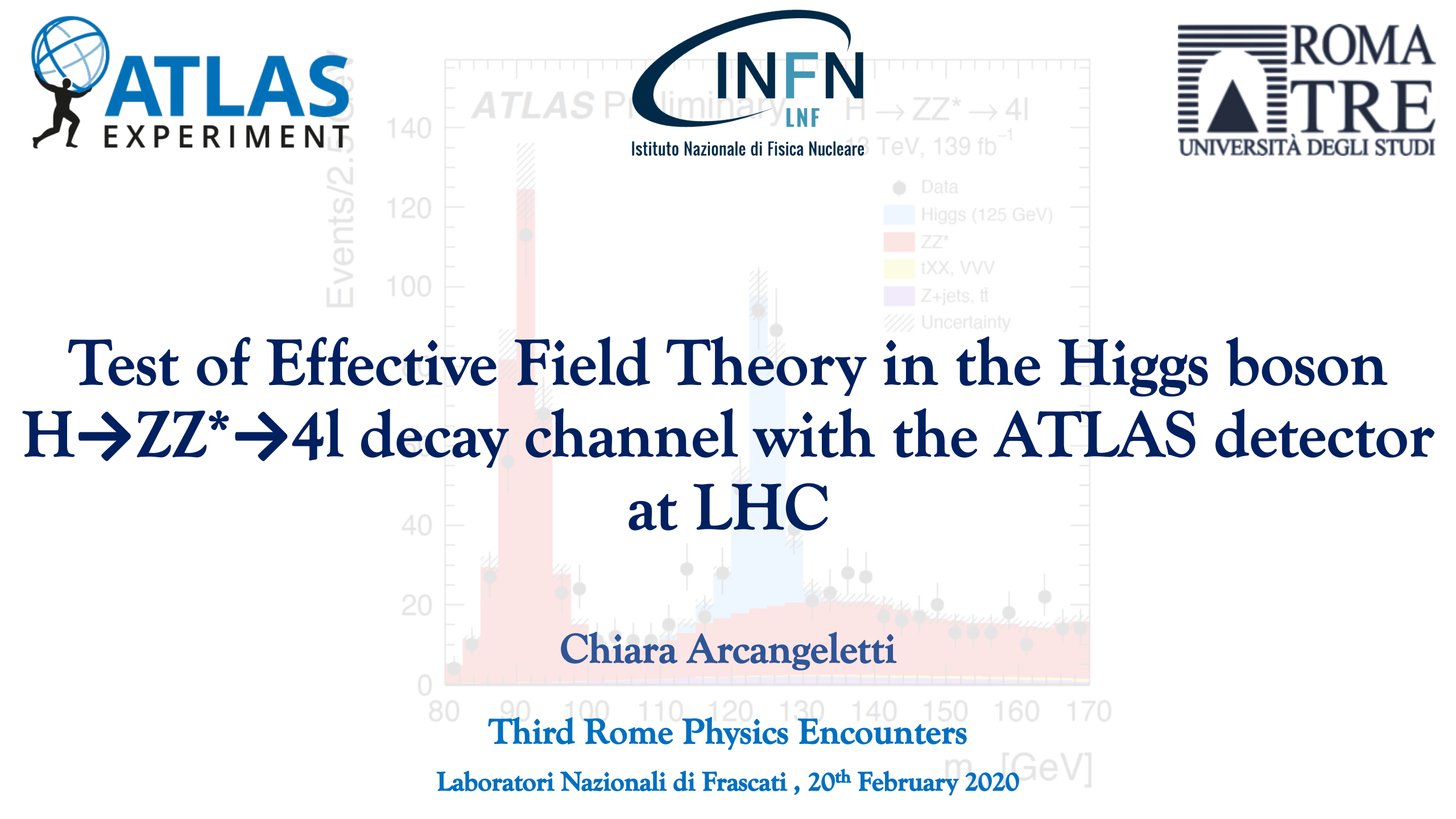


Test of Effective Field Theory in the Higgs boson H→ZZ*→4l decay channel with the ATLAS detector at LHC

Chiara Arcangeletti

Third Rome Physics Encounters

Laboratori Nazionali di Frascati , 20th February 2020

Outline

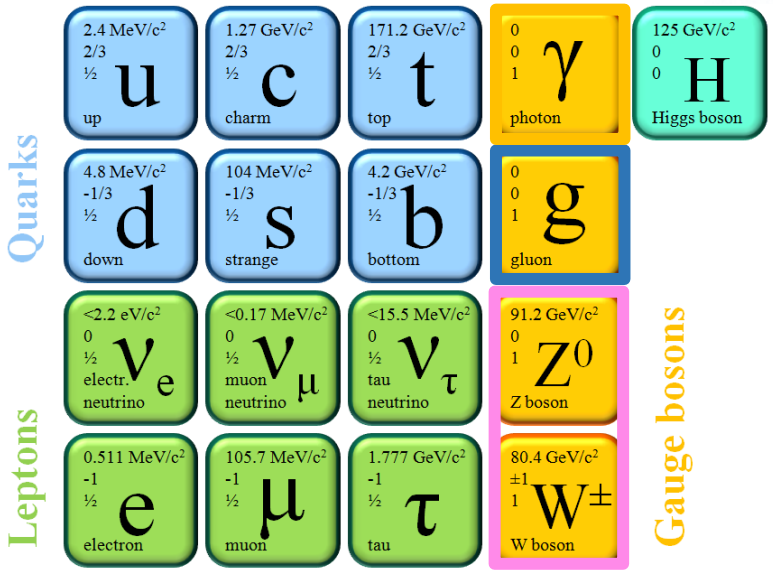
- The Standard Model and the Higgs Boson
- The ATLAS detector at LHC
- H→ZZ*→4l decay channel
  - Fiducial cross sections measurements
  - Interpretation: Pseudo – Observables

Outline

- The Standard Model and the Higgs Boson
- The ATLAS detector at LHC
- H→ZZ*→4l decay channel
  - Fiducial cross sections measurements
  - Interpretation: Pseudo – Observables

The Standard Model and the Higgs Boson

- Electromagnetic interaction
- Strong interaction
- Weak interaction



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

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

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

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

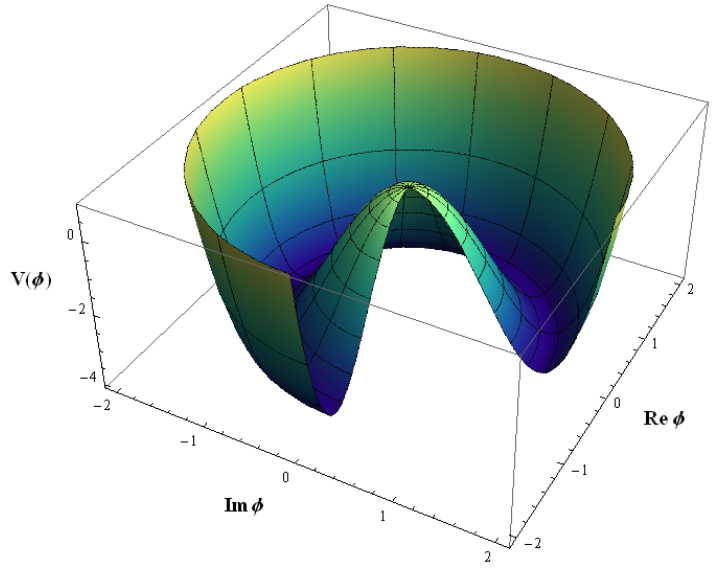
Gauge symmetry

- Gauge bosons, fermions, interactions, but...

...no masses...

Spontaneous symmetry breaking:

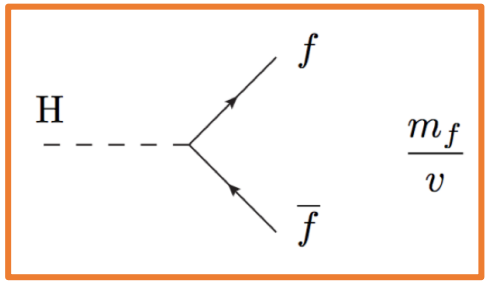
Higgs Mechanism



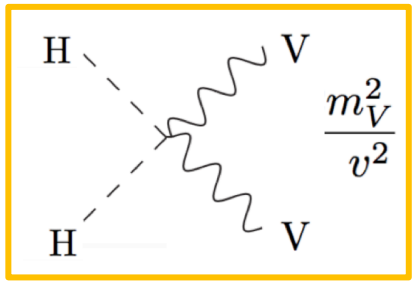
The Standard Model and the Higgs Boson

Yukawa interactions

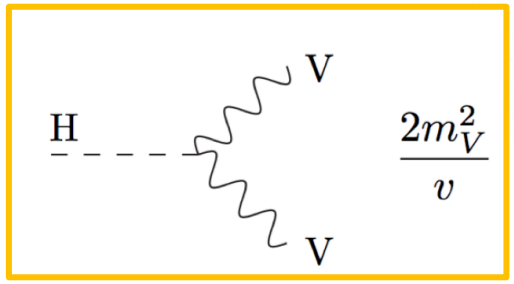
Fermion masses



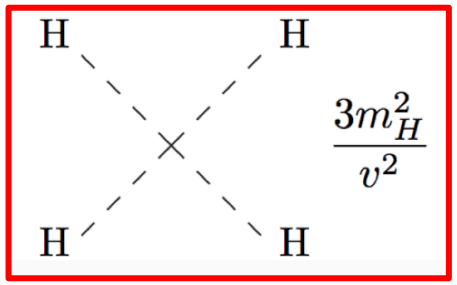
Gauge interactions

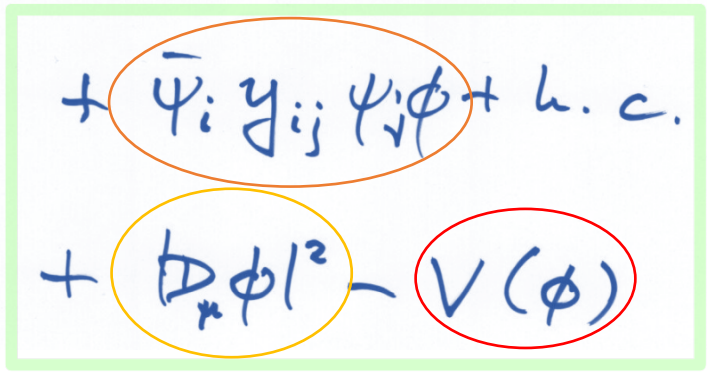


Gauge boson masses



Self – interactions





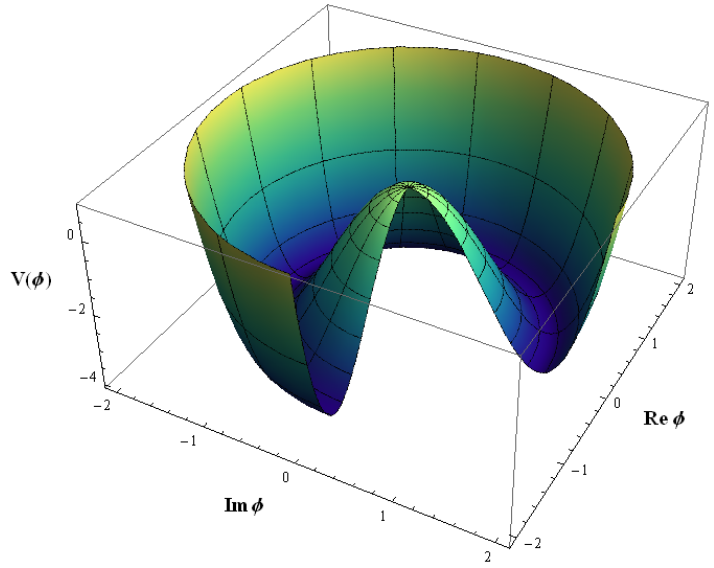
Gauge symmetry

- Gauge bosons, fermions, interactions, but...

...no masses...

Spontaneous symmetry breaking:

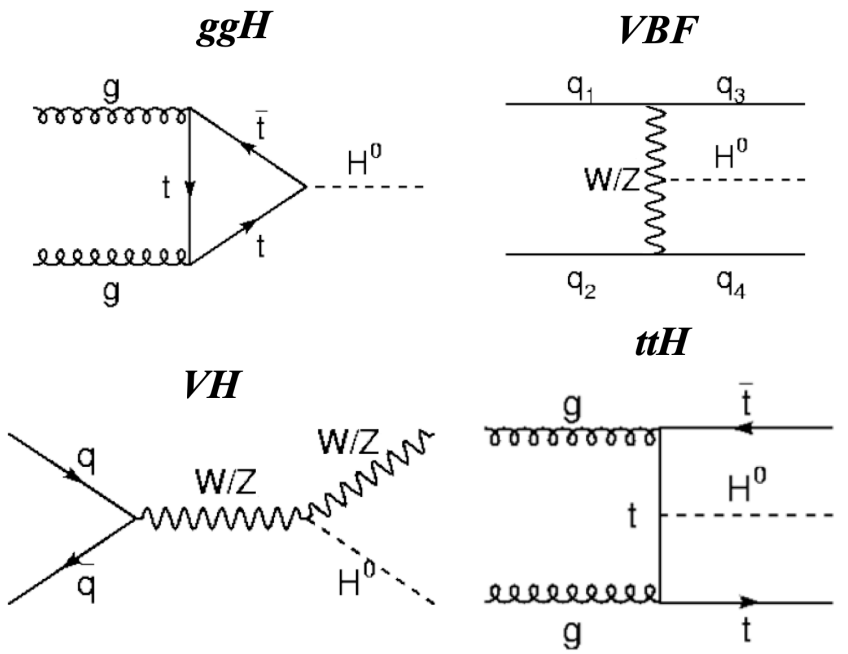
Higgs Mechanism



The Higgs Boson @ LHC

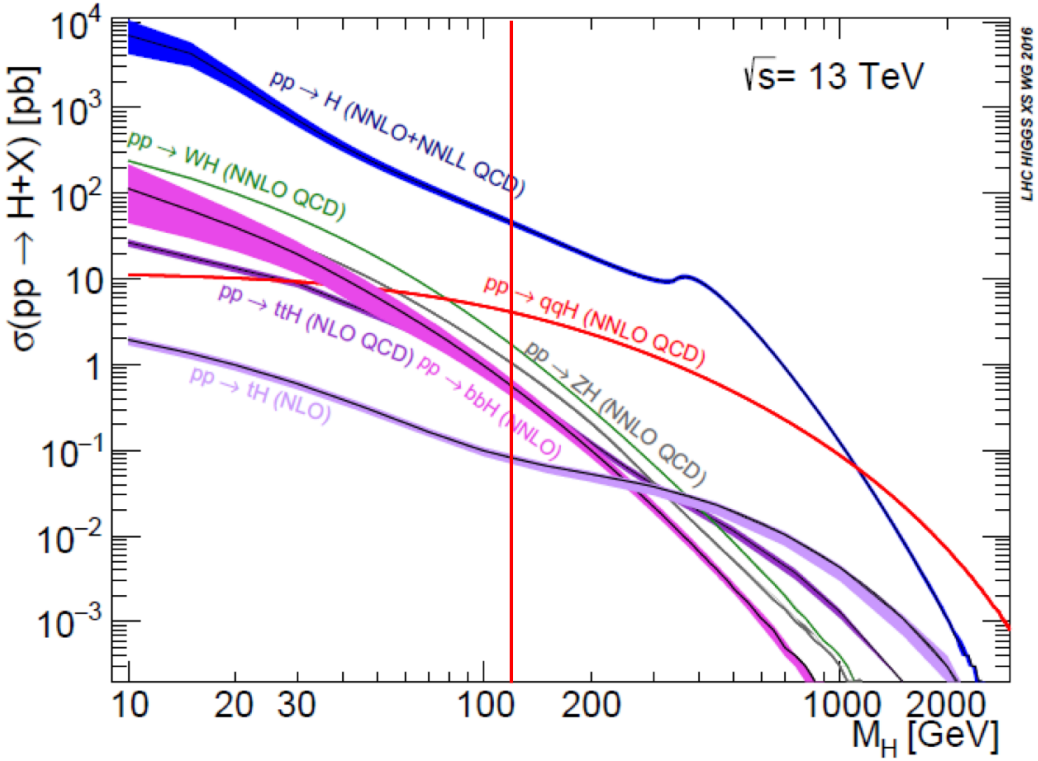
Production mechanisms

- Gluon – Gluon Fusion (ggF)
- Vector Boson Fusion (VBF)
- Associated production with a vector boson (VH)
- Associated production with a top quark pair (ttH)



@ 13 TeV

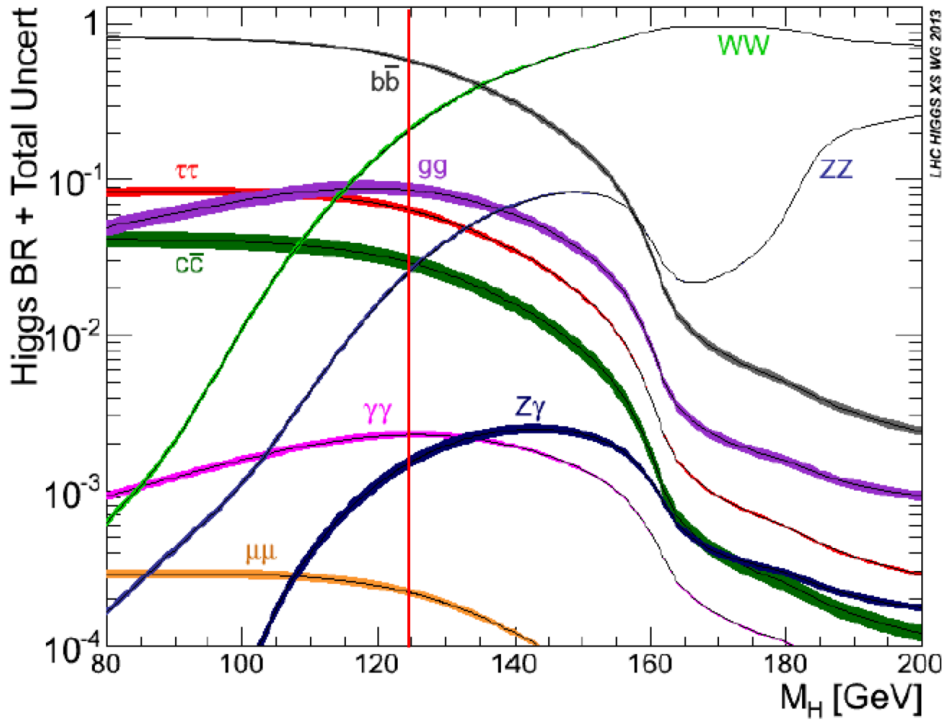
$\sigma_{ggH} \sim 44$ pb
$\sigma_{VBF} \sim 3.8$ pb
$\sigma_{WH} \sim 1.4$ pb
$\sigma_{ZH} \sim 0.9$ pb
$\sigma_{ttH} \sim 0.5$ pb



The Higgs Boson @ LHC

Production mechanisms

- Gluon – Gluon Fusion (ggF)
- Vector Boson Fusion (VBF)
- Associatied production with a vector boson (VH)
- Associated production with a top quark pair (ttH)



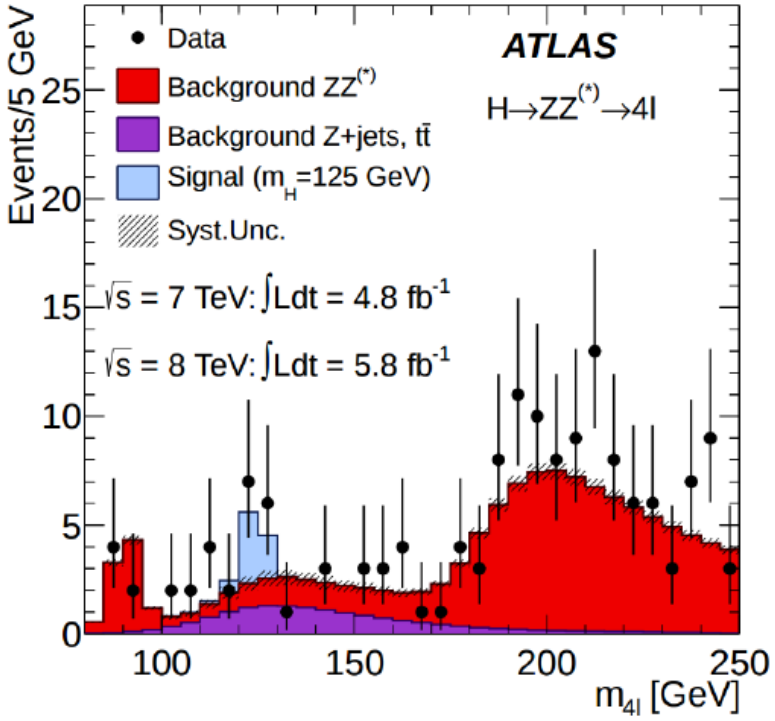
Decay Channels

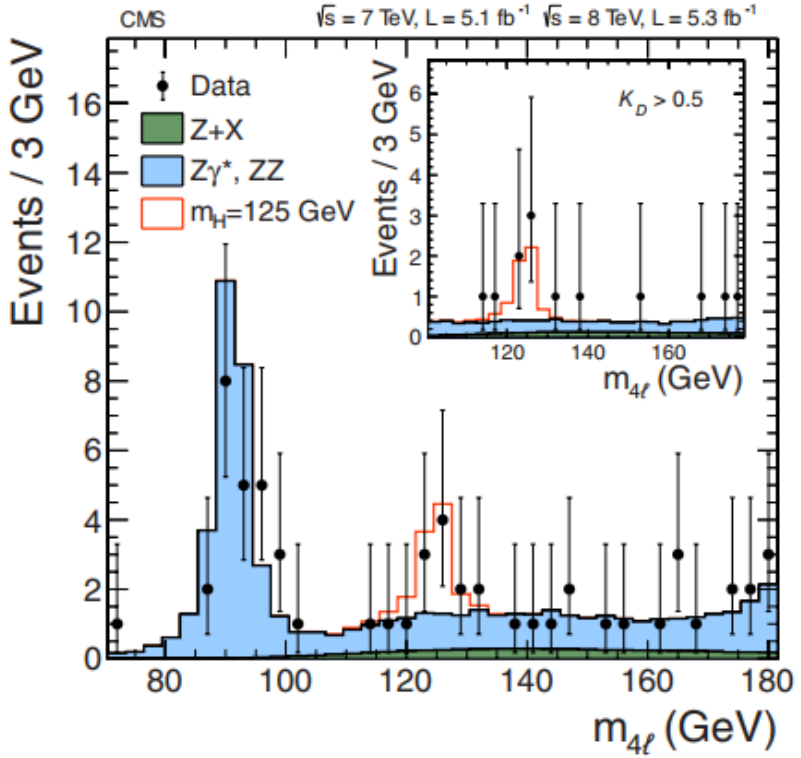
- H→ZZ: low BR, very good signal – background ratio, high mass resolution
- H→WW: high BR, low mass resolution
- H→ $\gamma\gamma$: low BR, large background, high mass resolution
- H→bb e H→$\tau\tau$: high BR, large background, low mass resolution

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

The Higgs Boson @ LHC

Higgs Boson Discovery 4th July 2012





ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B 716 (2012) 1-29.

CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B 716 (2012) 30.

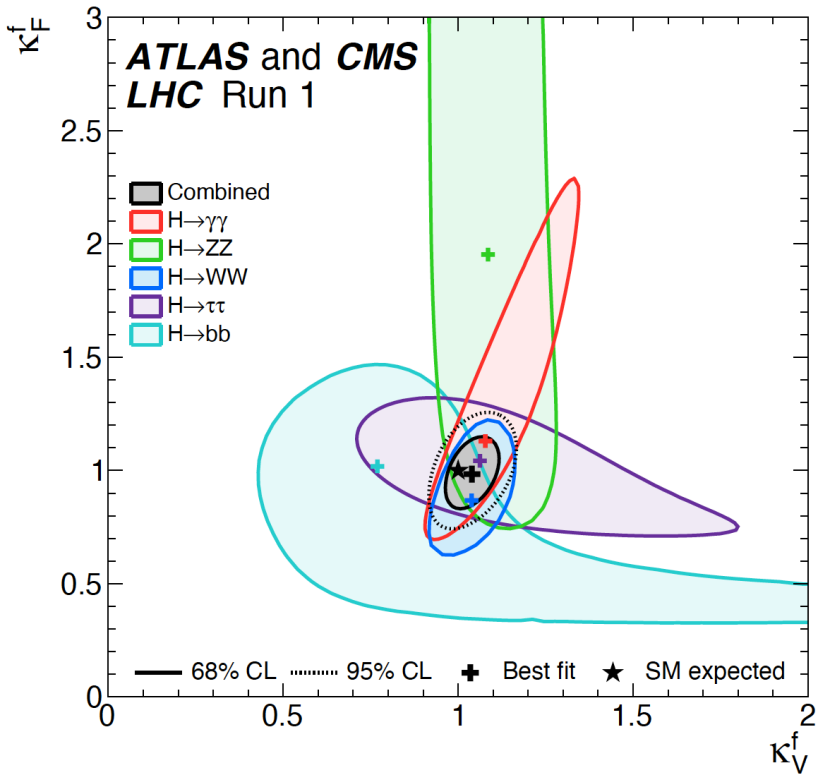
The Higgs Boson Beyond Standard Model

- At Run1 measurements of Higgs properties were reported in the "κ – framework"
  - **Couplings modifiers κ** introduced as scale factors of the cross sections or partial widths
    - Sensible only to the total rates and not to the kinematics → cannot describe deviations in differential distributions

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

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

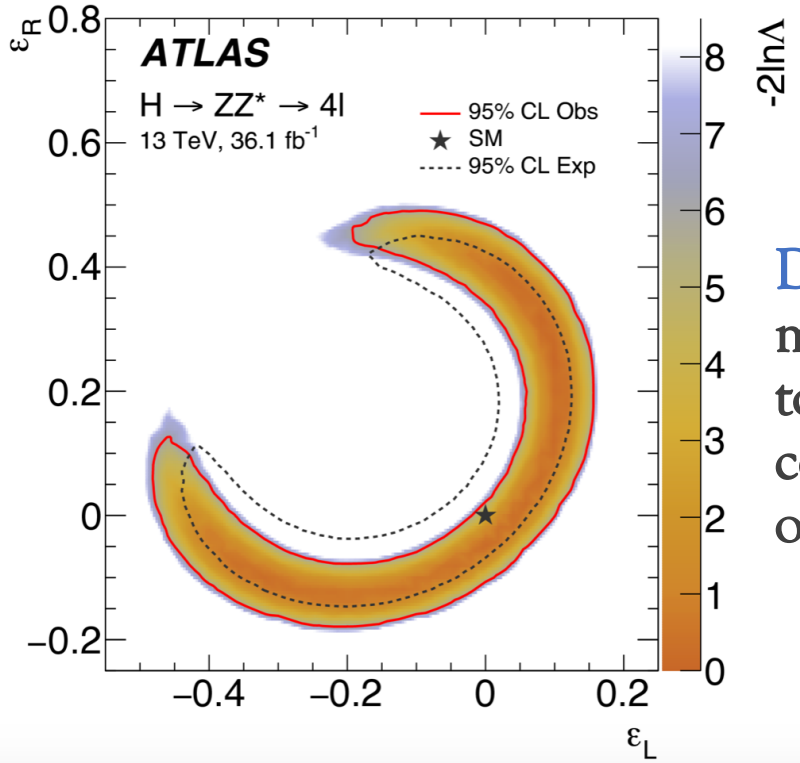
$$\kappa_j^2 = \frac{\Gamma^j}{(\Gamma^j)_{SM}}$$



BSM Physics in H→ZZ*→4l

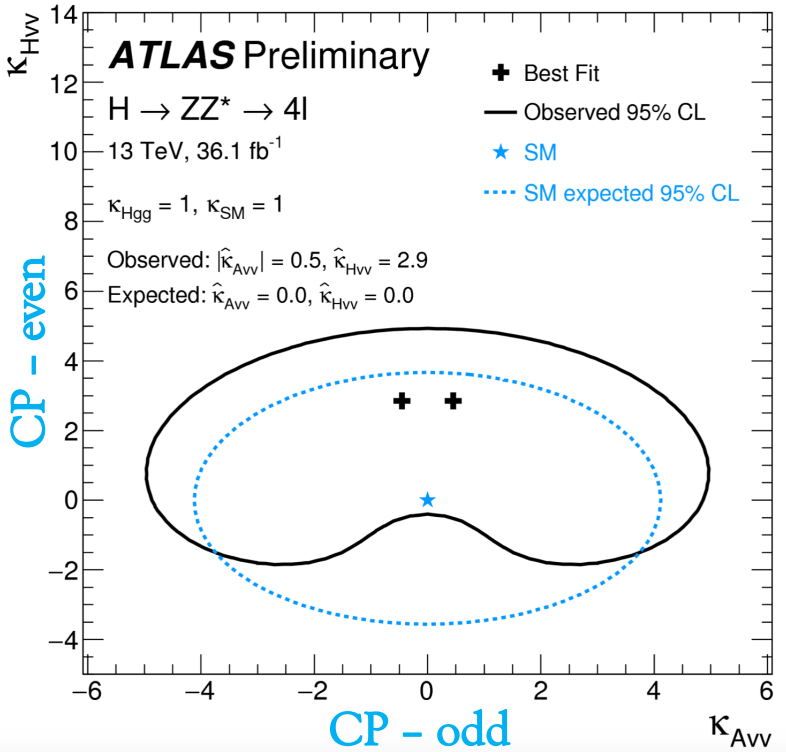
Kinematic distributions in production and decay modes may be sensitively modified by BSM effects

Simplified Template Cross Sections (STXS) framework to define exclusive regions for each production mode and allow to probe the tensor structure of the Higgs boson couplings with an EFT approach



Differential Cross Sections are more model independent and a powerful tool to put constraints on anomalous couplings of the Higgs boson with the other SM particles

→ **Pseudo – Observables framework**

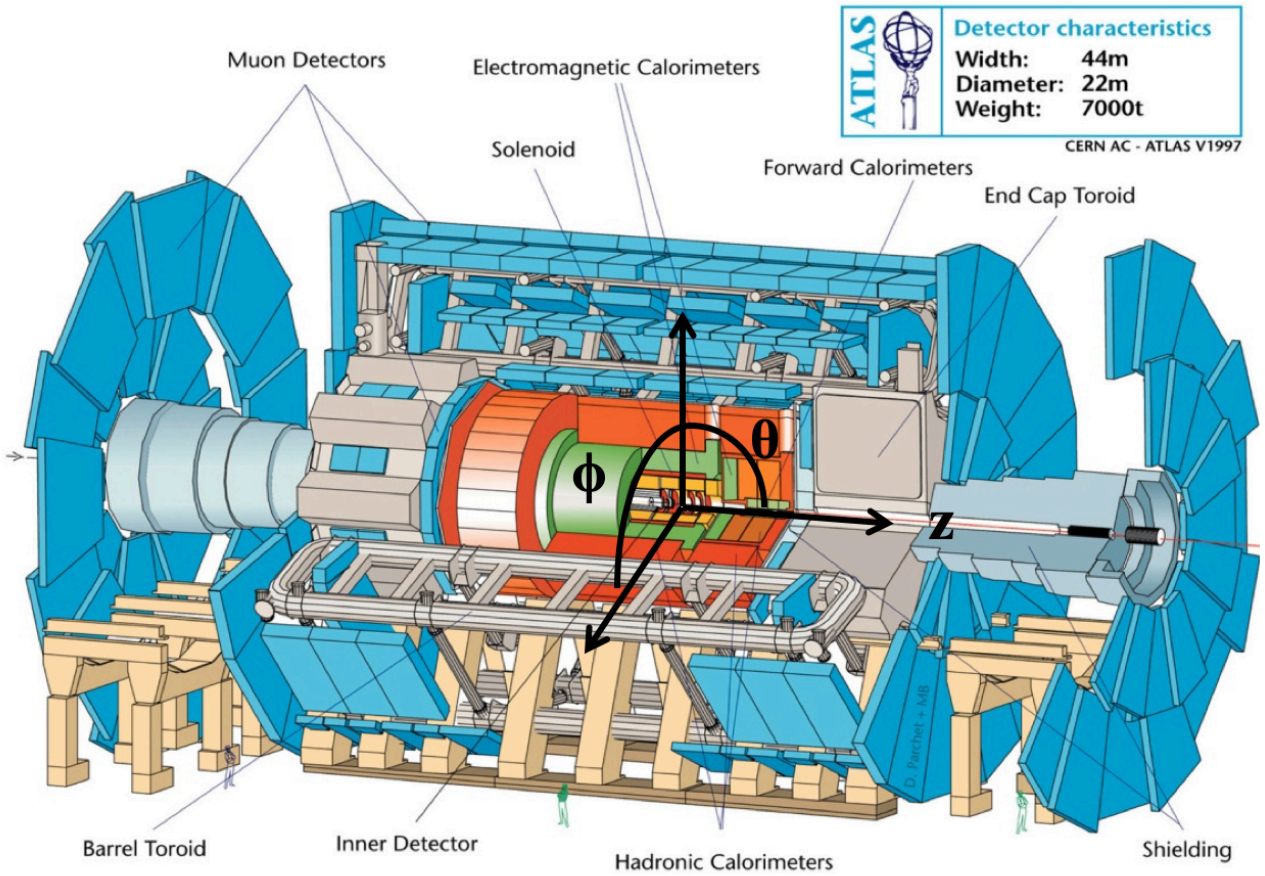


Outline

- The Standard Model and the Higgs Boson
- **The ATLAS detector at LHC**
- H→ZZ*→4l decay channel
  - Fiducial cross sections measurements
  - Interpretation: Pseudo – Observables

The ATLAS detector

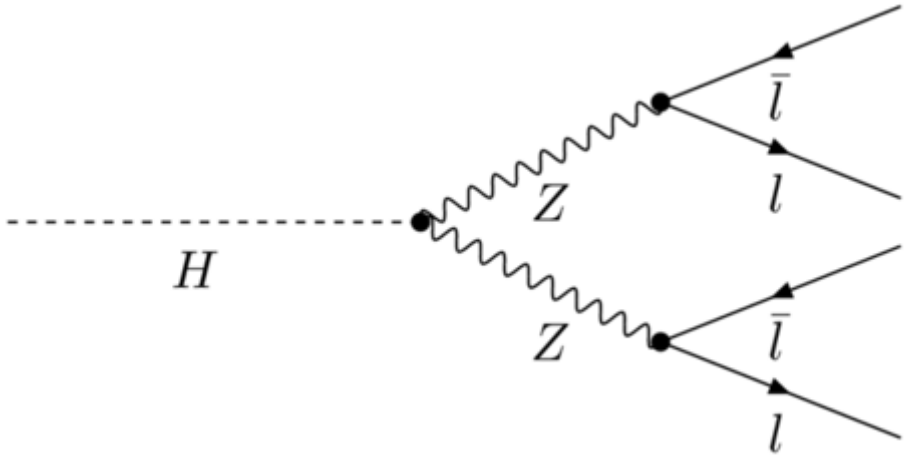
- Inner Detector
  - **Vertex detector:** pixel detector
  - **Trackers:** Semiconductor Tracker, Transition Radiation Tracker
- Magnet System
- Calorimeters
  - **Electromagnetic and Hadronic**
- Muon Spectrometer
  - **Trackers:** Monitored Drift Tubes, Cathod Strip Chambers
  - **Trigger:** Resistive Plate Chambers, Thin Gap Chambers



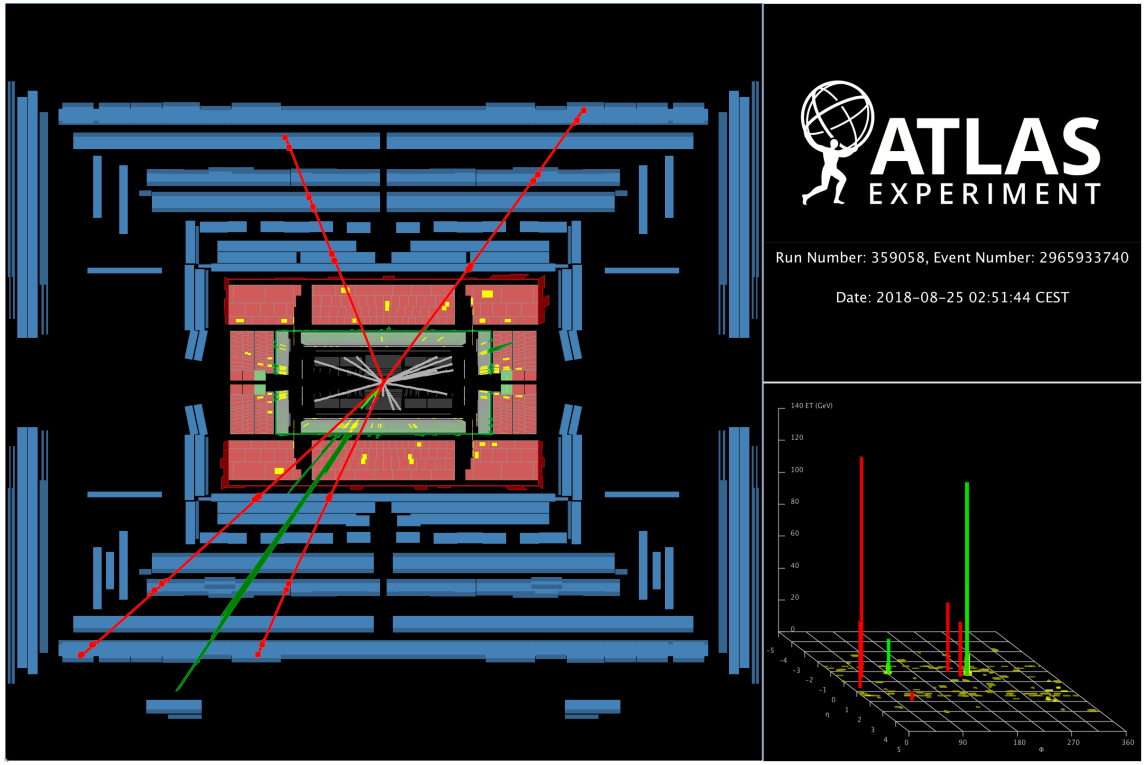
Outline

- The Standar Model and the Higgs Boson
- The ATLAS detector at LHC
- **H→ZZ*→4l decay channel**
  - Fiducial cross sections measurements
  - Interpretation: Pseudo – Observables

The *Golden Channel* H→ZZ*→4l



Final States: 4μ, 2μ 2e, 2e2μ, 4e

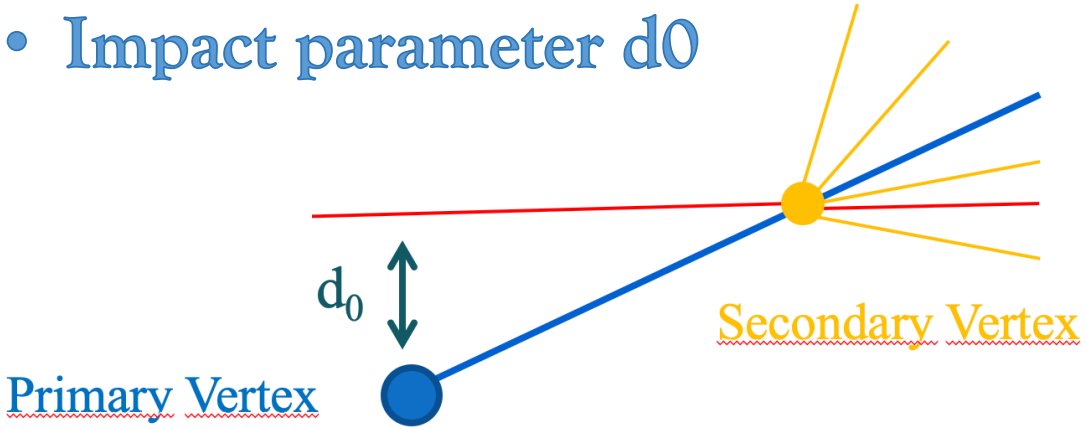


- Leptonic final state
  - Clear signature of the event
- Very good signal/background ratio
  - S/B ~ 2
- Very good resolution
- High efficiency of lepton reconstruction

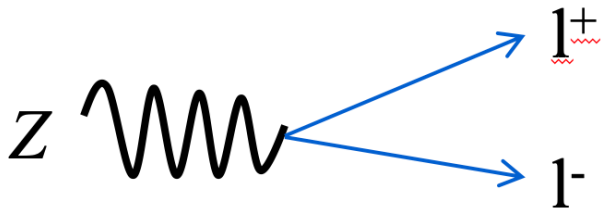
- Main backgrounds
  - Non resonant ZZ* (irreducible)
  - $t\bar{t}$ and Z+jets (reducible)

Event Selection

- Common Vertex
  - Impact parameter d0

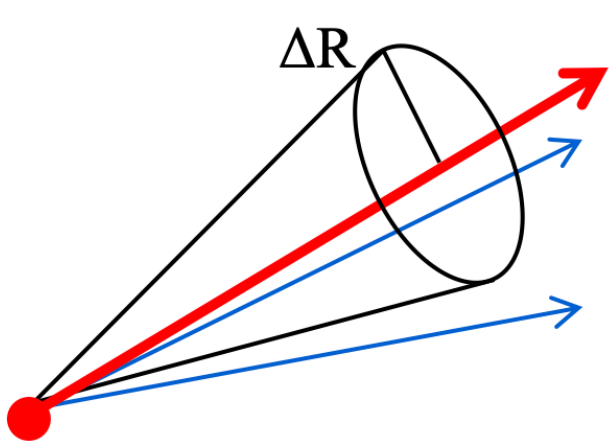


- Quadruplet selection
  - Same-flavour and opposite-sign lepton pairs
  - Invariant mass close to the Z boson mass



- Lepton Isolation
  - Several combination of track and calo isolation variables

$$\sum p_T/p_T \quad \sum E_T/E_T$$



$p_T = p \cdot \mathrm{sen}\theta \quad \Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$

Cross section measurement – I

The total cross section of a process with a given Branching Ratio (BR) is defined as:

- N_s = # observed signal events
- L_{int} = integrated luminosity
- C = detecting correction factor
  - A = kinematic and geometric acceptance

$$\sigma = \frac{N_S}{\mathcal{A} \times C \times BR \times \mathcal{L}_{\text{int}}}$$

$$C = \frac{N_{\text{Reco.}}}{N_{\text{Fid.}}} \qquad \mathcal{A} = \frac{N_{\text{Fid}}}{N_{\text{Tot}}}$$

- N_{Tot} = total # generated events
- N_{Fid} = # events pass selection fiducial criteria
- N_{Reco} = # reconstructed events

Definition of a fiducial cross section:

$$\sigma^{\text{fid}} = \sigma \times \mathcal{A} \times BR = \frac{N_S}{C \times \mathcal{L}_{\text{int}}}$$

Fiducial Phase Space

Lepton defintion	
Muons: $p_T^\mu > 5$ GeV, $\lvert\eta^\mu\rvert < 2.7$	Electrons: $p_T^e > 5$ GeV, $\lvert\eta^e\rvert < 2.7$
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 lepton $p_T > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R_{\ell_i \ell_j} > 0.1$ for all leptons
Jet/Lepton separation:	$\Delta R_{\ell_i jet} > 0.1$ between jets and leptons (else jet is vetoed)
J/ψ veto:	$m_{\ell_i \ell_j} > 5$ GeV for all SFOS lepton pairs
Mass window:	$115 < m_{4\ell} < 130$ GeV ($105 < m_{4\ell} < 160$ GeV)

Cross section measurement – II

- **Inclusive fiducial cross sections** for all final states (4mu, 4e, 2e2mu, 2mu2e, 4l sum, 4l combine, total)
- **Differential fiducial cross section** for several variables

Number of signal events extraction: invariant mass templates for the Higgs boson signal and the background processes are fit to the m_{4l} distribution in data
  - Profile Likelihood

$$\Lambda(m_{4l}|\sigma^{\text{fid}}) = \frac{L\left(m_{4l}|\sigma^{\text{fid}}, \hat{\hat{\theta}}\right)}{L\left(m_{4l}|\hat{\sigma}^{\text{fid}}, \hat{\theta}\right)}$$

Number of expected events N_i in each observable reconstruction bin *i*:

$$N_i(m_{4l}) = \sum_j \epsilon_{ij} \cdot (1 + f_i^{\text{nonfid}}) \cdot \sigma_j^{\text{fid}} \cdot P(m_{4l}) \cdot L_{int} + N_i^{bkg}(m_{4l})$$

$$\epsilon_{i,j} = \frac{\text{number of events in bin i truth matched to an event in bin j}}{\text{truth events in bin j}}$$

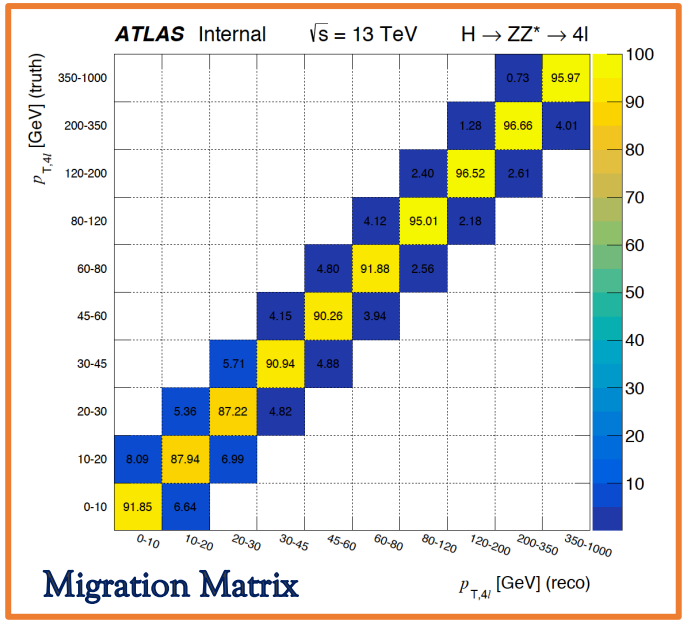
$P(m_{4l}) = m_{4l}$ signal shape

f_i^{nonfid} = Events outside the fiducial region reconstructed in bin i

$N_i^{bkg}(m_{4l})$ = Background contribution

Detector response matrix

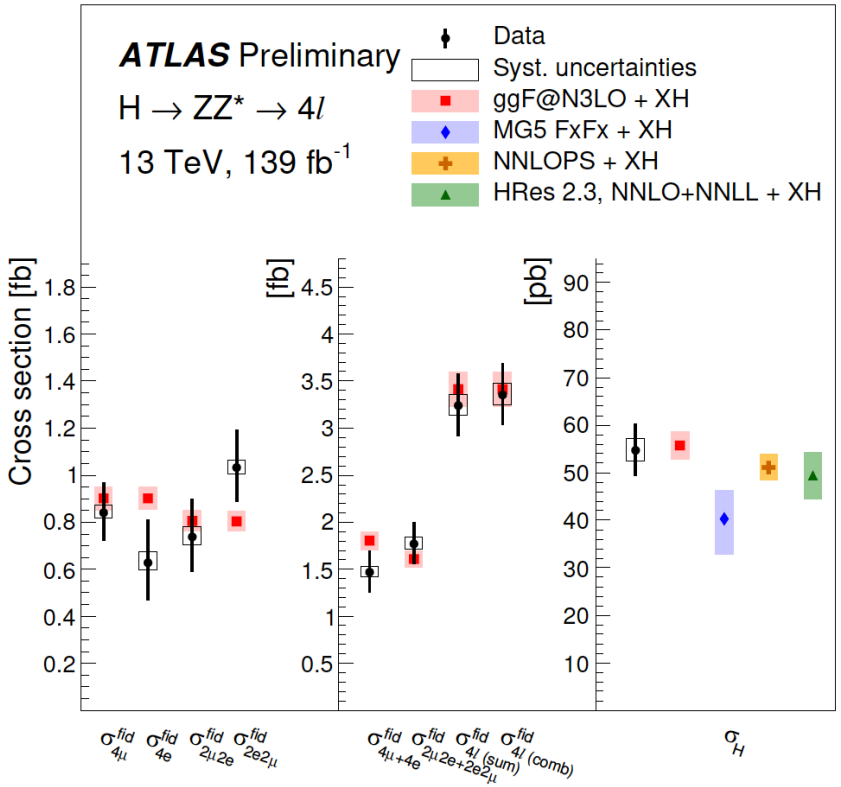
- Y– axis = x_{truth} and X – axis = x_{reco}
- For each truth bin the reco quantity is reported



Migration Matrix

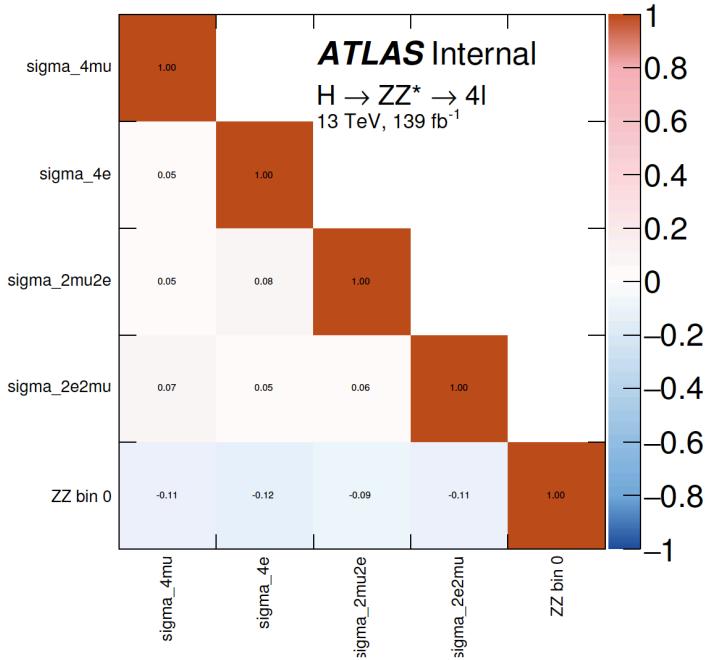
Inclusive Fiducial XS: Results

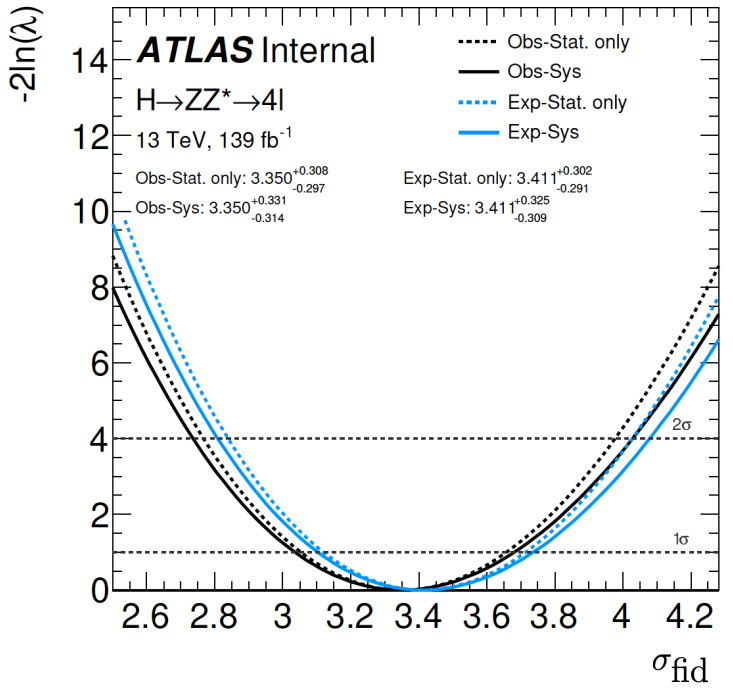
ATLAS – CONF – 2019 – 025



$115 < m_{4\ell} < 130$ GeV					
Final State	Signal	ZZ^*	redBkg	Total	Observed
4μ	77.9	37.9	2.9	118.7	118
$4e$	35.2	15.0	2.9	53.2	43
$2\mu 2e$	40.0	17.3	3.6	60.9	57
$2e2\mu$	52.8	26.0	3.0	81.8	98
incl	205.9	96.3	12.4	314.7	316

Correlation Matrix



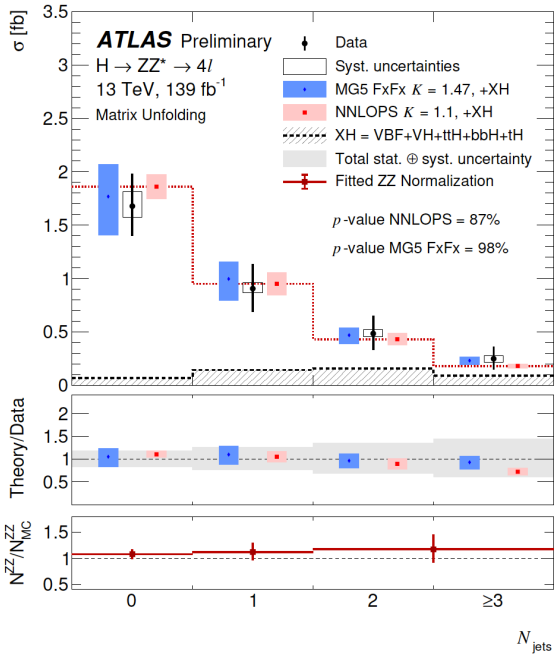


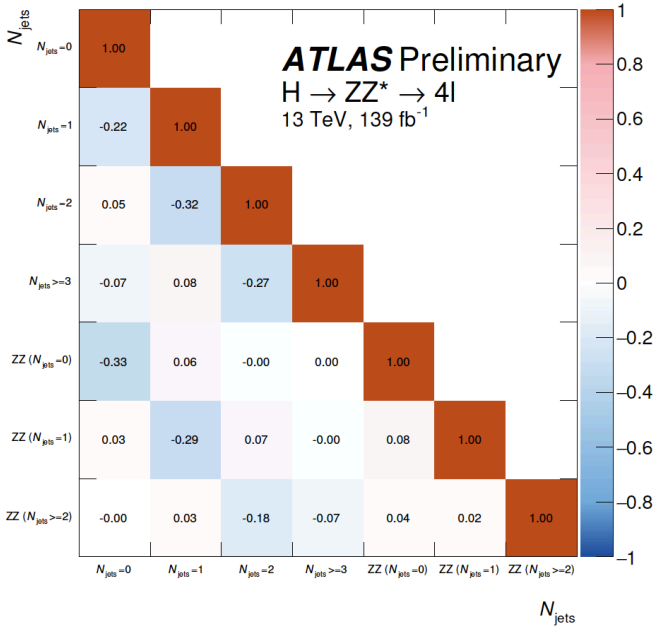
$$\sigma_{\text{fid}} = 3.35 \pm 0.30(\text{stat.}) \pm 0.12(\text{syst.})$$

Differential Fiducial XS: Results

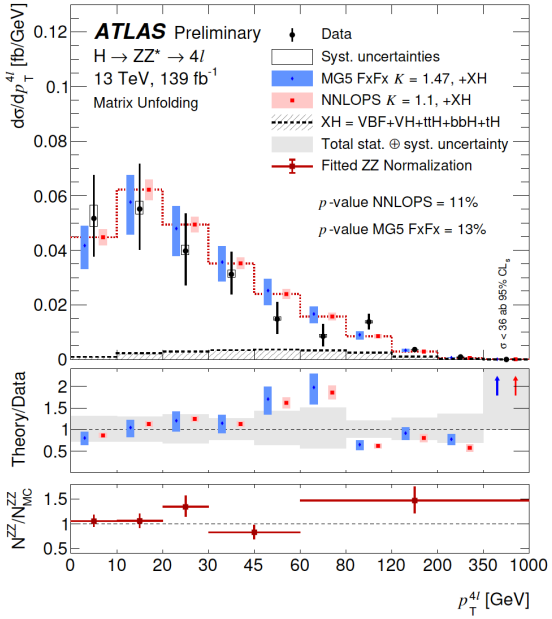
Differential cross sections defined in a fiducial region for several variables sensitive to the Higgs boson production and decay such as the transverse momentum of the Higgs boson and the number of jets produced in association with the Higgs boson

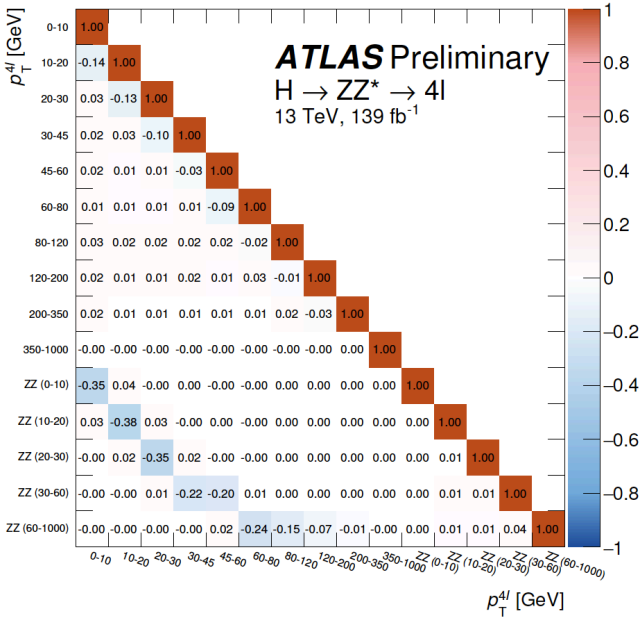
N_{jet}





P_T^{4l}





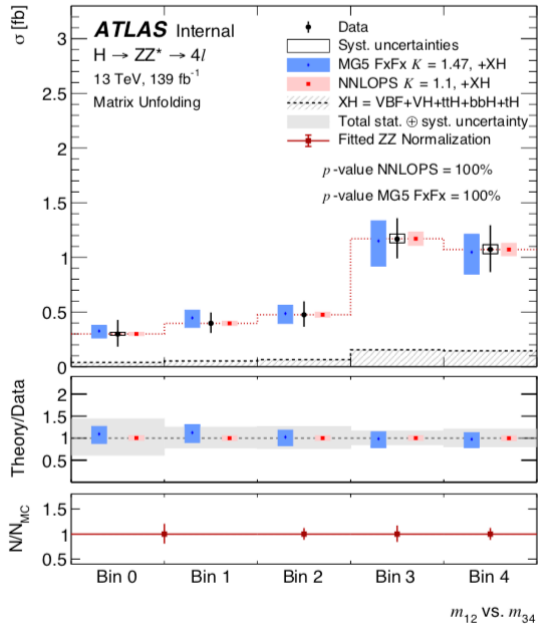
ATLAS – CONF – 2019 – 025

Double Differential Fiducial XS

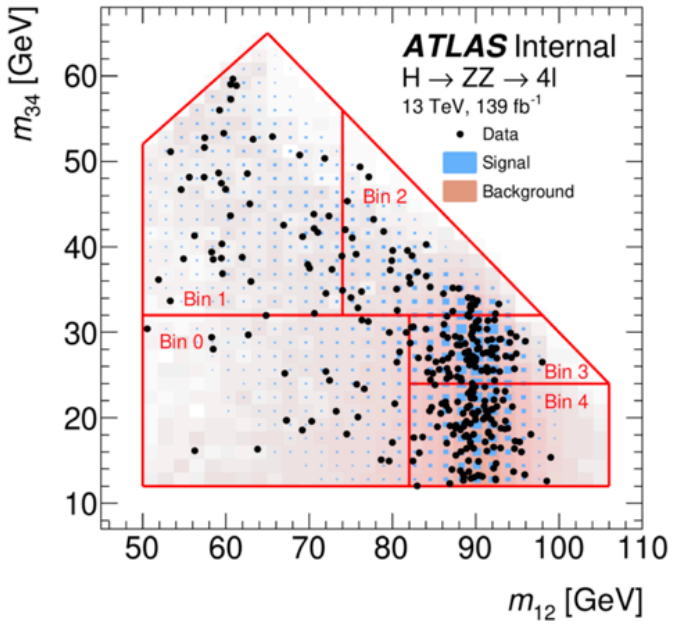
m_{12} vs m_{34}

Bin	m_{12} and m_{34} values [GeV]	Signal	ZZ	Z+jets/$t\bar{t}$	$t\bar{t}V + VVV$	S/B	σ	Z_0
0	$m_{12} < 82$ and $m_{34} < 32$	18.1077	11.3864	1.60462	0.482	1.344	3.2222	4.19394
1	$m_{12} < 74$ and $m_{34} > 32$	26.6605	5.94953	2.10079	0.407423	3.1522	4.49886	6.83158
2	$m_{12} > 74$ and $m_{34} > 32$	29.7446	5.91993	0.842119	0.20705	4.26807	4.90901	7.90712
3	$m_{12} > 82$ and $24 < m_{34} < 32$	69.4636	18.325	1.76739	0.418365	3.38669	7.32315	11.2757
4	$m_{12} > 82$ and $m_{34} < 24$	61.6381	54.4474	4.27011	0.807964	1.03549	5.59968	6.99677

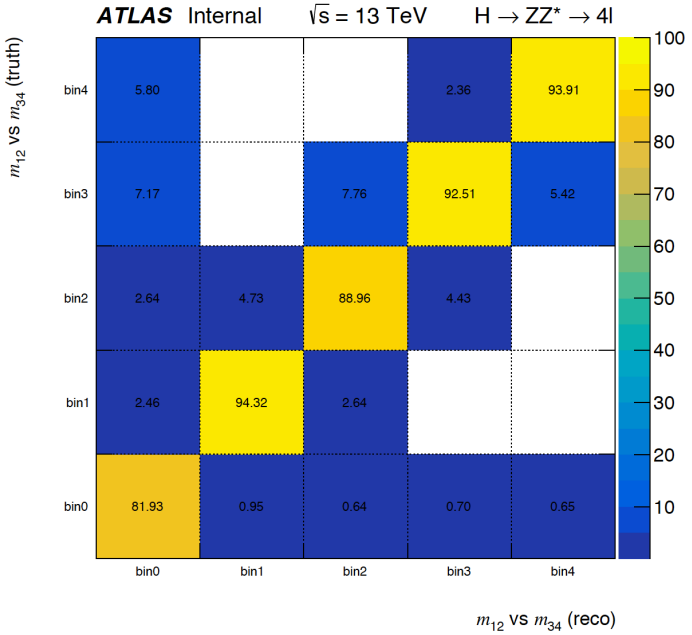
Expected Results



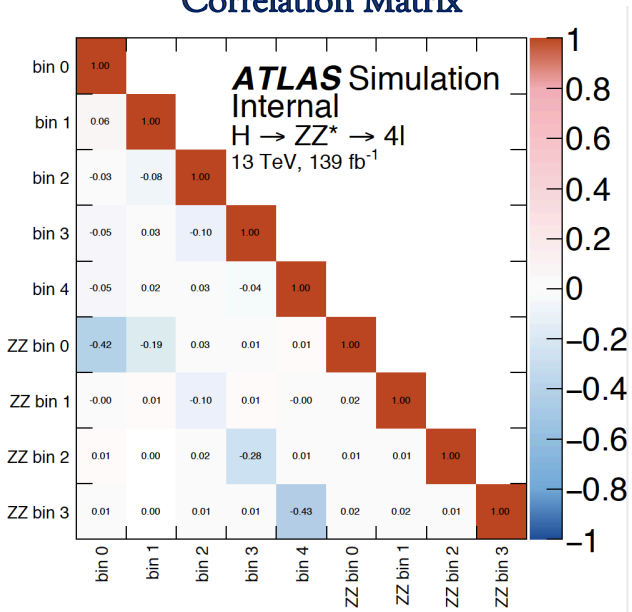
Binning



Migration Matrix



Correlation Matrix



Outline

- The Standar Model and the Higgs Boson
- The ATLAS detector at LHC
- **H→ZZ*→4l decay channel**
  - Fiducial cross sections measurements
  - Interpretation: Pseudo – Observables

Pseudo – Observables Framework

M. Gonzalez-Alonso, A. Greljo, G. Isidori and D. Marzocca, *Pseudo-observables in Higgs decays*, Eur. Phys. J. C75 (2015) 128

- Generalization of the "κ – framework"

- **Hypothesis: Effective Field theory approach**
  - h(125) spin zero particle
  - No new particle below or around $m_h \simeq 125$ GeV
  - Neglect terms in the decay amplitudes from non – vanishing tree – level contributions from local operators with D>6
  - No further assumptions (as CP invariance, lepton universality)

$$\mathcal{L} = \mathcal{L}^{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{d=6} + (\dim > 6)$$

- NP effects just of the Higgs decay amplitude

- ***h→4l* amplitudes** allow to investigate the effective hW^+W^- and hZZ interaction terms, characterizing the three – point function:

$$\langle 0 | \mathcal{T} \left\{ J_f^\mu(x), J_{f'}^\nu(y), h(0) \right\} | 0 \rangle$$

Study the effective coupling of the ***h*** to all the SM gauge bosons and its possible couplings to new massive state (Z')

$h \to 4f$ Neutral Current

- Extraction of the pseudo-observables from the double differential decay distribution in (q_1^2, q_2^2)

→ **Affect the dilepton invariant mass spectra**

Amplitude decomposition

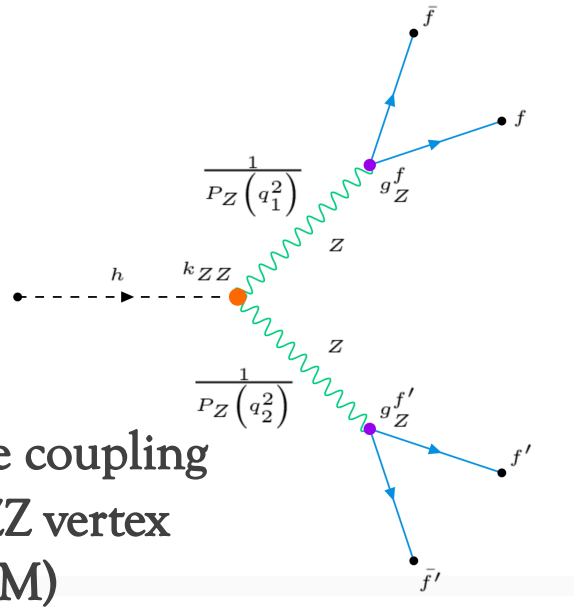
$$\mathcal{A}_{n.c.}\left[h \to f(p_1)\bar{f}(p_2)f'(p_3)\bar{f}'(p_4)\right] = i\frac{2m_Z^2}{v_F}\sum_{f=f_L,f_R}\sum_{f'=f'_L,f'_R}(\bar{f}\gamma_\mu f)(\bar{f}'\gamma_\nu f')\mathcal{T}^{\mu\nu}(q_1,q_2)$$

$$\mathcal{T}^{\mu\nu}(q_1,q_2) = \left[F_1^{ff'}(q_1^2,q_2^2)g^{\mu\nu} + F_3^{ff'}(q_1^2,q_2^2)\frac{q_1\cdot q_2\; g^{\mu\nu} - q_2^\mu q_1^\nu}{m_Z^2} + F_4^{ff'}(q_1^2,q_2^2)\frac{\varepsilon^{\mu\nu\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

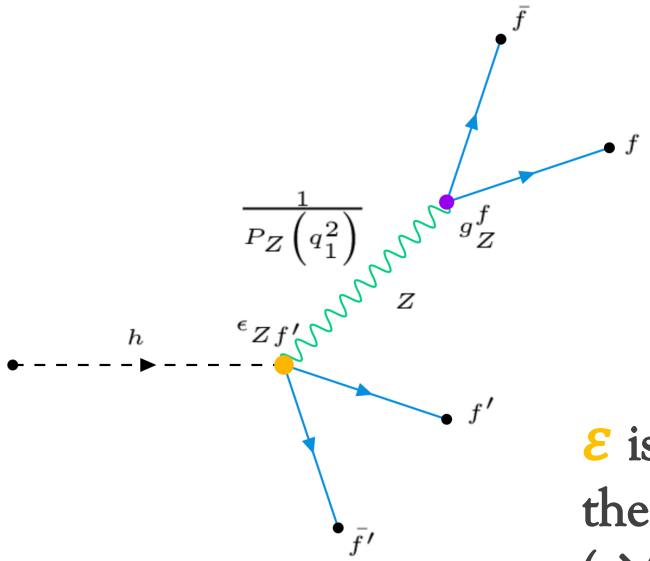
Most interesting effects (assuming CP invariance)

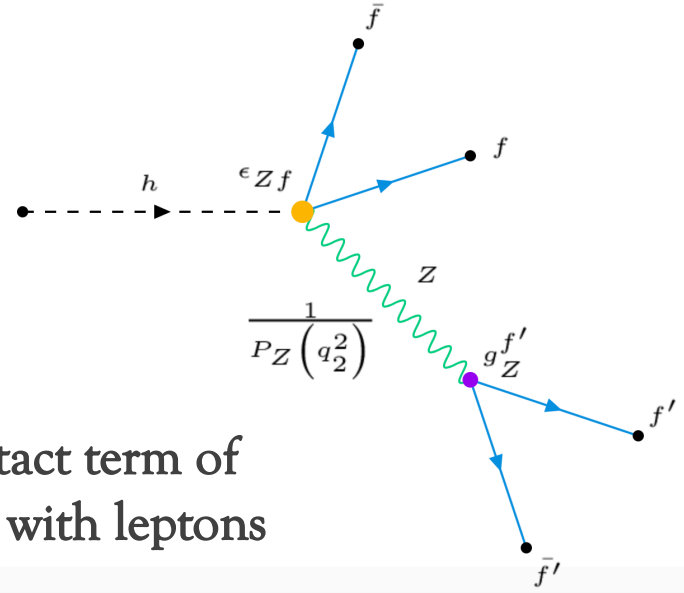
$$F_1^{ff'}(q_1^2,q_2^2) = \kappa_{ZZ}\frac{g_Z^f g_Z^{f'}}{P_Z(q_1^2)P_Z(q_2^2)} + \frac{\epsilon_{Zf}}{m_Z^2}\frac{g_Z^{f'}}{P_Z(q_2^2)} + \frac{\epsilon_{Zf'}}{m_Z^2}\frac{g_Z^f}{P_Z(q_1^2)}$$

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



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





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

Pseudo – Observables Scenarios

Lepton Flavour Universality

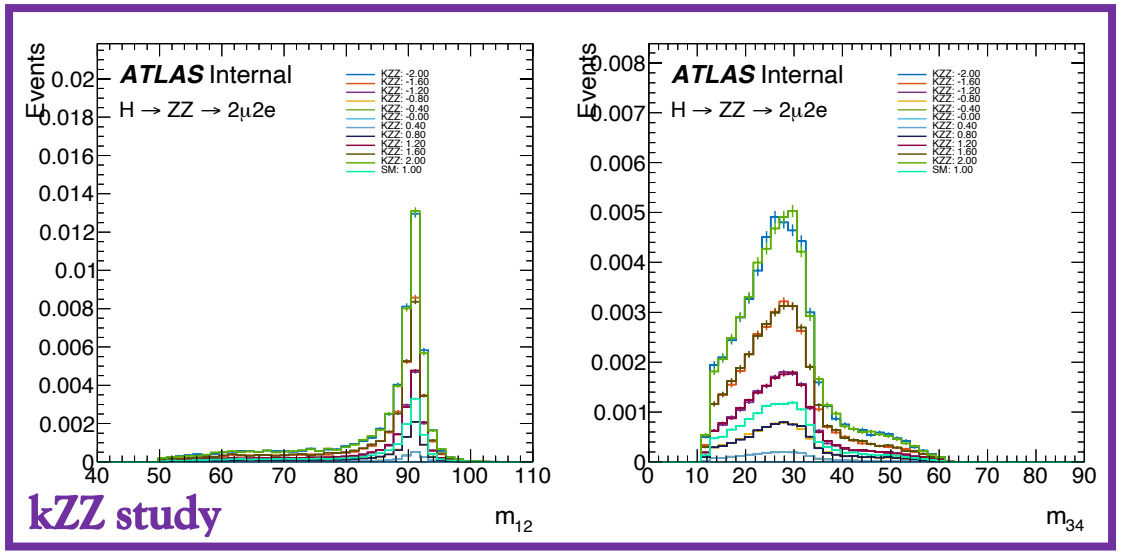
Imposing Lepton Flavour Universality: eMu = eEl

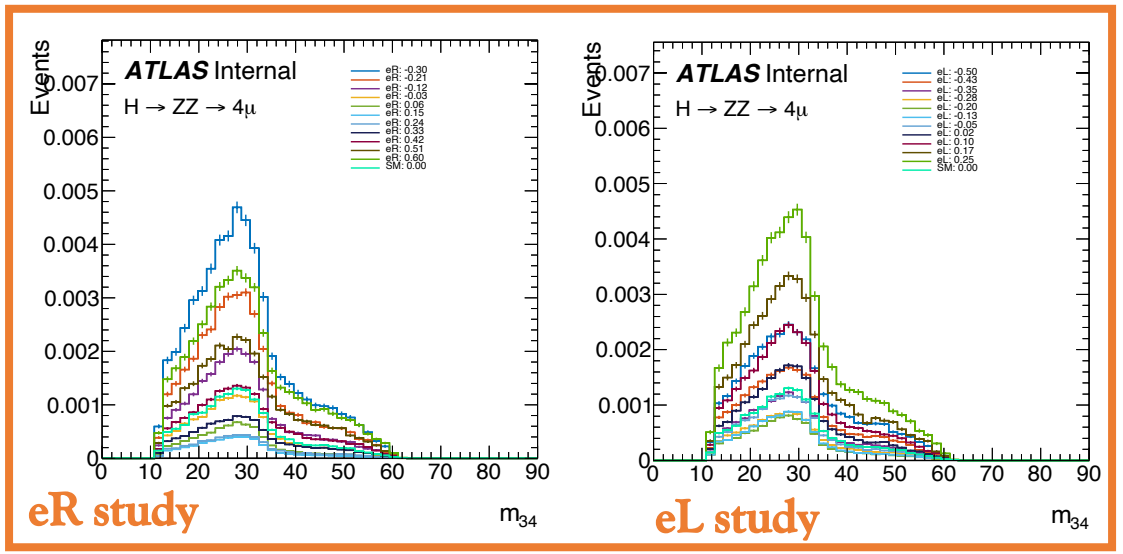
Linear EFT – inspired

- Assuming Higgs doublet: eR ≈ 0.48 * eL
- Parameter of Interest: **kZZ vs eL**
- Effect of different KZZ values on invariant masses
  - Affects the overall normalization of the decay
  - No sensibility to the sign of kZZ

Flavour Universal Contact Terms

- Looking for possible deviation in the Left and Right contact terms.
- Parameter of Interest: **eL vs eR**
- Effect of different eL/eR values on invariant masses
  - Effects in the shape and in the total rate





Pseudo – Observables Scenarios

Lepton Flavour non – Universality

- Lepton flavour violation: eMu ≠ eEl
- Looking for coupling of Z' particle with a lepton pair.
- Parameter of Interest: **eMu** vs **eEl**

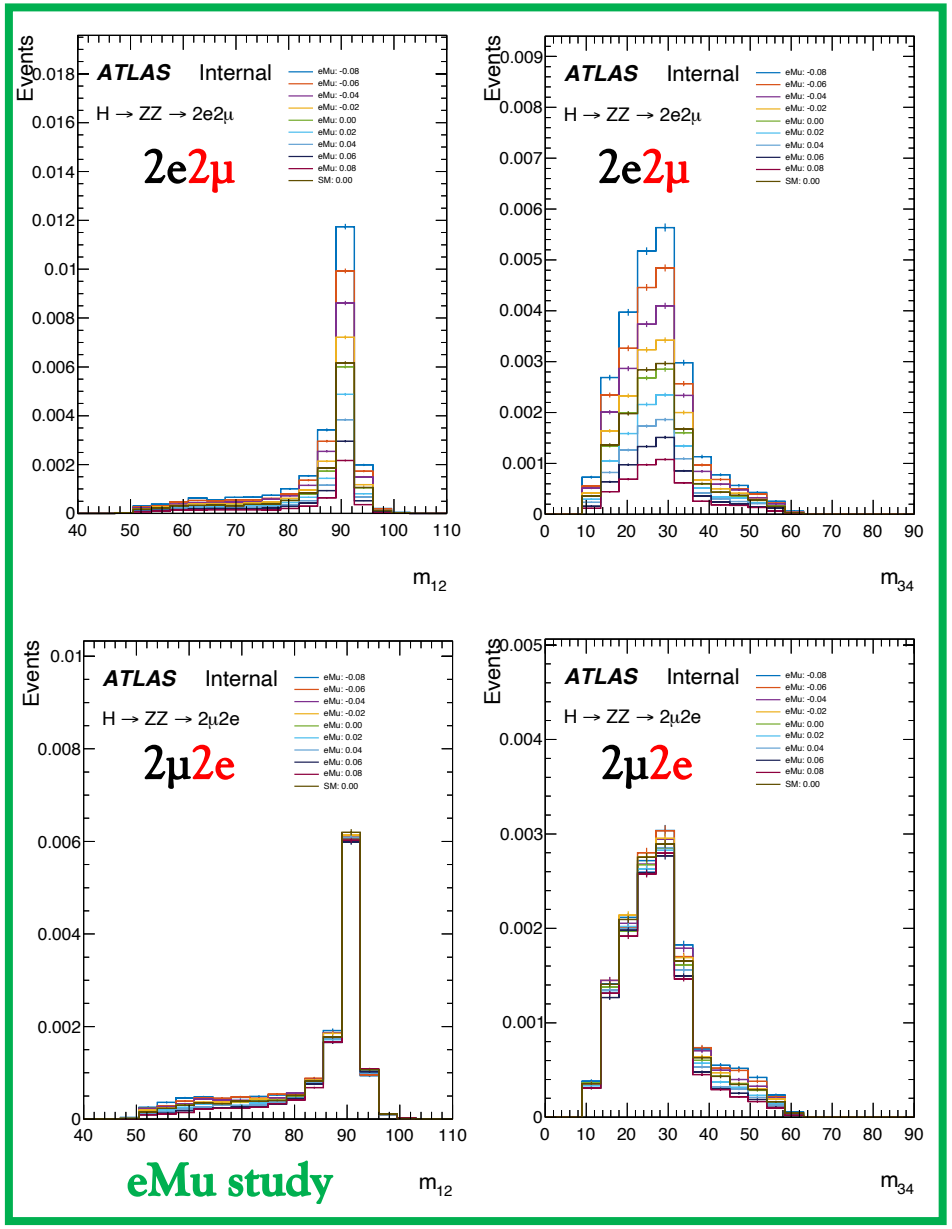
Flavour non – Universal Vector Contact Terms

- eLepL = eLepR

Flavour non – Universal Axial Contact Terms

- eLepL = –eLepR

- Effect of different eMu/eEl values on invariant mass
  - Impact on the channels with subleading lepton pair of the same flavour of the POI under study



Interpretation Strategy

Amplitude decomposition

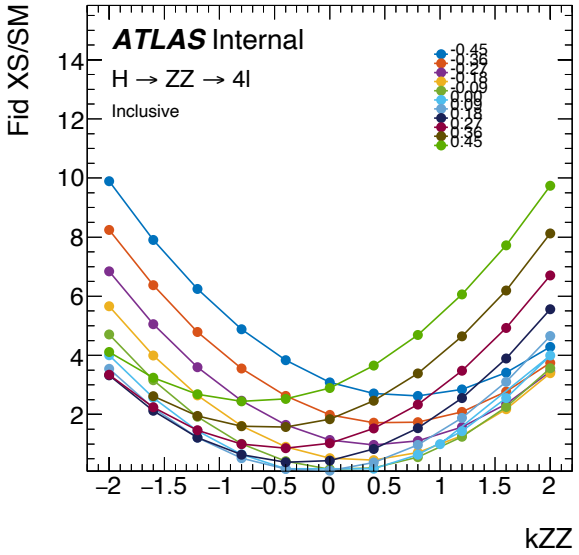
$$\mathcal{A}_{n.c.}\left[h \to f(p_1)\bar{f}(p_2)f'(p_3)\bar{f}'(p_4)\right] = i\frac{2m_Z^2}{v_F}\sum_{f=f_L,f_R}\sum_{f'=f'_L,f'_R}(\bar{f}\gamma_\mu f)(\bar{f}'\gamma_\nu f')\mathcal{T}^{\mu\nu}(q_1,q_2)$$

$$\mathcal{T}^{\mu\nu}(q_1,q_2) = \left[F_1^{ff'}(q_1^2,q_2^2)g^{\mu\nu} + F_3^{ff'}(q_1^2,q_2^2)\frac{q_1\cdot q_2\; g^{\mu\nu} - q_2{}^\mu q_1{}^\nu}{m_Z^2} + F_4^{ff'}(q_1^2,q_2^2)\frac{\varepsilon^{\mu\nu\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

The double differential decay distribution in q_1 and q_2 leads to a quadratic polynomial function in k = (kZZ; eElL; eElR; eMuL; eMuR), therefore, the decay amplitude can be written as a function of the POs as follow:

$$\frac{d^2\Gamma_{h\to 4l}}{dm_{12}dm_{34}} = \sum_{j\geq i} A_{ij}k_ik_j$$

1. Compute the cross sections for different couplings values



Interpretation Strategy

Amplitude decomposition

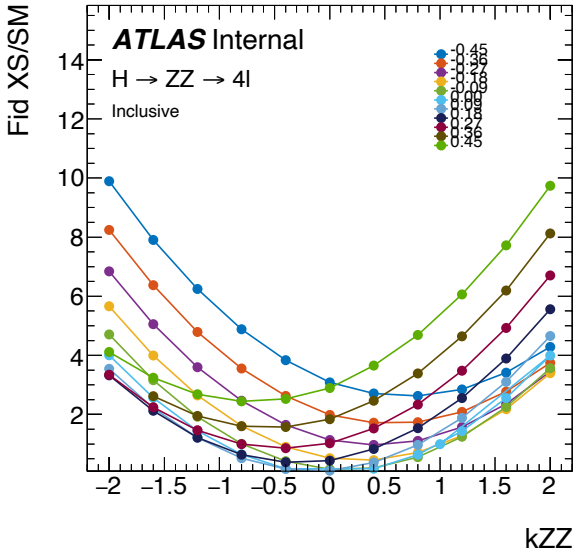
$$\mathcal{A}_{n.c.}\left[h \to f(p_1)\bar{f}(p_2)f'(p_3)\bar{f}'(p_4)\right] = i\frac{2m_Z^2}{v_F}\sum_{f=f_L,f_R}\sum_{f'=f'_L,f'_R}(\bar{f}\gamma_\mu f)(\bar{f}'\gamma_\nu f')\mathcal{T}^{\mu\nu}(q_1,q_2)$$

$$\mathcal{T}^{\mu\nu}(q_1,q_2) = \left[F_1^{ff'}(q_1^2,q_2^2)g^{\mu\nu} + F_3^{ff'}(q_1^2,q_2^2)\frac{q_1\cdot q_2\; g^{\mu\nu} - q_2{}^\mu q_1{}^\nu}{m_Z^2} + F_4^{ff'}(q_1^2,q_2^2)\frac{\varepsilon^{\mu\nu\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

The double differential decay distribution in q_1 and q_2 leads to a quadratic polynomial function in k = (kZZ; eElL; eElR; eMuL; eMuR), therefore, the decay amplitude can be written as a function of the POs as follow:

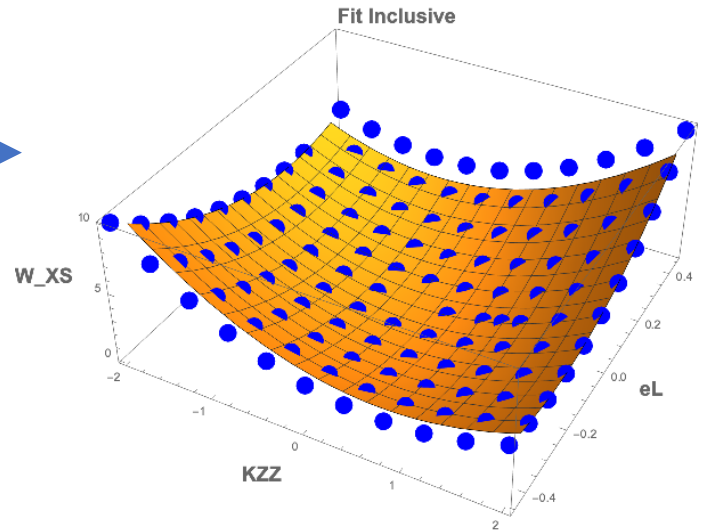
$$\frac{d^2\Gamma_{h\to 4l}}{dm_{12}dm_{34}} = \sum_{j\geq i} A_{ij}k_ik_j$$

1. Compute thes cross sections for these couplings values



2. Fit it with a parabolic function

$$f(x) = ax^2 + by^2 + cxy + dx + ey + f$$



Interpretation Strategy

Amplitude decomposition

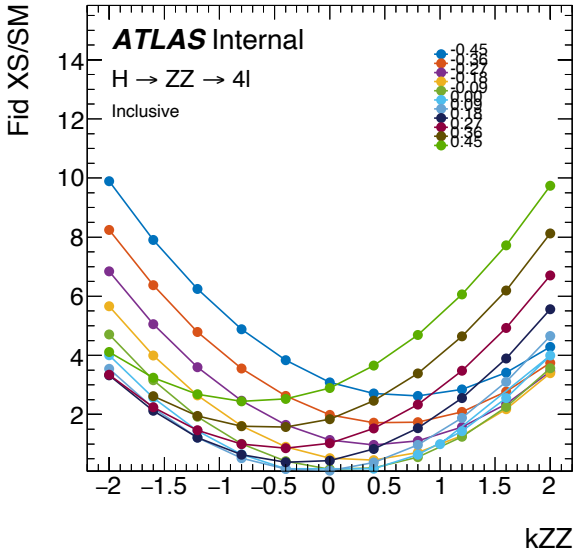
$$\mathcal{A}_{n.c.}\left[h \to f(p_1)\bar{f}(p_2)f'(p_3)\bar{f}'(p_4)\right] = i\frac{2m_Z^2}{v_F}\sum_{f=f_L,f_R}\sum_{f'=f'_L,f'_R}(\bar{f}\gamma_\mu f)(\bar{f}'\gamma_\nu f')\mathcal{T}^{\mu\nu}(q_1,q_2)$$

$$\mathcal{T}^{\mu\nu}(q_1,q_2) = \left[F_1^{ff'}(q_1^2,q_2^2)g^{\mu\nu} + F_3^{ff'}(q_1^2,q_2^2)\frac{q_1\cdot q_2\; g^{\mu\nu} - q_2^{\mu}q_1^{\nu}}{m_Z^2} + F_4^{ff'}(q_1^2,q_2^2)\frac{\varepsilon^{\mu\nu\rho\sigma}q_{2\rho}q_{1\sigma}}{m_Z^2}\right]$$

The double differential decay distribution in q_1 and q_2 leads to a quadratic polynomial function in k = (kZZ; eElL; eElR; eMuL; eMuR), therefore, the decay amplitude can be written as a function of the POs as follow:

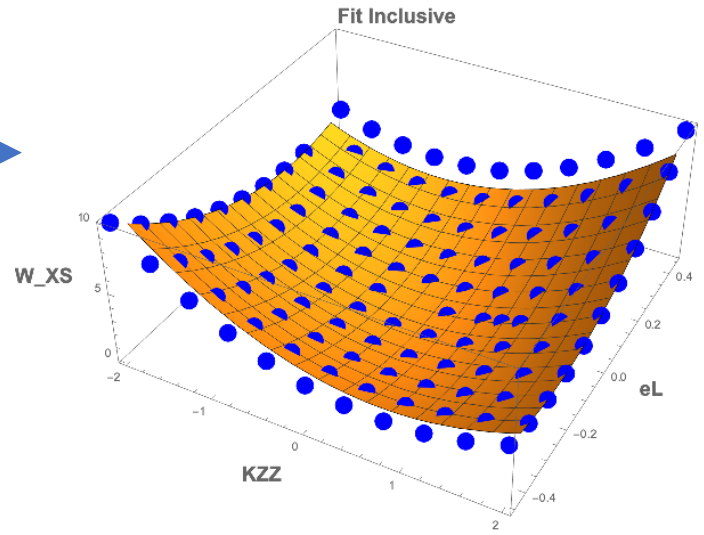
$$\frac{d^2\Gamma_{h\to 4l}}{dm_{12}dm_{34}} = \sum_{j\geq i} A_{ij}k_ik_j$$

1. Compute thes cross sections for these couplings values

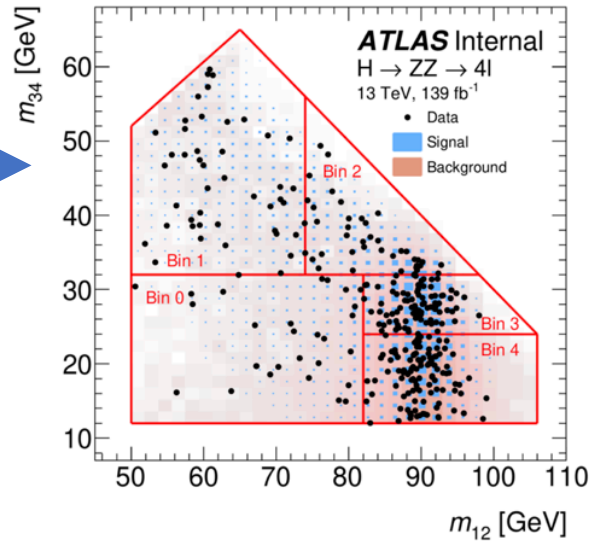


2. Fit it with a parabolic function

$$f(x) = ax^2 + by^2 + cxy + dx + ey + f$$



3. Reparametrize the measured cross section in differential bins m_{12} vs m_{34}



Statistical Method

- Include the parametrization in the PDF used to compute the **Negative Log – Likelihood ratio (NLL)**

$$NLL = -2\ln\frac{\mathcal{L}(\vec{\sigma},\hat{\hat{\vec{\theta}}}(\vec{\sigma}))}{\mathcal{L}(\hat{\vec{\sigma}},\hat{\vec{\theta}})}$$

- Likelihood ratio is always respect to another hypothesis
  - Test statistic computed with respect to the best fit from the model

$$-2\ln\frac{\mathcal{L}(\sigma(\vec{\kappa}),\hat{\hat{\vec{\theta}}}(\vec{\kappa}))}{\mathcal{L}(\sigma(\hat{\vec{\kappa}}),\hat{\vec{\theta}})}$$

- Wilk's Theorem: NLL is asymptotically χ^2_k – distributed with k degrees of freedom, which correspond to the number of variables being tested

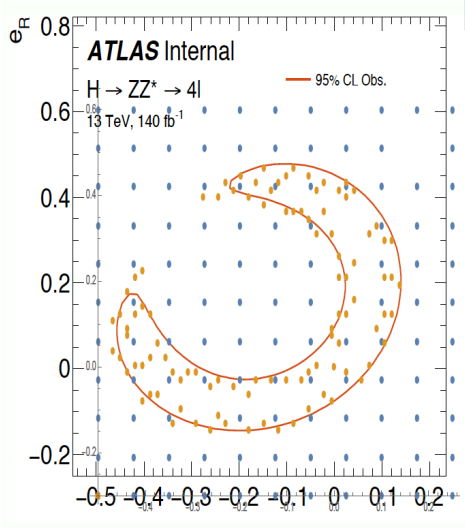
- We have more measurements than number of independent BSM couplings
  - Map 5 cross section measurements (one for each m_{12} vs m_{34} bin) to an exclusion plane in 2 coupling dimensions → 2 Degrees of Freedom

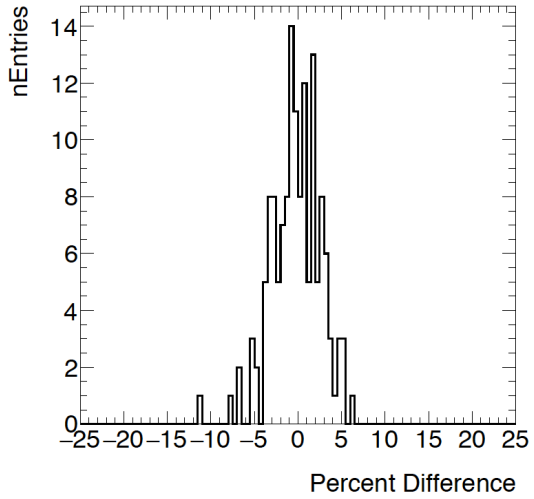
Validation Tests

Validate Cross Section Parametization

- Additional points has been generated around the expected 68% and 95% limits.
- Compare the NLL computed with the fitting function for a set of PO coordinates and NLL computed inputting the MC estimation of the cross section for the same set of PO

$$\frac{NLL(XS_{param}) - NLL(XS_{MC})}{NLL(XS_{MC})}$$

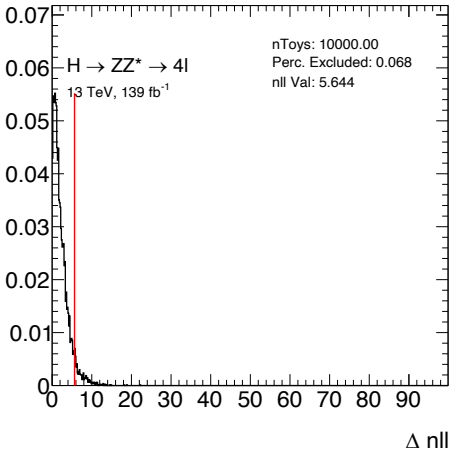


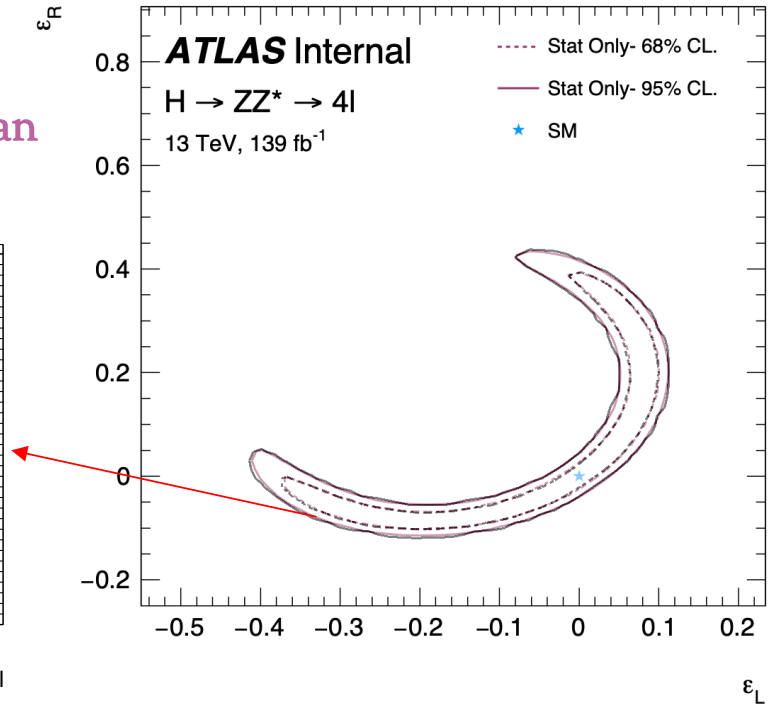


Differences are below 5%

Pink: Nominal NLL Scan

Grey: Toy Scan





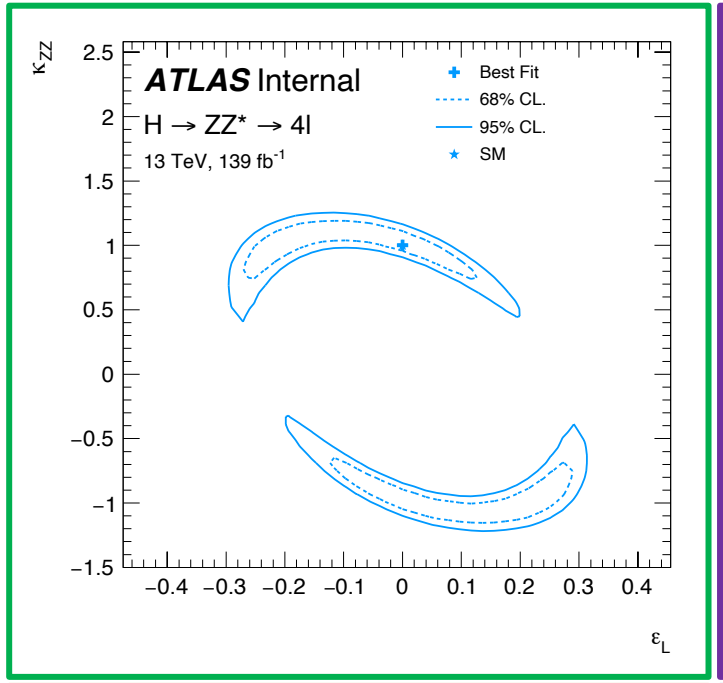
Validate the Coverage with Toys

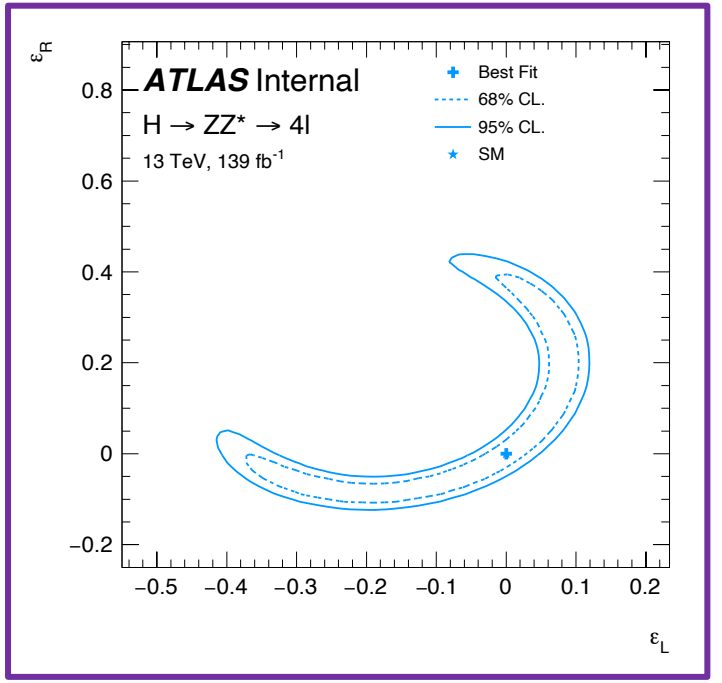
- Generate toys for a given couplings point
- Build a distribution of NLL for the toys
- Check the right exclusion area at that point (po1,po2) computing the integral of the:

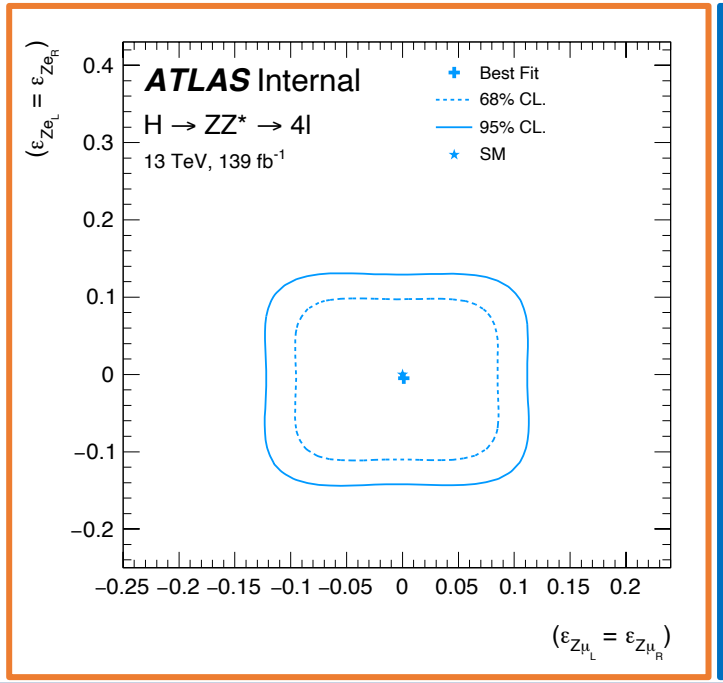
  NLL > Nominal_NLL(po1,po2)

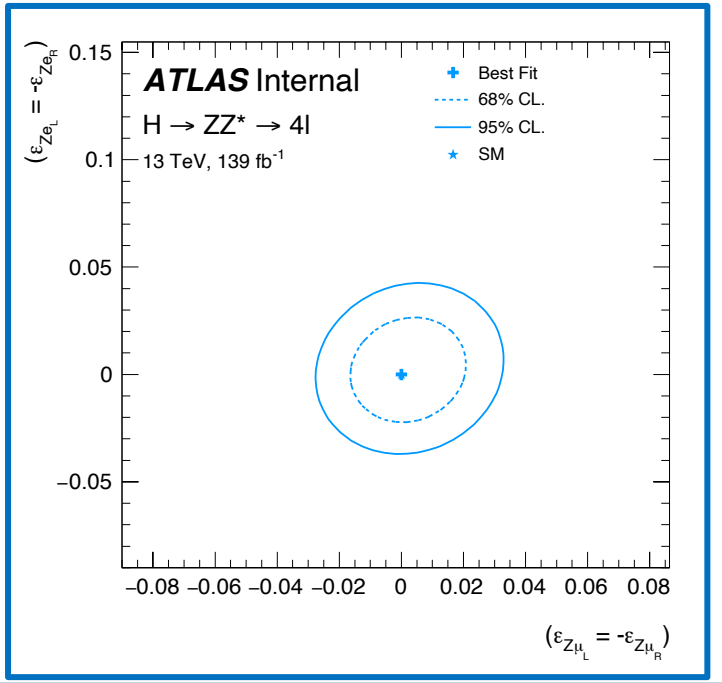
PO Expected Results

- Linear EFT – inspired
- Flavour – Universal Contact Terms
- Flavour Violation Vector Contact Terms
- Flavour Violation Axial Contact Terms





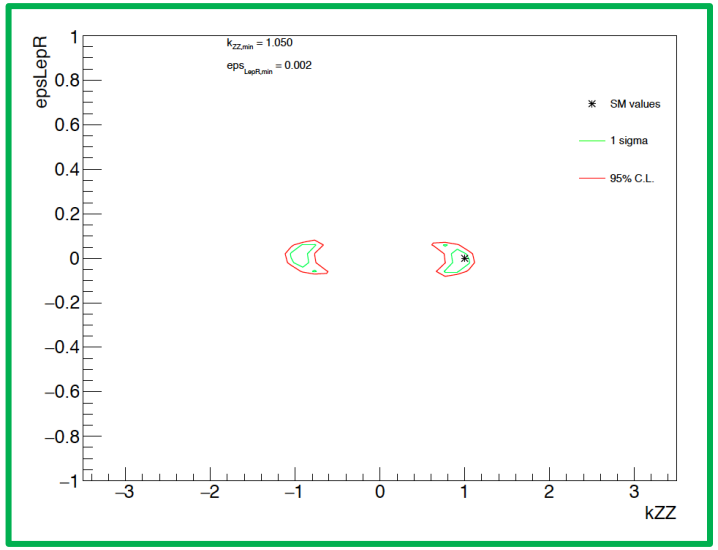


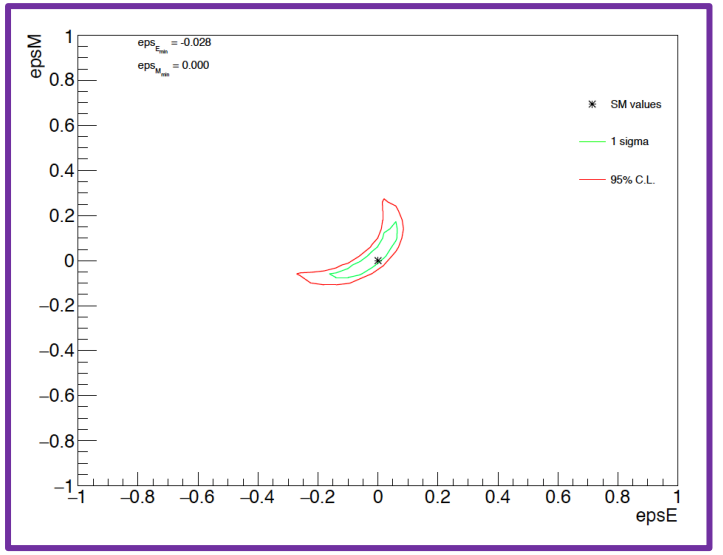


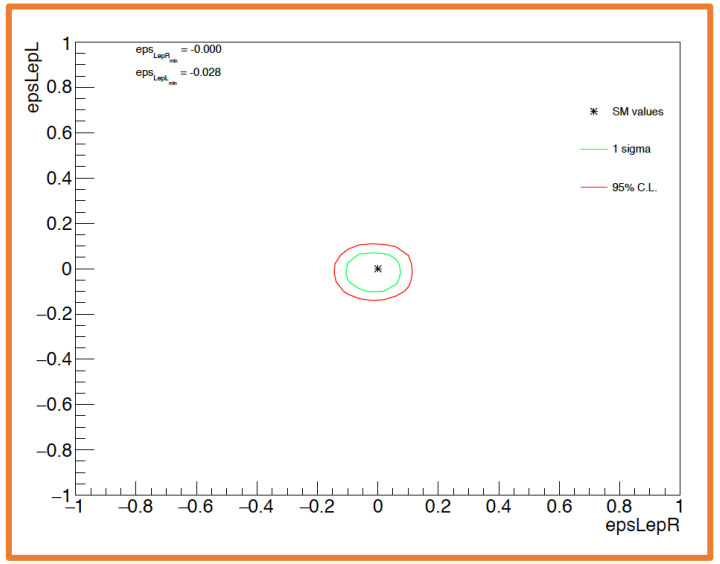
Prospect @ 300 fb^{-1}

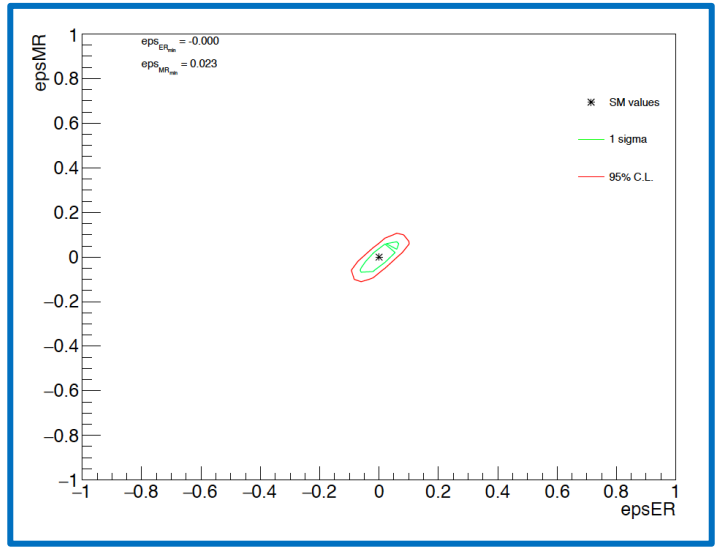
G. Mancini

- Linear EFT – inspired
- Flavour – Universal Contact Terms
- Flavour Violation Vector Contact Terms
- Flavour Violation Axial Contact Terms







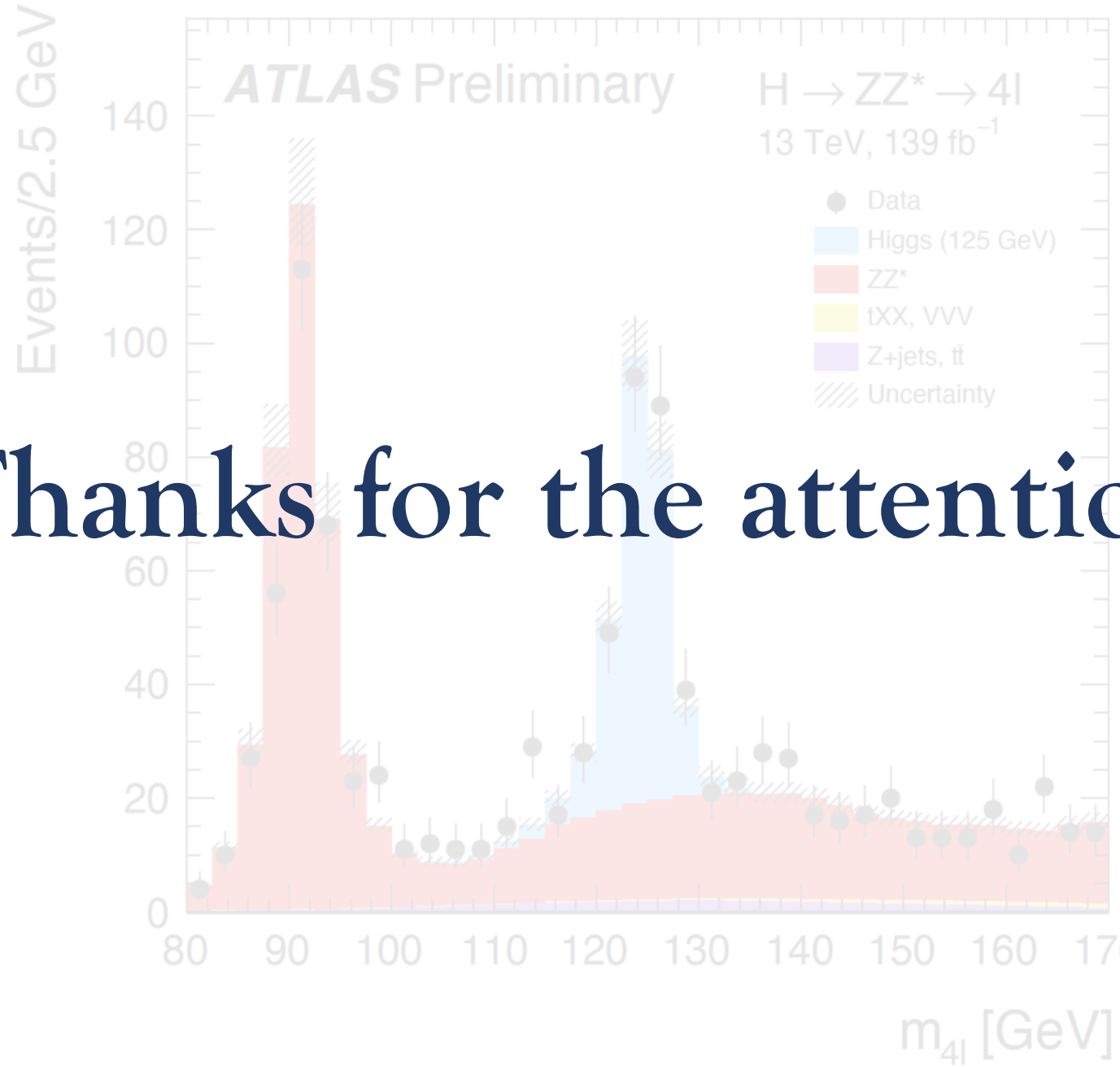


Conclusions

- Enhancement of the statistics with full Run2 dataset up to 139 fb^{-1} → precise measurements

- Measurements of the **fiducial inclusive and differential cross sections** in **H→ZZ*→4l** decay channel
  - Results compatible with SM expectation → precision improved of about 38 %
  - still statistically limited

- **Interpretation in the Pseudo – Observables framework**
  - Put constraint on BSM scanerios where contact terms interactions in the H→4l amplitudes are introduced
  - Lepton Flavour Violation scenarios have been investigated for the first time!



Thanks for the attention!