Higgs boson spin/parity and tensor structure (ATLAS+CMS)

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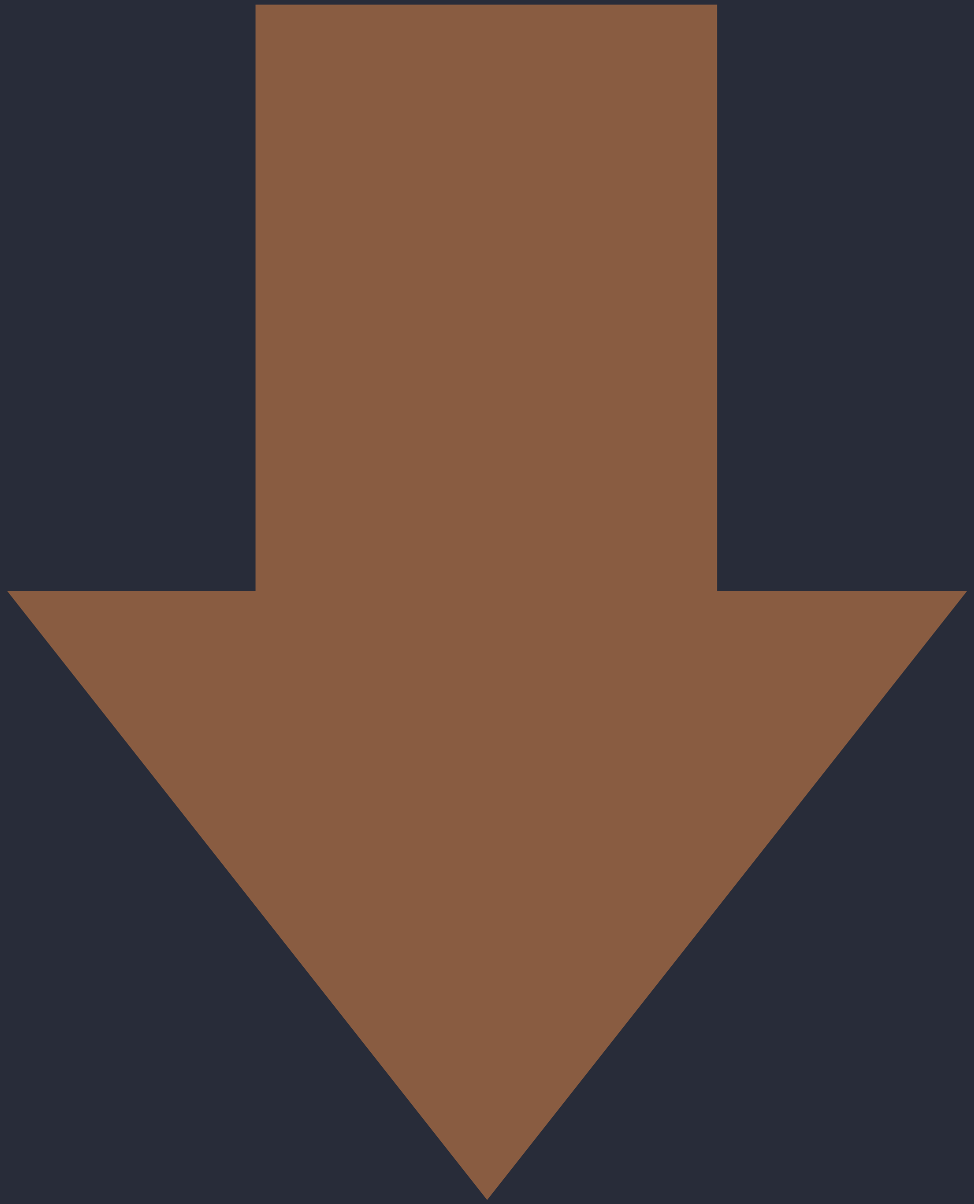

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Decay of a spin-0 resonance

Interaction between a spin-0 Higgs boson and two gauge bosons, V_1 and V_2

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

Equivalent to EFT Lagrangian, next slide.

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Equivalent to EFT Lagrangian, next slide.

Measurements

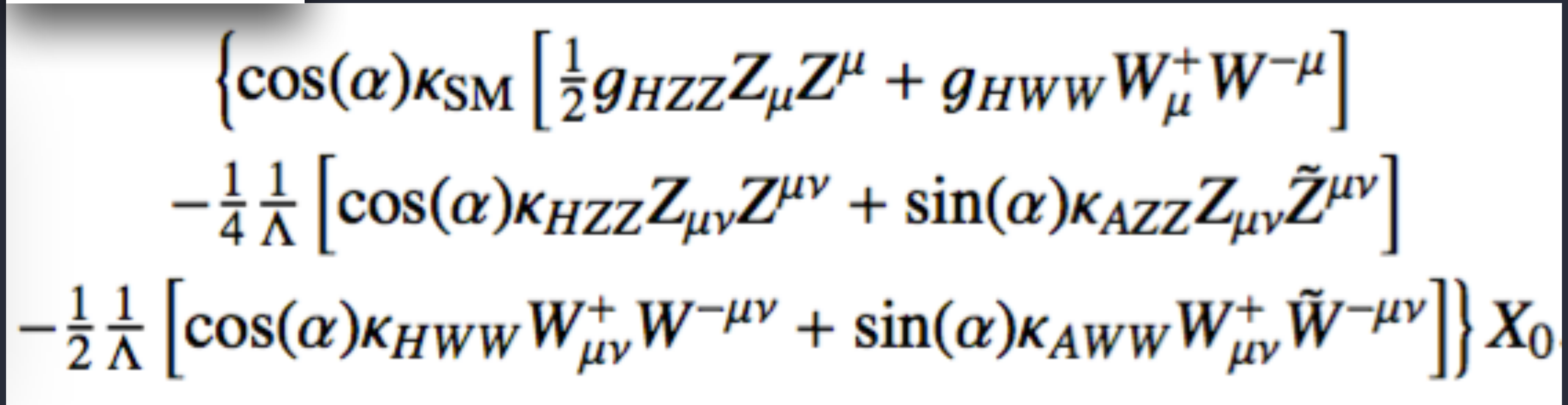
Hypothesis tests

Pure 0^- (a_3) or 0_h^+ (a_2) states

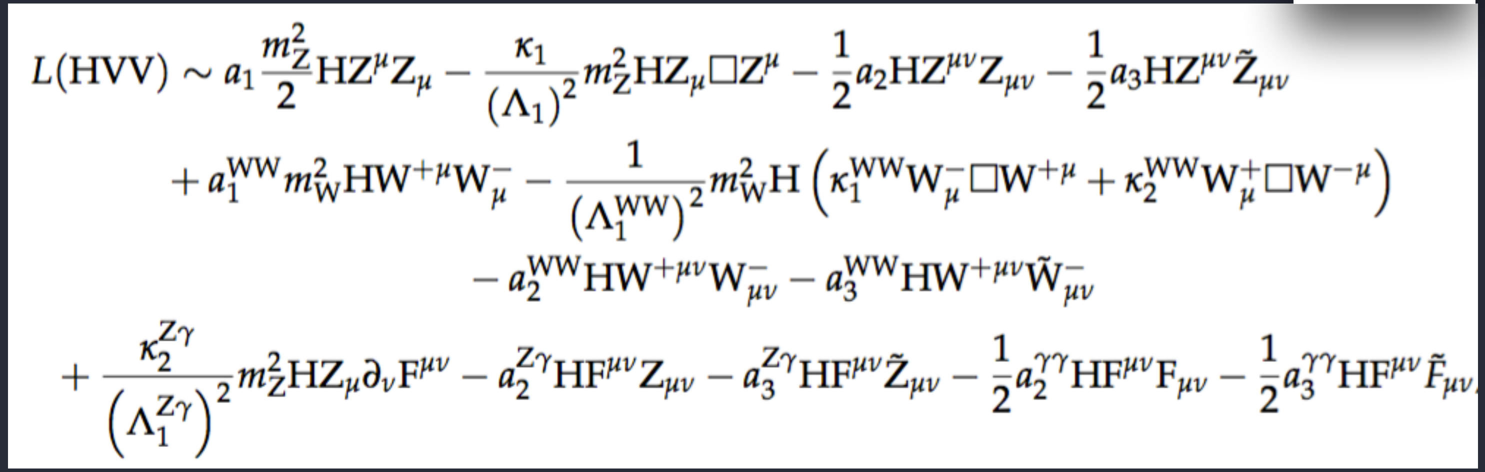
Tensor structure

11 anomalous couplings

EFT Lagrangian



$$\Big\{\cos(\alpha)\kappa_{\mathrm{SM}}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right]$$
$$-\frac{1}{4}\frac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]$$
$$-\frac{1}{2}\frac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0$$



$$L(\mathrm{HVV}) \sim a_1\frac{m_\mathrm{Z}^2}{2}\mathrm{HZ}^\mu\mathrm{Z}_\mu - \frac{\kappa_1}{(\Lambda_1)^2}m_\mathrm{Z}^2\mathrm{HZ}_\mu\Box\mathrm{Z}^\mu - \frac{1}{2}a_2\mathrm{HZ}^{\mu\nu}\mathrm{Z}_{\mu\nu} - \frac{1}{2}a_3\mathrm{HZ}^{\mu\nu}\tilde{\mathrm{Z}}_{\mu\nu}$$
$$+ a_1^{\mathrm{WW}}m_\mathrm{W}^2\mathrm{HW}^{+\mu}\mathrm{W}^-_\mu - \frac{1}{(\Lambda_1^{\mathrm{WW}})^2}m_\mathrm{W}^2\mathrm{H}\left(\kappa_1^{\mathrm{WW}}\mathrm{W}^-_\mu\Box\mathrm{W}^{+\mu} + \kappa_2^{\mathrm{WW}}\mathrm{W}^+_\mu\Box\mathrm{W}^{-\mu}\right)$$
$$- a_2^{\mathrm{WW}}\mathrm{HW}^{+\mu\nu}\mathrm{W}^-_{\mu\nu} - a_3^{\mathrm{WW}}\mathrm{HW}^{+\mu\nu}\tilde{\mathrm{W}}^-_{\mu\nu}$$
$$+ \frac{\kappa_2^{\mathrm{Z}\gamma}}{\left(\Lambda_1^{\mathrm{Z}\gamma}\right)^2}m_\mathrm{Z}^2\mathrm{HZ}_\mu\partial_\nu\mathrm{F}^{\mu\nu} - a_2^{\mathrm{Z}\gamma}\mathrm{HF}^{\mu\nu}\mathrm{Z}_{\mu\nu} - a_3^{\mathrm{Z}\gamma}\mathrm{HF}^{\mu\nu}\tilde{\mathrm{Z}}_{\mu\nu} - \frac{1}{2}a_2^{\gamma\gamma}\mathrm{HF}^{\mu\nu}\mathrm{F}_{\mu\nu} - \frac{1}{2}a_3^{\gamma\gamma}\mathrm{HF}^{\mu\nu}\tilde{F}_{\mu\nu}$$

EFT Lagrangian

$$\Big\{\cos(\alpha)\kappa_{\mathrm{SM}}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] \\ -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0$$

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{\mathrm{v}}{\Lambda}\kappa_{AVV} \text{ and } \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{\mathrm{v}}{\Lambda}\kappa_{HVV}$$

$$L(\mathrm{HVV}) \sim a_1\frac{m_Z^2}{2}\mathrm{HZ}^\mu\mathrm{Z}_\mu - \frac{\kappa_1}{(\Lambda_1)^2}m_Z^2\mathrm{HZ}_\mu\Box\mathrm{Z}^\mu - \frac{1}{2}a_2\mathrm{HZ}^{\mu\nu}\mathrm{Z}_{\mu\nu} - \frac{1}{2}a_3\mathrm{HZ}^{\mu\nu}\tilde{\mathrm{Z}}_{\mu\nu} \\ + a_1^{\mathrm{WW}}m_{\mathrm{W}}^2\mathrm{HW}^{+\mu}\mathrm{W}^-_\mu - \frac{1}{(\Lambda_1^{\mathrm{WW}})^2}m_{\mathrm{W}}^2\mathrm{H}\left(\kappa_1^{\mathrm{WW}}\mathrm{W}^-_\mu\Box\mathrm{W}^{+\mu} + \kappa_2^{\mathrm{WW}}\mathrm{W}^+_\mu\Box\mathrm{W}^{-\mu}\right) \\ - a_2^{\mathrm{WW}}\mathrm{HW}^{+\mu\nu}\mathrm{W}^-_{\mu\nu} - a_3^{\mathrm{WW}}\mathrm{HW}^{+\mu\nu}\tilde{\mathrm{W}}^-_{\mu\nu} \\ + \frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2}m_Z^2\mathrm{HZ}_\mu\partial_\nu\mathrm{F}^{\mu\nu} - a_2^{Z\gamma}\mathrm{HF}^{\mu\nu}\mathrm{Z}_{\mu\nu} - a_3^{Z\gamma}\mathrm{HF}^{\mu\nu}\tilde{\mathrm{Z}}_{\mu\nu} - \frac{1}{2}a_2^{\gamma\gamma}\mathrm{HF}^{\mu\nu}\mathrm{F}_{\mu\nu} - \frac{1}{2}a_3^{\gamma\gamma}\mathrm{HF}^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}$$

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$$-\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu}+\sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]$$
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$$+\frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2}m_{\mathrm{Z}}^2\mathrm{HZ}_{\mu}\partial_{\nu}\mathrm{F}^{\mu\nu}-a_2^{Z\gamma}\mathrm{HF}^{\mu\nu}\mathrm{Z}_{\mu\nu}-a_3^{Z\gamma}\mathrm{HF}^{\mu\nu}\tilde{\mathrm{Z}}_{\mu\nu}-\frac{1}{2}a_2^{\gamma\gamma}\mathrm{HF}^{\mu\nu}\mathrm{F}_{\mu\nu}-\frac{1}{2}a_3^{\gamma\gamma}\mathrm{HF}^{\mu\nu}\tilde{F}_{\mu\nu}$$

$$f_{a2}=\frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1+|a_2|^2\sigma_2+|a_3|^2\sigma_3+\tilde{\sigma}_{\Lambda1}/\left(\Lambda_1\right)^4+\ldots}$$

$$\frac{|a_i|}{|a_1|}=\sqrt{f_{ai}/f_{a1}}\times\sqrt{\sigma_1/\sigma_i}$$

EFT Lagrangian

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$$\Big\{\cos(\alpha)\kappa_{\mathrm{SM}}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] \\ -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} X_0$$

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CMS

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$$\frac{|a_i|}{|a_1|} = \sqrt{f_{ai}/f_{a1}} \times \sqrt{\sigma_1/\sigma_i}$$

Correspond to the ratios of tensor couplings a_3/a_1 and a_2/a_1.

Simulations

	Powheg	MadGraph5_aMC@NLO	JHUGEN
ggH SM Higgs boson	ATLAS EXPERIMENT CMS Compact Muon Solenoid		
BSM spin-0		HWW ATLAS EXPERIMENT	ATLAS EXPERIMENT CMS Compact Muon Solenoid
Spin-1			ATLAS EXPERIMENT CMS Compact Muon Solenoid
Spin-2		ATLAS EXPERIMENT	CMS Compact Muon Solenoid

Pros and cons of different channels

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$H \to \gamma\gamma$

- − High background, low number of sensitive variables, no sensitivity to spin-0 models
- \+ Sufficient statistics

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+ Most sensitive (angular variables + masses fully reconstructable), most significant signal

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$H \to WW$

− Neutrinos in the final state —> limited resolution

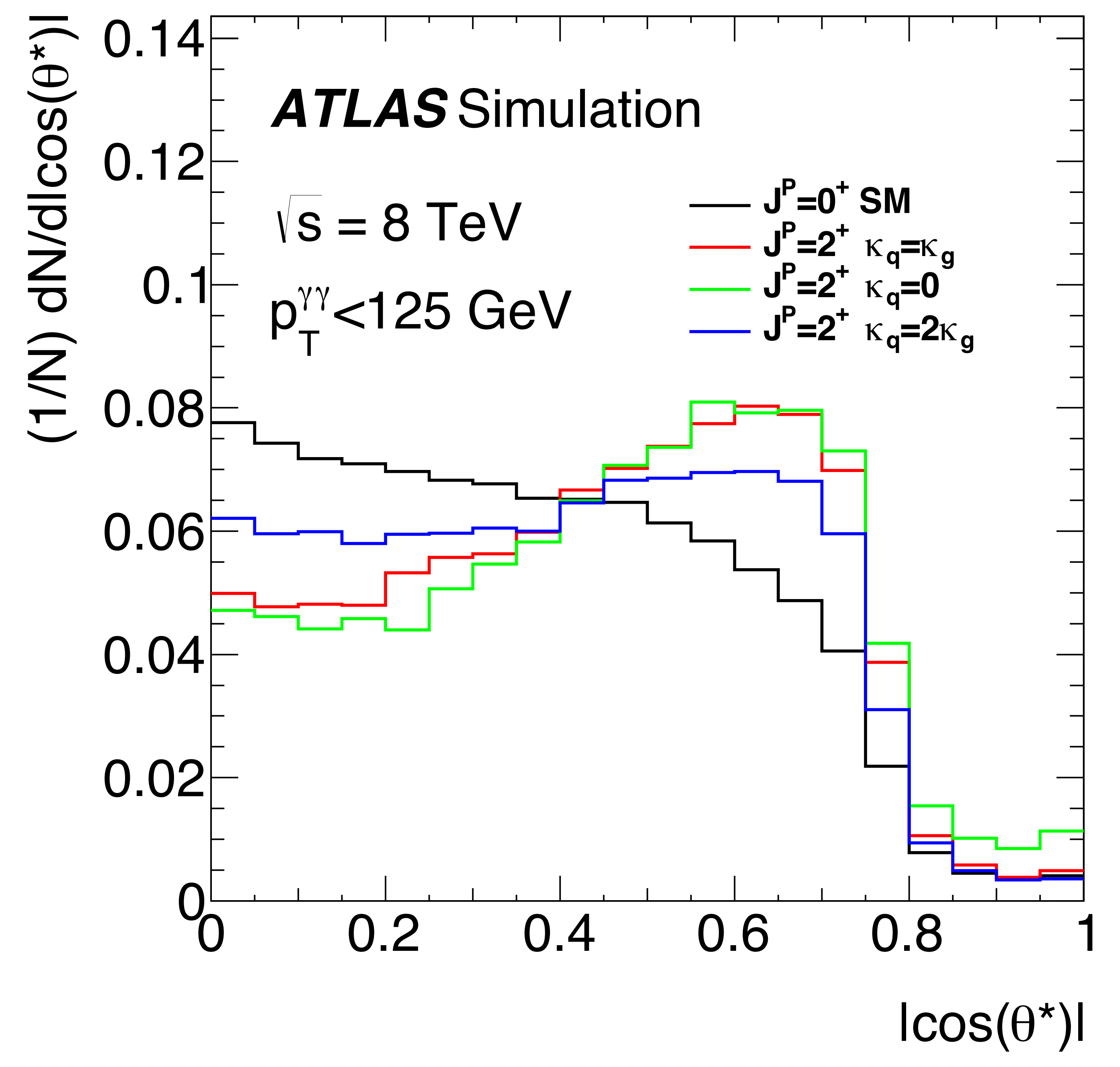
+ Large signal yield, angular information from leptons and MET

H → γγ analysis

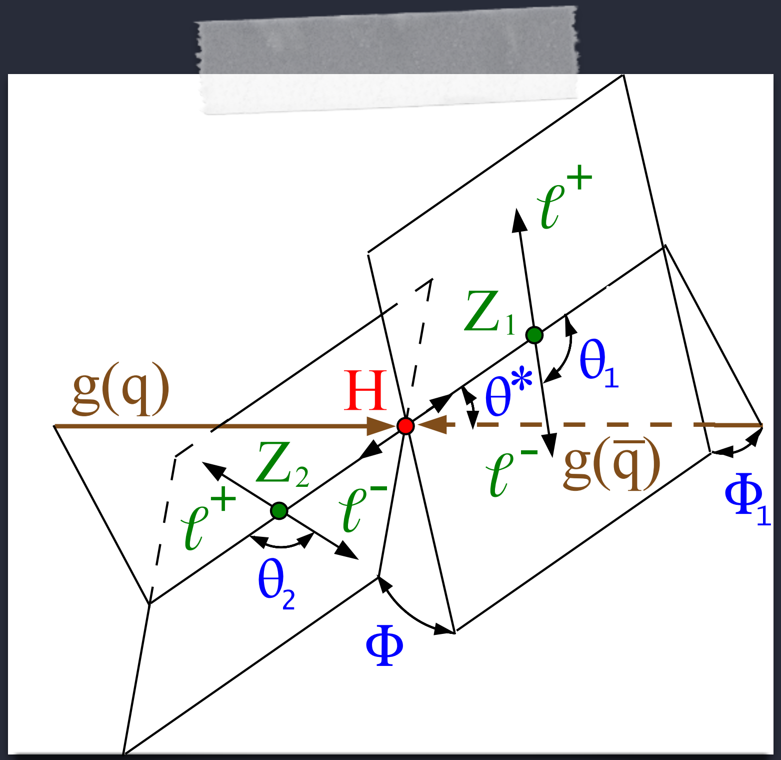
arXiv:1506.05669

- Landau-Yang theorem strongly disfavors spin-1 particle decay to γγ
- Sensitive to a possible spin-2 state
- Log-likelihood ratio test statistic
- cosθ* used to discriminate between the spin hypotheses

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\left(p_{\mathrm{T}}^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \frac{2p_{\mathrm{T}}^{\gamma_1} p_{\mathrm{T}}^{\gamma_2}}{m_{\gamma\gamma}^2}$$



H → ZZ analysis

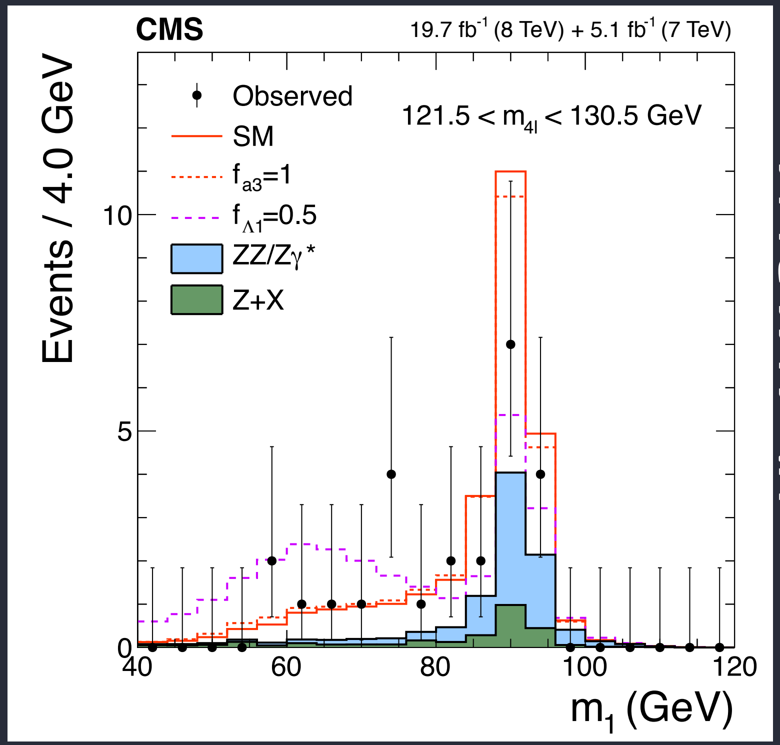


Kinematics can be fully described by 8 variables:

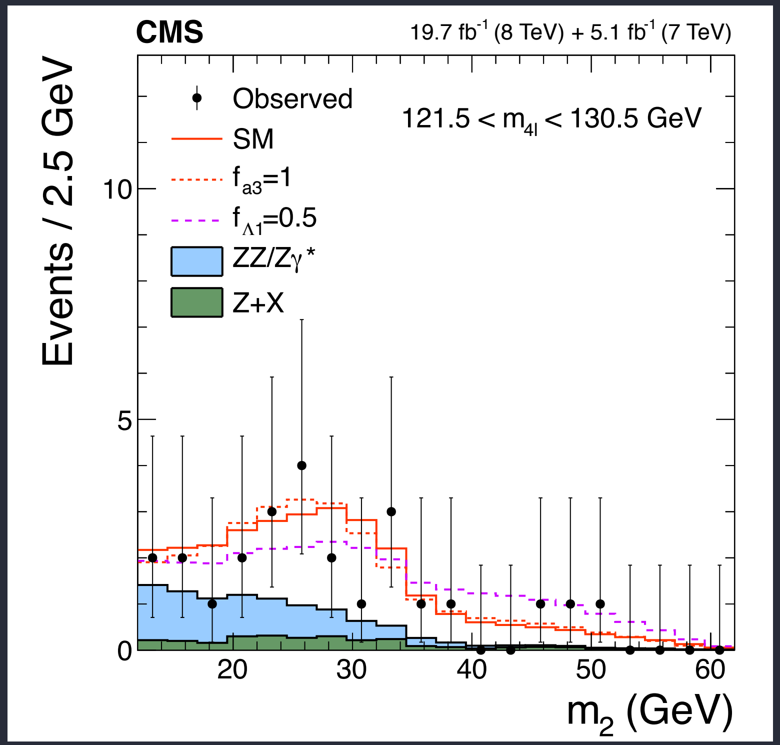
- 3 masses: m_{Z1} , m_{Z2} , m_{4l}
- 5 angles: θ^*, Φ_1, θ_1, θ_2, Φ

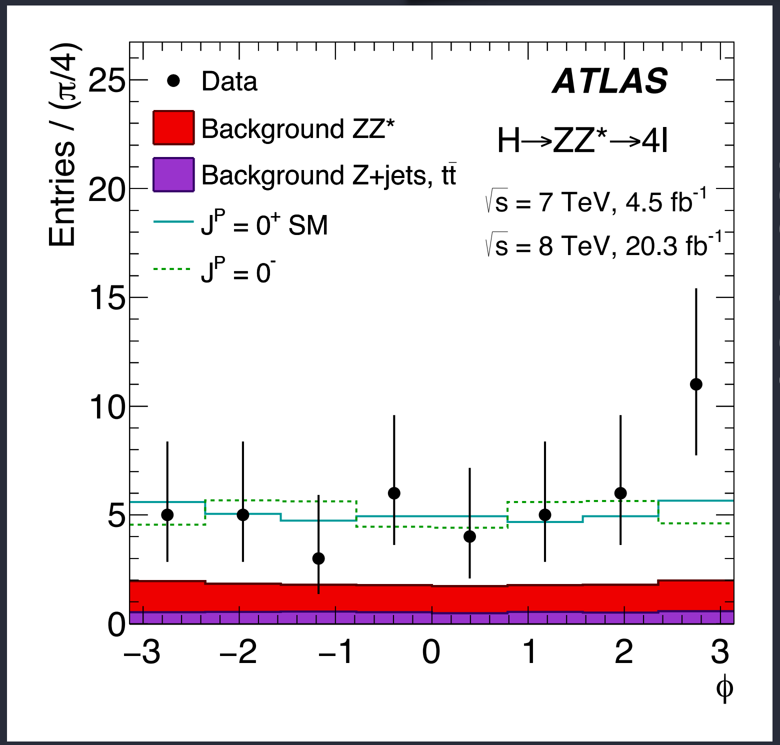
Main backgrounds:

- ZZ* (estimated from MC)
- Z+ X estimated from data in CR



arXiv:1411.3441





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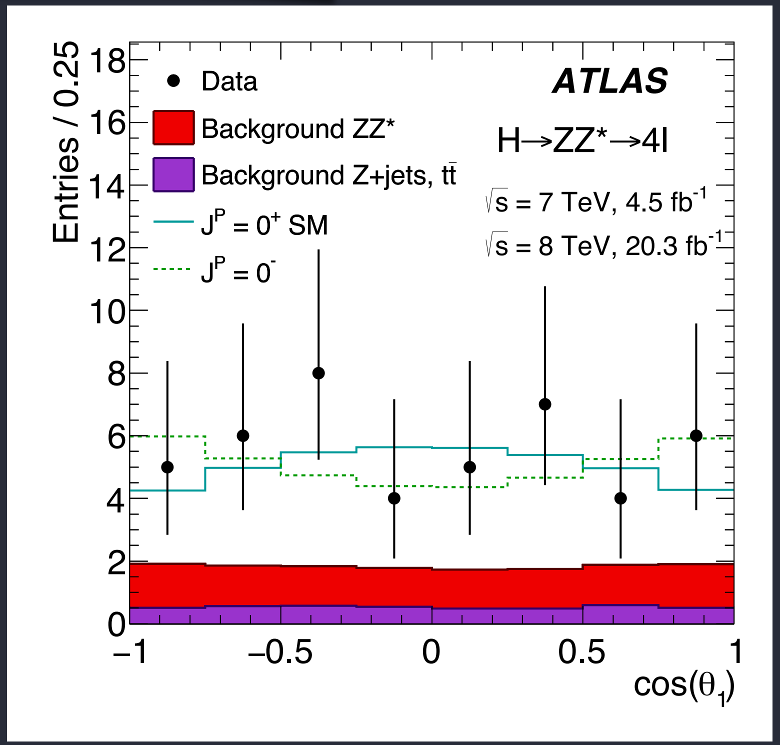
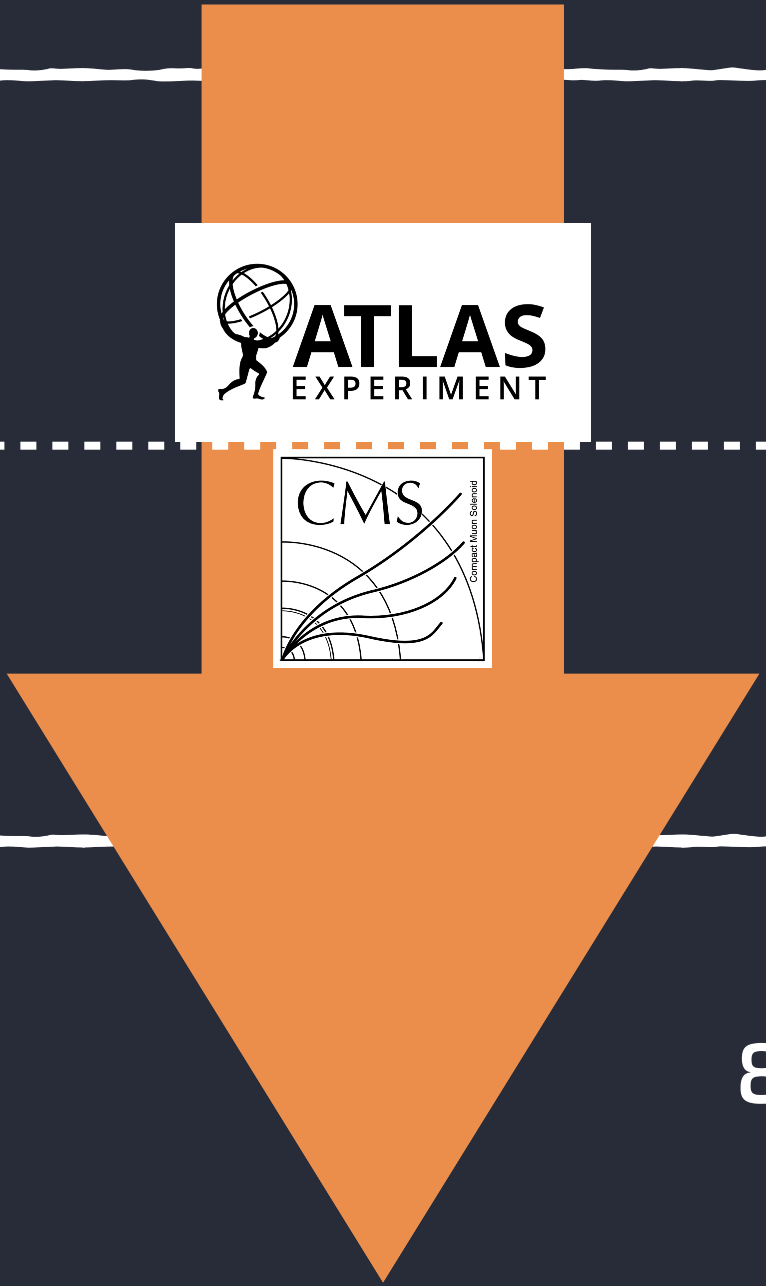


H → ZZ analysis (continued)



Hypothesis test	Tensor structure
0^+ vs J^P MELA or BDT Signal vs. bkg. BDT	ME based discriminants Signal vs. bkg. BDT
0^+ vs J^P MELA Signal vs. bkg. MELA	MELA Signal vs. bkg. MELA
Templates of discriminants	**Templates of discriminants or 8D/9D fit method as a crosscheck**

H → WW analysis

General

Only partial reconstruction is possible:

- Two isolated, high-p_T, charged leptons
- E_T^{miss} due to the presence of neutrinos in the final state

Important backgrounds: WW, W+jets, Z+jets, ttbar, single t and dibosons

H → WW analysis

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Two BDT classifiers to discriminate 0^+ vs. bkg and J^P vs. bkg both in the spin-parity tests and the tensor structure analyses

BDT input variables: m_{ll}, $\Delta\varphi_{ll}$, p_T^{ll}, m_T

$H \rightarrow WW$ analysis

General

Only partial reconstruction is possible:

- Two isolated, high-p_T, charged leptons
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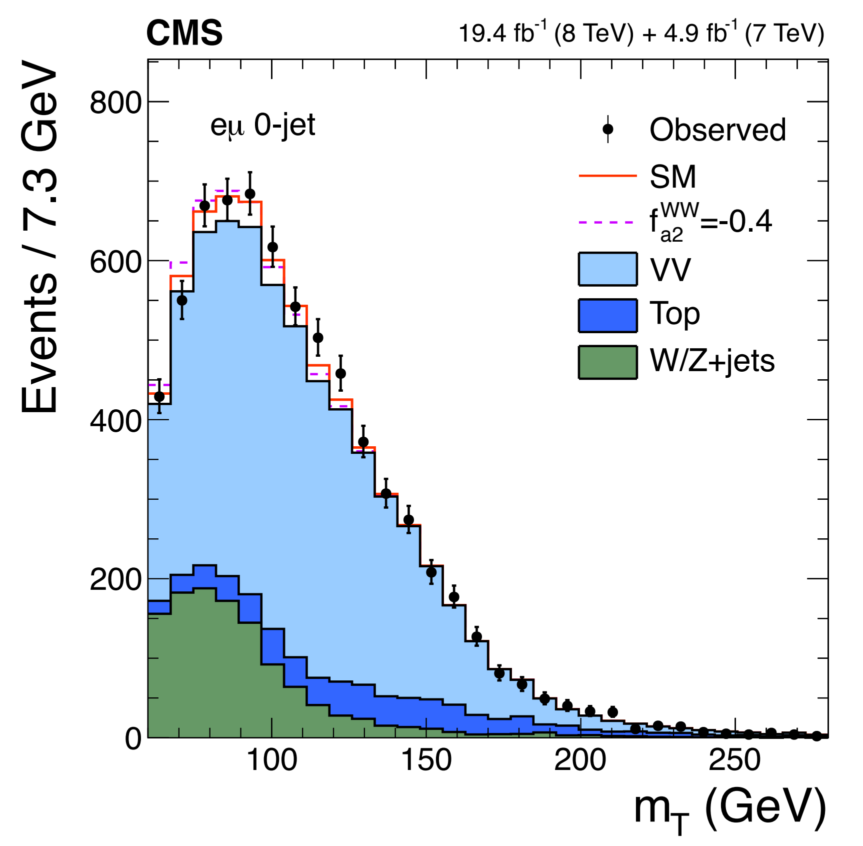
Two BDT classifiers to discriminate 0^+ vs. bkg and J^P vs. bkg both in the spin-parity tests and the tensor structure analyses

BDT input variables: m_{ll}, $\Delta\varphi_{ll}$, p_T^{ll}, m_T

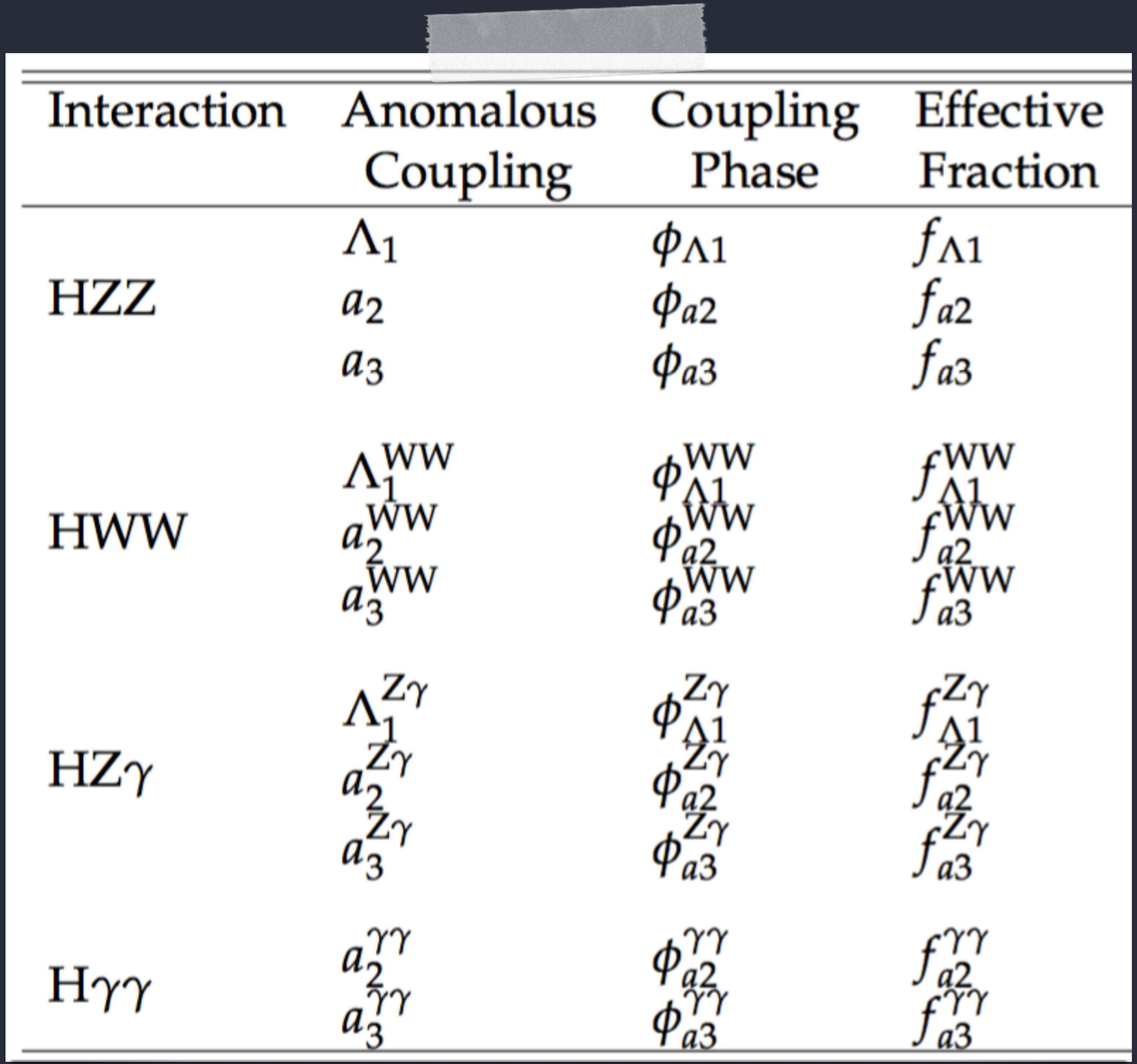
CMS

Two observables used in the final analysis: m_{ll} and m_T.

arXiv:1411.3441



HVV tensor structure measurements



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}	$\phi_{\Lambda 1}^{\mathrm{WW}}$	$f_{\Lambda 1}^{\mathrm{WW}}$
	a_2^{WW}	ϕ_{a2}^{WW}	f_{a2}^{WW}
	a_3^{WW}	ϕ_{a3}^{WW}	f_{a3}^{WW}
HZγ	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$
	$a_2^{Z\gamma}$	$\phi_{a2}^{Z\gamma}$	$f_{a2}^{Z\gamma}$
	$a_3^{Z\gamma}$	$\phi_{a3}^{Z\gamma}$	$f_{a3}^{Z\gamma}$
H$\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$	$f_{a3}^{\gamma\gamma}$

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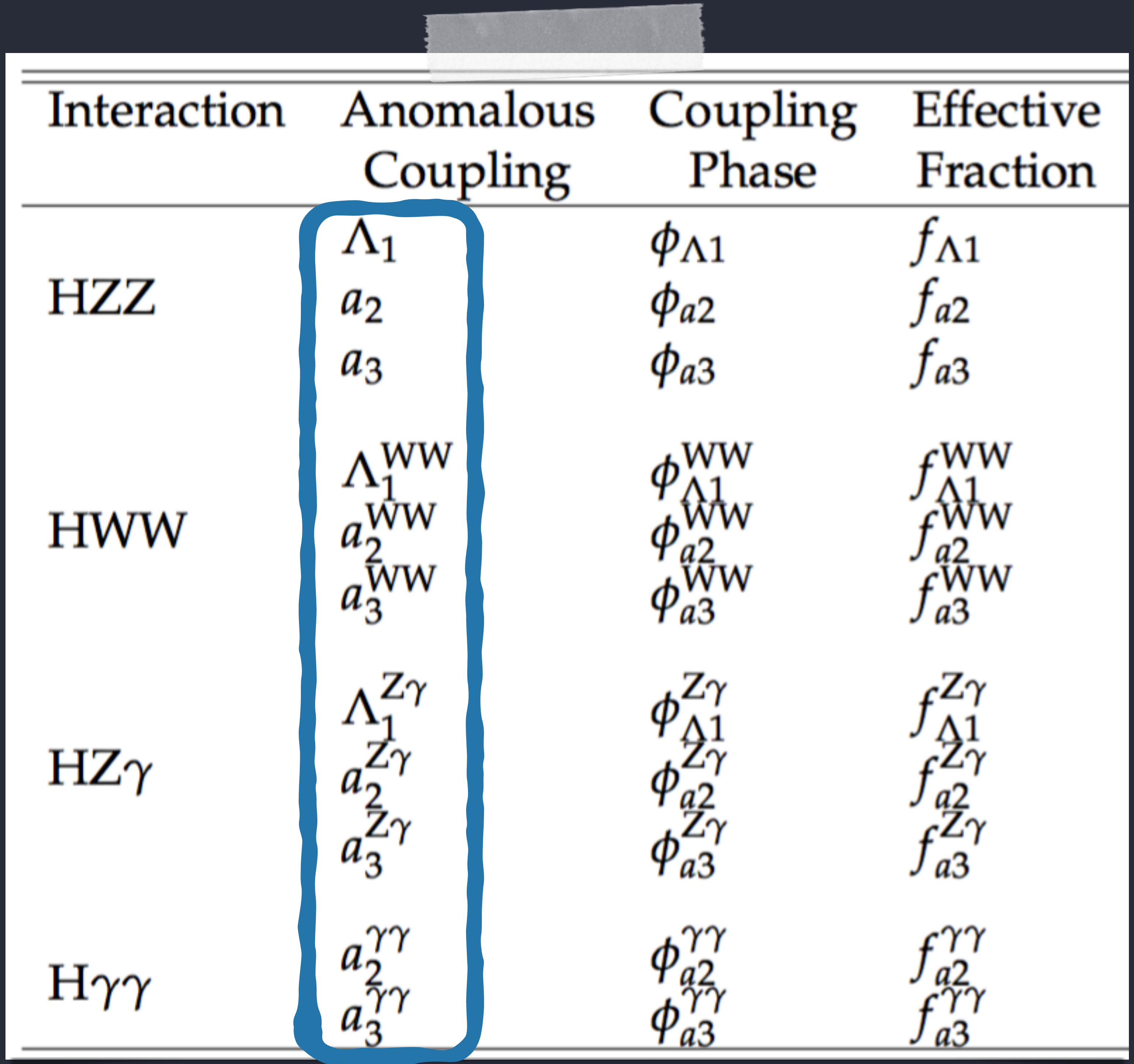
$$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$$

$$\tilde{\kappa}_{HVV}/\kappa_{SM}$$

CMS

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}$$

HVV tensor structure measurements



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HZγ	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$
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H$\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$
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ATLAS EXPERIMENT

$$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$$

$$\tilde{\kappa}_{HVV}/\kappa_{SM}$$

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$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\,(\Lambda_1)^4 + \ldots}$$

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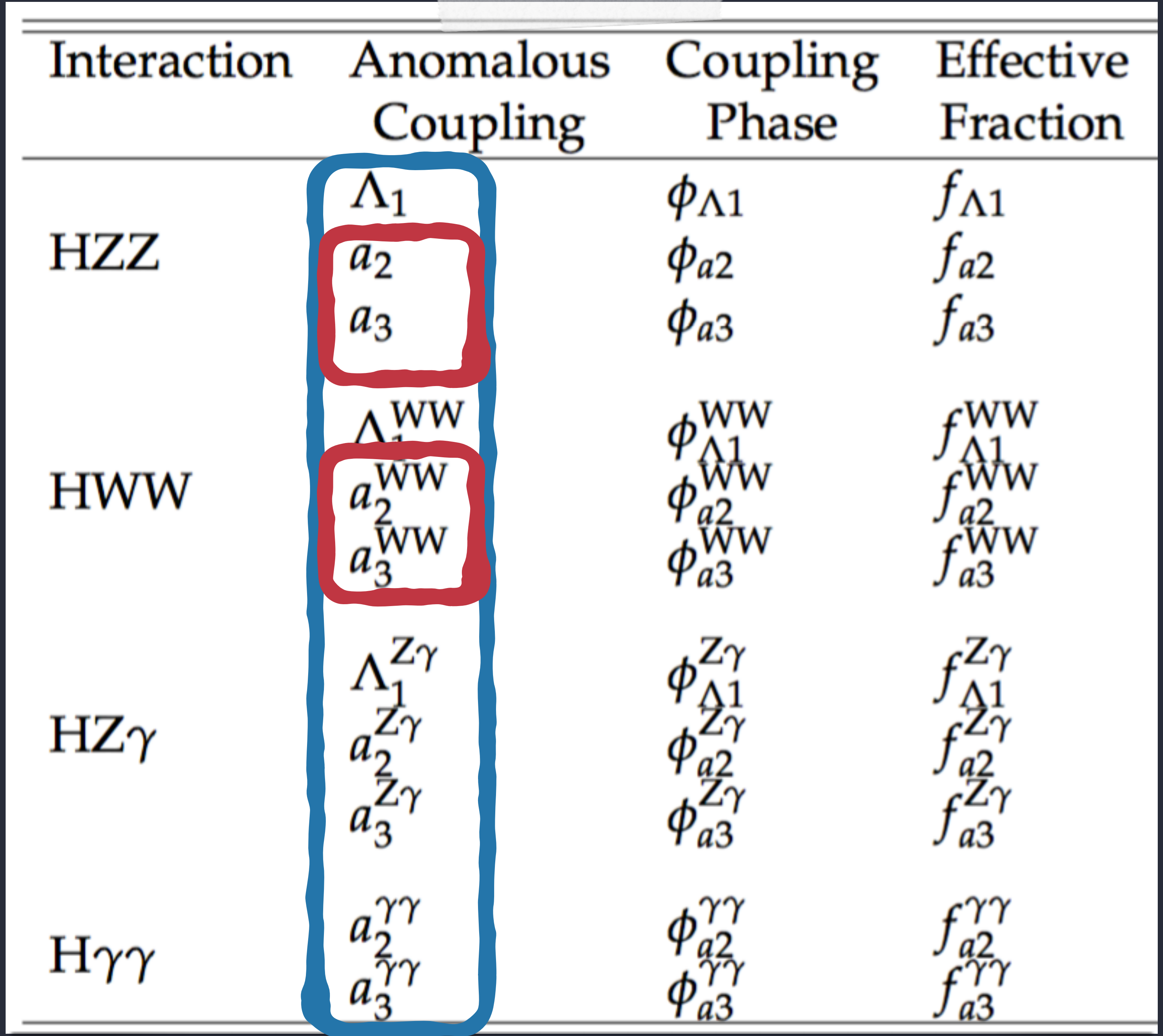

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HWW	Λ_1^{WW}	$\phi_{\Lambda 1}^{\mathrm{WW}}$	$f_{\Lambda 1}^{\mathrm{WW}}$
	a_2^{WW}	ϕ_{a2}^{WW}	f_{a2}^{WW}
	a_3^{WW}	ϕ_{a3}^{WW}	f_{a3}^{WW}
HZγ	$\Lambda_1^{Z\gamma}$	$\phi_{\Lambda 1}^{Z\gamma}$	$f_{\Lambda 1}^{Z\gamma}$
	$a_2^{Z\gamma}$	$\phi_{a2}^{Z\gamma}$	$f_{a2}^{Z\gamma}$
	$a_3^{Z\gamma}$	$\phi_{a3}^{Z\gamma}$	$f_{a3}^{Z\gamma}$
H$\gamma\gamma$	$a_2^{\gamma\gamma}$	$\phi_{a2}^{\gamma\gamma}$	$f_{a2}^{\gamma\gamma}$
	$a_3^{\gamma\gamma}$	$\phi_{a3}^{\gamma\gamma}$	$f_{a3}^{\gamma\gamma}$

ATLAS EXPERIMENT

$$(\tilde{\kappa}_{AVV}/\kappa_{SM})\cdot\tan\alpha$$

$$\tilde{\kappa}_{HVV}/\kappa_{SM}$$

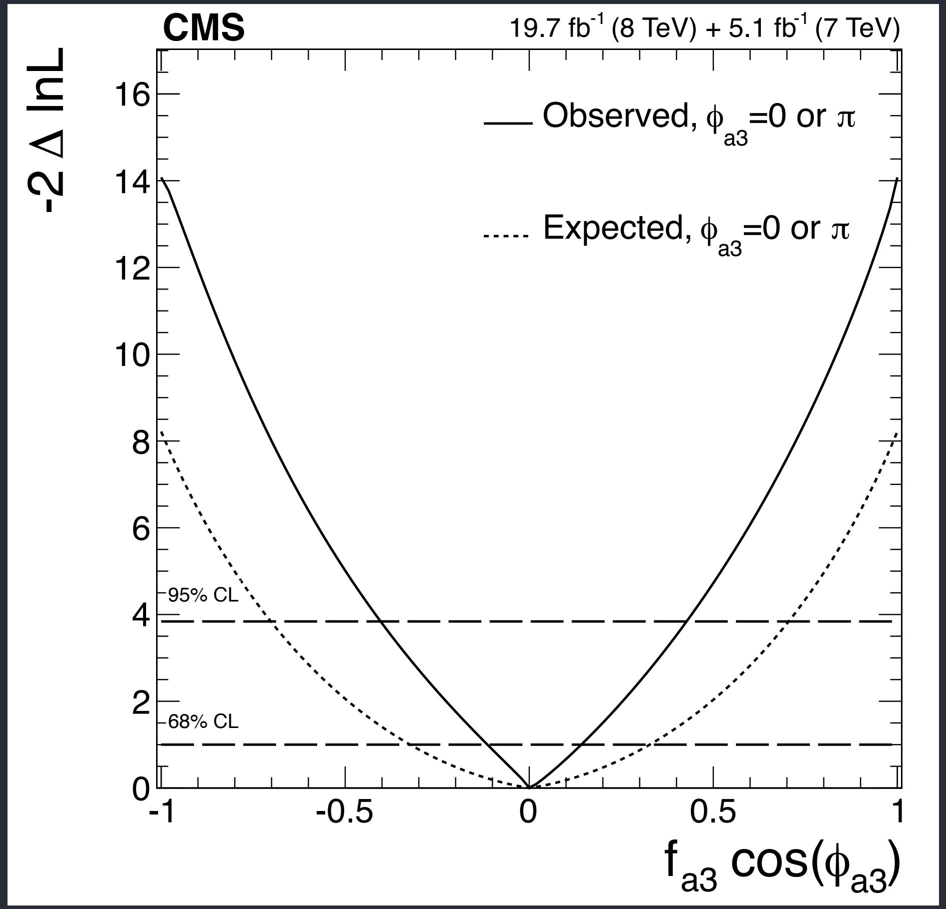
CMS

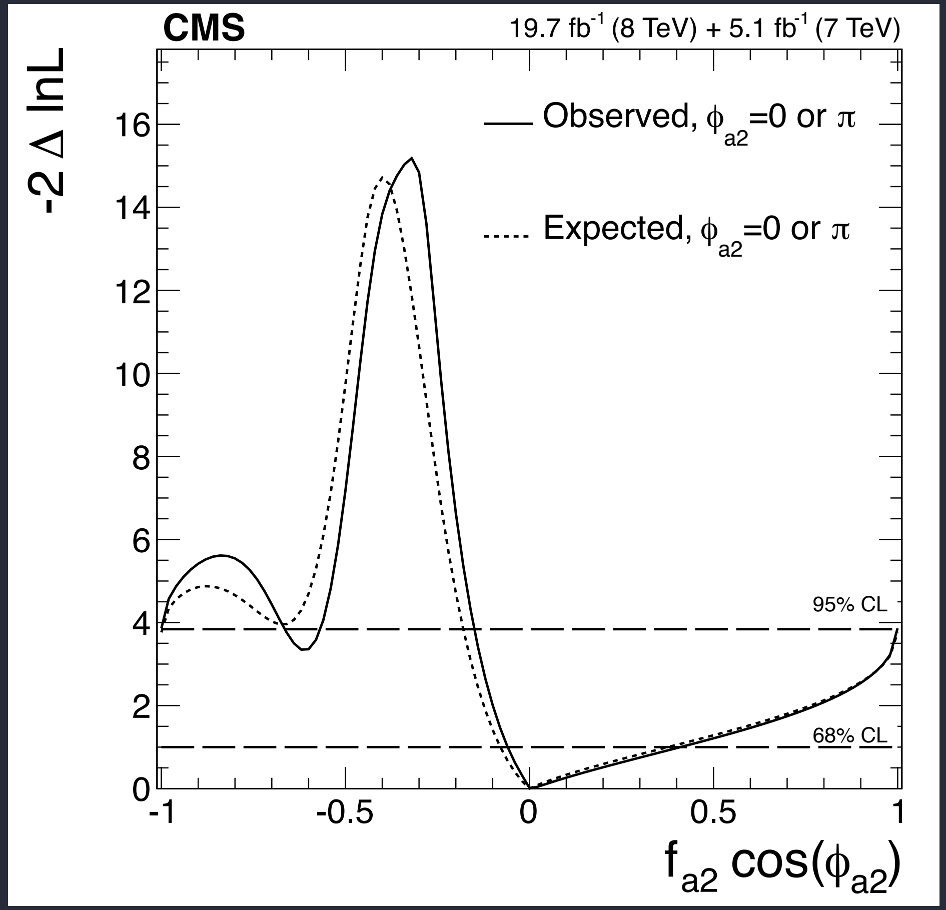
$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}$$

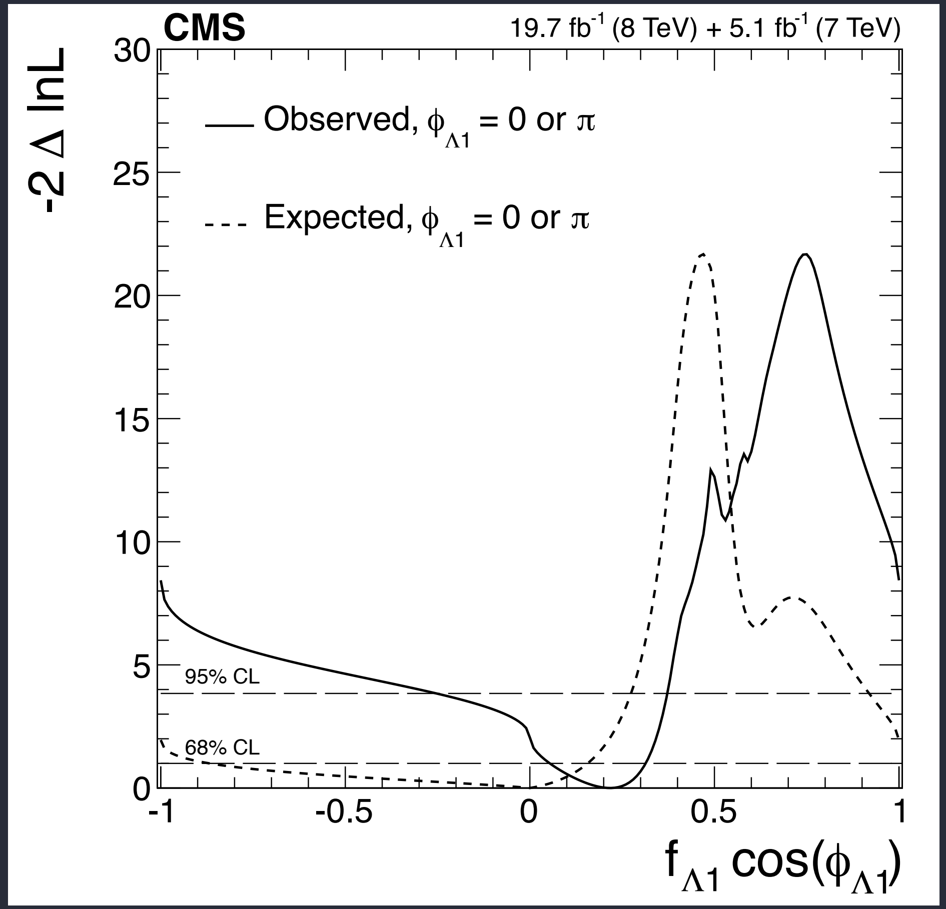
ai real

arXiv:1411.3441

HZZ tensor structure







Consistent with the SM?

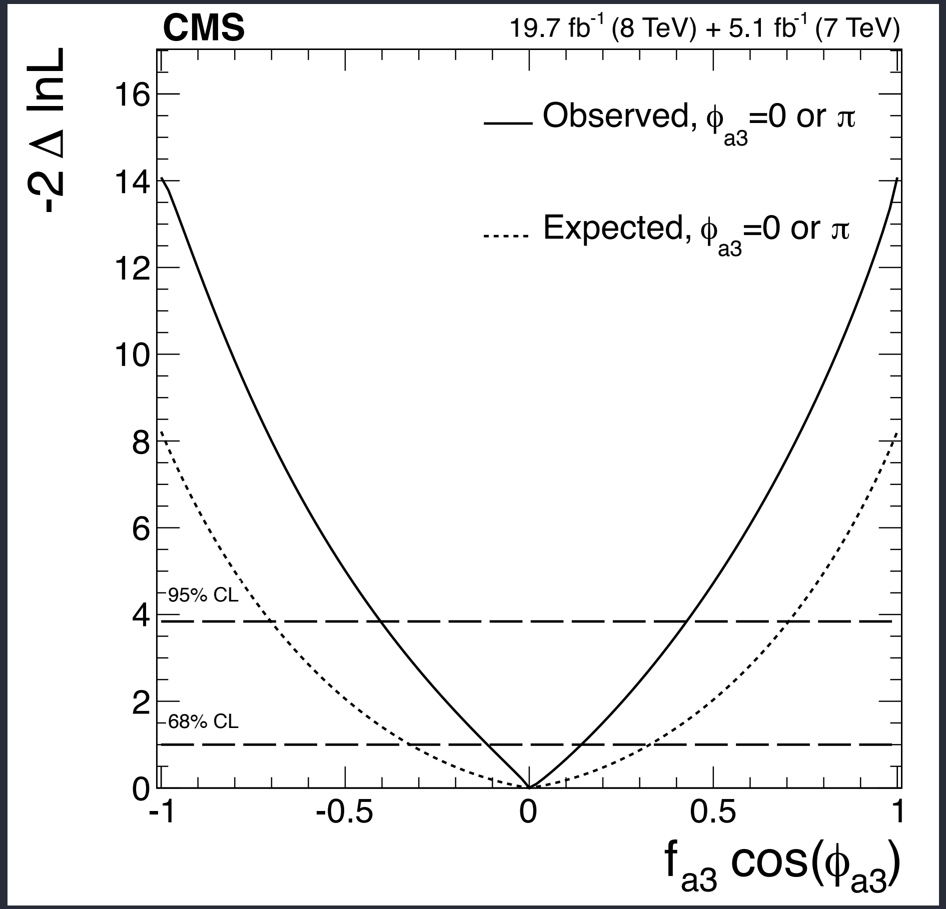
☐ YES

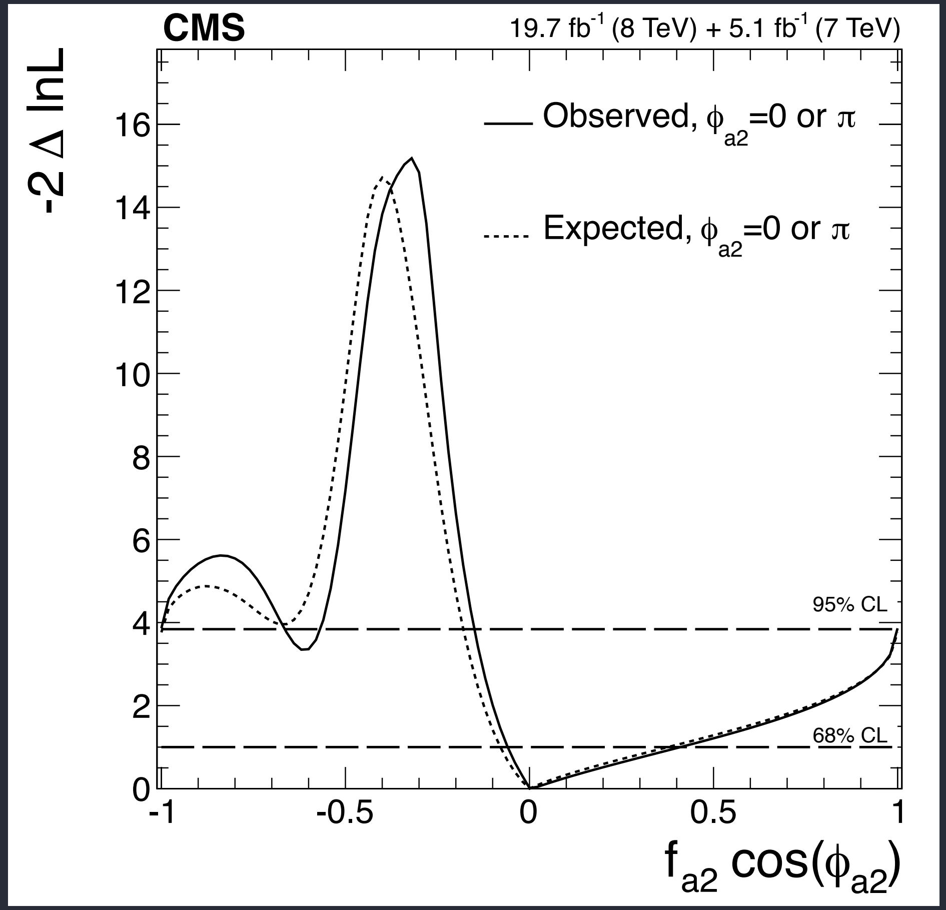
☐ NO

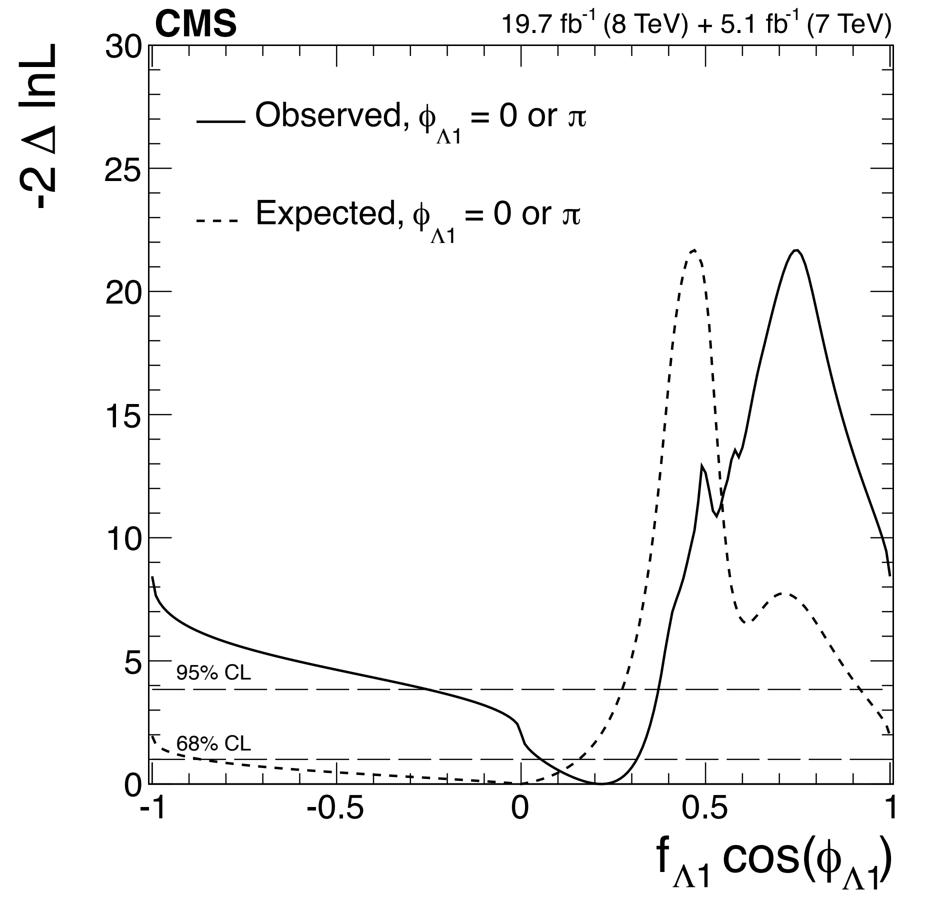
arXiv:1411.3441

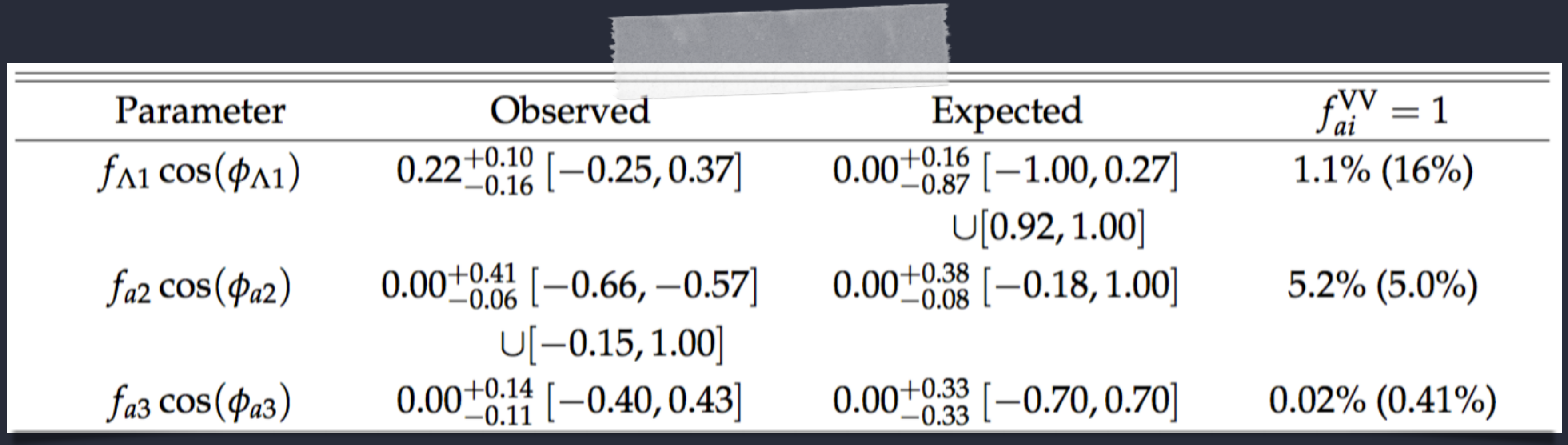
HZZ tensor structure

ai real









Parameter	Observed	Expected	$f_{ai}^{VV} = 1$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.22^{+0.10}_{-0.16}$ $[-0.25, 0.37]$	$0.00^{+0.16}_{-0.87}$ $[-1.00, 0.27]$ $\cup[0.92, 1.00]$	1.1% (16%)
$f_{a2}\cos(\phi_{a2})$	$0.00^{+0.41}_{-0.06}$ $[-0.66, -0.57]$ $\cup[-0.15, 1.00]$	$0.00^{+0.38}_{-0.08}$ $[-0.18, 1.00]$	5.2% (5.0%)
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.14}_{-0.11}$ $[-0.40, 0.43]$	$0.00^{+0.33}_{-0.33}$ $[-0.70, 0.70]$	0.02% (0.41%)

Consistent with the SM?

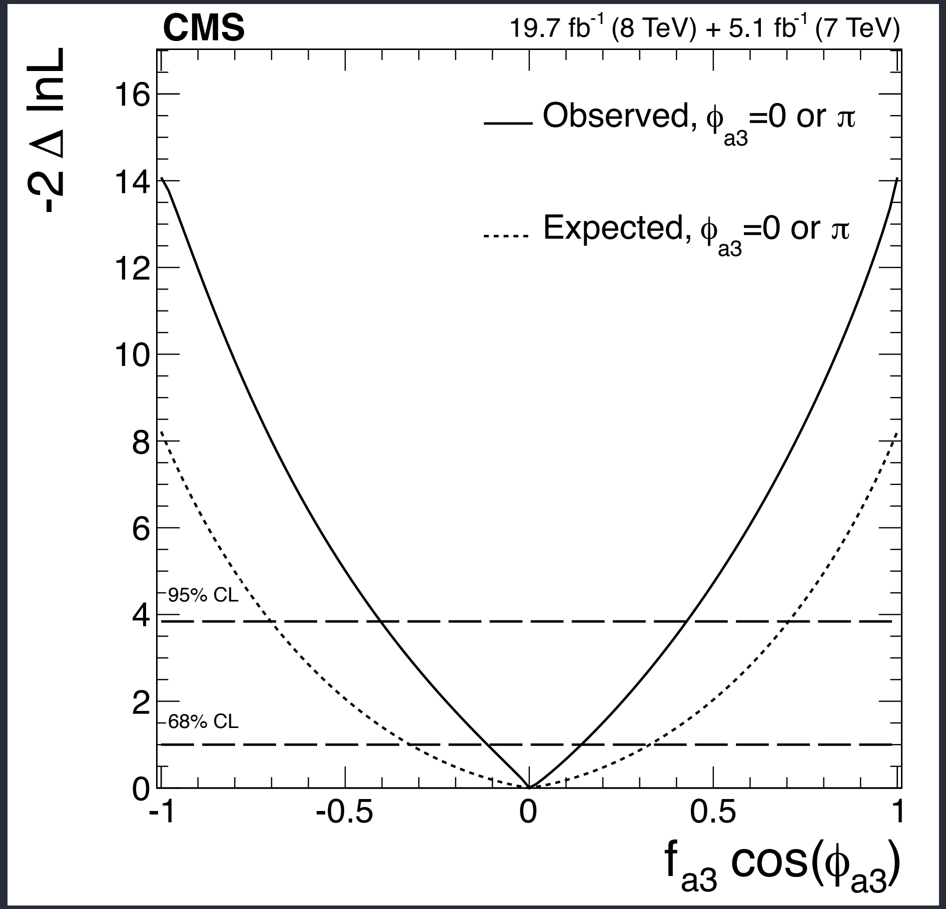
☐ YES

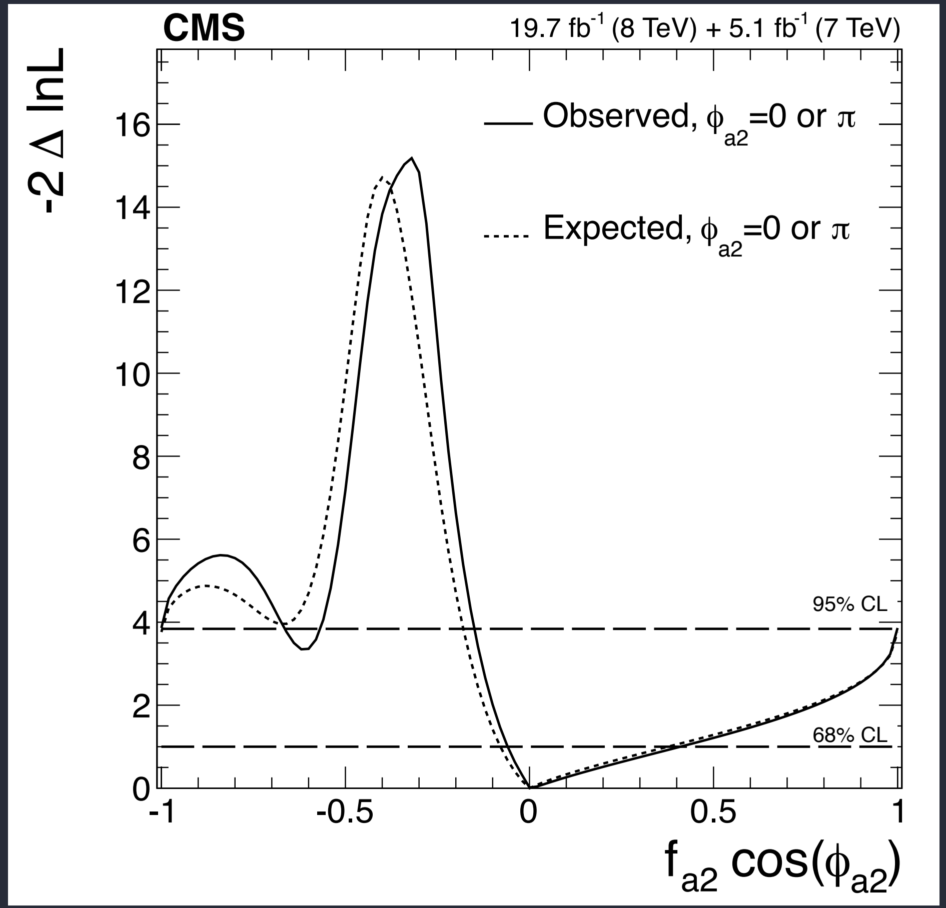
☐ NO

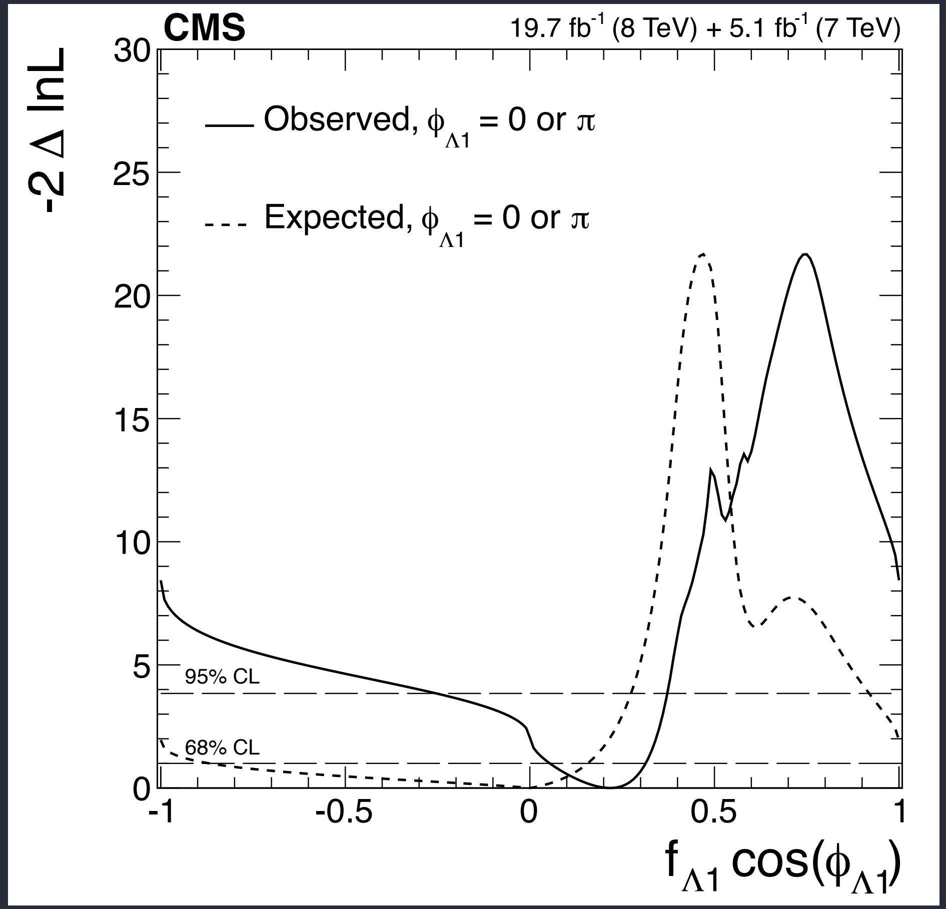
arXiv:1411.3441

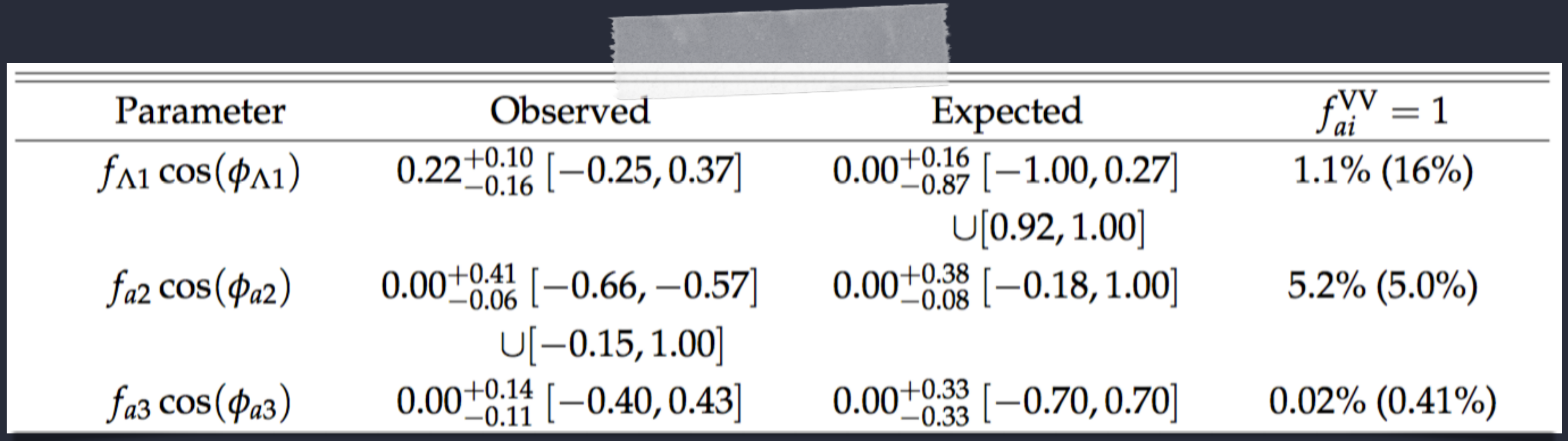
ai real

HZZ tensor structure









Parameter	Observed	Expected	$f_{ai}^{VV}=1$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.22^{+0.10}_{-0.16}$ $[-0.25, 0.37]$	$0.00^{+0.16}_{-0.87}$ $[-1.00, 0.27]$ $\cup[0.92, 1.00]$	1.1% (16%)
$f_{a2}\cos(\phi_{a2})$	$0.00^{+0.41}_{-0.06}$ $[-0.66, -0.57]$ $\cup[-0.15, 1.00]$	$0.00^{+0.38}_{-0.08}$ $[-0.18, 1.00]$	5.2% (5.0%)
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.14}_{-0.11}$ $[-0.40, 0.43]$	$0.00^{+0.33}_{-0.33}$ $[-0.70, 0.70]$	0.02% (0.41%)

Consistent with the SM?

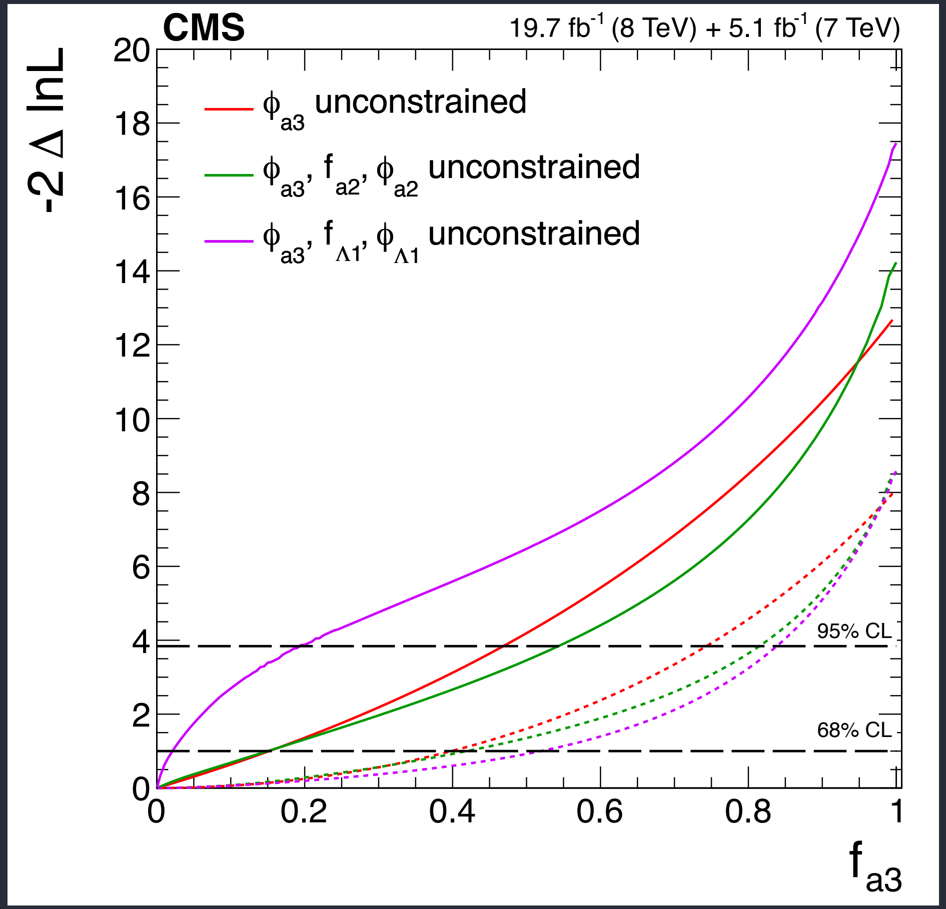
☑ YES

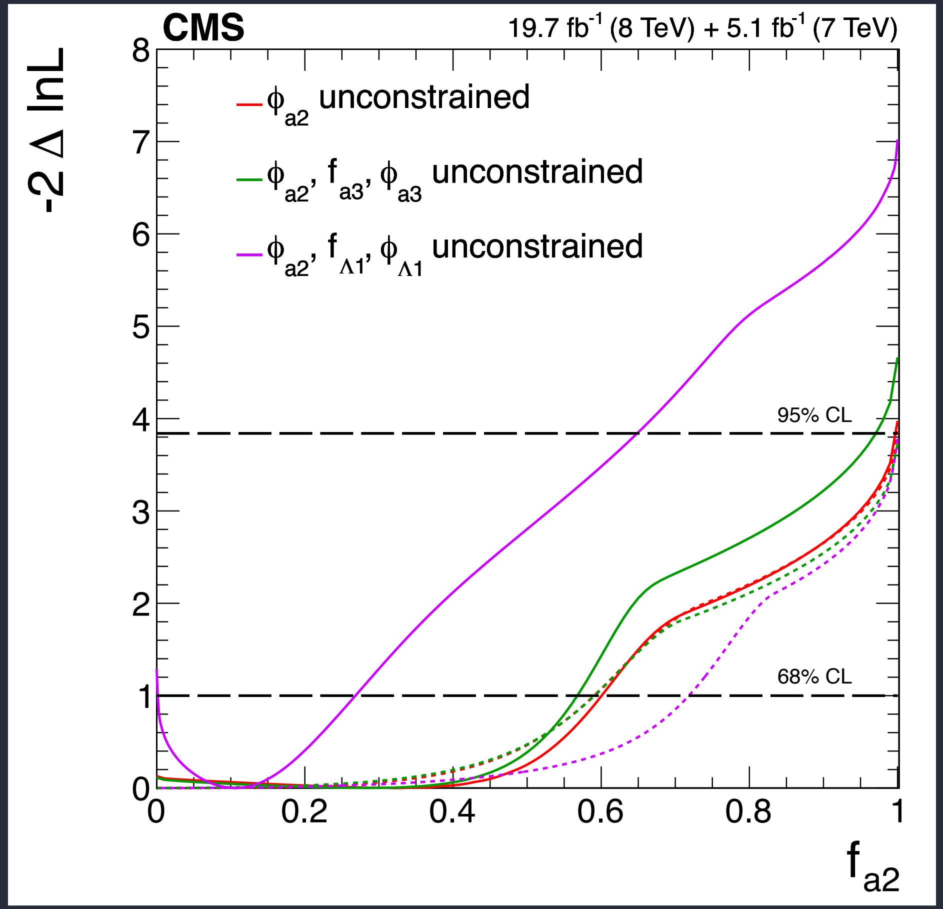
☐ NO

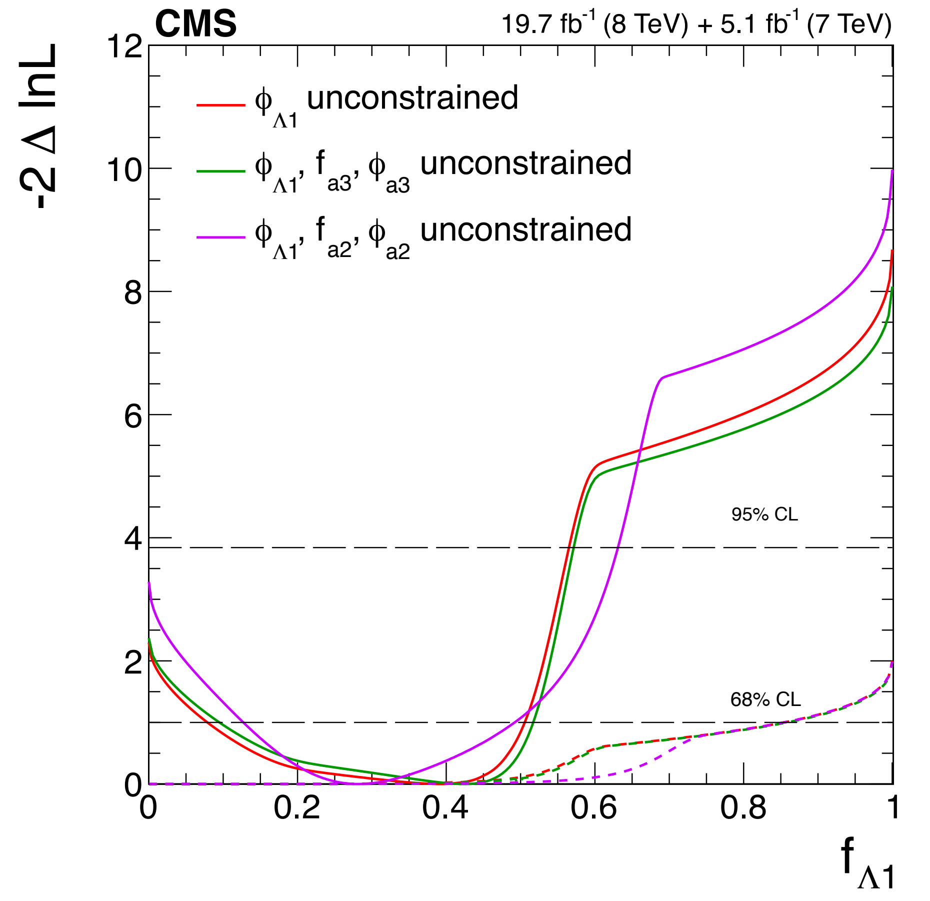
ai cmplx

arXiv:1411.3441

HZZ tensor structure







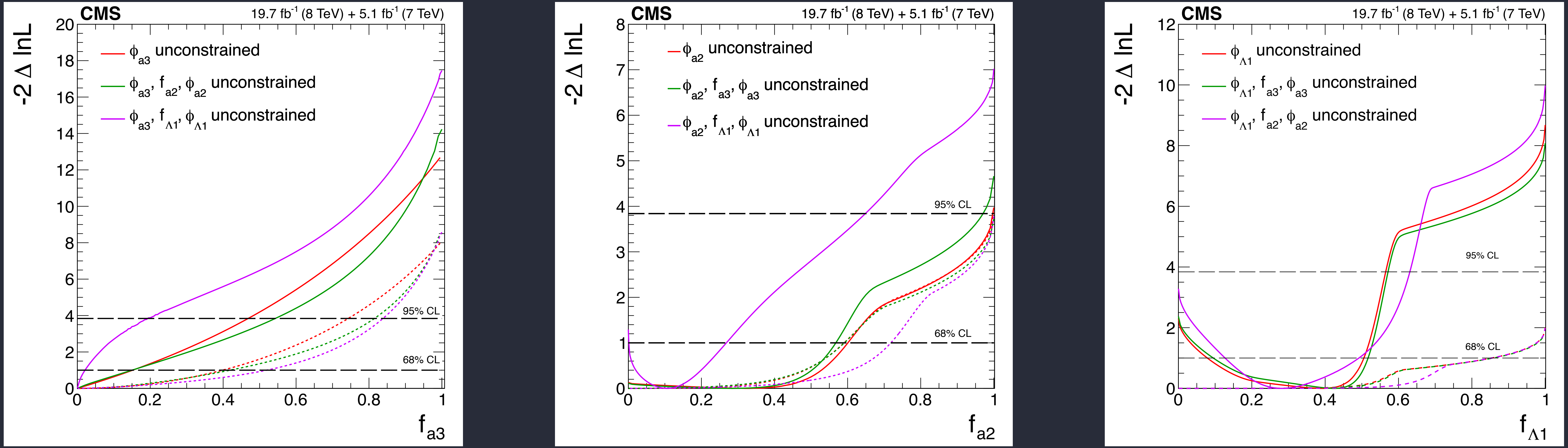
Consistent with the SM?

☐ YES

☐ NO

arXiv:1411.3441

HZZ tensor structure



Consistent with the SM?

☑ YES

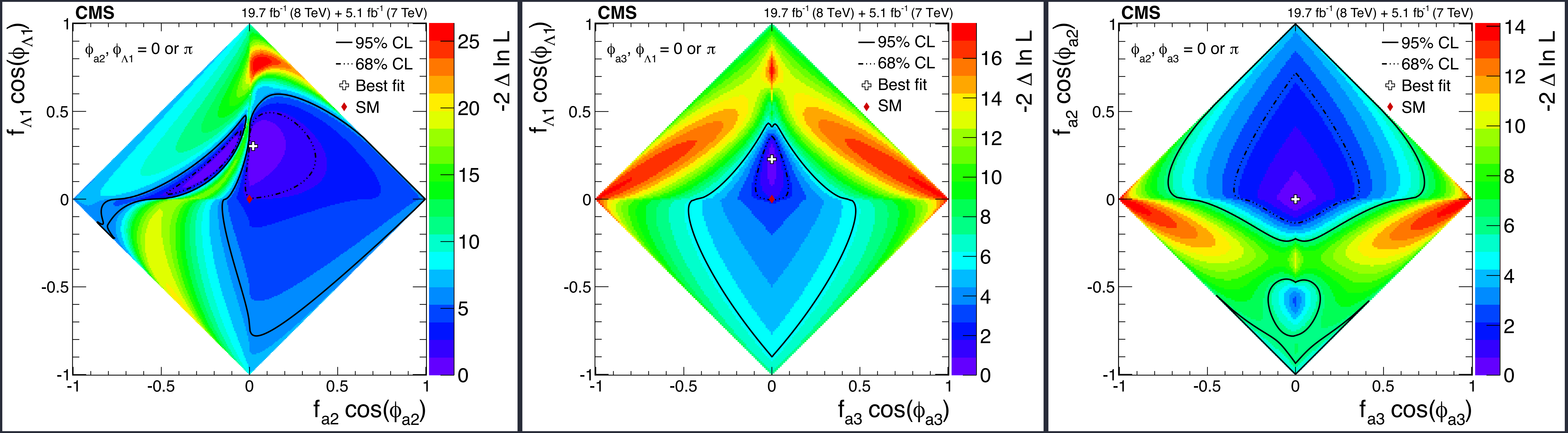
☐ NO

ai real

arXiv:1411.3441

HZZ tensor structure

Consider two anomalous contributions at the same time



Consistent with the SM?

☐ YES

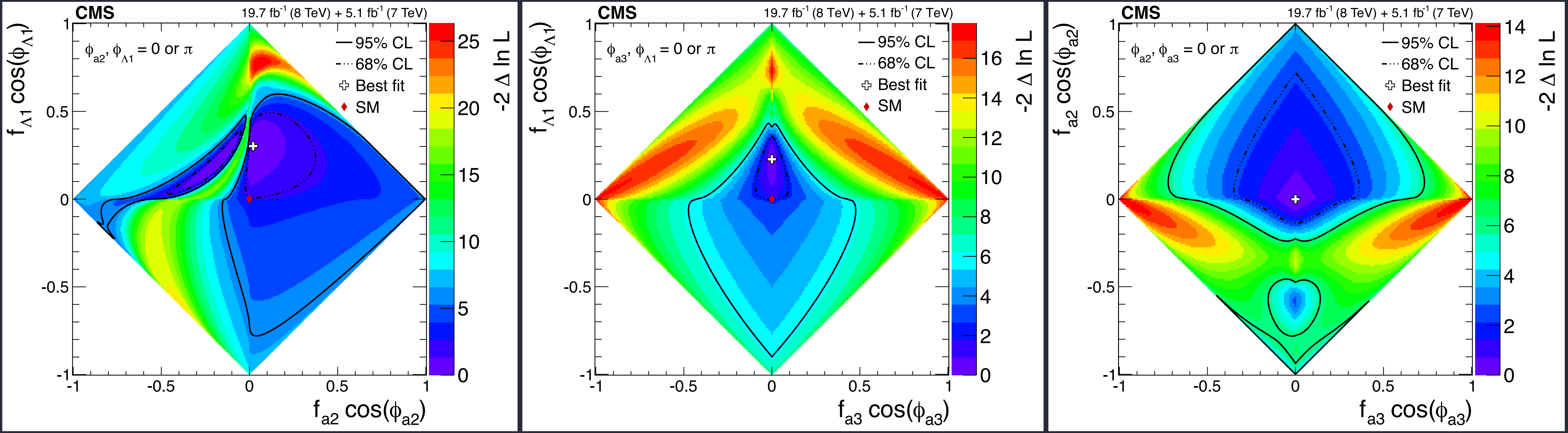
☐ NO

arXiv:1411.3441

ai real

HZZ tensor structure

Consider two anomalous contributions at the same time



Consistent with the SM?

☑ YES

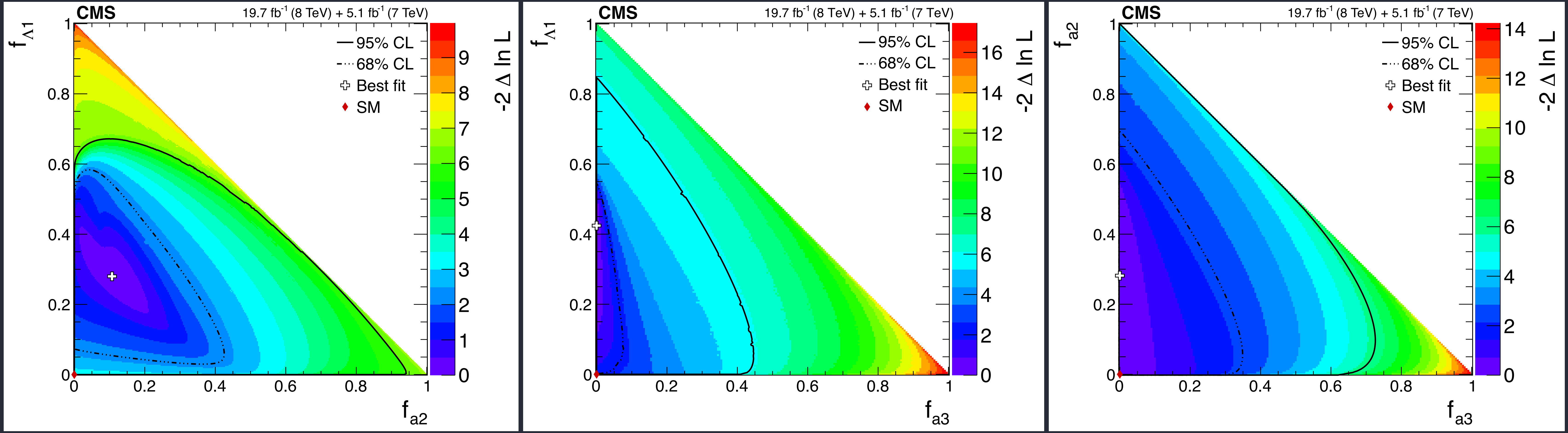
☐ NO

arXiv:1411.3441

ai cmplx

HZZ tensor structure

Consider two anomalous contributions at the same time



Less precision when phase not constrained.

Consistent with the SM?

☐ YES

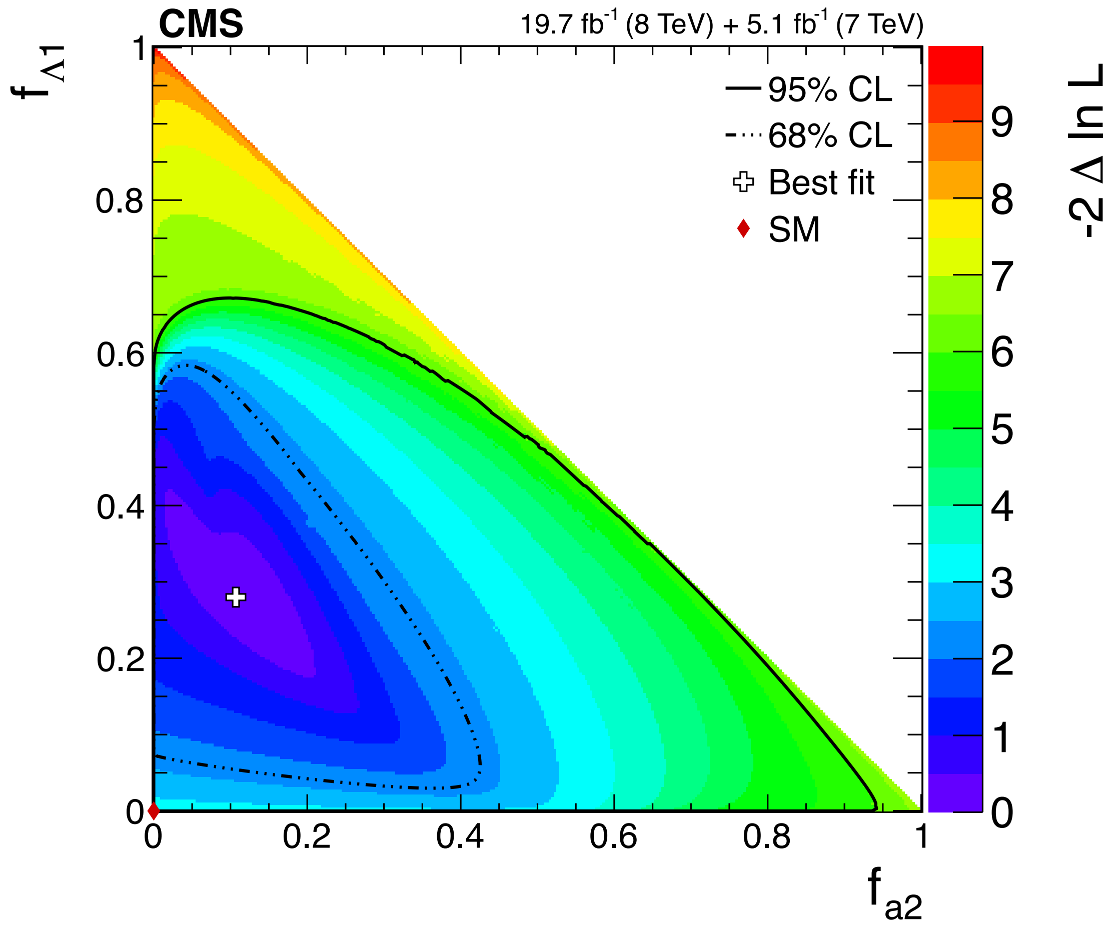
☐ NO

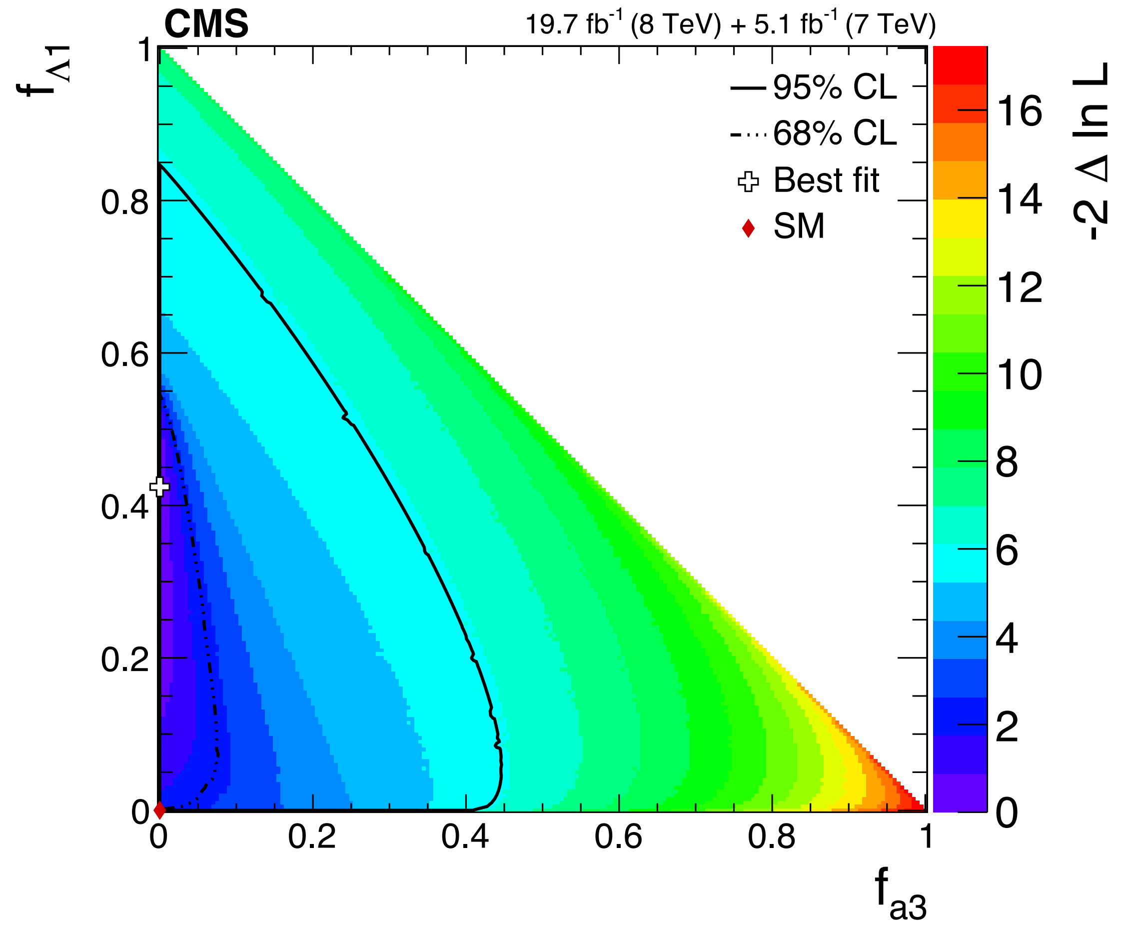
arXiv:1411.3441

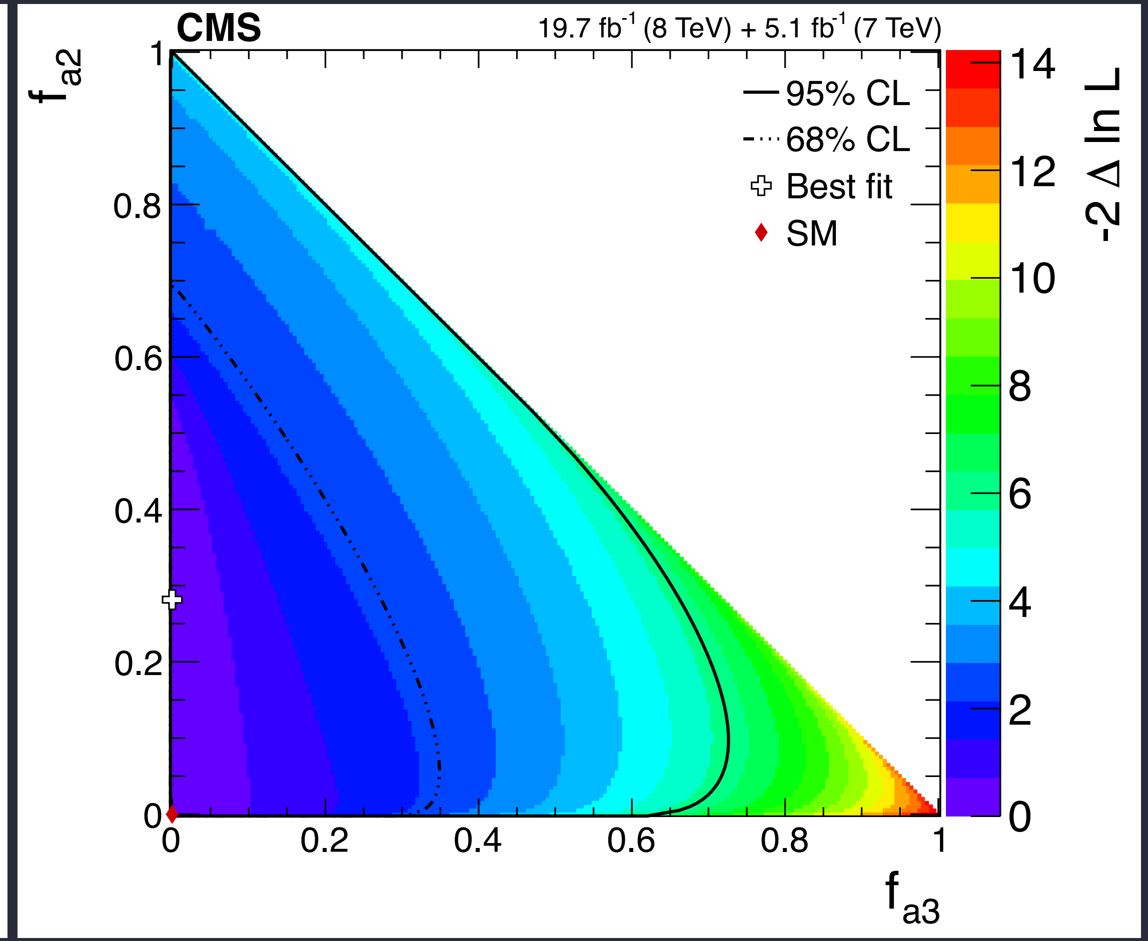
ai cmplx

HZZ tensor structure

Consider two anomalous contributions at the same time







Less precision when phase not constrained.

Consistent with the SM?

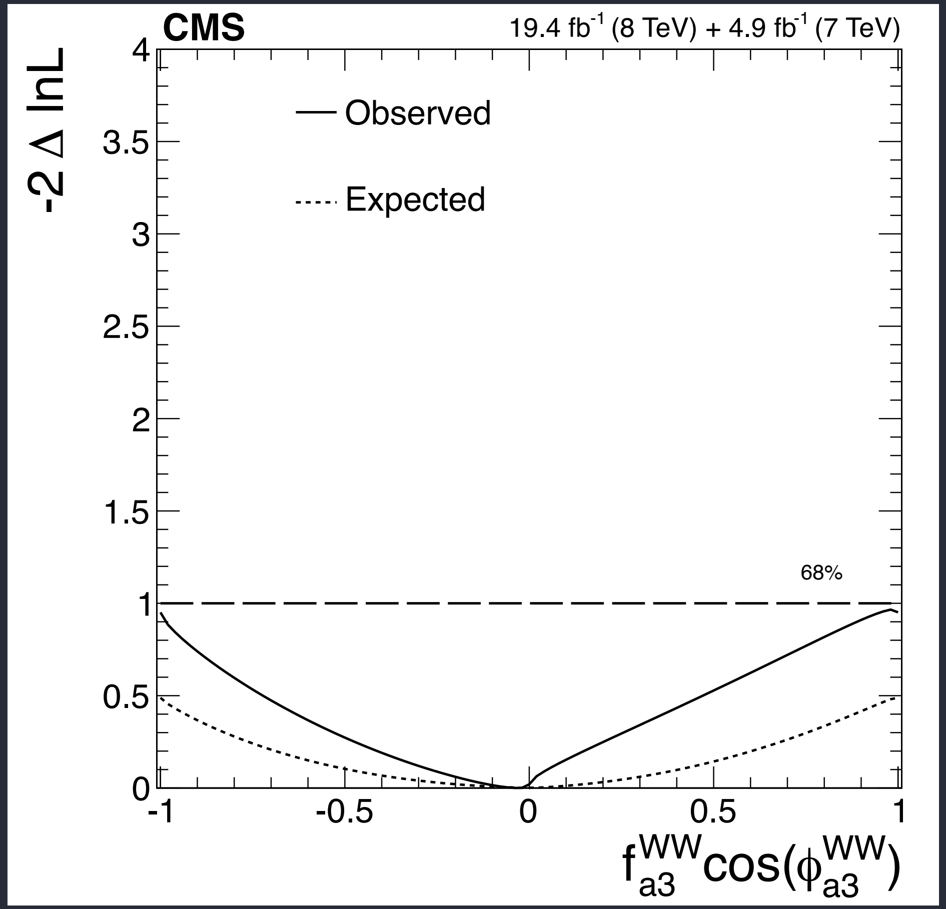
☑ YES

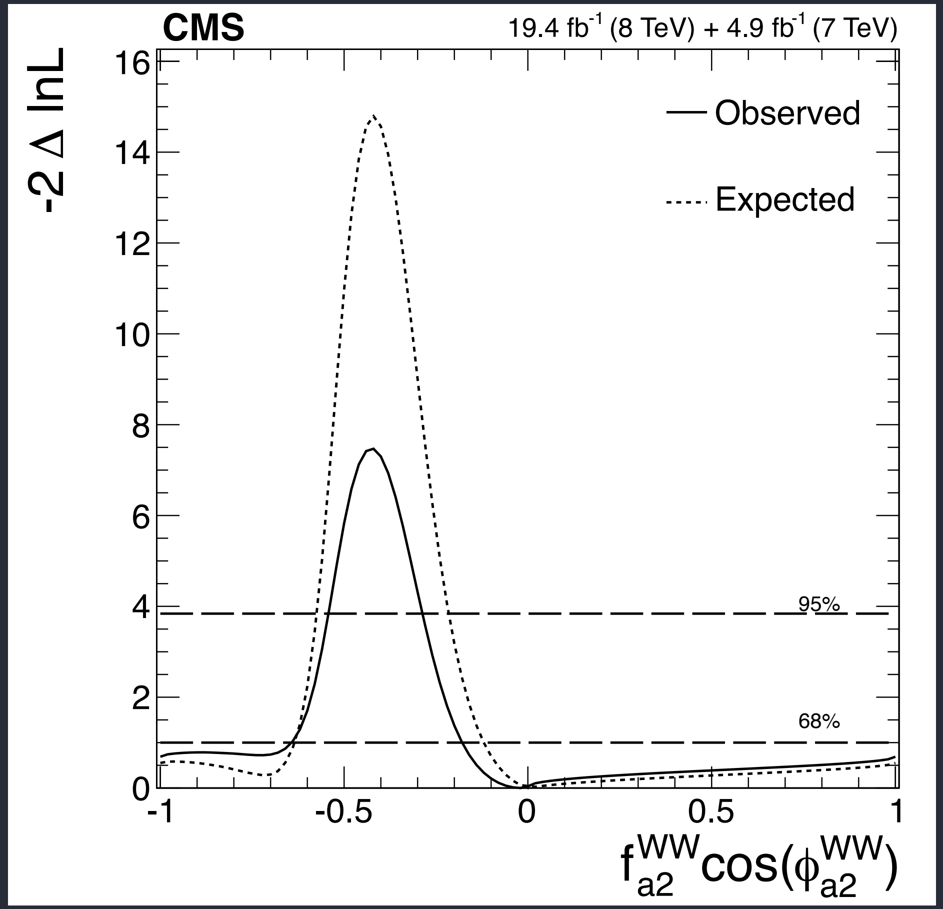
☐ NO

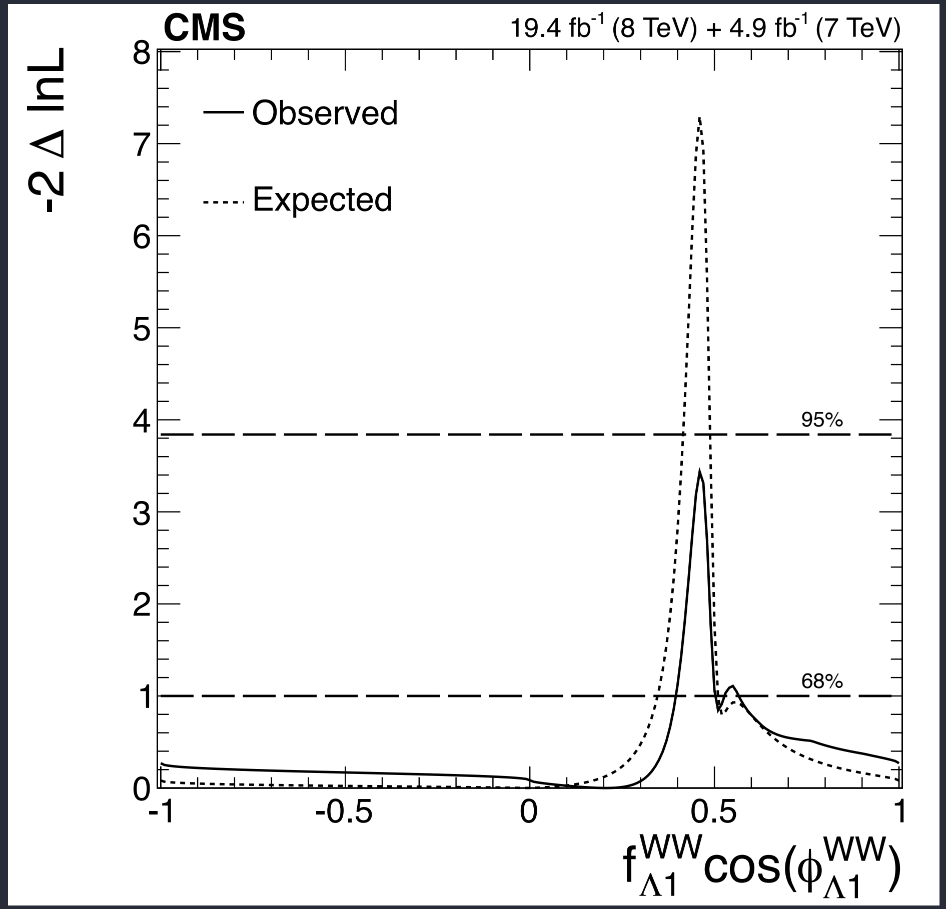
ai real

arXiv:1411.3441

HWW tensor structure







Consistent with the SM?

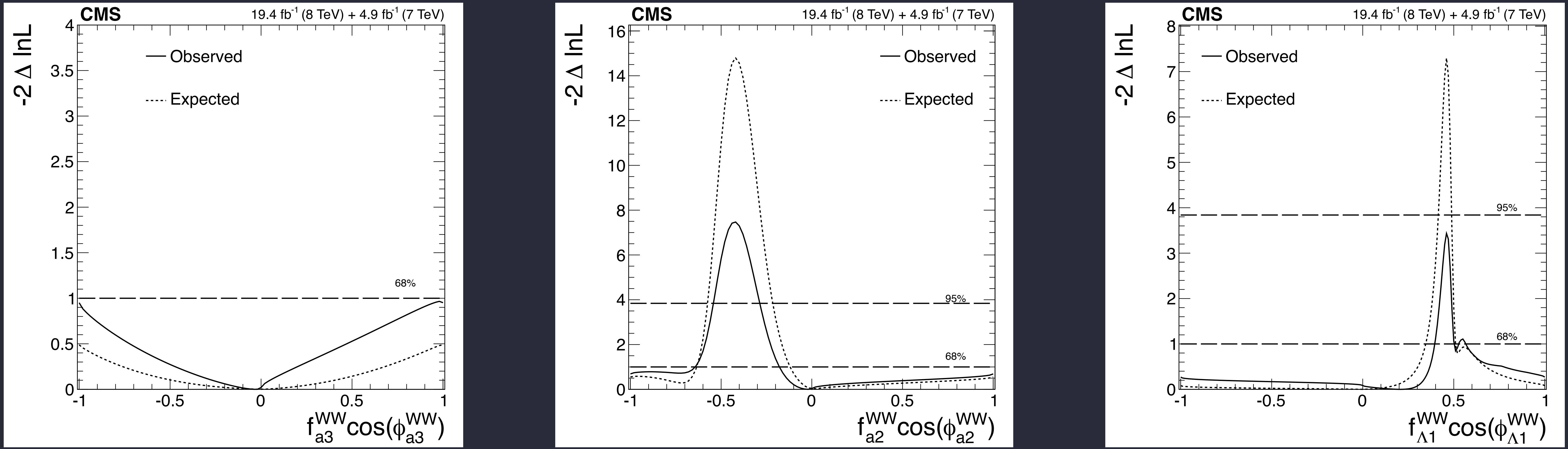
☐ YES

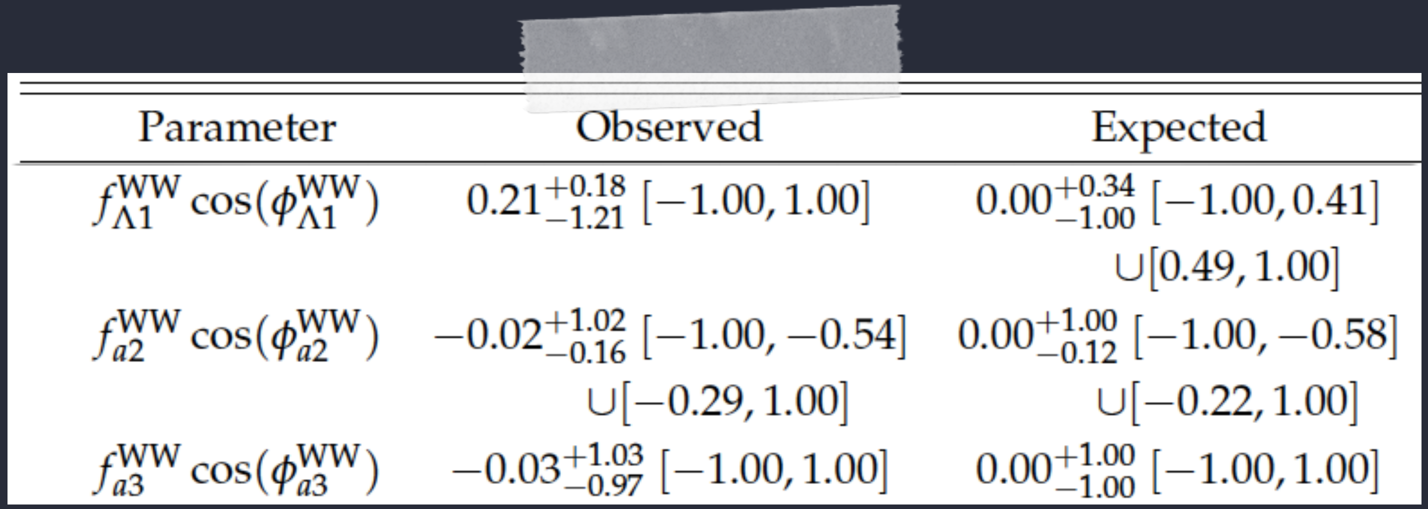
☐ NO

arXiv:1411.3441

ai real

HWW tensor structure





Parameter	Observed	Expected
$f_{\Lambda1}^{\mathrm{WW}}\cos(\phi_{\Lambda1}^{\mathrm{WW}})$	$0.21^{+0.18}_{-1.21}\ [-1.00, 1.00]$	$0.00^{+0.34}_{-1.00}\ [-1.00, 0.41]$ $\cup[0.49, 1.00]$
$f_{a2}^{\mathrm{WW}}\cos(\phi_{a2}^{\mathrm{WW}})$	$-0.02^{+1.02}_{-0.16}\ [-1.00, -0.54]$ $\cup[-0.29, 1.00]$	$0.00^{+1.00}_{-0.12}\ [-1.00, -0.58]$ $\cup[-0.22, 1.00]$
$f_{a3}^{\mathrm{WW}}\cos(\phi_{a3}^{\mathrm{WW}})$	$-0.03^{+1.03}_{-0.97}\ [-1.00, 1.00]$	$0.00^{+1.00}_{-1.00}\ [-1.00, 1.00]$

Consistent with the SM?

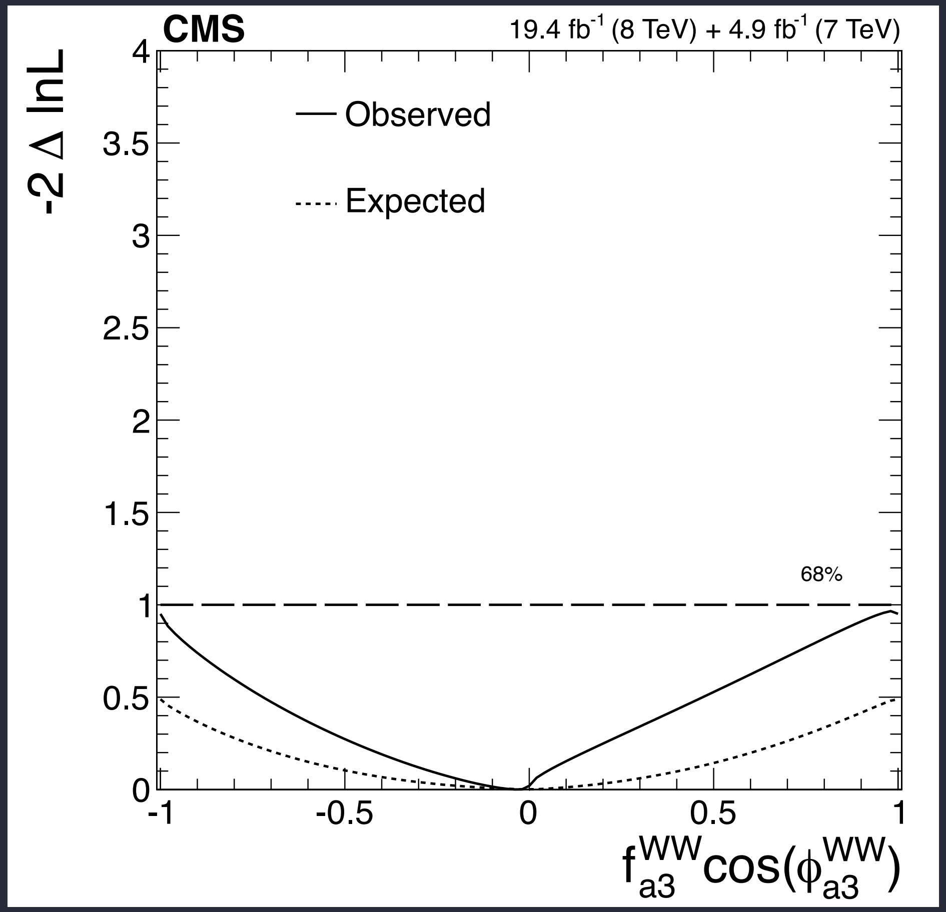
☐ YES

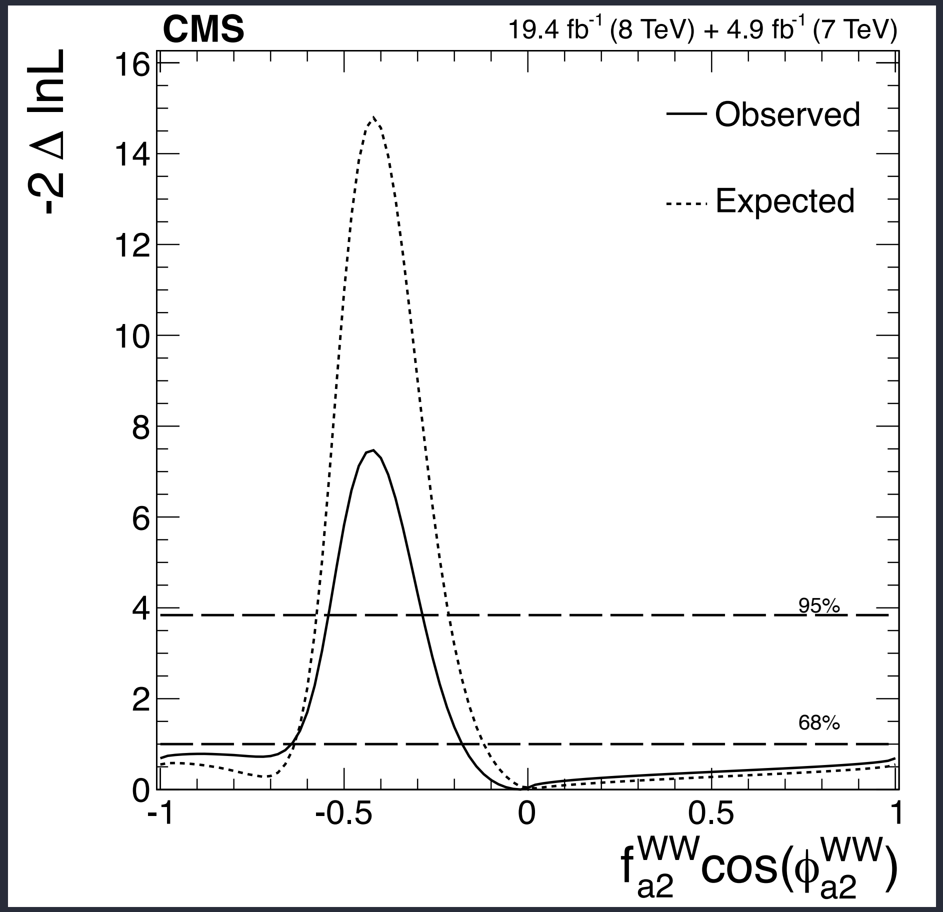
☐ NO

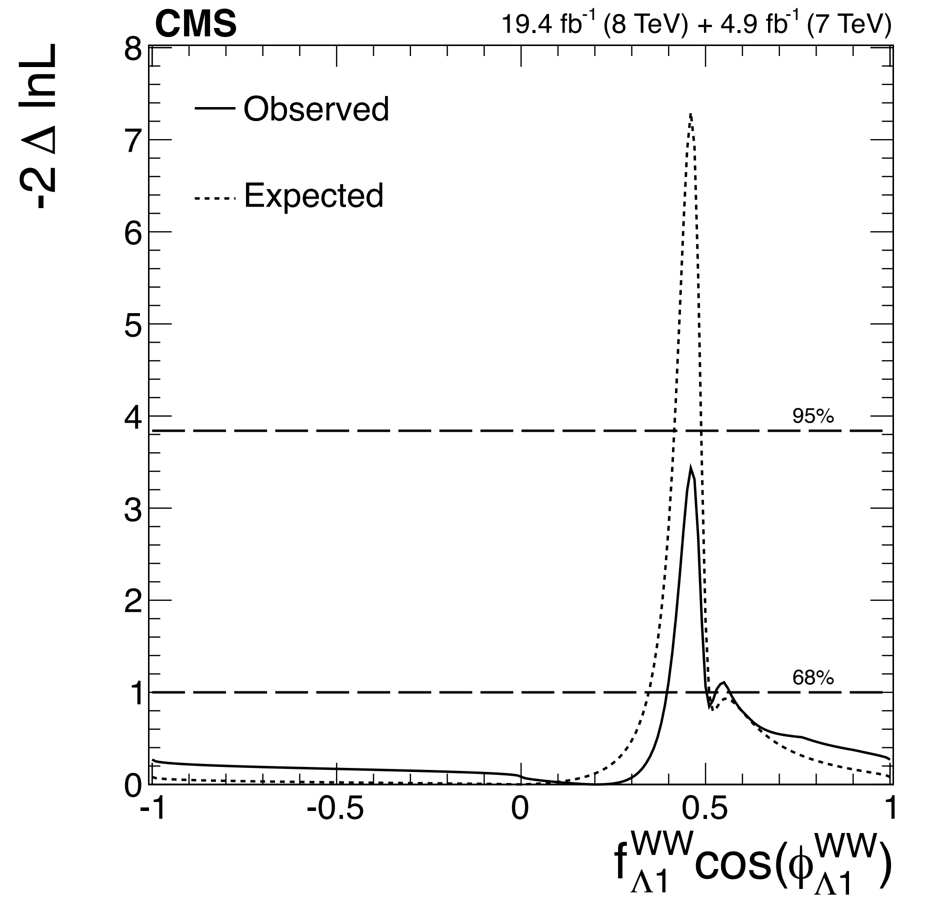
arXiv:1411.3441

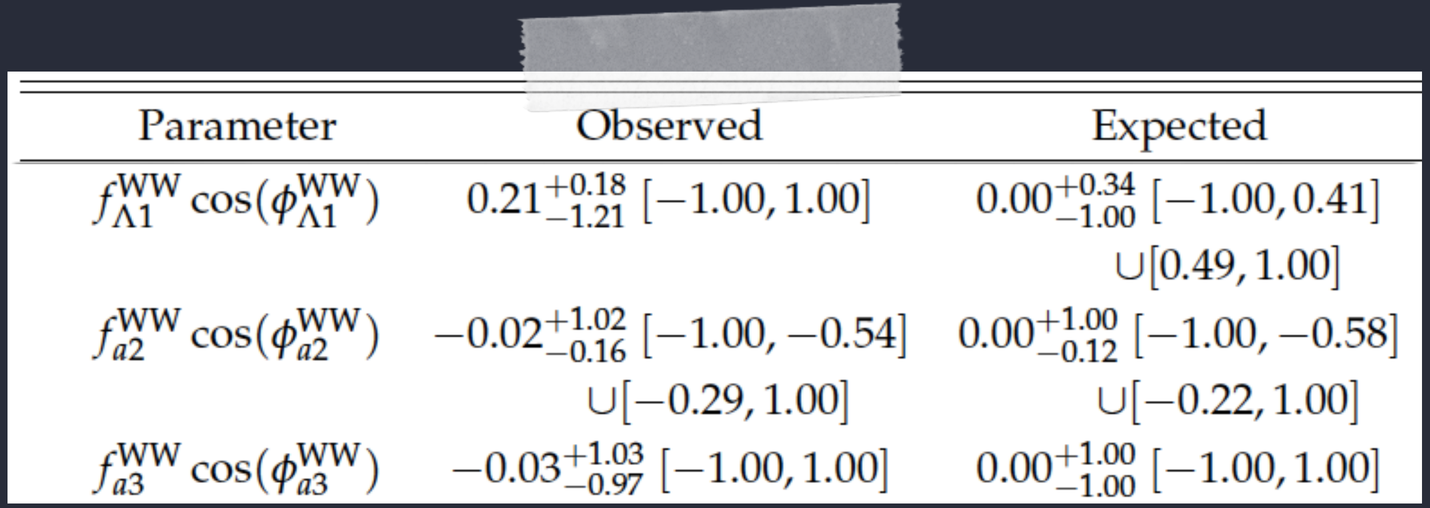
ai real

HWW tensor structure









Parameter	Observed	Expected
$f_{\Lambda1}^{WW}\cos(\phi_{\Lambda1}^{WW})$	$0.21^{+0.18}_{-1.21}$ $[-1.00, 1.00]$	$0.00^{+0.34}_{-1.00}$ $[-1.00, 0.41]$ $\cup[0.49, 1.00]$
$f_{a2}^{WW}\cos(\phi_{a2}^{WW})$	$-0.02^{+1.02}_{-0.16}$ $[-1.00, -0.54]$ $\cup[-0.29, 1.00]$	$0.00^{+1.00}_{-0.12}$ $[-1.00, -0.58]$ $\cup[-0.22, 1.00]$
$f_{a3}^{WW}\cos(\phi_{a3}^{WW})$	$-0.03^{+1.03}_{-0.97}$ $[-1.00, 1.00]$	$0.00^{+1.00}_{-1.00}$ $[-1.00, 1.00]$

Consistent with the SM?

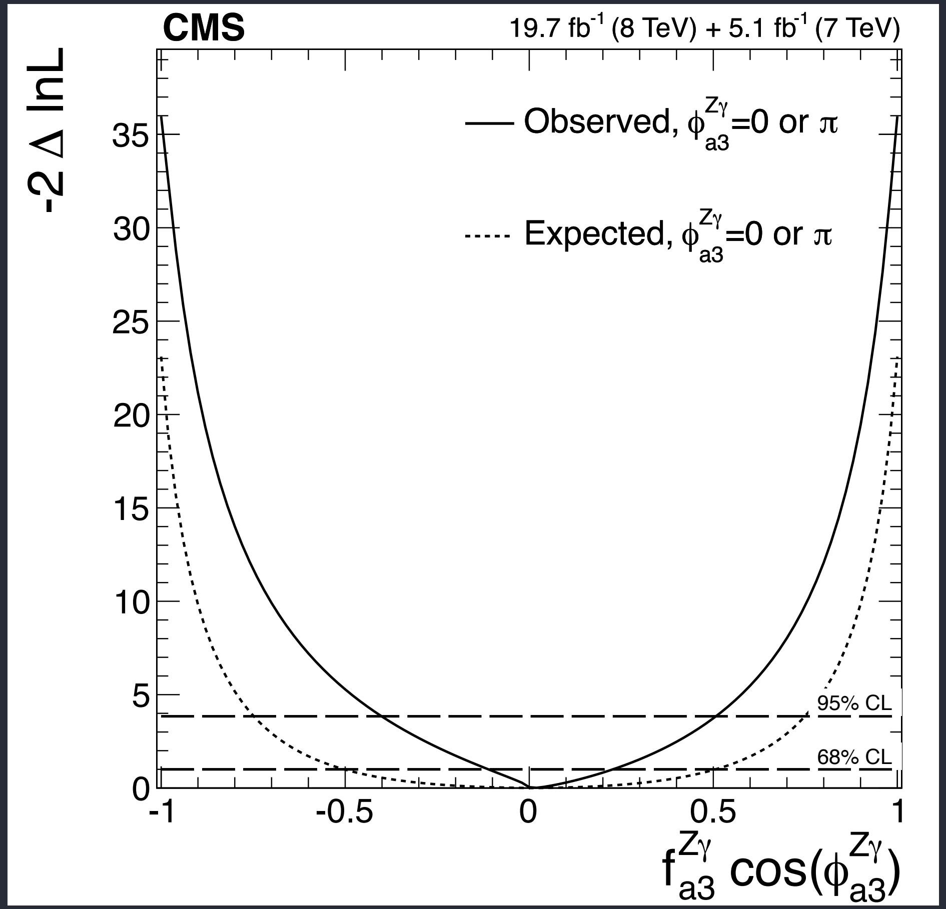
☑ YES

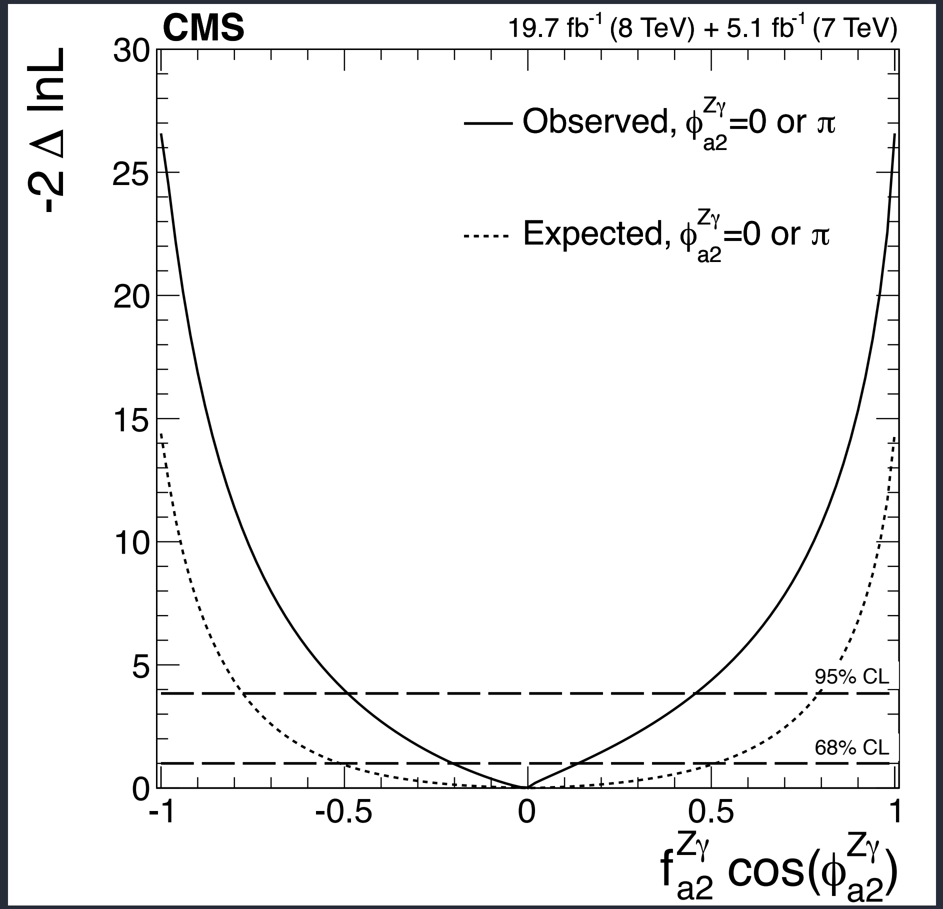
☐ NO

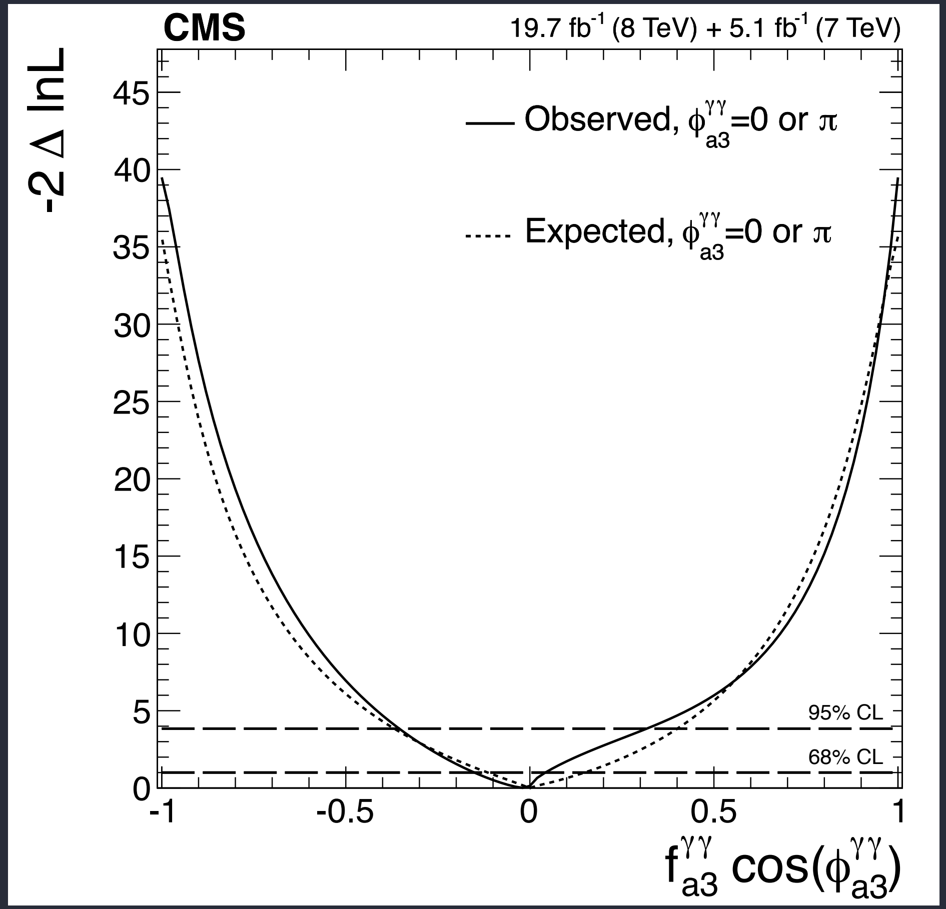
arXiv:1411.3441

ai real

HZγ, Hγγ tensor structure







H → 4l final state, Zγ and γγ are just intermediate virtual particles.

Consistent with the SM?

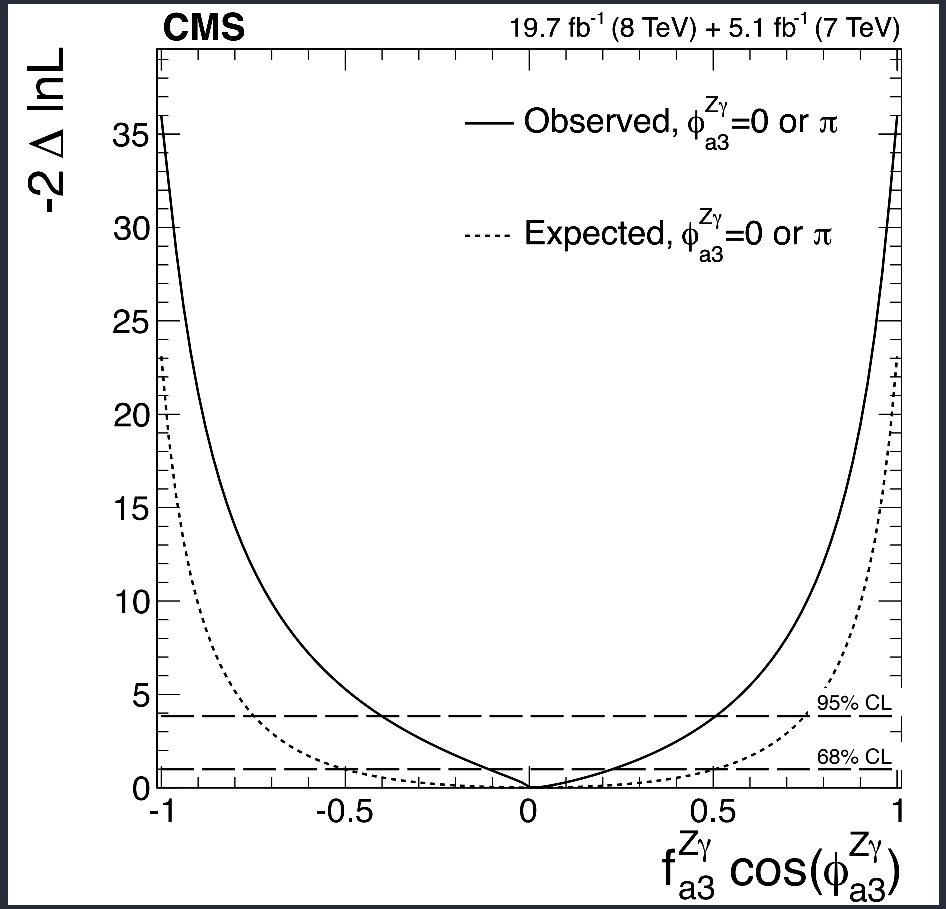
☐ YES

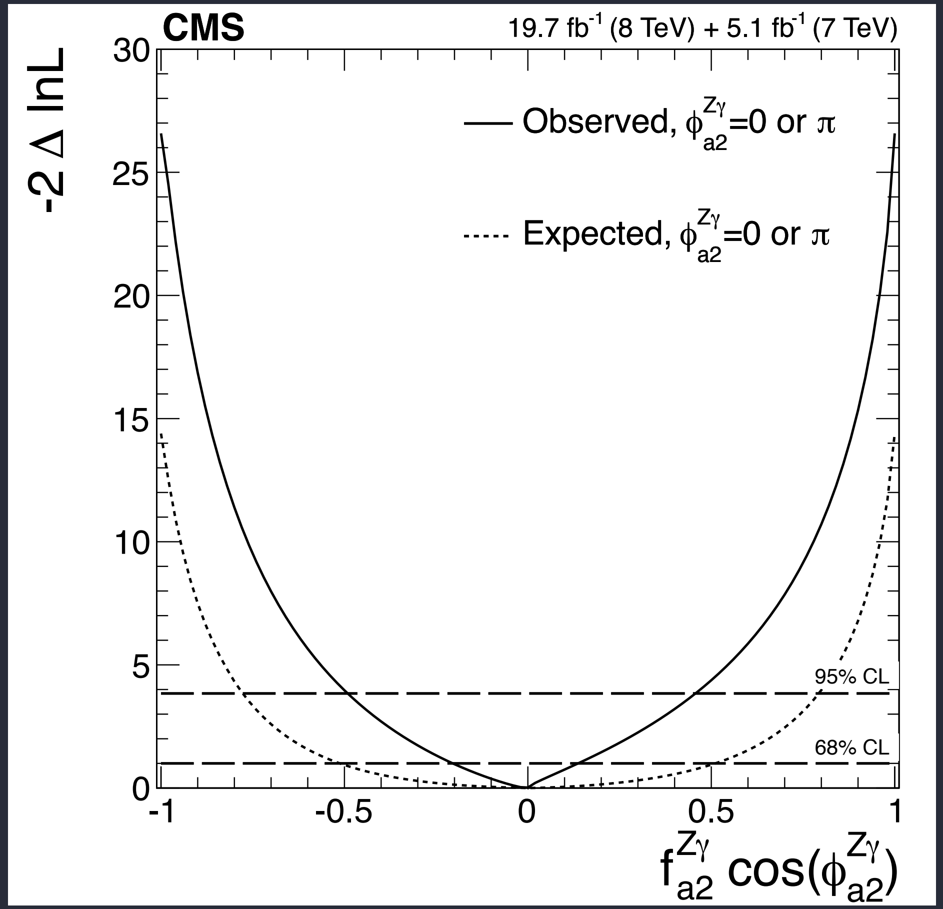
☐ NO

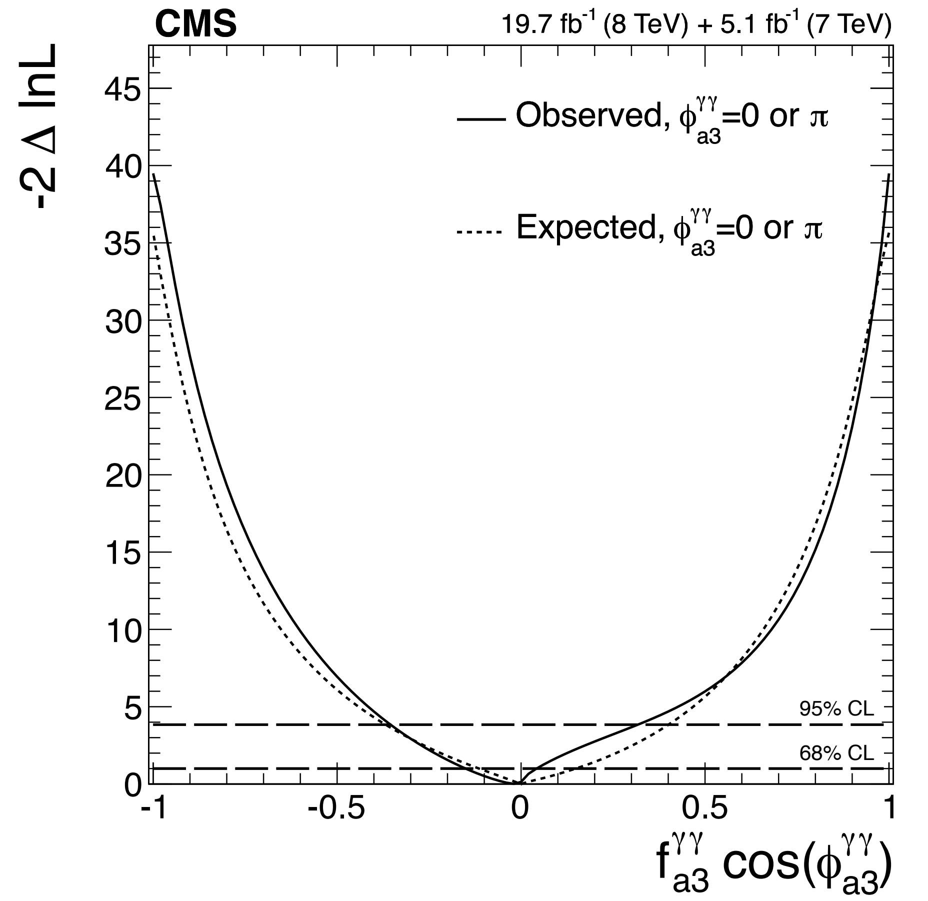
arXiv:1411.3441

ai real

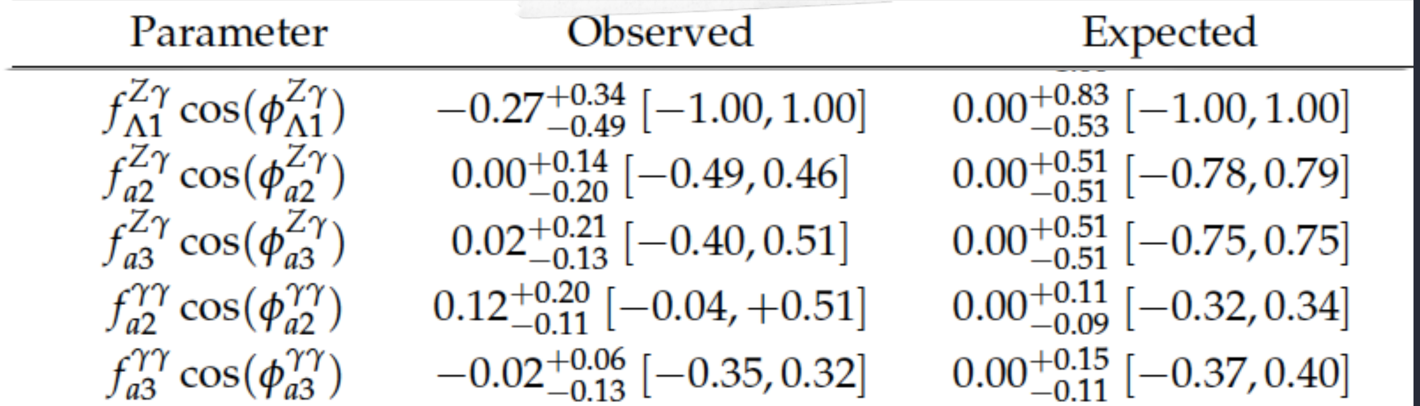
HZγ, Hγγ tensor structure







H → 4l final state, Zγ and γγ are just intermediate virtual particles.



Parameter	Observed	Expected
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}^{Z\gamma})$	$-0.27^{+0.34}_{-0.49}$ $[-1.00, 1.00]$	$0.00^{+0.83}_{-0.53}$ $[-1.00, 1.00]$
$f_{a2}^{Z\gamma}\cos(\phi_{a2}^{Z\gamma})$	$0.00^{+0.14}_{-0.20}$ $[-0.49, 0.46]$	$0.00^{+0.51}_{-0.51}$ $[-0.78, 0.79]$
$f_{a3}^{Z\gamma}\cos(\phi_{a3}^{Z\gamma})$	$0.02^{+0.21}_{-0.13}$ $[-0.40, 0.51]$	$0.00^{+0.51}_{-0.51}$ $[-0.75, 0.75]$
$f_{a2}^{\gamma\gamma}\cos(\phi_{a2}^{\gamma\gamma})$	$0.12^{+0.20}_{-0.11}$ $[-0.04, +0.51]$	$0.00^{+0.11}_{-0.09}$ $[-0.32, 0.34]$
$f_{a3}^{\gamma\gamma}\cos(\phi_{a3}^{\gamma\gamma})$	$-0.02^{+0.06}_{-0.13}$ $[-0.35, 0.32]$	$0.00^{+0.15}_{-0.11}$ $[-0.37, 0.40]$

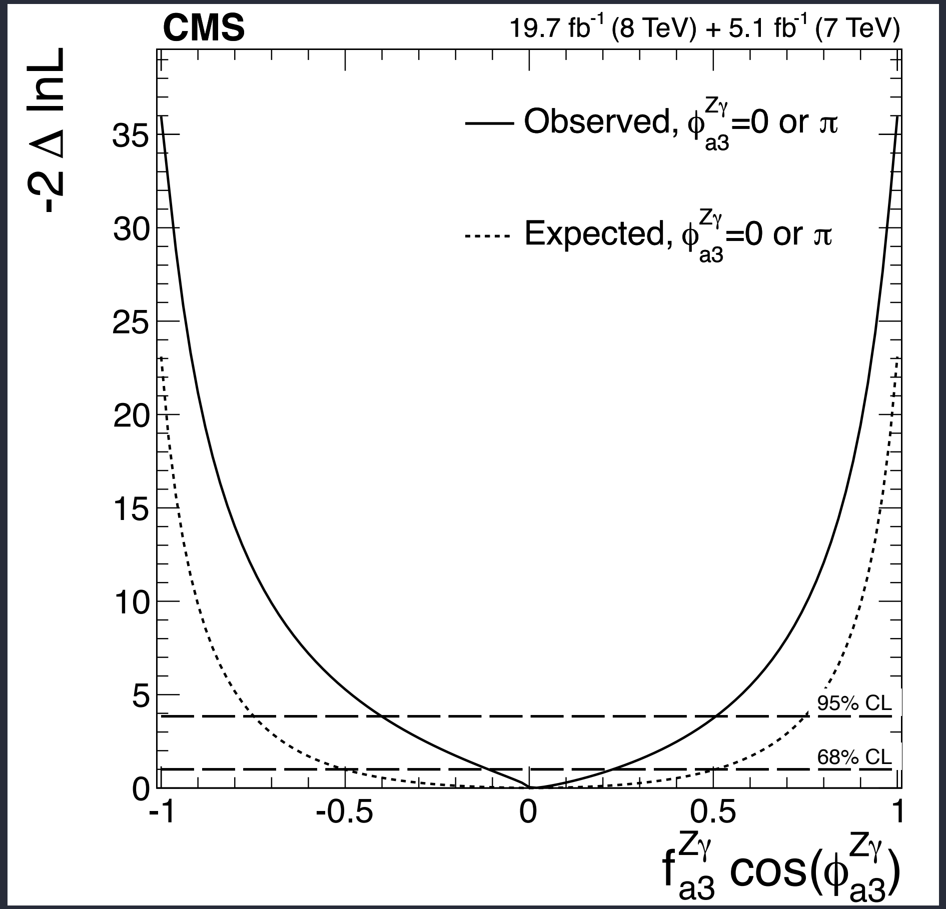
Consistent with the SM?

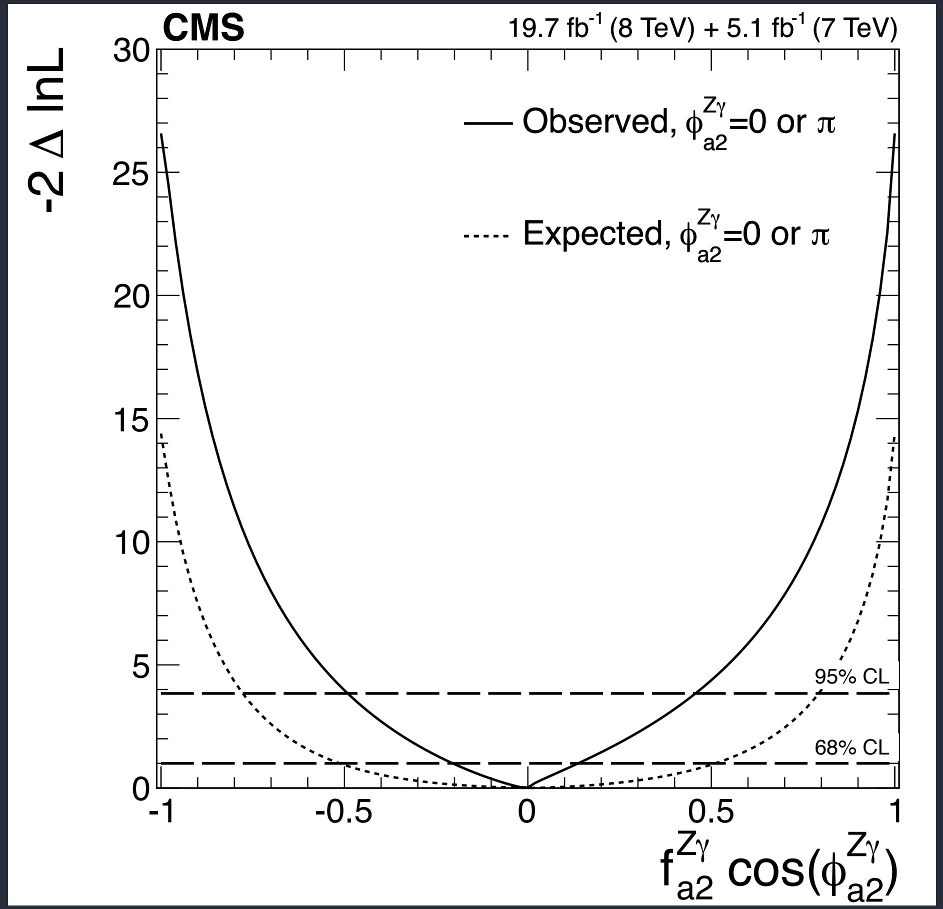
☐ YES

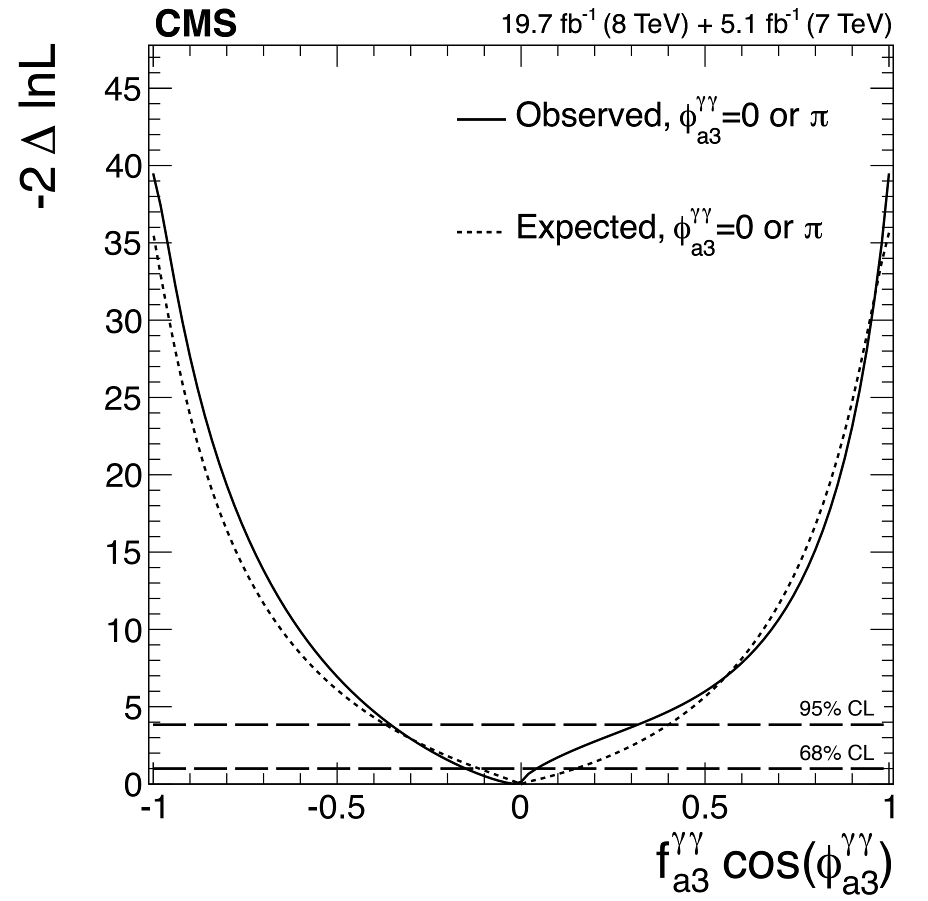
☐ NO

arXiv:1411.3441

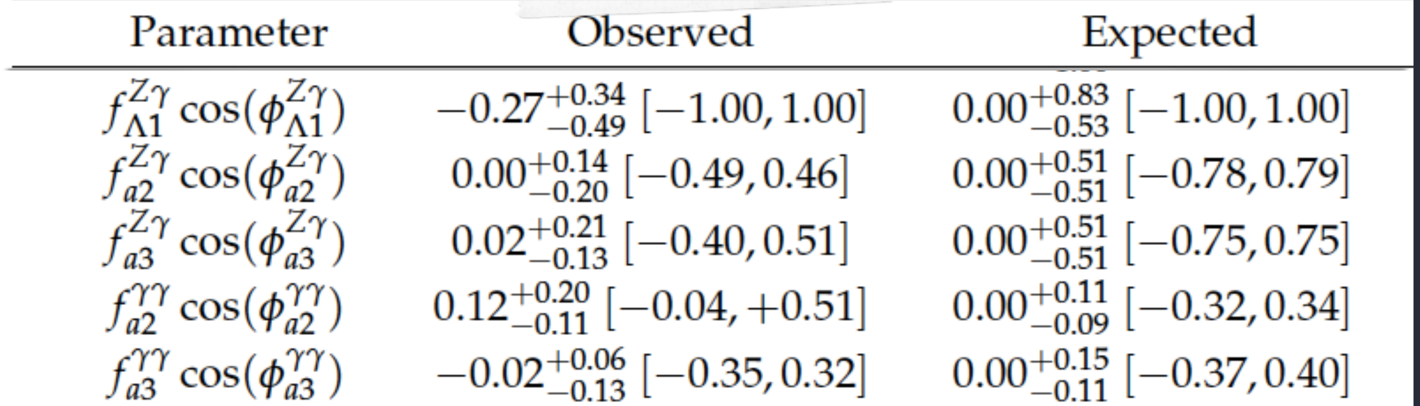
HZγ, Hγγ tensor structure







H → 4l final state, Zγ and γγ are just intermediate virtual particles.



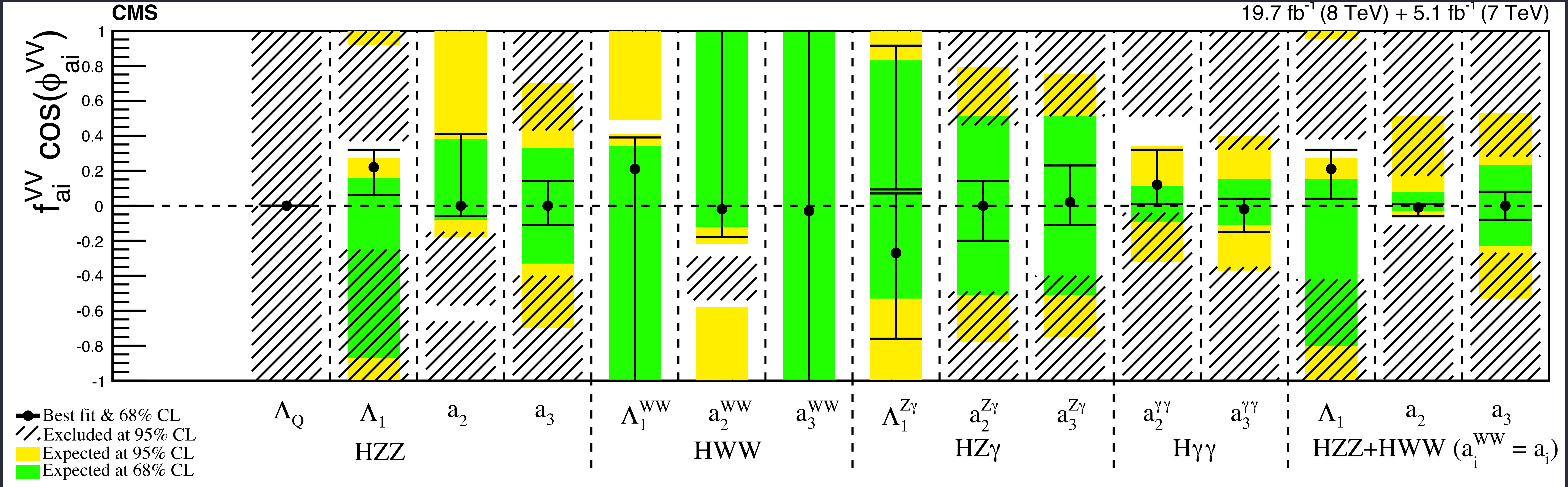
Parameter	Observed	Expected
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$-0.27^{+0.34}_{-0.49}$ $[-1.00, 1.00]$	$0.00^{+0.83}_{-0.53}$ $[-1.00, 1.00]$
$f_{a2}^{Z\gamma}\cos(\phi_{a2}^{Z\gamma})$	$0.00^{+0.14}_{-0.20}$ $[-0.49, 0.46]$	$0.00^{+0.51}_{-0.51}$ $[-0.78, 0.79]$
$f_{a3}^{Z\gamma}\cos(\phi_{a3}^{Z\gamma})$	$0.02^{+0.21}_{-0.13}$ $[-0.40, 0.51]$	$0.00^{+0.51}_{-0.51}$ $[-0.75, 0.75]$
$f_{a2}^{\gamma\gamma}\cos(\phi_{a2}^{\gamma\gamma})$	$0.12^{+0.20}_{-0.11}$ $[-0.04, +0.51]$	$0.00^{+0.11}_{-0.09}$ $[-0.32, 0.34]$
$f_{a3}^{\gamma\gamma}\cos(\phi_{a3}^{\gamma\gamma})$	$-0.02^{+0.06}_{-0.13}$ $[-0.35, 0.32]$	$0.00^{+0.15}_{-0.11}$ $[-0.37, 0.40]$

Consistent with the SM?

☑ YES

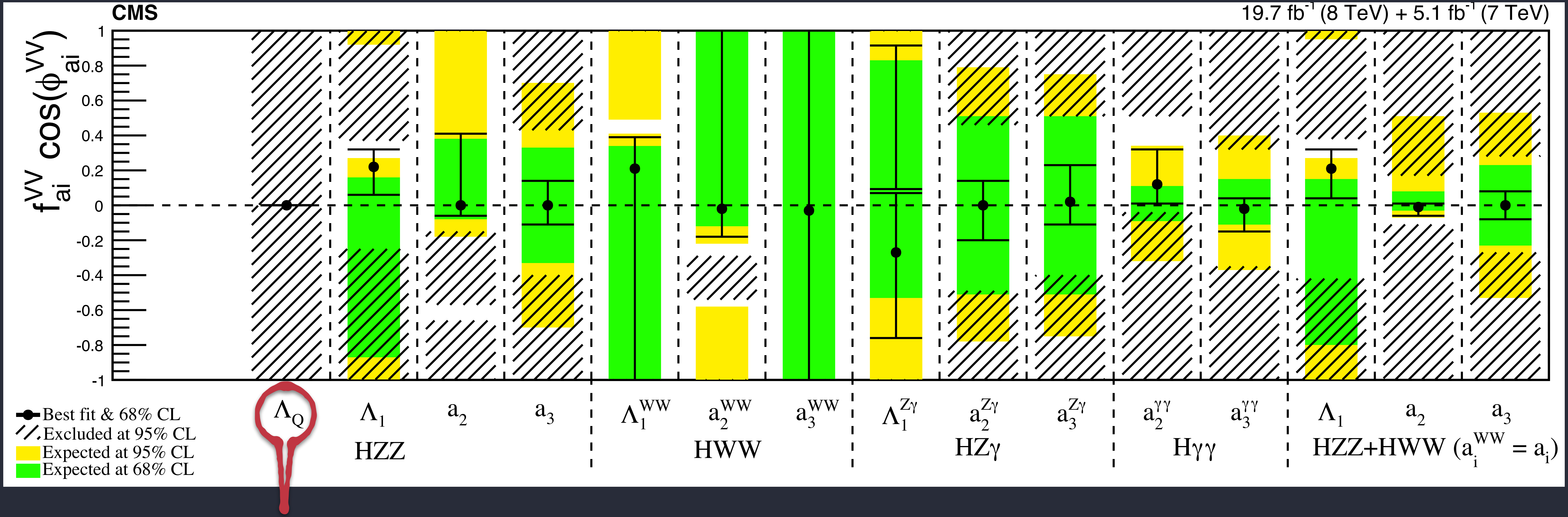
☐ NO

Combination and summary



All measurements are consistent with the SM.

Combination and summary

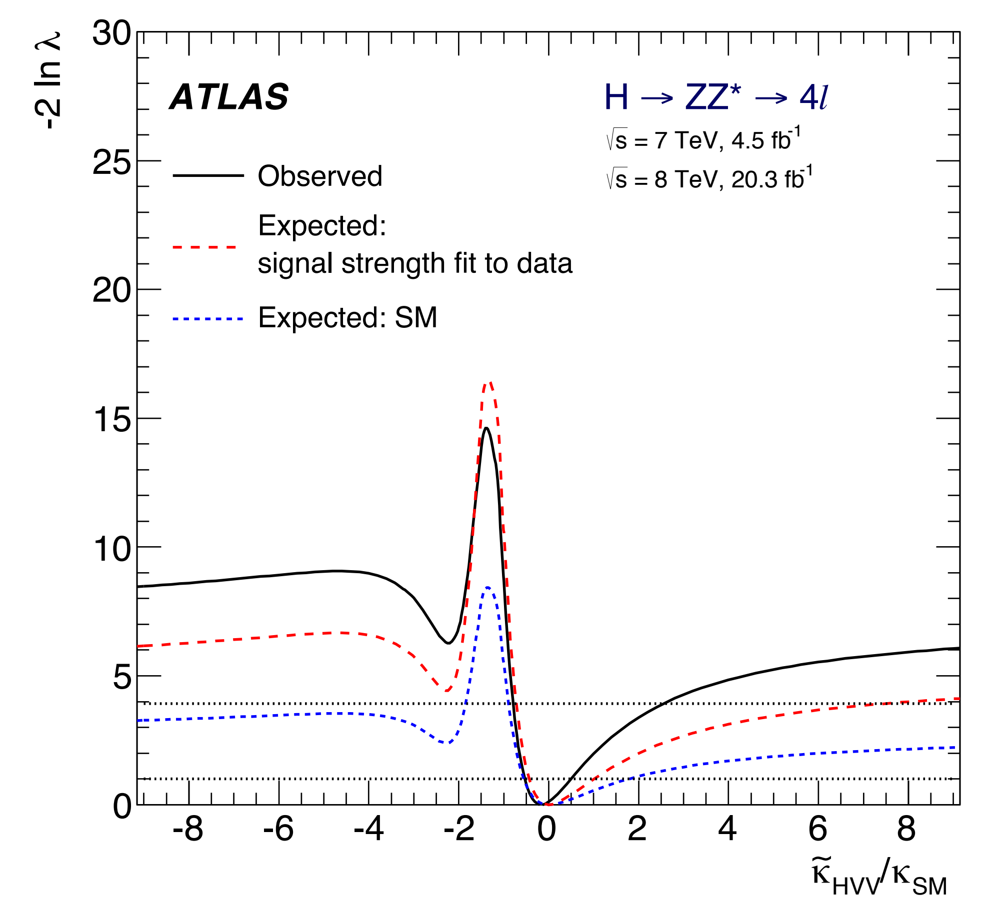


Talk by Candice.

All measurements are consistent with the SM.

arXiv:1506.05669

HZZ tensor structure

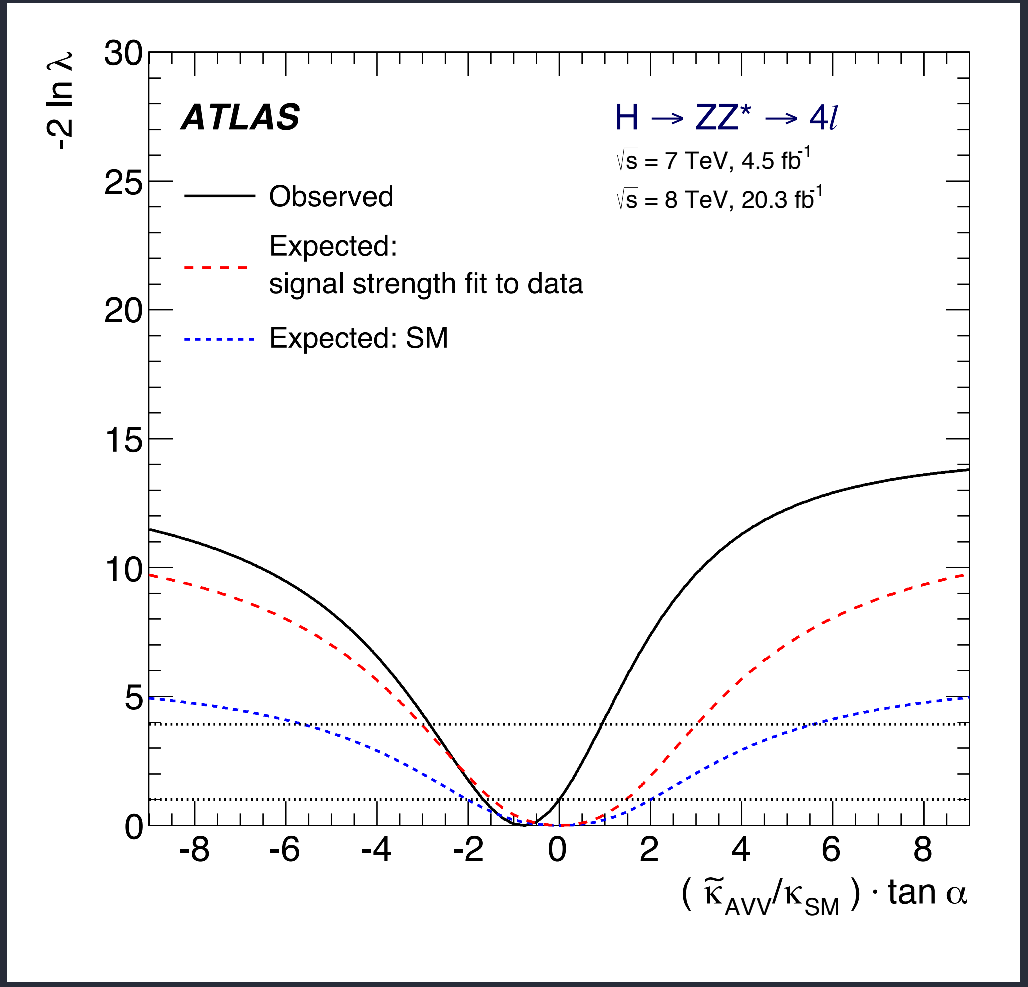


$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV} \text{ and } \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$

Consistent with the SM?

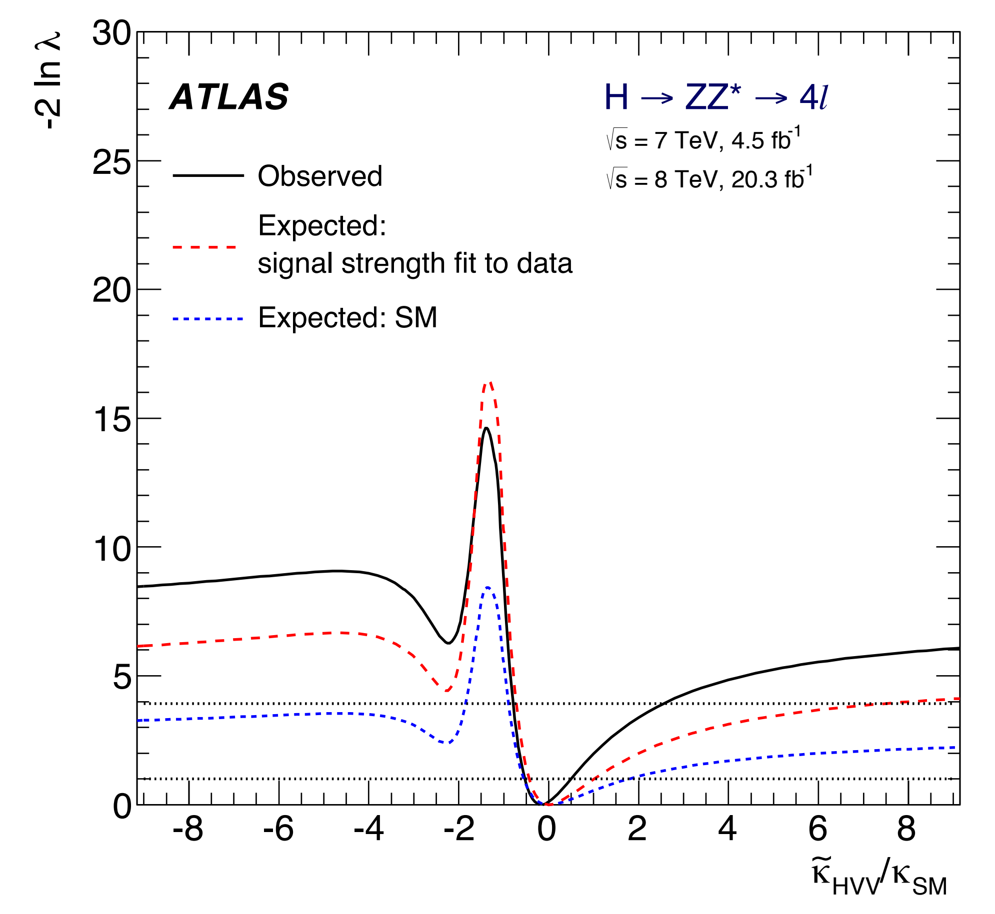
☐ YES

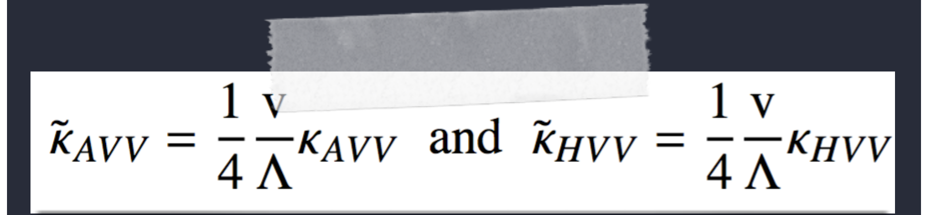
☐ NO



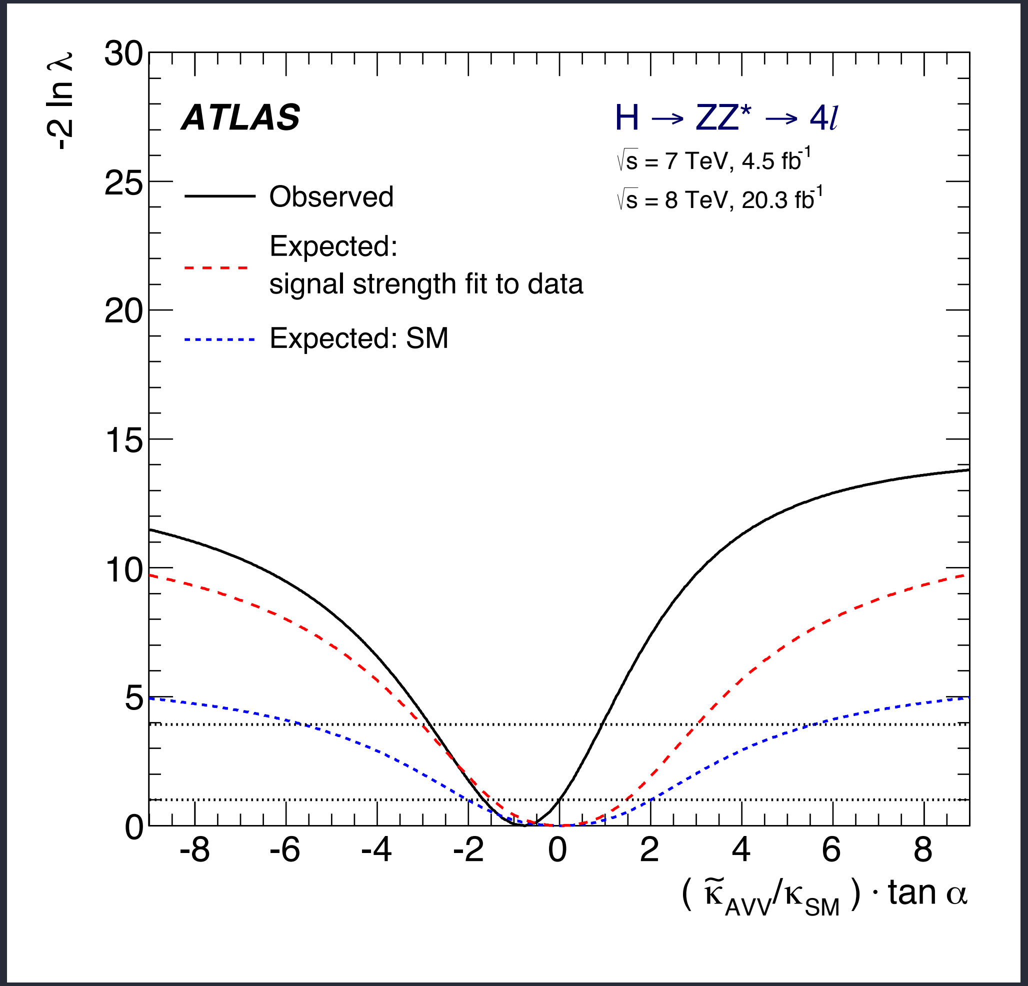
arXiv:1506.05669

HZZ tensor structure





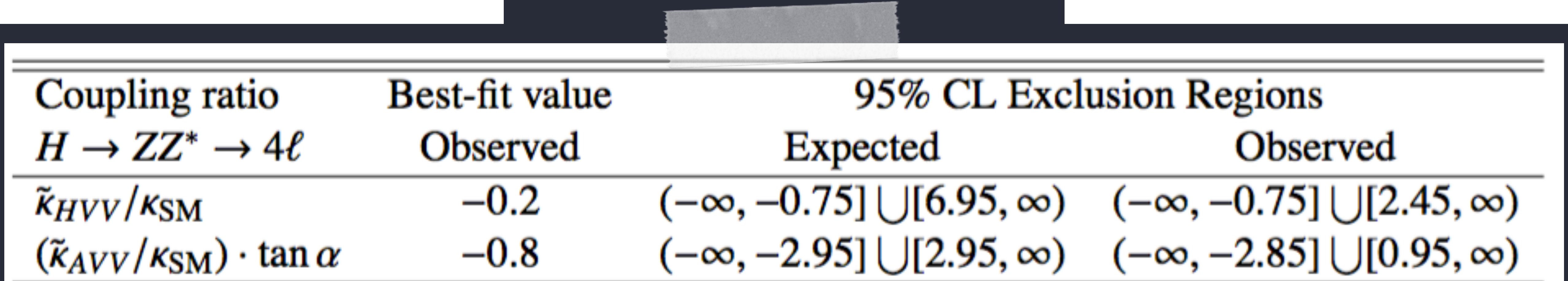
$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV} \text{ and } \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$



Consistent with the SM?

☐ YES

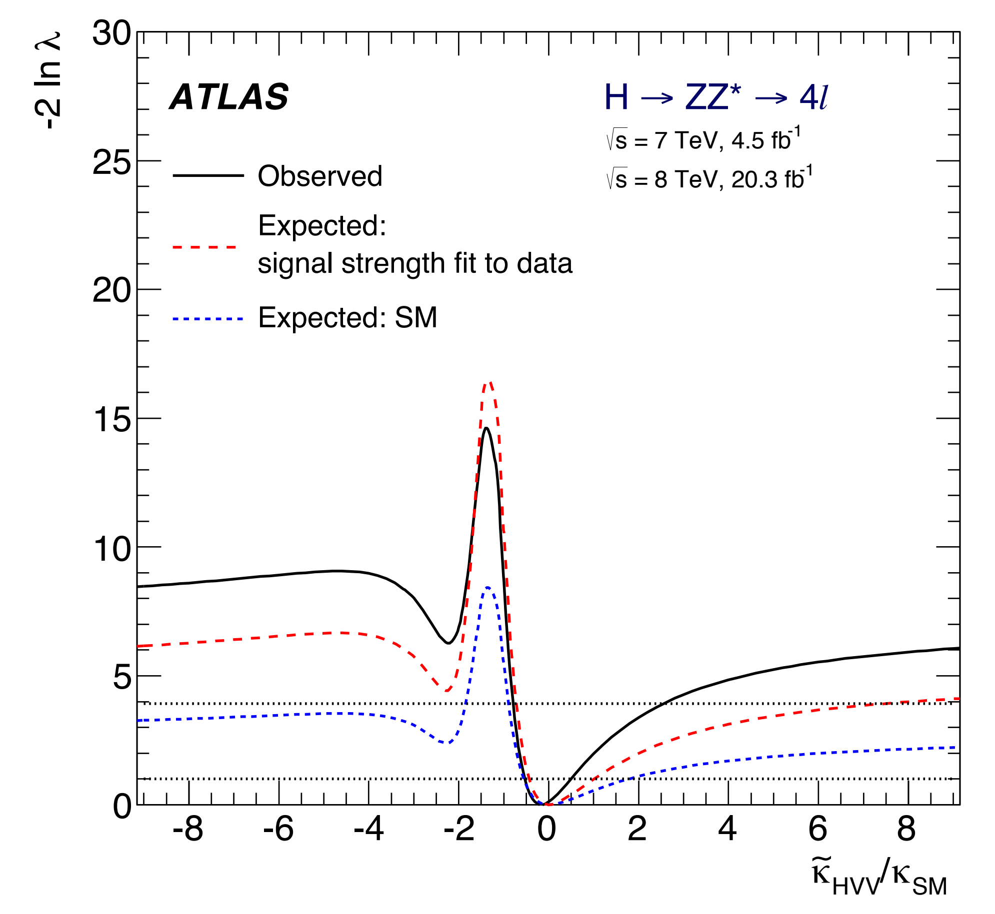
☐ NO

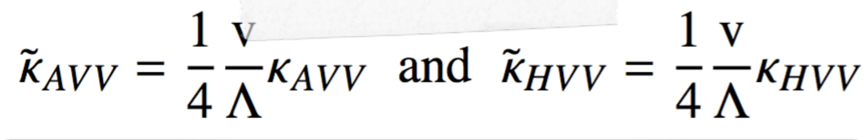


Coupling ratio $H \to ZZ^* \to 4\ell$	Best-fit value Observed	95% CL Exclusion Regions Expected	 Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	-0.2	$(-\infty, -0.75] \bigcup [6.95, \infty)$	$(-\infty, -0.75] \bigcup [2.45, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	-0.8	$(-\infty, -2.95] \bigcup [2.95, \infty)$	$(-\infty, -2.85] \bigcup [0.95, \infty)$

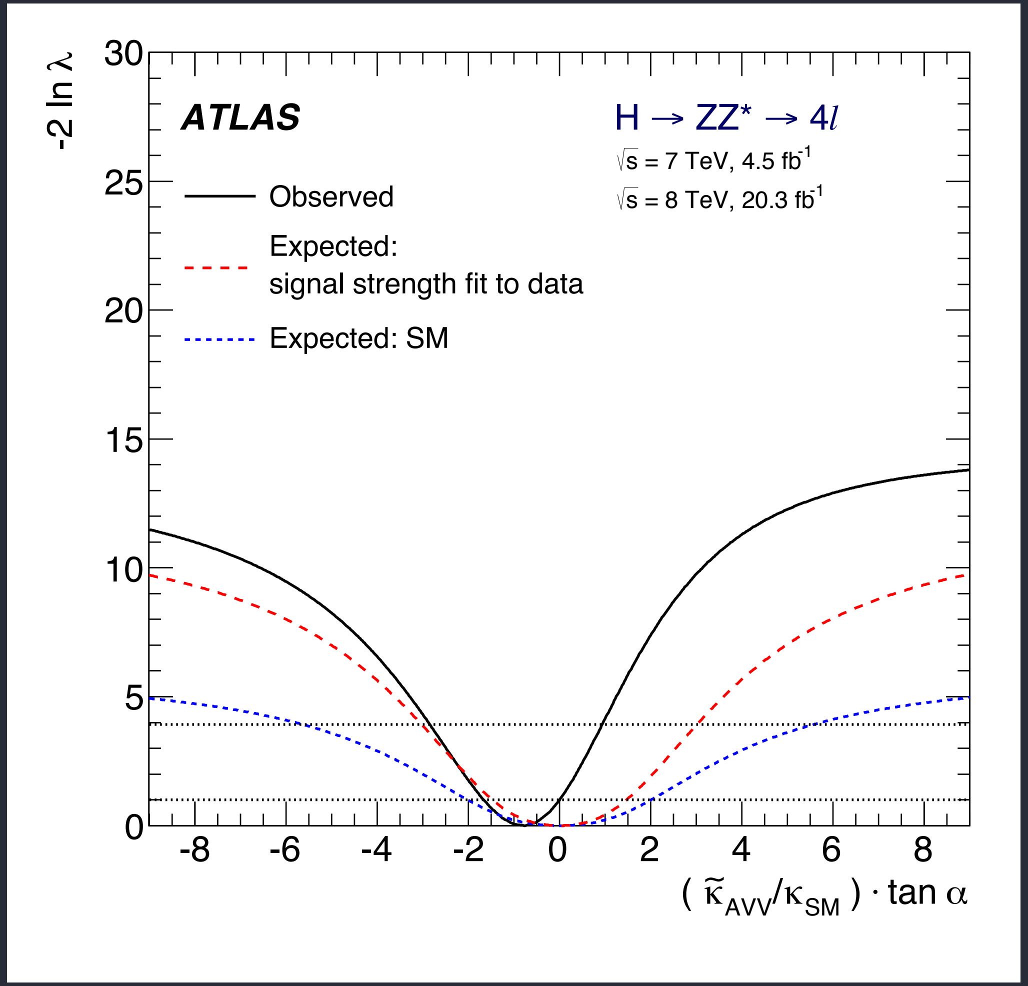
arXiv:1506.05669

HZZ tensor structure





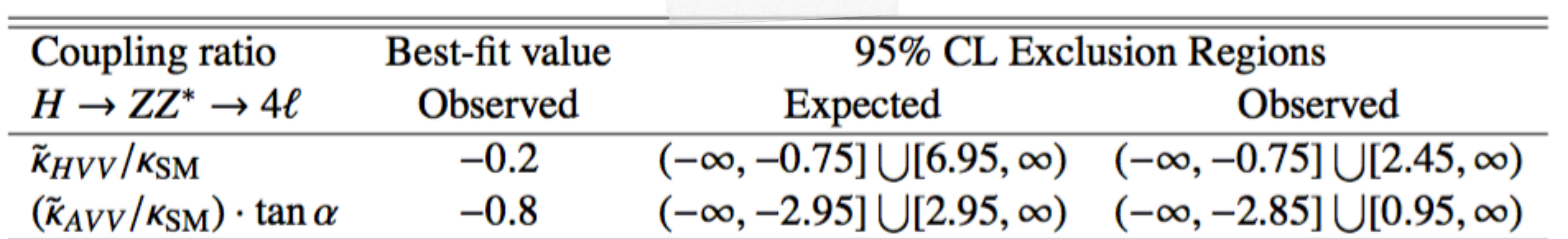
$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV} \text{ and } \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$



Consistent with the SM?

☑ YES

☐ NO



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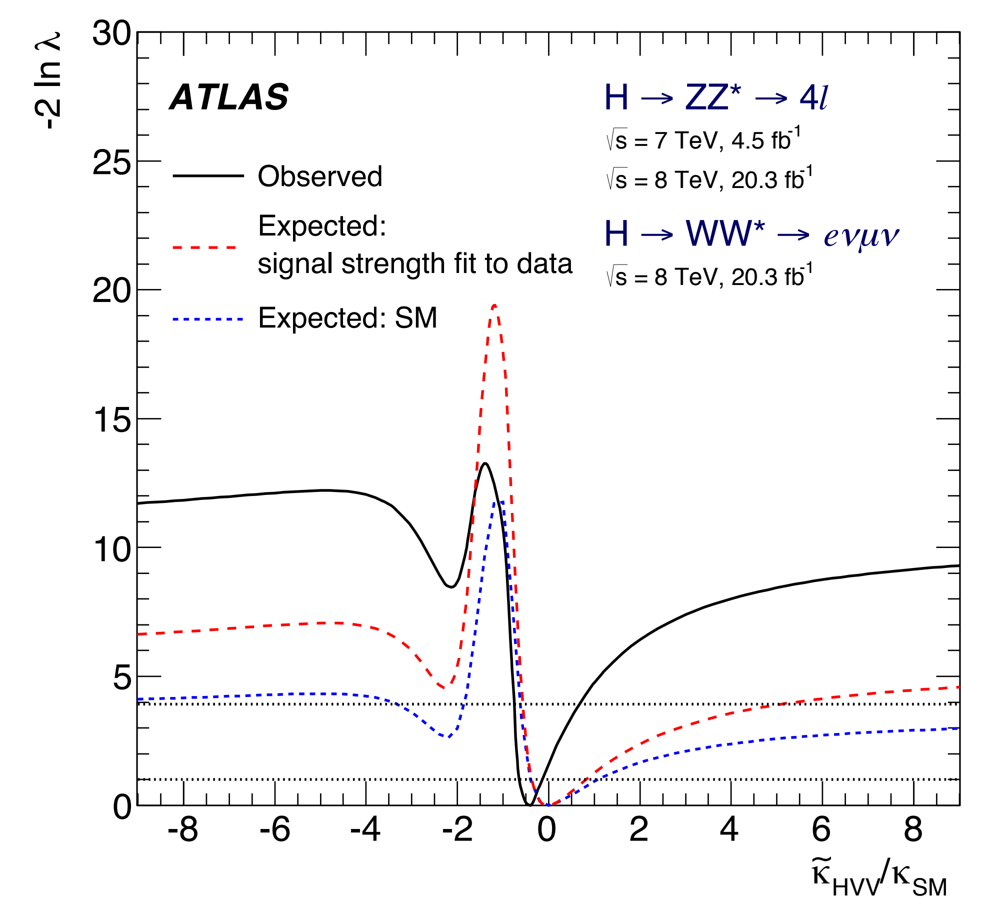
arXiv:1506.05669

HZZ and HWW combination

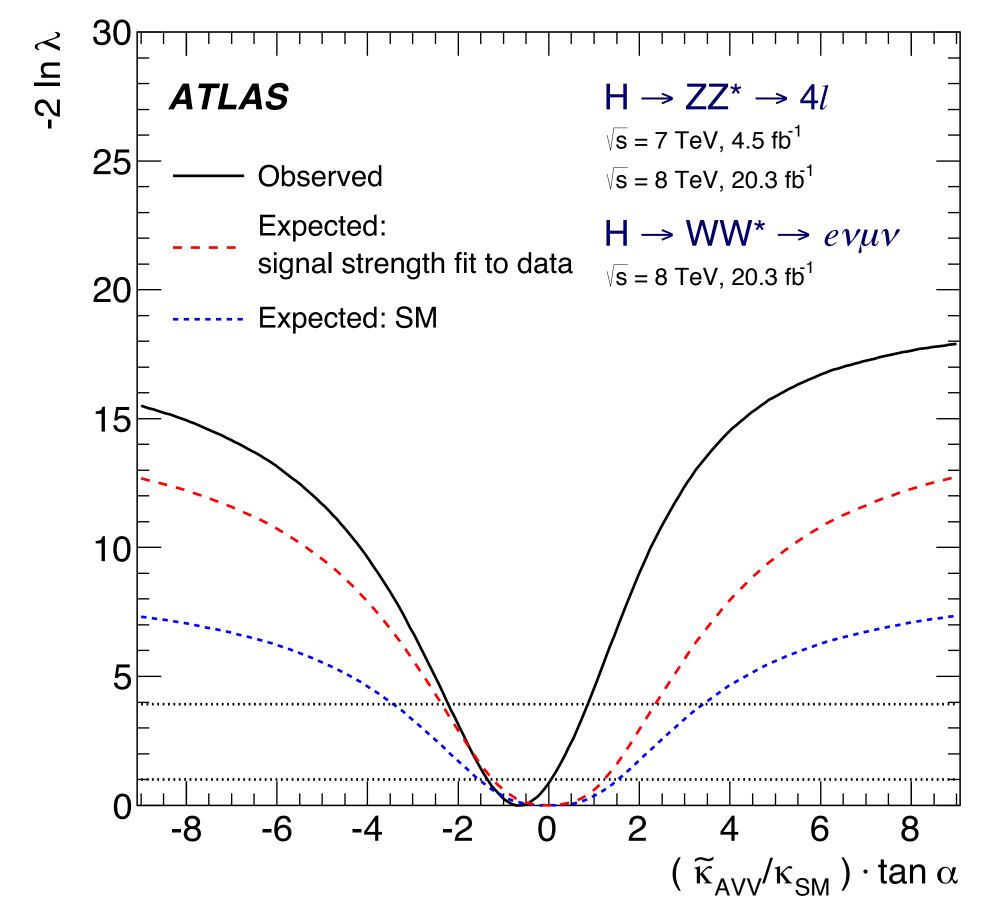


$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV} \text{ and } \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$

Consistent with the SM?

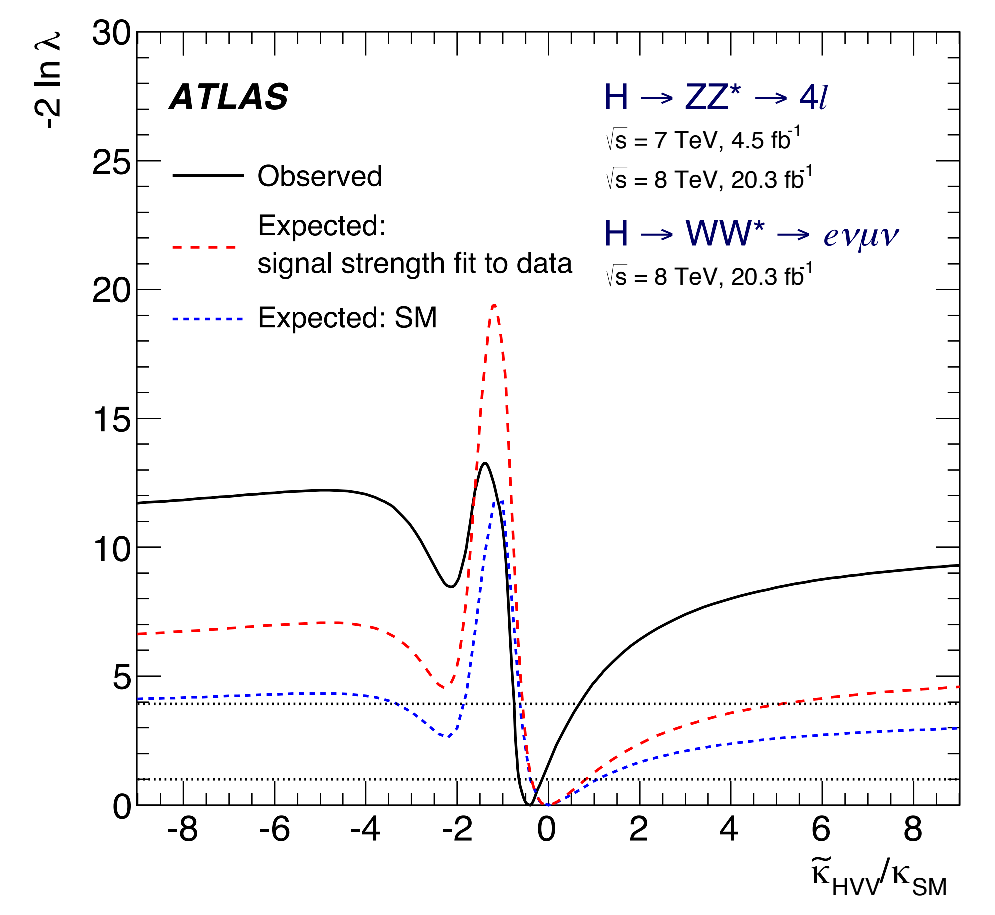
☐ YES

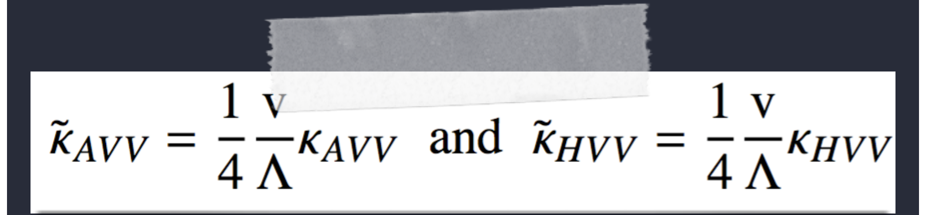
☐ NO



arXiv:1506.05669

HZZ and HWW combination





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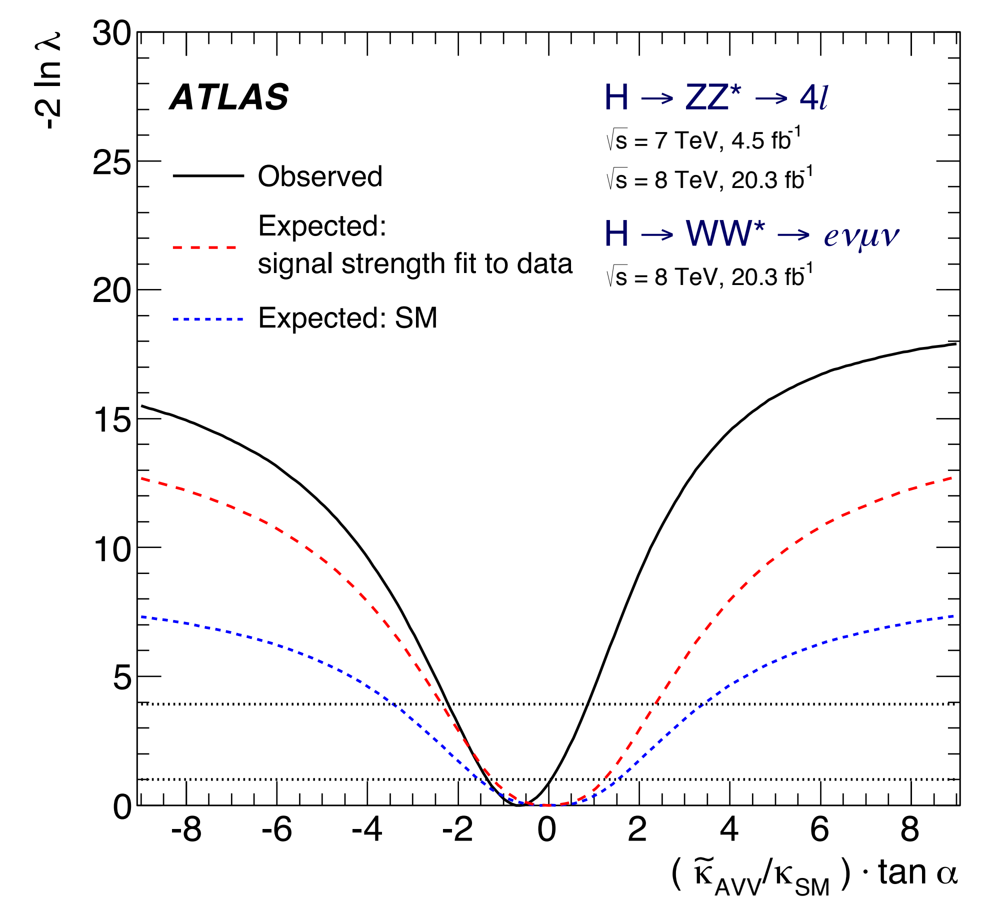
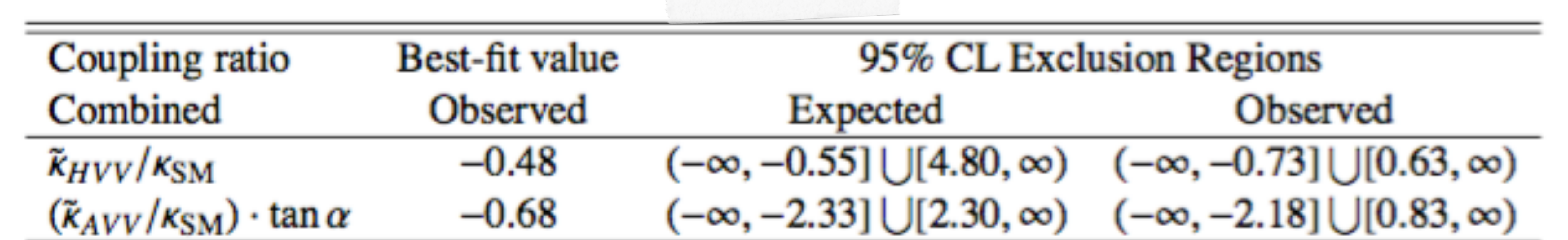
Consistent with the SM?

☐ YES

☐ NO

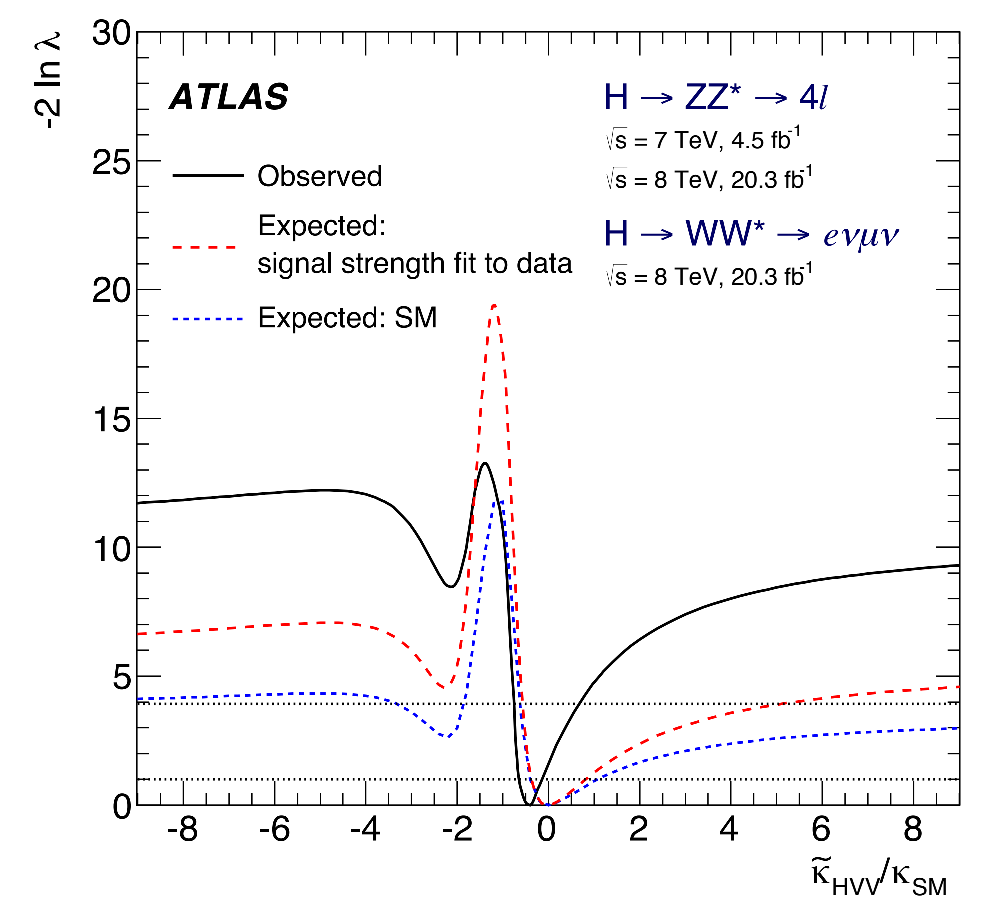


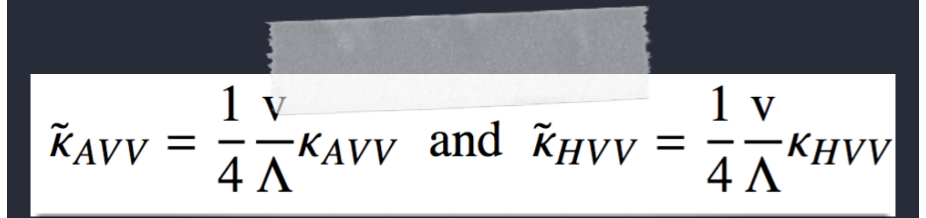


Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	−0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	−0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

arXiv:1506.05669

HZZ and HWW combination





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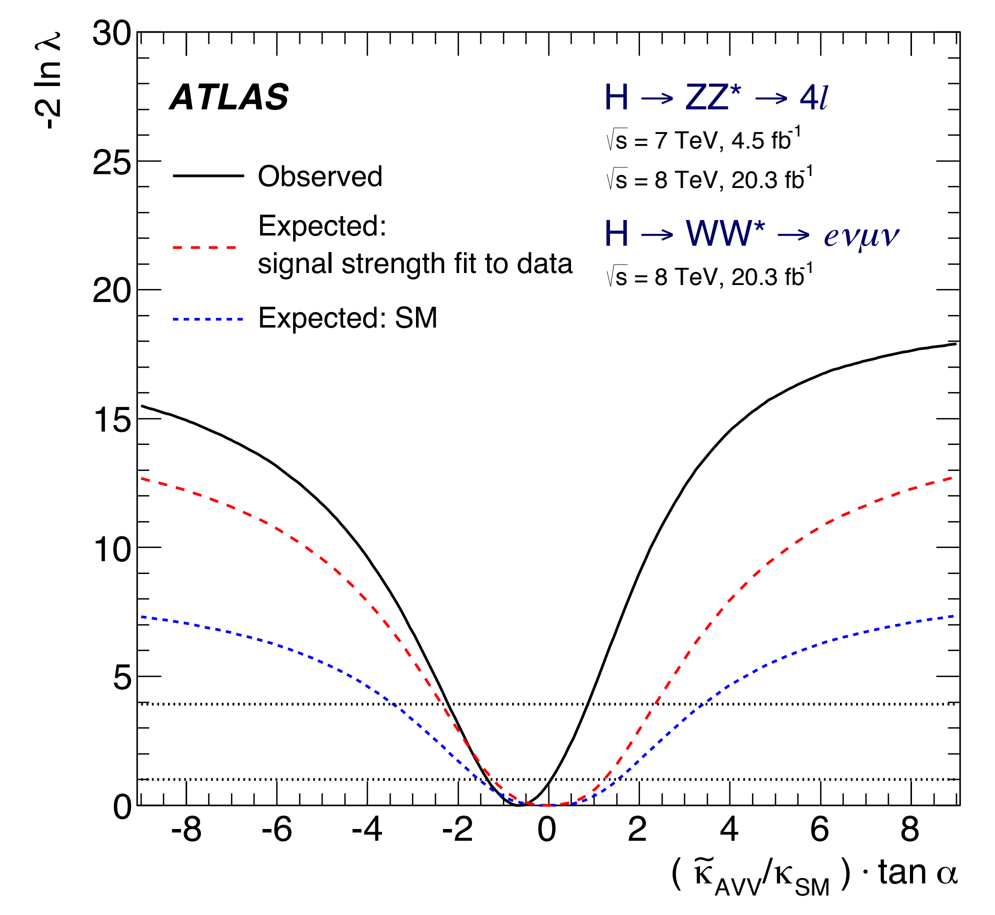
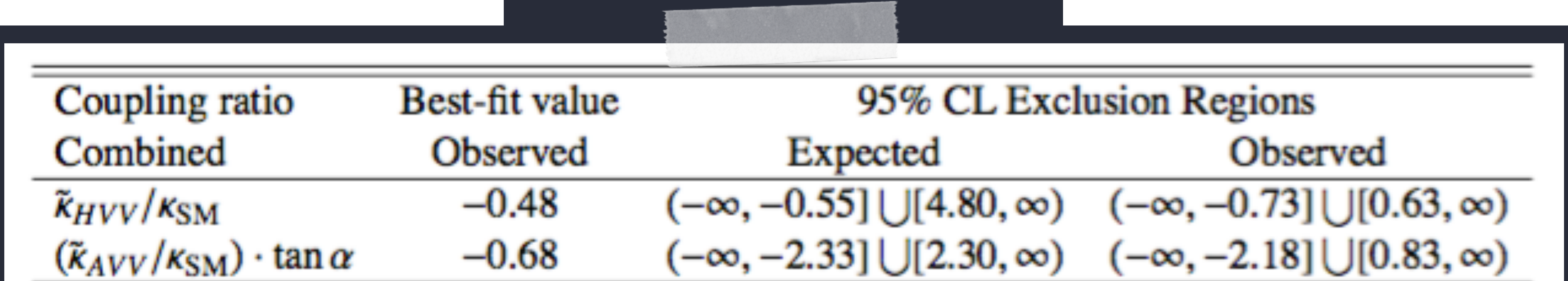
Consistent with the SM?

☑ YES

☐ NO





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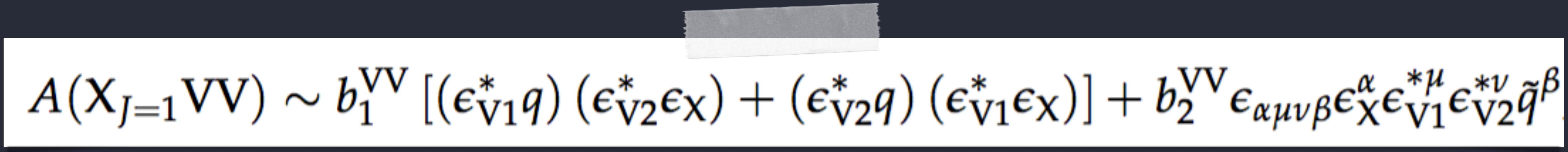
Decay of a spin-1 resonance

Interaction between the spin-1 resonance and two gauge bosons, V_1 and V_2



$$A(\mathrm{X}_{J=1}\mathrm{VV}) \sim b_1^{\mathrm{VV}} \left[\left(\epsilon^*_{\mathrm{V}1} q\right) \left(\epsilon^*_{\mathrm{V}2} \epsilon_{\mathrm{X}}\right) + \left(\epsilon^*_{\mathrm{V}2} q\right) \left(\epsilon^*_{\mathrm{V}1} \epsilon_{\mathrm{X}}\right) \right] + b_2^{\mathrm{VV}} \epsilon_{\alpha\mu\nu\beta} \epsilon_{\mathrm{X}}^{\alpha} \epsilon_{\mathrm{V}1}^{*\mu} \epsilon_{\mathrm{V}2}^{*\nu} \tilde{q}^{\beta}$$

Decay of a spin-1 resonance

Interaction between the spin-1 resonance and two gauge bosons, V_1 and V_2

$$A(\mathrm{X}_{J=1}\mathrm{VV}) \sim b_1^{\mathrm{VV}} \left[\left(\epsilon^*_{\mathrm{V1}} q\right) \left(\epsilon^*_{\mathrm{V2}} \epsilon_{\mathrm{X}}\right) + \left(\epsilon^*_{\mathrm{V2}} q\right) \left(\epsilon^*_{\mathrm{V1}} \epsilon_{\mathrm{X}}\right) \right] + b_2^{\mathrm{VV}} \epsilon_{\alpha\mu\nu\beta} \epsilon^{\alpha}_{\mathrm{X}} \epsilon^{*\mu}_{\mathrm{V1}} \epsilon^{*\nu}_{\mathrm{V2}} \tilde{q}^{\beta}$$

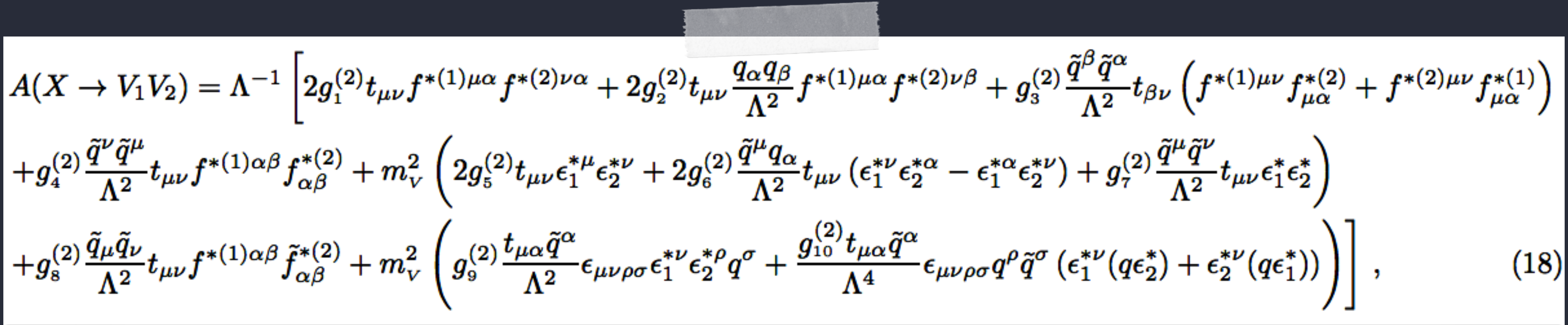
Measurements

Hypothesis tests 0^+ vs. mixture of $1^\pm$

($f_{b2} = 0$ pure vector, $f_{b2} = 1$ pure pseudo-vector)

Decay of a spin-2 resonance

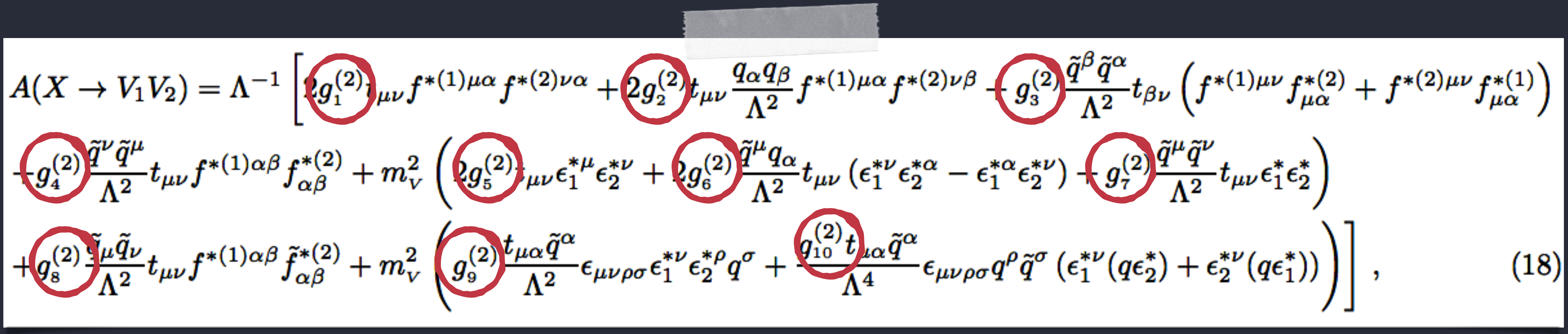
Interaction between the spin-2 resonance and two gauge bosons, V_1 and V_2



$$\begin{aligned}A(X \to V_1V_2) = \Lambda^{-1} \Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) \\ & + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\ & + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Big] , \end{aligned} \tag{18}$$

Decay of a spin-2 resonance

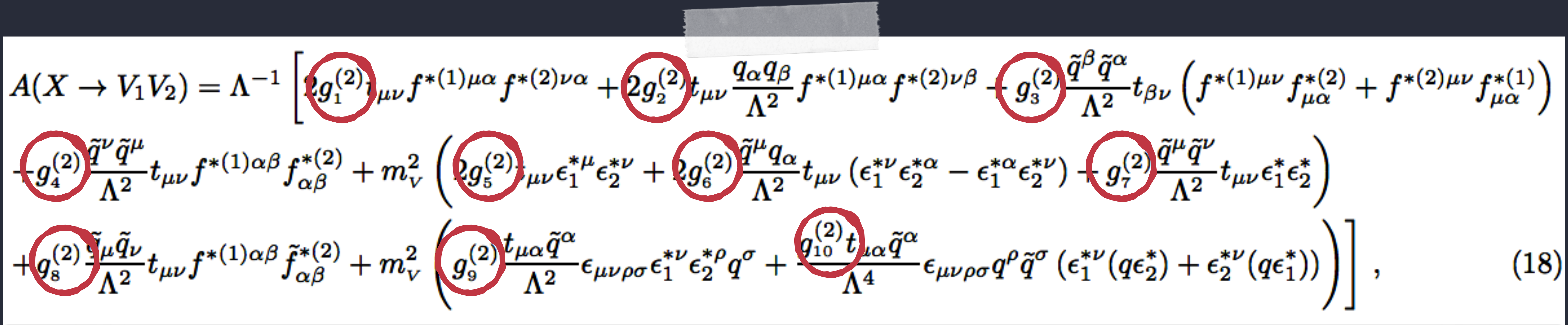
Interaction between the spin-2 resonance and two gauge bosons, V_1 and V_2



$$\begin{aligned} A(X \to V_1 V_2) = \Lambda^{-1} \Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) \\ & + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\ & + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Big] , \end{aligned} \tag{18}$$

Decay of a spin-2 resonance

Interaction between the spin-2 resonance and two gauge bosons, V_1 and V_2



$$A(X \to V_1 V_2) = \Lambda^{-1} \Big[2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right)$$
$$+ g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right)$$
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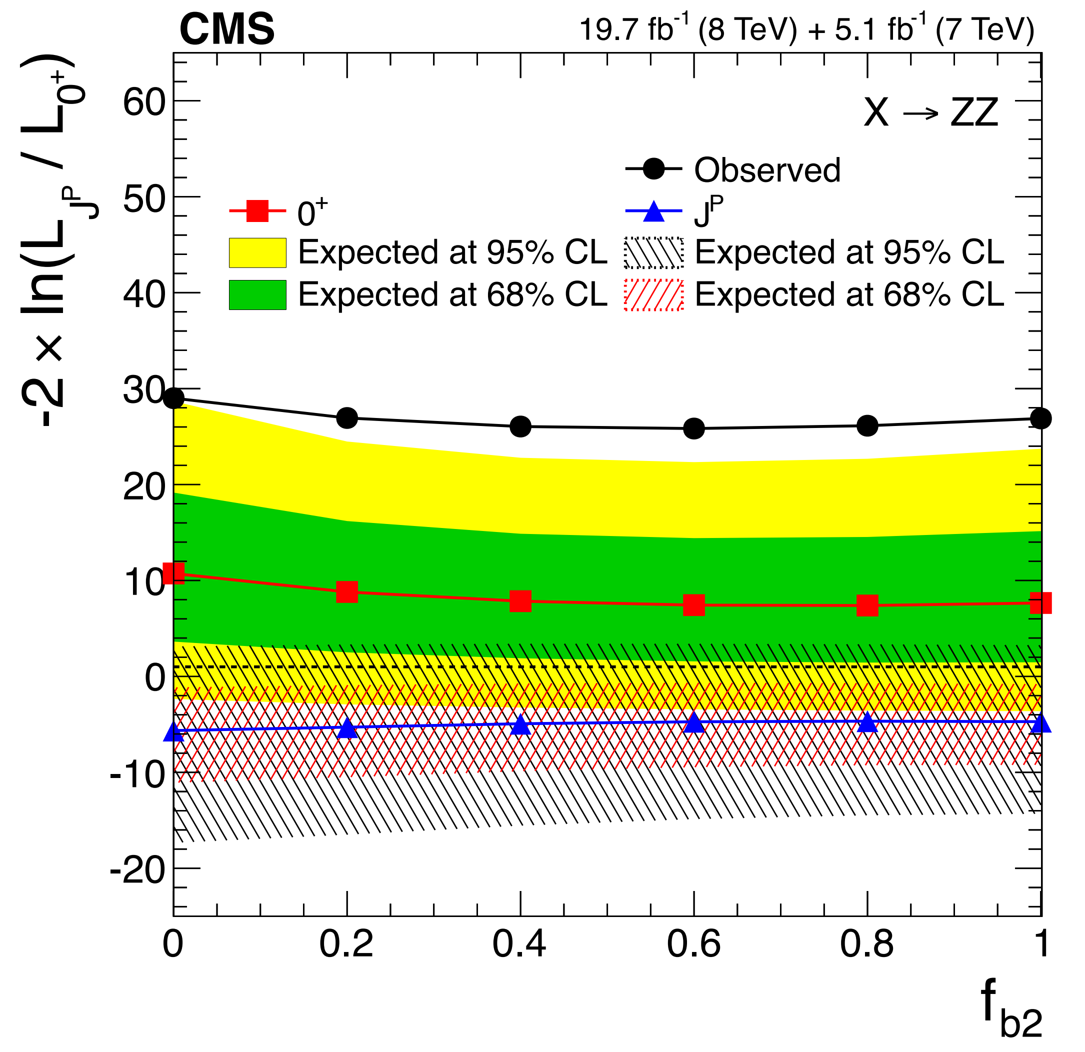
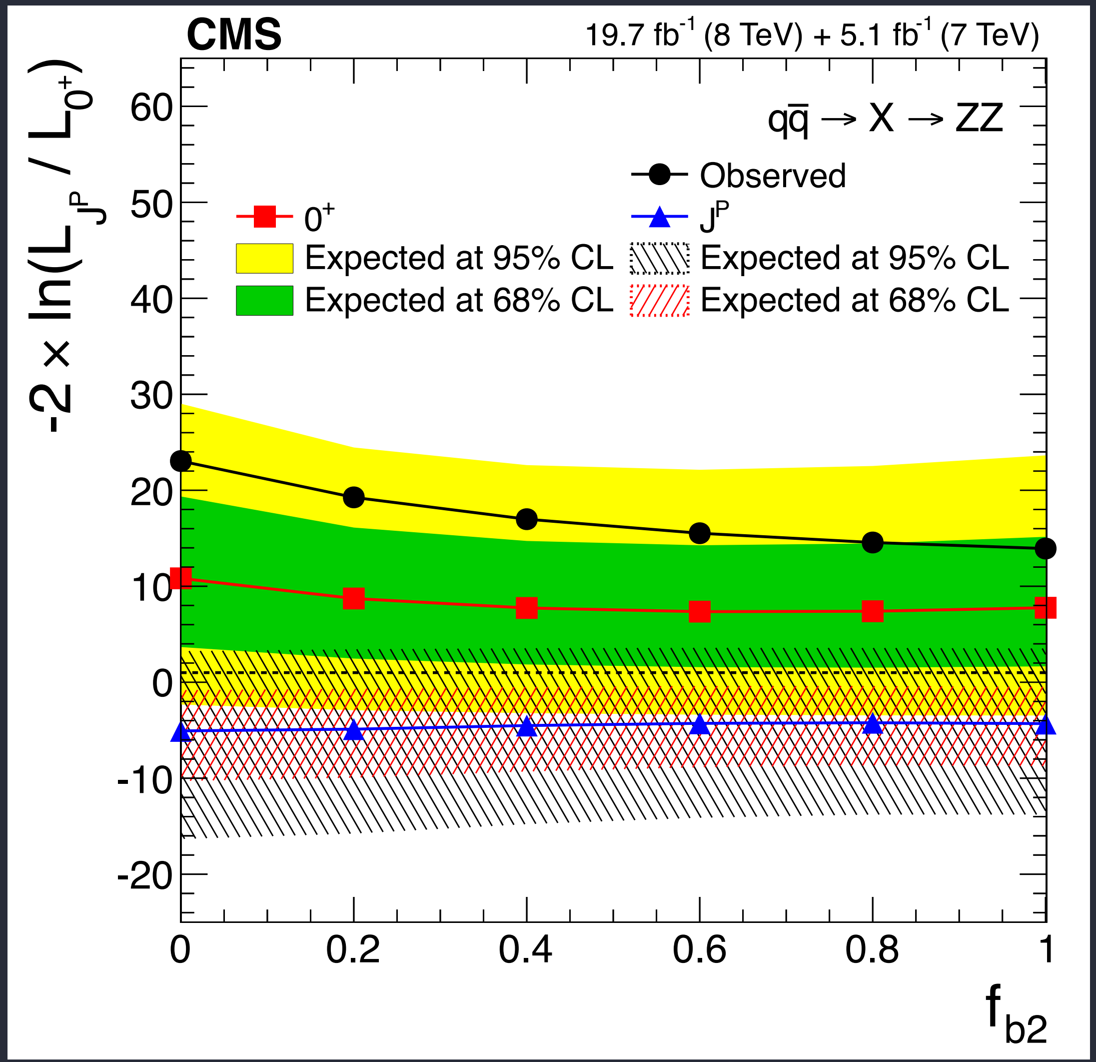
Measurements

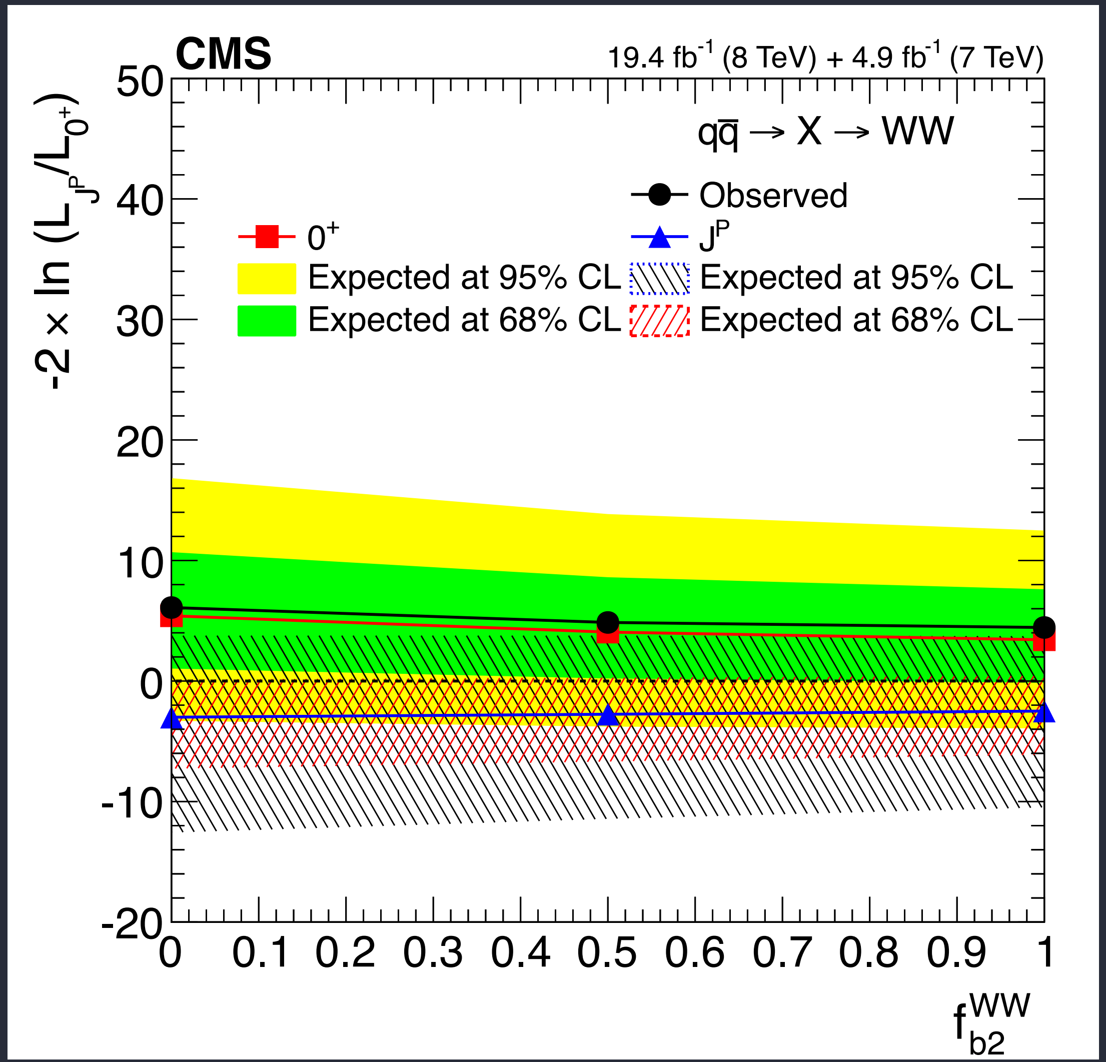
Hypothesis tests 0^+ vs. pure spin-2 models

arXiv:1411.3441

CMS: spin 1







Consistent with the SM?

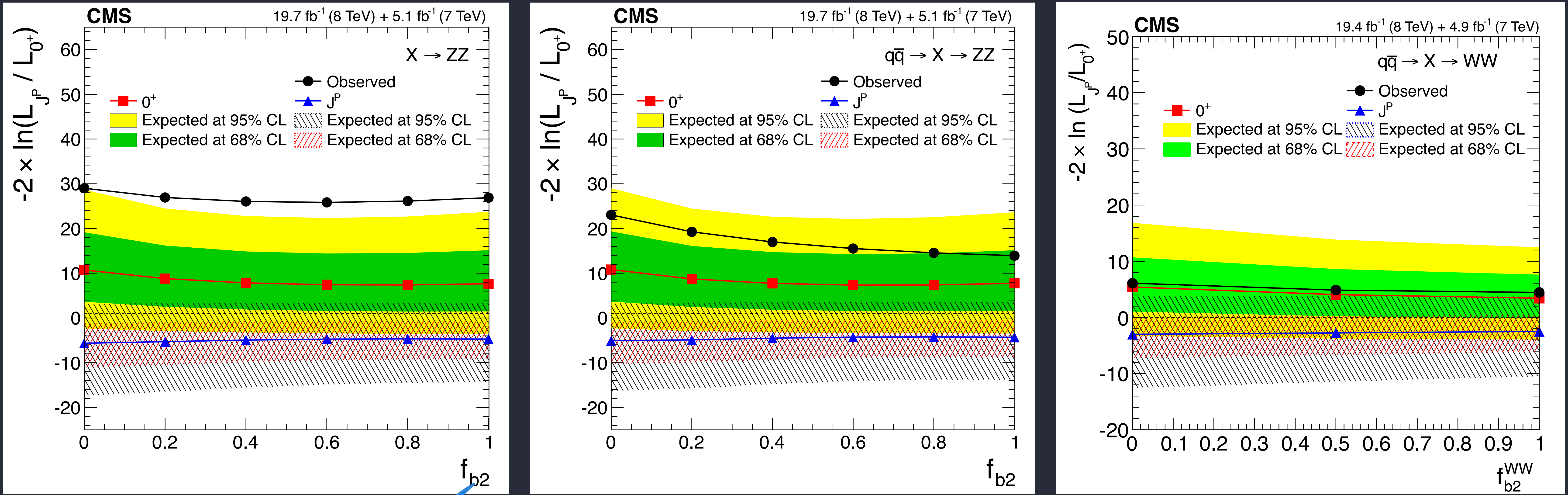
☐ YES

☐ NO

$$f_{b2}^{VV} = \frac{|b_2^{VV}|^2 \sigma_{b2}}{|b_1^{VV}|^2 \sigma_{b1} + |b_2^{VV}|^2 \sigma_{b2}}$$

arXiv:1411.3441

CMS: spin 1



Consistent with the SM?

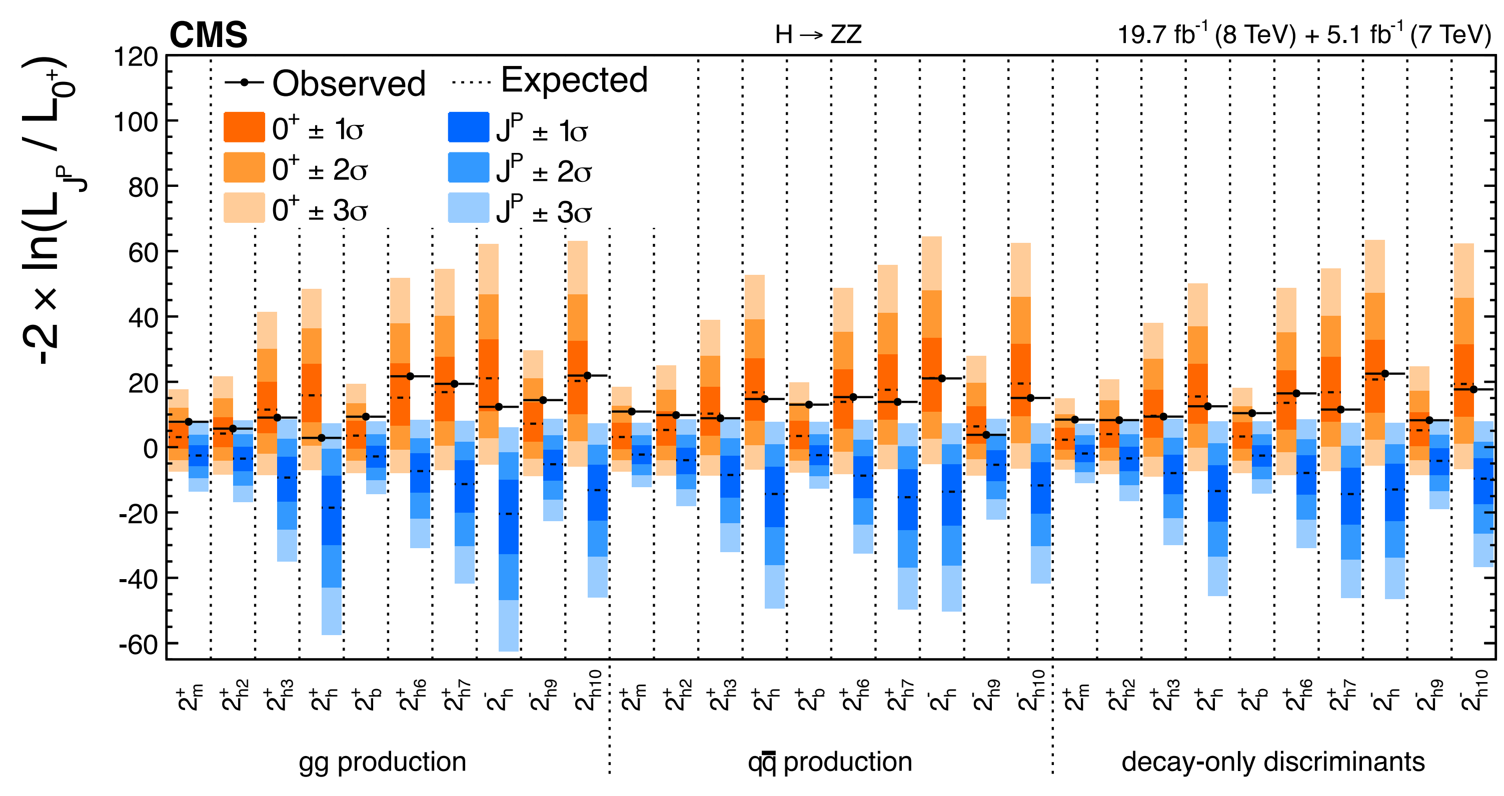
☑ YES

☐ NO

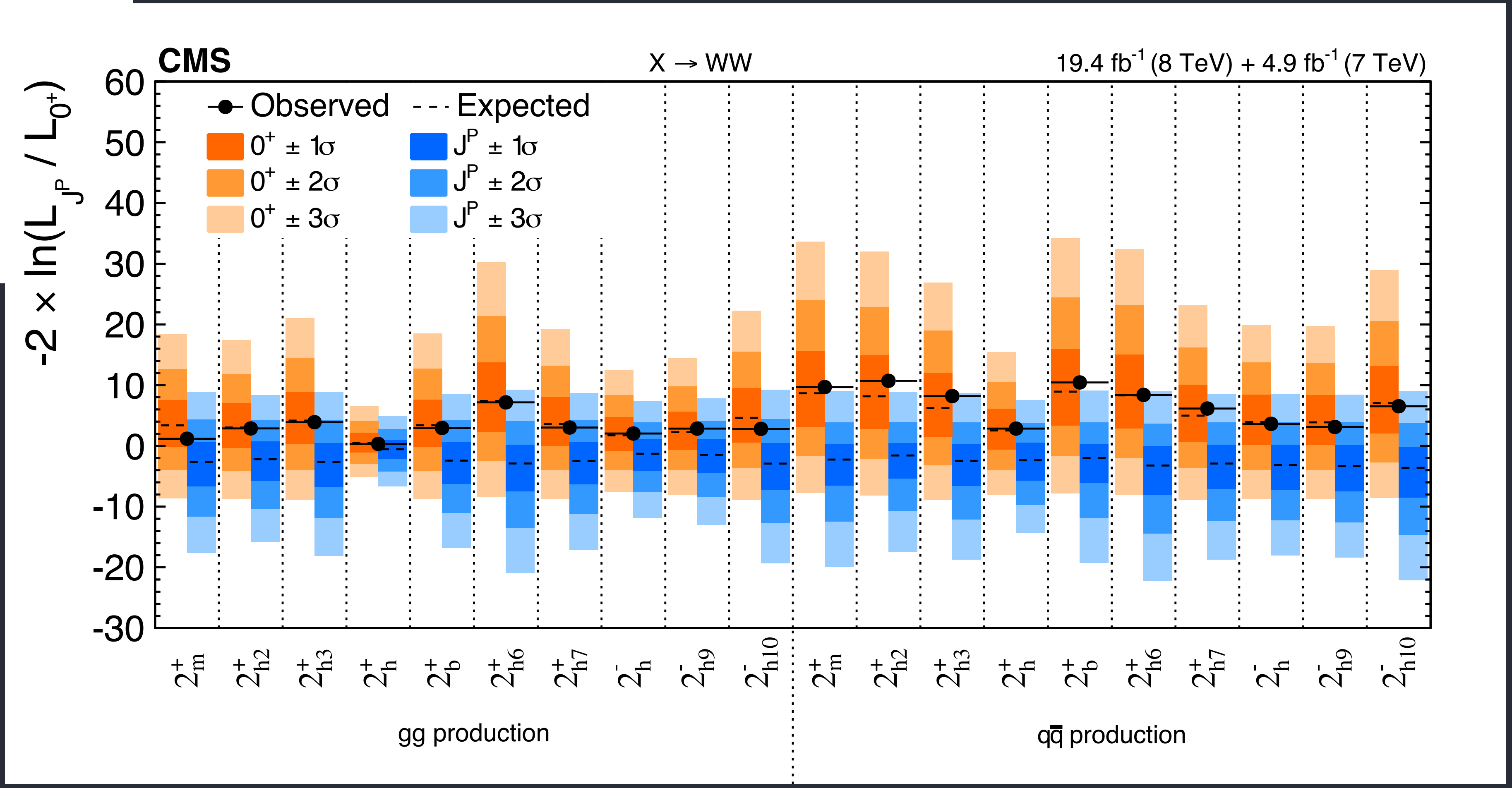
$$f_{b2}^{VV} = \frac{|b_2^{VV}|^2\sigma_{b2}}{|b_1^{VV}|^2\sigma_{b1} + |b_2^{VV}|^2\sigma_{b2}}$$

arXiv:1411.3441

CMS: spin 2



gg, qqbar and production independent tests for ZZ



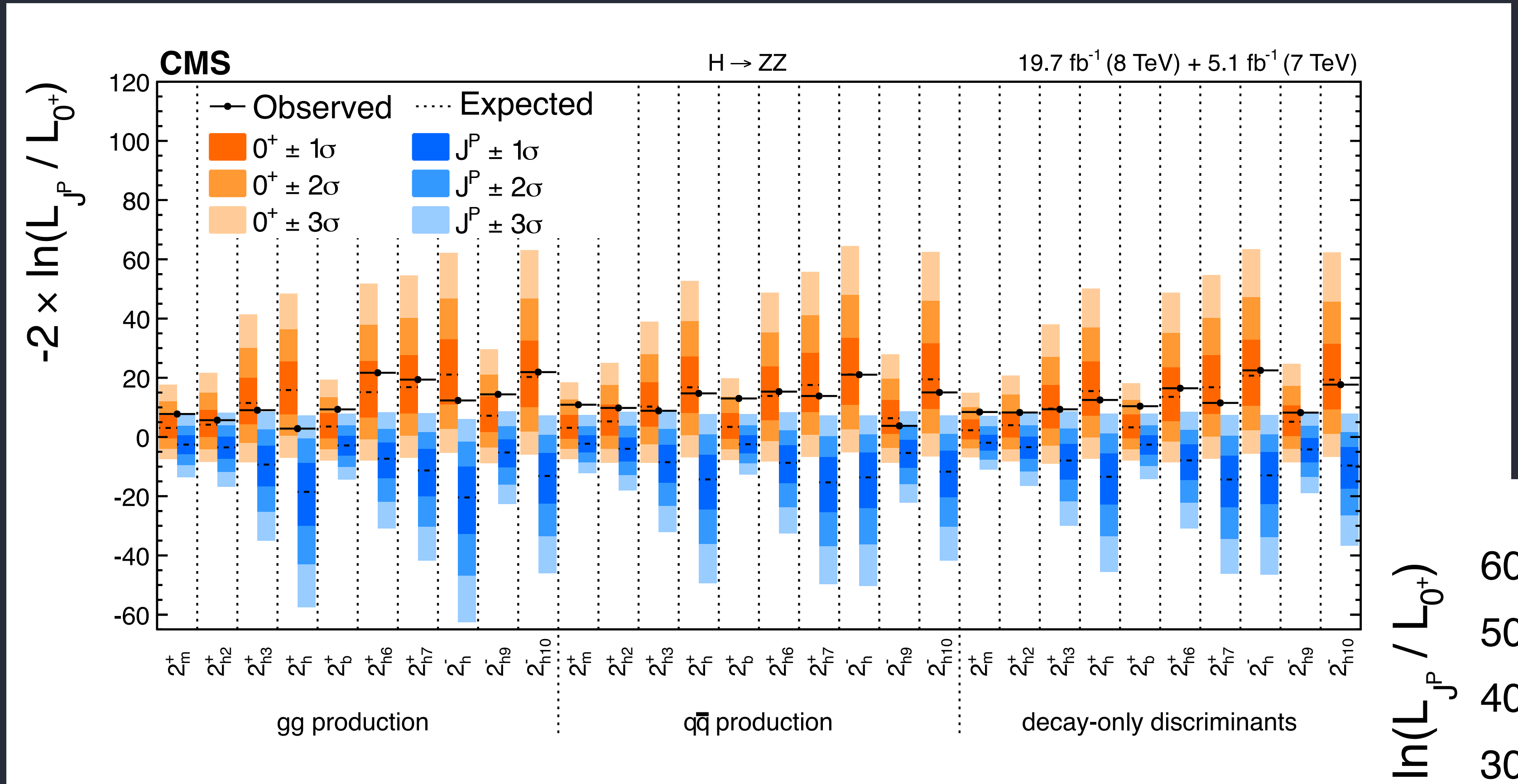
Consistent with the SM?

☐ YES

☐ NO

arXiv:1411.3441

CMS: spin 2



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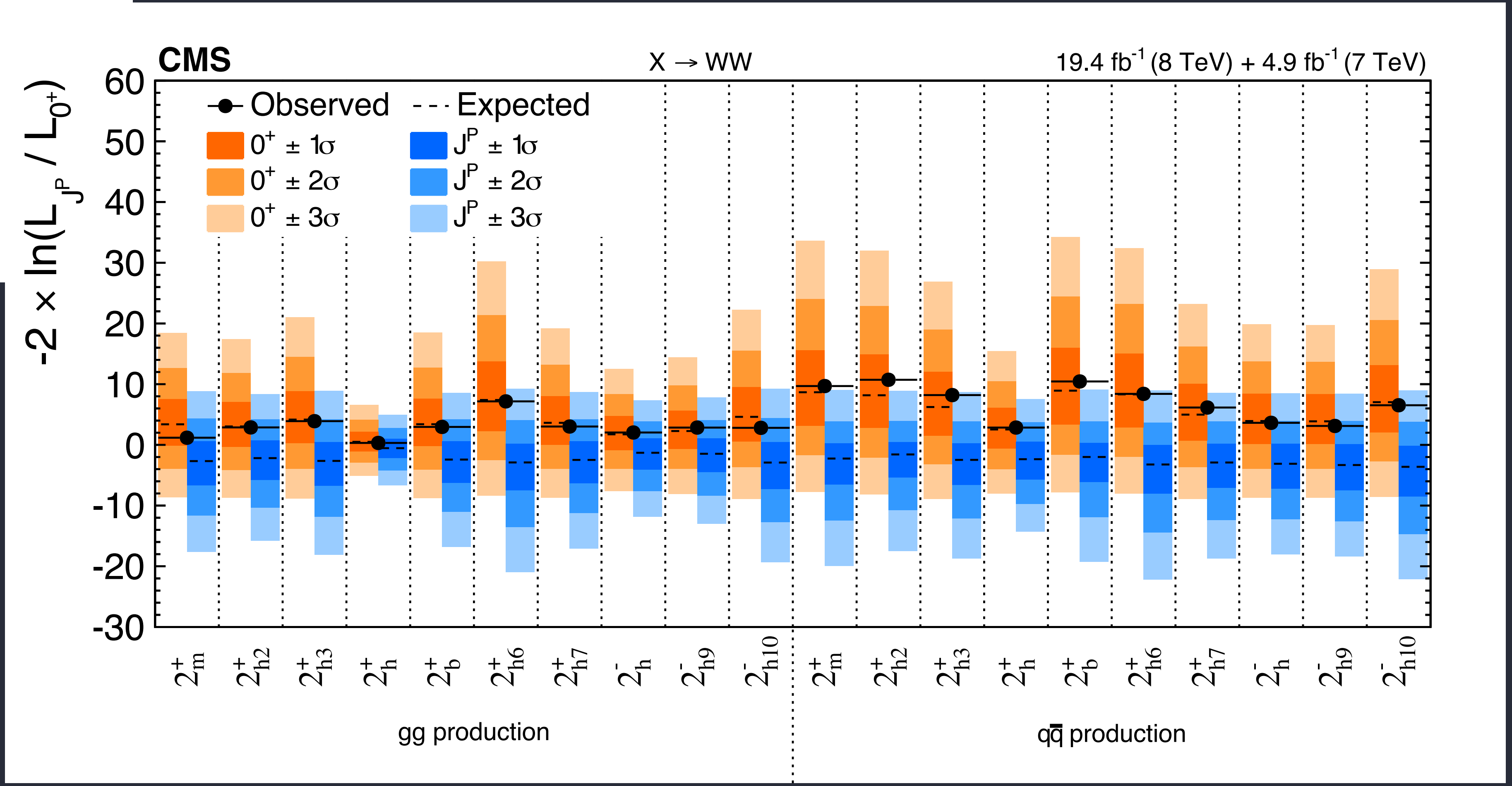


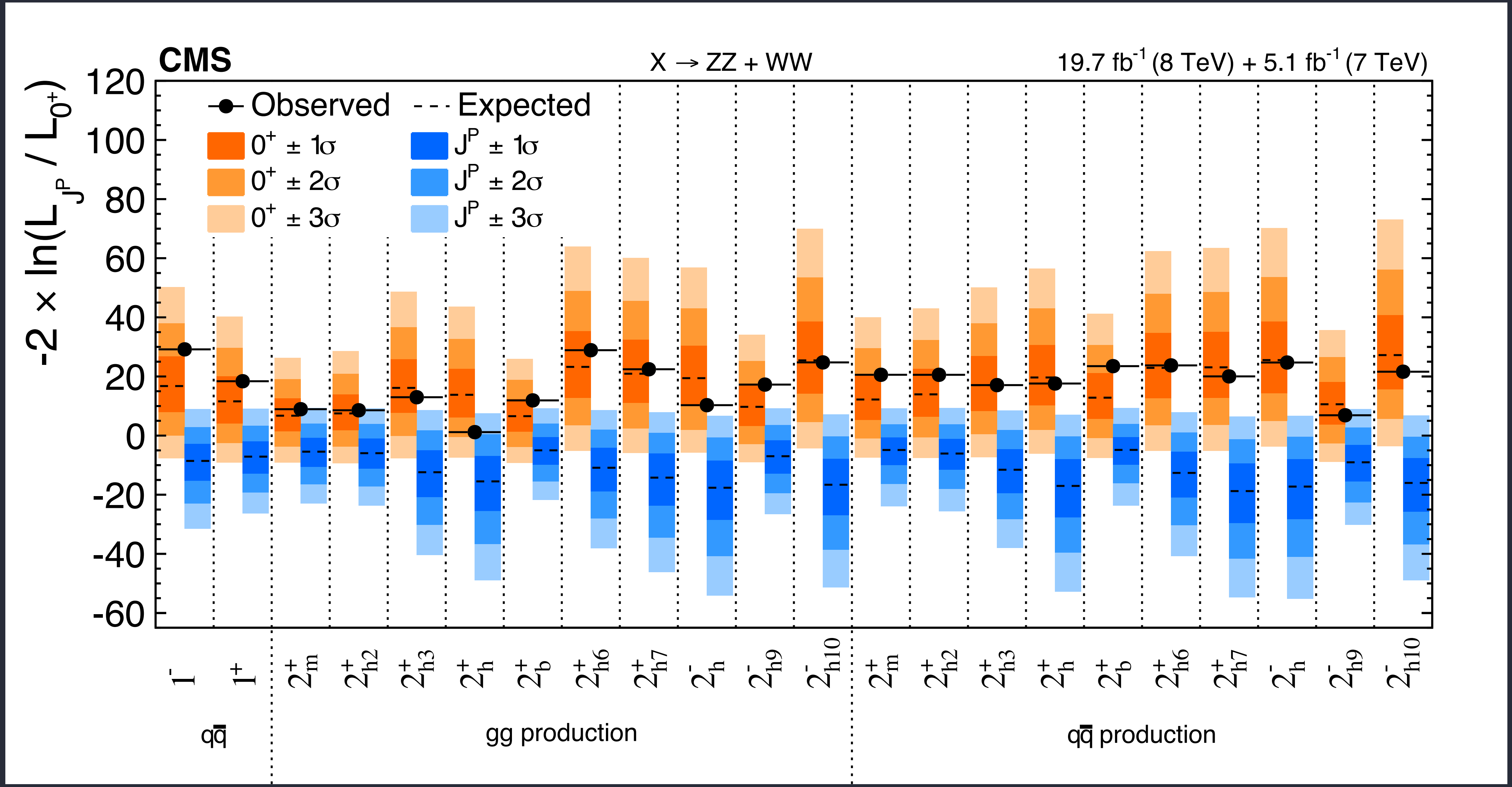
Consistent with the SM?

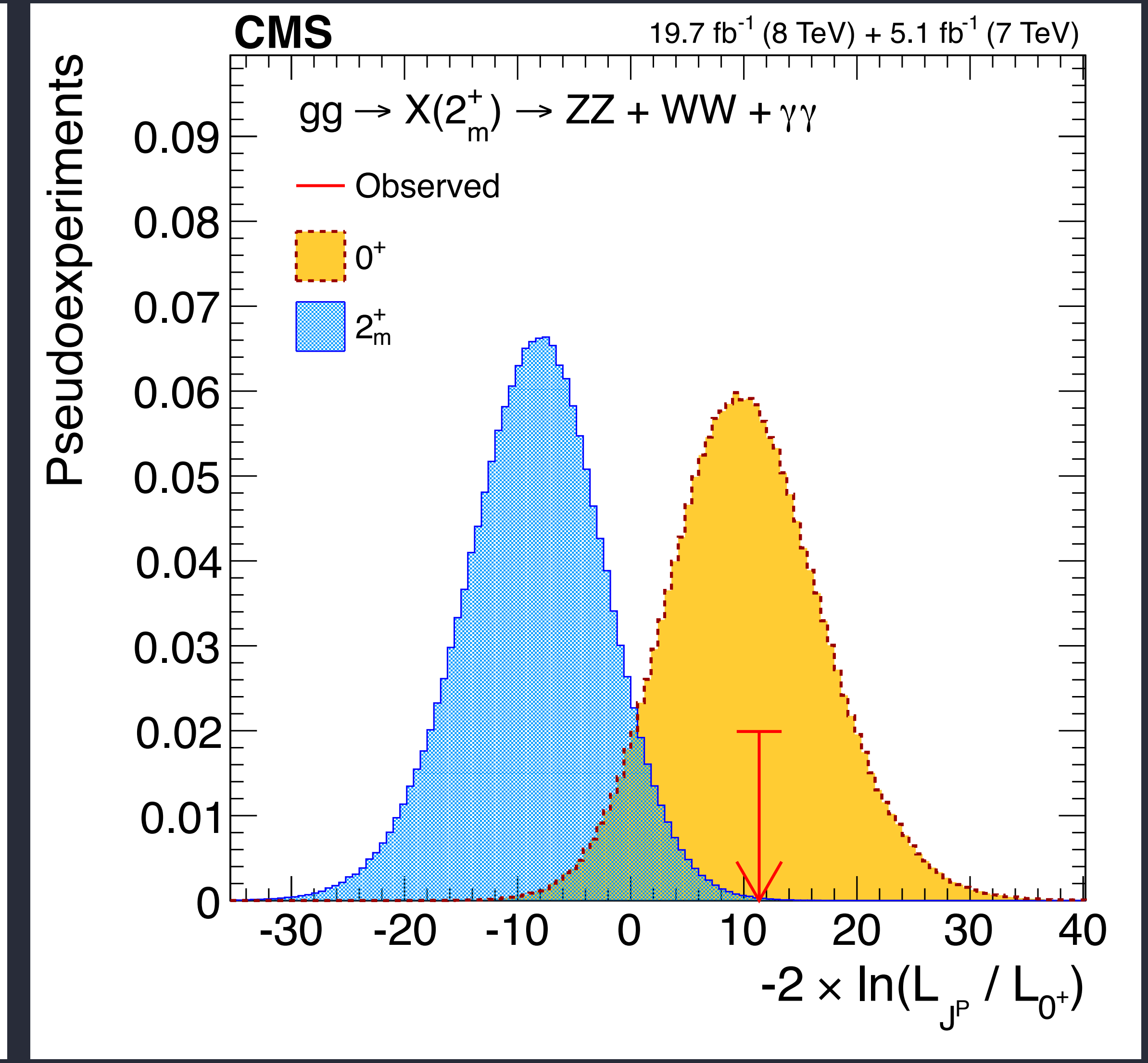
☑ YES

☐ NO

arXiv:1411.3441

Combined CMS results



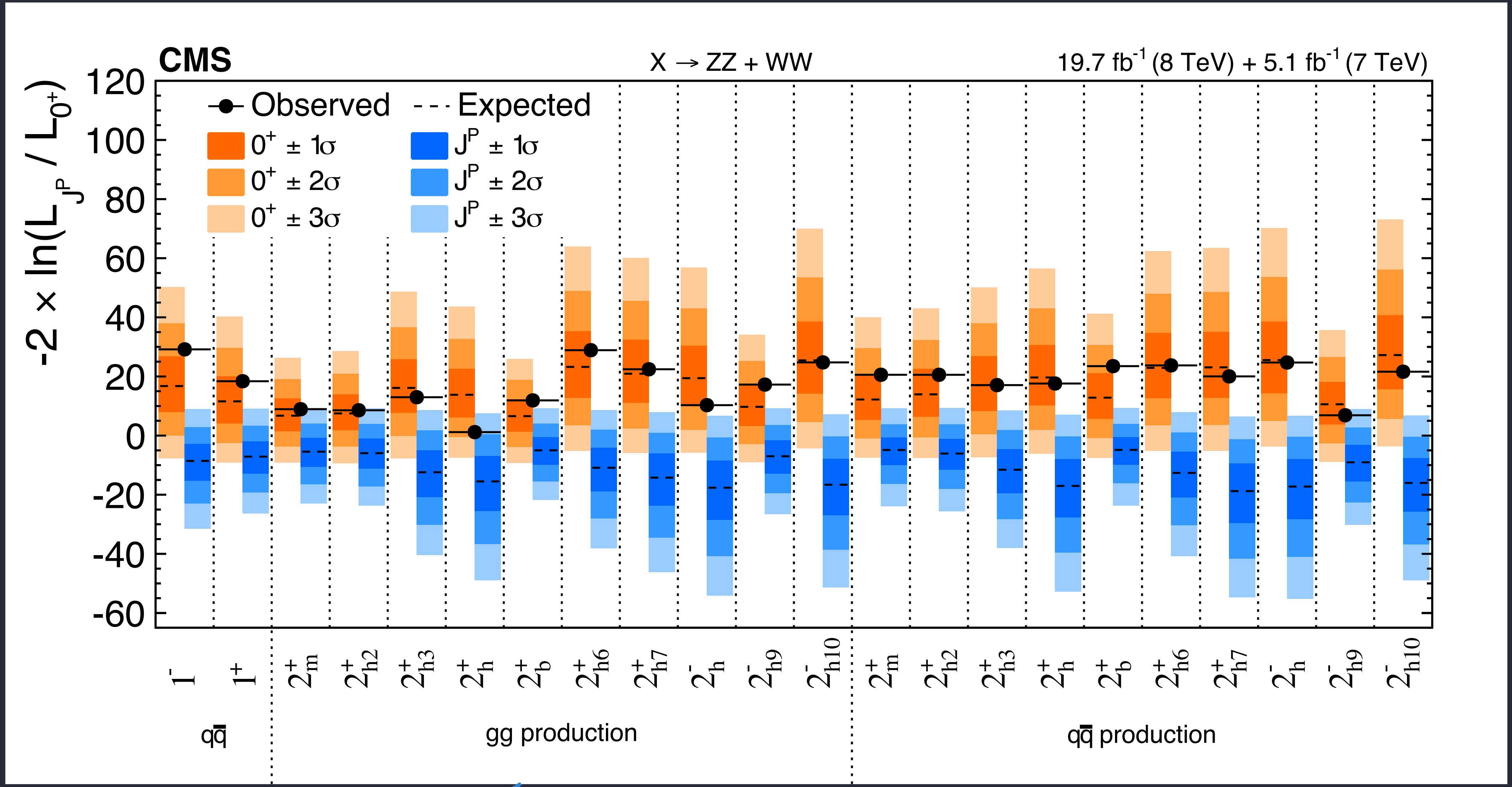


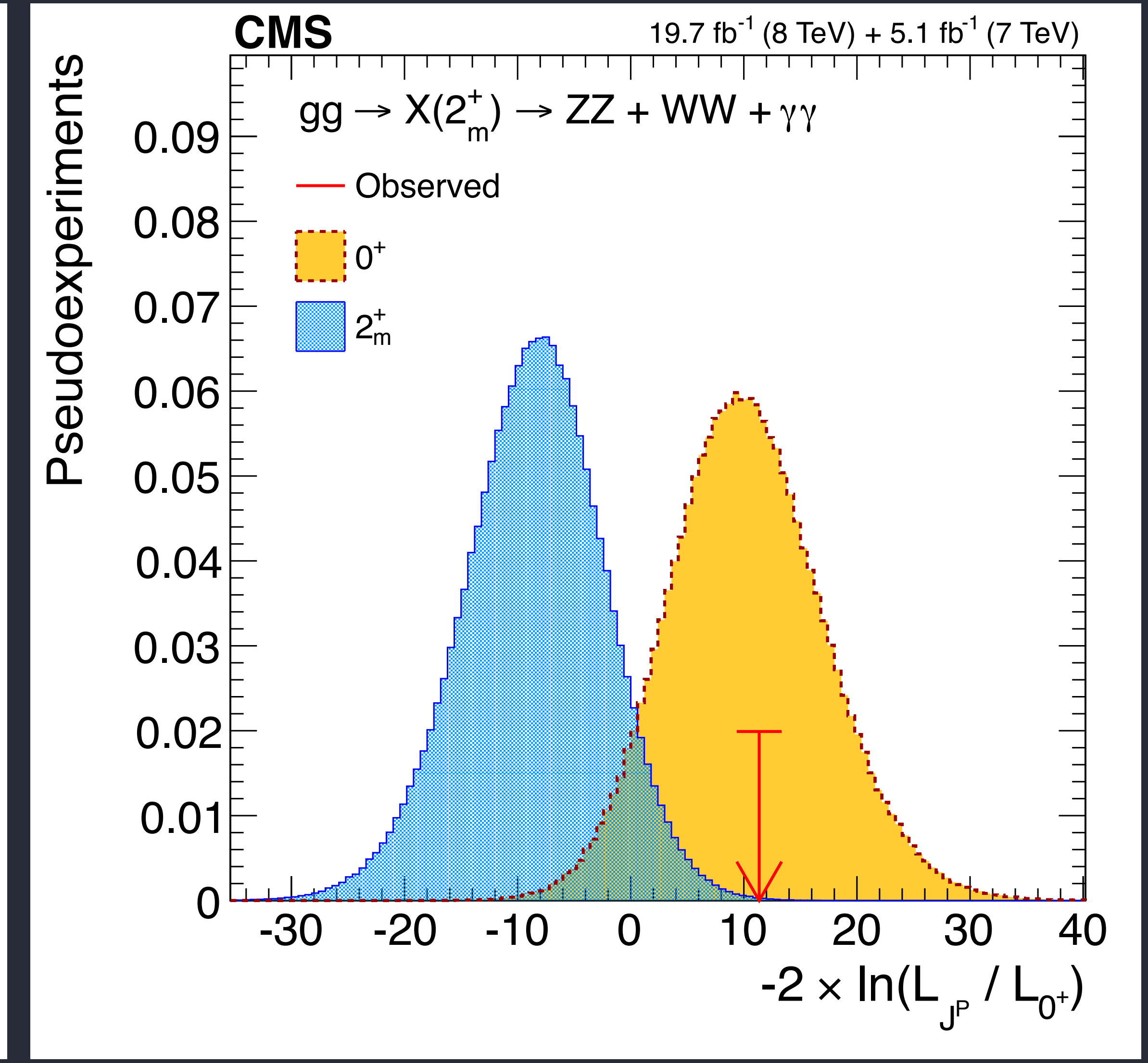
Consistent with the SM? ☐ YES ☐ NO

Spin-two models excluded at a 99% confidence level or higher.

arXiv:1411.3441

Combined CMS results





Consistent with the SM?

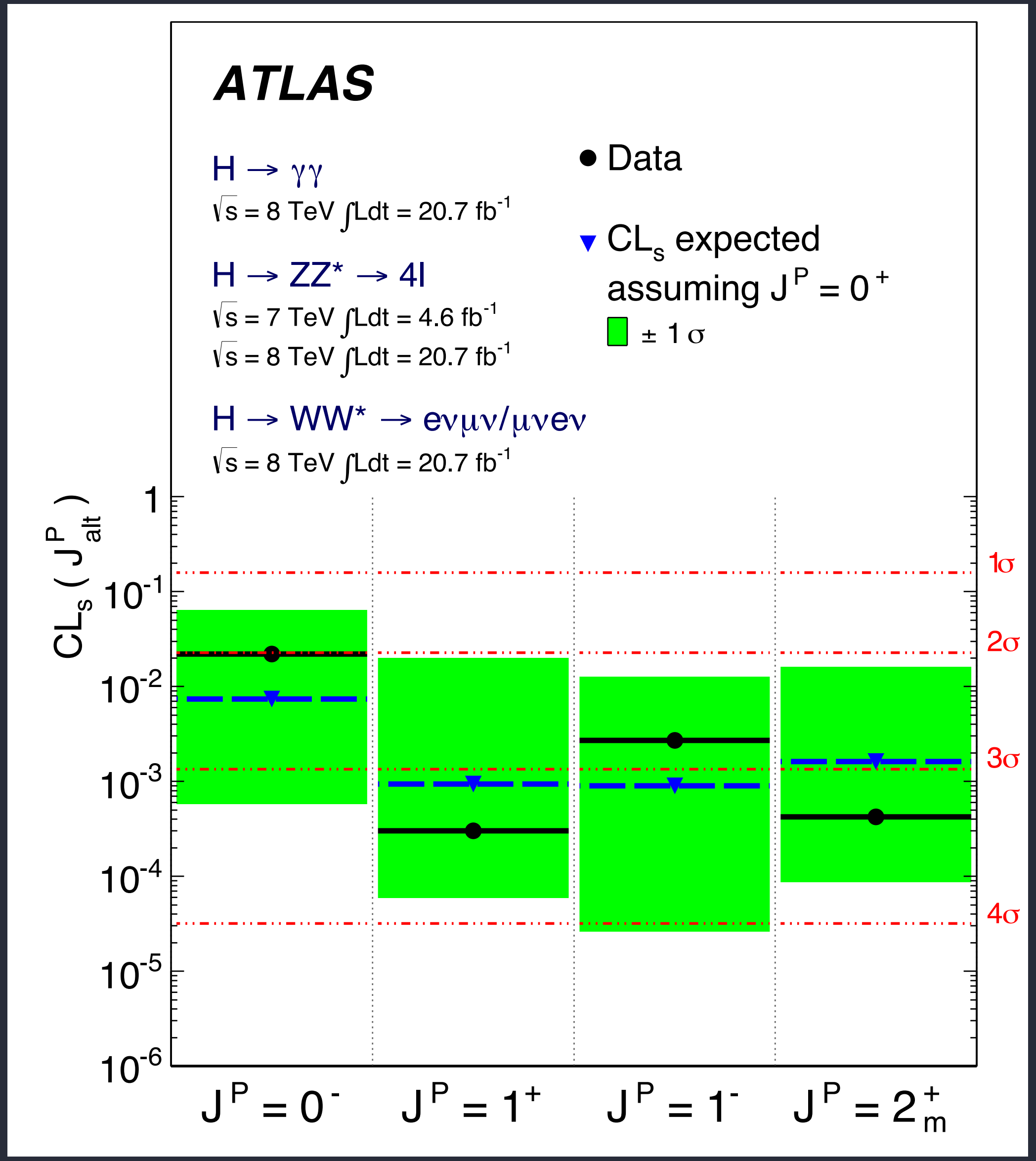
☑ YES

☐ NO

Spin-two models excluded at a 99% confidence level or higher.

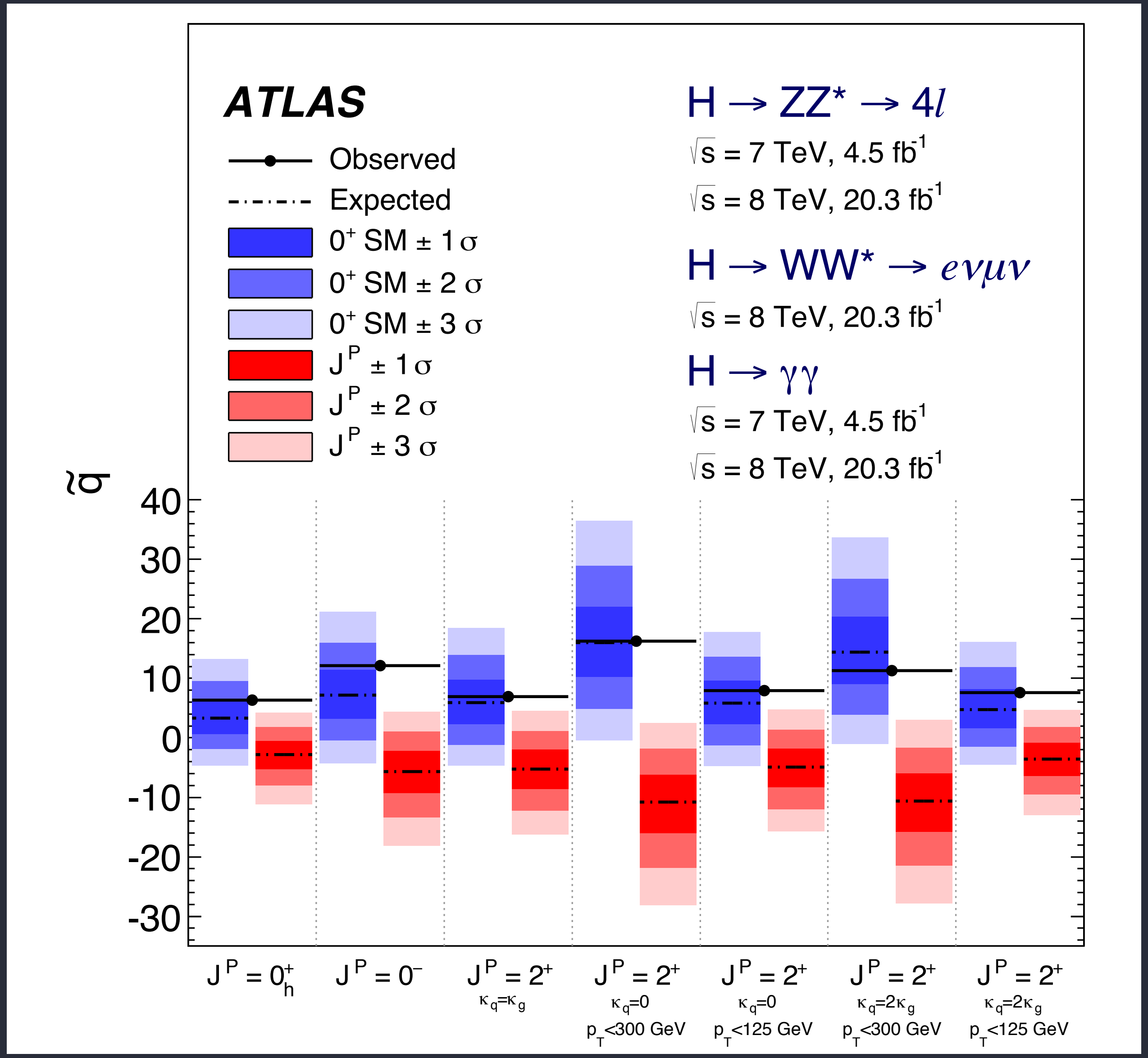
Combined ATLAS results

arXiv:1307.1432



Spin 1 rejected at 99.7% CL (WW and ZZ comb.)

arXiv:1506.05669



All tested alternative models are excluded in favor of the SM Higgs boson hypothesis at more than 99.9% confidence level.

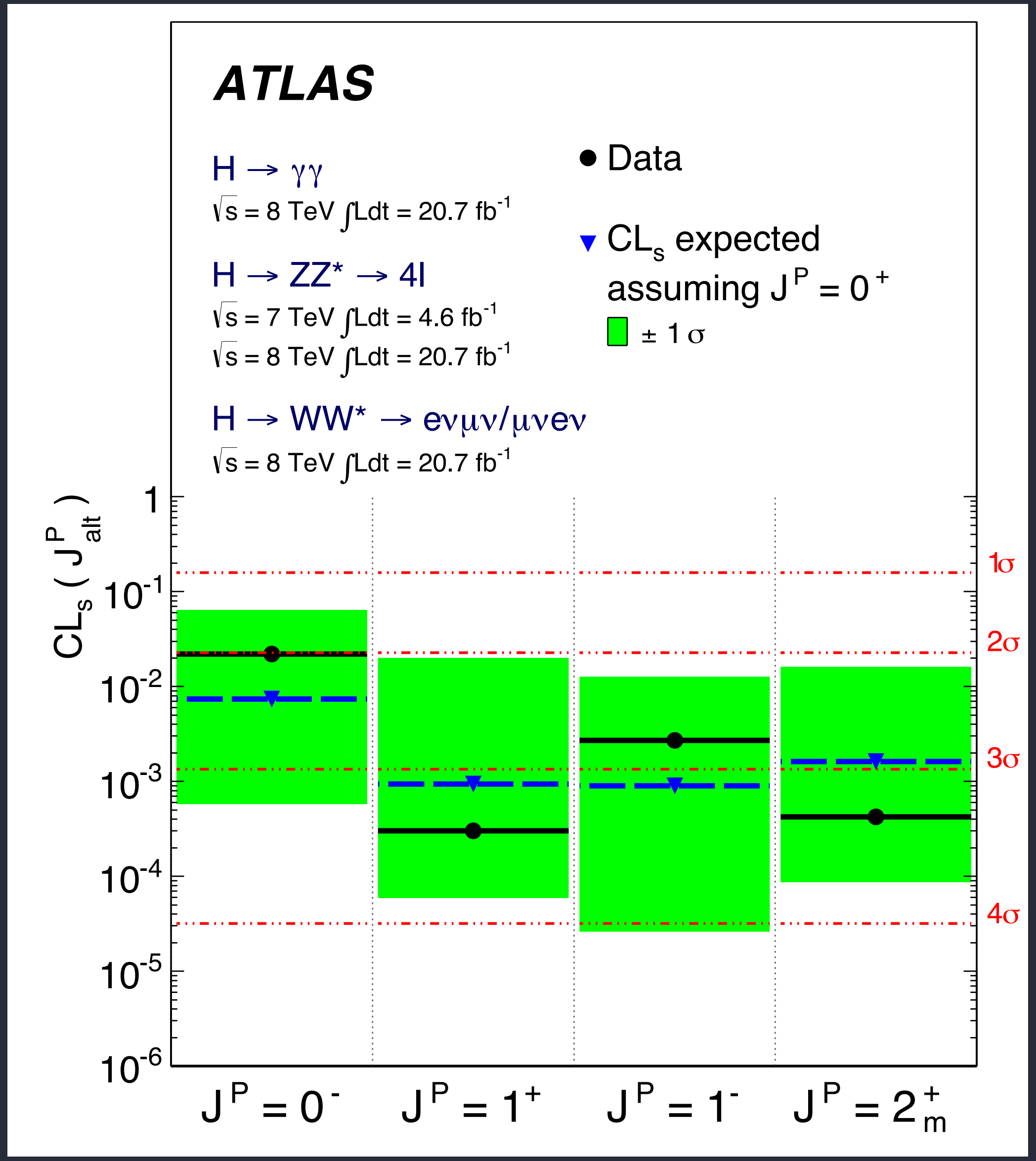
Consistent with the SM?

☐ YES

☐ NO

Combined ATLAS results

arXiv:1307.1432



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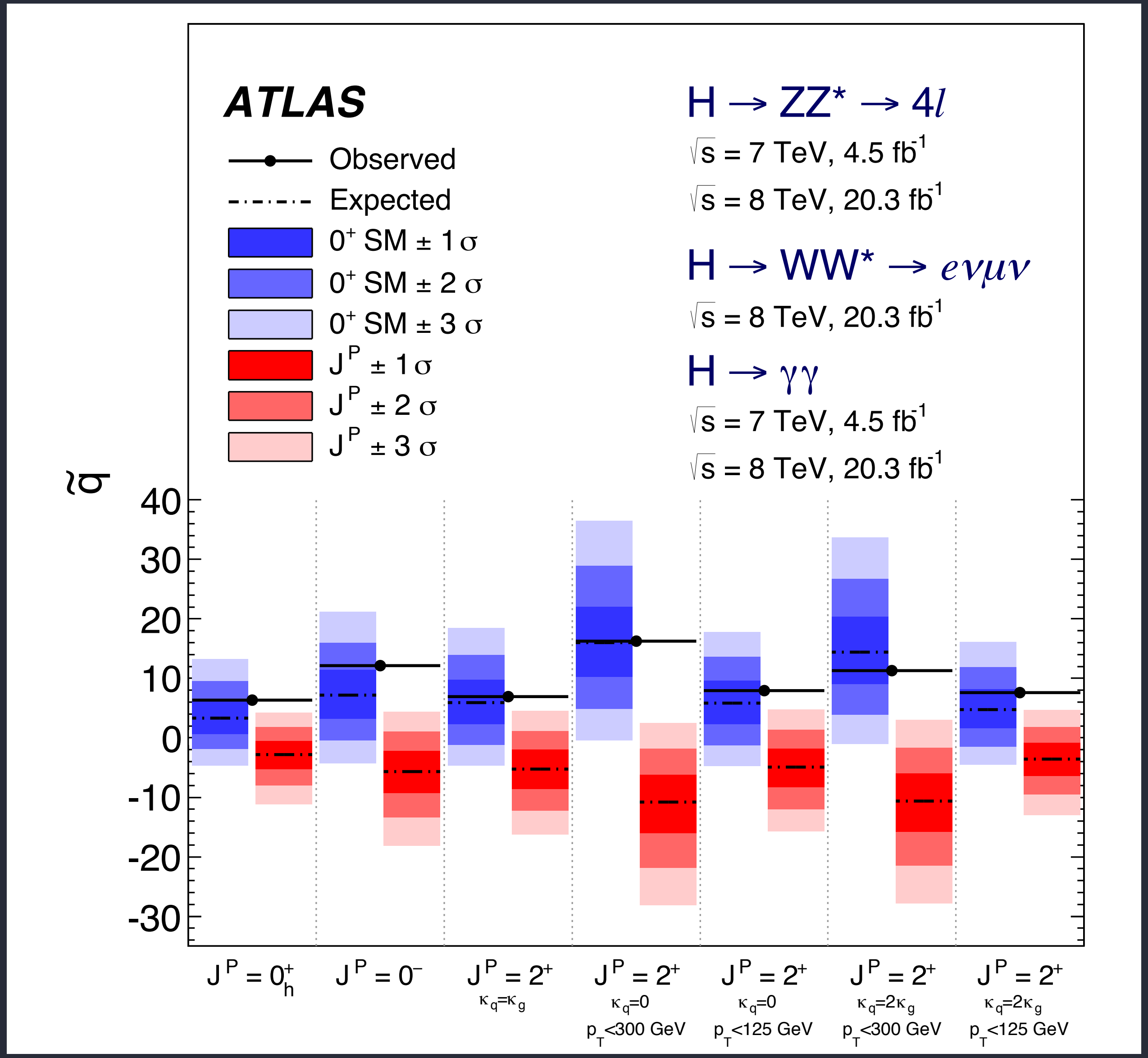


All tested alternative models are excluded in favor of the SM Higgs boson hypothesis at more than 99.9% confidence level.

Consistent with the SM?

☑ YES

☐ NO

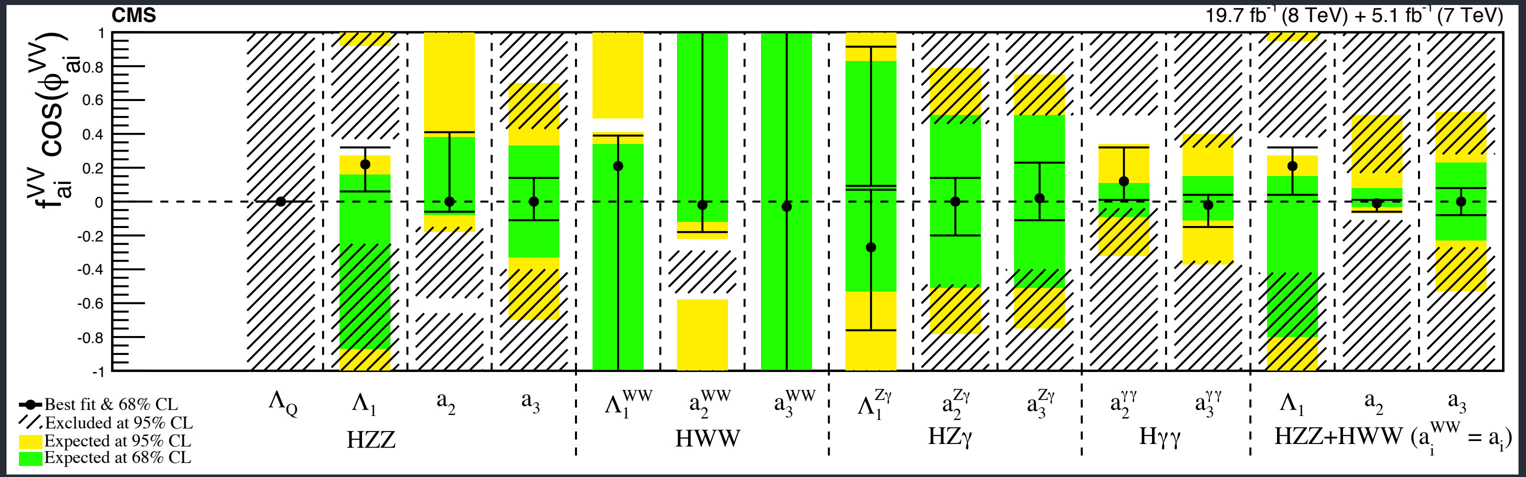
Conclusion

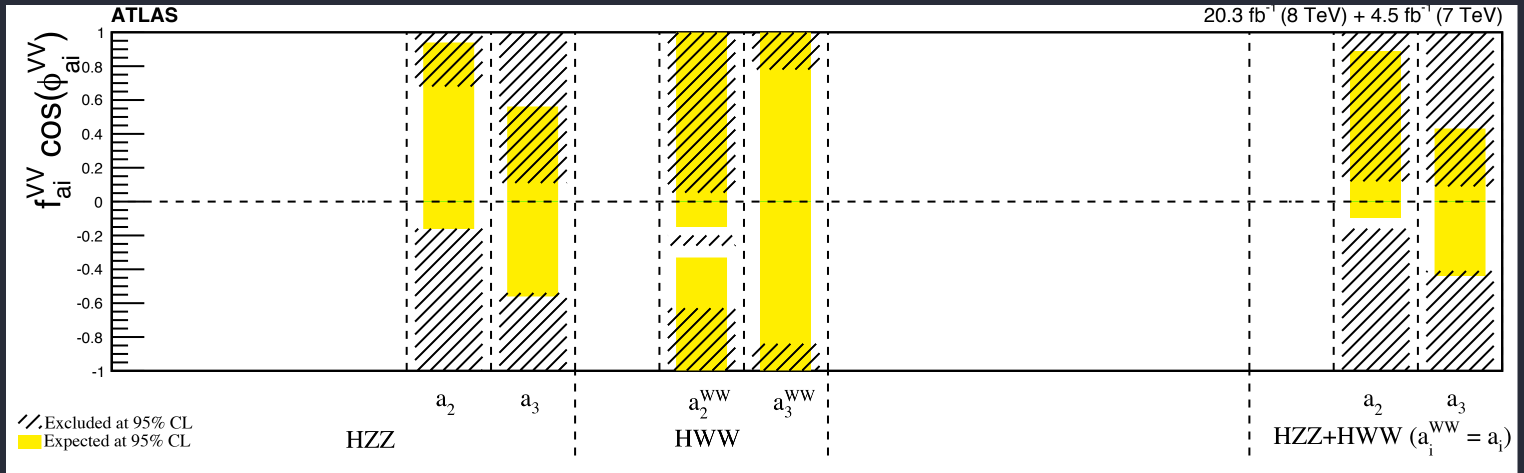
A comprehensive study of the the Higgs boson spin-parity and tensor structure

Exotic spin-parity hypotheses excluded at 99% or higher confidence level

Constraints on 11 anomalous couplings under spin-0 assumption

All observations consistent with the SM expectation





The future of these measurements is to improve anomalous coupling precision in spin-0.