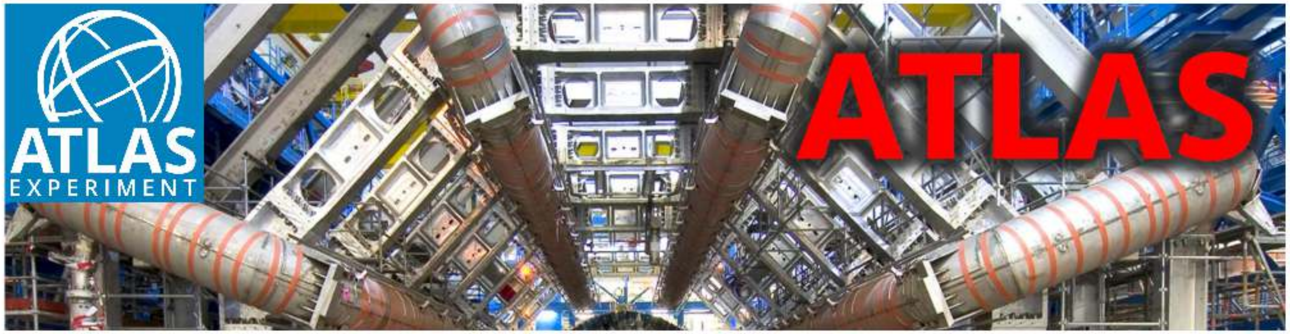
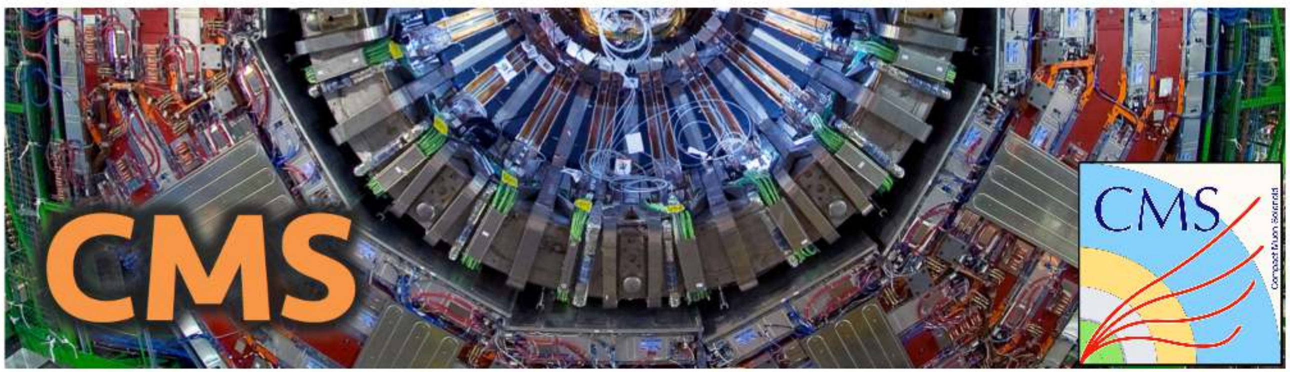
# The Higgs Boson




## Characterisation of its Nature




GK-Seminar, Freiburg, 26. April 2017

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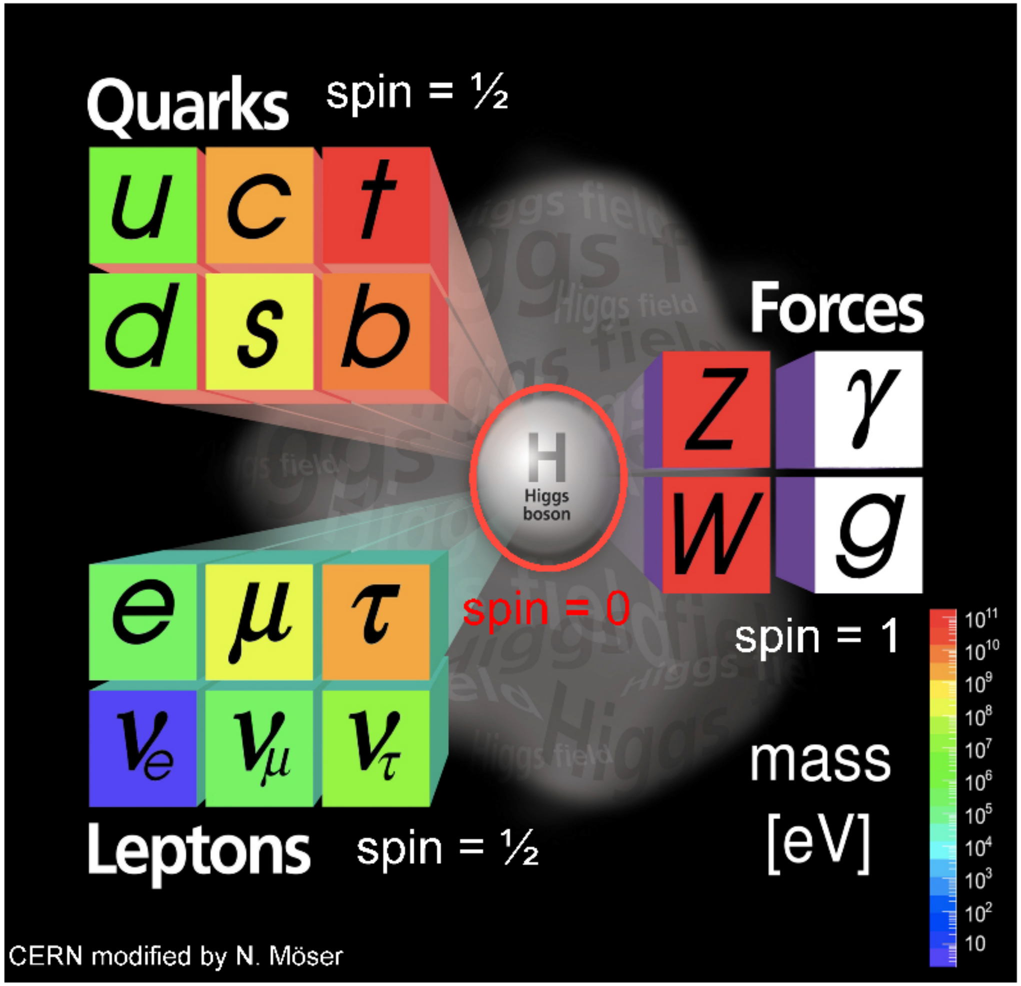
# The Brout-Englert-Higgs-Mechanism in the SM

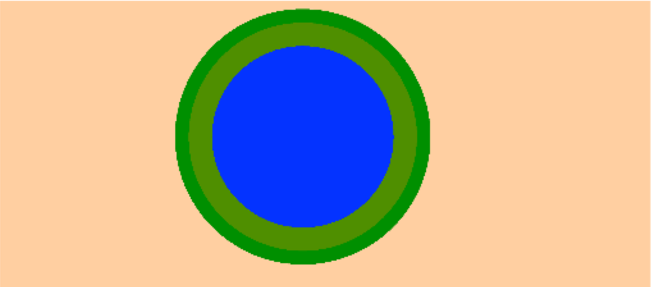
Brout,Englert; Higgs; Guralnik, Hagen, Kibble 1964




Scalar Higgs field

- develops a condensate
- excitation is Higgs boson

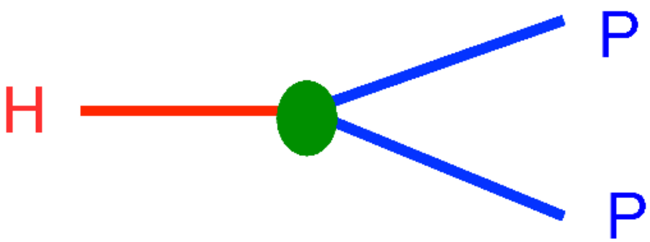
Interaction with condensate "provides" particle mass



particle P mass = coupling x vev

vev = vacuum expectation value

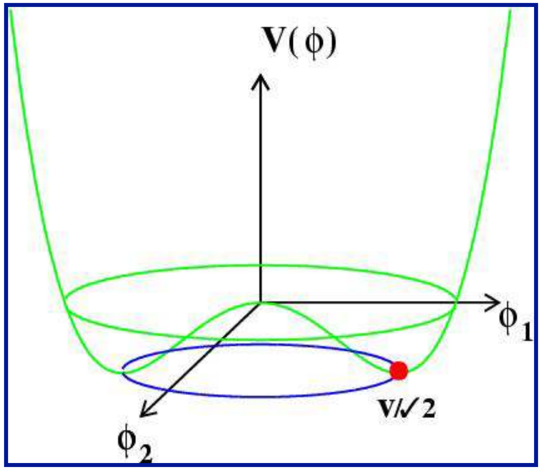
Higgs boson H interacts with particle P via same coupling




Allows to describe elementary particles masses w/o

- destroying renormalizibility / predictive power
- violating unitarity in high-energy scattering

# The BEH-Mechanism in the SM




$$v = \sqrt{\frac{2\mu^2}{\lambda}} = 247\text{GeV}$$

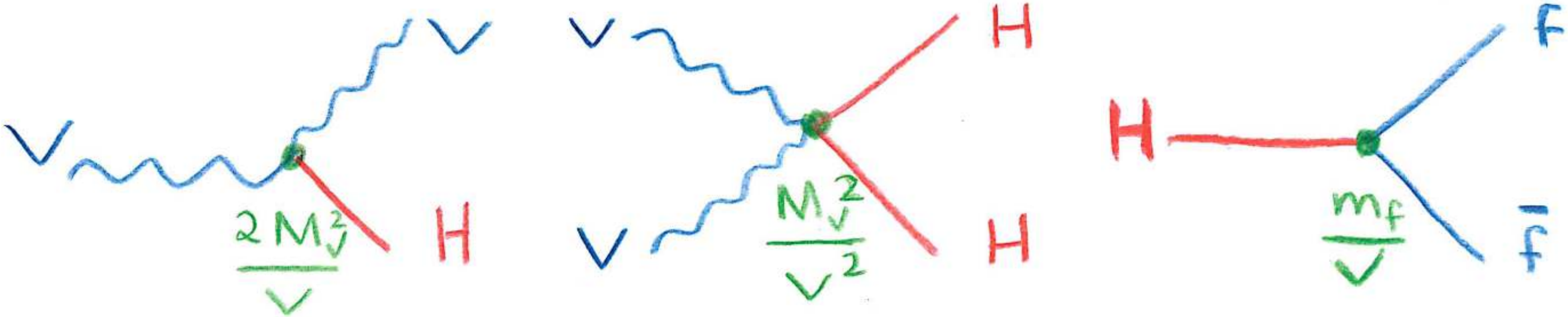
Most general renormalizable gauge invariant potential:

$$V(\phi) \simeq -\mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2 \qquad \mu^2, \lambda > 0$$

Condensate v hides symmetry of underlying Langrangian

$$M_W = \frac{g}{2} v \qquad m_f = \frac{\lambda_f}{\sqrt{2}} v \qquad M_H = \sqrt{\lambda} v$$

Coupling of Higgs boson to other particles fixed by particle mass and vev



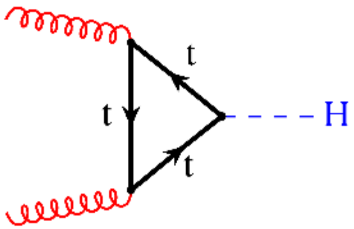

Higgs boson mass: - enters production and decay rates via phase space

- determines Higgs boson self coupling

# Higgs Boson Production at the LHC in the SM

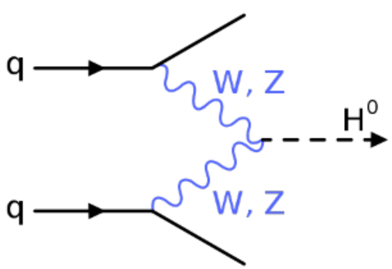
Four major production modes

Gluon Fusion gg→H

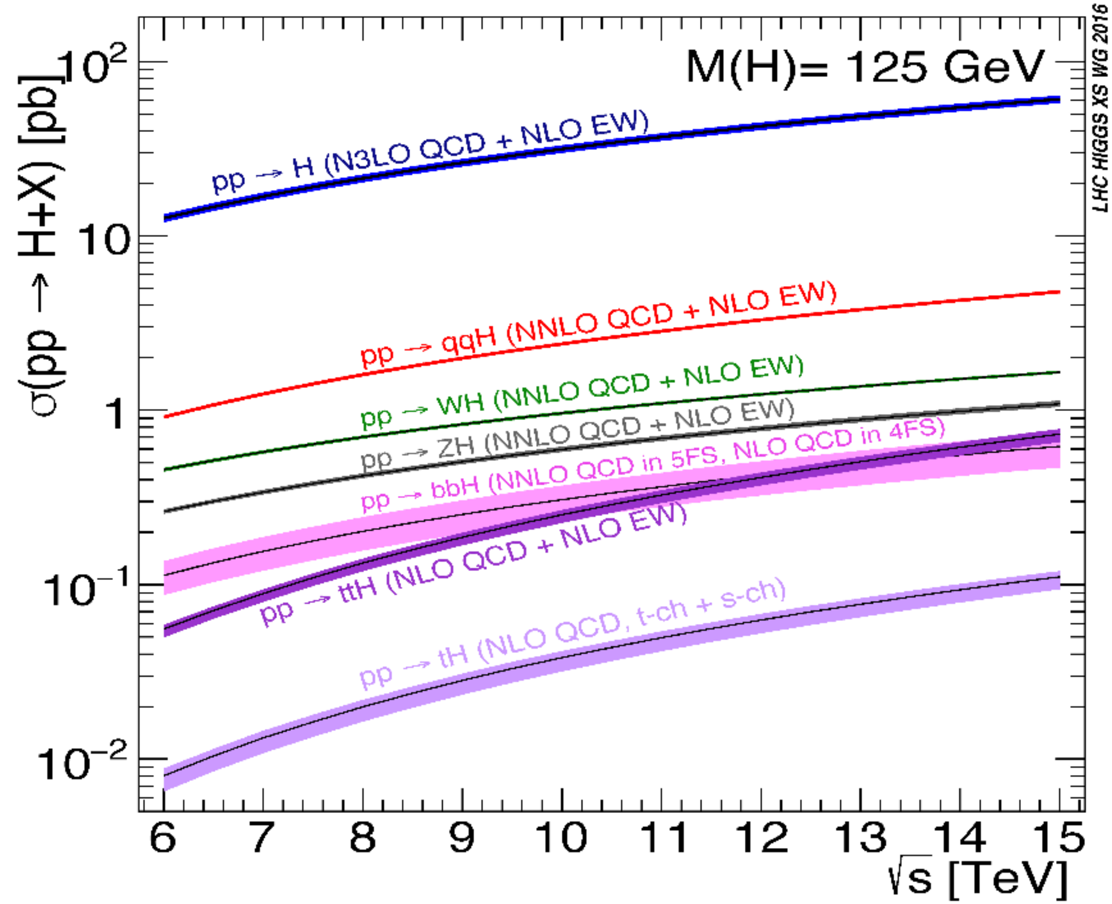



~ 88%

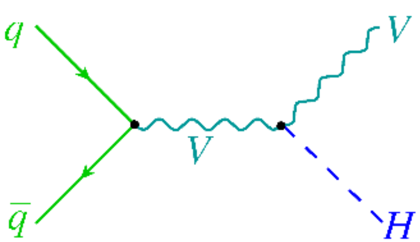
Vector Boson Fusion (VBF)




~ 7%

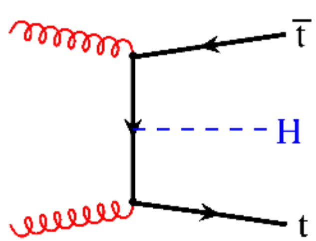



Higgs-Strahlung VH




~ 4%

ttH production



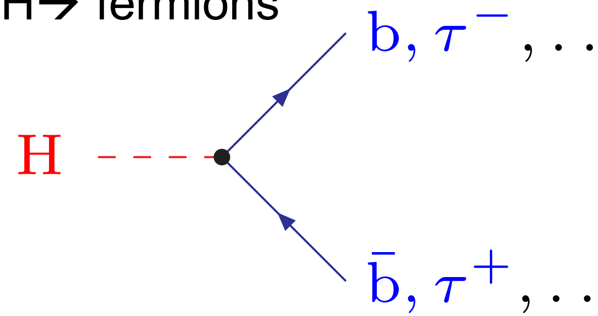

~ 1%

From √s=8 to 13 TeV:
increase of $\sigma_{H,tot}$ by factor 2.3

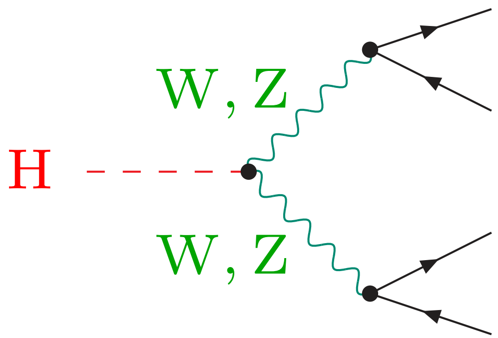
Major theoretical effort to reach this precision: LHCHXSWG

# Higgs Boson Decays in the Standard Model

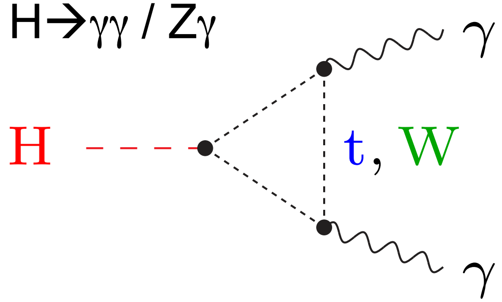
H→ fermions



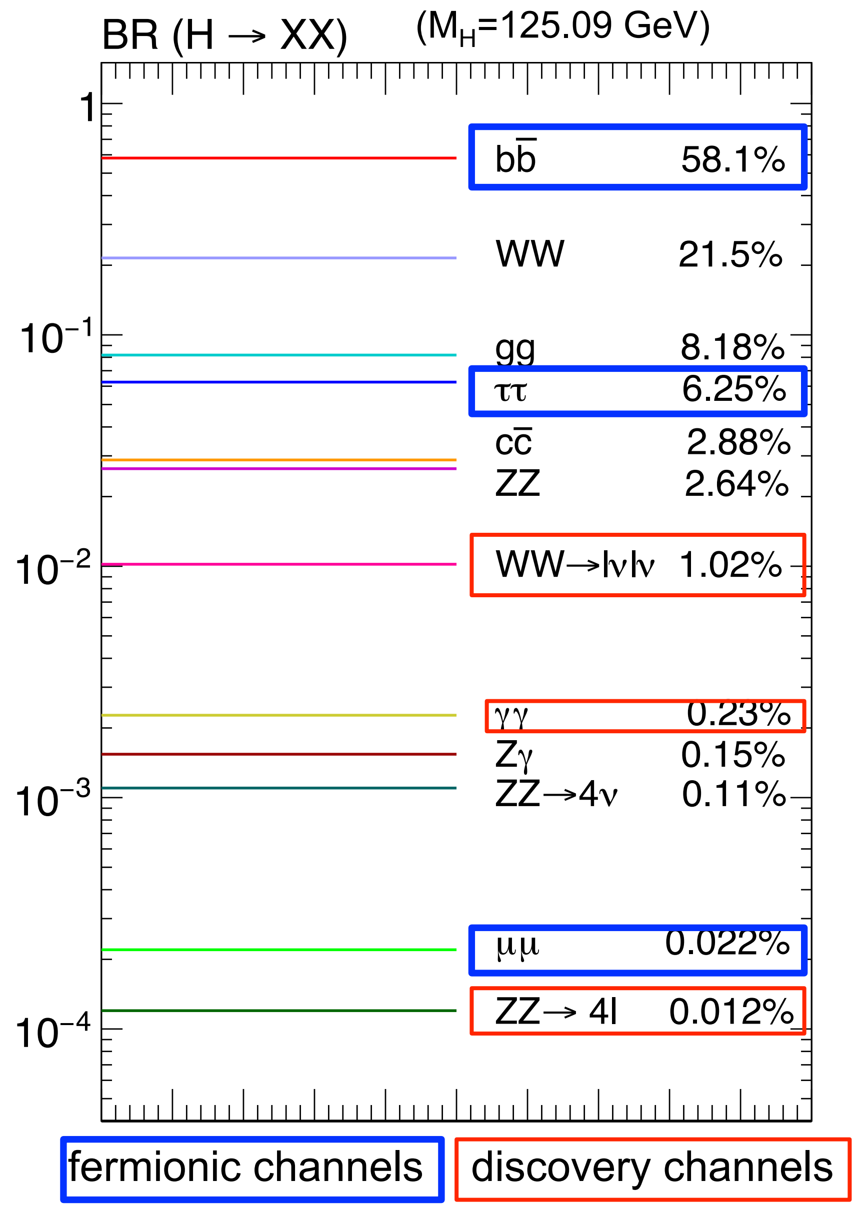

H→WW(ZZ)→4 fermions (l=e,μ)




H→γγ / Zγ




Higgs-Boson life time 1.6 x $10^{-22}$ s

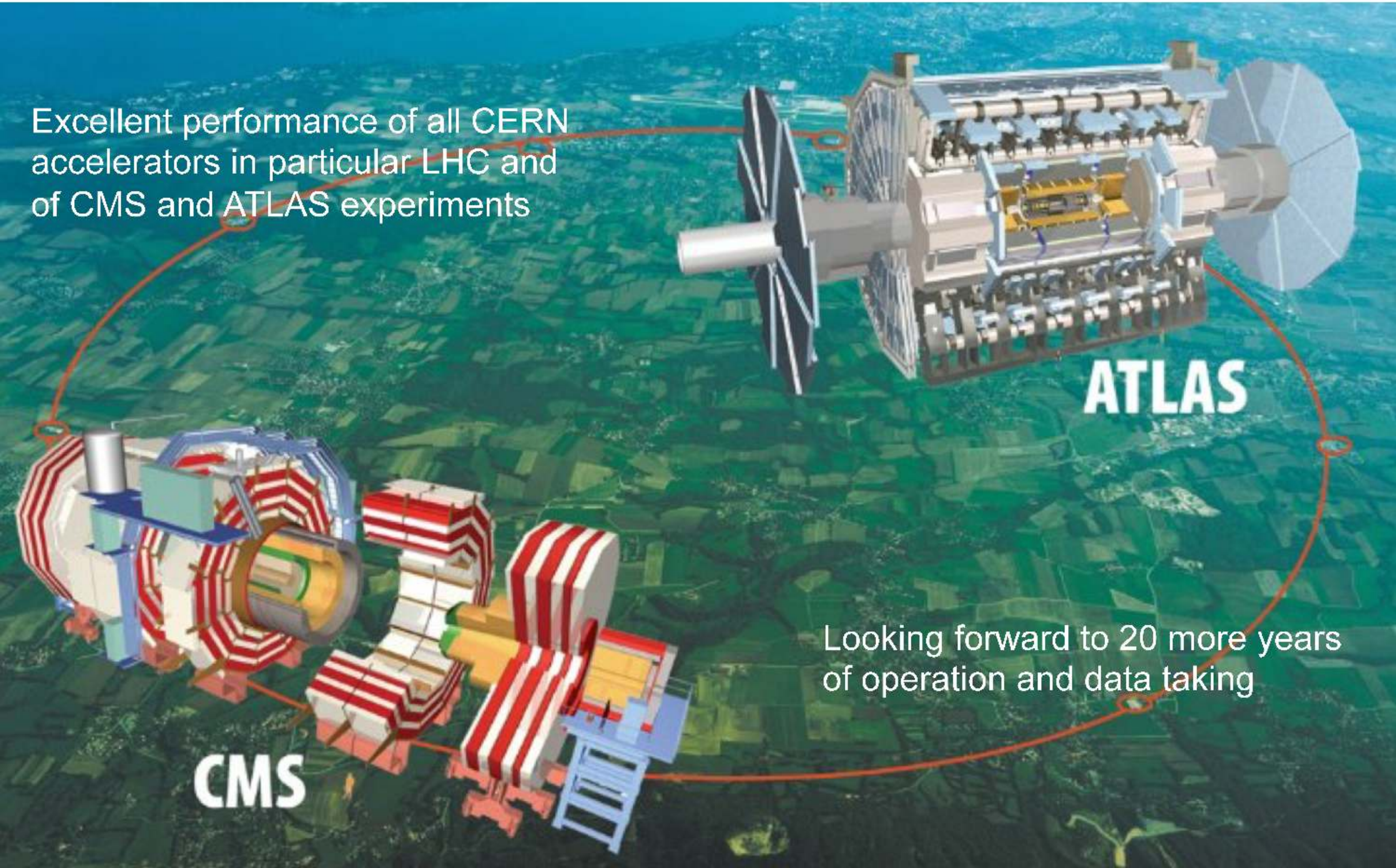



BR from LHCHXSWG 2016

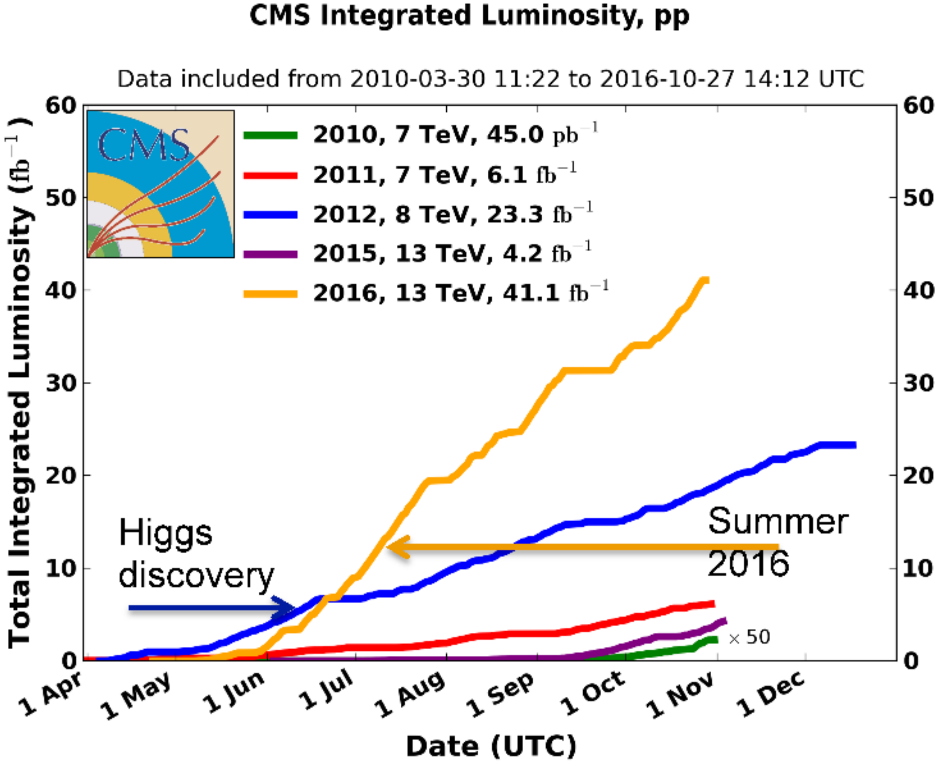
# LHC: pp Collisions at √s = 7 to 13 TeV

Run-1 2010-2012: √s = 7– 8 TeV

Run-2 since 2015: √s = 13 TeV



# LHC Data Sets and Event Rates




$N_{Process} = \sigma_{Process} \int L\, dt$

- $\sigma_{Process}$ = cross section
- $\int L\, dt$ = integrated luminosity
- Summer 2016: $\int L(13\text{TeV})\, dt = 13\ \text{fb}^{-1}$ ~ same sensitivity as Run-1
- Run-2 now: ~4 x Higgs boson events than in Run-1

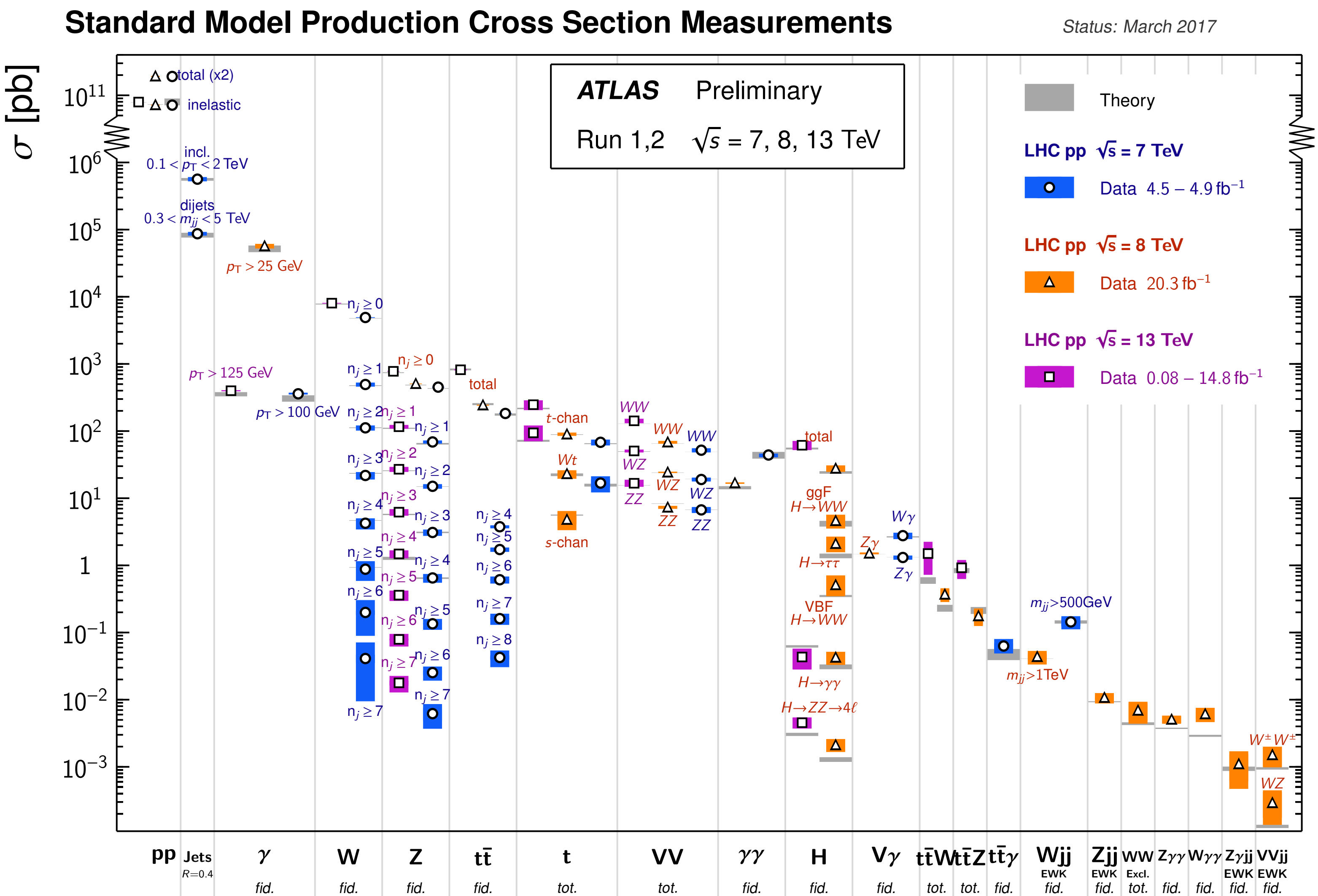
Number of produced events and Higgs bosons

| | | |
|---|---|---|
| July 2012 | $720 \times 10^{12}$ | 200 000 |
| Run-1 (11/12) | $1830 \times 10^{12}$ | 560 000 |
| Run-2 (15/16) | $3000 \times 10^{12}$ | 2 200 000 |

Branching ratios for two main discovery modes < 0.2%

Only 1 detectable Higgs particle per 1 000 000 000 000 collisions

# Reaction Probabilities at LHC

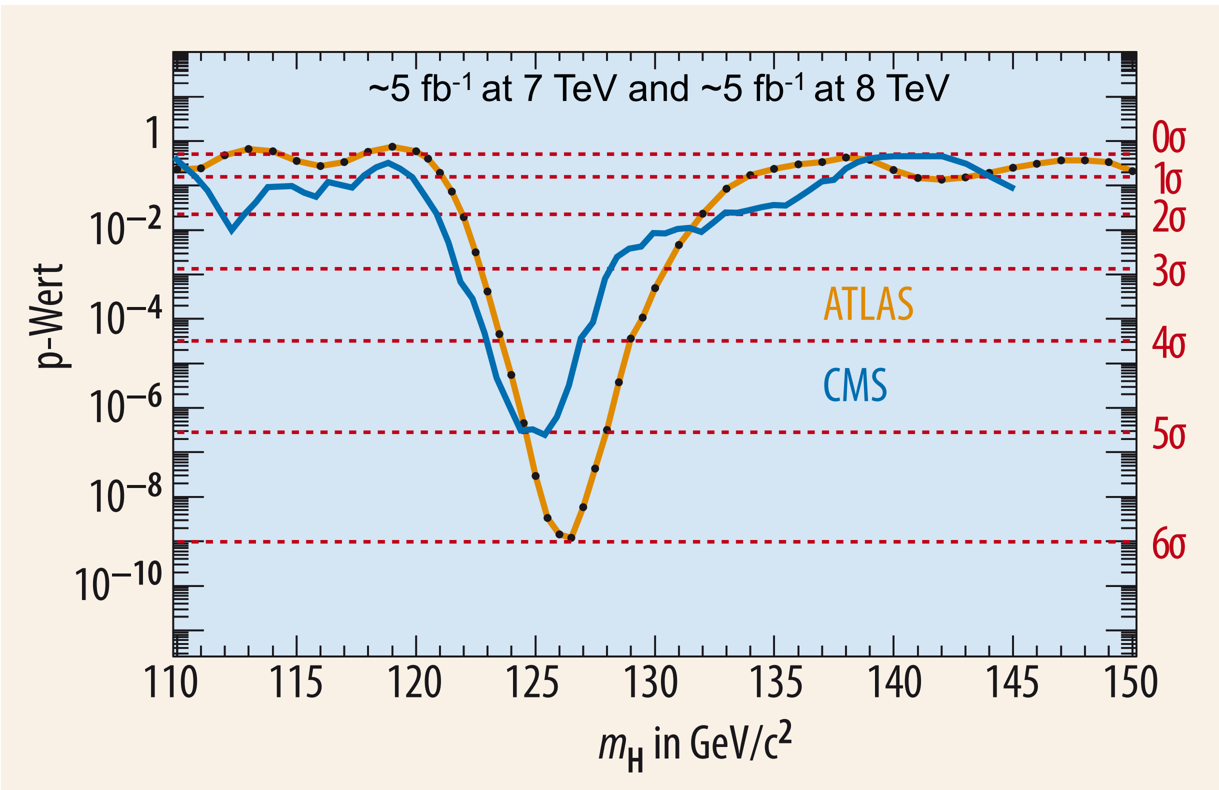


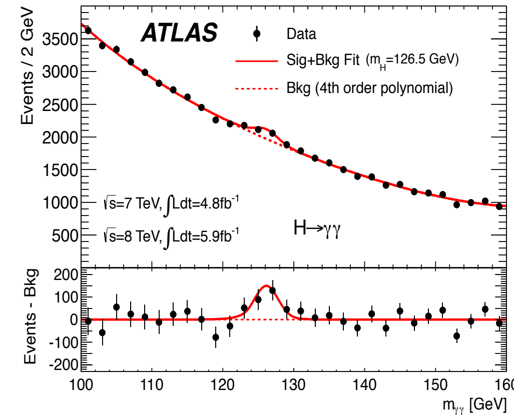

Excellent agreement between theory prediction and experimental measurements
due to very precise calculations and very good understanding of detector performance

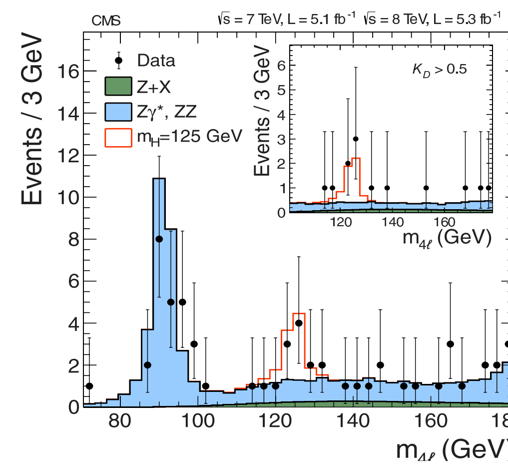
# July 2012: Discovery in the Search for the SM Higgs

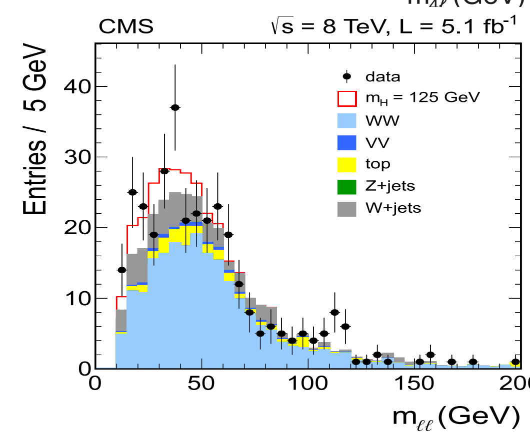
Observation in bosonic decay modes:

H→γγ, H→ZZ→4l and H→WW→lνlν




Neutral boson and mass of 125 to 126 GeV

Spin = 1 excluded from H→γγ (Landau Yang theorem)

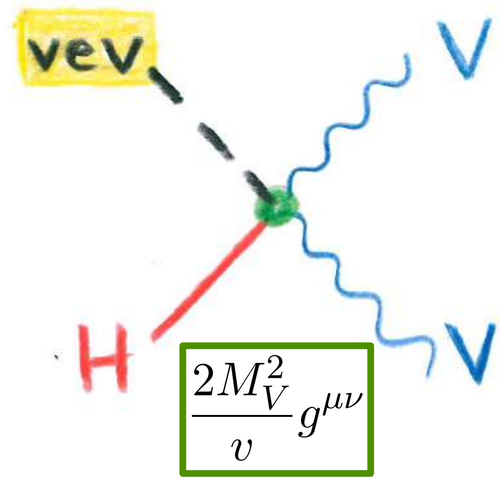
# Is it a Higgs Boson?

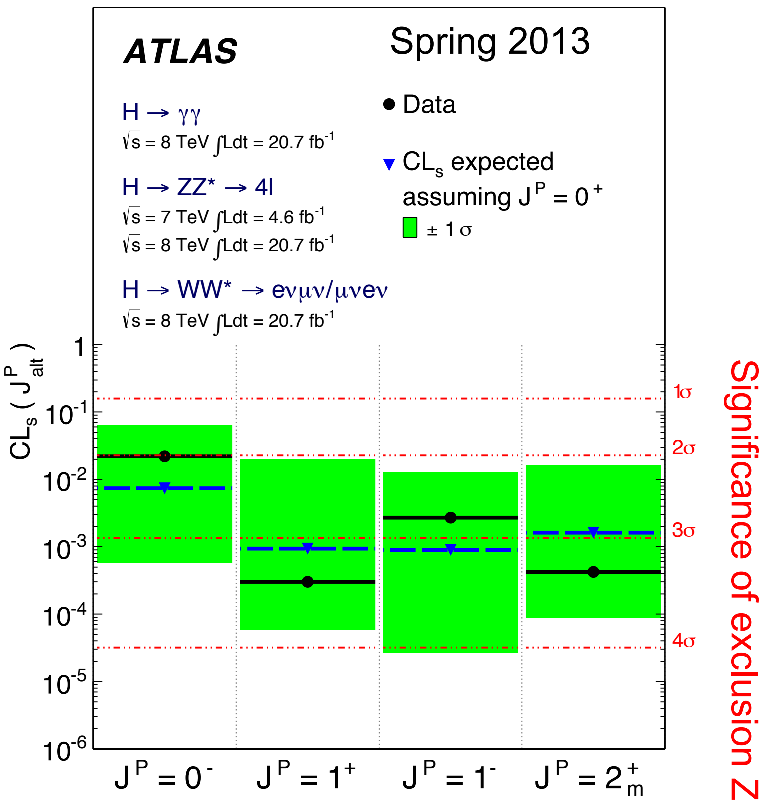

My definition of a Higgs boson:

Excitation of field, which provides vev for generation of $M_W$ and $M_Z$

Higgs boson has to be scalar, in order not to break isotropy of space

At least one Higgs field has to couple to W and Z bosons to provide mass terms → associated Higgs boson H has HVV vertex with CP-even SM coupling structure



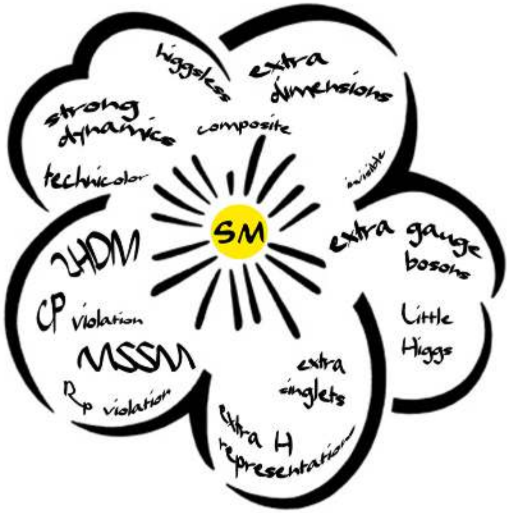

Now all alternative $J^{CP}$ hypotheses excluded with ≥ 99.9% CL

First evidence for scalar nature in spring 2013
→ Since then "It is a Higgs boson"

CMS has excluded twenty "spin=2 models"

# Deciphering the Nature of the Higgs Boson

The **BIG** Question: Is it the Higgs boson of the Standard Model (SM) or of an extended model?

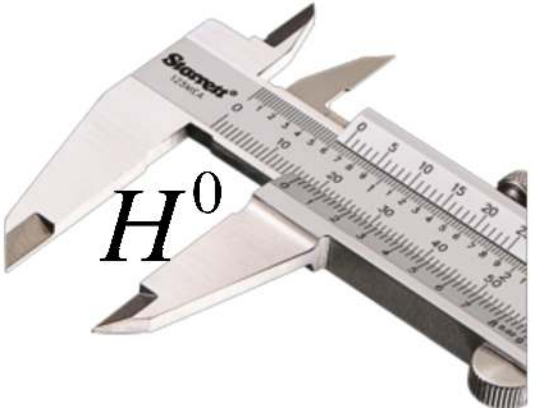



➢ Search for additional Higgs bosons

not discussed today, see talks by
- M. Mühlleitner, Ungelöste Rätsel und bisher keine Neue Physik in Sicht: Was lernen wir vom Higgsboson? T 27.2 Di, 9:10 Uhr
- R. Wolf, Die Akte Higgs - Fünf Jahre Higgsphysik am LHC T97.1 Do, 8:30 Uhr


➢ Determine properties of discovered boson and try to falsify Standard Model predictions

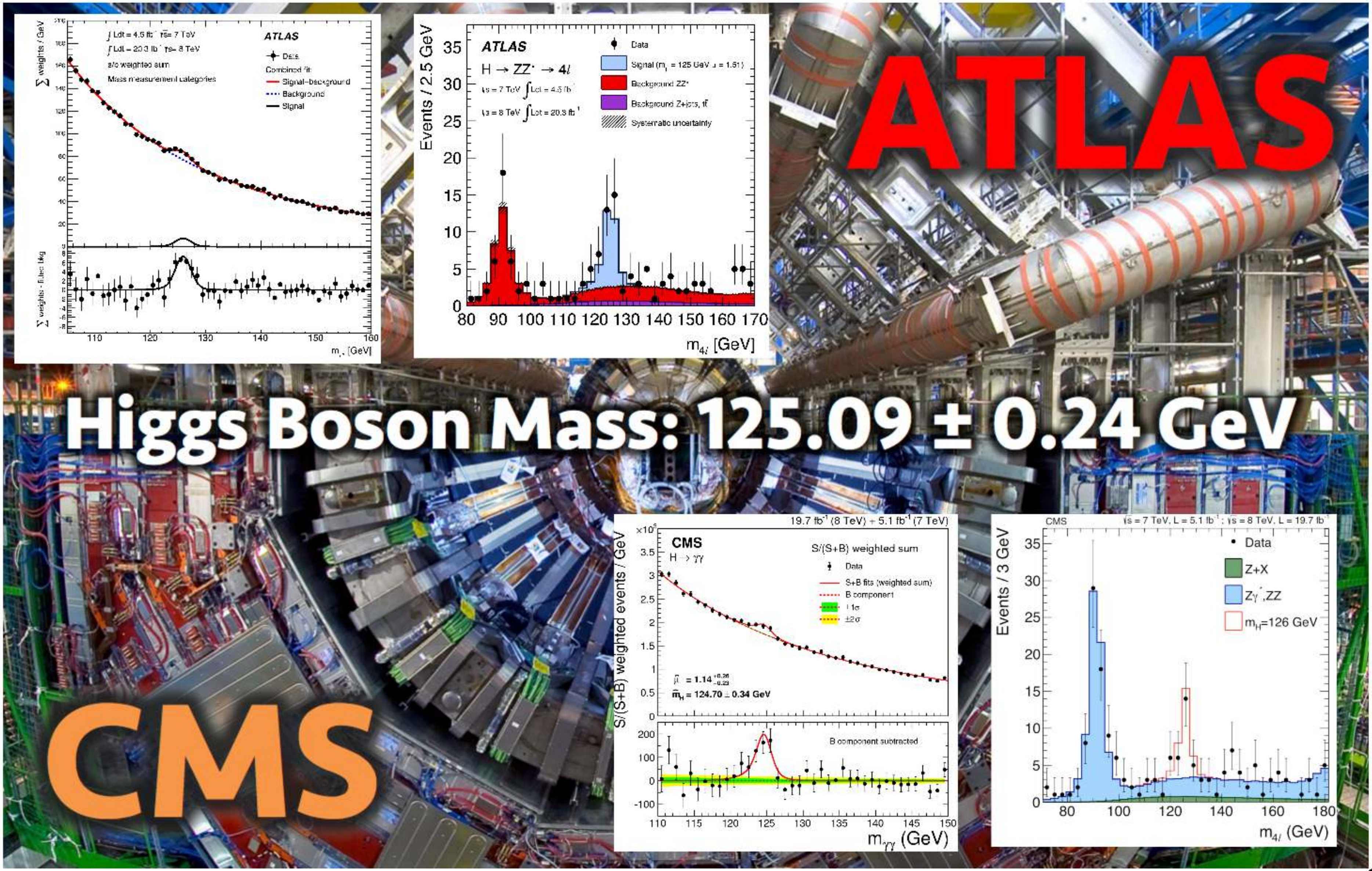
- determine mass, fixes all properties: measure cross sections, branching ratios, couplings, ...
- search for beyond SM phenomena: decay modes, coupling structures, ... violation of symmetries (CP, ... )



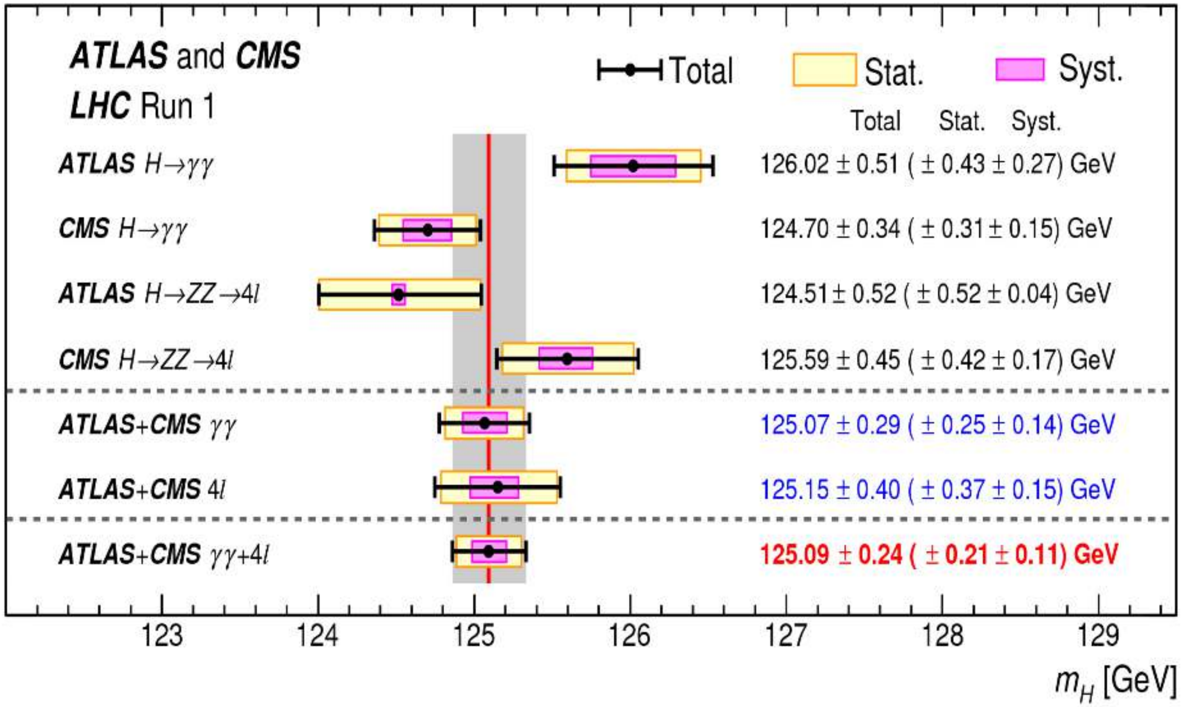

Disclaimer: No complete overview, selected and new results.

# Key Parameter: the Higgs Boson Mass

From peak position in H→γγ and H→ ZZ → 4 lepton mass spectra. Mass resolution 1-2%.



# Run-1 Combined + CMS Run-2 Mass Measurement




$M_H$ = 125.09 ± 0.24 GeV

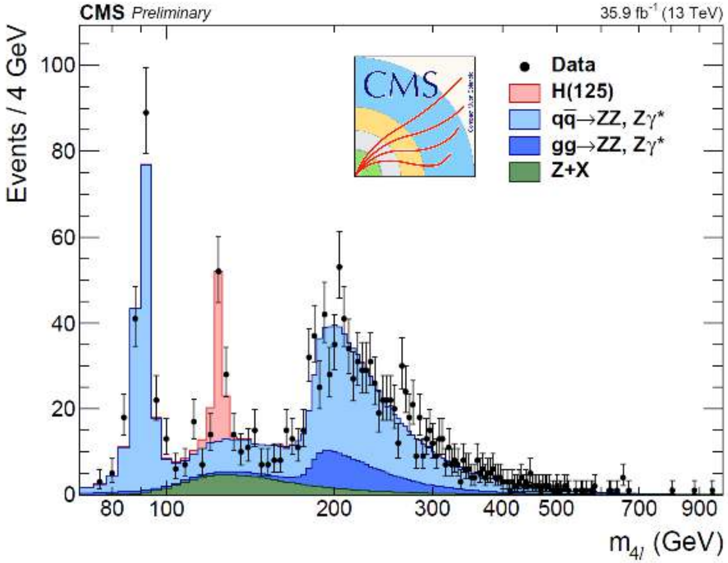
$\Delta_{stat}$ = 0.21 GeV
$\Delta_{syst}$ = 0.11 GeV

0.2% precision
dominated by stat. uncertainty

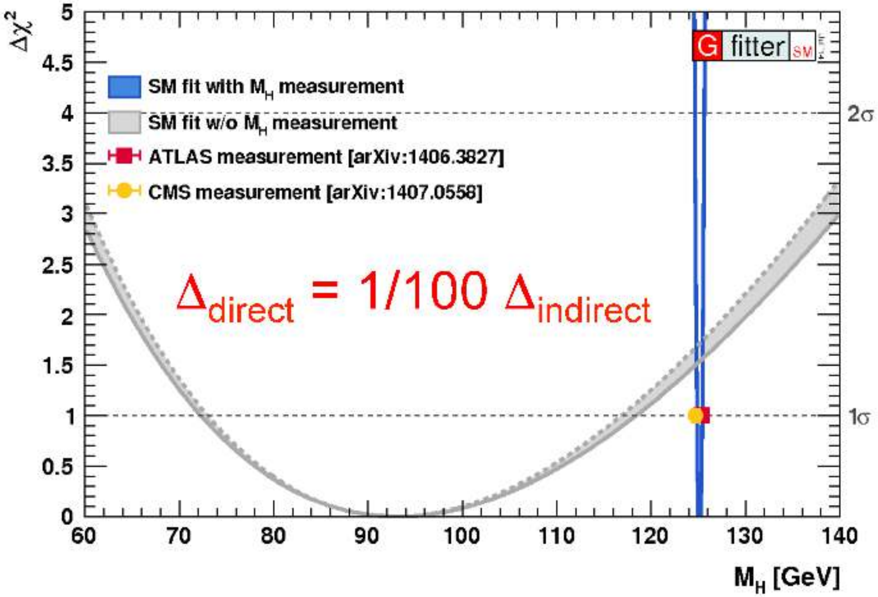
New result from H→ 4 leptons in Run-2

$M_H$ = 125.26 ± $0.20_{stat}$ ± $0.08_{syst}$ GeV
expected uncertainty: ~ 0.26 GeV

stat. and syst. uncertainty reduced by factor 2 with respect to Run-1 analysis

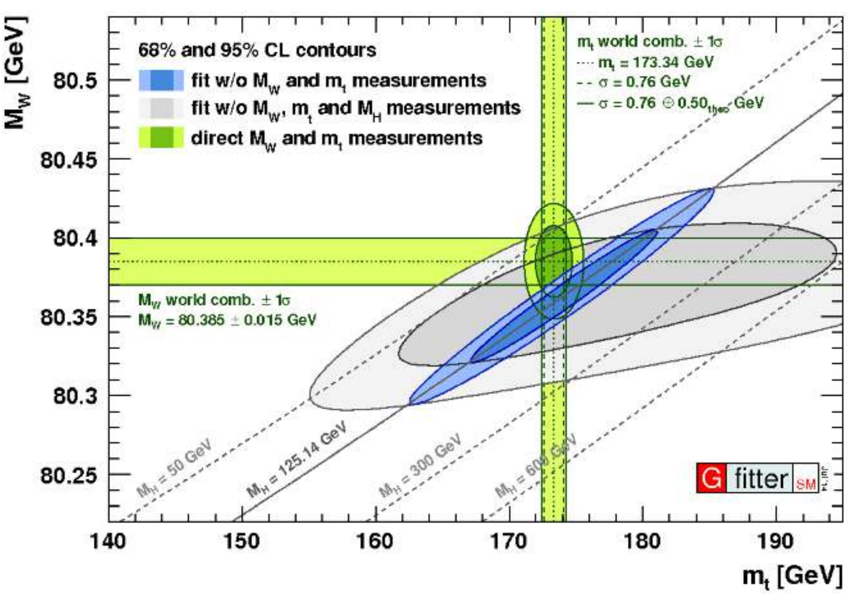


# $M_H$ as Precision Observable




Beyond Born-Level: $M_H$ not independent parameter, but $M_H = f(M_W, M_{top}, \ldots)$


Direct measurement: $125.09 \pm 0.24$ GeV
Indirect determination $93^{+25}_{-21}$ GeV



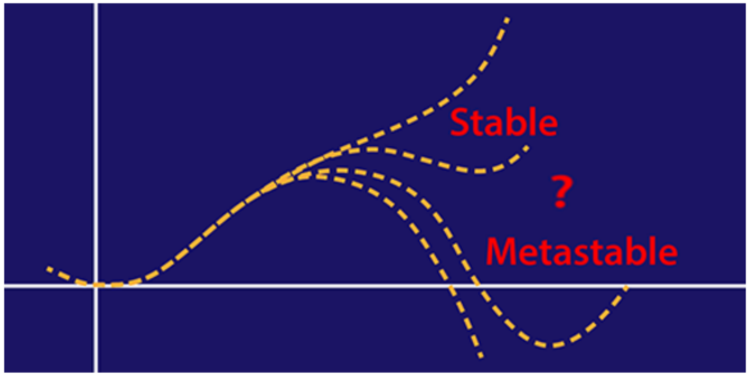

$M_H$ measurement improves precision of indirect $M_t$ and $M_W$ determination

Higher precision not needed e.g. for $M_W$

Indirect: $\Delta M_W$ = 8 MeV (0.1 MeV from $\Delta M_H$)
Direct: $\Delta M_W$ = 15 MeV

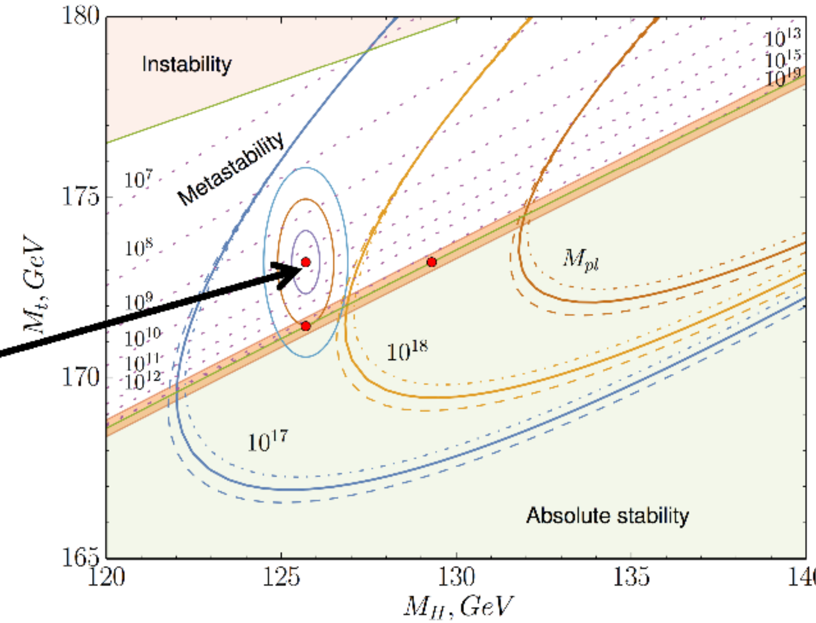
# $M_H$ as Precision Observable

Stability of the electroweak vacuum




($M_{top}$,$M_H$) in metastable region
two $\sigma$ away from stability area
more precise measurement
of $M_{top}$ higher priority

Bednyakov et al, PRL115 (2015) no.20, 201802




Parametric uncertainty $\Delta M_{HPar}$ from $M_H$
on cross-section and BR small compared to
- theory uncertainties $\Delta_{theo}$ (LHCHXSWG)
- experimental accuracy $\Delta_{exp}$ (A+C combination)

| | $\Delta_{theo}$ | $\Delta_{exp}$ | $\Delta M_{HPar}$ |
|---|---|---|---|
| BR(ZZ) | ±4.8% | ±22% | ±2.5% |
| $\sigma_{VBF}$ | ±2.8% | ±22% | ±0.3% |

→ No need to measure $M_H$ more precisely for now
but nice experimental challenge: understand energy/momentum scales to 0.1%

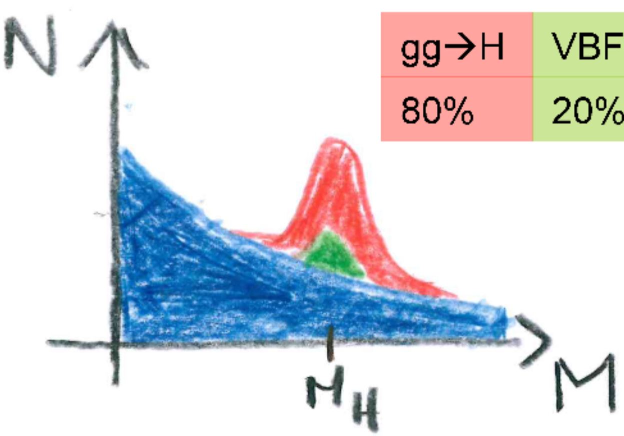
# Event Rates in i → H → f

Assumption: 1 CP even Higgs boson with SM tensor coupling structure and kinematics

- Large cross talk btw. production processes "i", negligible in decays "f"
- Signal categories: enrichment from one production process "i"

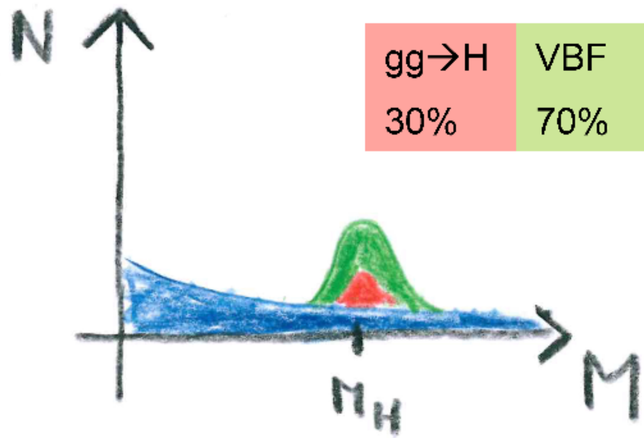
Event category A : "gg→H"-like

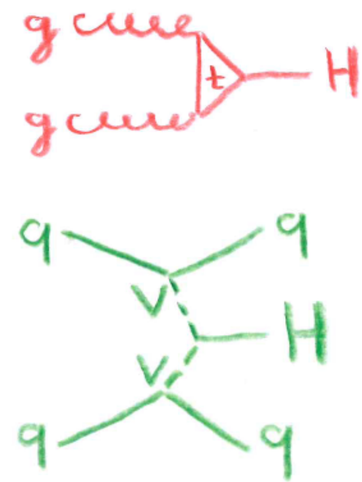
| gg→H | VBF |
|---|---|
| 80% | 20% |




Event category B: VBF-like

| gg→H | VBF |
|---|---|
| 30% | 70% |



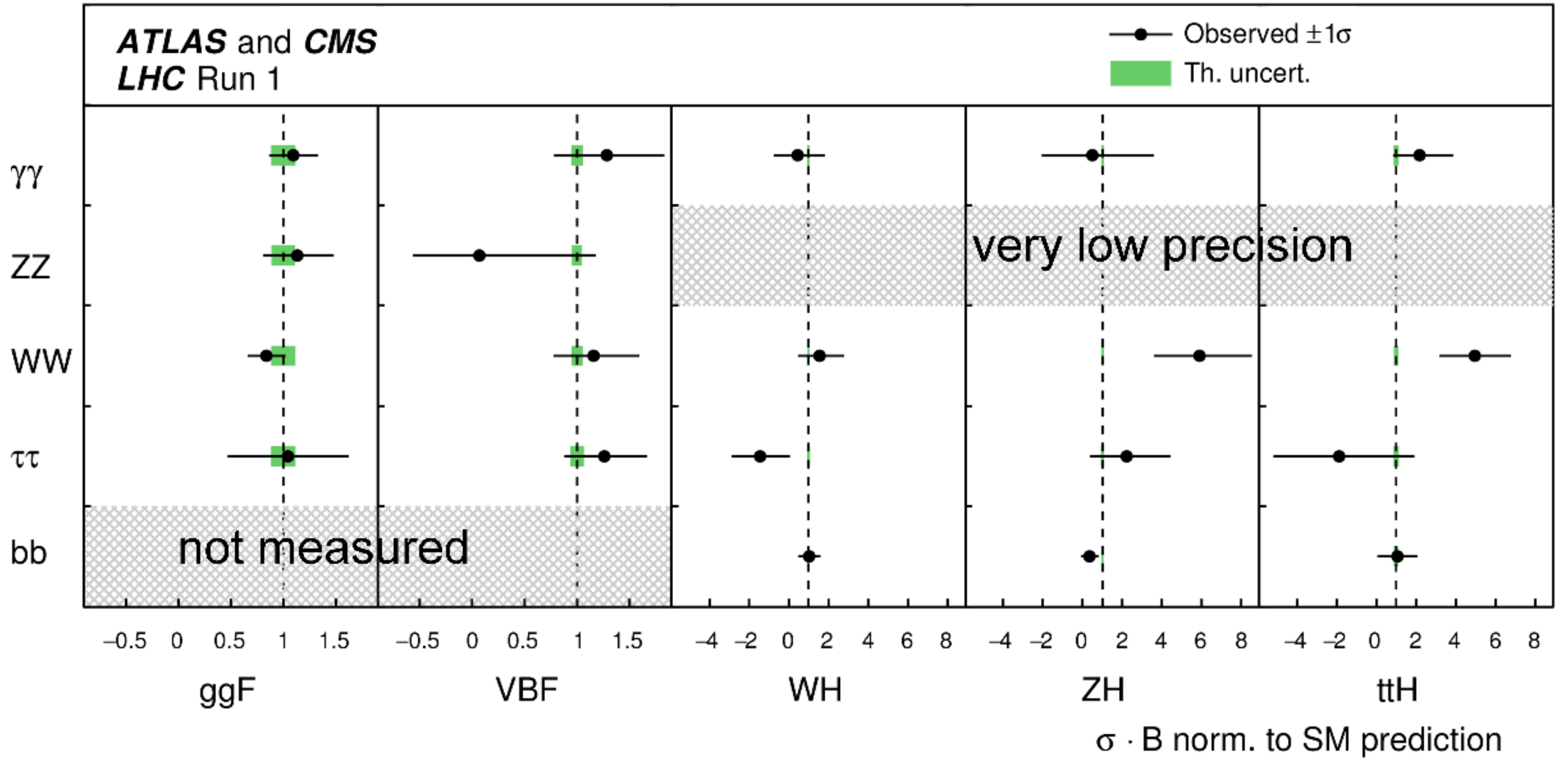




Background

$$n^f_{signal}(c) = \mathcal{L} \times BR^f \times \sum_i \sigma_i \times \epsilon_i(c)$$

ε = efficiency for production mode "i" to fall in category "c"

# Measurement of σ $_i$ x BR$^f$ in Run-1




Signal strength μ for : i→H→f

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

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

$$\sigma_i \times BR^f = \mu_i \times \mu^f \times (\sigma_i \times BR^f)_{SM}$$

without further assumptions only products of $\mu_i$ and $\mu^f$ can be determined

# Signal Strength μ in Run-1

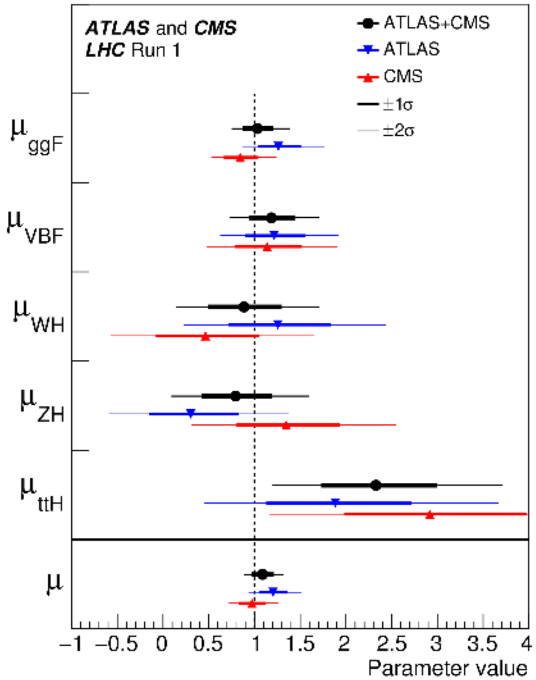
Global signal strength : all $\mu_i$ in production and $\mu^f$ in decay are the same

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

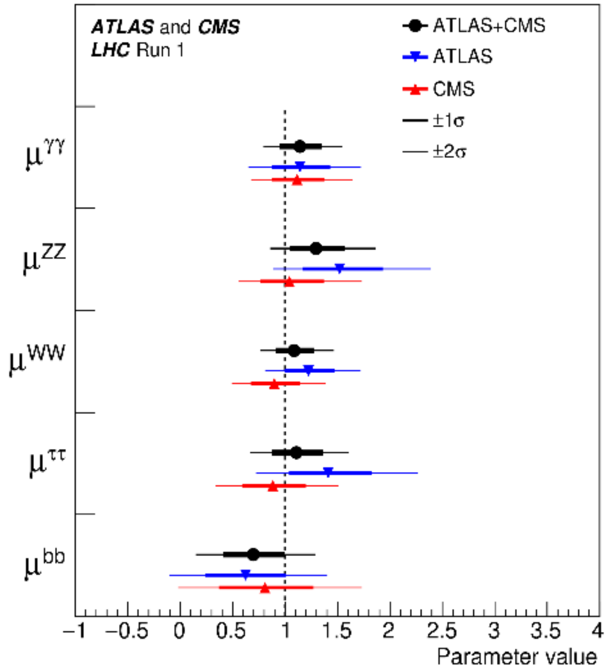
Statistical and signal theory uncertainty of same size

$N^2LO \rightarrow N^3LO$+new PDFs for $gg \rightarrow H$: $\sigma$ up by 10%, uncertainty reduced by 40%

**μ in Production:** assume $\mu^f = 1$




**μ in Decay:** assume $\mu_i = 1$




$gg \rightarrow H$, $H \rightarrow \gamma\gamma/WW/ZZ$ observed individually in ATLAS and CMS

Combination yields

Observation of VBF and $H \rightarrow \tau\tau$

Evidence for VH and ttH (Z=4.4, exp. =2.0)

Excess in ttH (2.3σ)

# LO Coupling Modifiers / Kappa-Framework

Cross section in narrow width approximation:

$$\sigma(i \to f) = \frac{\sigma_i \times \Gamma^f}{\Gamma_{tot}}$$

LO coupling modifiers $\kappa_i$:

$$\kappa = \frac{g_P}{g_P^{SM}}$$

$$\sigma_i = \kappa_i^2 \cdot \sigma_i^{SM}$$

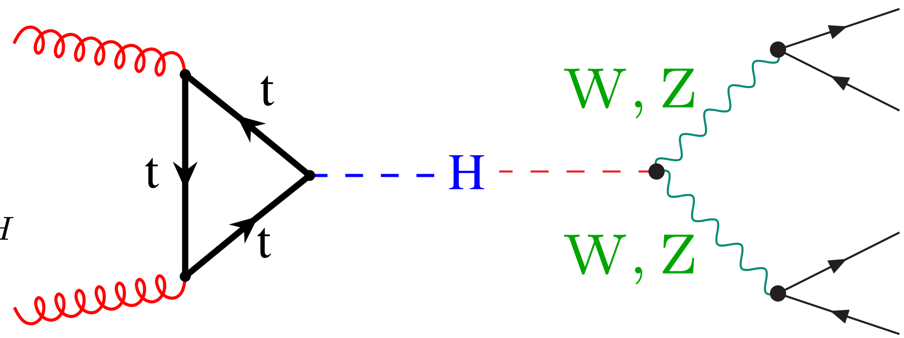
$$\Gamma^f = \kappa_f^2 \cdot \Gamma^{f,SM}$$

Look for deviation of κ from SM value = 1

Example: gg→H→WW (ZZ):

$$\sigma_{gg\to H} = \kappa_g^2 \sigma_{gg\to H}^{SM}$$

$$\sigma_{gg\to H} = f(\kappa_t, \kappa_b)\sigma_{gg\to H}^{SM}$$




$$\Gamma_{W/Z} = \kappa_{W/Z}^2 \Gamma_{SM}^{W/Z}$$

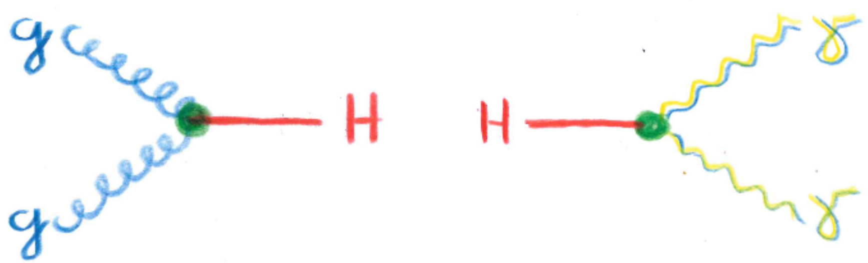
Total width $\Gamma_{H,SM}$ = 4.1 MeV (<< mass resolution in H→ 4l and H→γγ)

- scales all observed event rates
- lower limit from observed event rates

→ constrain total width with model dependent assumptions

# LO Coupling Modifiers: Scenario 1

Allow new contributions to loops
→ effective coupling for gg →H and H→γγ



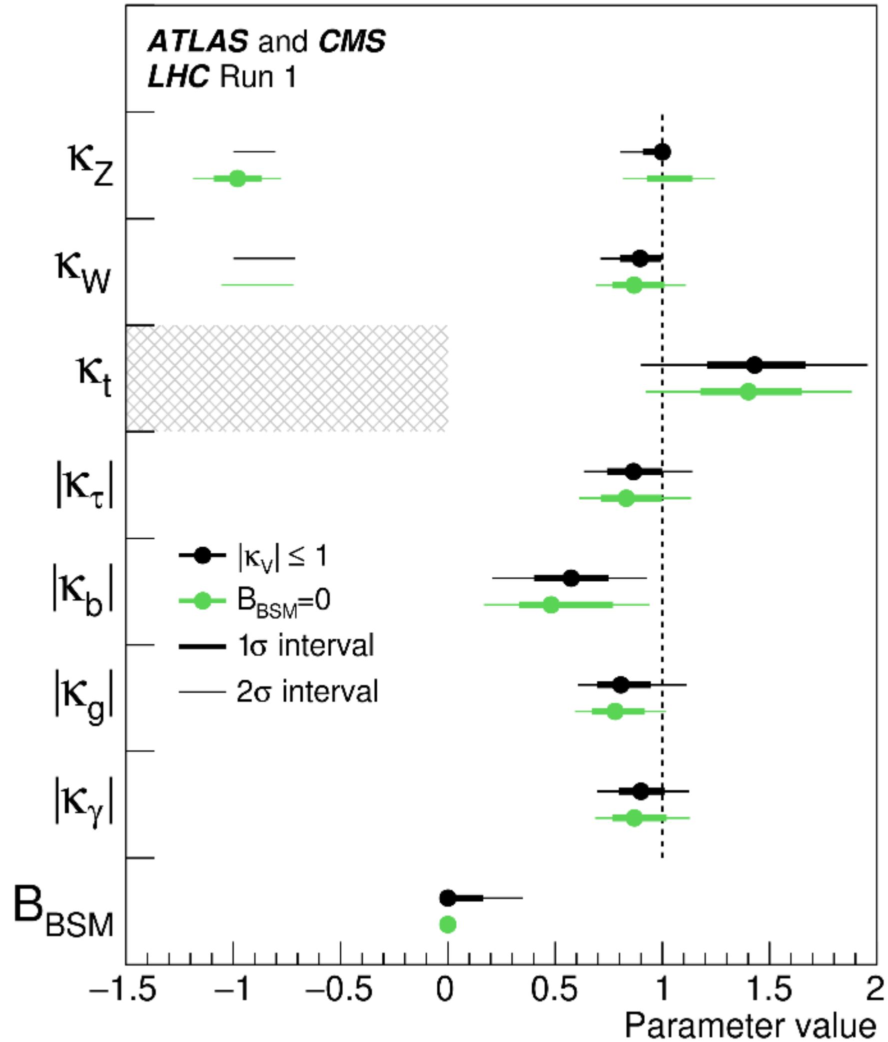

Upper limit on width from:
a) $|k_V| \leq 1$ or b) no BSM decays

Precision ~10% W / Z / g / γ
~ 12% τ, ~17% b, ~22% t

Expected deviation from SM
if new particles are heavy

| Model Class | $\Delta\kappa_V$ | $\Delta\kappa_t$ | $\Delta\kappa_b$ |
|---|---|---|---|
| Mixed-in Singlet | 6% | 6% | 6% |
| Composite Higgs | 8% | tens of % | tens of % |
| Minimal SUSY | <1% | 3% | 10-100% |

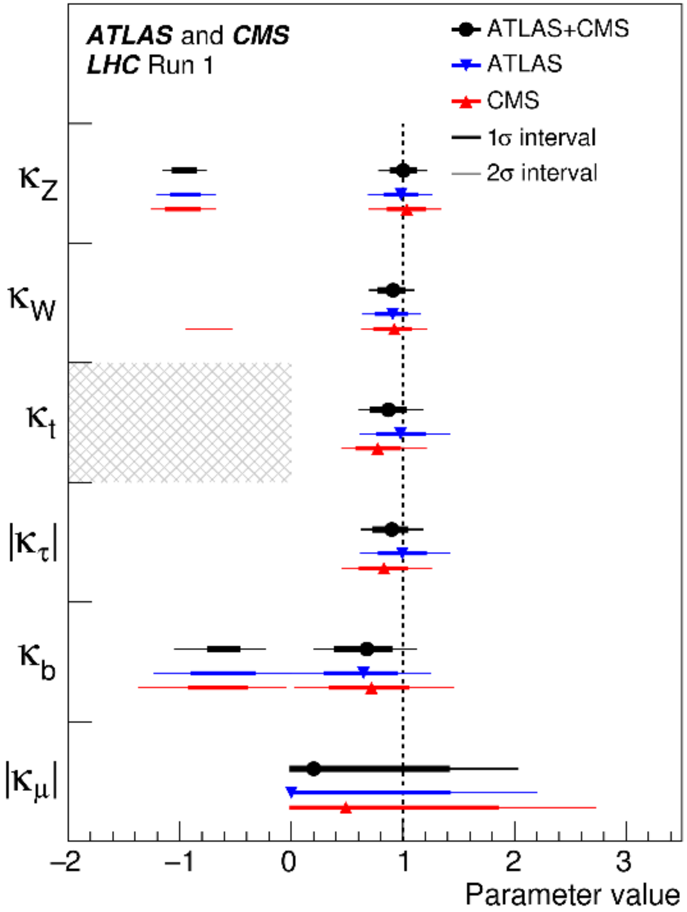
Gupta, Rzehak, Wells **Phys.Rev. D86 (2012) 095001**

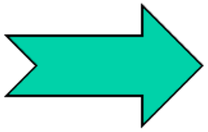


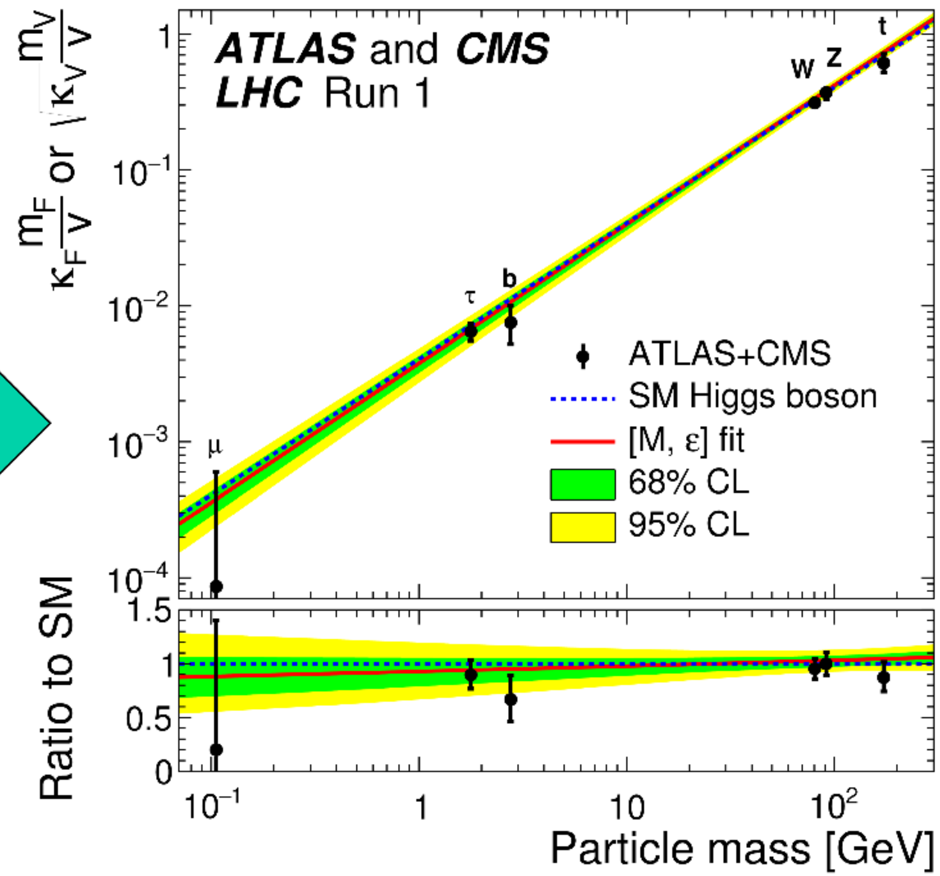

Limit on $BR_{BSM}$ < 34 (35 exp) %

# LO Coupling Modifiers: Scenario 2

Higgs only couples to SM particles → no new contributions to decay and loops



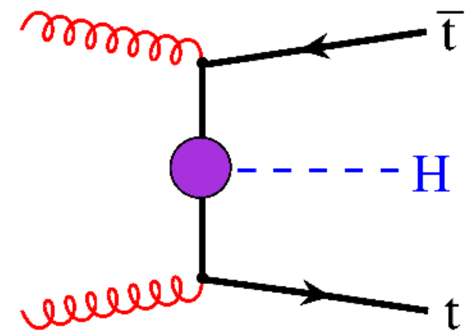



Precision: ~10% W/Z, ~ 14% t / τ, ~ 21% b

Not a model independent measurement of couplings

# ttH Production in Run-2

- Largest Yukawa coupling $Y_{ttH}$ of order
- Run-1combination: significance high by 2.3$\sigma$, $\mu = 2.3^{+0.7}_{-0.8}$
- $\sigma_{tth}$(13 TeV) / $\sigma_{ttH}$(8 TeV) = 3.9 → sensitivity increased




very complex final states:

6 fermions + Higgs decays (H→bb,$\gamma\gamma$,$\tau\tau$,WW,ZZ)

→ very sophisticated analyses with many signal categories

New

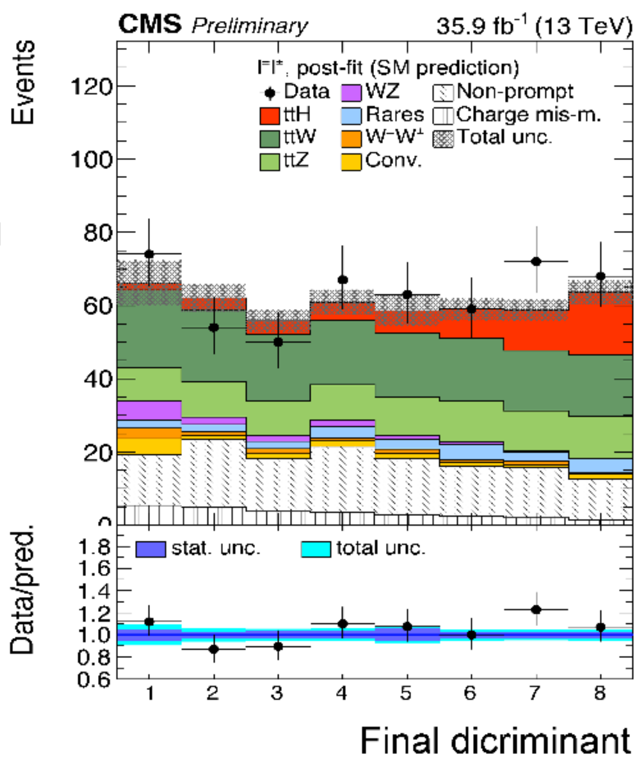
Run-2 35.9 $fb^{-1}$

ttH→2 $l^{\pm}$ $l^{\pm}$ X

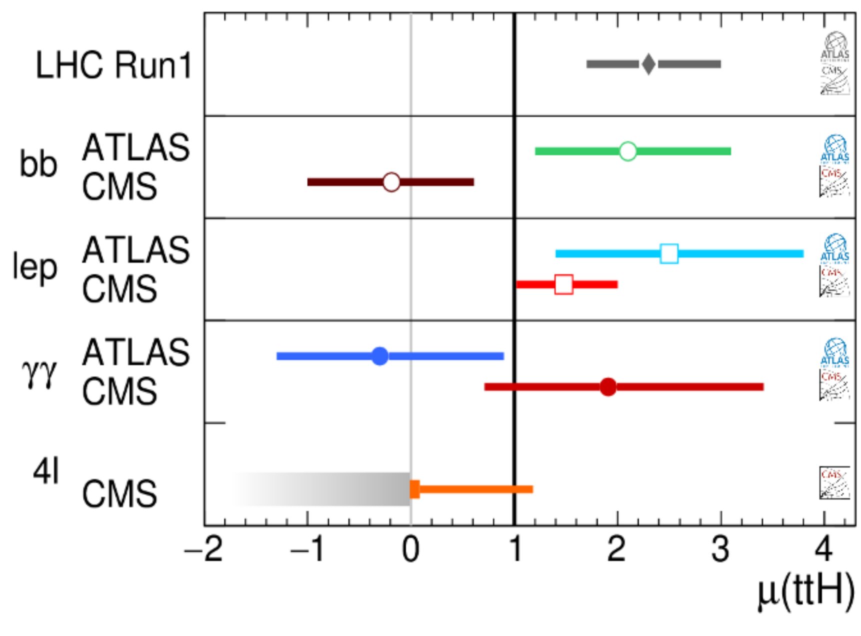
$\mu = 1.5 \pm 0.5$

Z = 3.3

(2.5 exp.)




μ still a bit high on average



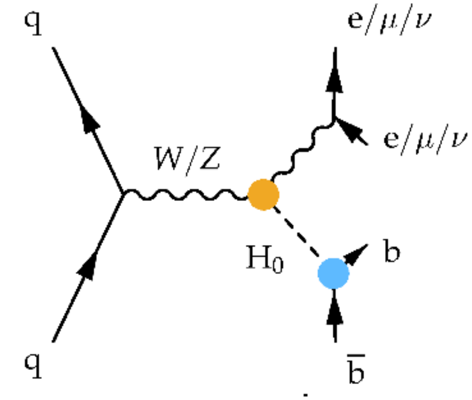

CMS 4l,lep 35.9 $fb^{-1}$ Rest 12.9-13.2 $fb^{-1}$

# Does the Higgs Boson Decay to a Pair of b-Quarks?

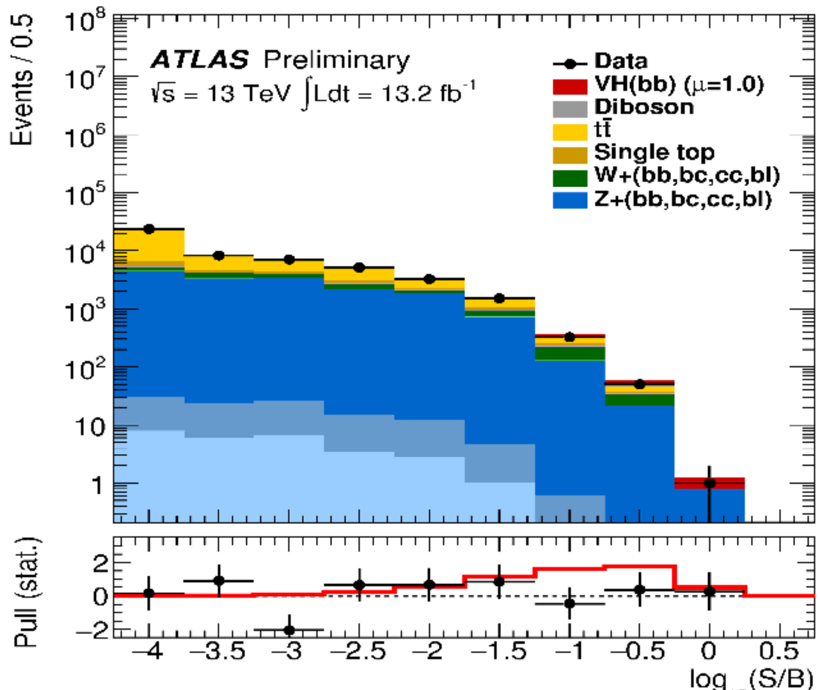
H→bb largest branching ratio 58.1%

Run1 not conclusive:
Z = 2.6 (exp. 3.7) $\mu = 0.7 \pm 0.3$
from ATLAS+CMS combination

Experimentally challenging:
- mass resolution 10 to 15%
- most sensitive pp→VH, H→bb
  V→ leptons




VH, H→bb
(13 TeV , 13.2 fb$^{-1}$)




Significance 0.42 (1.94 exp.)
$\mu = 0.21 \pm 0.50$

VBF, H→bb also searched for but factor 5 less sensitive

Still no evidence for H→bb

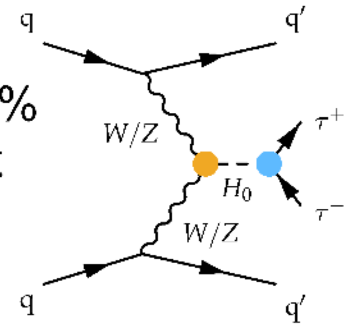
# Higgs Boson Coupling to Charged Leptons

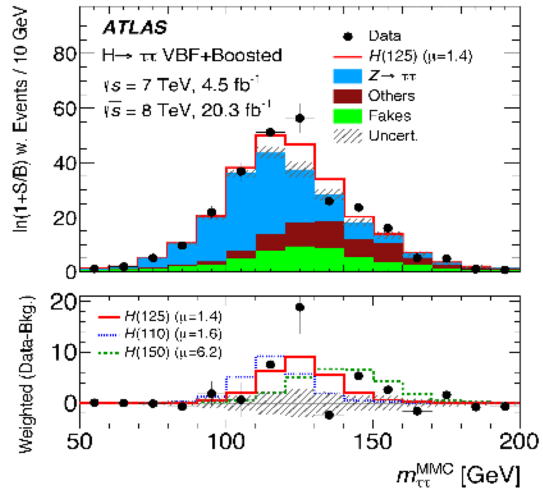
Coupling to $\gamma$ and Z universal for e, $\mu$, $\tau$

to H in SM: $Y_\tau / Y_\mu = m_\tau / m_\mu \sim 17$

## H→ττ

- $\Delta M/M$=15%
- VBF most sensitive




No results from 13 TeV yet

Run-1:

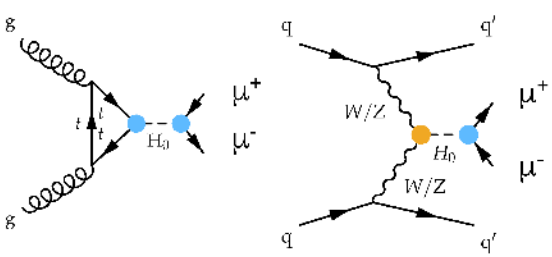
Individual evidence

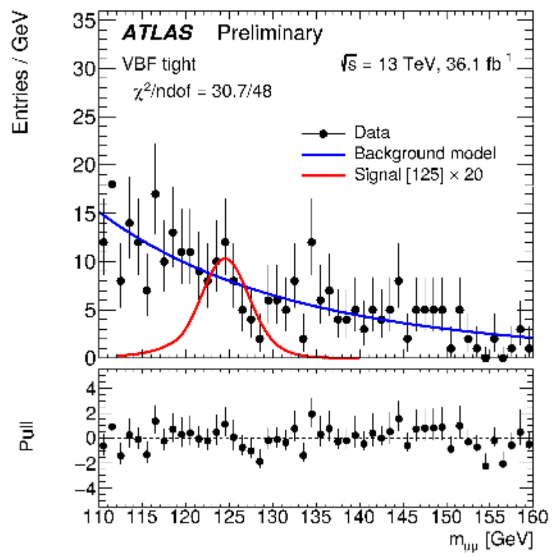
Observation in combination

Z= 5.5 $\mu$=1.1±0.2

## H→μμ

- $\Delta M/M$=1-2%
- gg→H and VBF usable




New

Run-2 36.1 $fb^{-1}$

$\mu$=-0.07±1.50

$\mu \leq$ 3.0 (3.1 exp) 95%CL

Run-1+Run-2:

$\mu$= -0.13+1.40

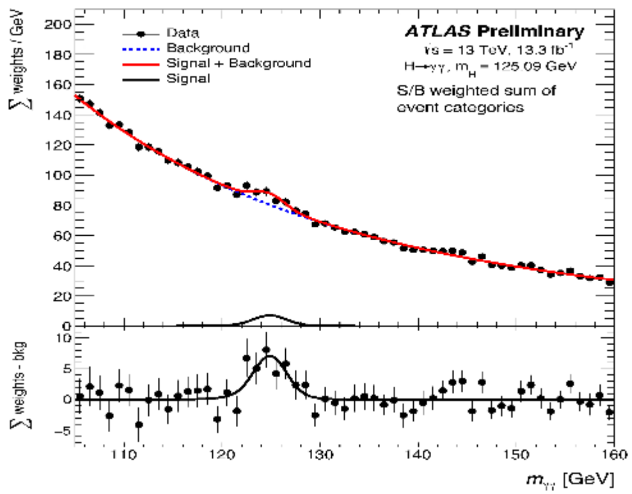
$\mu \leq$ 2.8 (2.9 exp.) 95%CL

$Y_\tau / Y_\mu$ > 8.3 → non universal coupling strength

# Observation of H→γγ / ZZ → 4 leptons in Run-2

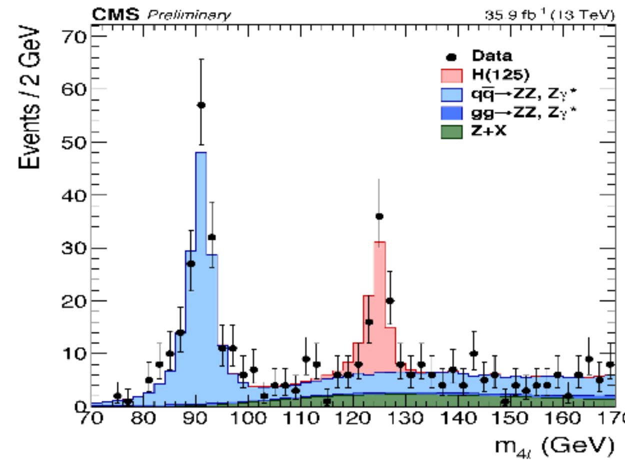
13.3 fb$^{-1}$

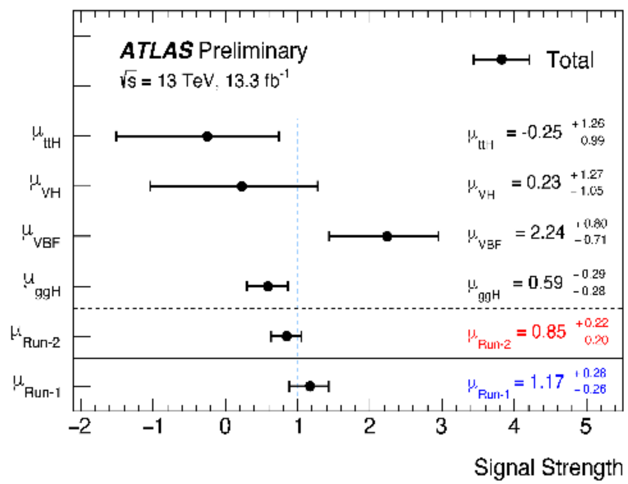
H→γγ

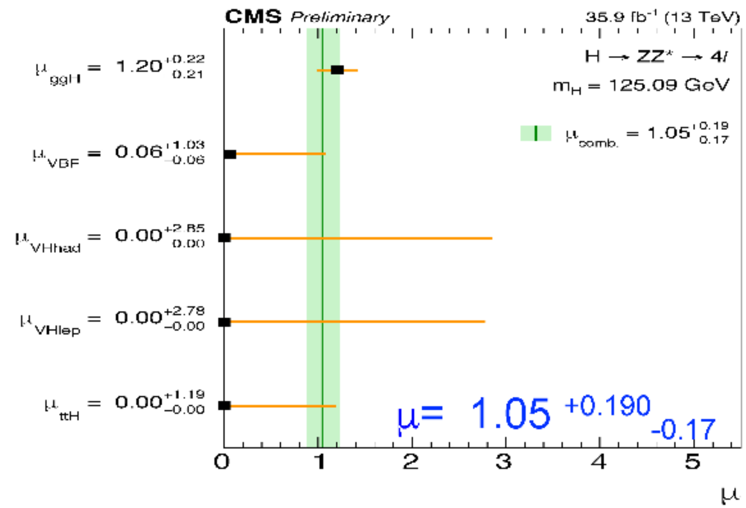



35.9 fb$^{-1}$

H→4l




ATLAS: Run-2 uncertainty ~3/4 of Run-1

CMS: Run-2 (12.9 fb$^{-1}$) $\mu=0.95^{+0.21}_{-0.18}$

CMS: Run-2 uncertainty ~2/3 of Run-1

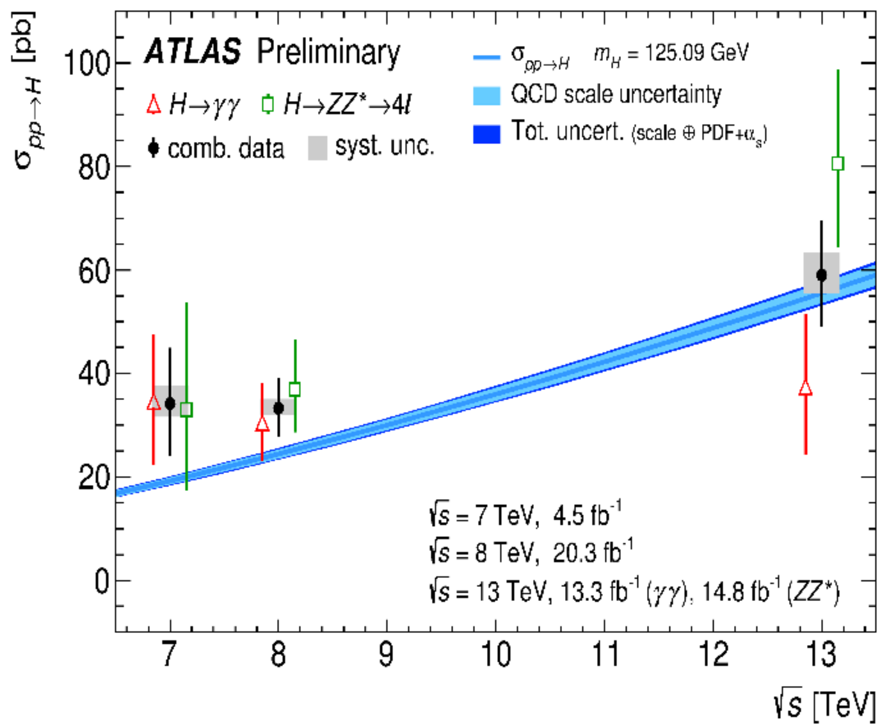
ATLAS: Run-2 (14.8 fb$^{-1}$) μ consistent with 1

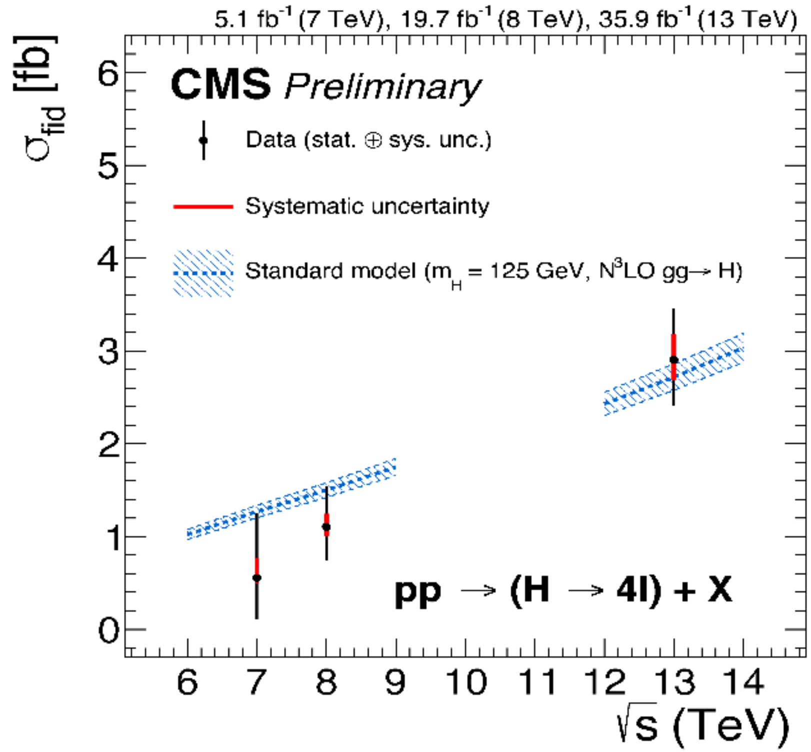
Run-2 obervation in both experiments in both decay modes. More precise than in Run-1.

# Total and Fiducial Cross Sections in Run-2

Total cross section $\sigma_{tot}(\sqrt{s})$ from $H \to \gamma\gamma$ and $H \to ZZ \to 4l$

Fiducial cross section $\sigma_{fid}(\sqrt{s})$ from $H \to ZZ \to 4l$

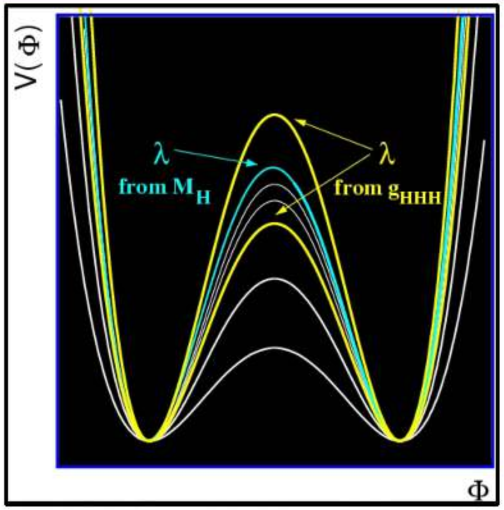



All compatible with Standard Model predictions

Both experiments also measure fiducial cross sections in many space regions and differential cross section in $P_H^T$, $N_{JET}$, .... → Test of QCD, Search for New Physics

# Triple Higgs Coupling / Higgs Boson Pair Production

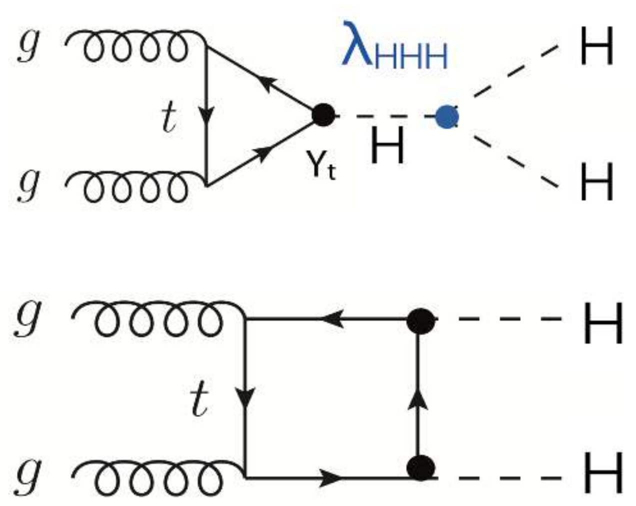



The “holy grail” : reconstruct the Higgs potential

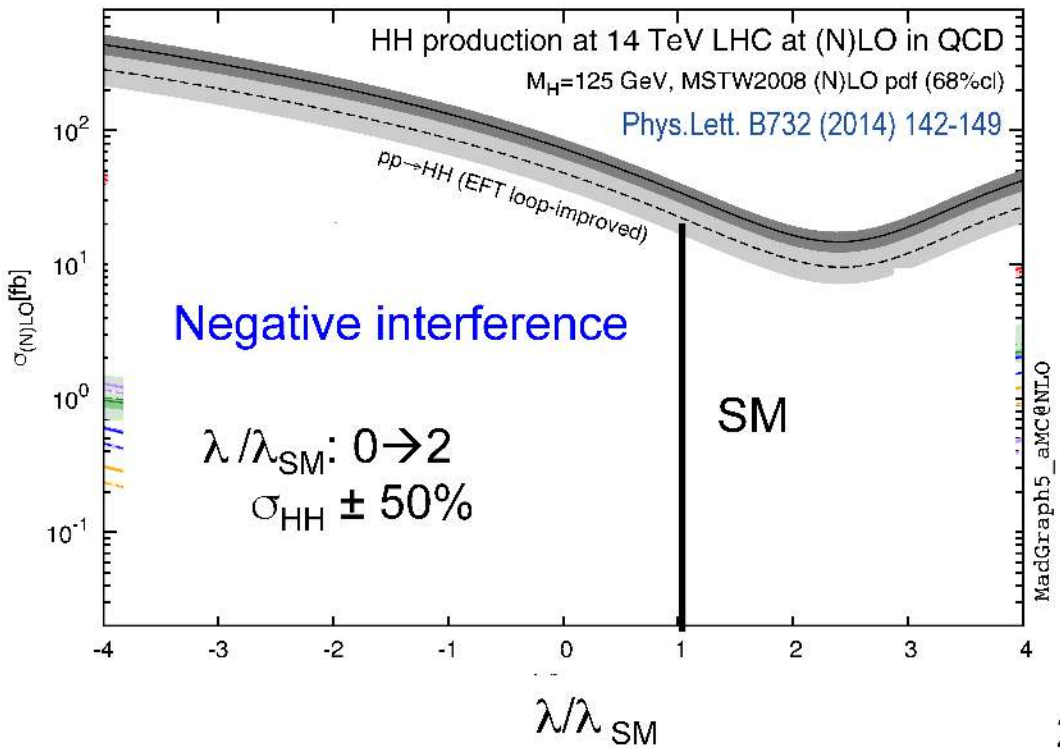
= measure triple Higgs coupling $\lambda_{HHH}$

In SM: $\mathcal{L}_H = -\frac{1}{2} M_H^2 H^2 - \boxed{\frac{M_H^2}{2v}} H^3 - \frac{M_H^2}{8v^2} H^4$

Accessible in Higgs boson pair production: gg→HH




Cross section depending on $\lambda/\lambda_{SM}$



# Limits on Cross Section for gg→HH

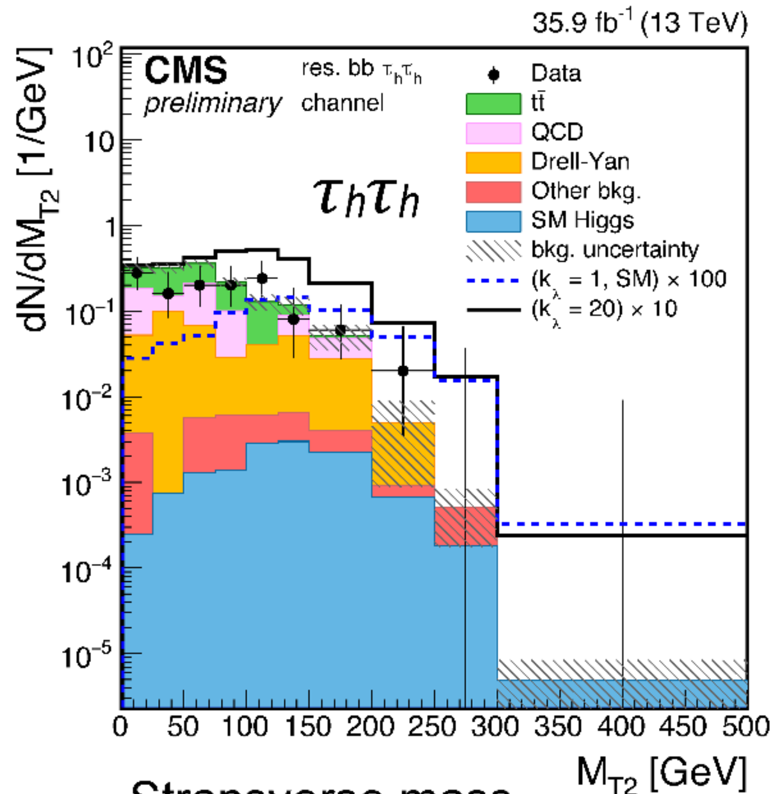
$\sigma_{HH}$ increased by 3.3 from $\sqrt{s}$ = 8 to 13 TeV

New

35.9 fb$^{-1}$

gg→HH→bb ττ

(BR=7.3% → 88 events)




Stransverse mass

most sensitive single result

$\mu_{hh}$ = σ(gg→HH) / σ(gg→HH)$_{SM}$ < 28 (exp 25)

assuming SM BR for Higgs

sensitivity improved ~ 3 w.r.t. Run-1

gg→ HH→bbbb (BR=33.6% → 150 events) with 13.3 fb$^{-1}$ from Run-2

$\mu_{hh}$ ≤ 29 (38) sensitivity improved by ~1.5 w.r.t. Run-1

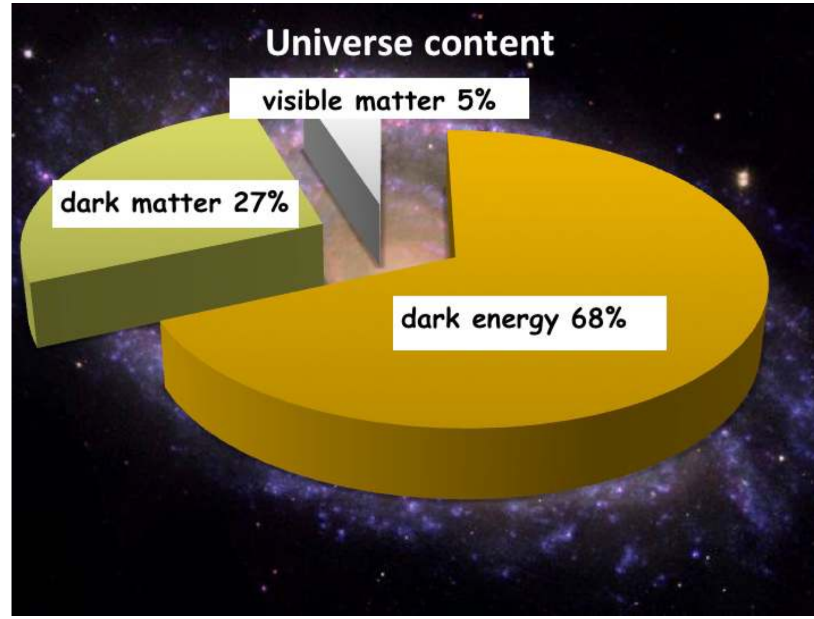
HL-LHC (3000 fb$^{-1}$): Combination of all channels and ATLAS and CMS will be crucial for observation of HH production

# Open Questions & Possible Connection to Higgs

Dark Matter contributes with ~25%
to energy content of the universe

In specific models (Higgs portal)
Dark Matter (DM) particle couples
only to Higgs boson

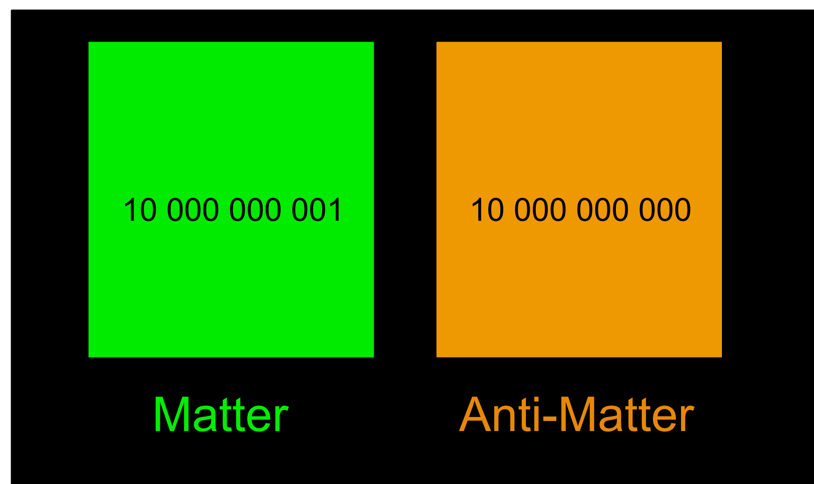
→ e.g. search for H→ invisible decays
for $M_{DM} < \frac{1}{2} M_H$




Baryon Asymmetry of the universe
$\eta$ = baryon / photon density ~ $5 \times 10^{-11}$

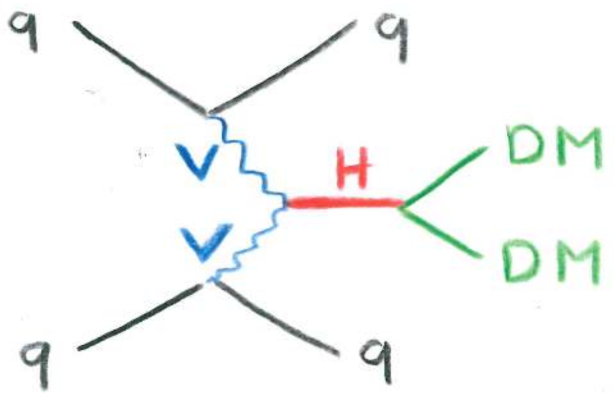
CP violation needed to explain asymmetry
CKM-CP violation too small to explain obs. $\eta$

→ search for new sources of CP-violation
in the Higgs sector



# Search for H→ invisible

Most sensitive: VBF production

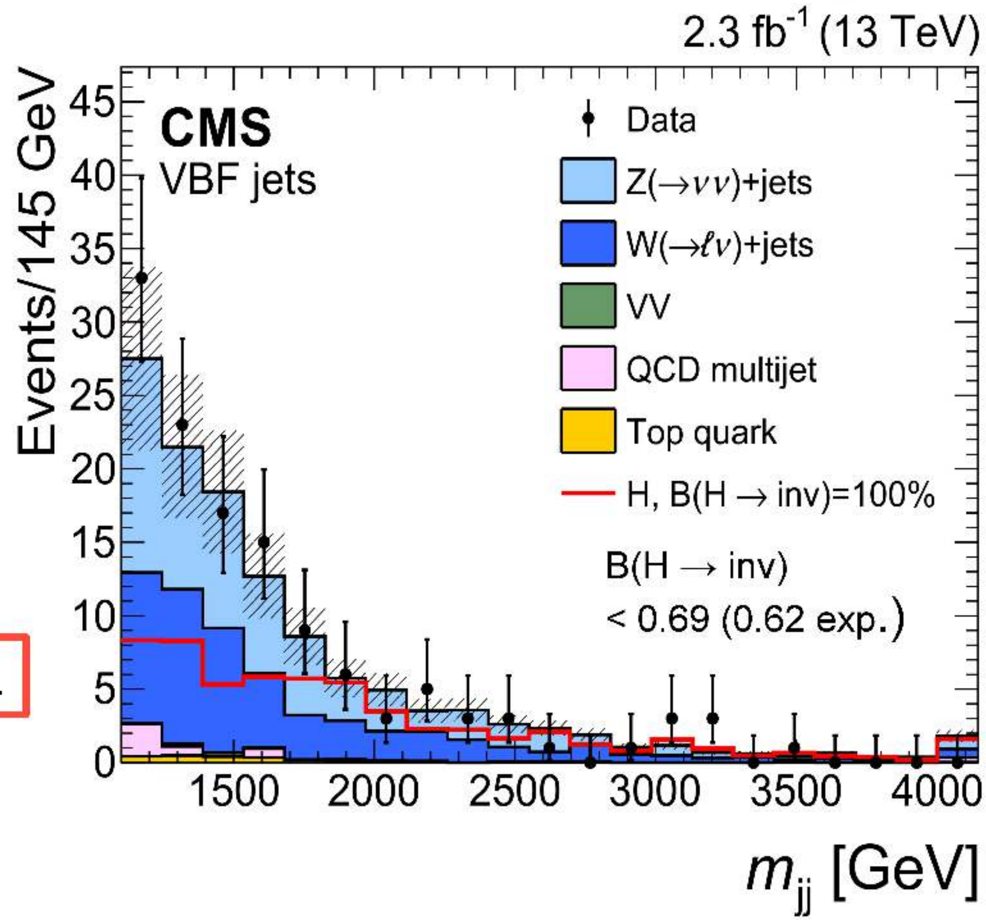



Run 1 + 2.3 fb-1 at 13 TeV

B(H → inv) < 0.24 (0.23 exp.) at 95% CL

combination of VBF, VH, gg→Hj
assuming SM production cross sections

Look for excess in di-jet mass $M_{jj}$



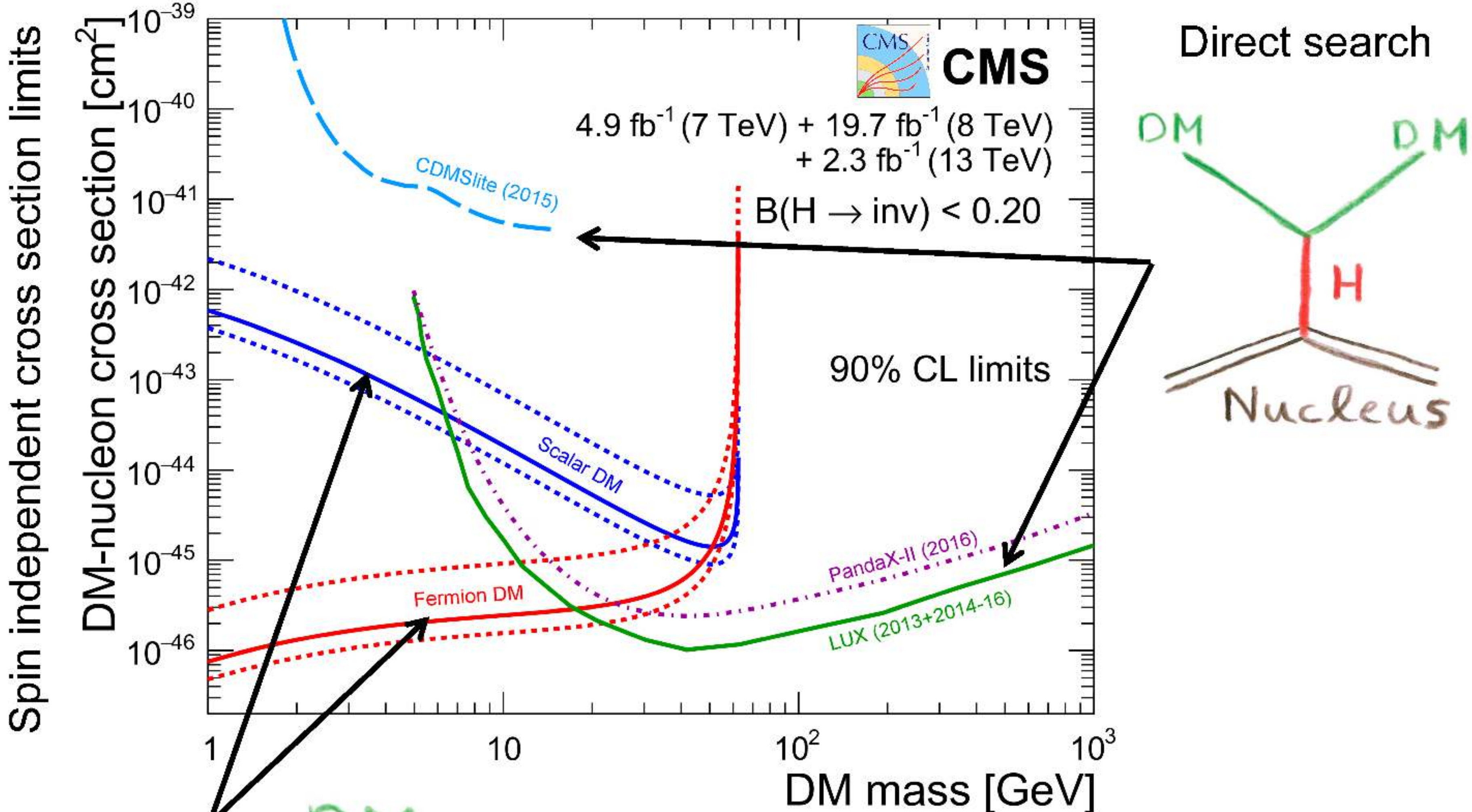

Run 1 limits @ 95% CL

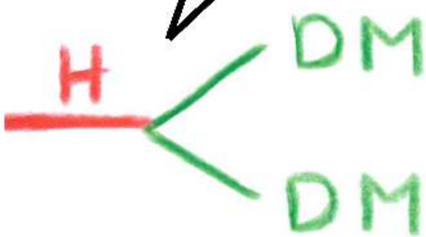
< 28 (exp. 31)%

<36 (exp. 32)%

No hints for invisible
Higgs boson decays

# Interpretation of Limits on BR(H→invisible)



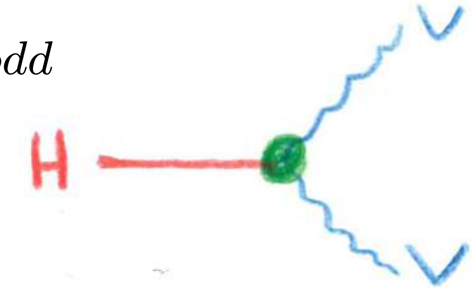

Limits stronger than from direct searches for $M_{DM}$ < 20 (5) GeV for fermionic (scalar) DM under certain assumptions

# New Sources of CP-Violation in the HVV Vertex?

Ansatz: $\mathcal{L} = \mathcal{L}_{SM} + \boxed{\lambda_{CP}} \cdot \mathcal{L}_{CPodd}$

Strength of CP-violation: $\lambda_{CP}$

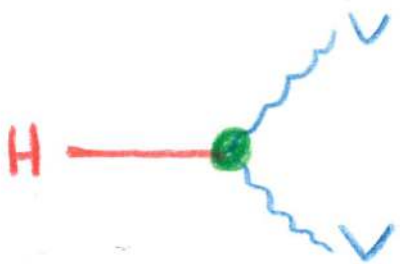
→ modified tensor structure
and kinematics



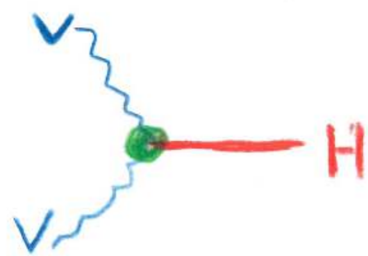

$$\frac{2M_V^2}{v} g^{\mu\nu} + \boxed{\lambda_{CP}} \epsilon^{\mu\nu\rho\sigma} p_\rho^{V_1} p_\sigma^{V_2}$$

HVV-vertex accessible in:

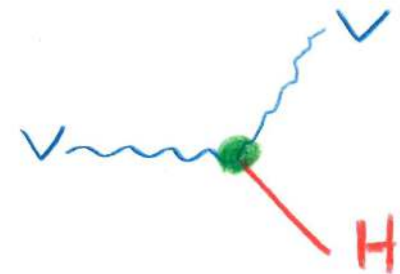
a) decay H→VV




b) VBF, qq→Hqq




c) Higgs-Strahlung V→VH




Optimal observables combine information from multidim. phase space in two scalars

$$OO_1 = \frac{2\mathcal{R}e(\mathcal{M}_{SM}\mathcal{M}^*_{CP\,odd})}{|\mathcal{M}_{SM}|^2}$$

CP-odd, sensitive to small $\lambda_{CP}$
$\lambda_{CP} \neq 0$ → $\langle OO_1 \rangle \neq 0$, asymmetry

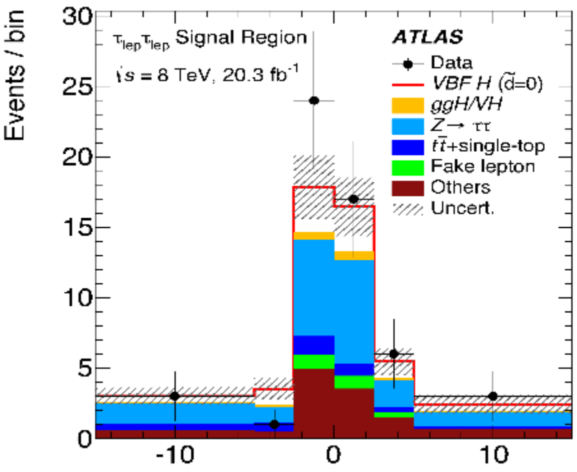
$$OO_2 = \frac{|\mathcal{M}_{CP\,odd}|^2}{|\mathcal{M}_{SM}|^2}$$

CP-even, sensitive to larger $\lambda_{CP}$

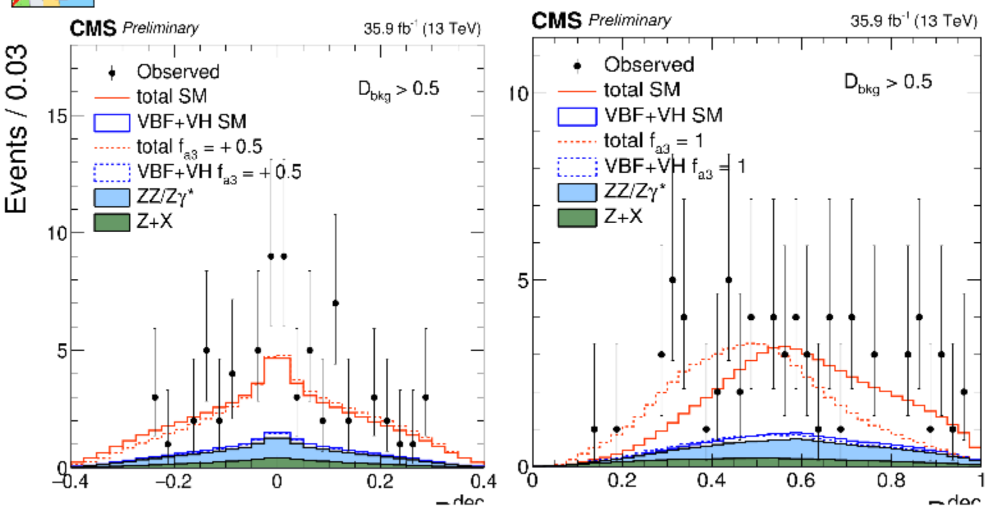
# Investigating the CP-Structure of HVV Vertex

(8TeV): VBF, H→ ττ

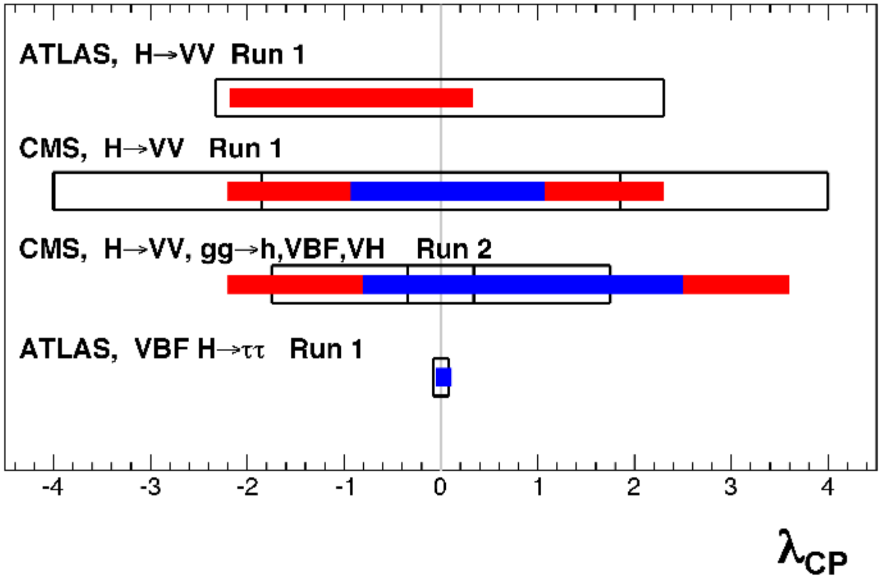
New (Run-2): VBF, H→VV in gg→H, VBF, VH



7 dim. phase space → $OO_1$



8 to 13 dim. phase space → ~ $OO_1$ & $OO_2$




No hints for CP-violation

VBF, H→ ττ most sensitive

But no sensitivity yet to 95% CL limits

95 % CL

68 % CL

expected

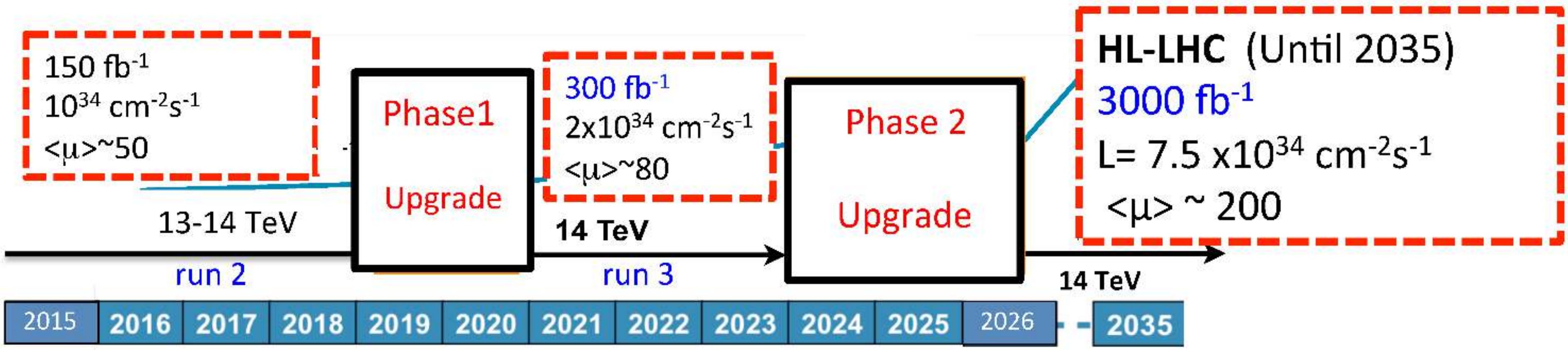
# Conclusions

**The observed Higgs boson seems to be quite SM-like**
$\Delta\kappa$ ~10 to 20 %, but deviations may be at (sub) percent level

**Knowledge today larger and more precise than we had dreamt of**
Interpretation in terms of Effective Field Theories etc. has started

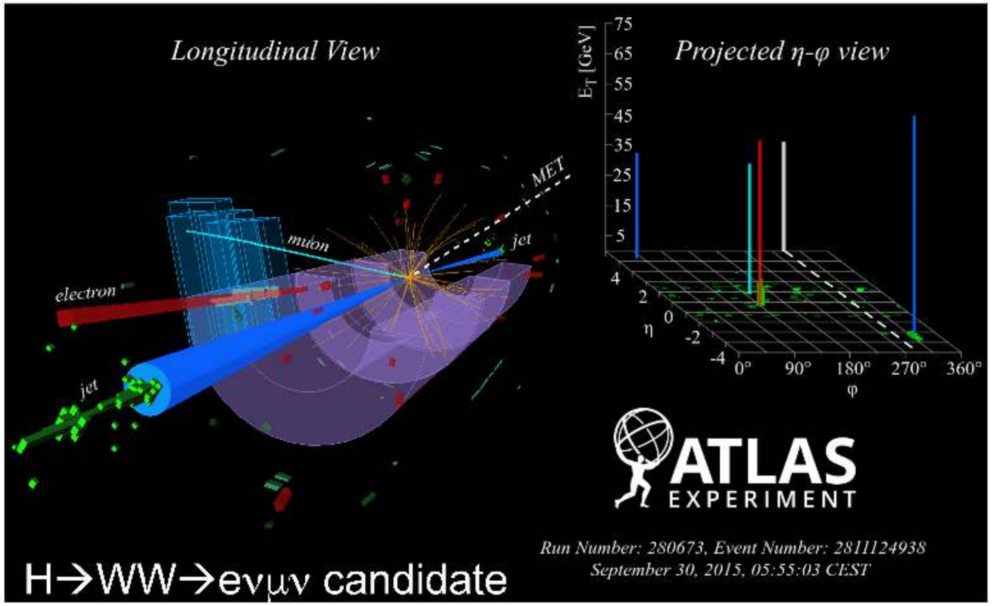
**Our hope: maybe Higgs boson "telescope" to New Physics?**

**Only ≤ 1/100 of expected full LHC data set collected and analysed.**
**Hopefully surprises in the next years or decades**



# H→WW→lν lν in Run-2

BR(H→WW→lνlν)= 1.02%   → most abundant among discovery channels



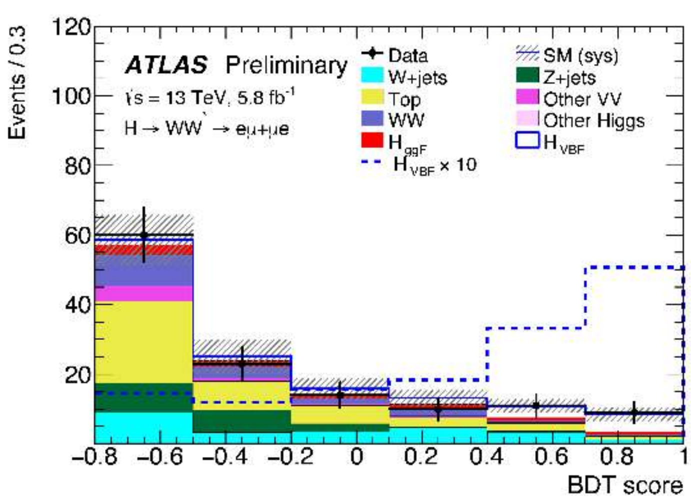

but very challenging:

- no mass reconstruction possible
- in particular for gg→H background control requires a lot of work and input from theory

5.8 fb$^{-1}$

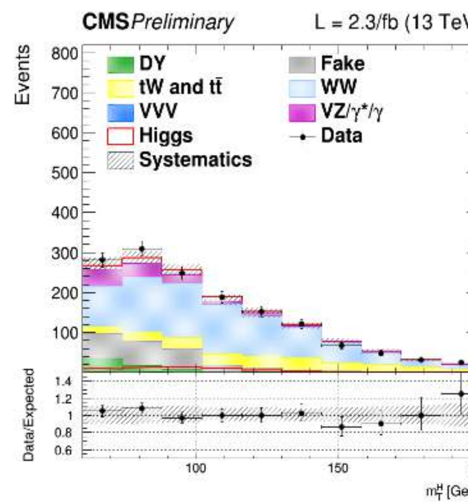
$\mu_{VBF}$= 1.7±1.0

$\mu_{WH}$ = 3.2±4.3




2.3 fb$^{-1}$

μ = 0.3±0.5



# Application: Constraining MCHM Parameters

In minimal composite Higgs models (MCHM) common reduction of coupling strength

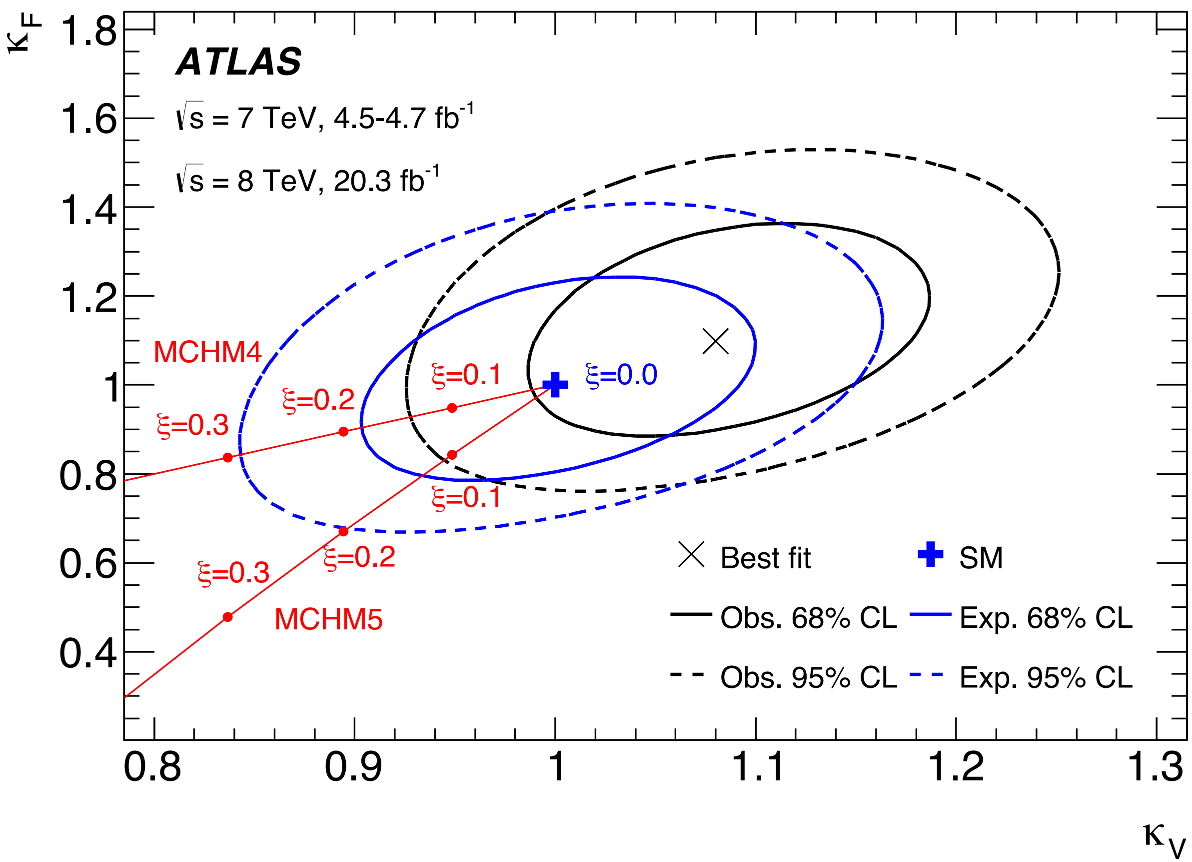
$$\xi = v^2 / f^2$$

f compositeness scale

MCHM4 $\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$

MCHM5 $\kappa_V = \sqrt{1-\xi}$

$$\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$




95% CL limits on f

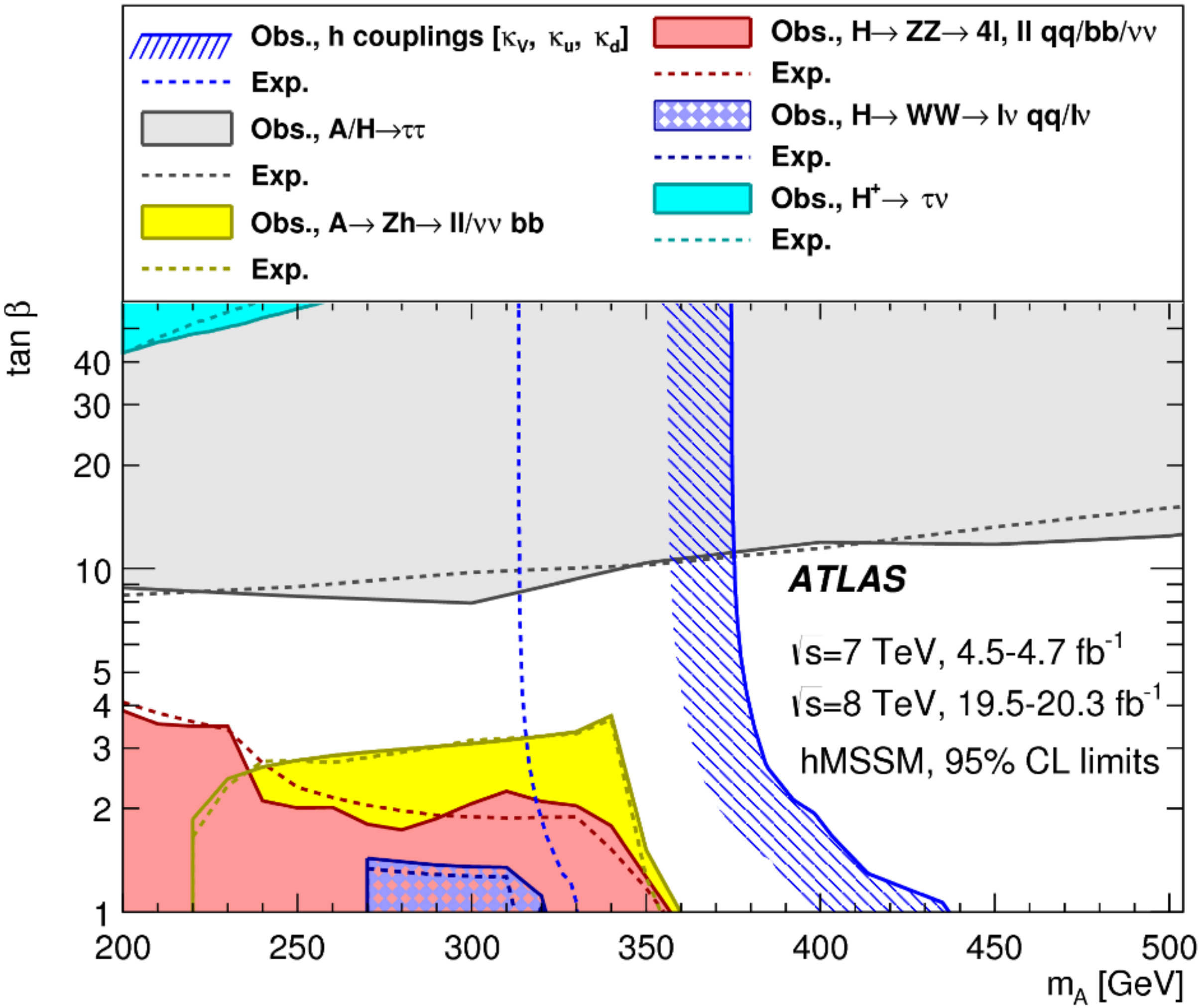
| Model | Lower limit on $f$ | |
|---|---|---|
| | Obs. | Exp. |
| MCHM4 | 710 GeV | 510 GeV |
| MCHM5 | 780 GeV | 600 GeV |

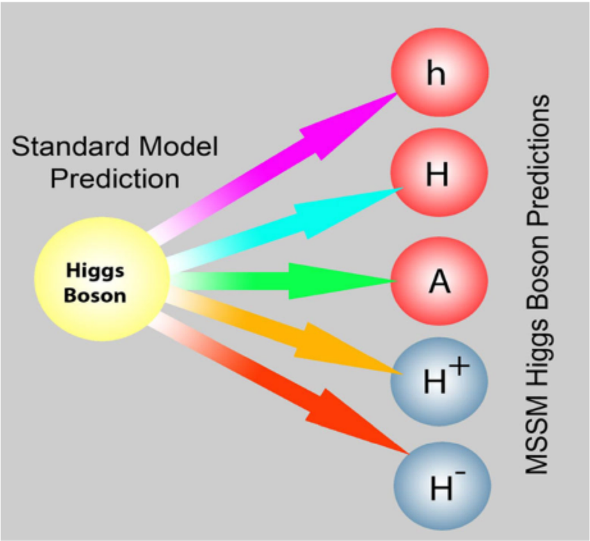
Rule of thumb for deviations

$$g(f)/SM = 1 + (3-9)\% \cdot \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

# Application: Constraining hMSSM Parameter Space

Simplified Minimal Supersymmetric extension of the SM hMSSM




Coupling for light h changed w.r.t. to SM

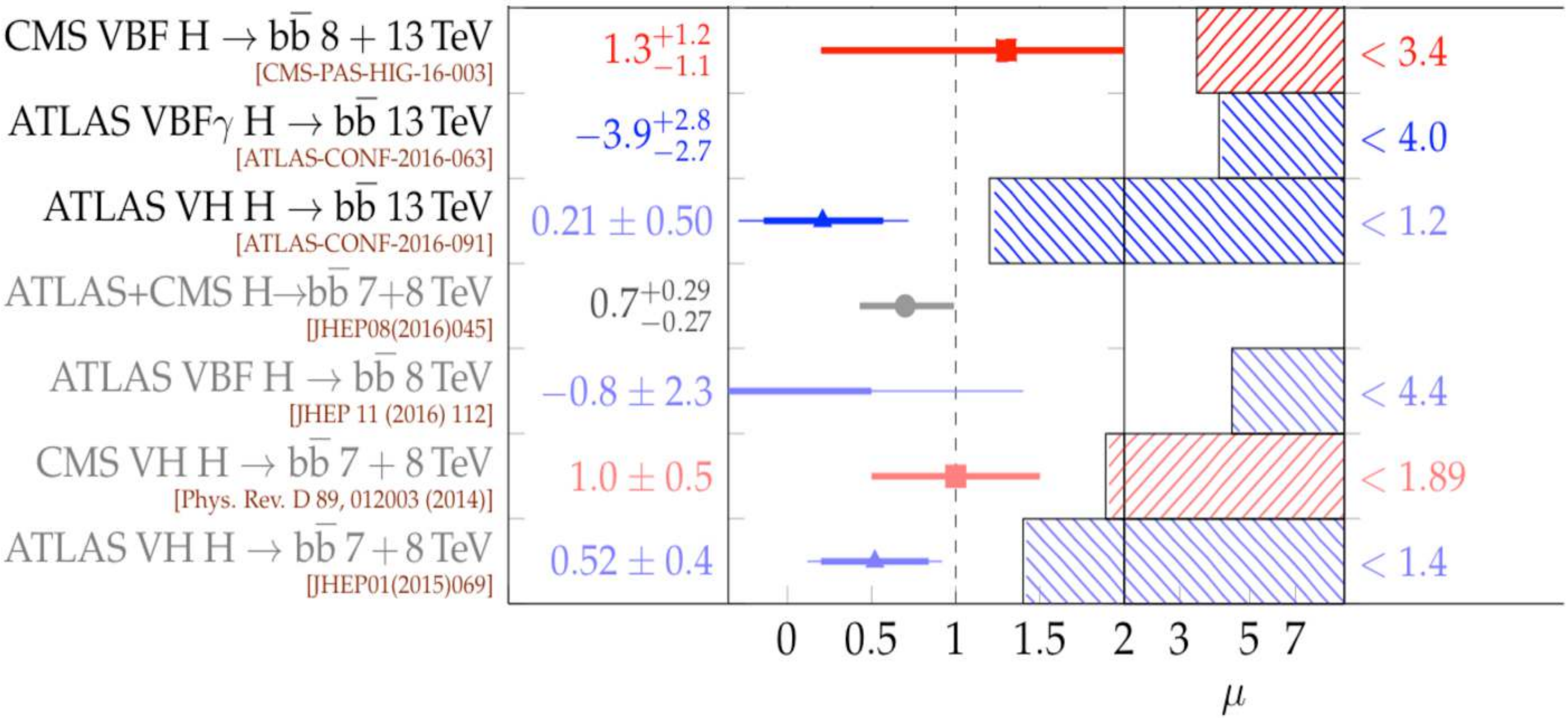
Rule of thumb for deviations

$$g(\tau)/SM = 1 + 10\% \left(\frac{400\ \mathrm{GeV}}{m_A}\right)^2$$

Exclusion from couplings complimentary to direct searches for H, A, H±

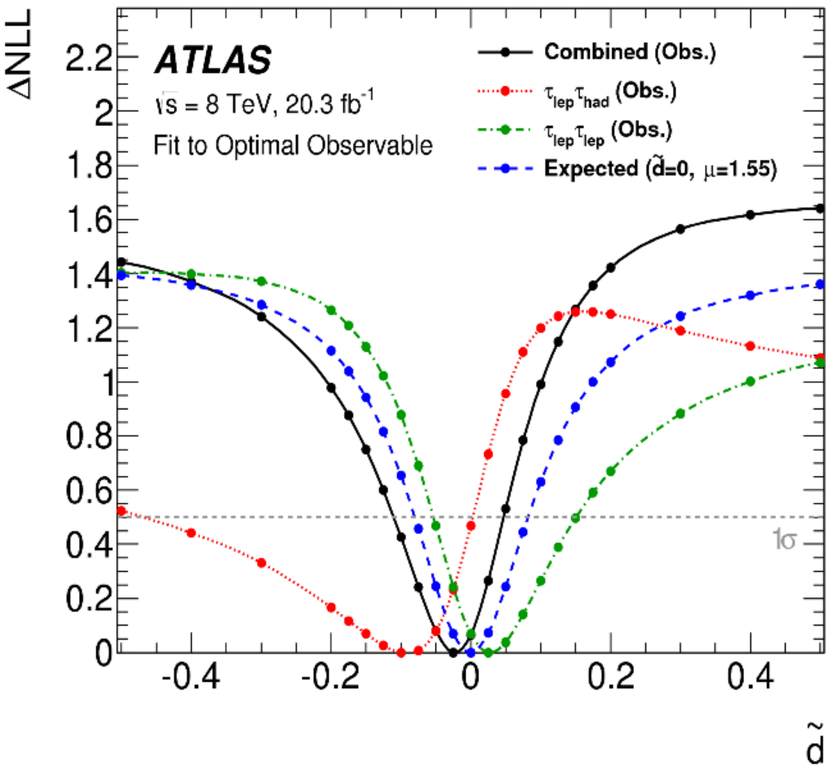
# Does the Higgs Boson Decay to a Pair of b-Quarks?

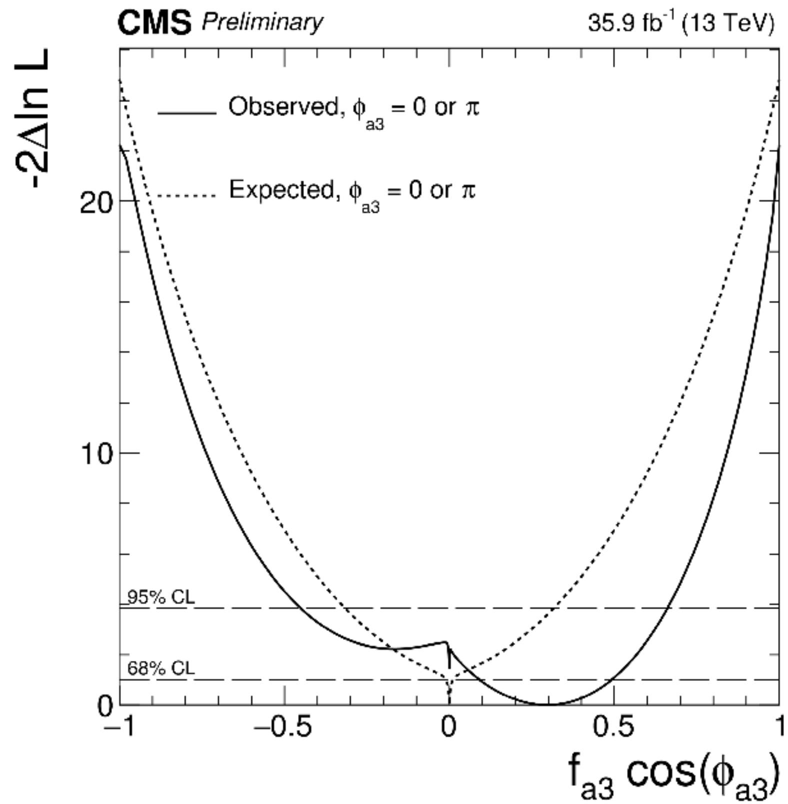
Overview of μ determination (G. Gaycken)




➢ Still no evidence for H→bb

# New Sources of CP-Violation in the HVV Vertex?



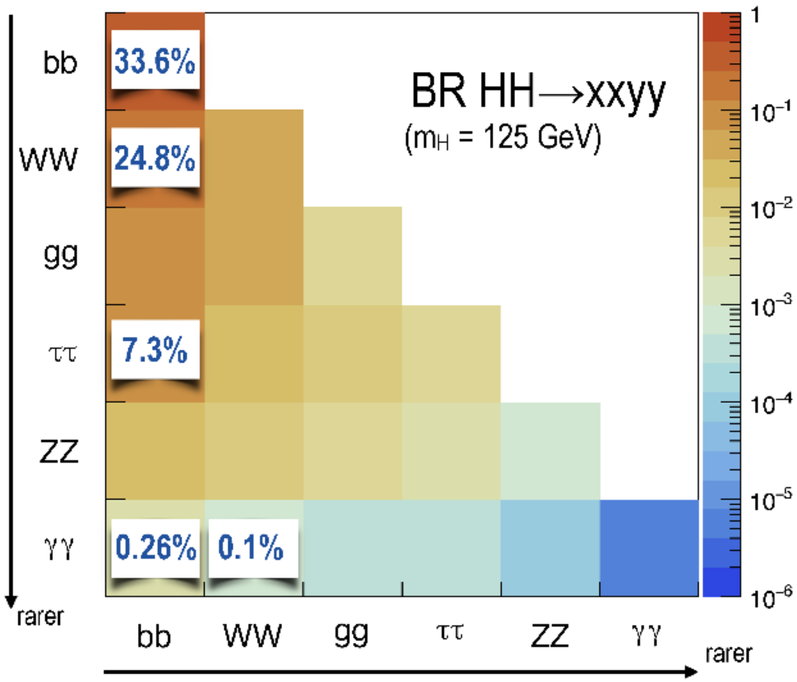




| Exp. | Data | Channel | 68% CL obs (exp) | 95% CL obs (exp) |
|---|---|---|---|---|
| CMS | Run-1 | H→VV | [-0.9,1.1] ([-1.9,1.9]) | [-2.2,2.3] ([-4.0,4.0]) |
| ATLAS | Run-1 | H→VV | --- | [-2.2,0.3] ([-2.3,2.3]) |
| ATLAS | 8 TeV | VBF, H→ττ | [-0.05,0.11] ([-0.08,0.08]) | Not sensitiv |
| CMS | Run-2 | H→VV,VBF,VH | [-1.0,0.8] ([-0.3, 0.3]) | [-2.3,3.6] ([-1.8,1.8]) |

# Tripe Higgs-Coupling / Higgs Boson Pair Production

Limits (exp.) on $\sigma(gg \rightarrow HH)/\sigma(gg \rightarrow HH)_{SM}$ at 95% CL assuming SM for $BR(H \rightarrow xx)$

| | | bbbb | bbWW | $bb\tau\tau$ | $bb\gamma\gamma$ | $WW\gamma\gamma$ | comb. |
|---|---|---|---|---|---|---|---|
| ATLAS | Run1 | 63 (63) | -- | 160 (130) | 220 (110) | 1150 (680) | 70 (48) |
| | Run2 | 29 (38) | -- | -- | 117 (161) | 747 (386) | -- |
| CMS | Run1 | | | 53 (84) | 74 | | |
| | Run2 | 342 (308) | 79 (89) | 28 (25) | 91 (90) | -- | -- |




2.3-3.2 $fb^{-1}$

13.3 $fb^{-1}$

35.9 $fb^{-1}$

# Limits on some Rare, LFV, Invisible Decay Modes

| H→ (95% CL limits (exp)) | ATLAS | CMS |
| --- | --- | --- |
| $\mu(\mu\mu)$ Run1 /Run 2<br>Combined | 7.0 (7.2) / 3.2(3.3)<br>2.8 (2.9) | 7.4( (6.5) |
| $\mu(ee)$ | | 3.7 x $10^5$ |
| $\mu(Z\gamma)$ | 11(9) | 9.5 (10) |
| $\mu(ll\gamma)$ with $m_{ll}$<20GeV | | 7.7 (6.4) |
| BR($\Upsilon$(1S,2S,3S) $\gamma$) | 1.3/1.9/1.3 x$10^{-3}$<br>(1.8/2.1/1.8) | |
| BR(J/$\Psi$ $\gamma$) | 1.5 (1.2) x$10^{-3}$ | |
| BR($\phi$ $\gamma$) | 1.4 (1.5) x$10^{-3}$ | |
| LFV BR($\tau\mu$) Run1 | 1.43 (1.01) % | 1.51 (0.75) % |
| Run 2 (2.3 $fb^{-1}$) | | 1.20 (1.62) % |
| LFV BR($\tau e$) Run1 | 1.04 (1.21) % | 0.69 (0.75) % |

- Non universal coupling to leptons.
- H->J/$\Psi\gamma$: test coupling to charm quark SM: BR= 2.9±0.2 x $10^{-6}$
  H→$\phi\gamma$ : test coupling to strange quark SM: BR= 2.3±0.1 x $10^{-6}$
- Lepton flavour violation (LFV): 2.3$\sigma$ excess at CMS H→$\tau\mu$ in Run1

# Search for H→ Quarkonia ($q\bar{q}$) + Photon

H→$\phi\gamma$ : test coupling to strange quark

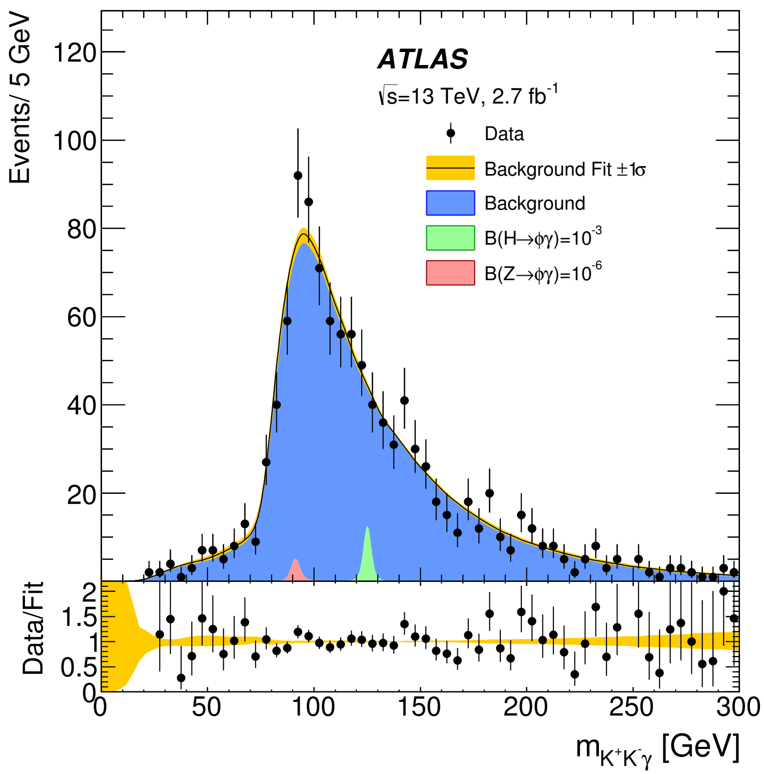
SM: BR= 2.3±0.1 x $10^{-6}$

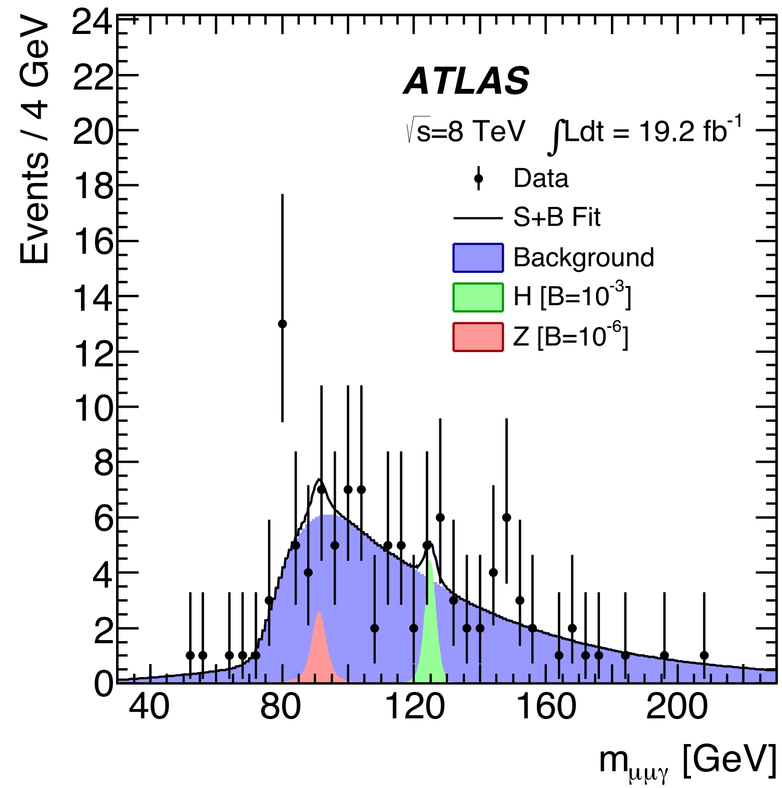
Limit 95% 1.4 x $10^{-3}$ (exp 1.5) x $10^{-3}$

H->J/$\Psi\gamma$: test coupling to charm quark

SM: BR= 2.9±0.2 x $10^{-6}$

Limit 95% 1.5 x $10^{-3}$ (exp 1.2) x $10^{-3}$




No hints for decays to quarkonia

Limits ~ 500 x SM prediction

# Total Width in Kappa-Framework

Almost model independent limits on width not useful for coupling analysis

Additional assumption needed to extract coupling modifiers $\kappa_i$

1) No BSM decays: $BR_{BSM}=0$ → total width function of $\kappa_i$ to SM particles

$$\Gamma_H(\vec{\kappa}) = \kappa_H^2(\vec{\kappa}) \cdot \Gamma_H^{SM}$$

$$\kappa_H^2 \sim \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + \\ + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

2) Upper limit on coupling of W and Z: $\kappa_V \leq 1$ → upper limit on width total width

Additional fit parameter $BR_{BSM}$

$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

BSM = invisible and undetectable (e.g. H→cc)

3) On-shell and off-shell kappas the same

$$\kappa_{g,\text{on-shell}}^2 \cdot \kappa_{V,\text{on-shell}}^2 \leq \kappa_{g,\text{off-shell}}^2 \cdot \kappa_{V,\text{off-shell}}^2$$

$$\frac{d\sigma_{gg\to H\to ZZ}}{dM_{ZZ}} \propto \frac{\kappa_g(M_{ZZ})^2 \kappa_Z(M_{ZZ})^2}{(M_{ZZ}^2 - M_H^2)^2 + M_H^2\Gamma_H^2}$$

$$\frac{\Gamma_H}{\Gamma_H^{SM}} \leq \frac{\sigma_{on-shell}/\sigma_{off-shell}}{\sigma_{on-shell}^{SM}/\sigma_{off-shell}^{SM}} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$$

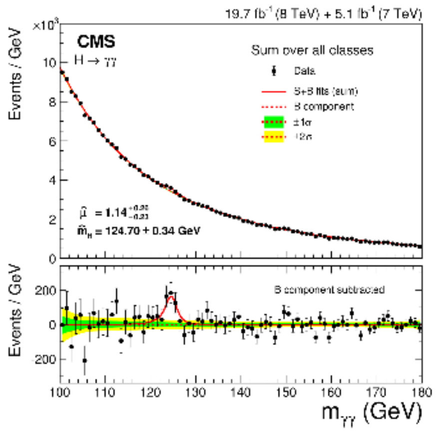
| Upper Limit on $\Gamma_{tot}$ [ MeV] | ATLAS obs | ATLAS exp | CMS obs | CMS exp |
|---|---|---|---|---|
| | 22.7 | 33.0 | 22 | 33 |

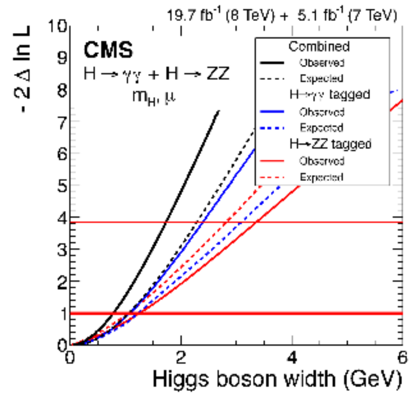
# Total Width in Kappa-Framework

**Total width:**
- scales all observed event rates
- lower limit from observed event rates

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

## Upper limit on total width from Breit-Wigner line shape



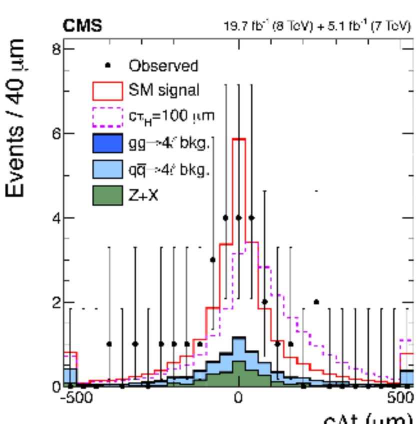



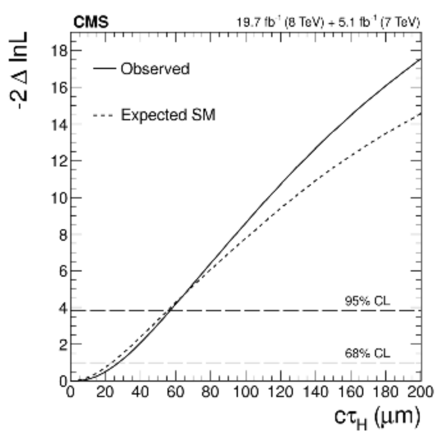

| $\Gamma_{tot}$ [GeV] | ATLAS obs | ATLAS exp | CMS obs | CMS exp |
|---|---|---|---|---|
| H→γγ | 5.0 | 6.2 | 2.4 | 3.1 |
| H→ZZ | 2.6 | 6.2 μ=1<br>3.5 $\mu_{obs}$ | 3.4<br>1.7 | 2.8<br>2.3 |

CMS combined: 1.7 (2.3 exp.) GeV

Limit ~ 500 times SM value

## Lower limit from flight path in H→ZZ→4l




$\tau_H < 1.9\times10^{-13}$ s $\quad \Gamma_H > 3.5\times10^{-9}$ MeV

$10^{-9}$ x SM value