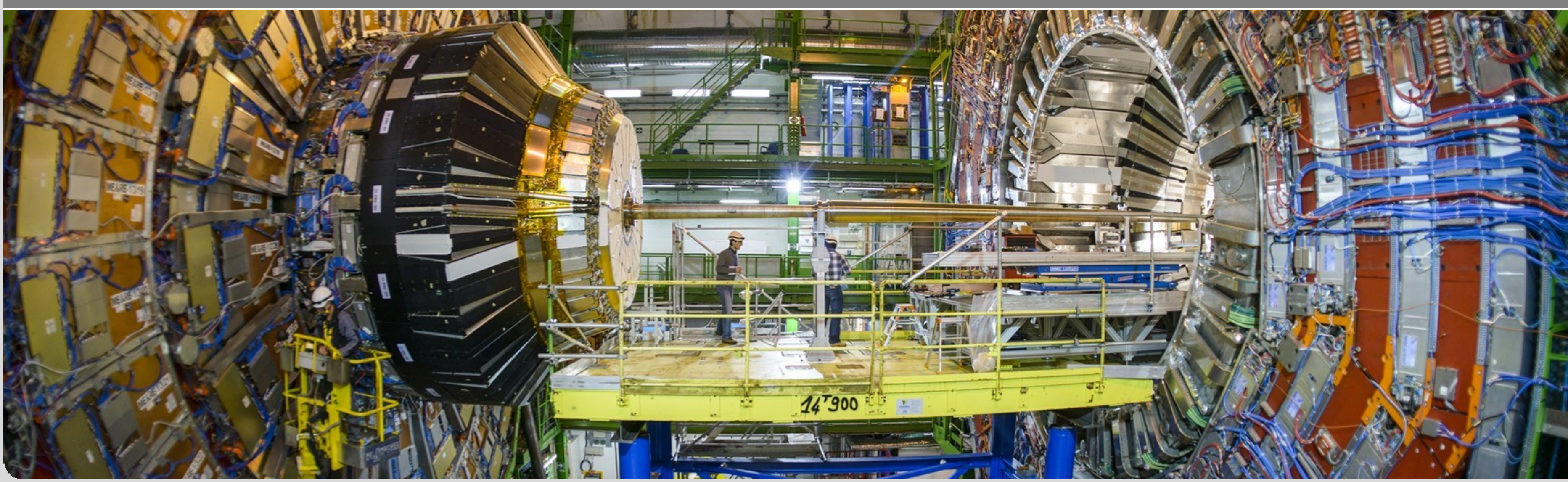
Higgs Physics

Roger Wolf

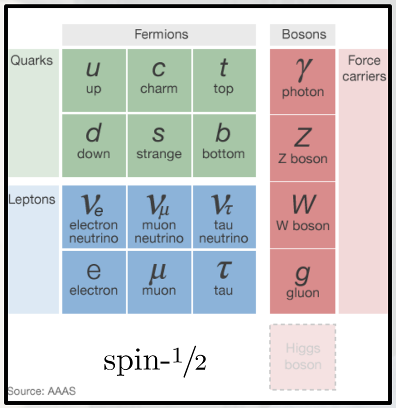
13. March 2018

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:



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

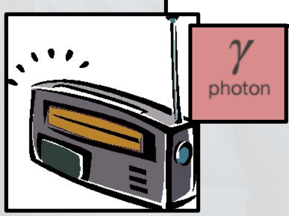
1d rotations

2d rotations

3d rotations

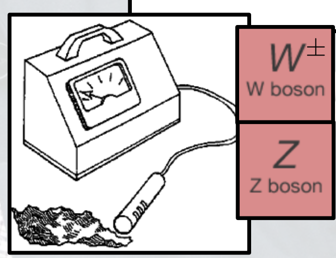
in a $\mathbb{C}(N)$ hyperspace (w/ $N \geq 5$)

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



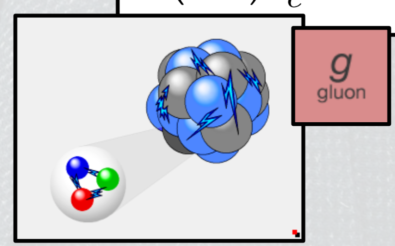
Electromagnetism

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



Weak force

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

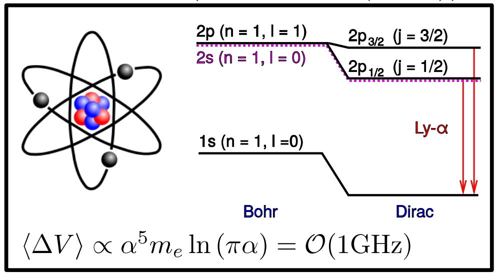


Strong force

The standard model of particle physics (SM)

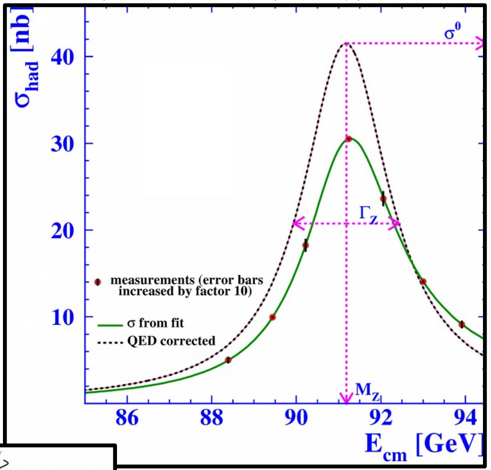
Precision observables:

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



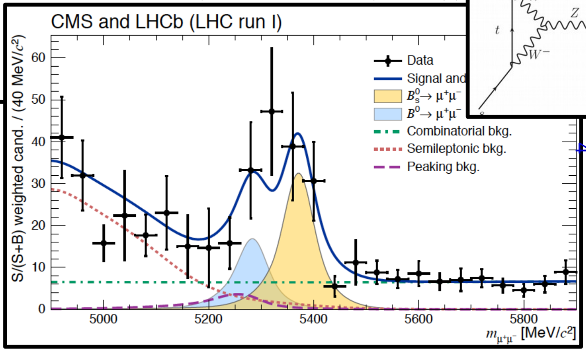
$\langle \Delta V \rangle \propto \alpha^5 m_e \ln(\pi\alpha) = \mathcal{O}(1\text{GHz})$

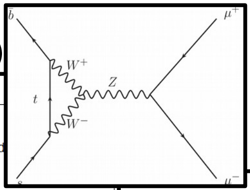
LEP: (precision $\mathcal{O}(10^{-5})$)



Phys. Rept 427 (2006)

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

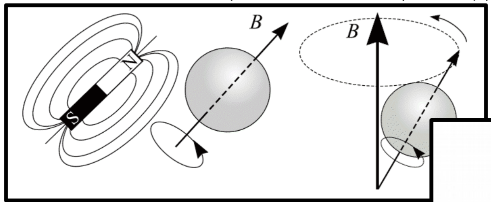


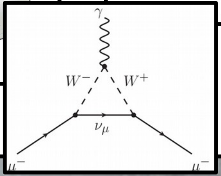


Nature (2015) 1447

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

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

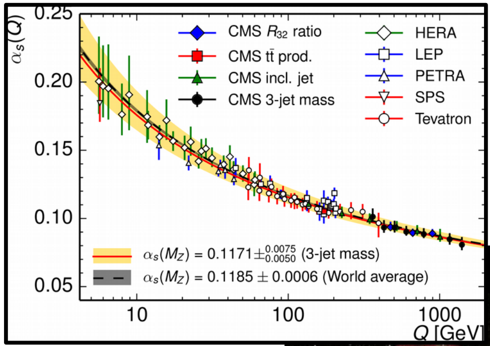




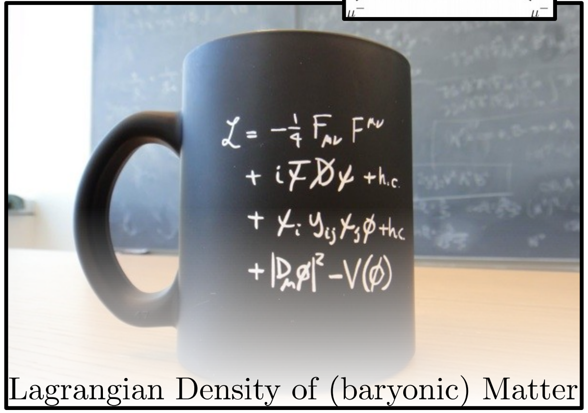
$\frac{(g-2)}{2} = 0.00115965218073(28)$

Striking features & global characteristics:

Asymptotic freedom:

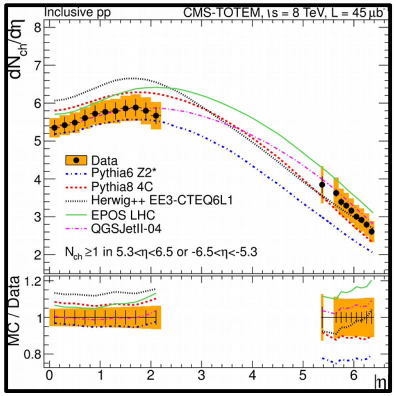


EPJC 75 (2015) 186



Lagrangian Density of (baryonic) Matter

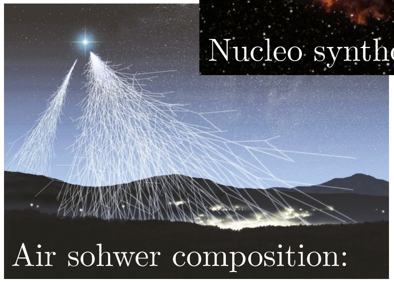
Inclusive pp collisions:



EPJC 74 (2014) 3053

History of the universe:

Nucleo synthesis:



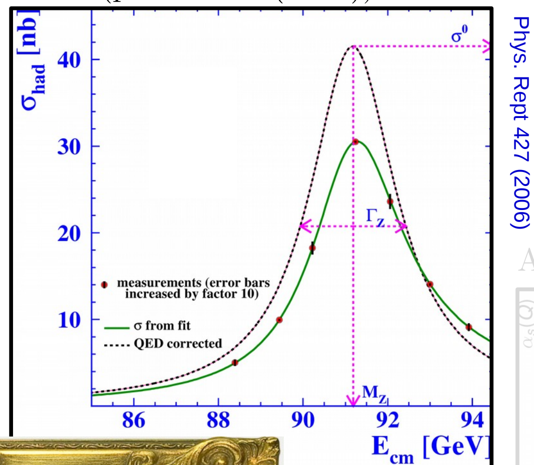
Air sohwer composition:

THE GRINCH

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

Precision observables:

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



Problem-1:

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

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

Problem-2:

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

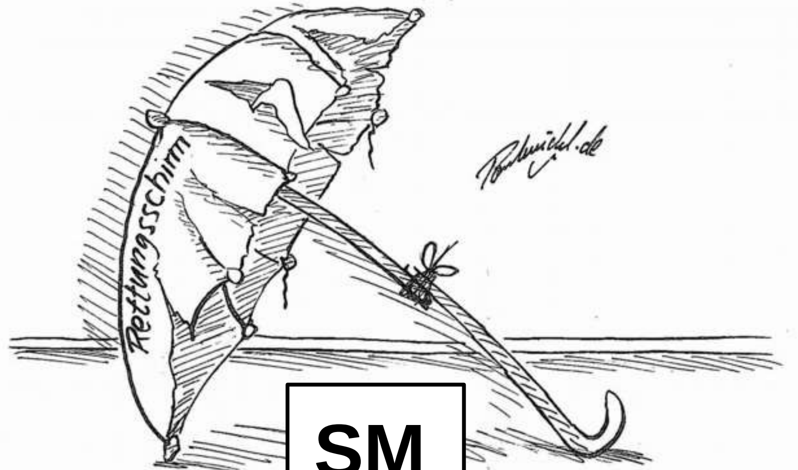
...ve pp collisions:

History of the universe:

Nucleo synthesis:

Air sohwer composition:

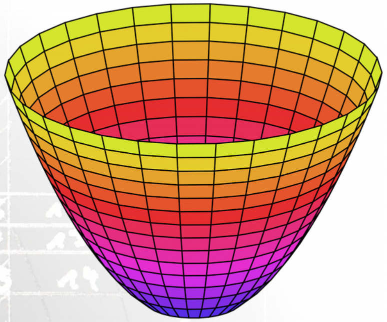
Wie kann eine Symmetrie zur gleichen Zeit erhalten und gebrochen sein?



SM

Problem: lokale Eichsymmetrien in Lagrangedichte sind durch massive Teilchen explizit gebrochen

Spontane Symmetrie-brechung:



$$f(x,y) = x^2 + y^2$$

$$x = r\cos\varphi$$

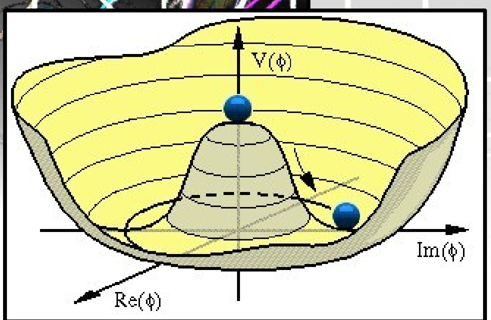
$$y = r\sin\varphi$$

$$f(x,y)\big|_{r,\varphi} = r^2\left(\cos\varphi^2 + \sin\varphi^2\right) = r^2$$

$$\tilde{f}(x,y) = (x-1)^2 + (y-1)^2$$

$$\tilde{f}(x,y)\Big|_{r,\varphi} = r^2 + 2\left(1 - r\left(\sin\varphi + \cos\varphi\right)\right)$$

("hidden symmetry")

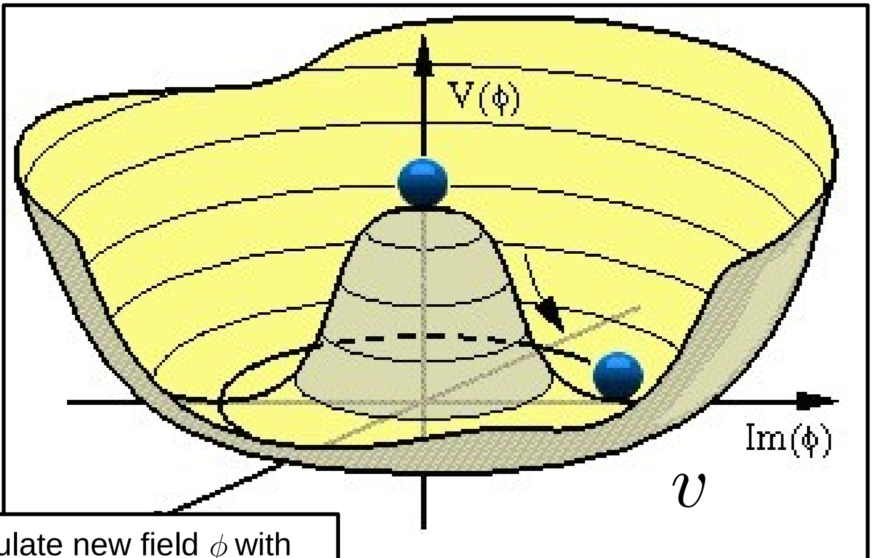


Führe Potential ein das den Grundzustand des Universums aus der Symmetrieachse der Bewegungsgleichungen zwingt.

→ Teilchenmasse als Kopplung an nicht verschwindenden Vakuumerwartungswert.

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?!?

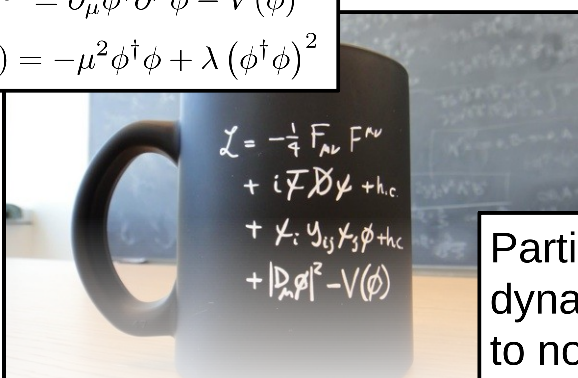
Spontaneous symmetry breaking:



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:

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

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

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

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

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

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*.

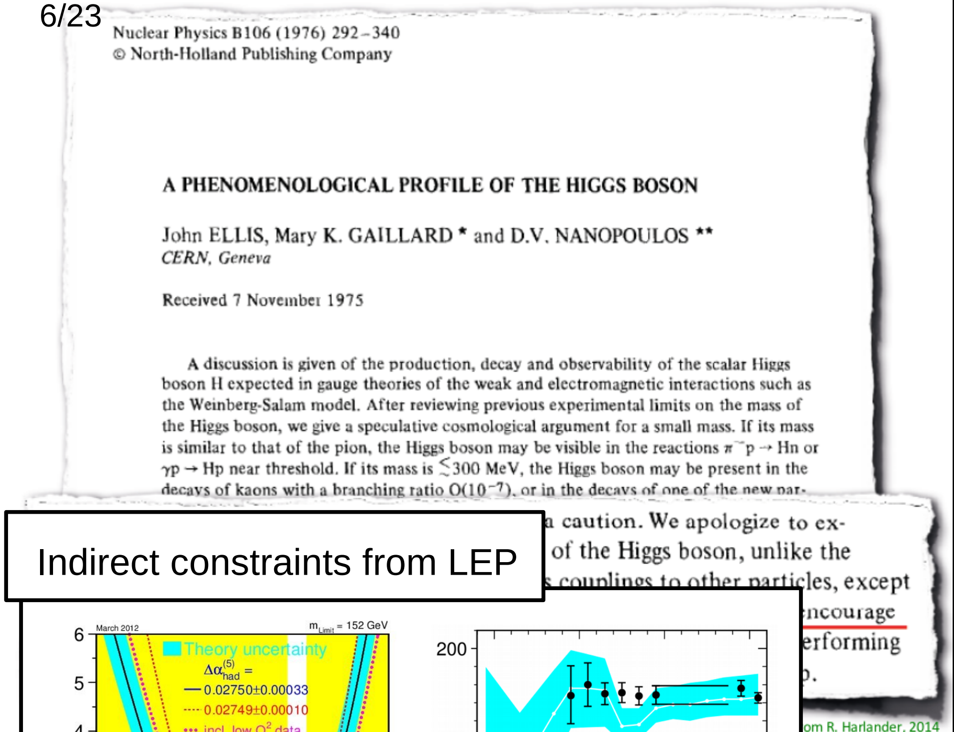
1983: Discovery of *W* and *Z*.

1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

2013: Nobel prize to Peter Higgs and Francois Englert.


Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

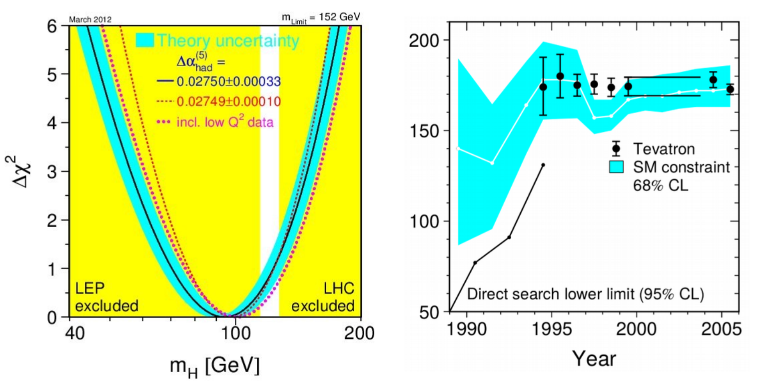
Received 7 November 1975

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-

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

om R. Harlander, 2014

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*.

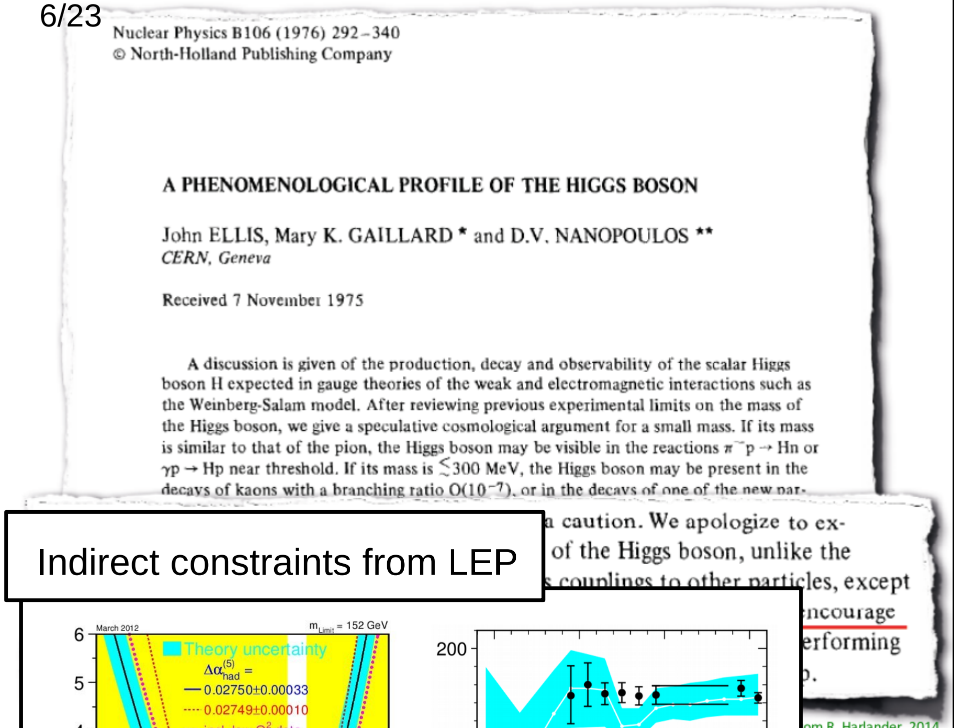
1983: Discovery of *W* and *Z*.

1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

2013: Nobel prize to Peter Higgs and Francois Englert.



Nuclear Physics B106 (1976) 292–340

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

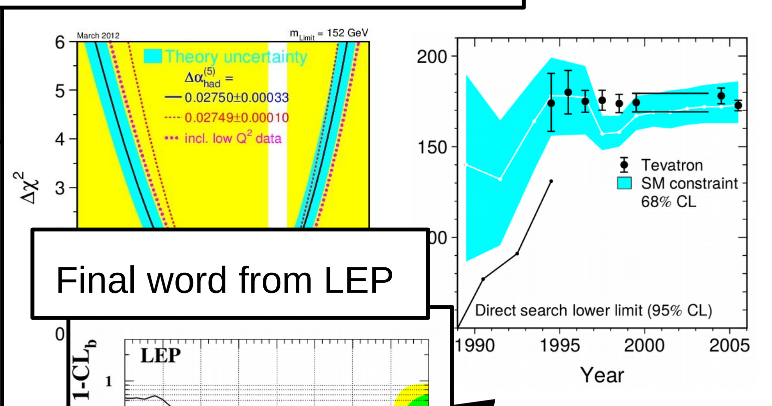
Received 7 November 1975

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-

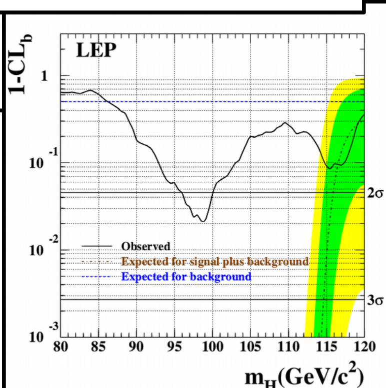
...a caution. We apologize to ex- ... of the Higgs boson, unlike the ... couplings to other particles, except ... encourage ... erforming ...

om R. Harlander, 2014

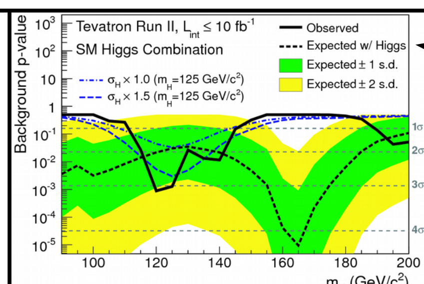
Indirect constraints from LEP



Final word from LEP



Final word from Tevatron



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*.

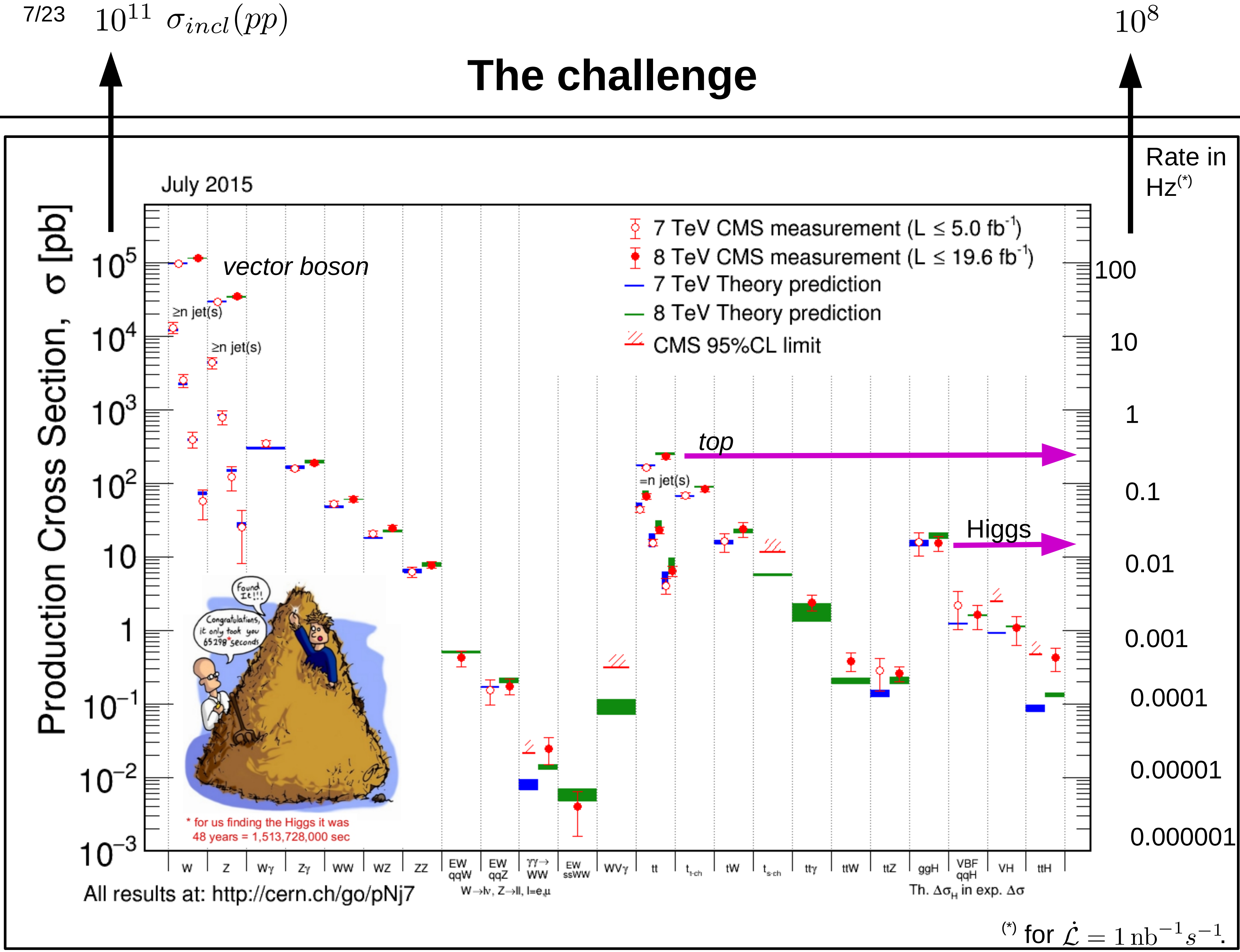
1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

2013: Nobel prize to Peter Higgs and Francois Englert.

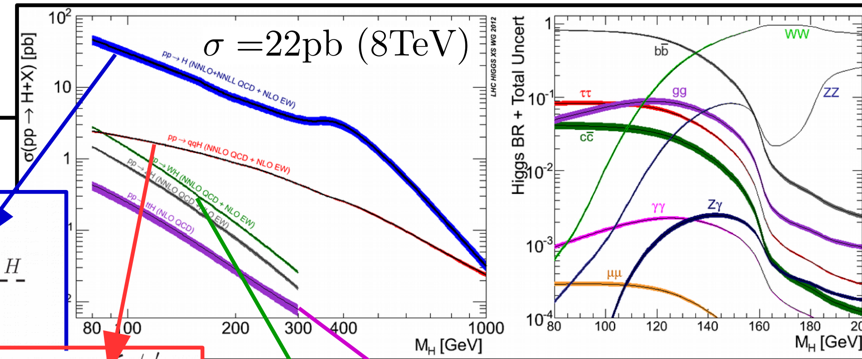
The challenge



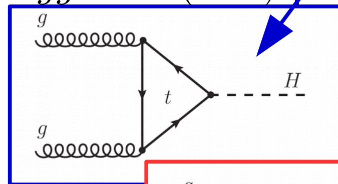
(*) for $\dot{\mathcal{L}} = 1\,\mathrm{nb}^{-1}s^{-1}$.

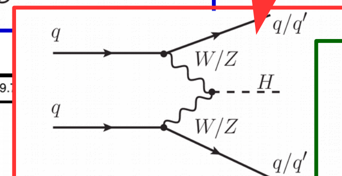
The discovery…

Production: Decay:

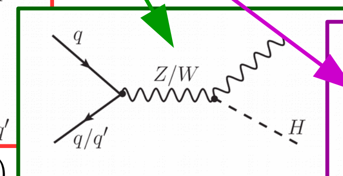


$gg \to H$ (87%)

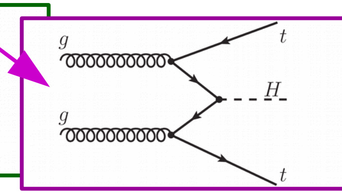




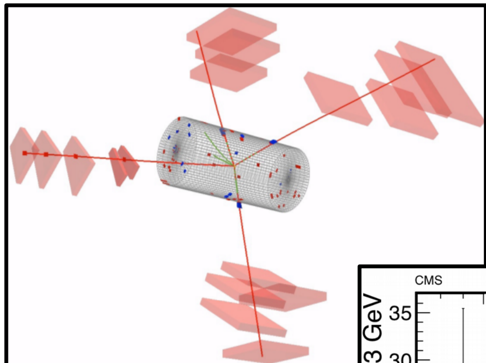
$qq \to H$ (7%)



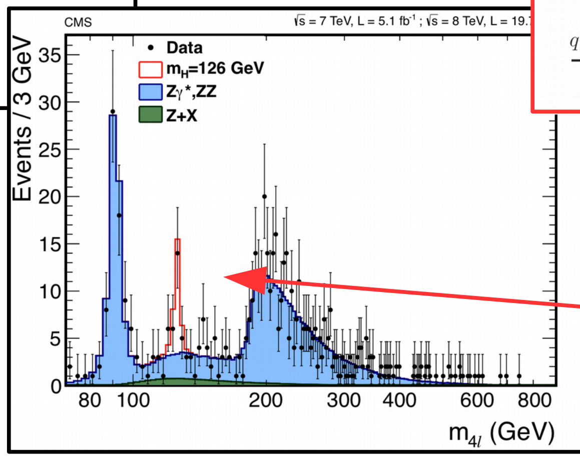
VH (5%)

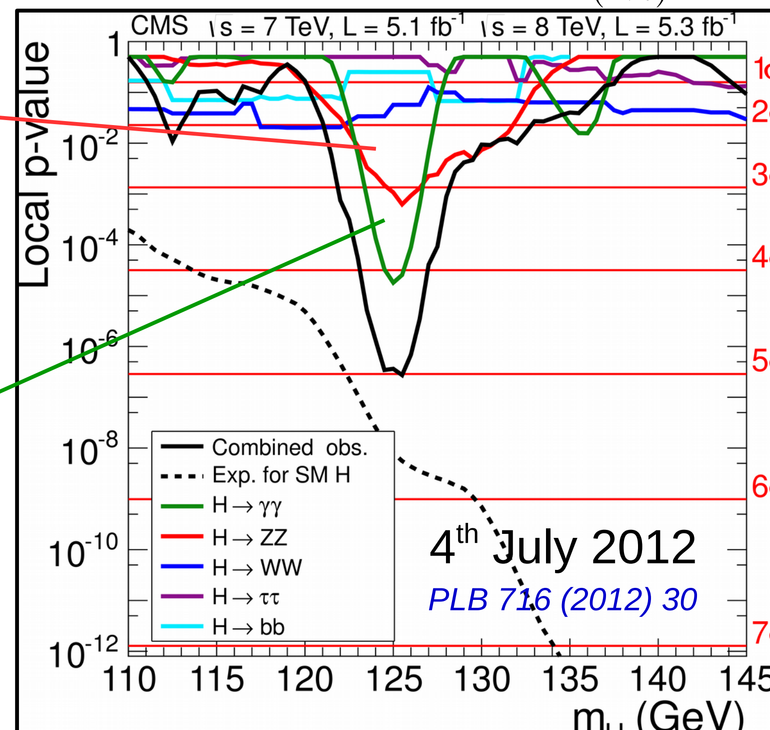


$t\bar{t}H$ (1%)

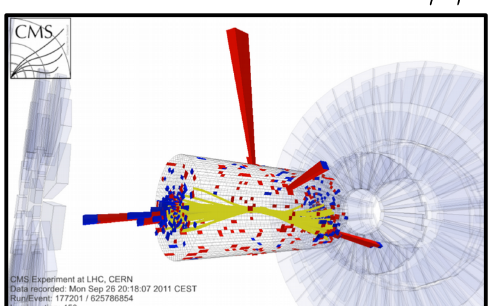


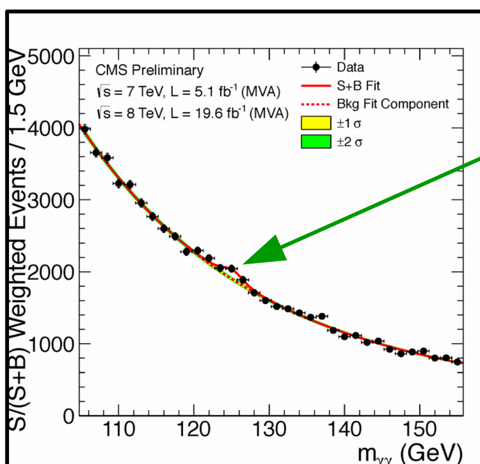
$H \to ZZ \to 4\ell$



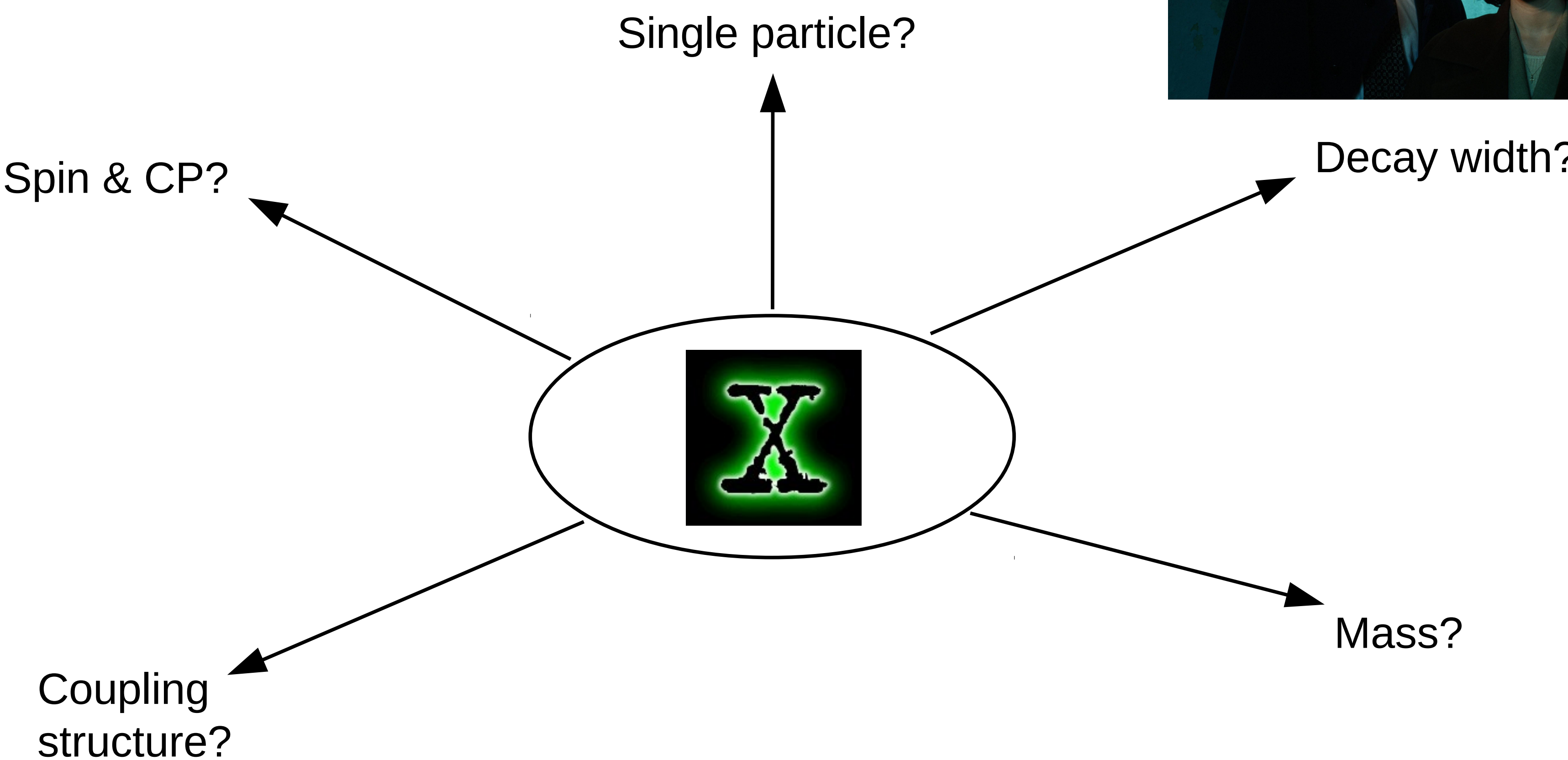


$H \to \gamma\gamma$



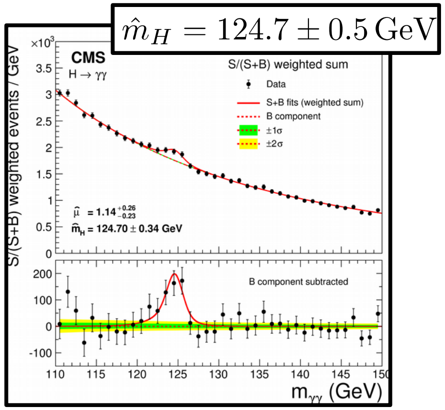


Anatomy of X

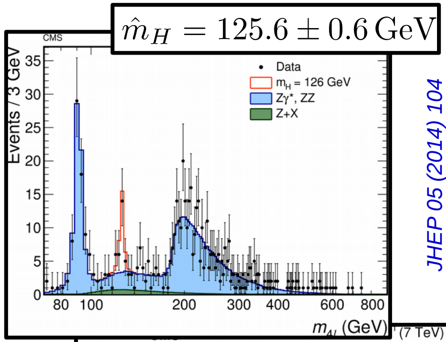

Single particle?
Spin & CP?
Decay width?
Coupling
structure?
Mass?

Compatibility

EPJ C 74 (2014) 3076

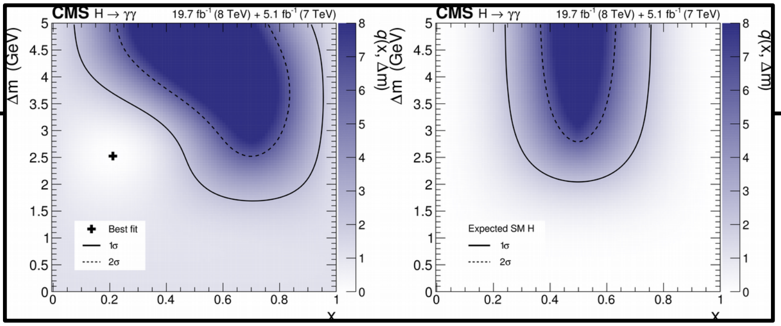


PRD 89 (2014) 092007

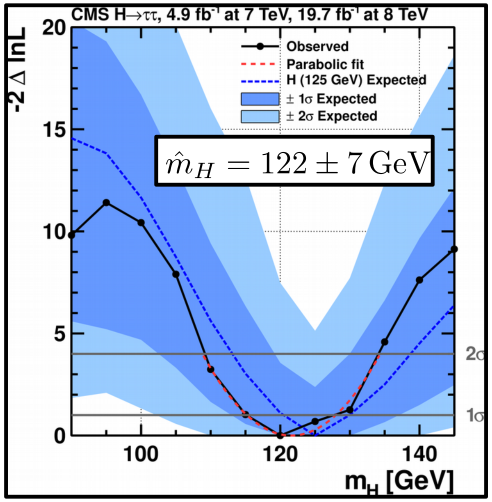


Second close-by resonance in $H \to \gamma\gamma$?

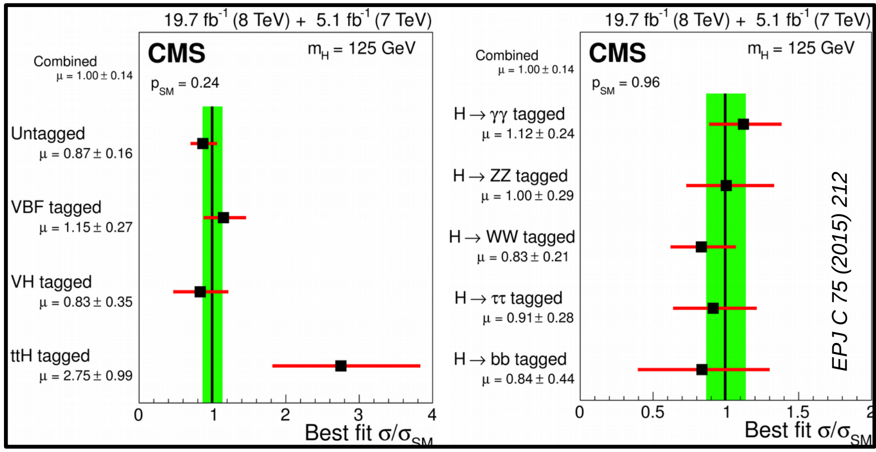
EPJ C 74 (2014) 3076



JHEP 05 (2014) 104

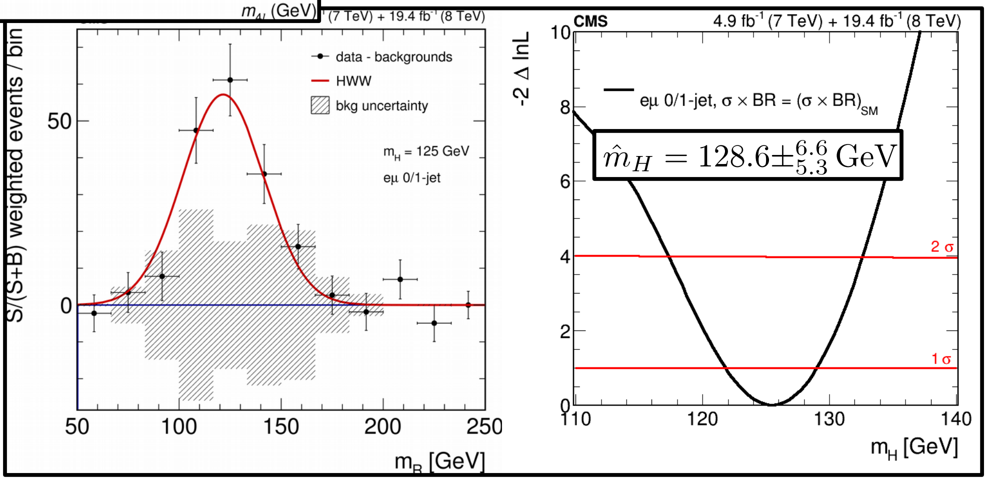


Coupling across production modes or decay channels:



EPJ C 75 (2015) 212

JHEP 01 (2014) 096



Overall coupling consistency:

EPJ C 75 (2015) 212

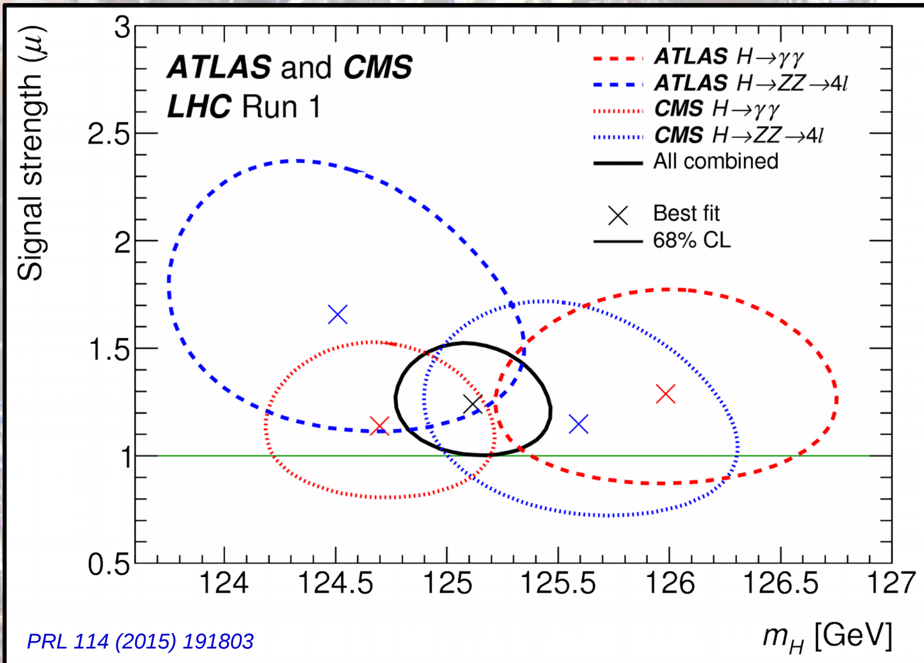
- Event categories : 227
- Nuisance parameters: $\mathcal{O}(2500)$
- 16 MB binary file of stat. model (~145 MB in human readable form).

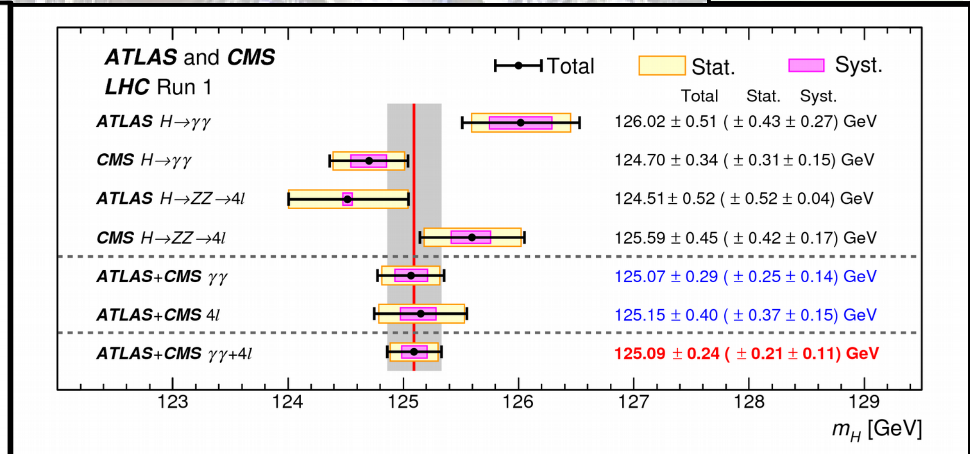
$\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.14$

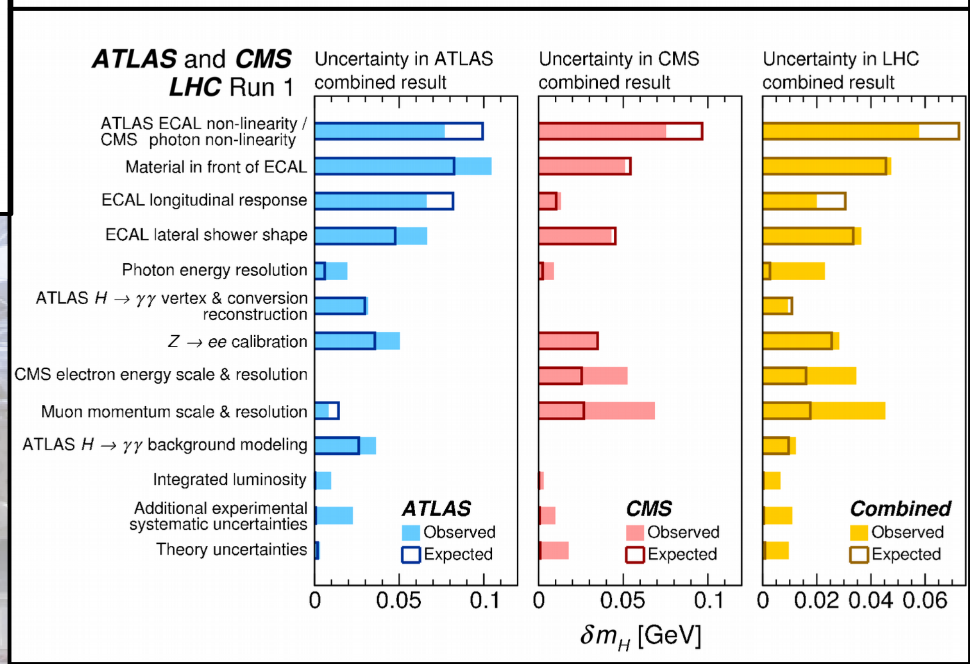
$p\text{-value} = 84\%$

Mass

- ATLAS+CMS LHC run-1 combination:





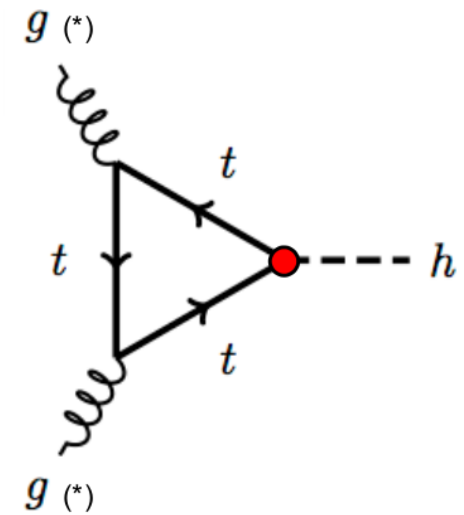


$$125.06 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})\ \text{GeV}$$

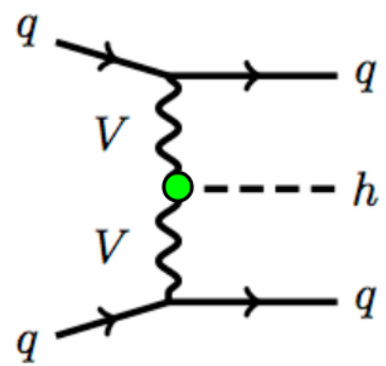
Coupling Estimates

- Determine couplings from production mode and decay channel:

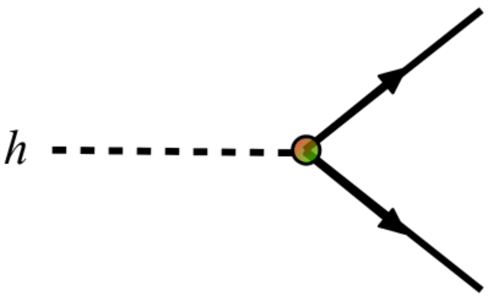
$gg \to H$ production:



$qq \to qqH$ production:



Decay to f or V:



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

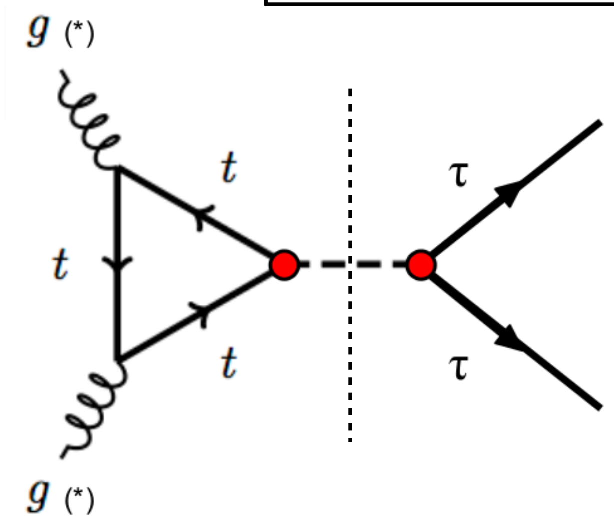
● V : $\kappa_{\mathrm{HVV}} = \frac{2m_V^2}{\mathrm{v}}$

- 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 $\Gamma_H = 4.04 \text{ MeV}$ and $m_H = 125 \text{ GeV}$.
- Propagator: $\frac{1}{(q^2-m^2+m^2\Gamma^2)} \to \frac{\pi}{m\Gamma}\delta(q^2-m^2)$ for $\Gamma \to 0$.



- 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

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

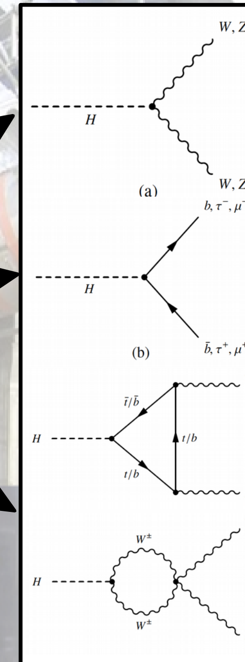
- ATLAS+CMS LHC run-1 combination:

Considered production modes:

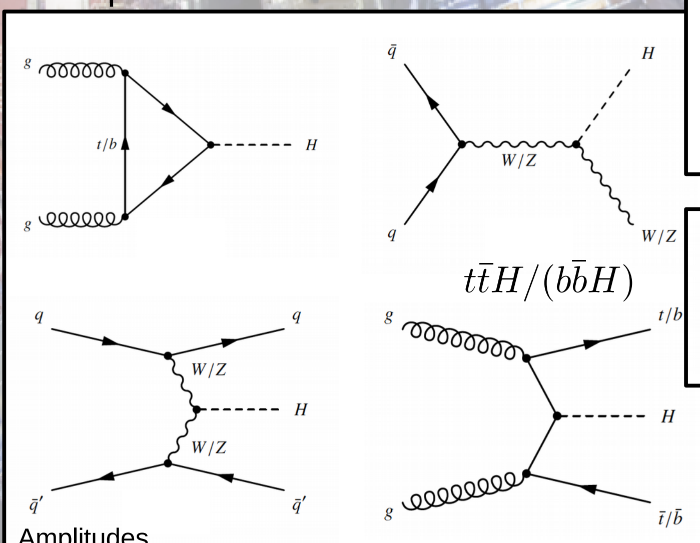
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)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

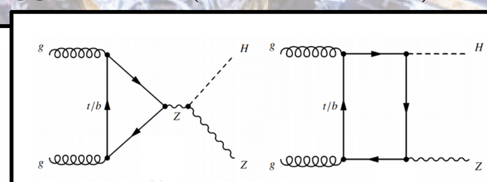
Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

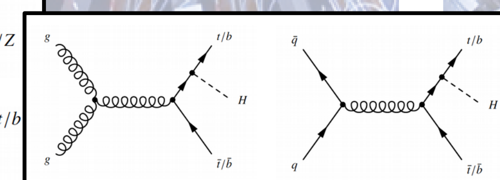


Main production modes:

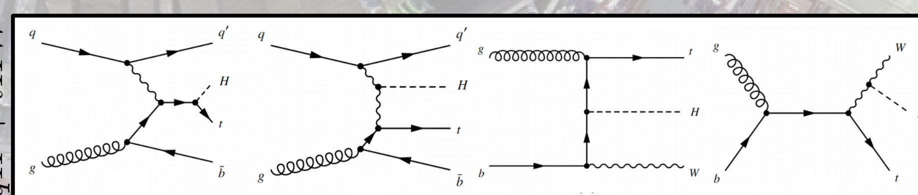


$gg \to ZH$ (10% to $ZHbb$)





$tqH + tHW$



The κ model

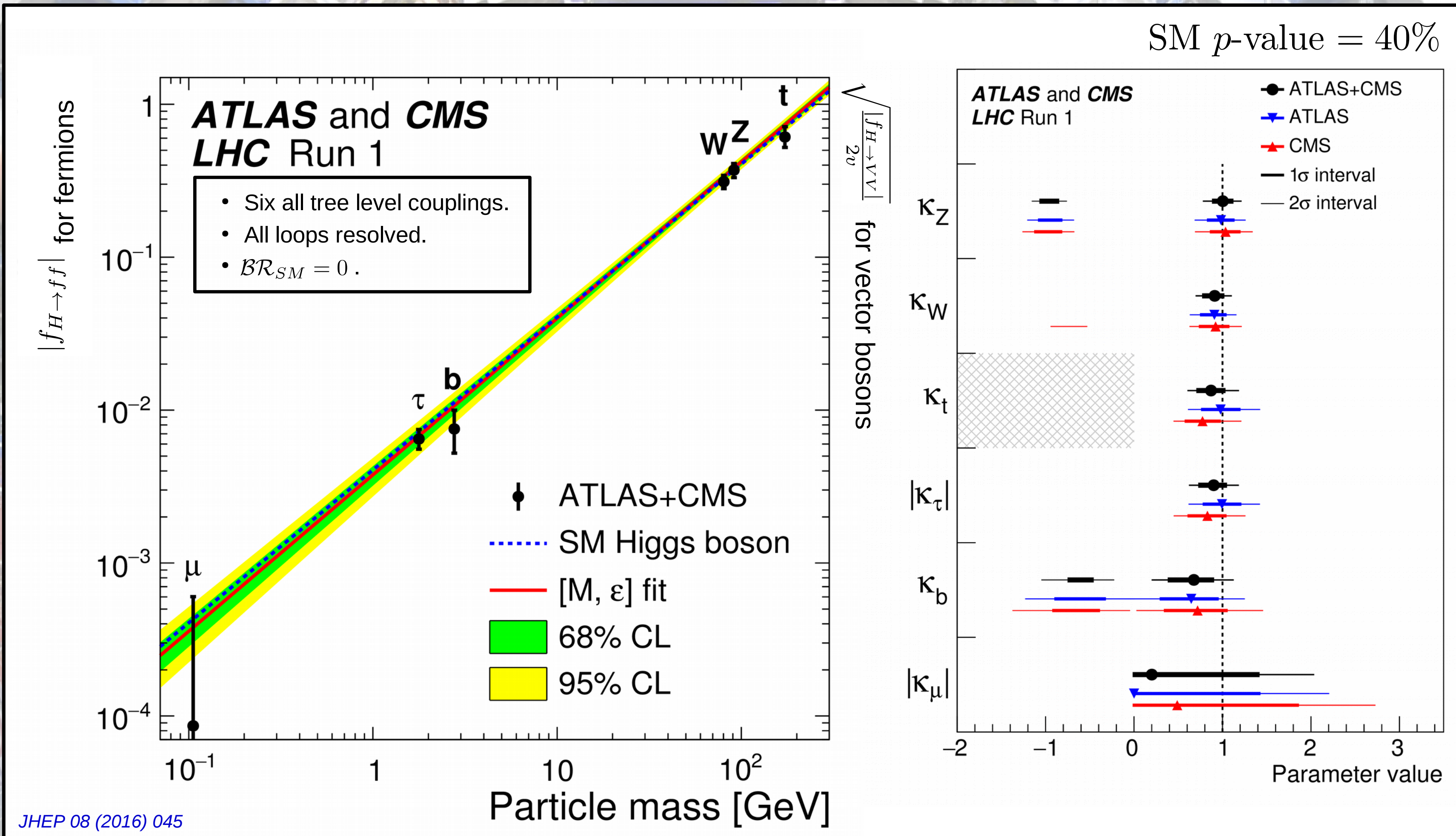
- Dress each coupling at tree-level with a scaling factor κ_i.
- Loops are resolved according to SM or treated as effective couplings.
- Comprise κ_i's to obtain simplified models.

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 $\mathrm{BR}_{\mathrm{BSM}} = 0$			
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: $\kappa_c = \kappa_t,\ \kappa_\mu = \kappa_\tau,\ \kappa_s = \kappa_b$.

“Money plot”



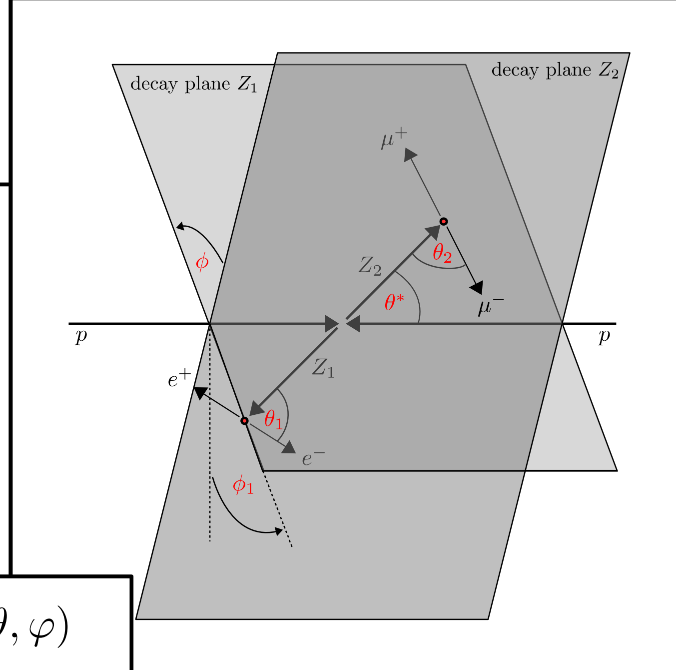
$$|f^{\text{obs}}_{H\to ff}| = \kappa_f \cdot |f^{\text{SM}}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

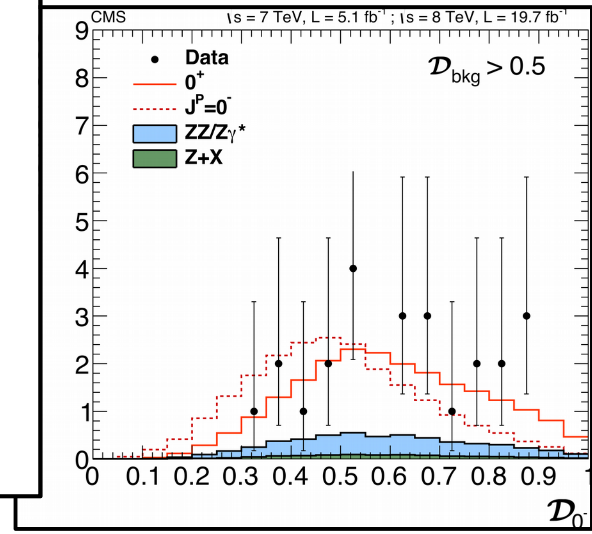
$$\sqrt{\frac{|f^{\text{obs}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{|f^{\text{SM}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \frac{m_V}{v} \qquad V = W, Z$$

Within measurement accuracy unique scaling as expected within the SM.

Spin & CP

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

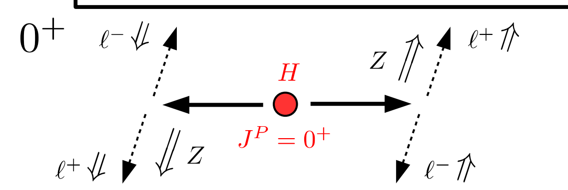




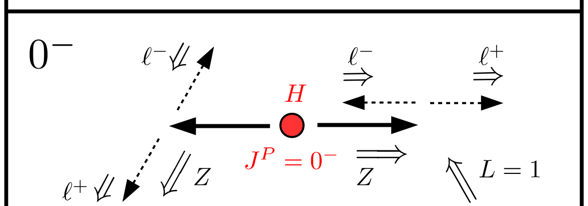
PRD 89 (2014) 092007

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

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

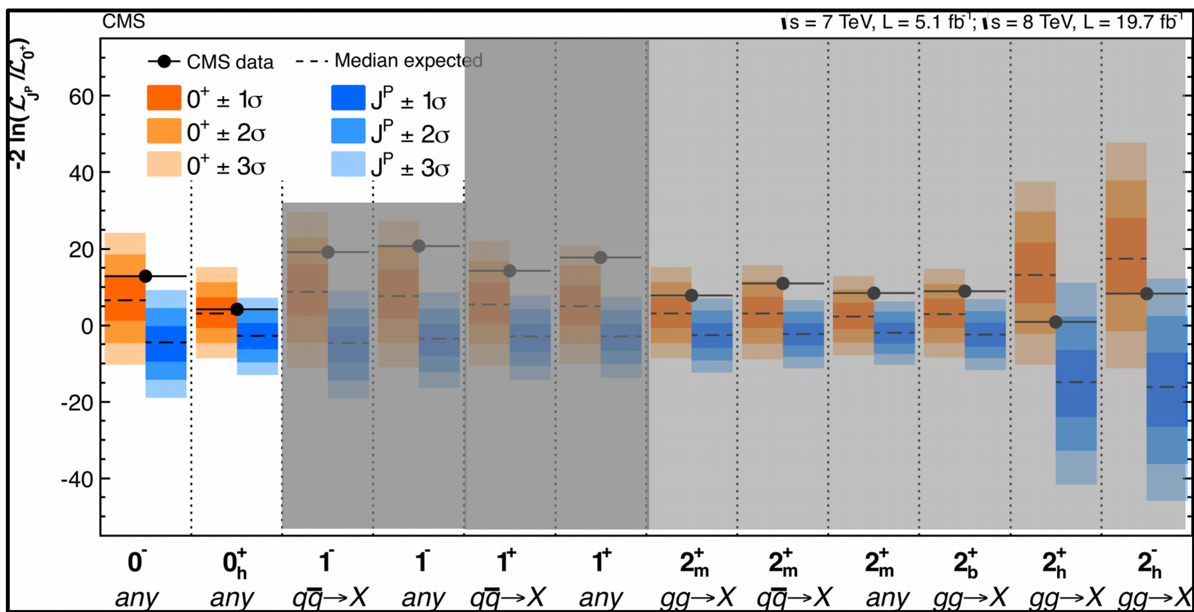


$$|0,0\rangle = \sqrt{\tfrac{1}{3}}|1,\ \ 1\rangle \otimes |1,-1\rangle - \sqrt{\tfrac{1}{3}}|1,0\rangle \otimes |1,0\rangle + \sqrt{\tfrac{1}{3}}|1,-1\rangle \otimes |1,\ \ 1\rangle$$



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

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



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.

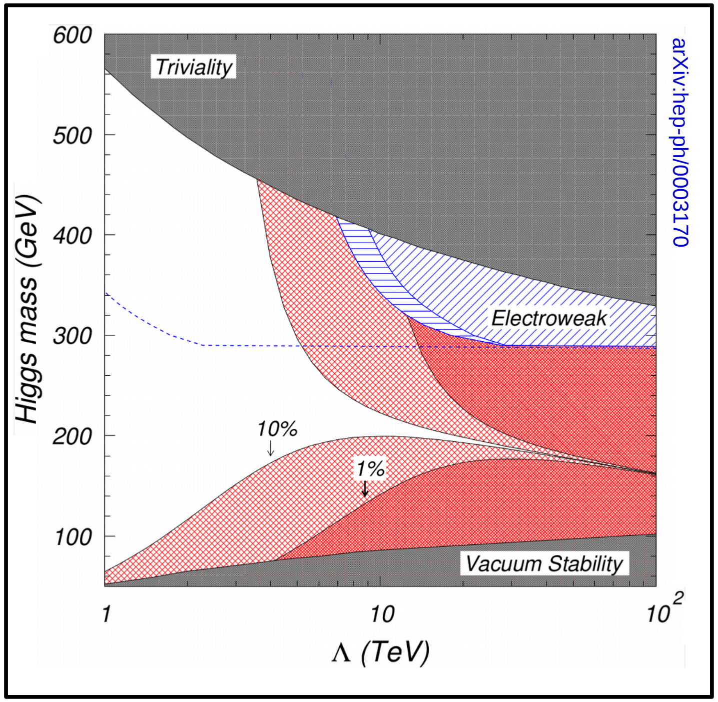
Coupling structure? ✓
- Non-trivial coupling structure of a SM-like Higgs boson.
- No sign for deviations so far!

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

MISSION ACCOMPLISHED?

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)

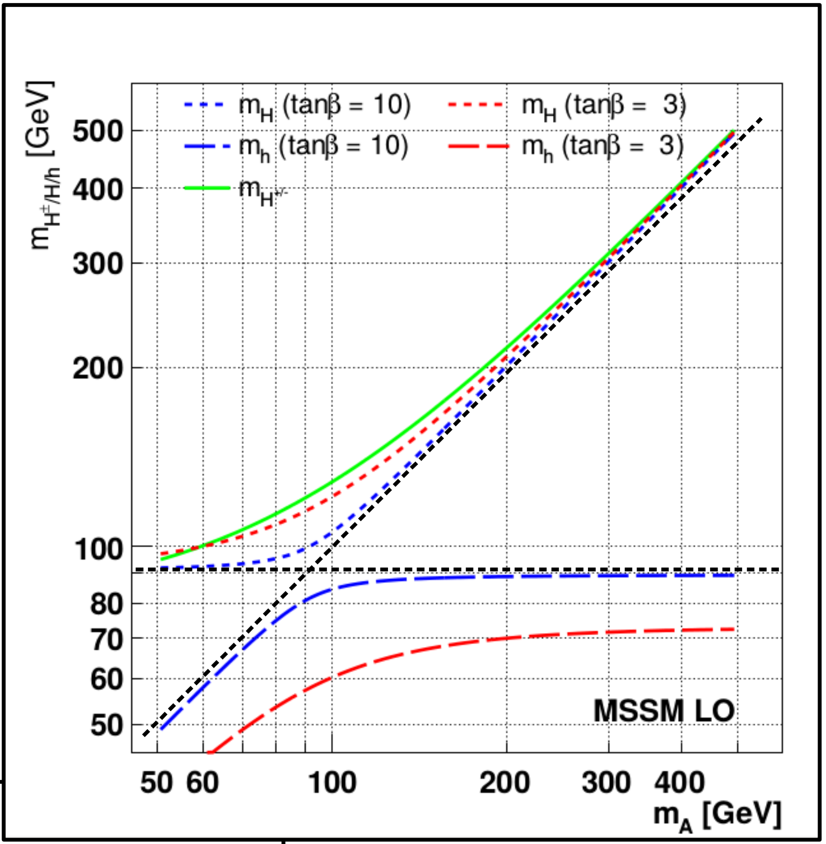
Higgs Bosons in the MSSM

- Any 2 Higgs Doublet Model (2HDM) predicts **five Higgs bosons**:

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

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

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



- **Strict mass requirements** at tree level:
 two free parameters: m_A, $\tan\beta = {}^{v_u}/_{v_d}$

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

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

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

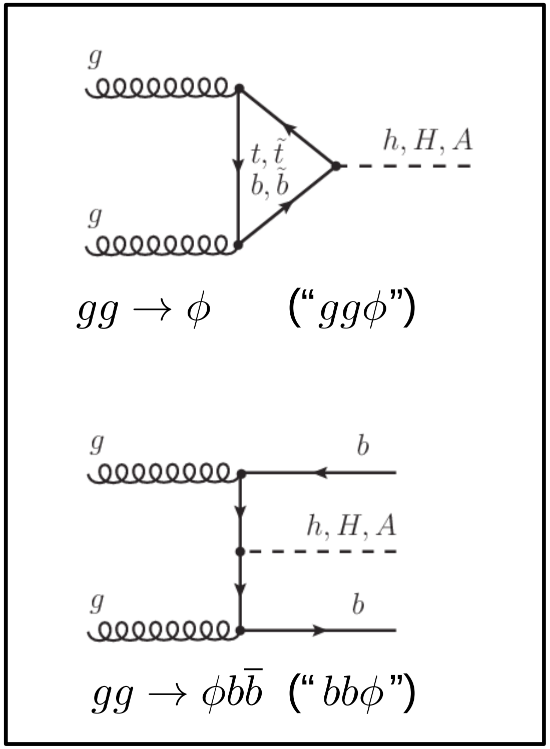
α : angle between H and h in mass matrix

Special 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	$\sin(\beta-\alpha) \rightarrow 1$	$\cos\alpha/\sin\beta \rightarrow 1$	$-\sin\alpha/\cos\beta \rightarrow 1$

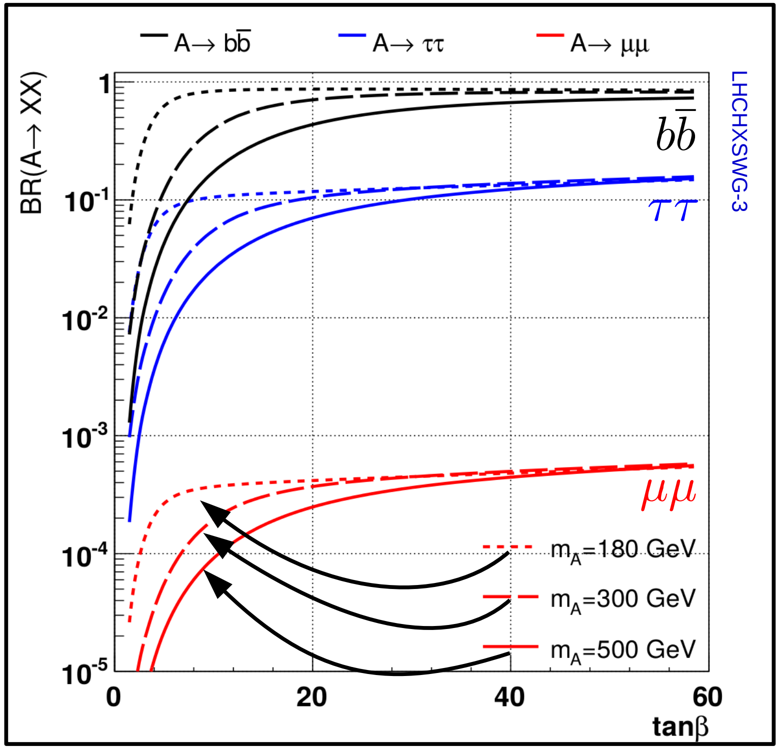
For $m_A \gg m_Z$: $\alpha \rightarrow \beta - \pi/2$ (coupling to down-type fermions enhanced by $\tan\beta$).

Production modes:

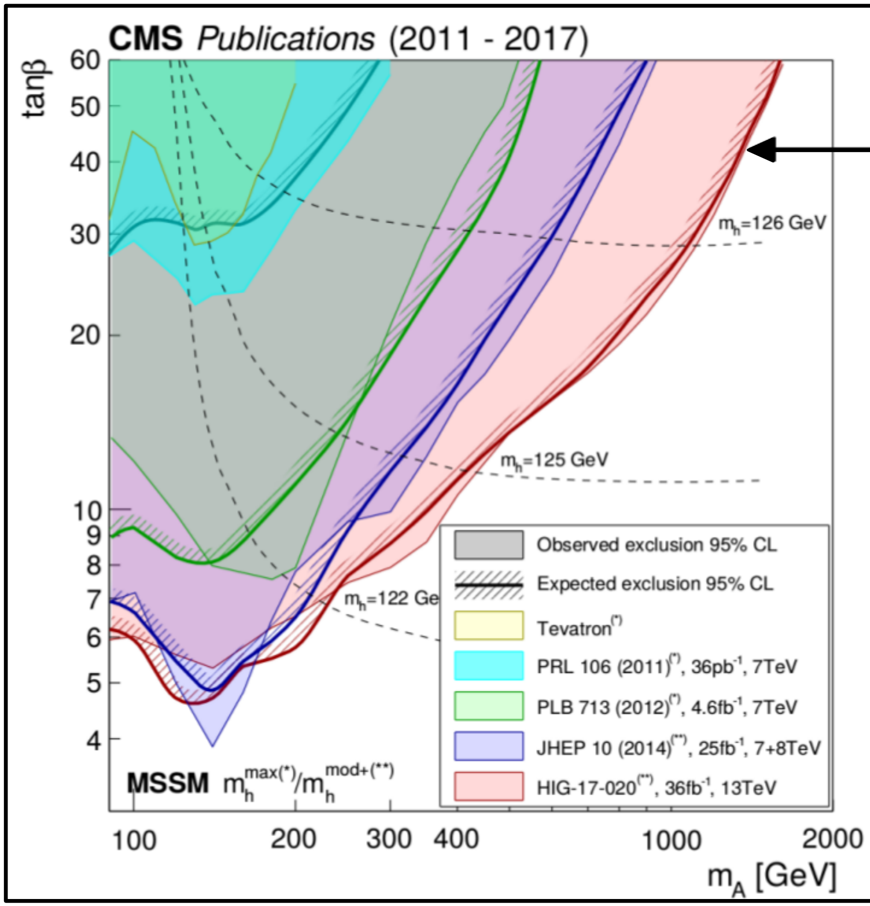


X

Decay channels:



History of MSSM $H \to \tau\tau$ searches @ CMS



- **Brand new CMS result** discussed in the following (based on 36/fb @ 13TeV).

Available on the CERN CDS information server CMS PAS HIG-17-020

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2017/12/06

Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search is presented for additional neutral Higgs bosons in the di-τ final state in pp collisions at the LHC. The search is performed in the context of the minimal supersymmetric extension of the standard model (MSSM), on the data collected with the CMS detector in 2016 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. To enhance the sensitivity to neutral MSSM Higgs bosons the search includes the case where the Higgs boson is produced in association with b quarks. No significant deviation above the expected background is observed. Model-independent limits are set on the product of the cross section and branching fraction for the production via gluon-fusion or in association with b quarks. These limits range from 18 pb (at 90 GeV) to 3.5×10^{-3} pb (at 3.2 TeV) for gluon-fusion and from 15 pb (at 90 GeV) to 2.5×10^{-3} pb (at 3.2 TeV) for b-associated production. In the m_h^{mod+} scenario these limits translate into an exclusion of $\tan\beta > 6$ for $m_h \lesssim 200$ GeV. The exclusion contour ranges up to 1.6 TeV for $\tan\beta < 60$.

Remaining lecture program

	Monday (12.03):	Tuesday (13.03.):
13:30 15:00	Introdu[illegible] particle physics[illegible]	Proton stru[illegible] QCD jets and flavor [illegible]
15:15 16:45	Particle [illegible]eration & detecti[illegible]); data analysis (MM).	Heavy qua[illegible]uge bosons (M[illegible] iggs bosons (RW).

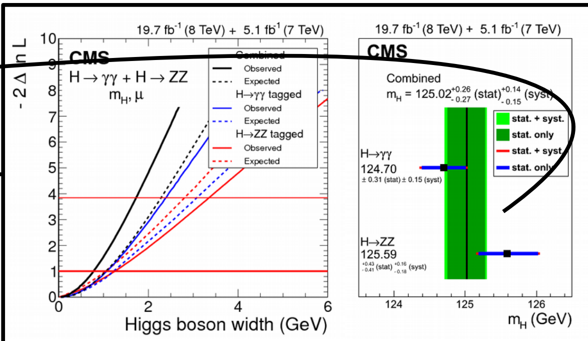
- In case of questions – contact us matthias.mozer@cern.ch (Bld. 30.23 Room 9-8)
  roger.wolf@cern.ch (Bld. 30.23 Room 9-20).

Backup

Mass & decay width

compatible within 1.6σ.

PRD 92 (2015) 012004



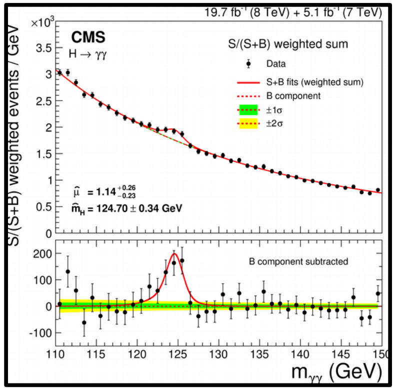
$$\hat{m}_H = 125.02 \pm^{0.26}_{0.27} \text{ (stat.) } \pm^{0.14}_{0.15} \text{ (syst.) GeV}$$

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

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

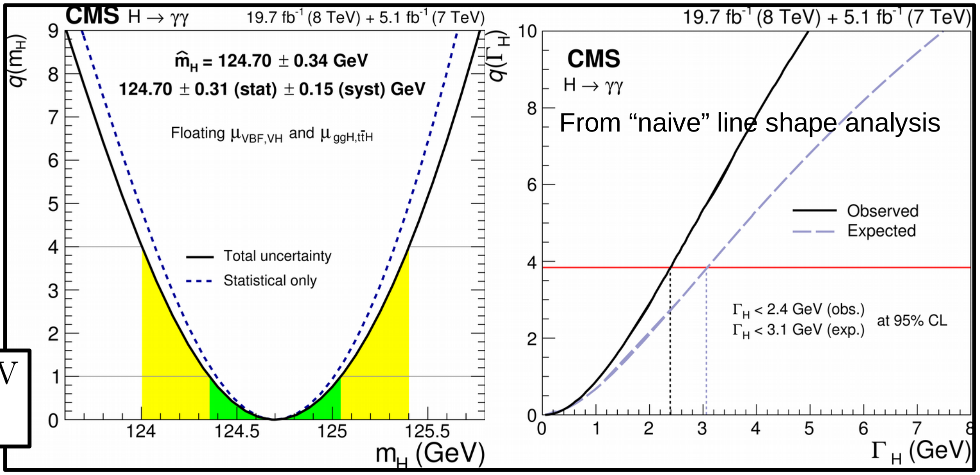
Expectation from SM:
$\Gamma_H(125 \text{ GeV}) = 4.04 \text{ MeV}$

EPJ C 74 (2014) 3076

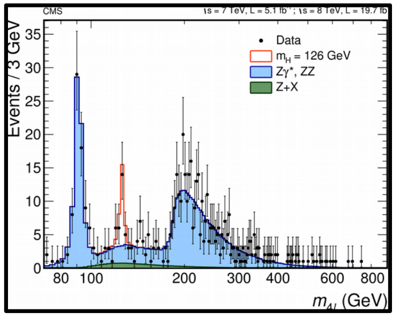


$$\hat{m}_H = 124.7 \pm^{0.5}_{0.31} \text{ (stat.) } \pm 0.15 \text{(syst.) GeV}$$

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

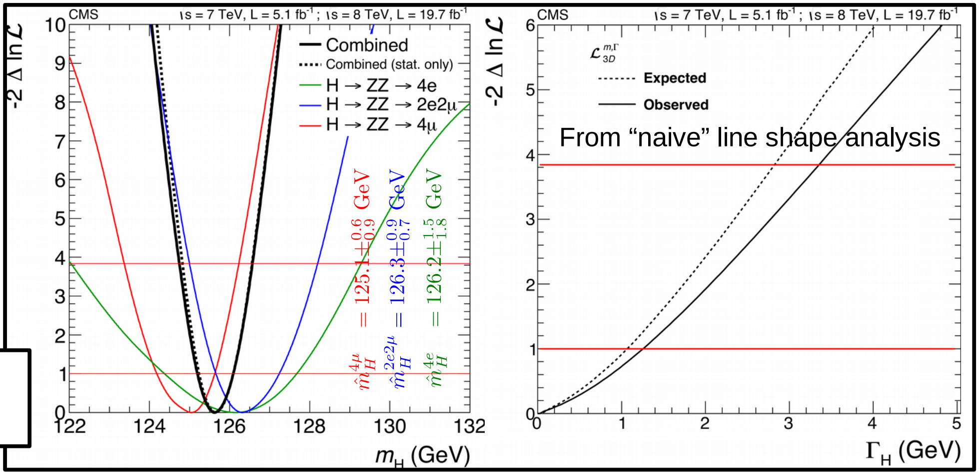


PRD 89 (2014) 092007

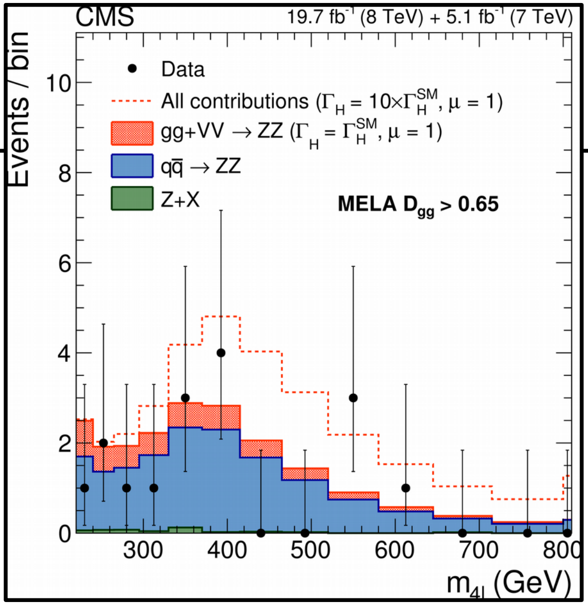


$$\hat{m}_H = 125.6 \pm^{0.5}_{0.4} \text{ (stat.) } \pm 0.1 \text{(syst.) GeV}$$

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



Mass & decay width



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

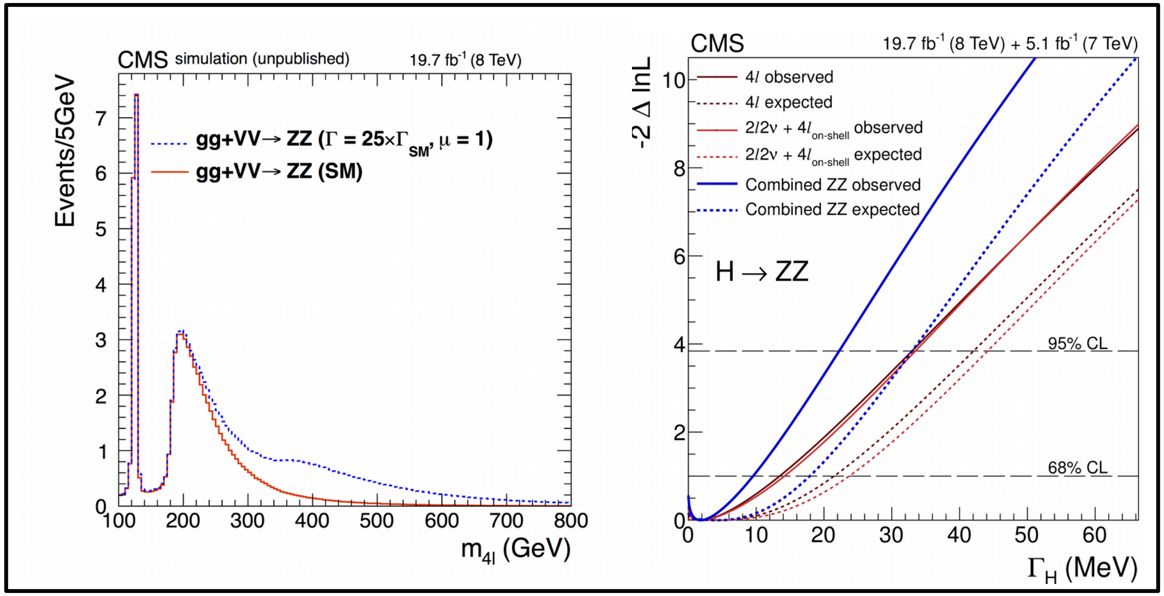
$$\frac{d\sigma(gg\to ZZ\to 4\ell)}{dm^2_{4\ell}} \propto \frac{\kappa_g^2\kappa_Z^2}{\left(m^2_{4\ell}-m^2_H\right)^2+m^2_H\Gamma^2_H}$$

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

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

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

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

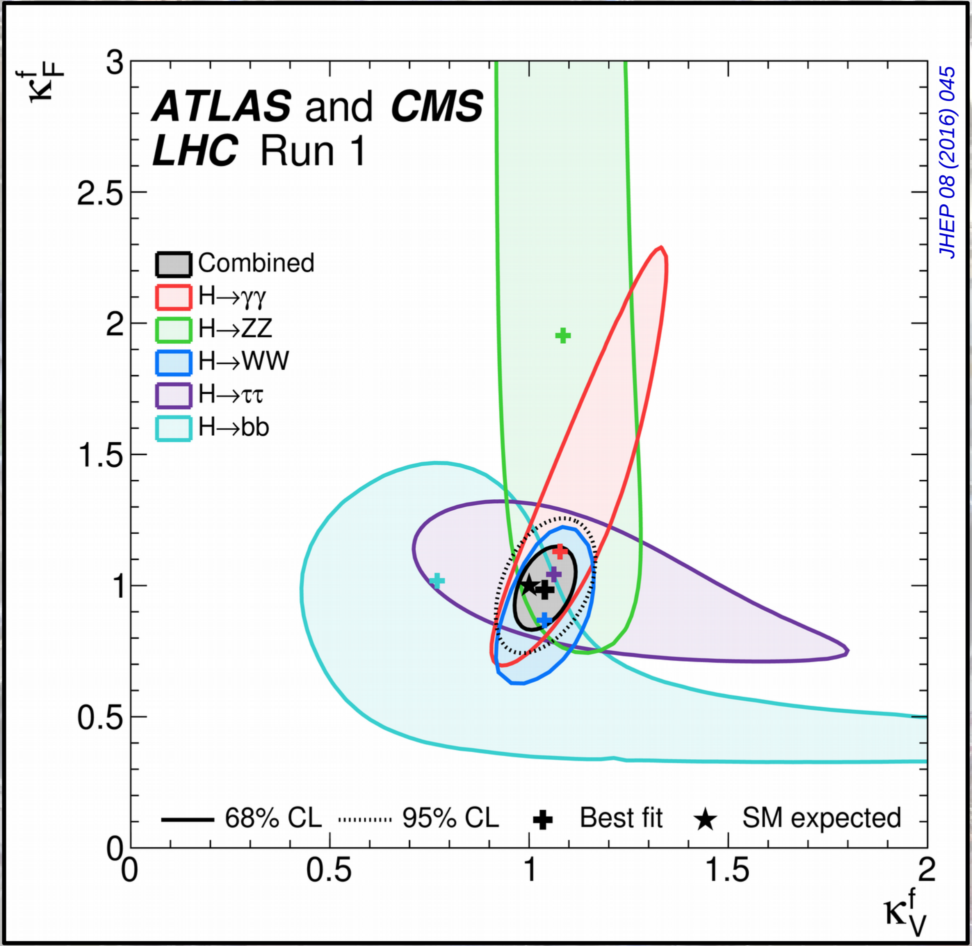


PLB 736 (2014) 64

κ_V- κ_F model

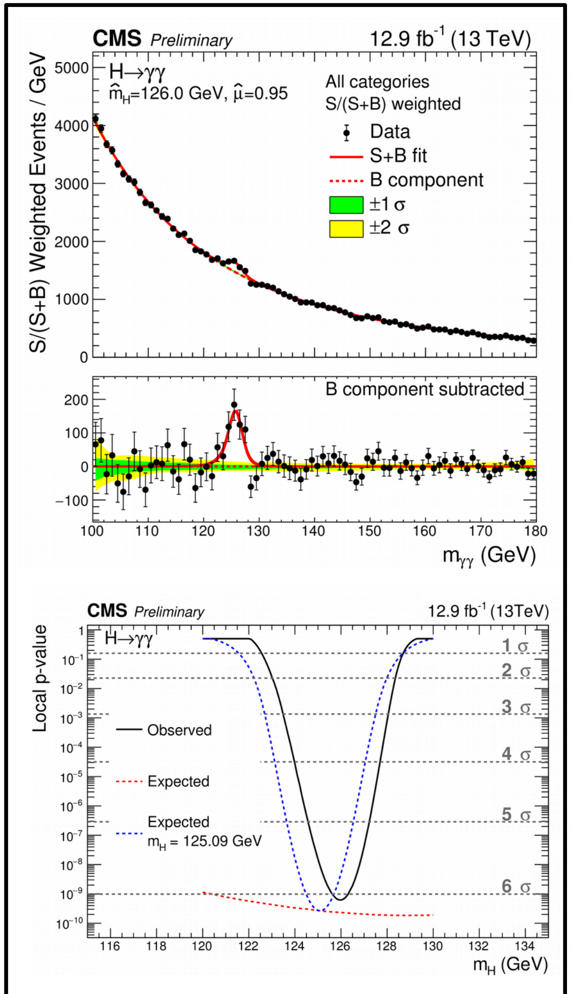
- Resolve loops according to SM.
- Combine tree-level couplings into κ_V (coupling to *W* & *Z* boson) and κ_F (couping to fermions).

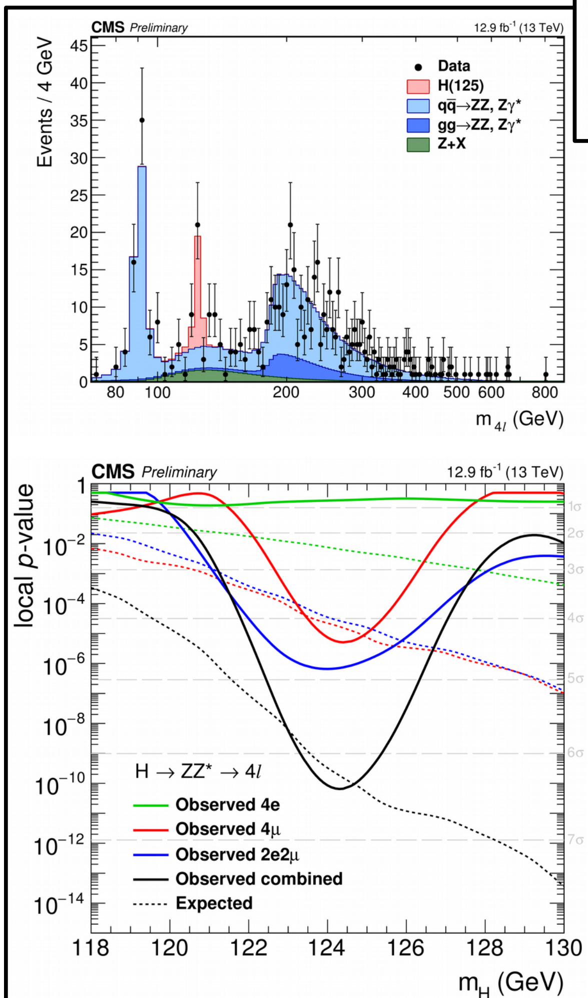
$\kappa_V \supset W, Z$ $\kappa_F \supset t, b, \tau, \ldots$

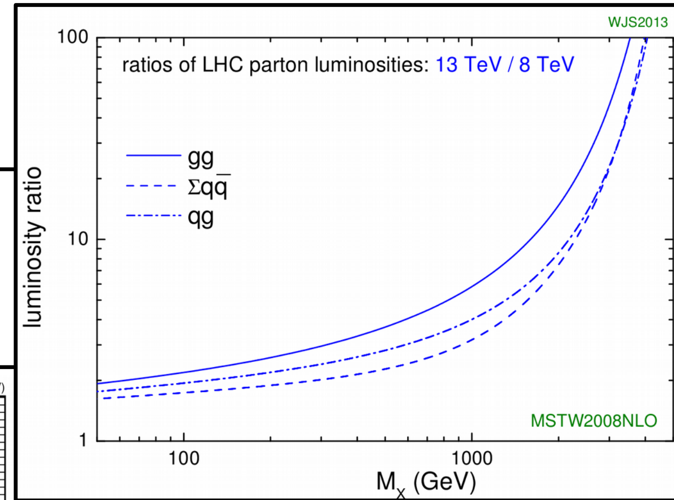


Higgs still there?

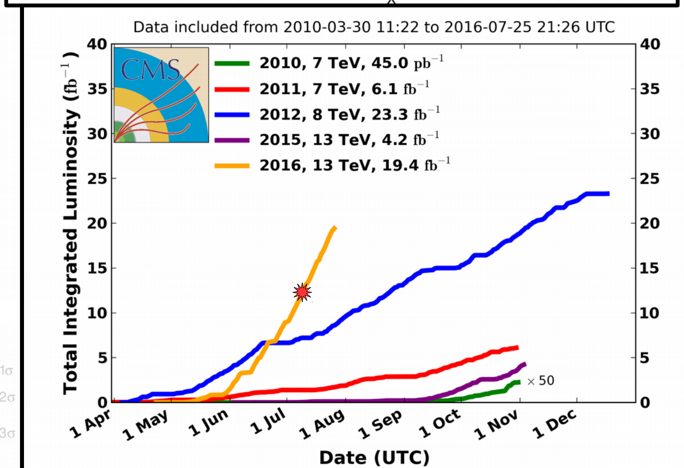
- Better find the new particle back where you saw it in LHC run-1…







James Stirling (arXiv:0901.0002)

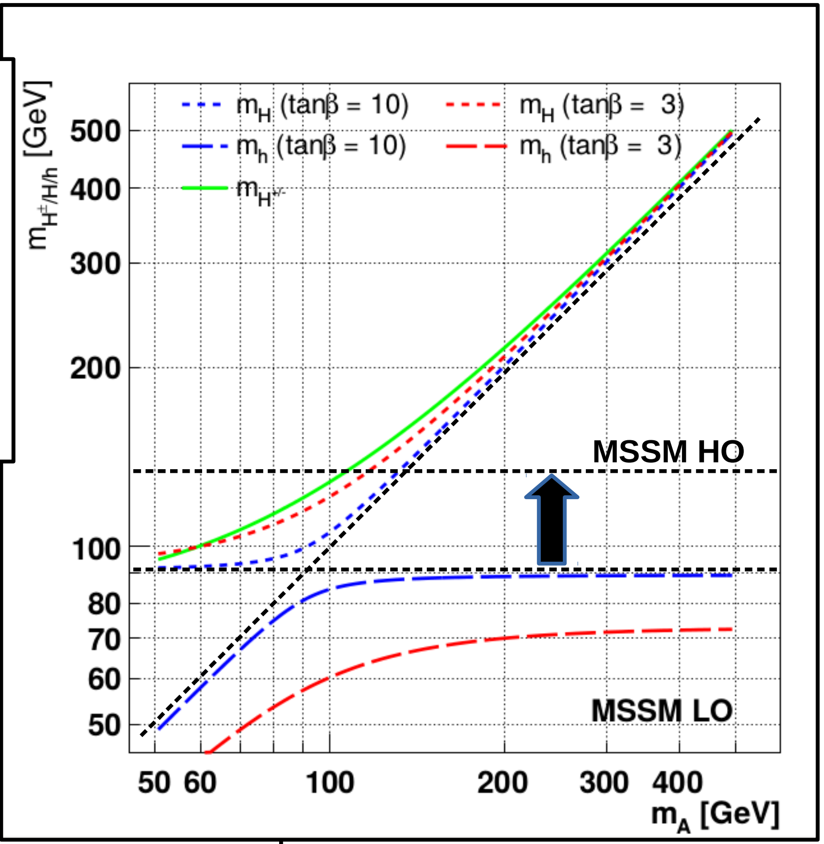


Mass of observed Higgs Boson and $\tan\beta$

$$\Delta m_h^2 \frac{3}{(4\pi)^2} \frac{m_t^4}{v^2} \left(\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right)$$

- 30% of m_h due to higher order corrections.
- Following factors help to increase m_h: large m_t, large $m_{\tilde{t}}$, large X_t and large $\tan\beta$.

$X_t = m_t\,(A_t - \mu \cot\beta)$



- **Strict mass requirements** at tree level:
  two free parameters: m_A, $\tan\beta = v_u/v_d$

$$\begin{aligned}
m_{H^\pm}^2 &= m_A^2 + m_W^2 \\
m_{H,\,h}^2 &= \tfrac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta}\right) \\
\tan\alpha &= \frac{-(m_A^2 + m_Z^2)\sin 2\beta}{(m_Z^2 - m_A^2)\cos 2\beta + \sqrt{\left(m_A^2+m_Z^2\right)^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta}}
\end{aligned}$$

α : angle between H and h in mass matrix