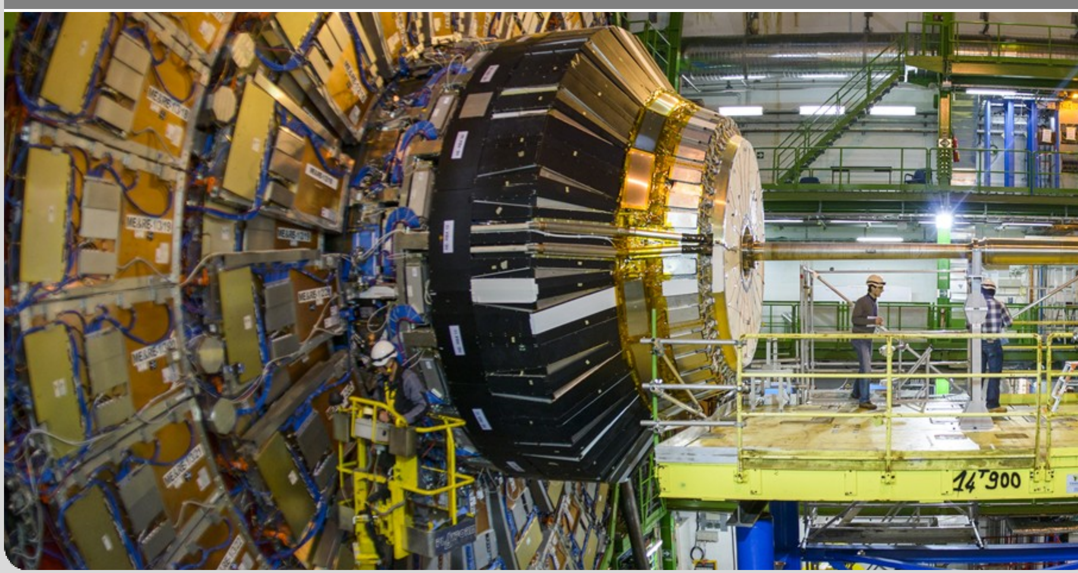
Karlsruhe Institute of Technology

Three Years of Higgs Boson Discovery

Roger Wolf

29. October 2015

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY

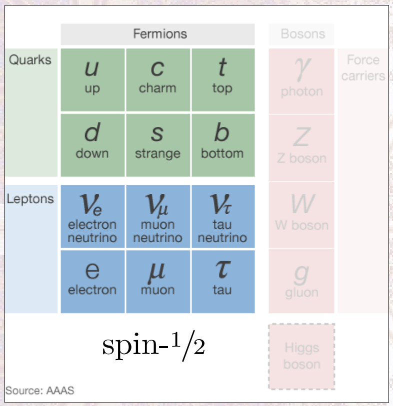


- Higgs mechanism in the standard model of particle physics
- History & present of the discovery at the LHC
- Anatomy of the discovered particle
- Searches for new physics in the Higgs sector and outlook for LHC run-2

The importance of symmetry

- Symmetries play an important role in nature. This is especially true for particle physics, where (almost) all forces we know can be derived from local symmetry requirements:

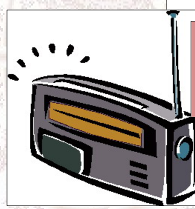
Baryonic matter:



1*d* rotations	2*d* rotations	3*d* rotations	in $\mathbb{C}(N)$ hyperspace (in at least 5 dim.)

$$U(1)_Y \times SU(2)_L \times SU(3)_c$$

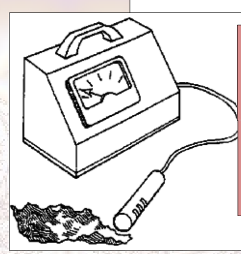
$$\psi \; e^{i\vartheta'}$$



γ photon

Electromagnetism

$$\begin{pmatrix} u \\ d \end{pmatrix}_L e^{it_a\vartheta_a}$$

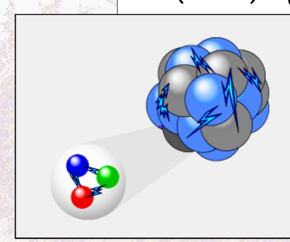


$W^{\pm}$ W boson

Z Z boson

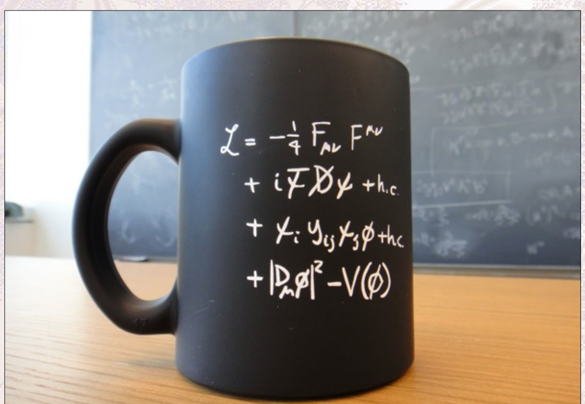
Weak force

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix}_c e^{iT_a\vartheta_a}$$



g gluon

Strong force

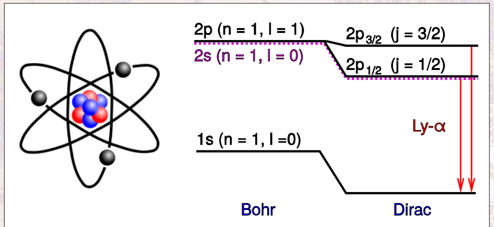


Lagrangian Density of (baryonic) Matter

The standard model of particle physics (SM)

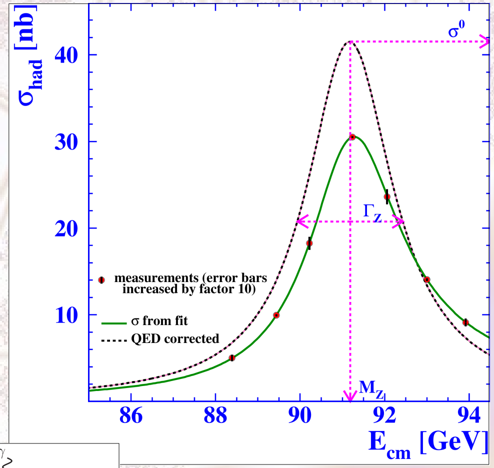
Precision observables:

Lamb shift: (precision $\mathcal{O}(10^{-7})$)



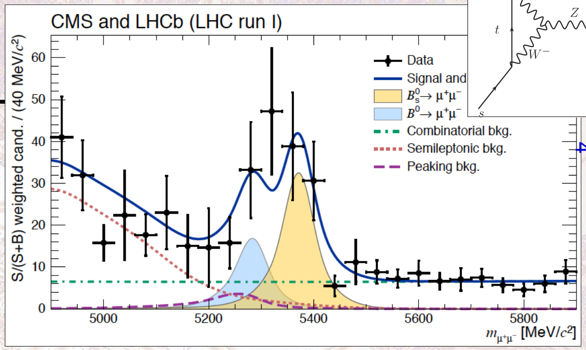
$\langle \Delta V \rangle \propto \alpha^5 m_e \ln(\pi\alpha) = \mathcal{O}(1\mathrm{GHz})$

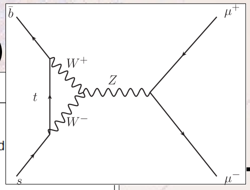
LEP: (precision $\mathcal{O}(10^{-5})$)



Phys. Rept 427 (2006)

Rare decays: (precision $\mathcal{O}(10^{-9})$)

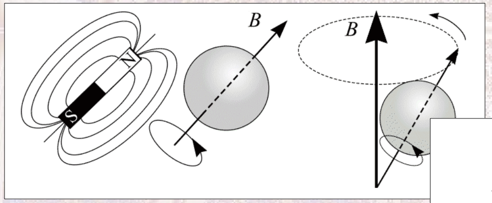


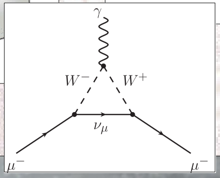


Nature (2015) 1447

$\mathcal{BR}(B_s \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.23) \times 10^{-9}$

μ mag. mom.: (precision $\mathcal{O}(10^{-9})$)

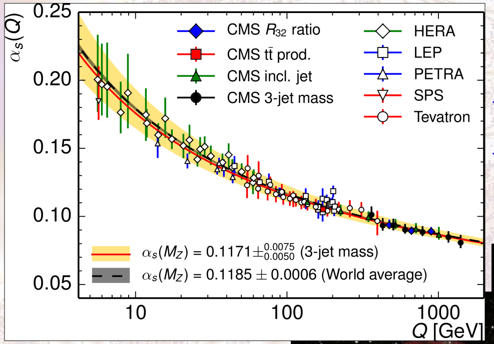




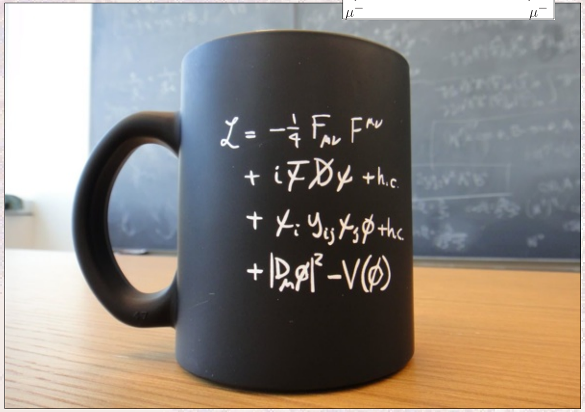
$\frac{(g-2)}{2} = 0.00115965218073(28)$

Striking features & global characteristics:

Asymptotic freedom:

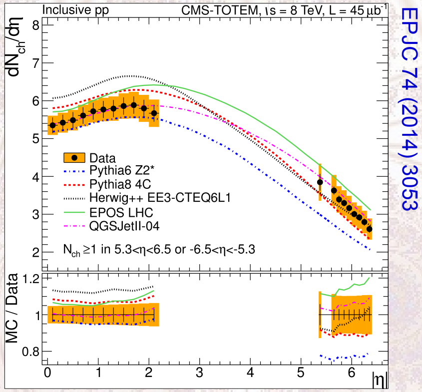


EPJC 75 (2015) 186

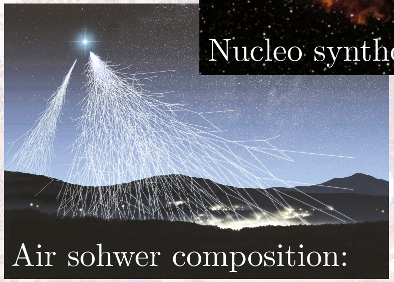


Lagrangian Density of (baryonic) Matter

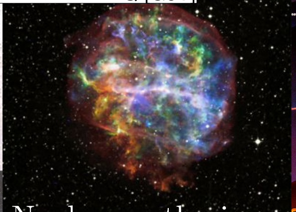
Inclusive pp collisions:



EPJC 74 (2014) 3053

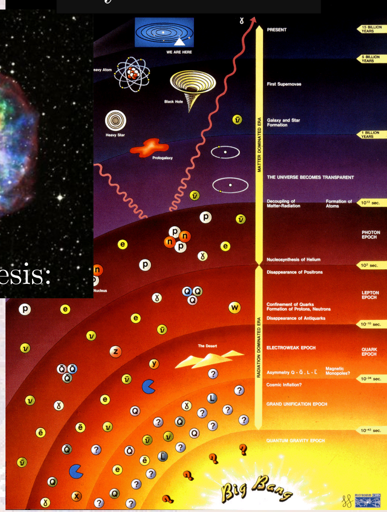


Air sohwer composition:



Nucleo synthesis:

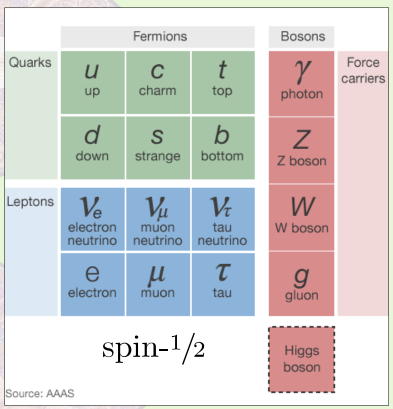
History of the universe:



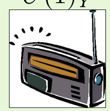
THE GRINCH

Problem-1:

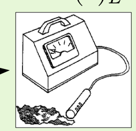
Symmetries strictly forbid **force mediators** to have mass $m_{A_\mu} \neq 0$.



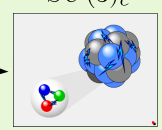
$m_\gamma = 0$ → $U(1)_Y$



$m_{W/Z} = \mathcal{O}(100\ \mathrm{GeV})$ → $SU(2)_L$



$m_g = 0$ → $SU(3)_c$



$$W_\mu m W^{\mu *} \neq W'_\mu m W'^{\mu *}$$

Problem-2:

Weak force distinguishes between left- and right-handed matter.

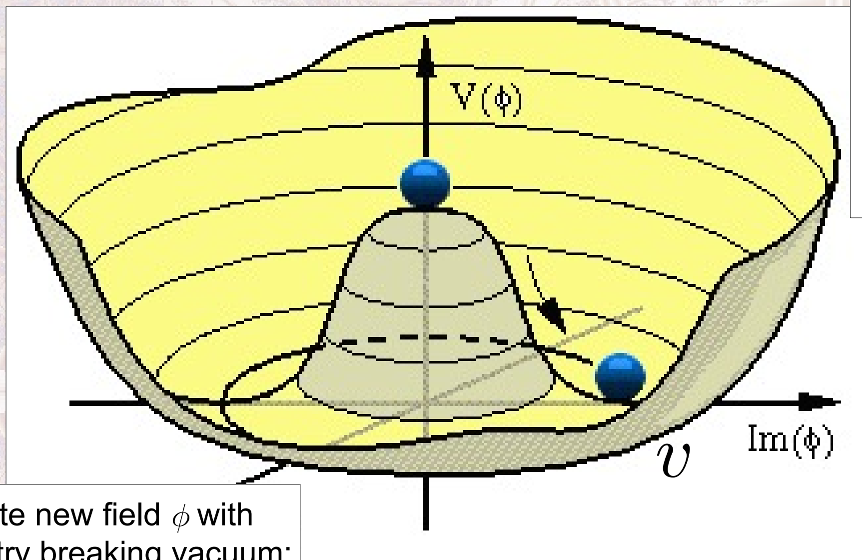
Breaks $SU(2)_L$ symmetry for **ALL** weakly interacting particles with $m_\psi \neq 0$.

$$\overline{\psi} m \psi \neq \overline{\psi}' m \psi'$$

$$\psi = \psi_L + \psi_R$$

How can $SU(2)_L$ symmetry be the source of weak interactions while at the same time all interacting particles with $m \neq 0$ explicitly break this symmetry?!?

- Spontaneous symmetry breaking:



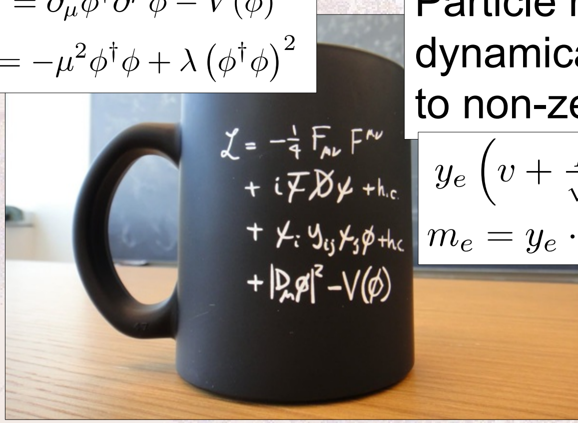
- Symmetry inherent to the system but not to its energy ground state (→ quantum vacuum).
- In the quantum world this can lead to the existence of new physical particles (→ Higgs).

Postulate new field ϕ with symmetry breaking vacuum:

$$\mathcal{L}^{\text{Higgs}} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$
$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

Particle masses created dynamically by coupling to non-zero vacuum.

$$y_e \left(v + \frac{H}{\sqrt{2}}\right) \bar{e}e$$
$$m_e = y_e \cdot v$$



Lagrangian Density of (baryonic) Matter

- Higgs, excitation of vacuum ground state.
- Characterized by very peculiar coupling structure, needed to preserve the symmetry of the system:

$$f_{H \to ff} = i \frac{m_f}{v} \qquad \text{(Fermions)}$$
$$f_{H \to VV} = i \frac{2m_V^2}{v} \qquad \text{(Heavy Bosons trilinear)}$$
$$f_{HH \to VV} = i \frac{2m_V^2}{v^2} \qquad \text{(Heavy Bosons quartic)}$$
$$f_{H \to HH} = i \frac{3m_H^2}{v} \qquad (H \text{ Boson trilinear})$$
$$f_{HH \to HH} = i \frac{3m_H^2}{v^2} \qquad (H \text{ Boson quartic})$$

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim$300 MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new par-

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

taken from R. Harlander, 2014

1961: First formulation of a unification of electromagnetic and weak force.

1962: Spontaneous symmetry breaking in super conductivity.

1964: Higgs mechanism in particle physics.

1967: Formulation of electroweak SM.

1971: Proof of renormalizability.

1974-77: Discovery of *charm*, τ and *bottom*.

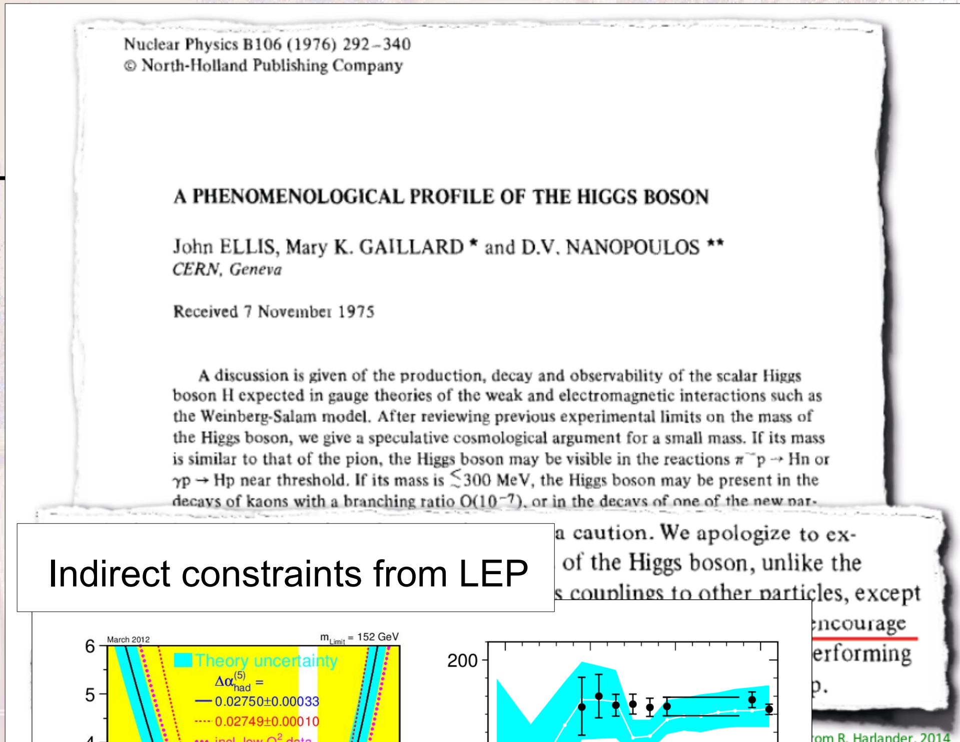
1983: Discovery of *W* and *Z*.

1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

2013: Nobel prize to Peter Higgs and Francois Englert.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... a caution. We apologize to ex-
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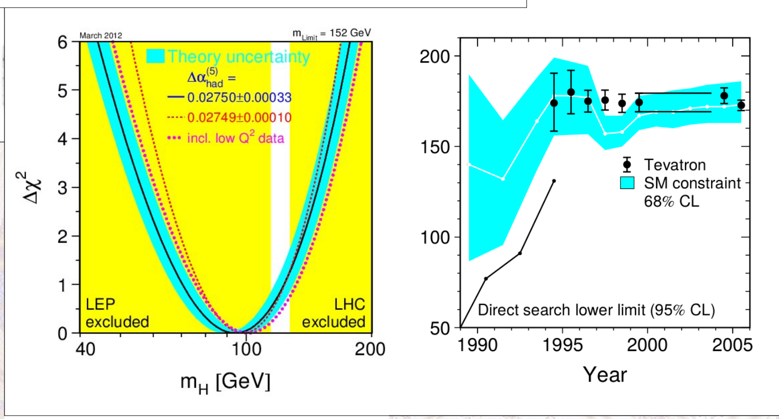
...s couplings to other particles, except
...ncourage
...erforming
...p.

Indirect constraints from LEP



$m_H = 98 \pm^{25}_{21}$ GeV $\quad m_t = 178.1 \pm^{10.9}_{7.8}$ GeV

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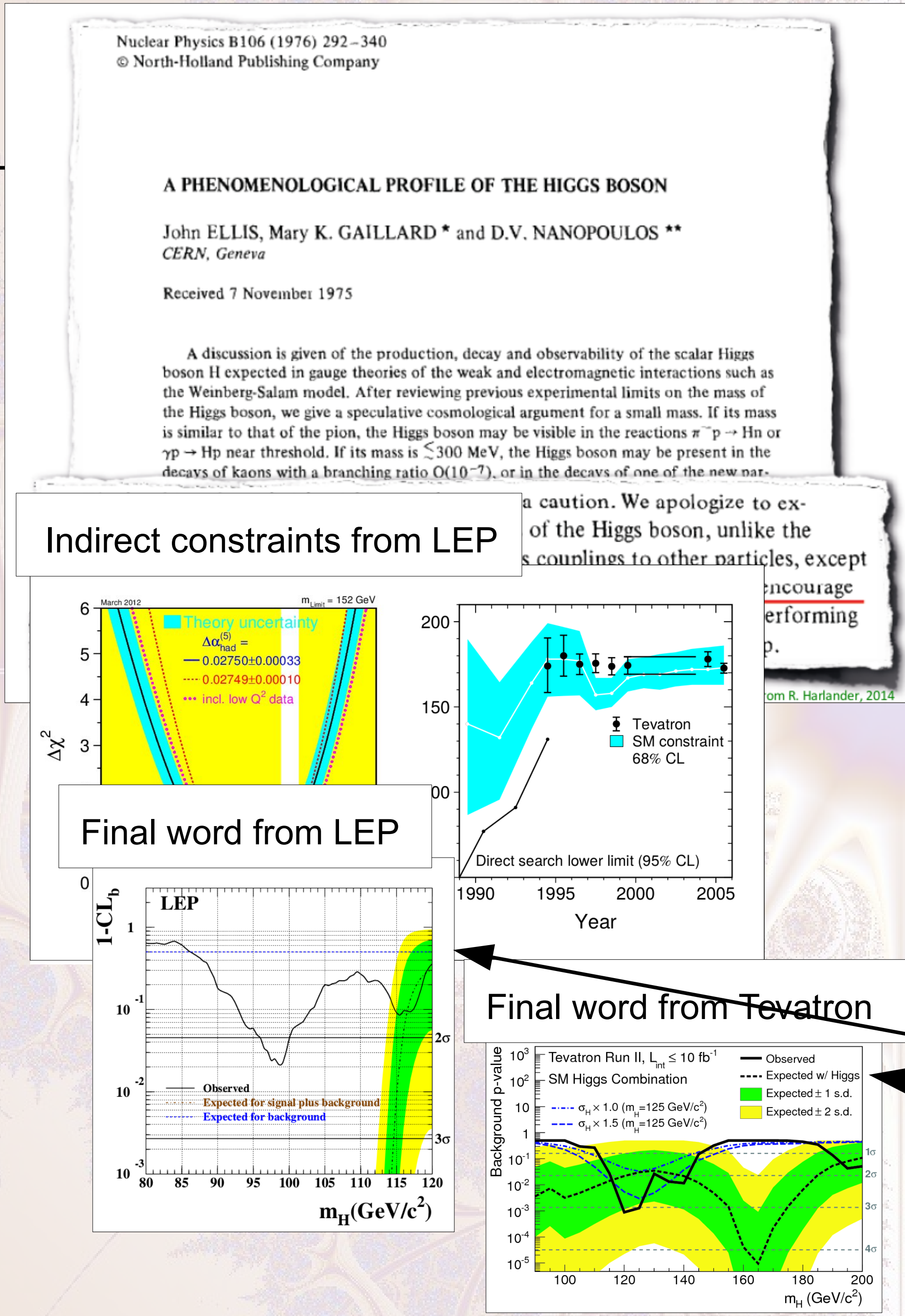

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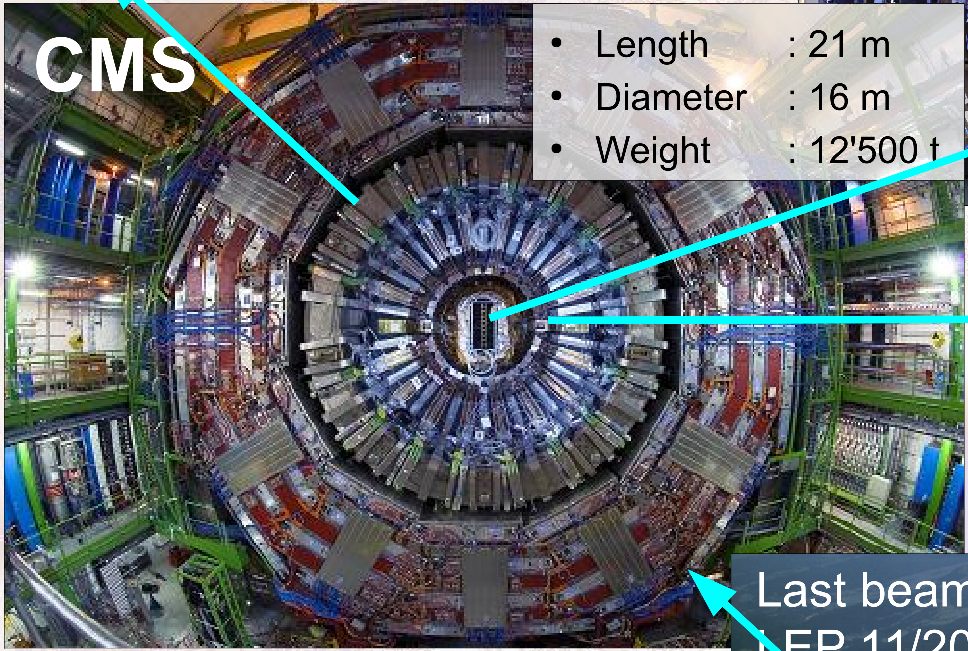
3.8T superconducting solenoid magnet:

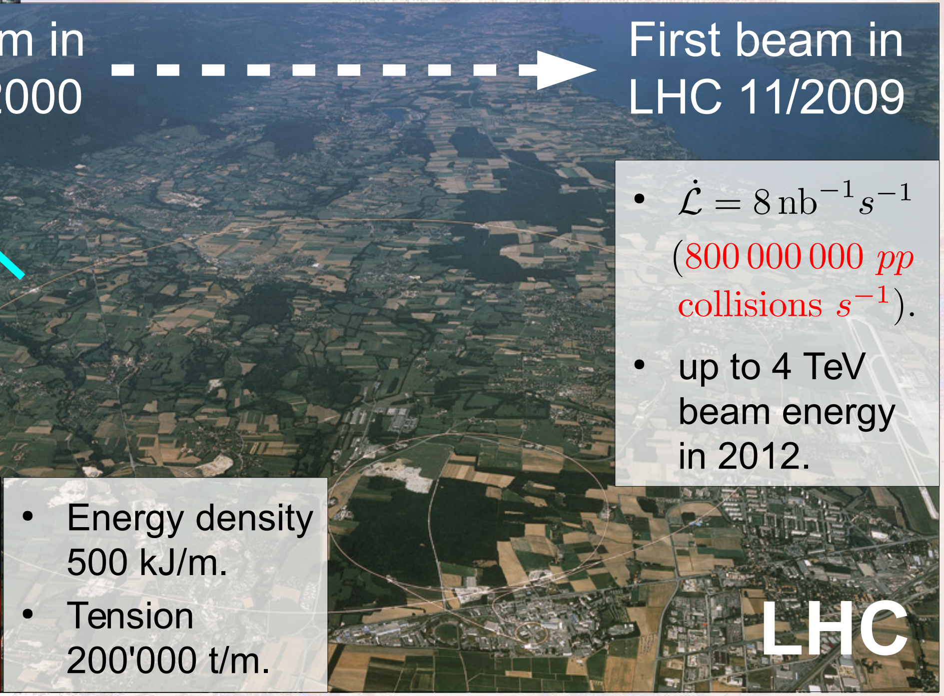


- Length : 21 m
- Diameter : 16 m
- Weight : 12'500 t

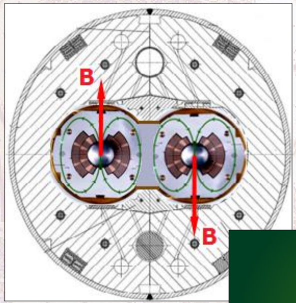
Silicon Tracker:

- Tracker: Si ($\delta p/p = 0.5\%$ for a 10 GeV track).
- ECAL: $\mathrm{PbWO_4}$($\delta E/E = 1\%$ for a 30 GeV e/γ).

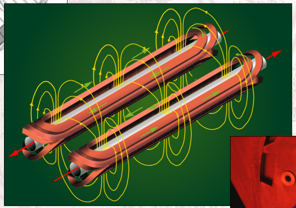
Electromagnetic Calo:



- $\dot{\mathcal{L}} = 8\,\mathrm{nb}^{-1}s^{-1}$ (800 000 000 pp collisions s^{-1}).
- up to 4 TeV beam energy in 2012.

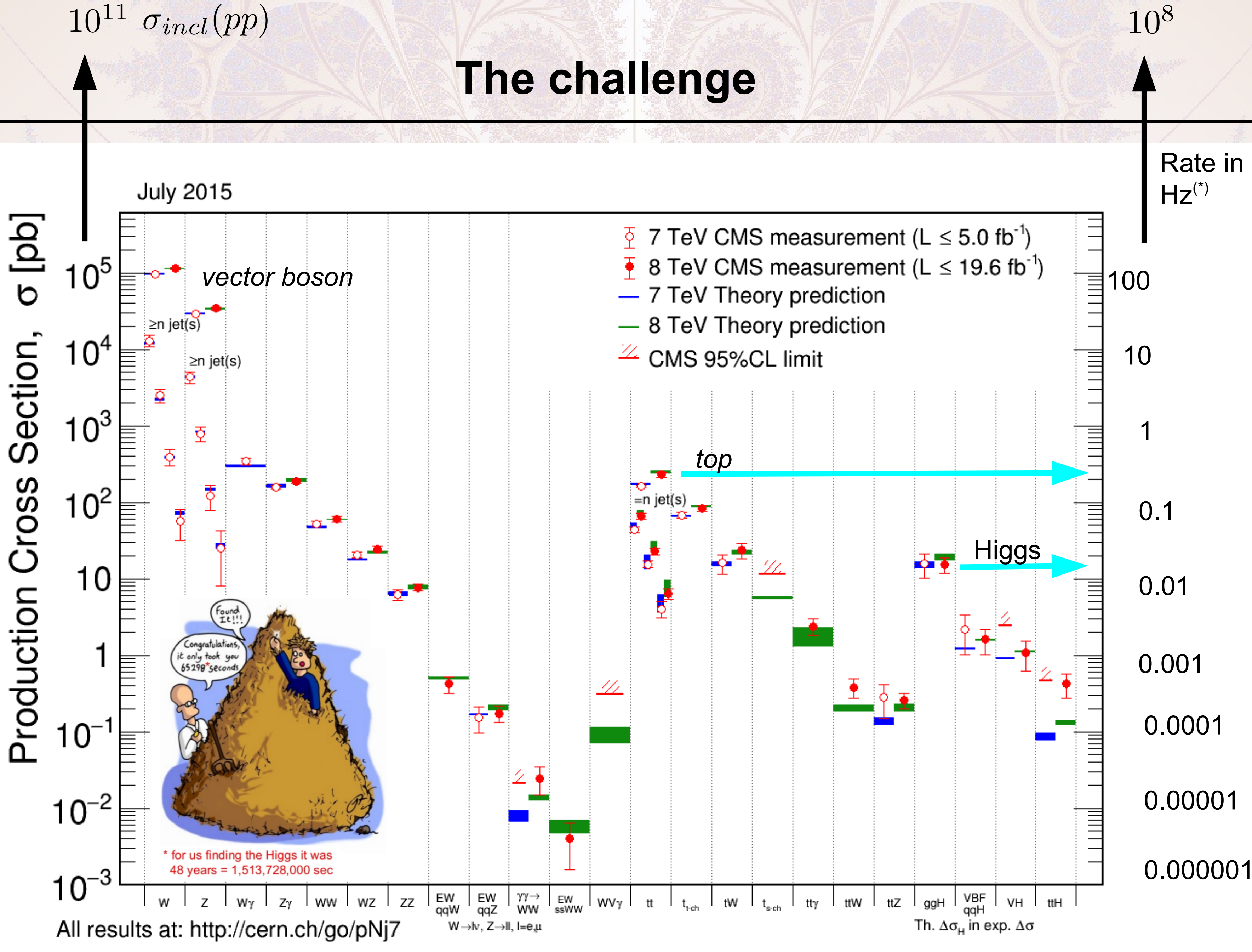


- 8.3 T
- 11.8 kA
- 160 cyc



- Energy density 500 kJ/m.
- Tension 200'000 t/m.

The challenge

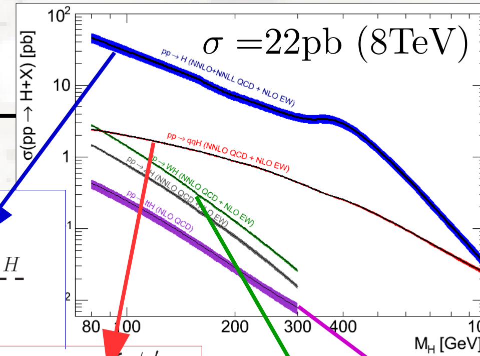


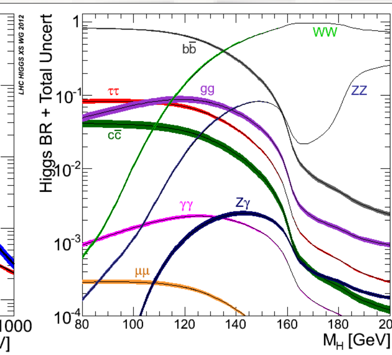
(*) for $\dot{\mathcal{L}} = 1\,\mathrm{nb}^{-1}s^{-1}$.

The discovery…

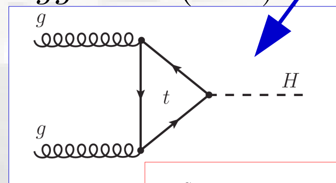
Production:

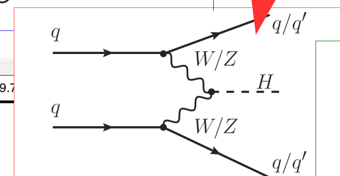
Decay:



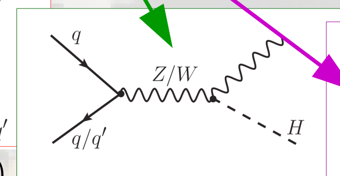


$gg \to H\ (87\%)$

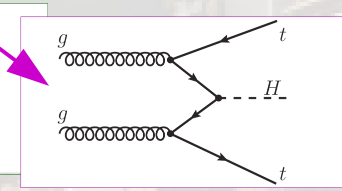




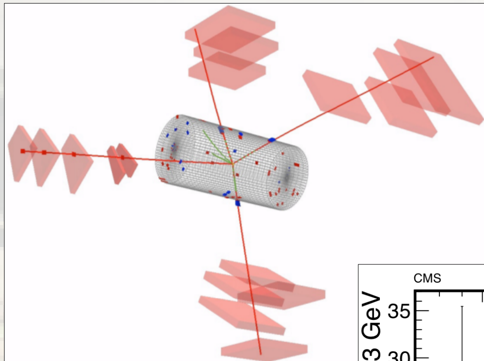
$qq \to H\ (7\%)$



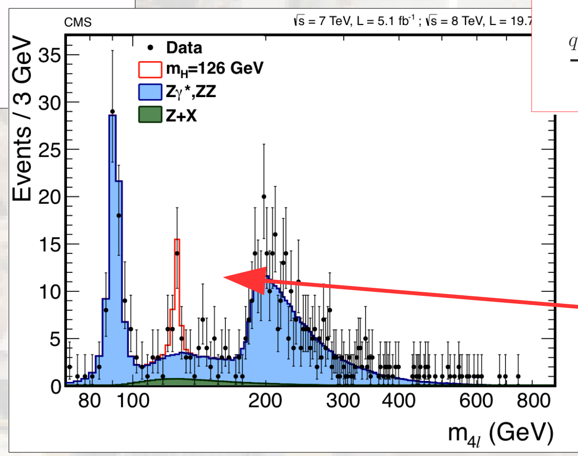
$VH\ (5\%)$

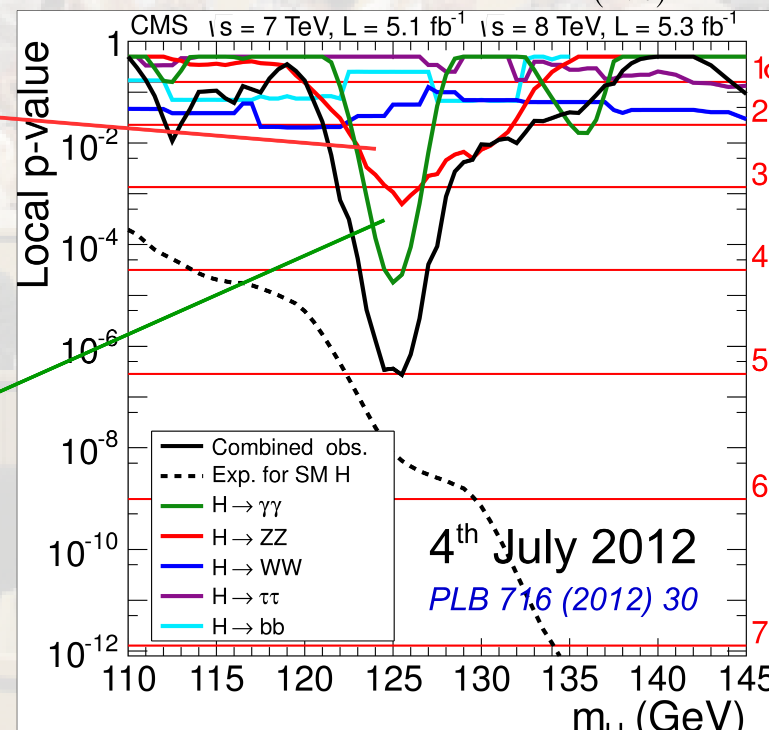


$t\bar{t}H\ (1\%)$

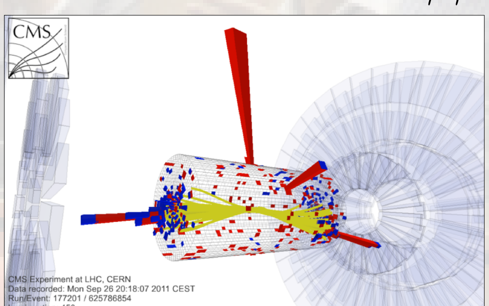


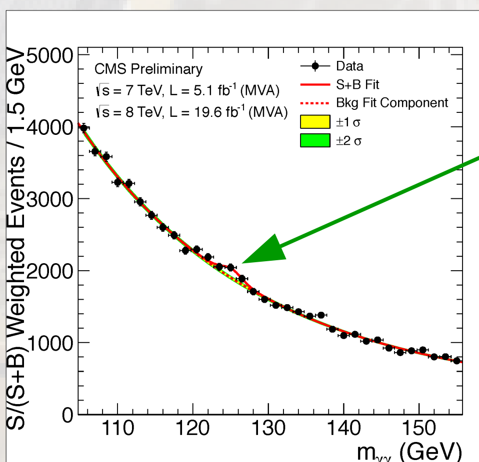
$H \to ZZ \to 4\ell$





$H \to \gamma\gamma$





… and beyond

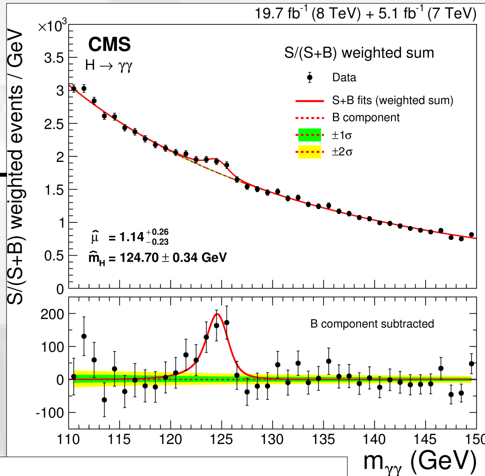
Impressive consolidation of discovery. Major LHC run-1 result!

"untagged"

Decay / Prod	$gg \to H$ 87%	$qq \to H$ 7%	VH 5%	$t\bar{t}H$ 1%
$H \to \gamma\gamma$	✓ (Part of discovery)	✓ (Part of discovery)	✓ (After LHC run-1)	✓ (After LHC run-1)
$H \to ZZ$	✓ (Part of discovery)	✓ (After LHC run-1)	✓ (After LHC run-1)	✓ (After LHC run-1)
$H \to WW$	✓ (Part of discovery)	✓ (Part of discovery)	✓ (After LHC run-1)	✓ (After LHC run-1)
$H \to \tau\tau$	✓ (Part of discovery)	✓ (After LHC run-1)	✓ (After LHC run-1)	✓ (After LHC run-1)
$H \to b\bar{b}$		✓ (After LHC run-1)	✓ (Part of discovery)	✓ (After LHC run-1)
$H \to \mu\mu$	✓ (After LHC run-1)	✓ (After LHC run-1)		

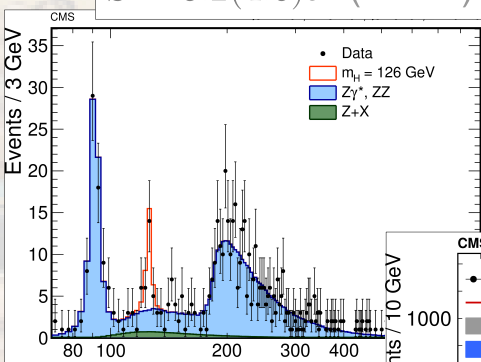
Part of discovery — After LHC run-1 — Not covered

EPJ C 74 (2014) 3076

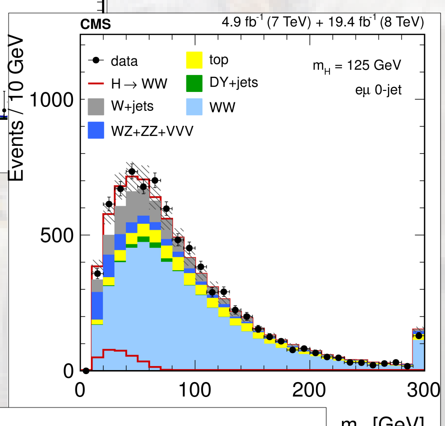


Significance:
$S = 5.7(5.2)\sigma$ (CMS)
$S = 5.2(4.6)\sigma$ (ATLAS)

PRD 89 (2014) 092007

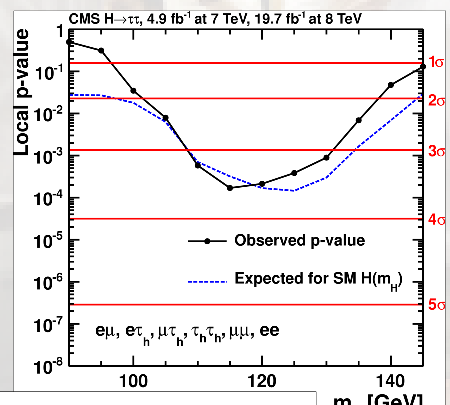


Significance:
$S = 6.8(6.7)\sigma$ (CMS)
$S = 8.1(6.2)\sigma$ (ATLAS)



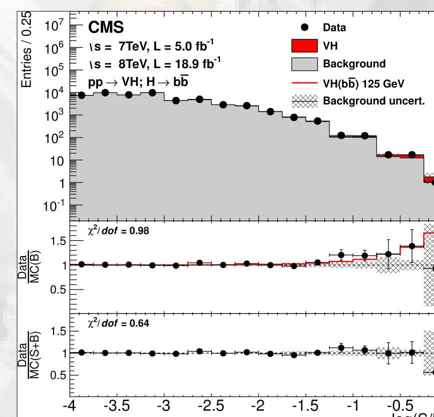
JHEP 01 (2014) 096

Significance:
$S = 4.3(5.8)\sigma$ (CMS)
$S = 6.1(5.8)\sigma$ (ATLAS)



JHEP 05 (2014) 104

Significance:
$S = 3.2(3.7)\sigma$ (CMS)
$S = 4.5(3.4)\sigma$ (ATLAS)



PRD 89 (2013) 012003

Significance:
$S = 2.1(2.5)\sigma$ (CMS)
$S = 1.4(2.6)\sigma$ (ATLAS)

44 (peer reviewed) publications since discovery announcement

$H \to \mu\mu$ decay channel

15 exclusive categories

- Clear signature, high mass resolution, extremely small $\mathcal{BR}$ ($\to$ similar to $H \to \gamma\gamma$):
- SM expectation:

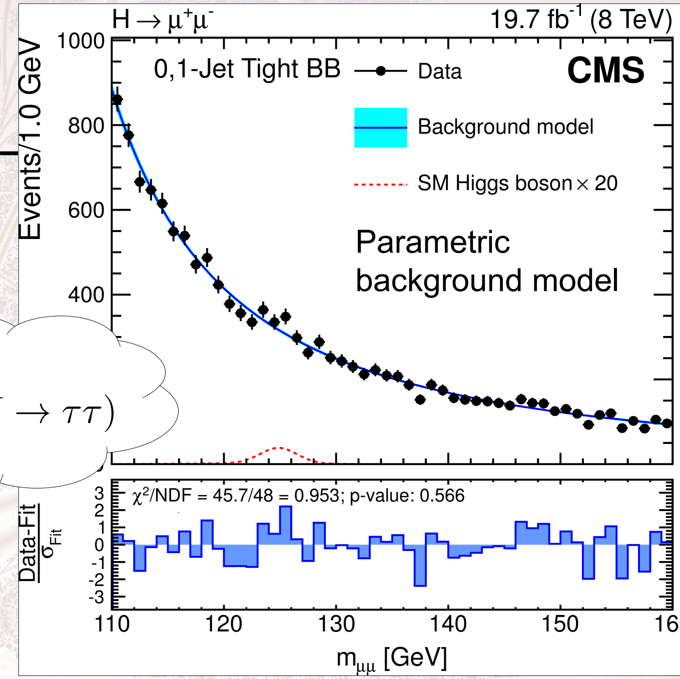
$$\mathcal{BR}(H \to \tau\tau) = 6.30 \pm 0.36\ \%$$

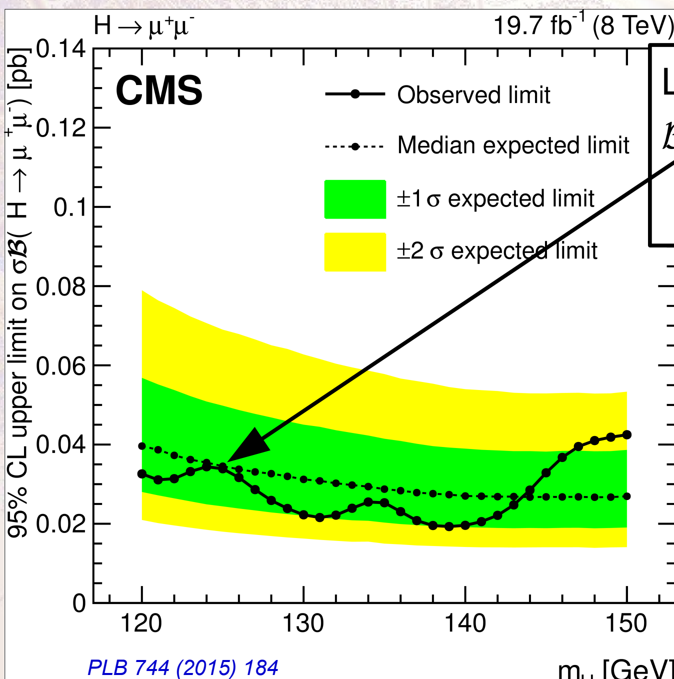
$$\mathcal{BR}(H \to \mu\mu) = 0.022 \pm 0.001\%$$

$$= \left(\frac{m_\mu}{m_\tau}\right)^2 \cdot \mathcal{BR}(H \to \tau\tau)$$

$$\left(\tfrac{106}{1777}\right)$$

- Non-universal coupling to leptons!

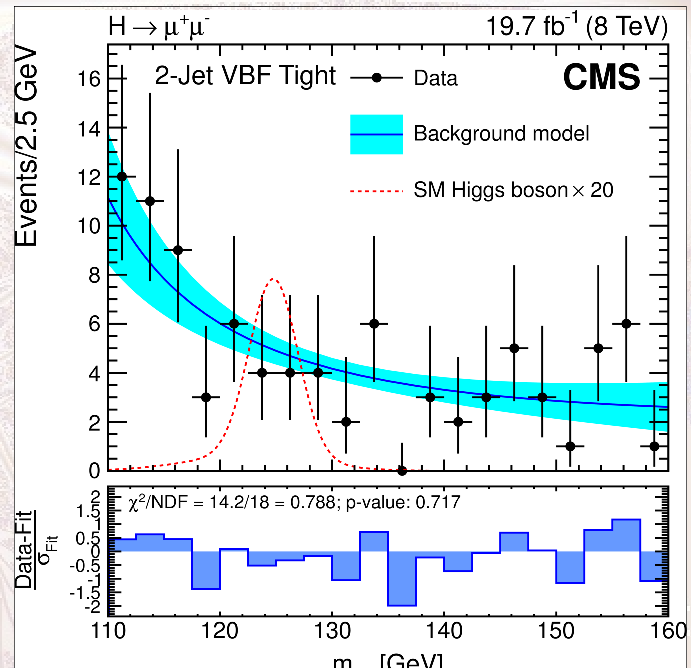




Limit (95% CL):

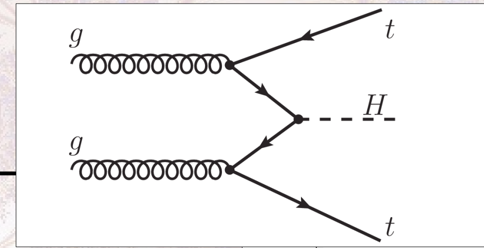
$$\mathcal{BR}(H \to \mu\mu) \leq 0.16\%$$

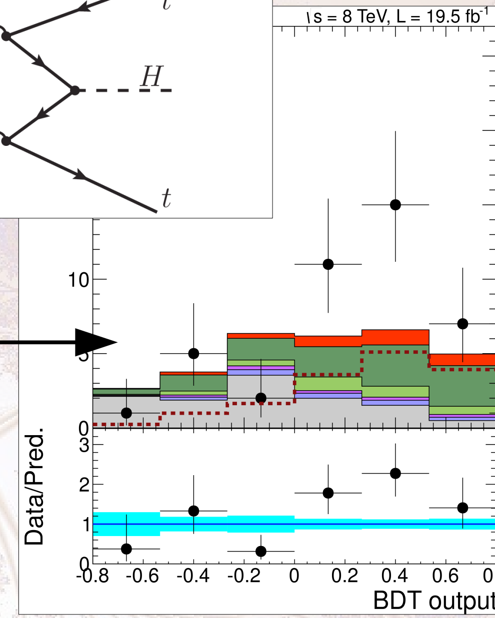
$$\left(7.4\,(6.5) \times SM\right)^{(*)}$$



(*) on 7+8TeV

$t\bar{t}H$ Production (1% of total production!)





- Complex multi-channel analysis on its own:

	$H \to$ hadrons			$H \to \gamma\gamma$		$H \to$ leptons		
	$\ell +$ jets	2ℓ	hadronic τ	leptonic	hadronic	$\ell^{\pm}\ell^{\pm}$	3ℓ	4ℓ
H decay	$b\bar{b}$		$\tau\tau/WW$	$\gamma\gamma$		$\tau\tau/WW$		ZZ
$t\bar{t}$ decay	$\ell\nu jj$	$\ell\nu\ell\nu$	$\ell\nu jj$	$\ell\nu\ell\nu/jj$	$jjjj$	$\ell\nu jj$		$\ell\nu\ell\nu$

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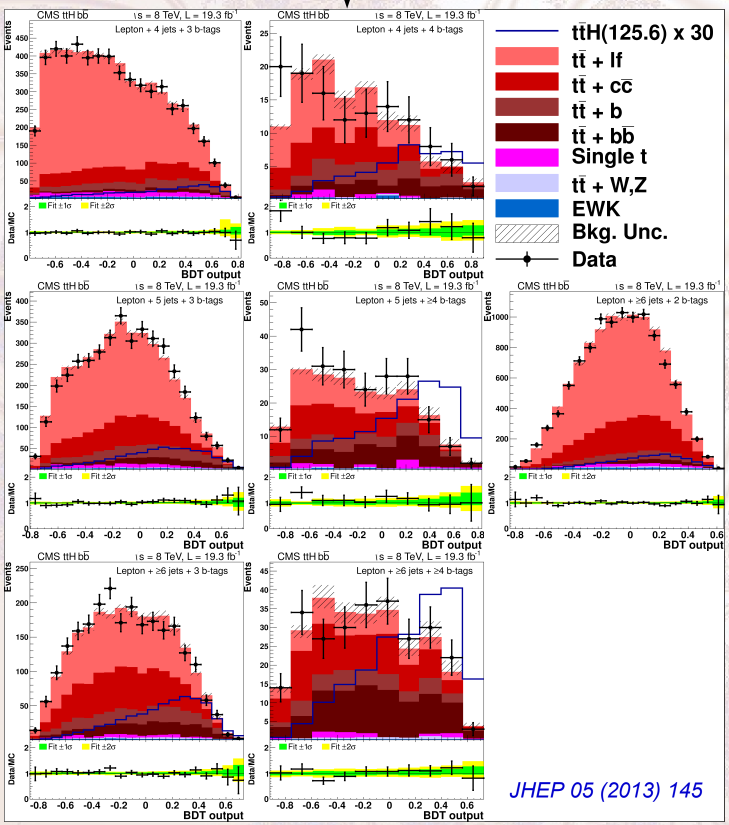
23 event categories
on the 8TeV dataset



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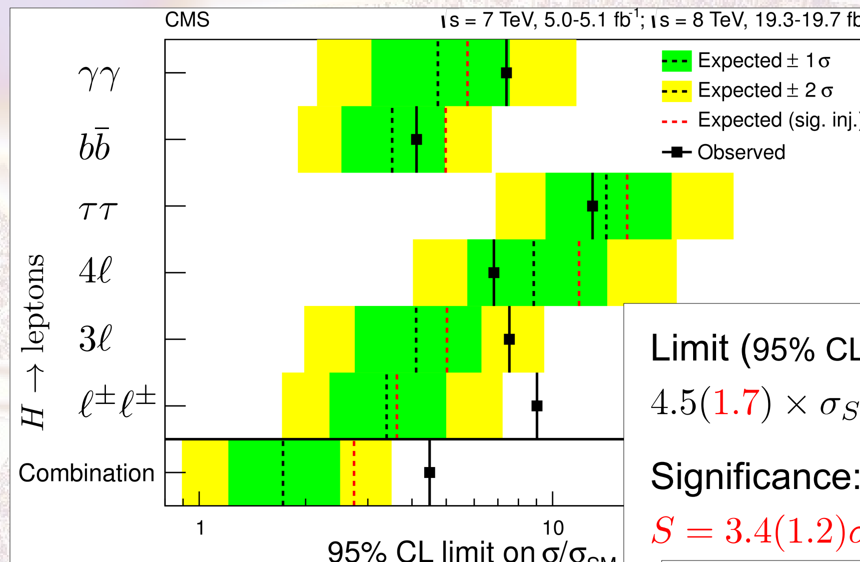
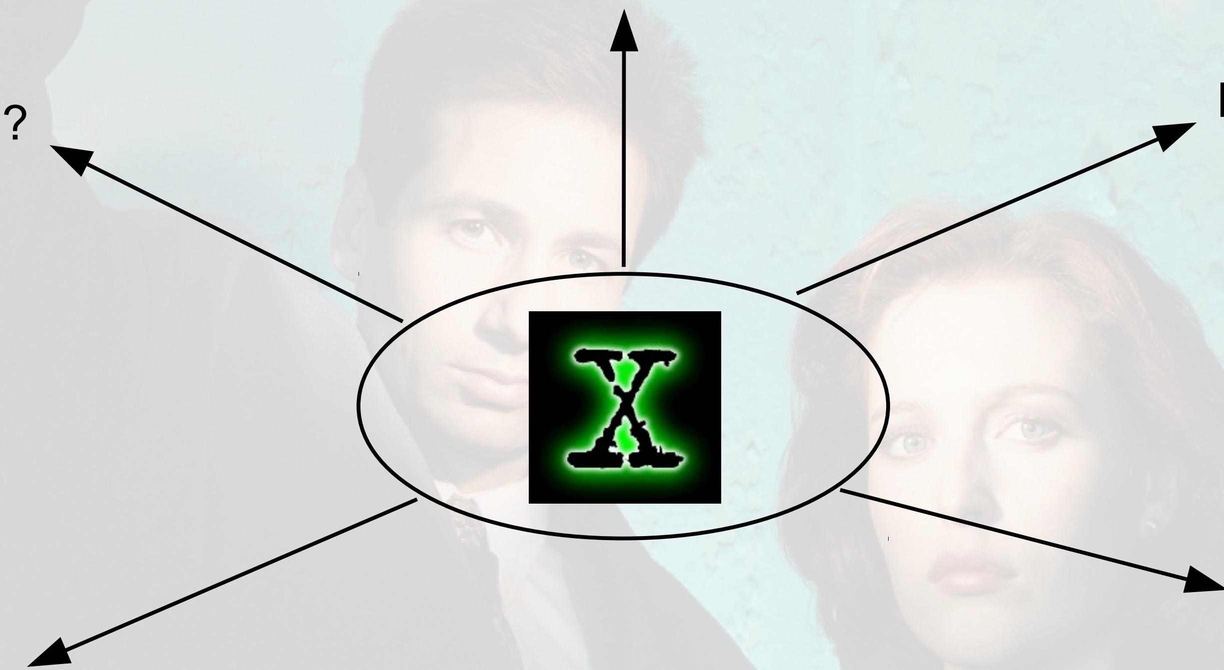


Limit (95% CL):
$4.5(1.7) \times \sigma_{SM}$

Significance:
$S = 3.4(1.2)\sigma$

($2.1\ \sigma$ above SM)

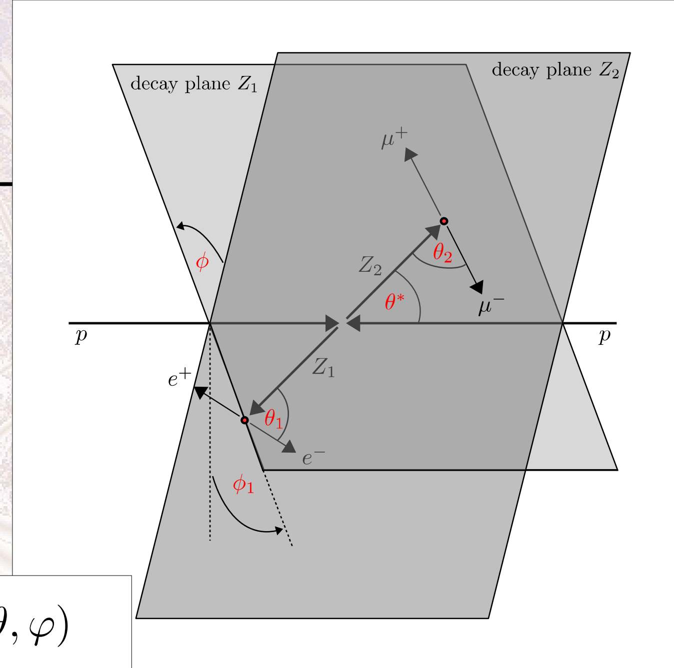
Anatomy of X

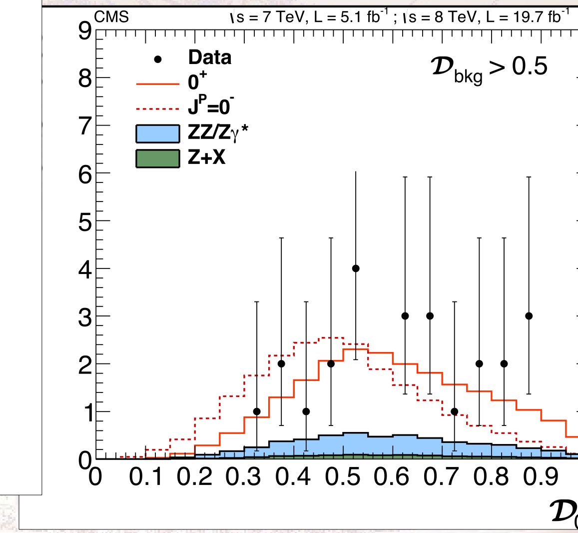


Single particle?
Spin & CP?
Decay width?
Mass?
Coupling structure?

Spin & CP

- Golden decay channel: $H \to ZZ \to 4\ell$

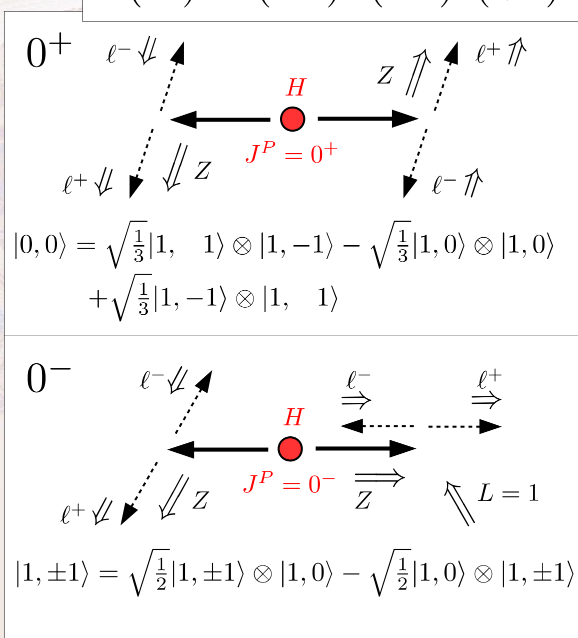




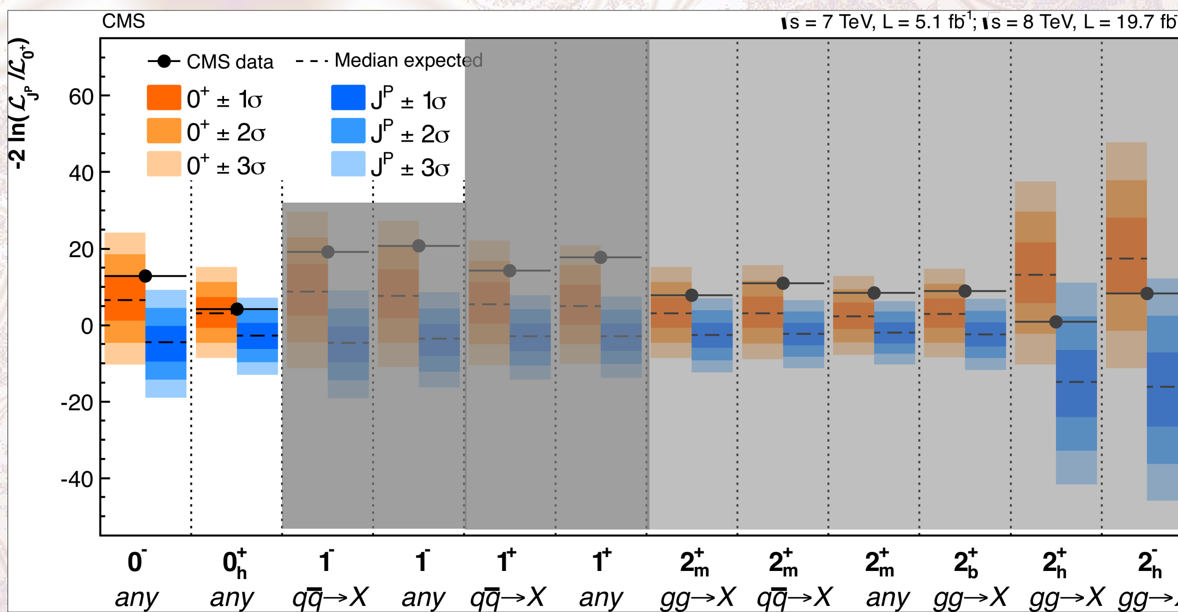
PRD 89 (2014) 092007

$$P(Y_L^m(\theta,\varphi)) = (-1)^L \cdot Y_L^m(\theta,\varphi)$$

$$P(4\ell) = (-1)^L(-1)^2(+1)^2 = (-1)^L$$



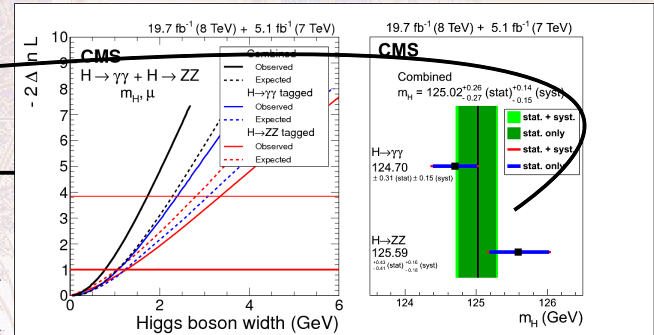
Test of pure spin hypotheses (based on $\mathcal{O}(50)$ evts):



Mass & decay width

compatible within 1.6σ.

- From high resolution channels: $H \to \gamma\gamma$ & $H \to ZZ \to 4\ell$



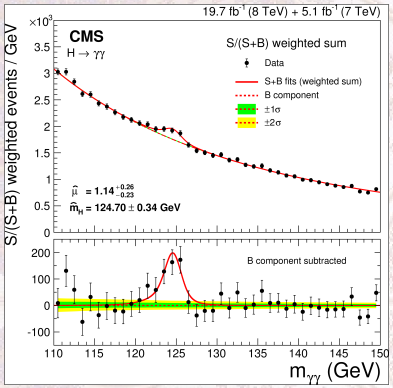
PRD 92 (2015) 012004

$$\hat{m}_H = 125.02 \pm^{0.26}_{0.27}\ (\text{stat.}) \pm^{0.14}_{0.15}\ (\text{syst.})\ \text{GeV}$$

$$\Gamma_H < 1.7\,(2.3)\ \text{GeV}\ (95\%\ \text{CL})$$

Expectation from SM:

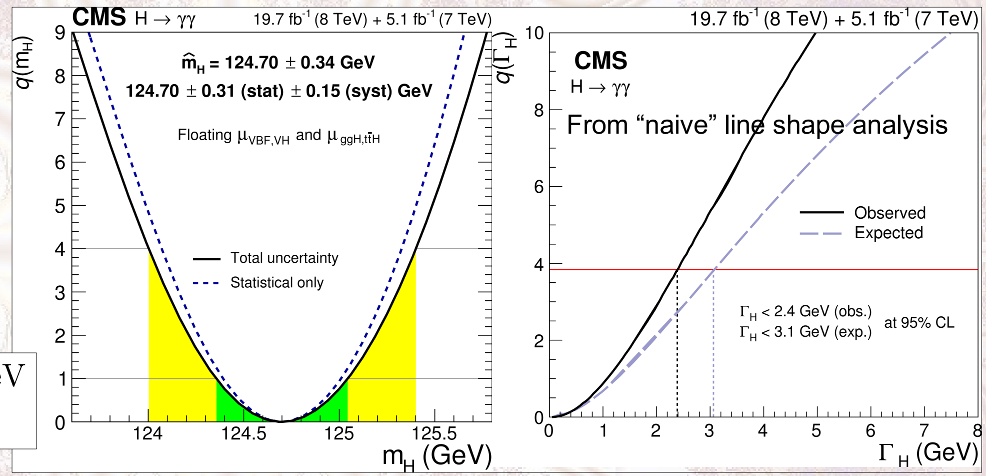
$$\Gamma_H(125\ \text{GeV}) = 4.04\ \text{MeV}$$

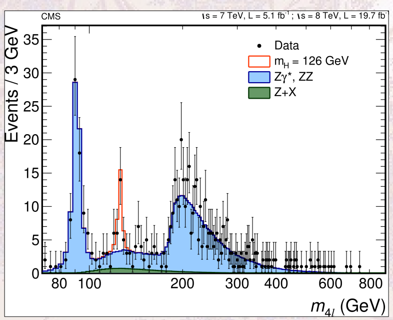


EPJ C 74 (2014) 3076

$$\hat{m}_H = 124.7 \pm^{0.5}_{0.31}\ (\text{stat.}) \pm 0.15(\text{syst.})\ \text{GeV}$$

$$\Gamma_H < 2.4\,(3.1)\ \text{GeV}\ (95\%\ \text{CL})$$

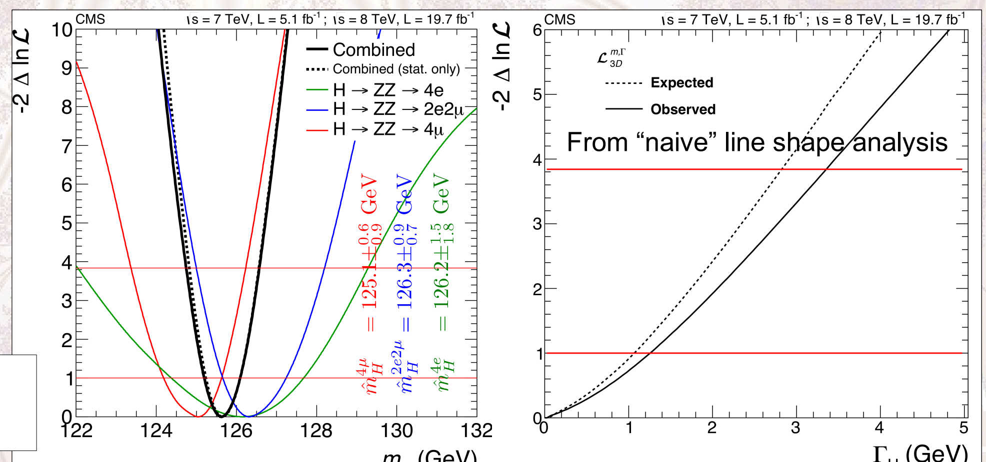




PRD 89 (2014) 092007

$$\hat{m}_H = 125.6 \pm^{0.5}_{0.4}\ (\text{stat.}) \pm 0.1(\text{syst.})\ \text{GeV}$$

$$\Gamma_H < 3.4\,(2.8)\ \text{GeV}\ (95\%\ \text{CL})$$



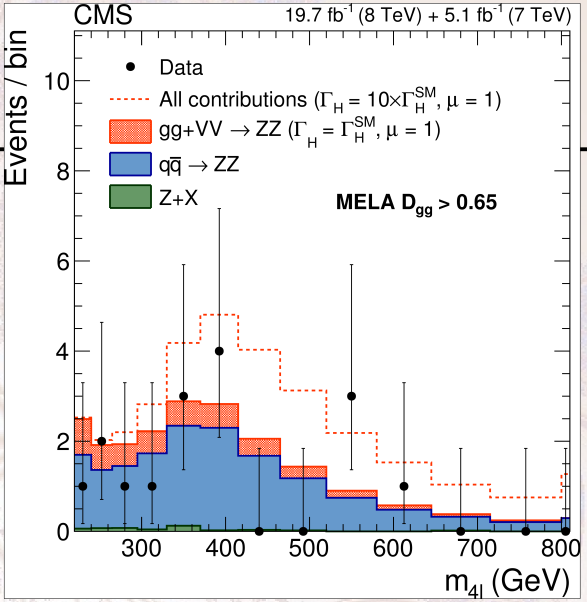
Mass & decay width

$$\frac{d\sigma}{dm^2} \propto \frac{1}{(q^2-m^2)^2+m^2\Gamma^2} \xrightarrow{\Gamma\to 0} \frac{\pi}{m\Gamma}\delta\left(q^2-m^2\right)$$

$$\frac{d\sigma(gg\to ZZ\to 4\ell)}{dm^2_{4\ell}} \propto \frac{\kappa_g^2\kappa_Z^2}{\left(m^2_{4\ell}-m^2_H\right)^2+m^2_H\Gamma^2_H}$$

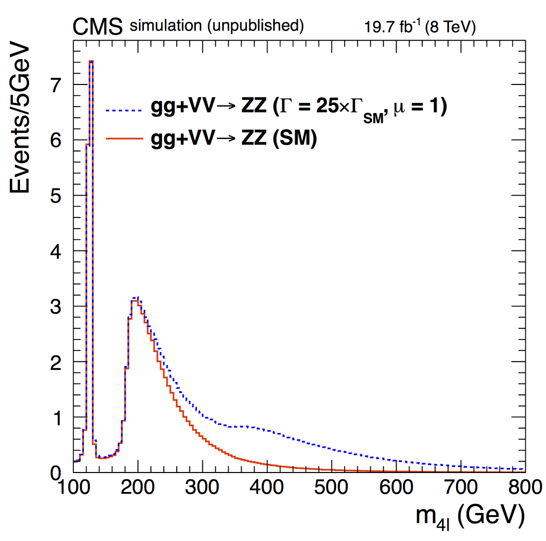
$$\propto \left.\frac{\kappa_g^2\kappa_Z^2}{m_H\Gamma_H}\right|_{m_{4\ell}\approx m_H}$$

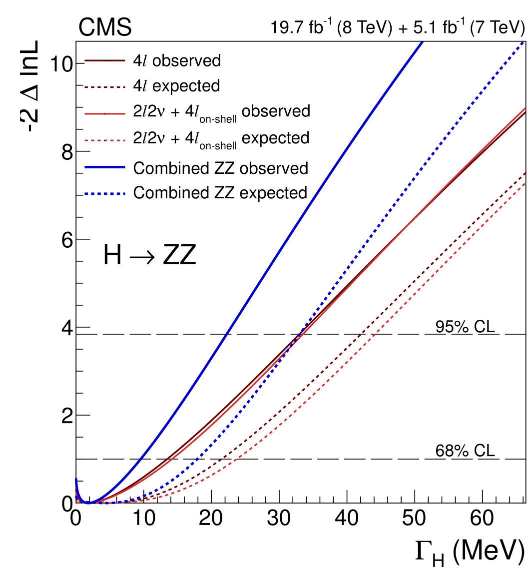
$$\propto \left.\frac{\kappa_g^2\kappa_Z^2}{m^4_{4\ell}}\right|_{m_{4\ell}\gg m_H}$$



From *offshell* cross section:
$\Gamma_H < 22(33)$ MeV (95% CL)

Expectation from SM:
$\Gamma_H(125\ \text{GeV}) = 4.04\ \text{MeV}$

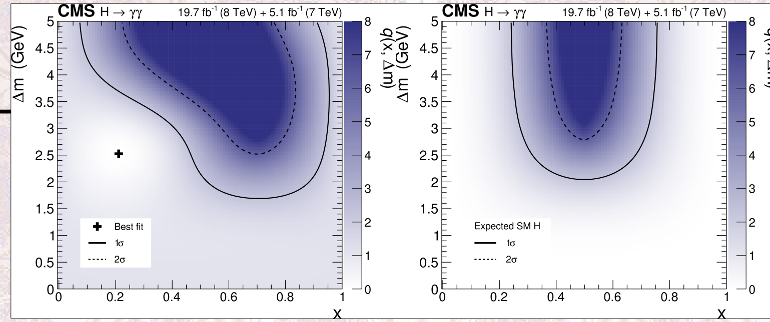




PLB 736 (2014) 64

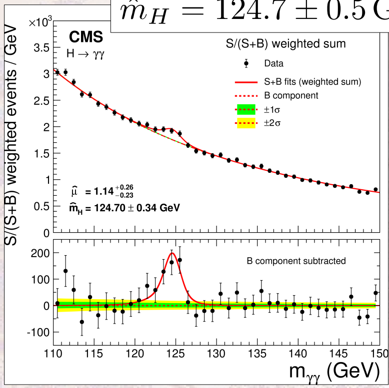
Compatibility

Second close-by resonance in $H \to \gamma\gamma$?



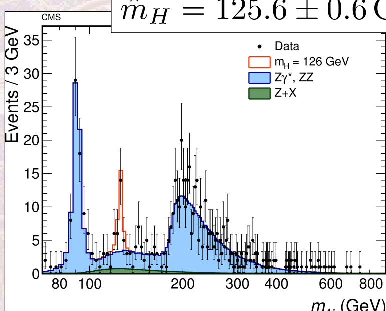
EPJ C 74 (2014) 3076

$\hat{m}_H = 124.7 \pm 0.5\,\mathrm{GeV}$



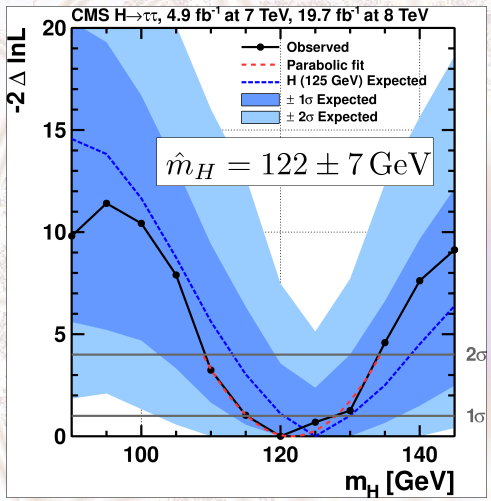
EPJ C 74 (2014) 3076

$\hat{m}_H = 125.6 \pm 0.6\,\mathrm{GeV}$



PRD 89 (2014) 092007

$\hat{m}_H = 122 \pm 7\,\mathrm{GeV}$



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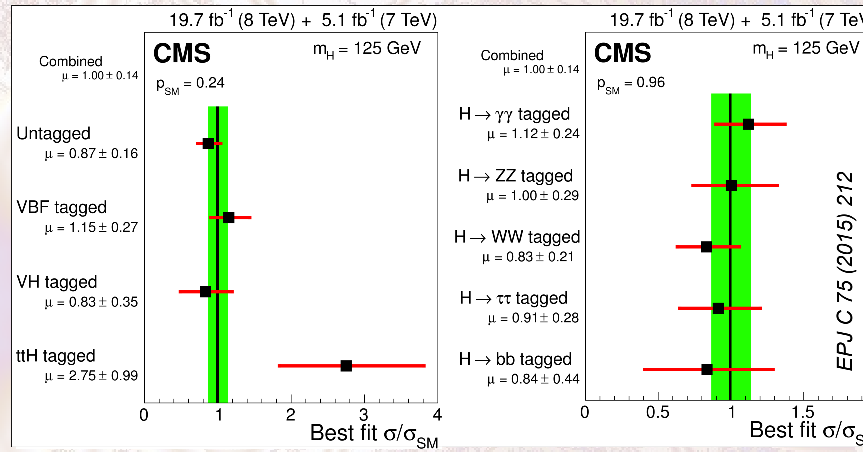
Coupling across production modes or decay channels:



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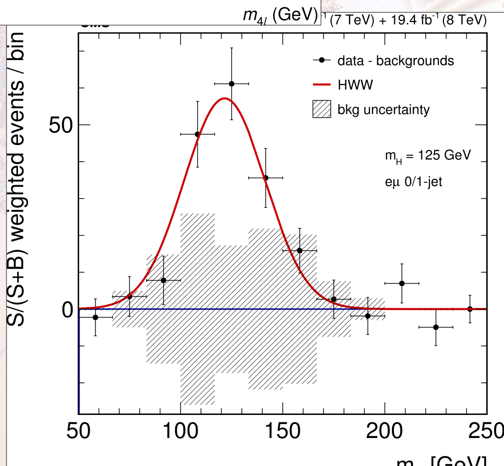
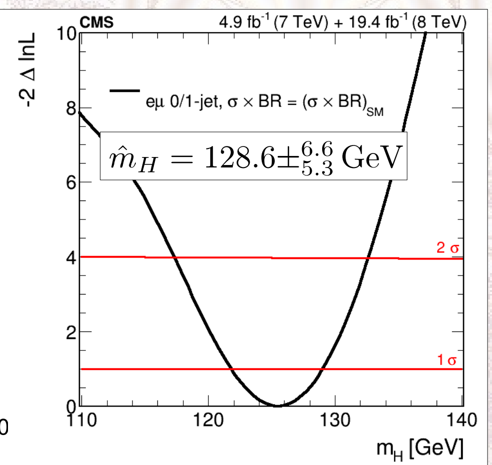


JHEP 01 (2014) 096

$\hat{m}_H = 128.6^{+6.6}_{-5.3}\,\mathrm{GeV}$



EPJ C 75 (2015) 212

Overall coupling consistency:

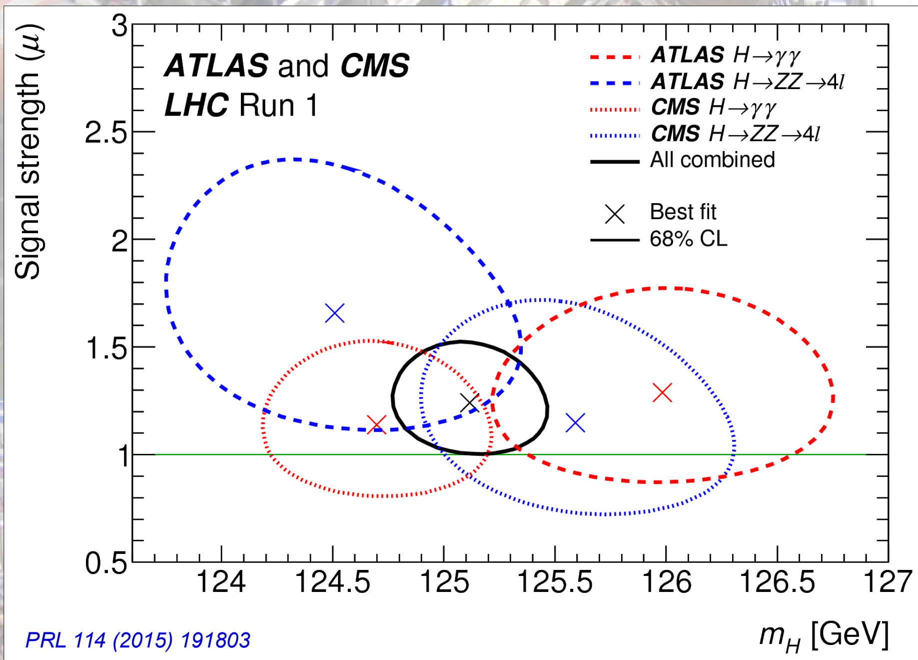
- Event categories : 227
- Nuisance parameters: $\mathcal{O}(2500)$
- 16 MB binary file of stat. model (~145 MB in human readable form).

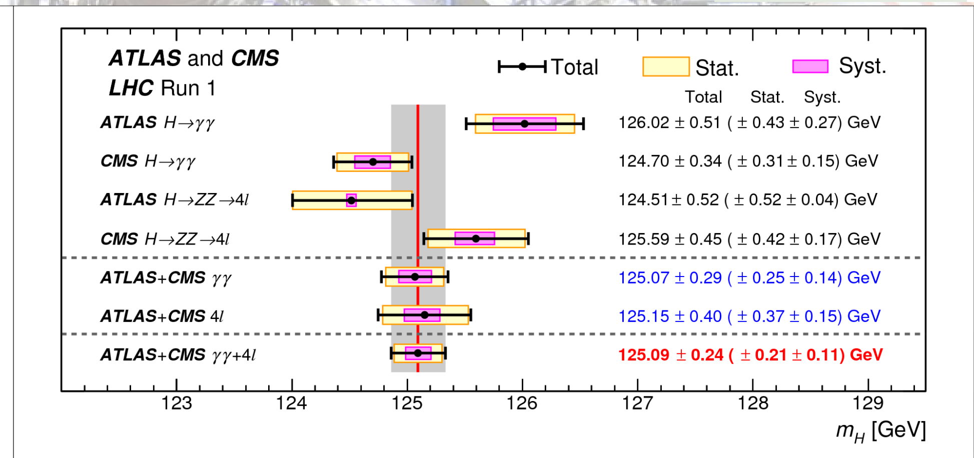
$\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.14$

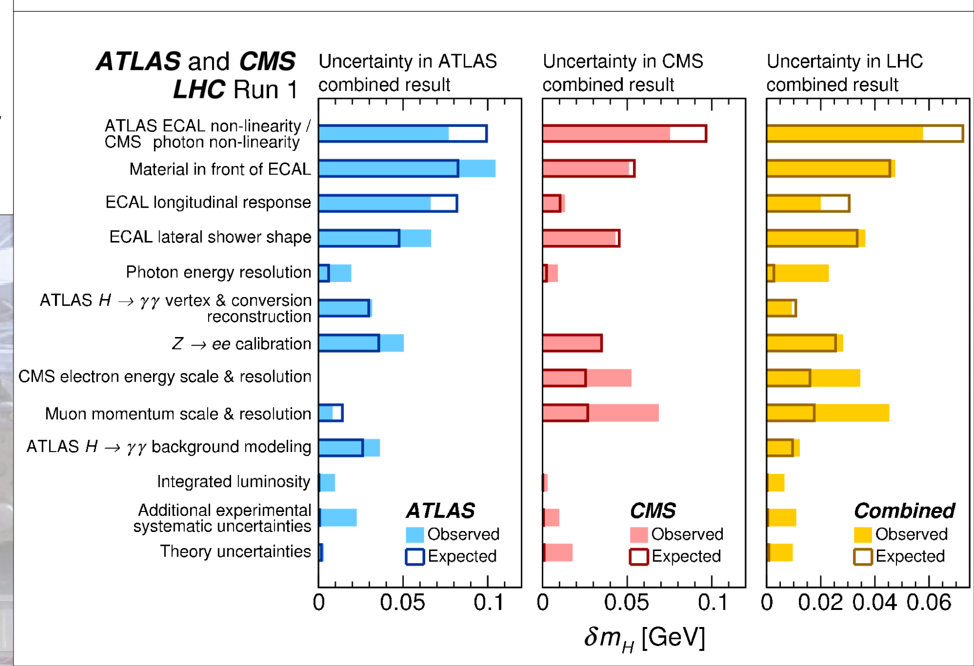
$p\text{-value} = 84\%$

Mass

- ATLAS+CMS LHC run-1 combination:







$$125.06 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})\ \text{GeV}$$

Coupling structure

CMS-PAS-HIG-15-002

- Event categories : 574
- Nuisance parameters: 4268

$\mu = \sigma/\sigma_{SM} = 1.09 \pm 0.11$

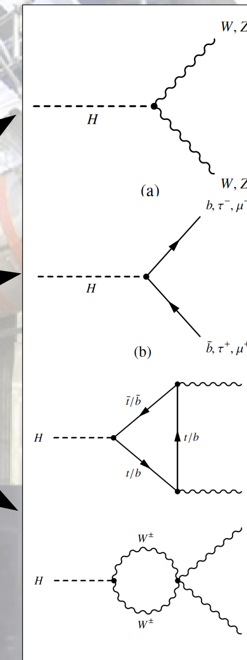
- ATLAS+CMS LHC run-1 combination:

Considered production modes:

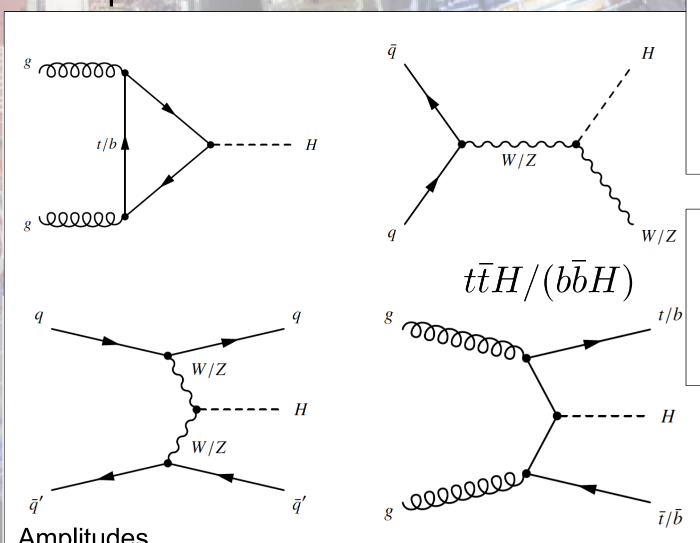
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

Considered decay channels:

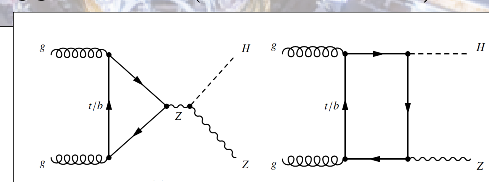
Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

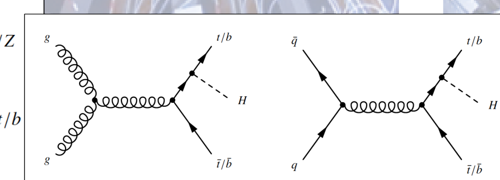


Main production modes:

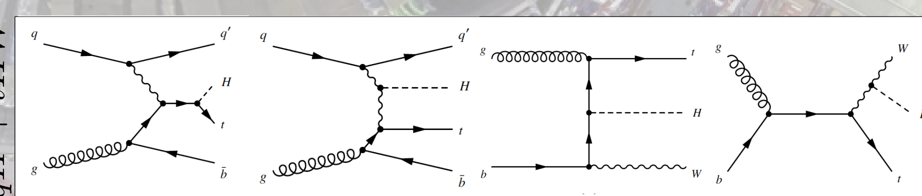


$gg \to ZH$ (10% to $ZHbb$)





$tqH + tHW$



The κ model

- Dress each coupling at tree-level with a scaling factor κ_i .
- Loops are resolved according to SM or treated as effective couplings.
- Comprise κ_i's to obtain simplified models.

Production	Loops	Interference	Multiplicative factor	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim$	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim$	κ_b^2
Partial decay width				
Γ^{ZZ}	–	–	$\sim$	κ_Z^2
Γ^{WW}	–	–	$\sim$	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
Total width for $BR_{BSM} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

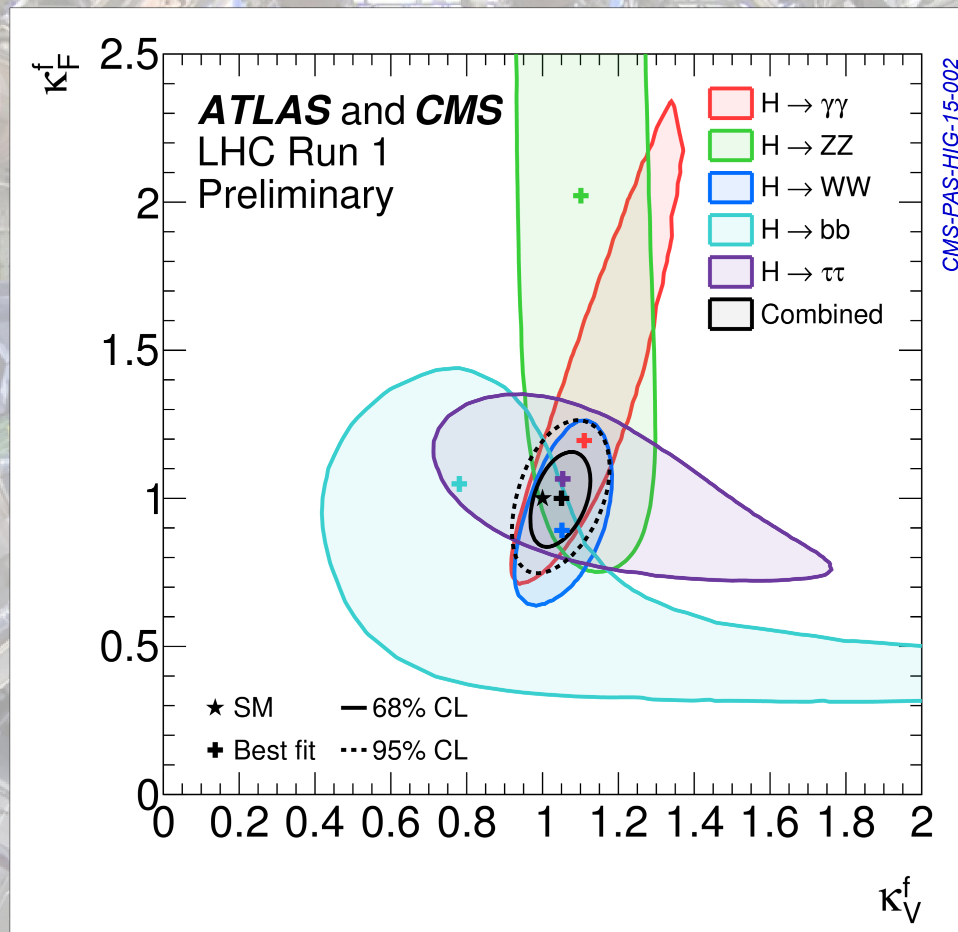
$\approx (1.26\kappa_W - 0.26\kappa_t)^2$

Non measurable couplings tied to measurable ones: $\kappa_c = \kappa_t$, $\kappa_\mu = \kappa_\tau$, $\kappa_s = \kappa_b$.

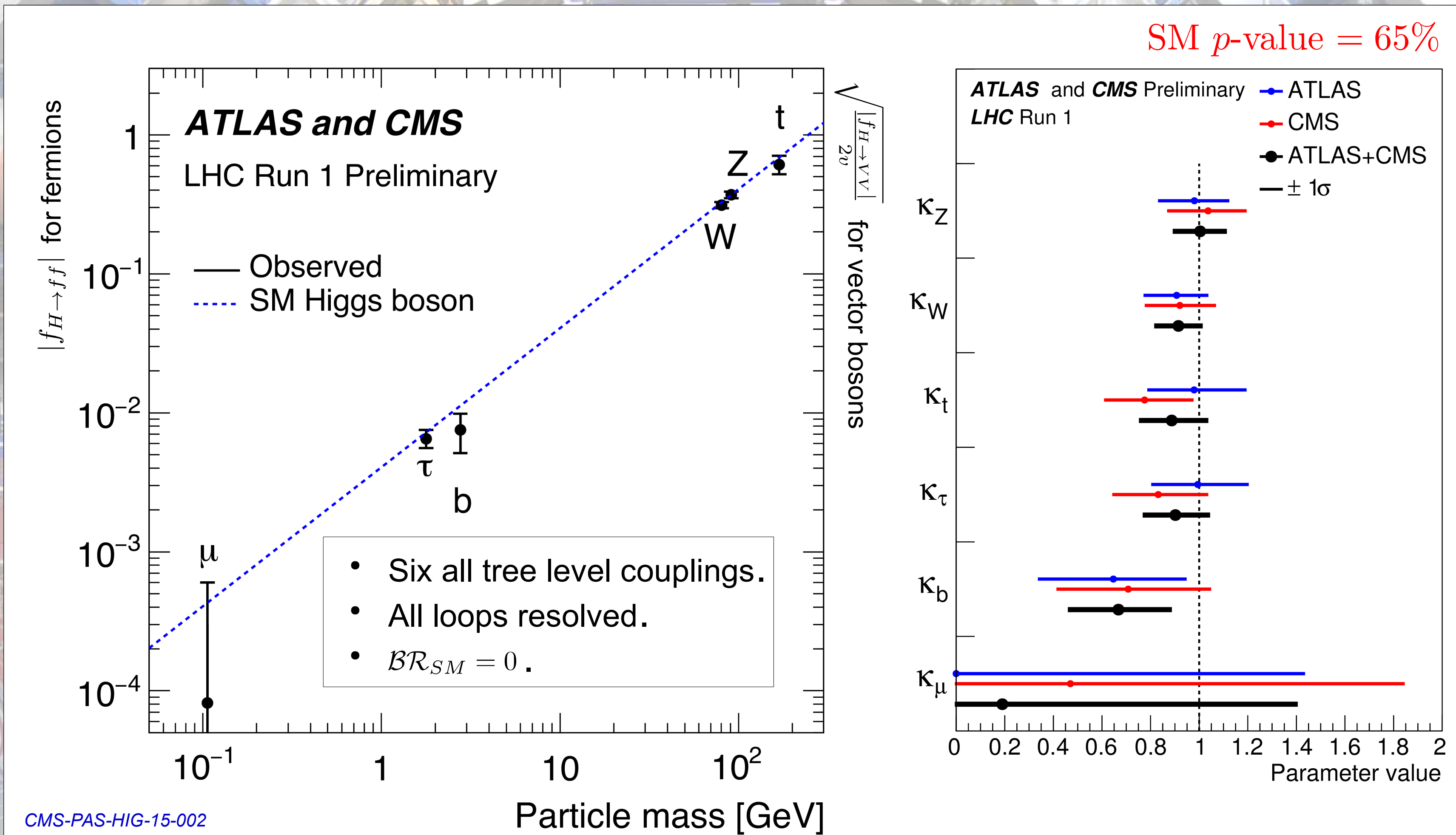
κ_V - κ_F model

- Resolve loops according to SM.
- Combine tree-level couplings into κ_V (coupling to *W* & *Z* boson) and κ_F (couping to fermions).

$\kappa_V \supset W, Z$ $\kappa_F \supset t, b, \tau, \ldots$



“Money plot”



$$|f^{\rm obs}_{H\to ff}| = \kappa_f \cdot |f^{\rm SM}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

$$\sqrt{\frac{|f^{\rm obs}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{|f^{\rm SM}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \frac{m_V}{v} \qquad V = W, Z$$

Within measurement accuracy unique scaling as expected within the SM.

X(125) → H(125)

- Higgs - a known suspect (within 10-30% accuracy):

Single particle? ✓
- checked mass
- checked couplings

Spin & CP? ✓
- Spin-1 and 2 excluded.
- CP-even.
- CP-odd admixture of up to 50% still possible.

Decay width? ✓
- $\Gamma_H < 22\,\mathrm{MeV}$ under SM assumptions.

Coupling structure? ✓
- Non-trivial coupling structure of a SM-like Higgs boson.
- No sign for deviations so far!

Mass? ✓
- $125.09\,\mathrm{GeV}$ one of the best known parameters in SM.

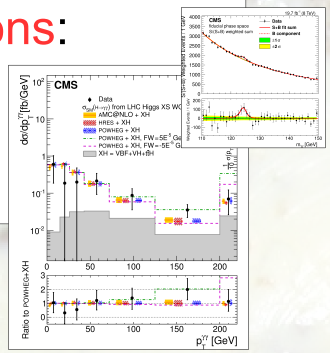
MISSION ACCOMPLISHED ?

Directives for 2015++

Pseudo-Observables/ Cross sections:

- fiducial
- simplified
- differential

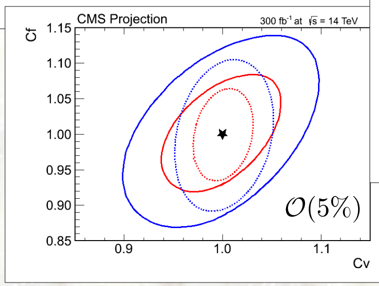
"up for 2015++"

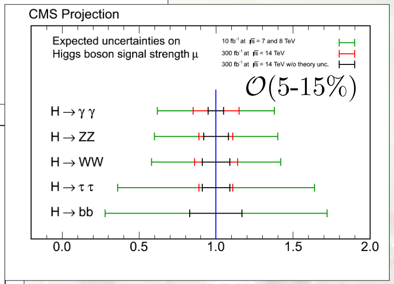


Subm. to EPJC

Precision on couplings

- EFT approaches
- $\kappa + +$





"expect lasting result ~2018/19 "

Expected deviations in models:

	g_{VV}	g_{uu}	$g_{dd,\ell\ell}$	g_{hhh}
mixed-in singlet	6%	6%	6%	18%
composite Higgs	8%	$\mathcal{O}(10\%)$	$\mathcal{O}(10\%)$	$\mathcal{O}(10\%)$
MSSM	$< 1\%$	3%	$< 10\%$	2%

Heidi Rzehak (2013)

CP-measurement

- Hope for $H \to \tau\tau$
- Clear prospects.
- Still experimentally very challenging.

"endurance required (>2018)"

Higgs self-coupling

- LHC project for 3/at.
- Studies for upgrade proposals.

"beyond scope"

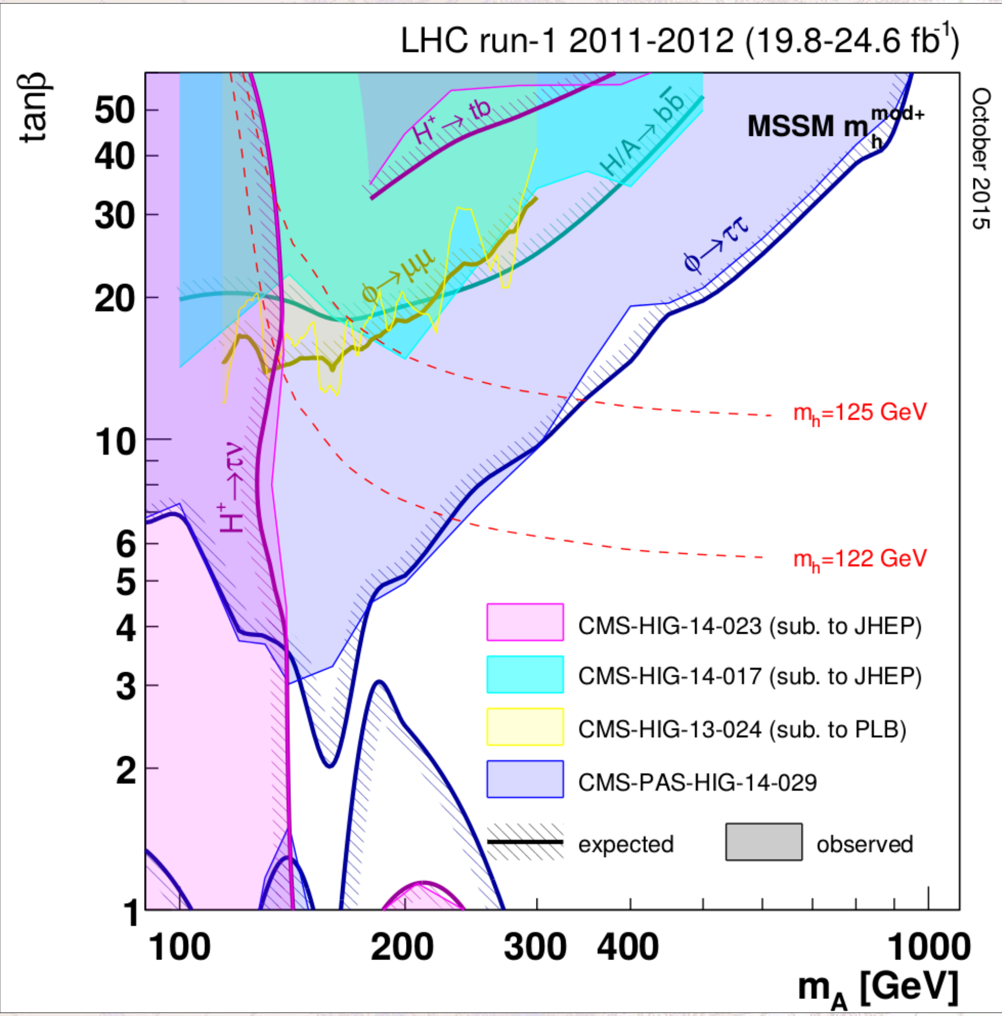
Find another Higgs boson

"on call for 2015++"

Extensions of the Higgs sector:

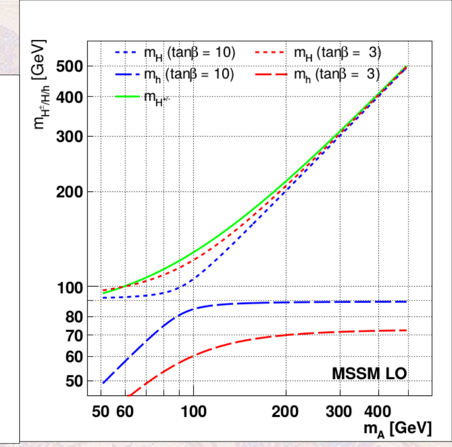
- additional singlet(s)
- additional doublet(s)
- additional triplet(s)
- …

MSSM and THDM?



Compiling several CMS results

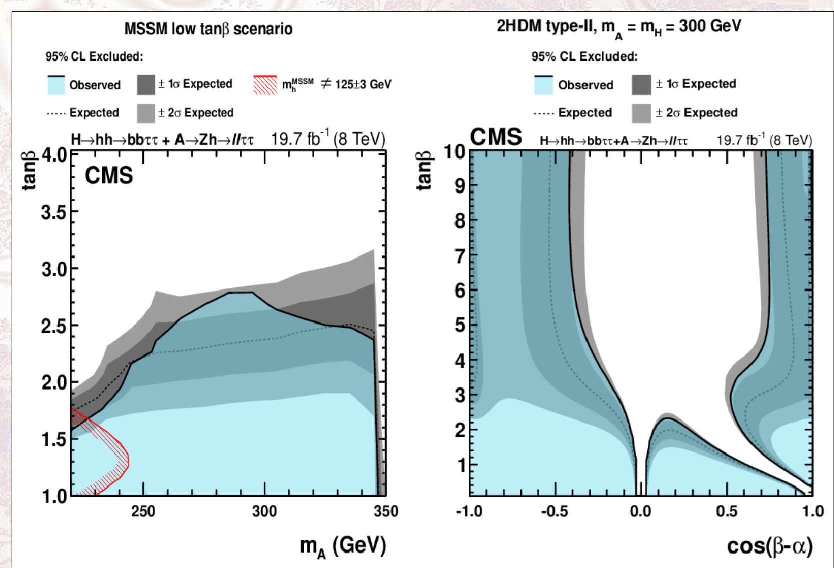
- Watch out for 2 charged ($H^{\pm}$) + 3 neutral (A, H, h) Higgs bosons.
- Rigid mass correlations governed by m_A and $\tan\beta$ (at LO).
- Well developed proxy for more general THDM.



	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \ \to 0$	$\sin\alpha/\sin\beta \ \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \ \to 1$	$\cos\alpha/\sin\beta \ \to \ 1$	$-\sin\alpha/\cos\beta \to \ 1$

For $m_A \gg m_Z$: $\alpha \to \beta - \pi/2$ (coupling to down-type fermions enhanced by $\tan\beta$).

Subm. to PLB



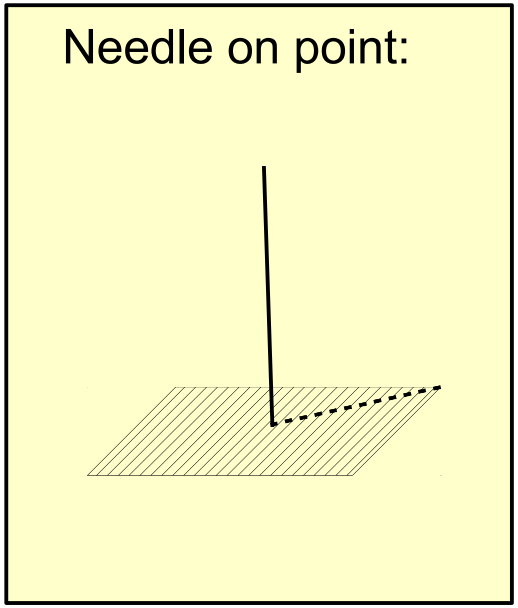
Conclusions

- Rich harvest of LHC run-1 (better than one could ever have dreamed of).
- Topped all expectations by ~1 order of magnitude.
- Rich program of BSM Higgs searches apart from consolidation of discovery.
- LHC run-1, an era of “SM Higgs boson discovery” (hardly prepared for more than that).
- For 2015++ even better prepared Higgs physics program than in 2010 (better know what to expect).
- This will be an era of:
  - SM Higgs boson measurements!
  - A next generation of BSM Higgs boson searches (coordinated by LHCHXSWG).

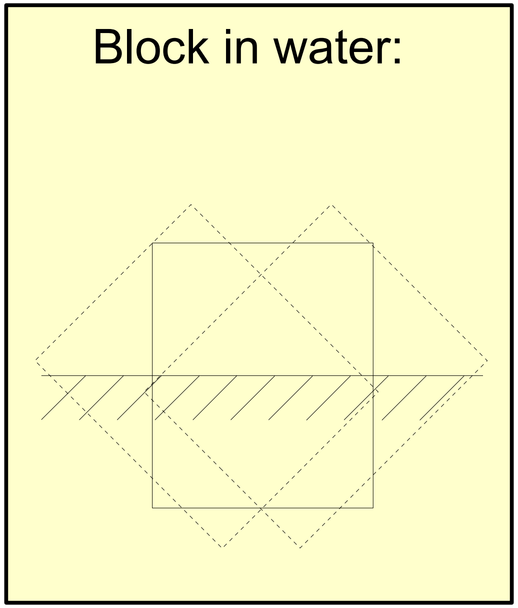
Backup

Spontaneous Symmetry Breaking

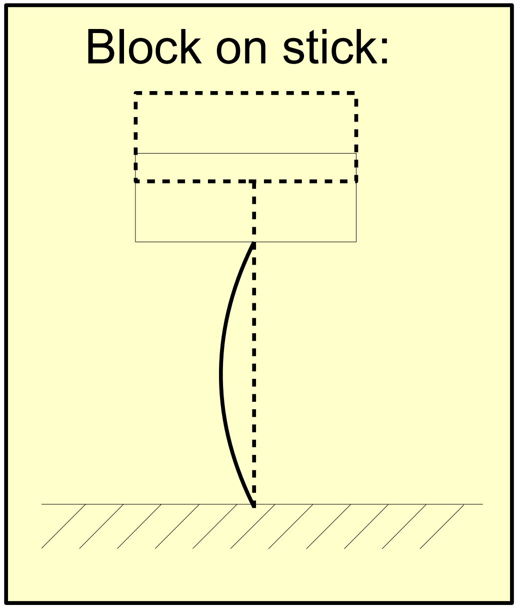
- Symmetry present in the system (i.e. in Lagrangian density $\mathcal{L}$).
- BUT symmetry broken in energy ground state of the system (=quantum vacuum).
- Three examples from classical mechanics:



φ symmetry



axis-symmetry



φ symmetry

Solution to the Problem of Fermion Masses

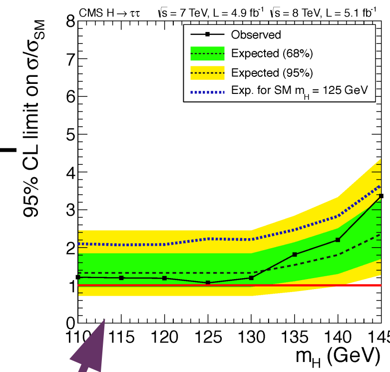
- Expand ϕ in its energy ground state to obtain the mass terms:

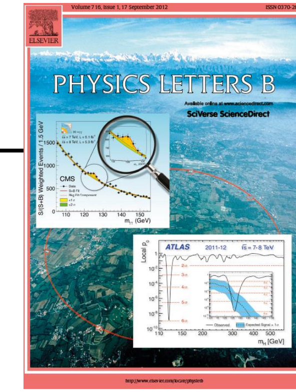
$$\mathcal{L}^{\text{Yukawa}} = \underbrace{-y_e \left(v + \frac{H}{\sqrt{2}}\right)}_{m_e \equiv y_e v} \underbrace{(\bar{e}_R e_L + \bar{e}_L e_R)}_{\bar{e}e} = -m_e \left(1 + \frac{1}{v}\frac{H}{\sqrt{2}}\right) \bar{e}e$$

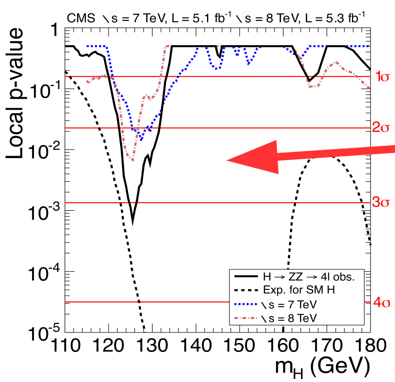
- We obtained the desired mass term and a coupling to the Higgs boson field, which is proportional to the fermion mass.

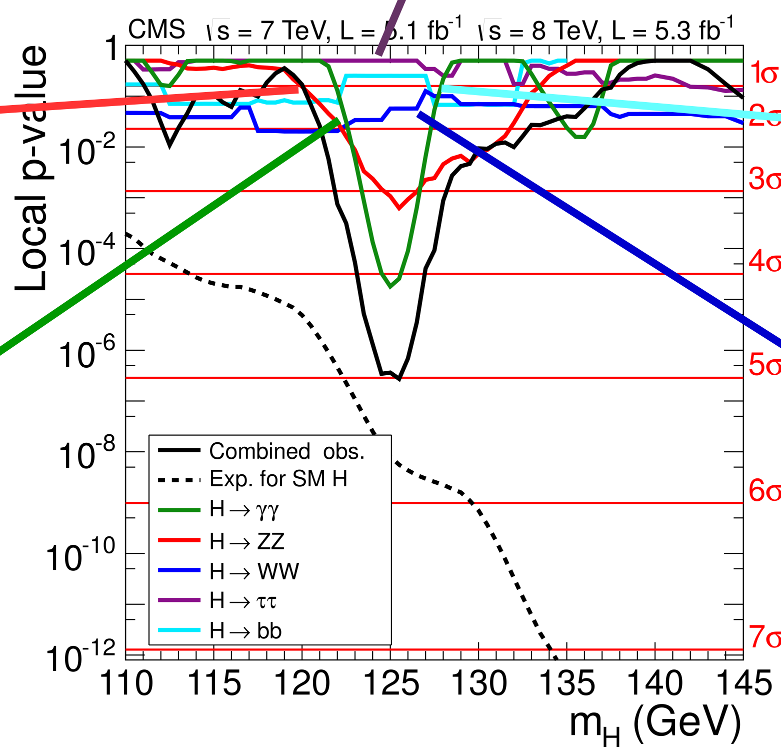
The discovery (4th July 2012)

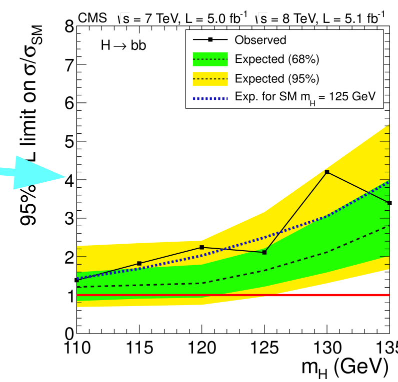
- PLB 716 (2012) 30 (July 2012).
- Science 338 (2012) 1569 (Sep. 2012).
- JHEP 06 (2013) 081 (Mar. 2013).

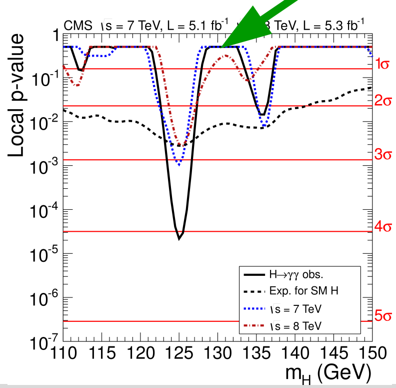


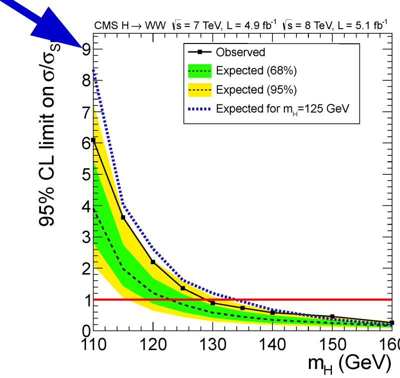












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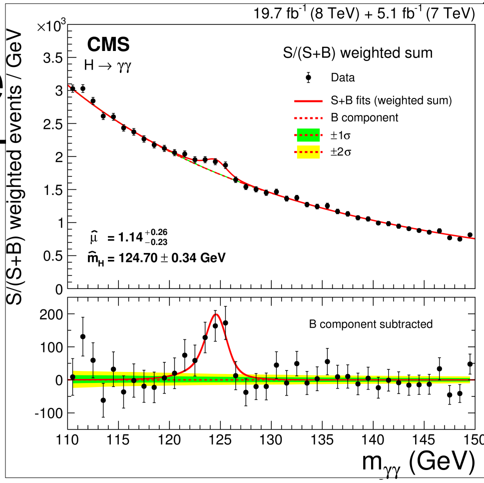
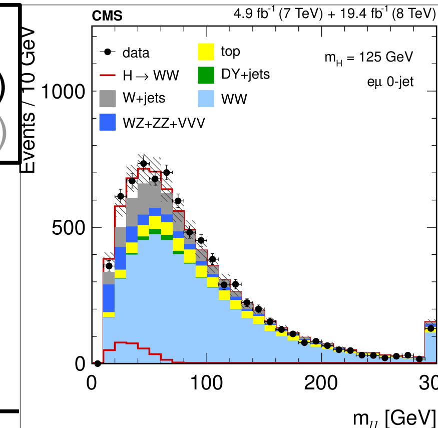


Significance:
$S = 5.7(5.2)\sigma$ (CMS)
$S = 5.2(4.6)\sigma$ (ATLAS)

Significance:
$S = 4.3(5.8)\sigma$ (CMS)
$S = 6.1(5.8)\sigma$ (ATLAS)

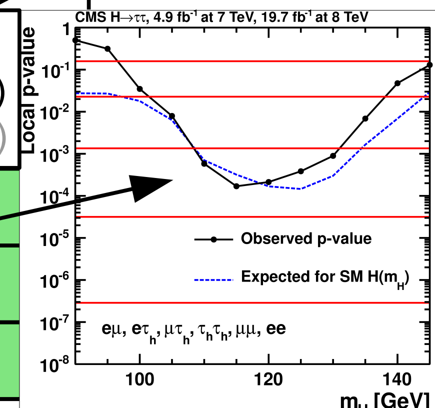


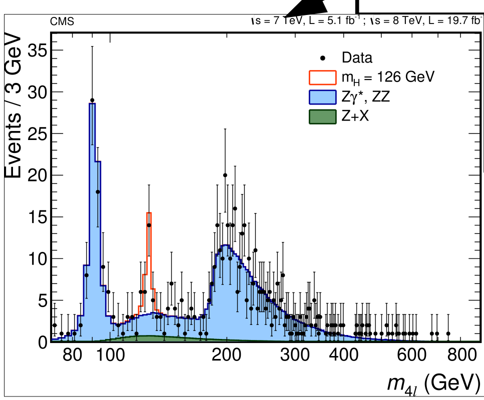
"untagged"

	$gg \to H$	$qq \to H$	VH	$t\bar{t}H$
$H \to \gamma\gamma$	EPJ C 74 (2014) 3076			
$H \to ZZ$	PRD 89 (2014) 092007			
$H \to WW$	JHEP 01 (2014) 096			✓
$H \to \tau\tau$	JHEP 05 (2014) 104			✓
$H \to b\bar{b}$		✓	PRD 89 (2013) 012003	✓
		✓		

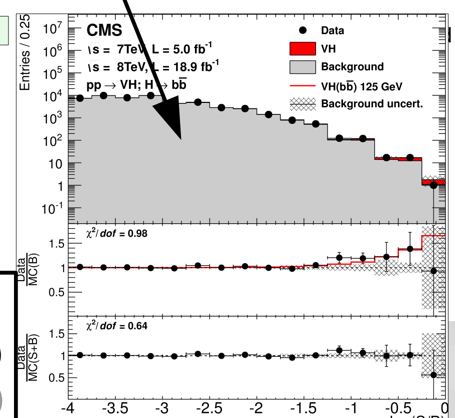
S+CMS

Significance:
$S = 3.2(3.7)\sigma$ (CMS)
$S = 4.5(3.4)\sigma$ (ATLAS)

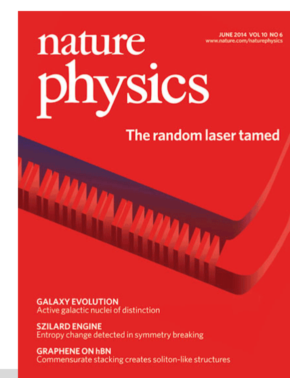




Significance:
$S = 6.8(6.7)\sigma$ (CMS)
$S = 8.1(6.2)\sigma$ (ATLAS)



Significance:
$S = 2.1(2.5)\sigma$ (CMS)
$S = 1.4(2.6)\sigma$ (ATLAS)

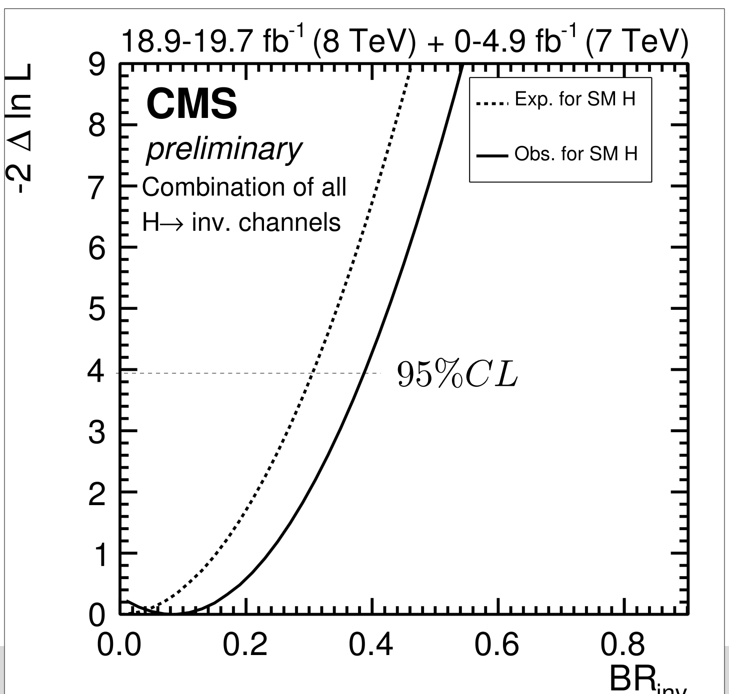


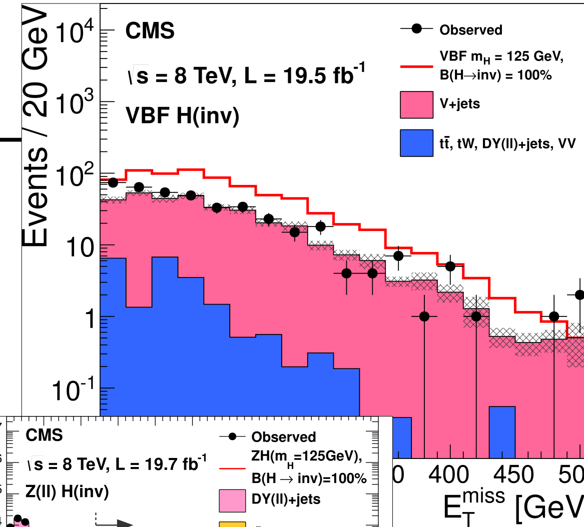
NP 10 (2014) 557-560

Searches for $H \to \text{inv.}$

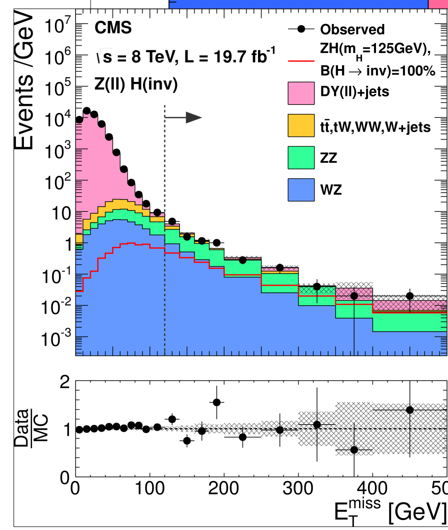
Channel	Observed (expected) upper limits on $\frac{\sigma}{\sigma_{SM}} \cdot \mathcal{BR}(H \to \text{inv.})$
VBF-tagged	0.57 (0.40)
VH-tagged	0.60 (0.69)
ggH-tagged	0.67 (0.71)
Combined	0.36 (0.30)

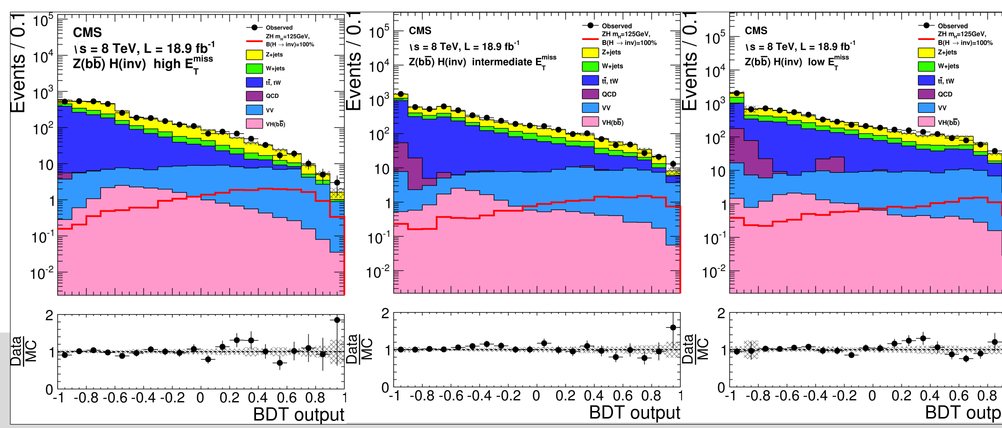
CMS-PAS-HIG-15-012



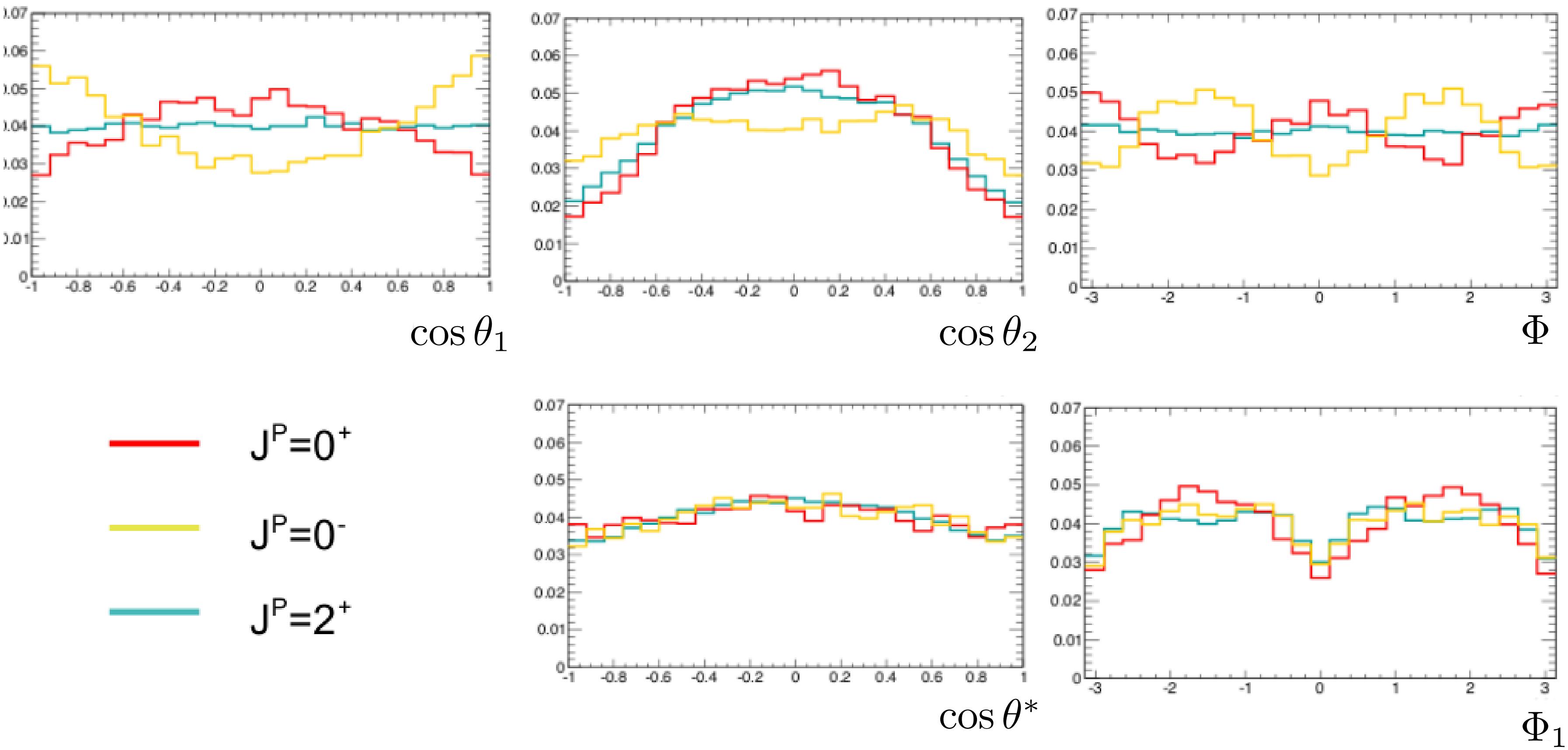


EPJC 74 (2014) 2980





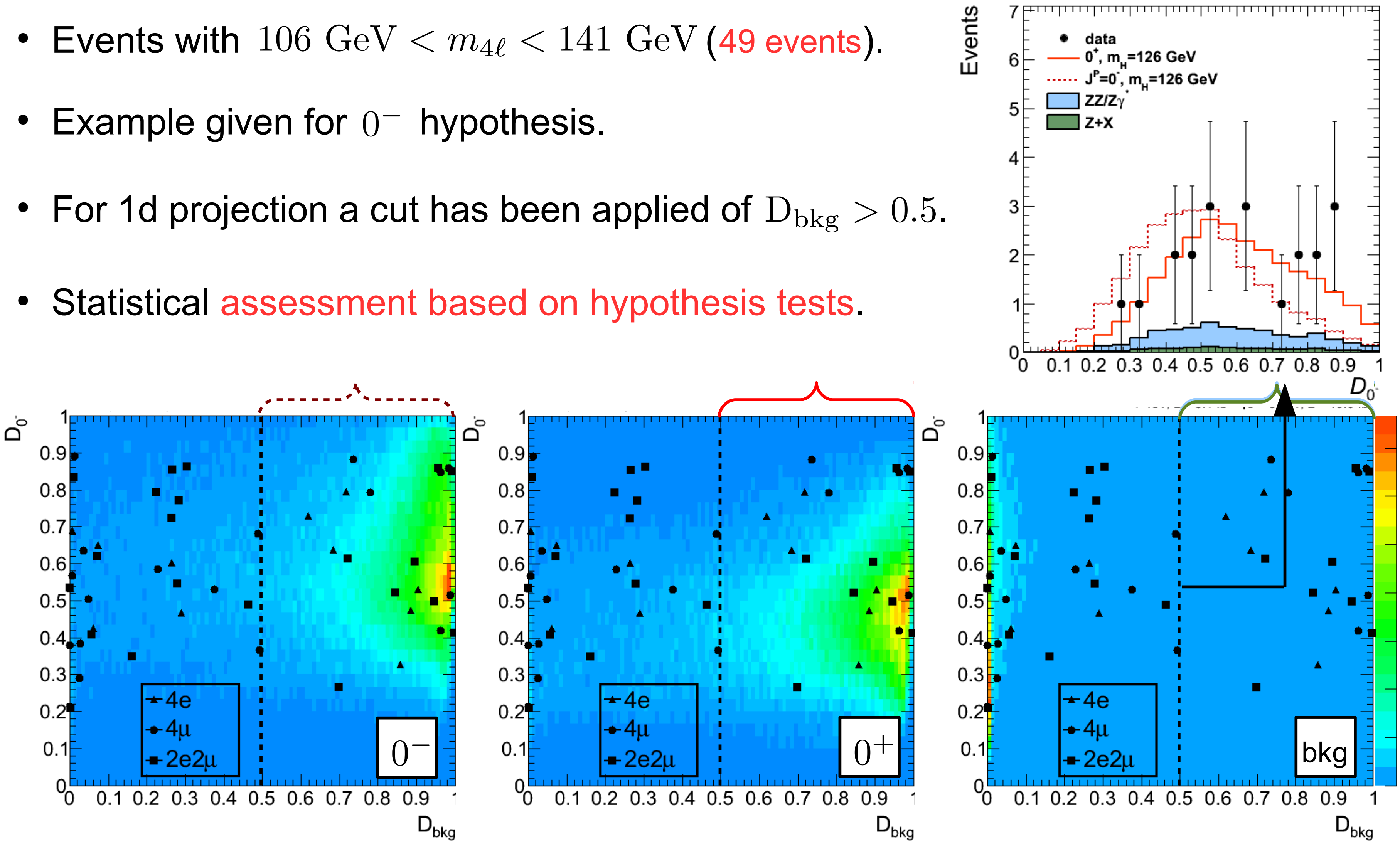
Discriminating Variables



- As obtained from MC simulation (http://www.pha.jhu.edu/spin/).
- Taking acceptance and resolution effects into account.

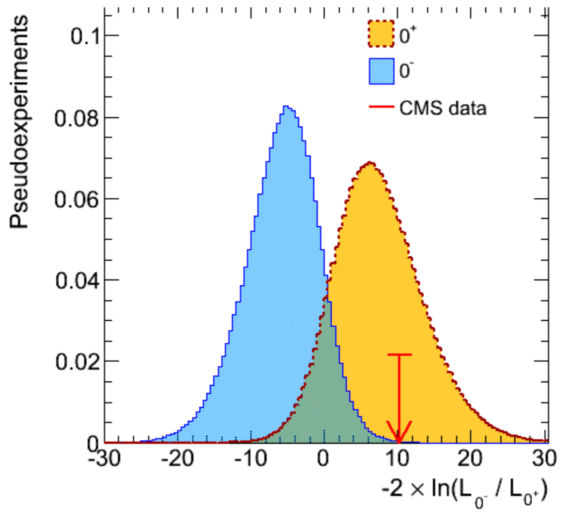
Combination into a Single Discriminating Variable

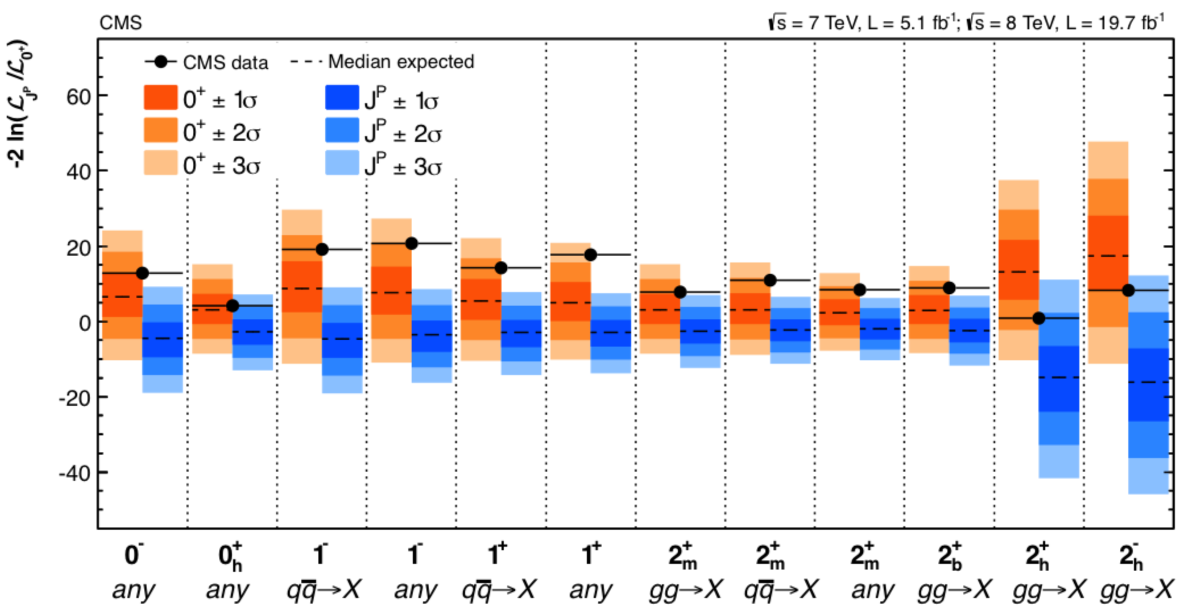
- Events with $106 \text{ GeV} < m_{4\ell} < 141 \text{ GeV}$ (49 events).
- Example given for 0^- hypothesis.
- For 1d projection a cut has been applied of $D_{bkg} > 0.5$.
- Statistical assessment based on hypothesis tests.



Combination into a Single Discriminating Variable

- Test statistic: $q = -2\ln\left(\frac{\mathcal{L}(0^+ + BG)}{\mathcal{L}(J^P + BG)}\right)$.
- Expectation for given hypothesis 0^+ or J^P obtained from toy experiments.
- SM hypothesis (0^+) tested against large number of alternative hypotheses. SM favored in each case.





CP admixtures

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- General phenomenology of non-*CP* conserving HVV couplings:

$$A(HVV) \propto \left[a_1^{VV} + \kappa_1^{VV}\frac{q_{V1}^2}{\Lambda^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* f_{\mu\nu} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{(1)} \tilde{f}^{*(2),\mu\nu}$$

(LO-amplitude formalism)

Applied to: $HWW,\ HZZ,\ HZ\gamma,\ H\gamma\gamma$.

PRD 92 (2015) 012004

SM CP-even

CP-even "higher dimension"

CP-odd admixture.

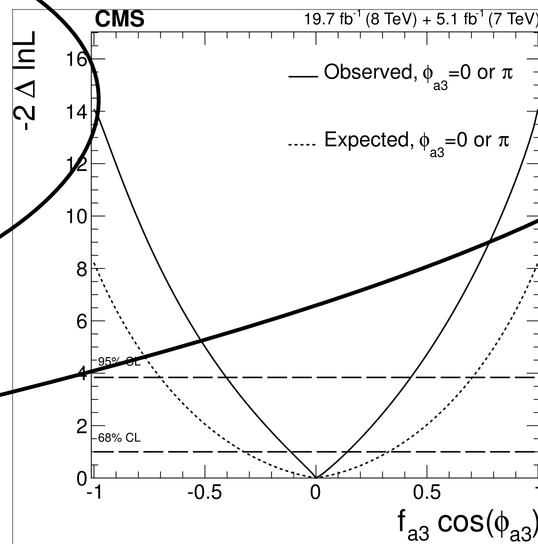
admixture of a_3 to overall amplitude

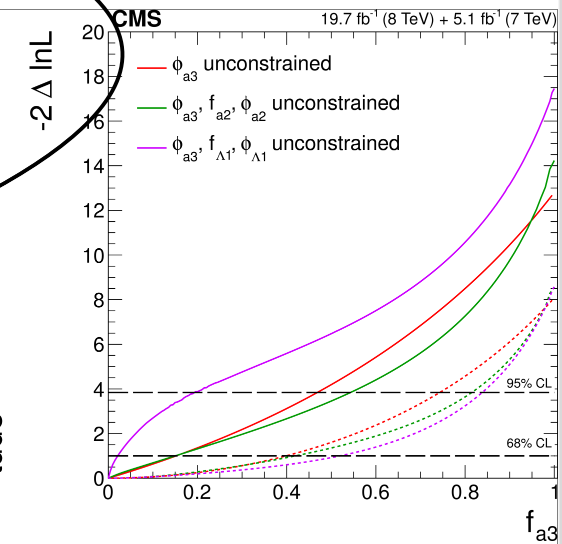
$$f^{(i),\mu\nu} = \epsilon_{Vi}^{\mu} q_{Vi}^{\nu} - \epsilon_{Vi}^{\nu} q_{Vi}^{\mu}$$

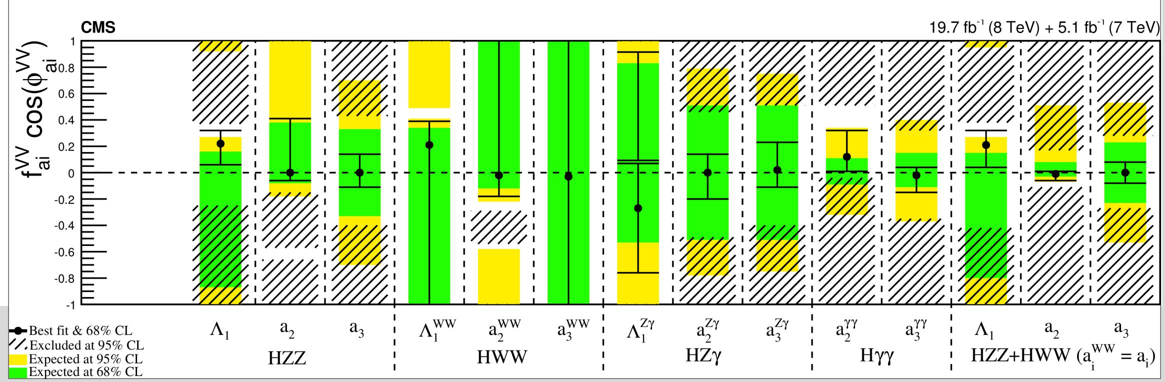
$$\tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} f^{(i),\rho\sigma}$$

m_{V1}^2 (vector boson mass)

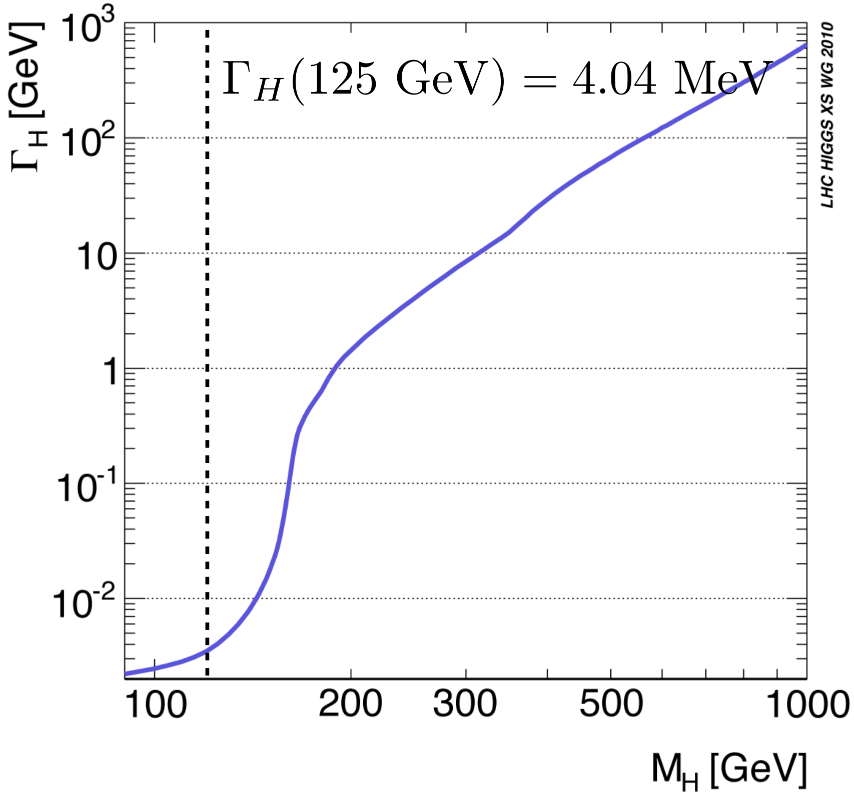
ϵ_{Vi} (polarization vector)



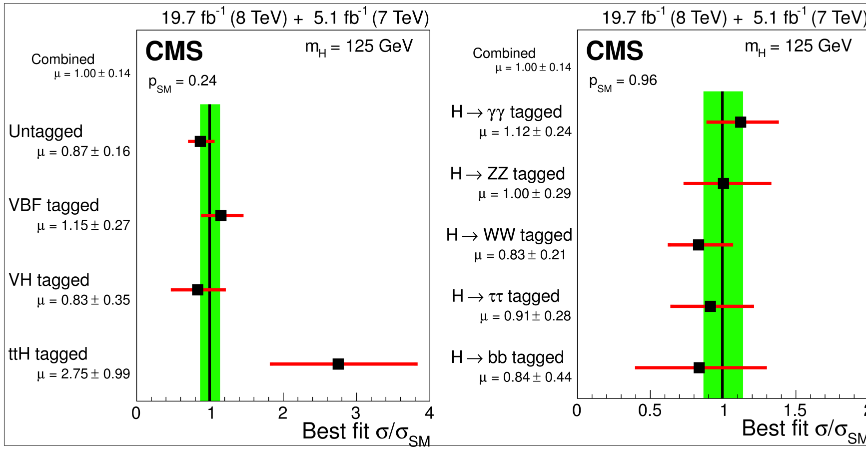




Higgs decay width (SM)



Inter-channel compatibility (rate)



EPJ C 75 (2015) 212

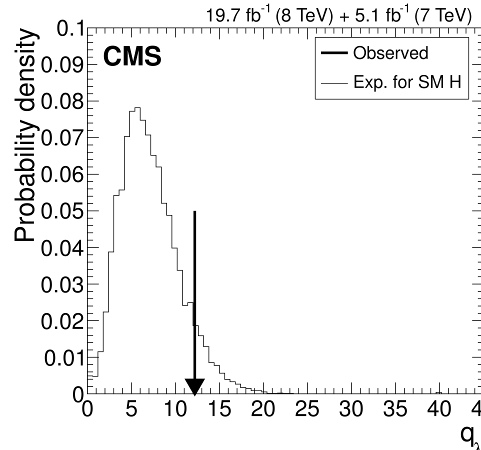
- Event categories : 227
- Nuisance parameters: $\mathcal{O}(2500)$
- 16 MB binary file of statistic model (~145 MB in human readable form).

$$\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.14 \qquad p\text{-value} = 84\%$$

Test proxy of single particle hypothesis (w/ 8 free parameters) against saturated model (w/ 20 free parameters).

All parameters constrained to be positive.

Signal model	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$
ggH	$\mu_{\gamma\gamma}$	μ_{ZZ}	μ_{WW}	$\mu_{\tau\tau}$	μ_{bb}
VBF	$\lambda_{VBF}\,\mu_{\gamma\gamma}$	$\lambda_{VBF}\,\mu_{ZZ}$	$\lambda_{VBF}\,\mu_{WW}$	$\lambda_{VBF}\,\mu_{\tau\tau}$	$\lambda_{VBF}\,\mu_{bb}$
VH	$\lambda_{VH}\,\mu_{\gamma\gamma}$	$\lambda_{VH}\,\mu_{ZZ}$	$\lambda_{VH}\,\mu_{WW}$	$\lambda_{VH}\,\mu_{\tau\tau}$	$\lambda_{VH}\,\mu_{bb}$
ttH	$\lambda_{ttH}\,\mu_{\gamma\gamma}$	$\lambda_{ttH}\,\mu_{ZZ}$	$\lambda_{ttH}\,\mu_{WW}$	$\lambda_{ttH}\,\mu_{\tau\tau}$	$\lambda_{ttH}\,\mu_{bb}$



p-value $= 8\% (1.4\sigma)$

† Events fulfilling the requirements of either selection are combined into one category.
‡ Values for analyses dedicated to the measurement of the mass that do not use the same categories and/or observables.
* Composition in the regions for which the ratio of signal and background $s/(s+b) > 0.05$.

μ_x^y ratios instead of μ_x values

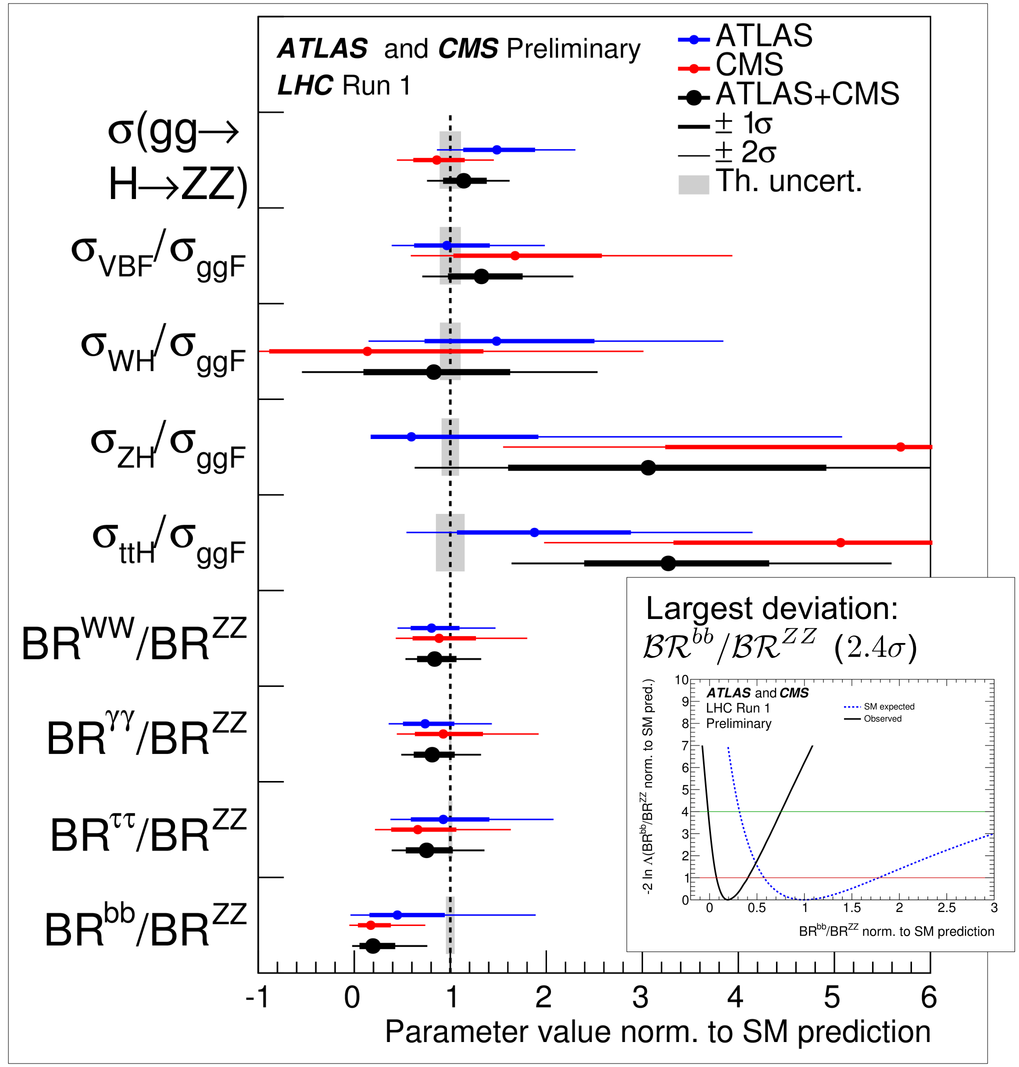
Advantage: no theory uncert's, no theory input.

- Nine parameter fit:
  - Choose one process as reference:
  - $\mu_{ggH}^{ZZ} = \sigma_{ggH} \mathcal{BR}^{ZZ}$.
  - Four cross section ratios: μ_{ggH}^{VBF}, μ_{ggH}^{HW}, μ_{ggH}^{ZW}, μ_{ggH}^{ttH}.
  - Four decay width ratios: $\mu_{ZZ}^{\gamma\gamma}$, μ_{ZZ}^{WW}, $\mu_{ZZ}^{\tau\tau}$, μ_{ZZ}^{bb}.
- Scale parameter for $i \to H \to f$:

$$\mu_i^f \cdot (\sigma_i \mathcal{BR}^f)_{SM} = \frac{\sigma_i \mathcal{BR}^f}{\sigma_{ggH} \mathcal{BR}^{ZZ}} \cdot \sigma_{ggH} \mathcal{BR}^{ZZ}$$

$$\mu_i^f = \frac{\mu_i}{\mu_{ggH}} \cdot \frac{\mu^f}{\mu^{ZZ}} \cdot \mu_{ggH} \mu^{ZZ}$$

μ_{ggH}^i μ_{ZZ}^f μ_{ggH}^{ZZ}



Driven by low $VHbb$ and overall high production rate estimate.

Coupling Estimates

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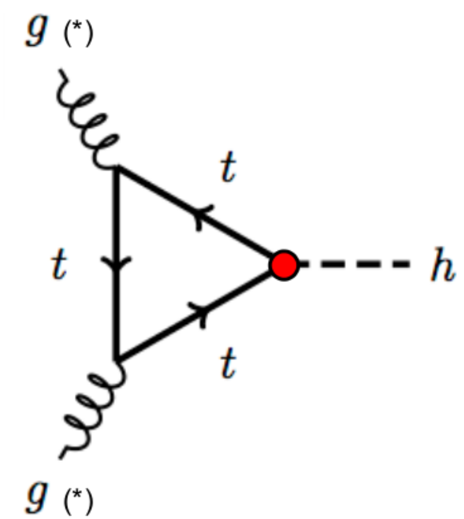
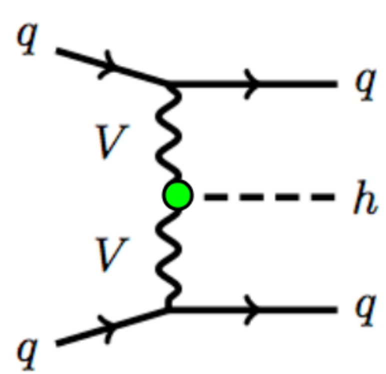
- Determine couplings from production mode and decay channel:

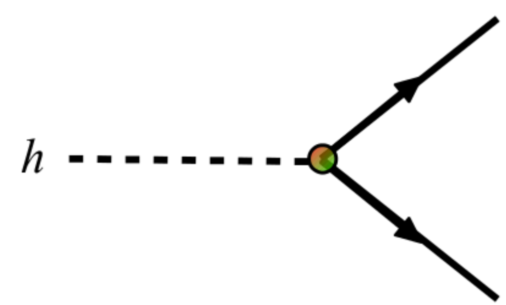
$gg \to H$ production:



$qq \to qqH$ production:



Decay to f or V:



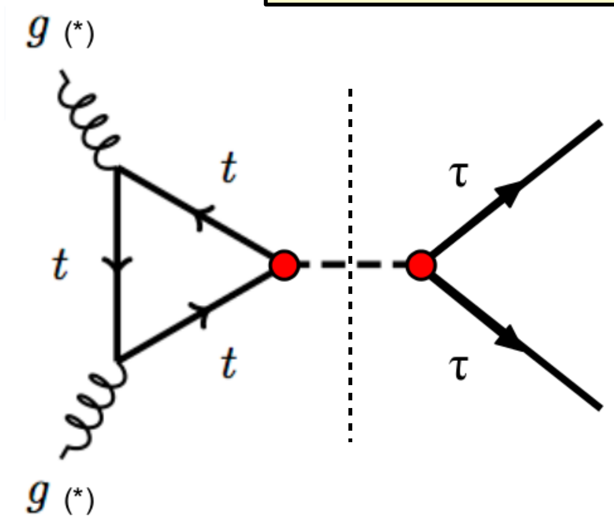
- f : $\kappa_{\mathrm{Hff}} = \frac{m_f}{\mathrm{v}}$
- V : $\kappa_{\mathrm{HVV}} = \frac{2m_V^2}{\mathrm{v}}$

- Coupling to gluon can be f or effective $^{(*)}$.
- Coupling to γ can be effective or a mixture of $f + V$.

- Direct measurement not possible since κ_i appear in nominator and denominator of $\mathrm{BR}_i = \frac{\Gamma_i \kappa_i}{\Gamma_h(\kappa_i)} = \frac{\Gamma_i \kappa_i}{\sum \Gamma_j \kappa_j}$

Narrow Width Approximation

- Assume $\Gamma_H \ll m_H$, which is well justified by $\Gamma_H = 4.04\ \mathrm{MeV}$ and $m_H = 125\ \mathrm{GeV}$.
- Propagator: $\frac{1}{(q^2 - m^2 + m^2\Gamma^2)} \rightarrow \frac{\pi}{m\Gamma}\delta(q^2 - m^2)$ for $\Gamma \rightarrow 0$.



- i.e. put propagating particle on shell.
- Calculate cross section as $\sigma \times \mathrm{BR}$.
- $\mathrm{BR}_X = \frac{\Gamma_X}{\Gamma_H}, \quad \Gamma_H = \sum_i \Gamma_i$.
- $\sigma \propto (\kappa_t \kappa_\tau)^2 \propto (\kappa_u \kappa_d)^2 \propto (\kappa_q \kappa_l)^2 \propto (\kappa_g \kappa_f)^2$.

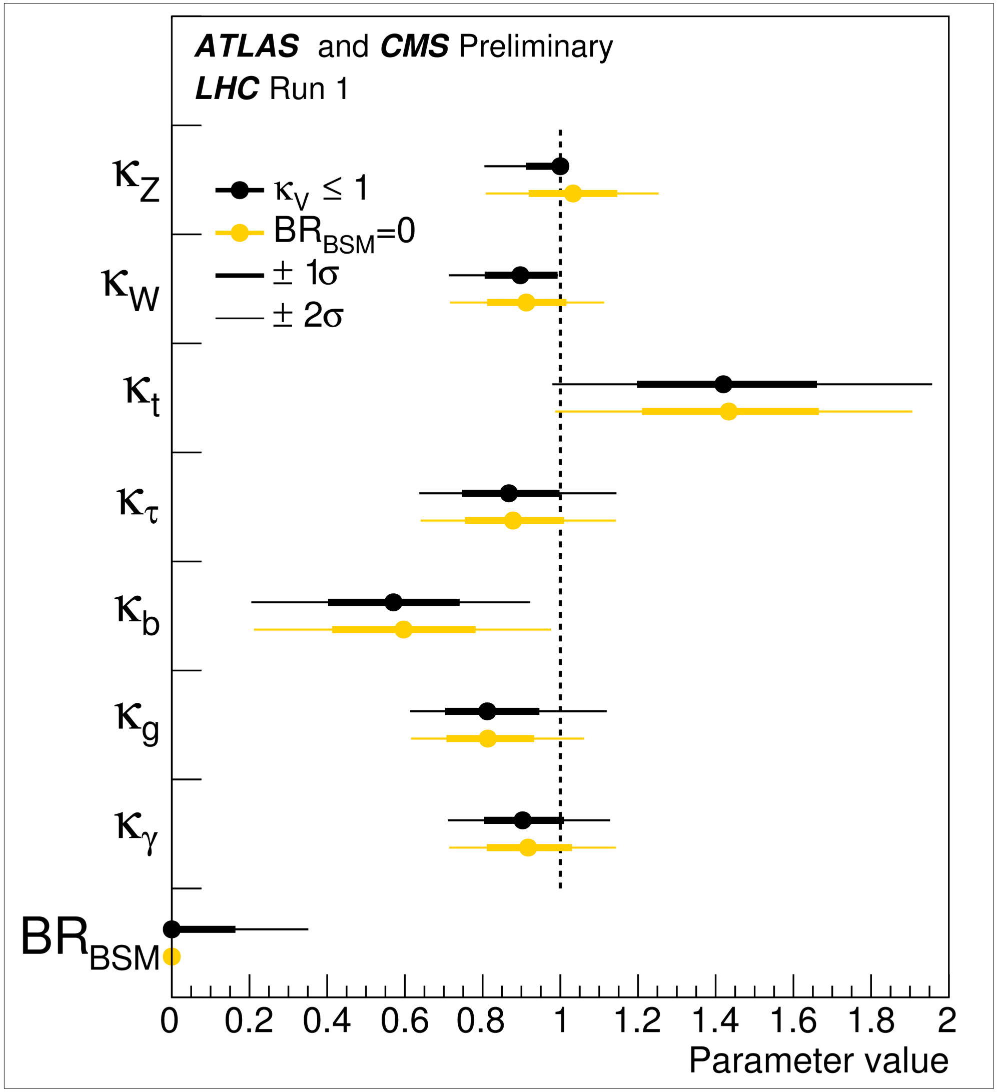
- For each production mode and decay channel collect κ_i and express Γ_H as sum of individual κ_i .

General fitting model

- Seven free parameters:
  - All accessible tree-level couplings.
  - κ_g and κ_γ as effective couplings.
  - Either set $\mathcal{BR}_{BSM} = 0$ (yellow) or apply $\kappa_V \leq 1$ (black) as constraint.
- Allowing for new physics:
  - $\mathcal{BR}_{BSM} = 0$: new physics at scale $Q^2 > (m_H/2)^2$.
  - $\kappa_V \leq 1$: fulfilled in many BSM models (e.g. MSSM), allows for new physics at lower scales.

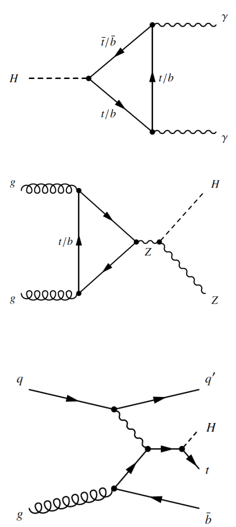
Limit (95% CL):
$\mathcal{BR}_{BSM} \leq 0.34\%$

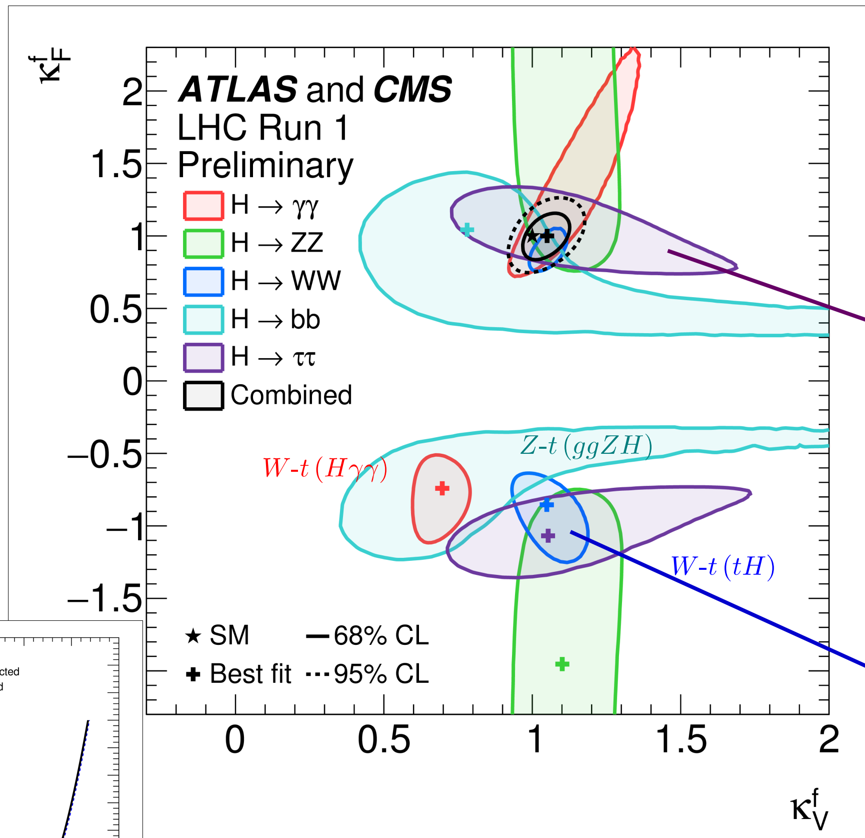
(cf slide 9)

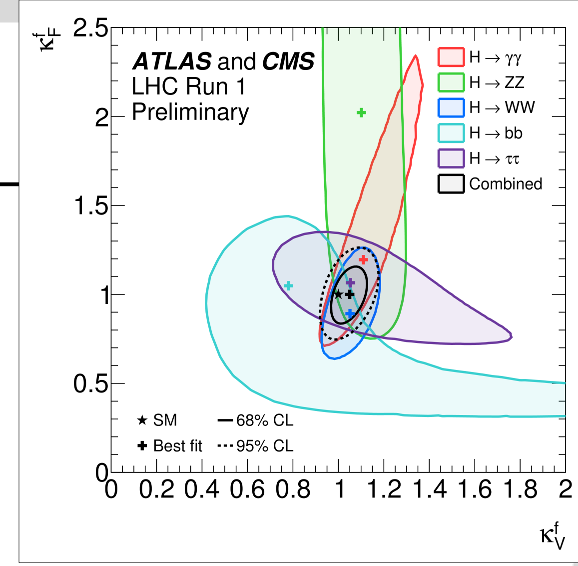


κ_V-κ_f model

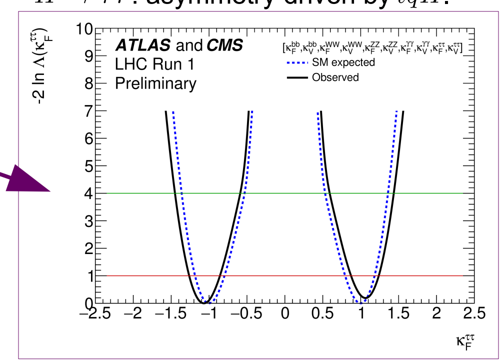
- Resolve loops according to SM.
- Combine tree-level couplings into κ_V and κ_f.



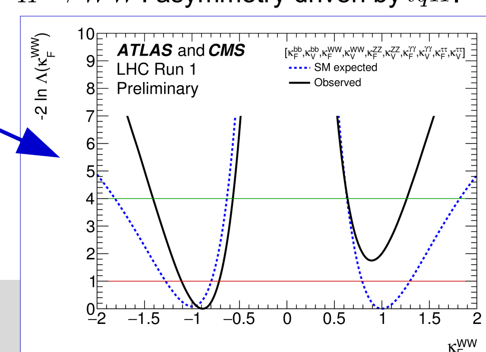


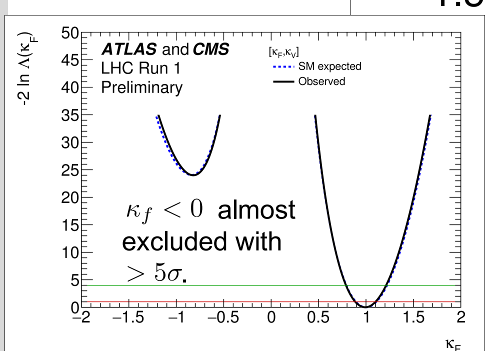


$H \to \tau\tau$: asymmetry driven by tqH.



$H \to WW$: asymmetry driven by tqH.





High mass Higgs boson search in WW and ZZ

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- Search in mass range of $m_H = 145\ldots1000$ GeV.
- Combination of several channels in WW and ZZ (55 channels/categories).

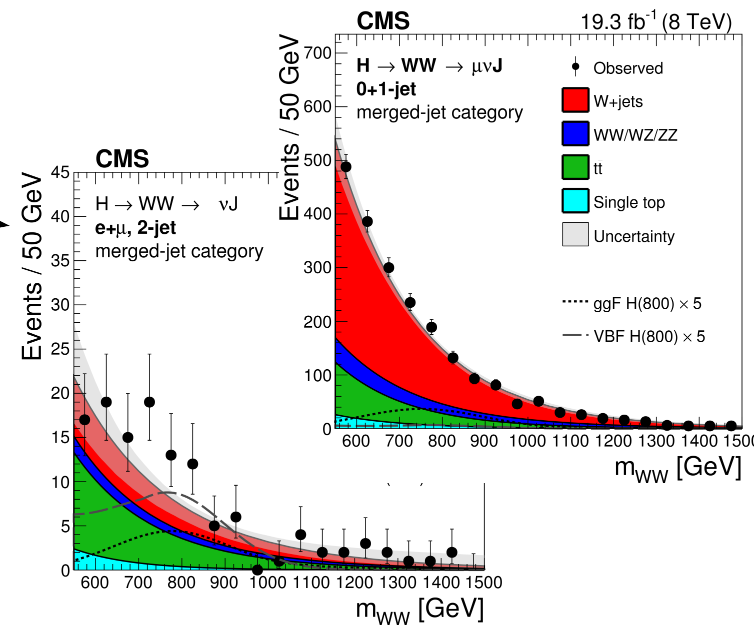
H decay mode	H production	Exclusive final states	No. of channels	m_H range [GeV]	m_H resolution
$WW \to \ell\nu\ell\nu$	untagged	$((ee, \mu\mu), e\mu) + (0$ or 1 jets$)$	4	145–1000 [a b]	20%
	VBF tag	$((ee, \mu\mu), e\mu) + (jj)_{VBF}$	2	145–1000 [a b]	20%
$WW \to \ell\nu qq$	untagged	$(e\nu, \mu\nu) + (jj)_W$	2	180–600	5–15%
	untagged	$(e\nu, \mu\nu) + (J)_W + (0{+}1$-jets$)$	2	600–1000 [b]	5–15%
	VBF tag	$(e\nu, \mu\nu) + (J)_W + (jj)_{VBF}$	1	600–1000 [b]	5–15%
$ZZ \to 2\ell2\ell'$	untagged	$4e, 4\mu, 2e2\mu$	3	145–1000	1–2%
	VBF tag	$(4e, 4\mu, 2e2\mu) + (jj)_{VBF}$	3	145–1000	1–2%
	untagged	$(ee, \mu\mu) + (\tau_h\tau_h, \tau_e\tau_h, \tau_\mu\tau_h, \tau_e\tau_\mu)$	8	200–1000	10–15%
$ZZ \to 2\ell2\nu$	untagged	$(ee, \mu\mu) + (0$ or ≥ 1 jets$)$	4	200–1000	7%
	VBF tag	$(ee, \mu\mu) + (jj)_{VBF}$	2	200–1000	7%
$ZZ \to 2\ell2q$	untagged	$(ee, \mu\mu) + (jj)_Z^{0,1,2\,b\ tags}$	6	230–1000 [c]	3%
	untagged	$(ee, \mu\mu) + (J)_Z^{0,1,2\,b\ tags}$	6	230–1000 [c]	3%
	VBF tag	$(ee, \mu\mu) + (jj)_Z^{0,1,2\,b\ tags} + (jj)_{VBF}$	6	230–1000 [c]	3%
	VBF tag	$(ee, \mu\mu) + (J)_Z^{0,1,2\,b\ tags} + (jj)_{VBF}$	6	230–1000 [c]	3%

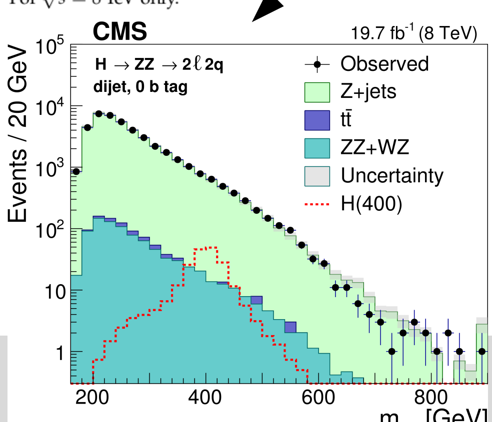
[a] EW singlet model interpretation starts at 200 GeV to avoid cont-

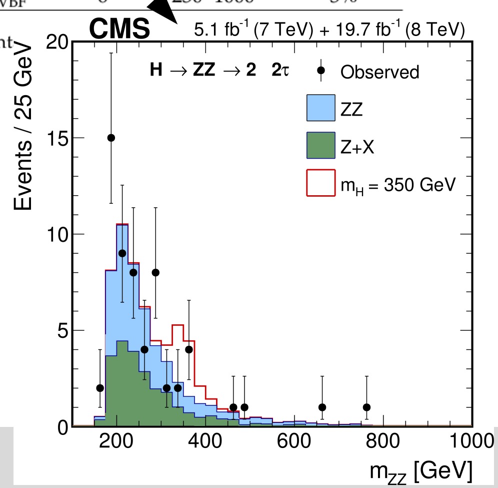
[b] 600-1000 GeV for $\sqrt{s} = 8$ TeV only.

[c] For $\sqrt{s} = 8$ TeV only.

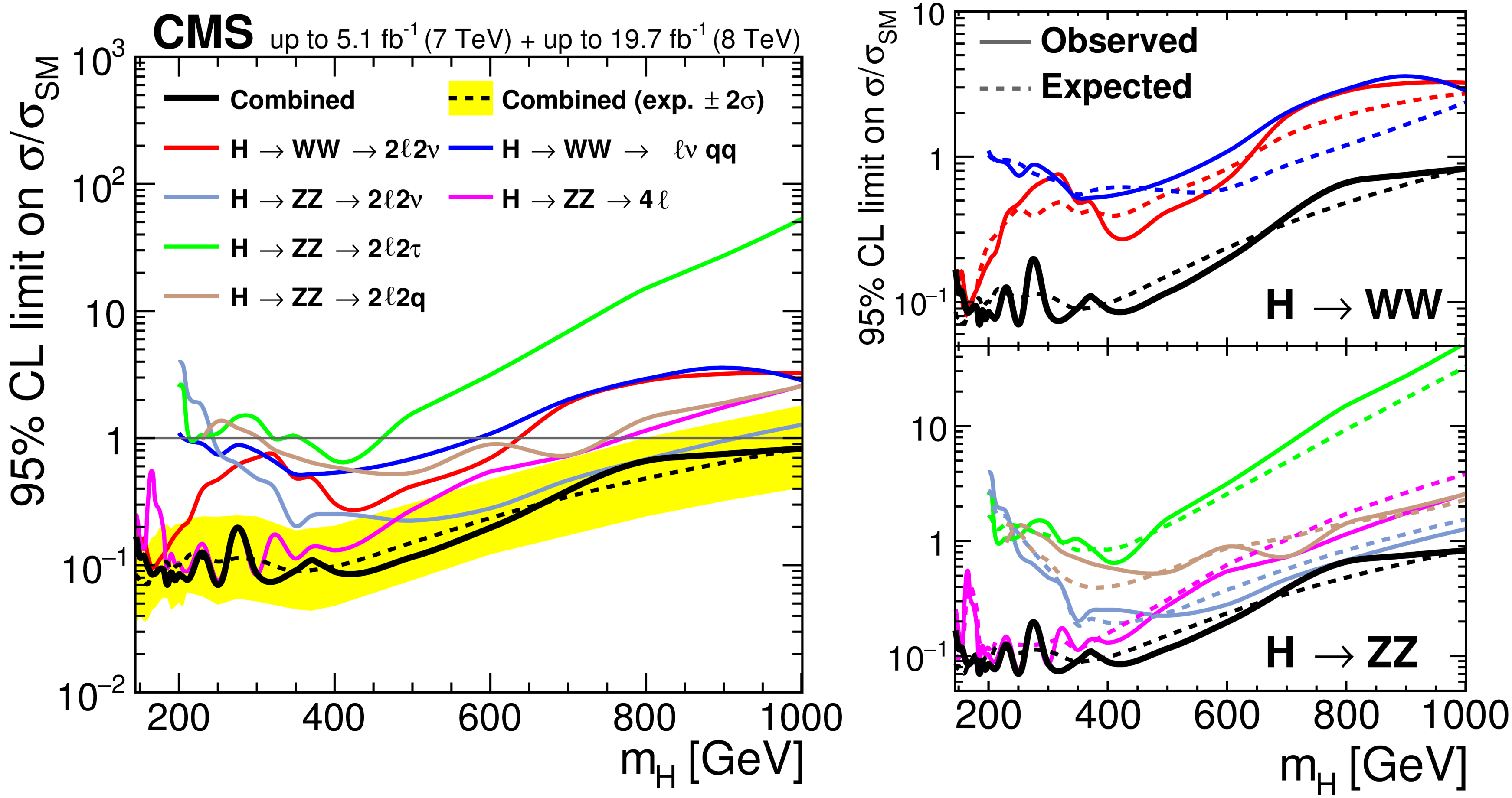
Merged jet event categories in WW:







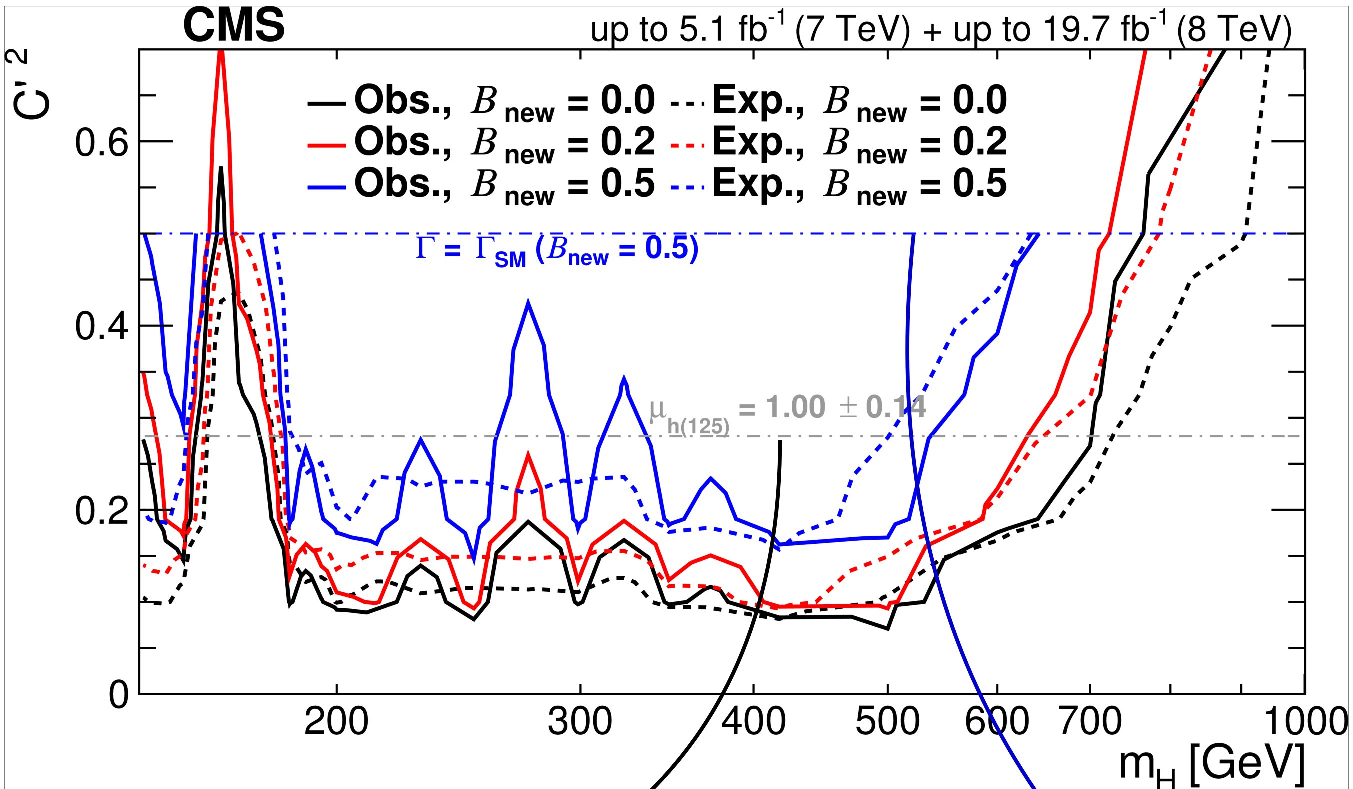
Additional SM-like Higgs boson?



- Additional Higgs boson with same production cross section and BR as expected for the SM (for given mass value).

EWK singlet admixtures?

Additional heavy Higgs (H) that mixes with $h(125)$.



Accepted by JHEP

- Unitarity constraint:

  C : coupling to h

  C': coupling to H

  $C'^2 + C^2 = 1$

  $\rightarrow$ couplings of h reduced by coupling to H.

- Allow additional $\mathcal{BR}$ for non-SM H decays:

  $\mu' = C'^2(1 - \mathcal{BR}_{new})$

  $\Gamma' = \frac{\Gamma_{SM}}{(1-\mathcal{BR}_{new})}$

Unitarity bound for:

$\mu_{h(125)} = 1 \pm 0.14$

$-2\sigma \sim C'^2\big|_{B_{new}=0} \leq 0.28$

Boundary for main assumption of analysis:

$\Gamma' \leq \Gamma_{SM}$ (based on CMS limit on $\mathcal{BR}_{BSM} \lesssim 0.5 (95\% CL)$ from couplings)

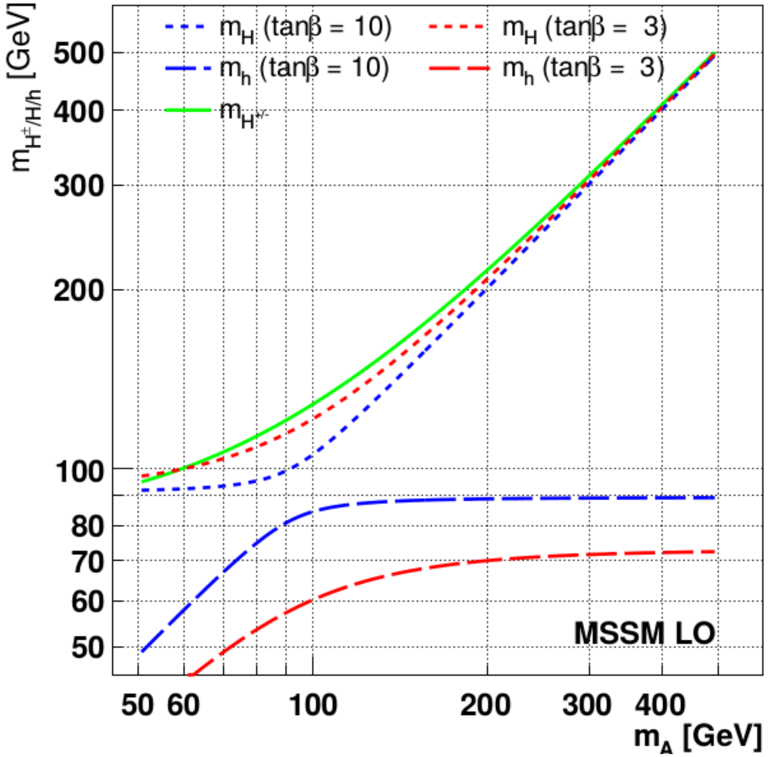
Higgs Bosons in the MSSM

- The MSSM, like any other Two Higgs Doublet Model (THDM) predicts five Higgs bosons:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} , \quad Y_{H_u} = +1 , \quad \mathrm{v}_u : \ \mathrm{VEV}_u$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} , \quad Y_{H_d} = -1 , \quad \mathrm{v}_d : \ \mathrm{VEV}_d$$

$$N_{\mathrm{ndof}} = 8 - \underbrace{3}_{W,\ Z} = \underbrace{5}_{H^\pm,\ H,\ h,\ A}$$



- Strict mass requirements at tree level:

two free parameters: m_A , $\tan\beta = \mathrm{v}_u/\mathrm{v}_d$

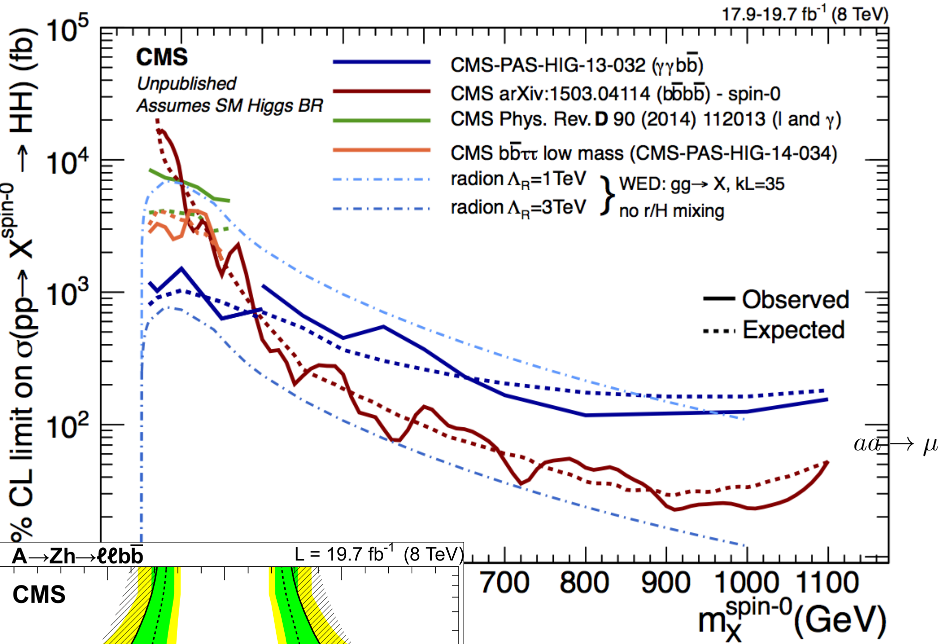
$$m^2_{H^\pm} = m^2_A + m^2_W$$

$$m^2_{H,\,h} = \frac{1}{2}\left(m^2_A + m^2_Z \pm \sqrt{\left(m^2_A + m^2_Z\right)^2 - 4m^2_A m^2_Z \cos^2 2\beta}\right)$$

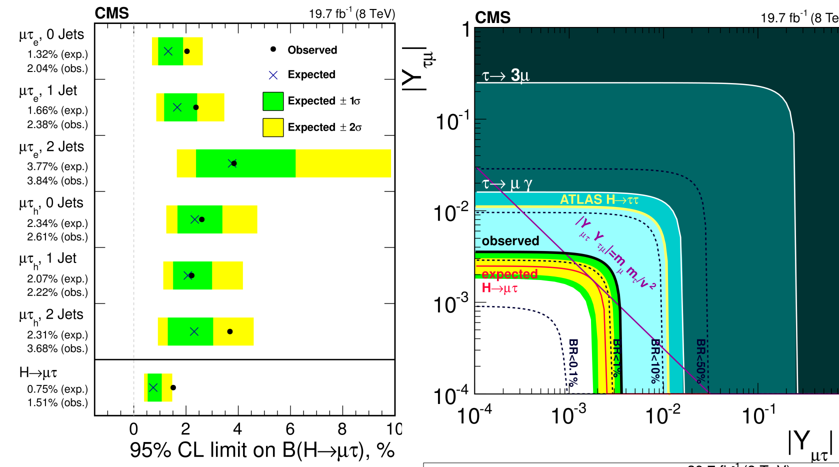
$$\tan\alpha = \frac{-(m^2_A + m^2_Z)\sin 2\beta}{(m^2_Z - m^2_A)\cos 2\beta + \sqrt{\left(m^2_A + m^2_Z\right)^2 - 4m^2_A m^2_Z \cos^2 2\beta}}$$

More searches!!!

Generic $X \to HH$ searches:



Lepton flavor violation in the Higgs sector



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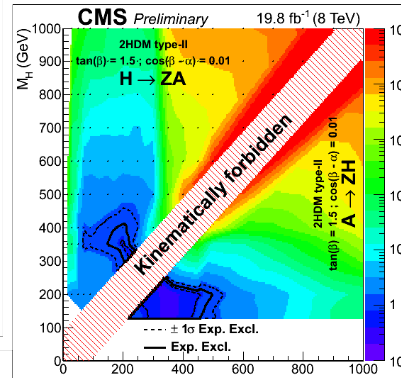
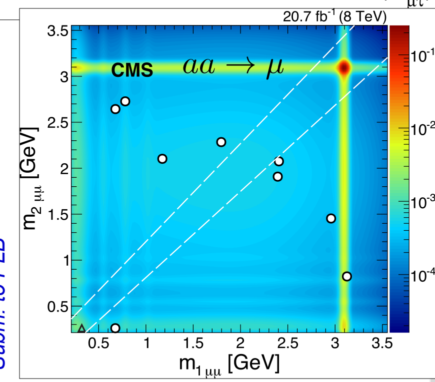
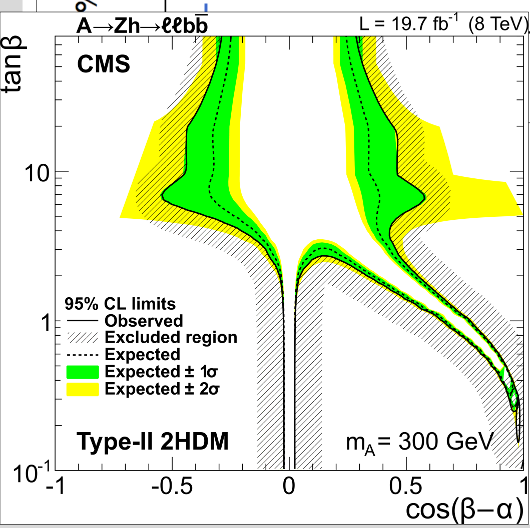


CMS-PAS-HIG-15-001

Subm. to PLB





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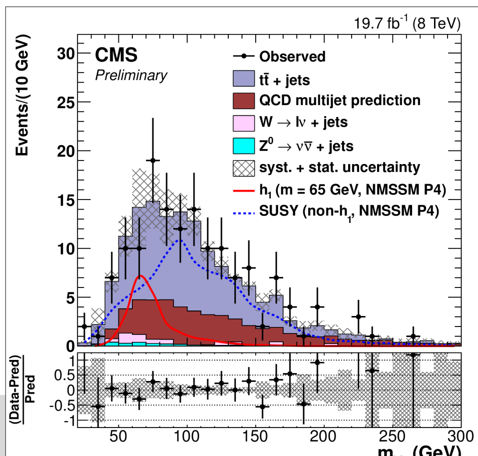

CMS-PAS-HIG-14-030