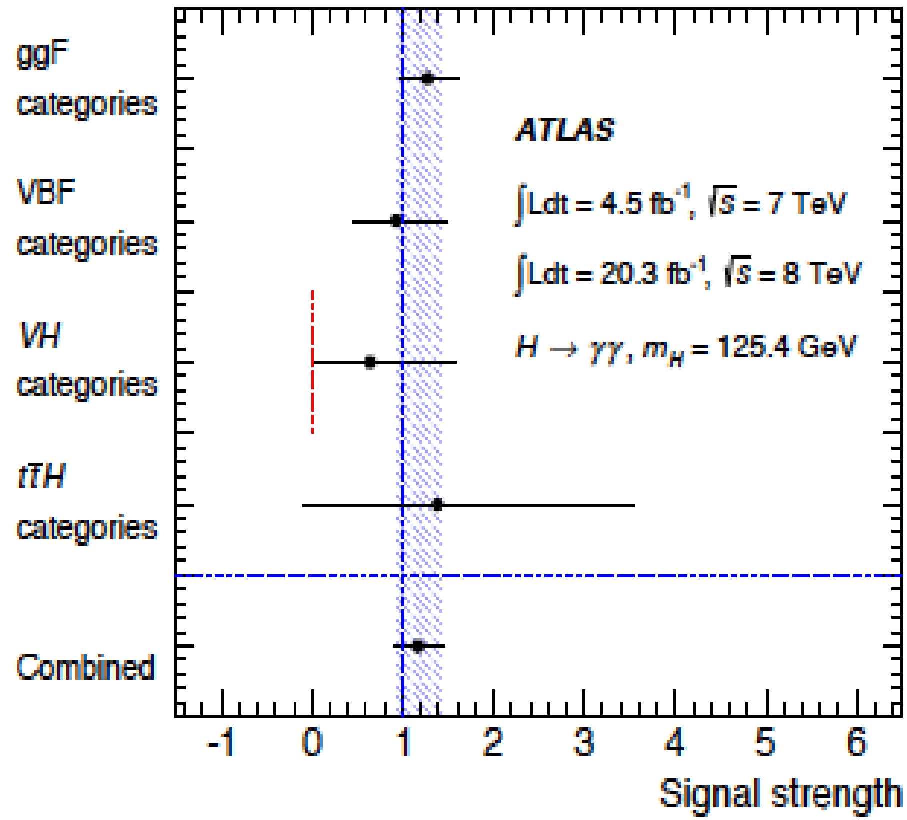
Status of Higgs analyses: Individual Channels

ATLAS: Higgs → γγ

arXiv:1408.7084

Significance: Expected 4.6σ Observed 5.2σ





arXiv:1408.7084

$$\mu = 1.17 \pm 0.27$$

For M_H=125.4 GeV

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

Especially new calibrations for electromagnetic showers…

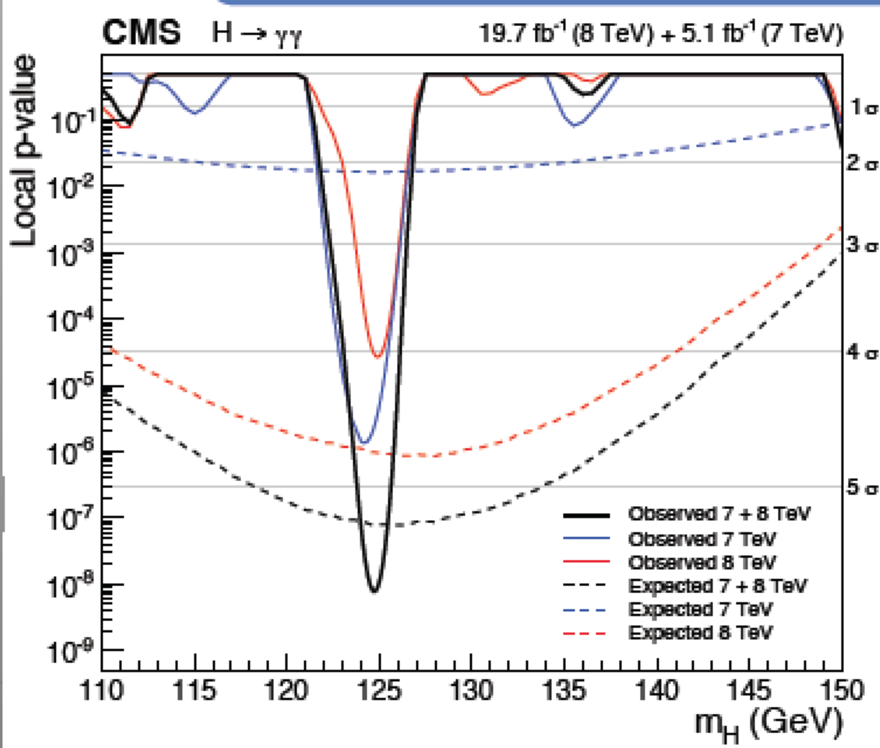
CMS: Higgs → γγ

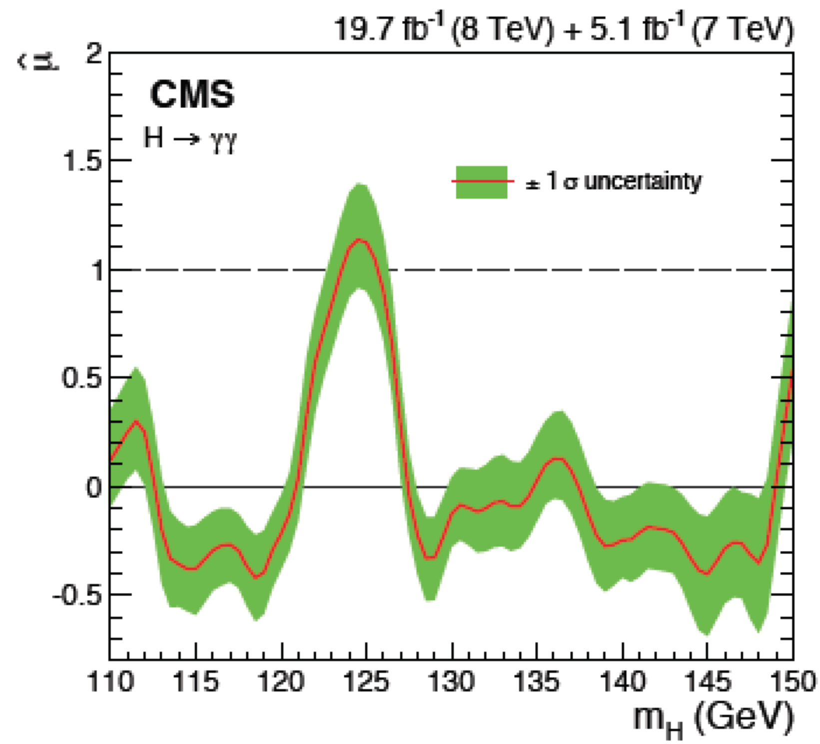
Signal Strength:

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**

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

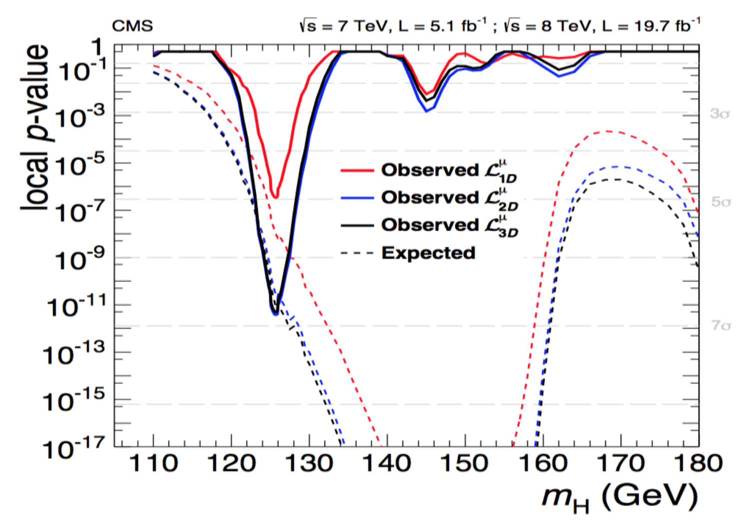


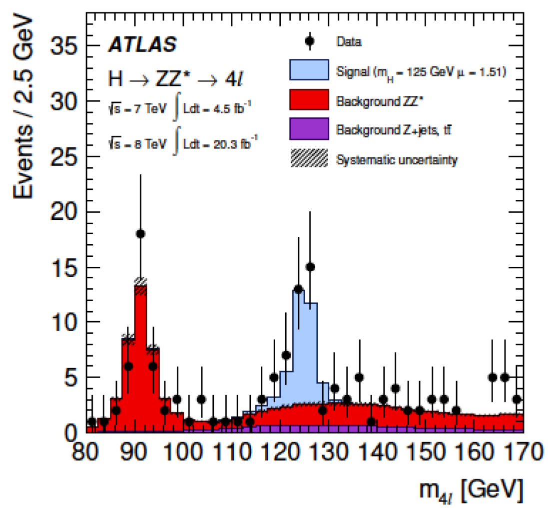


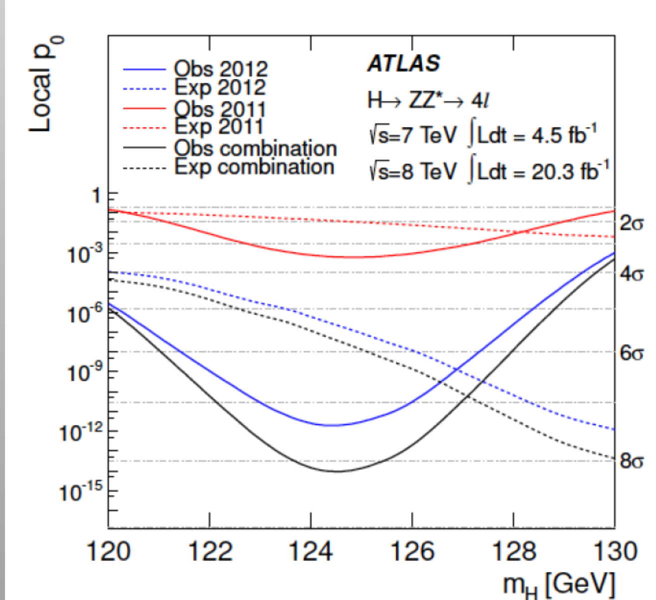
The Decay H → ZZ → 4l

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







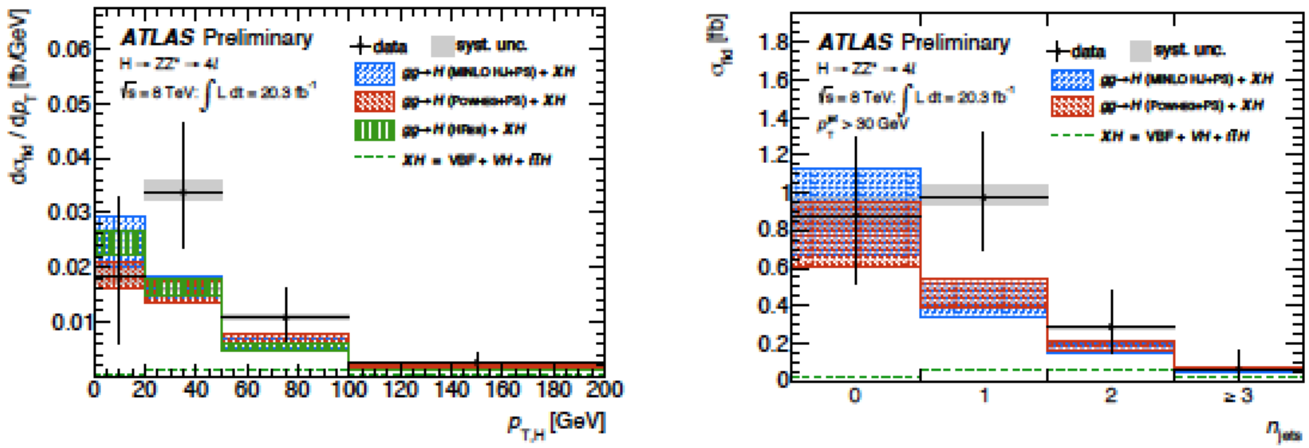
ATLAS: Expected: 6.0σ Observed: 8.1σ
→ $\mu = 1.44^{+0.40}_{-0.33}$
CMS: Expected: 6.7σ Observed: 6.8σ
→ $\mu = 0.93^{+0.29}_{-0.24}$

Significance is well over 6 standard deviations in this channel

ATLAS: Higgs → ZZ and γγ

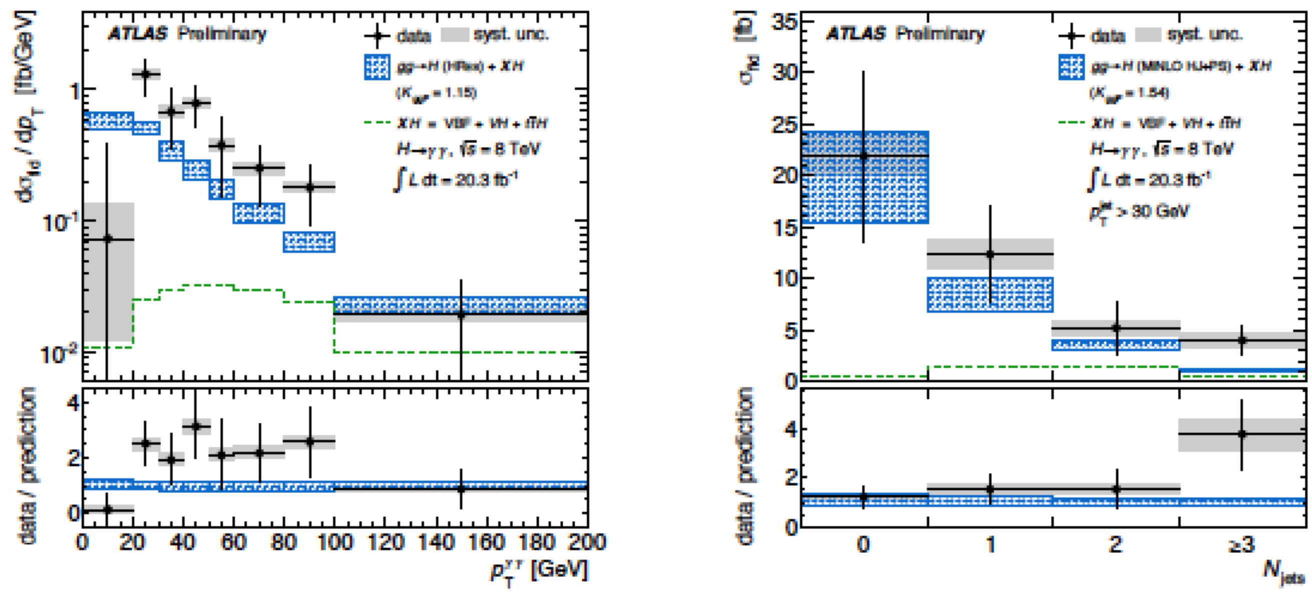
Differential distributions (& fiducial cross sections)

H→ ZZ



arXiv:1408.322
6
arXiv:1407.4222

H→ γγ

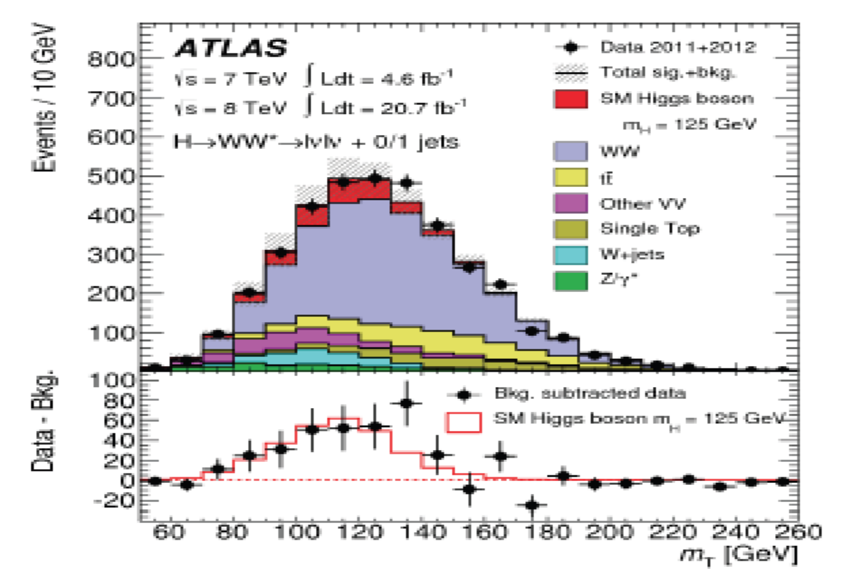


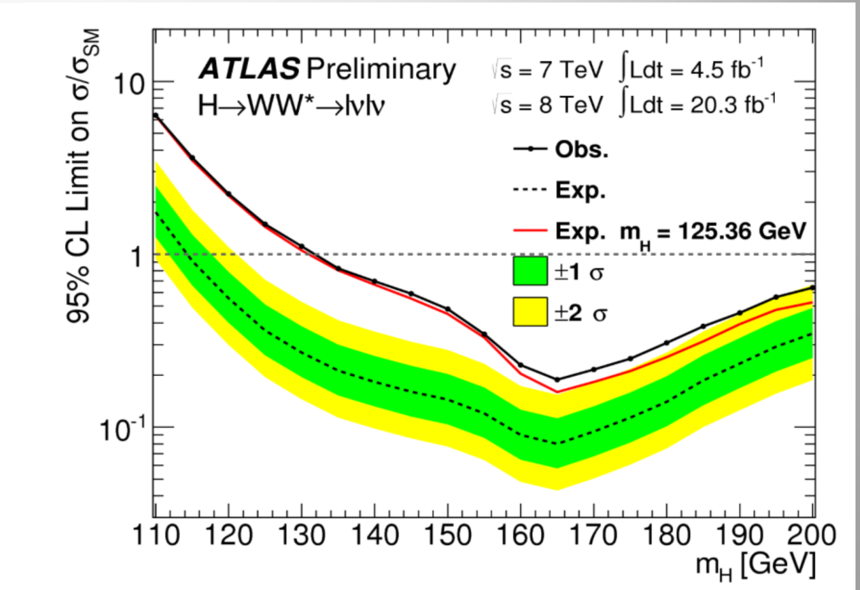
Still limited sensitivity
but shows the potential!

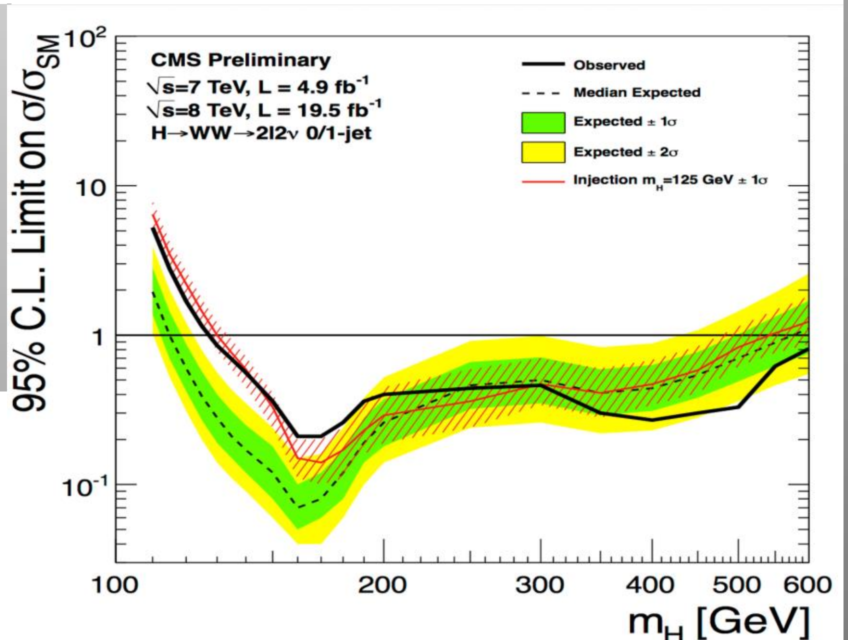
The Decay → WW → 2l 2ν

ATLAS: arXiv:1412.2641
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

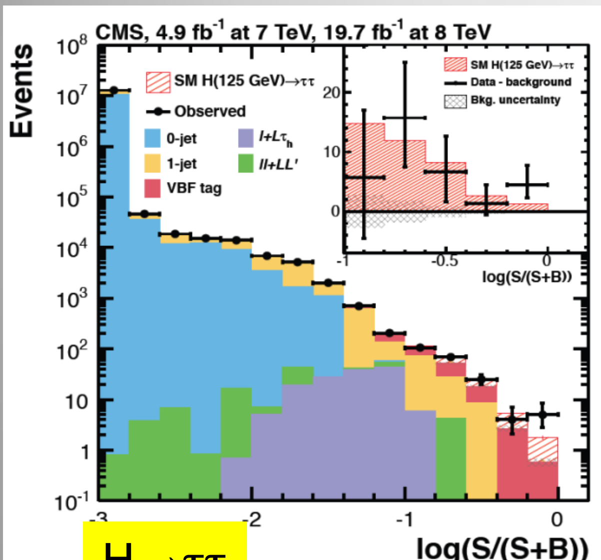




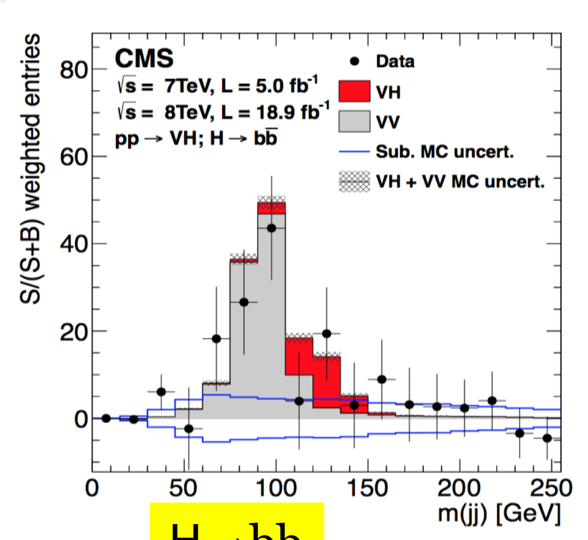


ATLAS @125.3 GeV: Expected: 5.8σ Obs: 6.1σ
→ $\mu = 1.09^{+0.23}_{-0.21}$
CMS @ 125 GeV: Expected: 5.8σ Obs: 4.3σ
→ $\mu = 0.72^{+0.20}_{-0.18}$

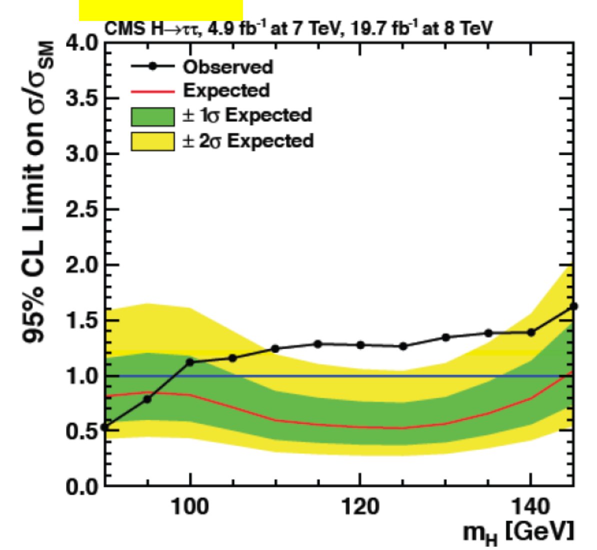
The Decay Higgs to Fermions

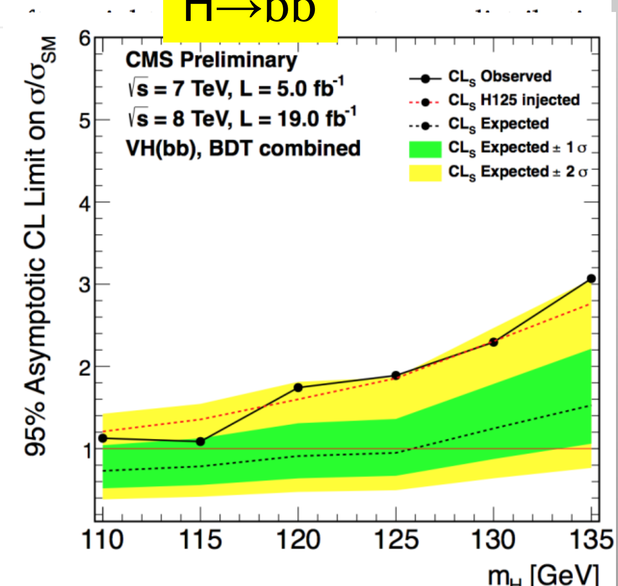


H→ττ



H→bb





H-> bb
Associated production channels: ZH and WH

H-> tau tau
Inclusive and with jets
All tau decay modes used

A (mild) excess seen in both channels
Poor mass resolution

arXiv1401.5041
arXiv1310.3687

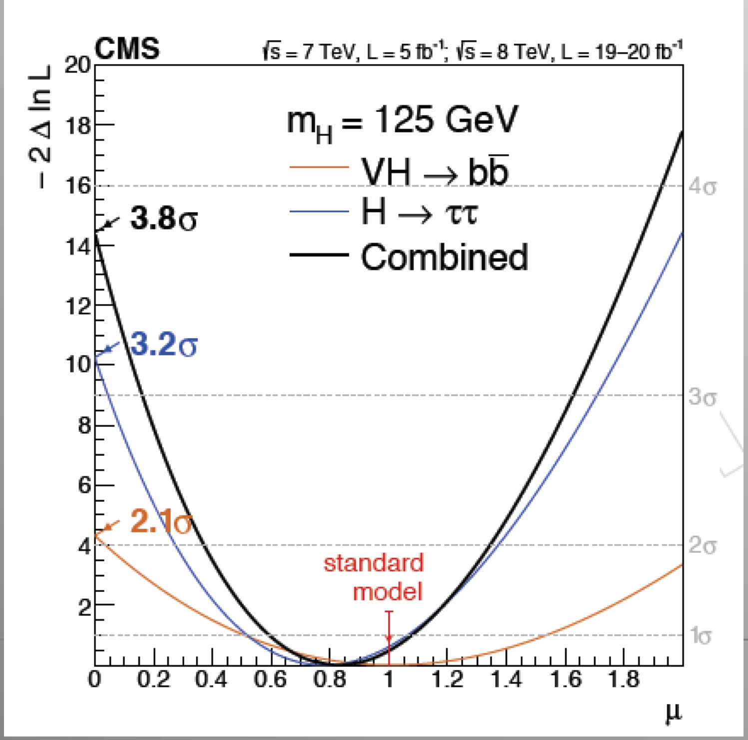
CMS @ 125 GeV
H→ττ 3.2σ (obs) 3.7σ (exp)
→ $\mu = 0.78^{+0.27}_{-0.27}$
H→bb 2.1σ (obs) 2.1σ (exp)
→ $\mu = 1.0 \pm 0.5$

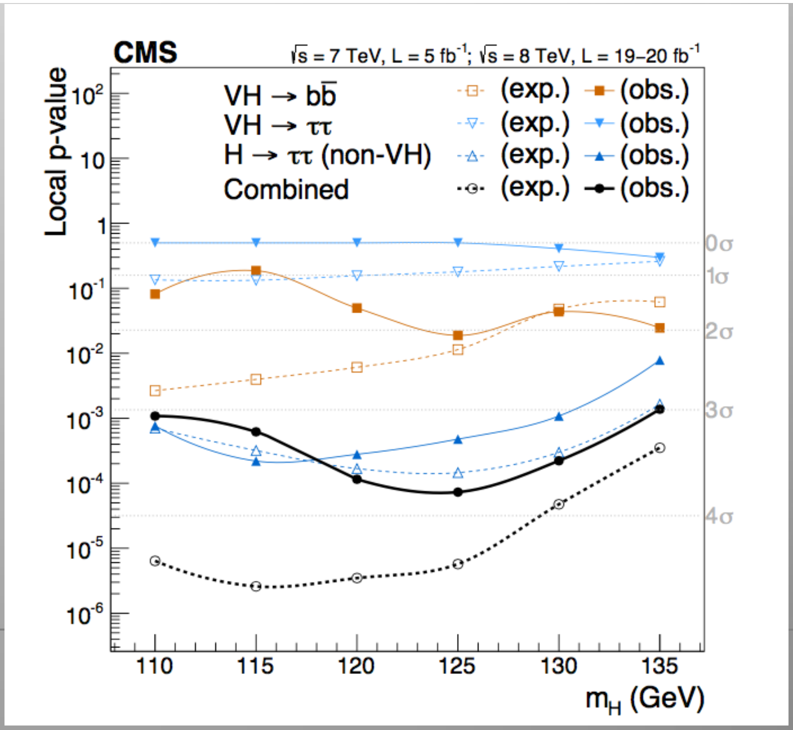
Higgs → Fermions Combination

- 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 ($m_H = 125\,\mathrm{GeV}$)	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 → Fermions Combination

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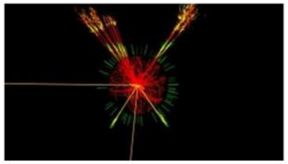
Evidence found for the Higgs boson direct decay into fermions

Jun 22, 2014



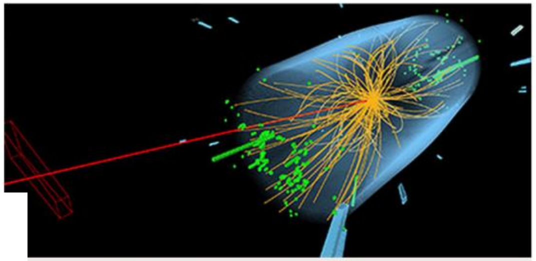
Simulated production of a Higgs event in ATLAS. Image credit: CERN.

For the first time, researchers at CERN have found evidence for the direct decay of the Higgs boson into fermions—another strong indication that the particle discovered in 2012 behaves in the way the standard model of particle physics predicts. Researchers

Higgs boson decays differently

Decay into quarks and leptons supports the standard model of particle physics

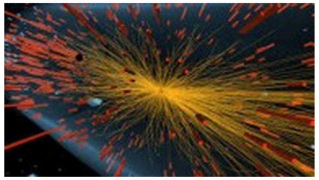
Confirmation for the Higgs: Physicists have for the first time demonstrated the second, postulated by the Standard Model decay of the Higgs boson. In data of the CMS experiment at the Large Hadron Collider (LHC), they discovered an excess of bottom quarks and tau leptons. This shows that the Higgs can not only decompose into other force particles, but also of matter, according to the researchers in the journal "Nature Physics".



:cay traces of a Higgs boson into a pair of tau leptons.
CMS Collaboration

23 giugno 2014

Nuove conferme per il bosone di Higgs



Cortesia Collaborazione CMS/CERN

La particella scoperta presso il Large Hadron Collider del CERN di Ginevra si comporta proprio come il bosone di Higgs previsto dal modello standard della fisica delle particelle. La conferma viene da una nuova analisi dei dati raccolti con l'esperimento CMS che ha mostrato che il bosone di Higgs può decadere anche in una coppia di fermioni, e non solo di bosoni

(red)

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June 23, 2014

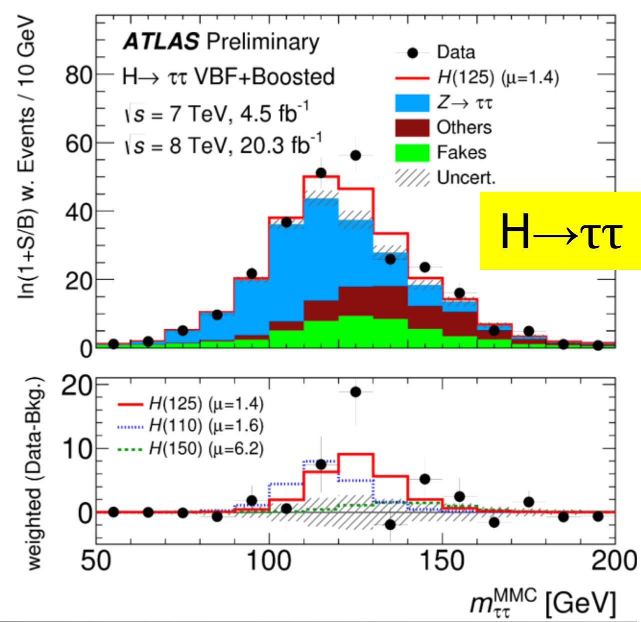
Nuevas medidas sc
Higgs

El descubrimiento del bosón de Higgs en 2012 portadores de fuerzas en la naturaleza. Ahora encontrado evidencias de la desintegración direc materia, y con una tasa que se ajusta al modelo est

http://www.altmetric.com/details.php?citation_id=2456622

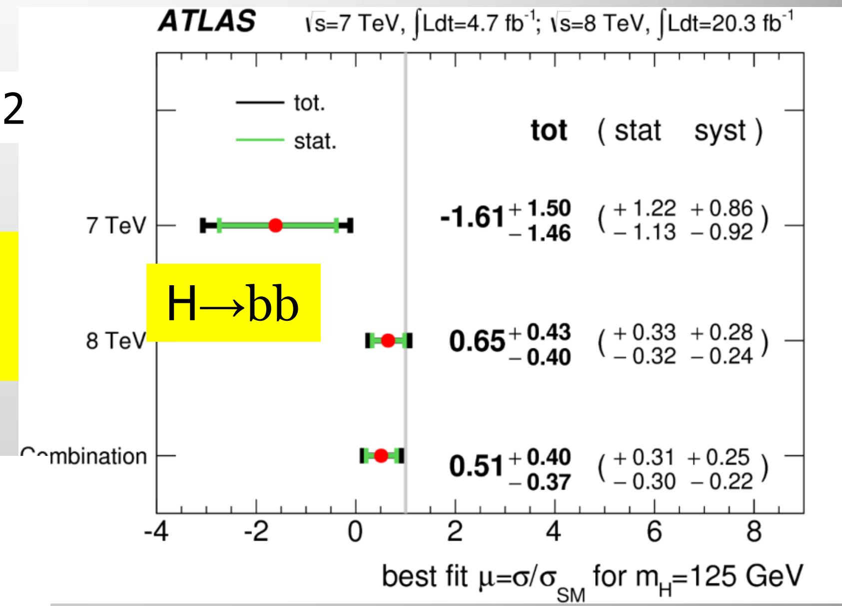
Altametric considers citations in blogs and social media.
The paper is actually the highest ranked Nature Physics paper.
It's actually the highest scoring article in this journal that we've seen so fa
It's in the top 5% of all articles (2,789,380) ever tracked by Altmetric

ATLAS: Higgs to Fermions



arXiv:1409.6212

H->bb in WH channel



H-> bb:

Expected: 2.6σ

Observed: 1.4σ

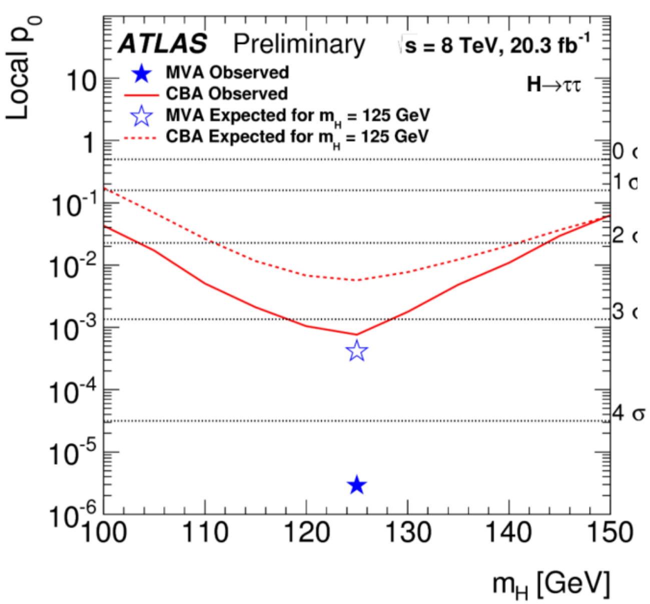
$\rightarrow \mu = 0.52^{+0.40}_{-0.37}$

H->tau tau

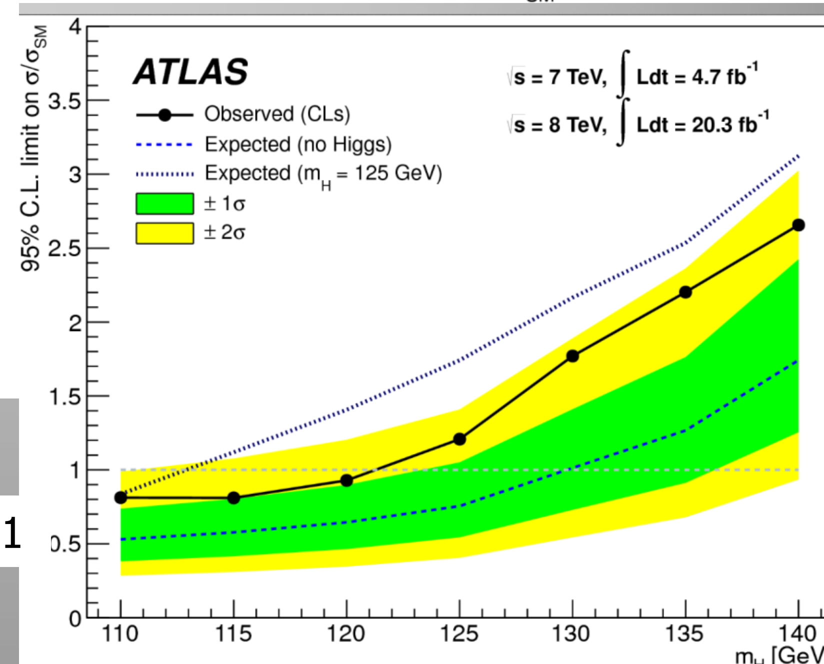
Expected: 3.5σ

Observed: 4.5σ

$\rightarrow \mu = 1.42^{+0.44}_{-0.38}$

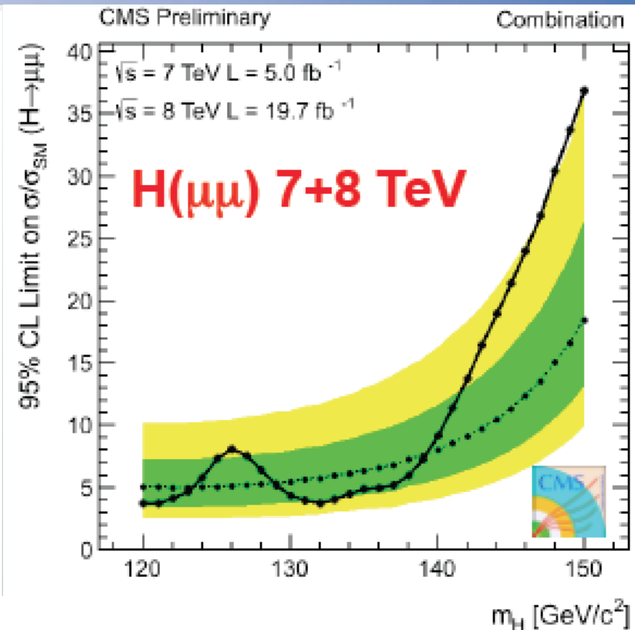


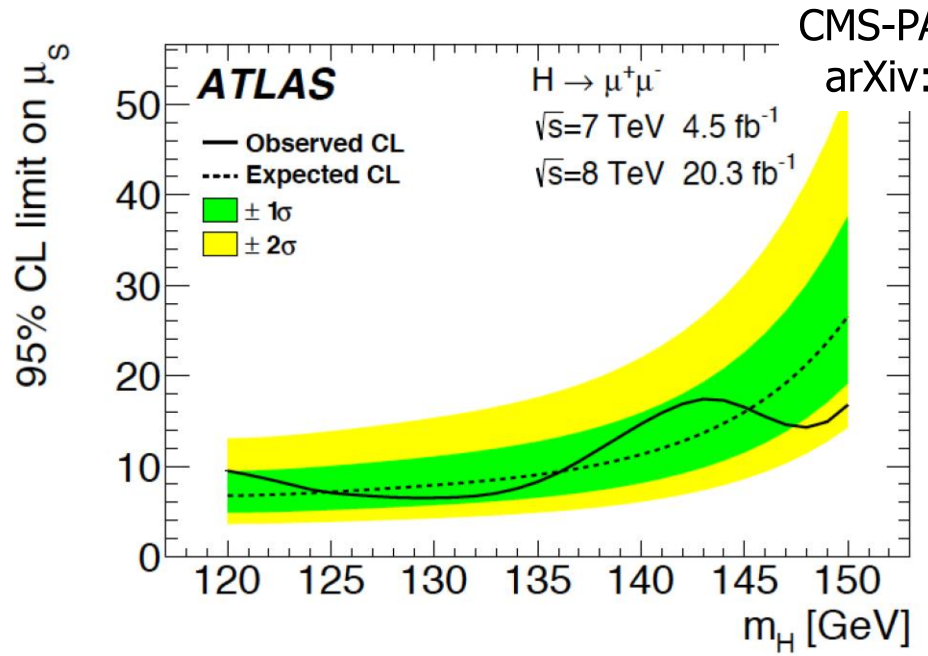
ATLAS-CONF-2014-061



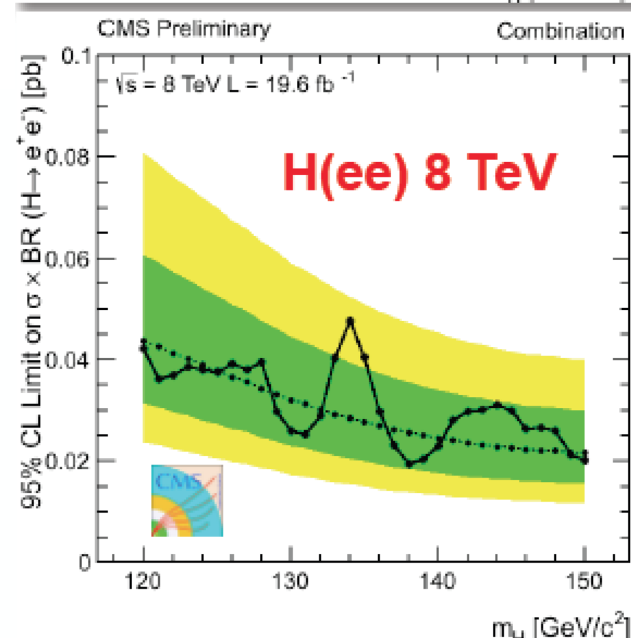
Higgs → μμ (ee)

- 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: μ < 7.0 (7.2 expected) @ 95% CL
  CMS: μ < 7.4 (5.1 expected) @ 95% CL
  BR(H→ee) < 1.7×10^{-3} @ 95% CL





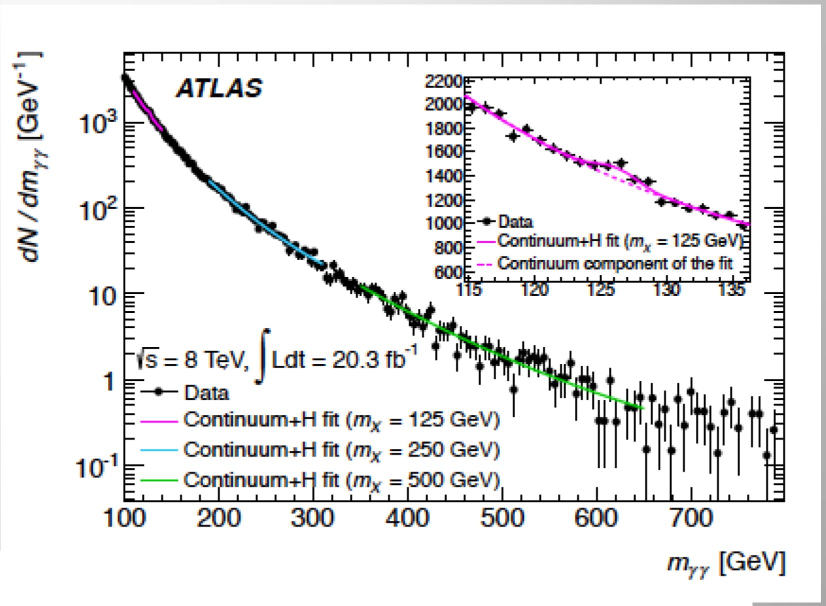
CMS-PAS-HIG-13-007
arXiv:1406.7663

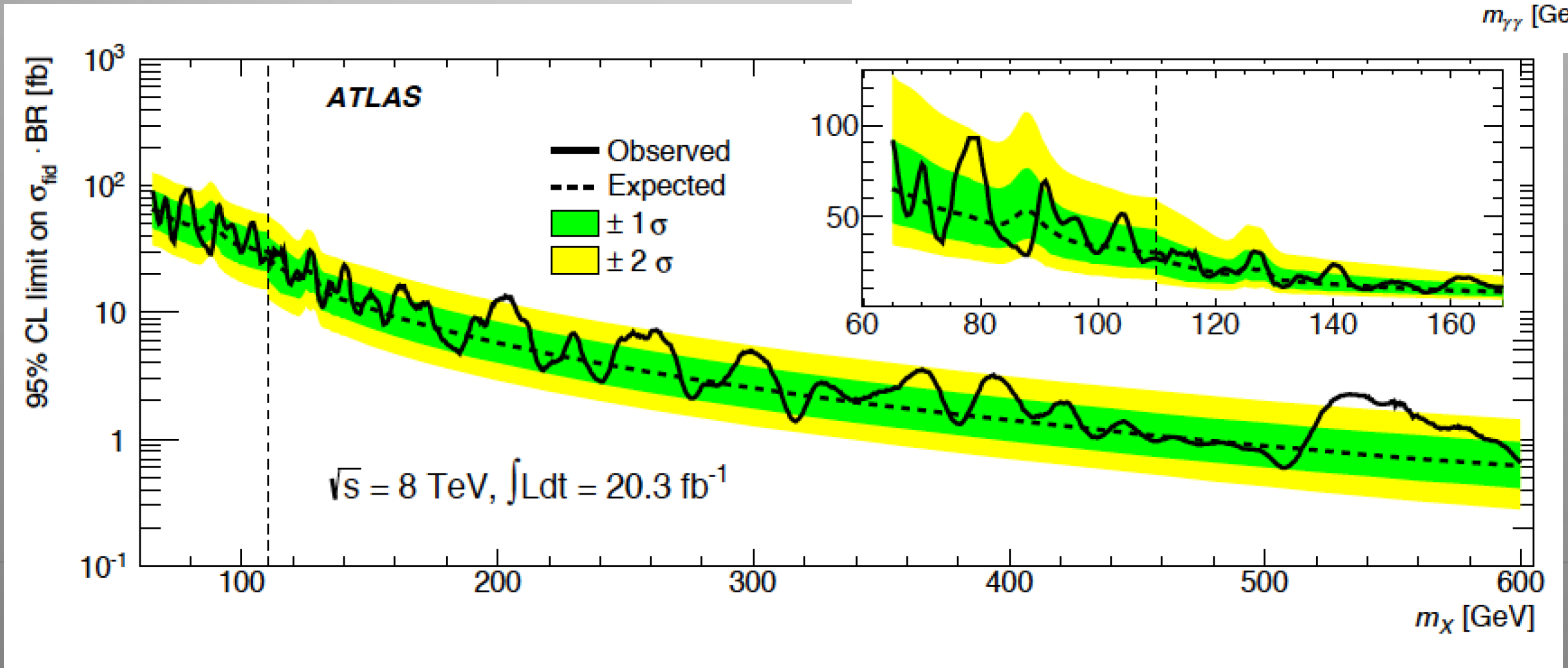


High Mass Search: Higgs → γγ

arXiv:1407.6583

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





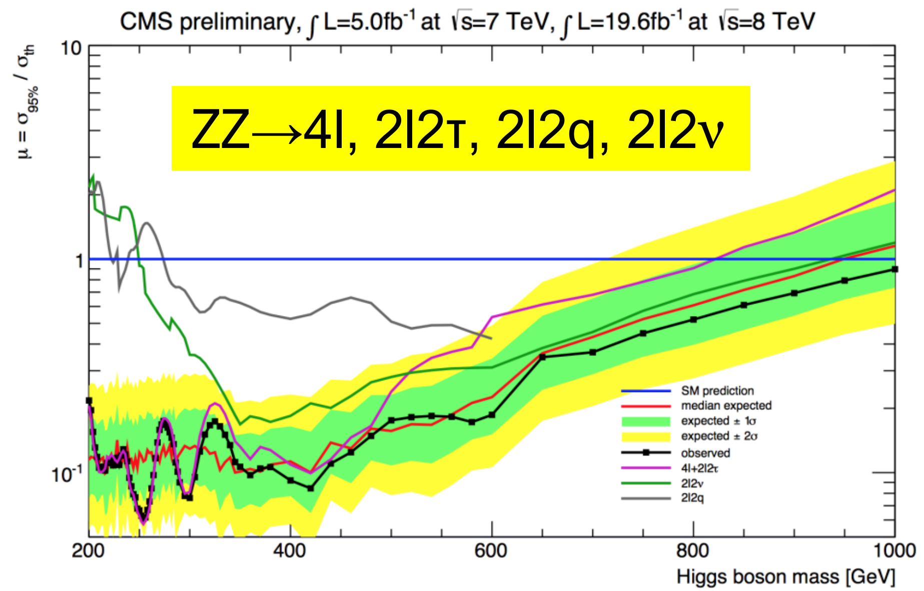
High Mass Search: Higgs → ZZ,WW

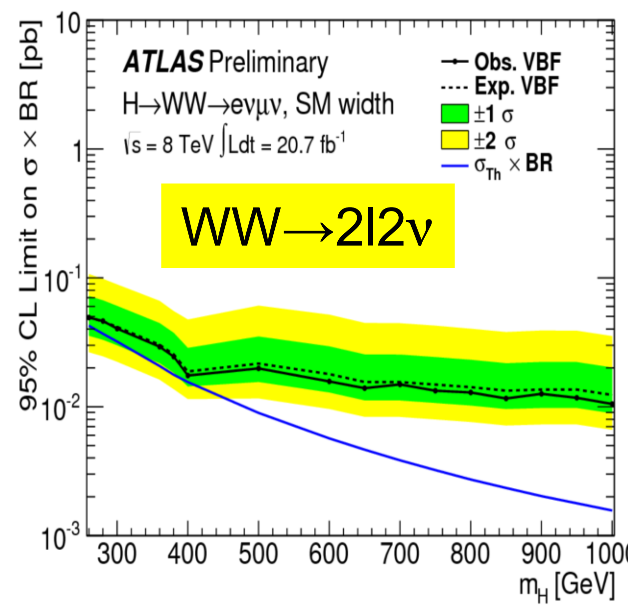
High mass Higgs searches with SM channels WW, ZZ updated with 2012 statistics

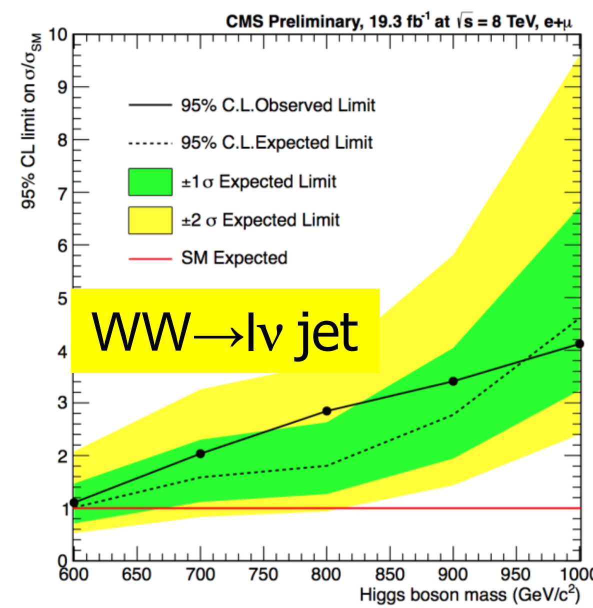
Sensitivity reaches now up to ~ 1 TeV

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

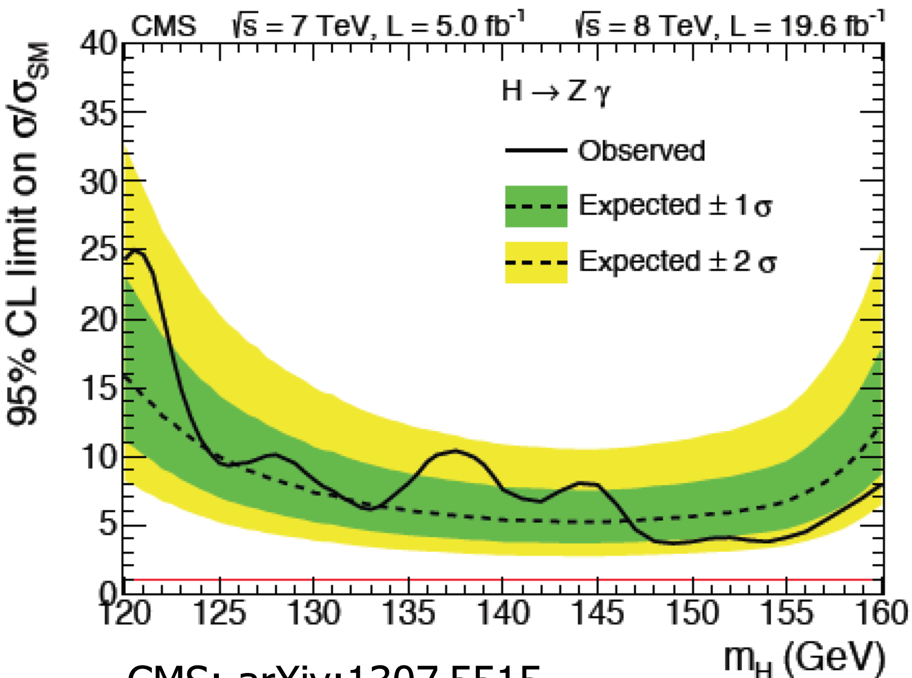
CMS-PAS-13-008
CMS-PAS-13-014
CMS-PAS-12-024
ATLAS-CONF-2013-067



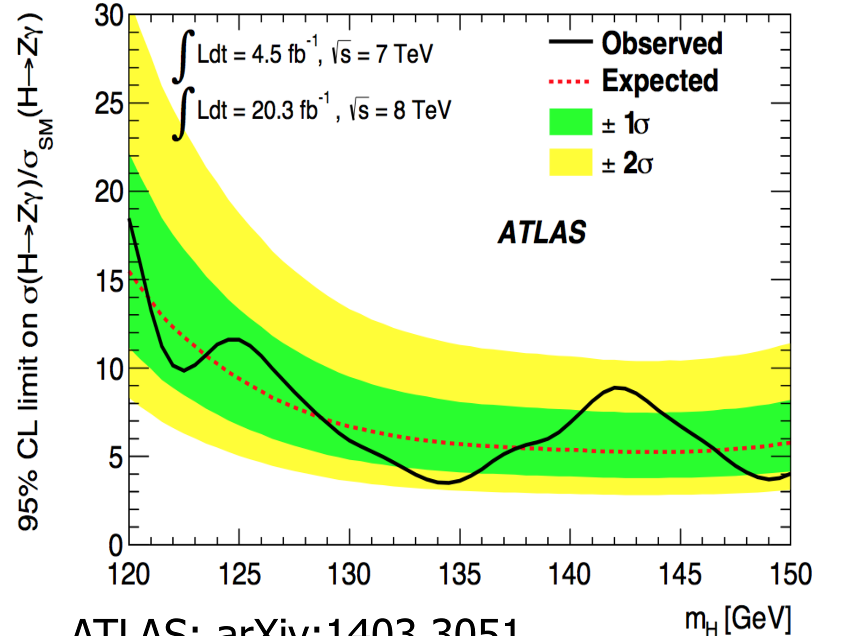




The Decay H→ Zγ



CMS: arXiv:1307.5515



ATLAS: arXiv:1403.3051

- 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

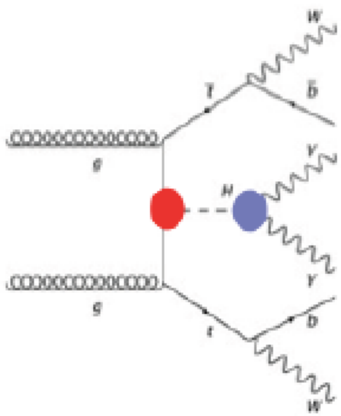
About a factor 10 above SM sensitivity

In certain models this channel could be largely enhanced via loops

Higgs-Top Associated Production

Various decay modes of the Higgs are considered

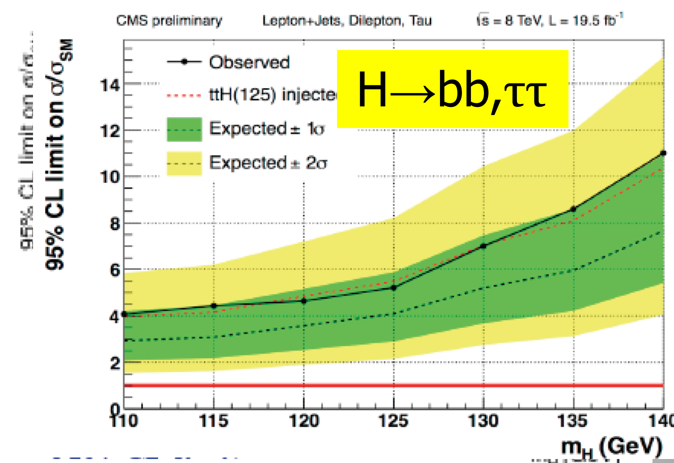
arXiv:1408.1682

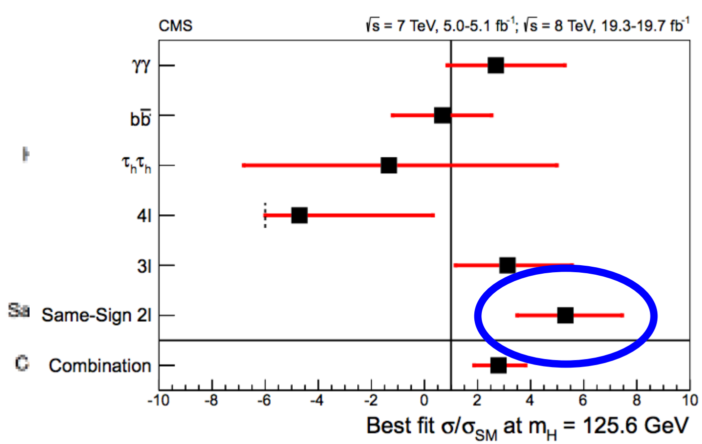


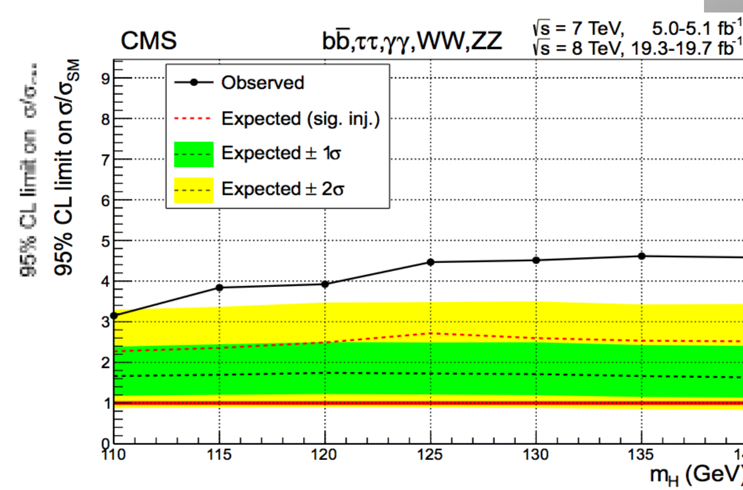
Probe of the H-top Yukawa coupling

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: $\mu < 4.5$ (1.7 expected) @ 95% CL $\mu = 2.8 \pm 1.0$

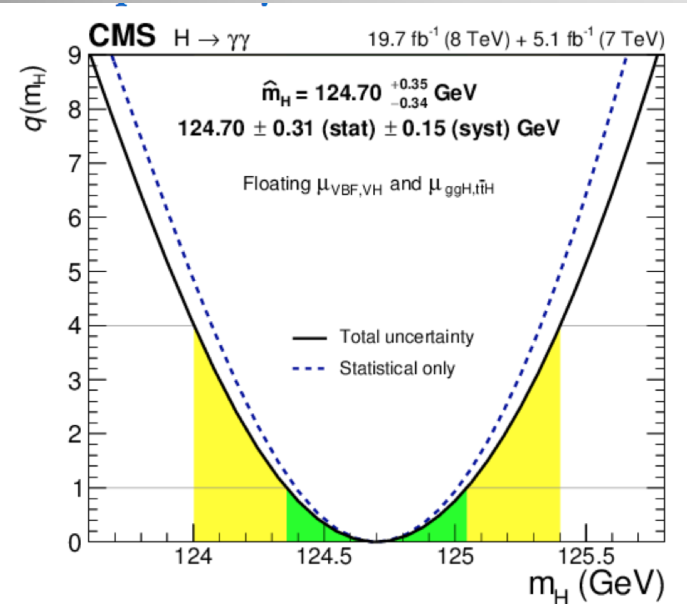
Improvement H->bb with matrix element methods: $\mu = 1.2{+1.6}{-1.5}$ CMS-PAS-HIG-14-010

The Mass of the New Particle

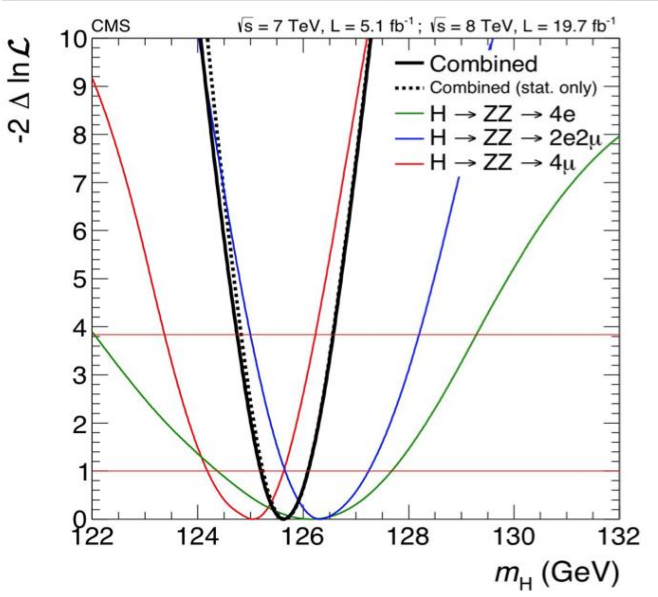
Determine the mass from ZZ and 2-photon channels which show a peak!

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

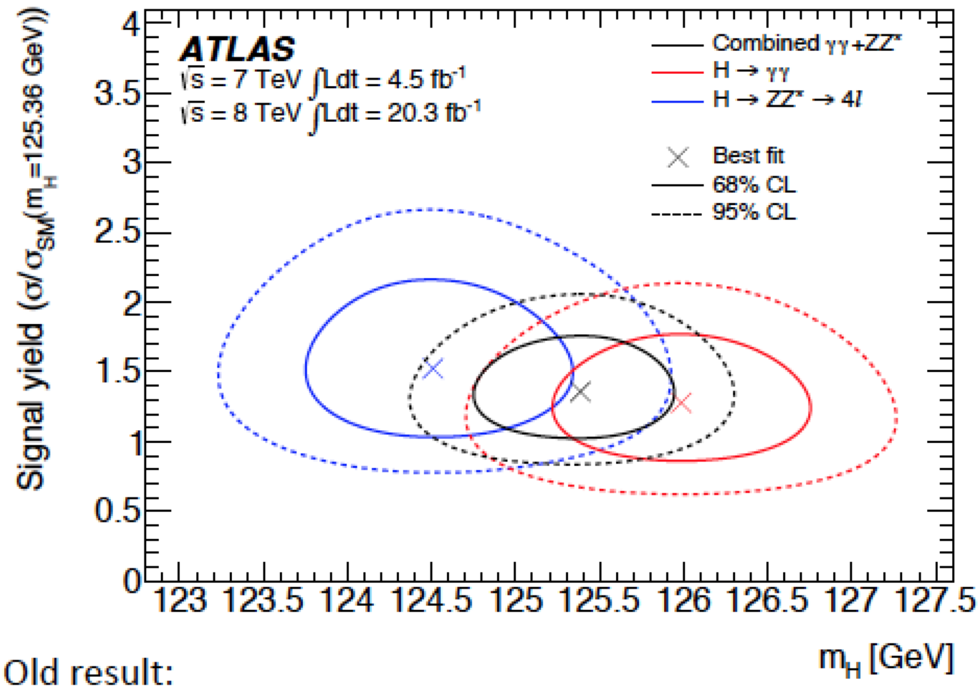
$$m_H = 125.02\,^{+0.26}_{-0.27}\,(\mathrm{stat})\,^{+0.14}_{-0.15}\,(\mathrm{syst})\,\mathrm{GeV} = 125.02\,^{+0.29}_{-0.31}\,(tot)\,GeV$$

Old value: 125.5 GeV

The Mass of the New Particle

Measurement of the Higgs boson mass
(and signal strengths)

ATLAS



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

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

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:

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

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

0.3% Precision measurement (statistical uncertainty dominant)

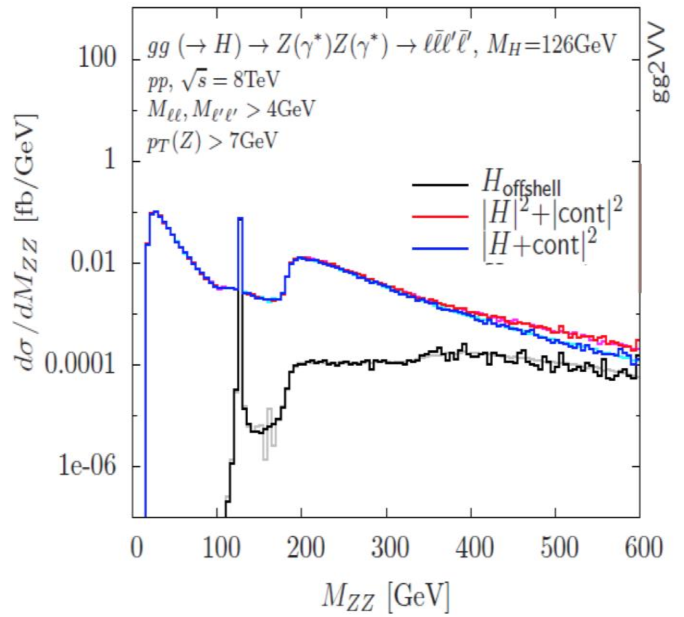
The Total Width of the Higgs

New in 2014

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



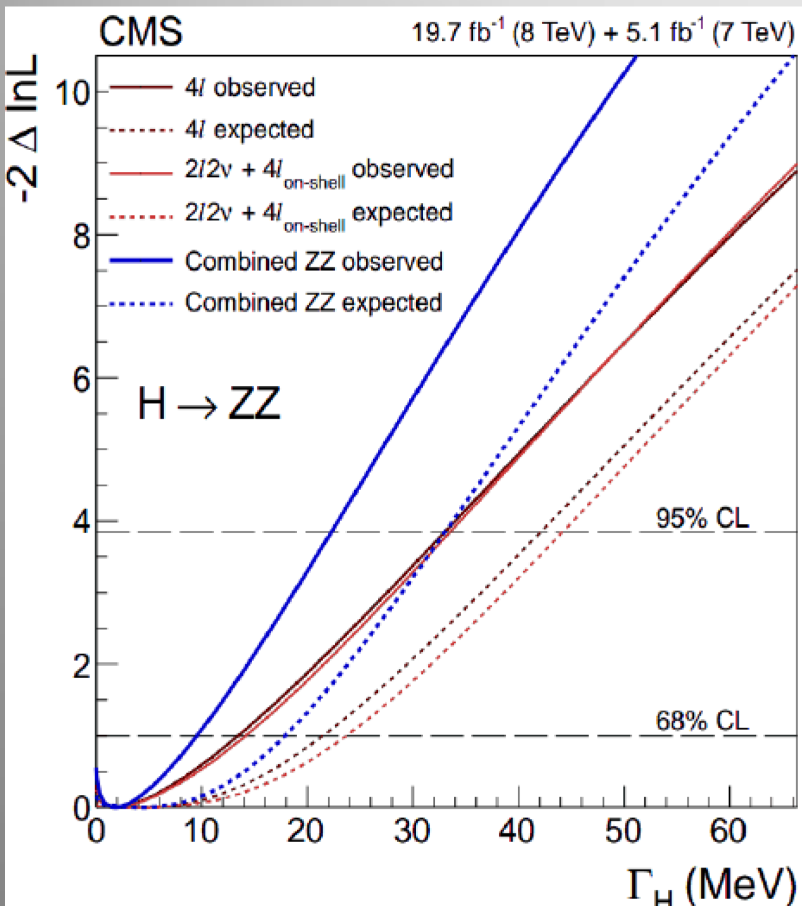
2012/13: Kauer, Passarino; Caola, Melnikov; Campbell, Ellis, Williams …

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

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

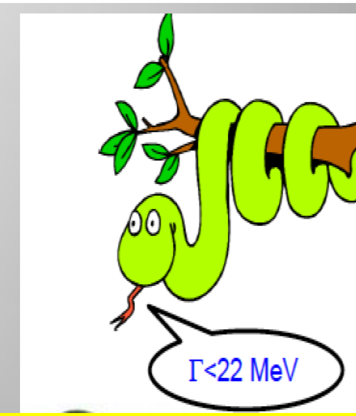
The Total Width of the Higgs

- 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

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



ICHEP: ATLAS!
ATLAS-CONF-2014-042

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

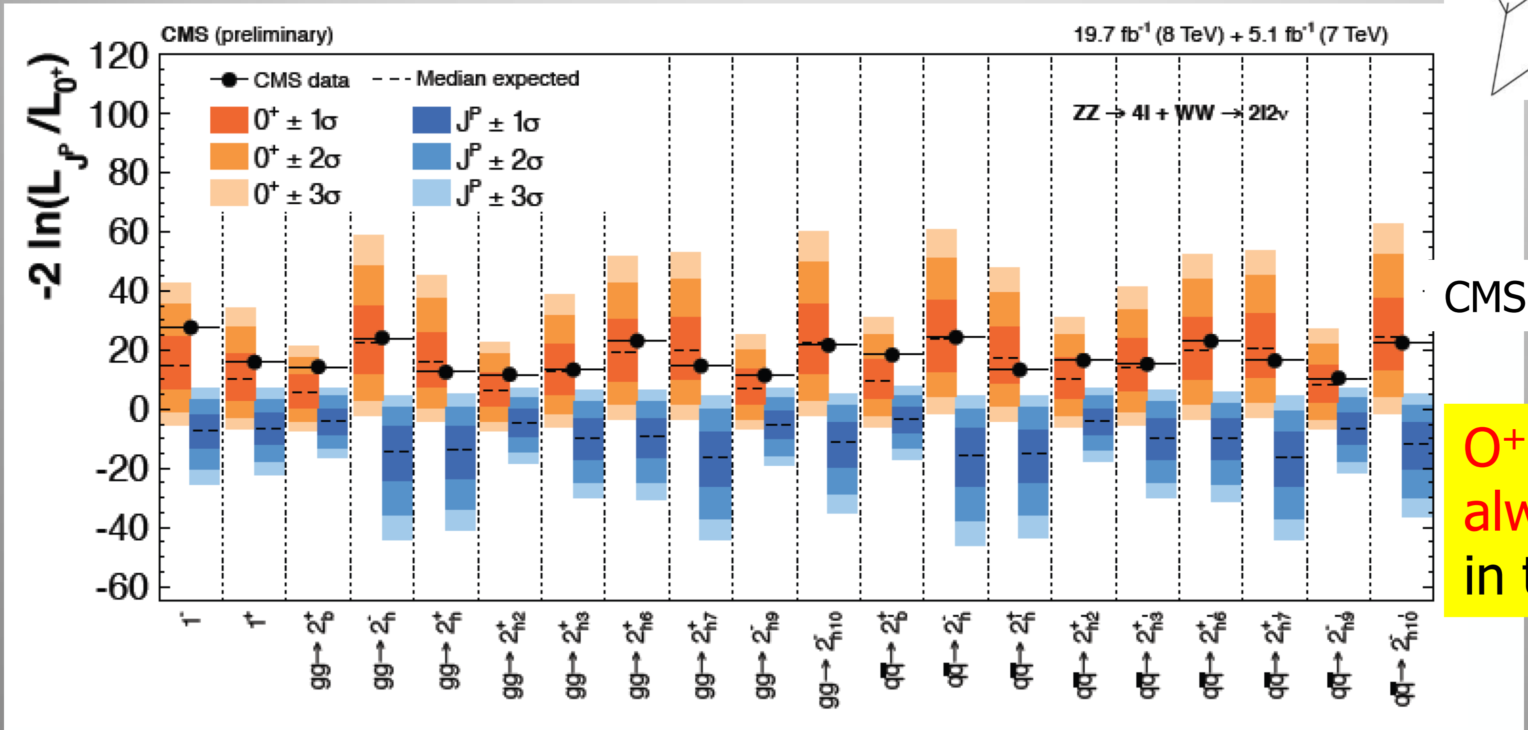
- **Combination** improves the individual limits by ~20%
- Compatibility between the observed results and the SM hypothesis lead to a **p-value of 0.24**

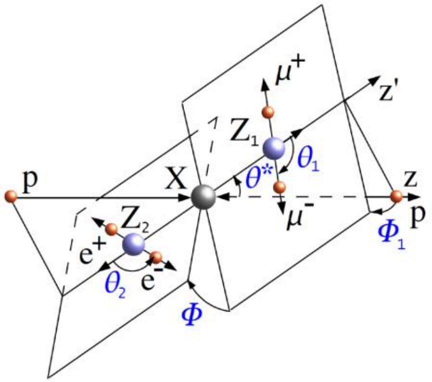
Issue with the Theory??

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

Spin-0 Amplitude in H→VV

- Anomalous couplings formalism:
  - a_1 is the SM amplitude.
  - Λ_1 is a higher-term of an expansion in momentum.
  - a_2 and a_3 control the CP-even and CP-odd amplitudes.
- Parameterized using fractions of cross-sections: f_{a1}, f_{a2}, f_{a3}, $f_{\Lambda 1}$.

$$A(X_{J=0} \to V_1 V_2) \sim v^{-1} \Bigg(\left[\boxed{a_1} - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{\left(\boxed{\Lambda_1}\right)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^*$$

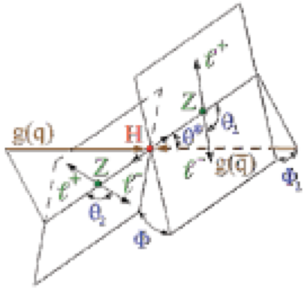
		a₂ terms CP-even (scalar)		a₃ terms CP-odd (pseudoscalar)
ZZ, WW	$+$	$a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu}$	$+$	$a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu}$
Zγ*	$+$	$a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu}$	$+$	$a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu}$
γ*γ*	$+$	$a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu}$	$+$	$a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \Bigg)$

a_2 terms
CP-even (scalar)

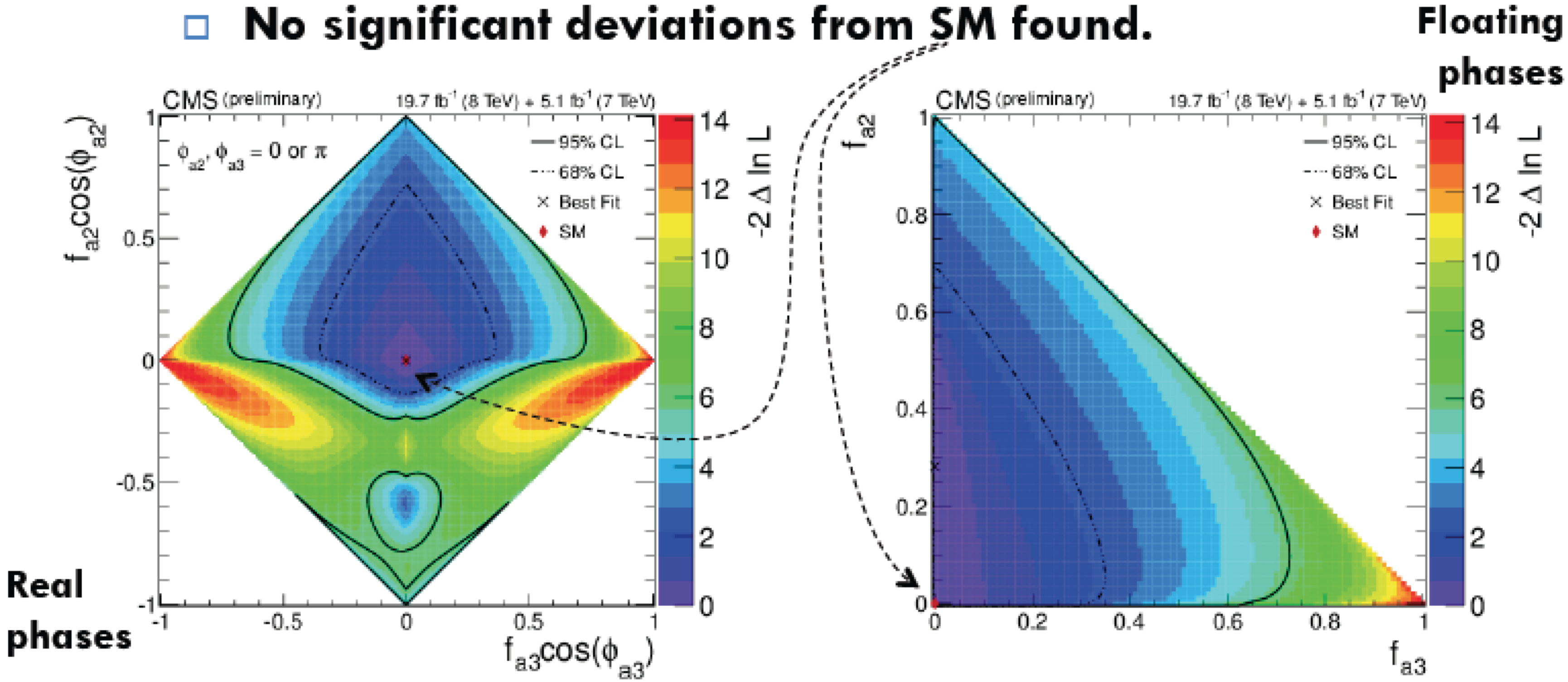
a_3 terms
CP-odd
(pseudoscalar)

Spin-0 Amplitude in H→ZZ→4l

arXiv:1411.3441



- Full final state available:
  - **Kinematic discriminants** reduce 8D to 2D or 3D.
- 2D scans of anomalous coupling fractions.
  - Assuming real phases and floating the phases.
- **No significant deviations from SM found.**



The state is compatible with a 0++ state

More details in the backup

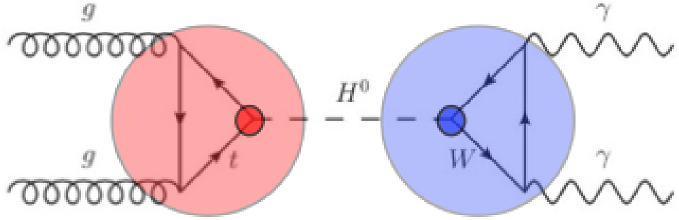
Higgs Combined analysis

Coupling Measurements

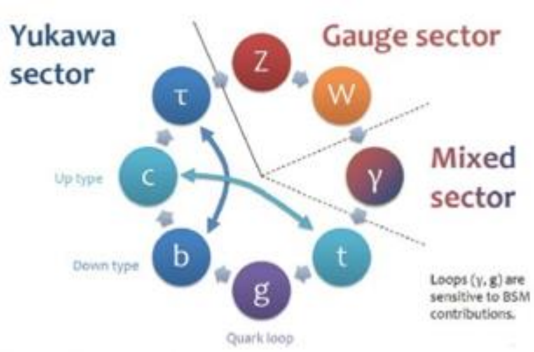
Assume the observed signal stems from one narrow resonance.

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

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
- ...

CMS-PAS-HIG-14-009

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.		✓	✓	

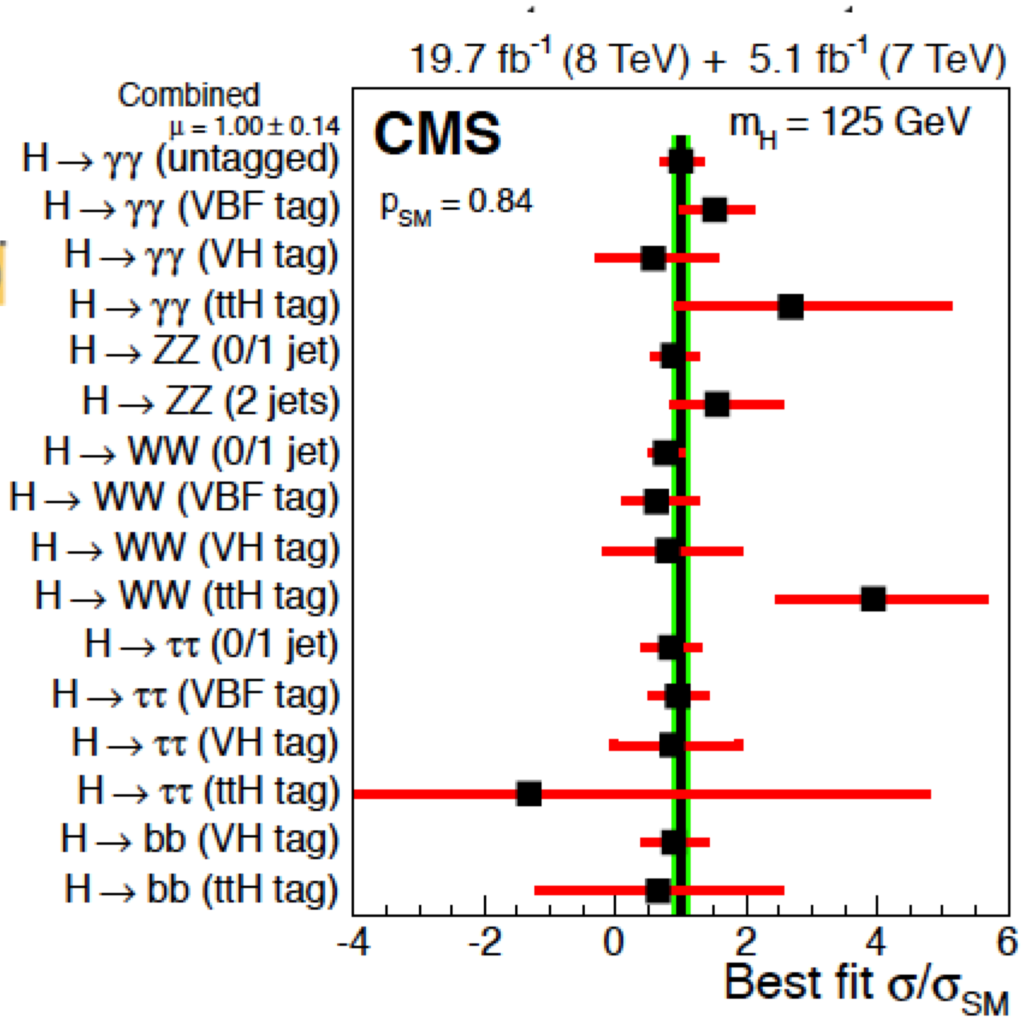
✔ **Used in the NEW combination**

- New update of overall combination since spring 2013 for CMS
- ATLAS update to be released

Combination of ATLAS & CMS being discussed

All Channels in Overview (CMS)

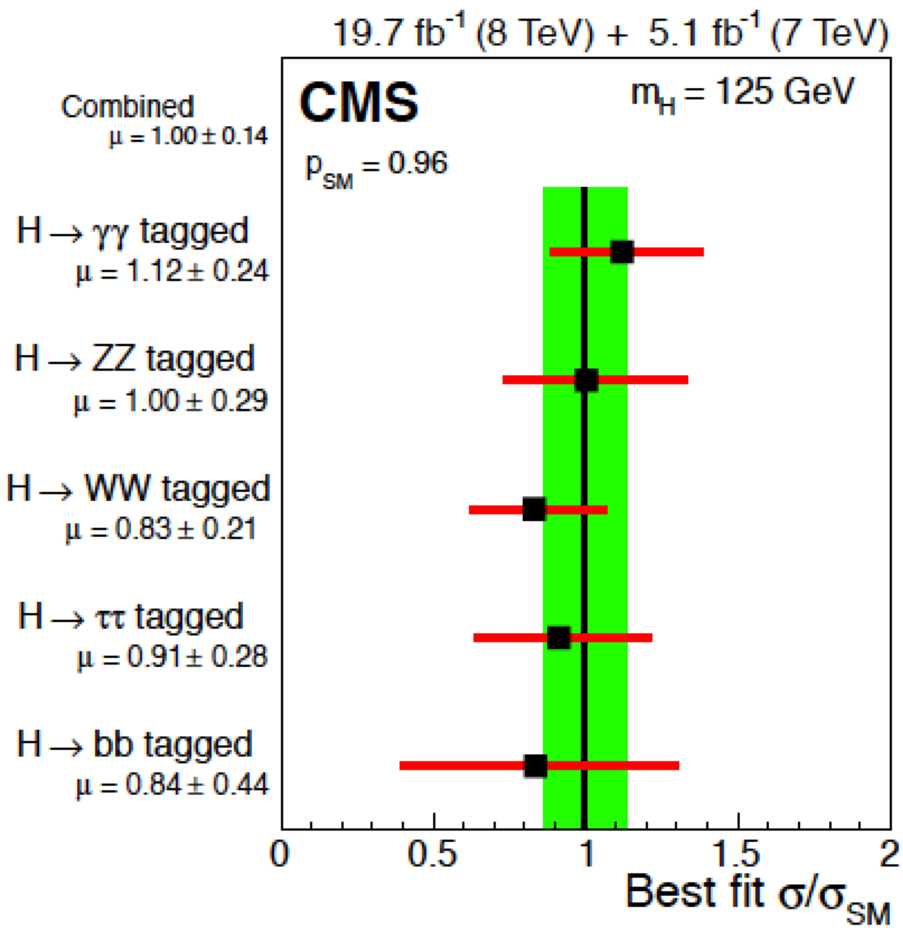
- Overall signal strength
  1.00 ± 0.13
  $1.00 \pm 0.09\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$
  - "theo." includes QCD scales, PDF+α_s, UEPS, and BR
- Per production and decay tag:
  - $\chi^2/\text{dof} = 10.5/16$
  - p-value = 0.84 (asymptotic)



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

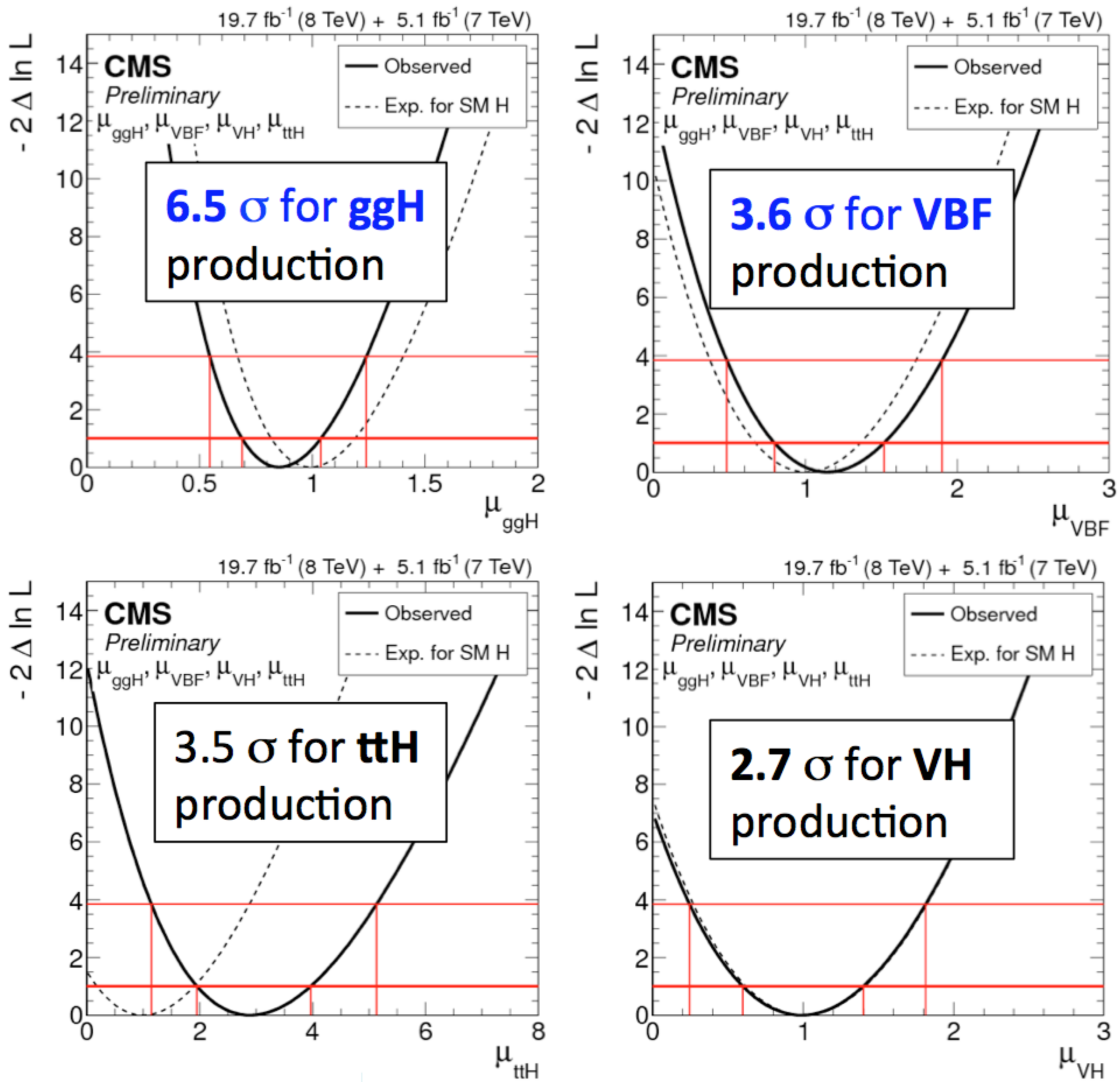
Signal Strength per Decay Channel

- Per decay tag:
  - χ^2/dof = 0.9/5
  - p-value = 0.97 (asymptotic)



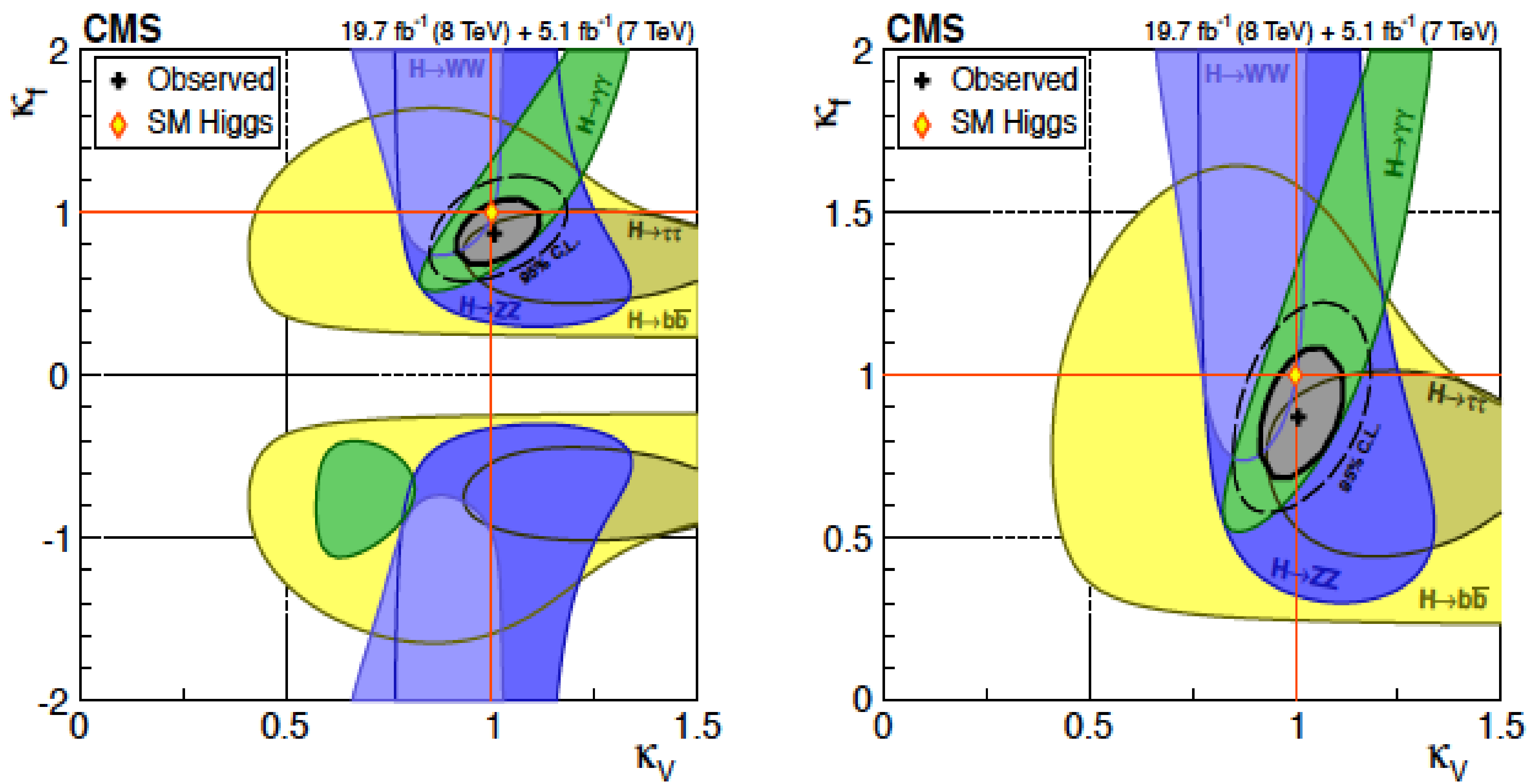
Significance of the 4 Prod. Channels

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



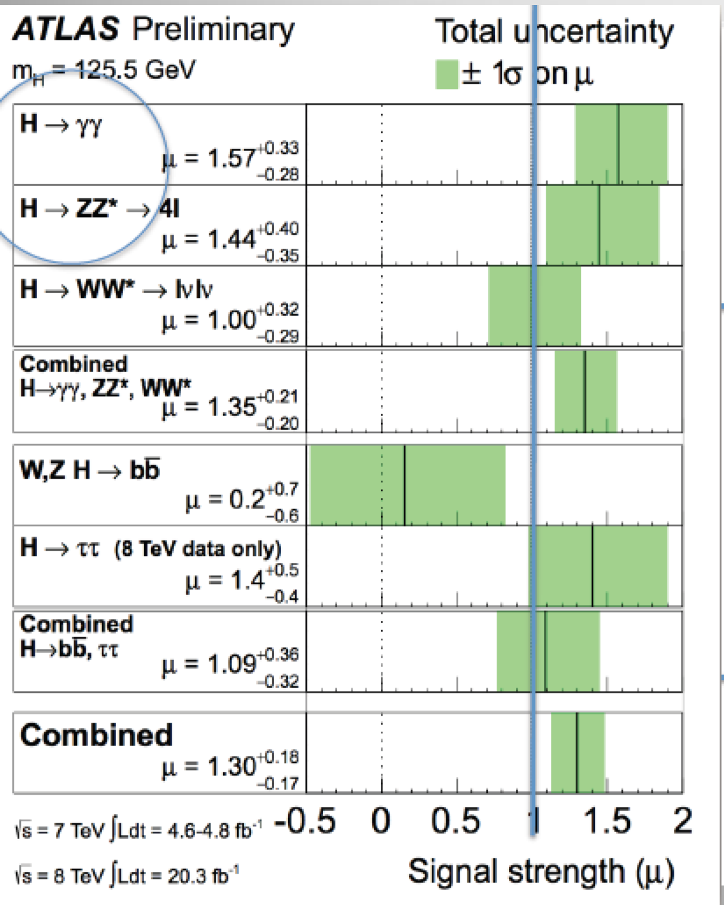
Coupling Modifiers

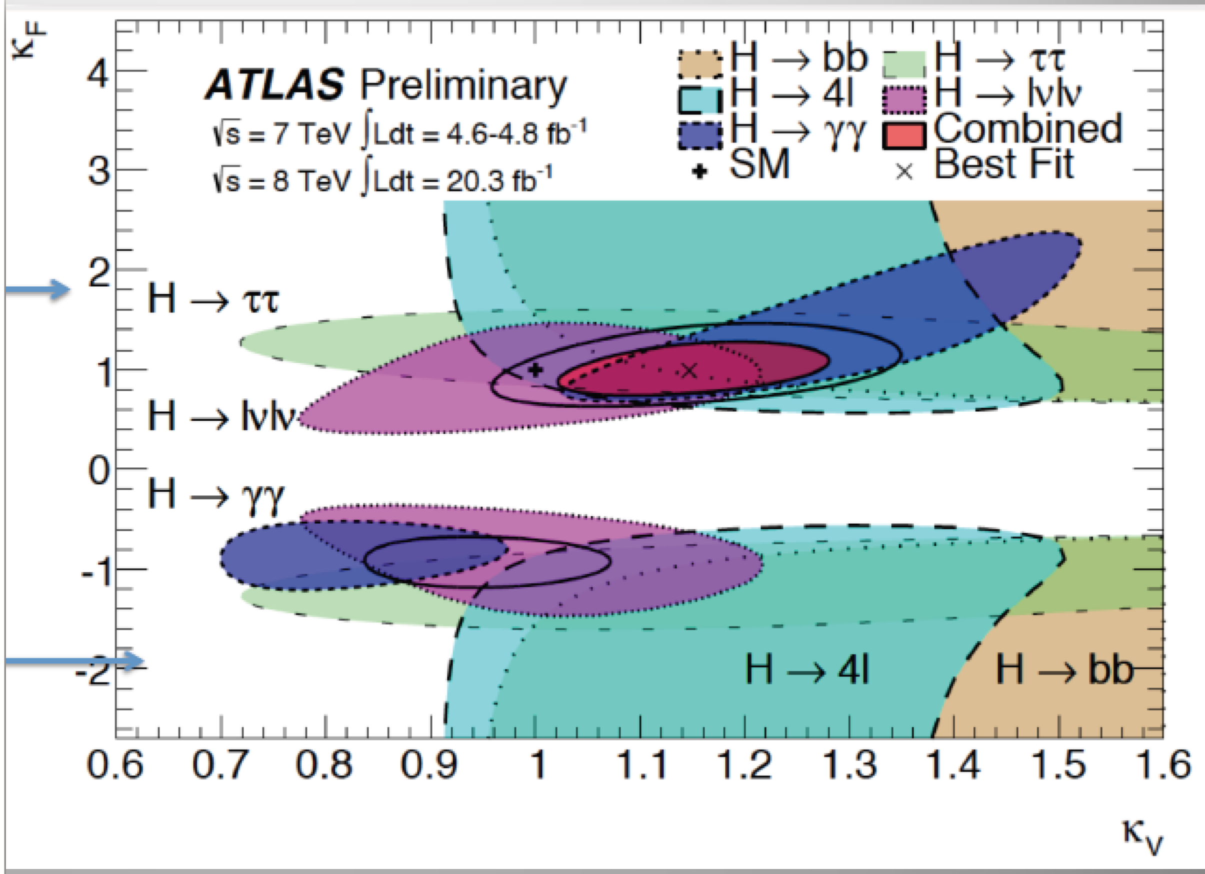
- Map vector-boson and fermionic couplings into κ_V and κ_f
- two-quadrant ⬋ and **one-quadrant** ⬊



ATLAS: Strength and Couplings

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

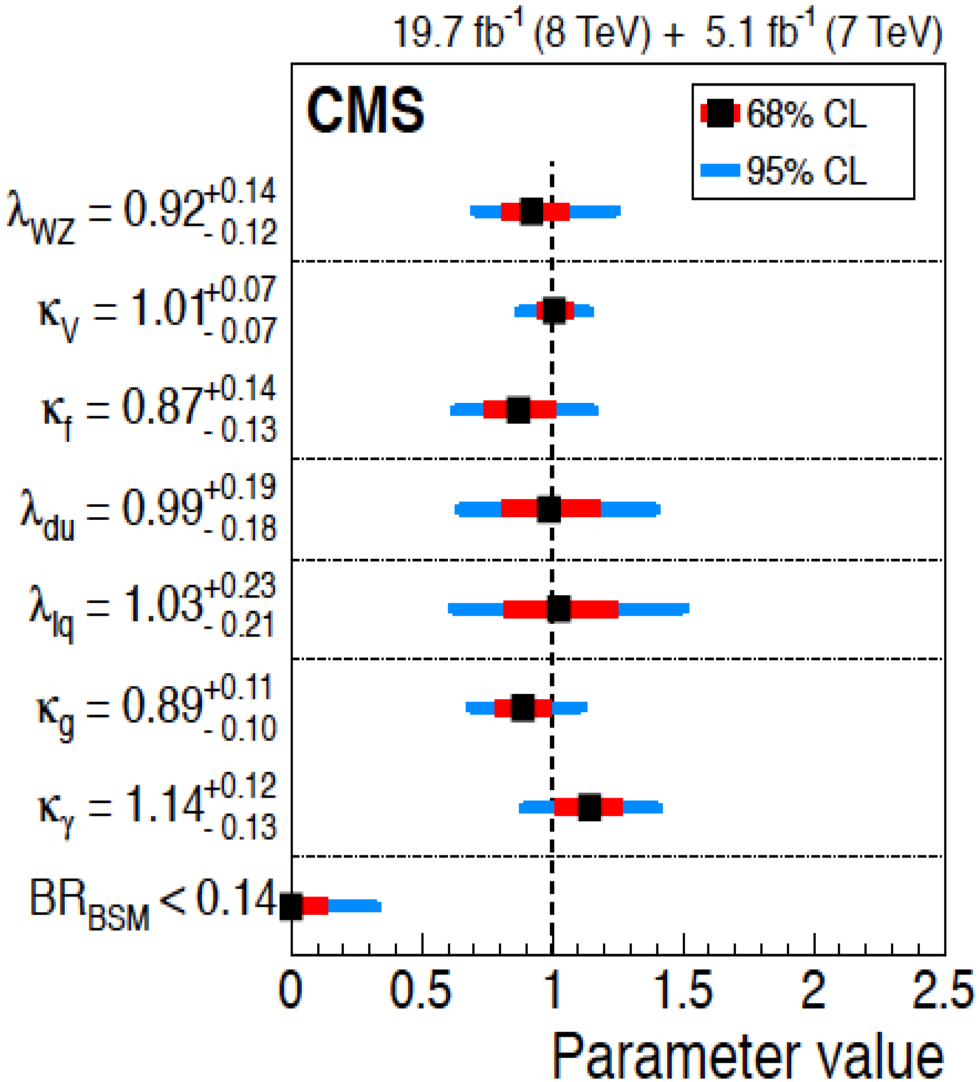




New results in preparation… (M. Kado ICHEP 2014)

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.**



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

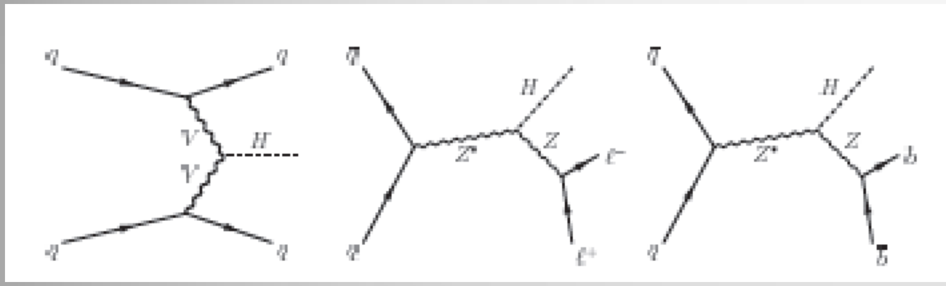
Exotic Higgs?

Searches for BSM Higgs

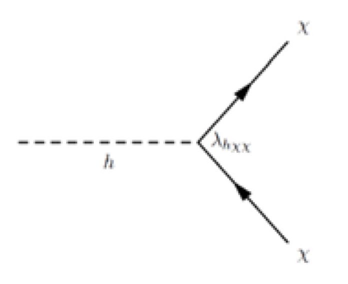
- MSSM neutral Higgs searches
- Charged Higgses (single, double…)
- Associated production
- Double Higgs production
- 2HDM searches
- FCNC tests
- Unusual decays (LFV, others…)

- No significant signal reported so far.

Invisible Higgs Decay Channel

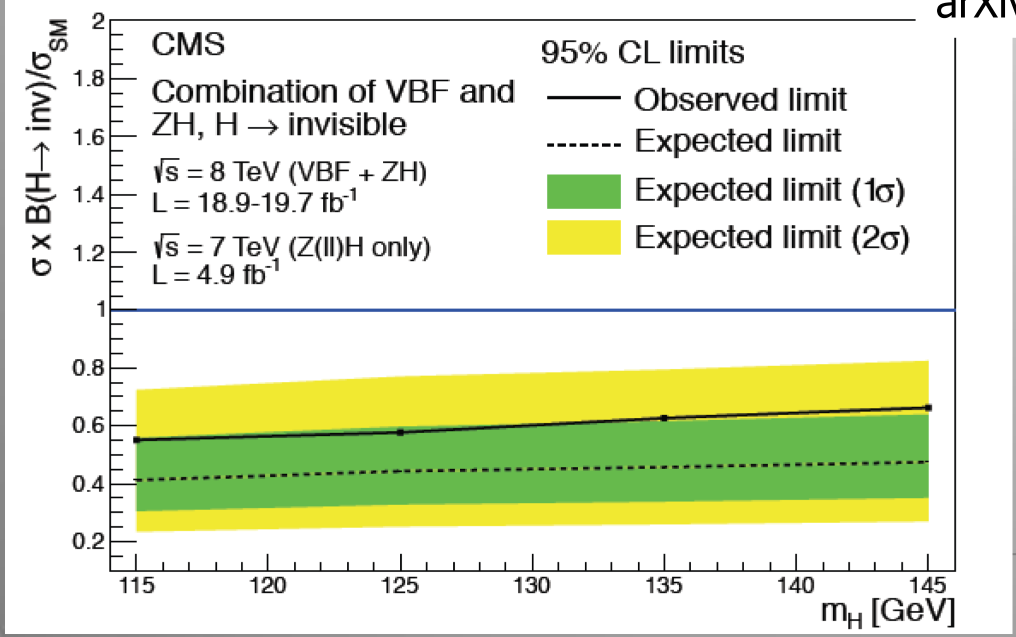


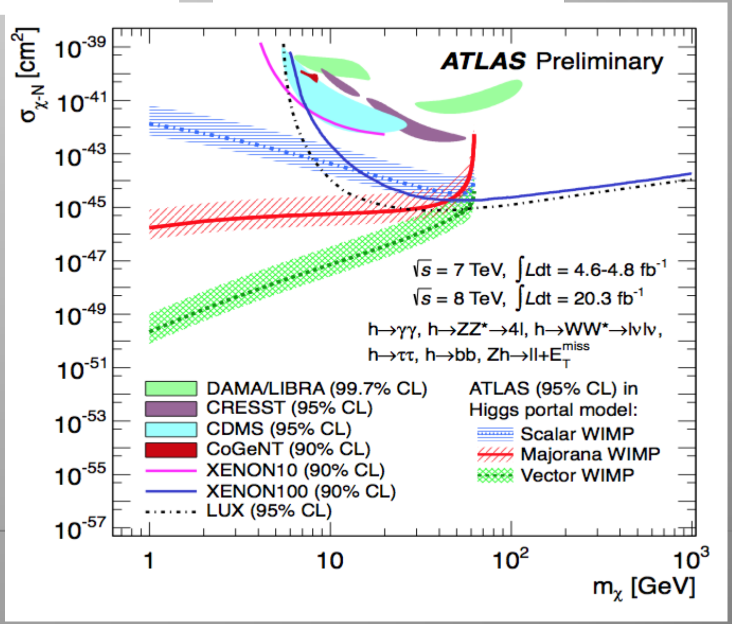
Search for invisible Higgs decays using
Z+H → 2 leptons + missing E_T
VBF H → 2 jets + missing E_T
Possible decay in Dark Matter particles (if $M<M_H/2$): Higgs Portal Models



Combined result from the three channels
BR(H→invisible)<58%(44% exp) at 95% CL.
for a Higgs with a mass of 125 GeV

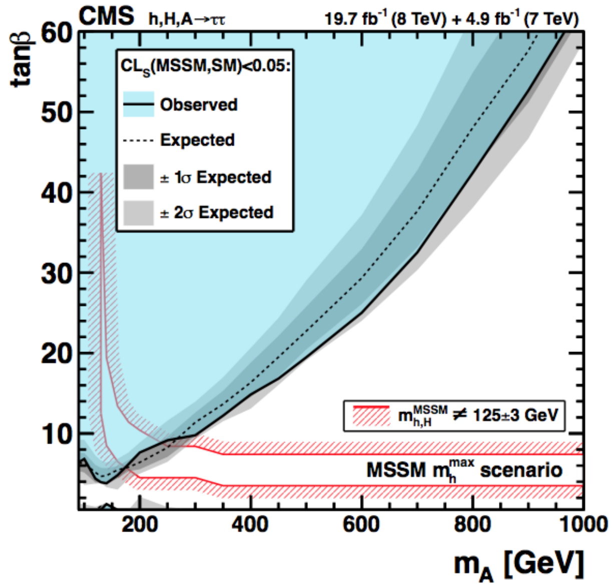
arXiv:1404.1344
arXiv:1402.3244





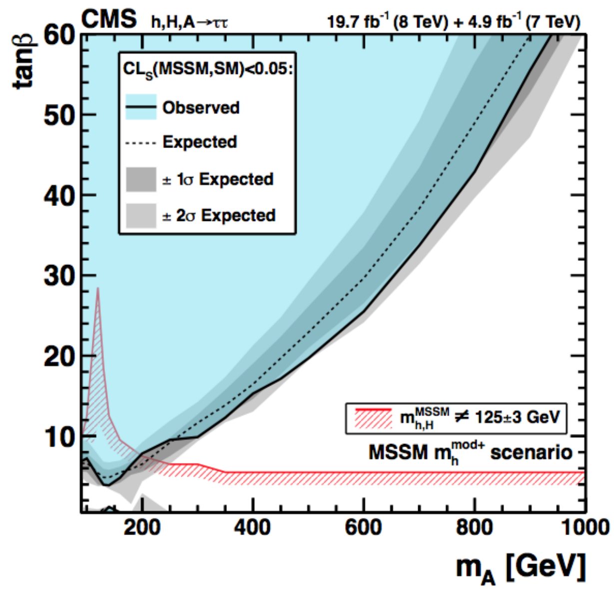
MSSM Neutral Higgs → tau tau

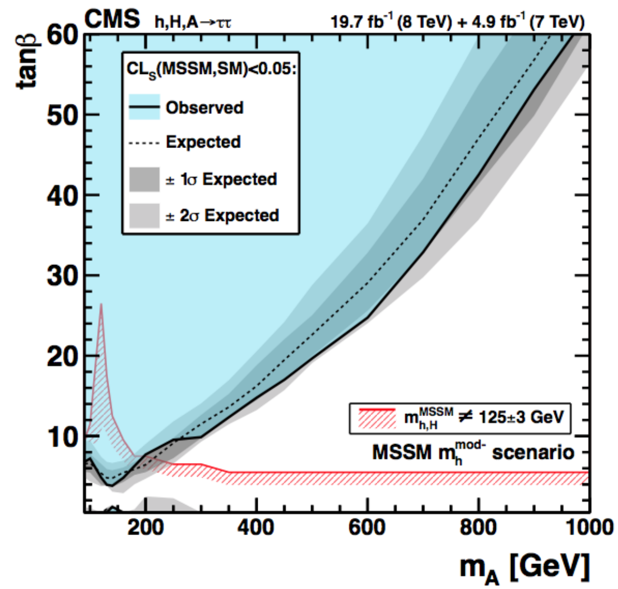
- Study of the Neutral Higgs
  h/H/A to tau tau
- Include channels with associated
  b-quark production
- No excess found so far
  –> exclusions (95% CL)



arXiv:1408.3316

m_h^{max} scenario;
m_h^{mod+} and m_h^{mod+}
scenarios
with modified
stop mixing
(arXiv:1302.7033)

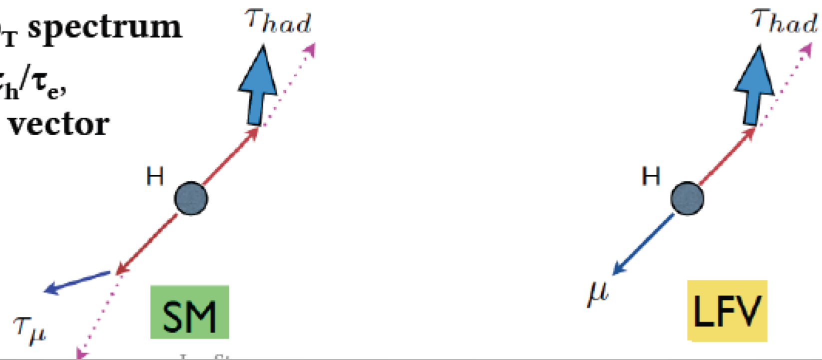




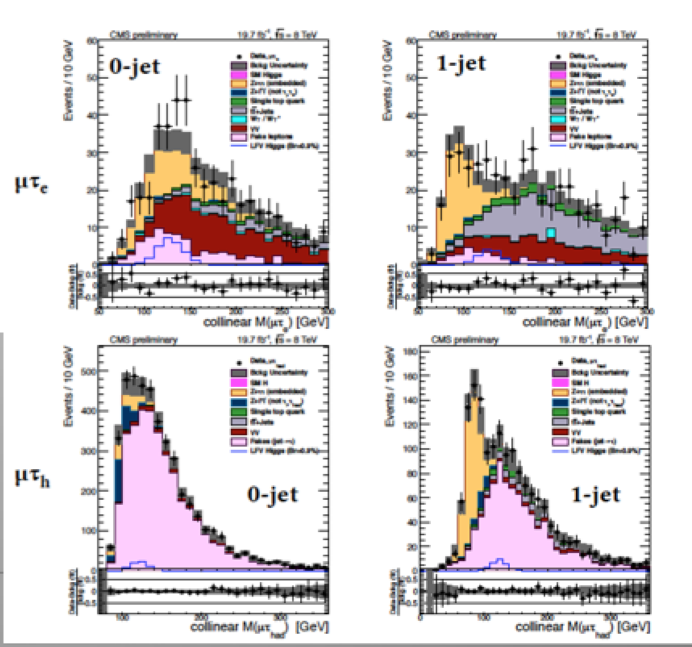
Search for LFV Decays: H $\rightarrow\mu\tau$

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**

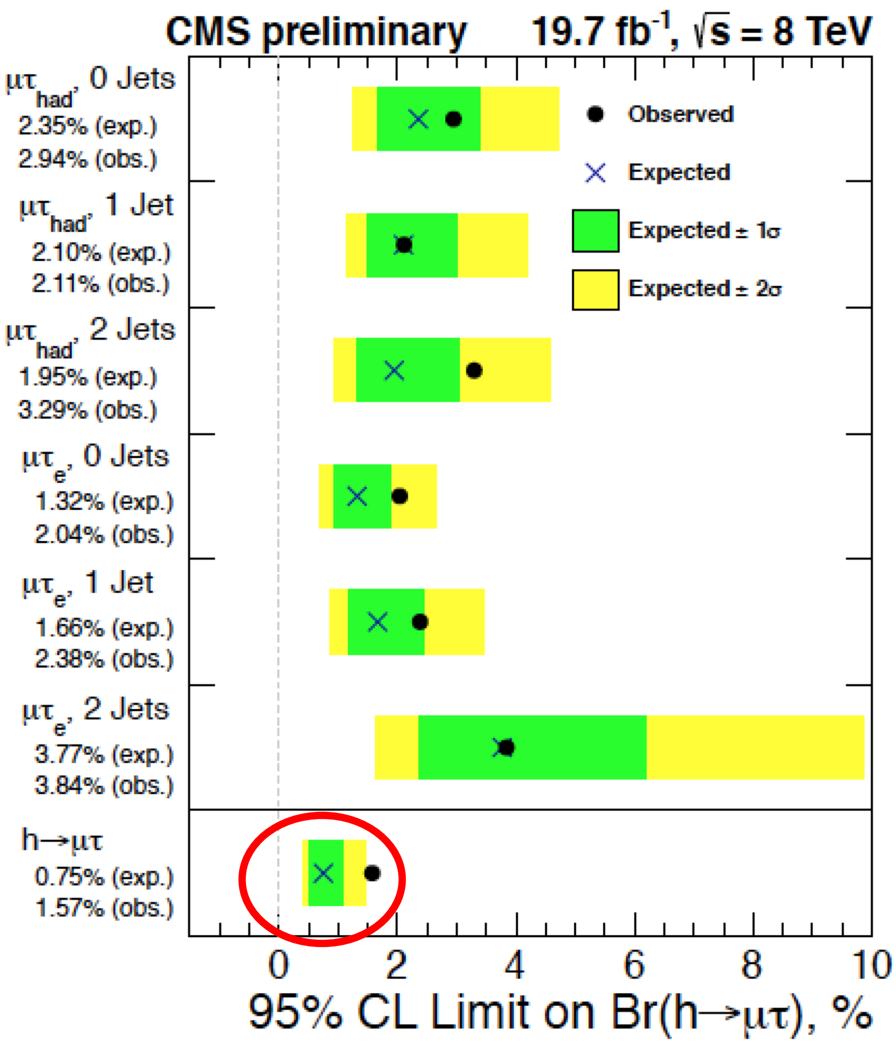


On public demand from our theory friends ☺



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

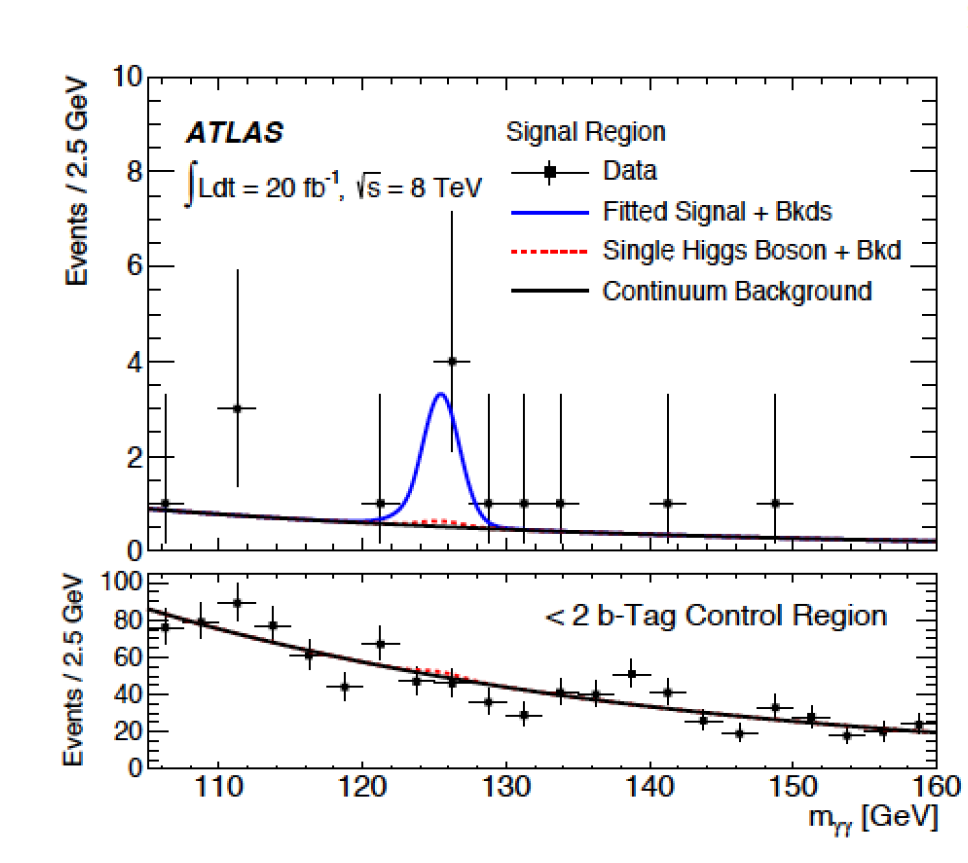
- Comparable sensitivity from all channels
- Observed limit 1.57% (exp. 0.75%)
- **Large improvement of previous limits**
- **Background-only p-value of 0.007 (2.46σ)**
  - Best-fit $B(H\rightarrow\mu\tau) = 0.89^{+0.40}_{-0.37}\%$



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

ATLAS: hh → γγbb

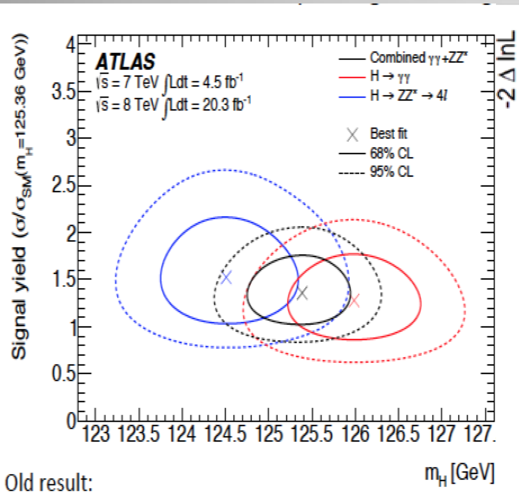
- No signal expected with the present collected luminosity for this channel
- Select events with 2 b jets and 2 photons. (non-resonant channel)
- 5 events within bin of $M\gamma\gamma \pm 2\sigma_{M\gamma\gamma}$ and 1.5 expected
  which is about 2.4σ significance…

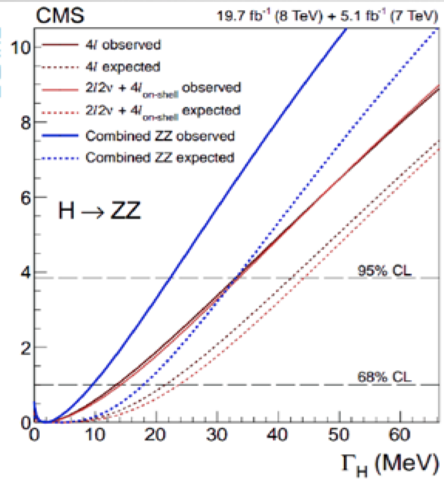


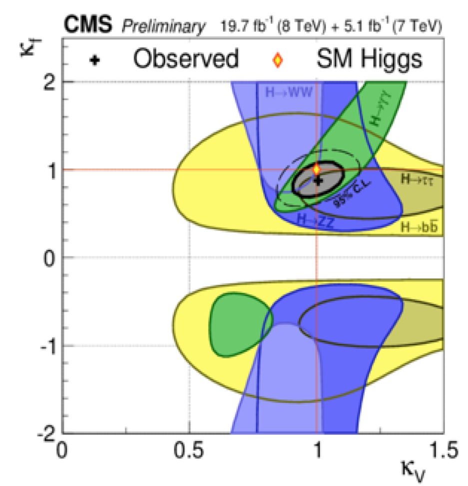
arXiv:1406.5053

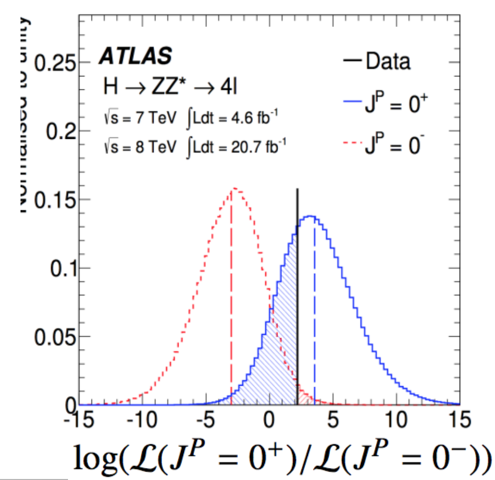
Brief Higgs Summary

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

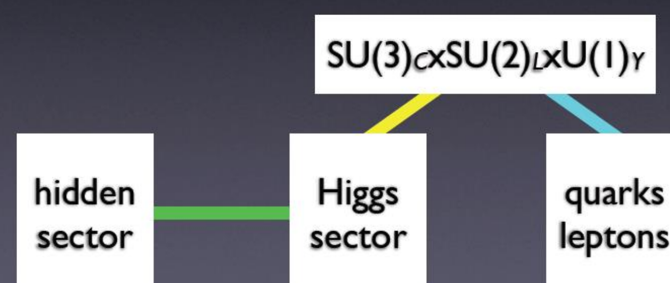
SM-like behaviour for most properties, but we look of course for anomalies, i.e. unexpected decay modes or couplings, multi-higgs production…

The Future: Studying the Higgs…

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

Higgs as a portal

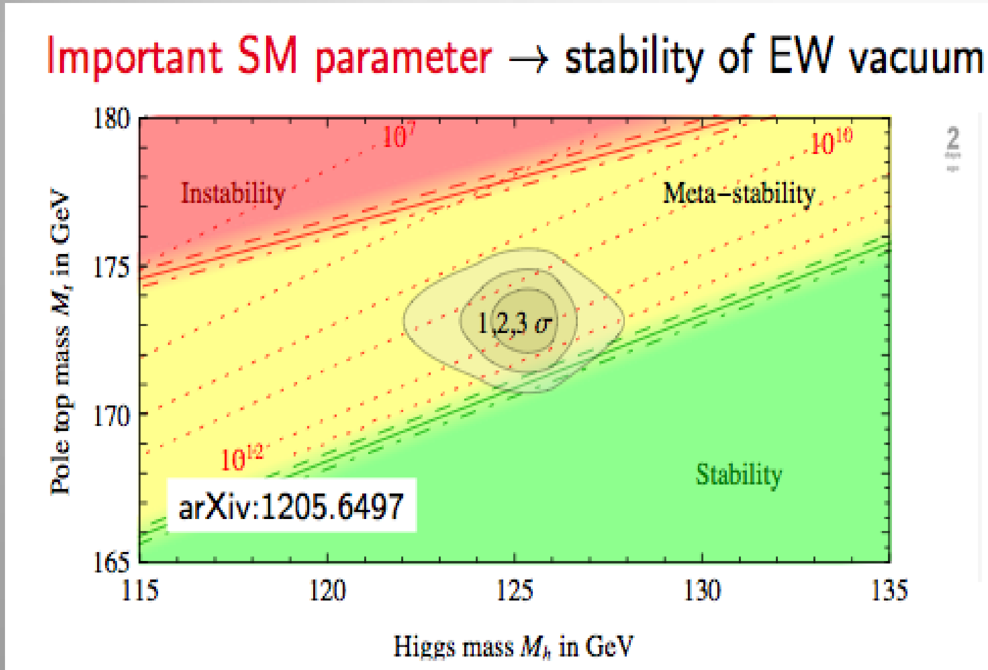
- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors"



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

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?

But Where Is Everybody?

N. Arkani-Hamed

...The May Issue...

Supersymmetry and the Crisis in Physics

LHC @ 2015

Decision to run at a **maximum** energy of 6.5 TeV per beam during the powering tests and during 2015.
(10 to 15 training quenches per sector are expected to be needed to reach that energy).

NO change of beam energy in 2015.

A decision regarding the possibility of increasing the energy will be taken later in 2015, based on the experience gained in all eight sectors at 6.5 TeV per beam during powering tests and operation with beams.

Integrated luminosity goal:
2015 : 10 fb^{-1}

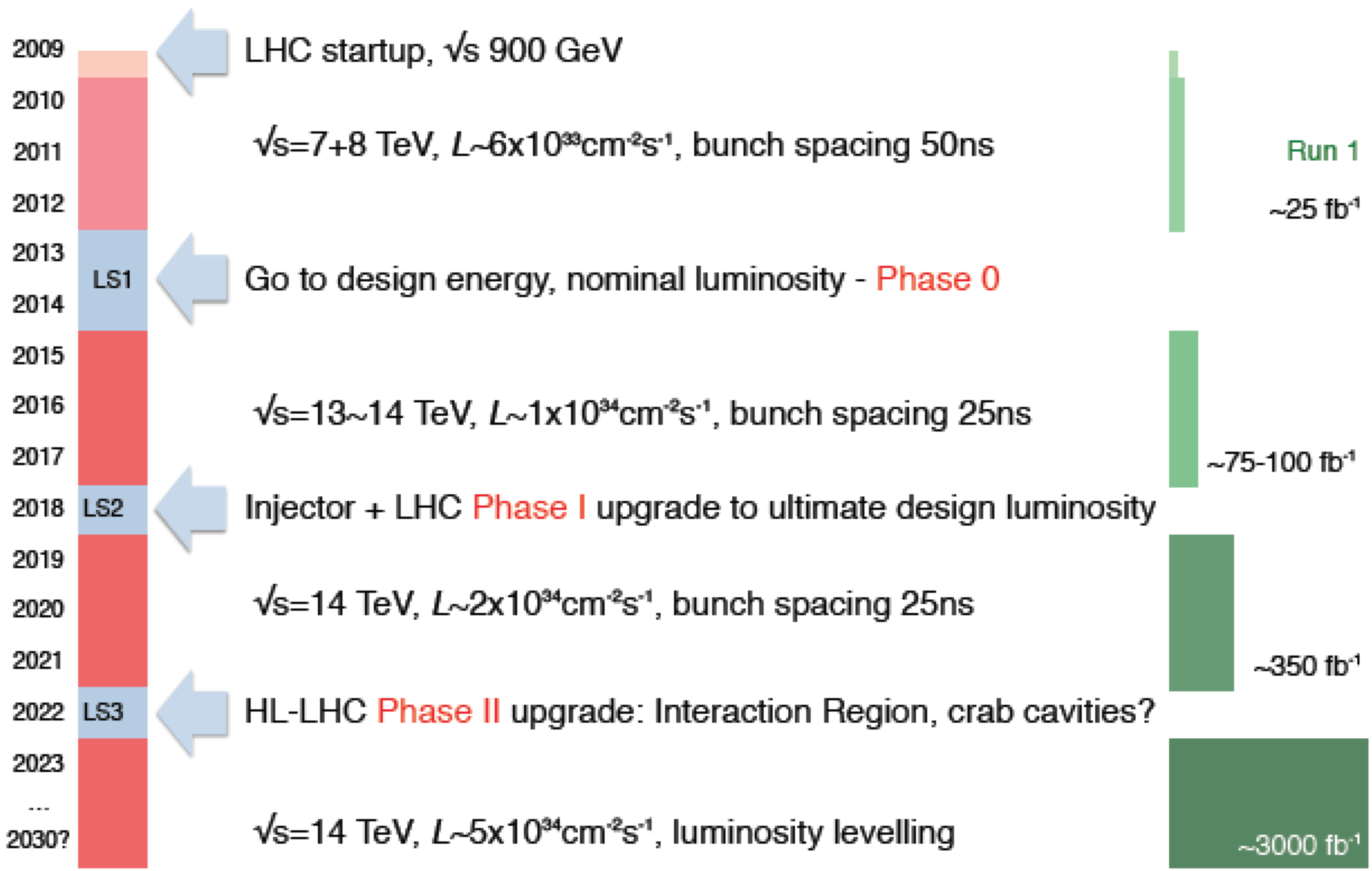
Run2: ~100-120 fb^{-1}
(better estimation by end of 2015)

300 fb^{-1} before LS3

S. Bertolucci
1/12/2014
Kruger meeting

The LHC Schedule

LHC roadmap to achieve full potential

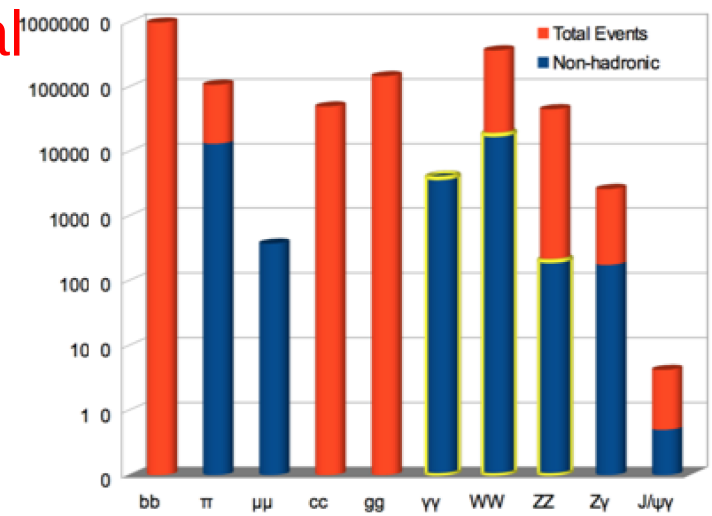


Preparing for Run-II Higgs…

- 2015: we expect about 15-20 fb^{-1}. This gives 2 times as many Higgses as collected in 2012 (and 4 times as many ttH events): Repeat 2012 analyses with increased precision. Faster increasing reach in high mass searches.
- 2016/2017: Increase total statistical sensitivity by factor 3-4 with respect to 2012.
- 2022: End of run-II: factor 6 increased statistical sensitivity

IFFFF we can keep the data qual

- Higgs mass precisions
  ~ 100-200 MeV enough?
- Higgs self-coupling precision
  Better than 20% needed?
- Higgs couplings? Few %? Better?
  (e.g. J. Wells et al., arXiv:1305.6397)



Higgs Cross Sections @ 14 TeV

With 100 fb^{-1} approx 10 x more signal (8 x more background) than run-I

Signal	14 TeV/8 TeV
ggF	2.6
VBF	2.6
ttH	4.7
WH	2.1
ZH	2.1
qq to WW background	2.1
gamma gamma bkg	2.1

ttH approx 20 x more signal

What can we measure in run II…

Coupling	LHC Run1	LHC (300 fb^{-1})
κ_W	15%	4-6%
κ_Z	20%	4-6%
κ_t	50%	14-15%
κ_b	40%	10-13%
κ_τ	25%	6-8%

Results for Snowmass and the European strategy group

- Example of expected deviations if new physics scale is at 1 TeV

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Typically, expect deviations:

$\Delta\kappa/\kappa < \sim 5\ \% / \Lambda^2$

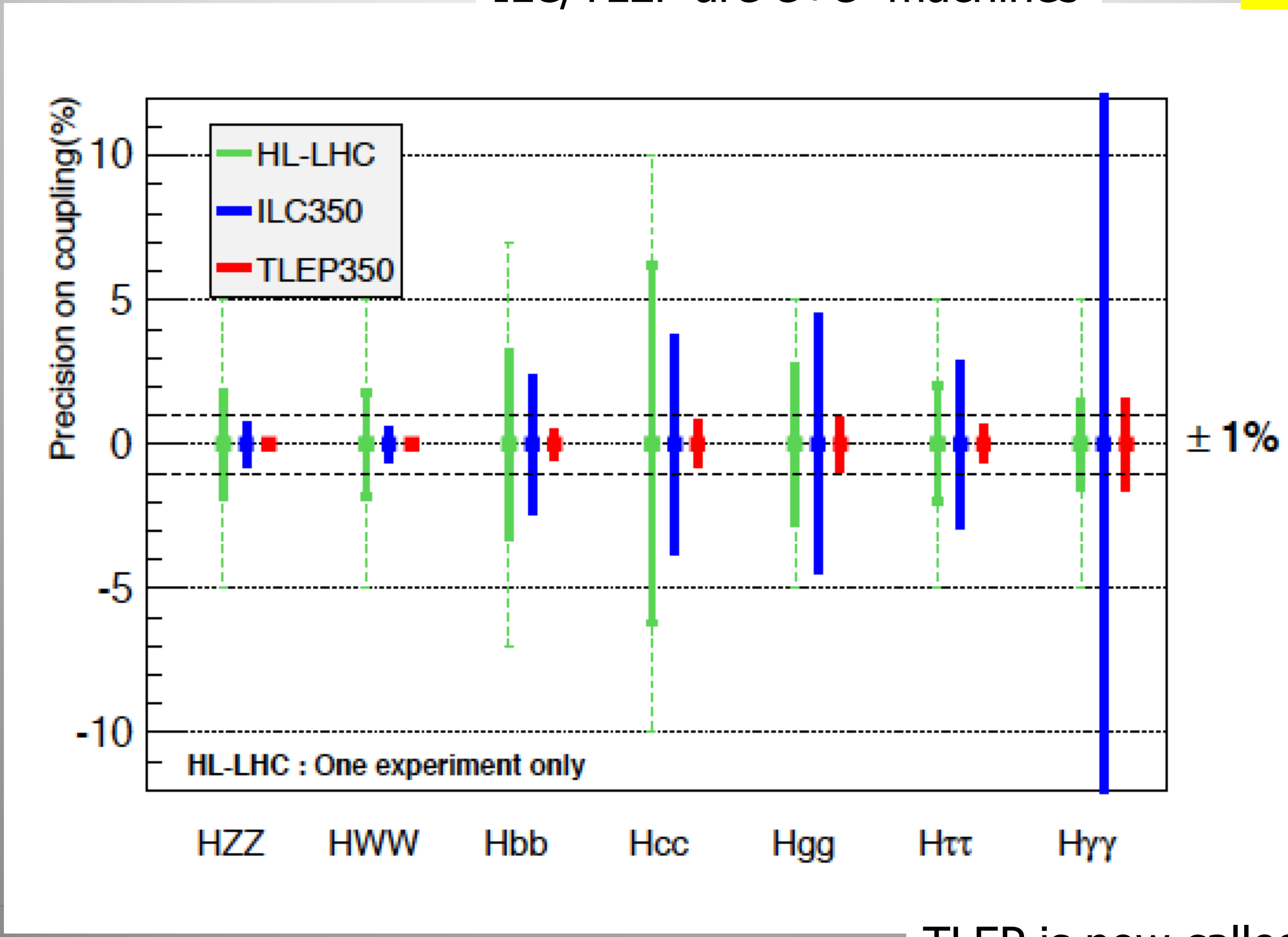
(with Λ in TeV)

TLEP publication
arXiv:1308.6176

Comparison on Couplings

ILC/TLEP are e+e- machines

arXiv1308.6176

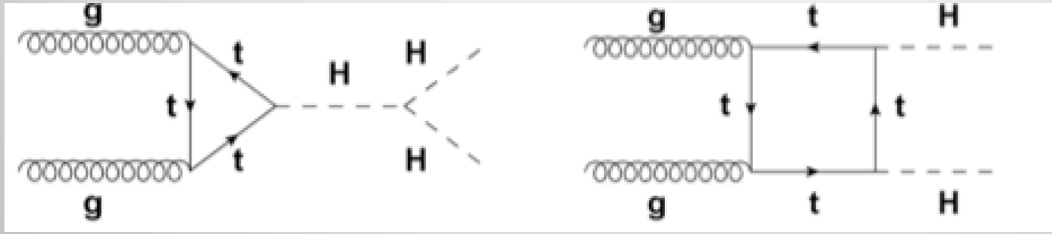


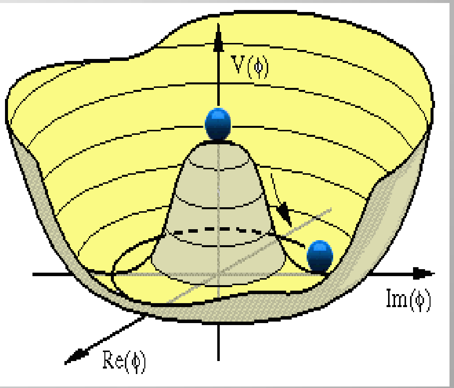
TLEP is now called FCC-ee

(Preliminary) The Higgs Self Coupling!

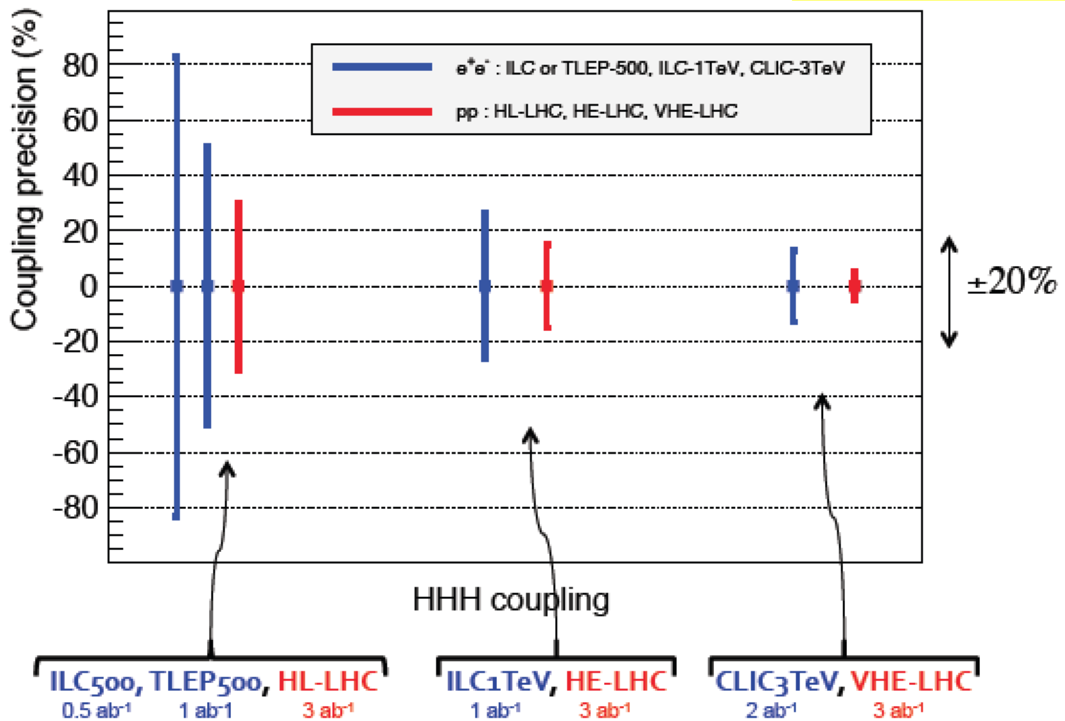
A key measurement for our understanding of the Higgs field potential!

in pp





arXiv1308.6176

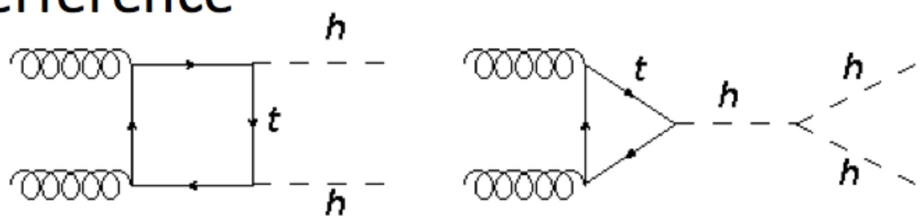


Difficult measurements!!:
Evaluation till ongoing
for HL-LHC sensitivity

e+e- machines with
sufficient energy and
FCC-hh can measure
this process

Di-Higgs Production

- One of the exciting prospects of HL-LHC
  - Cross section at $\sqrt{s}$=14 TeV is 40.2 fb [NNLO]
  - Challenging measurement
    - New preliminary results from ATLAS and CMS
- Destructive interference



- Final states shown today
  - bbγγ [320 expected events at HL-LHC, 3000fb^{-1}]
    - But relatively clean signature
  - bbWW [30000 expected events at HL-LHC, 3000fb^{-1}]
    - But large backgrounds
- bbbb and bbττ final states under consideration

Early days for these studies in ATLAS and CMS…

What we can measure in Run II / III…

- Many couplings to a precision of ~ 5% (b to 10%)
- Top Yukawa couplings to 15-20%
- Higgs to mumu to about 30%
- Higgs to Zgamma? Maybe combining ATLAS & CMS
- Access to more difficult channels such as VBF with H->bb
- Constrain invisible decay width to 20 %
- Total width of the Higgs if the theory follows data precision
- No access to triple Higgs coupling so far. With LH-LHC? Unless we have some new ideas!!
- Note: we will produce ~ 25 Million Higgses in run-II @ LHC Better experimental methods to use more than a few per mille? New Theoretical ideas to extract information from the data? New Theoretical precision? This is the job description

Summary

- In 2012 we discovered a new particle around 125 GeV. The data has shown that this particle has the properties of a Higgs Boson related to the EW-symmetry breaking.
- The mass is ~125 GeV with a precision of order ~0.3%. Rare processes now searched for: $H \rightarrow Z\gamma$, ttH, ($H \rightarrow \mu\mu$)… The couplings to fermions seem established
- This new particle could be the key to our 'contact' with the new physics side. Detailed study is imperative.
- So far, at the 20-30% level, this Higgs is SM-like; Run-II data and HL-LHC will bring a new level of precision (~ 2-5%) and access to new channels.

  It may just take ONE deviation to show us the way…
- Lot's of room for new ideas!! (for LHC and FCC-hh…)

Backup