technische universität dortmund

ATLAS EXPERIMENT

PUNCH 4NFDI

DFG Deutsche Forschungsgemeinschaft

Higgs Property Measurements

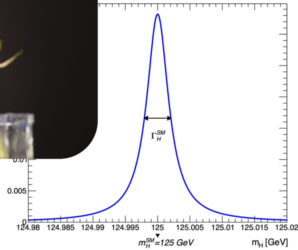
Higgs Hunting 2023
Paris

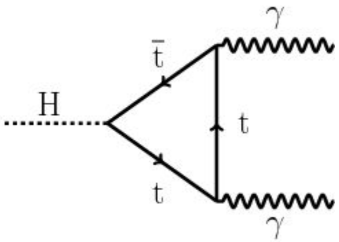
Carsten Burgard on behalf of the **ATLAS** collaboration

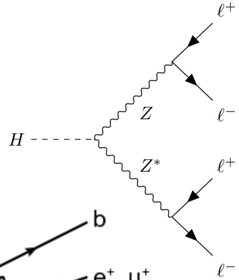
Introduction

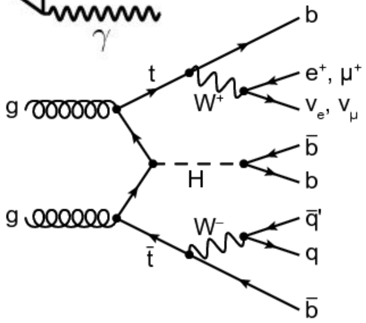
- Measurements of Higgs boson properties are one of our most promising windows into new physics
  - mass
  - width
  - CP
- Property measurements require clean signatures
  - H→ZZ→4ℓ
  - H→γγ
  - ttH associated production decaying to bb
  - VBF H→WW→eνμν
- Sensitivity can be greatly enhanced by combining results

background low or precisely modelled







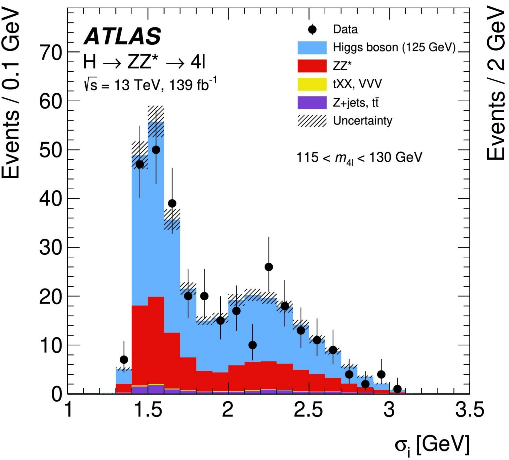


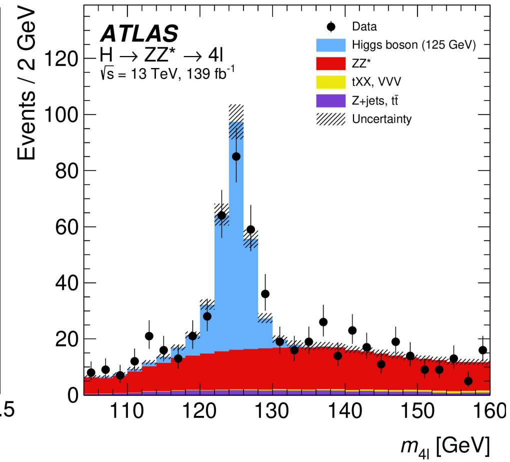
Chapter 1: Mass

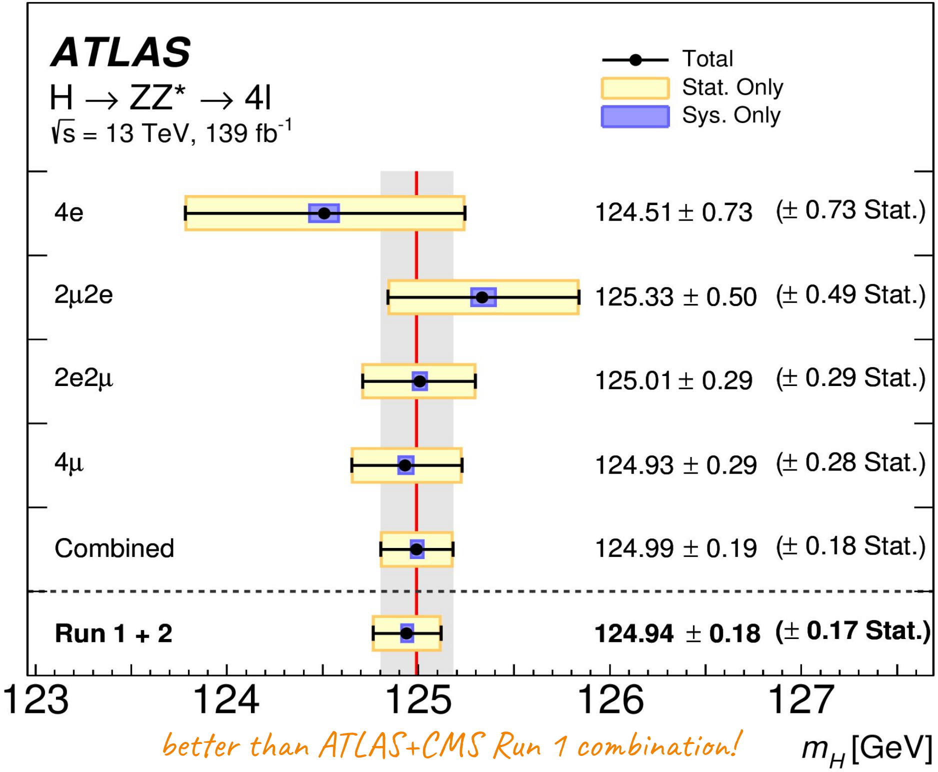
Measuring the Higgs mass with H→4ℓ

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

- 313 candidates in $115<m_{4\ell}<130$ GeV
- additional discrimination with DNN
  - based on p_T & η & ME discriminant
- estimation of per-event resolution using quantile regression neural network







better than ATLAS+CMS Run 1 combination!

doi.org/10.1016/j.physletb.2023.137880

Measuring the Higgs mass with H→γγ

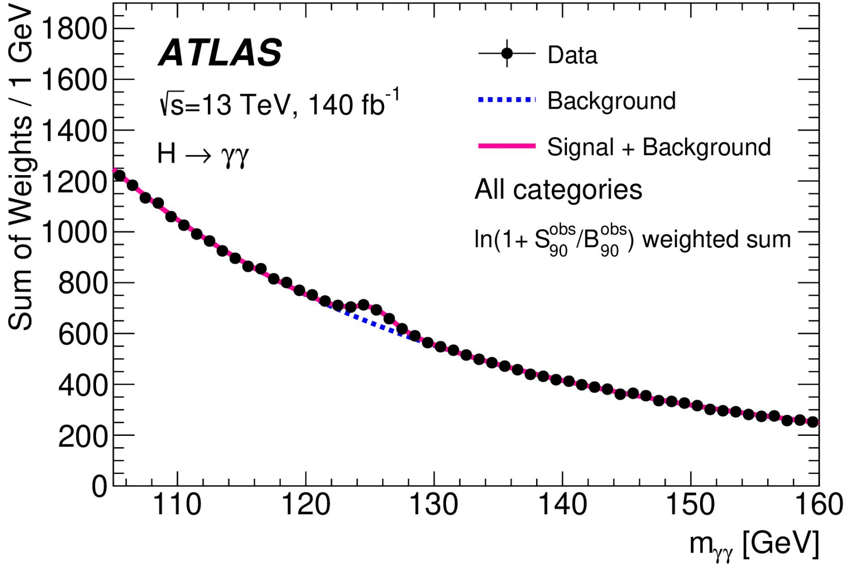
new

Category	$\sigma_{68}^{\gamma\gamma}$ [GeV]
U, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.10
U, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.38
U, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.47
U, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.24
U, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.52
U, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.75
U, Endcap	1.90
C, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.17
C, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.51
C, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.68
C, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.44
C, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.82
C, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.10
C, Endcap	2.23
Inclusive	1.82

- event selection based on cross-section measurement [2207.00348]
  - refined energy photon calibration →*leading uncertainty!*
  - reduction of E_T-dependent systematic

e/γ calib: CERN-EP-2023-128

Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^{\pm} \to \gamma$ 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



- Improved event categorization for mass measurement, precision increased by 17%

arXiv:2308.07216

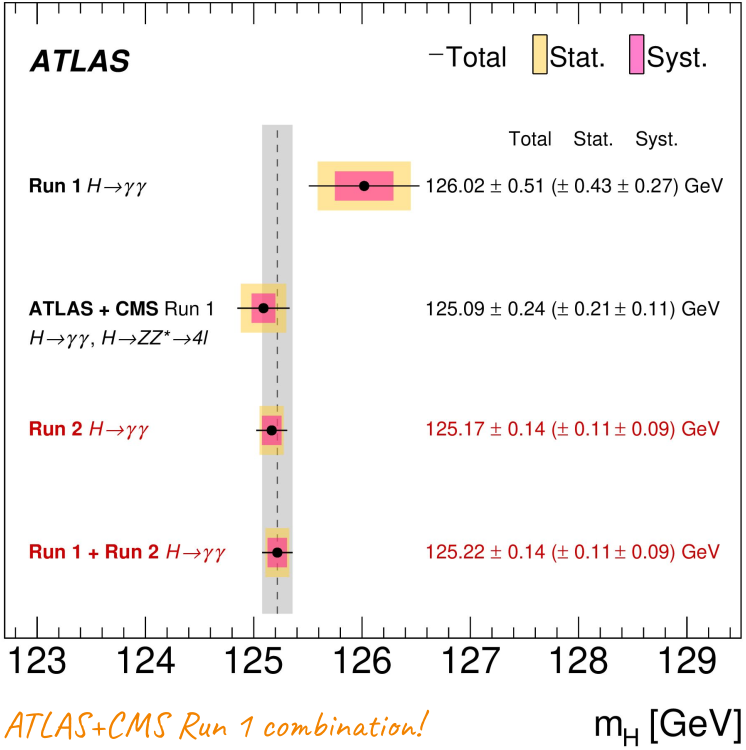
Measuring the Higgs mass with H→γγ

new

- signal modelled using double-sided CrystalBall shape fixed from simulation & parametric in m_H
- background model chosen empirically between exponential, power law, and exponentiated 2nd-order polynomial through χ^2>1%
  - shape parameters fit directly to data

Comparison of ATLAS H→γγ and H→4ℓ on 140 fb^{-1}

taken from arXiv:2308.04775

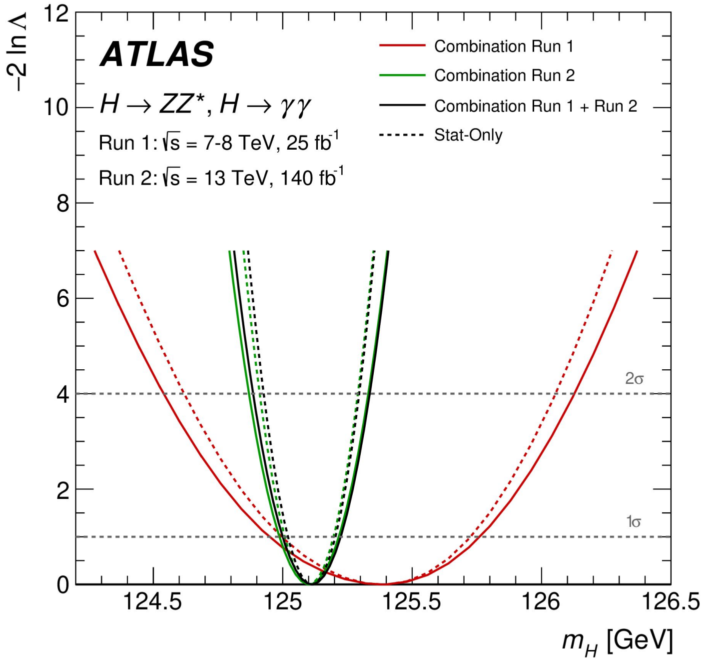


better than ATLAS+CMS Run 1 combination!

arXiv:2308.07216

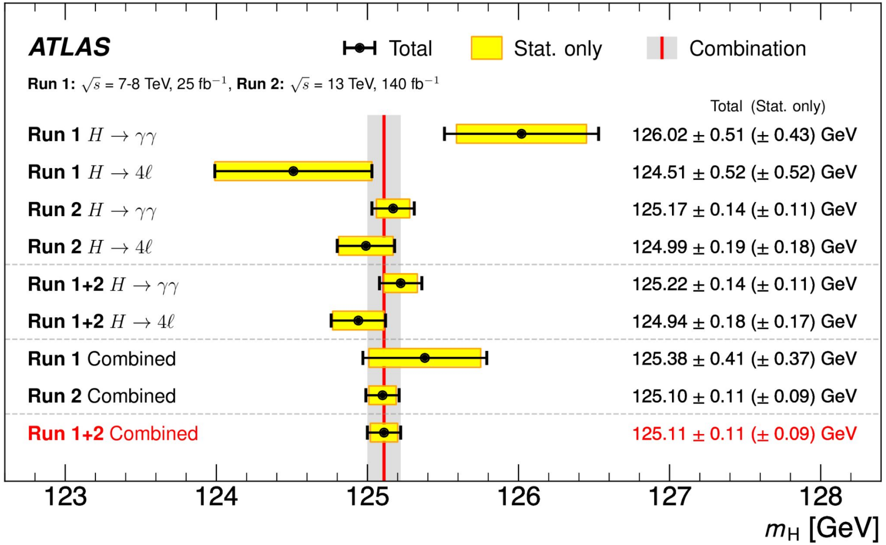
Combined mass measurement

- likelihood-level combination



Source	Systematic uncertainty on m_H [MeV]	
e/γ E_T-independent $Z \rightarrow ee$ calibration	44	≅as in Run 1
e/γ E_T-dependent electron energy scale	28	≅30% better
$H \rightarrow \gamma\gamma$ interference bias	17	
e/γ photon lateral shower shape	16	≅3x better
e/γ photon conversion reconstruction	15	≅3x better
e/γ energy resolution	11	≅2x better
$H \rightarrow \gamma\gamma$ background modelling	10	≅4x better
Muon momentum scale	8	≅20% better
All other systematic uncertainties	7	> 5x better

new



arXiv:2308.04775

Chapter 2: Width

Width measurement in H→ZZ

new

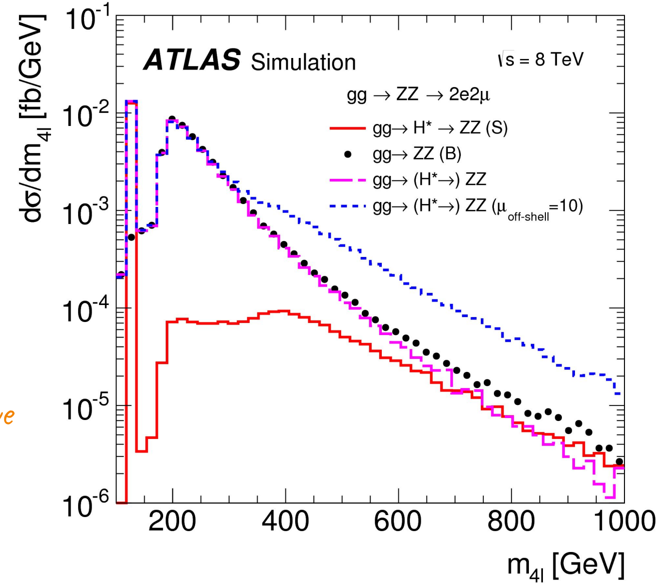
- cross-section for on-shell Higgs boson production scales with width Γ_H
  - the same is not true for off-shell

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H} \quad \text{vs.} \quad \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m^2_{ZZ}}$$

- measure on- and off-shell signal to infer width
- decompose cross-section in off-shell SR into signal and background

$$\sigma = \sigma_{bkg} + \mu_{off}\sigma_{sig} + \sqrt{\mu_{off}}\sigma_{int}$$

in practice, interference is negative contribution on total gg→ZZ

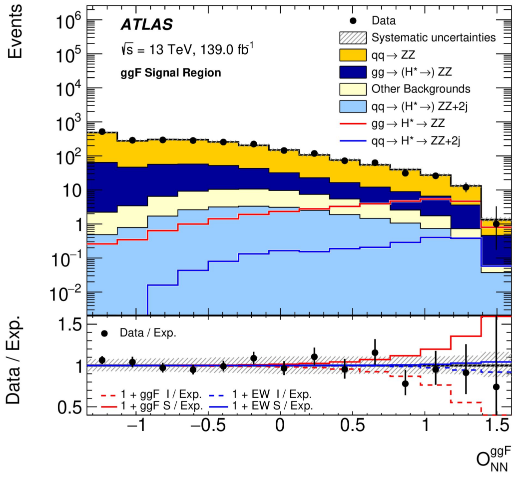


- combined with on-shell for measurement of μ_{on} and μ_{off}
  - use H→4ℓ and H→2ℓ2ν events for enhanced sensitivity

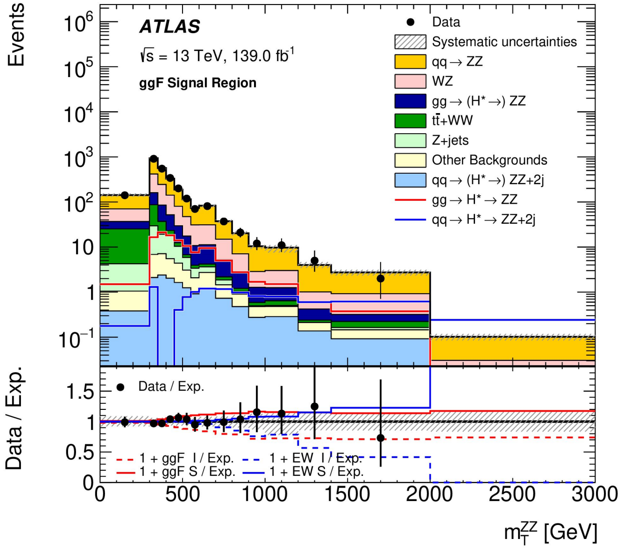
Width measurement in H→ZZ

- select off-shell H→4ℓ events with $m_{4\ell}$>220 GeV (180 GeV for CRs)
  - ggF, EW and mixed SR
  - multi-class NN with probability-like output to construct discriminant

$$O_{NN} = \log_{10}\left(\frac{P_S}{P_B + P_{NI}}\right)$$



- select off-shell H→2ℓ2ν events based on E_T^{miss} & lepton angles
  - ggF, EW and mixed SR
  - mass-variable m_T^{ZZ}



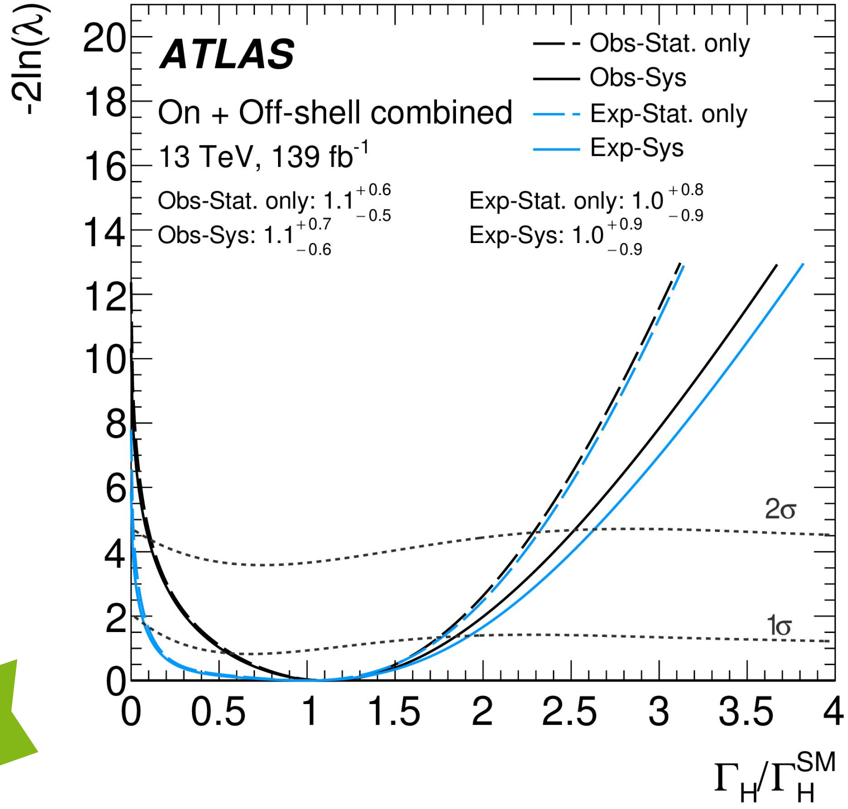
new

arxiv:1808.01191

Width measurement in H→ZZ

- Direct measurement of off-shell-higgs
  - 95% CL upper limit at μ = 2.4 (exp. 2.6)
  - significance observed 3.3 (exp. 2.2)
- Combination with on-shell analysis
  - correlate experimental uncertainties
  - decorrelate theory uncertainties between on- and off-shell
- measured $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
  - 95% C.L. interval $0.5<\Gamma_H<10.5$ MeV, expected $0.1<\Gamma_H<10.9$ MeV,
  - 1/2σ intervals determined with toys
  - asymptotic approximation not valid
- all findings compatible with SM

new

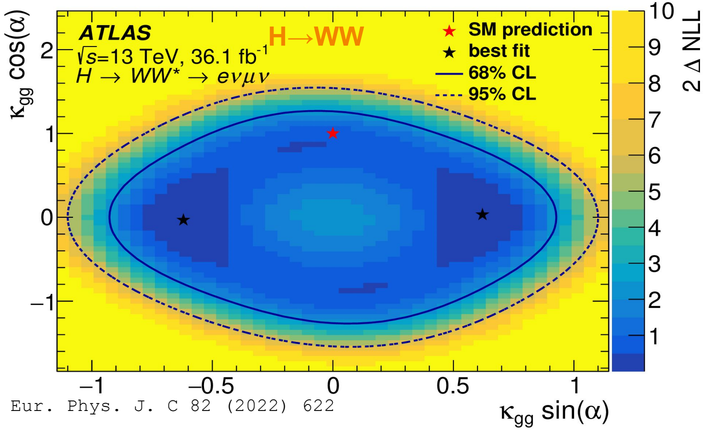


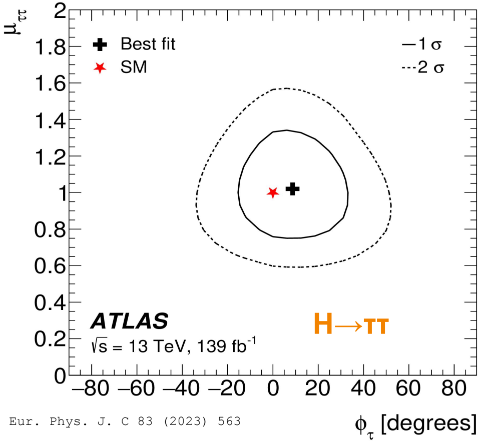
arxiv:1808.01191

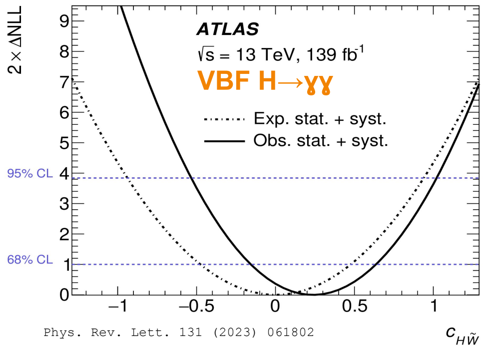
Chapter 3: CP

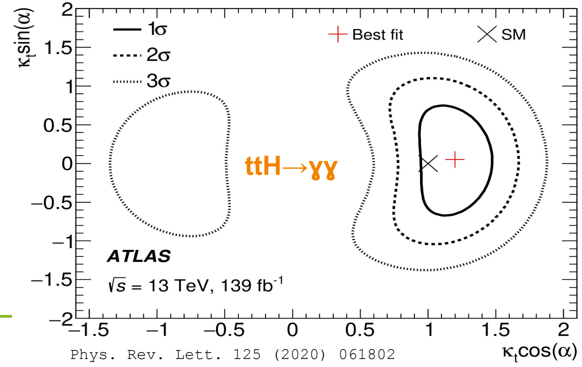
Previous ATLAS results on Higgs CP from LHC Run 2

- Plethora of CP measurements already available
  - top-yukawa coupling: ttH→γγ, ggF H→WW
  - HW coupling: VBF H→γγ
  - Hτ coupling: H→ττ
- new highlights:
  - VBF H→WW (EFT)
  - H→ZZ→4ℓ (CP)
  - t(t)tH associated production decaying to bb (CP)



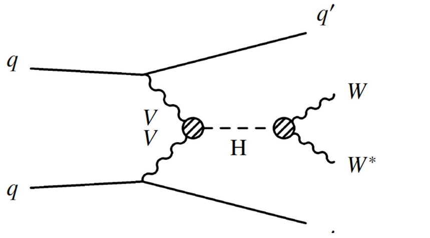




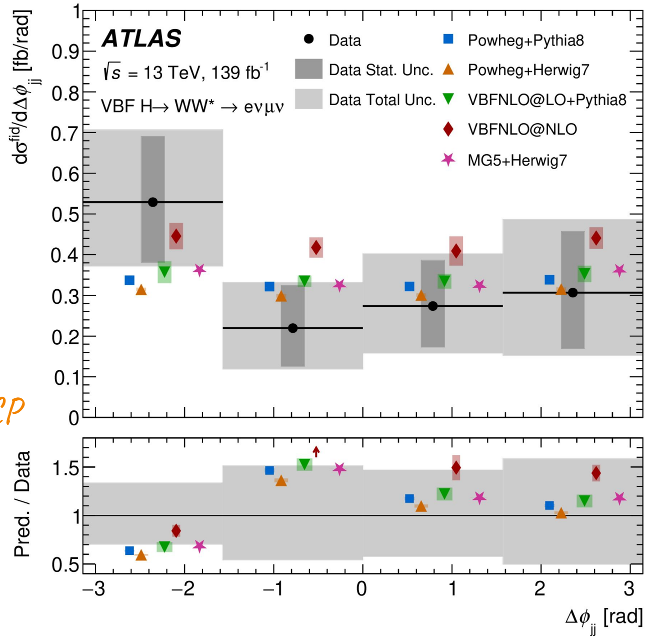


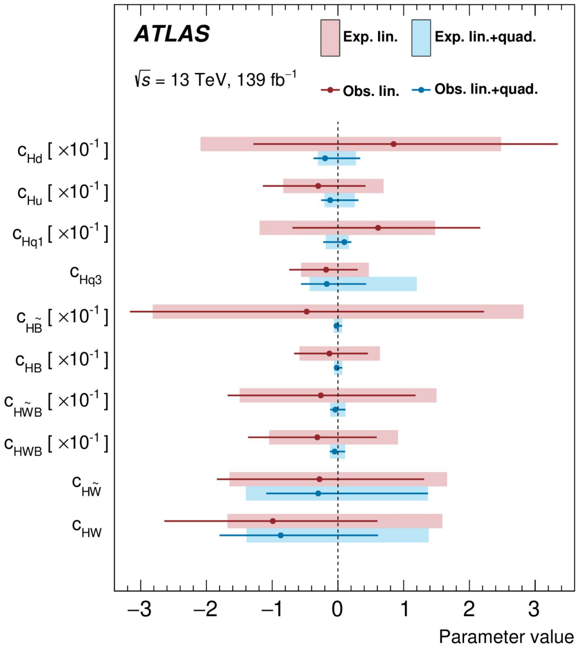
VBF H→WW

new



- leptonic W decays (trigger), select 1 DF OS pair
- 2 BDTs to enhance s/b: select VBF, reject top+VV
  - exploit VBF topology using m_{jj} and Δy_{jj}
  - bin SRs in both classifier outputs
  - independent ggF CR using third BDT
- profile LH unfolding to 13 observables
  - signed $\Delta\phi_{jj}$ *sensitive to CP*
- measure 3 CP-odd Wilson coefficients
  - no deviation found





arXiv:2304.03053

H→ZZ→4ℓ CP measurement

new

- Optimal observable based on matrix elements

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

- EFT-approach, targeting various CP-odd operators
  - only interference sensitive to CP
  - one OO constructed for each operator

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

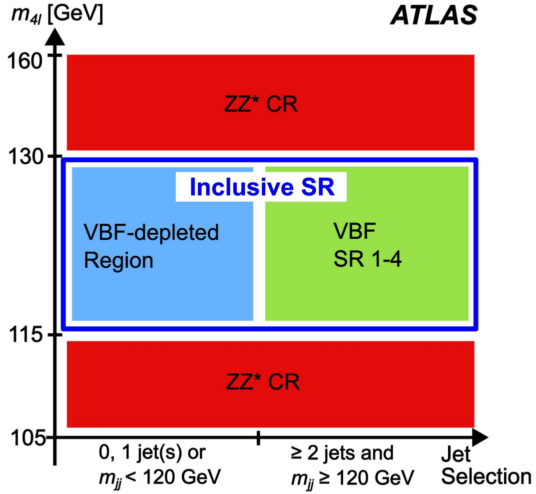
Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\widetilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\widetilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\widetilde{c}_{\gamma\gamma}$

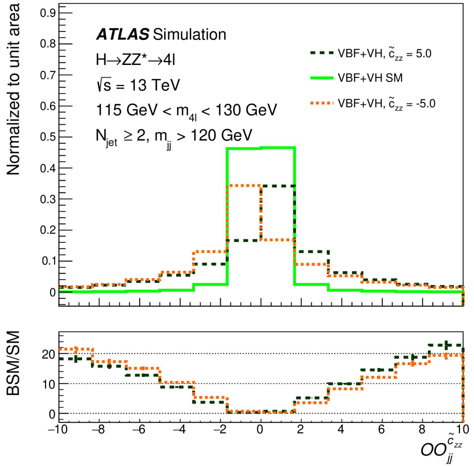
arxiv:2304.09612

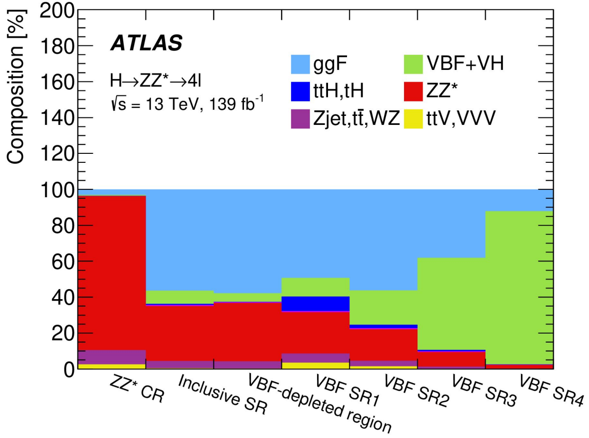
H→ZZ→4ℓ CP measurement

new

- Main background ZZ* (~30%)
  - normalized from data outside $m_{4\ell}$ window
- ≥2 jet: 3-class NN to distinguish VBF, VH and ggF
  - 2 regions high in ggF, 2 high in VBF
- Searching for CP violation in
  - production only
    using SR1-4
  - decay only
    using inclusive SR
  - production + decay
    using SR1-4 + depleted







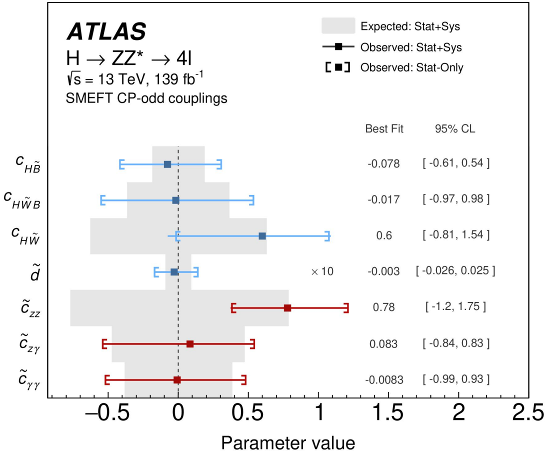
technische universität dortmund

arxiv:2304.09612

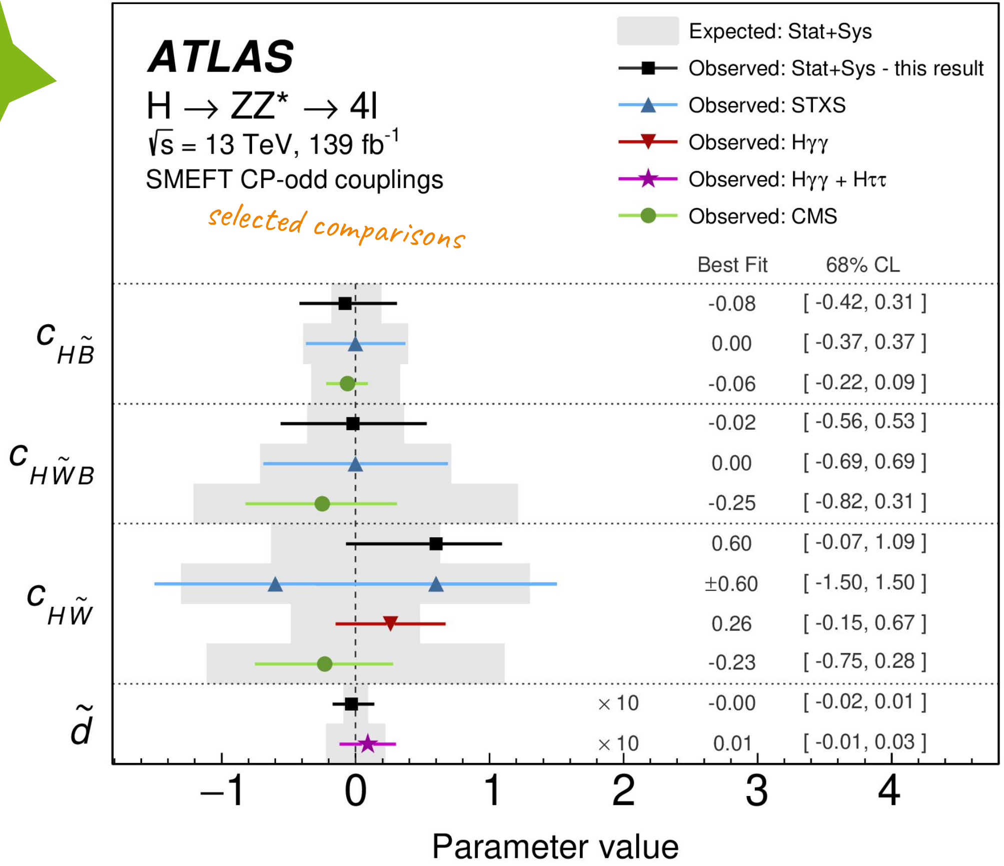
H→ZZ→4ℓ CP

- results from combined fit
  - compatible with SM
- competitive with H→γγ & H→ττ, STXS, CMS

all measured CP-odd coefficients



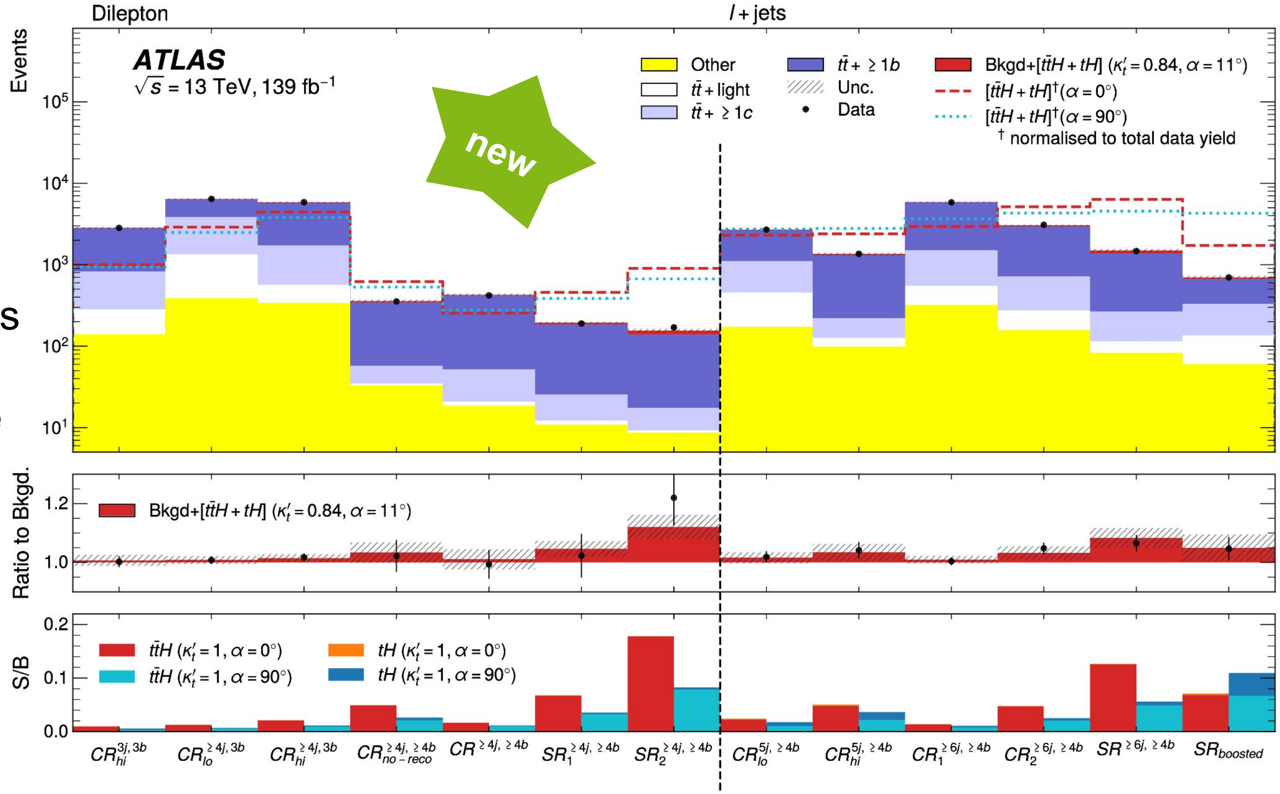
selected comparisons



arxiv:2304.09612

t(t)H→bb CP measurement

- multi-jet with b-tags
- many MVAs at work
  - NN: boosted Higgs
  - BDT: associate jets
    - Higgs vs. top
  - BDT: sig/bkg classes
    - SR vs. CR
- regions w. high/low true b-jet fractions through tight/loose tagging
- define CP-sensitive observable per region
- infer ν p_T from E_T^{miss}

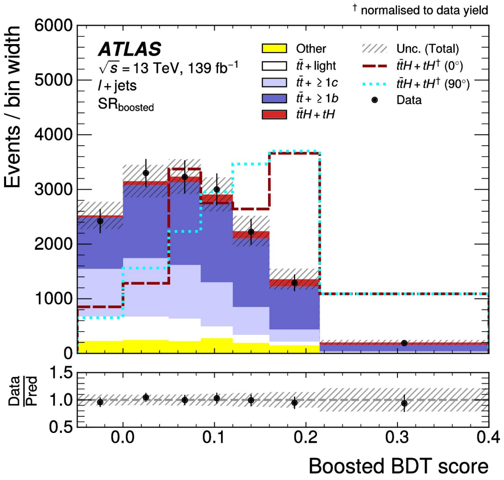


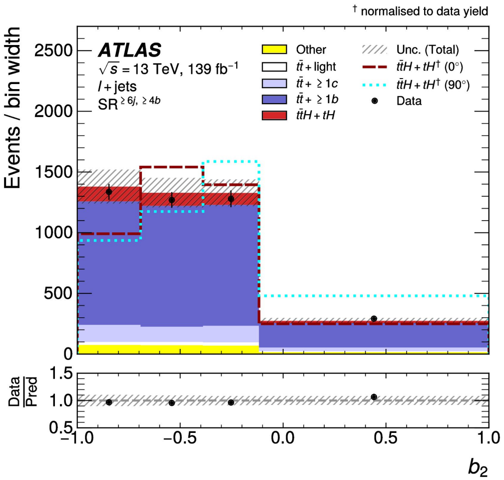
t(t)H→bb CP measurement

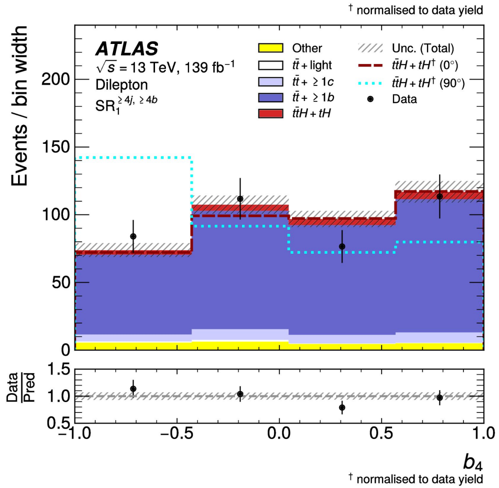
- boosted NN score, $\Delta\eta_{\ell\ell}$ as well as b_2 and b_4 constructed as CP-sensitive observables

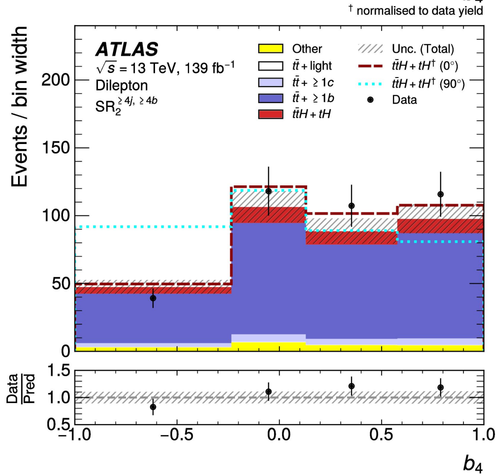
$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|} \quad b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|}$$

new







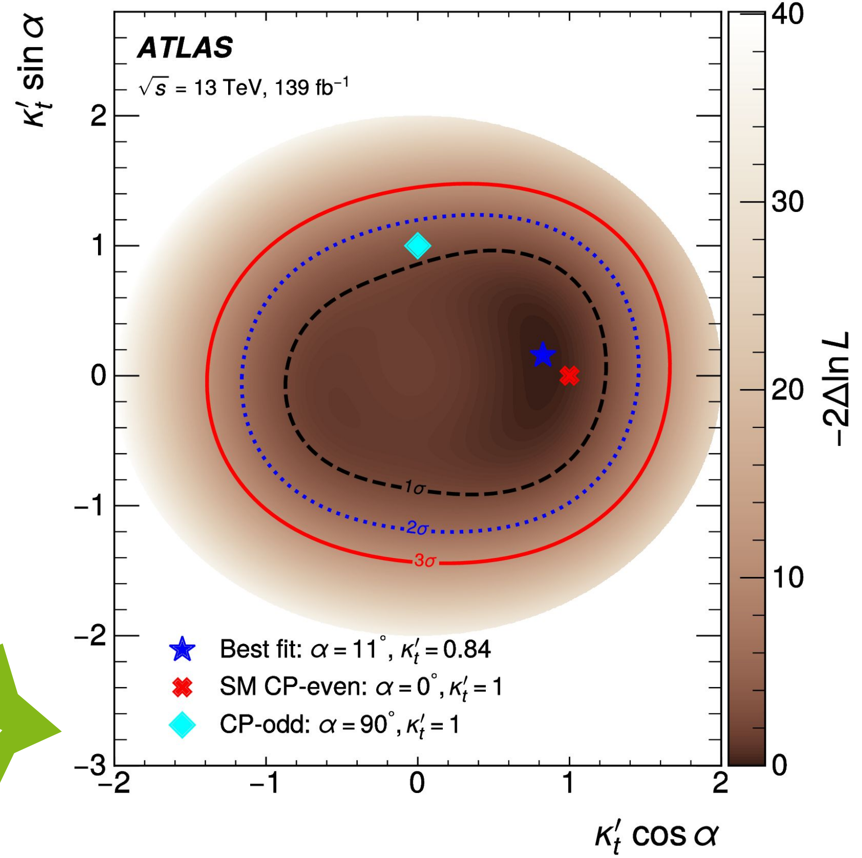


arxiv:2303.05974

t(t)H→bb CP measurement

- extracted via combined fit
  - coupling strength $\kappa_t = 0.84^{+0.3}_{-0.46}$
  - mixing angle $\alpha = 11°^{+52°}_{-73°}$
- compatible with SM (κ_t=1, α=0)
  - compatibility with cross-section measurement tested within 1σ

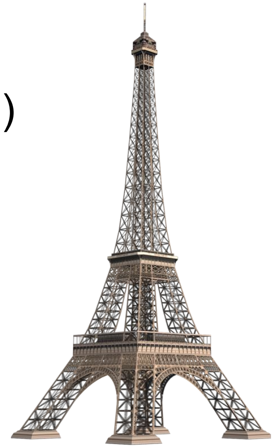
new



arxiv:2303.05974

Conclusions

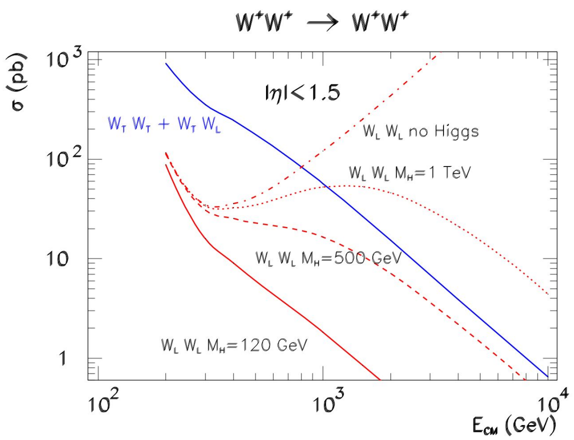
- ATLAS has produced a wide range of property measurements in LHC Run 2
  - mass: $H\to ZZ\to 4\ell$ and $H\to\gamma\gamma$
  - width: extension of $H\to ZZ$ to $2\ell 2\nu$ final states & into off-shell regime
  - CP: wide variety of channels, new: $H\to ZZ\to 4\ell$, t(t)t$H\to bb$, VBF $H\to WW$
- So far, no deviations from SM expectations observed
  - is it just a “boring old Higgs” after all?
  - don’t despair, many other interesting talks ahead
- Many great opportunities still untapped
  - off-shell measurements in other channels (e.g. $H\to WW$, last done in Run 1)
  - combined CP interpretation, maybe with our colleagues from CMS
  - powerful new analyses including Run 3 data



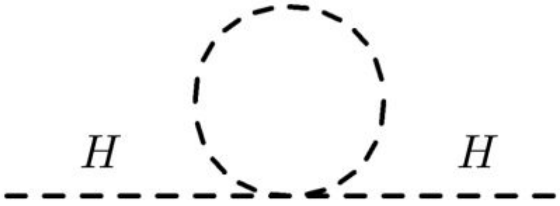
Backup

Why measure the mass?

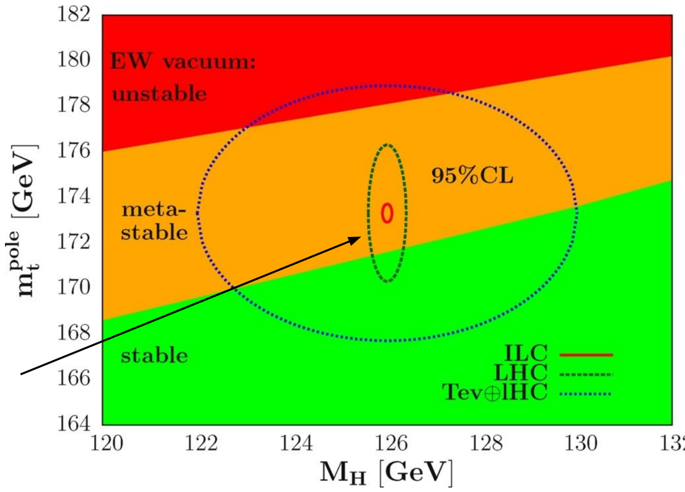
- Higg boson mass is free parameter of the theory
  - only unitarity constraints based on the WW cross-section
- several of the open questions of particle physics are intimately linked to the Higgs boson mass
  - quantum stability of the vacuum
  - hierarchy / fine tuning problem: how large are radiative corrections?
- Production cross-sections and decay branching ratios depend on the mass



arXiv:1412.8367v2



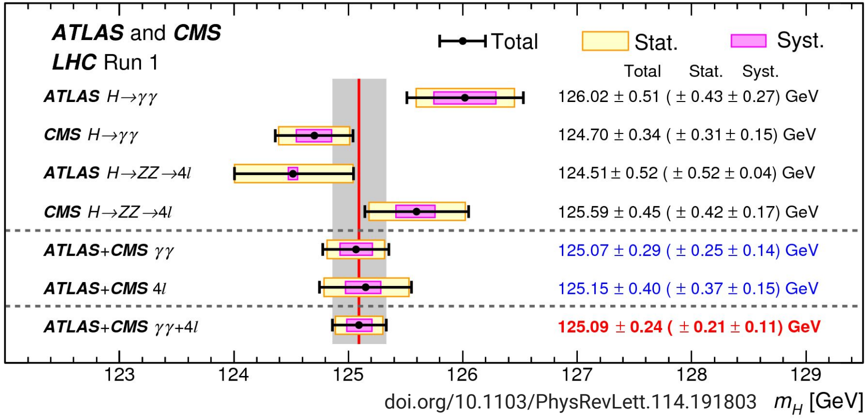
state of the art 2012



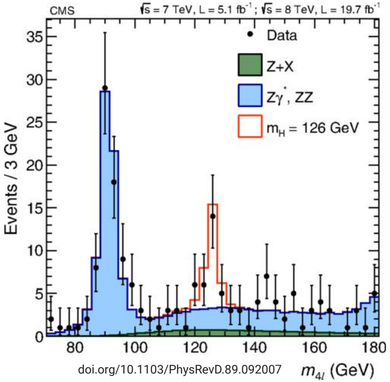
https://doi.org/10.1016/j.physletb.2012.08.024

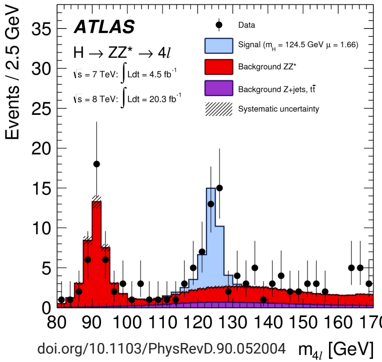
Where we are coming from

- Extensive efforts during LHC Run 1 from both ATLAS and CMS
- Most precise measurements of the Higgs boson mass up to that point

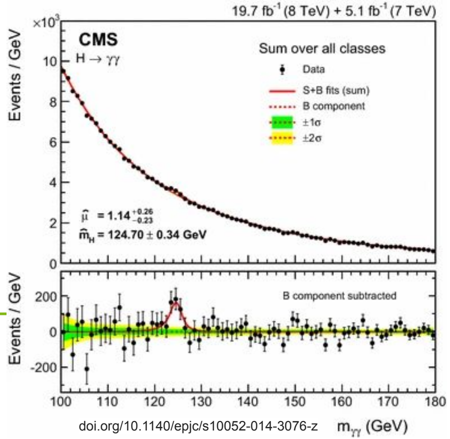


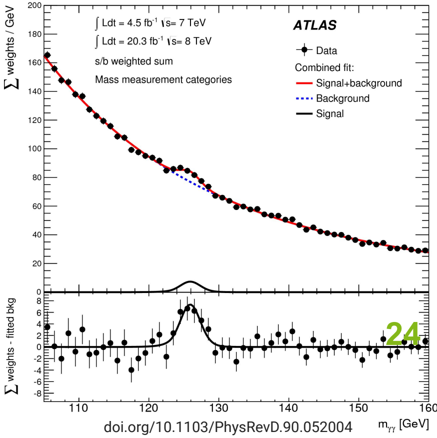
- $H \rightarrow ZZ \rightarrow 4\ell$: m_H approximate as $m_{4\ell}$
  - golden channel, low background





- $H \rightarrow \gamma\gamma$: m_H approximate as $m_{\gamma\gamma}$
  - peak on top of a smooth distribution





technische universität dortmund

Width measurement in H→ZZ

- allow for separate signal strengths for EW and ggF
- assume equality for width measurement

Process	ggF SR	Mixed SR	EW SR
$gg \to (H^* \to)ZZ$	341 ± 117	42.5 ± 14.9	11.8 ± 4.3
$gg \to H^* \to ZZ$	32.6 ± 9.07	3.68 ± 1.03	1.58 ± 0.47
$gg \to ZZ$	345 ± 119	43.0 ± 15.2	11.9 ± 4.4
$qq \to (H^* \to)ZZ + 2j$	23.2 ± 1.0	2.03 ± 0.16	9.89 ± 0.96
$qq \to ZZ$	1878 ± 151	135 ± 23	22.0 ± 8.3
Other backgrounds	50.6 ± 2.5	1.79 ± 0.16	1.65 ± 0.16
Total expected (SM)	2293 ± 209	181 ± 29	45.3 ± 10.0
Observed	2327	178	50