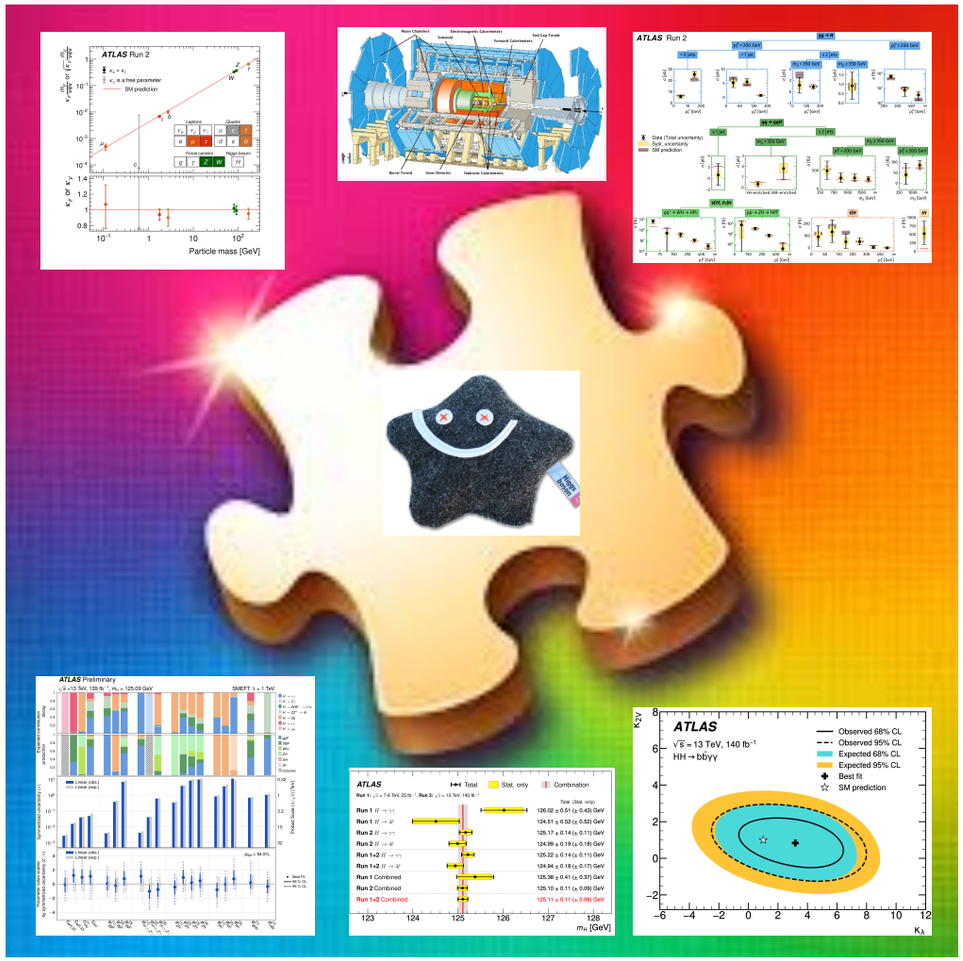
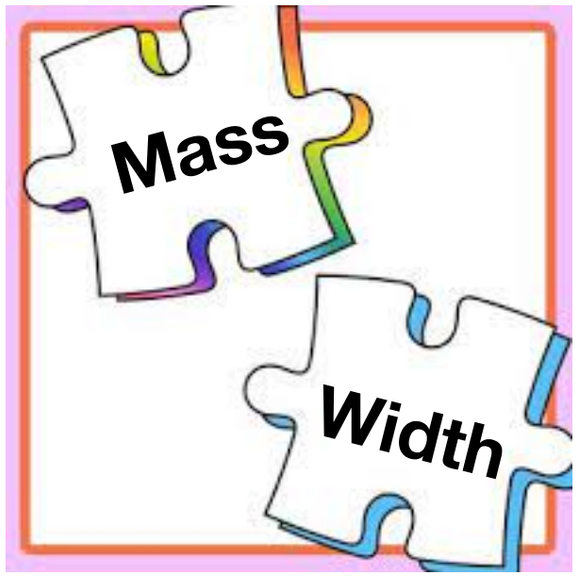
Higgs boson measurements at ATLAS

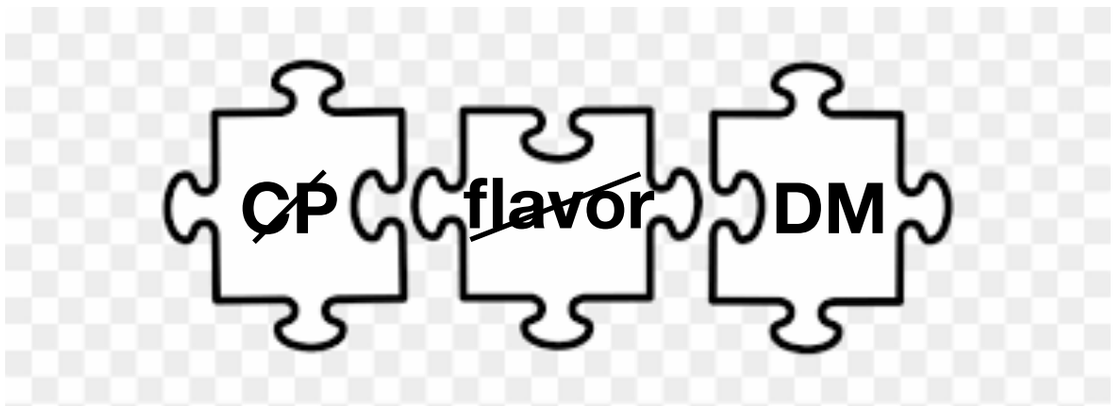


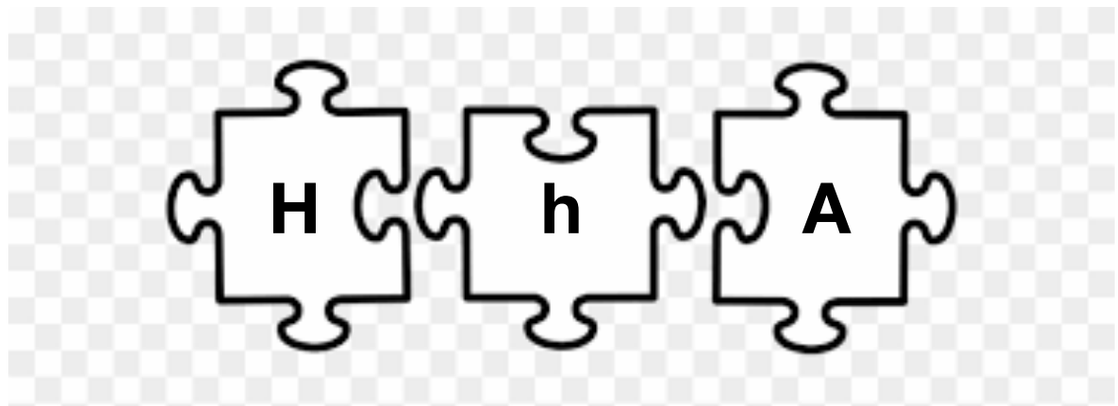
Chris Hays,
Oxford University

Completing the Higgsaw Puzzle
UK HEP Forum
21 November 2023

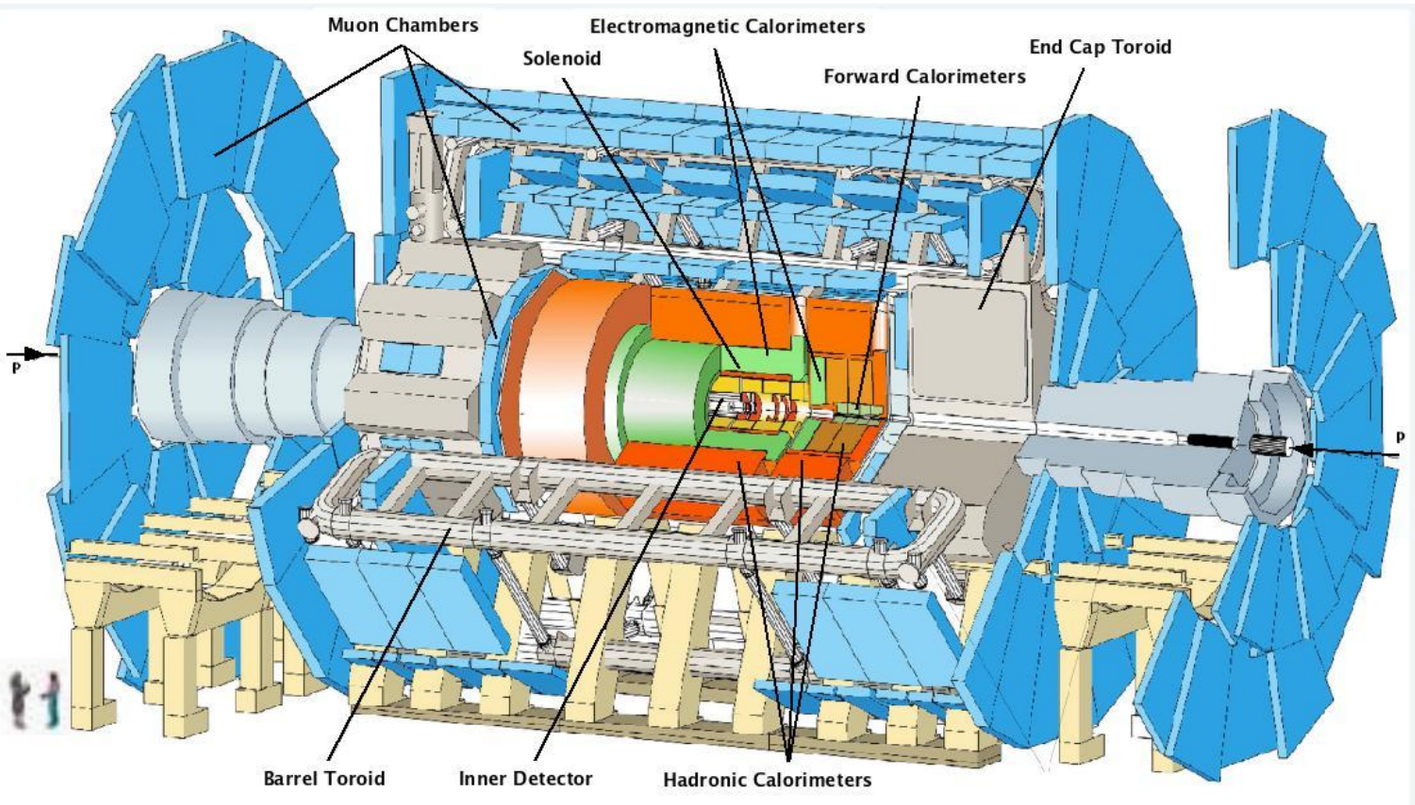
Overview

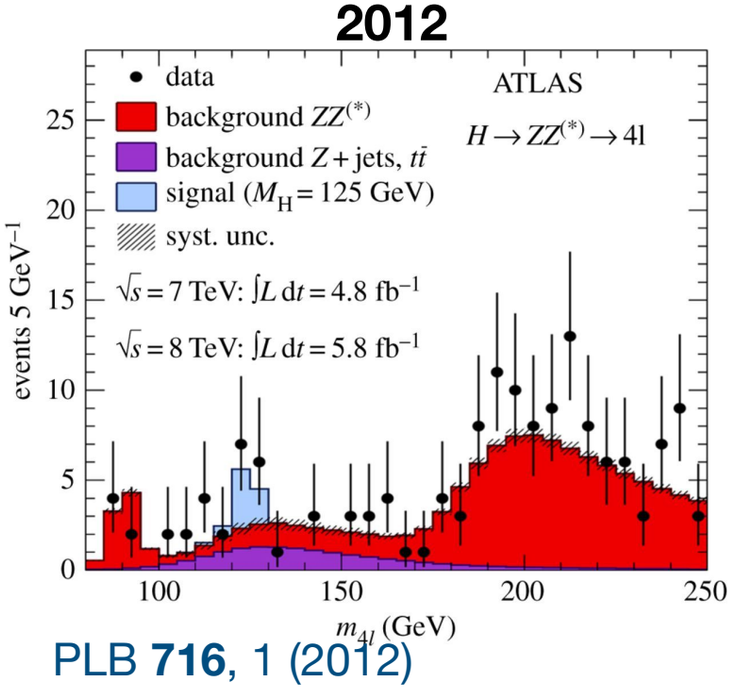




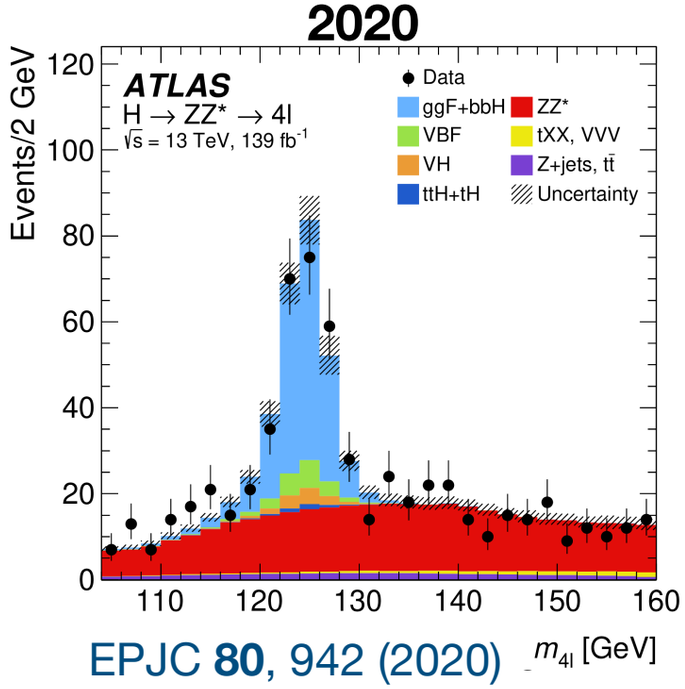


ATLAS

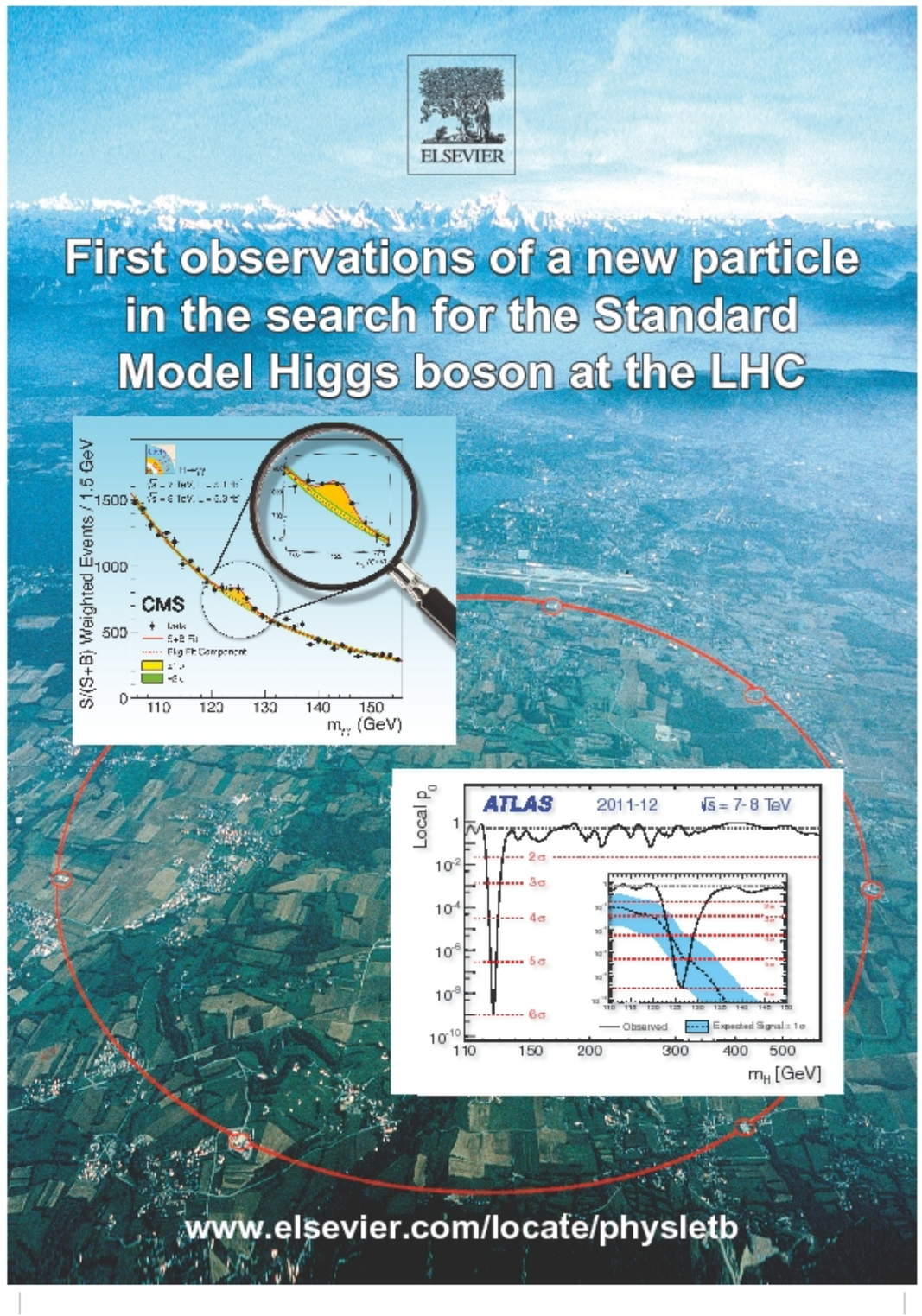




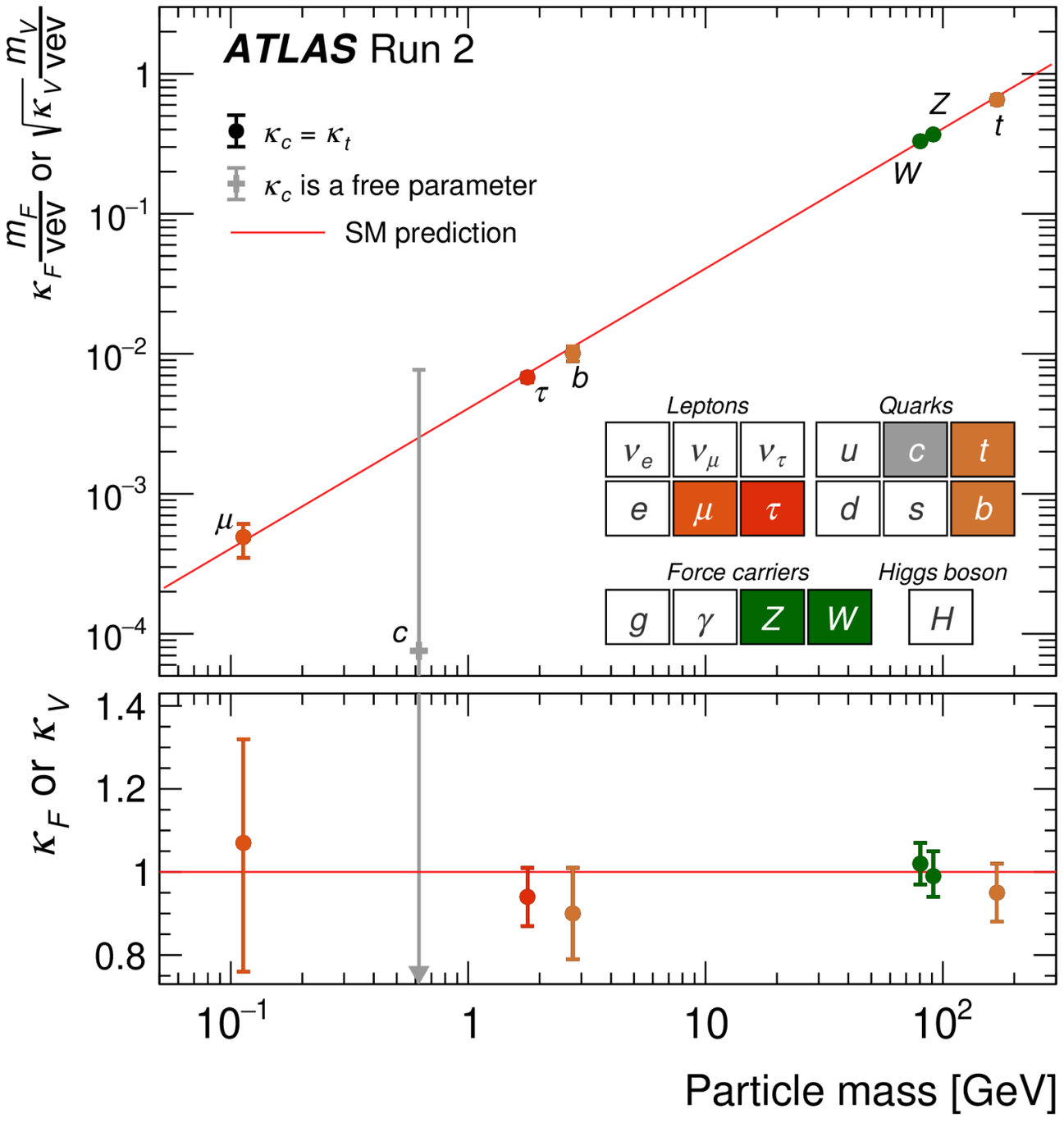
PLB **716**, 1 (2012)



EPJC **80**, 942 (2020)



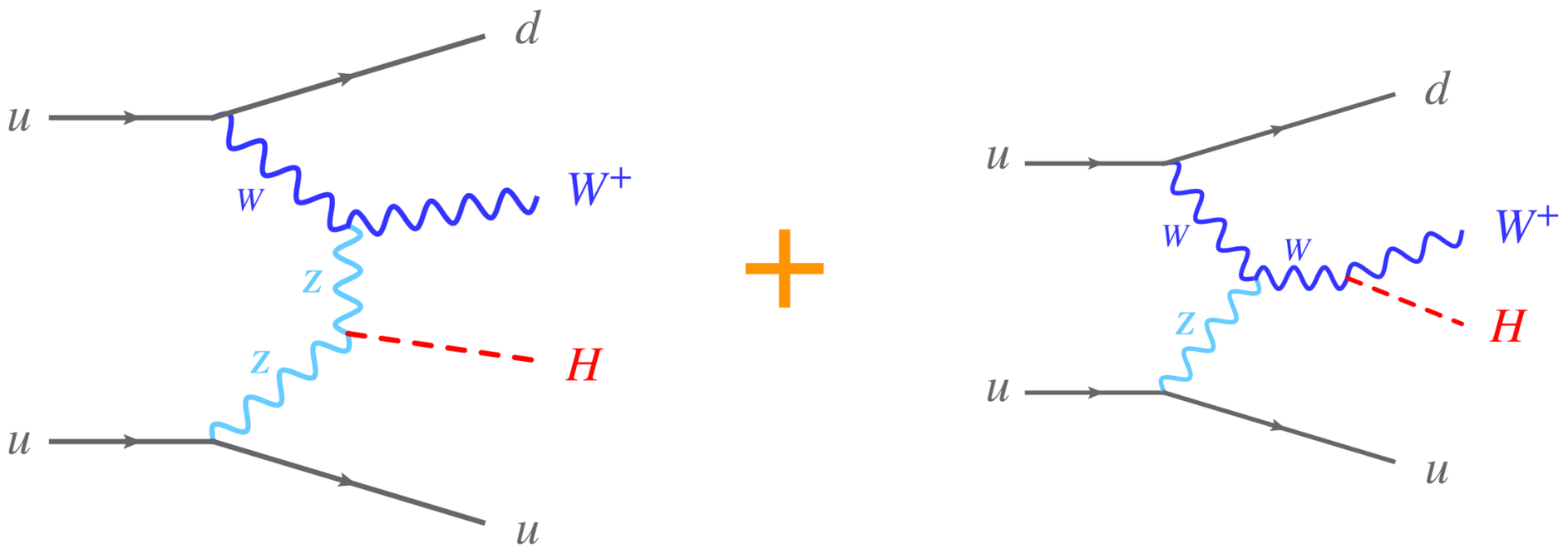
Higgs boson couplings



Nature **607**, 52 (2022)

Sign of Higgs boson couplings to W & Z

VBF WH production

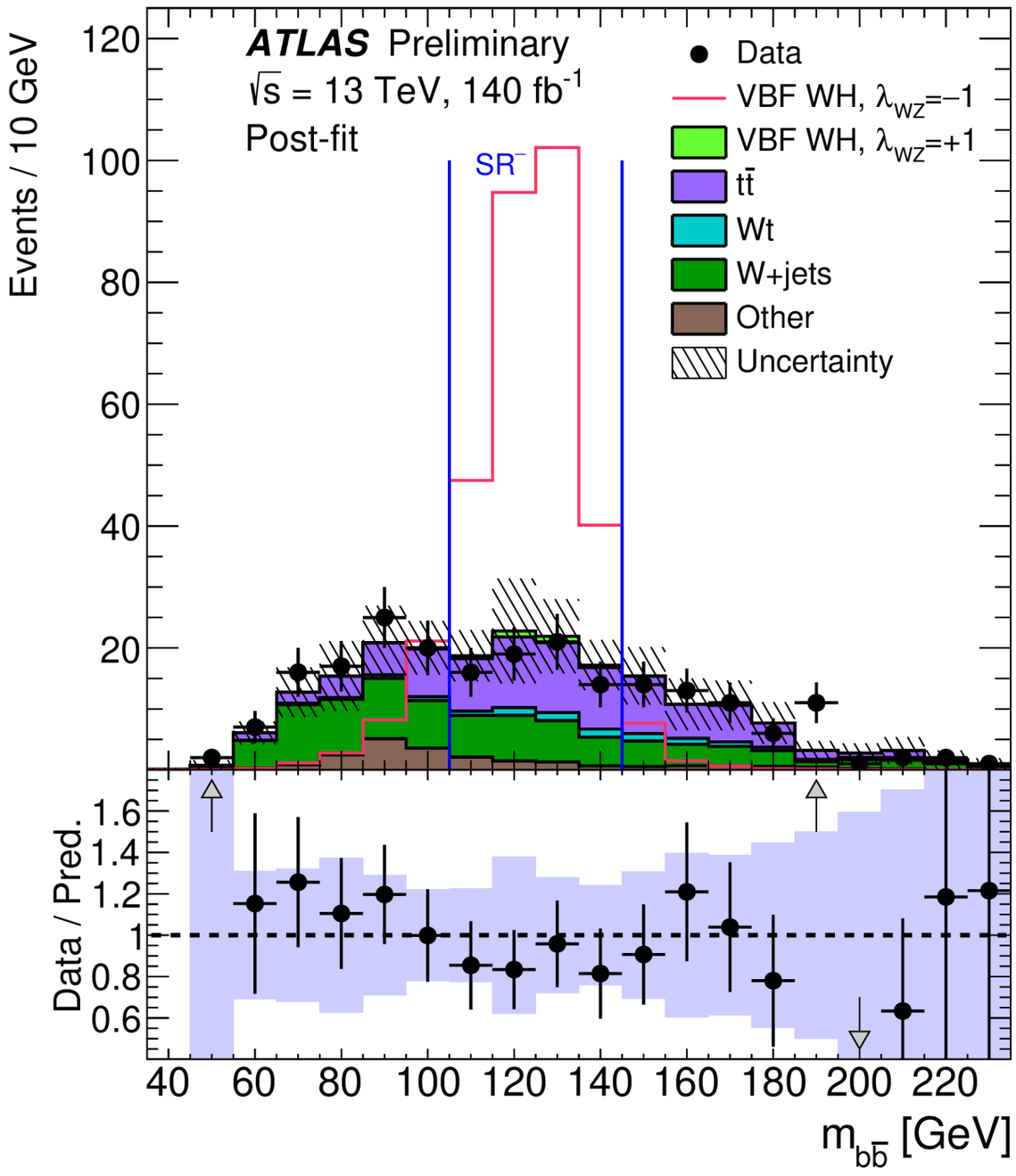


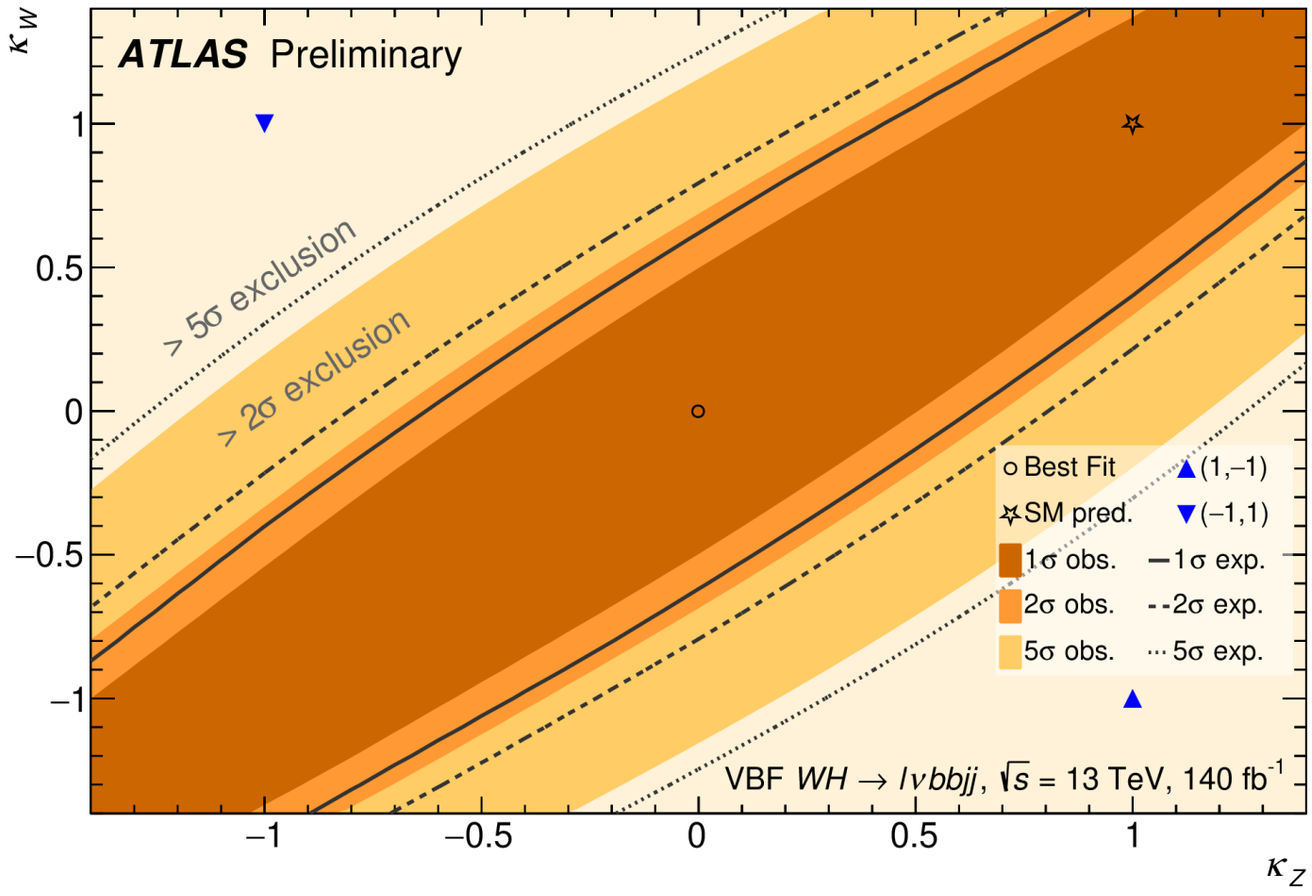
$\sim \kappa_Z^2$ Interference $\sim \kappa_W \kappa_Z$ $\sim \kappa_W^2$

$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\kappa_Z \kappa_W \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\kappa_Z^2 \boxed{\lambda_{WZ}} \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

ATLAS-CONF-2023-057

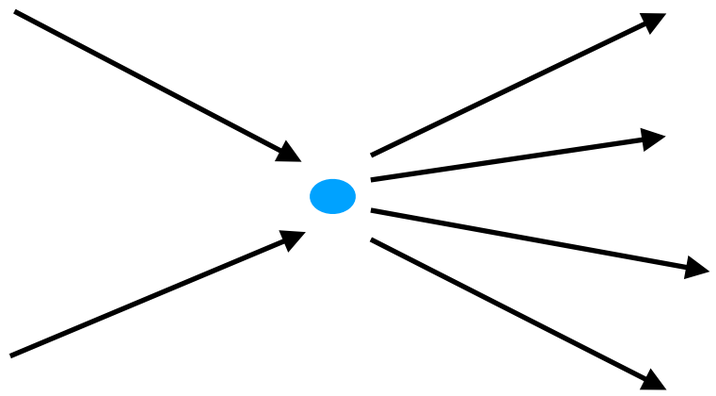
Sign of Higgs boson couplings to W & Z





Beyond the SM: The SMEFT

The SM EFT is a general framework for describing non-SM interactions at a high scale
It assumes the low (electroweak) scale is governed by the SM



$$d\sigma(exp) = d\sigma(SM) + d\sigma(d < TeV^{-1})$$

Expansion in orders of the new-physics scale: $\int d\sigma(d < TeV^{-1}) = \sigma_5\, v/\Lambda_{NP} + \sigma_6\, v^2/\Lambda_{NP}^2 + \ldots$

If NP distance scale is $<TeV^{-1}$ we can measure the SMEFT parameters affecting SM fields

If the low-mass fields are only SM then the $\sigma_5\, v/\Lambda_{NP}$ term is constrained by neutrino masses and the first term in the expansion relevant for Higgs is $\sigma_6\, v^2/\Lambda_{NP}^2$

The SMEFT: CP-even operators

Assuming gauge and flavor symmetries there are **60** parameters for CP-even interactions at mass-dimension 6 (arXiv:2012.11343)

Allowing for 3rd-generation-specific couplings increases this to **204** (“top” symmetry scheme)

Most parameters correspond to 4-fermion operators

Including constraints from precision EW physics reduces the number of parameters affecting Higgs physics to O(50)

Wilson coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_G	$f^{abc}G^{a\nu}_\mu G^{b\rho}_\nu G^{c\mu}_\rho$
c_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$
$c^{(1)}_{Hl,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_1\gamma^\mu l_1)$
$c^{(1)}_{Hl,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_2\gamma^\mu l_2)$
$c^{(1)}_{Hl,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_3\gamma^\mu l_3)$
$c^{(3)}_{Hl,11}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_1\tau^I\gamma^\mu l_1)$
$c^{(3)}_{Hl,22}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_2\tau^I\gamma^\mu l_2)$
$c^{(3)}_{Hl,33}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_3\tau^I\gamma^\mu l_3)$
$c_{He,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_1\gamma^\mu e_1)$
$c_{He,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_2\gamma^\mu e_2)$
$c_{He,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_3\gamma^\mu e_3)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$c^{(1)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$c^{(3)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$

Wilson coefficient	Operator
$c^{(1,1)}_{Qq}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$c^{(1,8)}_{Qq}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
$c^{(3,1)}_{Qq}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
$c^{(3,8)}_{Qq}$	$(\bar{Q}\sigma^iT^a\gamma_\mu Q)(\bar{q}\sigma^iT^a\gamma^\mu q)$
$c^{(3,1)}_{qq}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
$c^{(1)}_{tu}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
$c^{(8)}_{tu}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
$c^{(1)}_{td}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$
$c^{(8)}_{td}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$
$c^{(1)}_{Qu}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
$c^{(8)}_{Qu}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$c^{(1)}_{Qd}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
$c^{(8)}_{Qd}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$
$c^{(1)}_{tq}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$
$c^{(8)}_{tq}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$
$c_{eH,22}$	$(H^\dagger H)(\bar{l}_2e_2H)$
$c_{eH,33}$	$(H^\dagger H)(\bar{l}_3e_3H)$
c_{uH}	$(H^\dagger H)(\bar{q}Y^\dagger_u u\widetilde{H})$
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H}t)$
c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^At)\widetilde{H}\,G^A_{\mu\nu}$
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\,B_{\mu\nu}$
$c_{ll,1221}$	$(\bar{l}_1\gamma_\mu l_2)(\bar{l}_2\gamma^\mu l_1)$

Higgs/gauge

4-quark

Higgs Yukawa

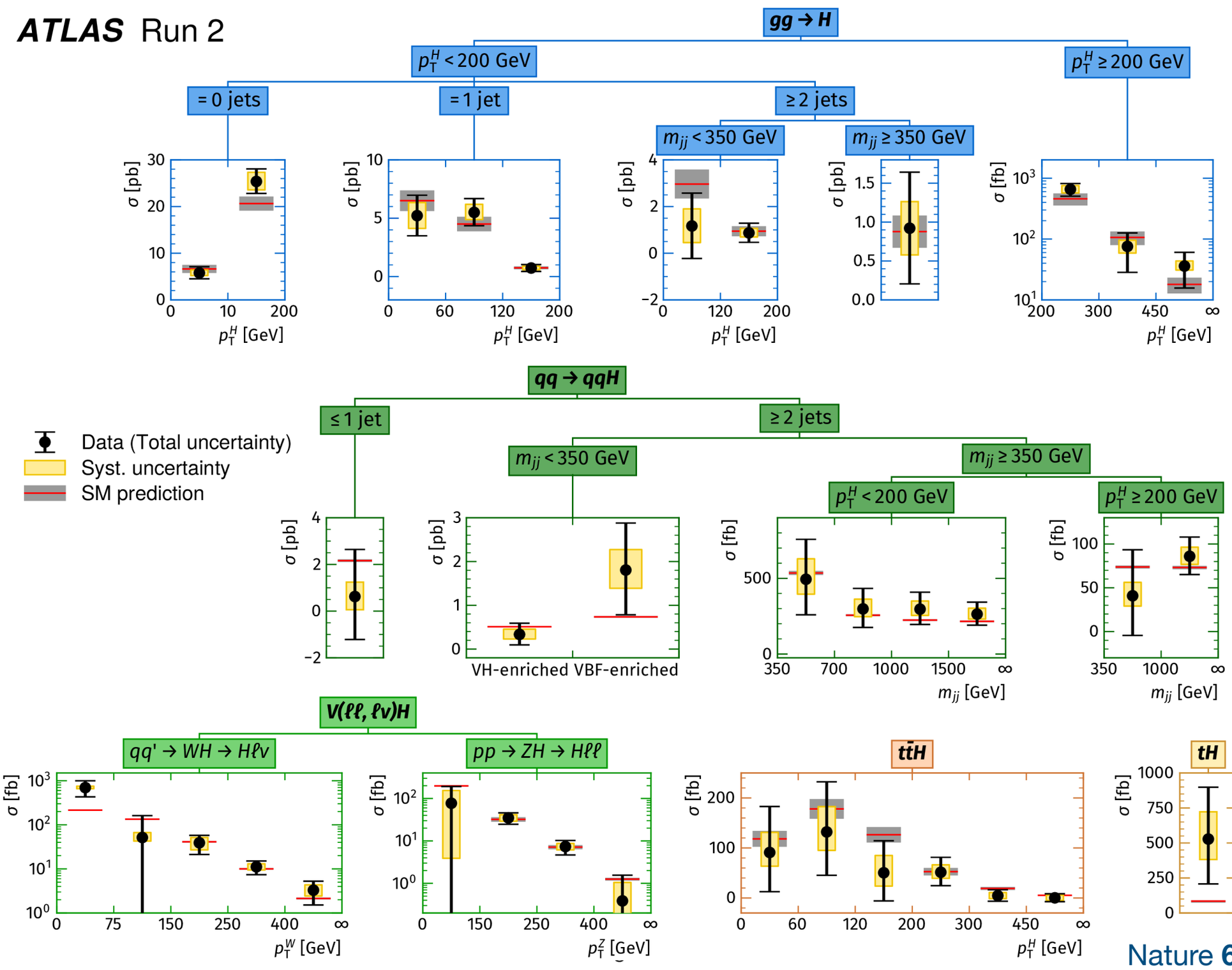
top gauge

Higgs/EW

G_F

ATLAS-CONF-2023-052

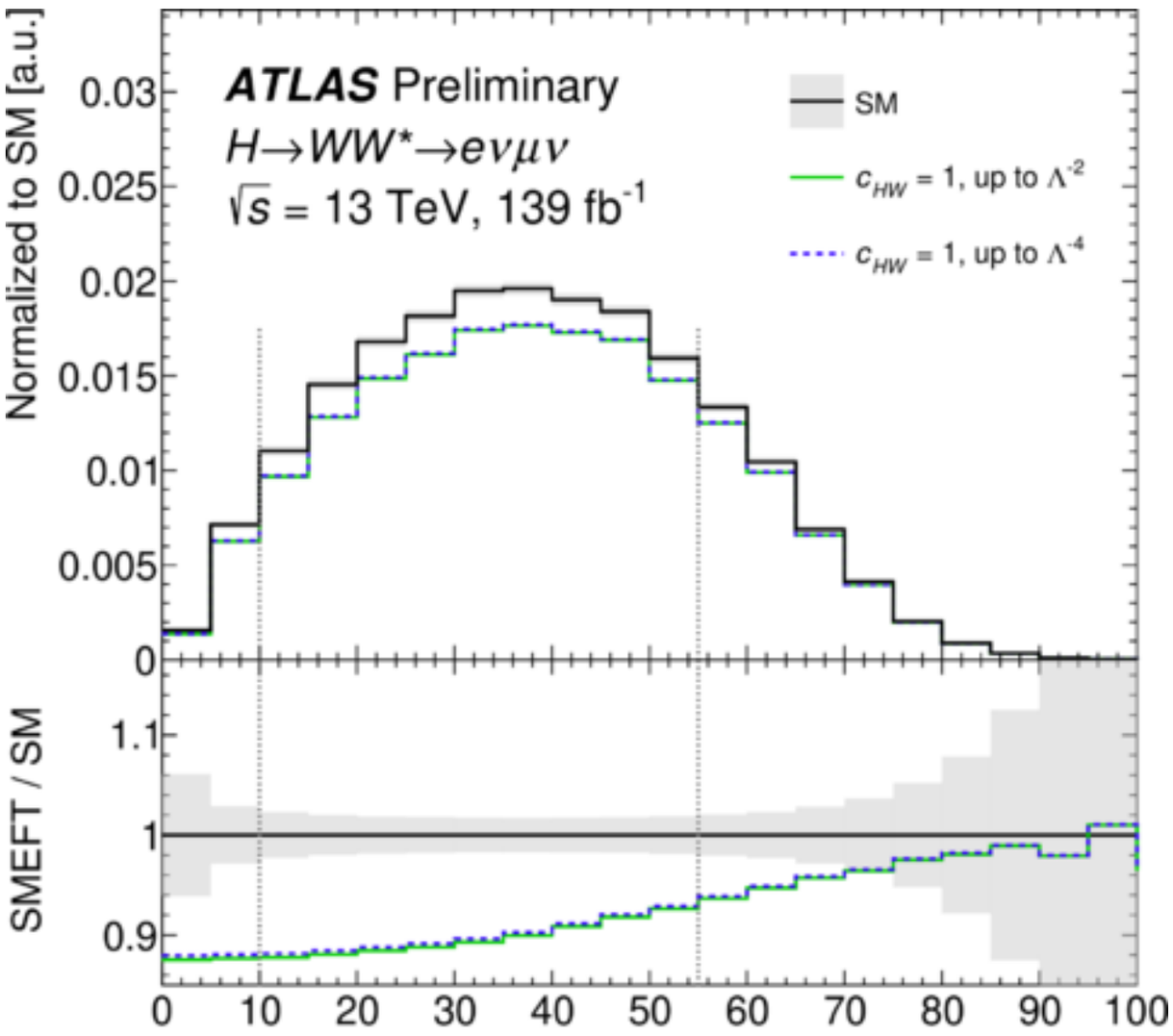
Simplified template cross sections

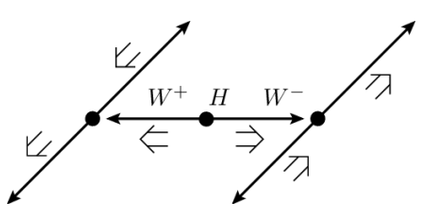


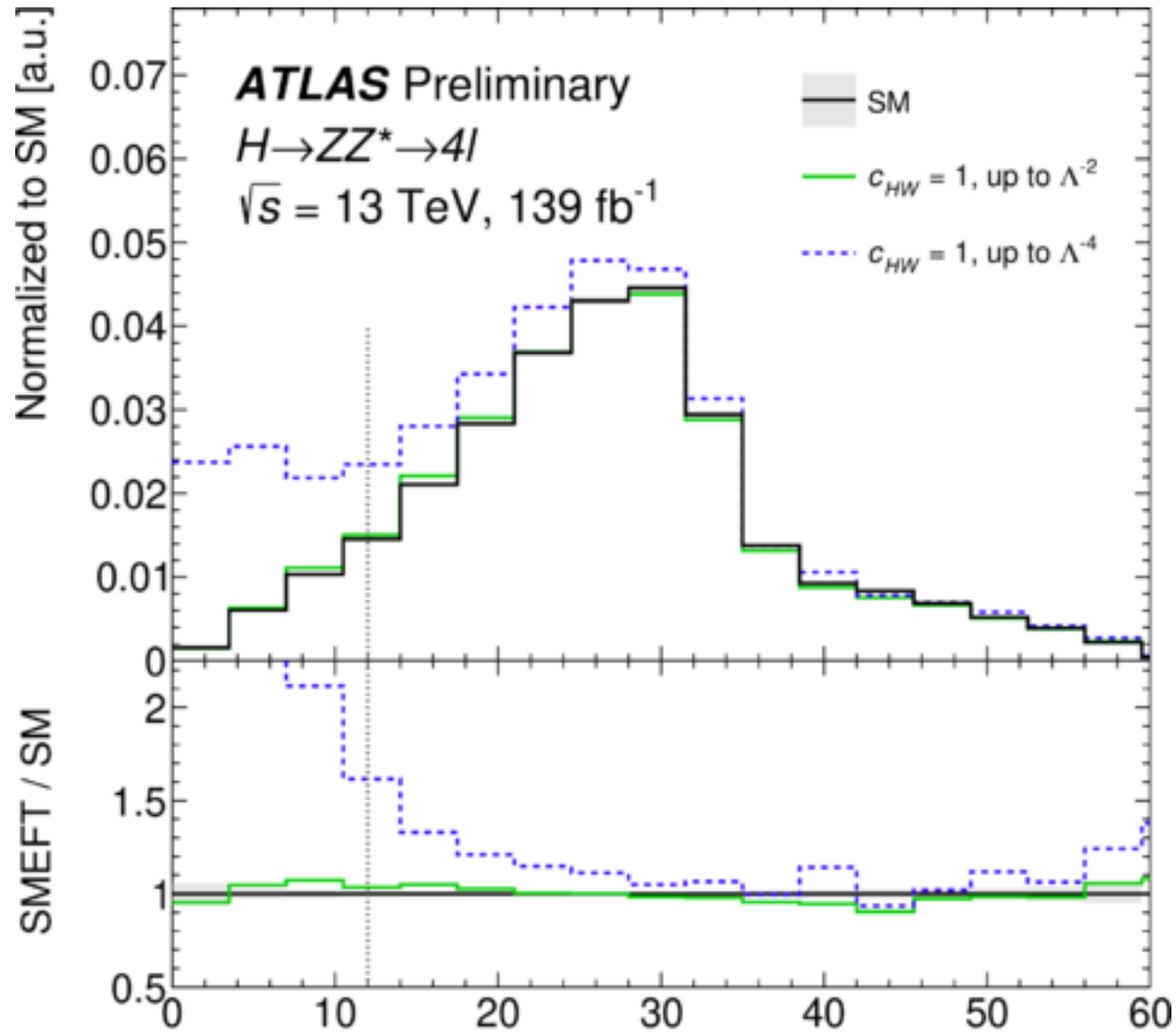
Nature **607**, 52 (2022)

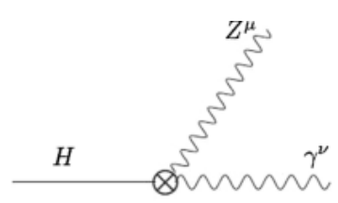
Acceptance corrections

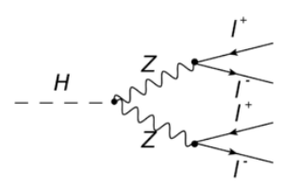
Current STXS definitions require fiducial acceptance corrections for EFT interpretation







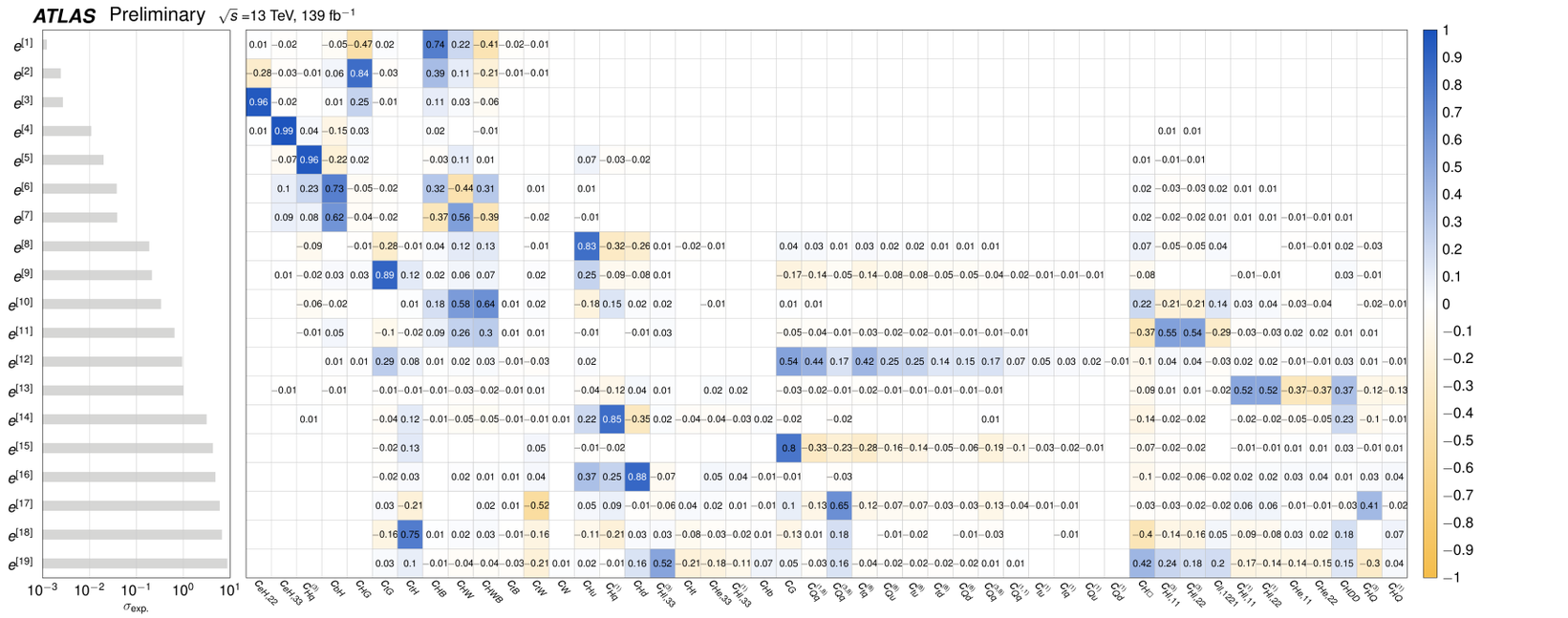




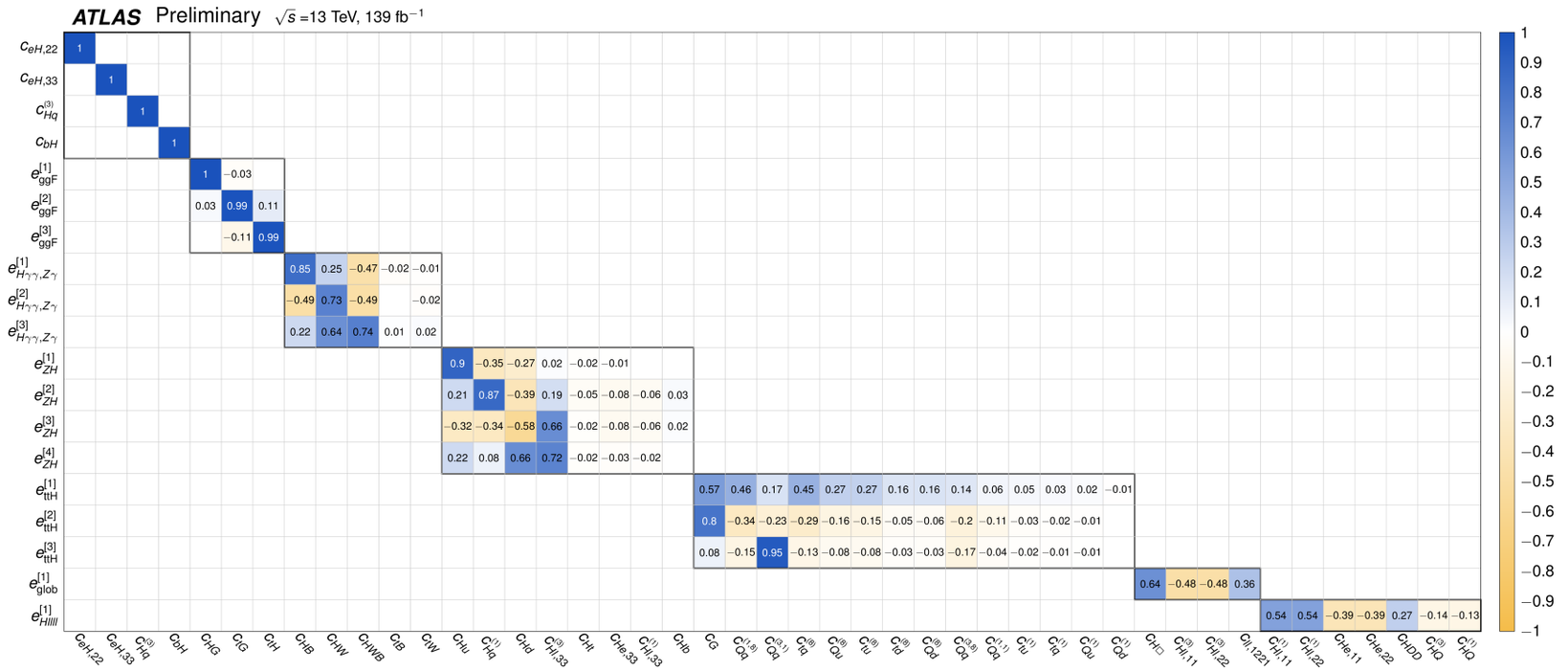
Eigenvectors

Decompose Fisher information matrix to get eigenvectors with experimental sensitivity

$$V^{-1}_{\mathrm{SMEFT}} = P^{T}_{(i,k',X)\to(j)}\, V^{-1}_{\mathrm{STXS}}\, P_{(i,k',X)\to(j)}\,.$$

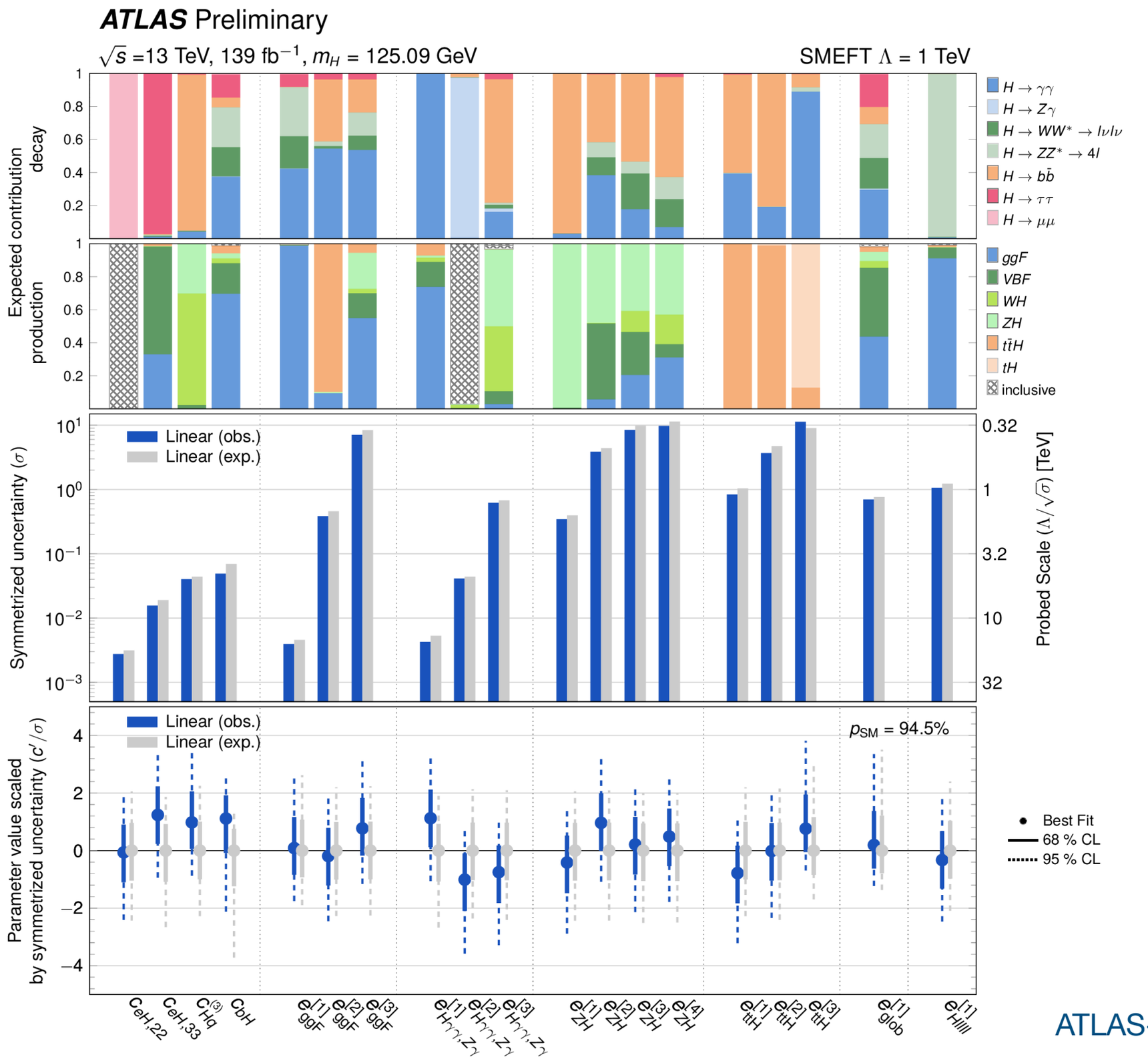


Use eigenvectors to define a fit basis



ATLAS-CONF-2023-052

Constraints on CP-even couplings



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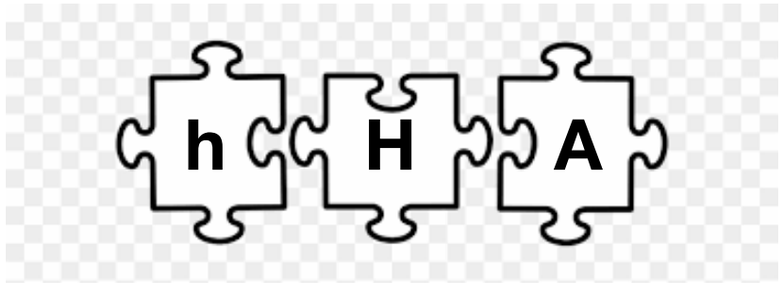
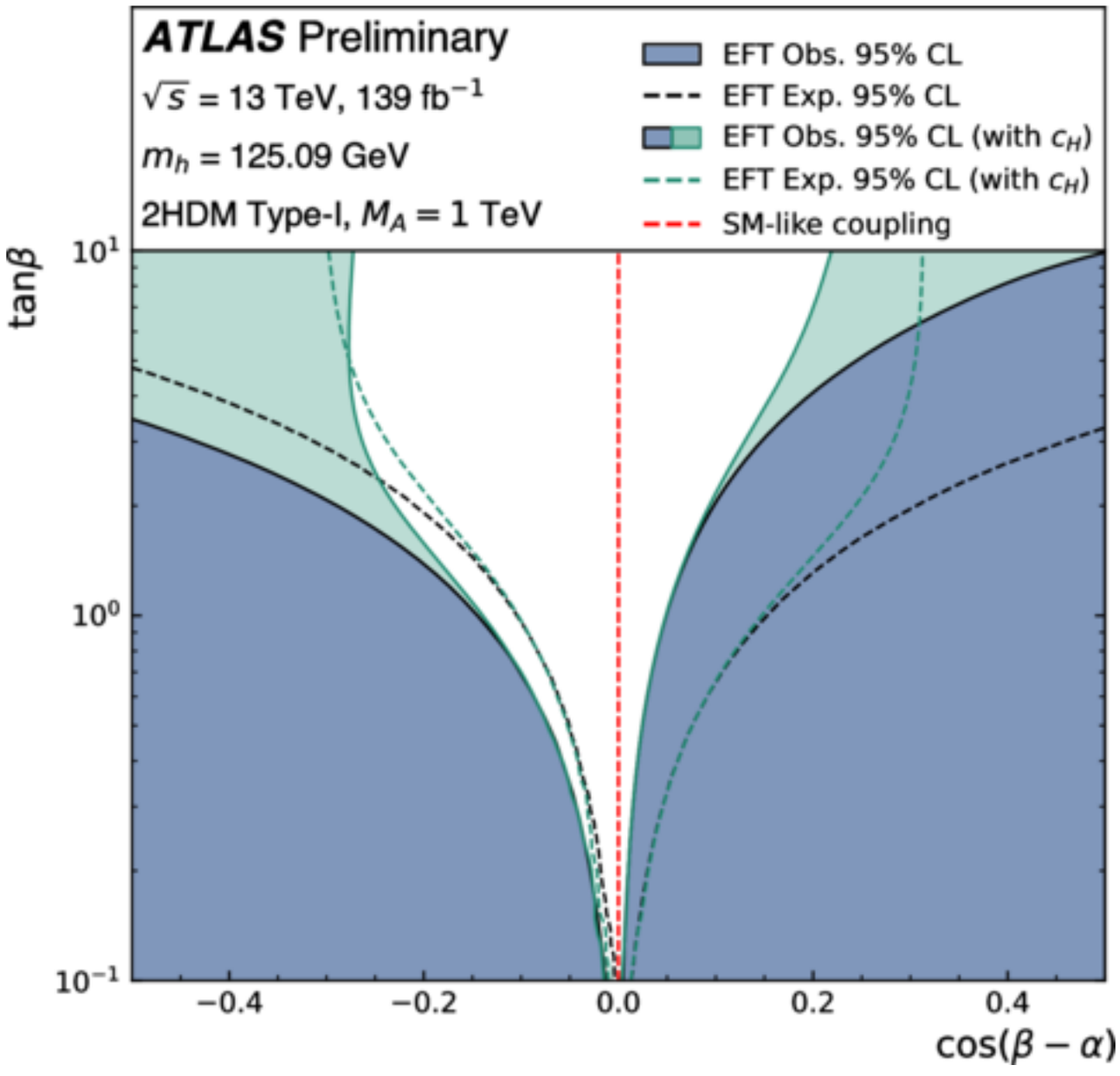
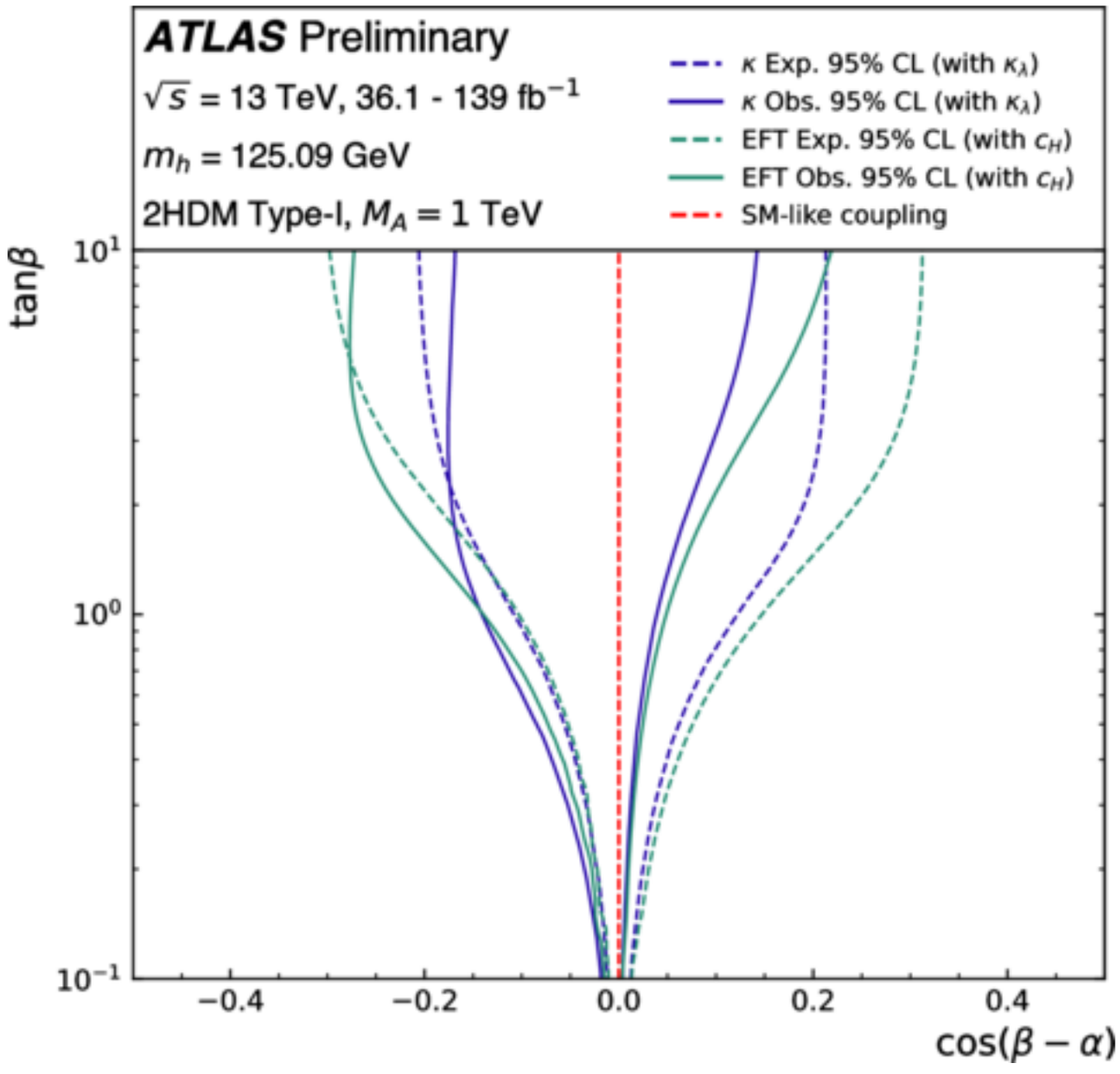
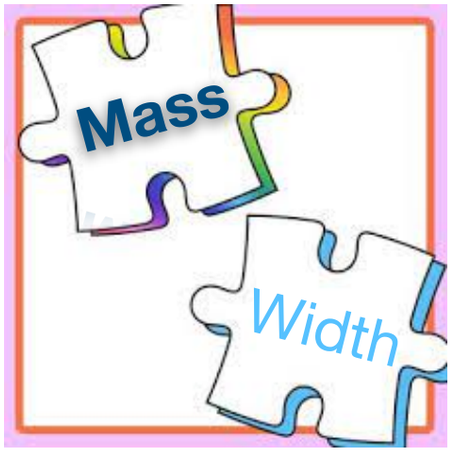
Constraints on CP-even couplings

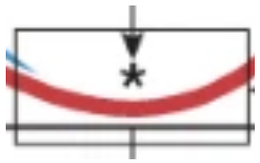






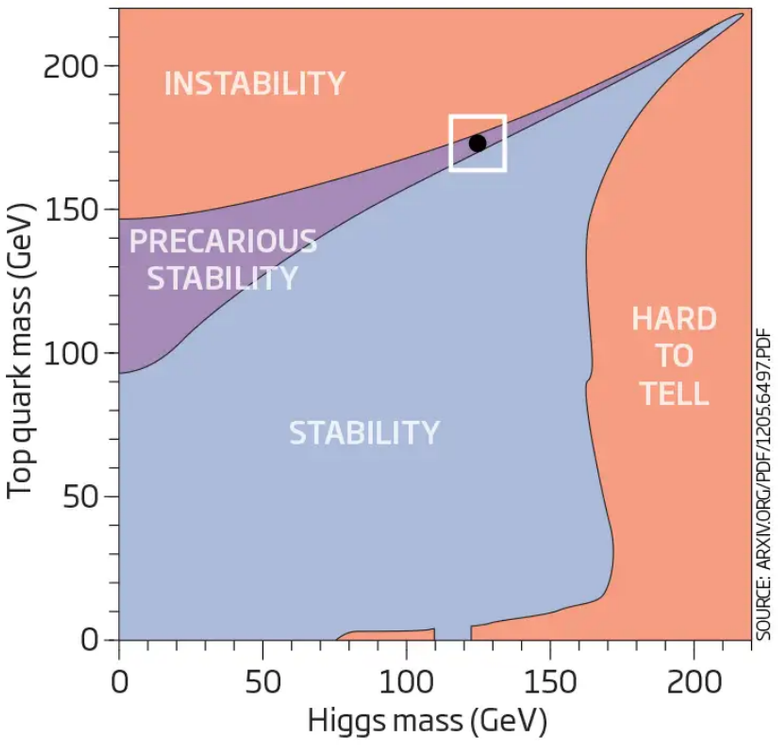
Higgs boson mass

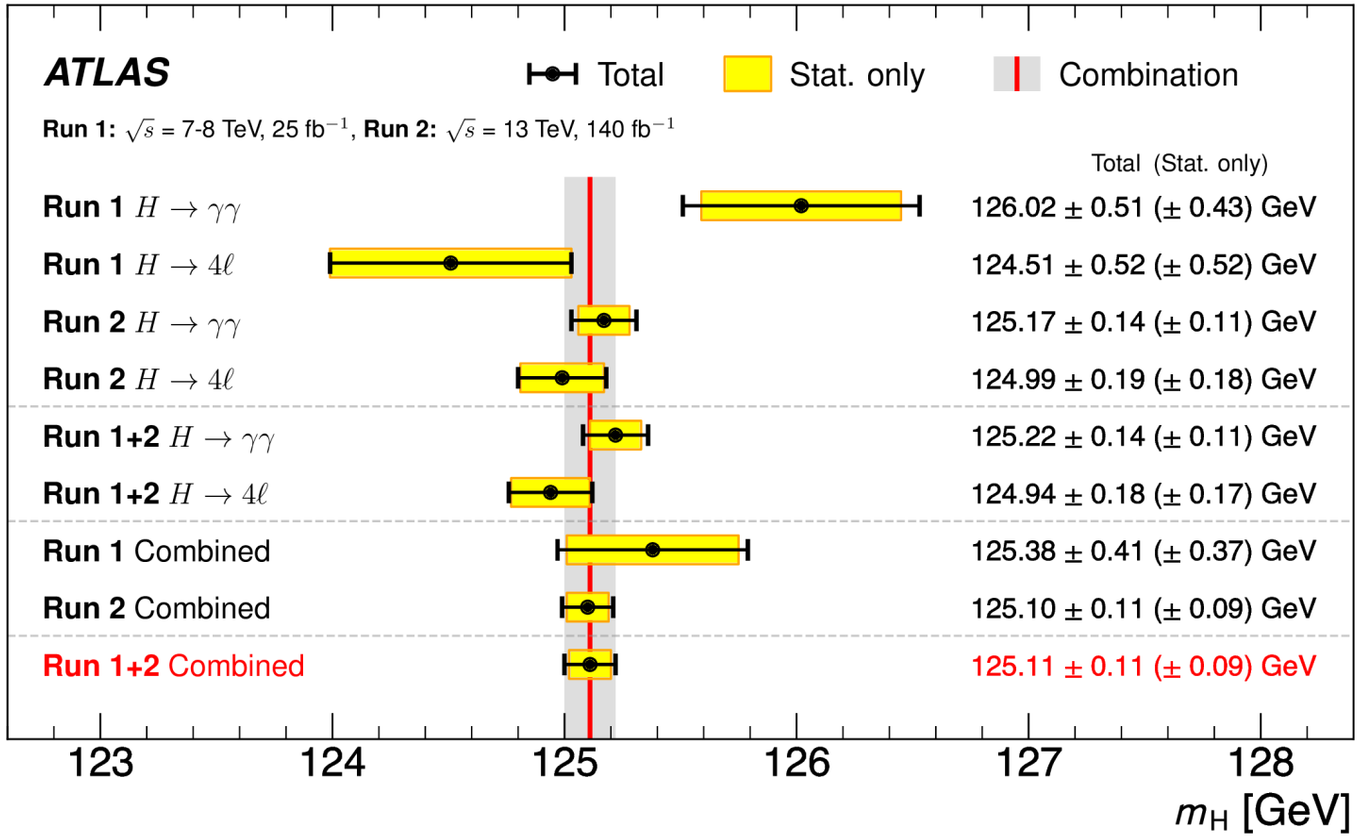




Massive coincidence

If the top quark were slightly heavier relative to the Higgs boson, the universe would have collapsed long ago

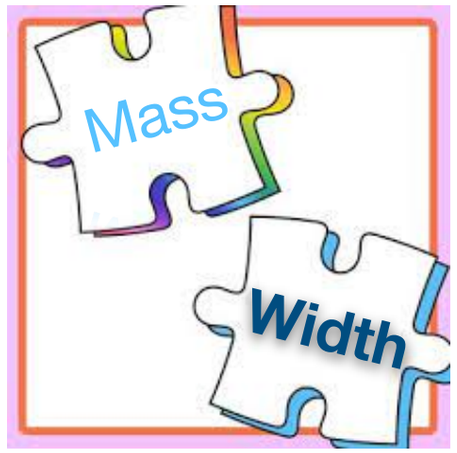


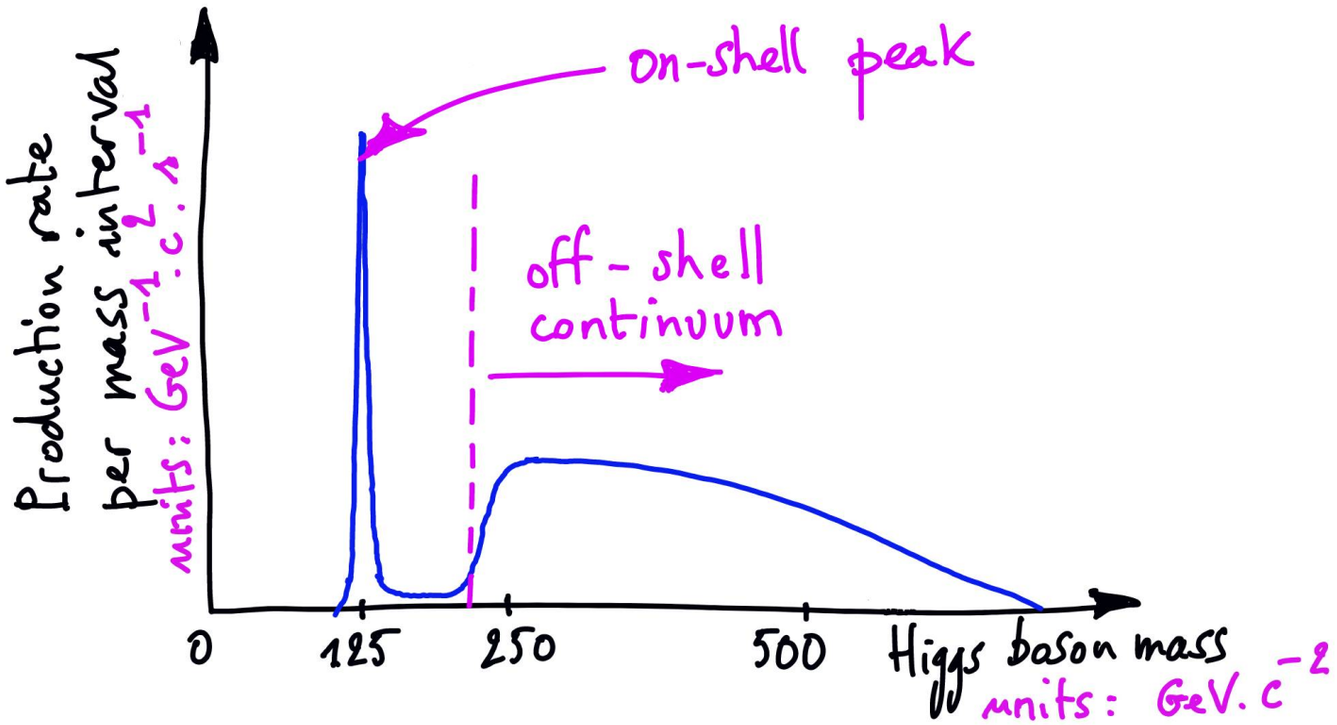


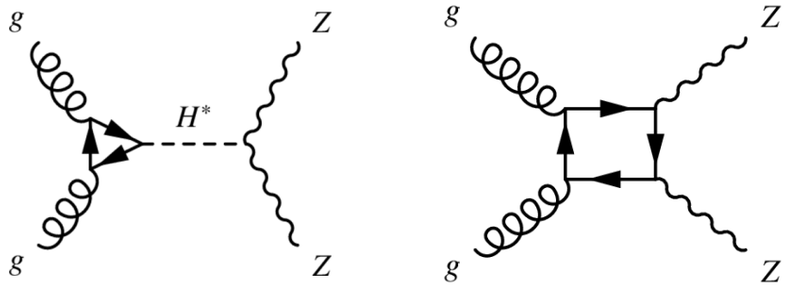
Source	Systematic uncertainty on m_H [MeV]
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7

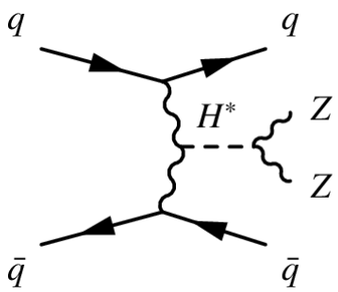
arXiv:2308.04775

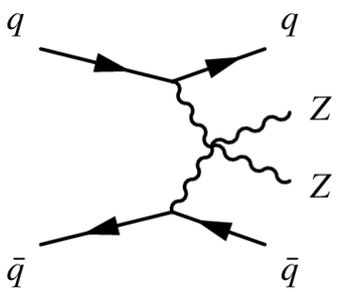
Higgs boson width





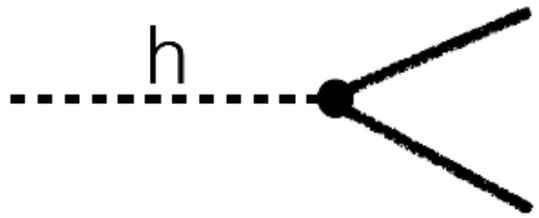


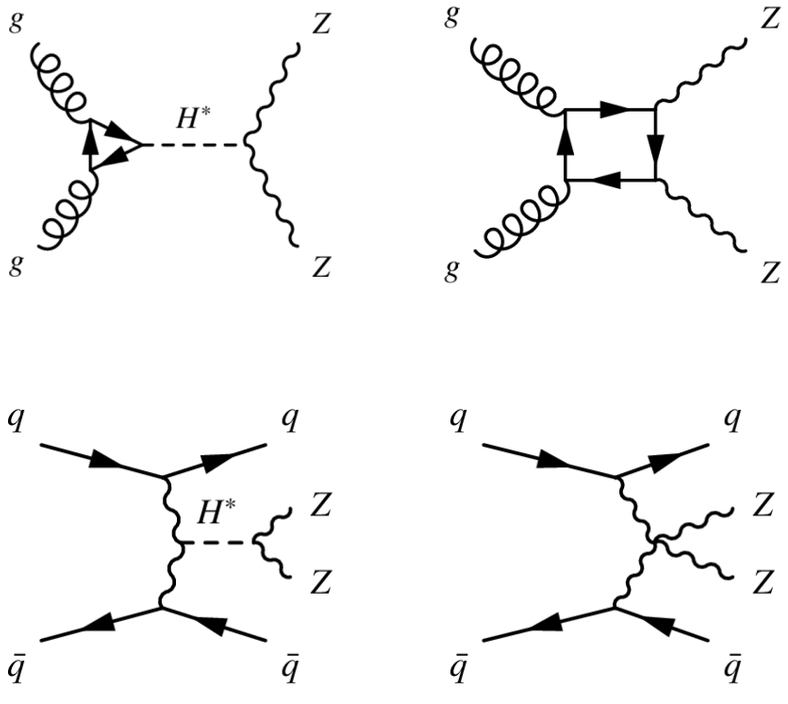


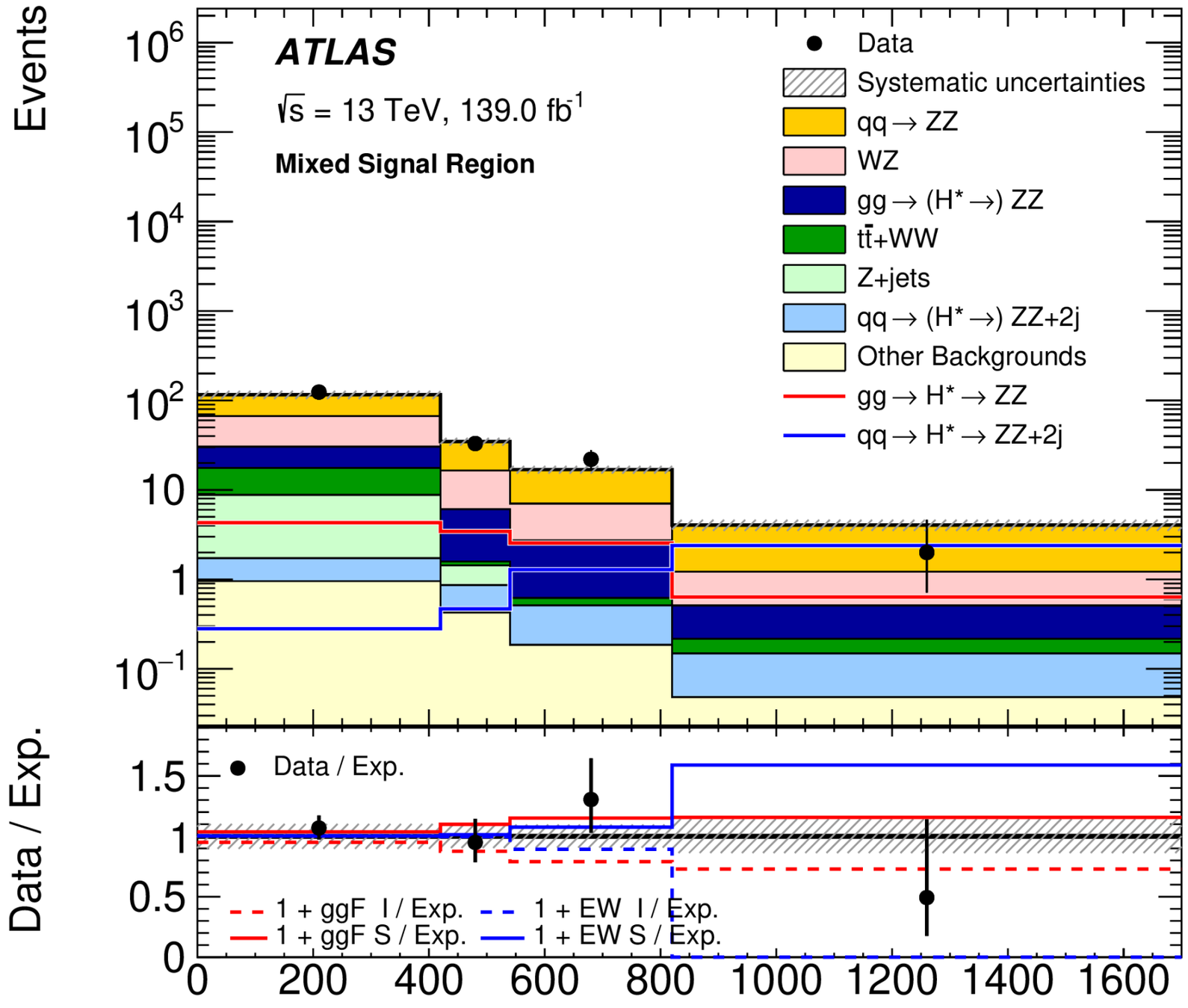


$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

Higgs boson width

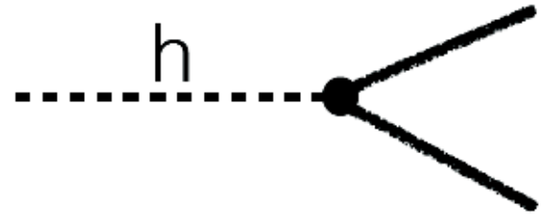


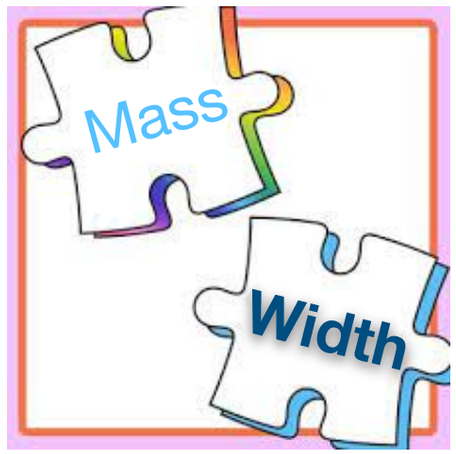


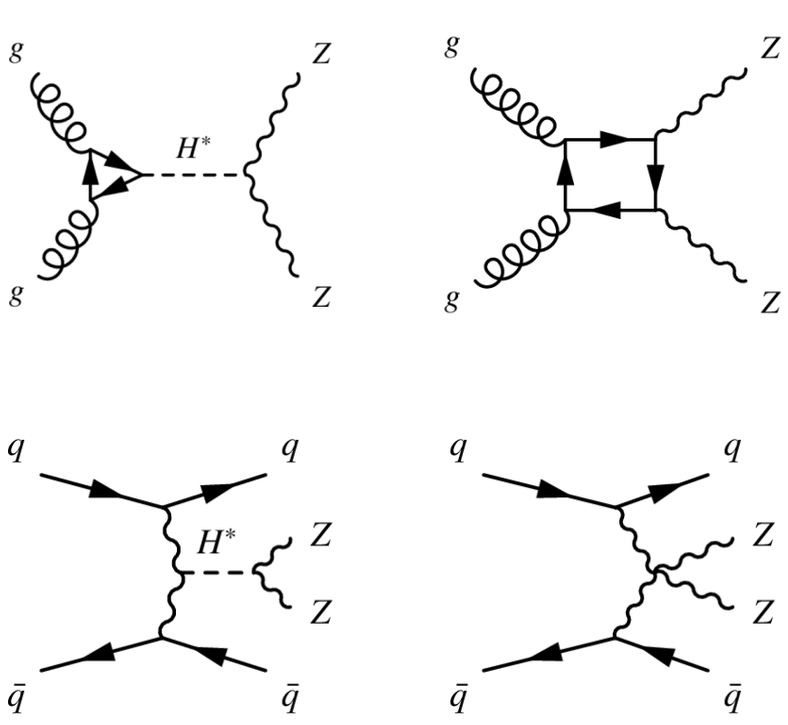


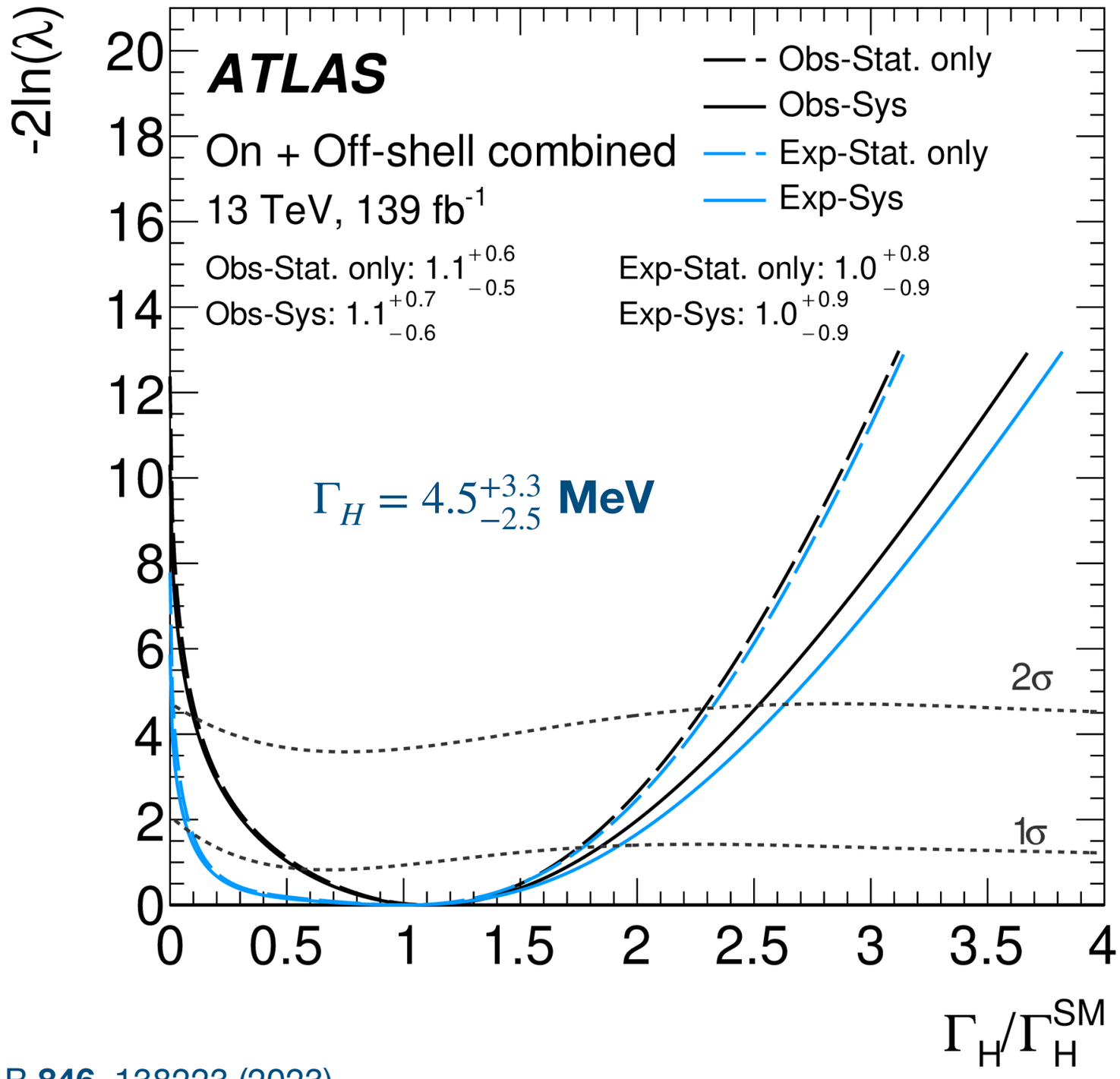
PLB **846**, 138223 (2023)

Higgs boson width



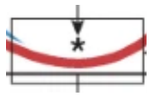


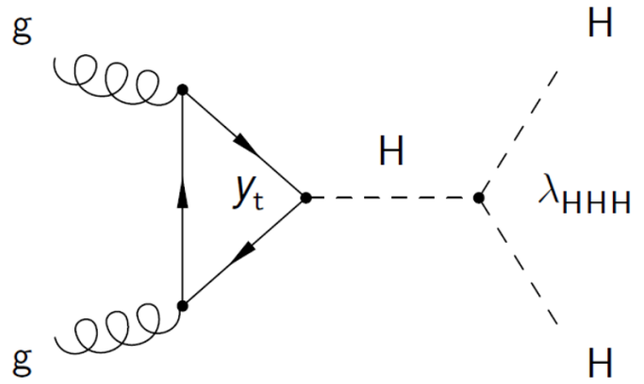


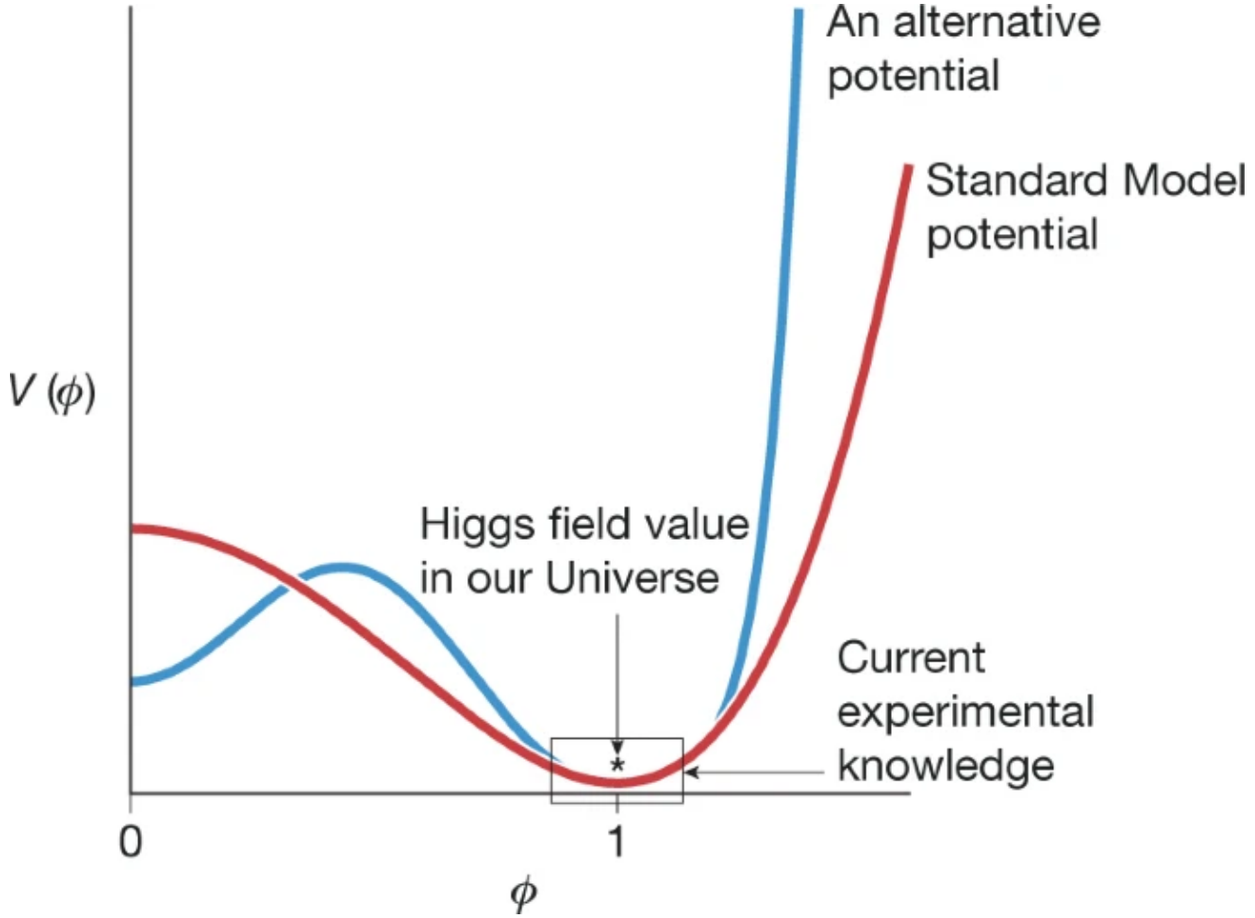


PLB **846**, 138223 (2023)

Higgs potential



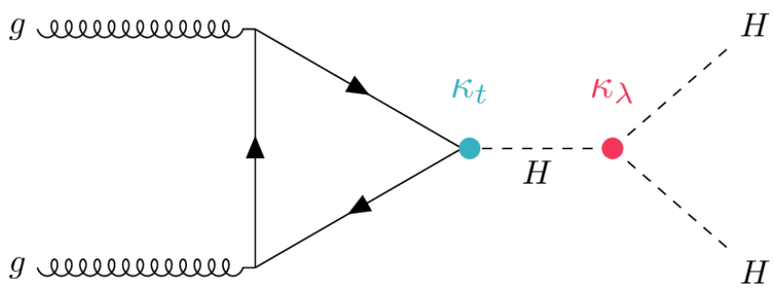


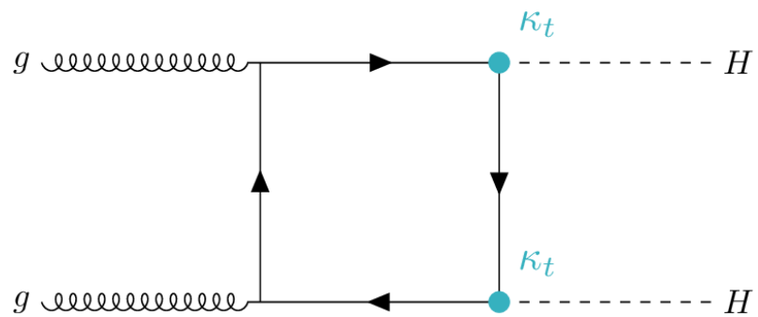


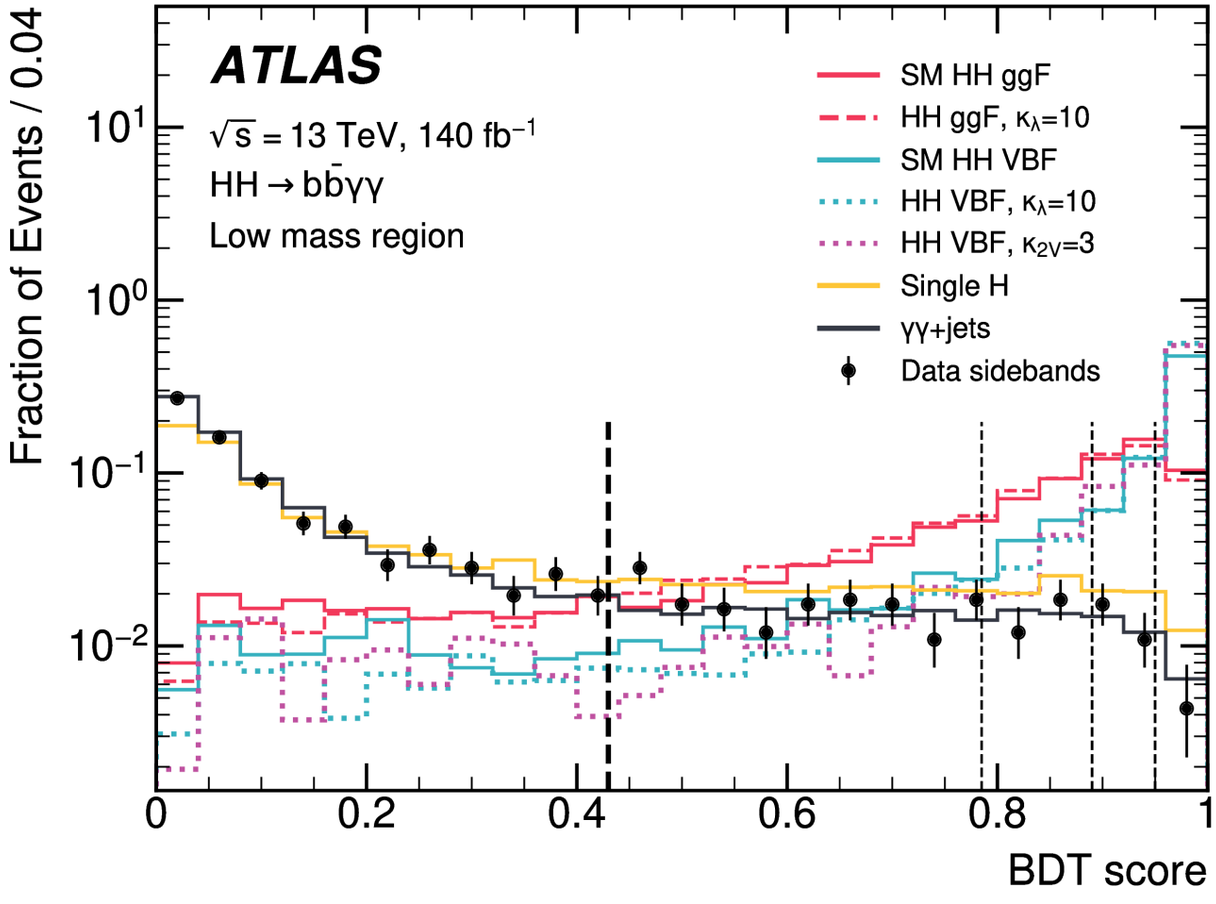
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

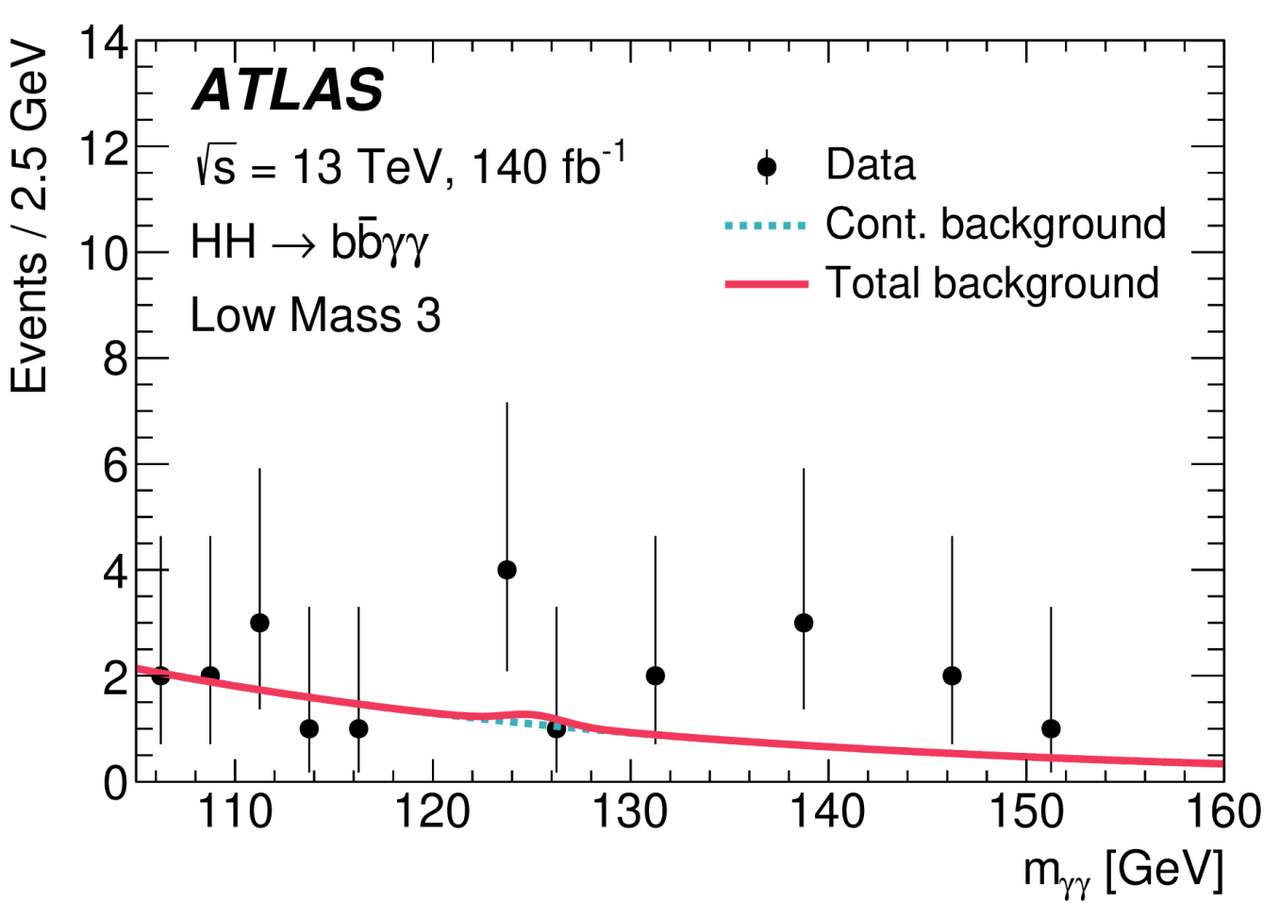
Nature **607**, 41 (2022)

Higgs potential



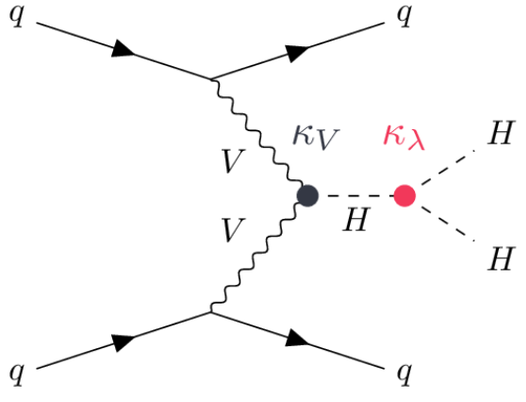


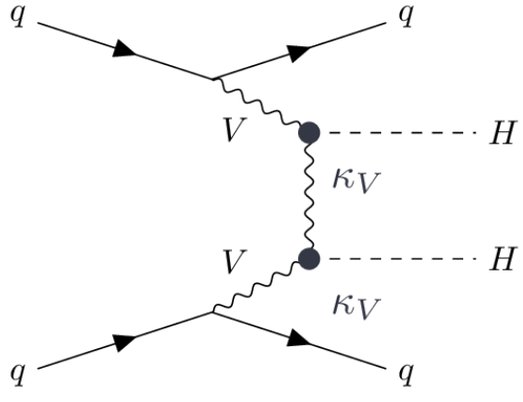


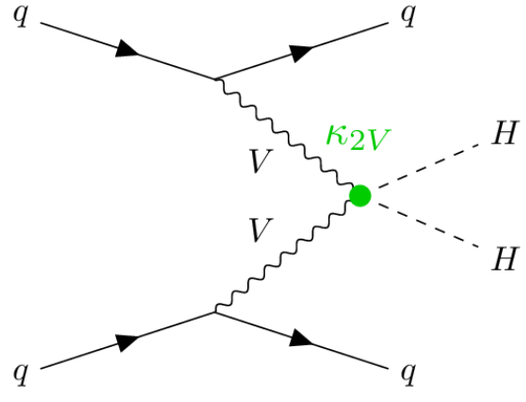


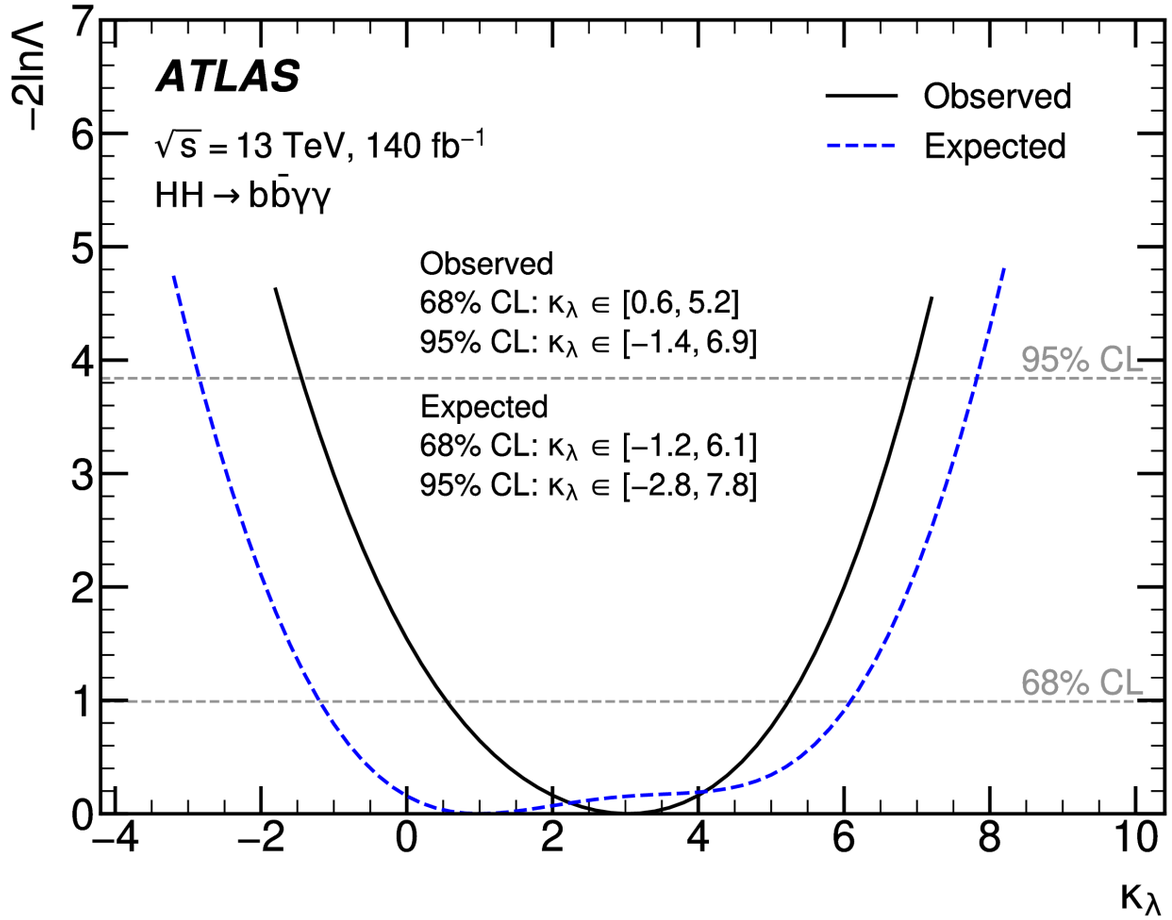
arXiv:2310.12301

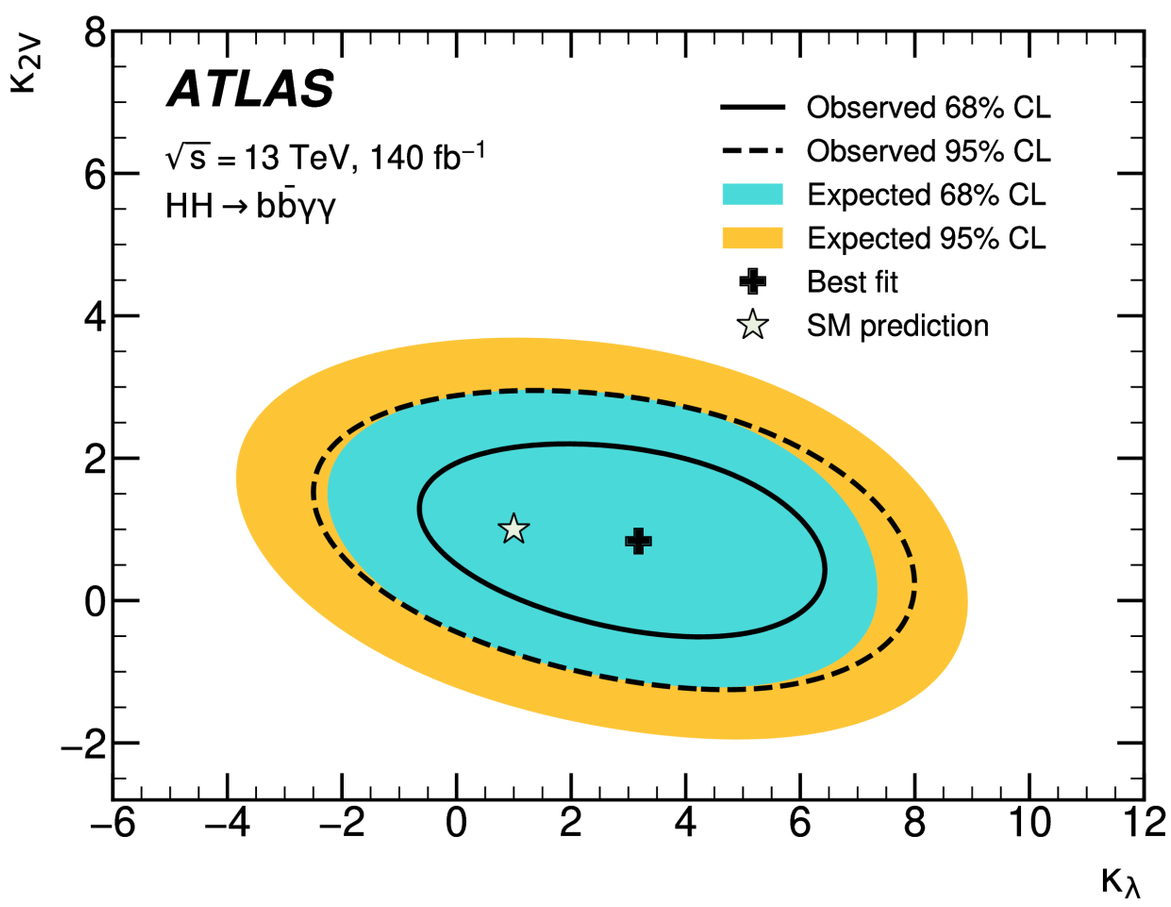
Higgs potential





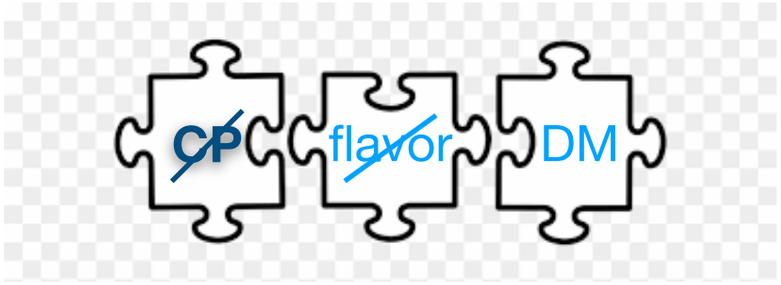


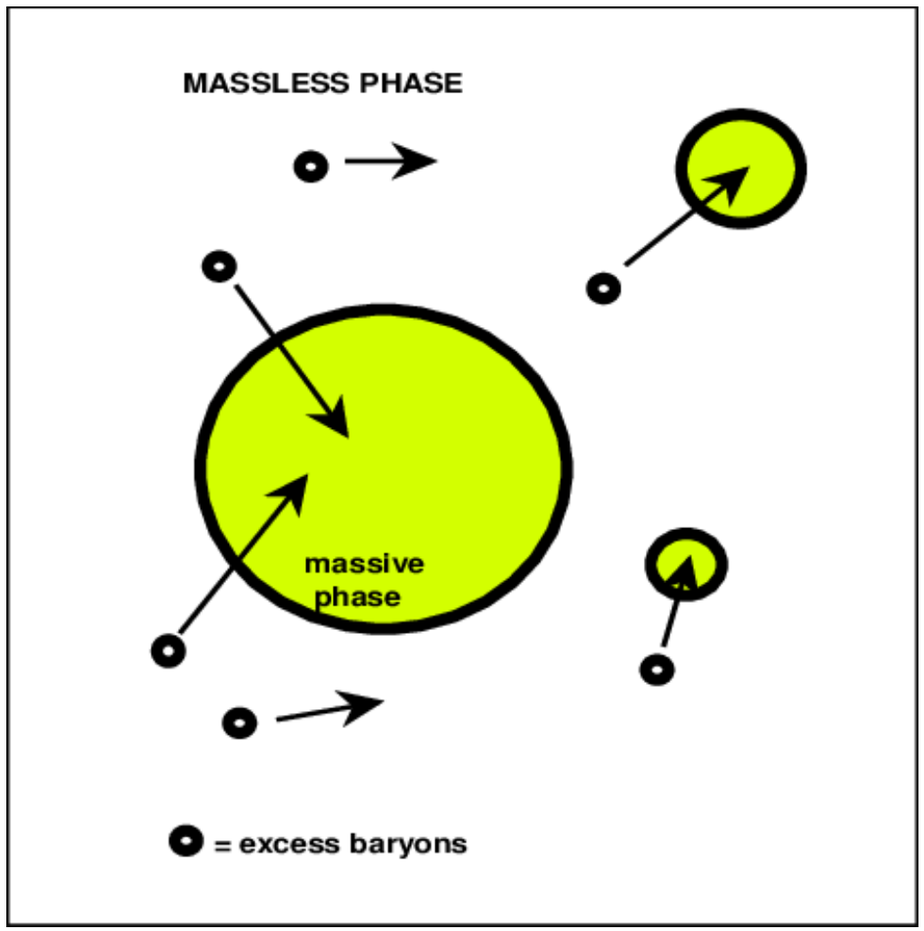


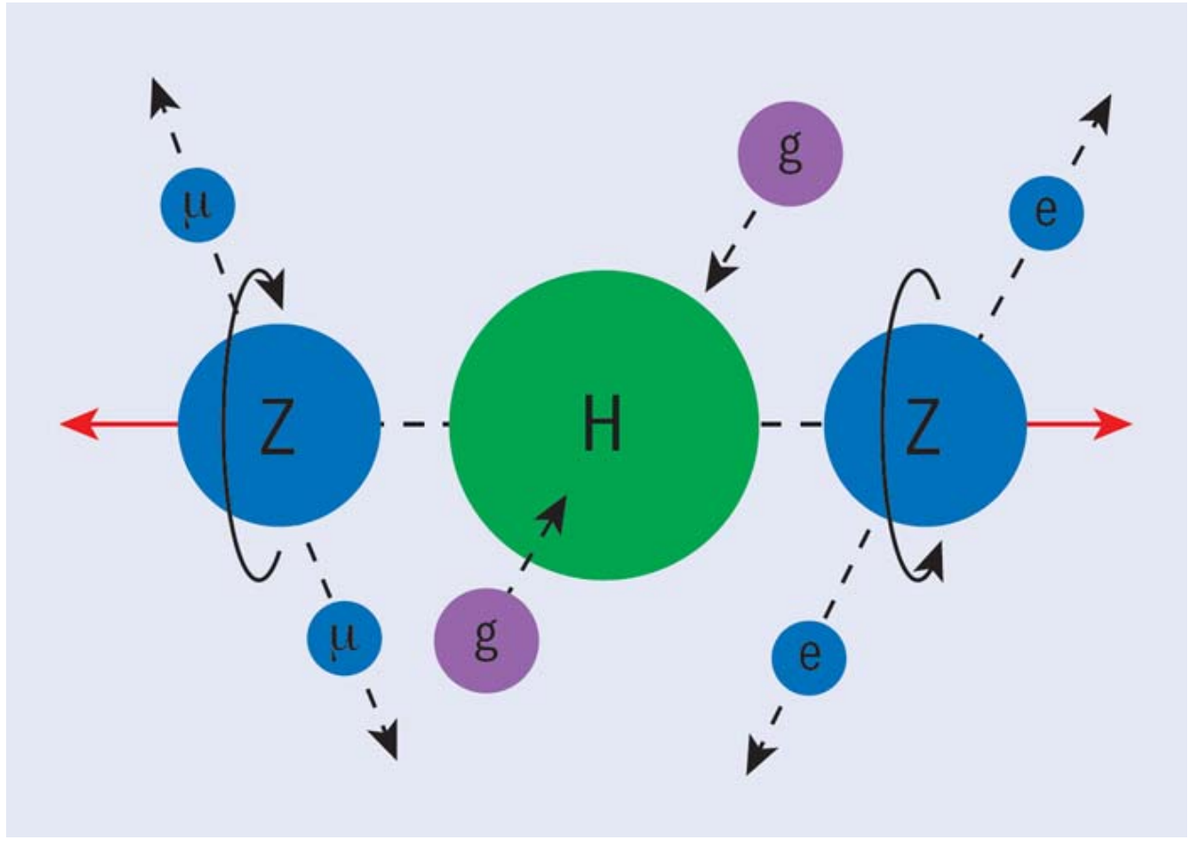


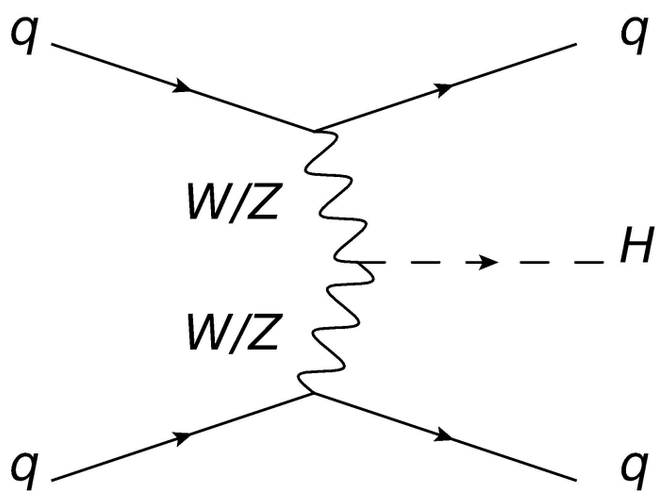
arXiv:2310.12301

CP-odd Higgs couplings









The SMEFT: CP-odd operators

In the “top” symmetry scheme there are **71** parameters for CP-odd interactions at mass-dimension 6 (arXiv:2012.11343)

$Q_{\widetilde{G}}$	$f^{abc}\widetilde{G}^{a\nu}_{\mu}G^{b\rho}_{\nu}G^{c\mu}_{\rho}$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk}\widetilde{W}^{i\nu}_{\mu}W^{j\rho}_{\nu}W^{k\mu}_{\rho}$
$Q_{H\widetilde{G}}$	$H^\dagger H\,\widetilde{G}^{a}_{\mu\nu}G^{a\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\,\widetilde{W}^{i}_{\mu\nu}W^{i\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger\sigma^i H\,\widetilde{W}^{i}_{\mu\nu}B^{\mu\nu}$

Higgs/gauge (6)

Q_{uH}	$(H^\dagger H)(\bar{q}\,Y_u^\dagger\,u\tilde{H})$	Q_{dH}	$(H^\dagger H)(\bar{q}\,Y_d^\dagger\,dH)$	Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$	Q_{bH}	$(H^\dagger H)(\bar{Q}Hb)$		

Higgs Yukawa (7)

Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\sigma^i HW^i_{\mu\nu}$	Q_{uW}	$(\bar{q}\,Y_u^\dagger\,\sigma^{\mu\nu}u)\sigma^i\tilde{H}W^i_{\mu\nu}$	Q_{uB}	$(\bar{q}\,Y_u^\dagger\,\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$	Q_{uG}	$(\bar{q}\,Y_u^\dagger\,\sigma^{\mu\nu}T^a u)\tilde{H}G^a_{\mu\nu}$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)HB_{\mu\nu}$	Q_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\sigma^i\tilde{H}W^i_{\mu\nu}$	Q_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\tilde{H}B_{\mu\nu}$	Q_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^a t)\tilde{H}G^a_{\mu\nu}$
Q_{dW}	$(\bar{q}\,Y_d^\dagger\,\sigma^{\mu\nu}d)\sigma^i HW^i_{\mu\nu}$	Q_{dB}	$(\bar{q}\,Y_d^\dagger\,\sigma^{\mu\nu}d)HB_{\mu\nu}$	Q_{dG}	$(\bar{q}\,Y_d^\dagger\,\sigma^{\mu\nu}T^a d)HG^a_{\mu\nu}$		
Q_{bW}	$(\bar{Q}\sigma^{\mu\nu}b)\sigma^i HW^i_{\mu\nu}$	Q_{bB}	$(\bar{Q}\sigma^{\mu\nu}b)HB_{\mu\nu}$	Q_{bG}	$(\bar{Q}\sigma^{\mu\nu}T^a b)HG^a_{\mu\nu}$		

Higgs/EW/QCD (20)

Q_{Hud}	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}\,Y_u Y_d^\dagger\,\gamma^\mu d)$	Q_{Htb}	$i(\tilde{H}^\dagger D_\mu H)(\bar{t}\gamma^\mu b)$

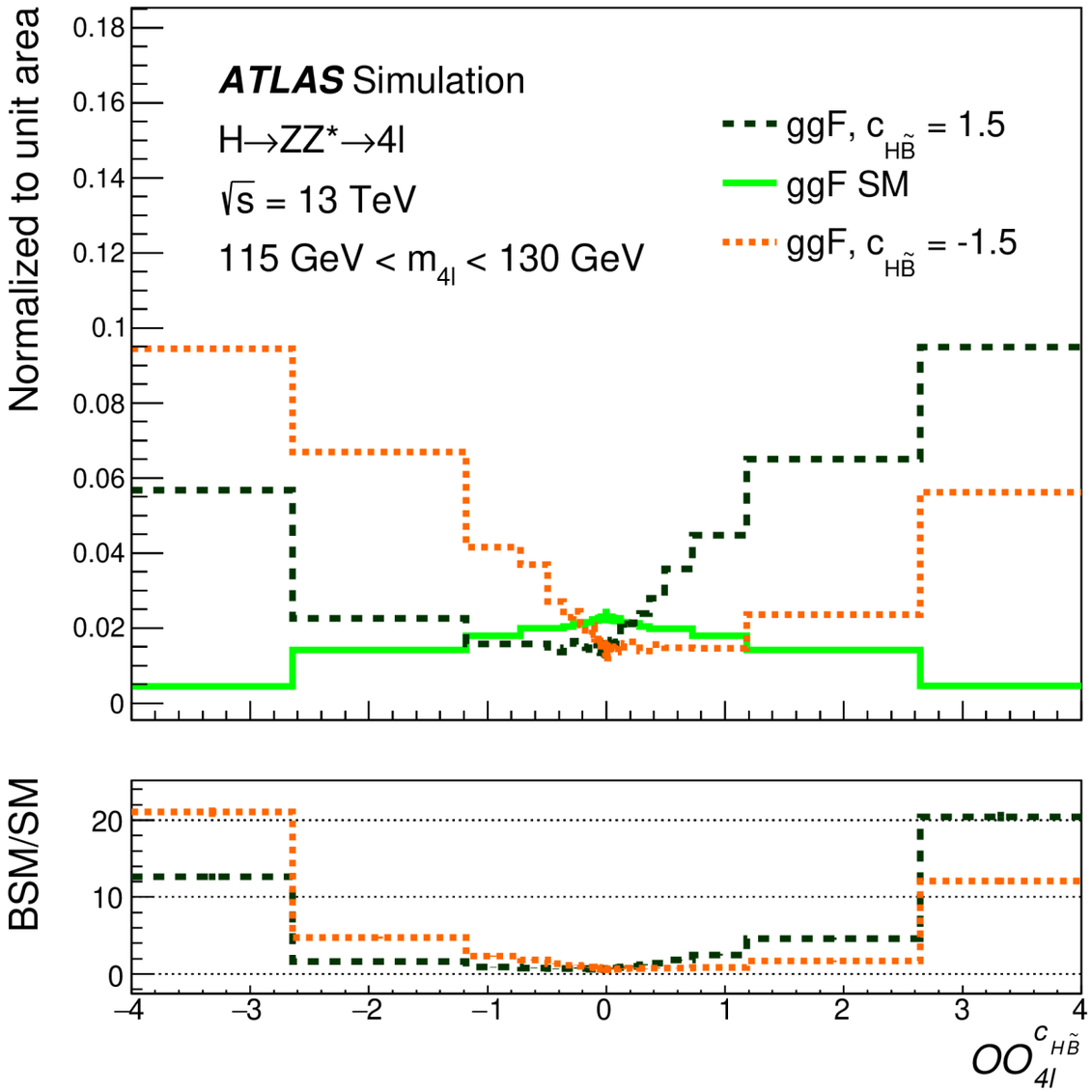
$Q^{(1)}_{utbd}$	$(Y_uY_d^\dagger)_{pr}(\bar{u}_p\gamma_\mu t)(\bar{b}\gamma^\mu d_r)$	$Q^{(8)}_{utbd}$	$(Y_uY_d^\dagger)_{pr}(\bar{u}_pT^a\gamma_\mu t)(\bar{b}T^a\gamma^\mu d_r)$

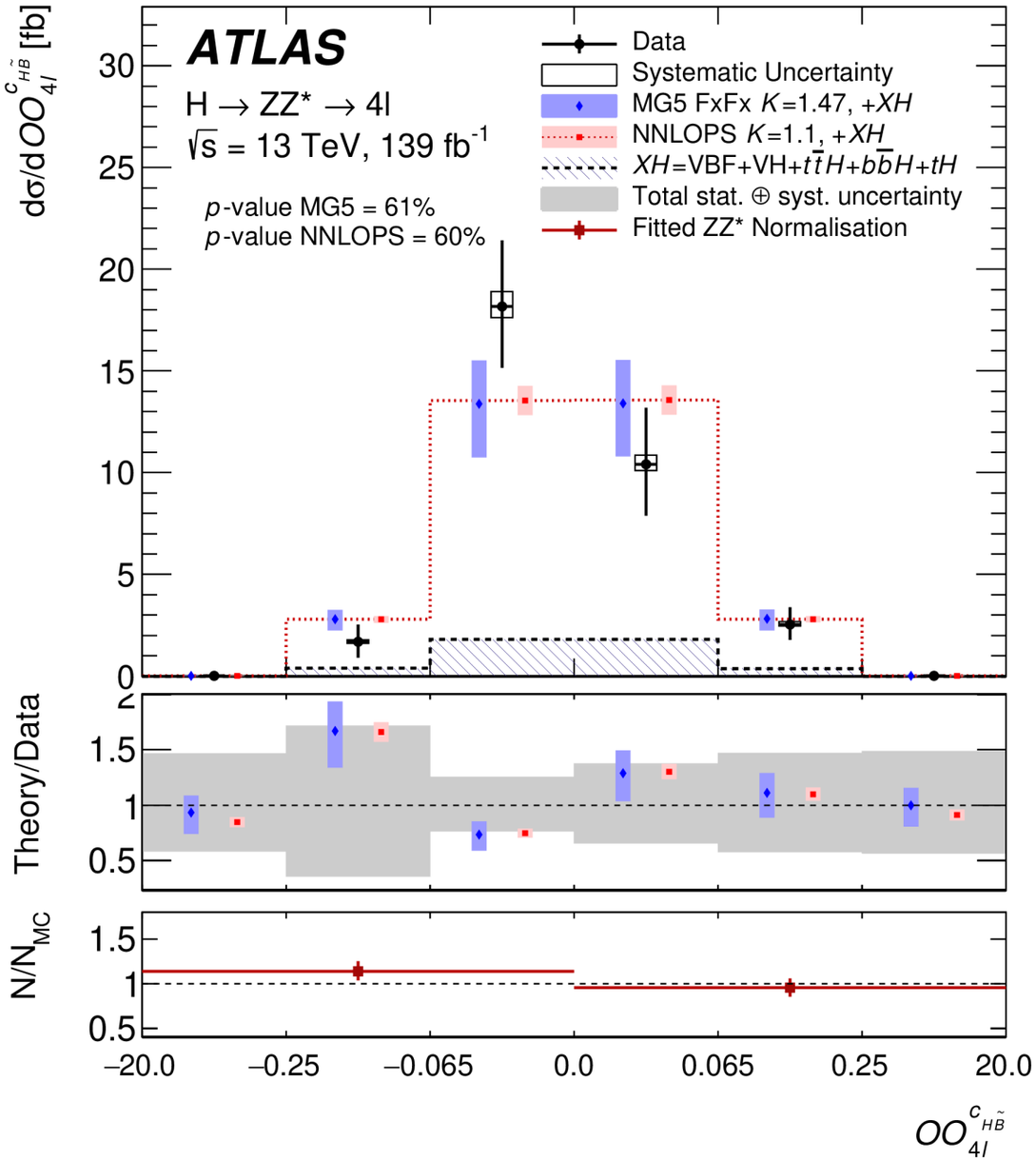
4-fermion (38)

$Q^{(1)}_{qQtu}$	$(Y_u^\dagger)_{pr}(\bar{q}_p\gamma_\mu Q)(\bar{t}\gamma^\mu u_r)$	$Q^{(8)}_{qQtu}$	$(Y_u^\dagger)_{pr}(\bar{q}_pT^a\gamma_\mu Q)(\bar{t}T^a\gamma^\mu u_r)$	$Q^{(1)}_{qQbd}$	$(Y_d^\dagger)_{pr}(\bar{q}_p\gamma_\mu Q)(\bar{b}\gamma^\mu d_r)$	$Q^{(8)}_{qQbd}$	$(Y_d^\dagger)_{pr}(\bar{q}_pT^a\gamma_\mu Q)(\bar{b}T^a\gamma^\mu d_r)$
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}\,Y_d\,q_j)$	Q_{lebQ}	$(\bar{l}^j_p e_r)(\bar{b}Q_j)$	$Q^{(1)}_{leQt}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{Q}^k\,t)$	$Q^{(3)}_{leQt}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{Q}^k\sigma^{\mu\nu}t)$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k\,Y_u^\dagger\,u)$	$Q^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k\,Y_u^\dagger\,\sigma^{\mu\nu}u)$	$Q^{(1)}_{QtQb}$	$(\bar{Q}^j\,t)\varepsilon_{jk}(\bar{Q}^k\,b)$	$Q^{(8)}_{QtQb}$	$(\bar{Q}^j\,T^a t)\varepsilon_{jk}(\bar{Q}^k\,T^a b)$
$Q^{(1)}_{quqd}$	$(\bar{q}^j\,Y_u^\dagger\,u)\varepsilon_{jk}(\bar{q}^k\,Y_d^\dagger\,d)$	$Q^{(8)}_{quqd}$	$(\bar{q}^j\,Y_u^\dagger\,T^a u)\varepsilon_{jk}(\bar{q}^k\,Y_d^\dagger\,T^a d)$	$Q^{(1)\prime}_{quqd}$	$(Y_u^\dagger)_{sr}(Y_d^\dagger)_{pt}(\bar{q}^j_p\,u_r)\varepsilon_{jk}(\bar{q}^k_s\,d_t)$	$Q^{(8)\prime}_{quqd}$	$(Y_u^\dagger)_{sr}(Y_d^\dagger)_{pt}(\bar{q}^j_p\,T^a u_r)\varepsilon_{jk}(\bar{q}^k_s\,T^a d_t)$
$Q^{(1)}_{Qtqd}$	$(\bar{Q}^j\,t)\varepsilon_{jk}(\bar{q}^k\,Y_d^\dagger\,d)$	$Q^{(8)}_{Qtqd}$	$(\bar{Q}^j\,T^a t)\varepsilon_{jk}(\bar{q}^k\,Y_d^\dagger\,T^a d)$	$Q^{(1)}_{quQb}$	$(\bar{q}^j\,Y_u^\dagger\,u)\varepsilon_{jk}(\bar{Q}^k\,b)$	$Q^{(8)}_{quQb}$	$(\bar{q}^j\,Y_u^\dagger\,T^a u)\varepsilon_{jk}(\bar{Q}^k\,T^a b)$
$Q^{(1)}_{Quqb}$	$(Y_u^\dagger)_{pr}\,(\bar{Q}^j\,u_r)\varepsilon_{jk}(\bar{q}^k_p\,b)$	$Q^{(8)}_{Quqb}$	$(Y_u^\dagger)_{pr}\,(\bar{Q}^j\,T^a u_r)\varepsilon_{jk}(\bar{q}^k_p\,T^a b)$	$Q^{(1)}_{qtQd}$	$(Y_d^\dagger)_{pr}\,(\bar{q}^j_p\,t)\varepsilon_{jk}(\bar{Q}^k\,d_r)$	$Q^{(8)}_{qtQd}$	$(Y_d^\dagger)_{pr}\,(\bar{q}^j_p\,T^a t)\varepsilon_{jk}(\bar{Q}^k\,T^a d_r)$

arXiv:2012.11343

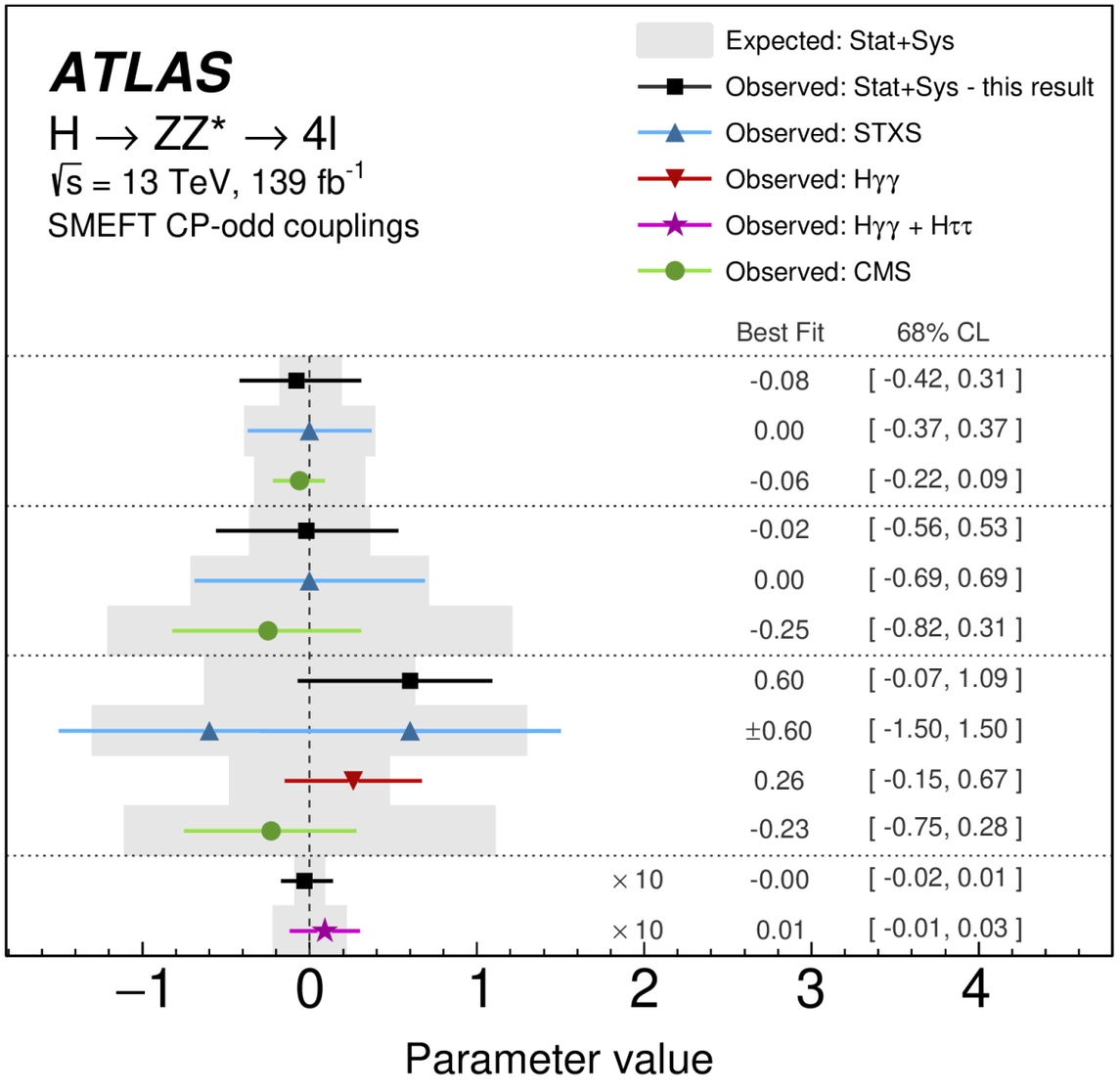
Sensitivity to CP-odd couplings

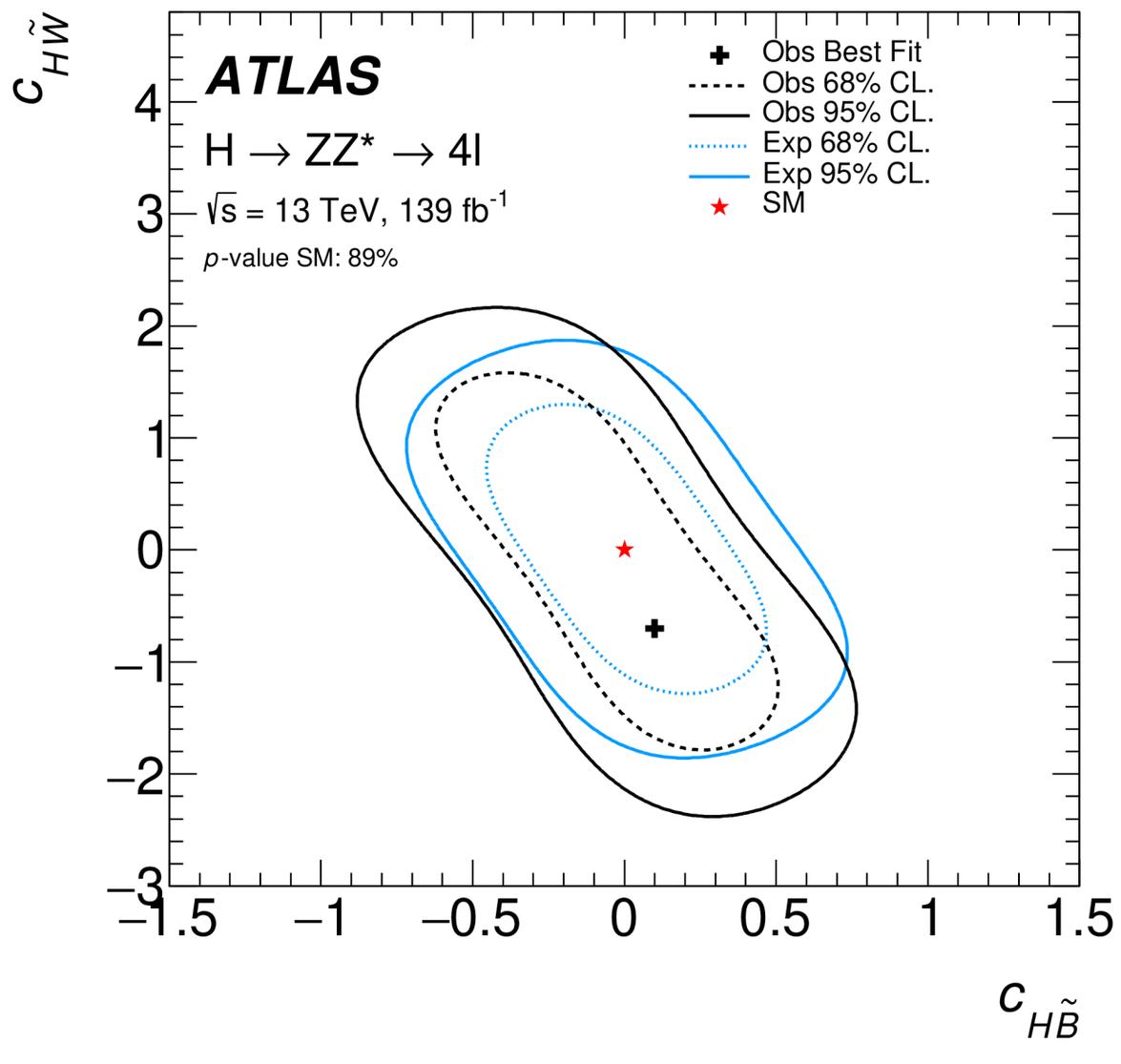




arXiv:2304.09612

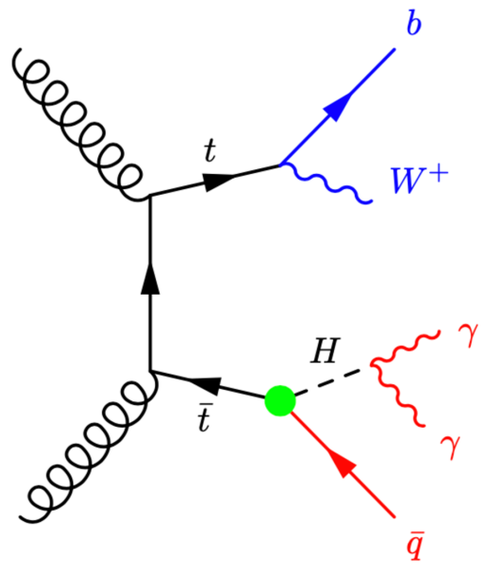
Constraints on CP-odd couplings

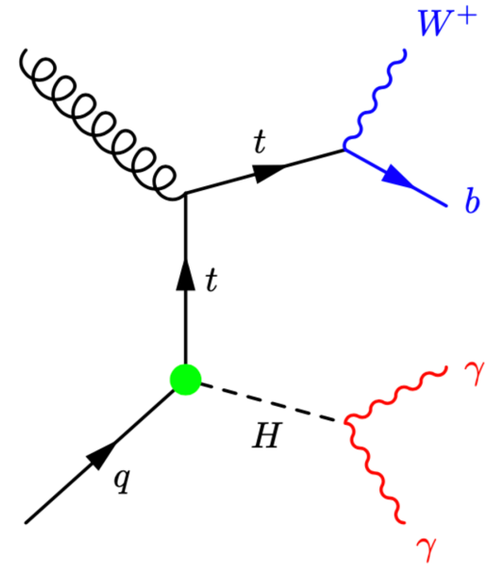


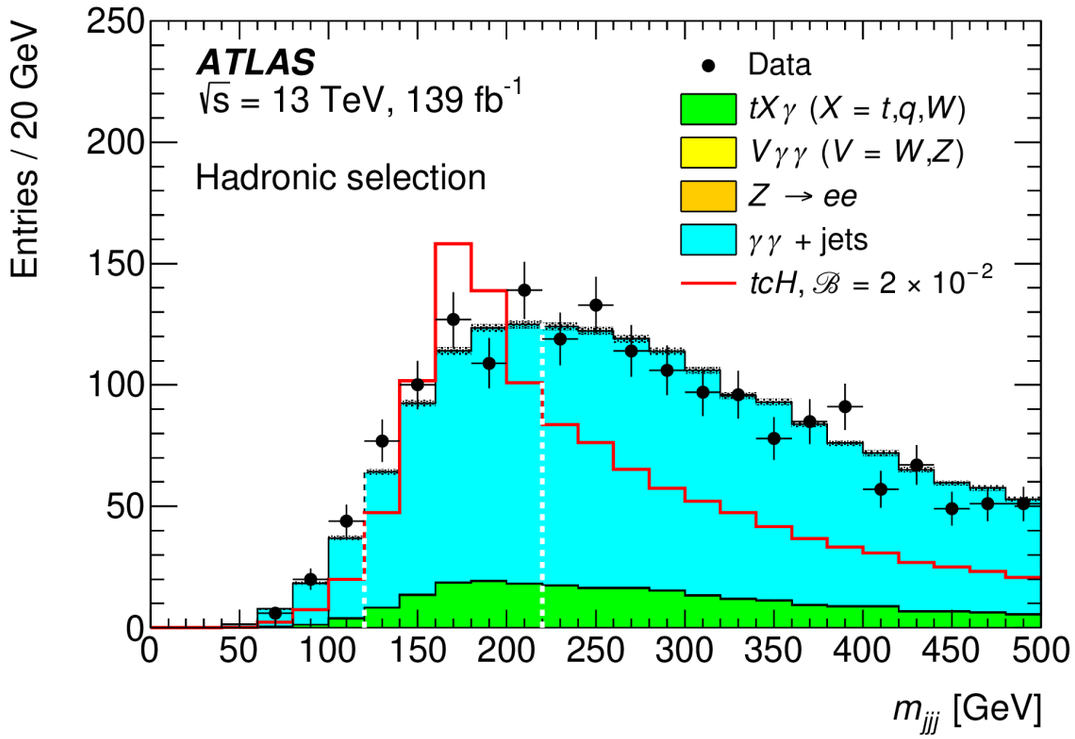


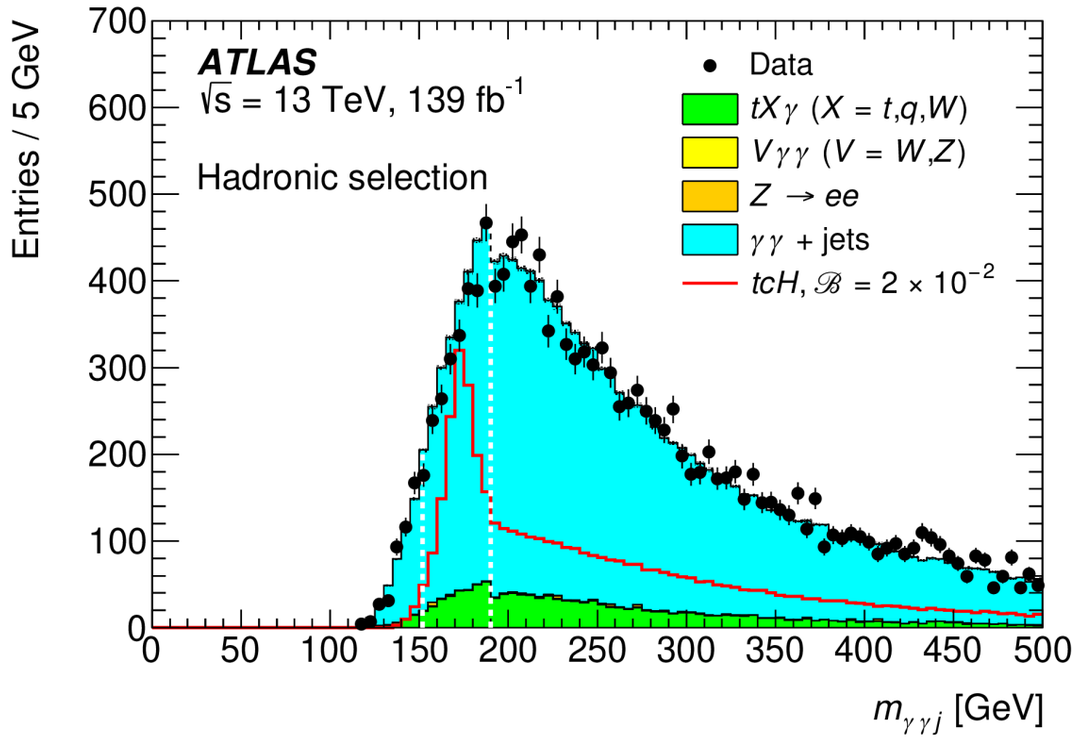
arXiv:2304.09612

Flavour-violating Higgs boson couplings



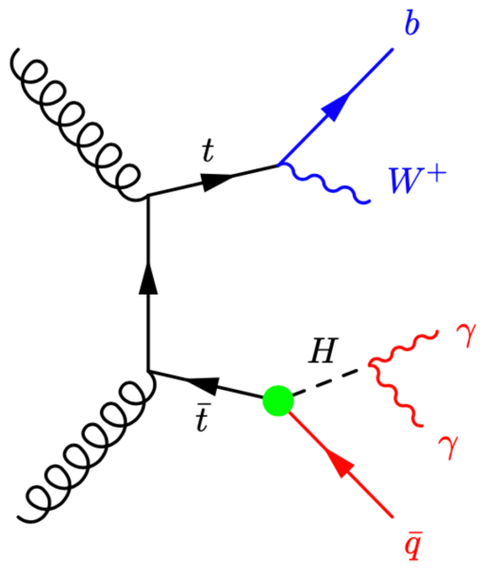


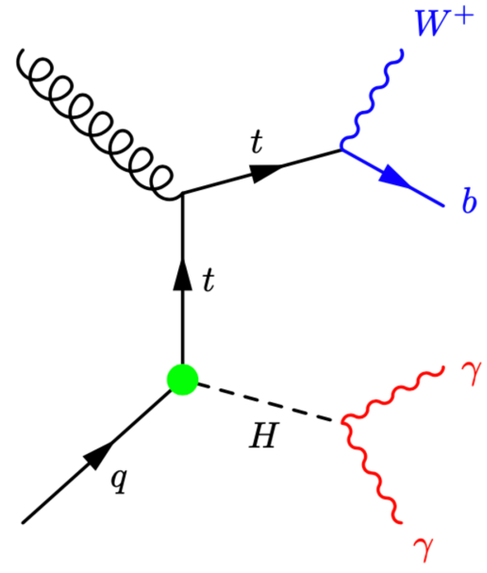


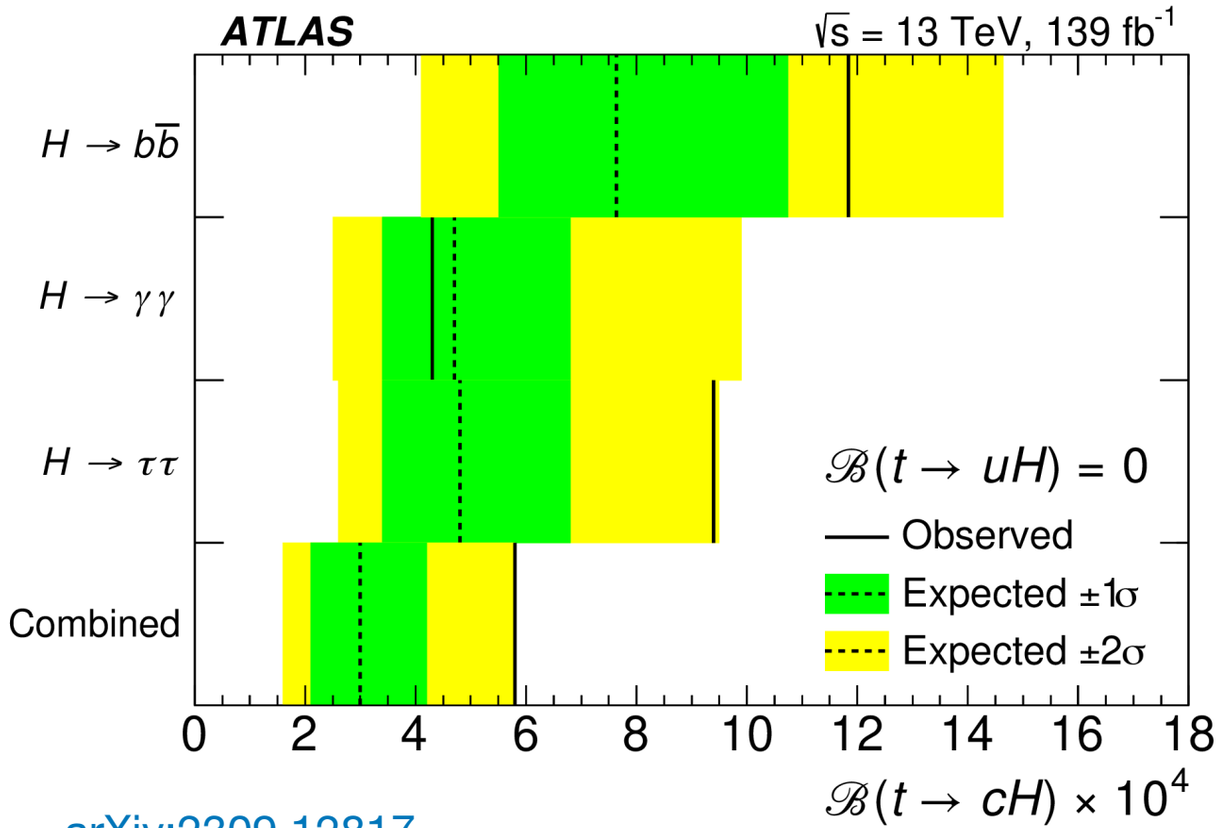


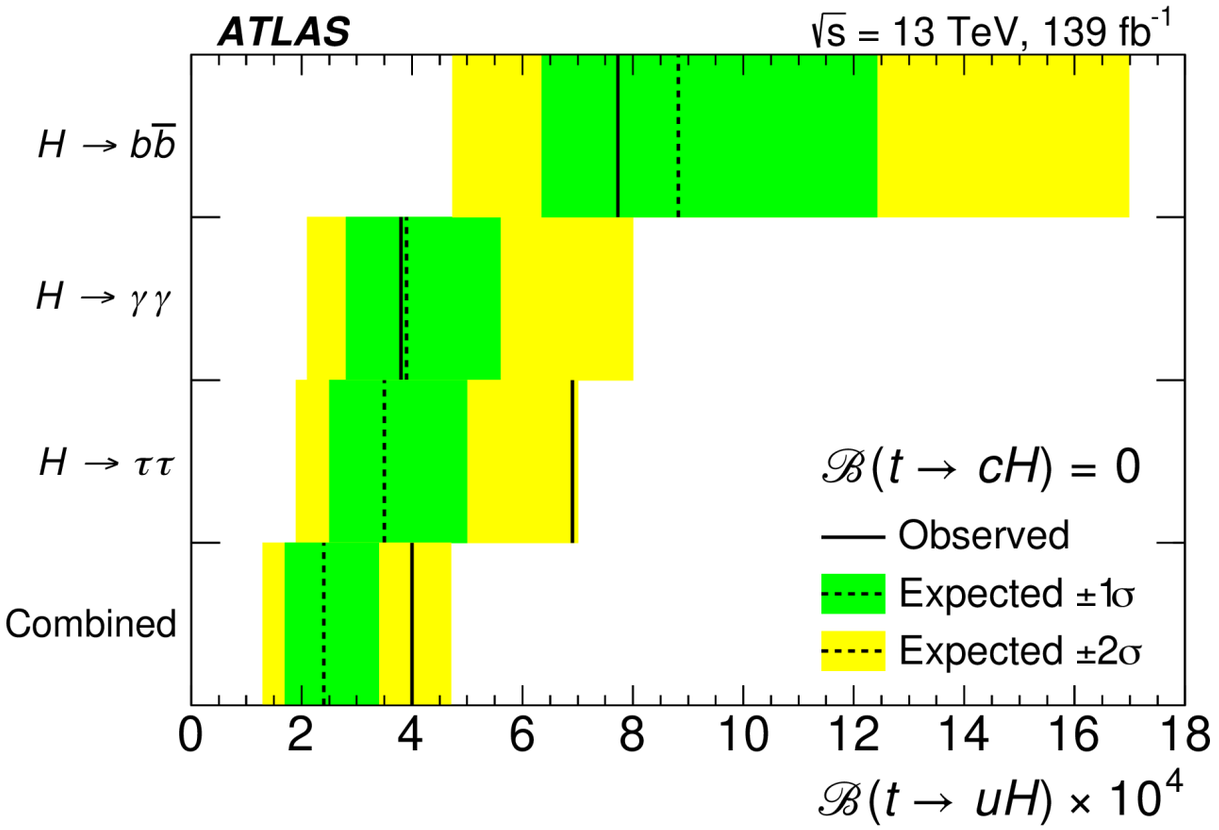
arXiv:2309.12817

Flavour-violating Higgs boson couplings









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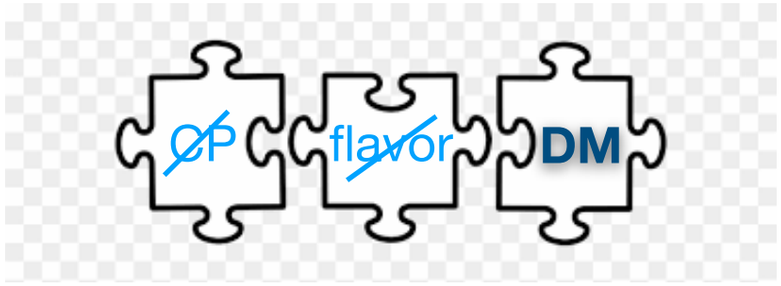
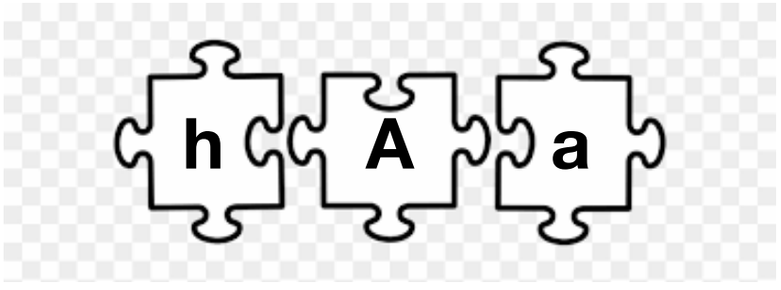
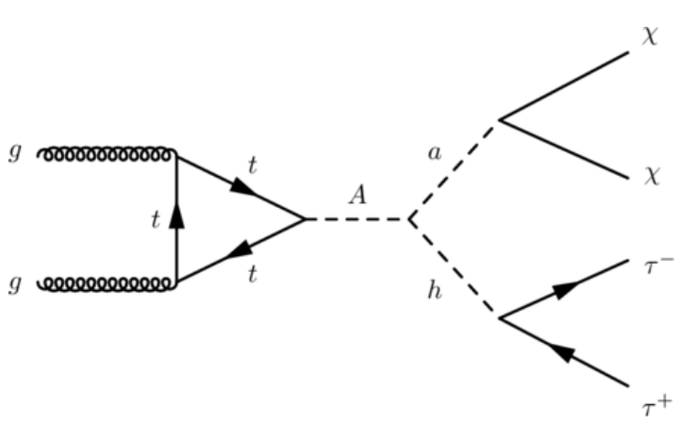
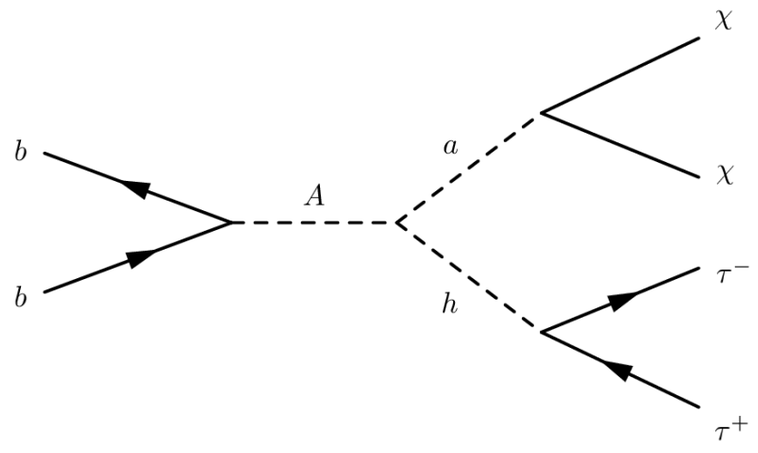
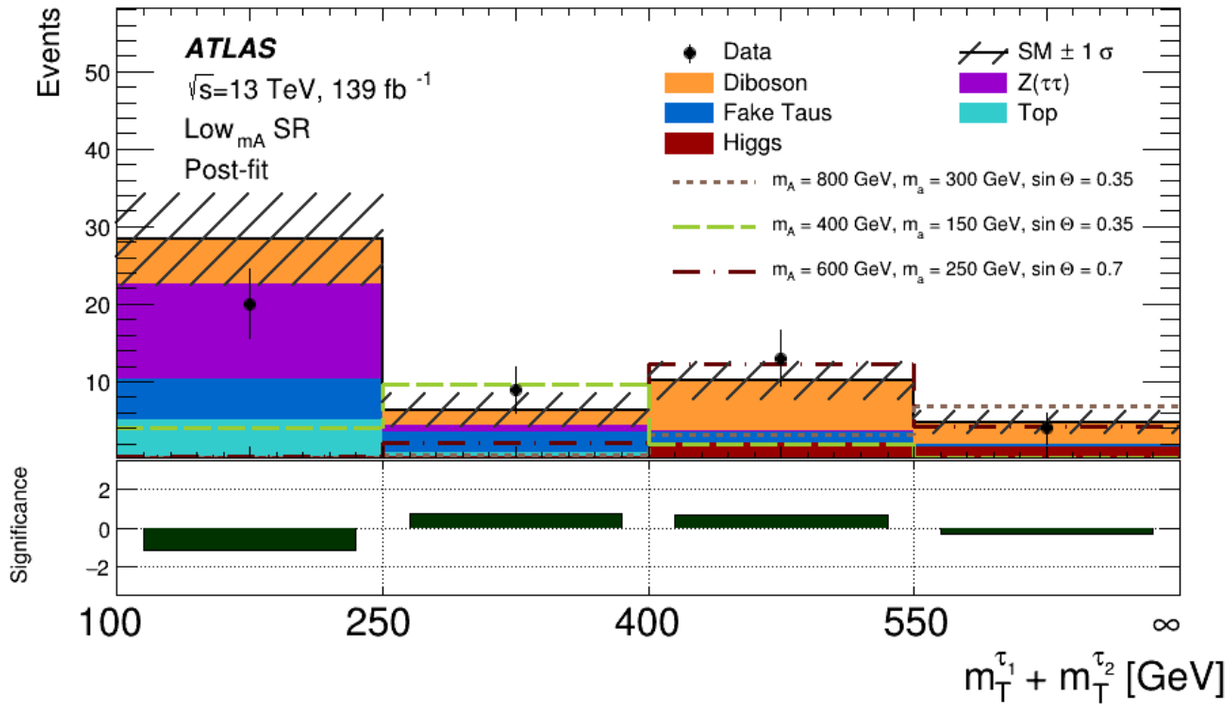


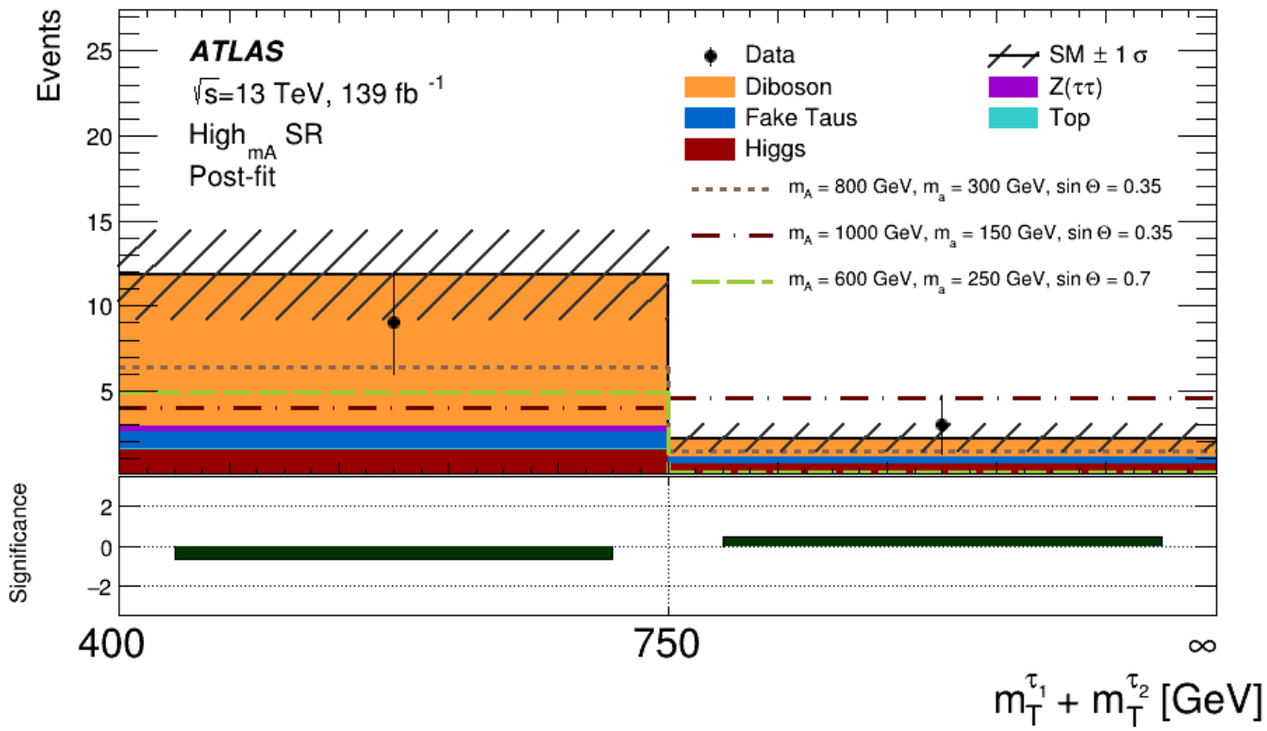


Higgs portal

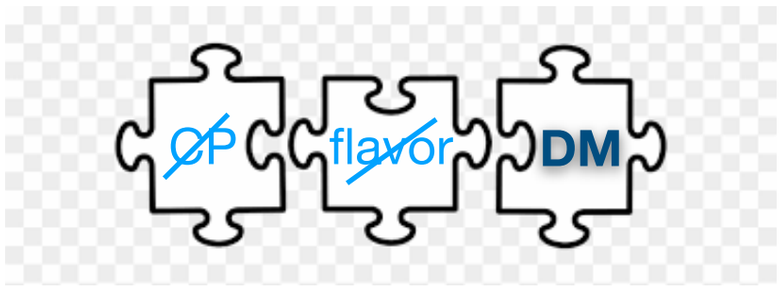


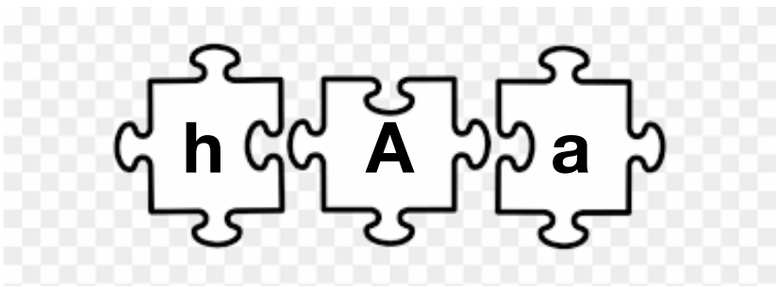




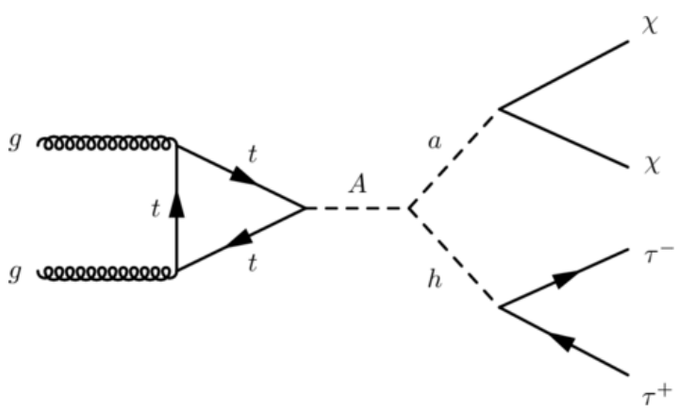


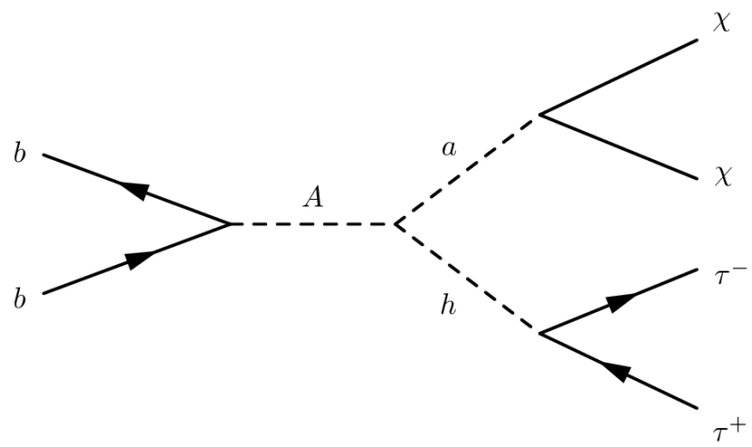
JHEP **09**, 189 (2023)

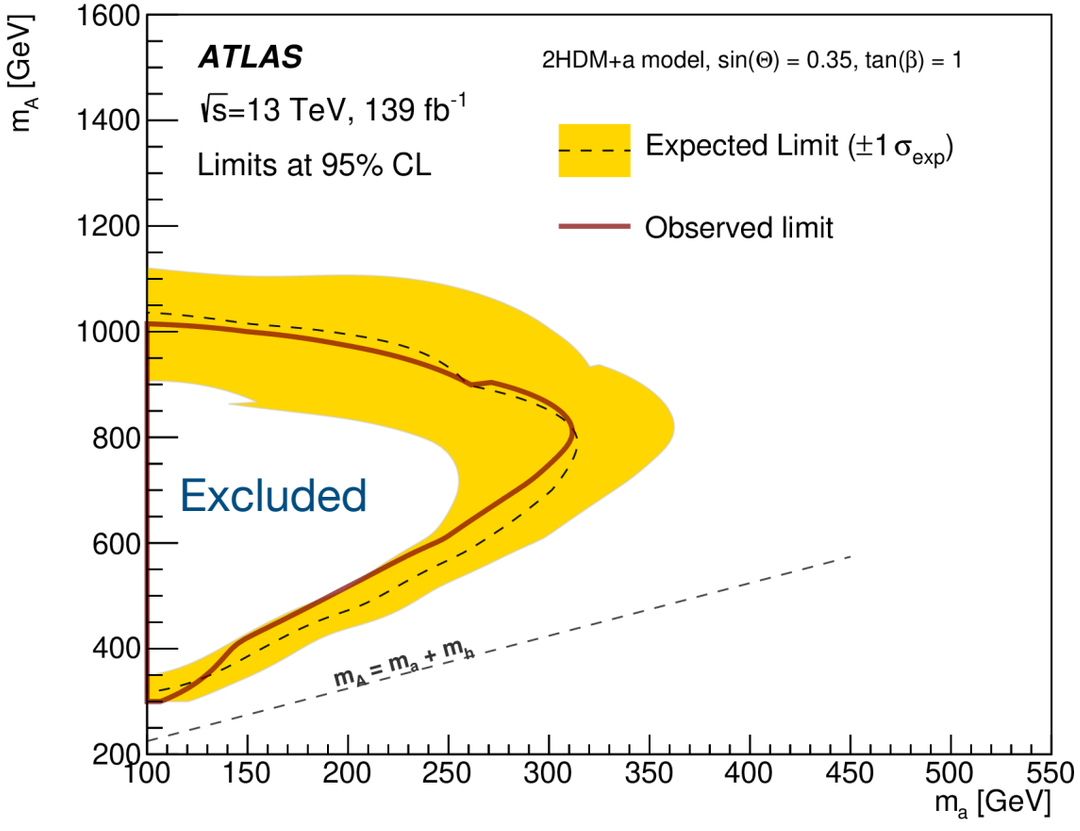


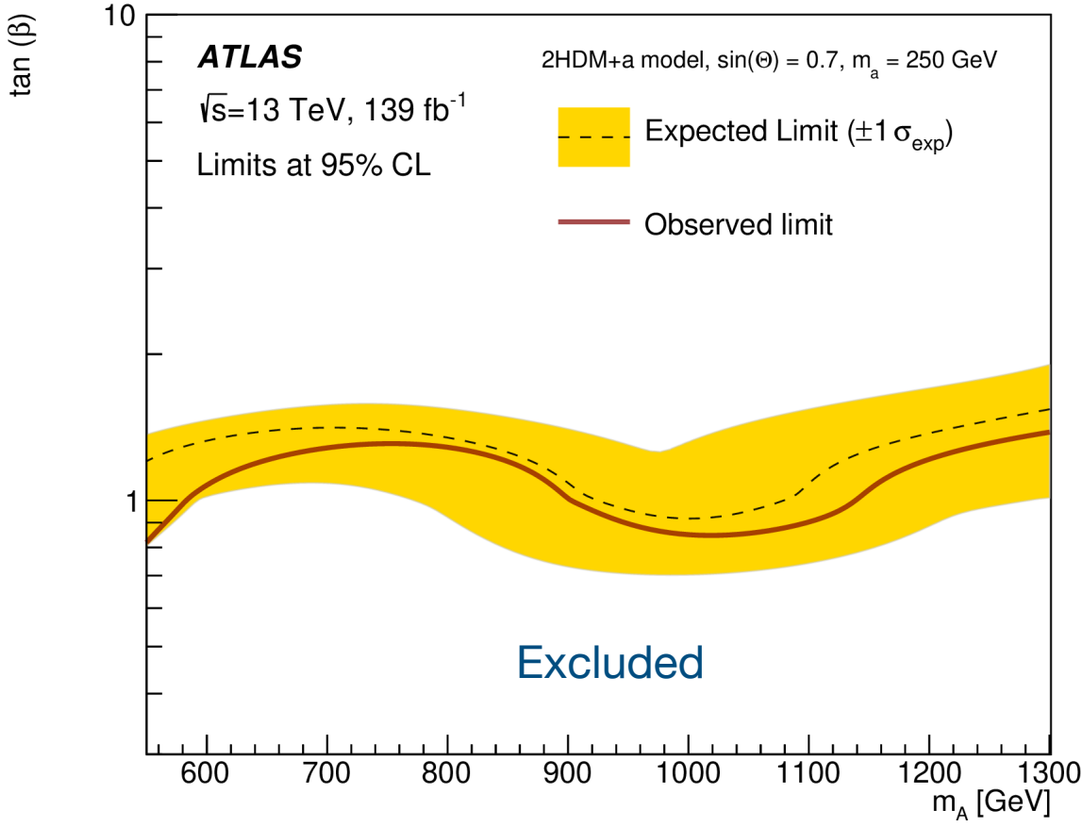


Higgs portal



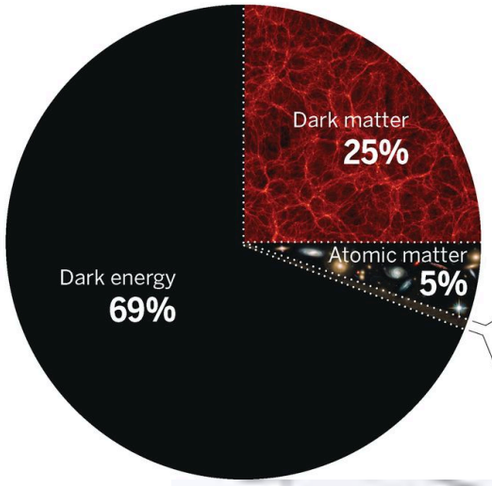


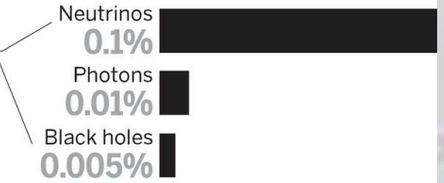




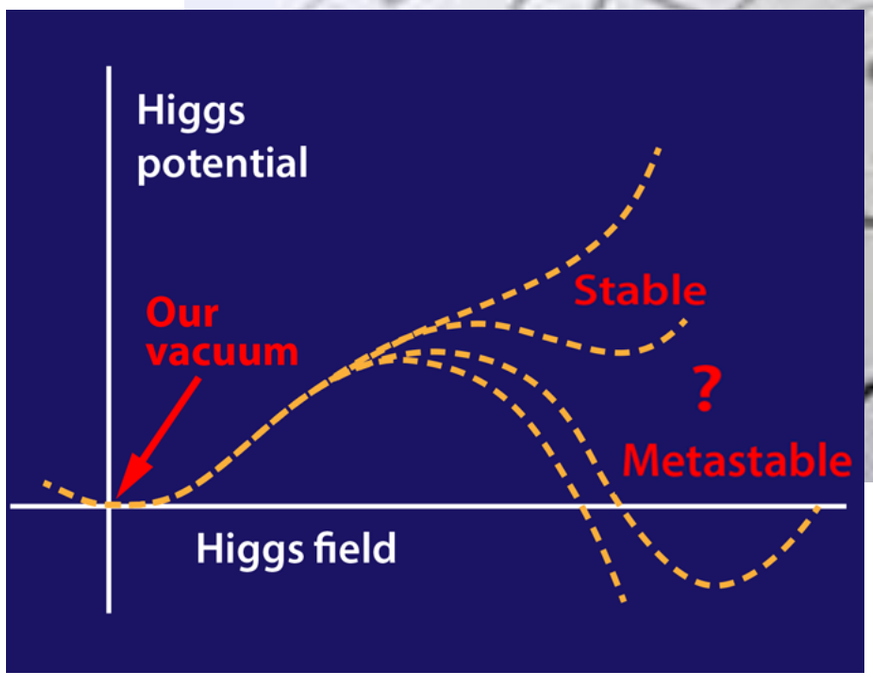
JHEP **09**, 189 (2023)

Summary

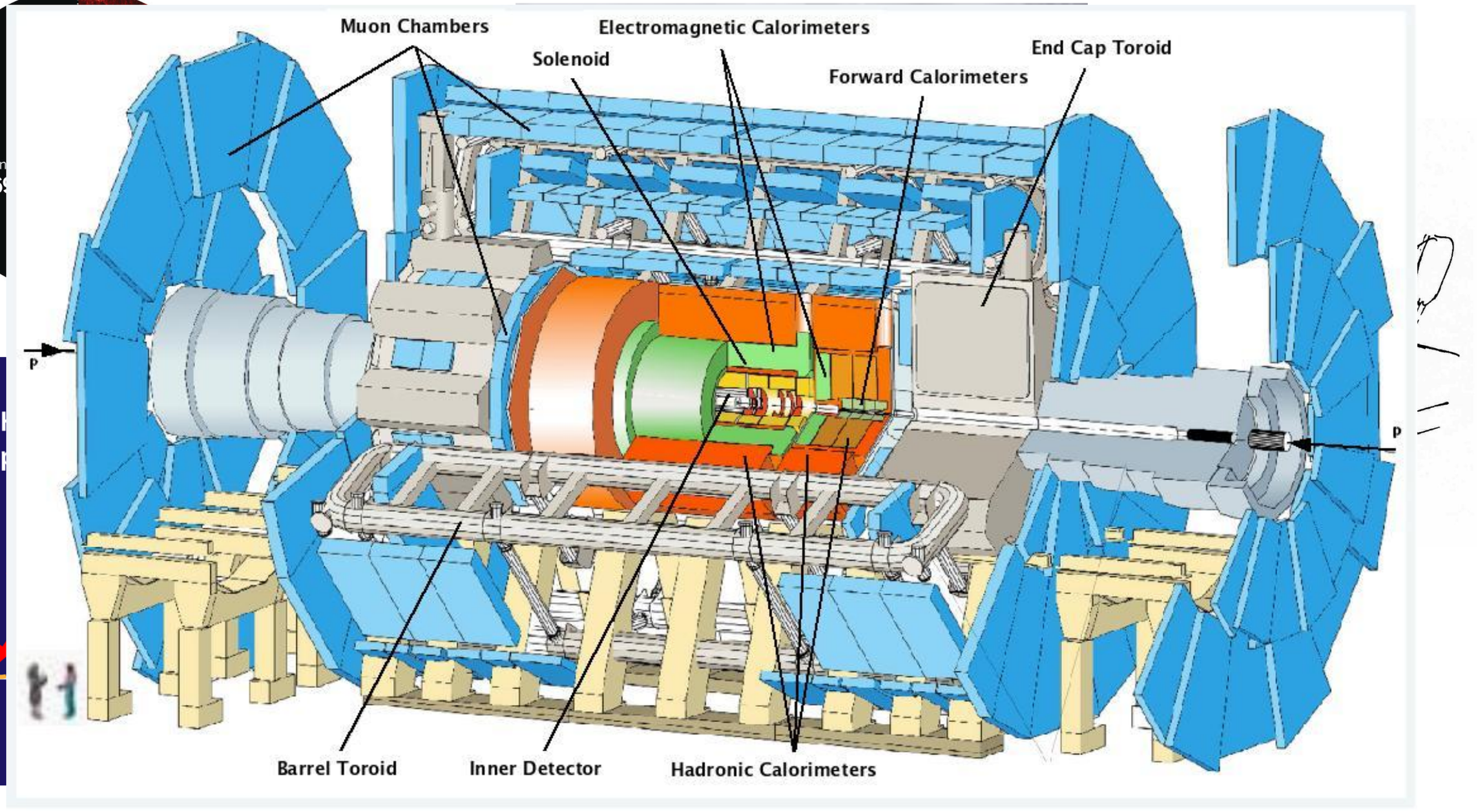

Dark matter
25%
Atomic matter
5%
Dark energy
69%


Neutrinos
0.1%
Photons
0.01%
Black holes
0.005%


MATTER
ANTI-MATTER
S.Harris


Higgs
potential
Our
vacuum
Stable
?
Metastable
Higgs field

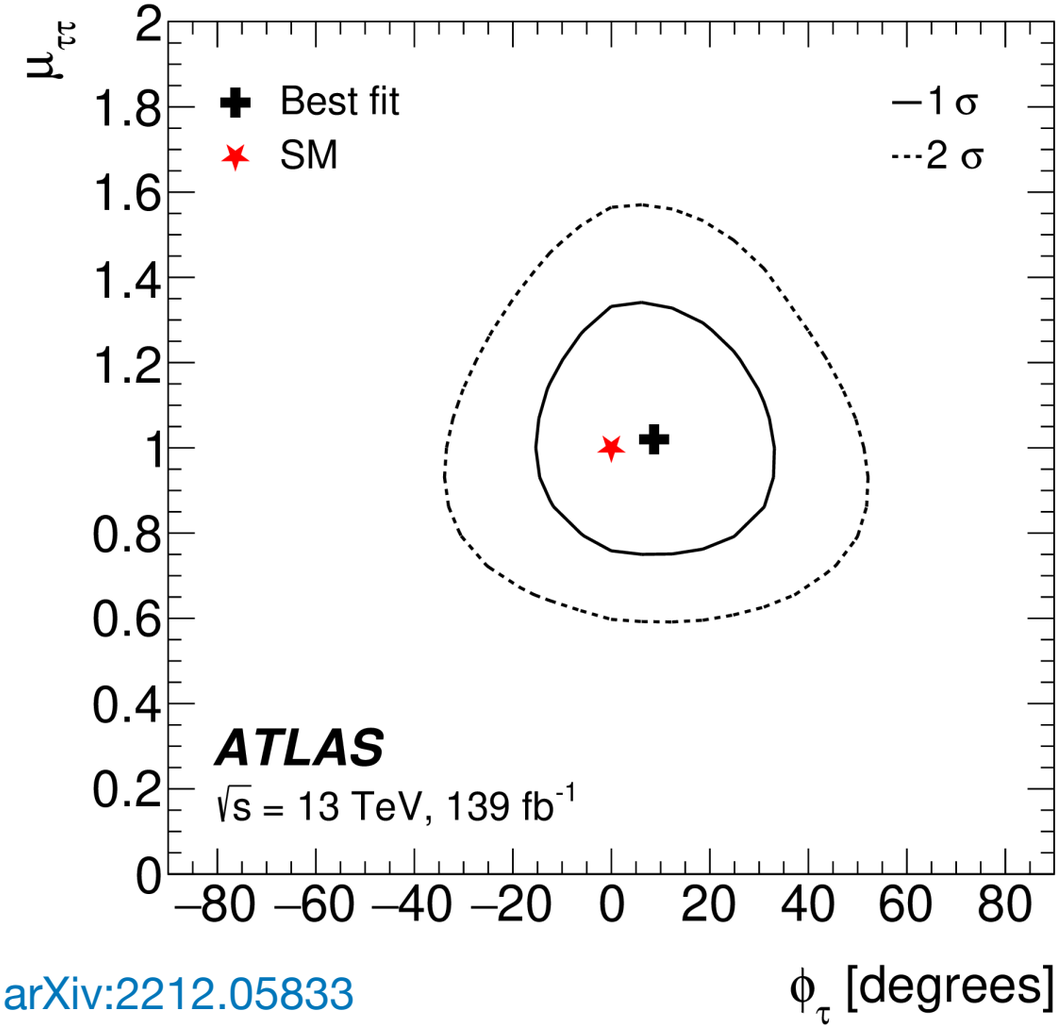
Summary


Muon Chambers
Electromagnetic Calorimeters
Solenoid
End Cap Toroid
Forward Calorimeters
P
P
Barrel Toroid
Inner Detector
Hadronic Calorimeters

Run 2 constraints on CP-odd couplings

Higgs Yukawa

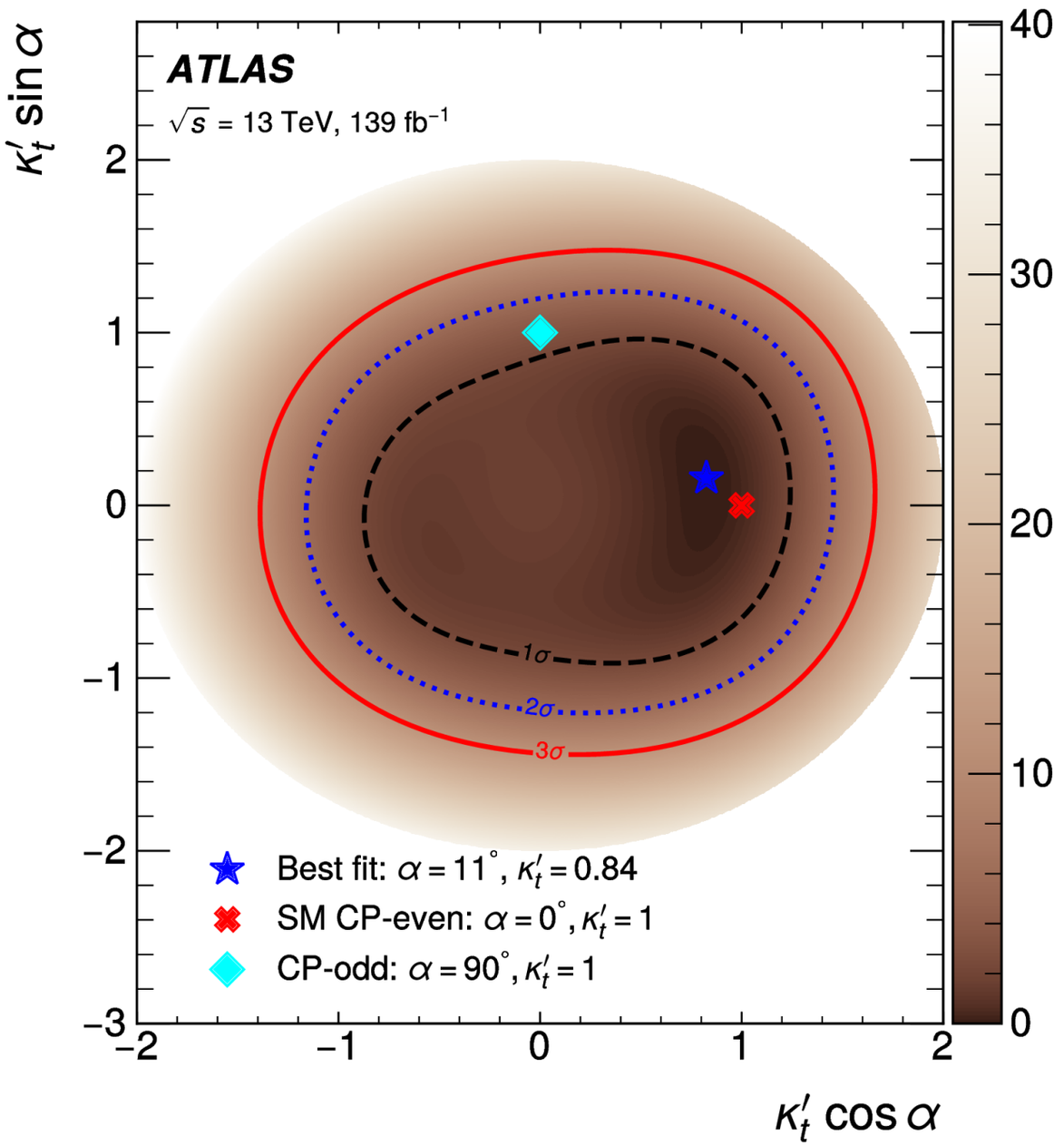
Q_{eH} | $(H^\dagger H)(\bar{l}_p e_r H)$



arXiv:2212.05833

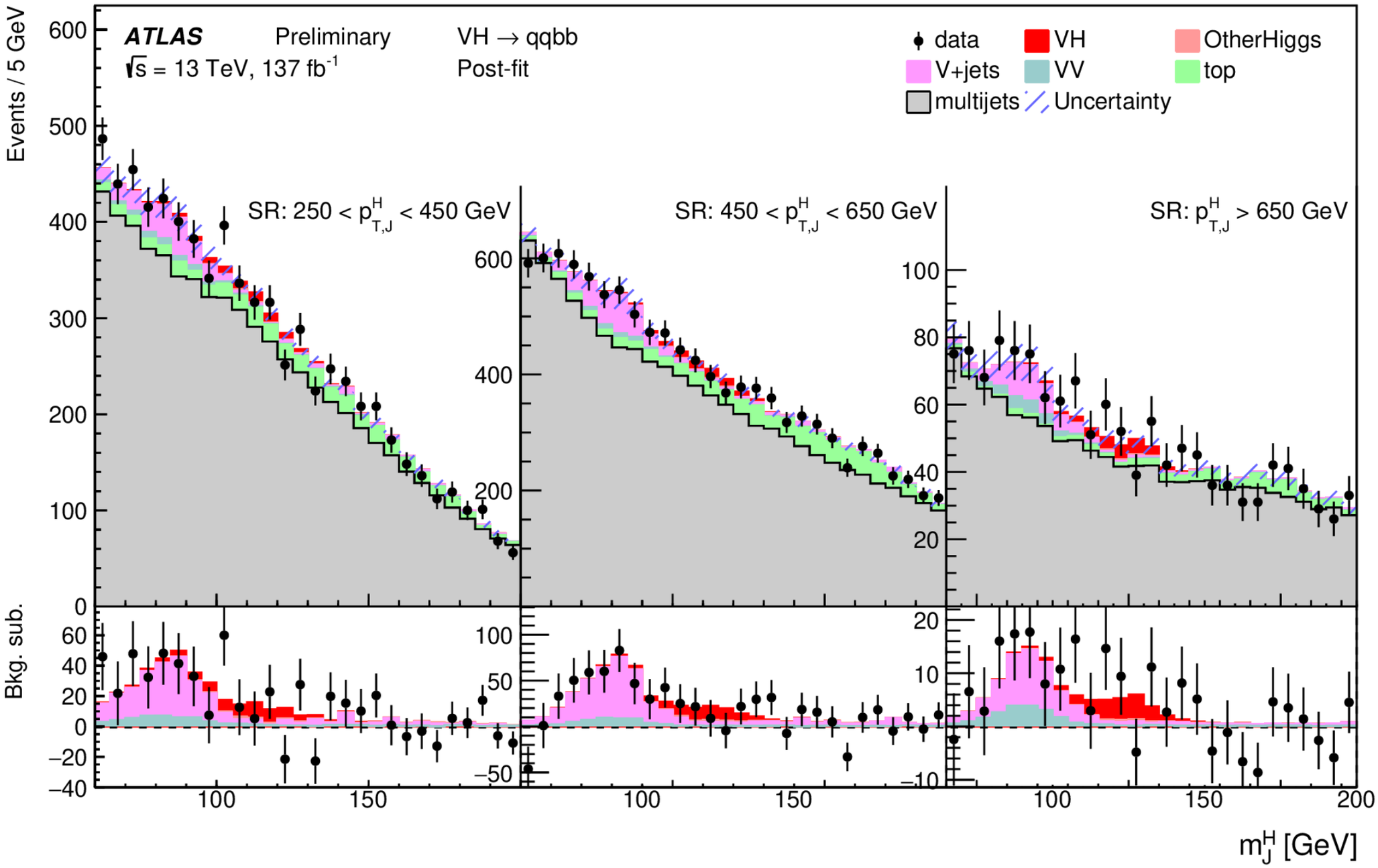
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{\upsilon}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

Q_{tH} | $(H^\dagger H)(\bar{Q}\tilde{H}t)$



arXiv:2303.05974

Higgs production at high momentum



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