Higgs boson couplings characterization in the 4-lepton channel with the Run 2 data of the ATLAS Experiment at the LHC

36^{th} IMPRS Workshop at Max Planck Institute of Physics

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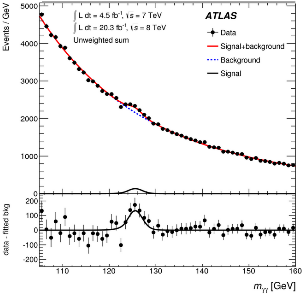

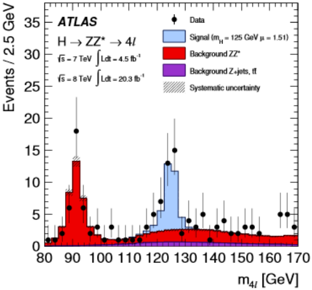

1. Higgs boson discovery from both ATLAS and CMS experiments
2. exclusion of spin 1 and 2 hypotheses with the Run 1 data
3. search for a discrepancy in the size and structure of the Higgs boson couplings with respect to the SM predictions
4. assuming v, the vacuum expectation value, the expected values of the Higgs couplings with the vector bosons V and fermions f are:

$$\mathbf{g_{HVV} = \frac{2m_V^2}{v}}\ , \qquad \mathbf{g_{Hff} = \frac{m_f}{v}}$$

Outline

The Lagrangian of interaction of a bosonic state X(J^P) with spin/parity assignments 0^+, 0^- with vector bosons can be written as follows [1]:

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

SM contribution

- $\kappa_{\rm SM} = 1$
- $c_\alpha = 1$
- all other κ-parameters not in the box equal to 0.

Assumption: $k_{HZZ} = k_{HWW} = k_{HVV}$ and $k_{AZZ} = k_{AWW} = k_{AVV}$

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\end{aligned}
$$

bSM couplings with W and Z studied in this analysis

Assumption: $k_{HZZ} = k_{HWW} = k_{HVV}$ and $k_{AZZ} = k_{AWW} = k_{AVV}$

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\end{aligned}
$$

bSM couplings with W and Z studied in this analysis

CP-conserving

Assumption: $k_{HZZ} = k_{HWW} = k_{HVV}$ and $k_{AZZ} = k_{AWW} = k_{AVV}$

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& - \frac{1}{2}\big[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}\big] \\
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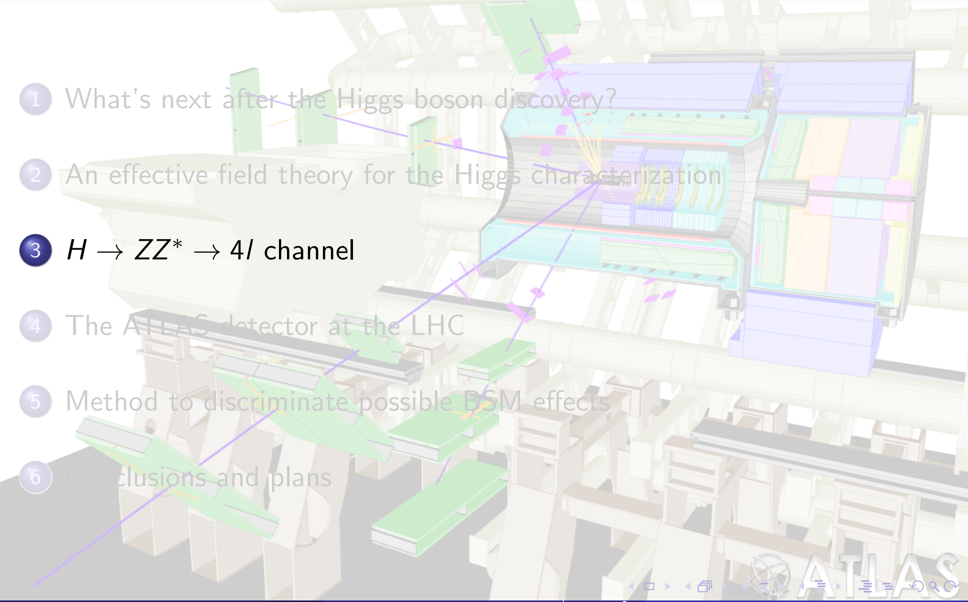
\end{aligned}
$$

bSM couplings with W and Z studied in this analysis

CP-violating

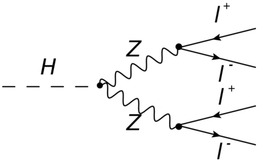
Assumption: $k_{HZZ} = k_{HWW} = k_{HVV}$ and $k_{AZZ} = k_{AWW} = k_{AVV}$

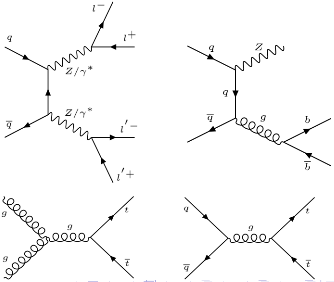
Outline

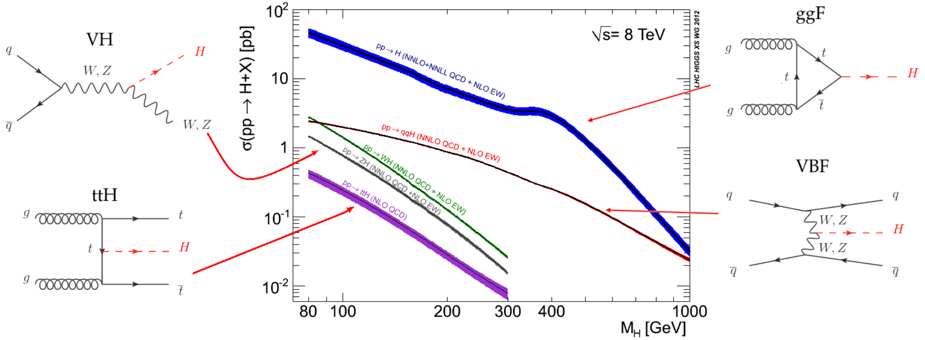


$H \to ZZ^* \to 4l$ channel

- $\mathrm{BR}(H \to ZZ^* \to 4l) = 1.25 \times 10^{-4}$ at $m_H = 125$ GeV
- $N_{events}^{exp} = \sigma_{SM} BR L_{int} \simeq 694$ with $L_{int} = 100\ fb^{-1}$ at $\sqrt{s} = 13$ TeV
- clean signature given by the presence of leptons (e and μ) in the final state
- single and dilepton trigger on e and μ
- Higgs boson candidate: quadruplet of two same-flavour, opposite-sign lepton pairs
- leptons in the quadruplet ordered in p_T: $p_T > 20$ GeV, > 15 GeV, > 10 GeV, > 6 GeV (μ) and > 7 GeV (e)
- main backgrounds: irreducible $pp \to ZZ^* \to 4l$, reducible Z+jets, $t\bar{t}$







Event candidates divided into three experimental categories: 0jet, 1jet, $\geq$2jets

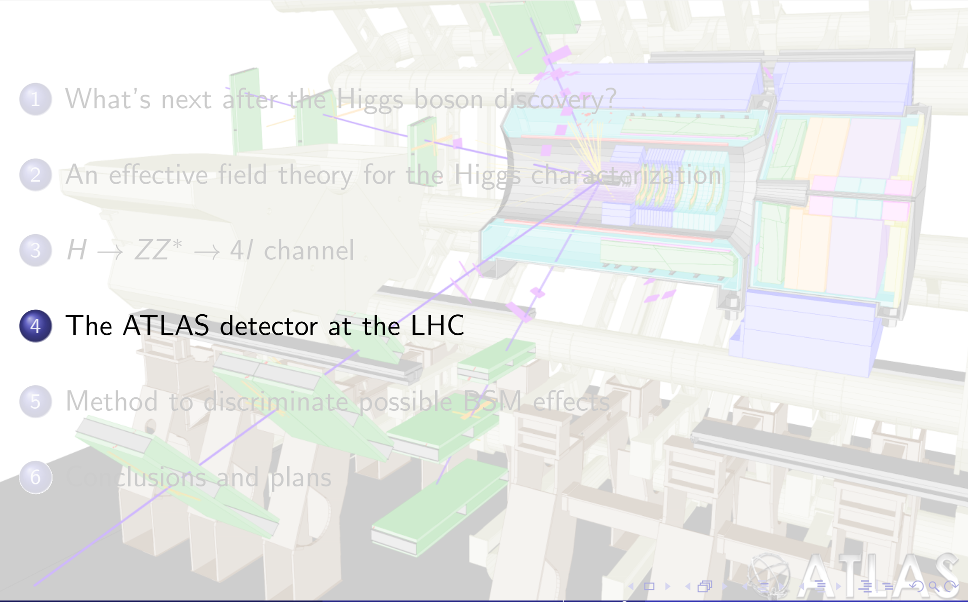
	VBF	hadronic VH	ggF
0jet	0.11	0.032	7.7
1jet	0.59	0.19	6.5
$\geq$2jets	2.1	0.62	4.5

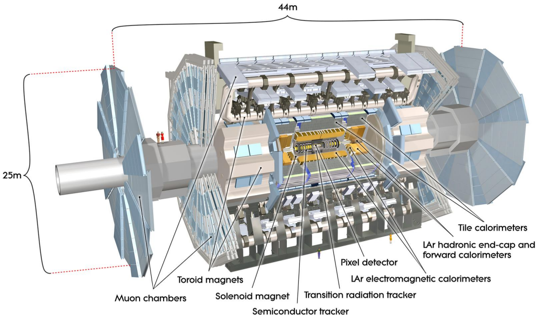
Table: Yields of VBF, hadronic VH and ggF in each category, for $L_{int} = 14.8\ fb^{-1}$ and $\sqrt{s} = 13$ TeV and after the event selection.

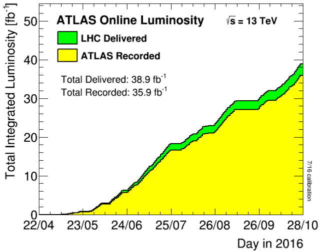
$\geq$2jets category divided into two categories with a cut on the reconstructed invariant mass of the two jets M_{jj}^{reco}:

- if $M_{jj}^{reco} \geq 120$ GeV: VBF-category
- if $M_{jj}^{reco} < 120$ GeV: VH-category

Outline



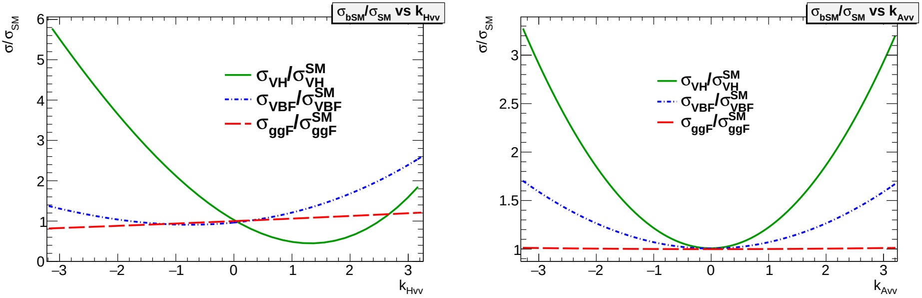




1. **Magnetic system**: one barrel and two end-cap toroids, central solenoid (2 T)
2. **Inner detector**: silicon pixels, semiconductor tracker (SCT) and transition radiation tracker (TRT)
3. **Electromagnetic calorimeter**: lead-liquid argon detector with accordion geometry
4. **Hadronic calorimeter**: iron as absorber and scintillating materials
5. **Muon spectrometer**: muon chambers with high resolution and standalone muons reconstruction

Outline

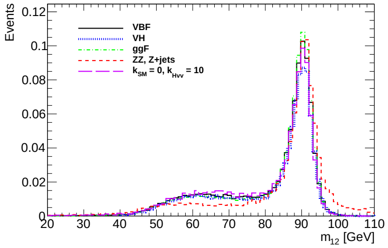
New physics effects on the signal strength [2]

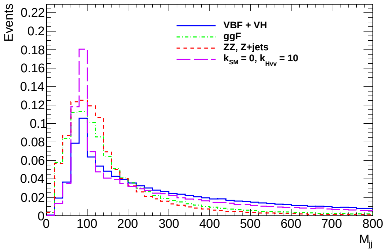


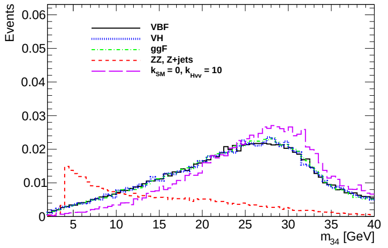
- VBF and VH mechanisms have a greater sensitivity to the BSM couplings
- The ggF mechanism depends only marginally from the BSM couplings
- The SM and BSM contributions interfere when $\mu = \frac{\sigma^{BSM}}{\sigma^{SM}}$ is a function of k_{HVV}. The interference is greater in the case of VH and has an opposite sign compared to that of VBF
- No interference expected when the cross section is a function of k_{AVV}

New physics effects on the shape of kinematic differential distributions of signal and backgrounds

Other discriminating variables



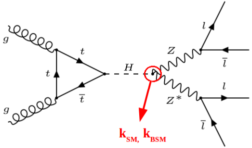




Need a multivariate analysis to combine the shape of many kinematic distributions. ⇒ Matrix element based observables

Definition of the matrix element of a process

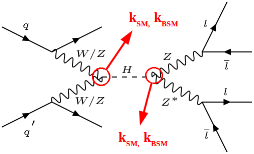
- **BSM coupling entering in production or decay vertex (ggF)**

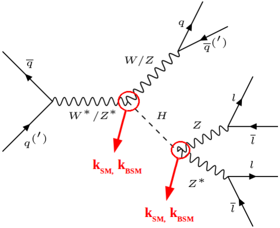


$$\mathcal{M}(k_{SM}, k_{BSM}) = k_{SM}\mathcal{M}_{SM} + k_{BSM}\mathcal{M}_{BSM} \qquad (1)$$

use of 4 leptons to build the matrix element

- **BSM coupling entering in both production and decay vertices (VBF and VH)**





$$\mathcal{M}(k_{SM}, k_{BSM}) = (k_{SM} \cdot \mathcal{M}_{SM,p} + k_{BSM} \cdot \mathcal{M}_{BSM,p}) \cdot (k_{SM} \cdot \mathcal{M}_{SM,d} + k_{BSM} \cdot \mathcal{M}_{BSM,d}). \qquad (2)$$

use of 4 leptons and 2 jets to build the matrix element

Optimal Observables (OO) for VBF and VH [3]

$$OO_1 = \frac{\text{Interference}}{|\mathcal{M}_{SM}|^2}$$

$$OO_2 = \frac{|\mathcal{M}_{BSM}|^2}{|\mathcal{M}_{SM}|^2}$$

$$\begin{aligned}|\mathcal{M}(k_{SM}, k_{BSM})|^2 = & \; k_{SM}^4 |\mathcal{M}_{SM,p}|^2 |\mathcal{M}_{SM,d}|^2 + k_{BSM}^4 |\mathcal{M}_{BSM,p}|^2 |\mathcal{M}_{BSM,d}|^2 + \\ & + k_{SM}^3 k_{BSM} \Big[|\mathcal{M}_{SM,p}|^2 \Re(|\mathcal{M}_{SM,d}|^* |\mathcal{M}_{BSM,d}|) + \\ & + \Re(|\mathcal{M}_{SM,p}|^* |\mathcal{M}_{BSM,p}|) |\mathcal{M}_{SM,d}|^2 \Big] + \\ & + k_{SM}^2 k_{BSM}^2 (|\mathcal{M}_{SM,p}|^2 |\mathcal{M}_{BSM,d}|^2 + |\mathcal{M}_{BSM,p}|^2 |\mathcal{M}_{SM,d}|^2) + \\ & + k_{BSM}^3 k_{SM} \Big[|\mathcal{M}_{BSM,p}|^2 \Re(|\mathcal{M}_{SM,d}|^* |\mathcal{M}_{BSM,d}|) + \\ & + \Re(|\mathcal{M}_{SM,p}|^* |\mathcal{M}_{BSM,p}|) |\mathcal{M}_{BSM,d}|^2 \Big]\end{aligned}$$

I considered as Interference all the terms that are highlighted in red:

$$\boxed{\begin{aligned}\text{Interference} = & \; |\mathcal{M}(k_{SM}, k_{BSM})|^2 - k_{SM}^4 |\mathcal{M}_{SM,p}|^2 |\mathcal{M}_{SM,d}|^2 - k_{BSM}^4 |\mathcal{M}_{BSM,p}|^2 |\mathcal{M}_{BSM,d}|^2 - \\ & - k_{SM}^2 k_{BSM}^2 (|\mathcal{M}_{SM,p}|^2 |\mathcal{M}_{BSM,d}|^2 + |\mathcal{M}_{BSM,p}|^2 |\mathcal{M}_{SM,d}|^2)\end{aligned}}$$

$\mathcal{M}_{BSM}$ can be $\mathcal{M}_{kHVV}$ or $\mathcal{M}_{kAVV}$ $\rightarrow$ define four optimal observables: OO_1^H, OO_2^H, OO_1^A, OO_2^A.

$\mathcal{M}_{SM}$

- $\Lambda = 10^3$ GeV;
- $k_{SM} = 1$;
- all BSM couplings $k_{BSM} = 0$;

$\mathcal{M}_{kHVV}$

- $\Lambda = 10^3$ GeV;
- $k_{SM} = 0$;
- $k_{HVV} = 10$;
- all other BSM couplings $k_{BSM} = 0$;

$\mathcal{M}_{kAVV}$

- $\Lambda = 10^3$ GeV;
- $k_{SM} = 0$;
- $k_{AVV} = 15$;
- all other BSM couplings $k_{BSM} = 0$;

Each matrix element should be created for both VBF and VH mechanisms.

VBF

MadGraph [2] NLO process

```
p p → j j x0,
x0 → z z → e+ e- mu+ mu-
```

- 6 particles in the final state: 2 jets and 4 leptons
- $jetP_T > 30$ GeV

VH

MadGraph NLO process

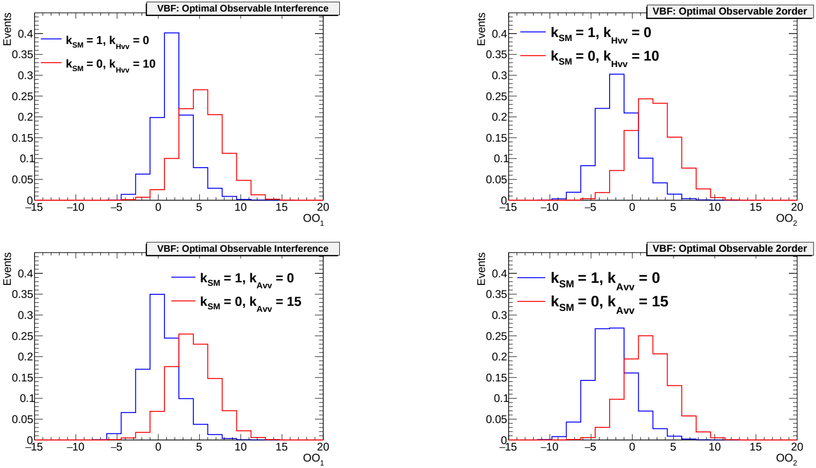
```
p p → v x0,
v → j j,
x0 → z z → e+ e- mu+ mu-
```

- 6 particles in the final state: 2 jets and 4 leptons
- $jetP_T > 30$ GeV

OO distributions for the VBF-category

OO for the VH-category

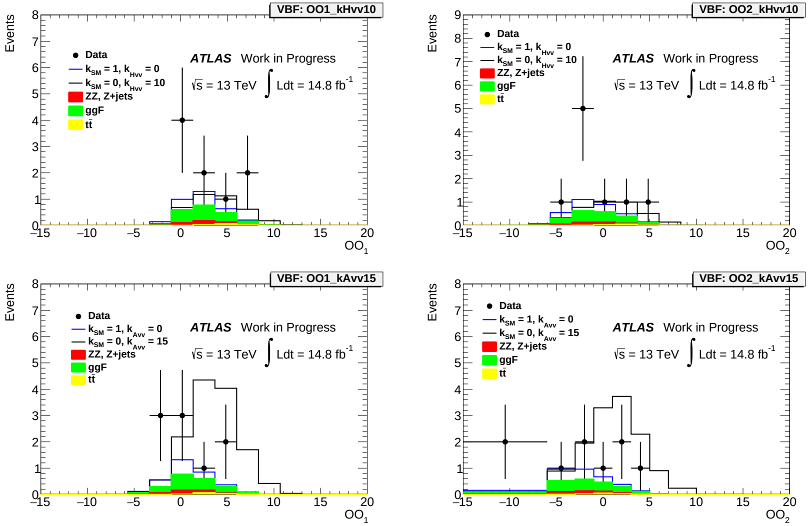
OO_1 OO_2



These distributions are made using full simulation samples. [1]

[1] Backup slides for those made using MadGraph samples.

OO distributions for the VBF-category with 14.8 fb^{-1} of data



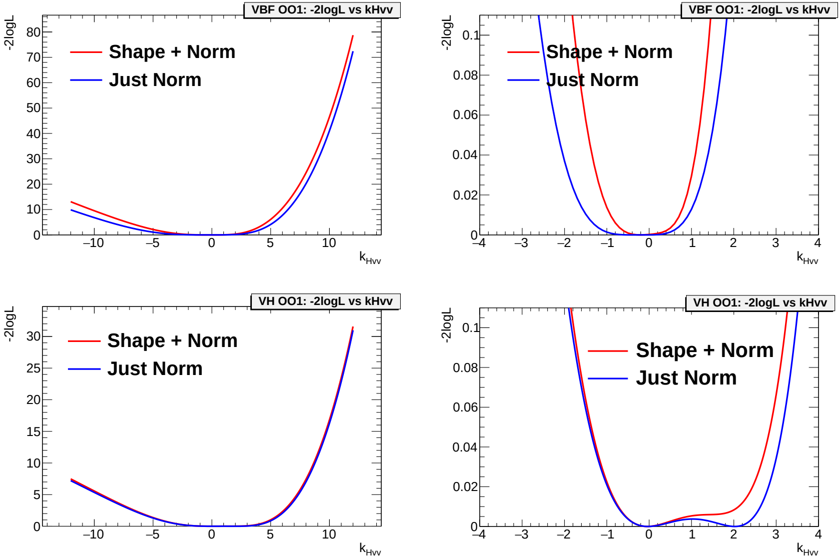
Estimation of expected OO sensistivity

- Use the binned OO distributions
- calculate the Poisson probability to obtain the number of events relative to a certain BSM coupling k_{test}, $n_i^{injected}(k_{test})$, if one expects a number $n_i^{expected}(k_{BSM})$
- $k_{SM} = 1$ in the fit
- ggF and backgrounds included but considered independent from the BSM coupling

$$L(k_{BSM}) = \prod_{i=1}^{N_{bin}} Poisson(n_i^{injected}(k_{test}), n_i^{expected}(k_{BSM}))$$

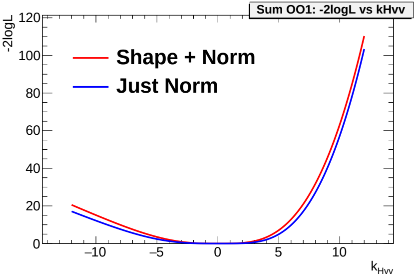
- $n_i^{expected}(k_{BSM})$, obtained using the morphing technique [4]
- $n_i^{injected}(k_{test})$, yield of the i^{th} bin of the injected histogram relative to k_{test};
- N_{bin}, total number of bins of the histograms.

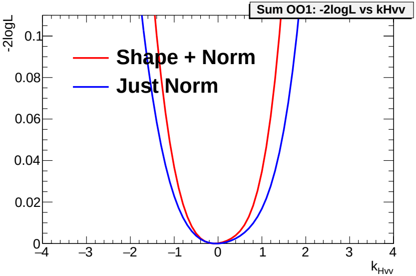
Fit to $k_{Hvv} = 0$ using OO_1^H $(L = 14.8\ fb^{-1})$



Fit to $k_{Hvv} = 0$ using OO_1^H $(L = 14.8\ fb^{-1})$

Fits using MadGraph samples

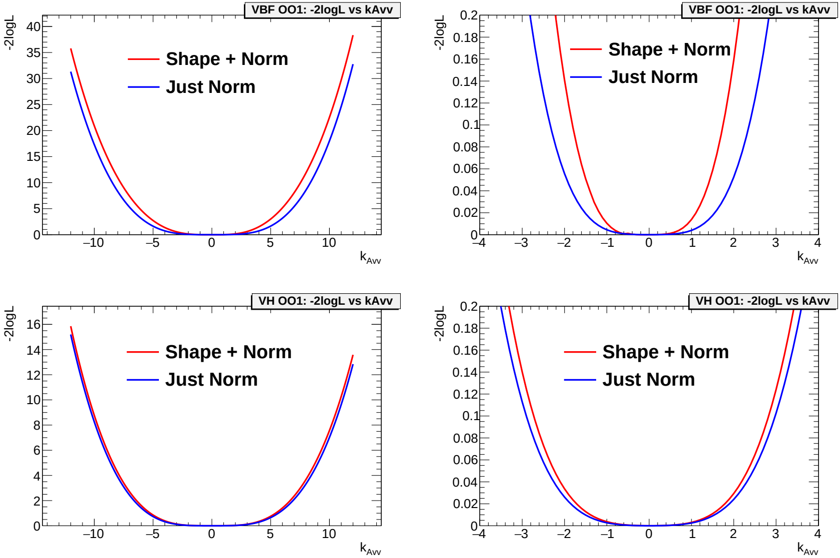




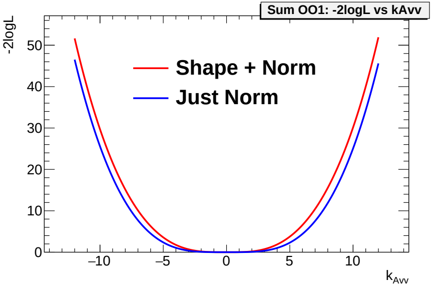
Optimal observables		**Cross section alone**	
Observable	k_{HVV}	Observable	k_{HVV}
OO_1^H	[-5.2, 4.1]	OO_1^H (single bin)	[-6.1, 4.7]

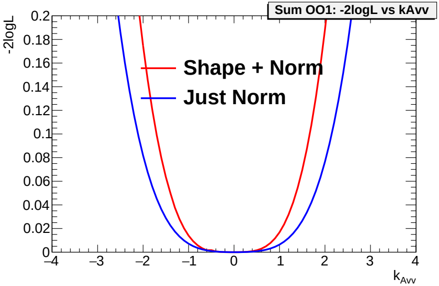
Table: Expected 95% confidence intervals on k_{HVV} for OO_1^H and for the sum between the VBF and VH loglikelihoods.

Fit to $k_{Avv} = 0$ using OO_1^A $(L = 14.8\ fb^{-1})$



Fit to $k_{AVV} = 0$ using OO_1^A $(L = 14.8\ fb^{-1})$



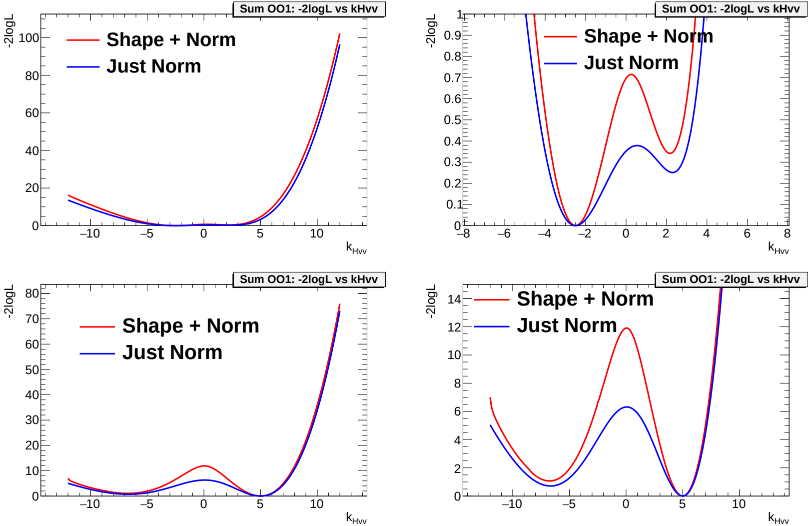


Optimal observables		**Cross section alone**	
Observable	k_{AVV}	Observable	k_{AVV}
OO_1^A	[-5.1, 5.0]	OO_1^A (single bin)	[-5.8, 5.8]

Table: Expected 95% confidence intervals on k_{AVV} for OO_1^A and for the sum between the VBF and VH loglikelihoods.

Fit to $k_{HVV} = -2.5$ and $k_{HVV} = 5$ using OO_1^H $(L = 14.8\ fb^{-1})$

Other fit closure tests



Outline

Conclusions and plans

Conclusions:

- The use of matrix element based observables enables to increase the sensitivity to the BSM couplings with respect to the one obtained using the cross section alone;
- with higher statistics, order of 100 fb^{-1}, it will be possible to further improve the expected 95% confidence levels on the BSM couplings [2].

Plans:

- addition of the 1jet category;
- exploit the OO to do a fit without fixing $k_{SM} = 1$ and discriminate between k_{HVV} and k_{AVV};

[2] The performances of this analysis on a dataset of 300 fb^{-1} can be found in the backup slides.

Bibliografy

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Dave Charleton, Alun Llyod, *"Measurement of Triple Gauge Coupling Parameters with Optimal Observables for* $W^+W^- \to l^+\nu l^-\bar{\nu}$ *Events at* $\sqrt{s} = 189$ *GeV"*, arXiv:hep-ph/0209229v1.

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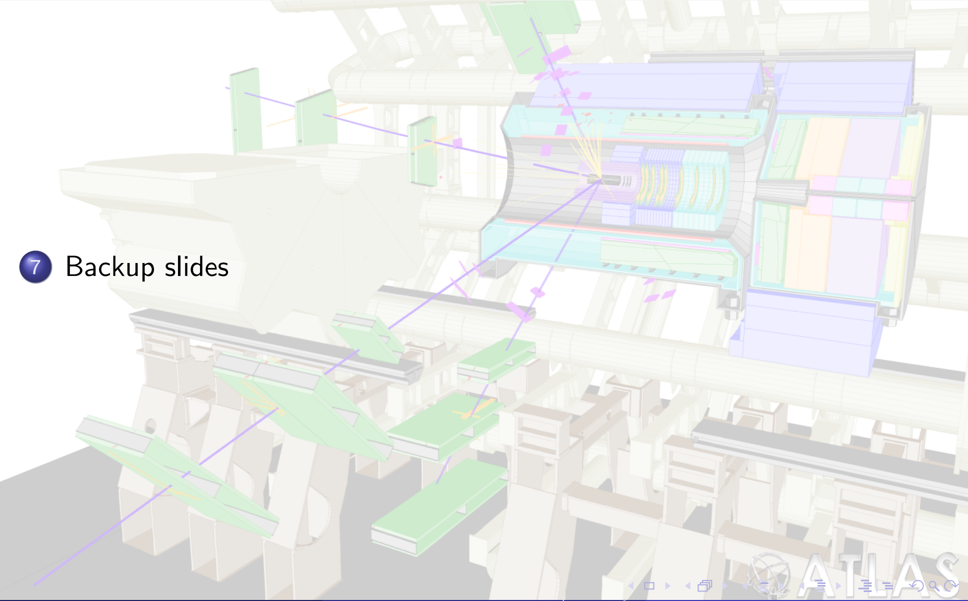
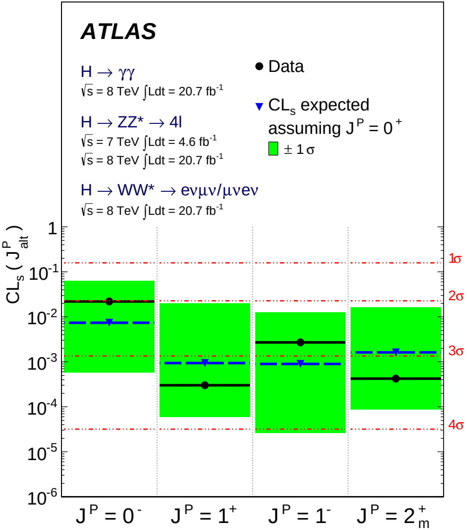
Outline



7 Backup slides

Evidence for the spin-0 nature of the Higgs boson



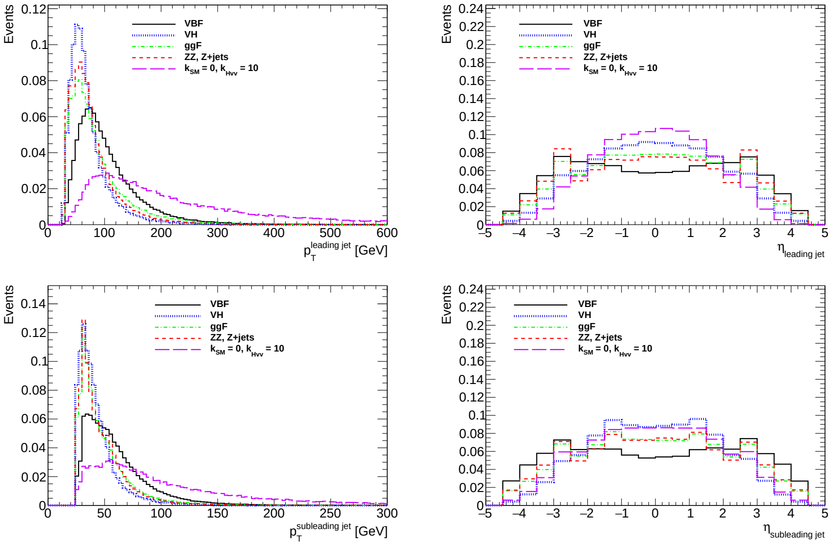
Event selection criteria

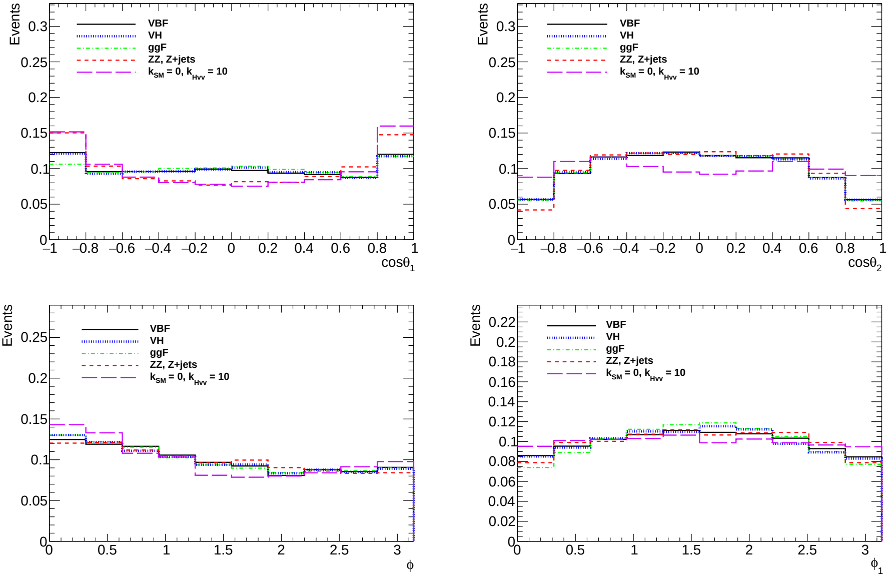
$H \rightarrow ZZ^* \rightarrow 4l$

p_T, E_T and η cuts
Electrons: $E_T > 7$ GeV, $\lvert\eta\rvert < 2.47$ Combined, standalone and segment-tagged muons: $p_T > 5$ GeV Calo-tagged muons: $p_T > 15$ GeV, $\lvert\eta\rvert < 0.1$ Jets: $p_T > 30$ GeV
Leptons in the quadruplets
First lepton: $p_T > 20$ GeV Second lepton: $p_T > 15$ GeV Third lepton: $p_T > 10$ GeV Maximum one calo-tagged or standalone muon per quadruplet *Leading dilepton mass*: $50 < m_{12} < 106$ GeV *Sub-leading dilepton mass*: $12 < m_{34} < 115$ GeV
Isolation
Electron track isolation ($\Delta R \leq 0.20$): $\sum E_T/E_T < 0.15$ Electron calorimetric isolation ($\Delta R \leq 0.20$): $\sum E_T/E_T < 0.20$ Muon track isolation ($\Delta R \leq 0.30$): $\sum p_T/p_T < 0.15$ Muon calorimetric isolation ($\Delta R \leq 0.20$): $\sum E_T/p_T < 0.30$
Impact parameter significance
Electrons: $\lvert d_0/\sigma_{d_0}\rvert < 5$ Muons: $\lvert d_0/\sigma_{d_0}\rvert < 3$ Leptons: $\lvert(z_0 - z_{pv})sin\theta\rvert < 0.5$ mm

Leptons and jets discriminating variables

Experimental categories




Events
VBF
VH
ggF
ZZ, Z+jets
$k_{SM} = 0, k_{Hvv} = 10$
$\cos\theta_1$
$\cos\theta_2$
ϕ
ϕ_1

Definition of interference between SM and BSM matrix elements

OO definition

One non-SM coupling in the production or decay vertex

$$\mathcal{M}(k_{SM}, k_{BSM}) = k_{SM}\mathcal{M}_{SM} + k_{BSM}\mathcal{M}_{BSM}$$

Squaring this expression, one obtains:

$$|\mathcal{M}(k_{SM}, k_{BSM})|^2 = k_{SM}^2|\mathcal{M}_{SM}|^2 + k_{BSM}^2|\mathcal{M}_{BSM}|^2 + 2k_{SM}k_{BSM}\Re(\mathcal{M}_{SM}^*\mathcal{M}_{BSM})$$

Therefore, the interference in the case of the ggF production mode is given by:

$$\boxed{\begin{aligned}\text{Interference} &= 2\Re(\mathcal{M}_{SM}^*\mathcal{M}_{BSM}) = \\ &= \frac{1}{k_{SM}k_{BSM}}\left(|\mathcal{M}(k_{SM}, k_{BSM})|^2 - k_{SM}^2|\mathcal{M}_{SM}|^2 - k_{BSM}^2|\mathcal{M}_{BSM}|^2\right)\end{aligned}}$$

Definition of interference between SM and BSM matrix elements

OO definition

One non-SM coupling in both production and decay

$$\mathcal{M}(k_{SM}, k_{BSM}) = (k_{SM} \cdot \mathcal{M}_{SM,p} + k_{BSM} \cdot \mathcal{M}_{BSM,p}) \cdot (k_{SM} \cdot \mathcal{M}_{SM,d} + k_{BSM} \cdot \mathcal{M}_{BSM,d}).$$

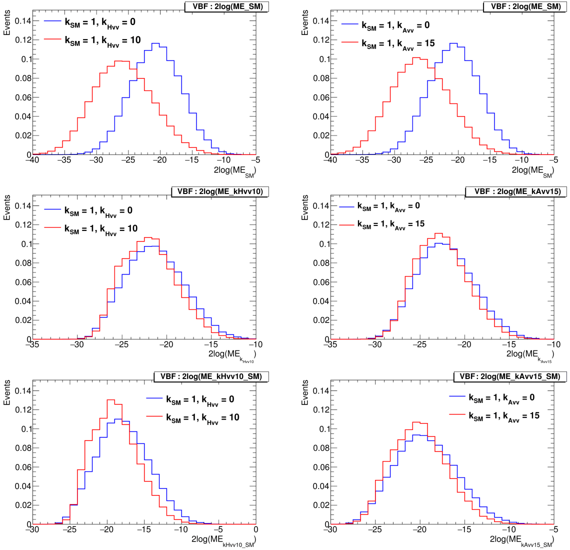
Squaring this expression, one obtains:

$$\begin{aligned}|\mathcal{M}(k_{SM}, k_{BSM})|^2 = {} & k_{SM}^4 |\mathcal{M}_{SM,p}|^2 |\mathcal{M}_{SM,d}|^2 + k_{BSM}^4 |\mathcal{M}_{BSM,p}|^2 |\mathcal{M}_{BSM,d}|^2 + \\ & + k_{SM}^3 k_{BSM} \Big[|\mathcal{M}_{SM,p}|^2 \Re(|\mathcal{M}_{SM,d}|^* |\mathcal{M}_{BSM,d}|) + \\ & + \Re(|\mathcal{M}_{SM,p}|^* |\mathcal{M}_{BSM,p}|) |\mathcal{M}_{SM,d}|^2 \Big] + \\ & + k_{SM}^2 k_{BSM}^2 (|\mathcal{M}_{SM,p}|^2 |\mathcal{M}_{BSM,d}|^2 + |\mathcal{M}_{BSM,p}|^2 |\mathcal{M}_{SM,d}|^2) + \\ & + k_{BSM}^3 k_{SM} \Big[|\mathcal{M}_{BSM,p}|^2 \Re(|\mathcal{M}_{SM,d}|^* |\mathcal{M}_{BSM,d}|) + \\ & + \Re(|\mathcal{M}_{SM,p}|^* |\mathcal{M}_{BSM,p}|) |\mathcal{M}_{BSM,d}|^2 \Big]\end{aligned}$$

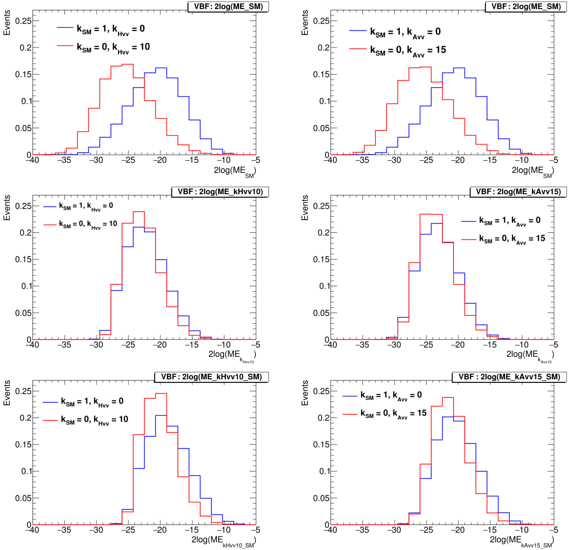
One can call Interference all the terms that are highlighted in red:

$$\boxed{\begin{aligned}\text{Interference} = {} & |\mathcal{M}(k_{SM}, k_{BSM})|^2 - k_{SM}^4 |\mathcal{M}_{SM,p}|^2 |\mathcal{M}_{SM,d}|^2 - k_{BSM}^4 |\mathcal{M}_{BSM,p}|^2 |\mathcal{M}_{BSM,d}|^2 - \\ & - k_{SM}^2 k_{BSM}^2 (|\mathcal{M}_{SM,p}|^2 |\mathcal{M}_{BSM,d}|^2 + |\mathcal{M}_{BSM,p}|^2 |\mathcal{M}_{SM,d}|^2)\end{aligned}}$$

ME distributions on VBF MadGraph samples



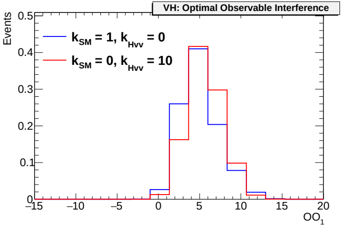
ME distributions using events of the VBF-category

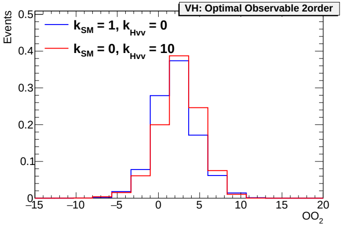


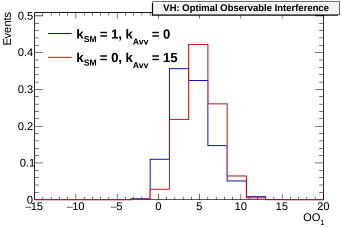
OO distributions for the VH-category

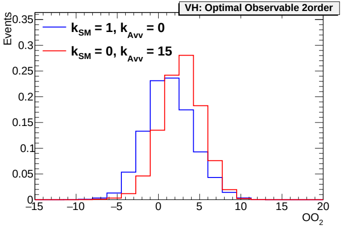
OO for the VBF-category

OO_1 OO_2





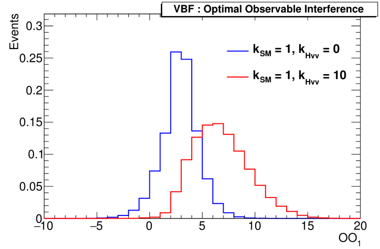


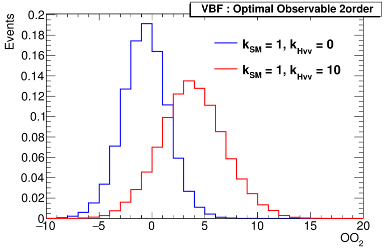


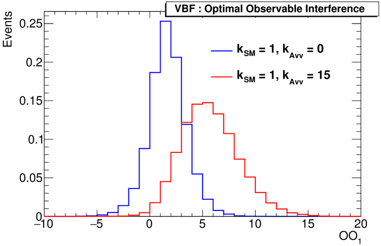
These distributions are made using full simulation samples.

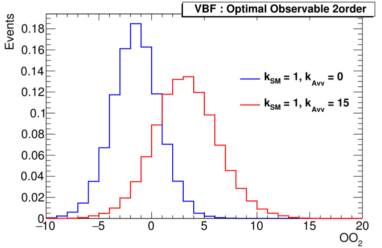
VBF OO distributions using MadGraph samples

OO_1 | OO_2









Implementation of the morphing technique

The morphing method can be introduce to describe the dependence of a given observable T on an arbitrary set of non-SM Higgs boson couplings $\vec{k}_{target} = k_{SM}, k_{BSM,1}, ..., k_{BSM,n}$ to known particles. This dependence is describes by a morphing function:

$$T_{out}(\vec{k}_{target}) = \sum_i w_i(\vec{k}_{target}; \vec{k}_i)\, T_{in}(\vec{k}_i),$$

where T_{in} are values or differential distributions obtained from Monte Carlo simulation of the signal for a given coupling configuration $\vec{k}_i$.

T_{in} are normalised to their expected cross sections such that the physical observable T_{out} includes both the correct shape and the correct cross section prediction.

Morphing with one non-SM coupling parameter in the production or decay vertex

Morphing method

The simpler case is that of the ggF process in which the k_{BSM} coupling with W and Z enters only in decay.
As $T(k_{SM}, k_{BSM}) \propto |\mathcal{M}(k_{SM}, k_{BSM})|^2$, one can write the input distributions for arbitrary input parameters $\vec{k}_i$:

$$T_{in}(k_{SM,i}, k_{BSM,i}) = k_{SM,i}^2 \cdot \mathcal{M}_{SM}^2 + k_{BSM,i}^2 \cdot \mathcal{M}_{BSM}^2 + 2k_{SM,i}k_{BSM,i} \cdot \Re(\mathcal{M}_{SM}^* \mathcal{M}_{BSM})$$

where $i = 1, 2, 3$.

$$\begin{aligned} T_{out}(k_{SM}, k_{BSM}) &= (a_{11}k_{SM}^2 + a_{12}k_{BSM}^2 + a_{13}k_{SM}k_{BSM}) T_{in}(k_{SM,1}, k_{BSM,1}) \ + \\ &= + \ (a_{21}k_{SM}^2 + a_{22}k_{BSM}^2 + a_{23}k_{SM}k_{BSM}) T_{in}(k_{SM,2}, k_{BSM,2}) \ + \\ &= + \ (a_{31}k_{SM}^2 + a_{32}k_{BSM}^2 + a_{33}k_{SM}k_{BSM}) T_{in}(k_{SM,3}, k_{BSM,3}) \end{aligned}$$

Morphing with one non-SM coupling parameter in the production or decay vertex

Morphing method

To find the unknown variables a_{ij} one can observe that if:

$$\vec{k}_{target} = \vec{k}_i \qquad \Rightarrow \qquad T_{out} = T_{in}$$

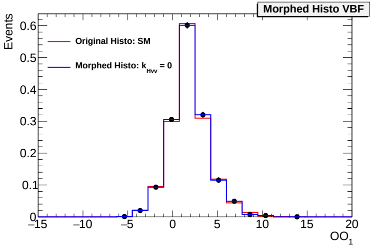
This suggests that a_{ij} coefficients can be found by solving the following condition:

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot \begin{pmatrix} k^2_{SM,1} & k^2_{SM,2} & k^2_{SM,3} \\ k^2_{BSM,1} & k^2_{BSM,2} & k^2_{BSM,3} \\ k_{SM,1}k_{BSM,1} & k_{SM,1}k_{BSM,1} & k_{SM,1}k_{BSM,1} \end{pmatrix} = \mathbb{I}$$

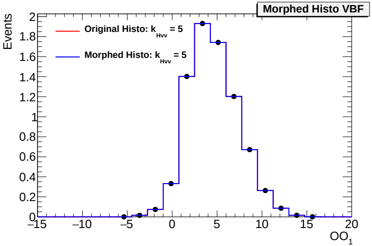
This procedure should be repeated also for the VBF process for which the number of T_{in} input distributions will be 5.

Morphing validation: VBF-category

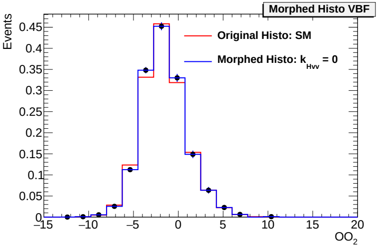
Not base



Base

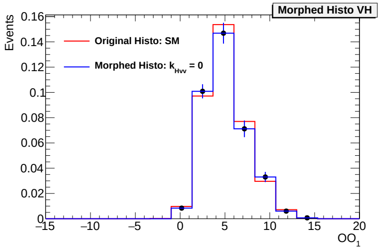


Not base

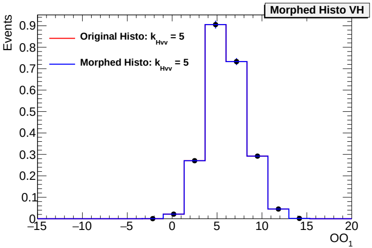


Morphing validation: VH-category

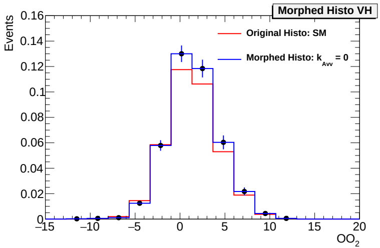
Not base



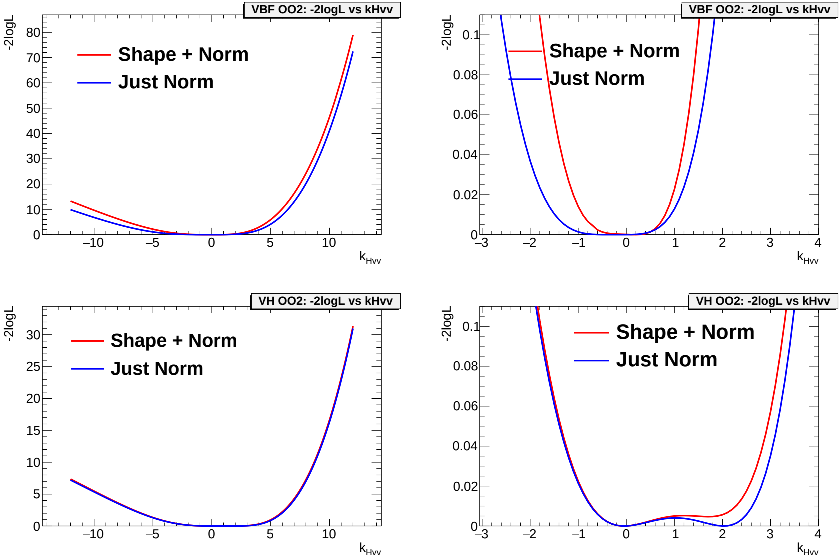
Base



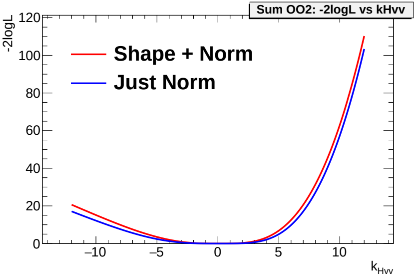
Not base

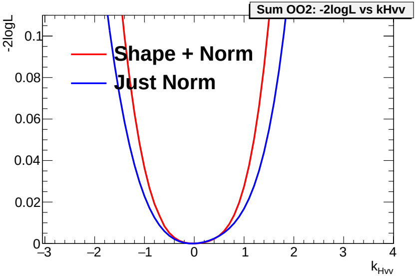


Fit to $k_{Hvv} = 0$ using OO_2^H $(L = 14.8\ fb^{-1})$



Fit to $k_{Hvv} = 0$ using OO_2^H ($L = 14.8\ fb^{-1}$)

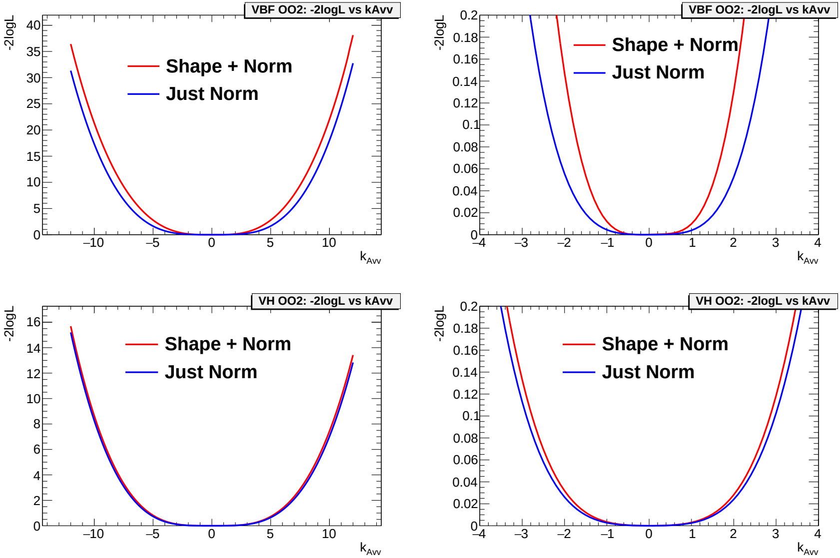




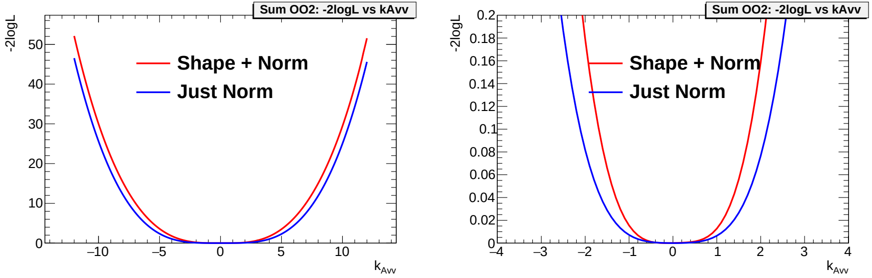
Optimal observables		Cross section alone	
Observable	k_{HVV}	Observable	k_{HVV}
OO_2^H	[-5.2, 4.2]	OO_2^H (single bin)	[-6.1, 4.7]

Table: Expected 95% confidence intervals on k_{HVV} for OO_2^H and for the sum between the VBF and VH loglikelihoods.

Fit to $k_{Avv} = 0$ using OO_2^A $(L = 14.8\ fb^{-1})$

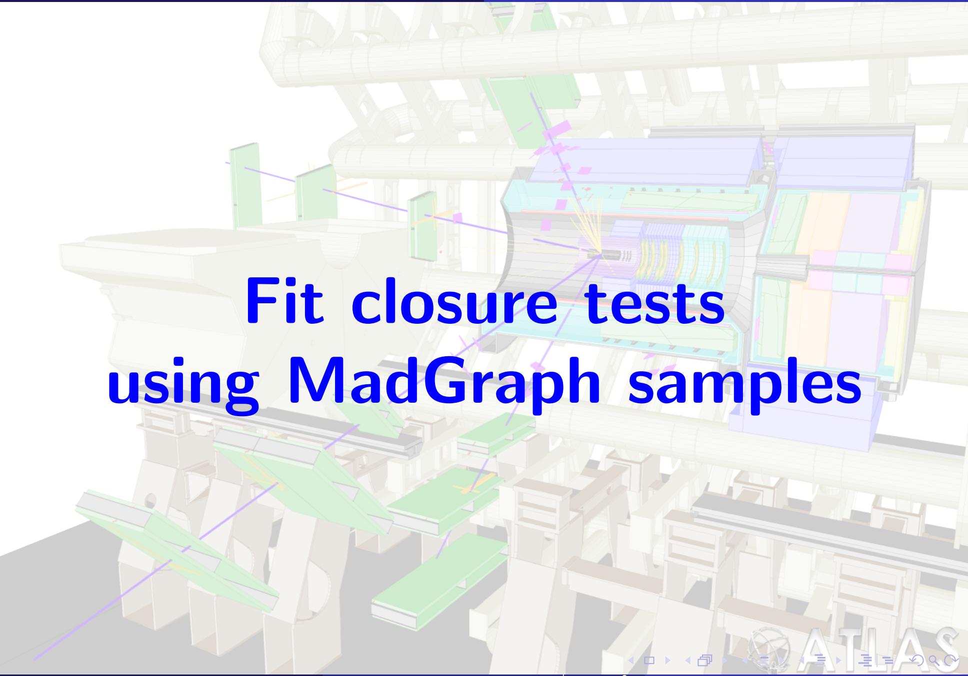


Fit to $k_{Avv} = 0$ using OO_2^A $(L = 14.8\ fb^{-1})$



Optimal observables		**Cross section alone**	
Observable	k_{AVV}	Observable	k_{AVV}
OO_2^A	[-5.1, 5.1]	OO_2^A (single bin)	[-5.8, 5.8]

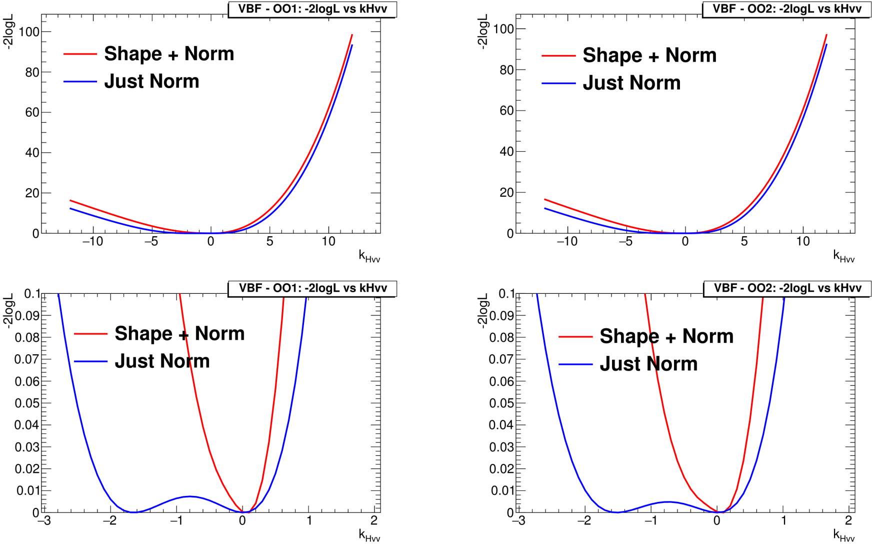
Table: Expected 95% confidence intervals on k_{AVV} for OO_2^A and for the sum between the VBF and VH loglikelihoods.



Fit closure tests using MadGraph samples

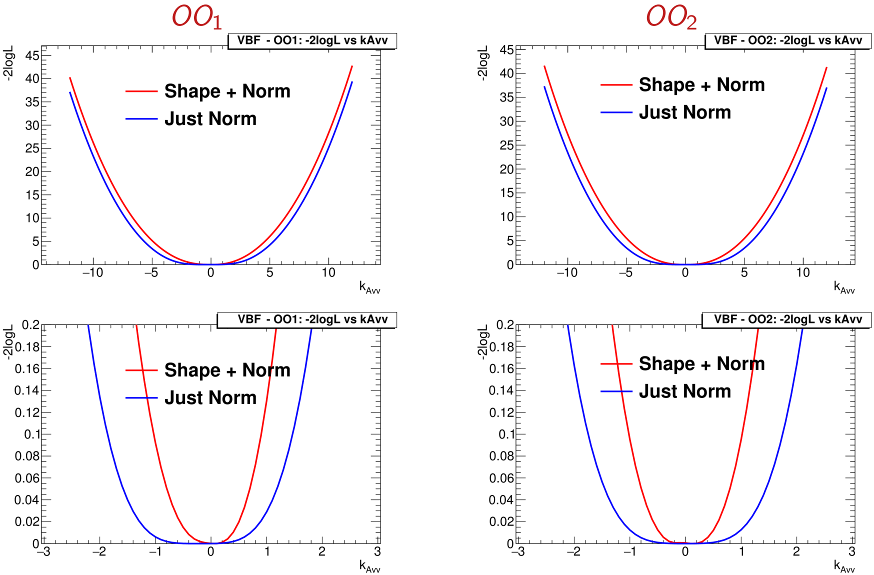
Fit to $k_{Hvv} = 0$ on a VBF sample $(L = 14.8\ fb^{-1})$

OO_1 OO_2



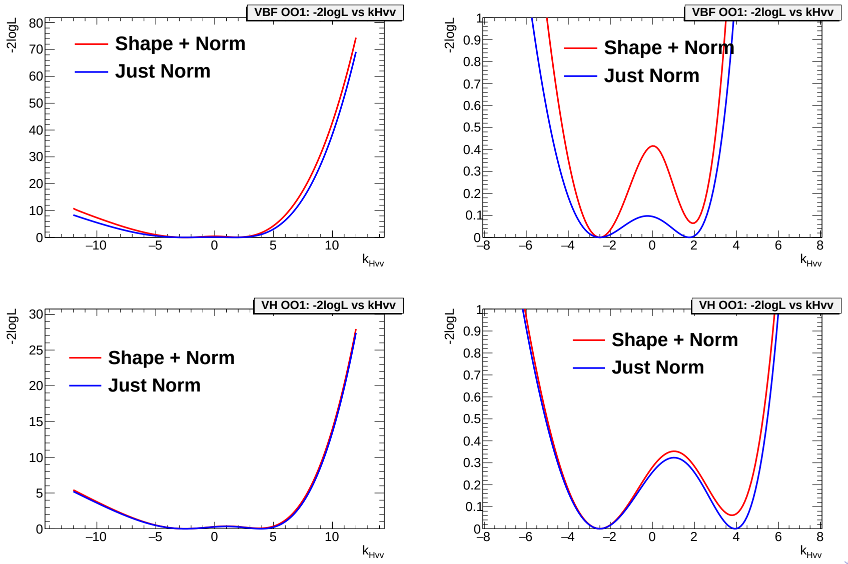
Fit to $k_{Avv} = 0$ on a VBF sample $(L = 14.8\ fb^{-1})$

Fits on full sim samples

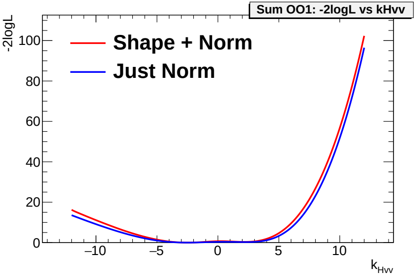


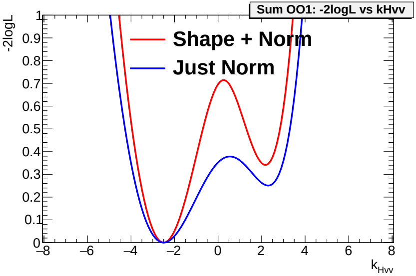
Other fit closure tests using full simulation samples

Fit to $k_{Hvv} = -2.5$ using OO_1^H $(L = 14.8\ fb^{-1})$

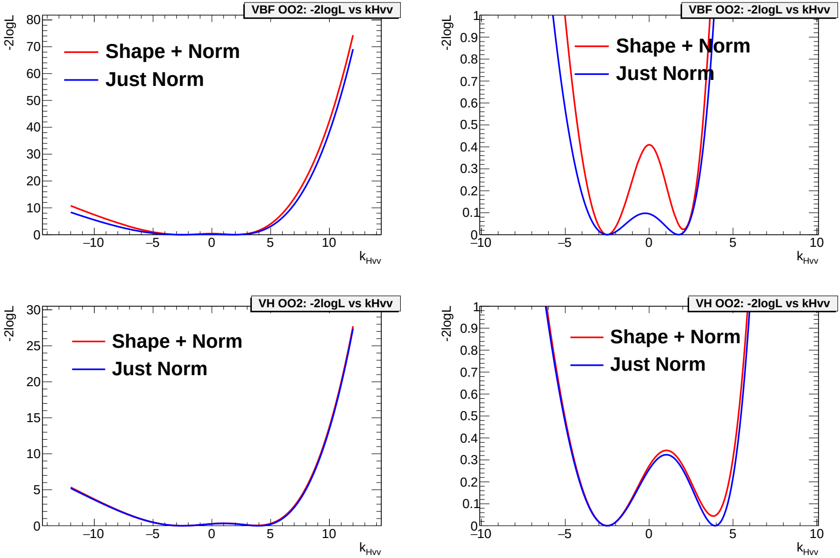


Fit to $k_{Hvv} = -2.5$ using OO_1^H $(L = 14.8\ fb^{-1})$

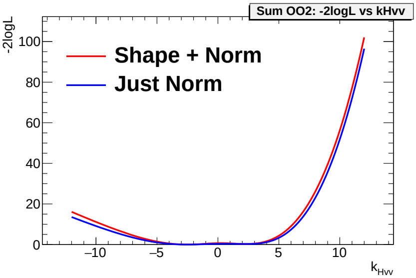


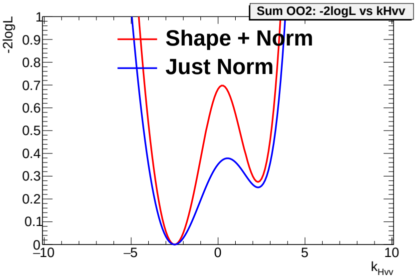


Fit to $k_{Hvv} = -2.5$ using OO_2^H $(L = 14.8\ fb^{-1})$

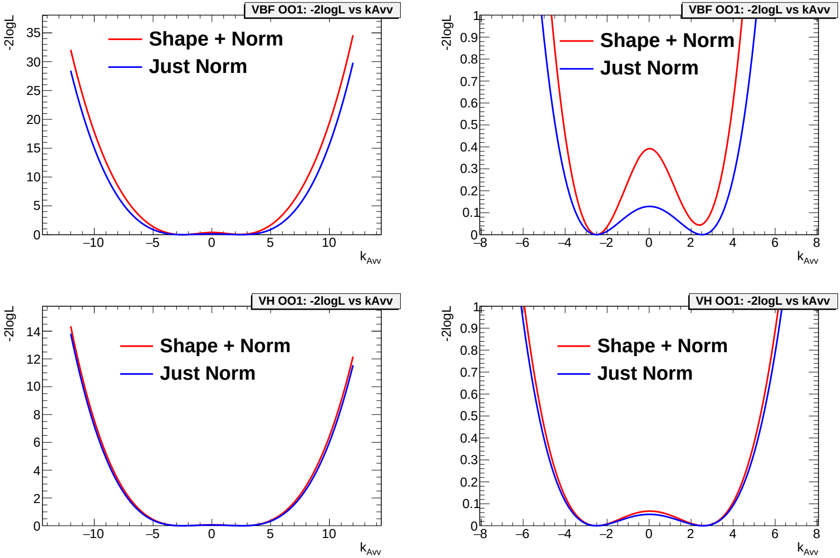


Fit to $k_{Hvv} = -2.5$ using OO_2^H $(L = 14.8\ fb^{-1})$

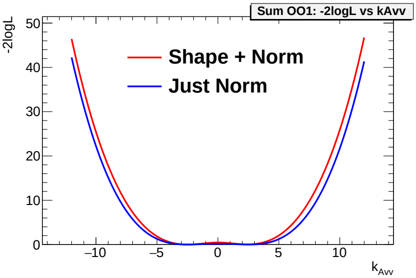


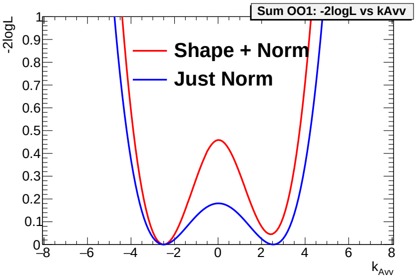


Fit to $k_{Avv} = -2.5$ using OO_1^A $(L = 14.8\ fb^{-1})$

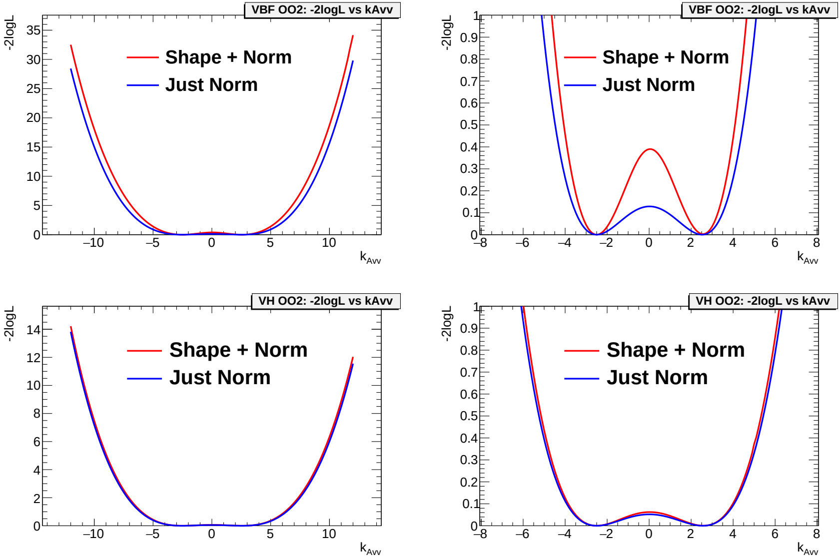


Fit to $k_{Avv} = -2.5$ using OO_1^A $(L = 14.8\ fb^{-1})$

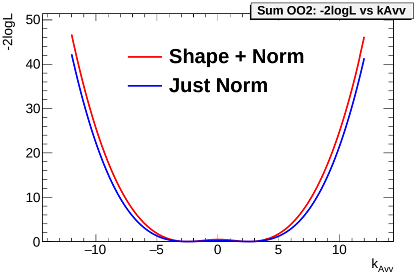


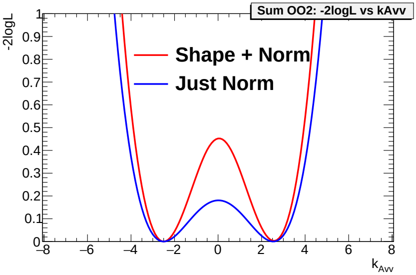


Fit to $k_{Avv} = -2.5$ using OO_2^A $(L = 14.8\ fb^{-1})$

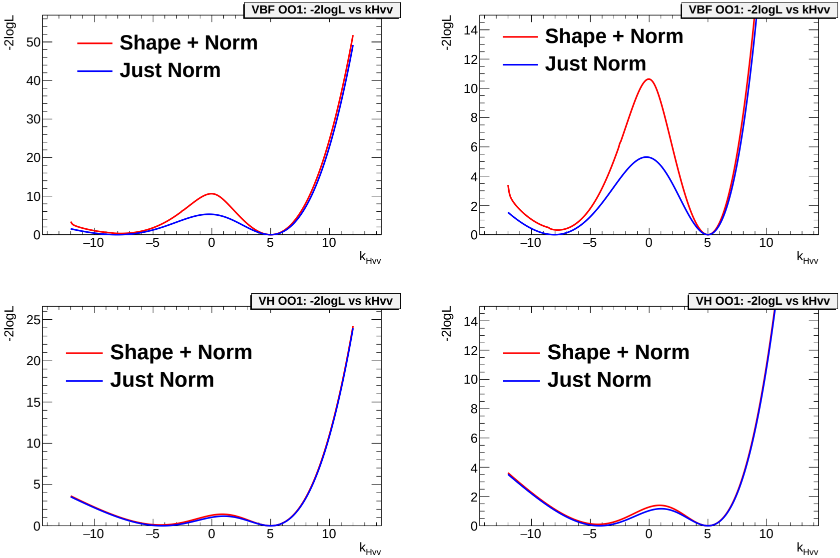


Fit to $k_{Avv} = -2.5$ using OO_2^A $(L = 14.8\ fb^{-1})$

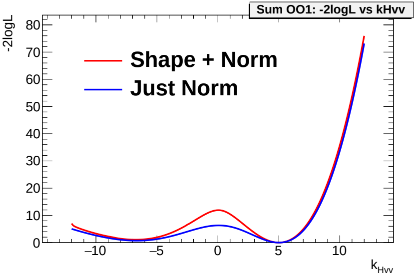


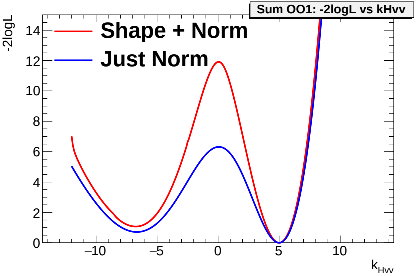


Fit to $k_{Hvv} = 5$ using OO_1^H $\quad (L = 14.8\ fb^{-1})$

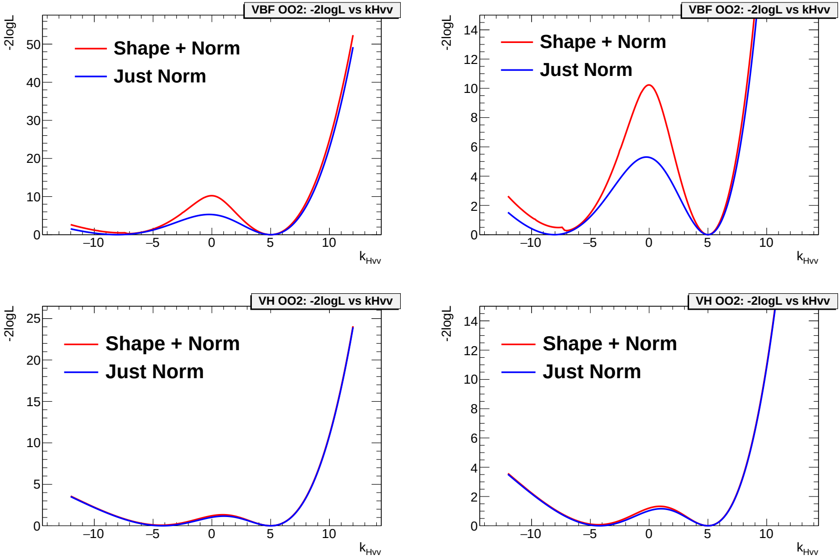


Fit to $k_{Hvv} = 5$ using OO_1^H $(L = 14.8\ fb^{-1})$

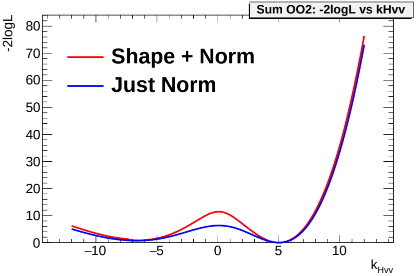


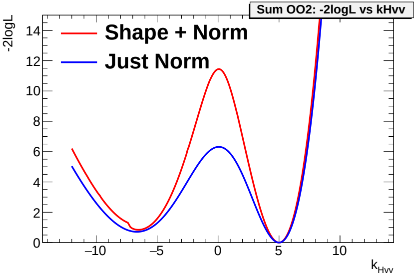


Fit to $k_{Hvv} = 5$ using OO_2^H $(L = 14.8\ fb^{-1})$

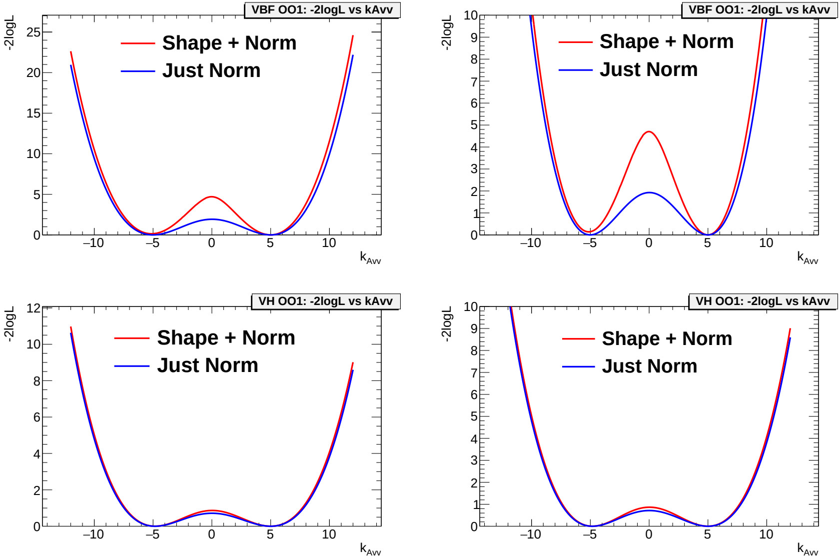


Fit to $k_{Hvv} = 5$ using OO_2^H $(L = 14.8\ fb^{-1})$

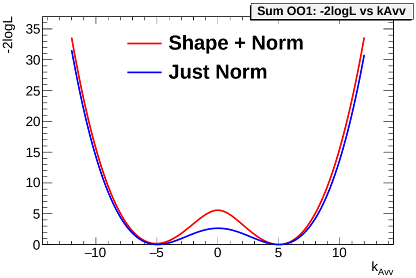


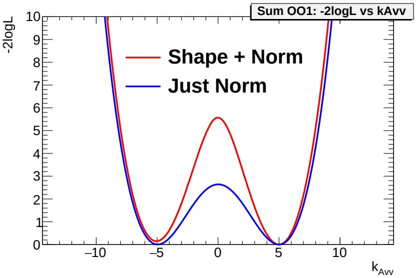


Fit to $k_{Avv} = 5$ using OO_1^A $(L = 14.8\ fb^{-1})$

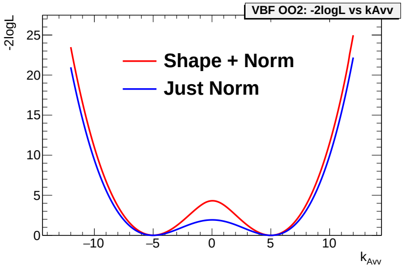


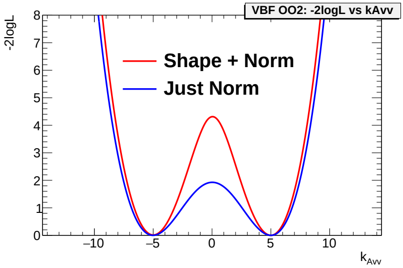
Fit to $k_{Avv} = 5$ using OO_1^A $(L = 14.8\ fb^{-1})$

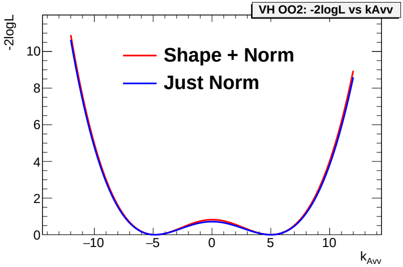


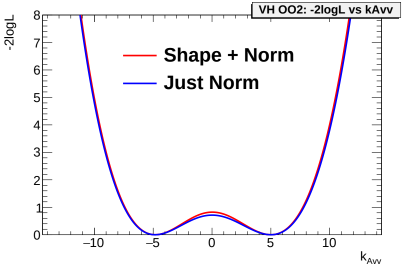


Fit to $k_{Avv} = 5$ using OO_2^A $(L = 14.8\ fb^{-1})$

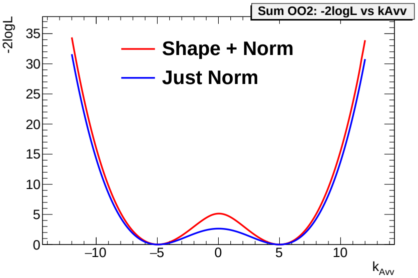


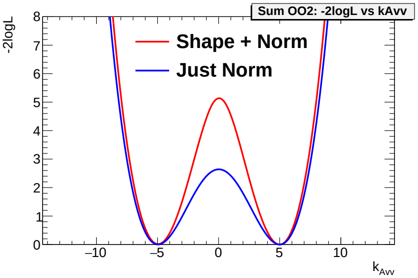


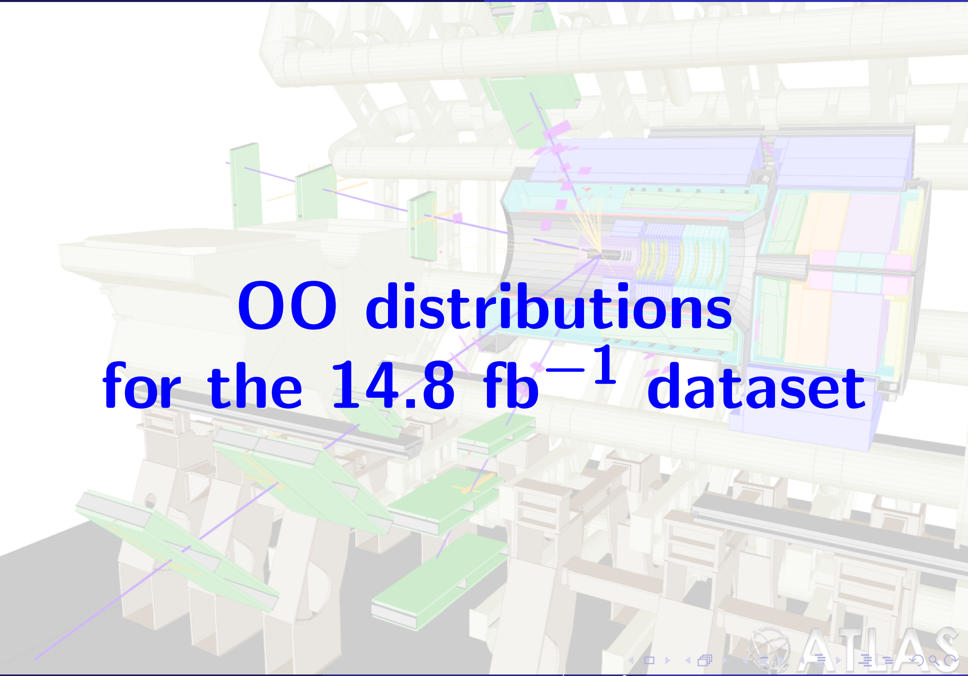




Fit to $k_{Avv} = 5$ using OO_2^A $(L = 14.8\ fb^{-1})$

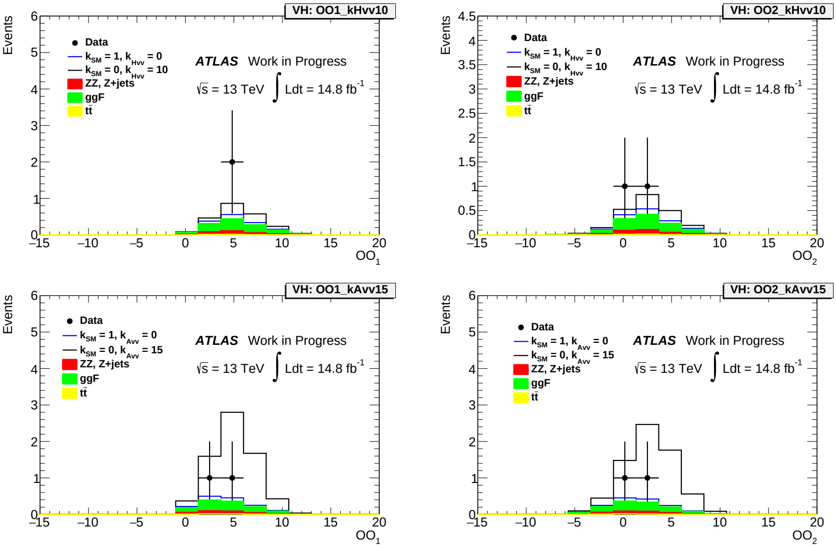


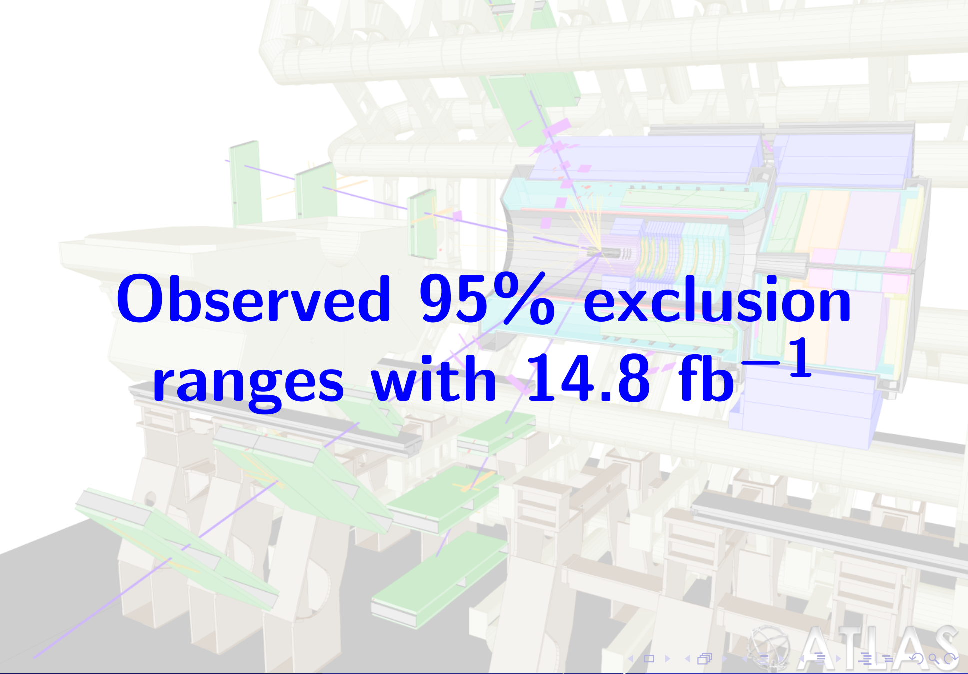




OO distributions for the 14.8 fb^{-1} dataset

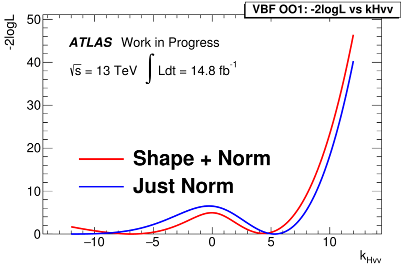
OO distributions for the VH-category

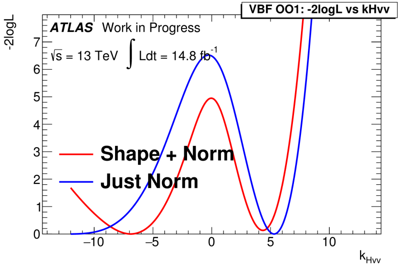


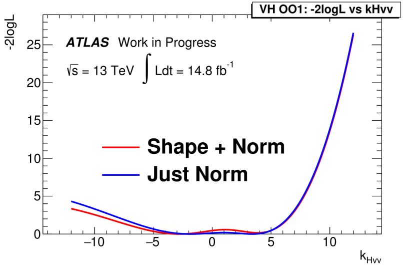


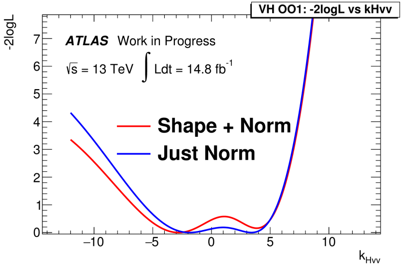
Observed 95% exclusion ranges with 14.8 fb^{-1}

Fit to $k_{Hvv} = 0$ using OO_1^H $(L = 14.8\ fb^{-1})$

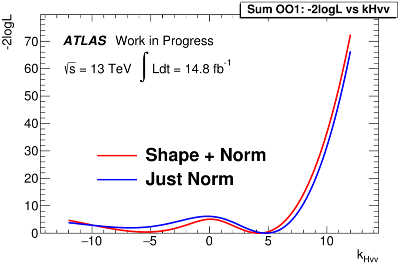


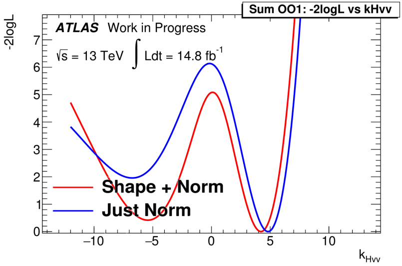






Fit to $k_{HVV} = 0$ using OO_1^H $(L = 14.8\ fb^{-1})$

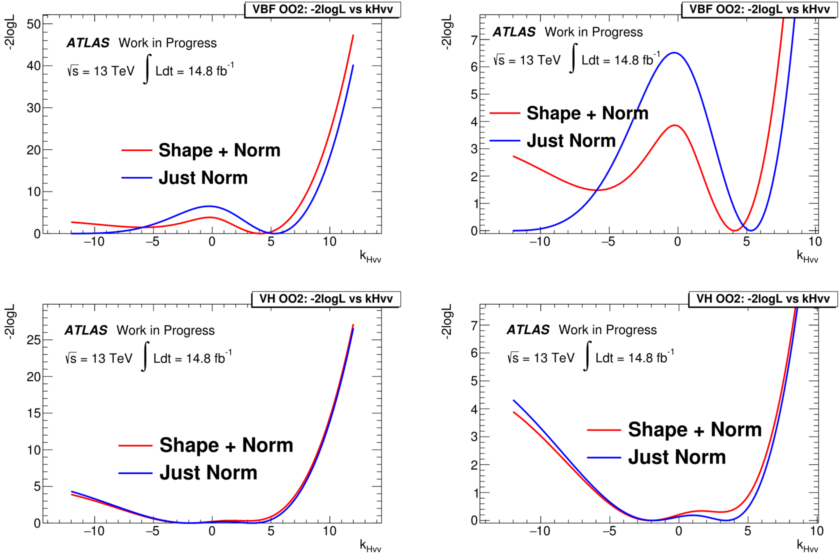




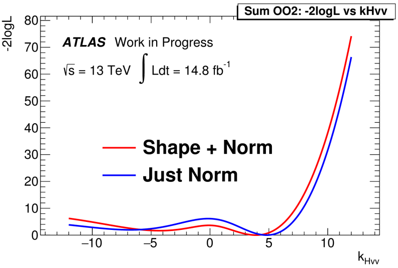
Optimal observables		Cross section alone	
Observable	k_{HVV}	Observable	k_{HVV}
OO_1^H	[-11, -1.3], [1.4, 6.3]	OO_1^H (single bin)	[-12, -3.1], [2.0, 6.8]

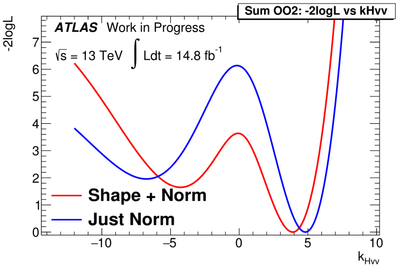
Table: Observed 95% confidence intervals on k_{HVV} for OO_1^H and for the sum between the VBF and VH loglikelihoods.

Fit to $k_{Hvv} = 0$ using OO_2^H $(L = 14.8\ fb^{-1})$



Fit to $k_{HVV} = 0$ using OO_2^H $(L = 14.8\ fb^{-1})$

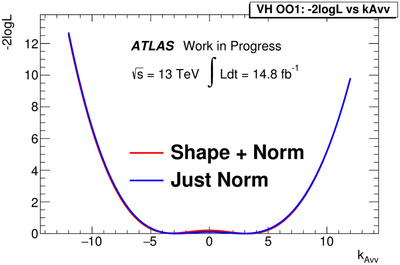


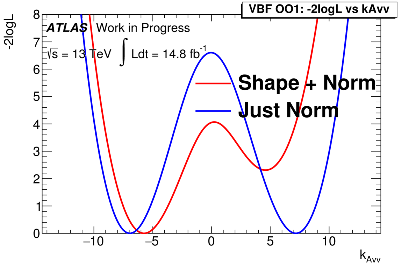


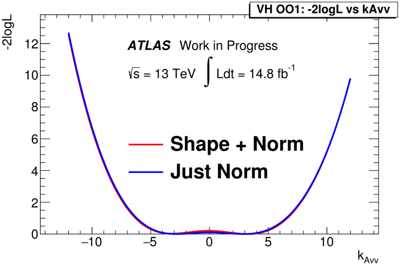
Optimal observables		Cross section alone	
Observable	k_{HVV}	Observable	k_{HVV}
OO_2^H	[-8.8, 6,1]	OO_2^H (single bin)	[-12, -3.1], [2.0, 6.8]

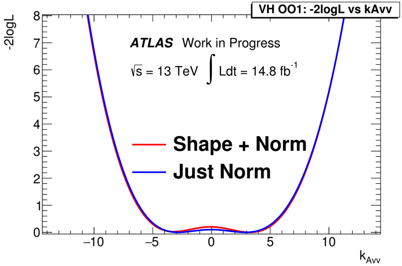
Table: Observed 95% confidence intervals on k_{HVV} for OO_2^H and for the sum between the VBF and VH loglikelihoods.

Fit to $k_{Avv} = 0$ using OO_1^A $(L = 14.8\ fb^{-1})$

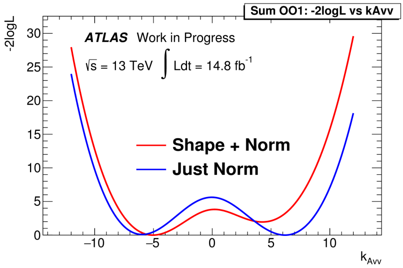


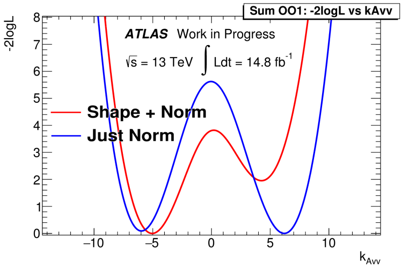






Fit to $k_{AVV} = 0$ using OO_1^A $(L = 14.8\ fb^{-1})$

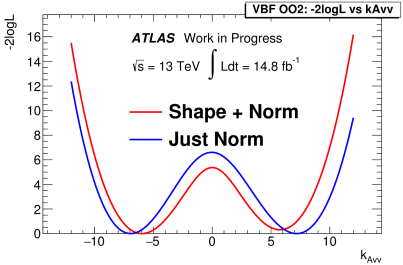


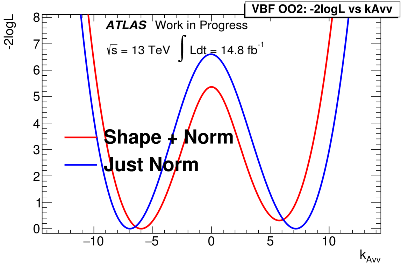


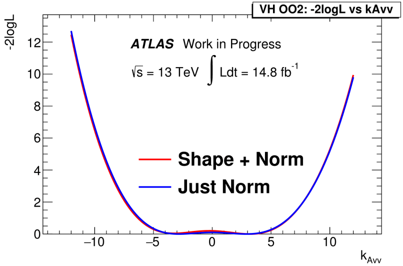
Optimal observables		Cross section alone	
Observable	k_{AVV}	Observable	k_{AVV}
OO_1^A	[-8.0 ,6.6]	OO_1^A (single bin)	[-8.6, -2.3], [2.2, 9.1]

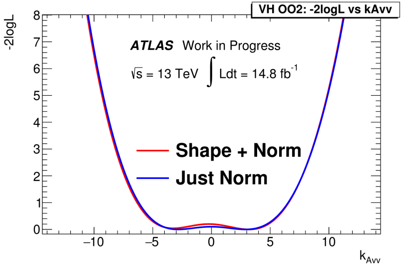
Table: Observed 95% confidence intervals on k_{AVV} for OO_1^A and for the sum between the VBF and VH loglikelihoods.

Fit to $k_{Avv} = 0$ using OO_2^A $(L = 14.8\ fb^{-1})$

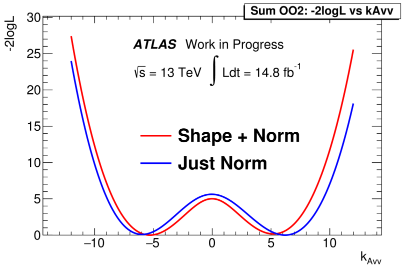


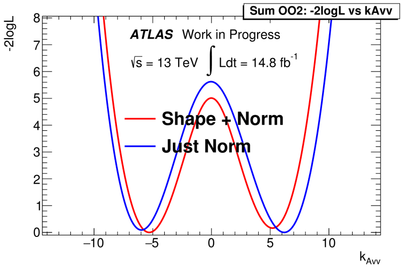






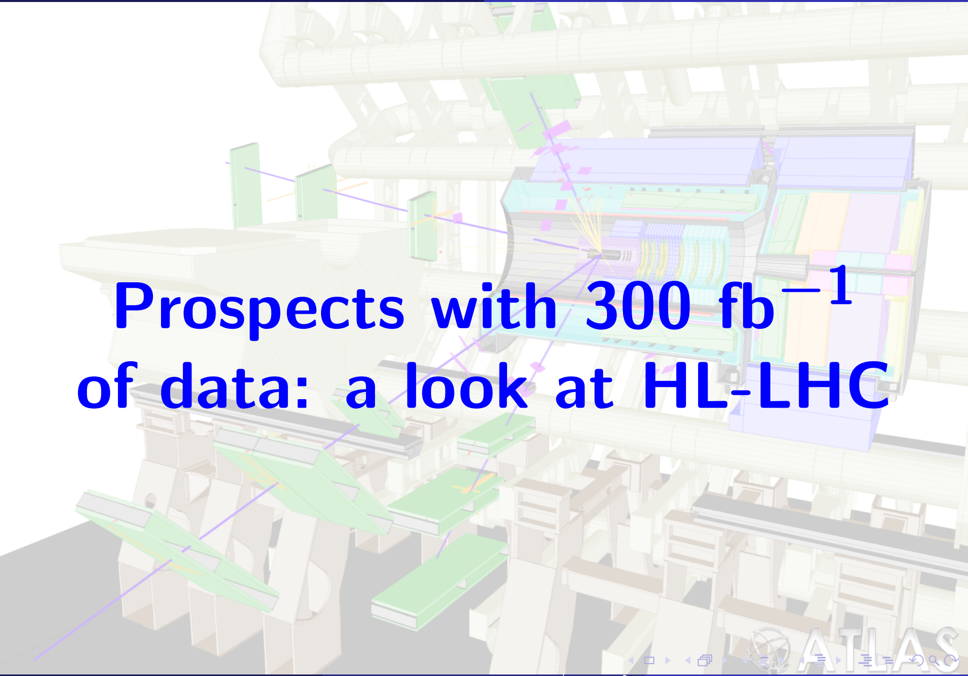
Fit to $k_{AVV} = 0$ using OO_2^A $(L = 14.8\ fb^{-1})$





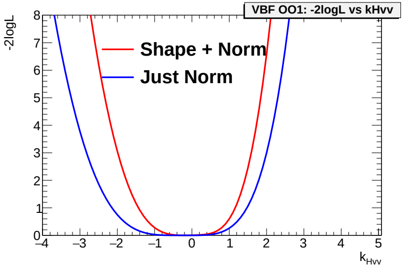
Optimal observables		Cross section alone	
Observable	k_{AVV}	Observable	k_{AVV}
OO_2^A	[-8.1, -1.5], [1.5, 8.1]	OO_2^A (single bin)	[-8.6, -2.3], [2.2, 9.1]

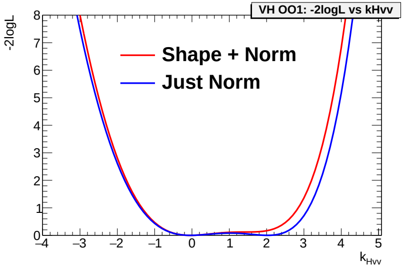
Table: Observed 95% confidence intervals on k_{AVV} for OO_2^A and for the sum between the VBF and VH loglikelihoods.

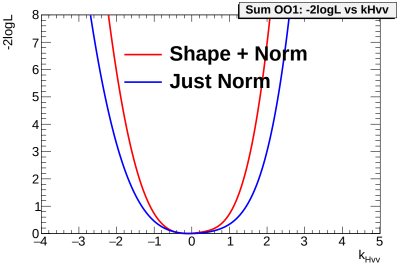


Prospects with 300 fb^{-1} of data: a look at HL-LHC

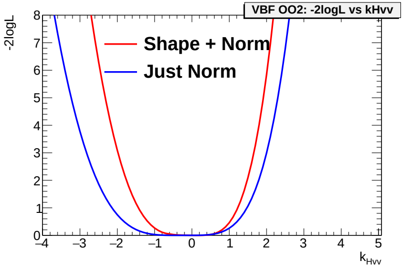
Fit to $k_{Hvv} = 0$ using OO_1^H $(L = 300\ fb^{-1})$

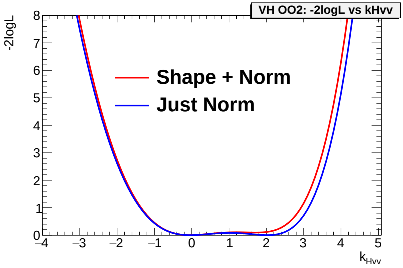


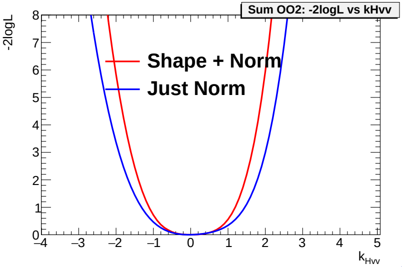




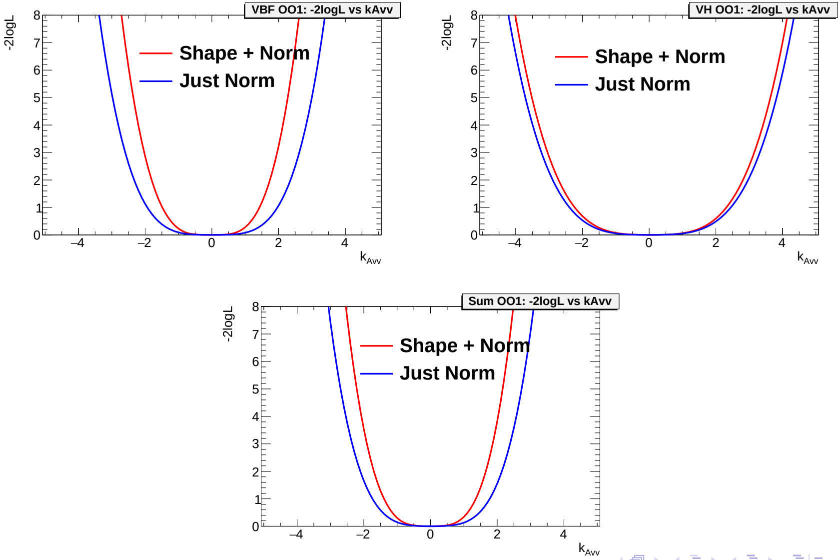
Fit to $k_{Hvv} = 0$ using OO_2^H $(L = 300\ fb^{-1})$



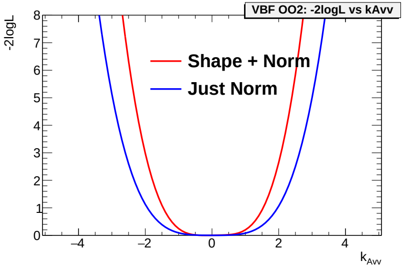


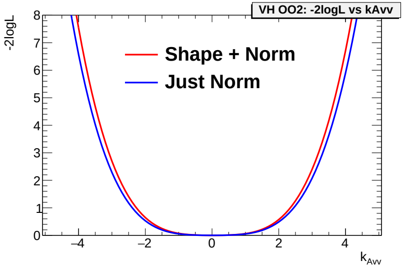


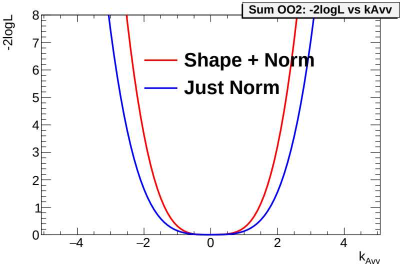
Fit to $k_{Avv} = 0$ using OO_1^A $(L = 300\ fb^{-1})$



Fit to $k_{Avv} = 0$ using OO_2^A $(L = 300\ fb^{-1})$







Results with 14.8 fb^{-1}

Table: Expected 95% confidence intervals on k_{HVV} and k_{AVV} for the sum between the VBF and VH loglikelihoods. These intervals have been obtained for $L_{int} = 300\ fb^{-1}$.

Optimal observables		
Observable	k_{HVV}	k_{AVV}
OO_1^H	[-1.7, 1.7]	-
OO_2^H	[-1.7, 1.8]	-
OO_1^A	-	[-2.0, 2.0]
OO_2^A	-	[-2.0, 2.1]
Cross section alone		
Observable	k_{HVV}	k_{AVV}
OO_1^H (single bin)	[-2.1, 2.1]	-
OO_2^H (single bin)	[-2.1, 2.1]	-
OO_1^A (single bin)	-	[-2.5, 2.6]
OO_2^A (single bin)	-	[-2.5, 2.6]