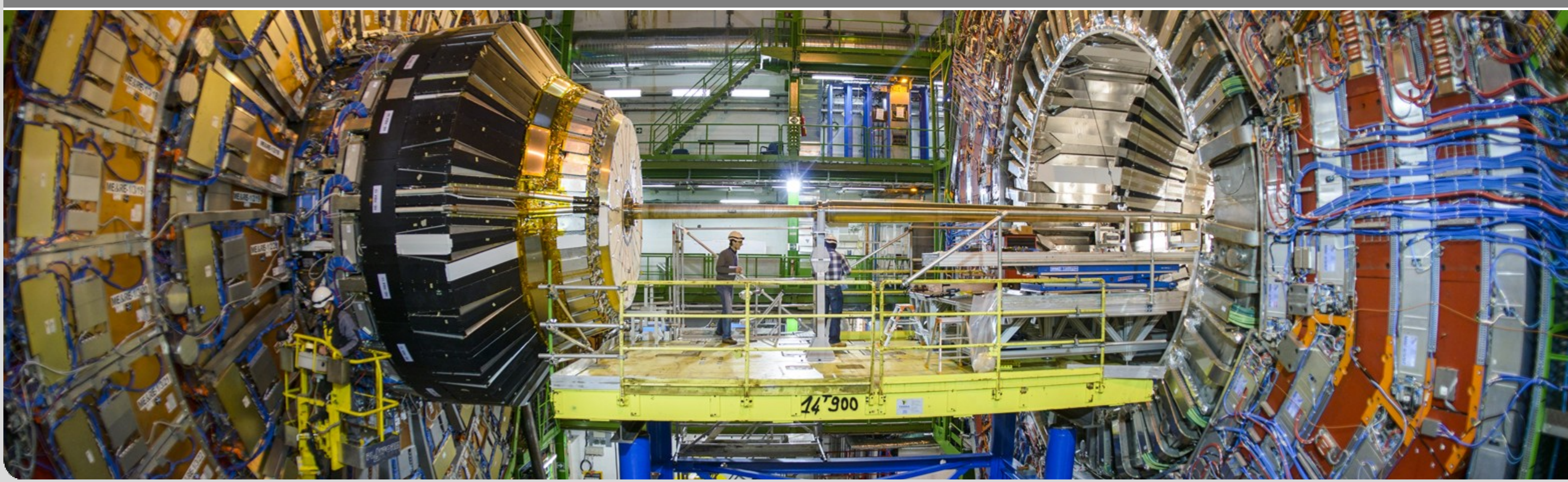
Karlsruhe Institute of Technology

Higgs Physics

Roger Wolf

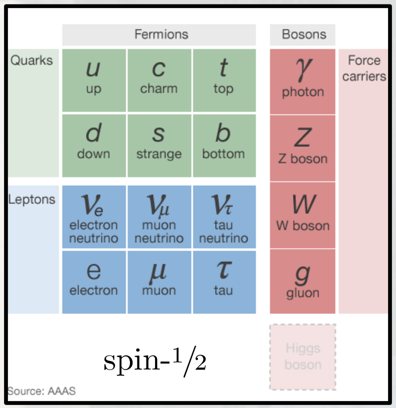
21. September 2016

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



The case of matter

- 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:



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

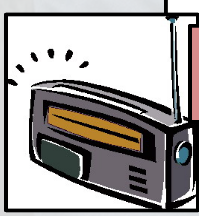
1d rotations

2d rotations

3d rotations

in a $\mathbb{C}(N)$ hyperspace (w/ $N \geq 5$)

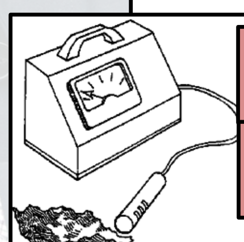
$\psi \; e^{i\vartheta'}$



γ photon

Electromagnetism

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

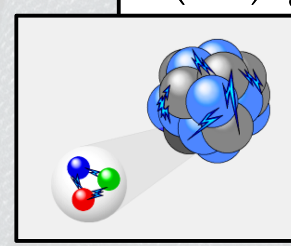


$W^{\pm}$ W boson

Z Z boson

Weak force

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

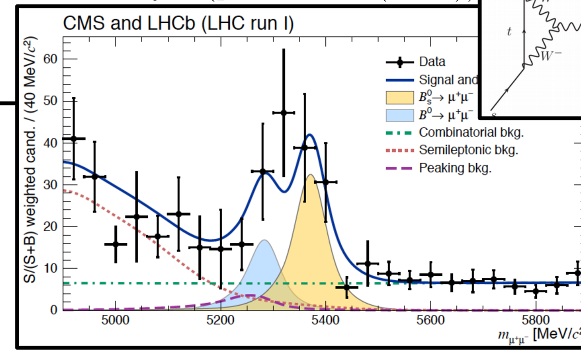


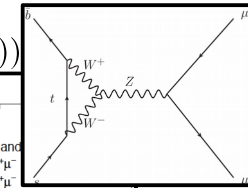
g gluon

Strong force

The standard model of particle physics (SM)

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

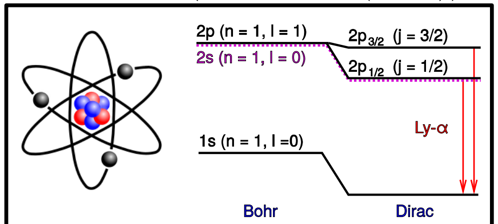




Nature (2015) 1447

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

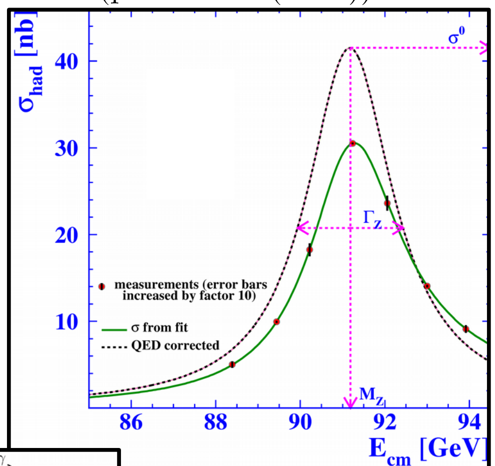
Lamb shift: (precision $\mathcal{O}(10^{-7})$)



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

Precision observables:

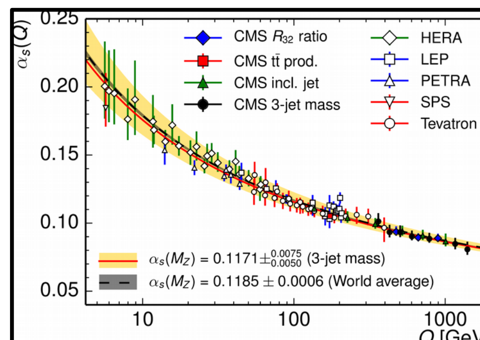
LEP: (precision $\mathcal{O}(10^{-5})$)



Phys. Rept 427 (2006)

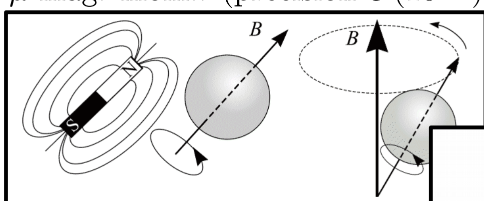
Striking features & global characteristics:

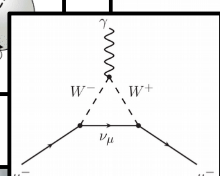
Asymptotic freedom:



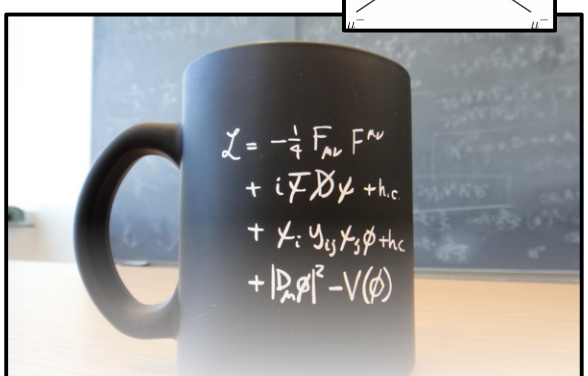
EPJC 75 (2015) 186

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



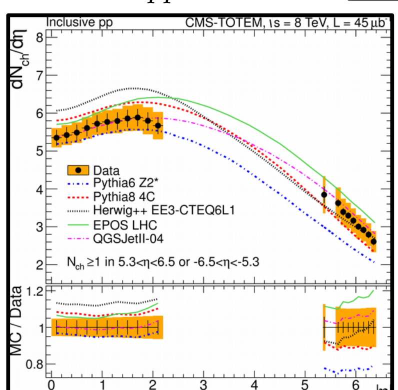


$$\frac{(g-2)}{2} = 0.00115965218073(28)$$



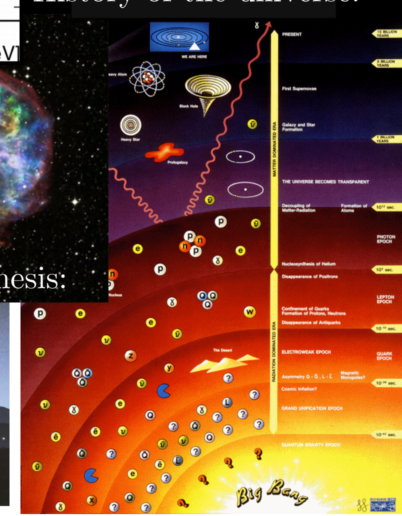
Lagrangian Density of (baryonic) Matter

Inclusive pp collisions:



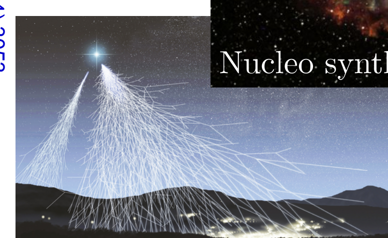
EPJC 74 (2014) 3053

History of the universe:



Nucleo synthesis:

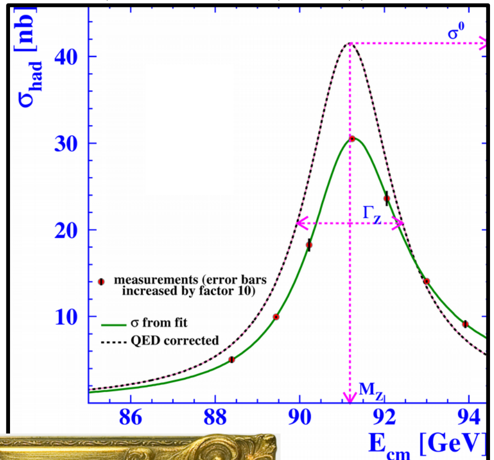
Air sohwer composition:



Precision observables:

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

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



Phys. Rept 427 (2006)

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

EPJC 75 (2015) 186

pp collisions:

EPJC 74 (2014) 3053

History of the universe:

Nucleo synthesis:

Air sohwer composition:

Problem-1:

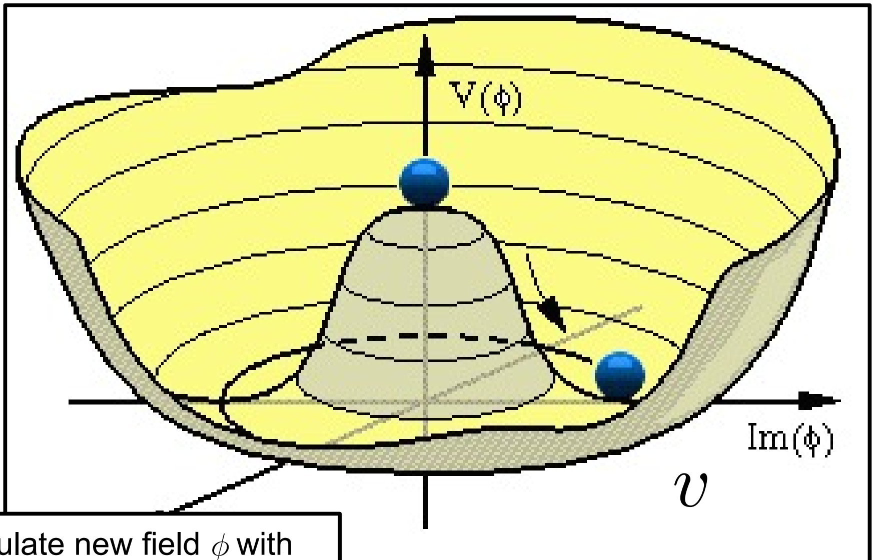
Symmetries strictly forbid **force mediators** to have mass $\neq 0$ (e.g. $M_Z^2 Z_\mu Z^{\mu *}$).

Problem-2:

Weak force distinguishes between left- and right-handed matter → breaks $SU(2)_L$ for **ALL** weakly interacting particles with mass $\neq 0$.

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?!?

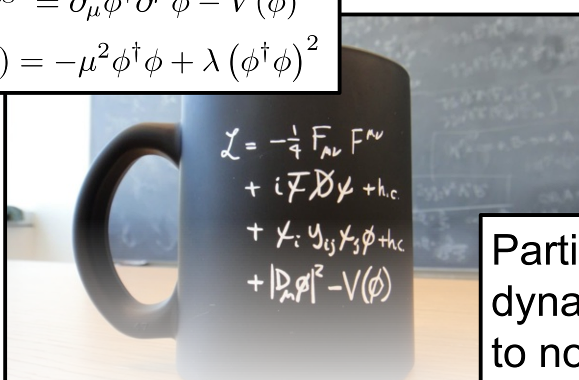
Spontaneous symmetry breaking:



Postulate new field ϕ with symmetry breaking vacuum:

$$\mathcal{L}^{\text{Higgs}} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$



Lagrangian Density of (baryonic)

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

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

- Symmetry inherent to the system but not to its energy ground state (→ quantum vacuum).
- Excitation of vacuum ground state leads to existence of a new particle, characterized by very peculiar coupling structure, needed to preserve the symmetry of the system:

$$f_{H\to ff} = i\frac{m_f}{v} \quad \text{(Fermions)}$$

$$f_{H\to VV} = i\frac{2m_V^2}{v} \quad \text{(Heavy Bosons trilinear)}$$

$$f_{HH\to VV} = i\frac{2m_V^2}{v^2} \quad \text{(Heavy Bosons quartic)}$$

$$f_{H\to HH} = i\frac{3m_H^2}{v} \quad \text{(H Boson trilinear)}$$

$$f_{HH\to HH} = i\frac{3m_H^2}{v^2} \quad \text{(H Boson quartic)}$$

Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

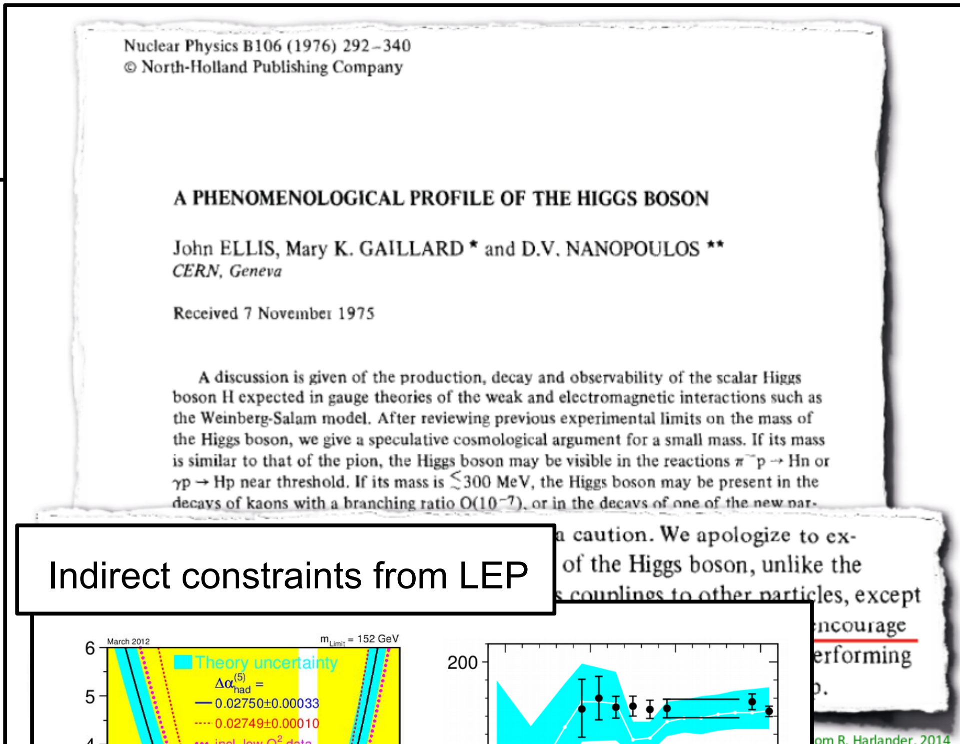
Received 7 November 1975

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.



Nuclear Physics B106 (1976) 292–340
© North-Holland Publishing Company

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

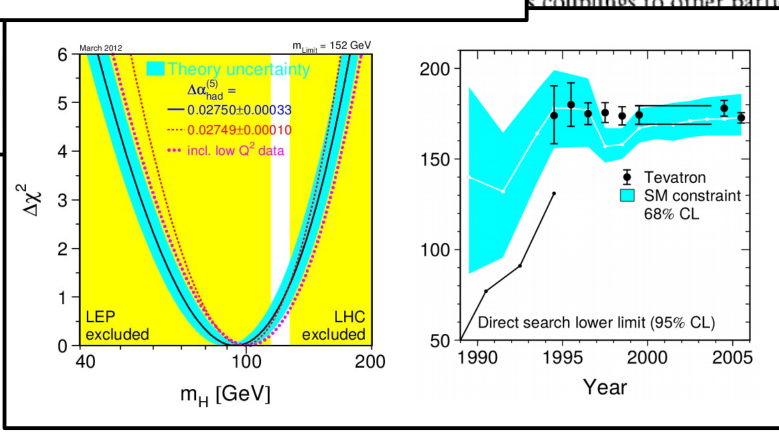
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

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-

a caution. We apologize to ex-
of the Higgs boson, unlike the
s couplings to other particles, except
ncourage
erforming
o.

Indirect constraints from LEP



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

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*.

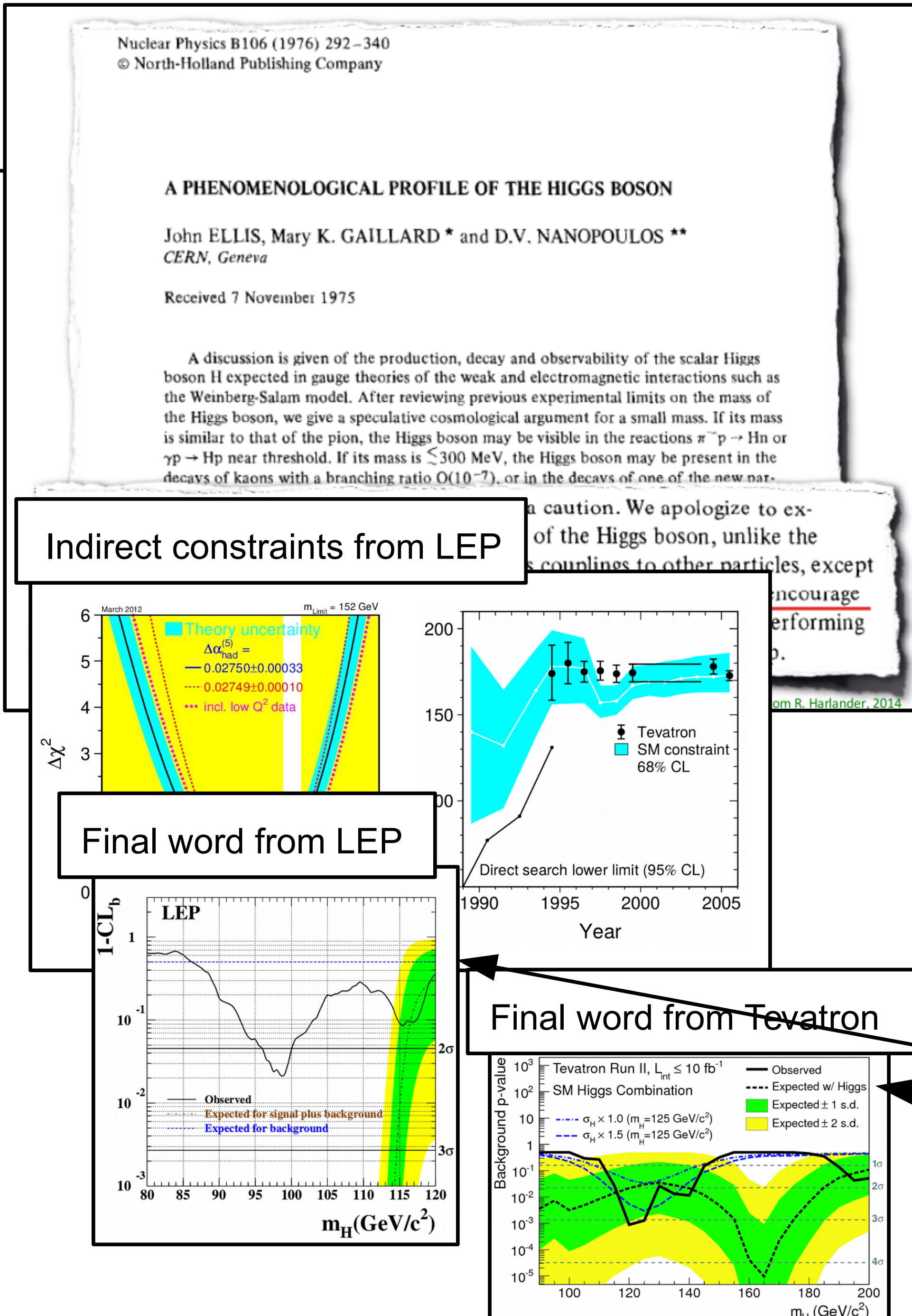
1983: Discovery of *W* and *Z*.

1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

2013: Nobel prize to Peter Higgs and Francois Englert.



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*.

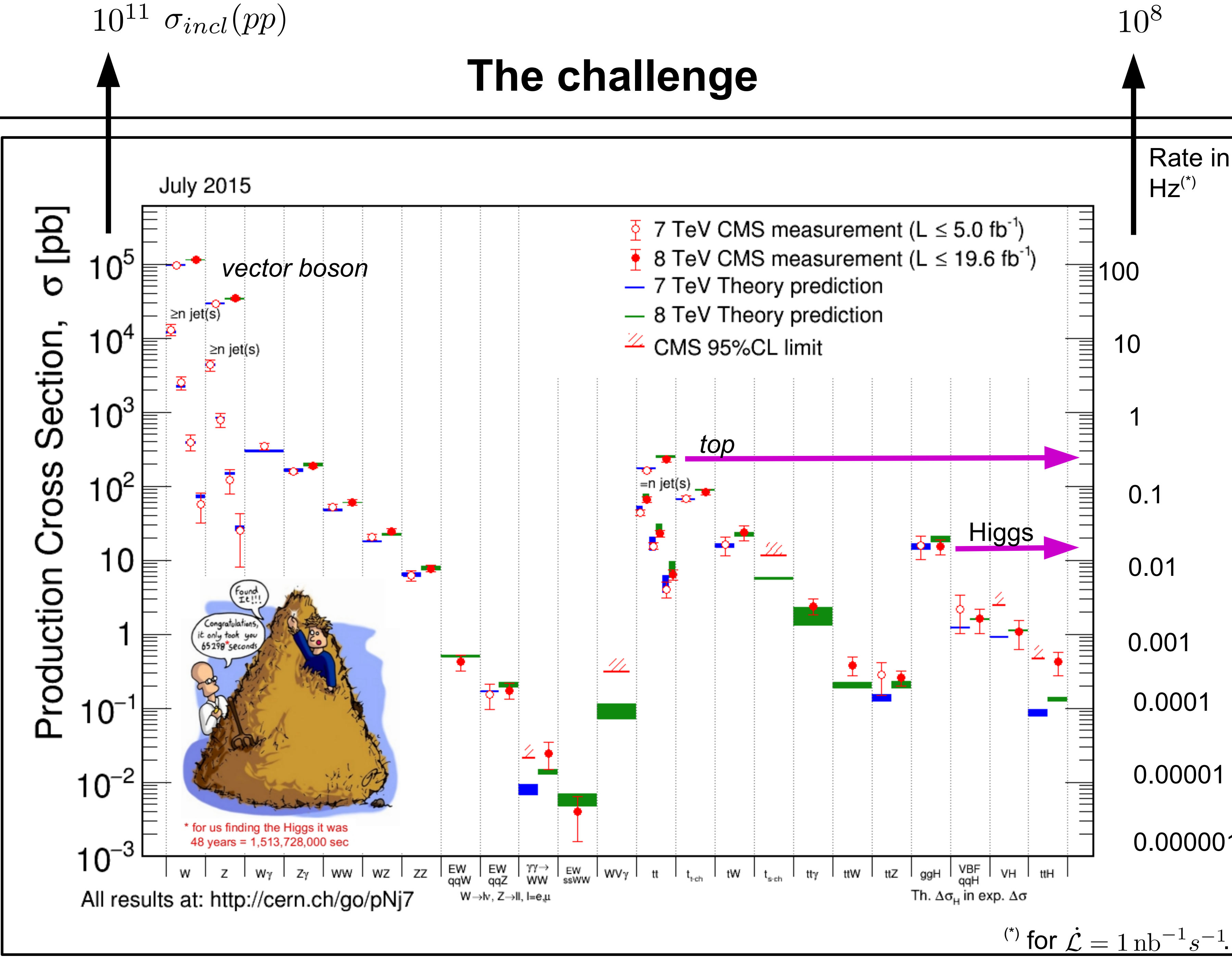
1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

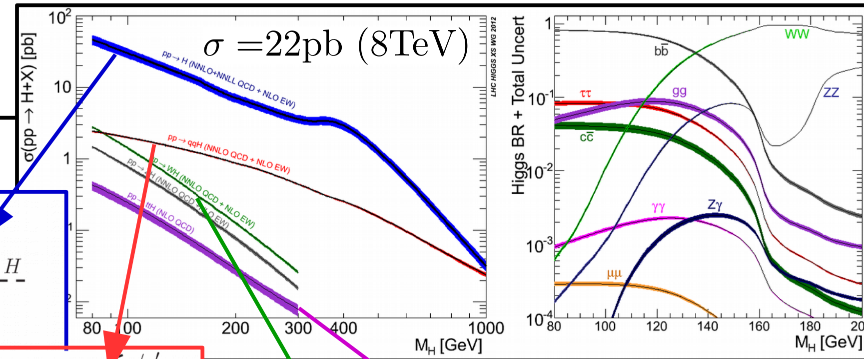
2013: Nobel prize to Peter Higgs and Francois Englert.

The challenge

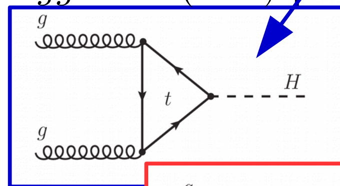


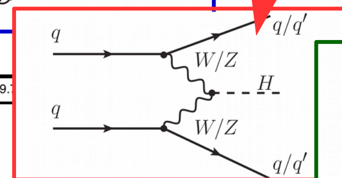
The discovery…

Production: Decay:

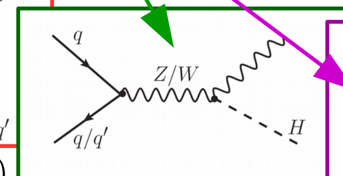


$gg \to H$ (87%)

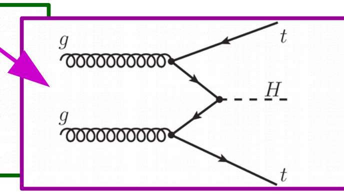




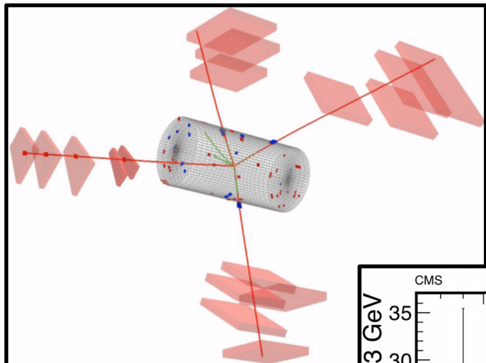
$qq \to H$ (7%)



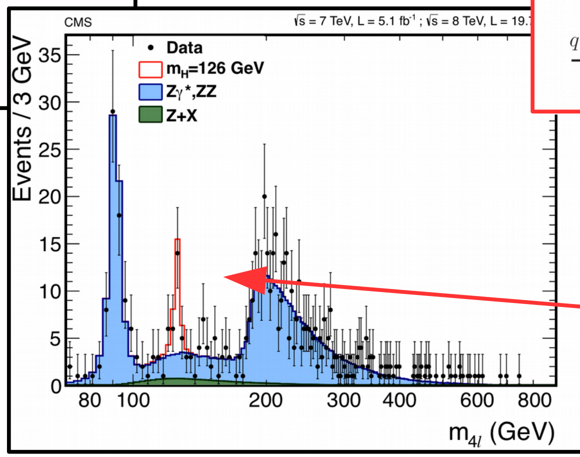
VH (5%)

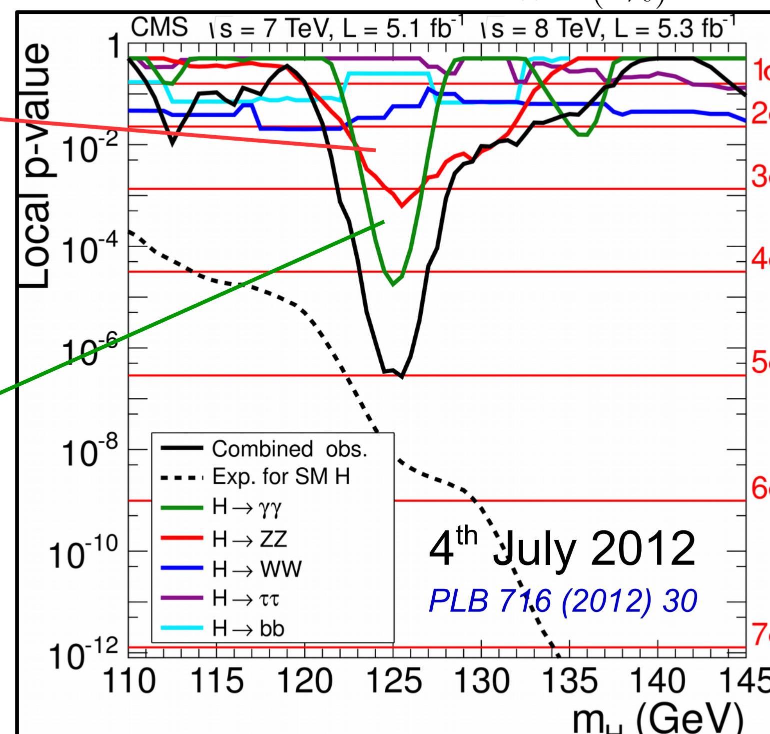


$t\bar{t}H$ (1%)

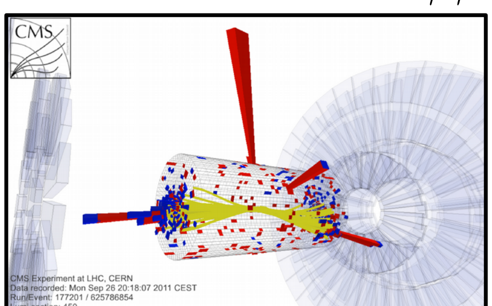


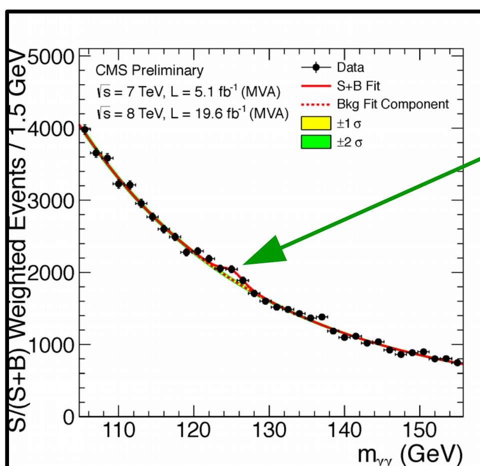
$H \to ZZ \to 4\ell$





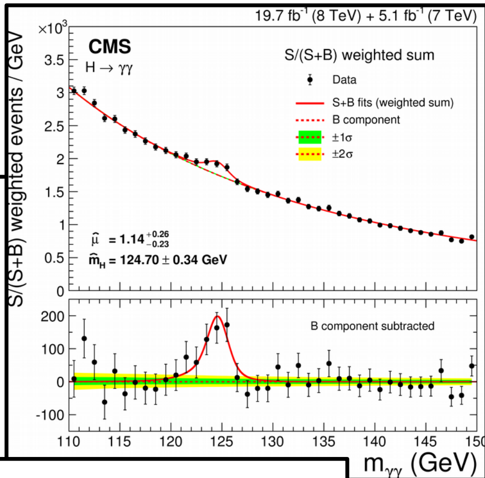
$H \to \gamma\gamma$





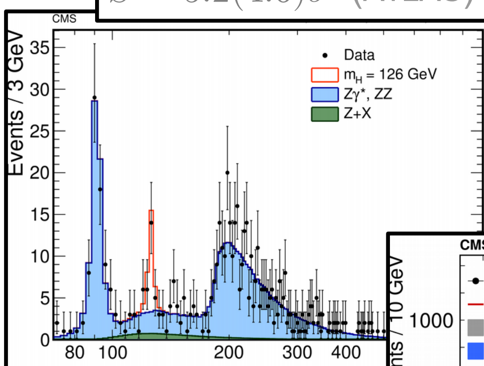
… and beyond

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



EPJ C 74 (2014) 3076

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



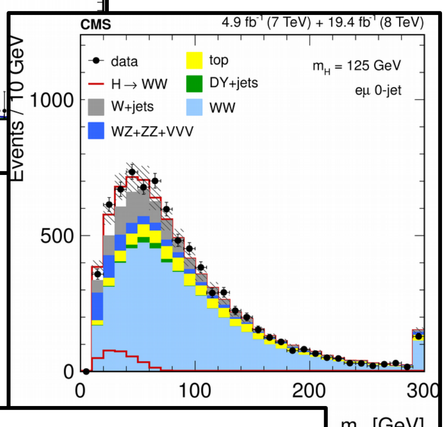
PRD 89 (2014) 092007

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

"untagged"

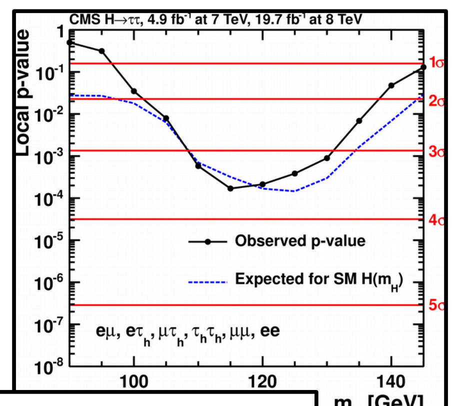
Decay / Prod	$gg \to H$ 87%	$qq \to H$ 7%	VH 5%	$t\bar{t}H$ 1%
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to ZZ$	✓	✓	✓	✓
$H \to WW$	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to b\bar{b}$		✓	✓	✓
$H \to \mu\mu$	✓	✓		

Part of discovery After LHC run-1 Not covered



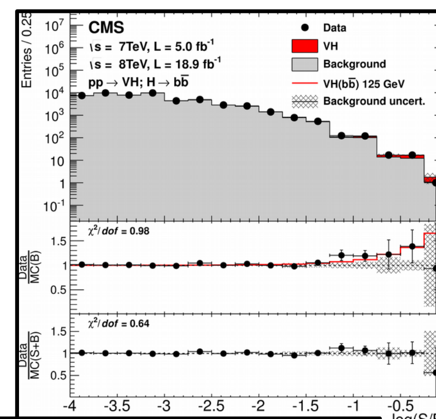
JHEP 01 (2014) 096

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)

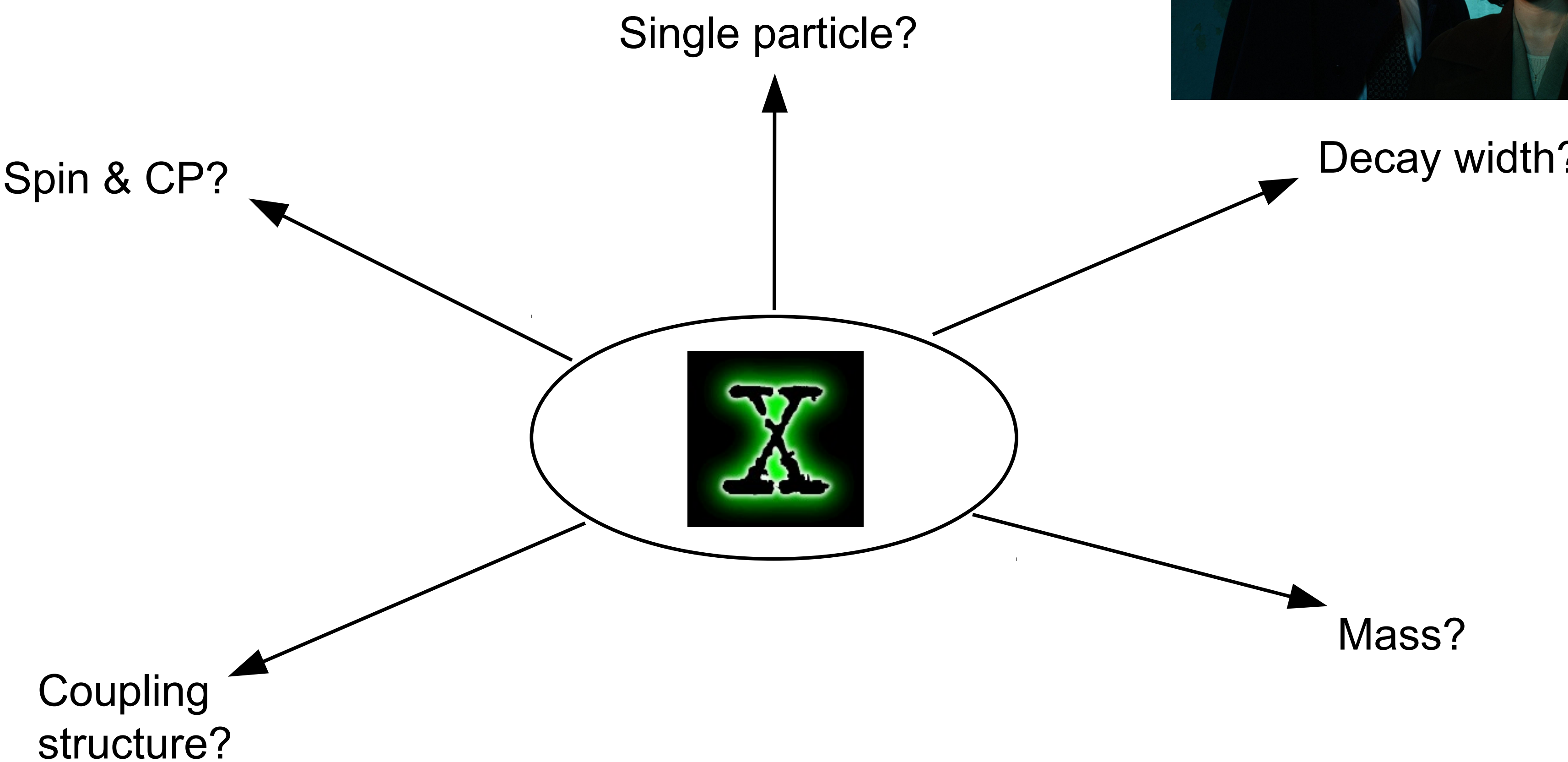


PRD 89 (2013) 012003

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

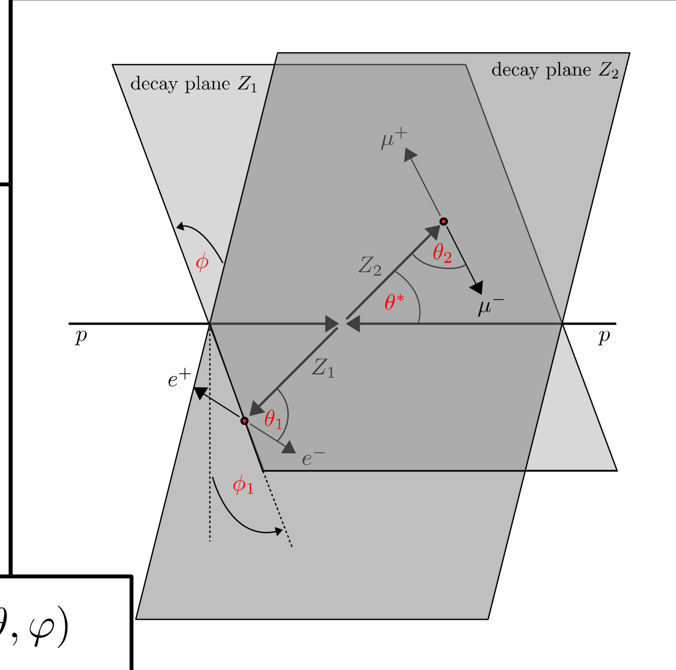
44 (peer reviewed) publications since discovery announcement

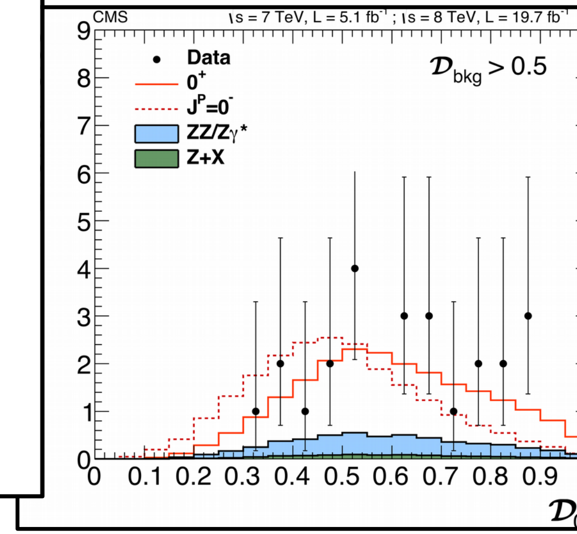
Anatomy of X


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

Spin & CP

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

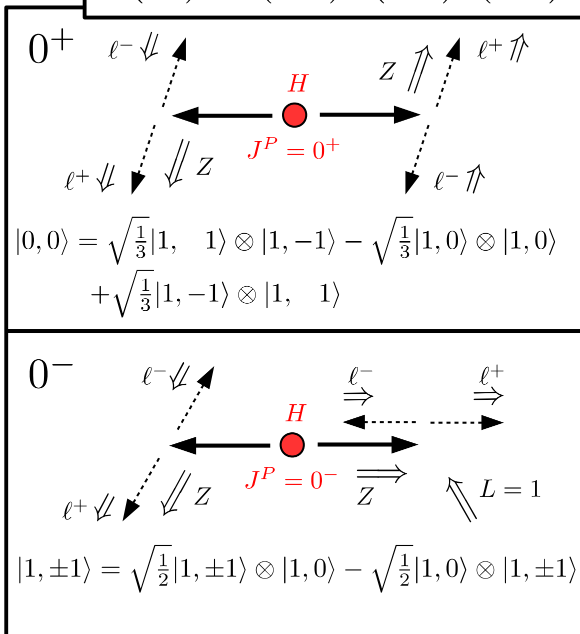




PRD 89 (2014) 092007

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

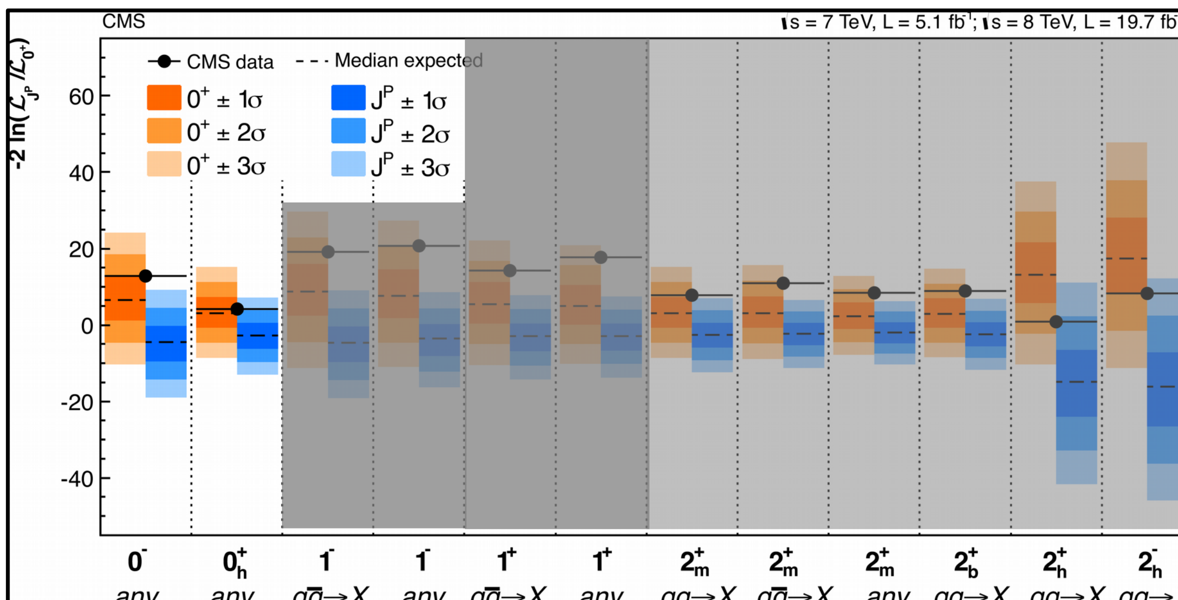
$$P(4\ell) = (-1)^L(-1)^2(+1)^2 = (-1)^L$$



$$|0,0\rangle = \sqrt{\tfrac{1}{3}}|1,\ \ 1\rangle \otimes |1,-1\rangle - \sqrt{\tfrac{1}{3}}|1,0\rangle \otimes |1,0\rangle + \sqrt{\tfrac{1}{3}}|1,-1\rangle \otimes |1,\ \ 1\rangle$$

$$|1,\pm1\rangle = \sqrt{\tfrac{1}{2}}|1,\pm1\rangle \otimes |1,0\rangle - \sqrt{\tfrac{1}{2}}|1,0\rangle \otimes |1,\pm1\rangle$$

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

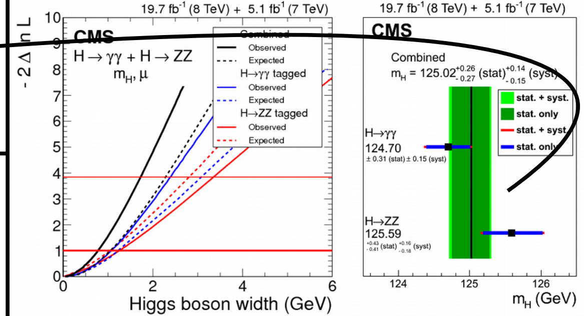


Mass & decay width

compatible within 1.6σ.

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

PRD 92 (2015) 012004

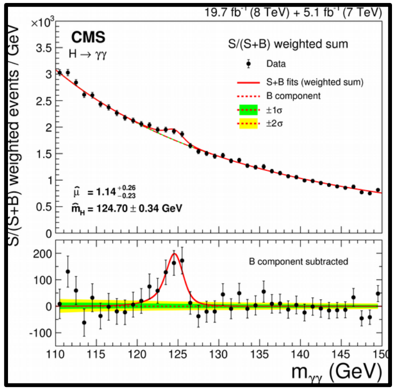


$$\hat{m}_H = 125.02 \pm^{0.26}_{0.27}\ \text{(stat.)} \pm^{0.14}_{0.15}\ \text{(syst.) GeV}$$

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

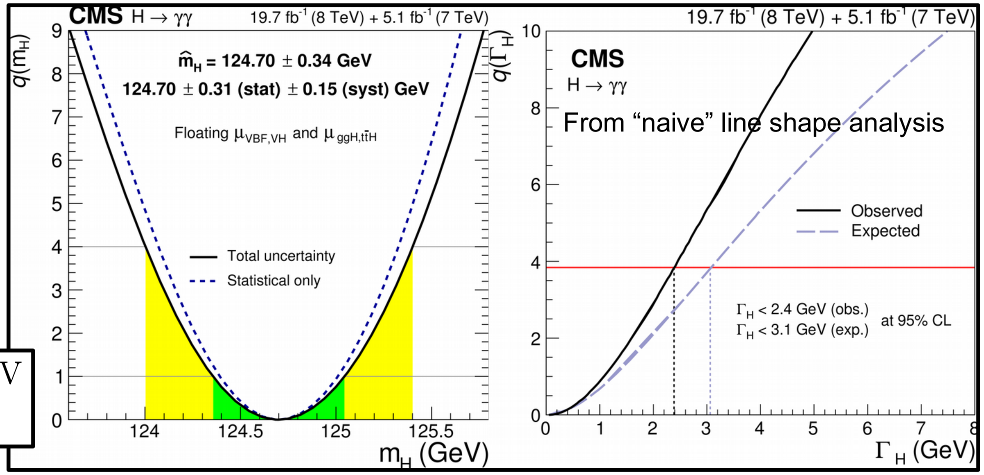
Expectation from SM:
$\Gamma_H(125\ \text{GeV}) = 4.04\ \text{MeV}$

EPJ C 74 (2014) 3076

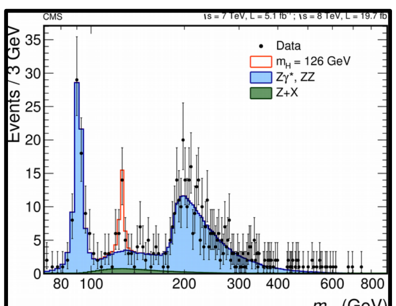


$$\hat{m}_H = 124.7 \pm^{0.5}_{0.31}\ \text{(stat.)} \pm 0.15\text{(syst.) GeV}$$

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

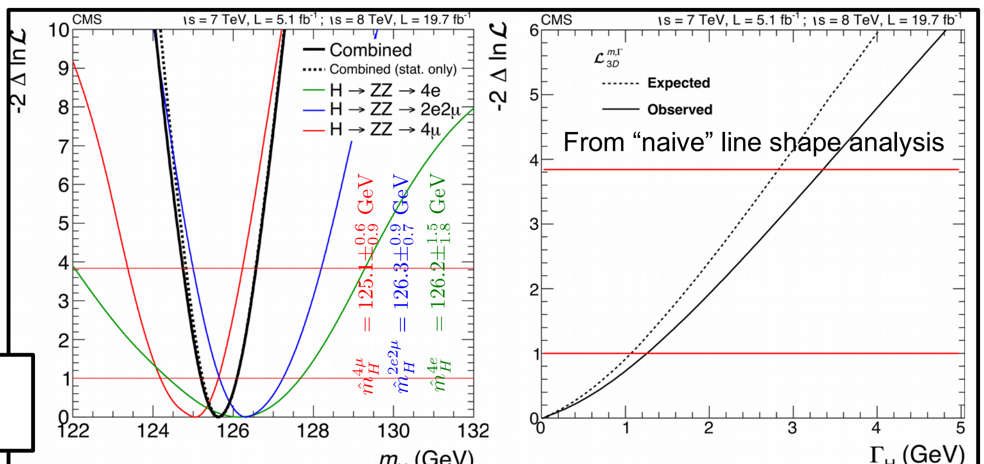


PRD 89 (2014) 092007



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

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



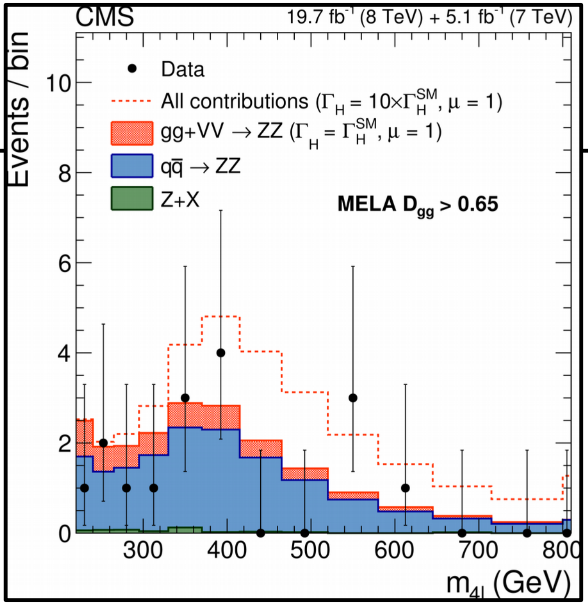
Mass & decay width

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

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

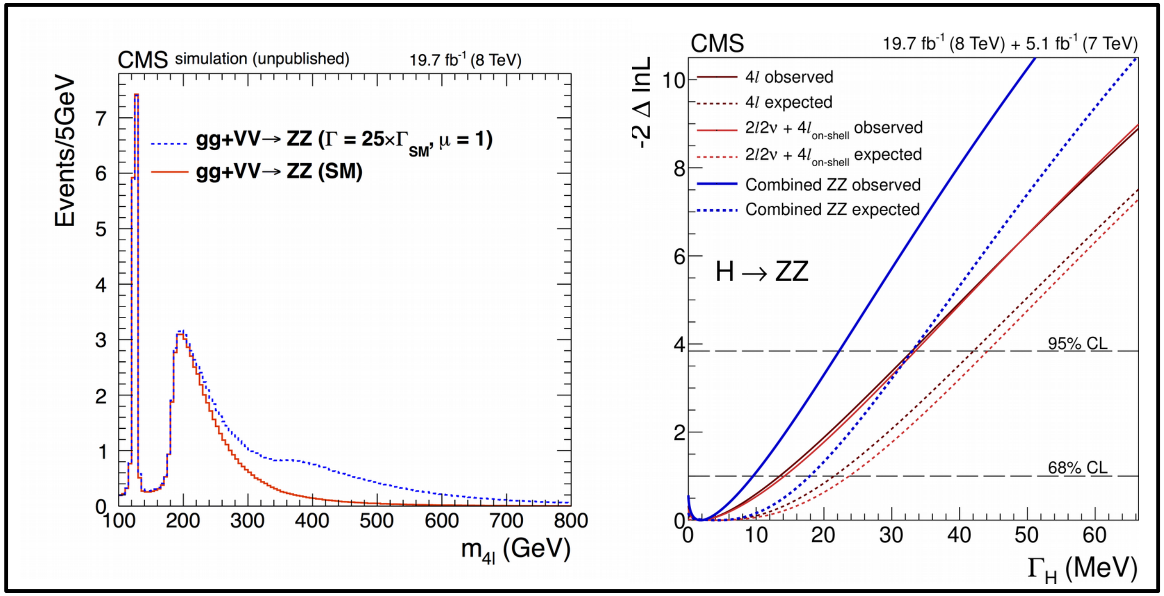
$$\propto \left.\frac{\kappa_g^2\kappa_Z^2}{m_H\Gamma_H}\right|_{m_{4\ell}\approx m_H}$$

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



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

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

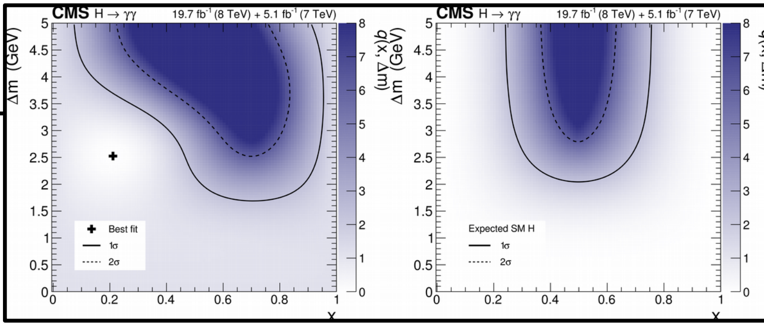


PLB 736 (2014) 64

Compatibility

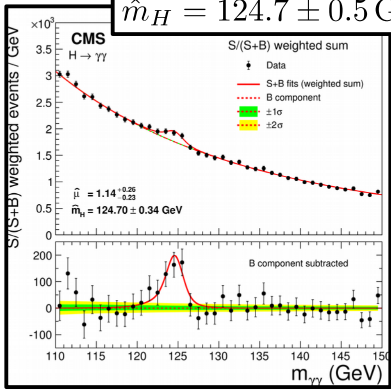
Second close-by resonance in $H \to \gamma\gamma$?

EPJ C 74 (2014) 3076



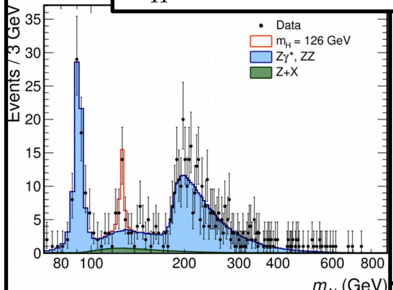
$\hat{m}_H = 124.7 \pm 0.5\,\mathrm{GeV}$

EPJ C 74 (2014) 3076

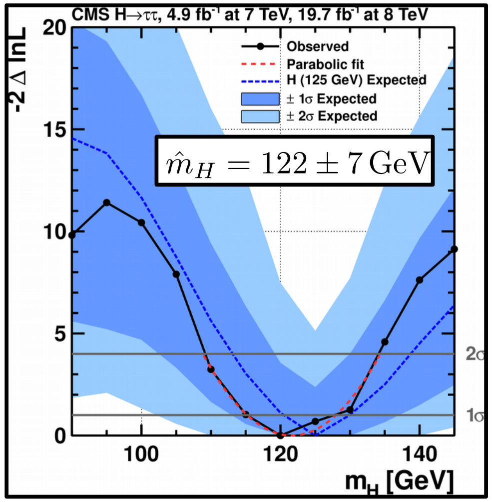


$\hat{m}_H = 125.6 \pm 0.6\,\mathrm{GeV}$

PRD 89 (2014) 092007

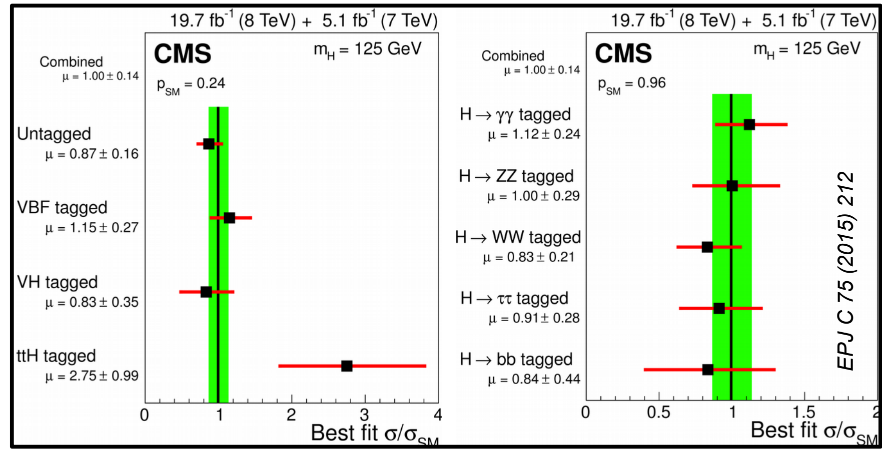


JHEP 05 (2014) 104



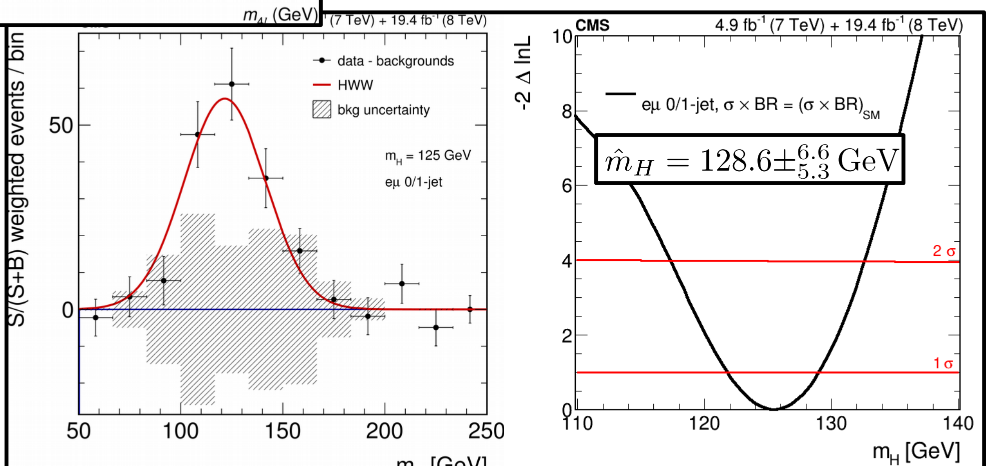
$\hat{m}_H = 122 \pm 7\,\mathrm{GeV}$

Coupling across production modes or decay channels:



EPJ C 75 (2015) 212

JHEP 01 (2014) 096



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

Overall coupling consistency:

EPJ C 75 (2015) 212

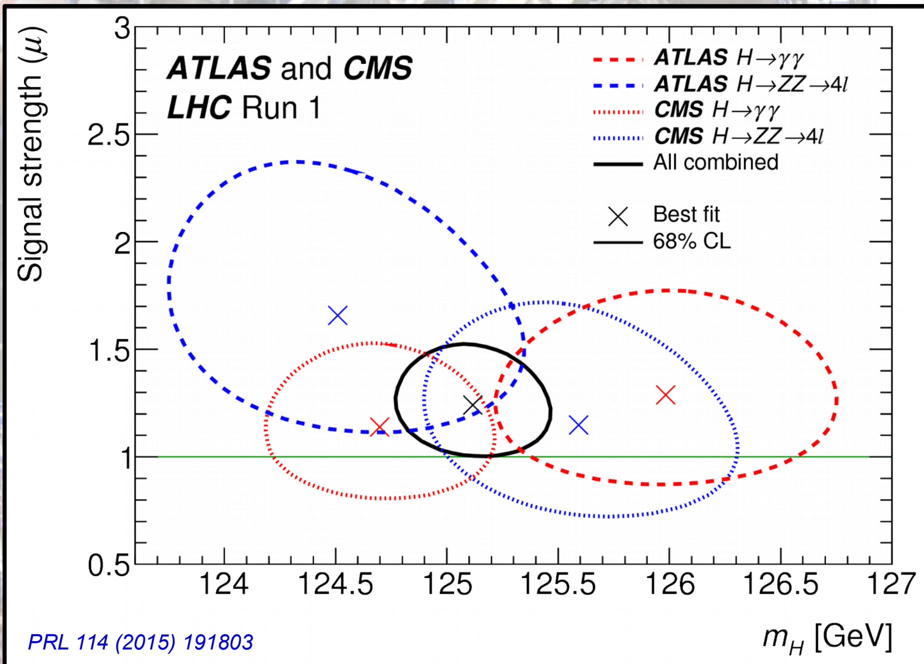
- Event categories : 227
- Nuisance parameters: $\mathcal{O}(2500)$
- 16 MB binary file of stat. model (~145 MB in human readable form).

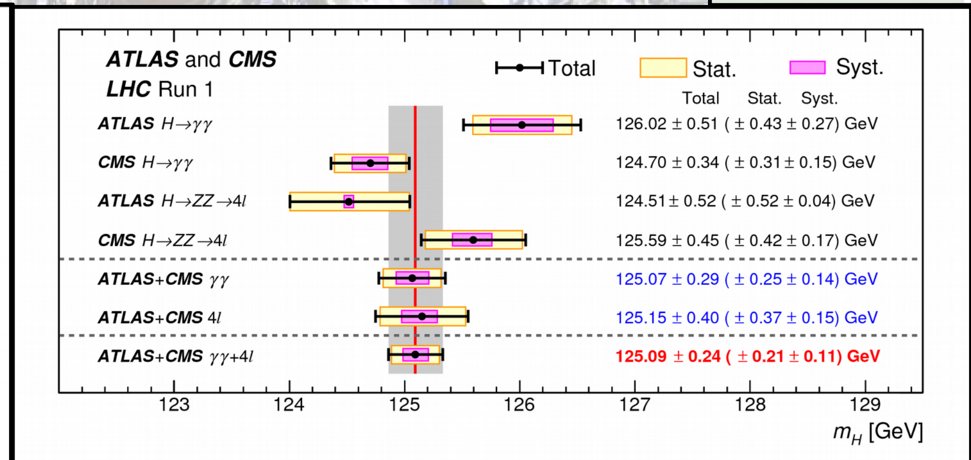
$\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.14$

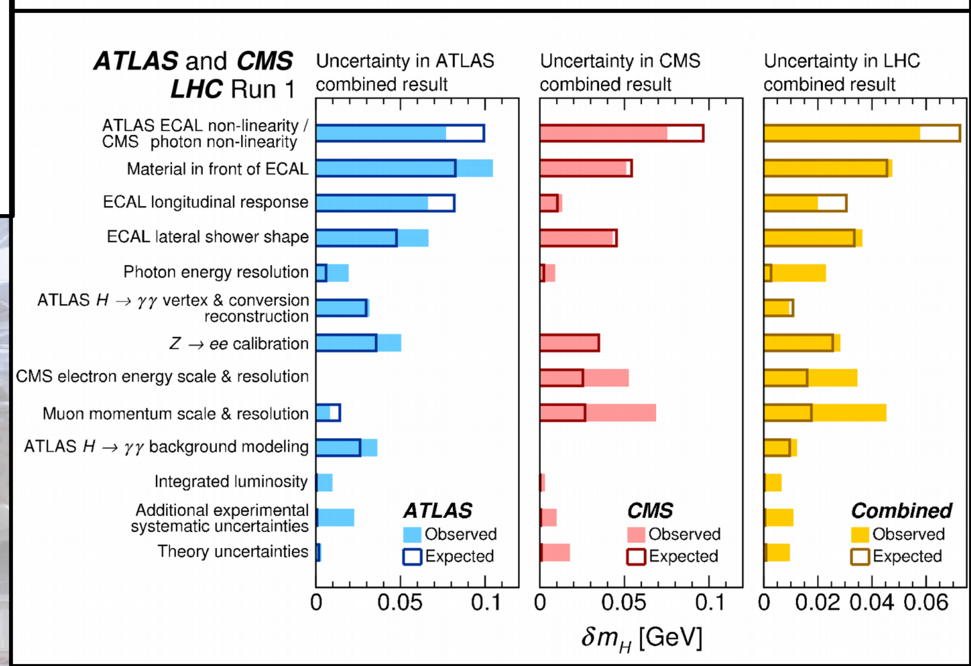
$p\text{-value} = 84\%$

Mass

- ATLAS+CMS LHC run-1 combination:





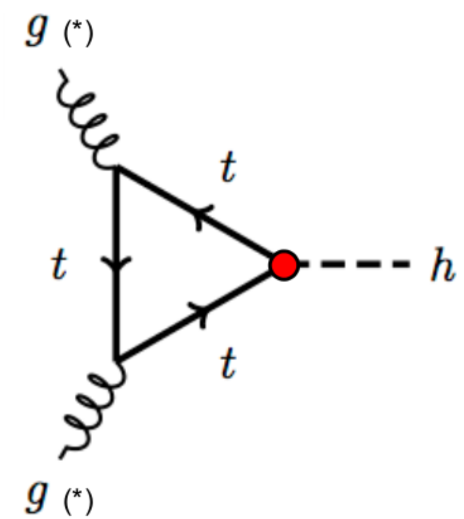


$$125.06 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})\ \text{GeV}$$

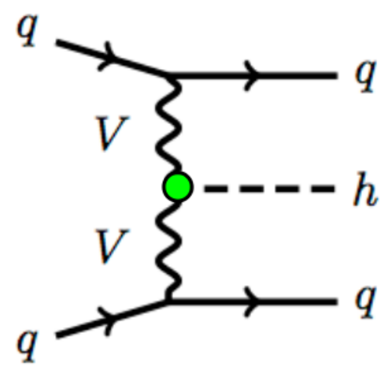
Coupling Estimates

- Determine couplings from production mode and decay channel:

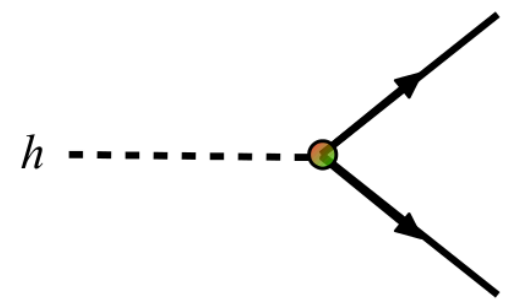
$gg \rightarrow H$ production:



$qq \rightarrow qqH$ production:



Decay to f or V:



● f : $\kappa_{\mathrm{Hff}} = \frac{m_f}{\mathrm{v}}$

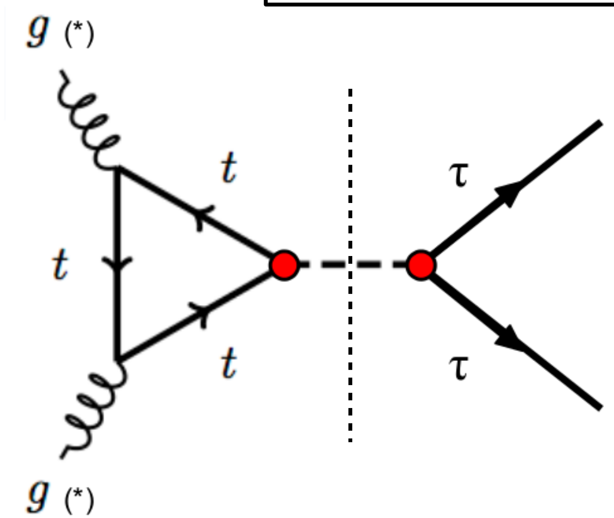
● V : $\kappa_{\mathrm{HVV}} = \frac{2m_V^2}{\mathrm{v}}$

- 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 $\Gamma_H = 4.04 \text{ MeV}$ and $m_H = 125 \text{ GeV}$.
- 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 $\sigma \times \text{BR}$.
- $\text{BR}_X = \frac{\Gamma_X}{\Gamma_H}, \quad \Gamma_H = \sum_i \Gamma_i$.
- $\sigma \propto (\kappa_t \kappa_\tau)^2 \propto (\kappa_u \kappa_d)^2 \propto (\kappa_q \kappa_l)^2 \propto (\kappa_g \kappa_f)^2$.

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

Coupling structure

JHEP 08 (2016) 045

- Event categories : 574
- Nuisance parameters: 4268

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

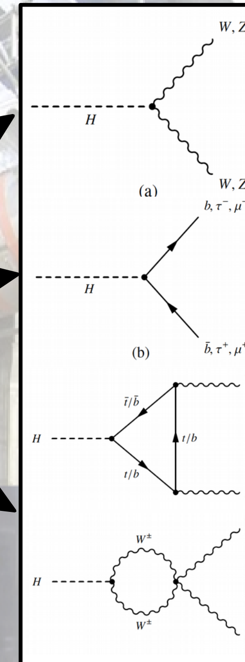
- ATLAS+CMS LHC run-1 combination:

Considered production modes:

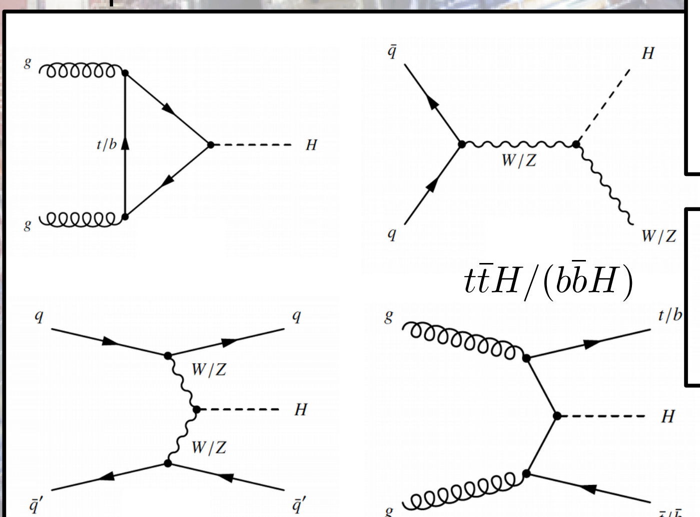
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	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



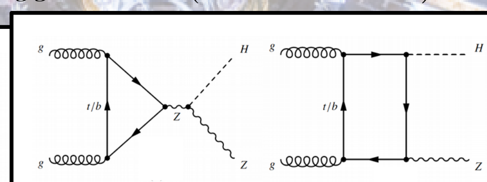
Main production modes:

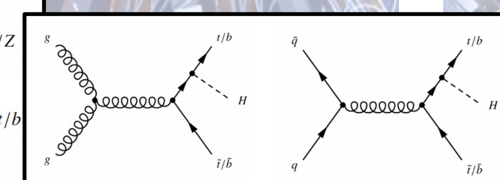


$t\bar{t}H/(b\bar{b}H)$

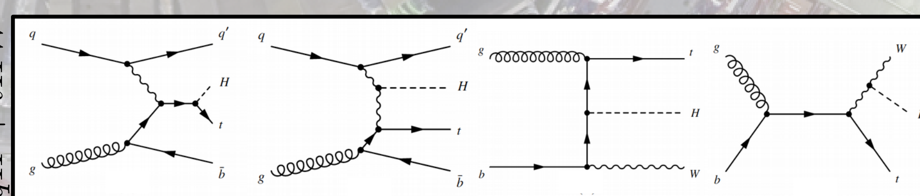
Amplitudes

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

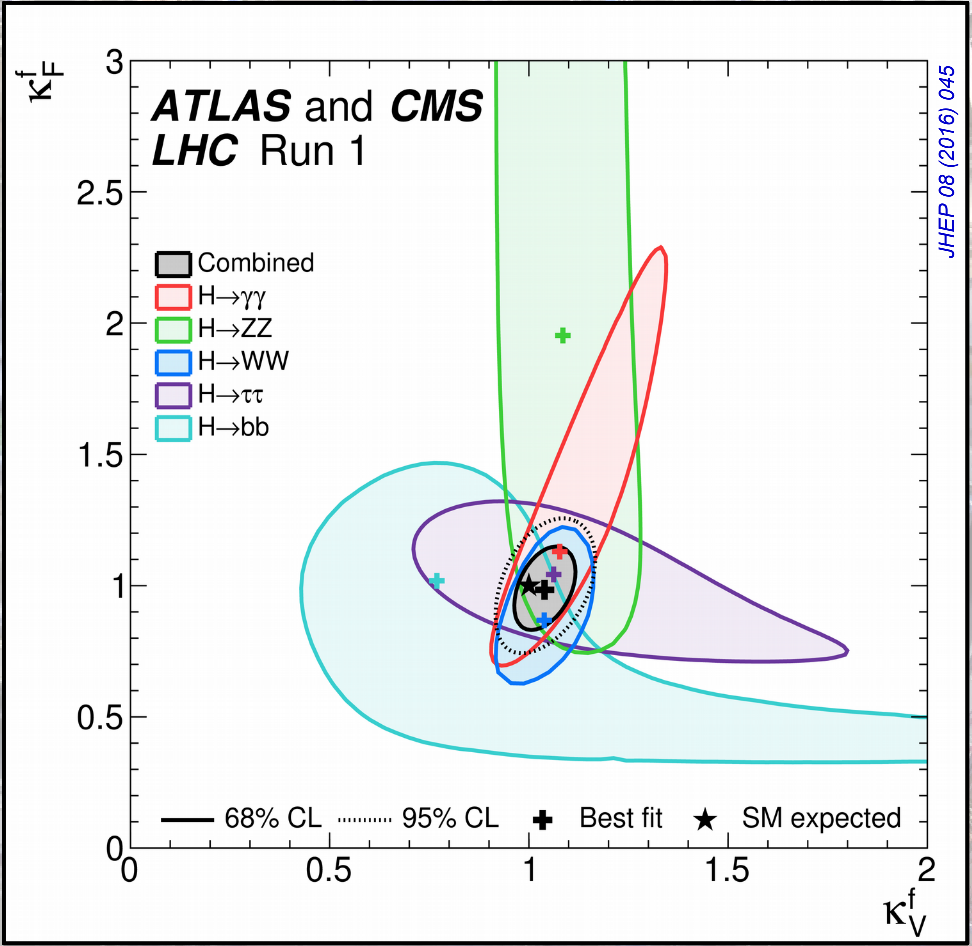
$\approx (1.26\kappa_W - 0.26\kappa_t)^2$

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

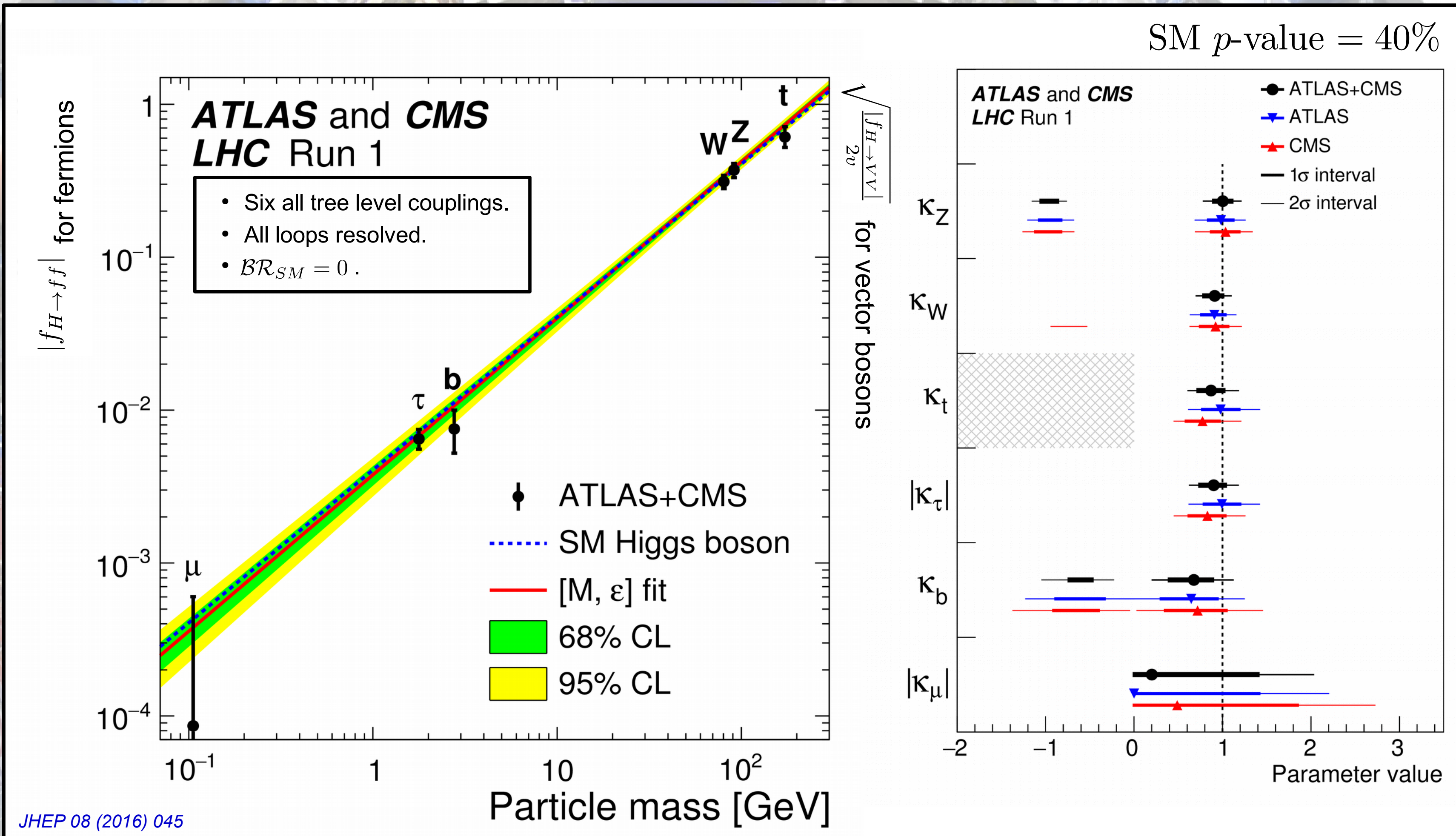
κ_V- κ_F model

- 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”



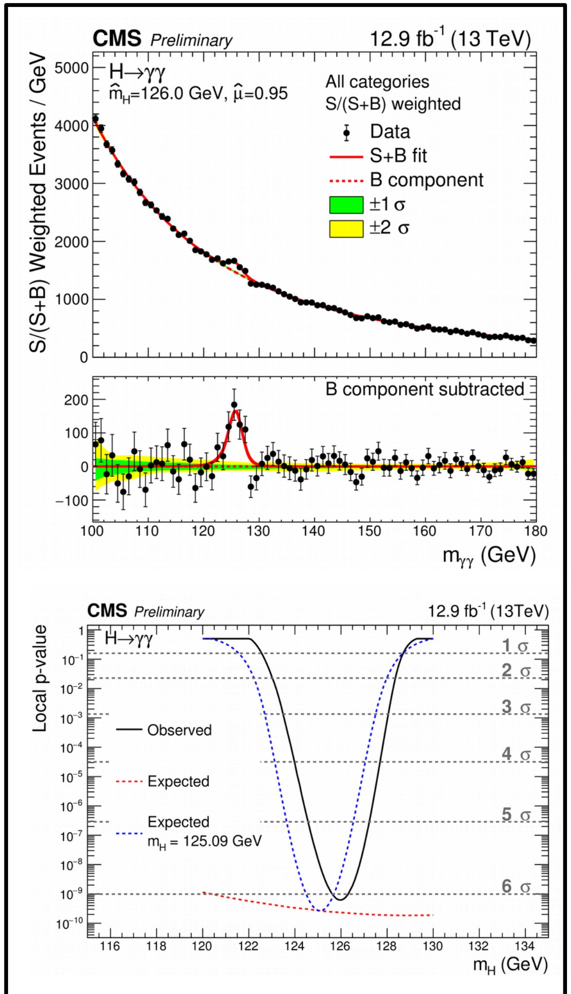
$$|f^{\mathrm{obs}}_{H\to ff}| = \kappa_f \cdot |f^{\mathrm{SM}}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

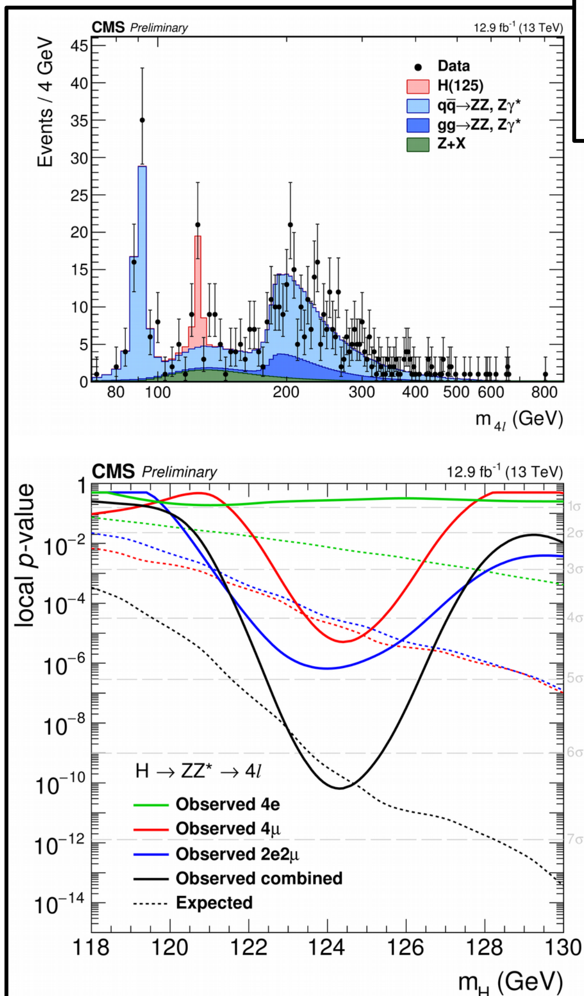
$$\sqrt{\frac{|f^{\mathrm{obs}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{|f^{\mathrm{SM}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \frac{m_V}{v} \qquad V = W, Z$$

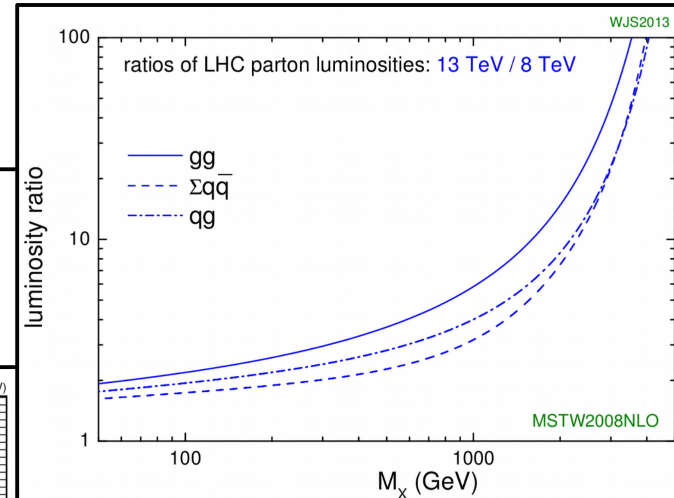
Within measurement accuracy unique scaling as expected within the SM.

Higgs still there?

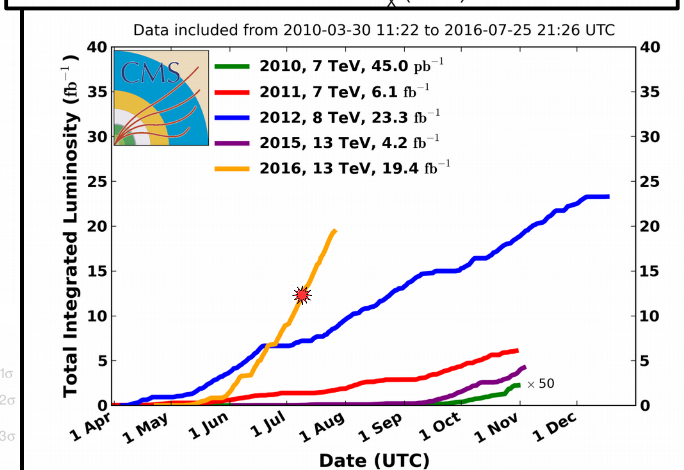
- Better find the new particle back where you saw it in LHC run-1…







James Stirling (arXiv:0901.0002)



X(125) → H(125)

- Mr. 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.

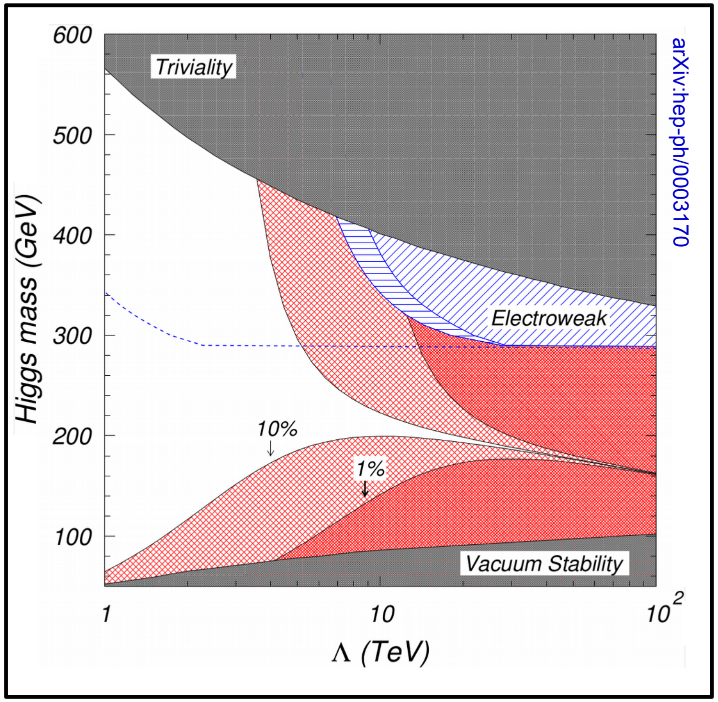
Mass? ✓
- $125.09\,\mathrm{GeV}$ one of the best known parameters in SM.

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

MISSION ACCOMPLISHED ?

Why the Higgs boson still is not THE *Higgs* boson [1]

- Gravity is not included in the SM.
- The SM suffers from the hierarchy problem.
- Dark matter is not included in the SM.
- Neutrino masses are not included in the SM.
- There are known deviations in $a_\mu \equiv \frac{g_\mu - 2}{2}$ from the SM expectation (3.6σ unresolved).



- There must be physics beyond the SM!
- At what scale does it set in?
- (How) Does it influence the Higgs sector?

[1] Arguments stolen from S. Heinemeyer (HH Higgs workshop 2014)

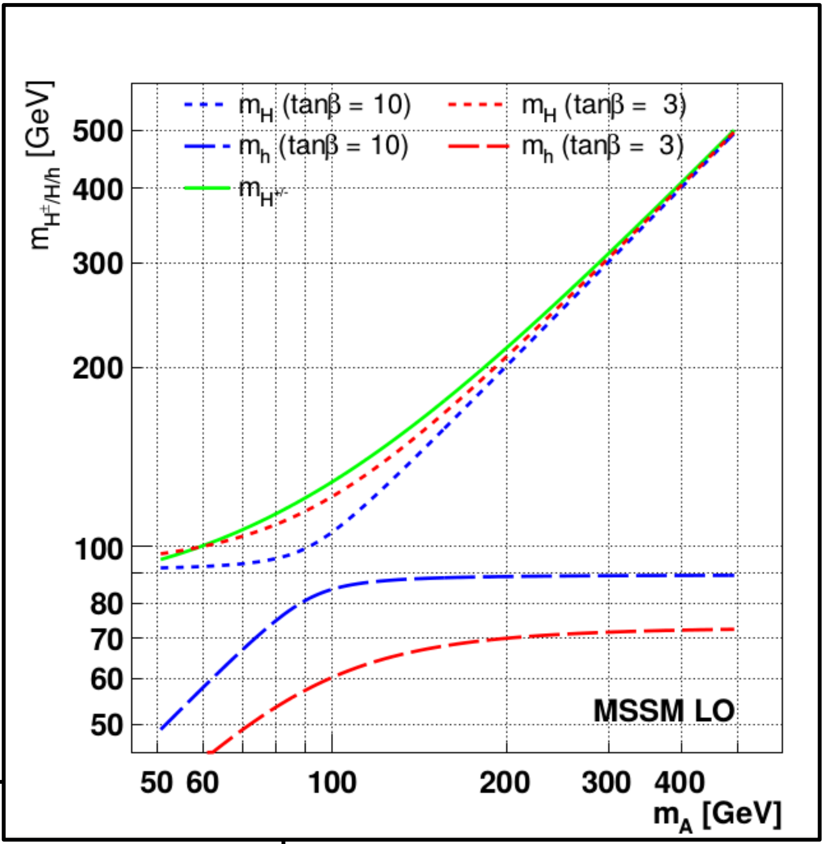
Extended Higgs sectors

- 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: $m_A\,,\quad \tan\beta = \mathrm{v}_u/\mathrm{v}_d$

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{H,\,h}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right)$$

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

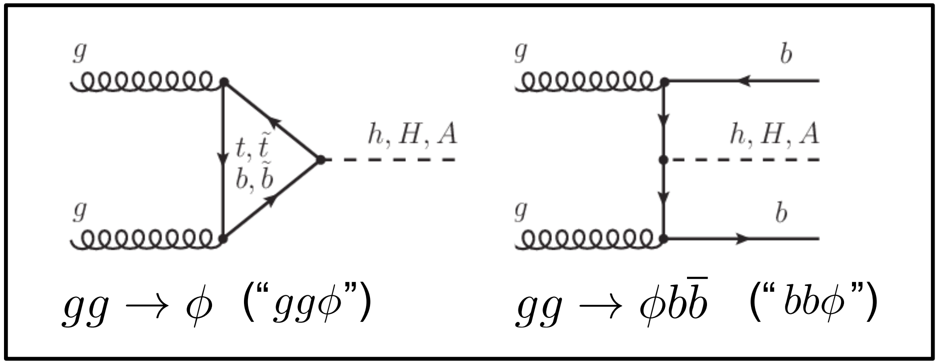
(angle btw. H_u & H_d in isospace)

The role of down-type fermions

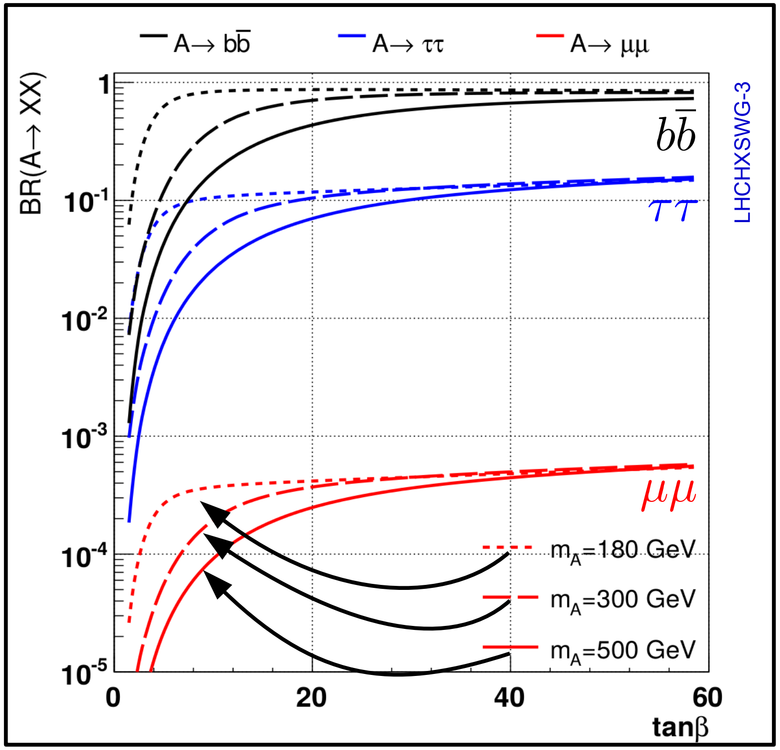
	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \rightarrow 0$	$\sin\alpha/\sin\beta \rightarrow \cot\beta$	$\cos\alpha/\cos\beta \rightarrow \tan\beta$
h	$\sin(\beta-\alpha) \rightarrow 1$	$\cos\alpha/\sin\beta \rightarrow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

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

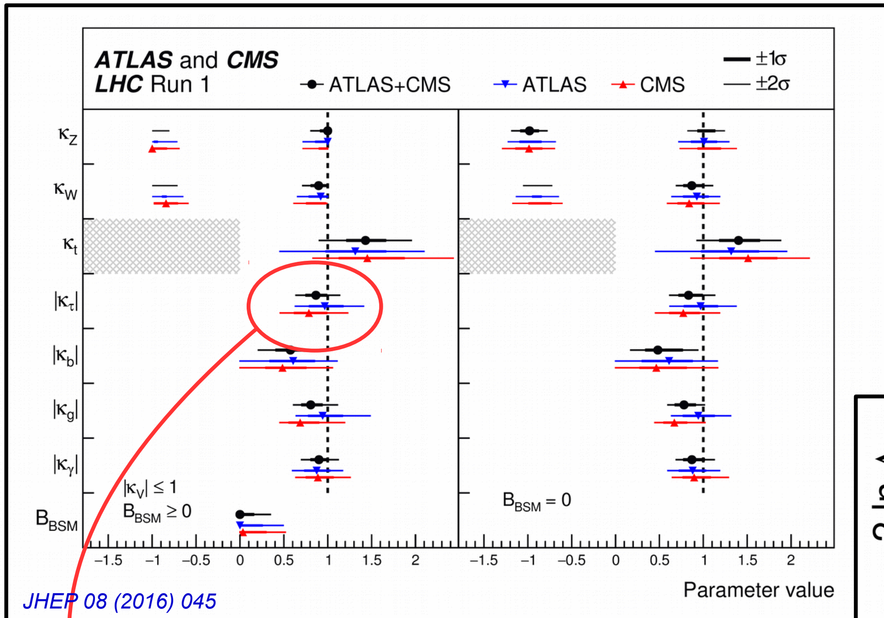
Interesting production modes:



Interesting decay channels:

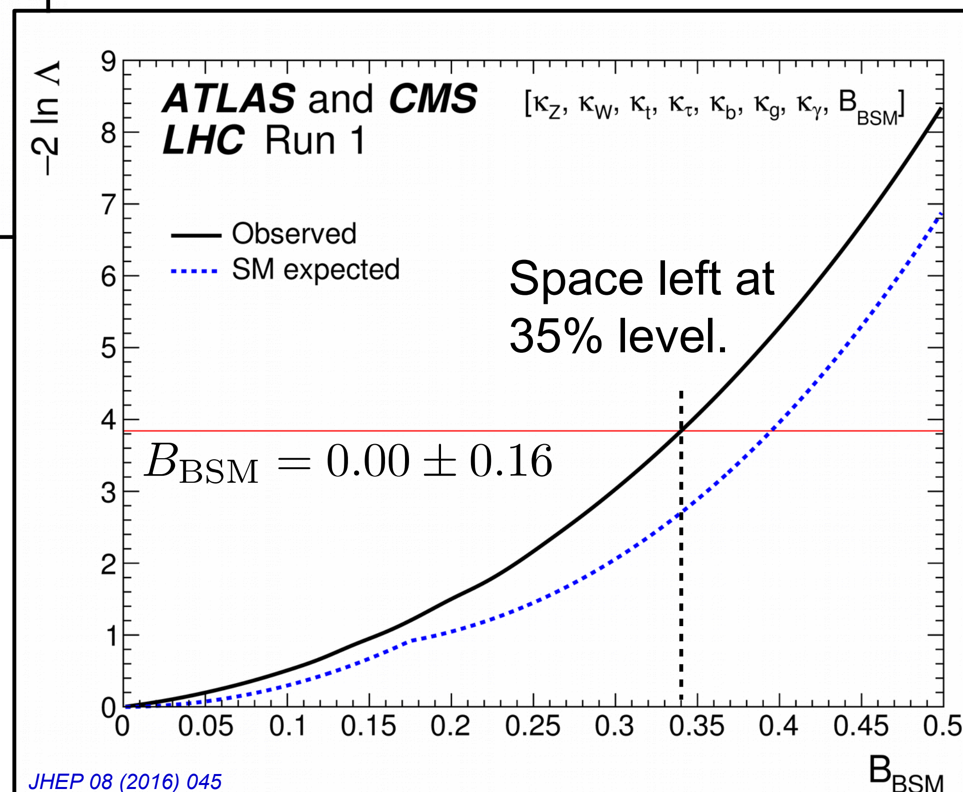


Space left for new physics in the Higgs sector



$$\kappa_\tau = 0.87 \pm^{0.12}_{0.11}$$

Space left at 20% level @ two sigma level.



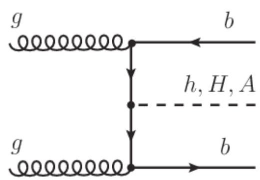
The search

- Search for additional peak(s) e.g. in $m_{\tau\tau}$ distribution.

b-tag category:

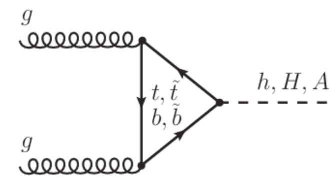
N(b-tag) ≥ 1

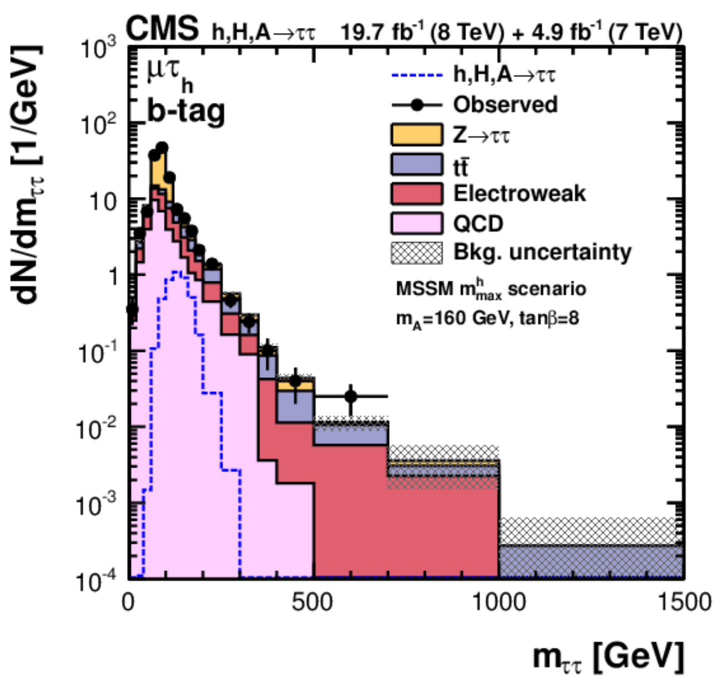
N(Jet) ≤ 1

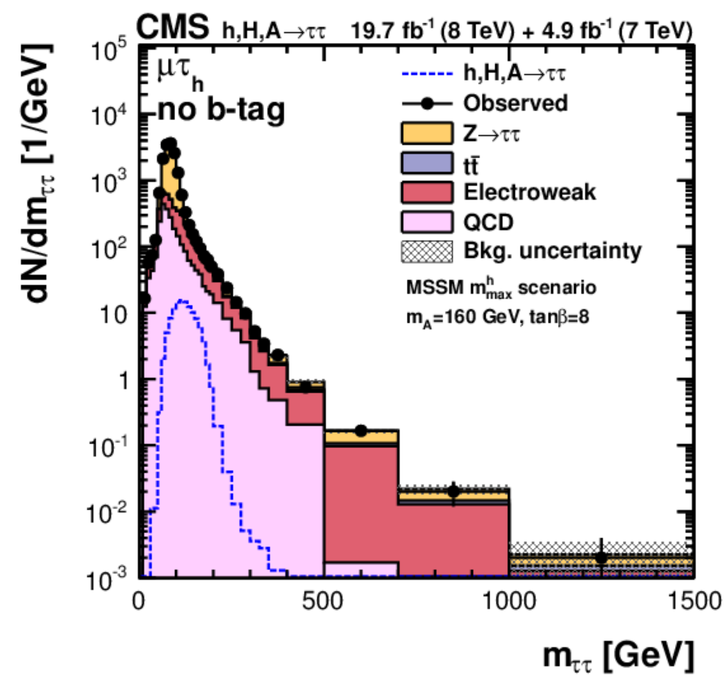


No b-tag category:

N(b-tag) $= 0$

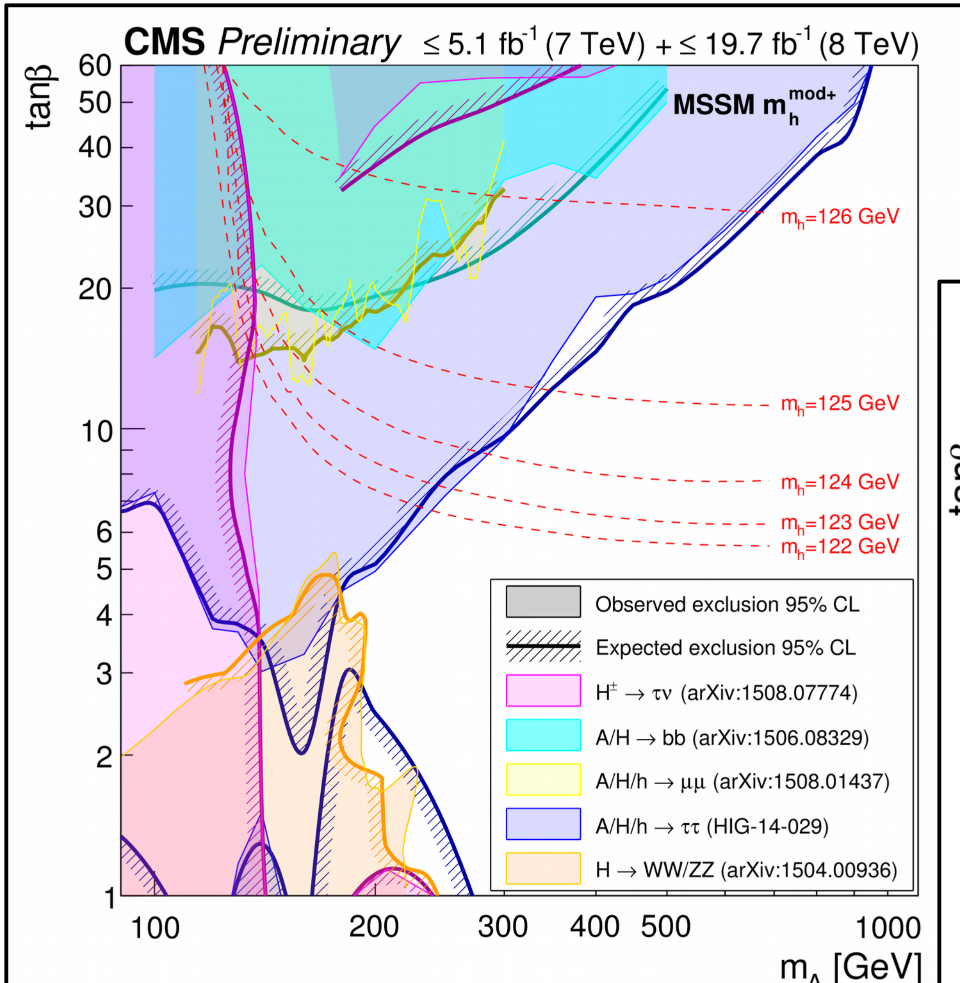




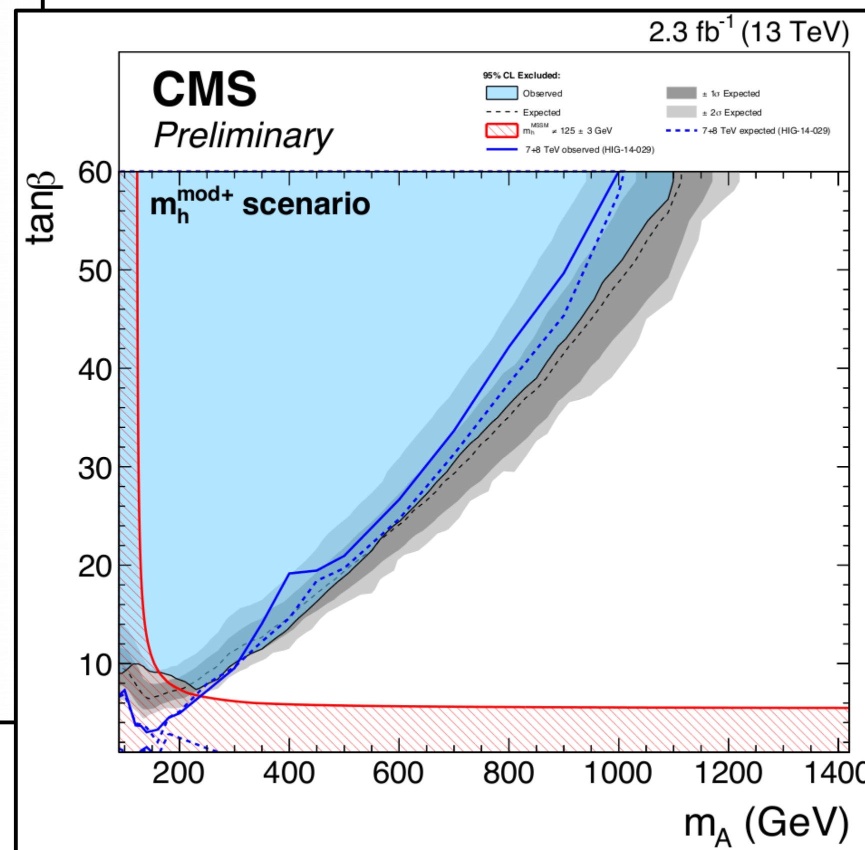


JHEP 10 (2014) 160

This and more CMS searches …



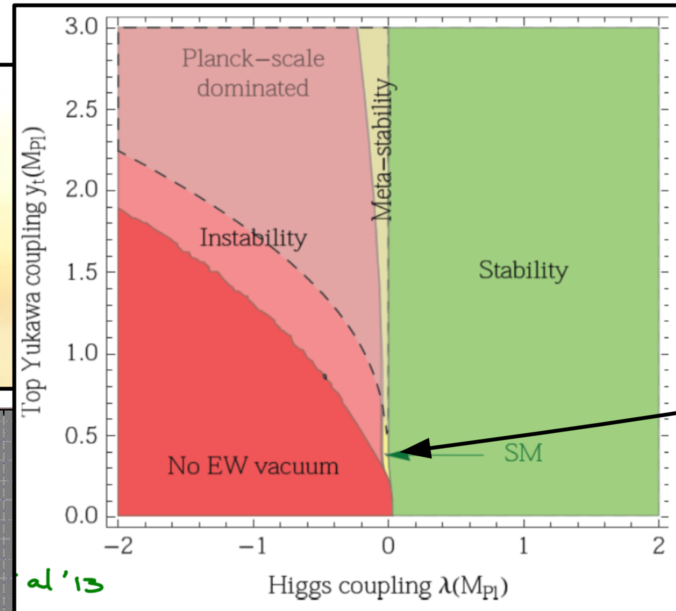
CMS-HIG-PAS-16-007

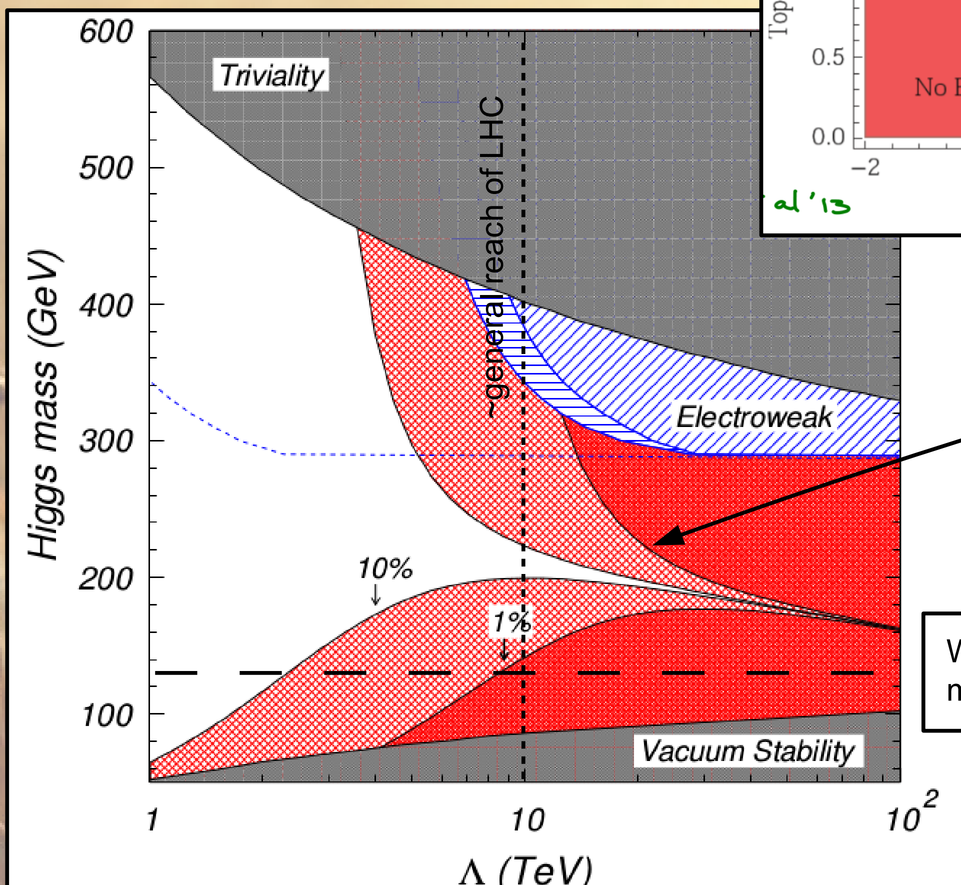


CMS-HIG-PAS-16-006

Closing in …

The SM in the stress field
of vacuum stability.





Different levels of fine tuning in the SM.

What we have found and measured for m_H.

Remaining lecture program

	Monday (19.09):	Tuesday (20.09.):	Wednesday (21.09.):
13:30 15:00	Introdu particle physics	Proton stru QCD and physics wi MM).	Flavor ph including top-quar).
15:15 16:45	Particle eration & detecti a analysis (RW).	Physics wi e bosons (MM).	Higgs ph RW).

- In case of questions – contact us matthias.mozer@cern.ch (Bld. 30.23 Room 9-8)
  roger.wolf@cern.ch (Bld. 30.23 Room 9-20).

- We hope you had fun (and learned something…).

Backup