Higgs results in ZZ final state with the CMS experiment

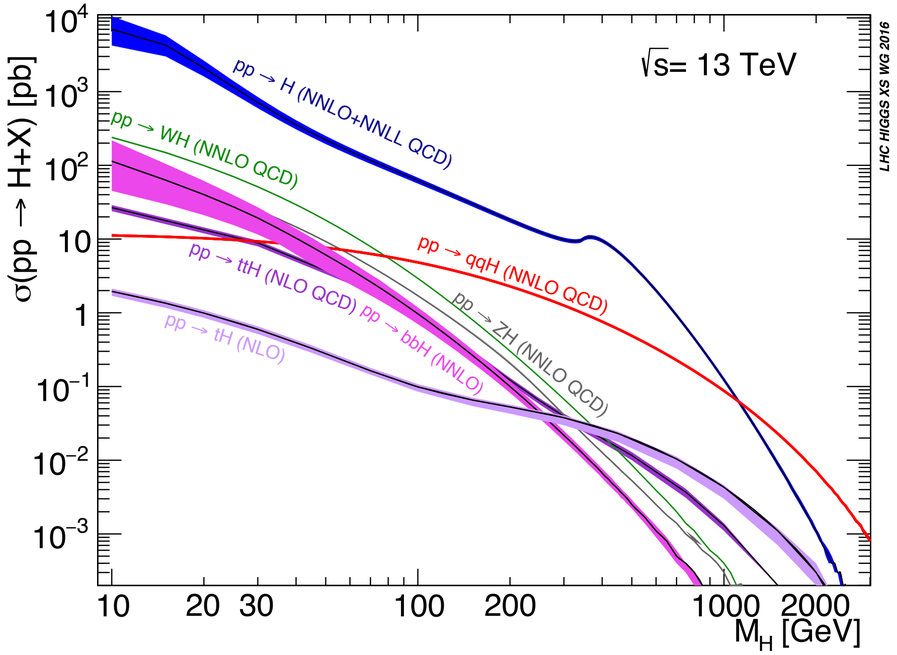
肖朦 (Johns Hopkins University)

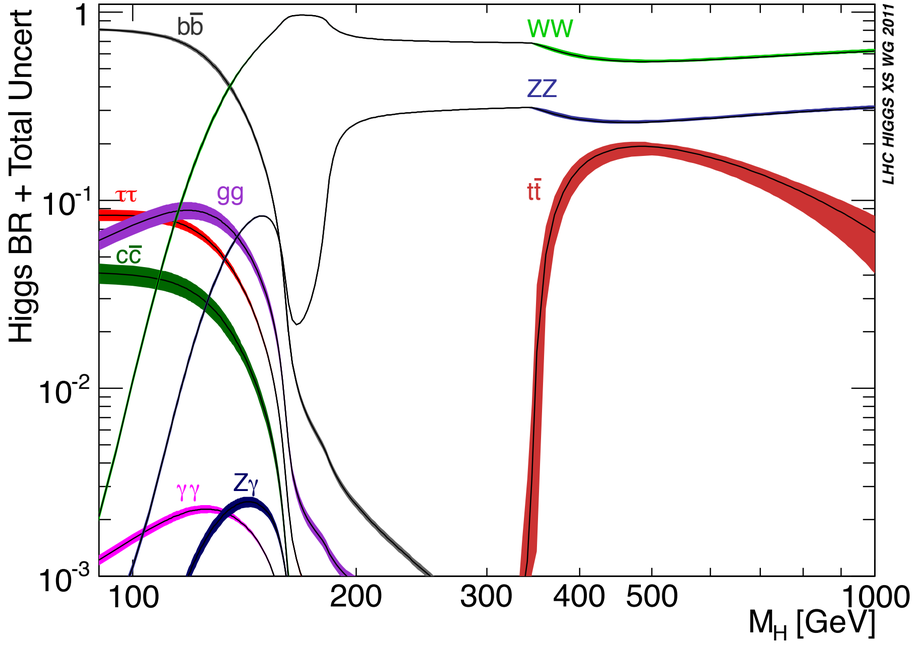
Page 1?

LHC, CMS

SM

Higgs boson





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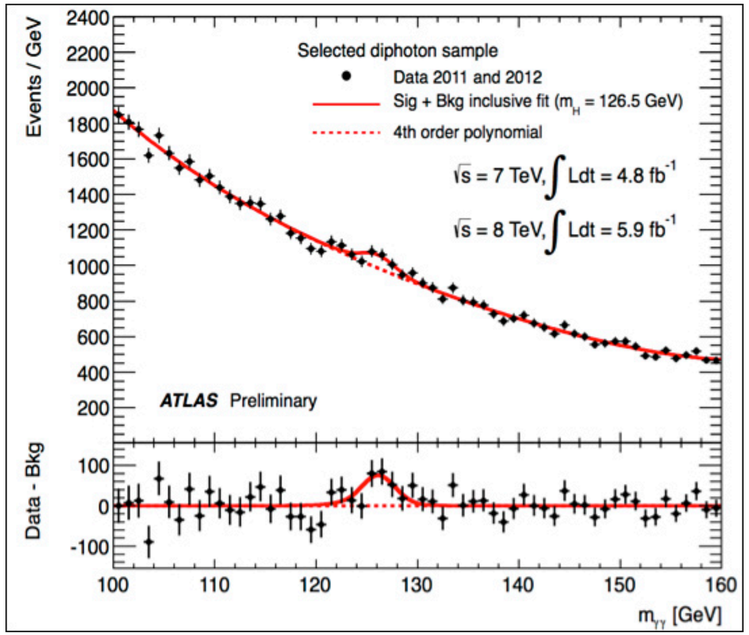
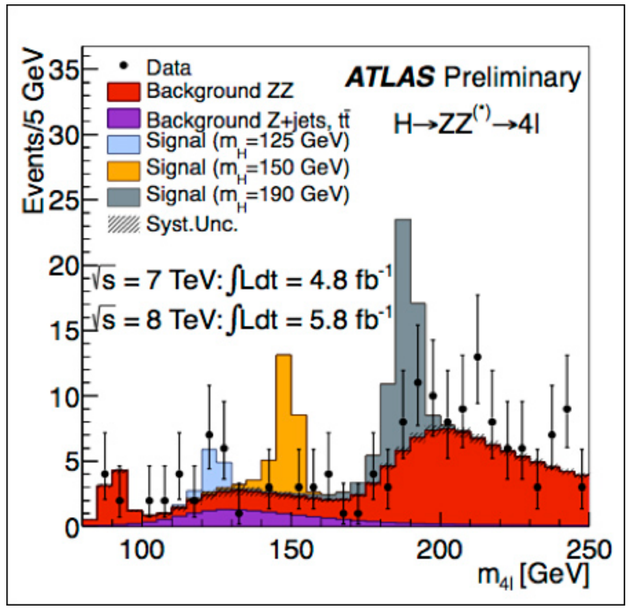
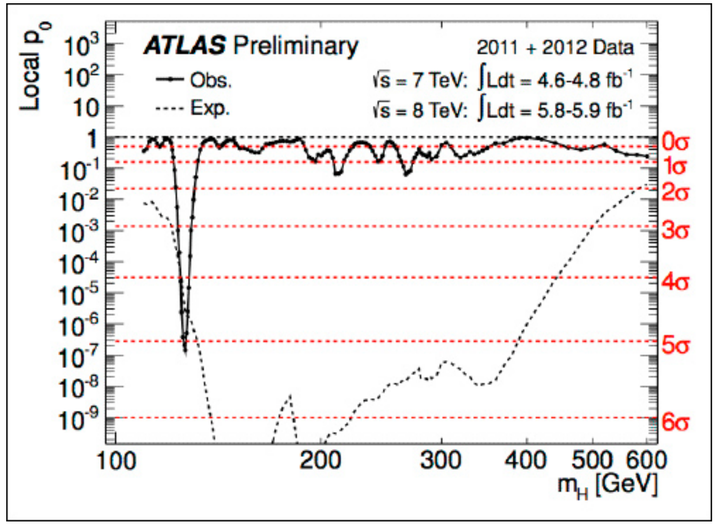
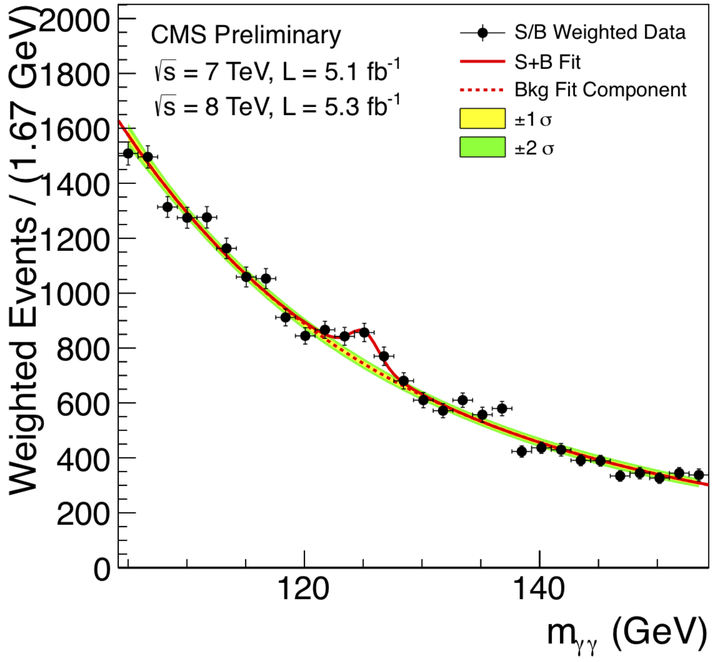
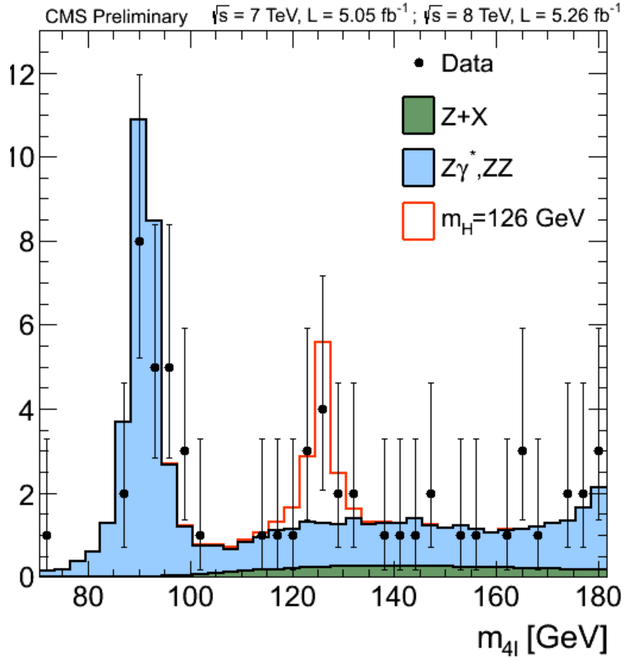
From July 4th, 2012 seminar

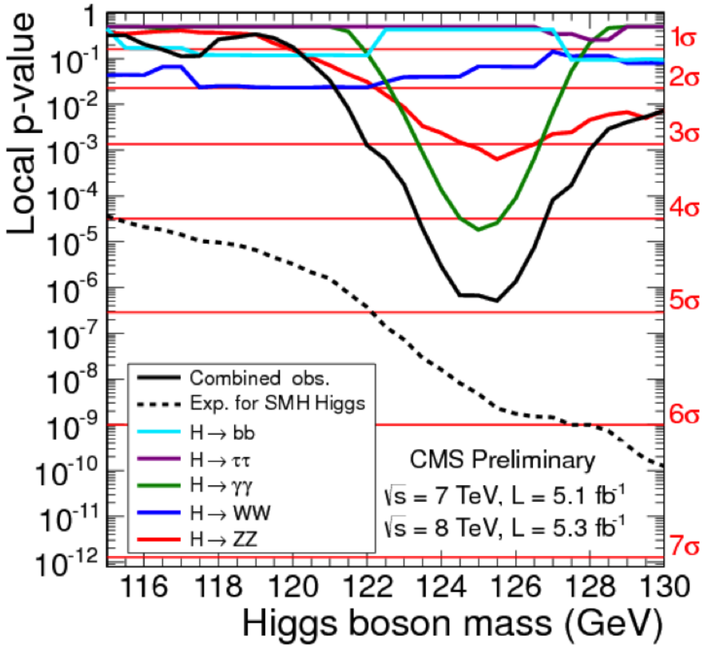












From Peskin, Higgs Hunting, 2012

Our understanding of this boson will advance in stages.

I expect 3 stages:

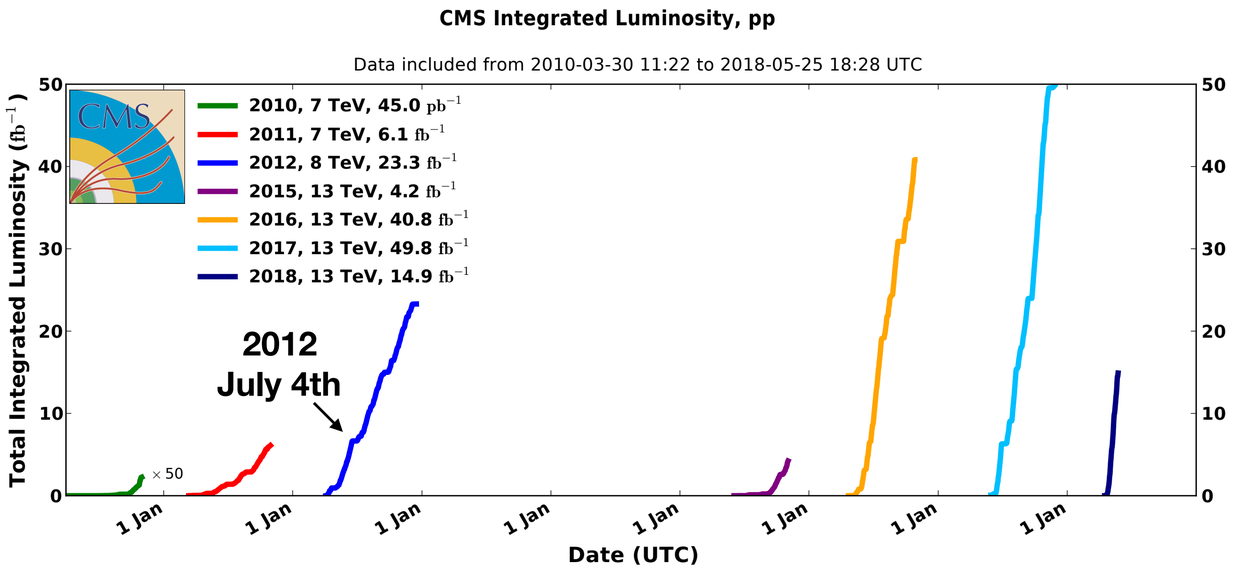
1. Are the major decay modes present ?

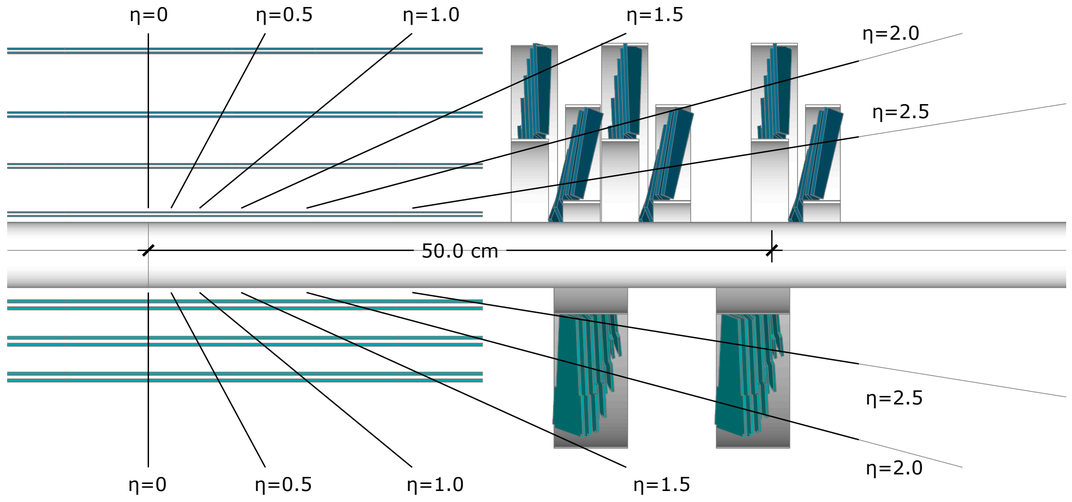
2. Standard-Model-like Higgs boson, or not ?

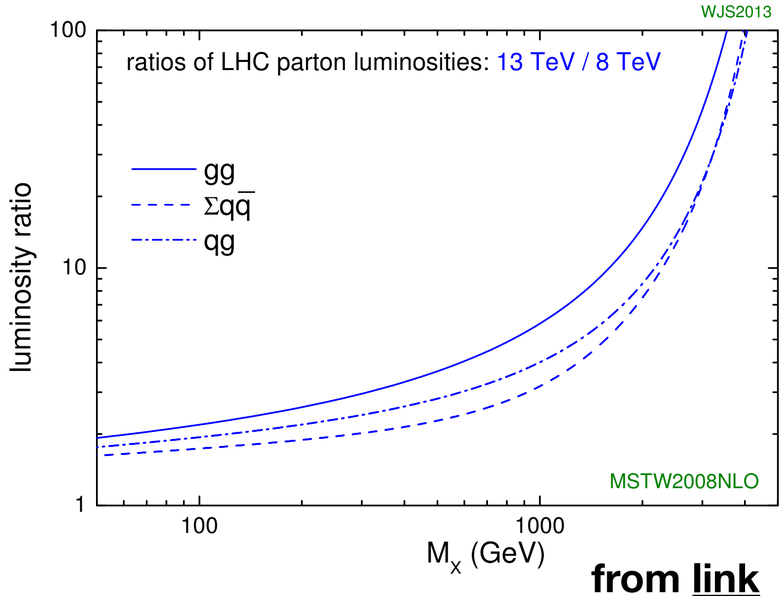
3. Are there small deviations from the Standard Model ?

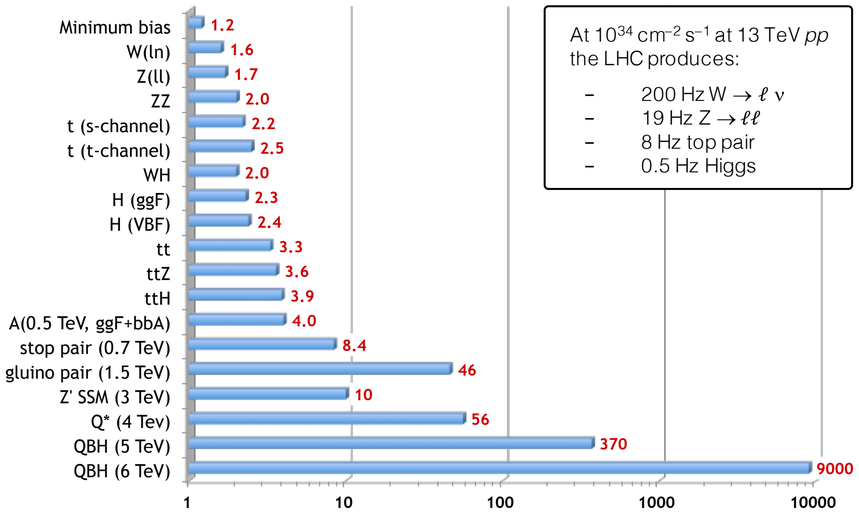
6 years later…

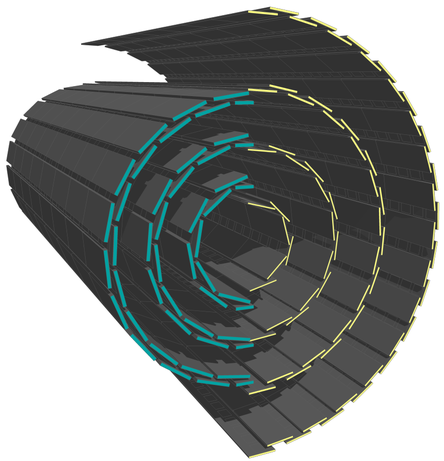
2012-2018











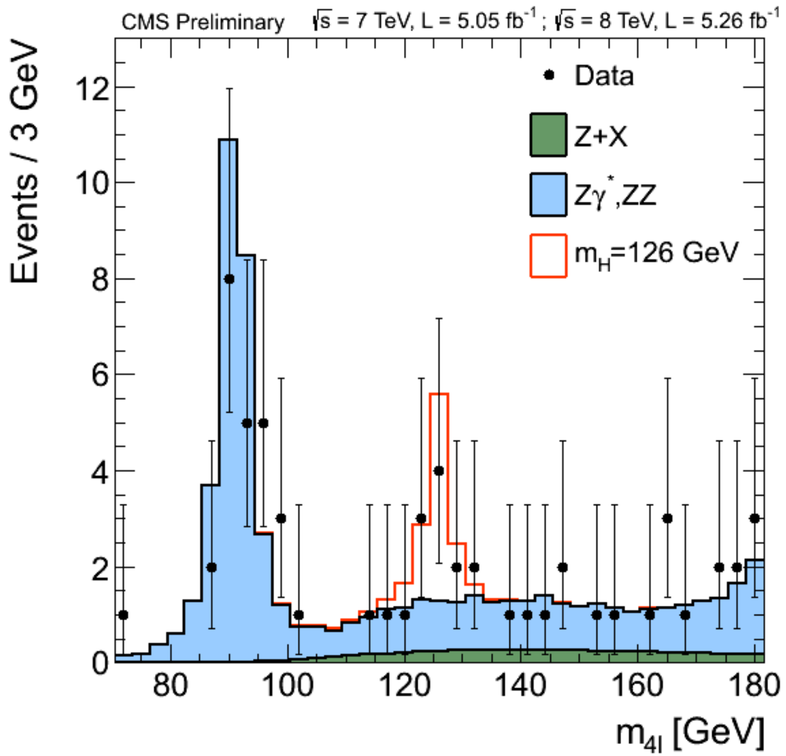
from link

Are the major decay/production modes present?

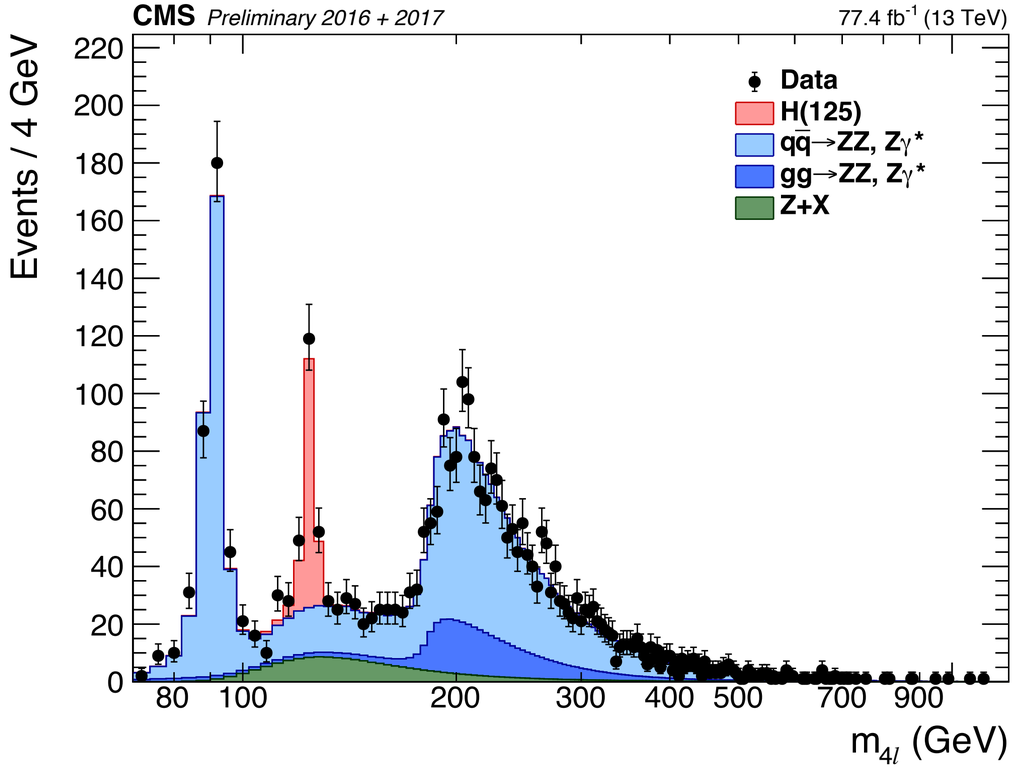
The ZZ(*)→ 4l decay mode

CMS-PAS-HIG-18-001

up to July 2012

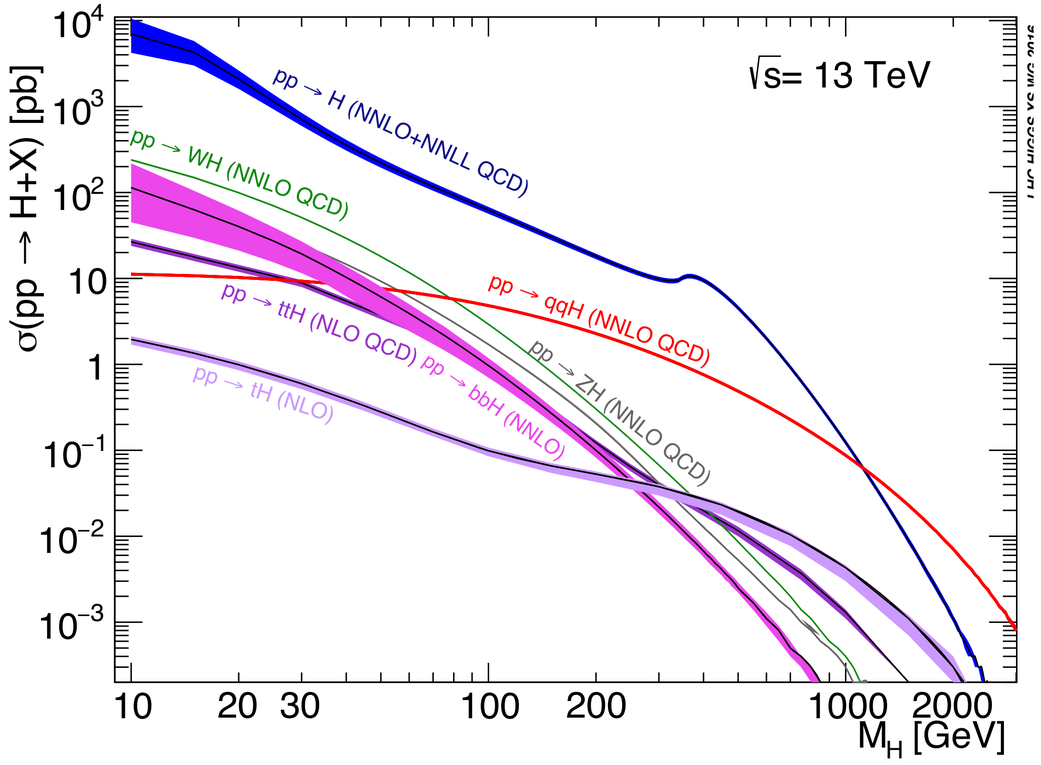


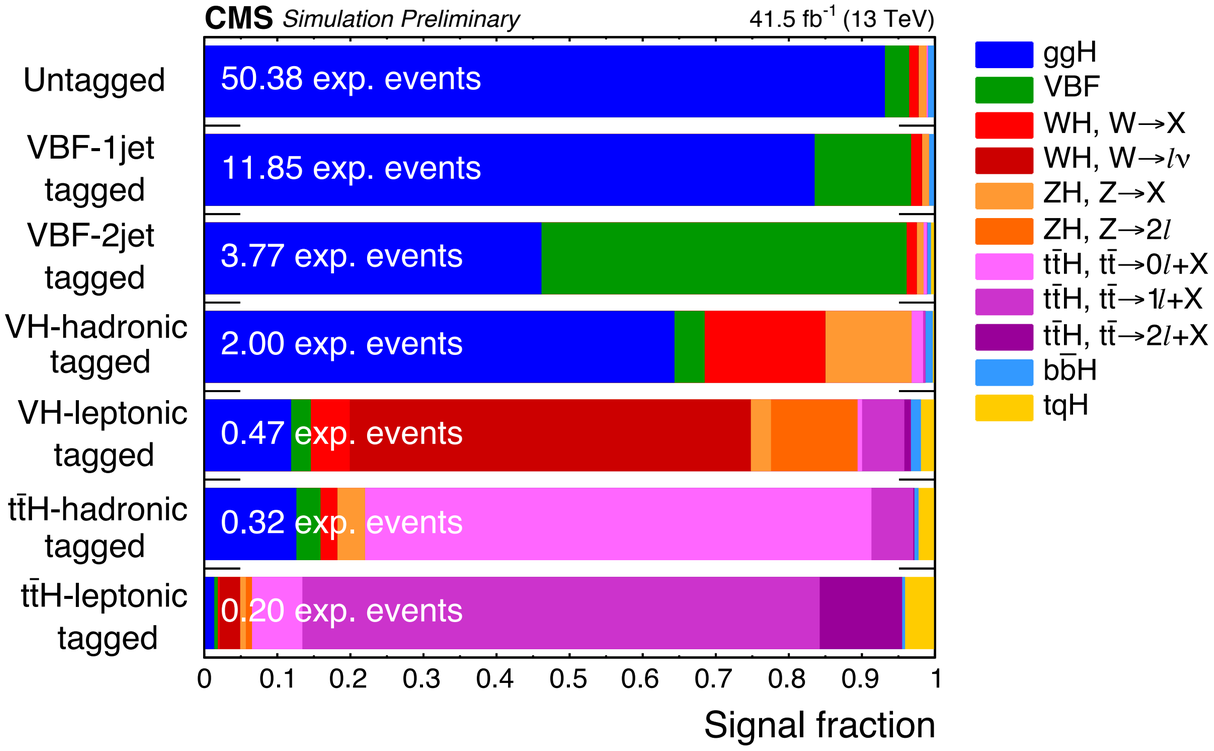
2016+2017



Far beyond 10σ

The production modes

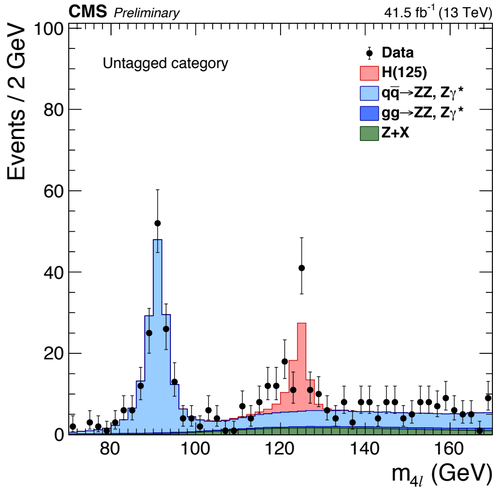




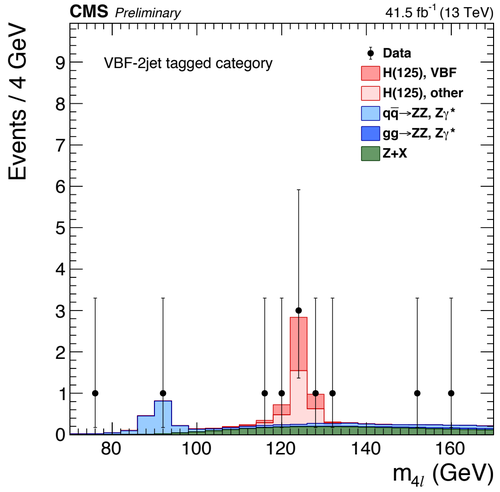
The production modes

CMS-PAS-HIG-18-001

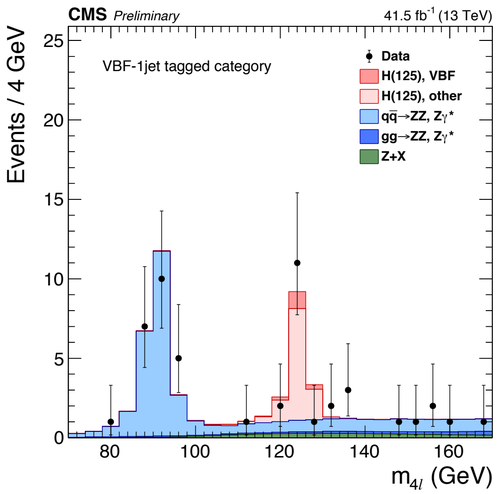
Untagged

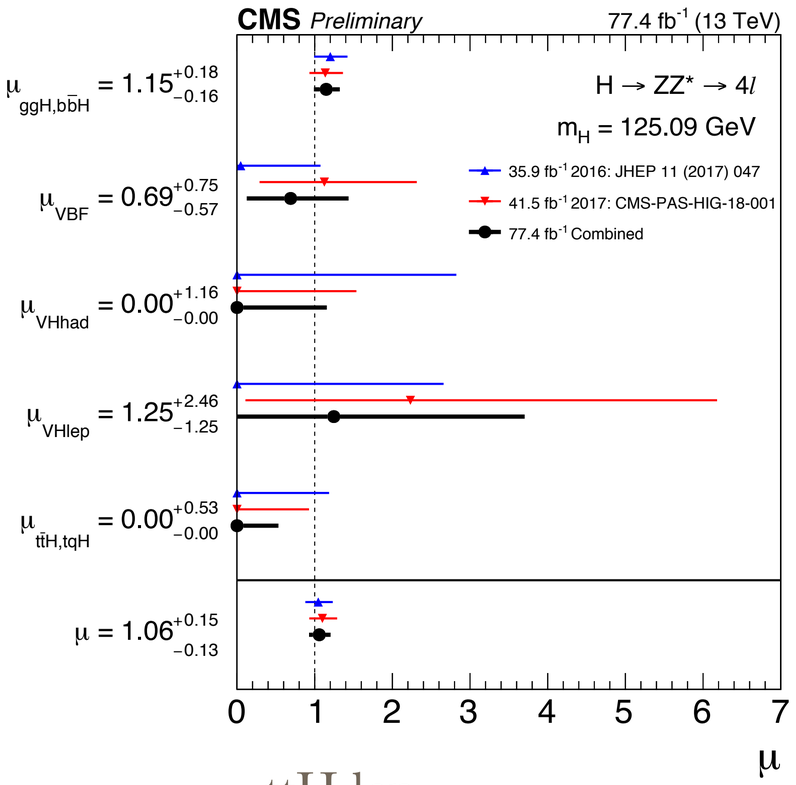


VBF 2jets

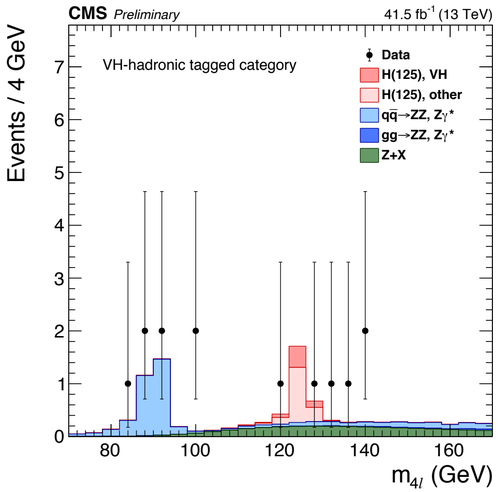


VBF 1jet

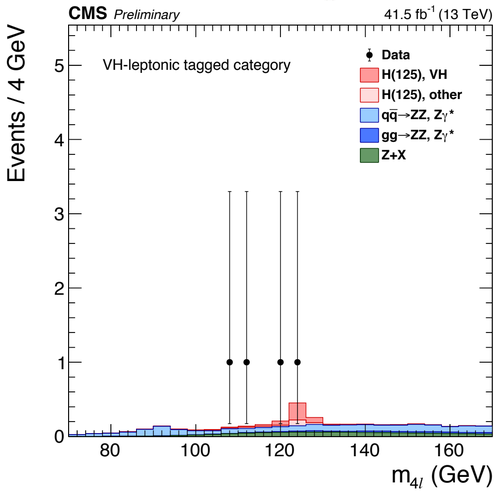




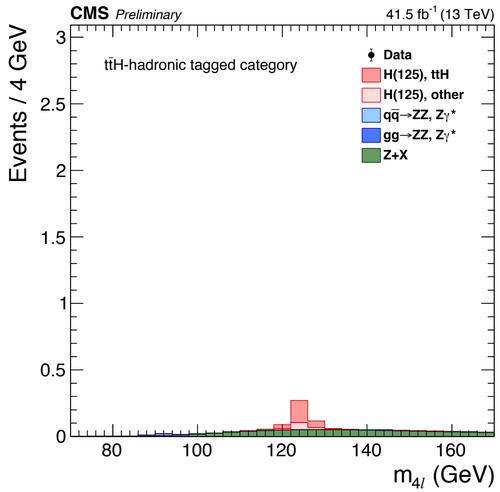
VH Had



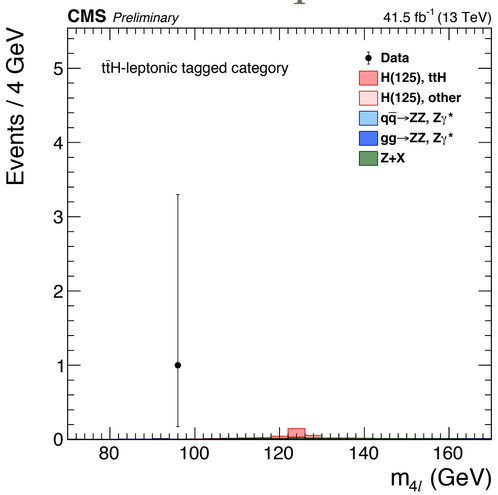
VH lep



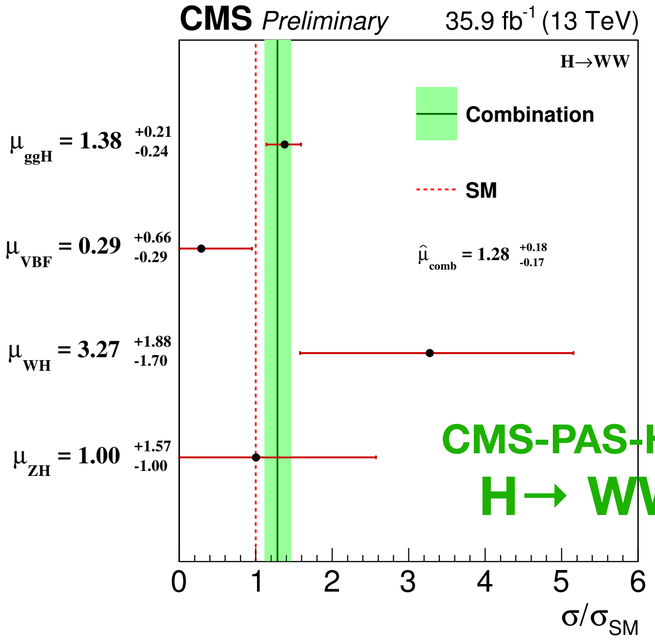
ttH had



ttH lep

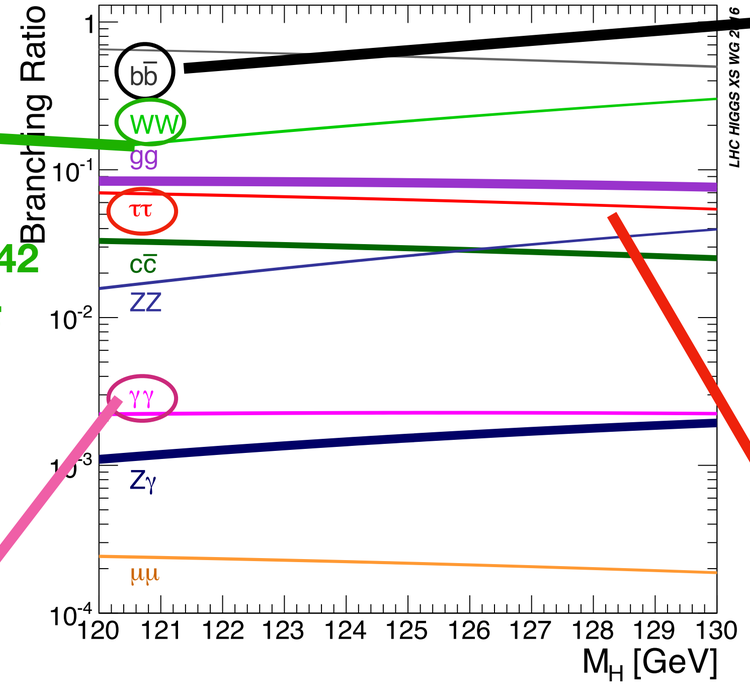


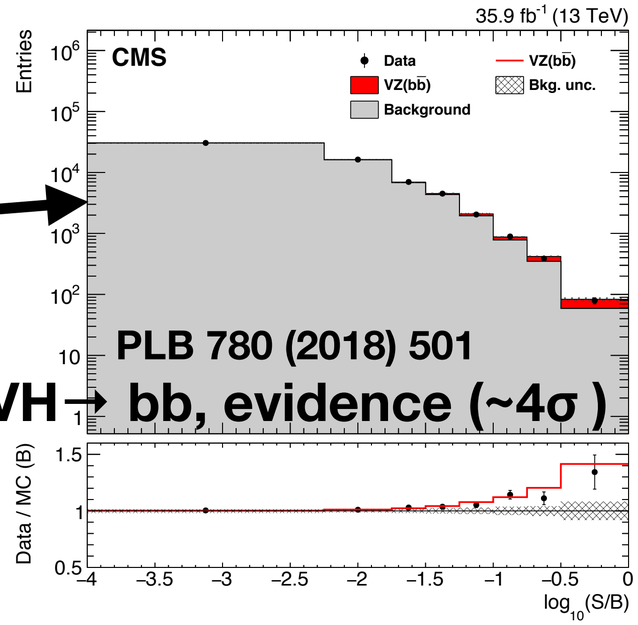
Other decay/production modes



CMS-PAS-HIG-16-042

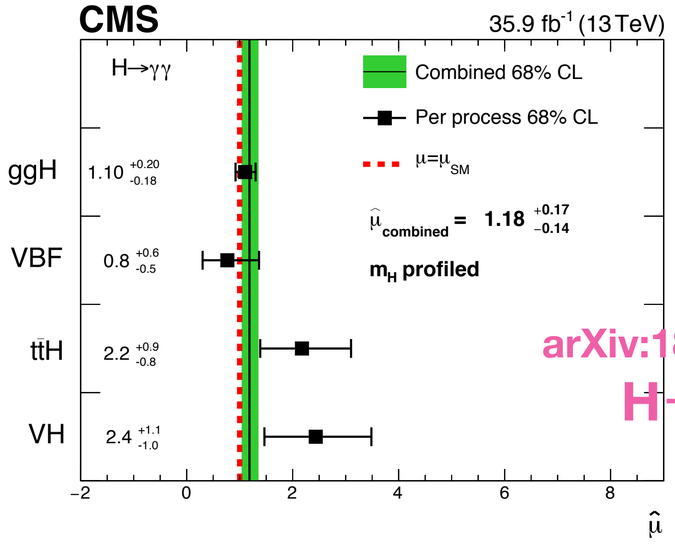
H→ WW, > 9σ





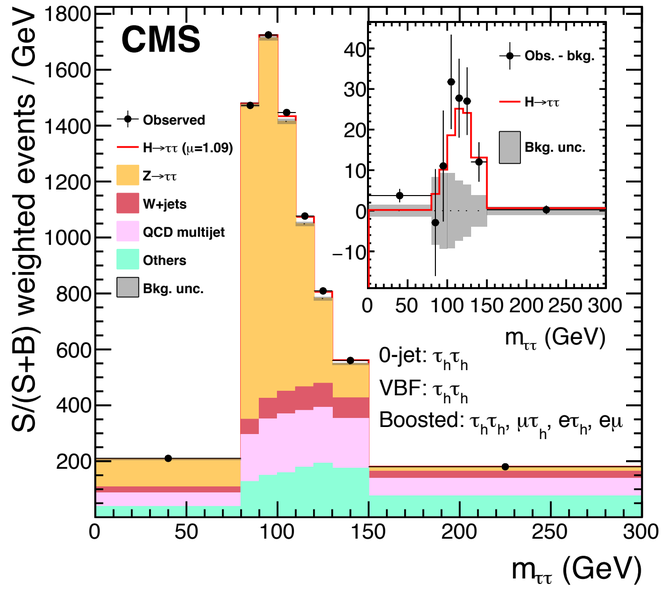
PLB 780 (2018) 501

VH→ bb, evidence (~4σ)



arXiv:1804.02716

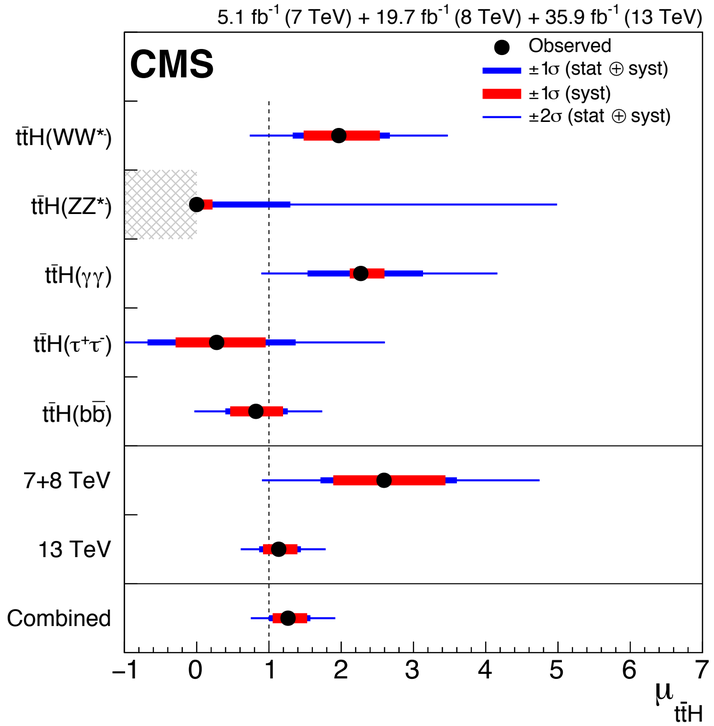
H→ γγ

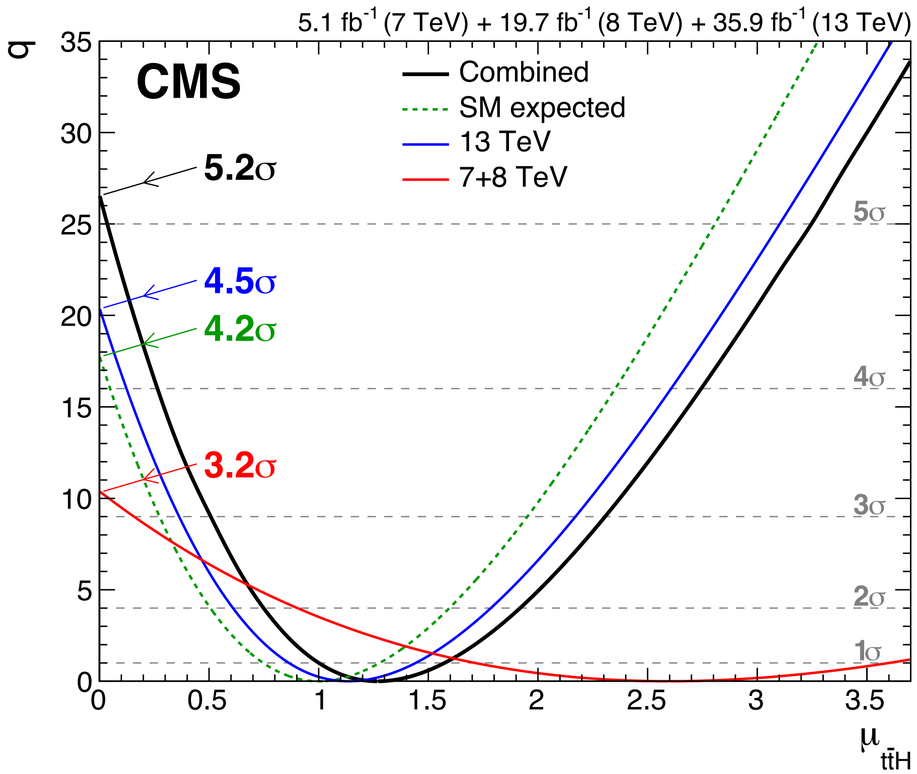


PLB 779 (2018) 283

H→ ττ, observed

Other decay/production modes





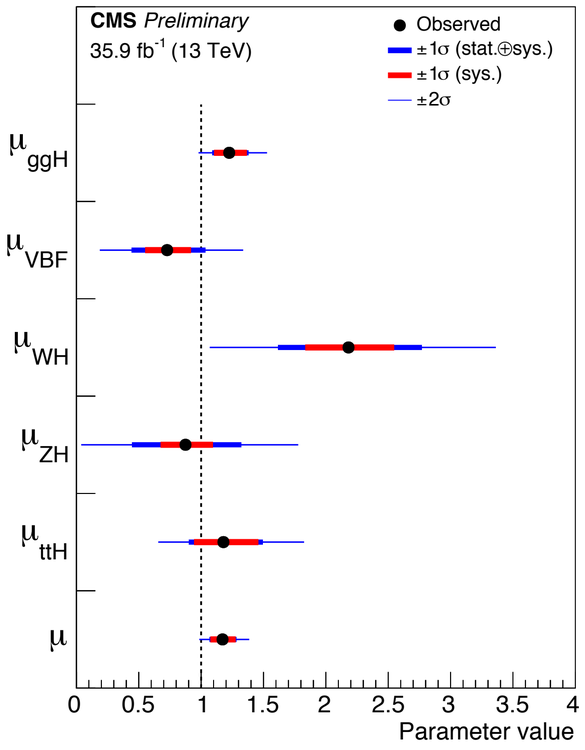
arXiv:1804.02610

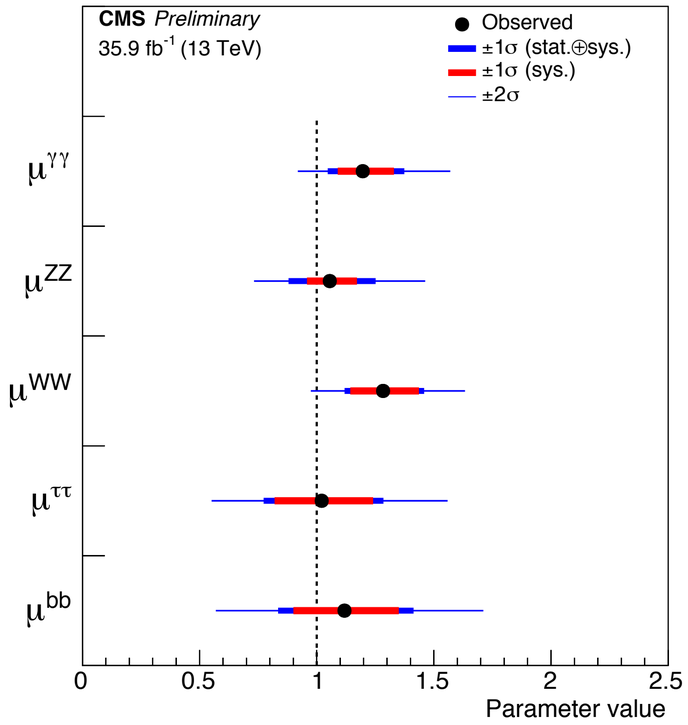
ttH observed

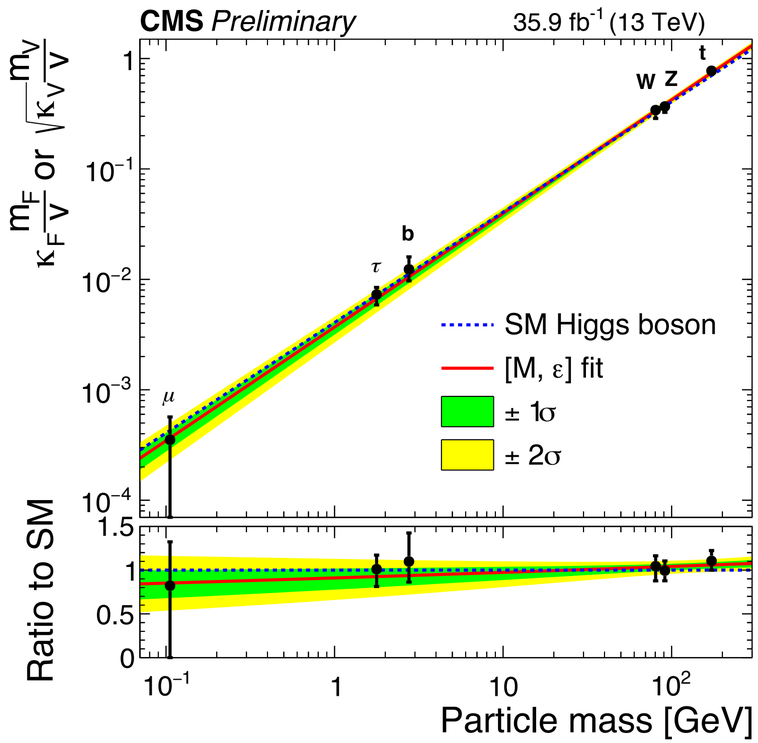
Standard Model like boson?

CMS-PAS-HIG-17-031

Consistency across channels



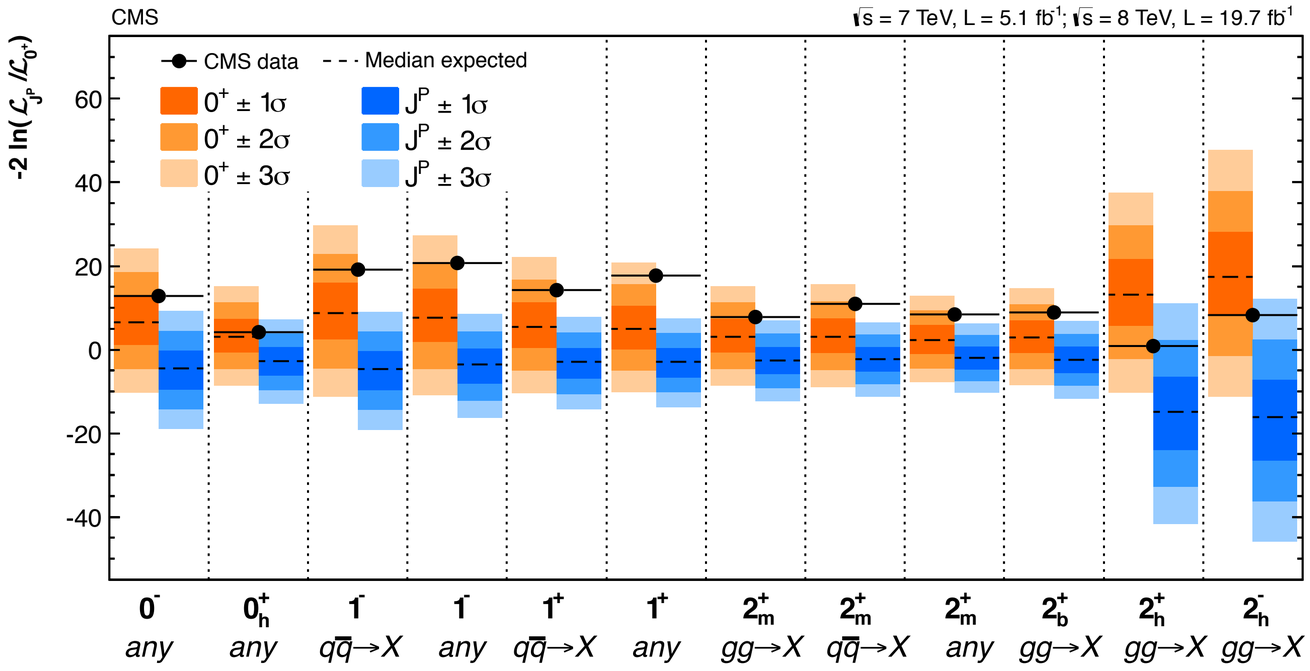




Spin-parity

PRD 89 (2014) 092007

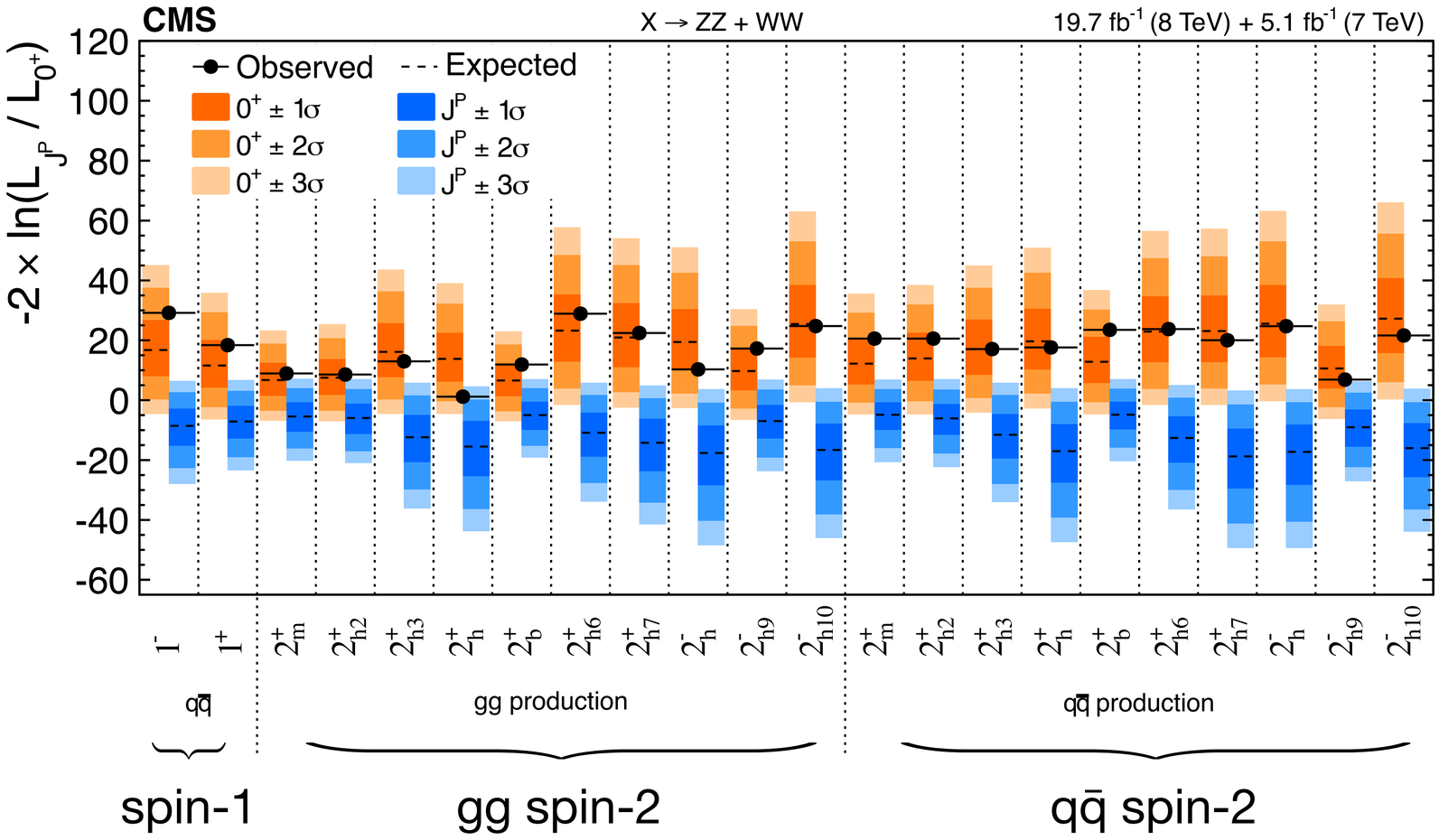
Data favor 0+ scalar state
H→ ZZ alone



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	$< o^{-10}$

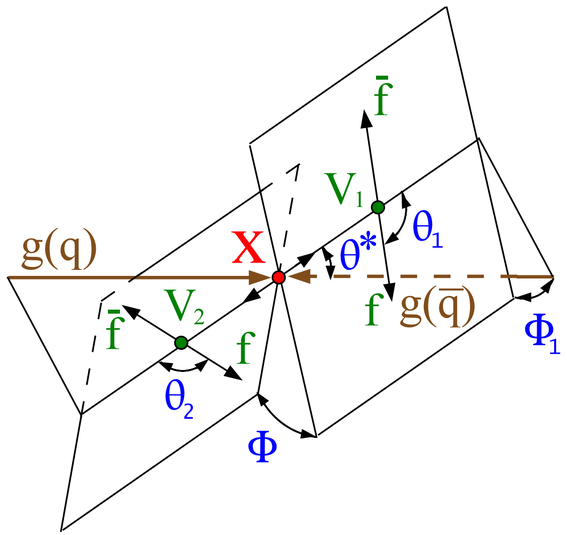
Measure $f_{ai} = \cos(\theta)\, a_i^2\, \sigma_i / (a_i^2\, \sigma_i + a_1^2\, \sigma_1)$

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

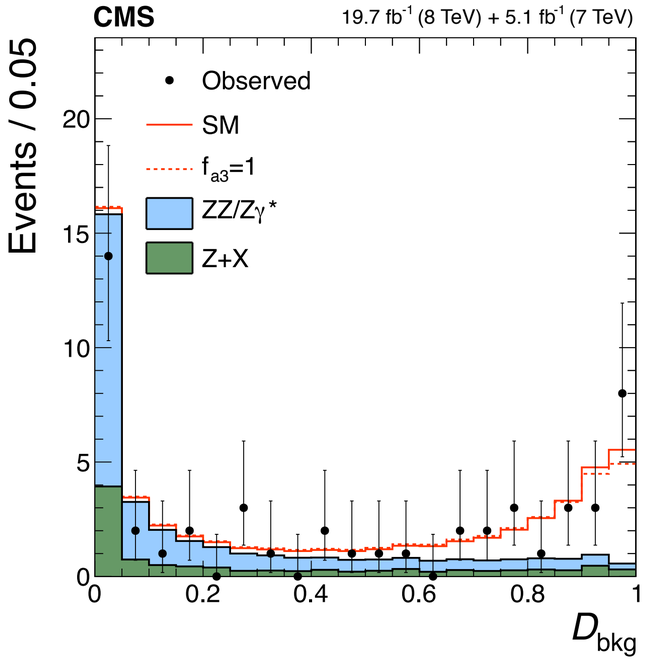


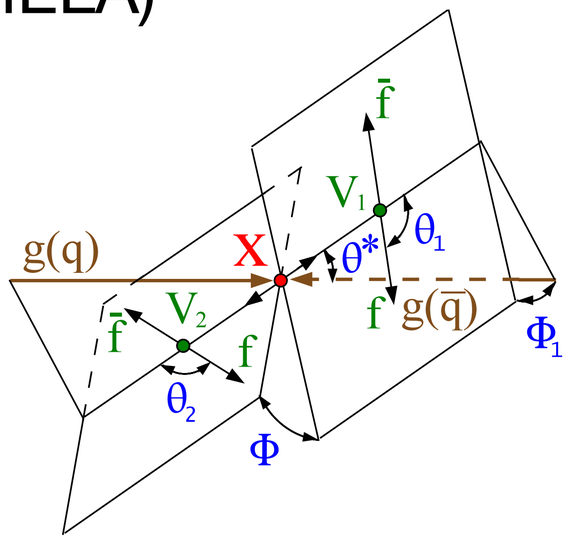
The measurement

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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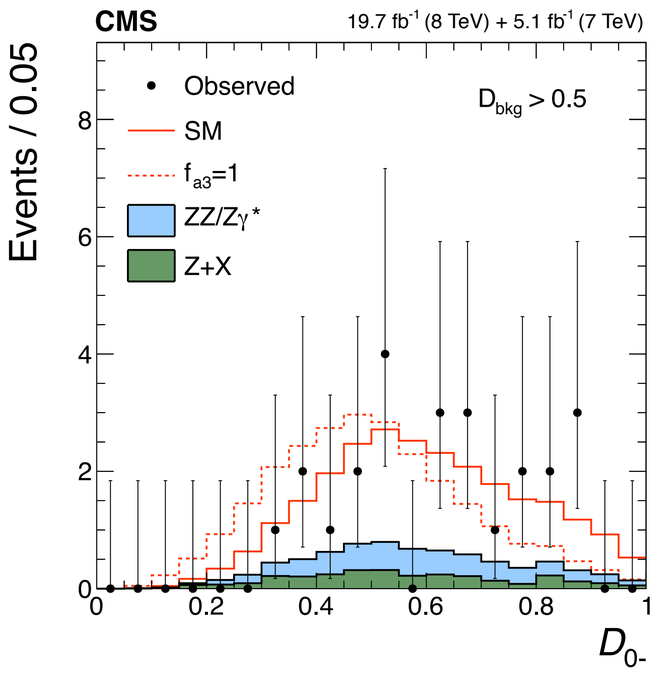
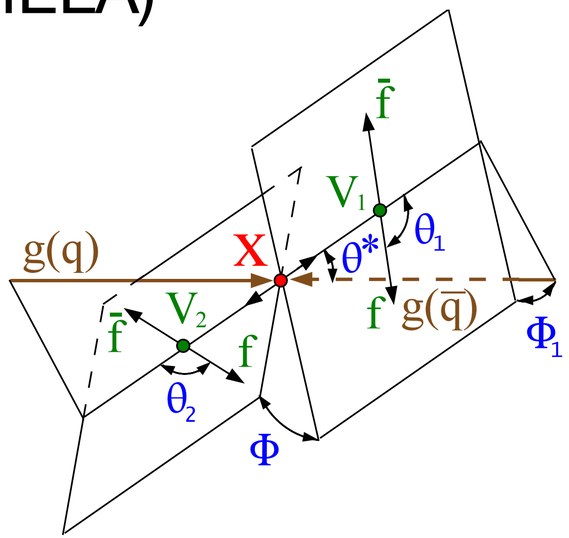
A. suppress background

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

B. separate BSM vs SM

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





The measurement

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A. suppress background

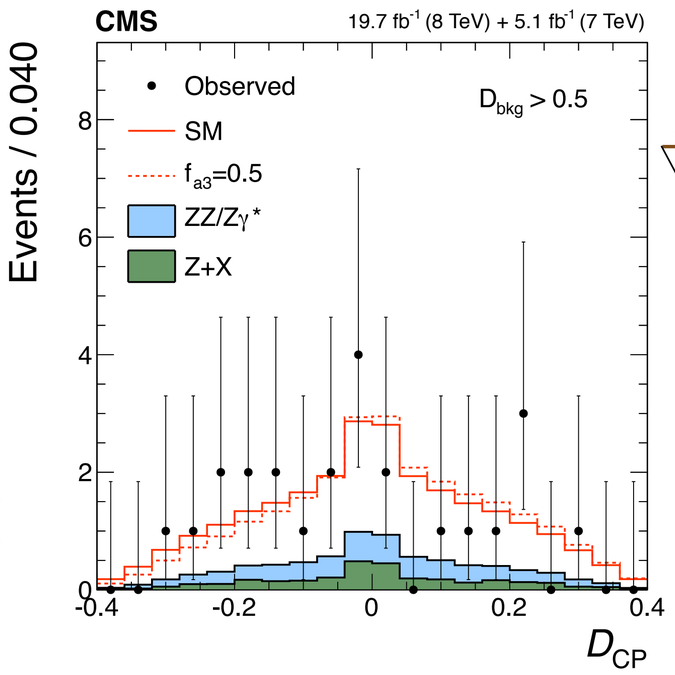
$$\mathcal{D}_{\rm bkg} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + c \times \mathcal{P}_{\rm q\bar{q}ZZ}}$$

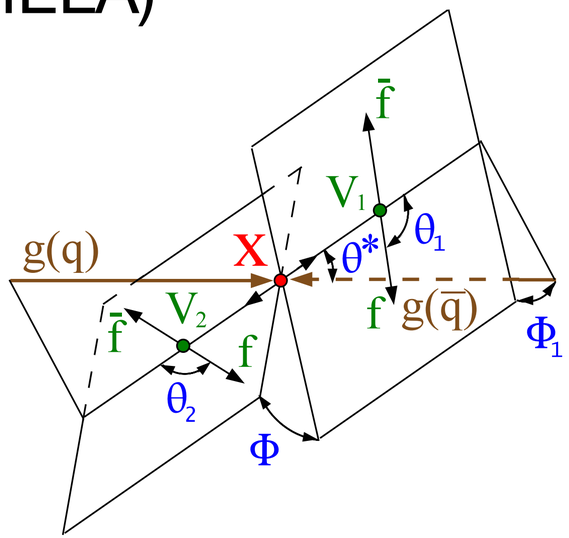
B. separate BSM vs SM

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

C. isolate interference of BSM and SM

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





The measurement

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

A. suppress background

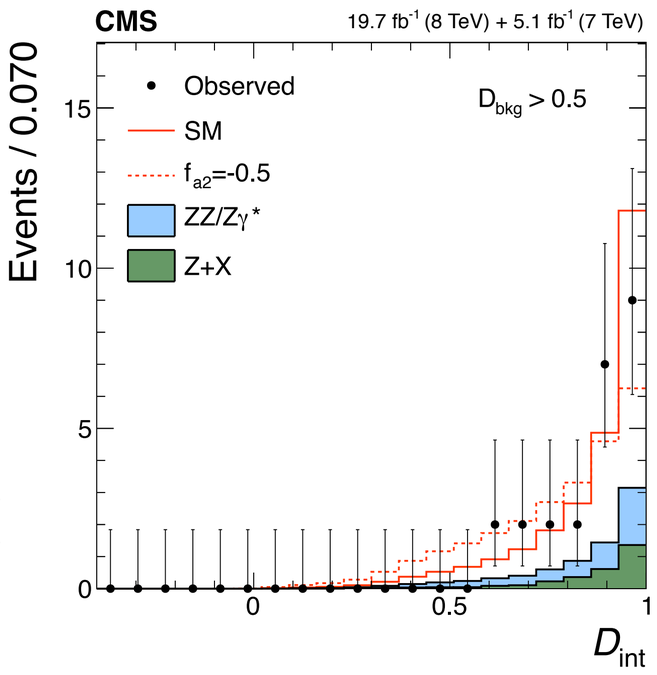
$$\mathcal{D}_{\rm bkg} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + c \times \mathcal{P}_{\rm q\bar{q}ZZ}}$$

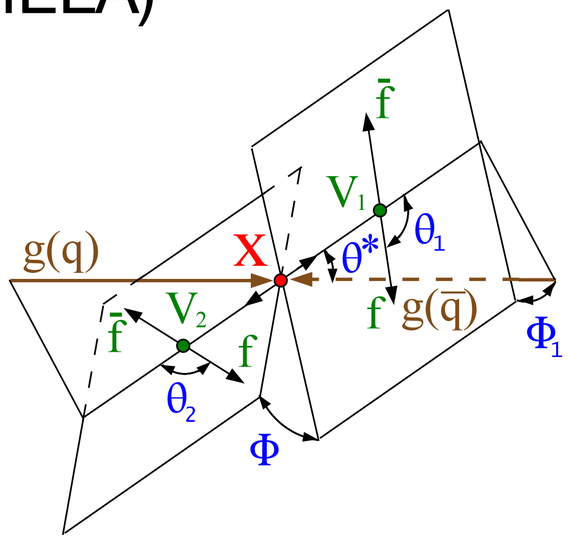
B. separate BSM vs SM

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

C. isolate interference of BSM and SM

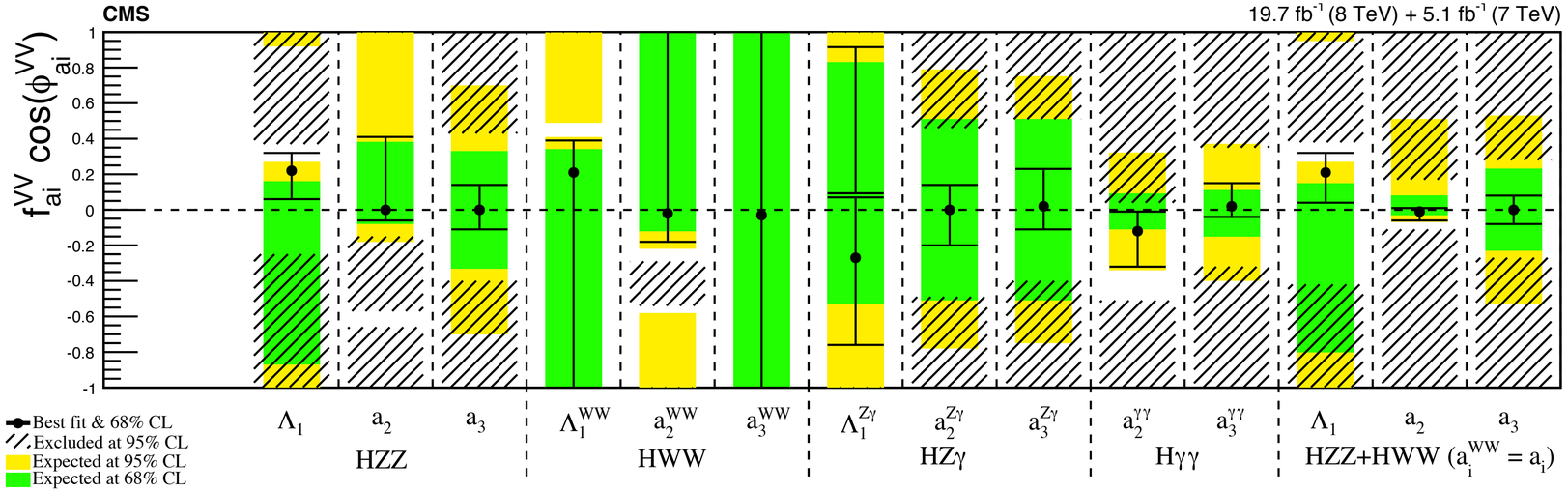
$$\mathcal{D}_{\rm int} = \frac{\mathcal{P}^{\rm int}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{\rm SM} + \mathcal{P}^{\rm kin}_{J^P}}$$





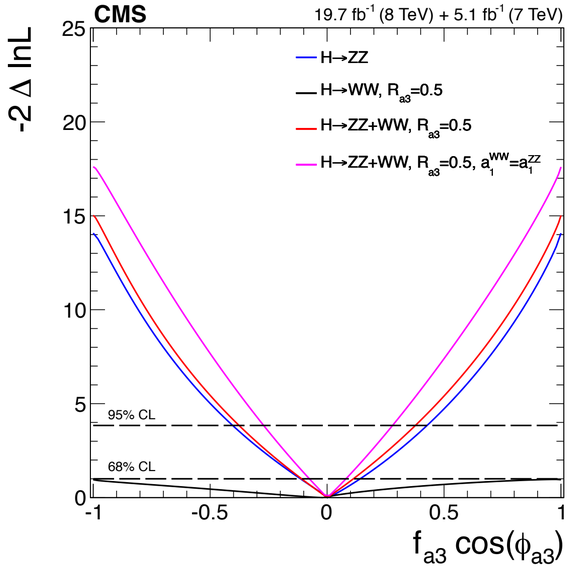
PRD 92 (2015) 012004

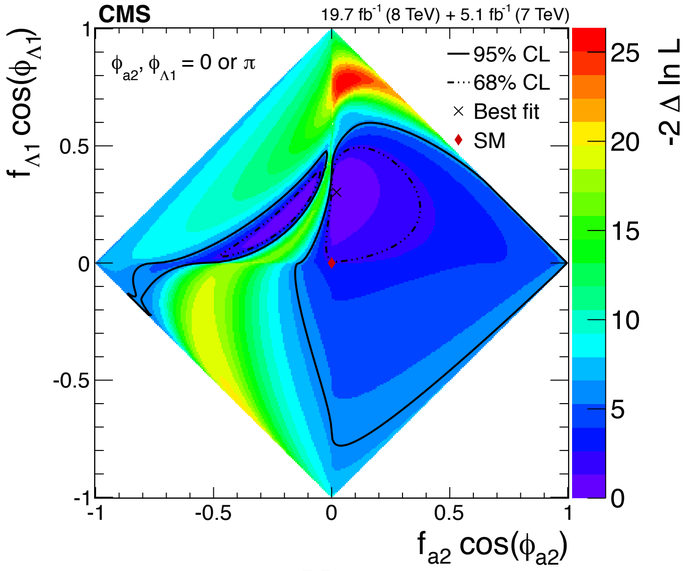
Anomalous coupling results at Run 1

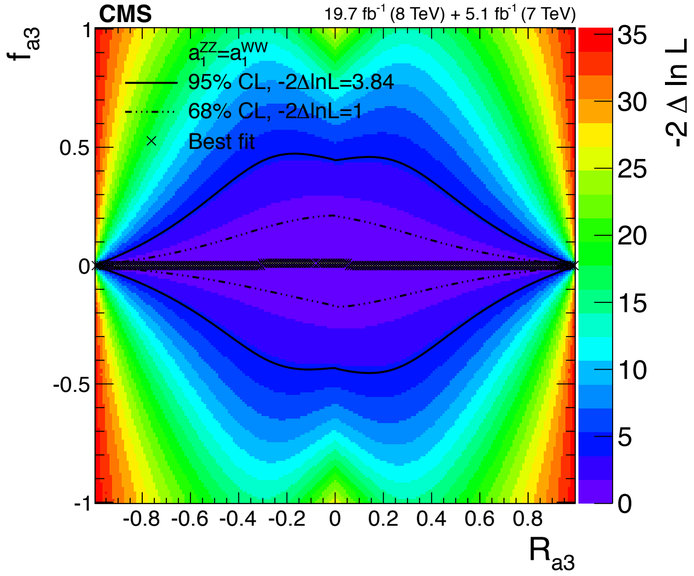


0^- and 0_h^+ excluded > 95% CL

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



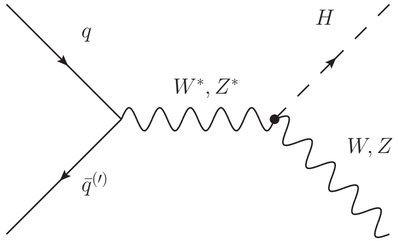


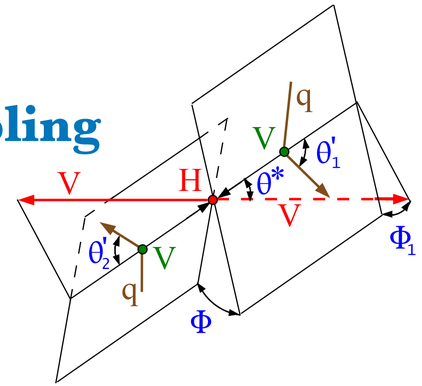


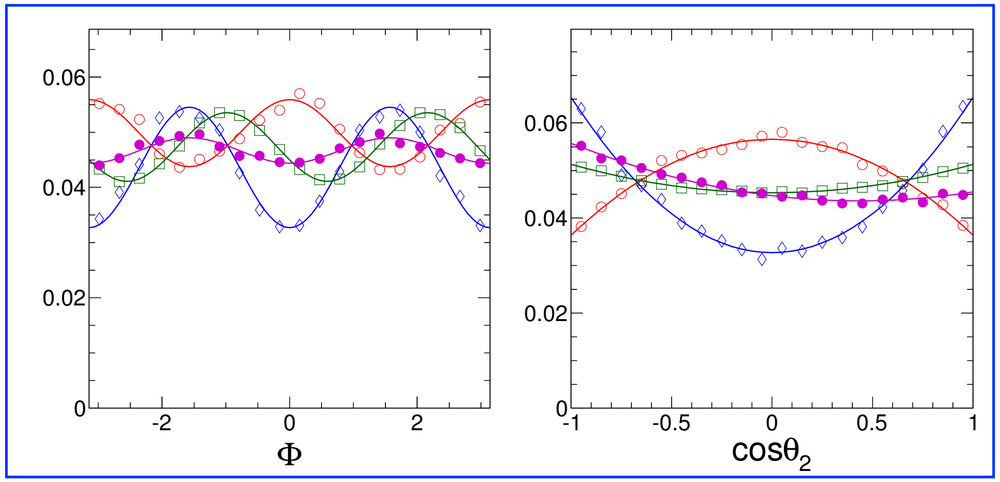
Anomalous coupling at Run2

VBF and VH modes

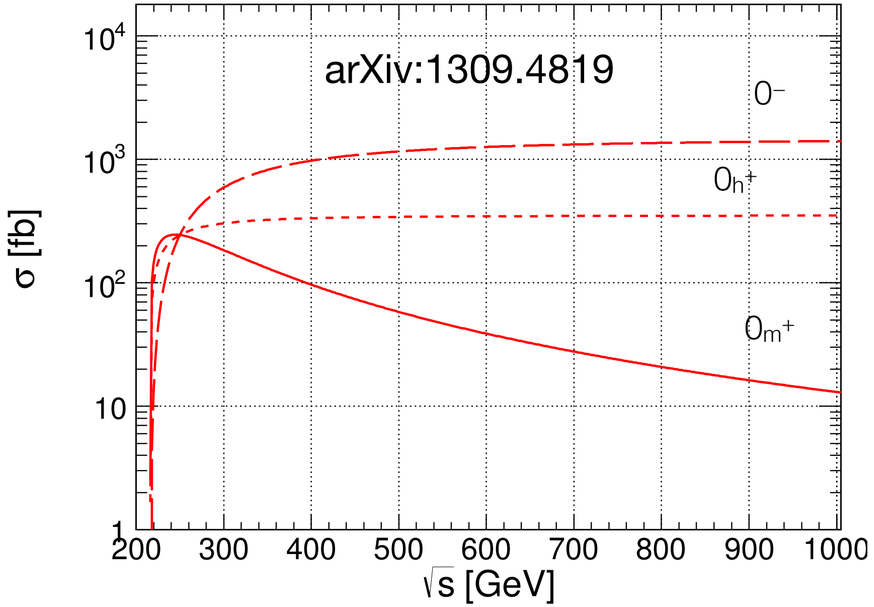
- **decay and production HVV coupling**
- **higher q^2 => better sensitivity**

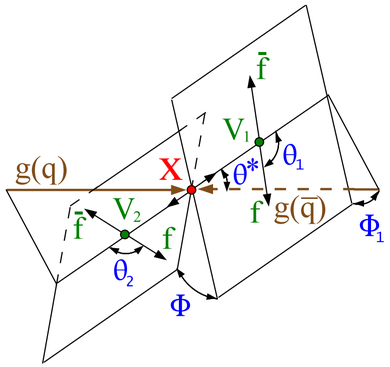


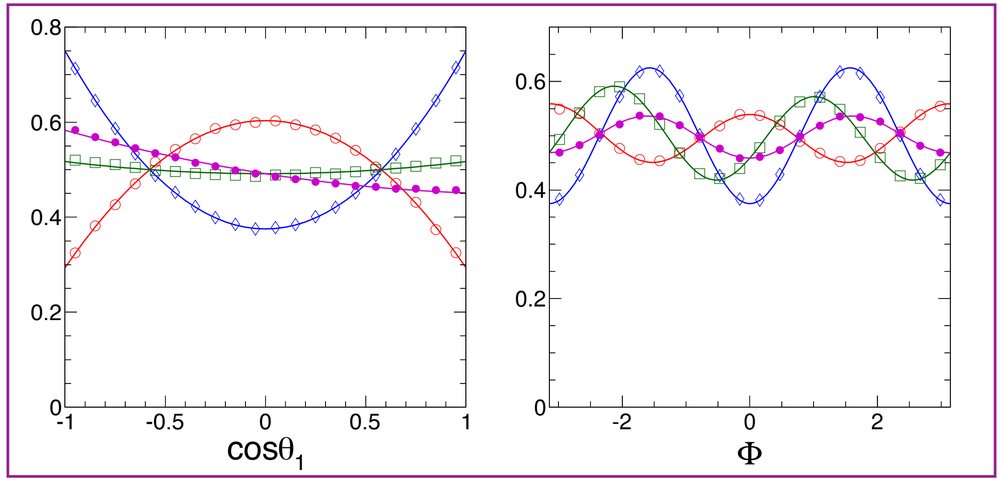




production vertex





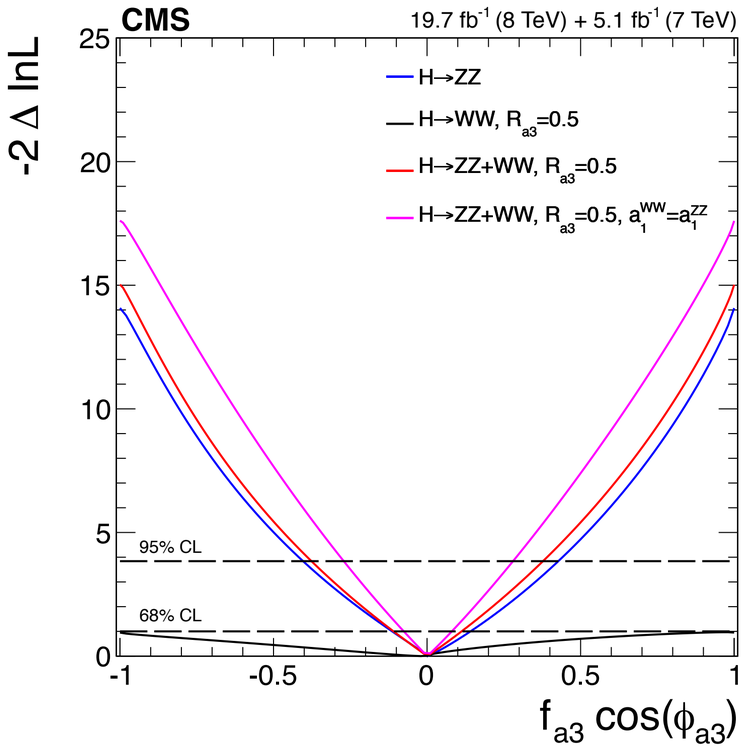


decay vertex

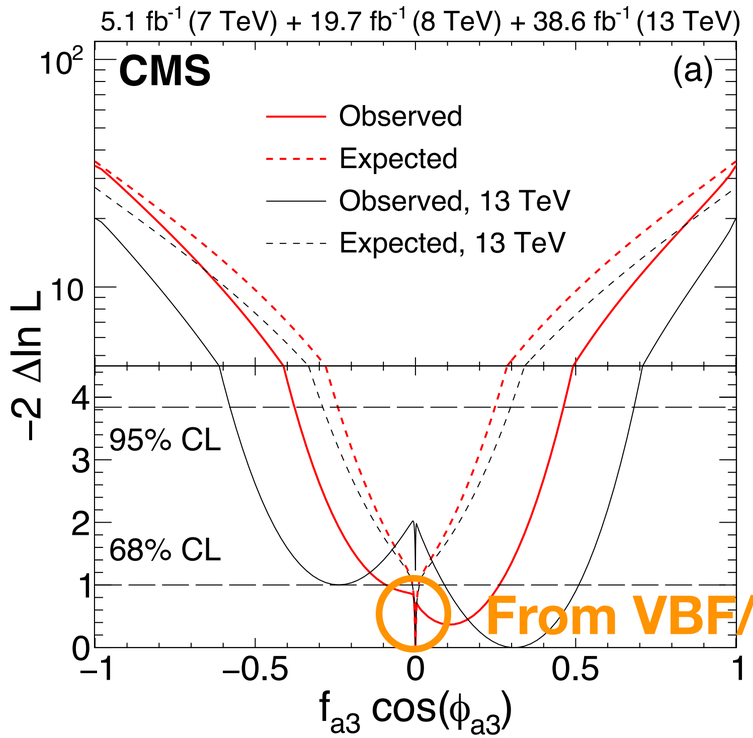
Anomalous coupling at Run2

Phys. Lett. B 775 (2017) 1

Run1



Run1 + Run2



From VBF/VH production

HZZ+HWW Expected:
fa3: 0 ± 0.23

Expected:
fa3: 0 ± 0.01

Mass measurement

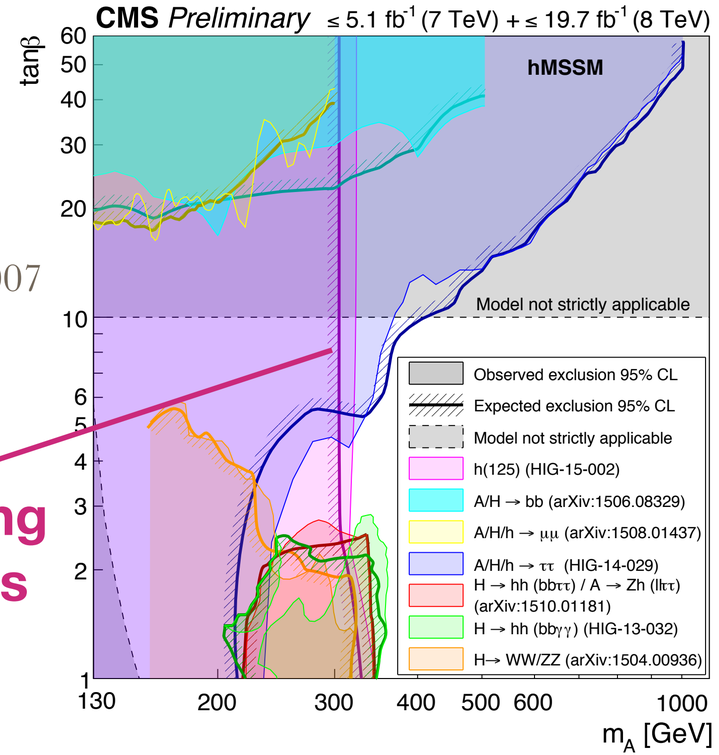
Why precise mass measurement?

- 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	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

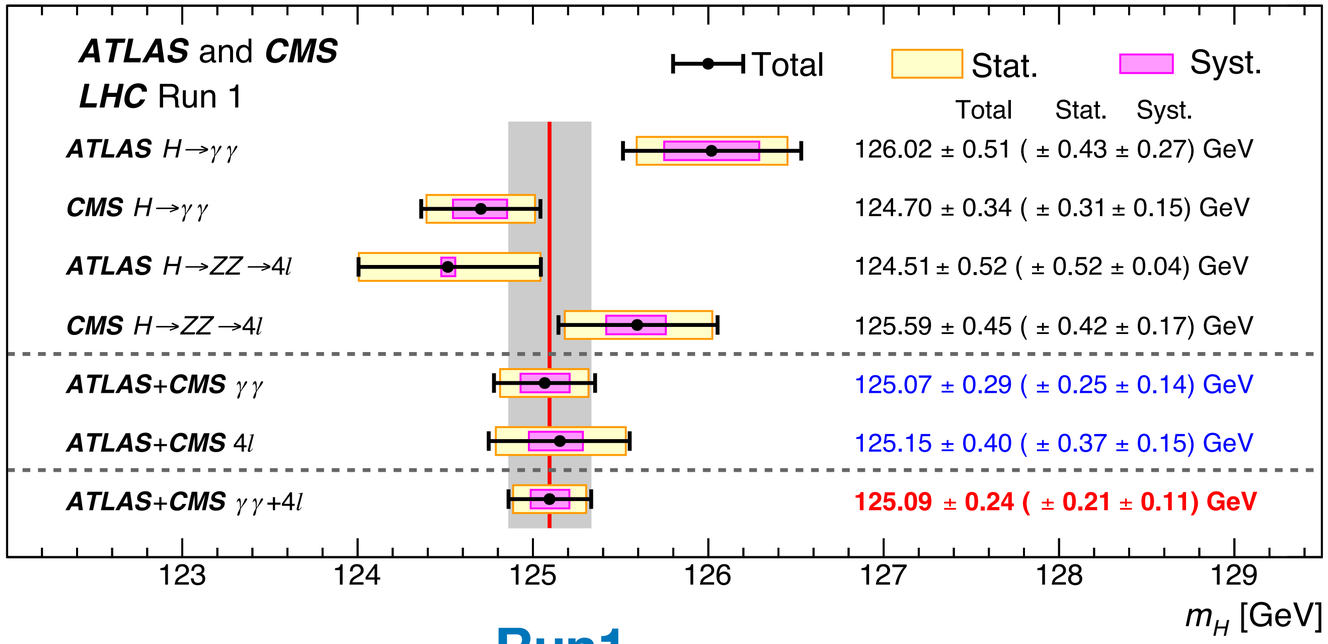
CMS-PAS-HIG-16-007



SM Coupling constraints

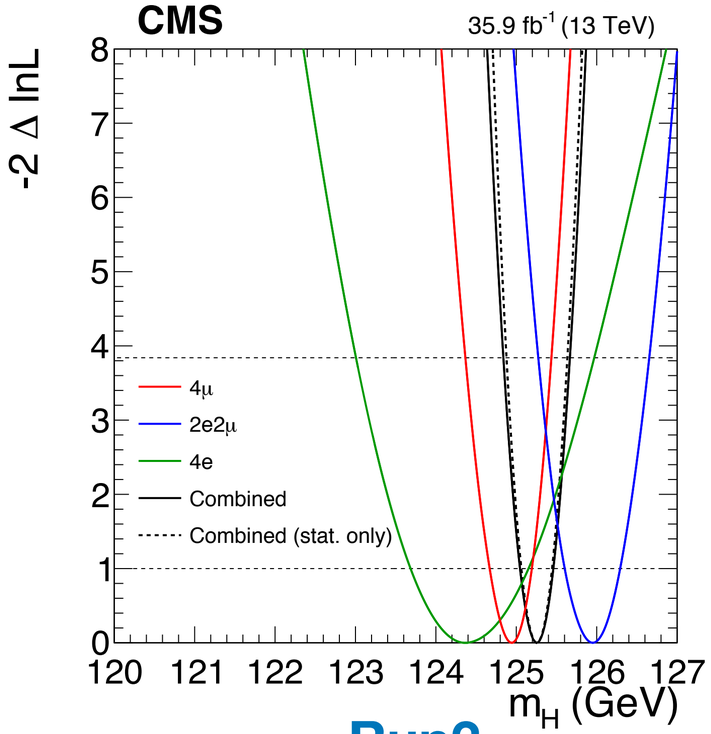
Mass measurement

PRL 114 (2015) 191803



Run1
CMS + ATLAS, γγ+4l

JHEP 11 (2017) 047



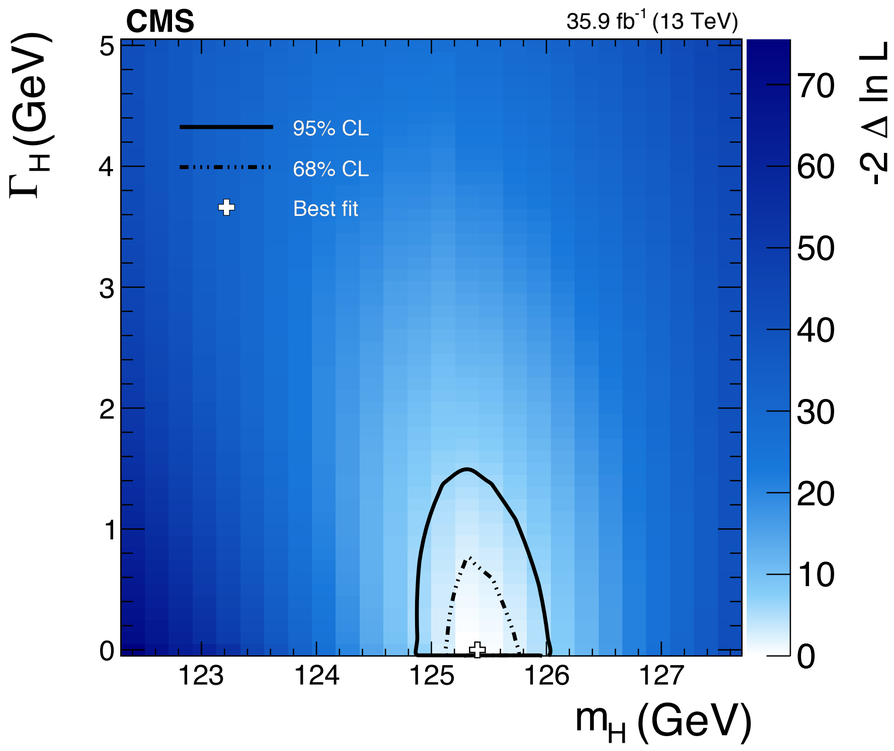
Run2
CMS 4l

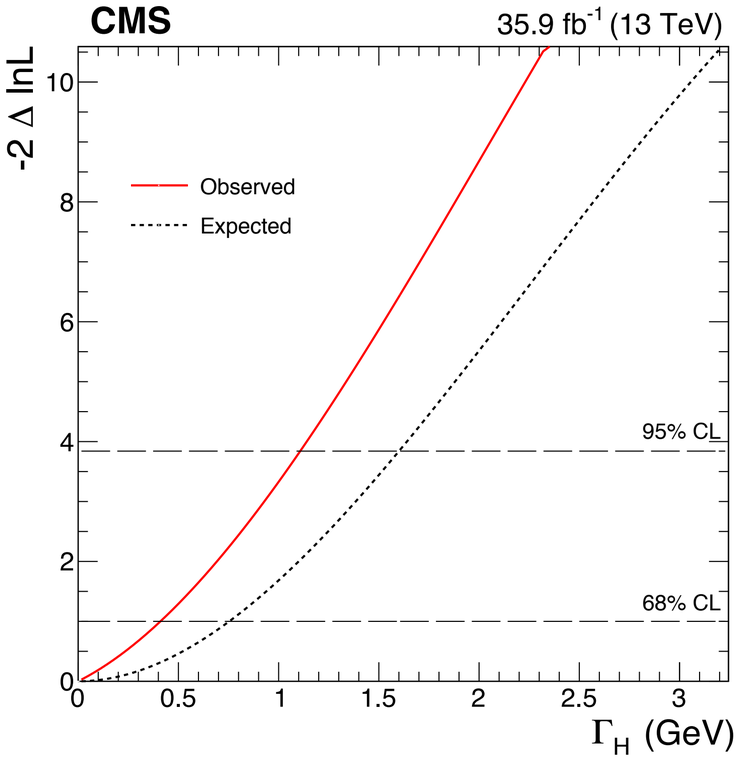
$\mathbf{m_H = 125.26 \pm 0.20(stat.) \pm 0.08(sys.)\ GeV}$

Most precise mass measurement so far

On-shell width measurement

JHEP 11 (2017) 047





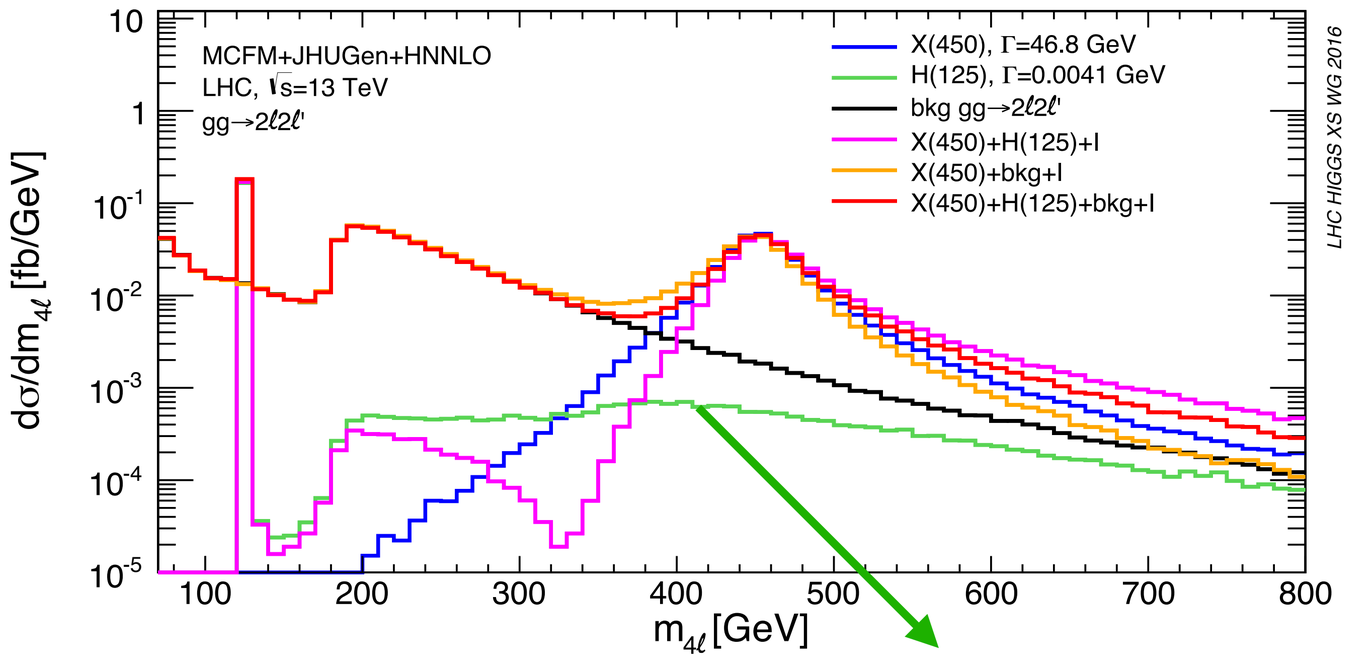
$\Gamma_H < 1.1$ GeV

Off-shell width measurement: Run1

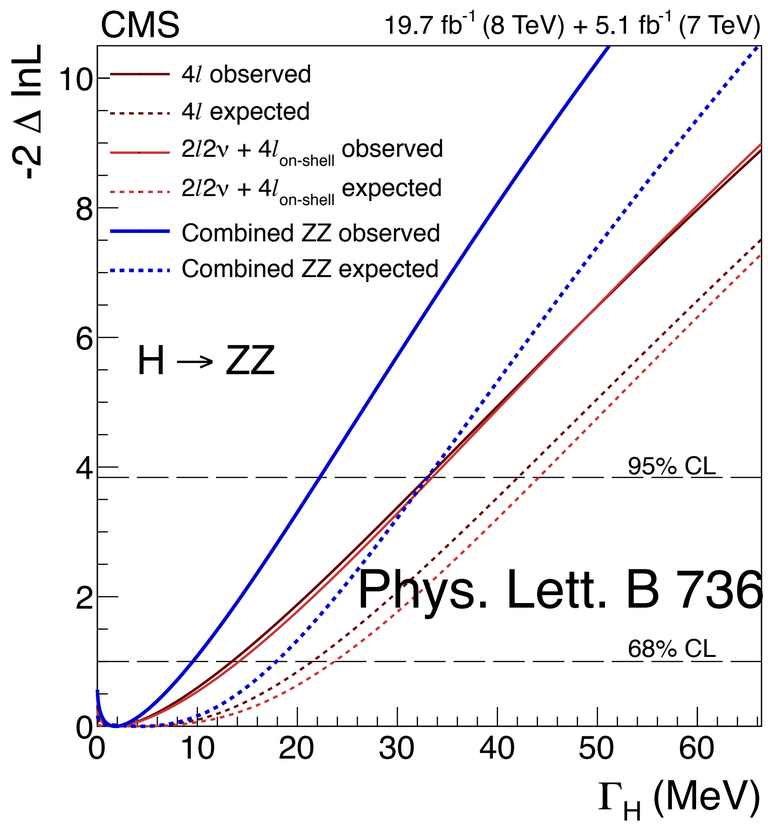
SM prediction: 4.15 MeV, extremely small compared to the mass ~ 125 GeV

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

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



Off-shell tail

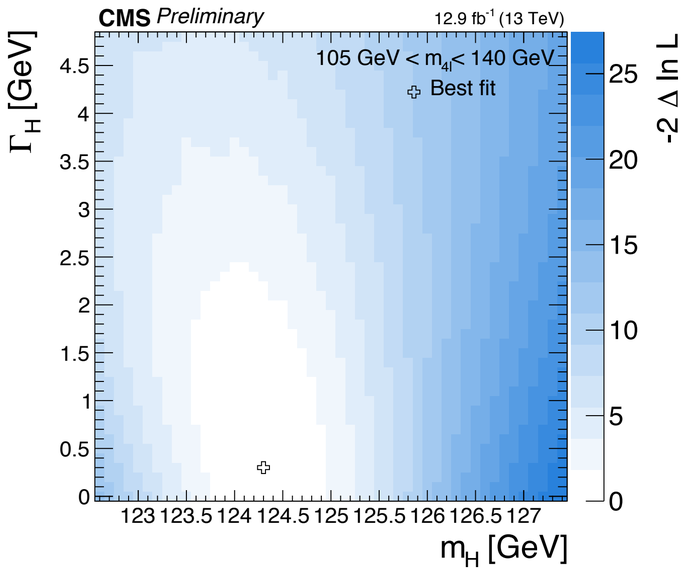


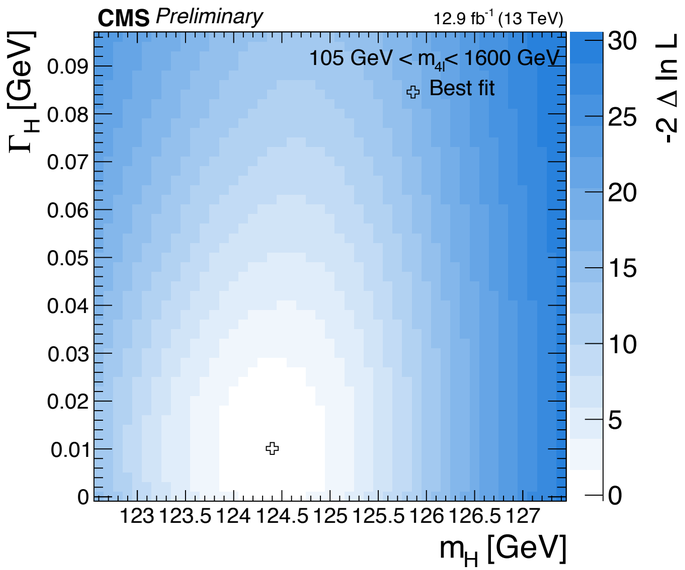
Phys. Lett. B 736 (2014) 64

Γ_H < 22 MeV at 95% CL

Mass & Width: Run2

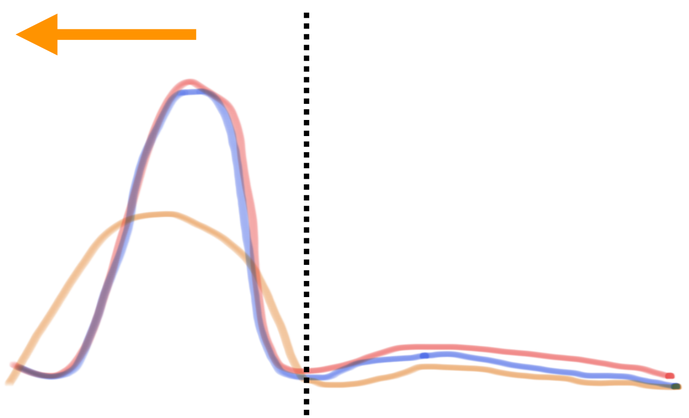
CMS-PAS-16-033



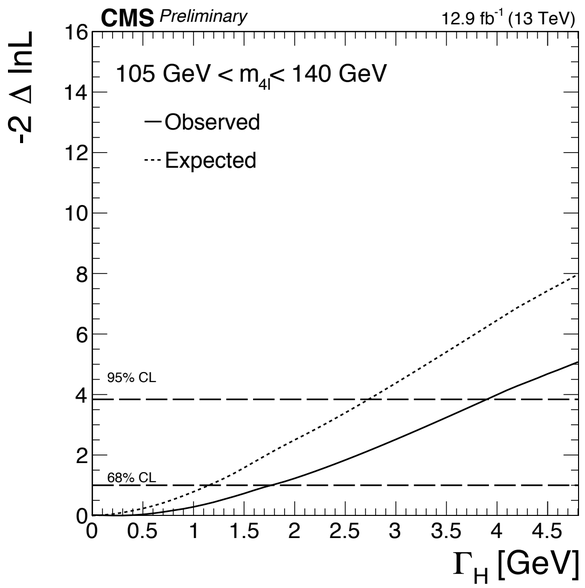


Measure mass and width at the same time

Describe mass shape in full range

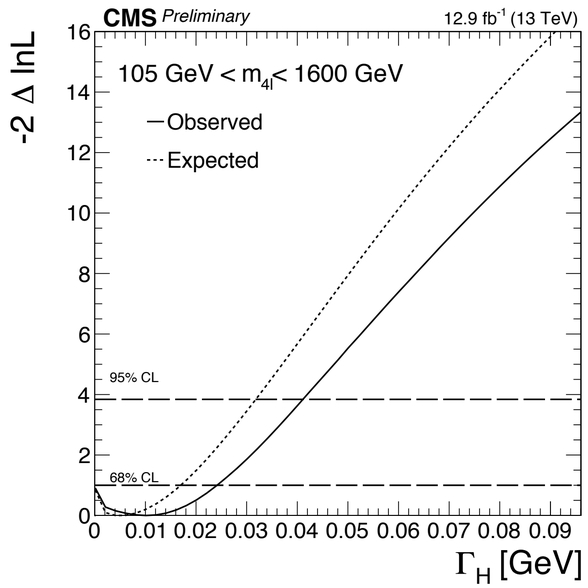


no approximation on-shell/off-shell
interference with bkg included

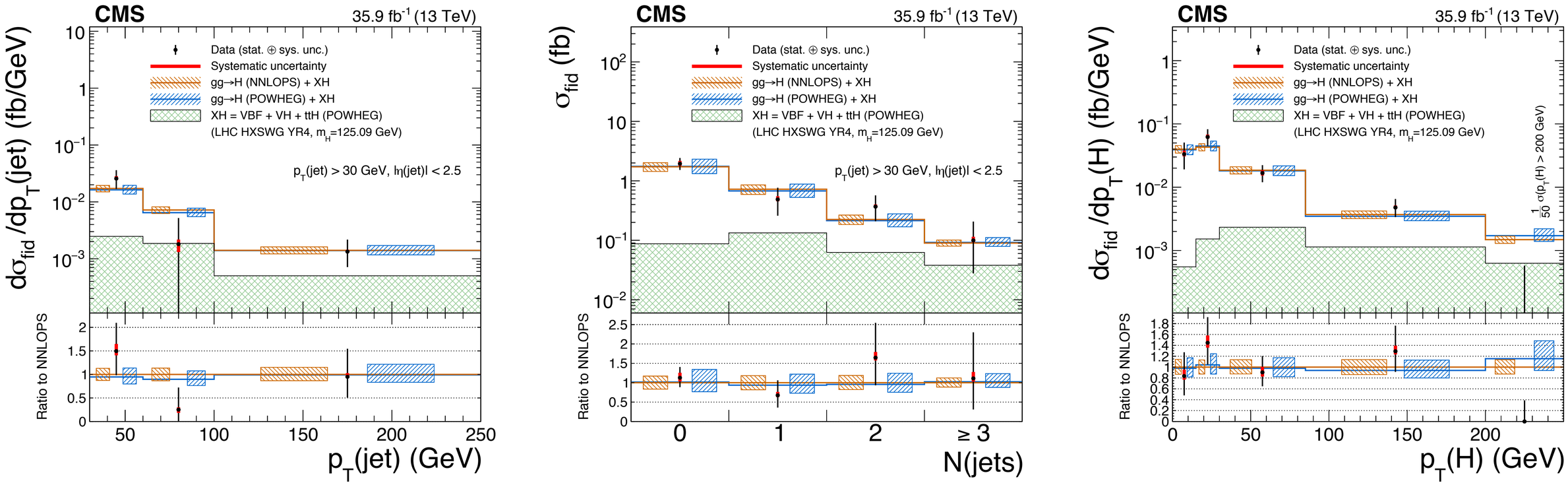


Γ < 3.9 GeV

Γ < 41 MeV



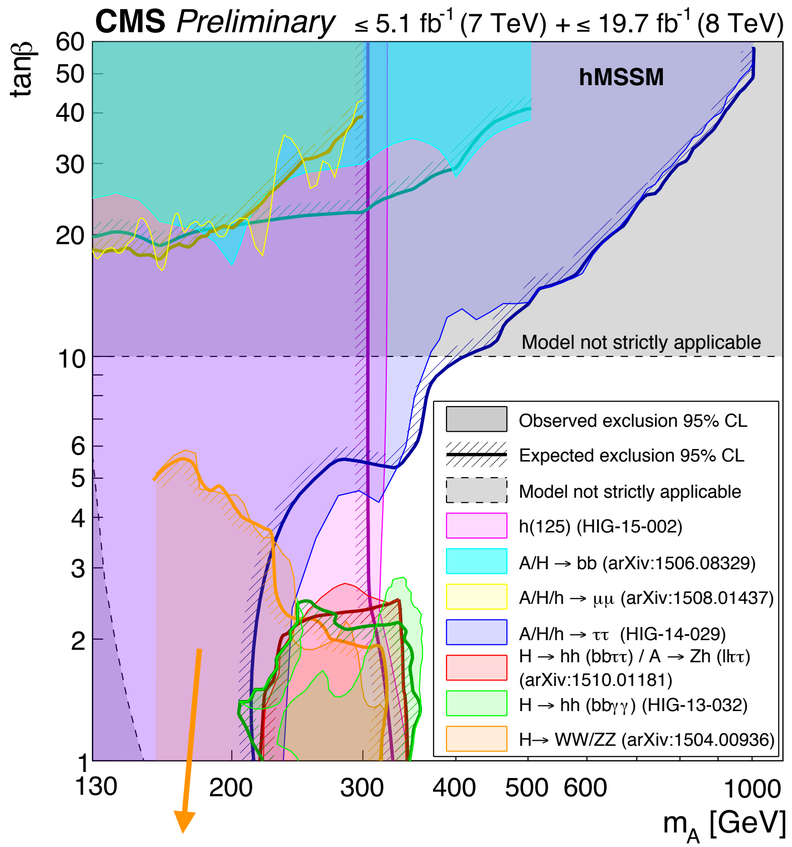
Any other deviation?



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

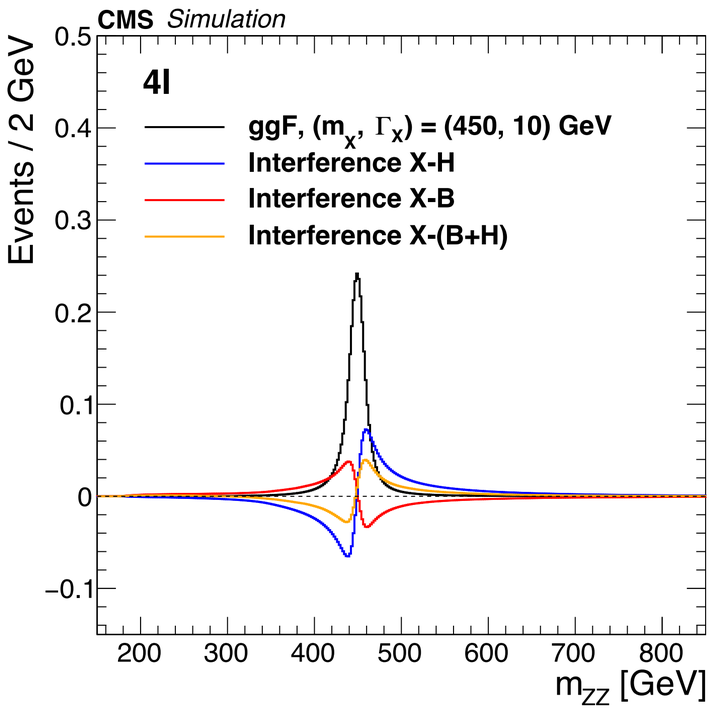
	4l	2l2v	2l2q
BR (%)	0.453	2.692	9.422
Resolution (%)	1-3	-	3-7
Mass range [GeV]	130-3000	200-3000	550-3000

Search for ggH and VBF production

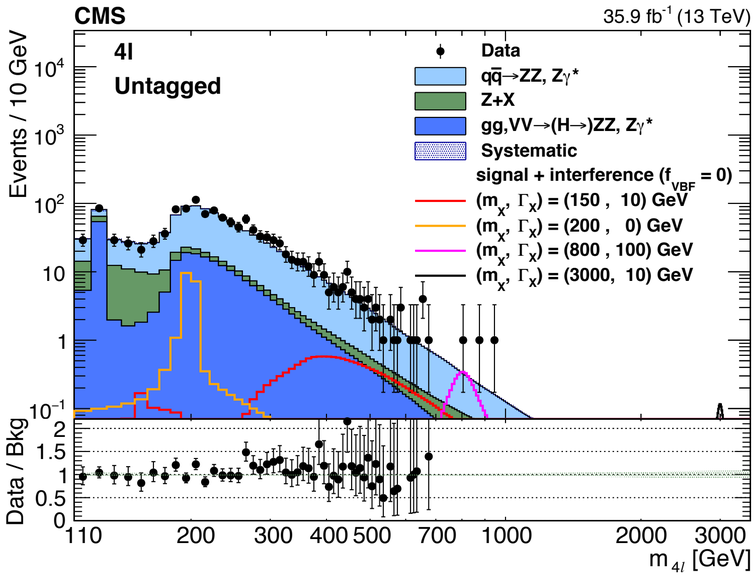
Search for additional Higgs

arXiv:1804.01939
submitted to JHEP

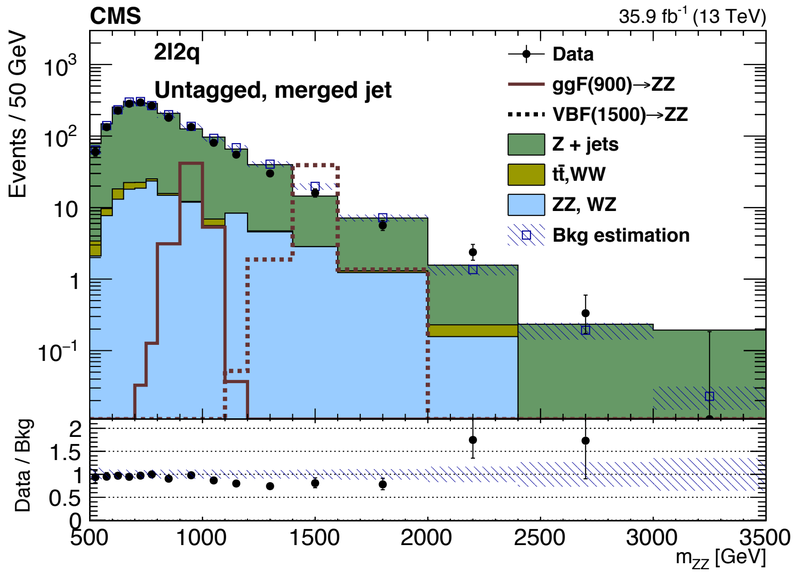
Fully analytical description for any (m_H, Γ_H) with the interference in 4l and 2l2q



H, h, B interference



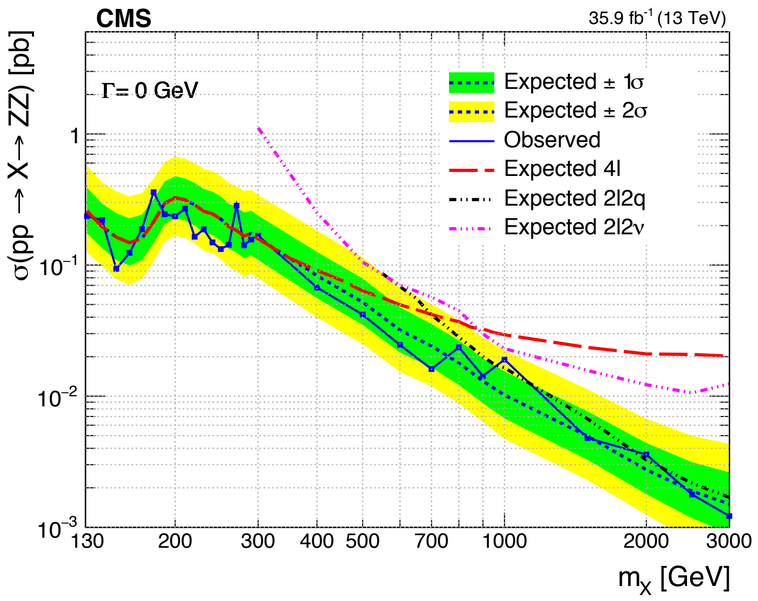
4l

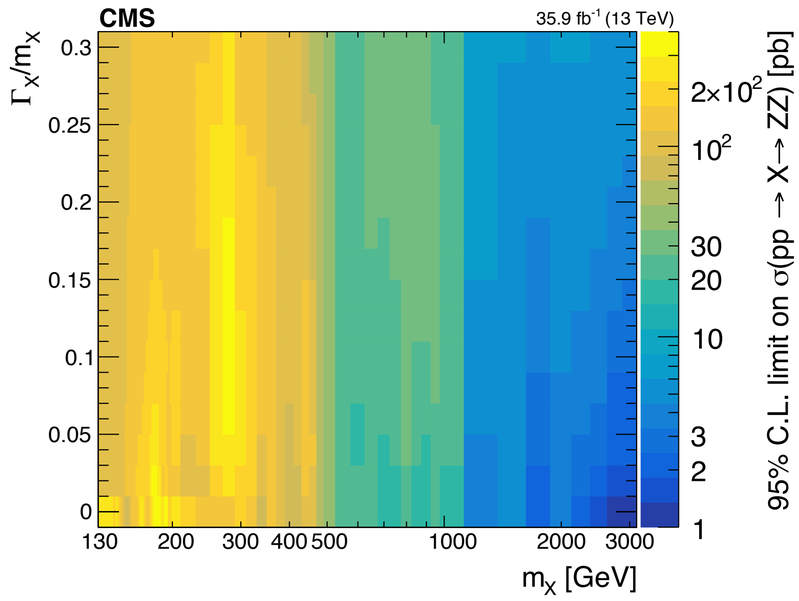


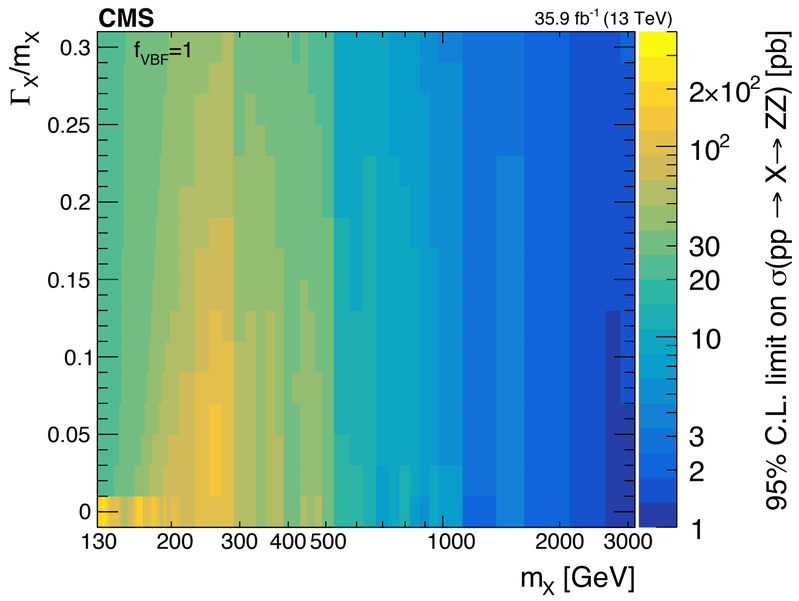
2l2q

arXiv:1804.01939
submitted to JHEP

Search for additional Higgs







No significant excess observed

ggF+VBF

VBF

Excluded xsec in the grid of

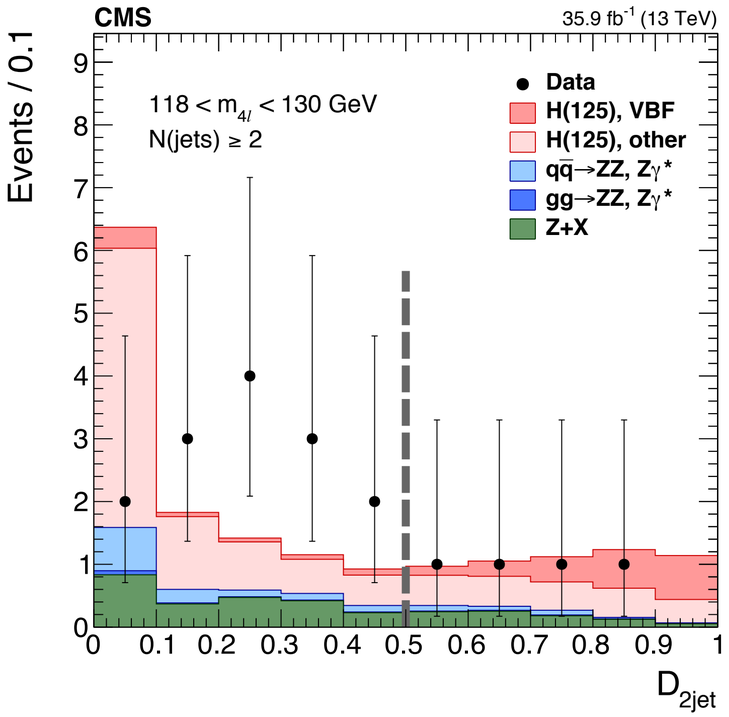
- **m_H (130 — 3000 GeV) , Γ_H (0—30%)**

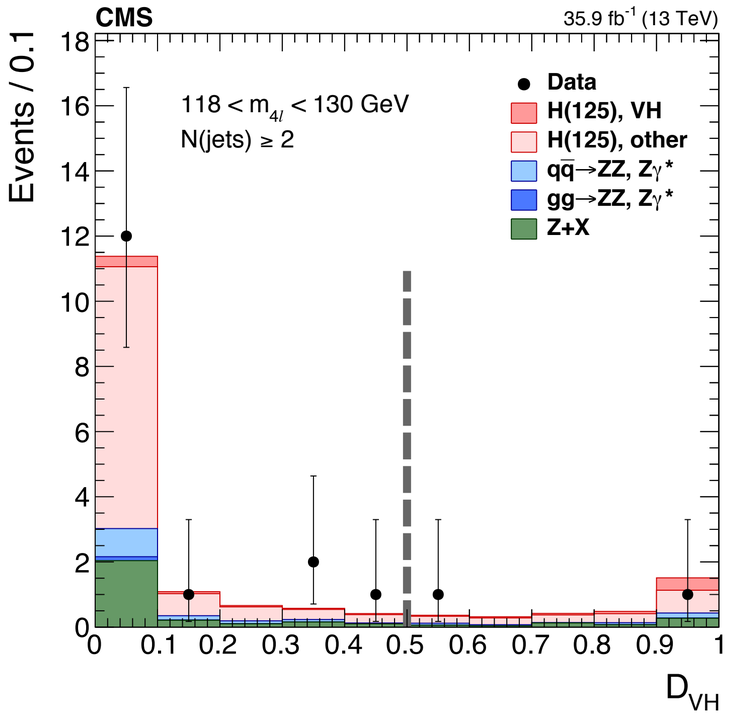
Model independent inputs for many BSM theories

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 < m_{4l} < 130 GeV
N(jets) ≥ 2
Data
H(125), VBF
H(125), other
$q\bar{q}\to ZZ, Z\gamma^*$
$gg\to ZZ, Z\gamma^*$
Z+X
D_{2jet}

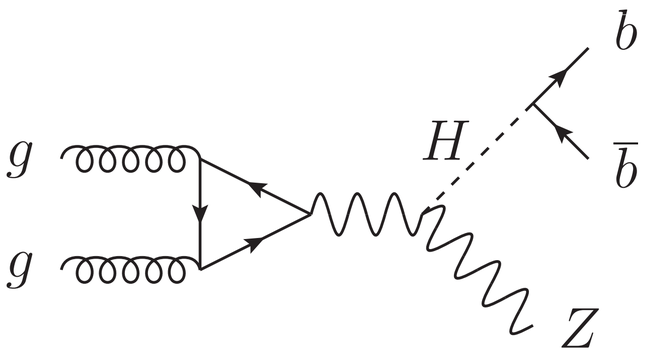

CMS
35.9 fb^{-1} (13 TeV)
Events / 0.1
118 < m_{4l} < 130 GeV
N(jets) ≥ 2
Data
H(125), VH
H(125), other
$q\bar{q}\to ZZ, Z\gamma^*$
$gg\to ZZ, Z\gamma^*$
Z+X
D_{VH}

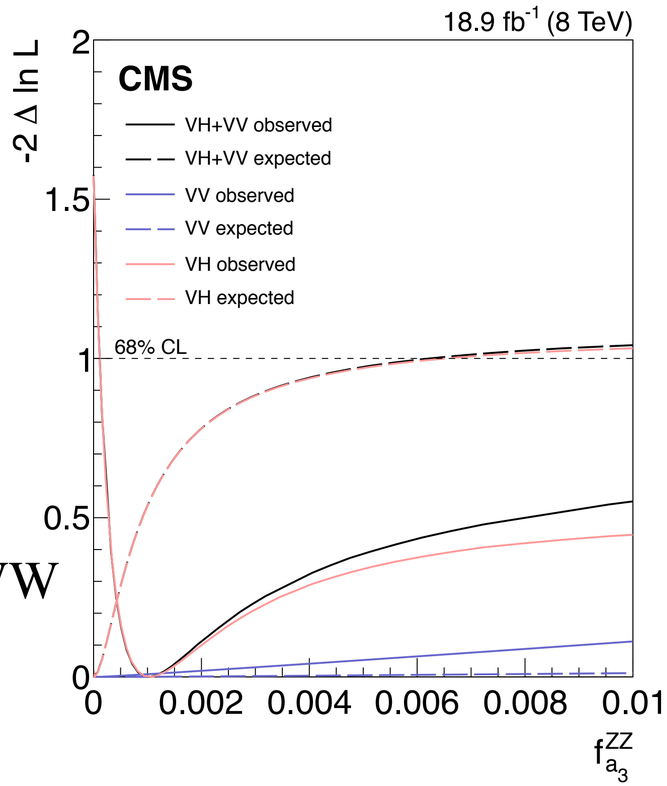
Anomalous coupling with production

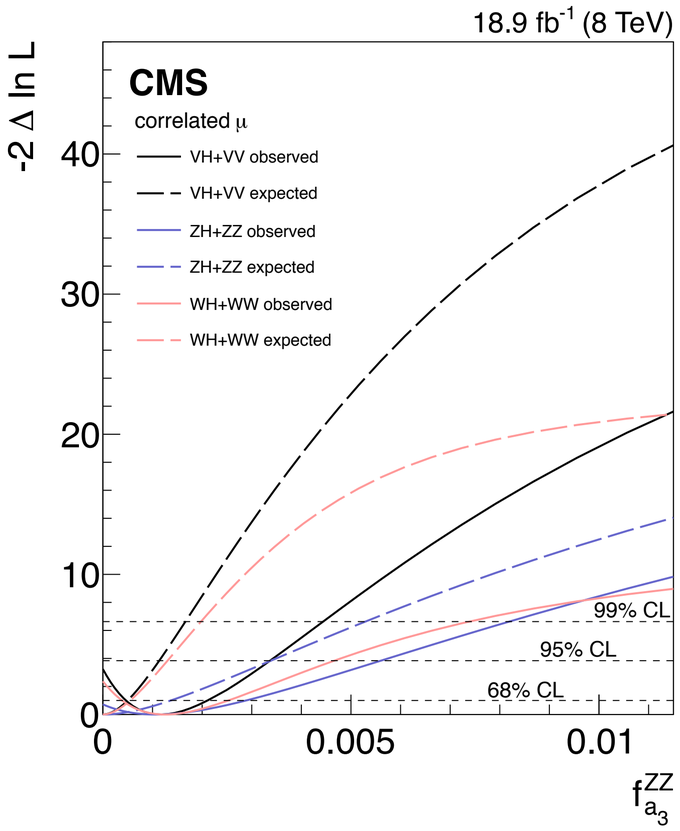
VH(bb) to measure HVV (V=Z,W) coupling

Phys. Lett. B 759 (2016) 672

sensitive to small anomalous couplings







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

$f_{a3} < 0.28$ at 95% using H→ ZZ/WW