Exploring Higgs Boson Properties

Insights from the ATLAS group @ LNF

Chiara Arcangeletti on behalf of the ATLAS-LNF group

IRN Terascale @ LNF, 17th April 2024

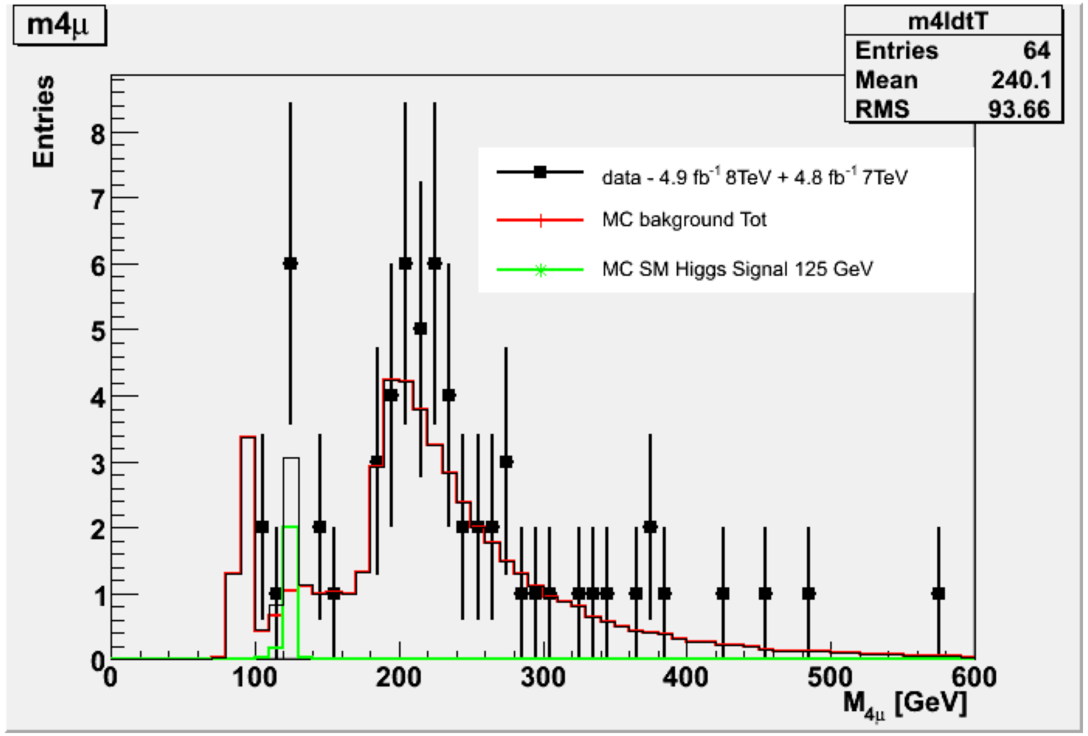
Introduction

It was a long journey until the Higgs boson discovery happened…

…In Spring 2012 the group that was working on the Higgs search in to ZZ decay channel were all depressed about no Higgs signal present in the 4 leptonic final state. Around March-April there was already some exciting about a Higgs signal at ~125 GeV.

A small team of Italian people (of which several LNF people) where performing the analysis…and finally in 18 June 2012 they got 2 candidates in the same run!

Crossing fingers the Data Quality for muons of this RUN was immediately checked: quoting a mail subject "**So BONI**”! (They are good”!)



event	run	Z1	Z2	M4mu	M4muConst
64671324	204763	93.9475	61.554	220.332	218.564
108344078	204763	92.1807	85.5061	361.782	363.089
71902630	**204769**	**86.3396**	**31.5661**	**124.088**	**125.09**
82599793	**204769**	**84.0118**	**34.2066**	**123.252**	**123.471**
84802829	204769	91.5958	89.2108	422.785	424.785

the mighty run

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pres… e
was

A sm…
peop… e
2012…

Cros…
immediately checked: quoting a mail subject "**So BONI**"! (They are good"!)

That is how our story begins…

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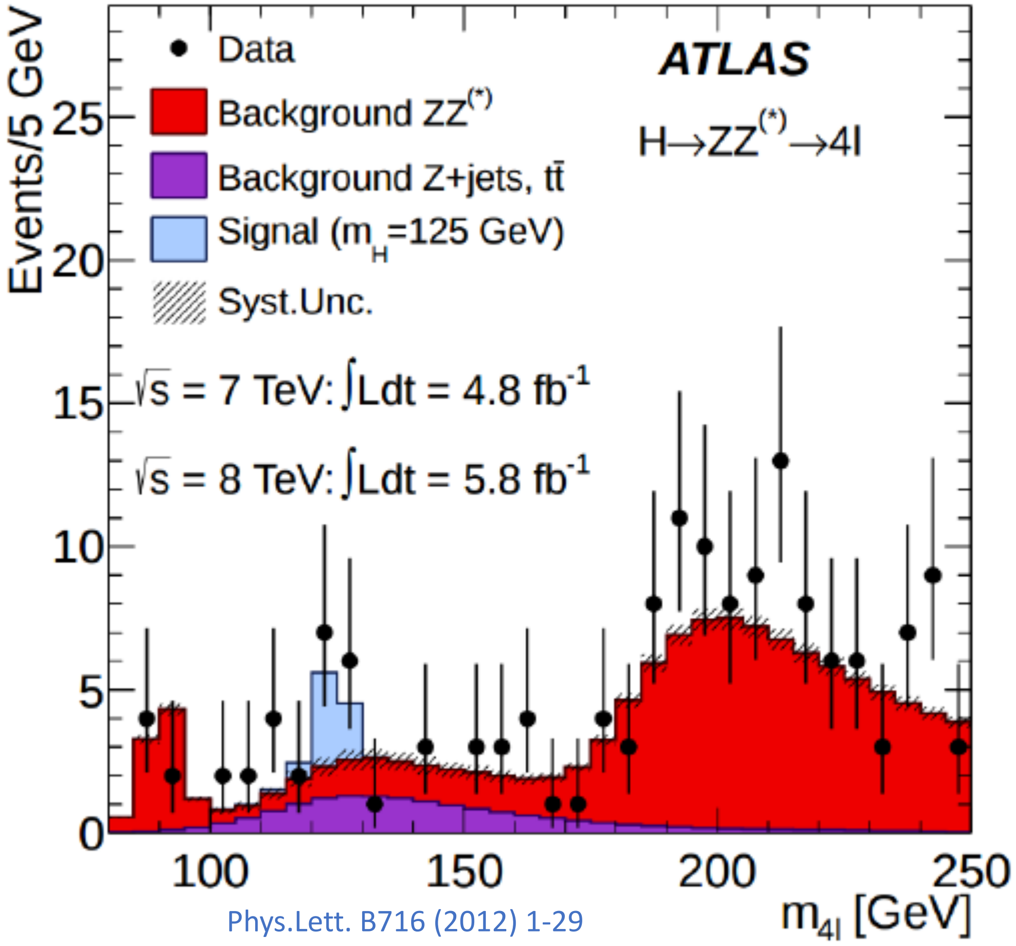
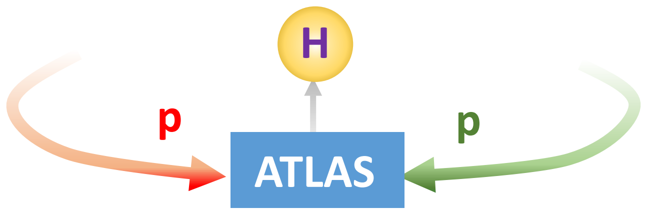
the mighty run

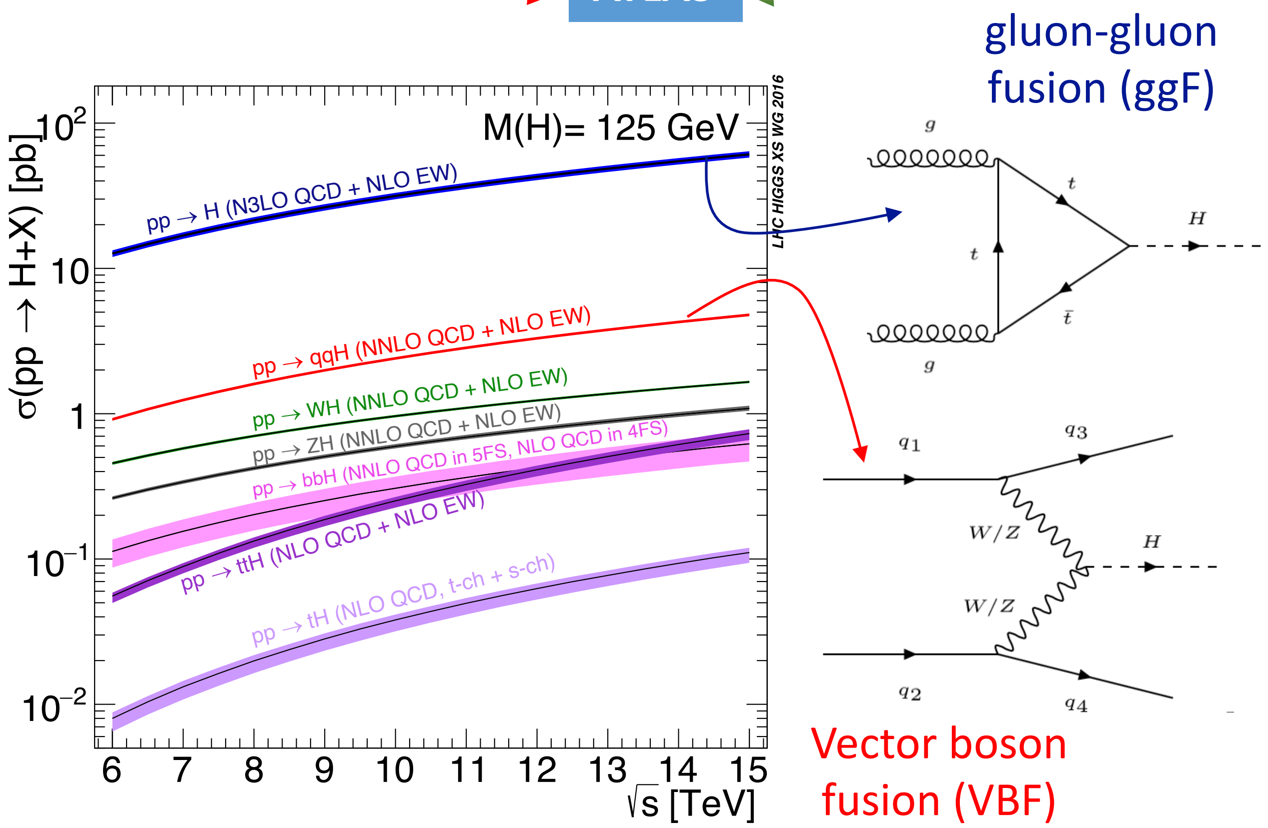


Phys.Lett. B716 (2012) 1-29

The Higgs boson @ LHC

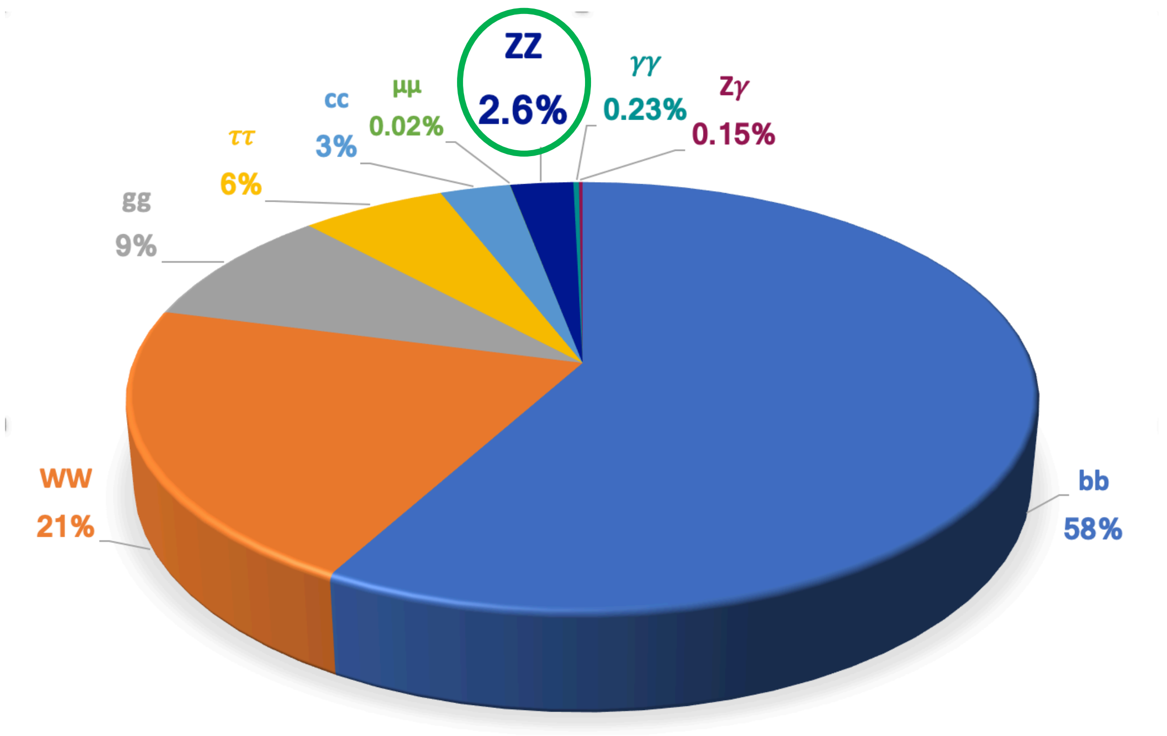
Production Mechanisms





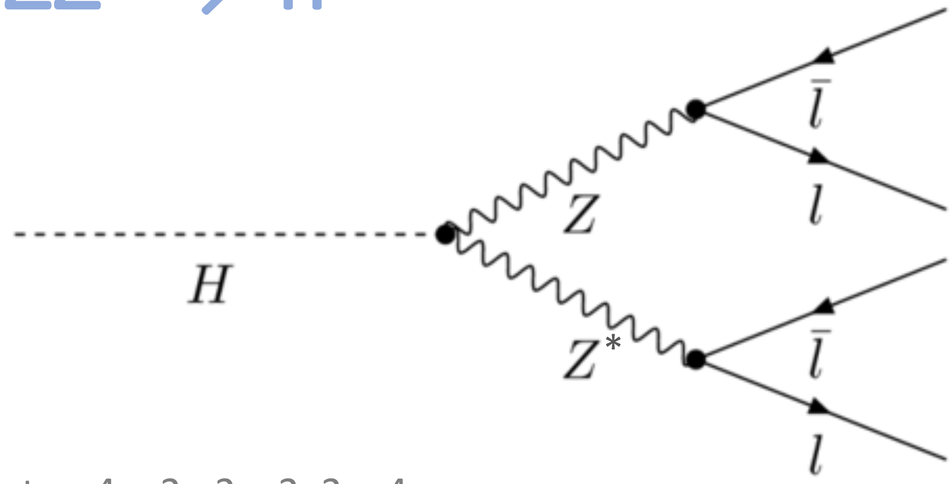
Decay Channels

H→ZZ*→4l (l=e,μ) very good S/B ratio, high mass resolution → **visible BR = 0.012 %**



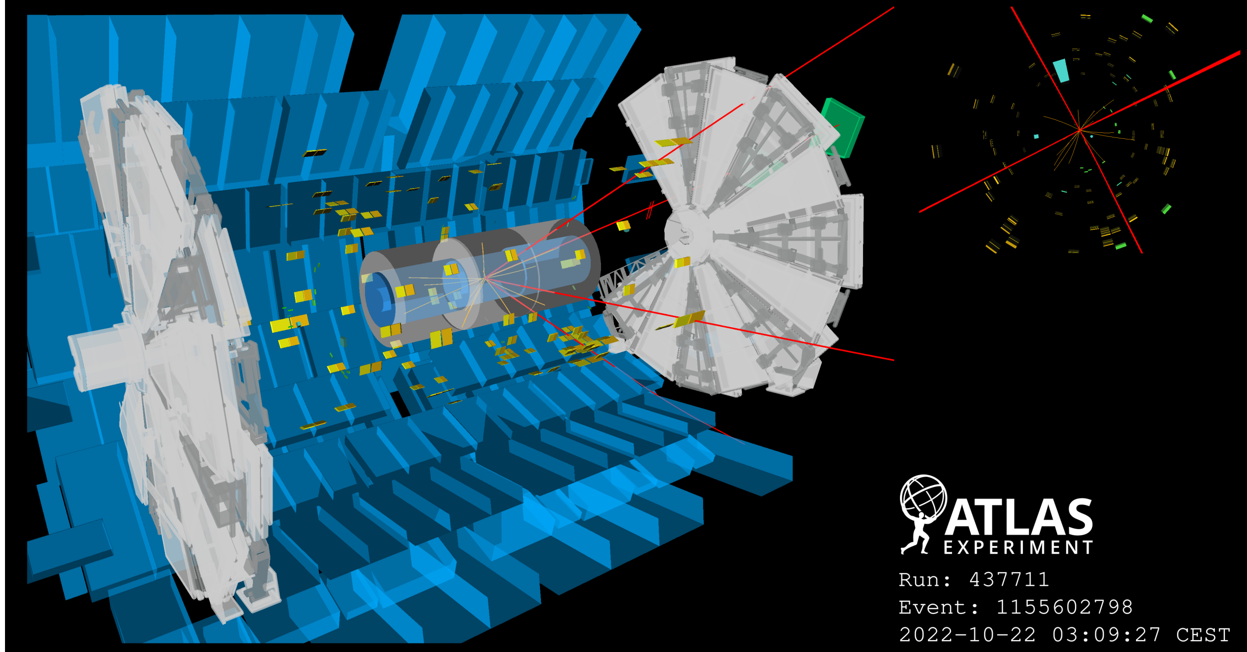
The *Golden* channel

H→ZZ*→4l



Final States: 4μ, 2μ 2e, 2e2μ, 4e

Example of H→ZZ*→4μ event with hit on the NSW



- Fully leptonic final state lead to a very clear signature of the event
- Very good mass resolution thanks to the excellent lepton reconstruction performance
- Very good Signal/Background ratio: S/B ~ 2
  - despite the low Branching Ratio, it makes this channel clearly identifiable

Optimal final state to measure Higgs boson properties

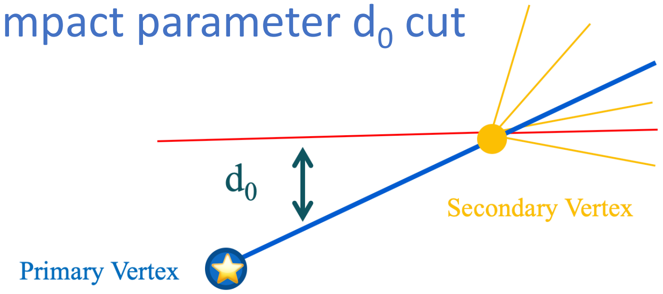
- Differential Cross sections
- Production Cross sections
- Couplings
- Spin/CP
- Mass

H→ZZ*→4l decay channel

Event selection and background estimation techniques used for Full Run 2 analyses as results of several years of studies and optimization work

Event Selection

- Quadruplet selection
  - Same flavour and opposite sign lepton pairs
  - Lepton separation: $\Delta R(l,l') > 0.10$
  - p_T(electron)>7 GeV, p_T(muons)> 5 GeV
  - 3 leading leptons: p_T>20, 15, 10 GeV
  - Mass requirements:
    - $50 < m_{12} < 106$ GeV; $m_{thr}^* < m_{34} < 115$ GeV; J/ψ veto: $m_{ll} > 5$ GeV
- Common vertex
- Lepton isolation
- Impact parameter d_0 cut



*m_{thr}= 12 GeV if m_{4l}<140 GeV and rises linearly to 50 GeV for m_{4l} = 190 GeV.

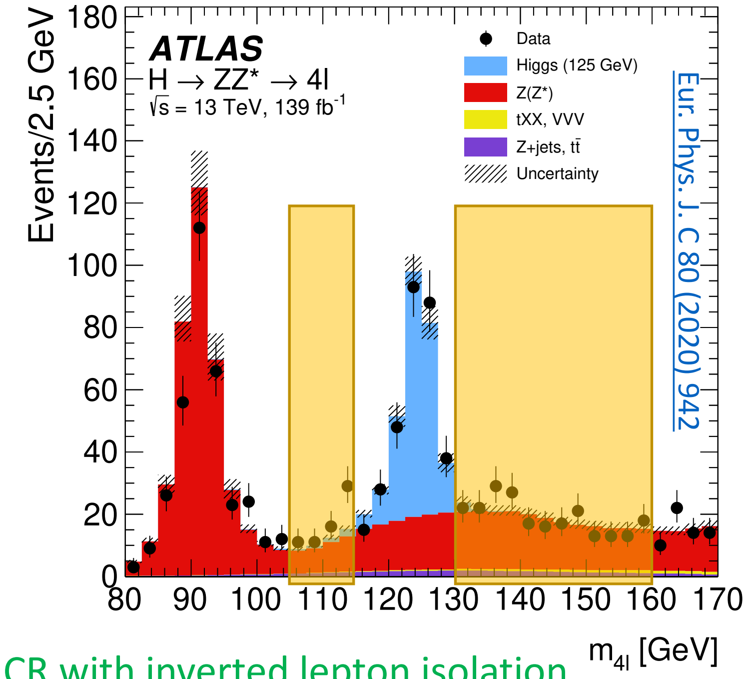
Background processes

- **ZZ* non-resonant production** (irreducible component)
  - Previoulsy estimated from MC. Full Run2 estimated from data defining m_{4l} sidebands: [105,115] GeV + [130,160] GeV
- **$t\bar{t}$ and Z+jets** (reducible component)
  - Estimated from data-driven technique
- **tXX, VVV** (very small component)

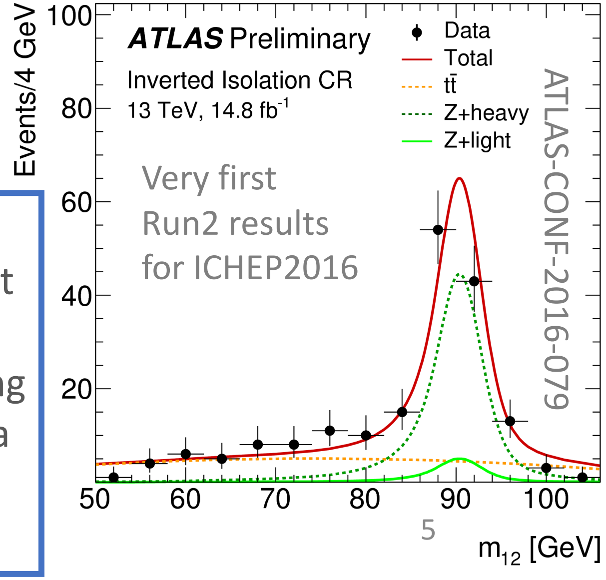
2 prompt leptons (Z) + 2 leptons from hadronic decays (b- or c-quark): different estimation for llμμ and llee

- Control Regions (CR) defined inverting or relaxing on event selection criteria → transfer factors to extrapolate the contribution in the signal region

m_{4l} sidebands for ZZ* bkg estimation



CR with inverted lepton isolation criteria for llμμ bkg estimation



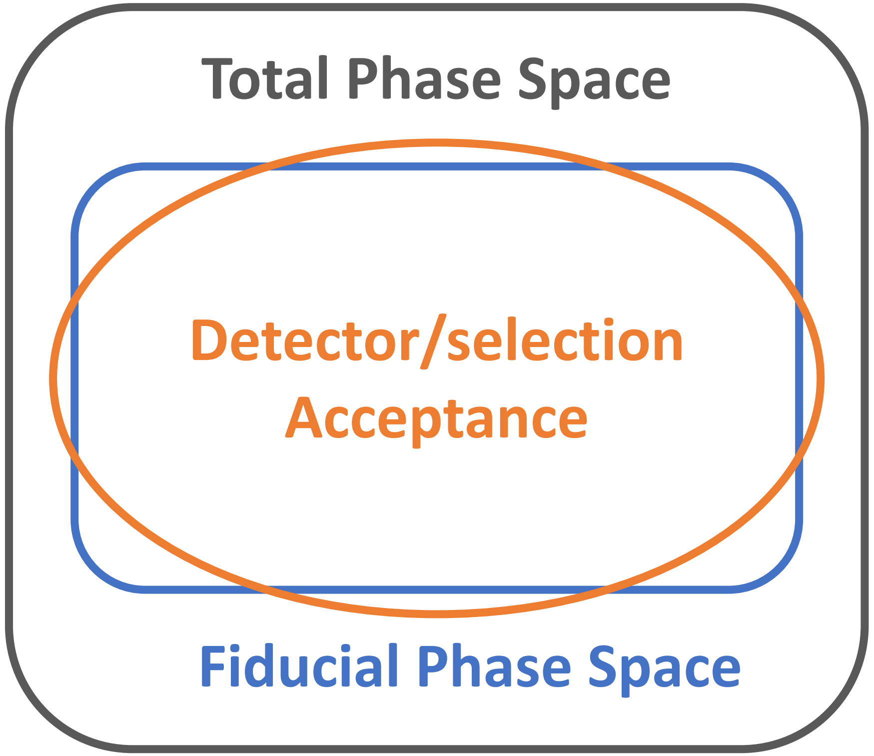
Fiducial Cross Sections measurement

The idea is to provide cross section measurements in the most model independent way

- **Fiducial phase space** definition based on detector and analysis selection acceptance to minimize the extrapolation effects. The fiducial cross section $\sigma_{fid} \cdot BR$ is defined as:

$$\sigma_{fid} \cdot BR = \sigma_{tot} \cdot BR \cdot A \qquad A = \frac{N_{fiducial}}{N_{total}}$$

where:
BR = Branching ratio
A = acceptance



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where:
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A = acceptance

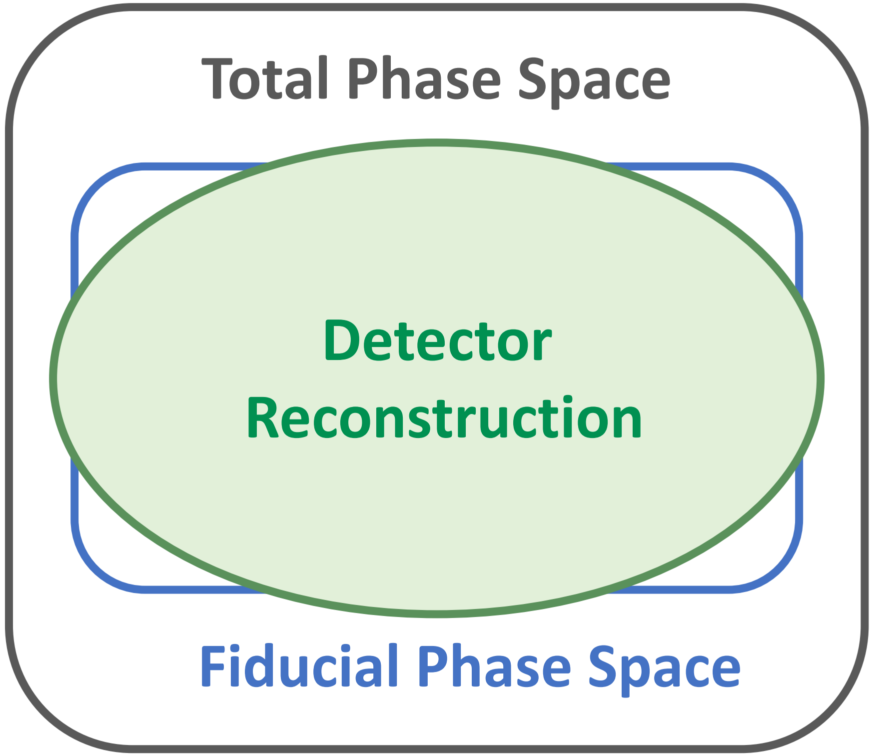
- **Correct for detector level effects**, efficiencies and resolution, defining the correction factor entering in the fiducial cross section extraction:

$$\sigma_{fid} \cdot BR = \frac{N_{signal}}{C_F \cdot L_{int}}$$

where:
L_{int} = integrated luminosity
C_F = correction factor

$$C_F = \frac{N_{reconstructed}}{N_{fiducial}}$$

N_{signal} = number of signal events extracted fitting the observable able to discriminate signal vs background.



It is possible to ***unfold*** the reconstructed distribution of a given observable to estimate the truth-level spectrum

The Higgs boson Differential Cross Sections

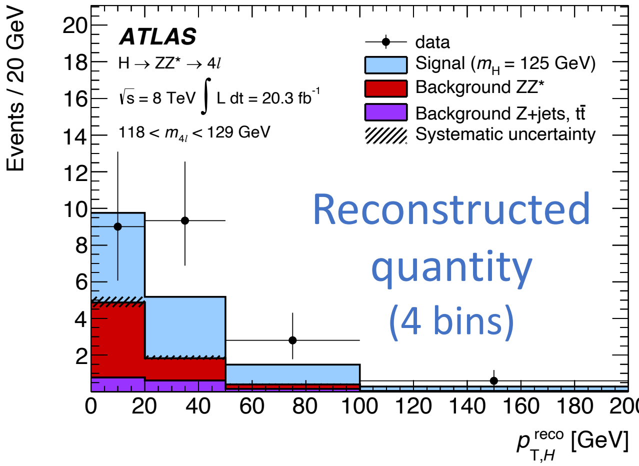
First differential cross section measurements performed in Run1 investigated six observables

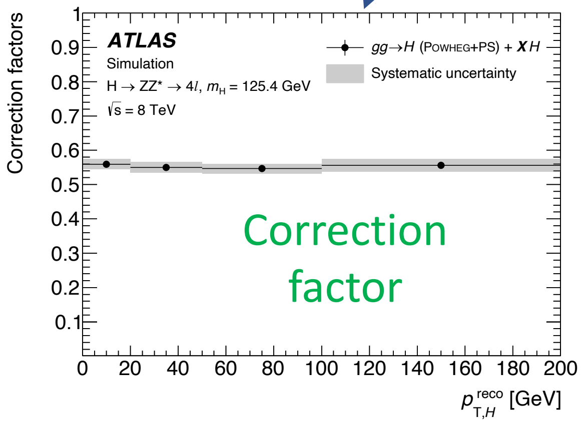
Higgs kinematic variables
p_T^{4l}: perturbative QCD
y^{4l}: parton density function
m_{34}, $\cos\theta^*$: CP–sensitive

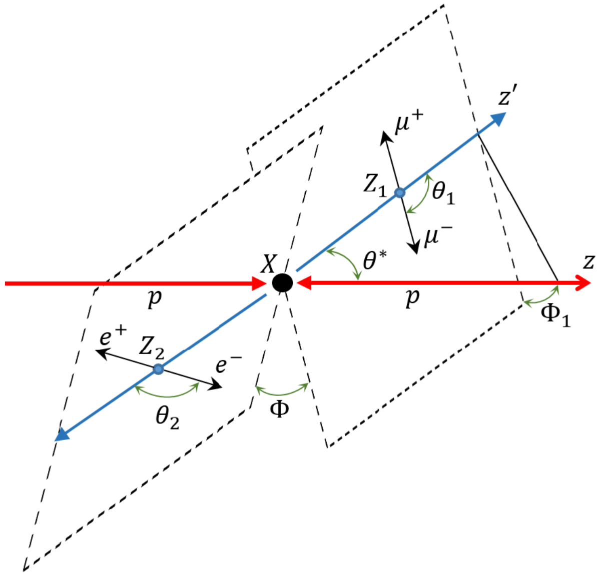
Jet – related variables
N_{jet} : different production mode
p_T^{j1} : quark gluon radiation

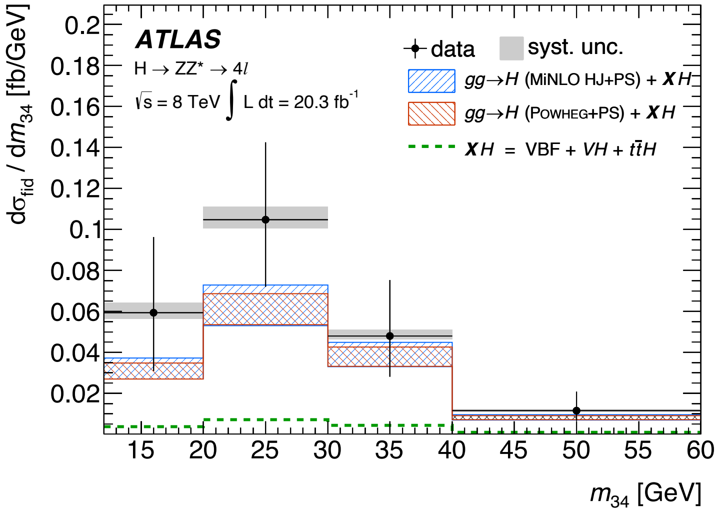
Physics Letters B 738 (2014) 234-253

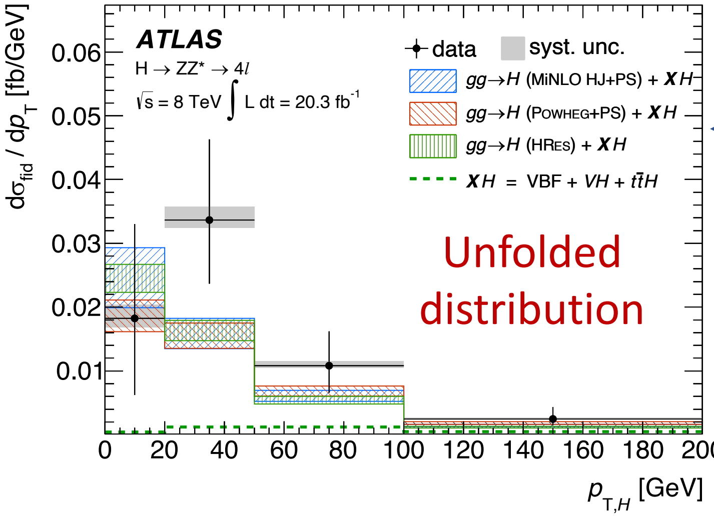
For differential distribution the number of events is extracted from a template fit on the m_{4l} distribution in each variable bin.











The Higgs boson Differential Cross Sections

Full Run 2 provided 19 differential and 8 double-differential cross section measurements

[Eur. Phys. J. C 80 (2020) 942]

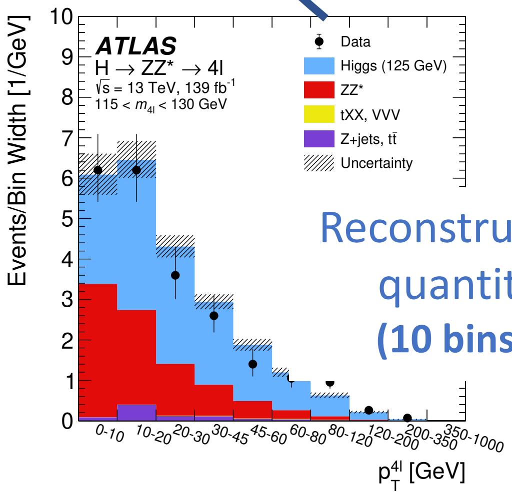
Higgs kinematic variables
p_T^{4l}: perturbative QCD, **light quark coupling**
y^{4l}: parton density function
m_{34}, $\cos\theta^*$, m_{12}, $\cos\theta_1$, $\cos\theta_2$, ϕ, ϕ_1: CP–sensitive

Jet – related variables
N_{jet}, m_{jj}, $\Delta\eta_{jj}$: different production mode
p_T^{j1}, p_T^{j2}: quark gluon radiation
p_T^{4l+j}, p_T^{4l+2j}, m_{4l+j}, m_{4l+2j}: jet activity
$\Delta\phi_{jj}$: CP–sensitive

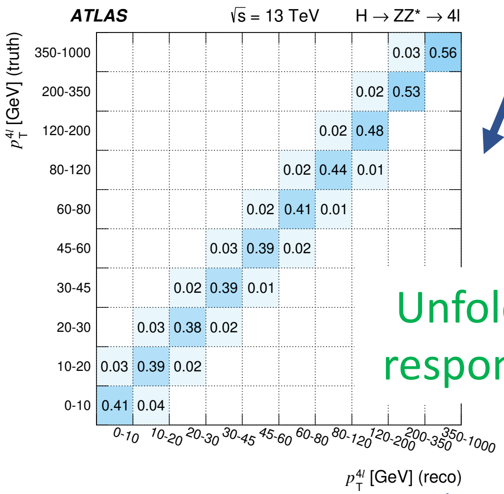
2D differential distributions
$m_{12}m_{34}$: modification *HZZ* vertex p_T^{4l} vs N_{jets}, $\lvert y^{4l}\rvert$, p_T^{j1}, p_T^{4l+j} p_T^{j1} vs p_T^{j2}, y^{j1} ; p_T^{4l+j} vs m_{4l+j} : QCD resummation effects

Increased sensitivity used to put constraints on possible anomalous Higgs boson couplings interpreting the results in different theoretical frameworks

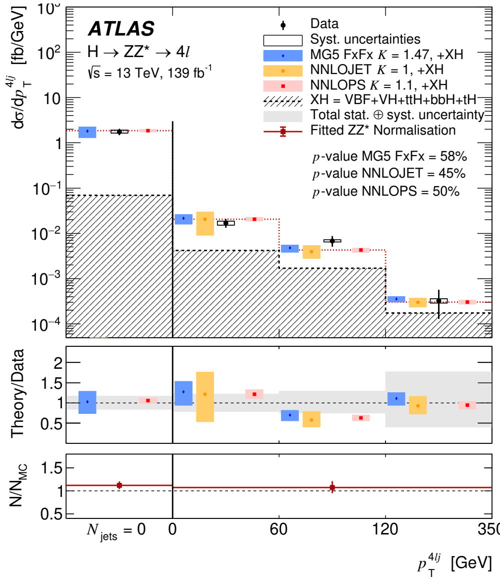
m_{4l} template fit in each variable bin

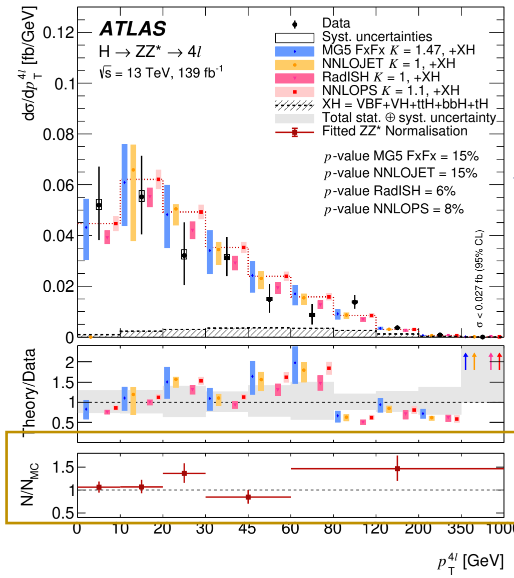


Reconstructed quantity **(10 bins!)**



Unfolding with response matrix





Unfolded distribution

ZZ* bkg estimation from data

Interpretation of Differential Cross Sections

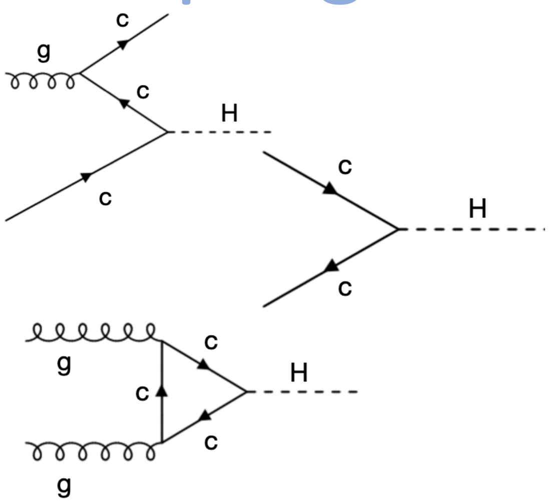
κ-framework: constraints on Yukawa couplings

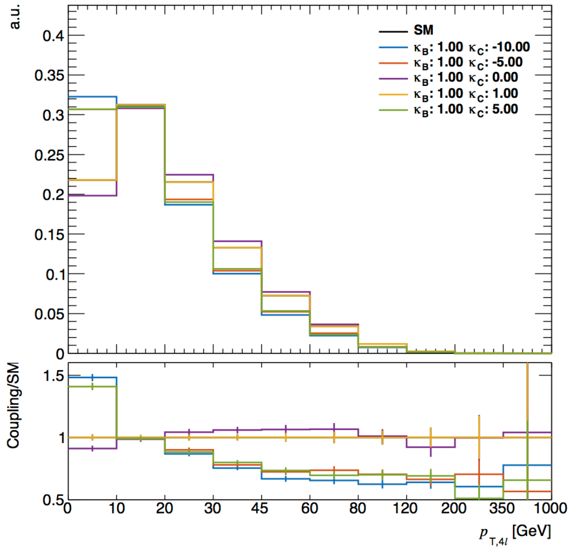
- Higgs coupling to light quarks (e.g. charm) may be possible to constrain without direct measurement

p_T^H is sensitive to the Yukawa coupling of the charm, bottom quark
→ constrain the charm coupling from the bottom

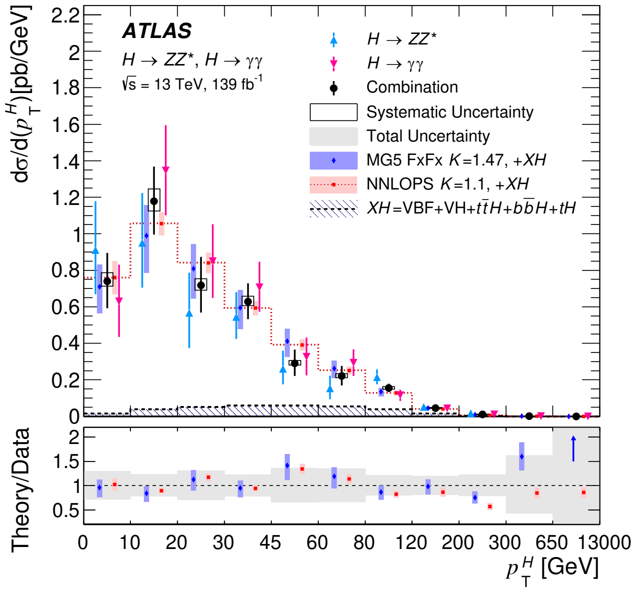
- non–SM values of the **coupling modifiers** κ_c and κ_b are investigated

This interpretation has been performed also on combined differential cross section measurements of the Higgs p_T between H→ZZ*→4l and H→$\gamma\gamma$ decay channels

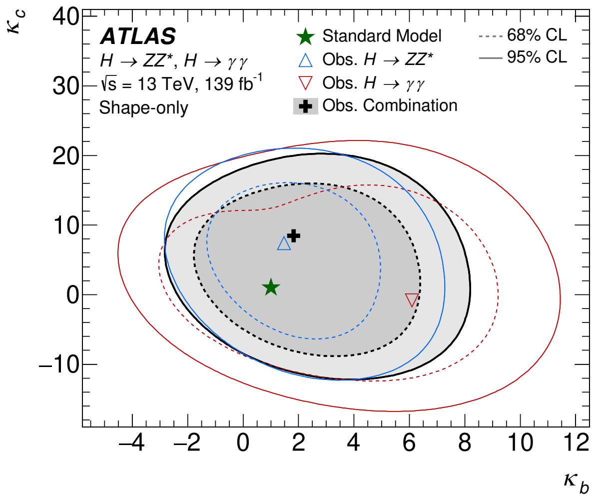




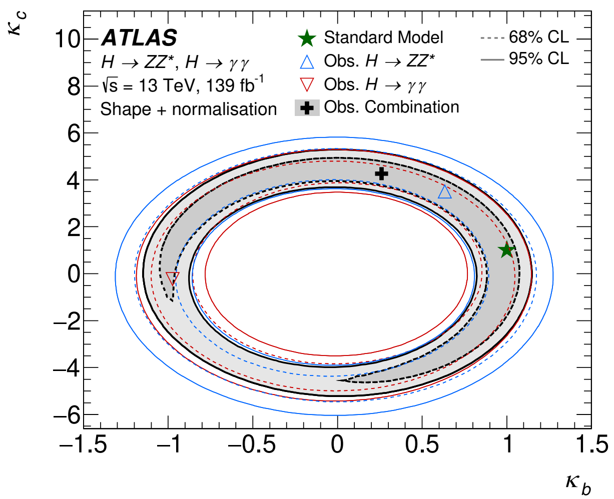
JHEP 05 (2023) 028



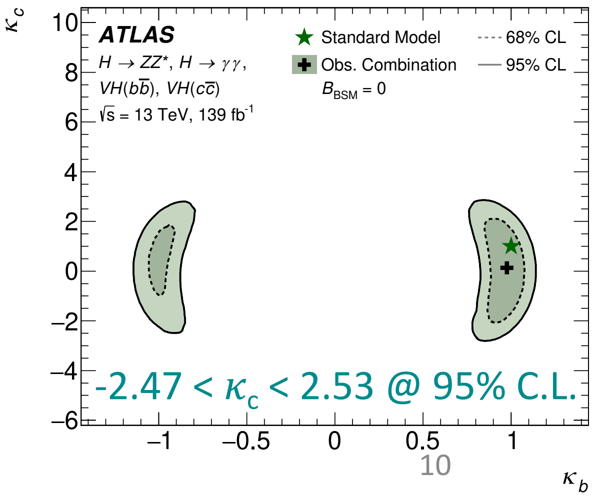
Anomalous couplings can only modify the p_T^H shape



Anomalous couplings can modify also the cross section and BR



Including direct measurements VH(bb) and VH(cc)

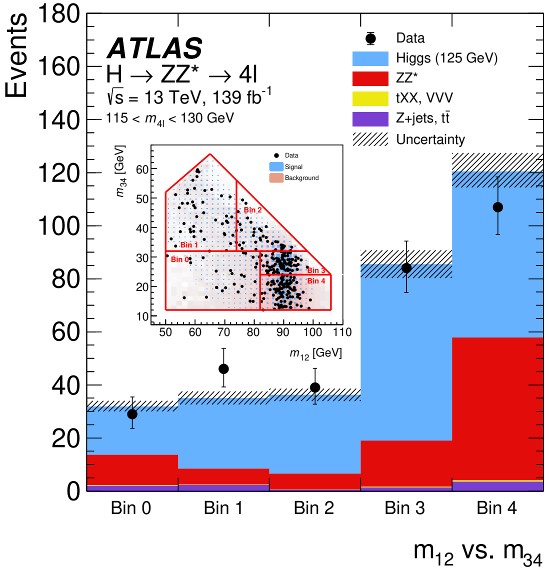


$-2.47 < \kappa_c < 2.53$ @ 95% C.L.

Interpretation of Differential Cross Sections

Pseudo-Observables

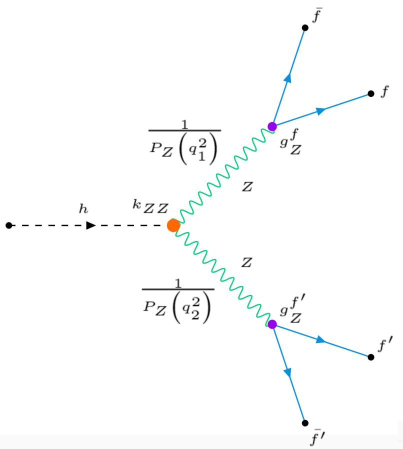
Eur. Phys. J. C 80 (2020) 942



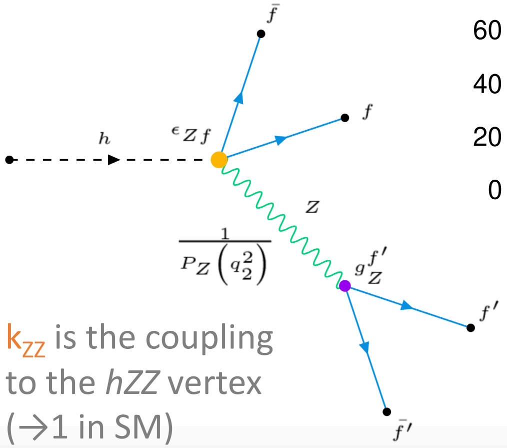
- Study the effective coupling of the Higgs boson to the SM gauge bosons using the invariant masses of the two Z **m_{12} vs. m_{34}** distribution
- From amplitude decomposition the most interesting terms (assuming CP-invariance) are:

$$F_1^{ff'}(q_1^2, q_2^2) = \kappa_{ZZ}\frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Zf}}{m_Z^2}\frac{g_Z^{f'}}{P_Z(q_2^2)} + \frac{\epsilon_{Zf'}}{m_Z^2}\frac{g_Z^f}{P_Z(q_1^2)}$$

- 5 parameters can be studied: κ_{ZZ}, ε_{ZeL}, $\varepsilon_{Z\mu L}$, ε_{ZeR}, $\varepsilon_{Z\mu R}$

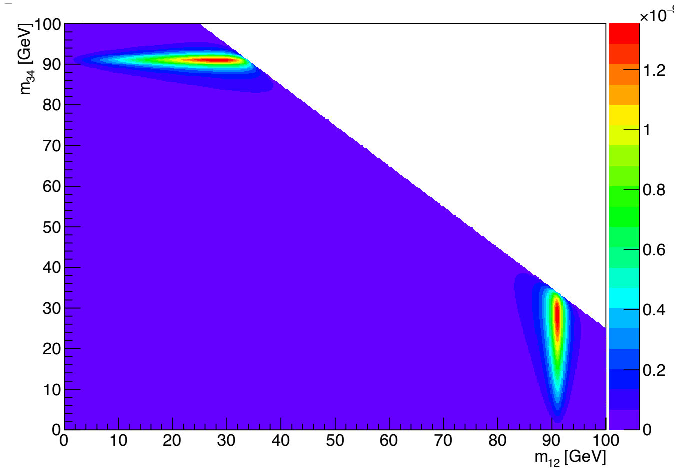


k_{ZZ} is the coupling to the *hZZ* vertex (→1 in SM)

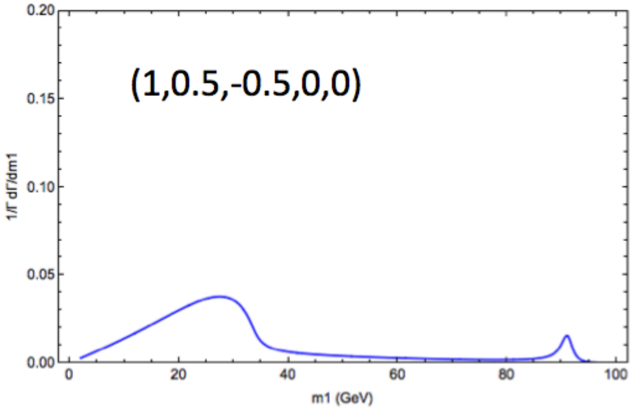


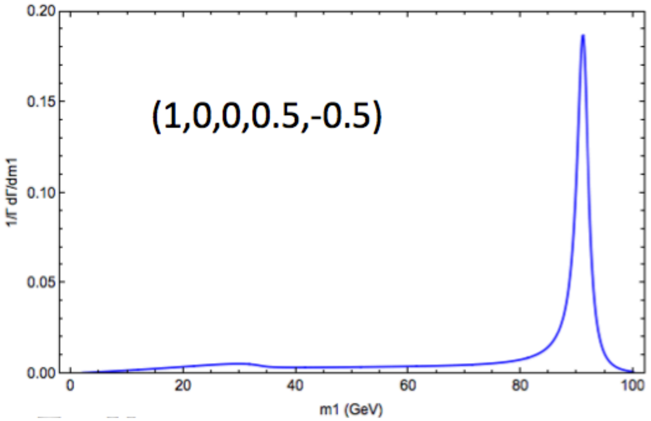
ε is the contact term of the Z boson with leptons (→0 in SM)

h→2e2μ decay amplitude generated setting parameters at SM values



Projection on m_{12} integrating on m_{34} for BMS values of the parameters





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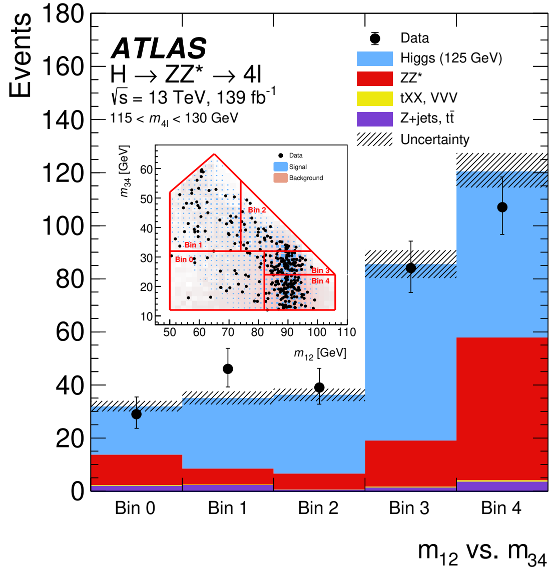
Interpretation of Differential Cross Sections

Pseudo-Observables

[Eur. Phys. J. C 80 (2020) 942](#)



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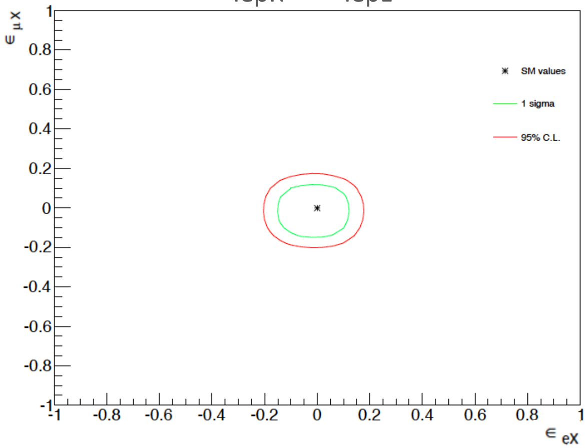
- 5 parameters can be studied: κ_{ZZ}, ε_{ZeL}, $\varepsilon_{Z\mu L}$, ε_{ZeR}, $\varepsilon_{Z\mu R}$

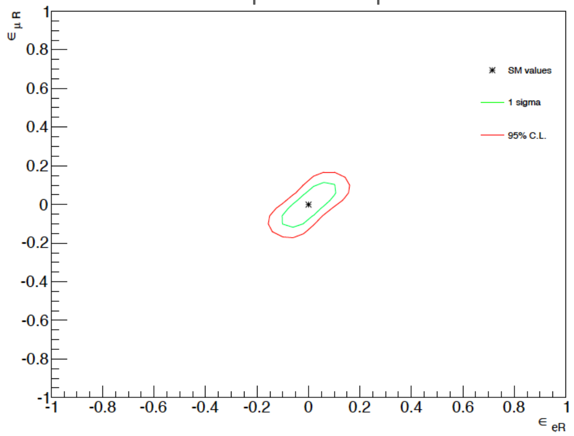
Projections @ 100 fb^{-1}

Lepton Flavour Non – Universal scenarios

"Vector Contact terms"
($\varepsilon_{lepR} = \varepsilon_{lepL}$)

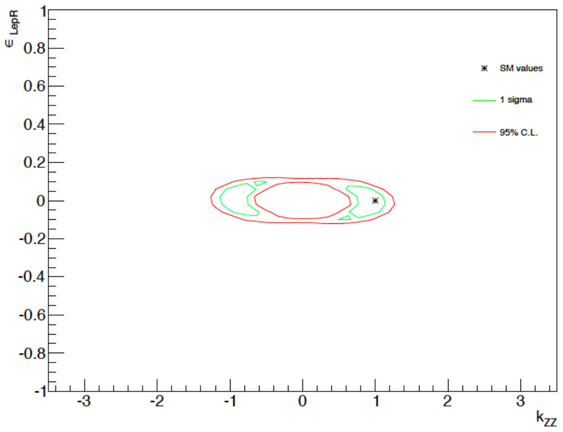


"Axial Contact terms"
($\varepsilon_{lepR} = -\varepsilon_{lepL}$)



Lepton Flavour Universal scenarios

"Linear EFT – inspired"
(assume Higgs as $SU(2)_L$ doublet)



"Contact terms"
(fixing $k_{ZZ}=1$)

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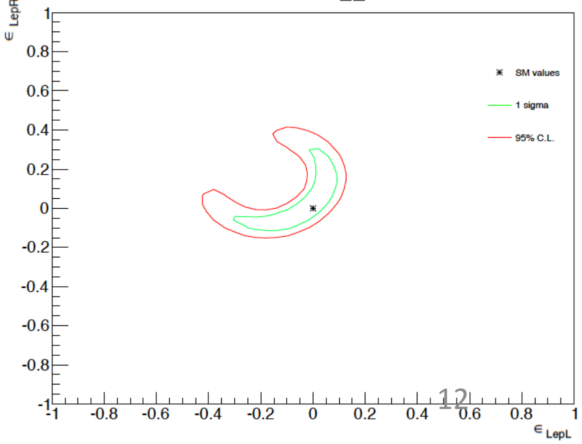
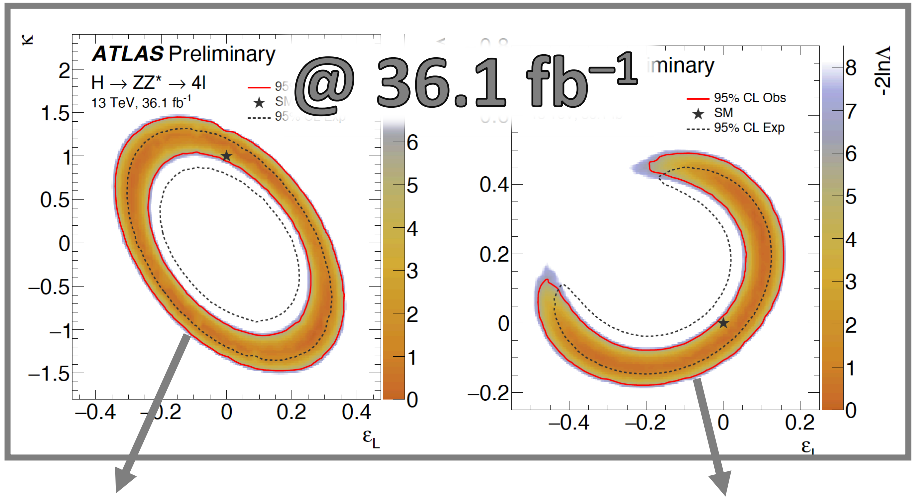


Interpretation of Differential Cross Sections

Pseudo-Observables Run 2 Results

JHEP 10 (2017) 132



- Scenarios that assume lepton flavour universality already studied with early Run 2 statistics: with full Run 2 limits improved ~ 20–30 %
- Lepton Flavour Non – Universal scenarios investigated for the first time with full Run 2 statistics → limits O(5–10 %)
- Good compatibility with projections!

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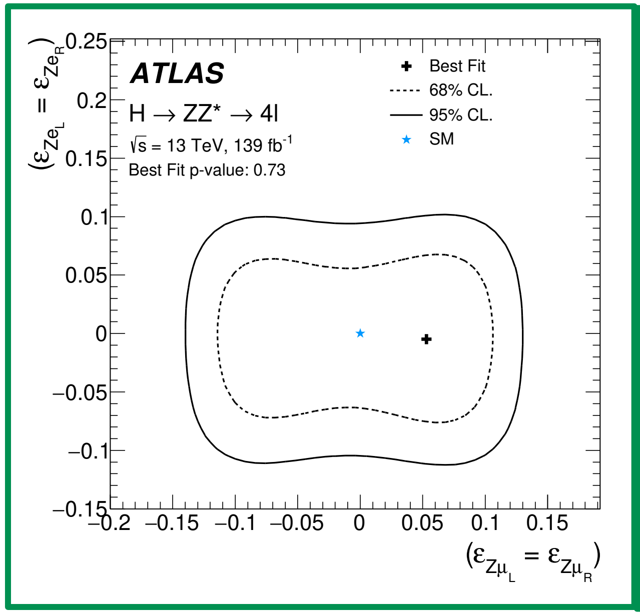
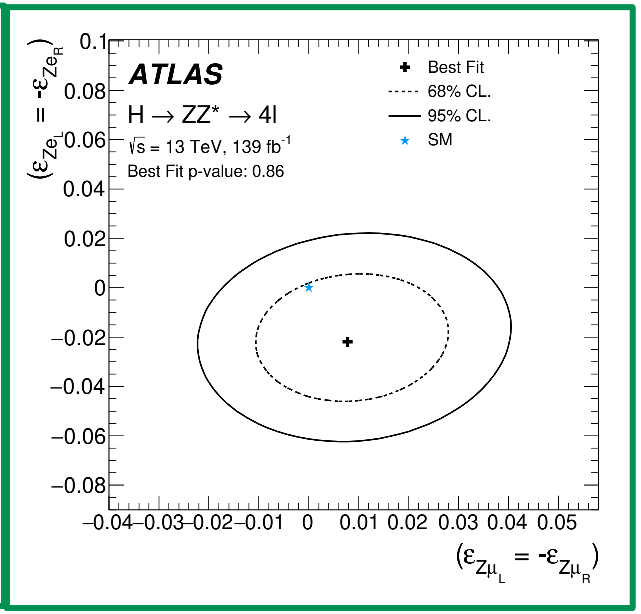
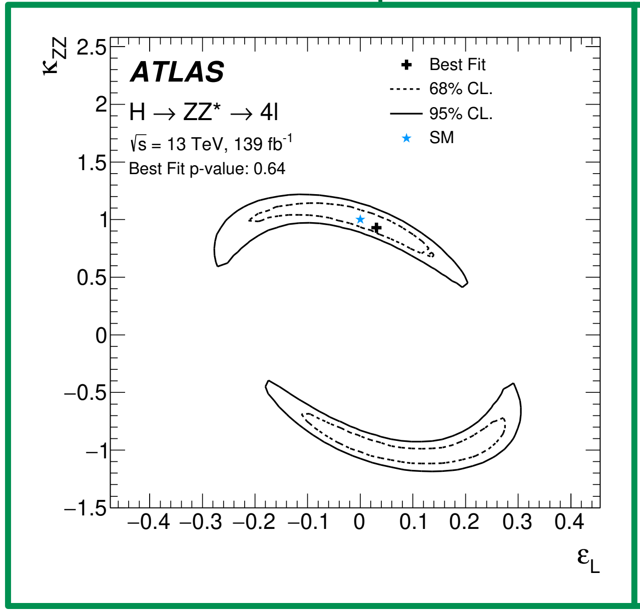
Vector Contact Terms



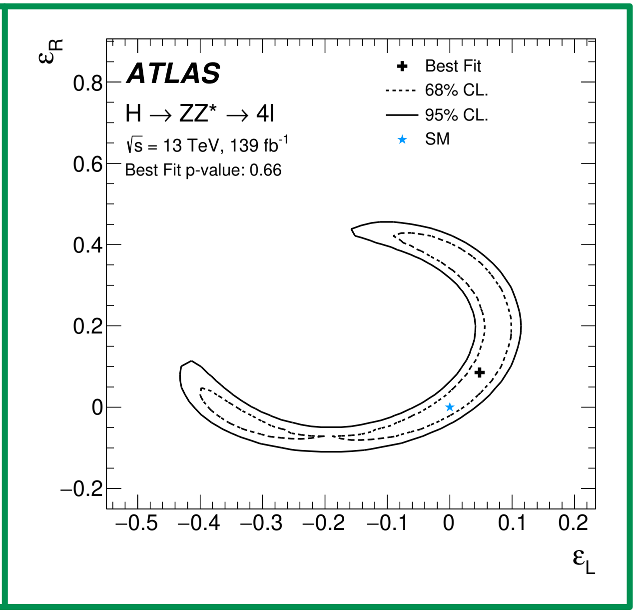
Axial Contact Terms



Linear EFT – inspired



Contact Terms

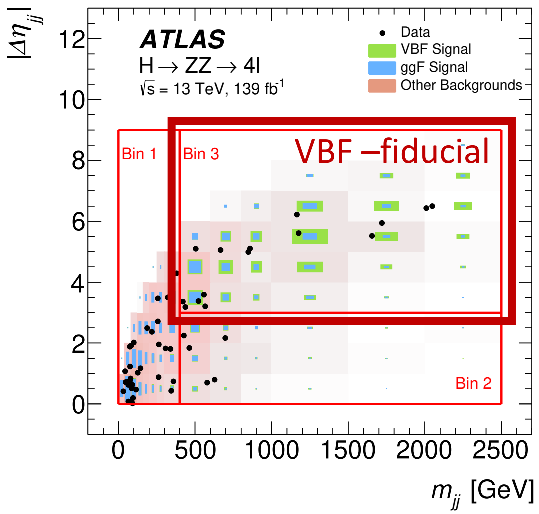


Interpretation of Differential Cross Sections

Pseudo-Observables Prospects

Constrain PO using also EW production modes → probe new PO κ_{ZZ}, κ_{WW}, ε_{ZuL}, ε_{ZdL}, ε_{ZuR}, ε_{ZdR}, ε_{WuL}

arXiv:2304.09612



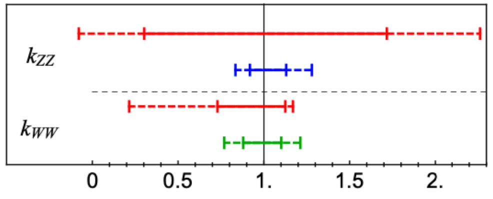
- VBF: double-differential distribution on p_T^{j1} vs p_T^{j2} to access the $F(q_1^2,q_2^2)$
- ZH (or WH): differential distribution of p_T^Z or $m_{Zh} \sim q^2$

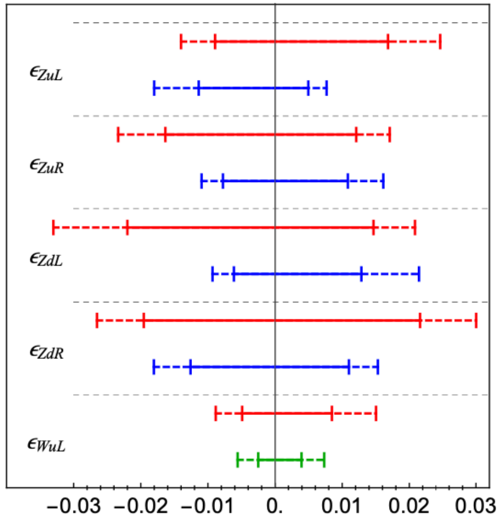
→ Define fiducial volume targeting specific production modes can improve sensitivity

- Already done in H→ZZ*→4l with Run 2 data to perform a fiducial VBF measurement applying a selection on 2-jet events on m_{jj} and $\Delta\eta_{jj}$.
- At the moment statistically limited (~40% of uncertainty)

arXiv:1512.06135

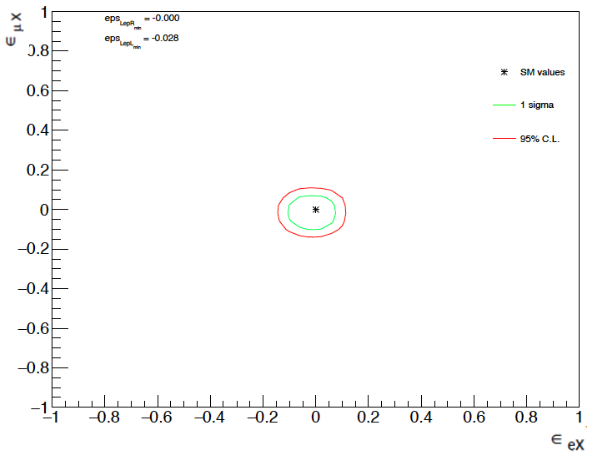
Prospects for Higgs PO in EW production @ the HL- LHC



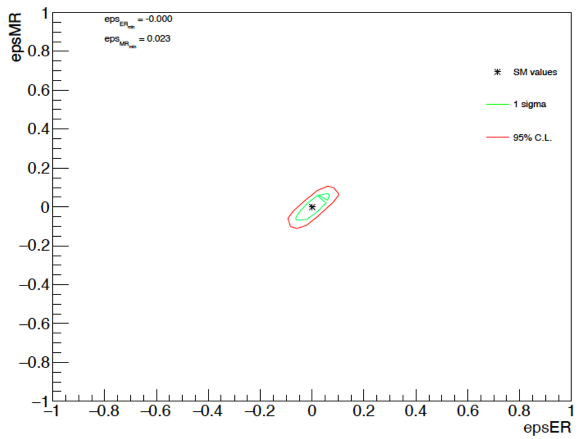


Projections with decay only PO @ 300 fb^{-1}

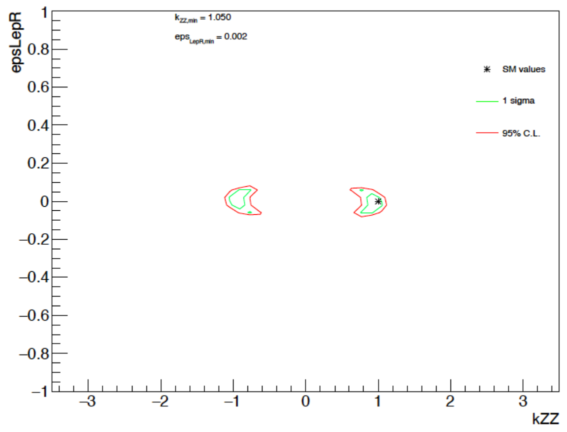
"Vector Contact terms"



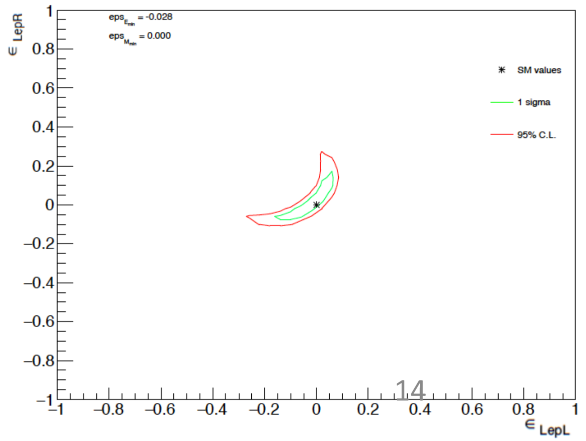
"Axial Contact terms"



"Linear EFT – inspired"



"Contact terms" G. Mancini

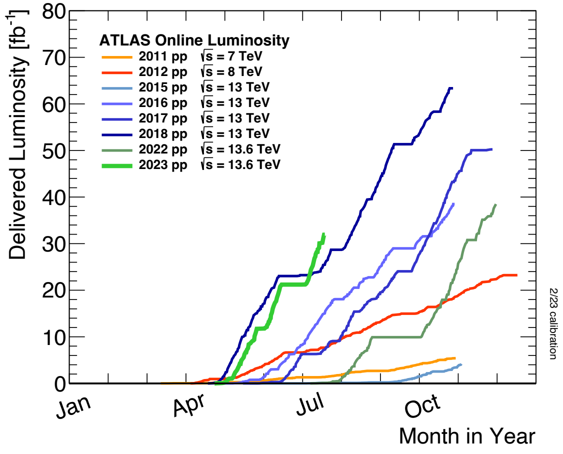


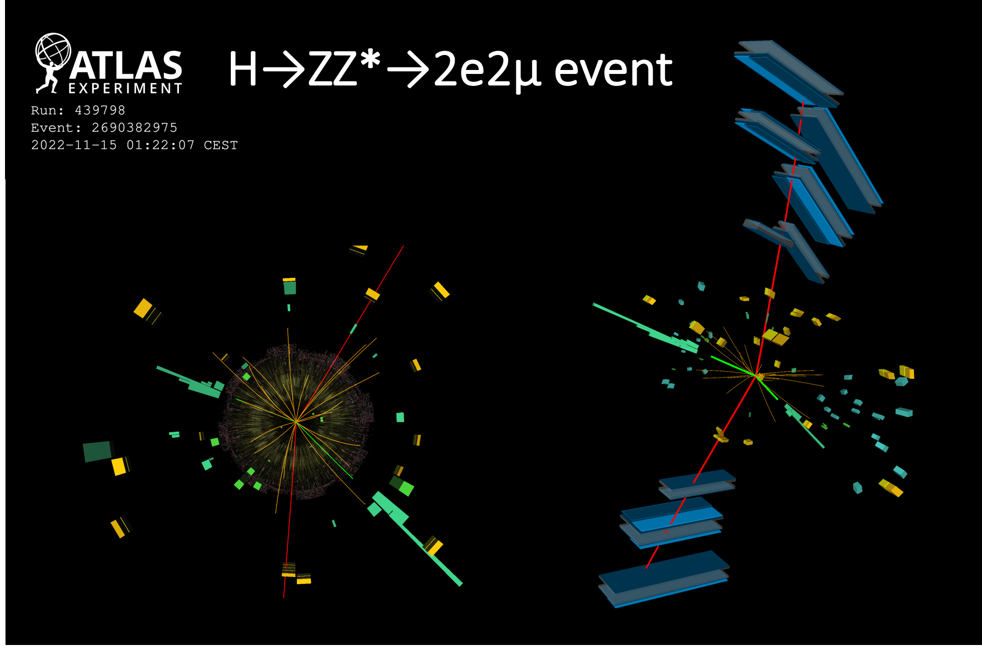
The Higgs boson @ 13.6 TeV

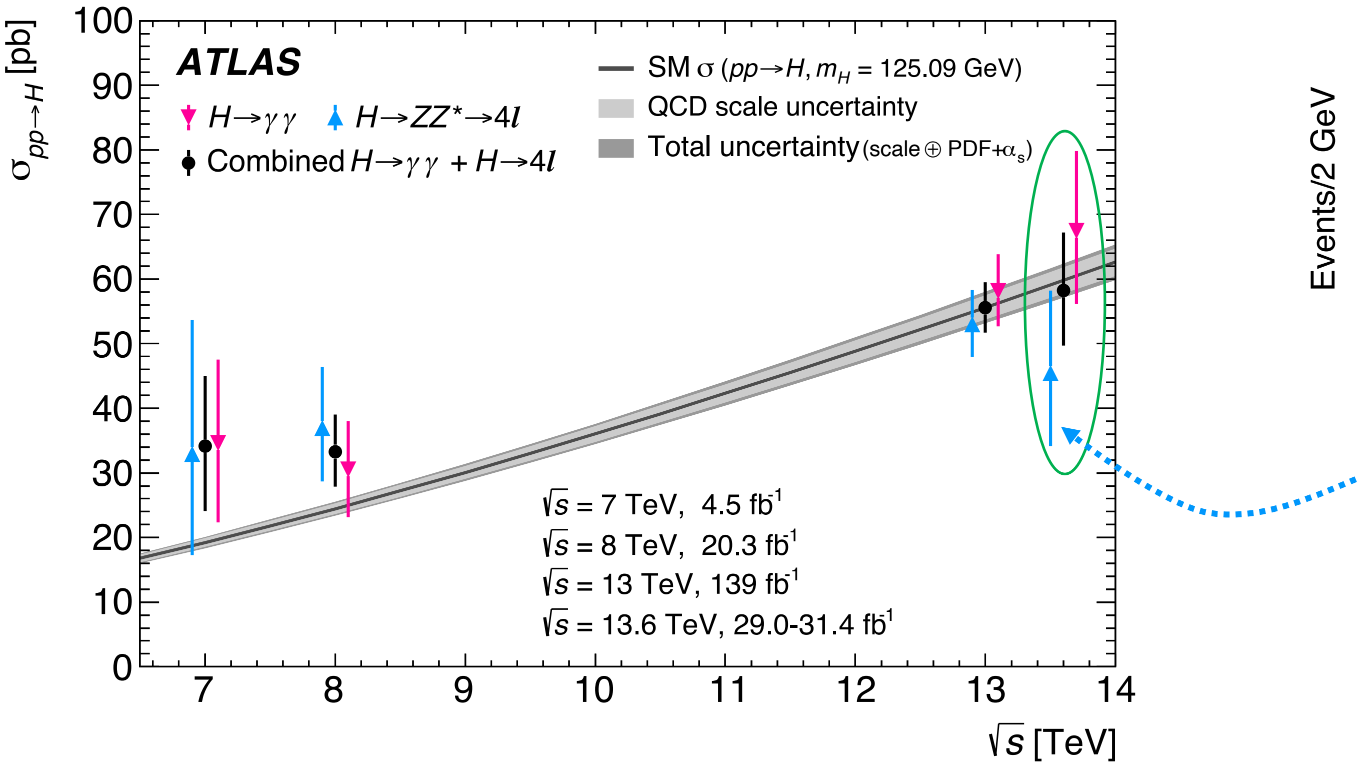
LHC collisions re-started in 2022 at 13.6 TeV

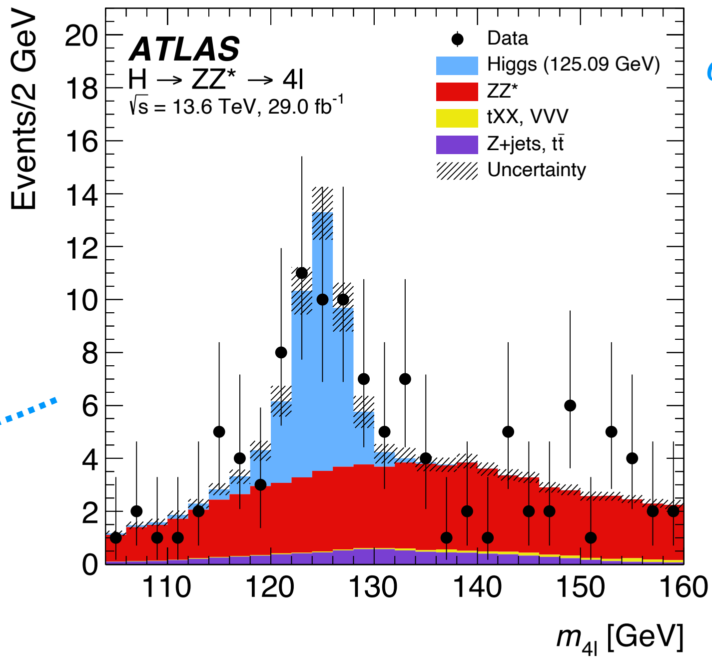
First measurement of the Higgs boson production cross section @ 13.6 TeV performed in the $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ decay channels with about 30 fb^{-1}

[Eur. Phys. J. C 84 (2024) 78]









$\sigma_{fid}^{4l} = 2.80 \pm 0.74$ fb

(SM: 3.67 ± 0.19 fb)

$\sigma_{fid}^{\gamma\gamma} = 76^{+14}_{-13}$ fb

(SM: 67.6 ± 3.7 fb)

$\sigma_{total} = 58.2 \pm 8.7$ pb

(SM: 59.9 ± 2.6 pb)

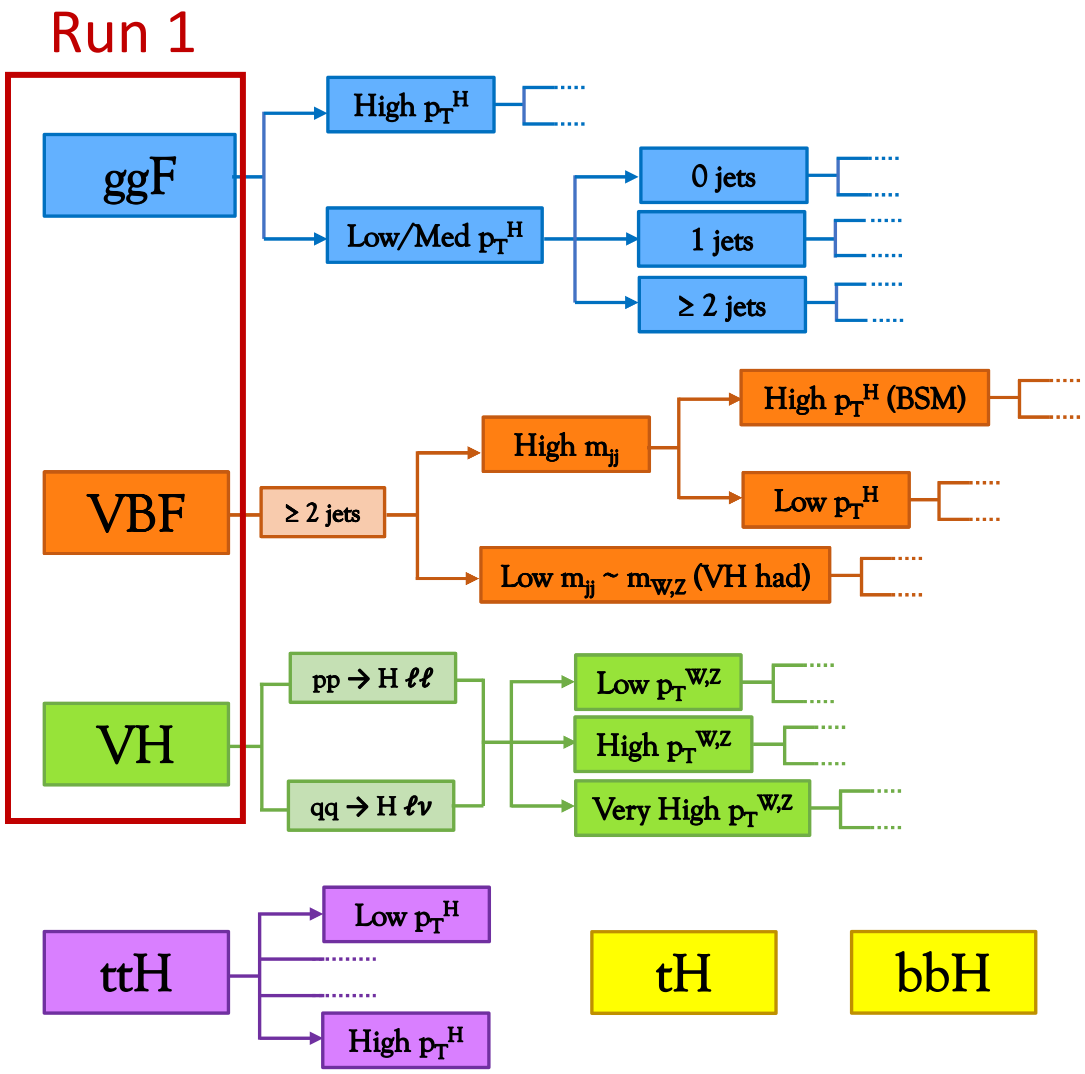
The Higgs boson production cross section

Production Cross sections are a way to probe the strength of the Higgs boson coupling with SM particles and possible BSM effects

Simplified Template Cross Section (STXS) framework define exclusive regions in the Higgs phase space of the Higgs production processes, based on the kinematics of the Higgs and of the particles/jets produced in association: p_T^{Higgs}, N_{jets}, m_{jj}, p_T^V

- Criteria:
  - Minimizing the dependence on theoretical uncertainties
  - Maximizing experimental sensitivity also to possible BSM effects
- Different STXS Stages definition, corresponding to increasingly fine granularity
- Not all the analyses are sensitive to all the STXS bins

Reco-level categorization in each analysis, in which the measurement is performed, as close as possible to the Particle-level categorization →minimize model-dependent extrapolation



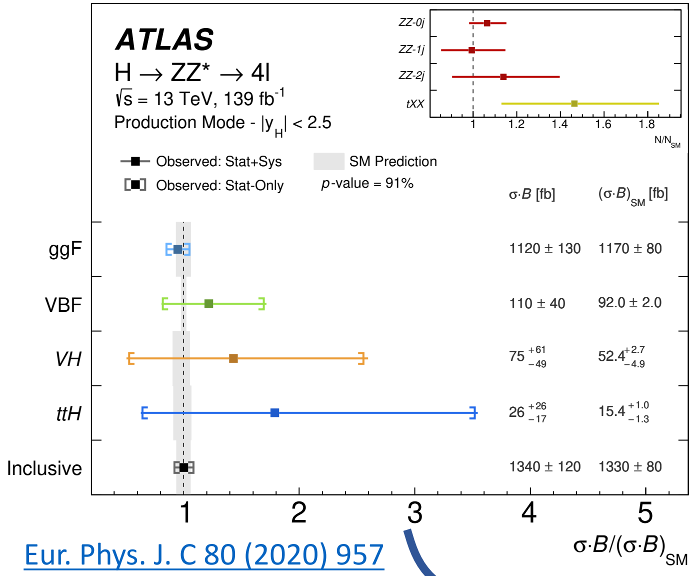
The Higgs boson Couplings

κ-framework

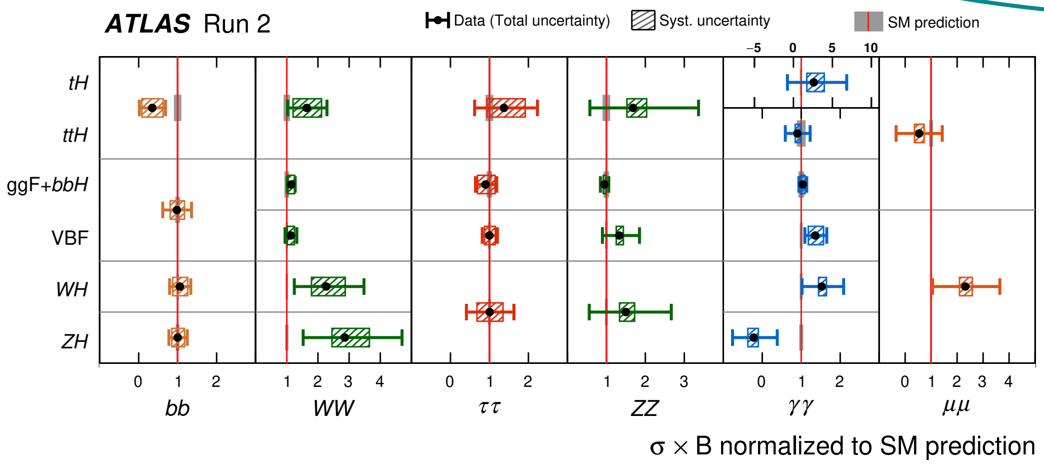
After 10 years from the discovery ATLAS provided the combined measurements of Higgs boson couplings with other SM particles

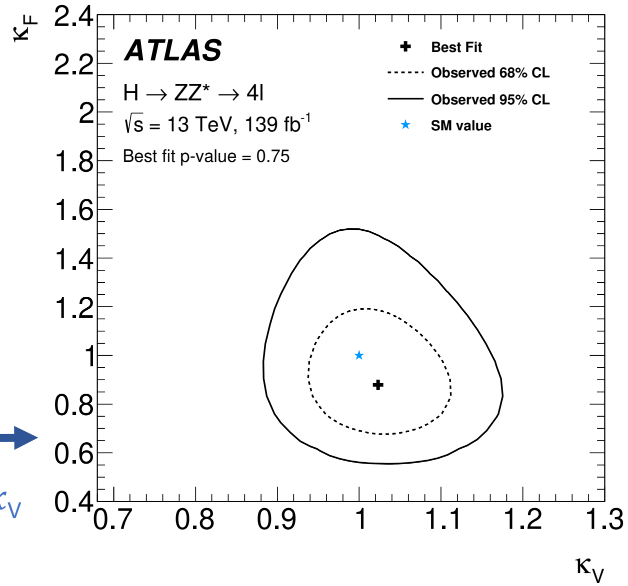
Production cross sections can be used to put constraint on the Higgs boson couplings modifiers.

- Parametrizing the cross section as function of the κ we can extract constraints on the relative modifiers, based on the assumptions behind



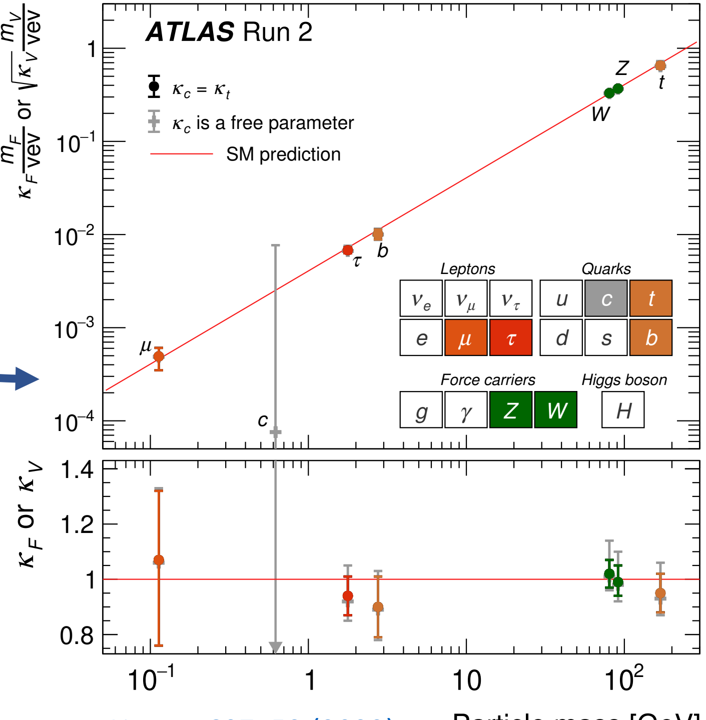
Eur. Phys. J. C 80 (2020) 957





Universal coupling strength modifiers κ_V (vector bosons) and κ_F (fermions)

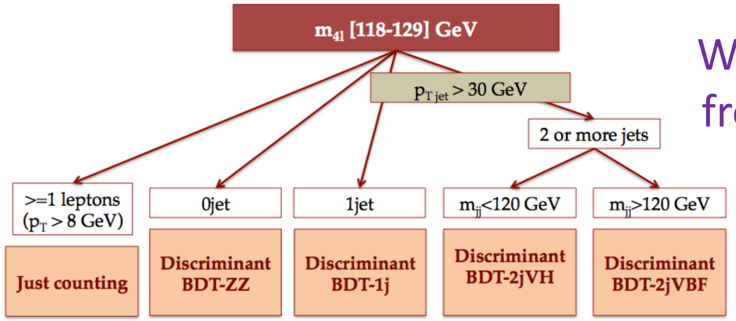
Generic parametrization with coupling strength modifiers for W, Z, t, b, c*, τ and μ treated independently



Nature 607, 52 (2022)

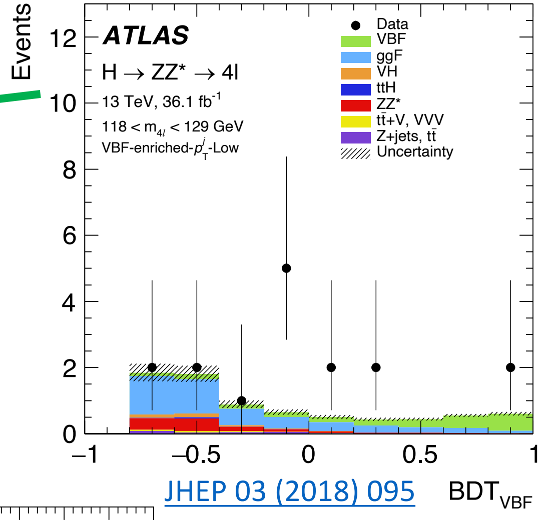
The Simplified Template Cross Section

- Huge optimization work done in Run 2 to define reco categories
- Development of discriminants dedicated in each category



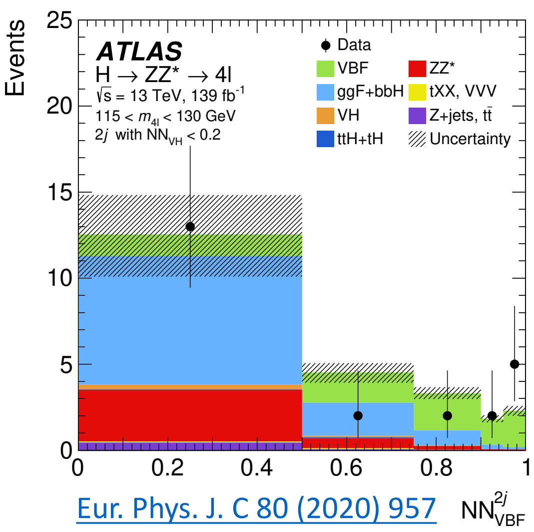
We started from this…

…to this@ 36.1 fb^{-1}…



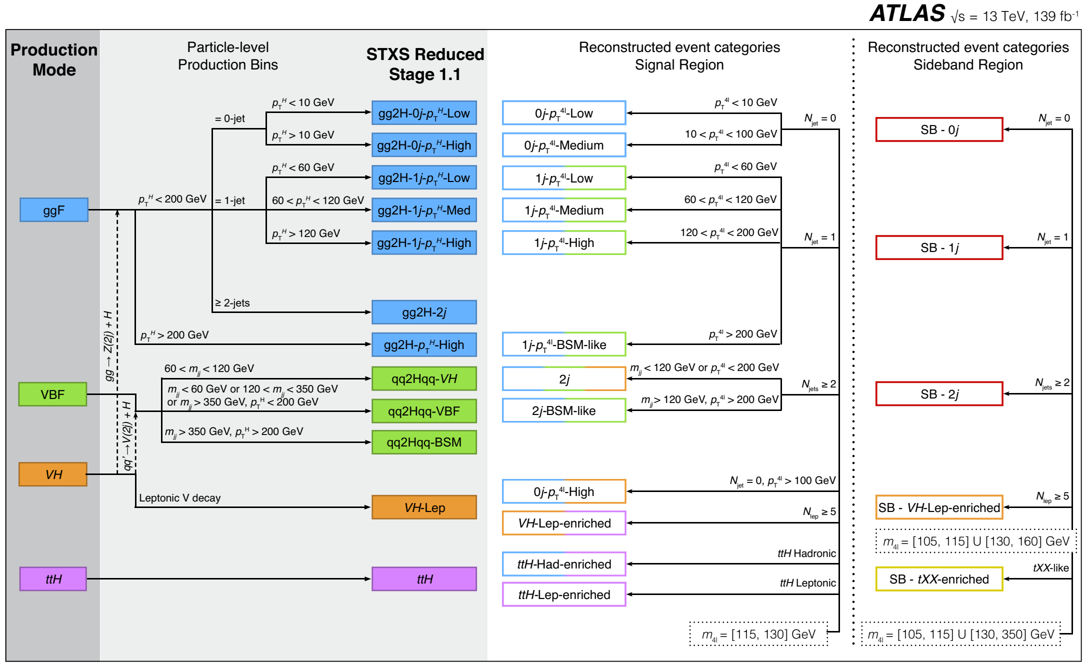
[JHEP 03 (2018) 095](#)

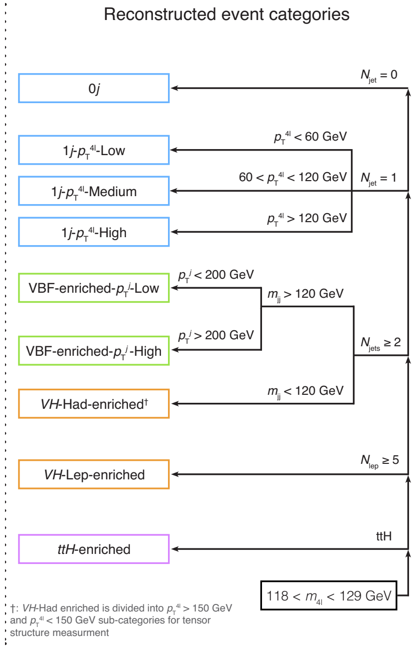
Full Run 2 analysis first use of Neural Networks in place of Boosted Decision Trees



[Eur. Phys. J. C 80 (2020) 957](#)

…to end up with 12 reco categories with full Run 2!

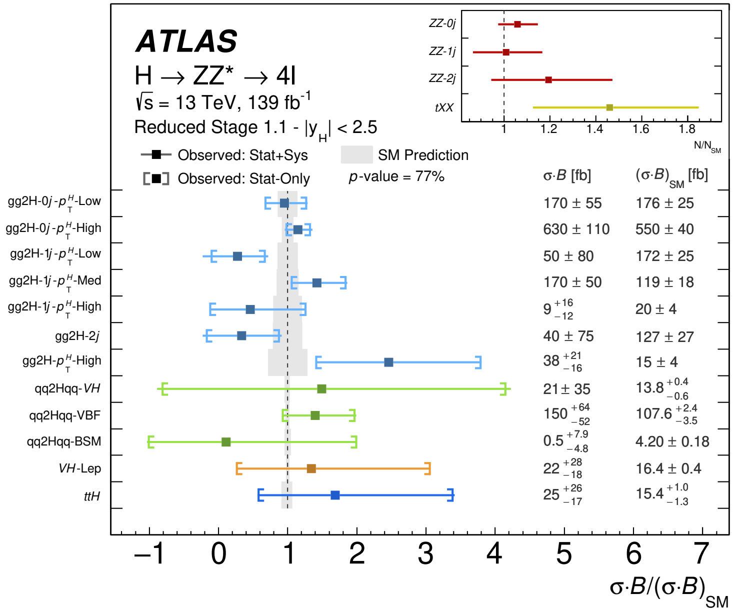




Tensor structure of the Higgs boson Couplings

Effective Field Theory (EFT)

Eur. Phys. J. C 80 (2020) 957



STXS measurements give enough sensitivity to probe anomalous Higgs boson couplings in EFT framework

- Run 1 and early Run 2 results started from Higgs Characterization (HC) model to put constraint on anomalous couplings with vector boson k_{HZZ} (CP-even) and k_{AZZ} (CP-odd)
- Full Run 2 moved to SMEFT to put constraints on Wilson coefficient in Warsaw basis C_i**

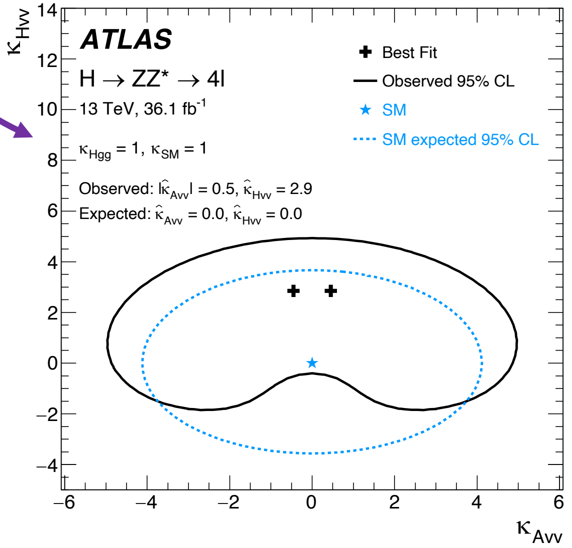
H→ZZ*→4l sensitive to just a sub-set of those coefficients

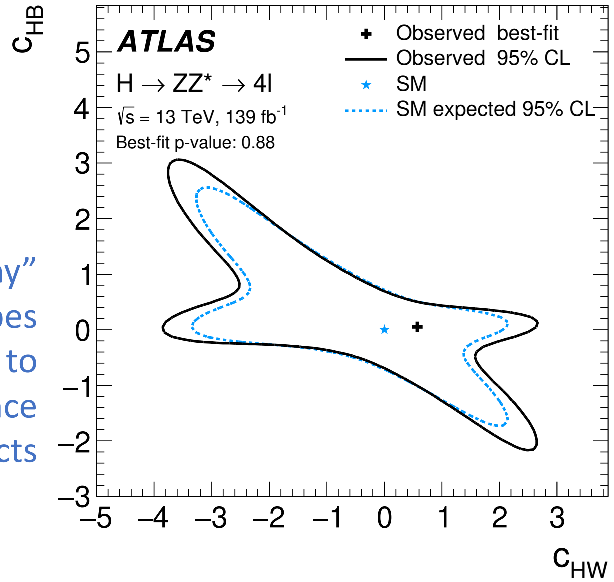
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} \quad \text{for } d > 4.$$

HC Lagrangian

$$\mathcal{L}_0^V = \Big\{ \kappa_{\text{SM}} \Big[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \Big] - \frac{1}{4} \Big[\kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + \tan\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \Big] - \frac{1}{4} \frac{1}{\Lambda} \Big[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \Big] - \frac{1}{2} \frac{1}{\Lambda} \Big[\kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + \tan\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \Big] \Big\} X_0.$$

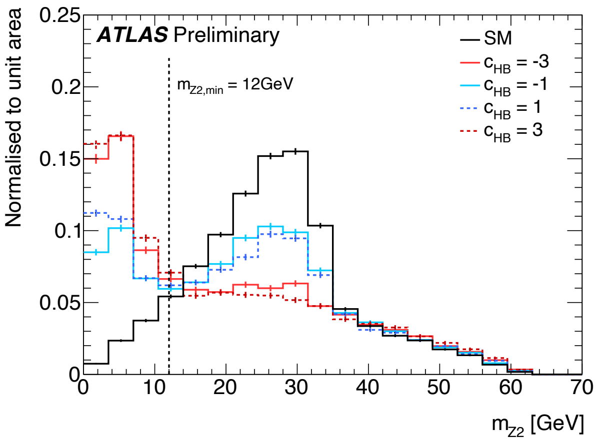
JHEP 03 (2018) 095

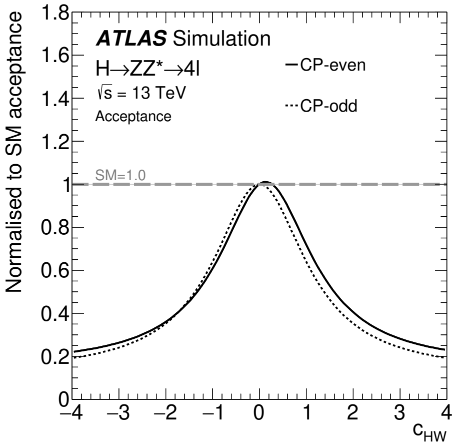




"funny" shapes related to acceptance effects

Acceptance parametrization needed due to the selection cuts





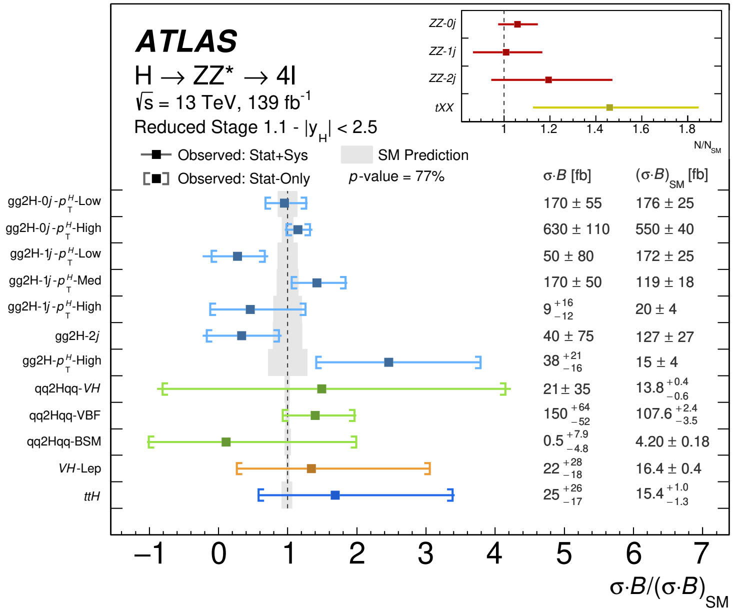
**

CP-even			CP-odd		
Operator	Structure	Coeff.	Operator	Structure	Coeff.
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\tilde{W}}$	$HH^\dagger \tilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\tilde{W}}$
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\tilde{W}B}$	$HH^\dagger \tau^l \tilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{W}B}$

Tensor structure of the Higgs boson Couplings

Effective Field Theory (EFT)

Eur. Phys. J. C 80 (2020) 957



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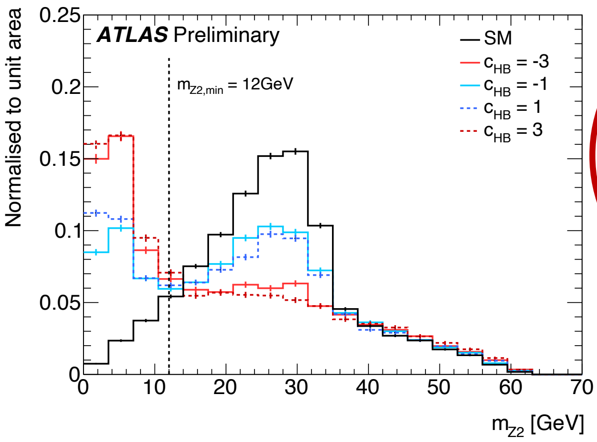
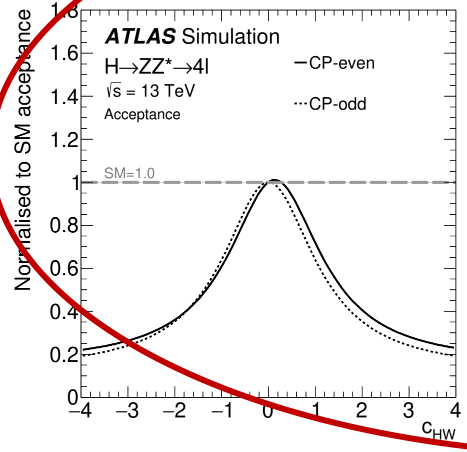
How to get rid of this?

Decay STXS

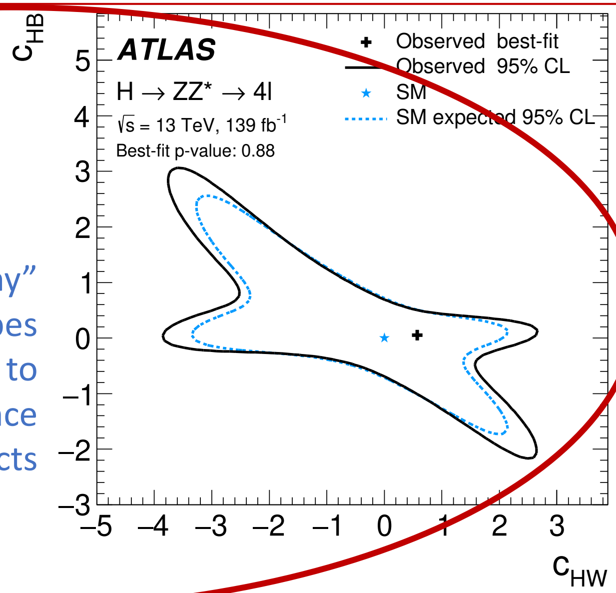
- Idea is to define STXS bins for Higgs decay modes analogous to the existing production mode bins
- Preliminary studies on a simple fiducial selection on H→4l which guarantee Lorentz invariance, lead flat acceptance for SM and BSM Montecarlo simulations

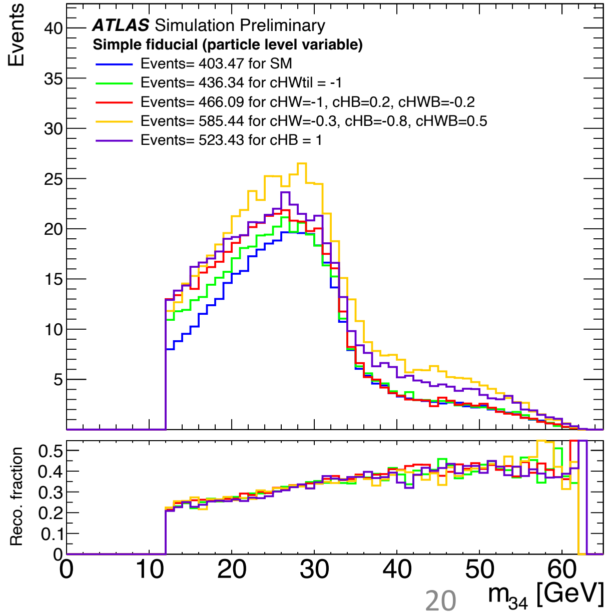
Acceptance parametrization needed due to the selection cuts





"funny" shapes related to acceptance effects

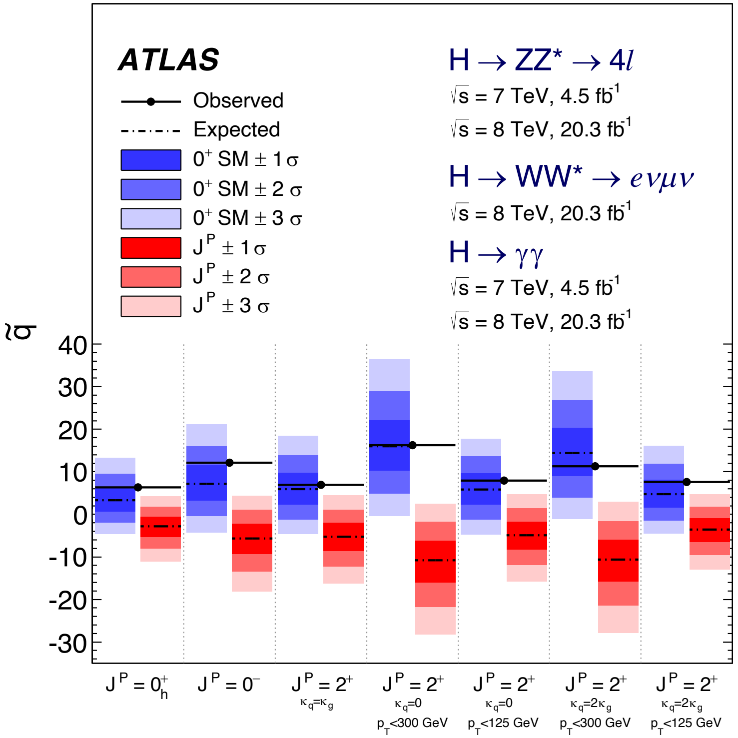




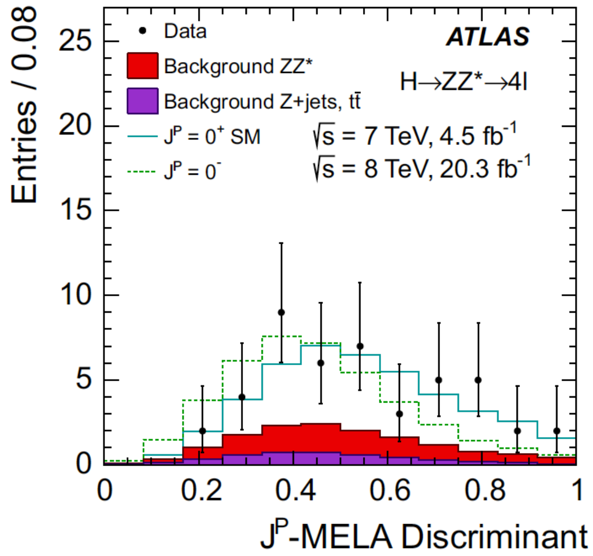
The Higgs boson CP structure

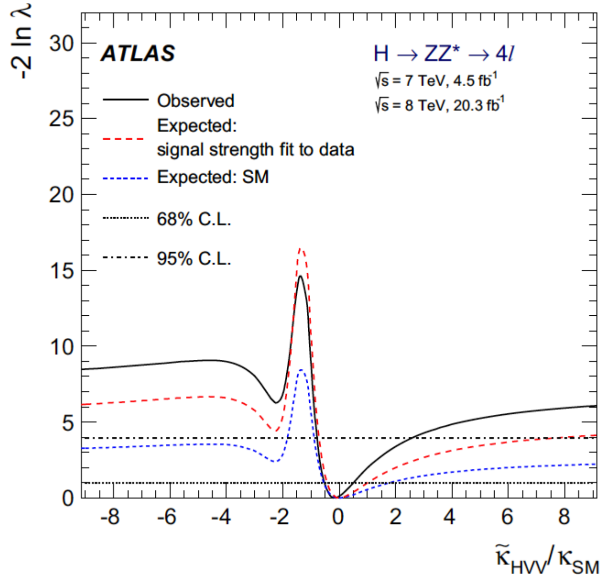
In Run 1 analyses aimed to assert that the Higgs boson is CP-even

Eur. Phys. J. C 75 (2015) 476



- Test of fixed spin and parity hypotheses
  - Using kinematic 4-lepton information
  - J^P MELA or BDT to discriminate different hypotheses
  - $J^P = 0^+$ compared with alternative spin models → non-SM hypothesis excluded with at least 99.9% CL in favor of SM Higgs boson with Spin/Parity 0^{++}
- Investigation of mixing CP-even and CP-odd state looking at HVV tensor structure
  - First use of the Optimal Observables…
  - EFT model based on Higgs Characterization
- In Run 2 the focus is mainly on production modes rather than decay only.

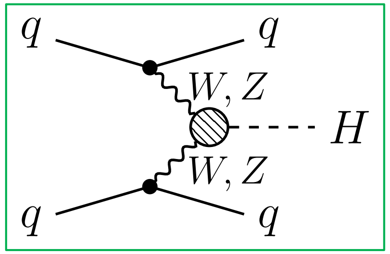




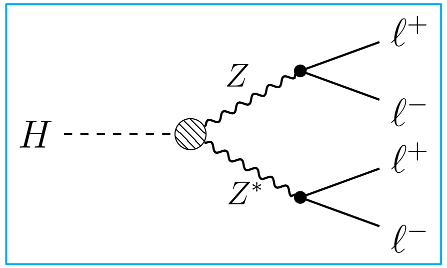
The Higgs boson CP structure

Looking for signs of CP-violation in the Higgs sector arXiv:2304.09612

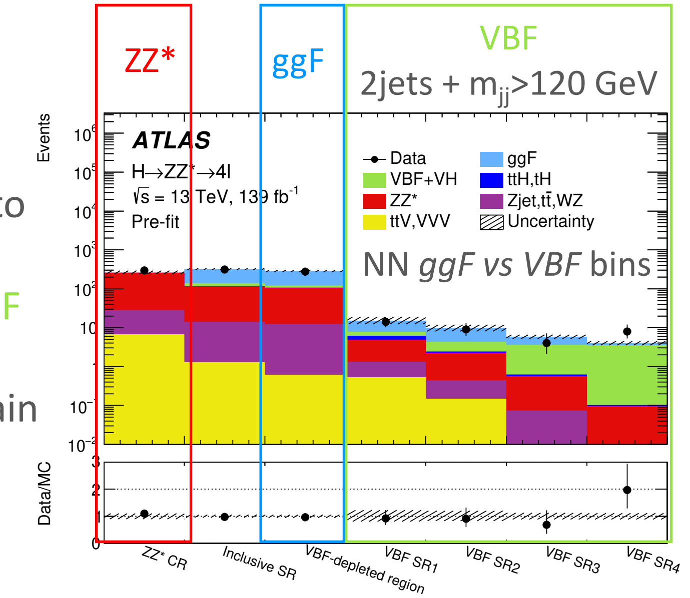
- Study the coupling with vector bosons (*HVV*) both at production level with Vector Boson Fusion (VBF) production and at decay level in the H→ZZ*→4l decay



VBF → high Q² process BSM effects expected to be higher



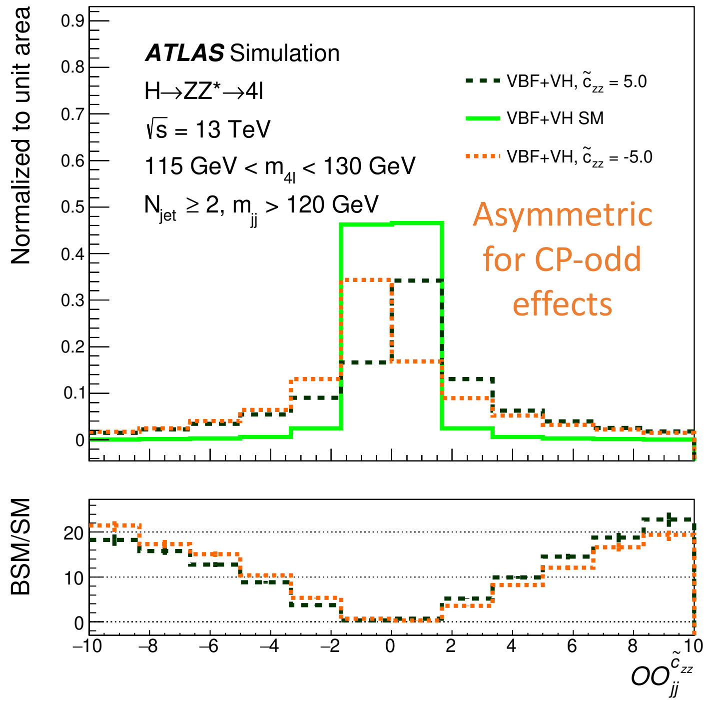
- **Categorization** to maximize the sensitivity to VBF production and estimate the main backgrounds



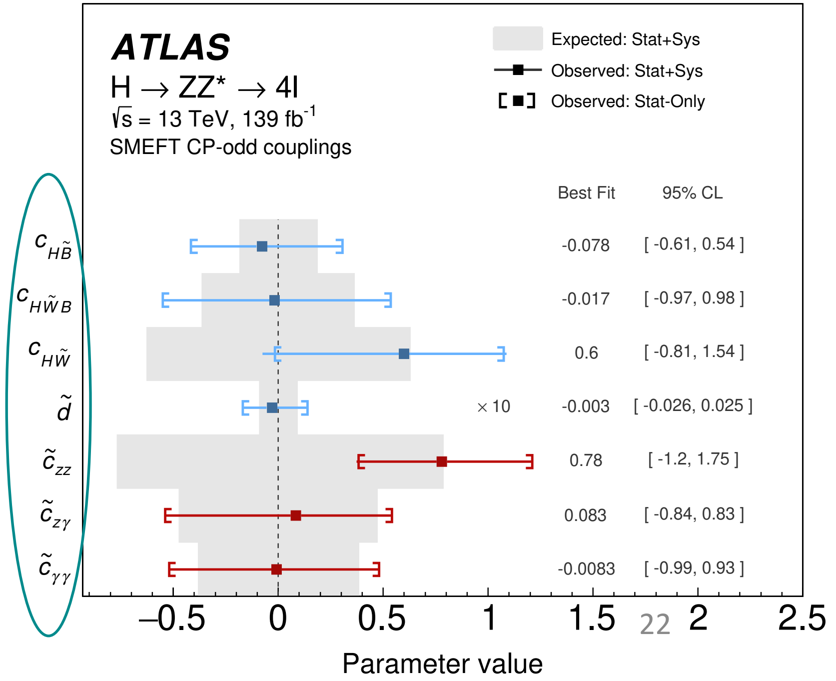
- Use of **observables** optimized to discriminate different CP hypothesis
  - Rate cannot disentangle anomalous CP-even or CP-odd effects, **observable shapes** does

→ Matrix – Element based variable called Optimal Observable (OO)

$$\mathcal{OO}_1(\boldsymbol{c}) = \frac{|\mathcal{M}_{\rm Mix}(\boldsymbol{c})|^2 - |\mathcal{M}_{\rm SM}|^2 - |\mathcal{M}_{\rm BSM}(\boldsymbol{c})|^2}{|\mathcal{M}_{\rm SM}|^2}$$



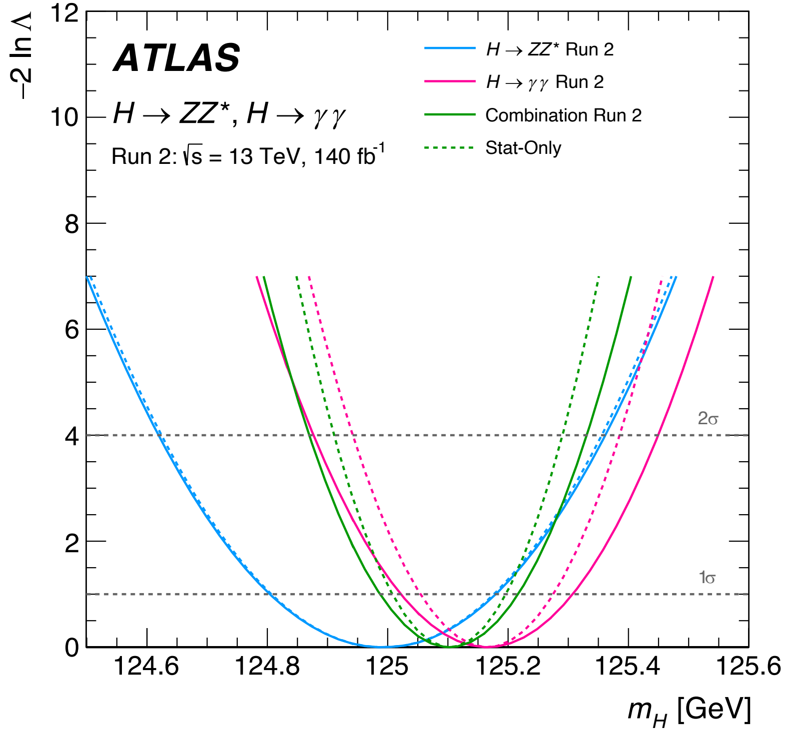
Constraint on EFT **CP-odd couplings**



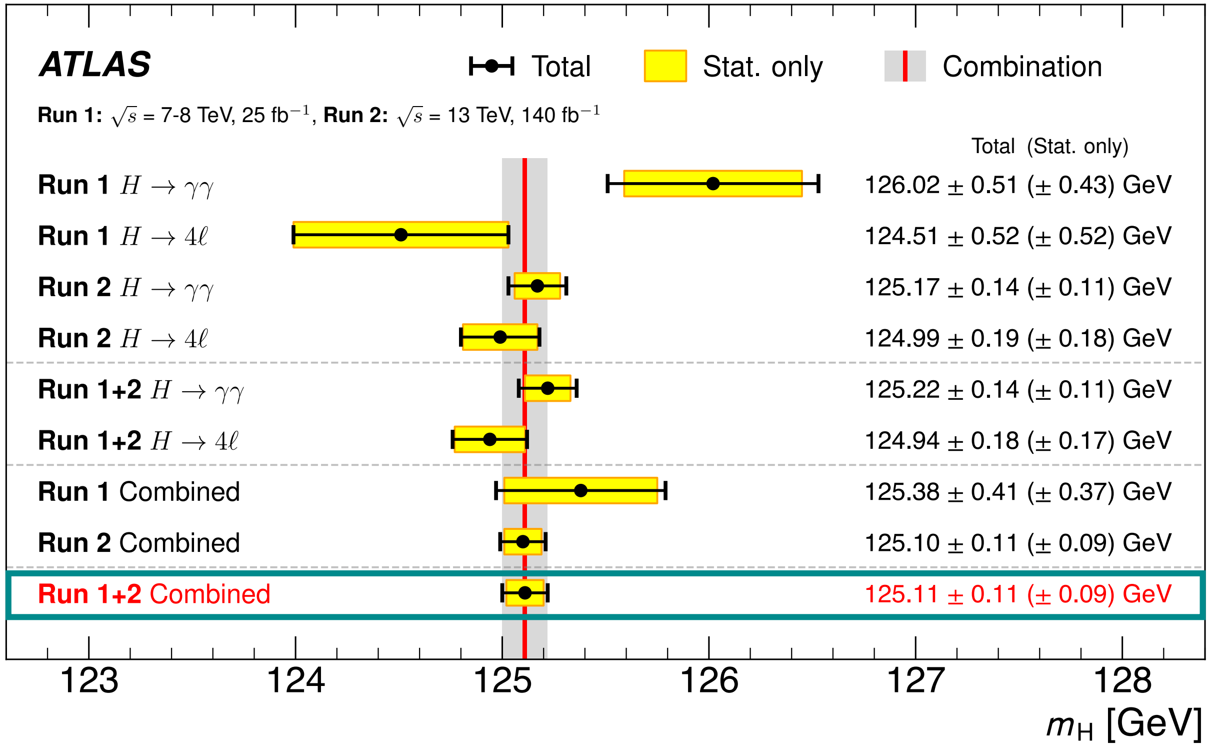
The Higgs boson Mass

H→ZZ*→4l and H→$\gamma\gamma$ are the most sensitive channels

- Clear signature final states
- High mass resolution 1-2 %
- Main uncertainties: Electron/Photon energy scale and Muon momentum scale
- Combination of the two channels and of the two runs lead to the **most precise measurement of the Higgs boson mass!**



Phys. Rev. Lett. 131 (2023) 251802



m_H = 125.11 ± 0.11 GeV

0.09% precision achieved on this fundamental parameter of the Standard Model of particle physics.

Conclusions

The ATLAS LNF group has been involved in the Higgs boson analyses since the very first searches aiming for its discovery and then to study its properties focusing on the $H \rightarrow ZZ^* \rightarrow 4l$ decay channel

- Besides the many results that has been provided in this years, we aim to extend the comprehension of the Nature looking for New Physics effects and the most recent discovered particle is a good starting point to do so
- The enhancement of the statistics expected in the future LHC runs will be fundamental to improve the precision of the Higgs boson measurements and be more sensitive to any kind of BSM effect

Stay Tuned!