Studying the CP nature of the Top-Yukawa coupling

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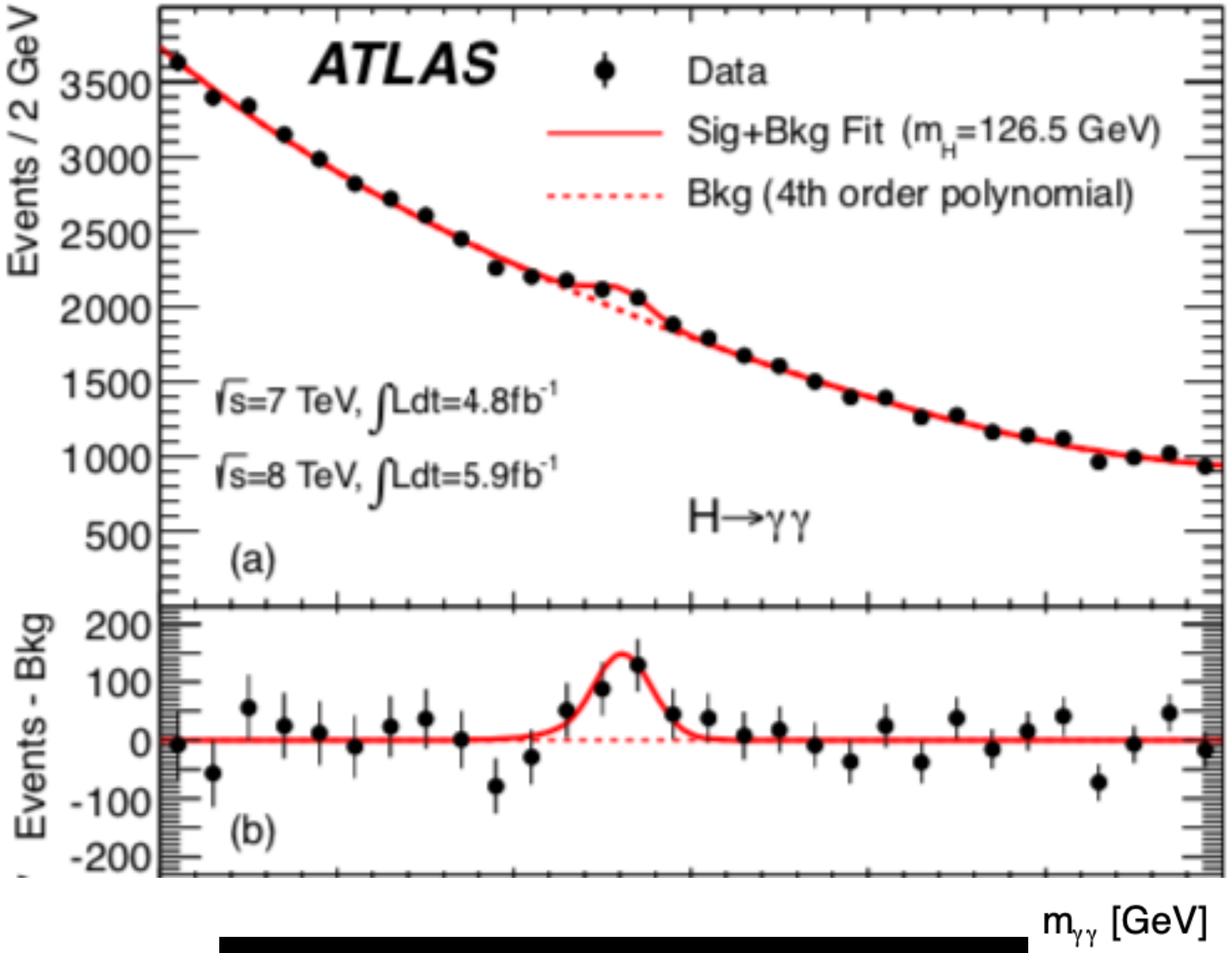
MISP 2020

INTRODUCTION

- Higgs boson discovered in 2012



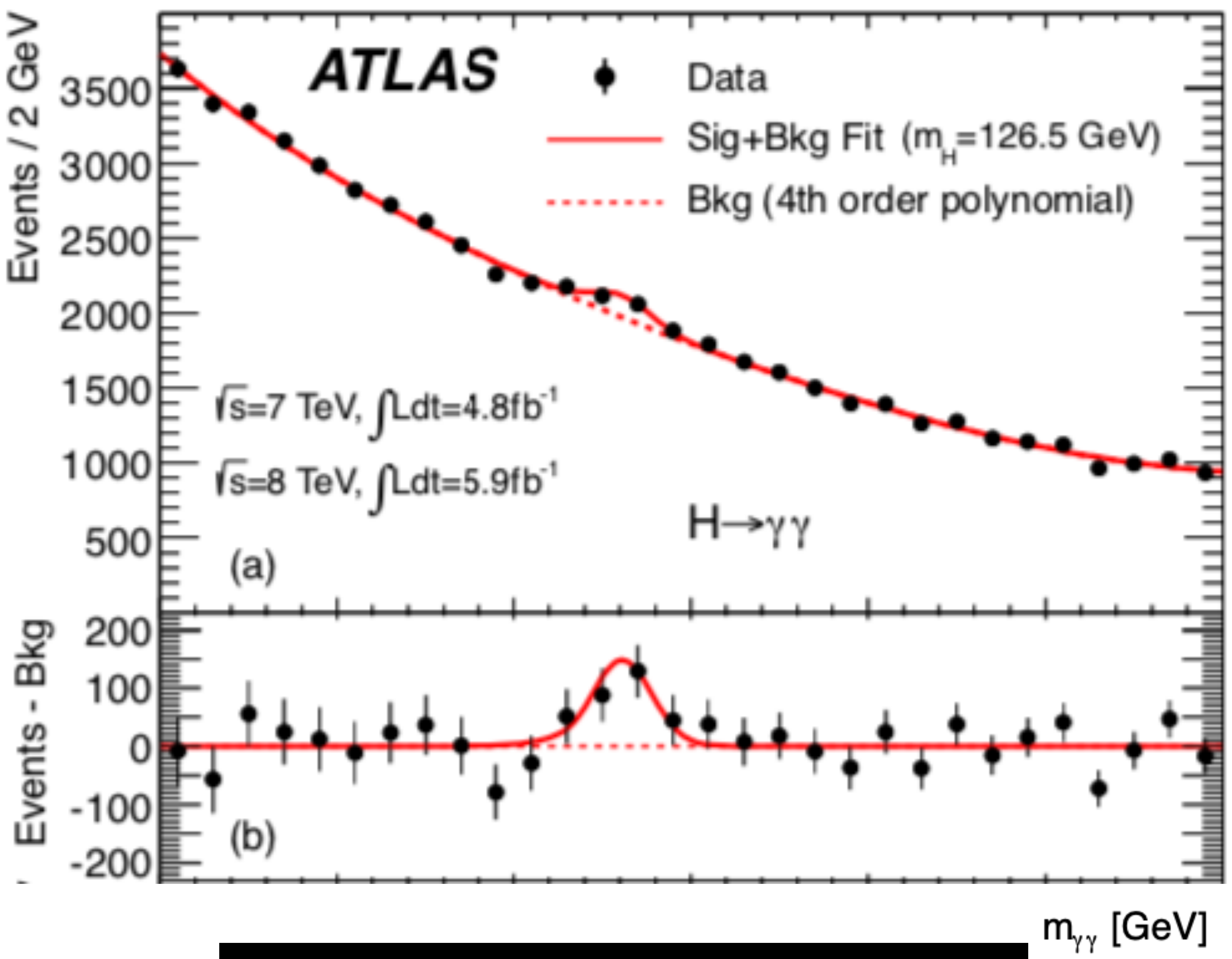
https://arxiv.org/abs/1207.7214

INTRODUCTION

- Higgs boson discovered in 2012
- CP nature of the Higgs boson not yet well measured
- $\mathscr{L}_{Higgs} = |D_\mu \Phi|^2 - \mu^2 |\Phi|^2 - \lambda^4 |\Phi|^4$

Different options available

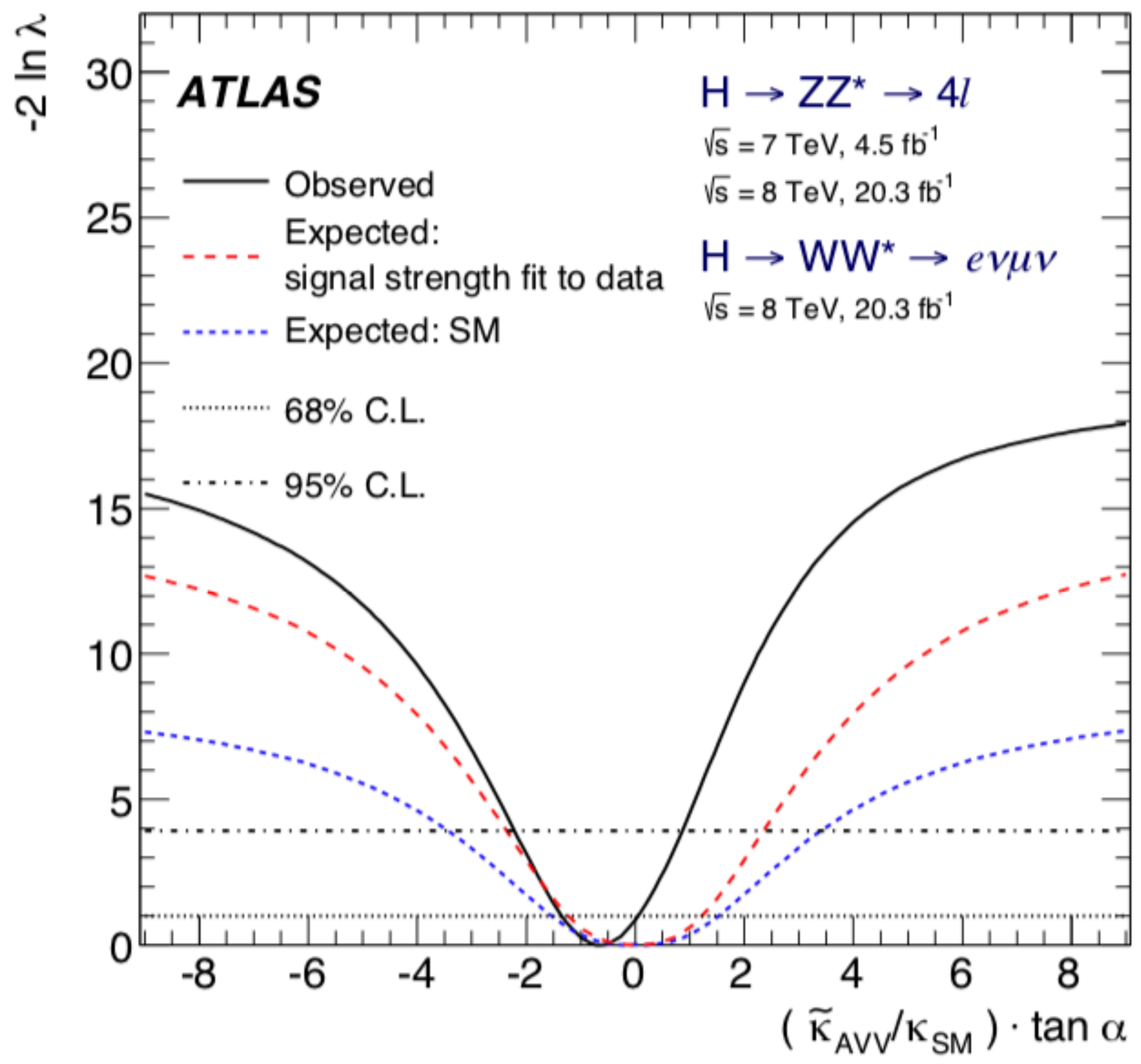
- CP even (SM) $CP|\Phi> = |\Phi>$
- CP odd $CP|\Phi> = -|\Phi>$
- CP mixed $CP|\Phi> \neq \pm|\Phi>$



https://arxiv.org/abs/1207.7214

THE AIM: SEARCH FOR CP VIOLATION

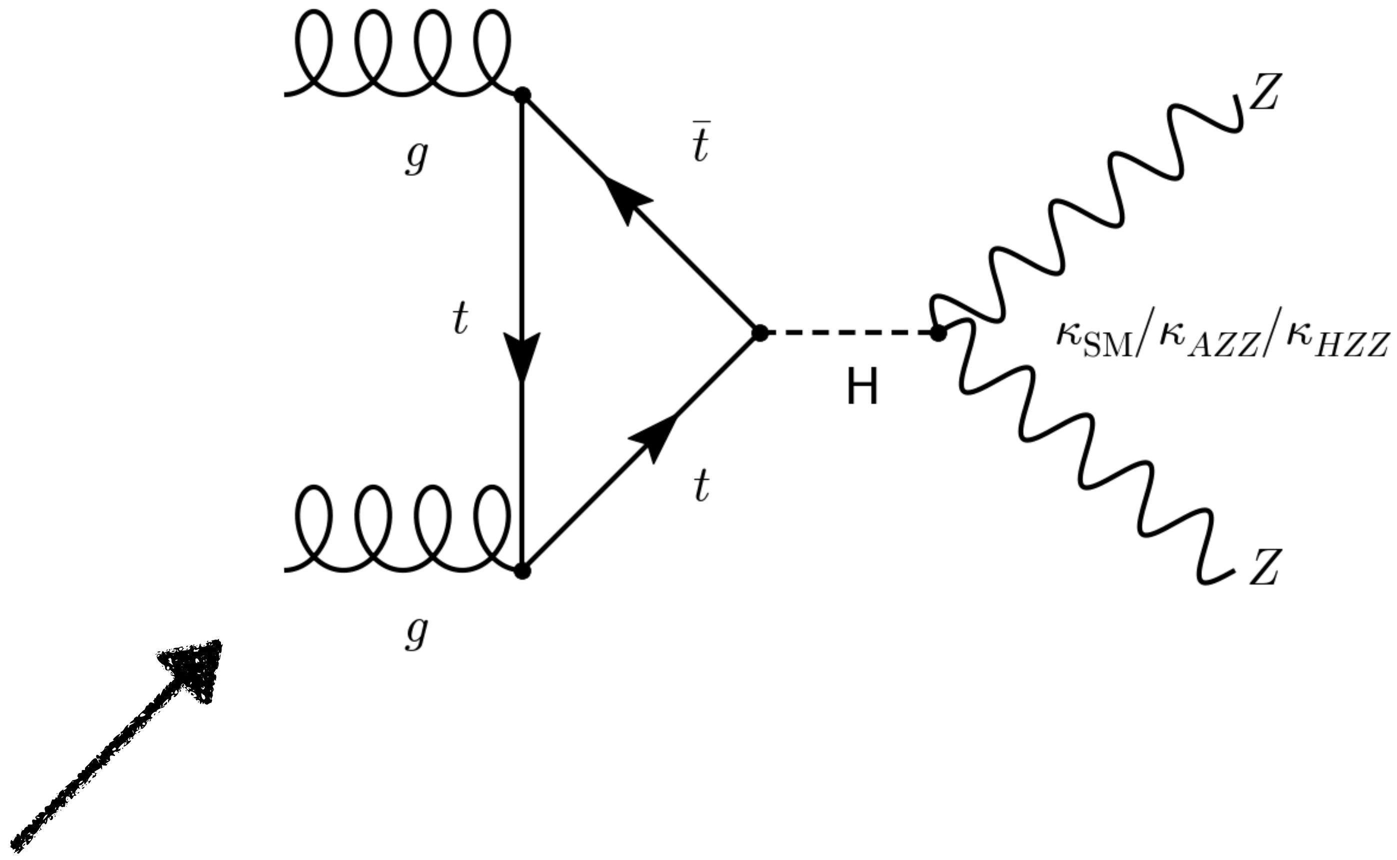
- Probe the CP nature of the Higgs boson in a model-independent way
- A non CP even Higgs boson hints at BSM physics
- In Run1 (0 jet channel) (combination of $WW^*, ZZ^*, \gamma\gamma$)
  - Excluded the pure CP odd scenario
  - Up to 30% “CP odd” possible in mixed scenario (95%CL)



https://arxiv.org/pdf/1506.05669.pdf

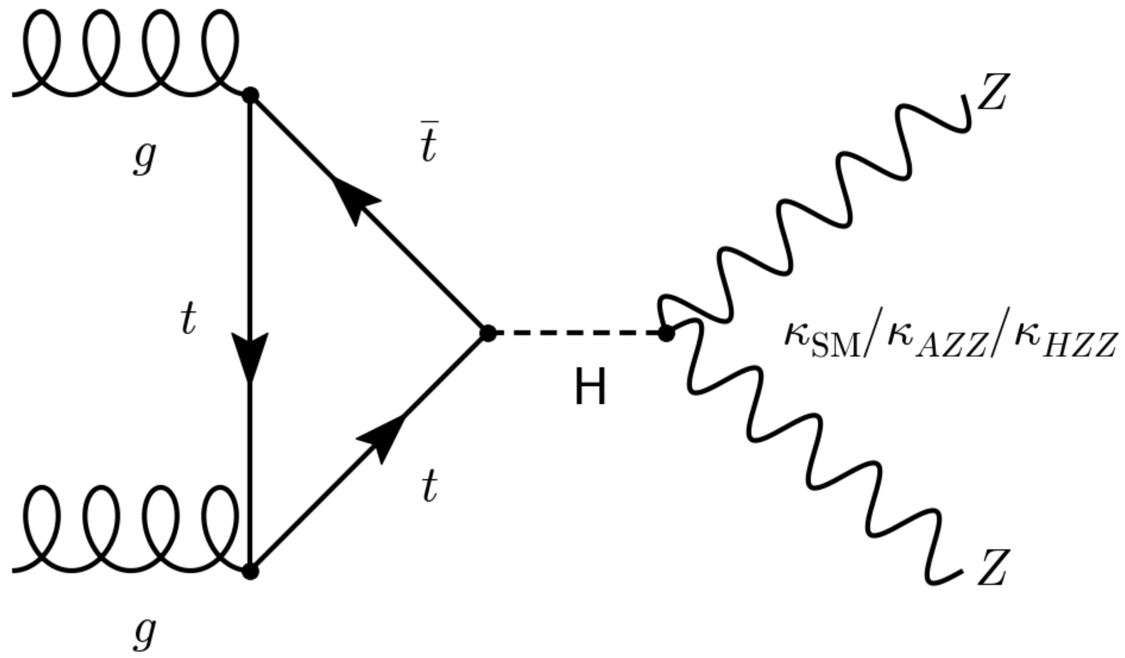
- In Run2 many CP analyses in different channels
  - H $\rightarrow ZZ^* \rightarrow 4l$, published with 36/fb https://arxiv.org/pdf/1712.02304.pdf ← in this talk

H $\rightarrow ZZ^* \rightarrow 4l$ - MAIN PICTURE



- Why?
  - clear signature and high signal-to-background ratio
- Analysis strategy
  - events are classified according their different production modes (ggF, VBF, VH)
  - assuming that the BSM changes in the Higgs sector do not to affect the SM background processes
- Signal samples
  - the signal is modelled by using POWHEG Monte Carlo at NLO with QCD corrections up to NLO and QCD soft-gluon re-summations up NNL logarithm applied
  - morphing technique used to interpolate the BSM signal scenarios
- Main Background
  - continuum $ZZ^{(*)}$ production
    - Use of BDT to better separate signal and background
- A maximum likelihood (ML) fit is used for the statistical interpretation of the results

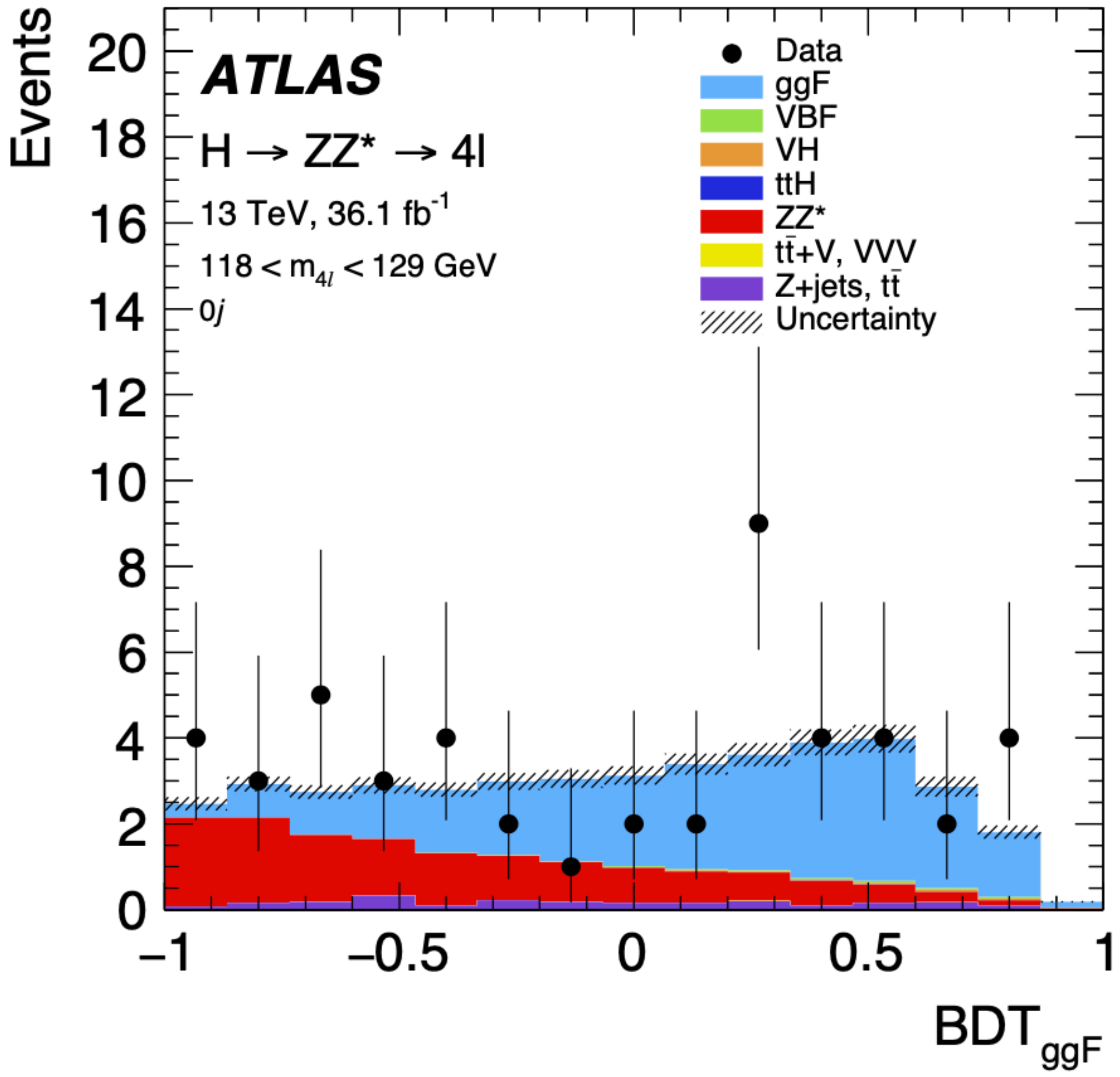
H $\rightarrow ZZ^* \rightarrow 4l$ - MAIN PICTURE



- Event Selection
  - 4 leptons selected
    - $4\mu, 2e2\mu, 2\mu2e, 4e$
    - The three highest-pT leptons required to have $p_T > 20$GeV, $p_T > 15$GeV, $p_T > 10$GeV, respectively
  - The leading lepton pair required to have $50 < m_{1,2} < 106$ GeV
  - The sub-leading lepton pair $m_{min} < m_{3,4} < 115$ GeV
    - Where m_{min} goes from 12 to 50 GeV depending on the four-lepton invariant mass m_{4l}
  - The two-lepton pairs must have an angular separation of $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2} > 0.1(0.2)$ for same-flavour (different-flavour) lepton pairs
  - Each electron (muon) must have a transverse impact parameter significance $|d_0|/\sigma(d_0) < 5(3)$

H $\rightarrow ZZ^* \rightarrow 4l$ - BDT

- Differences between H $\rightarrow ZZ^* \rightarrow 4l$ and the ZZ^* background incorporated in a BDT discriminant
  - Training done with fully simulated
    - signal events with $m_H = 125$ GeV
    - $qq \rightarrow ZZ^*$ continuos background distribution
  - Only events with $118 < m_{4l} < 129$ GeV
    - asymmetric around 125 GeV to include the residual effects of bremsstrahlung
  - Variables used
    - p_T^{4l} : transverse momentum of the four-lepton system
    - η_T^{4l}: pseudorapidity of the four-lepton system
    - D_{ZZ*} defined as $\ln(|\mathscr{M}_{sig}|^2/|\mathscr{M}_{ZZ}|^2)$ with $\mathscr{M}_x$ the matrix element for the considered process



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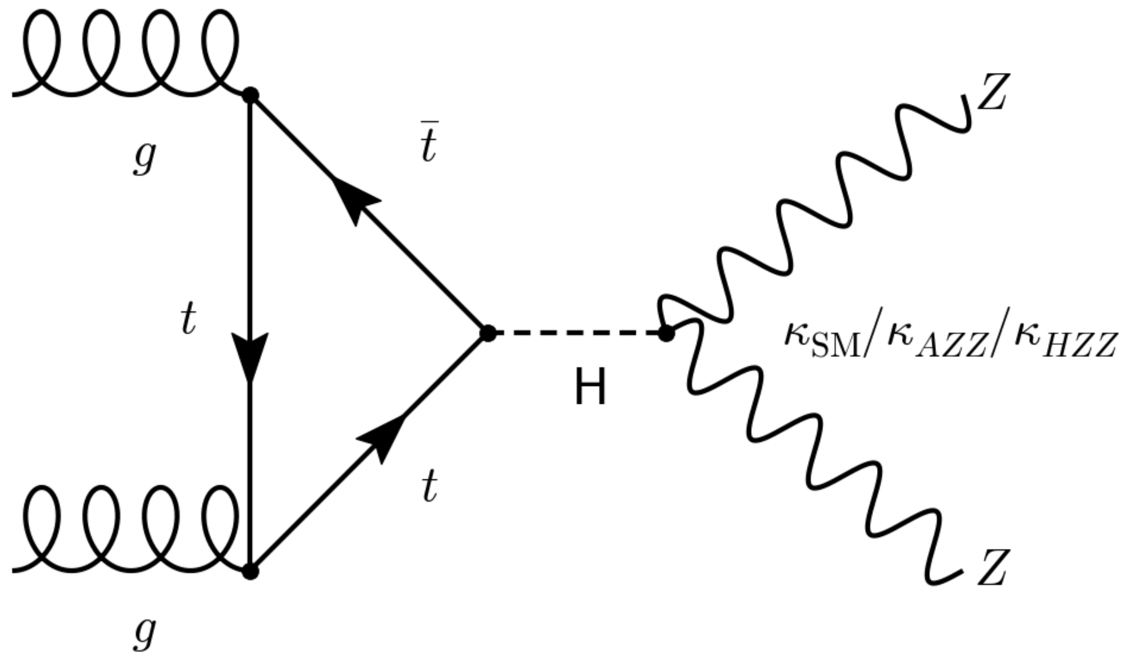
H → $ZZ^* \to 4l$ - MORPHING



- The morphing functionality allows to interpolate/extrapolate a given physical (possibly multi-dimensional) observable as a function of SM-like and BSM Higgs boson couplings to known particles.

	g_{SM}	g_{BSM}
SM	1	0
Mix	1	1
BSM	0	1

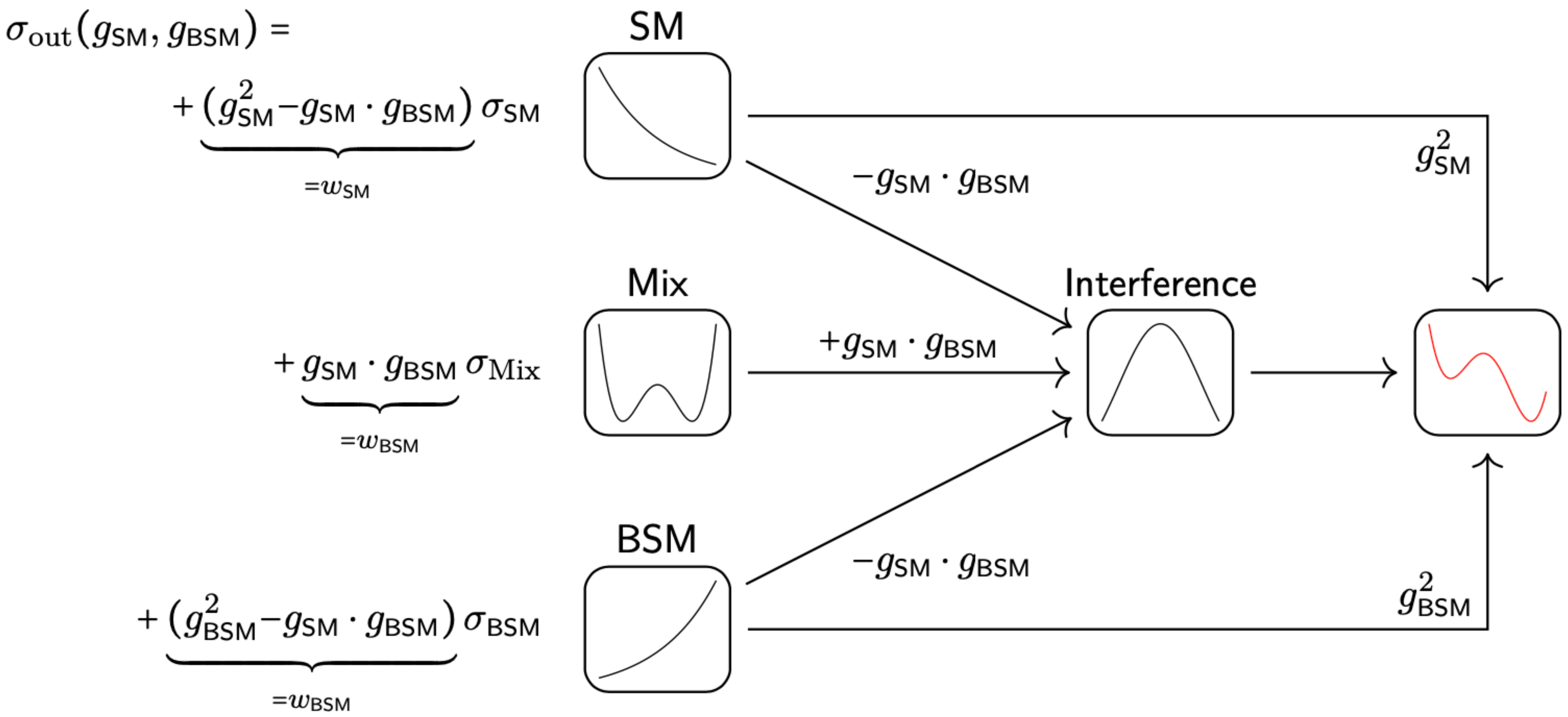
polynomials ⟹

$$\begin{array}{c|ccc} & g_{SM}^2 & g_{SM}g_{BSM} & g_{BSM}^2 \\ \text{SM} & 1 & 0 & 0 \\ \text{Mix} & 1 & 1 & 1 \\ \text{BSM} & 0 & 0 & 1 \end{array}$$

inversion ⟹

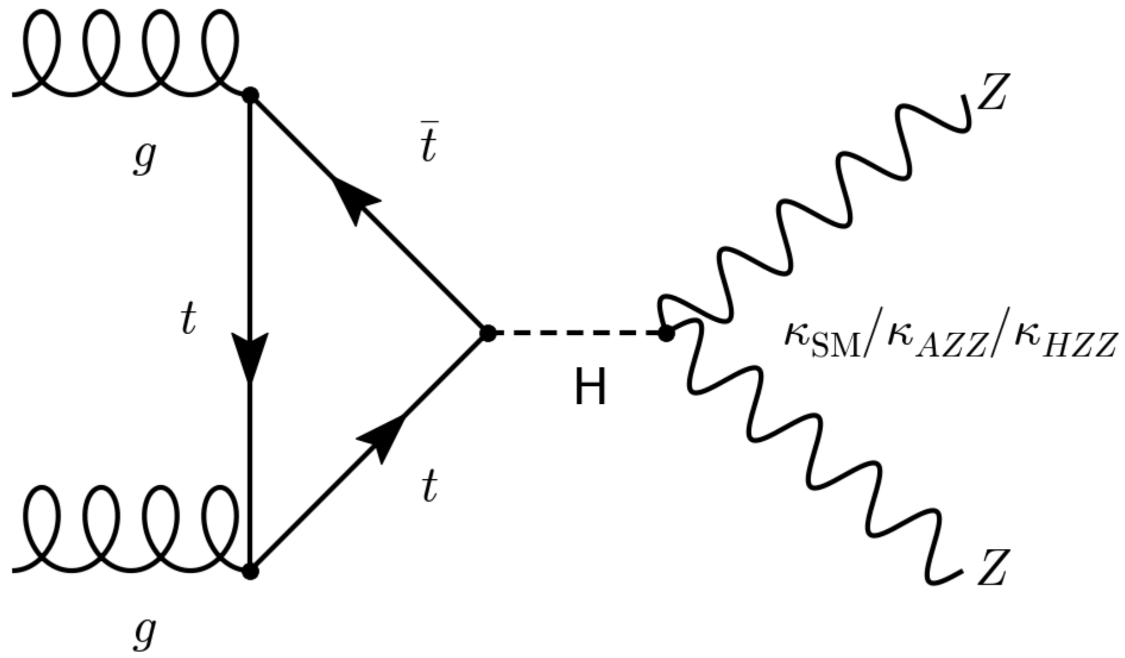
$$\begin{array}{c|ccc} & \text{SM} & \text{Mix} & \text{BSM} \\ g_{SM}^2 & 1 & 0 & 0 \\ g_{SM}g_{BSM} & -1 & 1 & -1 \\ g_{BSM}^2 & 0 & 0 & 1 \end{array}$$

http://cdsweb.cern.ch/record/2066980



N of base sample	ggF
$c_\alpha \kappa_{Hvv}$	3
$s_\alpha \kappa_{Avv}$	3
$s_\alpha \kappa_{Agg}$	3
$c_\alpha \kappa_{Hvv}$ vs. $s_\alpha \kappa_{Avv}$	6
$c_\alpha \kappa_{Hvv}$ vs. $s_\alpha \kappa_{Agg}$	9

H $\rightarrow ZZ^* \rightarrow 4l$ - HOW



- Measuring the CP state of the top-Yukawa coupling by using an EFT (effettive field theory) approach

Higgs Caraterization model
https://arxiv.org/abs/1306.6464

$$\mathcal{L}_0^V = \Big\{ \kappa_{SM}\Big[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\Big] - \frac{1}{4}\Big[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha\, \kappa_{Agg} g_{Agg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\Big] - \frac{1}{4}\frac{1}{\Lambda}\Big[\kappa_{HZZ} Z_{\mu\nu}Z^{\mu\nu} + \tan\alpha\, \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\Big] - \frac{1}{2}\frac{1}{\Lambda}\Big[\kappa_{HWW} W^+_{\mu\nu}W^{-\mu\nu} + \tan\alpha\, \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\Big]\Big\} X_0$$

- Λ set to 1 TeV, no new BSM particles below the energy scale Λ
- χ_0 bosonic state of spin 0
- α the mixing angle between the 0^+ and 0^- CP states
- $\kappa_{HVV}, \kappa_{AVV}$ and κ_{Agg} are considered as possible BSM admixtures to the corresponding SM interactions
- $\kappa_{HWW} = \kappa_{HZZ} \equiv \kappa_{HVV}$ and $\kappa_{AWW} = \kappa_{AZZ} \equiv \kappa_{AVV}$
- κ_{SM} and κ_{Hgg} are fixed to the SM value of 1 if not stated otherwise

- CP even $\alpha = 0$
- CP odd $\alpha = 1$
- CP mixed $0 < \alpha < 1$

H $\rightarrow ZZ^* \rightarrow 4l$ - HOW

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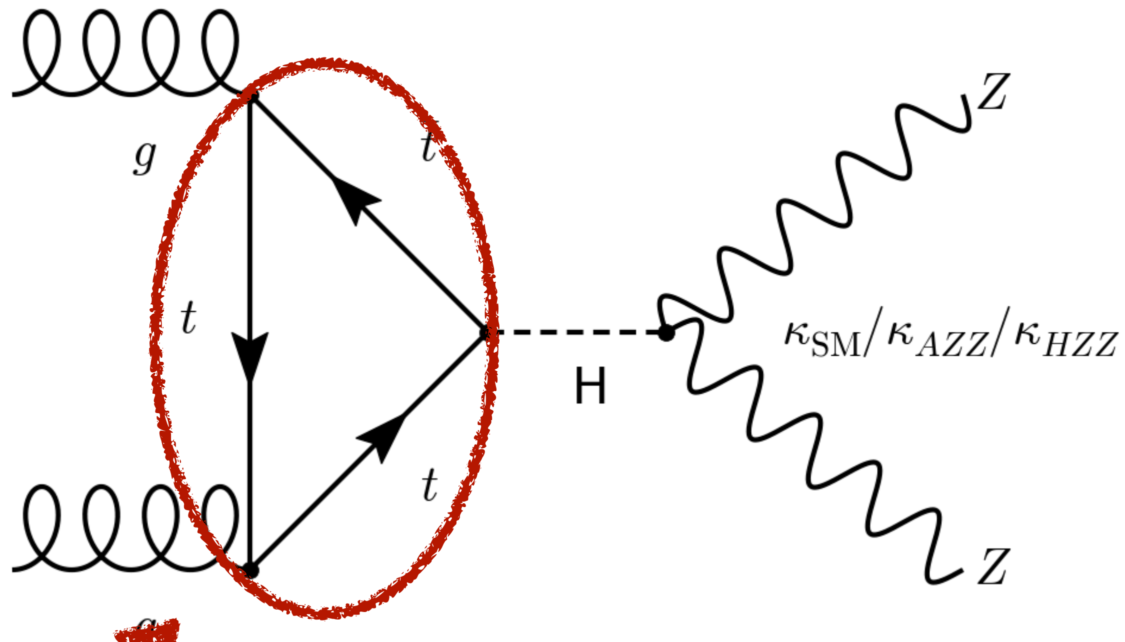

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$$- \frac{1}{4} \Big[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha \, \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \Big]$$
$$- \frac{1}{4} \frac{1}{\Lambda} \Big[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha \, \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \Big]$$
$$- \frac{1}{2} \frac{1}{\Lambda} \Big[\kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + \tan\alpha \, \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu}$$

This is what we are interested in

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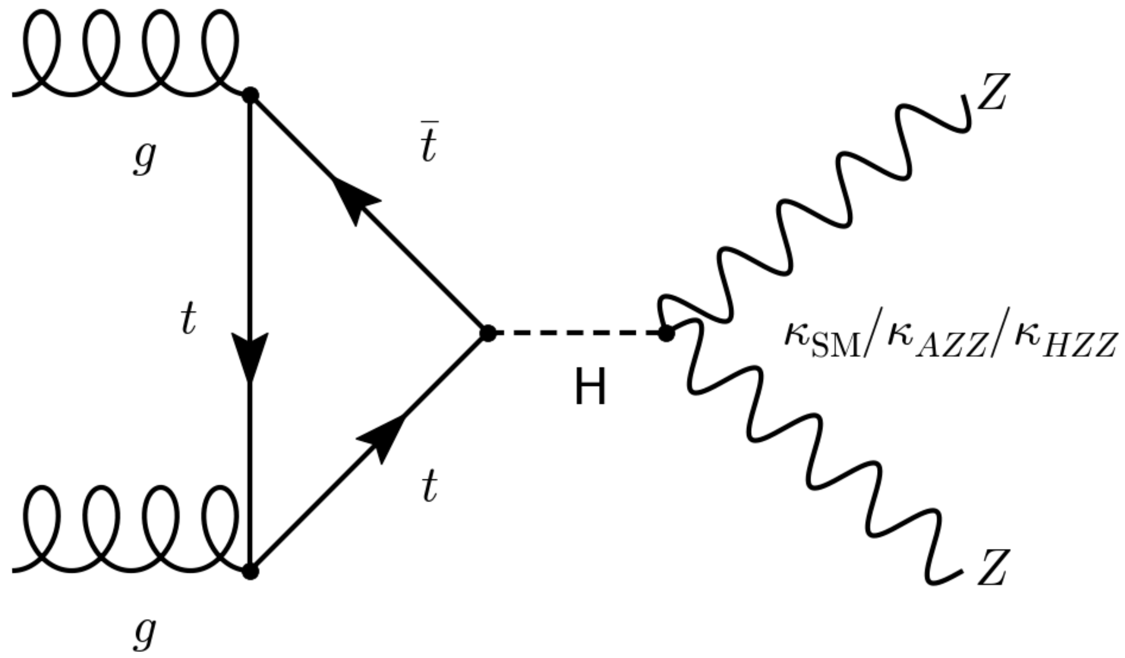
- CP odd $\alpha = \pi$
- CP mixed $0 < \alpha < \pi$

H $\rightarrow ZZ^* \rightarrow 4l$ - HOW



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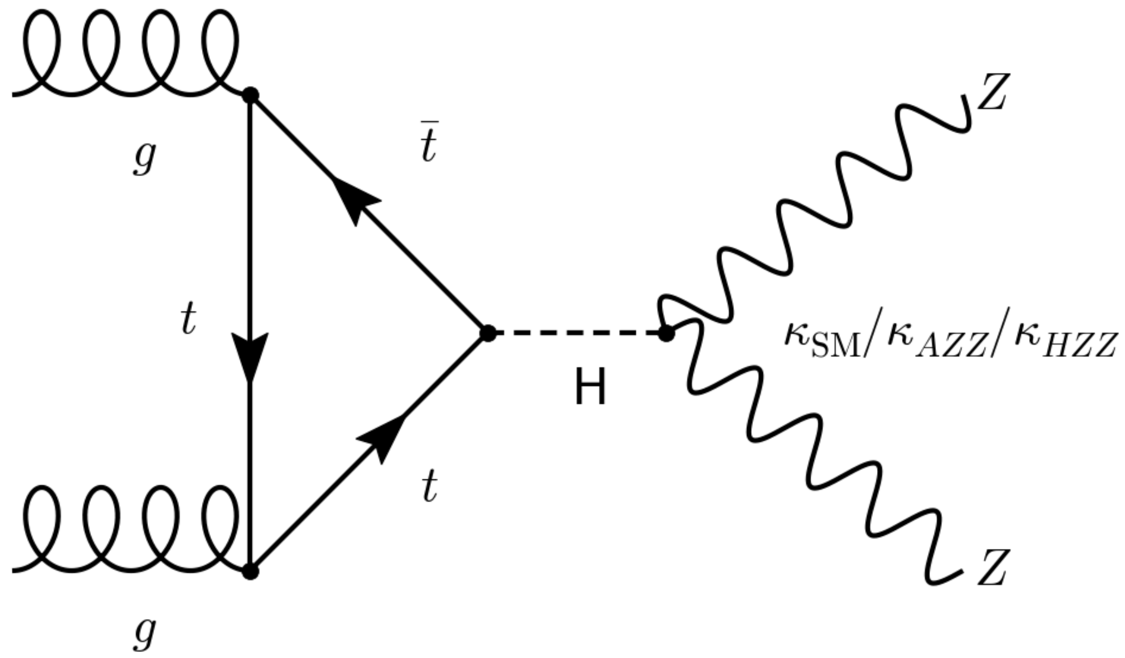
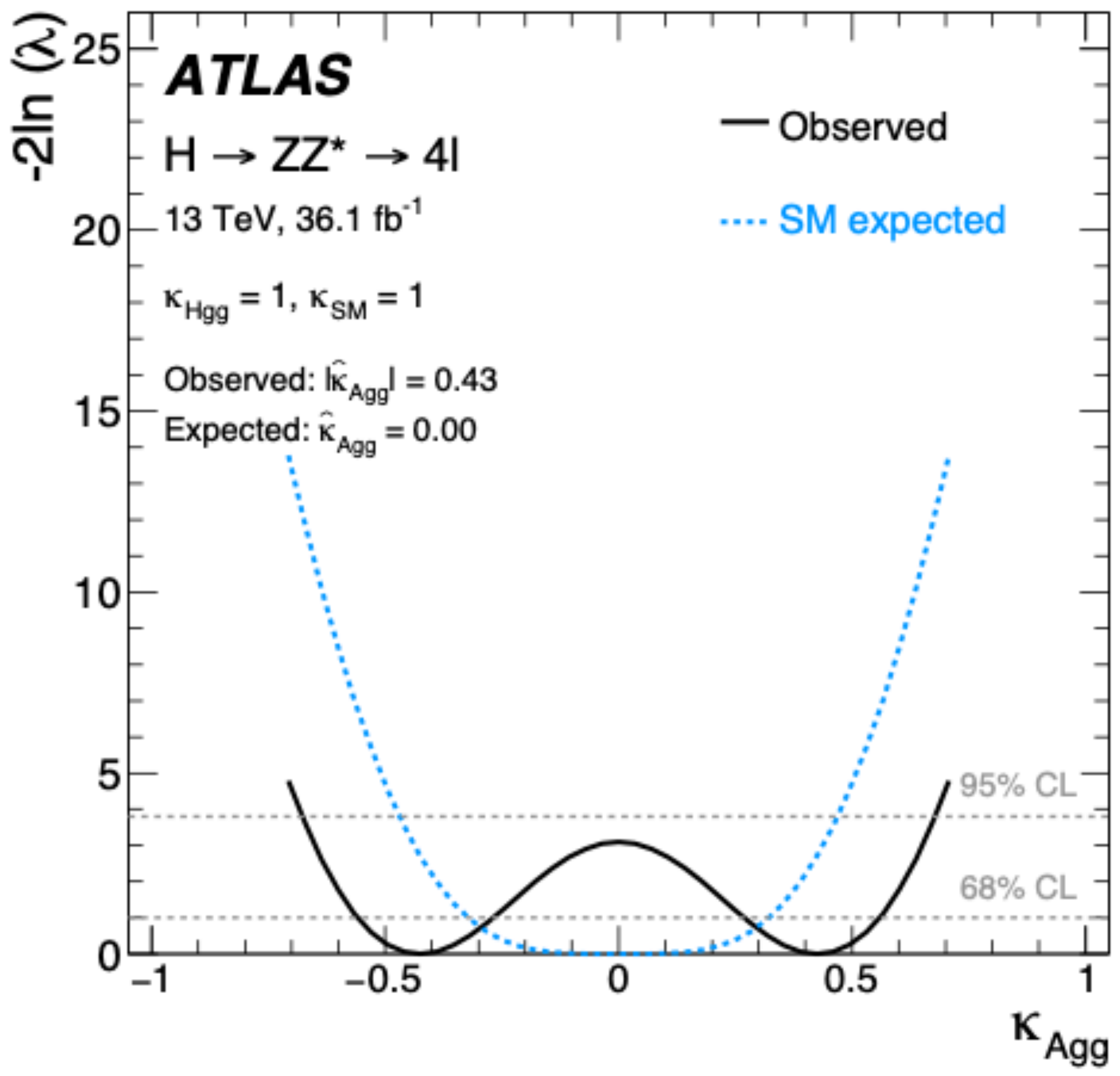
κ_{Agg} is measured assuming that all other BSM couplings are equal to 0

H $\rightarrow ZZ^* \rightarrow 4l$, κ_{Agg} FIT



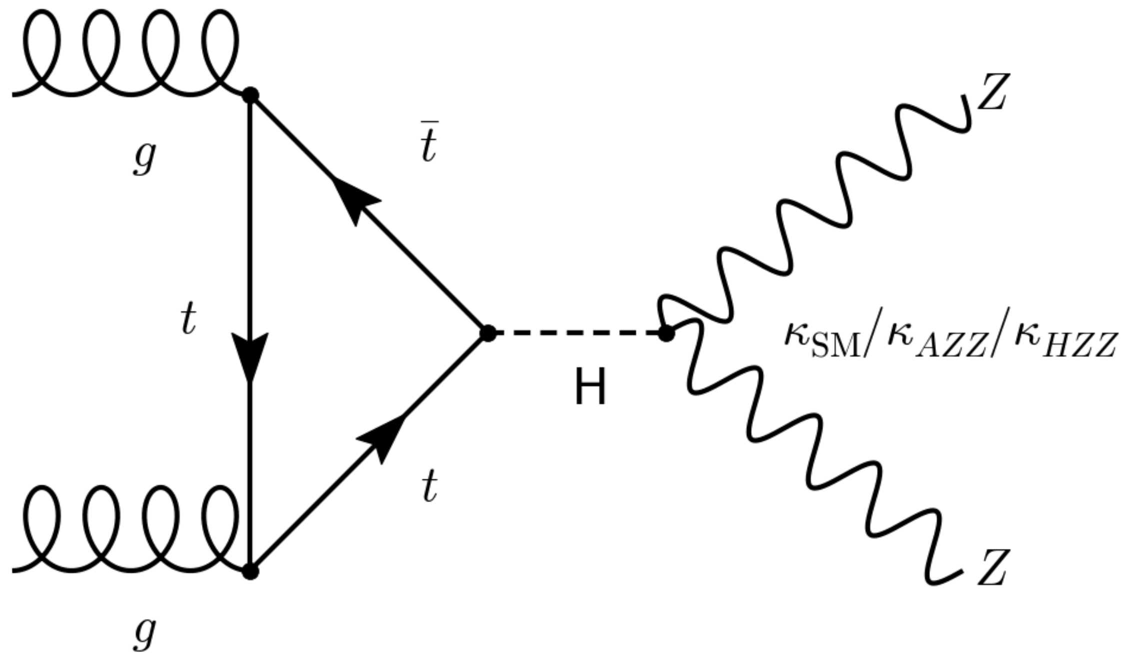


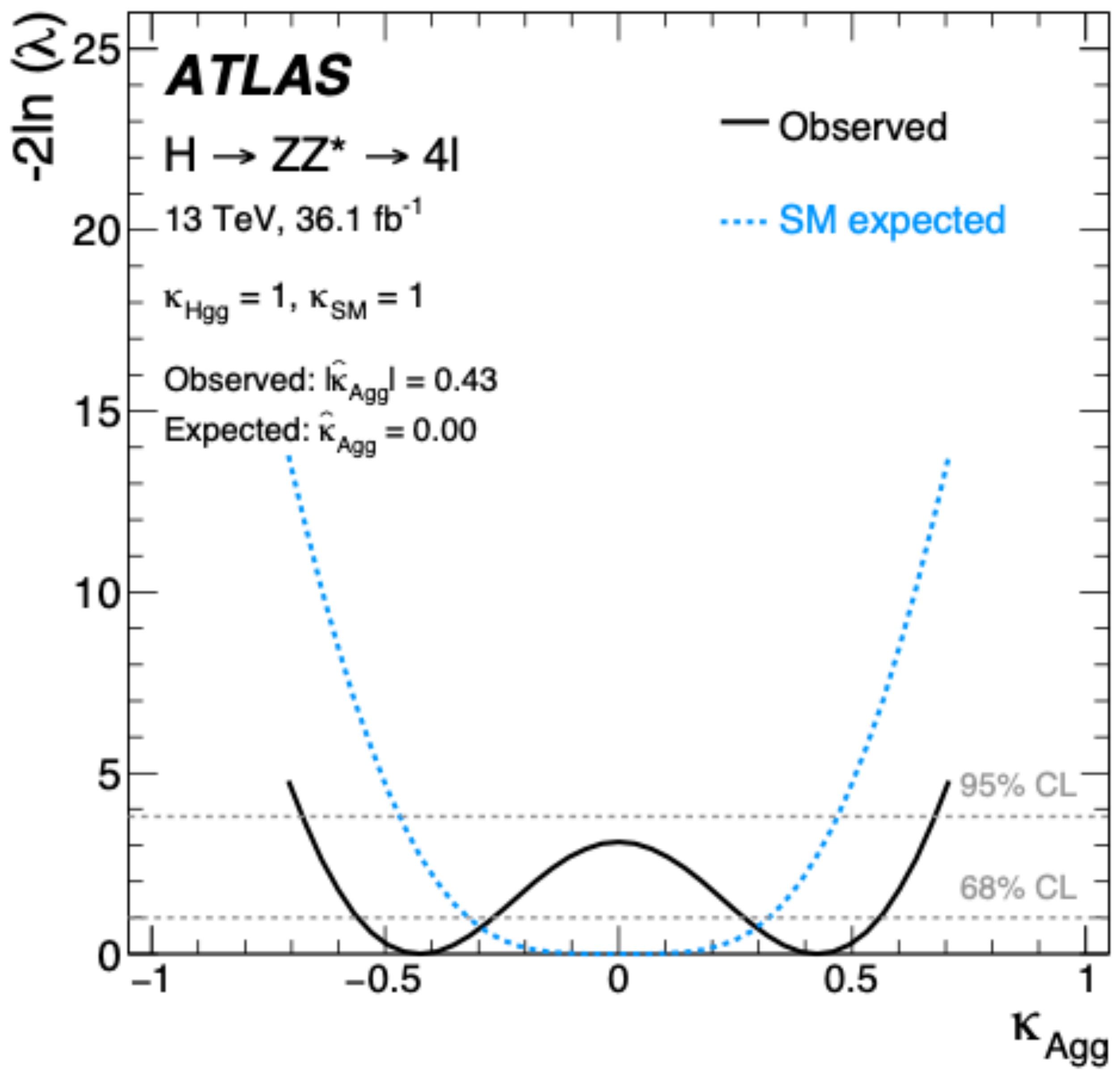
$$\mathcal{L}_0^V = - \frac{1}{4}\left[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right]$$

- Probing BSM couplings in the ggH vertex
  - “Rate only” fit : obtained with an event yield-only analysis
  - The total width of the Higgs boson is modified to take into account the changes in the Branching Ratio due to the BSM contributions

Nikhef

H → $ZZ^* \to 4l$, κ_{Agg} FIT





$$\mathcal{L}_0^V =$$

$$-\frac{1}{4}\left[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right]$$

- Probing BSM couplings in the ggH vertex
  - “Rate only” fit : obtained with an event yield-only analysis
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BSM coupling κ_{BSM}	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{BSM}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
κ_{Agg}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	$[-0.47, 0.47]$	$[-0.68, 0.68]$	± 0.43	-	1.8σ

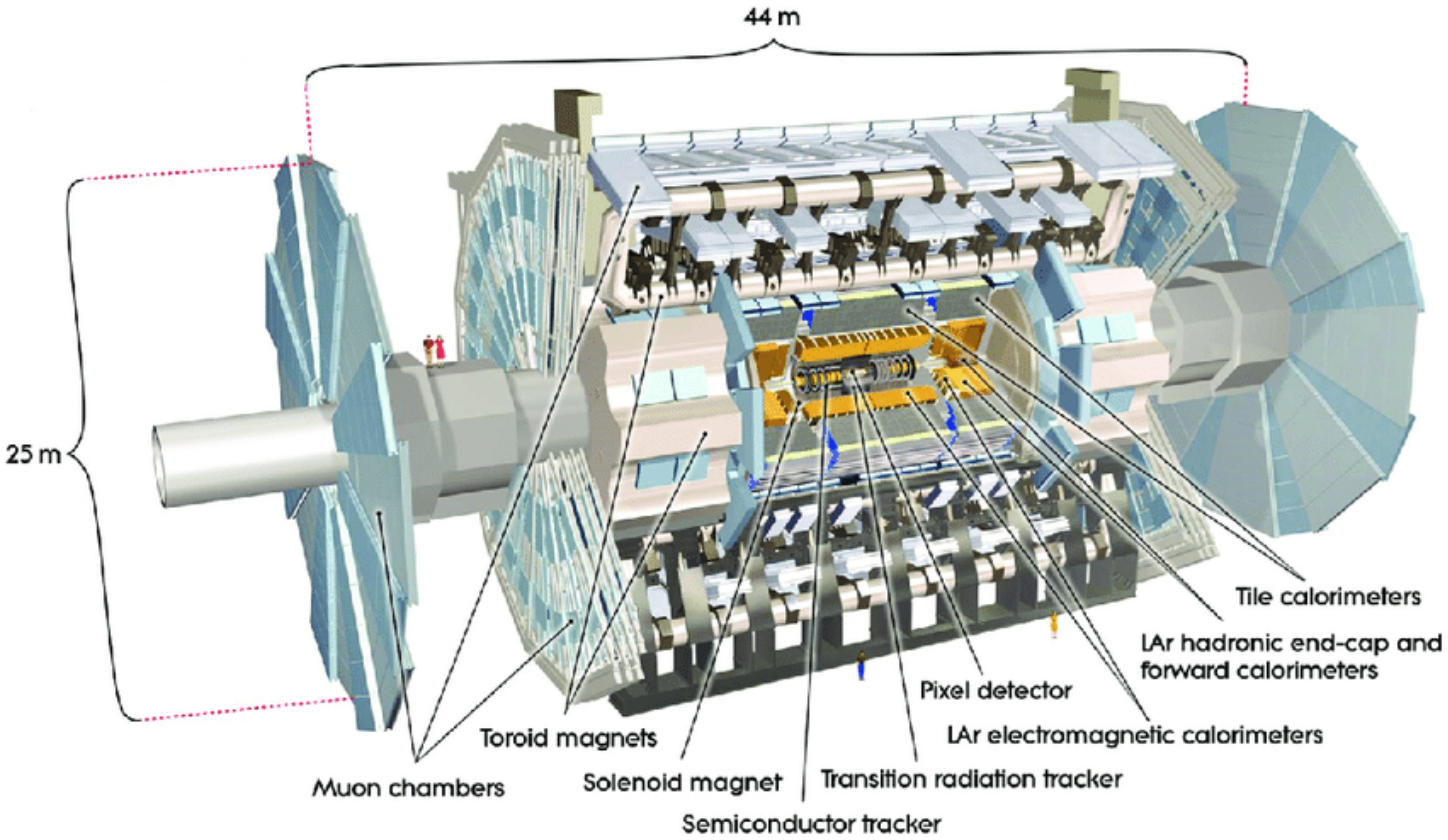
CONCLUSIONS

- Presented a study in Run2 of CP nature of the ggF production mode in H $\rightarrow ZZ^{*} \rightarrow 4l$
- Constraints are placed on possible BSM interactions of the Higgs boson within the framework of an effective Lagrangian extension of the SM
  - Pure CP odd scenario excluded
  - Up to 32% “CP odd” possible in mixed scenario (95%CL)
- Other measurements
  - H $\rightarrow \gamma\gamma$ https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2019-029/
  - H $\rightarrow WW^{*}$

Thanks!

Backup

ATLAS DETECTOR

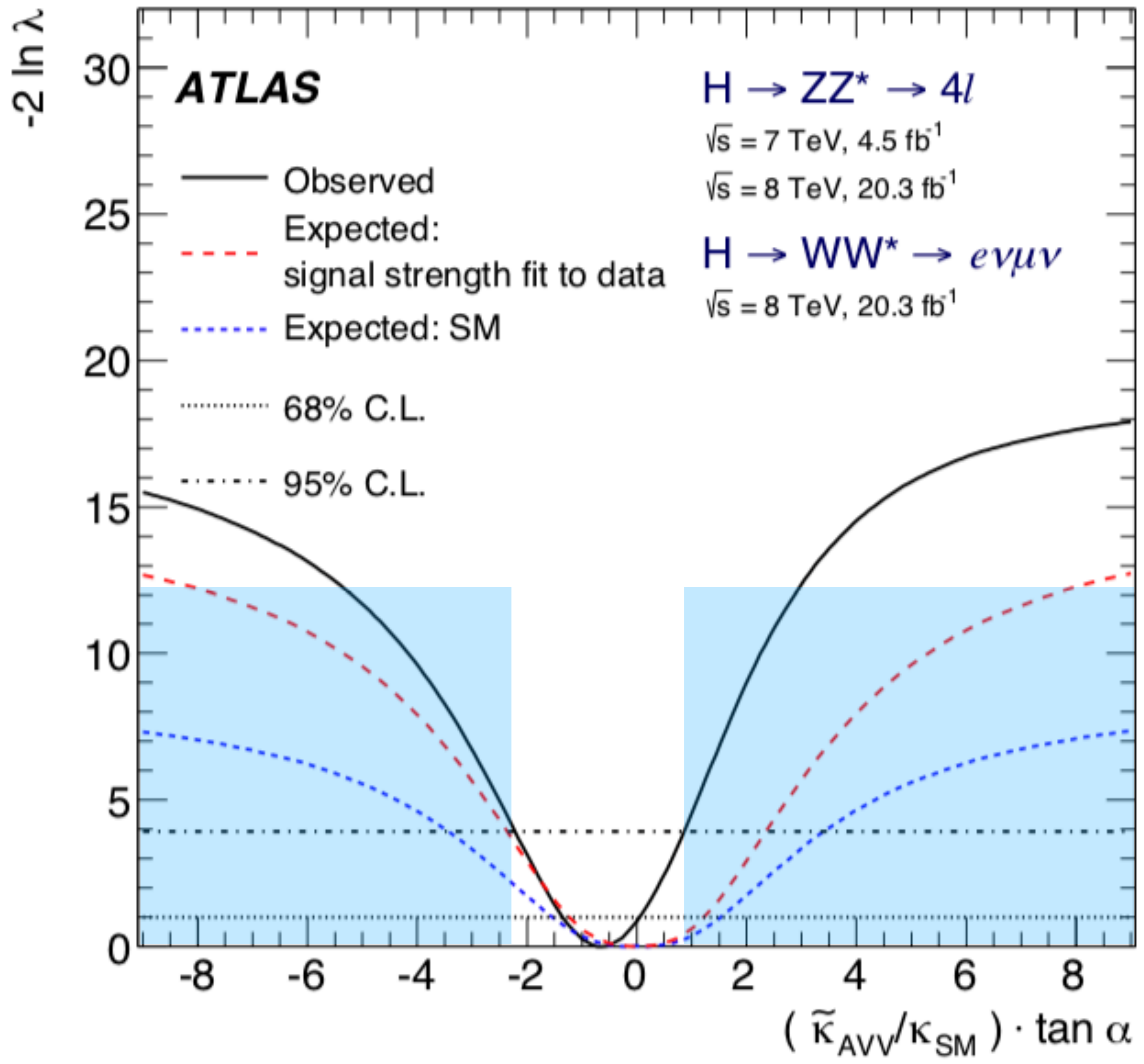


RUN1 EXCLUSION CALCULATION

atan(0.9)-atan(-2.3)=1.89

atan(inf)-atan(-inf)=6.28

1.89/6.28 ~ 30%



TENSOR STRUCTURE

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] - \tfrac{1}{4}\tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \tfrac{1}{2}\tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] - \tfrac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W} (W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.) \right] \Big\} \mathcal{X}_0$$

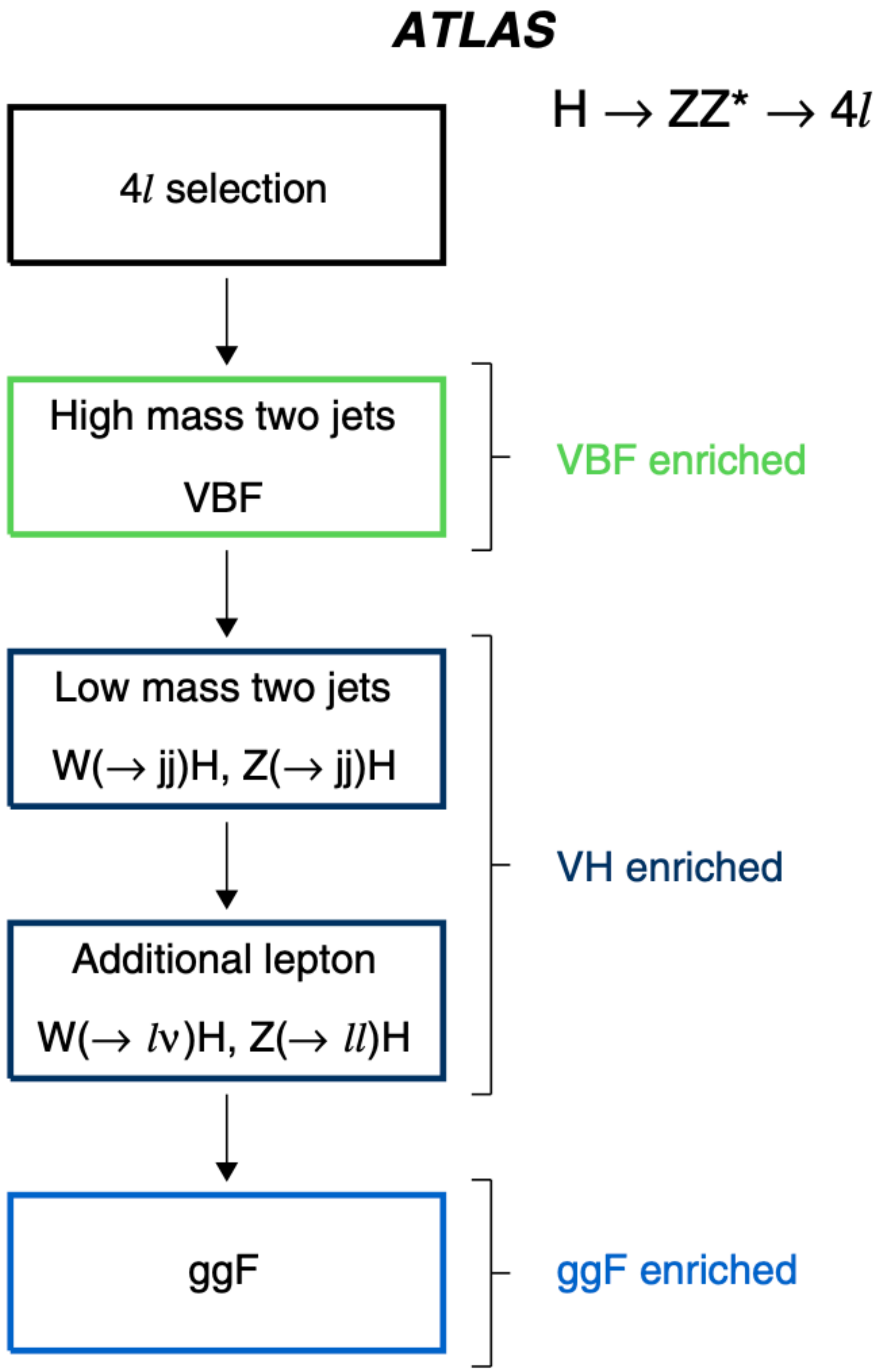
- V^μ represents the vector-boson field (V = Z, $W^\pm$), the $V^{\mu\nu}$ are the reduced field tensors and the dual tensor is defined as $\tilde{V}^{\mu\nu} = 1/2\epsilon^{\mu\nu\rho\sigma}V_{\rho\sigma}$.
- $\kappa_{H\partial Z}$ and $\kappa_{H\partial W}$ corresponds to higher-order derivative operatos, which have been neglected in this analysis
- Couplings are assumed to be real in order to ensure Lagrangian terms Hermitian
- $g_{HVV} \propto m_{Z/W}^2$

CLASSIFICATION OF THE HIGGS BOSON PRODUCTION MODES

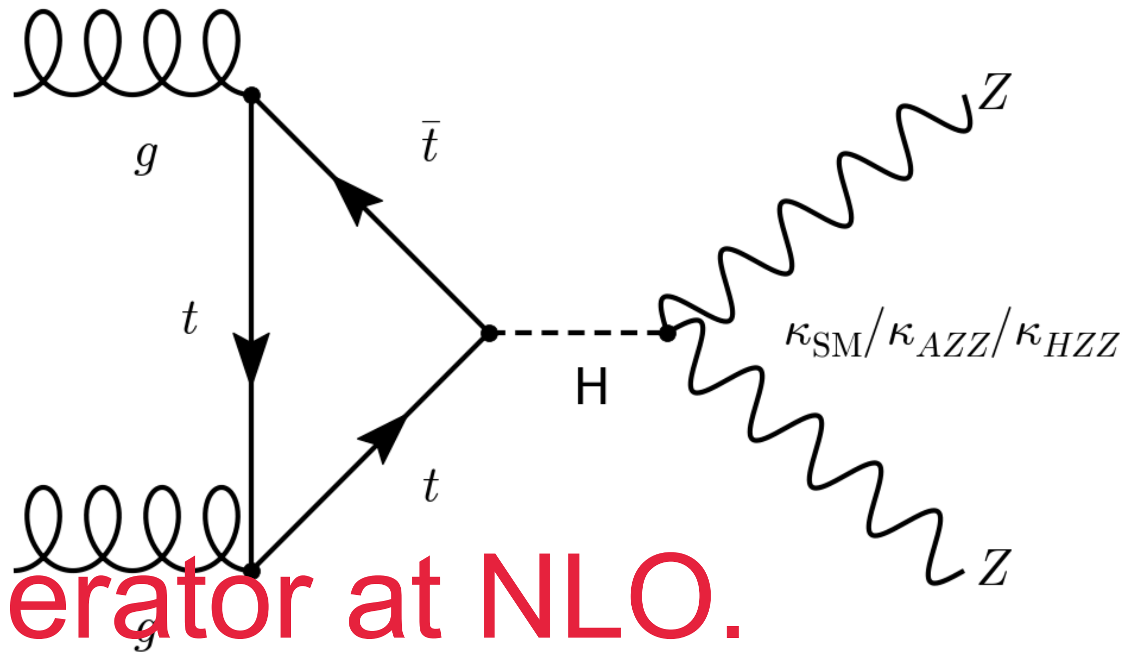
- In base of the production processes exclusive regions of the phase space are defined. These ones are called “production bins”.

- The bins are chosen in such a way that the measurement precision is maximized and at the same time possible BSM contributions can be isolated.

CATEGORIES


ATLAS
H → ZZ* → 4l
4l selection
High mass two jets
VBF
VBF enriched
Low mass two jets
W(→ jj)H, Z(→ jj)H
Additional lepton
W(→ lν)H, Z(→ ll)H
VH enriched
ggF
ggF enriched

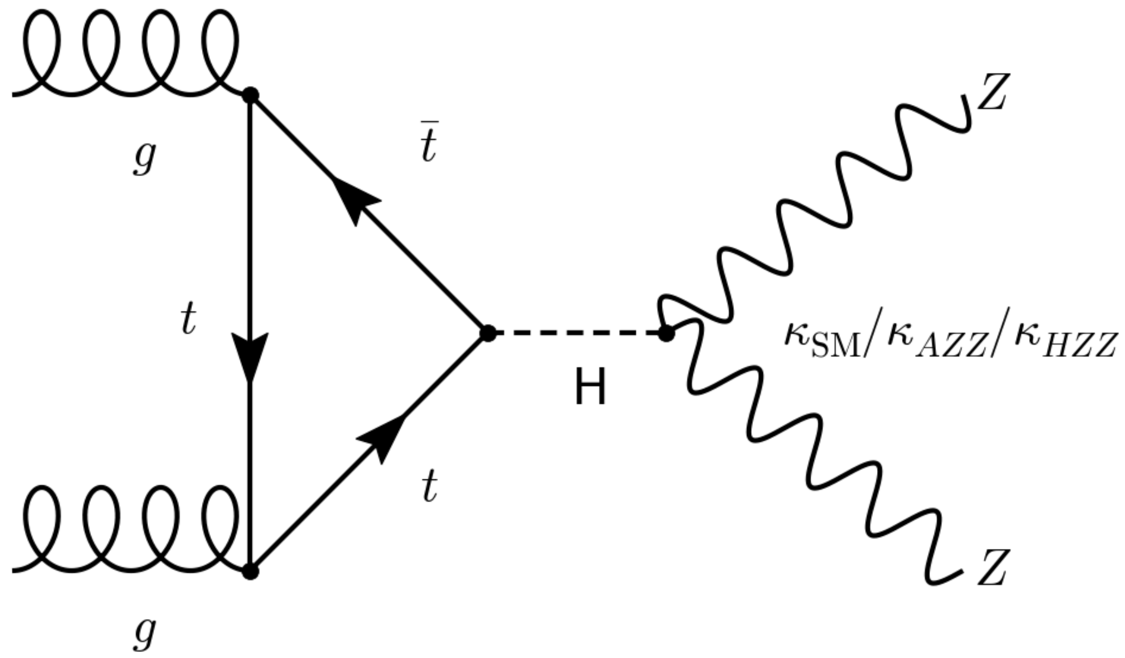
H $\rightarrow ZZ^* \rightarrow 4l$ - MAIN PICTURE



- Signal samples
  - The signal is modelled using the POWHEG Monte Carlo event generator at NLO.
  - QCD corrections up to NLO and QCD soft-gluon re-summations up to next-to-next-to-leading logarithm are applied.
  - The Higgs boson decay branching ratio in this final state is predicted by Prophecy4f, with includes NLO QCD+EW corrections, the interferences effects between identical final states and the leading two-loop heavy Higgs boson corrections to the four-fermion width.
- Main Background
  - continuum $((Z^{(*)}/\gamma^{(*)})(Z^{(*)}/\gamma^{(*)})$production
  - Sherpa 2.2.1 generator
  - Matrix elements contain all diagrams with four electroweak vertices. They are calculated for up to 1 parton at NLO and up to 3 partons at LO

Bonus:
CP study in the decay vertex

$H \to ZZ^* \to 4l$, κ_{HVV} AND κ_{AVV} FIT

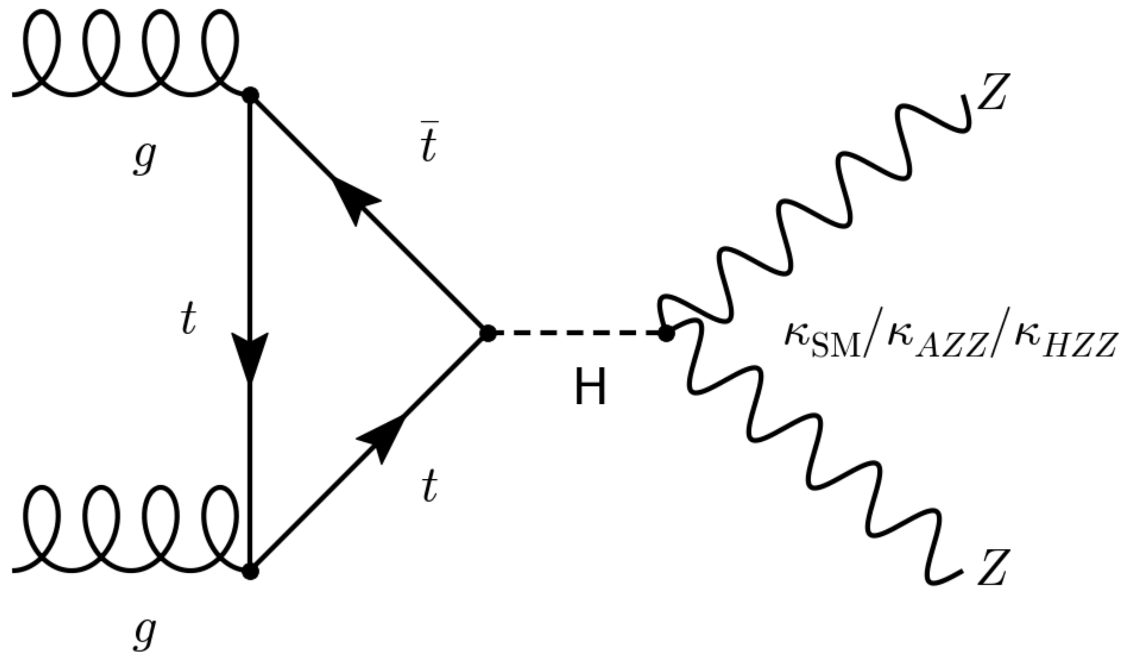


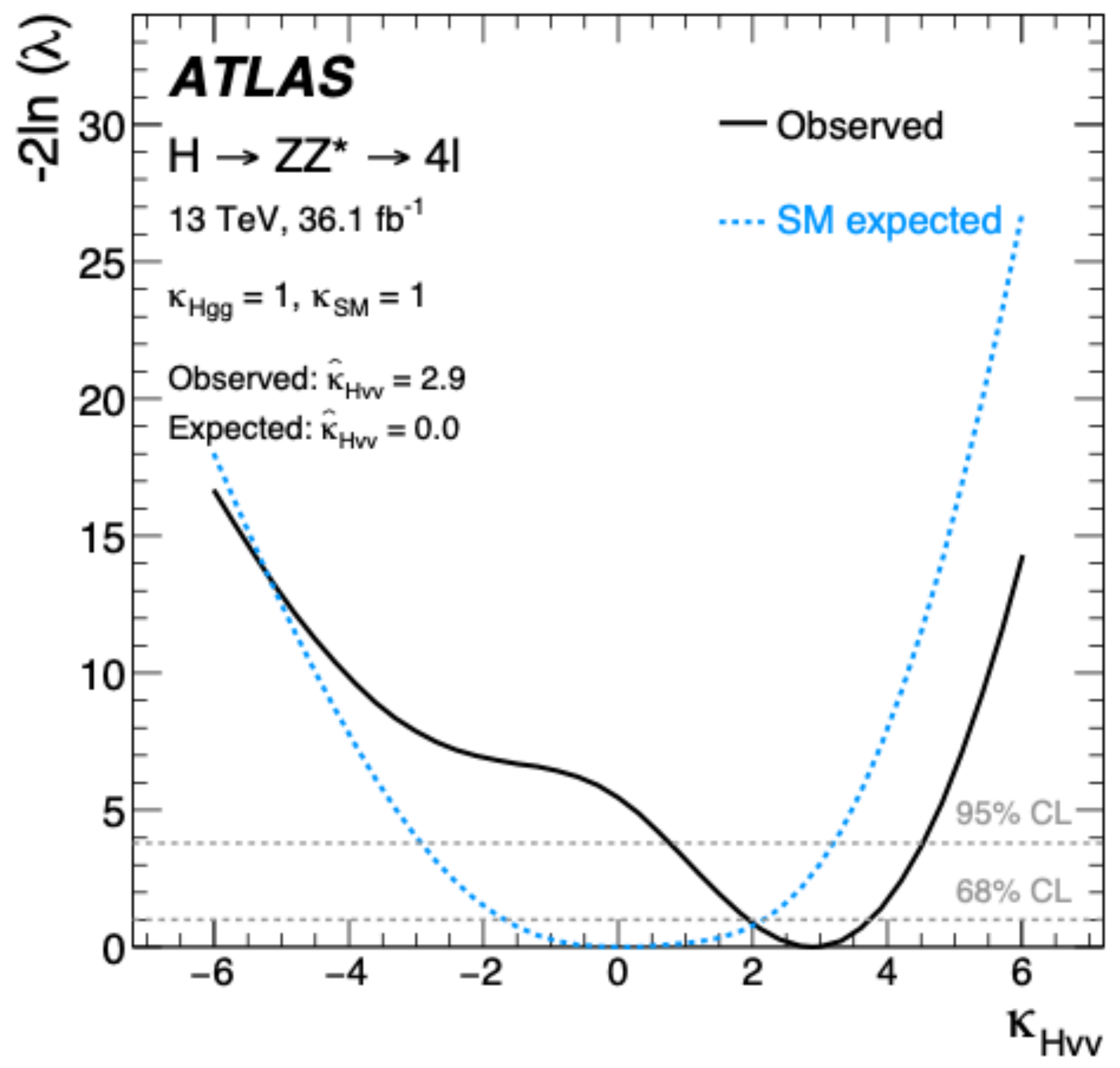
$$\mathcal{L}_0^V = $$

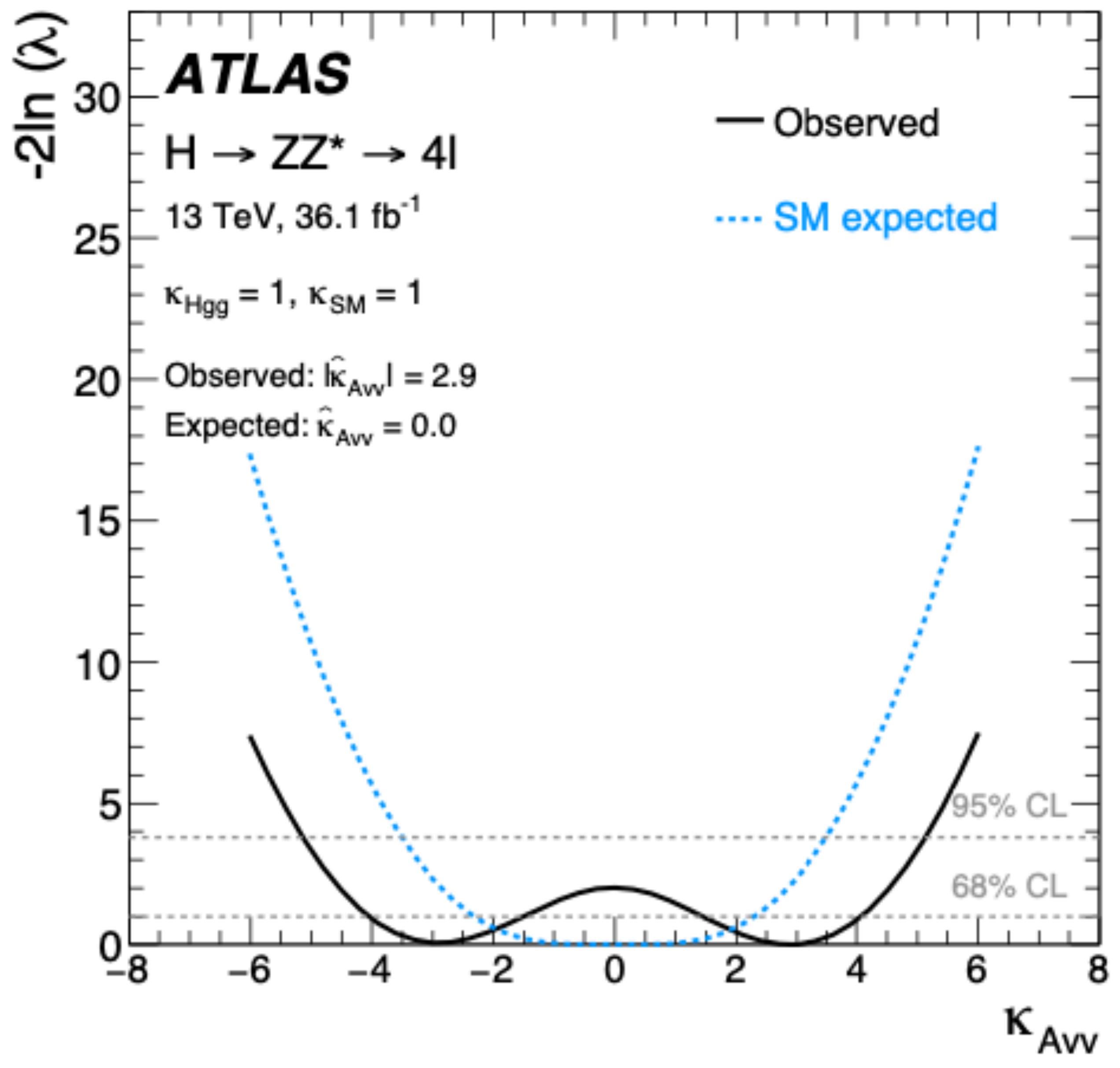
$$- \frac{1}{4}\frac{1}{\Lambda}\left[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha\, \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\right]$$
$$- \frac{1}{2}\frac{1}{\Lambda}\left[\kappa_{HWW} W^{+}_{\mu\nu} W^{-\mu\nu} + \tan\alpha\, \kappa_{AWW} W^{+}_{\mu\nu} \tilde{W}^{-\mu\nu}\right]\Big\}\chi_0$$

- Probing BSM couplings in the HVV vertex
  - The total width of the Higgs boson is modified to take into account the changes in the BR due to the BSM contributions

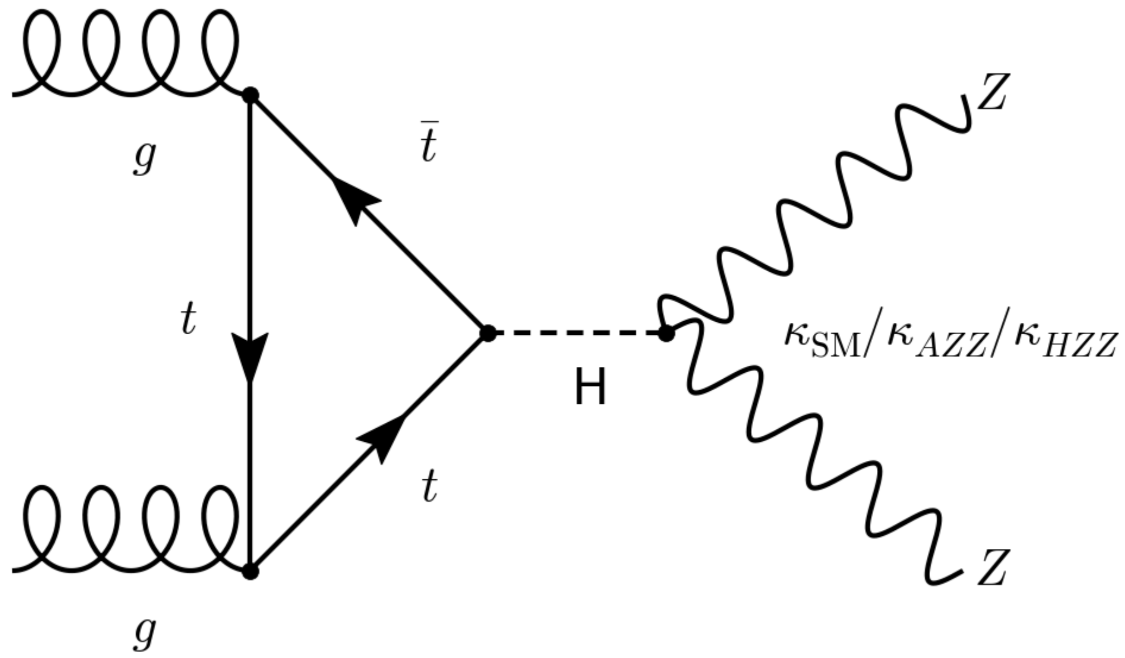
H → ZZ* → 4l, κ_{HVV} AND κ_{AVV} FIT



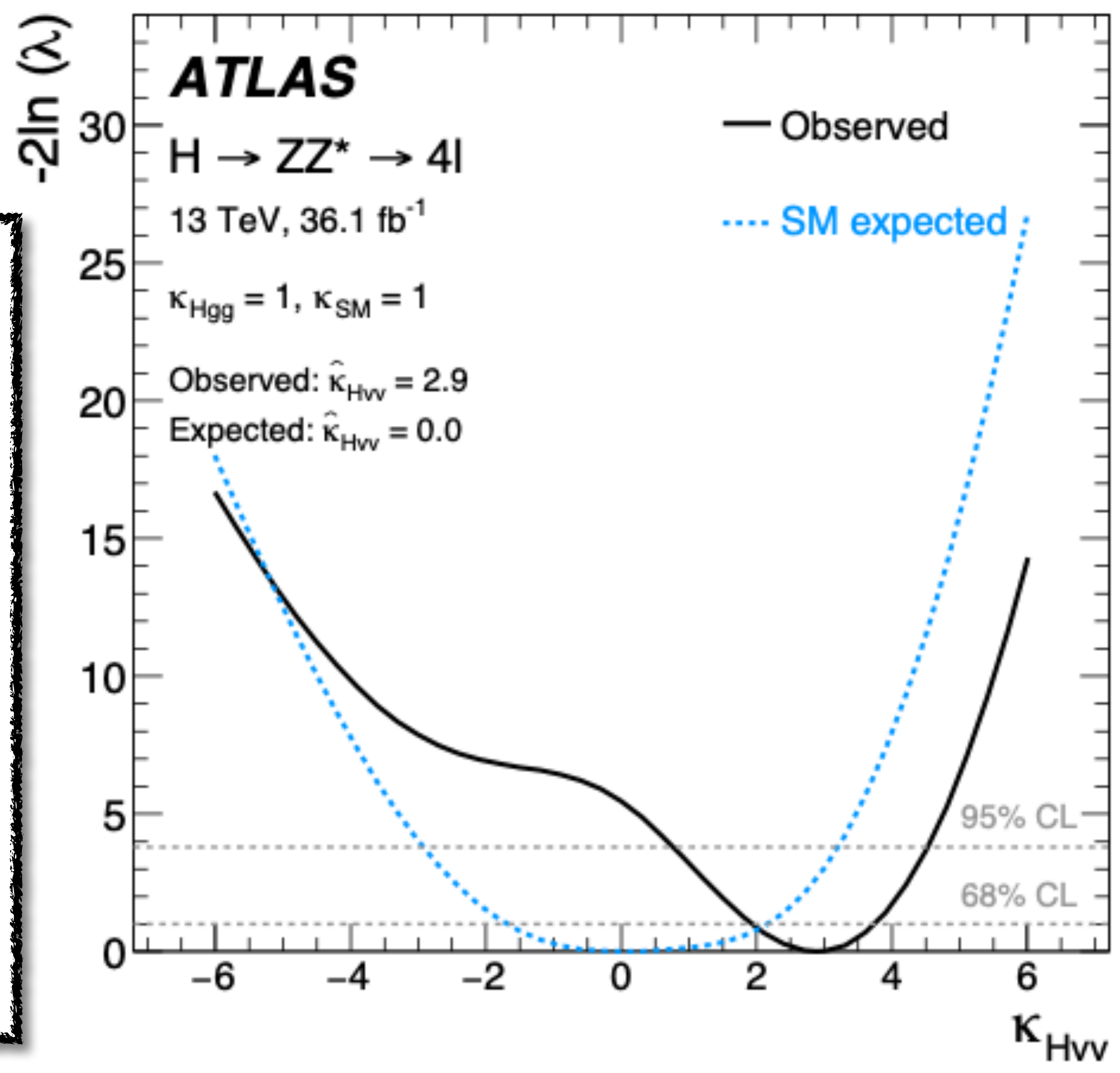


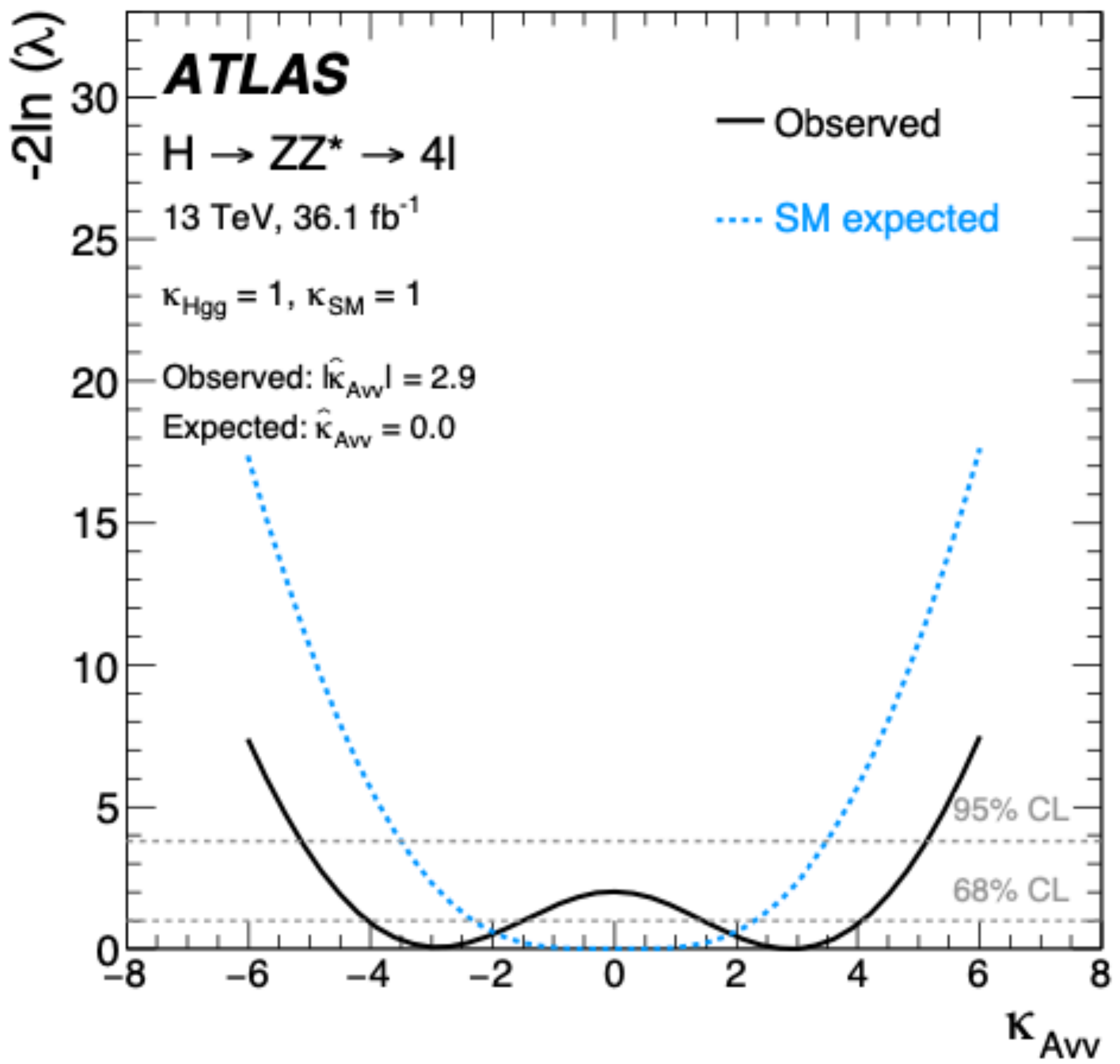


H → ZZ* → 4l, κ_{HVV} AND κ_{AVV} FIT



Asymmetry is expected due to the interference between SM and BSM contribution

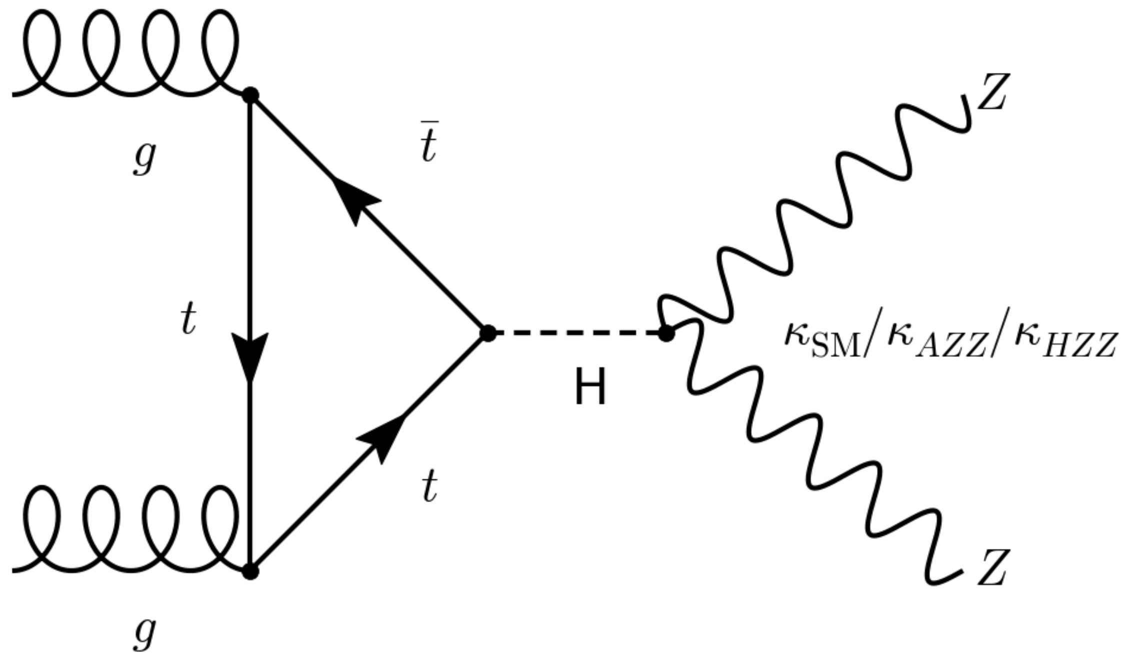


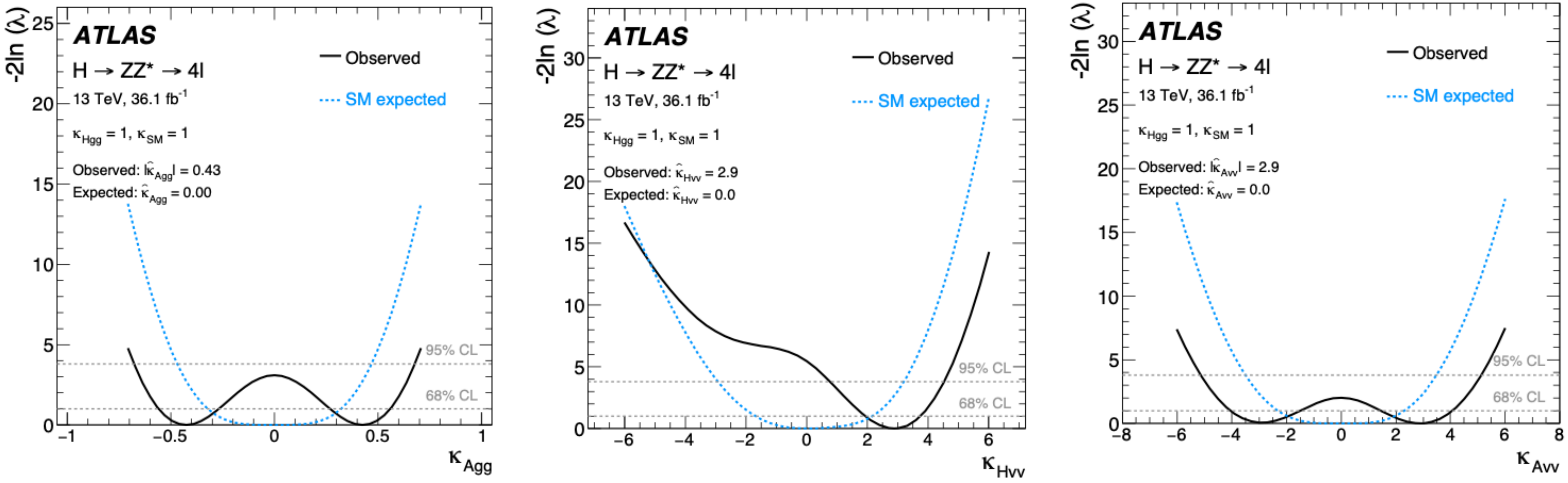


It is symmetric because the cross section scales at the same rate for negative and positive values of κ_{AVV}

Nikhef

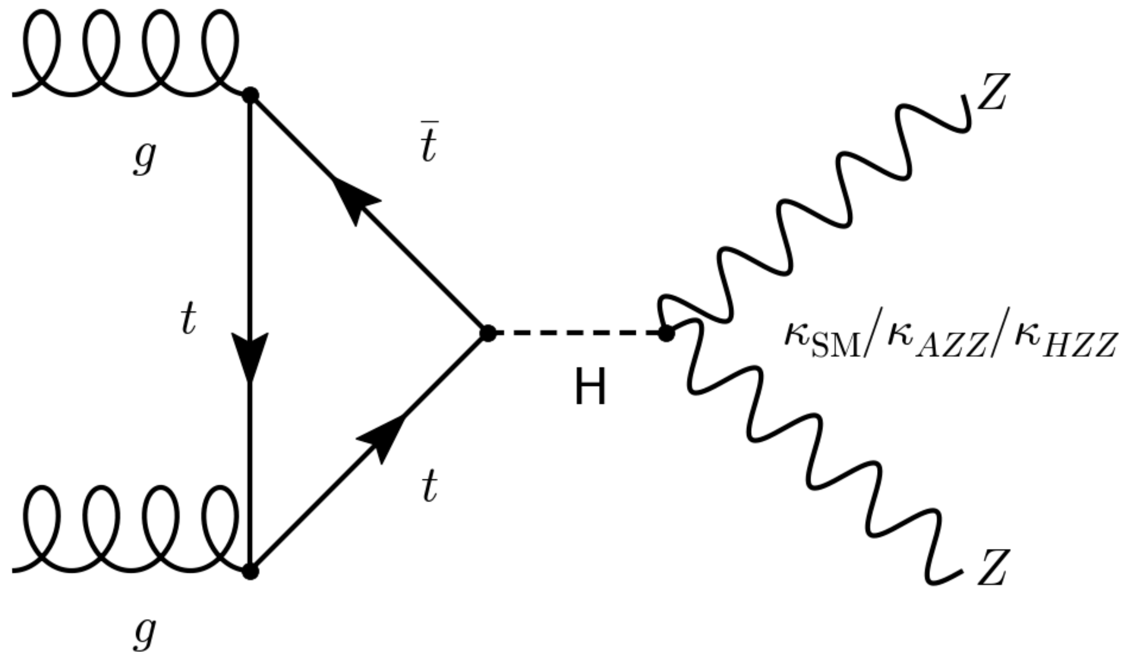
$H \rightarrow ZZ^* \rightarrow 4l$, κ_{Agg}, κ_{HVV} AND κ_{AVV} FIT

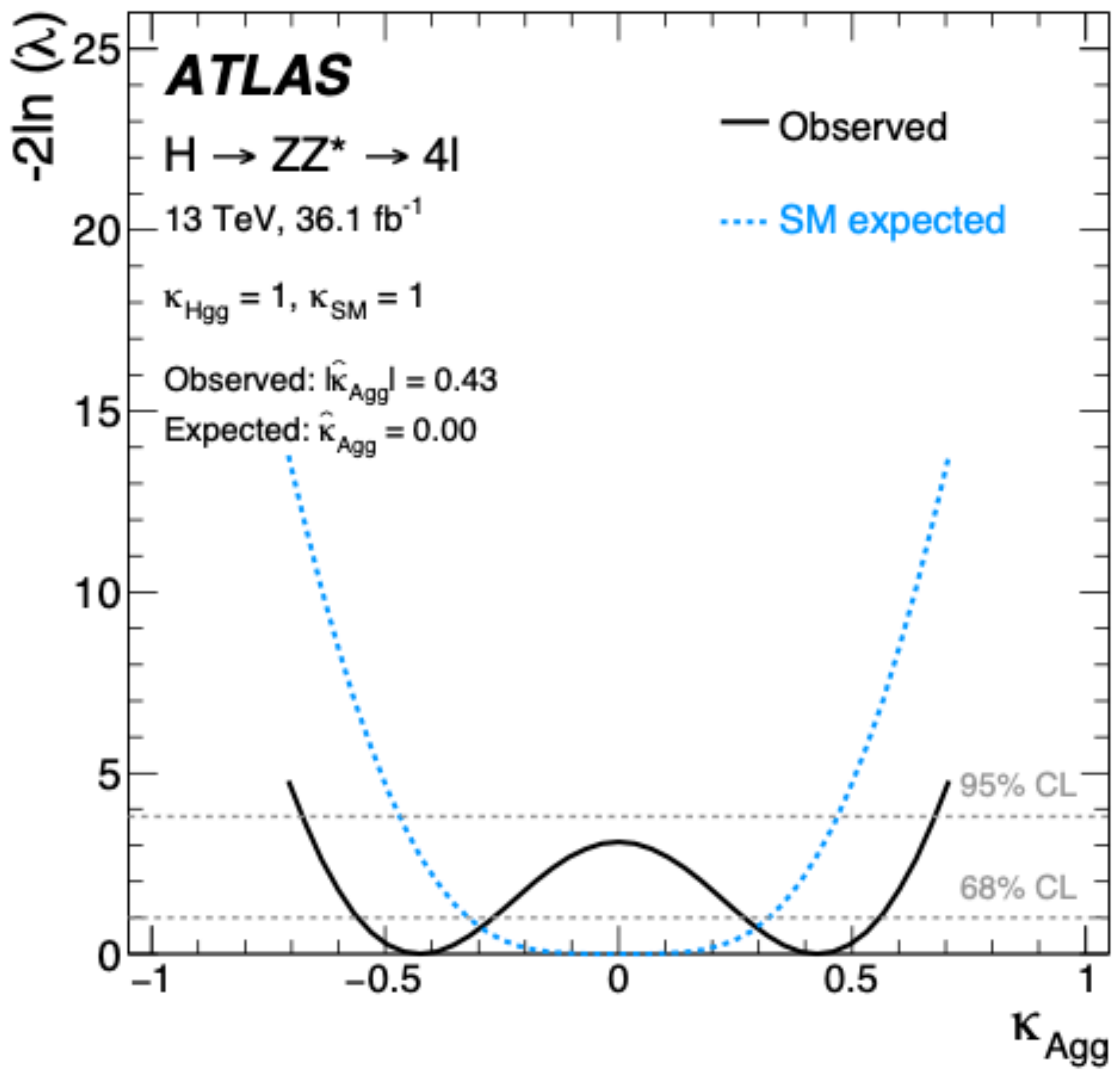


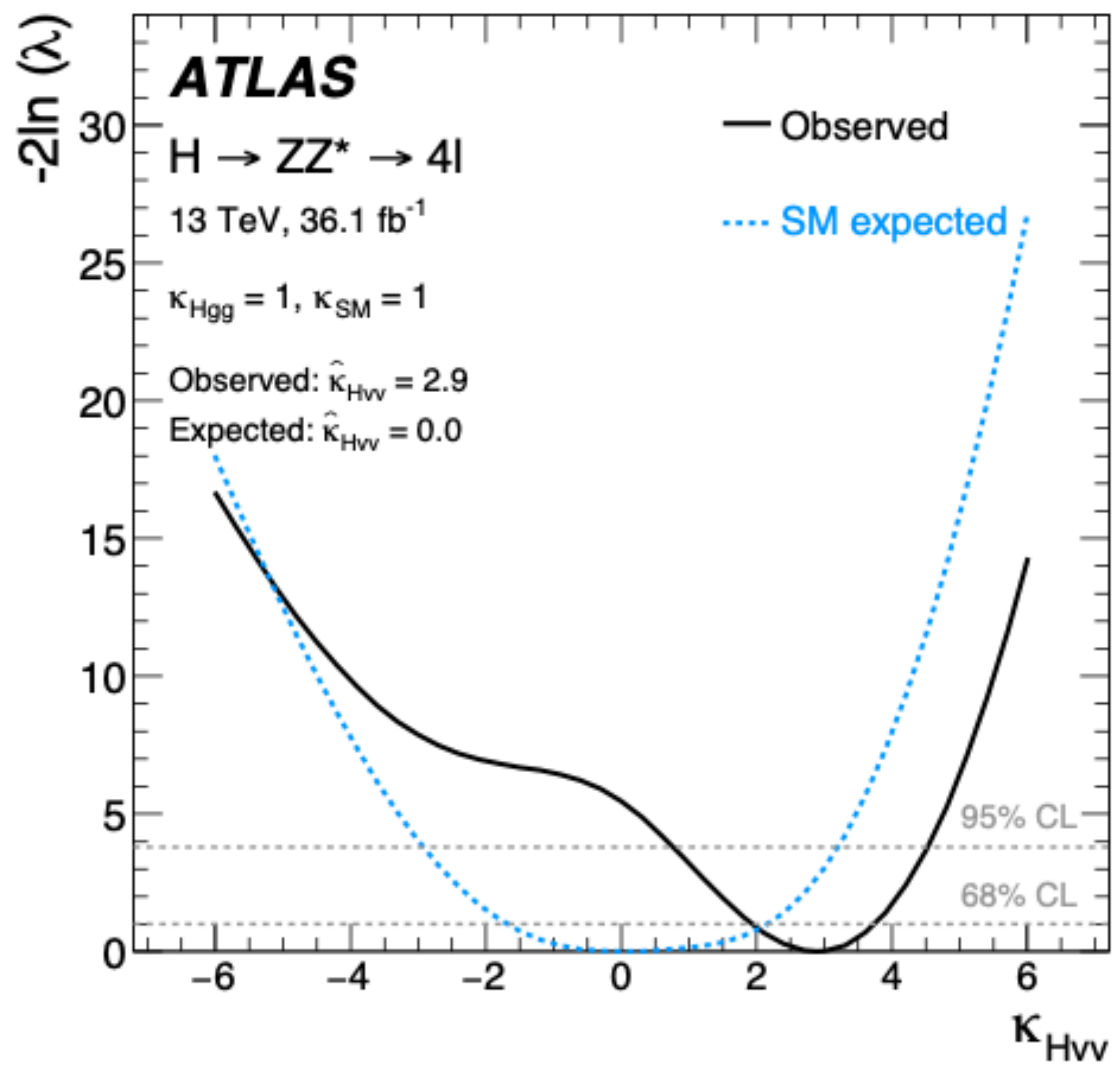


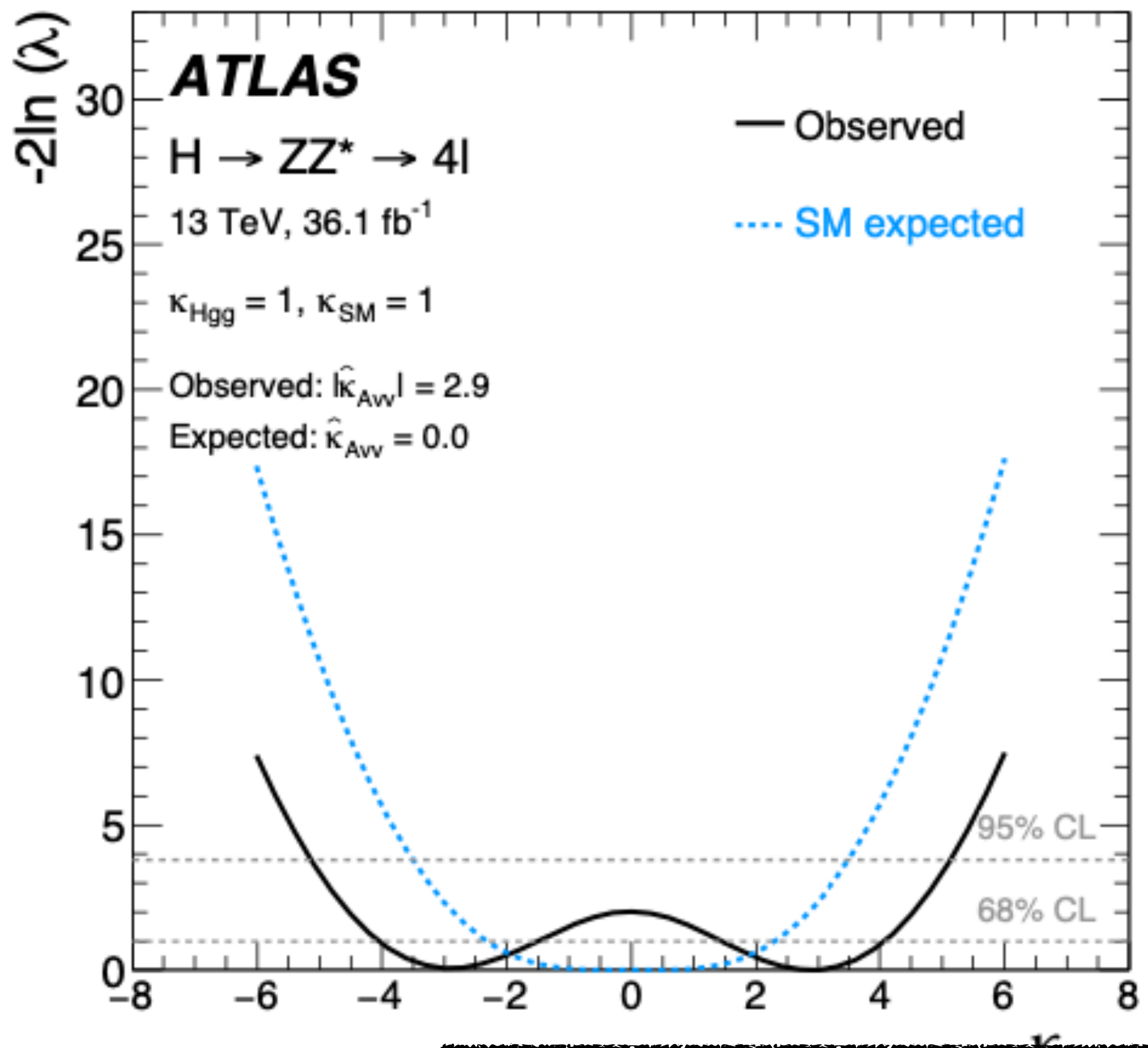
BSM coupling κ_{BSM}	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{BSM}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
κ_{Agg}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	$[-0.47, 0.47]$	$[-0.68, 0.68]$	± 0.43	-	1.8σ
κ_{HVV}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	$[-2.9, 3.2]$	$[0.8, 4.5]$	2.9	-	2.3σ
κ_{HVV}	$(\kappa_{Hgg} = 1, \kappa_{SM}$ free$)$	$[-3.1, 4.0]$	$[-0.6, 4.2]$	2.2	1.2	1.7σ
κ_{AVV}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	$[-3.5, 3.5]$	$[-5.2, 5.2]$	± 2.9	-	1.4σ
κ_{AVV}	$(\kappa_{Hgg} = 1, \kappa_{SM}$ free$)$	$[-4.0, 4.0]$	$[-4.4, 4.4]$	± 1.5	1.2	0.5σ

H → ZZ* → 4l, κ_{Agg}, κ_{HVV} AND κ_{AVV} FIT







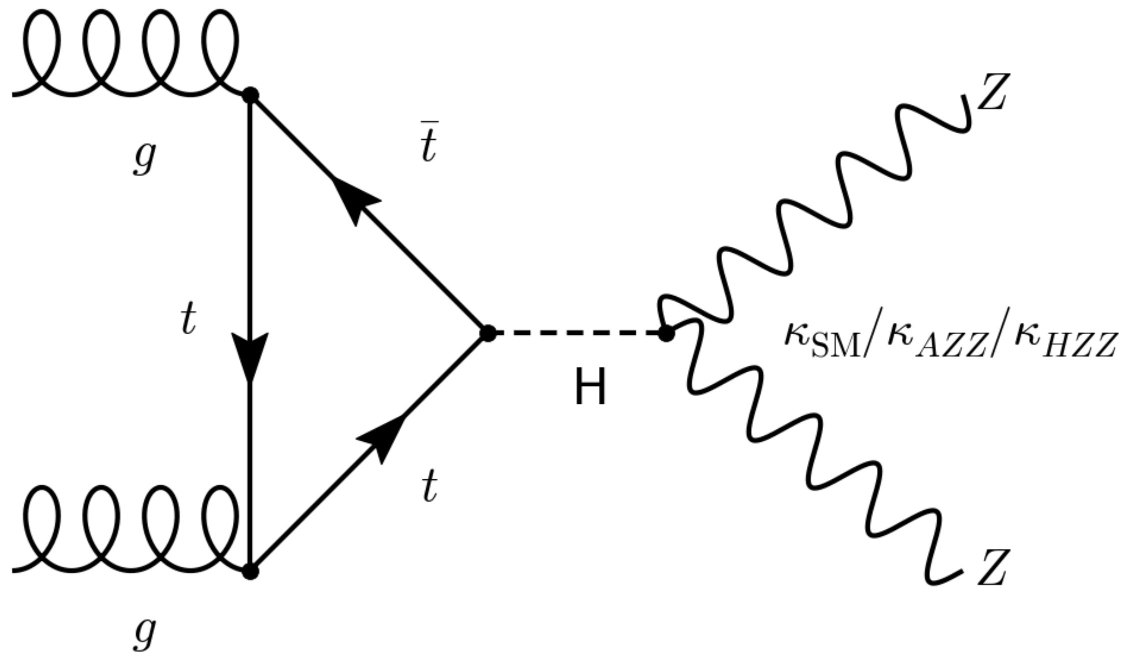


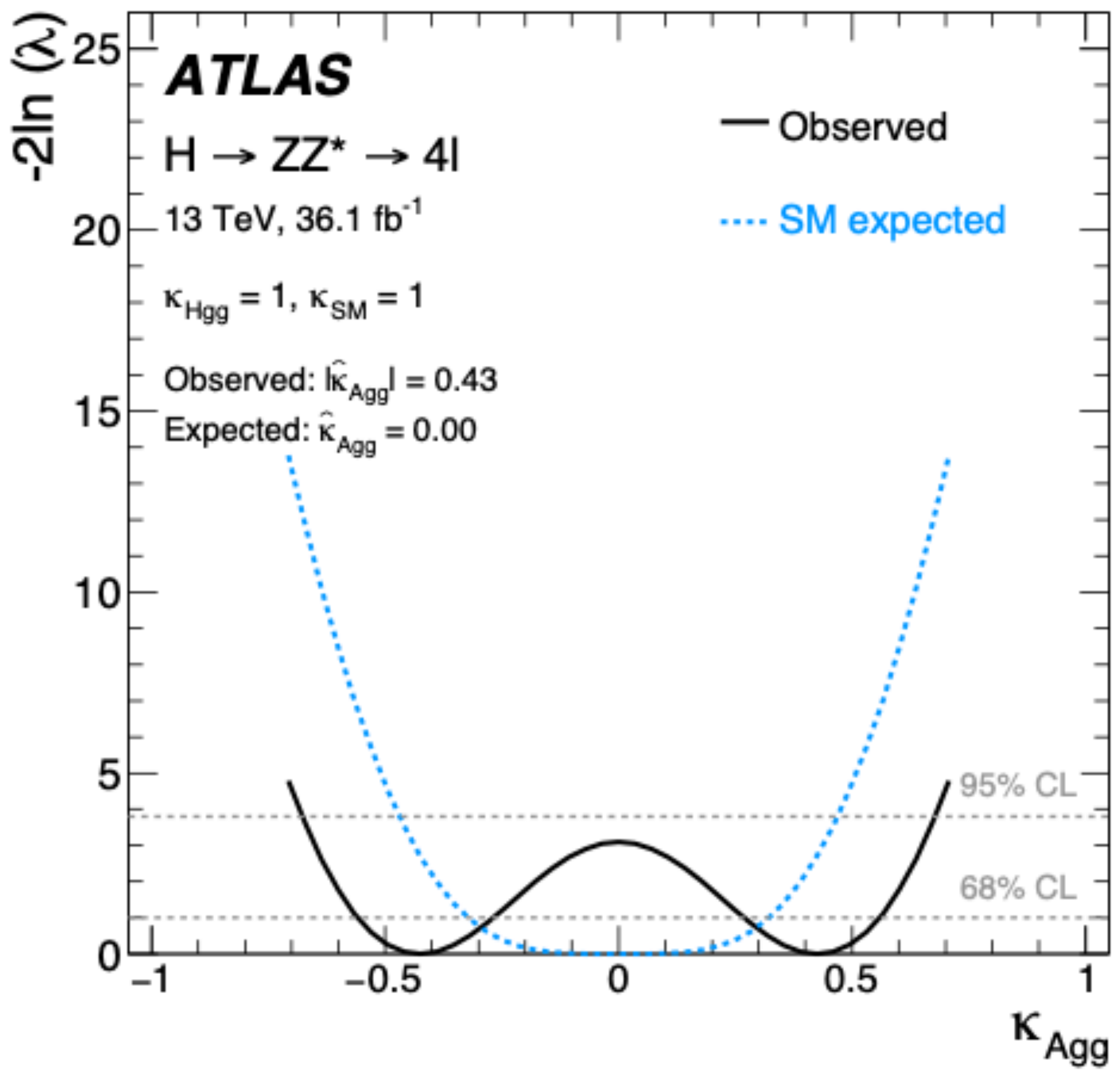
BSM coupling κ_{BSM}	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{BSM}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
κ_{Agg}	(κ_{Hgg} = 1, κ_{SM} = 1)	[−0.47, 0.47]	[−0.68, 0.68]	±0.43	-	1.8σ
κ_{HVV}	(κ_{Hgg} = 1, κ_{SM} = 1)	[−2.9, 3.2]	[0.8, 4.5]	2.9	-	2.3σ
κ_{HVV}	(κ_{Hgg} = 1, κ_{SM} free)	[−3.1, 4.0]	[−[illegible]6, 4.2]	2.2	1.2	1.7σ
κ_{AVV}	(κ_{Hgg} = 1, κ_{SM} = 1)	[−3.5, 3.5]	[−5.2, 5.2]	±2.9	-	1.4σ
κ_{AVV}	(κ_{Hgg} = 1, κ_{SM} free)	[−4.0, 4.0]	[−[illegible]4, 4.4]	±1.5	1.2	0.5σ

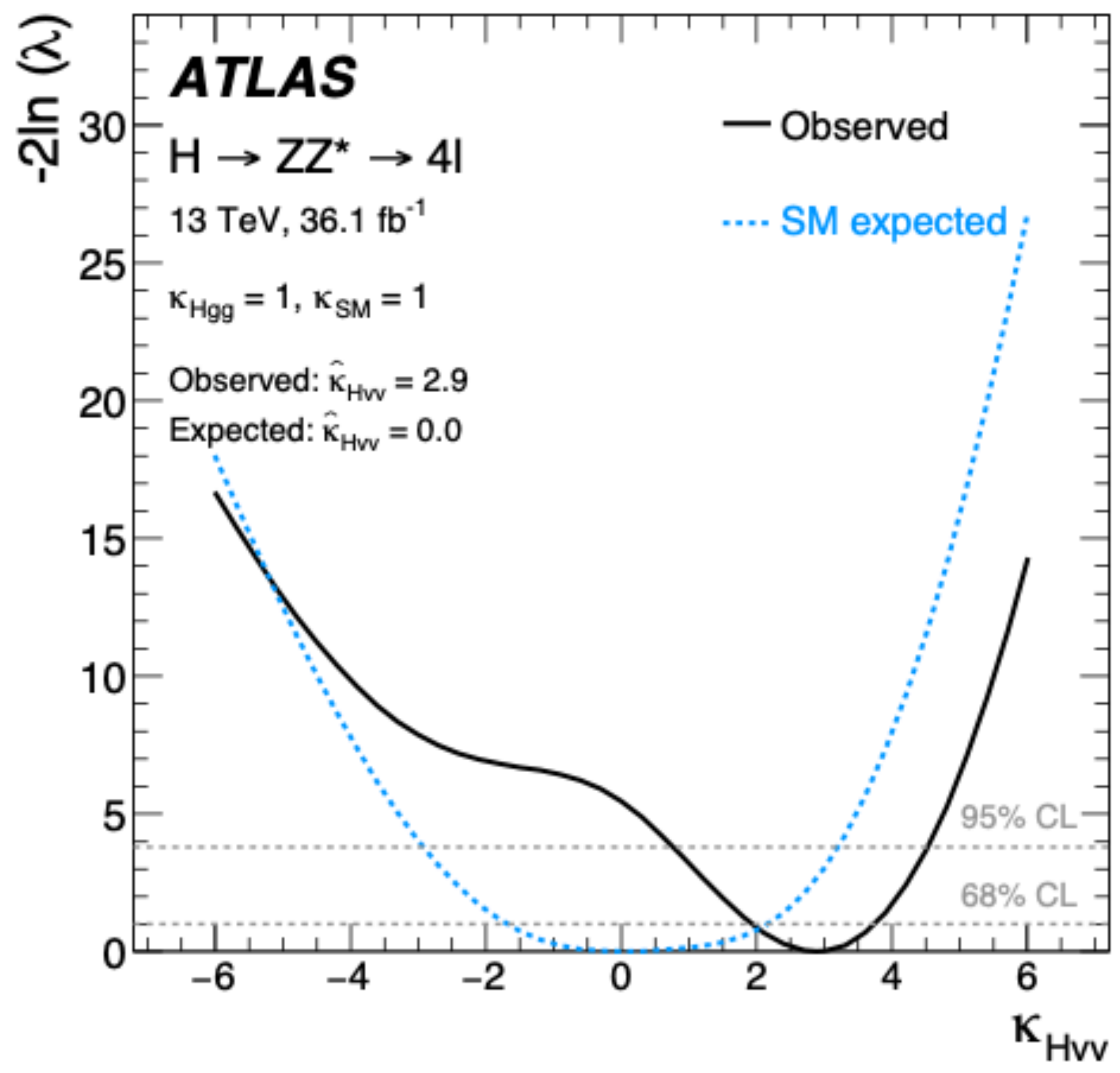
If κ_{SM} is left free in the fit, the expected limits on the BSM couplings decrease by up to 10%

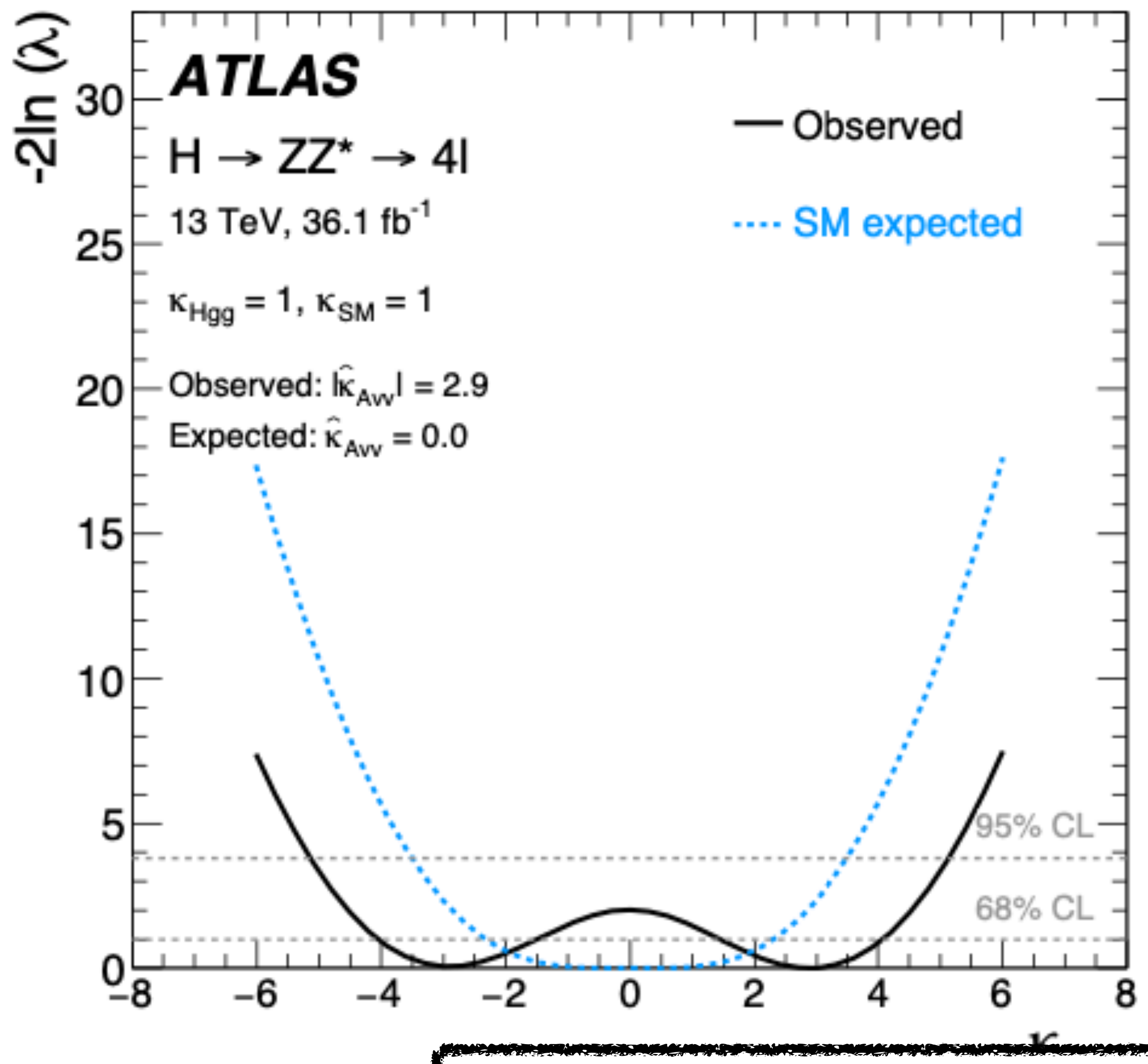
Nikhef

H → ZZ* → 4l, κ_{Agg}, κ_{HVV} AND κ_{AVV} FIT







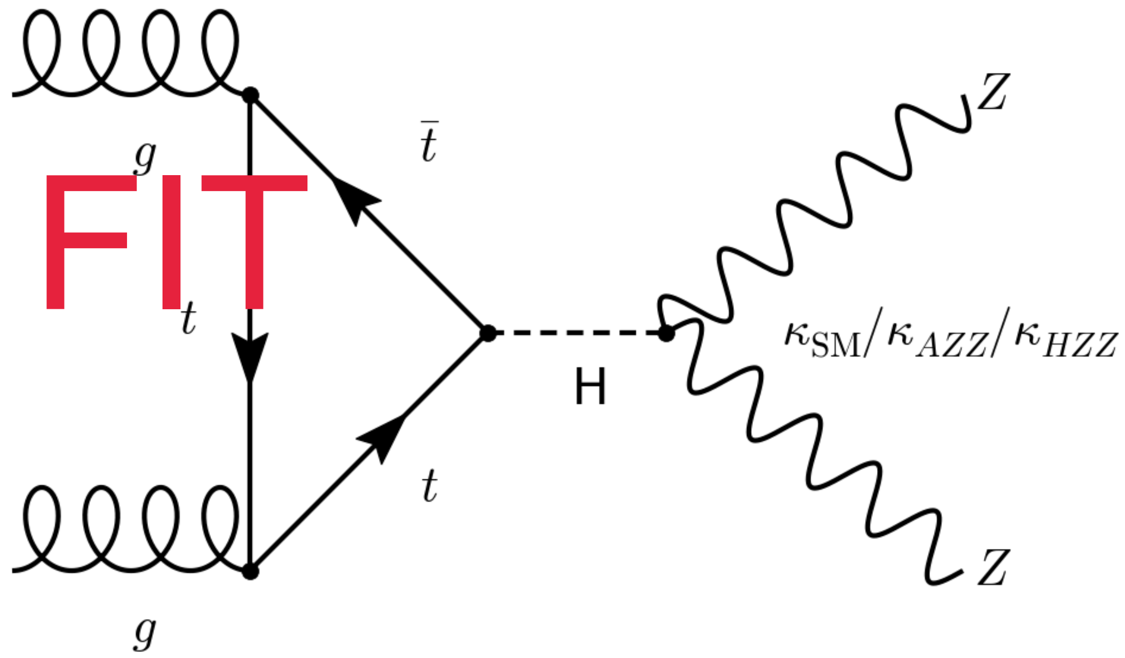


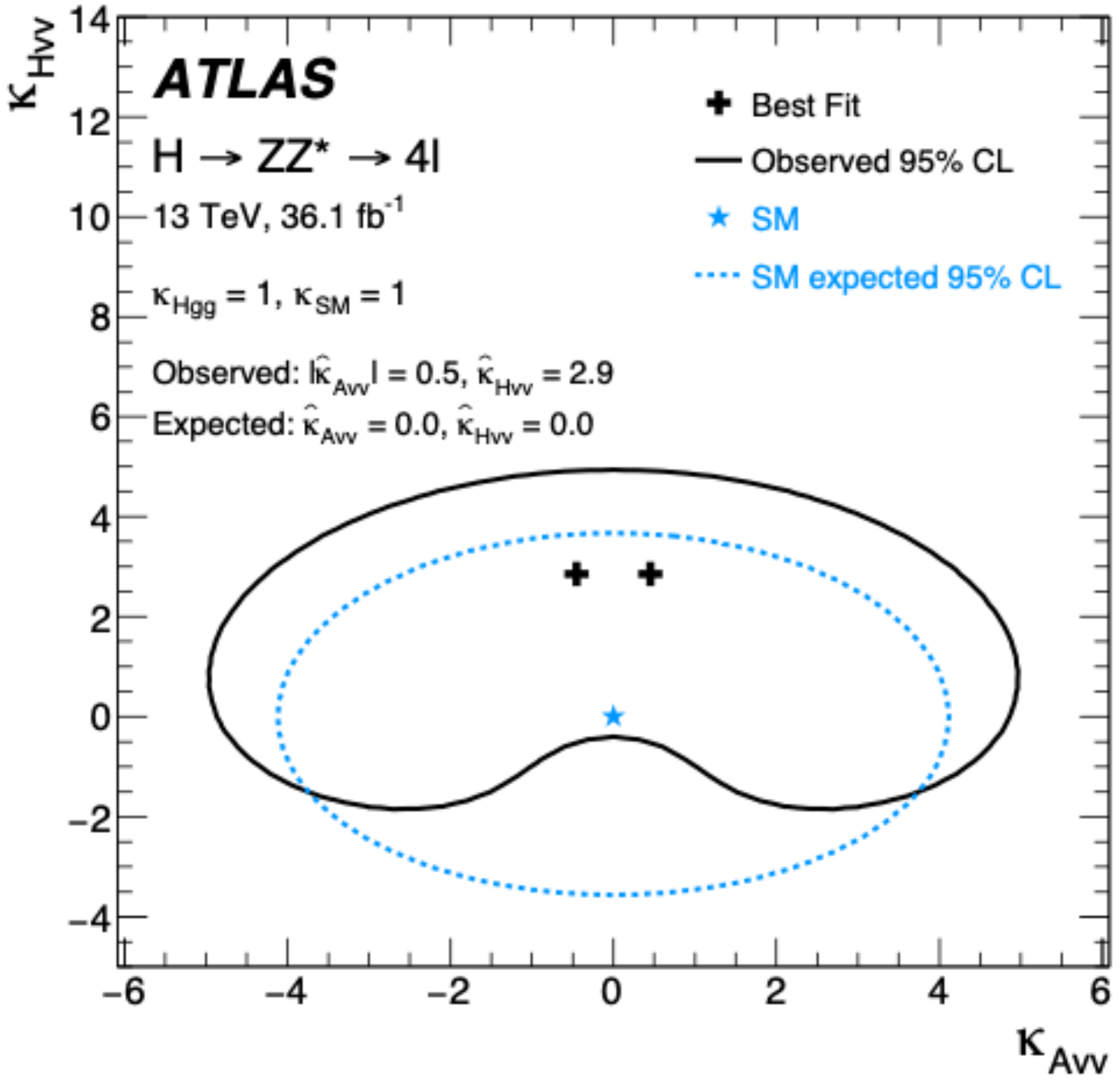
BSM coupling κ_{BSM}	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{BSM}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
κ_{Agg}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	[−0.47, 0.47]	[−0.68, 0.68]	±0.43	-	1.8σ
κ_{HVV}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	[−2.9, 3.2]	[0.8, 4.5]	2.9	-	2.3σ
κ_{HVV}	$(\kappa_{Hgg} = 1, \kappa_{SM}$ free)	[−3.1, 4.0]	[−0.6, 4.2]	2.2	1.2	1.7σ
κ_{AVV}	$(\kappa_{Hgg} = 1, \kappa_{SM} = 1)$	[−3.5, 3.5]	[−5.2, 5.2]	±2.9	-	1.4σ
κ_{AVV}	$(\kappa_{Hgg} = 1, \kappa_{SM}$ free)	[−4.0, 4.0]	[−4.4, 4.4]	±1.5	1.2	0.5σ

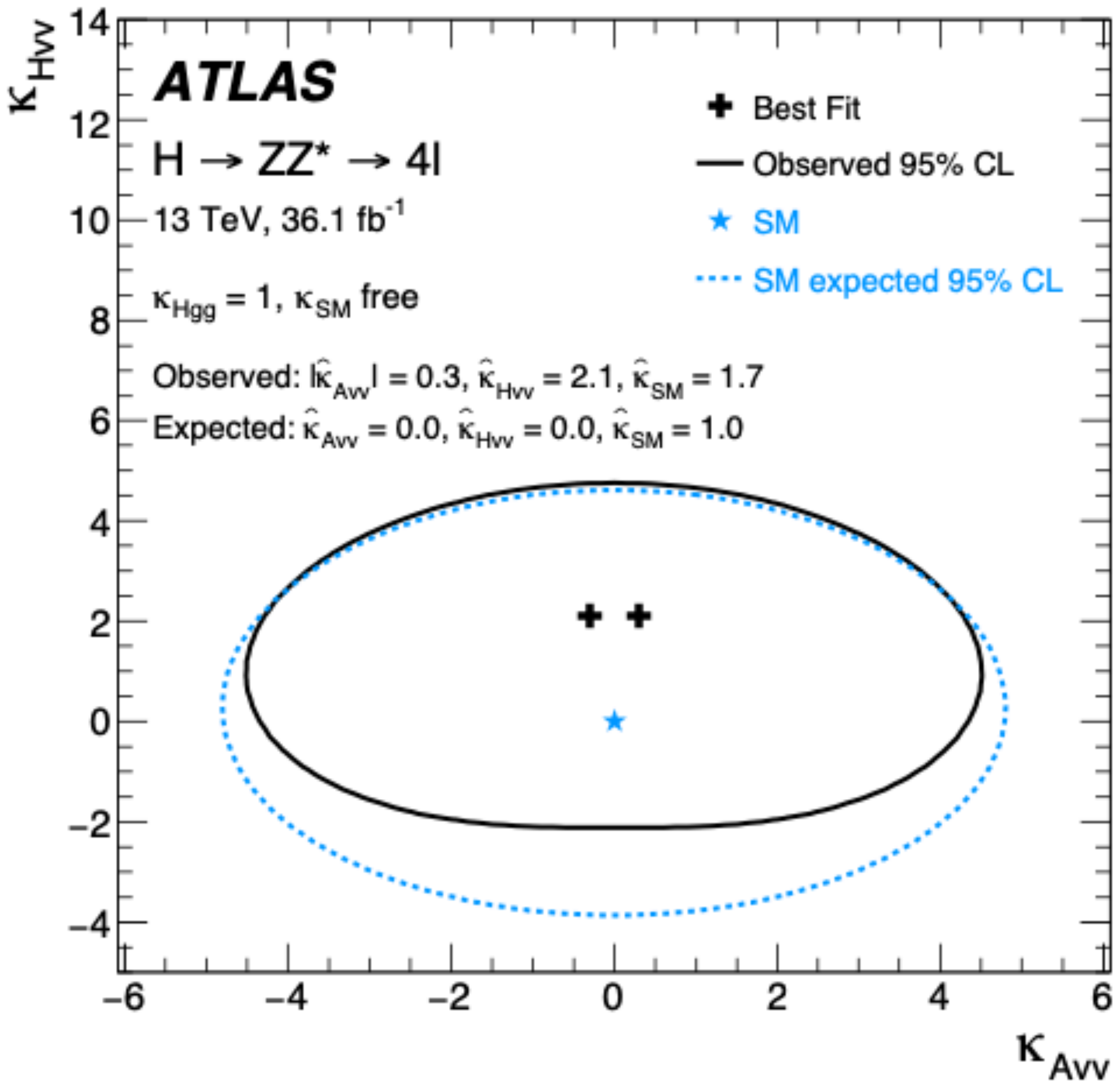
The deviation of the BSM couplings from the SM decreases because of the increase of the value of $\hat{\kappa}_{SM}$

Nikhef

$H \rightarrow ZZ^* \rightarrow 4l$, κ_{HVV}, κ_{AVV} SIMULTANEOUS FIT



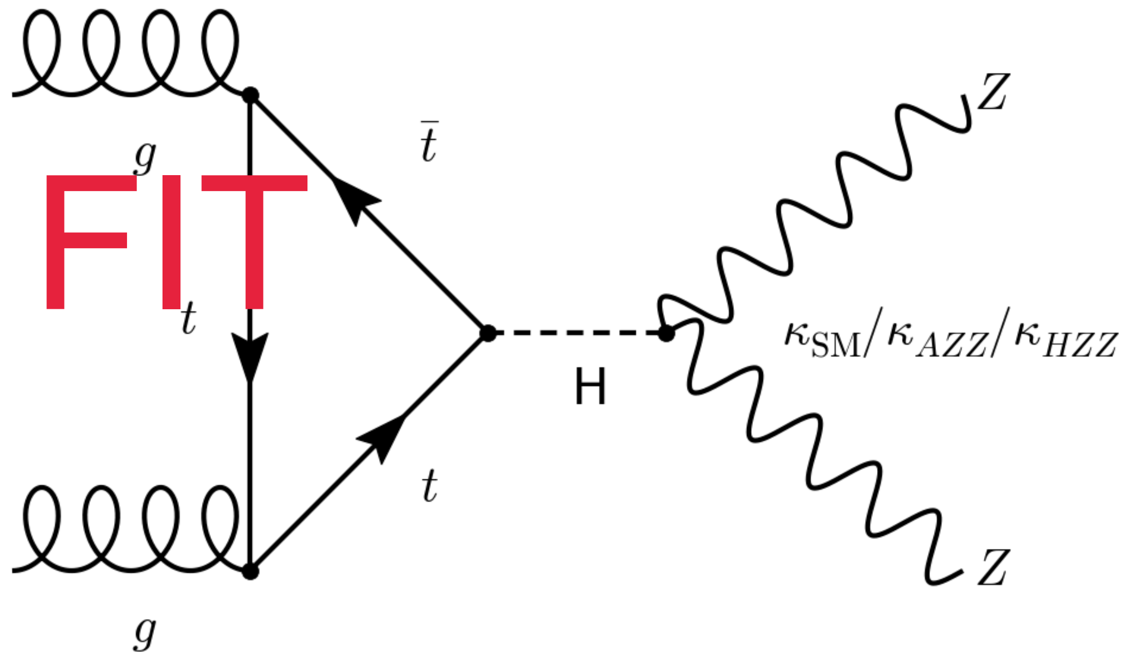


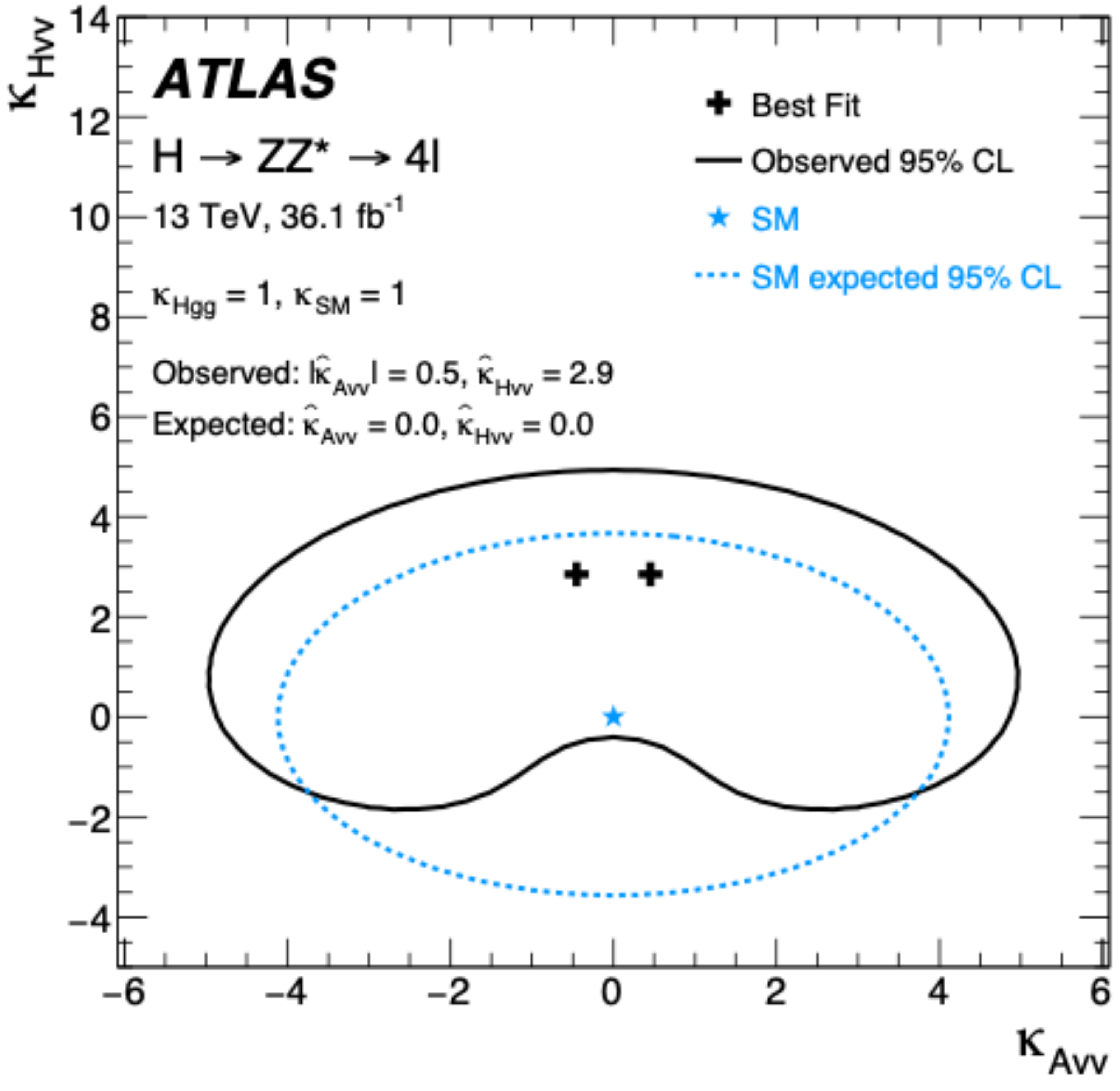


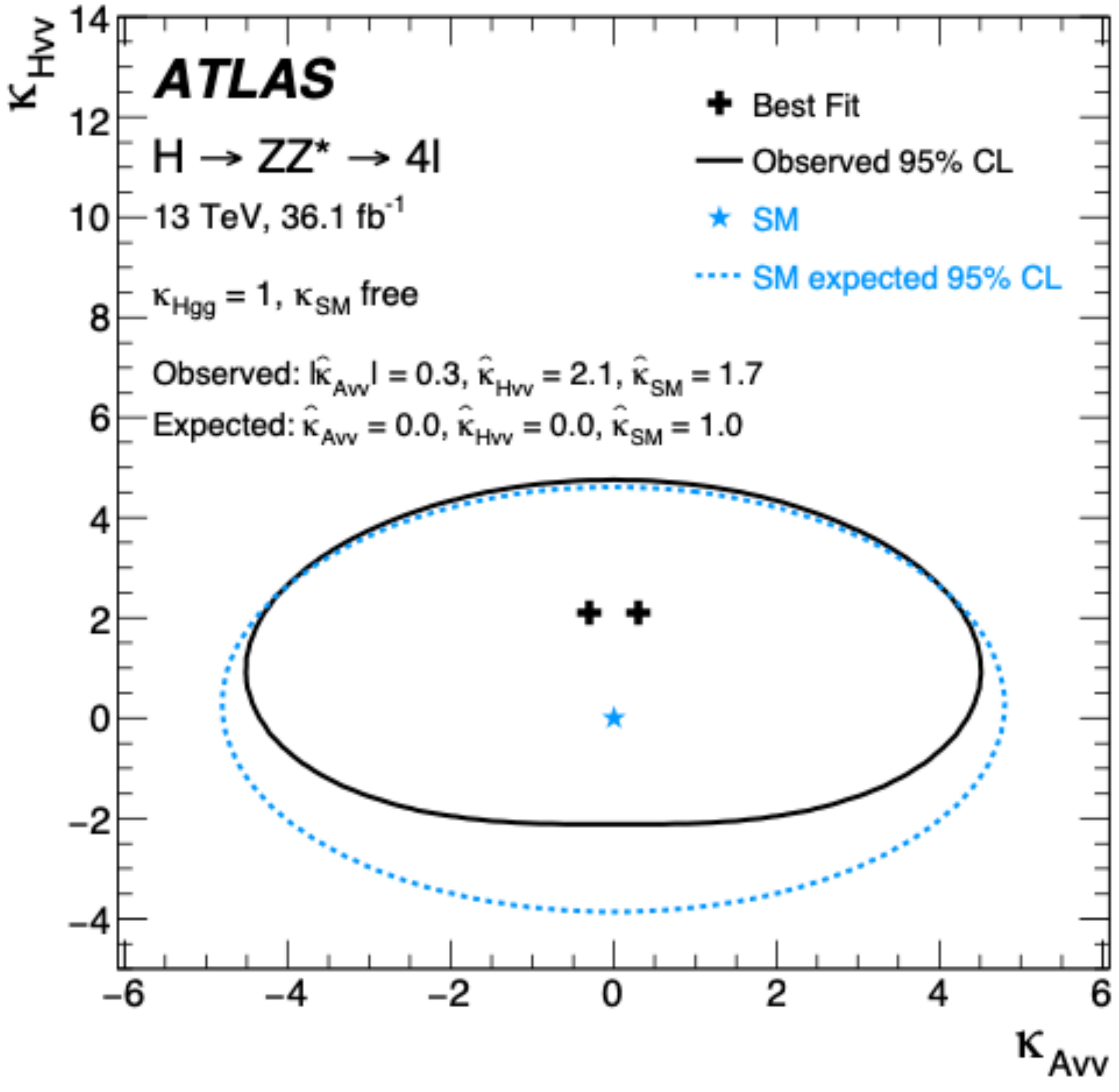
Asymmetric because of κ_{HVV}

κ_{SM} can contribute to absorb the asymmetry

$H \to ZZ^* \to 4l$, κ_{HVV}, κ_{AVV} SIMULTANEOUS FIT



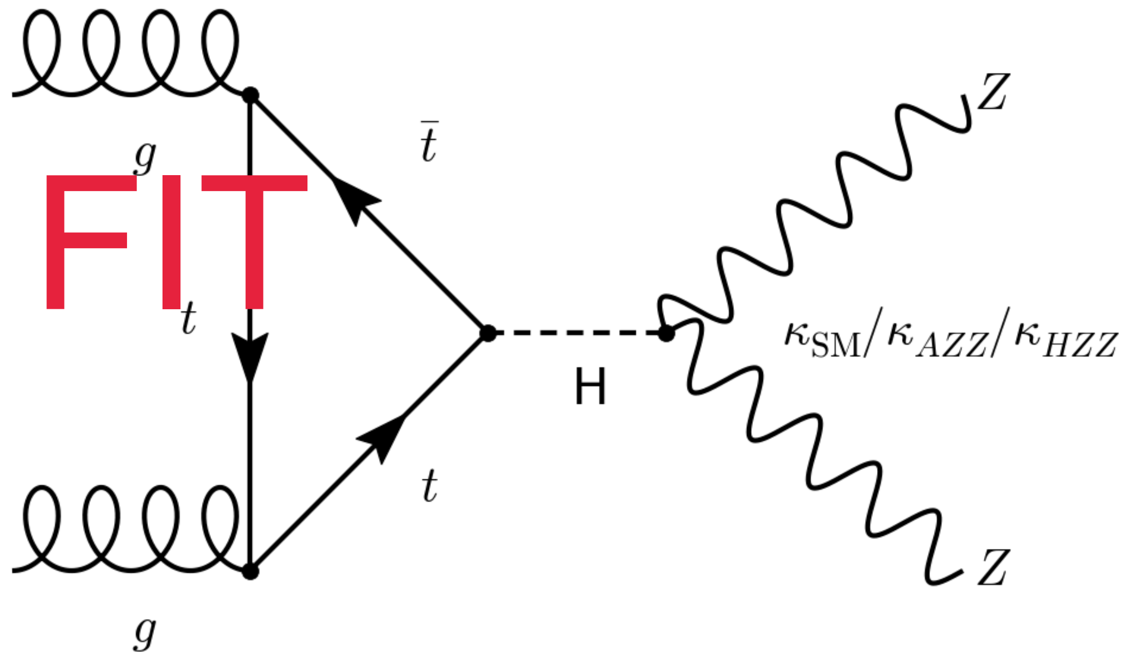


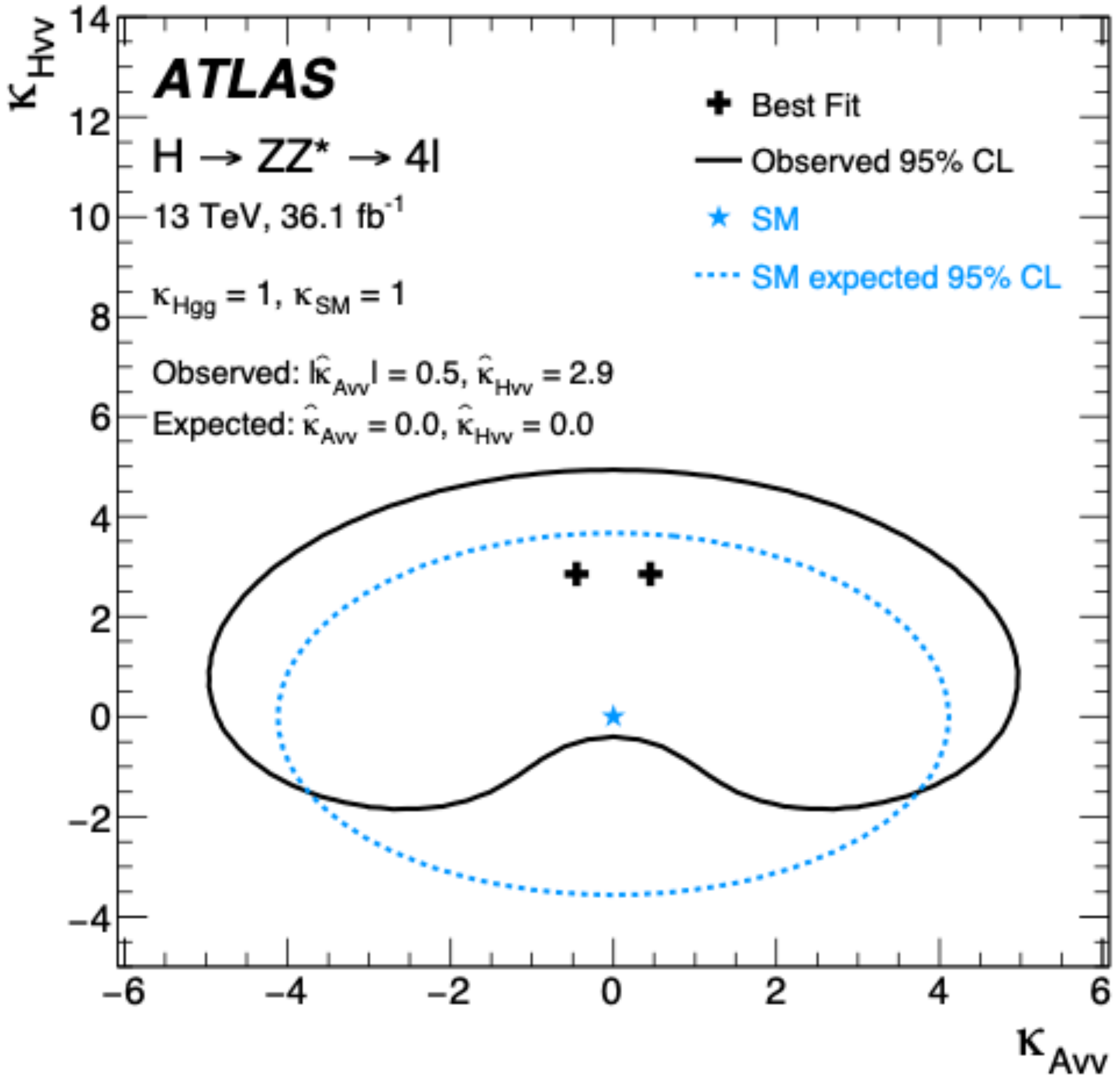


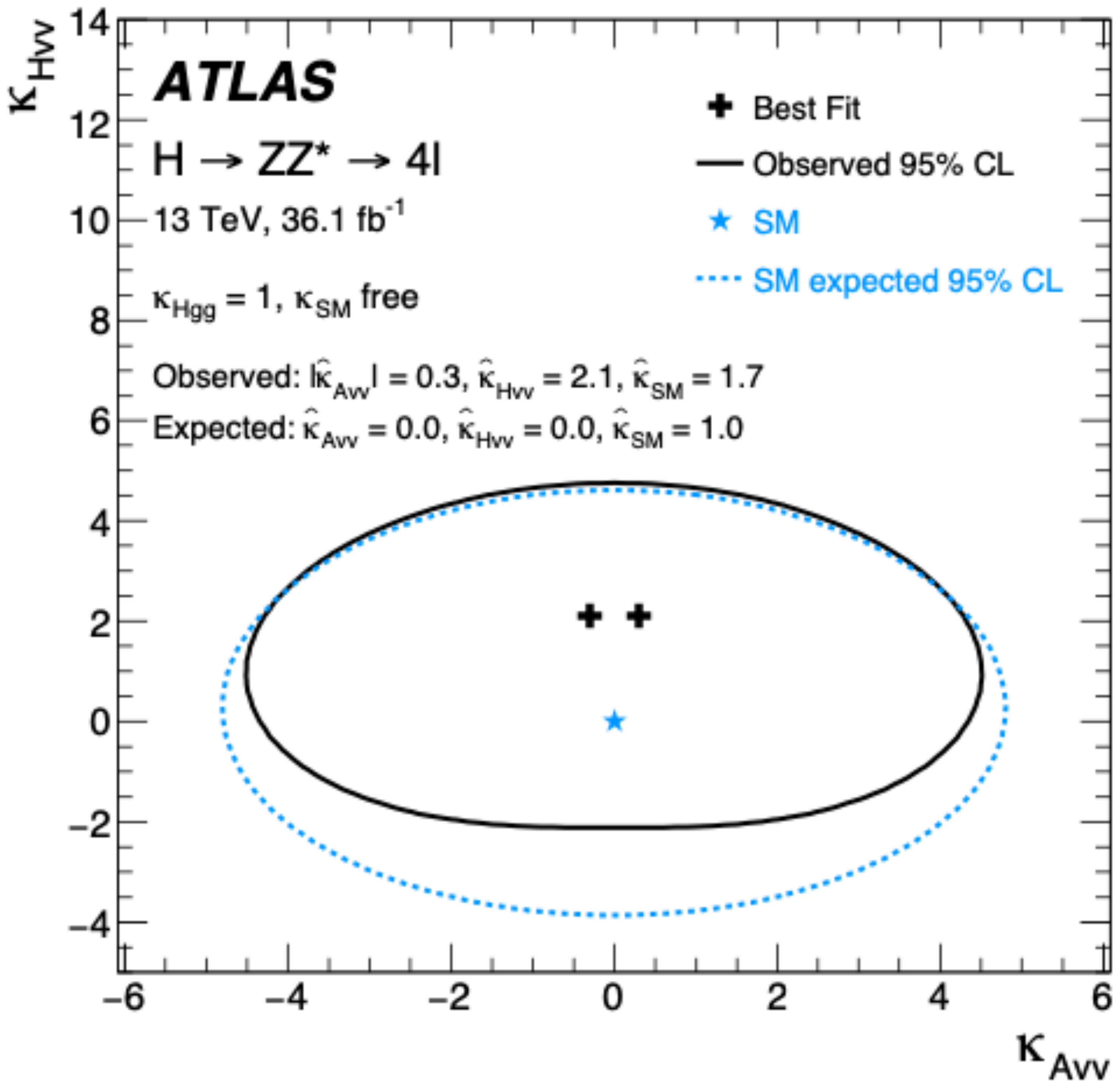
Fit configuration	Best-fit $\hat{\kappa}_{HVV}$	Best-fit $\hat{\kappa}_{AVV}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
$\kappa_{Hgg} = 1$, $\kappa_{SM} = 1$	2.9	± 0.5	-	1.9σ
$\kappa_{Hgg} = 1$, κ_{SM} free	2.1	± 0.3	1.7	1.2σ

Nikhef

H → $ZZ^* \to 4l$, $\kappa_{HVV}, \kappa_{AVV}$ SIMULTANEOUS FIT



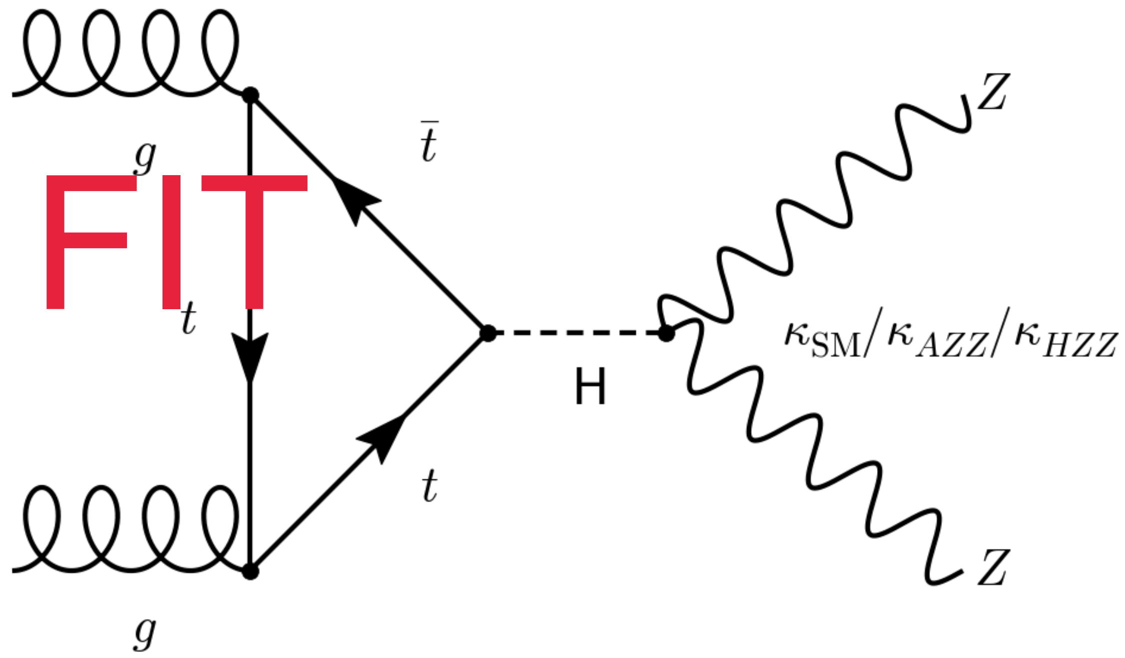


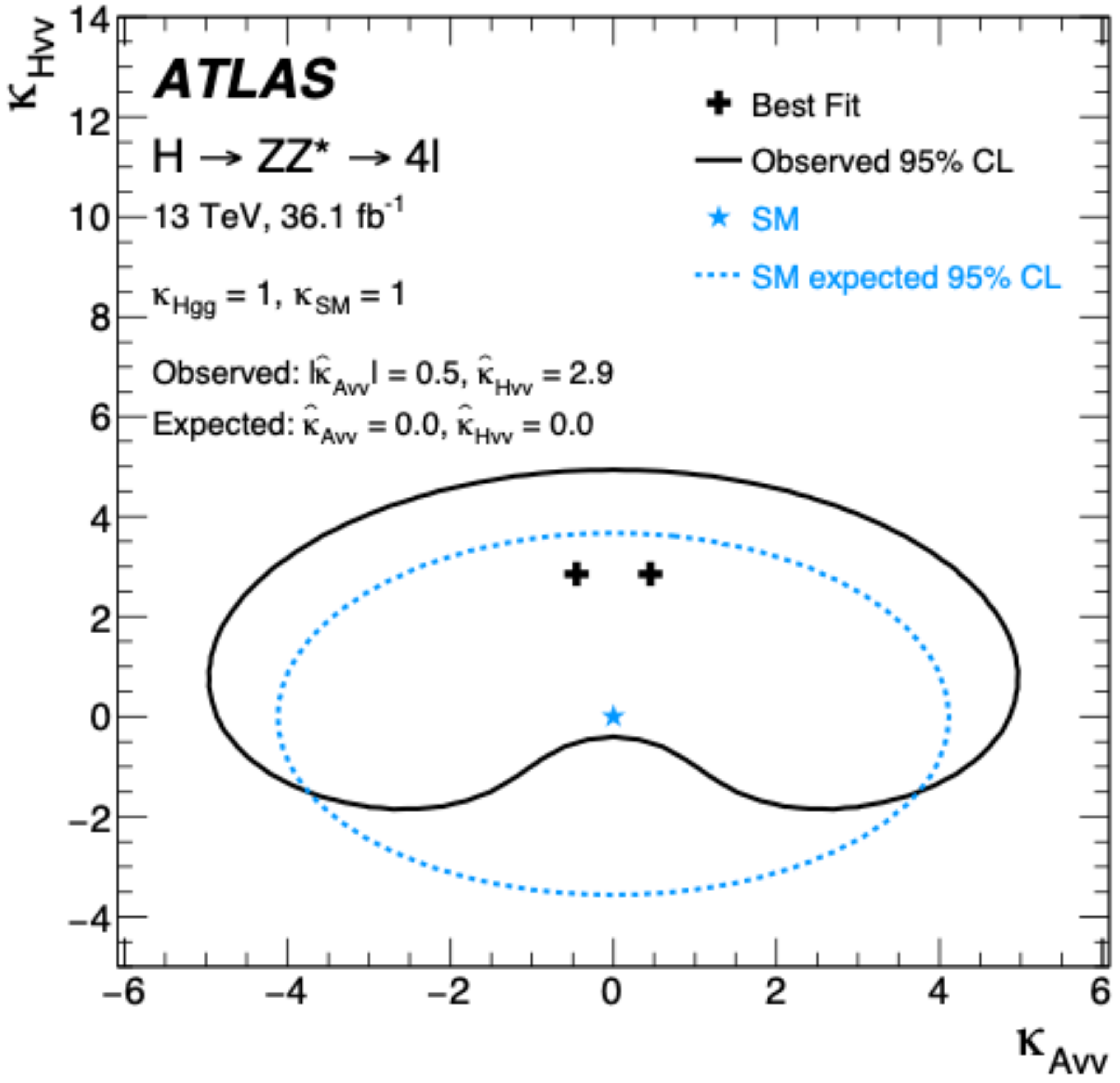


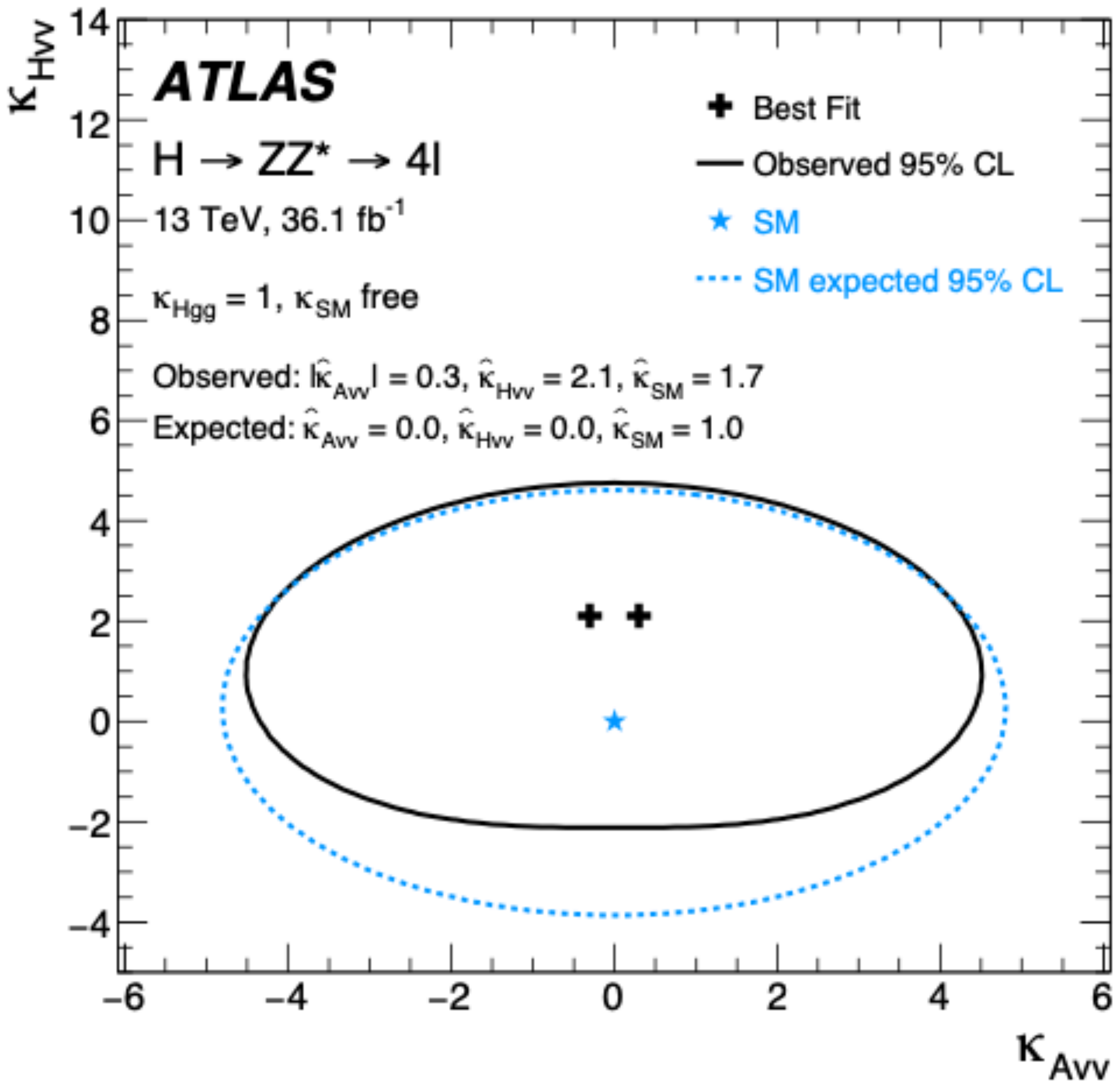
Fit configuration	Best-fit $\hat{\kappa}_{HVV}$	Best-fit $\hat{\kappa}_{AVV}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
$\kappa_{Hgg} = 1, \kappa_{SM} = 1$	2.9	±0.5		1.9σ
$\kappa_{Hgg} = 1, \kappa_{SM}$ free	2.1	±0.3	1.7	1.2σ

$\hat{\kappa}_{HVV}$ obtained from the 2D scan is similar to the one obtained in the 1D scan.

$H \rightarrow ZZ^* \rightarrow 4l$, $\kappa_{HVV}, \kappa_{AVV}$ SIMULTANEOUS FIT







Fit configuration	Best-fit $\hat{\kappa}_{HVV}$	Best-fit $\hat{\kappa}_{AVV}$	Best-fit $\hat{\kappa}_{SM}$	Deviation from SM
$\kappa_{Hgg} = 1$, $\kappa_{SM} = 1$	2.9	± 0.5		~~1.9σ~~
$\kappa_{Hgg} = 1$, κ_{SM} free	2.1	± 0.3	1.7	1.2σ

$\hat{\kappa}_{AVV}$ obtained from the 2D scan is closer to the SM than the corresponding value from the 1D scan.