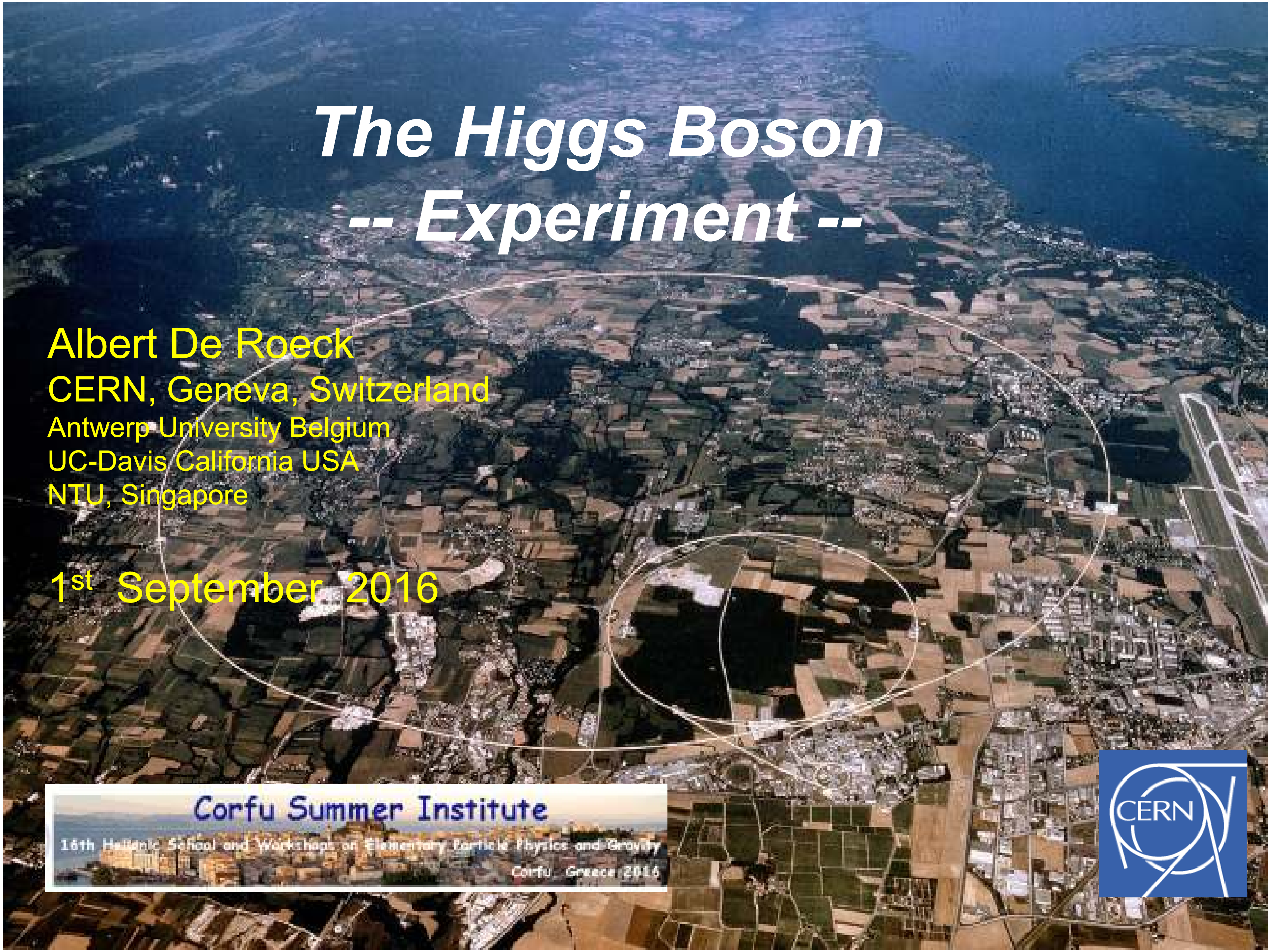

The Higgs Boson
-- Experiment --

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
UC-Davis California USA
NTU, Singapore

1st September 2016

Corfu Summer Institute
16th Hellenic School and Workshops on Elementary Particle Physics and Gravity
Corfu, Greece 2016

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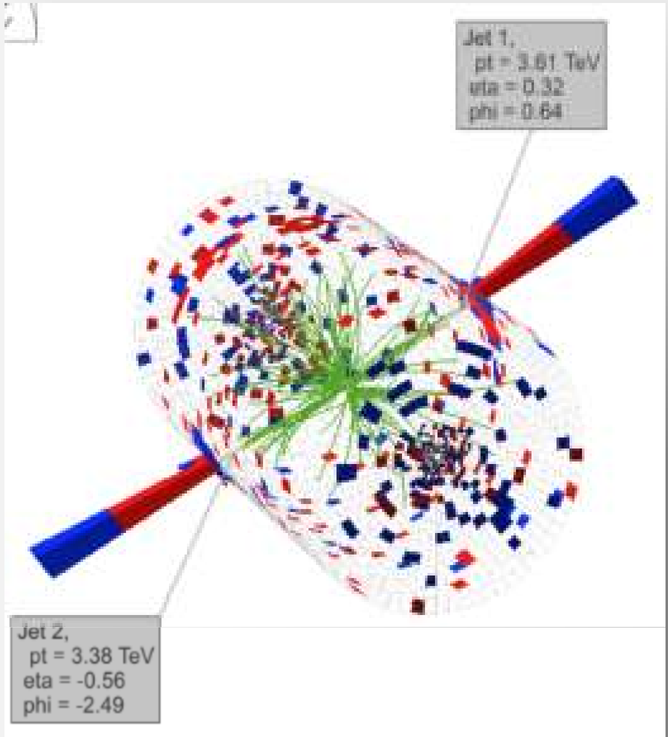


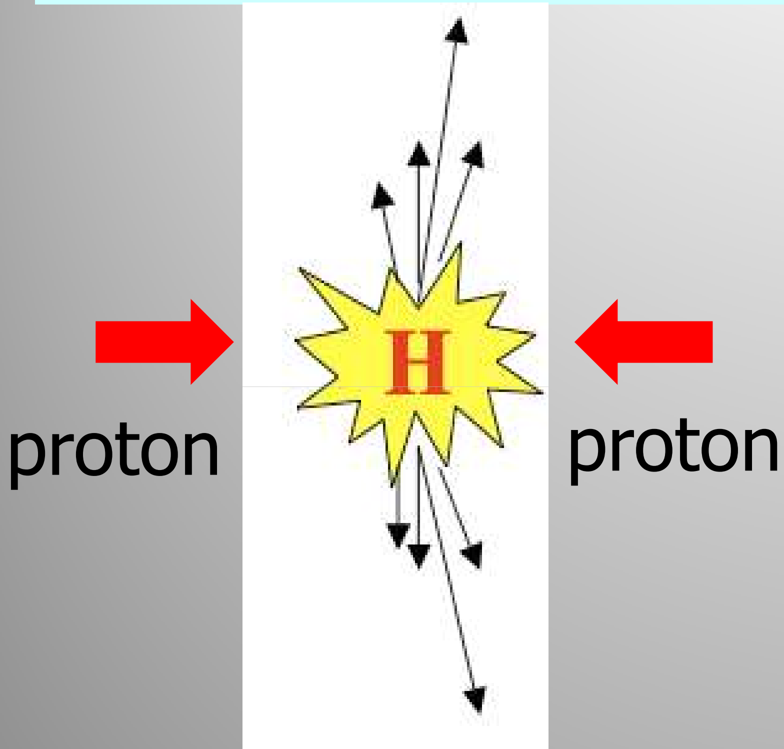
Outline

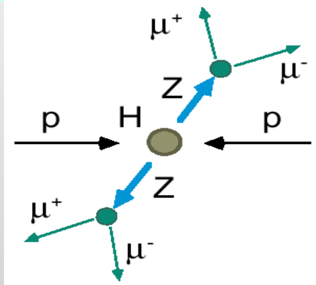
- Introduction
- The run-1 Legacy
  - Summary of results
  - Combination of ATLAS & CMS data
- New results from the 13 TeV CMS data
- Searches for BSM Higgses
- Summary/Outlook

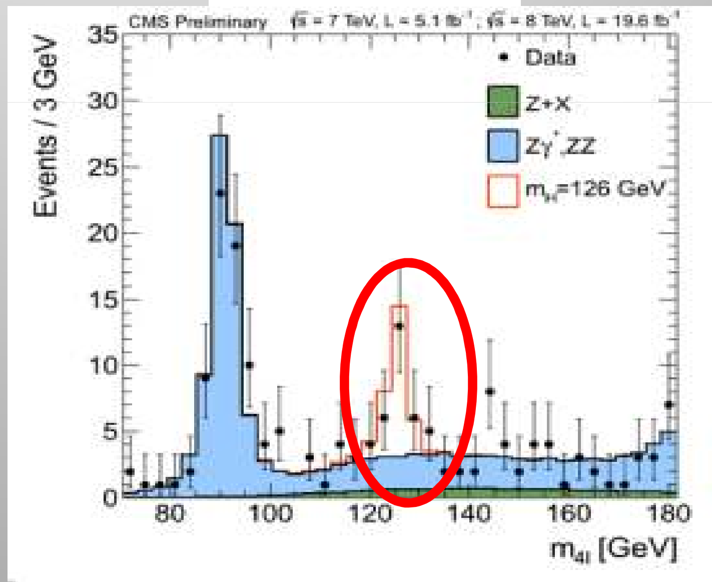
New ATLAS results in a workshop talk later this conference

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

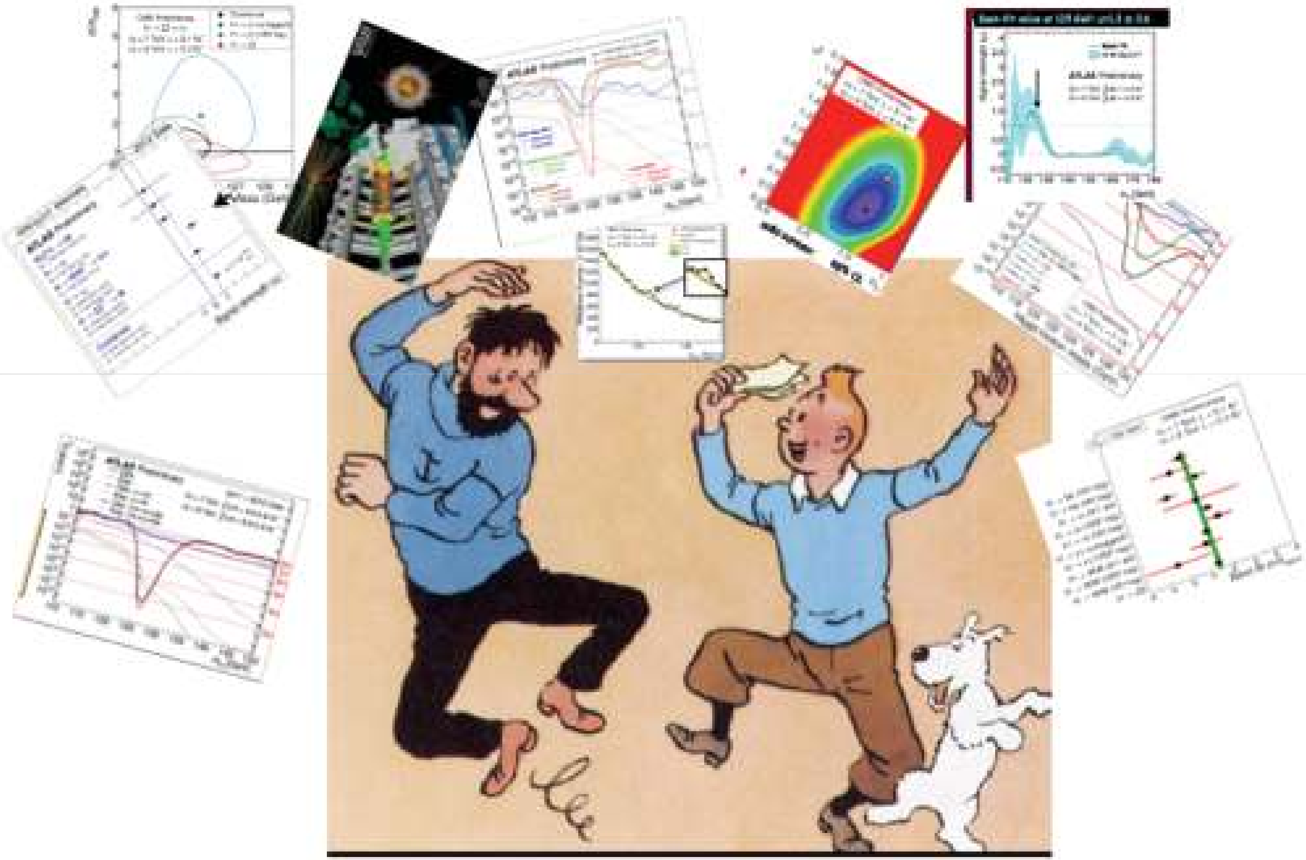
The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

The Theorist and Experimentalists

The party in 2012!

A. Pomarol ICHEP2012

Not everybody at the party
eg higgsless models…

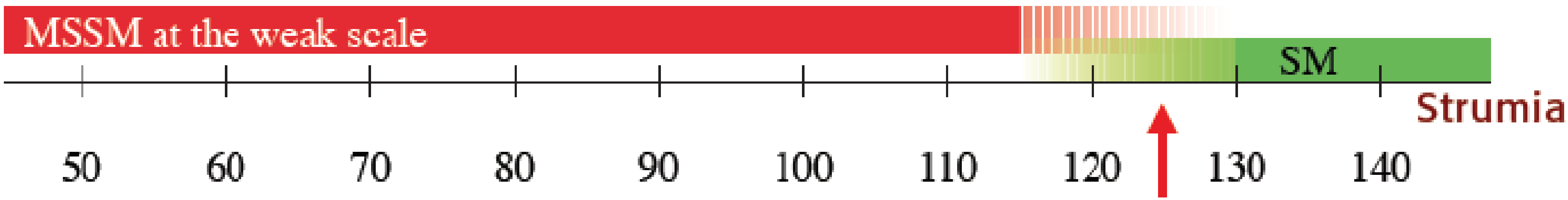


But careful about resurrections, Higgs imposters…

A Higgs @ 125 GeV…

A malicious choice!

$m_H = 125.0 \pm 0.2$ GeV



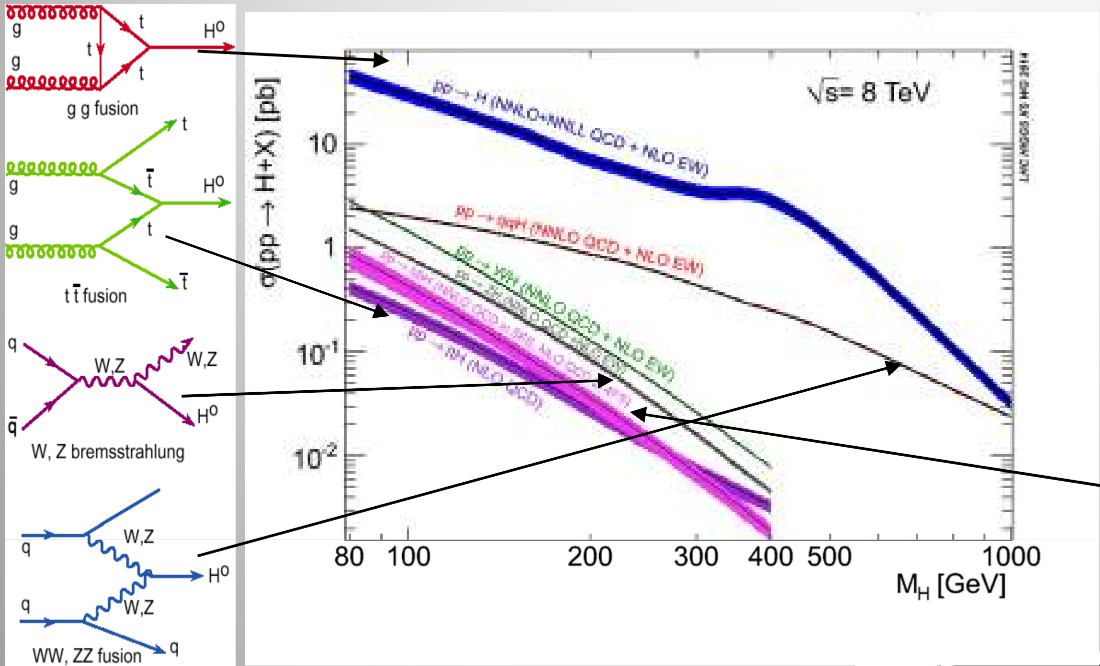
The Higgs:
so simple yet so unnatural

Guido Altarelli
1941-2015

Stockholm Nobel Symposium
May 2013

"We do not understand why the mass of the Higgs is 125 GeV
It most likely tells us something on what is Beyond the Standard Model"

Higgs Production & Decay

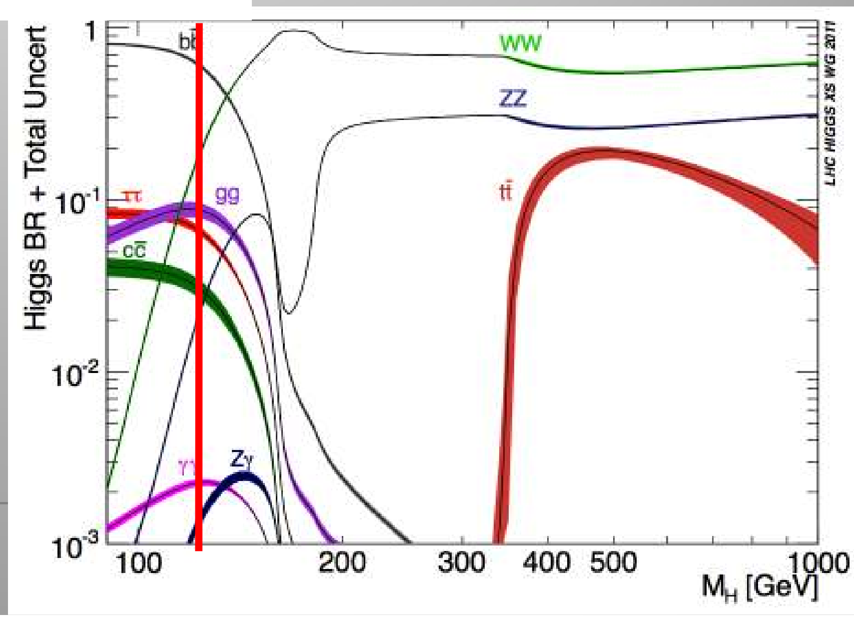


Processes

- 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)
YR4: Deciphering the nature of the
Higgs sector



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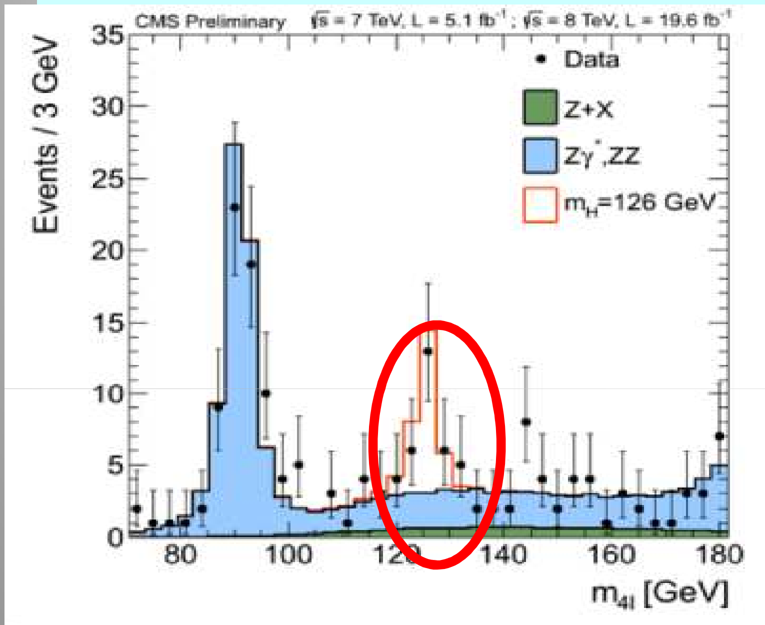
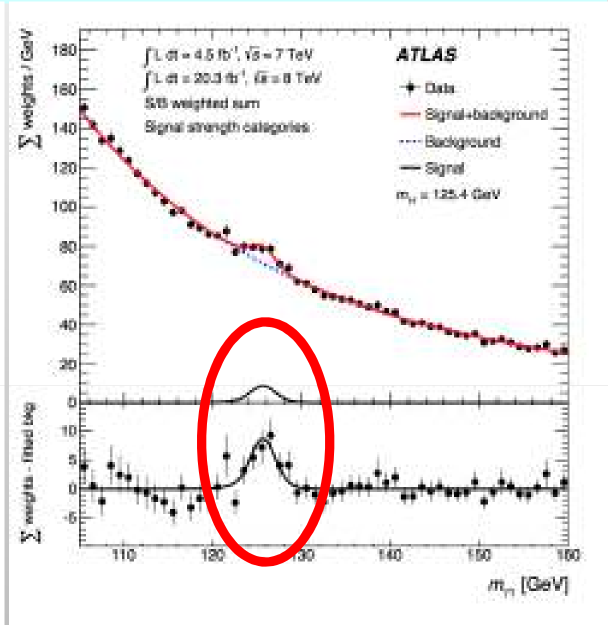




2015: Higgs Boson well established.

All accessible channels studied

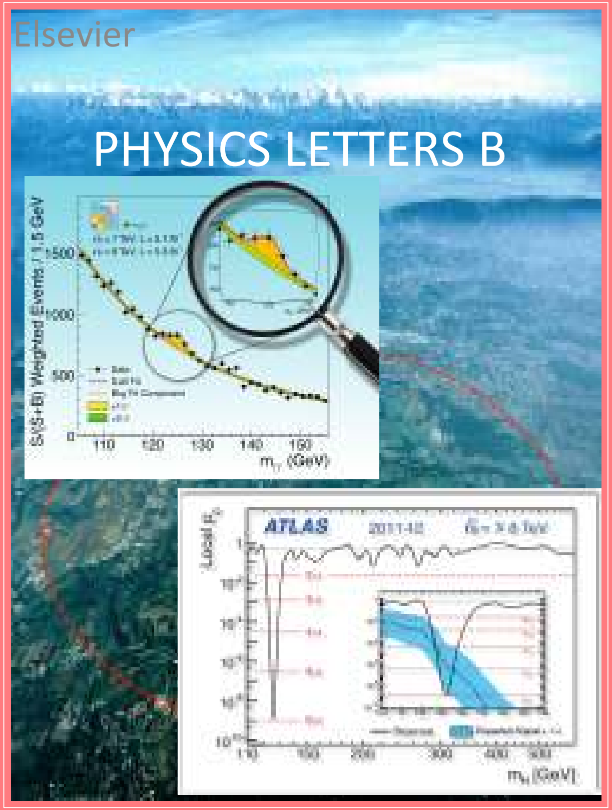
	untagged	VBF	VH	ttH
H-> gamgam				
H-> ZZ				
H->WW				
H-> bb				
H-> tau tau				
H-> Zgamma				
H-> mumu				
H-> invisible				

Results released

In progress

Most cited LHC paper so far…

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



Almost than 5000 times cited…

Also…

CMS 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?

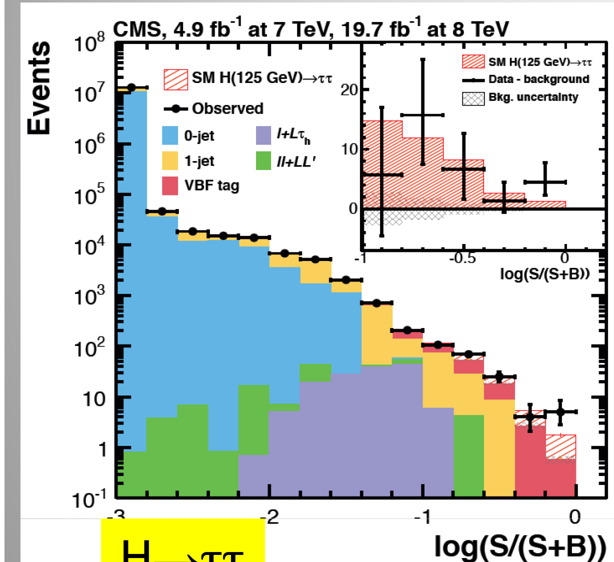
- More detailed analyses of the 125 GeV particle, in particular the search for direct decays into fermions, ttH channel,...
- More precise measurements of the "signal strength σ/σ_{SM}" and of the mass of the particle, and the spin.
- Searches for Higgs like particles at higher masses
- Searches for exotic, non-SM decays (none found so far)
- Searches for di-Higgs events (in BSM scenarios, none found so far)
- More detailed analyses of the properties (mass, spin, couplings…)
- Differential distributions + fiducial volume cross sections
- First data combination of ATLAS and CMS in 2015/16

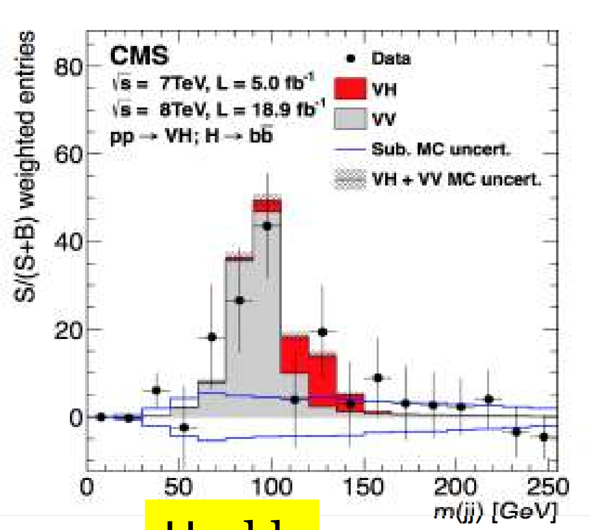
Results Summary @ 125 GeV

Individual Run-I Legacy papers

Channel	ATLAS Lumi [fb-1]	CMS Lumi [fb-1]	Specialty	σ Obs. (exp.)	Mass [GeV]	Signal strength μ	$J^P = 0^+$
H→γγ	4.8+20.7	5.1+19.6	mass, discovery, couplings	5.2 (4.6)	126.	1.17±0.27	✔
				5.7 (5.3)	124.7	1.14+ 0.26- 0.23	✔
H→ZZ→4l	4.6+20.7	5.1+19.7	mass, discovery, couplings	8.1 (6.0)	124.7	1.44 ± 0.4	✔
				6.8 (6.7)	125.6	0.93 +0.29- 0.25	✔
H→WW→2l2ν	4.6+20.7	4.9+19.4	cross section, couplings	6.1 (5.8)	Compatible with 125GeV	1.09 +023-0.21	✔
				4.3 (5.8)	125.5+3.6–3.8 (μ = 1)	0.72 +0.20- 0.18	✔
H→bb	4.5+20.3	5.1+18.9	couplings to fermions	1.4 (2.6)	--	0.52 +0.40- 0.27	--
				2.1 (2.1)	Compatible with 125GeV	1.0 ± 0.5	--
H→ττ	20.3	4.9+19.4	couplings to fermions	4.5 (3.4)	Compatible with 125GeV	1.43 +0.43–0.37	--
				3.2 (3.7)	122 ±7 GeV	0.78 ± 0.27	--

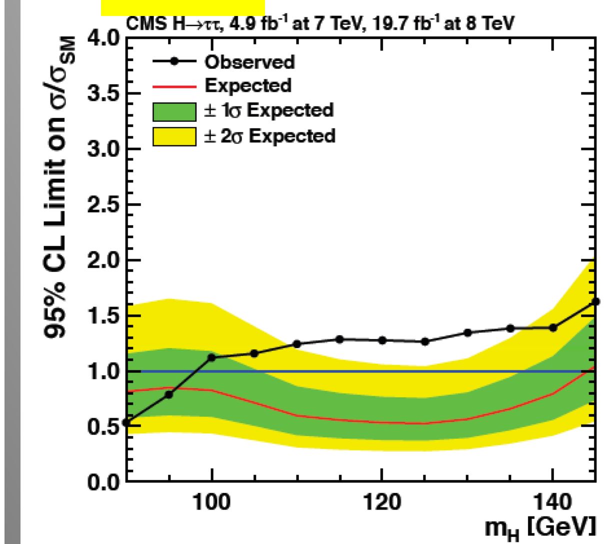
The Decay Higgs to Fermions

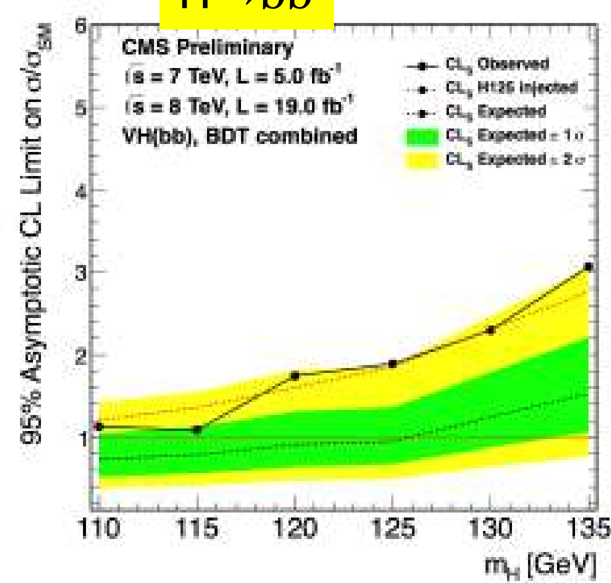




H→ττ

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

$H\to\tau\tau$ 3.2σ (obs) 3.7σ (exp)

$\to \mu = 0.78^{+0.27}_{-0.27}$

$H\to bb$ 2.1σ (obs) 2.1σ (exp)

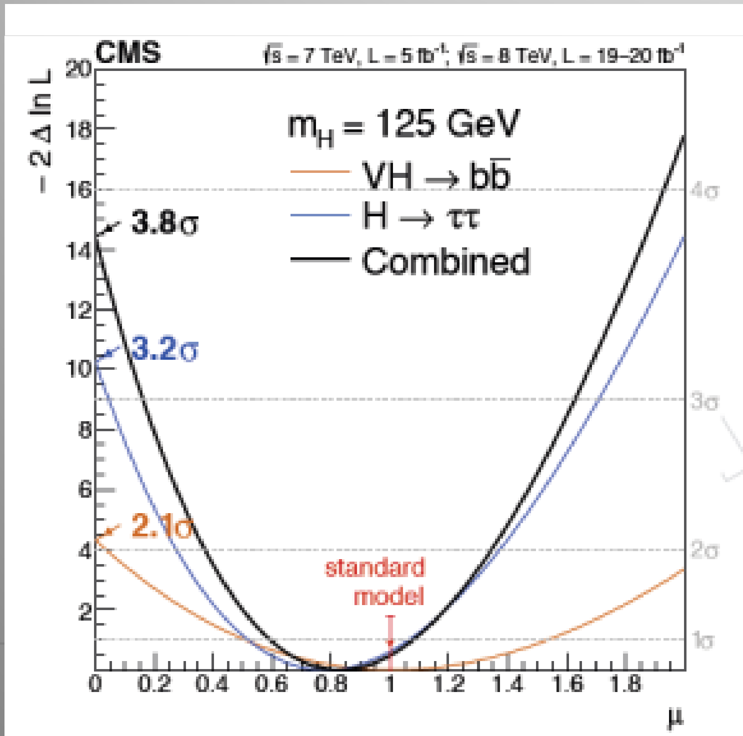
$\to \mu = 1.0 \pm 0.5$

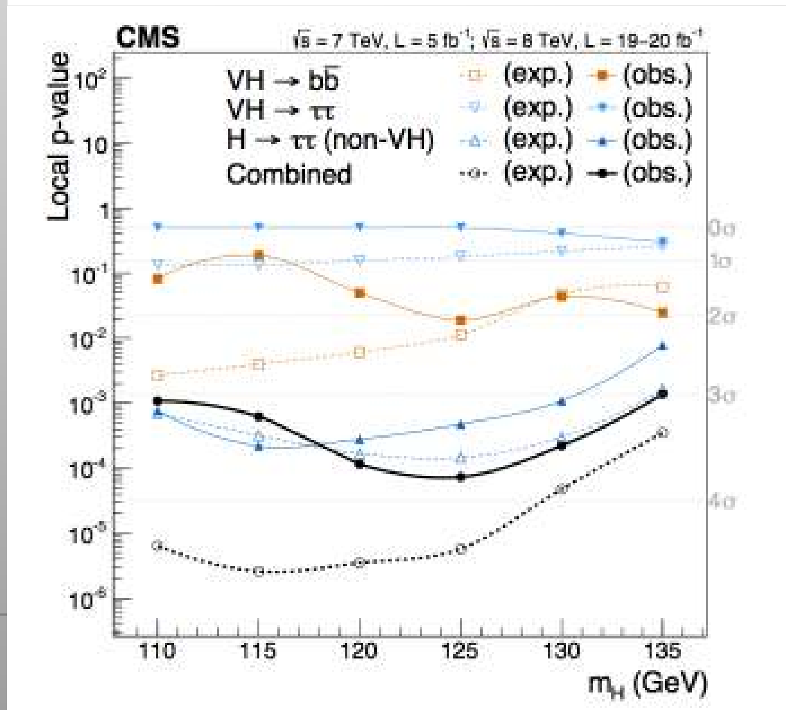
Higgs → Fermions Combination

- 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 ($m_H = 125$ 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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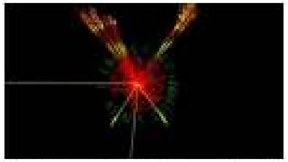
Home > Physics > General Physics > June 22, 2014

Evidence found for the Higgs boson direct decay into fermions

Jun 22, 2014



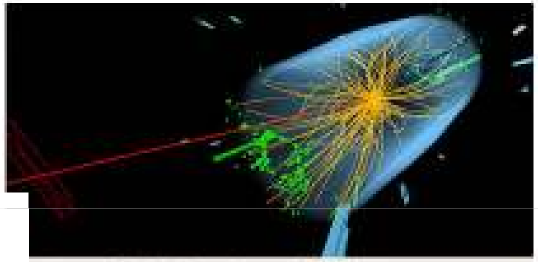
Simulated production of a Higgs event in ATLAS. Image credit: CERN.

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

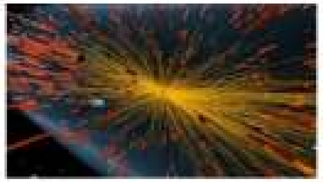
Confirmation for the Higgs: Physicists have for the first time demonstrated the second, postulated by the Standard Model decay of the Higgs boson. In data of the CMS experiment at the Large Hadron Collider (LHC), they discovered an excess of bottom quarks and tau leptons. This shows that the Higgs can 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 ... Higgs

El descubrimiento del bosón de Higgs ... portadores de fuerzas en la naturaleza. ... encontrado evidencias de la desintegració... materia, y con una tasa que se ajusta al mod...

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 (2014)

It's actually the highest scoring article in this journal that we've seen so far.

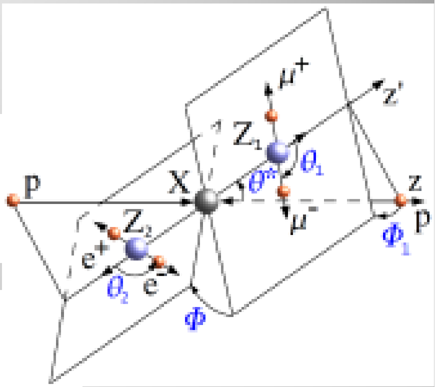
It's in the top 5% of all articles (2,789,380) ever tracked by Altmetric

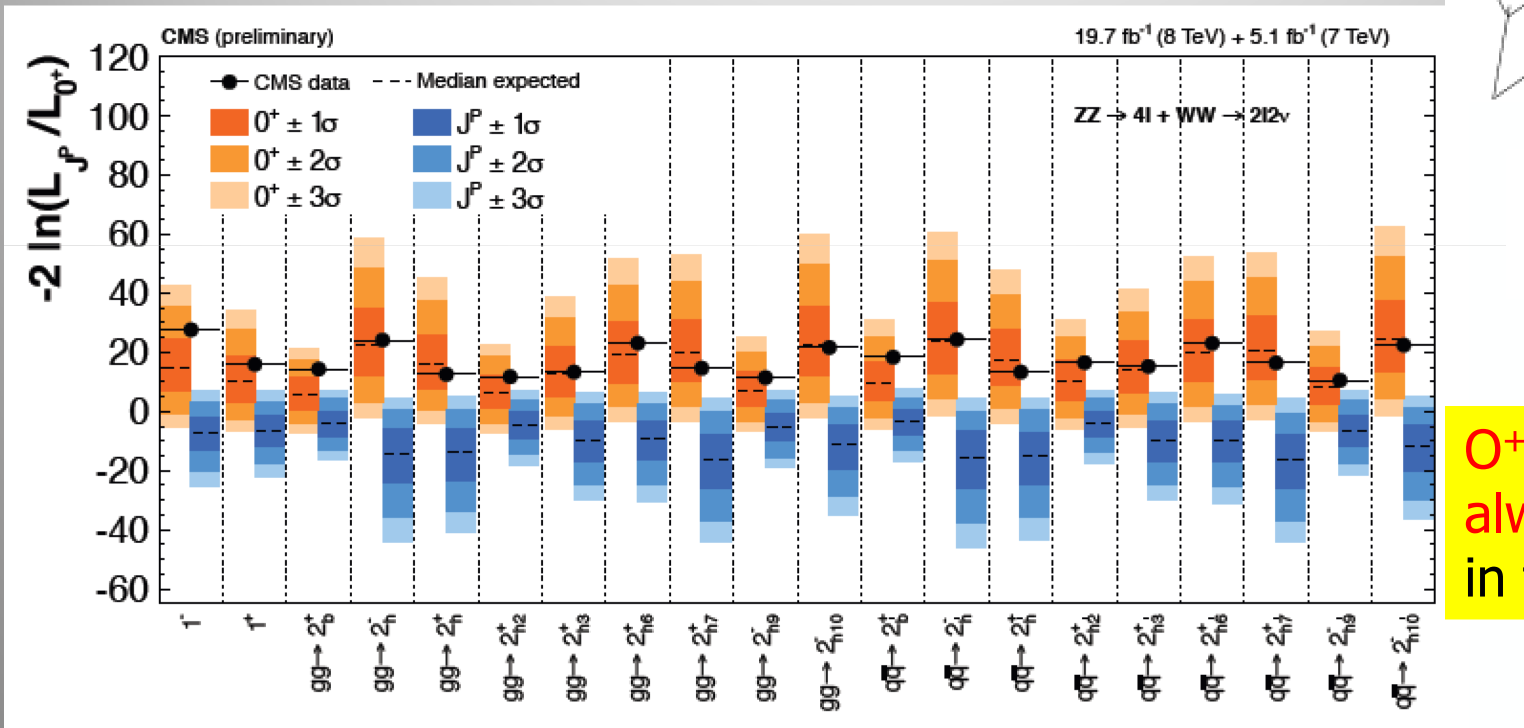
Spin/Parity Studies

Combined study of H→ZZ and H→WW

CMS-PAS-HIG-14-014

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





Similar results from ATLAS

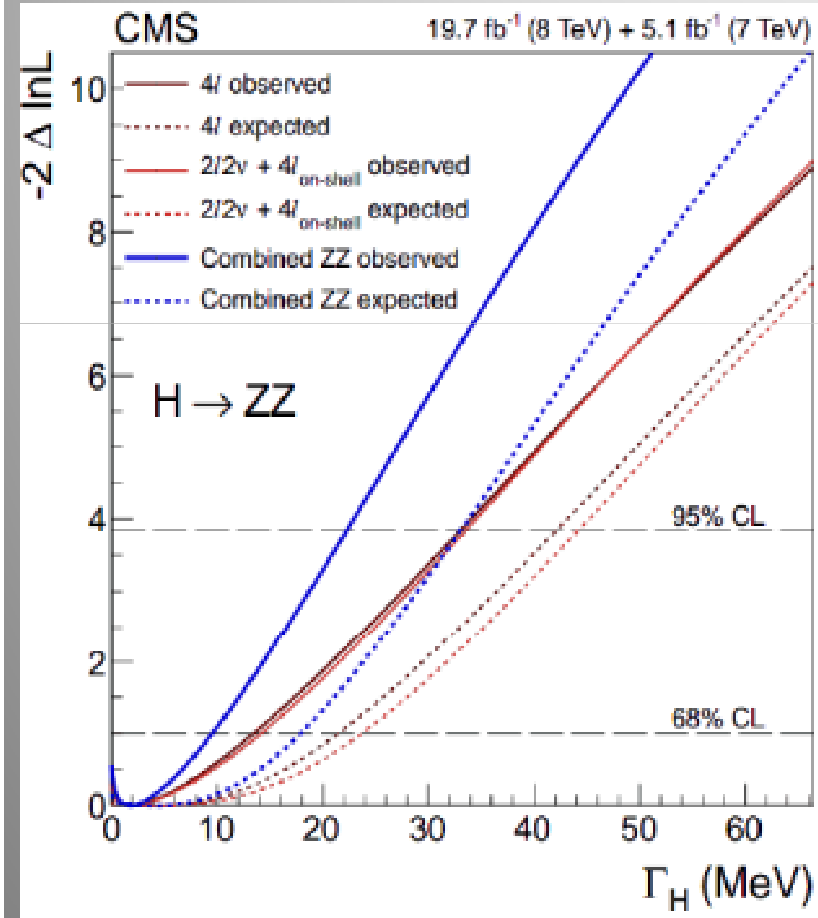
O⁺ hypothesis is always favoured in the comparison

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

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

The Total Width of the Higgs

- Study Higgs → ZZ in the 4 charged lepton and 2 charged lepton + 2ν decay
- Compare the off-shell and on-shell production
- 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

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

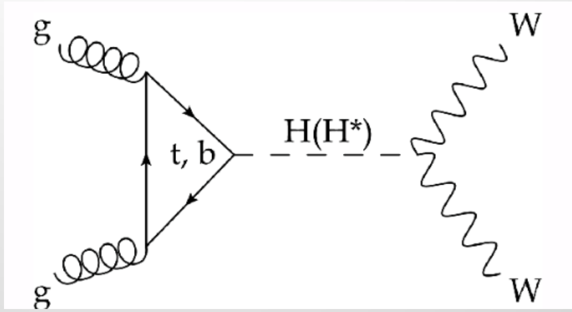
$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}\,.$$

- Compatibility between the observed results and the SM hypothesis lead to a **p-value of 0.24**

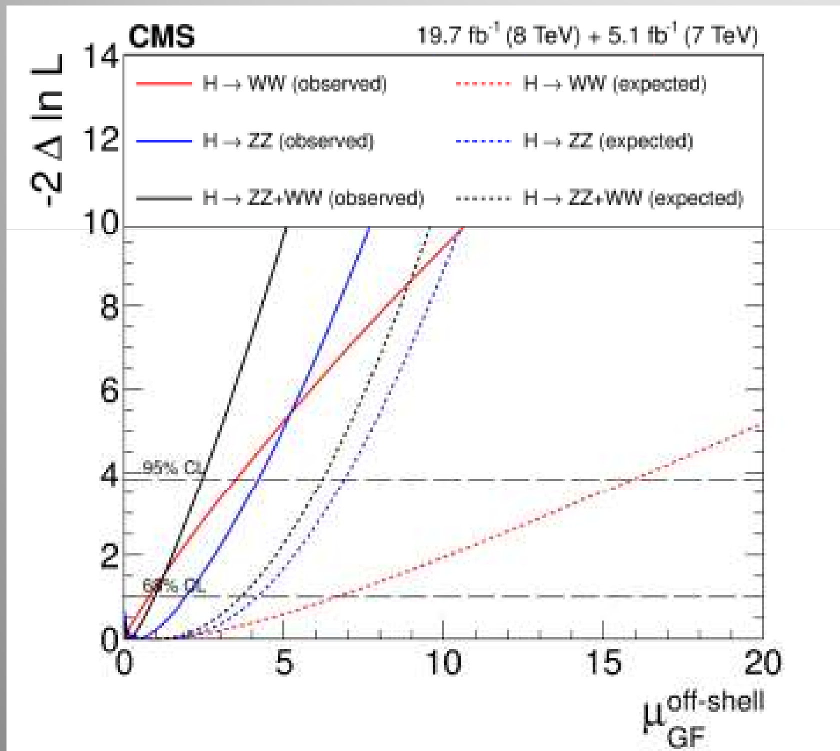
Limit on the width form ZZ is 22 MeV

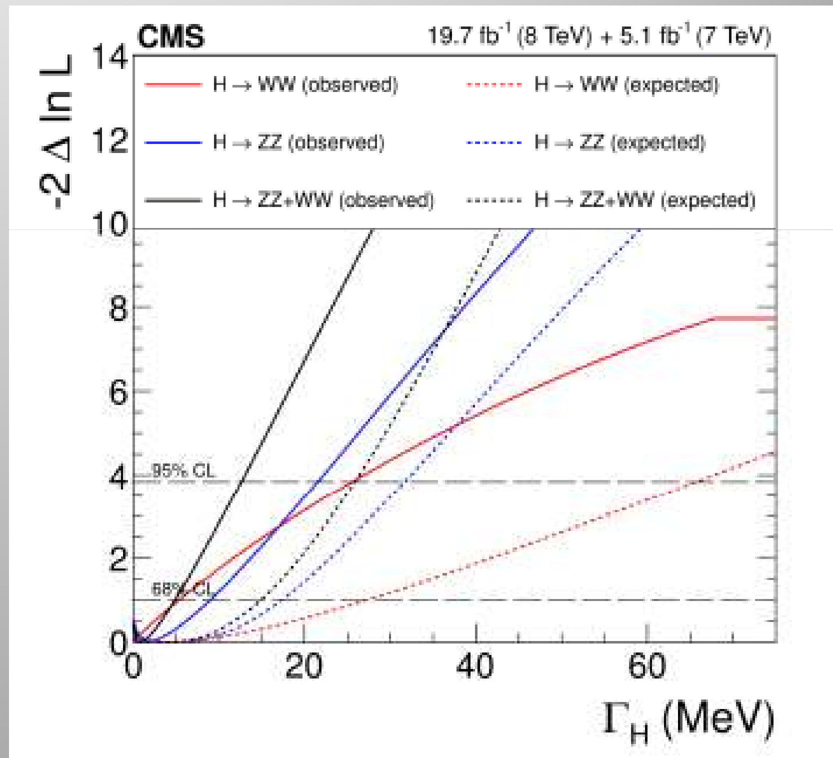
Total Width Study Including WW

arXiv:1604.02329



Recent update





Combined with the ZZ channel this leads to a total width limit of 13 MeV (26 MeV) for the ggF (VBF) process

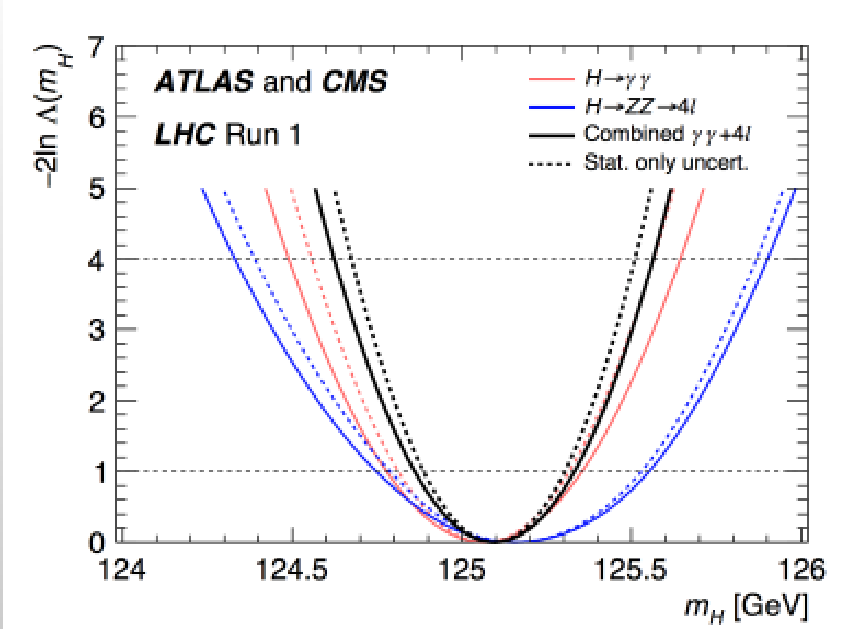
Higgs Combined analysis

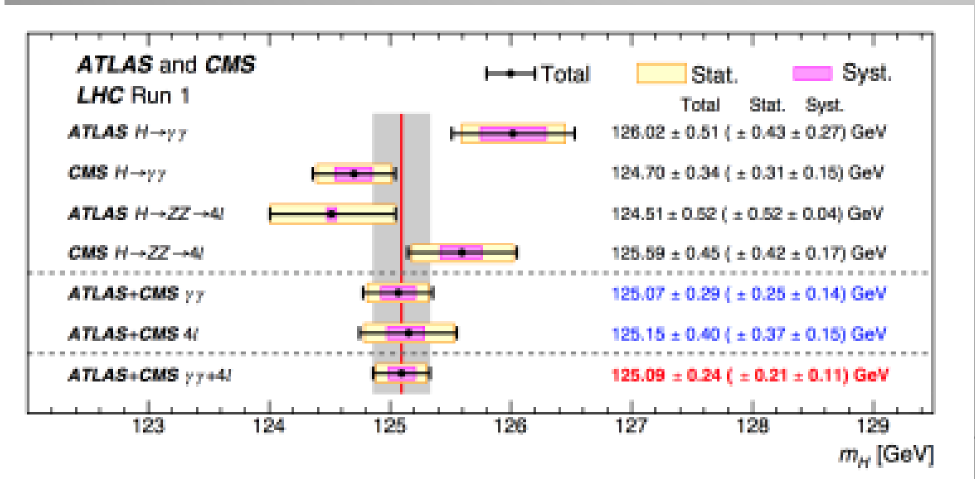
Mass of the Higgs

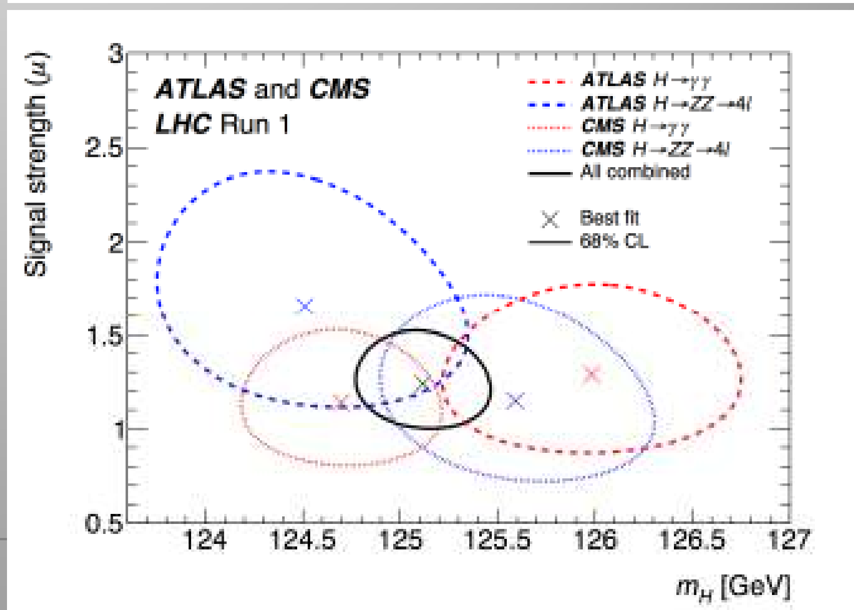
- The first combined result from CMS and ATLAS
- Combine the H->ZZ and H->γγ channels (most precise channels)
- Mass precision ~ 0.2%

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

arXiv:1503.07589







CMS+ATLAS Mass Paper

First common paper CMS+ATLAS!!

For the record

- 5153 authors.
  - One duplicate, 2×10^{-4} effect.
- Found that there are two:
  - Archana Sharma (both CMS)
  - **Andrea Bocci (one CMS, one ATLAS)**
  - Muhammad Ahmad (ditto)
  - F. M. Giorgi (ditto)

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NATURE | NEWS

Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

Davide Castelvecchi

15 May 2015

CERN

Thousands of scientists and engineers have worked on the Large Hadron Collider at CERN.

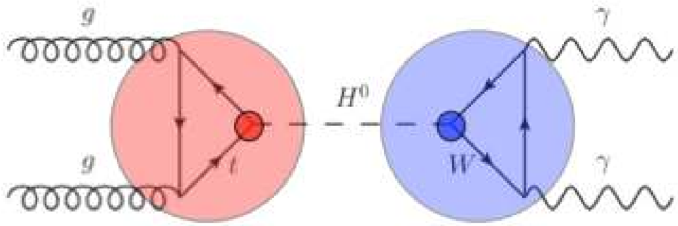
A physics paper with 5,154 authors has — as far as anyone knows — broken the record for the largest number of

Coupling Measurements

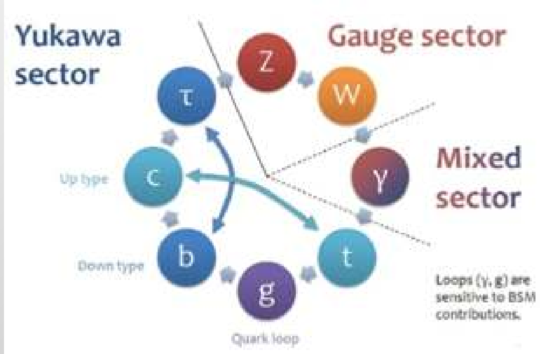
Assume the observed signal stems from one narrow resonance.

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

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

•Overall combinations from ATLAS and from CMS

CMS arXiv:1412.8662

ATLAS arXiv:1507.04548

Combination of ATLAS & CMS
arXiv:1606.02266

Combined Fit of ATLAS & CMS Data

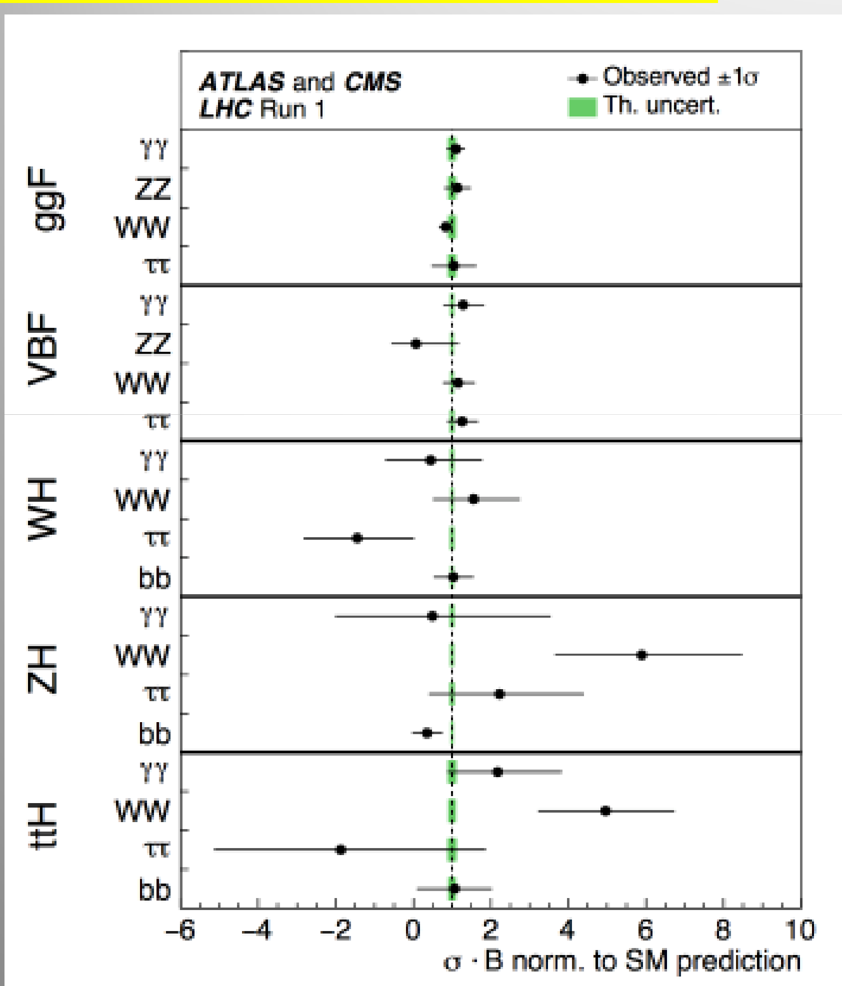
Overview of the decay channels included in the analysis

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[91]	[92]	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[93]	[94]	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[95, 96]	[97]	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[98]	[99]	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[100]	[101]	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[102]	[103]	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	[77, 104, 105]	[107]	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)

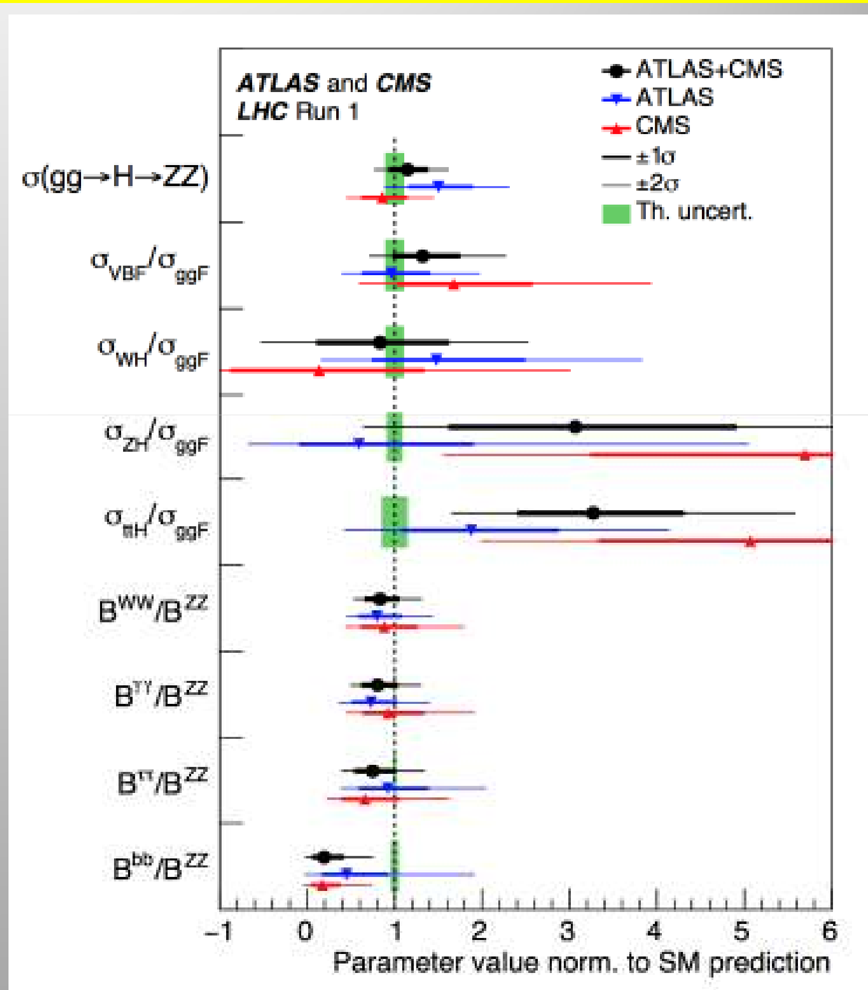
Values for a common mass M_H of 125.09 GeV

Combined Fit Results

Results for cross section x BR



Results normalized to σ(gg->H->ZZ)



$$\sigma_i \cdot \mathrm{B}^f = \sigma(gg \to H \to ZZ) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{\mathrm{B}^f}{\mathrm{B}^{ZZ}}\right),$$

Ratios of Higgs Coupling Modifiers

Coupling Modifiers

$$\kappa_j^2 = \sigma_j/\sigma_j^{SM}$$

$$\kappa_j^2 = \Gamma^j/\Gamma^j_{SM},$$

Ratios

$$\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$$

$$\lambda_{Zg} = \kappa_Z/\kappa_g$$

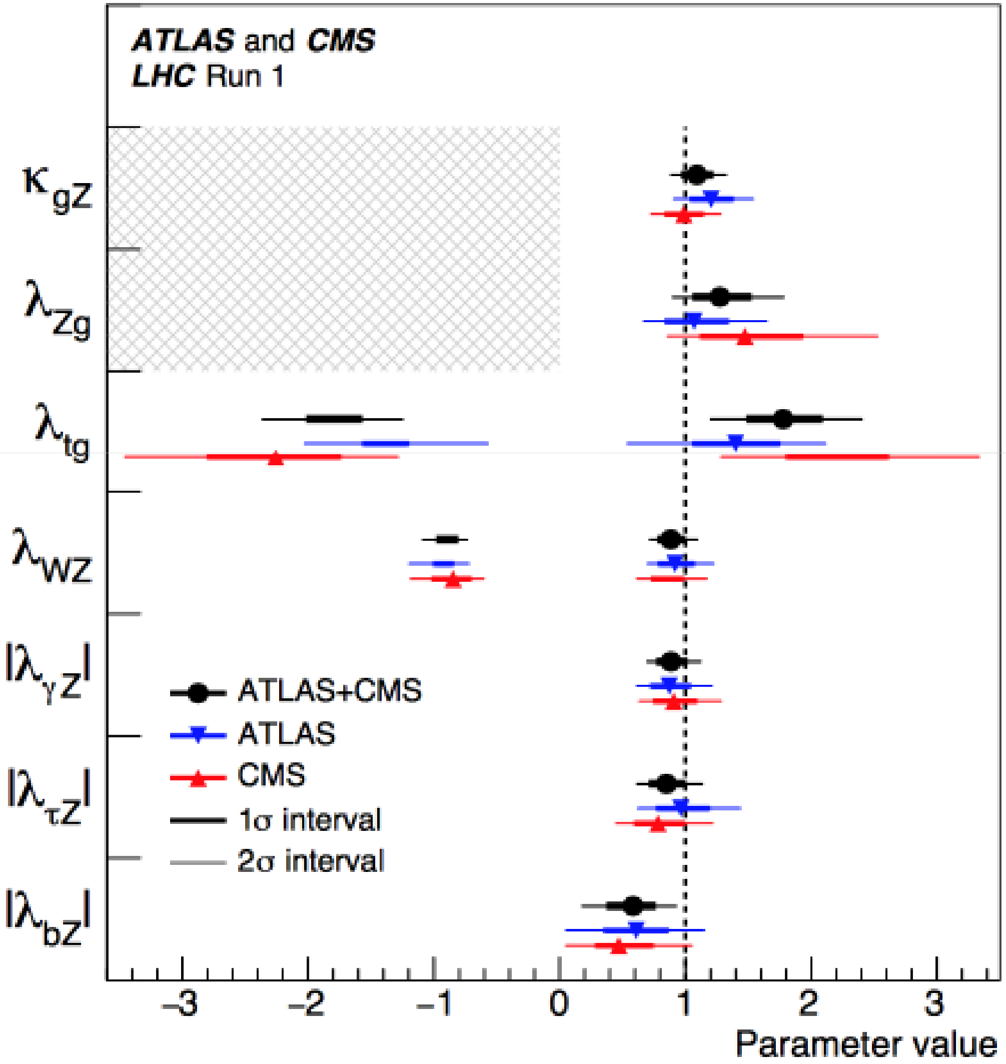
$$\lambda_{tg} = \kappa_t/\kappa_g$$

$$\lambda_{WZ} = \kappa_W/\kappa_Z$$

$$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$$

$$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$$

$$\lambda_{bZ} = \kappa_b/\kappa_Z$$



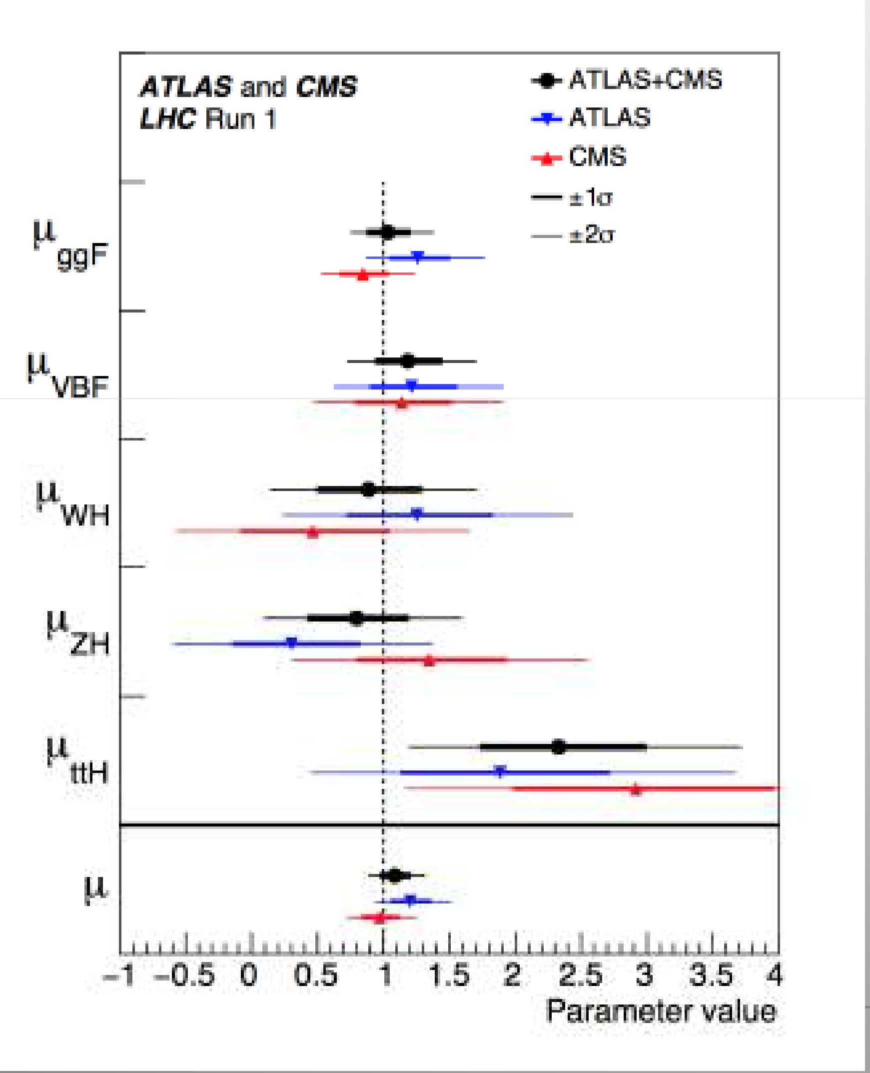
Hatched area: indicates we assume these parameters to be positive

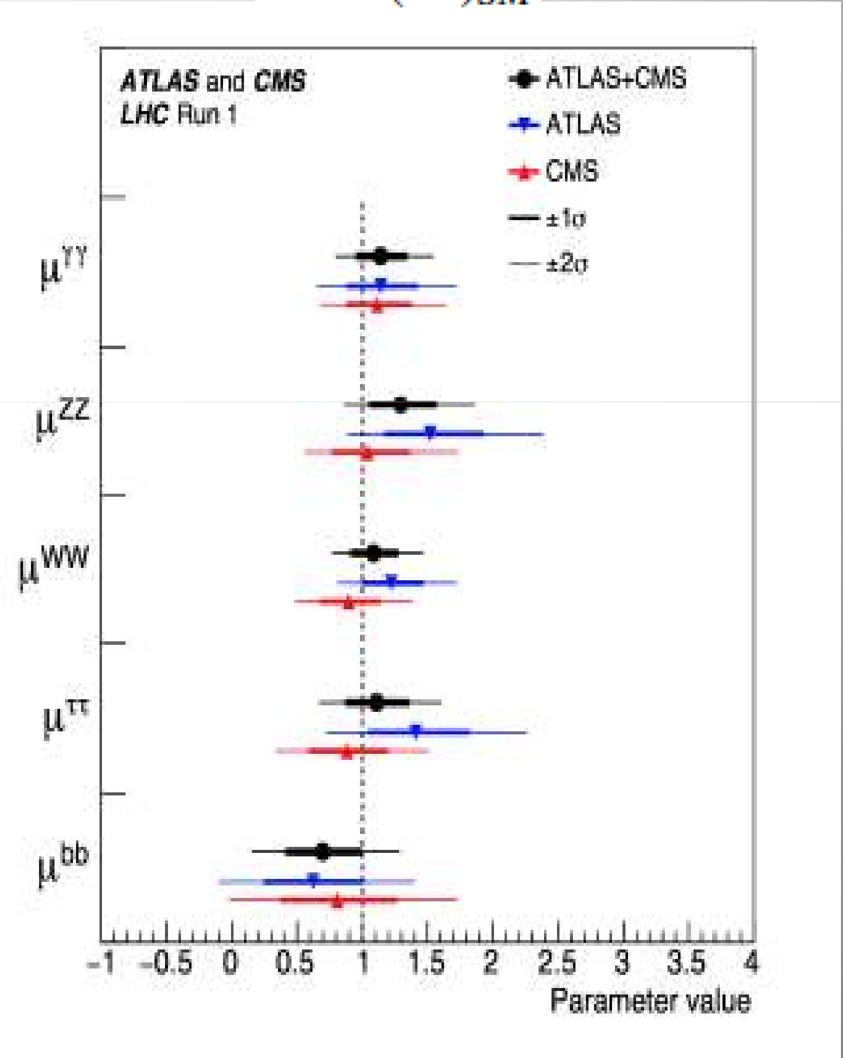
Production/Decay Signal Strength

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$

Signal strength

$$\mu^f = \frac{B^f}{(B^f)_{SM}}$$





Global Signal Strenght μ

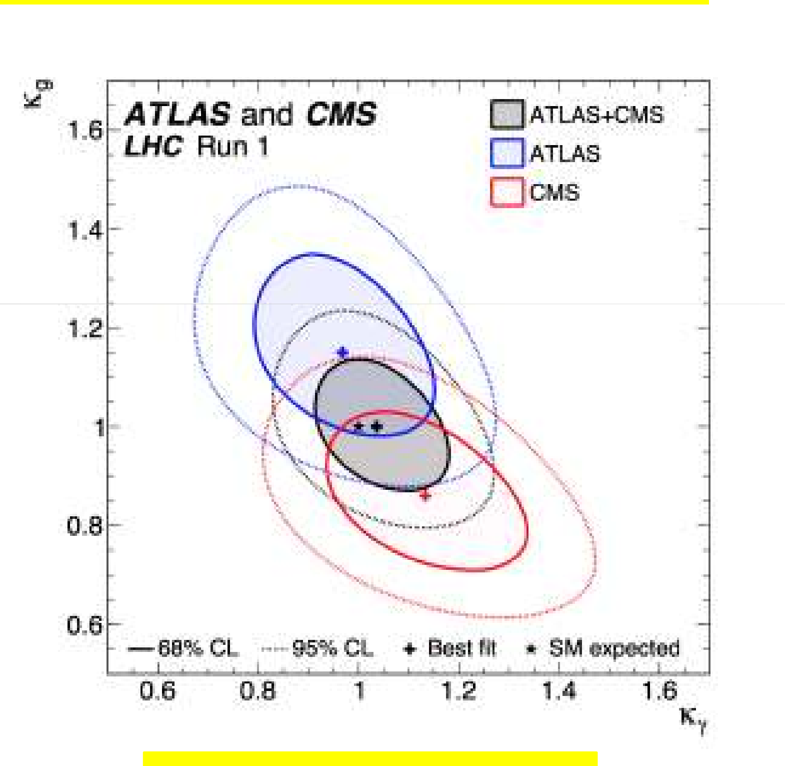
Results for ATLAS & CMS and for the combined data set

	Best fit μ	Uncertainty				
		Total	Stat	Expt	Thbgd	Thsig
ATLAS + CMS (measured)	1.09	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS + CMS (expected)		$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS (measured)	1.20	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$
ATLAS (expected)		$^{+0.14}_{-0.13}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.07}_{-0.06}$
CMS (measured)	0.97	$^{+0.14}_{-0.13}$	$^{+0.09}_{-0.09}$	$^{+0.05}_{-0.05}$	$^{+0.04}_{-0.03}$	$^{+0.07}_{-0.06}$
CMS (expected)		$^{+0.14}_{-0.13}$	$^{+0.09}_{-0.09}$	$^{+0.05}_{-0.05}$	$^{+0.04}_{-0.03}$	$^{+0.08}_{-0.06}$

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig}),$$

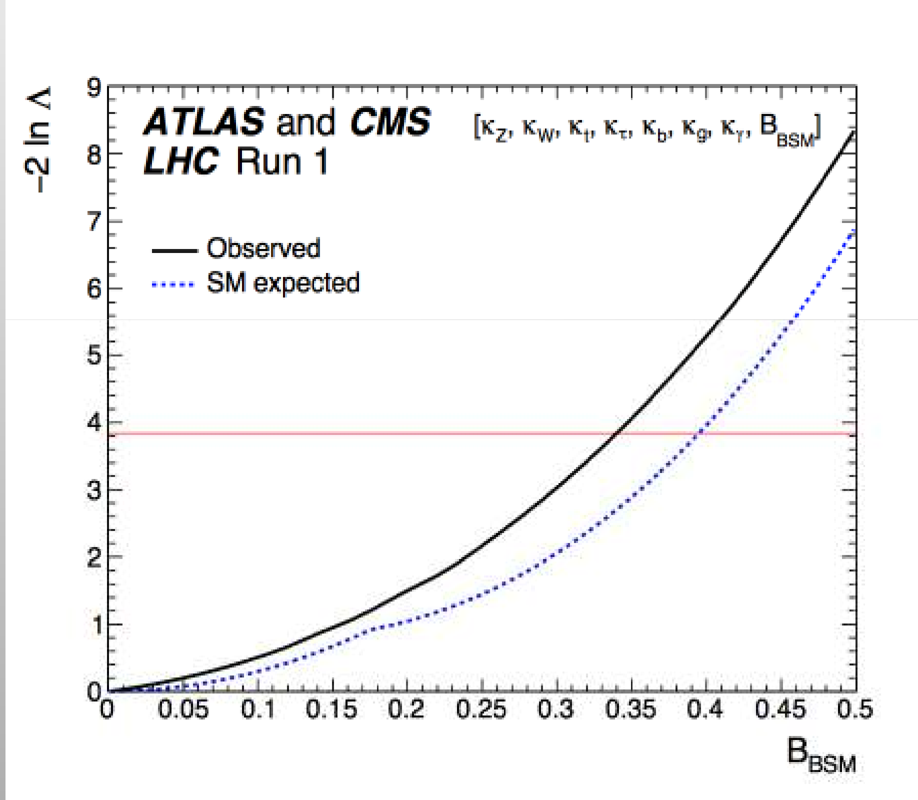
BSM Searches

Search for effects in loops in 2-photon decays and ggF



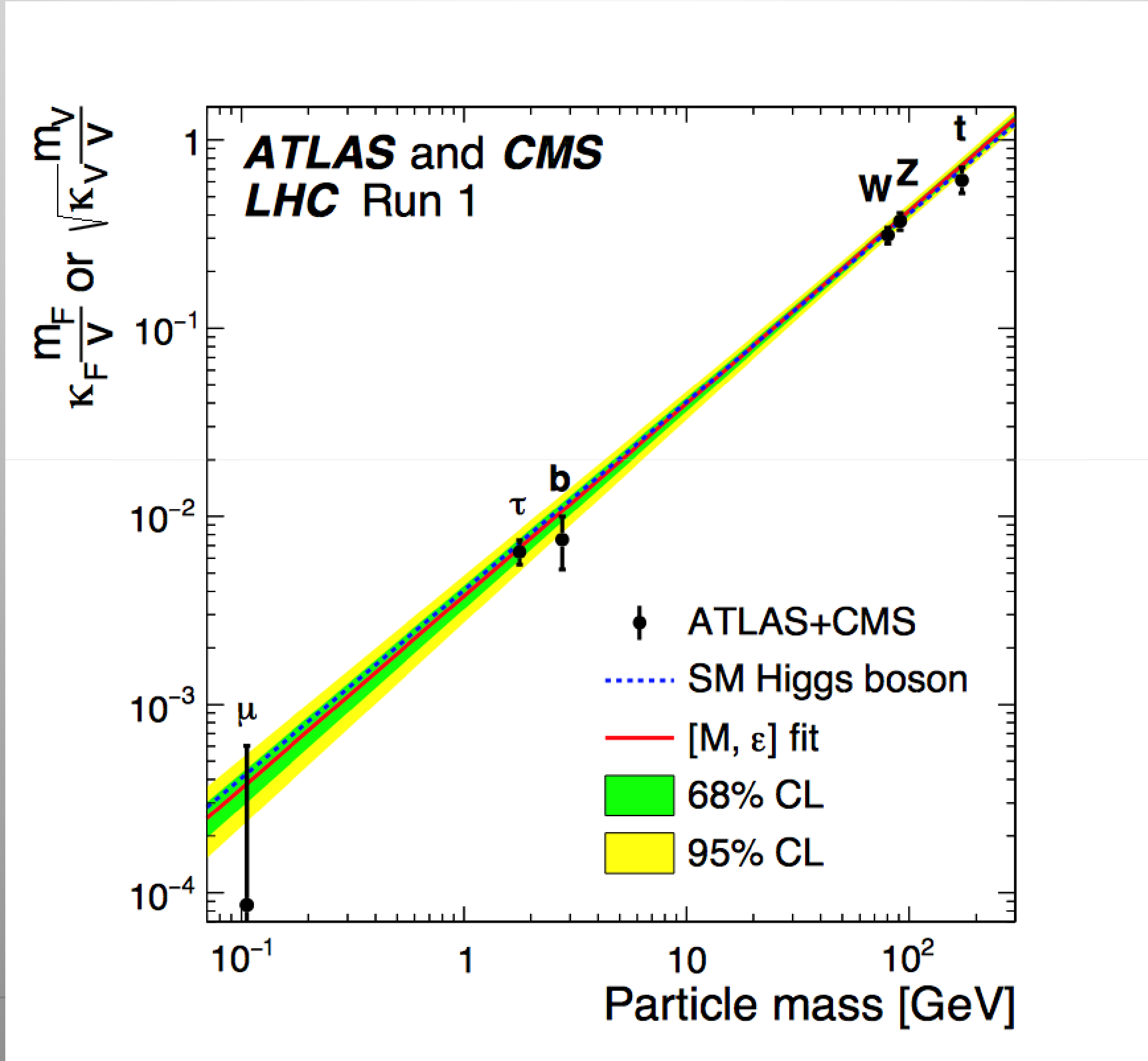
Assuming $B_{BSM}=0$

Allow for $B_{BSM}>0$



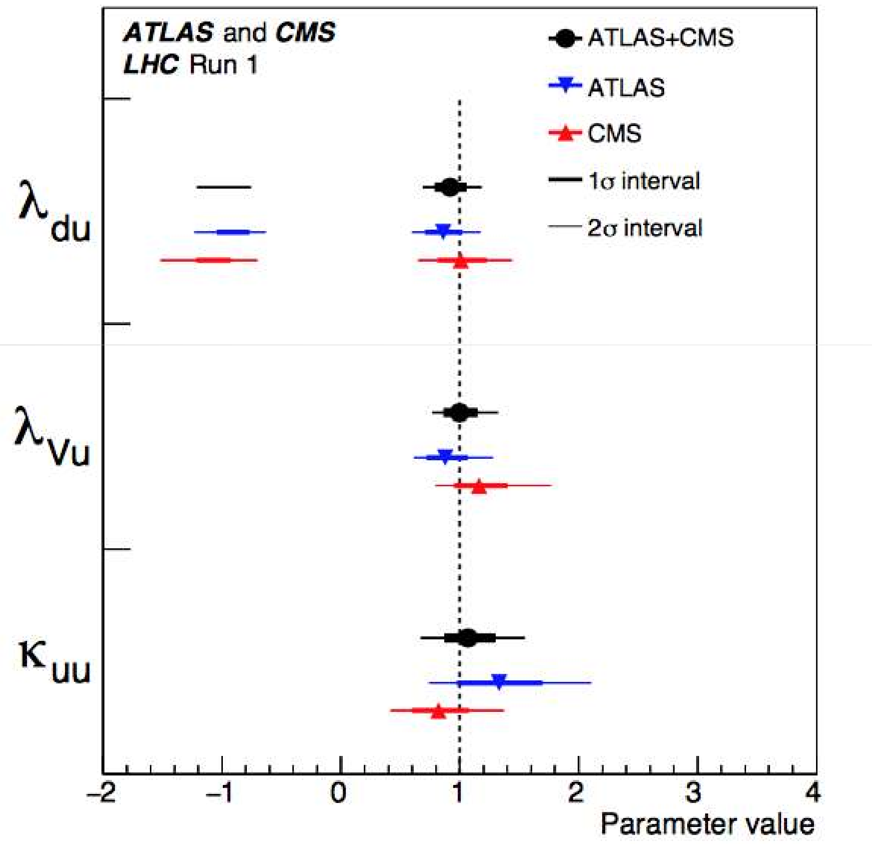
Data shows no deviation of SM!

Results as Function of Particle Mass

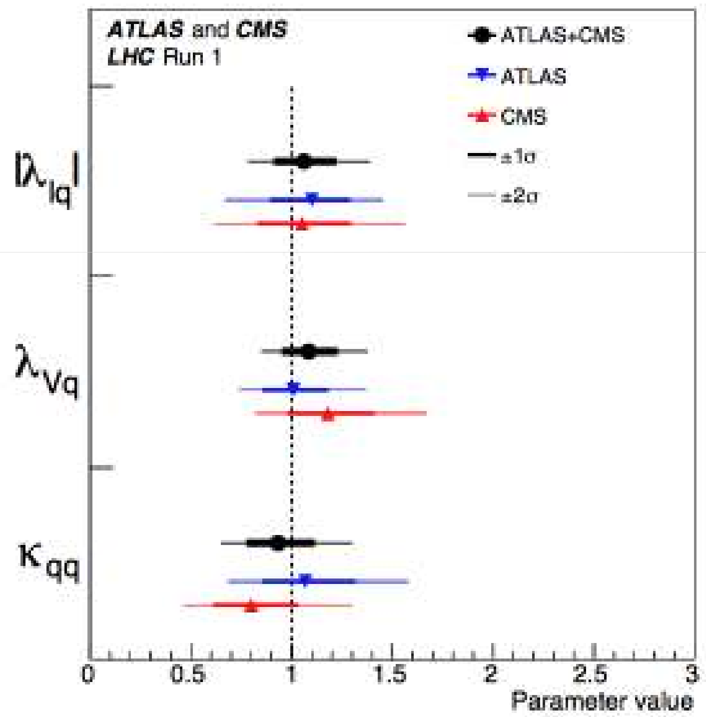


Testing u/d fermion/ lepton couplings

Up- and down-type fermion coupling ratios

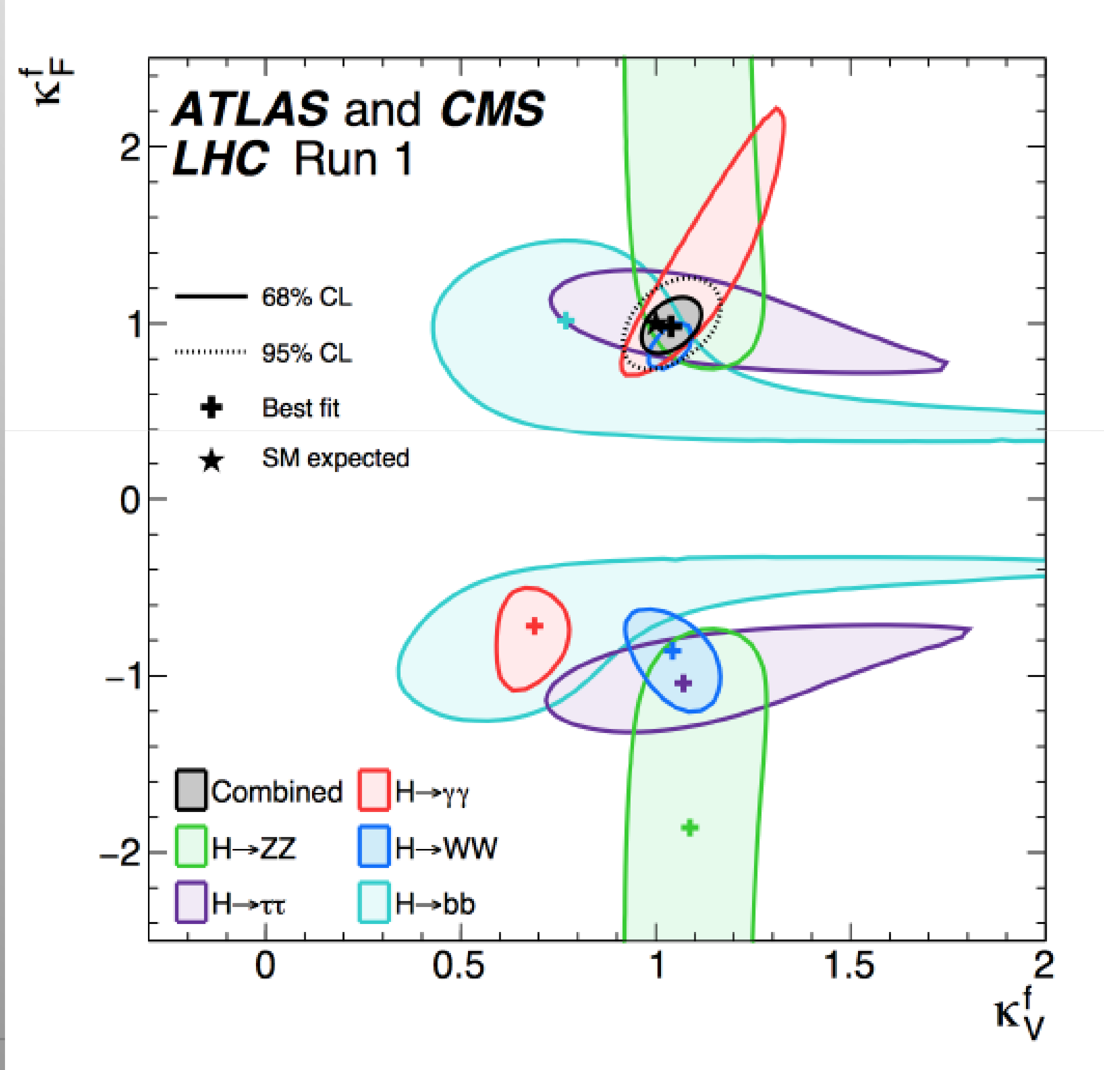


Lepton and quark coupling ratios



Fermion and Vector Boson Coupling Modifiers

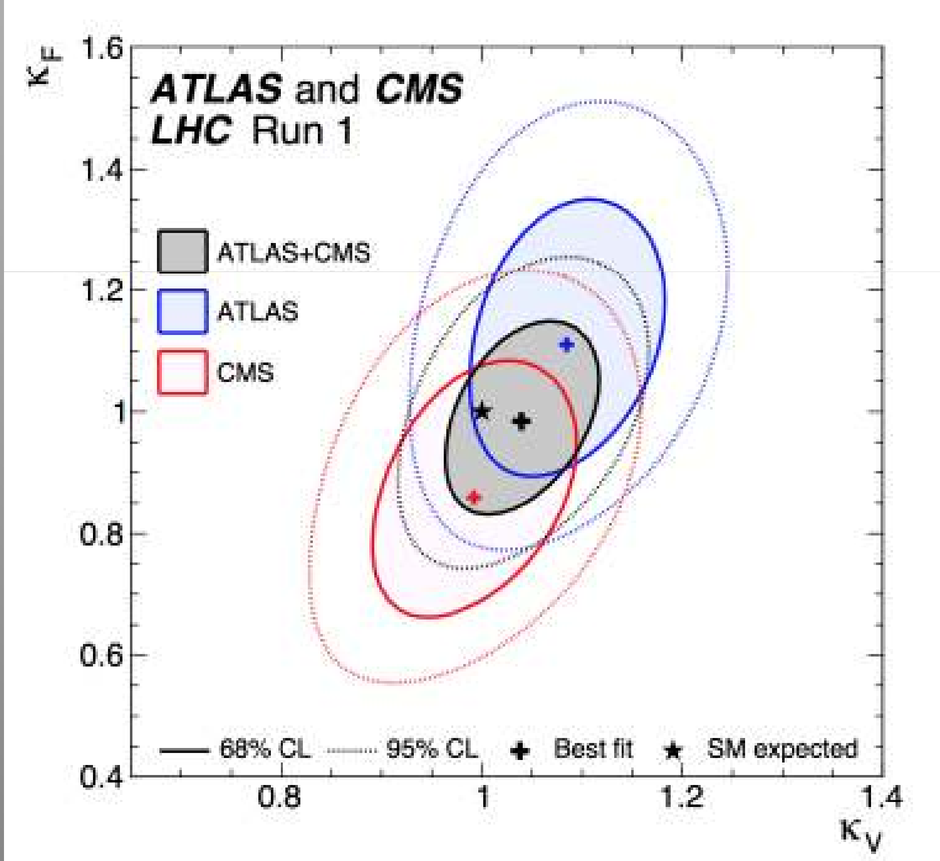
Results for the individual channels and the overall combination

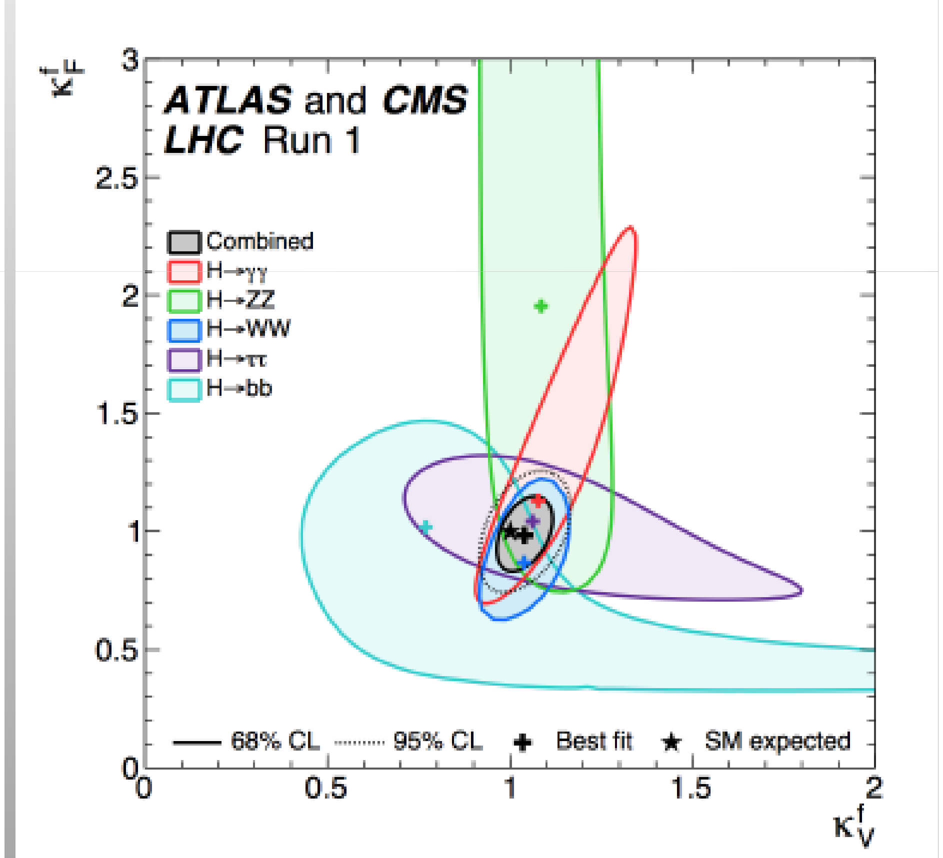


Fermion and Vector Boson Coupling Modifiers

Results for the individual channels and the overall combination

Zooming in on the interesting region…





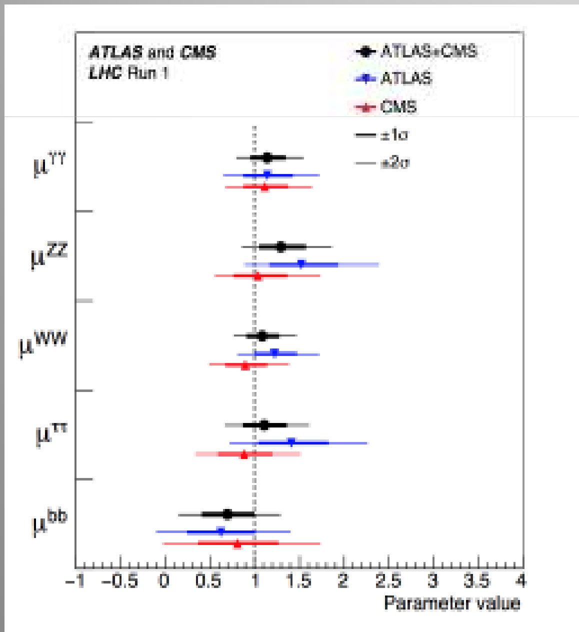
Higgs: ATLAS+CMS Combination

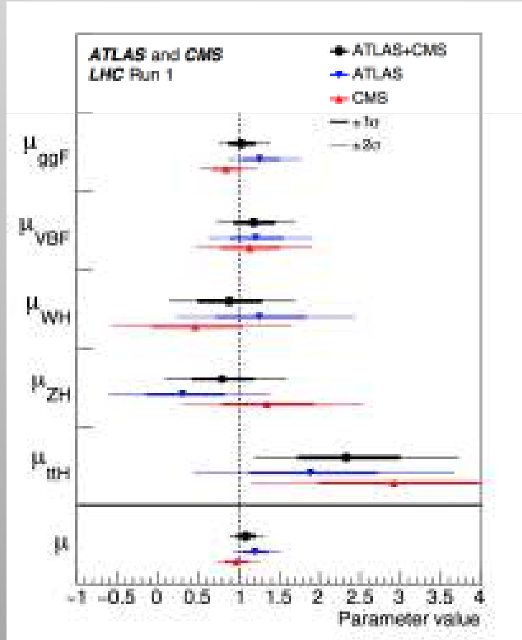
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \rightarrow \tau\tau$	5.5	5.0
$H \rightarrow bb$	2.6	3.7

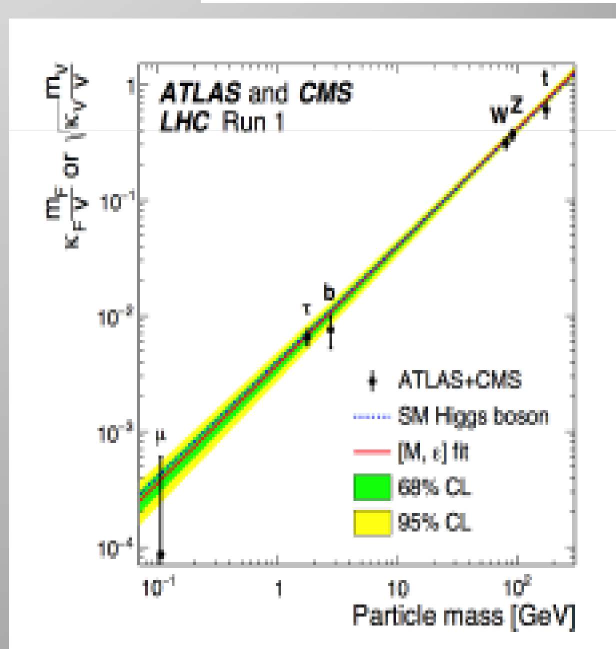
The Run-1 Higgs Legacy!

Vector Boson Fusion production mechanism and H-> tau tau decays established with 5σ significance in combination

arXiv:1606.02266





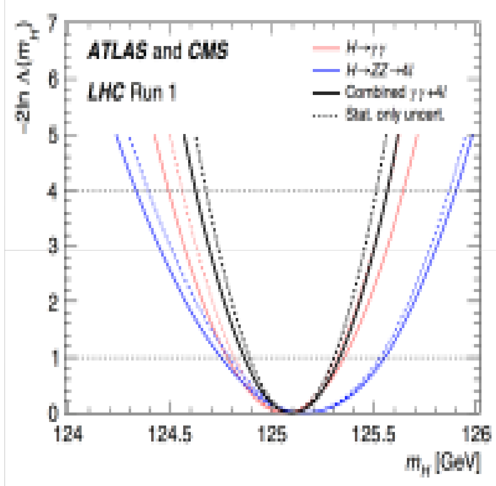


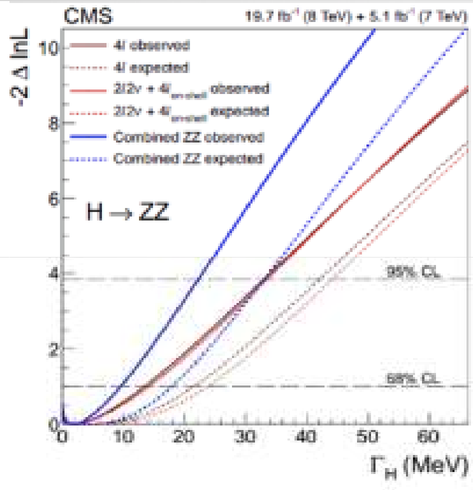
Signal strength/SM:

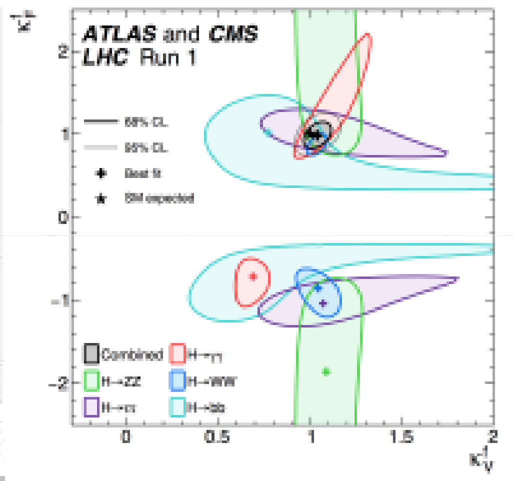
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig}),$$

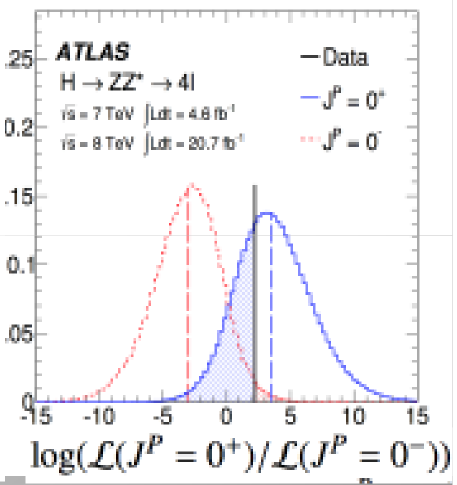
Brief Higgs Summary from Run-1

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









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

Width
< 24 MeV
(95%CL)

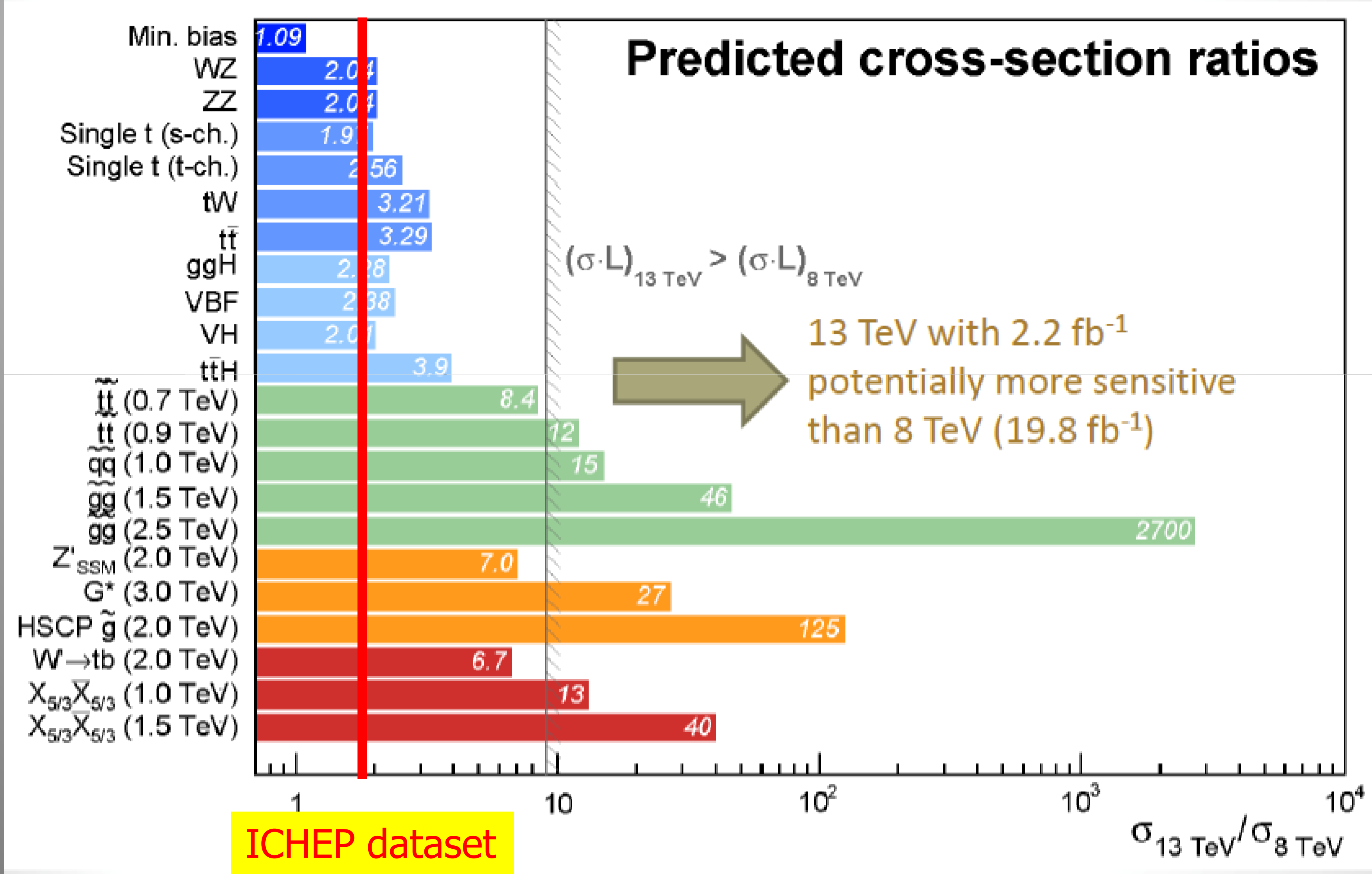
Couplings are within ~20% of the SM values

Spin = $0^{+(+)}$ preferred over 0^-,1,2

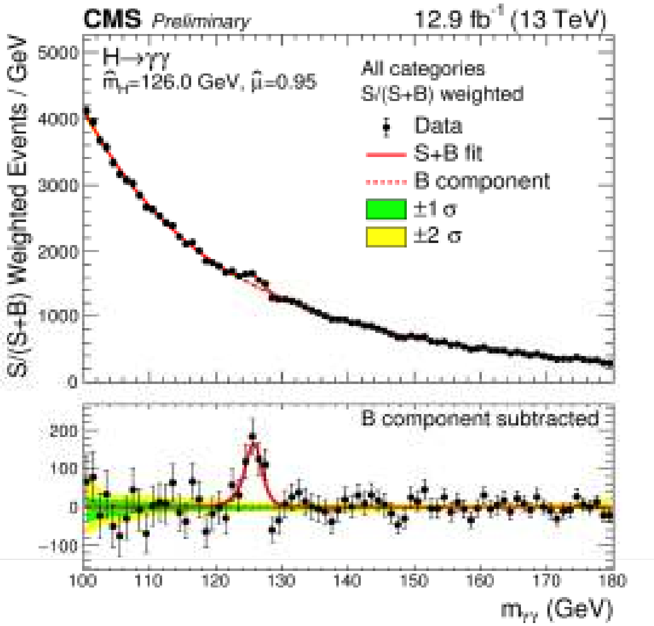
SM-like behaviour for most properties, but continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production…

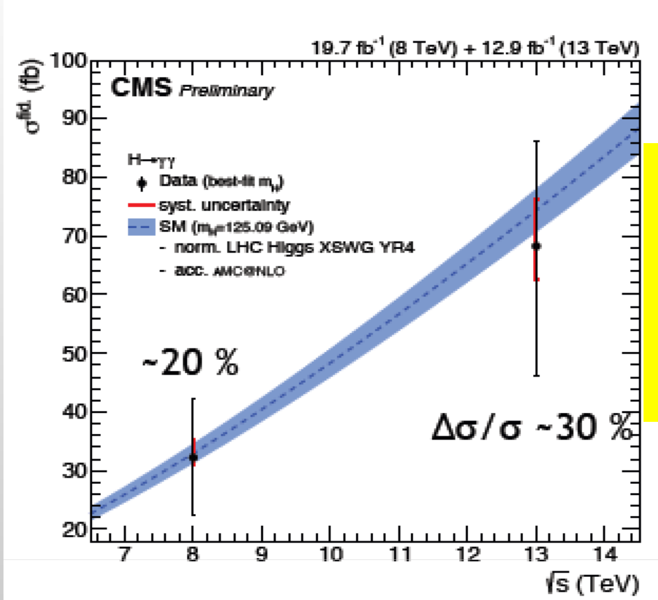
13 TeV Results

Run-II: From 8 TeV to 13 TeV

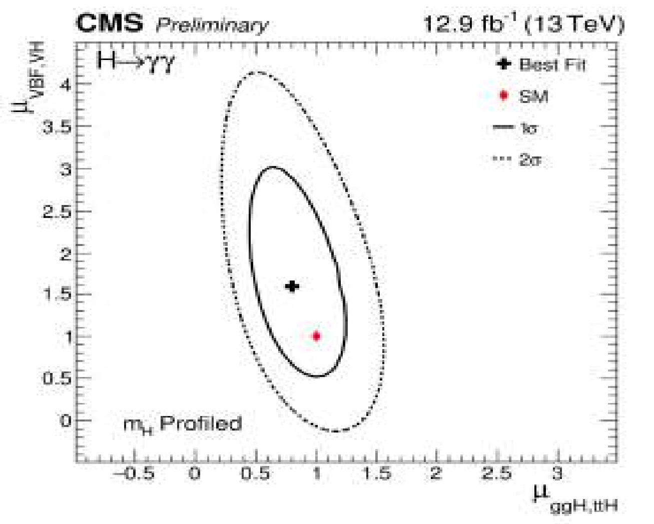


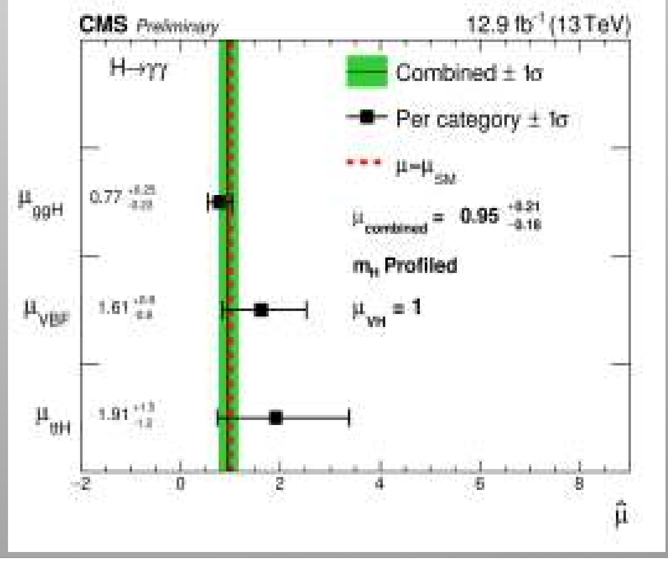
13 TeV Higgs Results: Higgs ->γγ





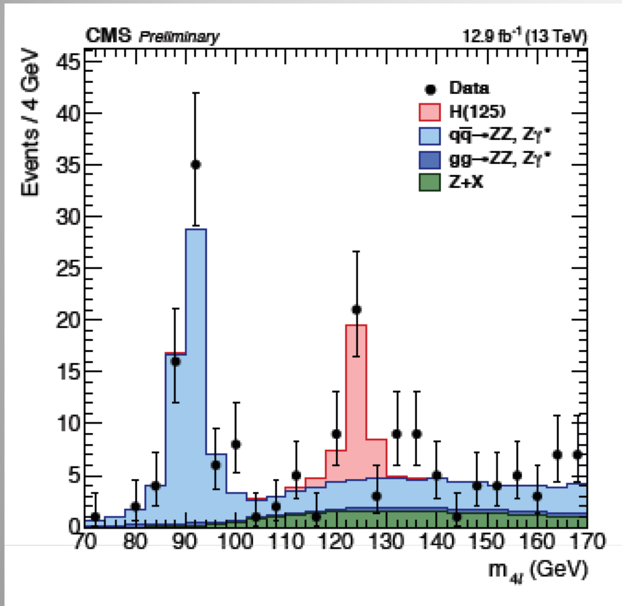
2016 data
Observed 5.6σ
Expected 6.2σ
μ= 0.91

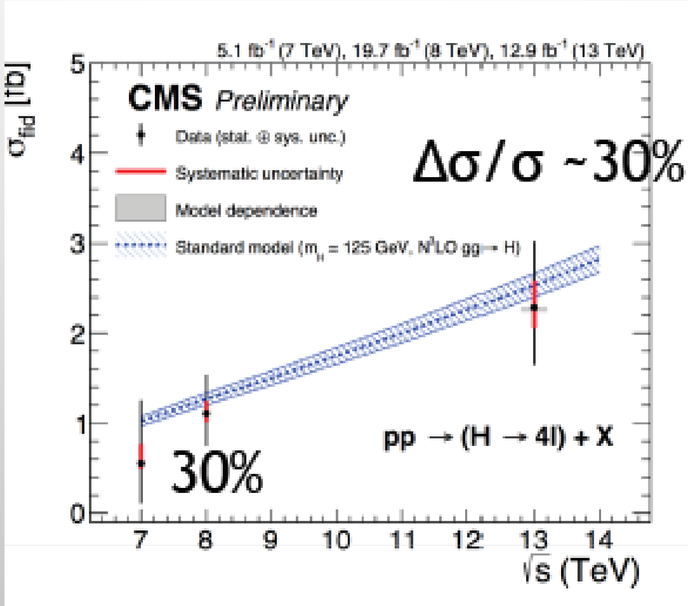




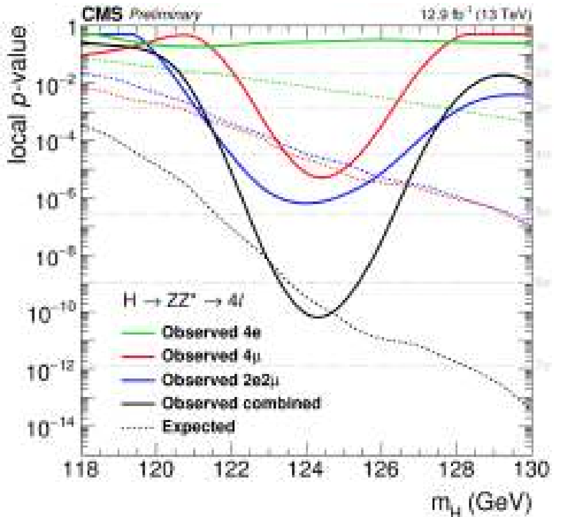
Fid. cross sec.	CMS (12.9 fb^{-1})	69^{+16}_{-22}(stat)$^{+8}_{-6}$(syst)	73.8±3.8

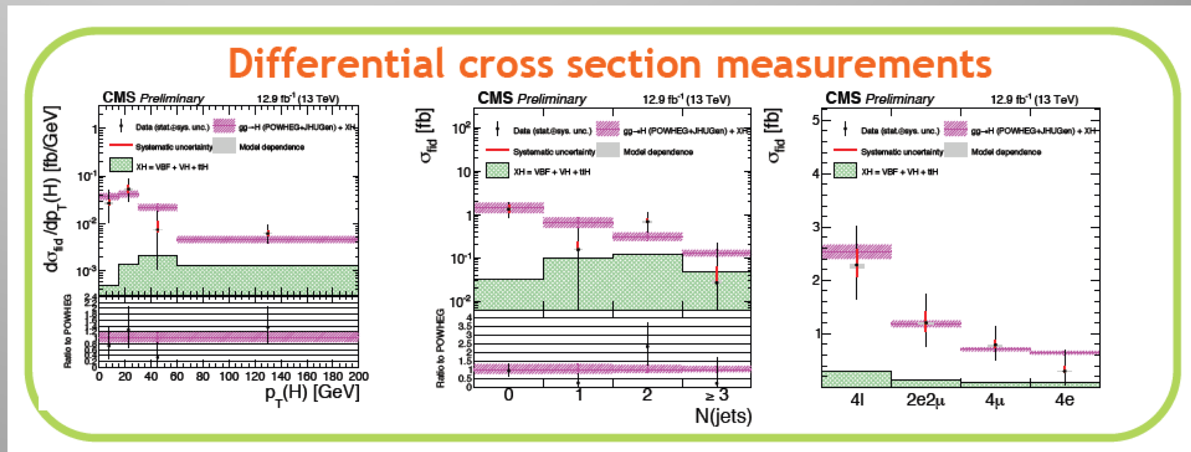
13 TeV Higgs Results: H-> ZZ





2016 data
Observed 6.2σ
Expected 6.5σ
μ= 0.99





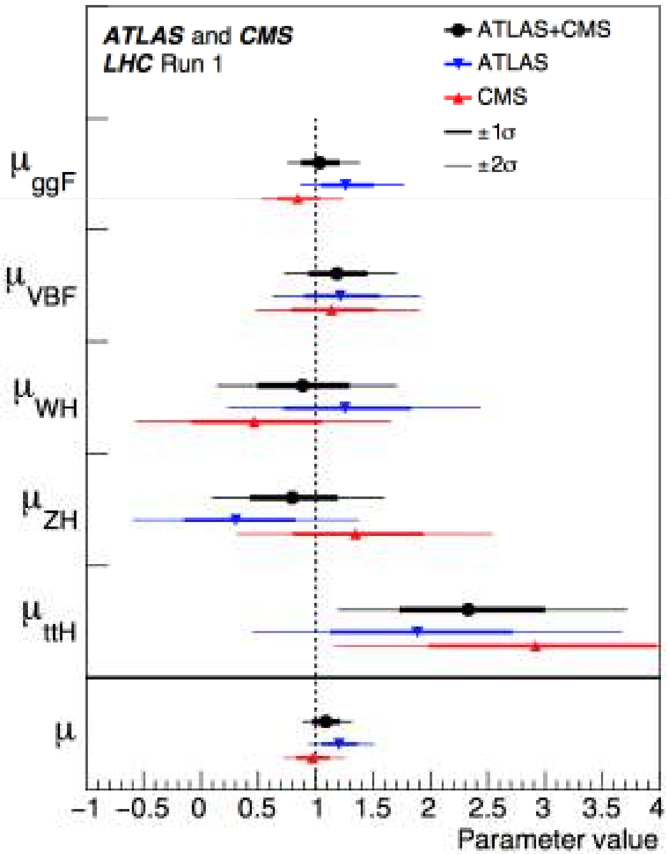
Fid. cross sec.	CMS (12.9 fb^{-1})	$2.29^{+0.74}_{-0.64}$(stat)$^{+0.30}_{-0.23}$(syst)	2.53±0.13

The Hunt for ttH @ 13 TeV

We saw a small an unexpected excess in run-I in the multi-lepton channel
Is this real? Is it in fact ttH or something else (we do not constrain the Higgs)

- Combination of all Higgs analysis channels
- μ_{ttH} dominated by: ttH(γγ), ttH(multilepton), ttH(bb)

The ttH cross section increases with a factor ~4 @ 13 TeV



	μ (ttH)
ATLAS	1.9 +0.8 -0.7
CMS	2.9 +1.0 -0.9
Combined	2.3 +0.7 -0.6

Observed (expected) significance
4.4σ (2.0σ)

2015 data

ttH(γγ) $\hat{\mu}_{obs} = 3.8^{+4.5}_{-3.6}$

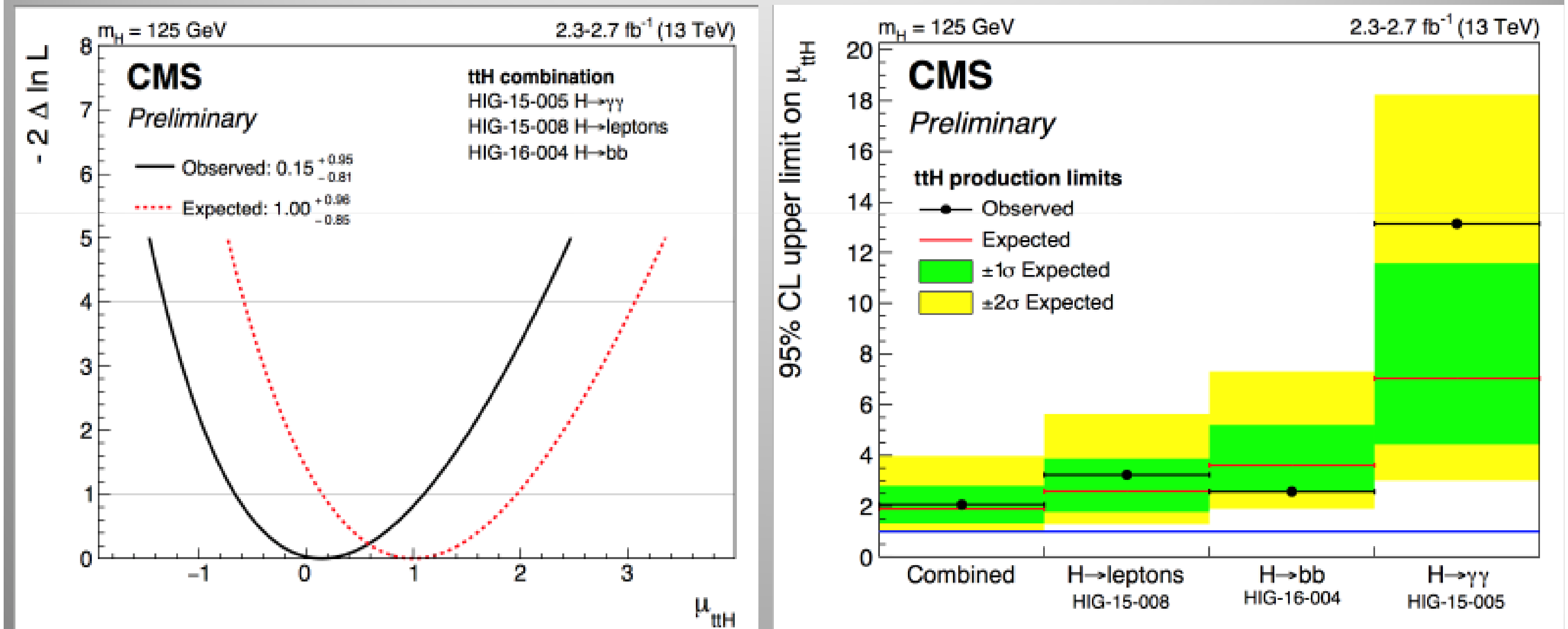
ttH(multilepton) $\hat{\mu}_{obs} = 0.6^{+1.4}_{-1.1}$

ttH(bb) $\hat{\mu}_{obs} = -2.0^{+1.8}_{-1.8}$

No significant excess in the new data.
But more data will referee

The Hunt for the ttH Channel

Measurements with the 13 TeV data in 2015



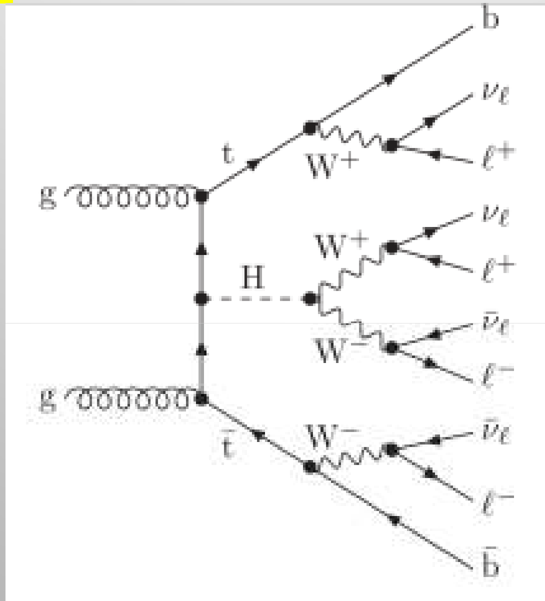
No upward fluctuation as in 8 TeV. So far ttH not clearly established yet

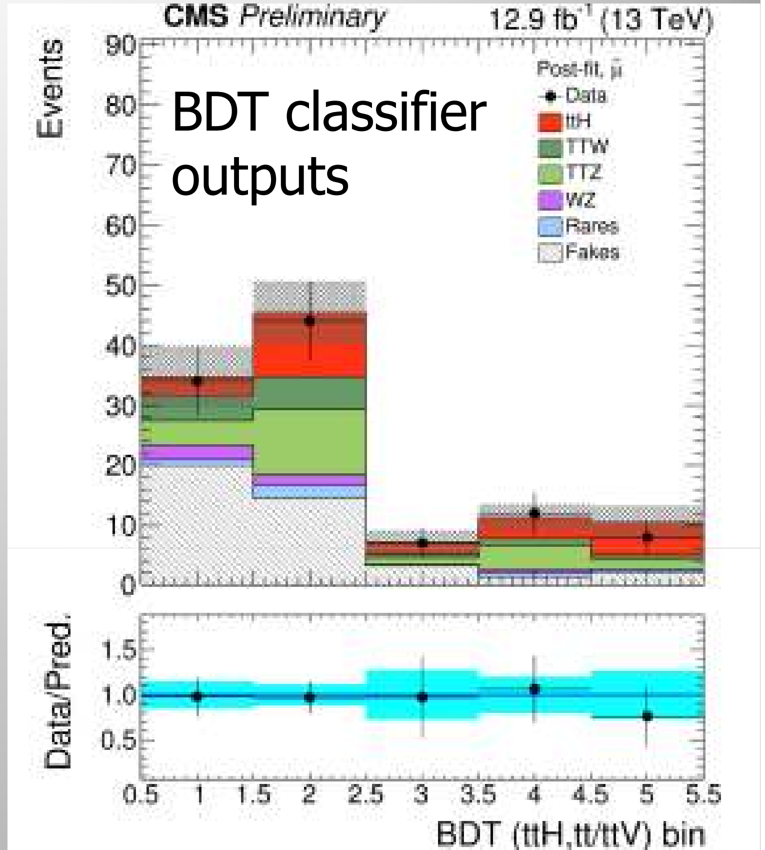
The Hunt for the ttH Channel

Update with 2016 data!
12.9 fb^{-1} of data

CMS-PAS-HIG-16-022

Search for associated production of Higgs bosons and top quarks in multilepton final states





Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit $\mu \pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

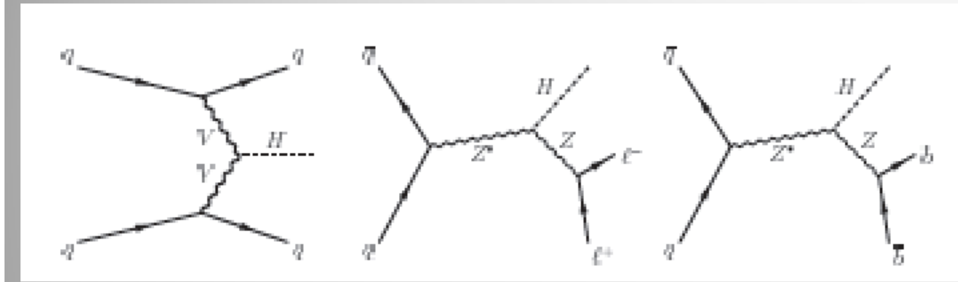
BSM Higgs Searches

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

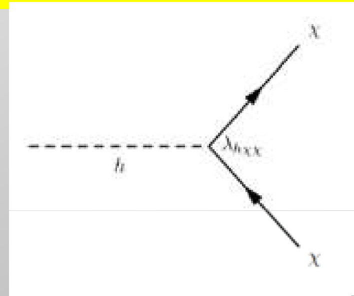


Search for invisible Higgs decays using

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

VBF $H \rightarrow$ 2 jets + missing E_T

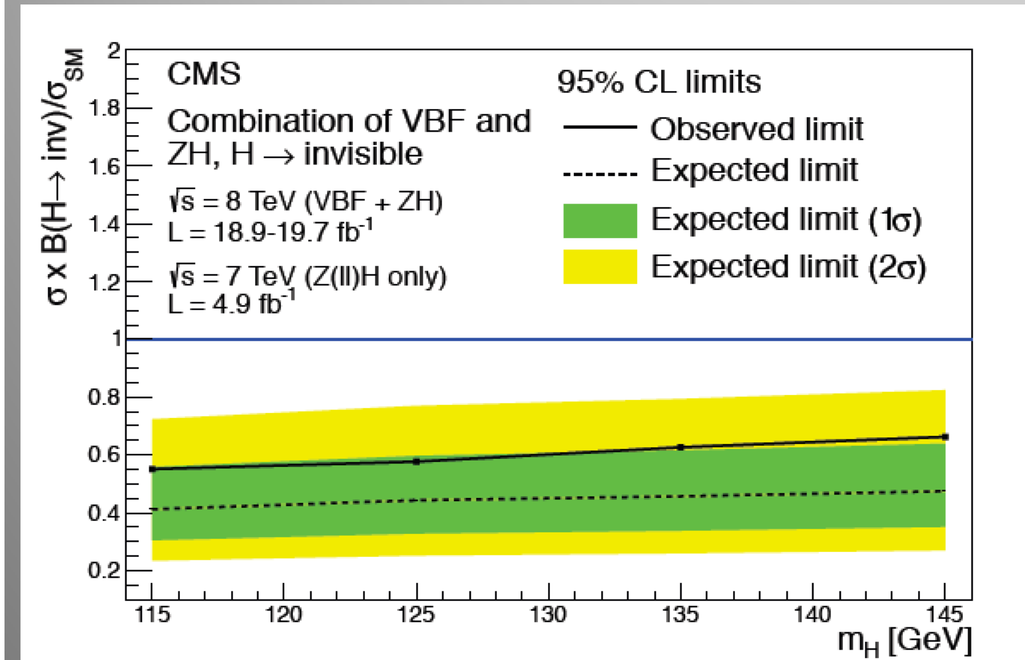
Possible decay in Dark Matter particles (if $M<M_H/2$): Higgs Portal Models



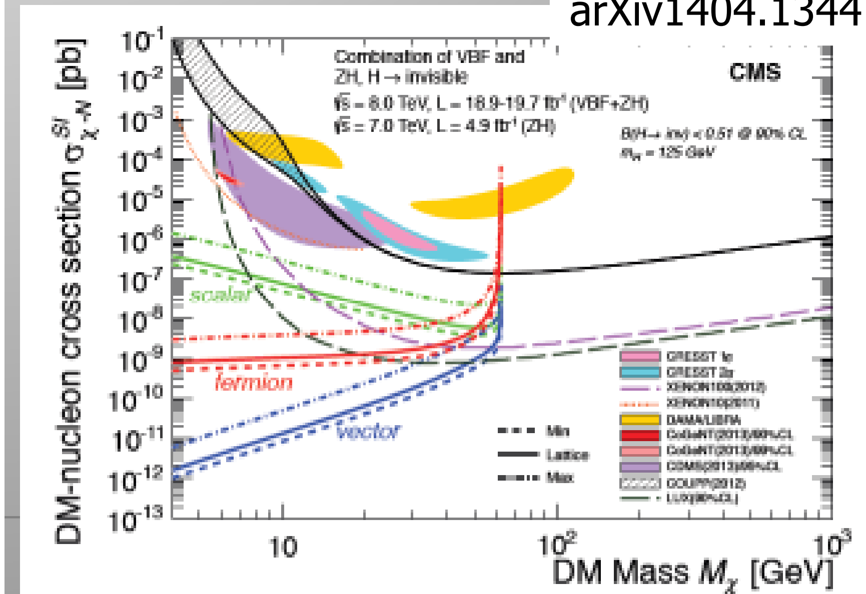
Combined result from the three channels

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

for a Higgs with a mass of 125 GeV

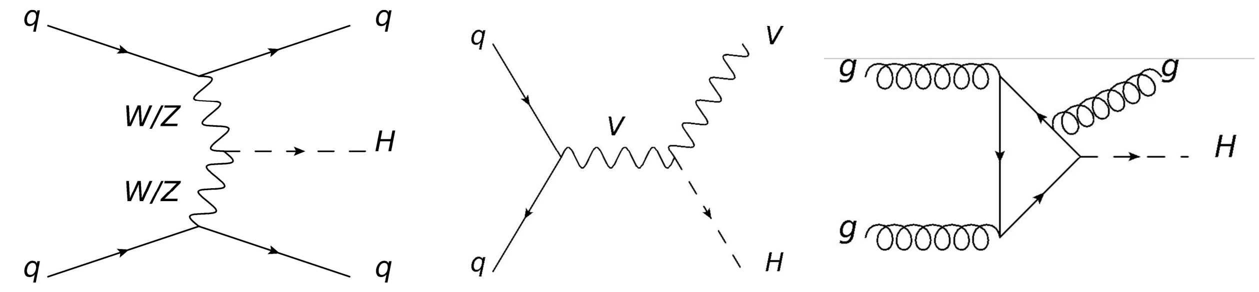


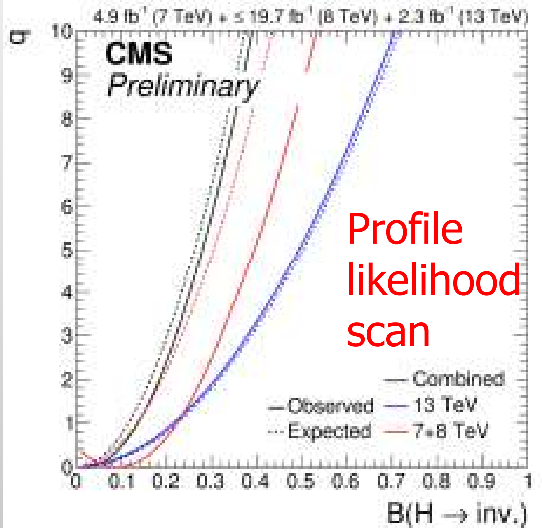
arXiv1404.1344



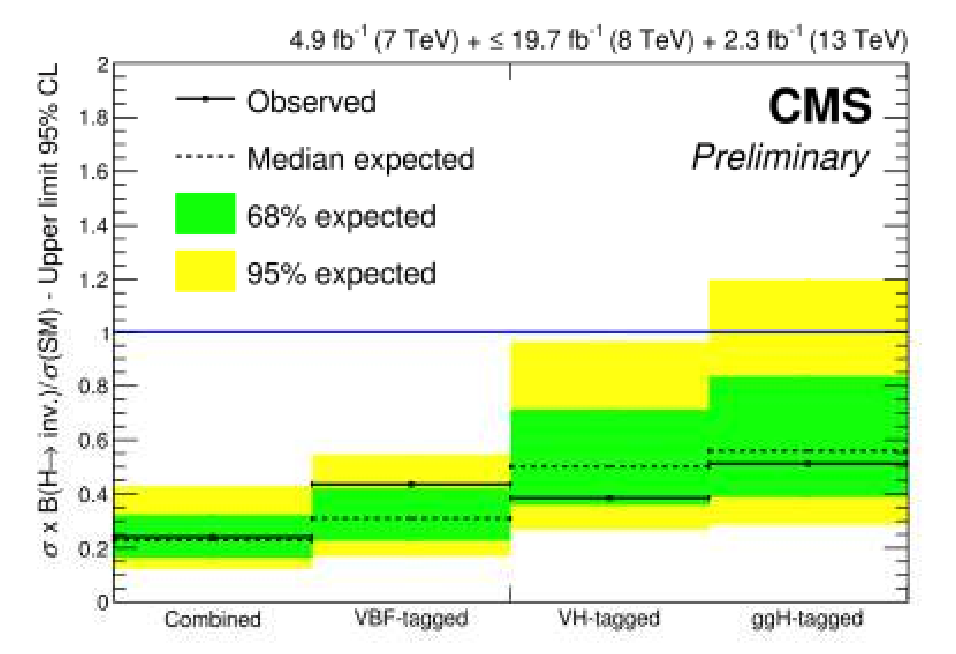
Invisible Channels Combination

Combination of all channels including also the mono-jet channel gives for a 125 GeV Higgs a limit of 24% (23% expected) at 95% CL

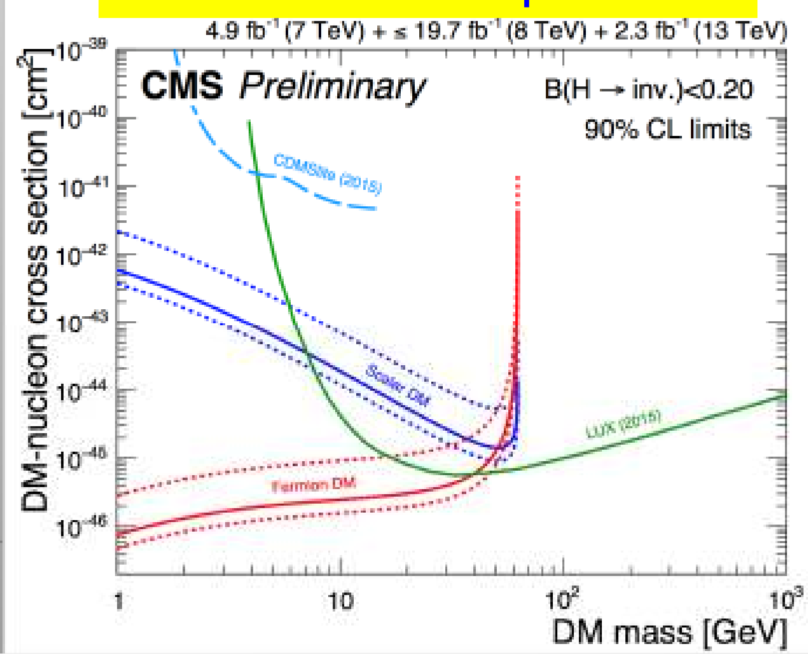




CMS-HIG-16-016



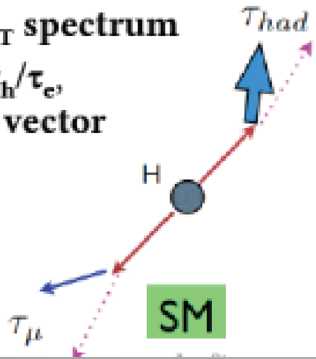
Dark Matter interpretation

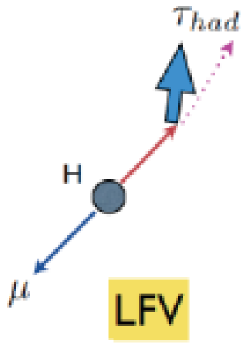


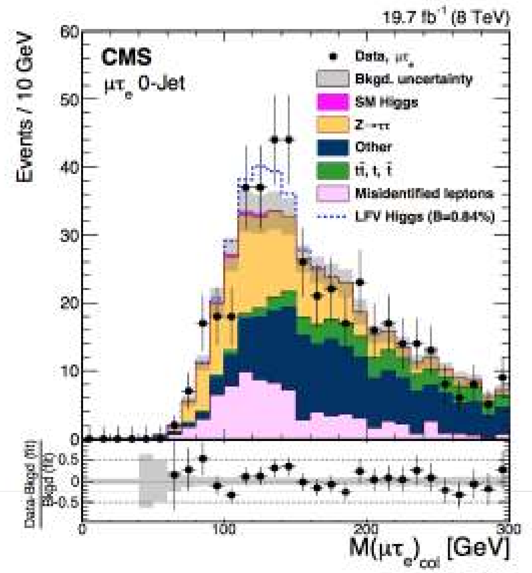
Search for LFV Decays: H $\rightarrow\mu\tau$

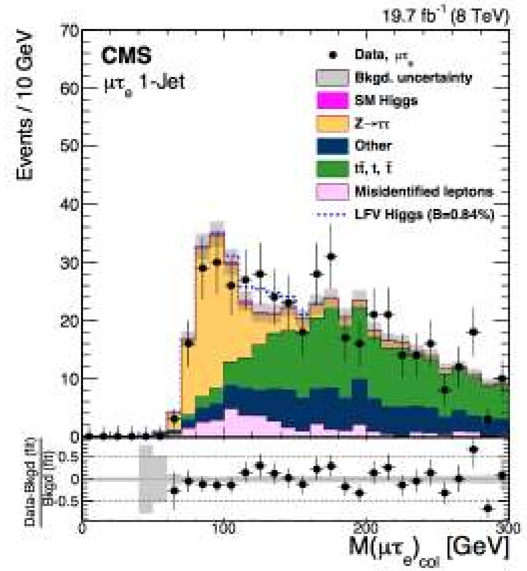
arXiv:1502.07400

- Previous best limits on B(H$\rightarrow\mu\tau$) <~ 10% from reinterpretation of LHC H$\rightarrow\tau\tau$ searches and from $\tau\rightarrow\mu\gamma$ 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$\rightarrow\tau\tau$ analysis (0-jet, 1-jet, VBF-tag)
- Differences in kinematics
  - **Harder muon p_T spectrum**
  - **$\Delta\phi$ between μ, τ_h/τ_e, missing energy vector**



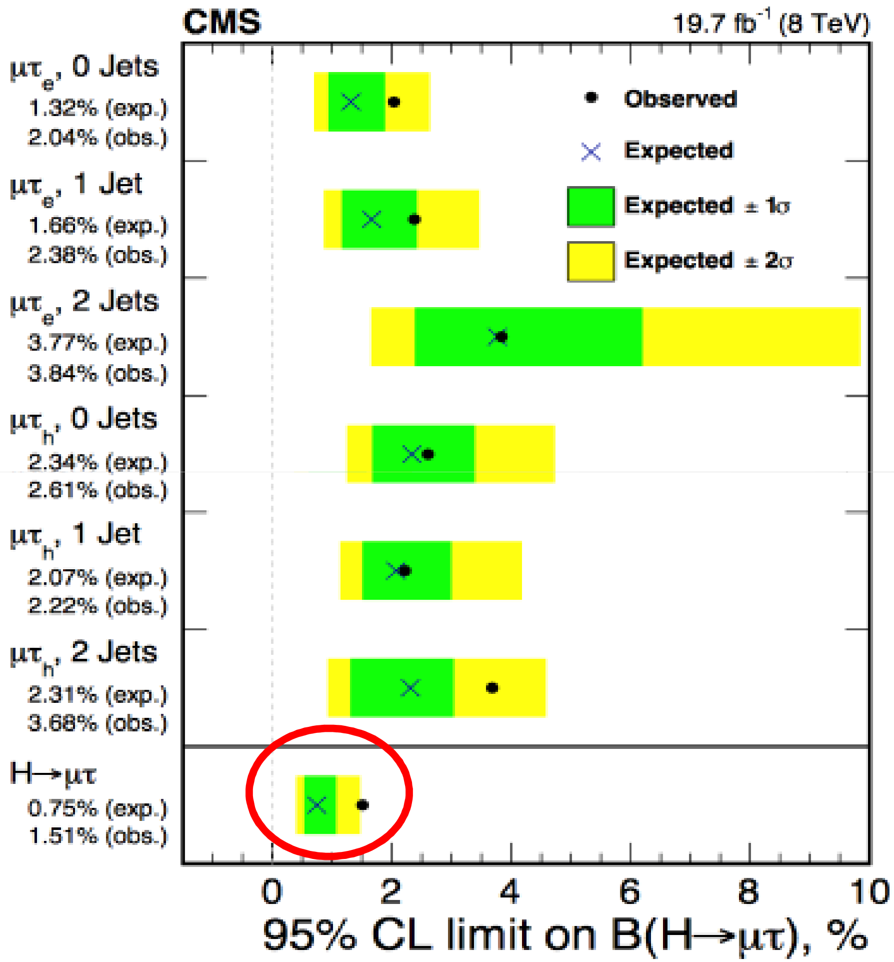






Search for LFV Decays: H $\rightarrow\mu\tau$

- Comparable sensitivity from all channels
- $\mathcal{B}(\mathrm{H} \to \mu\tau) < 1.51\%$ at 95%
- **Large improvement of previous limits**
- Background-only p-value of 0.010 (2.4 σ)
  - Best fit $\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$.



Mild excess giving a 2.4σ effect… To be watched!!!

Other Channels/New Data

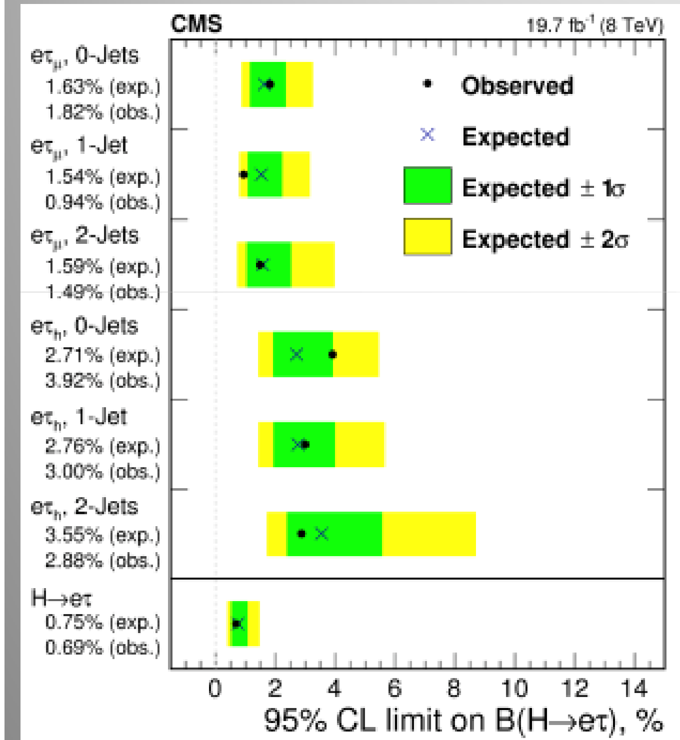
arXiv:1607.03561

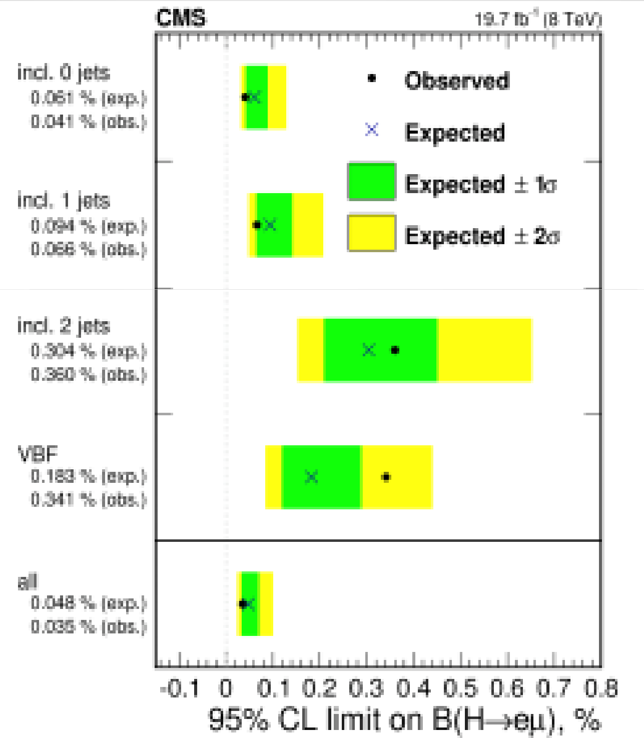
CMS-PAS-HIG-16-005

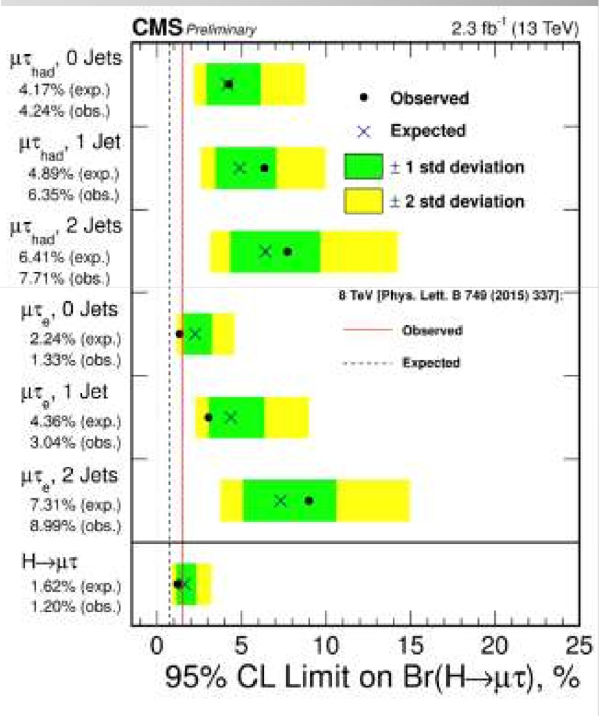
H -> eτ 8TeV

H -> eμ 8TeV

H -> μτ 13TeV







- All measurements are in agreement with expectation
- 13 TeV (2.3 fb^{-1}) H-> μτ channel is less sensitive than 8 TeV (20 fb^{-1}) one

=> Jury still out. Full 2016 data set will be the referee

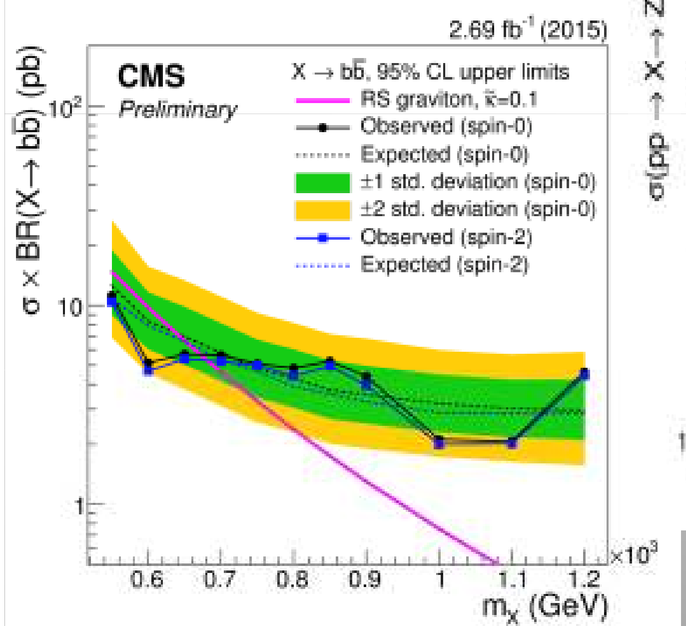
High Mass Searches

CMS-PAS-HIG-16-025

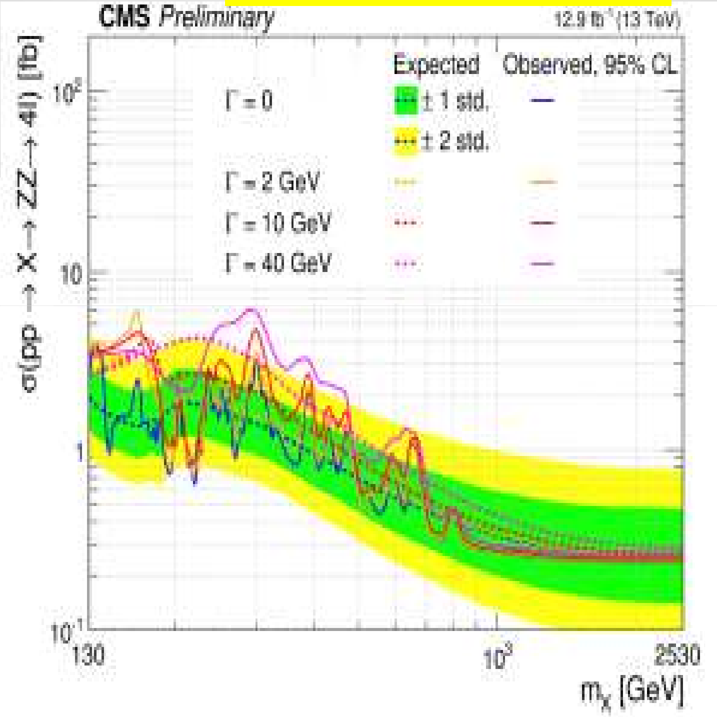
CMS-PAS-HIG-16-033

CMS-PAS-HIG-16-023

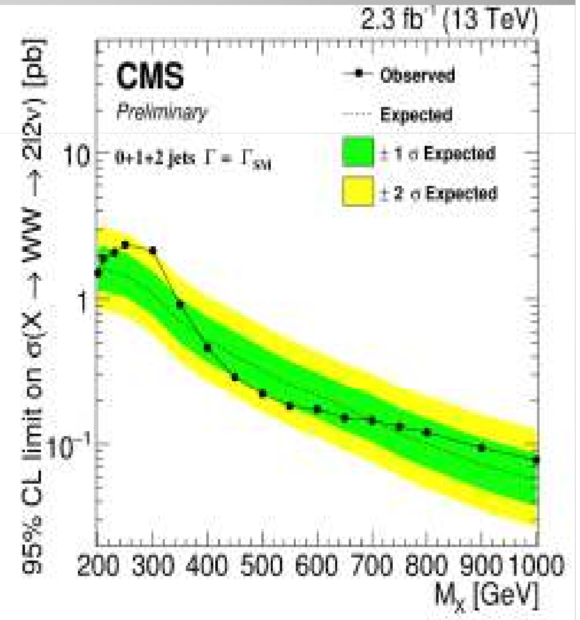
H->bb



H->ZZ (4 lepton)



H->WW (full leptonic)



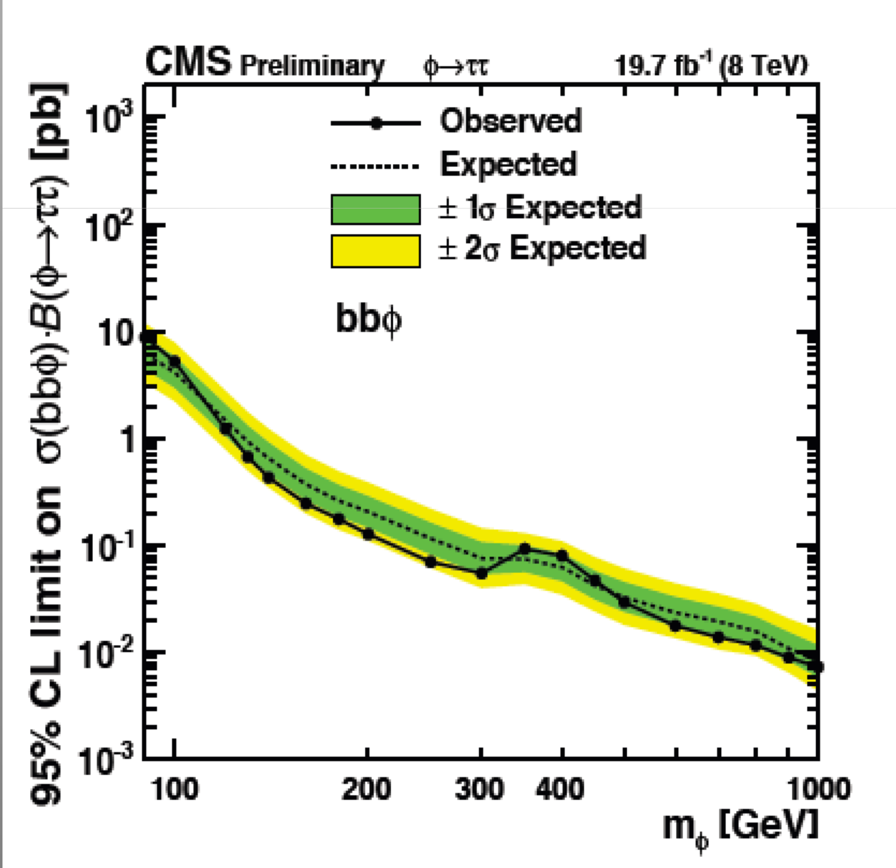
Not al channels analysed yet, but no signal so far

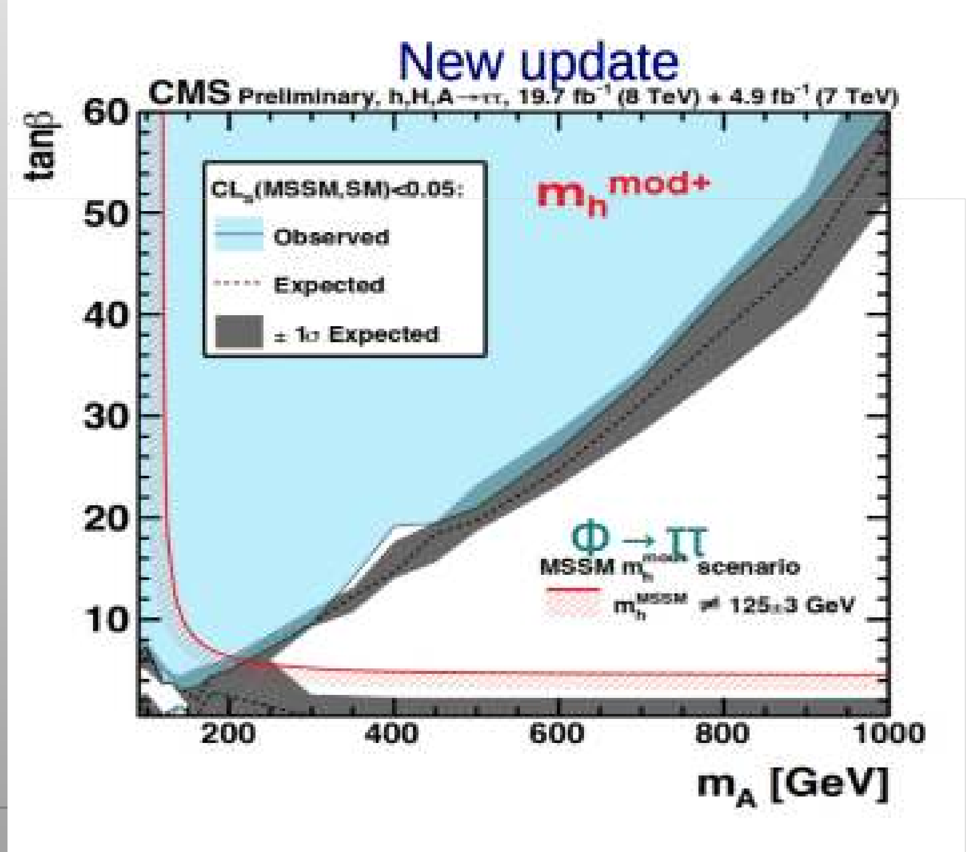
MSSM Neutral Higgs → ττ

Update of the published MSSM results with new tau finder. Reanalysis of the 2011/12 data.
MVA hadronic tau analysis, b-quark categories and hadronic tau p_T categories…

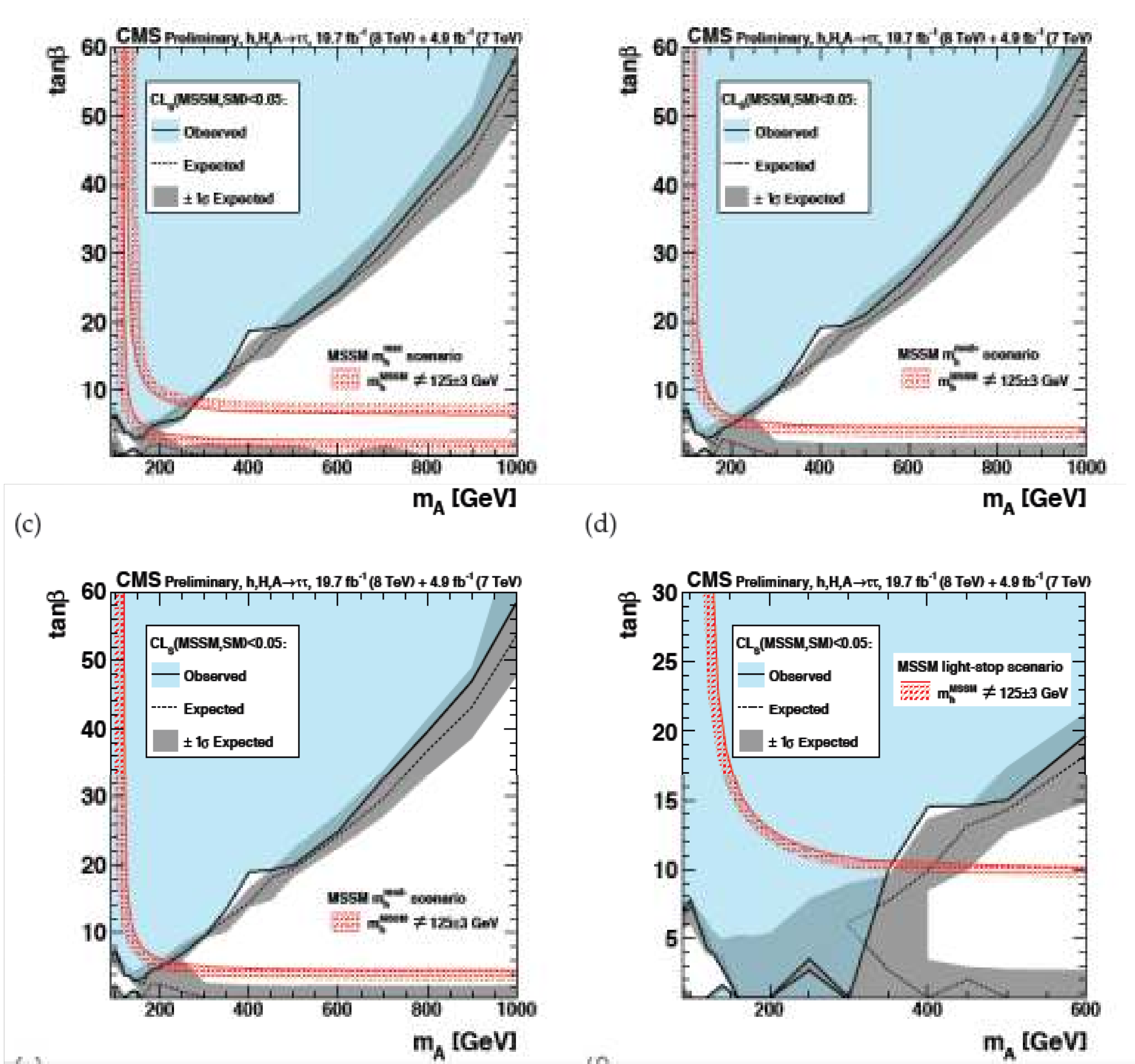
HIG-14-029

Huge gain ~70%!
i.e. like 3x the lumi





MSSM Neutral Higgs $\rightarrow \tau\tau$

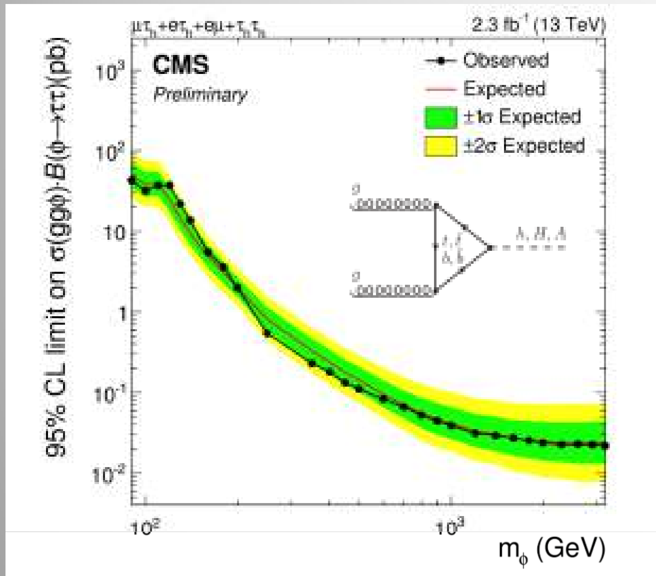


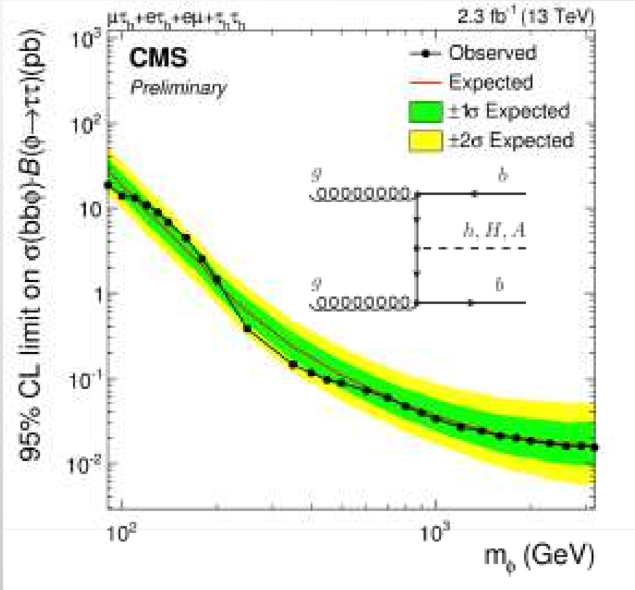
- Study of the Neutral Higgs h/H/A to tau tau
- Include channels with associated b-quark production
- No excess found so far –> exclusions (95% CL)

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

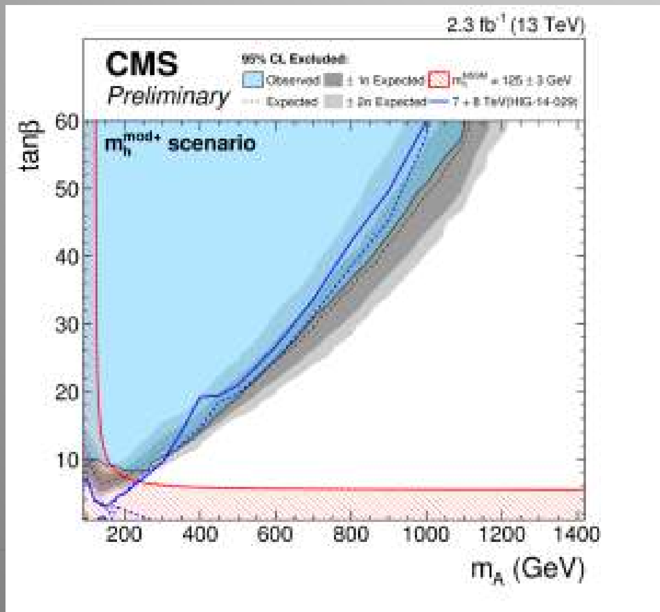
Light stop scenario

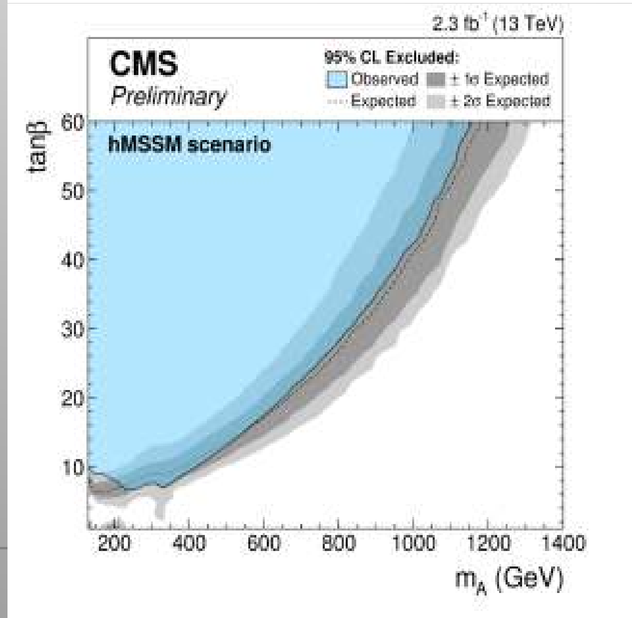
MSSM Higgs Boson in ττ @ 13 TeV





HIG-16-006





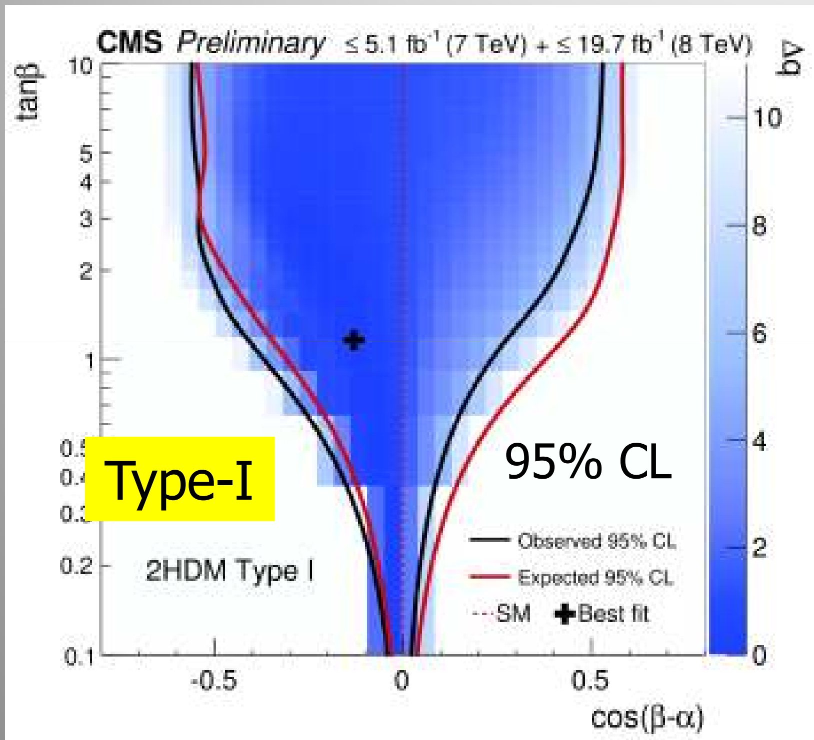
13 TeV data analysis

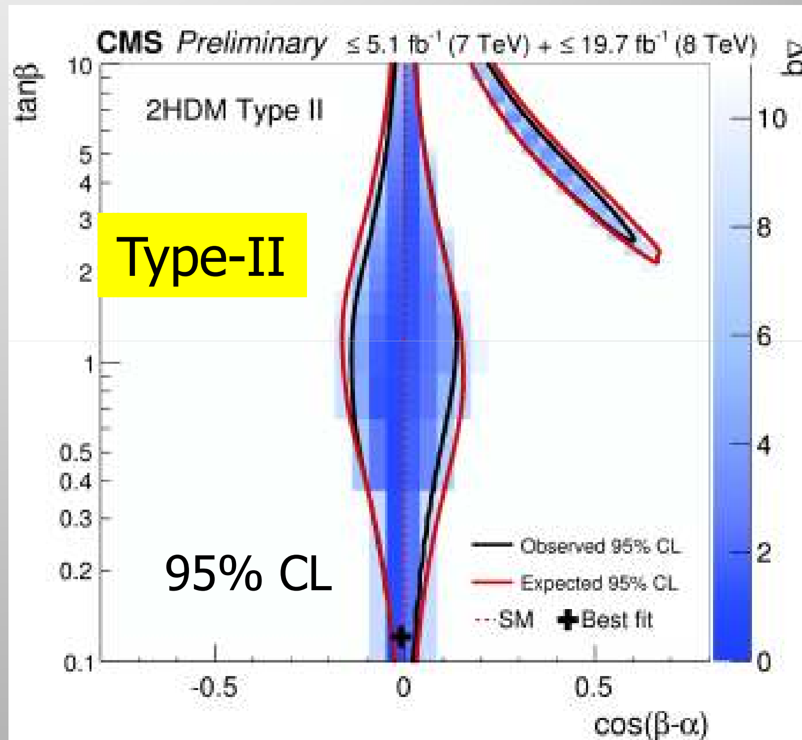
No signal yet

Run-1 High Mass BSM Higgs Searches

Constraints on 2HDM models

HIG-16-007





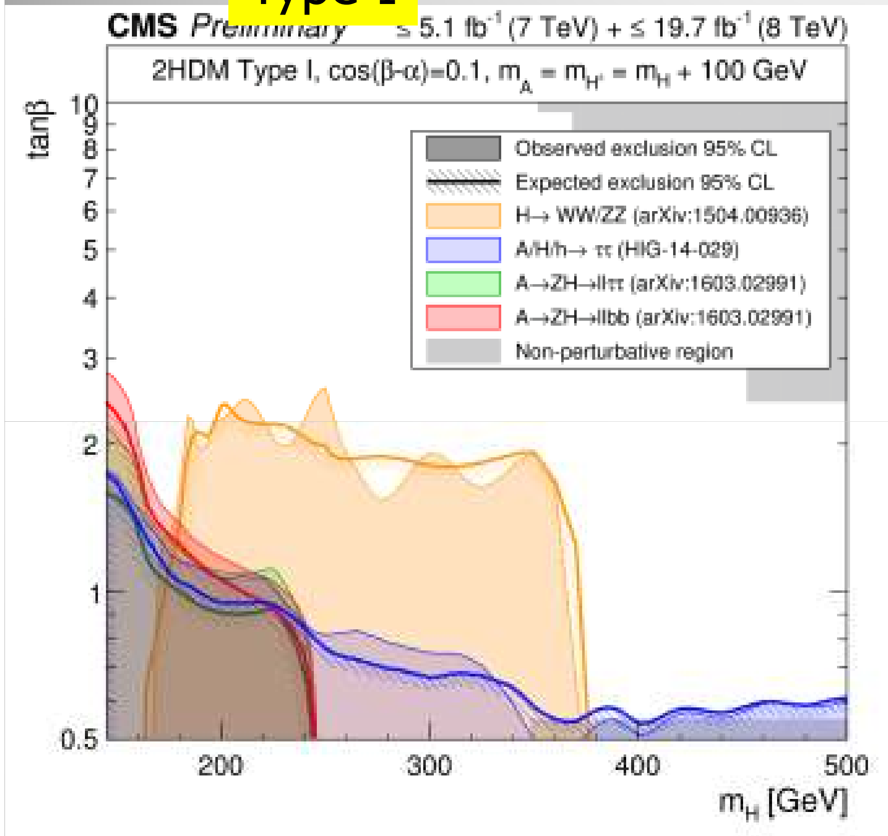
Data includes from Run-1:

•Indirect constraints from couplings from the Higgs

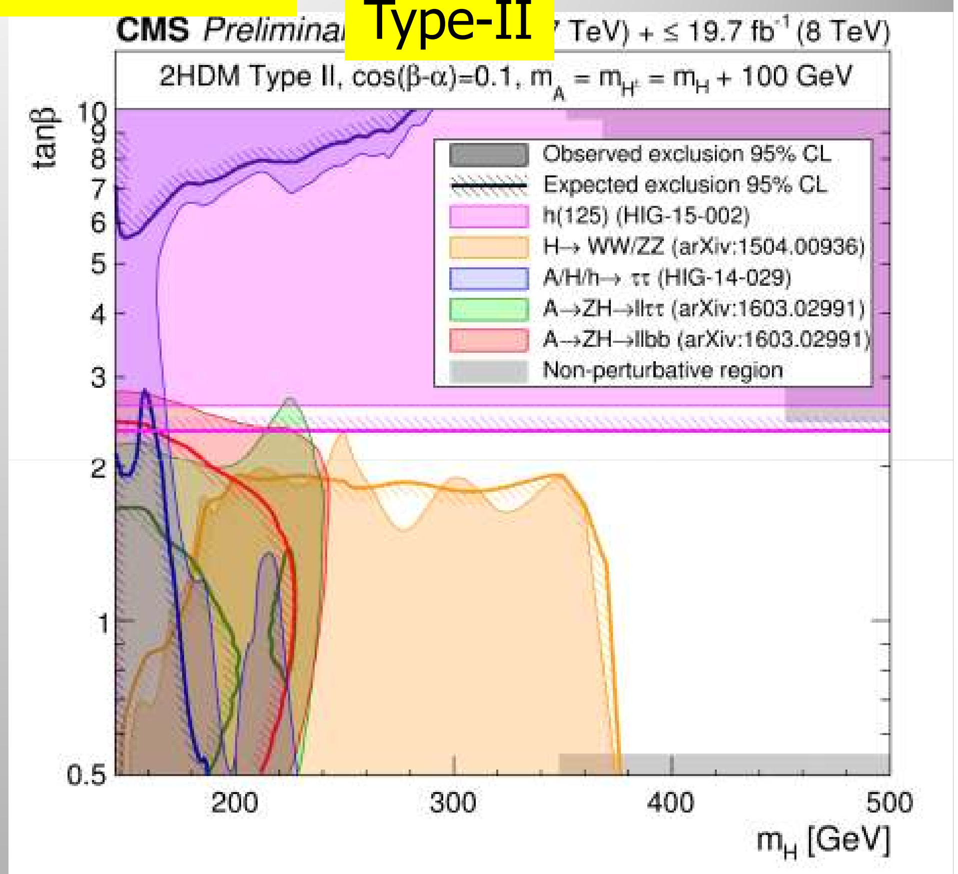
Run-1 High Mass BSM Higgs Searches

Constraints on 2HDM models

Type-I



Type-II



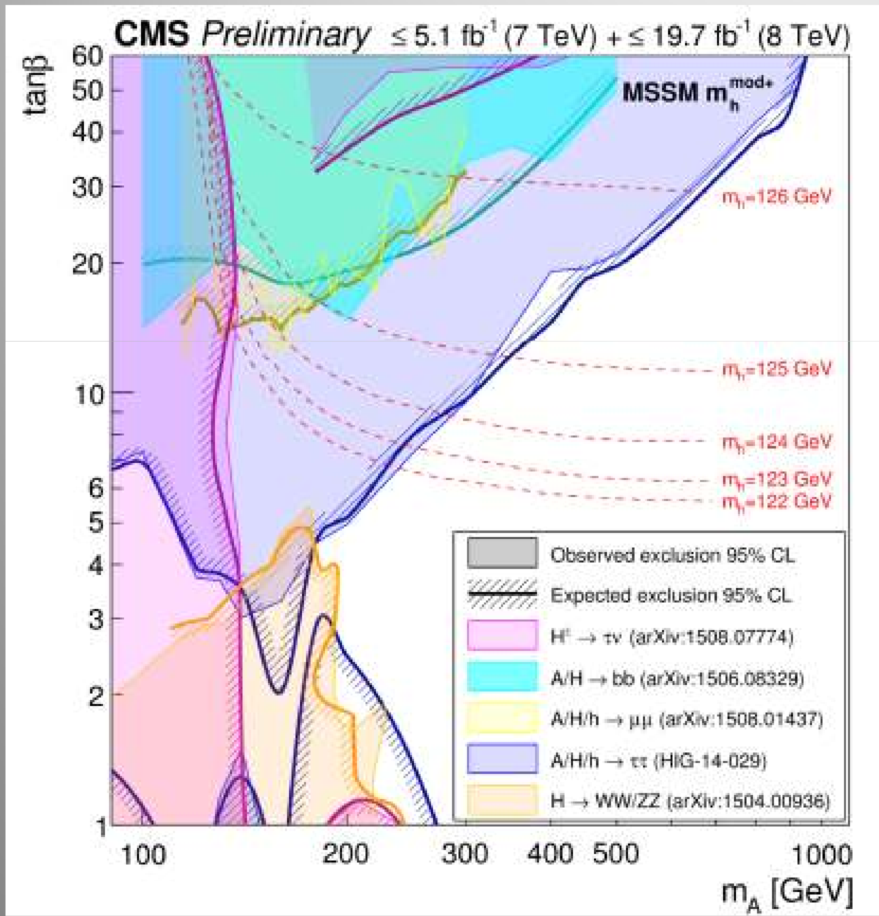
Data includes from Run-1:

- Indirect constraints from couplings from the Higgs
- Constraints from direct searches: A/H-> ττ, A/H->μμ,, AH->bb, charged Higgs, H->hh, A->ZH, H->WW/ZZ high mass search channels

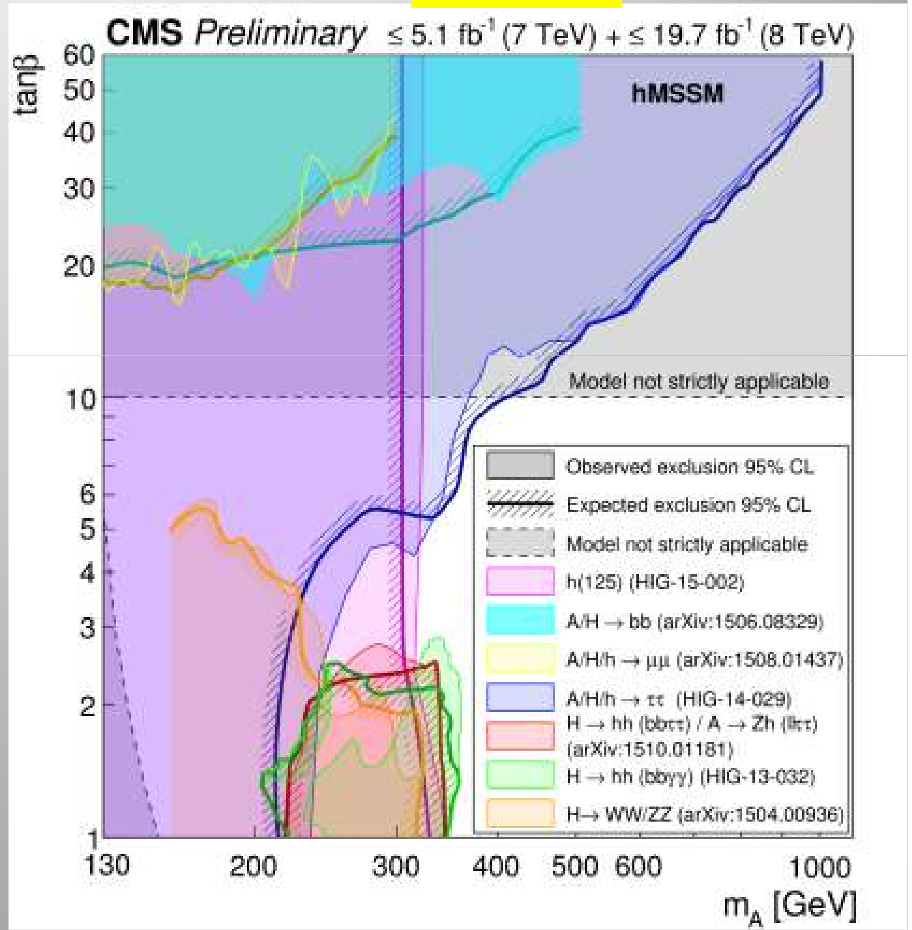
Run-1 High Mass BSM Higgs Searches

Constraints on MSSM model

MSSM M_h(mod+)



hMSSM

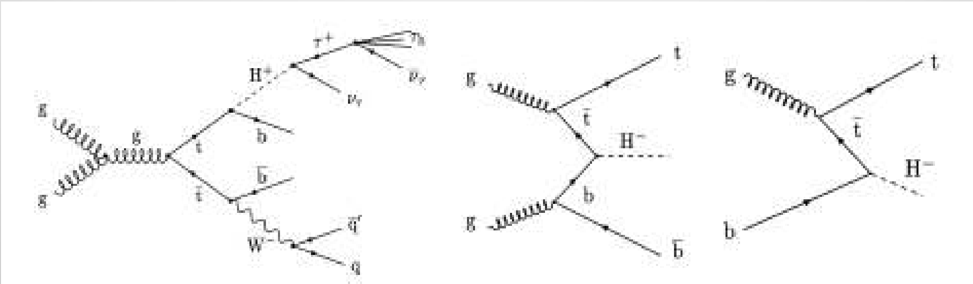


Charged Higgs Search

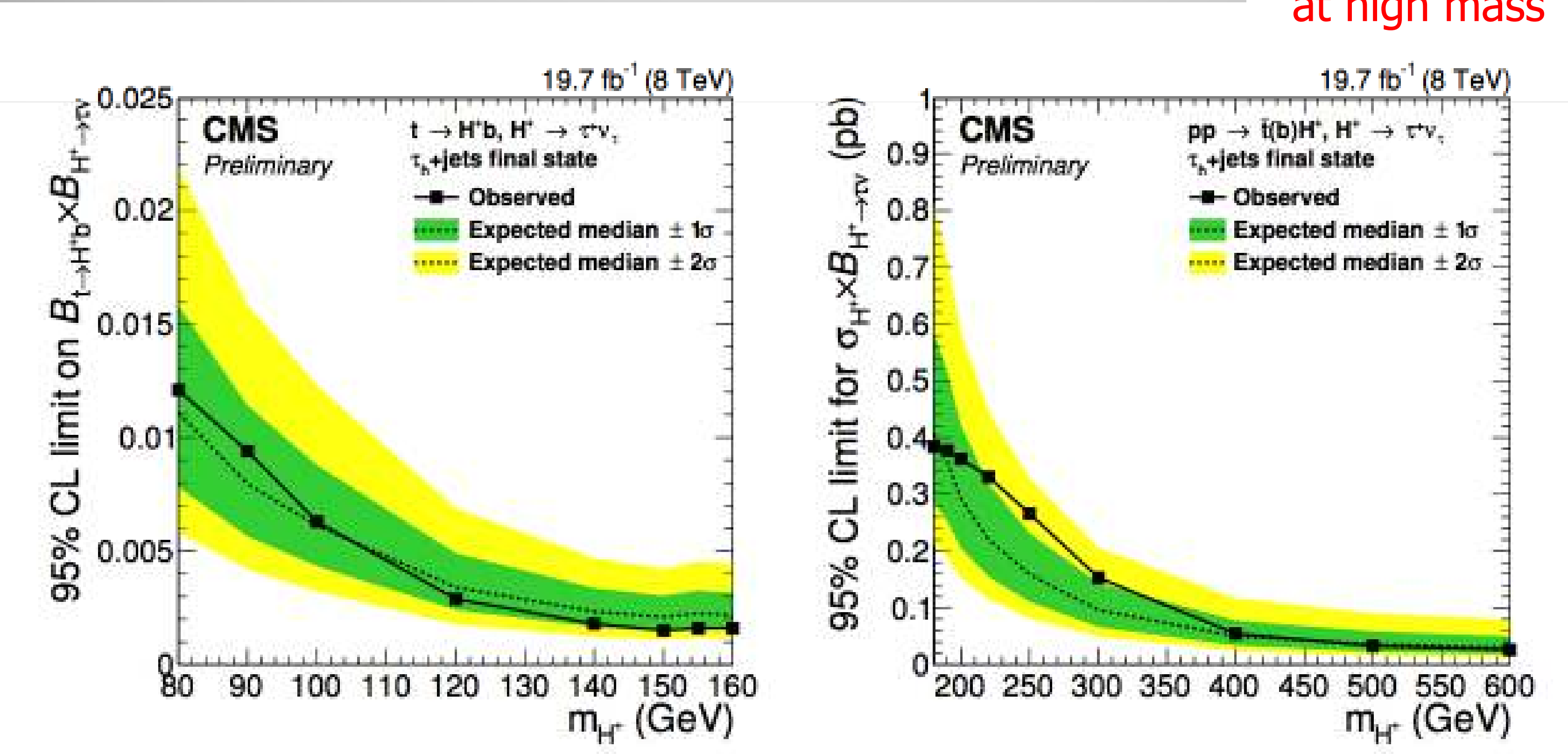
Both low and high mass, using full hadronic final states

$H^+ \rightarrow \tau^+ \nu_\tau$

CMS-PAS-HIG-14-020



- Limits now down to 0.16% for the low mass (95%CL)
- Cross section limits 0.38-0.026 pb at high mass

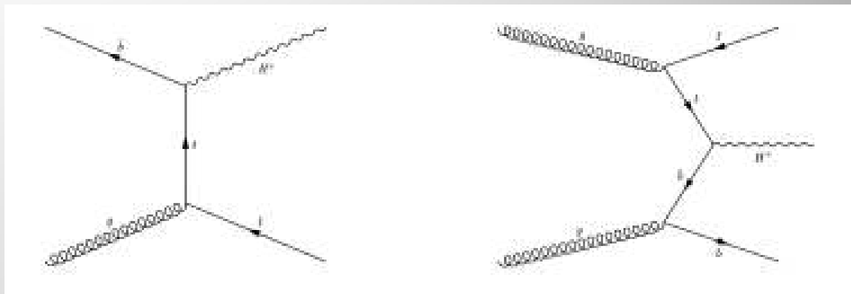


Heavy Charged Higgs Search

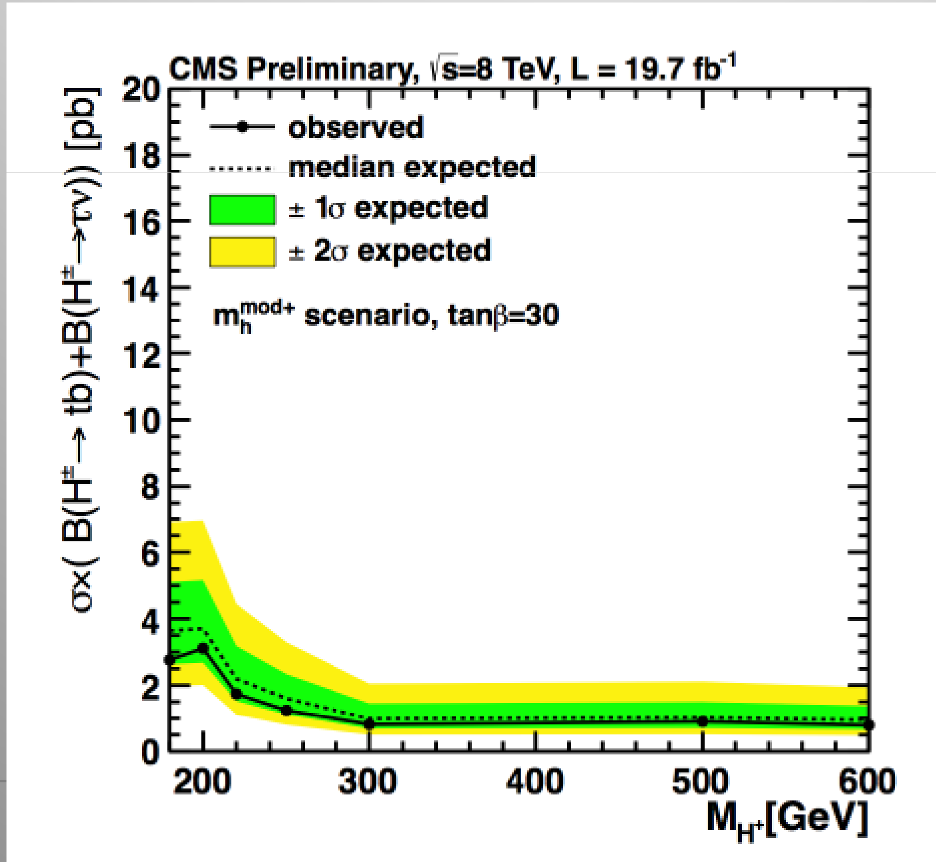
$$gg \rightarrow H^{+}tb$$

$$H^{+} \rightarrow tb$$

$$H^{+} \rightarrow \tau^{+}\nu$$



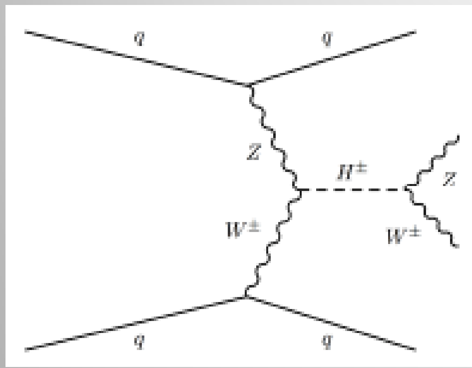
Final states with two leptons or
one lepton plus hadronic decaying tau



CMS-PAS-HIG-13-026

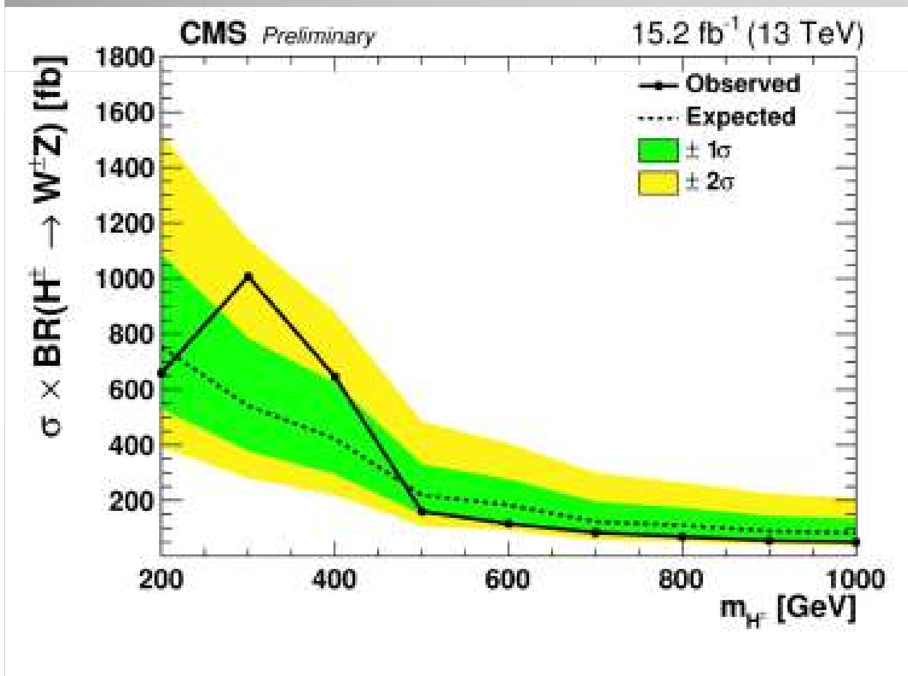
No excess observed

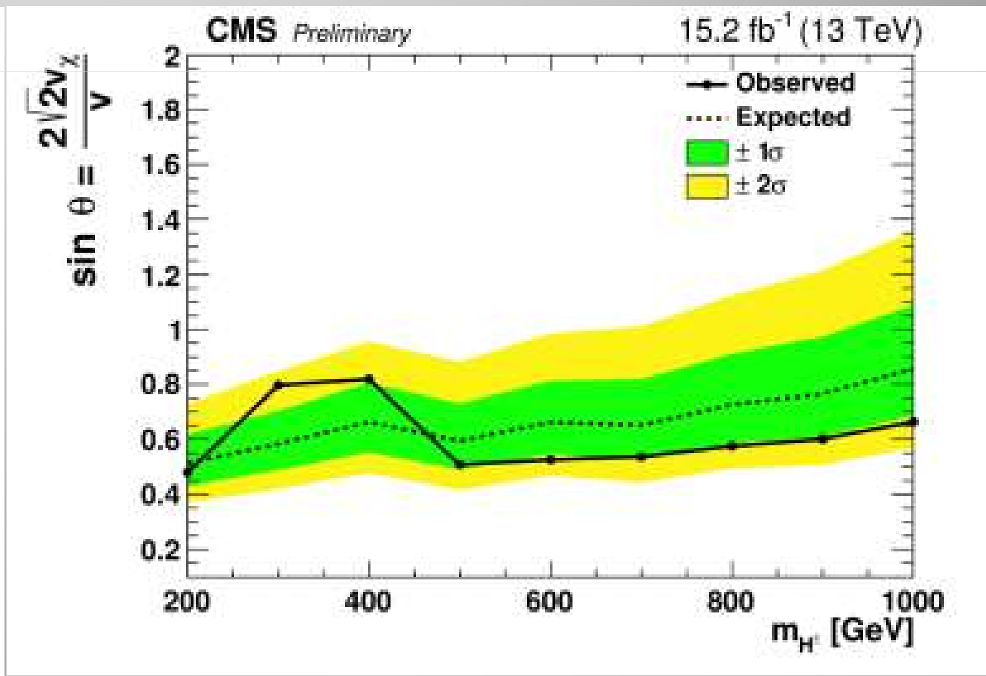
Charged Higgs to WZ Channel



CMS-PAS-HIG-16-027

High mass search with leptonic W,Z decays
-> 3 leptons + 2 or more jets

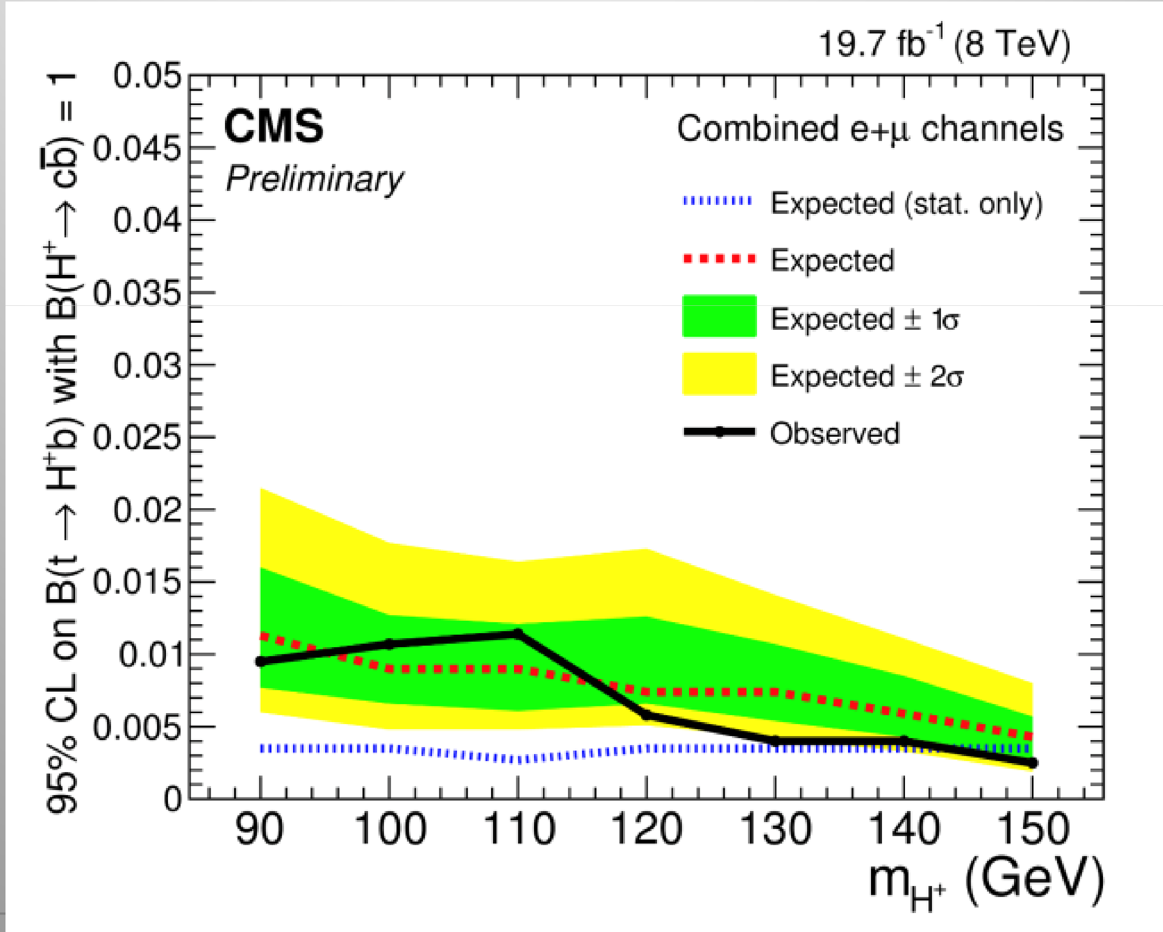




Search for Charged Higgs

CMS-PAS-HIG-16-030

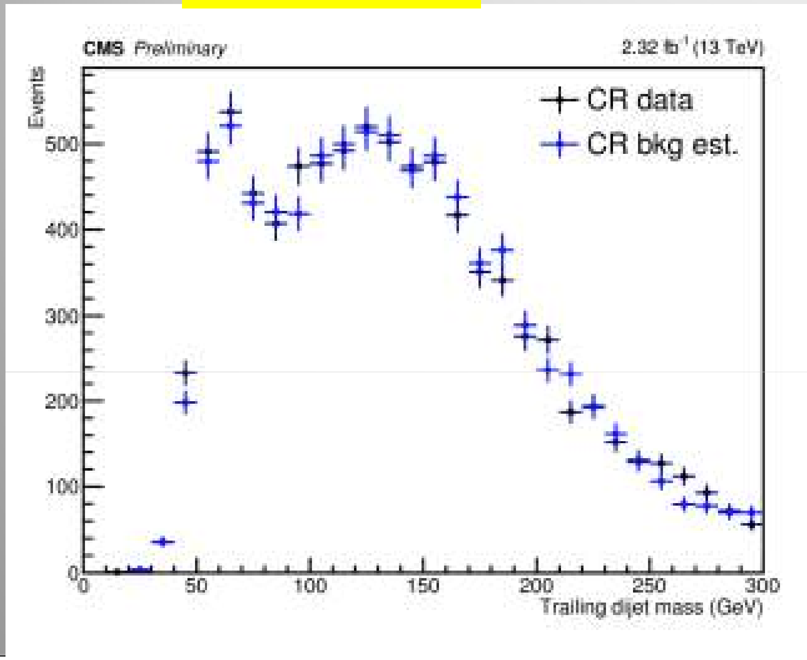
$H^+ \to cb$ in lepton+jets channel using top quark pair events



Search for non-Resonant Di-Higgs

CMS-PAS-HIG-16-026

4b channel



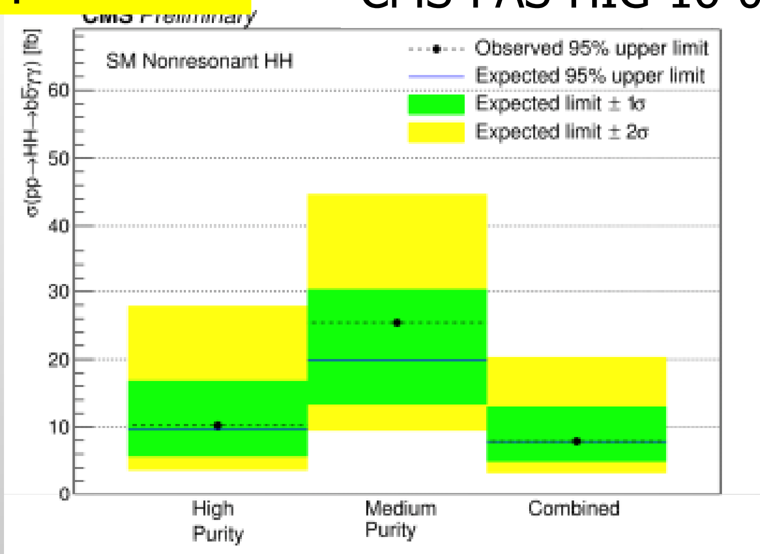
Category	Observed	Expected	-2σ	-1σ	$+1\sigma$	$+2\sigma$
		[fb]				
SM $H(b\bar{b})H(b\bar{b})$	3880	3490	2140	2540	5350	8350

95% CL on the cross section

No di-Higgs signal yet

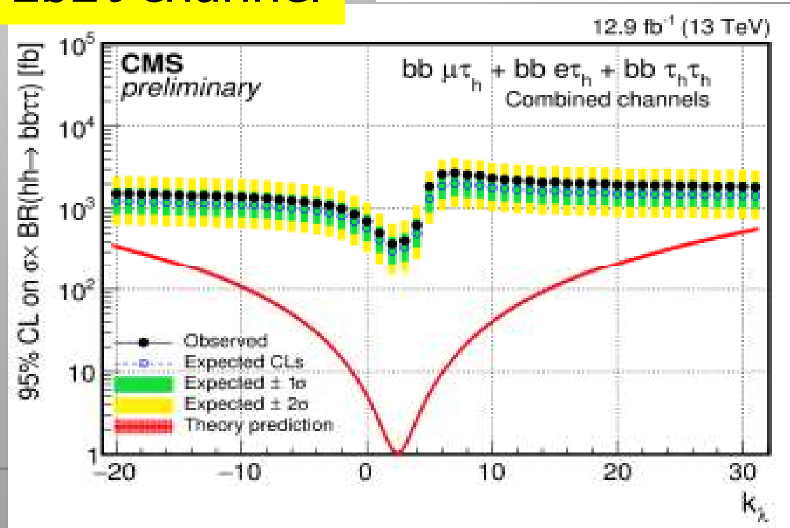
2b2γ channel

CMS-PAS-HIG-16-032



2b2τ channel

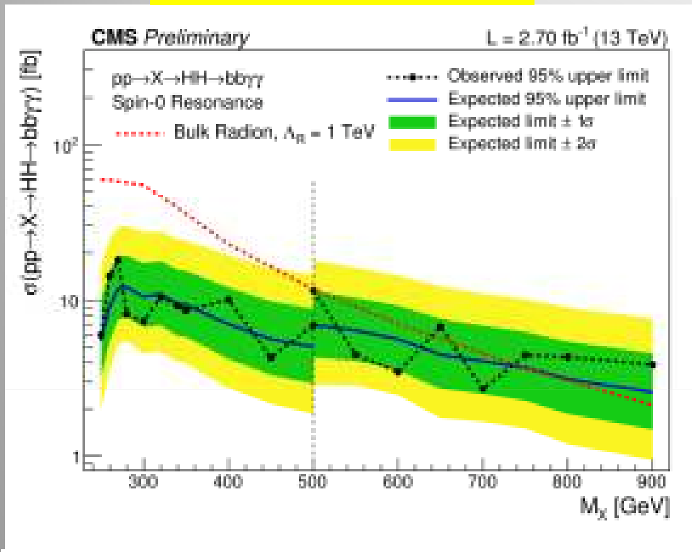
CMS-PAS-HIG-16-028

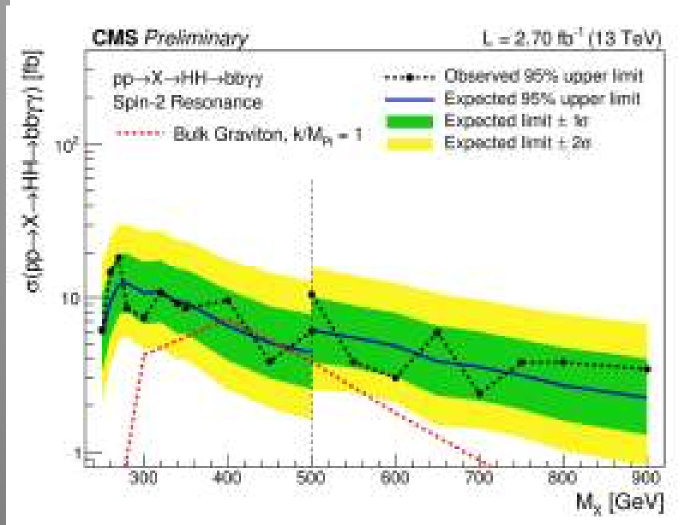


Search Resonant Di-Higgs Production

CMS-PAS-HIG-16-032

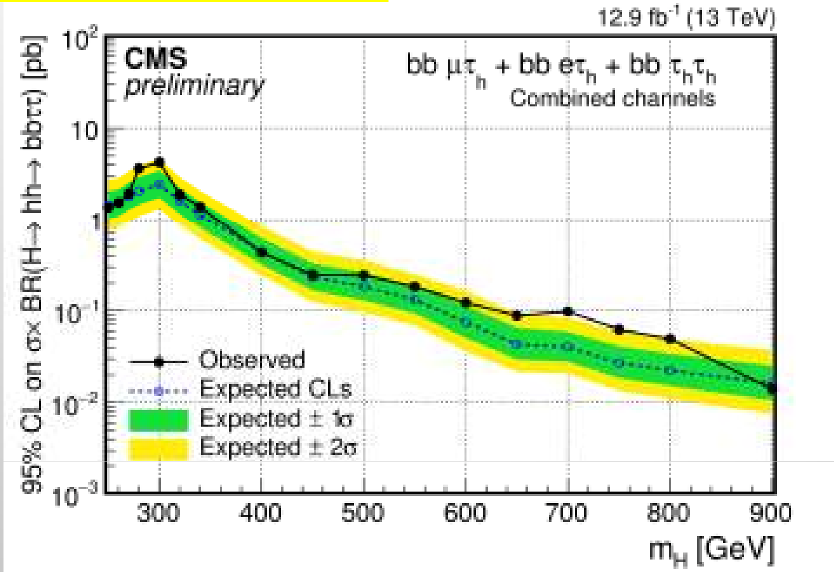
bbγγ channel

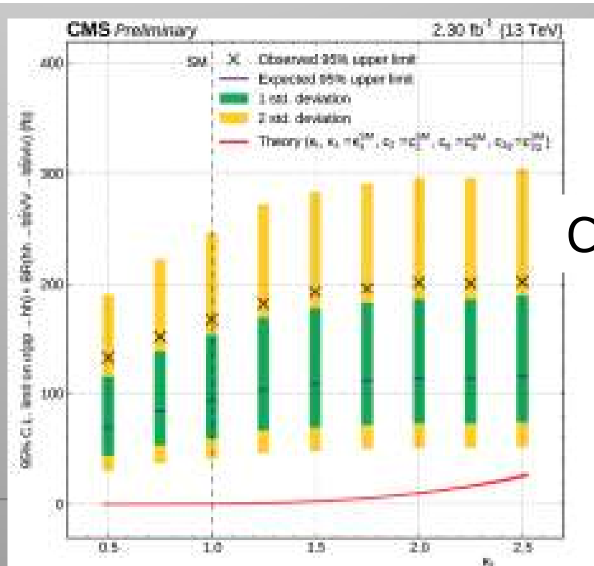




bbττ channel

CMS-PAS-HIG-16-029





bbVV channel

CMS-PAS-HIG-16-024

No di-Higgs signal yet

Summary

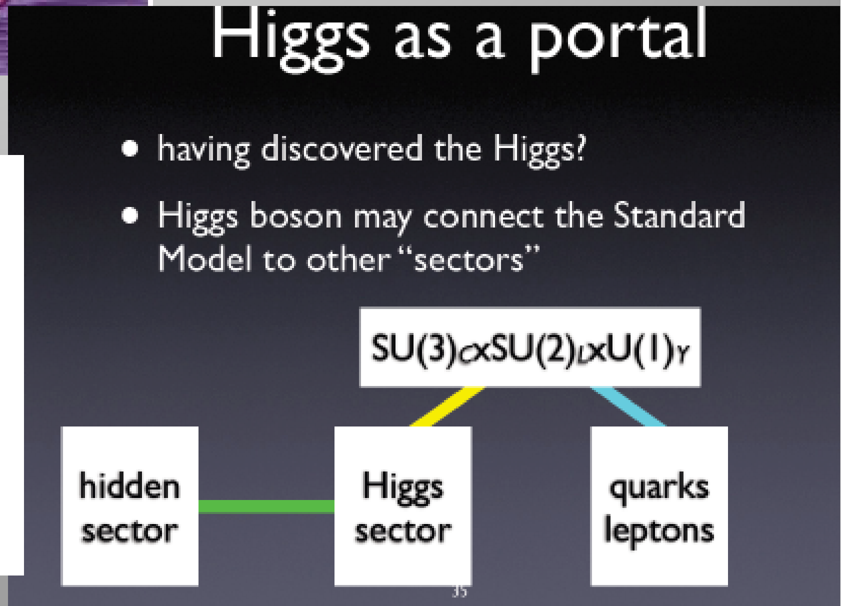
- In 2012 we discovered a new particle around 125 GeV. The data analysis in the last 3 years has shown that this particle has the properties of a Higgs Boson related to the EW-symmetry breaking.
- The mass is ~125 GeV with a precision of order ~0.2%.
- The legacy data of run-1, including a combined fit of ATLAS+CMS has been released. The particle has properties of a SM Higgs within present precision.
- This new particle could be the key to our 'contact' with the new physics side. Detailed study is imperative.
- No (clear) sign yet of other Higgses or exotic decays…
- Run-II data will bring a new level of precision (~ 5-10%) and access to new channels. And hopefully surprises…

It may just take ONE deviation to show us the way…

Backup

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 ~ 125 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤