Measurements of the mass, width and coupling CP structure of the Higgs-boson with the ATLAS detector

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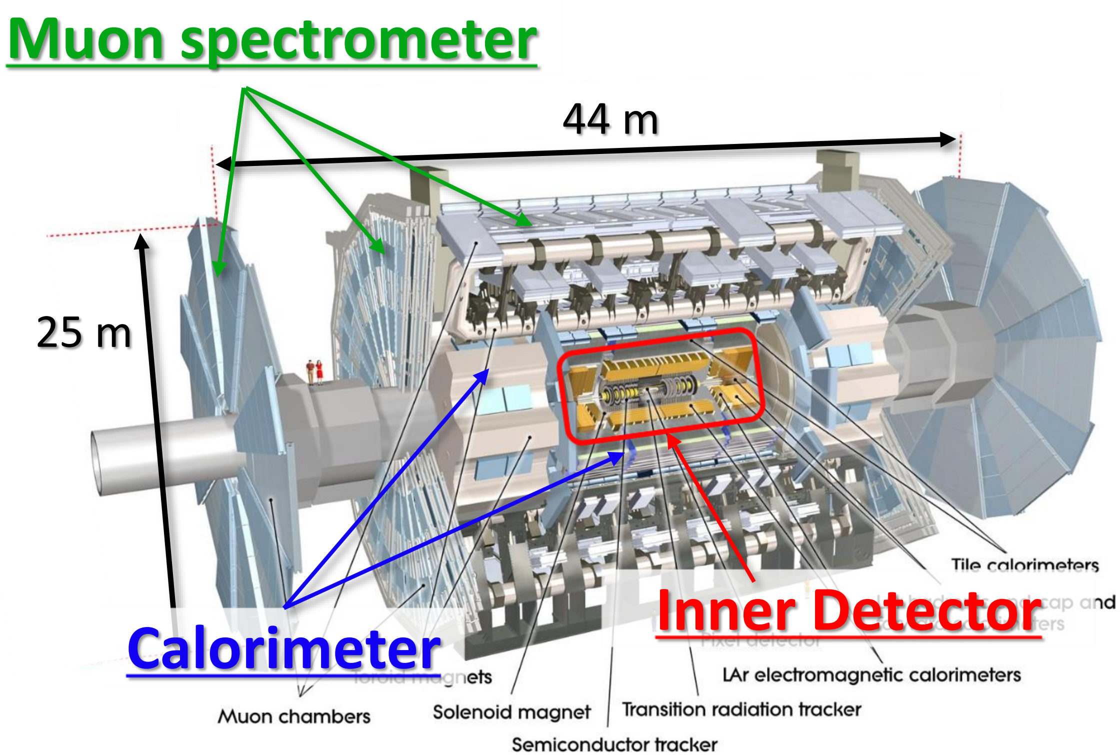
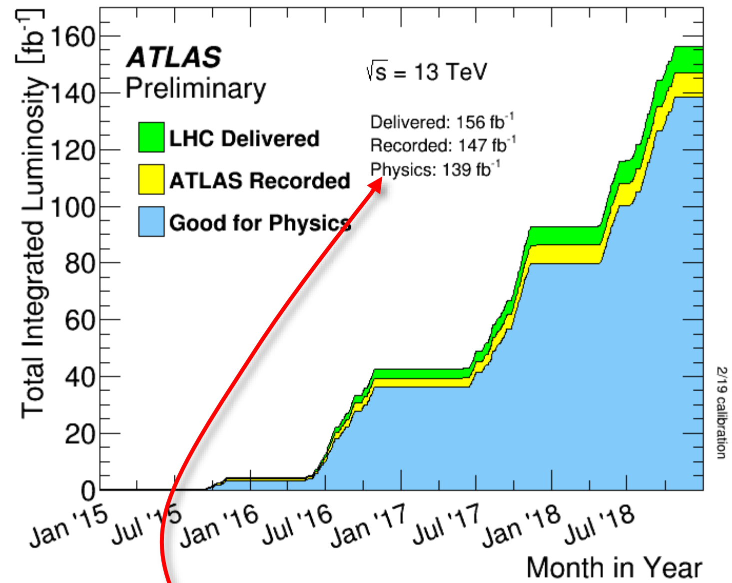
On behalf of the ATLAS Collaboration

ATLAS experiment at Run 2



Int. lumi. at Run 2 (2015-18)



139 fb^{-1} is usable for analyses!
(with >90% efficiency)

- ATLAS detector: complex of inner tracker, calorimeter and muon spectrometer
- 139 fb^{-1} data were collected during Run 2 (2015-18) at 13 TeV
  - Equivalent to 8M Higgs bosons

■ Higgs boson properties

- Higgs boson couplings to other elementary particles are being established (particularly in the vector bosons & the 3rd-gen.)
- Other fundamental properties are also important

CP property

- In the SM, Higgs boson is CP-even
- Can be an admixture of CP-even and CP-odd

Mass

- In the SM: $m_H = \sqrt{2\lambda}v$
  → Connected to fundamental constants of the SM

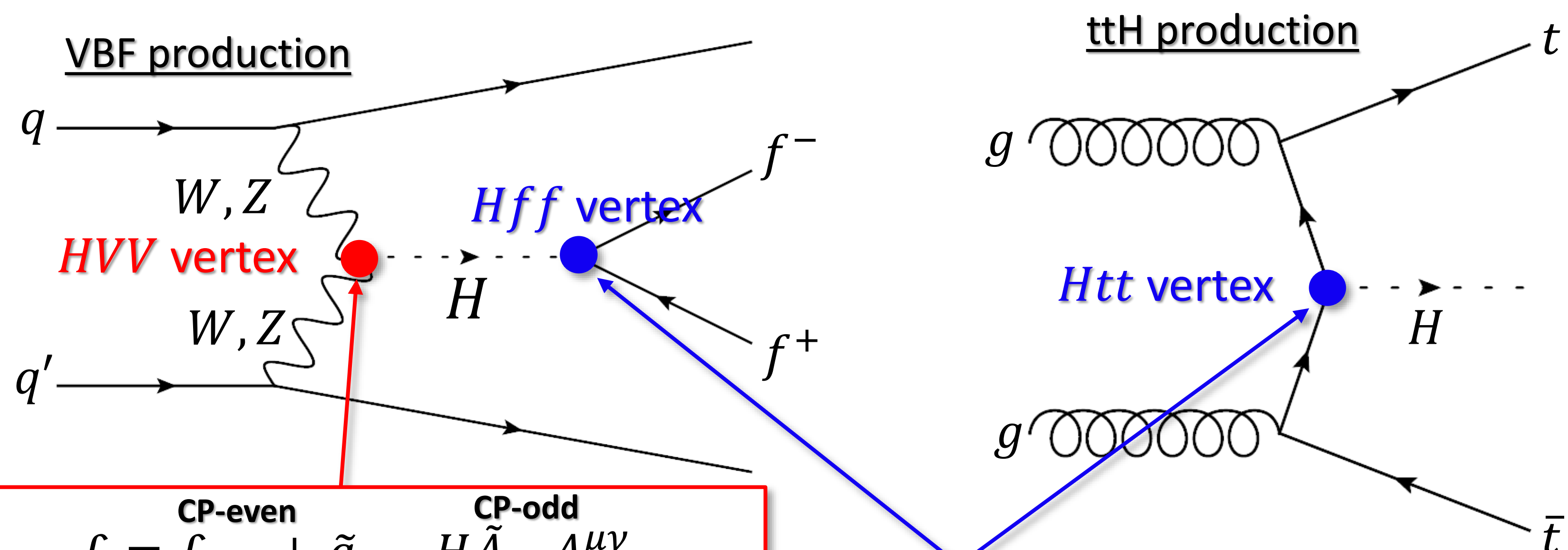
Total decay width

- ~4.1 MeV in the SM
- Can be different if there is an unknown decay mode (such as $H \to \chi^0\chi^0$ etc.)

- Any deviations from the SM expectations are the evidence of BSM

■ Higgs boson CP measurement

- Pure CP-odd is disfavoured by various experimental results
- However, a possibility of CP-even/odd admixture state is not completely excluded
- Should test the CP properties of all vertices because the CP-odd contribution could appear only on one / some of them



CP-even, CP-odd

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \widetilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

CP-odd, CP-odd

$$\mathcal{L} = -\frac{m_f}{v} \kappa_f \left(\cos\alpha \bar{f} f + \sin\alpha \bar{f}\, i\gamma_5 f \right) H$$

CP-even, CP-odd

■ CP on HVV vertex with VBF topology

Phys. Lett. B 805 (2020) 135426345

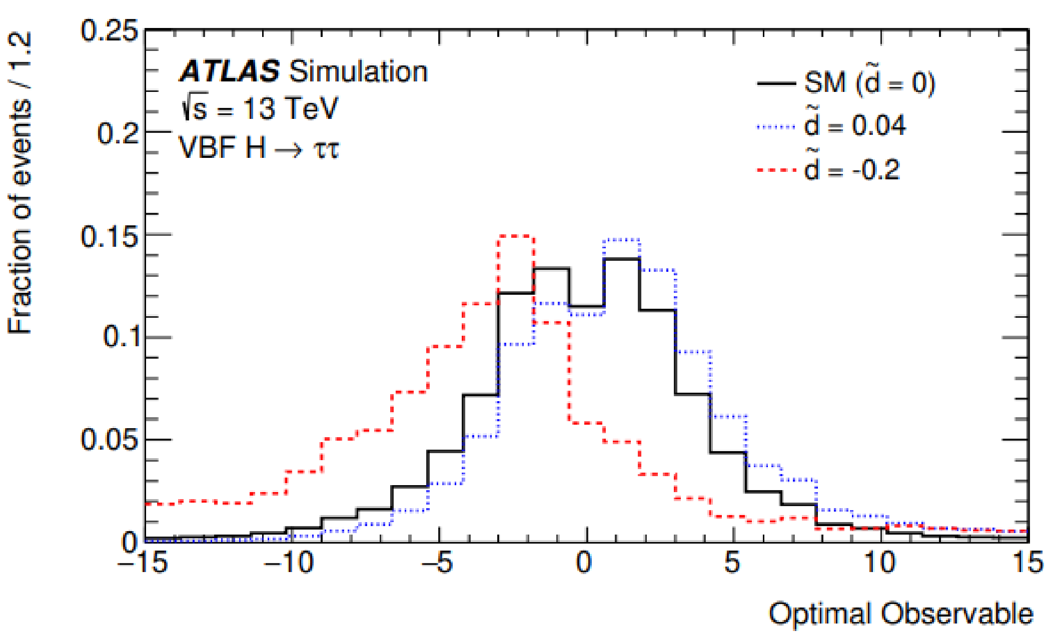
- Assume the CP-odd terms have a common coupling

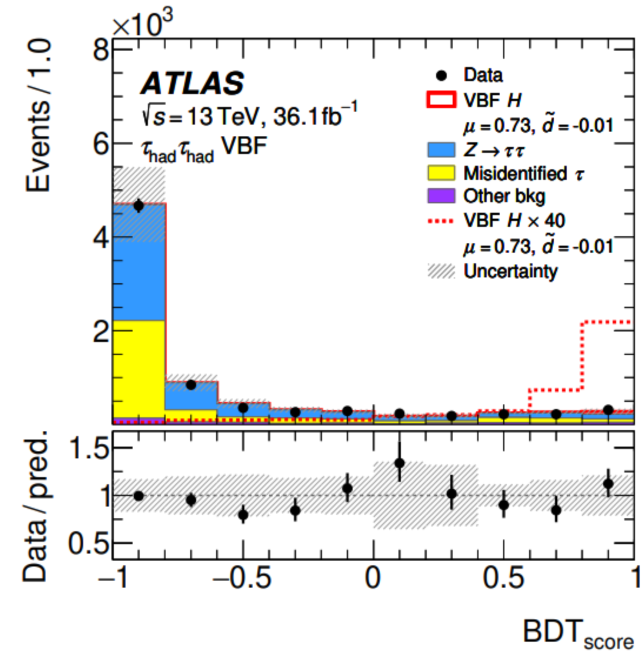
$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$$ → Parameter of interest

- CP-odd contribution can be detected in O_{opt}

$$O_{\mathrm{opt}} = \frac{2\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CPodd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$ → $\mathcal{M}$ are determined using jet kinematics

- A measurement with 36.1 fb^{-1} uses the $H \to \tau\tau$ decay
  - BDT trained using jet and τ kinematics





■ CP on HVV vertex with VBF topology

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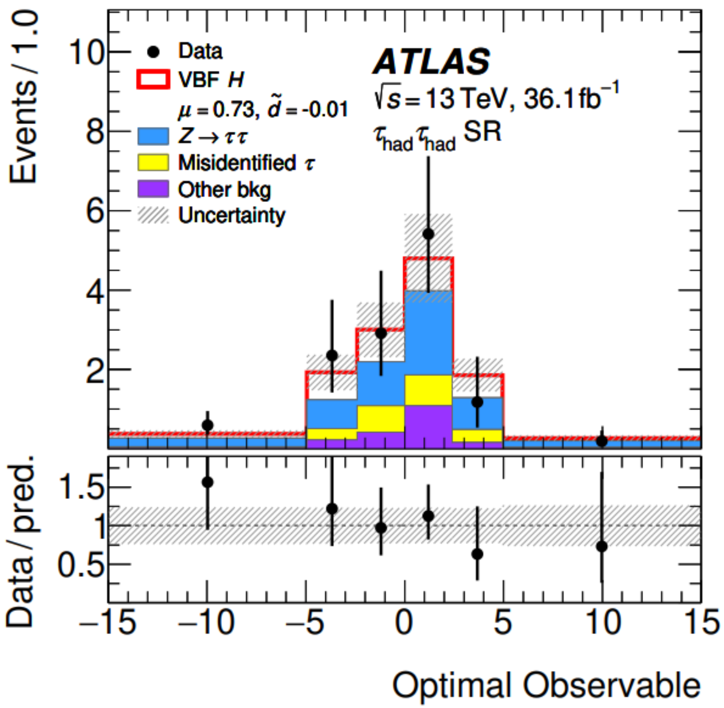
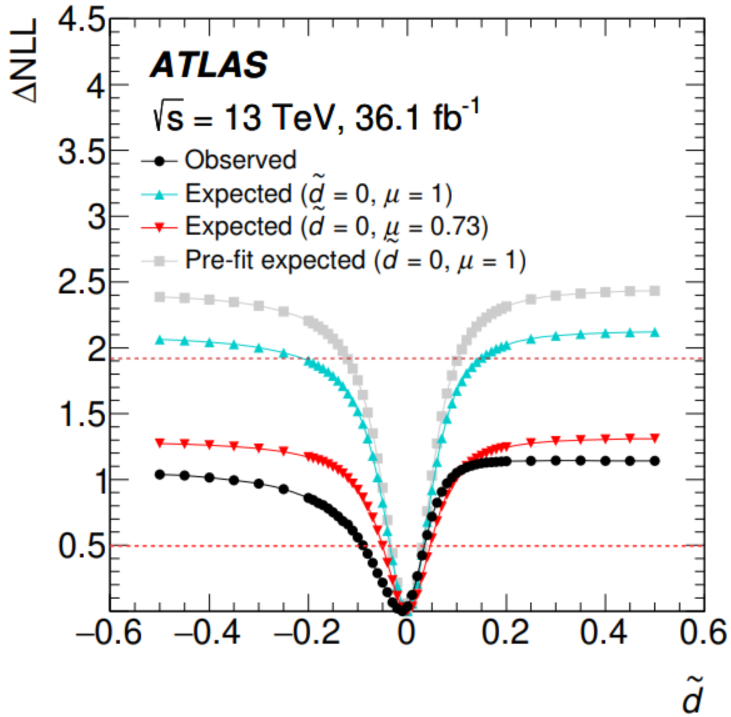




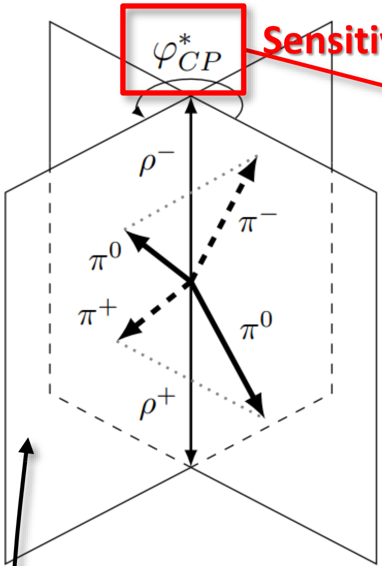
- Result

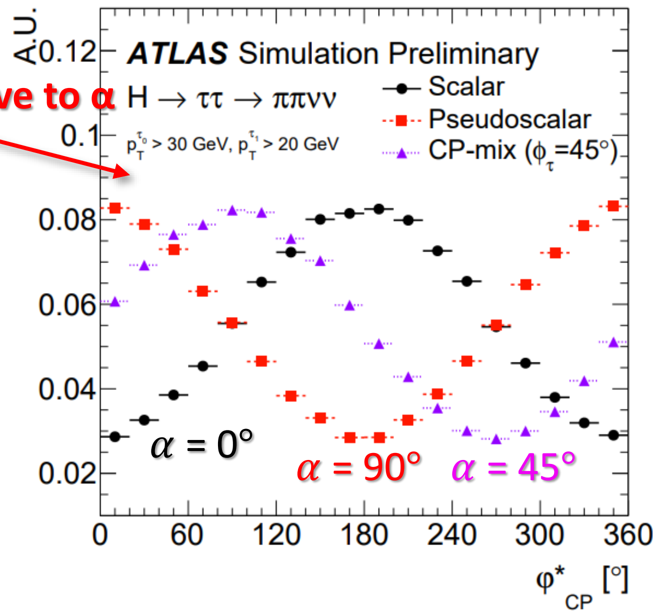
$$-0.090 < \tilde{d} < 0.035 \text{ at } 68\% \text{ CL}$$

- Sensitivity is statistically limited
  - Important to perform the measurement using full Run-2 dataset
- $H \to ZZ^*$ and $H \to \gamma\gamma$ can be also used to probe the CP-odd interaction in the VBF production

■ CP on $H\tau\tau$ vertex with ggF/VBF

ATLAS-CONF-2022-032





Combination of two τ decays

	$h^+\bar{\nu}_\tau$	$h^+\pi^0\bar{\nu}_\tau$	$\ell^+\nu_\ell\bar{\nu}_\tau$
$h^+\bar{\nu}_\tau$	1.3%	6.0%	8.1%
$h^+\pi^0\bar{\nu}_\tau$	6.0%	6.7%	18.3%
$h^+(\leq 2\pi^0)\bar{\nu}_\tau$	2.5%	5.6%	7.6%
$3h^+\bar{\nu}_\tau$	Not used	5.1%	6.9%

Same comb.

(Charge-conjugate is implied)

- Angle between the two τ decay planes in the H-rest frame is CP-sensitive
  - However, we cannot take this frame due to multiple neutrinos
    → Take the rest frame using only the visible decay products
- 10 decay combinations are used (ΣBR = 68.1%)
  - Each decay combination has different sensitivity

■ CP on $H\tau\tau$ vertex with ggF/VBF

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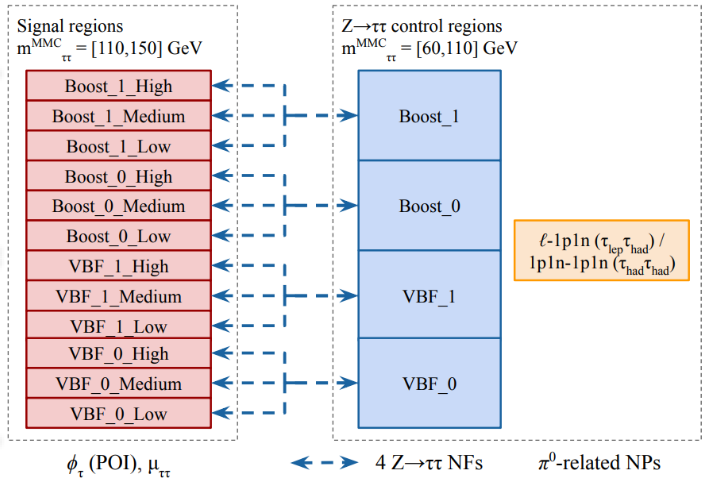
*_1 are cleaner SRs with lower statistics

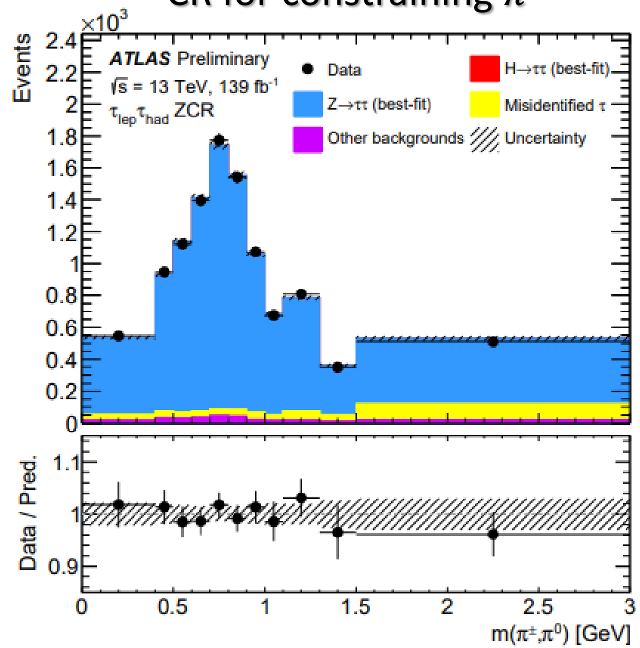
Categories for $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ channels are separately defined

ggF

VBF



CR for constraining π^0



- Very complex categorisation with 24 SRs and 10 CRs
  - A few decay mode combinations are merged into High / Middle / Low depending on sensitivities to gain statistics
- Energy and direction uncertainties on π^0 are important to define the angle ϕ^*_{CP}
  - They are controlled using fits on $m(\pi\pi^0)$

CP on $H\tau\tau$ vertex with ggF/VBF

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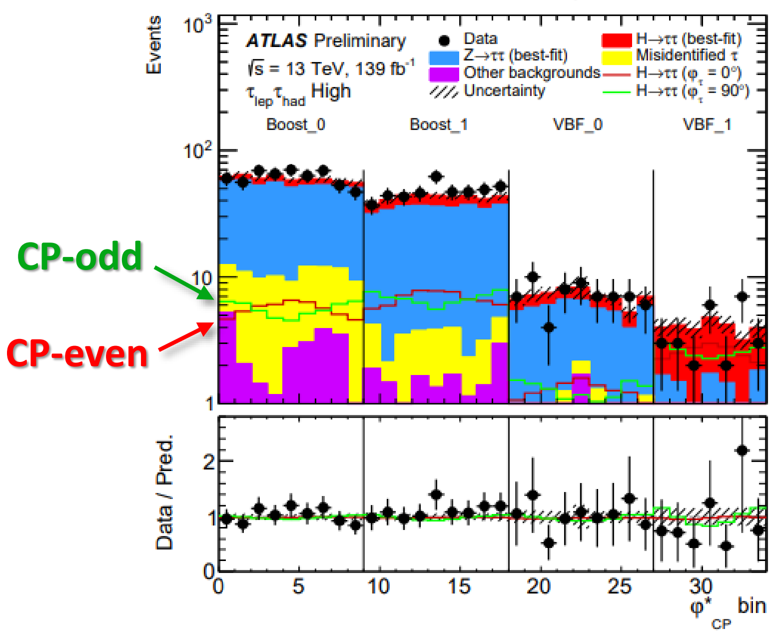
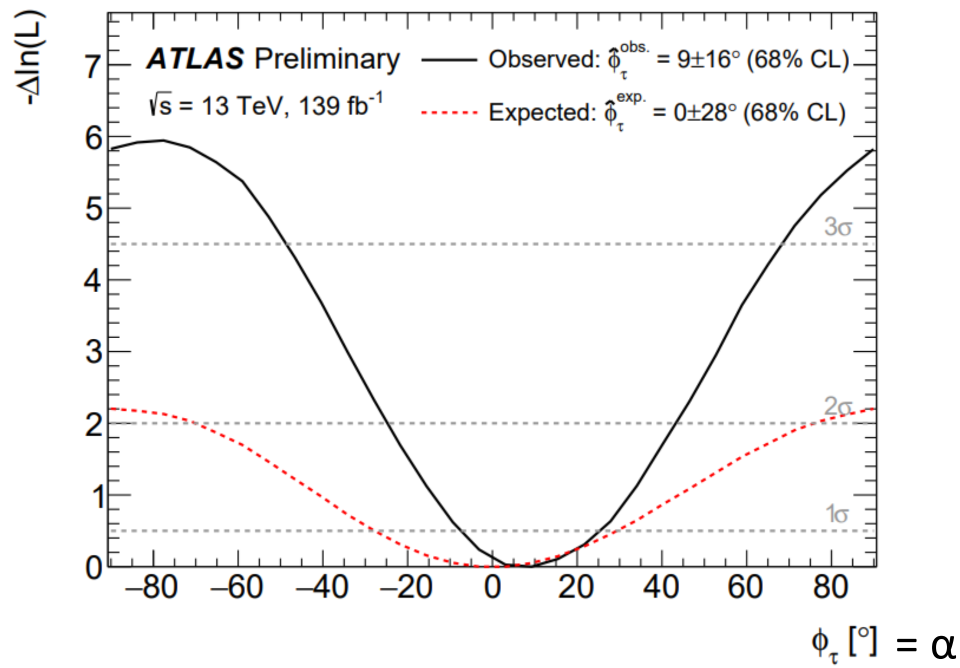
'High' SRs ($\tau_{lep}\tau_{had}$)





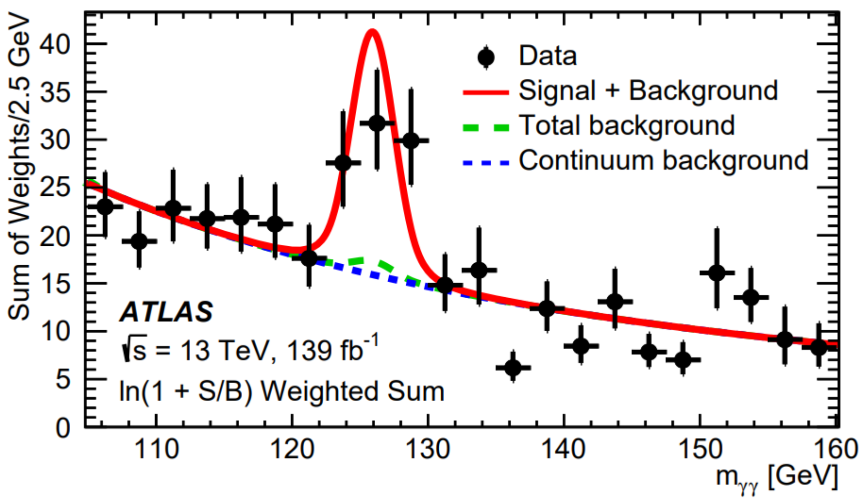
- Result:

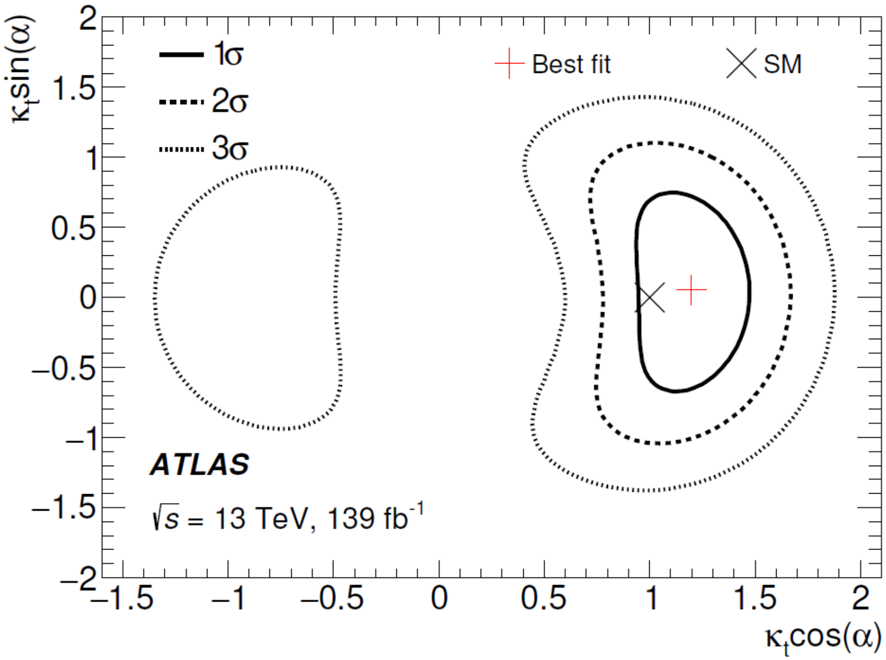
$\alpha = 9 \pm 16°$, pure CP-odd excluded at 3.4σ

  - Observed exclusion level of the pure CP-odd hypothesis is by 1.3σ higher than expectation due to statistical fluctuation
  - Uncertainties are completely dominated by statistics, while the leading systematics originates from jet calibrations

■ CP on Htt vertex with $t(\bar{t})H$ production

Phys. Rev. Lett. 125 (2020) 061802





- $t(\bar{t})H(\rightarrow \gamma\gamma)$ allows to extract clean signal events
  - Signal significance is >5σ → Good statistics to measure CP!
- Obtained result:

$|\alpha| > 43°$ excluded at 95% CL, pure CP-odd excluded at 3.9σ

  - Interesting to perform the CP measurement in the H-t interaction using other channels

CP on Htt vertex with $t(\bar{t})H$ production

ATLAS-CONF-2022-016

- $t \to bW(\to \ell\nu\nu)$
- $t \to bW(\to \ell\nu\nu)$
- $H \to bb$

- $t \to bW(\to \ell\nu\nu)$
- $t \to bW(\to qq)$
- $H \to bb$

Single large jet for the boosted category

Channel	Jet selection	Fit variable
Dilepton	≥4 jets; at least 4 are b-tagged	b_4
ℓ+jets	≥6 jets; at least 4 are b-tagged	b_2
ℓ+jets (boosted)	At least one boosted Higgs cand. ≥4 jets; at least 2 are b-tagged	BDT

CP-sensitive observables

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

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

$\vec{p}_{1(2)}$: momentum of leading (subleading) top
$\hat{n}$: unit vector to the beamline

- Analysis designed based on the $t(\bar{t})H(\to bb)$ cross-section measurement arXiv:2111.06712 (accepted by JHEP)
  - Large statistics thanks to BR($H \to bb$) = 58%, but controlling backgrounds from $t\bar{t}$ + heavy-flavour jets is important
- Sensitivity of the variables to CP is different depending on the SRs
  - Different variables are chosen for different channels

■ CP on Htt vertex with $t(\bar{t})H$ production

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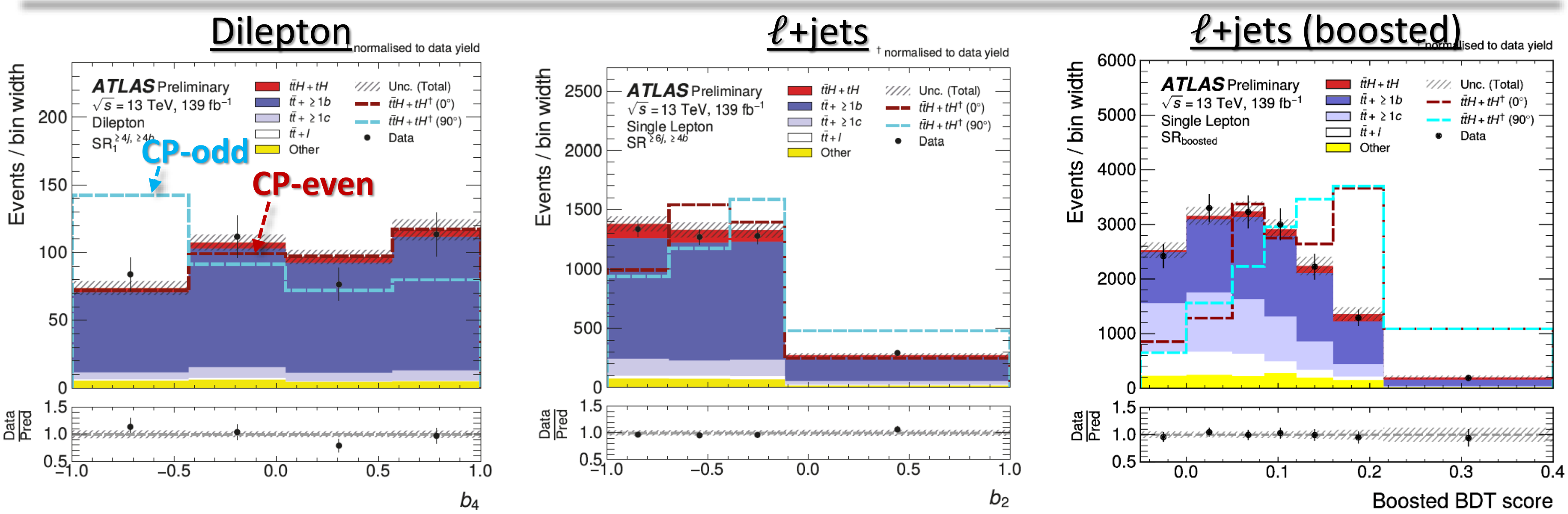


- Result

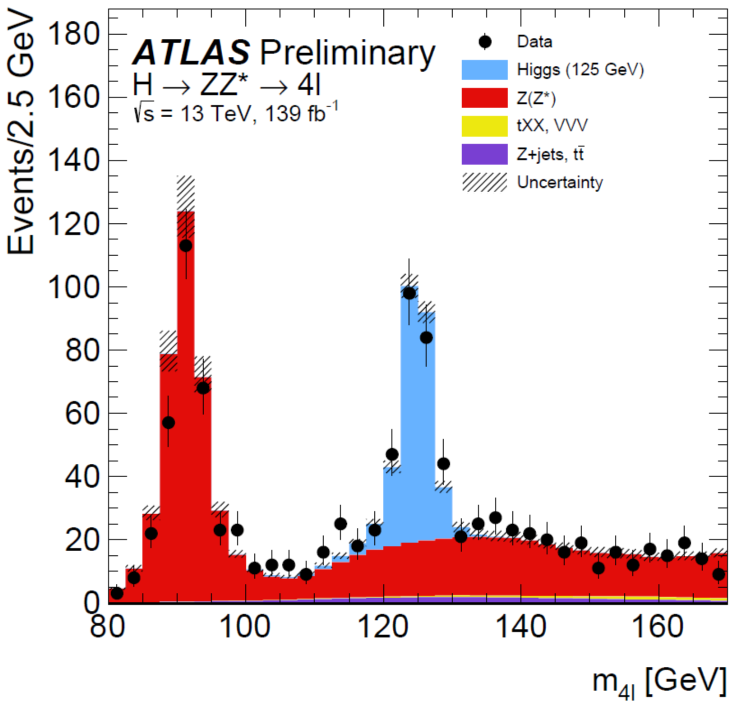
α = 11^{+55}_{-77}°, pure CP-odd excluded at 1.2σ

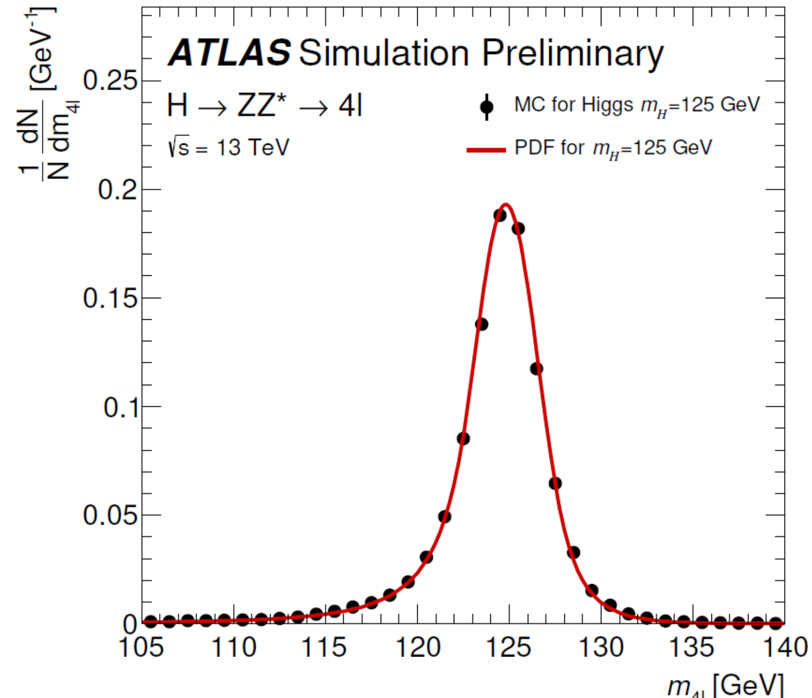
- The error dominated by systematics arising from the $t\bar{t}$ + HF modelling, while the statistics is also important to reduce the uncertainties

$t\bar{t} + \geq 1\ b$ modelling	$^{+40}_{-55}$ °
$t\bar{t} + \geq 1\ c$ modelling	$^{+7}_{-12}$ °
Signal normalisation (through correlation to α)	$^{+18}_{-35}$ °
Statistical error	$^{+34}_{-51}$ °

■ Higgs boson mass

ATLAS-CONF-2020-005



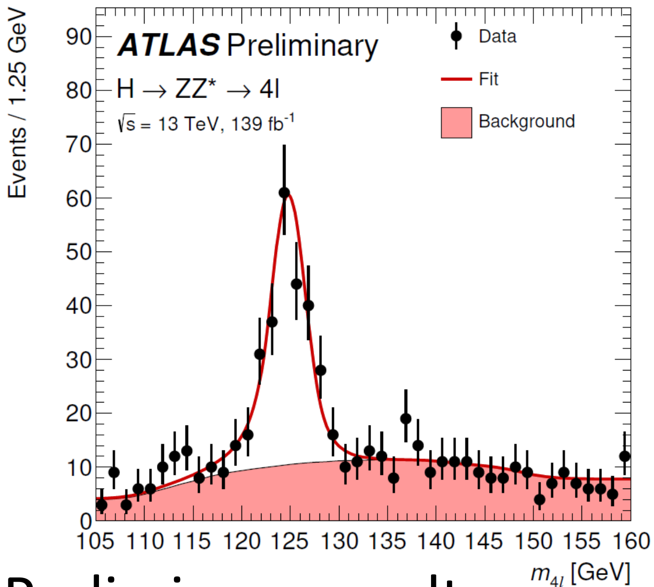


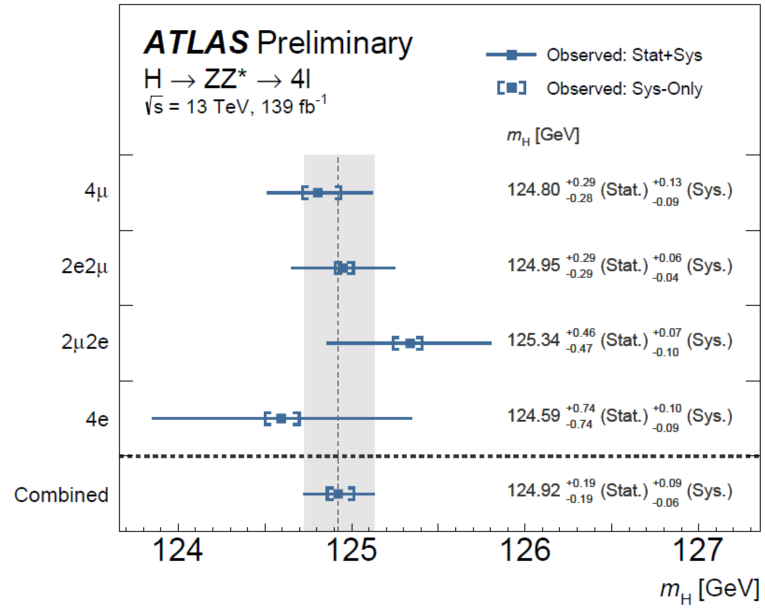
- Mass measurement using $H \to ZZ^{*}(\to 4\ell$, where $\ell = e, \mu)$
  - ☺ Good mass resolution and low background
  - ☹ Small branching fraction: BF($H \to ZZ^{*} \to 4\ell$) = 0.011%

    → 314 events observed in the SR
- Constraints of leading $m_{\ell\ell}$ to m_Z improves the resolution by 17%
- Signal shape modelled with double-sided Crystal Ball function

■ Higgs boson mass

ATLAS-CONF-2020-005





- Preliminary result:

  $124.92 \pm 0.19\ (\mathrm{stat})\ ^{+0.09}_{-0.06}\ (\mathrm{syst})\ \mathrm{GeV}$

  – Precision of 0.16%!
  – More data in Run 3 will allow us more precise measurement

- $H \to \gamma\gamma$ is another golden channel for mass measurement
  – The latest result with 36.1 fb^{-1}: Phys. Lett. B 784 (2018) 345

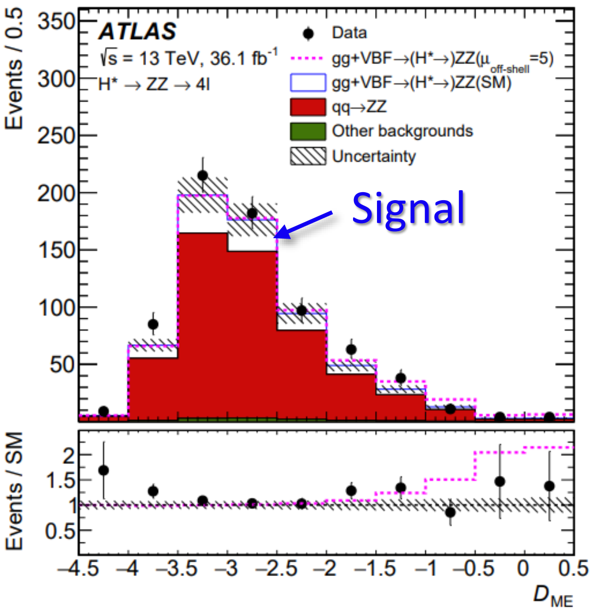
  $124.93 \pm 0.21\ (\mathrm{stat}) \pm 0.34\ (\mathrm{syst})$

  → Systematically limited
  - Calo. calibration
  - Detector materials

  → Analysis with 139 fb^{-1} is ongoing

Higgs boson decay width

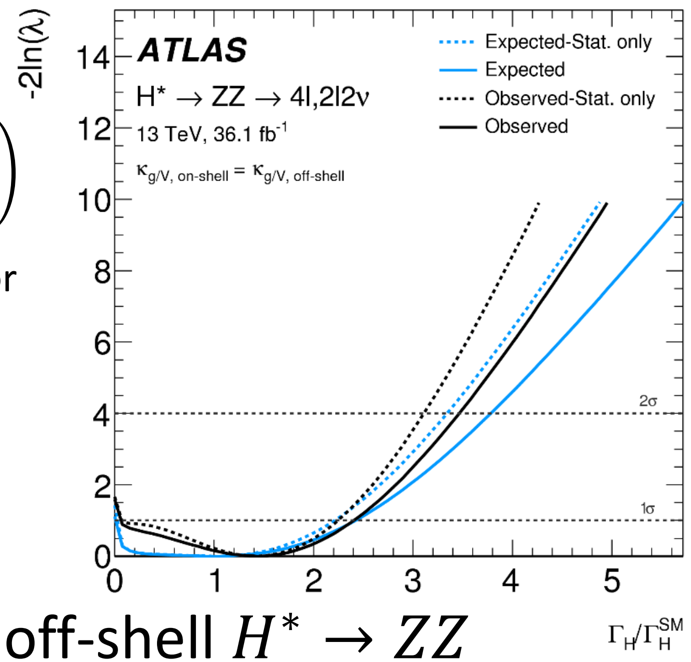
Phys. Lett. B 786 (2018) 223



$$D_{\mathrm{ME}} = \log_{10}\left(\frac{P_H}{P_{gg} + 0.1P_{q\bar{q}}}\right)$$

P: matrix element squared for the process denoted by the subscripts

- P_H: $H^* \to ZZ$
- P_{gg}: $gg \to ZZ$
- $P_{q\bar{q}}$: $q\bar{q} \to ZZ$



- Indirect determination possible by the off-shell $H^* \to ZZ$

$$\mu_{\mathrm{off-shell}}/\mu_{\mathrm{on-shell}} = \Gamma_H/\Gamma_H^{\mathrm{SM}}$$ → About 4.1 MeV

(With assumption that $\kappa_{\mathrm{off-shell}} = \kappa_{\mathrm{on-shell}}$)

LHC Higgs Xsec WG, arXiv:1610.07922

- Only the result with 36.1 fb^{-1} published
  - $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ are used

Γ_H < 14.4 MeV (< 15.2 MeV expected) at 95% CL

→ To be updated with full Run-2 dataset (139 fb^{-1})

Summary

- In Run 2, dataset equivalent to 8M Higgs bosons has been collected with the ATLAS detector
  - Various properties such as mass, CP, width, etc. are being investigated; so far all consistent with the SM expectations

    → Some more new results with 139 fb^{-1} are foreseen
  - These complicated measurements became possible also thanks to excellent performance of the LHC accelerator and ATLAS detector!

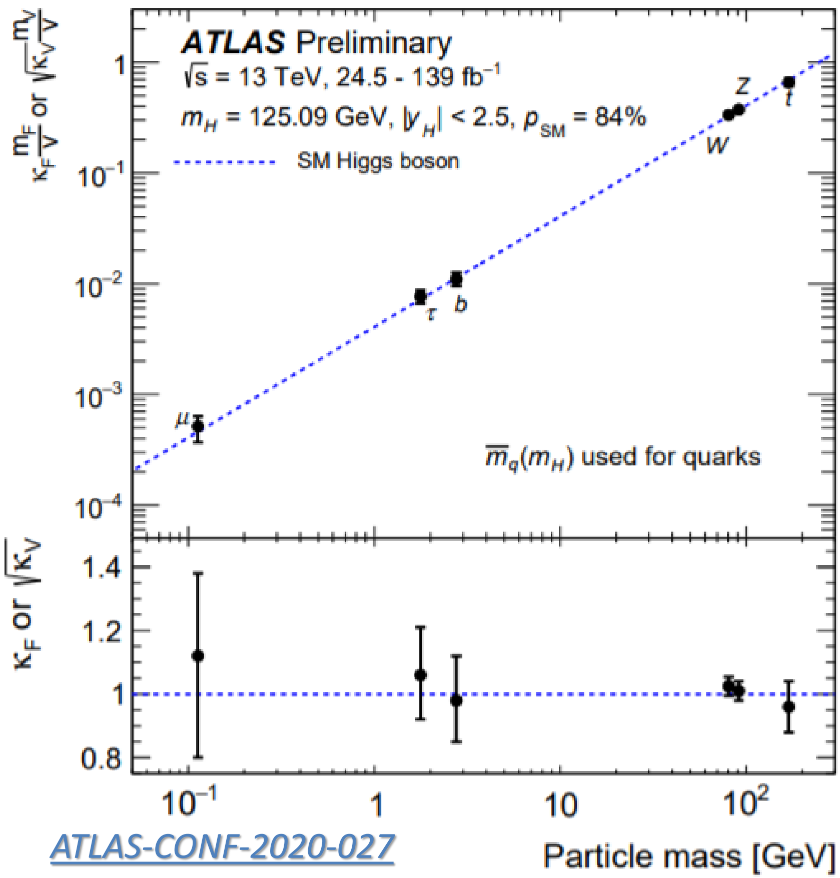
- Many of the measurements are statistically limited = Run 3 is important!
  - Run 3 operation has begun in April 2022; physics data-taking will come in about a month
  - Aiming for taking ~300 fb^{-1} by the end of 2025

Significant improvements on our understanding of the Higgs boson properties foreseen with fully exploiting the Run 2+3 data

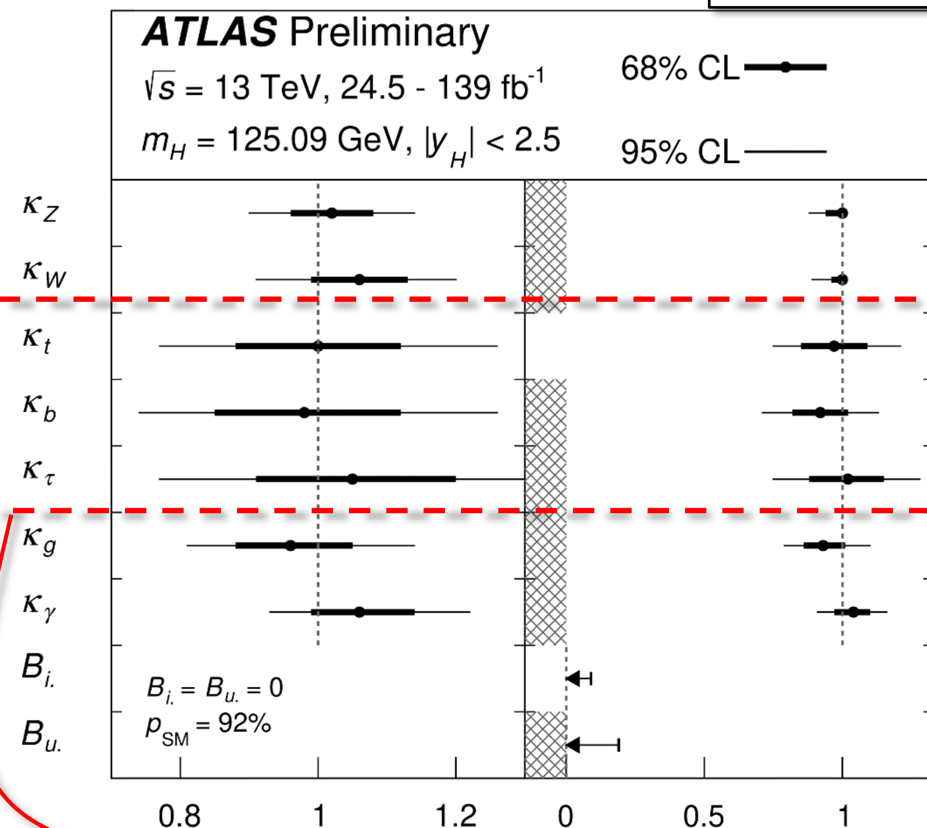
■ Combined coupling measurement

- Various different measurements are statistically combined
  - So far only a part of results with full Run-2 dataset are included
    → Will be updated soon

$$\kappa_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}}$$



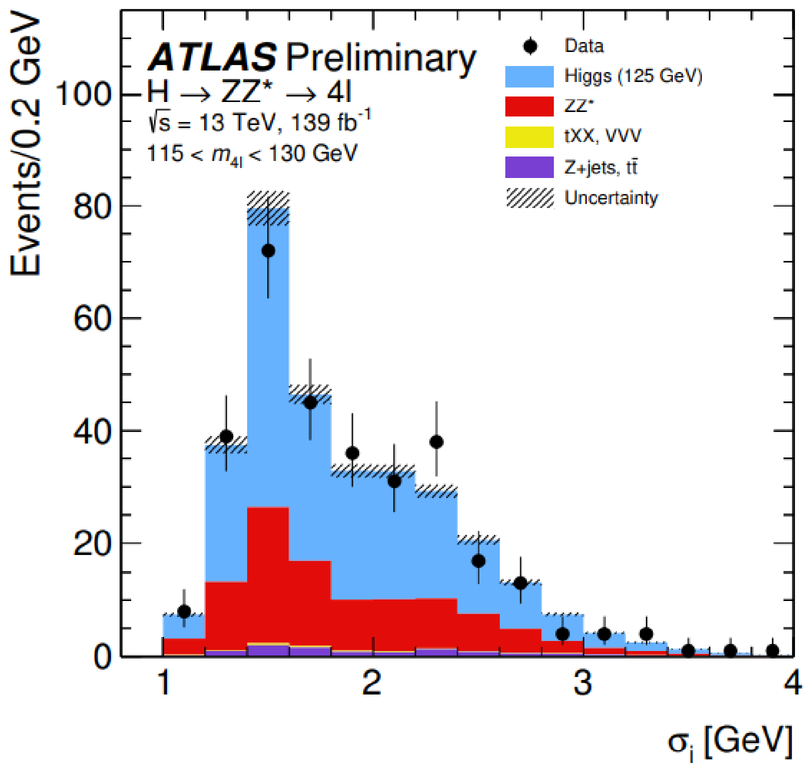
ATLAS-CONF-2020-027



κ for 3-gen fermions have been determined with less than 20%

■ Per-event resolution

[ATLAS-CONF-2020-005]

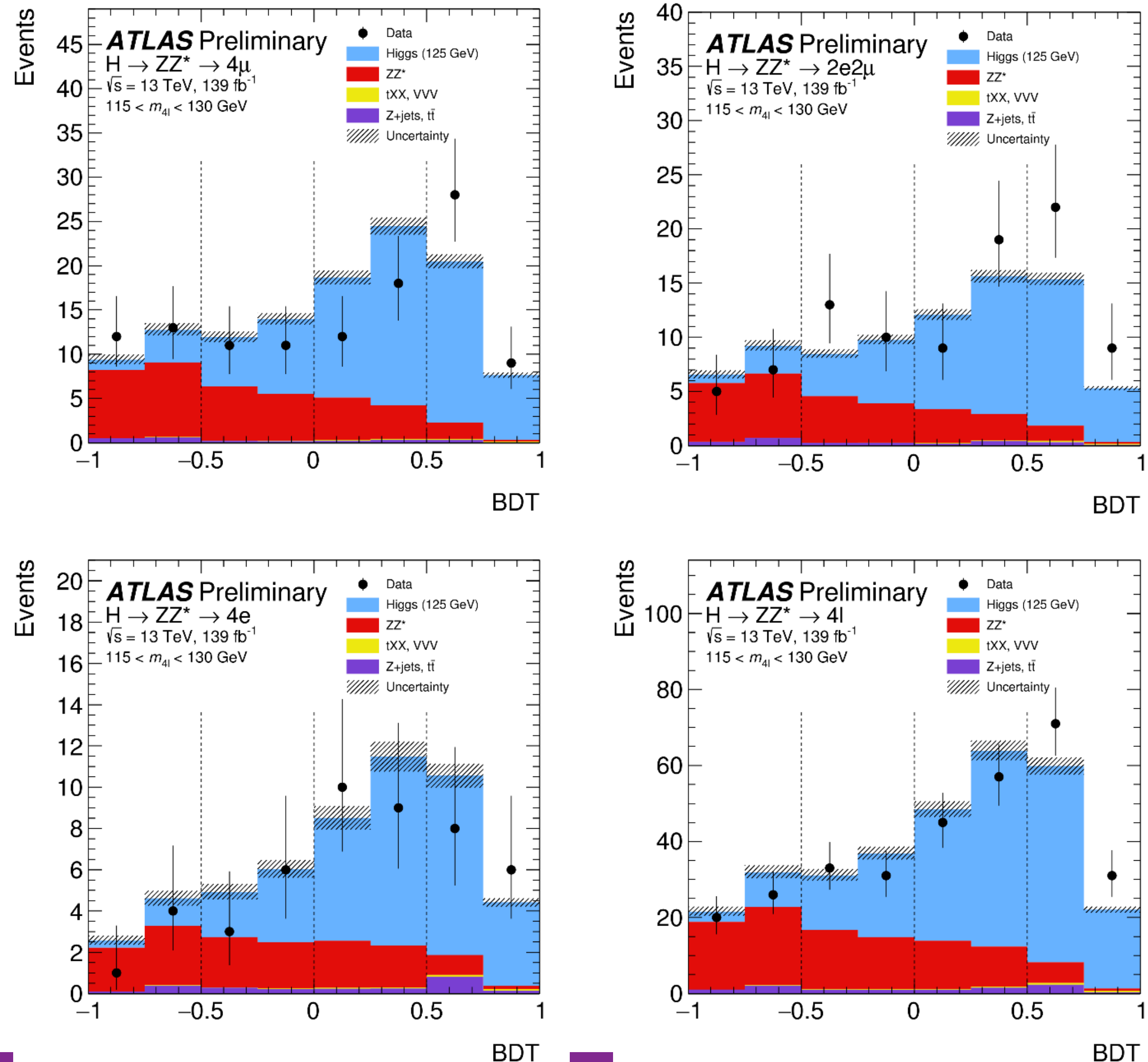


- Per-event mass resolution is estimated using a regression neural network
  - Inputs: lepton p_T, η, ϕ, constrained 4-momentum and uncertainties
  - Improved the total uncertainty by ~5%

■ BDT on mass measurement

ATLAS-CONF-2020-005

- Classification BDT is used to define SRs



■ Comparison: mass resolution

- Mass resolution is similar

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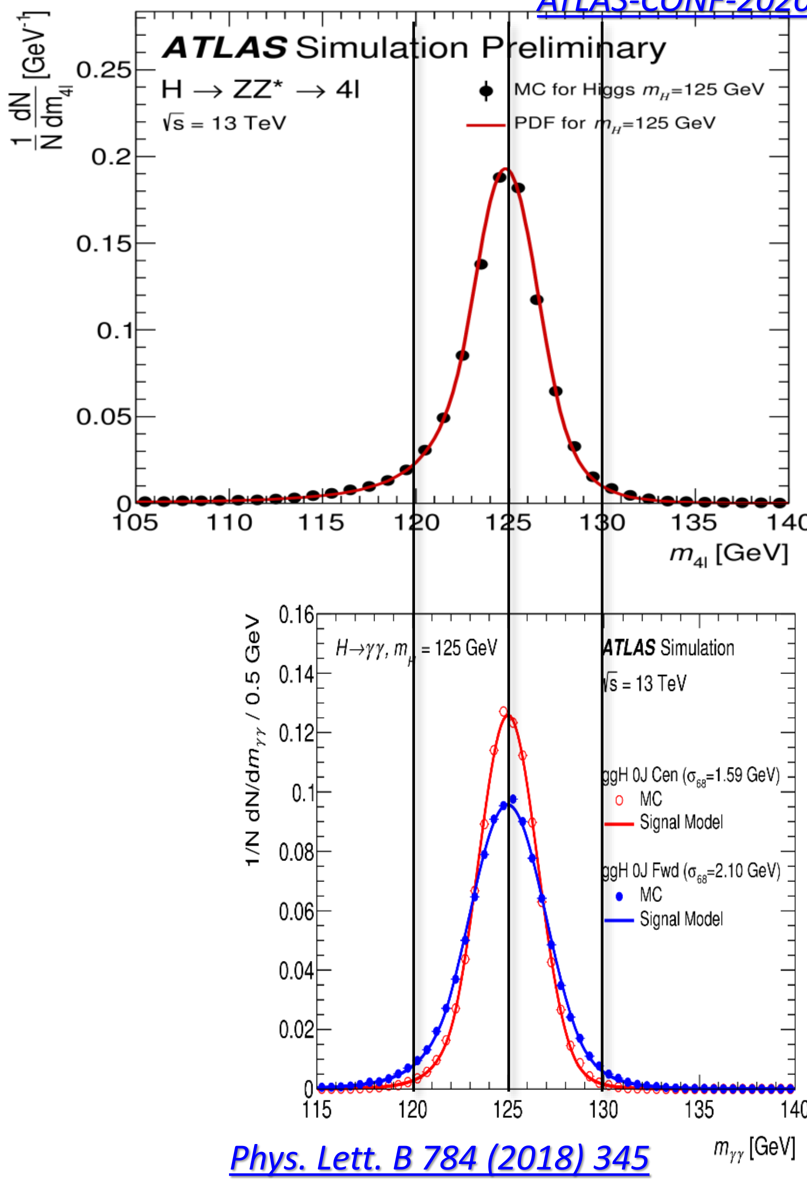


Phys. Lett. B 784 (2018) 345

Systematics on mass measurements

$H \to ZZ^*$ ATLAS-CONF-2020-005

Systematic Uncertainty	Impact (GeV)
Muon momentum scale	+0.08,−0.06
Electron energy scale	±0.02
Muon momentum resolution	±0.01
Muon sagitta bias correction	±0.01

(Non-closure of PDF: 0.006 GeV)

Total syst: $^{+0.09}_{-0.06}$
Statistical: $\pm$ 0.19

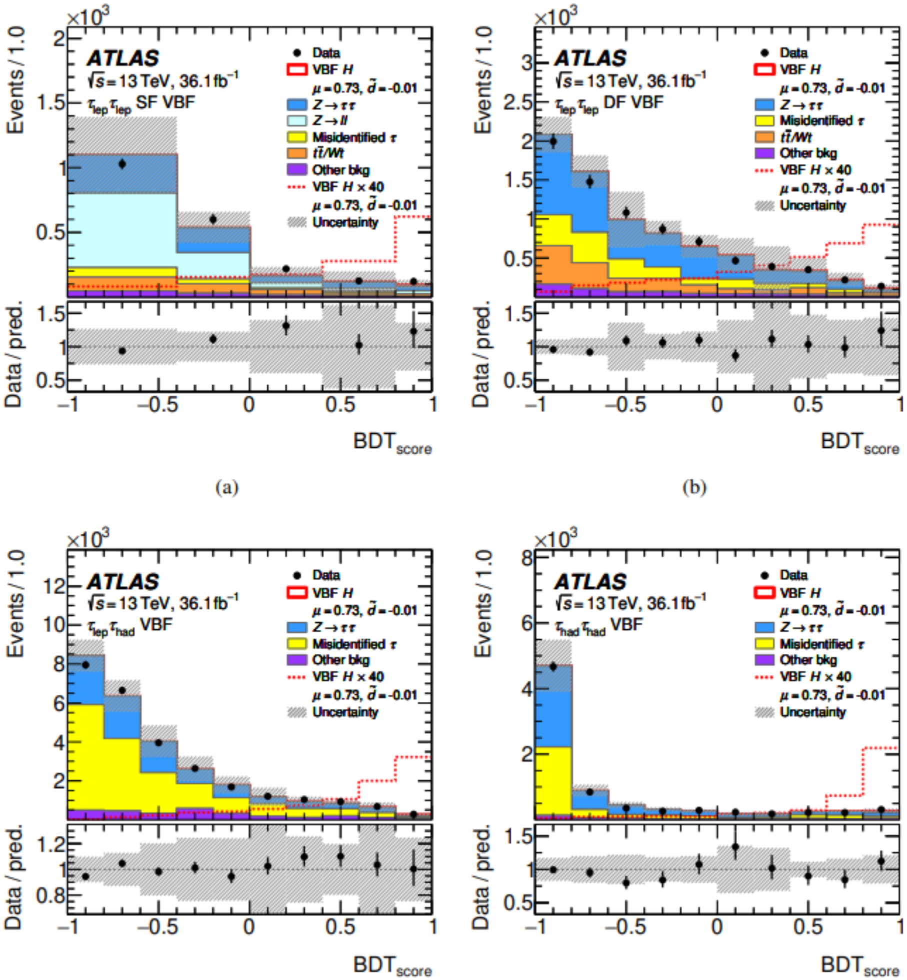
$H \to \gamma\gamma$ Phys. Lett. B 784 (2018) 345

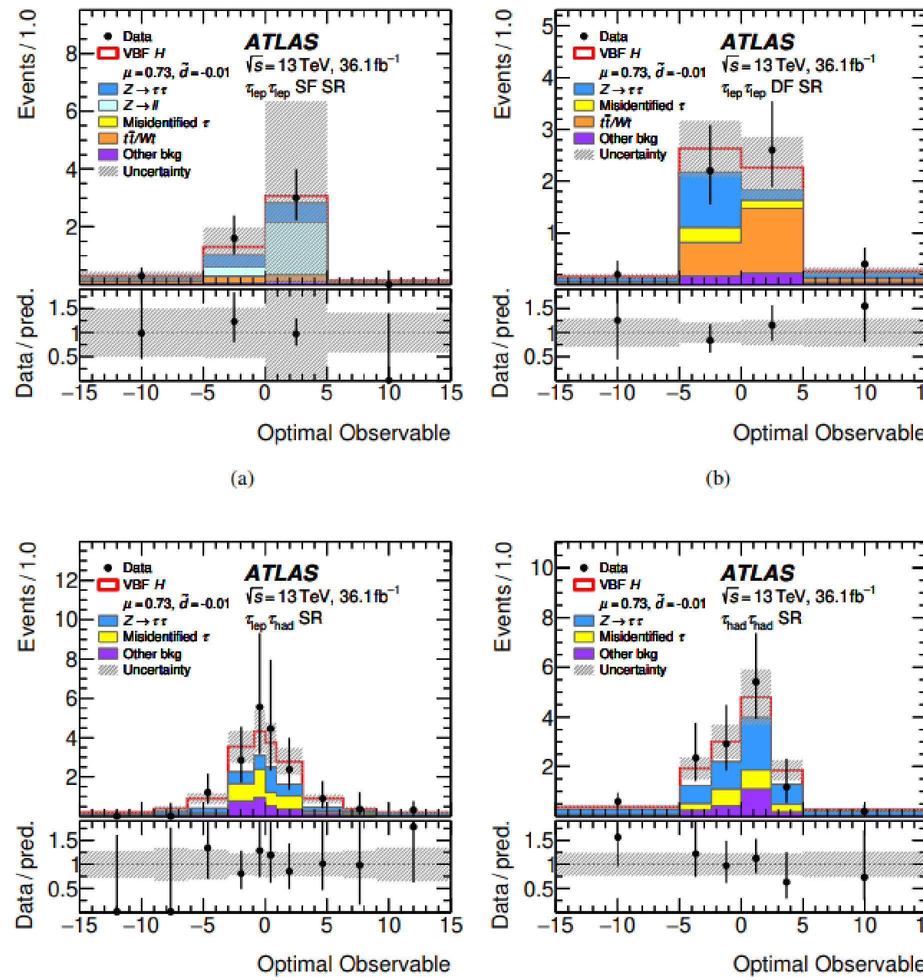
Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

Total syst: $\pm$ 0.34
Statistical: $\pm$ 0.21

■ VBF CP measurement with $H \to \tau\tau$

- Four signal categories depending on the tau decays





■ Decay CP $H \rightarrow \tau\tau$

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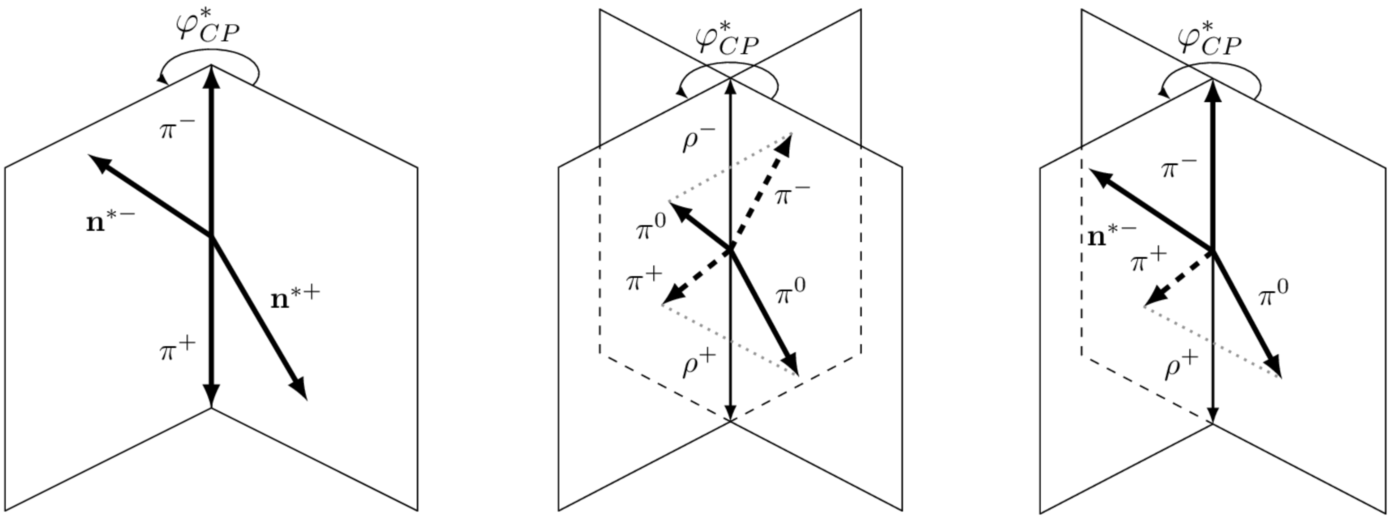
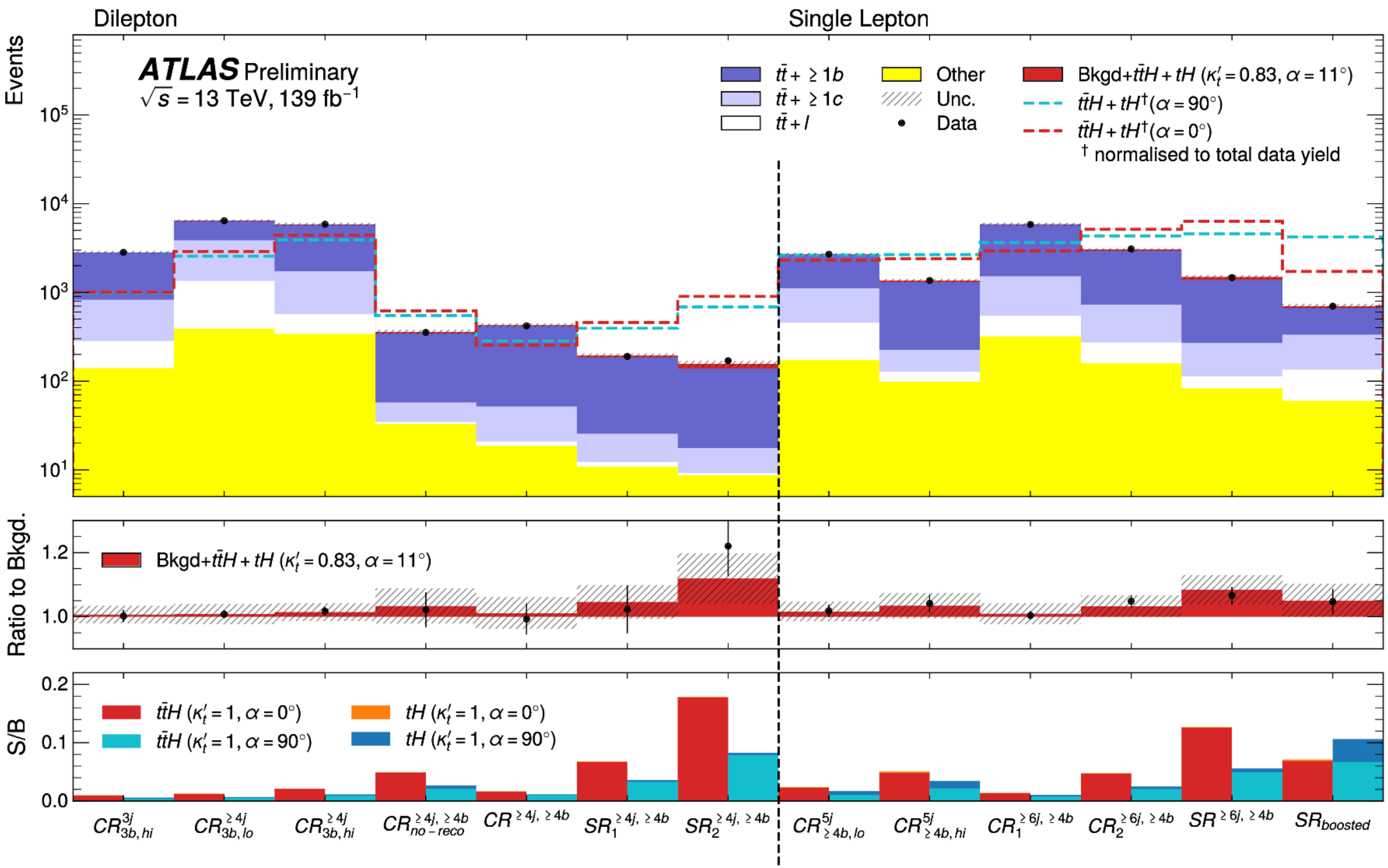


- Decay planes are defined depending on decay combinations
  - For the case of 1-prong with no neutral pions ($\tau^- \rightarrow \pi^- \nu_\tau$ and $\tau^- \rightarrow \ell^- \overline{\nu_\ell} \nu_\tau$), IP vector is used to define the decay plane
- Sensitivity is slightly better in $\tau_{had}\tau_{had}$
  - $\tau_{had}\tau_{had}$: 1.71σ (expected)
  - $\tau_{lep}\tau_{had}$: 1.14σ (expected)

■ CP measurement with $t(\bar{t})H(\rightarrow bb)$

ATLAS-CONF-2022-016

- 4 SRs and 9 CRs in total



■ cosα vs sinα

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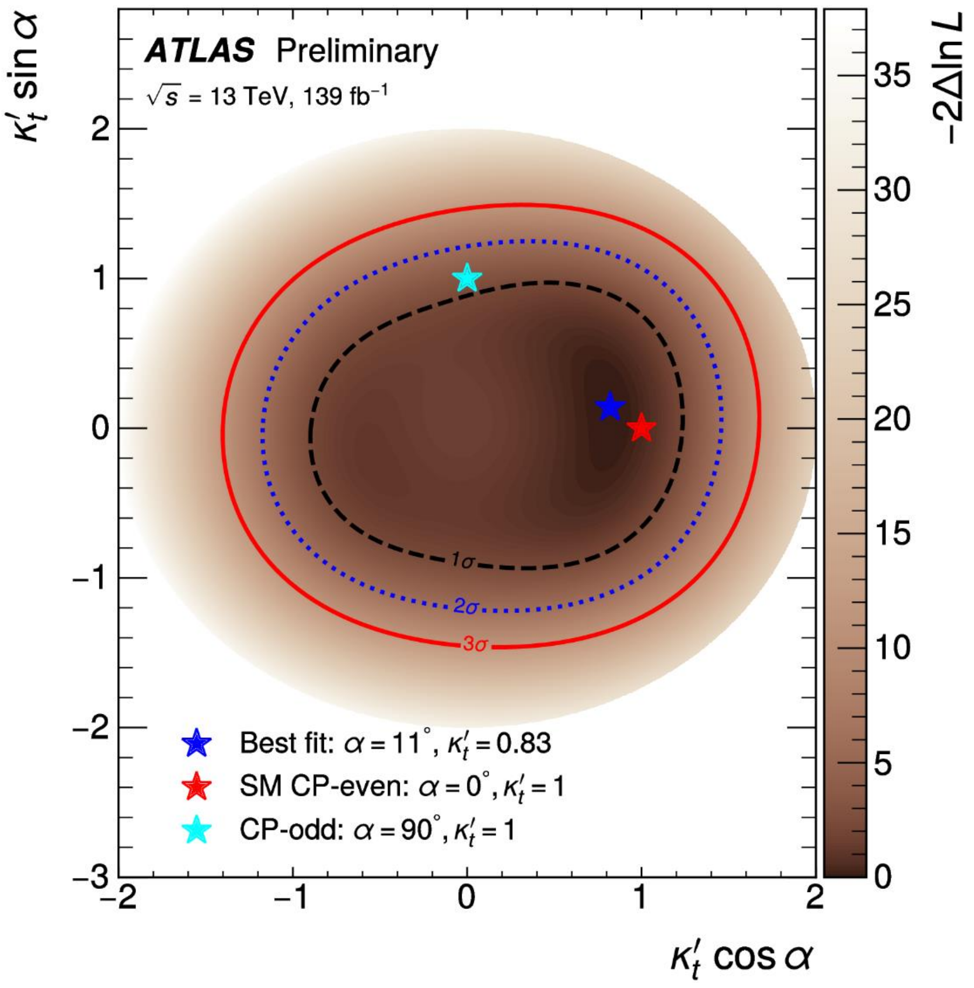

■ Off-shell H→ZZ