Higgs boson physics at LHC

Chiara Mariotti

on behalf of ATLAS and CMS

DIS17, Birmingham, April 3-7, 2017

The Higgs boson as of today

- Introduction

- The results from ATLAS+CMS

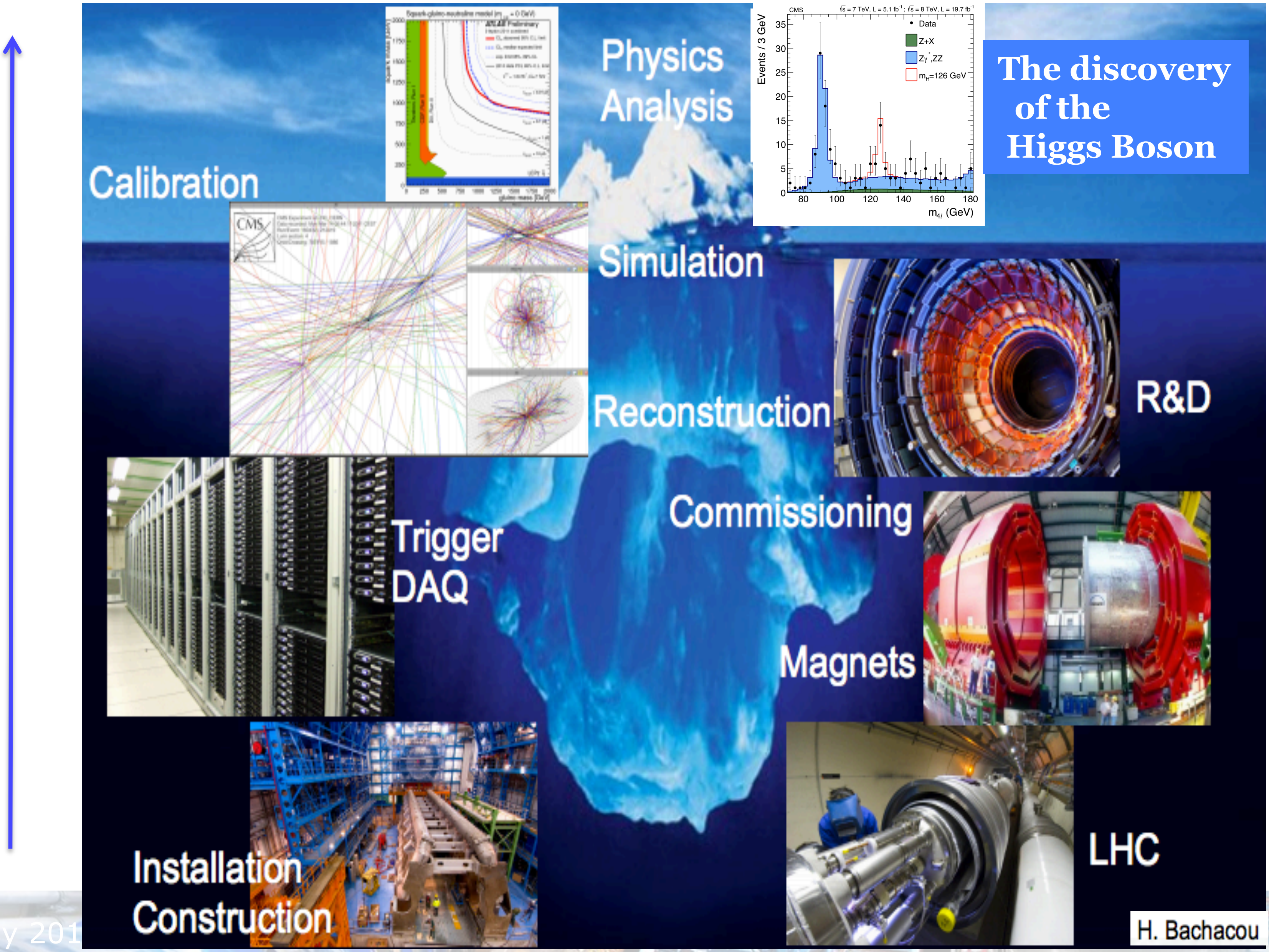
  - the Higgs mass
  - the Higgs width
  - spin and CP
  - the couplings
  - new results at 13 TeV

- The searches for additional BSM Higges

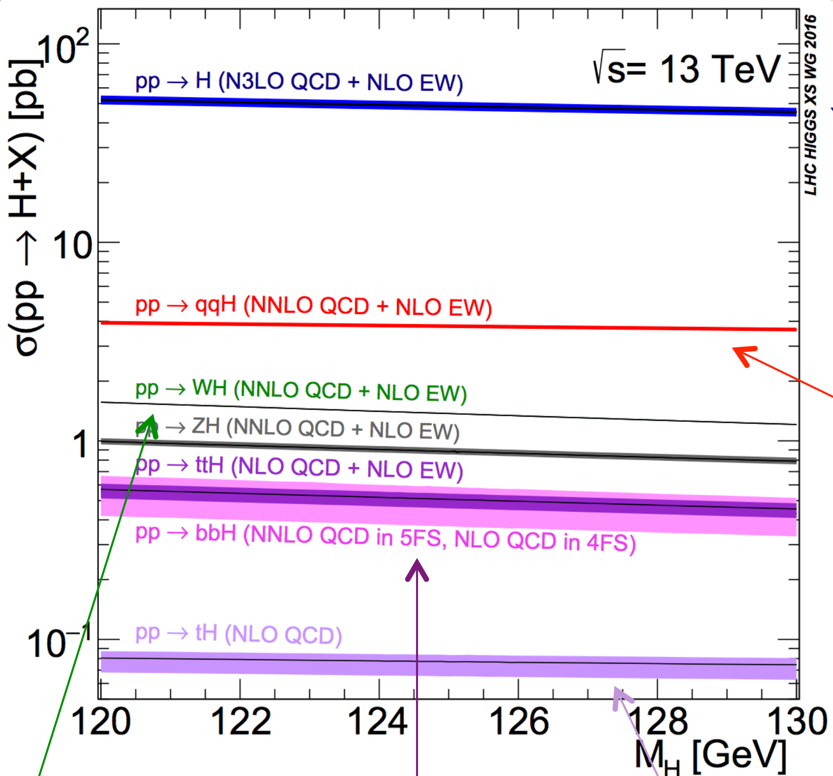
The SM: a long journey

54 Yang & Mills
61 Glashow
64 Brout, Englert, Higgs et al
67-68 Weinberg and Salam
70 ‘t Hooft
73 Gargamelle : discovery of the week neutral current
83: Ua1 & UA2: W and Z discovery
89-2000: LEP and HERA: the triumph of the SM
95: Tevatron: top quark discovery
2012: LHC: discovery of a Higgs like boson

…and the LHC, Atlas and CMS long journey

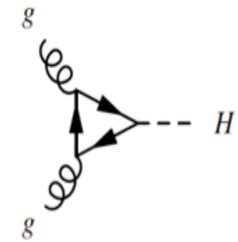


Higgs production at LHC

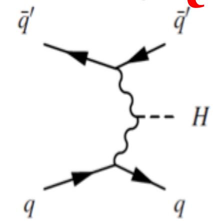


The LHC Higgs Cross Section WG
YR1, YR2, YR3, YR4

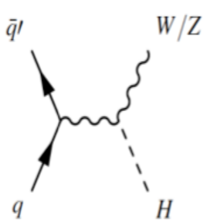
ggF: N3LO + NLO EW

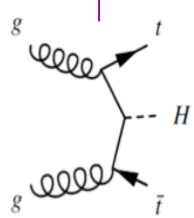


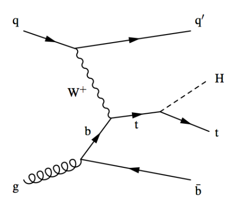
qqH: NNLO QCD + NLO EW



WH: NNLO QCD + NLO EW
ZH: NNLO QCD + NLO EW



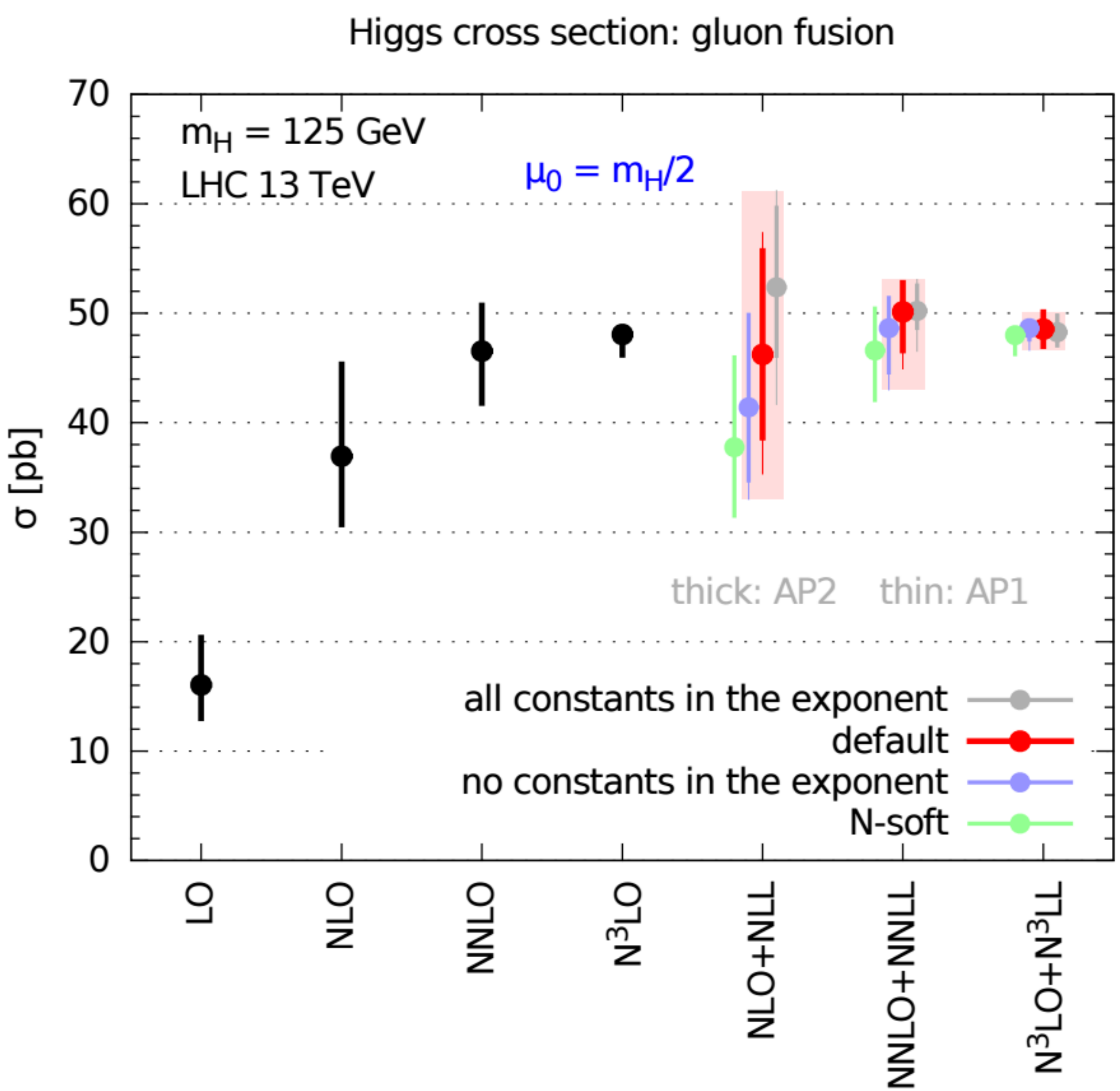




ttH: NNLO QCD
bbH: NNLO QCD
tH: NLO QCD

	Scale	PDF	Total error
ggF	4%	1.9%	~7-10%
VBF	0.4%	2.1%	2.5%
WH/ ZH	0.5 - 3%	1.5%	4-5%
ttH	+6% -9%	±3%	~13%

Higher order calculation for XS

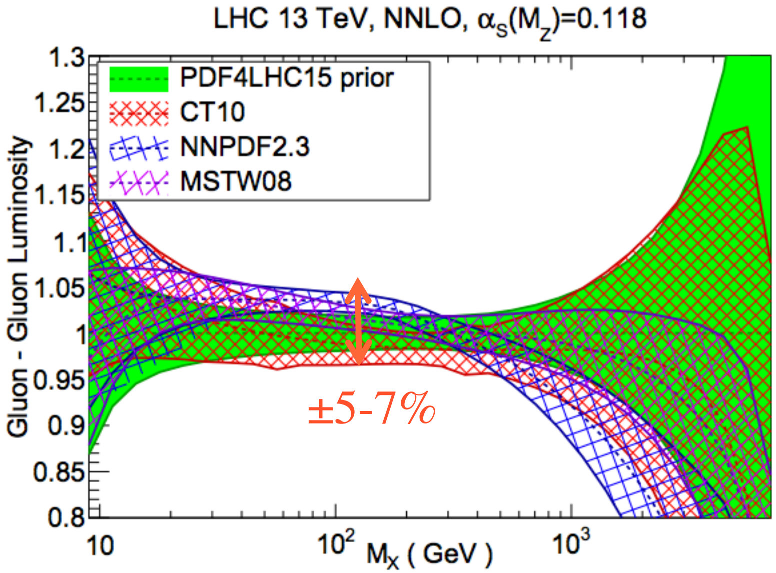


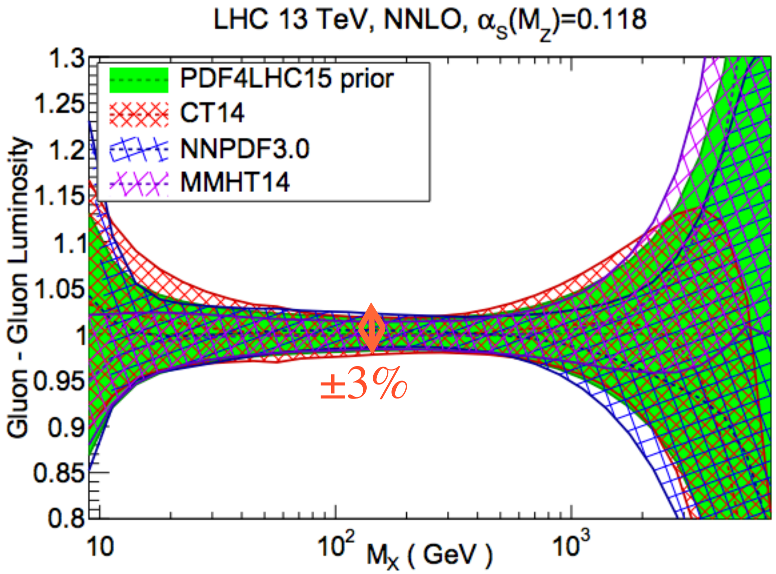
ggF

from NNLL to N3LO

For references see:
YR4 of the LHCHXSWG

A huge improvement in the gluon PDF understanding





ALL PDF now are up to NNLO and using LHC DATA

Latest PDF sets from global fits display a nice agreement for the gluon luminosity

High impact on Higgs production uncertainty.

The changes can be ascribed partially to the addition of new data sets used in the PDF fits,
but primarily to improvements in the fitting formalisms.

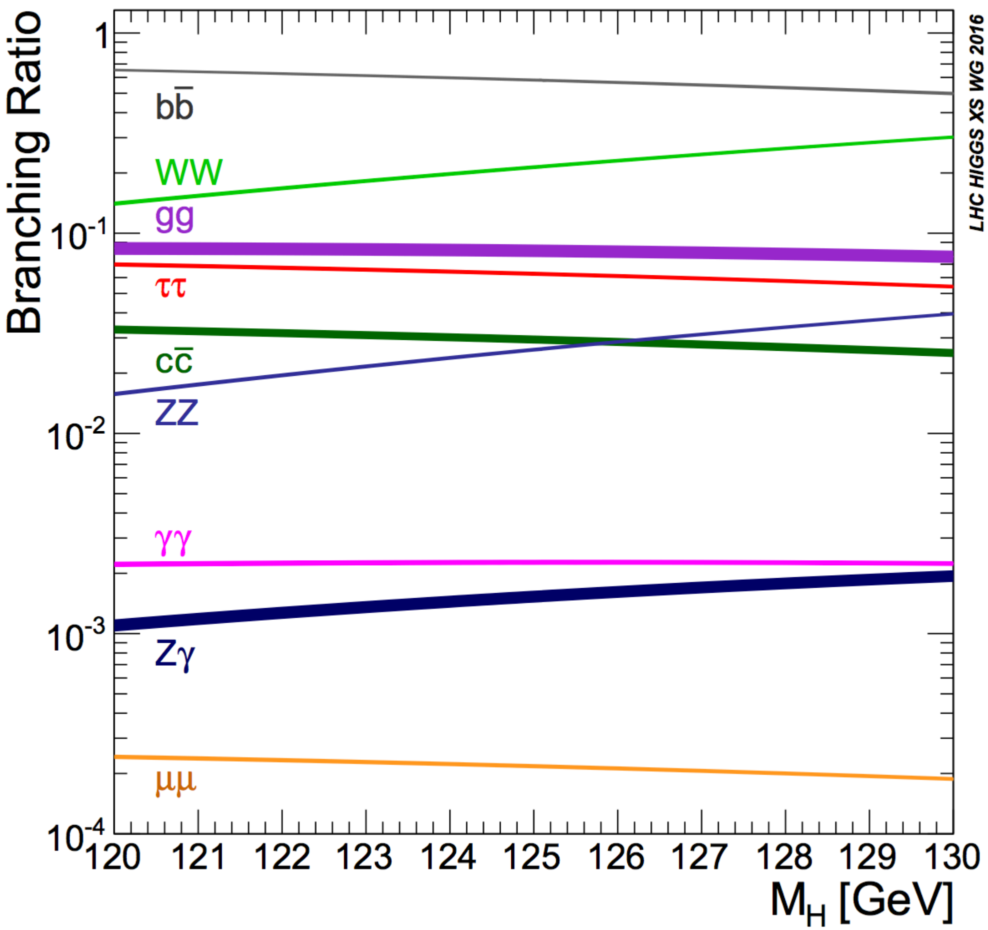
The channels at LHC

5 decay modes exploited

σ_M/M

- bb 10%
- ττ 10-20%
- WW 16%
- ZZ 1-2%
- γγ 1-2%

- and searches in Zγ, μμ



Improved treatment of the uncertainties on the BR, YR4 of the LHCHXSWG

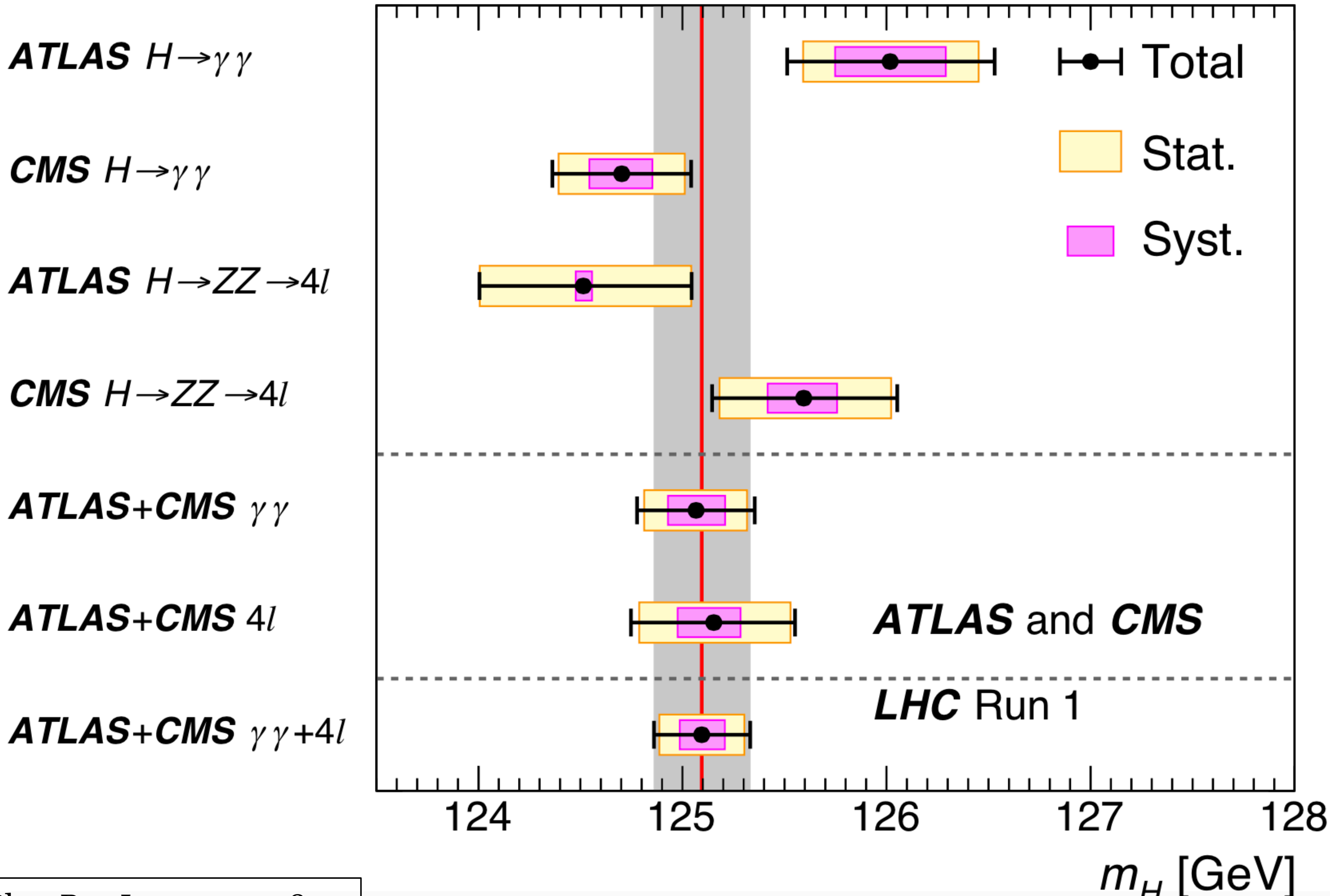
The mass

The mass is the most important property of the particle. Given the mass all the rest is precisely predicted by the SM.

The mass can be measured with very high precision from the $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ decay, since photons, electrons and muons are known with high accuracy.

Or can be inferred from the measured cross-section, assuming the SM, and thus using the theory predictions known at N3LO.

$$m_H = 125.09 \pm 0.24 \; (\pm 0.21 \text{ stat} \pm 0.11 \text{ syst}) \text{ GeV}$$



Phys Rev Lett 114, 191803

The result

Systematic contribution are evaluated sequentially "freezing" nuisance parameter groups to their best values and re-scanning the likelihood ratio

$$
\begin{aligned}
m_H = 125.09 \; & \pm 0.21 \quad \text{(stat)} \\
& \pm 0.11 \quad \text{(scales)} \\
& \pm 0.02 \quad \text{(others)} \\
& \pm 0.01 \quad \text{(theory)} \\
& \qquad\quad \text{GeV}
\end{aligned}
$$

< 0.2 % precision

Uncertainty is mostly statistical

E/p scale uncertainties dominate the systematic

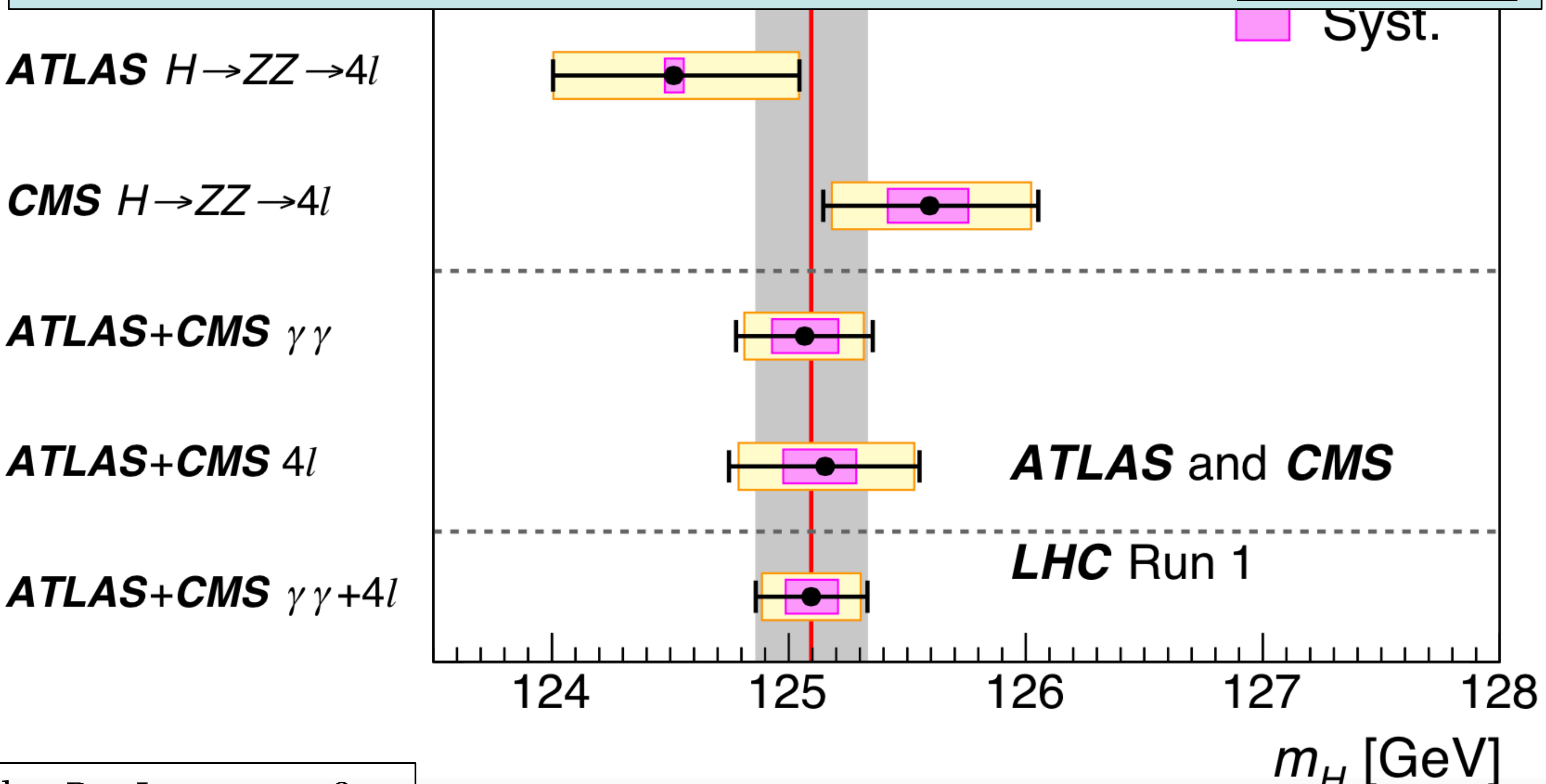
Theory uncertainties does not include interference

$$m_H = 125.09 \pm 0.24\ (\pm 0.21\ \text{stat} \pm 0.11\ \text{syst})\ \text{GeV}$$

!!NEW!! M(4l) from CMS with 35.9 fb^{-1} at 13 TeV

$$m_H = 125.26 \pm 0.20\,(\text{stat.}) \pm 0.08\,(\text{syst.})\ \text{GeV}$$

CMS HIG-16-041



Phys Rev Lett 114, 191803

The Higgs width: Γ_H from off-shell production

We can go from few GeV to ~tens of MeV using off-shell Higgs production

Kauer, Passarino: JHEP 1208 (2012) 116, Caola, Melnikov: Phys. Rev. D88 (2013) 054024

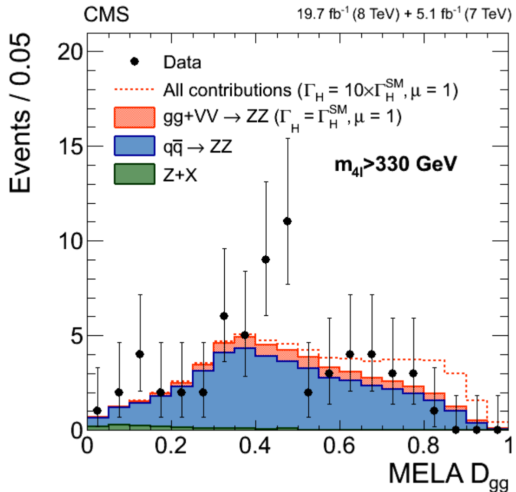
This method assumes that the couplings at the pole and off-shell are the same

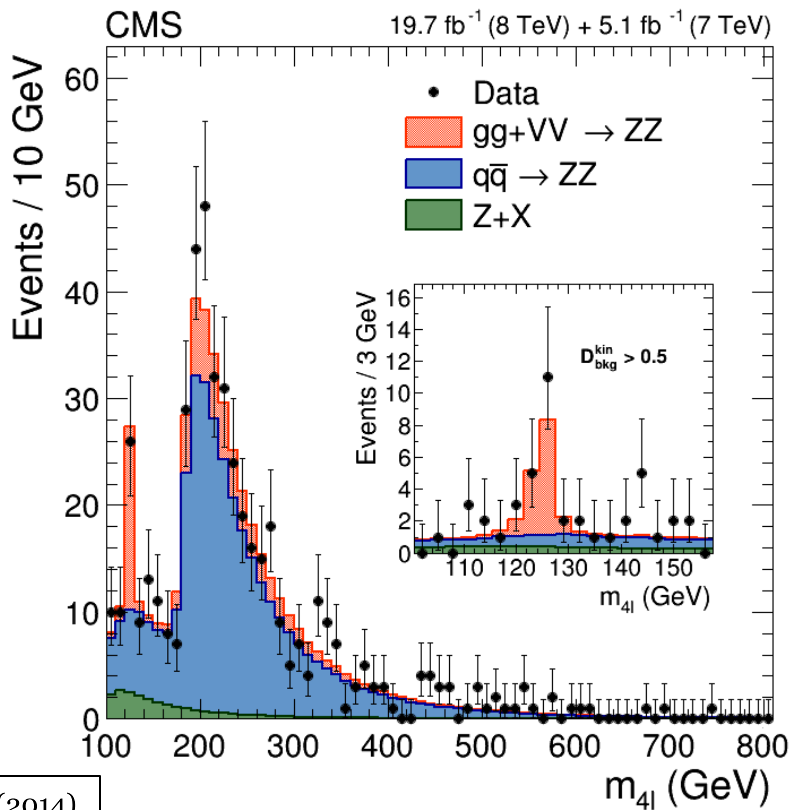
Off-shell Higgs boson production is small but the BR to 2 real Z is large above $2m_Z$

$$\sigma^{\mathrm{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\mathrm{off-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{2m_H^2}$$

Discriminant to enhance gg/qq production



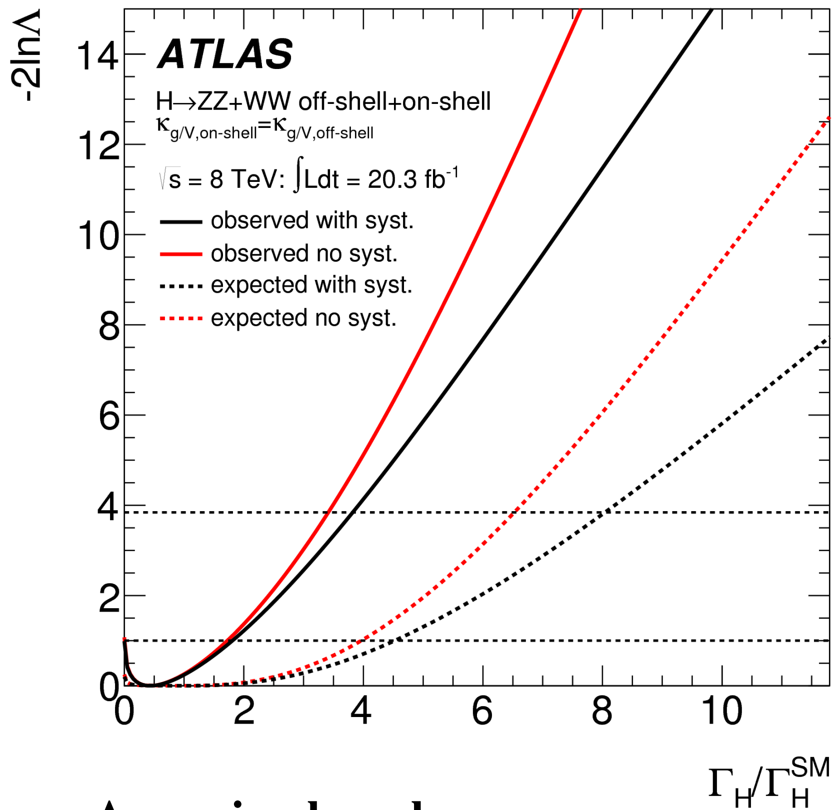


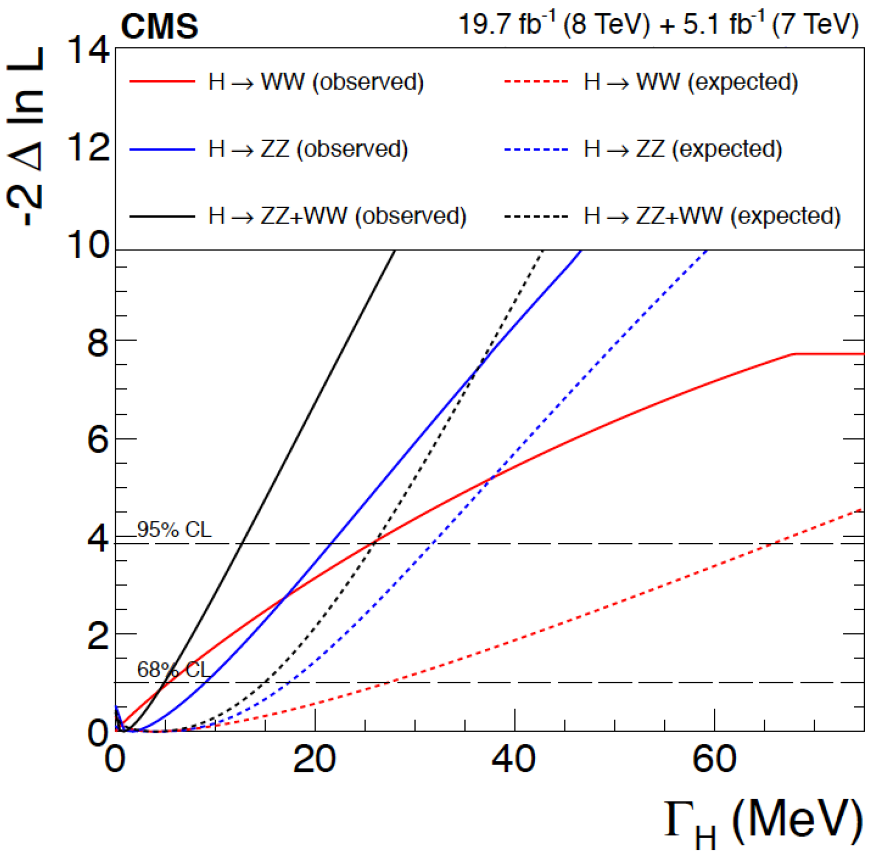
Phys. Lett. B736, 64 (2014)

The Higgs width: Γ_H from off-shell production

Eur. Phys. J. C75,335 (2015)

Phys. Lett. B736, 64 (2014)
JHEP 09, 051 (2016)





Assuming $k_{bck}=k_{sig}$

$\Gamma_H <$ 22.7 MeV (33 MeV expected)

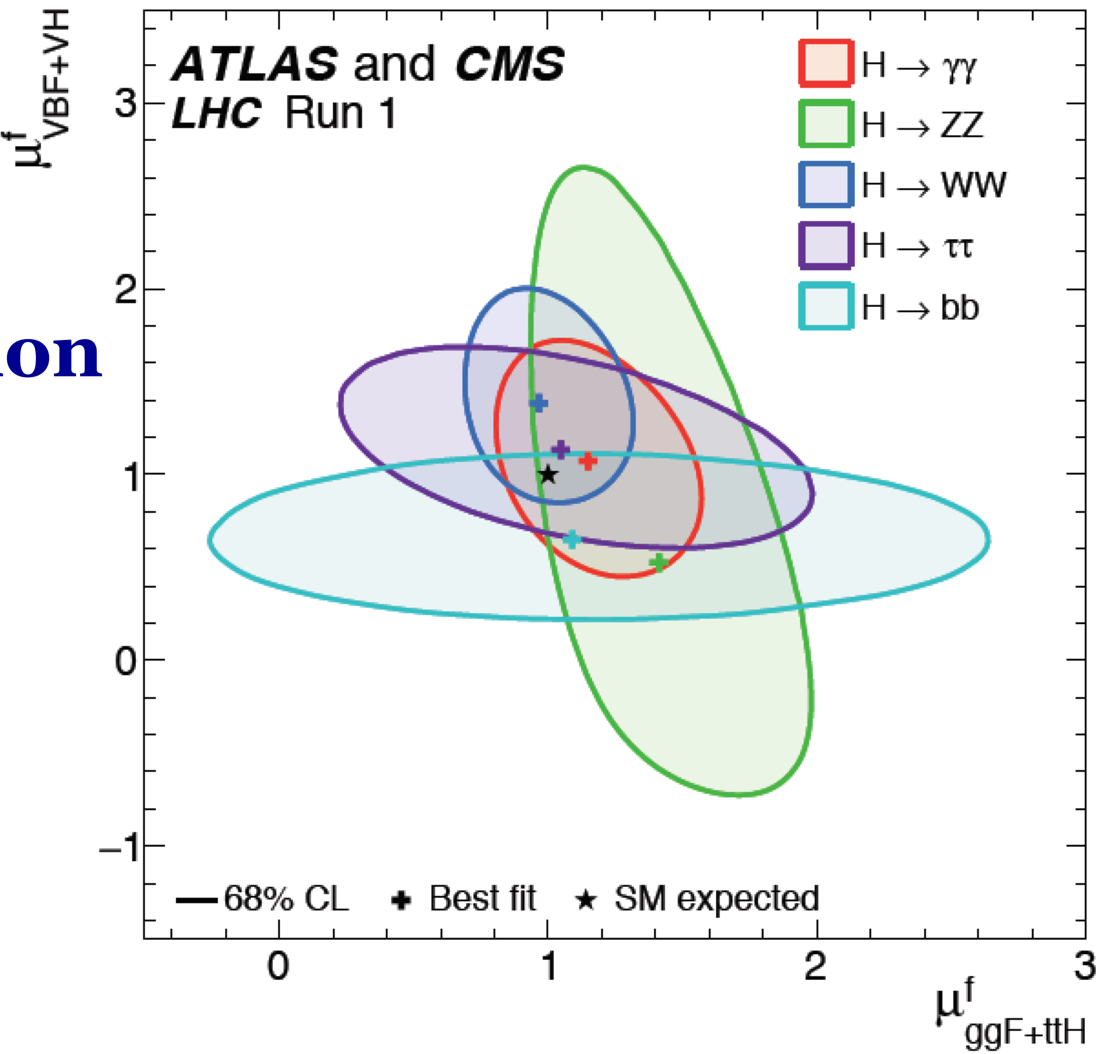
$\Gamma_H <$ 13 MeV (26 MeV expected)

SM H width = 4 MeV

Consistency with the SM hypothesis

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09 \pm 0.07(\text{stat}) \pm 0.04(\text{expt}) \pm 0.03(\text{th-bkgd})^{+0.07}_{-0.06}(\text{th-sig})$$

Production Modes

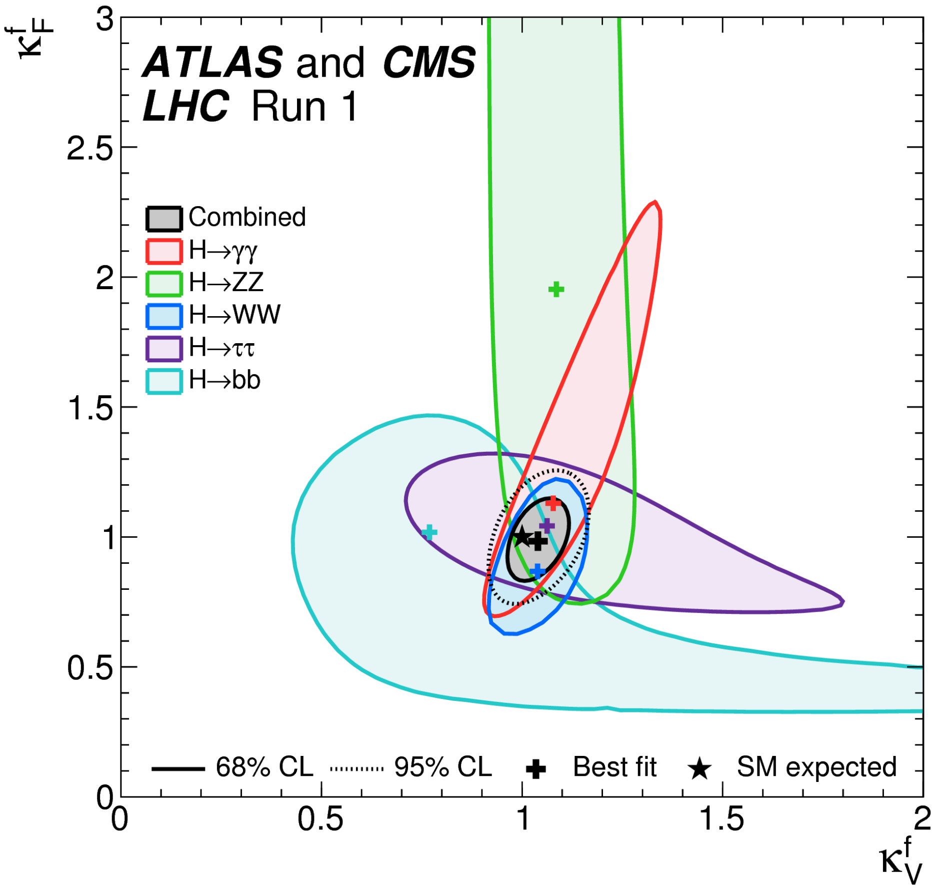


$$\boxed{\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}}$$

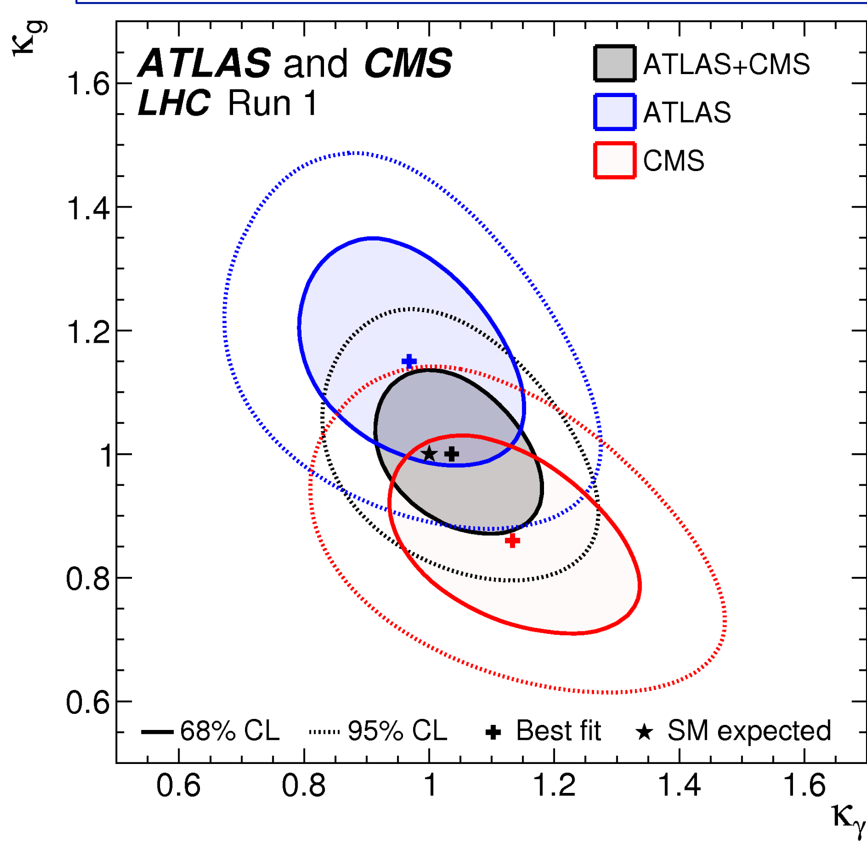
JHEP 11, (2016) 045

Couplings

Assume all fermion couplings scale as κ_F while all vector boson couplings scale as κ_V



Do not resolve gluon and photons couplings in case there are new particles in the loop



@ fitted m_H

JHEP 11, (2016) 045

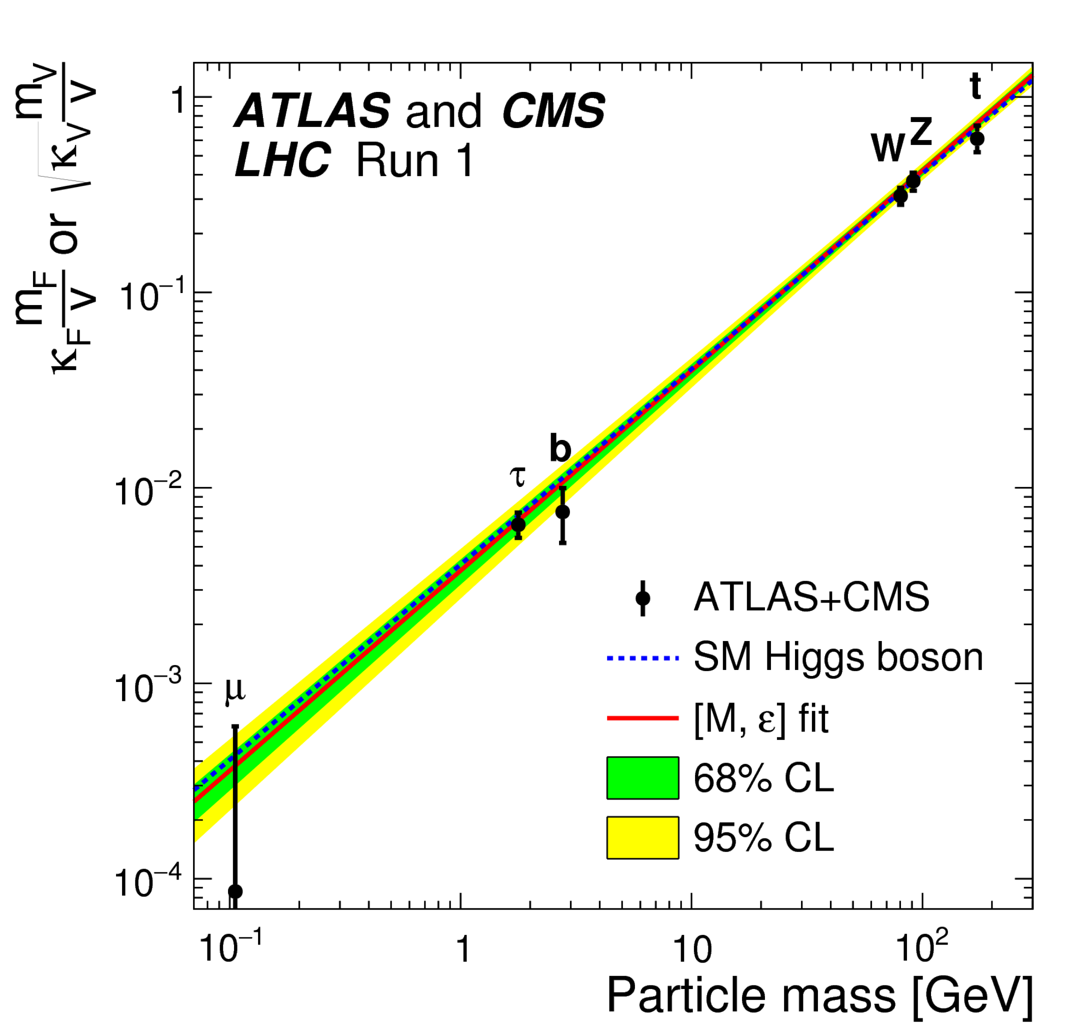
$\Gamma(H \rightarrow \gamma\gamma) \sim |\alpha\, \kappa_V + \beta\, \kappa_f|^2$, $\alpha/\beta = -0.2$

$\Gamma_{BSM} = 0$

Couplings vs mass

The Higgs couples to the mass of the particle:

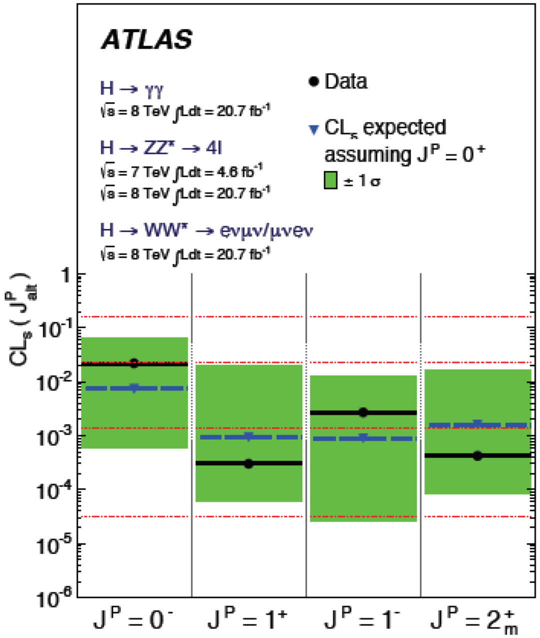
$$\boxed{\begin{aligned} \lambda_f &= \kappa_f m_f / v \\ g_V &= 2\kappa_V m_V^2 / v \end{aligned}}$$

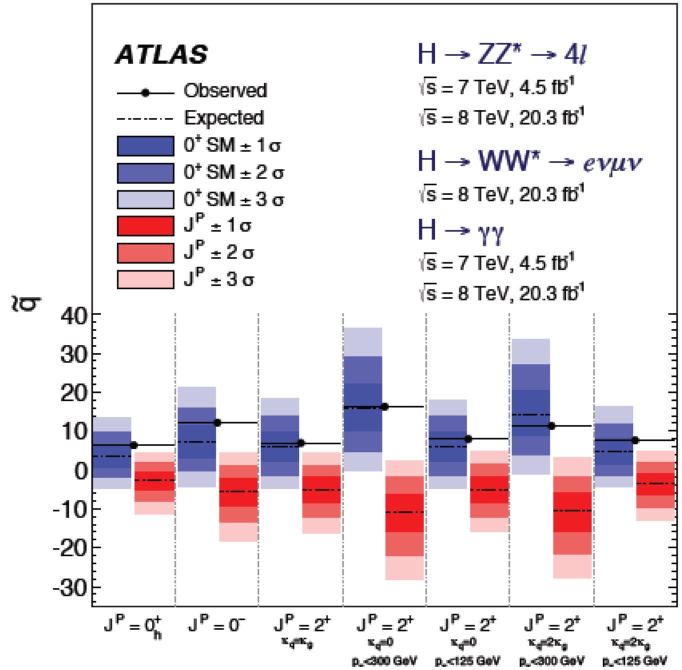


Perform a fit to the full Atlas / CMS combination, resolving gluon and photon loops in term of tree-level couplings

JHEP 11, (2016) 045

Spin and Parity from H→ZZ→4l, H→WW, H→γγ



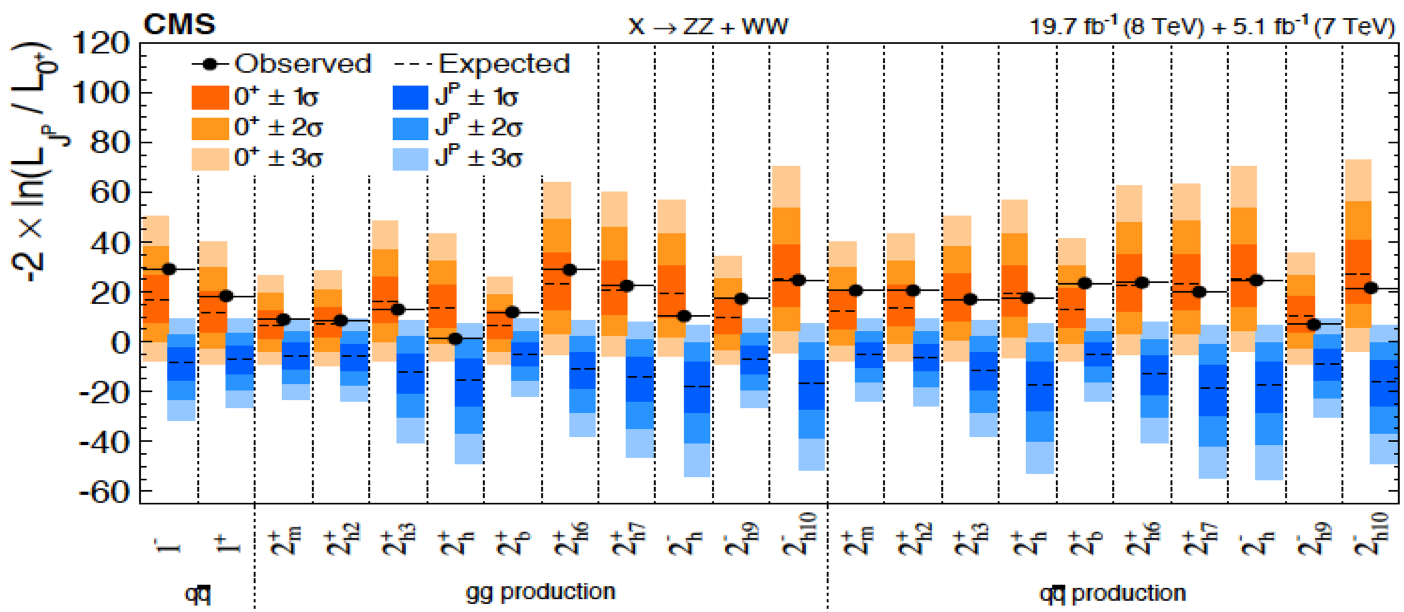


ATLAS and CMS many analyses, lots of results

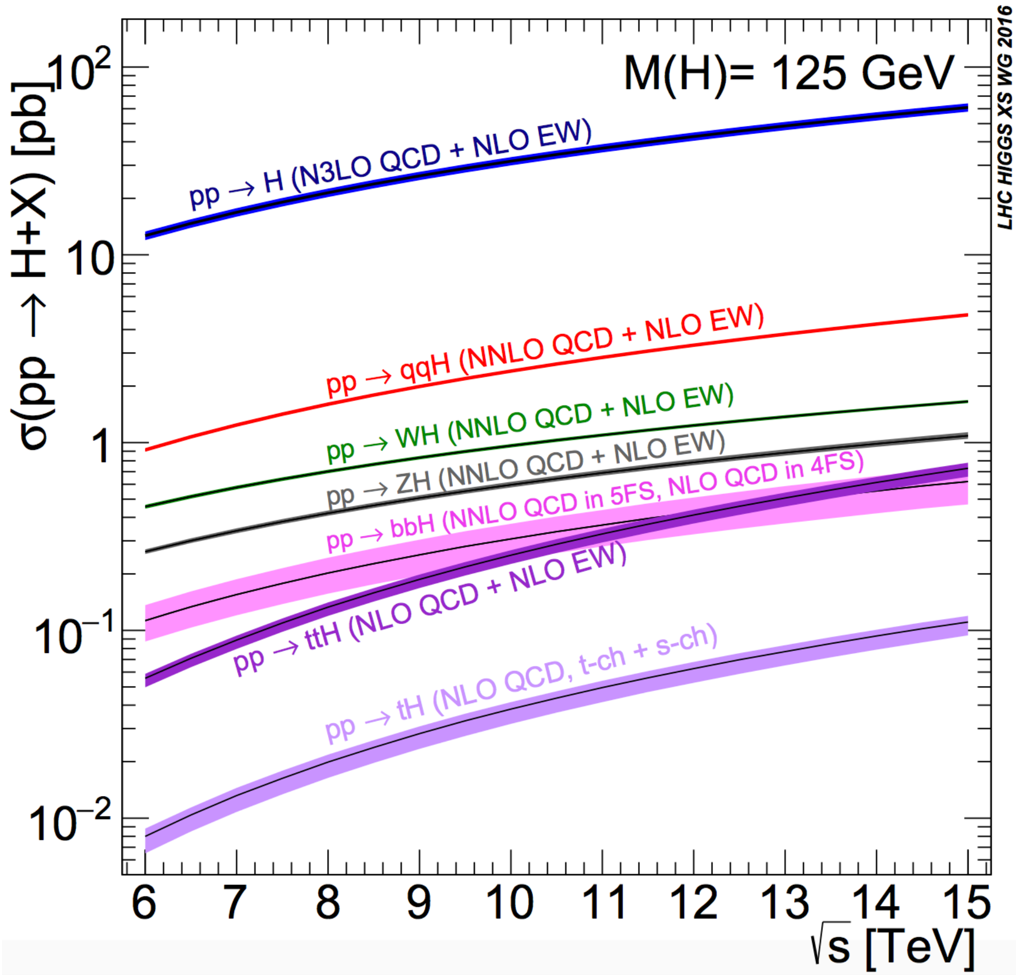
→

Spin O

Positive parity at > 99.9% CL



New results at 13 TeV



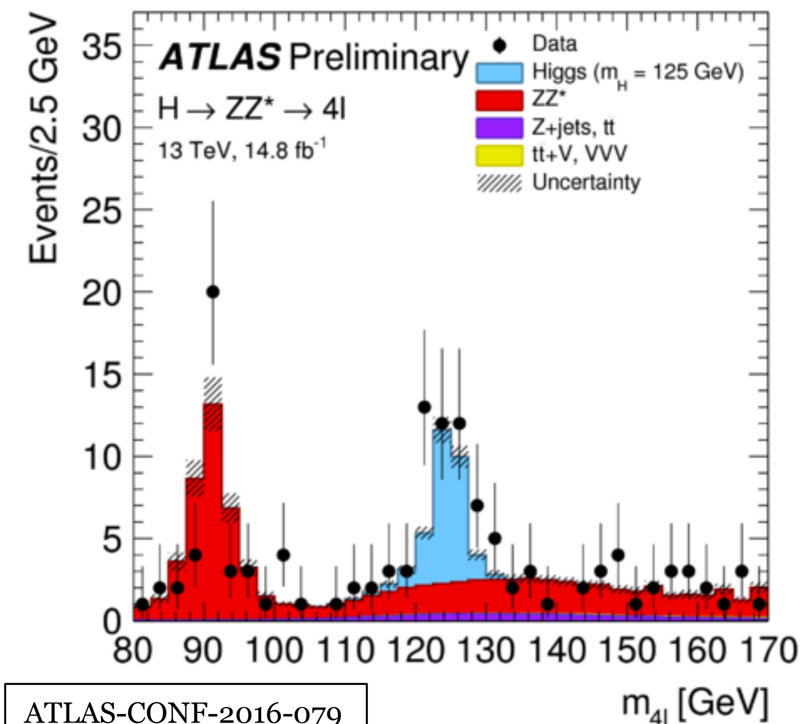
From 8 to 13 TeV

σ (ggF, VBF, VH) ~2 times larger

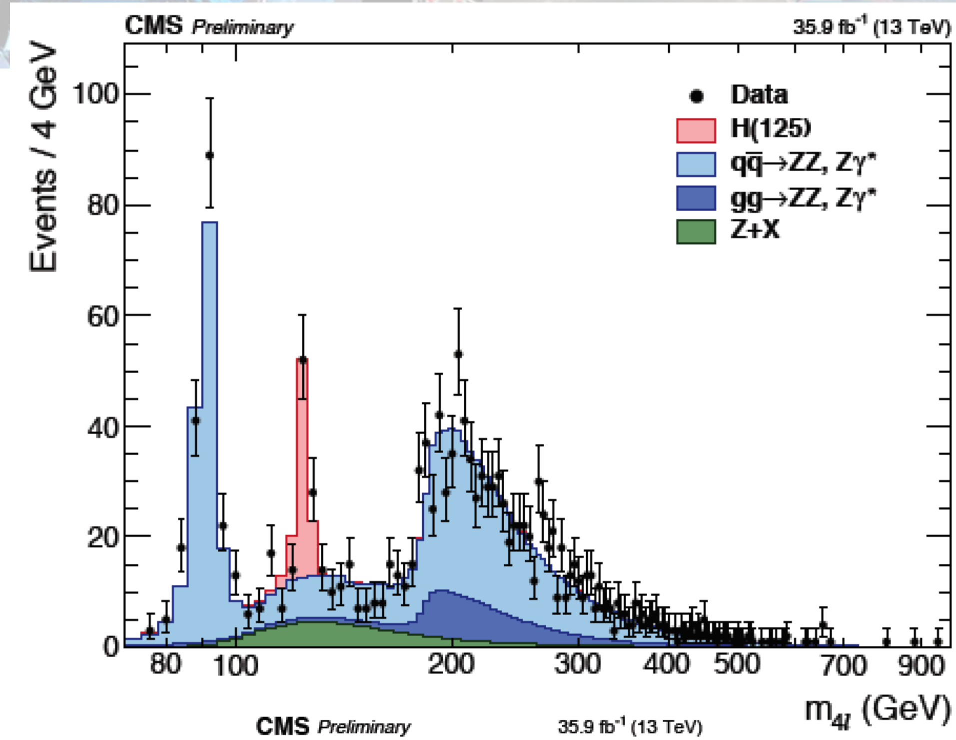
σ(ttH) ~4 times larger

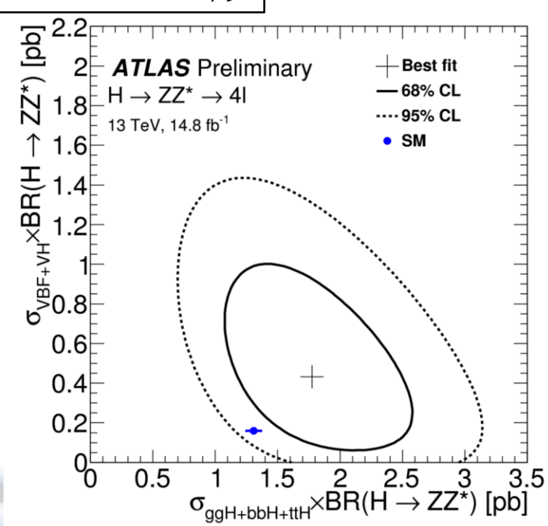
L= 35.9 fb^{-1} at 13 TeV

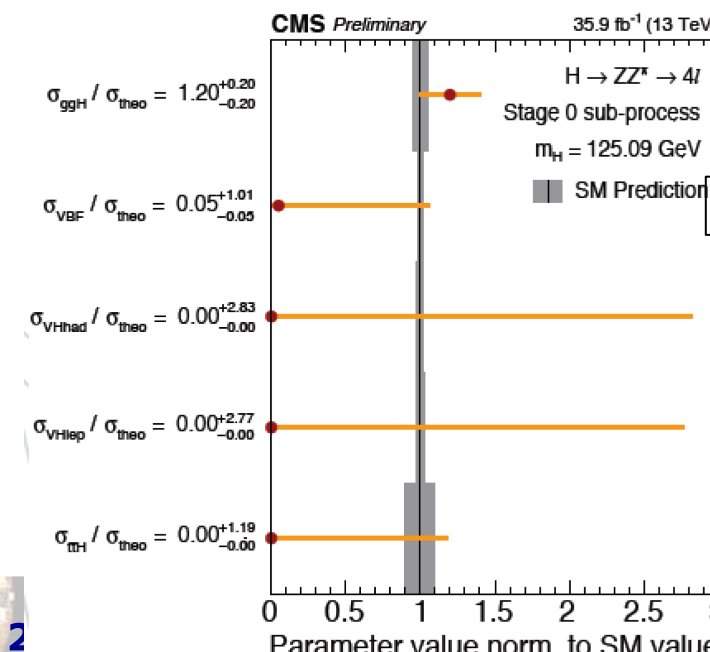
H → ZZ$^{(*)}$ → 4l



ATLAS-CONF-2016-079







NEW

CMS-HIG-16-041

Differential Cross Sections

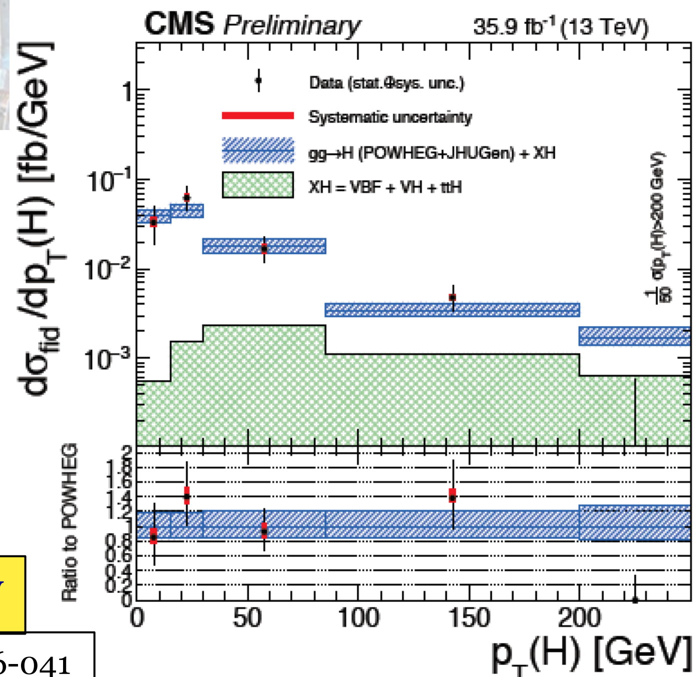
A fiducial phase space is defined to closely match the experimental acceptance in order to reduce the systematic uncertainty associated with the underlying model

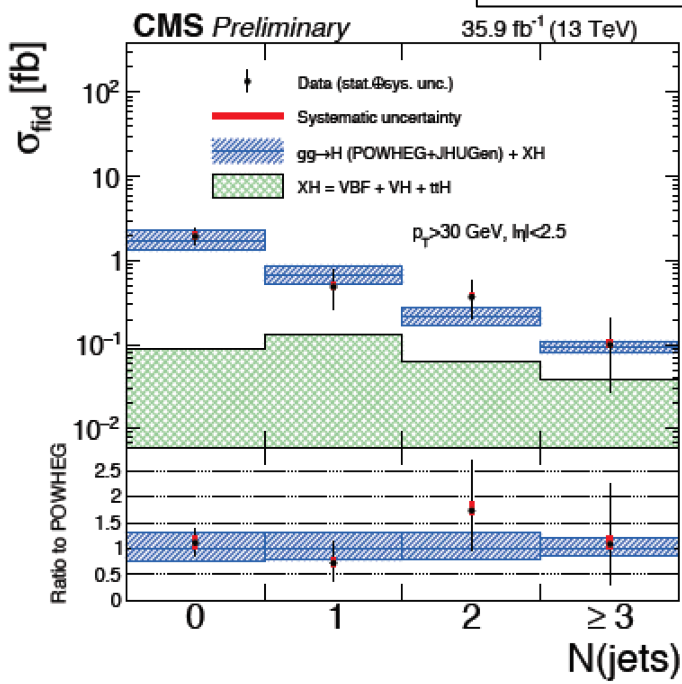
Each bin represents a specific fiducial sub-region

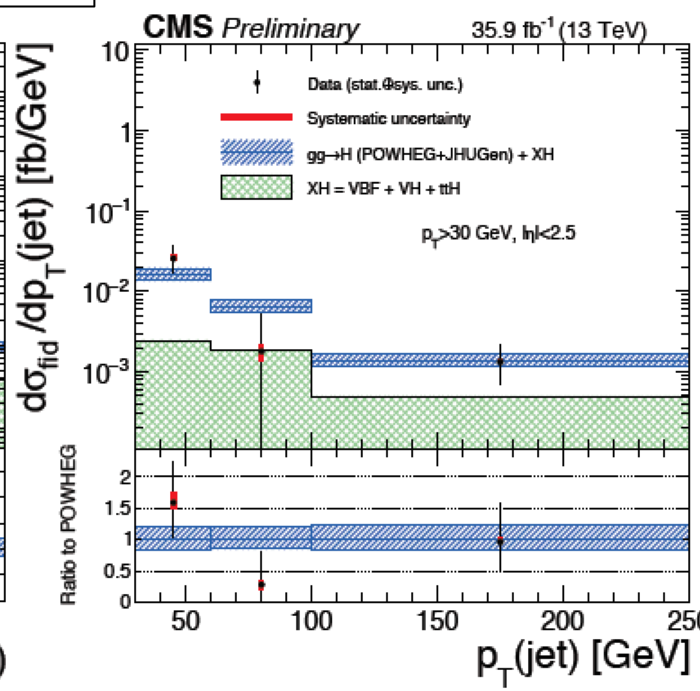
$$\frac{d\sigma_i}{dx} = \frac{\nu_i^{\text{sig}}}{c_i\, \Delta x_i \int L\, dt}$$

NEW

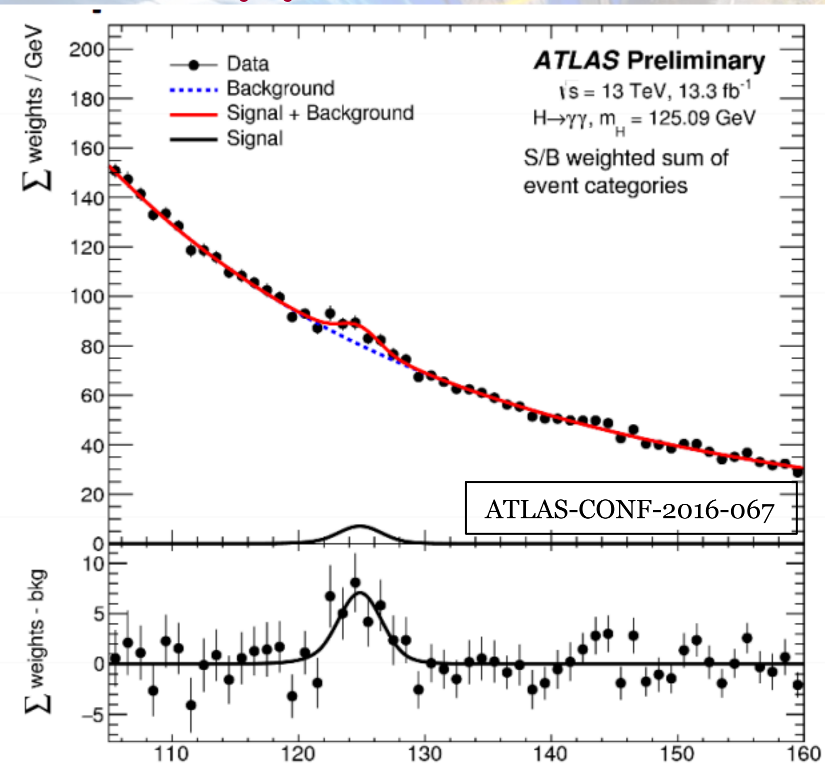
CMS-HIG-16-041

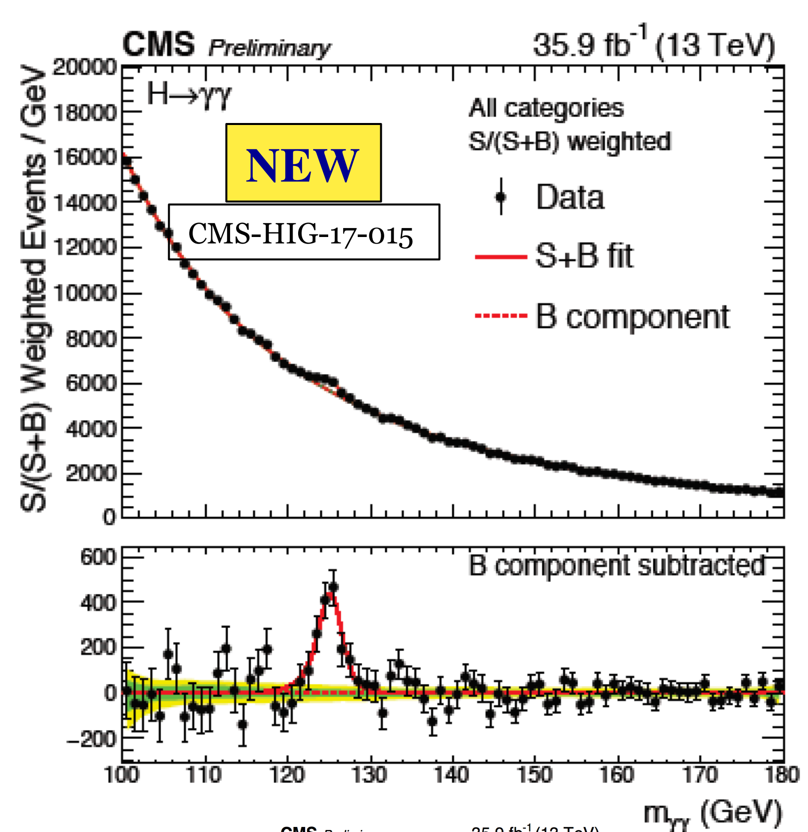


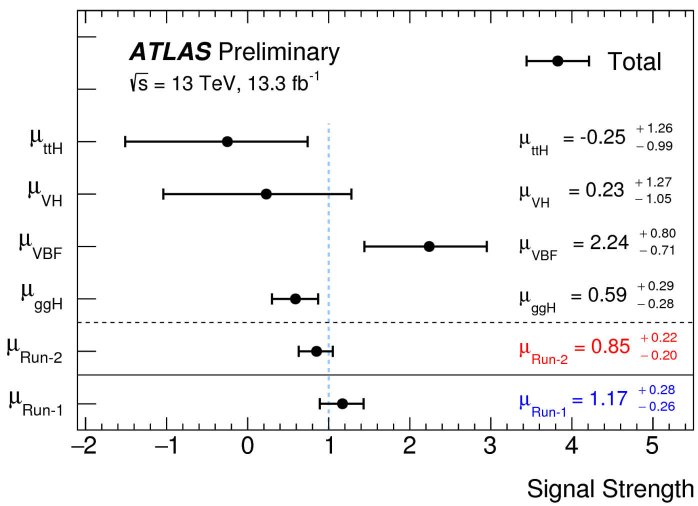


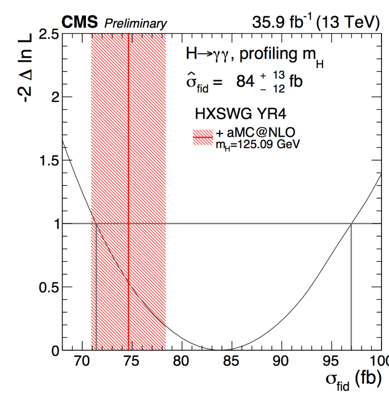


H to γγ









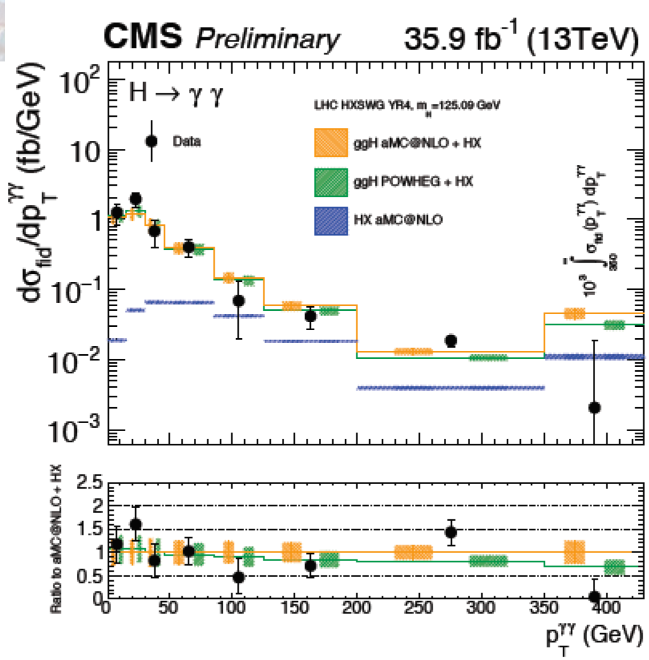
$$\hat{\sigma}_{\mathrm{fiducial}} = 84 \pm 11\ (\mathrm{stat}) \pm 7\ (\mathrm{syst})\ \mathrm{fb} = 84^{+13}_{-12}\ (\mathrm{stat{+}syst})\ \mathrm{fb}$$

Differential distributions

A fiducial phase space is defined to closely match the experimental acceptance in order to reduce the systematic uncertainty associated with the underlying model

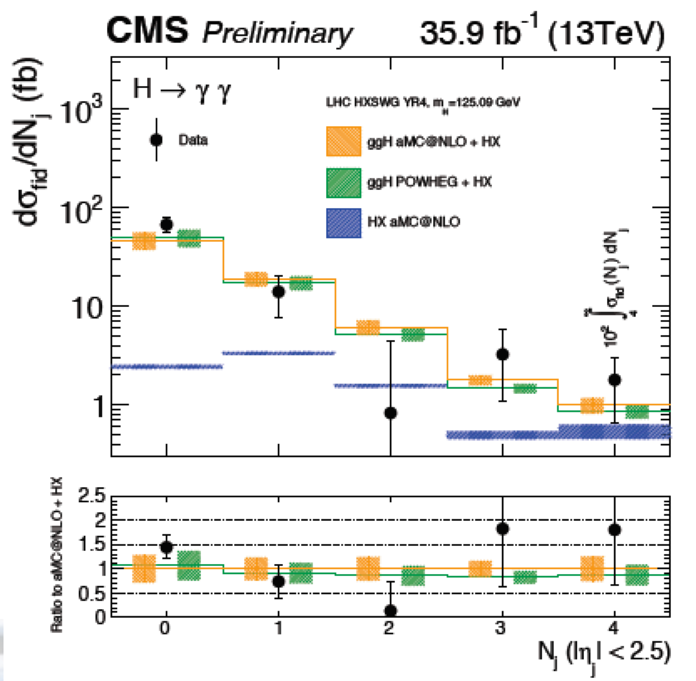
Each bin represents a specific fiducial sub-region

$$\frac{\mathrm{d}\sigma_i}{\mathrm{d}x} = \frac{\nu_i^{\mathrm{sig}}}{c_i \, \Delta x_i \int L \, \mathrm{d}t}$$

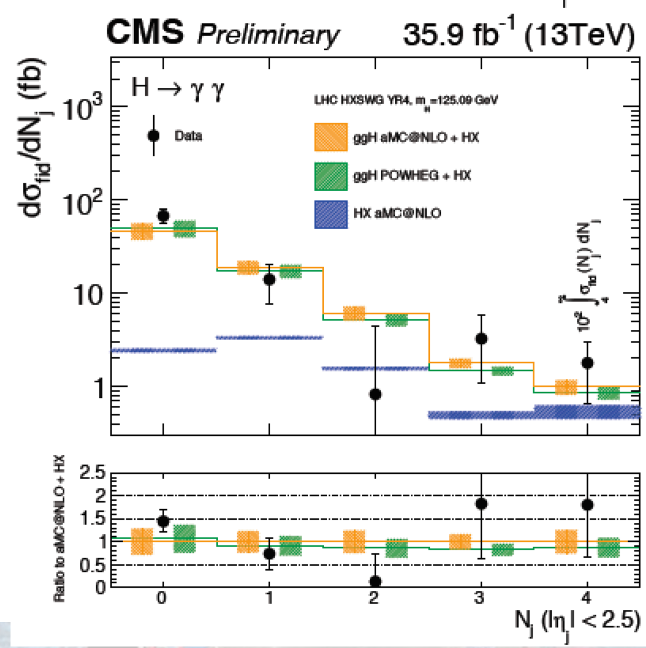


NEW

CMS-HIG-17-015

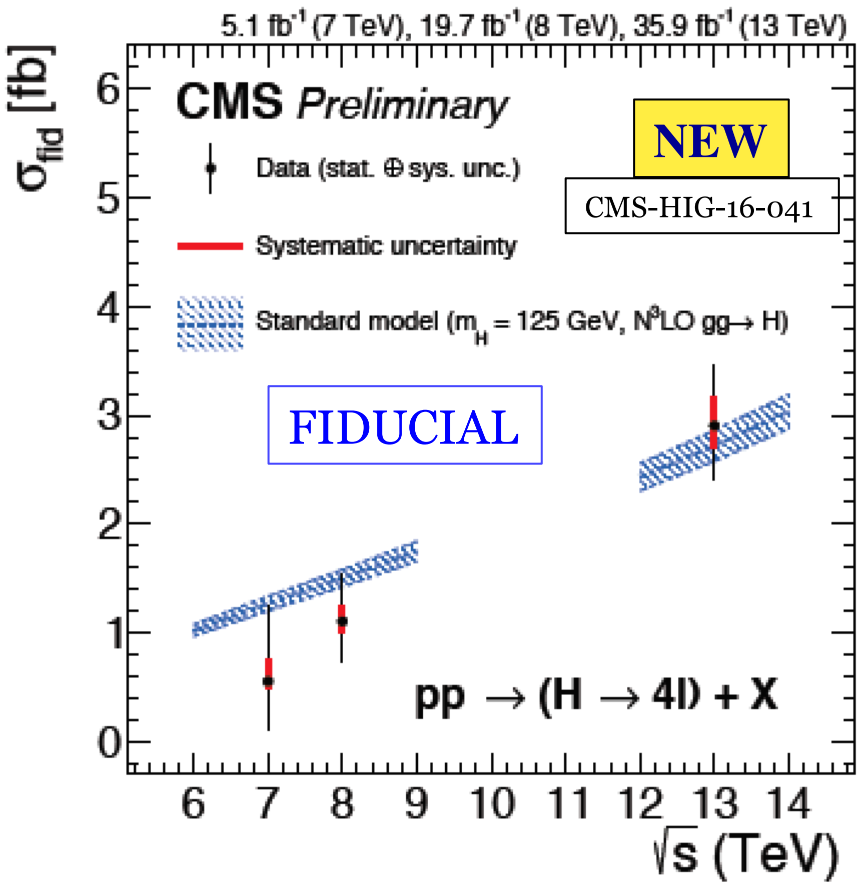


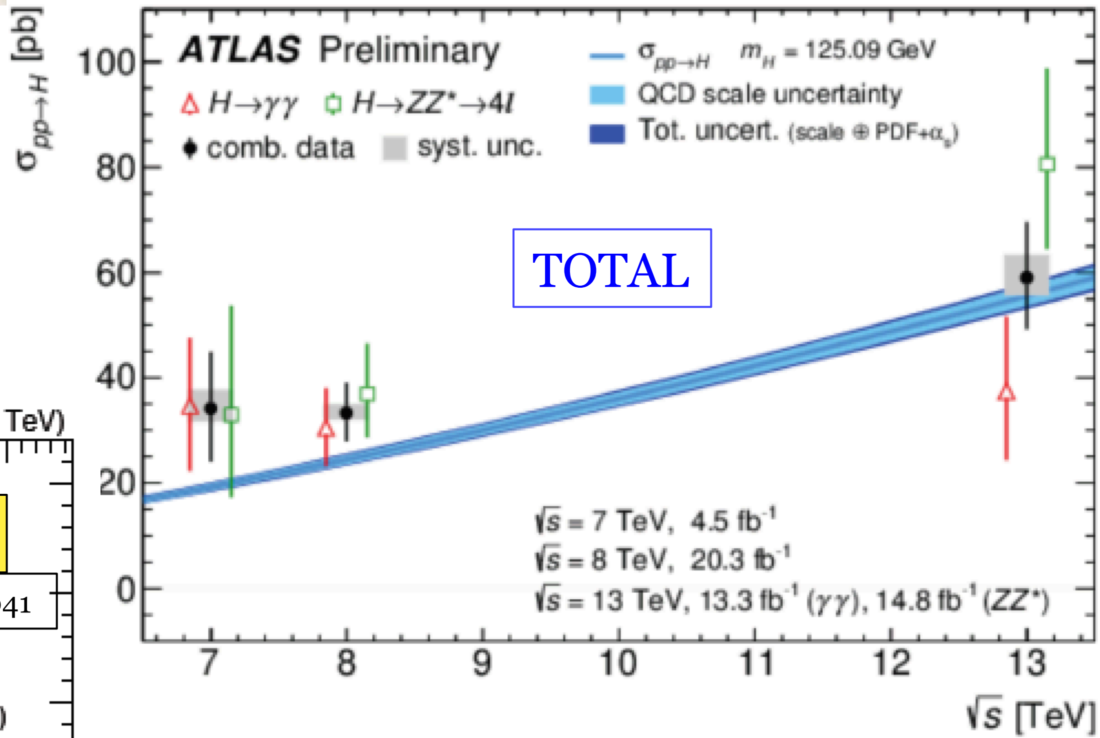
HX= (VBF+VH+ttH)



Total /Fiducial cross section VS E_{CM}

Good agreement with N3LO QCD + NLO EW prediction



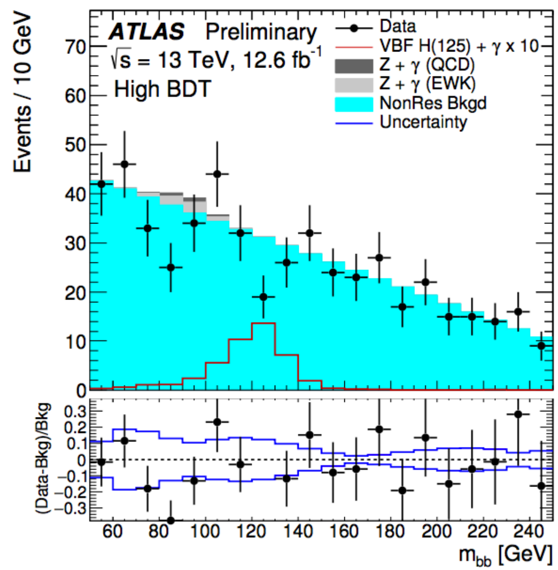


Search for H to bb at 13 TeV

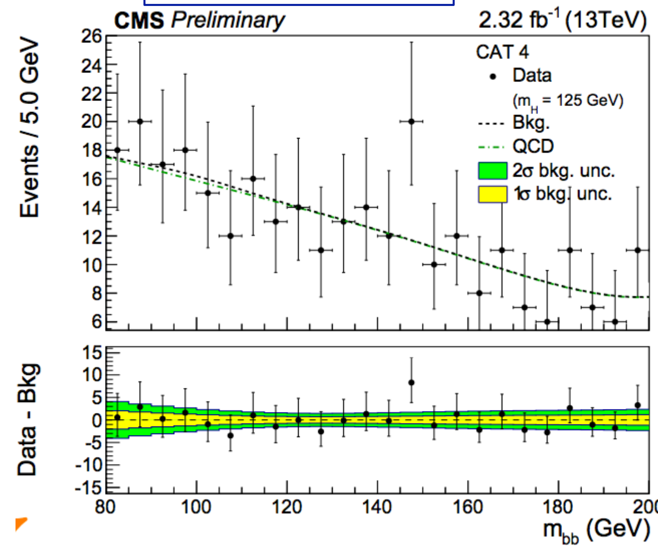
At the end of RUN1
there was no evidence of
VH, H→ bb
in the experiments

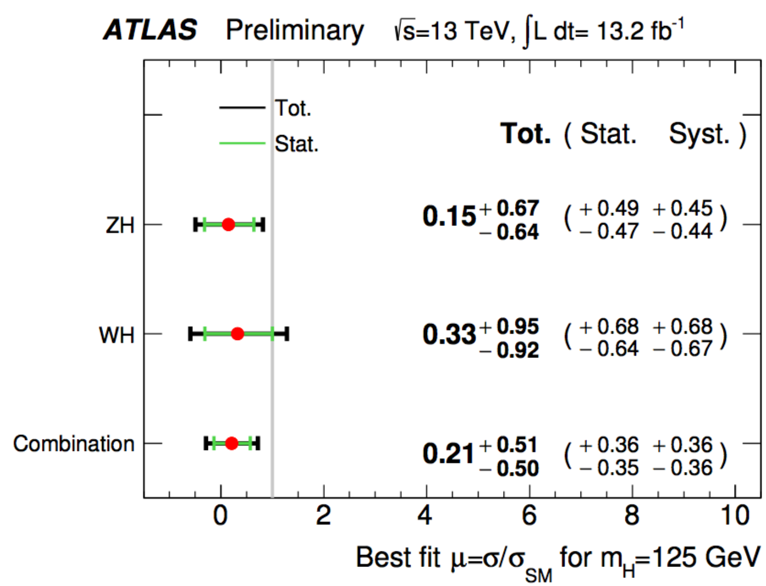
	significance	
ATLAS	1.2	(2.7)
CMS	2	(2.5)

VBF + γ, H→bb



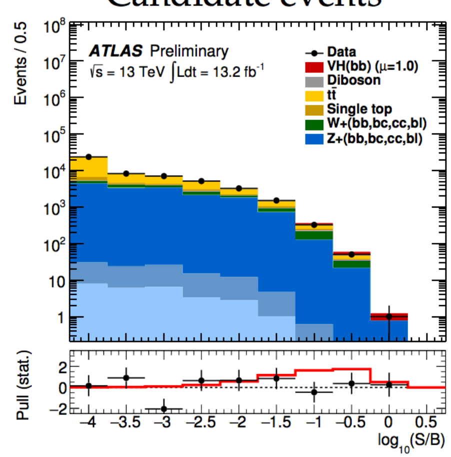
VBF, H→bb





VH, H→bb

Candidate events

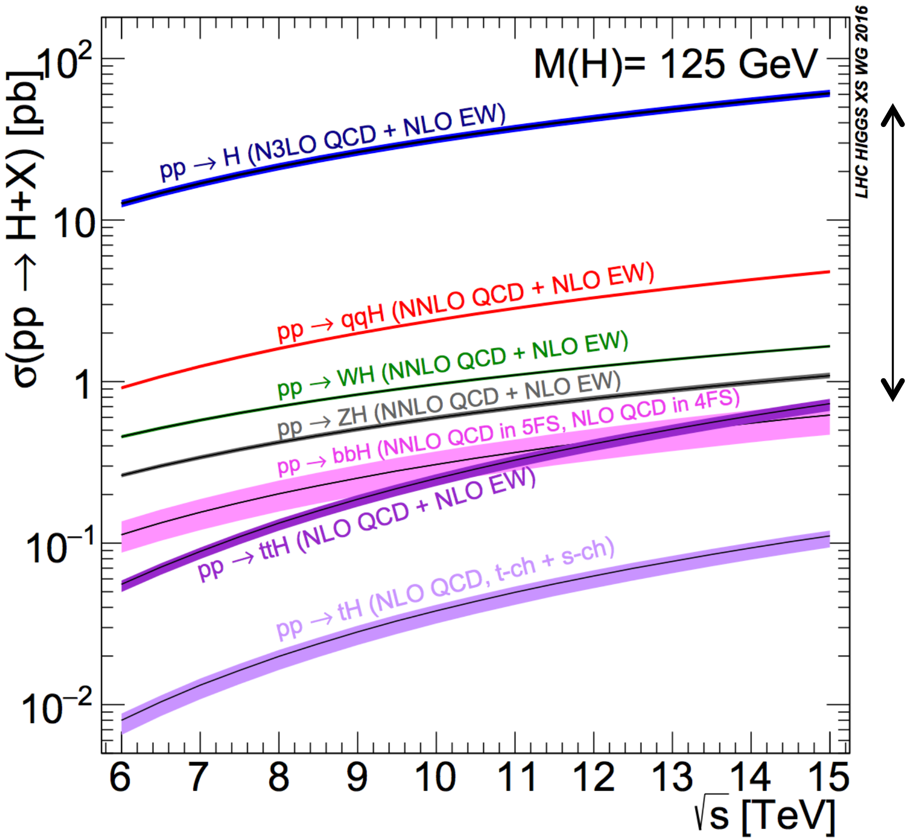


More production mode and final states investigated

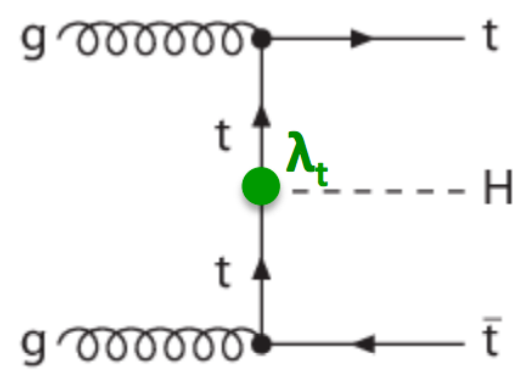
Only a small part of the 13 TeV statistics

New results soon

Search for ttH



At tree level direct probe of λ_t
Top Yukawa coupling



- **Hadronic**
  $H \to bb$, $H \to \tau_h \tau_h$
- **Leptonic**
  $H \to WW$, $H \to \tau_\ell \tau_{any}$
- **Bosonic:**
  $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$

higher yield

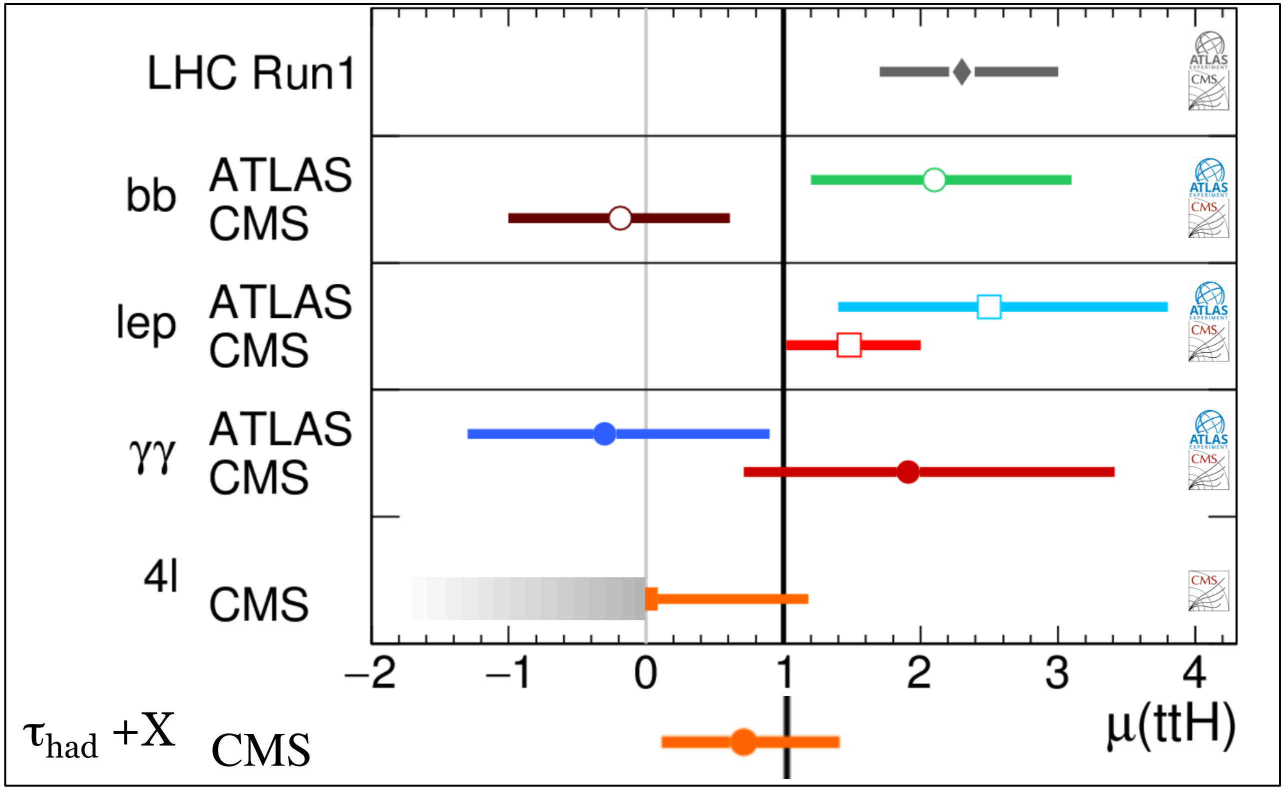
higher purity

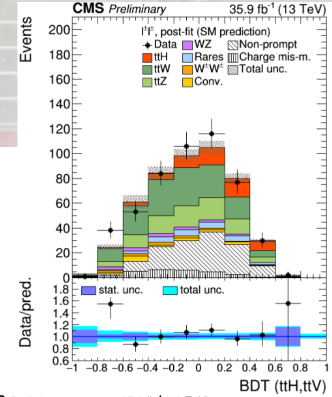
ttH 1/100 of the ggH production

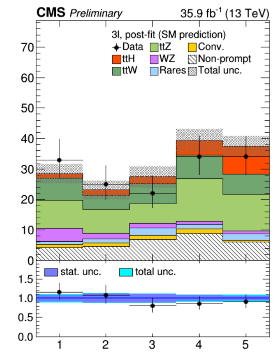
ttH increase ~2 times faster than the other production modes when going from 8 to 13 TeV

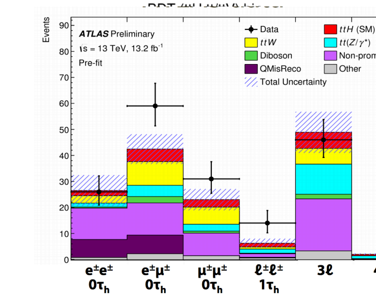
Search for ttH

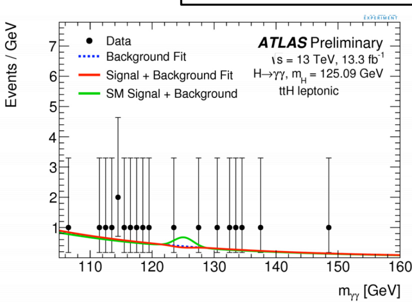
G.Petrucciani, Moriond 2017

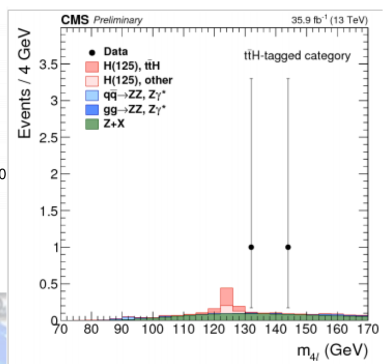


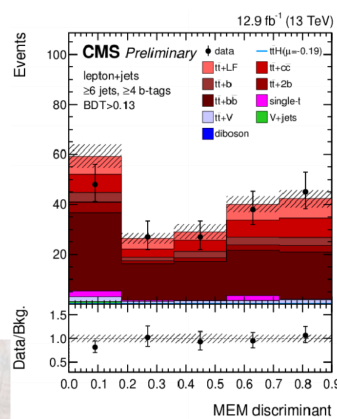


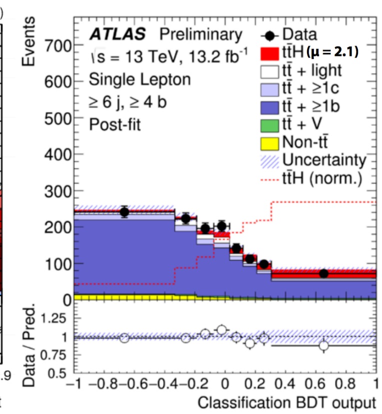


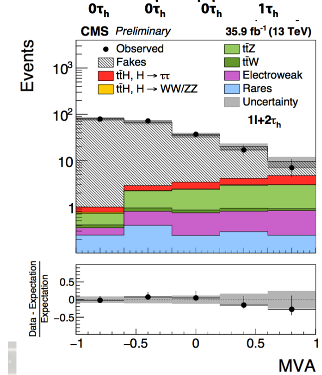












H to mumu

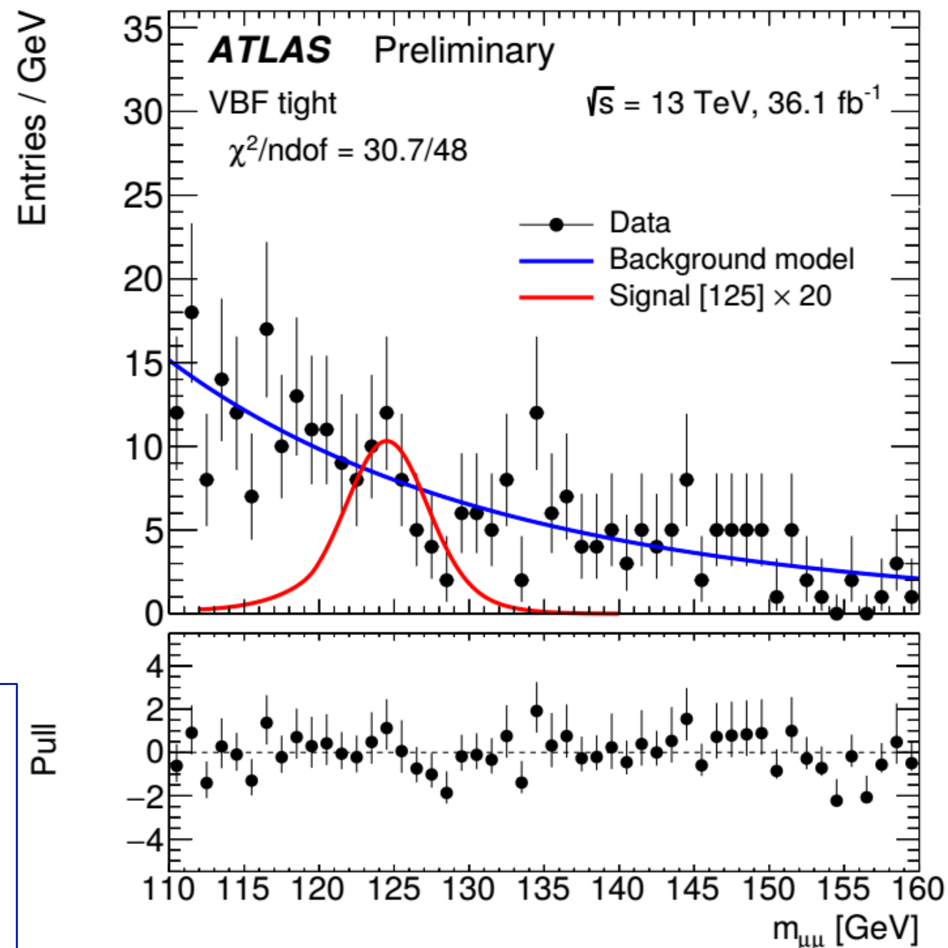
NEW

ATLAS-CONF-2017-014

ATLAS:

Search in ggF and VBF production
(separation with MVA)

Signal: Crystal-Ball + Gaussian
Background: exponential + Z



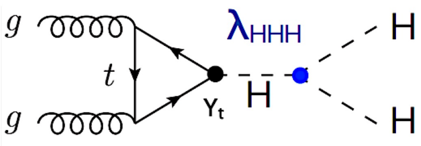
	Signal Strength μ	Limit @95%CL
13 TeV	-0.07 ±1.5	< 3.0 (3.1)
7+8+13 TeV	-0.13 ±1.4	< 2.8 (2.9)

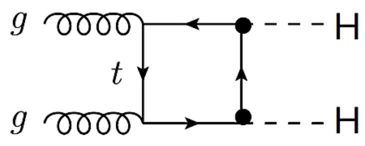
Observed (Expected)

Searches for HH production

$$V = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

Within the SM:





$\sigma_{gg\to HH} = 33.49^{+4.3}_{-6.0}$ (scale) ± 2.1 (PDF) ± 2.3 (α_s) fb

[13 TeV, NNLO + NNLL with top mass effects, HXSWG, arXiv:1610.07922]

σ_{HH} → Higgs trilinear coupling λ_{HHH}

Very small cross section due to the destructive interference of the two diagrams

BSM – resonant production:

- singlet: Extra H → h(125)h(125) M(H) < 1000 GeV
- 2HDM/MSSM: Extra H → h(125)h(125) M(H) < 400 GeV
- Extra dimension: X→ H(125) H(125) M(X) < 3000 GeV

Searches for HH production

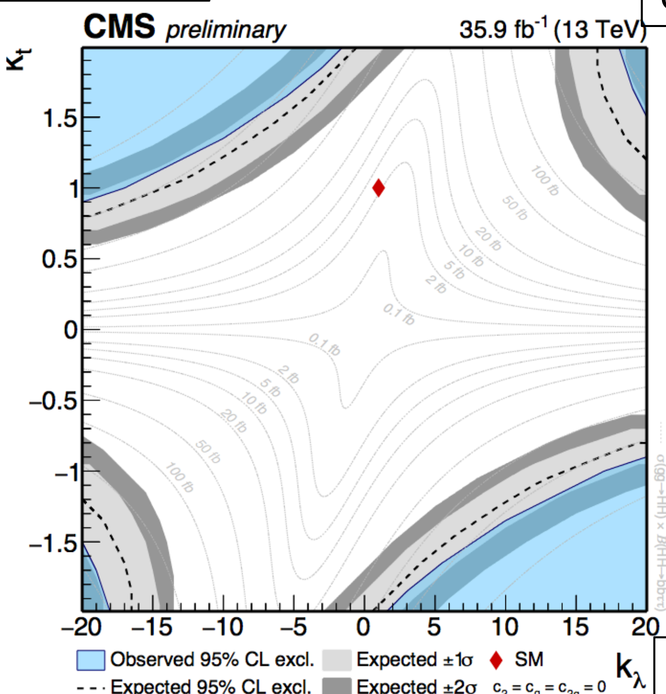
Searches in: bbbb, bbWW, bb$\tau\tau$, bb$\gamma\gamma$, $\gamma\gamma$WW

H→bb$\tau\tau$

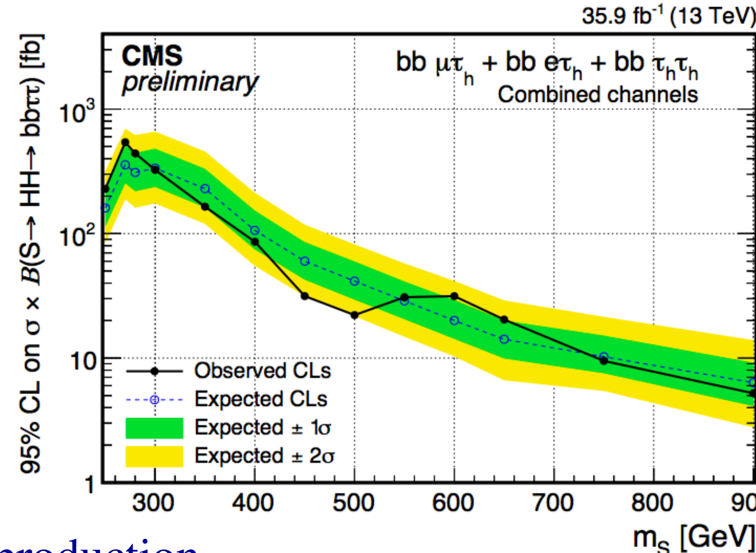
NEW

CMS-HIG-17-002

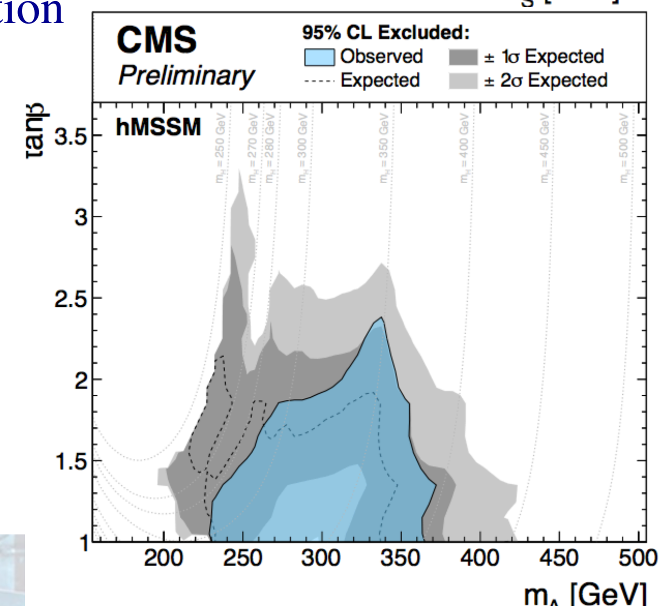
$k_t = y_t/y_t^{SM}$



$k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$



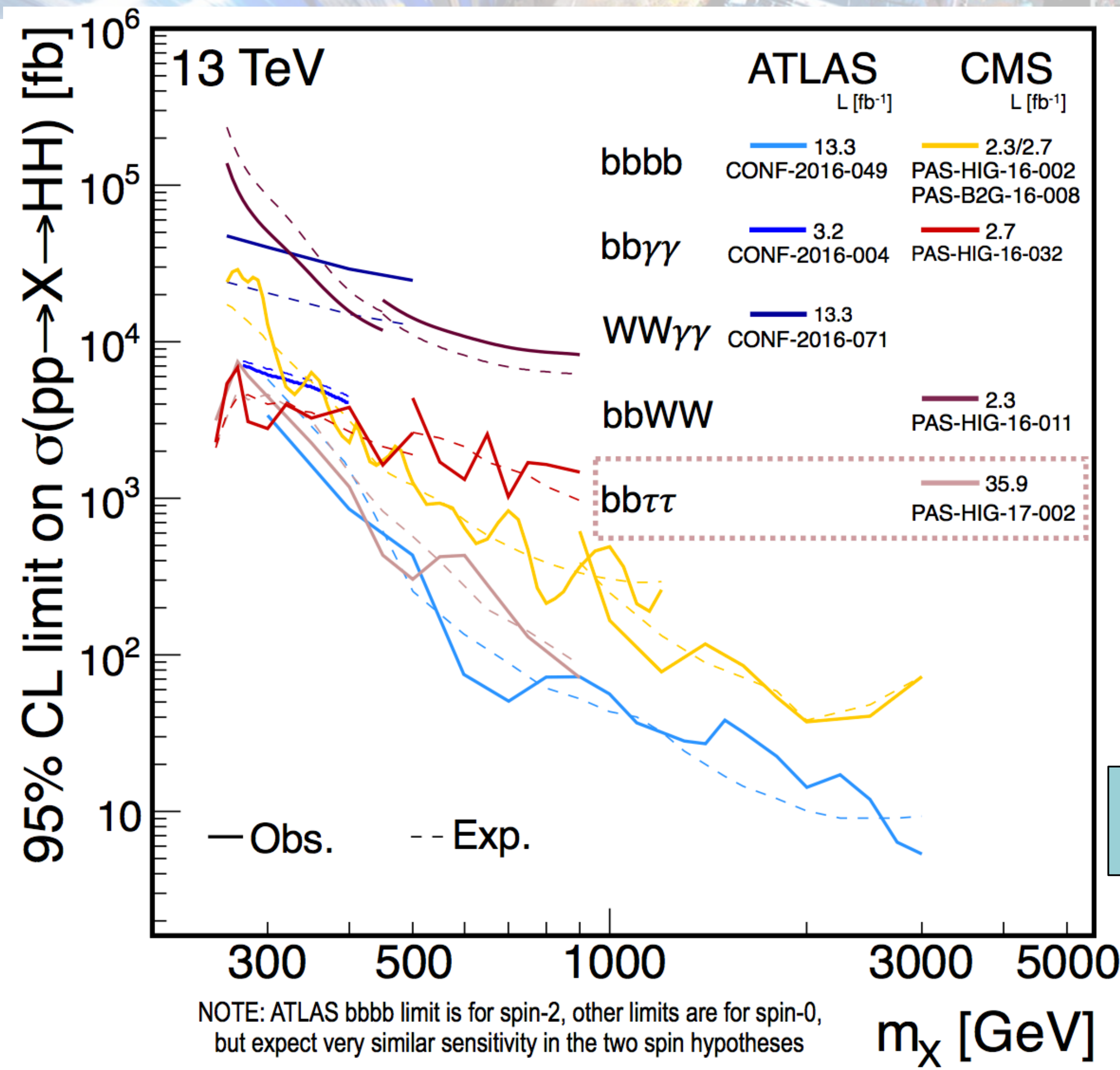
Resonant production tested up to mX = 900 GeV, and interpreted in the hMSSM



Non-resonant search excludes **28 times the SM**

Test of the anomalous λ_{HHH} and y_t couplings

Overview of results



Complementarity in different mass ranges

A combination will be very effective

Luca Cadamuro
Moriond 17

Is this Higgs the SM Higgs ?

We have discovered a scalar particle

- Spin = 0 and positive parity at >99.9%CL

- $\mu = 1.09^{+0.11}_{-0.10} = 1.09 \pm 0.07(\text{stat}) \pm 0.04(\text{expt}) \pm 0.03(\text{th-bkgd})^{+0.07}_{-0.06}(\text{th-sig})$

- The cross section ratios (the "kappas") are all compatible with 1 within 10% to 30%:
  - ggF is well established
  - VBF is at 5.4σ
  - WH+ZH combined at 3σ
  - Not yet sensitive to ttH

  - H→ZZ, WW, γγ well establishes
  - H→ ττ at 5σ when combining Atlas and CMS
  - H→bb not evidence yet.

Is this Higgs the SM Higgs ?

To understand if there new physics beyond the Standard Model we should proceed in two ways:

- keep measuring the properties of this particle to reach precision at least at the per-cent level (this precision allows to test most of the BSM models)
- Measure with high precision the scattering of longitudinal boson VV → VV (not covered by this talk)
- Search for new Higgses
- Search for new particles (see Beate talk)

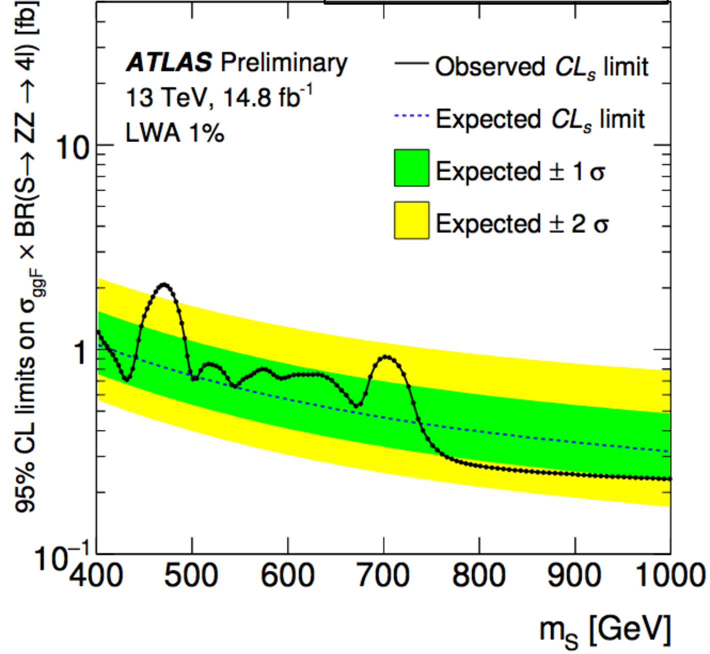
Searches for additional Higgs boson

- 1 more Higgs: EW singlet
  - The High mass search
- 2 doublets:
  - 2HDM
  - MSSM
- 2 doublets + 1 singlet:
  - 2HDM+S
  - nMSSM

And more….

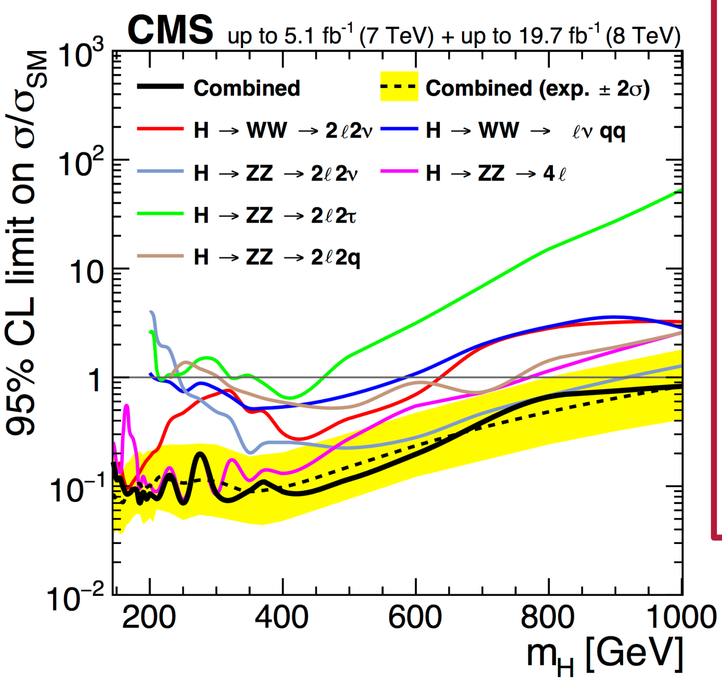
Is there another SM-like Higgs ?

ATLAS-CONF-2016-079



AT RUN1:
Combination of different channel looking for a high mass Higgs-like resonance:

With the higher energy the search started again. The width of the resonance is varied, and accordingly the interference with the background.



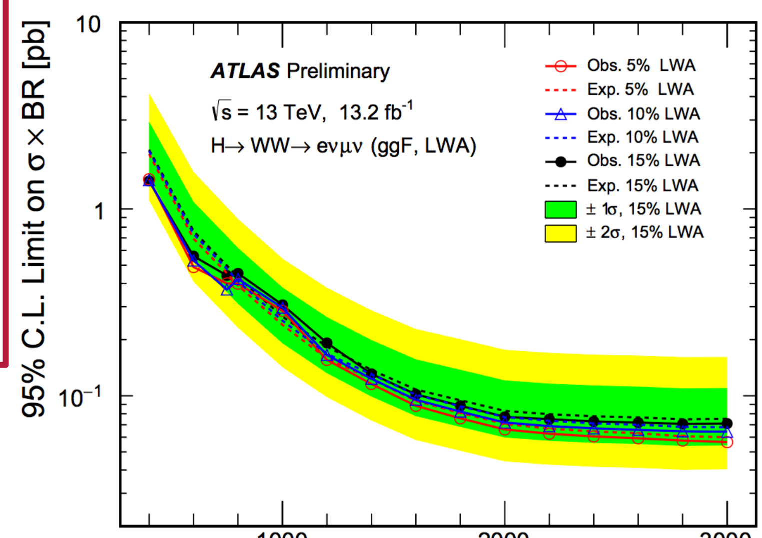
EW Singlet

$\mu_{SM} \rightarrow C^2\, \mu_{SM}$

$C'^2(1-BR_{new})\, \mu_{SM}$

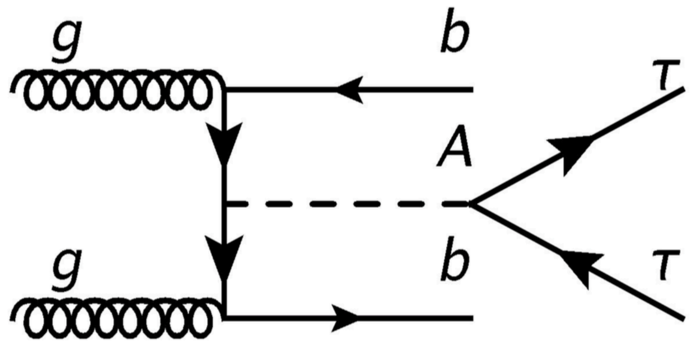
$\Gamma' = C'^2\Gamma/(1-BR_{new})$

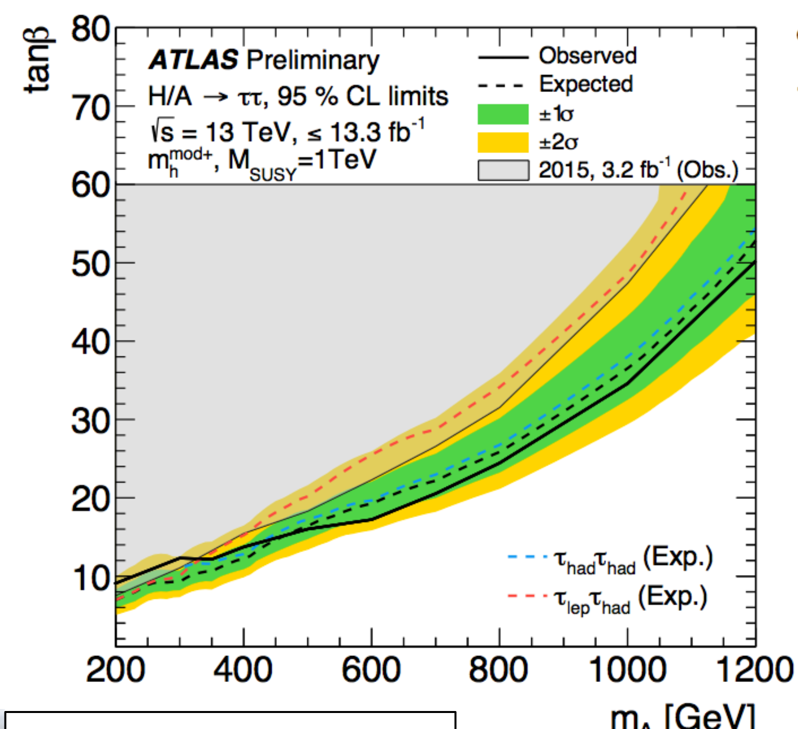
$C^2+C'^2=1$



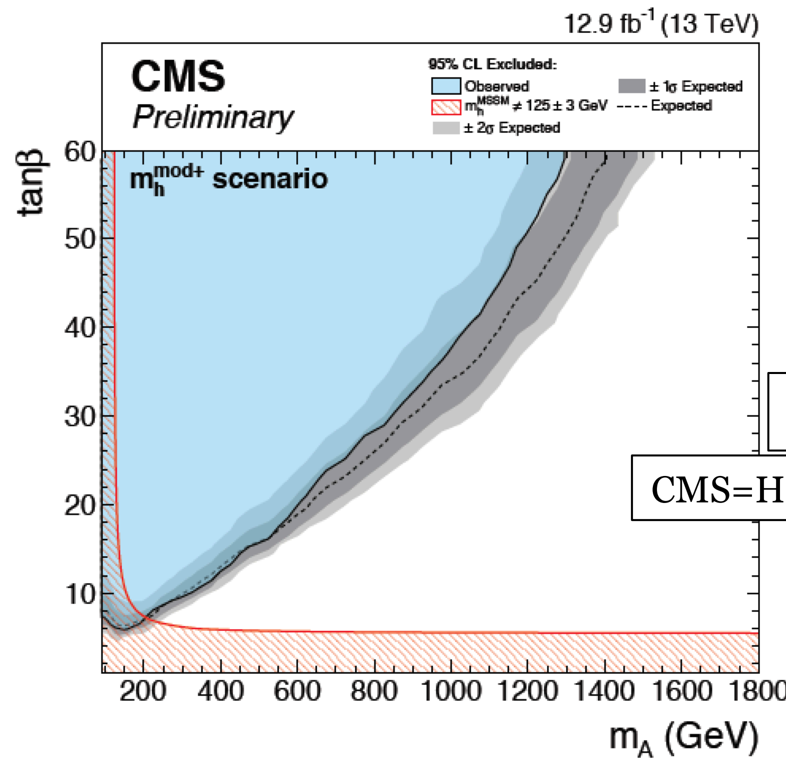
ATLAS-CONF-2016-074

2HDM and MSSM with A→tau tau





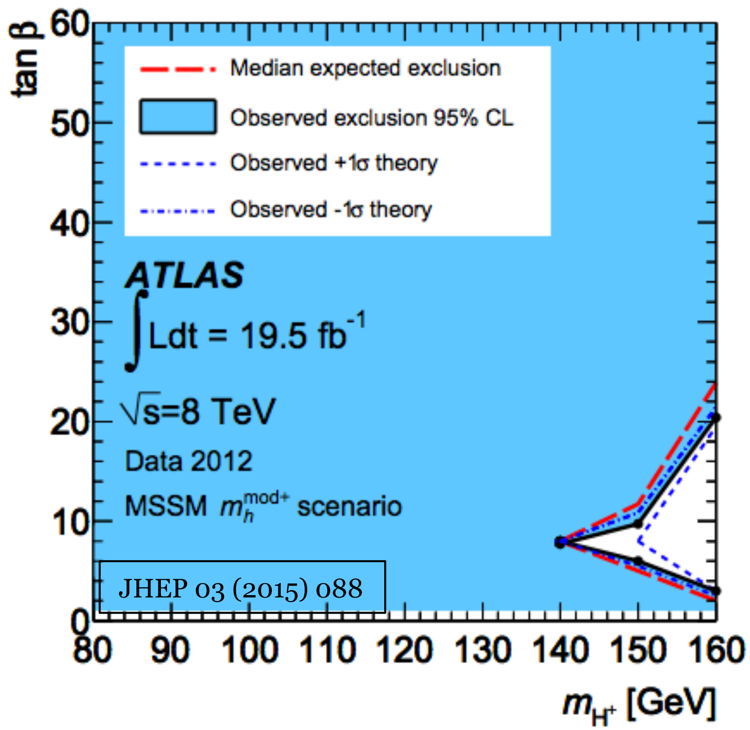
ATLAS-CONF-2016-085

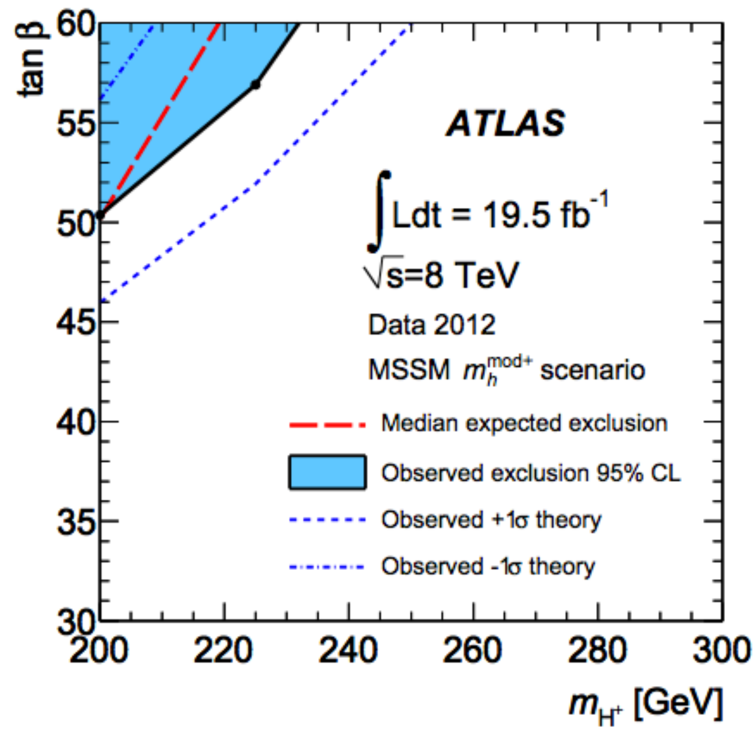


MSSM

CMS=HIG-16-037

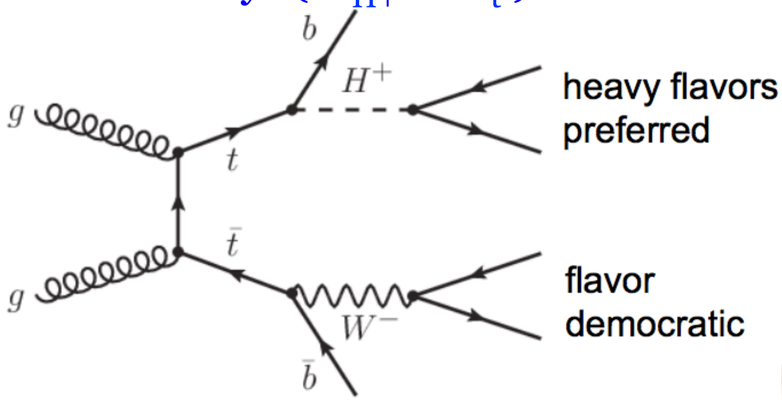
Charged Higgs



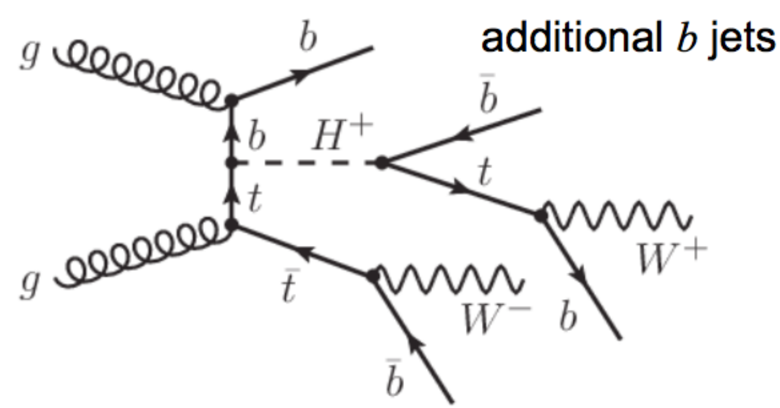


Most sensitive channels: $H^+ \rightarrow \tau\nu$, $H^+ \rightarrow tb$

In decay: ($m_{H+} < m_t$)

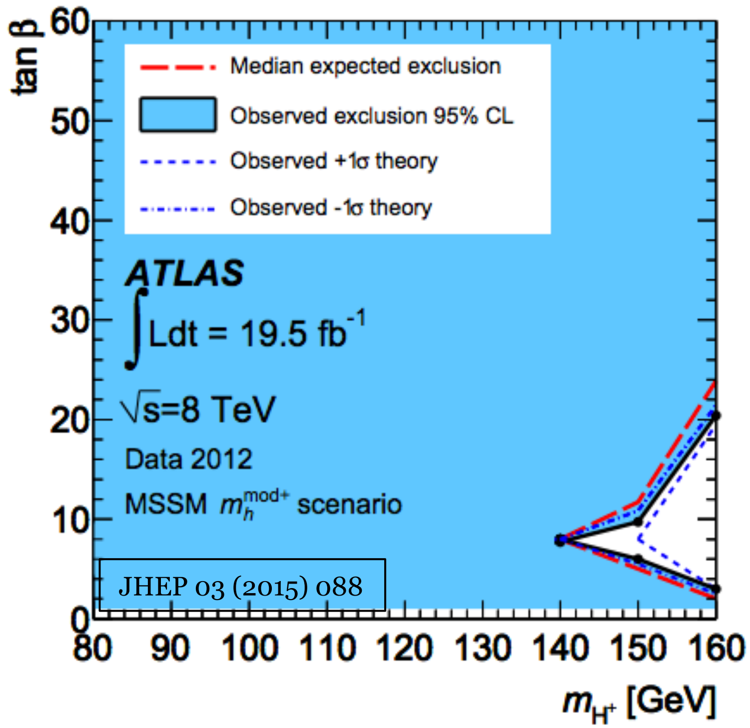


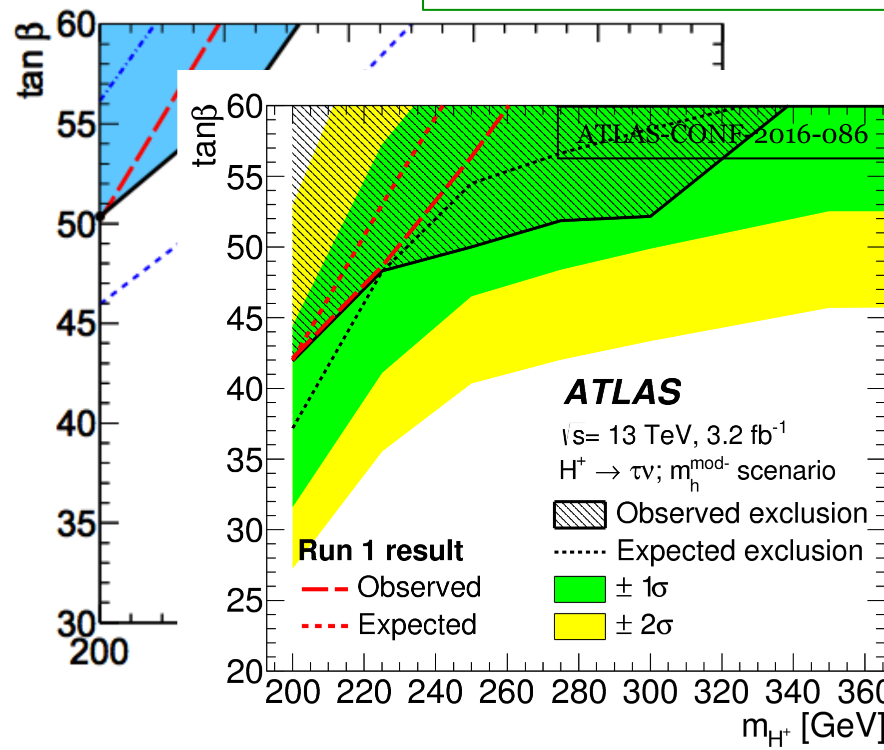
In production ($m_t < m_{H+}$)



Charged Higgs

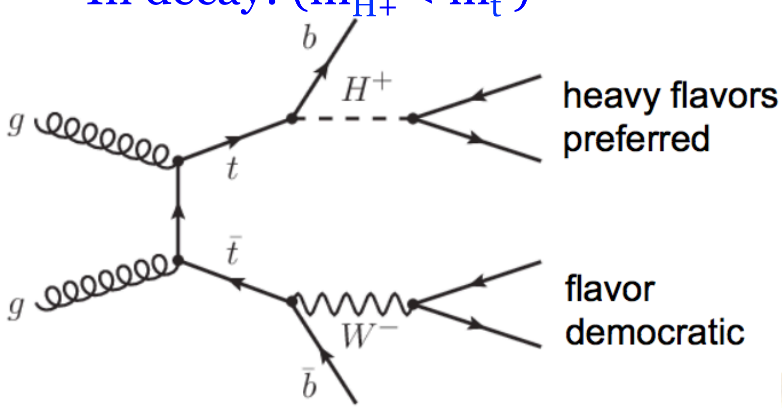
RESULTS AT 13 TeV improve the limits

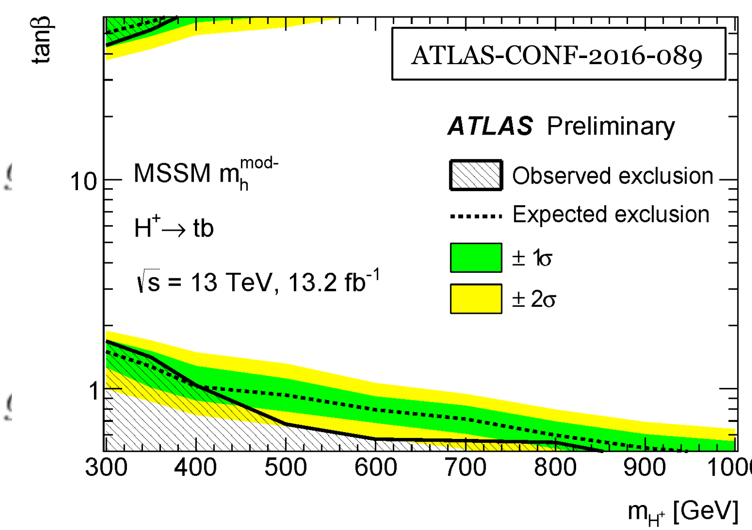




Most sensitive channels: $H^+ \to \tau\nu$, $H^+ \to tb$

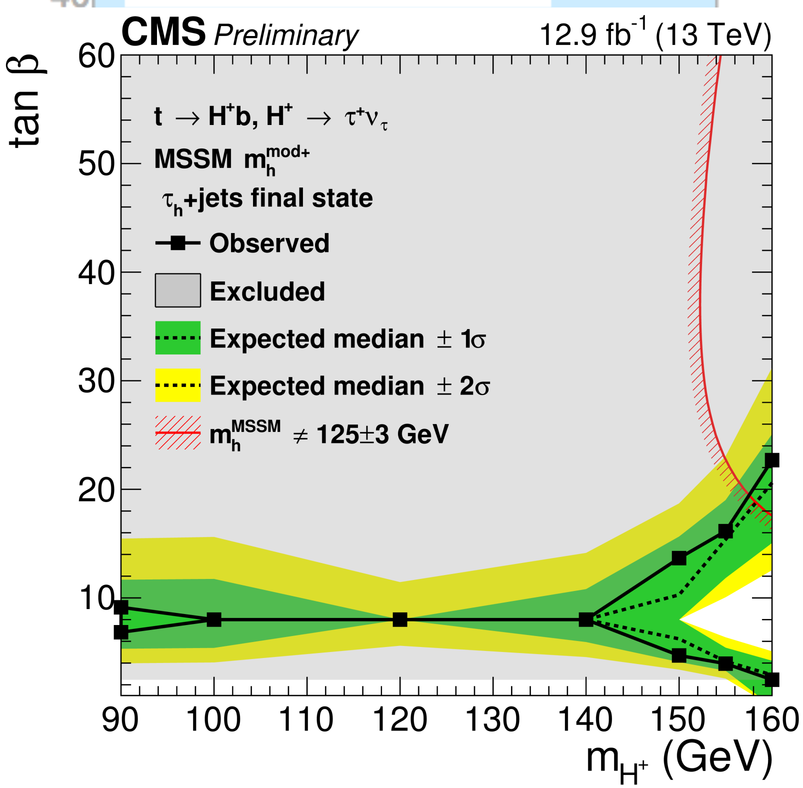
In decay: ($m_{H+} < m_t$)

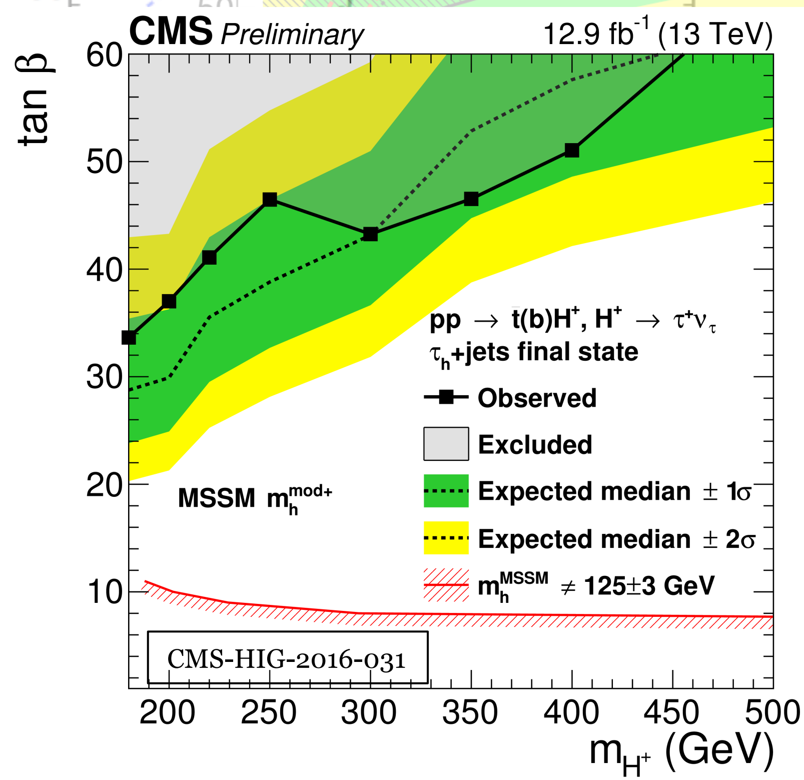




Charged Higgs

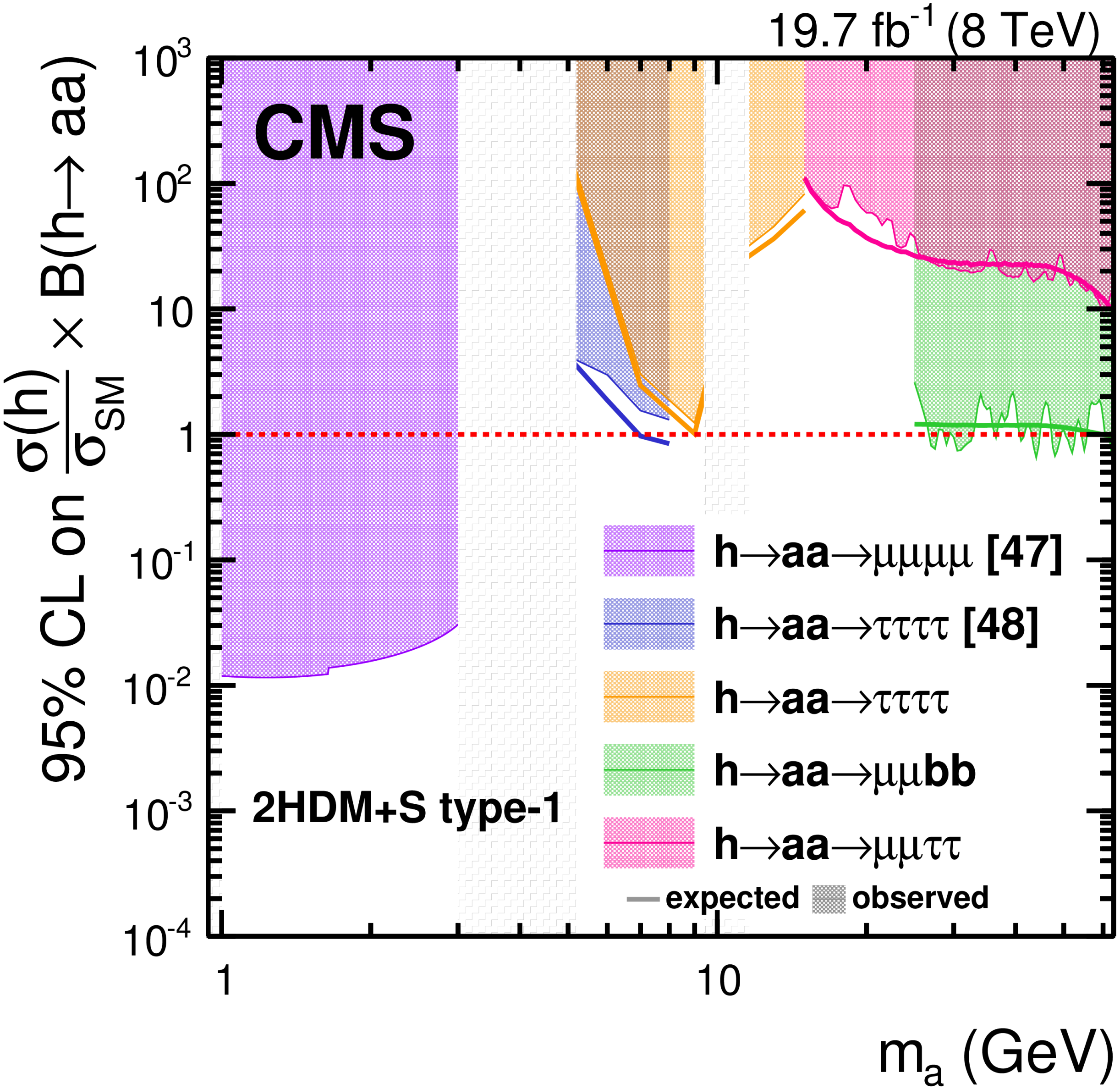
RESULTS AT 13 TeV improve the limits





Chiara Mariotti

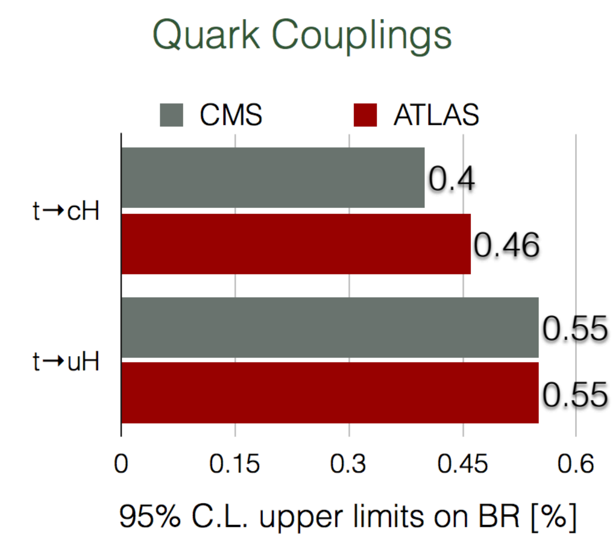
2HDM+S h→aa→4f

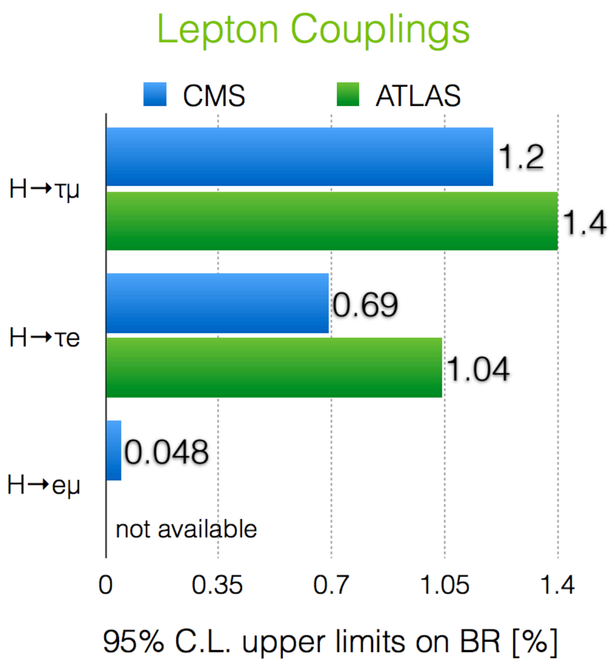


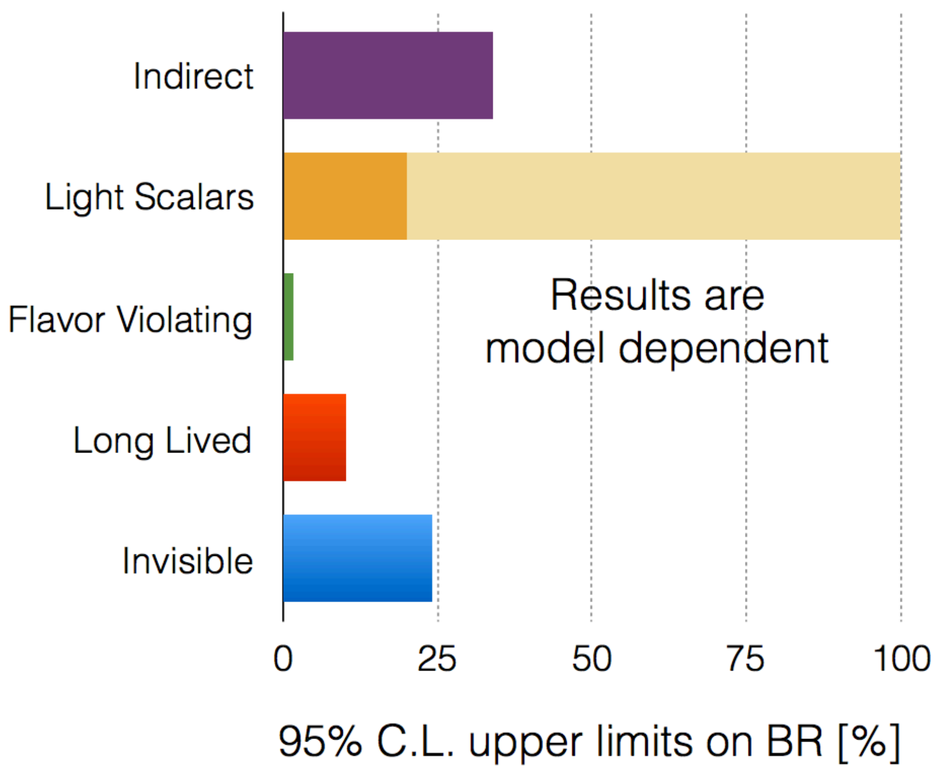
CMS-HIG-16-015

A summary on other searches:

FLAVOUR VIOLATING H DECAY







Verena Martinez Outschoorn
Moriond 17

Summary: precision physics and searches to explore new territory

- Precise (%) measurements of Higgs couplings and VV scattering
- Search for new Higgs bosons
- Search for new particles

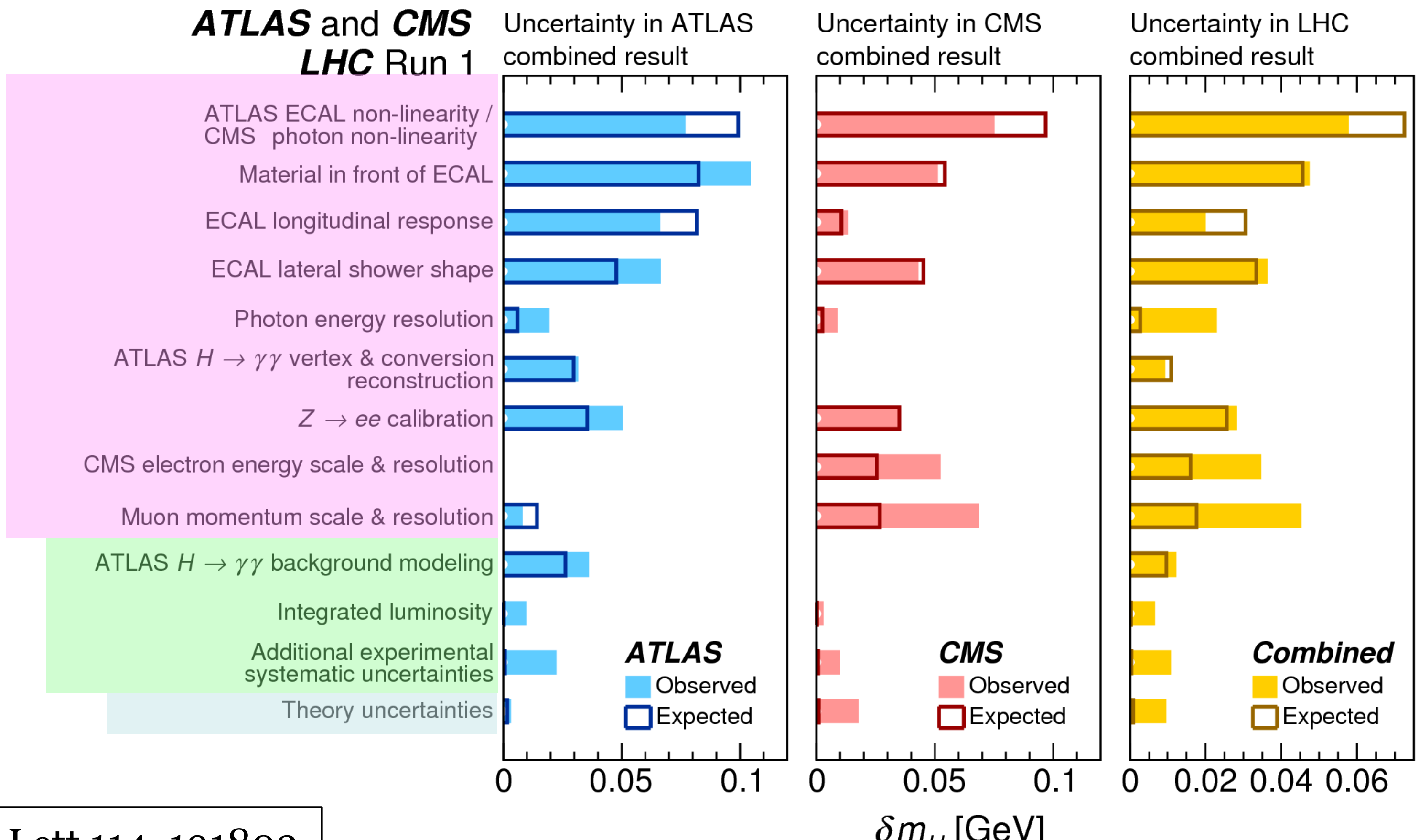
backup

Systematic uncertainties

Energy/momentum scale of μ, e and γ dominate the systematic uncertainty

Background, jet energy scale and luminosity (partially correlated between exp.)

Theory unceertainty (QCD scale, PDF, BR) -100% correlated between exp.



Phys Rev Lett 114, 191803

The Higgs width: Γ_H

Very narrow resonance at low mass:
~**4 MeV** at **125 GeV**

Signal model: analytic convolution of a :
Breit-Wigner distribution
(modeling a **non-zero decay width**)
Gaussian distribution (modeling the
non-zero detector resolution)

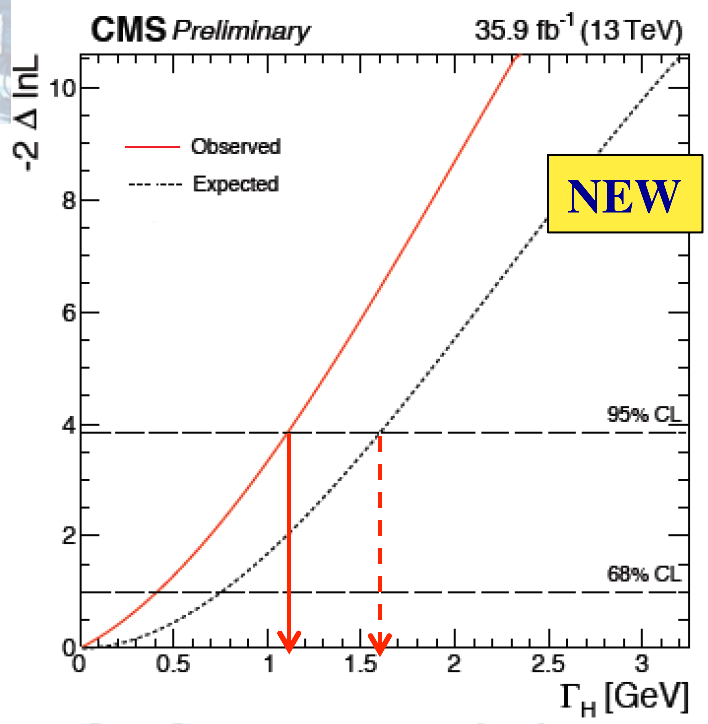
Method: profile likelihood estimator is used
to calculate **upper limits** on the **width**

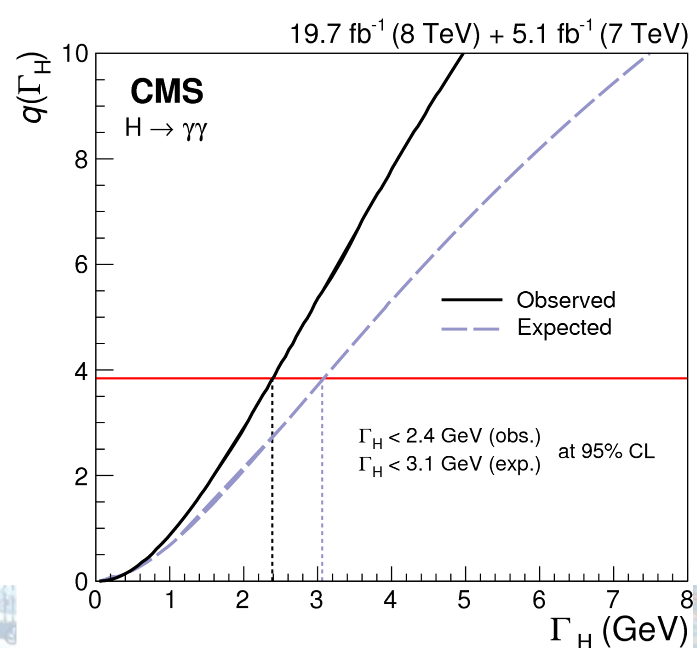
First direct **upper limit** on the Higgs boson
width:

H →ZZ→4l:
- **1.1 GeV** at 95% CL (- **1.6** expected)

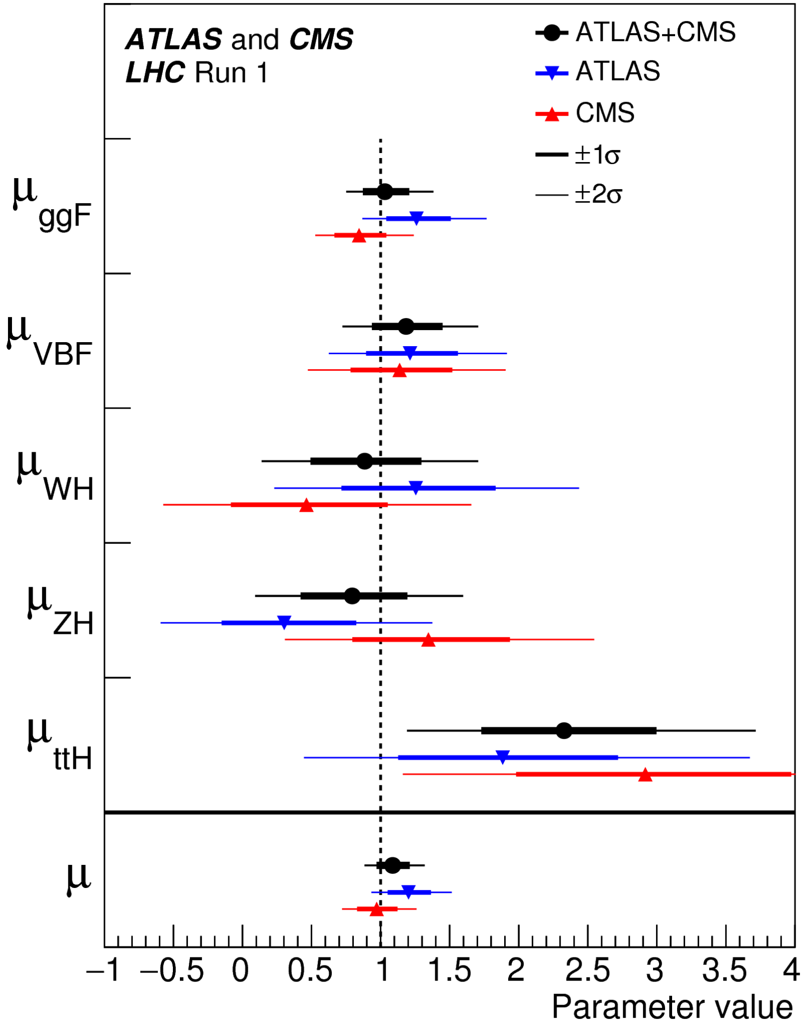
H→γγ:
- **2.4 GeV** at 95% CL (- **3.1** expected)

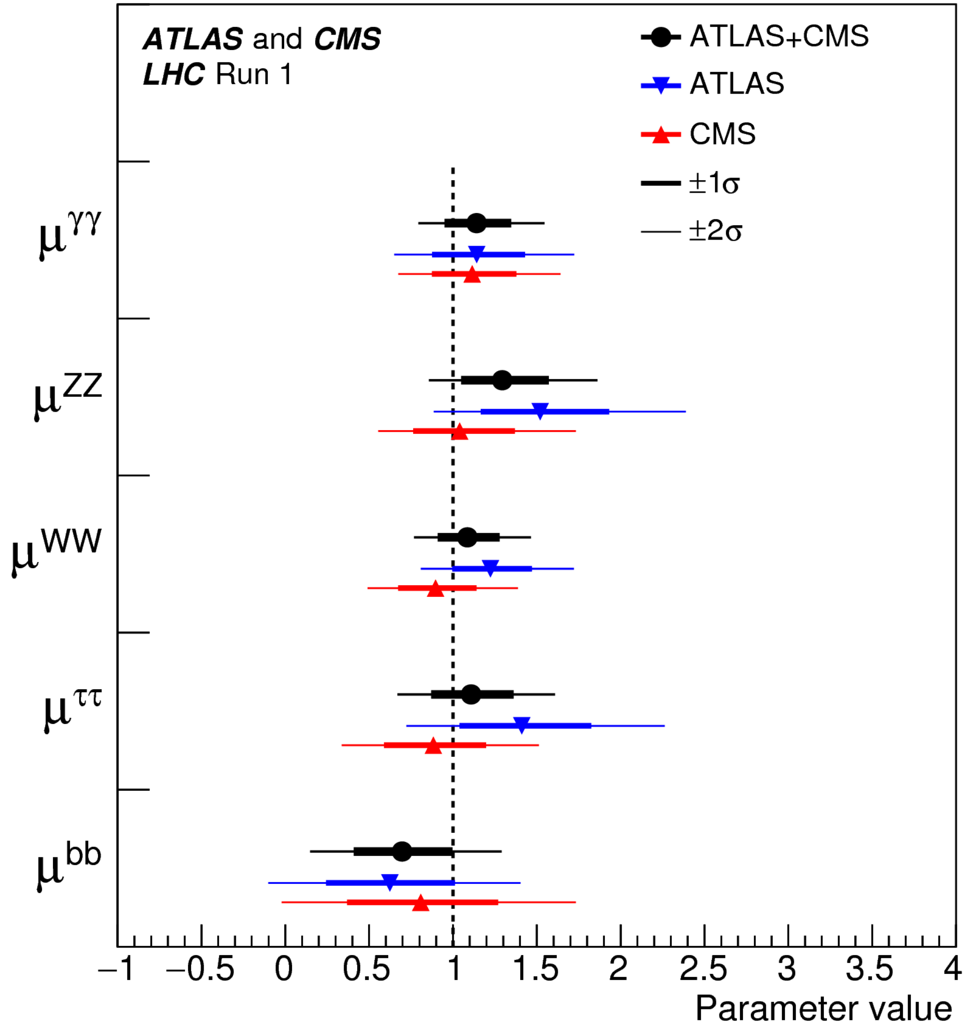
$$\boxed{\Gamma < 600 \cdot \Gamma_{SM}}$$





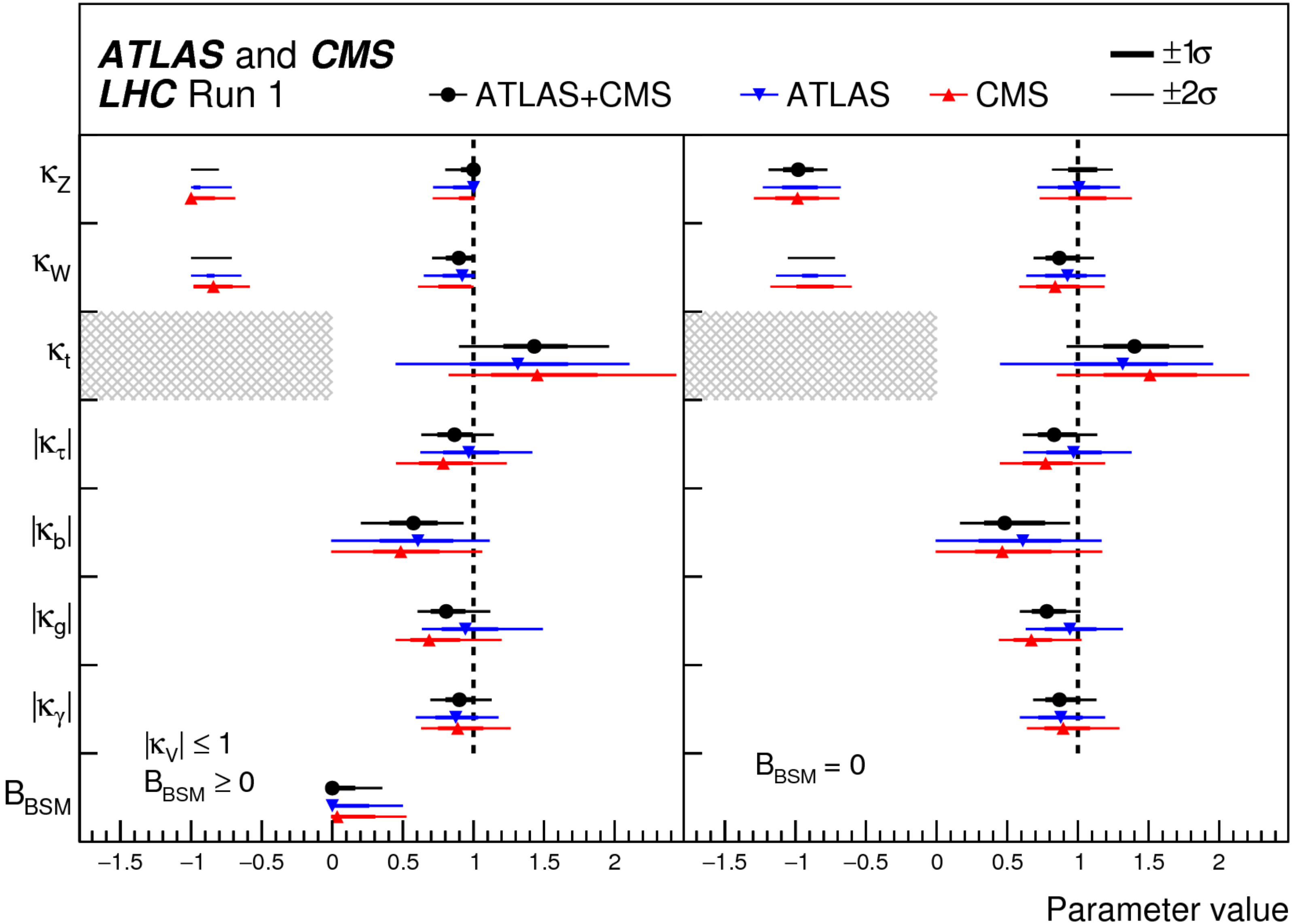
Consistency with the SM hypothesis





JHEP 11, (2016) 045

Couplings



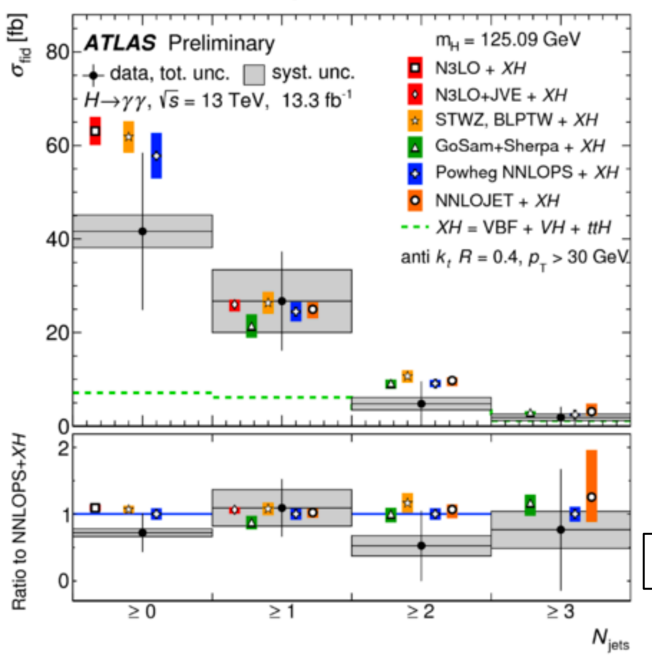
JHEP 11, (2016) 045

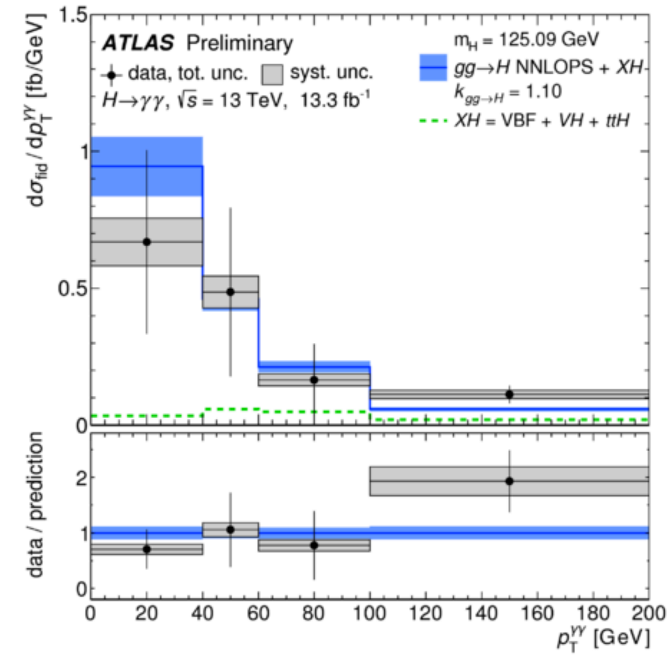
Differential distributions

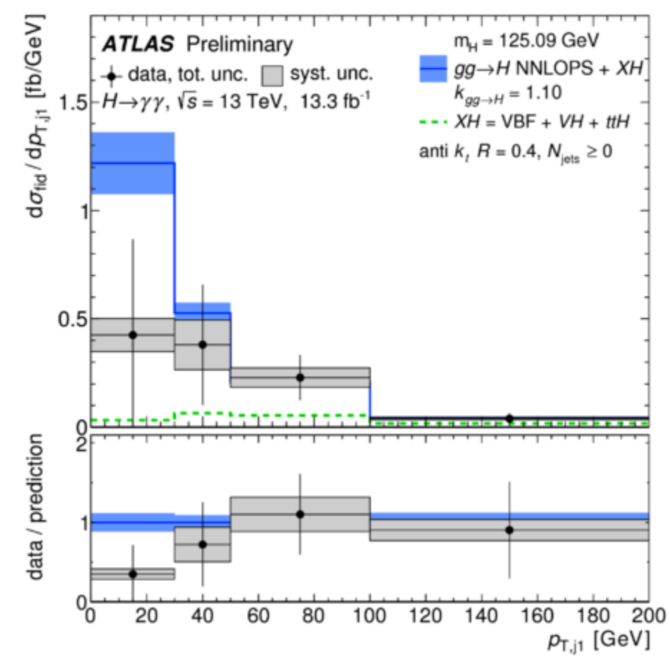
A fiducial phase space is defined to closely match the experimental acceptance in order to reduce the systematic uncertainty associated with the underlying model

Each bin represents a specific fiducial sub-region

$$\frac{d\sigma_i}{dx} = \frac{\nu_i^{\text{sig}}}{c_i\, \Delta x_i \int L\, dt}$$



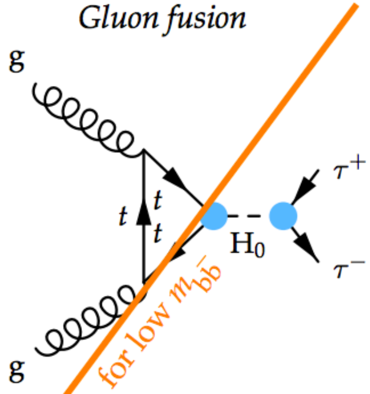




ATLAS-CONF-2016-067

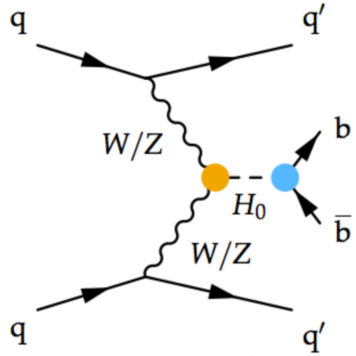
Search for H to bb

Gluon fusion



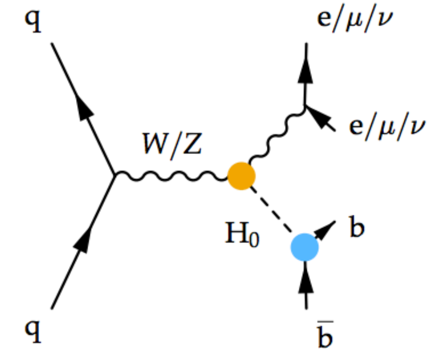
- ~~large multijet background~~
- ~~challange for the trigger~~

Vector Boson Fusion(VBF)



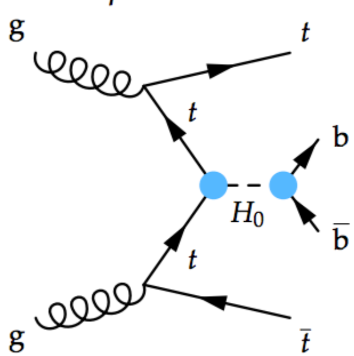
- challange for the trigger

Associate production with vector bosons(VH)



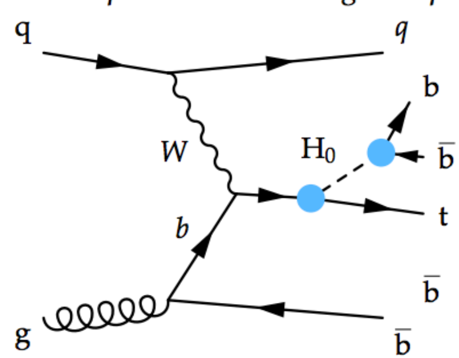
- leptons, $E_T^{mis.}$ to trigger and suppress backgrounds

Associate production with $t\bar{t}$



- see previous talk

Associate production with signle top



- small cross-section

G. Gaycken

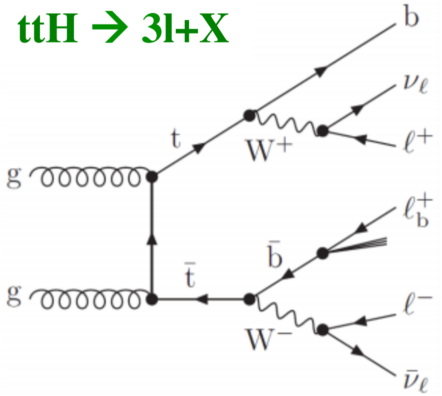
Moriond 2017

Search for ttH in multi leptons final states

ttH → 4l, 3l, 2l

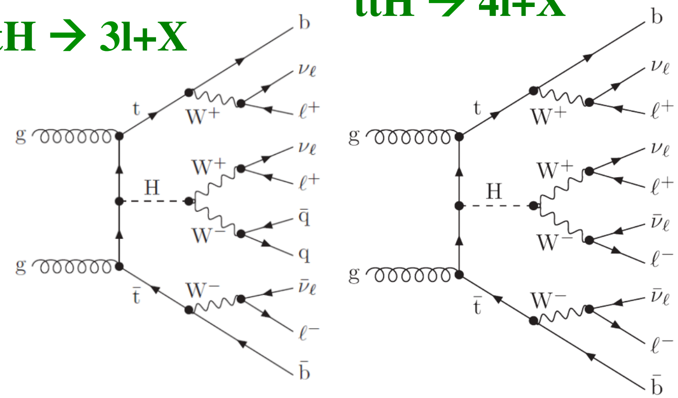
CMS HIG-17-004 **NEW**

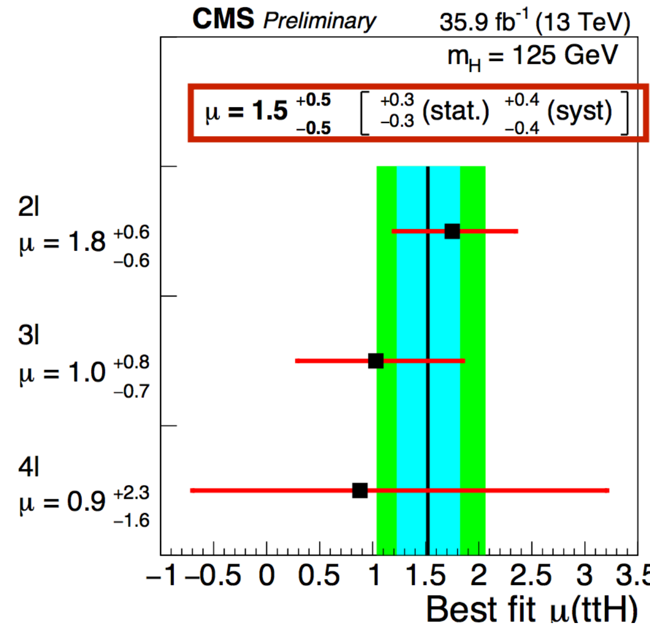
ttH → 3l+X



ttH → 3l+X

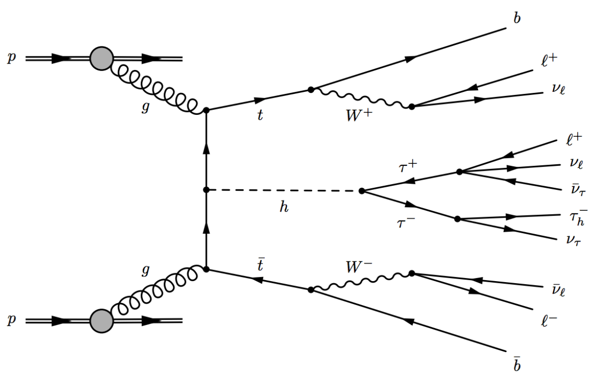
ttH → 4l+X



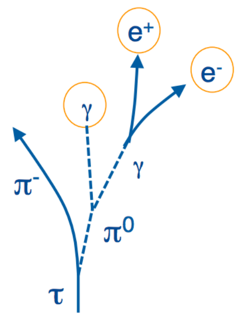


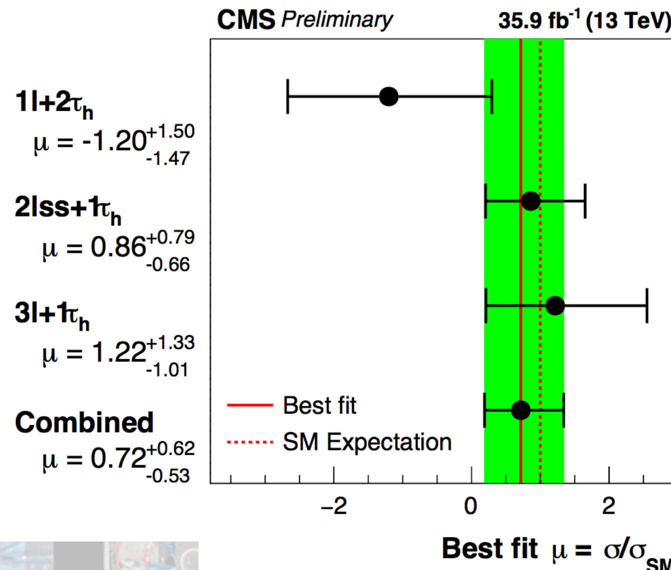
ttH → ττ + X

CMS HIG-17-003 **NEW**

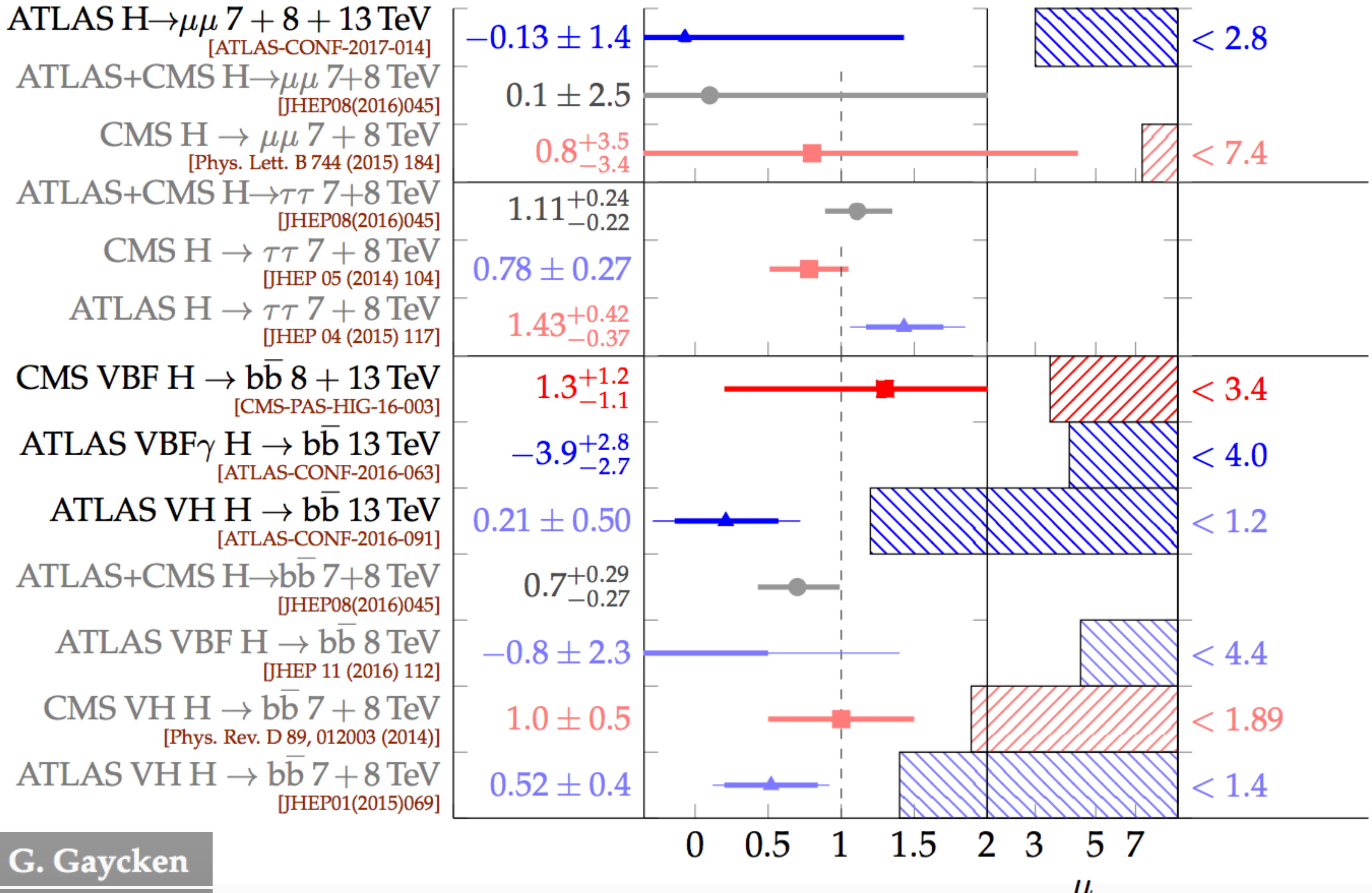


Orthogonal to ttH multi-lepton
- 1ℓ+2τ_{had}
- 2ℓSS + 1τ_{had}
- 3ℓ+1 τ_{had}



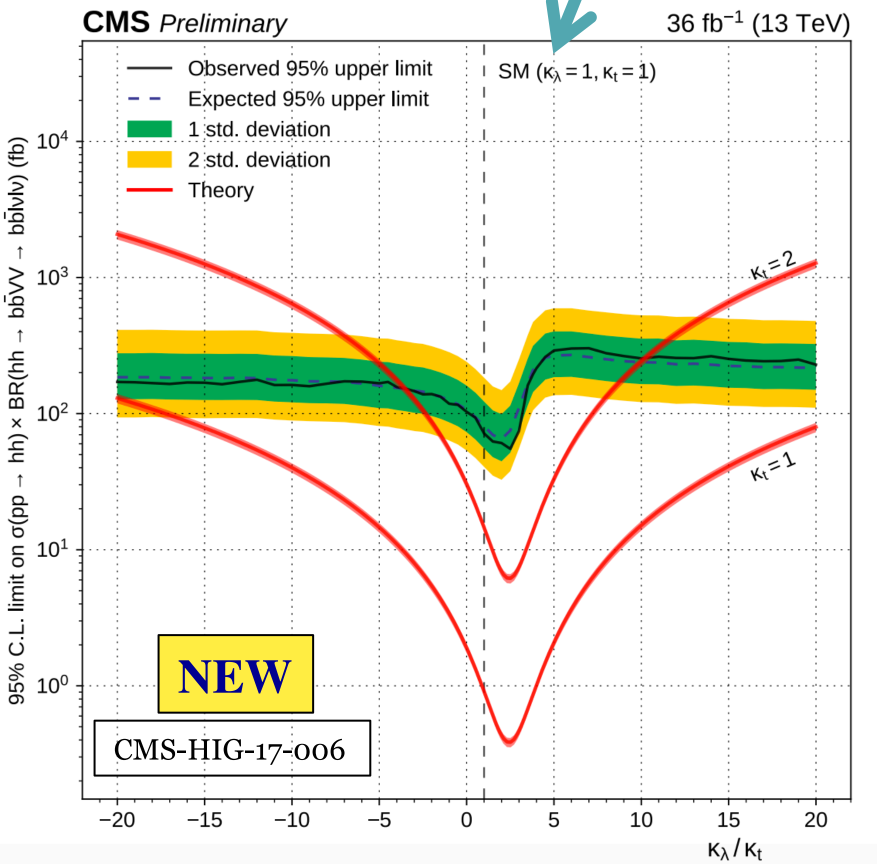


A summary on μμ, ττ, bb



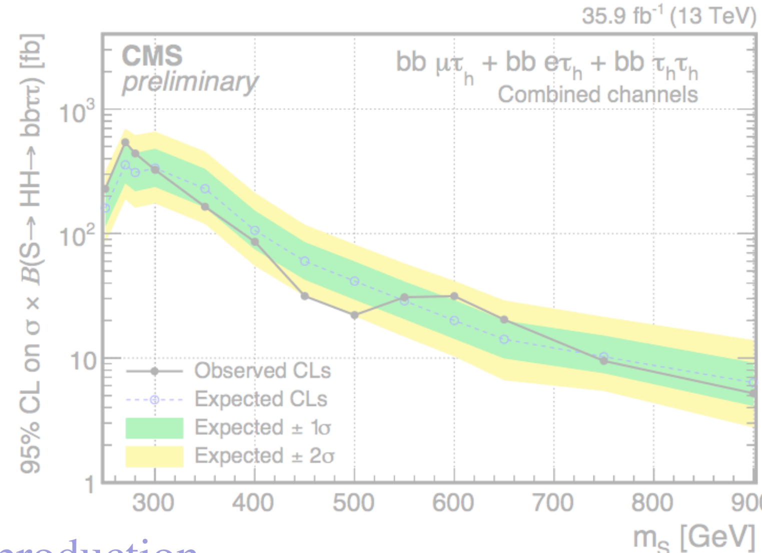
Searches for HH production

Searches in: bbbb, bbWW, bbττ, bbγγ, γγWW

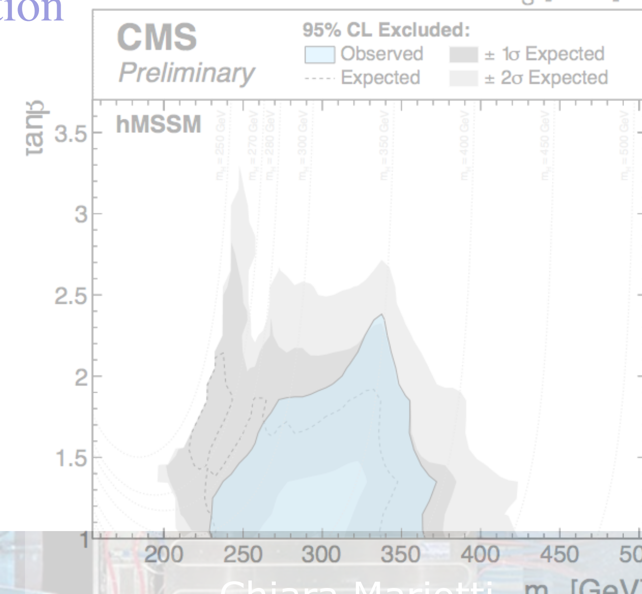


NEW

CMS-HIG-17-006



esonant production
sted up to
X = 900 GeV,
nd interpreted
the hMSSM



SM
HHH

Non-resonant search excludes **79 times the SM**

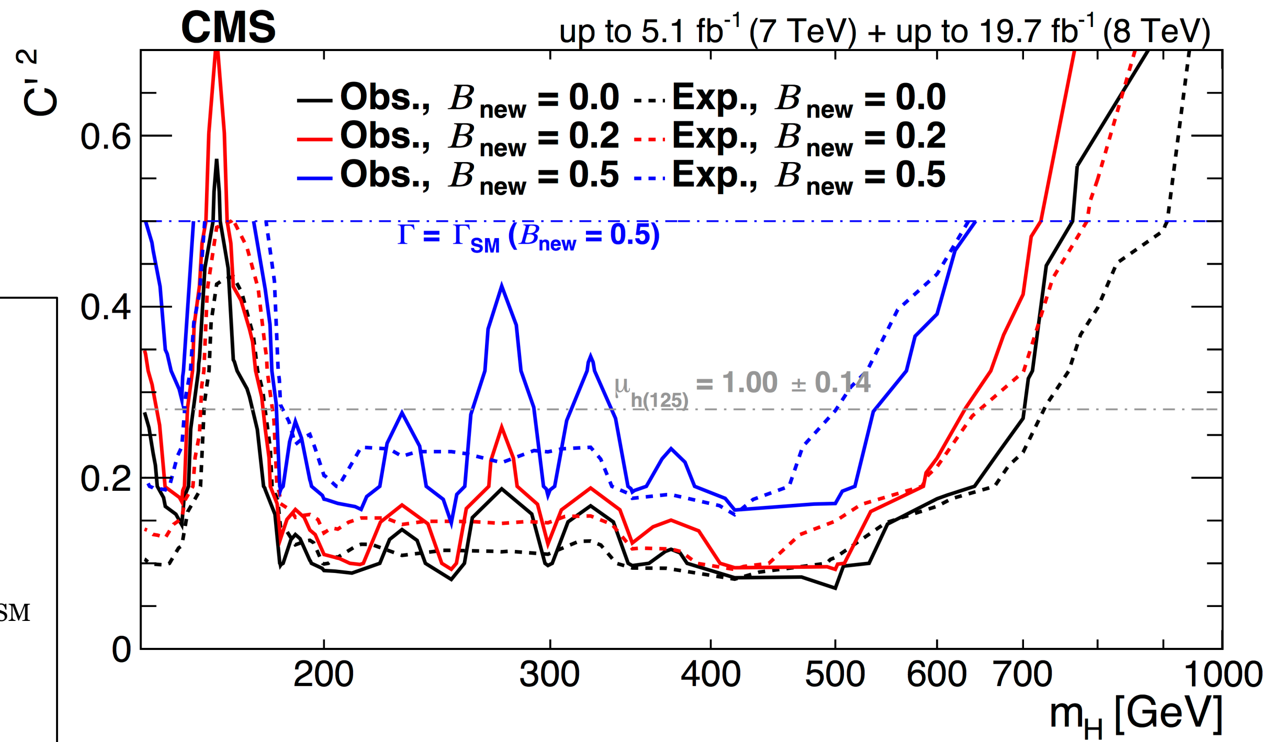
EWK singlet

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

Use the 125 GeV Higgs boson to constraint $C'^2 = 1 - C^2$

Direct search for an additional boson

Use the full CMS combination $\mu_{h125} = 1.00 \pm 0.14$



We assume that h and h' mix with each other

Reduction of the SM coupling strength $\mu_{SM} \rightarrow C^2 \mu_{SM}$

The second singlet h couples with strength $C'^2(1-BR_{new})\, \mu_{SM}$

Unitary implies: $C^2+C'^2=1$

The 2 Higgs Doublet Model

A simple addition to the SM is a second Higgs Doublet

A second Higgs doublet gives rise to 5 Higgs Bosons:

h, H (CP even, neutrals), $H^{\pm}$ (charged), A (CP odd)

- **2 parameters: tanβ=v2/v1** and α = **h-H mixing angle**

Is the boson at 125 GeV the lightest of 5 Higgs Bosons?

→ **Direct search for a heavier Higgs.**

2HDM theories are classified depending on the couplings of the two doublets:

- Type I: 1 Higgs doublet couples only to fermions
- Type II: 1 doublet couples to up quark, the other to down quark

	Type I	Type II
ξ_h^V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^l	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_H^V	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^l	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$

Predictions with SusHi , 2HDMC, Madgraph

- **M. Carena, S. Heinemeyer, O. Stal, C. Wagner, G. Weiglein: 1302.7033**

The well-known benchmark scenarios Mhmax, nomixing, small α_{eff} and gluophobic Higgs used in the past permit the interpretation of the observed Higgs signal at ~ 125.5 GeV in as the light CP-even Higgs boson of

New low-energy MSSM scenarios that are compatible with the mass and production rates of the observ Higgs boson signal at ~ 125.5 GeV:

1. **Mhmax:** mass of the light CP-even Higgs boson is maximized for fixed tan β and large M_A
2. **Mhmod+:** modified Mhmax: reduces the mixing in the stop sector compared to the value that maximize
3. **Mhmod-:** similar to Mhmod+
4. **Lightstop:** suppression of the lightest CP-even Higgs gluon fusion rate
5. **Lightstau:** enhanced decay rate of $h \rightarrow \gamma\gamma$ at large tan β
6. **Tauphobic:** the lightest Higgs has suppressed couplings to down-type fermions
7. **LowMh:** fixes the value of M_A (=110 GeV) and varies μ

1-6: the discovered Higgs is the CP-even lightest Higgs; look for the heavy partner

7: the discovered Higgs is the CP-even heavy Higgs; look for the lighter partner

The LHC exclusion regions inferred from analyses searching for MSSM Higgs bosons:

[φ=h,H,A]: 1) $pp \rightarrow \varphi \rightarrow \tau^+\tau^-$ (inclusive); $bb^-\varphi, \varphi \rightarrow \tau^+\tau^-$ (with b-tag); 2) $bb^-\varphi, \varphi \rightarrow bb^-$(with b-tag),

$pp \rightarrow tt^- \rightarrow H^{+-}W^{\mp}bb^-, H^{+-} \rightarrow \tau\nu_\tau$, $gb \rightarrow H^-t$ or $gb^- \rightarrow H^+t^-, H^{+-} \rightarrow \tau\,\nu_\tau$

nMSSM

- NMSSM introduces a singlet field on top of the 2 Higgs doublets in MSSM, leads to 7 physical Higgs bosons ($a_{1,2}$, $h_{1,2,3}$, $H^{\pm}$) which one or two of them can be lighter than 125 GeV

NMSSM offers a rich phenomenology not yet excluded by experimental data.
MSSM is highly constrained

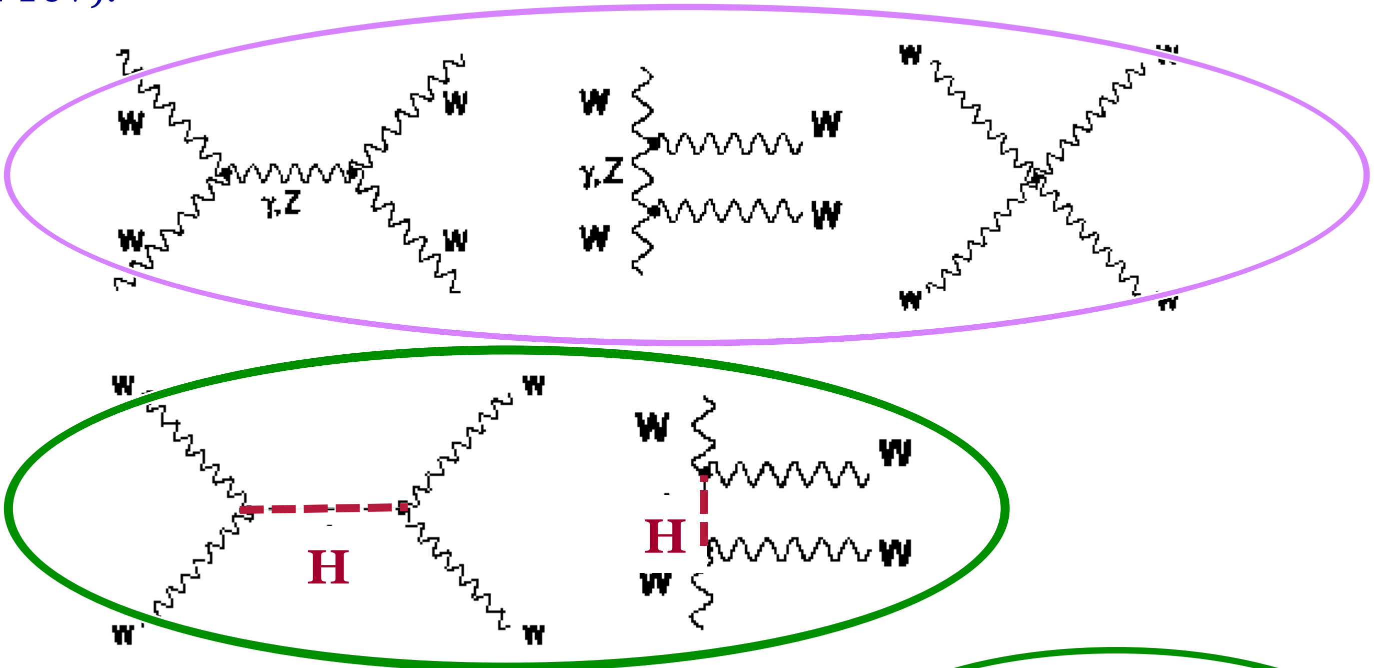
-charged H bosons are ~ excluded to be light than 180 GeV, disfavoring a light h ($h<H(125)$, thus assuming $H=H(125)$).

- assuming $h=H(125)$ is disfavored by the large radiative corrections needed to push h to be much heavier than the Z.

The SM Higgs

The Higgs mechanism explains how the elementary particles get mass.
The W and Z acquire the longitudinal degree of freedom (W_L, Z_L).

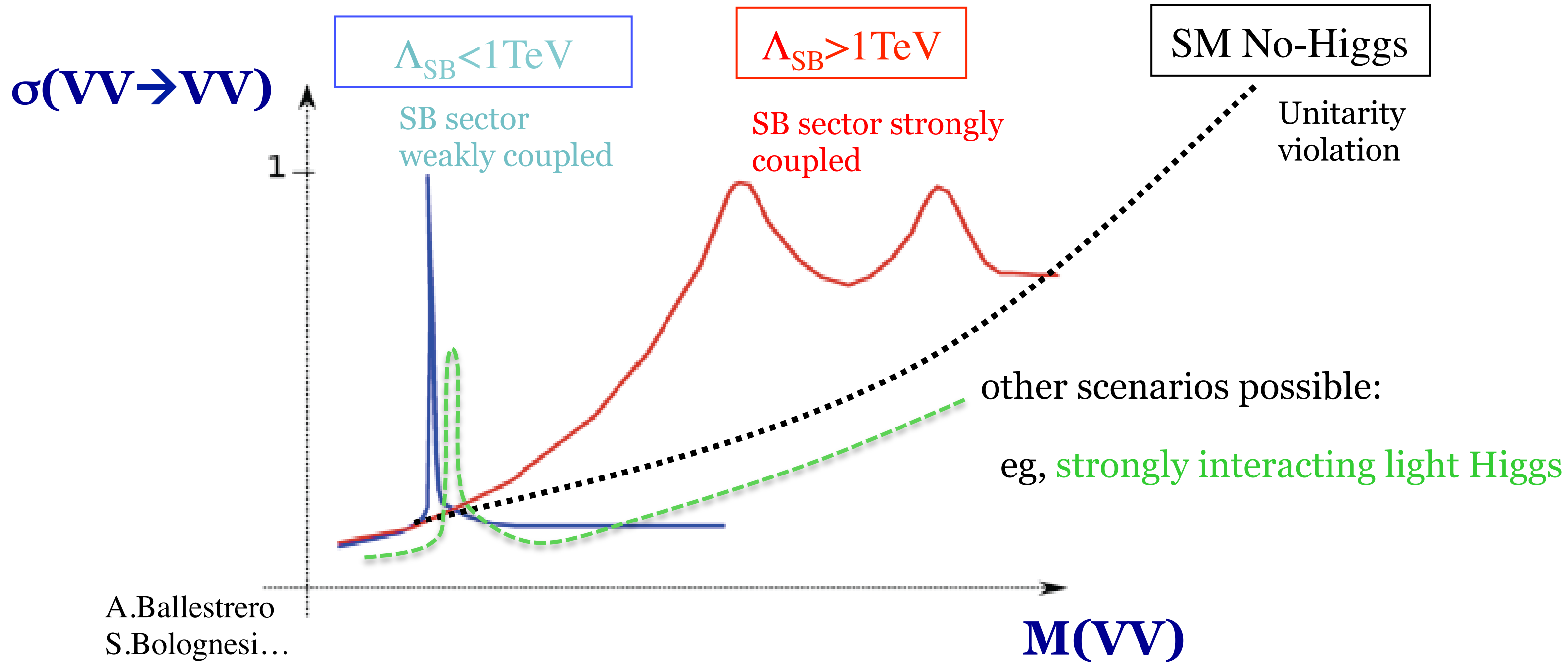
Without the Higgs, $V_L V_L \rightarrow V_L V_L$ would break perturbative unitarity
(for $\sqrt{s} > \sim 1.2$ TeV).



$$\sigma_{V_L V_L \to V_L V_L} \propto \left[-s - t + \frac{s^2}{s - m_{\mathrm{H}}^2} + \frac{t^2}{t - m_{\mathrm{H}}^2} \right]$$

VV scattering as a probe of EWSB

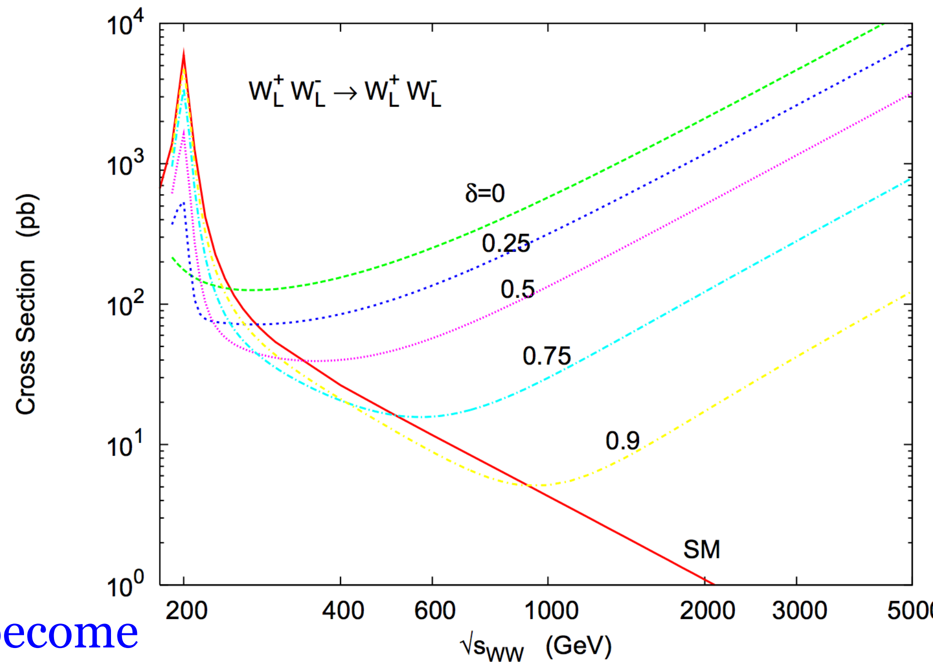
The identity of the Higgs comes from **its role in EWSB: unitarisation of $V_LV_L \rightarrow V_LV_L$**



More the 125 boson will be constrained to be similar to SM
→ more the XS of the second heavy resonance will be suppressed
→ more the VV strong interaction scale will move to high energy

Partially Strong $W_L W_L$ Scattering

If the cancellation of the Higgs diagrams is not complete, then we expect a g_{hWW} coupling smaller than the SM.
The $W_L W_L$ will keep growing with $\sqrt{s}$, up to the the new resonance, or more generally to the new physics scale Λ.



Cheung, Chiang, Yuan

Suppose the Higgs-WW coupling is **$\sqrt{\delta}$ of the SM** value, then the amplitudes become

$$
\begin{aligned}
i\mathcal{M}^{\text{gauge}} &= -i\frac{g^2}{4m_W^2}\,u + \mathcal{O}((E/m_W)^0) \\
i\mathcal{M}^{\text{higgs}} &= i\frac{g^2}{4m_W^2}\,u\,\delta + \mathcal{O}((E/m_W)^0) \\
i\mathcal{M}^{\text{all}} &= -i\frac{g^2}{4m_W^2}u(1-\delta) + \mathcal{O}((E/m_W)^0)
\end{aligned}
$$

→ Measure with high precision hVV coupling and $V_L V_L$ scattering