Higgs results in ZZ final state with the CMS experiment

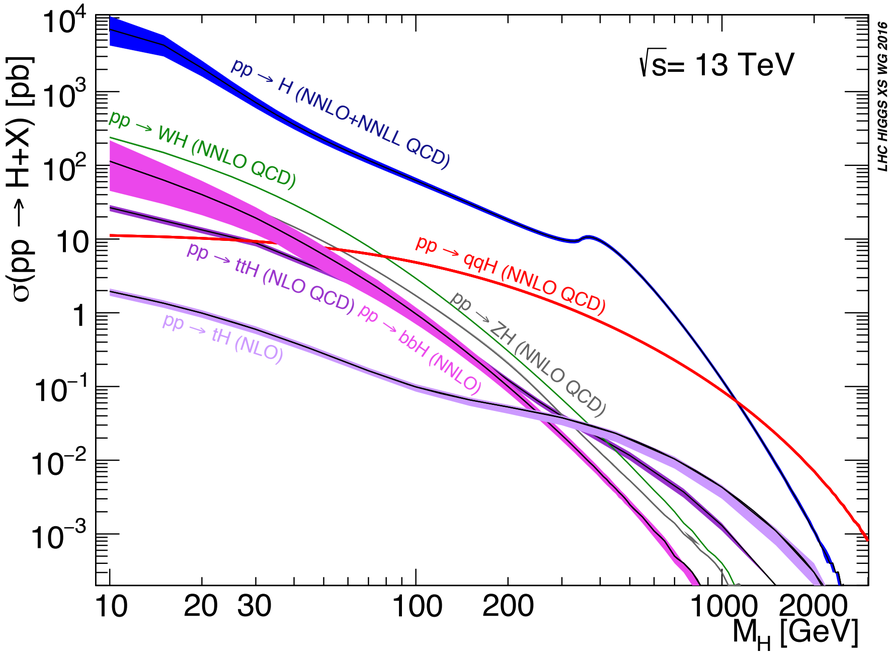
Meng Xiao (Johns Hopkins University)

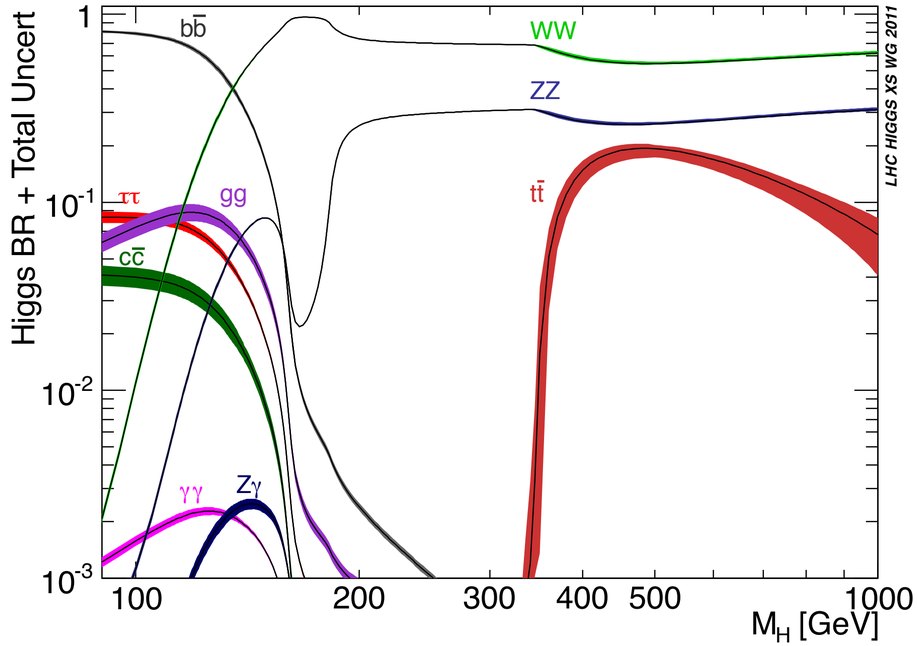
Page 1?

LHC, CMS

SM

Higgs boson





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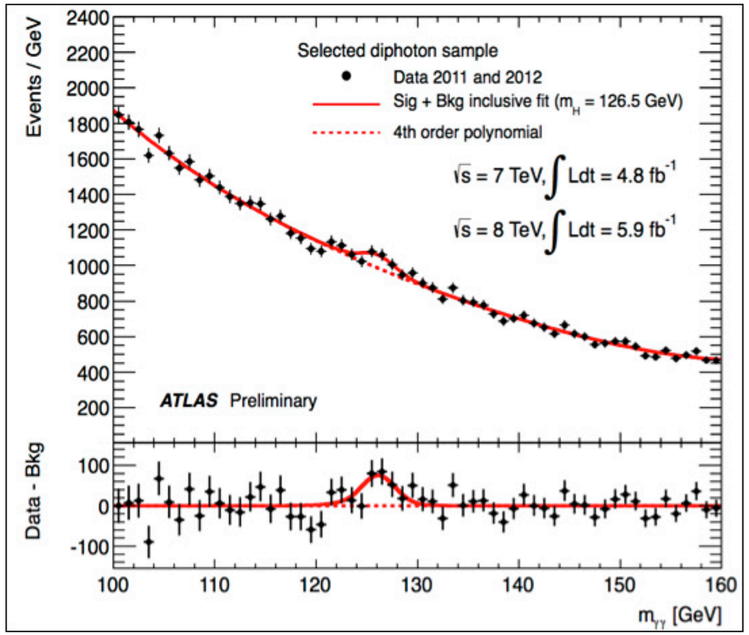
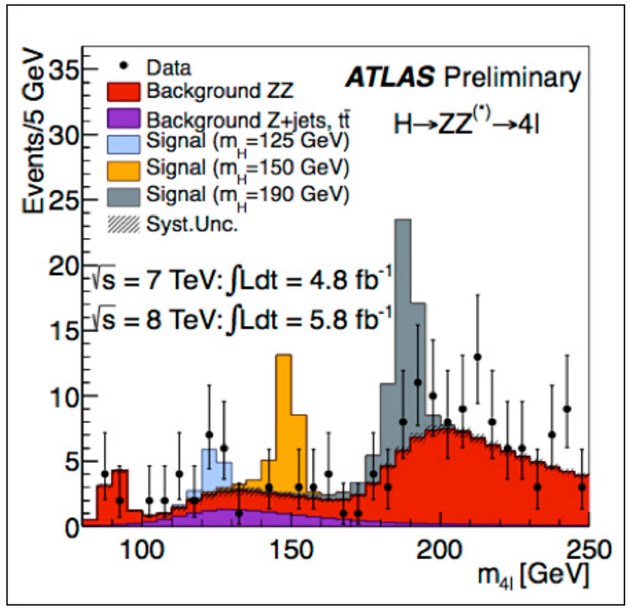
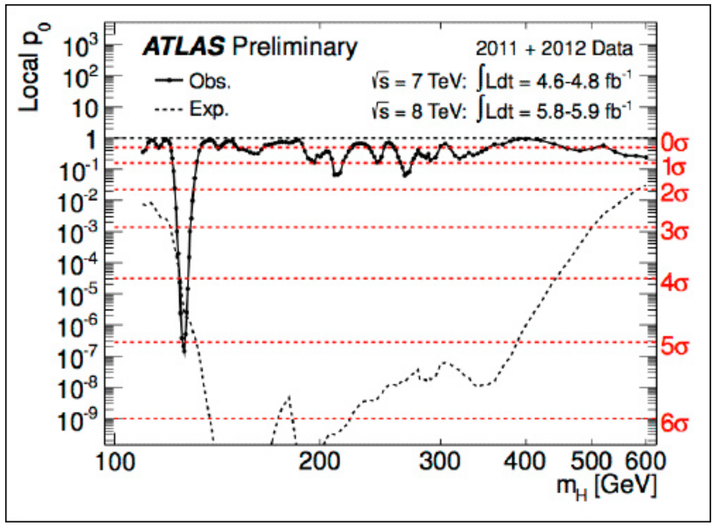
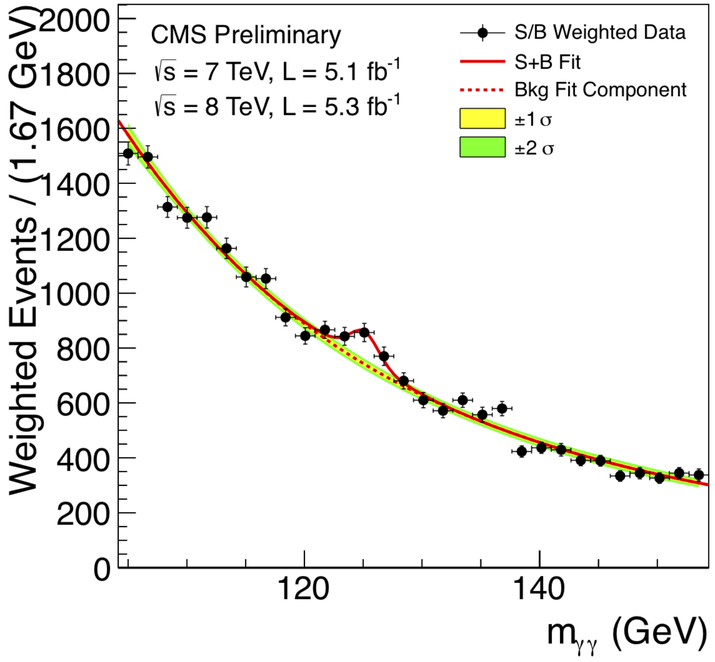
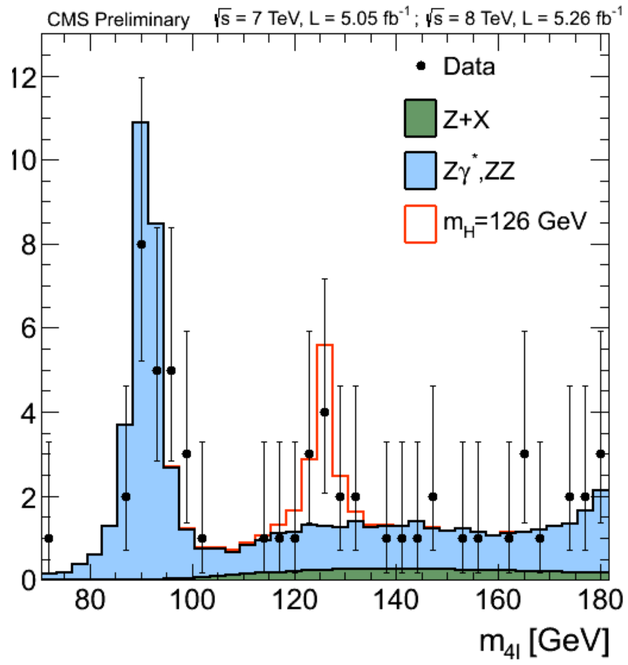
From July 4th, 2012 seminar

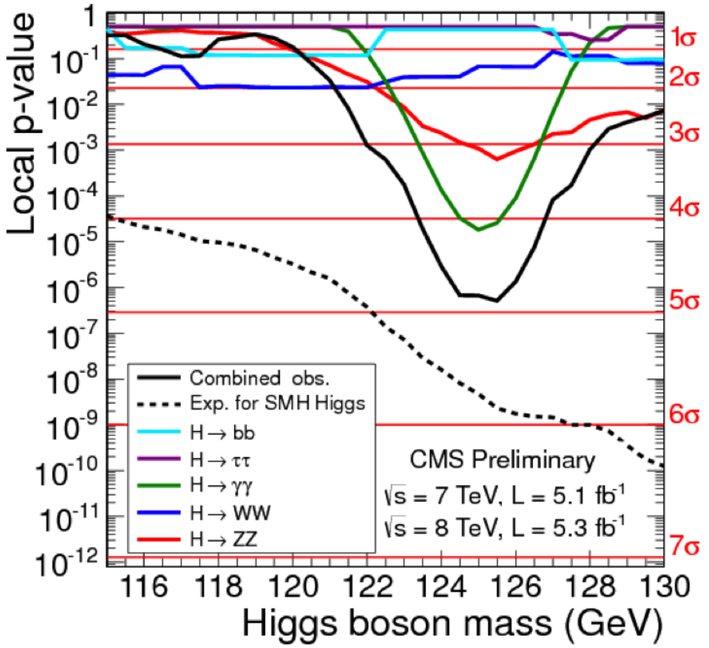












From Peskin, Higgs Hunting, 2012

Our understanding of this boson will advance in stages.

I expect 3 stages:

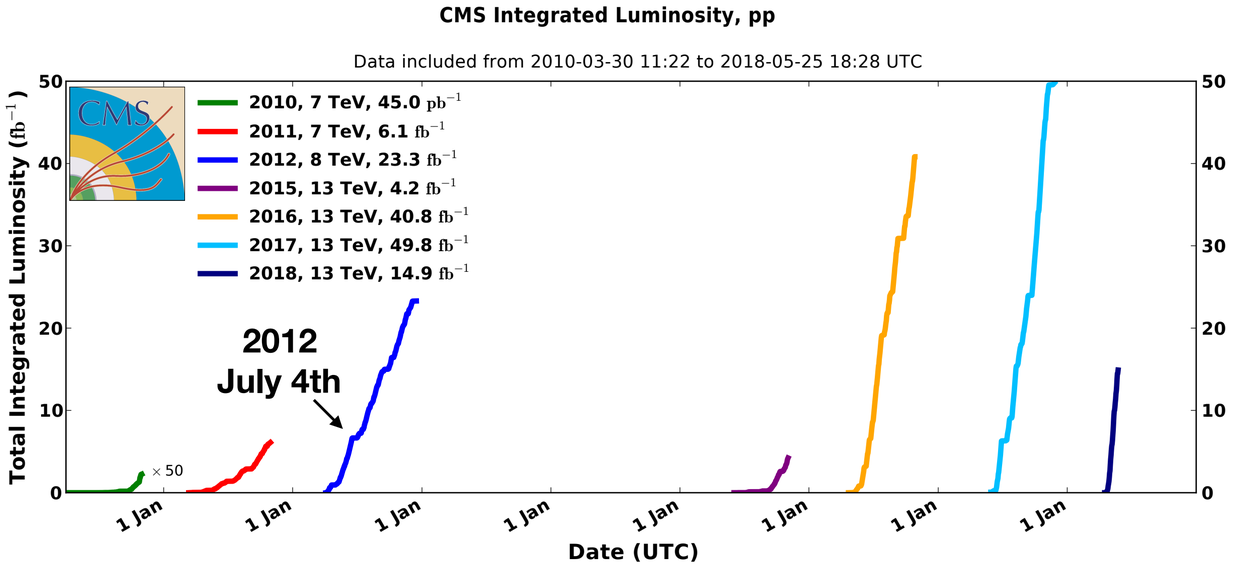
1. Are the major decay modes present ?

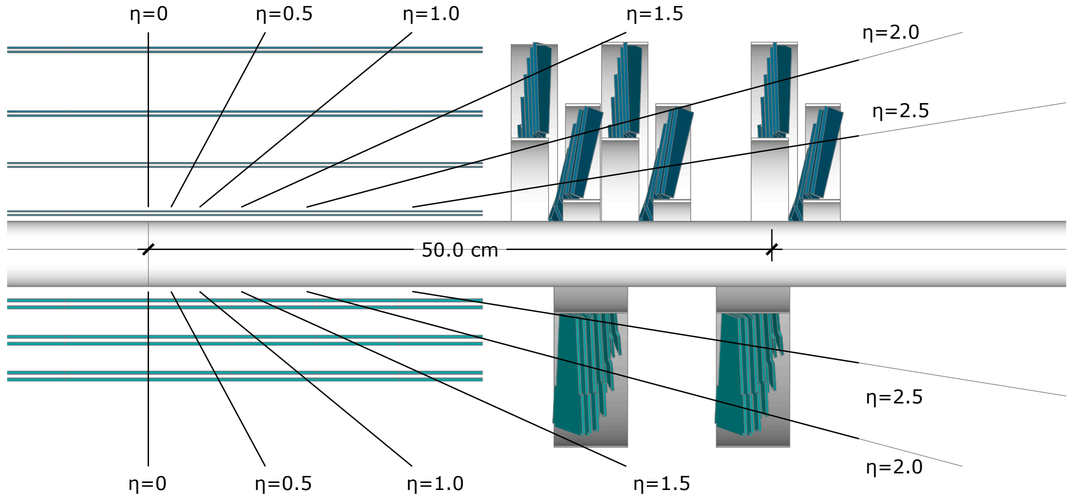
2. Standard-Model-like Higgs boson, or not ?

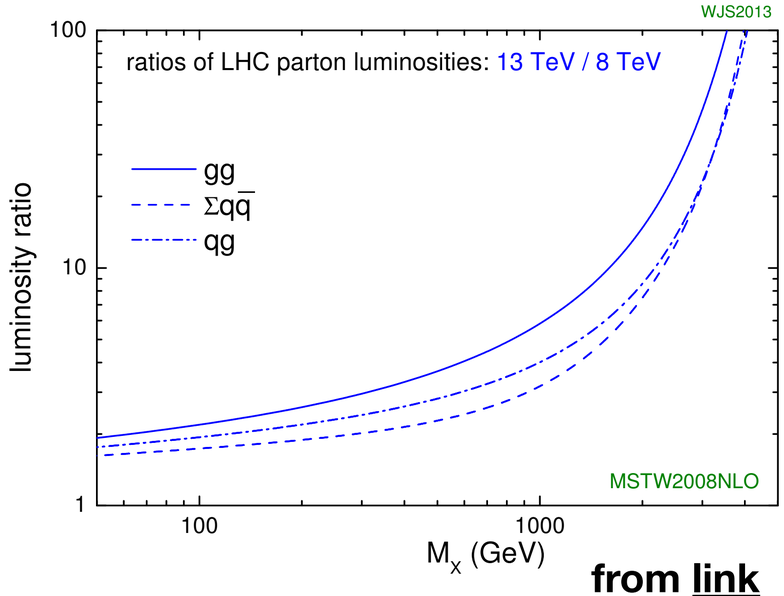
3. Are there small deviations from the Standard Model ?

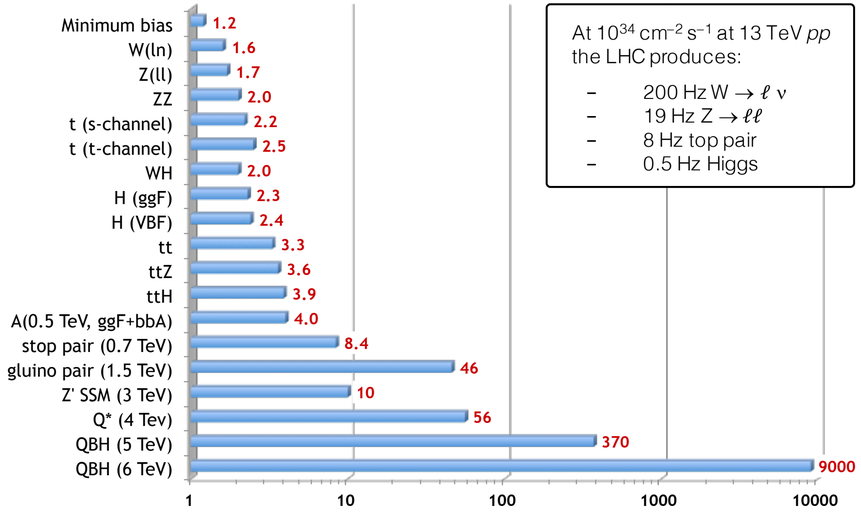
6 years later…

2012-2018



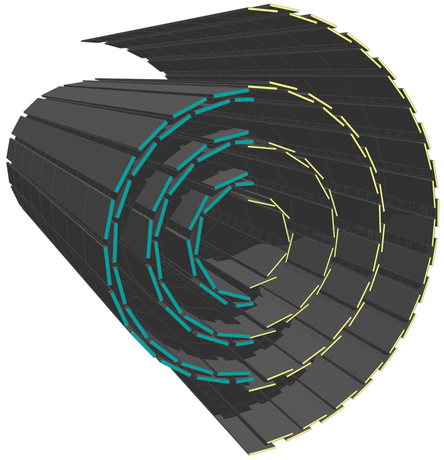






At 10^{34} cm^{-2} s^{-1} at 13 TeV *pp* the LHC produces:

- 200 Hz W $\rightarrow \ell\ \nu$
- 19 Hz Z $\rightarrow \ell\ell$
- 8 Hz top pair
- 0.5 Hz Higgs



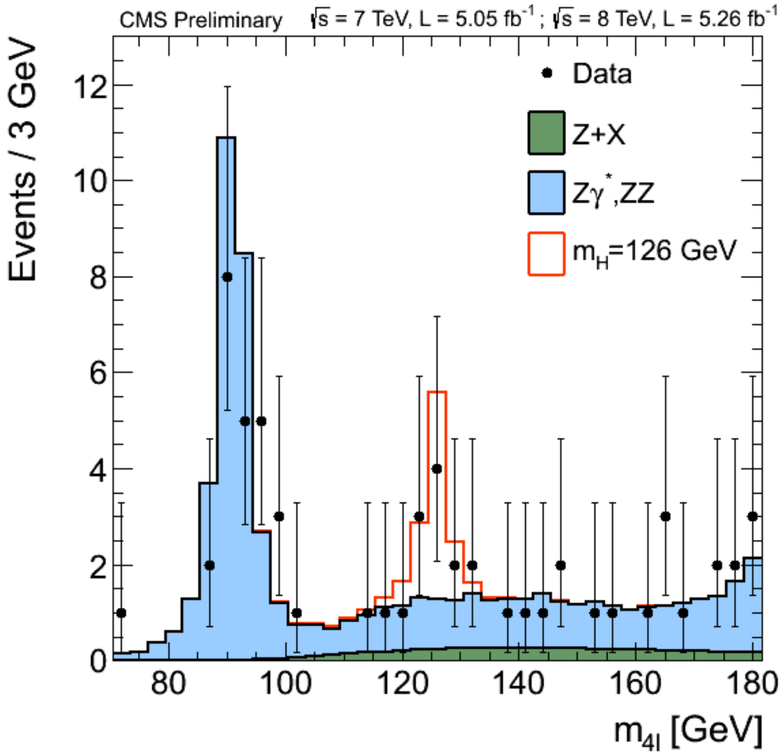
from link

Are the major decay/production modes present?

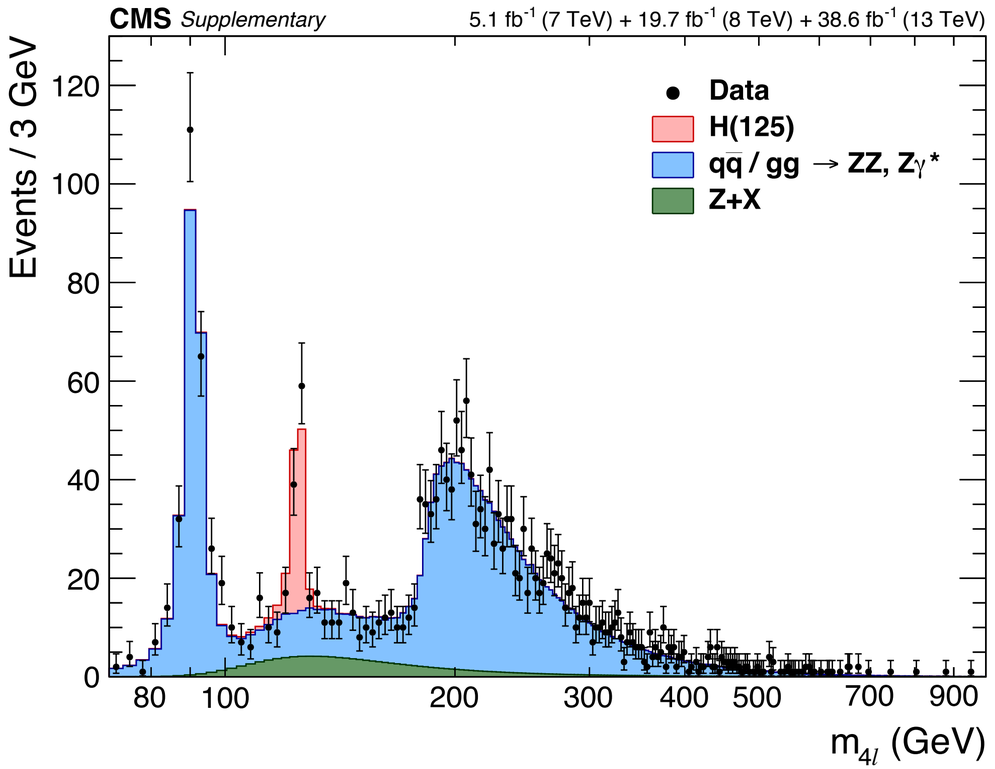
The ZZ(*)→ 4l decay mode

JHEP 11 (2017) 047

up to July 2012

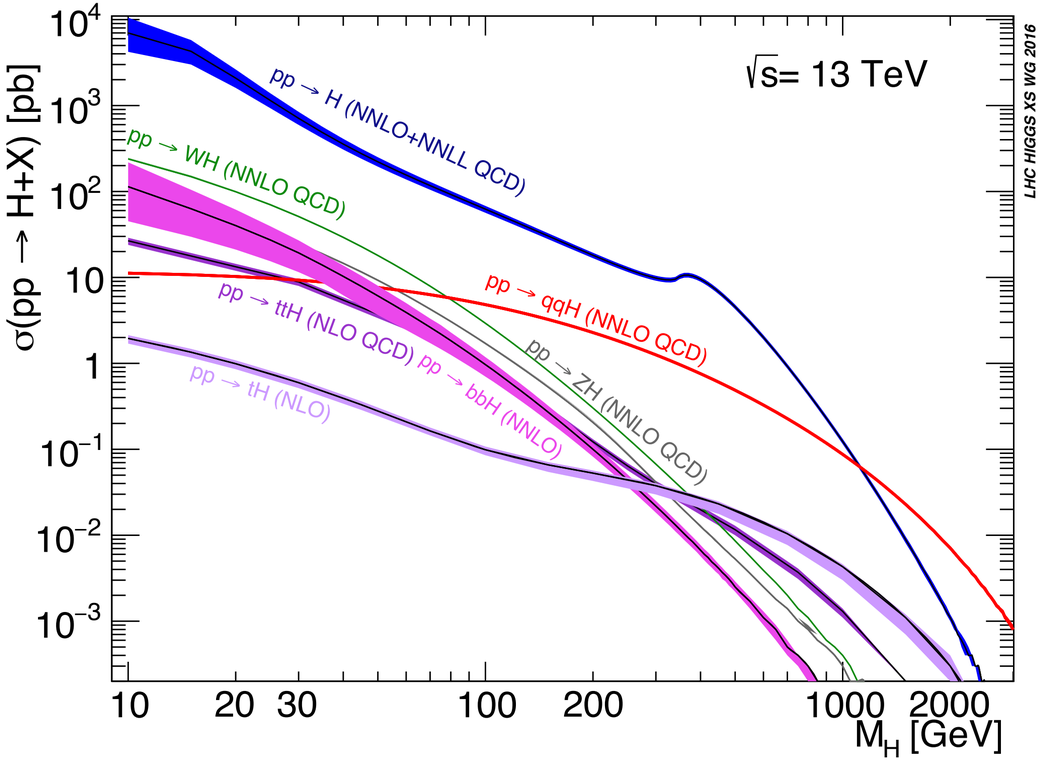


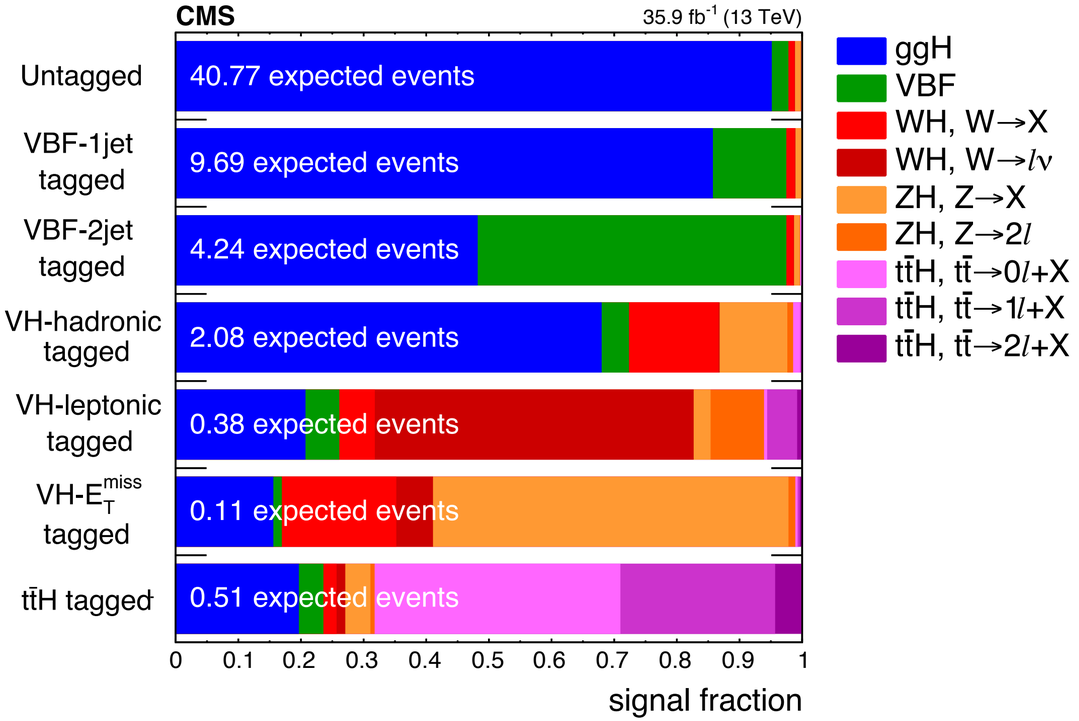
up to 2016



Far beyond 10σ

The production modes

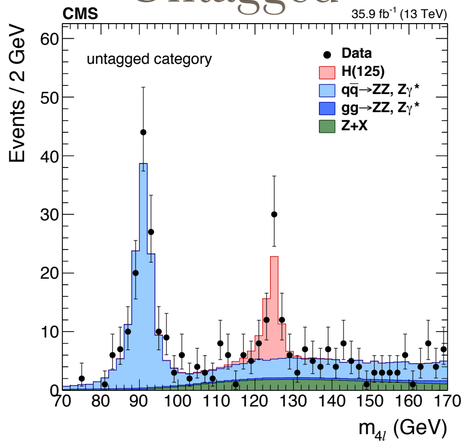




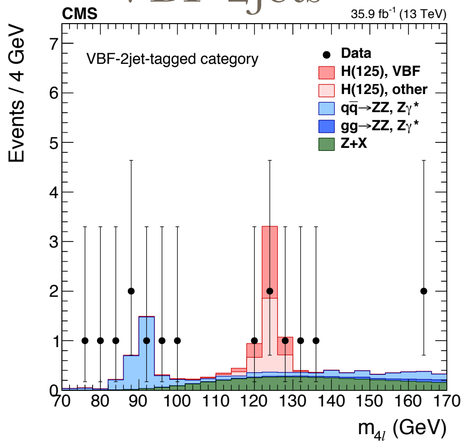
The production modes

JHEP 11 (2017) 047

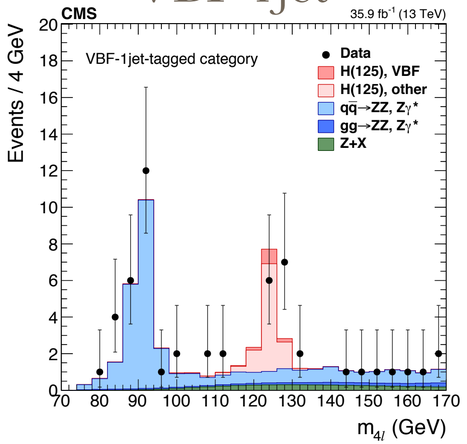
Untagged

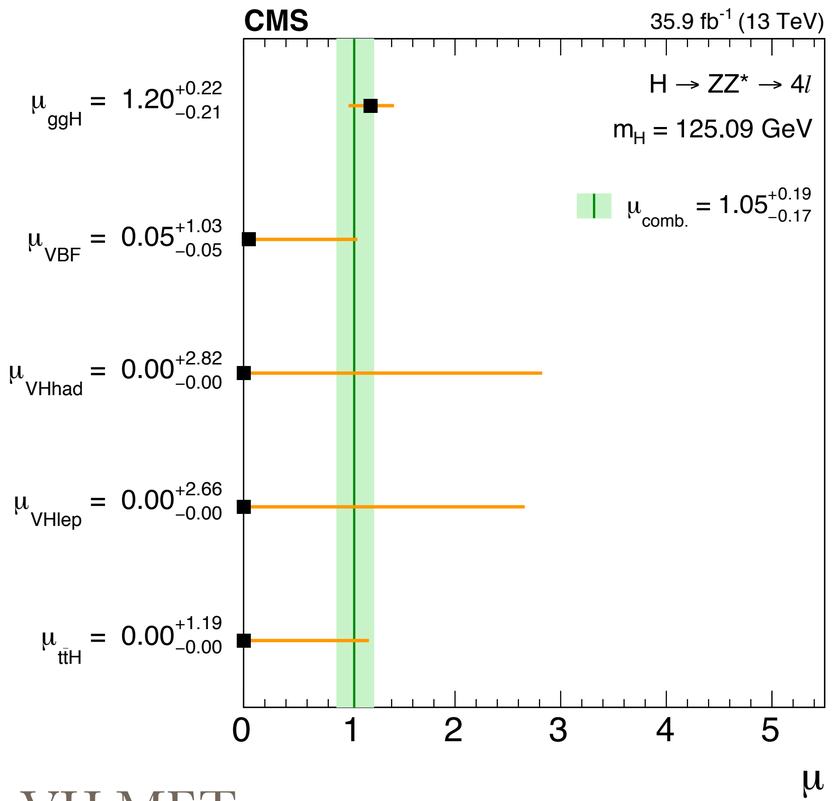


VBF 2jets

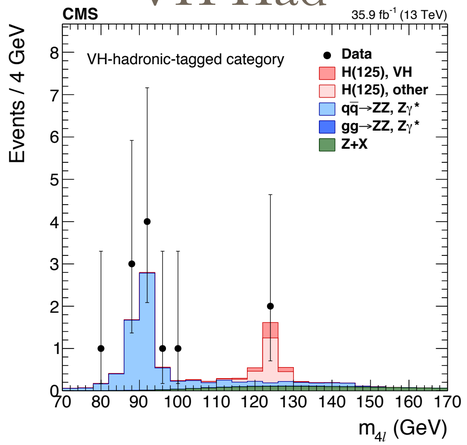


VBF 1jet

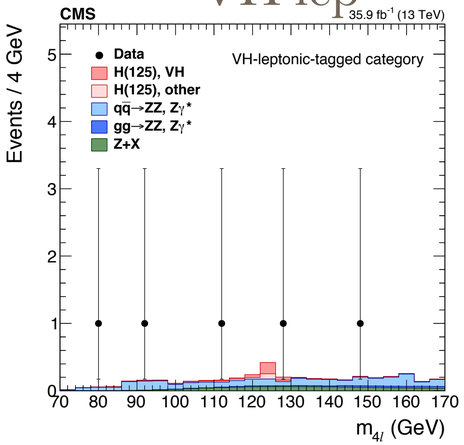




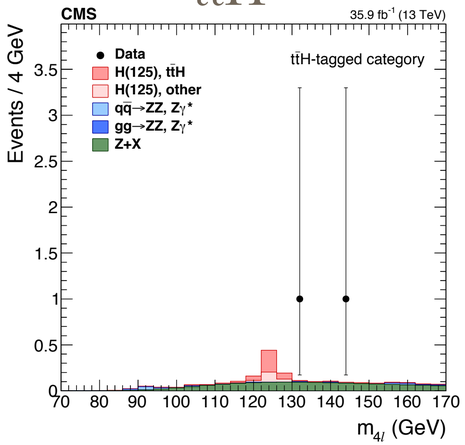
VH Had



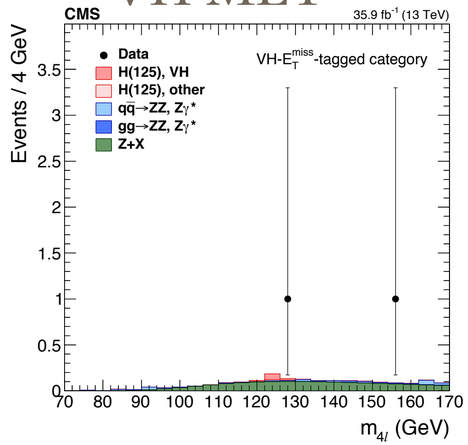
VH lep



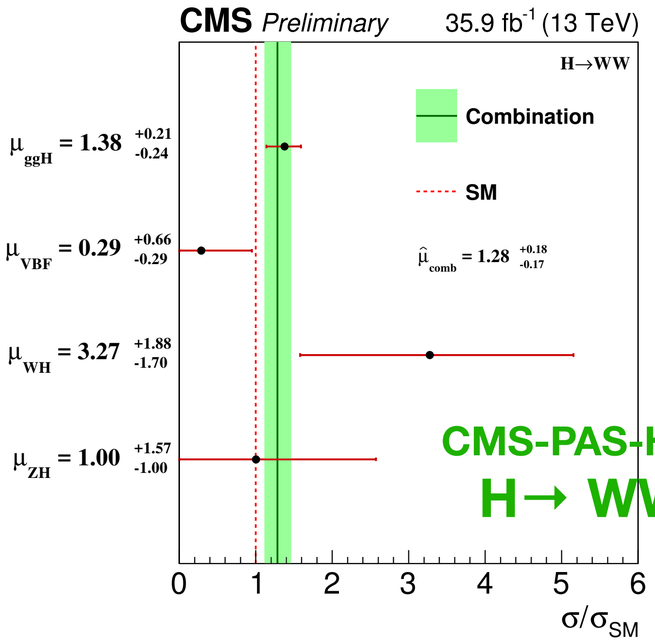
ttH



VH MET

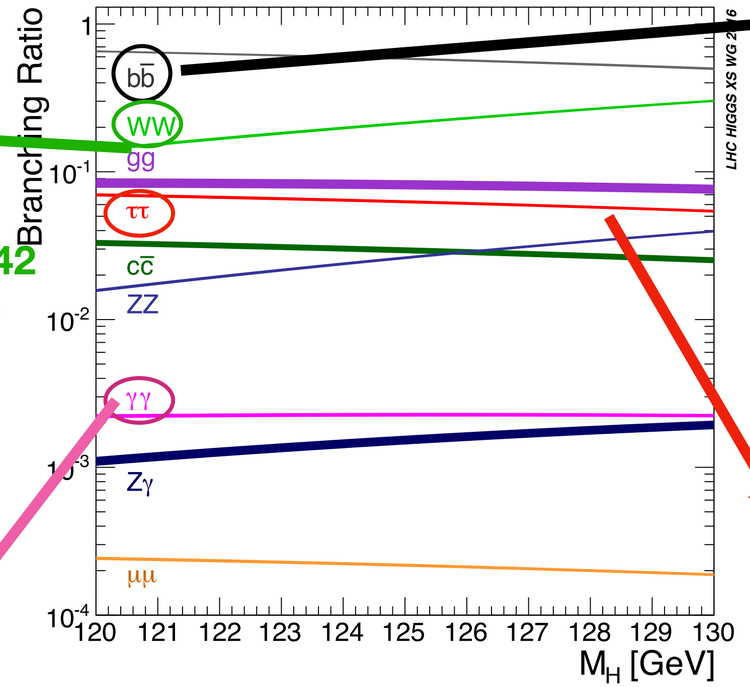


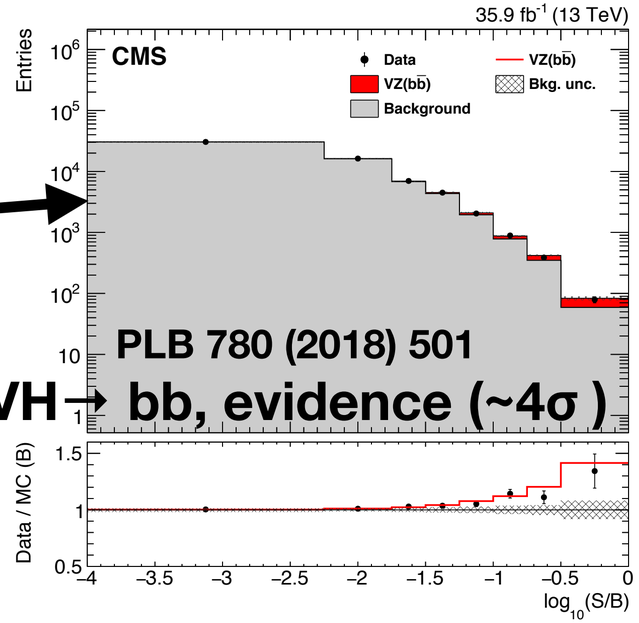
Other decay/production modes



CMS-PAS-HIG-16-042

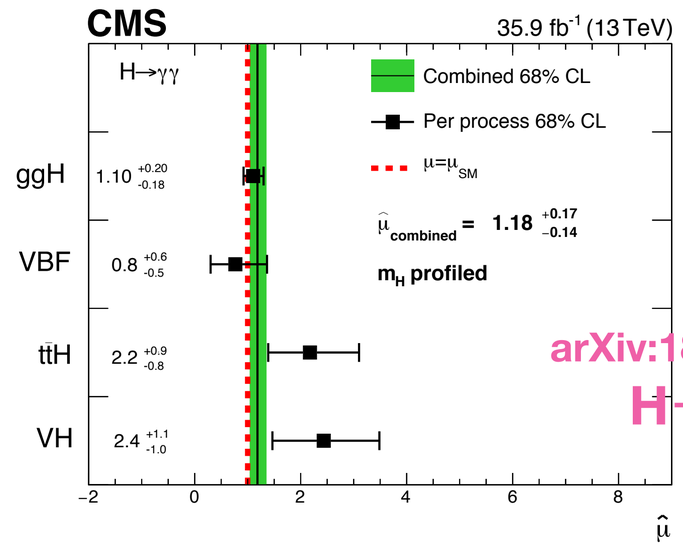
H→ WW, > 9σ





PLB 780 (2018) 501

VH→ bb, evidence (~4σ)

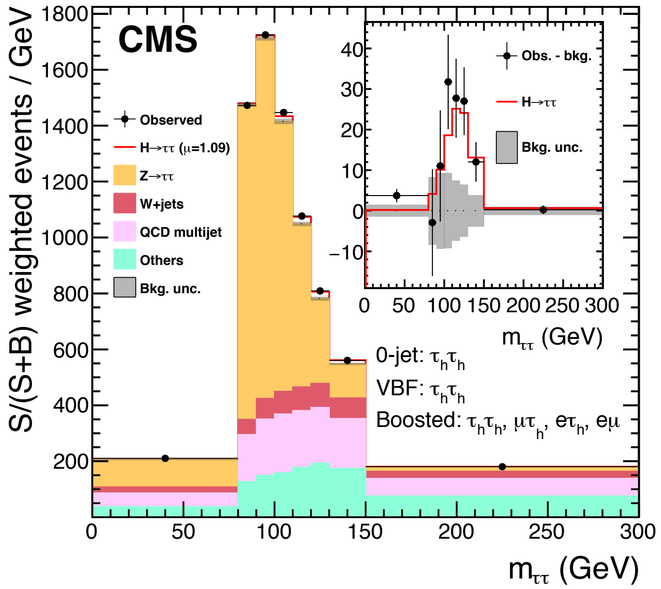


arXiv:1804.02716

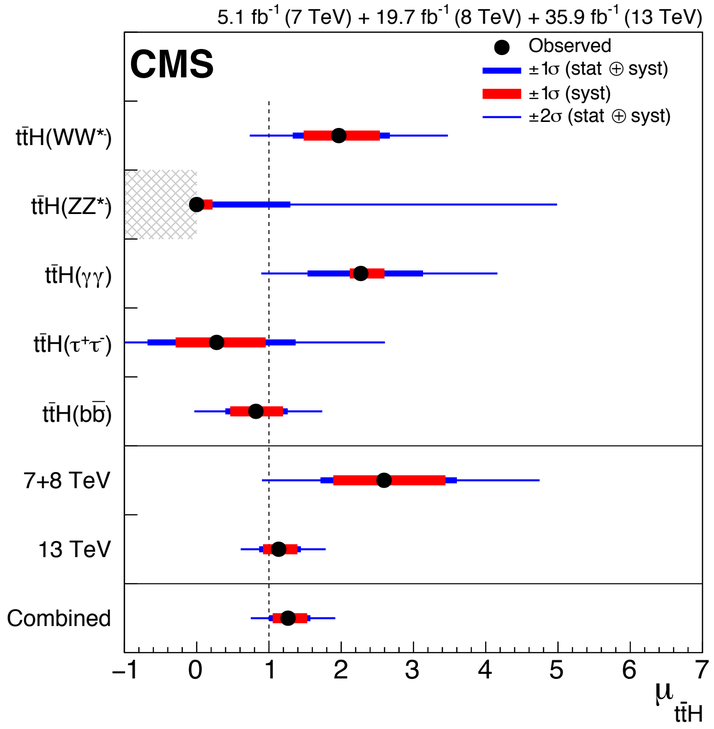
H→ γγ

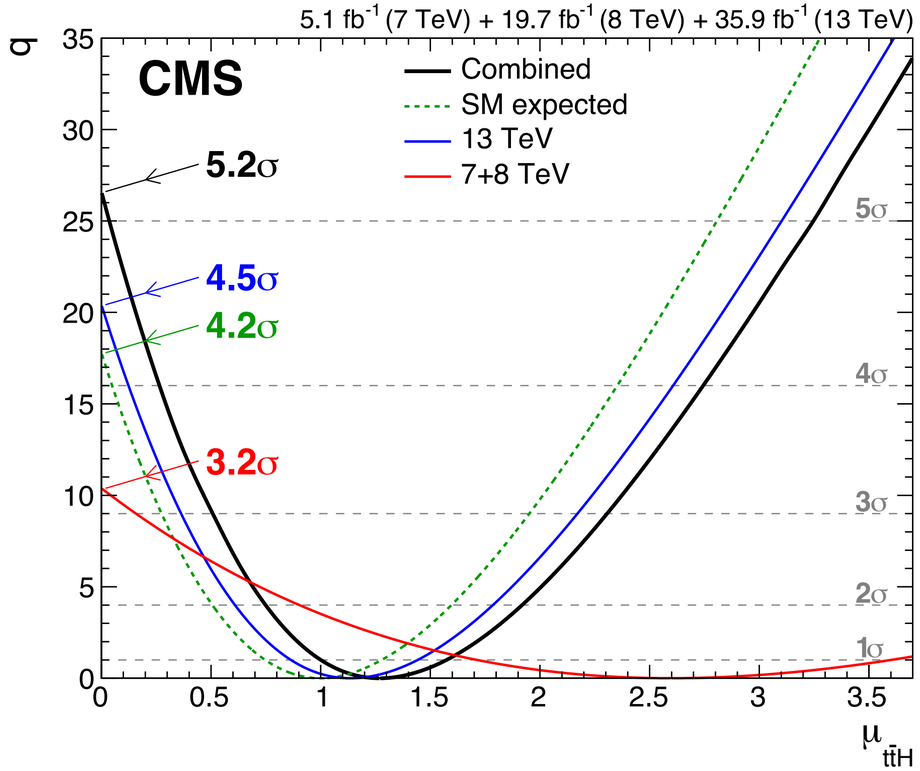
PLB 779 (2018) 283

H→ ττ, observed



Other decay/production modes





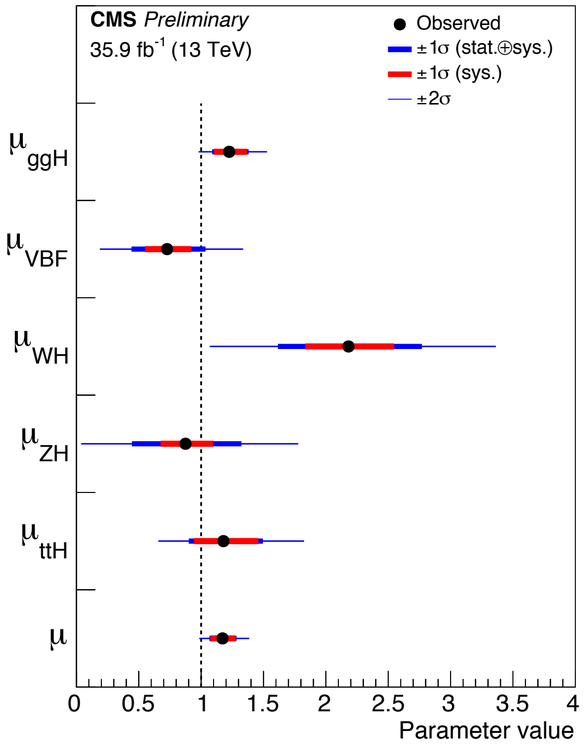
arXiv:1804.02610

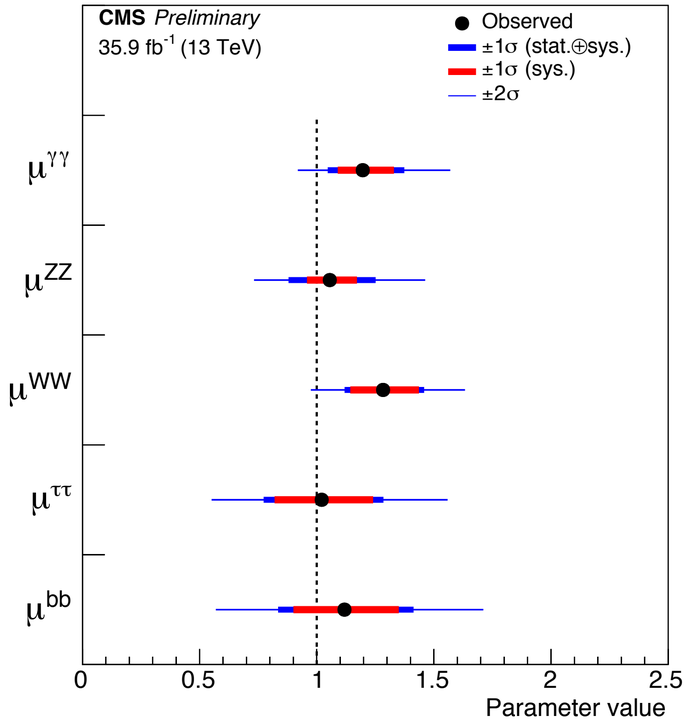
ttH observed

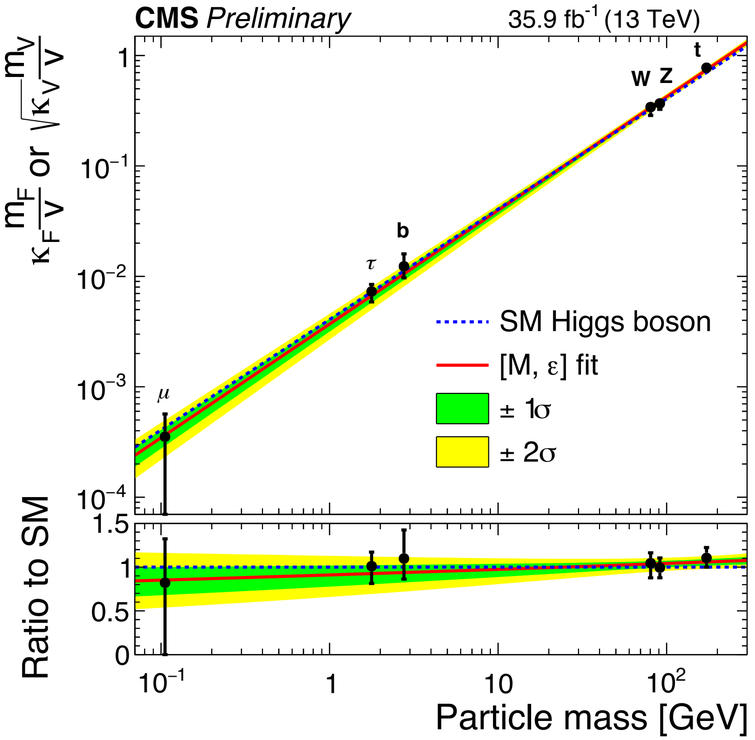
Standard Model like boson?

CMS-PAS-HIG-17-031

Consistency across channels



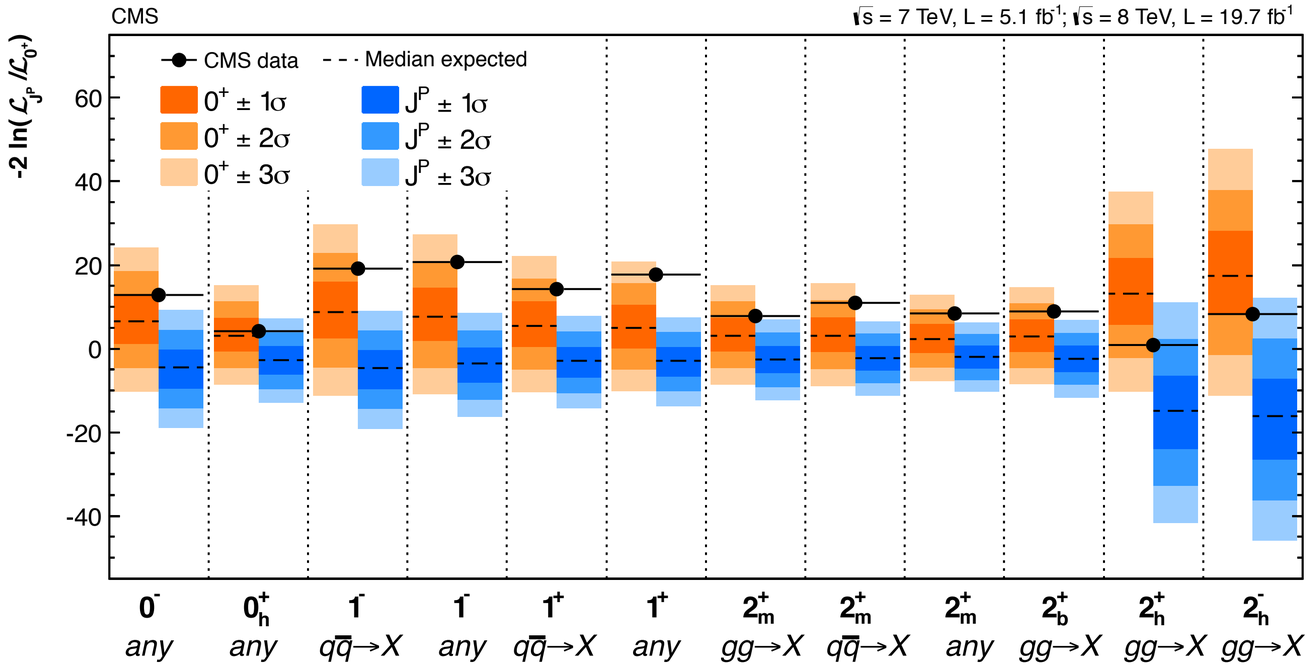




Spin-parity

PRD 89 (2014) 092007

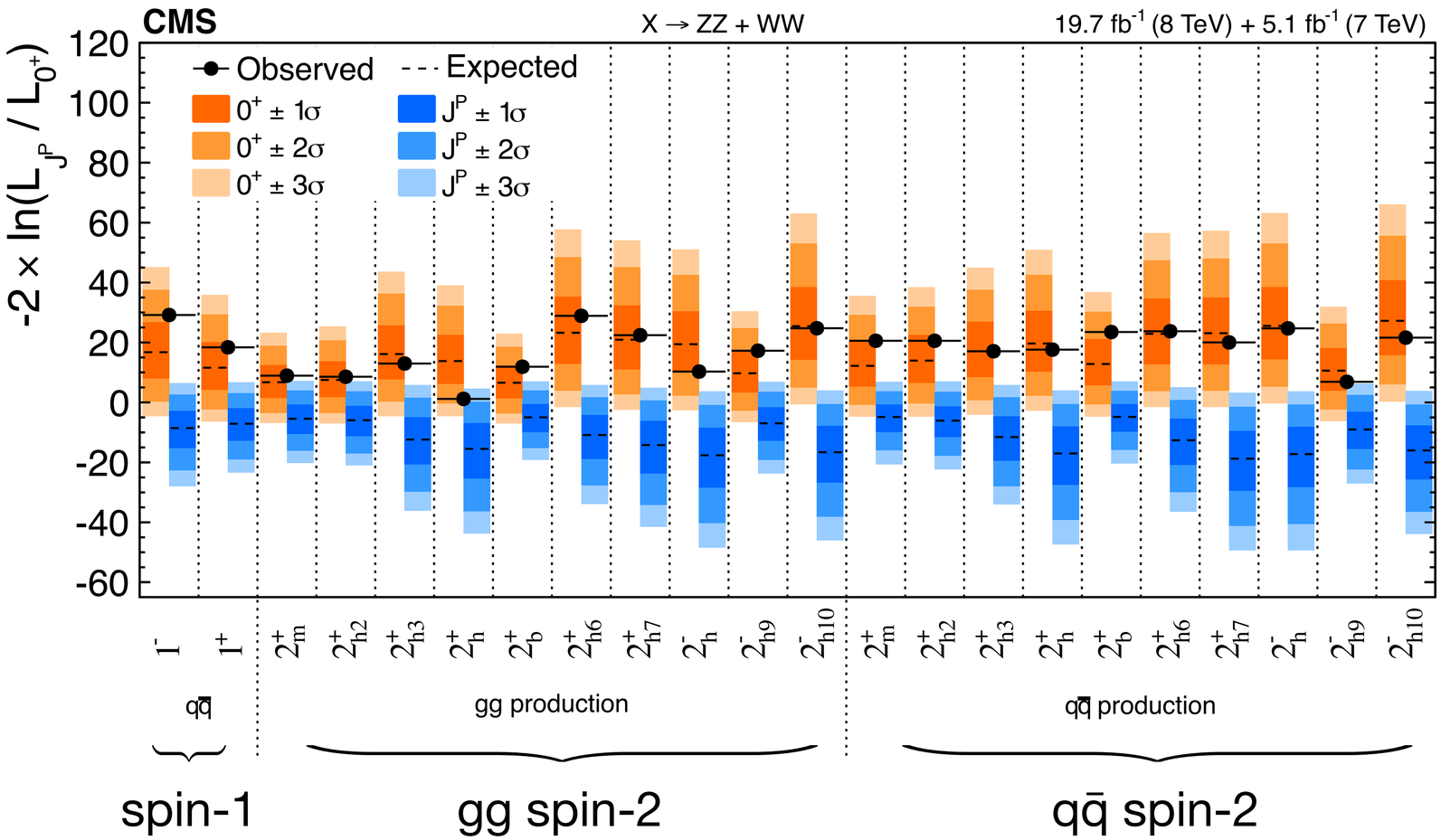
Data favor 0+ scalar state
H→ ZZ alone



Spin-parity

PRD 92 (2015) 012004

All exotic models excluded > 98% CL



Small deviations from the SM?

CP mixture?

PRD 92 (2015) 012004

Spin-0: 0^+, 0^-, 0_h^+

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu} + a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}$$

Λ_1 term
leading momentum expansion

a_2 term
CP even state

a_3 term
CP odd state

SM values of the couplings

	a_1	q^2/Λ_1^2	a_2	a_3
HZZ(WW)	2	$o^{-3} - o^{-2}$	$o^{-3} - o^{-2}$	$< o^{-10}$
HZγ	-	$o^{-3} - o^{-2}$	0.0035	$< o^{-10}$
H$\gamma\gamma$	-	-	-0.004	$< o^{-10}$

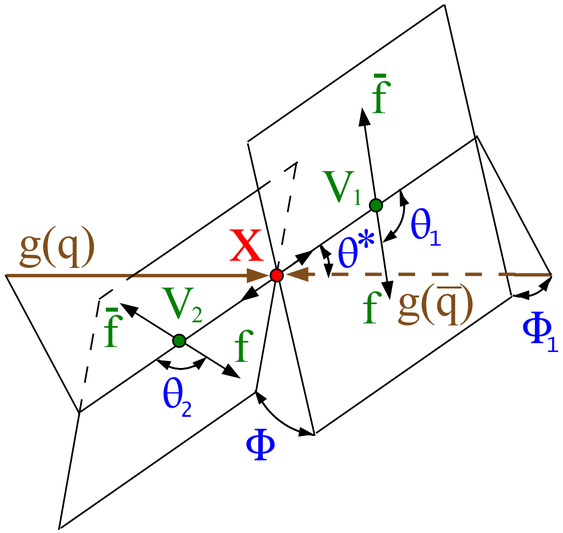
Measure $f_{ai} = \cos(\theta)\, a_i^2\, \sigma_i / (a_i^2\, \sigma_i + a_1^2\, \sigma_1)$

How and where to measure

H→ γγ: only sensitive to non-spin0

H→ WW: no full kinematic information available

H→ Z(γ*)Z*(γ*) → 4l: full kinematics available, angular information

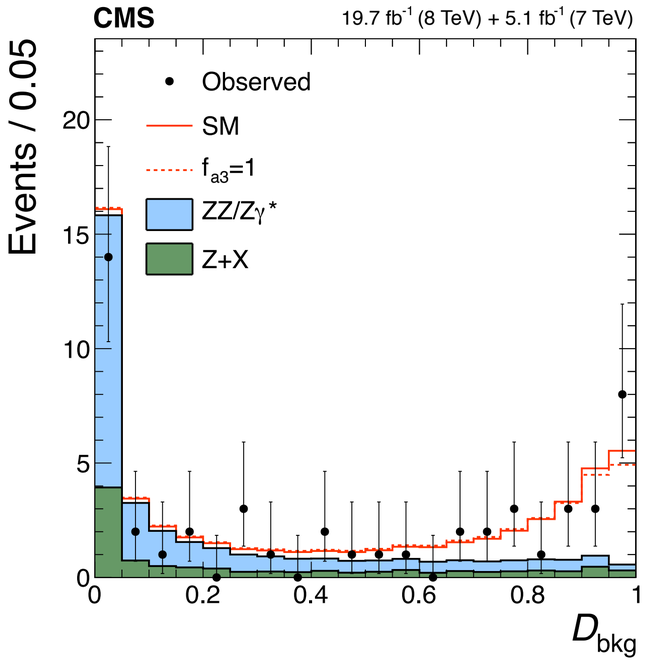


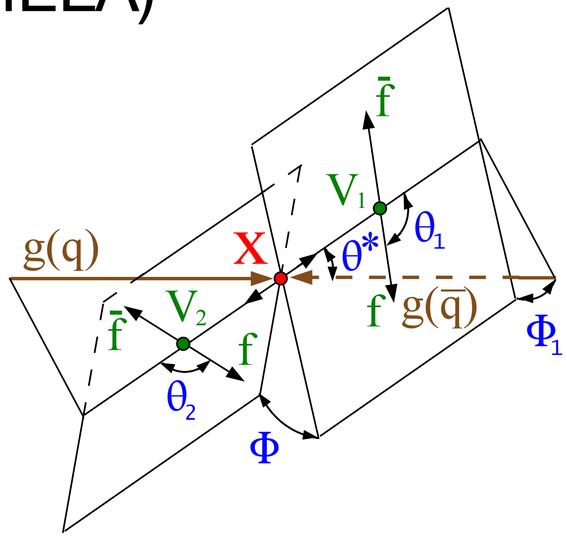
The measurement

H→ Z(γ*)Z*(γ*) → 4l, Matrix Element likelihood Analysis (MELA)

A. suppress background

$$\mathcal{D}_{\rm bkg} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + c \times \mathcal{P}_{\rm q\bar{q}ZZ}}$$





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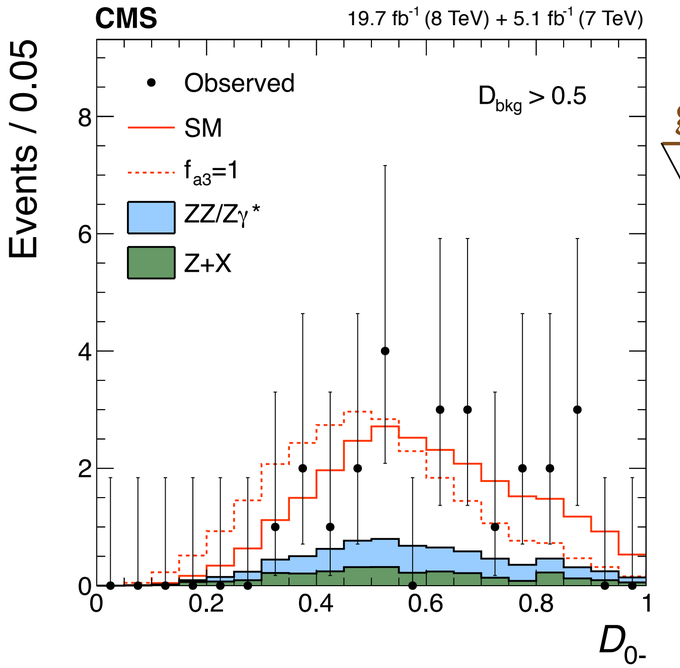
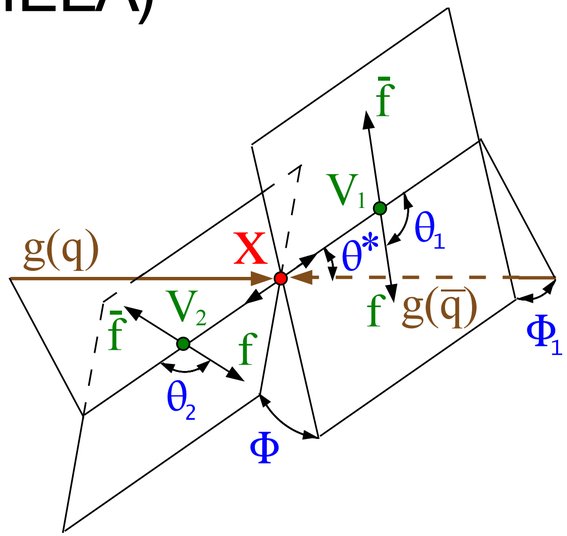
B. separate BSM vs SM

$$\mathcal{D}^{\rm kin}_{J^P} = \frac{\mathcal{P}^{\rm kin}_{\rm SM}}{\mathcal{P}^{\rm kin}_{\rm SM} + \mathcal{P}^{\rm kin}_{J^P}}$$





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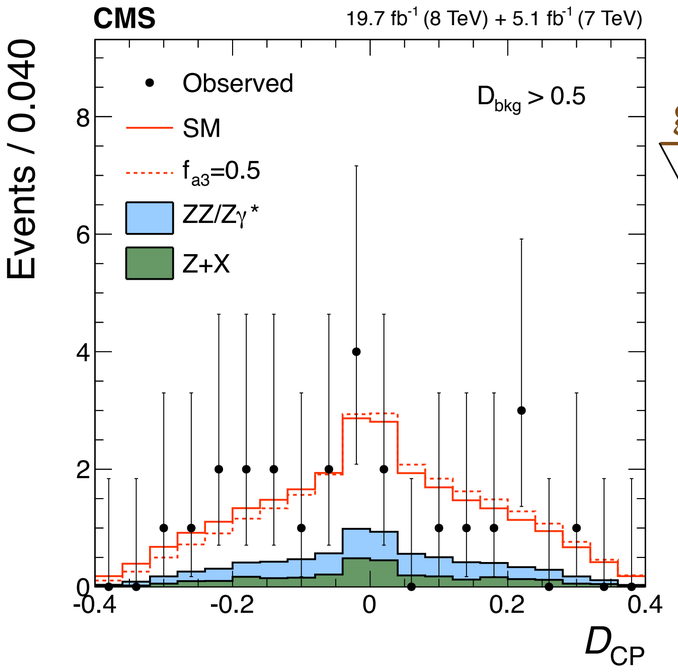
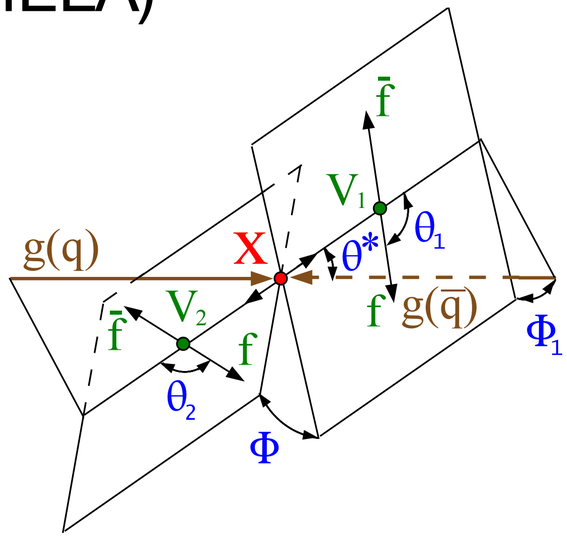
B. separate BSM vs SM

$$\mathcal{D}^{\rm kin}_{J^P} = \frac{\mathcal{P}^{\rm kin}_{\rm SM}}{\mathcal{P}^{\rm kin}_{\rm SM} + \mathcal{P}^{\rm kin}_{J^P}}$$

C. isolate interference of BSM and SM

$$\mathcal{D}_{\rm int} = \frac{\mathcal{P}^{\rm int}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{\rm SM} + \mathcal{P}^{\rm kin}_{J^P}}$$





The measurement

H→ Z(γ*)Z*(γ*) → 4l, Matrix Element likelihood Analysis (MELA)

A. suppress background

$$\mathcal{D}_{\rm bkg} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + c \times \mathcal{P}_{\rm q\bar{q}ZZ}}$$

B. separate BSM vs SM

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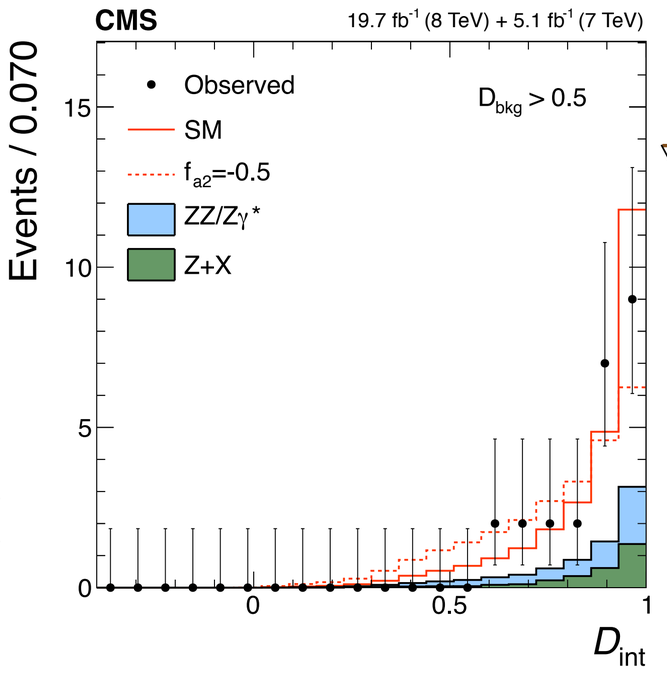
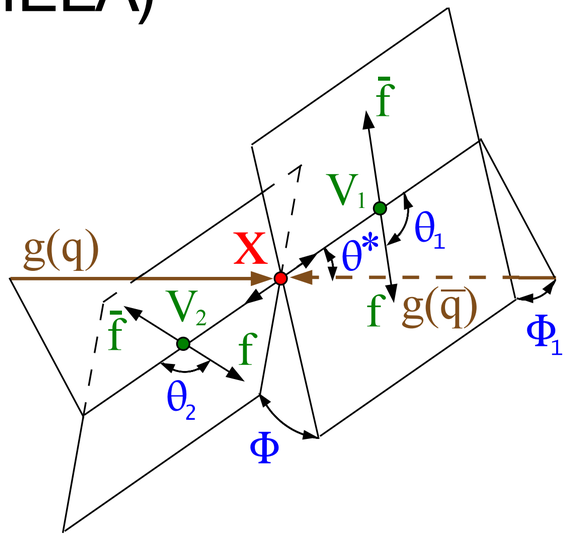
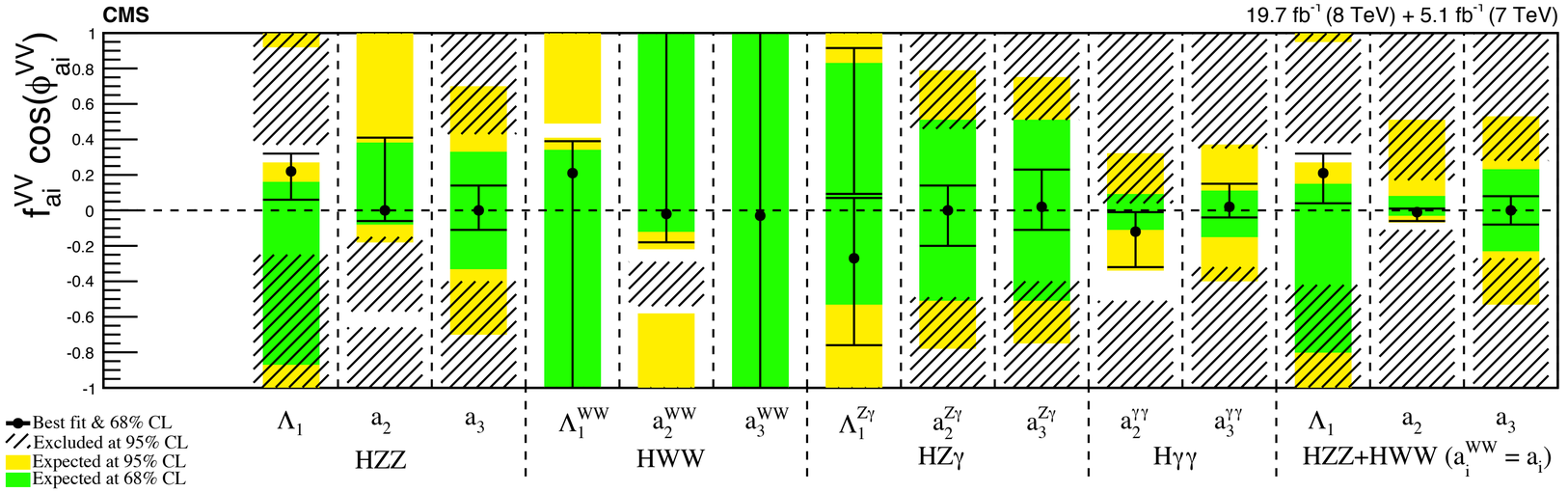




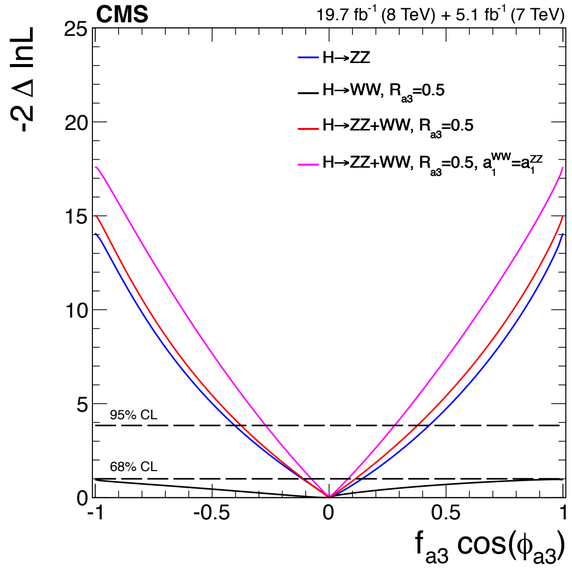
PRD 92 (2015) 012004

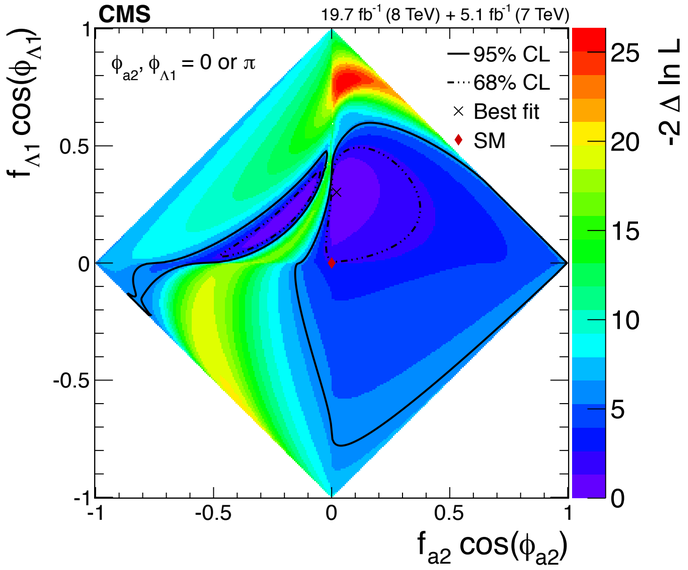
Anomalous coupling results at Run 1

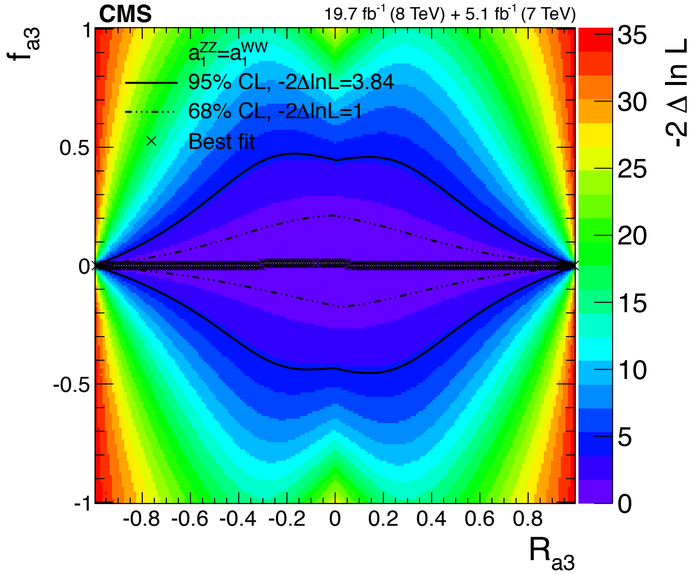


0^- and 0_h^+ excluded > 95% CL

CP mixture fa3 [-0.27, 0.28]
a3/a1 [-1.54, 1.57]



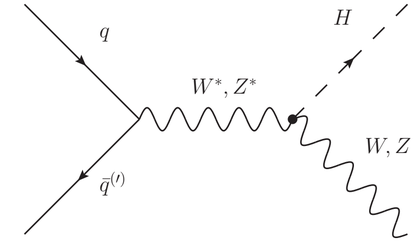


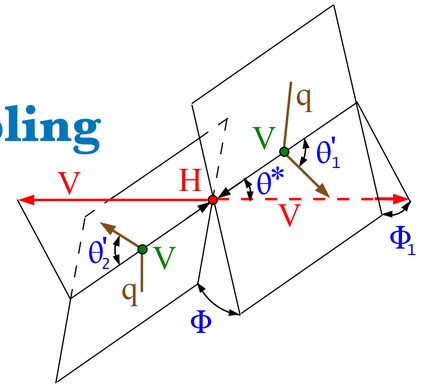


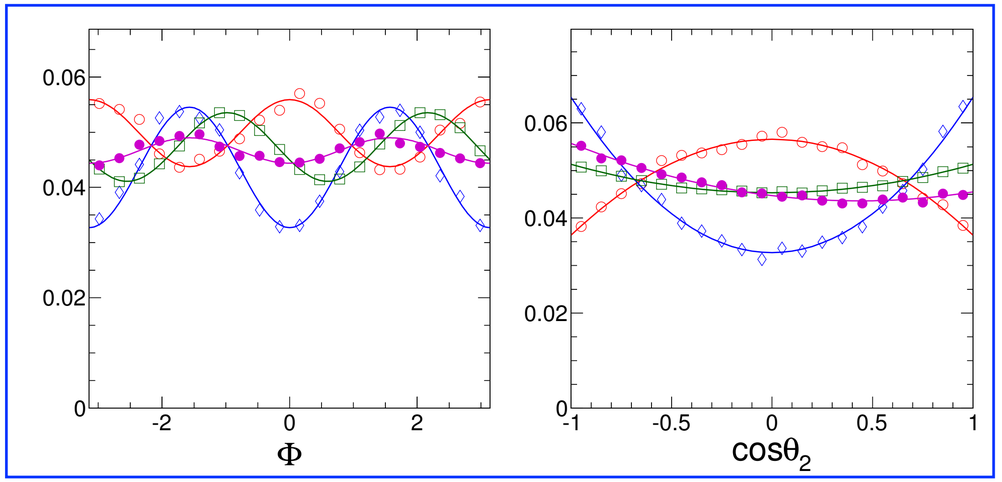
Anomalous coupling at Run2

VBF and VH modes

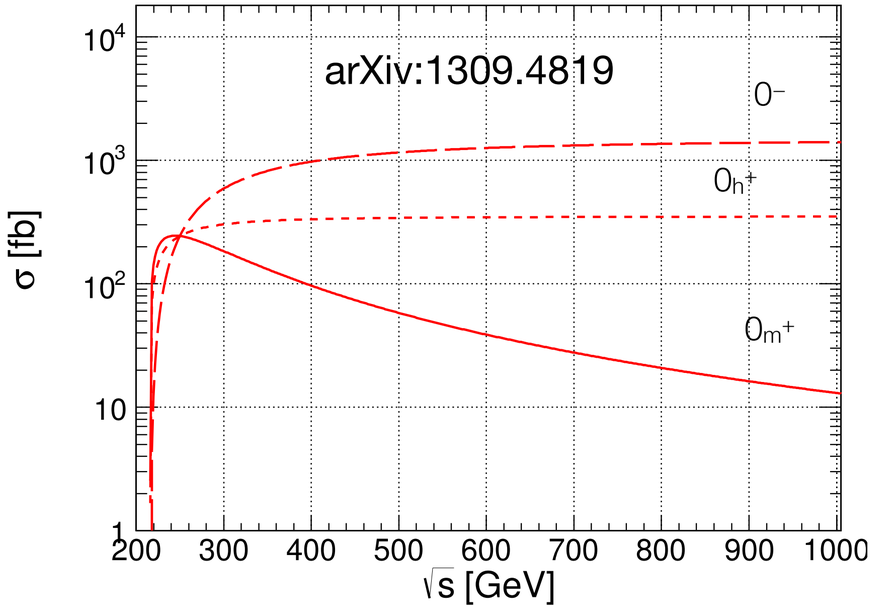
- **decay and production HVV coupling**
- **higher q^2 => better sensitivity**

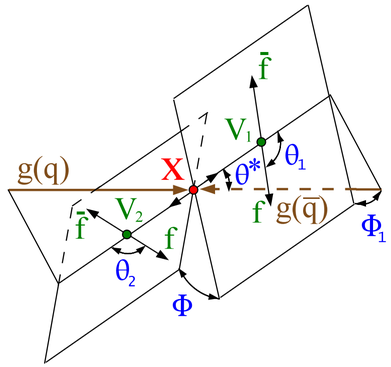


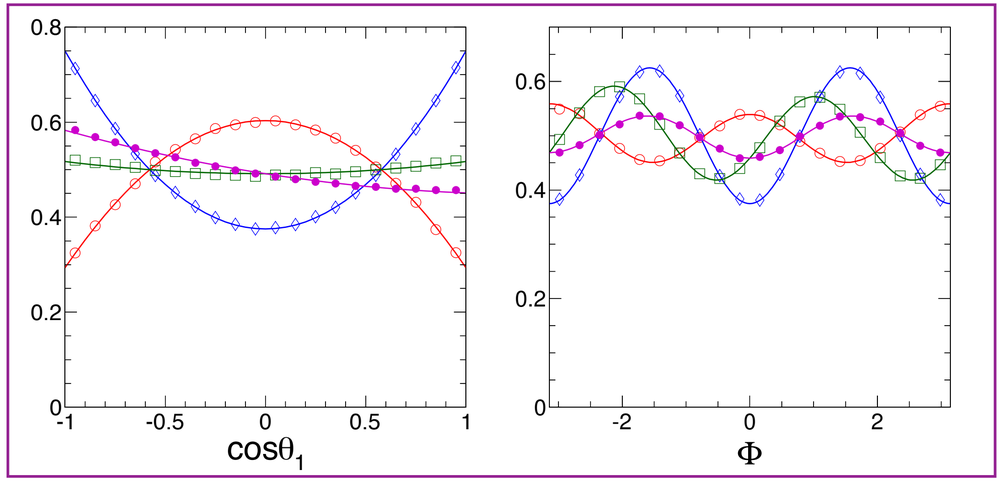




production vertex





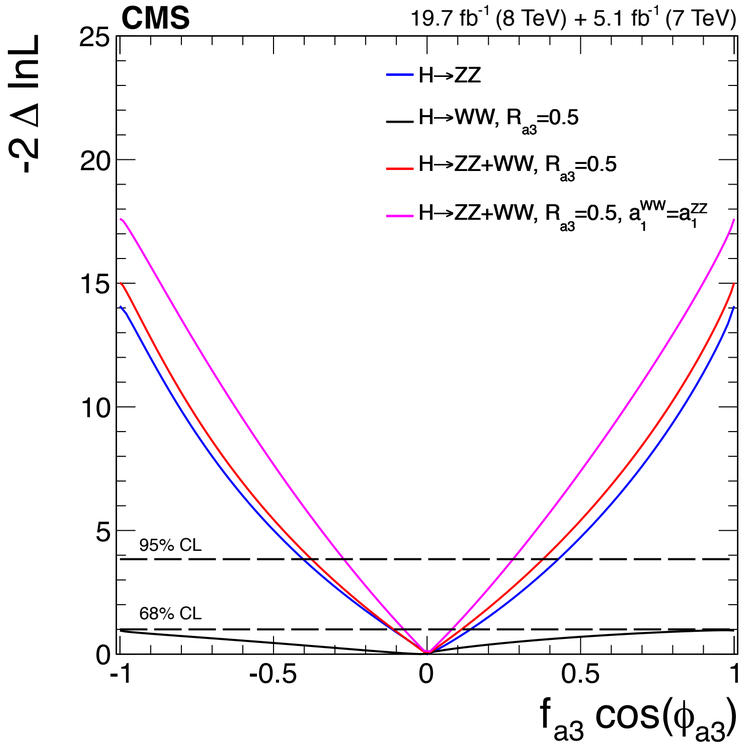


decay vertex

Anomalous coupling at Run2

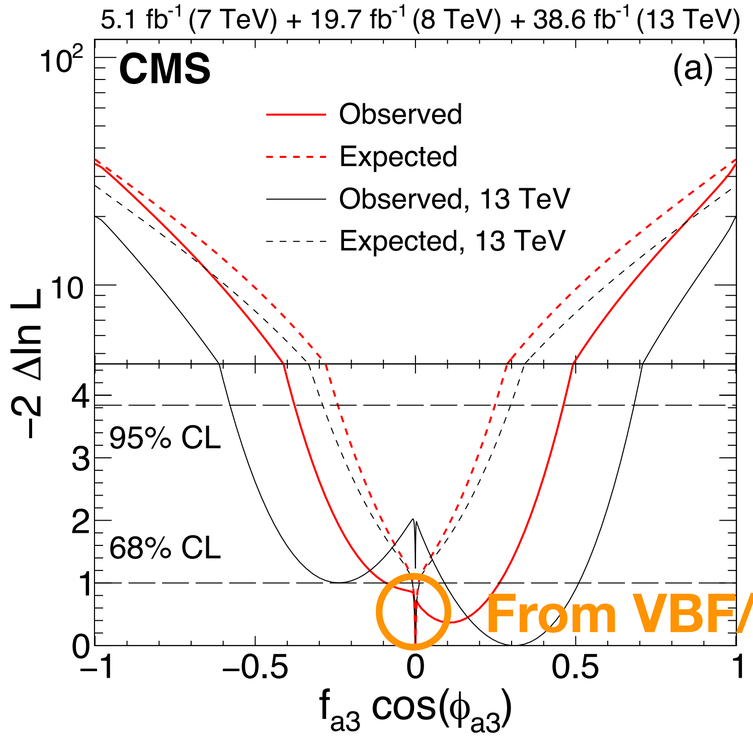
Phys. Lett. B 775 (2017) 1

Run1



HZZ+HWW Expected:
fa3: 0 ± 0.23

Run1 + Run2



From VBF/VH production

Expected:
fa3: 0 ± 0.01

Mass measurement

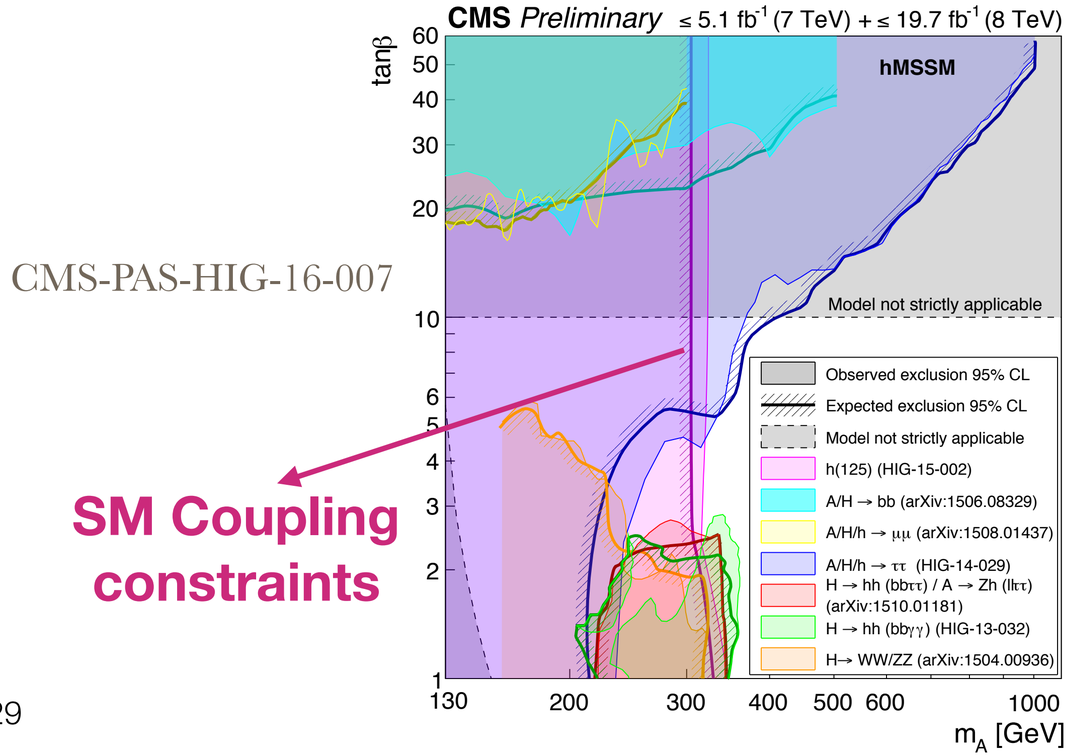
Why precise mass measurement?

- SM self-consistency check, m_H contribute to m_W
- determine the EW vacuum stability
- affect the coupling uncertainties
  - 100 MeV ΔmH => 0.9% ΔBR
  - BSM correction to the couplings might be subtle

arXiv:1310.8361v2

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

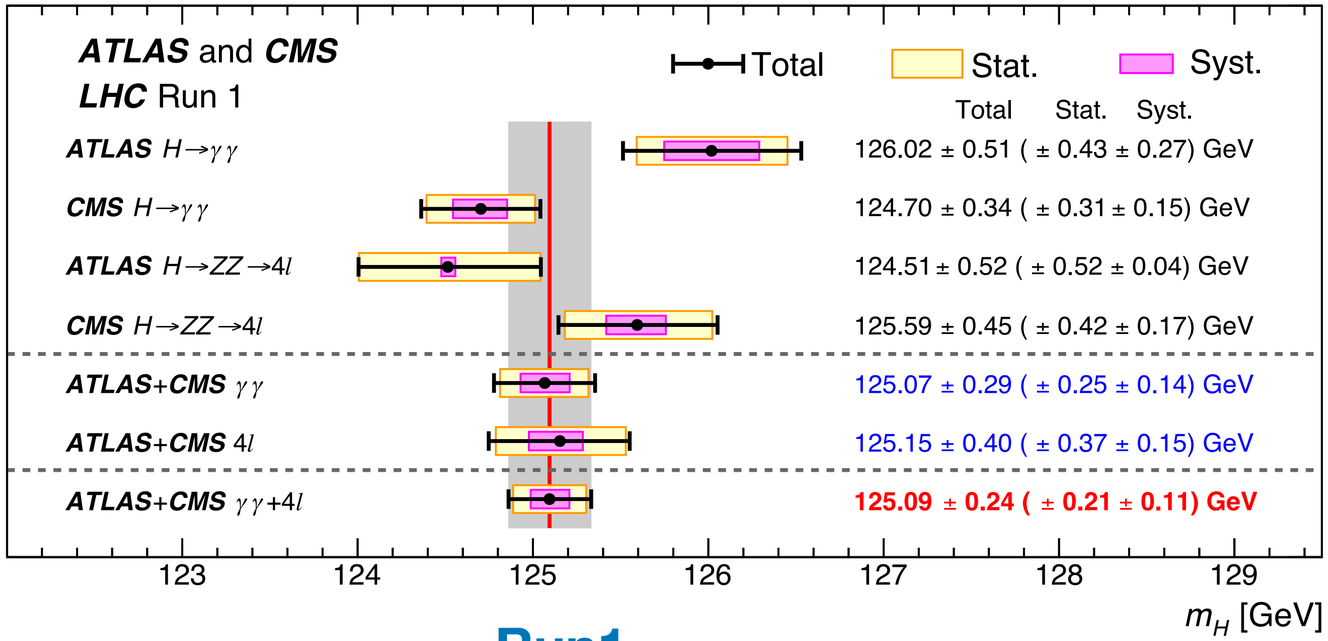
CMS-PAS-HIG-16-007



SM Coupling constraints

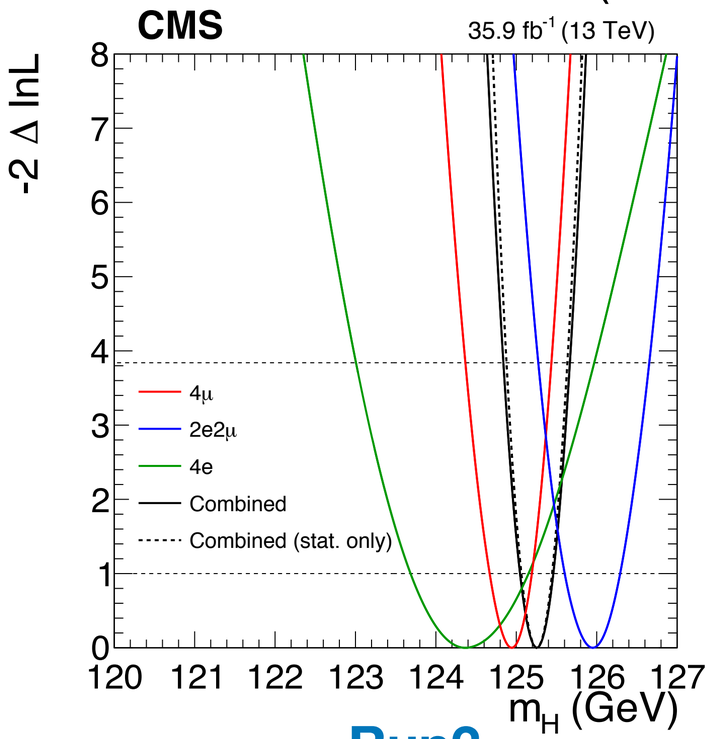
Mass measurement

PRL 114 (2015) 191803



Run1
CMS + ATLAS, γγ+4l

JHEP 11 (2017) 047



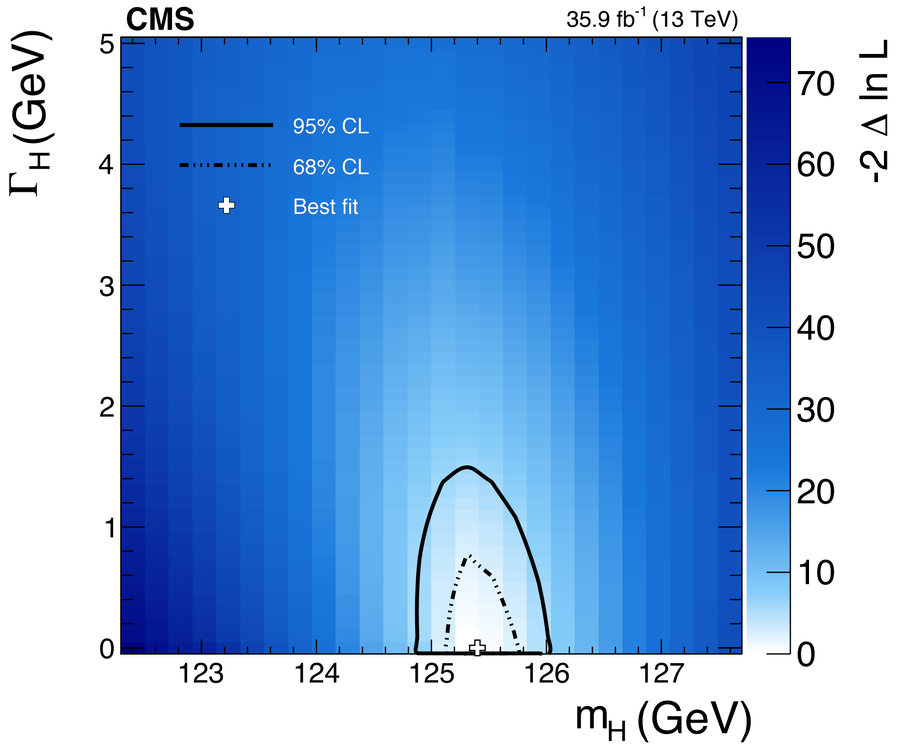
Run2
CMS 4l

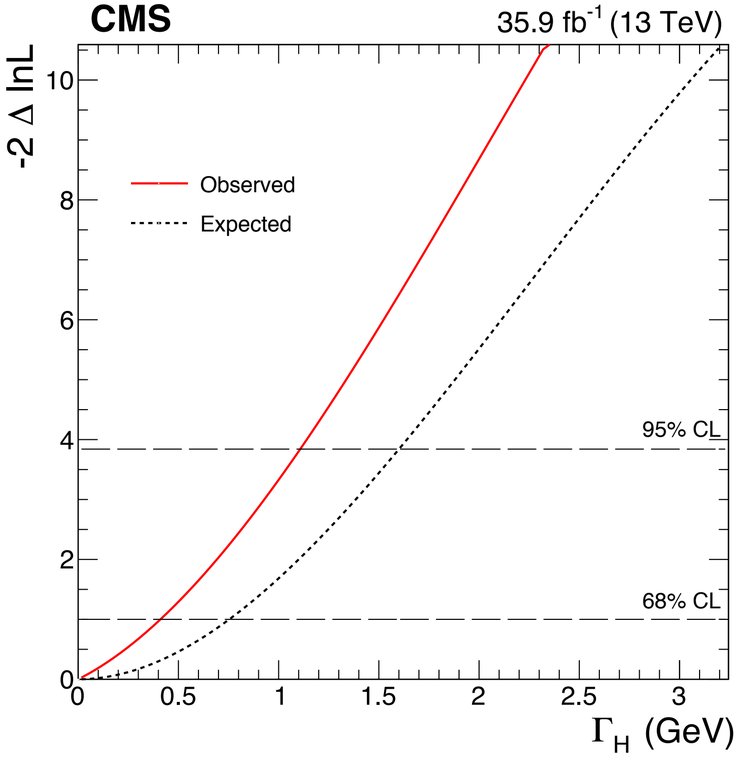
$\mathbf{m_H = 125.26 \pm 0.20(stat.) \pm 0.08(sys.)\ GeV}$

Most precise mass measurement so far

On-shell width measurement

JHEP 11 (2017) 047





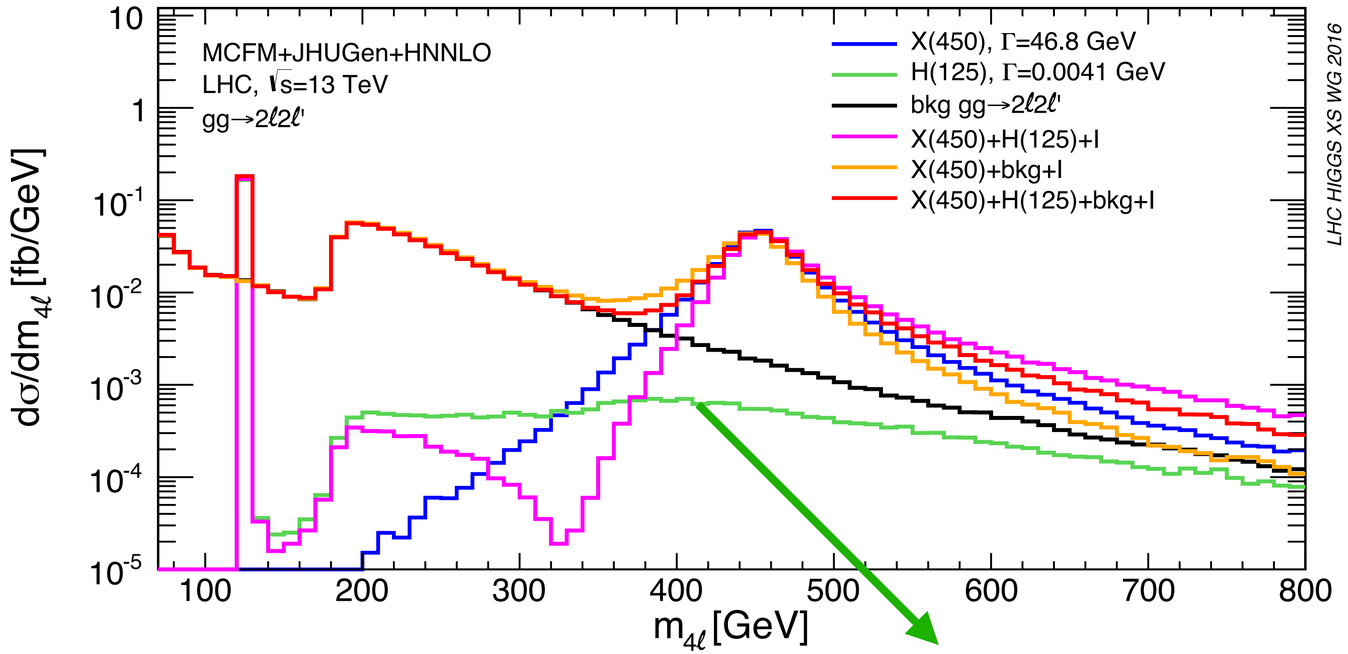
$\Gamma_H < 1.1$ GeV

Off-shell width measurement: Run 1

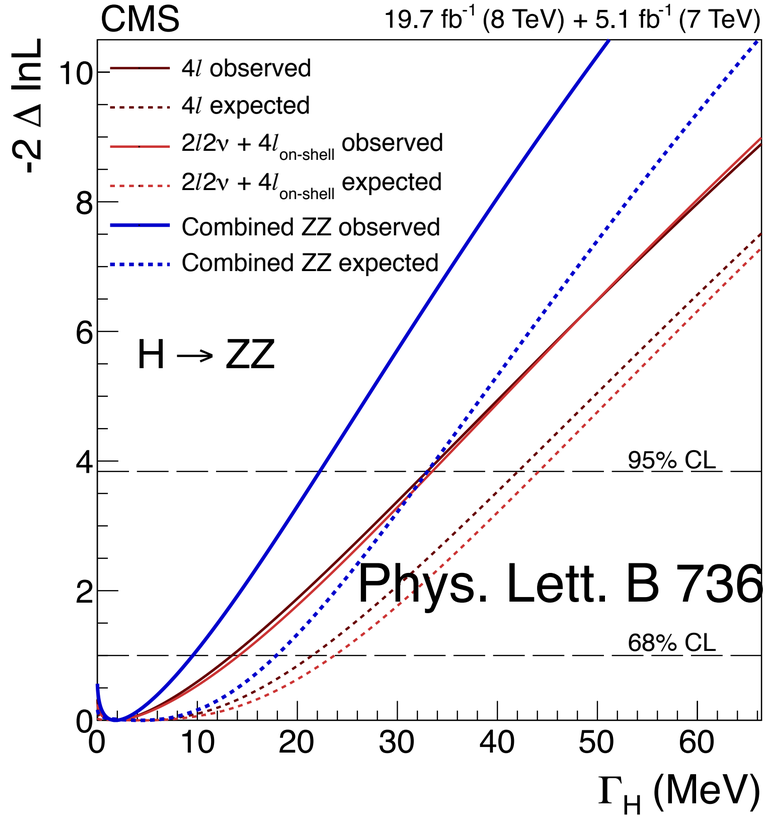
SM prediction: 4.15 MeV, extremely small compared to the mass ~ 125 GeV

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

$$\sigma_{\text{off-shell}} / \sigma_{\text{on-shell}} \sim \Gamma_H$$



Off-shell tail

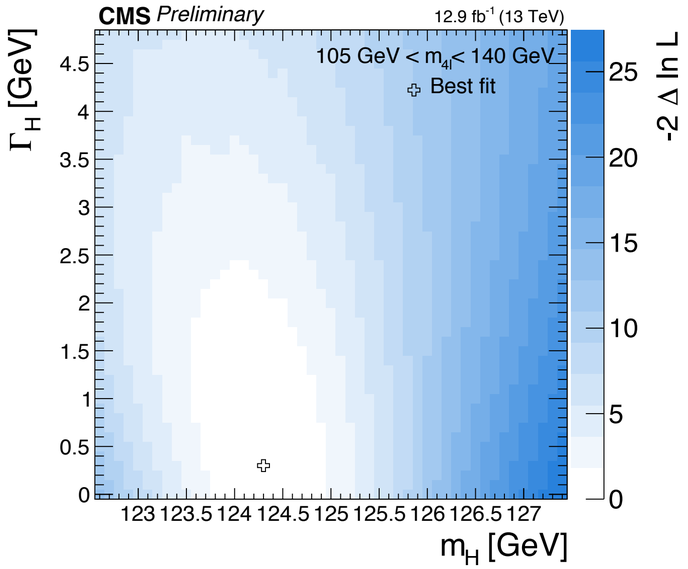


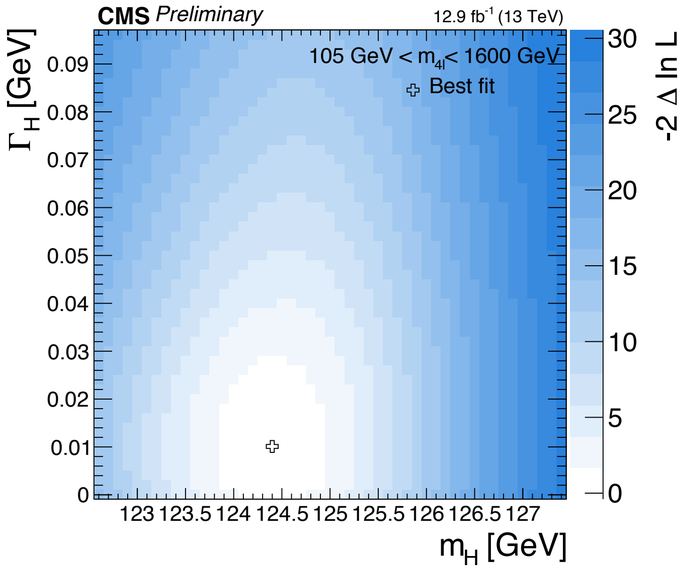
Phys. Lett. B 736 (2014) 64

$\Gamma_H < 22$ MeV at 95% CL

Mass & Width: Run2

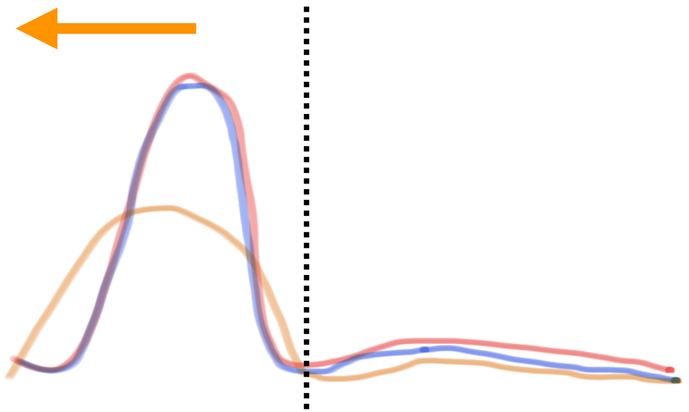
CMS-PAS-16-033



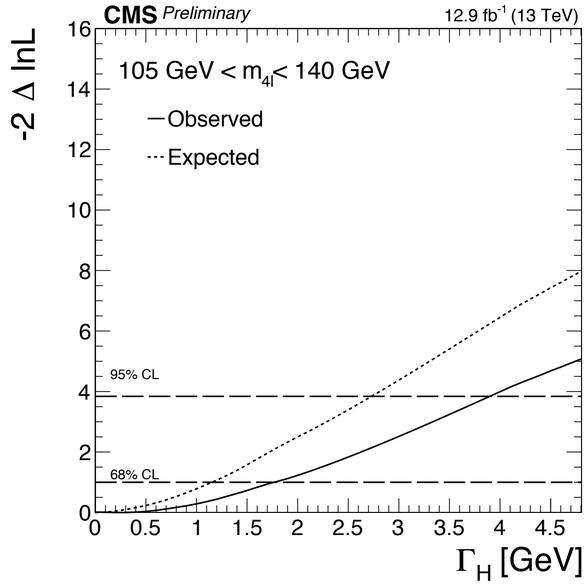


Measure mass and width at the same time

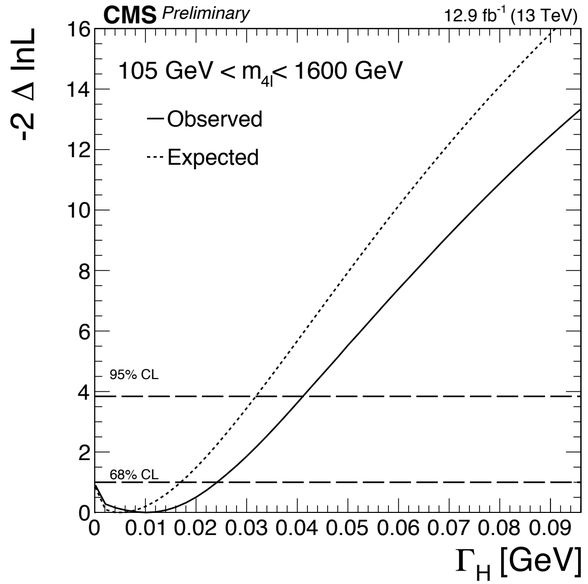
Describe mass shape in full range



no approximation on-shell/off-shell interference with bkg included

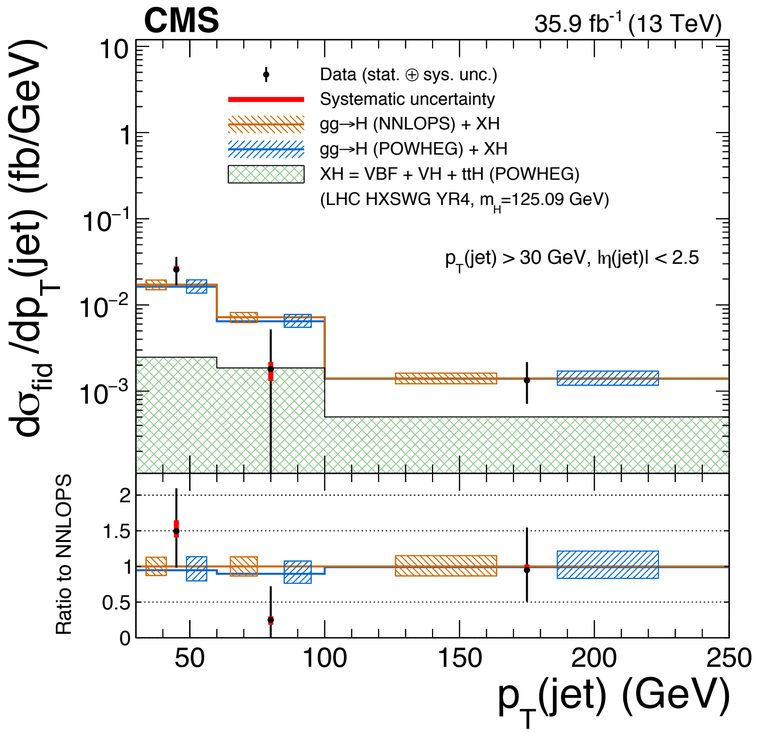


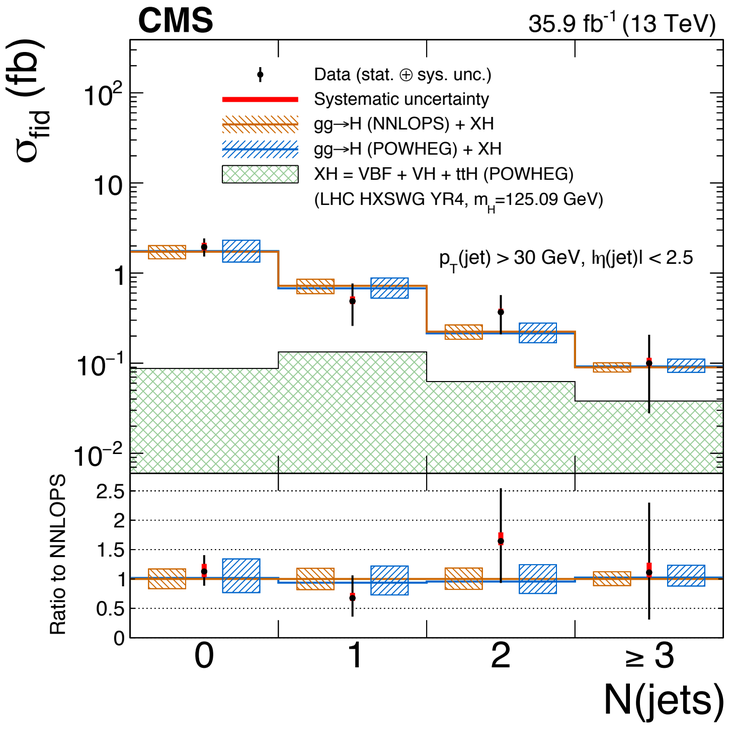
Γ < 3.9 GeV

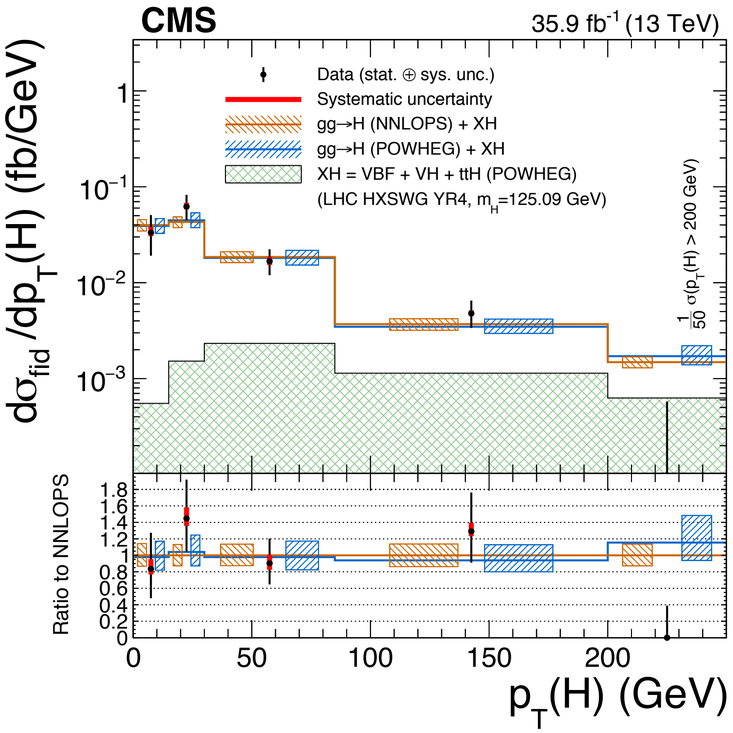


Γ < 41 MeV

Any other deviation?



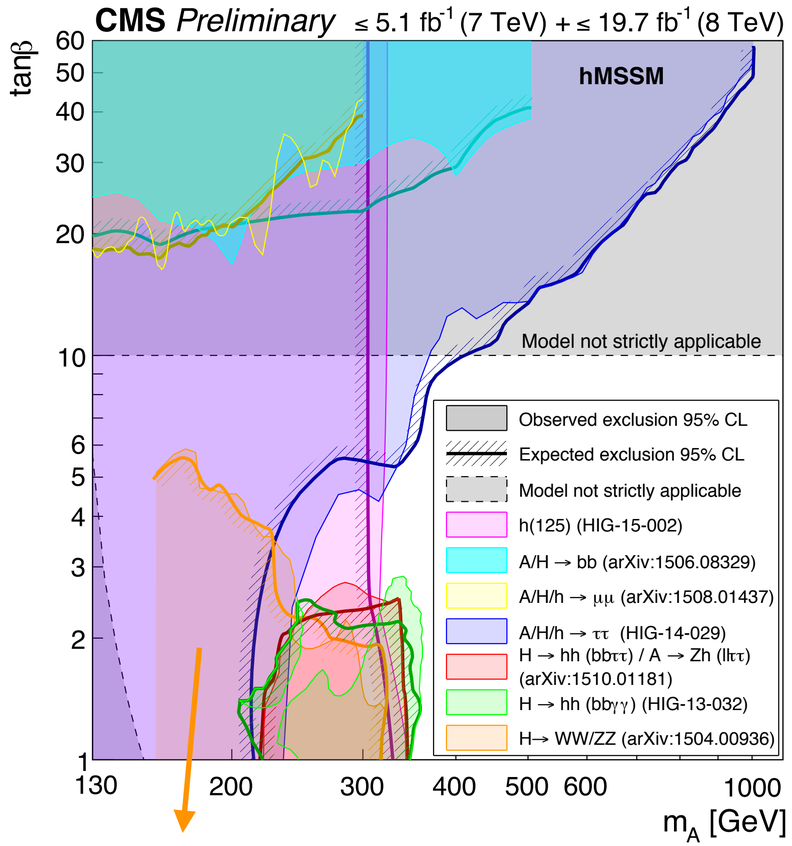




Direct search for BSM?

arXiv:1804.01939
submitted to JHEP

Search for additional Higgs



Direct search in H→ ZZ/WW

H→ ZZ, 3 final states

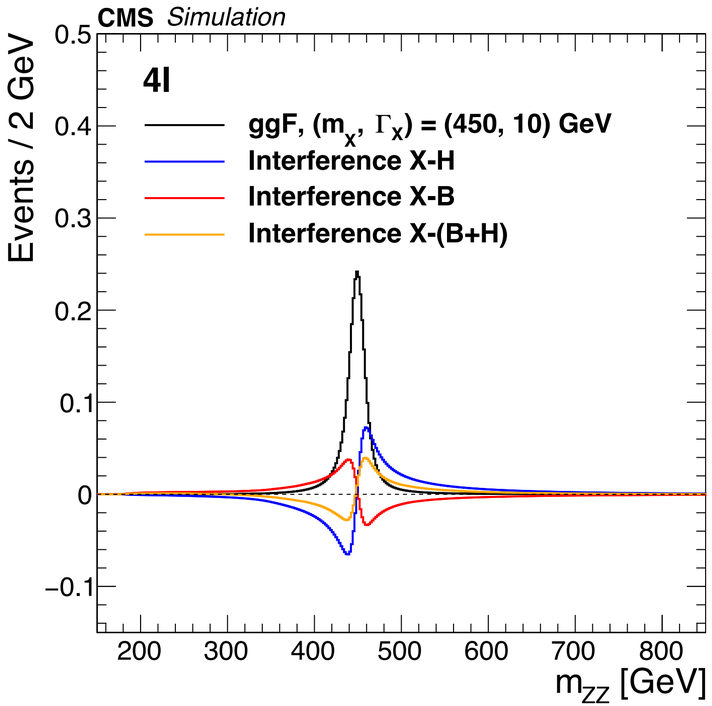
	4l	2l2v	2l2q
BR (%)	0.453	2.692	9.422
Resolution (%)	1-3	-	3-7
Mass range [GeV]	130-3000	200-3000	550-3000

Search for ggH and VBF production

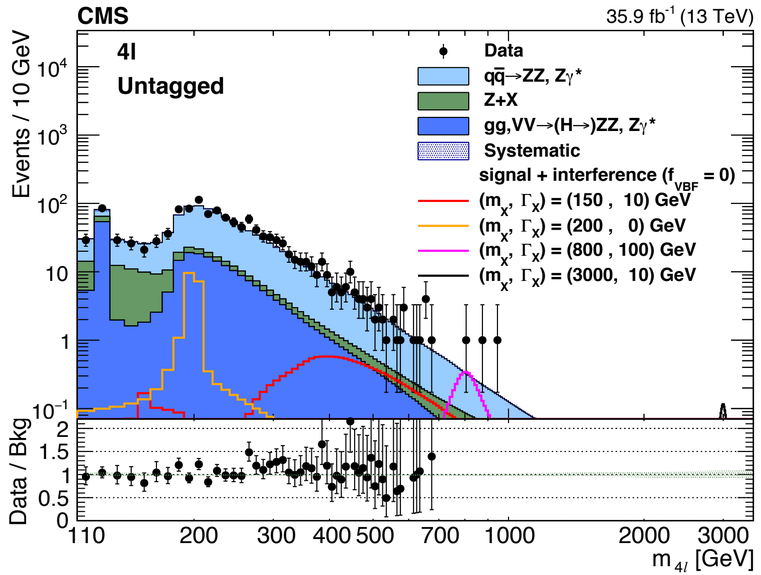
arXiv:1804.01939
submitted to JHEP

Search for additional Higgs

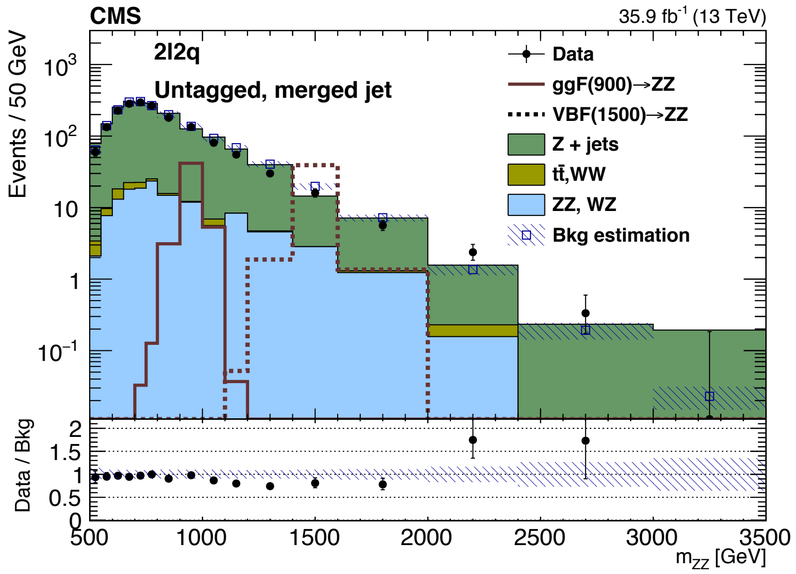
Fully analytical description for any (m_H, Γ_H) with the interference in 4l and 2l2q



H, h, B interference



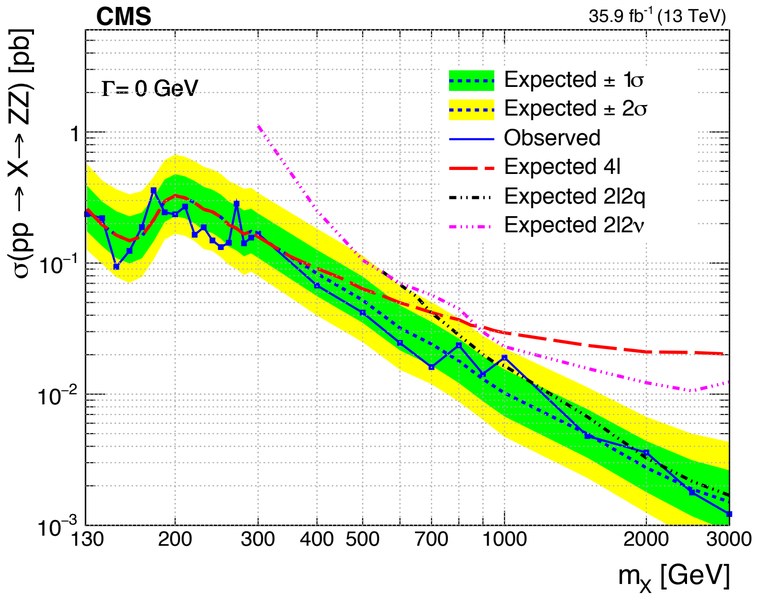
4l

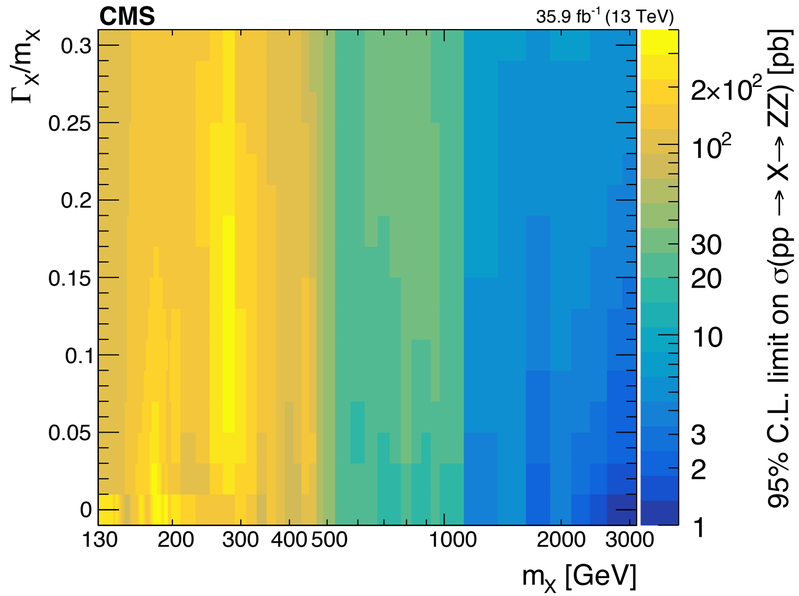


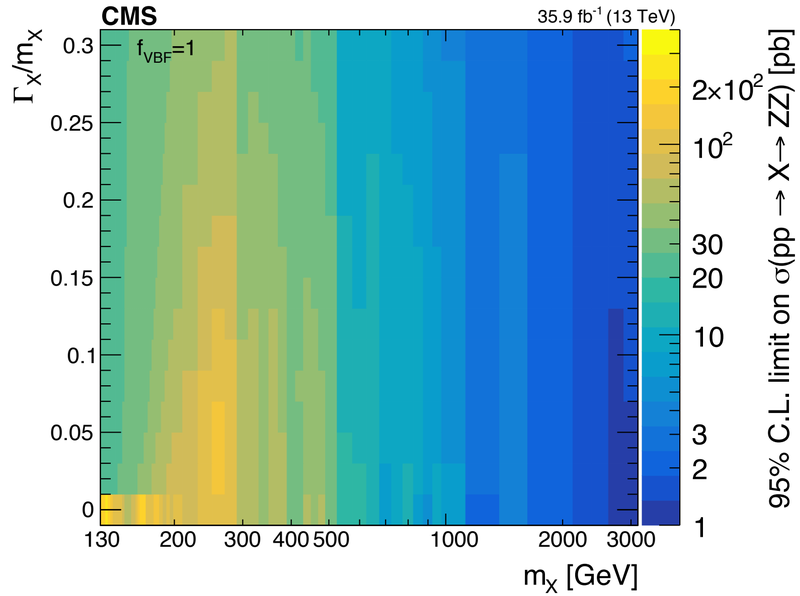
2l2q

arXiv:1804.01939
submitted to JHEP

Search for additional Higgs







No significant excess observed

ggF+VBF

VBF

Excluded xsec in the grid of

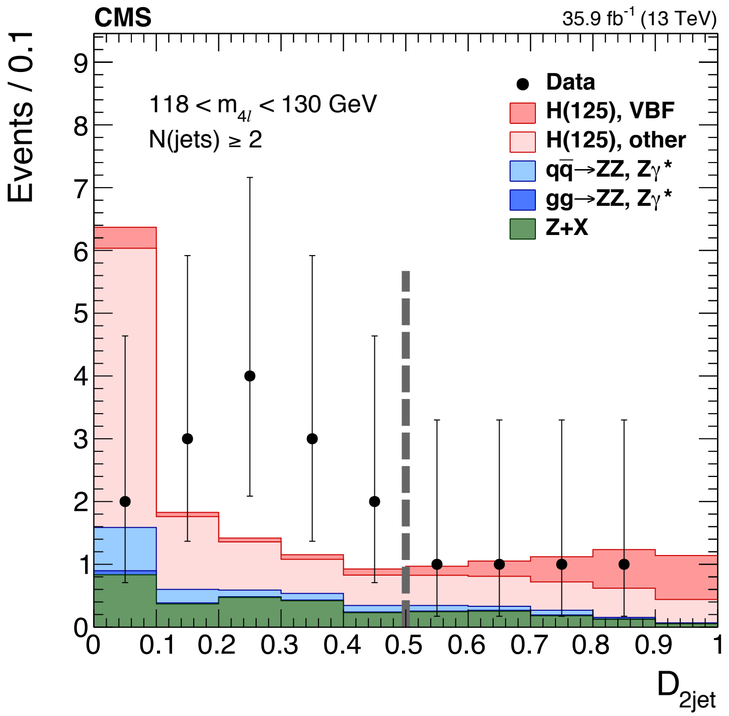
- **m_H (130 — 3000 GeV) , Γ_H (0—30%)**

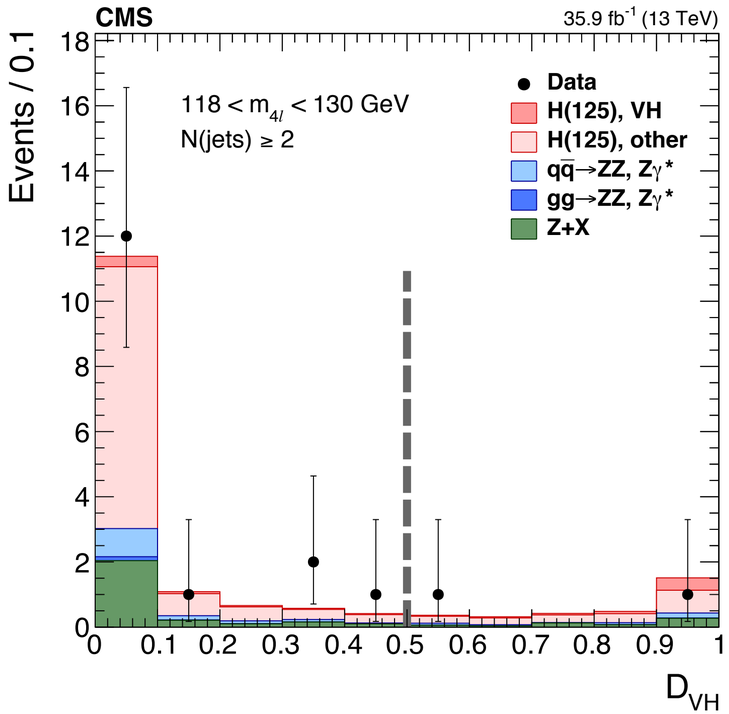
Model independent inputs for many BSM theories

Summary

- The ZZ final state provides a long list to check things about the Higgs boson
  - Existence? ✓
  - SM like? ✓
  - Precisely SM???
    - Couplings of decay and productions?
    - Anomalously couplings ?
    - Mass?
    - Width?
    - Differential distributions?
  - BSM Higgs search?
- We are in an era of precision measurement, and the list is expanding
  - Off-shell differential..
- More data (3000 fb^{-1}) and more ideas waiting for us! So far only analyzed ~70 fb^{-1}

Additional slides


CMS
35.9 fb-1 (13 TeV)
Events / 0.1
118 < m4l < 130 GeV
N(jets) ≥ 2
Data
H(125), VBF
H(125), other
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
D2jet

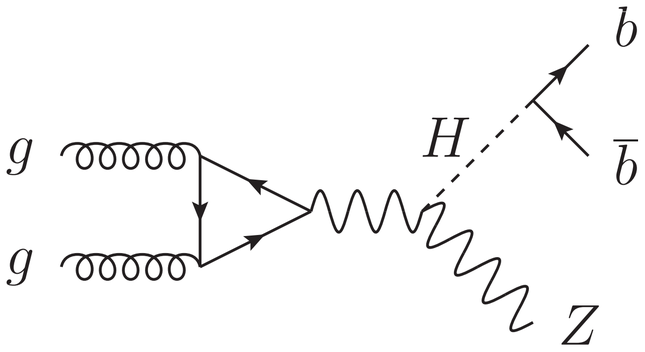

CMS
35.9 fb-1 (13 TeV)
Events / 0.1
118 < m4l < 130 GeV
N(jets) ≥ 2
Data
H(125), VH
H(125), other
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
DVH

Anomalous coupling with production

VH(bb) to measure HVV (V=Z,W) coupling

sensitive to small anomalous couplings

Phys. Lett. B 759 (2016) 672



$f_{a3} < 0.0034$ at 95% combined with H→ZZ/WW
assuming μ_t/μ_b= SM
$f_{a3} < 0.28$ at 95% using H→ ZZ/WW