Measurements of the CP structure of Higgs-boson couplings with the ATLAS detector

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on behalf of the ATLAS collaboration

ATLAS EXPERIMENT

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CP Violation in the Higgs Sector?

- **CP violating processes are necessary** requirement to explain matter-/antimatter (baryon) asymmetry in the universe (Sakharov conditions)

- Direct and indirect CP violation is **experimentally well established in the SM**:
  - Complex phases in CKM-matrix (quark mixing) and possibly in PNMS-matrix (neutrino mixing)
  - Not sufficient to explain observed baryon asymmetry in the universe

- Could Higgs boson interactions be another source of CP violation?
  - Pure CP-odd Higgs boson at $m_H \approx 125$ GeV has been ruled out during Run 1
  - Mixing of scalar (CP-even) and pseudo-scalar (CP-odd) Higgs bosons in extended Higgs sector models (2HDM, …)
  - BSM particles contributing to loops (e.g. ggF production)

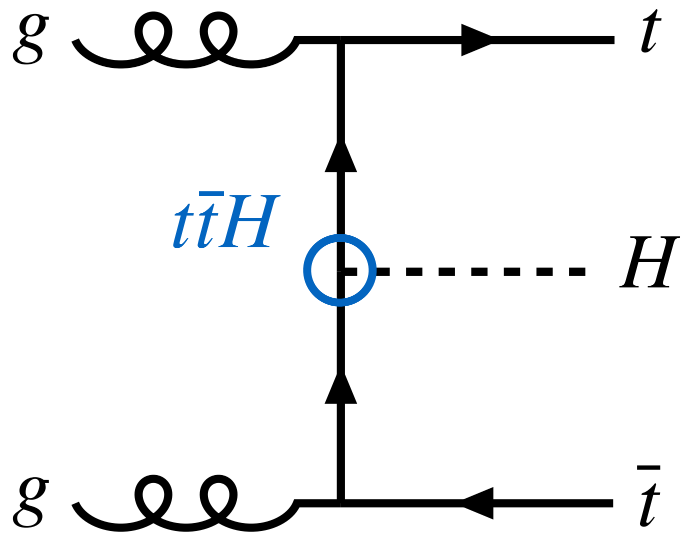
Overview

- Higgs CP analyses covered in this talk using Run 2 data:
  - $ttH(\to\gamma\gamma)$ [Phys. Rev. Lett. 125 (2020) 061802], $\mathscr{L}_{int} = 139\,\text{fb}^{-1}$, probing ttH
  - $ttH(\to bb)$ [ATLAS-CONF-2022-016], $\mathscr{L}_{int} = 139\,\text{fb}^{-1}$, probing ttH
  - $pp \to jjWW(\to e\nu\mu\nu)$ [arxiv:2109.13808], $\mathscr{L}_{int} = 36.1\,\text{fb}^{-1}$, probing ggH

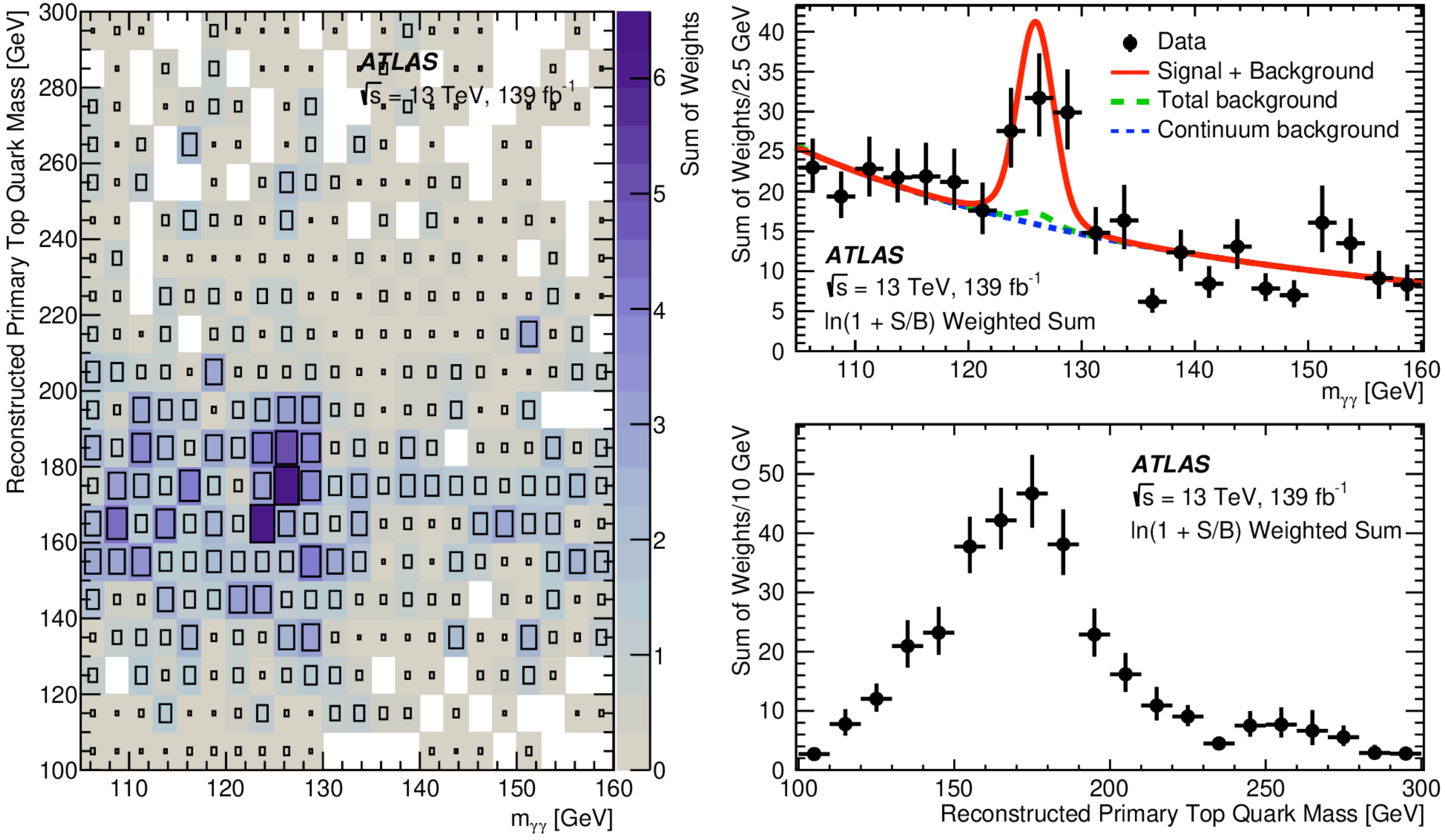
- Previous results by ATLAS (not covered here)
  - $H \to \tau\tau$ in VBF production [Phys. Lett. B 805 (2020) 135426], $\mathscr{L}_{int} = 36.1\,\text{fb}^{-1}$, $\sqrt{s} = 13$ TeV, probing VVH
  - $H \to \tau\tau$ in VBF production [Eur. Phys. J. C 76 (2016) 658], $\mathscr{L}_{int} = 20\,\text{fb}^{-1}$, $\sqrt{s} = 8$ TeV, probing VVH
  - $H \to WW \to e\nu\mu\nu$, $H \to ZZ \to 4\ell$, $(H \to \gamma\gamma)$ [Eur. Phys. J. C 75 (2015) 476], $\mathscr{L}_{int} = 25\,\text{fb}^{-1}$, $\sqrt{s} = 7$ and 8 TeV, probing VVH

Higgs CP in $t\bar{t}H(\rightarrow \gamma\gamma)$

- 2 isolated "tight" photons with $p_T^{\gamma_1} > 35$ GeV, $p_T^{\gamma_2} > 25$ GeV, at least one b-tagged jet with $p_T > 25$ GeV (77% eff. WP)
- Reconstruction of t-quark candidates:
  - **Had category**: lepton veto, reconstruct hadronic t-quark decay candidate using a BDT: find most-likely 3 jet combination, repeat for second hadronic t-quark decay using remaining jets
  - **Lep category**: no t-quark reconstruction in case of 2ℓ. For 1ℓ build W-candidate from $\ell + E_T^{\text{miss}}$, combine with jet that forms highest top BDT, find second hadronic t-quark decay with BDT from remaining jets



Phys. Rev. Lett. 125 (2020) 061802

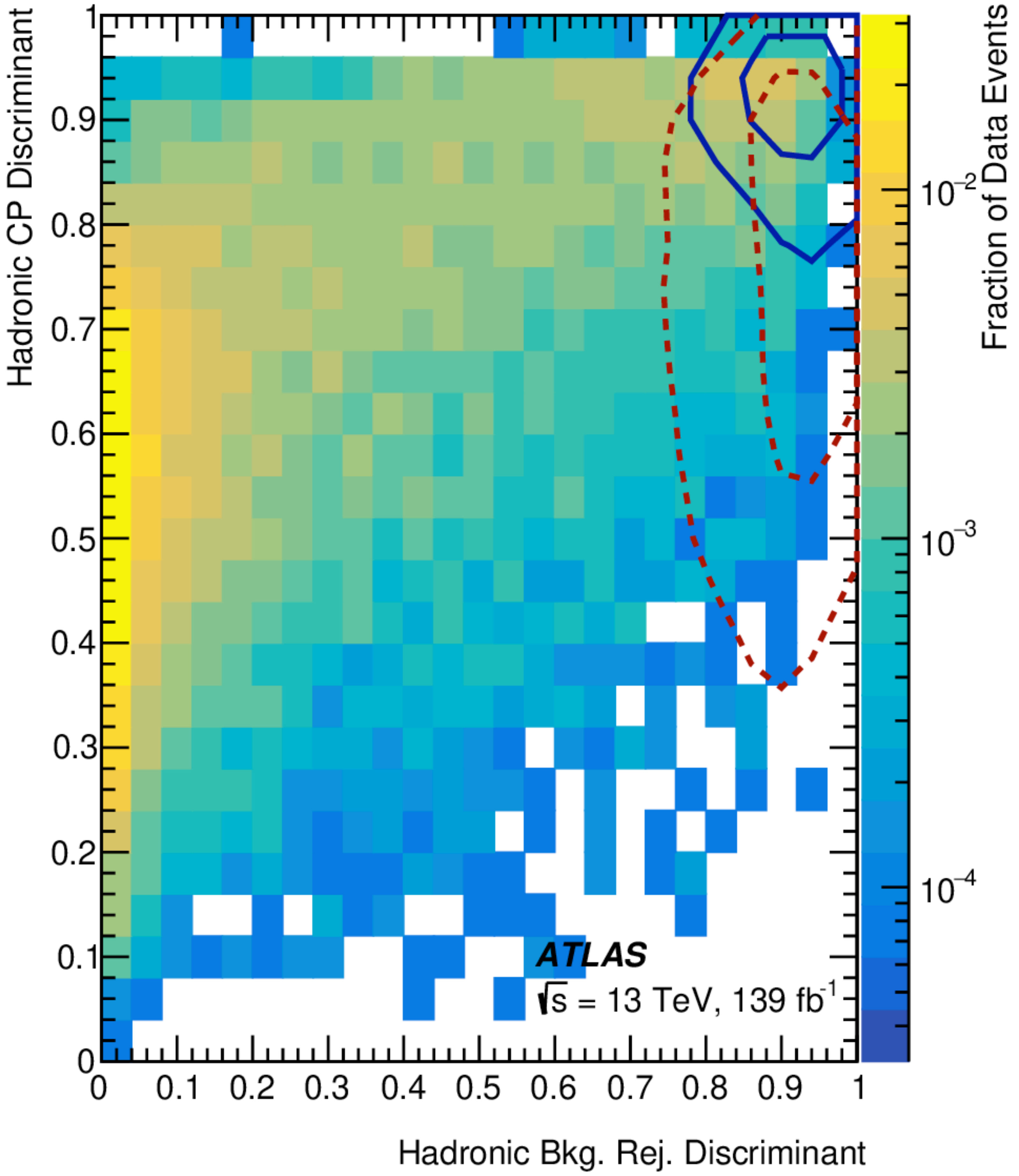


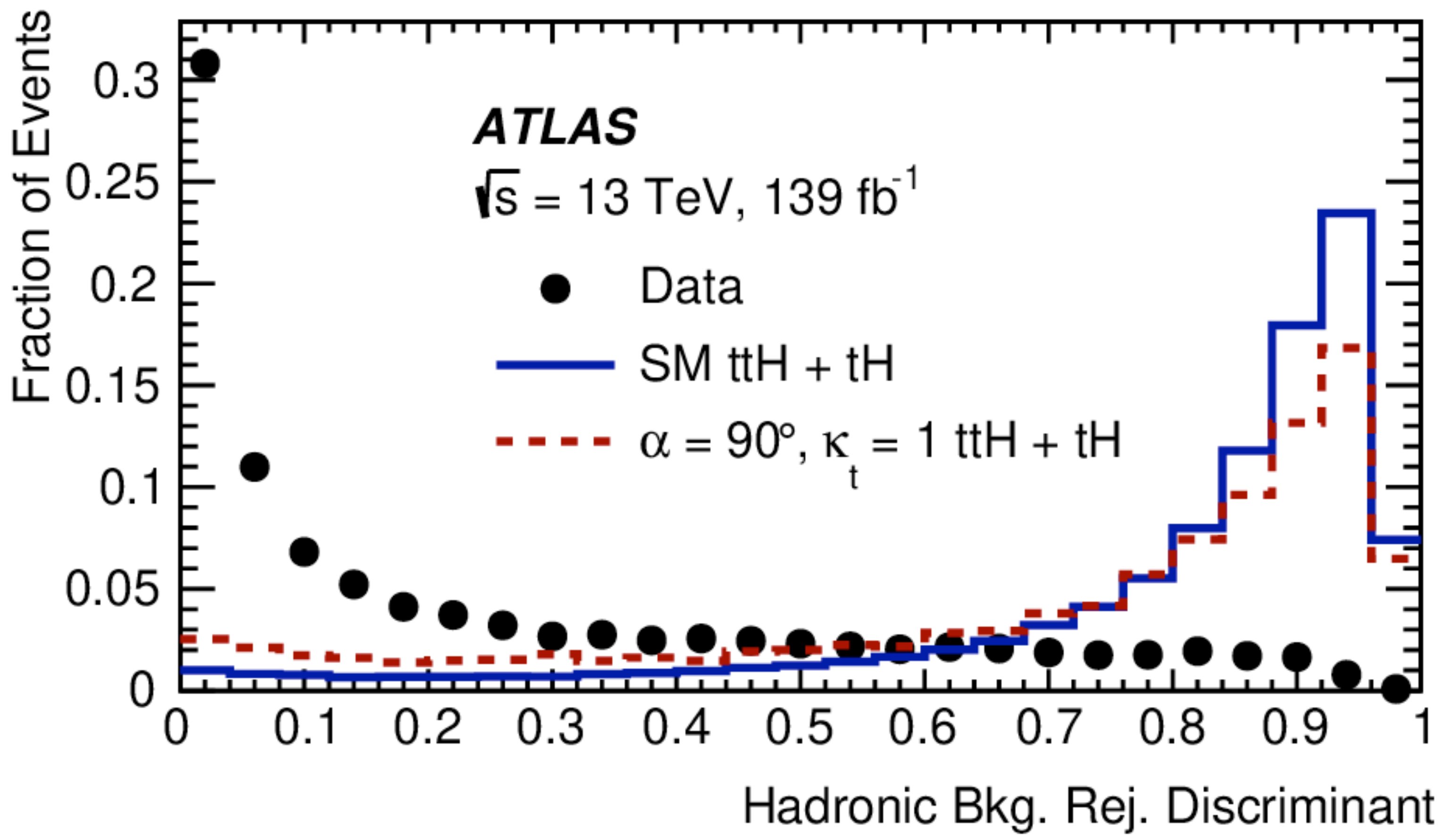
Selection and $t\bar{t}$ reconstruction follows closely $ttH(\rightarrow\gamma\gamma)$ measurement (Phys. Lett. B 784 (2018) 173)

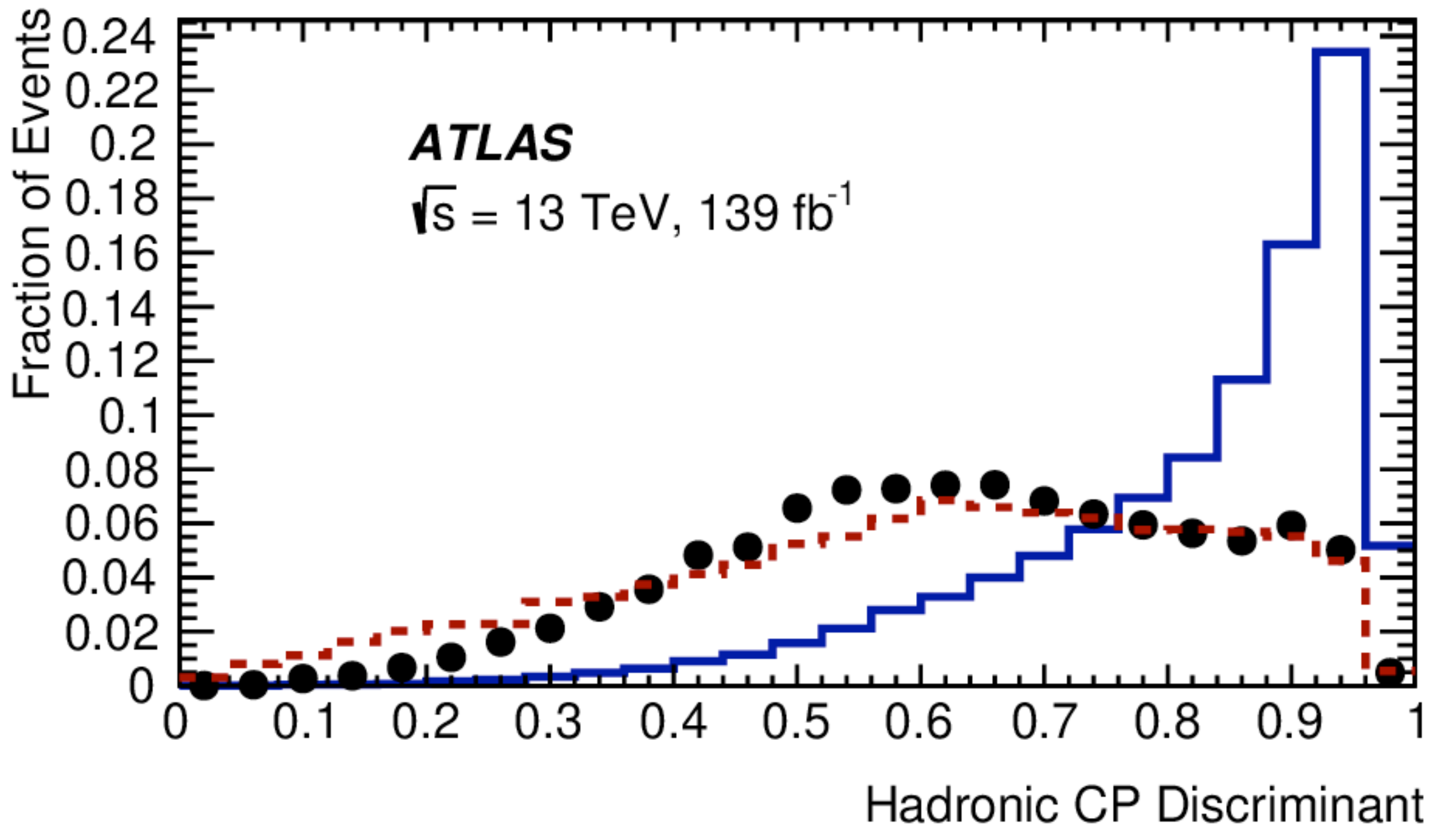
Higgs CP in $t\bar{t}H(\rightarrow \gamma\gamma)$

Phys. Rev. Lett. 125 (2020) 061802

- Dedicated Lep and Had **BDTs to reject background** from $\gamma\gamma +$ jets and $t\bar{t}\gamma\gamma$ (using 4-vectors of γ's, ℓ's, jets and b-tag information)
- Used BDT score to define 20 signal regions (12 in Had and 8 in Lep category)
- **CP BDT to separate CP-even and CP-odd** signal hypothesis (p_T, η of $\gamma\gamma$ and t-quark systems, invariant masses, angular differences, E_T^{miss})



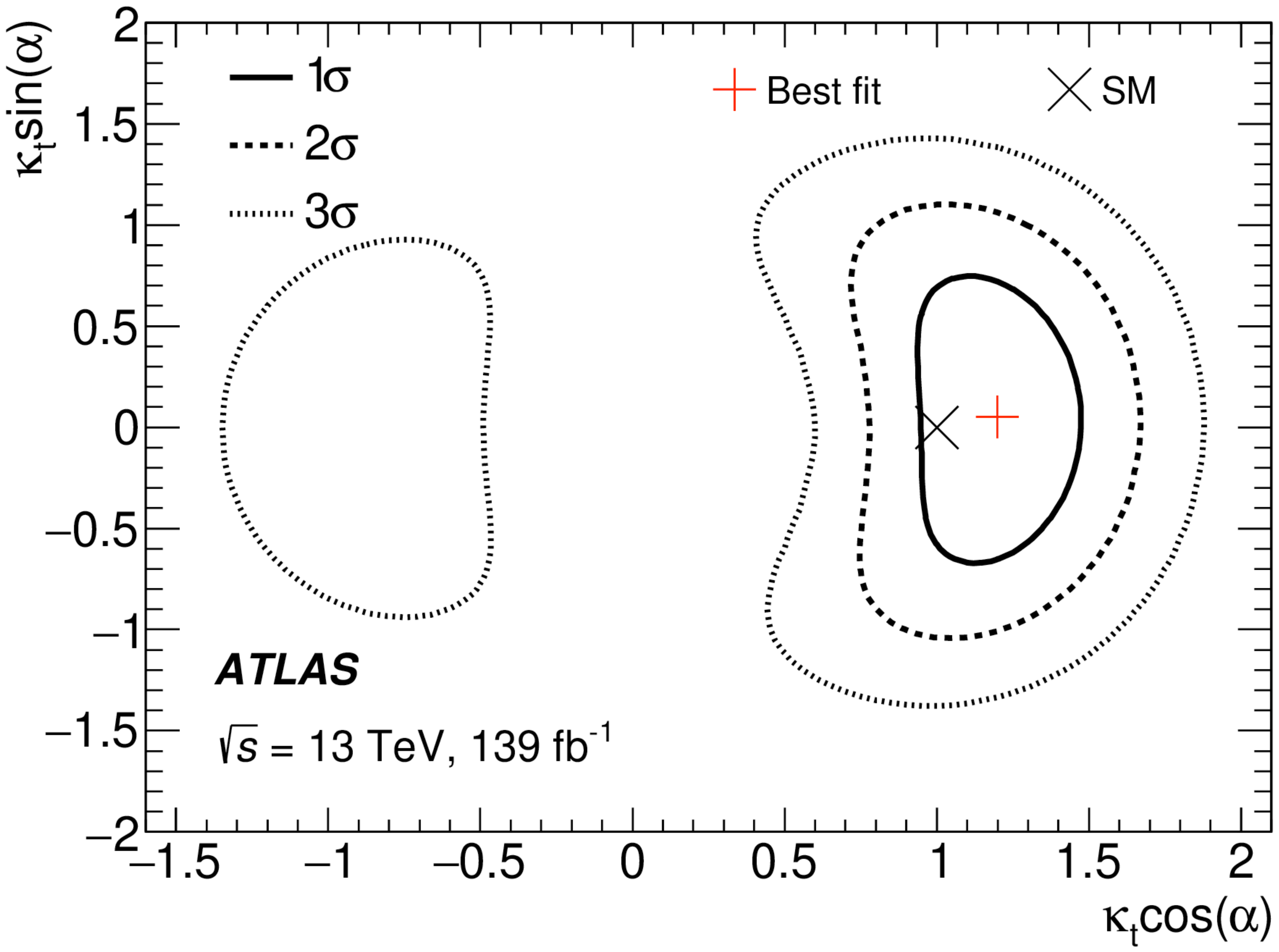




Higgs CP in $t\bar{t}H(\rightarrow \gamma\gamma)$

Phys. Rev. Lett. 125 (2020) 061802

- Simultaneous maximum likelihood fit in all signal regions to constrain CP-mixing angle α and coupling strength κ_t
- Best fit result:
  $\mu_{ttH} = 1.43^{+0.33}_{-0.31}$ (stat.)$^{+0.17}_{-0.14}$ (sys.)
  (assuming SM $BR_{H\rightarrow\gamma\gamma}$)
- Pure CP-odd coupling excluded at 3.9σ (2.5σ expected)
- $|\alpha| < 43^\circ$ (56° expected)
- The result is limited by statistical uncertainties



$$\mathscr{L} = -\frac{m_t}{v}\left\{\tilde{\Psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\Psi_t\right\} H$$

Higgs CP in $t\bar{t}H(\rightarrow b\bar{b})$

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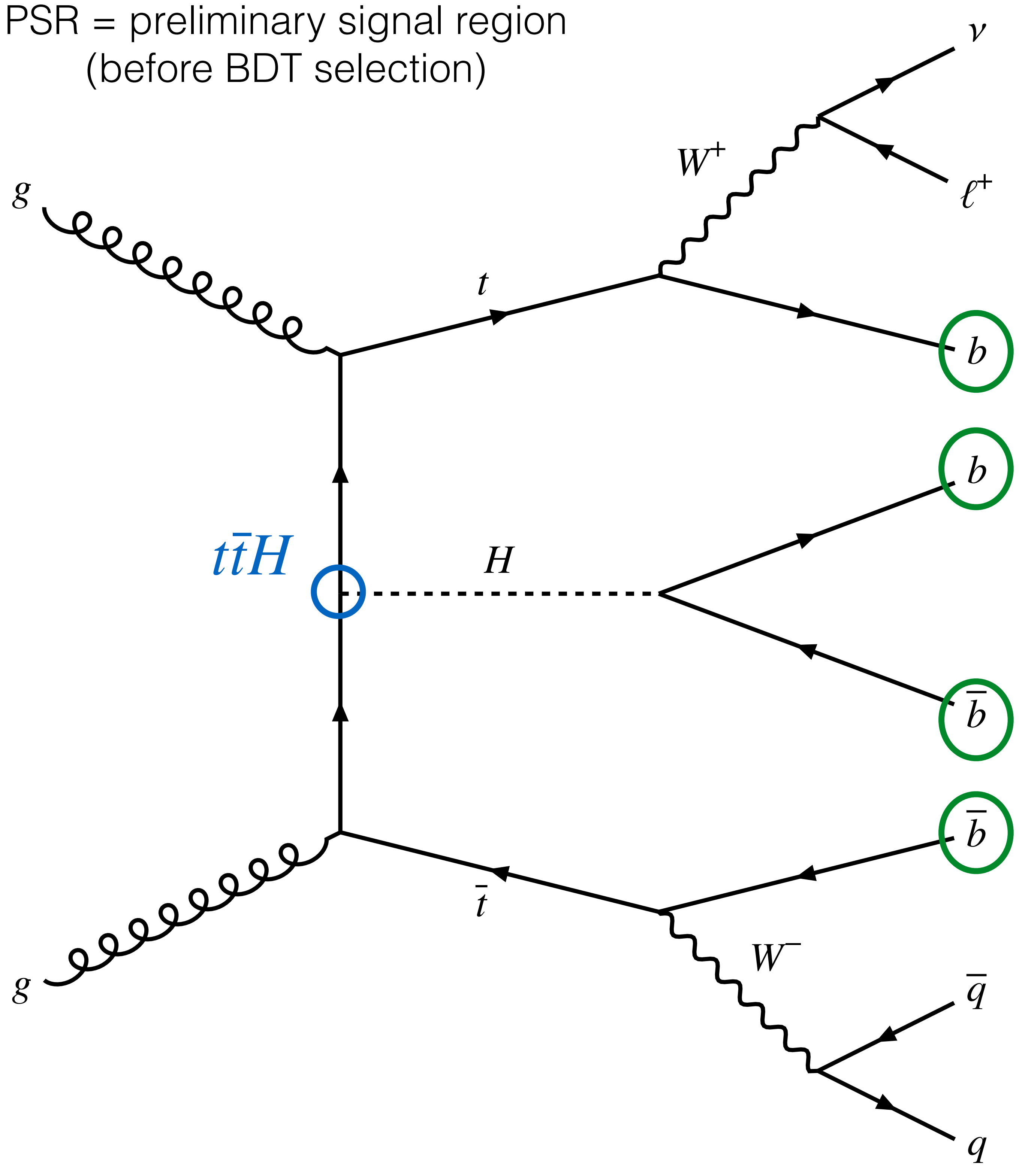
Region		Dilepton				ℓ+jets			
		$\mathrm{PSR}^{\geq 4j,\geq 4b}$	$\mathrm{CR}^{\geq 4j,3b}_{\mathrm{hi}}$	$\mathrm{CR}^{\geq 4j,3b}_{\mathrm{lo}}$	$\mathrm{CR}^{3j,3b}_{\mathrm{hi}}$	$\mathrm{PSR}^{\geq 6j,\geq 4b}$	$\mathrm{CR}^{5j,\geq 4b}_{\mathrm{hi}}$	$\mathrm{CR}^{5j,\geq 4b}_{\mathrm{lo}}$	$\mathrm{PSR}_{\mathrm{boosted}}$
N_{jets}		≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
$N_{b\mathrm{-tag}}$	@85%	–				≥ 4			
	@77%	–				–			$\geq 2^{\dagger}$
	@70%	≥ 4	$= 3$			≥ 4			–
	@60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
$N_{\mathrm{boosted\ cand.}}$		–				0			≥ 1

PSR = preliminary signal region
(before BDT selection)



- Complex final state with 4 b-quarks and additional jets and leptons
- ℓ+jets channel: 1 isolated lepton, at least 5 jets and 4 b-tagged jets
    - Boosted H production covered in dedicated category: require an $R = 1.0$ anti-k_T jet with $m_{jet} > 50$ GeV and $p_T > 200$ GeV
- Di-lepton channel: 2 (oppositely charged) leptons, at least 3 jets and 3 b-tagged jets
- Define various signal and control regions depending on the number of jets and number of b-tagged jets

Higgs CP in $t\bar{t}H(\rightarrow b\bar{b})$

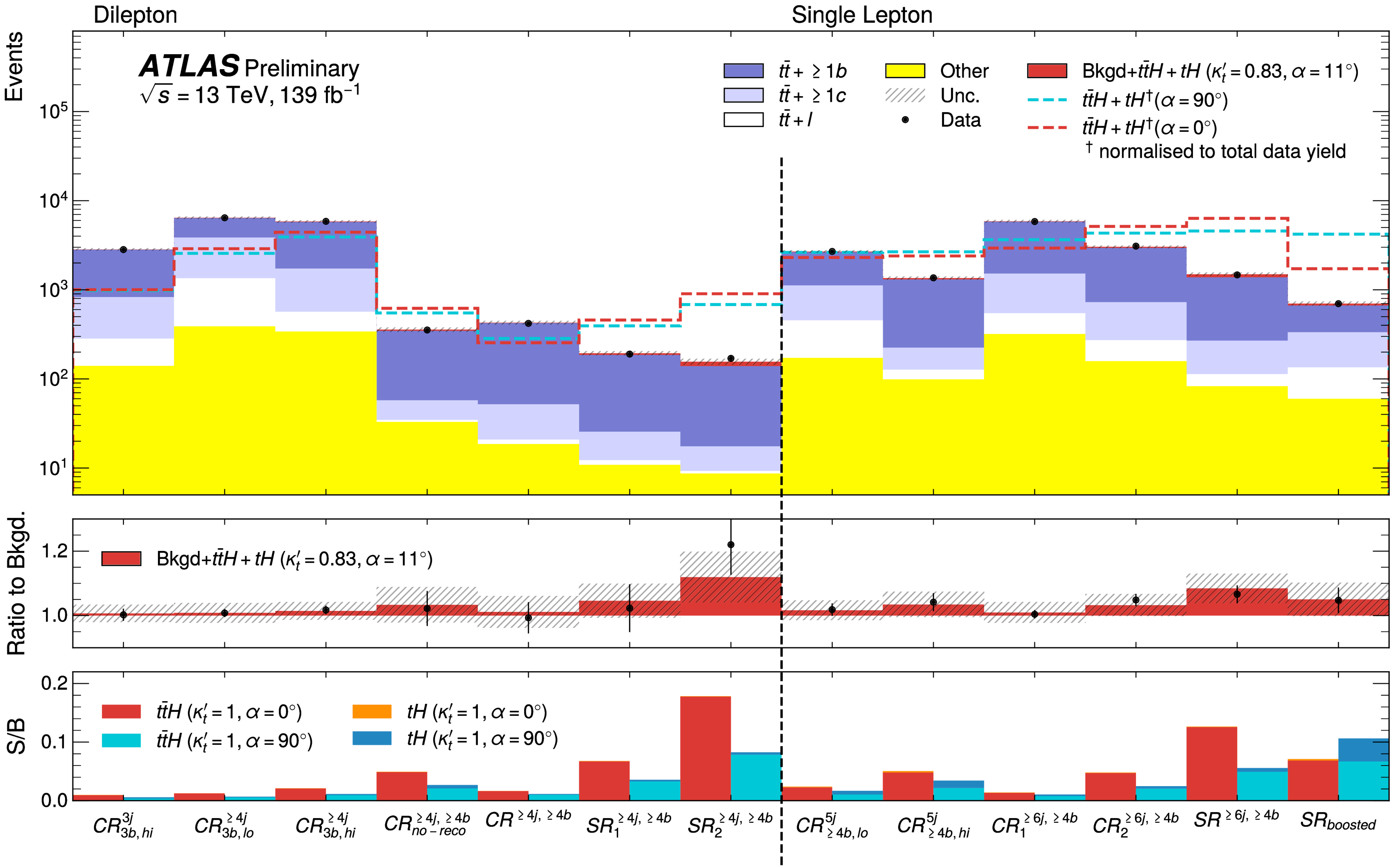
ATLAS-CONF-2022-016

- Dedicated BDTs trained for each category to assign the jets to H and t-quark candidates (permutation with highest score)

- Additional BDT is used to separate signal (SM ttH) and backgrounds

- In the boosted category a Neural Network is used to identify $H \rightarrow b\bar{b}$ candidates from the large R jets

- $S/B > 8\,\%\,(5\%)$ in all SRs for CP-even (CP-odd) signal



Higgs CP in $t\bar{t}H(\rightarrow b\bar{b})$

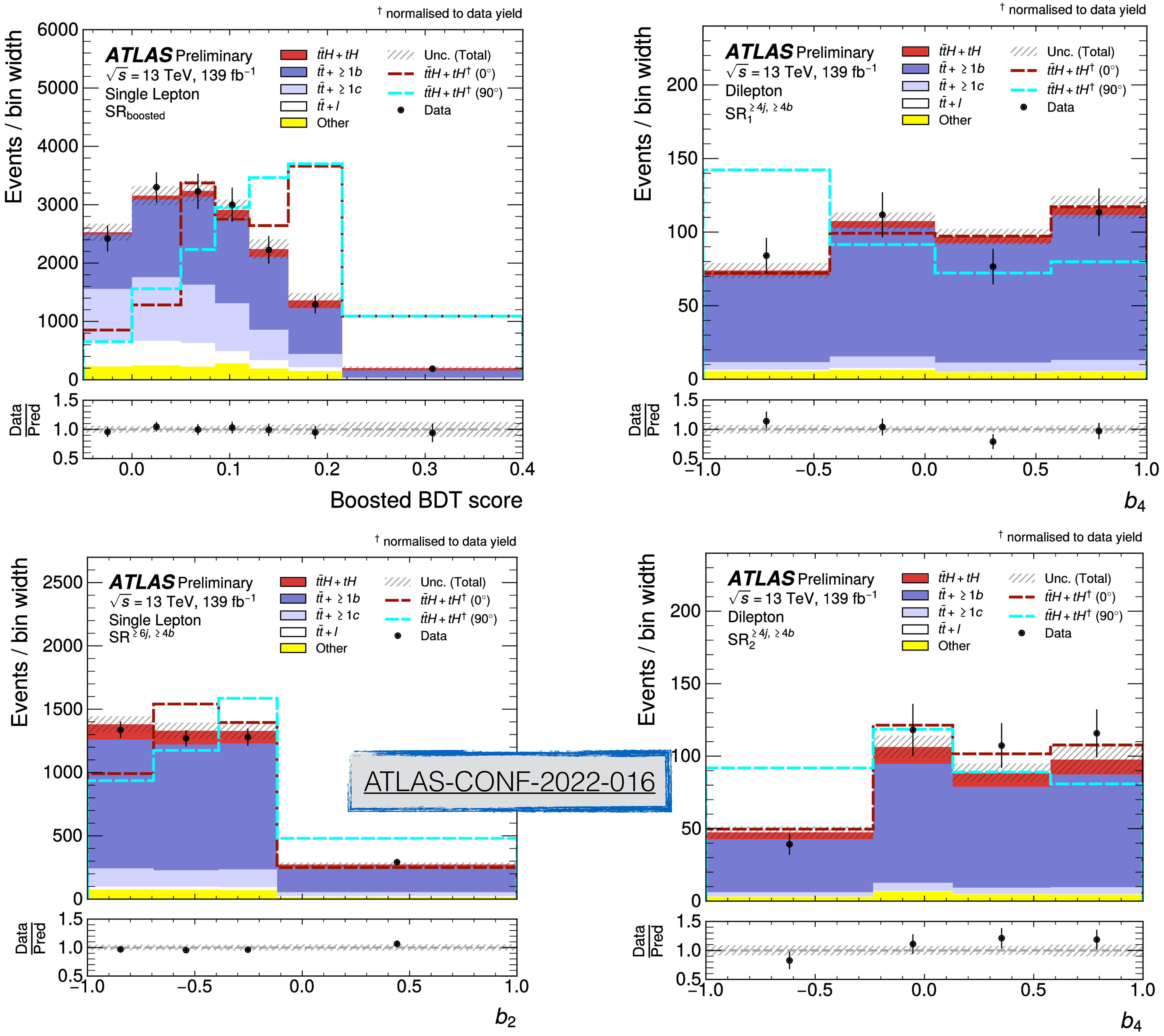
Channel (PSR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{PSR}^{\geq 4j, \geq 4b}$)	$\mathrm{CR}^{\geq 4j, \geq 4b}_{\text{no-reco}}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j, \geq 4b}$	BDT∈ $[-1, -0.086)$	b_4
	$\mathrm{SR}_1^{\geq 4j, \geq 4b}$	BDT∈ $[-0.086, 0.186)$	b_4
	$\mathrm{SR}_2^{\geq 4j, \geq 4b}$	BDT∈ $[0.186, 1]$	b_4
ℓ+jets ($\mathrm{PSR}^{\geq 6j, \geq 4b}$)	$\mathrm{CR}_1^{\geq 6j, \geq 4b}$	BDT∈ $[-1, -0.128)$	b_2
	$\mathrm{CR}_2^{\geq 6j, \geq 4b}$	BDT∈ $[-0.128, 0.249)$	b_2
	$\mathrm{SR}^{\geq 6j, \geq 4b}$	BDT∈ $[0.249, 1]$	b_2
ℓ+jets ($\mathrm{PSR}_{\text{boosted}}$)	$\mathrm{SR}_{\text{boosted}}$	BDT∈ $[-0.05, 1]$	Classification BDT score

- Use $\Delta\eta_{\ell\ell}$, boosted BDT score or CP sensitive observable distributions in each region for the combined fit:

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}$$

$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

- $\vec{p}_1$ and $\vec{p}_2$ are the 3-momenta of the reconstructed t-quarks, $\hat{n}$ is the direction of the beam axis



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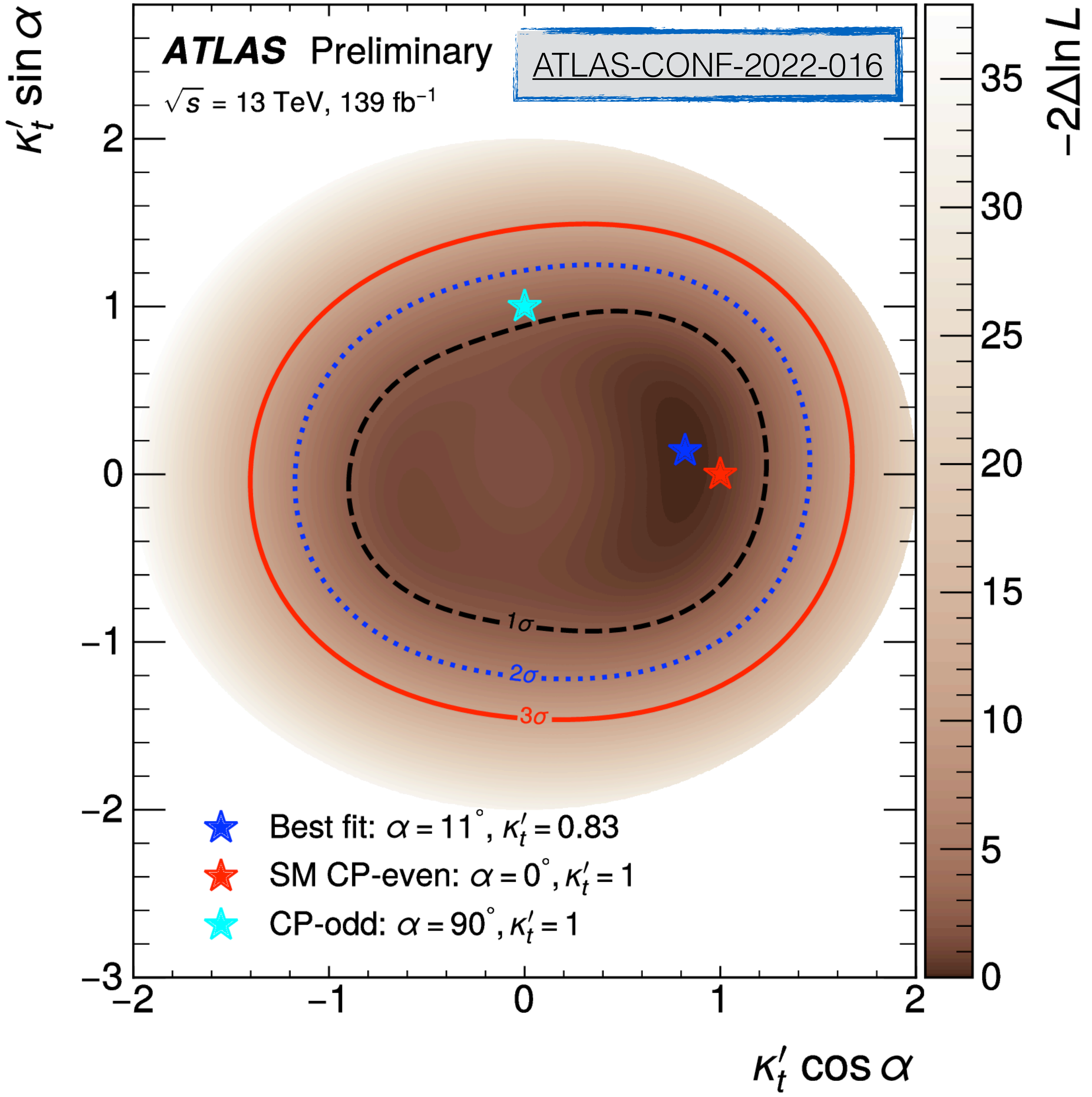
Higgs CP in $t\bar{t}H(\rightarrow b\bar{b})$

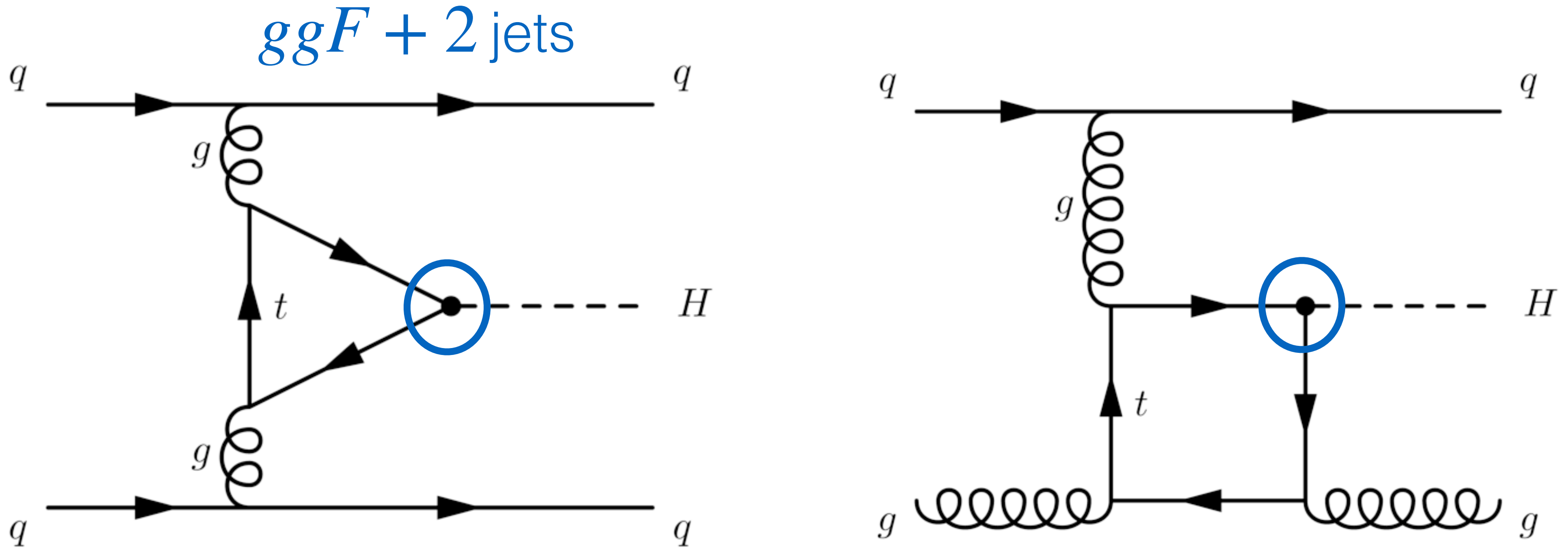
- Simultaneous maximum likelihood fit in all signal and control regions to constrain CP-mixing angle α and coupling strength κ_t
- Best fit result: $\mu_{ttH} = 0.83^{+0.30}_{-0.46}$ $(1.0^{+0.25}_{-0.27}$ expected) - assuming SM $BR_{H\rightarrow b\bar{b}}$
- Pure CP-odd coupling disfavoured at 1.2σ
- $\alpha = 11^{+55}_{-77}{}^{\circ}$ $(0^{+49}_{-50}{}^{\circ}$ expected)
- Dominant uncertainties from modelling of $t\bar{t} + \geq 1b$ (NLO matching, PS and hadronisation, flavour scheme), experimental effects are sub-dominant

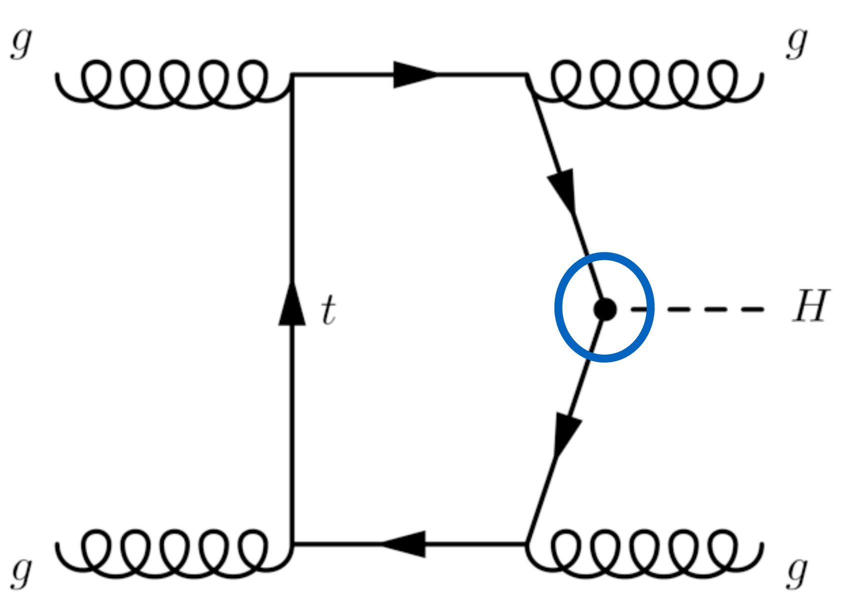


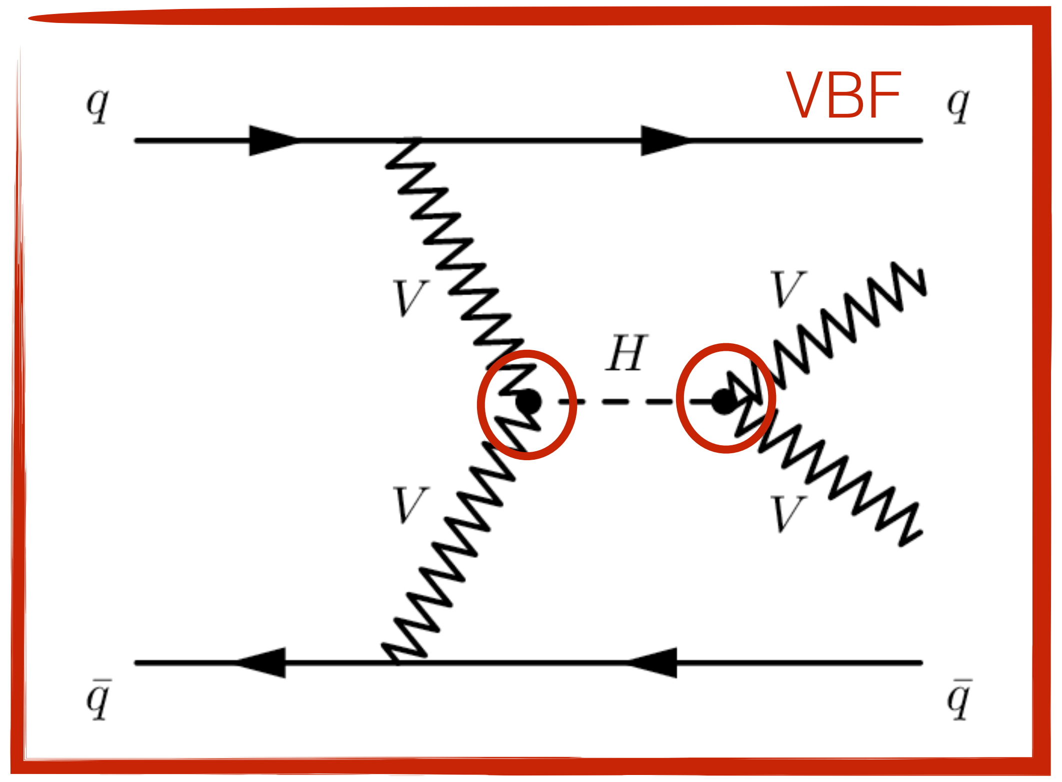
$$\mathscr{L} = -\frac{m_t}{v}\left\{\tilde{\Psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\Psi_t\right\} H$$

Higgs CP in $pp \rightarrow jjWW(\rightarrow e\nu\mu\nu)$

arXiv:2109.13808







	ggF + 2 jets	VBF
Preselection	Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge $p_{\mathrm{T}}^{\mathrm{lead}} > 22\ GeV,\ p_{\mathrm{T}}^{\mathrm{sublead}} > 15\ GeV$ $m_{\ell\ell} > 10\ GeV$ $N_{\mathrm{jet}} \geq 2$	
Background rejection	$N_{b\text{-jet},p_{\mathrm{T}}>20\ GeV} = 0$ $m_{\tau\tau} < 66\ GeV$	
	$\Delta R_{jj} > 1.0$ $p_{\mathrm{T},\ell\ell} > 20\ GeV$ $m_{\ell\ell} < 90\ GeV$ $m_{\mathrm{T}} < 150\ GeV$	central jet veto outside lepton veto
BDT input variables	$m_{\ell\ell},\ m_{\mathrm{T}},\ p_{\mathrm{T},\ell\ell},\ \Delta\phi_{\ell\ell}$ $\min \Delta R(\ell_1, j_i),\ \min \Delta R(\ell_2, j_i)$	$m_{jj},\ \Delta y_{jj},\ m_{\ell\ell},\ m_{\mathrm{T}},\ \Delta\phi_{\ell\ell}$ $\sum_\ell C_\ell,\ \sum_{\ell,j} m_{\ell,j},\ p_{\mathrm{T}}^{\mathrm{tot}}$

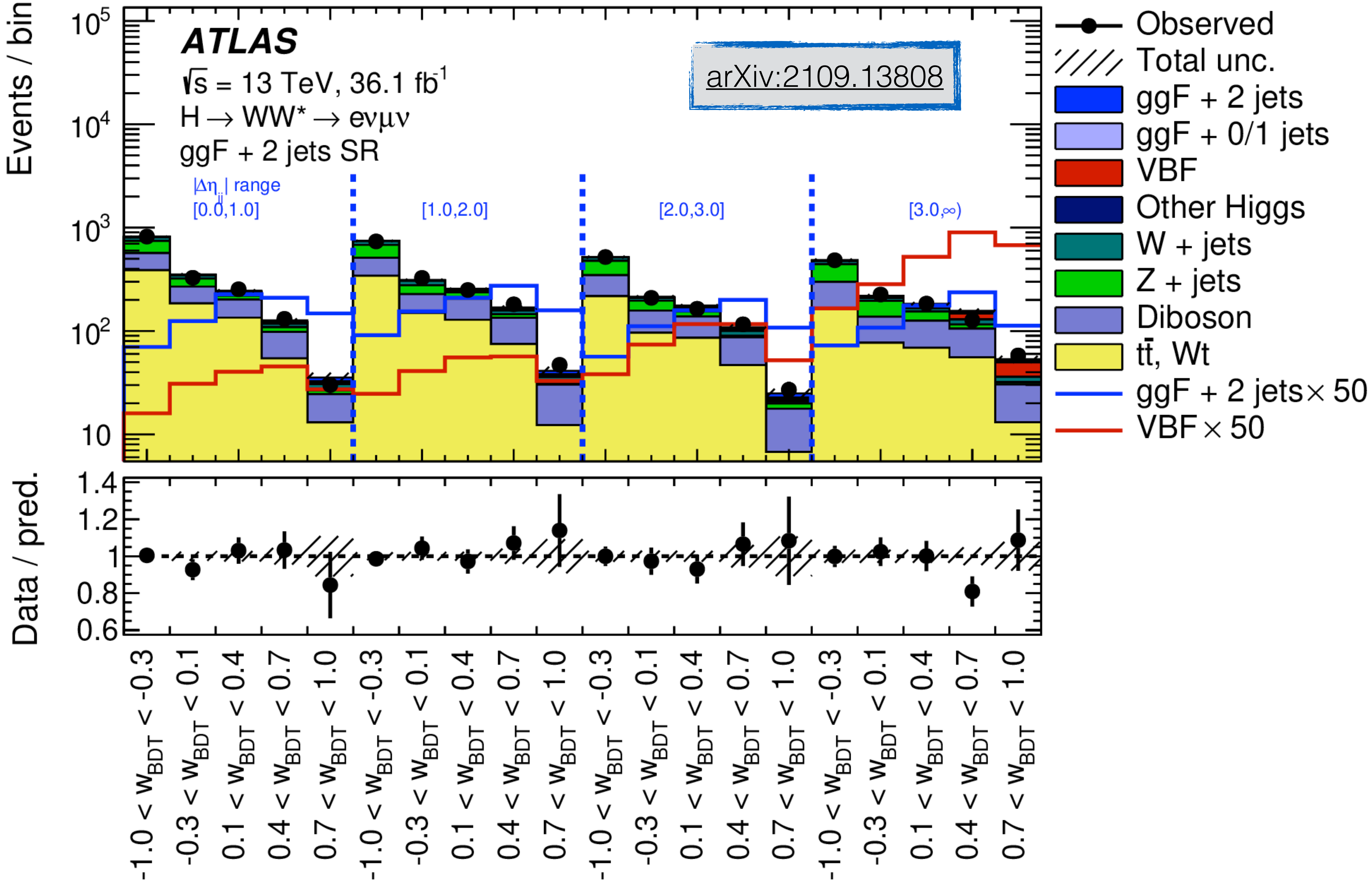
- Depending on the Higgs production mode the jjH can be used to probe CP violation in ggH (either ttH or BSM particles in the loop) or VVH couplings

- VBF channel is used to probe V-polarisation and will not be discussed here

Control region	ggF + 2 jets	VBF
Top CR	$N_{b\text{-jet},(p_{\mathrm{T}}>30\ GeV)} = 1$	$N_{b\text{-jet},(p_{\mathrm{T}}>20\ GeV)} = 1$
$Z \rightarrow \tau\tau$ CR	$\lvert m_{\tau\tau} - m_Z \rvert \leq 25\ GeV$ $p_{\mathrm{T},\ell\ell}$ requirement is omitted	$m_{\ell\ell}$ ¡ 80 GeV
WW CR	$m_{\ell\ell} > 90\ GeV$ m_{T} requirement is omitted	—-

Higgs CP in $pp \rightarrow jjWW(\rightarrow e\nu\mu\nu)$

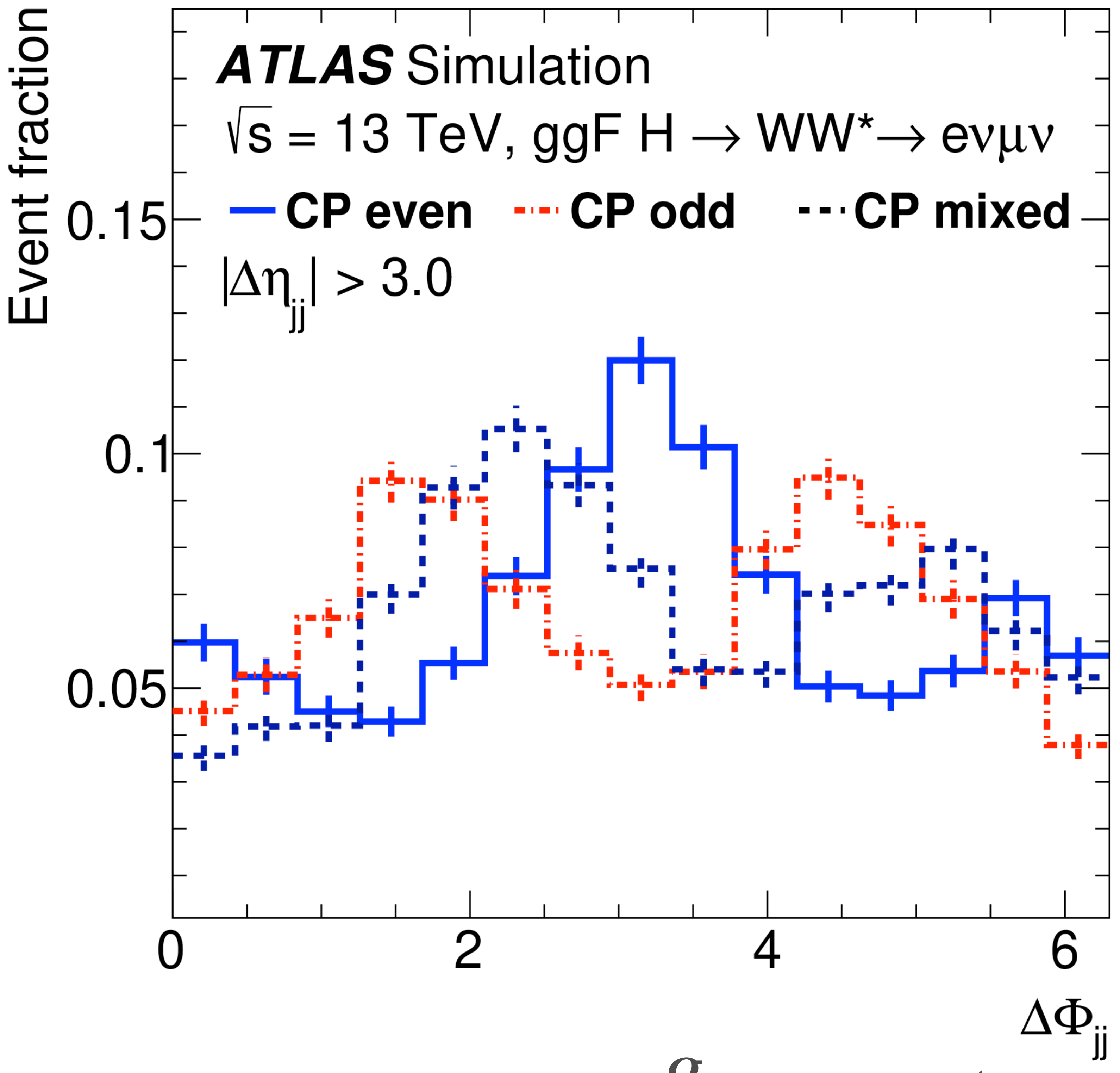
- Use BDTs in both channels to separate signal and background (no CP sensitivity) using $m_{\ell\ell}$, m_T, $\Delta\phi_{\ell\ell}$, etc.
- Split $ggF + 2$ jets in 4x5 bins depending on $|\Delta\eta_{jj}|$ and BDT score
- Define highest 3 BDT score regions in all $|\Delta\eta_{jj}|$ bins as signal regions (12 total)

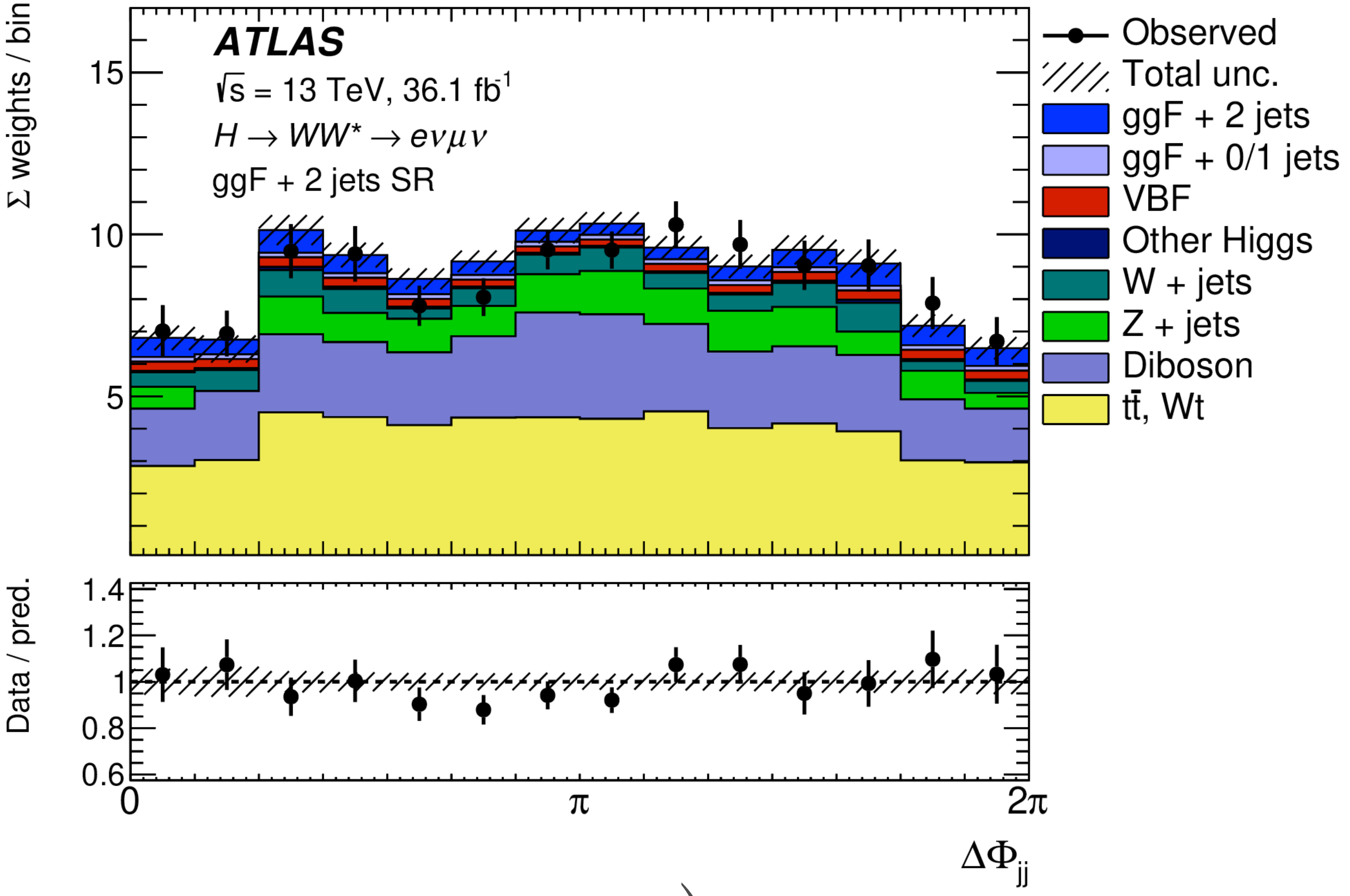


Higgs CP in $pp \to jjWW(\to e\nu\mu\nu)$

arXiv:2109.13808

$ggF + 2$ jets



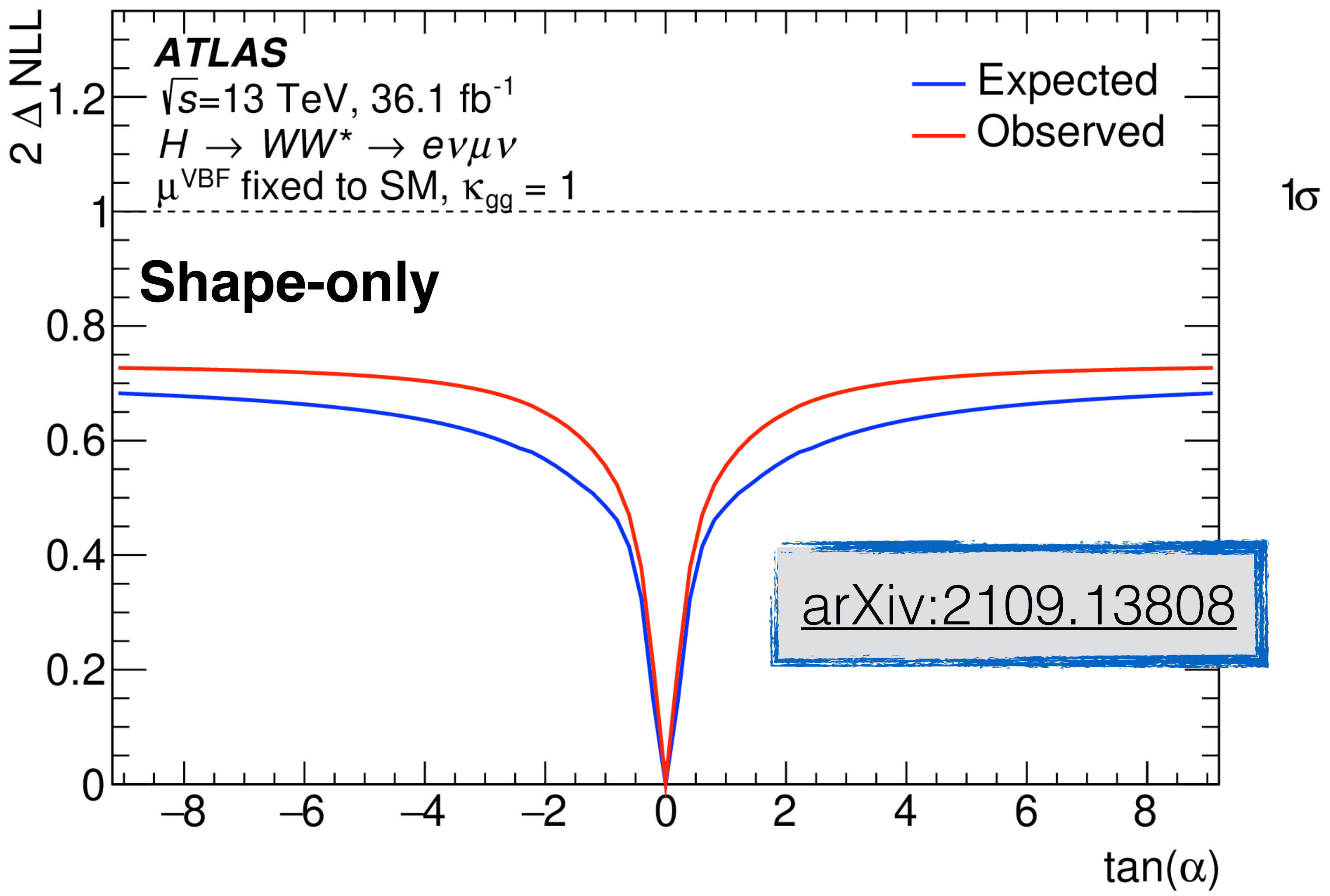


$$\mathscr{L}_{loop} = -\frac{g_{Hgg}}{4}\kappa_{gg}\left(\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$

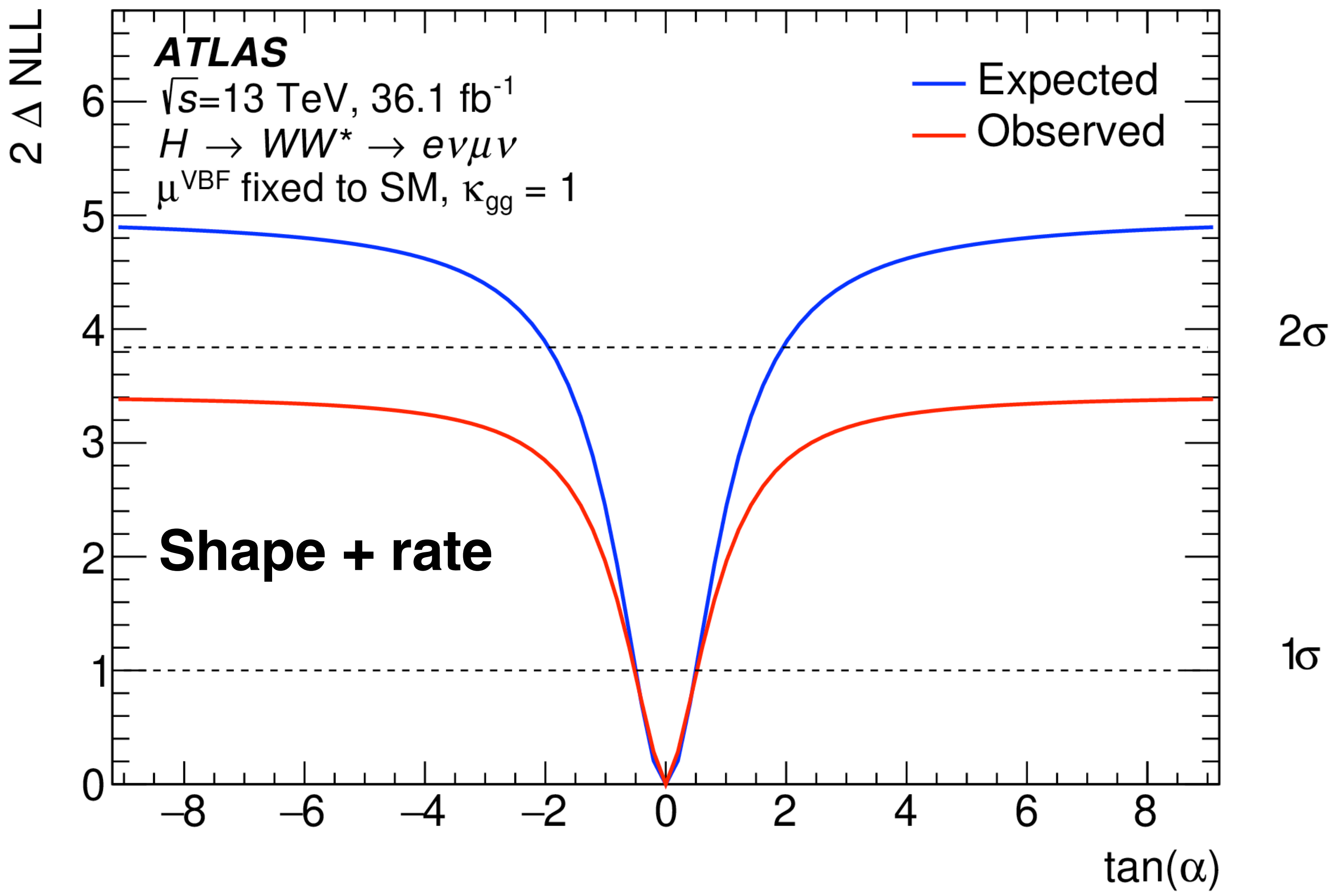
- CP-even and CP-odd mixing affects the signed $\Delta\Phi_{jj}$ distribution
- Combined ML fit using $\Delta\Phi_{jj}$ distribution in all signal regions

Higgs CP in $pp \rightarrow jjWW(\rightarrow e\nu\mu\nu)$

$ggF + 2$ jets



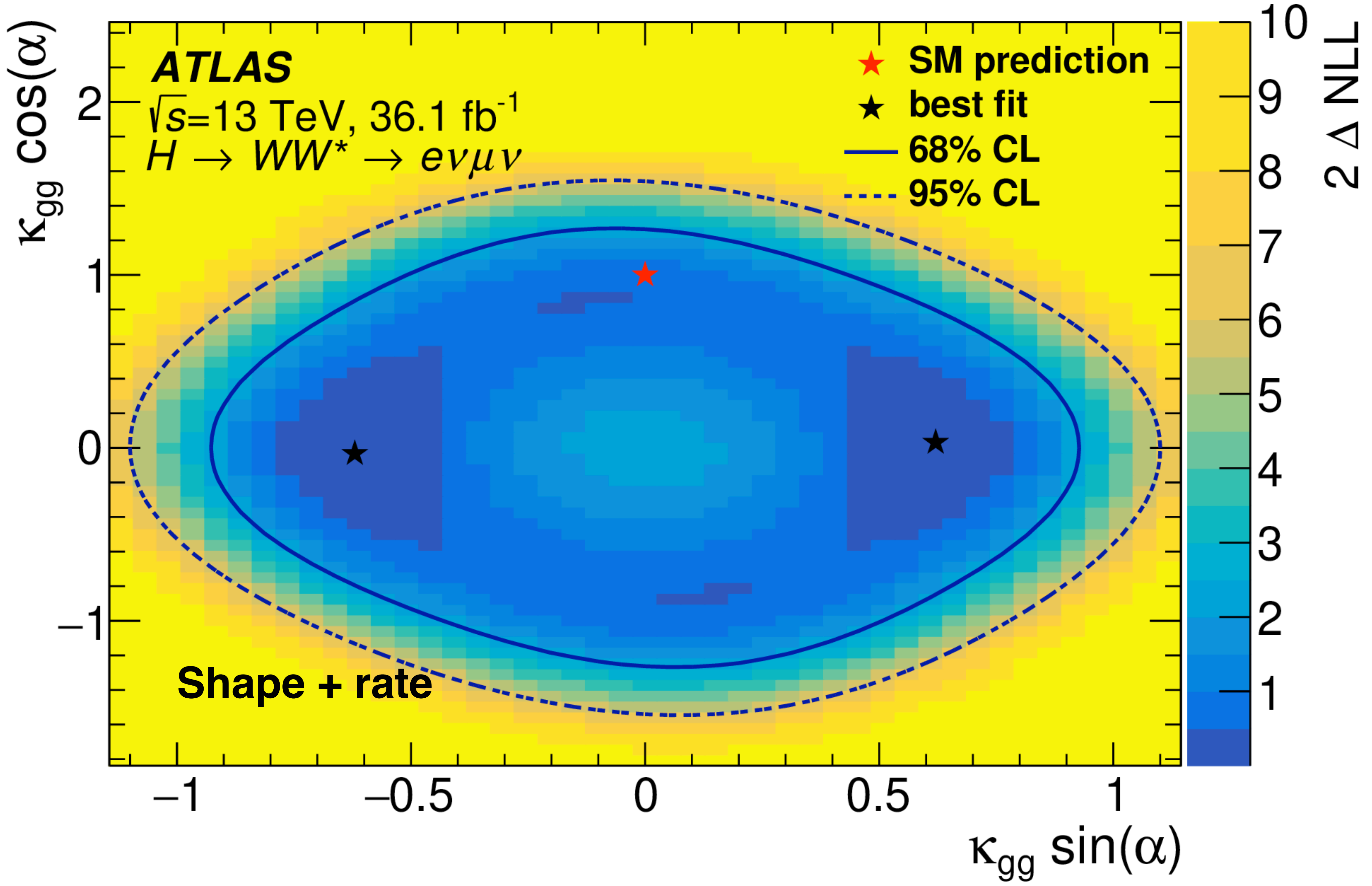
arXiv:2109.13808



$$\mu_{ggF+2jets} = 0.5 \pm 0.4(\text{stat.})^{+0.7}_{-0.6}(\text{sys.})$$

$$\tan\alpha = 0 \pm 0.4\,(\text{stat.}) \pm 0.3\,(\text{sys.})$$

- Leading uncertainties from statistics, t quark background modelling and b-tagging

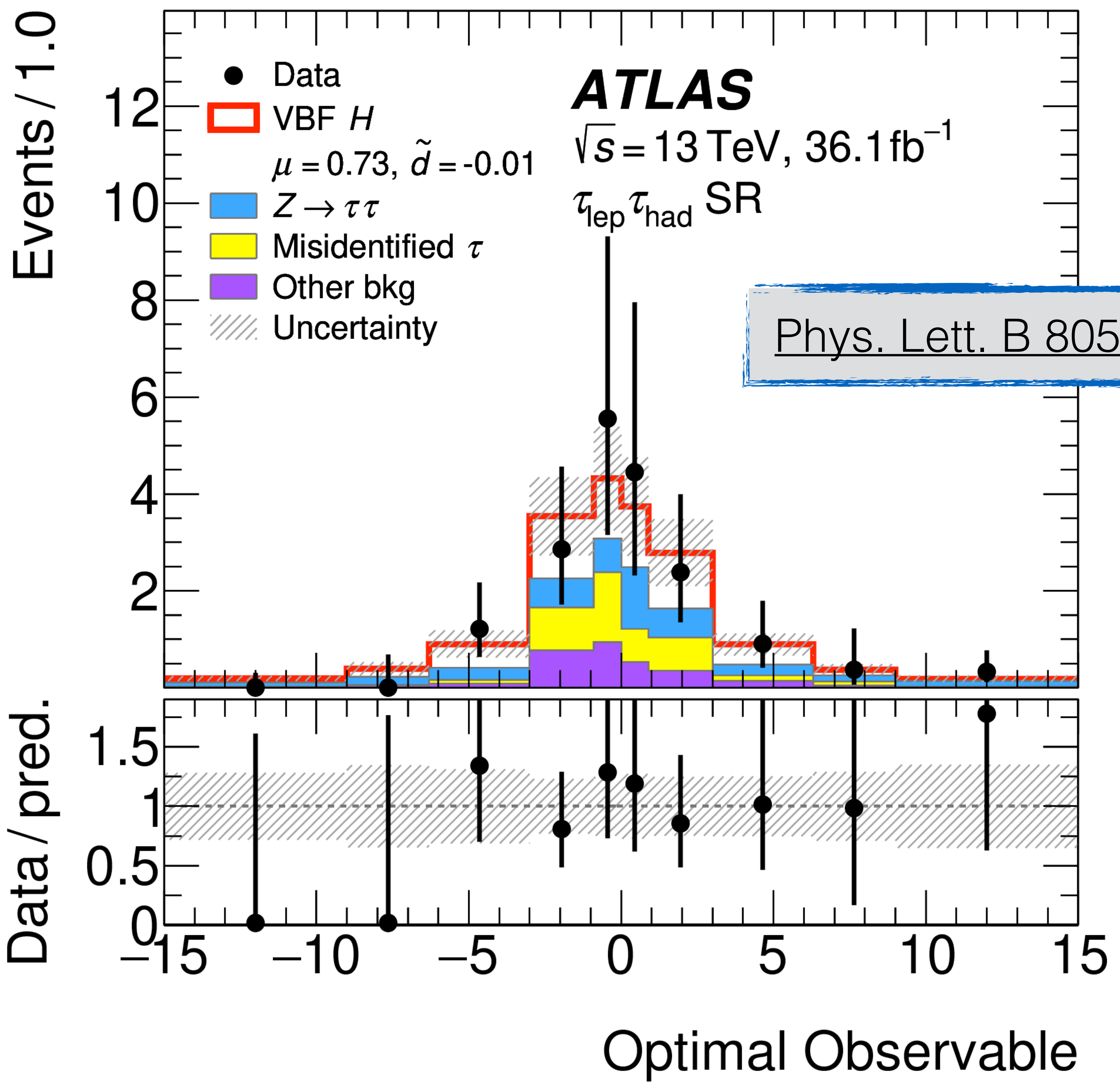


Conclusion and Outlook

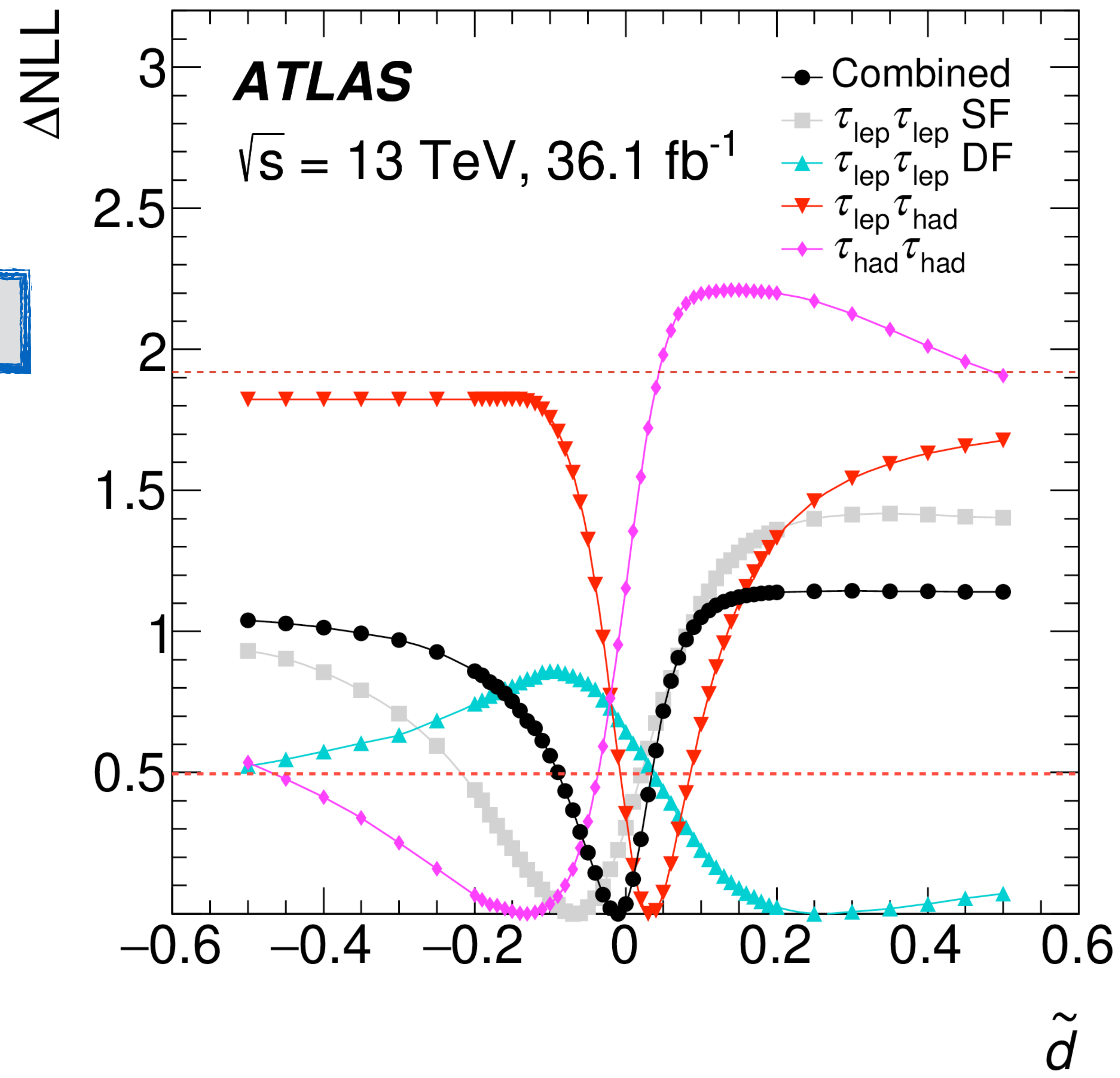
- Continue to probe CP-properties of the Higgs boson: presented new results in $ttH(\rightarrow \gamma\gamma)$, $ttH(\rightarrow b\bar{b})$, $pp \rightarrow jjH(\rightarrow WW^*)$; first ATLAS results to probe **Higgs CP-properties in Yukawa couplings**
    - $ttH(\rightarrow \gamma\gamma)$ and $ttH(\rightarrow b\bar{b})$ both probe the ttH coupling directly (exploiting rate and shape information) while $pp \rightarrow jjH(\rightarrow WW^*)$ exploits the $ggF + 2$ jets signature to indirectly probe ttH or BSM contributions in the loop using shape-only or rate + shape information
- Anomalous couplings that include a CP-odd component will (usually) modify differential cross-sections as well as coupling strength → in order to prove CP-violation in the Higgs sector need to measure CP-sensitive quantities directly (shape-only) as coupling strength can be modified by many BSM extensions
- Stronger exclusion limits on pure CP-odd Higgs and so far **no sign of significant CP-odd component** in VVH or ffH couplings
- Expect results on **more final states probing CP** in different Higgs couplings in the future
- **Looking forward to restart of the LHC** ~next month and more than doubling of data in Run 3!

Backup

CP Properties in Vector Boson Couplings

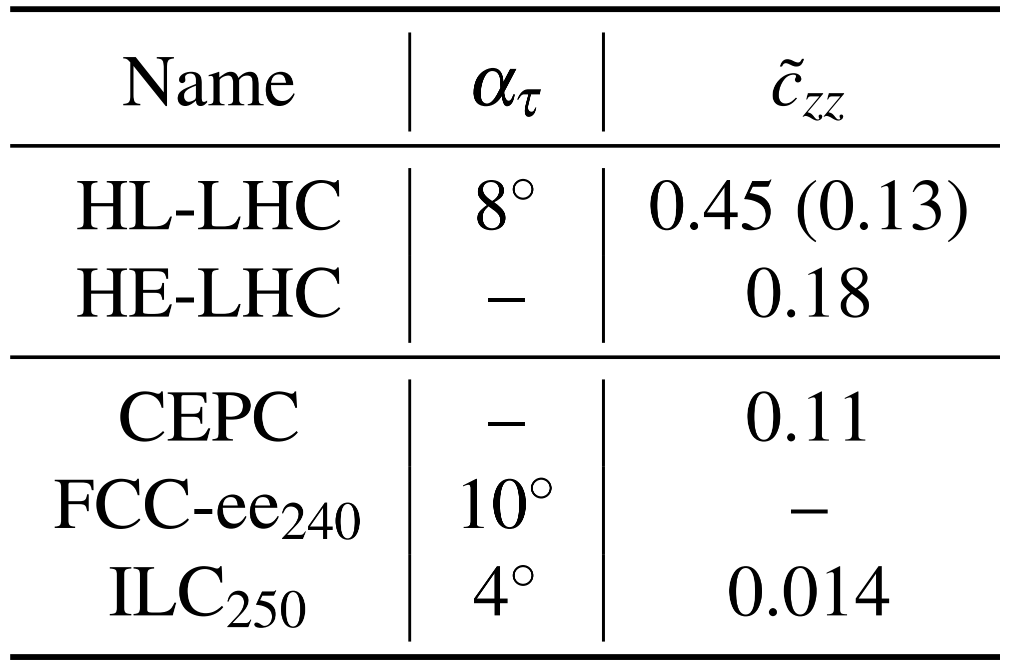


Phys. Lett. B 805 (2020) 135426



arXiv:1905.03764

Future collider prospects



Name	α_τ	$\tilde{c}_{zz}$
HL-LHC	8°	0.45 (0.13)
HE-LHC	–	0.18
CEPC	–	0.11
FCC-ee$_{240}$	10°	–
ILC$_{250}$	4°	0.014

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + \tilde{d}\,2\,\Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd}) + \tilde{d}^2|\mathcal{M}_{CP-odd}|^2 \quad \Rightarrow \quad \mathcal{O}_{opt} = \frac{2\,\Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})}{|\mathcal{M}_{SM}|^2}$$

- Calculate $\mathcal{O}_{opt}$ event-by-event in HAWK using reconstructed jets and $H \to \tau\tau$ system
- Captures full phase space information and can be used in any Higgs decay mode

Higgs CP in $t\bar{t}H(\rightarrow b\bar{b})$

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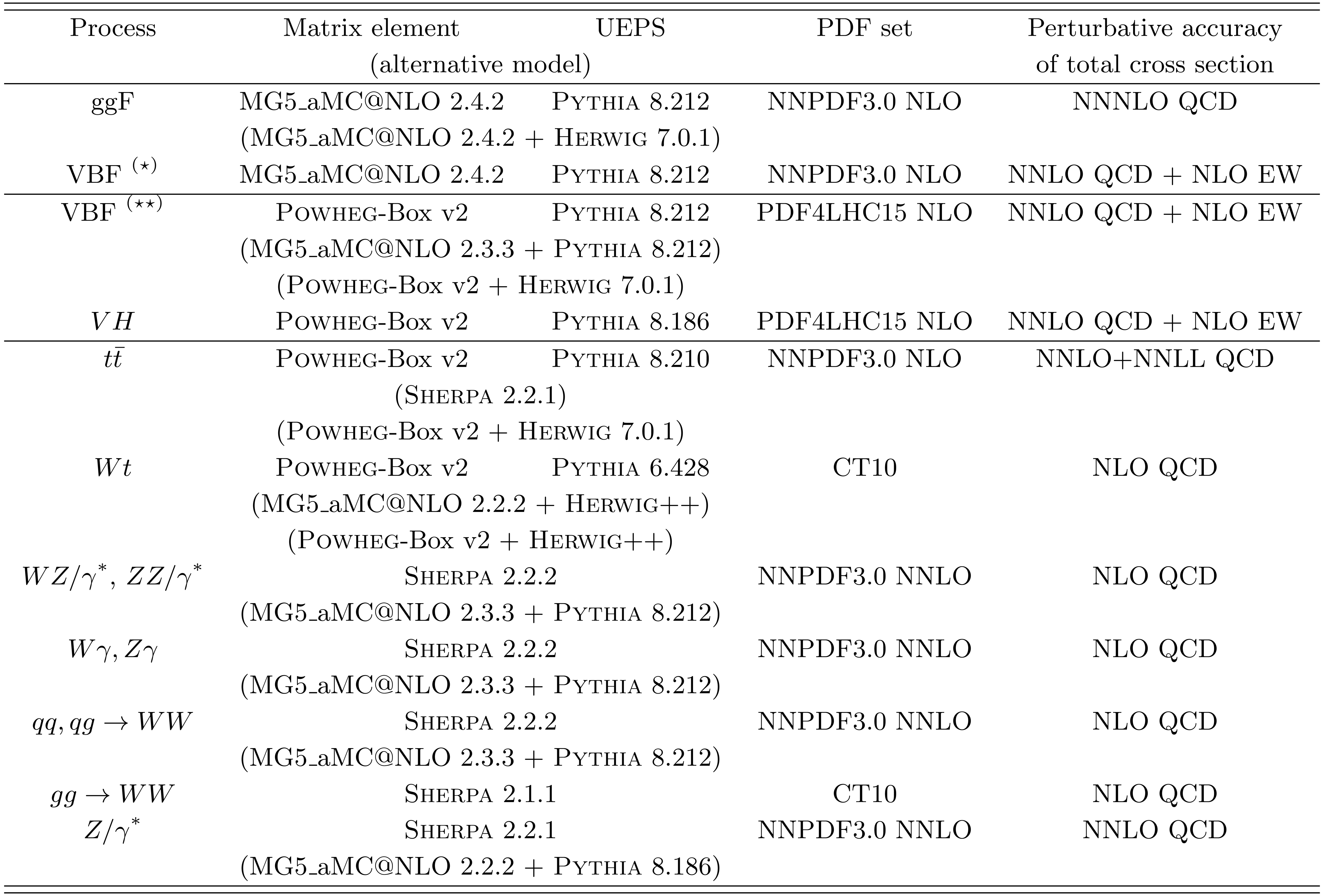
Uncertainty source	$\Delta\alpha[^\circ]$	
Process modelling		
Signal modelling	+7.9	-13
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+26	-40
$t\bar{t}+\geq 1b$ NLO matching	+24	-36
$t\bar{t}+\geq 1b$ fractions	+15	-23
$t\bar{t}+\geq 1b$ FSR	+5.2	-9.9
$t\bar{t}+\geq 1b$ PS & hadronisation	+17	-27
$t\bar{t}+\geq 1b$ $p_T^{b\bar{b}}$ shape	+5.7	-5.3
$t\bar{t}+\geq 1b$ ISR	+15	-26
$t\bar{t}+\geq 1c$ modelling	+7.4	-12
$t\bar{t}$ + light modelling	+2.7	-4.8
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+9.7	-17
c-mis-tag rates	+7.4	-12
l-mis-tag rates	+2.5	-3
Jet energy scale and resolution		
b-jet energy scale	+1.9	-4.2
Jet energy scale (flavour)	+8.8	-13
Jet energy scale (pileup)	+5.9	-9.2
Jet energy scale (remaining)	+9	-15
Jet energy resolution	+6.2	-10
Luminosity	$\leq \pm 1$	
Other sources	+5.4	-8.8
Total systematic uncertainty	+43	-58
$t\bar{t}+\geq 1b$ normalisation	+8.9	-15
κ_t'	+18	-35
Total statistical uncertainty	+34	-51
Total uncertainty	+55	-77

Uncertainty source	$\Delta\kappa_t'$	
Process modelling		
Signal modelling	+0.09	-0.09
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ 4V5 FS	+0.08	-0.24
$t\bar{t}+\geq 1b$ NLO matching	+0.15	-0.30
$t\bar{t}+\geq 1b$ fractions	+0.09	-0.22
$t\bar{t}+\geq 1b$ FSR	+0.02	-0.02
$t\bar{t}+\geq 1b$ PS & hadronisation	+0.08	-0.20
$t\bar{t}+\geq 1b$ $p_T^{b\bar{b}}$ shape	+0.07	-0.11
$t\bar{t}+\geq 1b$ ISR	+0.06	-0.17
$t\bar{t}+\geq 1c$ modelling	+0.04	-0.10
$t\bar{t}$ + light modelling	+0.01	-0.01
b-tagging efficiency and mis-tag rates		
b-tagging efficiency	+0.06	-0.12
c-mis-tag rates	+0.03	-0.07
l-mis-tag rates	+0.01	-0.03
Jet energy scale and resolution		
b-jet energy scale	+0.02	-0.02
Jet energy scale (flavour)	+0.01	-0.05
Jet energy scale (pileup)	+0.02	-0.05
Jet energy scale (remaining)	+0.04	-0.08
Jet energy resolution	+0.03	-0.09
Luminosity	$\leq \pm 0.01$	
Other sources	+0.03	-0.07
Total systematic uncertainty	+0.29	-0.45
$t\bar{t}+\geq 1b$ normalisation	+0.05	-0.15
α	+0.09	-0.07
Total statistical uncertainty	+0.09	-0.10
Total uncertainty	+0.30	-0.46

Higgs CP in $pp \to jjWW(\to e\nu\mu\nu)$



Process	Matrix element (alternative model)	UEPS	PDF set	Perturbative accuracy of total cross section
ggF	MG5_aMC@NLO 2.4.2	PYTHIA 8.212	NNPDF3.0 NLO	NNNLO QCD
	(MG5_aMC@NLO 2.4.2 + HERWIG 7.0.1)			
VBF $^{(\star)}$	MG5_aMC@NLO 2.4.2	PYTHIA 8.212	NNPDF3.0 NLO	NNLO QCD + NLO EW
VBF $^{(\star\star)}$	POWHEG-Box v2	PYTHIA 8.212	PDF4LHC15 NLO	NNLO QCD + NLO EW
	(MG5_aMC@NLO 2.3.3 + PYTHIA 8.212)			
	(POWHEG-Box v2 + HERWIG 7.0.1)			
VH	POWHEG-Box v2	PYTHIA 8.186	PDF4LHC15 NLO	NNLO QCD + NLO EW
$t\bar{t}$	POWHEG-Box v2	PYTHIA 8.210	NNPDF3.0 NLO	NNLO+NNLL QCD
	(SHERPA 2.2.1)			
	(POWHEG-Box v2 + HERWIG 7.0.1)			
Wt	POWHEG-Box v2	PYTHIA 6.428	CT10	NLO QCD
	(MG5_aMC@NLO 2.2.2 + HERWIG++)			
	(POWHEG-Box v2 + HERWIG++)			
WZ/γ^*, ZZ/γ^*	SHERPA 2.2.2		NNPDF3.0 NNLO	NLO QCD
	(MG5_aMC@NLO 2.3.3 + PYTHIA 8.212)			
$W\gamma, Z\gamma$	SHERPA 2.2.2		NNPDF3.0 NNLO	NLO QCD
	(MG5_aMC@NLO 2.3.3 + PYTHIA 8.212)			
$qq, qg \to WW$	SHERPA 2.2.2		NNPDF3.0 NNLO	NLO QCD
	(MG5_aMC@NLO 2.3.3 + PYTHIA 8.212)			
$gg \to WW$	SHERPA 2.1.1		CT10	NLO QCD
Z/γ^*	SHERPA 2.2.1		NNPDF3.0 NNLO	NNLO QCD
	(MG5_aMC@NLO 2.2.2 + PYTHIA 8.186)			

Higgs CP in $pp \to jjWW(\to e\nu\mu\nu)$

$ggF + 2$ jets

Process	Top CR	WW CR	$Z \to \tau\tau$ CR	SR
ggF + 2 jets	20 ± 20	< 0.1	10 ± 10	60 ± 80
ggF + 0/1 jets	4 ± 1	< 0.1	3 ± 1	40 ± 20
VBF	8 ± 1	< 0.1	7 ± 1	70 ± 10
Other Higgs	6 ± 3	2 ± 1	20 ± 10	30 ± 10
$t\bar{t}$, Wt	17800 ± 200	3100 ± 500	390 ± 60	2300 ± 300
WW	180 ± 80	1400 ± 500	200 ± 70	1200 ± 400
Z + jets	220 ± 30	16 ± 3	1960 ± 70	1000 ± 100
W + jets	600 ± 200	140 ± 30	90 ± 20	390 ± 80
Non-WW dibosons	40 ± 30	100 ± 30	120 ± 50	240 ± 80
Observed	18886	4778	2800	5209

Source	$\Delta\,(\tan(\alpha))$
Total data statistical uncertainty	0.4
SR statistical uncertainty	0.33
CR statistical uncertainty	0.10
MC statistical uncertainty	0.14
Total systematic uncertainty	0.28
Theoretical uncertainty	0.23
Top-quark bkg.	0.15
ggF signal	0.14
WZ, ZZ, $W\gamma$, $Z\gamma$ bkg.	0.06
WW bkg.	0.06
Z/γ^* bkg.	0.016
VBF bkg.	0.015
Experimental uncertainty	0.21
b-tagging	0.16
Modelling of pile-up	0.10
Jets	0.07
Misidentified leptons	0.04
Luminosity	0.034
Total	0.5

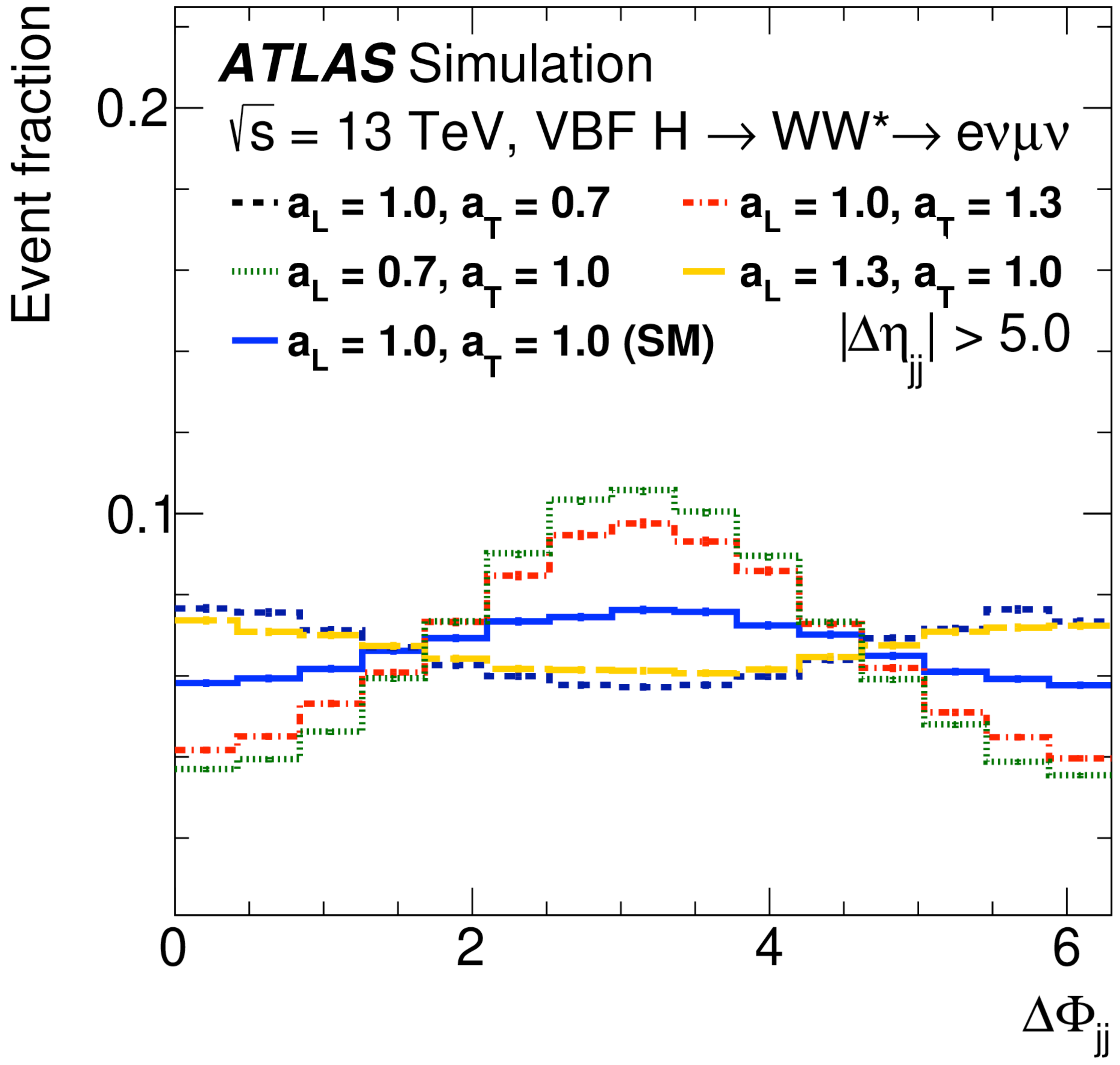
V Polarisation in $pp \to jjWW(\to e\nu\mu\nu)$

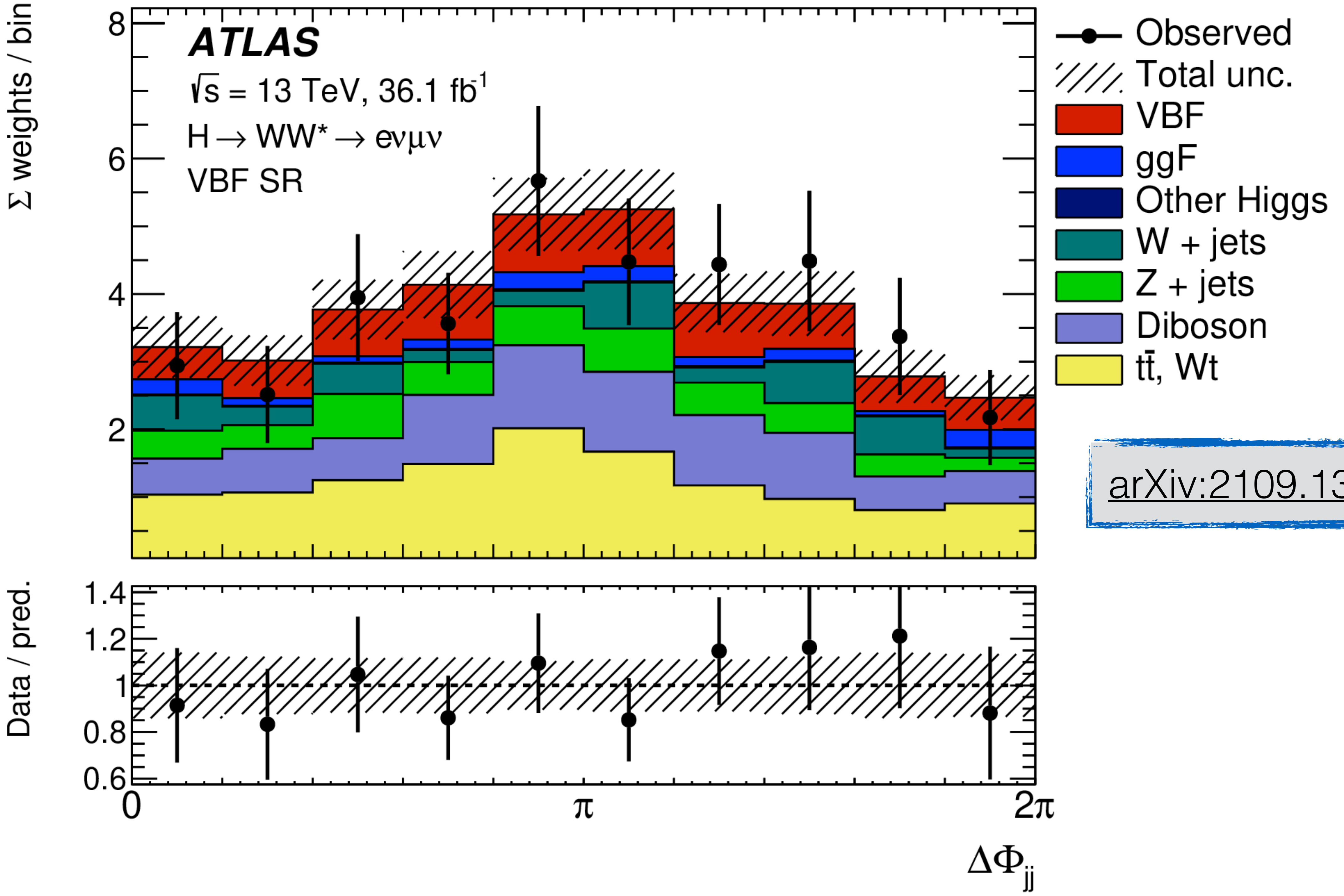
VBF

$$\mathscr{L} = \kappa_{VV}\left(\frac{2m_W^2}{v}HW_\mu^+W^{-\mu} + \frac{2m_Z^2}{v}HZ_\mu Z^\mu\right) - \frac{\epsilon_{VV}}{2v}\left(2HW_{\mu\nu}^+W^{-\mu\nu} + HZ_{\mu\nu}Z^{\mu\nu} + HA_{\mu\nu}A^{\mu\nu}\right)$$

- Parametrise model as polarisation dependent coupling modifiers:

$$a_L = \frac{g_{HV_LV_L}}{g_{HVV}^{SM}}, \quad a_T = \frac{g_{HV_TV_T}}{g_{HVV}^{SM}}, \quad \kappa_{VV} \approx a_L, \quad \epsilon_{VV} \approx 0.5 \cdot (a_T - a_L)$$



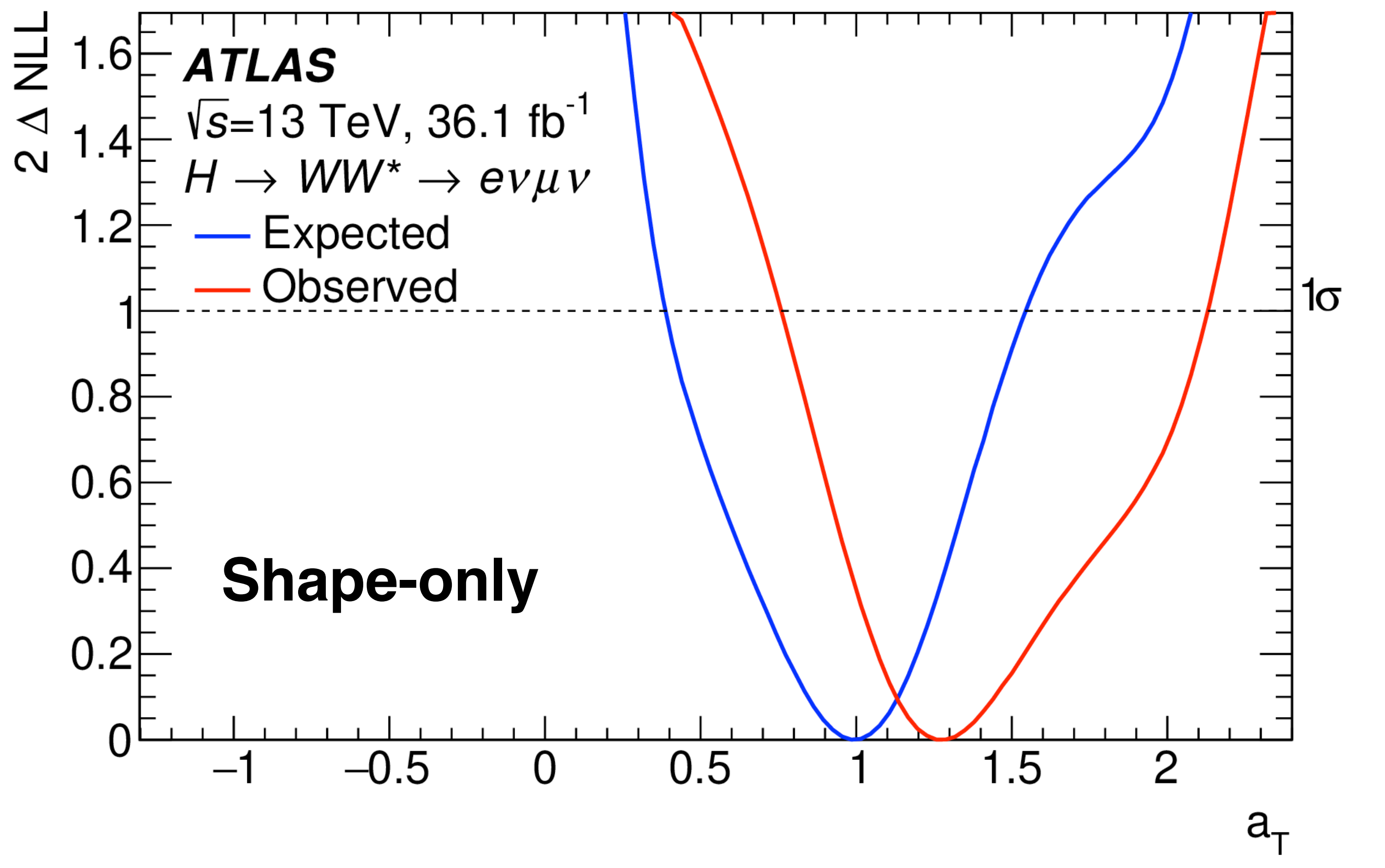


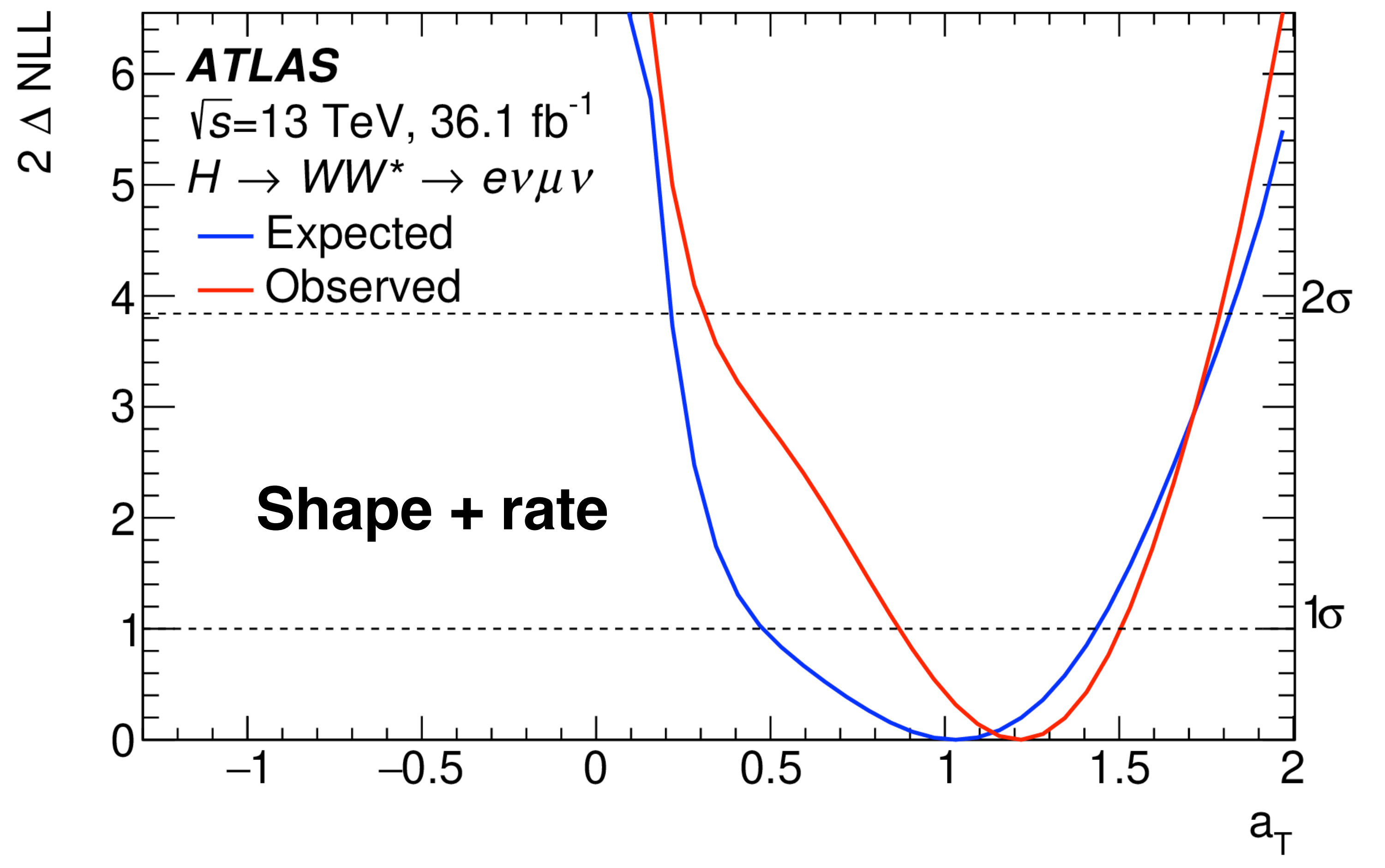
arXiv:2109.13808

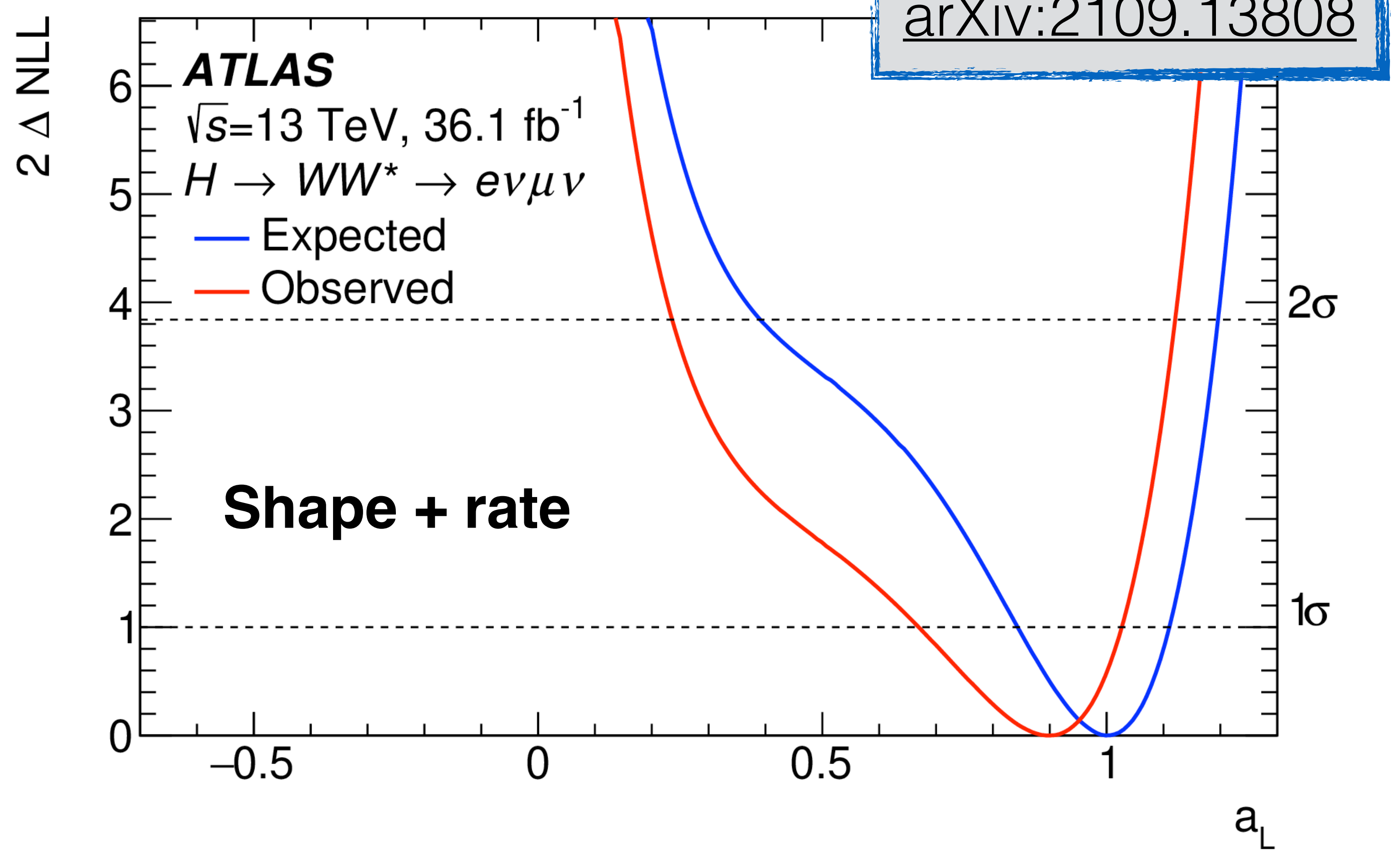
V Polarisation in $pp \to jjWW(\to e\nu\mu\nu)$

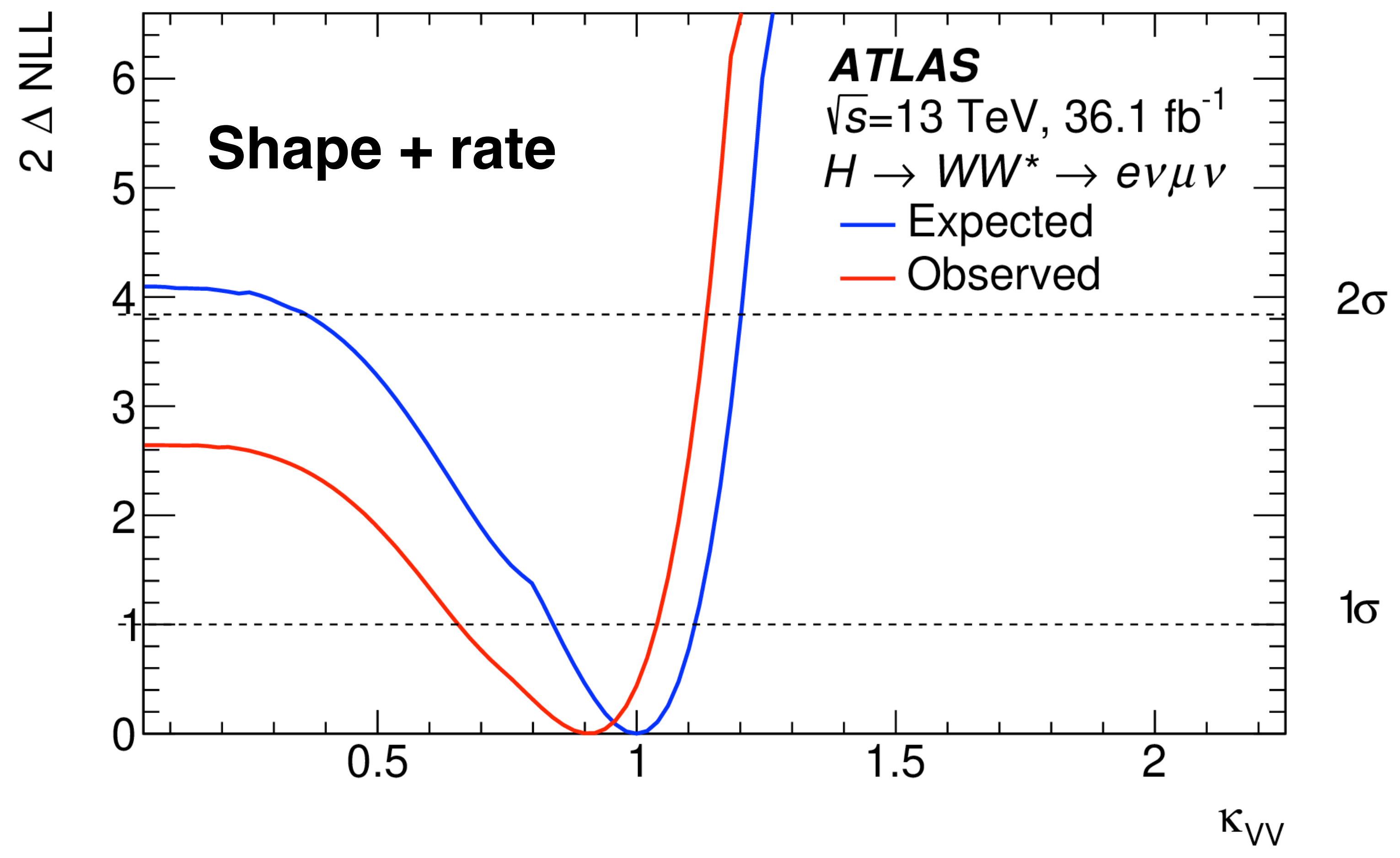
VBF

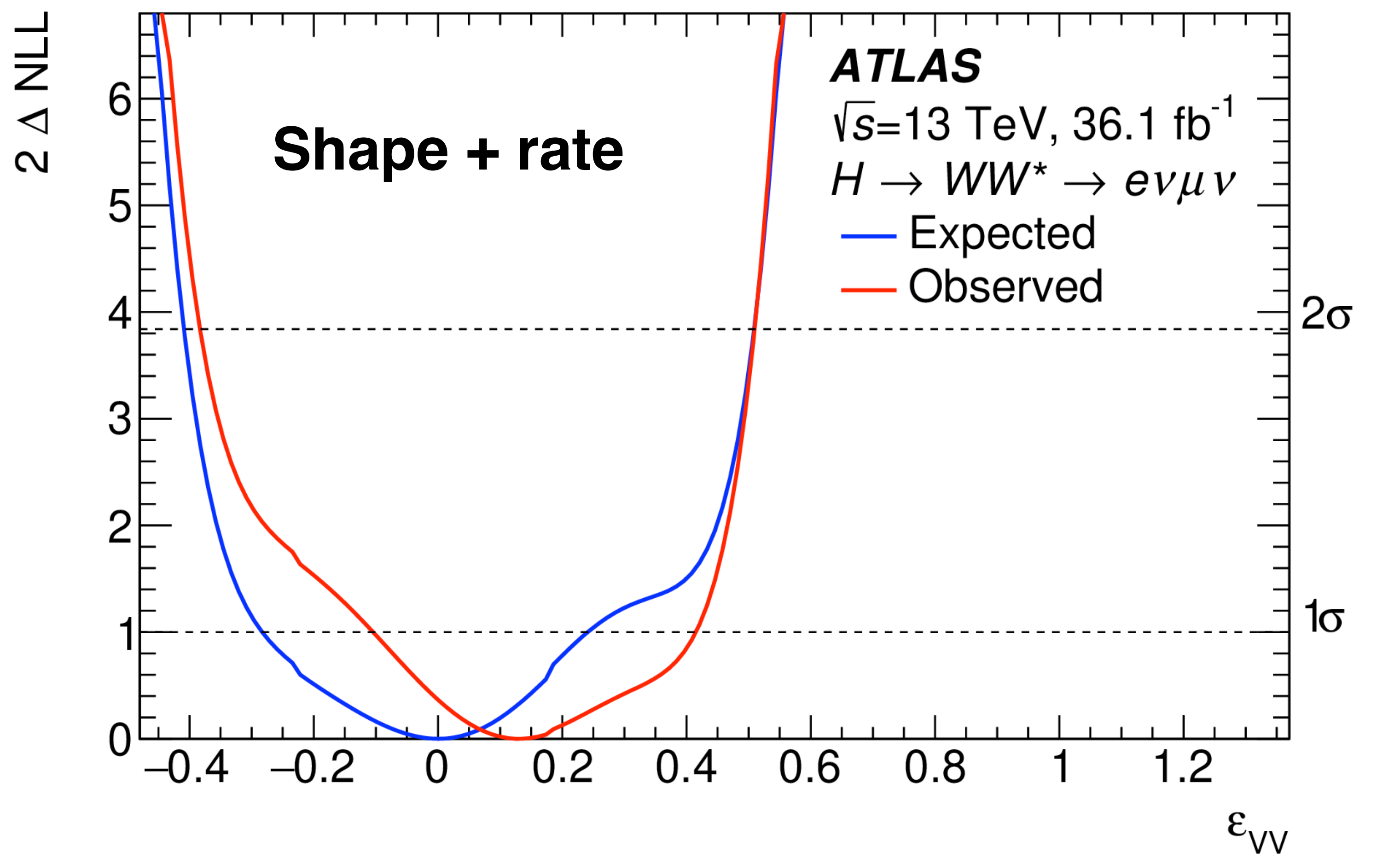
arXiv:2109.13808





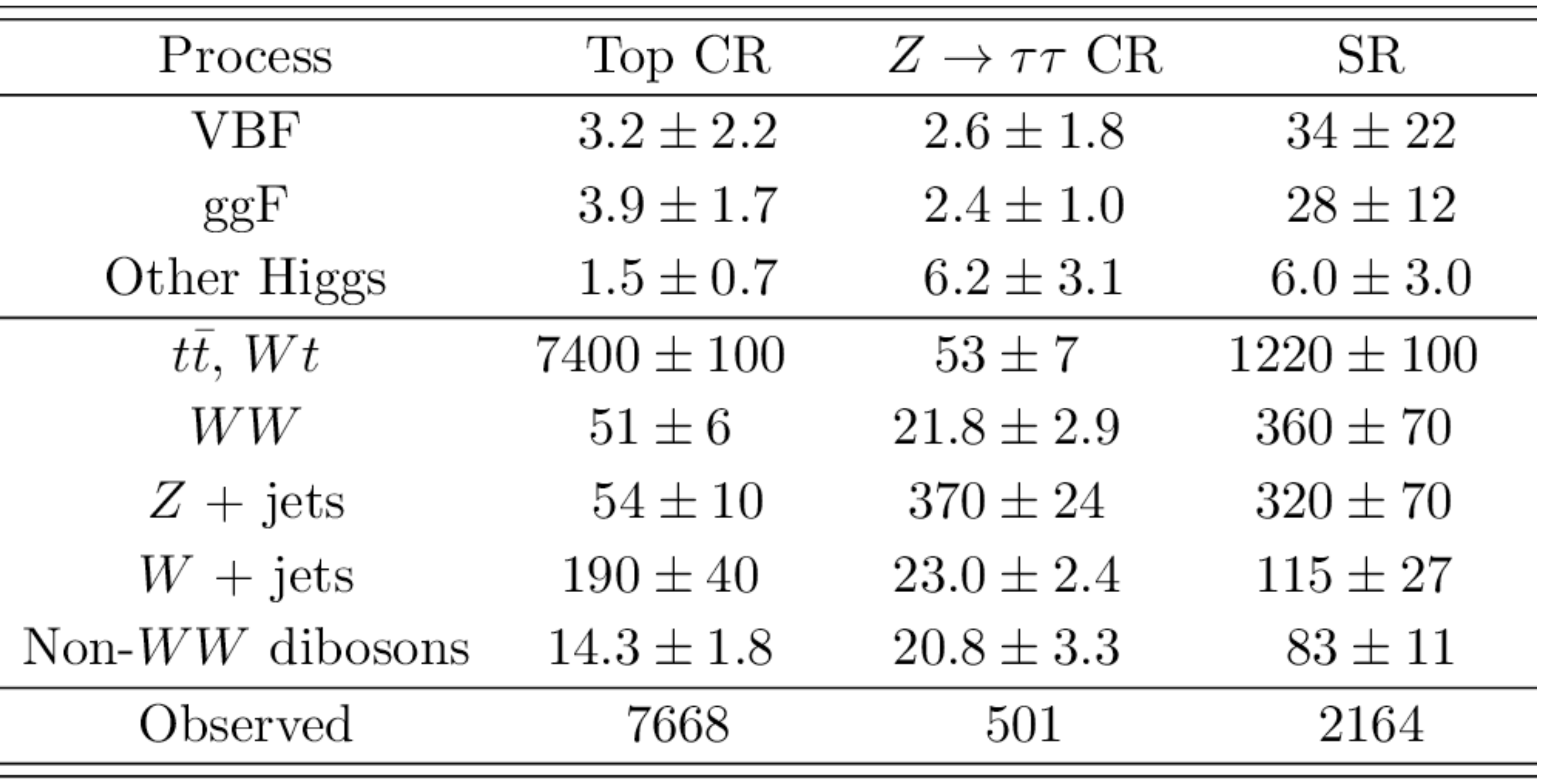




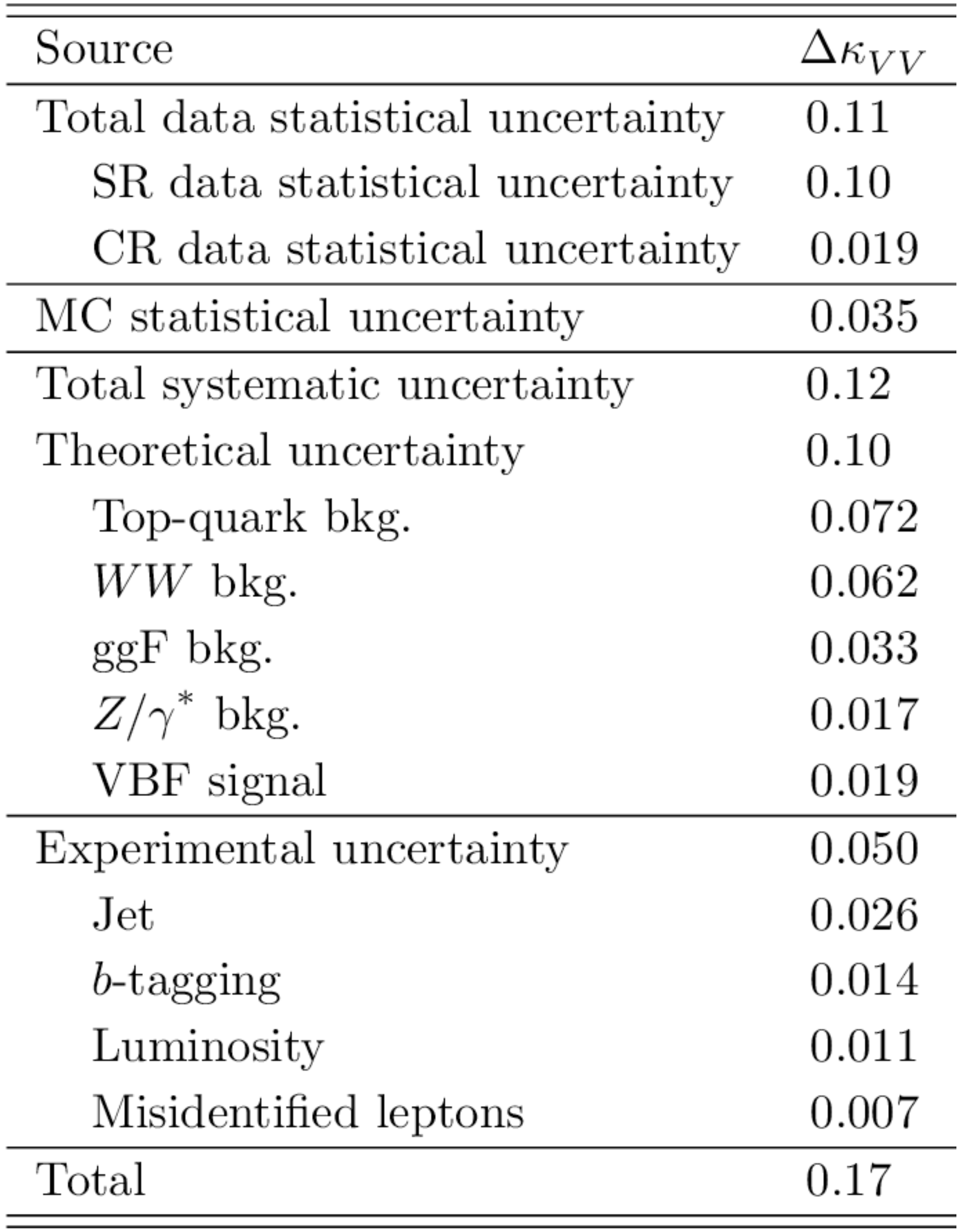


- $\kappa_{VV} = 1.0^{+0.08}_{-0.10}\,(\text{stat.})^{+0.08}_{-0.13}\,(\text{sys.})$
- $\epsilon_{VV} = 0.00^{+0.22}_{-0.24}\,(\text{stat.})^{+0.11}_{-0.15}\,(\text{sys.}$
- Leading uncertainties from t-quark and WW background modelling, jet uncertainties and pile-up

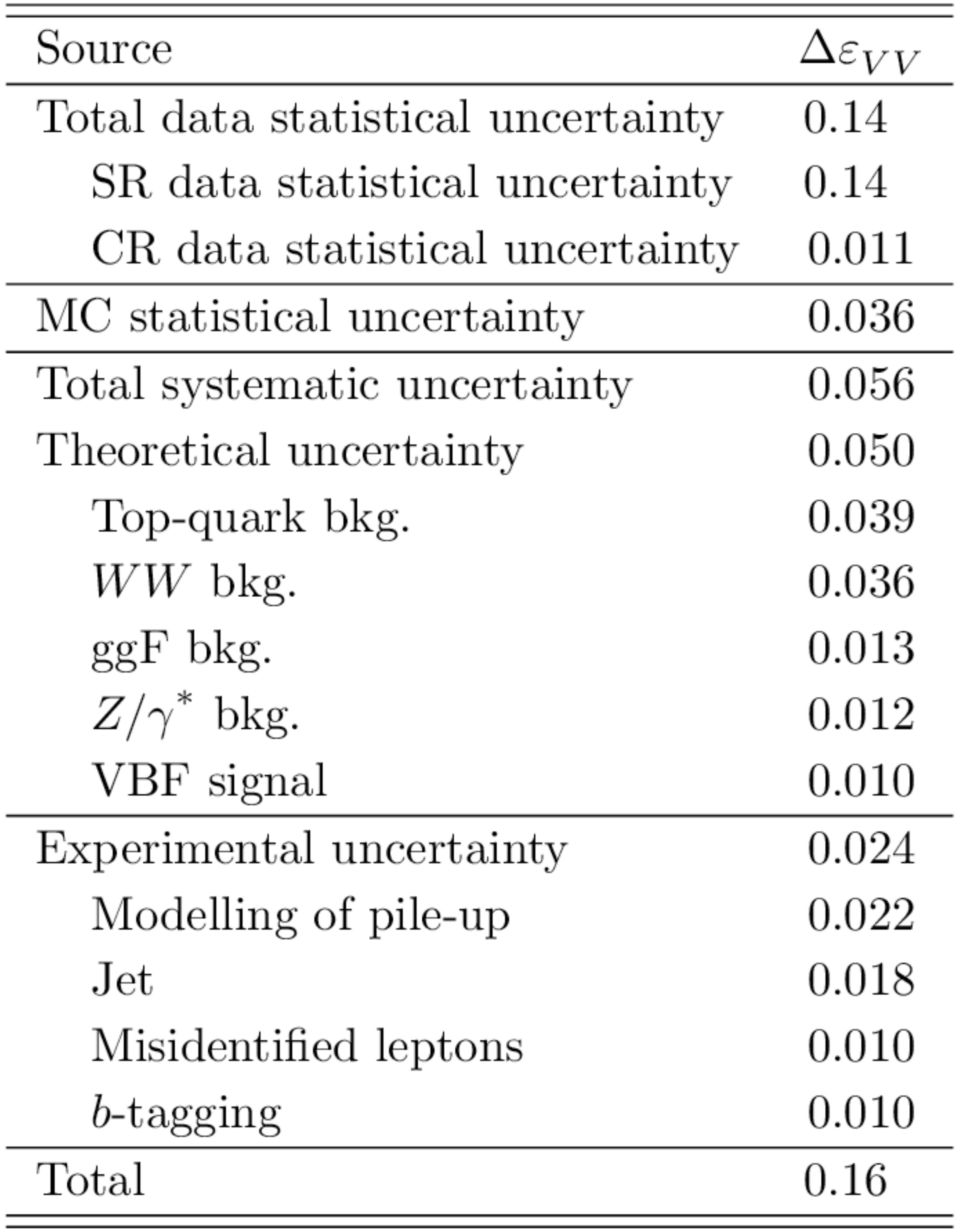
V Polarisation in $pp \to jjWW(\to e\nu\mu\nu)$



Process	Top CR	$Z \to \tau\tau$ CR	SR
VBF	3.2 ± 2.2	2.6 ± 1.8	34 ± 22
ggF	3.9 ± 1.7	2.4 ± 1.0	28 ± 12
Other Higgs	1.5 ± 0.7	6.2 ± 3.1	6.0 ± 3.0
$t\bar{t}$, Wt	7400 ± 100	53 ± 7	1220 ± 100
WW	51 ± 6	21.8 ± 2.9	360 ± 70
Z + jets	54 ± 10	370 ± 24	320 ± 70
W + jets	190 ± 40	23.0 ± 2.4	115 ± 27
Non-WW dibosons	14.3 ± 1.8	20.8 ± 3.3	83 ± 11
Observed	7668	501	2164

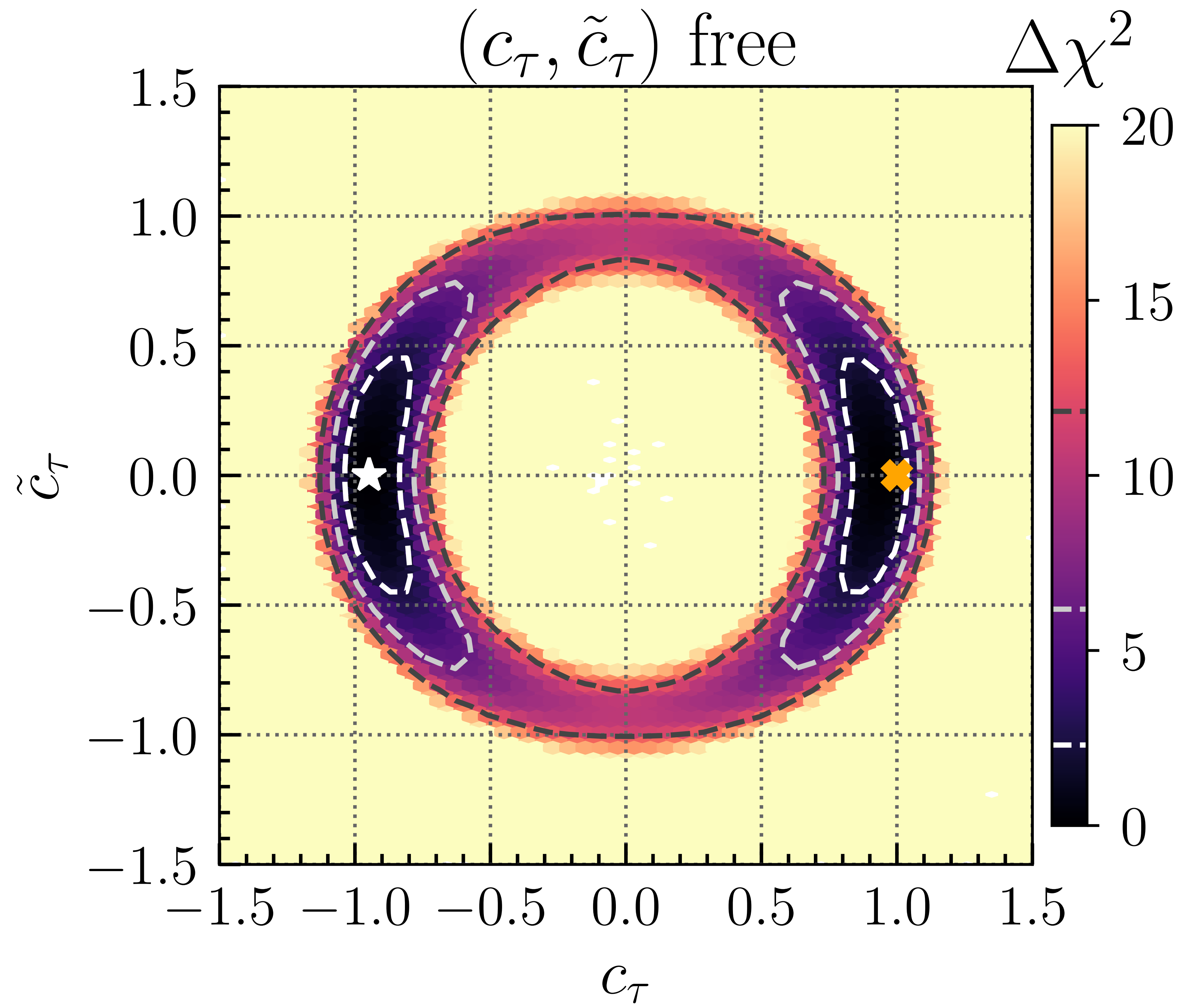


Source	$\Delta\kappa_{VV}$
Total data statistical uncertainty	0.11
SR data statistical uncertainty	0.10
CR data statistical uncertainty	0.019
MC statistical uncertainty	0.035
Total systematic uncertainty	0.12
Theoretical uncertainty	0.10
Top-quark bkg.	0.072
WW bkg.	0.062
ggF bkg.	0.033
Z/γ^* bkg.	0.017
VBF signal	0.019
Experimental uncertainty	0.050
Jet	0.026
b-tagging	0.014
Luminosity	0.011
Misidentified leptons	0.007
Total	0.17

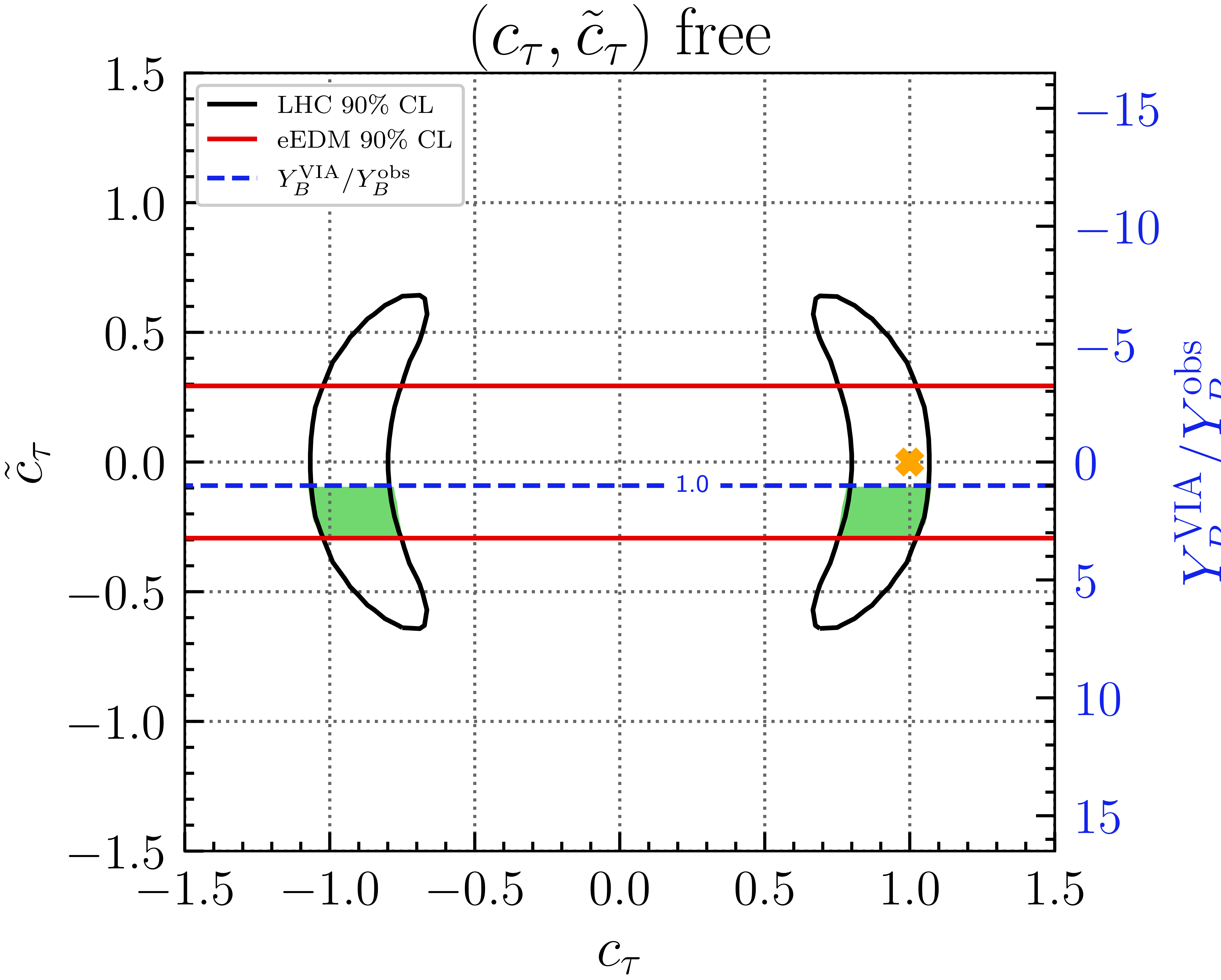


Source	$\Delta\varepsilon_{VV}$
Total data statistical uncertainty	0.14
SR data statistical uncertainty	0.14
CR data statistical uncertainty	0.011
MC statistical uncertainty	0.036
Total systematic uncertainty	0.056
Theoretical uncertainty	0.050
Top-quark bkg.	0.039
WW bkg.	0.036
ggF bkg.	0.013
Z/γ^* bkg.	0.012
VBF signal	0.010
Experimental uncertainty	0.024
Modelling of pile-up	0.022
Jet	0.018
Misidentified leptons	0.010
b-tagging	0.010
Total	0.16

CP Violation and Global Constraints



arXiv:2202.11753



- Combine $H\tau\tau$ coupling and CP measurements, with constraints from electron dipole moment (EDM) and Baryon asymmetry in the universe
- Current limits on CP violation in $H\tau\tau$ is sufficient to explain Baryon asymmetry!