Study of the production modes of the Higgs boson and EFT interpretations in the decay channel H->ZZ->4l at 13 TeV with the ATLAS detector*

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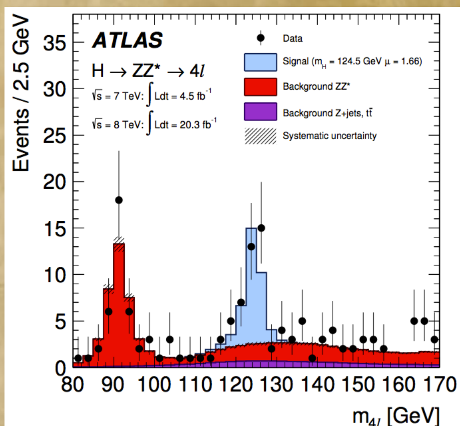
Introduction

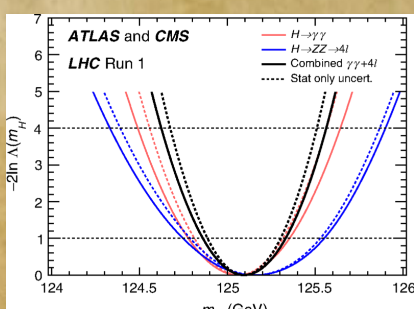
Run1

Observation of the Higgs boson in the H->ZZ*->4l decay channel:



m_H = 125.09 ± 0.24 GeV

(ATLAS+CMS ZZ* e γγ)



- **The Higgs boson was the missing piece of the Standard Model (SM):**
  responsible of the spontaneous symmetry breaking that allows elementary particles to acquire mass.
- **The SM, despite being very successful:**
  - It does not explain the matter-antimatter asymmetry of the universe, the dark matter, it does not include a description of gravity…

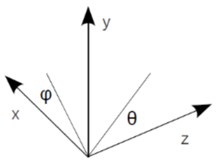
  Higgs boson properties: possible deviations from the SM and New Physics effects, can be hidden in the Higgs sector.
- **It is crucial to study the h(125) properties!**

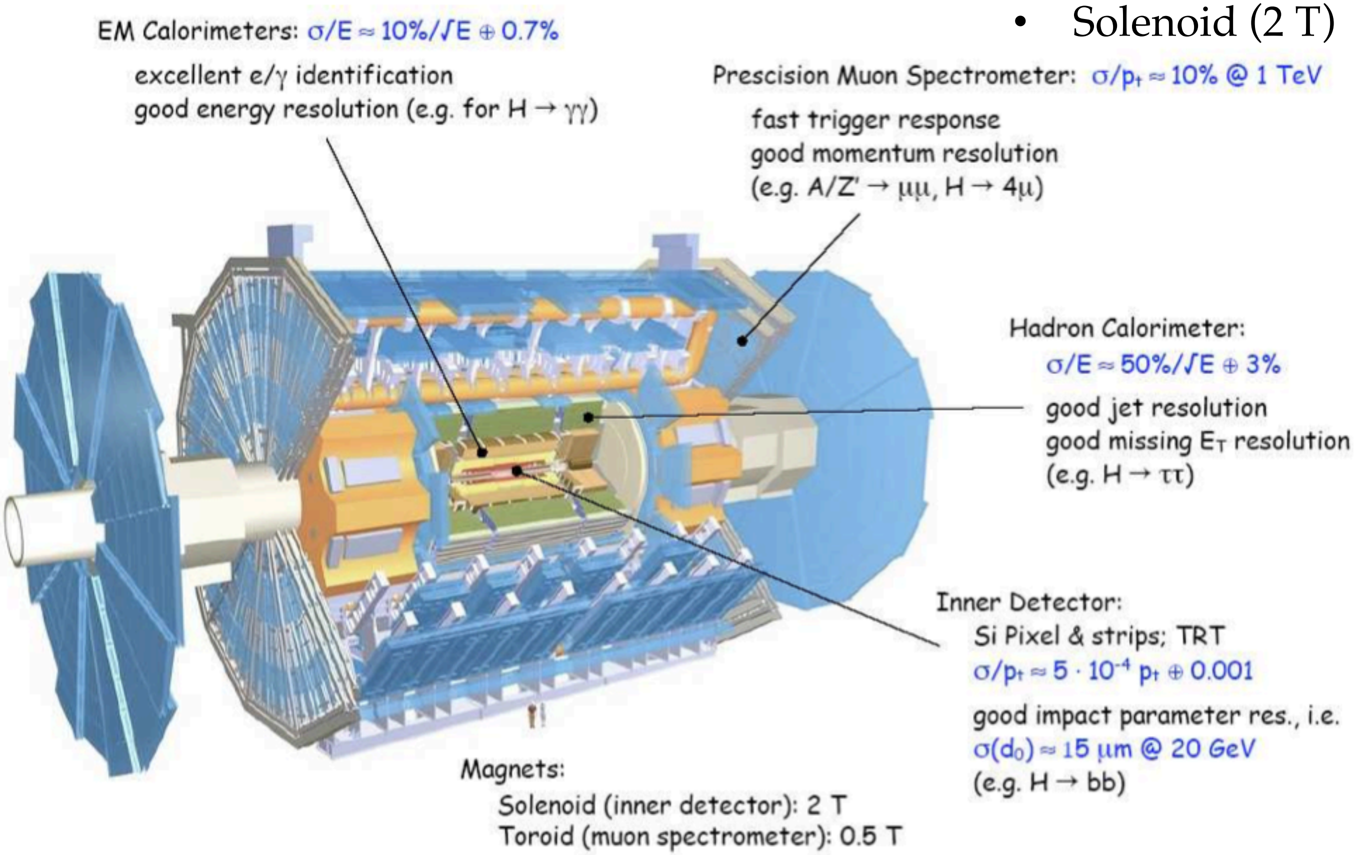
In this presentation:

- **Introduction**
  - ATLAS detector
  - Higgs @ LHC
  - Overview of Run1 measurements
  - Present the H->ZZ*->4l decay channel
- **Studies on the Higgs boson properties**
  - Cross section per production mode, RunII, 14.8 fb^{-1} @ 13 TeV
  - Sensitivity study based on an EFT parameterization of the decay amplitude (Isidori et al.)
- **Conclusions and future perspective**

ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

A Thoroidal Lhc ApparatuS





Inner Detector:

- Silicon trackers (pixel e microstrip)
- Gas trackers (with measurement of the transition radiation, TRT)
- Solenoid (2 T)

Electromagnetic Calorimeter:

- Sampling Pb+LAr

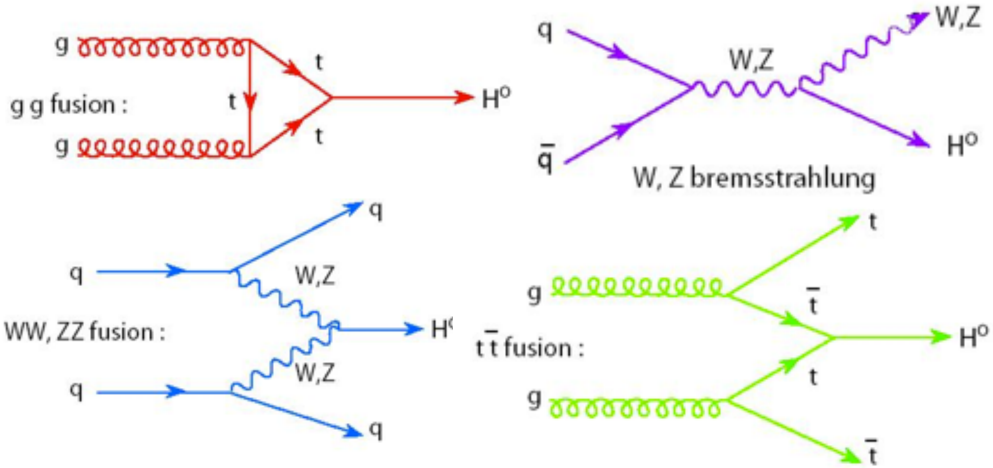
Hadronic Calorimeter:

- Fe+scintillator
- LAr technology

Muon System:

- Superconducting thoroids
- Precision tracking chambers
- trigger chambers

The Higgs production at LHC can occur through the following mechanisms:



ggF: is the dominant production mode, $\sigma^{ggF}/\sigma^{TOT}$ = 87% @ 13 TeV.

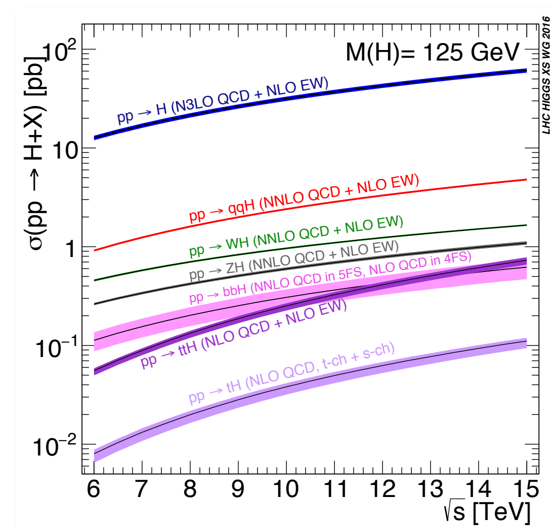
VBF: whose signature is characterized by H +2jet forward, $\sigma^{VBF}/\sigma^{TOT}$ = 7% @ 13 TeV.

VH: whose signature is composed by a H associated to a W or a Z boson, σ^{VH}/σ^{TOT} = 4% @ 13 TeV.

ttH-bbH: in which the H is associated to tt-bar/bb-bar pairs, $\sigma^{ttH+bbH}/\sigma^{TOT}$ = 2% @ 13 TeV.

Decay channels:

- H->ZZ*->4l: pure channel by very low statistics ($BR_{H\to ZZ^*\to 4l}$~ 2 10^{-4})
- H->γγ : "easy" final state but low BR
- H->WW*: good sensitivity but low mass resolution
- VH->bb-bar & H->ττ: interesting for the measurements of couplings to fermions (huge bkgs)
- H->Zγ & H->μμ: low BR



Analyses in RunI have been optimized for the discovery

- The first measurements of the properties have shown that the observed boson was compatible, within the uncertainties, with the Higgs predicted by the SM

Measurements in terms of:

- **Signal strenght**: defined as the ratio of the XS • BR with respect to the SM (more model dependent): $\mu = (\sigma\, BR)_{obs}/(\sigma\, BR)_{SM}$

- **Coupling modifiers (k_j)**, added as multiplying terms in the Higgs boson couplings to fermions and bosons in the SM Lagrangian, in order to take into account for New Physics (NP) effects that can occur both in production and decay:

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}} \qquad \text{where} \qquad \kappa_j^2 = \Gamma^j/\Gamma^j_{\mathrm{SM}} \;,\quad \kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}}$$

-> k_j=1 refers to the Standard Model case (SM)

Overview of Run1 results

- Discovery of the Higgs with mass
  $m_H = 125.09 \pm 0.24 \ (\pm 0.21 \text{ stat.} \pm 0.11 \text{ syst.})$ GeV

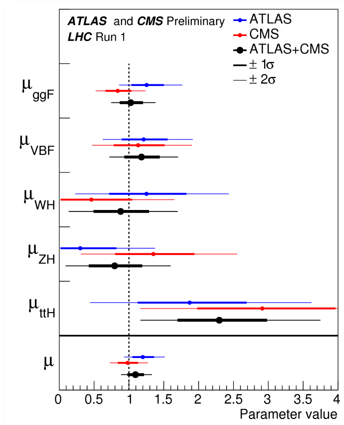
- Measurements of the **couplings to SM particles consistent with the SM within uncertainties**

- Combined signal strength:
  $\mu = 1.09 \pm 0.07\text{stat} \pm 0.04\text{exp.syst.} \pm 0.03\text{th.bkg}\ {}^{+0.07}_{-0.06}\text{th.sig}$

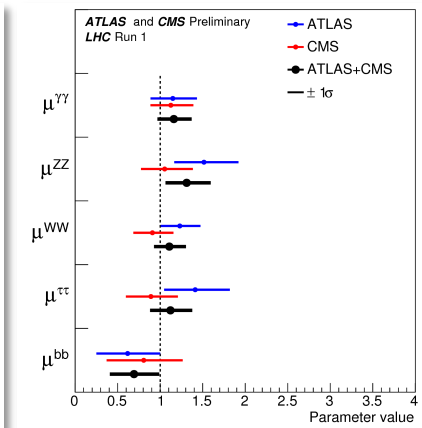
- **Non-SM hyp.** ($J^P_{SM} = 0^+$) **excluded at > 99.9% CL**

- Indirect limits on the width: $\Gamma_H/\Gamma_H^{SM} < 5$ @95%CL

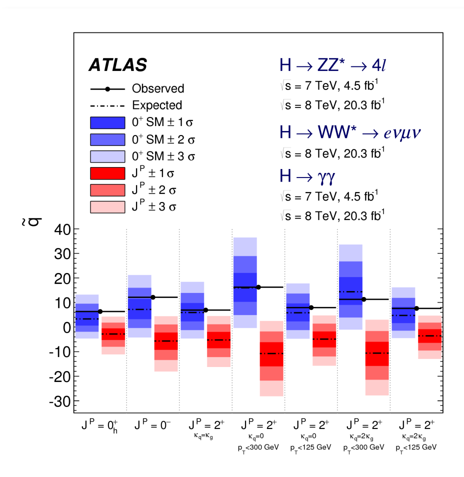
Signal strength: $\mu = (\sigma\ BR)_{obs}/(\sigma\ BR)_{SM}$
(kinematics distributions assumed as from SM)

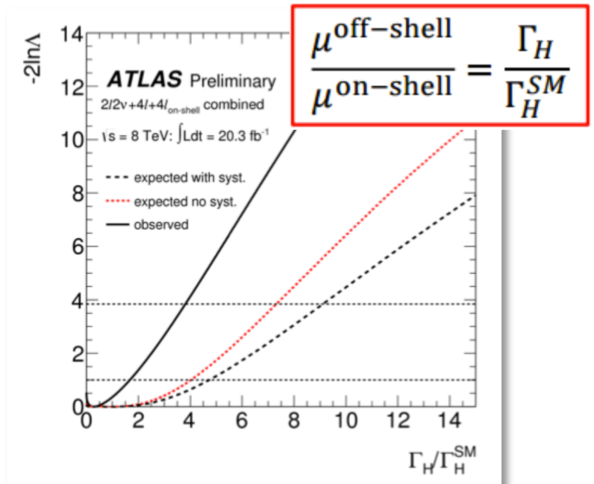


(Assuming BR_{SM})

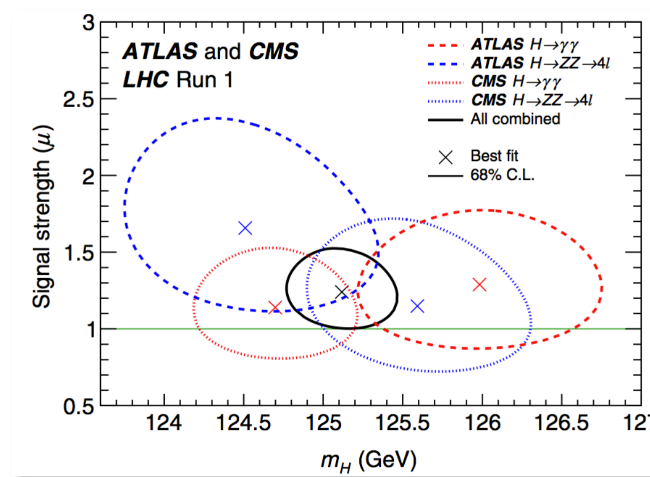


(Assuming XS_{SM} and $XS_{SM(7TeV)} = XS_{SM(8TeV)}$)





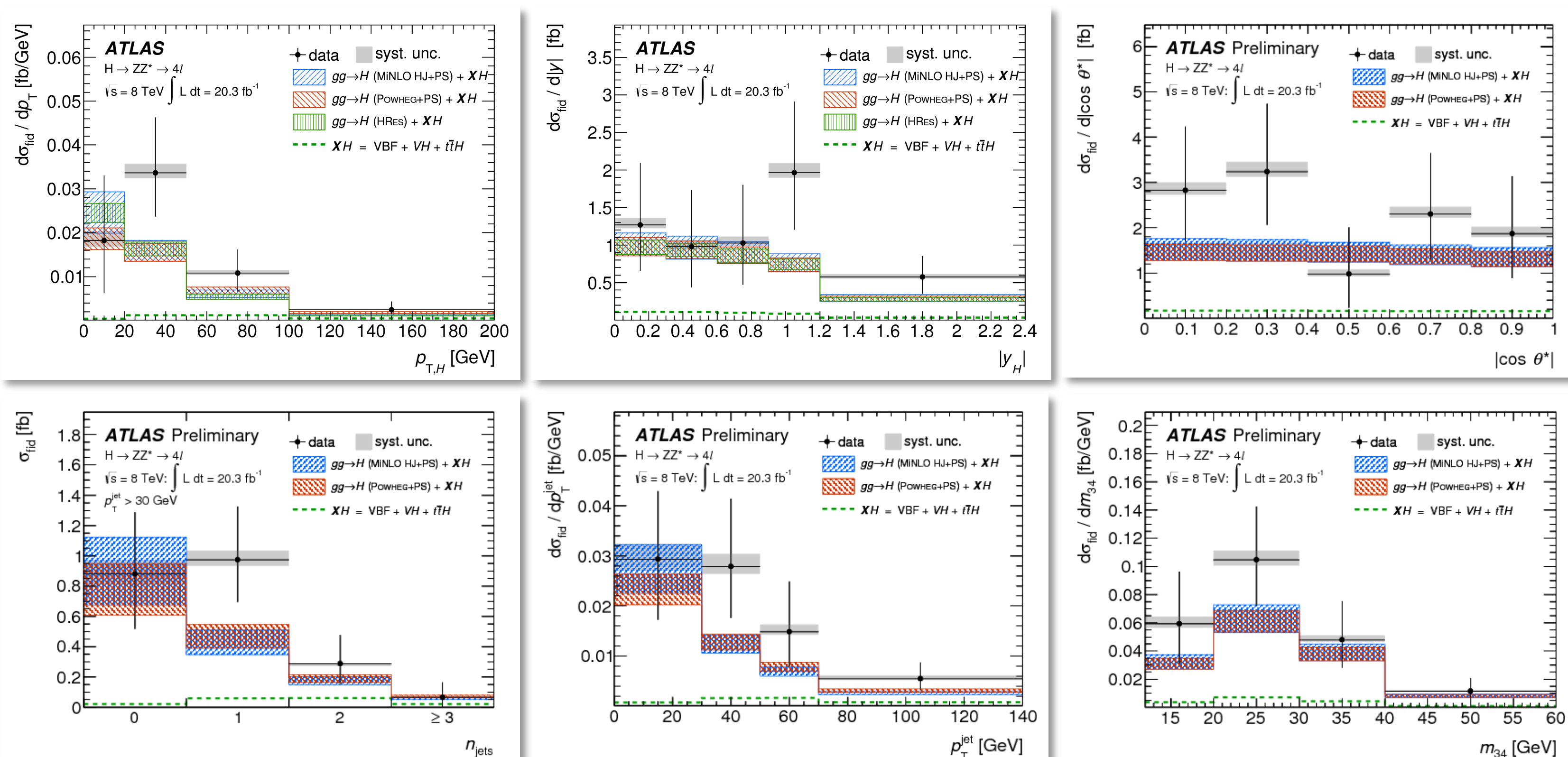
$$\frac{\mu^{off-shell}}{\mu^{on-shell}} = \frac{\Gamma_H}{\Gamma_H^{SM}}$$



Measurement of the differential fiducial cross section:

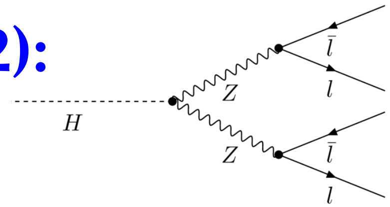
$$\frac{d\sigma_{\text{fid},i}}{dx_i} = \frac{n_i^{\text{sig}}}{c_i \cdot \mathcal{L}_{\text{int}} \cdot \Delta x_i}$$

- Fiducial phase space (to minimize the model dependency)
- Corrected for detection efficiency and resolution effects
- Variables sensitive to the H boson properties have been chosen (production modes, spin and parity, proton pdfs, QCD effects)
- Results have been compared to several theo. predictions

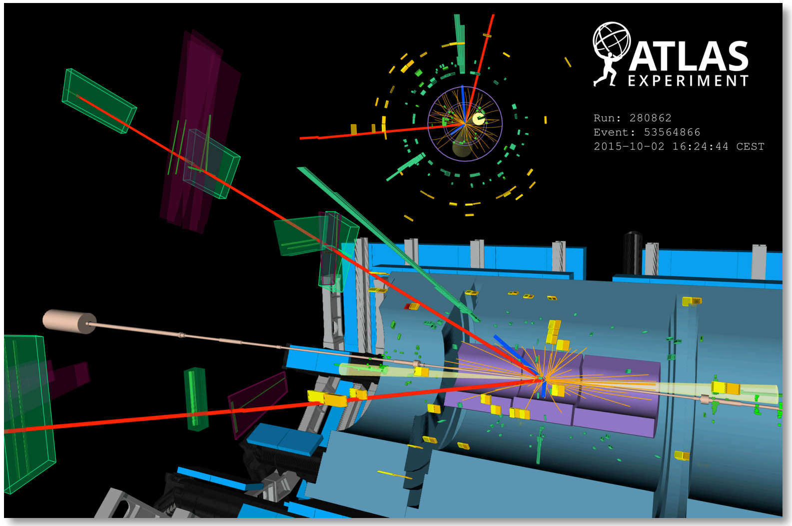


Golden channel (S/B~2):

Cut-based event selection

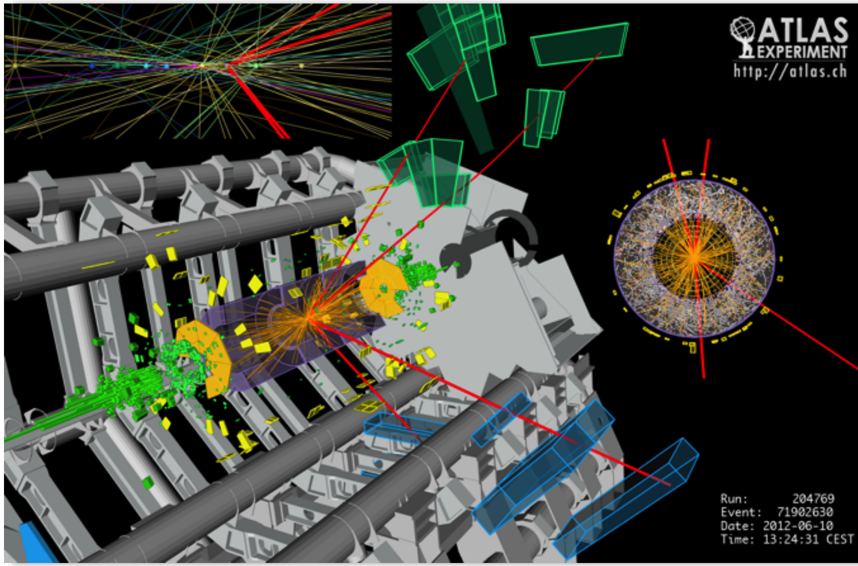


Lepton definition	
Muons: $p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$	Electrons: $p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection	
Lepton kinematics:	Leading leptons $p_T > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same(opposite)-flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$118 < m_{4\ell} < 129$ GeV



Experimental signature:

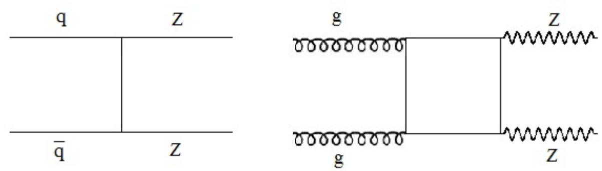
- 2 lepton pairs
- Opposite charge
- Same flavour
- High p_T
- isolated
- Coming from the primary vertex

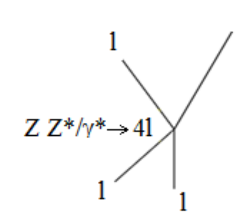


Main backgrounds

Irriducible background:

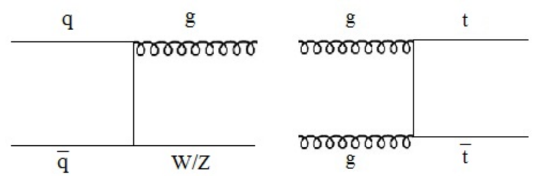
- Same final state as for the signal.

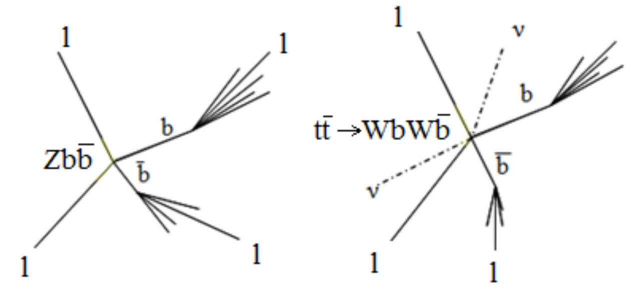


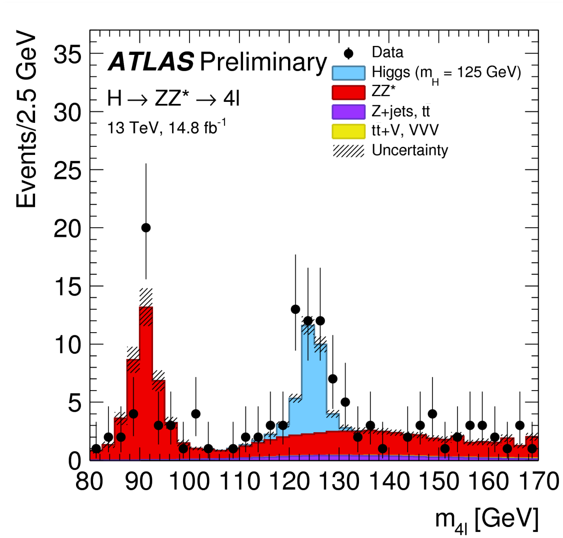


Reducible background:

- Leptons from secondary vertex
- Not isolated







ZZ* bkg estimated from MC

Z+jets & ttbar: estimated from Control Regions (CR)

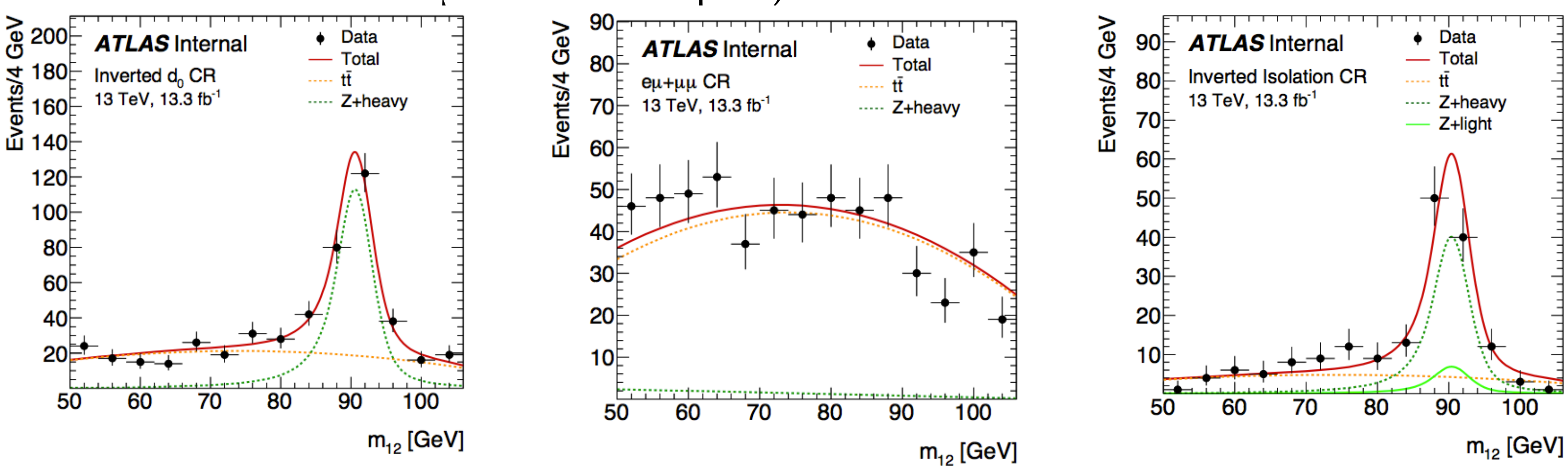
$\sigma_{Z+jets} \sim 10^3\ \sigma_{signal}$
$\sigma_{ttbar} \sim 10^4\ \sigma_{signal}$
-> high rejection factor

- Data-driven methods for the bkgs estimate using control regions
- Likelihood fit
- Transfer factors to estrapolate the contributions to the signal region

Common Background estimates

ll+μμ:

- Fit of m_{12}
- 3 bkg components: ttbar, Z+heavy flavour, Z+light flavour
- 2 CR used for a simultaneous fit of ttbar and Z+heavy components (eμ+μμ, ttbar enriched, and inverted-d0, enriched in Z+heavy)
- the inverted-iso CR (enriched in Z+light) is then used to estimate Z+light component
- SR estimates obtained using MC based transfer factors from CRs (description of cuts checked from Z+μ control samples)



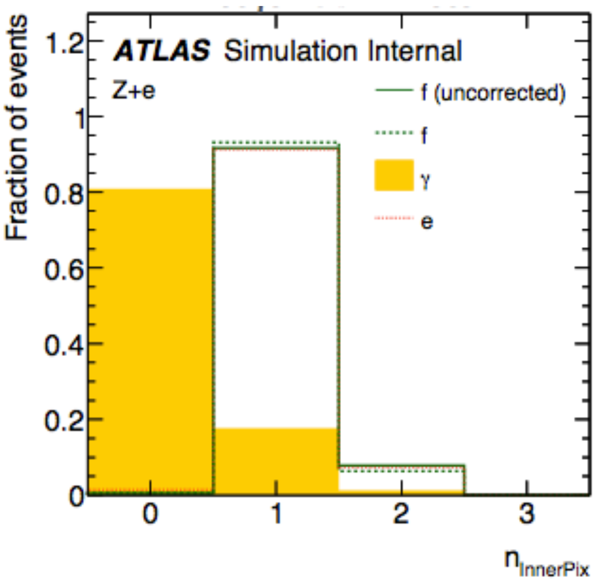
Background	Fit yields	Extrapolation factor [%]	Yield in SR
Z+heavy flavour jets	310+-27	0.60+-0.04	1.85+-0.16+-0.11
ttbar	323+-13	0.21+-0.03	0.68+-0.03+-0.09
Z+light flavour jets	14+-14	2.3+-0.3	0.32+-0.33+-0.04
WZ	(MC-based estimation)		0.63+-0.27

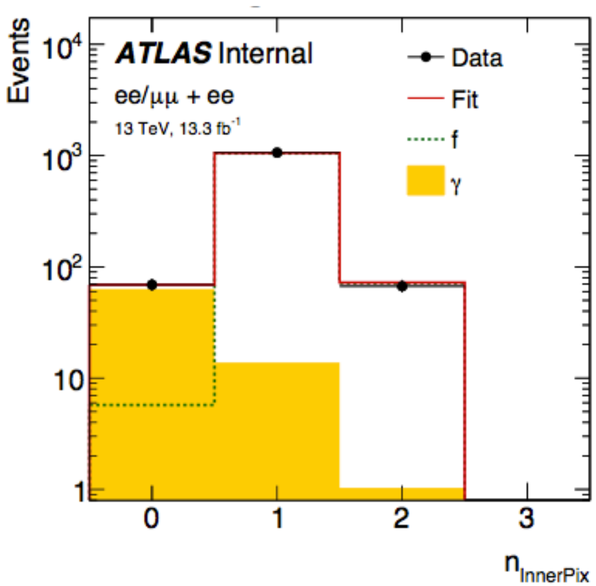
ll+ee:

- Fit of $n_{InnerPix}$ (# of innermost pixel hits or next-to-innermost in case)
- 3 bkg components: misID of light-flavour jets as electrons (f), electrons from photon conversion (γ), electrons from semi-leptonic decays of heavy flavour hadrons (q)
- the 3l+X CR is used to estimate the f and γ bkg (templates taken from MC in the Z +X CR and corrected to the data with fake-enriched control samples)
- q bkg is estimated from MC

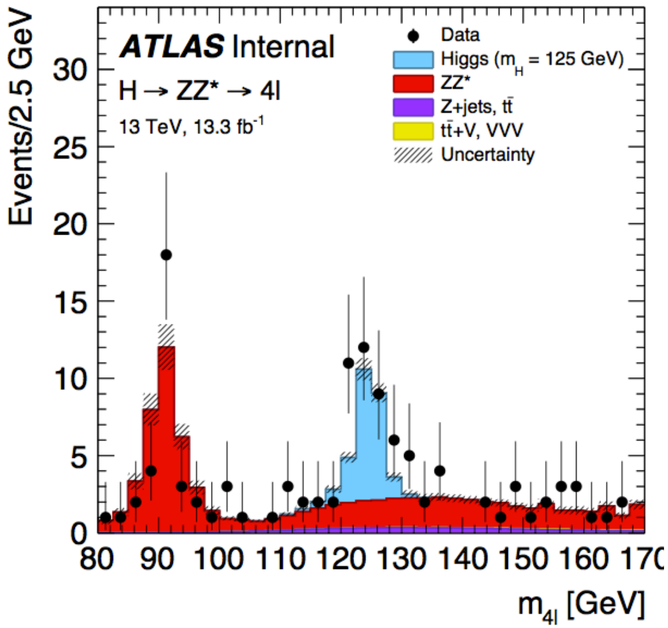
4e+2μ2e			
type	data fit	efficiency [%]	SR yield
f	1121 ± 34	0.24 ± 0.03	2.47 ± 0.08 ± 0.34
γ	78 ± 10	0.76 ± 0.05	0.56 ± 0.08 ± 0.04
q	(MC-based estimation)		2.45 ± 0.75

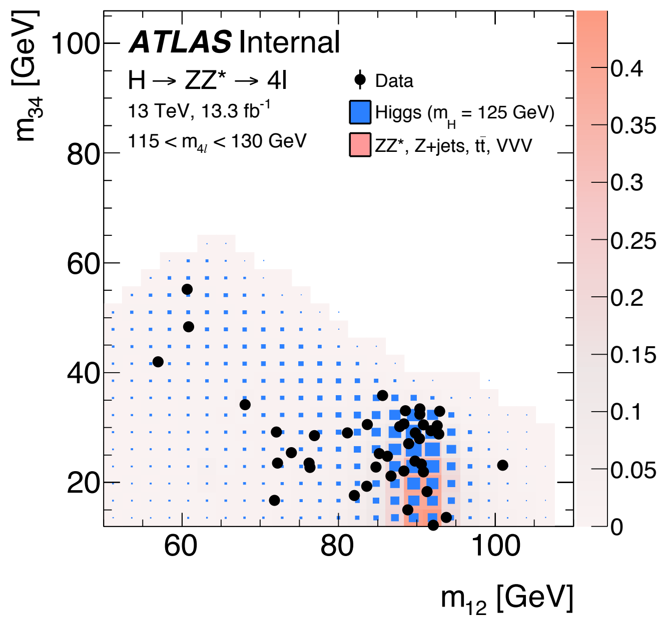
- *Split per channel:* 4e/total is 53% for *f*, 60% for *γ*

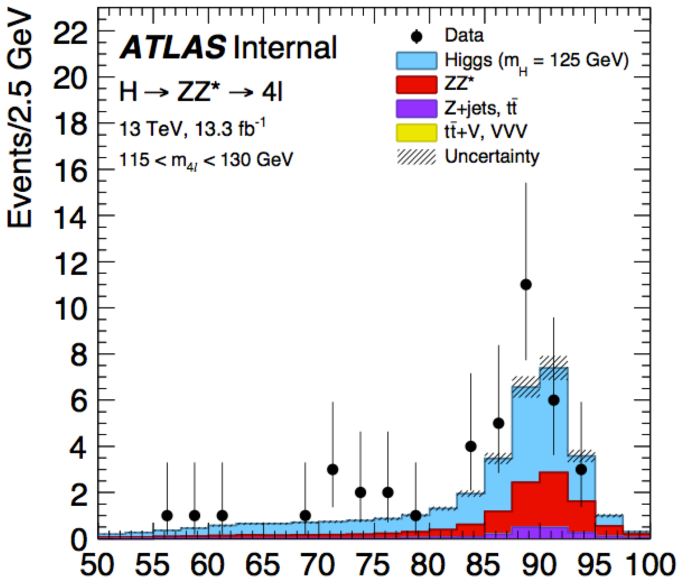


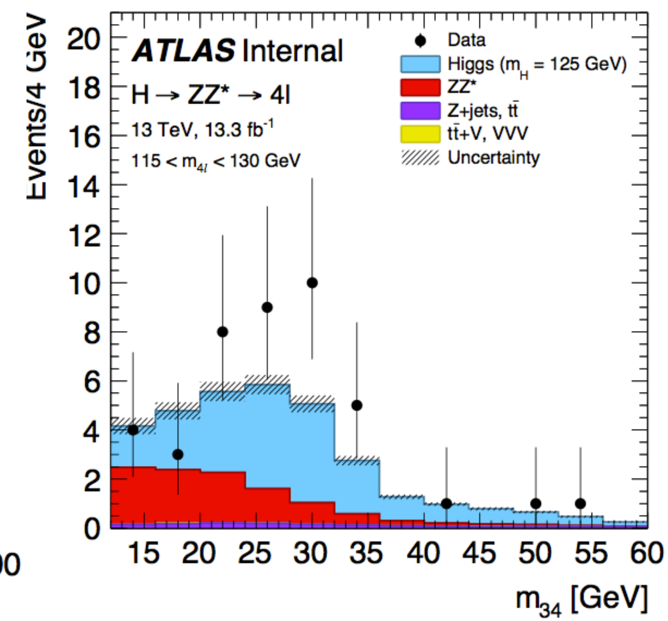


Data-simulation comparison









- Kinematic distributions of the events recorded with 13 TeV.

To investigate possible deviations from the SM:

Interesting to study a categorization which allows to have **more sensitivity to production modes:**

- Observation of exclusive production modes in each channel splitting the events in more restricted phase
- "measure" the BSM deviations
- better precision on the coupling measurements

From the k-framework to the effective field theories (EFT)

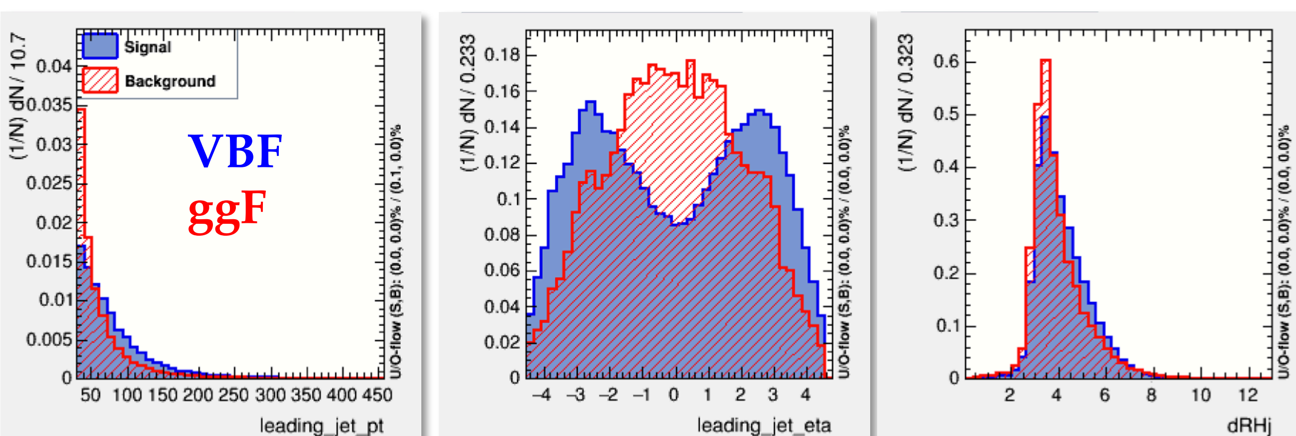
- To use a more general model for the signal: POs, EFT -> have assumptions on the model but allow to use all the experimental information in a coherent way

Measurement of the cross sections per production mode with 14.8 fb^{-1} during RunII (ICHEP2016)

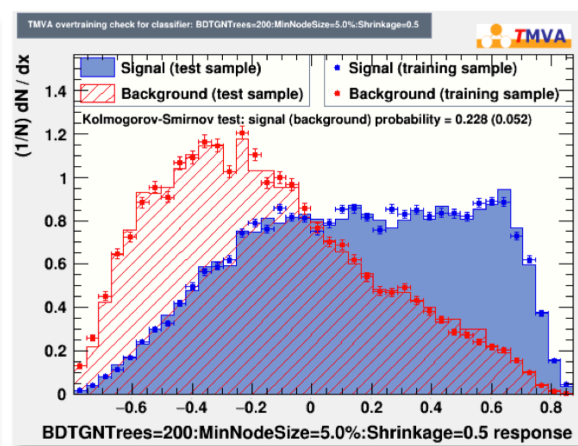
In order to gain sensitivity to different production modes a categorization of the Higgs candidate events has been performed:

- Exclusive categories: additional lepton and number of jets associated to the events
- Dedicated discriminants in each category
- Particular care for the 1jet category (~30% ggF events and ~30% VBF)

BDT 1jet training variables

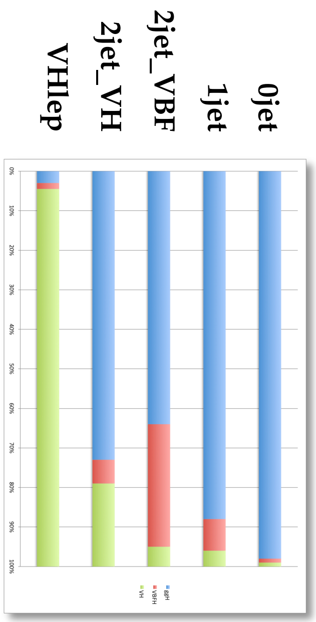


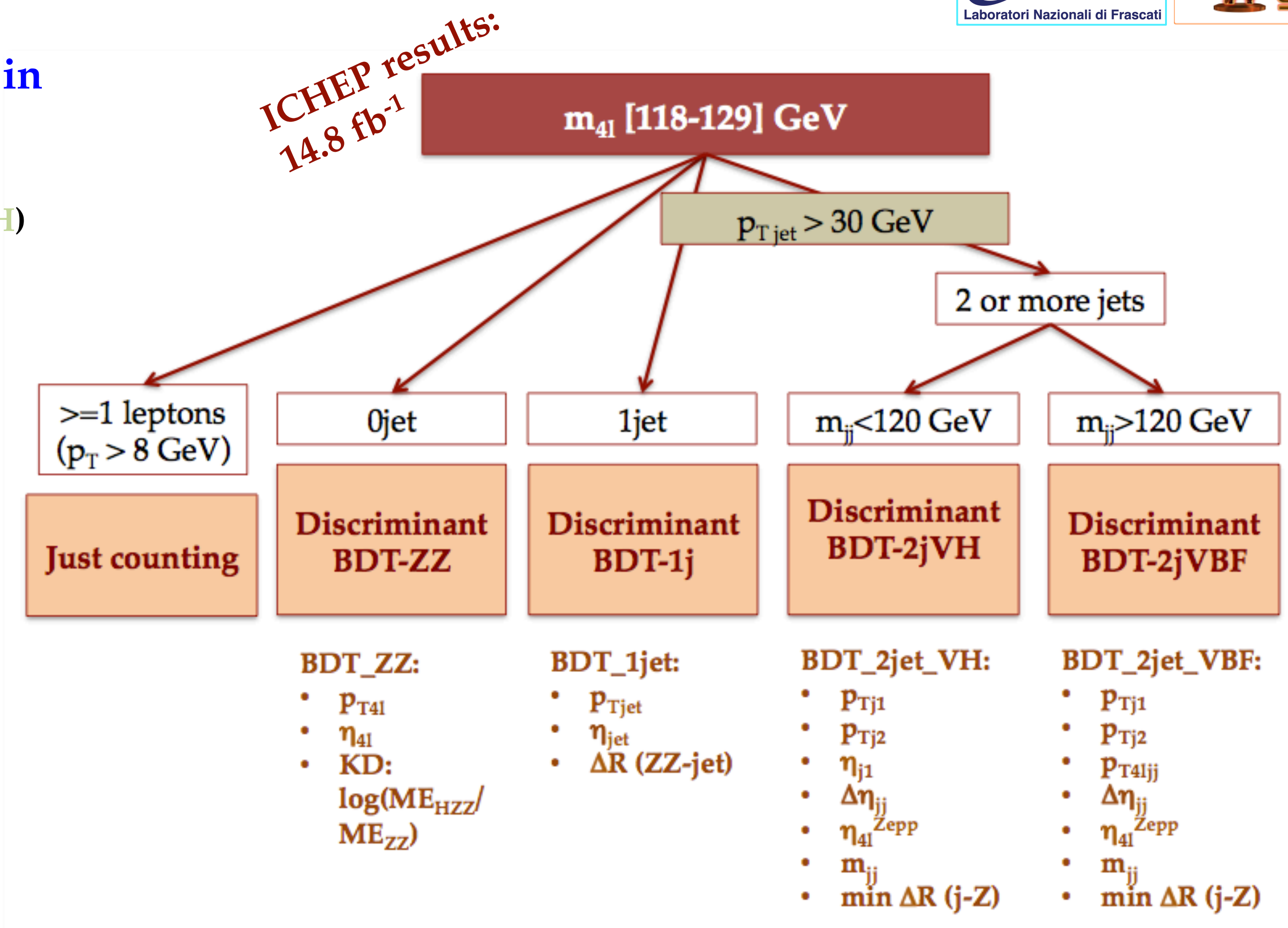
BDT 1jet



Fraction of events in each category.

(ggF+ttH+bbH VBF VH)



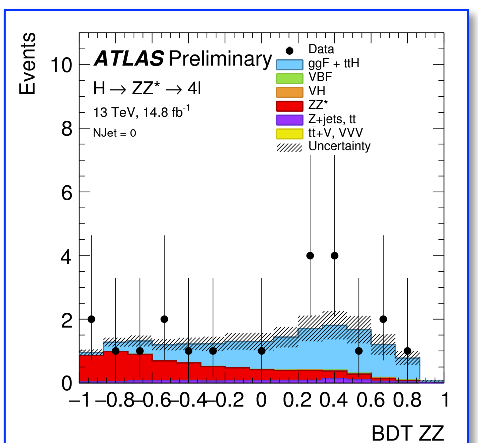


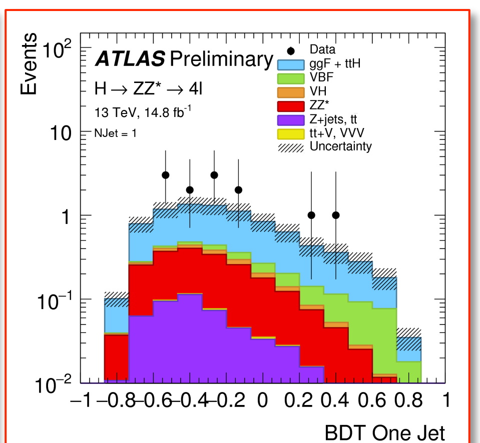
The same categorization has been used in order to put limits on EFT couplings without using discriminants.

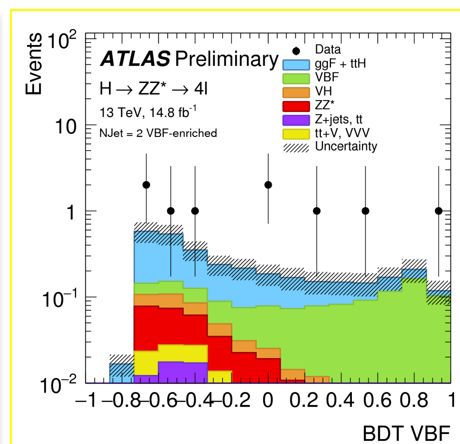
Higgs candidates in the m4l [118-129] GeV in each category

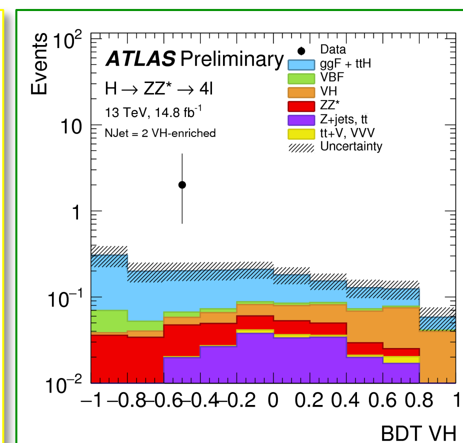
BDT based discriminants are used to separate the contribution per production mode in each category.

Analysis category	Signal: ggF + $b\bar{b}H$ + $t\bar{t}H$	Signal: VBF	Signal: WH	Signal: ZH	Background: ZZ^*	Background: Z + jets, $t\bar{t}$	Total expected	Observed
0-jet	11.2 ± 1.4	0.120 ± 0.019	0.047 ± 0.007	0.060 ± 0.006	6.2 ± 0.6	0.84 ± 0.12	18.4 ± 1.6	21
1-jet	5.7 ± 2.4	0.59 ± 0.05	0.137 ± 0.012	0.091 ± 0.008	1.62 ± 0.21	0.44 ± 0.07	8.5 ± 2.4	12
2-jet VBF enriched	1.9 ± 0.9	0.92 ± 0.07	0.074 ± 0.007	0.052 ± 0.005	0.22 ± 0.05	0.24 ± 0.11	3.4 ± 0.9	9
2-jet VH enriched	1.1 ± 0.5	0.084 ± 0.009	0.143 ± 0.012	0.101 ± 0.009	0.166 ± 0.035	0.088 ± 0.011	1.6 ± 0.5	2
VH-leptonic	0.055 ± 0.004	< 0.01	0.067 ± 0.004	0.011 ± 0.001	0.016 ± 0.002	0.012 ± 0.010	0.16 ± 0.01	0
Total	20 ± 4	1.71 ± 0.14	0.47 ± 0.04	0.315 ± 0.027	8.2 ± 0.9	1.62 ± 0.07	32 ± 4	44







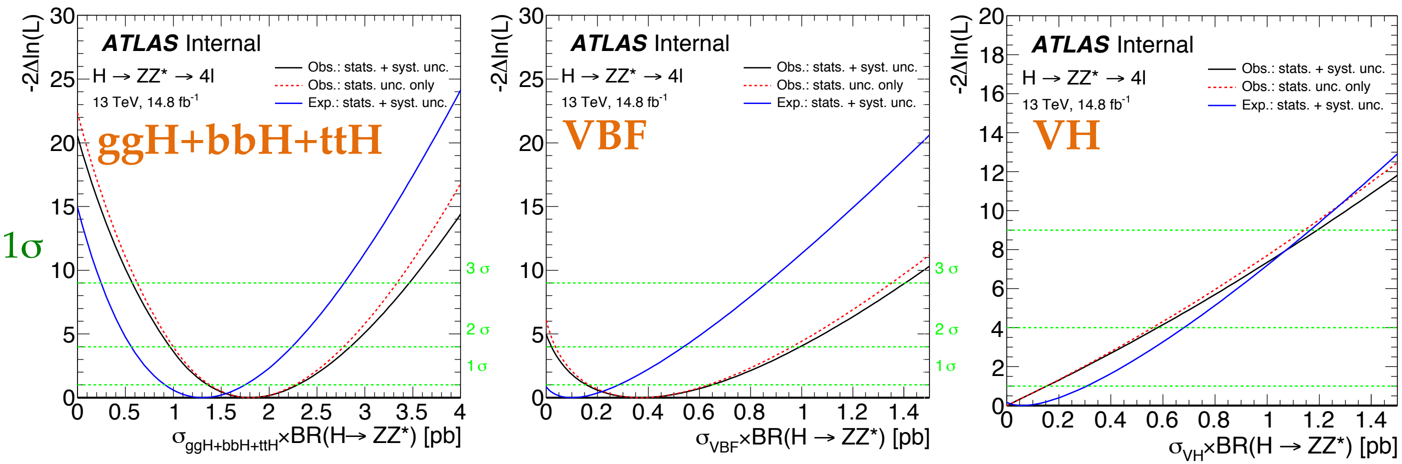


Signal extraction: Likelihood fit to the BDT discriminants distributions in each category

Compatibility with the SM:

$\sigma_{ggF+bbH+ttH}$ B(H->ZZ*) @ 1.1σ

σ_{VBF} B(H->ZZ*) @ 1.4σ



Cross section per production mode compared to the SM prediction:

Observed:

$$\sigma_{ggF+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \text{pb}$$

$$\sigma_{VBF} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \text{pb}$$

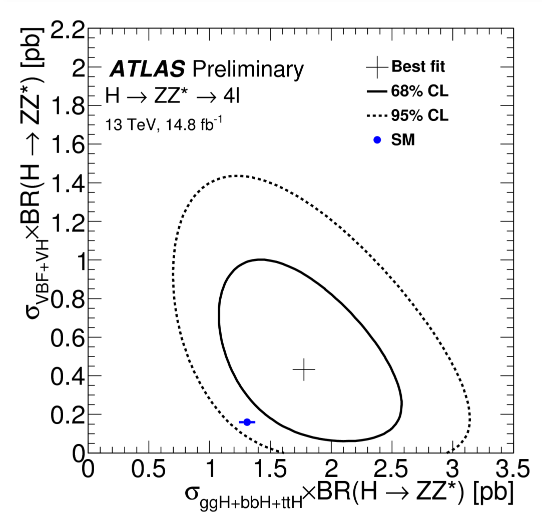
$$\sigma_{VH} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \text{pb}$$

Expected:

$$\sigma_{SM,ggF+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07\ \text{pb}$$

$$\sigma_{SM,VBF} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \text{pb}$$

$$\sigma_{SM,VH} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002\ \text{pb}$$

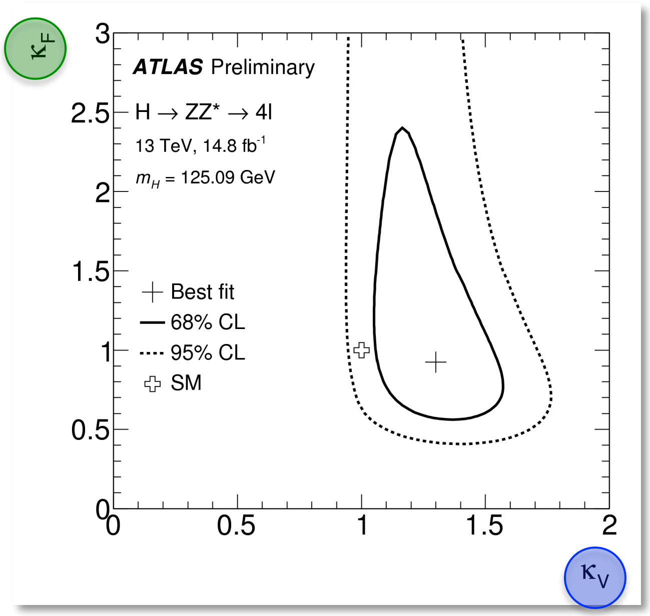


Cross section per production mode

The **same results** can be expressed in terms of **couplings with fermions (*ggF, bbH, ttH*)** or **vector bosons (*VBF, WH, ZH*)**.

Potential deviations of this couplings from the SM can affect the coupling modifiers (*k*) :

- **k_F** for the production mechanisms mediated by fermions
- **k_V** for those mediated by vector bosons.



Results obtained with the current statistic does not show significant deviations with respect to the SM

- Higgs mass fixed to m_H = 125.09 GeV
- Only the k_F>0 and k_V>0 quadrant is shown since the H->ZZ*->4l channel is not sensitive to the relative sign of the k

EFT are excellent ways to characterize the properties of any new state

EFT description for the BSM-containing process in Higgs production and decay presents:

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \bar{c}_i^{(6)} O_i^{(6)}$$

- the assumption of some high scale of NP (Λ) adding higher dimension BSM operators to the SM Lagrangian (SM reproduces the low-energy limit of a more fundamental description)
- Narrow-width approximation -> 2$^{\mathrm{nd}}$ order polynomial both in production and decay

BSM effects in the Higgs sector can be probed in an Effective Field Theory (EFT) approach:

New physics at high mass scale introduces new types/structures of Higgs boson couplings, which change the Higgs boson kinematics with respect to the SM.

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The defined categorization shows a good sensitivity to BSM interactions in the HVV vertex, parameterized by Lagrangian terms:

$$\begin{aligned}\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right] \\ & - \frac{1}{4}\left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu}\tilde{A}^{\mu\nu}\right] \\ & - \frac{1}{2}\left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu}A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu}\tilde{A}^{\mu\nu}\right] \\ & - \frac{1}{4}\left[c_\alpha \kappa_{Hgg} g_{Hgg} G^a_{\mu\nu}G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right] \\ & - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu}Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W^+_{\mu\nu}W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right] \\ & - \frac{1}{\Lambda} c_\alpha\left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + \left(\kappa_{H\partial W} W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\right)\right]\Big\} X_0\end{aligned}$$

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Contributo SM

$k_{SM}=1$, $\Lambda=1$ TeV

Contributo BSM

$k_{HZZ}=k_{HWW}=k_{HVV}$

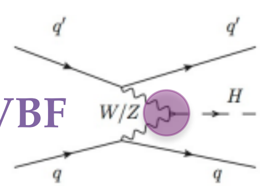
$k_{AZZ}=k_{AWW}=k_{AVV}$

Preliminary study on the k_{HVV} and k_{AVV} coupling constants, which represent respectively the coupling to scalar and pseudoscalar particles with the W and Z SM bosons.

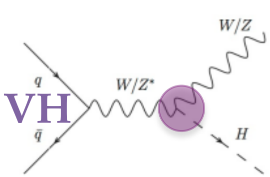
- The highest sensitivity in this study comes from the VBF and VH production modes → the number of events scales as k_{BSM}^4
- Contributes are proportional to k_{BSM}^2 in the BR(H->ZZ*) for ggF

Production:

VBF

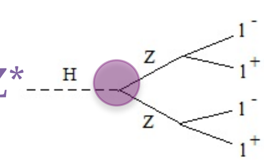


VH



Decay:

H->ZZ*



Constraints on BSM couplings:

- Categories are used to give sensitivity to BSM interactions between the Higgs and the W-Z SM vector bosons
  - major impact on the VBF and VH: factor k_{BSM}^4 in the yields but also change in the BR (H->ZZ*) proportional to k_{BSM}^2 included for ggF
- we follow the Higgs Characterization model parameterization: only the effective Lagrangian terms related to the BSM couplings k_{HVV} and k_{AVV} are considered (coupling to scalar and pseudoscalar respectively, V=W,Z, Λ=1TeV)
- Standard Model Lagrangian component fixed to unity (k_{SM}=1)
- one coupling at a time studied
- only using event counting per category
- Signal samples have been generated using MG5aMCatNLO and used to emulate every value of the coupling via the morphing technique in order to obtain a continuous signal parameterization of all the physical as a function of the BSM couplings. Impact of the BSM couplings on total width also included.

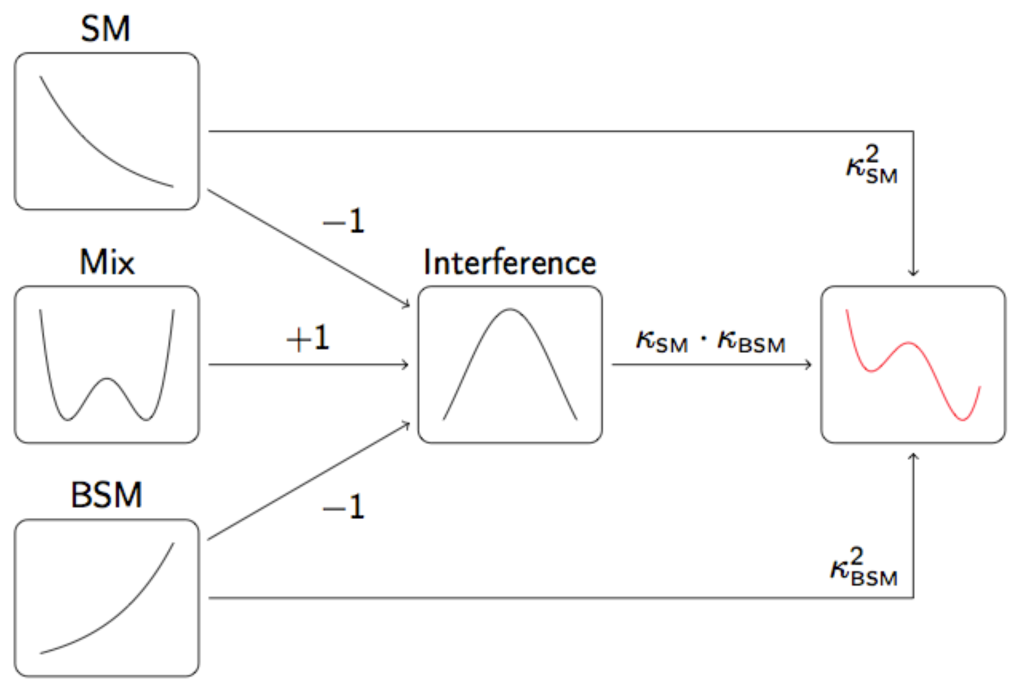
The plan is to combine measurements of shape and rates within an EFT framework.

In order to **model the contributions of different operators independently** by independent MC samples -> **Morphing Idea**:

- The final histogram can be produced starting from the histograms from individual MC samples
- Allows to model easily BSM contributions by mixing a finite set of base samples.
    - Allows to use a large set of EFT parameters to describe k_{BSM} couplings
    - Continuous modelling of Physics distributions and rate predictions
- Morphing is applicable beyond the EFT framework
- Independent of specific generators
- Only requires that any xs can be expressed as polynomial in BSM operators

Morphing

- Morphing an histogram has been introduced to describe the dependence of a given physical observable to an arbitrary configuration of k_{BSM}
- The morphing function linearly combines the values or differential distributions at a number of selected discrete coupling configurations
- The input distributions are normalized to their expected cross sections such that they include not only the correct shape, but also the correct XS prediction.



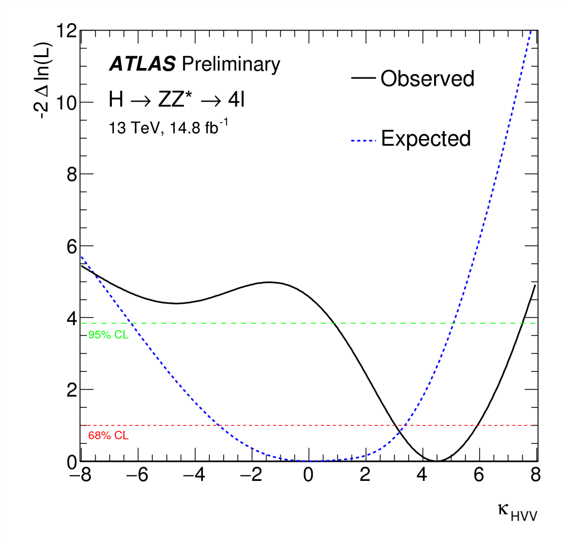
The **minimal number of samples required** to describe a particular production + decay process depends on:

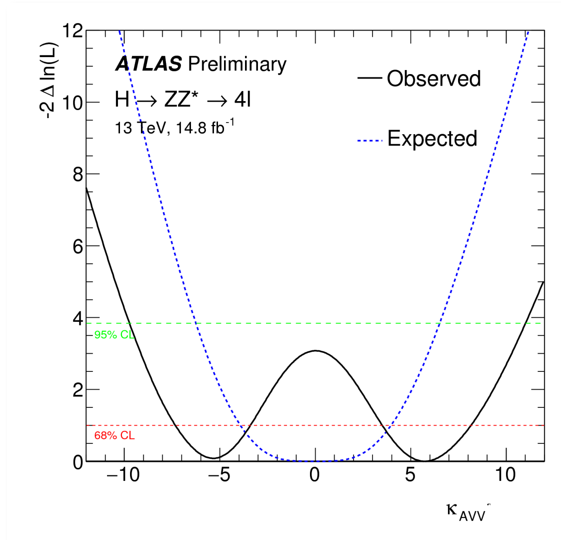
- How many couplings we consider in each of the vertices
- Whether some of the couplings are equal for production and decay

Challenge: number of samples grows quickly with EFT parameters (e.g. 1BSM op. -> 3 samples)

Limits have been obtained fitting the number of events in each category:

- k_{SM}=1
- k_{HVV} e k_{AVV} studied separately





Exclusion limits observed are less stringent than what expected due to the excess of events in the VBF 2jet enriched category.

Compatibility with the SM:

k_{HVV} =0 compatible @ 2.1σ
k_{AVV} =0 compatible @ 1.8σ

Exclusion limits:

Not excluded range at 95% CL	κ_{HVV} expected	κ_{HVV} observed	κ_{AVV} expected	κ_{AVV} observed
	[−6.3, 5.1]	[0.9, 7.5]	[−6.3, 6.5]	[−9.7, 11.0]

Next steps: interesting to add the BSM discriminant contributions in each category, evaluate p_{TH} subcategories (BSM contribution at high p_{TH})

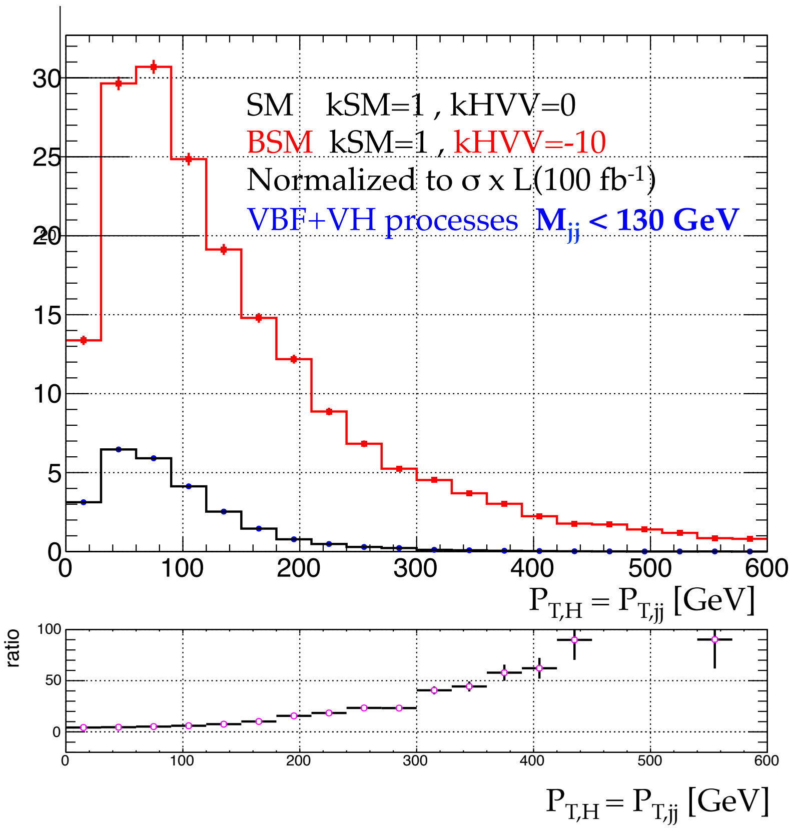
MC studies on the sensitivity to BMS:

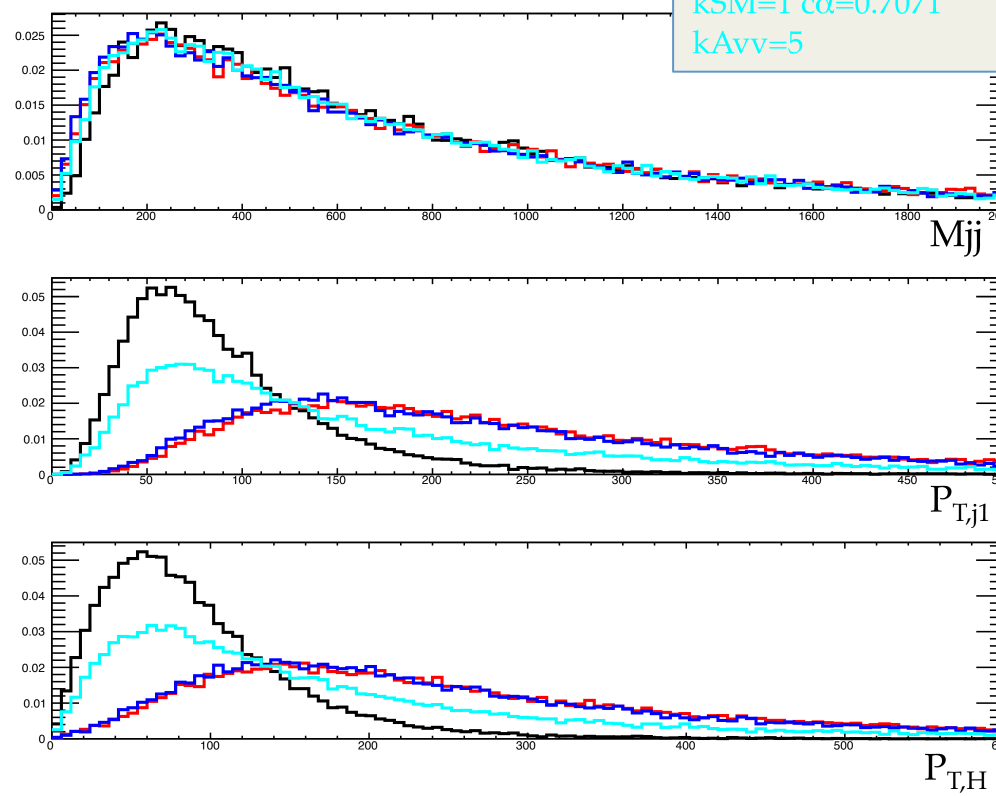
To increase sensitivity to BSM terms divide 2-jet category in bins:

- $p_{T,H}$ <> 120 GeV

kSM =1
kAzz=20 kSM=0
kAzz=kAww=kAvv =20 kSM=0
kSM=1 cα=0.7071 kAvv=5

VBF process



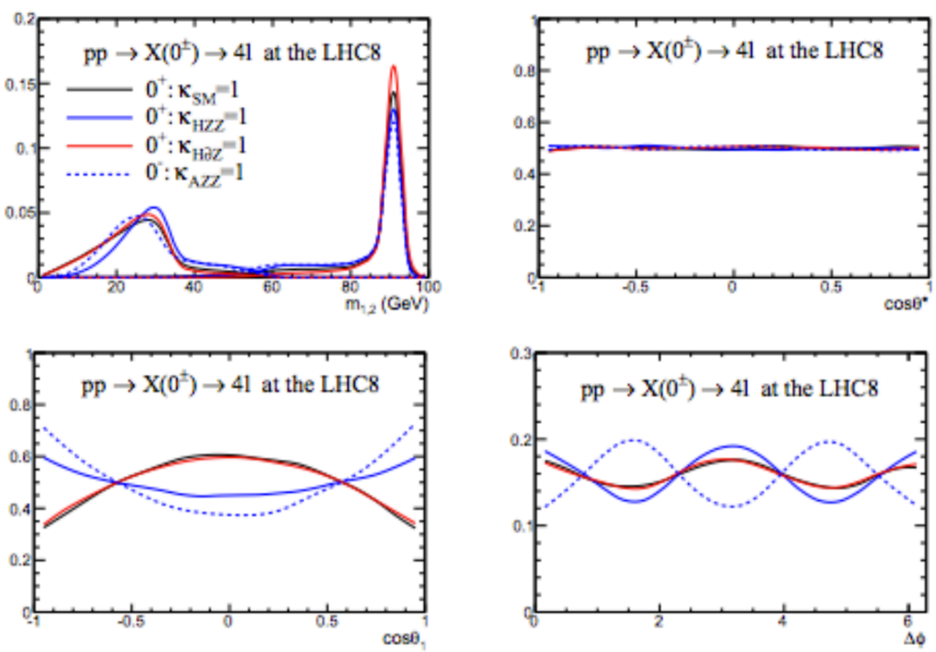


$p_{T,H}$ and $p_{T,j1}$: sensitive to EFT terms

Next steps: H->ZZ*

Ideas for the next steps:

- Study new couplings
- Improve the analysis with observables (some preliminary studies on OOs in the 2jet category have been already performed)
- Perform multidimensional analysis (e.g. k_{HVV}, k_{AVV} 2D scan)

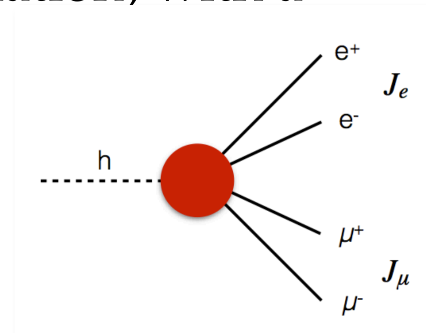


Normalized distributions in pp → 2e2μ for different choices of the couplings.

Representative set of distributions for key spin-correlation observables.

Higher-dimensional operators corresponding to **κ_{HZZ} (CP-even) and κ_{AZZ} (CP-odd)** have dramatic **effects on angular distributions ($\cos\theta_1$, $\Delta\phi$)** while the derivative operators corresponding to **$\kappa_{H\partial Z}$ mainly affect m_{12} and m_{34}**.

The decay amplitute of the h->2e2μ can be expressed, using a general EFT approach (which combines both kinematics and rate information) with a parameterization in the invariant masses of the lepton pairs ($q_1=m_{12}$, $q_2=m_{34}$) -> *Isidori et al. (arXiv:1412.6038v1)*



$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\ \sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$

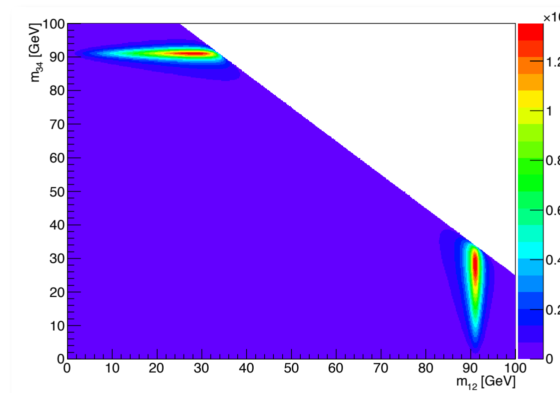
$$\left[F_1^{e\mu}(q_1^2,q_2^2)g^{\alpha\beta} + F_3^{e\mu}(q_1^2,q_2^2)\frac{q_1\cdot q_2\, g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} + F_4^{e\mu}(q_1^2,q_2^2)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

CP invariance

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

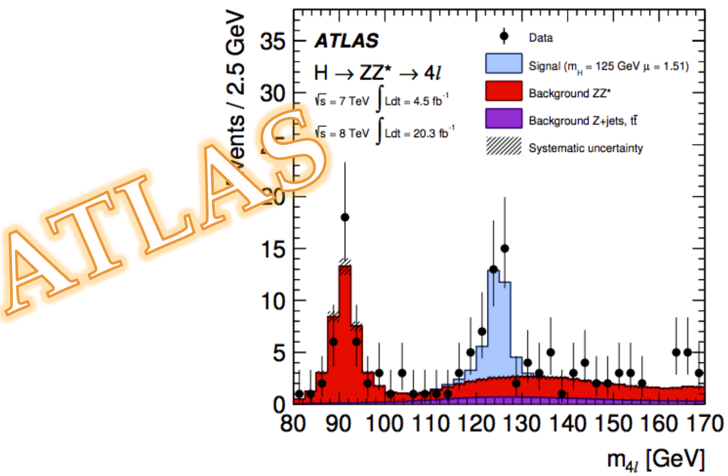
κ_{ZZ}, ε_{ZeL}, $\varepsilon_{Z\mu L}$, ε_{ZeR}, $\varepsilon_{Z\mu R}$ -> 5 parameters!

-> $d^2\Gamma_{h\rightarrow 2e2\mu}/dm_{12}\, dm_{34} = \Sigma_{j\geq I} A_{ij}\, \kappa_i\, \kappa_j$
function generated with the parameters set to SM values: ($\kappa_{ZZ}=1$, $\varepsilon_{ZeL}=0$, $\varepsilon_{Z\mu L}=0$, $\varepsilon_{ZeR}=0$, $\varepsilon_{Z\mu R}=0$)



Studies performed to gave the sensitivity to the contact terms never considered before.

Asimov dataset normalized to the statistics recorded by ATLAS+CMS in the Run1 at LHC (7+8 TeV, ~15 events in the 2e2μ channel in the signal region [120-130GeV])



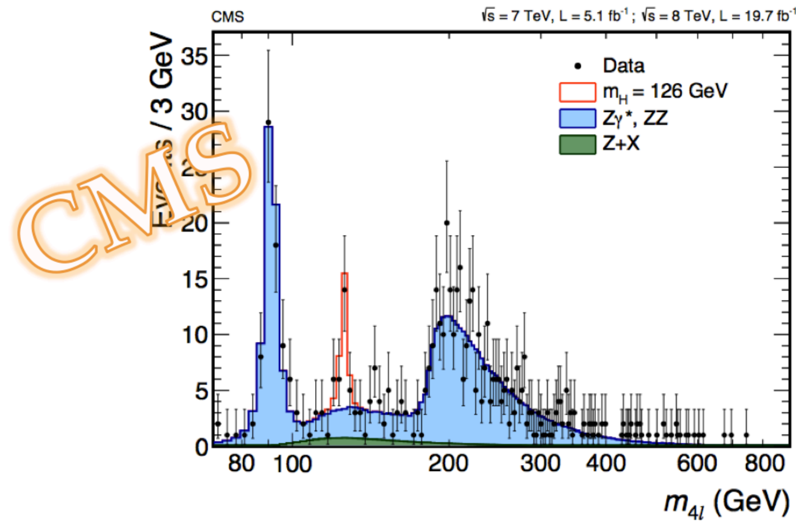


Table 11: The number of events expected and observed for a m_H=125 GeV hypothesis for the four-lepton final states in a window of $120 < m_{4\ell} < 130$ GeV. The second column shows the number of expected signal events for the full mass range, without a selection on $m_{4\ell}$. The other columns show for the 120–130 GeV mass range the number of expected signal events, the number of expected ZZ^* and reducible background events, and the signal-to-background ratio (S/B), together with the number of observed events, for 4.5 fb^{-1} at $\sqrt{s}$ = 7 TeV and 20.3 fb^{-1} at $\sqrt{s}$ = 8 TeV as well as for the combined sample.

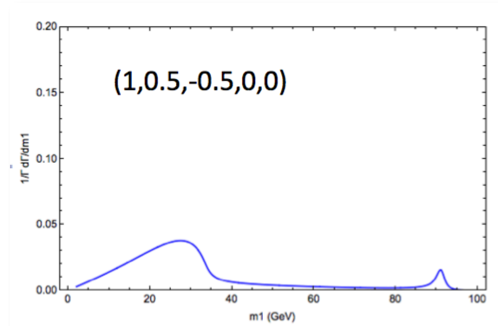
Final state	Signal full mass range	Signal	ZZ^*	$Z+$jets, $t\bar{t}$	S/B	Expected	Observed
			$\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV				
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

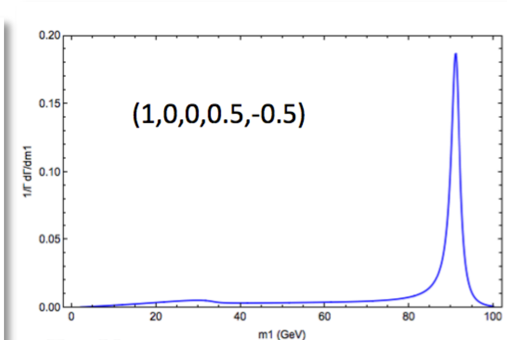
Table 4: The number of observed candidate events compared to the mean expected background and signal rates for each final state. Uncertainties include statistical and systematic sources. The results are integrated over the mass range from 121.5 to 130.5 GeV and for 7 and 8 TeV data combined.

Channel	4e	$2e2\mu$	4μ	4ℓ
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
Z + X background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
m_H = 125 GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
m_H = 126 GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

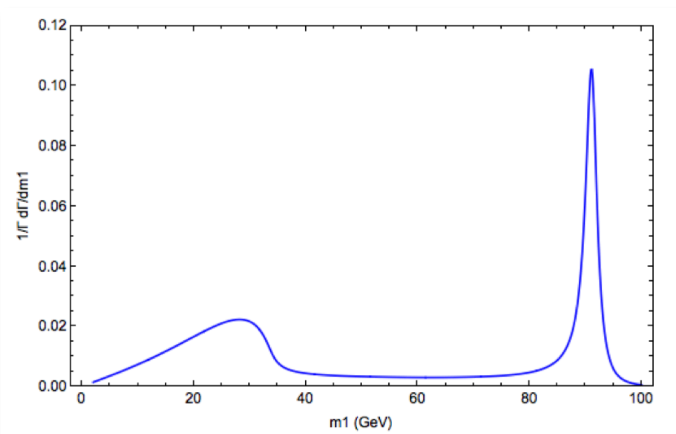
Distribution of the $d^2\Gamma/dm_{12}dm_{34}$ varying the parameters taken into account.

- Projection along m_{12} integrating over m_{34}.
- The integration over the angle as been implemented analytically at amplitude level.





(κ_{ZZ}=1, ε_{ZeL}=0, $\varepsilon_{Z\mu L}$=0, ε_{ZeR}=0, $\varepsilon_{Z\mu R}$=0)



Analyses:

- Extraction of the events from the $d^2\Gamma$: Asimov dataset normalized to the number of events expected
- Binned Likelihood (Poissonian statistics) varying the parameters under study (2D scans)
- Studies performed with the statistics available in the LHC RunI, but also (rescaling the expectations) for 300 fb^{-1} @ 13TeV (~expected for RunII at LHC)

-> ATT: at the moment bkgs are not considered, events are assumed to be truth (in future trasfer function from truth to reco)

Assumptions:

- h(125) is a spin-0 particle
- No new particles with mass up to 125 GeV able to distort the decay amplitude of the Higgs in SM particles

Different cases under study:

Different combinations of the parameters have been studied, fixing some of those to their SM expectations and fitting the others;
The cases here reported are the most interesting ones to study:

A) Scan on (κ_{ZZ} , ε_{ZeR}); -> $\varepsilon_{Z\mu L}$, ε_{ZeL} , $\varepsilon_{Z\mu R}$ fixed
in order to study the sensitivity on the contact term

B) Scan on (κ_{ZZ} , ε_{ZLepR}); -> essendo ε_{ZLepL}=2.*ε_{ZLepR} & $\varepsilon_{Z\mu X}=\varepsilon_{ZeX}$
imposing LFU and the Higgs to be part of an $SU(2)_L$ doublet

C) Scan on (ε_{ZLepR} , ε_{ZLepL}); -> κ_{ZZ} fixed & $\varepsilon_{ZeX}=\varepsilon_{Z\mu X}$
imposing LFU

D) Scan on (ε_{ZeR} , $\varepsilon_{Z\mu R}$); -> κ_{ZZ} fixed & $\varepsilon_{ZeR}=-\varepsilon_{ZeL}$, $\varepsilon_{Z\mu R}=-\varepsilon_{Z\mu L}$
Exotic: No LFU, axial coupling of a Z′ with pairs of leptons

E) Scan on (ε_{ZeR} , $\varepsilon_{Z\mu R}$); -> κ_{ZZ} fixed & $\varepsilon_{ZeR}=\varepsilon_{ZeL}$, $\varepsilon_{Z\mu R}=\varepsilon_{Z\mu L}$
Exotic: No LFU, vectorial coupling of a Z′ with pairs of leptons

Scan on (κ_{ZZ} , ε_{ZeR}); -> $\varepsilon_{Z\mu L}$, ε_{ZeL} , $\varepsilon_{Z\mu R}$ fixed

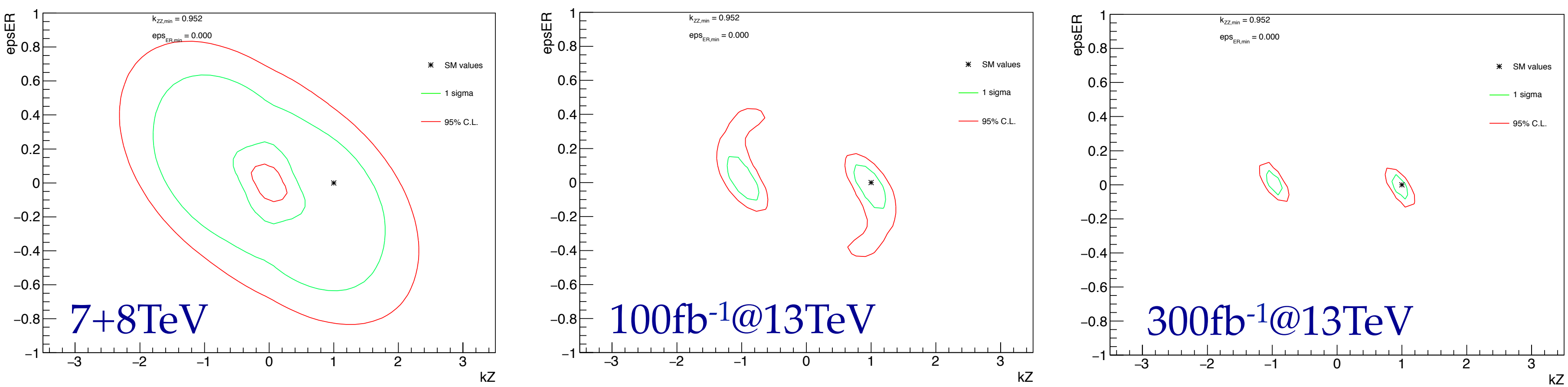
- Interesting in order to give an estimate of the sensitivity to the contact terms (~end of Run2 the sensitivity becomes interesting in order to exclude possible EFT theories ε_X~0.2).
- k_{ZZ} differs from the signal strength reported by ATLAS and CMS since it is linked to a defined kinematic distribution (SM like).

$\Delta\chi^2$ as a function of the number of free parameters for 1sigma and 95% C.L.

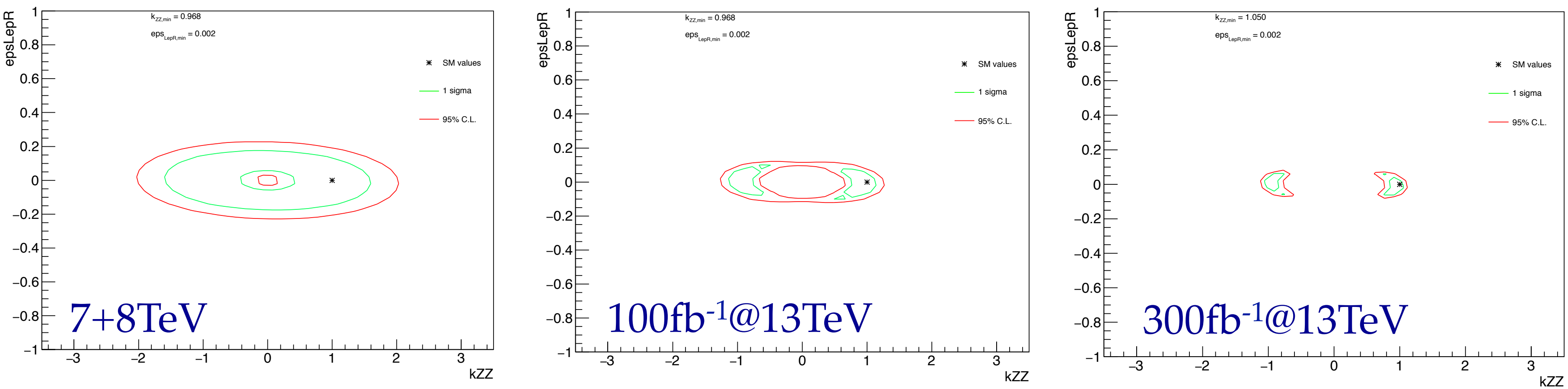
$1-\alpha$ [%]	$m=1$	$m=2$
68.27	1.00	2.30
95.	3.84	5.99

Results are shown for the statistics available in RunI and projections to 300 fb^{-1} for the RunII at LHC.

A) Scan on (κ_{ZZ} , ε_{ZeR}); -> $\varepsilon_{Z\mu L}$, ε_{ZeL} , $\varepsilon_{Z\mu R}$ fixed

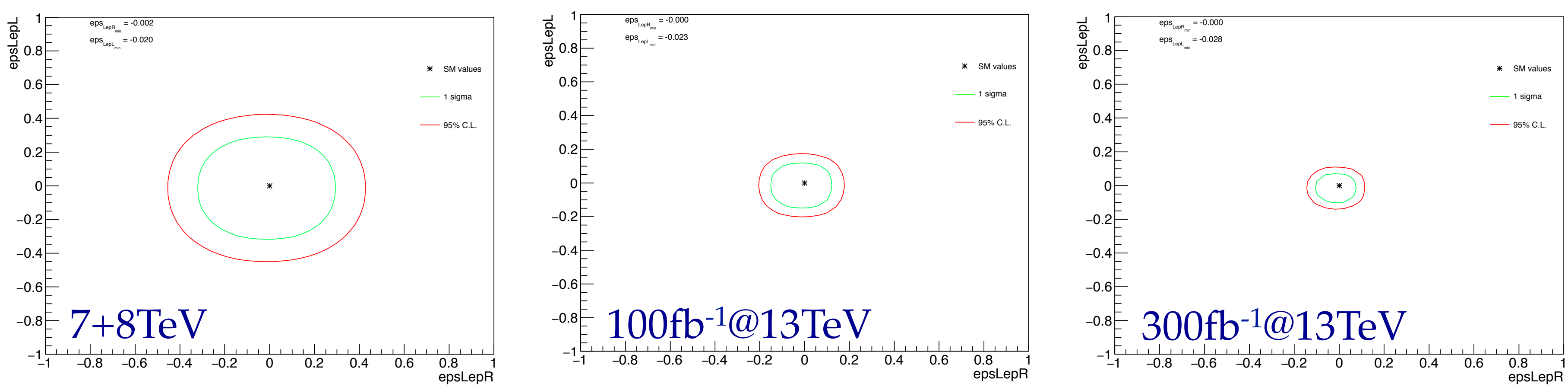


B) Scan on (κ_{ZZ} , ε_{ZLepR}); -> being ε_{ZLepL}=2.*ε_{ZLepR} & $\varepsilon_{Z\mu X}$=ε_{ZeX}



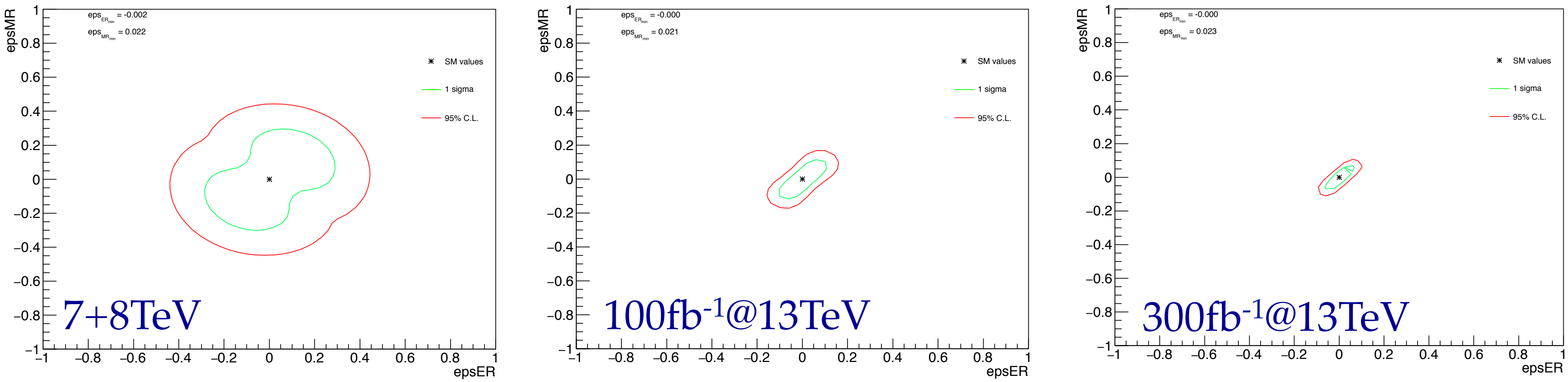
C) Flavor Universal contact terms

Scan su (ε_{ZLepR} , ε_{ZLepL}); -> κ_{ZZ} fixed & ε_{ZeX}=$\varepsilon_{Z\mu X}$



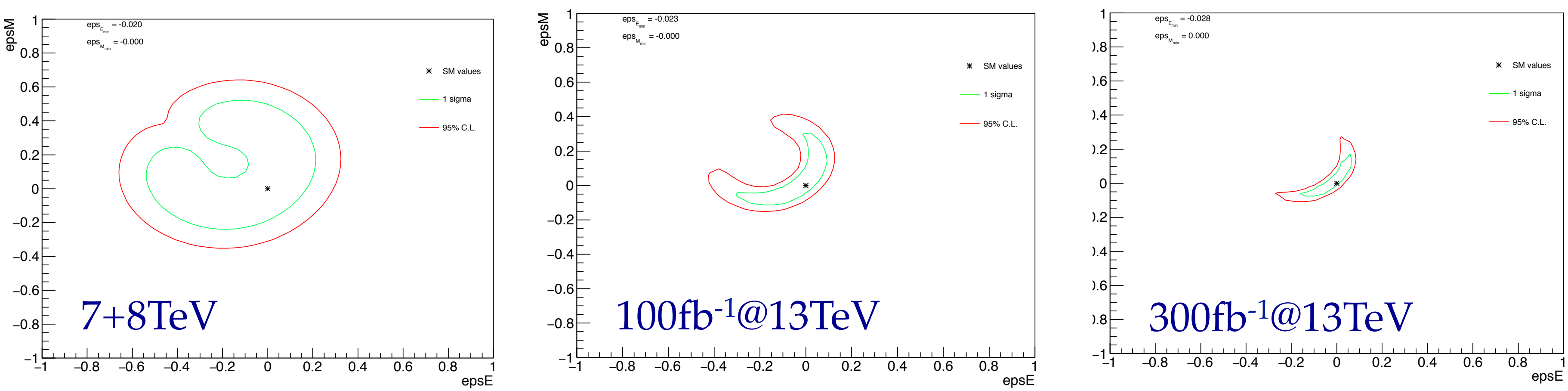
D) Flavor Non-universal axial couplings

Scan on (ε_{ZeR} , $\varepsilon_{Z\mu R}$); -> κ_{ZZ} fixed & $\varepsilon_{ZeR}=-\varepsilon_{ZeL}$, $\varepsilon_{Z\mu R}=-\varepsilon_{Z\mu L}$



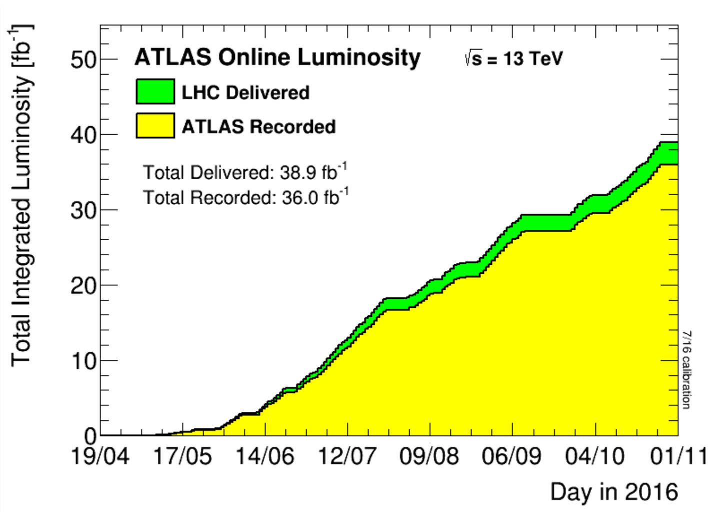
E) Flavor Non-universal vector couplings

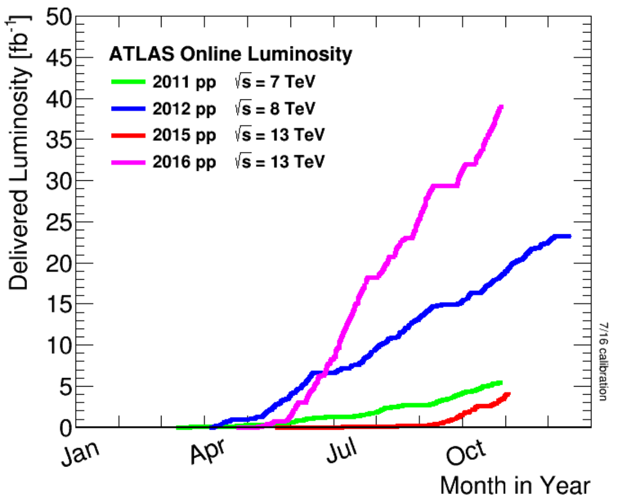
Scan su (ε_{ZeR} , $\varepsilon_{Z\mu R}$); -> κ_{ZZ} fixed & $\varepsilon_{ZeR}=\varepsilon_{ZeL}$, $\varepsilon_{Z\mu R}=\varepsilon_{Z\mu L}$



Conclusions

- I have shown results focused on the study of the Higgs boson properties, analyzing data collected up to ICHEP16 at LHC with the ATLAS experiment in the Higgs-> ZZ*-> 4l decay channel
- Measurements performed shows that results are compatible with the SM predictions within the uncertainties
- Measurements presents limits due to the low statistics
- Info from observables and yields should be combined in the EFT context!
- Run2: 36.47 fb^{-1} of data
- Expected increasing in sensitivity ICHEP2016-end of Run2 by a factor ~5!

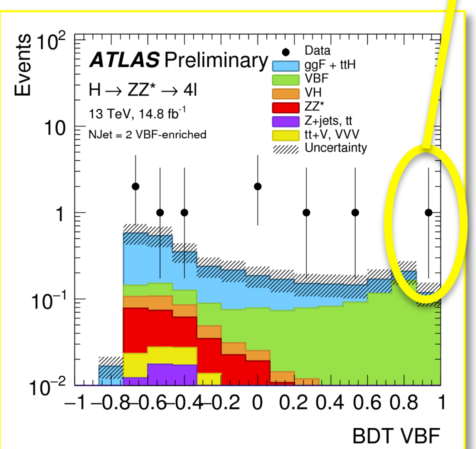


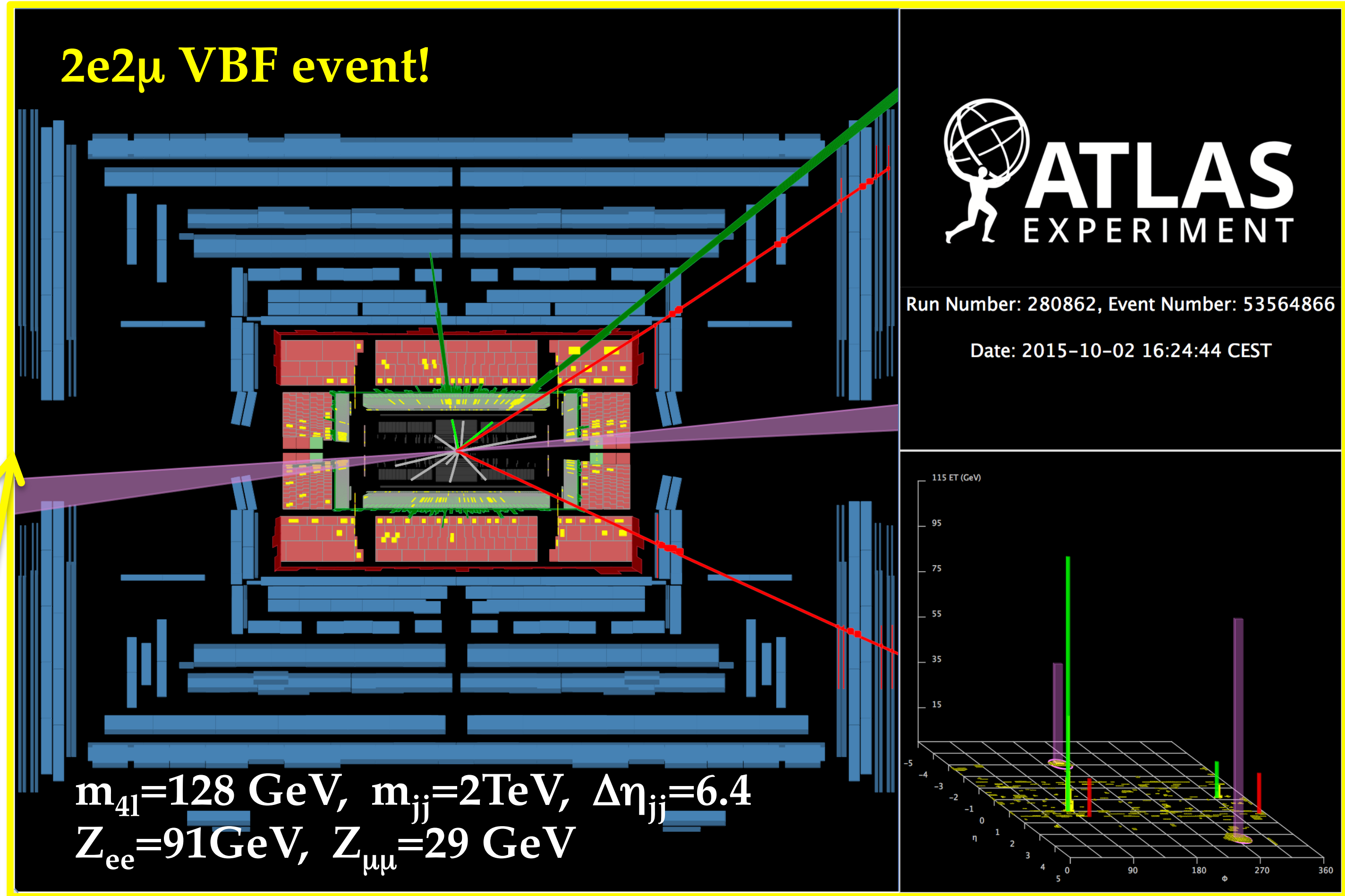


Thanks for your attention!

Backup

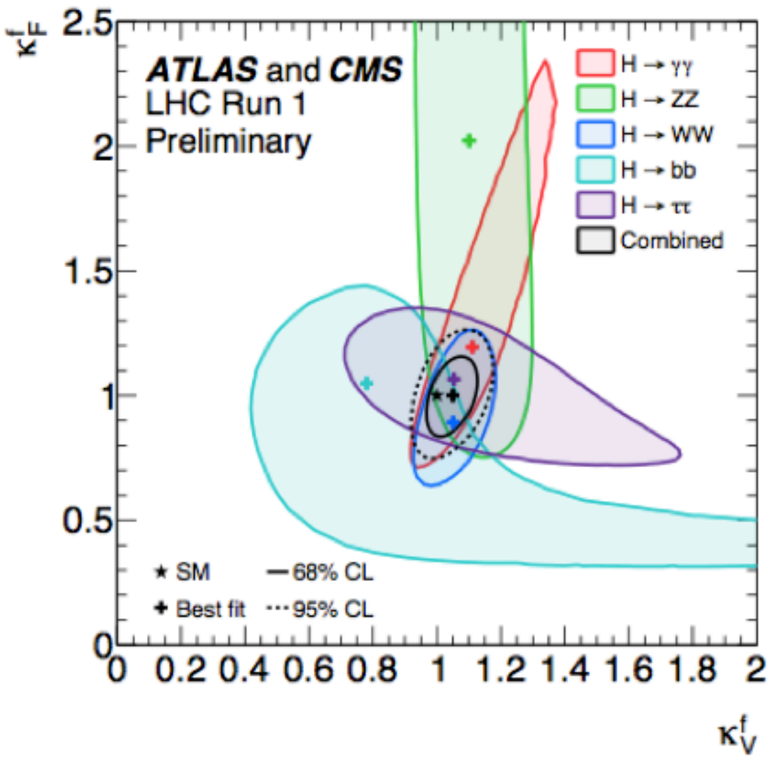
Discriminants in each category

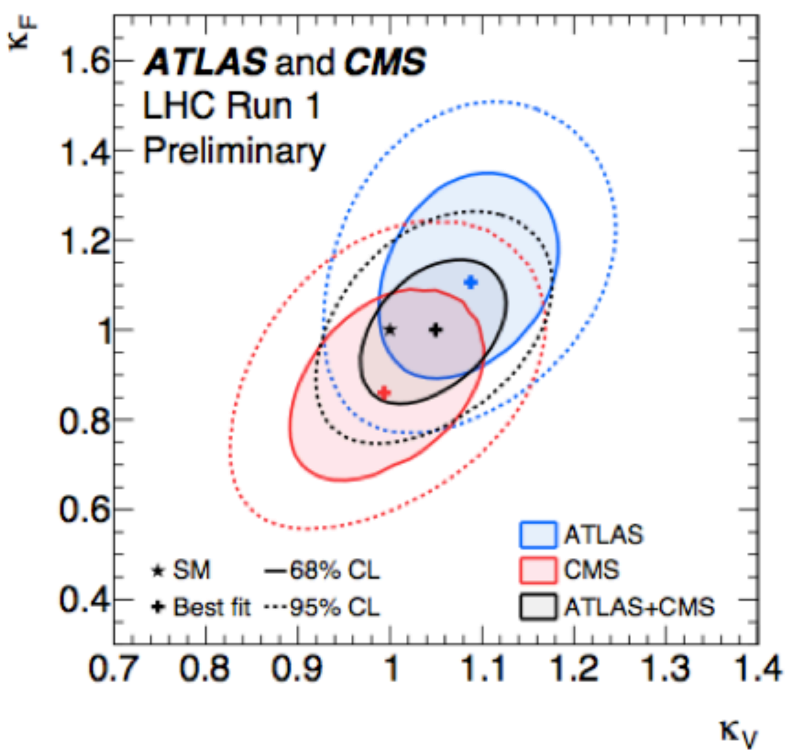




Couplings: ATLAS + CMS

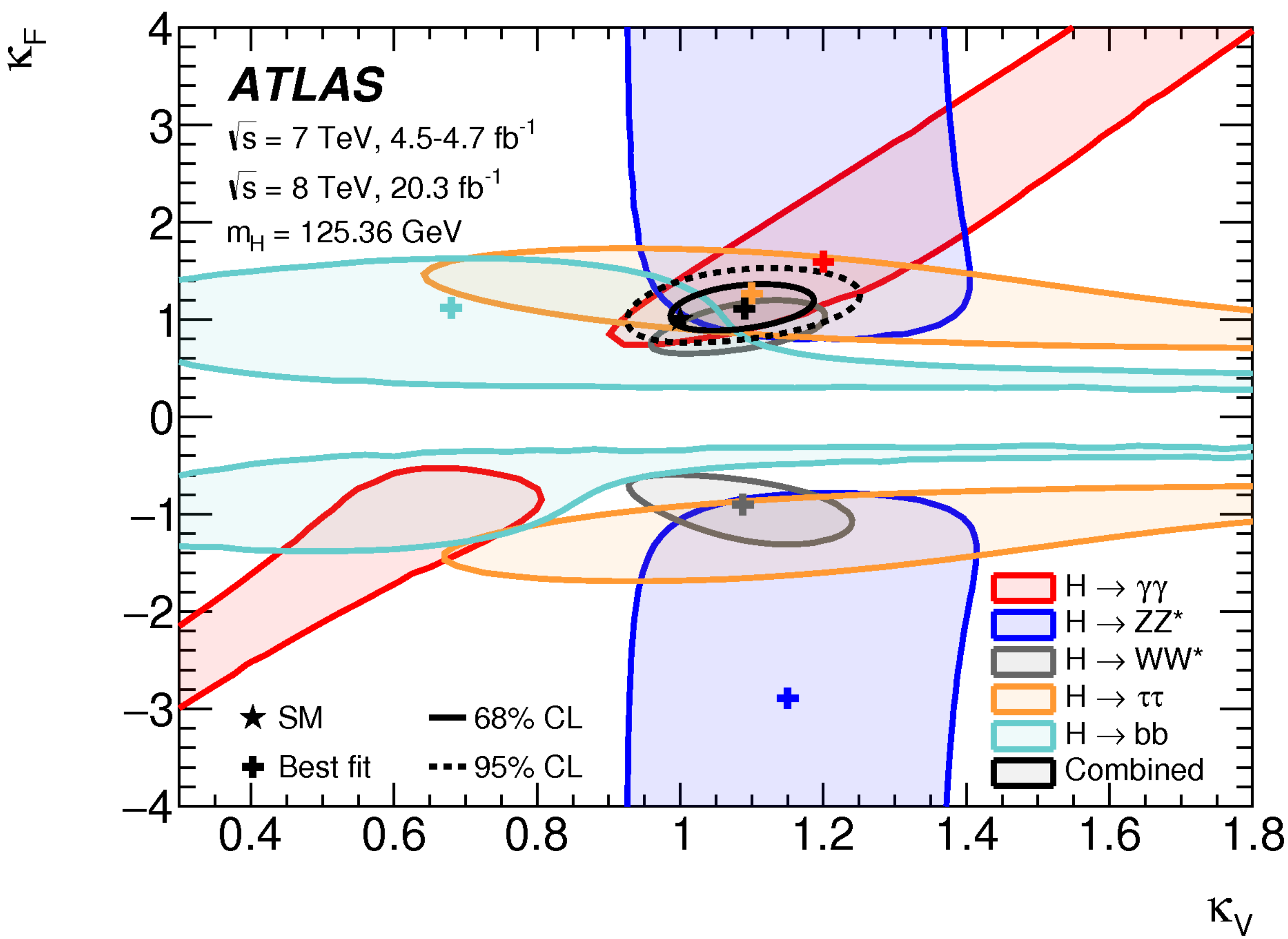
Yukawa sector and Higgs boson couplings are of different origin and structure, therefore **comparing fermions to boson couplings is a crucial test of the SM**





Good agreement with SM expectations.

Demonstrates the power of combining all the analyses.


ATLAS
√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
m_H = 125.36 GeV
κ_F
κ_V
SM
Best fit
68% CL
95% CL
H → γγ
H → ZZ*
H → WW*
H → ττ
H → bb
Combined

Introduction

Higgs boson measurements are typically divided into:

- **Coupling measurements** (event counts in various phase-space regions)
- **Property measurements** (quantum numbers and other properties using dedicated analyses)

-> both sectors influence each other: m_H determine the SM expectation for couplings

$m_W = gv/2$ $\quad$ $m_W/m_Z = \cos\theta_W$ $\quad$ m_H

$$\mathcal{L}_{EW} = \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{g^2}{4}(v+H)^2(W_\mu^+ W^{-\mu} + \frac{1}{2\cos^2\Theta_W} Z_\mu Z^\mu) + \frac{1}{2}(-2\mu^2)H^2 - \lambda v H^3 - \frac{1}{4}\lambda H^4 + \ldots$$

HVV and HHVV vertices $\quad$ HHH and HHHH self-interaction vertices

$\sim g^2 v\ (\sim m^2/v)$ $\quad$ $\sim g^2\ (\sim m^2/v^2)$

$$\mathcal{L}_{\text{Yuk,u.-gauge}} = -\frac{\lambda_f v}{\sqrt{2}}\bar{\Psi}_{f_L}\Psi_{f_R} - \frac{\lambda_f}{\sqrt{2}}\bar{\Psi}_{f_L}\Psi_{f_R} H + \ldots$$

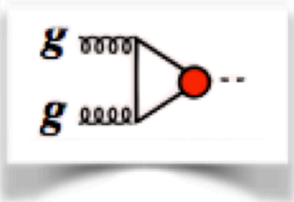
$m_f \sim \lambda_f v$ $\quad$ Hff vertices $\quad$ $\sim m_f / v$

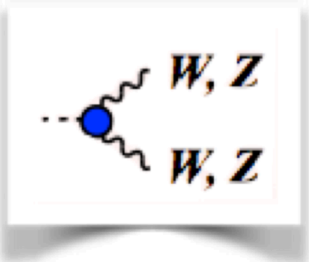
Signal strength:

- can attempt to isolate different **production** and **decay modes**
  - Measure event yields in various phase-space regions enriched in different production/decay modes

- **Primary observable: number of events per bin** after counting for bkg

$$\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_f}{(\sigma_i \times \mathrm{BR}_f)_{\mathrm{SM}}} \equiv \mu_i \times \mu_f, \quad \text{with } \mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \text{ and } \mu_f = \frac{\mathrm{BR}_f}{(\mathrm{BR}_f)_{\mathrm{SM}}}$$





- Combining all the channels/categories, the **number of signal events** can be defined as follows:

$$n_s^c = \sum_i \sum_f \mu_i (\sigma_i)_{\mathrm{SM}} \times \mu_f (\mathrm{BR}_f)_{\mathrm{SM}} \times A_{if}^c \times \varepsilon_{if}^c \times \mathcal{L}^c$$

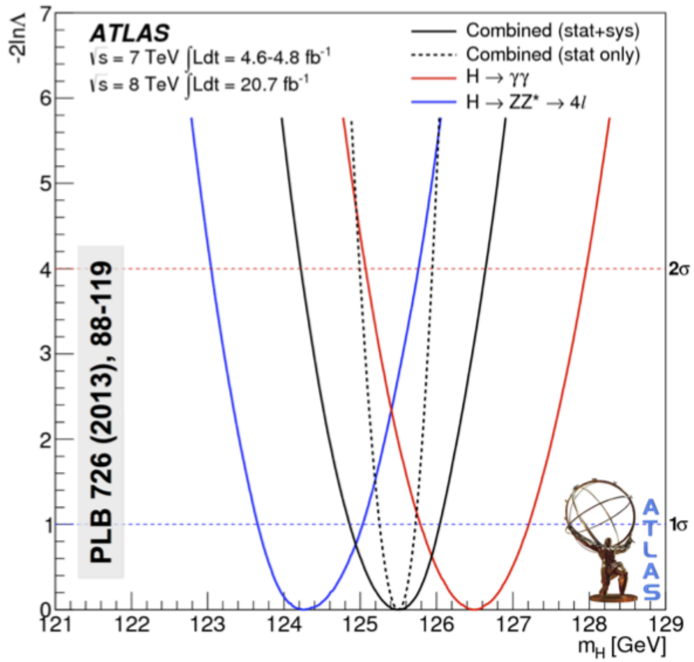
Measurements of the **parameters of interest (α)** such as the Higgs boson **signal strength (μ)**, the Higgs boson **mass (m_H)**, the **coupling strength scale factors (κ) and their ratios (λ)** are performed via a profiled likelihood ratio test statistics.

- The likelihood function is built using sums of signal and background pdfs of the discriminating variables

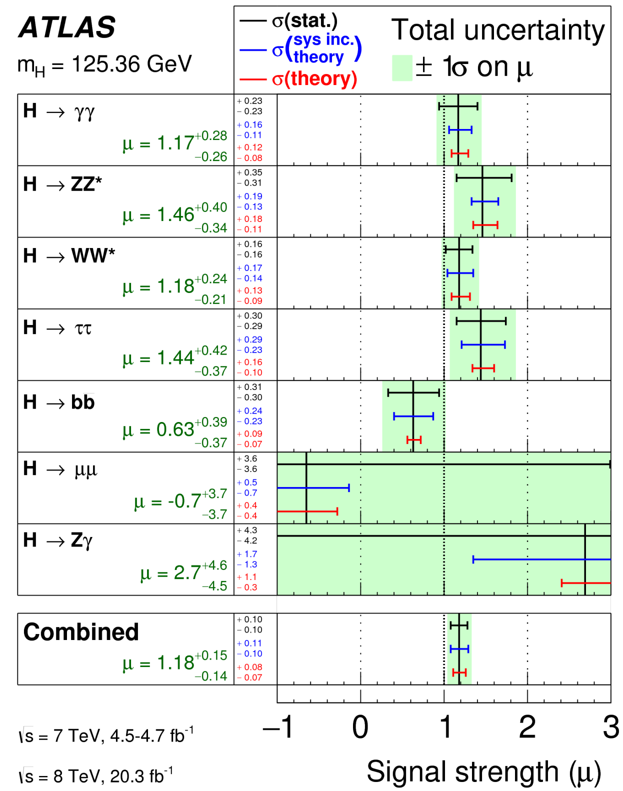
$$\Lambda(\alpha) = \frac{L(\alpha\,,\,\hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha},\hat{\theta})}$$

1D scan mass measurement combining H->ZZ*->4l and H->γγ channels:

m_H = 125.36 ± 0.37 (stat) ± 0.18 (syst) = 125.36 ± 0.41



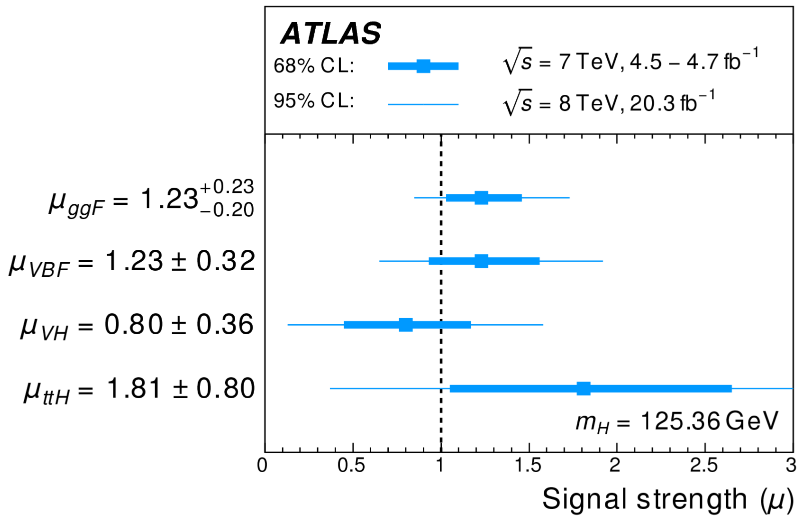
Signal strength for different decay channels and their combination (m_H = 125.36 GeV):



Combined measurement assuming a common μ to all decay modes -> compatibility with SM: 18%

$$\mu = 1.18\,^{+0.15}_{-0.14} = 1.18 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})\,^{+0.08}_{-0.07}\,(\text{theo.})$$

Decoupling different production modes:



- **Assuming SM Higgs decay BRs**
- Compatibility with SM at 1σ

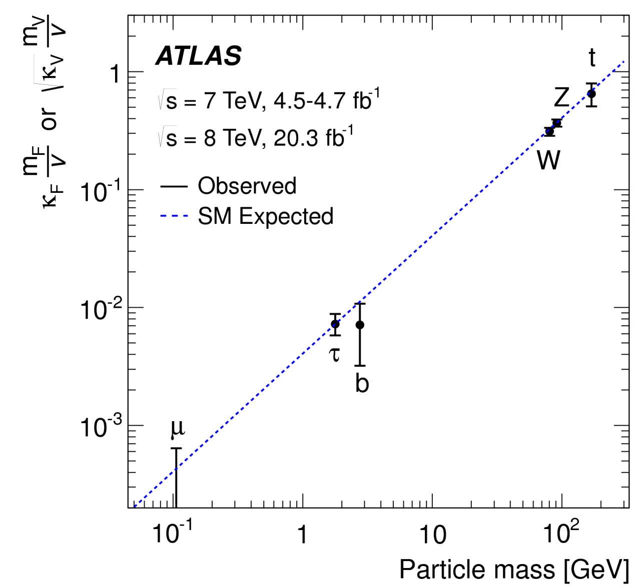
Mass dependence:

- **Generic model of tree-level coupling factors** (no BSM contribution to loop induced process and total width).

$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

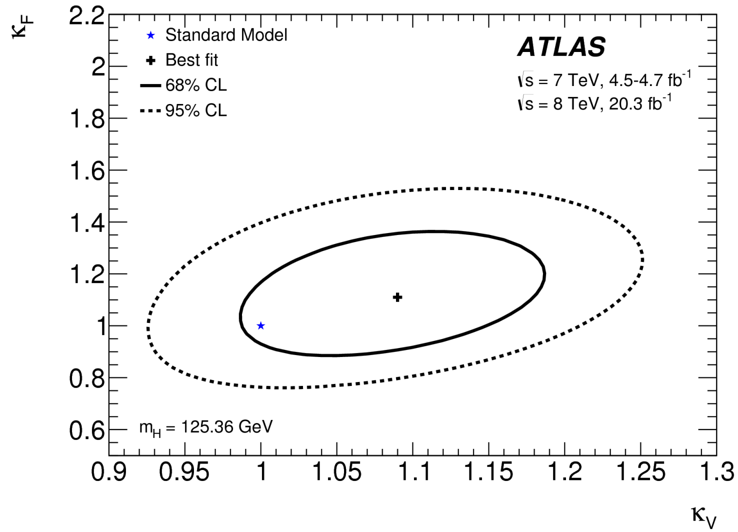
$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v}$$

- Compatibility with the SM hypotheses: 57%



Fermion vs boson couplings:

- **Yukawa sector and bosonic Higgs boson couplings are of a different structure** -> comparing them is a crucial test of the SM
- Good agreement with the SM expectation

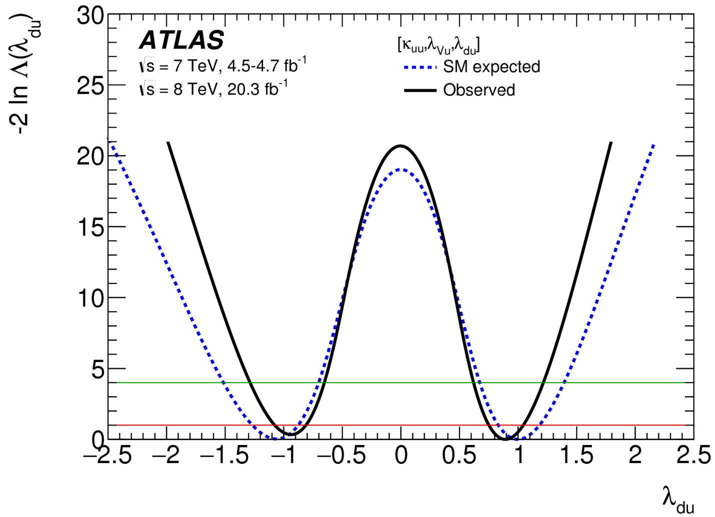


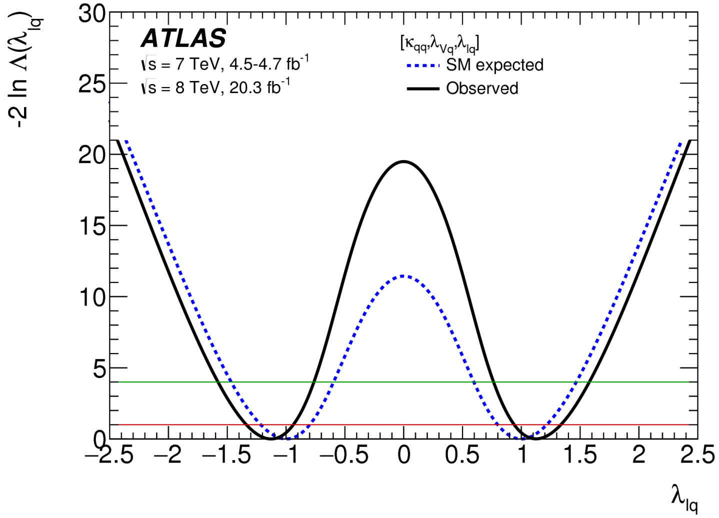
Probing relations within the coupling sector:

Many **extensions of the SM** (two Higgs-doublet models) **contain different coupling strengths of the Higgs boson.**

Interesting to probe the:

- up-type and down-type fermions symmetry (k_u: gg->H via top loop, k_d: H->bb and H->ττ, H->μμ in ttH production)
- leptons and quarks symmetry (k_l: H->ττ, H->μμ)





$\lambda_{du} = 0$ provides 4.5σ evidence of the coupling of the Higgs boson to down-type fermions

$\lambda_{lq} = 0$ is excluded at 4.4σ from $H \rightarrow \tau\tau$ measurement.

Kappa Framework

Coupling modifiers (κ) to parametrize the signal contribution:

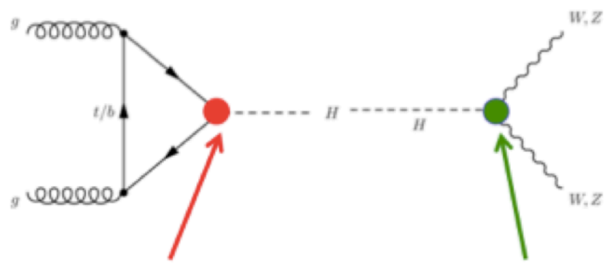
$$\sigma \cdot B(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left(\frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \right)$$

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}} \qquad \kappa_H^2 = \frac{\sum \Gamma_f}{\sum \Gamma_f^{SM}}$$

Production **Decay** **Total width**

- Assumes **SM like coupling structure** ($J^{CP} = 0^{++}$) -> **only account for rates!**
- Signal in different channels from the same resonance
- **Narrow width approximation**
- Kappas correspond to **tree-level H couplings to the different particles**

ggF production of H->VV

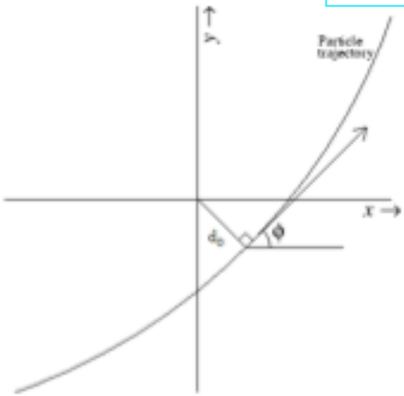


$\sigma_{ggF} = (1.06\,\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_b\kappa_t)\,\sigma_{ggF}(SM)$ $\quad \Gamma_{W,Z} = \kappa^2_{W,Z}\Gamma_{W,Z}(SM)$

-> Useful as long as the overall picture is SM like

Tagli cinematici:

- muoni (elettroni) con $p_T > 6$ GeV $(E_T > 7$ GeV$)$
  p_T cuts $= 20, 15, 10, 6$ GeV
- nel range $|\eta| < 2.47$ $(|\eta| < 2.7)$

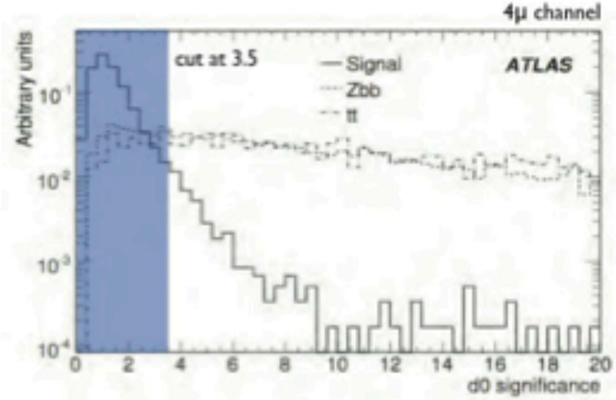


IP = distanza di minimo approccio dal vertice primario (PV)

Tagli in parametro di impatto:

- d_0 < 1 mm (rigettare CR ed eventi non dal PV)
- $\frac{d0}{\sigma(d0)} < 3.5\ (6.5)$ per muoni (elettroni)

gli elettroni sono affetti da Bremmstrahlung



Tagli in isolamento:

- Isolamento di traccia: $\frac{\Sigma p_T}{p_T} < 0.30$ delle tracce in un cono di raggio $\Delta R < 0.2$ intorno al leptone
- Isolamento calorimetrico: $\frac{\Sigma p_T}{p_T} < 0.15$ dei depositi calorimetrici in un cono di raggio $\Delta R < 0.2$ intorno al leptone

$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, $\eta = -\ln tg\frac{\theta}{2}$, $p_T = p\sin\theta$

Traccia isolata Traccia non isolata

Selezione del quadrupletto:

Coppie con stesso sapore e segno opposto: $m_{Z_1} > 50$ GeV (on-shell) $m_{Z_2} > 12$ GeV

Event Selection

Changes wrt previous public results:

- Muon p_T cut relaxed to 5 GeV gives an improvement in the signal acceptance by ~5%
- Jet p_T cut tightened to 30 GeV in order to optimize the categories definition
- Vertex cut added to cut the additional background that appear after relaxing muon p_T cut (Z+jet reduction ~ 25%)

PHYSICS OBJECTS	
ELECTRONS	
	Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7$ GeV and $\|\eta\| < 2.47$
MUONS	
	Loose identification
	Calo-tagged muons with $p_T > 15$ GeV and $\|\eta\| < 0.1$
	Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_T > 5$ GeV
JETS	
	anti-k_T jets with $p_T > 30$ GeV, $\|\eta\| < 4.5$ and passing pile-up jet rejection requirements
EVENT SELECTION	
QUADRUPLET SELECTION	Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements:
	p_T thresholds for three leading leptons in the quadruplet - 20, 15 and 10 GeV
	Maximum one calo-tagged or standalone muon per quadruplet
	Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the Z mass
	Leading di-lepton mass requirement: 50 GeV $< m_{12} < 106$ GeV
	Sub-leading di-lepton mass requirement: $12 < m_{34} < 115$ GeV
	Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5$ GeV
	$\Delta R(\ell, \ell') > 0.10$ (0.20) for all same (different) flavour leptons in the quadruplet
ISOLATION	Contribution from the other leptons of the quadruplet is subtracted
	Muon track isolation ($\Delta R <= 0.30$): $\Sigma p_T / p_T < 0.15$
	Muon calorimeter isolation ($\Delta R <= 0.20$): $\Sigma E_T / p_T < 0.30$
	Electron track isolation ($\Delta R <= 0.20$) : $\Sigma E_T / E_T < 0.15$
	Electron calorimeter isolation ($\Delta R <= 0.20$) : $\Sigma E_T / E_T < 0.20$
IMPACT PARAMETER SIGNIFICANCE	Apply impact parameter significance cut to all leptons of the quadruplet.
	For electrons : $d_0/\sigma_{d_0} < 5$
	For muons : $d_0/\sigma_{d_0} < 3$
VERTEX SELECTION	Require a common vertex for the leptons χ^2/ndof < 6 for 4μ and < 9 for others.

Background estimates:

Irreducible ZZ* (both qq,gg initiated) production is the dominant one:

- modeled using MC (qqZZ:Powheg, ggZZ low mass:gg2VV, ggZZ high mass:Sherpa) simulations and validated in side-bands
- NNLO QCD and NLO EW corrections applied
- k=1.7 for higher order QCD+EW corrections for ggZZ with 60% unc.
- qqZZ: Sherpa samples have been used for systematics in n-jet based categories
- shapes (m_{4l} and BDT) are taken from MC and validated with single resonant and high mass data vs MC comparison

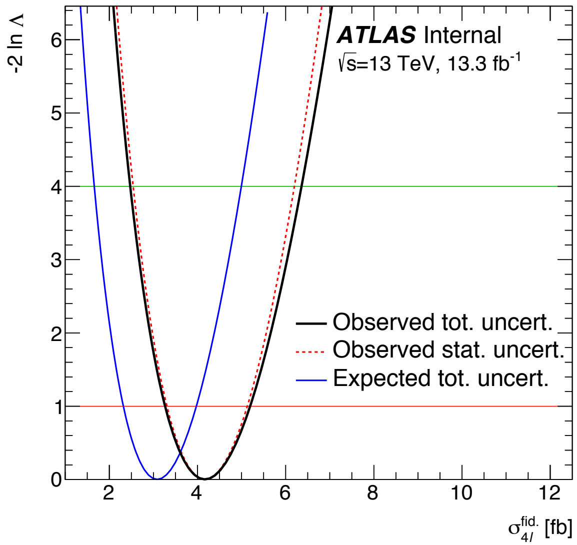
Reducible bkg:

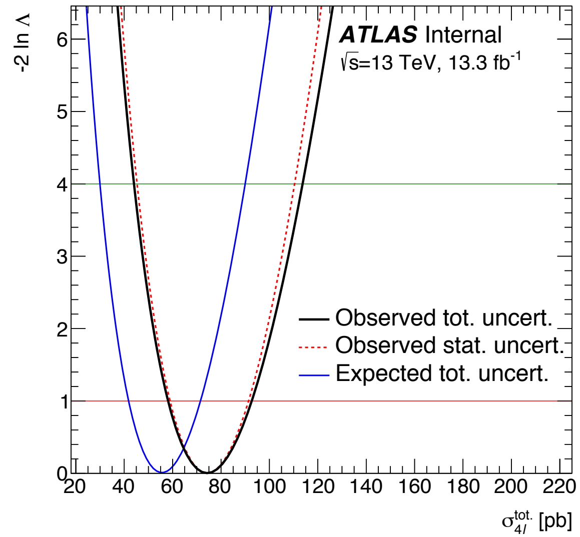
- Z+jets and ttbar estimated from data using Control Regions (CR)
- WZ production is included in the data-driven results for the ll+ee and taken from MC simulation for the ll+μμ
- ttbarV and VVV contributions are minor and taken from MC
- shapes taken from the Z+jets and ttbar MC and validate in CR (m_{4l} shapes smoothed using the kernel density estimation method)

XS x prod mode

$XS^{fiducial}_{prod.mode}$ are different POI in the fit; total XS can be given as:

- the sum (without assumptions on the relative Higgs boson BRs, more model-independent but slightly reduces the statistical sensitivity.)
- combining the 4 decay channels assuming the SM BRs (combination)



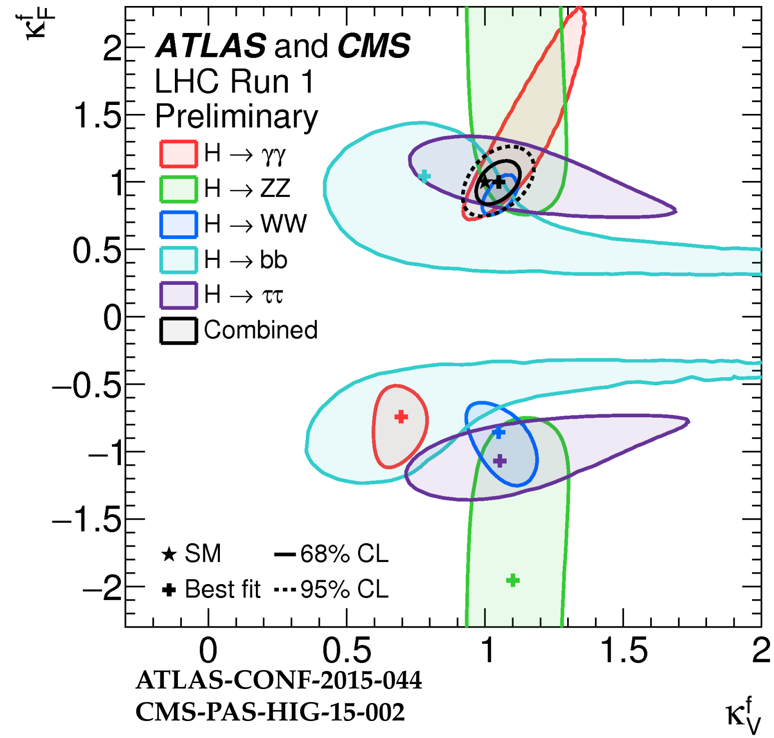


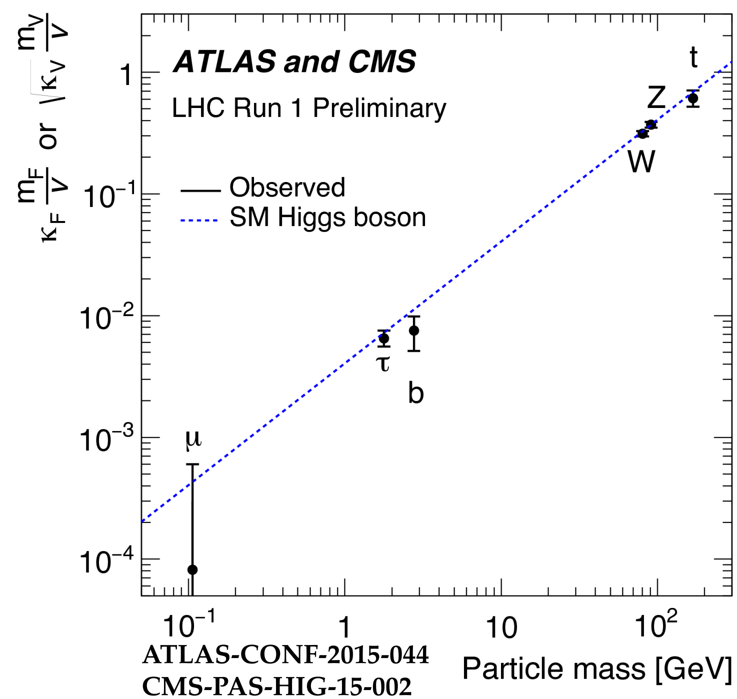
	Inclusive	4μ	$4e$	$2e2\mu$	$2\mu2e$	**SF**	**OF**
Expected [fb]	$3.087\,^{+0.888}_{-0.771}$	$0.934\,^{+0.441}_{-0.353}$	$0.731\,^{+0.509}_{-0.377}$	$0.665\,^{+0.448}_{-0.332}$	$0.762\,^{+0.449}_{-0.346}$	$1.663\,^{+0.636}_{-0.525}$	$1.426\,^{+0.611}_{-0.505}$
Observed [fb]	$4.166\,^{+1.030}_{-0.903}$	$1.325\,^{+0.510}_{-0.420}$	$0.547\,^{+0.466}_{-0.334}$	$1.057\,^{+0.548}_{-0.432}$	$1.100\,^{+0.524}_{-0.420}$	$1.978\,^{+0.681}_{-0.574}$	$2.154\,^{+0.741}_{-0.628}$

Systematic uncertainties on event categorization:

- ggF prediction in n-jet categories based on updated ST method (impact on VBF XS of the order of ~15%). Shape uncertainties on ggF in 1 and 2 jet categories: envelop between Powheg-box vs MC@NLO 0,1,2 jets merging and theory unc. on MC@NLO
- ggF Showering and PDF unc.
- ZZ* bkg migration unc. comparing Powheg-Box to Sherpa 2.1.1, also validated with single resonant and high mass data vs MC
- the reducible background uncertainty on the BDT shapes is obtained by varying the isolation cut
- jets syst. unc. affect the measurements based on the event categories and the high mass searches for the results given in the ggF and VBF categories

Interference effects (as in H→γγ, t-W interference in the loop) allows to test the relative sign of κ_V and κ_F (universal coupling constant of the Higgs boson to vector bosons and fermions)





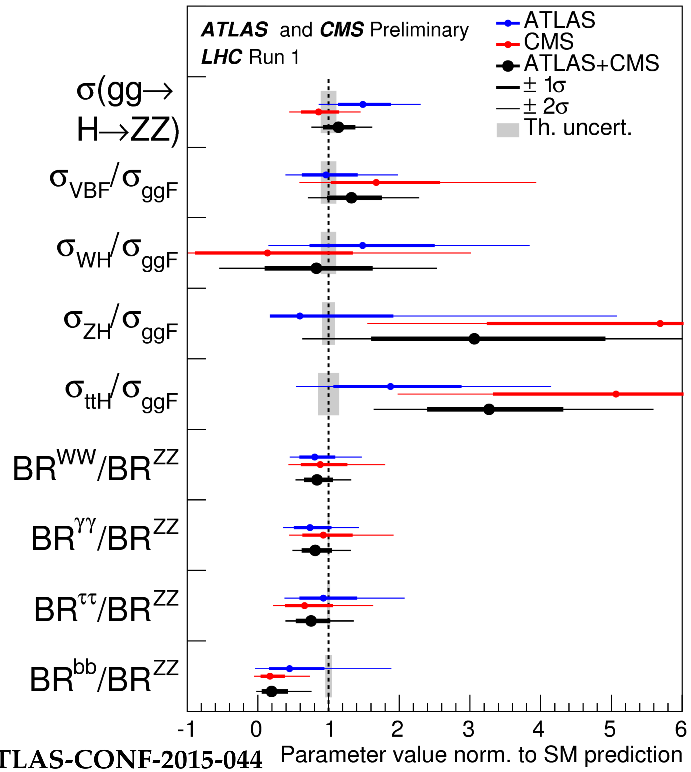
Reduced-k can be also defined:

$$y_{F,i} = \kappa_{F,i}\frac{m_{F,i}}{v} \quad \text{e} \quad y_{V,i} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

where v is the vev of the Higgs field. Indicates in a qualitative way the consistency with the SM predictions.

Rate measurement -> information on XS • BR

Expressing the results in terms of a reference process, the ratios of XS • BR can be extracted.



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CMS-PAS-HIG-15-002

-> Ratios are independent on theoretical predictions (and relative incertezze) on the inclusive XS per production mode (syst. relative unc. ~4%).

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$

- gg->H->ZZ* is the refetrence process, since it has the less syst. unc. associated.
- The values of the ratios obtained are compatible with the SM predictions.

Run 1

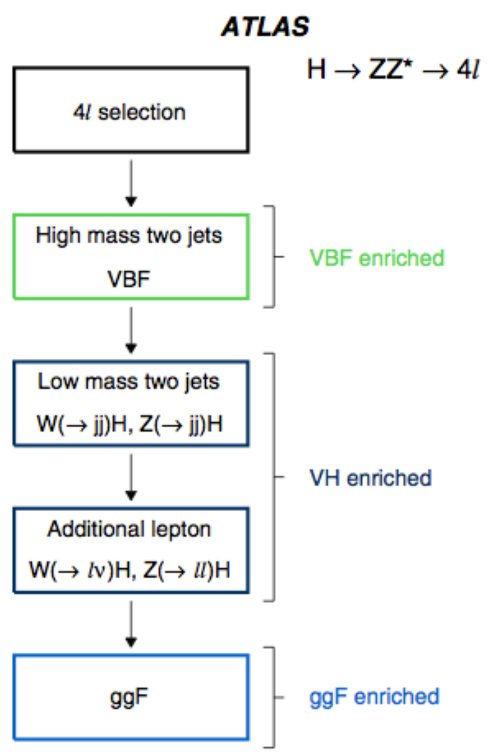
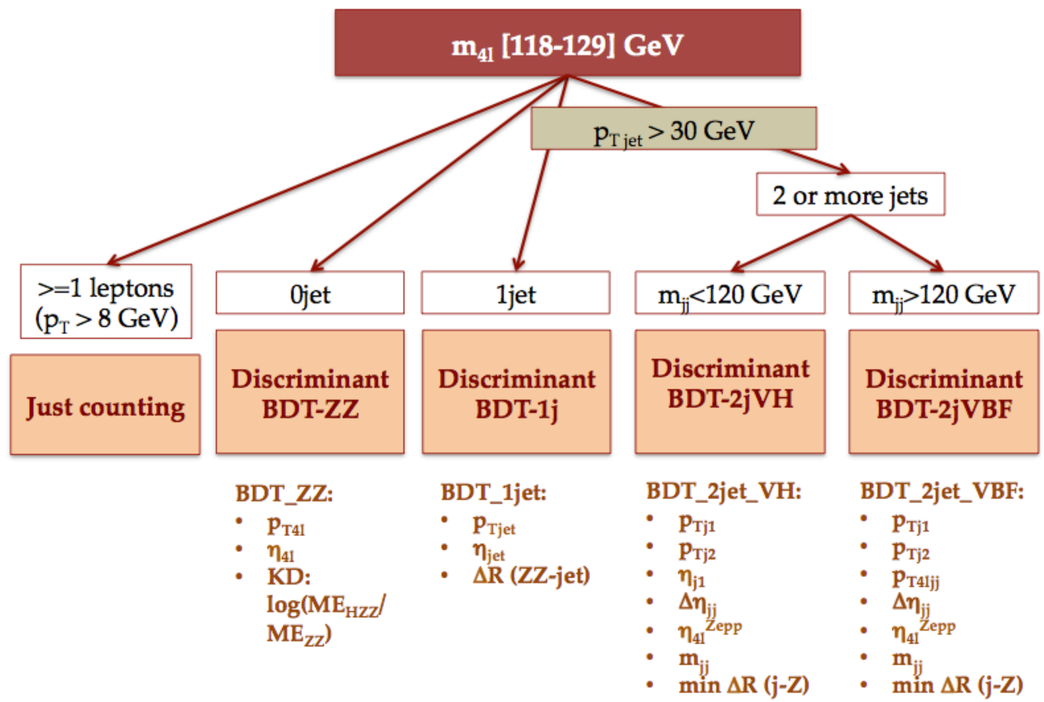


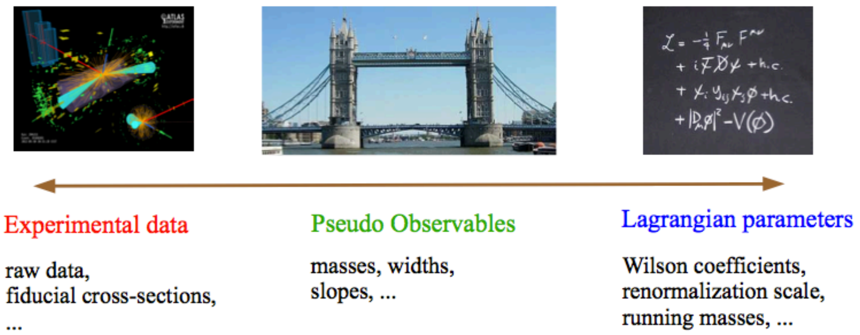
FIG. 2 (color online). Schematic view of the event categorization. Events are required to pass the four-lepton selection, and then they are assigned to one of four categories which are tested sequentially: VBF enriched, VH-hadronic enriched, VH-leptonic enriched, or ggF enriched.

Run 2



POs

POs should be defined from kinematical properties of on-shell processes.



Correspondence between PO and combinations of couplings of the most general Higgs EFT:

- "Ideal observables" such as m_H, $\Gamma_{(H\to\gamma\gamma)}$, $\Gamma_{(H\to gg)}$, $\Gamma_{(H\to 4l)}$, $d\sigma_{(pp\to hZ)}/dm_{hZ}$ …
- "Effective on-shell couplings" such as $k_{\gamma\gamma}$, k_{gg}, k_{WW}, k_{ZZ}, ε_{ZZ}, ε_{Zf} …

The PO can be computed in terms of Lagrangian parameters in a specific theoretical framework (SM, SM-EFT, Susy,…)

-> **the goal is to provide a general encoding of the experimental results in terms of a limited number of observables of easy theoretical interpretation.**

The experimental determination of an appropriate set of PO will help any explicit NP approach to Higgs Physics (including EFT)!

There is more to extract from data other than the k_i in case of a non trivial kinematical structure (e.g. h->4l, pp->Vh, …):

- Form factors $f_i(s)$ -> EFT parametrization of the $f_i(s)$ -> $f_i(s) = f_{i0}(1+\lambda_i s)$

Momentum expansion of the *f.f.* around leading poles

E.g.: $$f_i^{SM+NP} = \frac{\kappa_i}{s - m_Z^2 + i m_Z \Gamma_Z} + \frac{\varepsilon_i}{m_Z^2} + O(s/m_Z^4)$$

k_i and ε_i are well defined PO!

Interaction of a scalar particle with a vector boson pair can be described as follows (most general EFT approach) assuming:

- h(125) is a spin-0 particle
- No new particles with m<125 GeV able to produce distorsions of the decay amplitude of the Higgs in SM particles.

$$\mathcal{A} = i\frac{2m_Z^2}{v_F}\sum_{e=e_L,e_R}\sum_{\mu=\mu_L,\mu_R}(\bar{e}\gamma_\alpha e)(\bar{\mu}\gamma_\beta\mu)\times$$
$$\left[\left(\kappa_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Ze}}{m_Z^2}\frac{g_Z^\mu}{P_Z(q_2^2)} + \frac{\epsilon_{Z\mu}}{m_Z^2}\frac{g_Z^e}{P_Z(q_1^2)}\right)g^{\alpha\beta} + \right.$$
$$+\left(\epsilon_{ZZ}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \kappa_{Z\gamma}\epsilon_{Z\gamma}^{\text{SM-1L}}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \kappa_{\gamma\gamma}\epsilon_{\gamma\gamma}^{\text{SM-1L}}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{q_1\cdot q_2\, g^{\alpha\beta} - q_2{}^\alpha q_1{}^\beta}{m_Z^2} +$$
$$\left.+\left(\epsilon_{ZZ}^{CP}\frac{g_Z^e g_Z^\mu}{P_Z(q_1^2)P_Z(q_2^2)} + \epsilon_{Z\gamma}^{CP}\left(\frac{eQ_\mu g_Z^e}{q_2^2 P_Z(q_1^2)} + \frac{eQ_e g_Z^\mu}{q_1^2 P_Z(q_2^2)}\right) + \epsilon_{\gamma\gamma}^{CP}\frac{e^2 Q_e Q_\mu}{q_1^2 q_2^2}\right)\frac{\varepsilon^{\alpha\beta\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

$$\epsilon_{\gamma\gamma}^{\text{SM-1L}} \simeq 3.8\times10^{-3}$$
$$\epsilon_{Z\gamma}^{\text{SM-1L}} \simeq 6.7\times10^{-3}$$

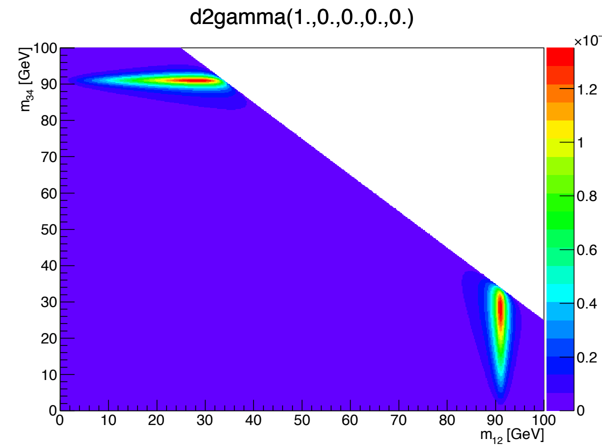
$$P_Z(q^2) = q^2 - m_Z^2 + i m_Z \Gamma_Z$$

Sensitivity studies

Imposing CP invariance -> κ_{ZZ}, ε_{ZeL}, $\varepsilon_{Z\mu L}$, ε_{ZeR}, $\varepsilon_{Z\mu R}$: 5 parameters that contain possible NP effects to fit!

Sensitivity studies with the parametrization from Isidori et al. (arXiv:1412.6038v1) in the 2e2μ channel:

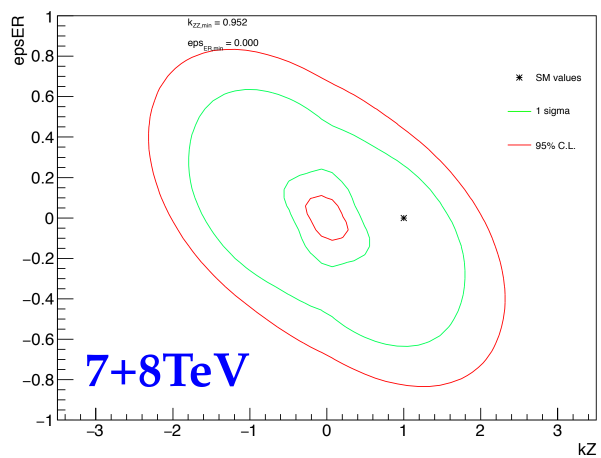
The double differential rate is a quadratic polynomial funciton in $\kappa \equiv (\kappa_{ZZ}, \varepsilon_{ZeL}, \varepsilon_{Z\mu L}, \varepsilon_{ZeR}, \varepsilon_{Z\mu R})^T$, therefore, given the decay amplitude as a function of the parameters (X_{ij}): $d\Gamma_{h\to 2e2\mu}/dm_{12}\, dm_{34} = \Sigma_{j\geq i} X_{ij}\, \kappa_i\, \kappa_j$

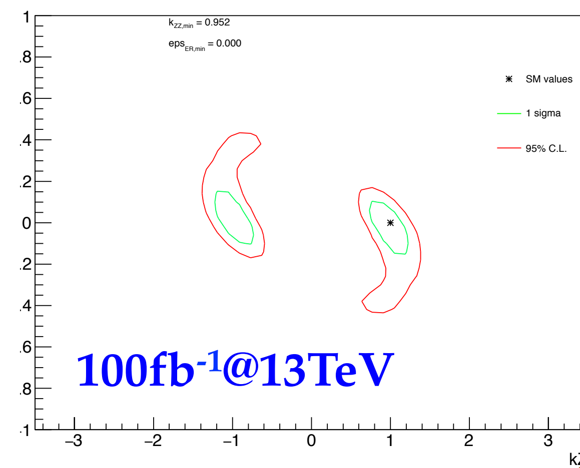


Asimov dataset normalized to the statistics recorded by ATLAS+CMS in RunI (7+8 TeV, ~15 evens in the 2e2μ channel in the signal region [120-130GeV]) -> binned Likelihood fit

Scan on (κ_{ZZ}, ε_{ZeR}) -> $\varepsilon_{Z\mu L}$, ε_{ZeL}, $\varepsilon_{Z\mu R}$ fixed

- sensitivity on the contact term, never considered before
- k_{ZZ} differ from the "usual" μ since it is not related to a defined kinematic distribution

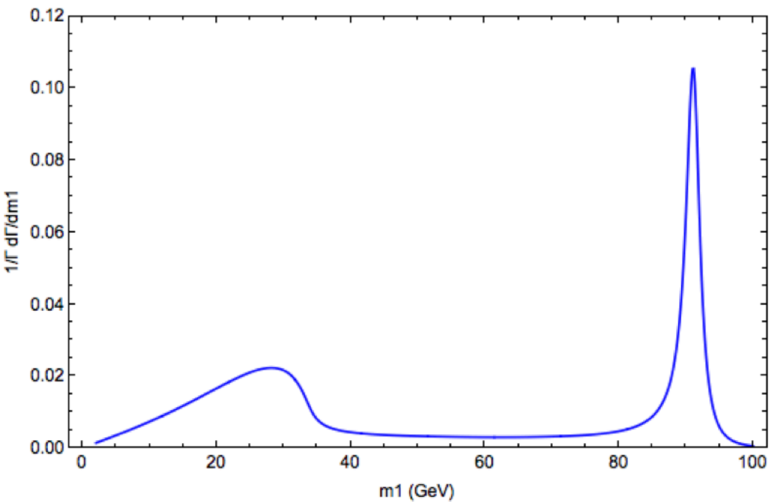


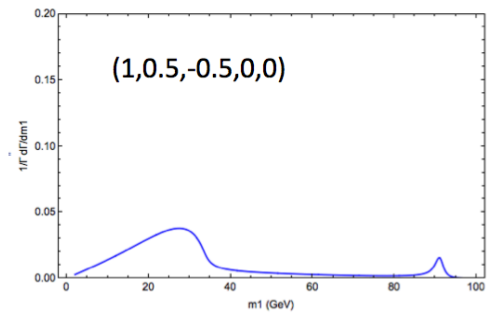


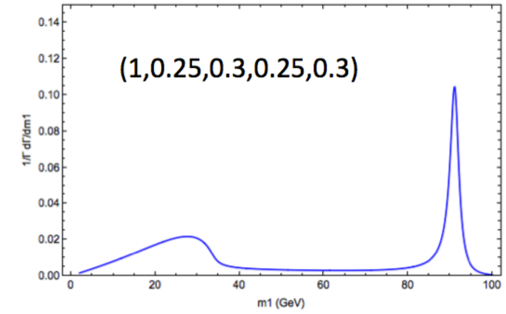
$d^2\Gamma/dm_{12}dm_{34}$ as a function of the parameters under study:

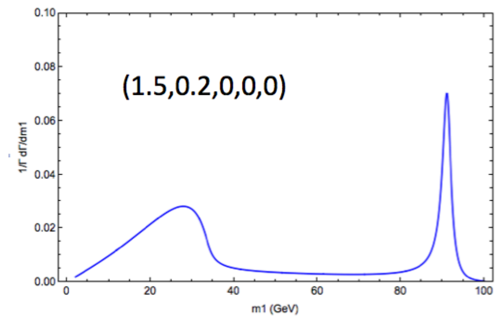
- Projection along m_{12} integrating over m_{34}.
- The integration over the angle is analitically implemented at amplitude level.

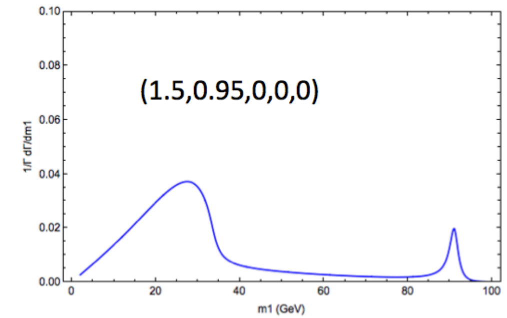
(κ_{ZZ}=1, ε_{ZeL}=0, $\varepsilon_{Z\mu L}$=0, ε_{ZeR}=0, $\varepsilon_{Z\mu R}$=0)

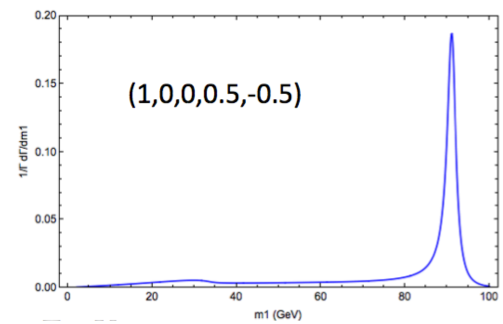


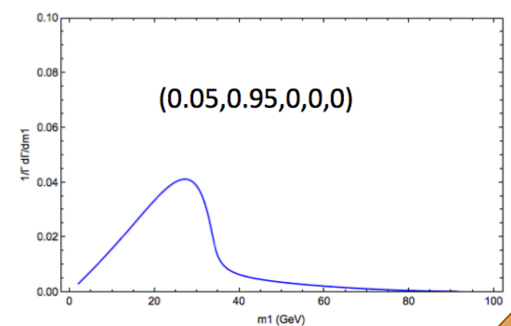












Espression of the double differential rate as a function of F_1:

$$\frac{\Gamma_{e^+e^-\mu^+\mu^-}}{\Gamma^{SM}_{e^+e^-\mu^+\mu^-}} = 1 + 2\delta\kappa_{ZZ} - 2.5\epsilon_{Ze_R} + 2.9\epsilon_{Ze_L} - 2.5\epsilon_{Z\mu_R} + 2.9\epsilon_{Z\mu_L}$$

$$\kappa_{ZZ} \equiv 1 + \delta\kappa_{ZZ}$$

k_{ZZ} is linked to a defined kinematics distribution.

κ_{ZZ} and contact terms

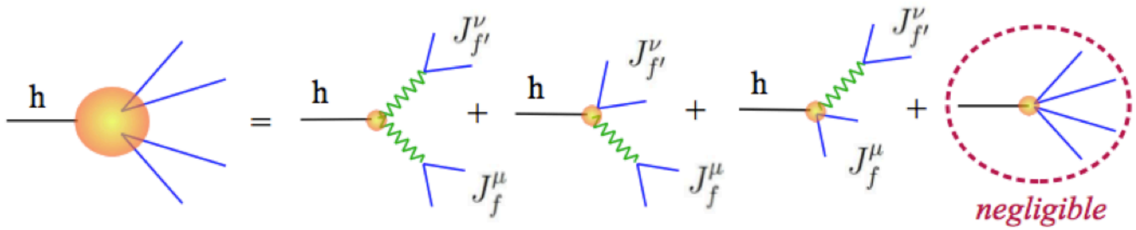
$$\frac{d\Gamma}{dq_1^2 dq_2^2} = \frac{\lambda_p}{2^{10}(2\pi)^7 m_h}\left(\frac{2m_Z^2}{v_F}\right)^2 \frac{128\pi^2}{9} q_1^2 q_2^2 \frac{3 + 2\beta_1\beta_2 - 2(\beta_1^2 + \beta_2^2) + 3\beta_1^2\beta_2^2}{(1-\beta_1^2)(1-\beta_2^2)} \sum_{f,f'} F_1^{ff'} F_1^{ff'*}$$

$$\sum_{f,f'} F_1^{ff'} F_1^{ff'*} = \frac{(1 + 2\delta\kappa_{ZZ})\sum_{f,f'}(g_Z^f g_Z^{f'})^2}{|P_Z(q_1^2)|^2 |P_Z(q_2^2)|^2} + \frac{2(q_1^2 - m_Z^2)\sum_{f,f'} \epsilon_{Zf} g_Z^f (g_Z^{f'})^2}{m_Z^2 |P_Z(q_1^2)|^2 |P_Z(q_2^2)|^2} + \frac{2(q_2^2 - m_Z^2)\sum_{f,f'} \epsilon_{Zf} g_Z^{f'} (g_Z^f)^2}{m_Z^2 |P_Z(q_1^2)|^2 |P_Z(q_2^2)|^2}.$$

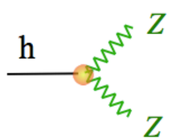
$$\lambda_p = \sqrt{1 + \left(\frac{q_1^2 - q_2^2}{m_h^2}\right)^2 - 2\frac{q_1^2 + q_2^2}{m_h^2}}, \quad \beta_{1(2)} = \sqrt{1 - \frac{4q_{1(2)}^2 m_h^2}{(q_{1(2)}^2 - q_{2(1)}^2 + m_h^2)^2}}$$

Two main hypoteses:

- Fermion couples to the Higgs via helicity-conserving local currents
- Neglecting short distance modes corresponding to local operator with D > 6



Double Z-pole

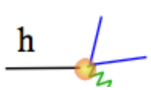


$$\Gamma(h \to Z_L Z_L) \equiv \frac{\Gamma(h \to 2e2\mu)[\kappa_{ZZ}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.209\ |\kappa_{ZZ}|^2\ \text{MeV}$$

$$\Gamma(h \to Z_T Z_T) \equiv \frac{\Gamma(h \to 2e2\mu)[\epsilon_{ZZ}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.0189\ |\epsilon_{ZZ}|^2\ \text{MeV}$$

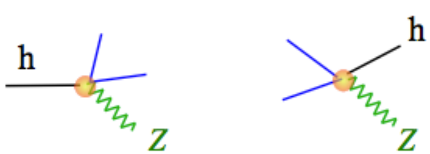
$$\Gamma^{\text{CPV}}(h \to Z_T Z_T) \equiv \frac{\Gamma(h \to 2e2\mu)[\epsilon_{ZZ}^{\text{CP}}]}{\mathcal{B}(Z \to 2e)\mathcal{B}(Z \to 2\mu)} = 0.00799\ |\epsilon_{ZZ}^{\text{CP}}|^2\ \text{MeV}$$

Single Z-pole



$$\Gamma(h \to Z\ell^+\ell^-) = 0.0366|\epsilon_{Z\ell}|^2\ \text{MeV}$$

Z&γ-pole
+
Double γ-pole



$$\Gamma(h \to Z\gamma) \quad \Gamma(h \to \gamma\gamma)$$

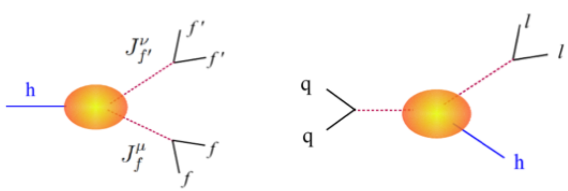
HC Model

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

PO	*Physical* PO	Relation to the eff. coupl.
$\kappa_f,\ \delta_f^{\mathrm{CP}}$	$\Gamma(h\to f\bar f)$	$= \Gamma(h\to f\bar f)^{(\mathrm{SM})}[(\kappa_f)^2+(\delta_f^{\mathrm{CP}})^2]$
$\kappa_{\gamma\gamma},\ \delta_{\gamma\gamma}^{\mathrm{CP}}$	$\Gamma(h\to\gamma\gamma)$	$= \Gamma(h\to\gamma\gamma)^{(\mathrm{SM})}[(\kappa_{\gamma\gamma})^2+(\delta_{\gamma\gamma}^{\mathrm{CP}})^2]$
$\kappa_{Z\gamma},\ \delta_{Z\gamma}^{\mathrm{CP}}$	$\Gamma(h\to Z\gamma)$	$= \Gamma(h\to Z\gamma)^{(\mathrm{SM})}[(\kappa_{Z\gamma})^2+(\delta_{Z\gamma}^{\mathrm{CP}})^2]$
κ_{ZZ}	$\Gamma(h\to Z_L Z_L)$	$= (0.209\ \mathrm{MeV})\times\lvert\kappa_{ZZ}\rvert^2$
ϵ_{ZZ}	$\Gamma(h\to Z_T Z_T)$	$= (1.9\times10^{-2}\ \mathrm{MeV})\times\lvert\epsilon_{ZZ}\rvert^2$
$\epsilon_{ZZ}^{\mathrm{CP}}$	$\Gamma^{\mathrm{CPV}}(h\to Z_T Z_T)$	$= (8.0\times10^{-3}\ \mathrm{MeV})\times\lvert\epsilon_{ZZ}^{\mathrm{CP}}\rvert^2$
ϵ_{Zf}	$\Gamma(h\to Zf\bar f)$	$= (3.7\times10^{-2}\ \mathrm{MeV})\times N_c^f\ \lvert\epsilon_{Zf}\rvert^2$
κ_{WW}	$\Gamma(h\to W_L W_L)$	$= (0.84\ \mathrm{MeV})\times\lvert\kappa_{WW}\rvert^2$
ϵ_{WW}	$\Gamma(h\to W_T W_T)$	$= (0.16\ \mathrm{MeV})\times\lvert\epsilon_{WW}\rvert^2$
$\epsilon_{WW}^{\mathrm{CP}}$	$\Gamma^{\mathrm{CPV}}(h\to W_T W_T)$	$= (6.8\times10^{-2}\ \mathrm{MeV})\times\lvert\epsilon_{WW}^{\mathrm{CP}}\rvert^2$
ϵ_{Wf}	$\Gamma(h\to Wf\bar f')$	$= (0.14\ \mathrm{MeV})\times N_c^f\ \lvert\epsilon_{Wf}\rvert^2$
κ_g	$\sigma(pp\to h)_{gg-\mathrm{fusion}}$	$= \sigma(pp\to h)_{gg-\mathrm{fusion}}^{\mathrm{SM}}\kappa_g^2$
κ_t	$\sigma(pp\to t\bar th)_{\mathrm{Yukawa}}$	$= \sigma(pp\to t\bar th)_{\mathrm{Yukawa}}^{\mathrm{SM}}\kappa_t^2$
κ_H	$\Gamma_{\mathrm{tot}}(h)$	$= \Gamma_{\mathrm{tot}}^{\mathrm{SM}}(h)\kappa_H^2$

PO:

- Description of Production and Decay amplitudes as expansion around physical poles:
  - Double poles (κVV, εVV)
  - Poles + contact terms (εVf)
- Weak assumptions
  - Analyticity
  - Crossing symmetry



- Focused mainly on EW
  - Can be combined with STXS for detailed description of ggF
  - Finer description of ttH being developed

- Matched to independent observables: corresponds to maximum available experimental observables
  - depends on availability of CP measurements, etc.
  - Less constrained than SMEFT
- Not dependent on computation order
  - But mapping to perturbative results will be
- No influence on backgrounds
  - Encodes specifically Higgs amplitudes only

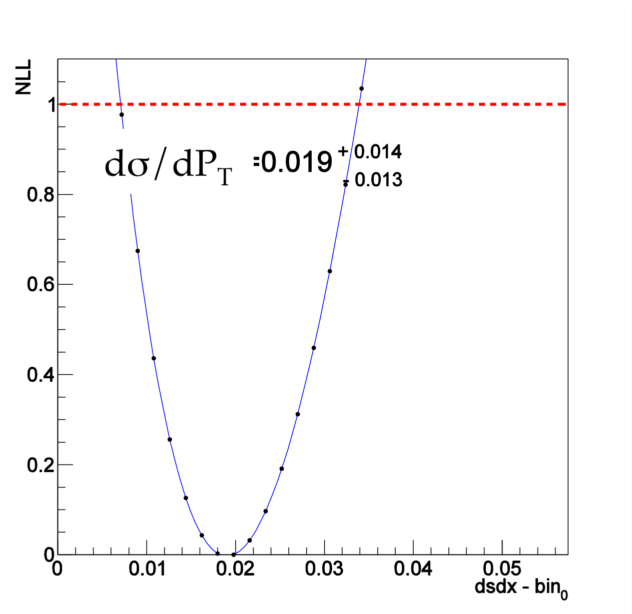
Diff XS

Differential fiducial cross sections in sensitive variables

$$\frac{d\sigma_{\text{fid},i}}{dx_i} = \frac{n_i^{\text{sig}}}{c_i \cdot \mathcal{L}_{\text{int}} \cdot \Delta x_i}$$

where L_{int}=20.3 fb^{-1}, c_i are the CF defined bin by bin and for each variable of interest $c_i = \frac{N_i^{\text{reco}}}{N_i^{\text{fid}}}$ (mainly detector efficiency and also resolution effects), Δx is the bin width, $(d\sigma/dx)_i$ is the cross section for all the production modes.

$20.3\ \text{fb}^{-1} @ \sqrt{s} = 8$ TeV, $118 < m_{4\ell} < 129$ GeV				
SM Signal	ZZ	Reducible	Total Background	Observed
14.1	6.7	2.4	9.0	34

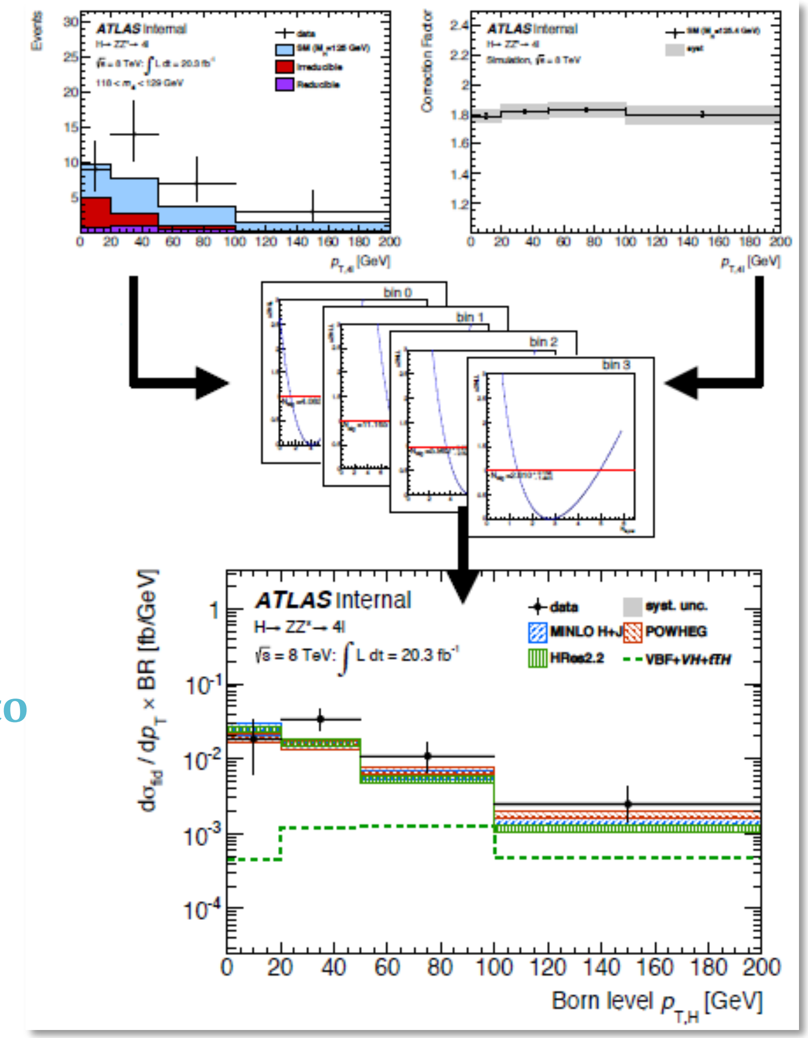


Signal extraction performed building a profiled Likelihood as the product of Poissonian distributions in each bin for each variable and extracting the n^{sig}_i (i.e. $(d\sigma/dx)_i$) fitted values.

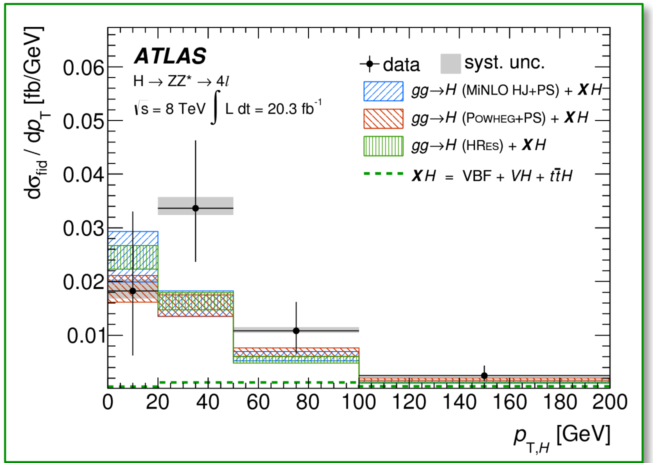
- errors are estimated from |2ΔNLL|=1

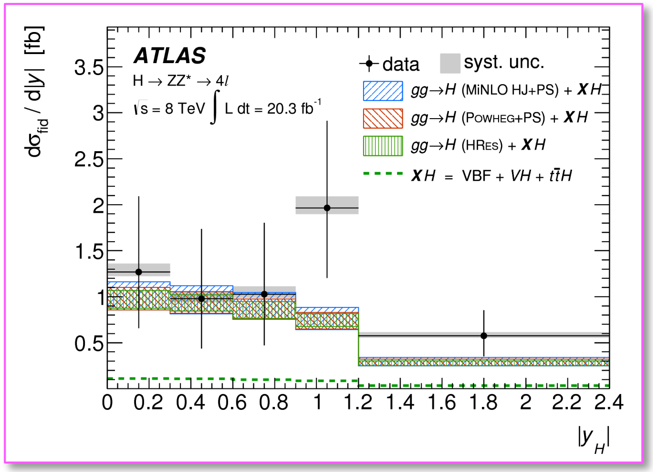
Measurement at a glance:

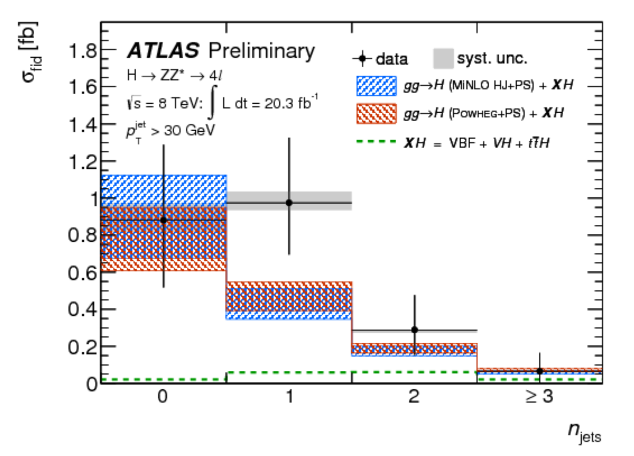
- H->ZZ*->4l event selection
- Event counting measurement in mass window ($118<m_{4l}<129$ GeV optimized to maximize $S/\sqrt{(S+B)}$)
- Bin events in each variable of interest
- Background subtraction
- Unfold the reconstructed signal distribution to the truth one in fiducial volume (CFs)
- Profiled likelihood fit to perform the measurement (previous slide)
- Comparison of the measured cross sections to different theoretical calculations/generators which differ for the QCD treatment
  - HRes 2.2 for $P_{T,H}$ and $|y|_H$, (NNLO+NNLL prediction; not including jets)
  - MINLO HJ for all, (0+1jet NLO)
  - POWHEG for all (NLO, nominal in ATLAS)

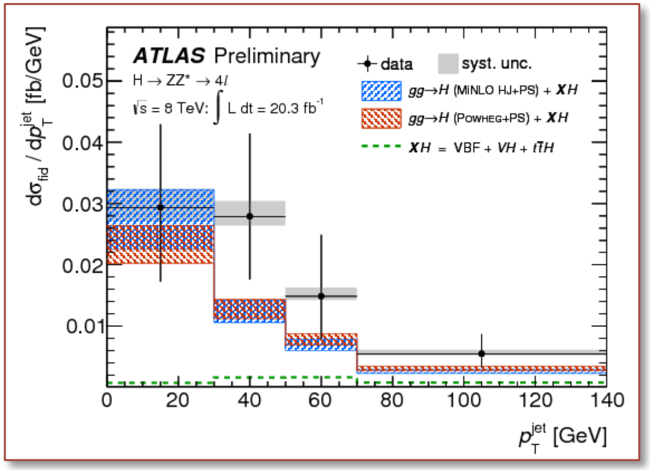


Results in the sensitive variables

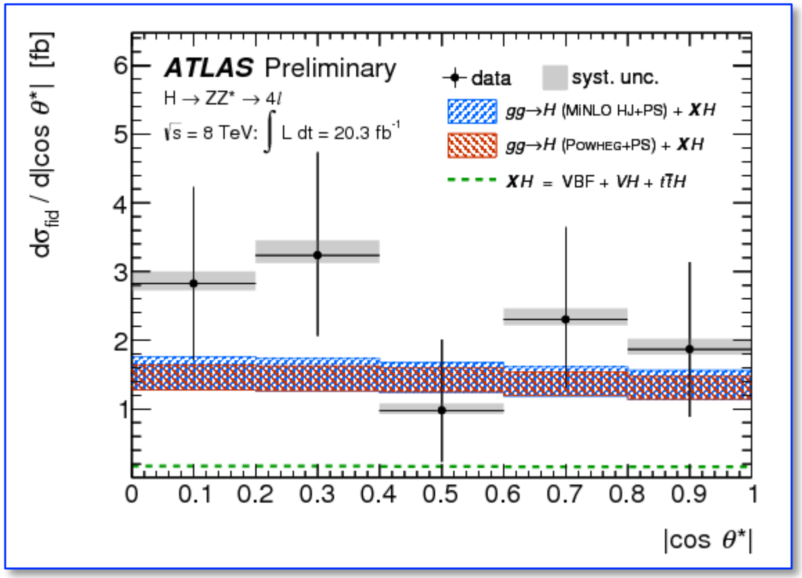


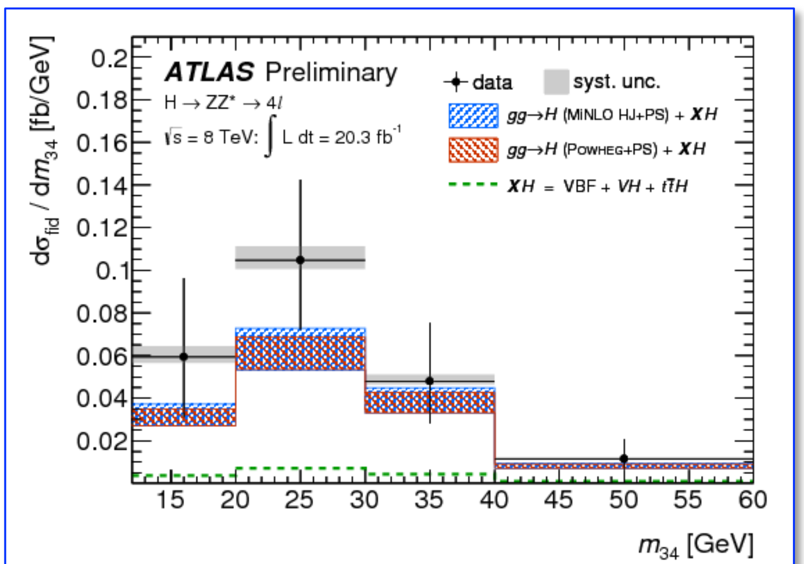






- P_{TH}: interesting to probe pertubative QCD calculations and the relative rates in production modes
- $|y_H|$: sensitive to radiative QCD corrections, protons PDF and relative rates in production modes
- N_{jet}: sensitive to the relative rate in production modes and radiative corrections
- P_{Tj1}: corresponds in ggH to the most hard QCD and can be compared to higher-order predictions, relative rates in production modes





- The distributions of the **m_{34} and |cosθ*|** (angle between the Z_1 and the beam axis) are **sensitive to the Lagrangian structure of the Higgs boson interactions**: e.g. quantum numbers of **spin/CP and higher-dimensional operators** (useful also for EFT studies)

No significant deviations from the SM expectations.

	Compatibility (%)		
Variable	Powheg	Minlo	HRes2
$p_{T,H}$	30	23	16
$\lvert y_H \rvert$	37	45	36
m_{34}	48	60	-
$\lvert \cos(\theta^*) \rvert$	35	45	-
n_{jets}	37	28	-
p_T^{jet}	33	26	-

Compatibility to theoretical predictions computed as the χ^2 probability for n dof (n=$\#_{\text{bins}}$).
The different predictions have been normalized to the most precise value measured by LHC XS-WG.

WW* and $\gamma\gamma$

Higgs-EFT ZZ* and WW*

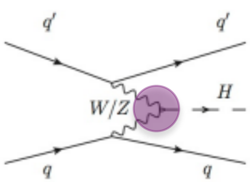
Several basis have been **proposed for the EFT: Higgs Characterization (HC)** has been used up to now (WW* and ZZ*) and will be used in the near future (also γγ):

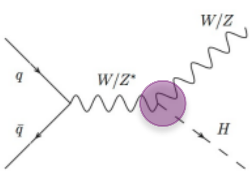
Effective Lagrangian (spin-0 hypothesis) includying CP-even and CP-odd terms:

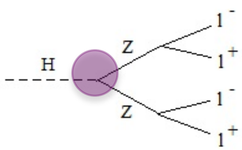
$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{SM}\left[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W_\mu^+ W^{-\mu}\right] \\
& - \frac{1}{4}\left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\right] \\
& - \frac{1}{2}\left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\right] \\
& - \frac{1}{4}\left[c_\alpha \kappa_{Hgg} g_{Hgg}\, G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G_{\mu\nu}^a \widetilde{G}^{a,\mu\nu}\right] \\
& - \frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\right] \\
& - \frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha \kappa_{HWW}\, W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W_{\mu\nu}^+ \widetilde{W}^{-\mu\nu}\right] \\
& - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \left(\kappa_{H\partial W}\, W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.\right)\right]\Big\} X_0
\end{aligned}
$$

EFT (last three terms)

CP even
CP odd
Λ=1 TeV





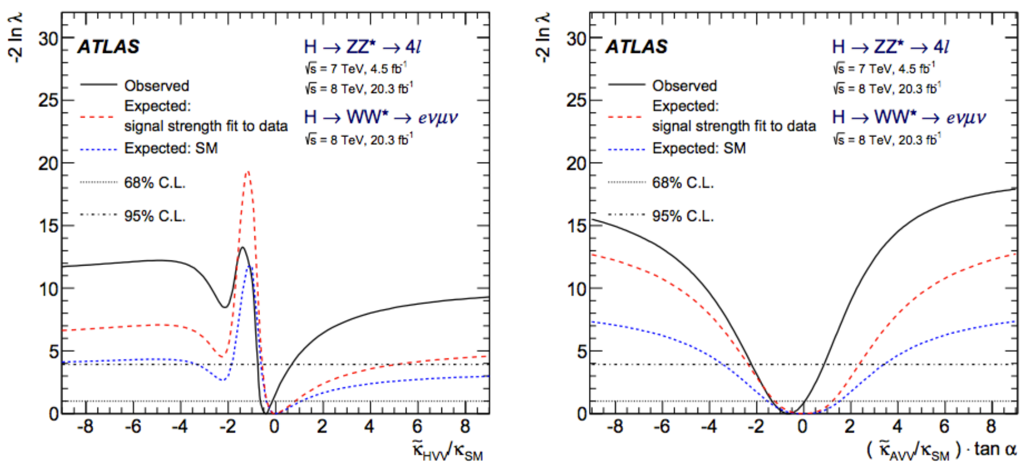


Contributes to the XS proportional to k_{BSM}^2 : effects in the production and decay rates (strong sensitivity for VBF and VH for the H->ZZ* and H->WW*)

The **spin-0 particle interaction with pairs of W or Z bosons is given through the following interaction Lagrangian** (considering SM spin-0 and BSM spin-0 CP-even, κ_{HZZ}, and CP-odd , κ_{AZZ}, contributions):

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV} \quad \text{and} \quad \tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$

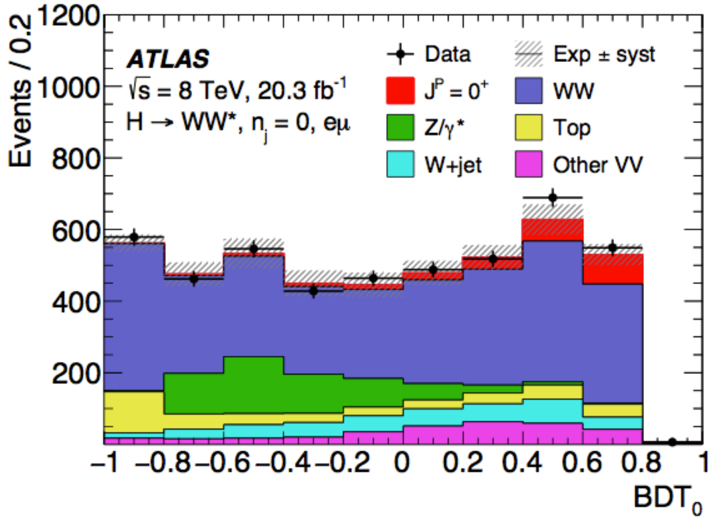
$$\begin{aligned}\mathcal{L}_0^V = \; & \Big\{\cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0.\end{aligned}$$

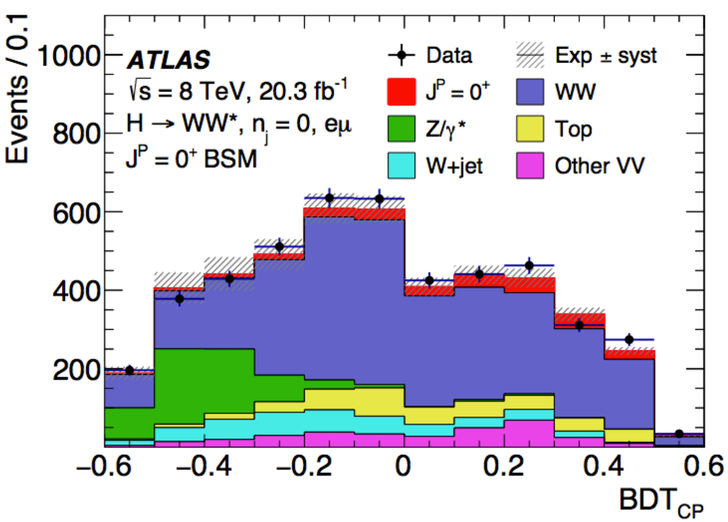


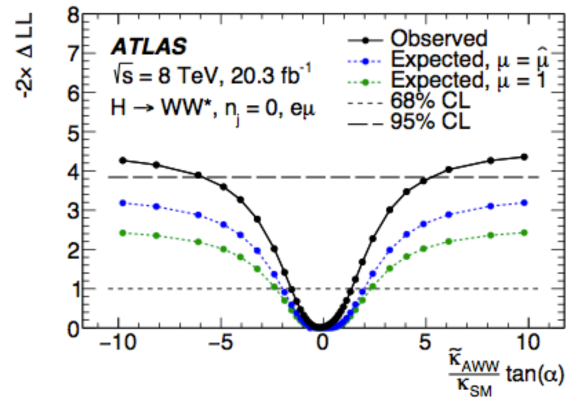
Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\rm SM}$	-0.48	$(-\infty,-0.55]\bigcup[4.80,\infty)$	$(-\infty,-0.73]\bigcup[0.63,\infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\rm SM})\cdot\tan\alpha$	-0.68	$(-\infty,-2.33]\bigcup[2.30,\infty)$	$(-\infty,-2.18]\bigcup[0.83,\infty)$

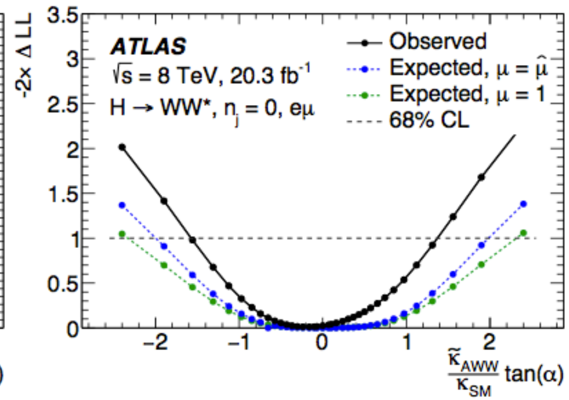
- **To quantify the presence of BSM contributions** in $H \to ZZ^*$ and $H \to WW^*$ decays, the ratios of couplings $(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$ and $\tilde{\kappa}_{HVV}/\kappa_{SM}$ are measured one at a time, while the other one is assumed to be absent.
- The measurement is performed via a fit on a set of CP discriminating variables

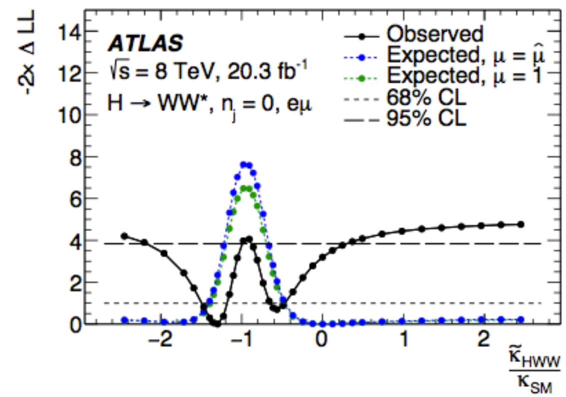
H-> WW*











The asymmetric shape of the expected and observed limits in the ˜κHVV/κSM results is mainly due to the interference between the BSM and the SM contributions that gives maximum deviation from
the SM predictions for negative relative values of the BSM couplings.

Next steps: H->WW*

Purpose of analysis:

- **measure/set limits on EFT parameters** (correlating *HWW* and *HZZ* coupling use cross-section (rate) and kinematics (shape) information) **-> later combination with ZZ* channel**
- use Higgs Characterization model implemented in MADGRAPH5_AMC@NLO using the Morphing method
- Perform multidimensional fits
- Apply for the EFT studies, the same pre-selection as in the nominal analysis separate in 0 and ≥2 jets channels
  -> work in progress:
  find phase-space to separate EFT signals from SM by training BDTs

$$
\begin{aligned}
\mathcal{L}_0^V = \Big\{ & c_\alpha \kappa_{SM} \left[\frac{1}{2} \tilde{g}_{HZZ} Z_\mu Z^\mu + \tilde{g}_{HWW} W^+_\mu W^{-\mu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} \tilde{g}_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} \tilde{g}_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
& - \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} \tilde{g}_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} \tilde{g}_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{Hgg} \tilde{g}_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} \tilde{g}_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right] \\
& - \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right] \\
& - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W} \left(W^+_\nu \partial_\mu W^{-\mu\nu} + h.c. \right) \right] \Big\} X_0
\end{aligned}
$$

- SM
- effective couplings from SM/2HDM
- effective couplings from EFT
- CP even
- CP odd

floating paramters: $\kappa_{\mathrm{SM/BSM}}$

fixed paramters: $s_\alpha = \sin(\alpha) = \frac{1}{\sqrt{2}}$, $c_\alpha = \cos(\alpha) = \frac{1}{\sqrt{2}}$, $\Lambda = 1$ TeV

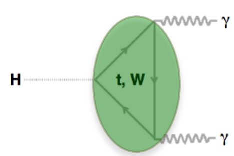
(Λ-suppressed couplings derived from EFT $\mathcal{L}_{eff} = \mathcal{L}_0^{SM} + \sum_n \frac{c_n}{\Lambda^2} O_n$)

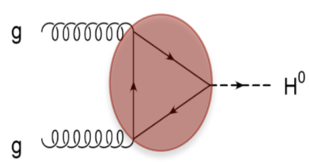
EFT H-> γγ

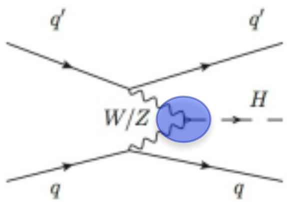
Run 1

First EFT studies in the H->γγ channel were performed including possible additional CP-even ($\tilde{c}_i$) and CP-odd ($\bar{c}_i$) contributions to the Lagrangian (SILH basis) -> this reflects in modifying the kinematics properties of the Higgs boson and in the spectrum of the associated jets w.r.t. the SM case.

$$\mathcal{L}_{\text{eff}} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$





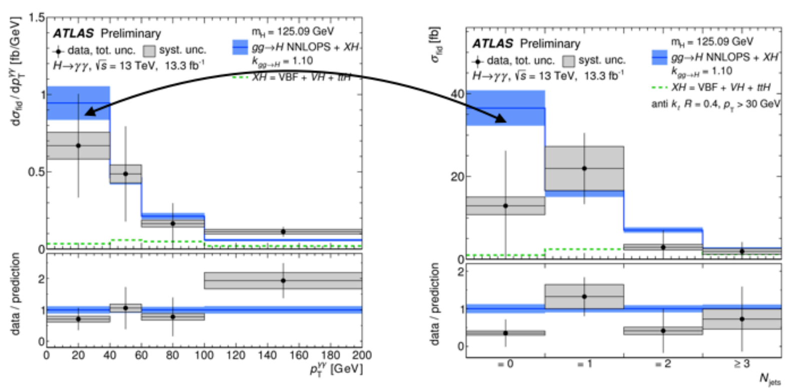


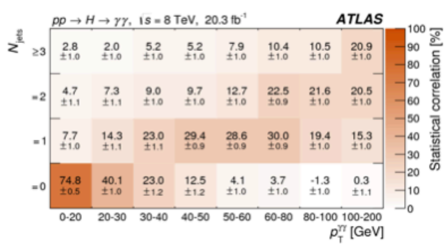
- Theoretical prediction determined at fixed values of Wilson coefficient in each bin by reweighting the SM prediction to the EFT prediction

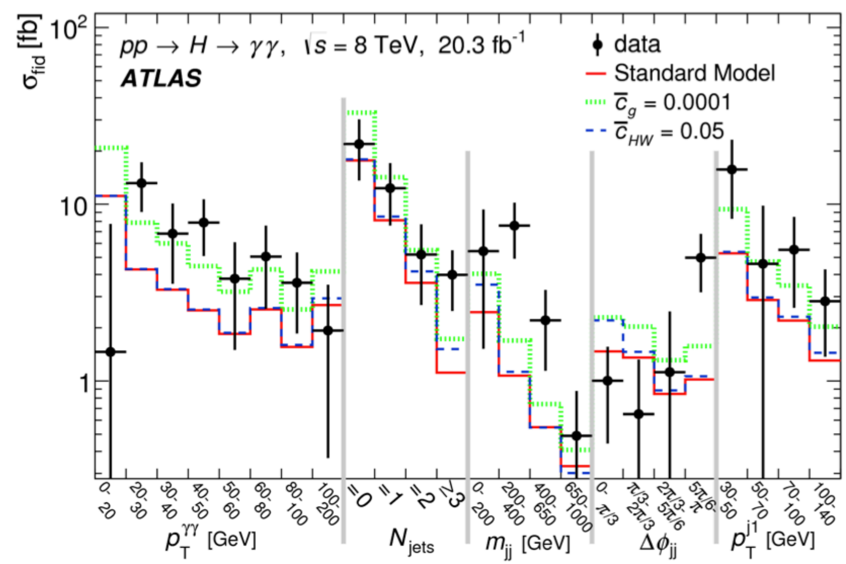
$$\frac{d\sigma}{dX} = \sum_j \left(\frac{d\sigma_j}{dX}\right)^{\text{ref}} \cdot \left(\frac{d\sigma_j}{dX}\right)^{\text{MG5}}_{c_i} \Big/ \left(\frac{d\sigma_j}{dX}\right)^{\text{MG5}}_{c_i=0}$$

Measurements have been performed via a global fit at the 5 differential distributions simultaneously (statistical correlation between bins of distributions have been performed and taken into account)

Limits have been obtained on the Wilson coefficients by performing Likelihood scans of new CP-even and CP-odd interactions.



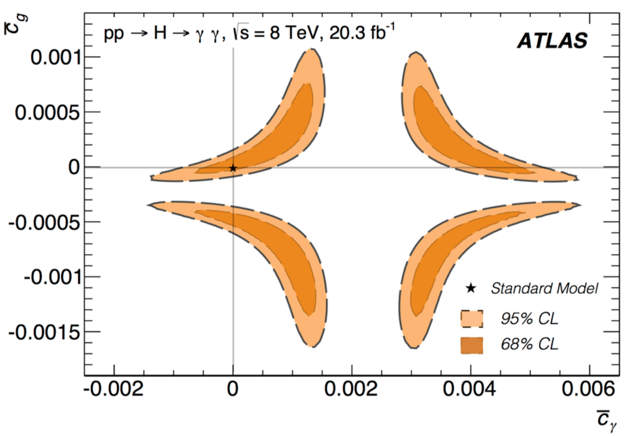




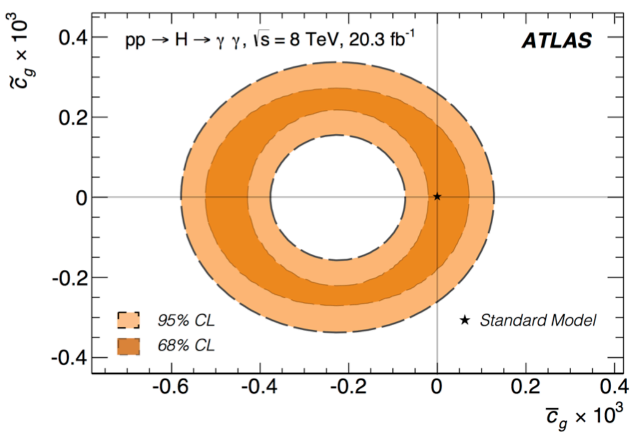
- Wilson coefficients produce large shape changes in all distributions and the obtained limits are strongest when fitting all five distributions simultaneously
- Results have been also translated within the HC basis for $\tilde{c}_{HW}$ and $\tilde{c}_{HW}$

Coefficient	95% $1-CL$ limit
$\bar{c}_\gamma$	$[-7.4, 5.7]\times10^{-4} \cup [3.8, 5.1]\times10^{-3}$
$\tilde{c}_\gamma$	$[-1.8, 1.8]\times10^{-3}$
$\bar{c}_g$	$[-0.7, 1.3]\times10^{-4} \cup [-5.8, -3.8]\times10^{-4}$
$\tilde{c}_g$	$[-2.4, 2.4]\times10^{-4}$
$\bar{c}_{HW}$	$[-8.6, 9.2]\times10^{-2}$
$\tilde{c}_{HW}$	$[-0.23, 0.23]$

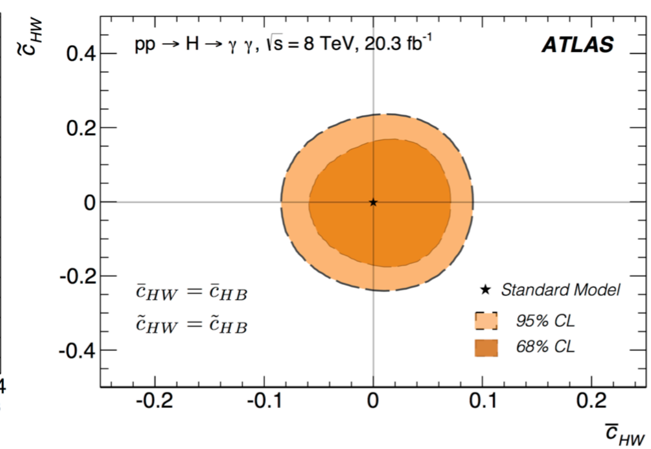
$$-0.08 < \tilde{\kappa}_{HVV}/\kappa_{SM} < 0.09 \text{ and } -0.22 < \tan(\alpha)\cdot\tilde{\kappa}_{AVV}/\kappa_{SM} < 0.22,$$



Gluon fusion: enhanced gluon coupling (X) can be balanced by reduced photon coupling (1/X)



CP-odd and CP-even operators can be constrained simultanously



Even without the HVV decay channels, competitive/ improved limit w.r.t to dedicated analysis of HVV angular decays.

Future plans:

- **repeat the analysis for H→γγ using diff. & fid. cross sections**
- **Better statistical precision and new differential spectra** motivated by the EFT
- **Timescale: Moriond** and to be included in the HGam main publication

- About the basis: both **SILH** and **HC can be used (or use SILH and then translate with Rosetta)**, as long as the final result can be comparable with the other channels

- STXS: No concrete plans yet to use this for EFT limits; likely more worth doing with several channels