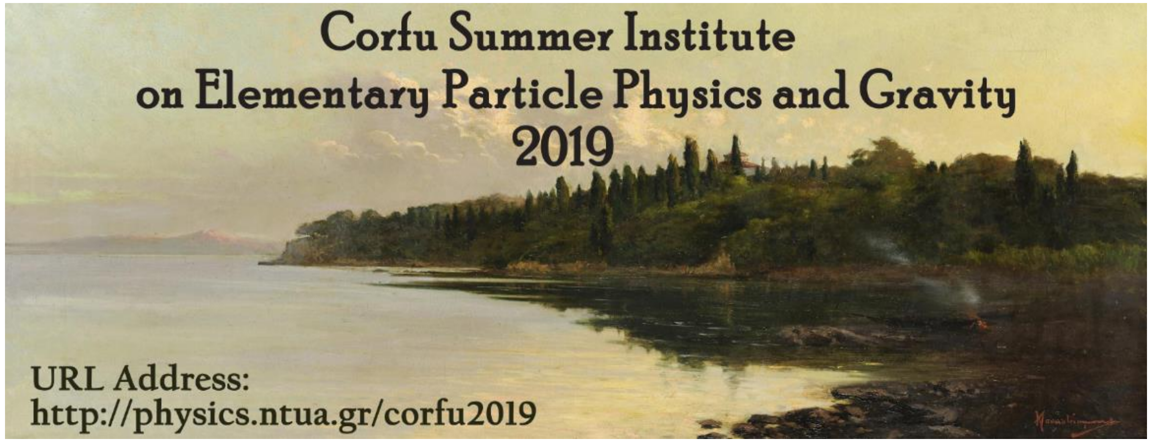
Event selection and differential cross section measurements in H->4l decays

Panagiotis Bellos

On behalf of the ATLAS Collaboration

National and Kapodistrian UNIVERSITY OF ATHENS

ATLAS EXPERIMENT



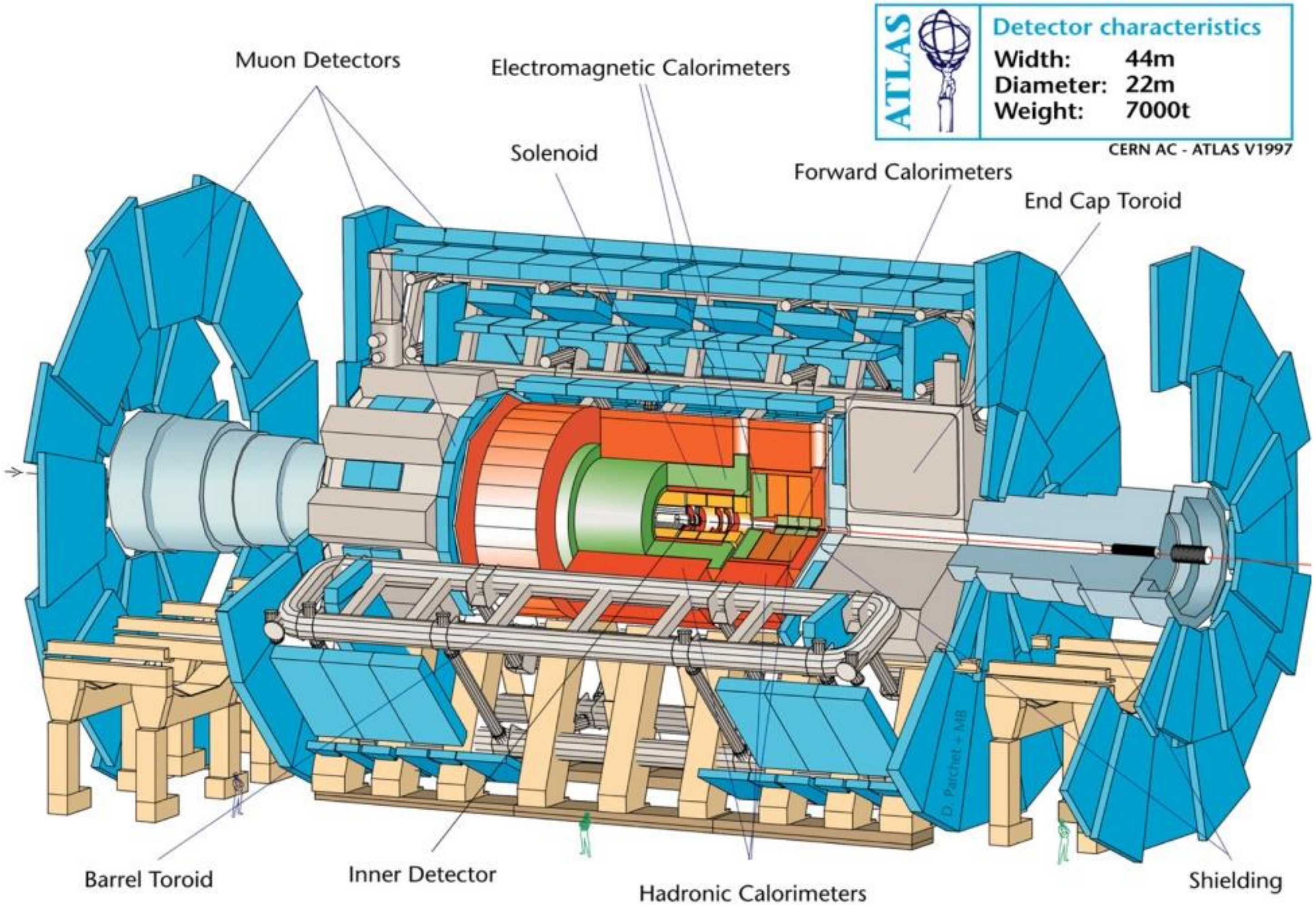
This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme «Human Resources Development, Education and Lifelong Learning» in the context of the project "Strengthening Human Resources Research Potential via Doctorate Research" (MIS-5000432), implemented by the State Scholarships Foundation (IKY)

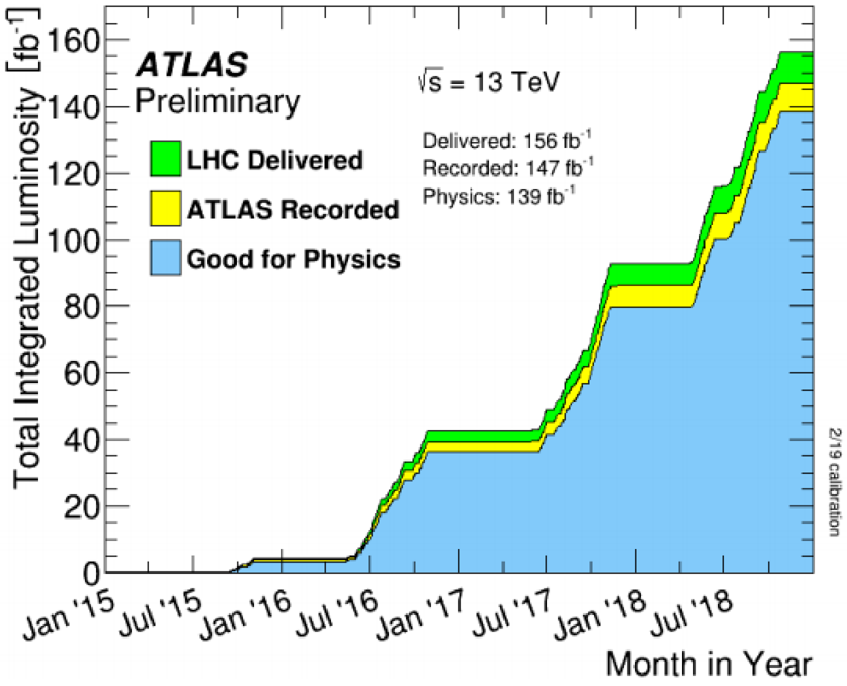
2/9/2019

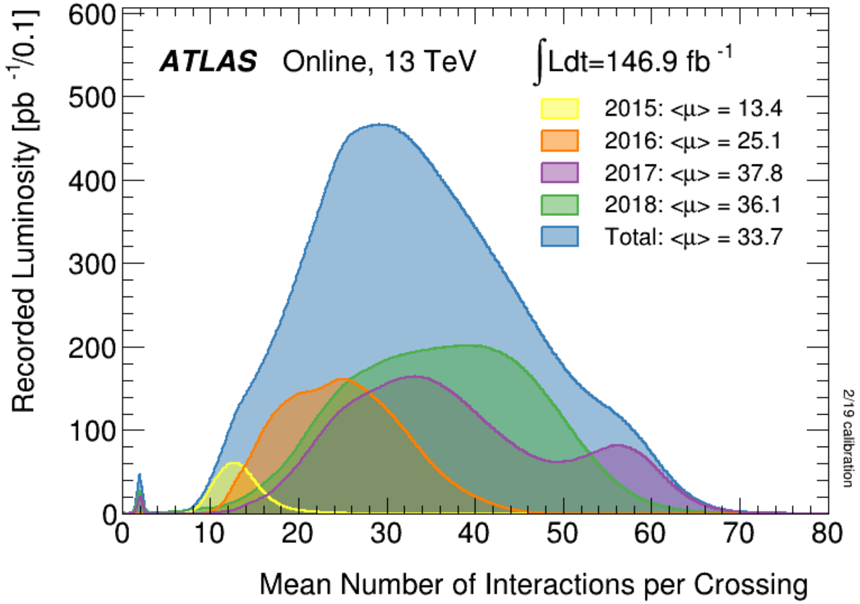
Contents

- ATLAS experiment
- Higgs boson production, decays and backgrounds
- Event selection and background estimation
- Cross Sections measurements

ATLAS Experiment





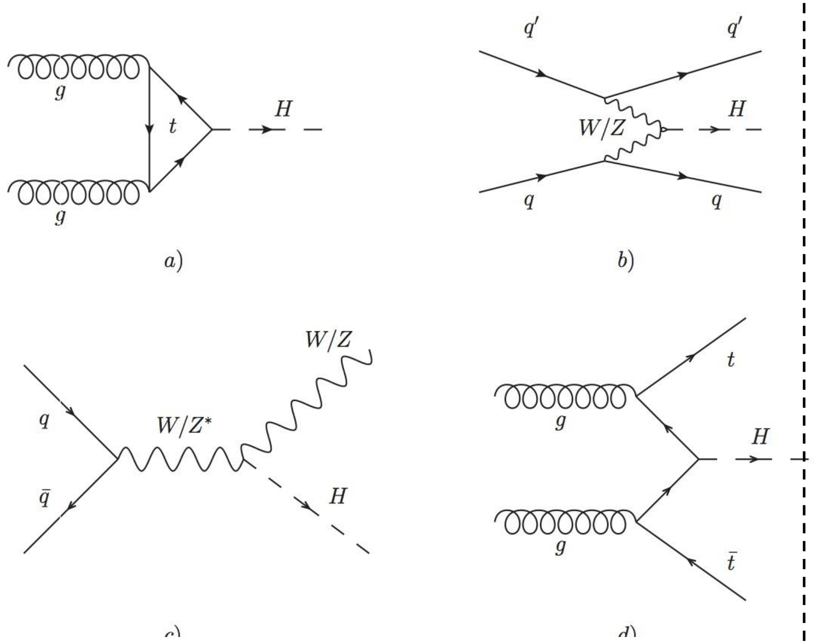


– ATLAS Detector collected ~ 140 fb^{-1} good for physics data during Run II working very successfully in a high pile-up environment

Higgs Boson Production-Decays-Bkgs

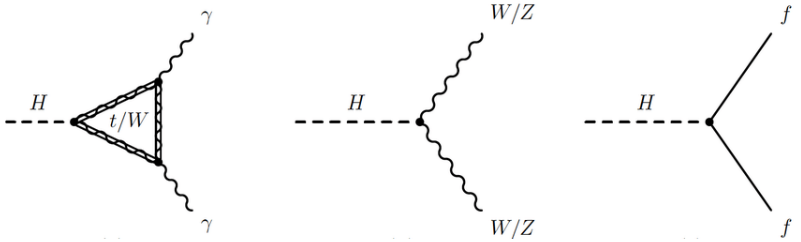
Higgs Boson production

Gluon fusion
Vector boson fusion
Associated production W/Z
Associated production $t\bar{t}$



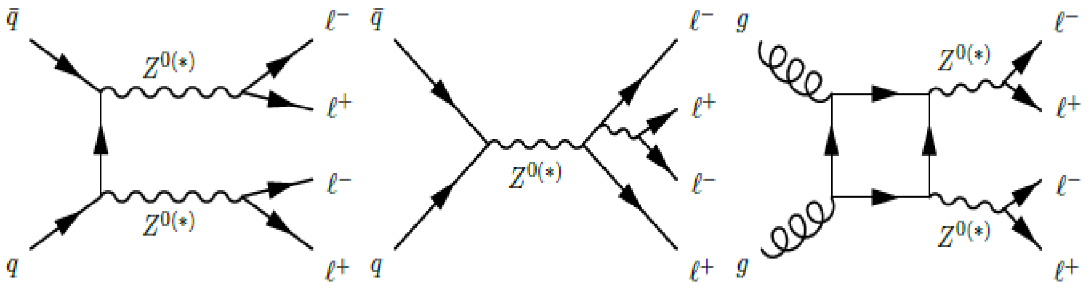
Higgs Boson Decays

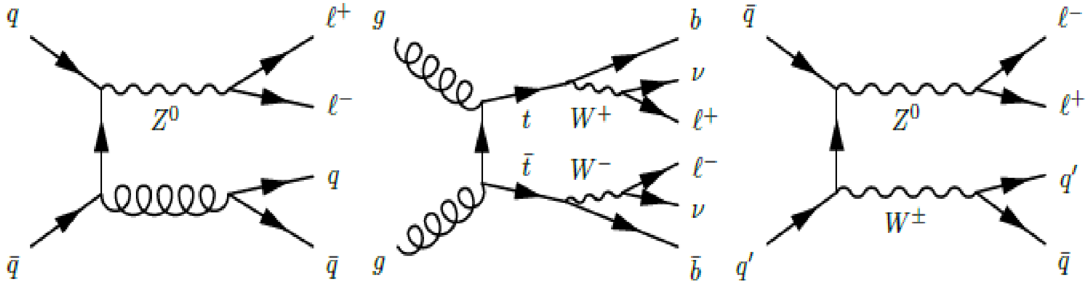
$\gamma\gamma$
W^+W^- / ZZ
$f\bar{f}$



The decay $\boldsymbol{H \rightarrow ZZ^{(*)} \rightarrow 4\ell}$ **(ℓ: e or μ)** is the "golden" channel for Higgs boson studies, due to:

- **High signal-to-background ratio**
- **Ability to completely reconstruct the final state**





$H \rightarrow 4\ell$

Non-resonant ZZ bkgs

qq $\rightarrow ZZ$
$gg \rightarrow ZZ$
VVV
$t\bar{t} + V$

$H \rightarrow 4\ell$

Reducible bkgs

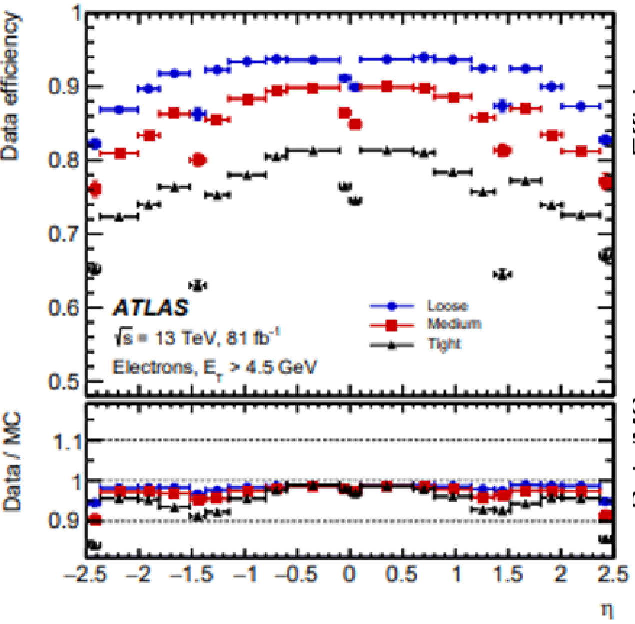
$Z + Jets$
$t\bar{t}$
WZ

4ℓ Event Selection

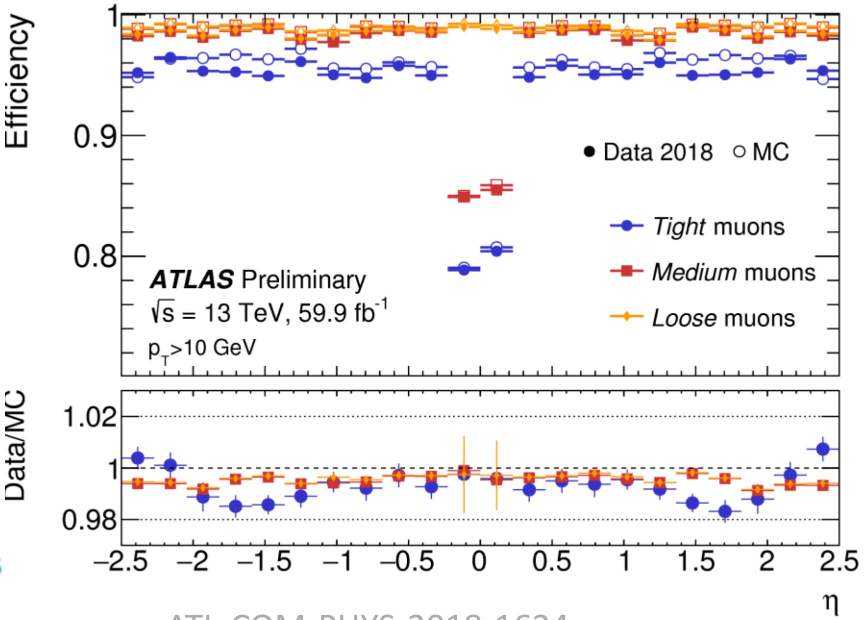
- **Leptons are crucial** to some of the most important physics analyses
- **Very high efficiency** for both e and μ
- 3 different working points (loose, medium, tight)
- Use loose identification criteria for the leptons of our analysis e (~ 90%) and μ (~ 99%) efficiencies

Event Selection Summary

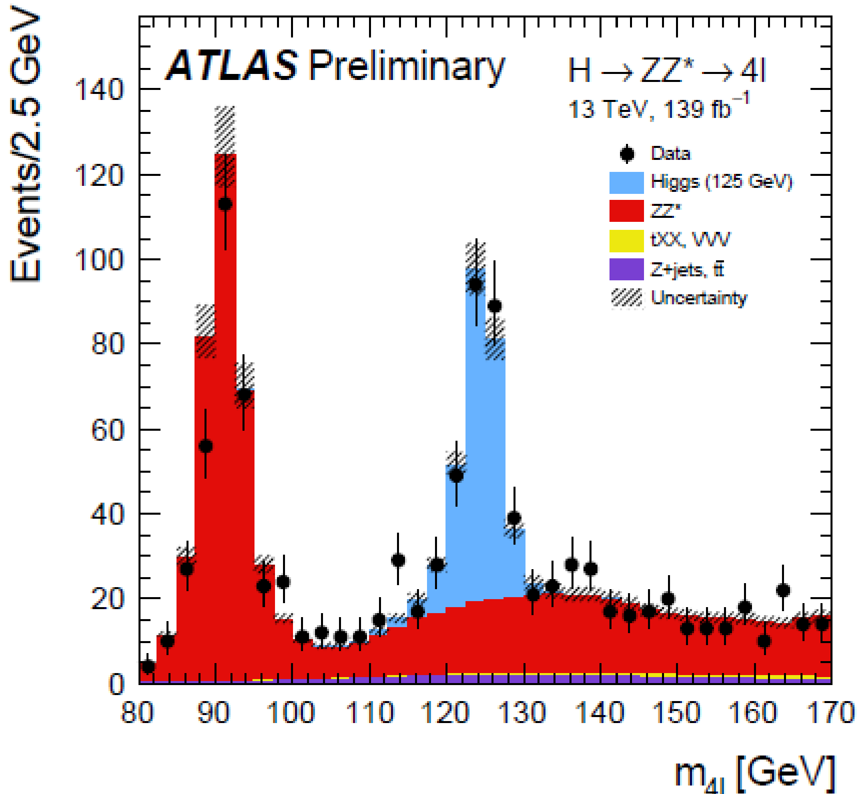
- 2 pairs of leptons (dileptons) with invariant masses, flavor and charge compatible with the decayed ZZ* assumption
- Isolated (to reject leptons inside Jets)
- Small impact parameter significance
- Coming from the same vertex (to reject leptons from heavy flavor Jets)
- Best quadruplet according to Matrix Element



arXiv:1908.00005v1



ATL-COM-PHYS-2018-1624



ATLAS-CONF-2019-025

Background Data Driven Estimation

- **The bkg is estimated in a Data Driven way** in order to avoid the theoretical and simulation uncertainties.

- The properties of the reducible bkg are determined mainly by the subleading dilepton.

- So it is separated to :
  - $\ell\ell\mu\mu$, mostly **Heavy Flavor jets** produced in association with a **Z** boson or in $t\bar{t}$ decays. Minor **Z+LF jets** contribution.
  - $\ell\ell ee$, mainly coming from **light-flavor jets mis-identified** as electrons **(f)** and **Photon conversions or FSR (γ).** Lower contribution from **HF jets.**

- Inverting/changing some selection criteria, special **Control Regions** (CRs) with high bkg purity are constructed, suitable for the bkg estimation.

- CRs are fitted and the yields are extrapolated to the Signal Region (SR).

- **The irreducible bkg (ZZ*) is also estimated in a data driven way.**

- Consists of mainly of **qq->ZZ** and minor contributions from **gg->ZZ, qq->ZZjj.**

- Estimated in the final fit including both the Signal Region and the side bands

2 types of Cross Sections Measurements

The Cross Sections can be used to **test SM predictions** and **constrain beyond SM effects** (Yukawa couplings, Higher Order QCD corrections sensitivity, new physics via EFT, etc)

Fiducial XS

- Cross Sections are measured in the **fiducial phase space** which closely **follow the kinematic and event selection criteria**
- No assumption is made for production mode (model independent)
- Results are extrapolated to the full phase space to be combined with the rest the Higgs boson decay channels
- Differential distributions are also measured

$$\sigma^{fid} = \sigma \cdot A \cdot BR(H \rightarrow 4l) = \frac{N_s}{C \cdot L_{int}}$$

N_s : *number of signal events*

$A = \frac{N_{fid}}{N_{truth}}$: *Detector Acceptance*

$C = \frac{N_{rec}}{N_{fid}}$: *Detector Efficiency*

BR : *Branching Ratio*

L_{int} : *Integrated Luminosity*

Production XS

- Cross sections are also measured according to the **production modes** within the **theory defined phase-space**
- Measurements are performed using a **simplified template (STXS)**, targeting sensitivity to the different couplings.

$$\sigma^{pm} = \sigma \cdot BR(H \rightarrow ZZ) = \frac{N_s}{A \cdot C \cdot L_{int} \cdot BR(ZZ \rightarrow 4l)}$$

Systematic Uncertainties

The uncertainties affect

- Signal acceptance
- Physics object reconstruction and identification efficiency
- Selection efficiency
- Response matrices
- NN discriminant distributions
- Background estimates

Experimental uncertainties

– Luminosity
– Electron/muon reconstruction and identification efficiencies and pile-up modelling
– Jet energy scale/resolution and b-tagging efficiencies
– Uncertainties on reducible background

Theoretical uncertainties

– Theoretical uncertainties on ZZ and tXX background
– Theoretical uncertainties on signal :
Parton Density Function
QCD scale
Showering algorithm
– Uncertainties on Signal composition

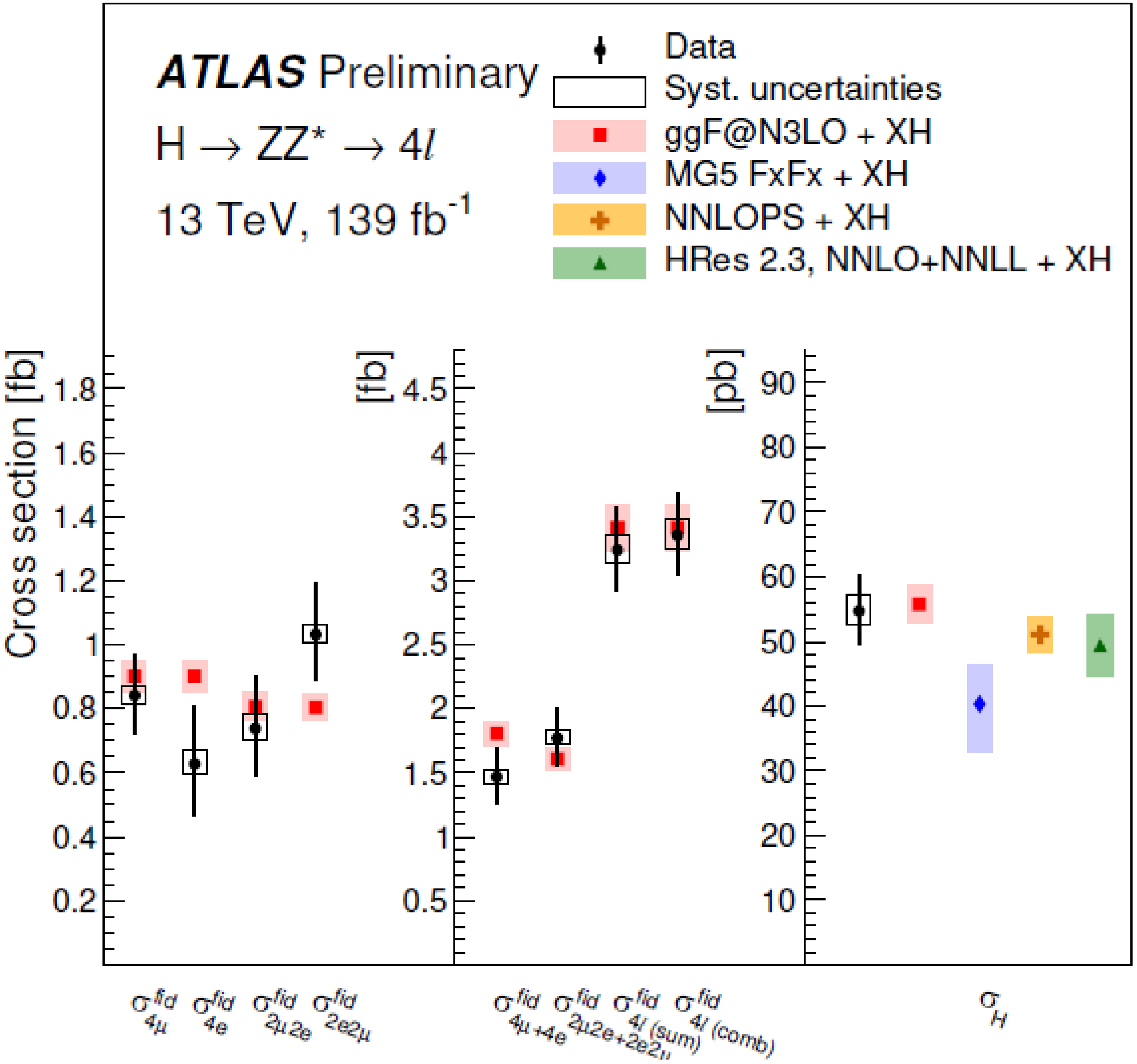
Measurement	Experimental uncertainties [%]				Theory uncertainties [%]					
	Lum.	e, μ, pile-up	Jets, flavour tagging	Reducible backgr.	ZZ^* backgr	tXX backgr.	Signal PDF	Signal QCD scale	Signal Parton Shower	Signal Composition
Fiducial cross section										
σ_{comb}	1.7	2.5	–	< 0.5	1	< 0.5	< 0.5	2	1	< 0.5
Per decay final state fiducial cross sections										
4μ	1.7	2.5	–	0.5	1	< 0.5	< 0.5	2	1	< 0.5
$4e$	1.7	7	–	0.5	1.5	< 0.5	< 0.5	2	0.5	< 0.5
$2\mu 2e$	1.7	5.5	–	0.5	1	< 0.5	< 0.5	2	1.5	< 0.5
$2e2\mu$	1.7	2.0	–	0.5	1	< 0.5	< 0.5	2	1	< 0.5
Stage-0 production bin cross sections										
ggF	1.7	1.5	1	0.5	1.5	< 0.5	0.5	1	2	–
VBF	1.7	1	4.5	0.5	2	0.5	1.5	8	6	–
VH	1.8	1.5	3.5	1	5	0.5	2	12	8	–
ttH	1.7	1	4.5	1	1	0.5	0.5	8	4	–

Fiducial and Total Cross Sections

- The cross sections are measured using a binned **profile likelihood- ratio fit on m_{4l}**
- The likelihood function includes the shape and normalization **uncertainties as nuisance parameters**
- The cross sections are extrapolated to the total phase space and compared to the predictions of various event generators

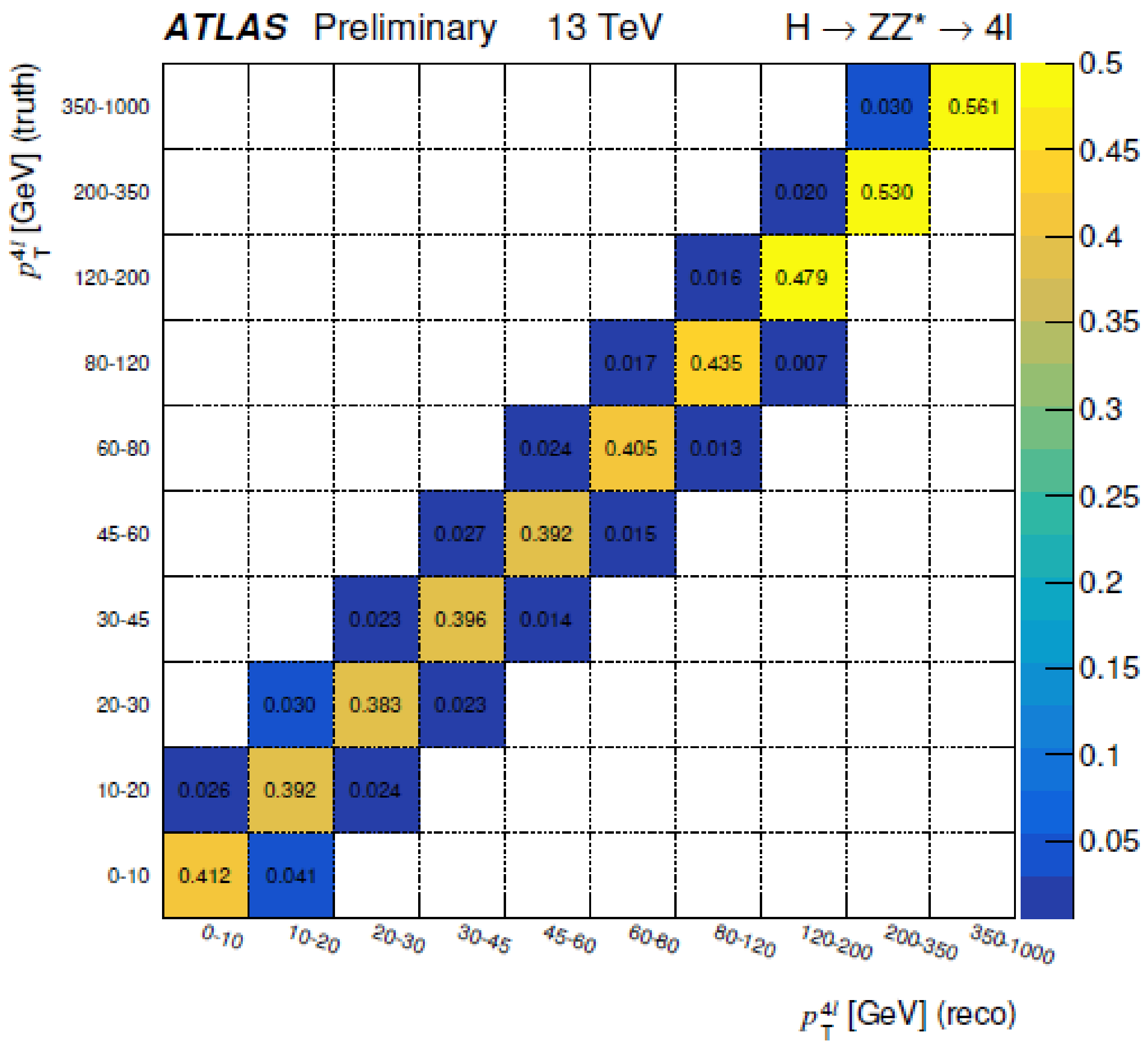
$$\sigma_{fid} = 3.35 \pm 0.30 \pm 0.12 \text{ fb}$$

$$\sigma_{tot} = 54.7 \pm 4.9 \pm 2.3 \text{ pb}$$



Differential Cross Section

- Measurement of a quantity by a real detector is effected by 3 ways
  - Limited acceptance
  - Finite resolution
  - Transformation (measure p_{T4l} instead p_{TH})
- An unfolding method is needed to extract the information at truth level
- The detector response matrix allows to account for bin-to-bin migrations in the unfolding
- It corresponds to the probability that an event generated with the fiducial volume in the observable bin j is reconstructed in the bin i.
- The response matrix is included in the likelihood fit in order to take into account all the migrations
- Migrations are small compared to the statistical uncertainty



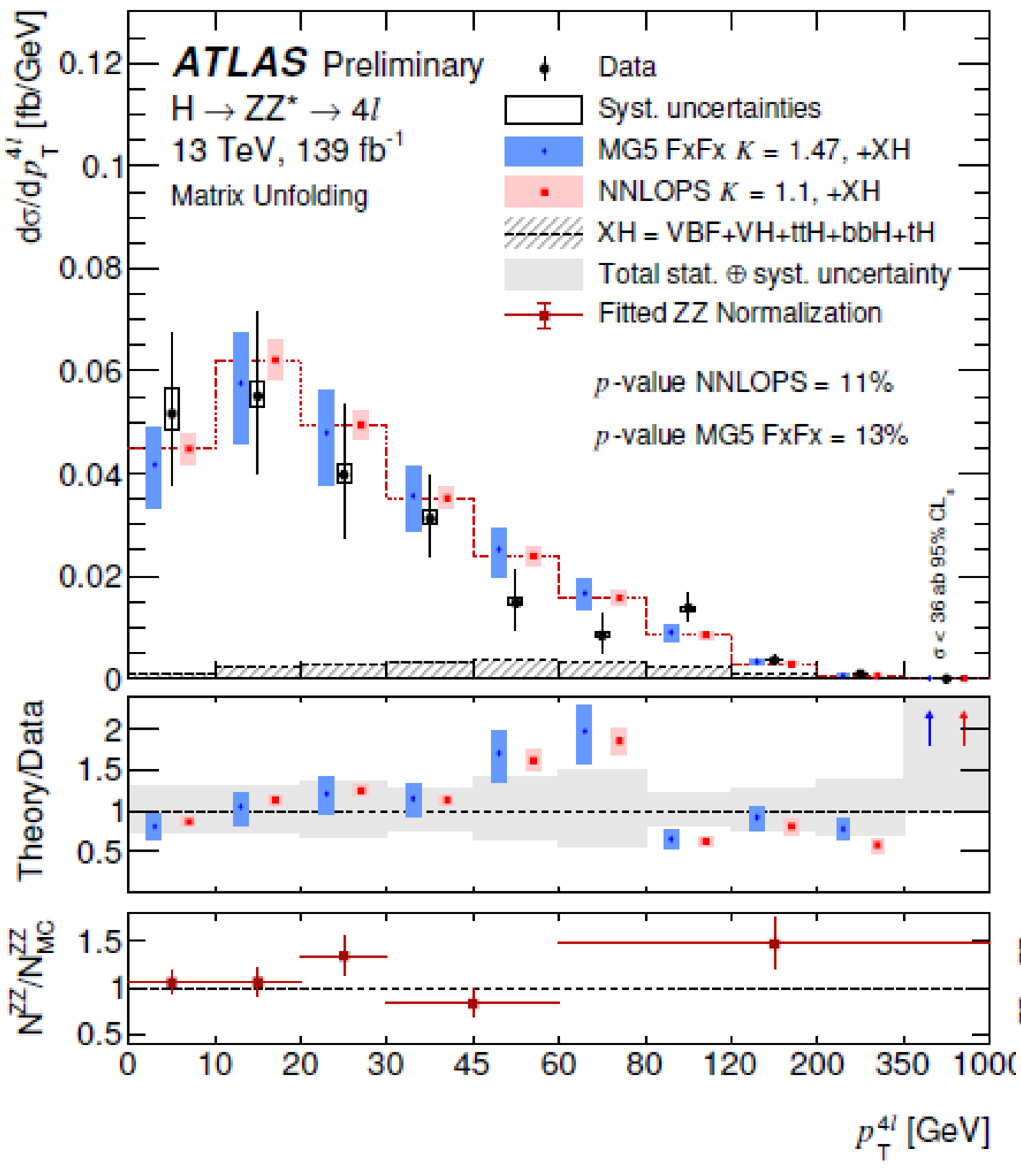
ATLAS-CONF-2019-025

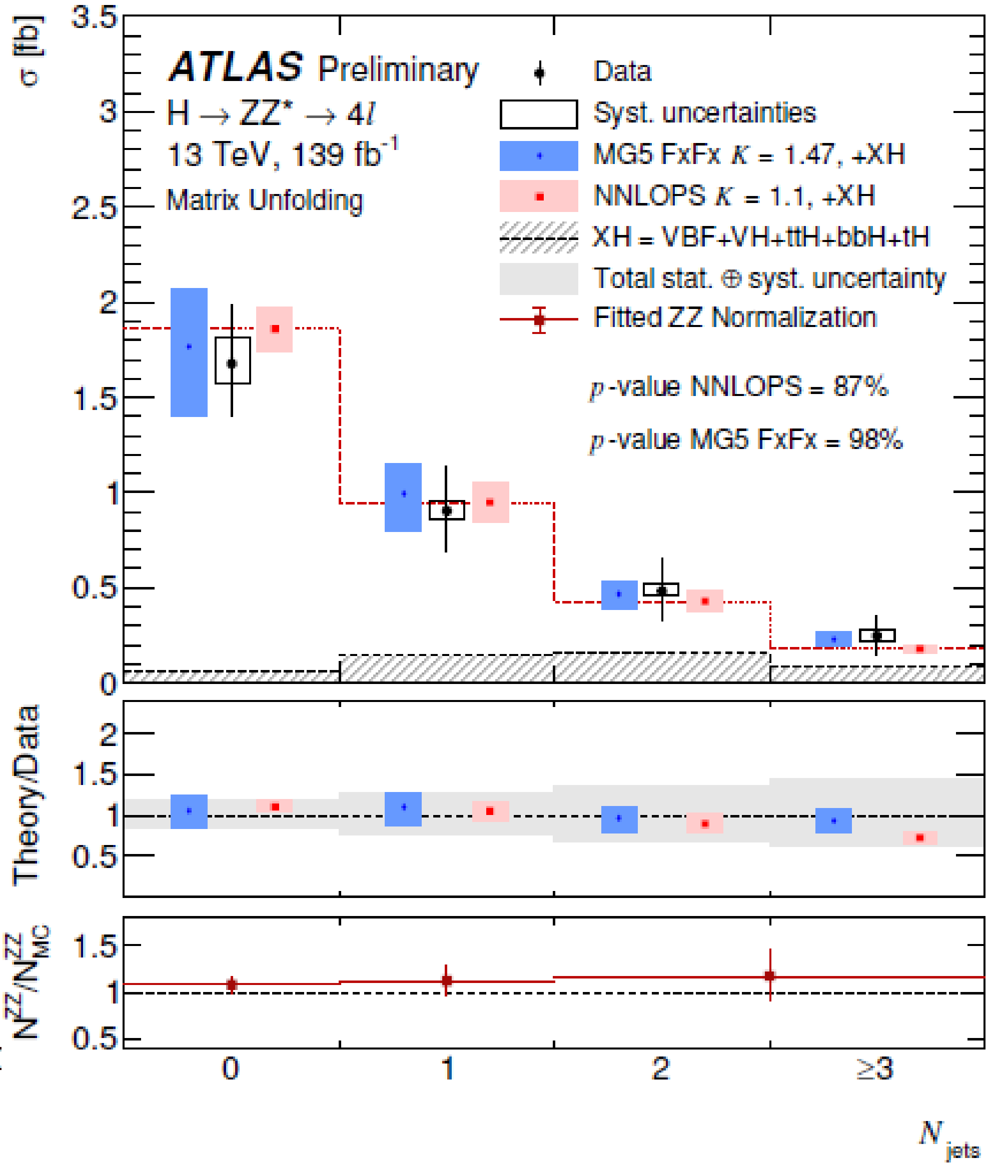
Differential Cross Sections

ATLAS-CONF-2019-025

- Differential fiducial cross sections. **Transverse Momentum** and **Number of jets** produced in association with the Higgs boson

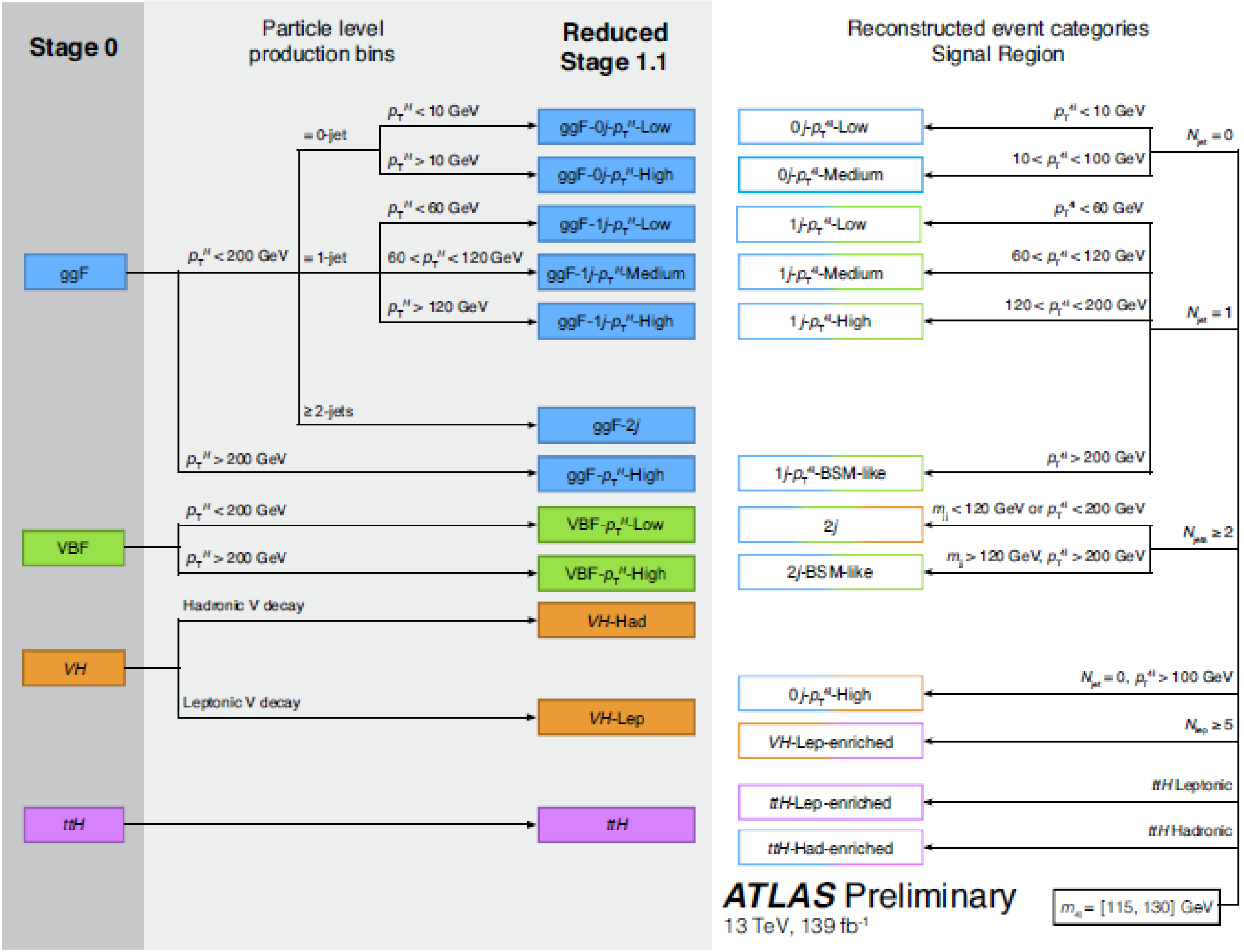
- Fitted values of the ZZ normalization factors are also shown

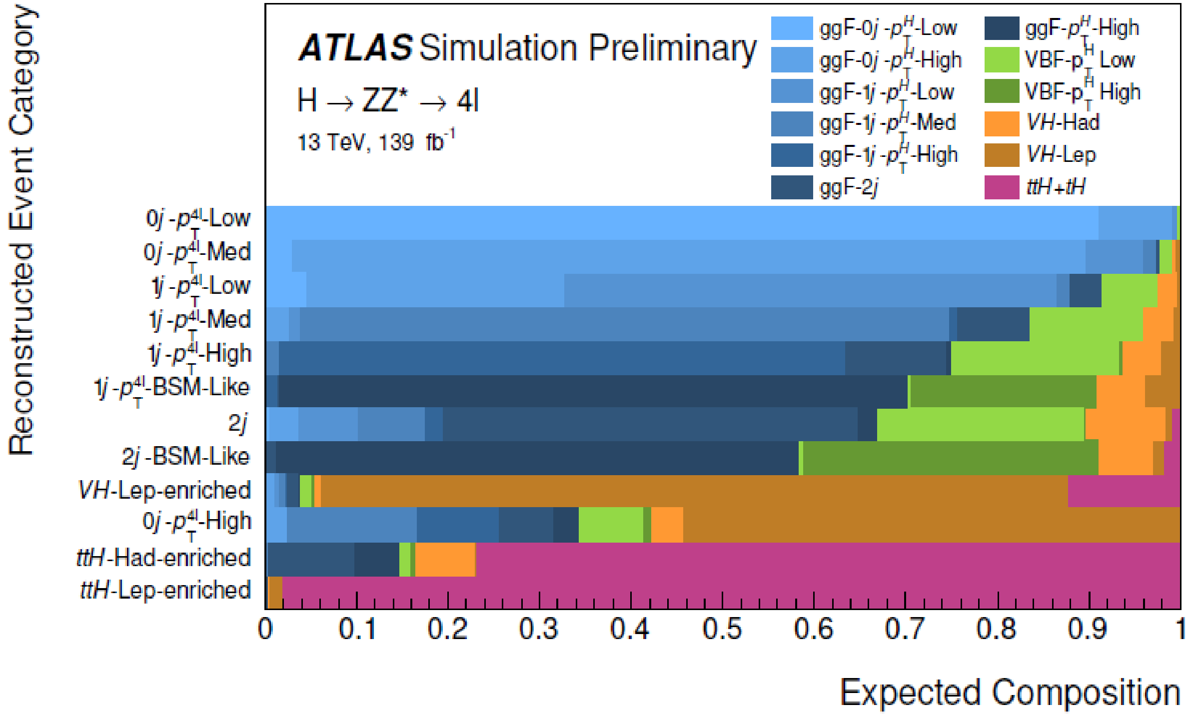




Production Modes

- Higgs events are classified into **12 categories** using N_{jet} and p_T of Higgs or jets



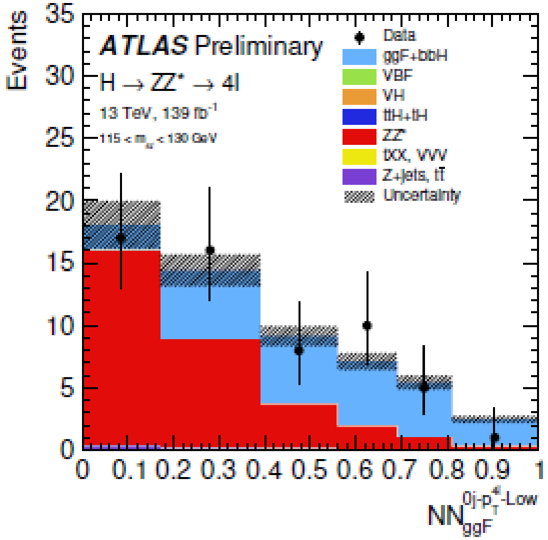


- Each of them is **sensitive to a different production mechanism** or kinematic region

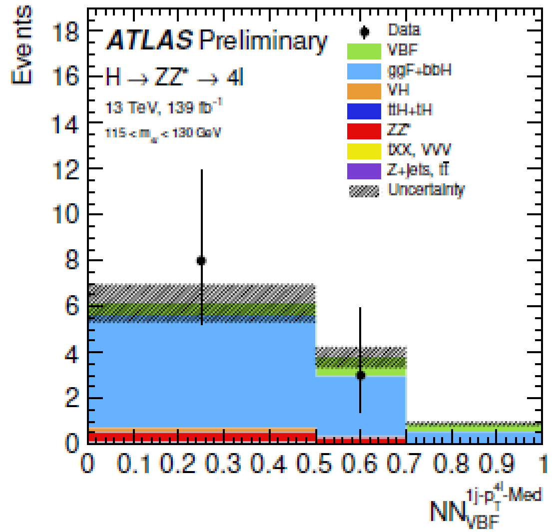
- The categories are chosen to
  Maximize measurement precision and
  Probe possible Beyond Standard Model (BSM) contributions

Production Modes NN

- **Neural Networks** are introduced for the reconstructed categories to **increase sensitivity**
- The NNs are trained on simulated SM Higgs boson signal and non-Higgs background or the other production processes
- The NNs have two or three output nodes depending on the category
- **The NN discriminants are fitted** to extract the signal contribution of each category



Category	Processes	MLP	Lep rNN	Jet rNN
$0j$	ggF,ZZ	$p_{\mathrm{T}}^{4\ell}$, D_{ZZ^*}, m_{12}, m_{34}, $\cos\theta^*$, $\cos\theta_1$, ϕ_{ZZ}	$p_{\mathrm{T},\ell}$, η_ℓ	n/a
$1j$-$p_{\mathrm{T}}^{4\ell}$-Low	ggF,VBF,ZZ	$p_{\mathrm{T}}^{4\ell}$, $p_{\mathrm{T},j}$, η_j, $\Delta R_{4\ell j}$, D_{ZZ^*}	$p_{\mathrm{T},\ell}$, η_ℓ	n/a
$1j$-$p_{\mathrm{T}}^{4\ell}$-Med	ggF, VBF, ZZ	$p_{\mathrm{T}}^{4\ell}$, $p_{\mathrm{T},j}$, η_j, $E_{\mathrm{T}}^{\mathrm{miss}}$, $\Delta R_{4\ell j}$, D_{ZZ^*}, $\eta_{4\ell}$	-	n/a
$1j$-$p_{\mathrm{T}}^{4\ell}$-High	ggF, VBF	$p_{\mathrm{T}}^{4\ell}$, $p_{\mathrm{T},j}$, η_j, $\Delta R_{4\ell j}$, $\eta_{4\ell}$, $E_{\mathrm{T}}^{\mathrm{miss}}$	$p_{\mathrm{T},\ell}$	n/a
$2j$	ggF, VBF, VH	m_{jj}, $\Delta\eta_{\mathrm{jj}}$, $p_{\mathrm{T},4\ell jj}$	$p_{\mathrm{T},\ell}$, η_ℓ	$p_{\mathrm{T},j}$, η_j
$2j$-BSM-like	ggF, VBF	$\Delta\eta_{\mathrm{jj}}$, $\Delta\eta_{4\ell jj}$, $p_{\mathrm{T},4\ell jj}$	$p_{\mathrm{T},\ell}$, η_ℓ	$p_{\mathrm{T},j}$, η_j
VH-Lep-enriched	$t\bar{t}H$, VH	N_{jets}, $N_{b-\mathrm{jets}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, HT, $\ln(\lvert\mathcal{M}_{sig}\rvert^2)$	$p_{\mathrm{T},\ell}$	n/a
$t\bar{t}H$-Had-enriched	$t\bar{t}H$, tXX, ggF	$p_{\mathrm{T}}^{4\ell}$, m_{jj}, $\Delta\eta_{\mathrm{jj}}$, $p_{\mathrm{T},jj}$, $\min(\Delta R_{Zj})$, $\Delta\eta_{4\ell jj}$, N_{jets}, $N_{b-\mathrm{jets}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, $\min(\Delta R_{4\ell j})$, HT, $\ln(\lvert\mathcal{M}_{sig}\rvert^2)$	$p_{\mathrm{T},\ell}$, η_ℓ	$p_{\mathrm{T},j}$, η_j

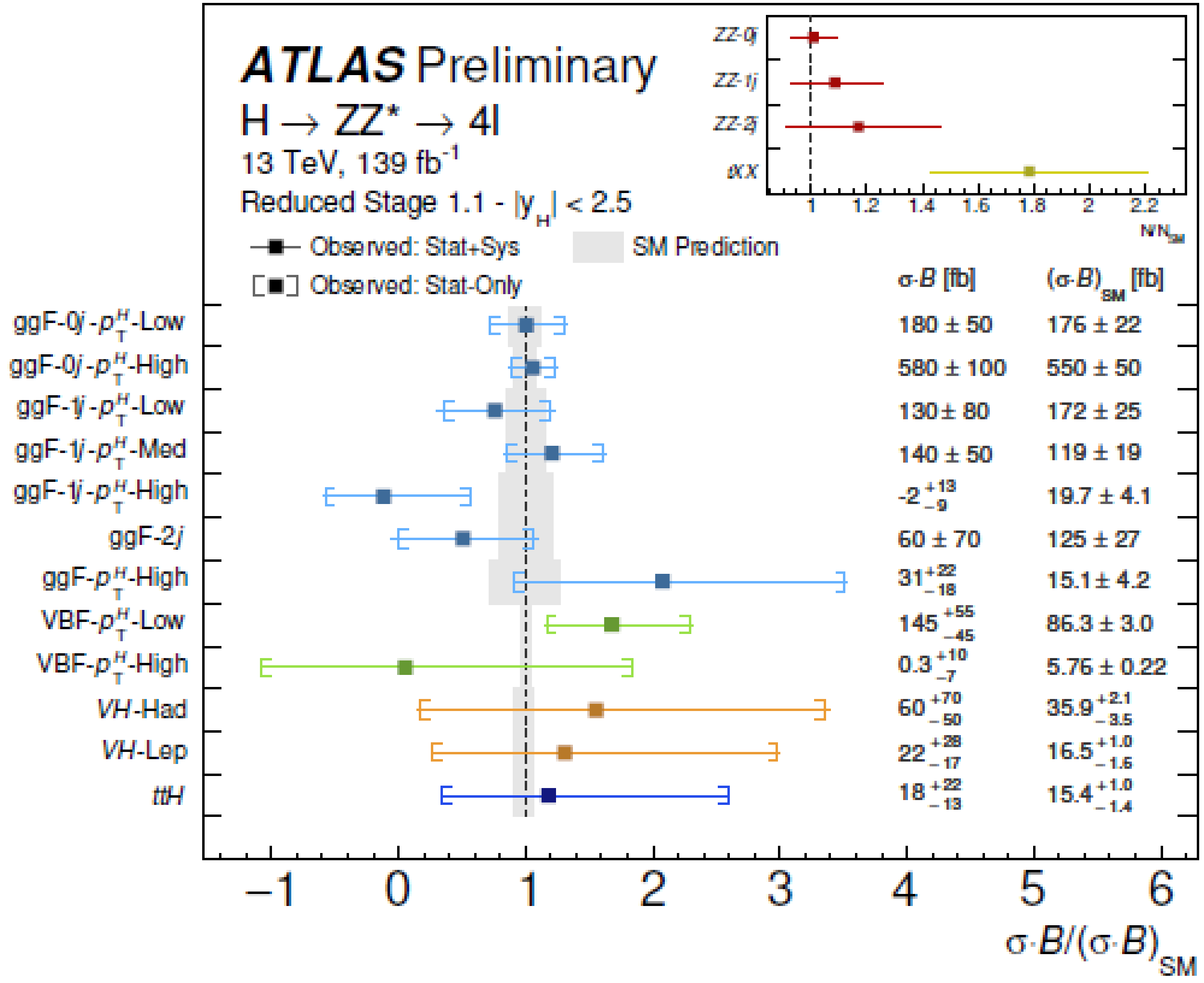


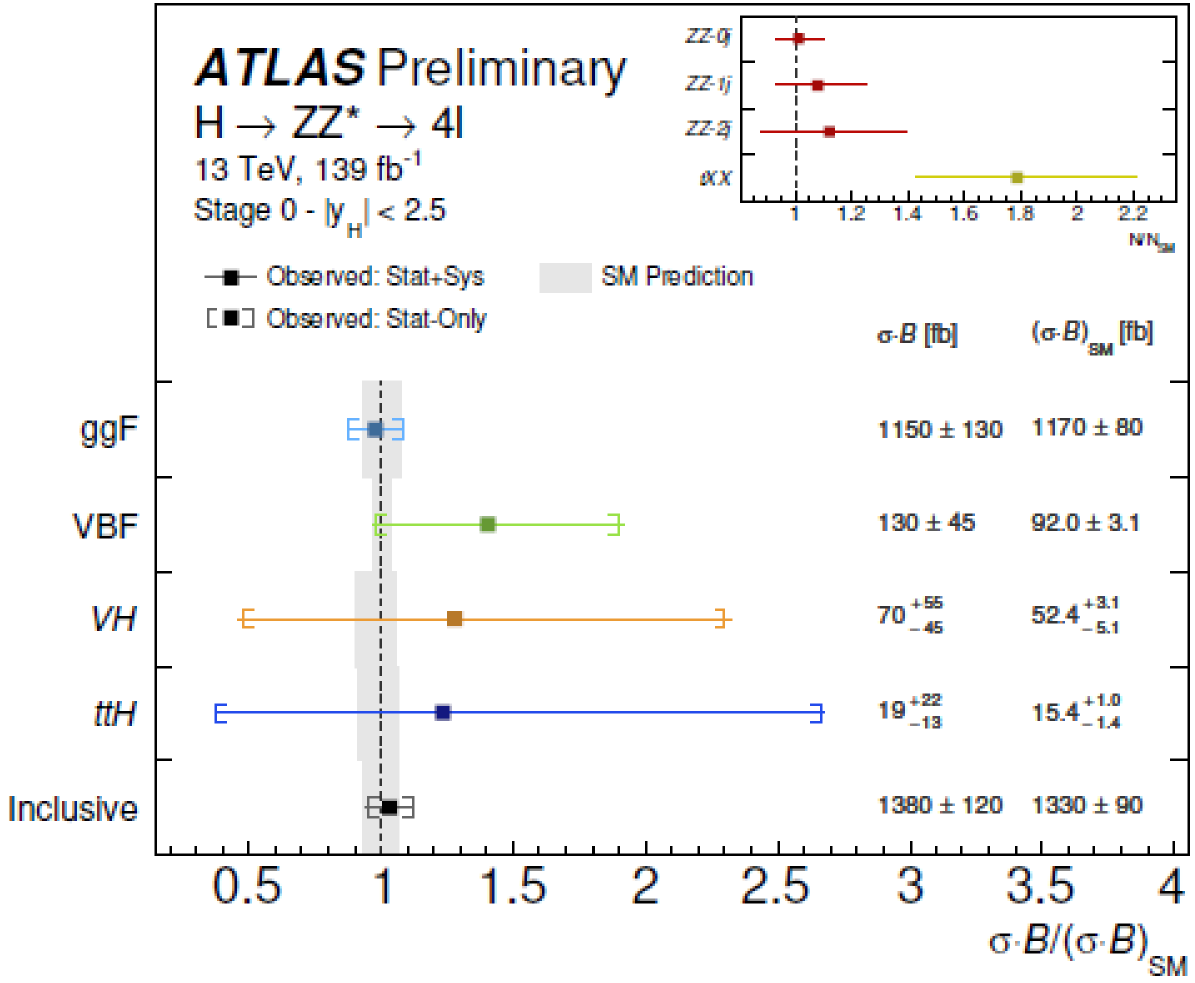
- The bin boundaries are chosen to maximize the significance of the targeted signal in each category

ATLAS-CONF-2019-025

Production Modes Cross Sections

The observed and expected SM values of the production cross sections





ATLAS-CONF-2019-025

ZZ and tXX backgrounds are allowed to float and constrained by the sidebands

Summary

- The ATLAS experiment collected ~ 140 fb^{-1} during Run II

- Inclusive, differential and production XSs were measured close to the theoretically predicted values

- For the inclusive $\sigma_{fid} = 3.35 \ \pm 0.30 \ \pm 0.12$ fb , $SM\ expectation : 3.41 \ \pm 0.18$ fb

- The differential XSs shapes are in agreement with the event generators expectation

- For the significant production modes ggF and VBF
  ggF : $\sigma \cdot \mathrm{B}(\mathrm{H} \to \mathrm{ZZ}^{*}) = 1.15 \ \pm 0.13$ pb , $SM\ expectation : 1.17 \pm 0.08$ pb
  VBF: $\sigma \cdot \mathrm{B}(\mathrm{H} \to \mathrm{ZZ}^{*}) = 0.13 \ \pm 0.04$ pb , $SM\ expectation : 0.0920 \pm 0.0031$ pb

- The uncertainties in all measurements are statistically dominated
  So we expect a considerably improved precision in Run III and even more with HL-LHC later on

Back up

Cross sections

$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125$ GeV					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+5\%}_{-5\%}$	$1.24^{+2\%}_{-2\%}$	$0.58^{+3\%}_{-3\%}$	$0.34^{+4\%}_{-4\%}$	$0.09^{+8\%}_{-14\%}$	19.1
8	$21.4^{+5\%}_{-5\%}$	$1.60^{+2\%}_{-2\%}$	$0.70^{+3\%}_{-3\%}$	$0.42^{+5\%}_{-5\%}$	$0.13^{+8\%}_{-13\%}$	24.2
13	$48.6^{+5\%}_{-5\%}$	$3.78^{+2\%}_{-2\%}$	$1.37^{+2\%}_{-2\%}$	$0.88^{+5\%}_{-5\%}$	$0.50^{+9\%}_{-13\%}$	55.1
14	$54.7^{+5\%}_{-5\%}$	$4.28^{+2\%}_{-2\%}$	$1.51^{+2\%}_{-2\%}$	$0.99^{+5\%}_{-5\%}$	$0.60^{+9\%}_{-13\%}$	62.1

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	$^{+5.0\%}_{-4.9\%}$
$H \to ZZ$	2.62×10^{-2}	$^{+4.3\%}_{-4.1\%}$
$H \to W^+W^-$	2.14×10^{-1}	$^{+4.3\%}_{-4.2\%}$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$^{+5.7\%}_{-5.7\%}$
$H \to b\bar{b}$	5.84×10^{-1}	$^{+3.2\%}_{-3.3\%}$
$H \to Z\gamma$	1.53×10^{-3}	$^{+9.0\%}_{-8.9\%}$
$H \to \mu^+\mu^-$	2.18×10^{-4}	$^{+6.0\%}_{-5.9\%}$

Cross section [fb]	Data (± (stat.)	± (syst.))		Standard Model prediction	p-value [%]
$\sigma_{4\mu}$	0.84	±0.12	±0.03	0.901 ± 0.048	63
σ_{4e}	0.63	±0.17	±0.04	0.901 ± 0.048	14
$\sigma_{2\mu 2e}$	0.74	±0.15	±0.04	0.805 ± 0.043	66
$\sigma_{2e2\mu}$	1.03	±0.15	±0.03	0.805 ± 0.043	11
$\sigma_{4\mu+4e}$	1.47	±0.21	±0.06	1.80 ± 0.10	14
$\sigma_{2\mu 2e+2e2\mu}$	1.77	±0.21	±0.06	1.61 ± 0.09	46
σ_{sum}	3.24	±0.31	±0.11	3.41 ± 0.18	60
σ_{comb}	3.35	±0.30	±0.12	3.41 ± 0.18	85
σ_{tot} [pb]	54.7	±4.9	±2.3	55.7 ± 2.8	85

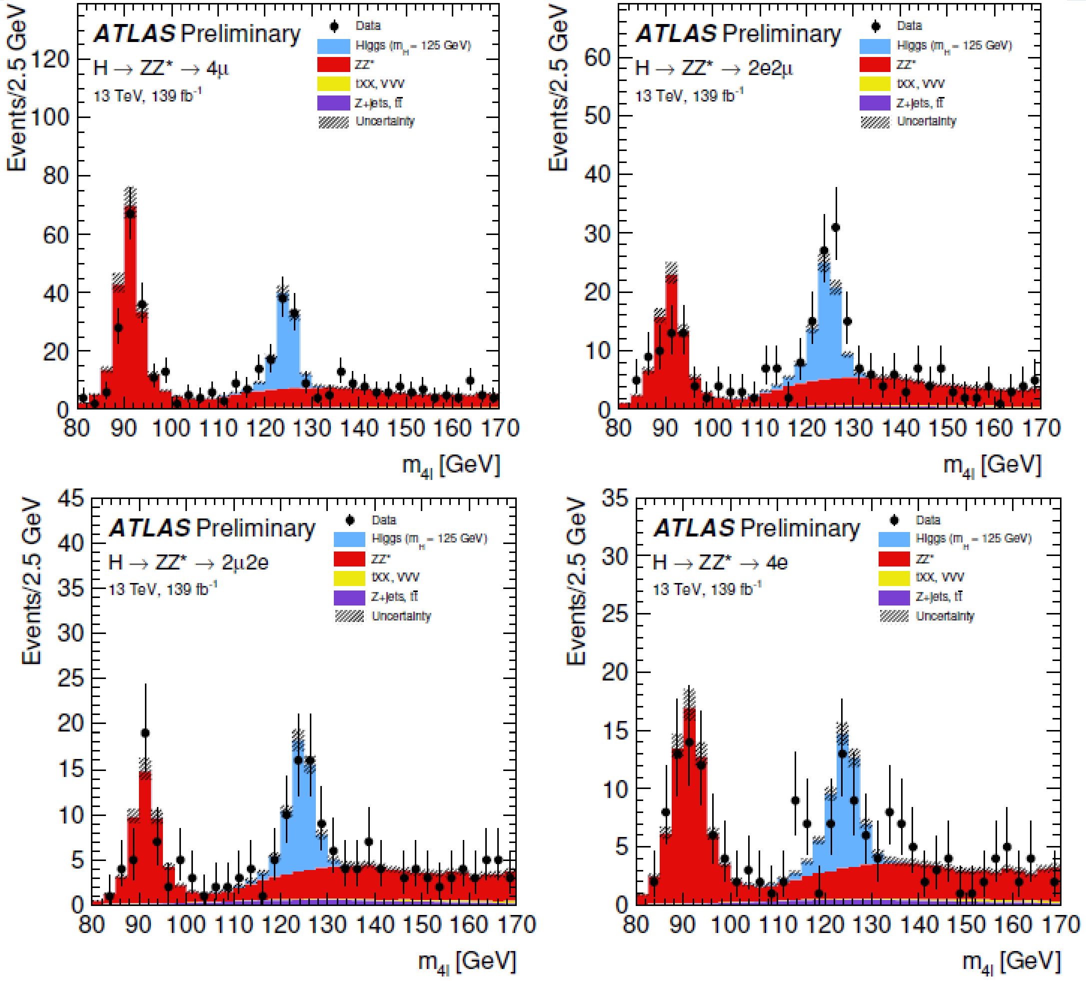
Event Selection & Fiducial Phase Space

Physics Objects
ELECTRONS
Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7$ GeV and $\|\eta\| < 2.47$
Interaction point constraint: $\|z_0 \cdot \sin\theta\| < 0.5$ mm (if ID track is available)
MUONS
Loose identification with $p_T > 5$ GeV and $\|\eta\| < 2.7$
Calo-tagged muons with $p_T > 15$ GeV and $\|\eta\| < 0.1$, segment-tagged muons with $\|\eta\| < 0.1$
Stand-alone and silicon-associated forward restricted to the $2.5 < \|\eta\| < 2.7$ region
Combined, stand-alone (with ID hits if available) and segment-tagged muons with $p_T > 5$ GeV
Interaction point constraint: $\|d_0\| < 1$ mm and $\|z_0 \cdot \sin\theta\| < 0.5$ mm (if ID track is available)
JETS
anti-k_T jets with *bad-loose* identification, $p_T > 30$ GeV and $\|\eta\| < 4.5$
Jets with $p_T < 60$ GeV and $\|\eta\| < 2.4$ are required to pass the pile-up jet rejection at the 92% working point (JVT score > 0.59).
Jets with $p_T < 50$ GeV and $\|\eta\| > 2.5$ are required to pass the forward pile-up jet rejection at the 90% working point.
b-TAGGING
Previously selected jets with $\|\eta\| < 2.5$ are assigned a b-tagging weight by the `MV2_c10` algorithm
OVERLAP REMOVAL
Jets within $\Delta R < 0.2$ of an electron or $\Delta R < 0.1$ of a muon are removed

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 - At most 1 calo-tagged, stand-alone or silicon-associated muon per quadruplet - Leading di-lepton mass requirement: $50 < m_{12} < 106$ GeV - Sub-leading di-lepton mass requirement: $m_{\text{threshold}} < m_{34} < 115$ GeV - $\Delta R(\ell, \ell') > 0.10$ for all lepton pairs in the quadruplet - Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5$ GeV - Keep all quadruplets passing the above selection
ISOLATION	- Contribution from the other leptons of the quadruplet is subtracted max(ptcone20_TightTTVA_pt500, ptvarcone30_TightTTVA_pt500) + 0.4 · neflowisol20/p_T < 0.16 (Variables defined in the text below)
IMPACT PARAMETER SIGNIFICANCE	- Apply impact parameter significance cut to all leptons of the quadruplet - For electrons: $d_0/\sigma_{d_0} < 5$ - For muons: $d_0/\sigma_{d_0} < 3$
BEST QUADRUPLET	- If more than one quadruplet has been selected, choose the quadruplet with highest Higgs decay ME according to channel: 4μ, $2e2\mu$, $2\mu2e$ and $4e$
VERTEX SELECTION	- Require a common vertex for the leptons: - χ^2/ndof < 6 for 4μ and < 9 for others decay channels

Lepton defintion	
Muons: $p_T^\mu > 5$ GeV, $\|\eta^\mu\| < 2.7$	Electrons: $p_T^e > 5$ GeV, $\|\eta^e\| < 2.7$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
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)

MC – Data Comparison



m_{4l} 115-130 GeV

Final state	Signal	ZZ^* background	Other backgrounds	Total expected	Observed
4μ	78 ± 5	38.1 ± 2.2	2.87 ± 0.18	119 ± 5	118
$2e2\mu$	52.8 ± 3.1	26.1 ± 1.4	3.01 ± 0.19	81.9 ± 3.4	98
$2\mu 2e$	40.0 ± 2.9	17.4 ± 1.3	3.5 ± 0.5	60.9 ± 3.2	57
$4e$	35.3 ± 2.6	15.1 ± 1.5	2.9 ± 0.4	53.3 ± 3.1	43
Total	206 ± 13	97 ± 6	12.3 ± 0.9	315 ± 14	316

ATLAS-CONF-2019-025

Leptons can be produced by the semileptonic decays of heavy flavor hadrons

Muons can be produced by light flavor hadrons (π/K) in-flight decays

LF jets and γ can also produce fake electrons

Background Data Driven Estimation

$\ell\ell\mu\mu$ strategy

Com/s : ZHF – ZLF – $t\bar{t}$ (& WZ)

CRs : Inverted d0 (HF enriched)
Inverted Iso (ZLF enriched)
Same Sign (ZLF enriched)
eμ ($t\bar{t}$ enriched)
Relax Iso d0 (intermediate region)

Fit : Simultaneous fit (4 CRs) of m_{12}

SR : Fractions from CRs to RR & Transfer factors. TFs are controlled with Z+μ sample

MC : WZ

$\ell\ell ee$ strategy

Com/s : f - γ (& q)

CRs : 3ℓ + X

Fit : Fit of $N_{innerPix}$
Template taken from Z+X γ/f enriched samples

SR : Efficiency Scale Factors (function of njets and pT). ESFs controlled with Z + X sample

MC : q – controlled in a HF enriched 3ℓ + X region

ZZ strategy

Com/s : qqZZ, ggZZ, qqZZjj, (ttV)

CRs : Signal Region Side bands
(105-115 & 130-160 GeV)

Fit : Fit of m4l

tVV is also Data driven estimated for production XSs