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Mass, width and CP-measurements - ATLAS

Valerie Lang
On behalf of the ATLAS Collaboration

Higgs Hunting 2024
Orsay Paris, 23 September 2024

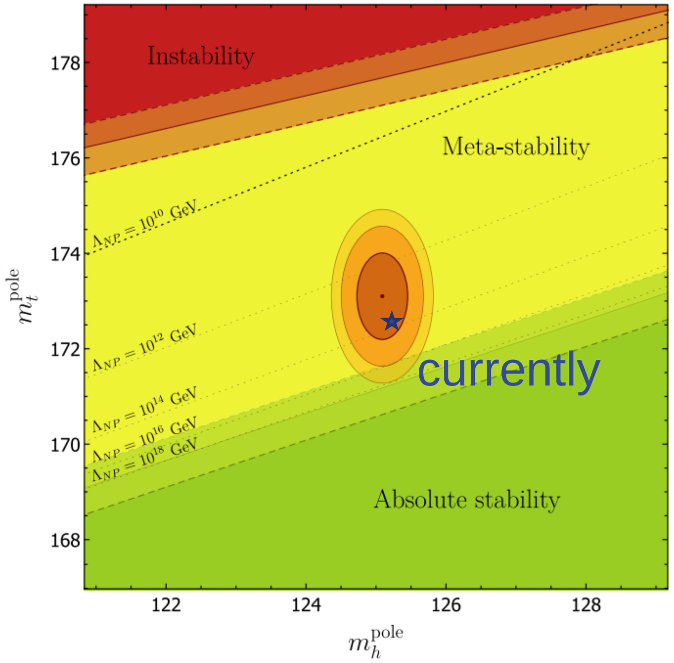
Is the *Higgs boson* the Standard Model (SM) Higgs boson?

Need to test Higgs boson properties!

- Mass → Input parameter in SM → Determines production cross section and branching ratio
- Width → SM: ~4 MeV for m_H = 125 GeV
- Charge-conjugation-Parity (CP) → SM: 0^+

→ Currently (PDG):

$$m_H = (125.20 \pm 0.11)\ \text{GeV}$$
$$m_t = (172.57 \pm 0.29)\ \text{GeV}$$



Modified from Andreassen, Frost, Schwartz, PhysRev D 97 056006 (2018)

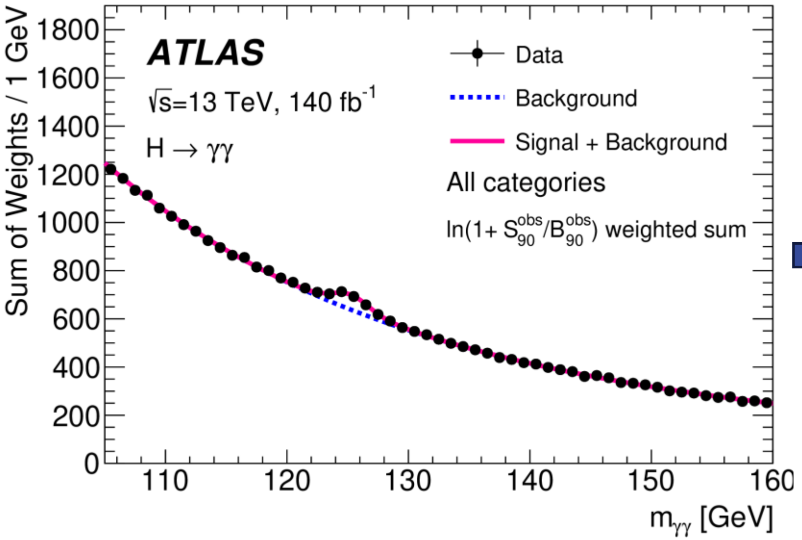
→ Why are these relevant?

- Mass → Stable electro-weak (EW) vacuum?
- Width → Coupling of Higgs boson also to other, **invisible** particles?
- CP → Another source of CP-violation to explain abundance of matter vs. anti-matter?

Measurement of the Higgs boson mass

Best suited: High resolution channels $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$

- Provide reconstructed Higgs mass peak, good mass resolution
  - Good control of the lepton and photon energy scales by calibration via $Z \rightarrow \ell\ell$ and J/ψ and ϒ signals



Phys. Lett. B 847 (2023) 138315

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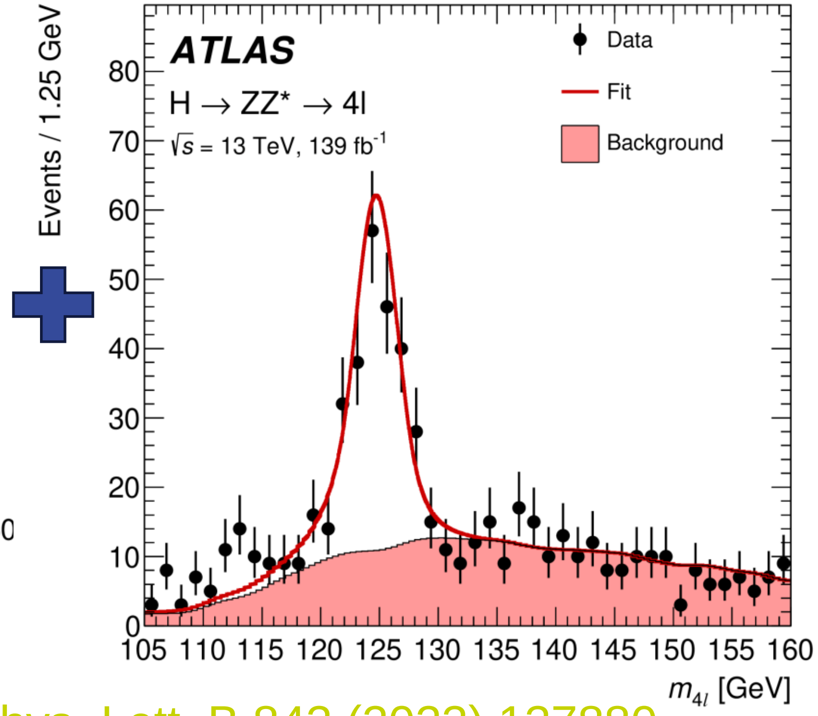

Phys. Lett. B 843 (2023) 137880

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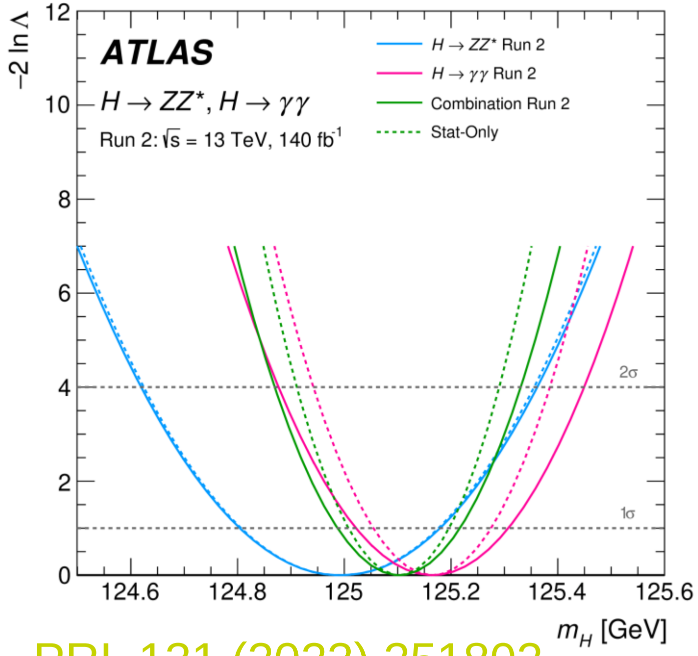
Combination via profile likelihood ratio Λ

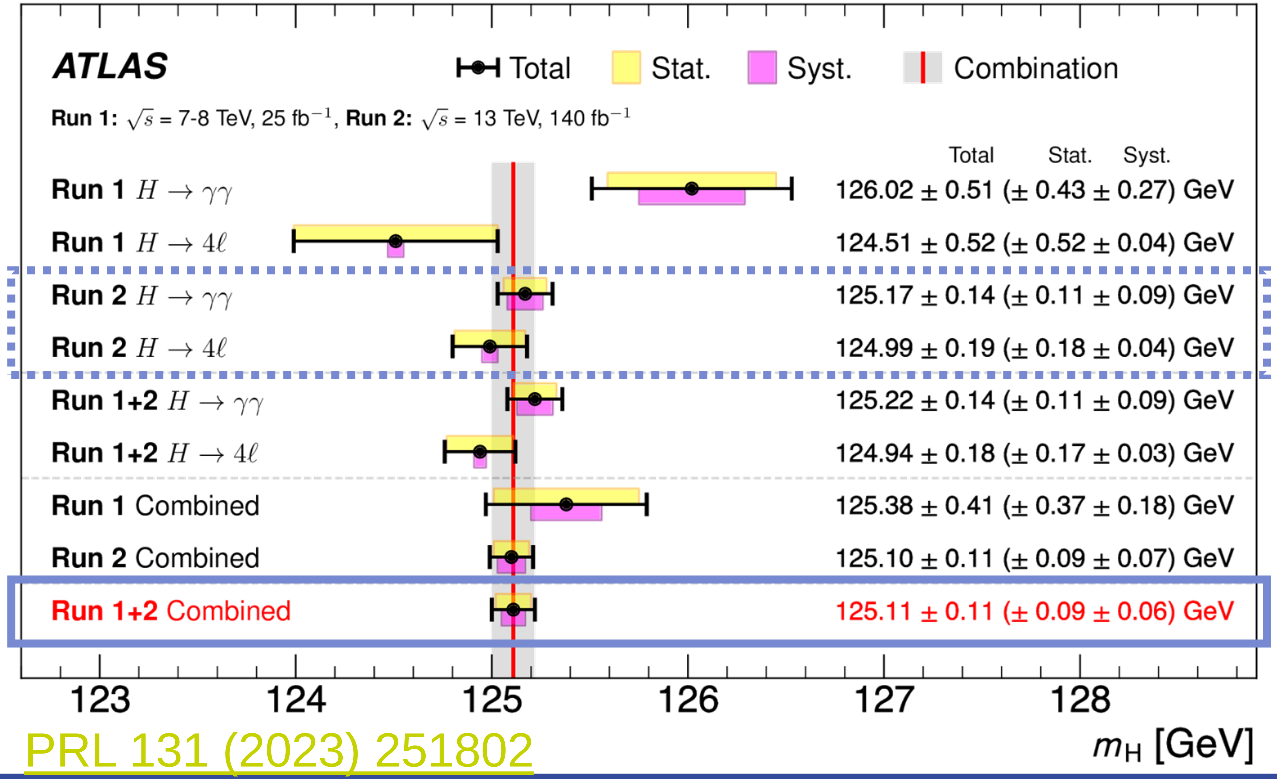


PRL 131 (2023) 251802

Measurement of the Higgs boson mass

Combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ with Run 2 data

- Correlations between uncertainties of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ accounted for in profile likelihood
- Also combine with Run 1 data



PRL 131 (2023) 251802

→ In the long term: $H \rightarrow ZZ^* \rightarrow 4\ell$ likely dominant, due to smaller systematic uncertainty

→ However: Impressive that $H \rightarrow \gamma\gamma$ still most precise

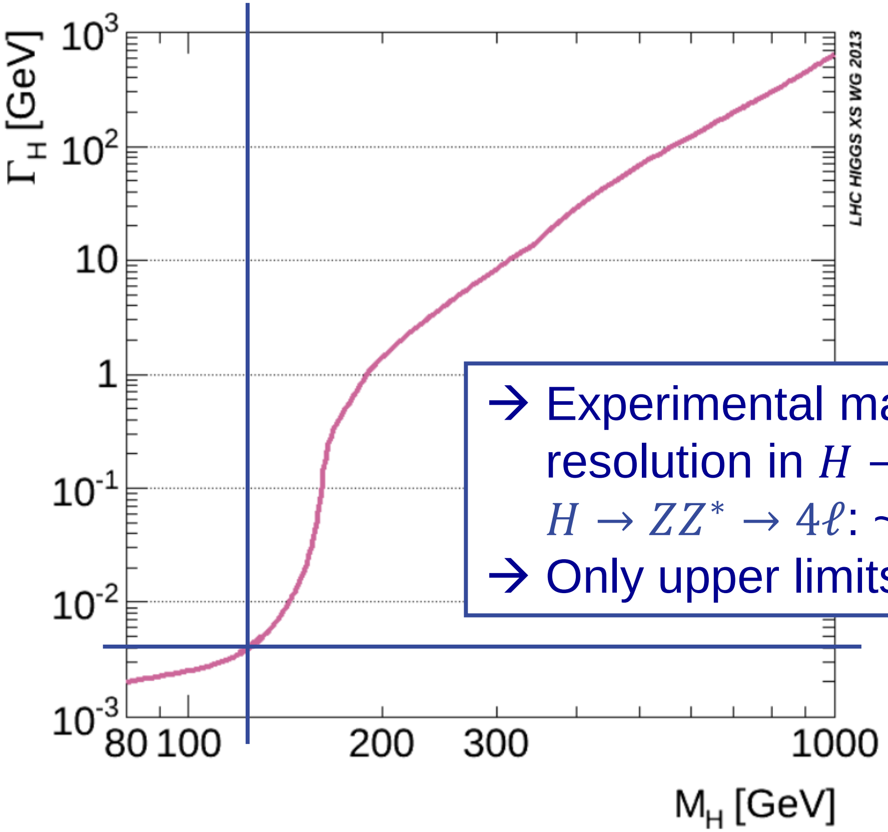
→ Major effort to reduce systematic uncertainties

→ Precision of 0.09% on m_H!

Determination of the Higgs boson width

Very small Higgs boson width Γ expected in SM

- At m_H = 125 GeV: $\Gamma = 4.1\ \mathrm{MeV}$



→ Experimental mass resolution in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$: ~1 - 2 GeV

→ Only upper limits possible

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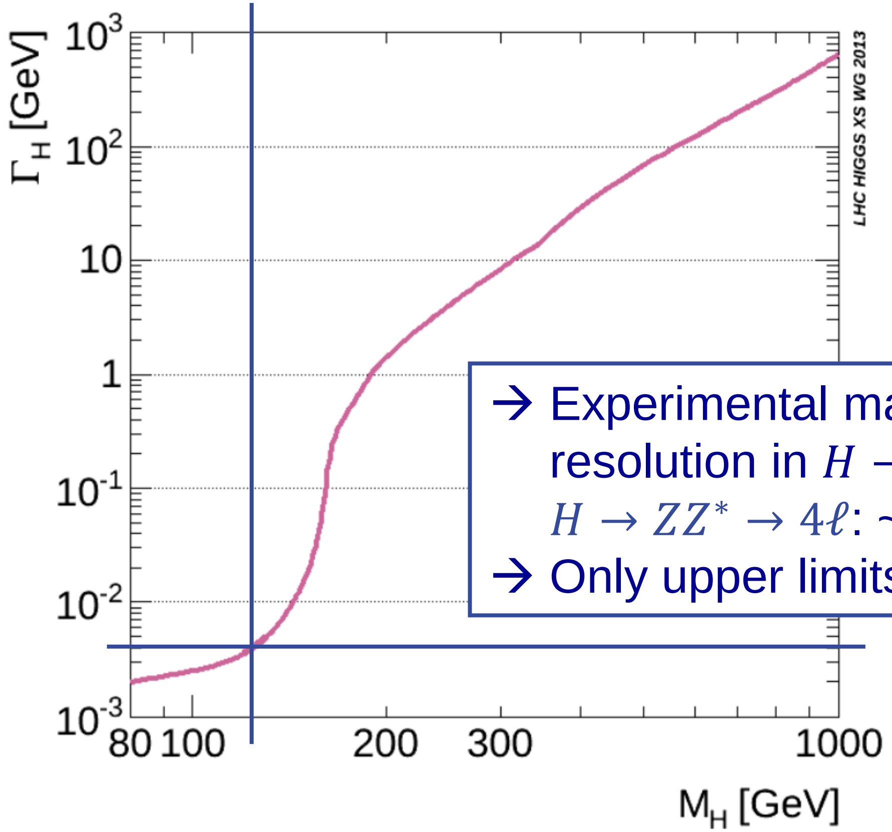
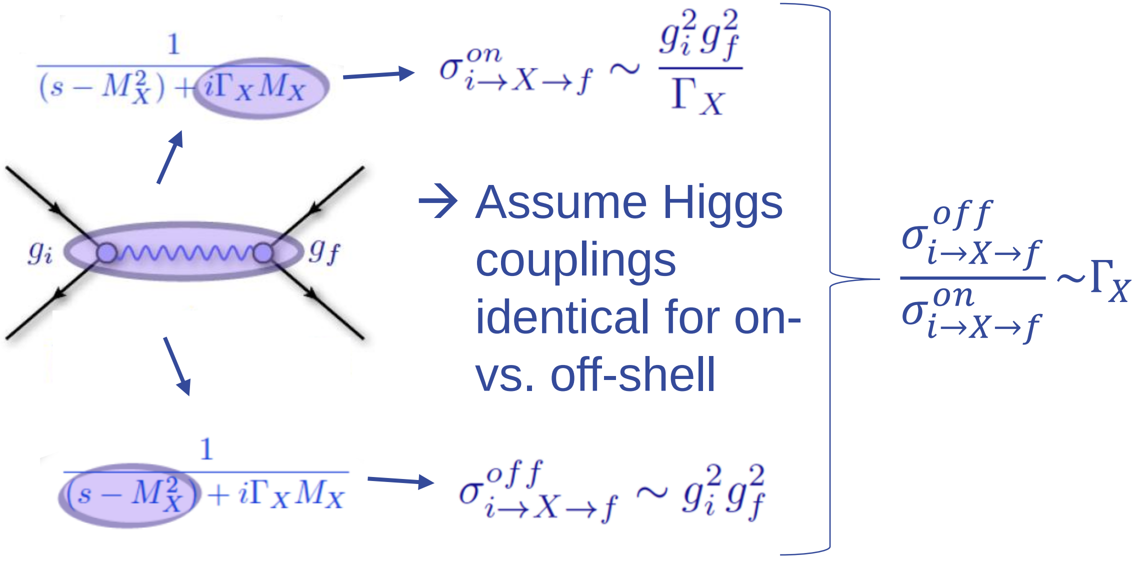


→ Experimental mass resolution in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$: ~1 - 2 GeV

→ Only upper limits possible

Indirect constraint from “off-shell“ to “on-shell“ cross section ratio:

On-shell



$$\frac{1}{(s-M_X^2)+i\Gamma_X M_X} \rightarrow \sigma^{on}_{i\to X\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_X}$$

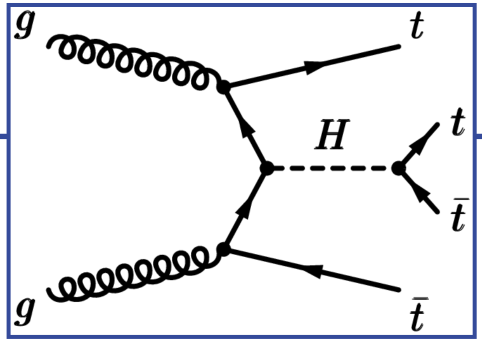
→ Assume Higgs couplings identical for on- vs. off-shell

$$\frac{1}{(s-M_X^2)+i\Gamma_X M_X} \rightarrow \sigma^{off}_{i\to X\to f} \sim g_i^2 g_f^2$$

$$\frac{\sigma^{off}_{i\to X\to f}}{\sigma^{on}_{i\to X\to f}} \sim \Gamma_X$$

Off-shell

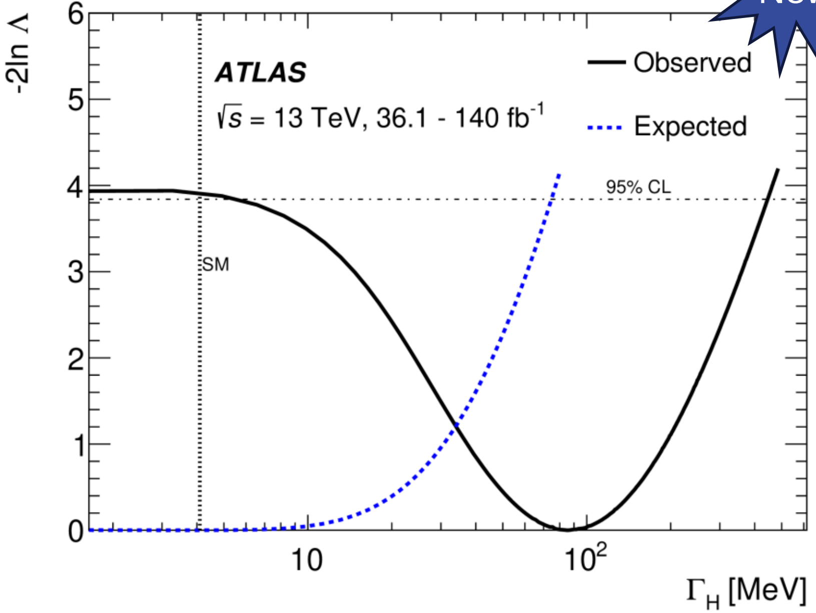
Determination of the Higgs boson width



Off-shell Higgs production through 4 top-quarks

- Compare to different on-shell production and decay modes
- Extract Γ_H in a profile likelihood fit to multivariate classifiers and invariant masses

New

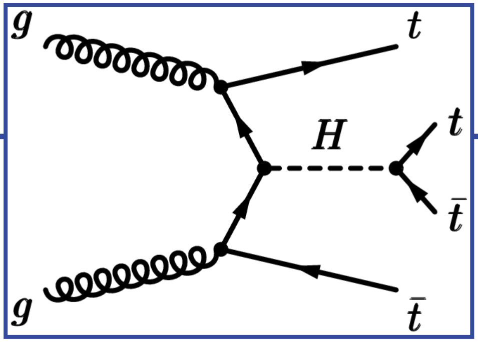


arXiv:2407.10631

→ $\Gamma_H = 86^{+110}_{-49}\text{MeV}$ → 2.0σ away from SM expectation

Determination of the Higgs boson width

Off-shell Higgs production through 4 top-quarks



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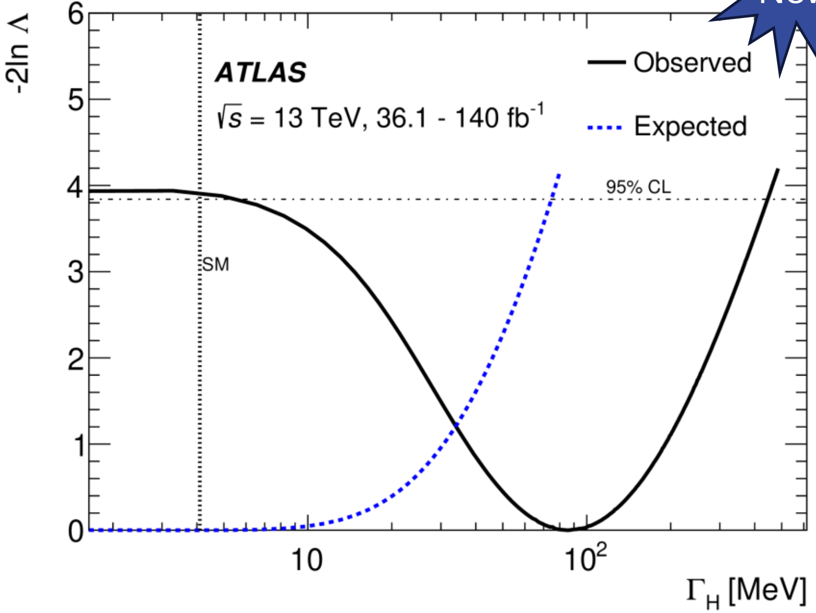
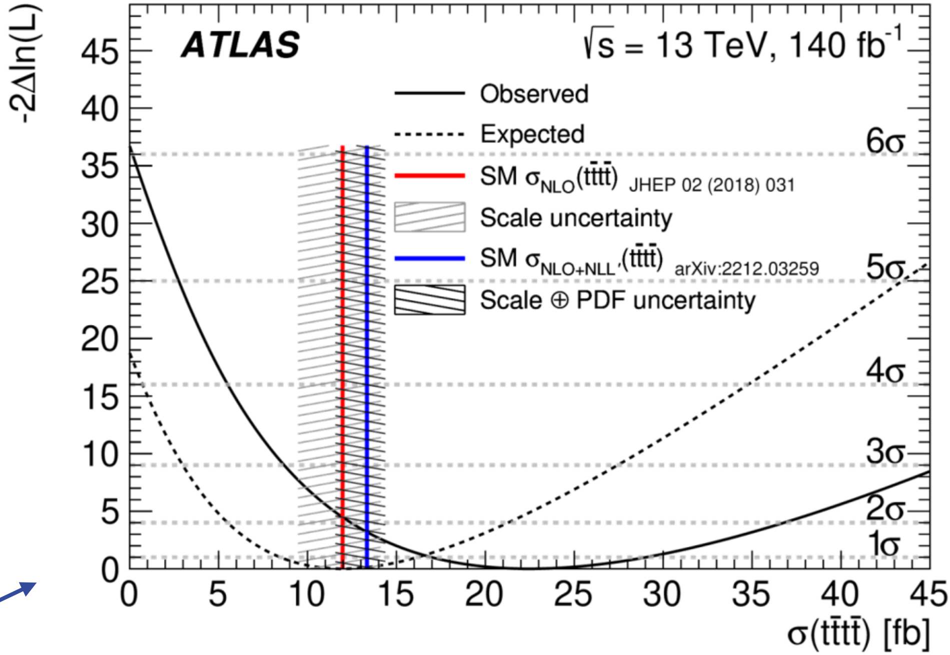
New



arXiv:2407.10631

→ Reason: Higher measured $t\bar{t}t\bar{t}$ cross section than predicted

→ Agreement slightly improved with additional NLL corrections

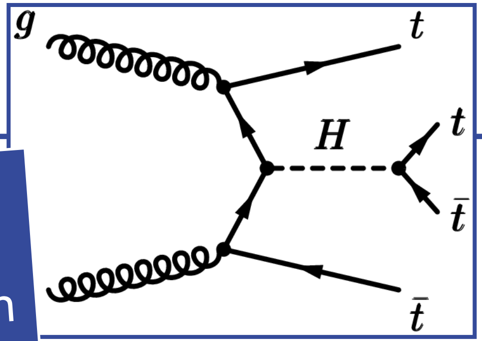


EPJC 83 (2023) 496

→ Improve by factor of ~2 if no beyond-SM (BSM) contributions assumed in loop-induced on-shell couplings: gluon-gluon-fusion, $H \to \gamma\gamma$, $H \to Z\gamma$

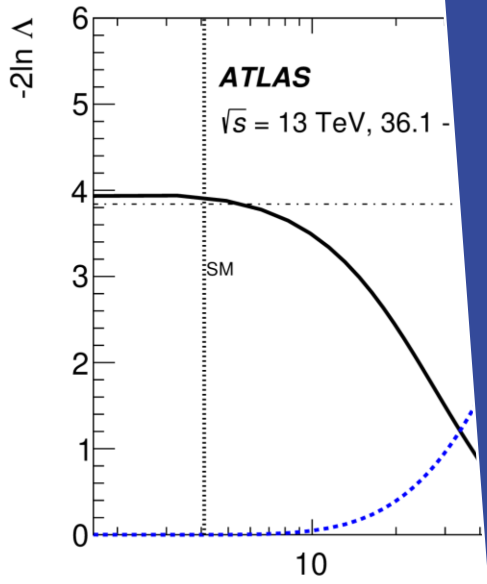
→ $\Gamma_H = 86^{+110}_{-49}\,\mathrm{MeV}$ → 2.0σ away from SM expectation

Determination of the Higgs boson width



Off-shell Higgs production through 4

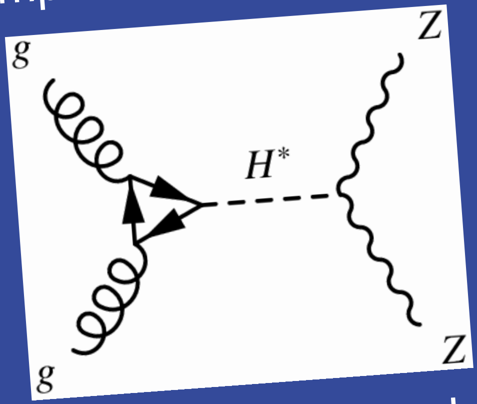
- Compare to differen
- Extract Γ_H in a profil and invariant masse

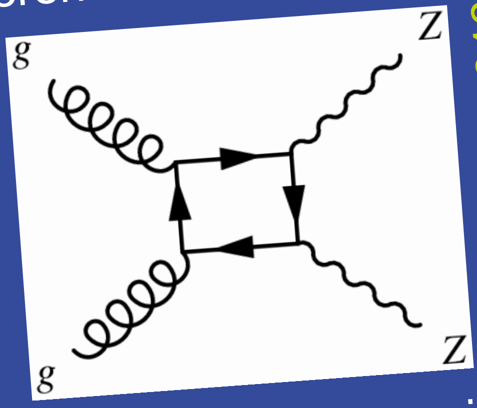


→ $\Gamma_H = 86^{+100}_{-49}$MeV → 2 … from SM expectation

→ Again assuming no BSM contributions in loop-induced couplings: Can also use $H \rightarrow ZZ \rightarrow 4\ell$ and $2\ell 2\nu$ process

→ Complication: Negative interference for off-shell production





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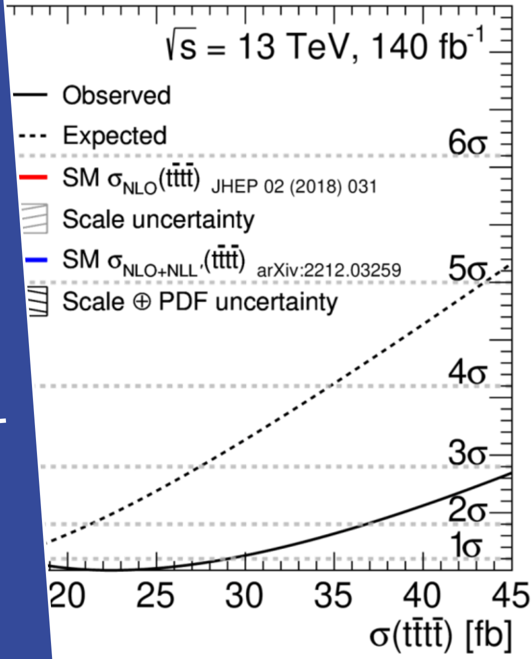
→ Signal for off-shell production: Less events than with background only → Evidence for off-shell production seen

→ Fitting signal strengths μ: $\frac{\mu_{off-shell}}{\mu_{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$

→ $\Gamma_H = 4.5^{+3.0}_{-2.5}$ MeV! → In good agreement with SM!



EPJC 83 (2023) 496

f no beyond-SM (BSM) … contributions assumed in loop-induced on-shell couplings: gluon-gluon-fusion, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$

What about CP-violation?

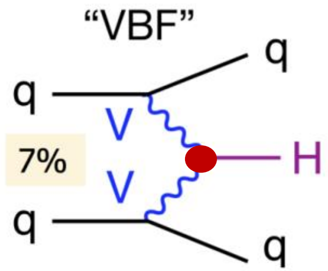
Invariance of Higgs couplings to vector bosons/fermions under CP-transformation?

- Higgs boson spin (J), parity (P) and charge-conjugation (C) measured as: $J^{PC} = 0^{++}$
  → Based on assumption of C- and CP-parity conservation in Higgs boson interactions

→ Are these assumptions correct? → Search for CP-violation (CPV) in production or decay of the Higgs boson

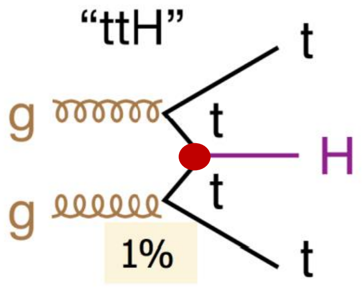
  - CPV = admixture of CP-odd (pseudoscalar) terms in addition CP-even (scalar) SM Higgs boson
  - Probe different couplings:

VVH coupling



→ Accessible in vector-boson-fusion (VBF) production

ttH coupling



→ Accessible in $t\bar{t}H$ production

What about CP-violation? @ ttH vertex

Phys. Lett. B 849 (2024) 138469

Consider $t\bar{t}H$ and tH production with $H \rightarrow b\bar{b}$

- Add CP-odd admixture to top-quark Yukawa coupling

Higgs field

Top-quark spinor

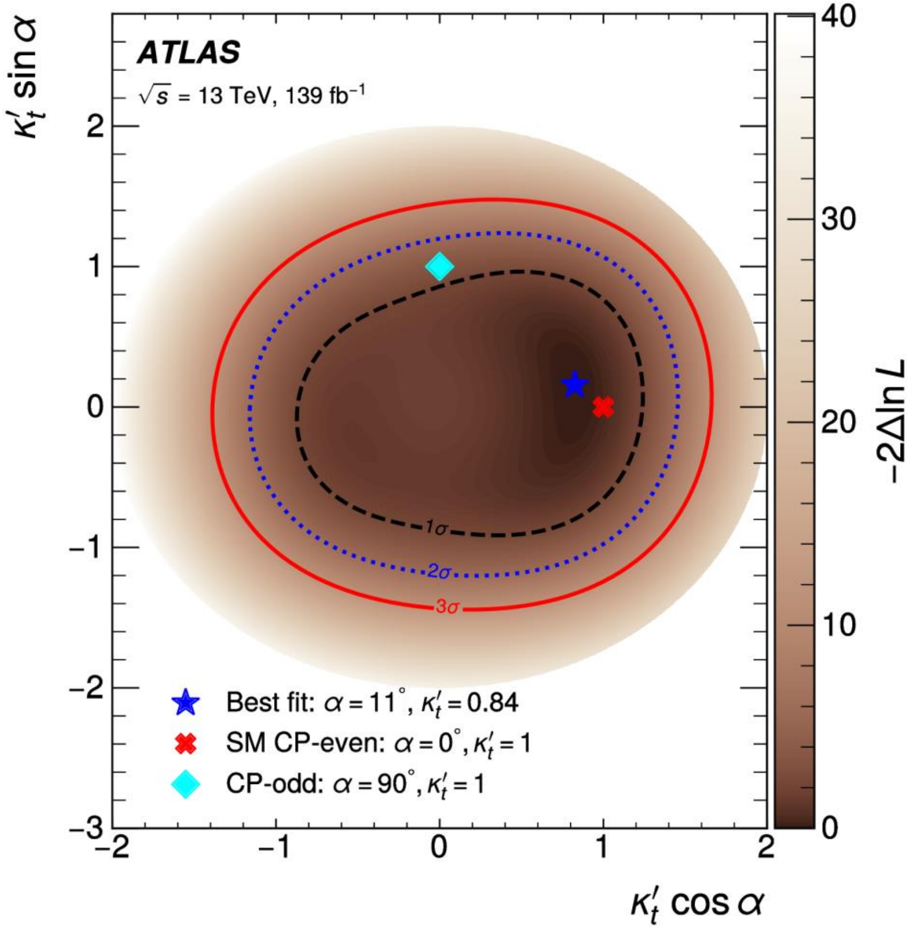
$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

Coupling modifier

Yukawa coupling

CP-mixing angle

  - SM: $\alpha = 0, \kappa_t' = 1$ (at tree level)
    → Higher order corrections push κ_t' below 1
- Extract α and κ_t' from a simultaneous fit to several regions
  - Defined based on jet multiplicity, b-tagging, and 1 or 2 light leptons (e, μ) – signal and control regions
  - Using multivariant analysis techniques (MVAs) for signal enhancement, and yields or CP-sensitive observables in fit



→ Compatible with SM → In line with earlier measurement using $H \rightarrow \gamma\gamma$

What about CP-violation? @ VVH vertex

Use SM-Effective Field Theory (SMEFT)

- Build higher-dimensional Lagrangian terms from SM fields

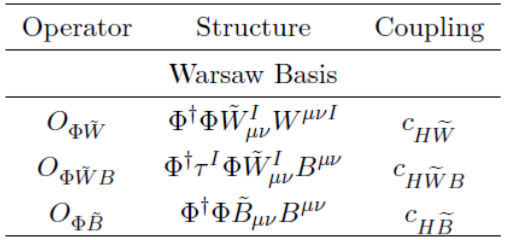
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

Wilson coefficient

Dimension-6 operator

EFT energy cutoff scale

  - Warsaw basis: Use fields of unbroken gauge symmetry
- For VBF $H \rightarrow ZZ^* \rightarrow 4\ell$
  - 3 CP-odd operators contribute to production and decay



Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$

- For VBF $H \rightarrow \gamma\gamma$
  - 3 CP-odd operators, keeping only $c_{H\widetilde{W}}$ non-zero
- Newest: For VBF $H \rightarrow \tau\tau$
  - 3 CP-odd operators, contribute only via production

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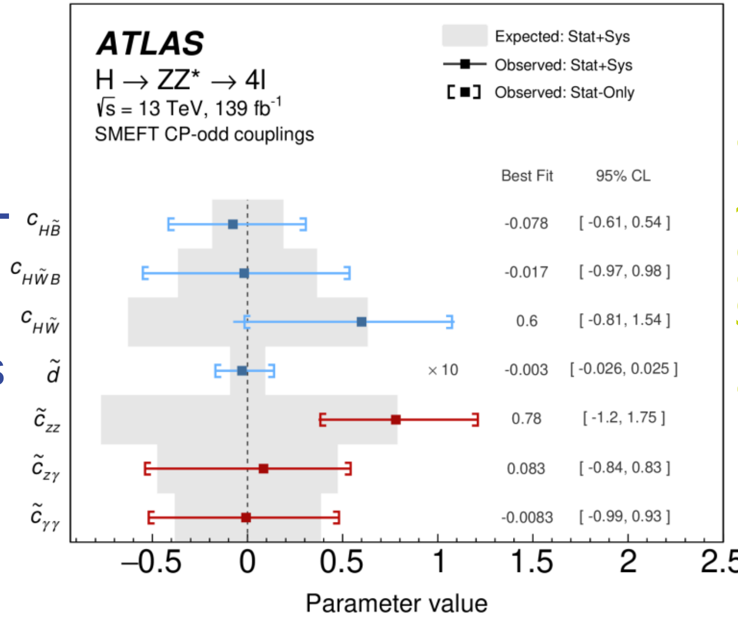
	95% (obs.)
$c_{H\tilde{W}}$ (inter. only)	$[-0.53, 1.02]$

PRL 131 (2023) 061802

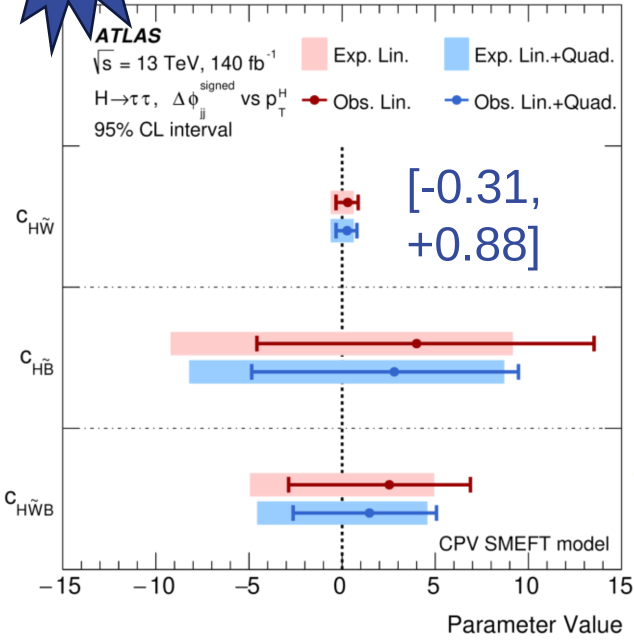
- For VBF $H \rightarrow \gamma\gamma$
  - 3 CP-odd operators, keeping only $c_{H\tilde{W}}$ non-zero
- Newest: For VBF $H \rightarrow \tau\tau$
  - 3 CP-odd operators, contribute only via production

Only small sensitivity to $\mathcal{O}(\Lambda^{-4})$ terms



JHEP 05 (2024) 105

New



[-0.31, +0.88]

arXiv:2407.16320

→ Constraints on $c_{H\tilde{W}}$ strongest to date from any channel

→ No significant CP-odd component observed

Summary

Is the *Higgs boson* the Standard Model (SM) Higgs boson?

- Looks very much like it!
  - Mass measurements → Now reached 0.09% precision!
  - Width determinations → Rely on off-shell to on-shell cross section ratios
    → Now even use 4-top cross section fits
    → Narrow in on MeV range! → Beware of model sensitivity though
  - CP-violation → Currently no signs in Higgs boson interactions

→ Should we give up?

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    → Narrow in on MeV range! → Beware of model sensitivity though
  - CP-violation → Currently no signs in Higgs boson interactions

→ Should we give up? → NO!

- More data from LHC and future machines: HL-LHC and e^+e^- needed
  - Fully map the Higgs potential → Understand stability of the electroweak vacuum
  - Model independent determination of Higgs boson width
  - CP-violation? → Let‘s not leave any stone unturned

→ Nature is holding onto her secrets and building up the suspense
→ More human ingenuity needed to access them ☺

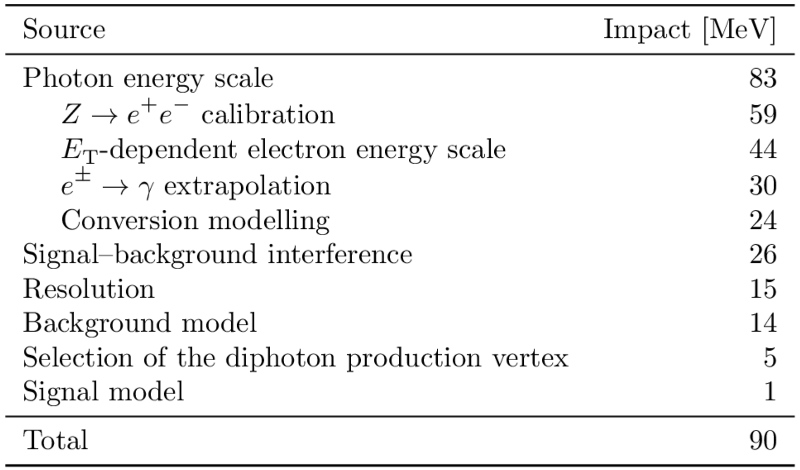
Thank you for your attention

Backup

Measurement of the Higgs boson mass

Systematic uncertainties for $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ Run 2 measurements

$H \rightarrow \gamma\gamma$

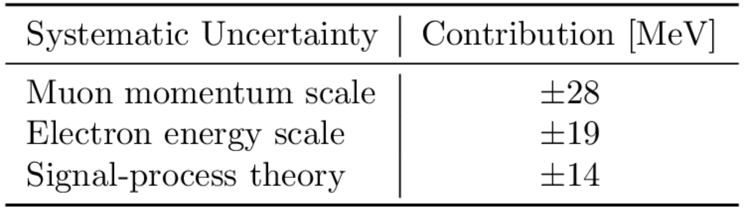


Source	Impact [MeV]
Photon energy scale	83
$Z \rightarrow e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \rightarrow \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

Phys. Lett. B 847 (2023) 138315

$H \rightarrow ZZ^* \rightarrow 4\ell$

Largest contributing uncertainties:



Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

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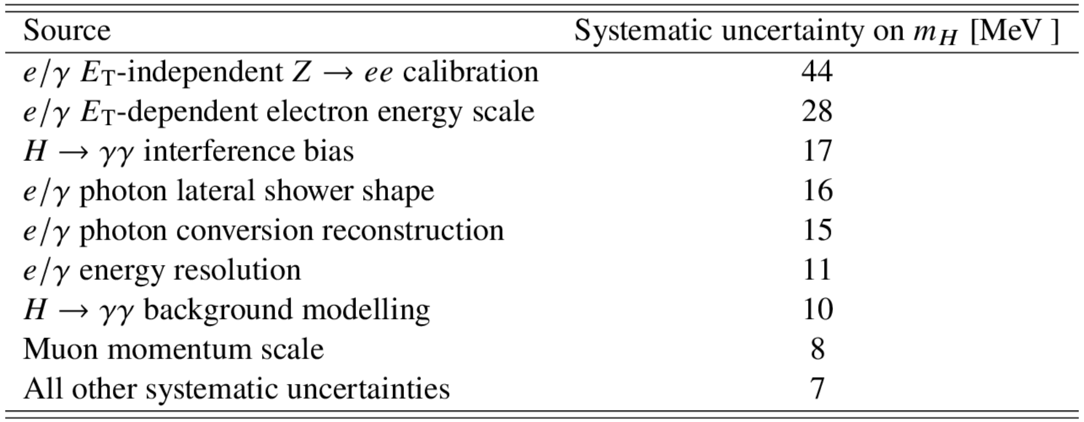
Run 2 Combination



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

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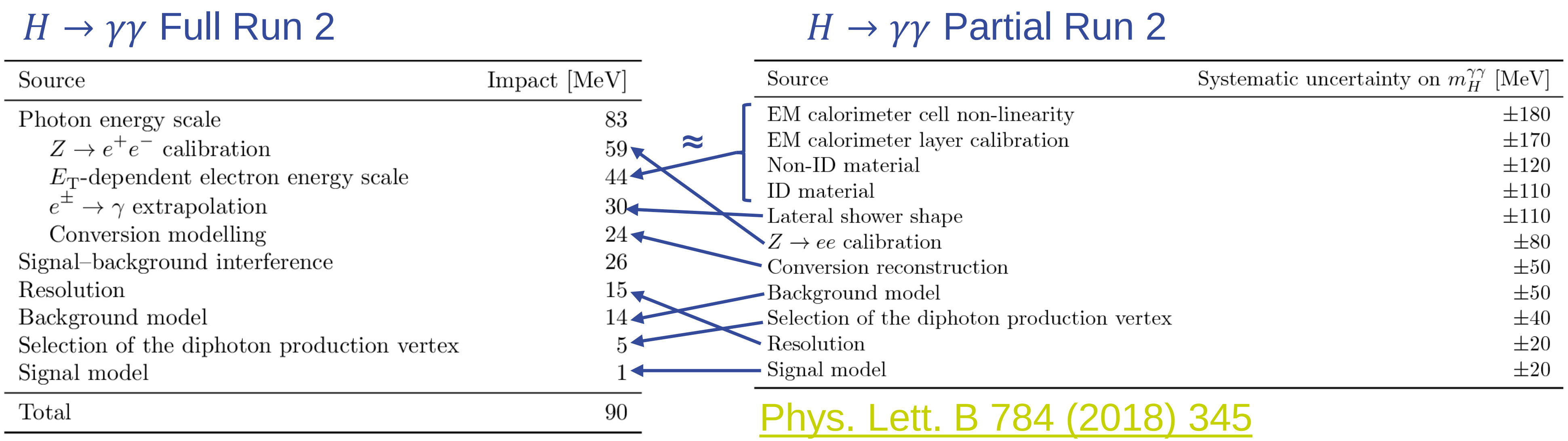
Measurement of the Higgs boson mass

Systematic uncertainties for $H \rightarrow \gamma\gamma$ in comparison to previous measurement



$H \rightarrow \gamma\gamma$ Full Run 2

Source	Impact [MeV]
Photon energy scale	83
$Z \rightarrow e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \rightarrow \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

Phys. Lett. B 847 (2023) 138315

≈

$H \rightarrow \gamma\gamma$ Partial Run 2

Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
EM calorimeter cell non-linearity	±180
EM calorimeter layer calibration	±170
Non-ID material	±120
ID material	±110
Lateral shower shape	±110
$Z \rightarrow ee$ calibration	±80
Conversion reconstruction	±50
Background model	±50
Selection of the diphoton production vertex	±40
Resolution	±20
Signal model	±20

Phys. Lett. B 784 (2018) 345

Details on improved electron and photon energy calibration in Run 2: JINST 19 (2024) P02009

For full Run 2

→ New auxiliary measurement (linearity fit) of the data-to-MC electron scale correction as function of electron E_T using the larger $Z \rightarrow e^+e^-$ sample from full Run 2

→ More accurate description of material upstream of the EM calorimeter in the simulation, lower sensitivity of new clustering algorithm to effects of interactions with detector material

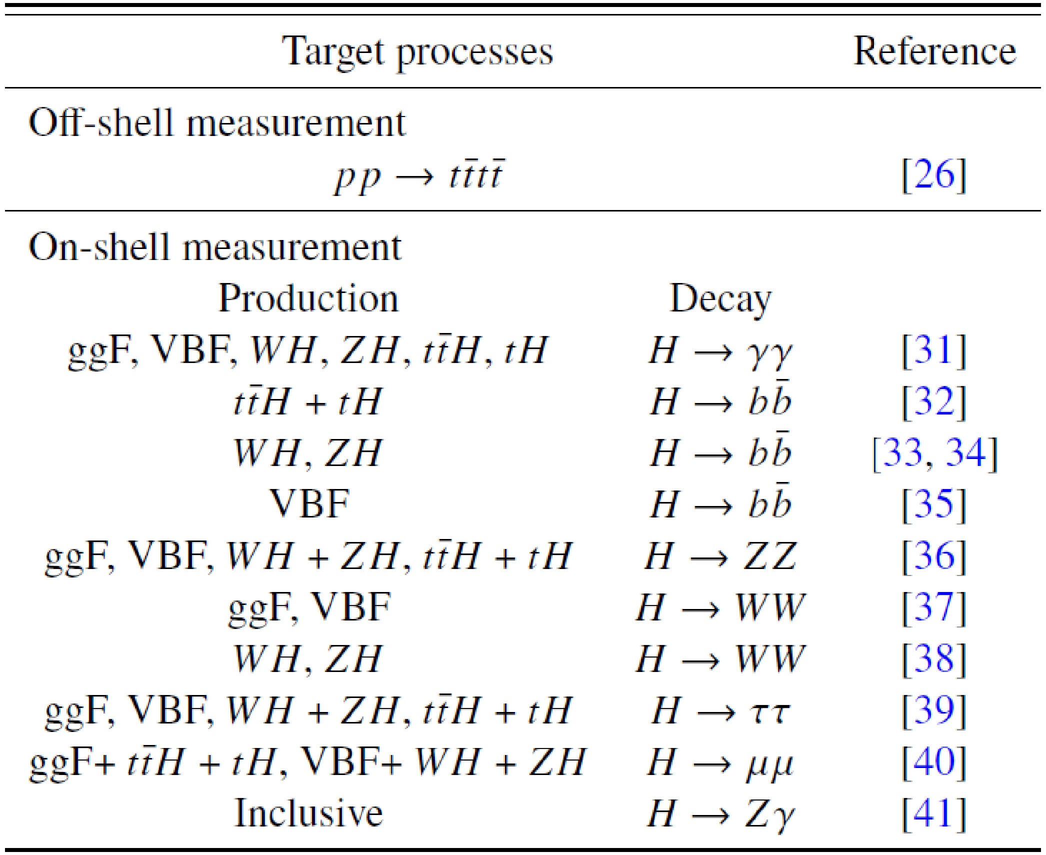
→ More precise study of $e^\pm \rightarrow \gamma$ extrapolation in larger dataset

Determination of the Higgs boson width

Off-shell Higgs production through 4 top-quarks

arXiv:2407.10631

- Used off- and on-shell analyses

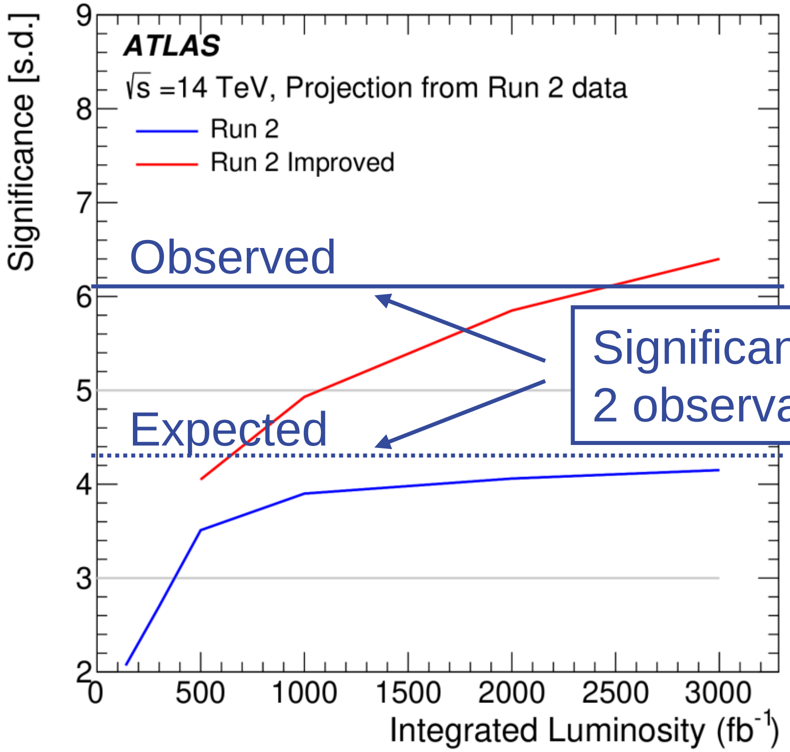


Target processes		Reference
Off-shell measurement		
$pp \to t\bar{t}t\bar{t}$		[26]
On-shell measurement		
Production	Decay	
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$	[31]
$t\bar{t}H + tH$	$H \to b\bar{b}$	[32]
WH, ZH	$H \to b\bar{b}$	[33, 34]
VBF	$H \to b\bar{b}$	[35]
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$	[36]
ggF, VBF	$H \to WW$	[37]
WH, ZH	$H \to WW$	[38]
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$	[39]
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$	[40]
Inclusive	$H \to Z\gamma$	[41]

Determination of the Higgs boson width

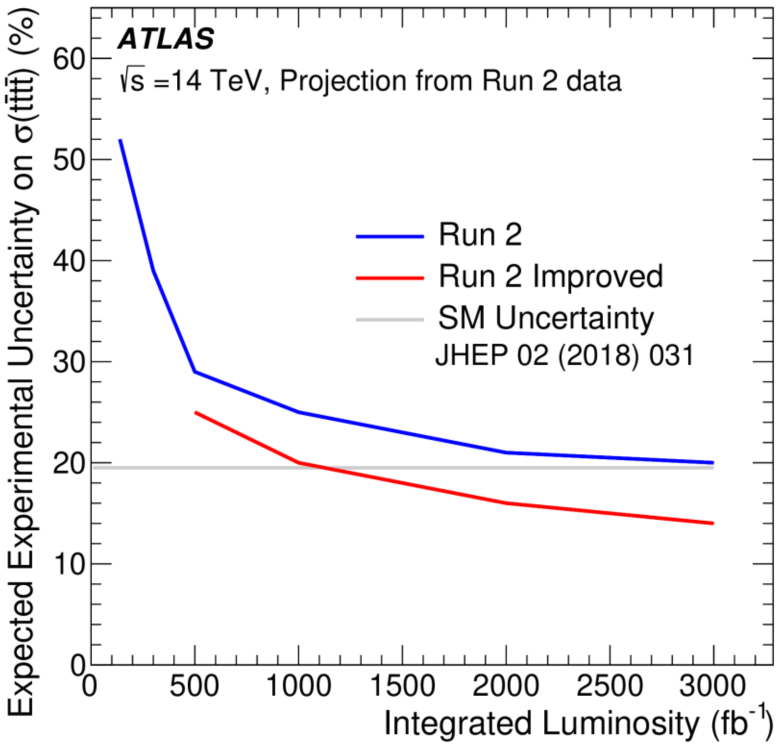
4-top production at the HL-LHC

- Extrapolation based on previous Run 2 4-top analysis – obtained evidence: Eur. Phys. J. C 80 (2020) 1085



Significances in Run 2 observation paper

EPJC 83 (2023) 496



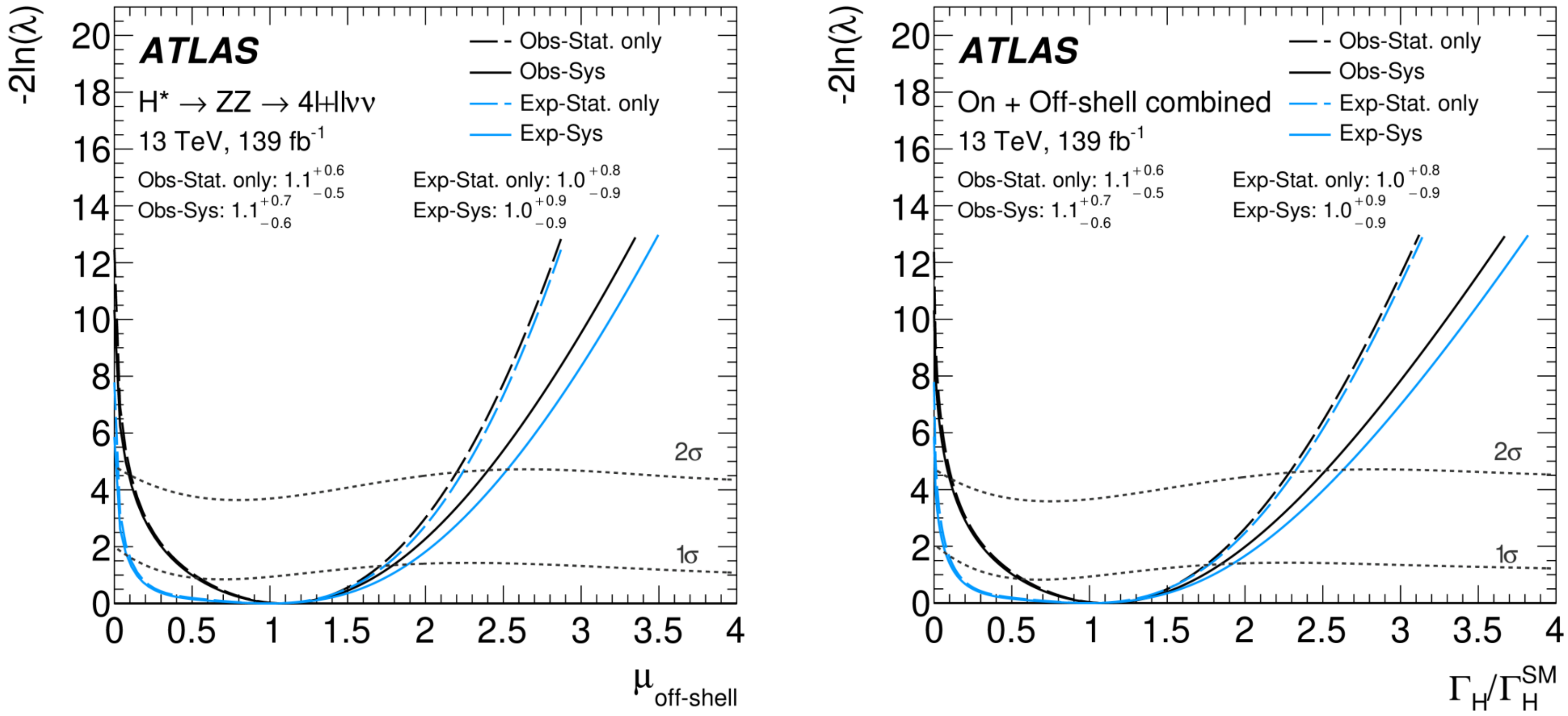
ATL-PHYS-PUB-2022-004

→ Extrapolations already exceeded with updated Run 2 analysis

Determination of the Higgs boson width

Using $H \rightarrow ZZ^* \rightarrow 4\ell/2\ell2\nu$

Phys. Lett. B 846 (2023) 138223

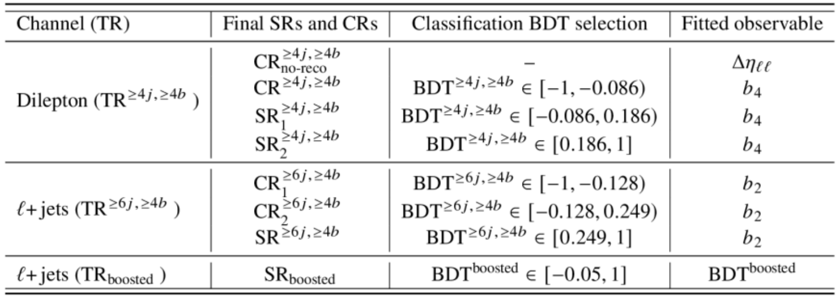


What about CP-violation?

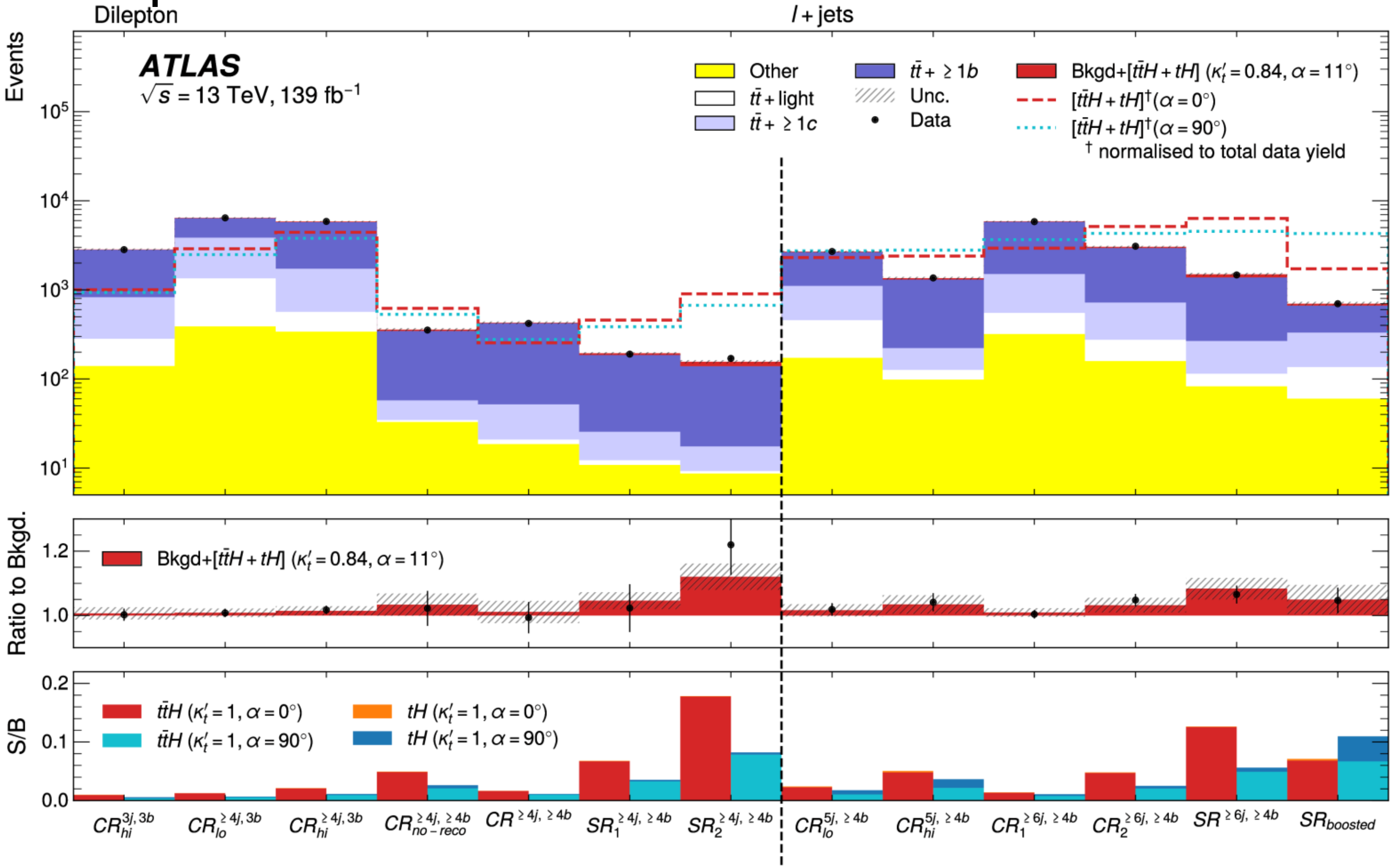
Phys. Lett. B 849 (2024) 138469

CP-violation tested with $t\bar{t}H$ and tH production with $H \rightarrow b\bar{b}$

- Fit of signal regions (SRs) and control regions (CRs) with binned profile likelihood method



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

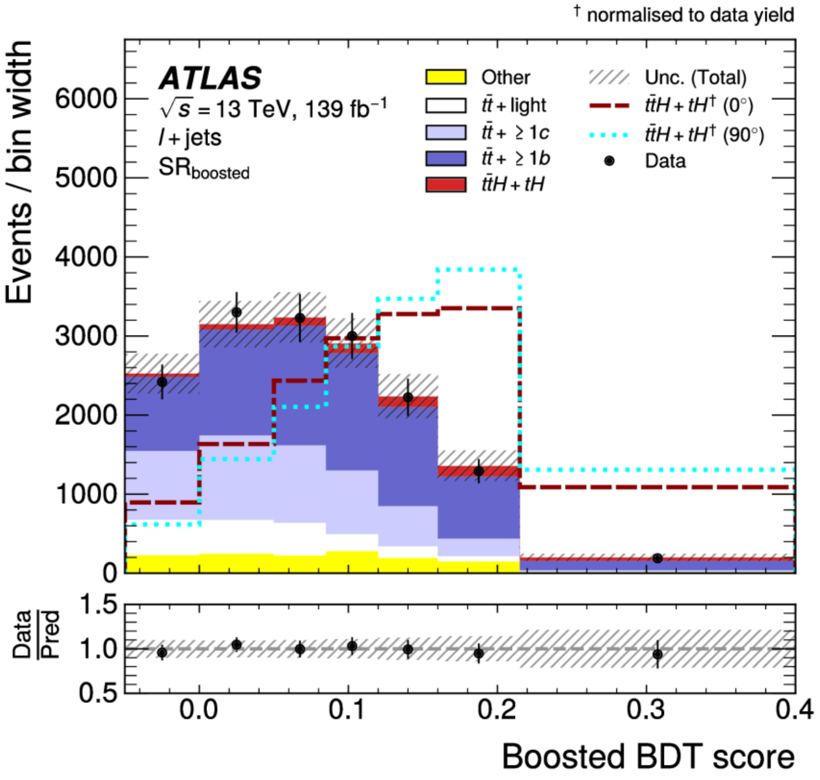


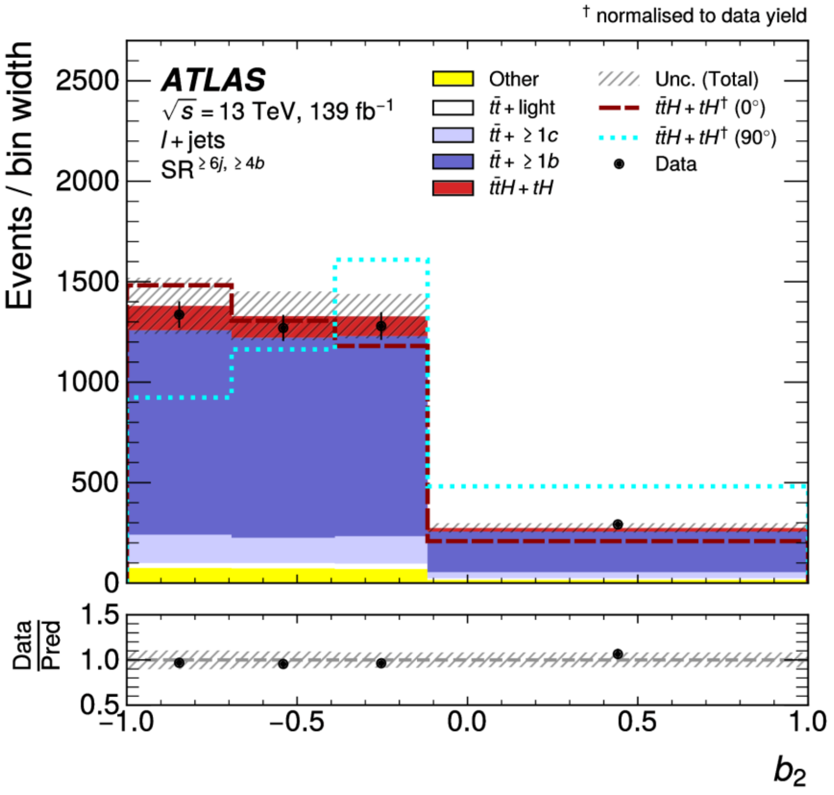
What about CP-violation?

[Phys. Lett. B 849 (2024) 138469]

CP-violation tested with $t\bar{t}H$ and tH production with $H \rightarrow b\bar{b}$

- Examples for CP-sensitive observables





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

With $\vec{p}_i$ with $i = 1{,}2$ = momentum three-vector s of two top-quarks in the events

What about CP-violation?

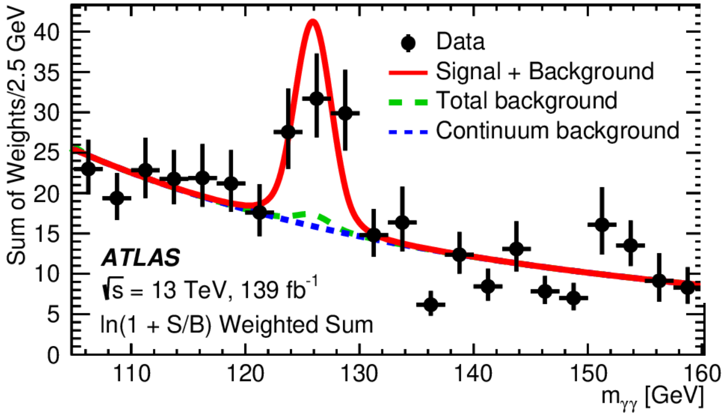
Phys. Rev. Lett. 125 (2020) 061802

Consider $t\bar{t}H$ and tH production with $H \to \gamma\gamma$

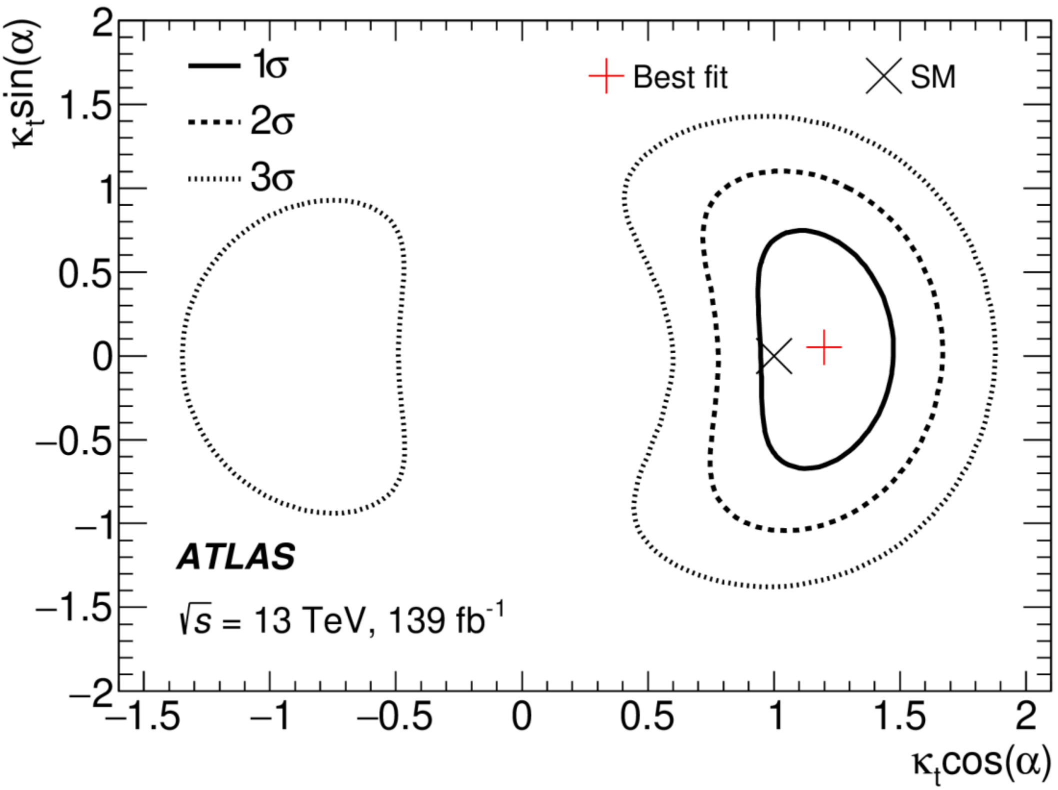
- Add CP-odd admixture to top-quark Yukawa coupling

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

  - Impacts both, production and decay, through top-quark loop in $H \to \gamma\gamma$ decay
  - Train BDT to separate CP-even and CP-odd couplings
- Simultaneous maximum-likelihood fit to $m_{\gamma\gamma}$ in all regions
  - Need to input couplings to photons (for branching ratio of $H \to \gamma\gamma$) and gluons (to subtract gluon-gluon-fusion contribution)



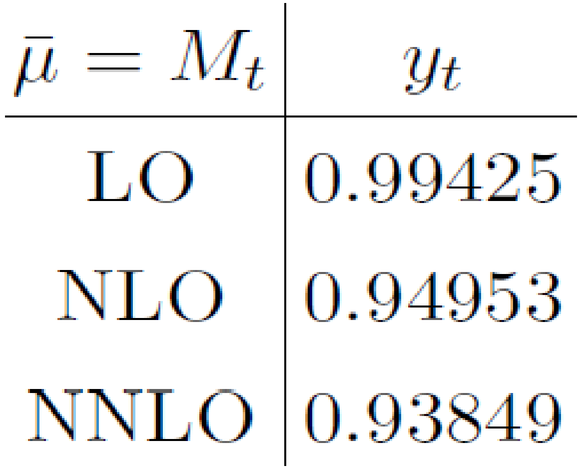
→ From Run 2 coupling com-bination (without $t\bar{t}H$ and tH)



→ $|\alpha| > 43°$ excluded at 95% CL

What about CP-violation?

Higher order corrections for top-quark Yukawa coupling (from theory)



$\bar{\mu} = M_t$	y_t
LO	0.99425
NLO	0.94953
NNLO	0.93849

JHEP12 (2013) 089

What about CP-violation?

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_{\mathrm{BSM},i}\right|^2$$

$$= |\mathcal{M}_{\mathrm{SM}}|^2 + 2\sum_i \frac{c_i}{\Lambda^2}\Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM},i}\right) + \sum_i\sum_j \frac{c_i c_j}{\Lambda^4}\Re\left(\mathcal{M}^*_{\mathrm{BSM},i}\mathcal{M}_{\mathrm{BSM},j}\right)$$

Linear term → CP-odd

Quadratic term → CP-even

For VBF $H \to ZZ^* \to 4\ell$

- Extract constraints with optimal observables (OOs)

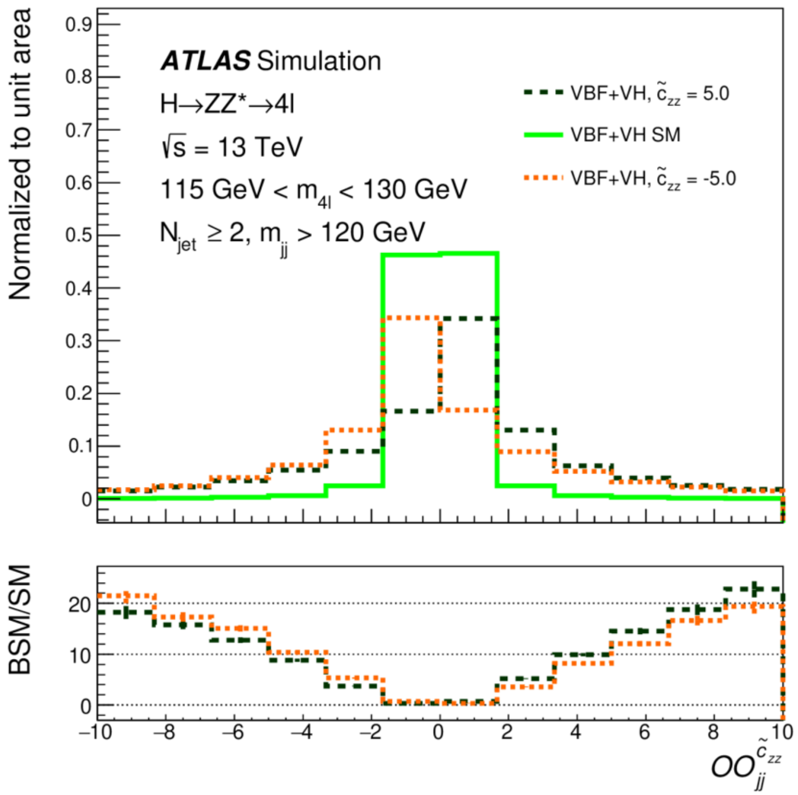
$$\mathcal{OO} = \frac{2\Re\left(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{BSM}}\right)}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

  - Intrinsically CP-odd → Symmetric = CP-even Higgs, asymmetric = CP-odd admixture

→ If restricting to single BSM CP-odd Higgs coupling: $\tilde{d}$ (assuming that different CP-violating contributions could not be distinguished experimentally)

  - In Warsaw basis: Set $c_{H\widetilde{W}} = c_{H\tilde{B}}$ → $c_{H\widetilde{W}B} = 0$

- Alternative basis:
  - Higgs basis: Use fields after EW symmetry breaking, i.e. physical states of SM gauge bosons: W^+, W^-, Z, γ



JHEP 05 (2024) 105

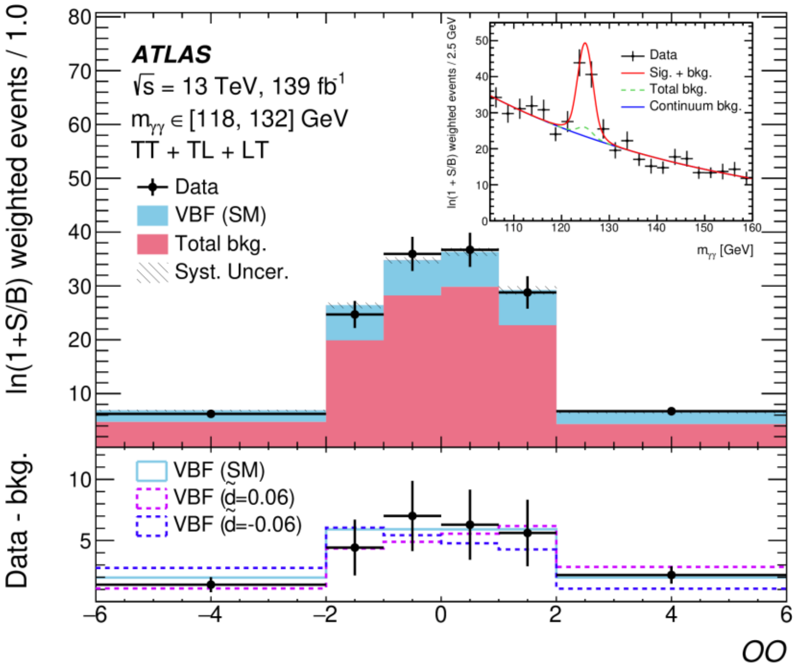
→ Only shape-information (CP-odd) used in fit

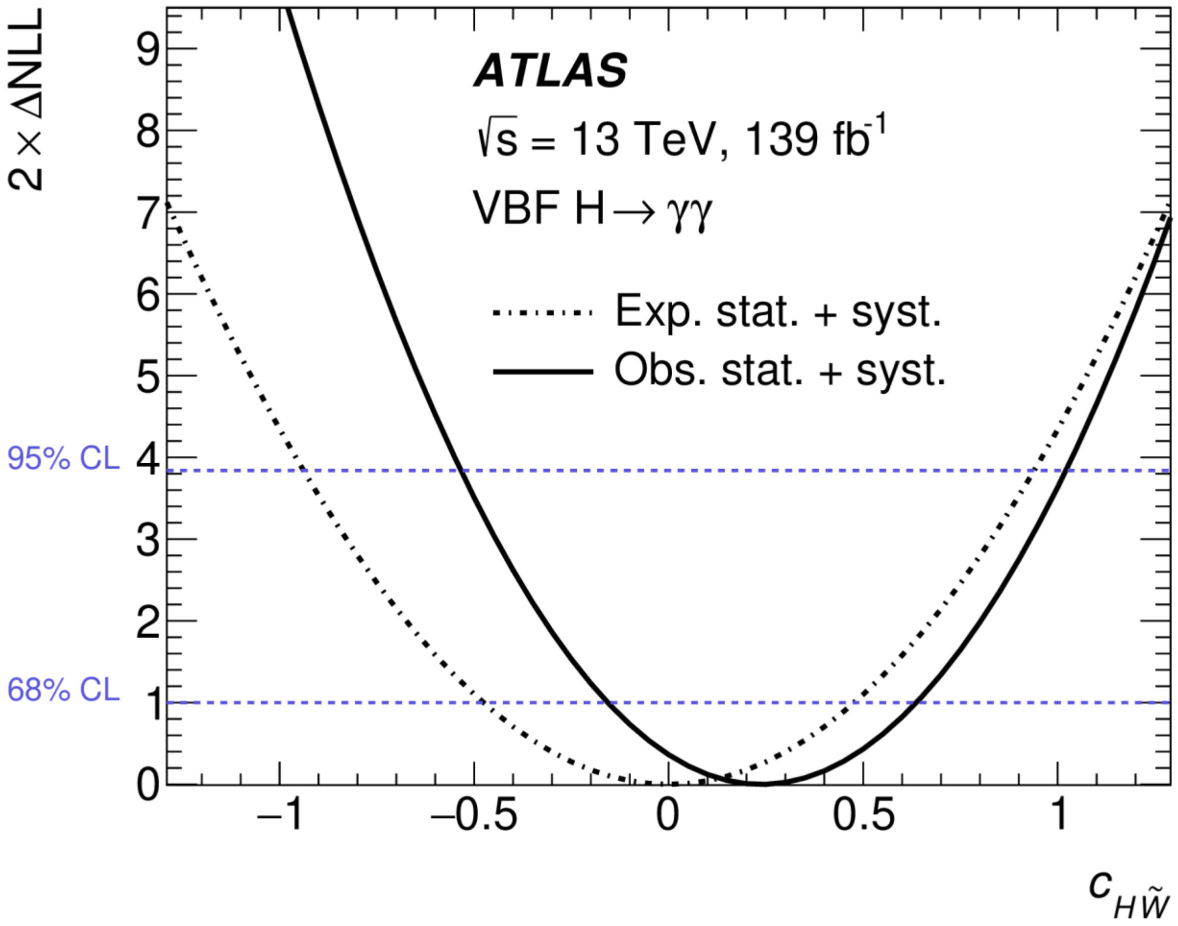
What about CP-violation?

Phys. Rev. Lett. 131 (2023) 061802

For VBF $H \to \gamma\gamma$

- Extract constraints with optimal observable (OO)
- Use regions of tight (T) or loose (L) requirements on BDTs enhancing VBF over ggF or the continuum



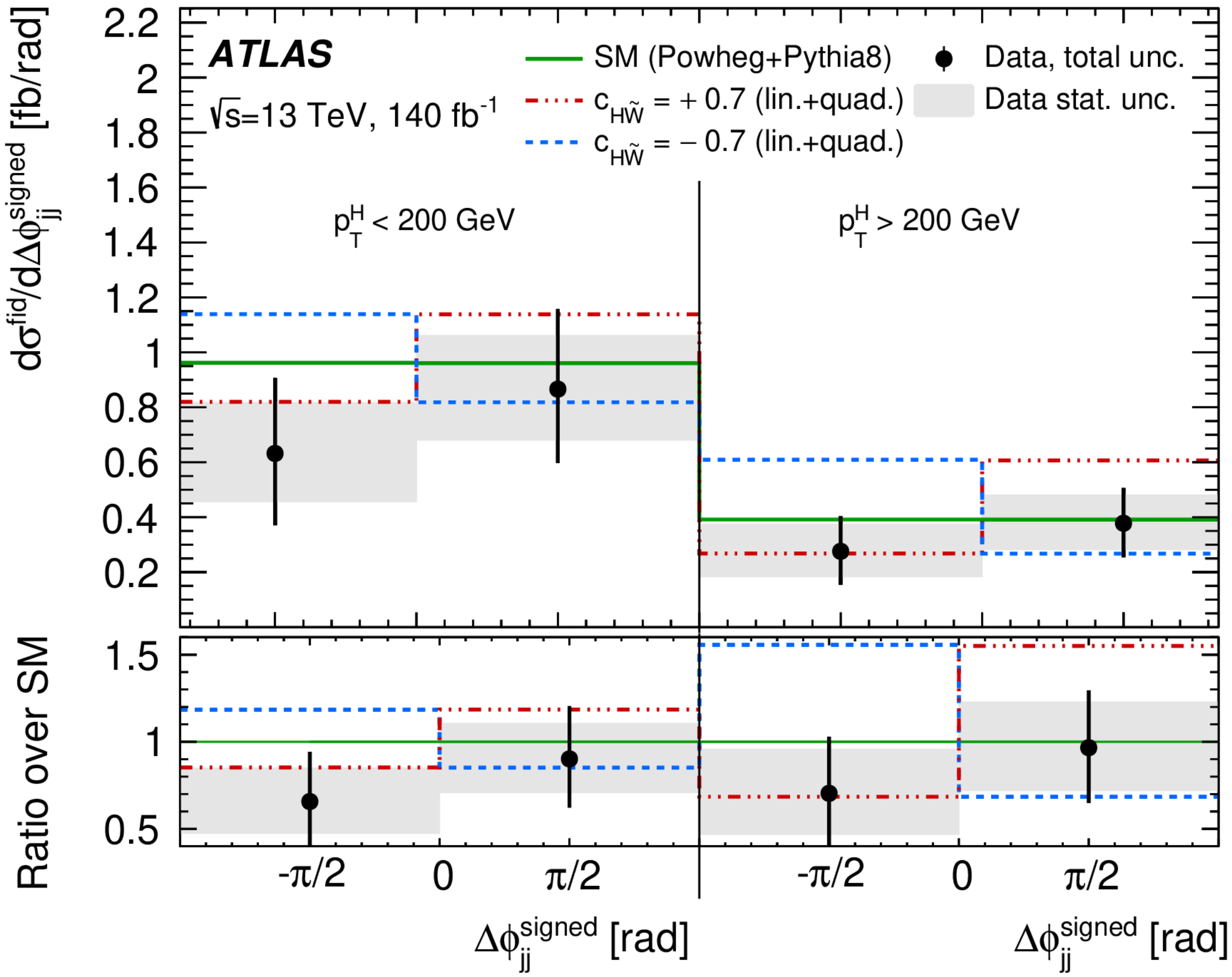


→ Only shape-information used in fit

What about CP-violation?

For VBF $H \rightarrow \tau\tau$

- Use unfolded differential cross sections
  - For CP-odd operators

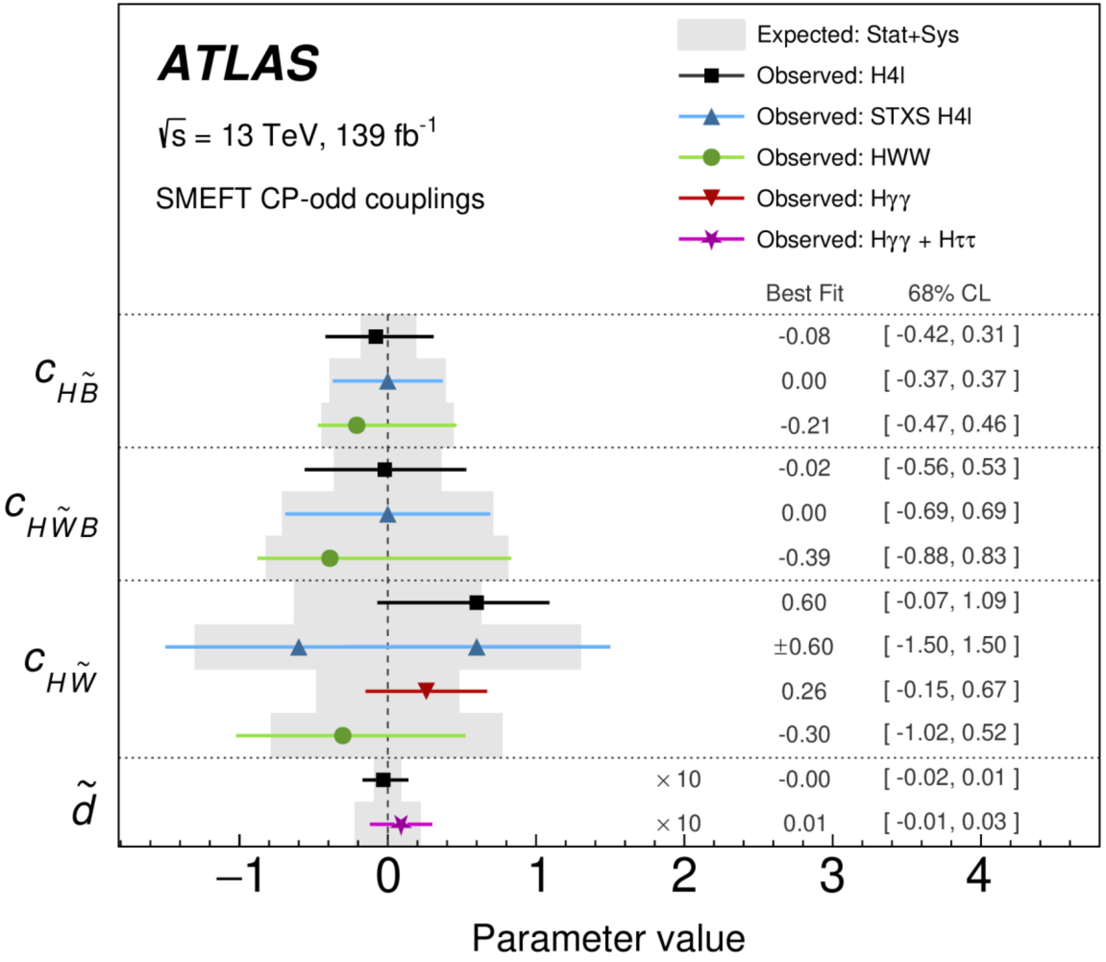


arXiv:2407.16320

What about CP-violation?

VBF combination

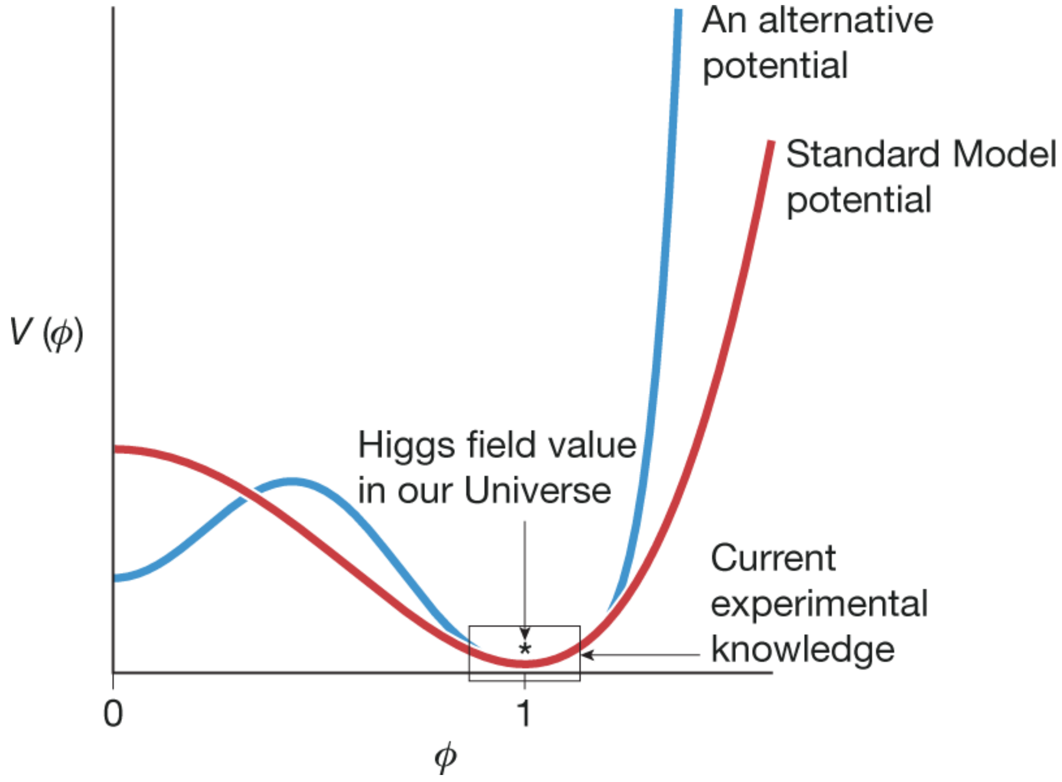
- Prior to latest $H \to \tau\tau$ measurement



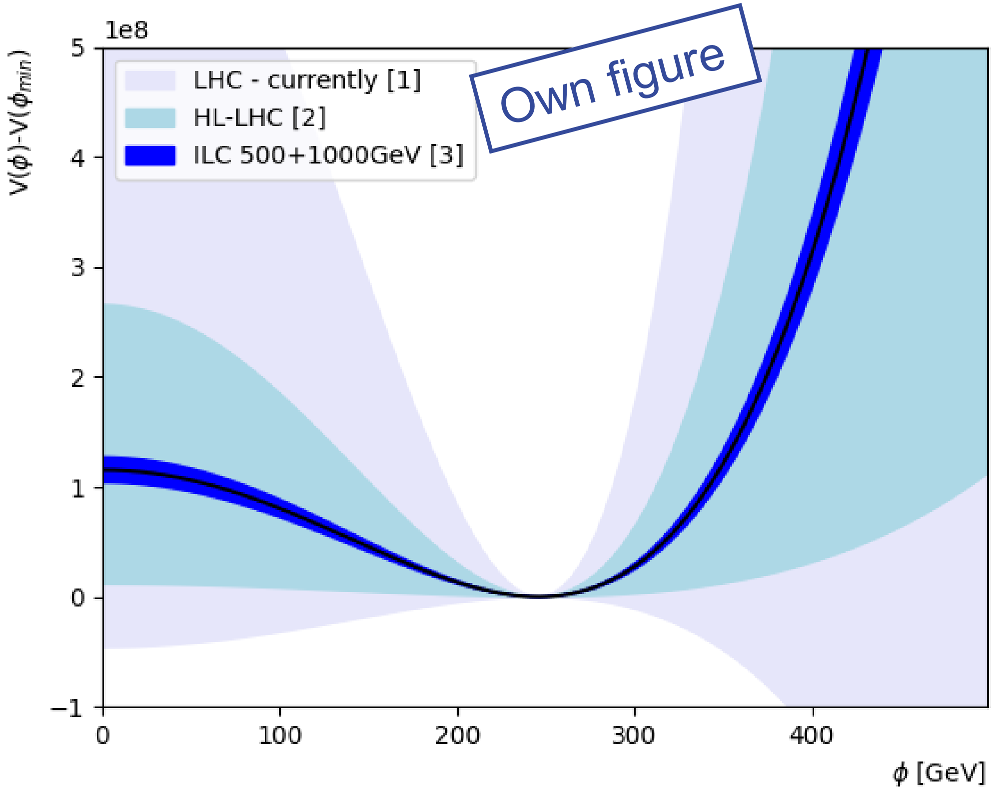
arXiv:2404.05498

Higgs potential with HL-LHC and e^+e^- machine

Possibilities of the Higgs potential



Nature 607 (2022) 41-47



Own figure

[1] Phys Lett B 843 (2023) 137745
[2] ATL-PHYS-PUB-2022-018, Fig. 11
[3] ILD-PHYS-PROC–2023-001 , Tab. 2