Exploring Higgs Boson Properties

From Precision Measurements to Interpretation

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Queen Mary University of London - Seminar, 11th February 2026
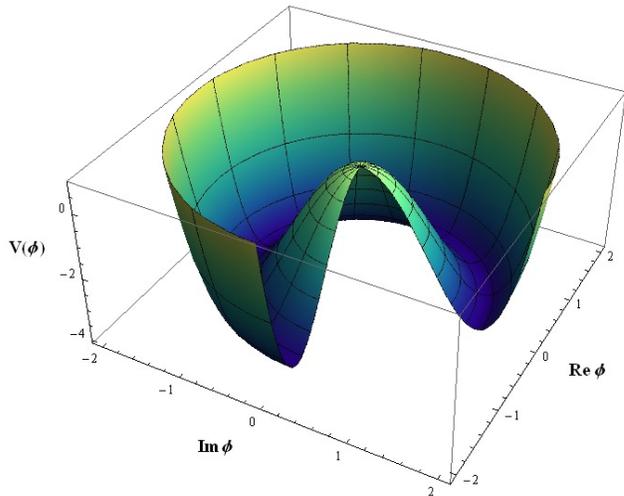
The Standard Model and the Higgs boson

- **Electromagnetic interaction**
- **Strong interaction**
- **Weak interaction**

Gauge bosons, fermions, interactions, but...

...no masses...

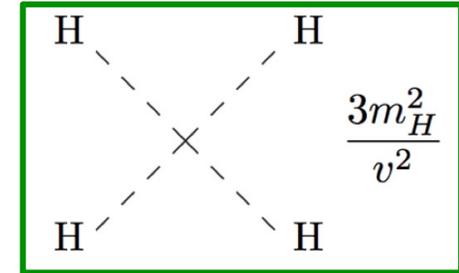Spontaneous symmetry breaking:

Higgs Mechanism

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \slashed{D} \psi$$

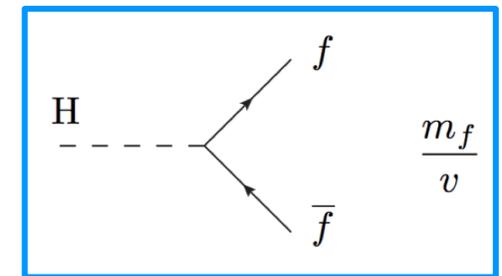$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Self - interactions

$$\frac{3m_H^2}{v^2}$$

Yukawa interactions

Fermion masses

$$\frac{m_f}{v}$$

Gauge interactions

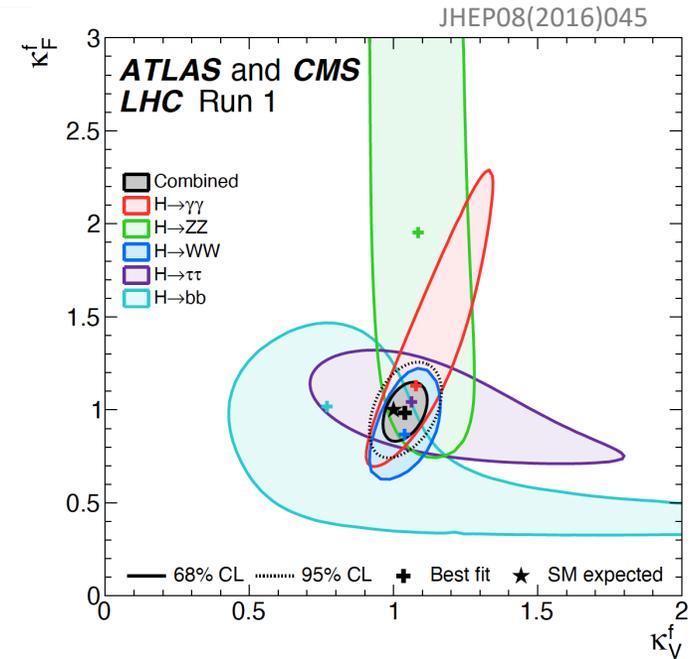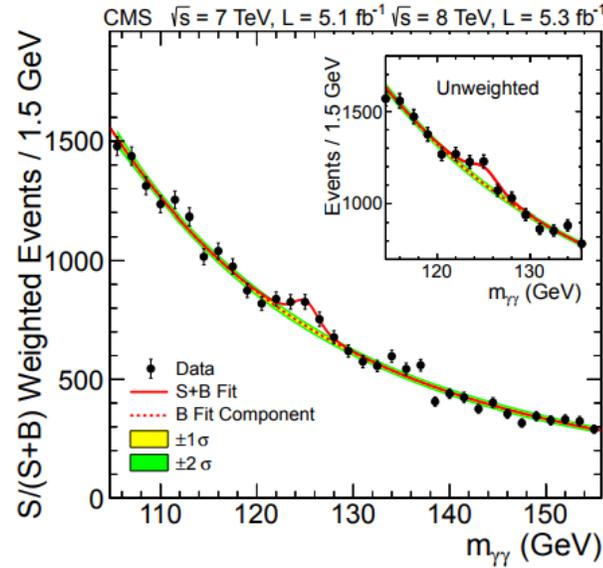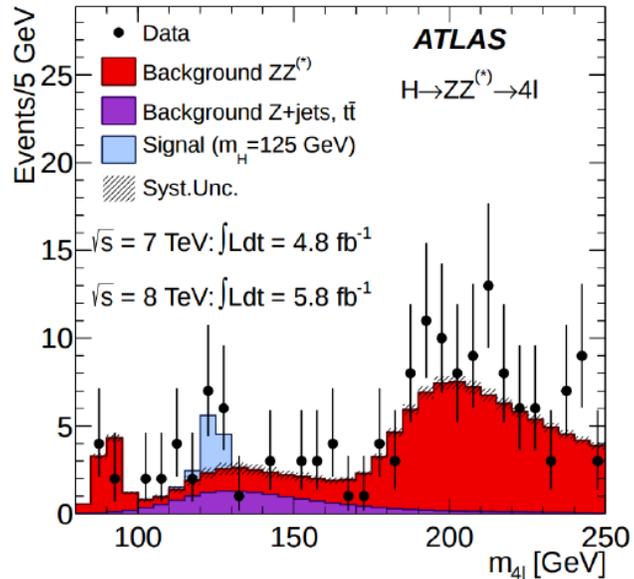$$\frac{m_V^2}{v^2}$$
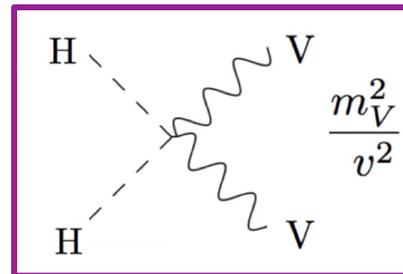
Gauge boson masses

$$\frac{2m_V^2}{v}$$
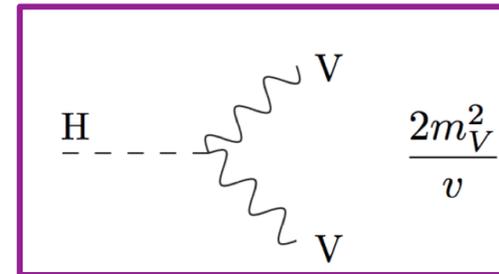
Couplings of the Higgs boson with the other particles as **fingerprints** of the Standard Model

The evolution of the Higgs boson

Discovery of the Higgs boson... and first measurements of its properties!

JHEP08(2016)045

Beginning of *Precision Era...*

More precise measurements
of the Higgs mass, width, couplings and cross sections

More stringent constraints on anomalous Higgs boson couplings with other SM particles
Interpretation of the results in different theoretical framework

...walking towards higher energy and higher luminosity

looking to the Higgs boson production at 13.6 TeV!

The Large Hadron Collider

## Proton – Proton collider of 27 km with 4 interaction points

Why protons? Protons consist of quarks and gluons → their interactions produce other particles

Higher Energy collisions with respect to electron-positron colliders → hadron colliders are for *"Discovery"*

Run 1 (2011-2012)
$\sqrt{s} = 7 - 8$ **TeV**

Run 2 (2015-2018)
$\sqrt{s} = 13$ **TeV**

Run 3 (2022-now)
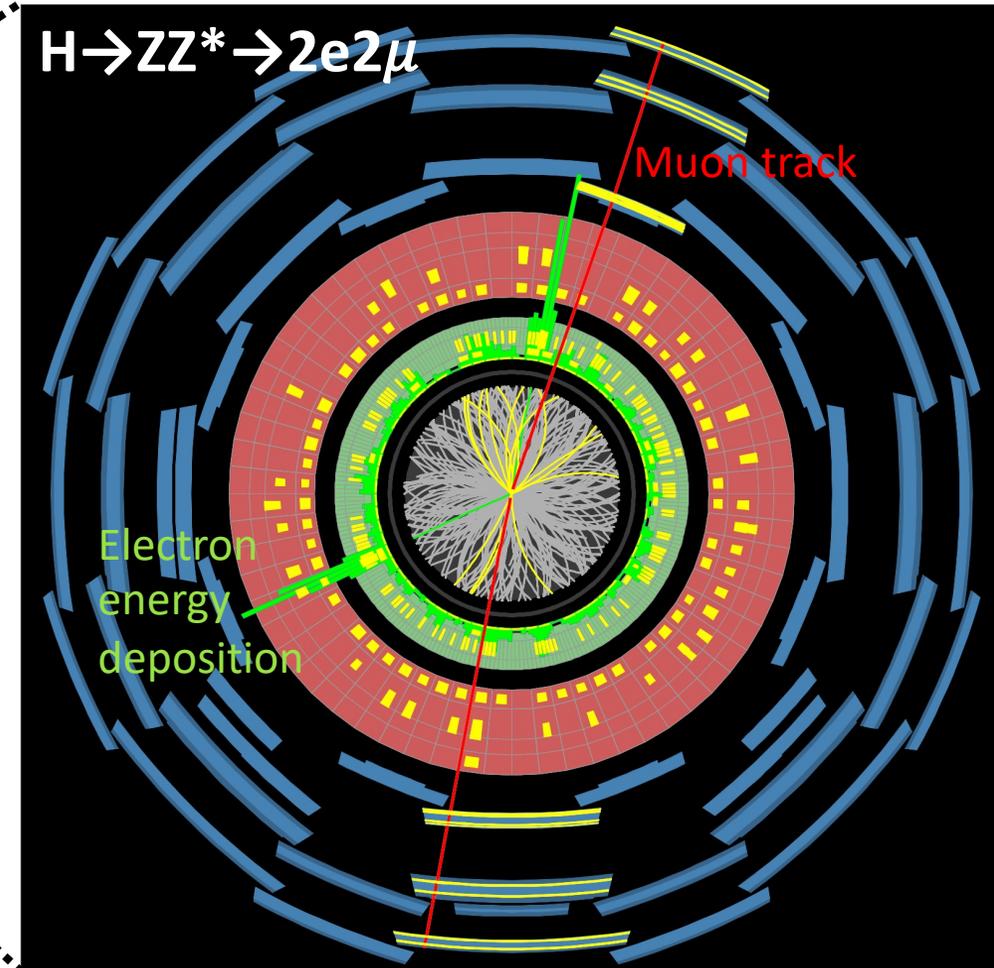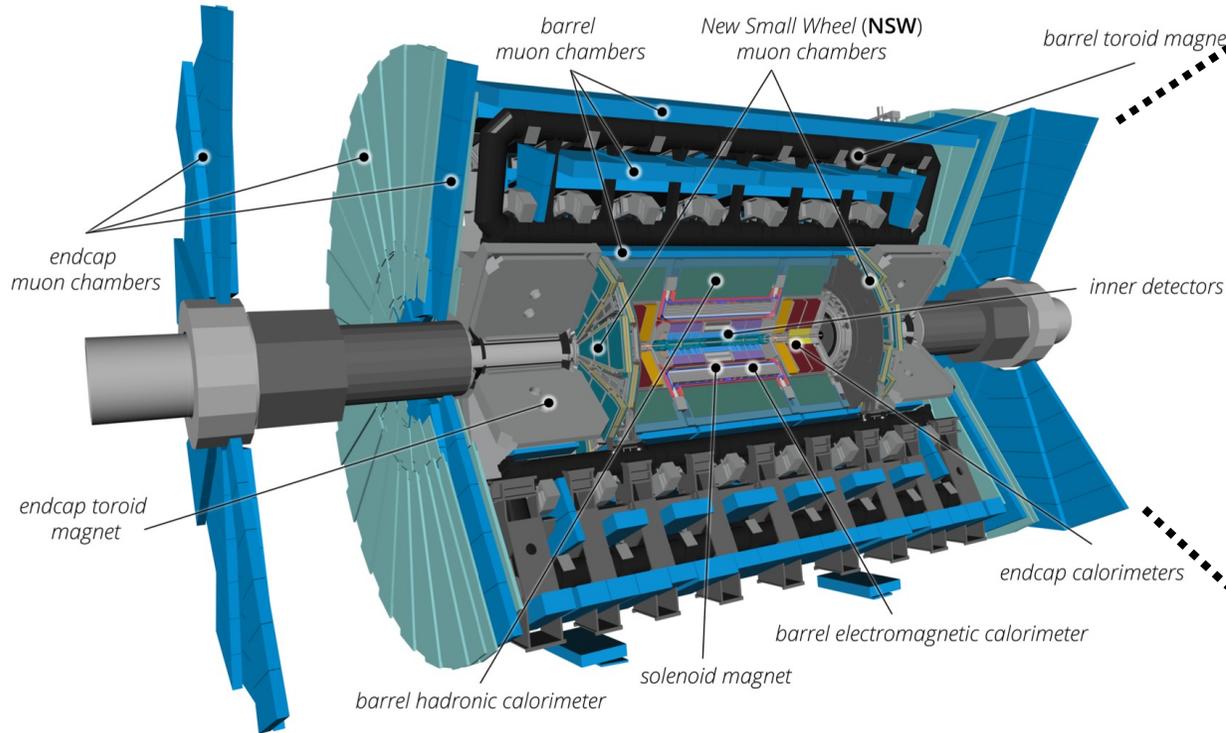$\sqrt{s} = 13.6$ **TeV**

Amount of data collected in the collisions is called **Luminosity**
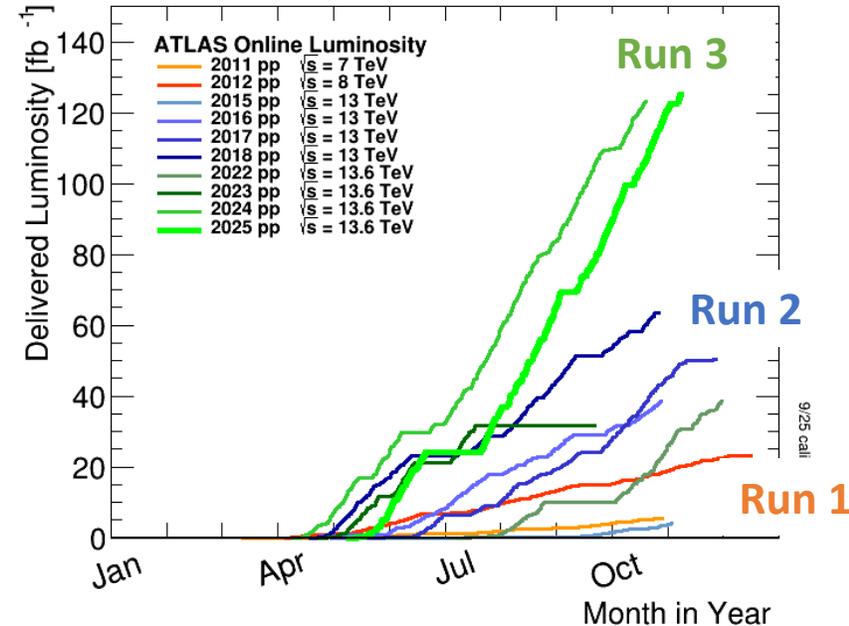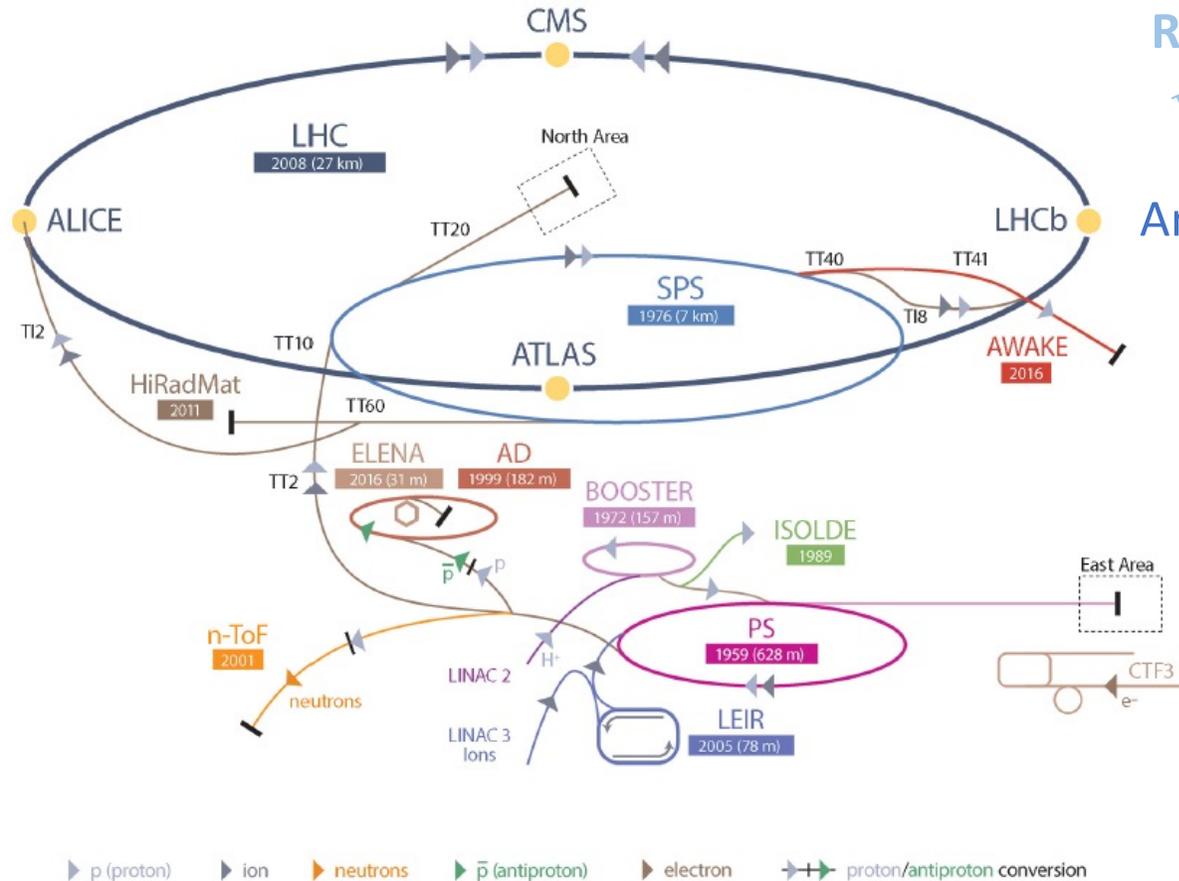
LHC collected **more than 450 fb⁻¹** of integrated luminosity until today since 2011

The ATLAS Detector

H→ZZ*→2e2μ

Muon track

Electron energy deposition

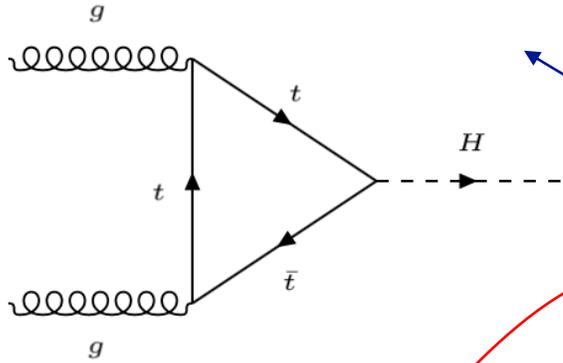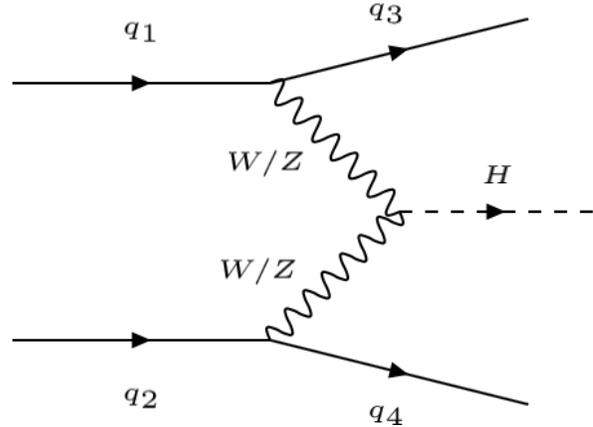- **Inner Detector**
  - **Vertex detector**: pixel detector
  - **Trackers**: SCT, TRT

- **Calorimeters**
  - **Electromagnetic (ECAL)** : sampling Lar + lead
  - **Hadronic (HCAL)** : TileCal + LAr (endcap)

- **Magnet System**
  - **Solenoid** (2 T) + **Toroid** (0.5 – 1 T)

- **Muon Spectrometer (MS)**
  - **Trackers**: MDT, Micromegas
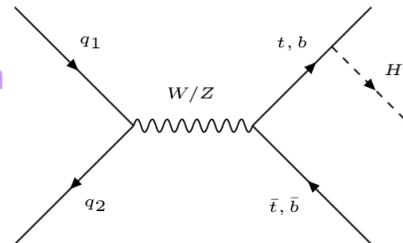 - **Trigger**: RPC, TGC, sTGC

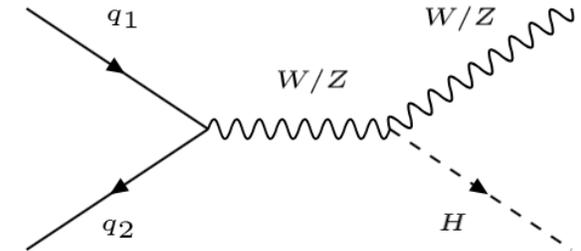# The Higgs boson production @ LHC

gluon-gluon fusion (ggF)

Associated production with a vector boson (VH)

Vector boson fusion (VBF)

Associated production with top/bottom quark pair (ttH/bbH)

Associated production with single top (tH)

$\sigma(pp \rightarrow H+X)$ [pb]

M(H)= 125 GeV

LHC HIGGS XS WG 2016

$pp \rightarrow H$ (N3LO QCD + NLO EW)

$pp \rightarrow qqH$ (NNLO QCD + NLO EW)

$pp \rightarrow WH$ (NNLO QCD + NLO EW)

$pp \rightarrow ZH$ (NNLO QCD + NLO EW)

$pp \rightarrow bbH$ (NNLO QCD in 5FS, NLO QCD in 4FS)

$pp \rightarrow ttH$ (NLO QCD + NLO EW)

$pp \rightarrow tH$ (NLO QCD, t-ch + s-ch)

$\sqrt{s}$ [TeV]
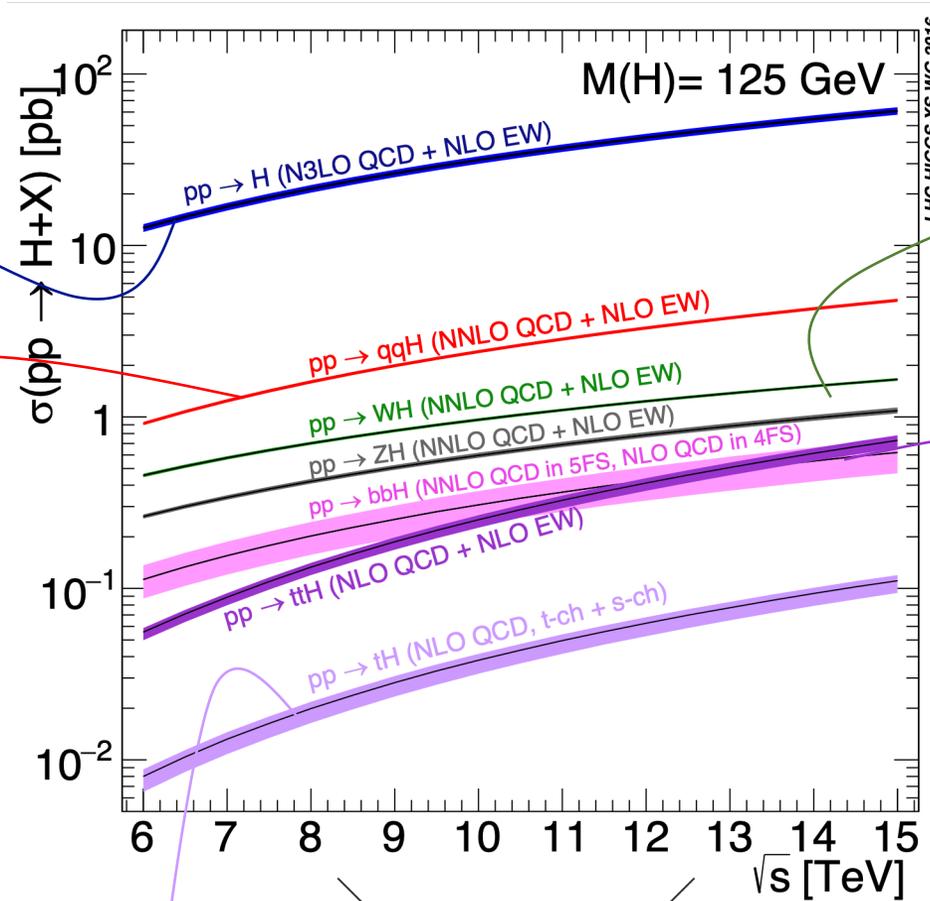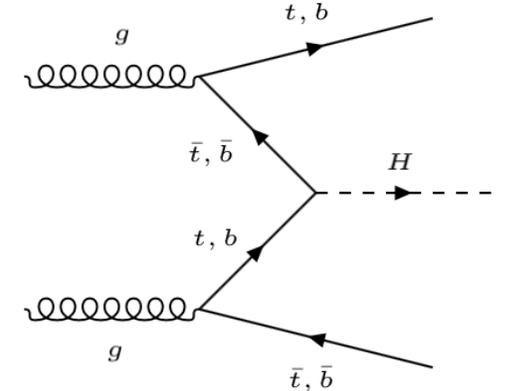
The Higgs boson decay modes

Hard to detect decays

$H \rightarrow c\bar{c}$

$H \rightarrow gg$
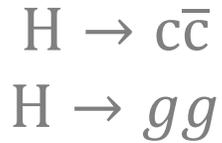
Most precise decays

$H \rightarrow ZZ^*$

$H \rightarrow \gamma\gamma$

High mass resolution

High probable decays

$H \rightarrow b\bar{b}$

$H \rightarrow W^+W^-$

$H \rightarrow \tau^+\tau^-$
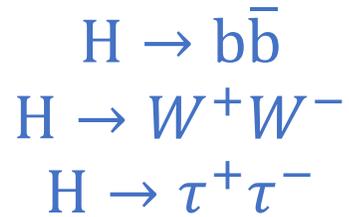
high backgrounds and
poor mass resolution

Rare decays

$H \rightarrow \mu^+\mu^-$

$H \rightarrow Z\gamma$

ZZ
2,60%

$\gamma\gamma$
0,2%

Zγ
0,15%

μμ
0,02%

cc
3%

gg
9%

$\tau\tau$
6%

WW
21%

bb
58%

The *Golden Channel*: H→ZZ*→4l
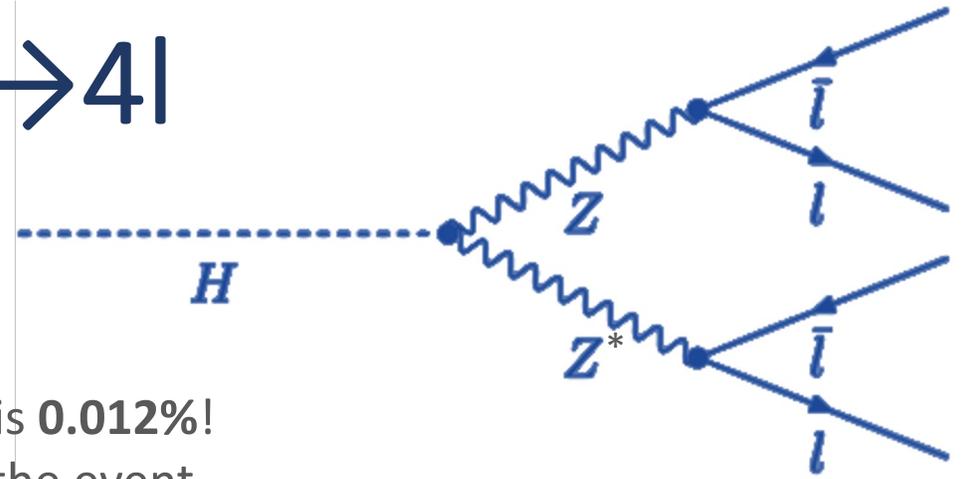
Fully leptonic final state
→ probability to detect it is **0.012%**!
→ very clear signature of the event

Final States: 4μ, 2μ2e, 2e2μ, 4e

Very good mass resolution thanks to the excellent lepton reconstruction performance
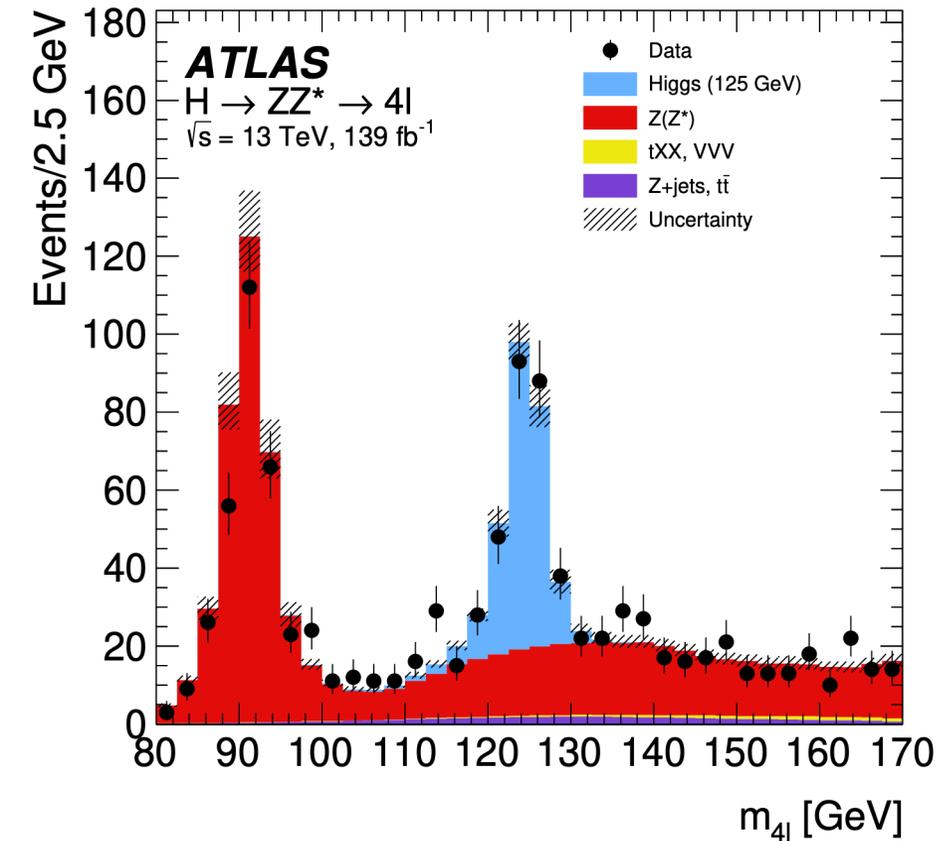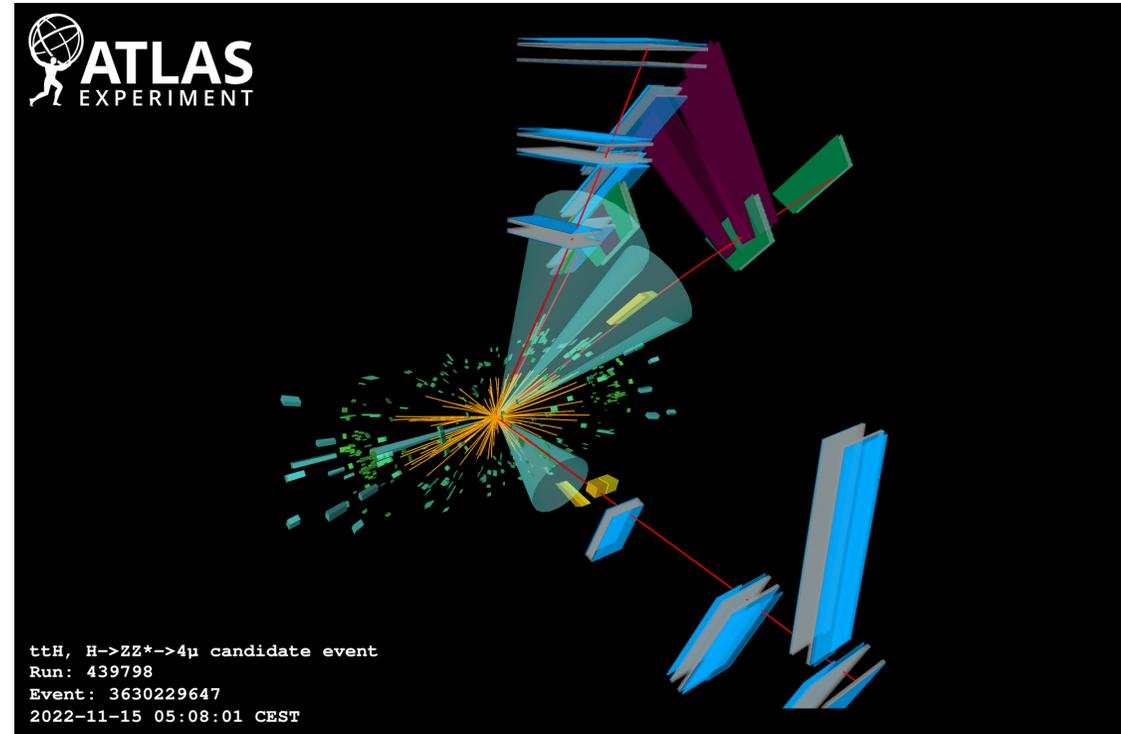
Very good Signal/Background ratio ~ 2

→ clearly identifiable over the background

H→ZZ*→4l: Higgs candidate selection

Two Same-Favour and Opposite-Sign (SFOS) lepton pairs

Leptons are required to be well separated and with $p_T > 20,15,10$ GeV
and coming from a **common vertex**
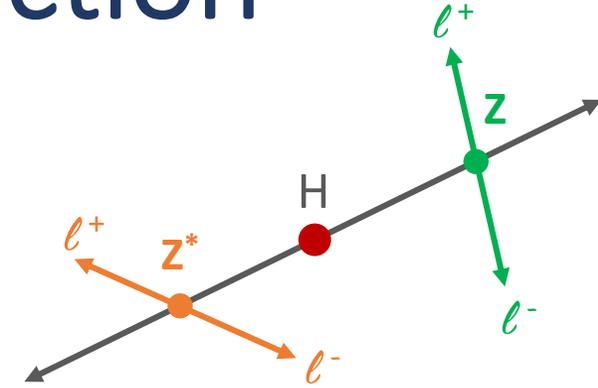
Mass requirements

On-shell Z
$50 < m_{12} < 106$ GeV

Off-shell Z
$m_{thr}* < m_{34} < 115$ GeV
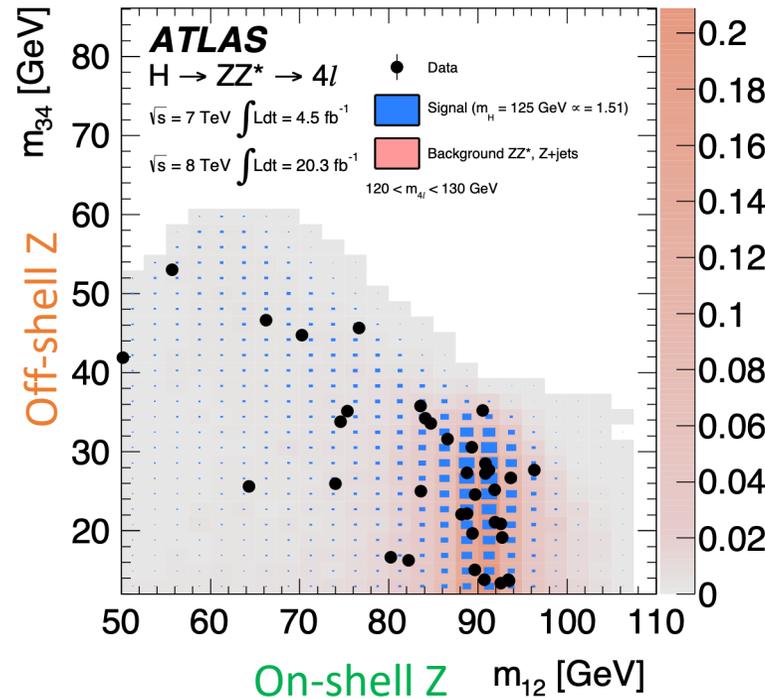
Lepton Isolation
Track- and calorimeter- based
isolation requirements applied

Impact parameter
d_0 significance cut
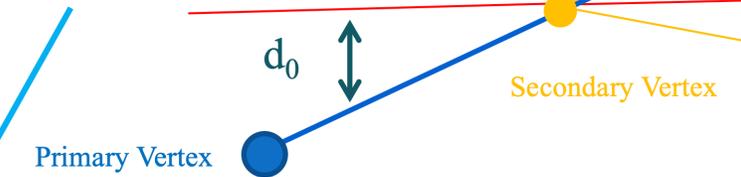
Suppress $t\bar{t}$ and Z+jets background

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

H→ZZ*→4l: background estimation
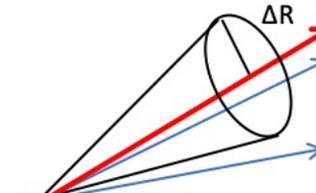
Irreducible Background (with 4 prompt leptons)

- ZZ* non-resonant production: 4 prompt leptons → estimated **from data** in the mass sidebands [105-115] + [130-160] GeV

- VVV and tXX from simulation
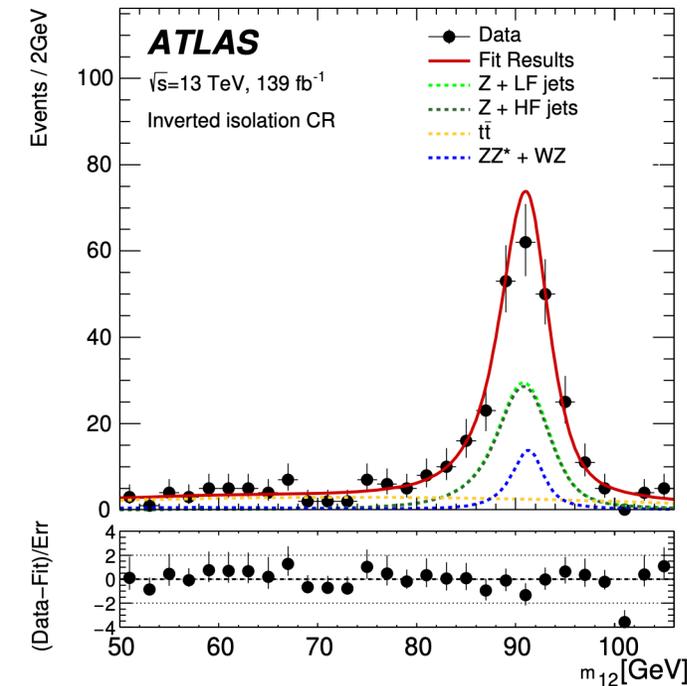
Reducible Background ($t\bar{t}$, Z+jets, WZ)

2 prompt leptons (Z) + 2 leptons from semi-leptonic decays (b- or c- quark)

- Control Regions (CR) defined inverting or relaxing Higgs candidate requirements

- Data-driven estimation in the CRs of the single components → extrapolated into the Signal Region
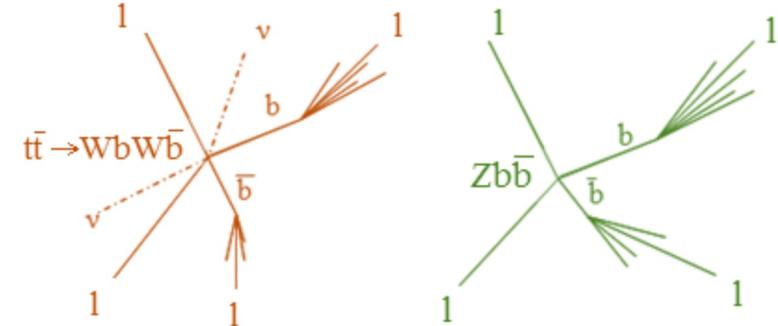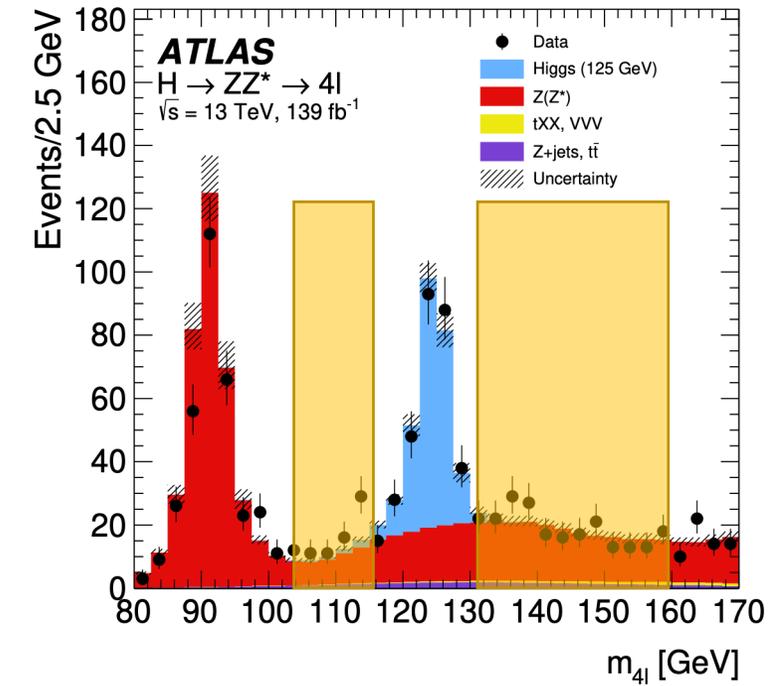
Higgs Cross Sections as Precision Observables

Cross section measurements are the core of the Higgs boson precision physics
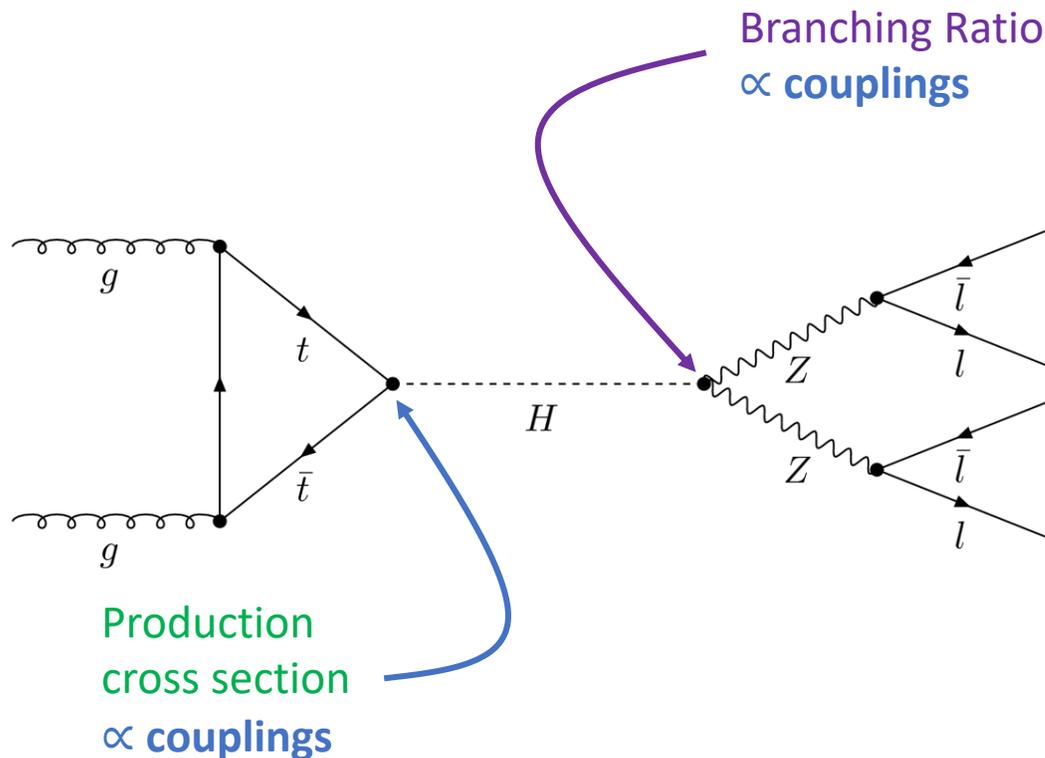
σ: **cross sections** as probability to produce Higgs bosons

BR: **Branching Ratios** as probability that the Higgs decay in a specific channel

What do we measure? $\sigma \times$ **BR**

How do we measure it?

Branching Ratio $\propto$ **couplings**

$\propto$ selection efficiency

$$N_{obs} = \sigma \times BR \times L \times \varepsilon$$

$\propto$ Luminosity

Experimentally, we can only measure **number of events** selected as Higgs candidate

Production cross section $\propto$ **couplings**

From inclusive to differential measurements

Measure σ × BR for different **Production Modes**

Measure σ × BR in bins of **Final-State Observables**
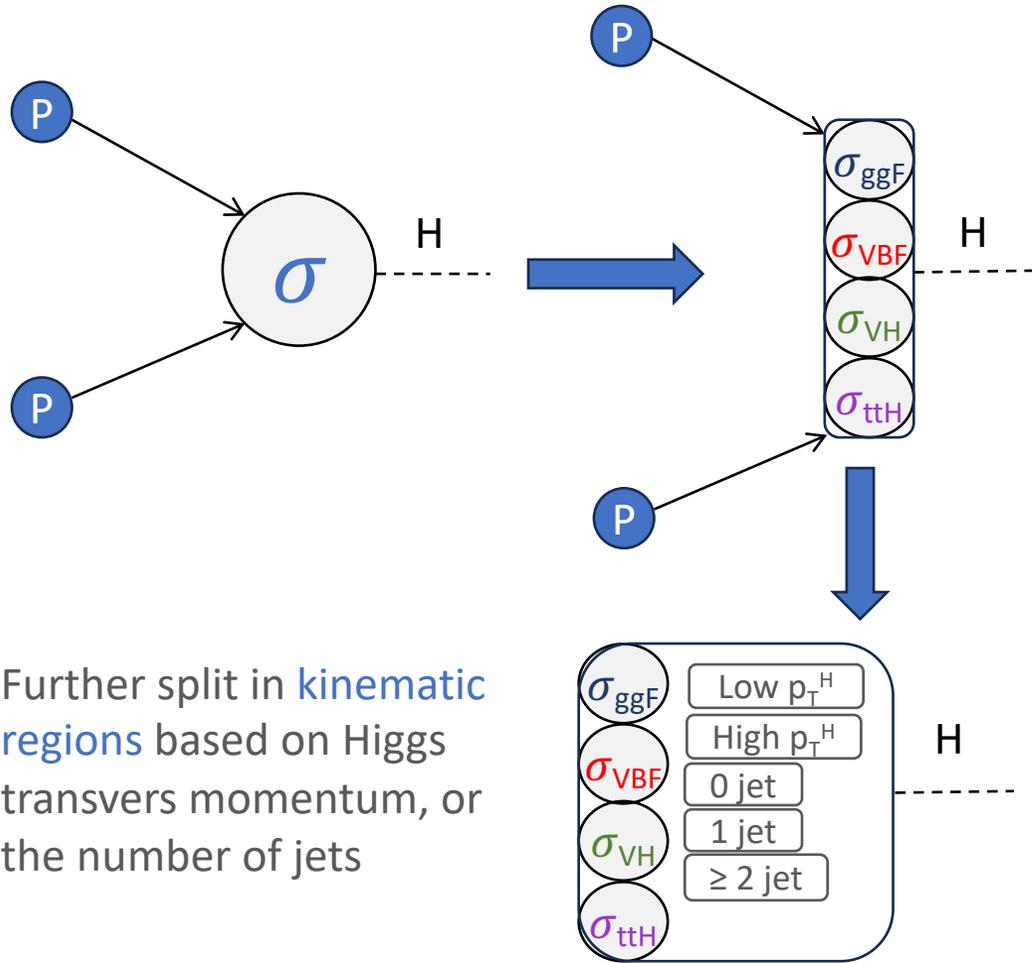
Further split in kinematic regions based on Higgs transvers momentum, or the number of jets
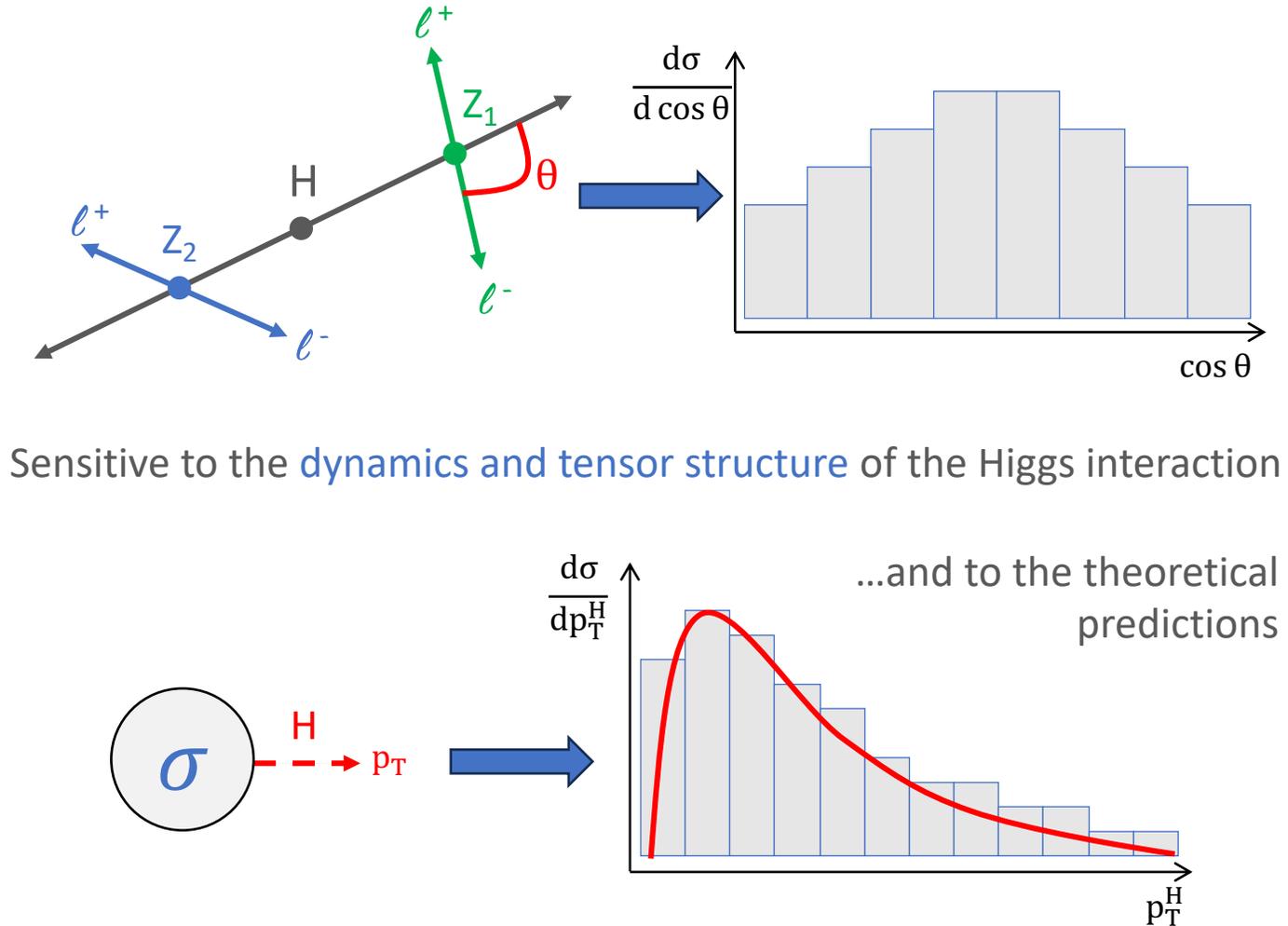
Sensitive to the dynamics and tensor structure of the Higgs interaction

…and to the theoretical predictions

Interpretations frameworks

Kappa-framework

Rescale Standard Model couplings

$$\sigma_i \times \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H}$$

$$\kappa_j^2 = \frac{\sigma_j}{(\sigma_j)_{SM}} \qquad \kappa_j^2 = \frac{\Gamma^j}{(\Gamma^j)_{SM}}$$

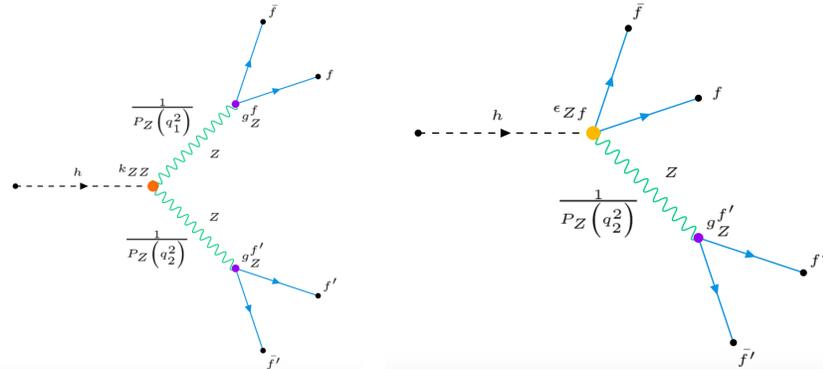- Directly links rates to coupling strengths
- Simple, intuitive, widely used
- Sensitive only to effects on the rate

Pseudo - Observables

Parametrize momentum expansion of the on-shell Higgs decay amplitude

$$\frac{d\Gamma}{dm_{12}dm_{34}} \propto \sum_{f,f'} |F^{ff'}(m_{12}^2, m_{34}^2)|^2$$

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

- Test kinematic structure of the interaction
- Easy interpretation of the effective coupling POs

Effective Field Theory

Add higher-dimensional operators to SM Lagrangian

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

- Directly access possible anomalous couplings (*Wilson coefficients*) and new heavy physical states
- Interpret both shapes and rates in a field-theory framework

Different frameworks extract *different kinds* of information about Higgs couplings.

CP violation: anomalous Higgs couplings
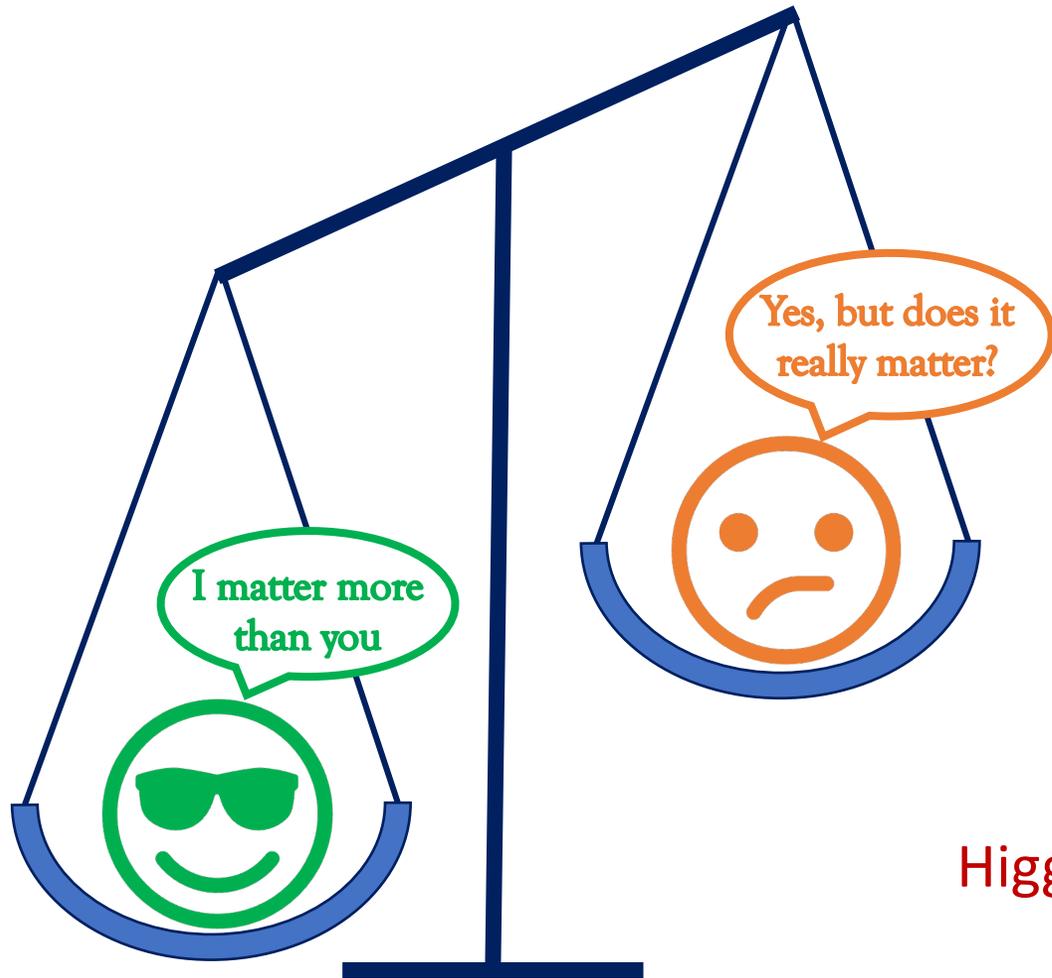
The asymmetry between the **matter** and **antimatter** content in the universe is one of the unsolved problems in Physics

It implies the violation of the charge conjugation and parity symmetry

Standard Model can explain just a small level of the CP-violation required

→ Other sources of CP-violation must exist Beyond the Standard Model

Higgs is a good candidate to look at!

SM: Spin 0 and CP-even particle

We can look at the tensor stucture of the Higgs interactions to identify possible mixed CP-even and CP-odd state

From Precision Measurements...

Fiducial and Production Cross Sections

Fiducial Cross Sections measurement

Provide cross section measurements in the most model independent way
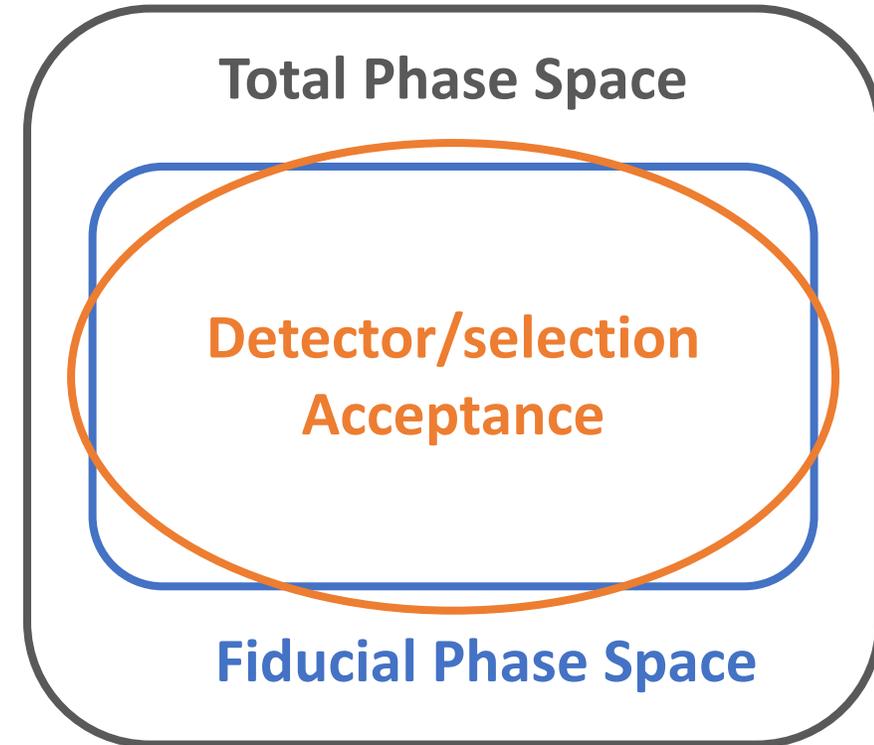
- **Fiducial phase space at particle-level** definition based on detector and analysis selection acceptance to minimize the extrapolation effects. The **fiducial cross section $\sigma_{fid} \cdot BR$** is defined as:

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

where:
BR = Branching ratio
A = acceptance

Total Phase Space

Detector/selection Acceptance

Fiducial Phase Space

Fiducial Cross Sections measurement

Provide cross section measurements in the most model independent way

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

$$\sigma_{fid} \cdot BR = \sigma_{tot} \cdot BR \cdot A$$

$$A = \frac{N_{fiducial}}{N_{total}}$$

where:
BR = Branching ratio
A = acceptance

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

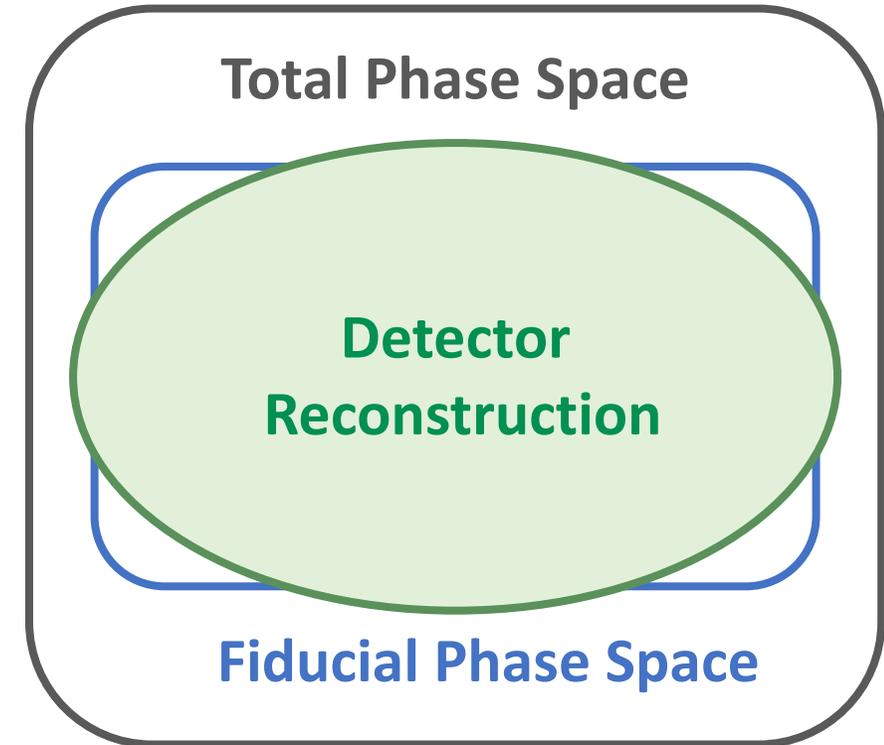$$\sigma_{fid} \cdot BR = \frac{N_{signal}}{C_F \cdot L_{int}}$$

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

where:
L_{int} = integrated luminosity
C_F = correction factor
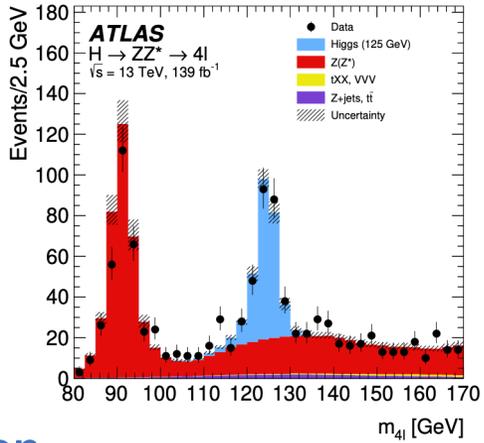N_{signal} = number of signal events extracted **fitting the observable able to discriminate signal vs background.**

Total Phase Space

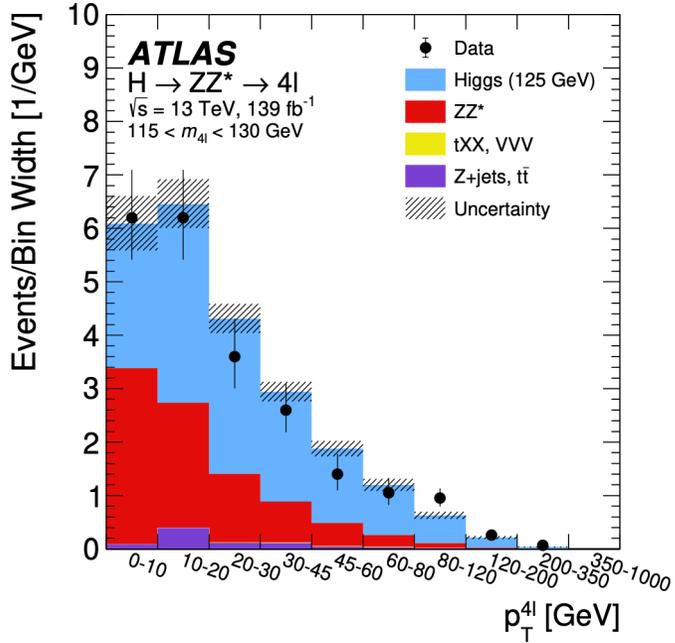**Detector Reconstruction**

Fiducial Phase Space

We ***unfold*** the reconstructed distribution of a given observable to estimate the particle-level spectrum

Fiducial Differential Cross Sections measurement

Discriminant Signal vs Background
Observable is m_{4l}
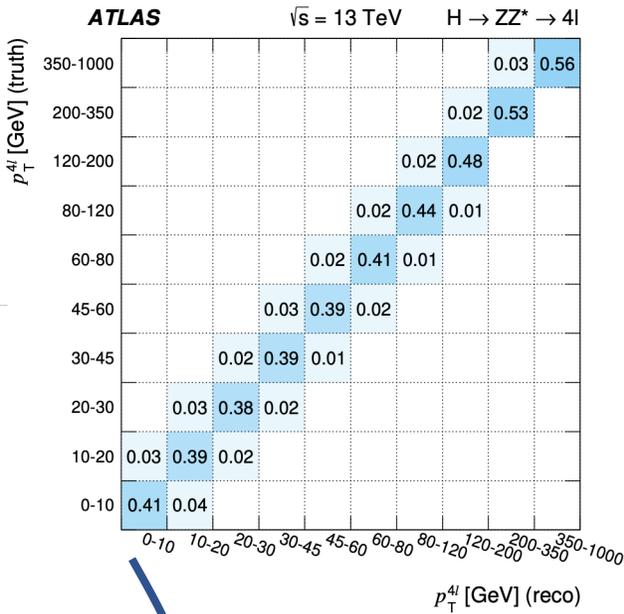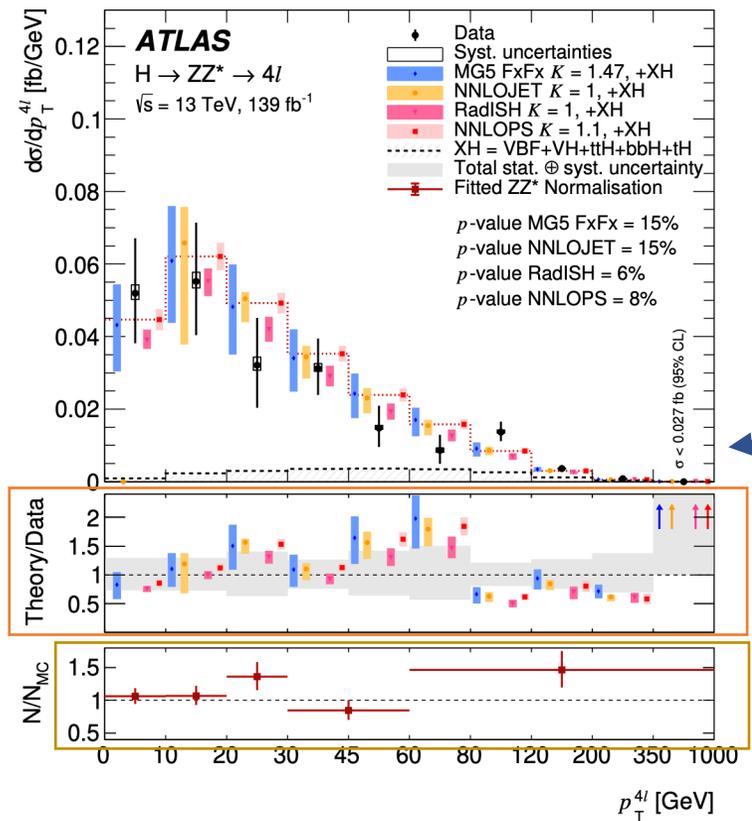template fit in each variable bin

Reconstructed distribution

Particle – level distribution

Unfolding correcting for detector effects:
acceptance and fiducial efficiency

Compatibility between data and different theoretical predictions

ZZ* background estimation from data

Fiducial Differential Cross Sections measurement

Observables studied are sensitive to different Higgs boson properties or theoretical predictions

Higgs kinematic variables (some)

p_T^{4l}: perturbative QCD, light quark coupling

y^{4l}: parton density function

m_{12}, m_{34}, $\cos\theta_1$, $\cos\theta_2$, ϕ, ϕ_1, $\cos\theta^*$: Sensitive to spin/parity properties in the decay vertex
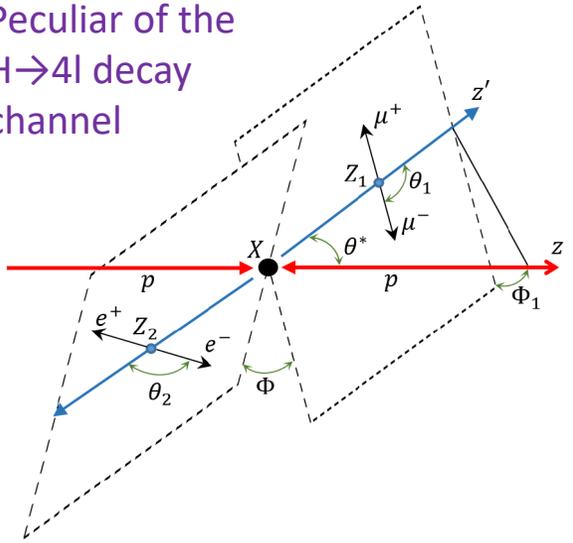
Jet – related variables (some)

N_{jet}, m_{jj}, $\Delta\eta_{jj}$: different production mode

p_T^{j1}, p_T^{j2}: quark gluon radiation

$\Delta\phi_{jj}$: Sensitive to spin/parity properties in the VBF production vertex
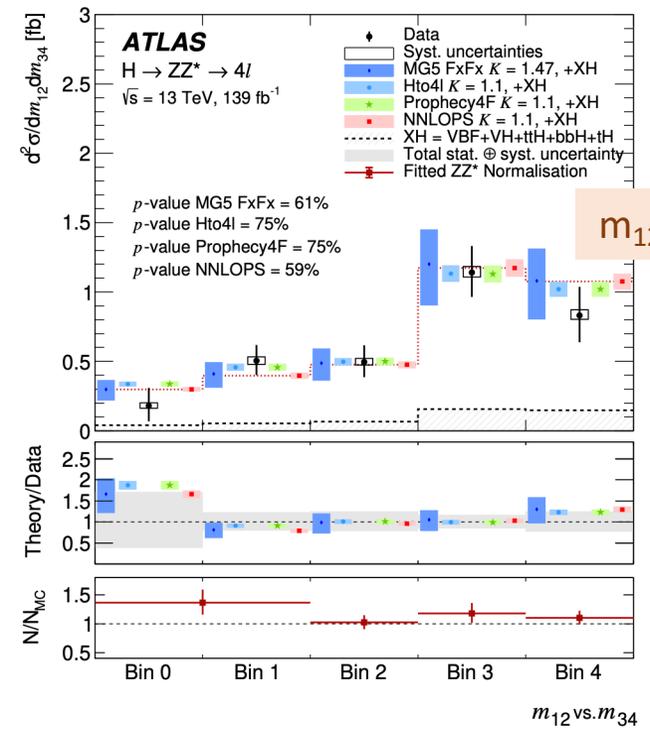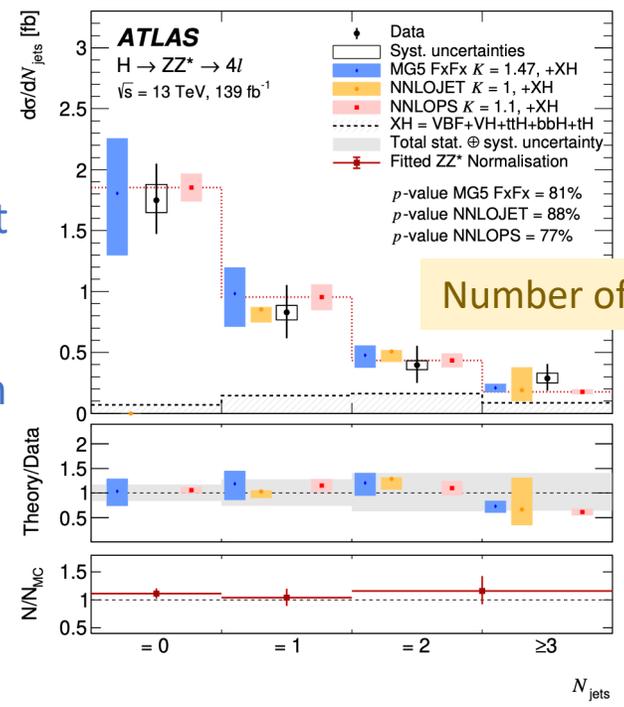
2D differential distributions (some)

$m_{12}m_{34}$: modification HZZ vertex
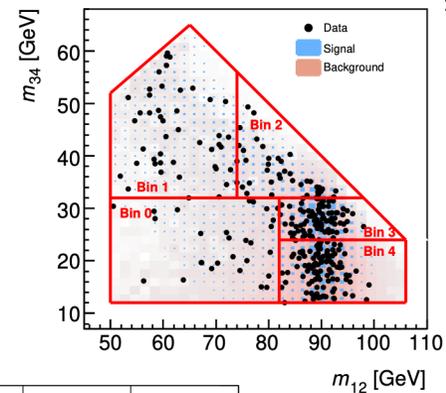
Peculiar of the H→4l decay channel

Run 2 provided very large dataset of 140 fb^{-1} increasing the sensitivity in each differential bin

Number of jets

m$_{12}$ vs m$_{34}$

Selection of results from Run 2 paper

Fiducial Differential Cross Sections measurement

Observables studied are sensitive to different Higgs boson properties or theoretical predictions

Higgs kinematic variables (some)
m_{12}, m_{34}, $\cos\theta_1$, $\cos\theta_2$, ϕ, ϕ_1, $\cos\theta^*$: **Sensitive to spin/parity properties in the decay vertex**

| Jet – related variables (some) |
|---|
| $\Delta\phi_{jj}$: **Sensitive to spin/parity properties in the VBF production vertex** |

Lepton and jets kinematic information can be combined in a much more powerful observable sensitive to CP effects → **Optimal Observable**

The matrix element of the process is the sum of a SM CP-even contribution plus a BSM CP-odd one
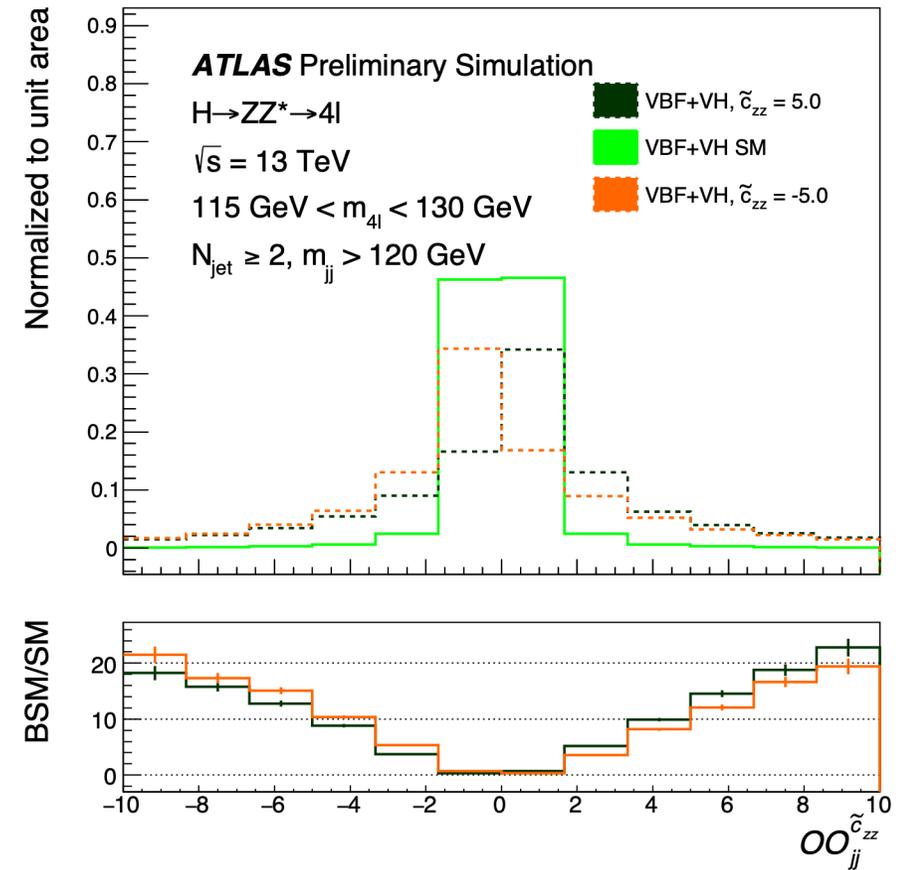
$$|\mathcal{M}|^2 = \left| \mathcal{M}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_{BSM,i} \right|^2$$

Interference term become our Optimal Observable
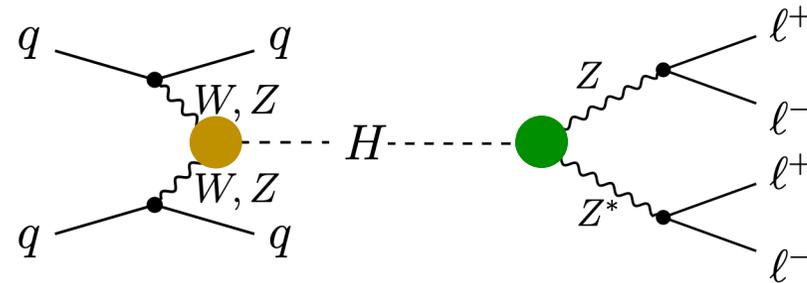
$$OO = \frac{2\Re\left(\mathcal{M}_{SM}^* \mathcal{M}_{BSM}\right)}{|\mathcal{M}_{SM}|^2}$$

| The interference become asymmetric in presence of CP-odd contribution in the coupling→ sensitive to the sign

ATLAS Preliminary Simulation
H→ZZ*→4l
√s = 13 TeV
115 GeV < m_{4l} < 130 GeV
N_{jet} ≥ 2, m_{jj} > 120 GeV

VBF+VH, $\tilde{c}_{zz}$ = 5.0
VBF+VH SM
VBF+VH, $\tilde{c}_{zz}$ = -5.0

Fiducial Differential Cross Sections measurement

Observables studied are sensitive to different Higgs boson properties or theoretical predictions

Different Optimal Observables can be studied looking for anomalous CP-odd coupling at the production and/or decay vertex
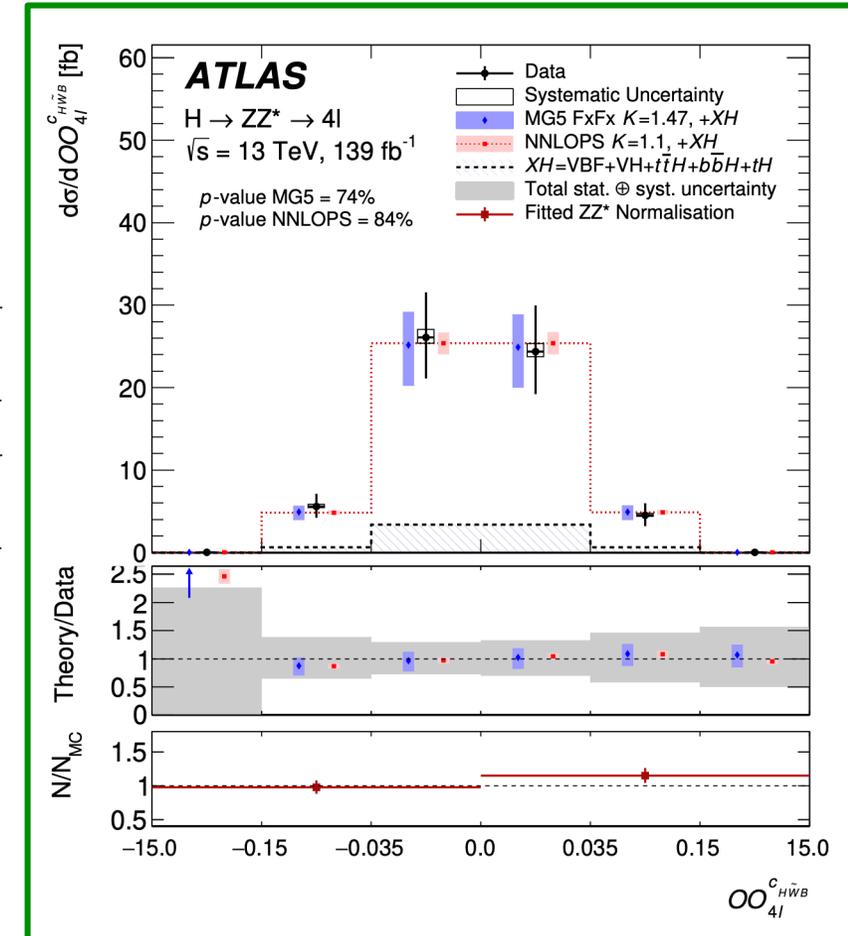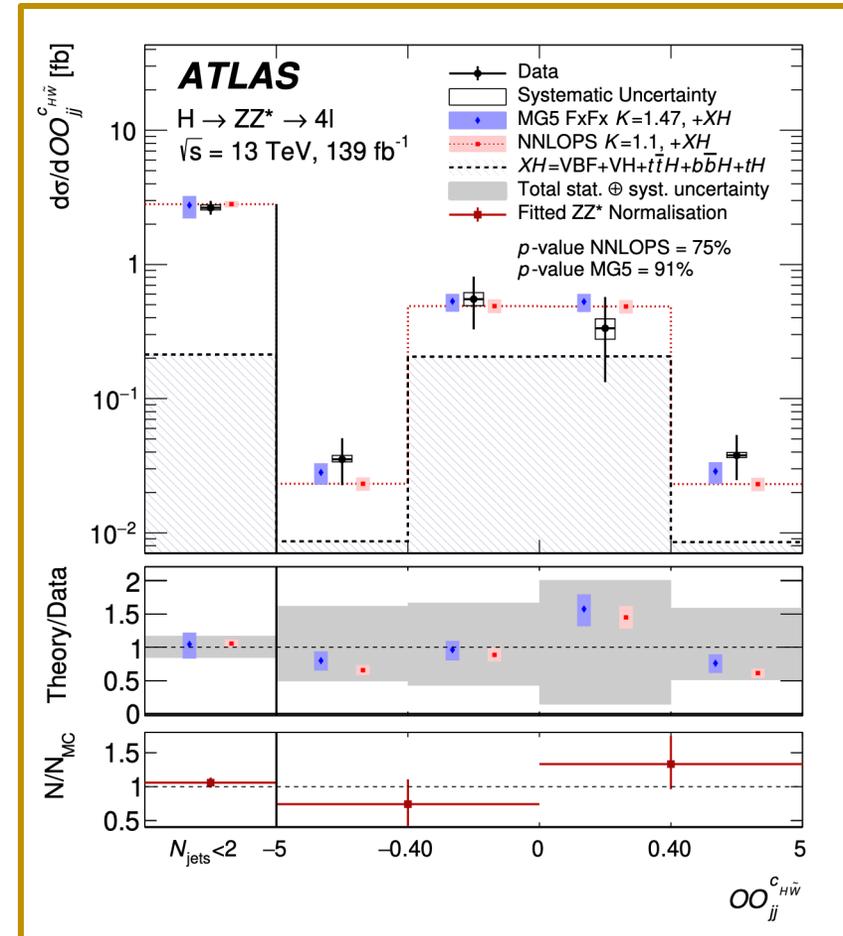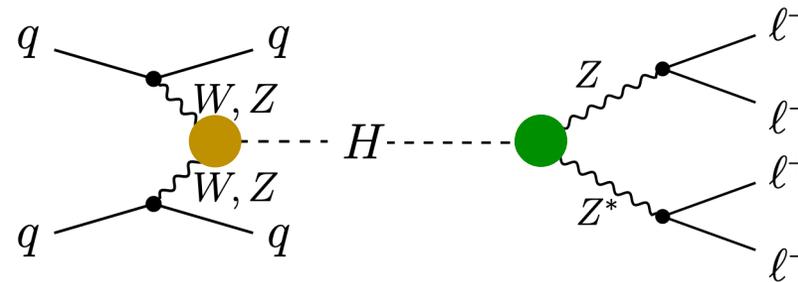
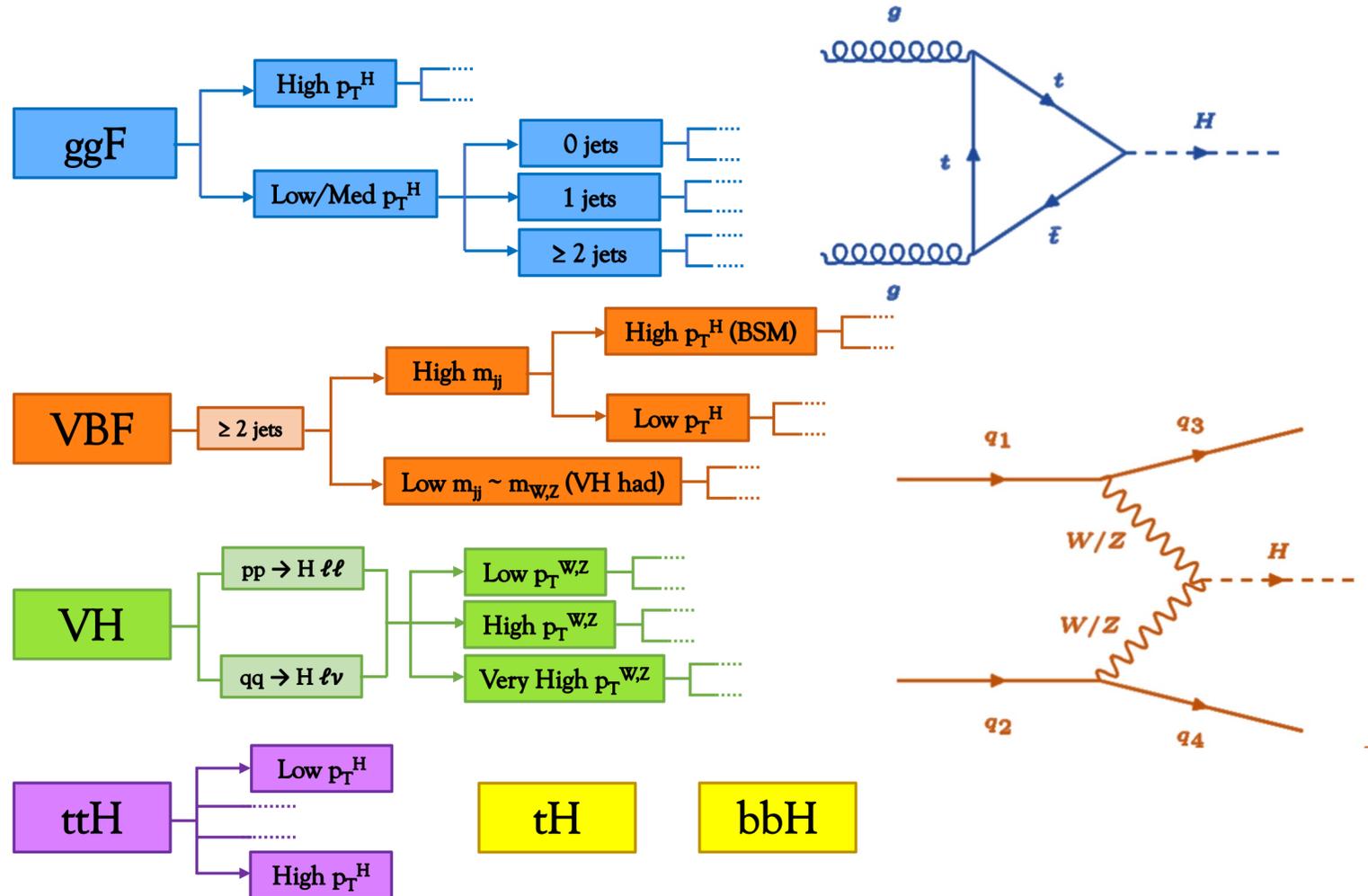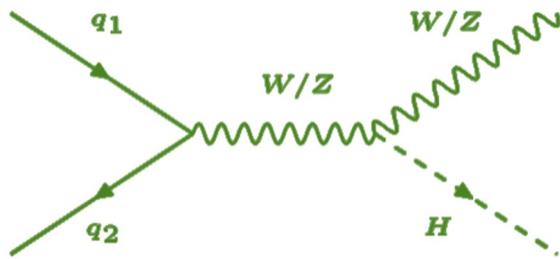# Production Cross Section measurements: STXS

Simplified Template Cross Section Framework

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

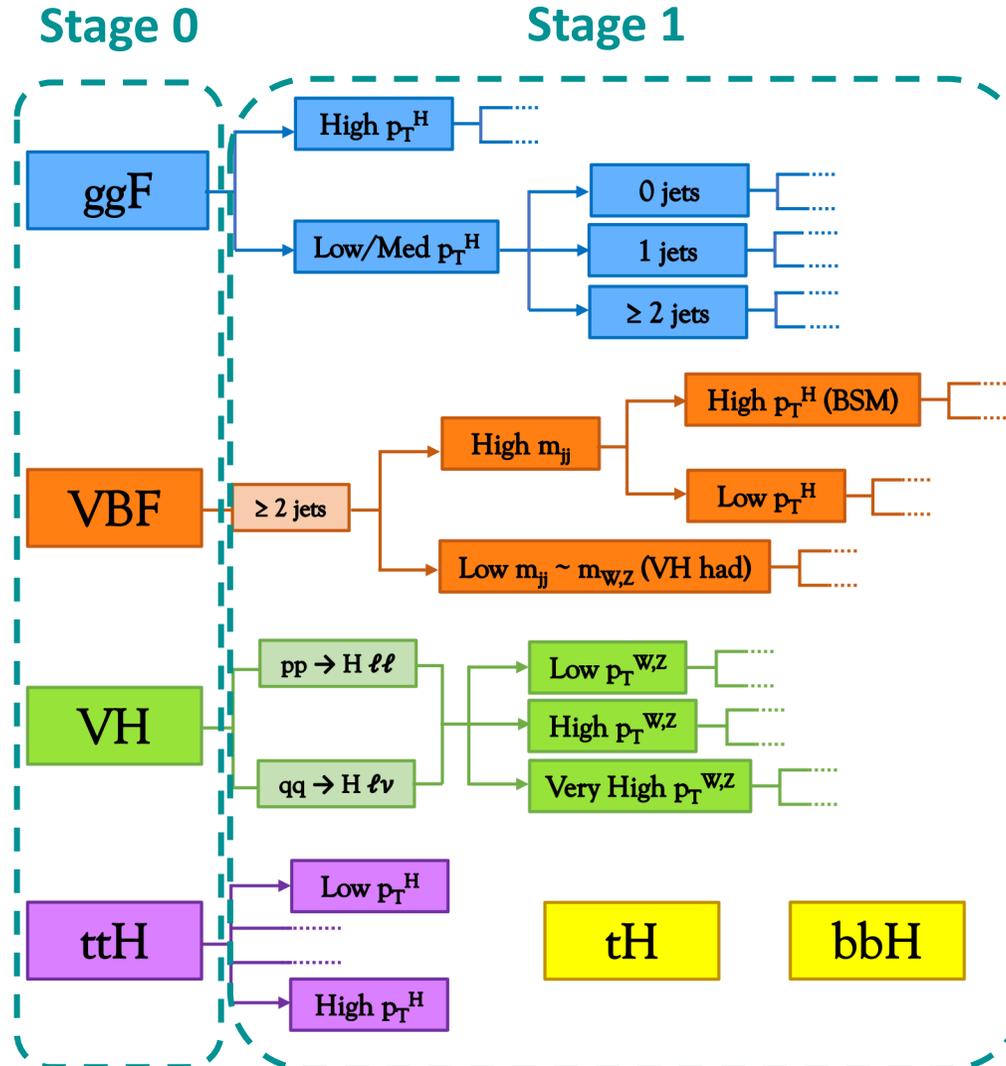Maximize the experimental sensitivity to possible BSM effects
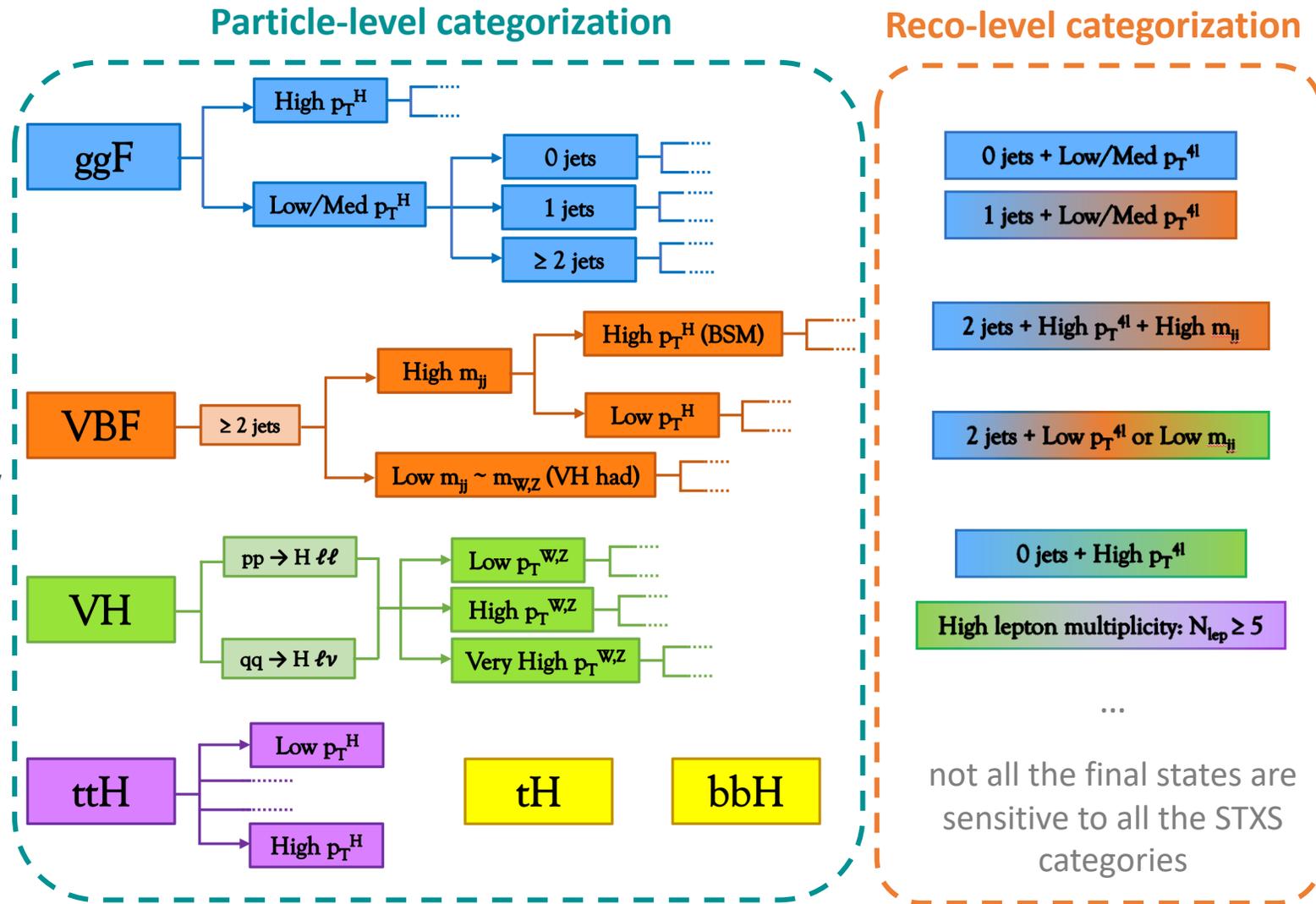
Production Cross Section measurements: STXS

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

Maximize the experimental
sensitivity to possible BSM effects

Different STXS Stages definition at
particle-level, increasingly fine granularity

Production Cross Section measurements: STXS

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

Maximize the experimental
sensitivity to possible BSM effects

**Different STXS Stages definition at
particle-level**, increasingly fine granularity

Reconstructed event categorization
as close as possible to this definition
→ minimize model–dependent extrapolation

Different production modes can
populate a reco-level categories
→ **discriminant observables to
extract production cross sections**

Particle-level categorization

Reco-level categorization

... not all the final states are
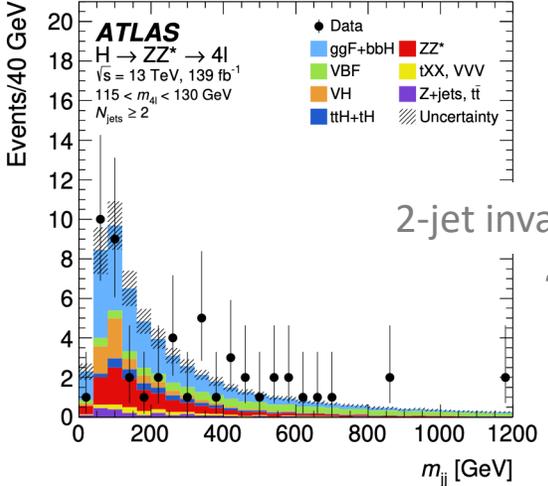sensitive to all the STXS
categories

Production Cross Section measurements: STXS

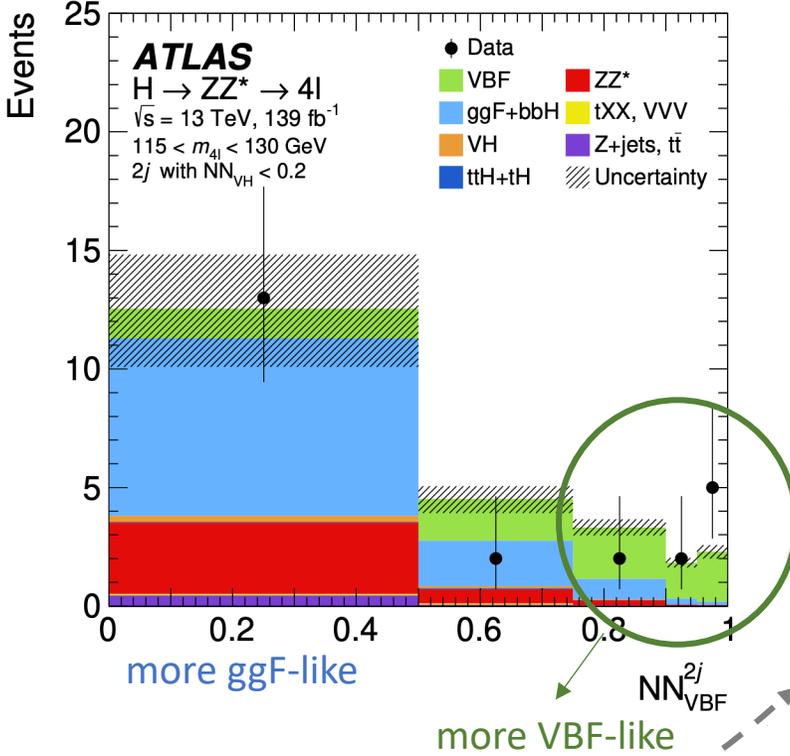Discriminant Observable between different production modes: **Neural Networks**
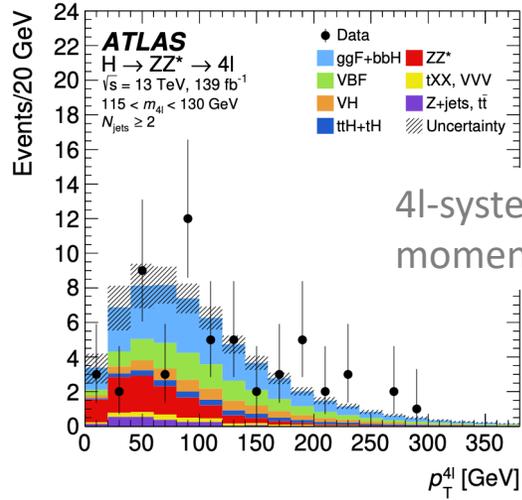
4l-system transverse momentum in for $N_{jets} \geq 2$

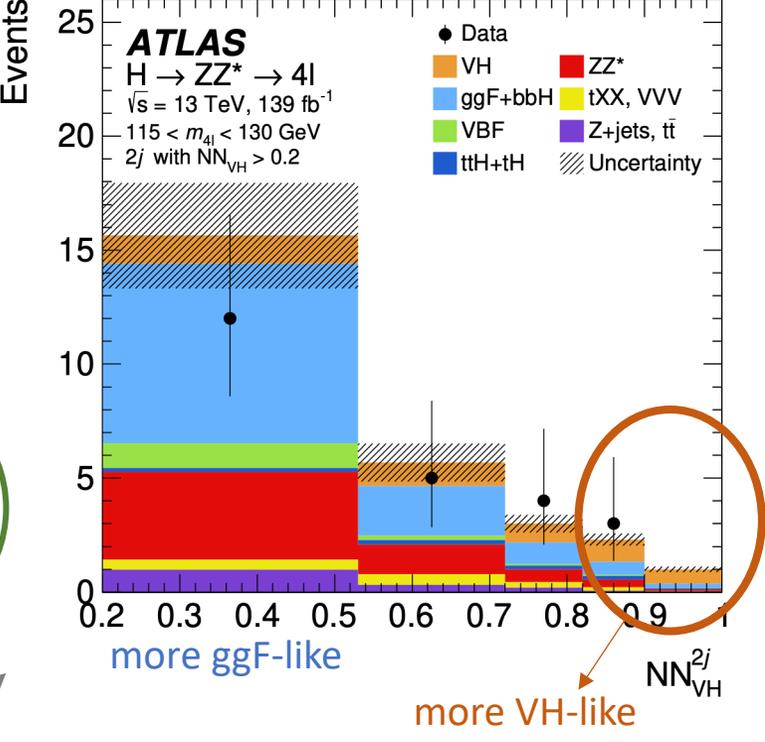Only kinematic observables not powerful enough as discriminant...
but can be used as input of the NN

2-jet invariant mass

more ggF-like

more VBF-like
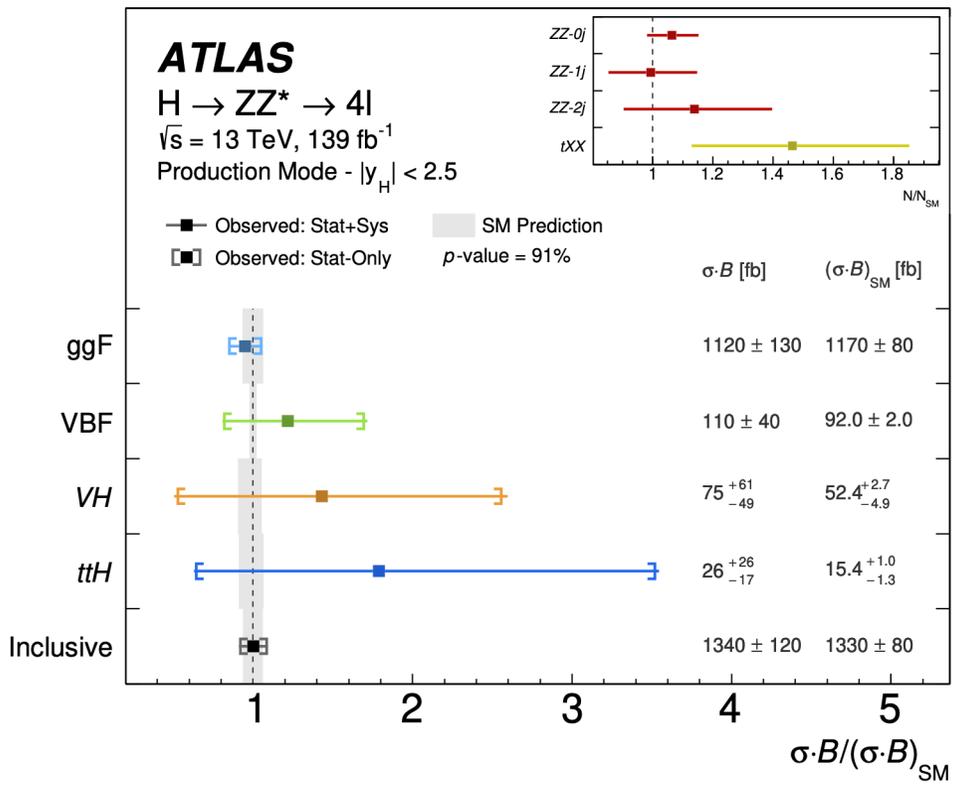
NN_{VBF}^{2j}

more ggF-like

more VH-like

NN_{VH}^{2j}

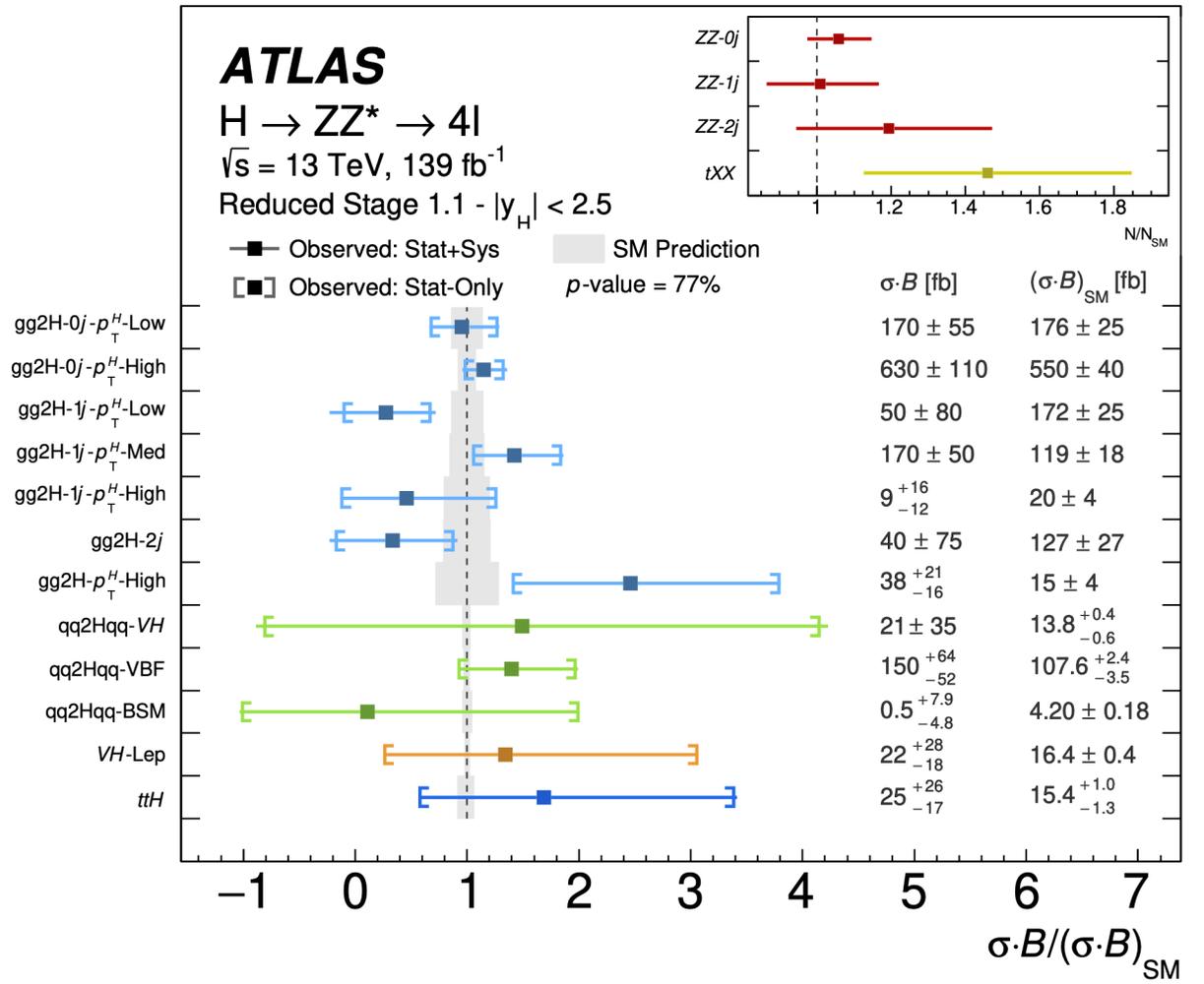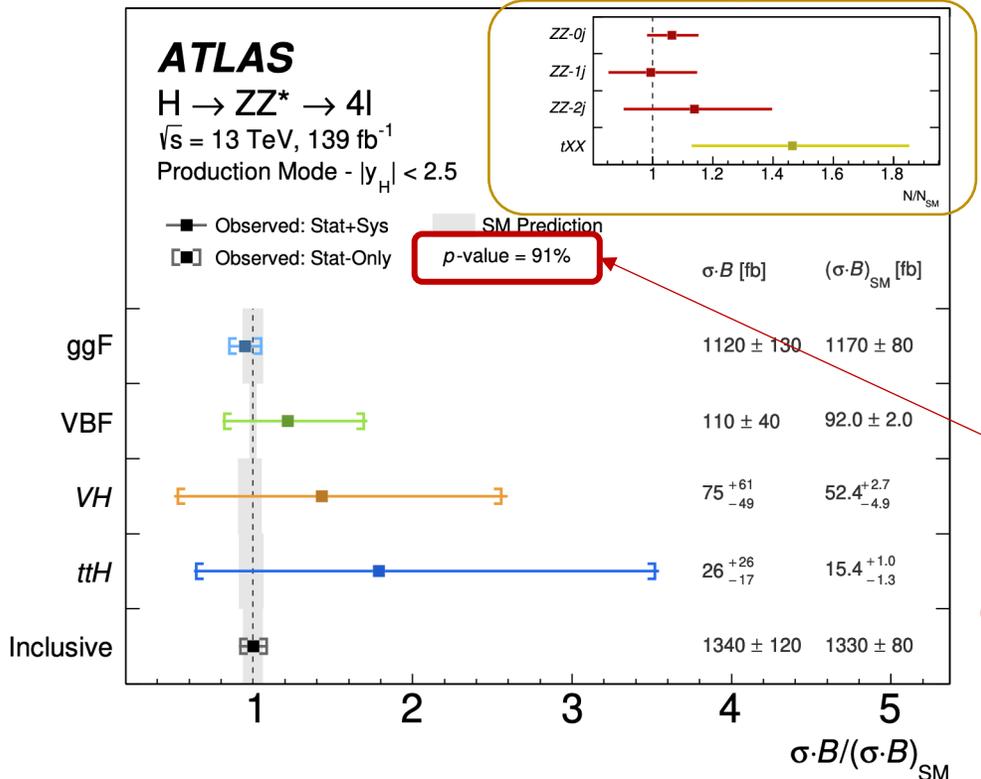# Production Cross Section measurements: STXS

## Results from Run 2

Sensitivity is statistically limited, but large Run 2 dataset allowed to probe more STXS regions than previous analyses

Production Mode Stage (Stage 0)

(Reduced) Stage 1.1

Production Cross Section measurements: STXS

Results from Run 2

ZZ* and tXX background estimated from data in ad-hoc categories

Sensitivity is statistically limited, but large Run 2 dataset allowed to probe more STXS regions than previous analyses
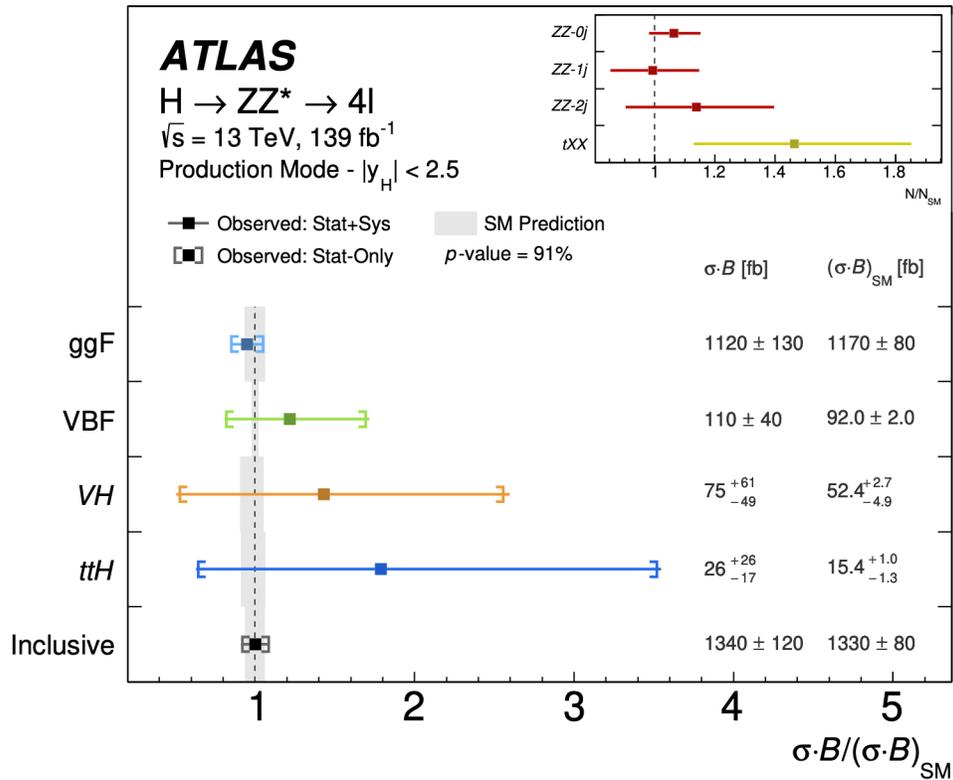

Excellent compatibility with Standard Model expectation
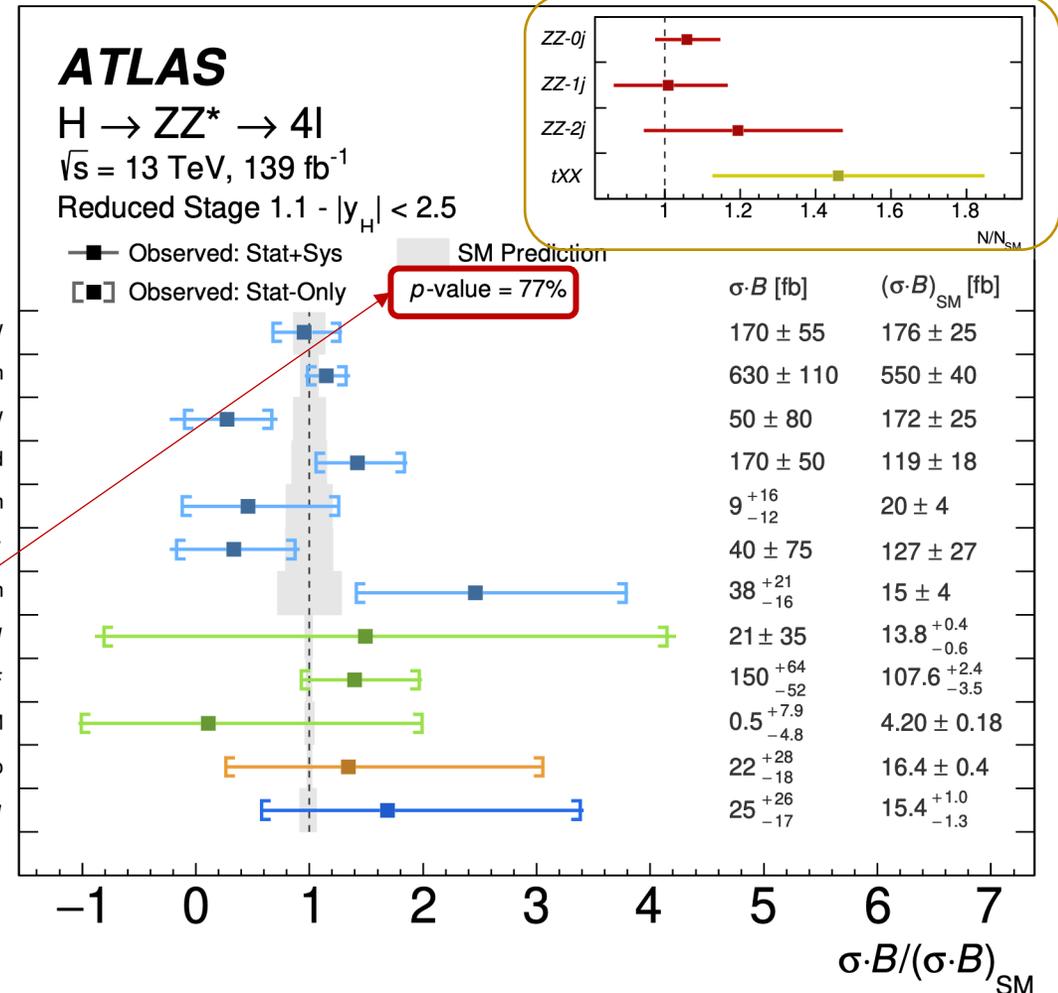
Production Cross Section measurements

STXS approach comes with several model dependencies

- Measurements are extrapolated to a phase space with the only selection that $|y_H| < 2.5$
- The Neural Network are trained on Standard Model predictions

Can we be more model-independent?

Production Cross Section measurements

STXS approach comes with several model dependencies

- Measurements are extrapolated to a phase space with the only selection that $|y_H| < 2.5$
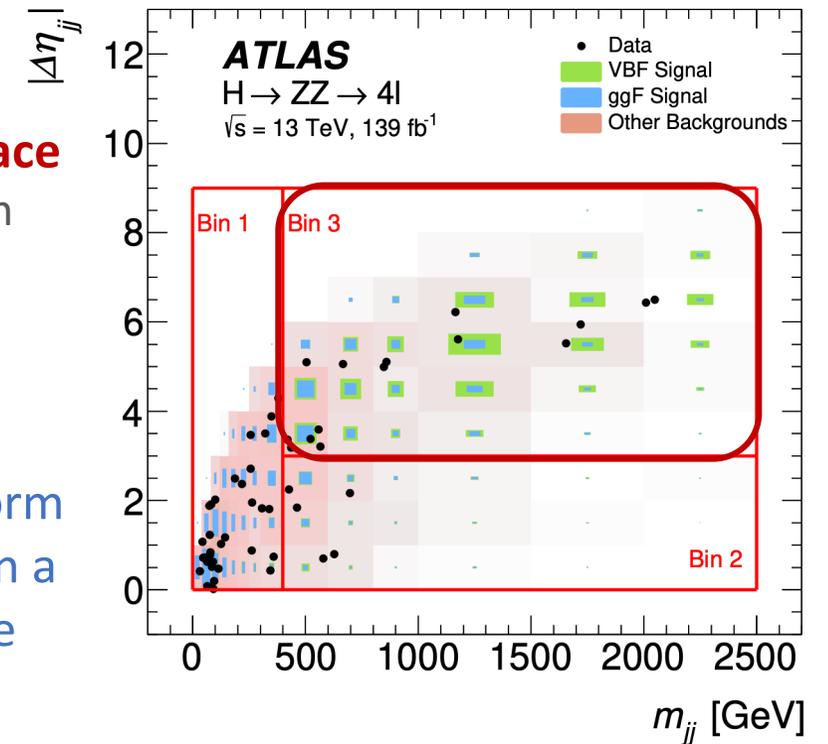- The Neural Network are trained on Standard Model predictions

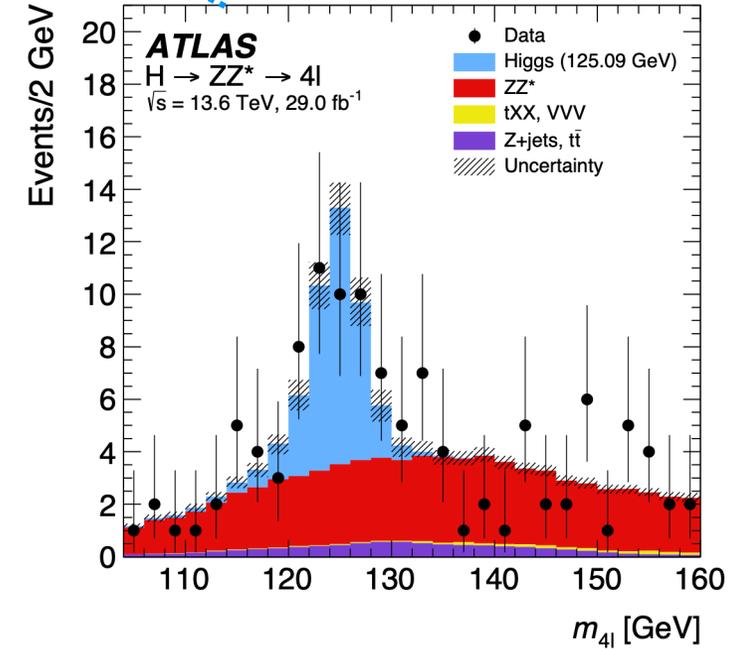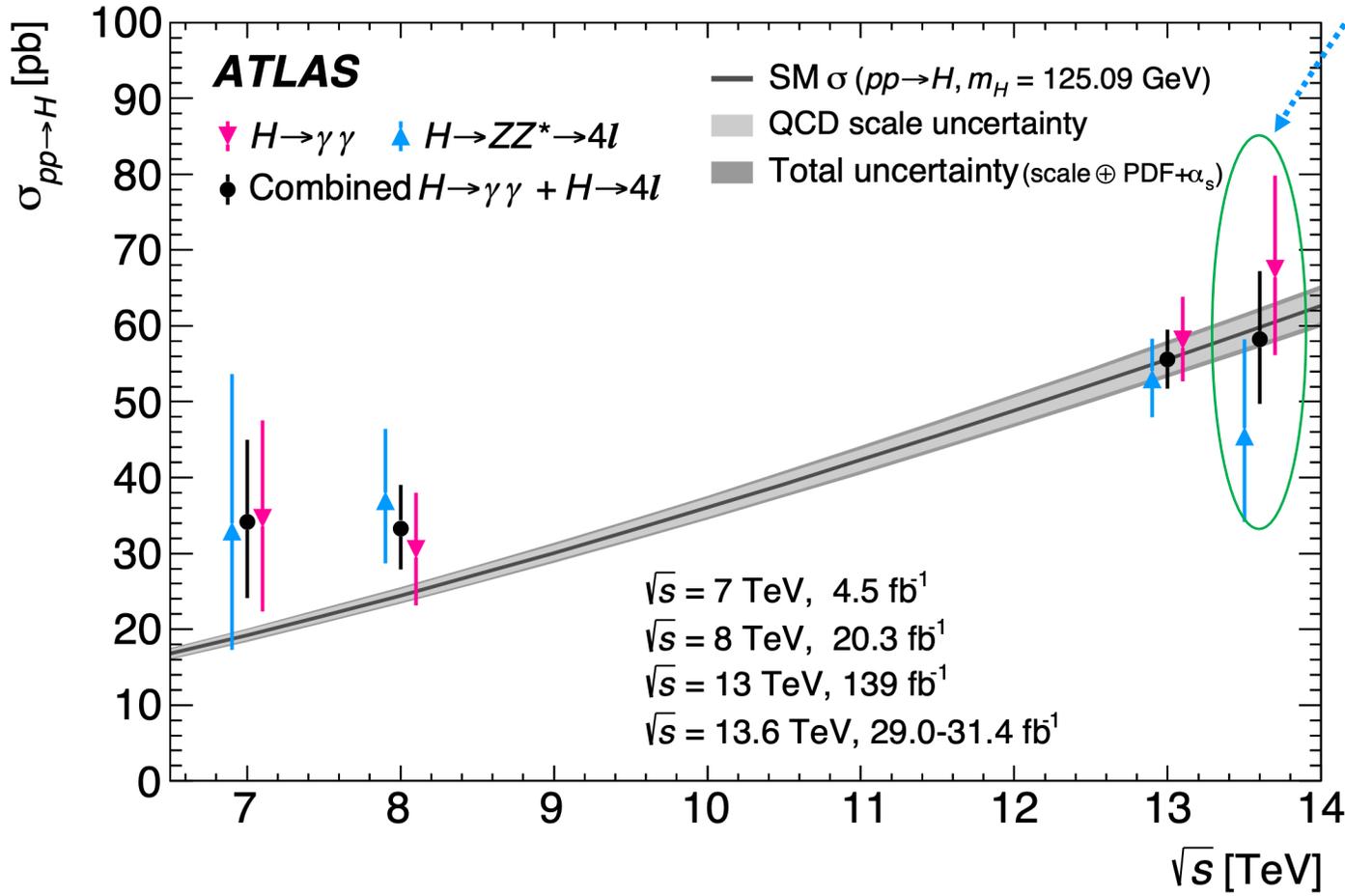## Fiducial Phase Space is the answer!
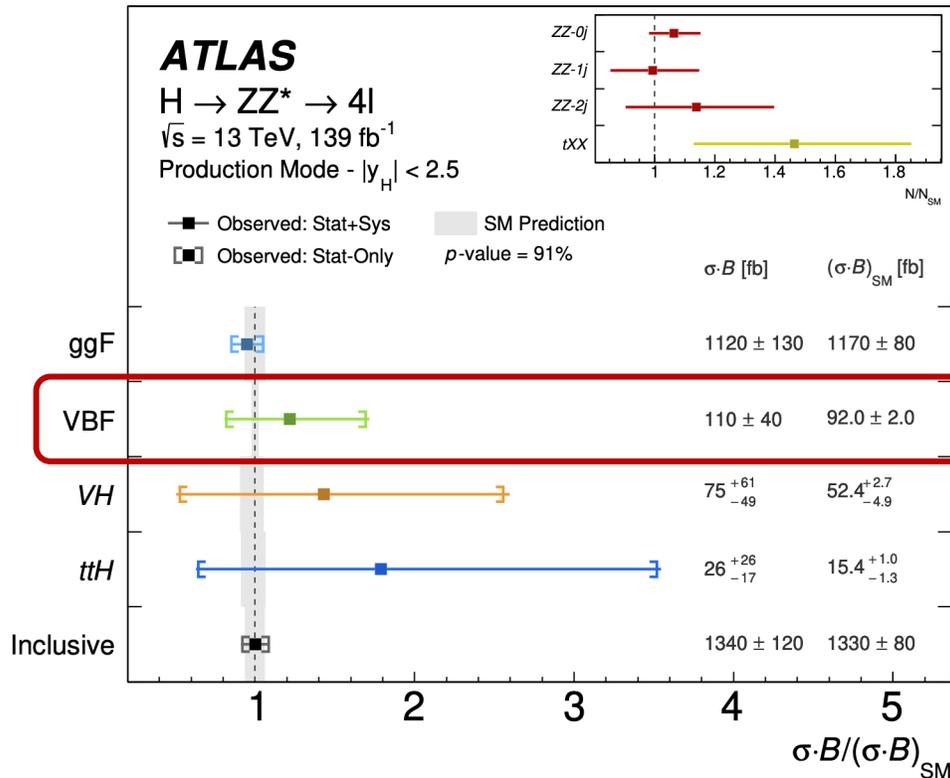
Apply "simple" kinematic selection to select a more

VBF-like fiducial phase space

- Minimize the extrapolation
- Less assumptions

Open the possibility to perform differential measurements in a purer VBF-like phase space

Cross Section scale with collision energy

ATLAS

$\blacktriangledown$ $H \to \gamma\gamma$ $\blacktriangle$ $H \to ZZ^* \to 4l$

$\bullet$ Combined $H \to \gamma\gamma + H \to 4l$

— SM σ ($pp \to H$, m_H = 125.09 GeV)

QCD scale uncertainty

Total uncertainty (scale $\oplus$ PDF+α_s)

$\sqrt{s}$ = 7 TeV, 4.5 fb^{-1}
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$\sqrt{s}$ = 13.6 TeV, 29.0-31.4 fb^{-1}

ATLAS
$H \to ZZ^* \to 4l$
$\sqrt{s}$ = 13.6 TeV, 29.0 fb^{-1}

- Data
- Higgs (125.09 GeV)
- ZZ*
- tXX, VVV
- Z+jets, t$\bar{t}$
- Uncertainty

σ_{fid}^{4l} = 2.80 ± 0.74 fb
(SM: 3.67 ± 0.19 fb)

$\sigma_{\text{fid}}^{\gamma\gamma}$ = 76$^{+14}_{-13}$ fb
(SM: 67.6 ± 3.7 fb)

σ_{total} = 58.2 ± 8.7 pb
(SM: 59.9 ± 2.6 pb)

First measurement of the Higgs boson production cross section @ **13.6 TeV**
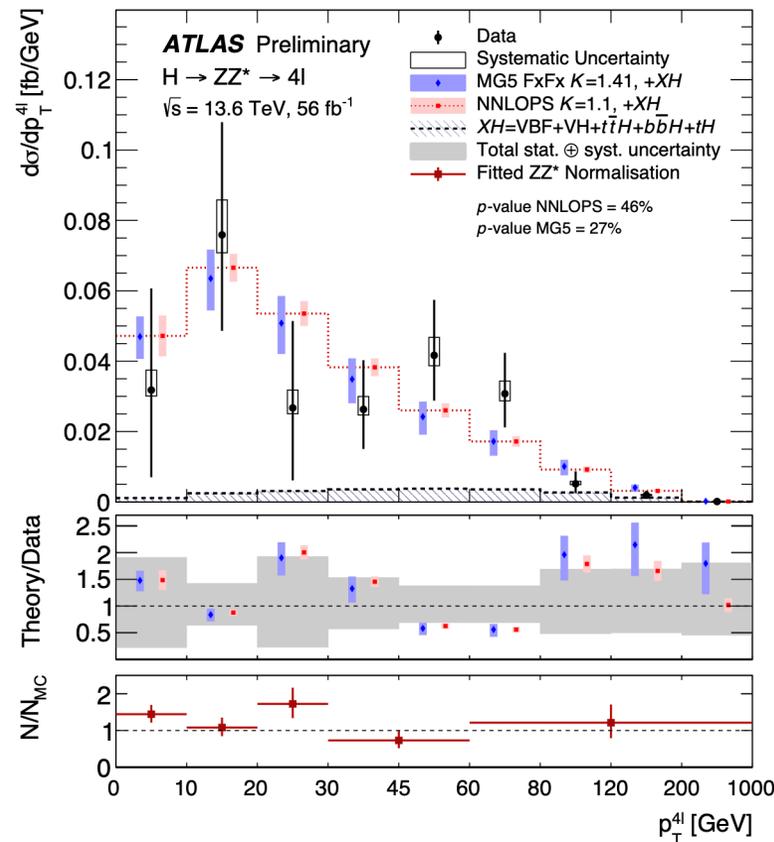
Cross Section measurements @ 13.6 TeV

First differential measurements at 13.6 TeV, with partial Run 3 dataset of 56 fb⁻¹ (~1/3 of the full Run 2 dataset)

→ much more statistically limited
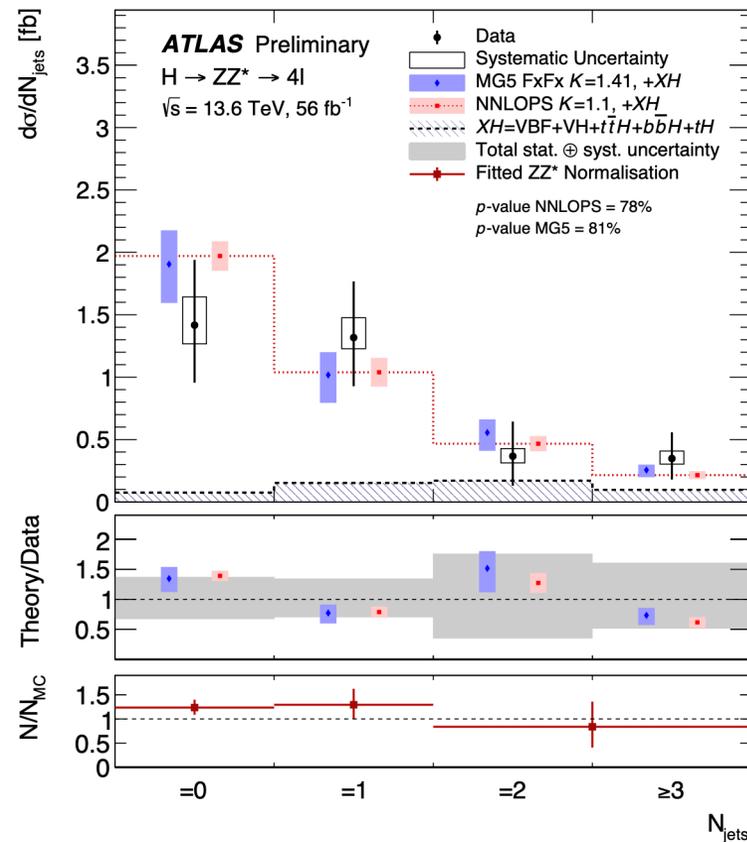
→ kinematic observables related to the Higgs production change their shape with the energy

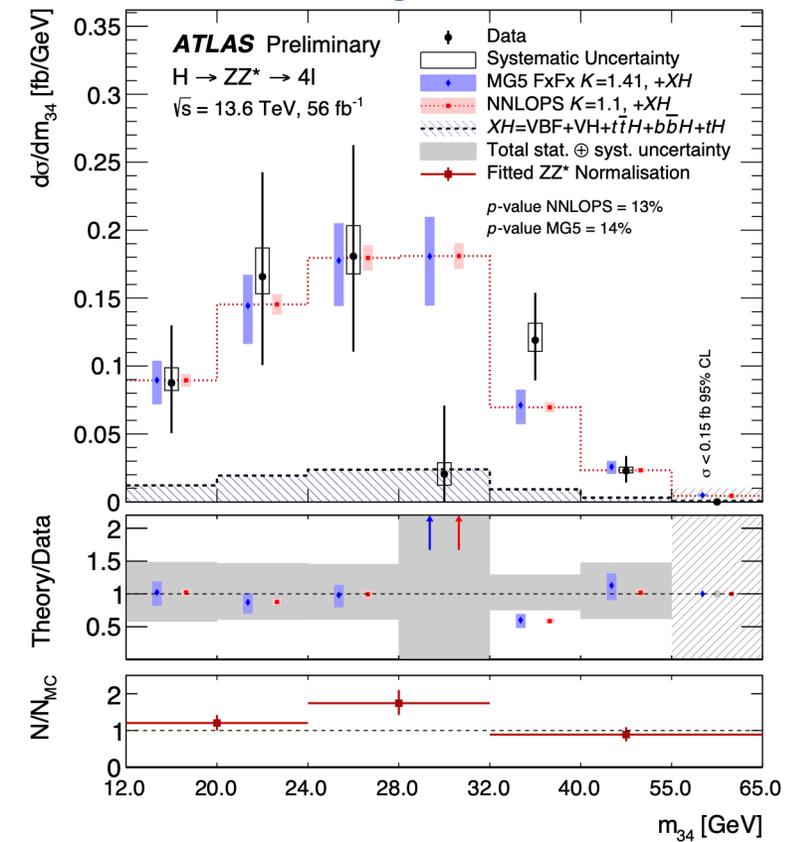(hard to appreciate 13 TeV →13.6 TeV scale due to the low statistics)

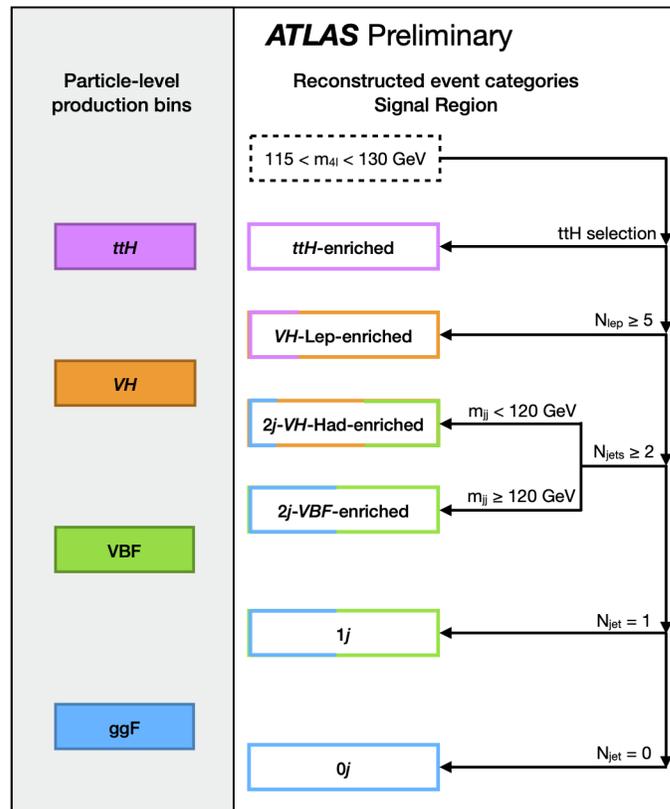Higgs is produced at higher p$_T$

H + jets production changes

Decay kinematic observables do not change distribution
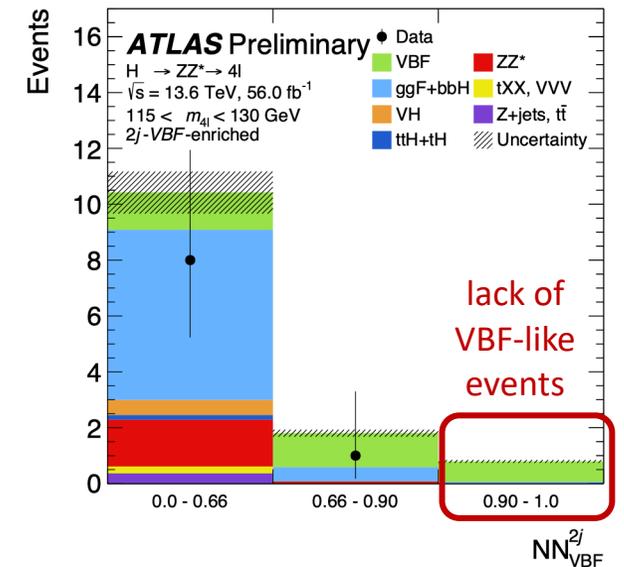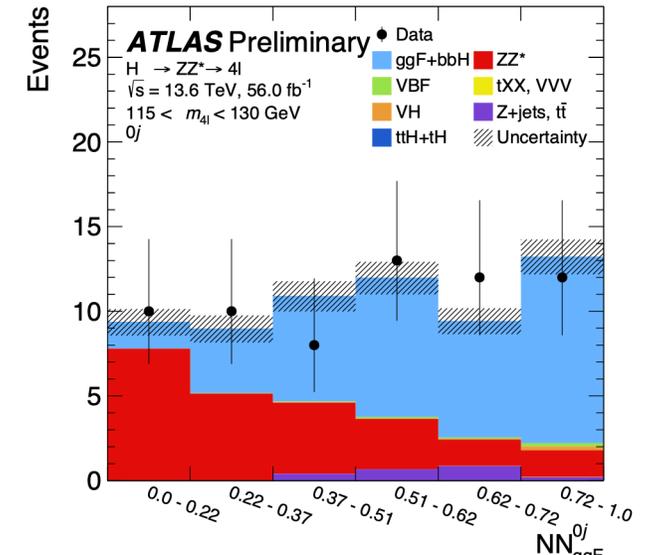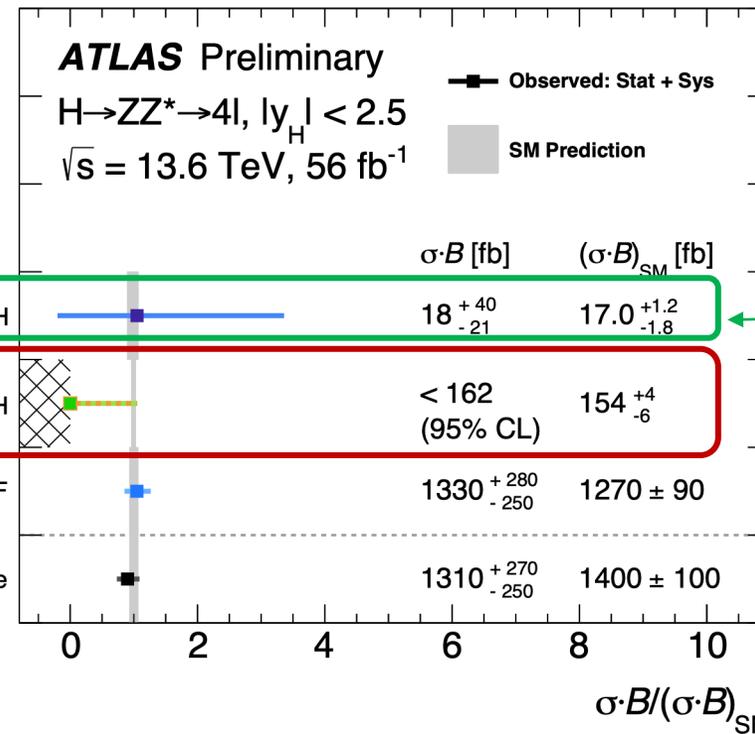
Cross Section measurements @ 13.6 TeV

First production mode measurements at 13.6 TeV, with partial Run 3 dataset of 56 fb^{-1} (~1/3 of the full Run 2 dataset)

→ only Production Cross Section Stage (Stage 0) could be measured

→ much more statistically limited

No data observed in the categories with highest sensitivity to VBF and VH

One ttH candidate!

lack of VBF-like events

# …to Interpretations
(Anomalous) Higgs Couplings

κ-framework: constraint on Yukawa couplings

Higgs coupling to light quarks (e.g. charm) may be possible to constrain without direct measurement (e.g. H→cc decay)

Higgs transverse momentum 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
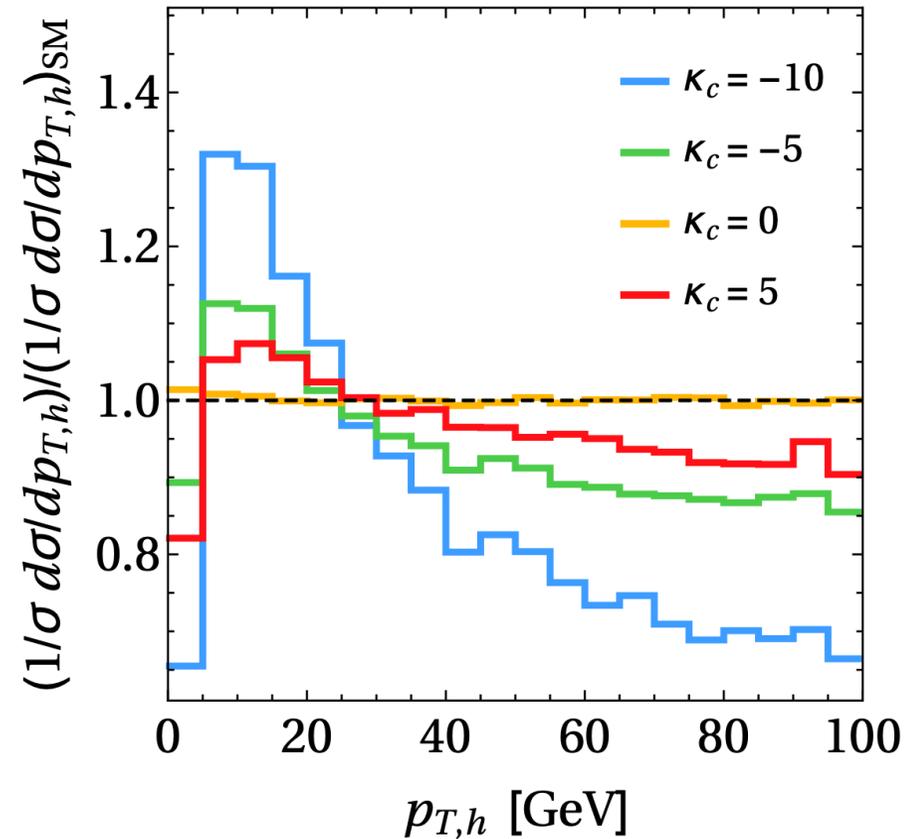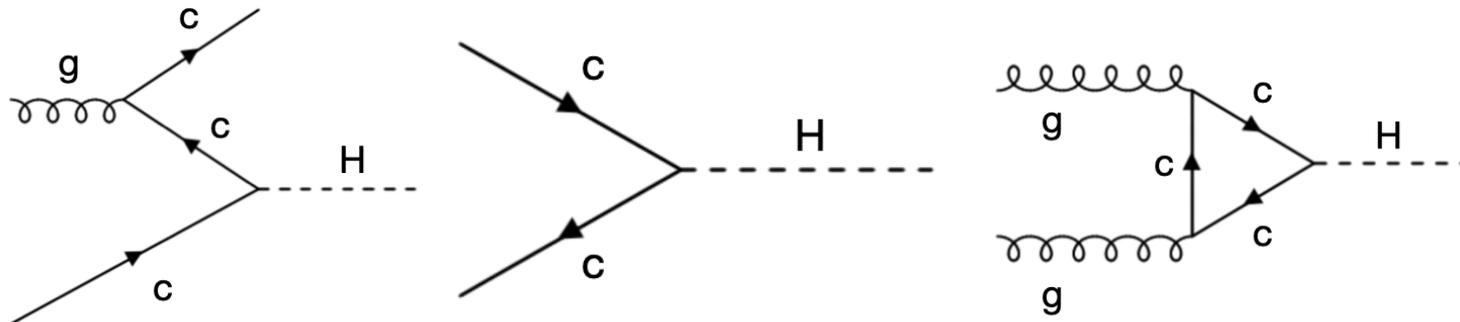
The variation of the coupling modifiers can impact both the Cross Sections, the Branching Ratio and the Shape → different tests can be performed with different level of model dependency

κ-framework: constraint on Yukawa couplings
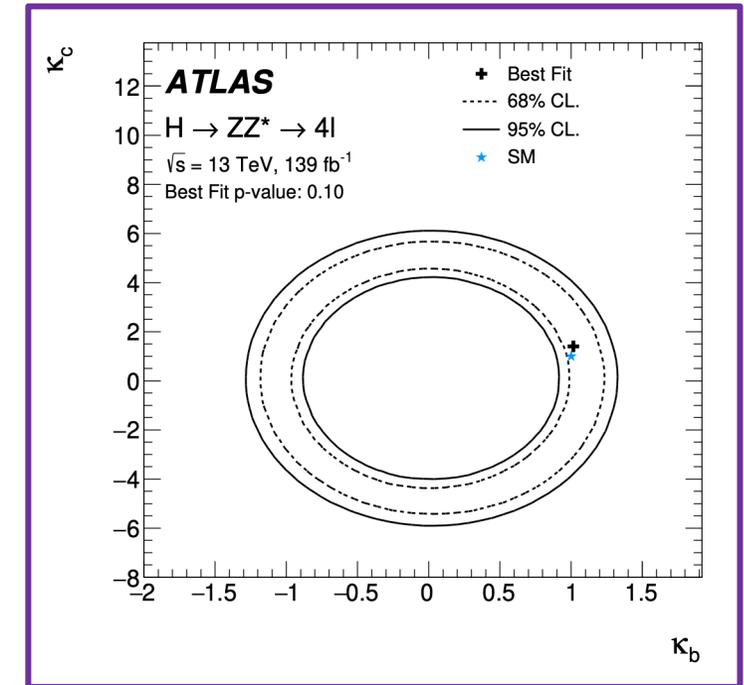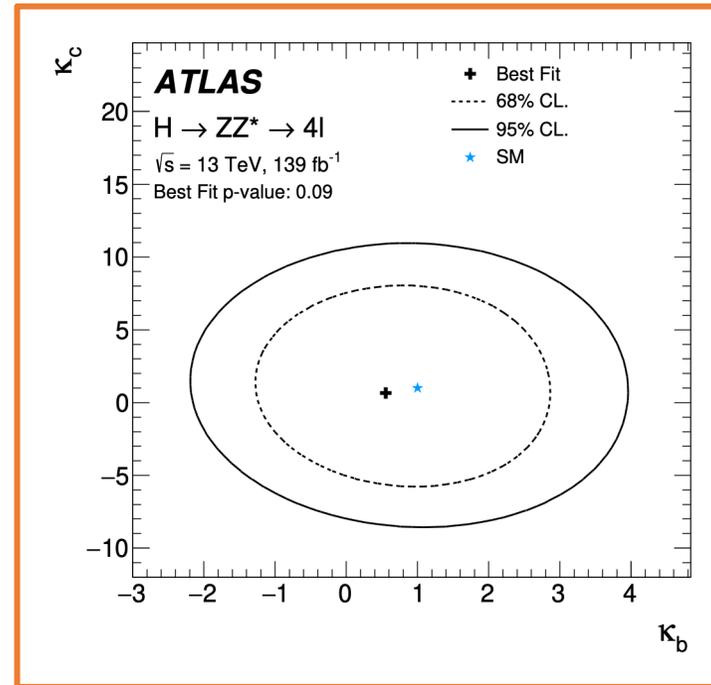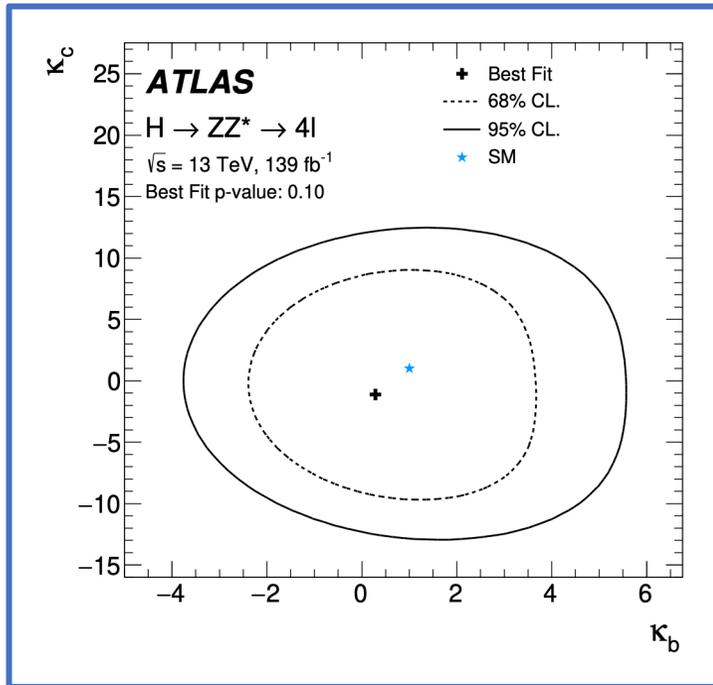
Only the p_T^H shape can be modified

- Cross sections and BR are "free to float"

  - less assumptions

The cross section and the p_T^H shape can be modified

- Intermediate approach with no assumptions on the BR

The cross section, the p_T^H shape and the Branching Ratio can be modified
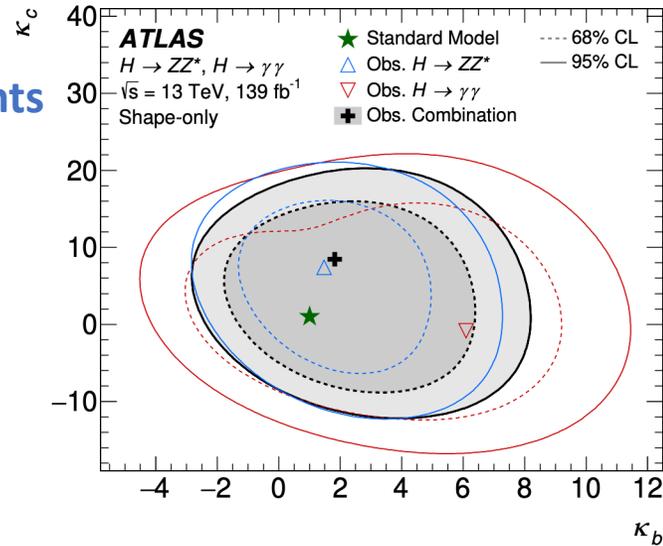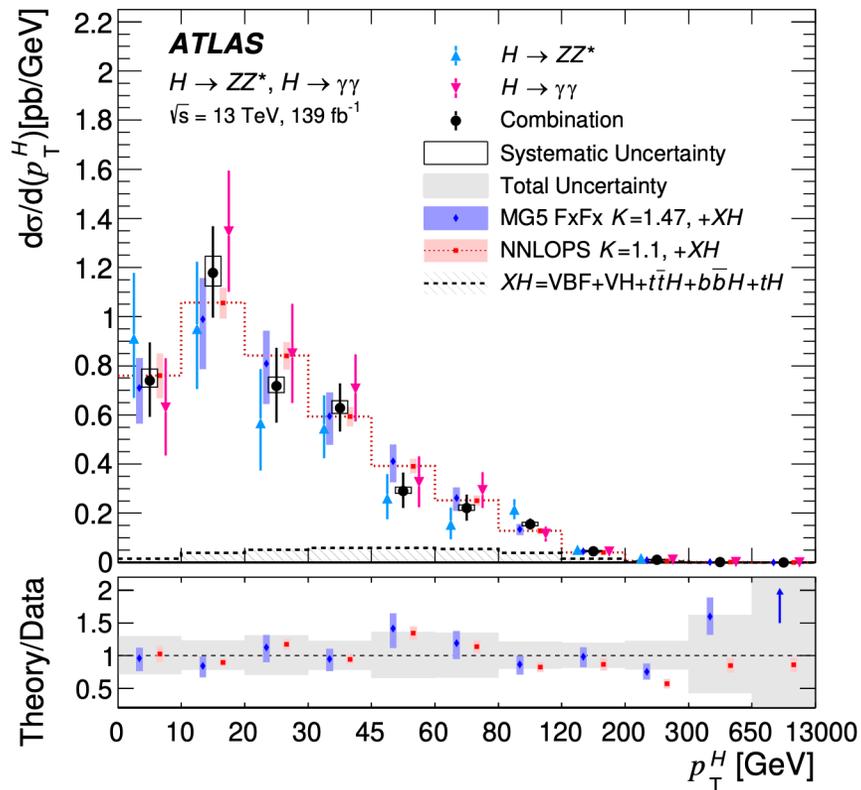
- more assumptions

- more stringent constraint

Results from H→ZZ*→4l analysis with full Run2

Shape dependency become subdominant → still sensitive to the sign!

κ-framework: constraint on Yukawa couplings

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**

Anomalous couplings can only modify the p_T^H shape

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

-2.47 < κ_c < 2.53 @ 95% C.L.
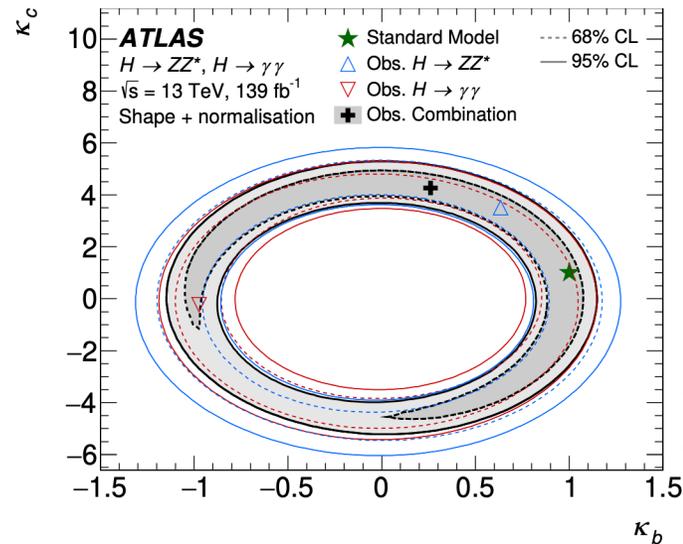
Anomalous couplings can modify also the cross section and BR
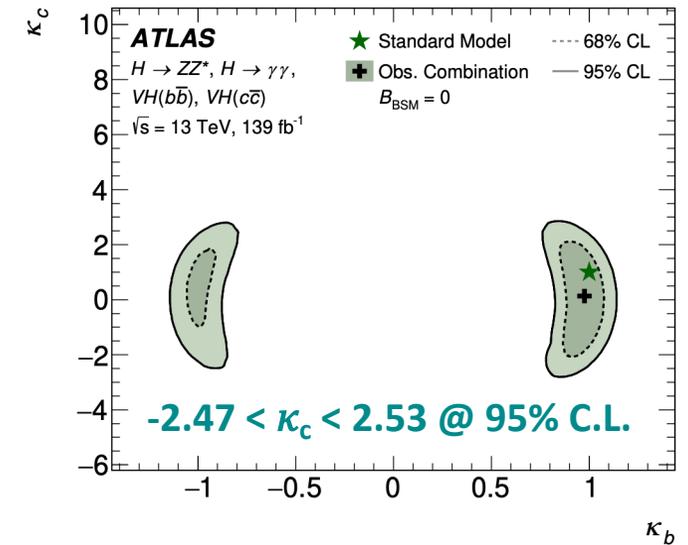
κ-framework: vector vs fermion couplings

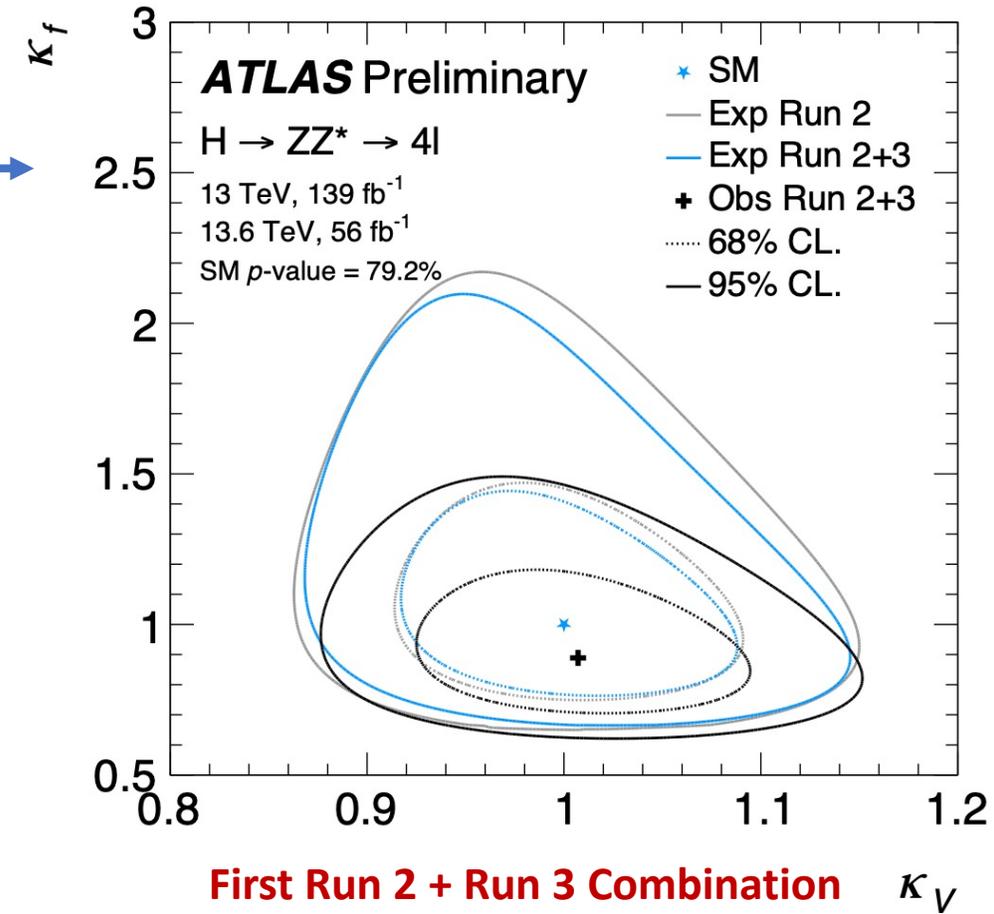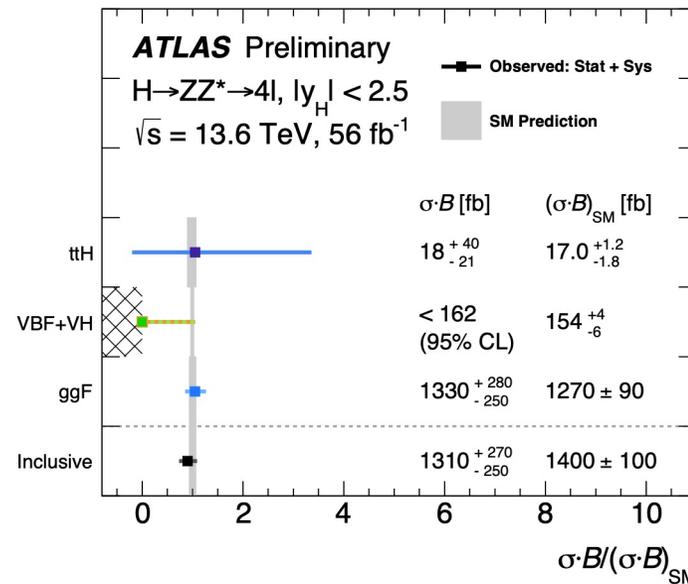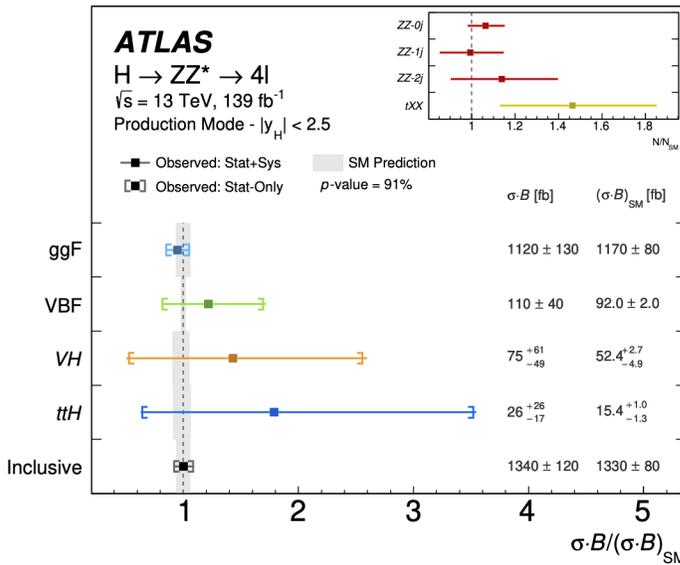Production cross sections can be used to put constraint on the Higgs boson couplings modifiers

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

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

H→ZZ*→4l Run 2 results

Combined to increase the statistical power

H→ZZ*→4l Run 3 results


First Run 2 + Run 3 Combination

κ-framework: independent couplings

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

Production Mode cross section measurement can be performed in different Decay Channels and then Combined
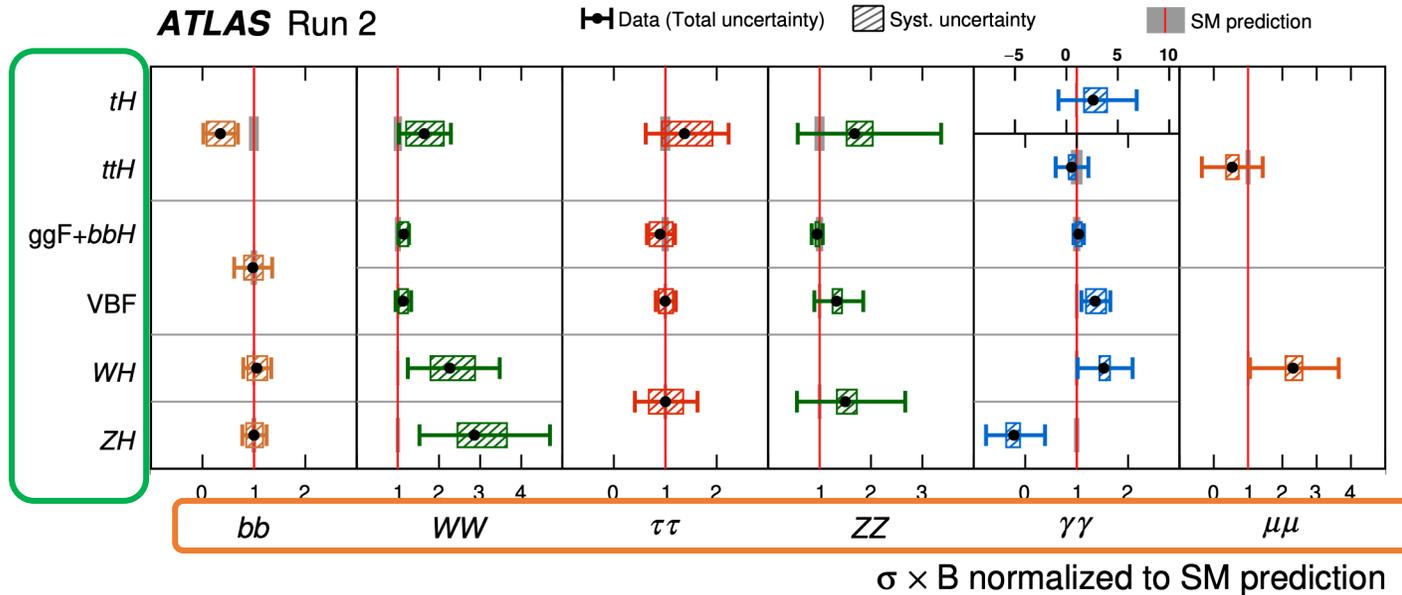
Generic parametrization with coupling strength modifiers for W, Z, t, b, c*, τ and μ treated independently
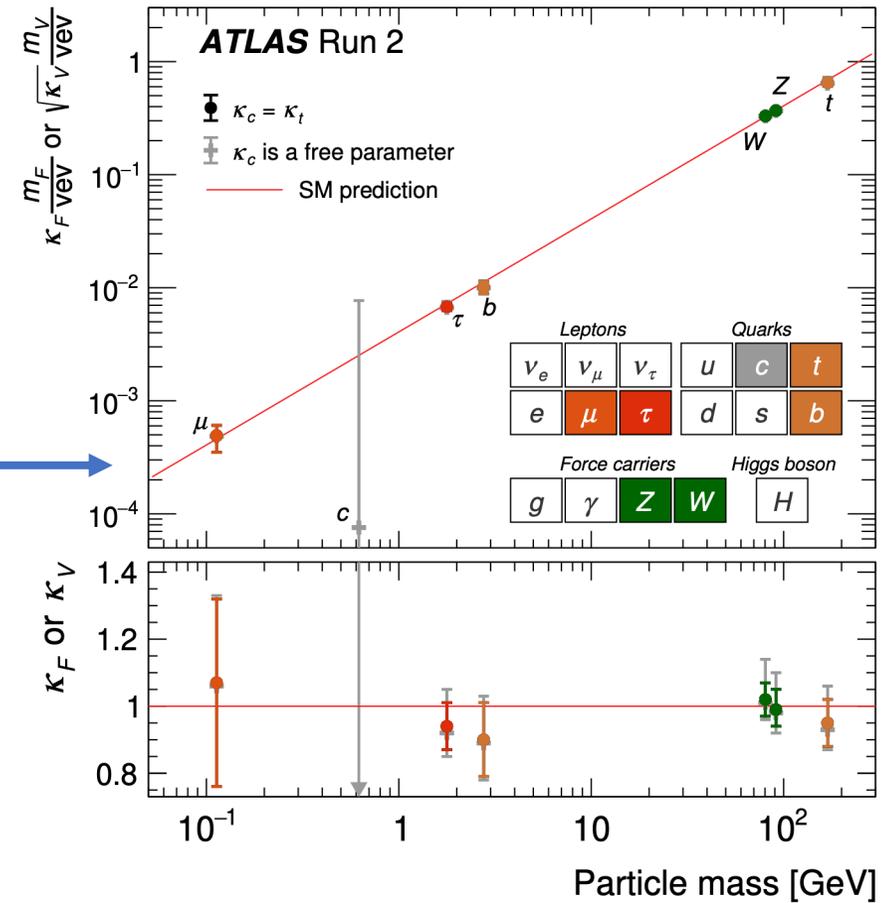
Pseudo Observables
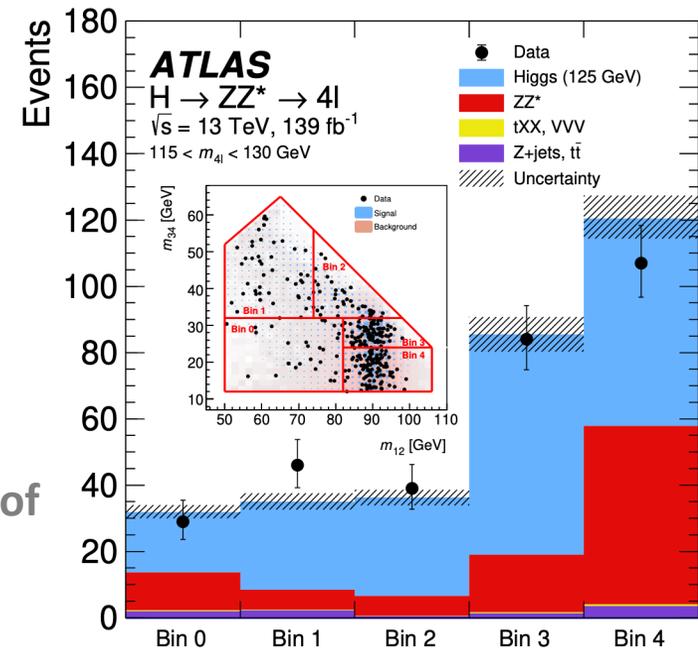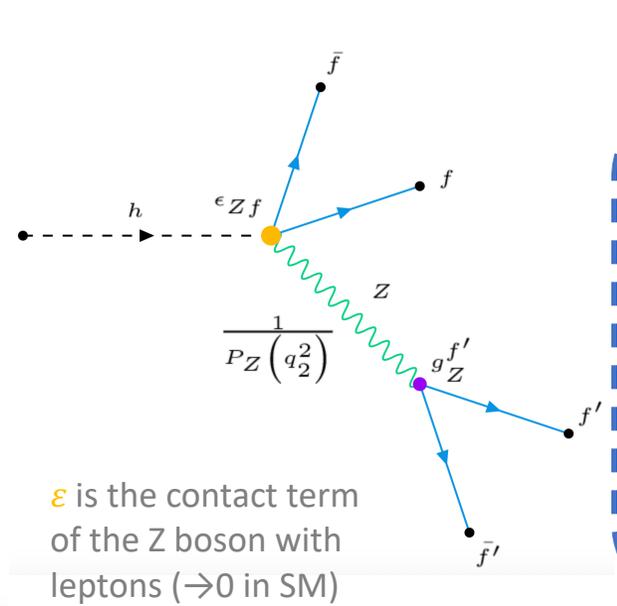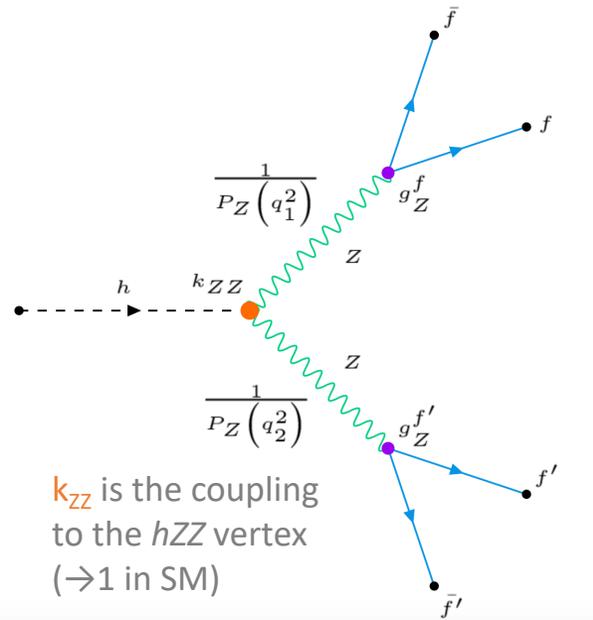
Study the effective coupling of the Higgs boson to the SM gauge bosons using the invariant masses of the two Z m_{12} vs. m_{34} distribution

- From amplitude decomposition the most interesting terms (assuming CP-invariance) are:

$$F_1^{ff'}(q_1^2, q_2^2) = \kappa_{ZZ} \frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2) P_Z(q_2^2)} + \frac{\epsilon_{Zf}}{m_Z^2} \frac{g_Z^{f'}}{P_Z(q_2^2)} + \frac{\epsilon_{Zf'}}{m_Z^2} \frac{g_Z^f}{P_Z(q_1^2)}$$
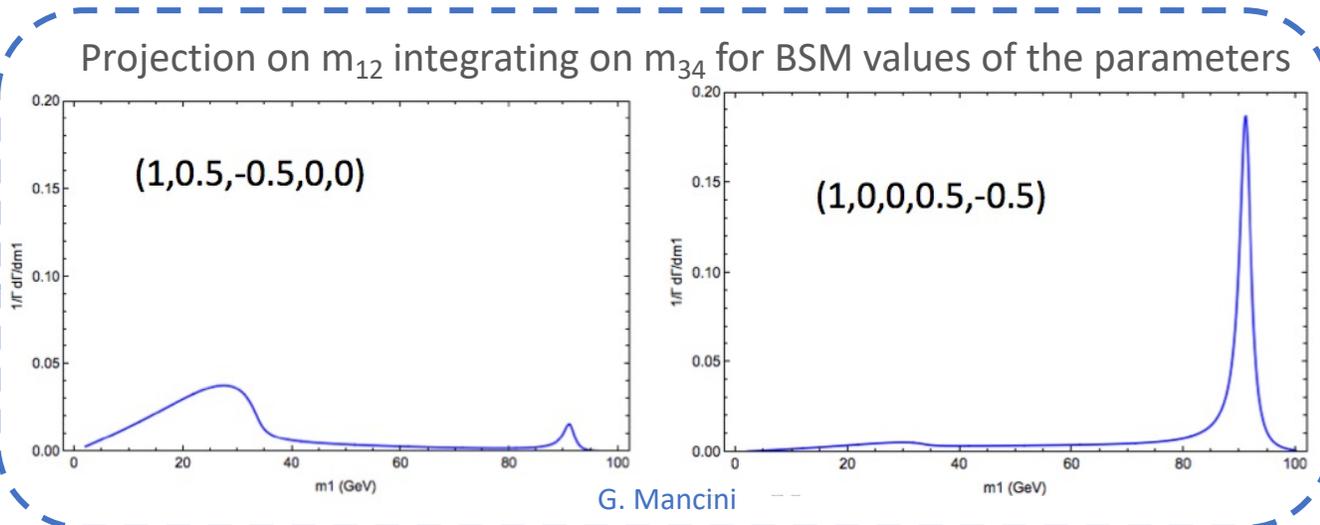
- k_{ZZ} ~ coupling modifier
- ϵ_{Zf} only possible source of flavor non-universality!

Momentum expansion around physical pole $P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$

m_{12} vs. m_{34}

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

k_{ZZ} is the coupling to the hZZ vertex ($\rightarrow$1 in SM)

ϵ is the contact term of the Z boson with leptons ($\rightarrow$0 in SM)

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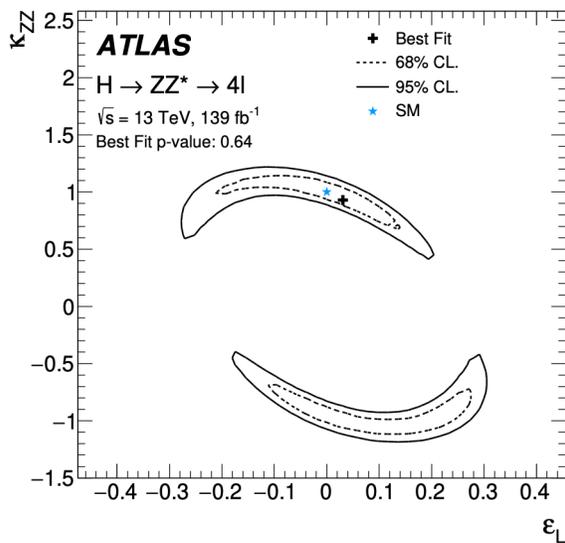

(1,0.5,-0.5,0,0)

(1,0,0,0.5,-0.5)

G. Mancini

Pseudo Observables: Run 2 results

Different scenarios have been investigated with Run 2 analysis
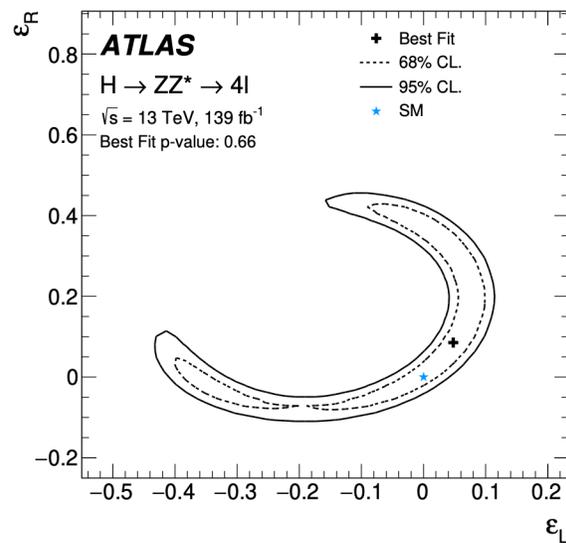
Lepton Flavor Universal scenarios

Lepton Flavor Non – Universal scenarios

Linear EFT – inspired

Assume Higgs as part of a doublet
$\varepsilon_R \sim 0.48\, \varepsilon_L$

Contact Terms

No assumption on ε_R and ε_L
Assume $\varepsilon_\mu = \varepsilon_e$

Vector Contact Terms

No assumption on ε_μ and ε_e
Assume $\varepsilon_L = \varepsilon_R$
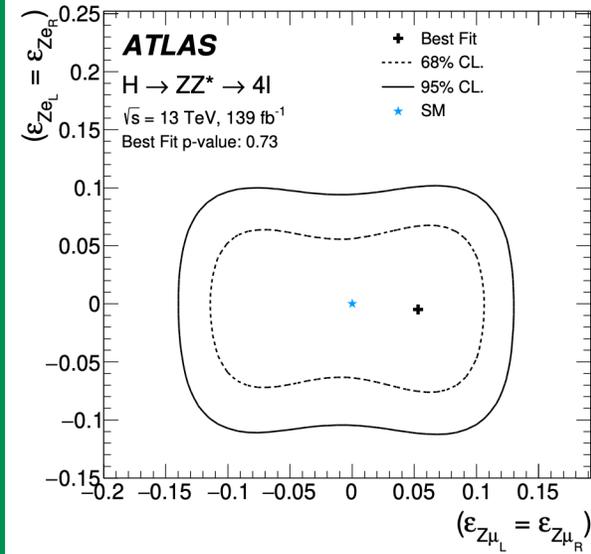
Axial Contact Terms

No assumption on ε_μ and ε_e
Assume $\varepsilon_L = -\varepsilon_R$
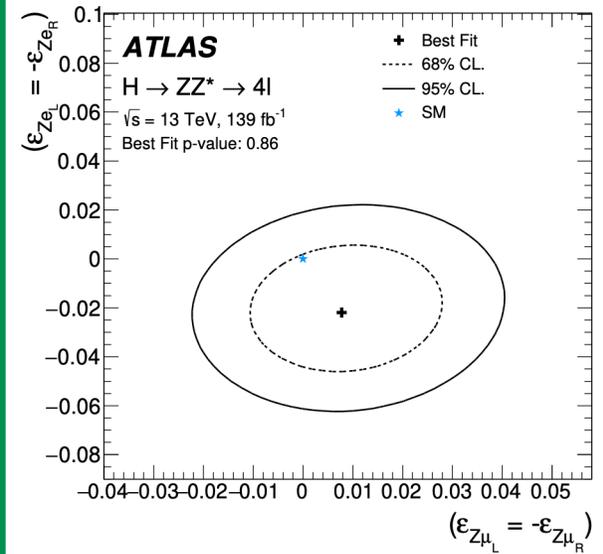
Effective Field Theory

A powerful tool to interpret results in terms of New Physics without assumptions of the underlying theory (or just partically) → Perturbative expansion of the Standard Model Lagrangian adding new operatore suppressed at a new high energy scale Λ

Wilson coefficients (free parameter of the theory) → constrained from the experimental measurements

$$\sum_n \mathcal{L}_{\mathrm{LE}}^{(n)} \quad \rightarrow \quad \mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{c^{(5)}}{\Lambda} \mathcal{O}^{(5)} + \sum_i \frac{c^{(6)}}{\Lambda^2} \mathcal{O}^{(6)} + \dots$$

Operators from SM fields with higher mass dimension

Effective Field Theory

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Dimension-5 (and Dim-7) operator violates the Lepton (and B-L) Number → neglected because suppressed by previous experiments

Operators from SM fields with higher mass dimension

Standard Model Effective Field Theory (SMEFT) Lagrangian

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$
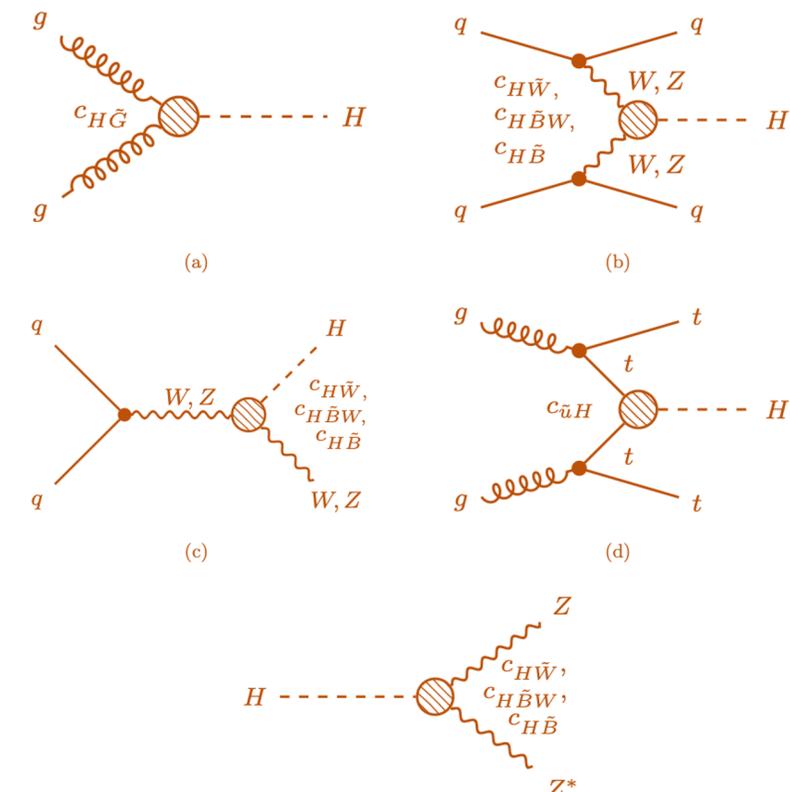
Leading contributions of New Physics are from dimension-six operators

Effective Field Theory

A powerful tool to interpret results in terms of New Physics without assumptions of the underlying theory (or just partically) → Perturbative expansion of the Standard Model Lagrangian adding new operatore suppressed at a new high energy scale Λ

Standard Model Effective Field Theory (SMEFT) Lagrangian

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$
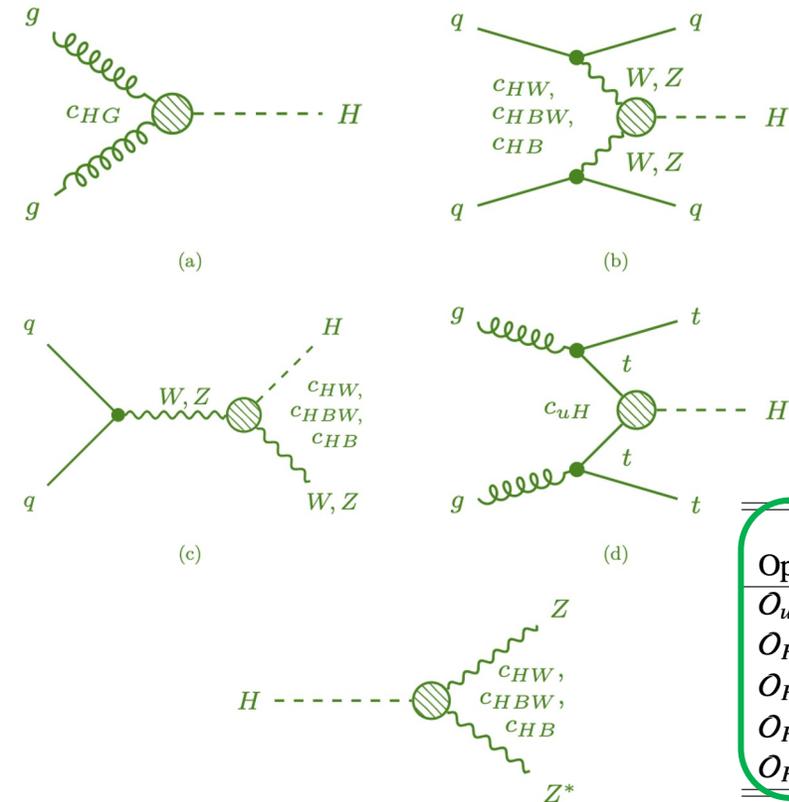
Production modes and H→ZZ*→4l decay channel are sensitive just to a subset of all the Wilson coefficient

| 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}	$HH^{\dagger}\bar{q}_p u_r \tilde{H}$	$c_{\widetilde{u}H}$
O_{HG}	$HH^{\dagger}G^A_{\mu\nu}G^{\mu\nu A}$	c_{HG}	$O_{H\widetilde{G}}$	$HH^{\dagger}\widetilde{G}^A_{\mu\nu}G^{\mu\nu A}$	$c_{H\widetilde{G}}$
O_{HW}	$HH^{\dagger}W^l_{\mu\nu}W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^{\dagger}\widetilde{W}^l_{\mu\nu}W^{\mu\nu l}$	$c_{H\widetilde{W}}$
O_{HB}	$HH^{\dagger}B_{\mu\nu}B^{\mu\nu}$	c_{HB}	$O_{H\widetilde{B}}$	$HH^{\dagger}\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
O_{HWB}	$HH^{\dagger}\tau^l W^l_{\mu\nu}B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^{\dagger}\tau^l \widetilde{W}^l_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$

Effective Field Theory in Run 2

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

Parametrize the STXS cross sections and Branching Ratios as function of the Wilson coefficients

Constraint CP-even couplings

Constraint CP-odd couplings (not sensitive to the sign)
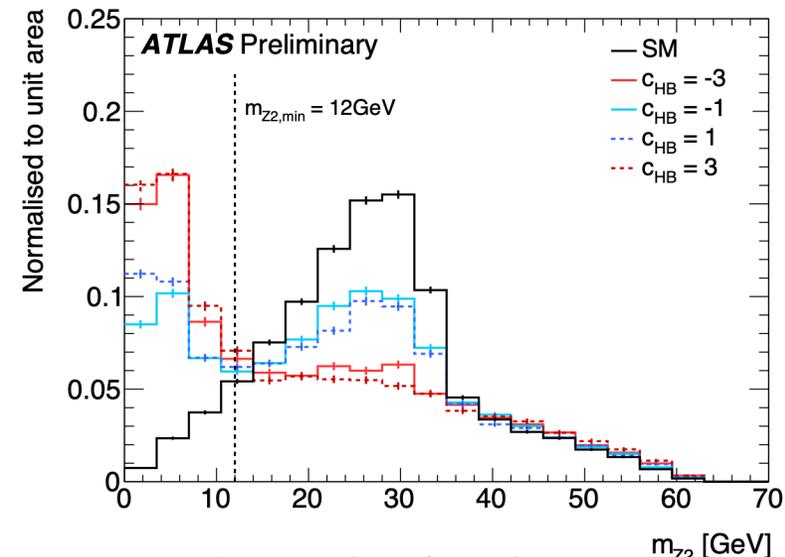
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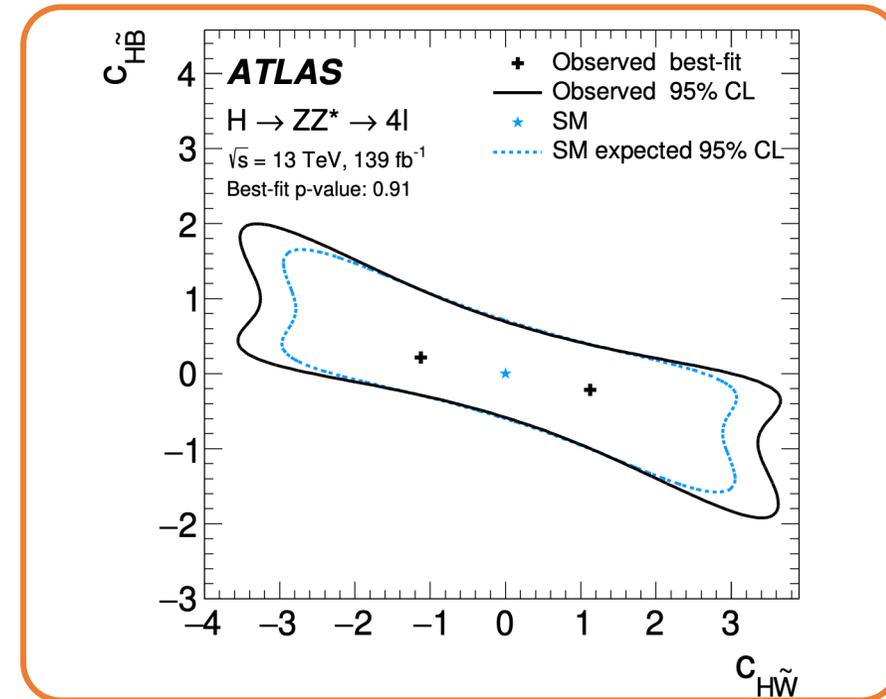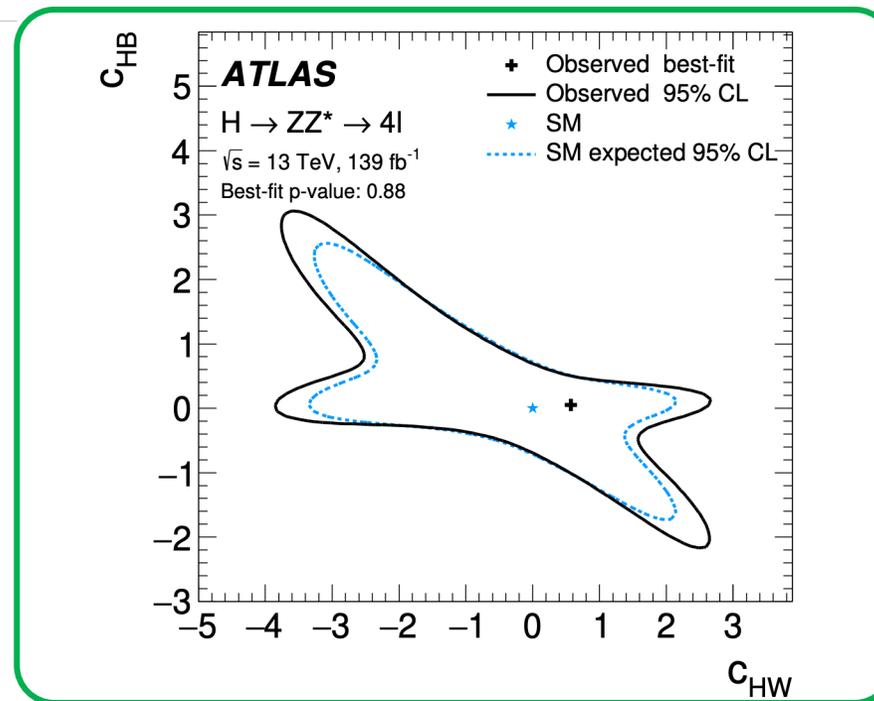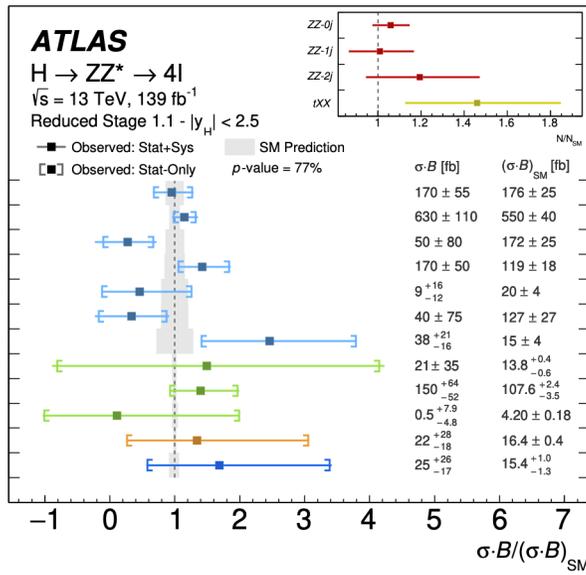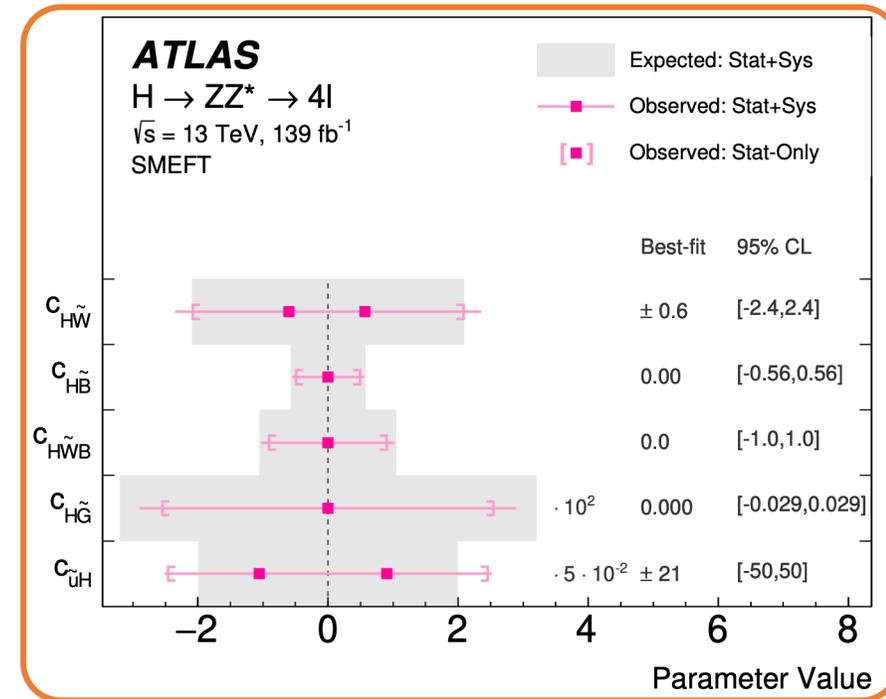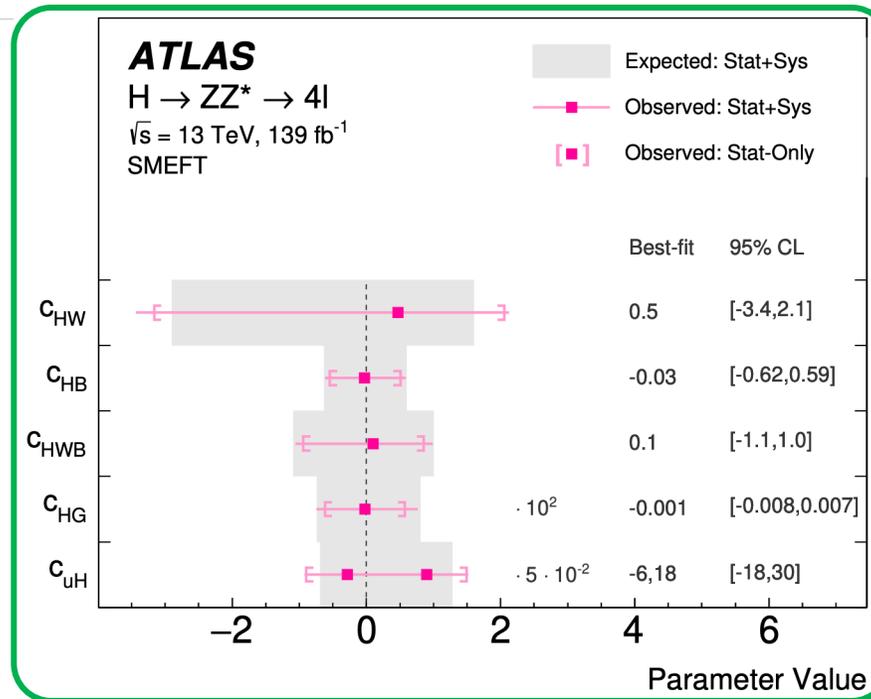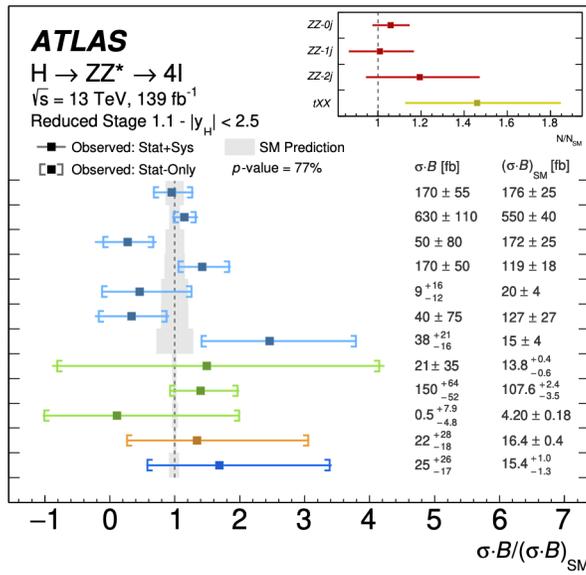
Effective Field Theory in Run 3

Off-shell Z distribution of m_{34} sensitive to BSM effects

Parametrize the fiducial
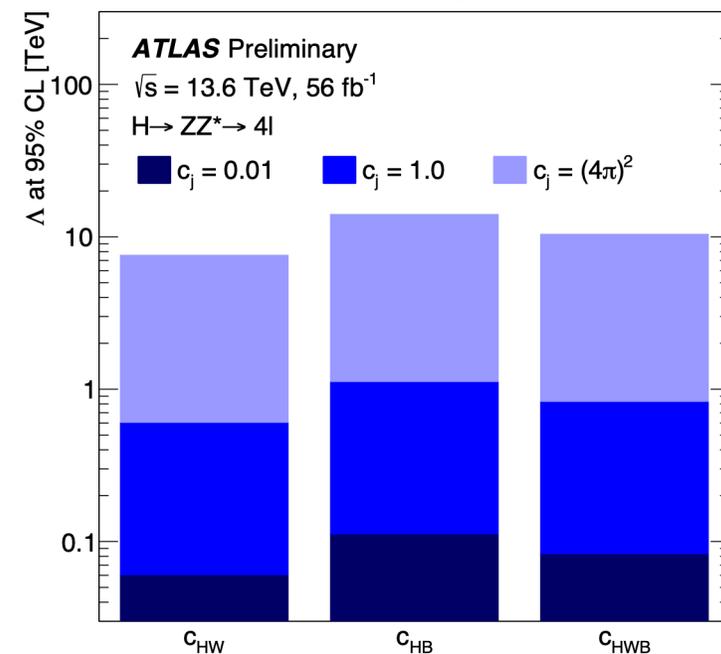cross sections as function
of the Wilson coefficients

Constraint on CP-even couplings

Limits on the Λ scale
based on coupling values
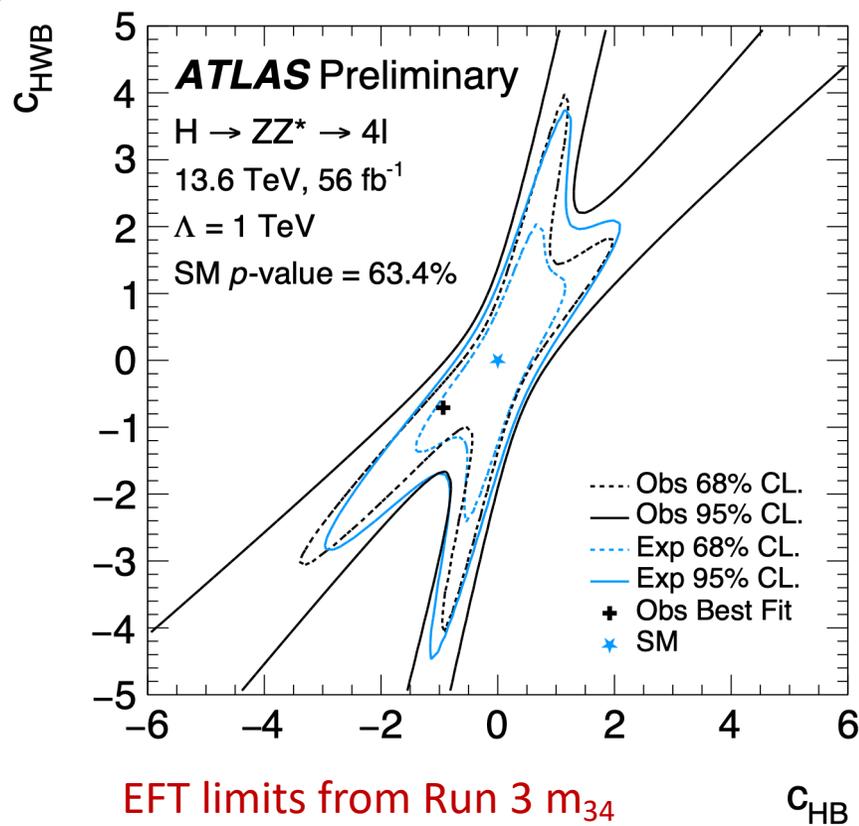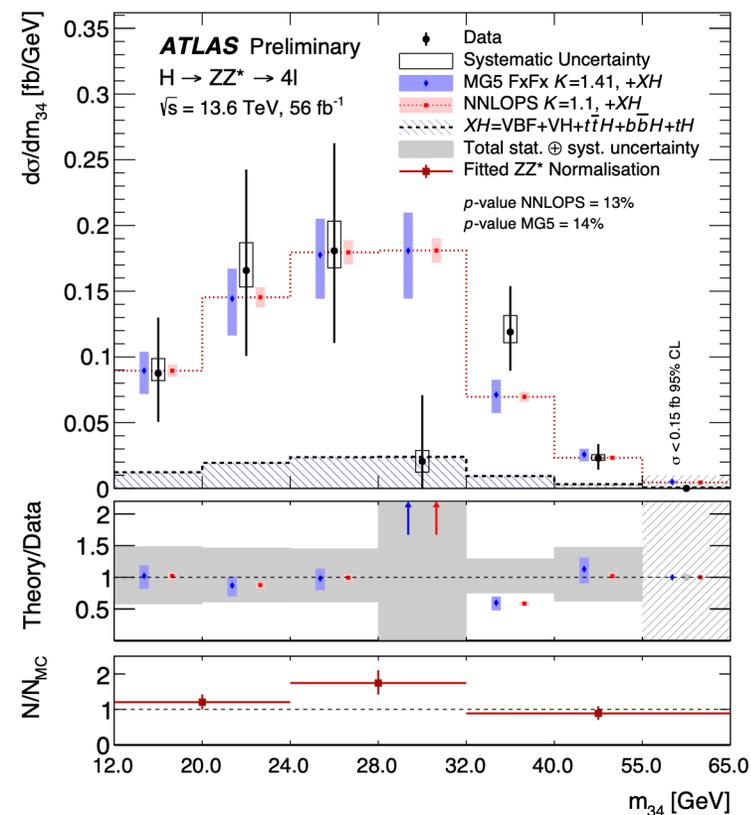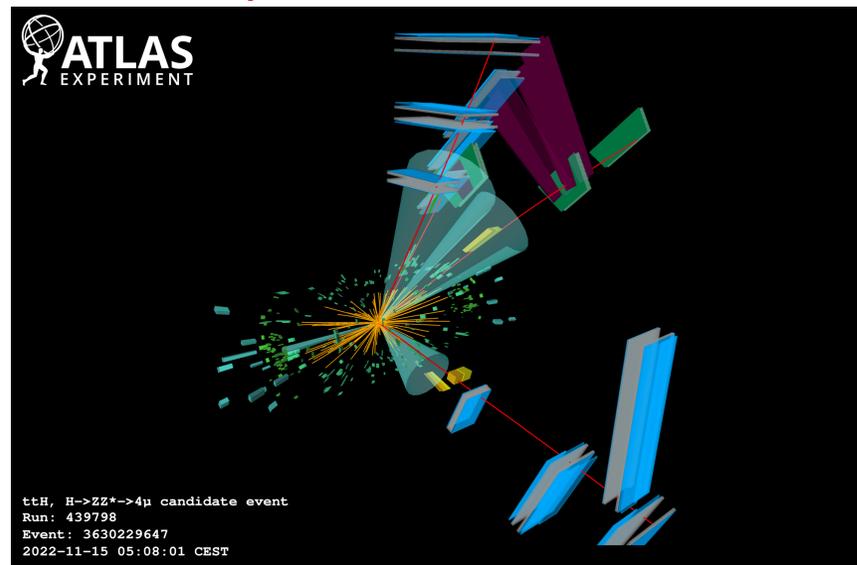

EFT limits from Run 3 m_{34}
interpretation comparable
with one from Run 2 STXS

Conclusions

Cross section measurements to study the Higgs boson couplings with other Standard Model particles and to probe possible New Physics phenomena

- Presented results from full Run 2 analyses and preliminary picture using Run 3 dataset

Experimental Data Observable Measurements Lagrangian parameters
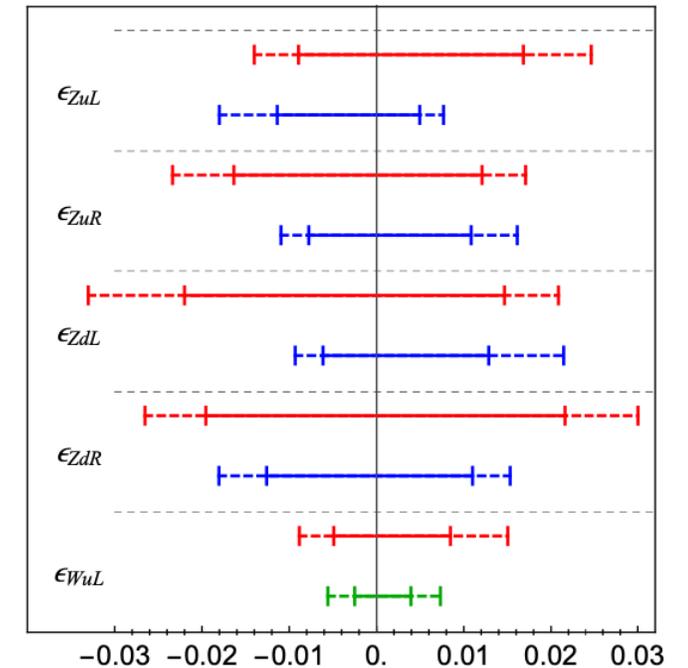

More Run 3 data coming,

Stay Tuned!

Thanks for the attention

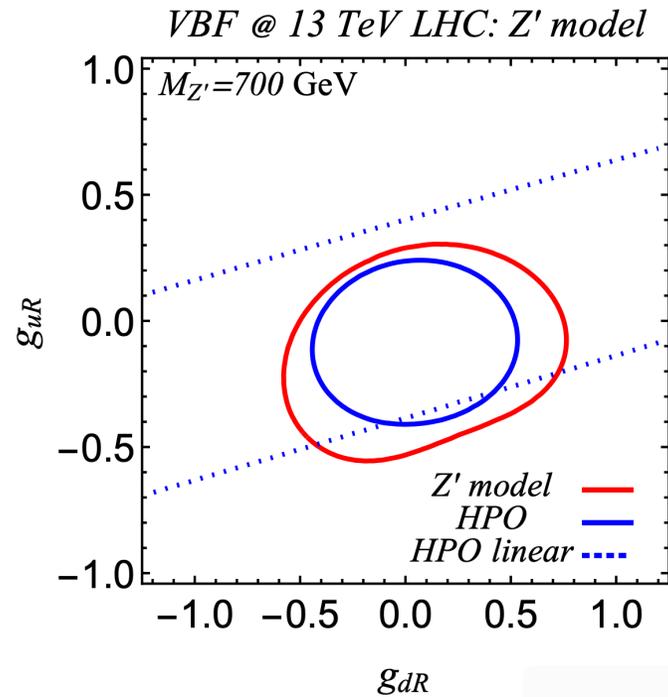# Pseudo Observables: Prospects

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

- **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 $m_{Zh} \sim q^2$

Prospects for Higgs PO in EW production @ the HL-LHC
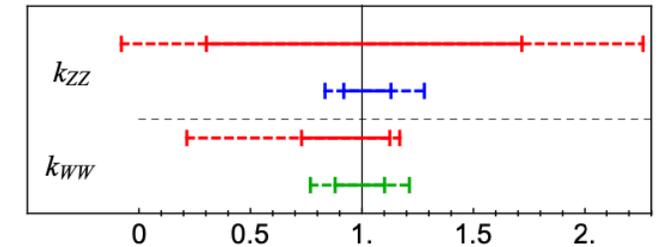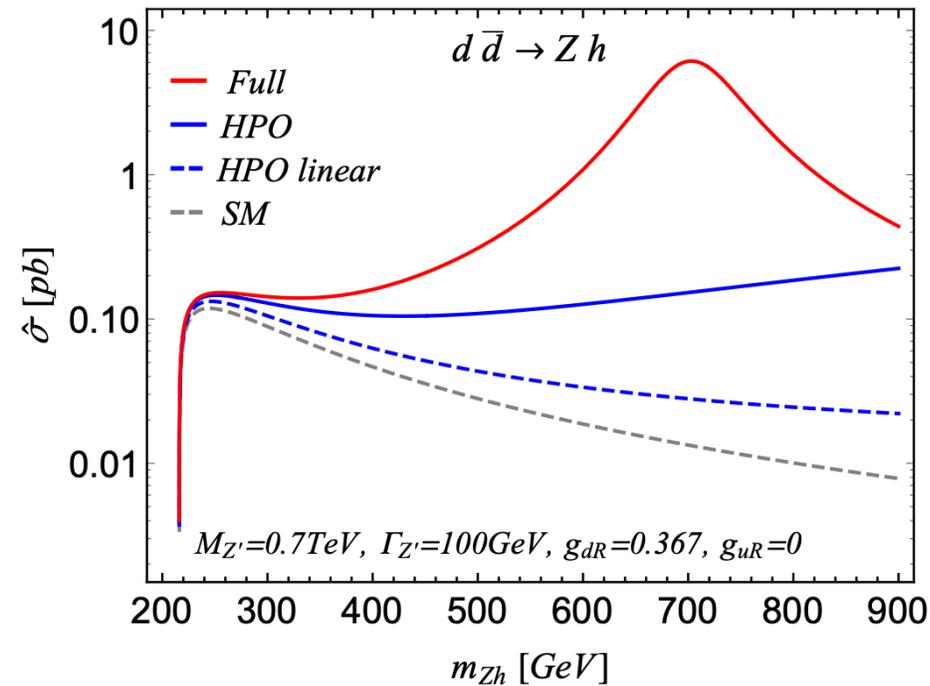
→ Define fiducial volume targeting specific production modes can improve sensitivity

The Higgs boson Mass

H→ZZ*→4l and H→γγ 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
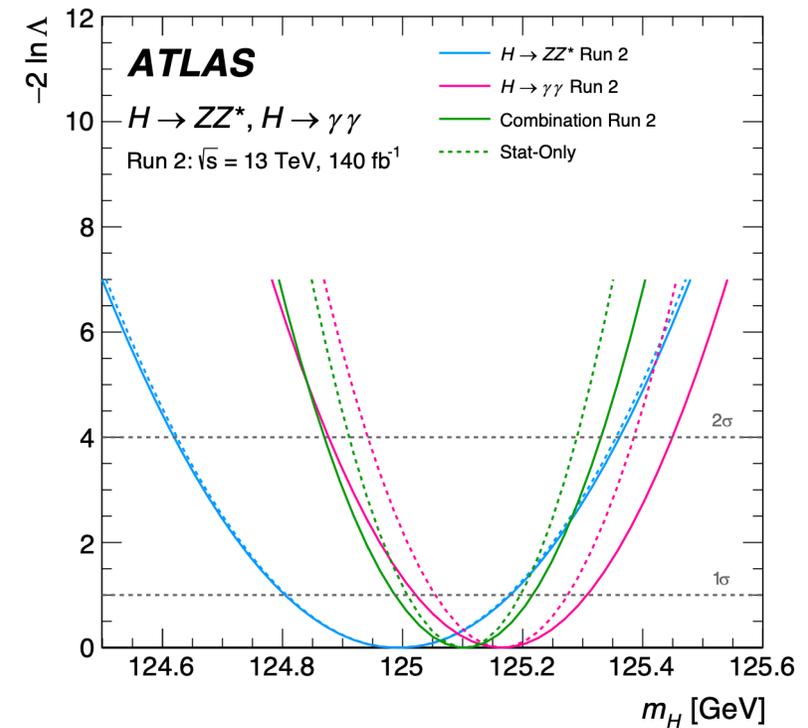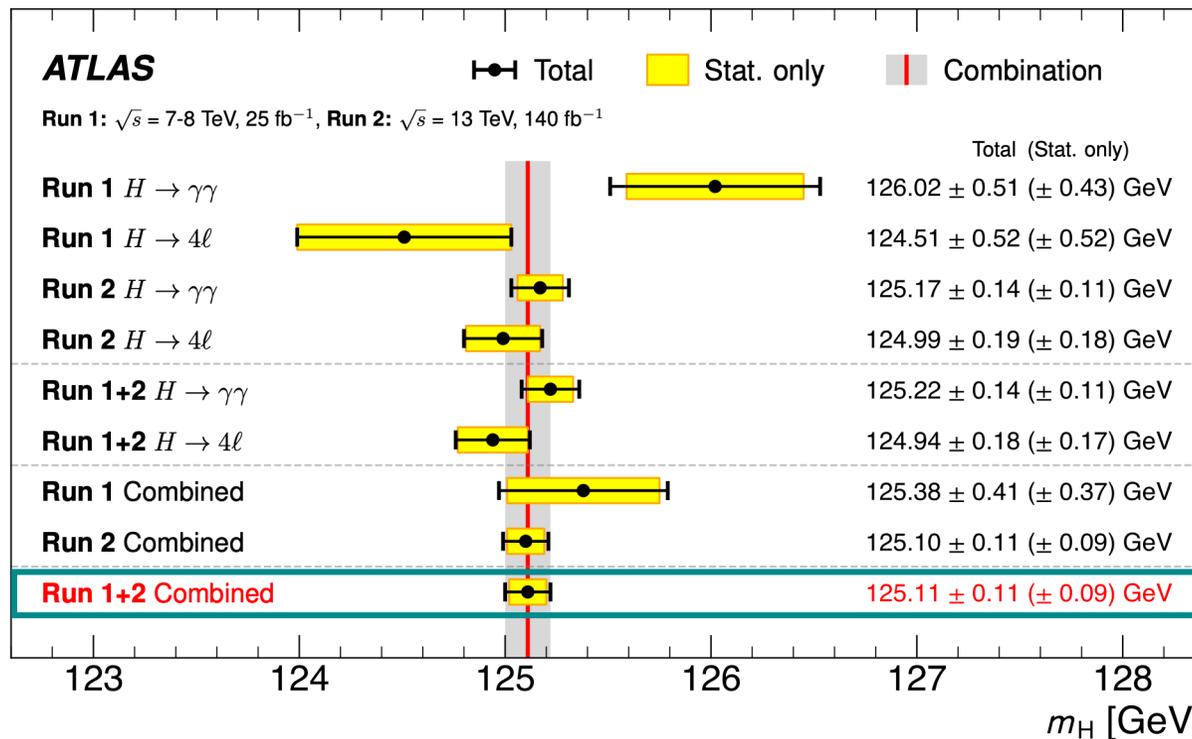
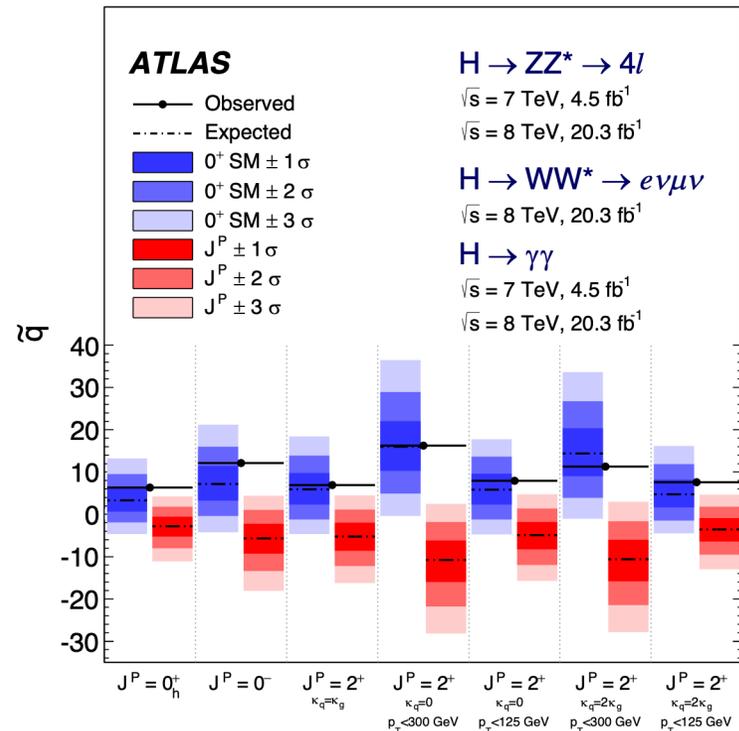$$m_H = 125.11 \pm 0.11 \text{ GeV}$$

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

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

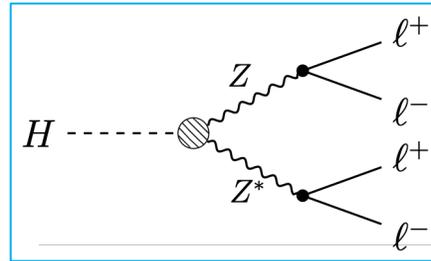- In Run 2 the focus is mainly on production modes rather than decay only.
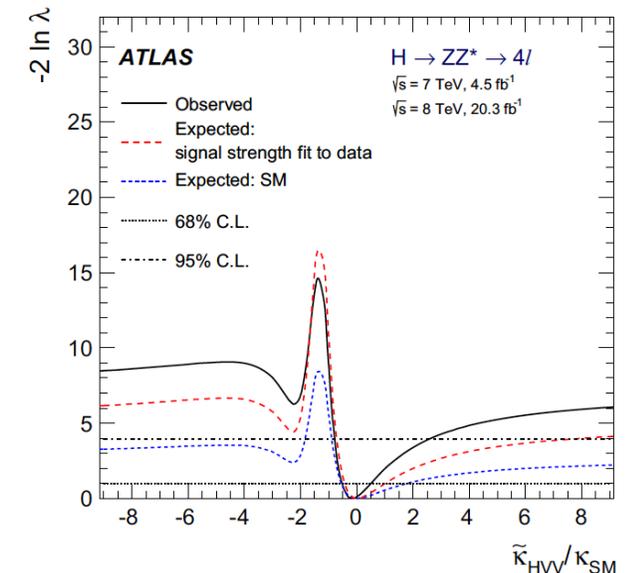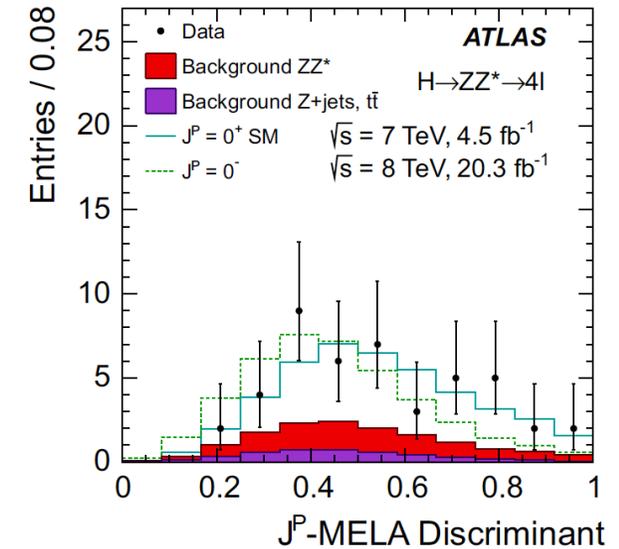
The Higgs boson CP structure

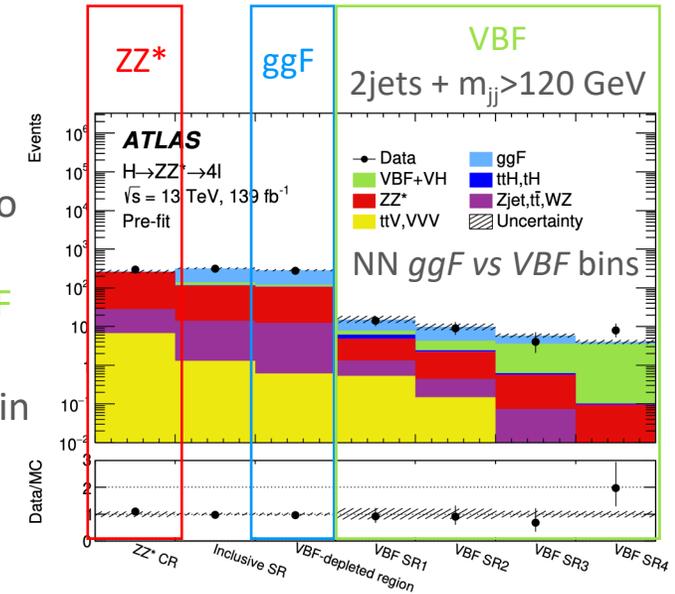Looking for signs of CP-violation in the Higgs sector arXiv:2304.09612

- 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
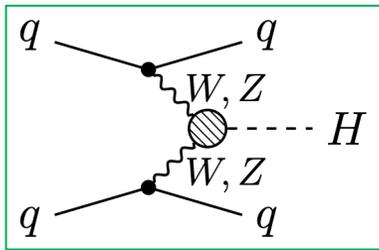
VBF → high Q^2 process BSM effects expected to be higher

- 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)

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

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

NN *ggF vs VBF* bins

Asymmetric for CP-odd effects
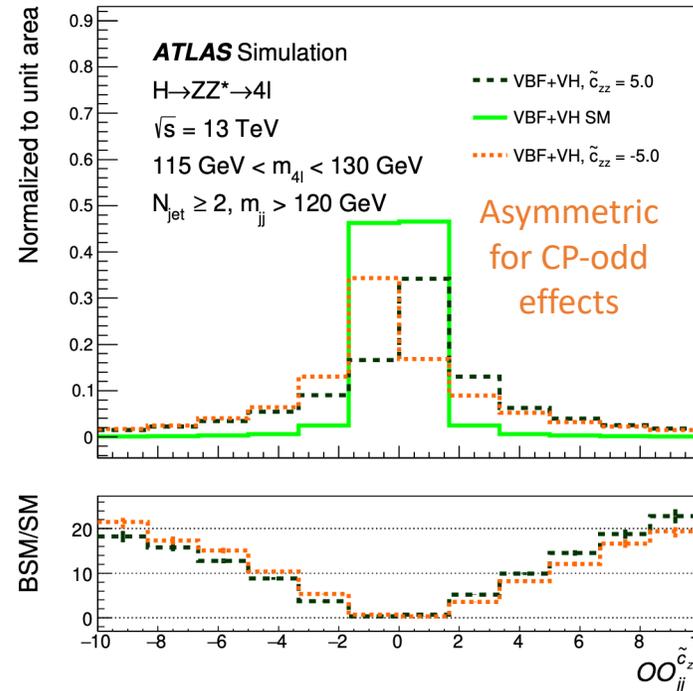
Constraint on EFT **CP-odd couplings**