Search for heavy ZZ resonances in the 4ℓ and $\ell\ell\nu\nu$ final states with the ATLAS detector

Dr. Marc Bret Cano
mcanobre@cern.ch
Shanghai Jiao Tong University
On behalf of the ATLAS Collaboration

CLHCP 2017
Nanjing, China

December 22, 2017

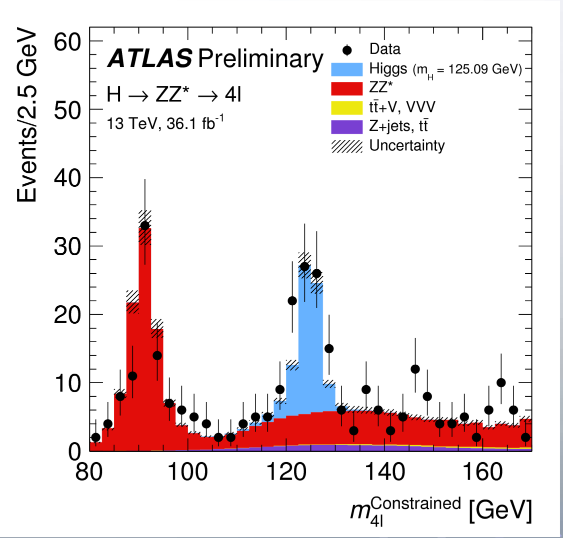
Introduction: $ZZ \to 4\ell$

Many useful features:

- Crucial channel for Higgs discovery, can also be used to search for possible high mass Higgs bosons
- Fully reconstructible final state
- *qqZZ* is the main background to this search
- Main draw-back is the small branching ratio ($\sim 0.02\%$) $\to$ limited statistics

Analysis strategy:

- Use the invariant mass of the four-lepton system ($m_{4\ell}$) as an observable
- Generally hard to distinguish between signal and the continuum ZZ background



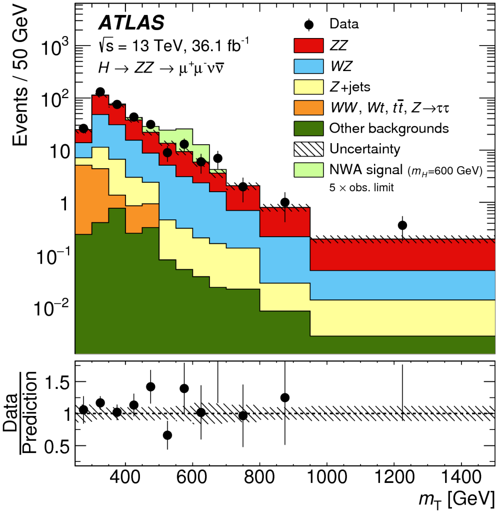
Introduction: $\ell\ell\nu\nu$

- Not a fully reconstructible final state due to the presence of neutrinos
- More significant backgrounds...
- But larger branching ratio than the 4ℓ final state
- The $\ell\ell\nu\nu$ drives the combination from 600 GeV onwards (ℓ stands for electrons and muon only)

Analysis strategy:

- Use the tranverse mass of the $\ell\ell\nu\nu$ system

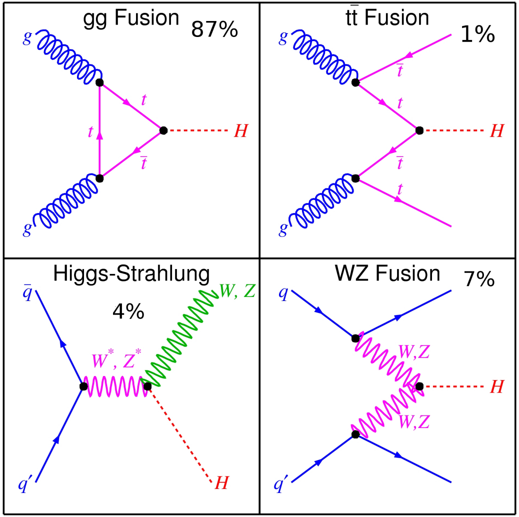
$$m_T \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_T^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_T^{\text{miss}}\right)^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right|^2}$$



Introduction: Higgs Production Mechanisms

	ggF	VBF	WH	ZH	bbH	ttH
8 TeV	21.4	1.60	0.70	0.42	0.20	0.13
13 TeV	48.6	3.78	1.37	0.88	0.49	0.51
ratio	2.3	2.4	2.0	2.1	2.5	3.9

- Largely dominated by gluon-gluon fusion
- Vector boson fusion is distinguished by the presence of widely separated jets in the event, but statistics are very limited
- Rest of production mechanisms have an expectation below one event
- Separate between ggF and VBF depending on the jet topology (other production modes are not investigated)



Event Selection

4ℓ:

- Events with four well-isolated leptons fulfilling quality cuts, with the leading lepton $p_T > 20$ GeV
- Both Z bosons have to be within the Z mass (both are on-shell)
- Categorize events depending on the leptonic composition (4μ, $4e$ & $2\mu 2e$)
- Search starts from 200 GeV
- Precise measurement of electron and muon momentum is key

$\ell\ell\nu\nu$:

- Look for events with two opposite-charged leptons and a large amount of missing transverse momentum
- Expect the dilepton system and the missing tranverse momentum to be back-to-back in the azimuthal angle, hence require $\delta\phi(p_{T_{\ell\ell}}, E_{\mathrm{T}}^{\mathrm{miss}}) > 2.7$
- $E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV to reduce the contribution from Z+jets background
- Z mass constraint on the ee/$\mu\mu$ pair
- Search starts from 300 GeV


WARNING
STRANGE PHYSICS
AHEAD

BSM Higgs & Signal Modelling

Two Higgs Doublet models (2HDM):

- Already used in previous versions of the analysis
- Introduces four additional Higgses, tan β (ratio of vev) and mixing between the two neutral CP states h (SM Higgs) and H
- Four different model types

Type I : one doublet couples to bosons only, the other to fermions

Type II : one doublet couples to up-like quarks, the other to down-like

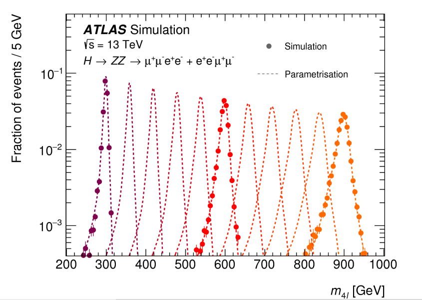
Type III : same couplings to leptons as in type I and to leptons as in type II

Type IV : reverse couplings from type III

- Focus on Type I and II models

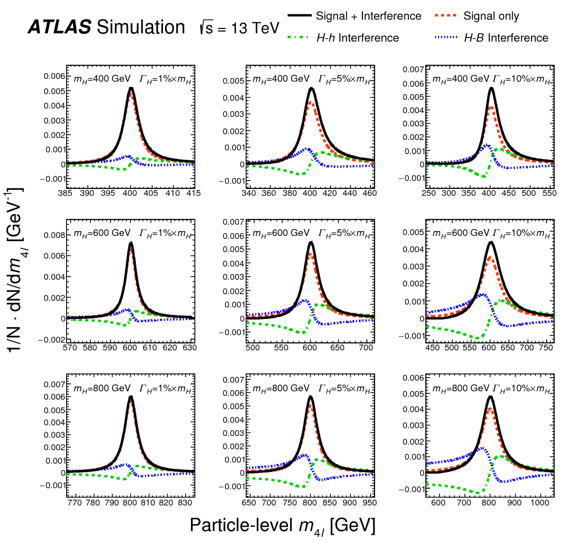
Signal distribution is parametrised for any value of m_H for the 4ℓ final state, while MC simulation is reweighted to any value of m_T for $\ell\ell\nu\nu$, various scenarios considered:

- Narrow Width Approximation
- Large Width Approximation (1, 5 & 10%)



Signal Interference

- Interference effects can be neglected in NWA...
- but in LWA inteference between the SM Higgs mass boson, the ZZ continuum and the heavy scalar H can have effects of 10% on the cross-section
- Samples with interference with the SM background (B) and with the SM Higgs boson (h) are generated
- Interference contribution is extracted by subtracting the individual contributions from signal and background-only samples



Background modelling (4ℓ)

- The dominant $q\bar{q} \to ZZ$ background (about 86%) is estimated through the use of MC simulation with Sherpa
- Normalised to an NNLO cross-section of 1.45 *pb* and parton-showered with Pythia8
- Other minor contributions such as $t\bar{t}W$ and $ggZZ$ also estimated with MC simulation
- EW Vector-Boson Scattering has a larger contribution for the VBF category due to the presence of jets, making up 16% of the total background

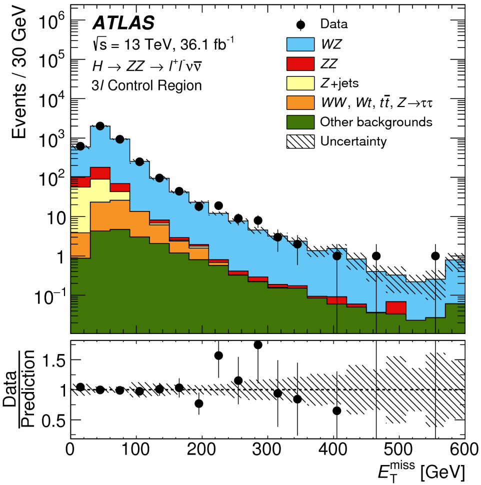
Process	ggF-enriched categories: 4μ channel	$2e2\mu$ channel	$4e$ channel	VBF-enriched category
ZZ	$297 \pm 1 \pm 40$	$480 \pm 1 \pm 60$	$193 \pm 1 \pm 25$	$15 \pm 0.1 \pm 6.0$
ZZ (EW)	$1.92 \pm 0.11 \pm 0.19$	$3.36 \pm 0.14 \pm 0.33$	$1.88 \pm 0.12 \pm 0.20$	$3.0 \pm 0.1 \pm 2.2$
Z + jets/$t\bar{t}$/WZ	$3.7 \pm 0.1 \pm 0.8$	$7.8 \pm 0.1 \pm 1.1$	$4.4 \pm 0.1 \pm 0.8$	$0.37 \pm 0.01 \pm 0.05$
Other backgrounds	$5.1 \pm 0.1 \pm 0.6$	$8.7 \pm 0.1 \pm 1.0$	$4.0 \pm 0.1 \pm 0.5$	$0.80 \pm 0.02 \pm 0.30$
Total background	$308 \pm 1 \pm 40$	$500 \pm 1 \pm 60$	$203 \pm 1 \pm 25$	$19.5 \pm 0.2 \pm 8.0$
Observed	357	545	256	31

- Reducible backgrounds such as Z+jets are estimated through the use of data-driven methods
- More relevant for electron final states, given that they are more easily faked by light-flavour jets
- Estimated in data control regions with relaxed identification and isolation requirements

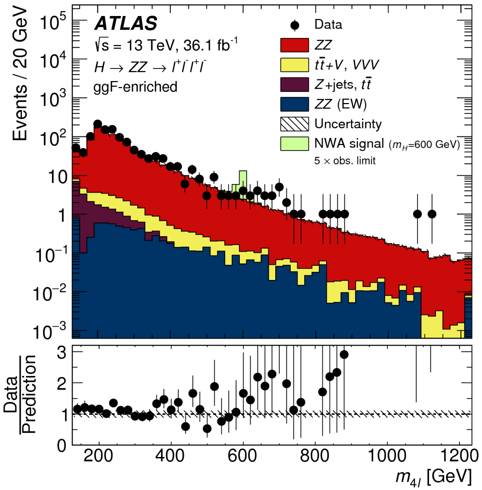
Background modelling ($\ell\ell\nu\nu$)

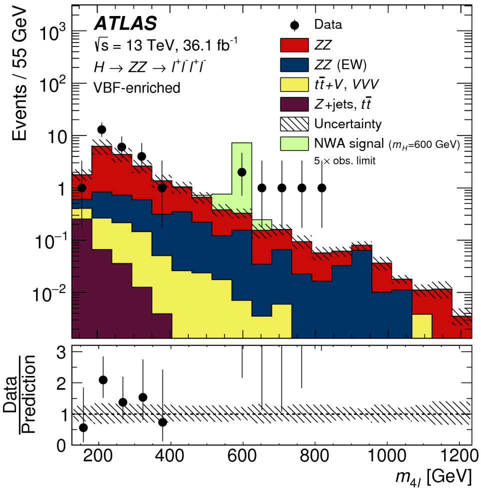
- The dominant $q\bar{q} \to ZZ$ background (about 60%) is estimated through the use of MC simulation using Powheg
- Z+jets is estimated through the use of data-driven methods
- Contribution from WZ makes up about 30% of the background in $\ell\ell\nu\nu$ and is estimated through MC simulation corrected in a 3ℓ CR

Process	ggF-enriched categories e^+e^- channel	ggF-enriched categories $\mu^+\mu^-$ channel	VBF-enriched category
ZZ	177 ± 3 ± 21	180 ± 3 ± 21	2.1 ± 0.2 ± 0.7
WZ	93 ± 2 ± 4	99.5 ± 2.3 ± 3.2	1.29 ± 0.04 ± 0.27
$WW/t\bar{t}/Wt/Z \to \tau\tau$	9.2 ± 2.2 ± 1.4	10.7 ± 2.5 ± 0.9	0.39 ± 0.24 ± 0.26
Z + jets	17 ± 1 ± 11	19 ± 1 ± 17	0.8 ± 0.1 ± 0.5
Other backgrounds	1.12 ± 0.04 ± 0.08	1.03 ± 0.04 ± 0.08	0.03 ± 0.01 ± 0.01
Total background	297 ± 4 ± 24	311 ± 5 ± 27	4.6 ± 0.4 ± 0.9
Observed	320	352	9

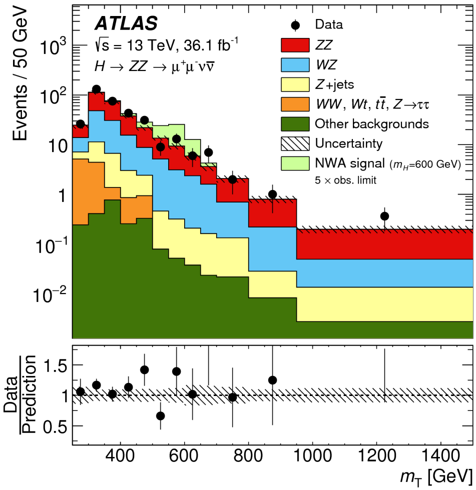


Results: $m_{4\ell}$

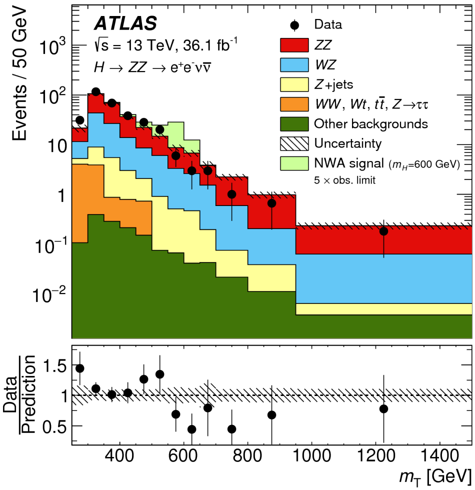




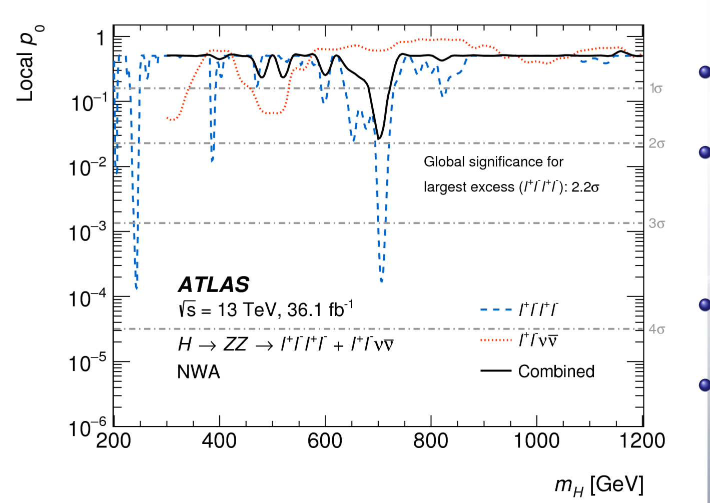
Results: m_T



ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → μ+μ-νν̄
Data
ZZ
WZ
Z+jets
WW, Wt, tt̄, Z→ττ
Other backgrounds
Uncertainty
NWA signal (mH=600 GeV)
5 × obs. limit
Events / 50 GeV
Data / Prediction
mT [GeV]

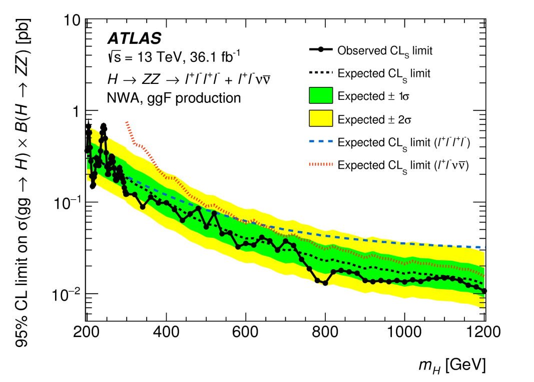


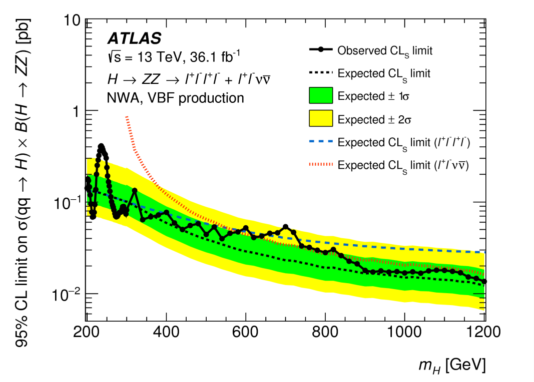
ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → e+e-νν̄
Data
ZZ
WZ
Z+jets
WW, Wt, tt̄, Z→ττ
Other backgrounds
Uncertainty
NWA signal (mH=600 GeV)
5 × obs. limit
Events / 50 GeV
Data / Prediction
mT [GeV]



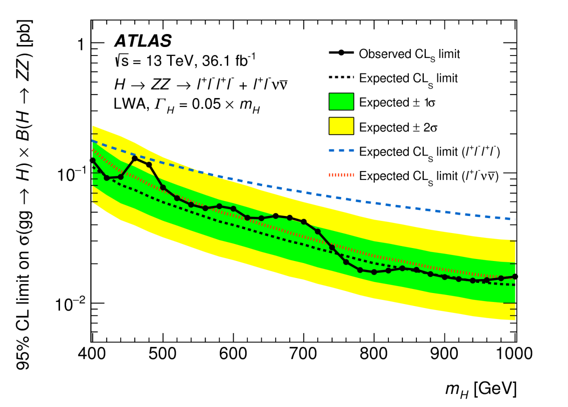
- Two excesses found in the 4ℓ channel: 240 and 705 GeV
- Excess at 240 GeV is driven by an excess in the $4e$ category, while the 705 GeV one appears in all categories
- Each excess represents a 2.2σ global significance
- Excess not found in the $\ell\ell\nu\nu$ channel, which is more sensitive

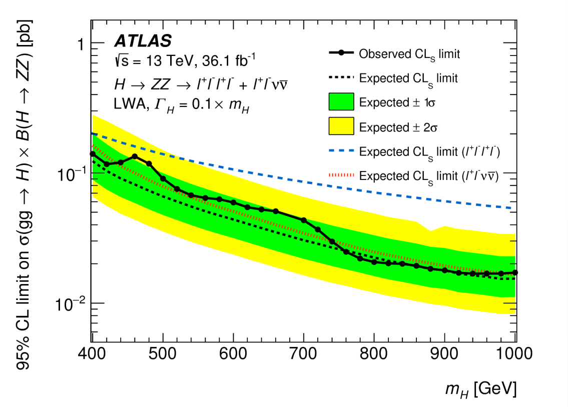
Results: NWA ggF & VBF 95% CL



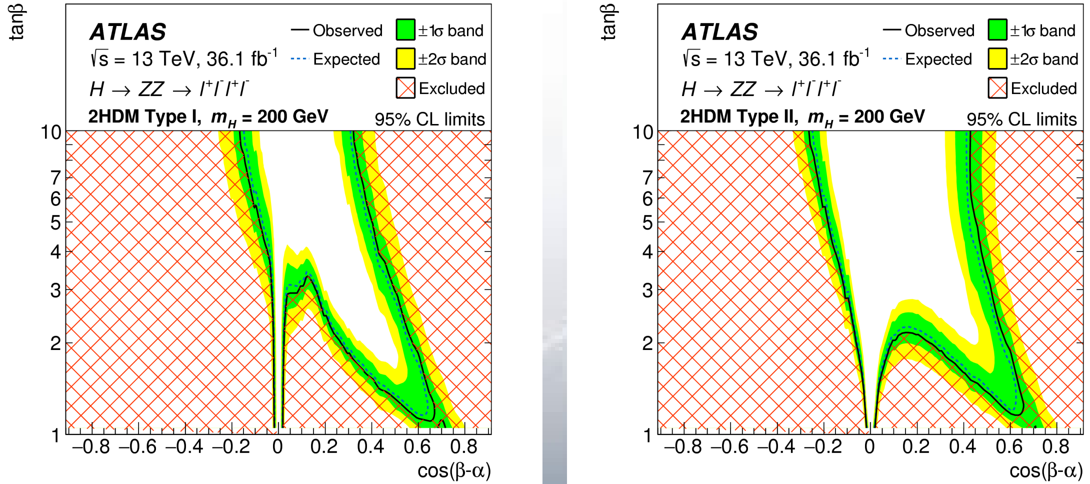


Results: LWA 5 & 10% 95% CL

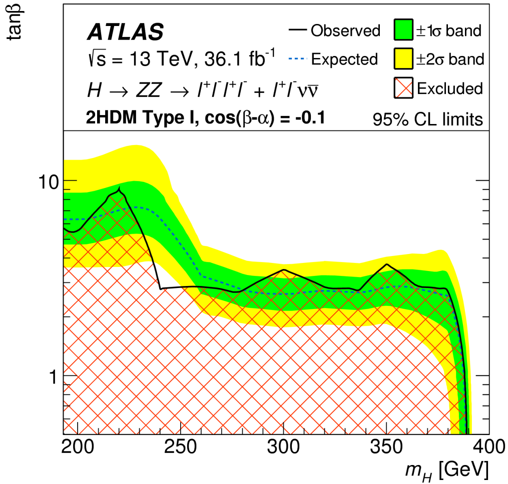


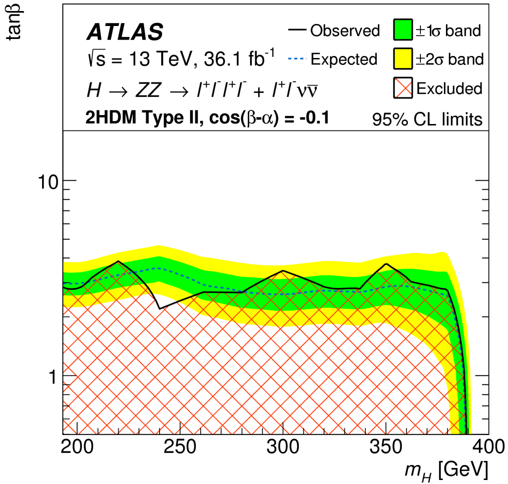


2HDM exclusion contour $tan(\beta)$ vs $cos(\beta - \alpha)$ m_H=200 GeV

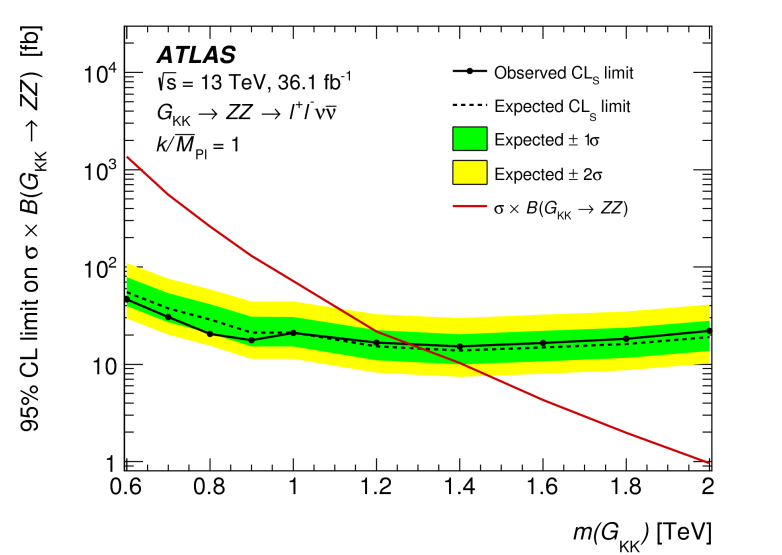


2HDM Exclusion Contour $tan(\beta)$ vs m_H $cos(\beta - \alpha)$=-0.1





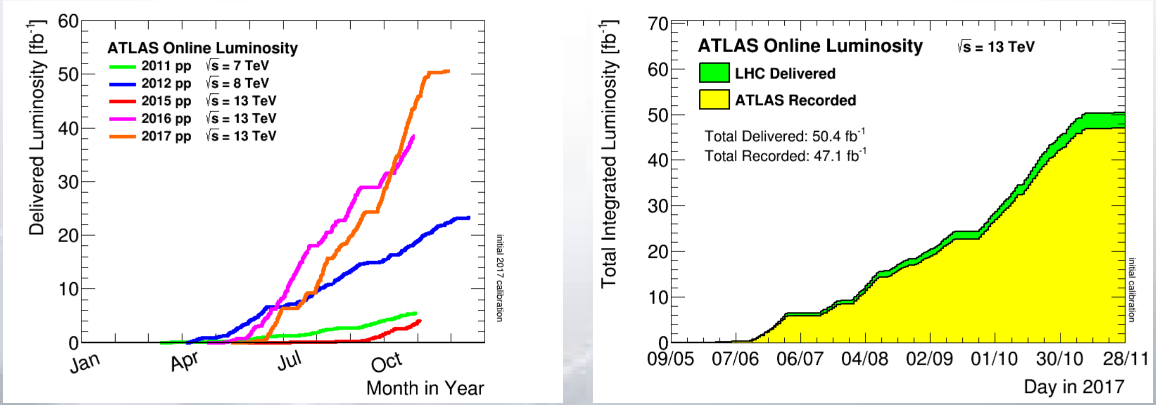
95% CL Spin-2 Kaluza-Klein Graviton



Conclusions

- Search for heavy ZZ resonances presented
- Still fairly limited by statistics in the 4ℓ channel
- But we have had a glorious year of data collection! And there is more to come
- So far all compatible with SM expectation but aim to have updates on the 4ℓ excesses as soon as possible
- For further details, the paper can be found in: `https://arxiv.org/pdf/1712.06386.pdf`

Performance of the LHC

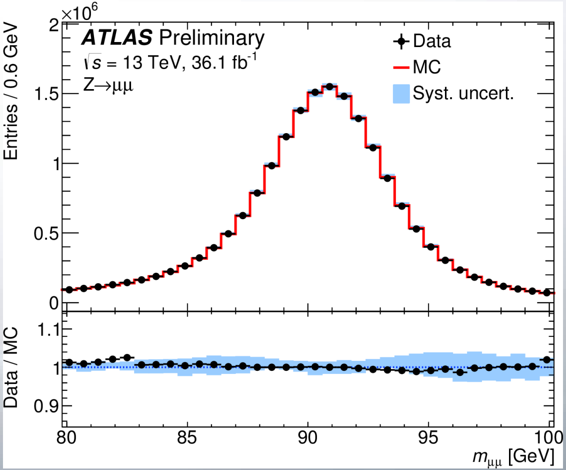


- The LHC has been working remarkably well
- The ATLAS Experiment has exceeded the data collected in 2016

BACKUP SLIDES

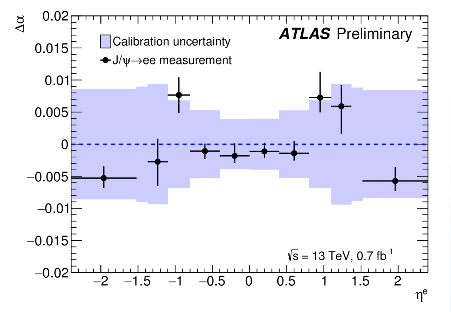
Muon calibrations

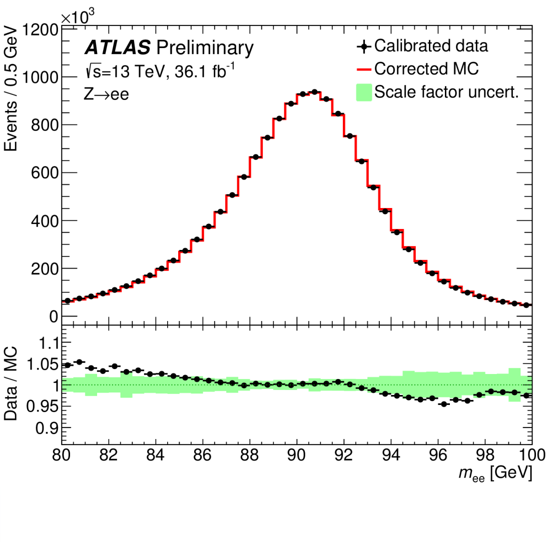
- Track reconstructed combining information from Inner Detector and muon chamber hits
- Correct momentum resolution and scale in simulation to account for differences with data:
  - Misalignements in the detector
  - Simulation of the traversed material
  - Magnetic field
- Very precise knowledge of the muon momentum resolution and scale in the Higgs mass range
- Approximately 10% muon momentum resolution in the 1 TeV range



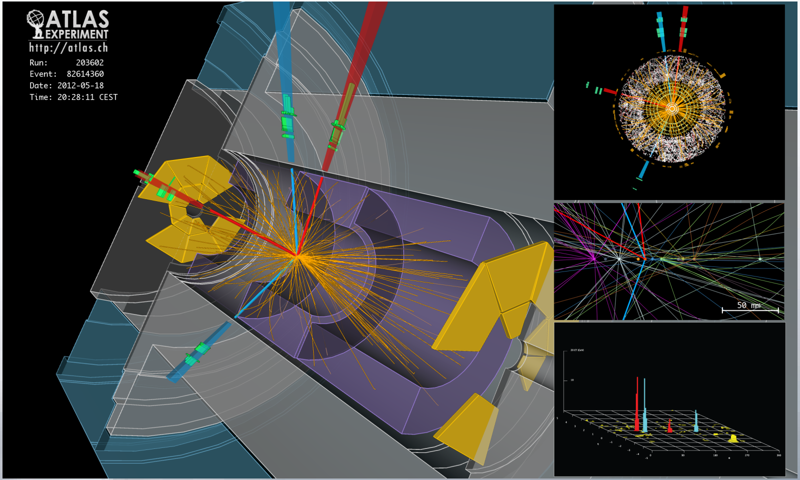
Electron corrections

- Corrects the response at reco cluster in the simulation with an MVA and corrections from $Z/J/\psi$ analysis
- Correct simulation for energy loss in inactive materials





Four electron event with $m_{4\ell} = 124.6$ GeV



Signal acceptance & systematics

Mass	Production mode	ggF-enriched categories 4μ channel	$2e2\mu$ channel	$4e$ channel	VBF-enriched category
300 GeV	ggF	56%	48%	40%	1%
	VBF	36%	30%	24%	21%
600 GeV	ggF	64%	56%	48%	3%
	VBF	36%	34%	32%	26%

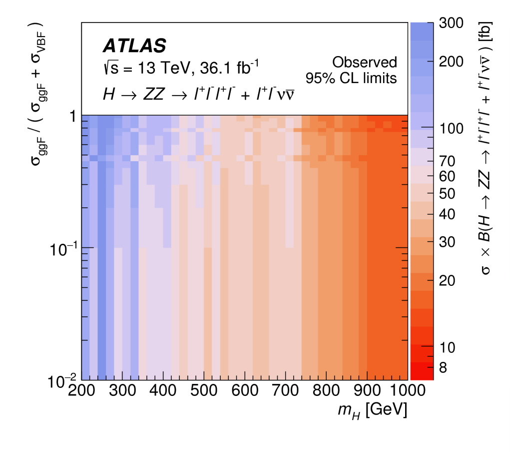
- Low acceptance for VBF process due to the stringent requirements
- Any event not classified as VBF enters the ggF category
- The contribution from final states with τ leptons decaying to electrons or muons is found to be negligible

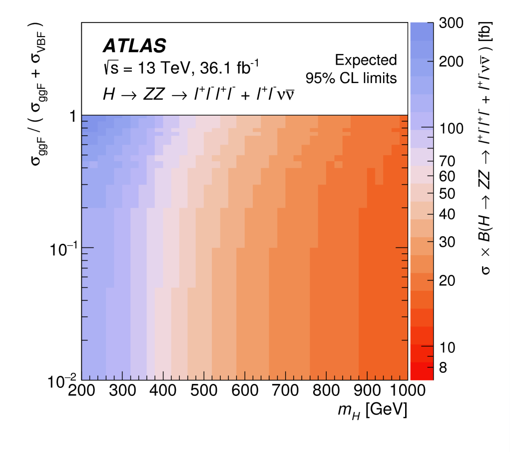
Mass	Production mode	ggF-enriched categories $\mu^+\mu^-$ channel	e^+e^- channel	VBF-enriched category
300 GeV	ggF	6%	5%	<0.05%
	VBF	2.6%	2.4%	0.7%
600 GeV	ggF	44%	44%	1%
	VBF	27%	27%	13%

- The uncertainty on the integrated luminosity enters both in the normalisation of the fitted number of signal events as well as in the background expectation from simulation

ggF production: Systematic source	Impact [%]	VBF production: Systematic source	Impact [%]
$m_H = 300$ GeV			
Luminosity	4	Parton showering	9
Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	3.3	Jet energy scale	4
Parton showering	3.2	Luminosity	4
$e\mu$ statistical uncertainty $\ell^+\ell^-\nu\bar{\nu}$	3.2	$q\bar{q} \to ZZ$ QCD scale (VBF-enriched category)	4
$m_H = 600$ GeV			
Luminosity	6	Parton showering	6
Pileup reweighting	5	Pileup reweighting	6
Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	4	Jet energy scale	6
QCD scale of $q\bar{q} \to ZZ$	3.1	Luminosity	4
$m_H = 1000$ GeV			
Luminosity	4	Parton showering	6
QCD scale of $gg \to ZZ$	2.3	Jet energy scale	5
Jet vertex tagger	1.9	Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	4
Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)	1.8	Luminosity	4

Results: ggF Fraction vs mH Limit





Convert those limits in 2HDM exclusion contours

Background modelling ($\ell\ell\nu\nu$)

- Contribution from WZ is estimated with the use of data-driven corrections factors applied on simulation
- The correction factor is extracted as the ratio of data to simulated events in a WZ-enriched region with 3ℓ
- Control region built looking at $Z \to \ell\ell$ events with an additional lepton
- Contributions from other SM processes in the control region are subtracted using MC simulation
- The correction factor derived is found to be 1.29$\pm$0.09