CMS Higgs Couplings and Spin/CP

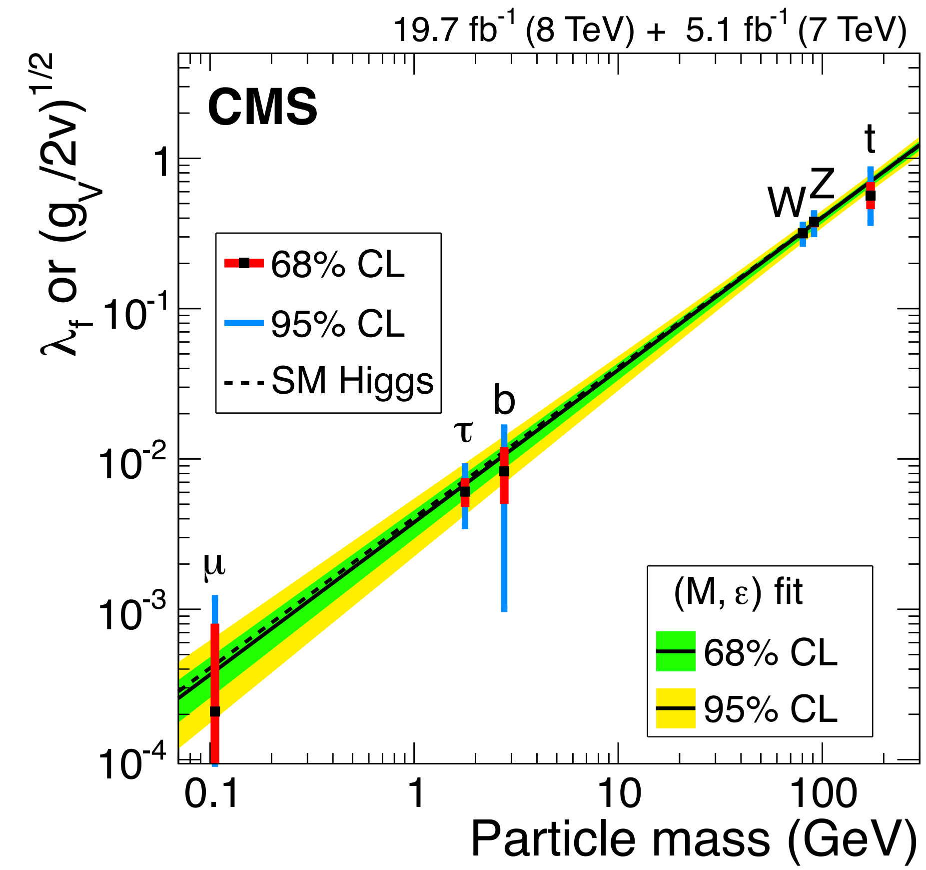
Ben Kreis (FNAL)

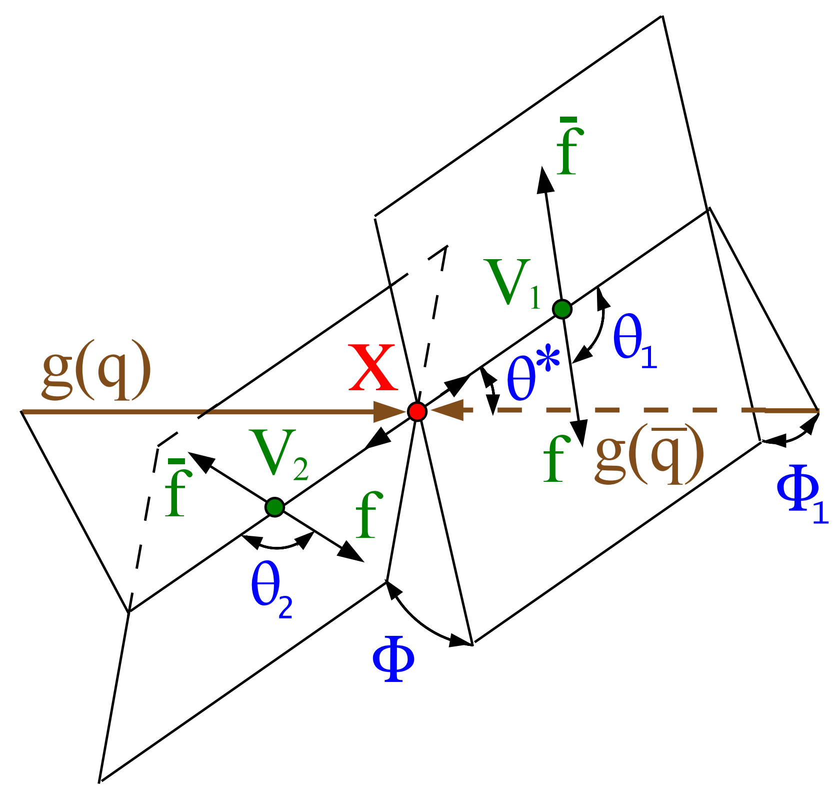
Higgs Hunting, Orsay, France

July 31, 2015

Outline

- Couplings
  - Signal strengths
  - Coupling modifiers
    - Vector bosons and fermions
    - Generic modifier ratios
    - New physics
- Spin/CP
  - Exotic spin
  - Spin 0 anomalous couplings





Up to 5.1 fb^{-1} (7 TeV) and 19.7 fb^{-1} (8 TeV)
Eur. Phys. J. C 75 (2015) 212
Phys. Rev. D 92, 012004 (2015)

Combined Higgs Channels

- Comprehensive set of production and decay modes targeted
- Over 250 mutually exclusive event categories

Event category targets

✔ Included in coupling combinations

✔ Considered in certain interpretations

production

decay	ggH	VBF	VH	ttH
$H \to \gamma\gamma$	✔	✔	✔	✔
$H \to ZZ$	✔	✔	✔	✔
$H \to WW$	✔	✔	✔	✔
$H \to \tau\tau$	✔	✔	✔	✔
$H \to bb$		✔	✔	✔
$H \to \mu\mu$	✔ (considered)	✔ (considered)	✔ (considered)	
$H \to$ invisible		✔ (considered)	✔ (considered)	

- m_H=125.0 GeV and narrow-width approximation assumed
  - Off-shell measurements treated separately
  - See David Sperka's talk yesterday on CMS diboson results

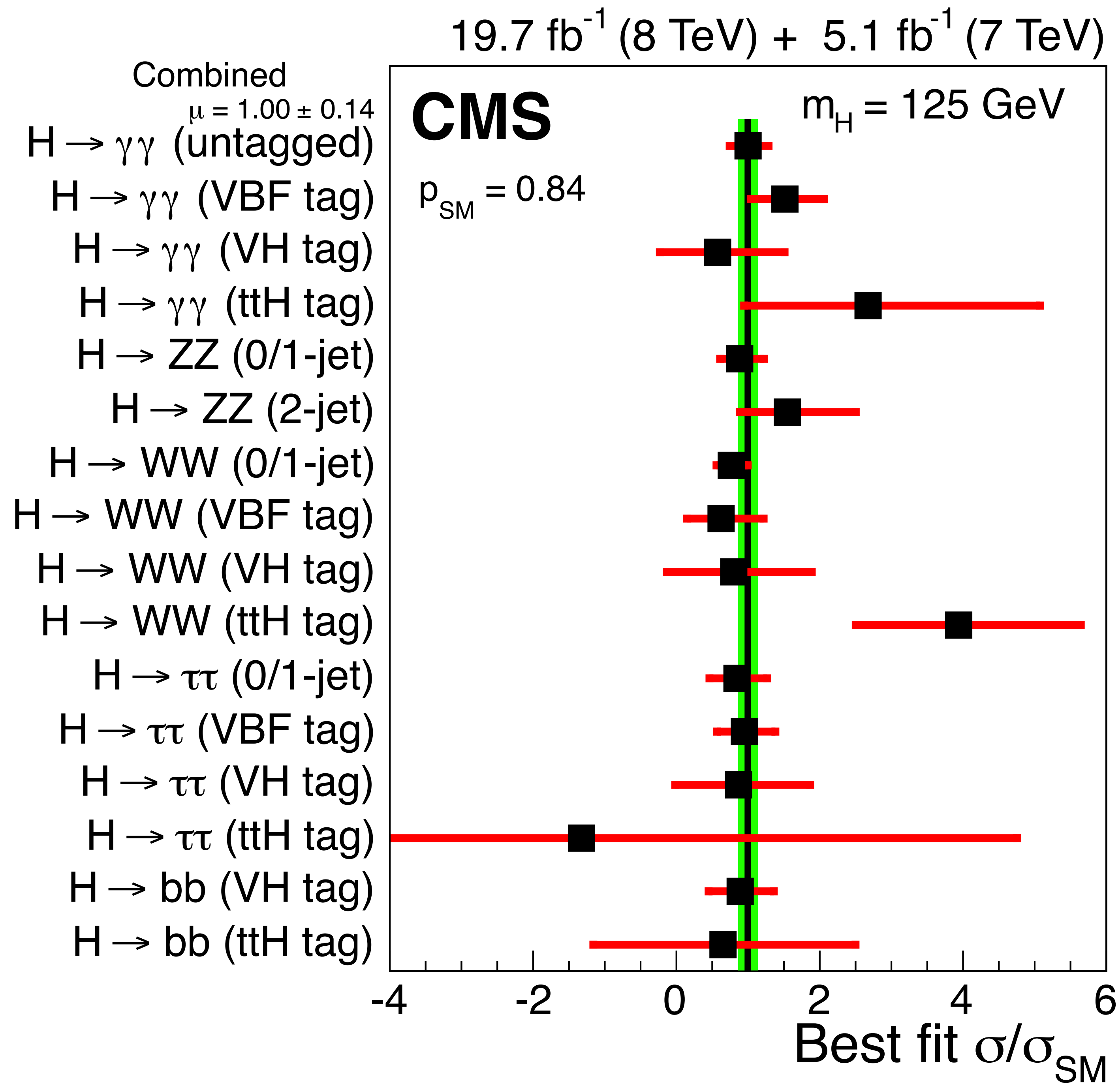
Signal Strength (σ/σ_{SM})

- Best fit signal strength for production- and decay-tag pairs
  - Tag by production and decay mode expected to dominate sensitivity in SM
  - All signal contributions to tag pair scaled together
  - p-value wrt SM = 0.84

- Overall combination

$$1.00 \pm 0.09(\text{stat})^{+0.08}_{-0.07}(\text{theo}) \pm 0.07(\text{syst})$$

  - Theory uncertainties: QCD scales PDFs, branching fractions, underlying event



Coupling Modifiers (κ_i)

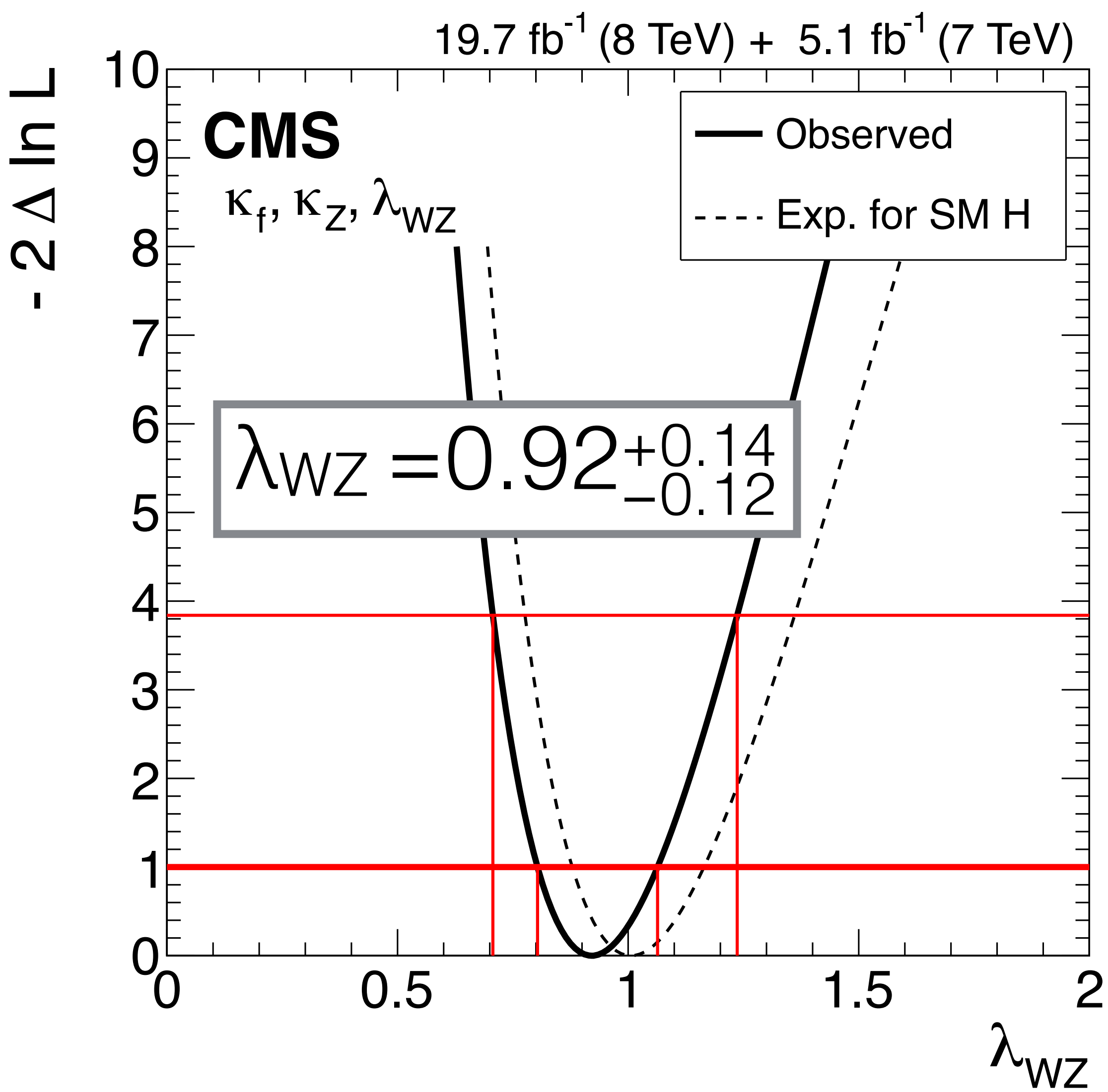
- With additional assumption that signal arises from single particle with $J^{PC} = 0^{++}$,

$$(\sigma \mathcal{B})\,(x \to \mathrm{H} \to yy) = \frac{\sigma_x\, \Gamma_{yy}}{\Gamma_{\mathrm{tot}}}$$

- $\Gamma_{\mathrm{tot}} = \Sigma\Gamma_{ii} + \Gamma_{\mathrm{BSM}}$, where $\Gamma_{\mathrm{BSM}} = \Gamma_{\mathrm{inv}} + \Gamma_{\mathrm{undet}}$

- Introduce coupling modifiers (κ_i) to test for deviations from SM
  - Production: $\kappa_i^2 = \sigma_i/\sigma_i^{SM}$
  - Decay: $\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$
  - Total width: $\kappa_H^2 = \Gamma_{tot}/\Gamma_{SM}$

Couplings to Massive Vector Bosons and Fermions

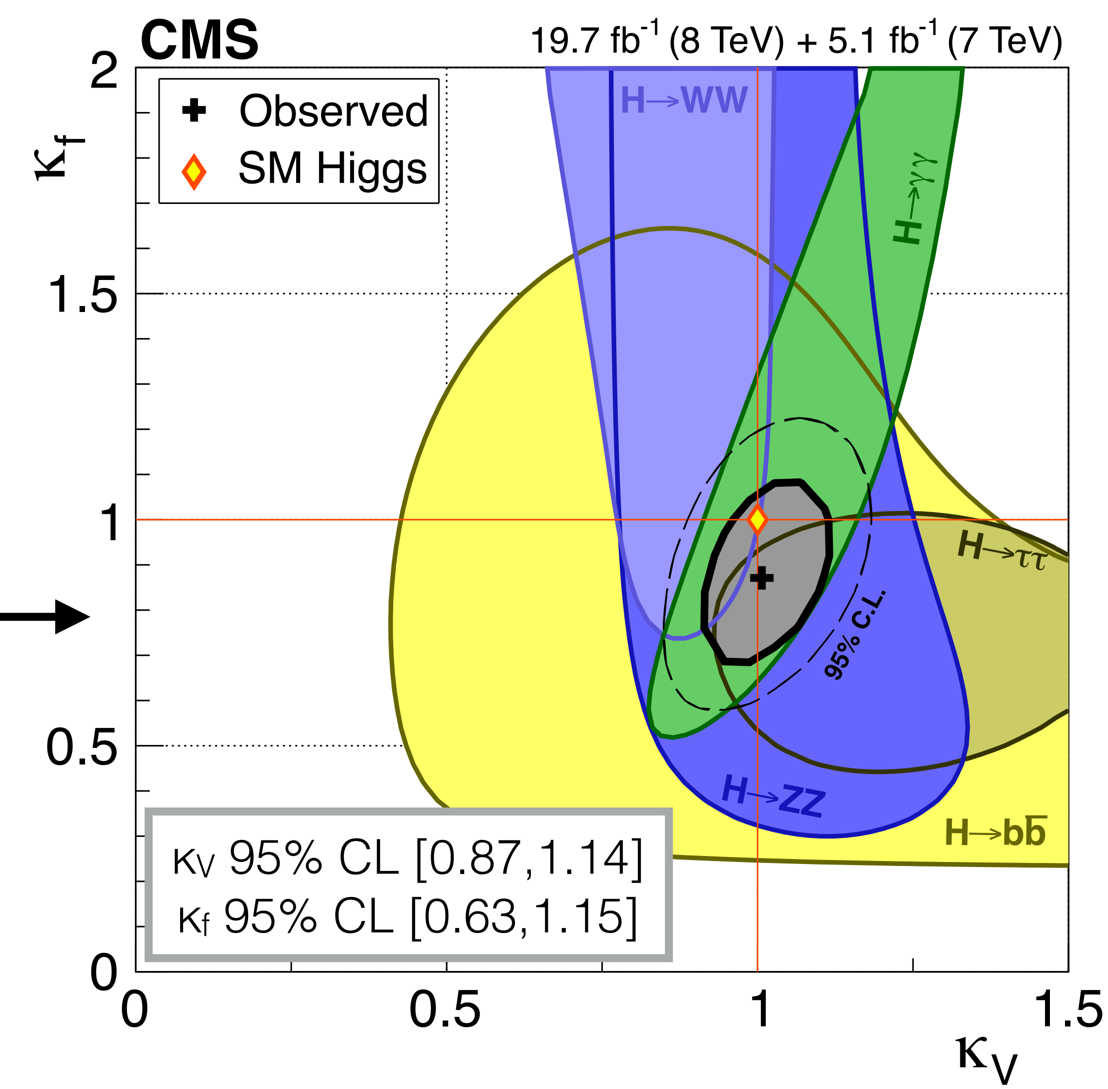


Test of custodial symmetry

- Likelihood scan of $\lambda_{WZ} = \kappa_W/\kappa_Z$ while profiling κ_Z and κ_f
- Assume single κ_f and $\Gamma_{BSM} = 0$
- Consistent with SM value of 1, resulting from protection against large radiative corrections

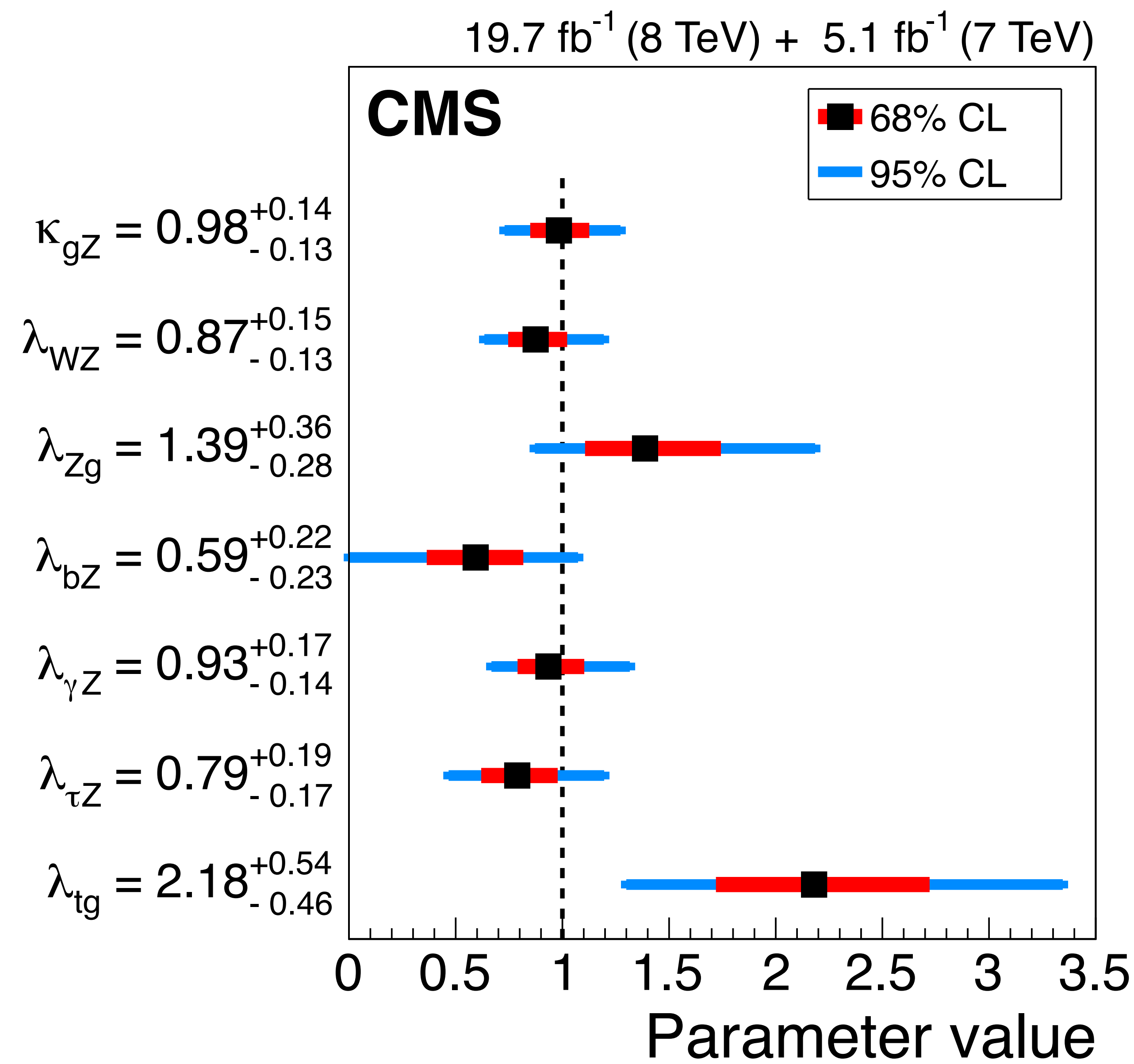
Couplings to vector boson and fermions

- 68% CL regions for κ_V and κ_f
- Assume $\Gamma_{BSM} = 0$
- Shows complementarity of combined channels
- Consistent with SM value of (1,1)



Generic Modifier Ratio Model

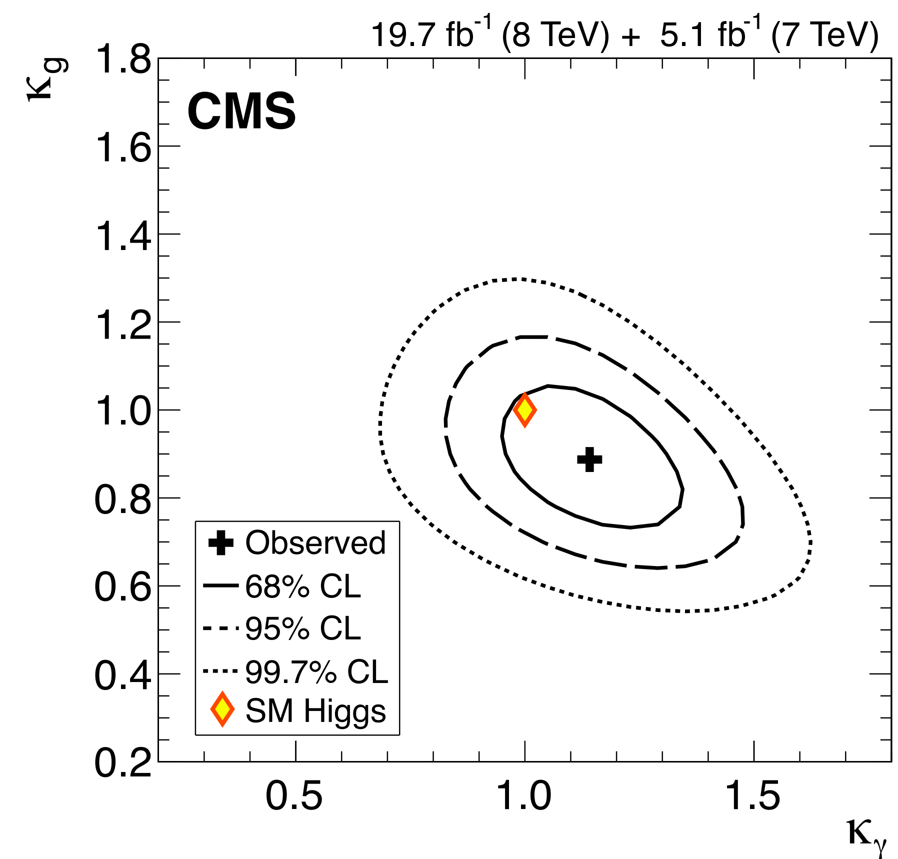
- Most general model proposed by LHCXSWG (arXiv:1307.1347)
- Parameters are
  - $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$, where $\kappa_H^2 = \Gamma_{tot}/\Gamma_{SM}$ modifies the width
  - Ratios of couplings $\lambda_{ij} = \kappa_i/\kappa_j$
- No assumption on scaling of total width.
- Most significant deviation is driven by excess in ttH channels



New Physics

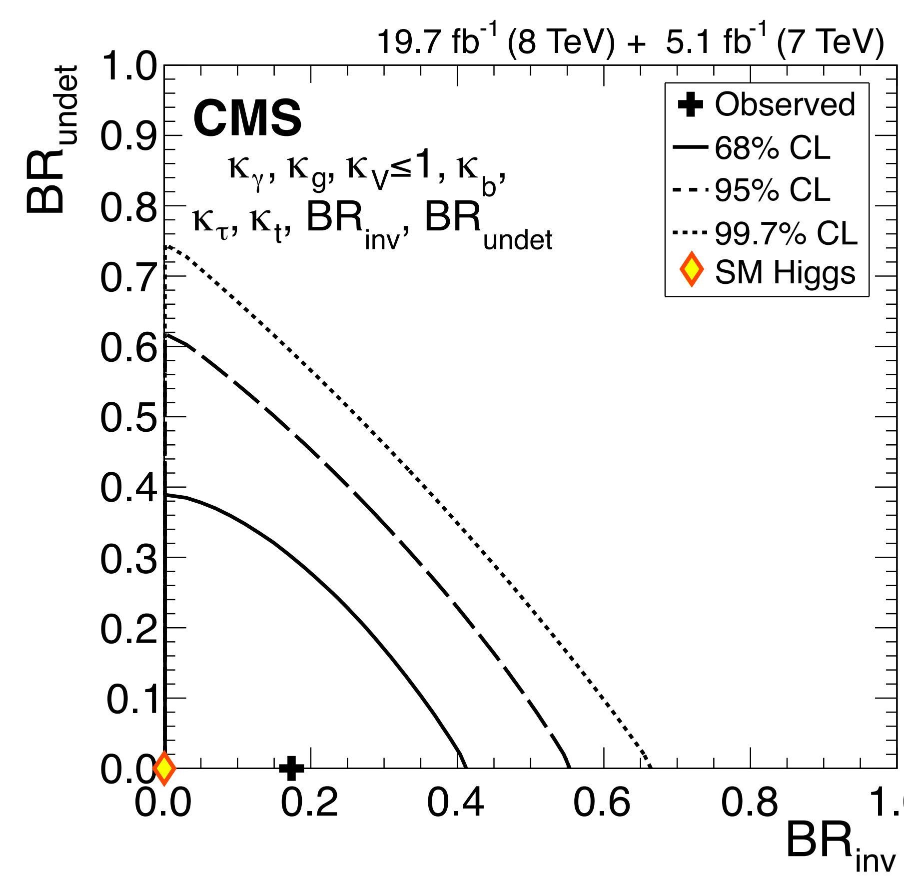
In loops

- ggH production and H→γγ decay are loop-induced at leading order
- Likelihood scan of κ_g and κ_γ assuming SM tree-level couplings and $\Gamma_{BSM} = 0$
- Best fit $(\kappa_g, \kappa_\gamma) = (1.14, 0.89)$ is compatible with SM within 68% CL region



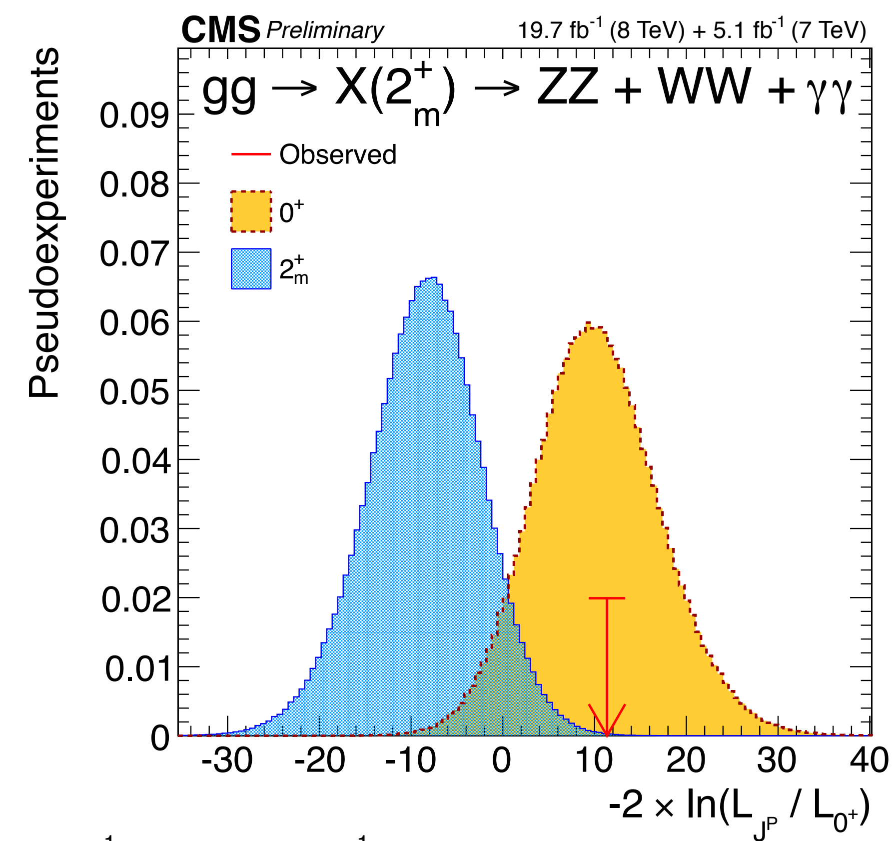
Undetected and invisible decays

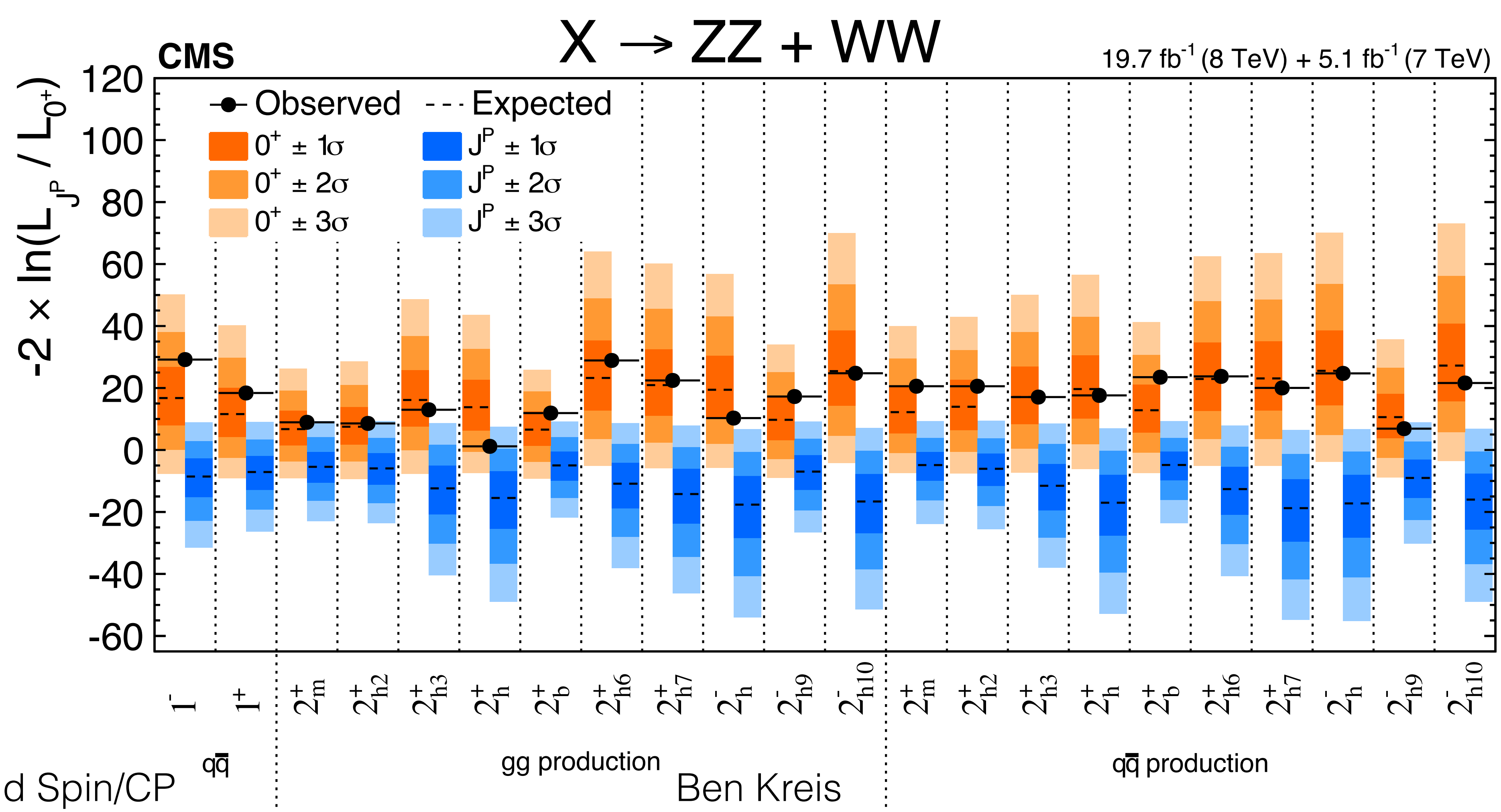
- Include H→inv search results to constrain $BR_{inv} = \Gamma_{inv}/\Gamma_{tot}$
  - Uncombined: BR_{inv} observed (expected) 95% CL upper limit = 0.58 (0.44)
- Simultaneous fit for BR_{inv} and $BR_{undet} = \Gamma_{undet}/\Gamma_{tot}$ while profiling κ_γ, κ_g, $\kappa_V \leq 1$, κ_b, κ_τ, κ_t
  - Very general!



Exotic Spin Scenarios

- Spin-two
  - with gravity-like minimal couplings excluded at 99.87% CL in combination of H→ZZ, H→WW, and H→γγ.
  - Another ten models excluded at 99% CL or higher.
- Any mixed-parity spin-one state is excluded at >99.999% CL in combination of H→ZZ and H→WW
- Fraction of non-interfering exotic spin state in addition to $J^P=0^+$ state also considered.





Spin 0 Anomalous Couplings Phenomenology

- Generic HV_1V_2 (V=W, Z, γ, g) scattering amplitude, expanded up to q^2

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

tree level scalar (0^+) — leading momentum expansion — 0^+_h — pseudoscalar (0^-)

higher order scalar

Interaction	Anomalous Coupling	Coupling Phase	Effective Fraction
HZZ	Λ_1	$\phi_{\Lambda 1}$	$f_{\Lambda 1}$
	a_2	ϕ_{a2}	f_{a2}
	a_3	ϕ_{a3}	f_{a3}
HWW	Λ_1^{WW}	$\phi_{\Lambda 1}^{WW}$	$f_{\Lambda 1}^{WW}$
	a_2^{WW}	ϕ_{a2}^{WW}	f_{a2}^{WW}
	a_3^{WW}	ϕ_{a3}^{WW}	f_{a3}^{WW}
$HZ\gamma$	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$
	$a_2^{Z\gamma}$	$\phi_{a2}^{Z\gamma}$	$f_{a2}^{Z\gamma}$
	$a_3^{Z\gamma}$	$\phi_{a3}^{Z\gamma}$	$f_{a3}^{Z\gamma}$
$H\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$	$f_{a3}^{\gamma\gamma}$

Example phase and effective fraction:

$$\phi_{a2} = \arg\left(\frac{a_2}{a_1}\right) \qquad f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/\left(\Lambda_1\right)^4}$$

where σ_i is the cross section for a_i=1 and $a_{j\neq i}$=0

A,B,C,D

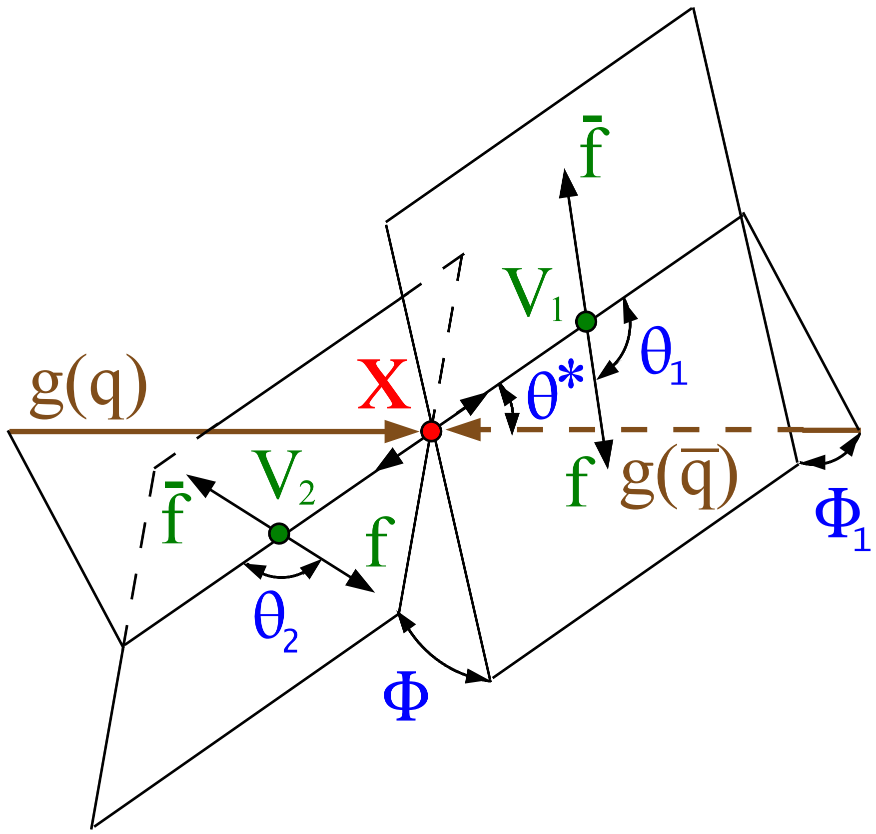
A

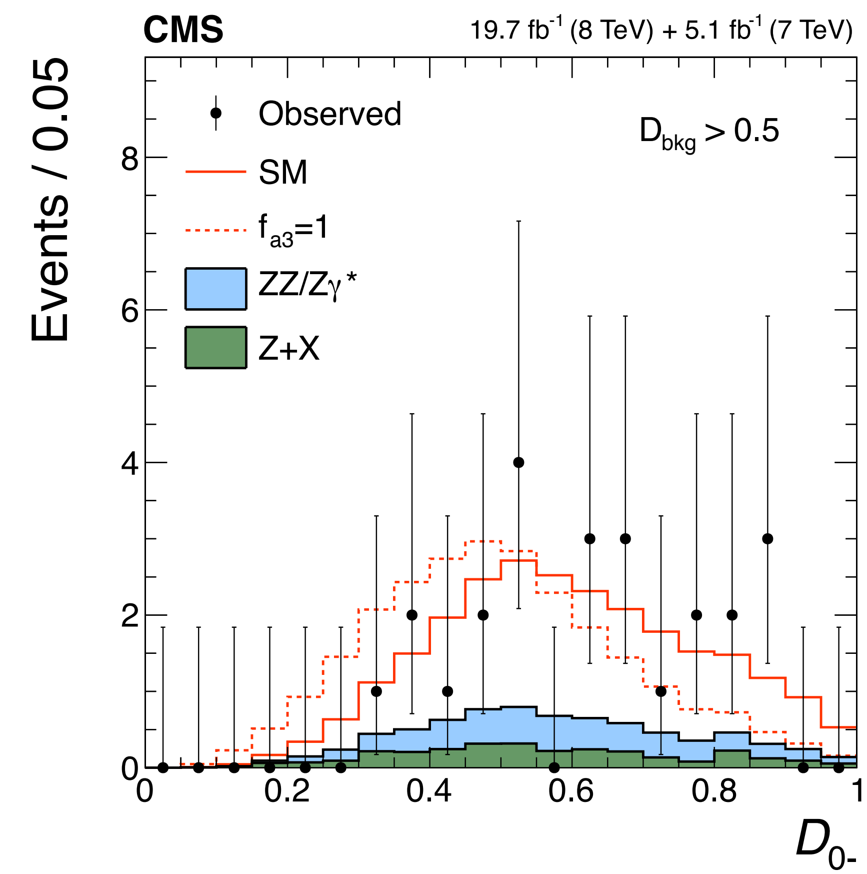
One non-zero anomalous coupling:
- A. real, ϕ_{ai} = 0, π
- B. complex, ϕ_{ai} unconstrained

Two non-zero anomalous couplings:
- C. real, $\phi_{ai,aj}$ = 0, π
- D. complex, $\phi_{ai,aj}$ unconstrained

Simulated with JHUGen or POWHEG+JHUGen

Observables

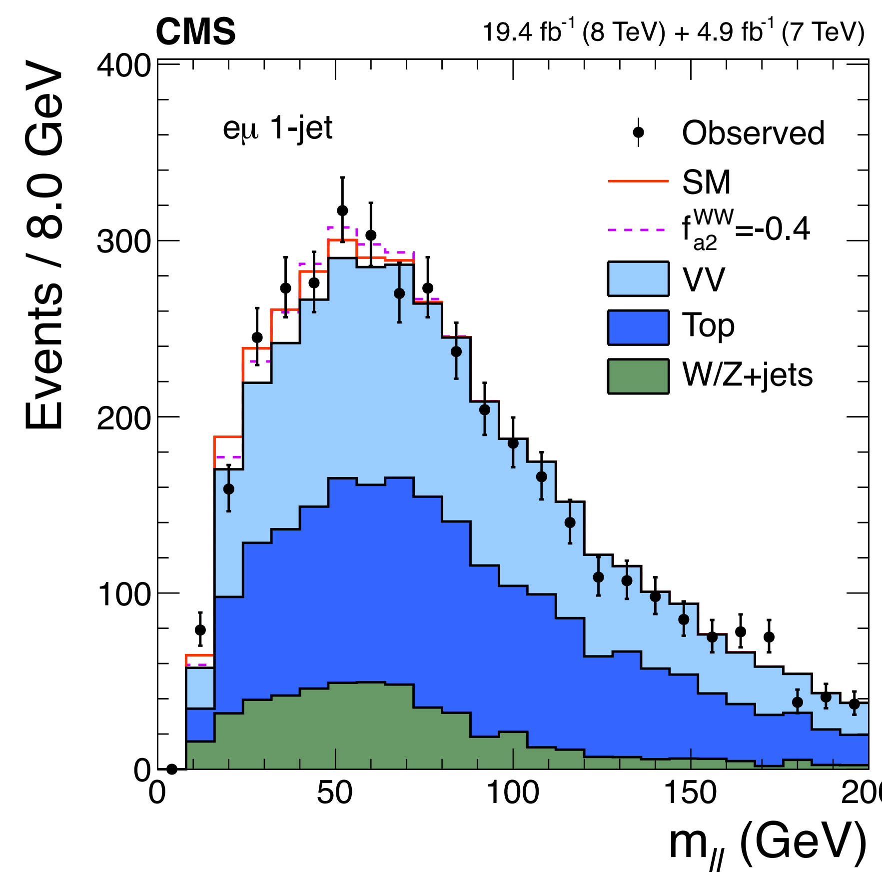




- Use 5 angles and 3 masses to describe H→VV→4l kinematics
  - Matrix elements define event by event probabilities for observed kinematics (MELA)
  - Construct kinematic discriminants from probabilities

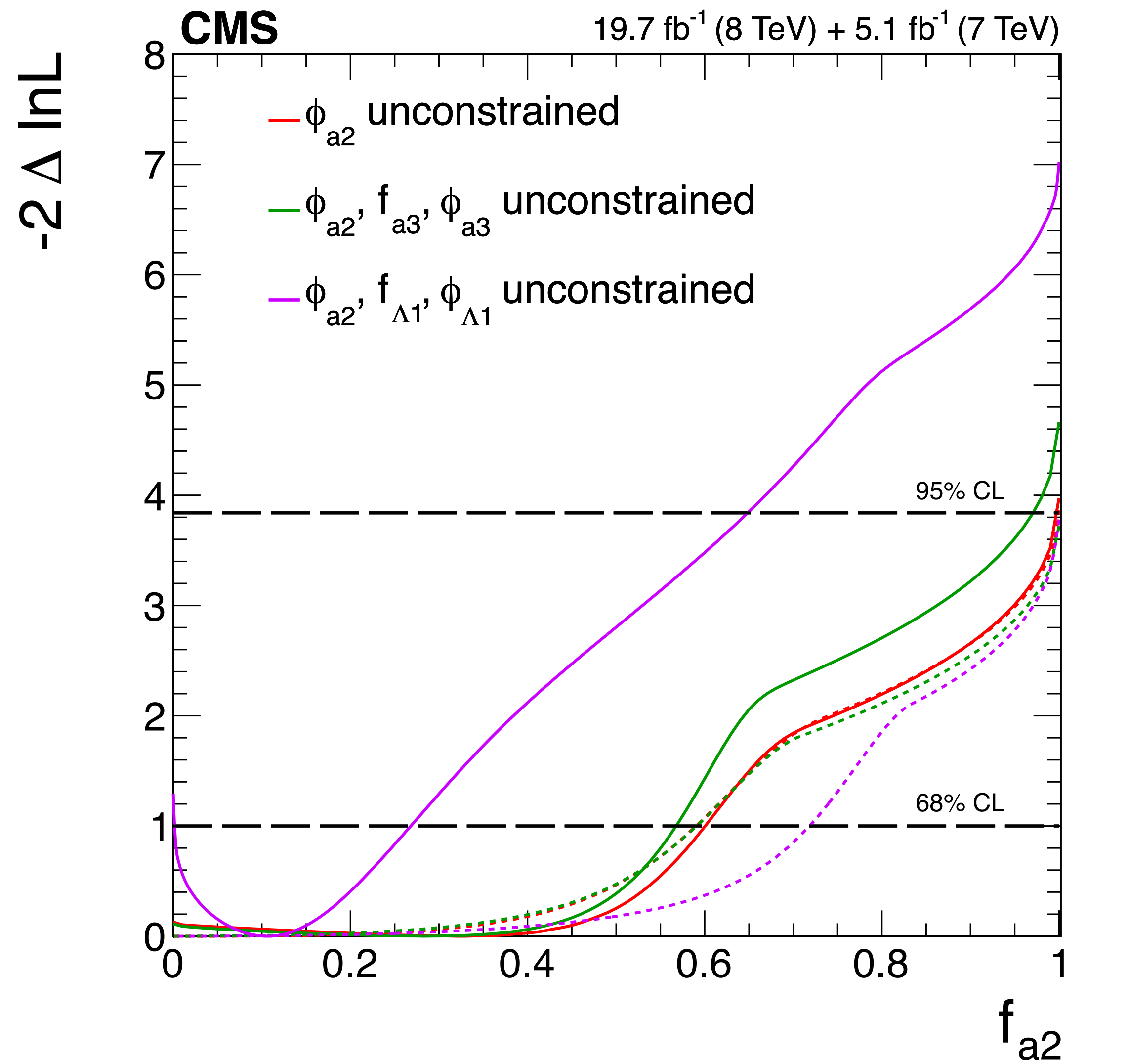
e.g. $$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}}$$

- H→WW→lνlν contains reduced information due to ν's
  - Use m_{ll} and m_T distinguish signal models



HZZ: complex a_i

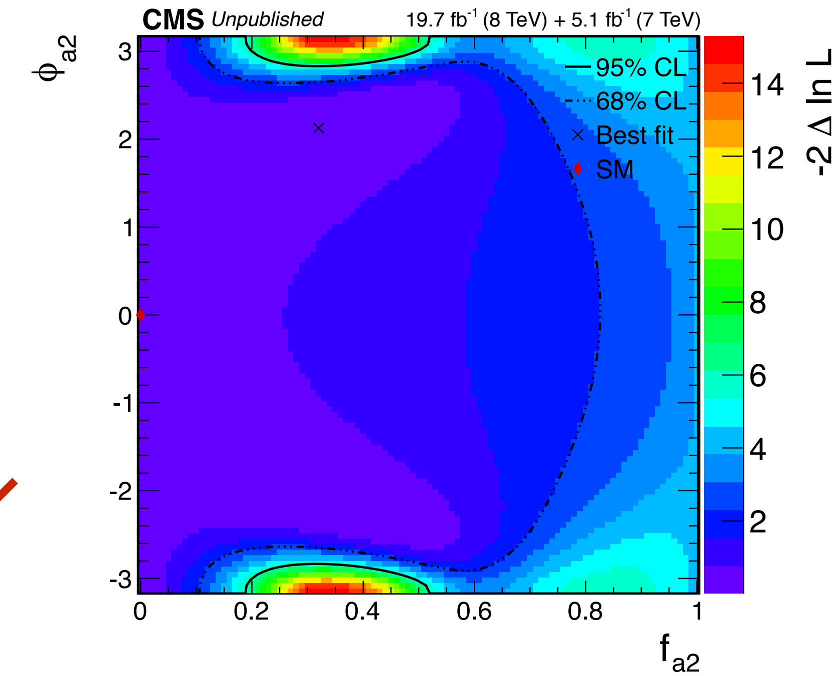
Example: f_{a2}



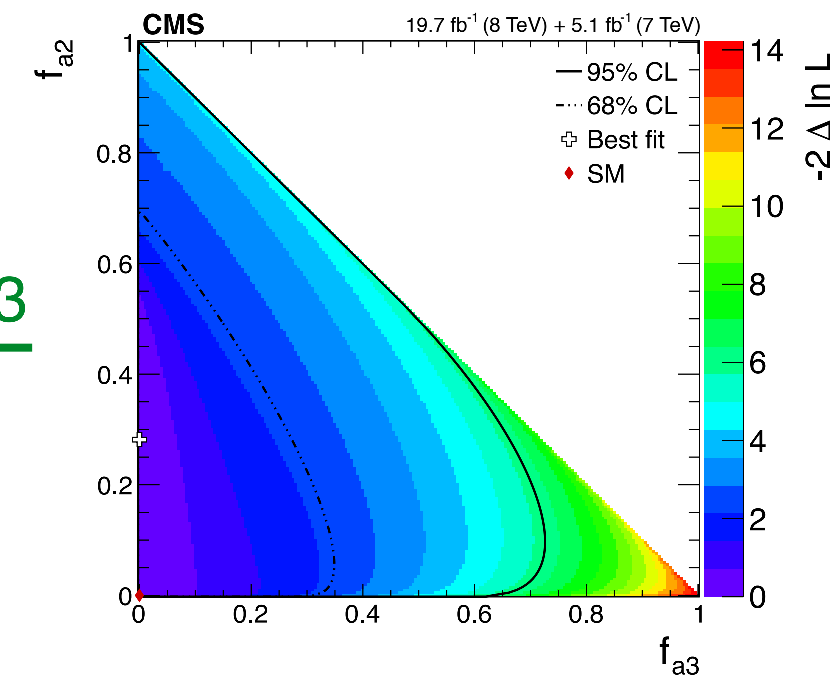
SM ⟶ 0^+_h

all consistent with SM

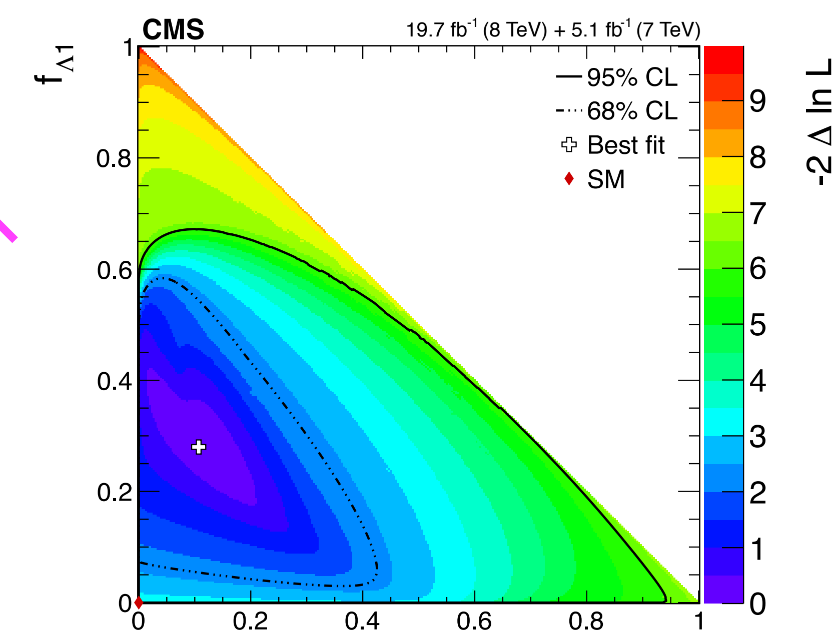
profile ϕ_{a2}



profile f_{a3}

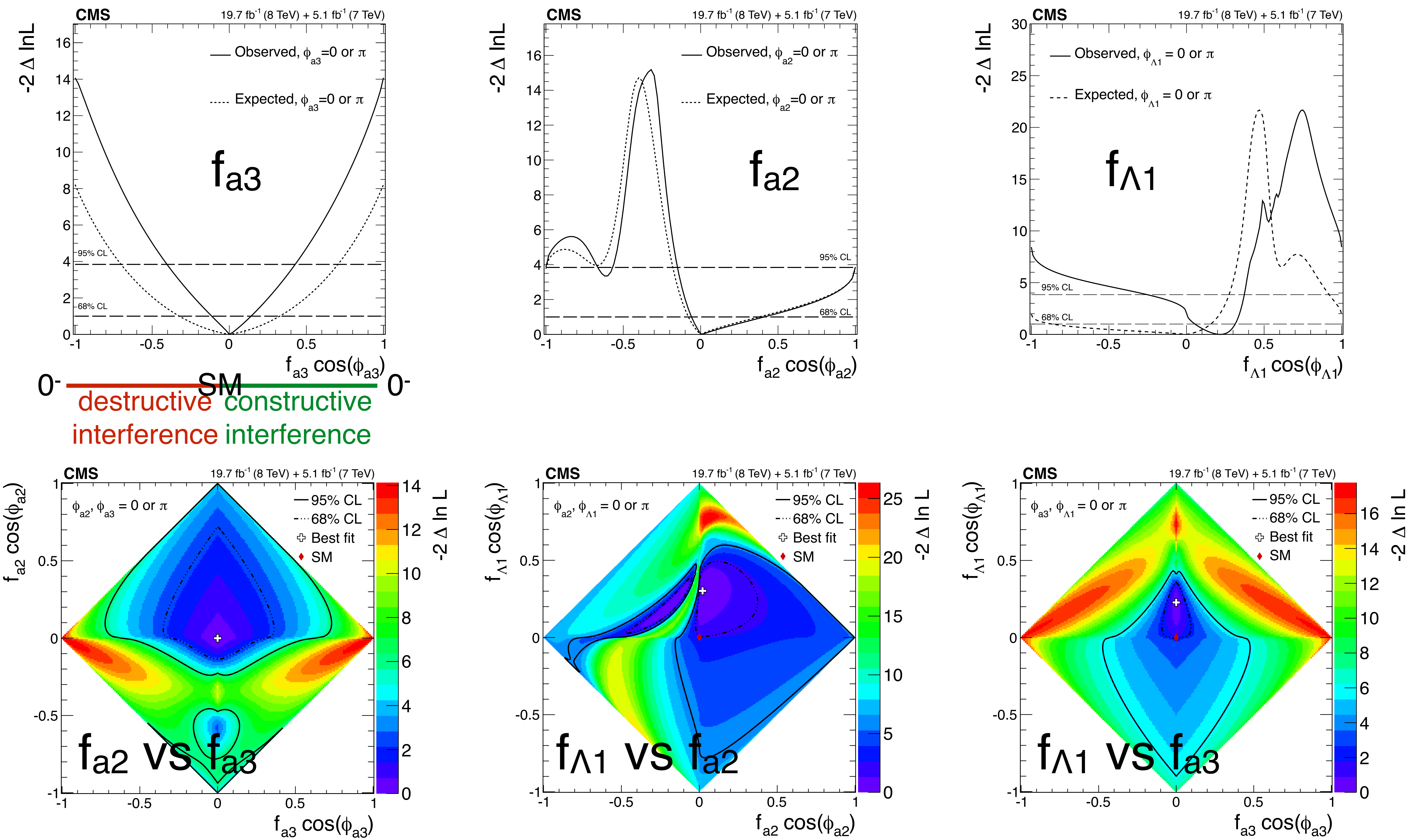


profile $f_{\Lambda 1}$



HZZ: real a_i

- Couplings assumed to be real, so ϕ_{ai} = 0 or π and cos(ϕ_{ai}) = 1 or -1



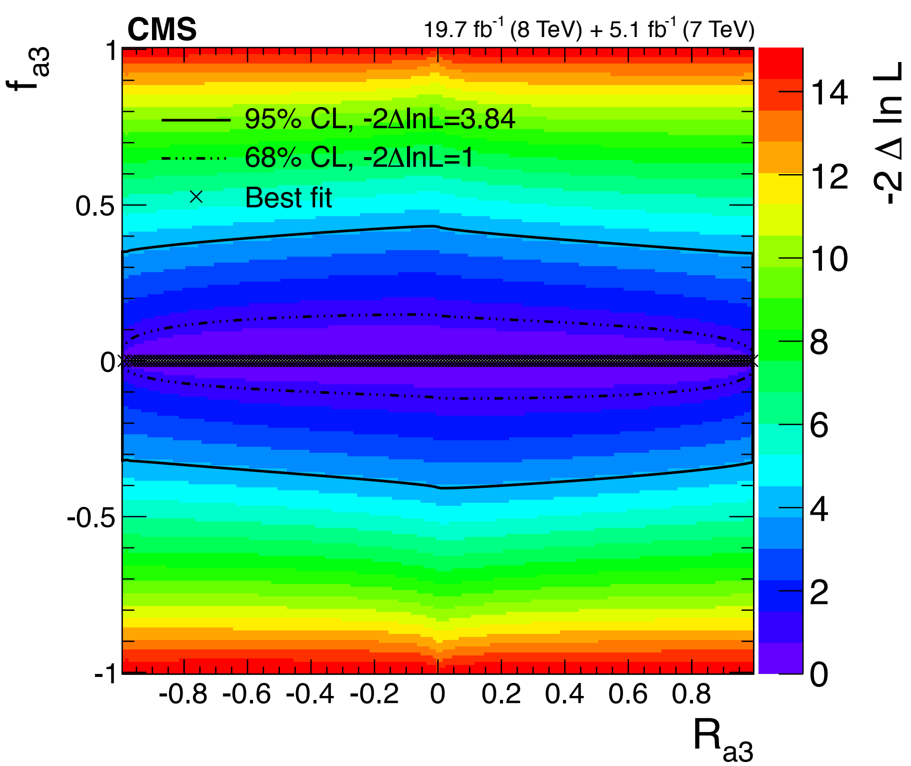
all consistent with SM

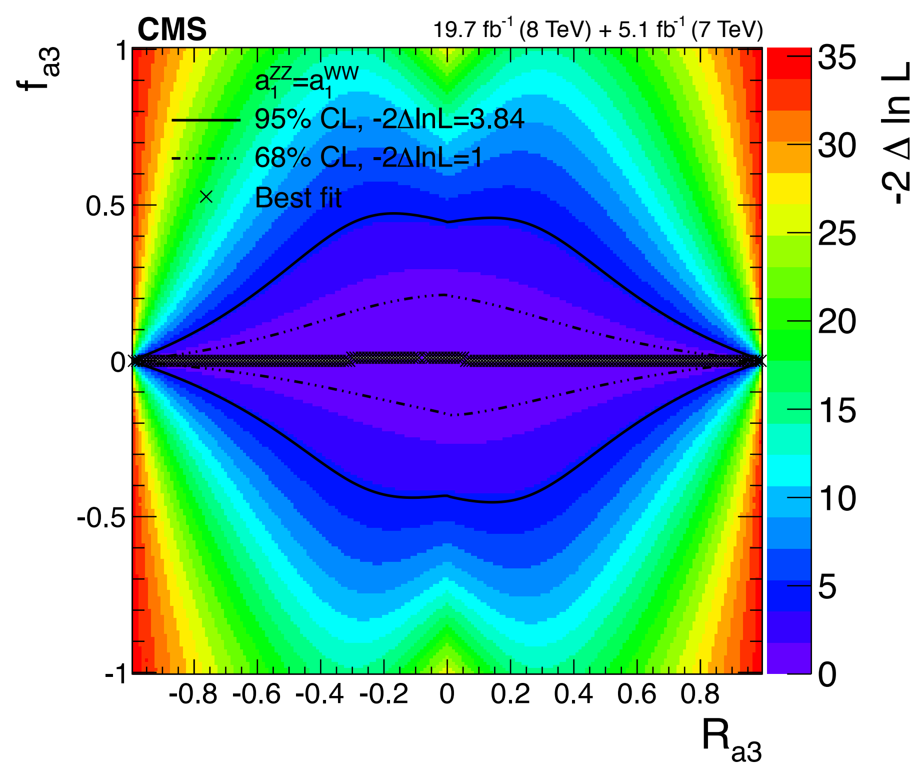
H→ZZ + H→WW Combination

- *A priori*, no relationship between HZZ and HWW couplings
- Combine H→ZZ and H→WW after assuming a relationship

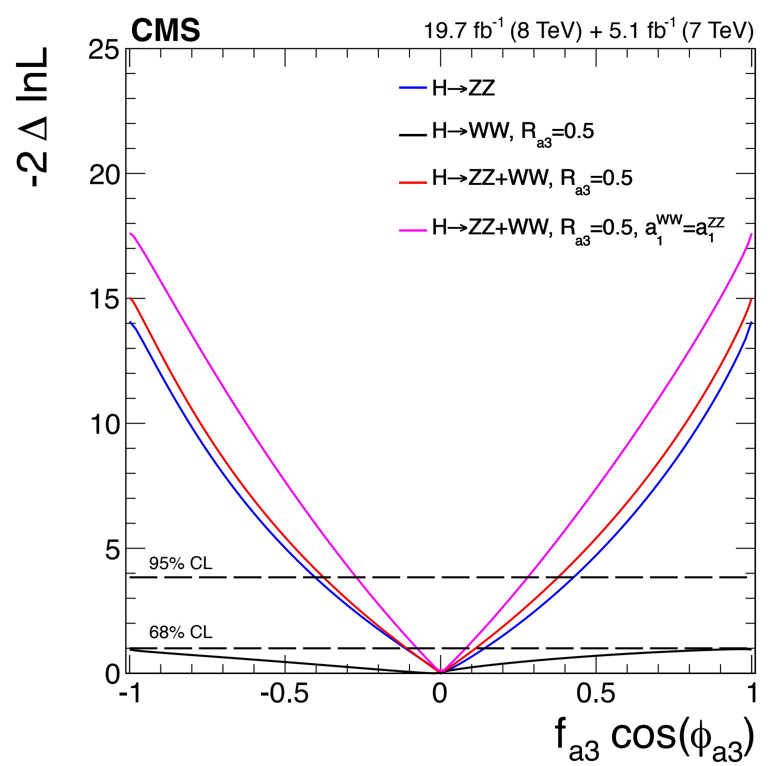
$$r_{ai} = \frac{a_i^{WW}/a_1^{WW}}{a_i/a_1}, \text{ or } R_{ai} = \frac{r_{ai}|r_{ai}|}{1+r_{ai}^2}.$$

- Custodial symmetry implies $a_1 = a_1^{WW}$





$a_1 = a_1^{WW}$



$r_{ai} = 1$, or $R_{a3} = 0.5$

$f_{\Lambda 1}$ and f_{a2} in backup
all consistent with SM

$f_{\Lambda Q}$ NEW! arXiV:1507.06656

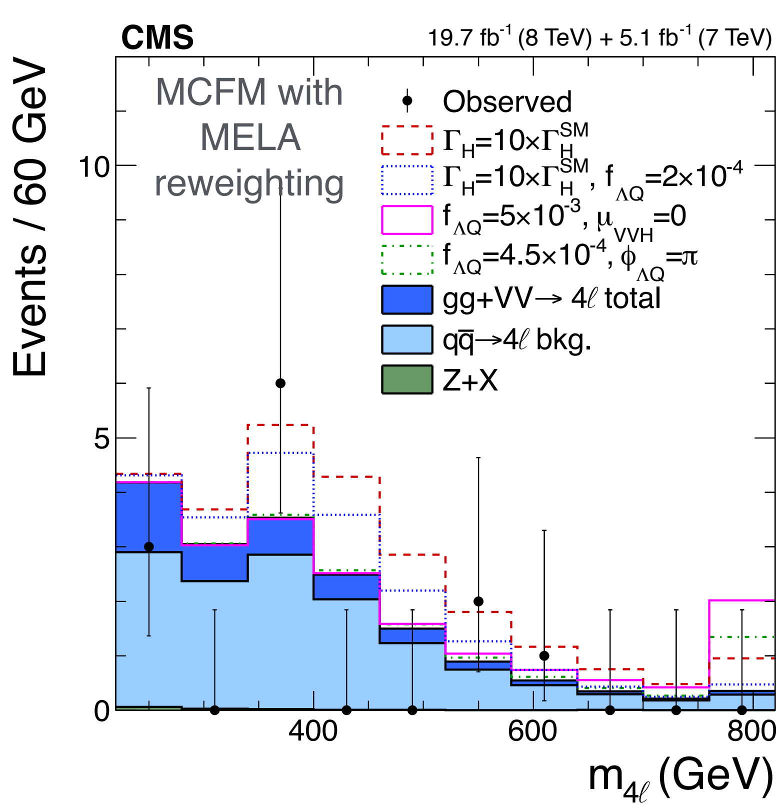
- Additional term depending only on invariant mass of Higgs boson

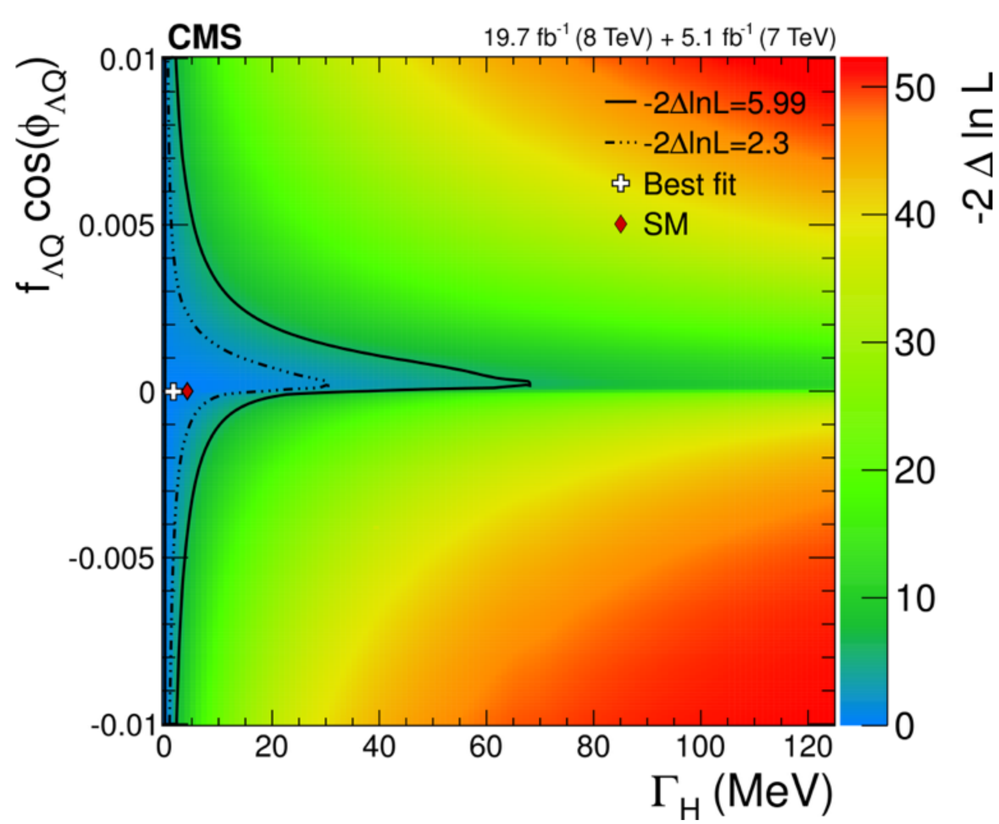
$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

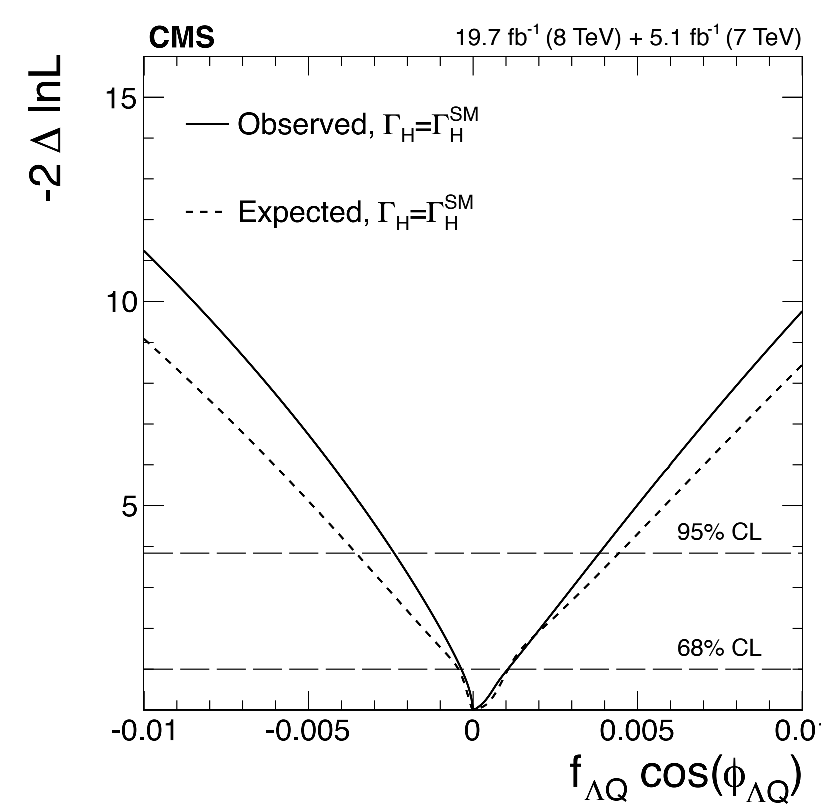
- Must be tested in off-shell region

$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}$$

- Joint constraint on width and Λ_Q anomalous coupling

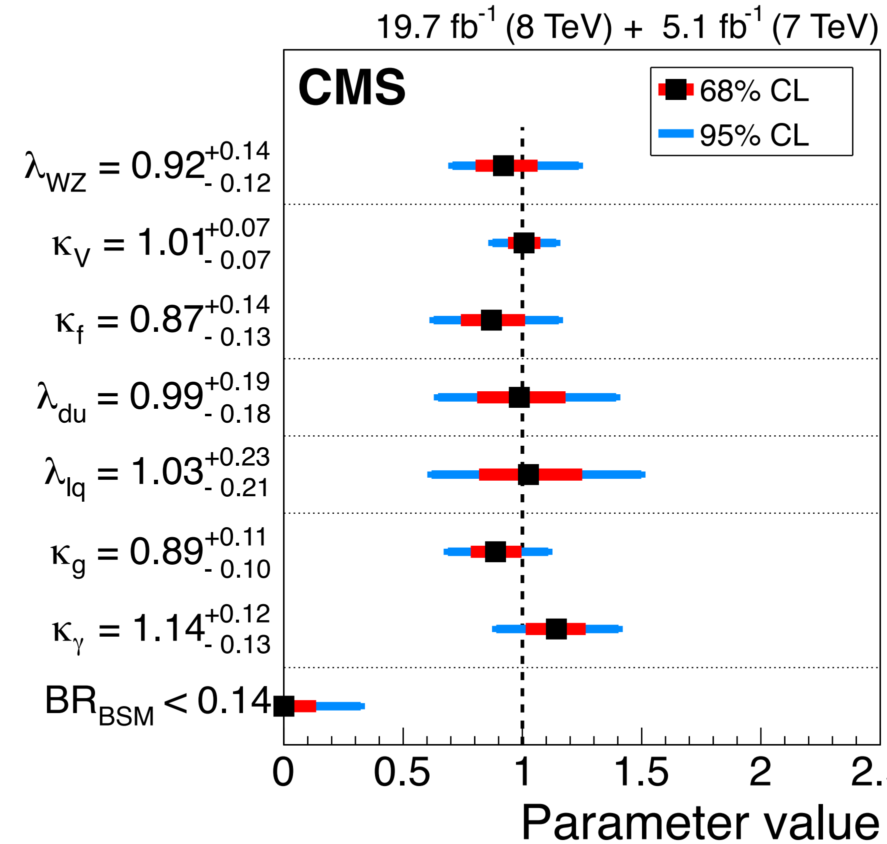


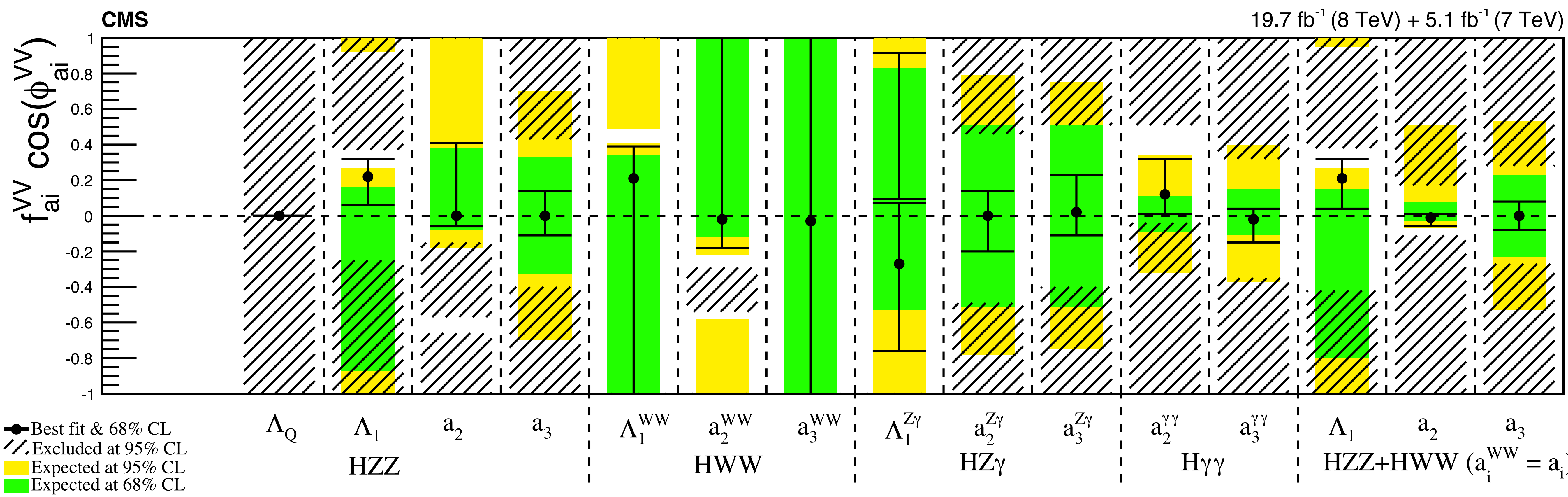




Conclusions

- Comprehensive sets of Higgs measurements combined to test compatibility of couplings with SM
- Constraints placed on exotic spin states and spin-zero anomalous couplings,
  - Including new results on $f_{\Lambda Q}$
- All observations are consistent with the standard model scalar $J^{PC}=0^{++}$

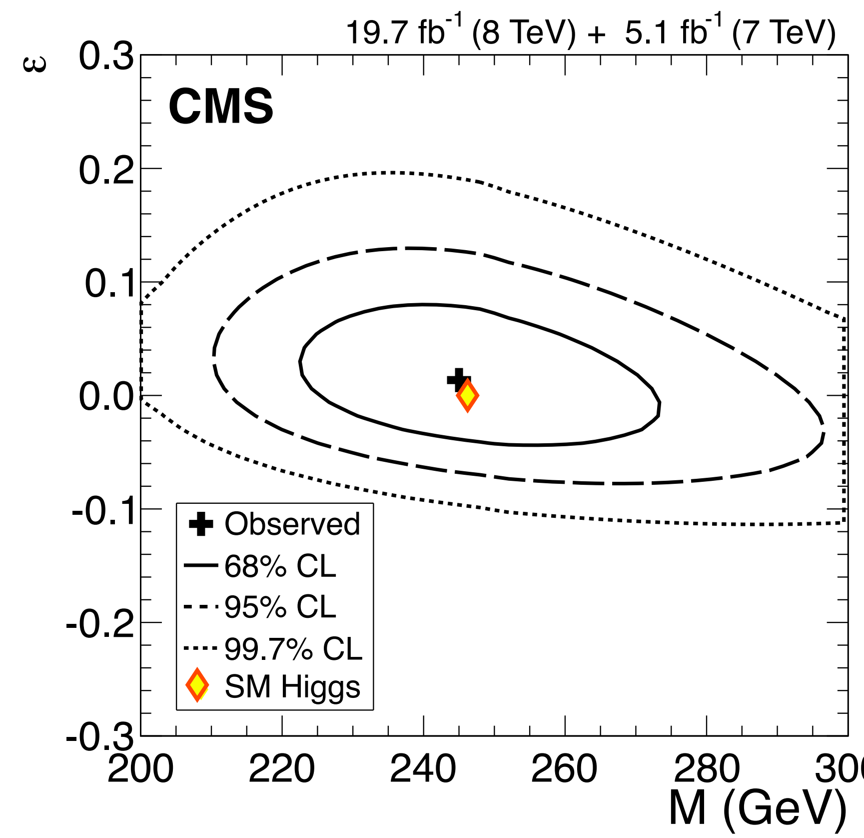


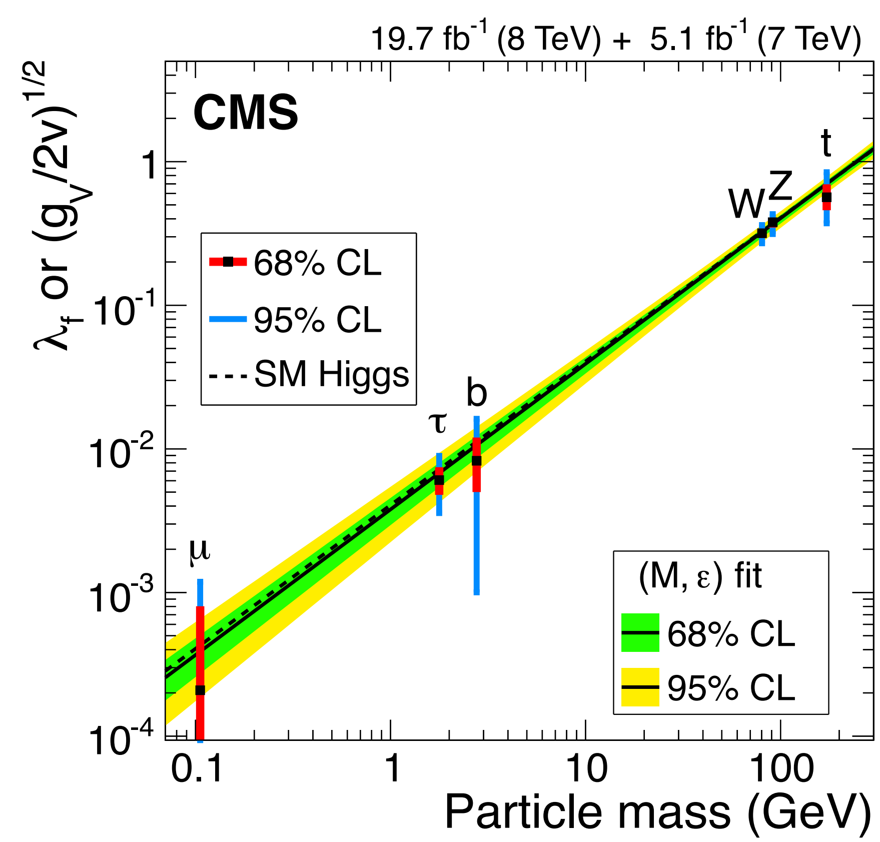


Backup

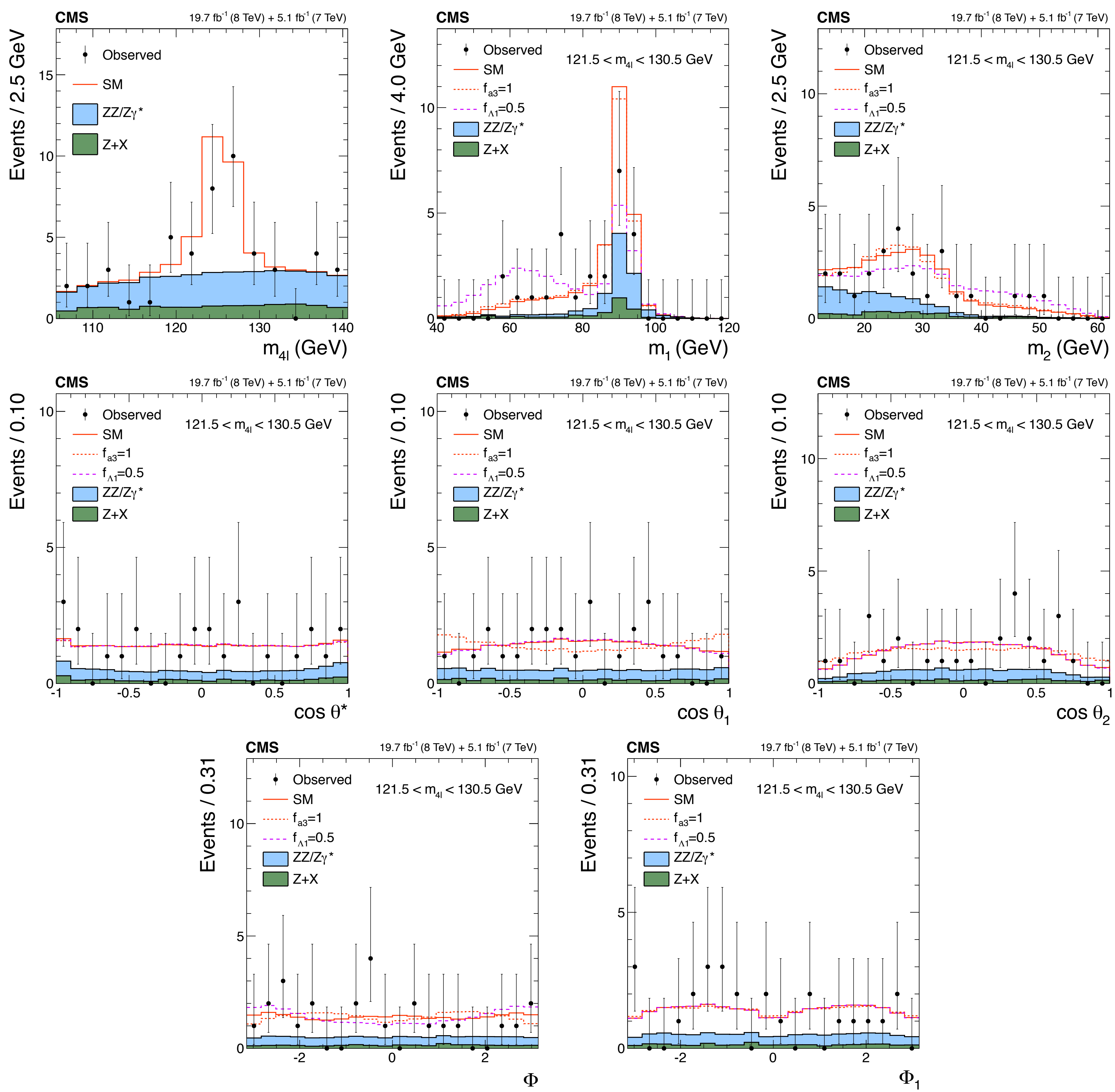
Scaling of couplings with mass

- Phenomenological parameterization relating masses to coupling modifiers with two parameters
  - $\kappa_f = v\, m_f^{\varepsilon}/M^{1+\varepsilon}$
  - $k_V = v\, m_V^{2\varepsilon}/M^{1+2\varepsilon}$
- SM recovered for (M,ε) = (v,0), where v = 246 GeV
- Assume
  - Coupling to massive SM particles only, one parameter per tree-level coupling
  - SM loop structure

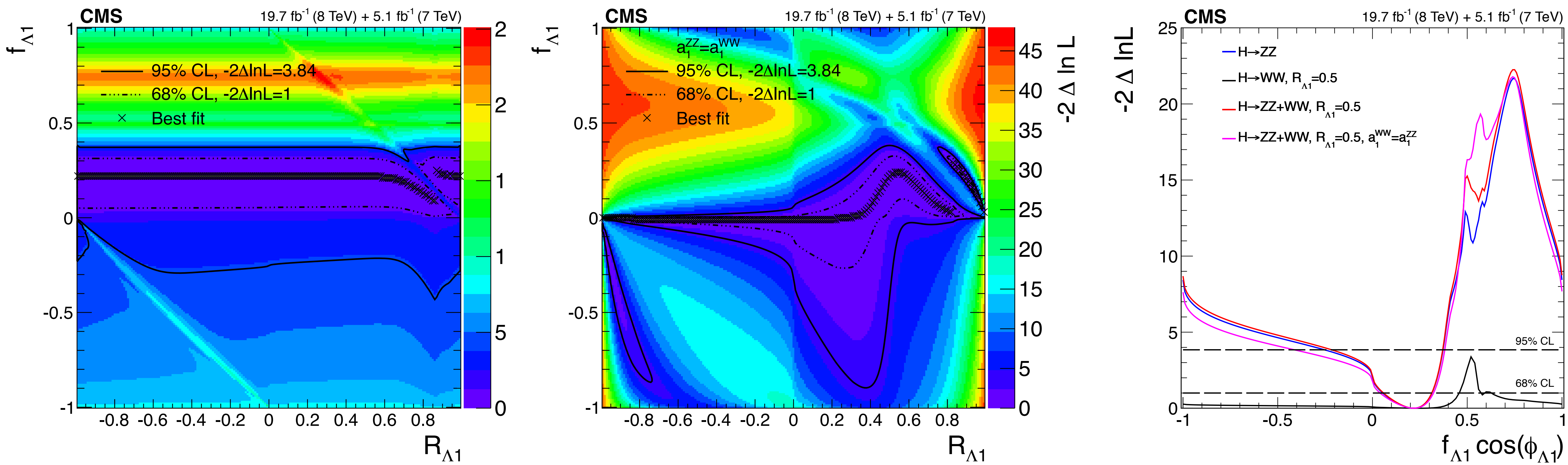




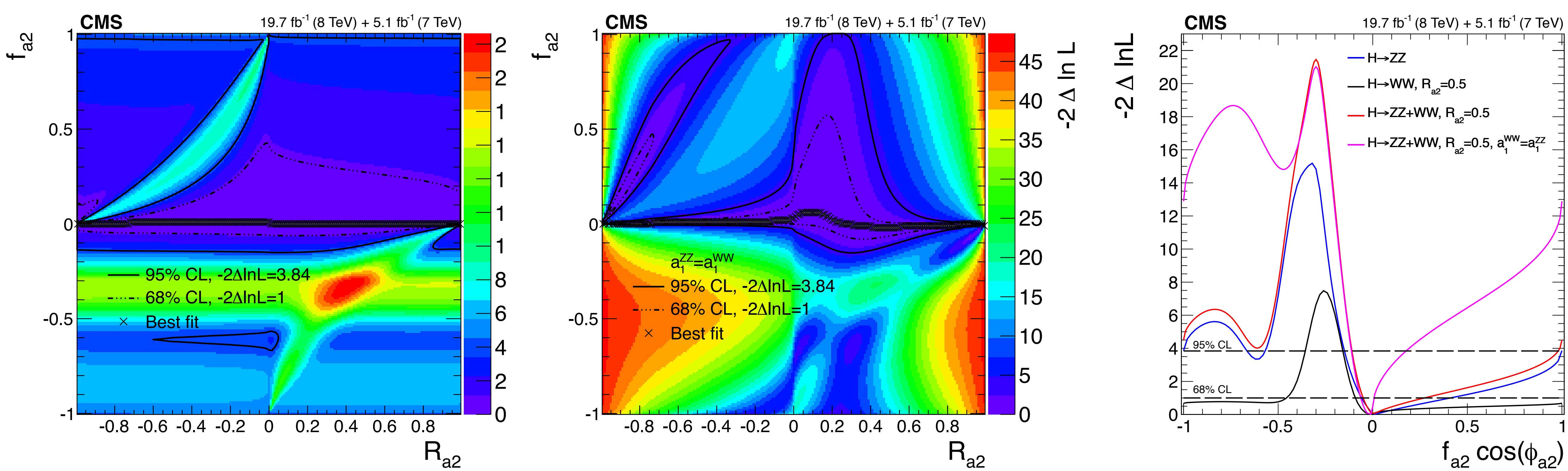
H→VV→4l Kinematics



H→ZZ + H→WW Combination

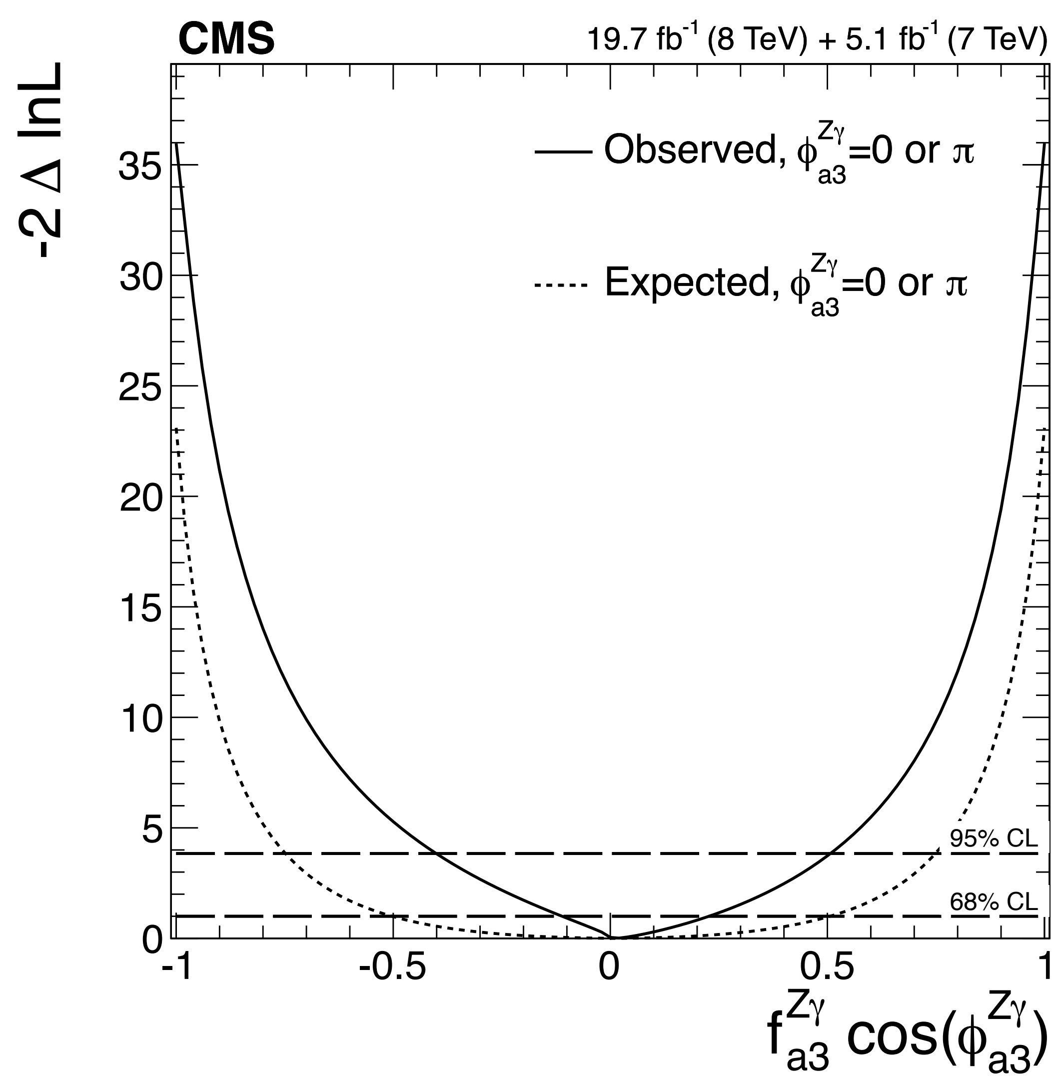


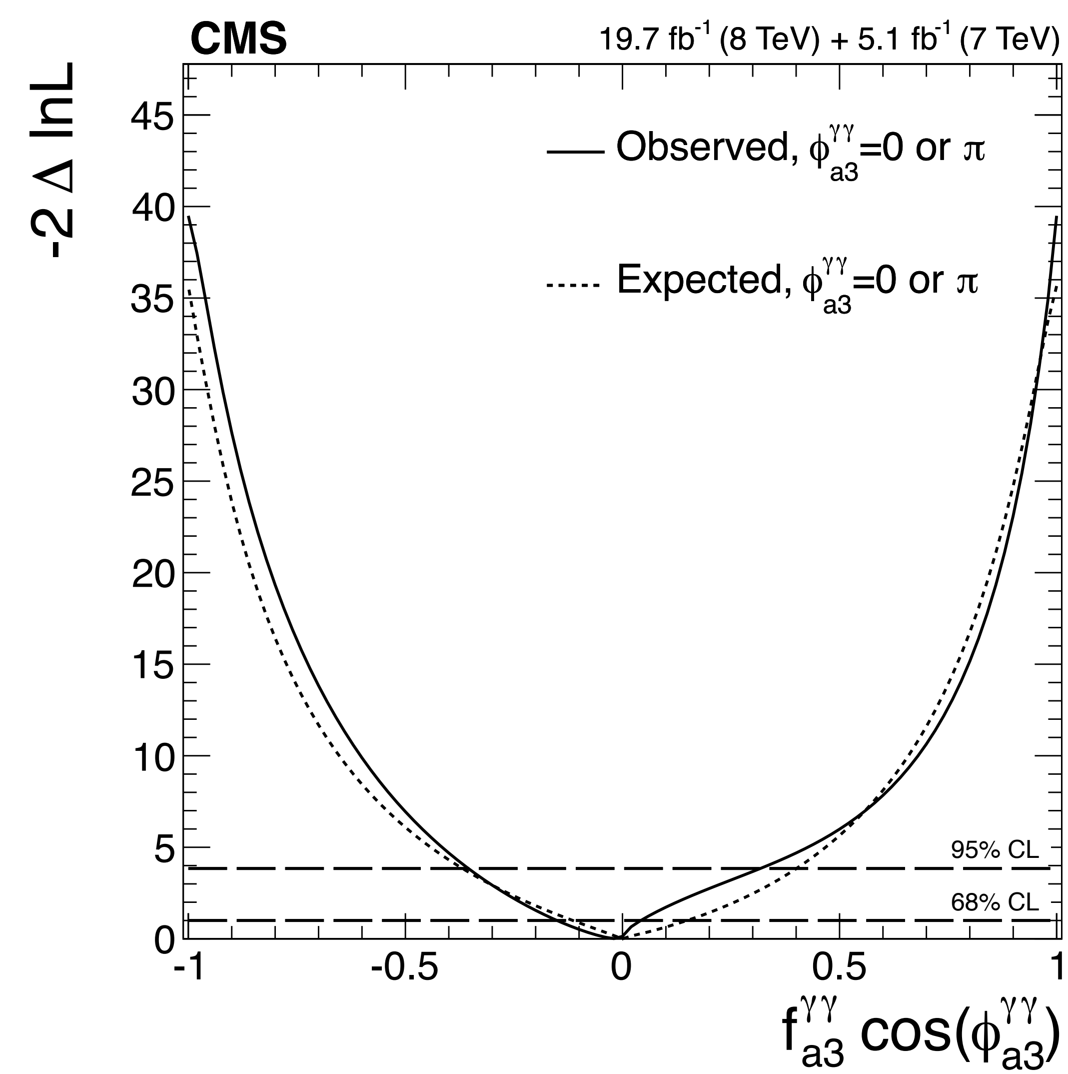
$a_1 = a_1^{WW}$



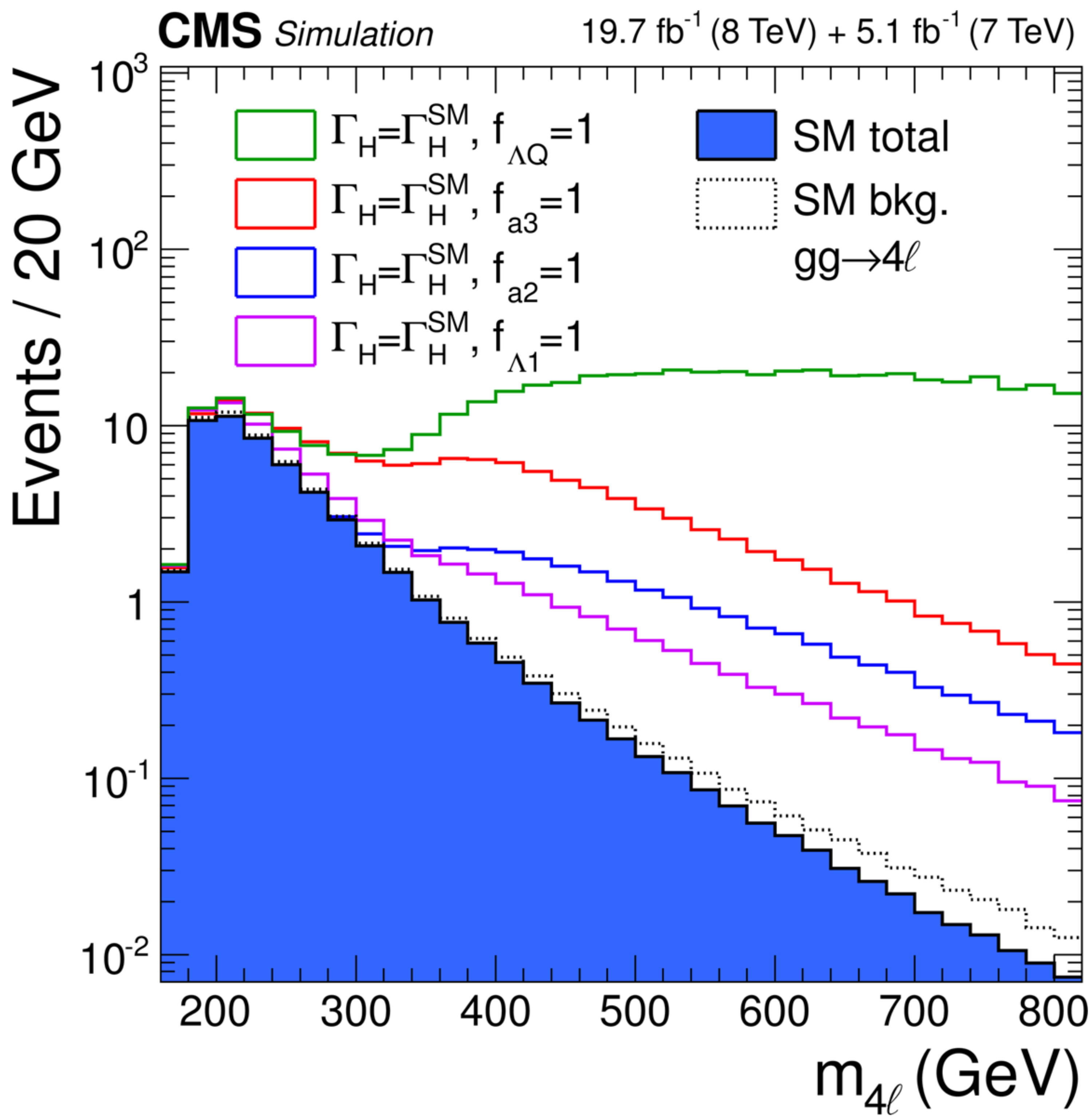
HZγ and Hγγ

- H→VV→4l, where VV = Zγ*, γ *γ*
- Currently, not competitive with direct cross section measurements from on-shell H→Zγ or H→γγ
- However, with sufficient luminosity, $f_{a3}^{V\gamma}$ and $f_{a2}^{V\gamma}$ can be measured separately in this channel. Also $f_{\Lambda 1}^{Z\gamma}$.





$f_{\Lambda Q}$



CMS Simulation
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
Events / 20 GeV
ΓH=ΓHSM, fΛQ=1
ΓH=ΓHSM, fa3=1
ΓH=ΓHSM, fa2=1
ΓH=ΓHSM, fΛ1=1
SM total
SM bkg.
gg→4ℓ
m4ℓ (GeV)