EFT FITS AT CMS EXPERIMENT

P. Milenovic (CERN)
EFT workshop @ IPPP, Durham, 7th September, 2017

ABOUT EFT APPROACHES AND CMS EXPERIMENT

Early results with EFT Lagrangians and towards more complete EFT fits

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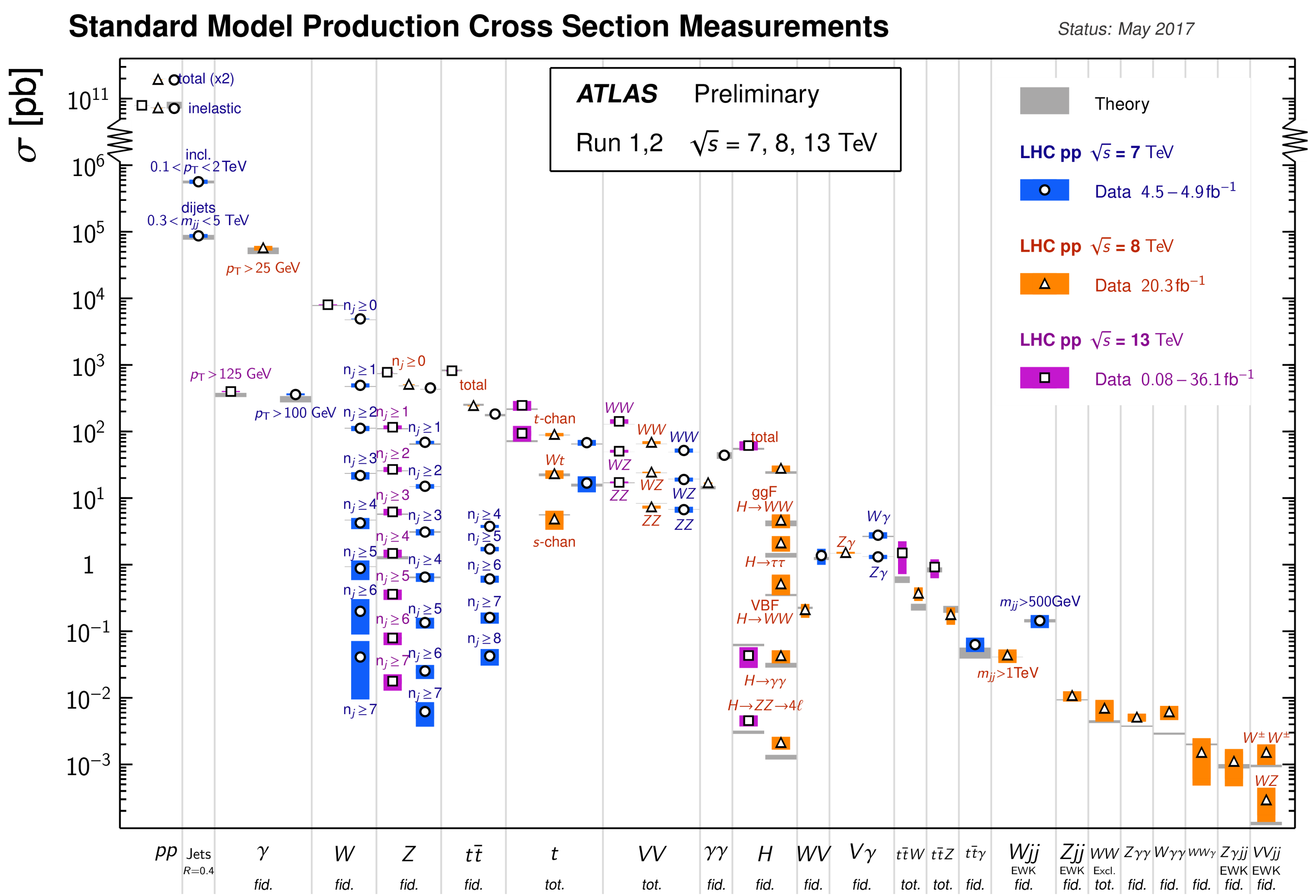
Preface

Higgs discovery: Triumph of LHC and its experiments @ Run 1

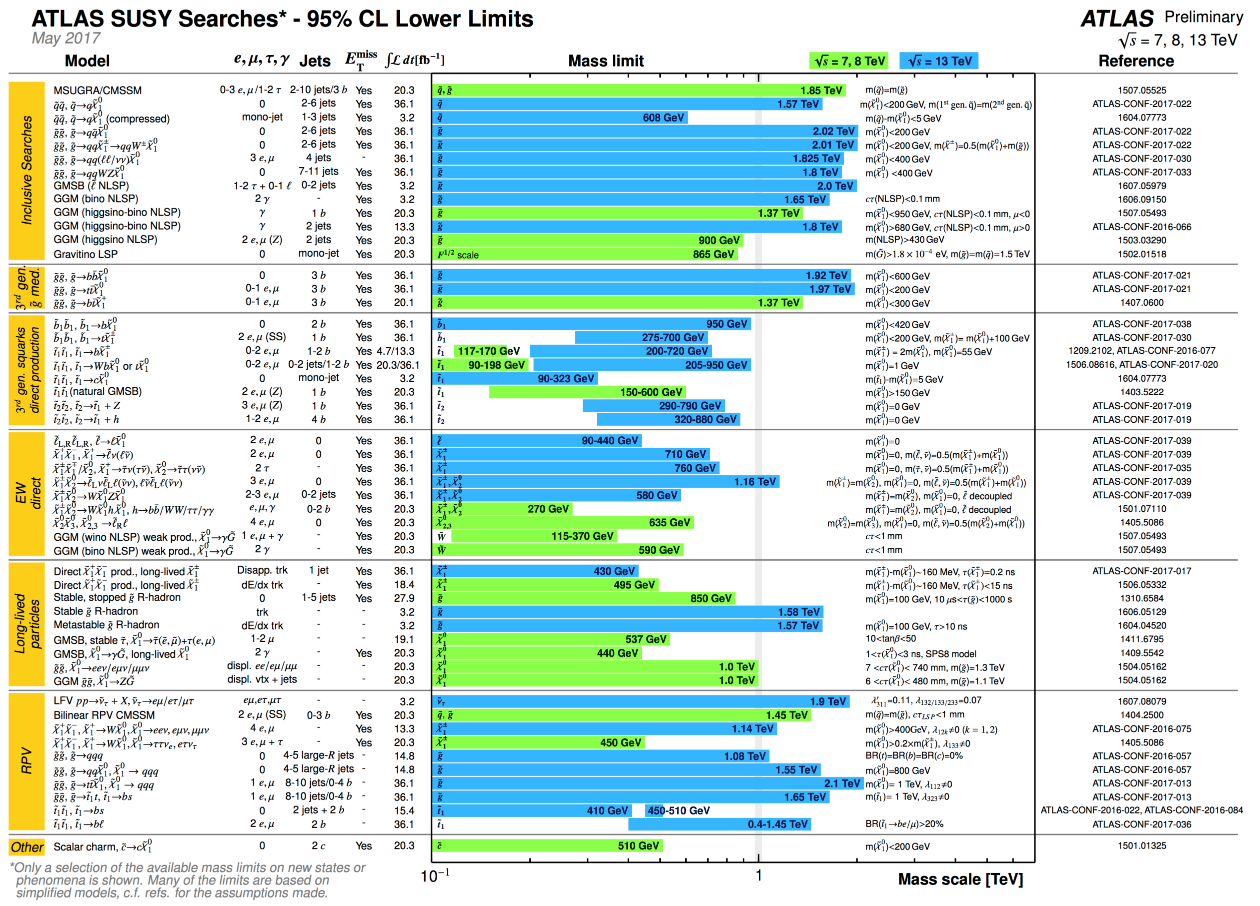
Excellence of LHC/experiments: Enabled rich physics program @13 TeV in Run 2

Plethora of SM measurements and searches for new physics:

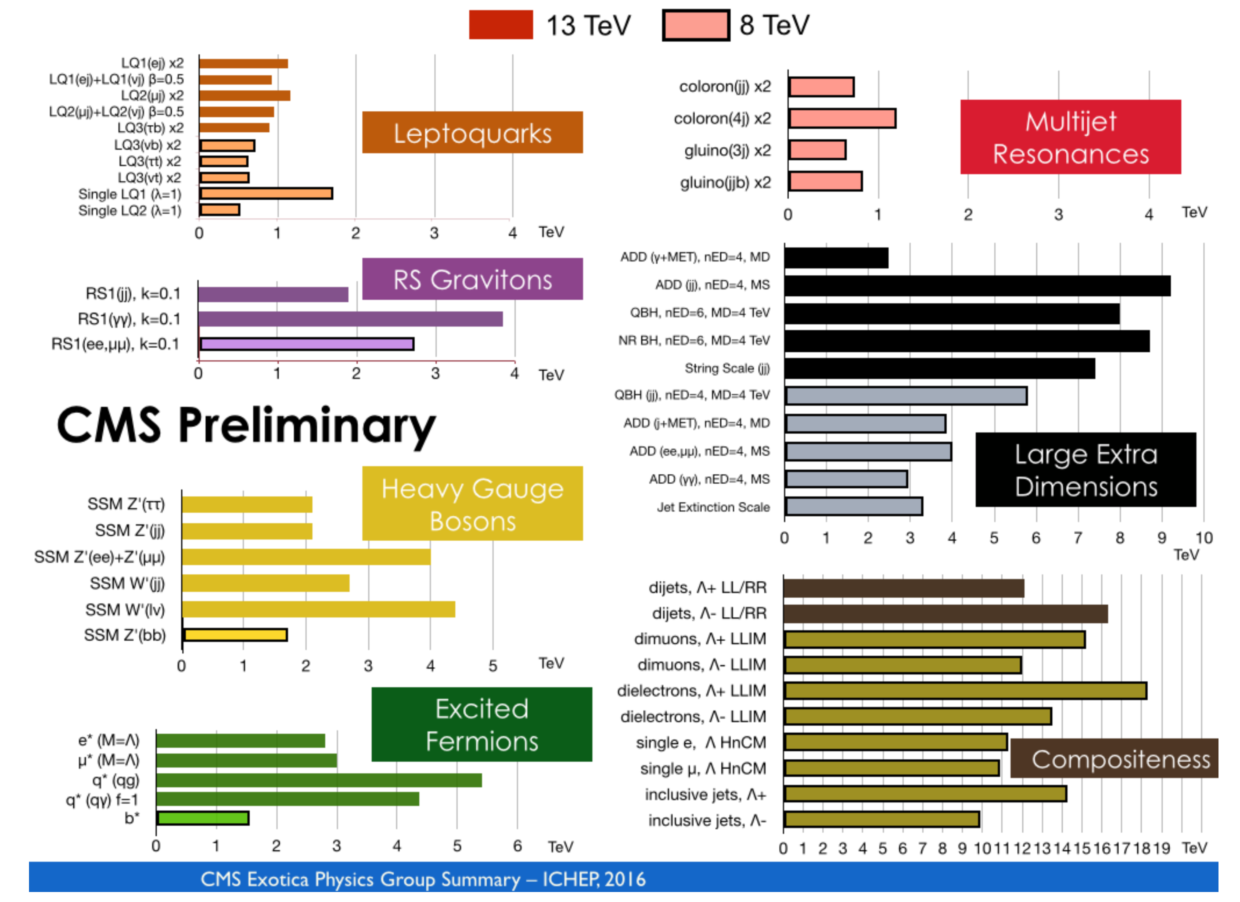
SM measurements



SUSY searches



Exotic searches



➡ No deviation from SM

➡ No indications for new physics phenomena

Run 2: Exploit the Higgs boson as a tool to probe for new physics

Preface

Higgs boson measurements:

1. Characterisation of the SM Higgs boson
2. Search for BSM phenomena in Higgs physics

(as model-independent as possible)

- signal strengths
- pseudo-observables
- Simp.Temp. XS
- Fid.XS and diff. distributions

Interpretation of results:

1. Internally within experiments
2. externally by TH colleagues

(requires close EXP-TH interaction and recommendations)

- coupling strength modifiers
- pseudo-observables
- EFT approaches
- simplified/explicit BSM models

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CMS analyses

Early days... and effective Lagrangians...

Testing effective Lagrangian of HVV interactions

- **Spin-1** interactions with a pair of gauge bosons (Z, W)

$$L(X_{J=1}VV) \sim b_1 \partial_\mu X_\nu Z^\mu Z^\nu + b_2 \epsilon_{\alpha\mu\nu\beta} X^\alpha Z^\mu \partial^\beta Z^\nu + b_1^{WW} \partial_\mu X_\nu \left(W^{+\mu} W^{-\nu} + W^{-\mu} W^{+\nu}\right) + b_2^{WW} \epsilon_{\alpha\mu\nu\beta} X^\alpha \left(W^{-\mu} \partial^\beta W^{+\nu} + W^{+\mu} \partial^\beta W^{-\nu}\right)$$

  - Test for an **arbitrary mixture of vector and pseudo-vector** (qq and production independent).

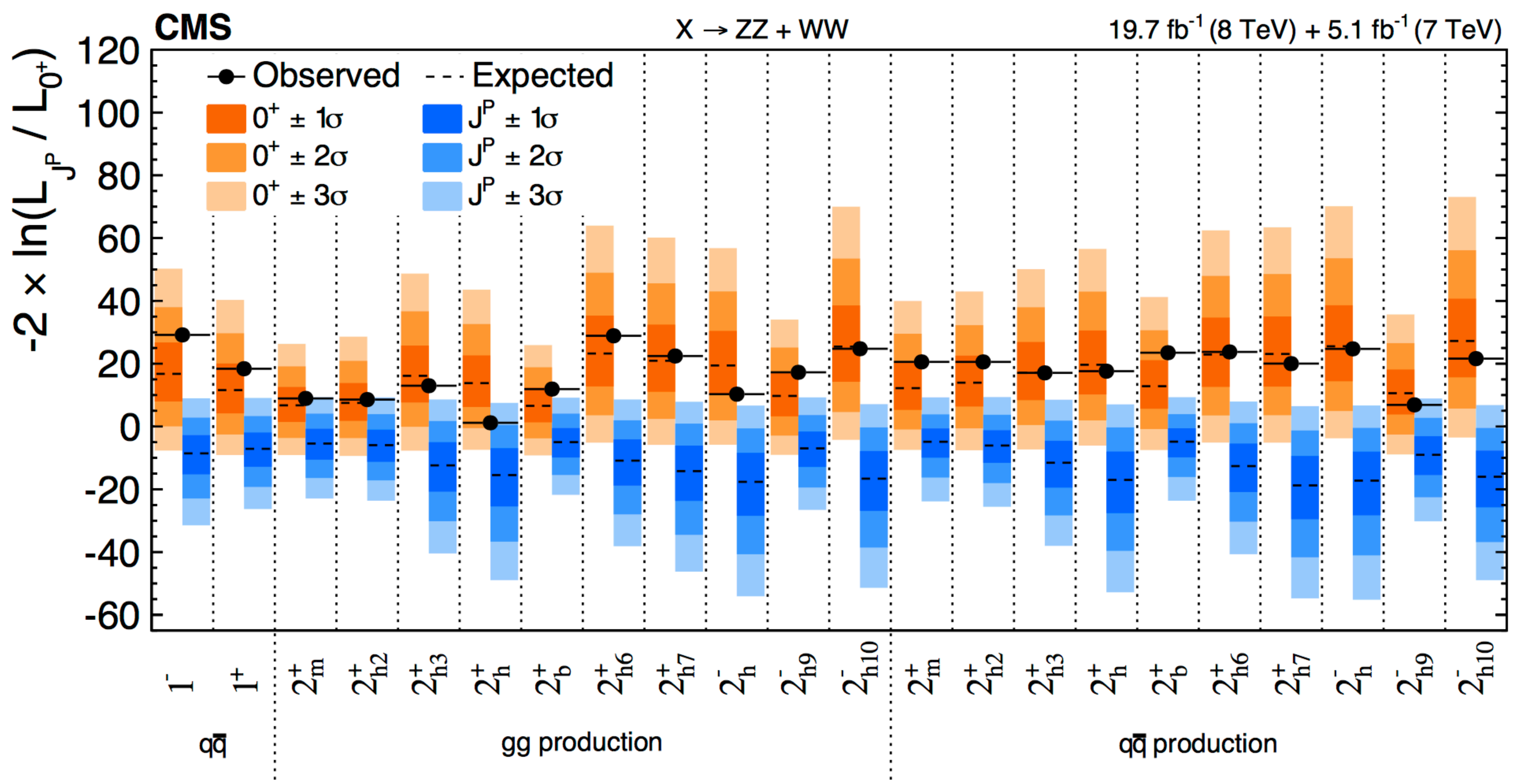
- **Spin-2** interactions with a pair of gauge bosons (Z, W, γ)

$$L(X_{J=2}ZZ) \sim \Lambda^{-1} \Big(-c_1 X_{\mu\nu} Z^{\mu\alpha} Z^\nu_{\ \alpha} + \frac{c_2}{\Lambda^2} (\partial_\alpha \partial_\beta X_{\mu\nu}) Z^{\mu\alpha} Z^{\nu\beta} + \frac{c_3}{\Lambda^2} X_{\beta\nu} \left[\partial^\alpha, \left[\partial^\beta, Z^{\mu\nu}\right]\right] Z_{\mu\alpha} + \frac{c_4}{2\Lambda^2} X_{\mu\nu} \left[\partial^\mu, \left[\partial^\nu, Z^{\alpha\beta}\right]\right] Z_{\alpha\beta} + c_5 m_Z^2 X_{\mu\nu} Z^\mu Z^\nu + \frac{2 c_6 m_Z^2}{\Lambda^2} \partial_\alpha X_{\mu\nu} [\partial^\mu, Z^\nu] Z^\alpha - \frac{c_7 m_Z^2}{2\Lambda^2} X_{\mu\nu} [\partial^\mu, [\partial^\nu, Z_\alpha]] Z^\alpha + \frac{c_8}{2\Lambda^2} X_{\mu\nu} \left[\partial^\mu, \left[\partial^\nu, Z^{\alpha\beta}\right]\right] \tilde{Z}_{\alpha\beta} - \frac{c_9 m_Z^2}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \partial^\sigma X^{\mu\alpha} Z_\nu \partial_\alpha Z^\rho + \frac{c_{10} m_Z^2}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} \partial^\rho \partial^\beta X^{\mu\alpha} [\partial^\sigma, [\partial_\alpha, Z^\nu]] Z_\beta \Big)$$

  - Test for **pure state terms only** (qq production, gg production and production independent).

Testing effective Lagrangian of HVV interactions

- **Excluded spin-1 and spin-2 interactions** with a pair of gauge bosons (Z, W, γ)



Excluded all pure state spin-two hypotheses at 96.9% CL or better!

Excluded an arbitrary mixture of vector and pseudo-vector (99.99% CL)!

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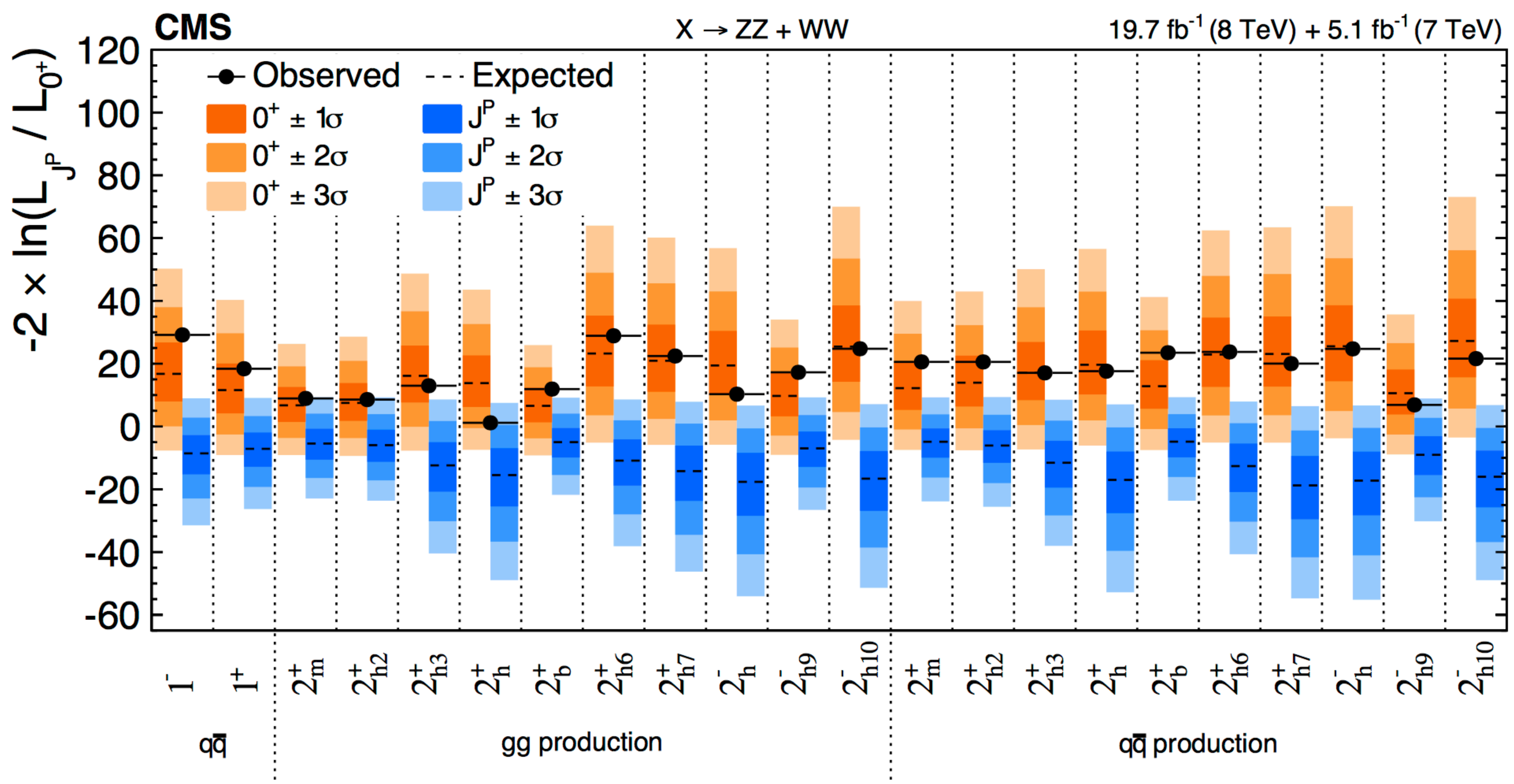

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- **Spin-0** interactions with a pair of gauge bosons (Z, W, γ)

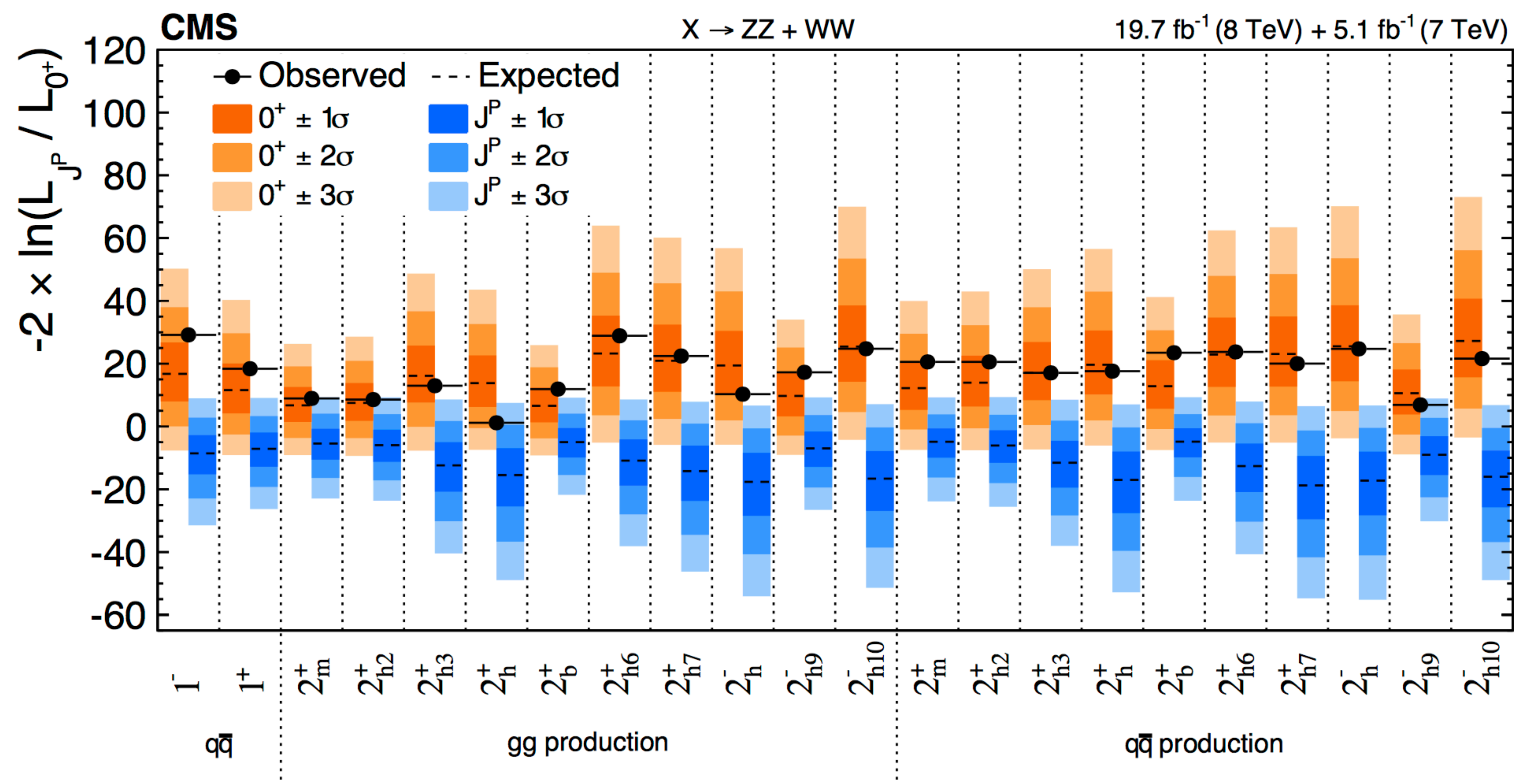
$$L(\mathrm{HVV}) \sim a_1 \frac{m_Z^2}{2} \mathrm{HZ}^\mu \mathrm{Z}_\mu + \frac{1}{(\Lambda_1)^2} m_Z^2 \mathrm{HZ}_\mu \Box \mathrm{Z}^\mu - \frac{1}{2} a_2 \mathrm{HZ}^{\mu\nu} \mathrm{Z}_{\mu\nu} - \frac{1}{2} a_3 \mathrm{HZ}^{\mu\nu} \tilde{\mathrm{Z}}_{\mu\nu}$$
$$+ a_1^{\mathrm{WW}} \frac{m_W^2}{2}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

Main focus at the end of Run 1 and beyond

- Consider terms that correspond the lowest order operators in EFT Lagrangian:

Testing effective Lagrangian of HVV interactions

- **Excluded spin-1 and Spin-2 interactions** with a pair of gauge bosons (Z, W, γ)



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

- Main focus at the end of Run 1 and beyond

  - Consider terms that correspond the lowest order operators in EFT Lagrangian:

HVV anomalous couplings (Run 2)

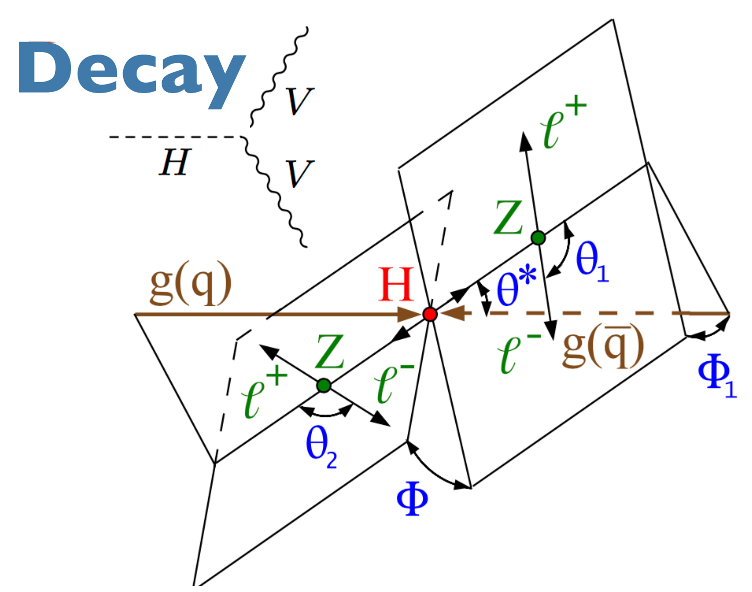
Exploit full decay-, and production-related information:

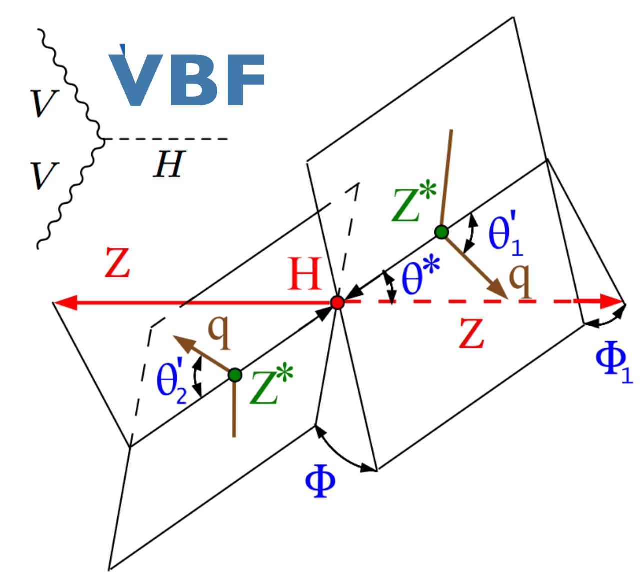
- Parametrisation of decay amplitude:

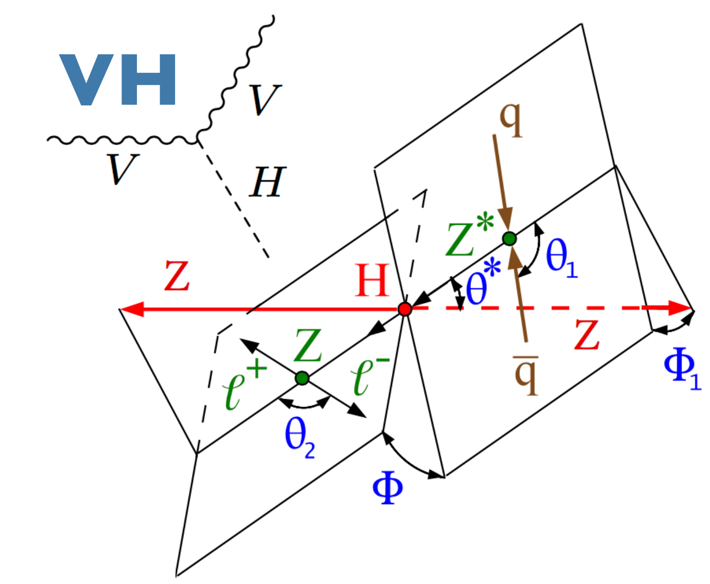
SM — leading momentum expansion — higher order cp-even — cp-odd

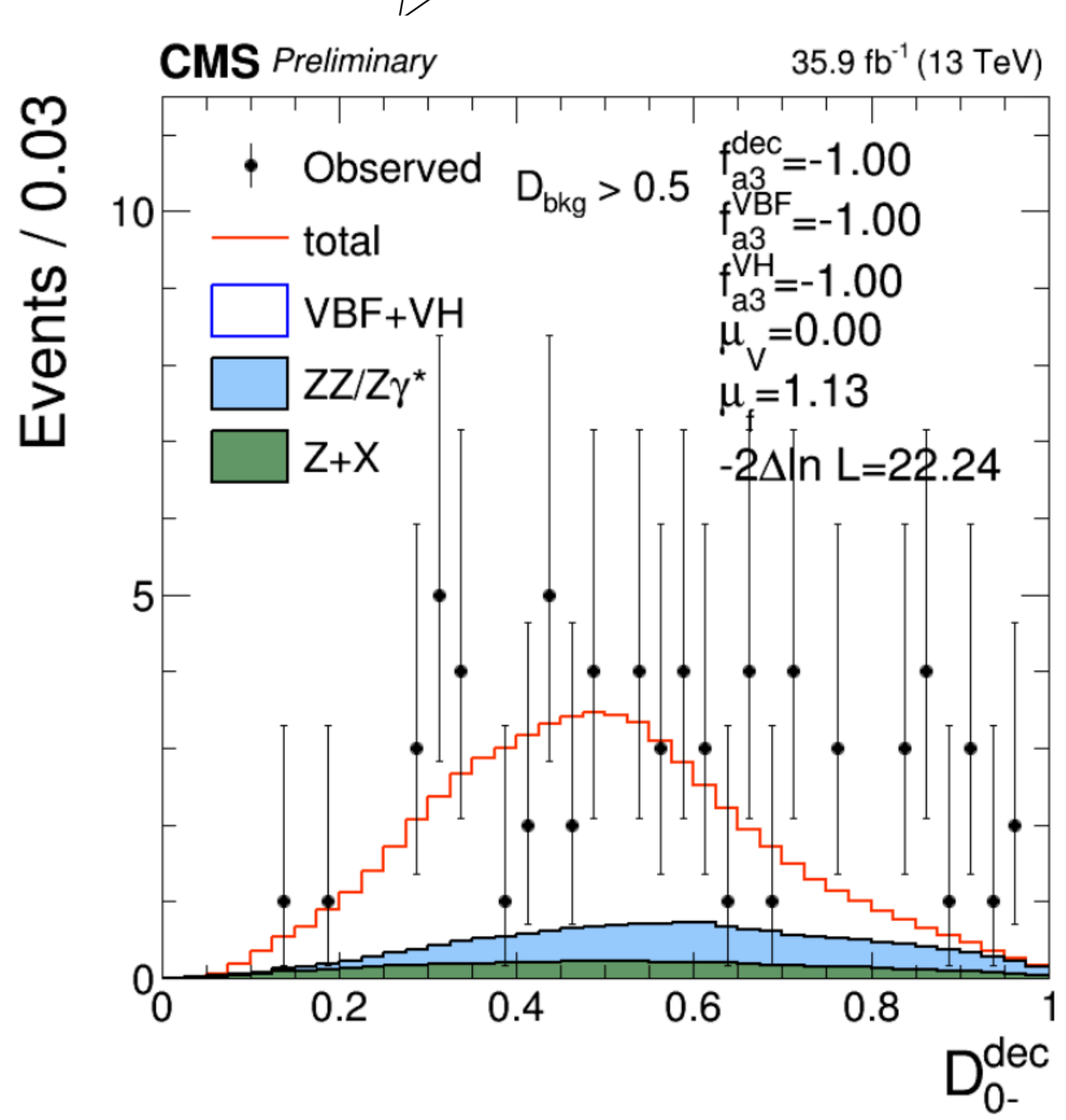
$$A = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

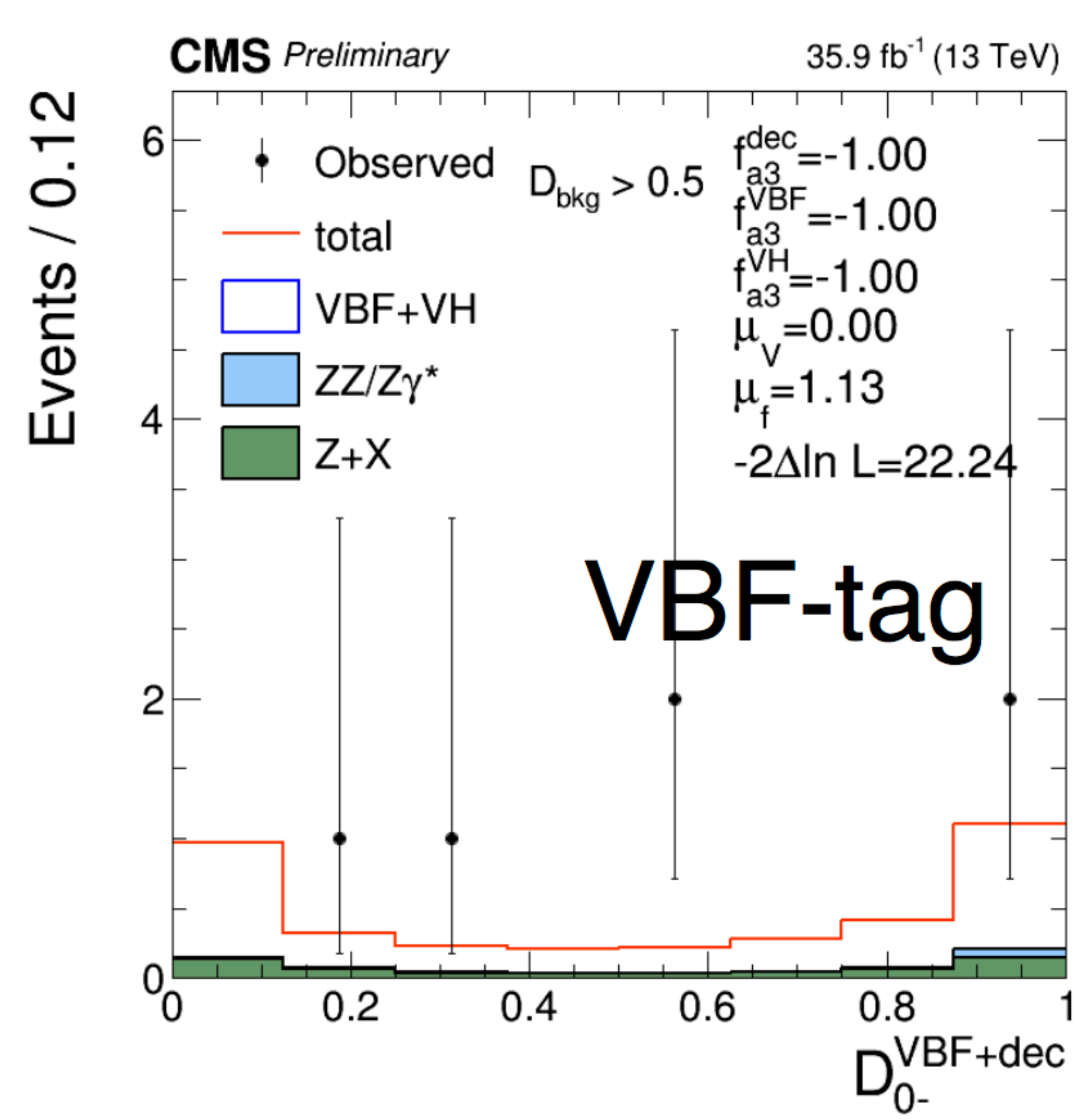
- Untagged, VBF, VH categories: 3 ME-based discriminants encoding both decay and production information

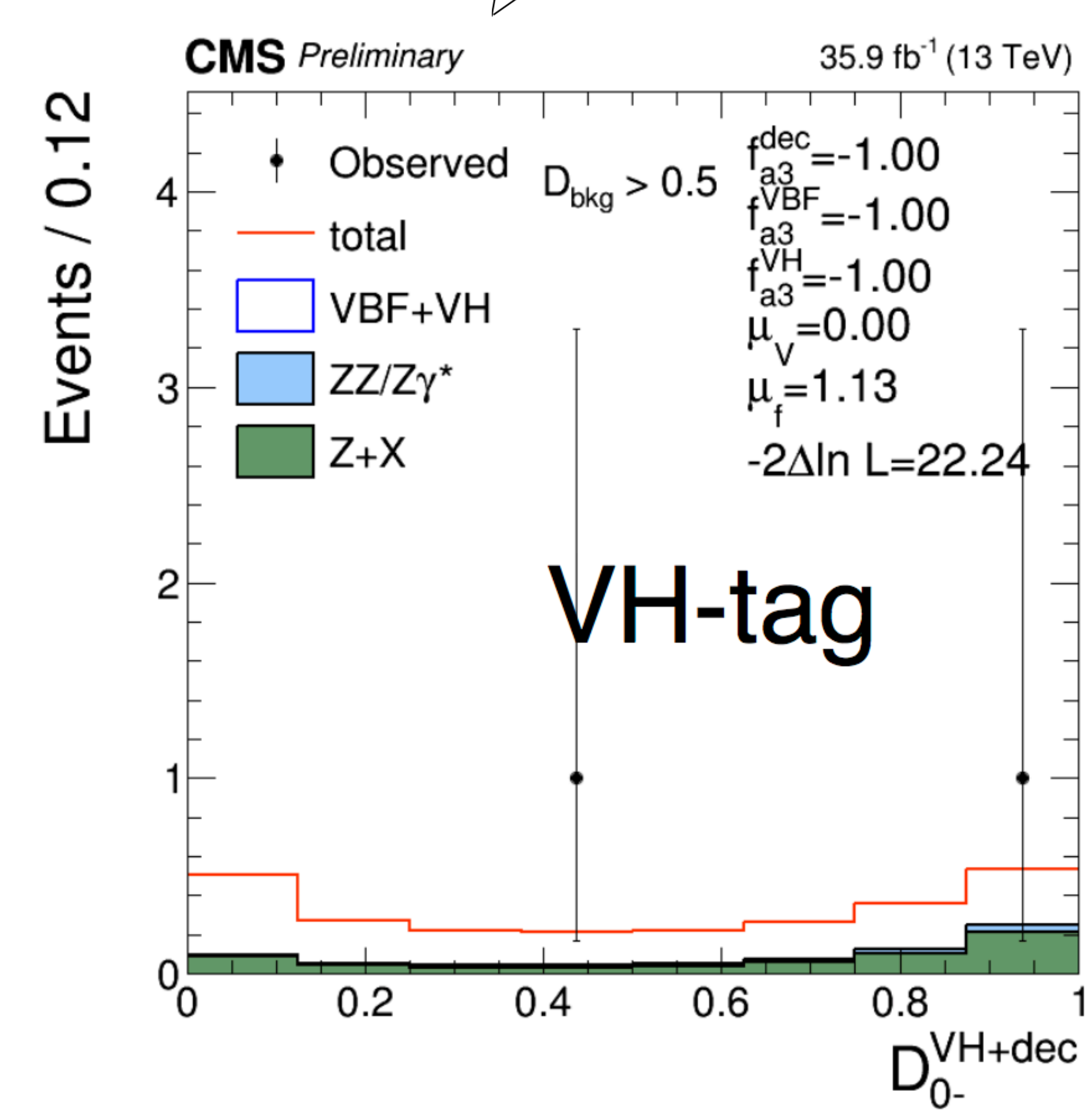








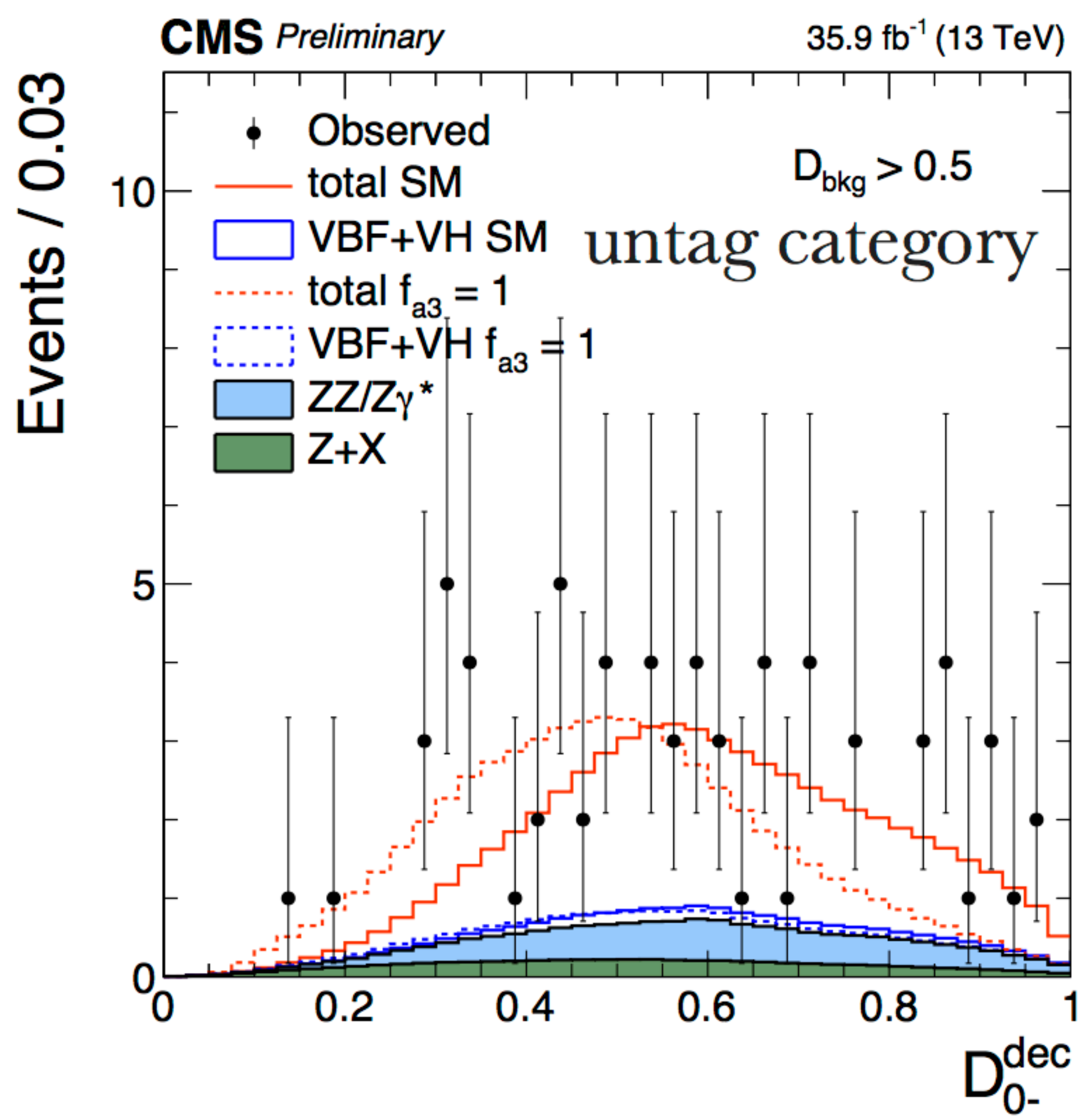


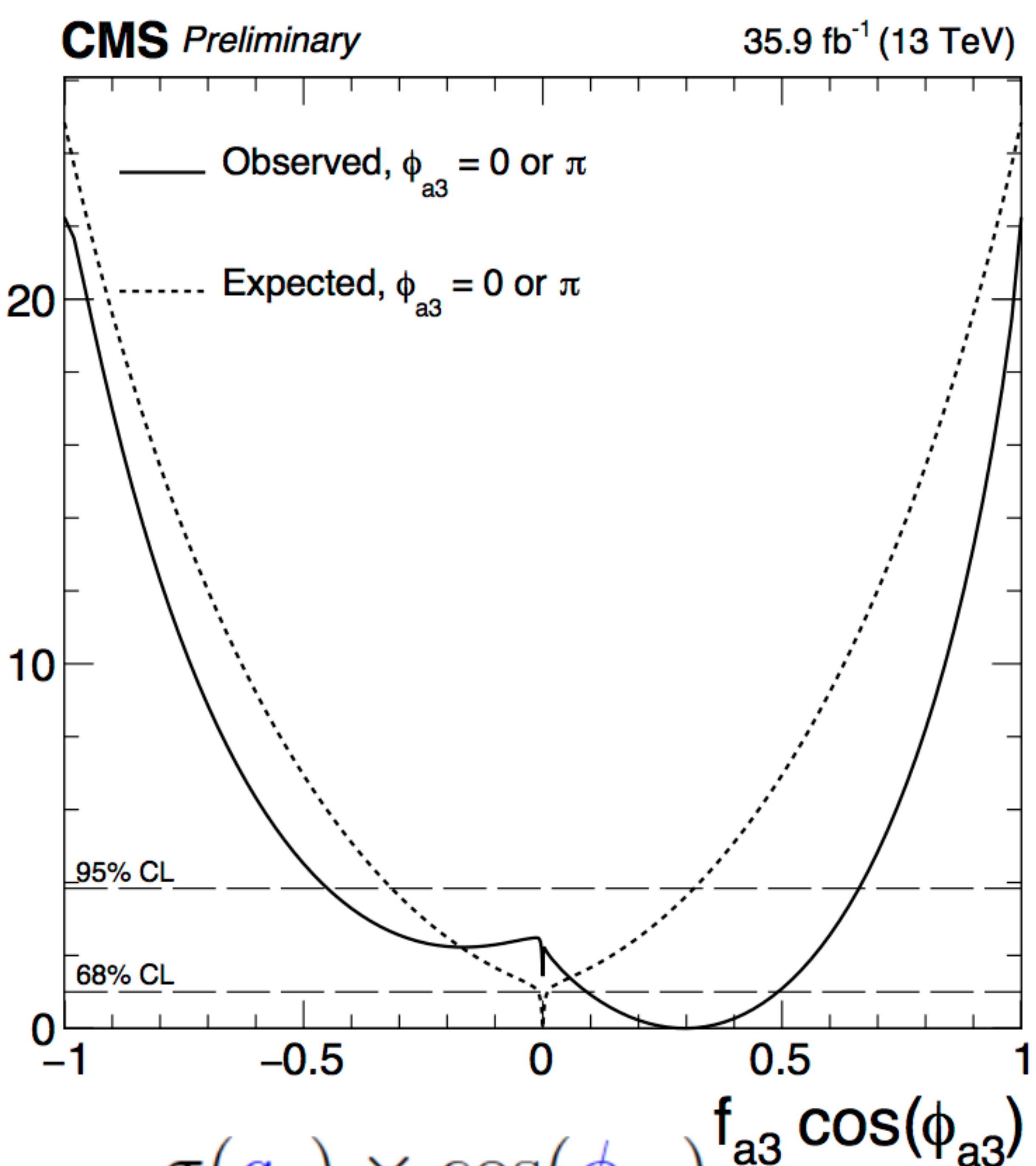


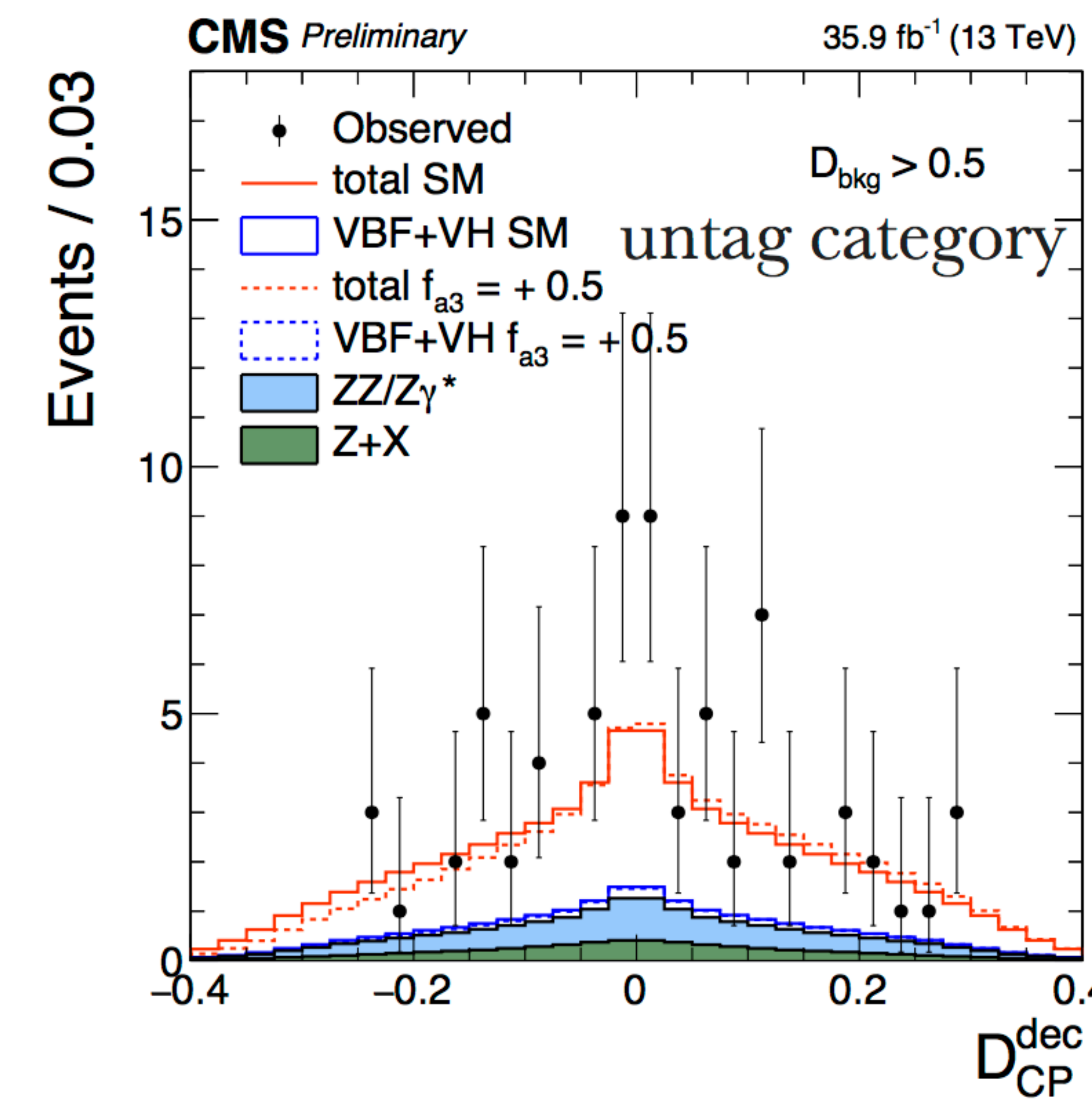
HVV anomalous couplings (Run 2)

CMS-PAS-HIG-17-011

In Run 2 : Exploit full decay-, and production-related information:





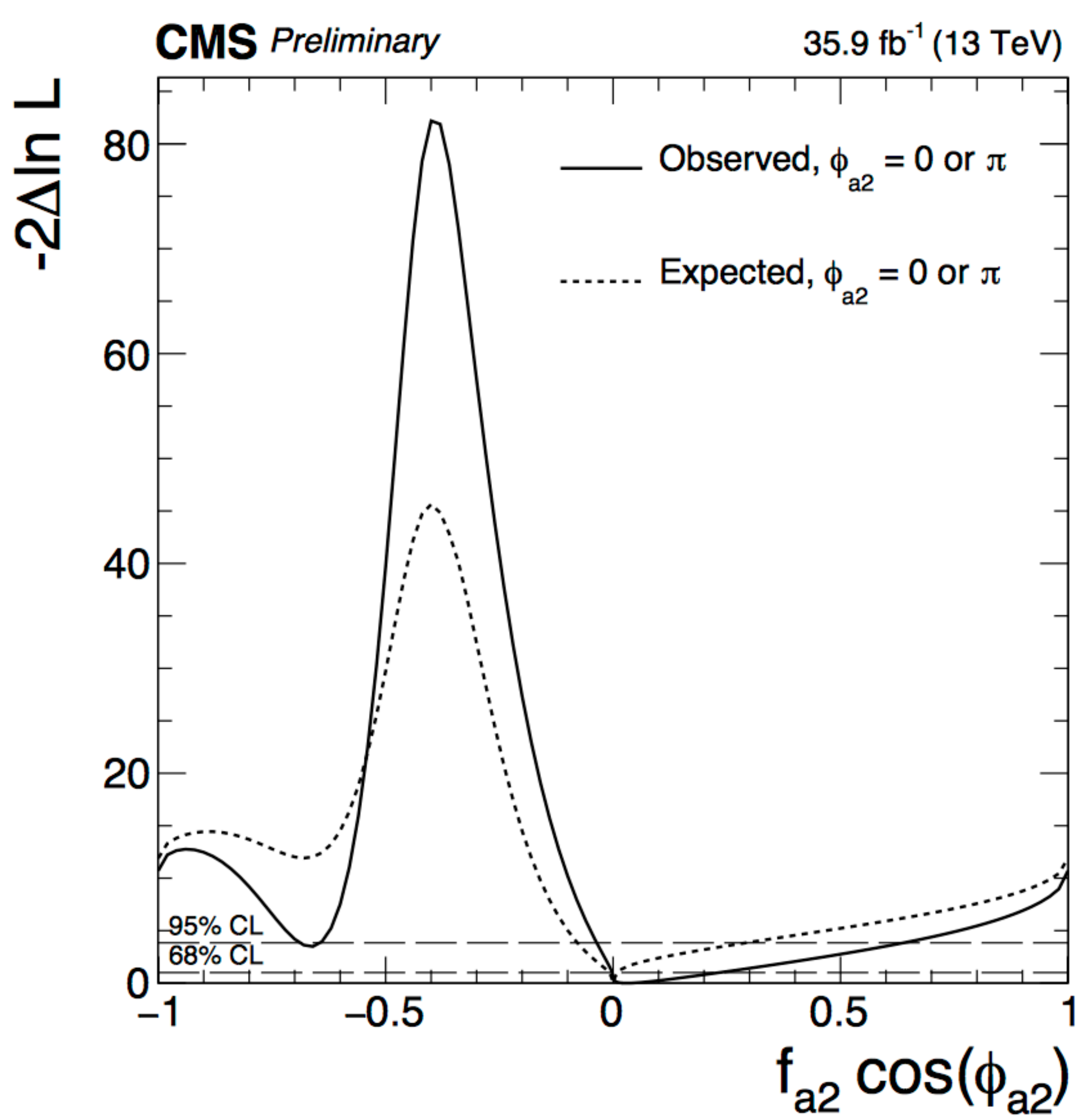


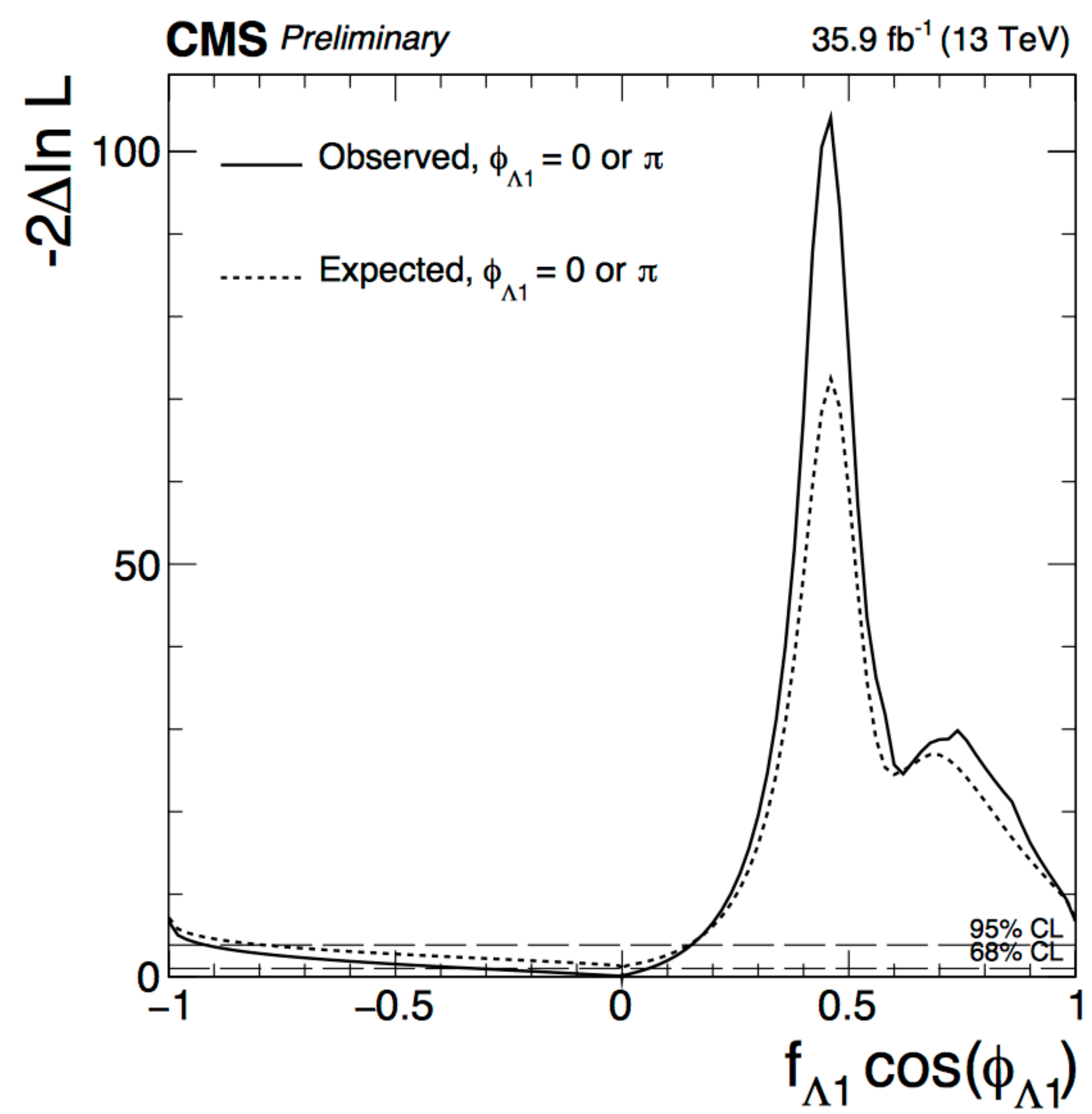
$$f_{a3} \Rightarrow \frac{\sigma(a_3) \times \cos(\phi_{a3})}{\sigma(a_1) + \sigma(a_3)}$$

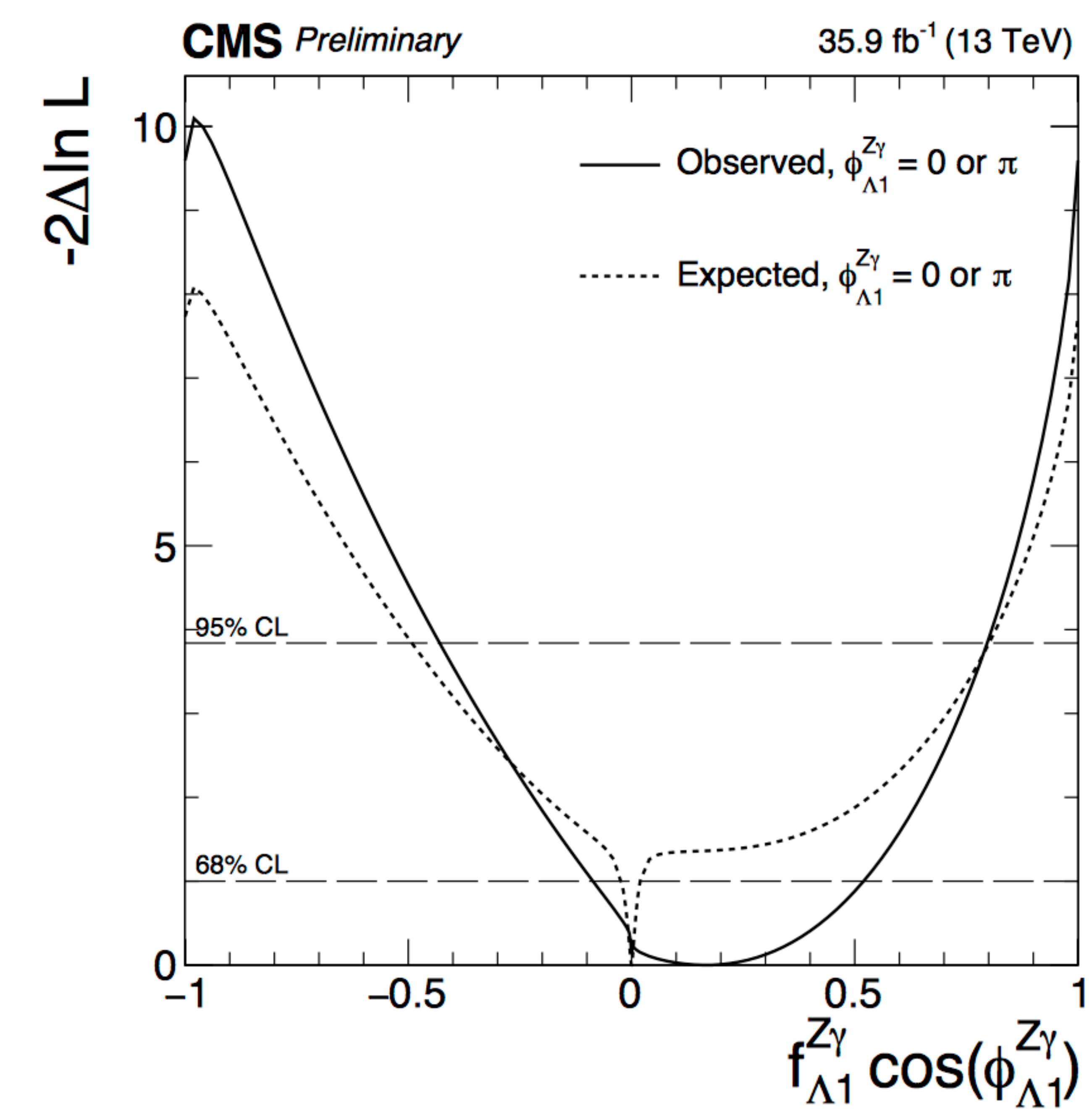
Parameter	Observed	Expected	Run1 exp (HZZ+HWW):
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$	$0^{+0.23}_{-0.23}$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$	$0^{+0.08}_{-0.03}$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$	$0^{+0.15}_{-0.08}$
$f_{\Lambda 1}^{Z\gamma}\cos(\phi_{\Lambda 1}^{Z\gamma})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$	

HVV anomalous couplings (Run 2)

In Run 2 : Exploit full decay-, and production-related information:







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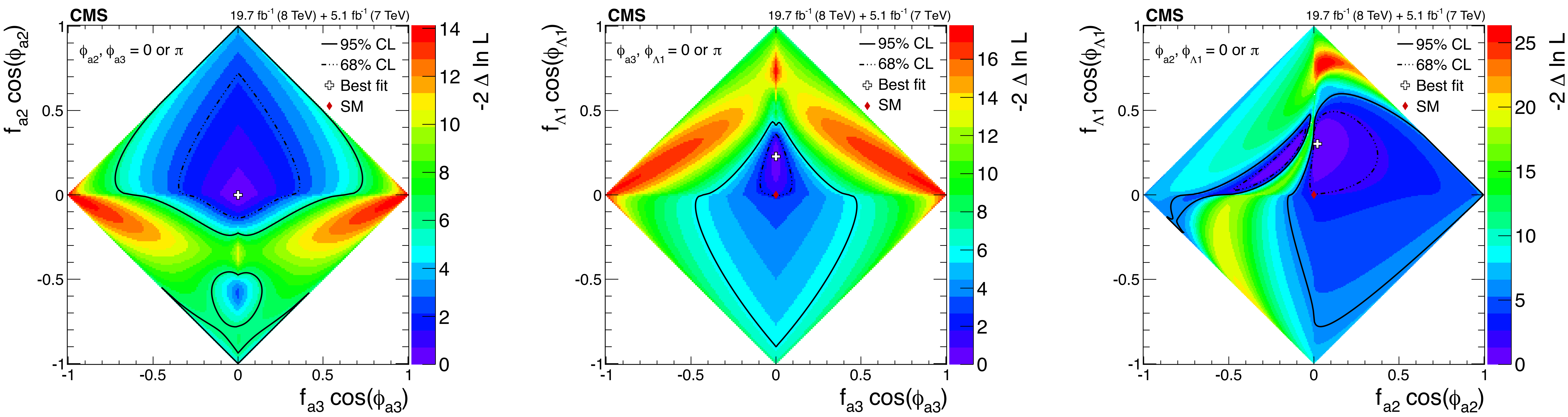
$f^{Z\gamma}_{\Lambda1}\cos(\phi^{Z\gamma}_{\Lambda1})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$	

CMS-HIG-14-018

Pairs of HVV anomalous couplings (Run I)

In Run I : also performed fits for pairs of anomalous couplings:



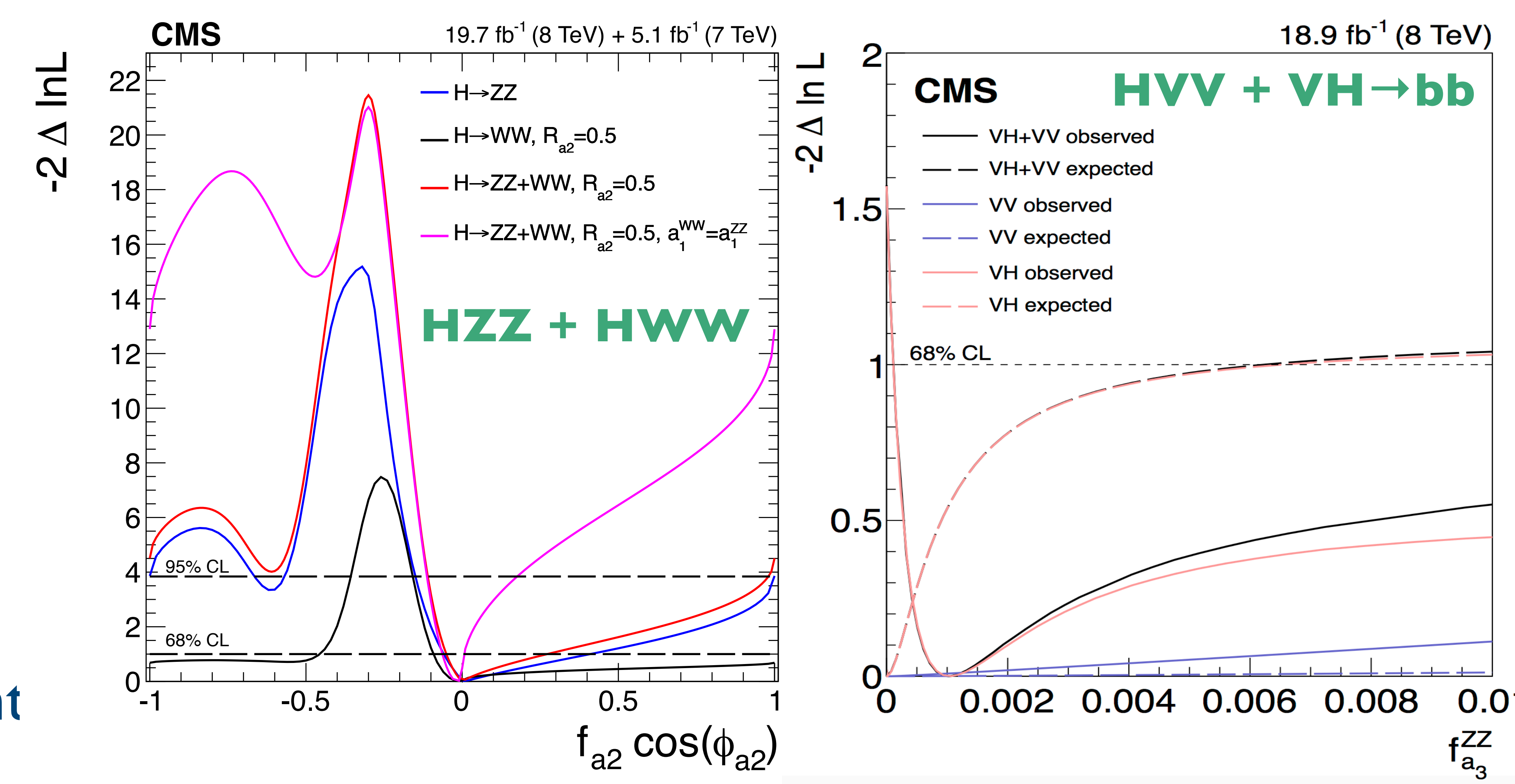
Simultaneous fits in H→ZZ, H→WW, and VH→bb:

- HZZ and HWW related by symmetries assumption
  - considered custodial symmetry ($a_{iZZ} = a_{iWW}$) or no relation ($a_{iZZ} \neq a_{iWW}$)

parameterised HWW and HZZ relation:

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

- Signal strengths μ_{VV} and μ_{VH} treated and (in)dependent



HVV anomalous couplings @ HL-LHC

CMS-PAS-FTR-16-002

Performance estimated using the H → 4ℓ analysis @12.9 fb⁻¹ (13 TeV).

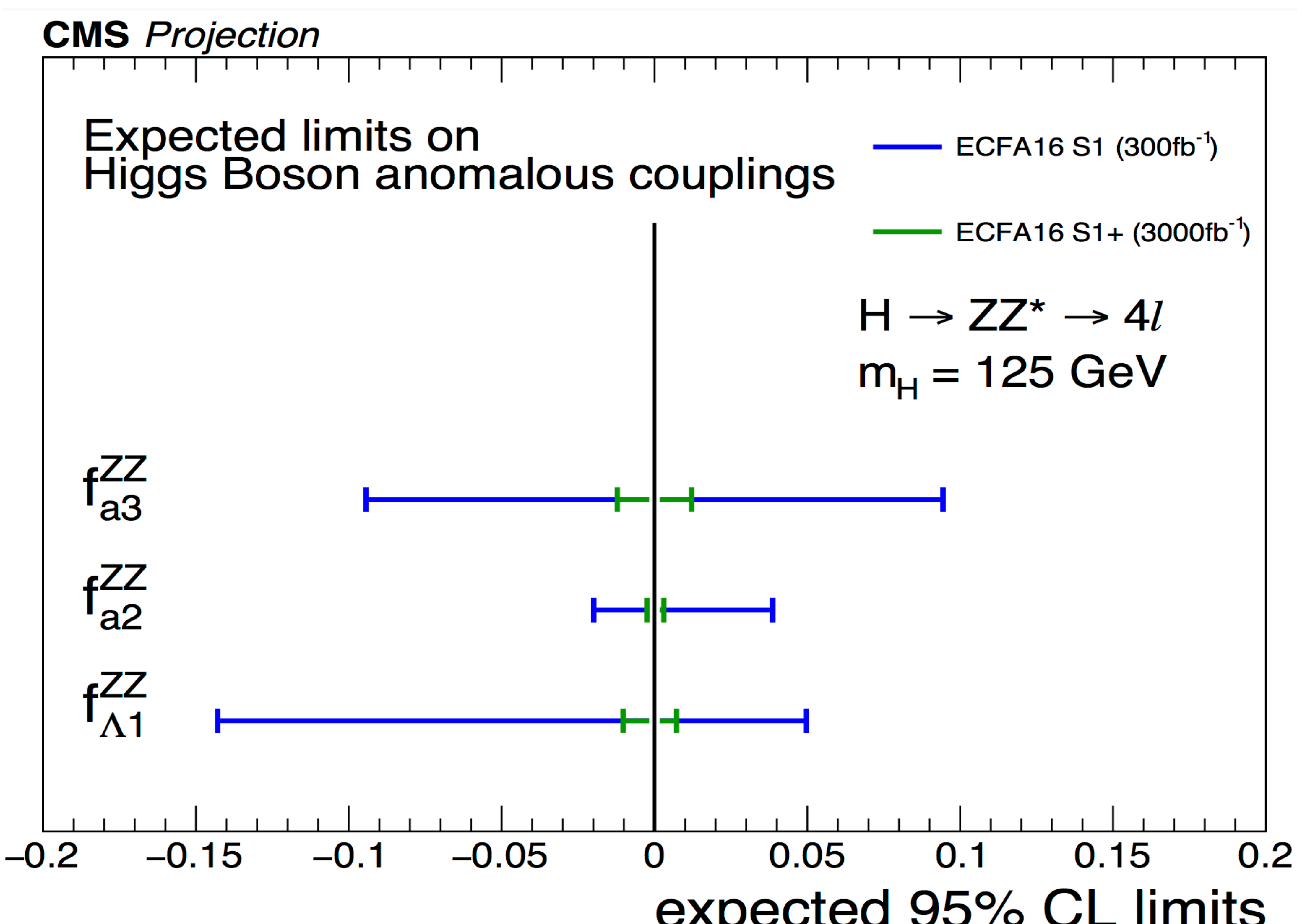
- Parameterisation of decay amplitude:

SM — leading momentum expansion — higher order cp-even — cp-odd

$$A = \frac{1}{v}\left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV}(q_1+q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

Effects of high pileup and detector performance @3ab⁻¹ estimated:

- Lepton misidentification rates, and efficiencies



Towards the small values of fractional presence sensitivity pre-dominantly comes from the interference effects between different decay amplitude terms

Projected 95% CIs:

Parameter	300 fb^{-1}	3000 fb^{-1}
$f_{a3} \times cos(\phi_{a3})$	[-0.094, 0.094]	[-0.012, 0.012]
$f_{a2} \times cos(\phi_{a2})$	[-0.020, 0.039]	[-0.0025, 0.0031]
$f_{\Lambda 1} \times cos(\phi_{\Lambda 1})$	[-0.14, 0.05]	[-0.010, 0.0072]

VV anomalous couplings

CMS-SMP-16-017

Measurements performed in numerous production channels @ 7/8/13 TeV.

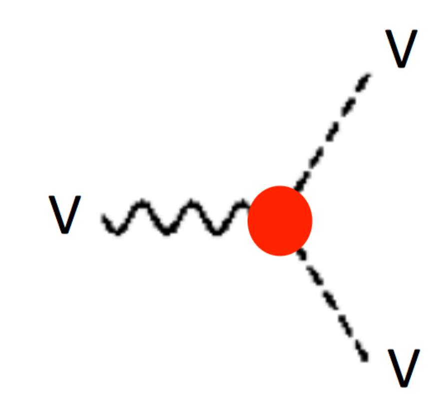
- Parameterisation of effective Lagrangian:

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{1}{\Lambda^{d_i-4}} c_i \mathcal{O}_i$$

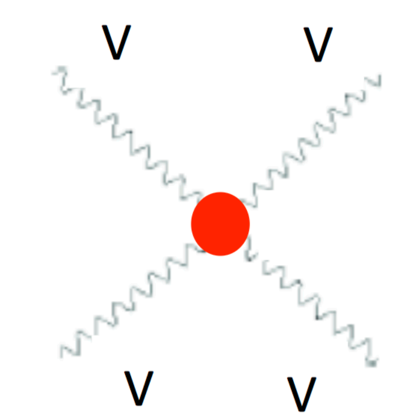
c_i - **Willson coefficient**
Λ - **new physics scale**

- Mostly probing strongly coupled BSM

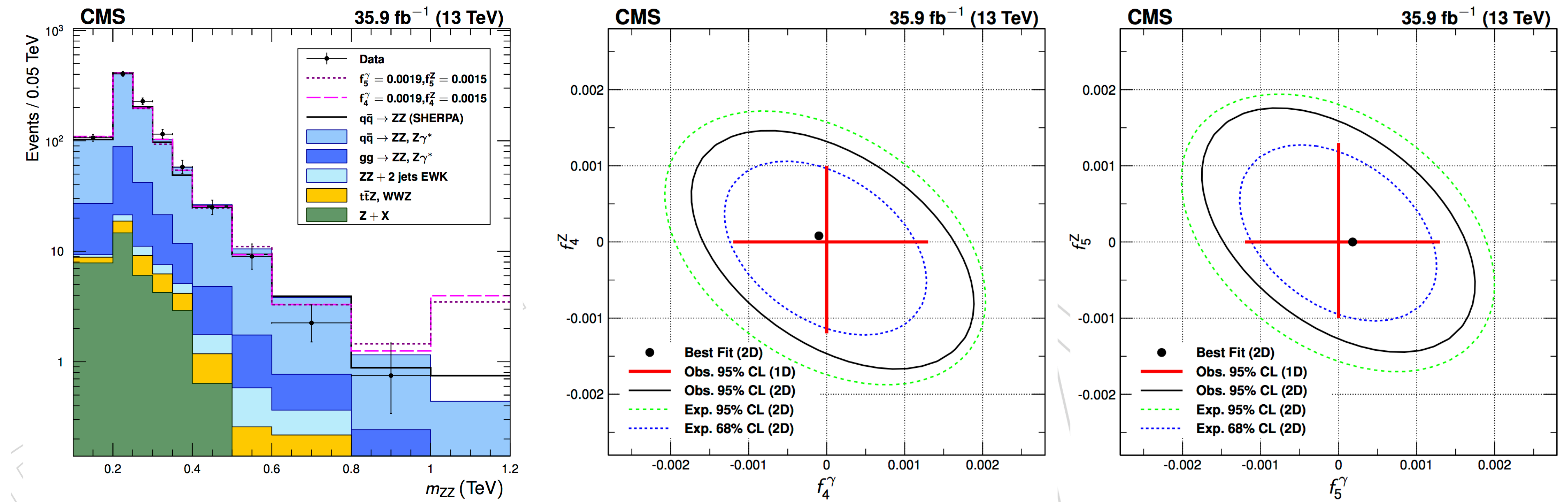
anomalous TGC



anomalous QGC



Limits on single or pairs of anomalous TGC couplings:



For more complete info on aTGC see talk by Darren and Kirstin:
https://indico.cern.ch/event/663240/contributions/2707994/attachments/1519832/2373744/EFTDurham_2.pdf

Towards extended Lagrangians and EFT interpretations…

On various aspects and challenges

Important EFT aspects/challenges:

- **Choice of a EFT EWK/Higgs basis**
  (e.g. Higgs/HISZ/SILH or Warsaw basis)
- **Choice of a (manageable) subset of HIG/EWK operators**
  (need to impose certain assumptions to reduce number of operators)

➡ **Prefer consensus and recommendations from TH community**

- **Handling of EFT validity range**
  (as set by kinematics of measurement, e.g. in hadron collisions)
- **Important advantage:** Allows global fits with results of diff. experiments

Some EXP aspects/challenges (HIG+EWK):

- **For internal EFT fits:**
  Not always possible to fit all degrees of freedom (limited resources):
  → Need to determine/build most sensitive observables (with TH).
  Implementation of the existing EWK precision limits.
  Further automation of MC tools/procedures (already well advanced).

➡ **Need interaction between EXPs and TH community**

- **Providing results for external EFT fits:**
  For gaussian likelihoods: results fully defined with central values + 1σ errors + correlation matrix
  → For non-gaussian effects: Need to agree how to provide results ("simplified" likelihood functions).

Next steps...

Understanding of the true nature of the Higgs boson is one of the central subjects in the particles physics today

- Both ATLAS and CMS have already performed plethora of important measurements
- Future measurements @ 13/14 TeV and later @ HL-LHC could provides us with some hints, where Higgs boson might be **a portal to the new physics** phenomena

EFT approach is one of the important ways to interpret the measurements

- **TH and EXP need to work together** to get ready to exploit the maximum from the available data (observables, presentation of results, MC tools, etc.)
- Need to converge towards common recommendations from TH community (basis, operators, validity, etc.)
- Needs to harmonise approaches between experiments (binning, observables, uncertainties, correlations)

Common effort within inter EXP/TH groups is the key

- Need to have synergy with all similar efforts/meetings (HXSWG, Les Houches, HiggsTools, etc.)