CP-VIOLATION SEARCHES AT THE (HL-)LHC

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INTRODUCTION

- Focusing on the CP-violating Higgs boson interactions with vector bosons
- Overview of the latest CMS and ATLAS CP-violation searches based on the full set of LHC Run 2 data
- HL-LHC projections based on CMS inputs: Snowmass White Paper 2022 (arXiv:2205.07715) and relation to more recent LHC Run 2 results

Parametrisation of CP-odd contributions to a given measurement:

$$\sigma \propto |\mathcal{M}_{SM}|^2 + 2\mathcal{R}(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})\,\tilde{c} + |\mathcal{M}_{CP-odd}|^2\,\tilde{c}^2 + \ldots$$

SM term

Linear term:
interference
between CP-odd and CP-even

Quadratic term:
no direct CP-violation.
Affecting the total event rate, similar to CP-even BSM effects.

Directly probing the CP-violating interaction.
Affecting the differential (angular) distributions.

Matrix elements $\mathcal{M}_i$ defined via a scattering amplitude or a Lagrangian.

CP-VIOLATION IN HIGGS INTERACTIONS WITH GAUGE BOSONS

Usually fitting one parameter at once, while others are set to zero, mutually correlated or profiled.

Scattering amplitude with anomalous couplings ($VV \equiv WW, ZZ, Z\gamma, \gamma\gamma$):

$$\mathscr{A}(HVV) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} p_1^2 + \kappa_2^{VV} p_2^2}{(\Lambda_1^{VV})^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

CP-even

CP-odd

SMEFT in the Warsaw basis (Warsaw basis coefficient = linear combination of Higgs basis coefficients $\tilde{c}_{ZZ}, \tilde{c}_{Z\gamma}, \tilde{c}_{\gamma\gamma}$):

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{1}{\Lambda}\phi^\dagger\phi \left[c_{HW} W^I_{\mu\nu} W^{I\mu\nu} + c_{HB} B_{\mu\nu} B^{\mu\nu} + c_{HWB} W^I_{\mu\nu} B^{\mu\nu} \right]$$
$$+ \frac{1}{\Lambda}\phi^\dagger\phi \left[c_{H\tilde{W}} \tilde{W}^I_{\mu\nu} W^{I\mu\nu} + c_{H\tilde{B}} \tilde{B}_{\mu\nu} B^{\mu\nu} + c_{H\tilde{W}B} \tilde{W}^I_{\mu\nu} B^{\mu\nu} \right] + \ldots$$

CP-even

CP-odd

CMS Approach 1: $a_i^{WW} = a_i^{ZZ}$ (similar to ATLAS $\tilde{d}$)

SMEFT Warsaw basis:

$c_{H\tilde{W}} = c_{H\tilde{B}}$ & $c_{H\tilde{W}B} = 0$

SMEFT Higgs basis:

$\tilde{c}_{ZZ} = \cos^2\theta_W\ \tilde{c}_{WW} = \cos^2\theta_W \sin^2\theta_W\ \tilde{c}_{\gamma\gamma}$ & $\tilde{c}_{Z\gamma} = 0$

Relation: $\tilde{c}_{ZZ} = A \cdot \cos^2\theta_W \cdot\ c_{H\tilde{W}}$

CMS Approach 2 (SMEFT-like): $a_3^{WW} = cos^2\theta_W\ a_3^{ZZ}\ ;\ a_3^{\gamma\gamma} = a_3^{Z\gamma} = 0$

SMEFT Warsaw basis:

$c_{H\tilde{W}} = (\sin^2\theta_W / cos^2\theta_W)\ c_{H\tilde{B}} = (2\sin\theta_W / cos\theta_W)\ c_{H\tilde{W}B}$

SMEFT Higgs basis:

$\tilde{c}_{ZZ} = \tilde{c}_{WW}$ & $\tilde{c}_{Z\gamma} = \tilde{c}_{\gamma\gamma} = 0$

Relation: $\tilde{c}_{ZZ} = A \cdot\ c_{H\tilde{W}}$

Fractional cross sections and relation to $\tilde{d}$

$$f_{a3} = \frac{a_3}{|a_3|} \cdot \frac{|a_3|^2 \cdot \sigma_3}{|a_1|^2 \cdot \sigma_1 + |a_2|^2 \cdot \sigma_2 + |a_3|^2 \cdot \sigma_3 + |\kappa_1|^2 \cdot \sigma_{\Lambda_1} + |\kappa_1^{Z\gamma}|^2 \cdot \sigma_{\Lambda_1^{Z\gamma}}}$$

Special case where only the CP-odd coupling is allowed to be different from SM:

$$f_{a3} = \frac{a_3}{|a_3|} \cdot \frac{|a_3|^2 \cdot \frac{\sigma_3}{\sigma_{SM}}}{1 + |a_3|^2 \cdot \frac{\sigma_3}{\sigma_{SM}}}, \quad \text{where} \quad \frac{\sigma_3}{\sigma_{SM}} = 0.153$$

Relation to the CP-odd parameter $\tilde{d}$ in ATLAS measurements:

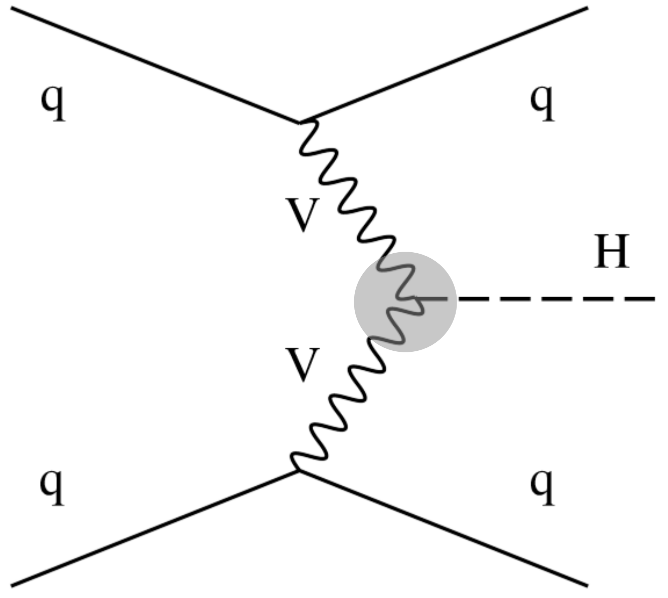
$$\tilde{d} = a_3^{ZZ} = \frac{f_{a3}}{|f_{a3}|} \cdot \sqrt{\frac{|f_{a3}|}{1 - |f_{a3}|} \cdot \frac{\sigma_{SM}}{\sigma_3}}$$

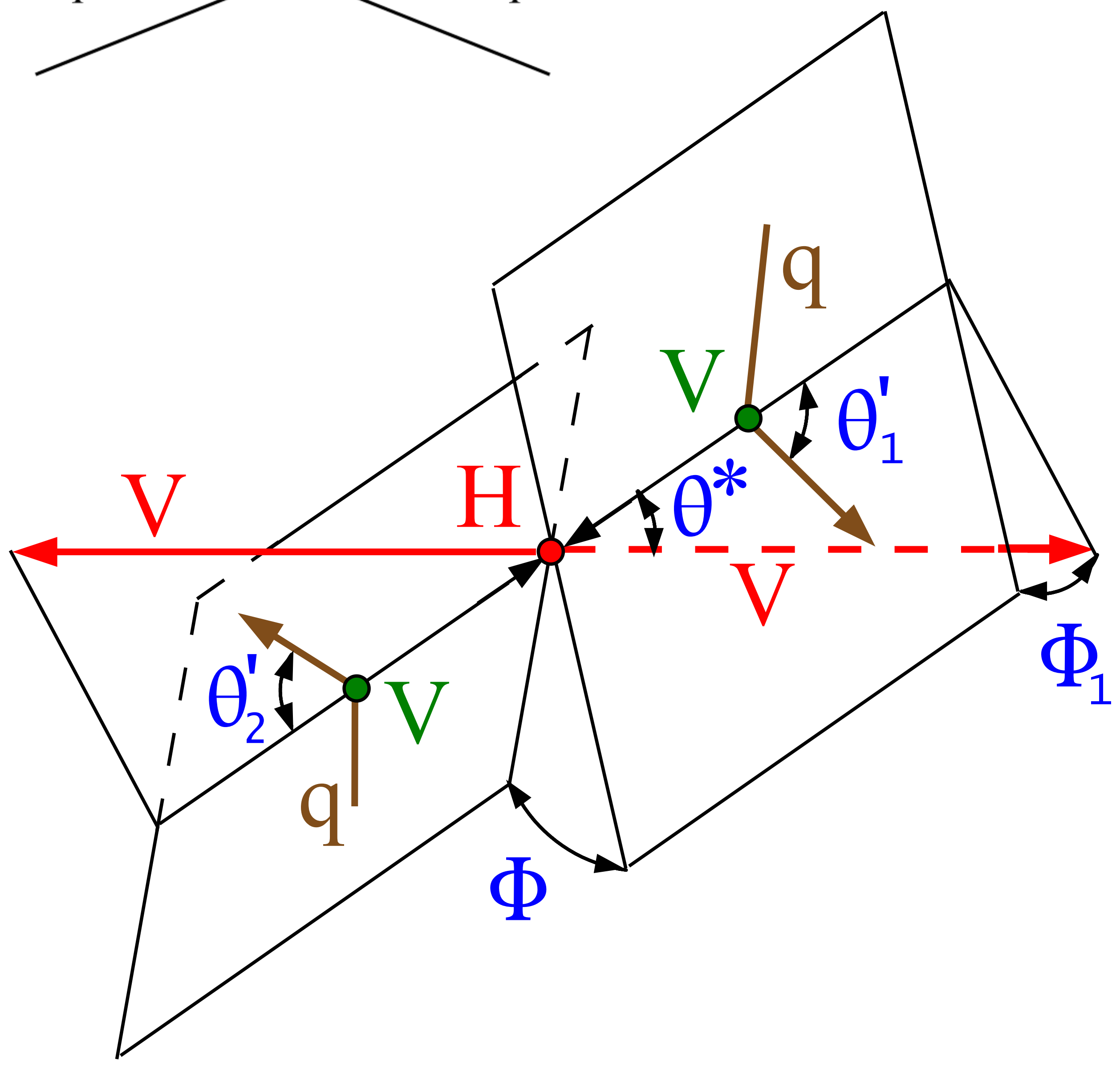
$$\text{with } \mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{g}{2m_W} \tilde{d} \left(A_{\mu\nu}A^{\mu\nu} + Z_{\mu\nu}Z^{\mu\nu} + 2W^{+}_{\mu\nu}W^{-\mu\nu} \right) H$$

Angular information in the HVV vertex (production and decay)

Vector Boson Fusion (VBF) production

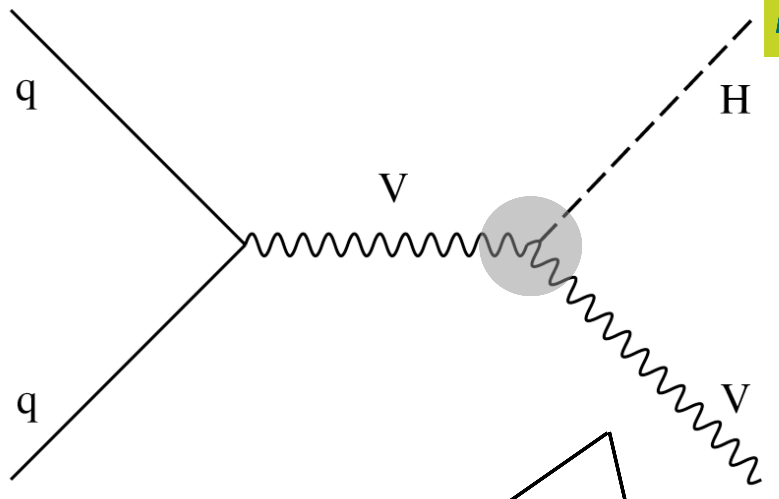
Measured in different decay channels

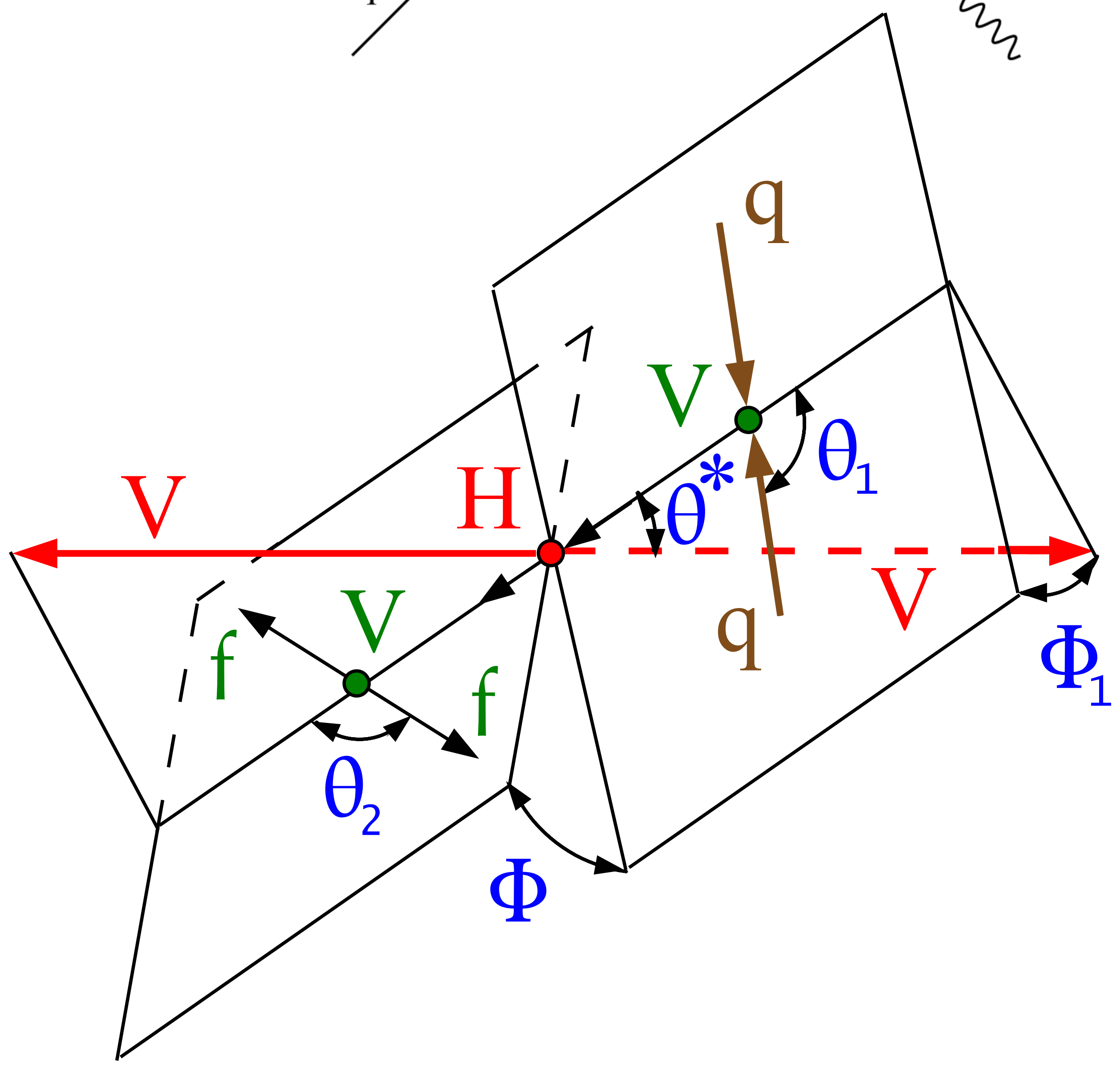




VH associated production

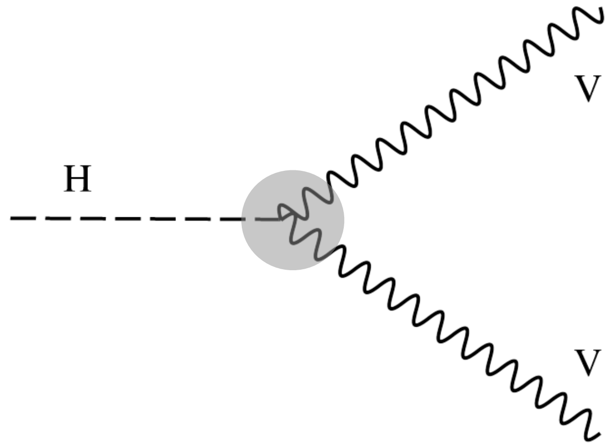
Measured in different decay channels

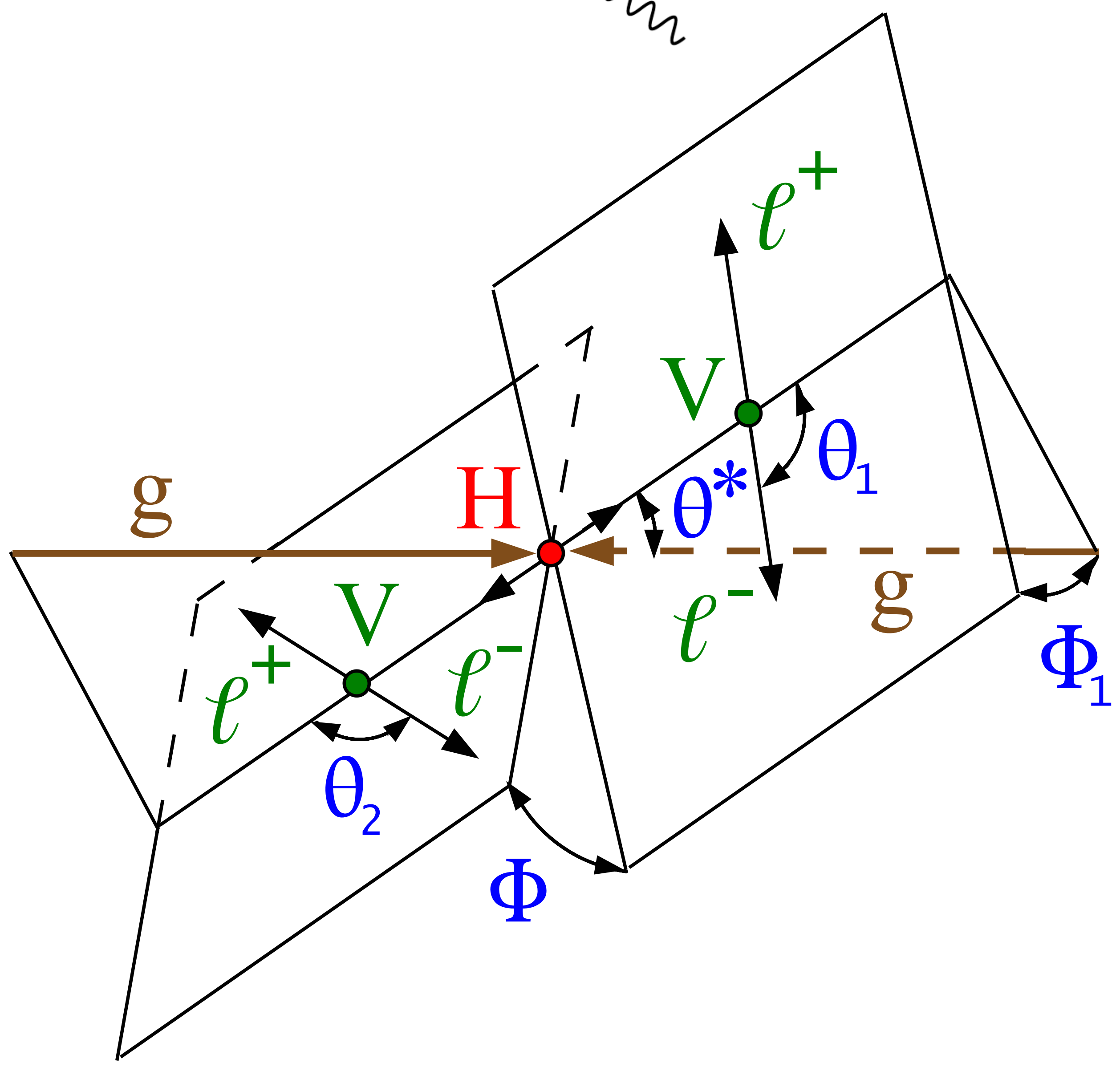




$H \to VV^* \to 4\ell$ decay

Measured predominantly in the ggH production mode





Discrimination between the SM and CP-odd contributions by means of matrix-element calculation using a given set of of kinematic observables or jet & lepton four-momenta as an input.

Overview of recent CP-violation searches at the LHC

CMS *H -> 4l*	prod + decay	Full R1 + 80/fb R2	arxiv:1901.00174
CMS *H -> 4l*	prod + decay	Full R2 (137/fb)	arXiv:2104.12152
CMS H -> *WW*	prod + decay	Full R2 (138/fb)	arxiv:2403.00657
CMS H- > tautau	prod	Full R2 (138/fb)	arXiv:2205.05120
CMS H->(tautau, 4l)	prod + decay	Full R2 (138/fb)	arXiv:2205.05120
ATLAS H -> tautau	prod	36.1/fb R2	arxiv:2002.05315
ATLAS H -> *yy*	prod	Full R2 (139/fb)	arXiv:2208.02338
ATLAS H -> *(yy, tautau)*	prod	R2 (139/fb; 36.1/fb)	arXiv:2208.02338
ATLAS H -> *4l*	prod + decay	Full R2 (139/fb)	arXiv: 2304.09612

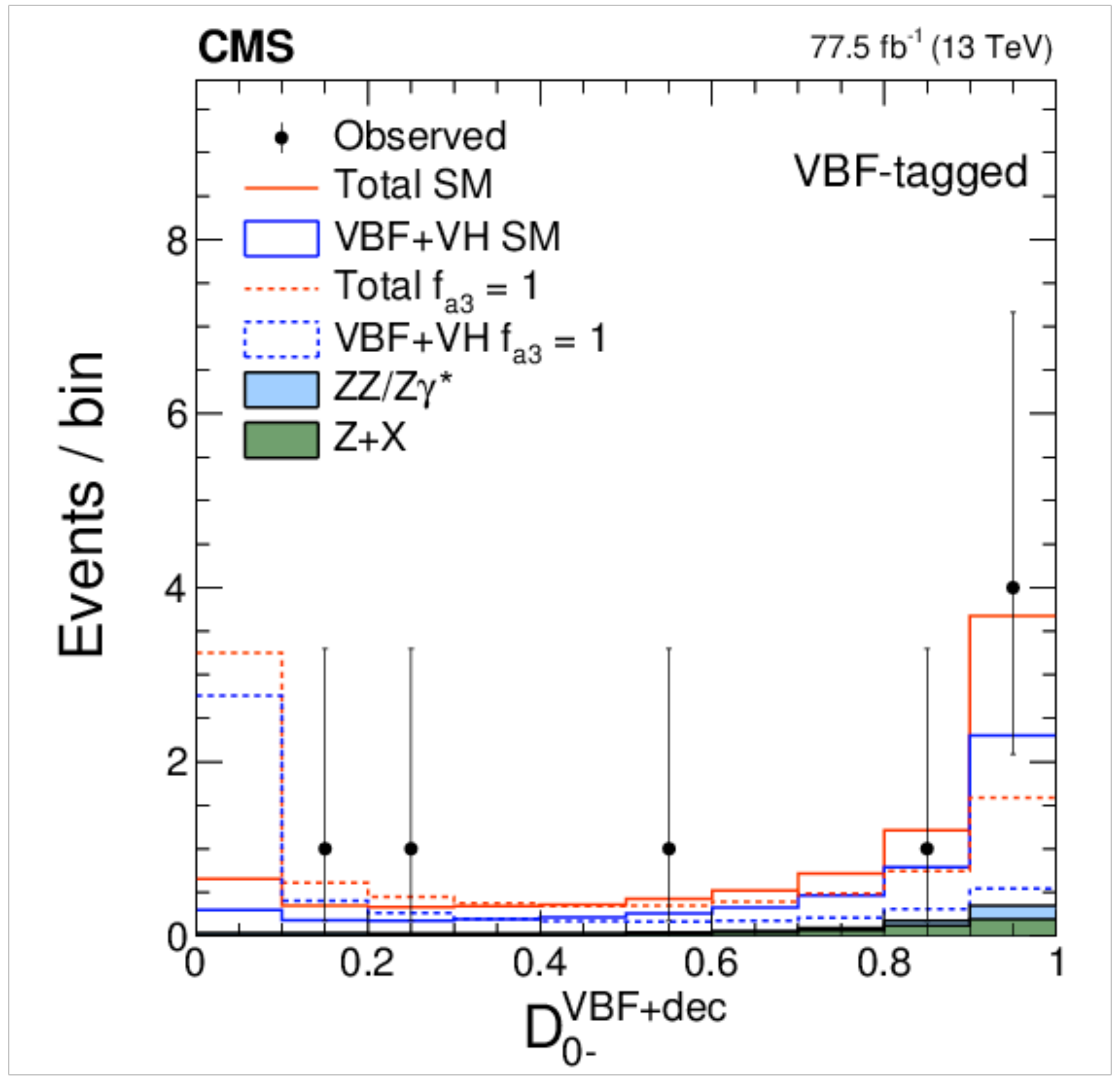
Input for an HL-LHC projection, CMS-PAS-FTR-18-011

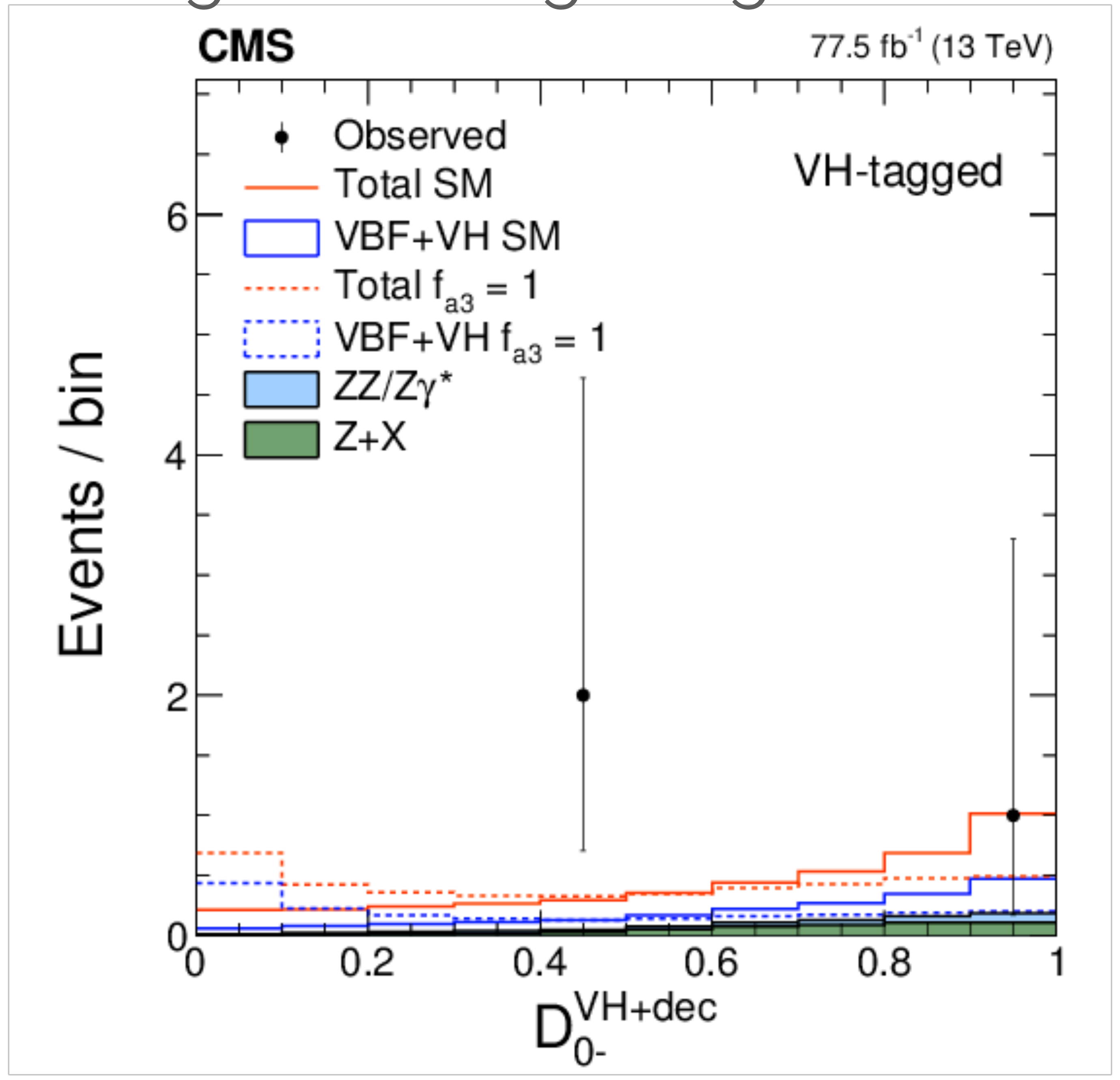
Input for an HL-LHC projection, HIG-20-007

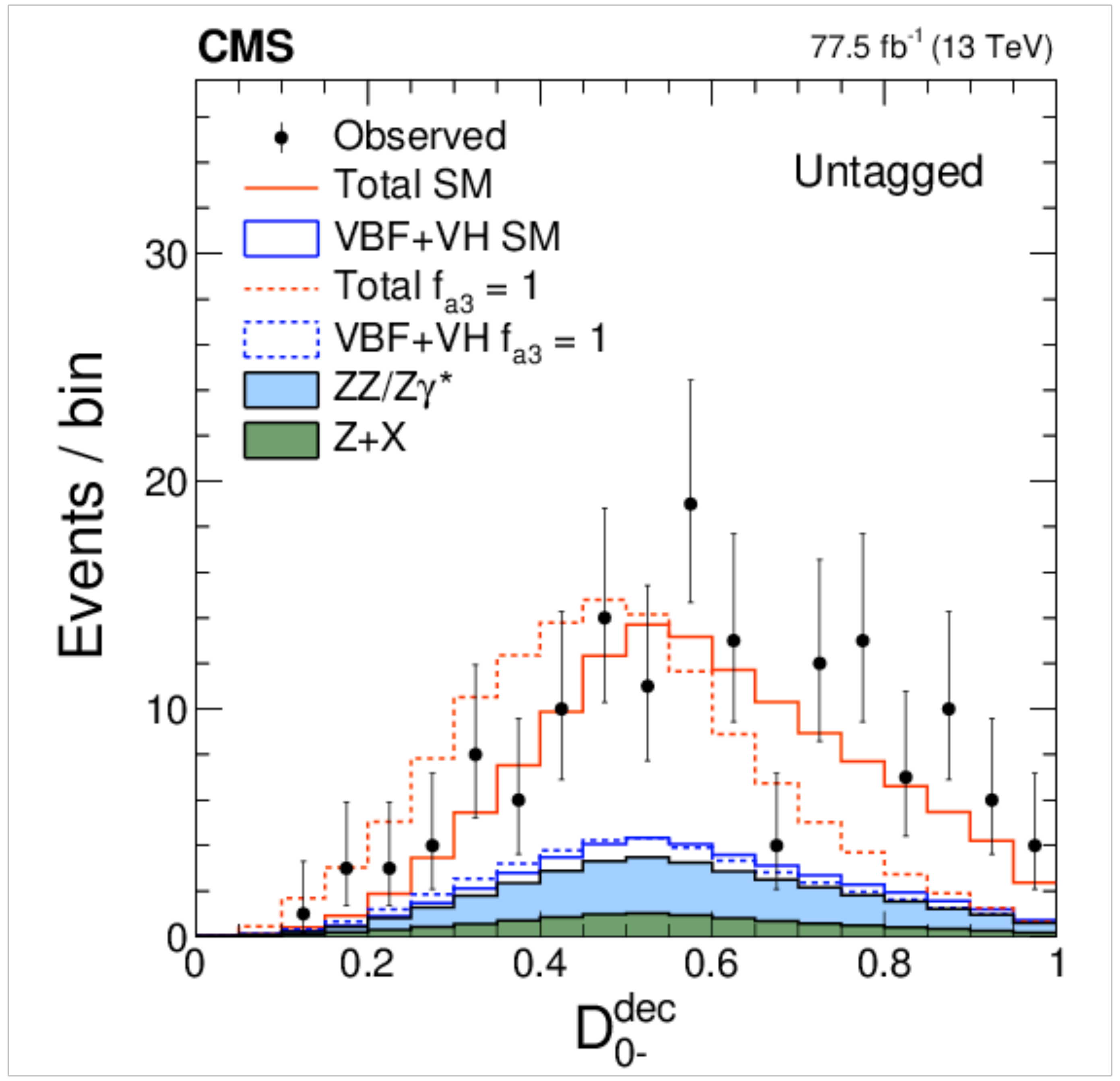
CMS $H \to ZZ^* \to 4\ell$ channel (production & decay vertex)

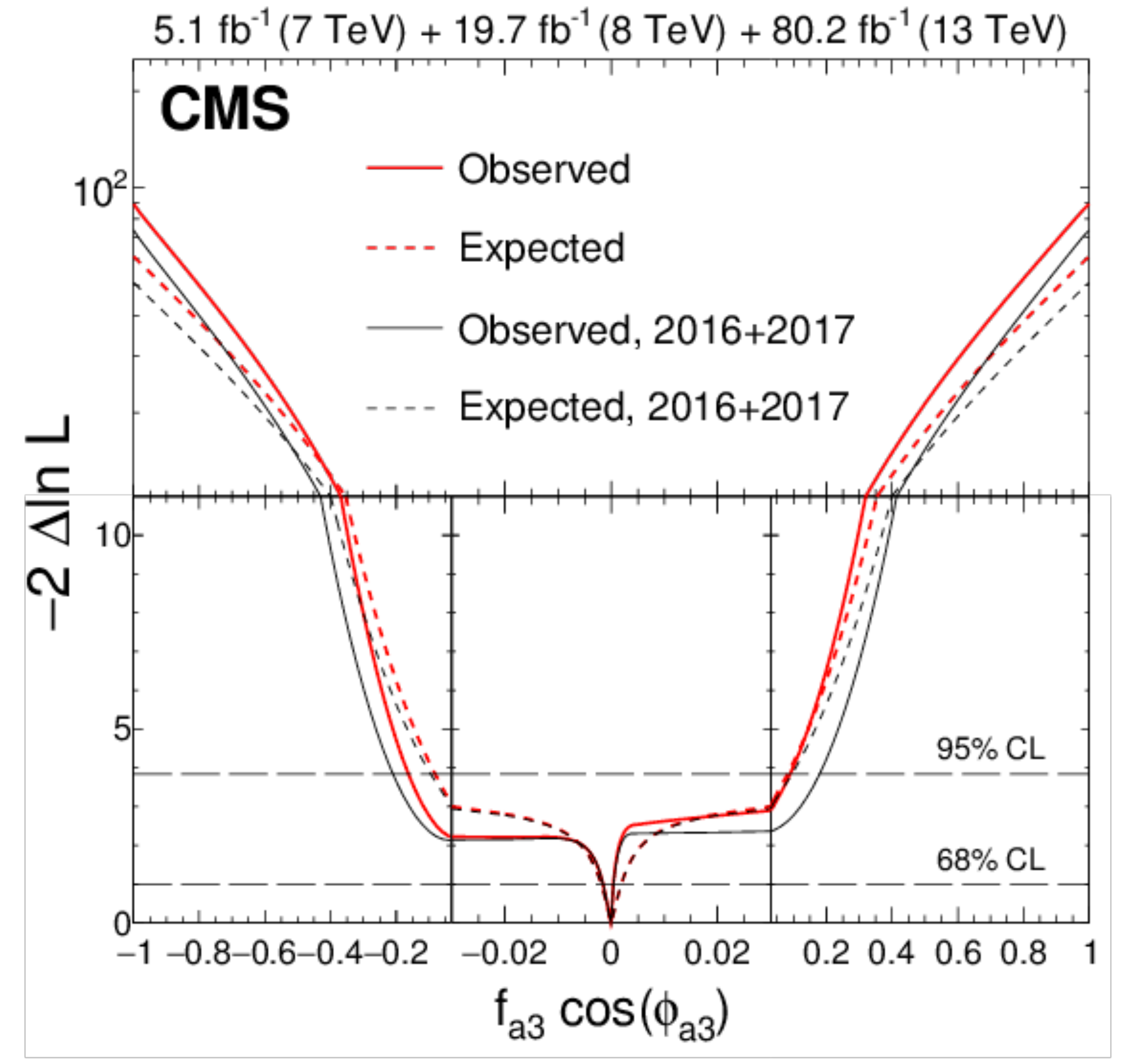
arxiv:1901.00174

Events categorized into three event categories targeting different production modes.









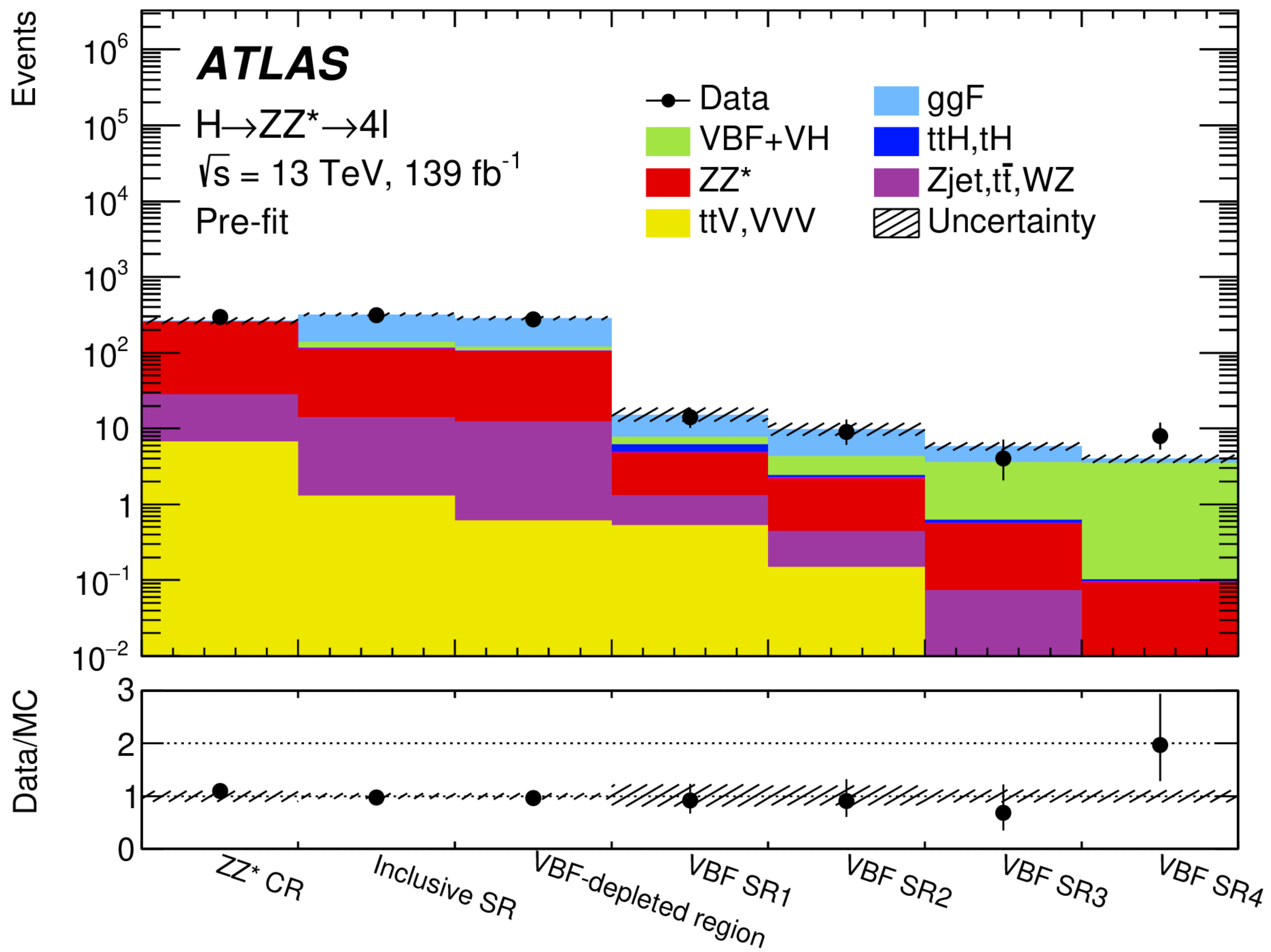
Limits on f_{a3} obtained from the simultaneous fit to several MELA discriminants, designed separately for each event category.

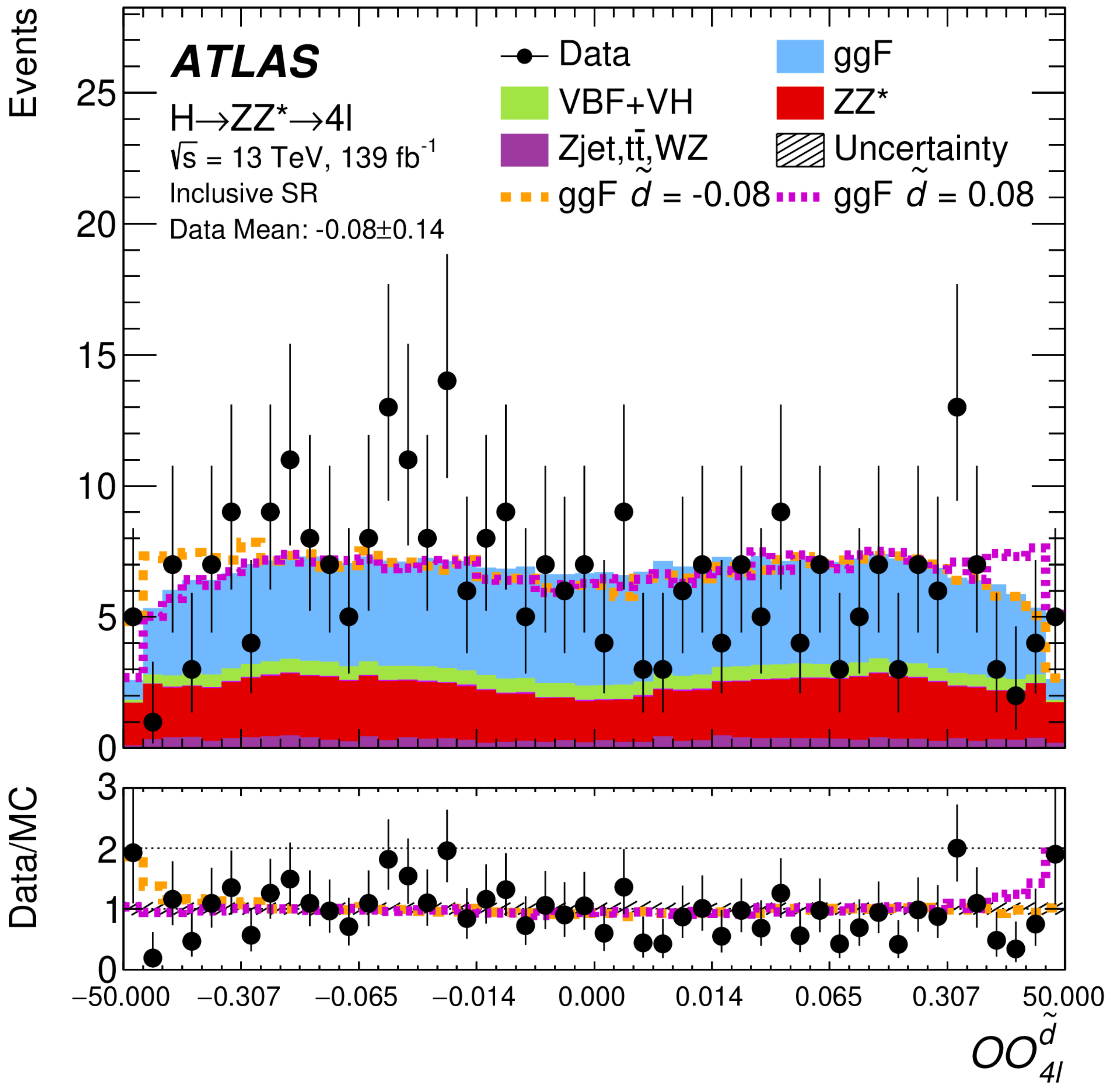
$$\text{Expected } f_{a3}/10^{-3} : \quad 0.0^{+1.9}_{-1.9} \; ; \; [-82,82] \; @95\,\%\,\text{CL}$$

ATLAS $H \to ZZ^* \to 4\ell$ channel (production & decay vertex)

arXiv: 2304.09612

- Four VBF-enriched signal regions for the production, one VBF-depleted signal region for the decay.
- Dedicated Optimal Observables (OO), defined separately for the production and the decay vertices, $OO \propto 2Re\left(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd}\right)$.





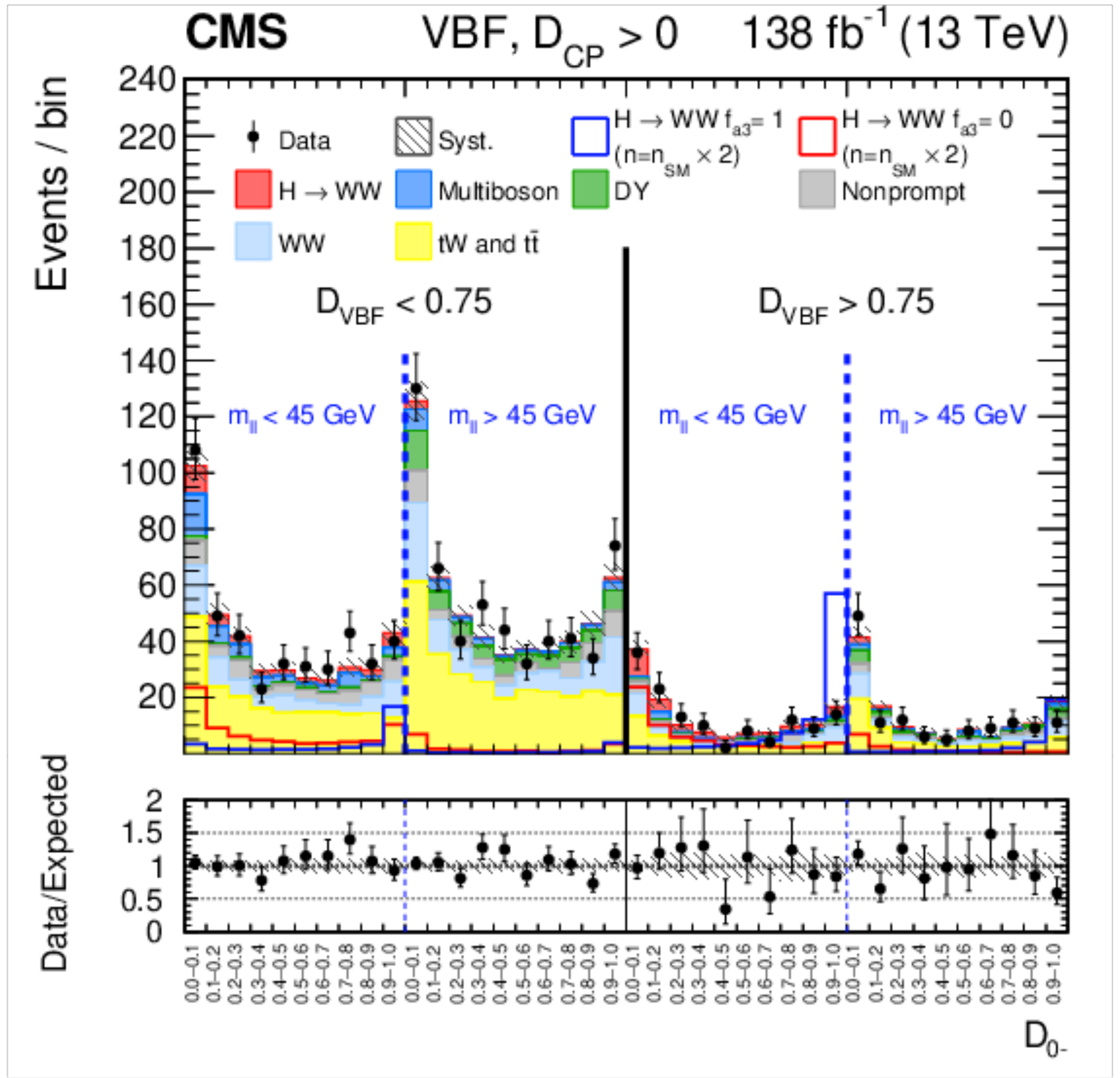
Expected $\tilde{d}$: $0.000^{+0.009}_{-0.009}$; $[-0.018, 0.018]$ @ 95 % CL $\Rightarrow$ $f_{a3}/10^{-3} < 0.05$ @ 95 % CL

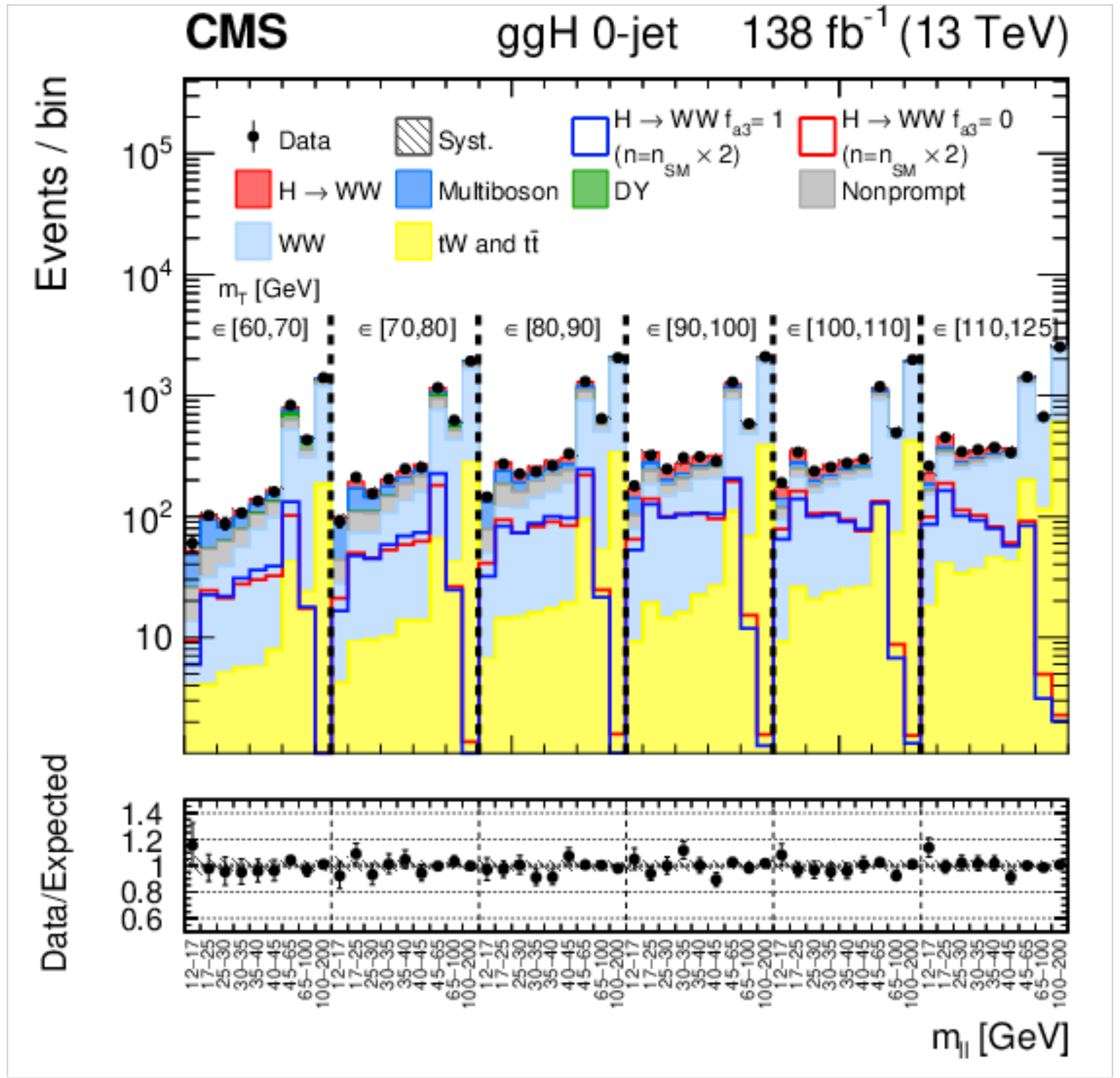
CMS $H \to WW^* \to e\nu\mu\nu$ channel (production & decay vertex)

arxiv:2403.00657

Events categorized into three several categories targeting different production modes:
VBF, VH-resolved, VH-boosted, ggH-0jet, ggH-1jet, ggH-2jet.

Signal discrimination based on several discriminants, dedicated for each category, e.g.:





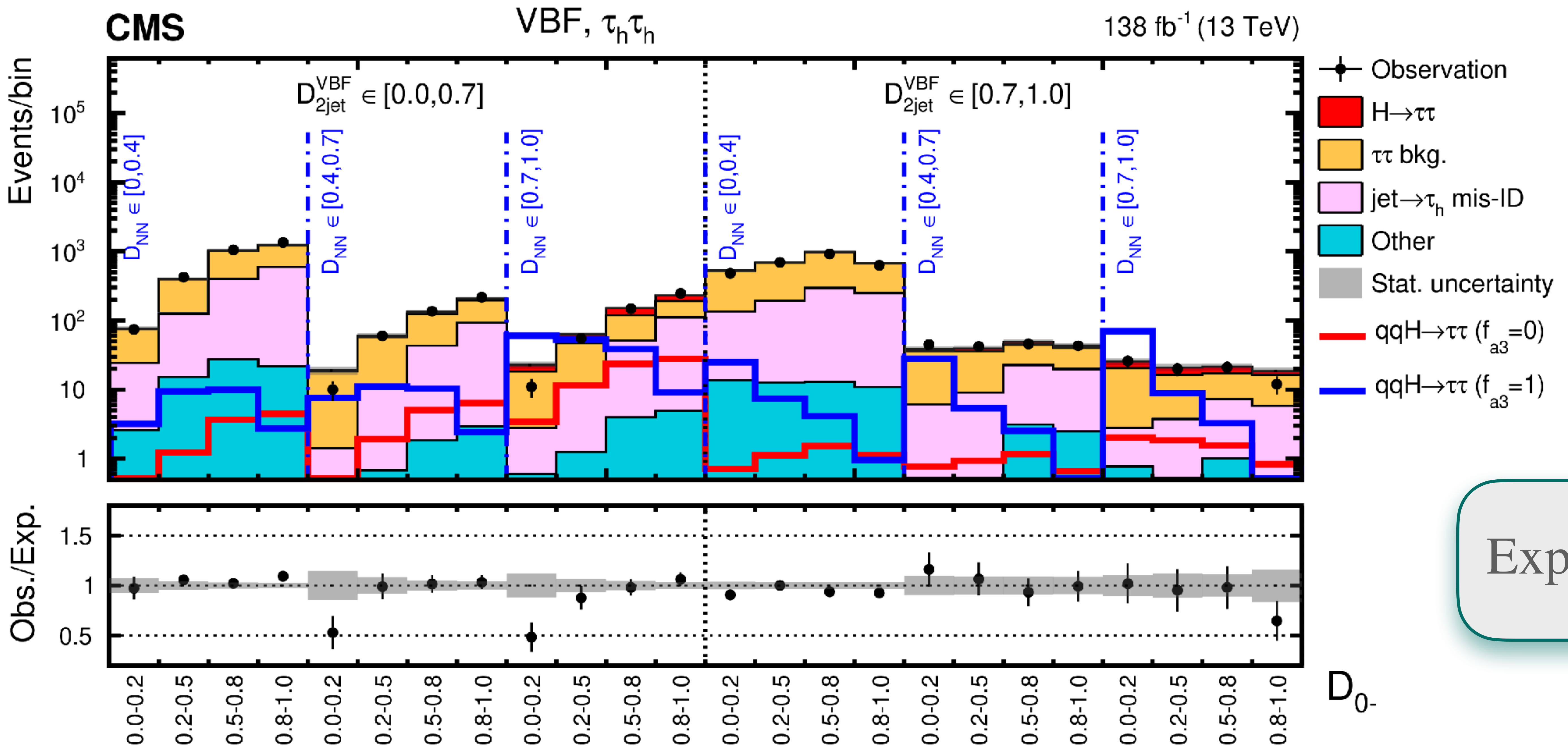
Expected $f_{a3}/10^{-3}$:

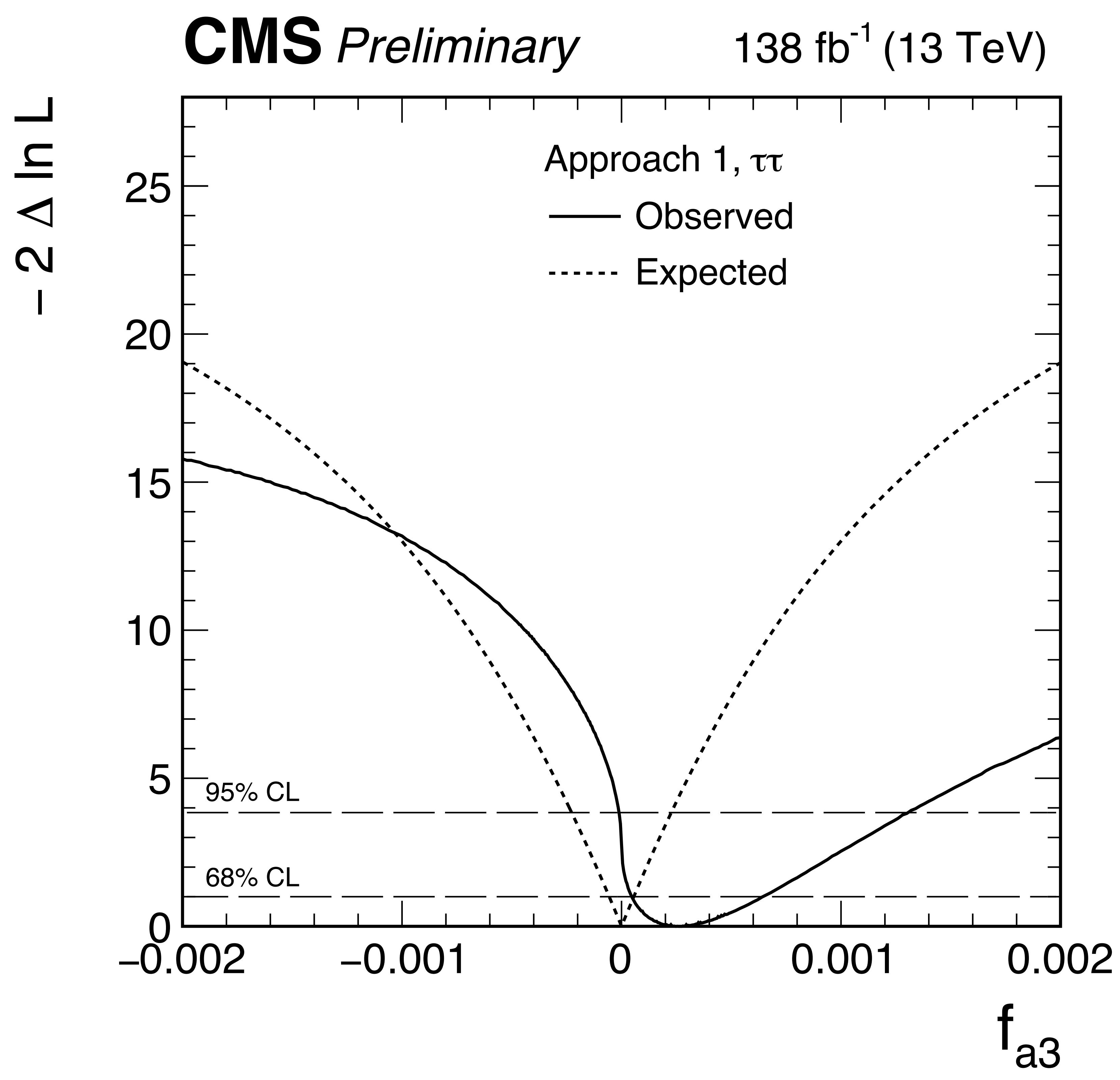
$0.0^{+0.7}_{-0.7}$; $[-2.8, 2.9]$ @ 95 % CL

CMS $H \to \tau\tau$ channel (VBF production vertex)

arXiv:2205.05120

- Events categorized into VBF and ggH production modes.
- MELA observables to separate VBF CP-odd signal from background ($\mathscr{D}_{NN}$), ggF ($\mathscr{D}_{2jet}^{VBF}$), and CP-even VBF ($\mathscr{D}_{0-}$).
- 3D-fit of the MELA observables.
- Much larger sensitivity compared to the CMS 4l channel.



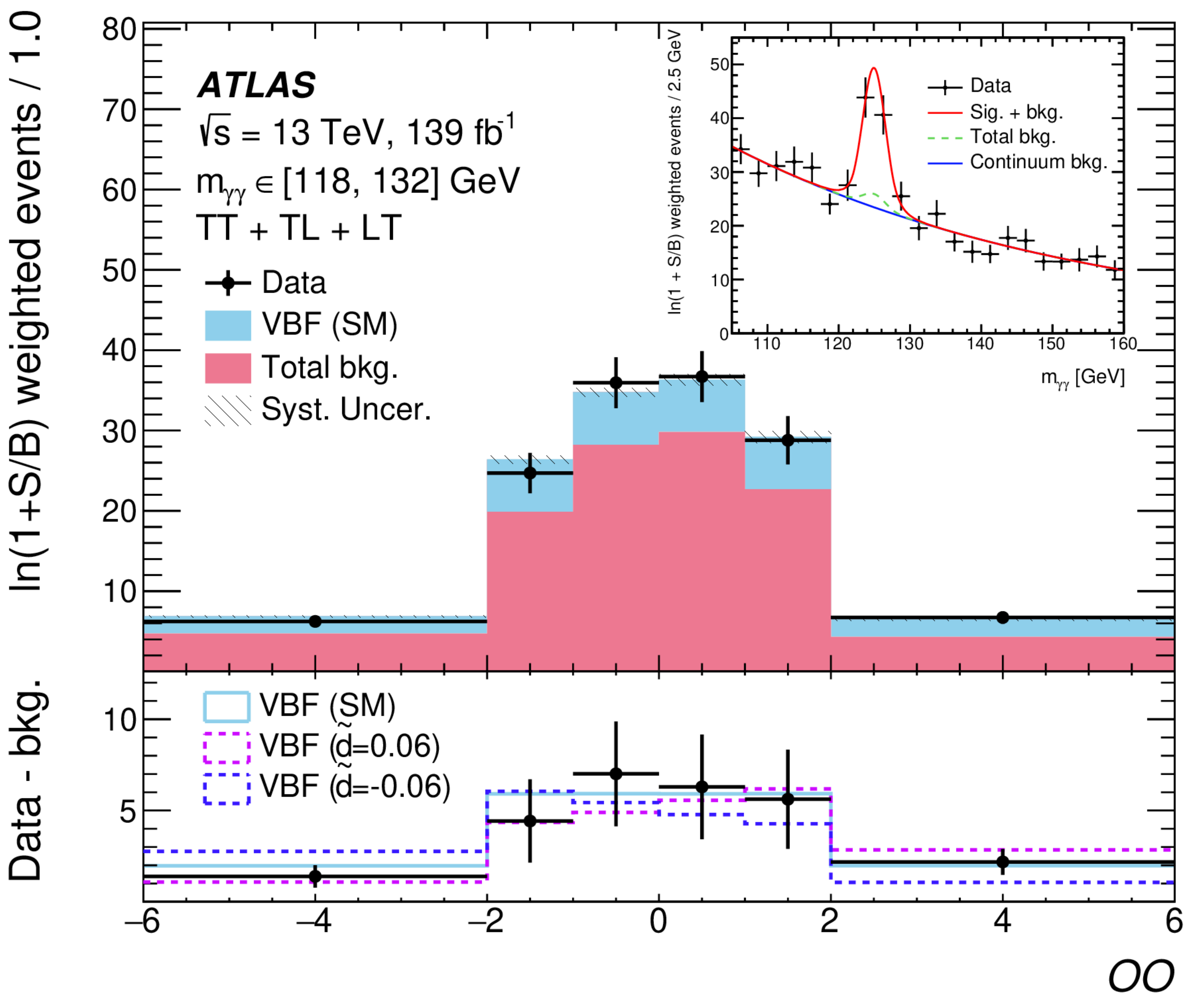


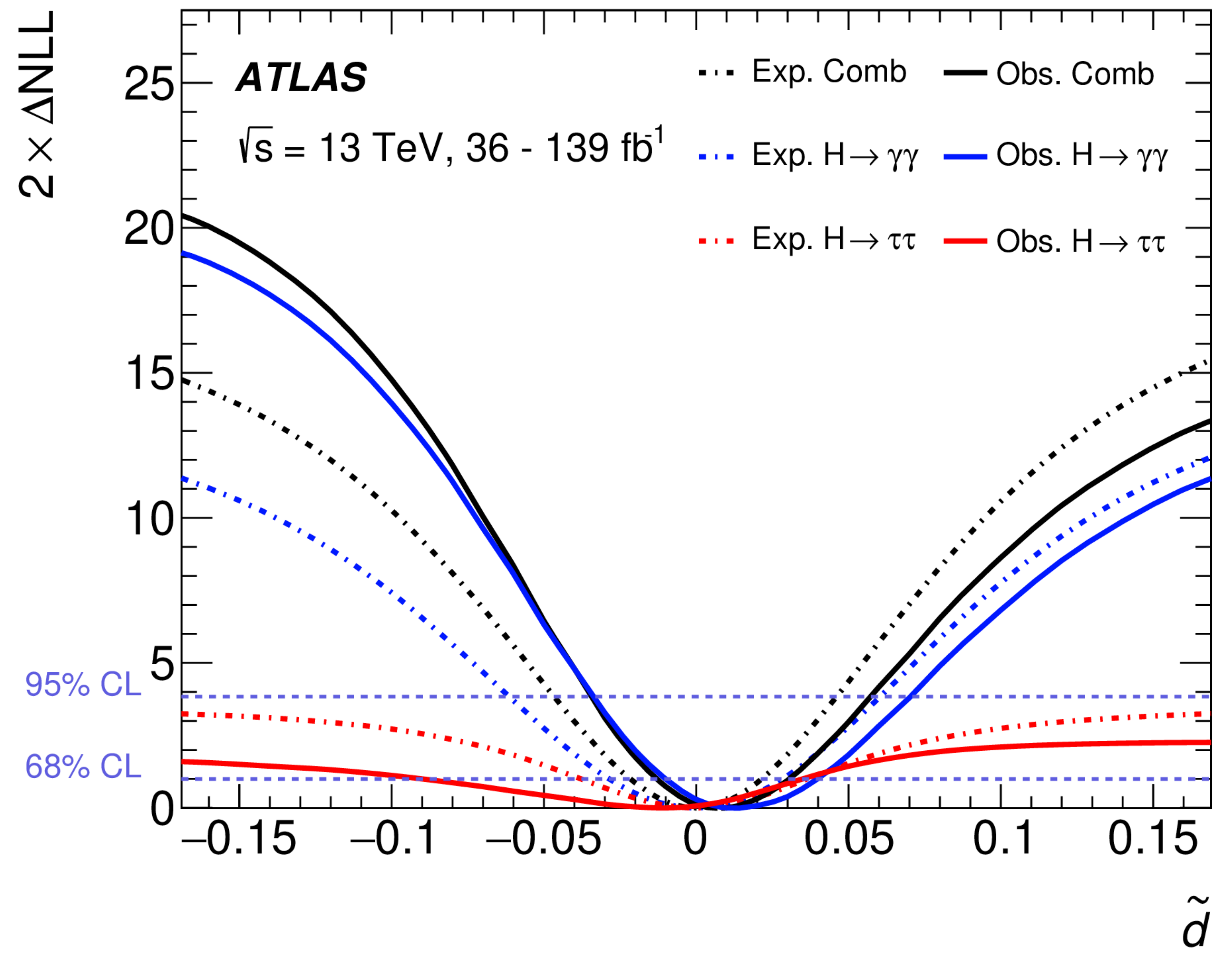
Expected $f_{a3}/10^{-3}$: $0.00^{+0.06}_{-0.06}$; $[-0.23,0.23]$ @95 % CL

ATLAS $H \to \gamma\gamma$ channel (VBF production vertex)

arXiv:2208.02338

- Constraints based on $m_{\gamma\gamma}$ spectra in each bin of Optimal Observable distribution, separately for three signal regions.

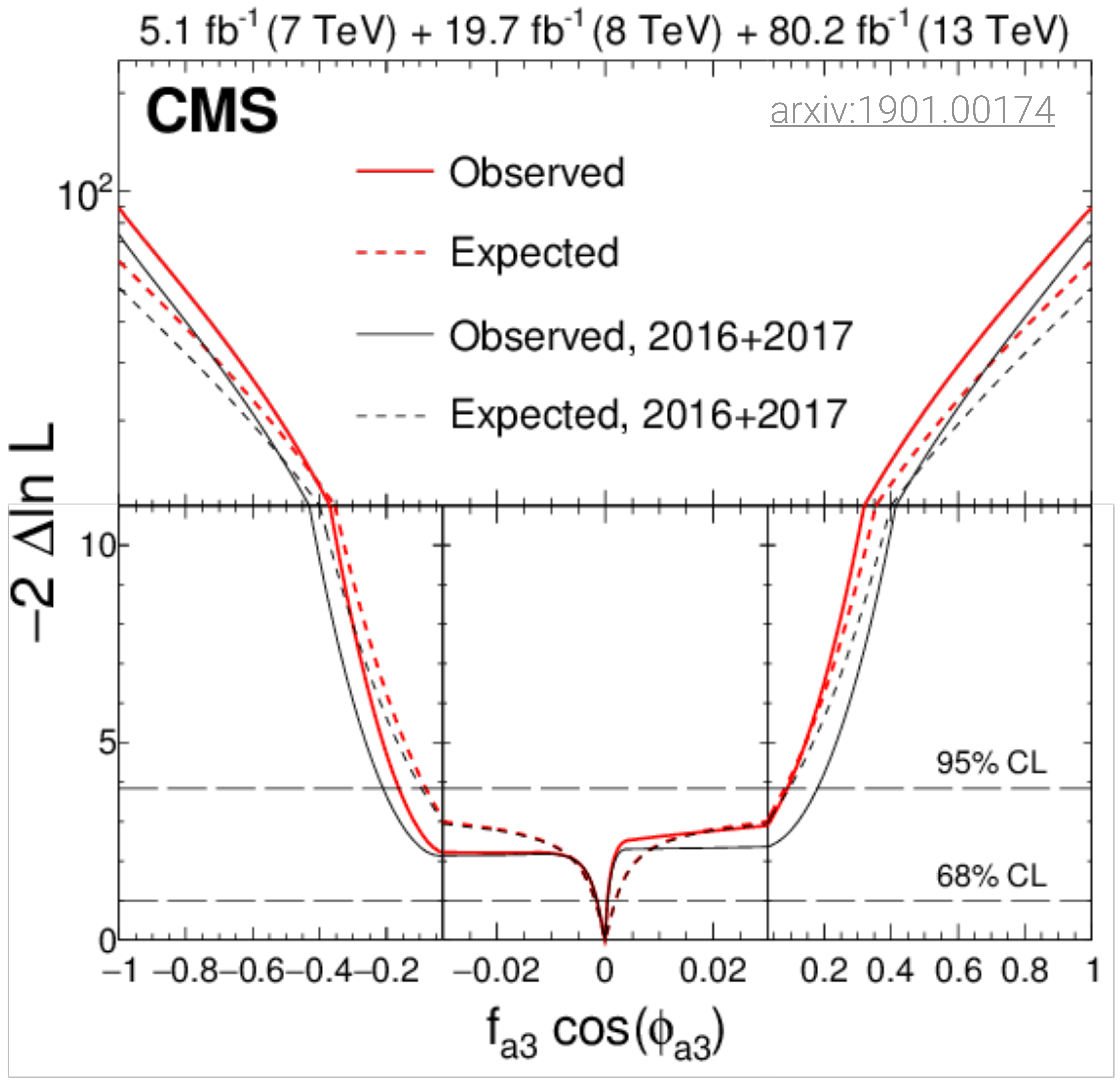


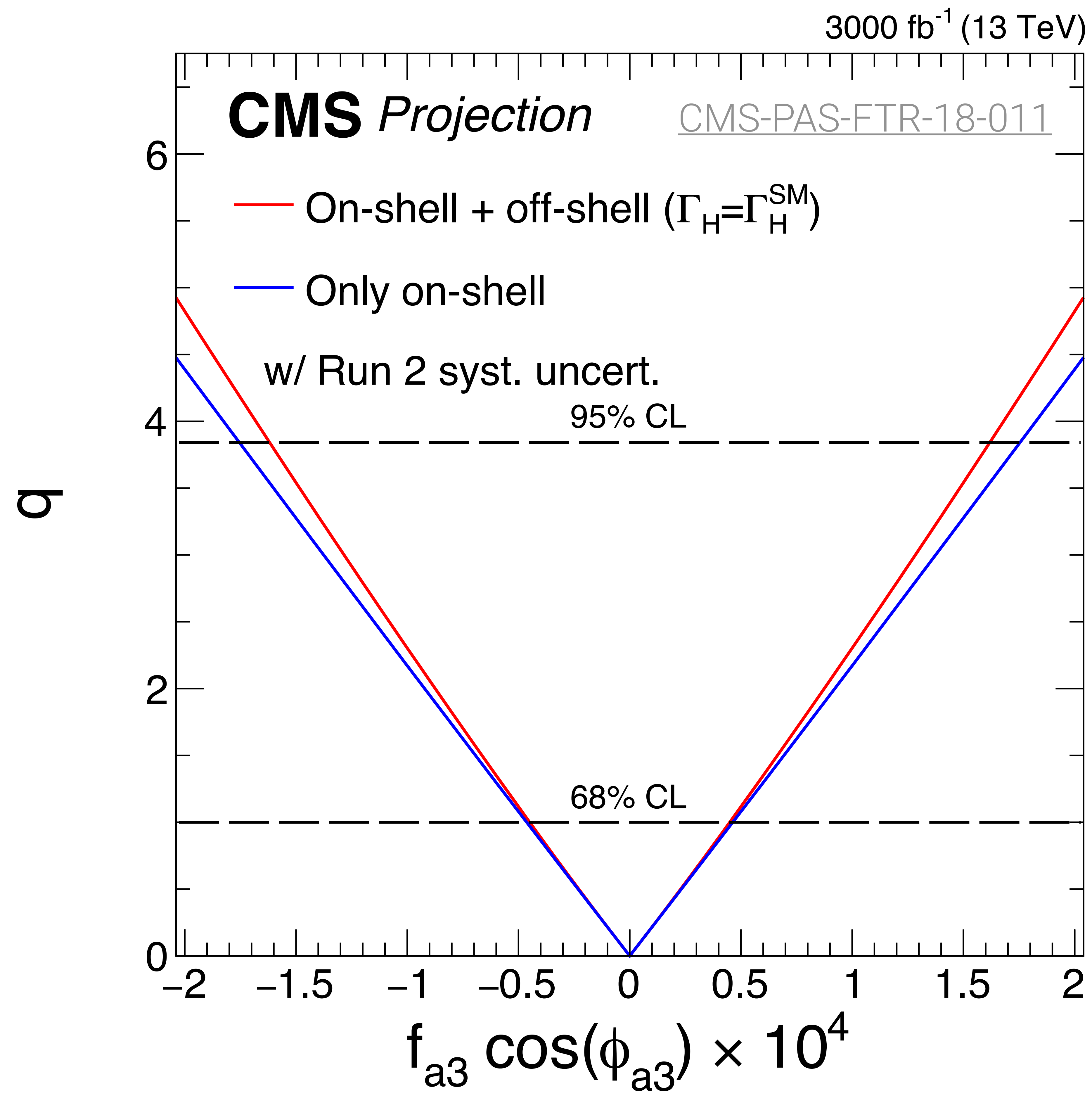


Expected $\tilde{d}$: $0.000^{+0.028}_{-0.028}$; $[-0.061, 0.060]$ @ 95 % CL

$\Rightarrow f_{a3}/10^{-3} < 0.5$ @ 95 % CL

HL-LHC projection based on the CMS $H \to ZZ^* \to 4\ell$ channel





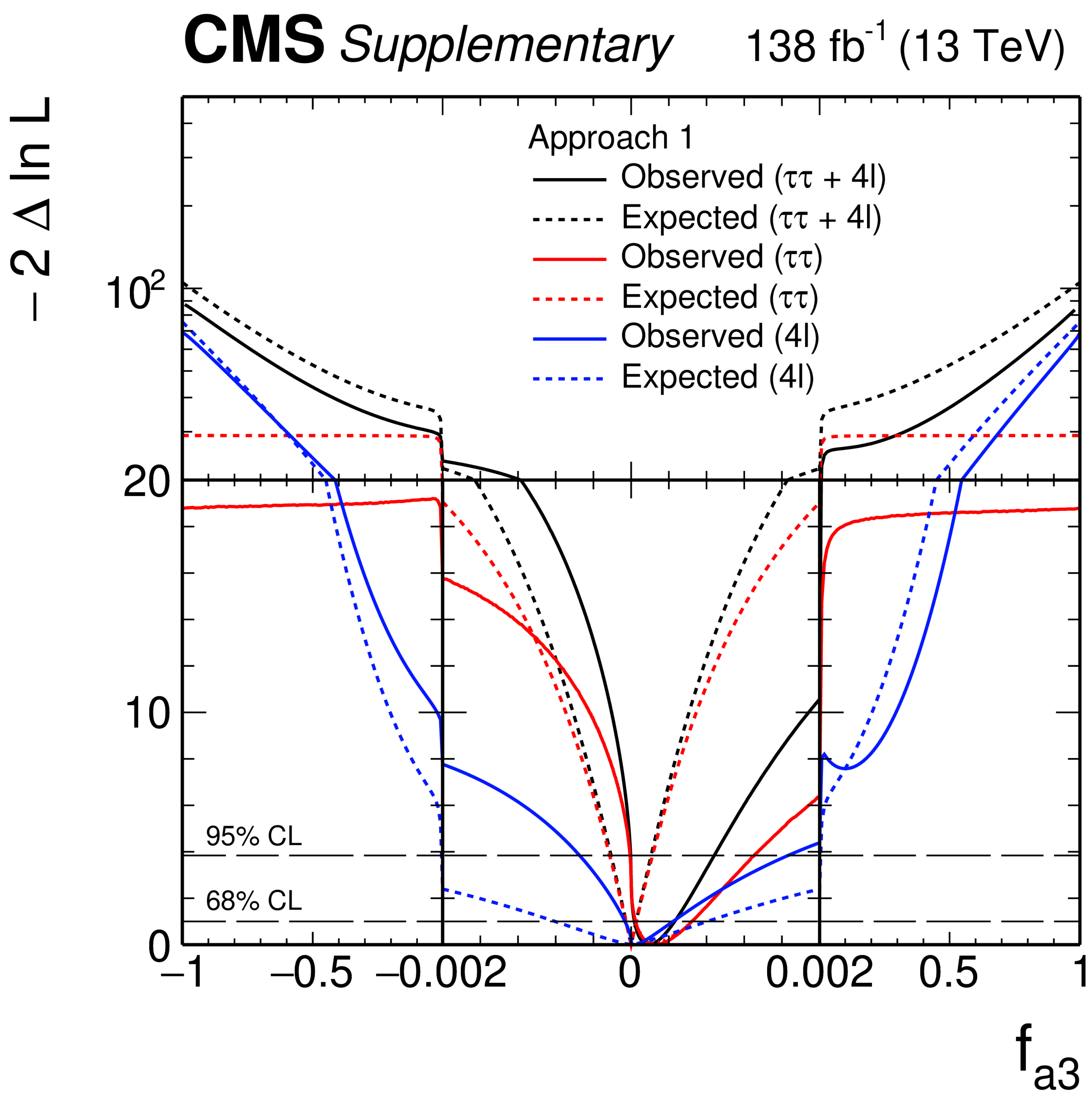
Expected $f_{a3}/10^{-4}$: $[-19,\ 19]$ @ 68 % CL

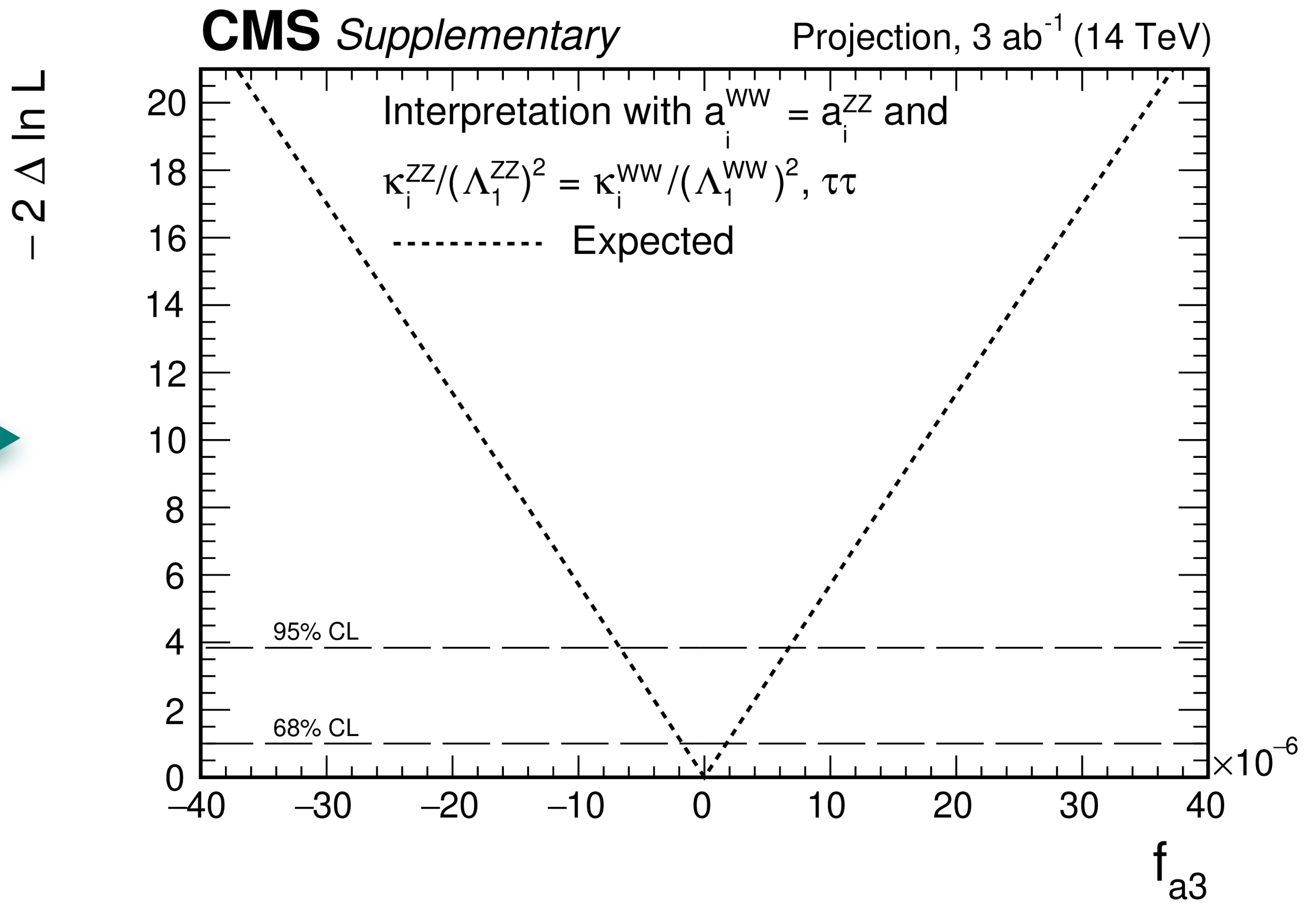
Expected $f_{a3}/10^{-4}$: $[-0.450,\ 0.450]$ @ 68 % CL

HL-LHC projection based on the CMS $H \to (\tau\tau, 4\ell)$ measurements

arXiv:2205.05120

HIG-20-007





Expected $f_{a3}/10^{-4}$: $[-0.5, 0.5]$ @68 % CL

Expected $f_{a3}/10^{-4}$: $[-0.017, 0.017]$ @68 % CL

Constraints from recent CP-violation searches at the LHC

				Expected upper limit @ 68% CL		Expected upper limit @ 95% CL	
				$\|f_{a3}\| * 1000$	$\|\tilde{d}\|$	$\|f_{a3}\| * 1000$	$\|\tilde{d}\|$
CMS *H -> 4l*	prod + decay	Full R1 + 80/fb R2	arxiv:1901.00174	1.9	0.110	8.2	0.760
CMS *H -> 4l*	prod + decay	Full R2 (137/fb)	arXiv:2104.12152	0.81	0.072	4.1	0.164
CMS H -> *WW*	prod + decay	Full R2 (138/fb)	arxiv:2403.00657	0.70	0.068	2.8	0.135
CMS H- > tautau	prod	Full R2 (138/fb)	arXiv:2205.05120	0.06	0.020	0.23	0.039
CMS H->(tautau, 4l)	prod + decay	Full R2 (138/fb)	arXiv:2205.05120	0.05	0.018	0.21	0.037
ATLAS H -> tautau	prod	36.1/fb R2	arxiv:2002.05315		0.035		0.200
ATLAS H -> *yy*	prod	Full R2 (139/fb)	arXiv:2208.02338		0.028		0.061
ATLAS H -> *(yy, tautau)*	prod	R2 (139/fb; 36.1/fb)	arXiv:2208.02338		0.022		0.046
ATLAS H -> *4l*	prod + decay	Full R2 (139/fb)	arXiv: 2304.09612		0.009		0.018

Constraints from LHC and projections to HL-LHC

Numbers in yellow in the last column are only a rough private estimate, based only on the luminosity scaling.

				Expected upper limit @ 68% CL (LHC)		Expected upper limit @ 68% CL (HL-LHC)
				$\|f_{a3}\| * 1000$	$\|\tilde{d}\|$	$\|f_{a3}\| * 1000$
CMS *H -> 4l*	prod + decay	Full R1 + 80/fb R2	arxiv:1901.00174	1.9	0.110	0.0450
CMS *H -> 4l*	prod + decay	Full R2 (137/fb)	arXiv:2104.12152	0.81	0.072	
CMS H -> *WW*	prod + decay	Full R2 (138/fb)	arxiv:2403.00657	0.70	0.068	0.0340
CMS H- > tautau	prod	Full R2 (138/fb)	arXiv:2205.05120	0.06	0.020	
CMS H->(tautau, 4l)	prod + decay	Full R2 (138/fb)	arXiv:2205.05120	0.05	0.018	0.0017
ATLAS H -> tautau	prod	36.1/fb R2	arxiv:2002.05315		0.035	0.0017
ATLAS H -> *yy*	prod	Full R2 (139/fb)	arXiv:2208.02338		0.028	0.0058
ATLAS H -> *(yy, tautau)*	prod	R2 (139/fb; 36.1/fb)	arXiv:2208.02338		0.022	
ATLAS H -> *4l*	prod + decay	Full R2 (139/fb)	arXiv: 2304.09612		0.009	0.0006

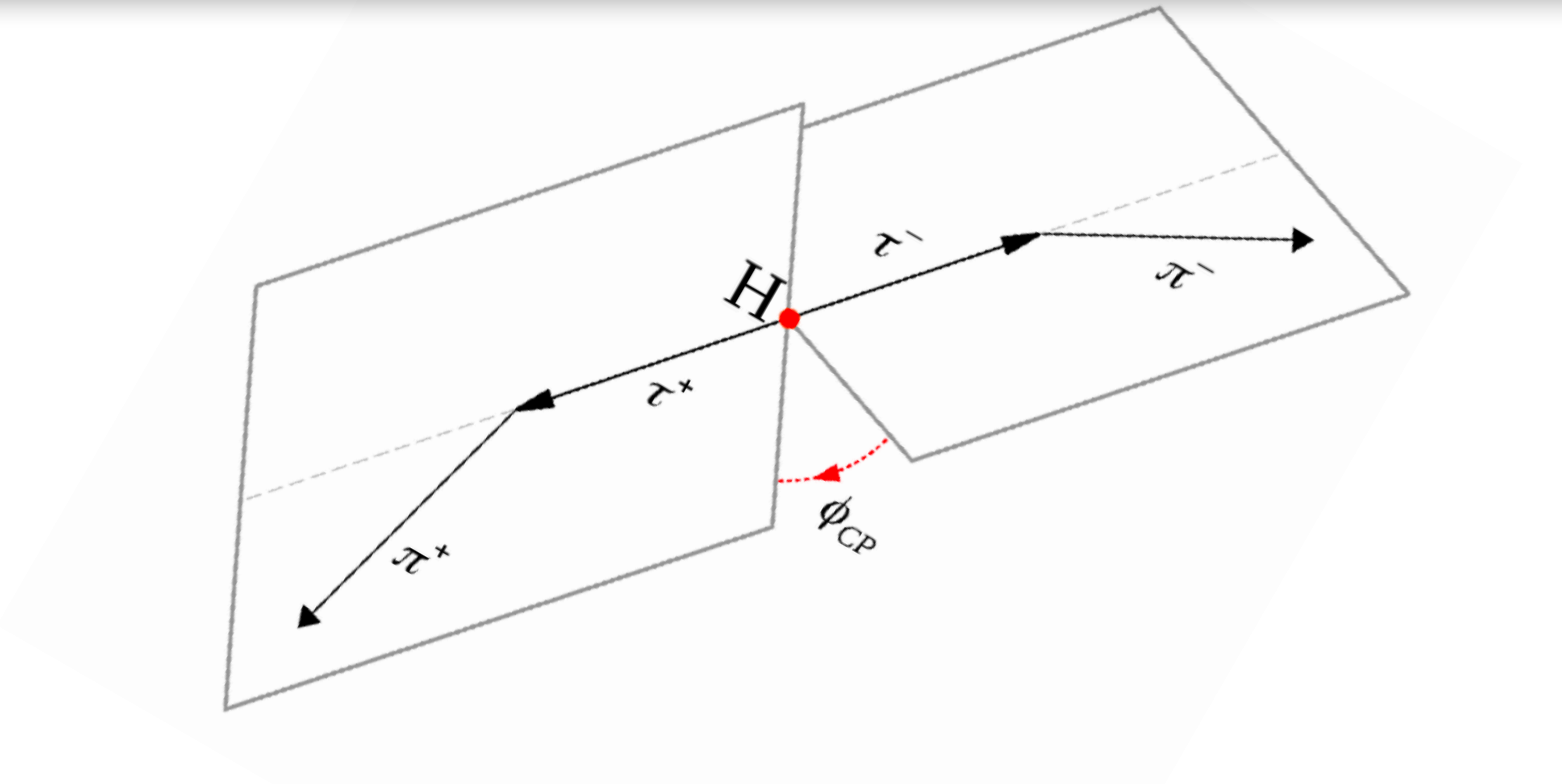
Current best HL-LHC projection: $f_{a3} < 1.7 \cdot 10^{-6}$ @ $68\,\%\,CL$.

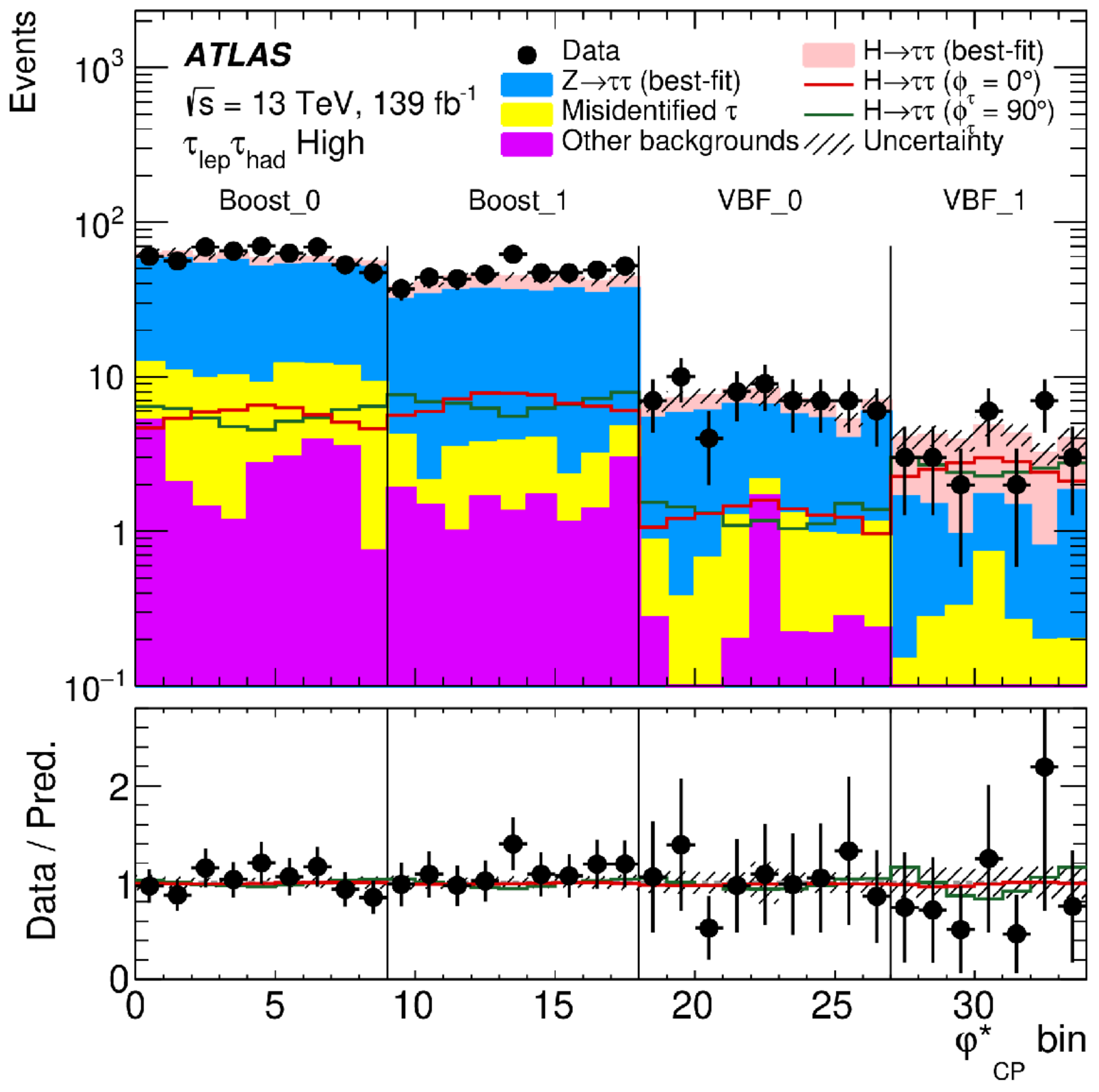
Improvements expected after adding other channels, improving observables, and combining ATLAS+CMS.

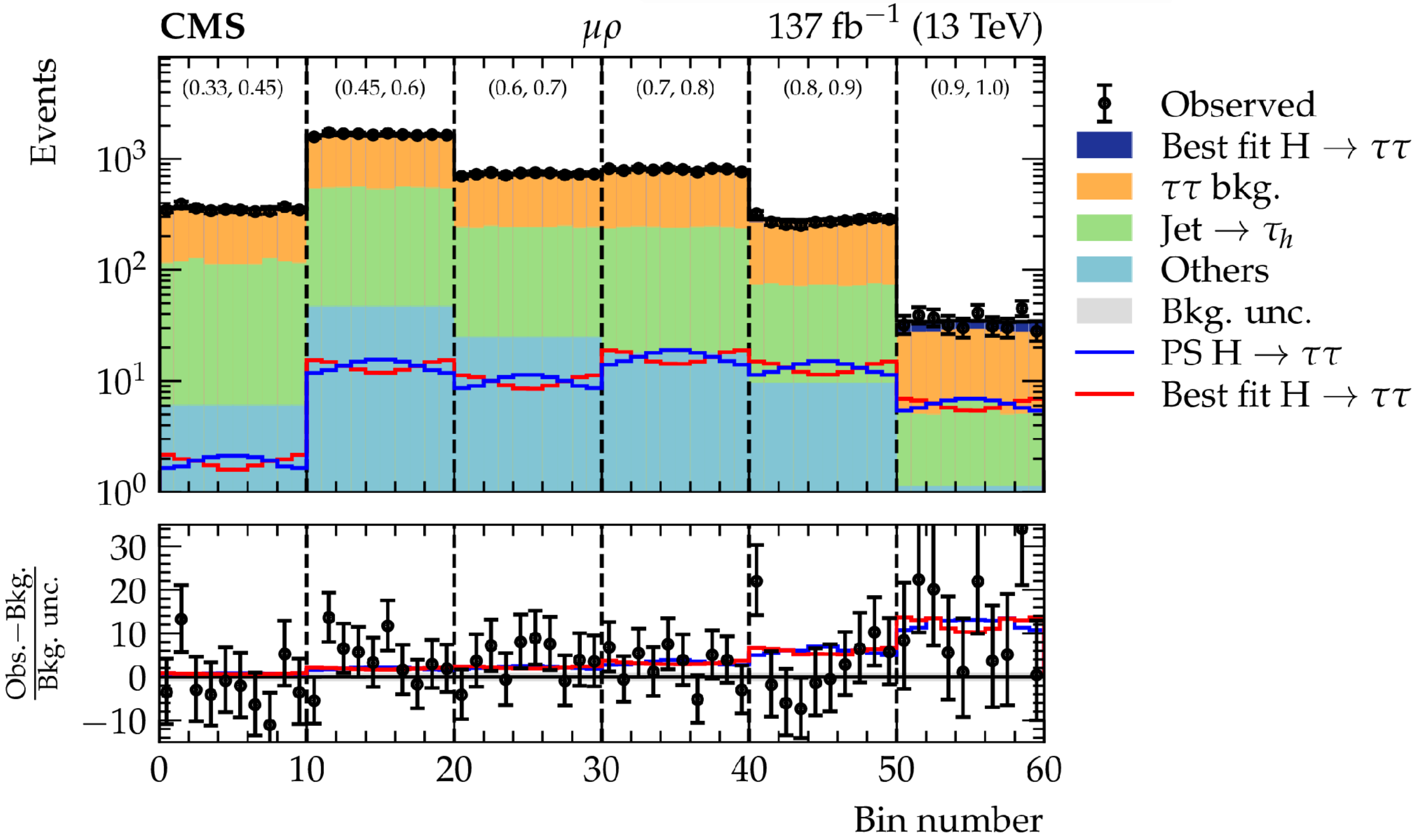
BACKUP

CP-VIOLATION in Hff: $H \to \tau\tau$

- Events categorized according to τ_h decay modes.
- BDT_{bkg} (VBF/Boost) criteria to separate signal from background.
- ϕ_{CP} reconstructed using different decay-mode-dependent methods.
- Simultaneous fit to ϕ_{CP} in different BDT_{bkg} (VBF/Boost) categories.







CP-VIOLATION in Hff

Similar performance of ATLAS & CMS for published individual analyses.

$$\mathcal{L}_{Hff} = \frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\gamma_5\tilde{\kappa}_f\right)\psi_f H = \frac{m_f}{v}\bar{\psi}_f\,\kappa_f'\left[\cos(\alpha) + i\gamma_5\sin(\alpha)\right]\psi_f H$$

CP-even CP-odd

$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} = \sin^2(\alpha_{Hff})$$

α_f: CP-mixing angle

$H\tau\tau$ vertex		Expected upper limit $\lvert\alpha_{H\tau\tau}\rvert$ @ 68% CL	Expected upper limit $\lvert\alpha_{H\tau\tau}\rvert$ @ 95% CL	Pure CP-odd excl. (expected)	Pure CP-odd excl. (observed)
CMS	arXiv:2110.04836	21^0	49^0	2.6σ	$3.0\,\sigma$
ATLAS	arXiv: 2212.05833	28^0	75^0	2.1σ	$3.4\,\sigma$

CMS projection: $f_{CP}^{\tau\tau}$ < 0.008 at 3,000 fb^{-1} @68% CL ($|\alpha_{H\tau\tau}| < 5.1^o$ @68% CL).