

*Studies of ZZ production
in leptonic final states with ATLAS*

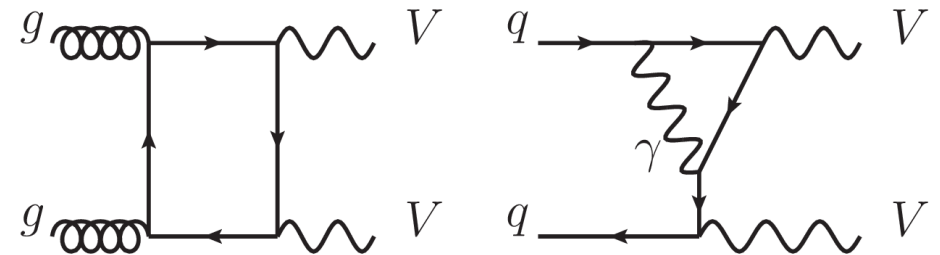
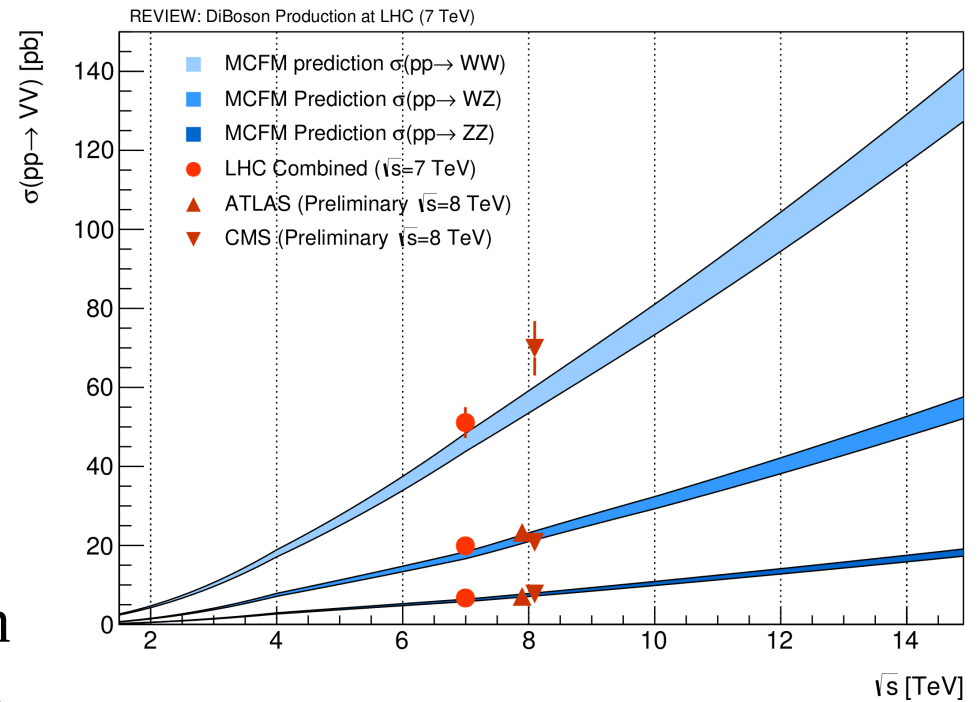
GK Seminar Freiburg
14 December 2016

Jochen Meyer



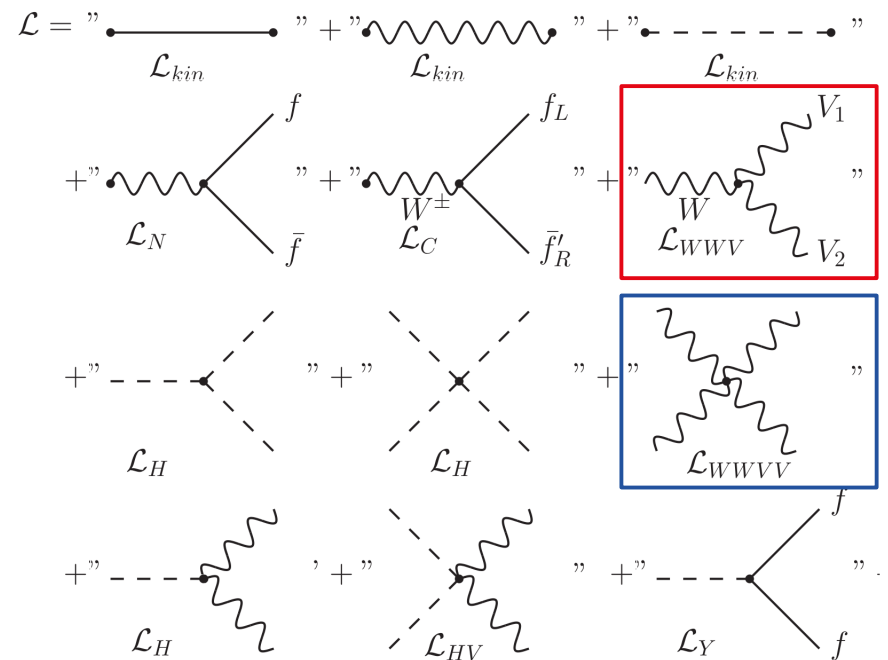
measurements of total and differential cross sections to ...

- ... probe validity of Standard Model (SM) at TeV scale/ search for new physics
- ... understand irreducible diboson background in Higgs analyses
- ... compare modeling of higher order QCD and EW effects

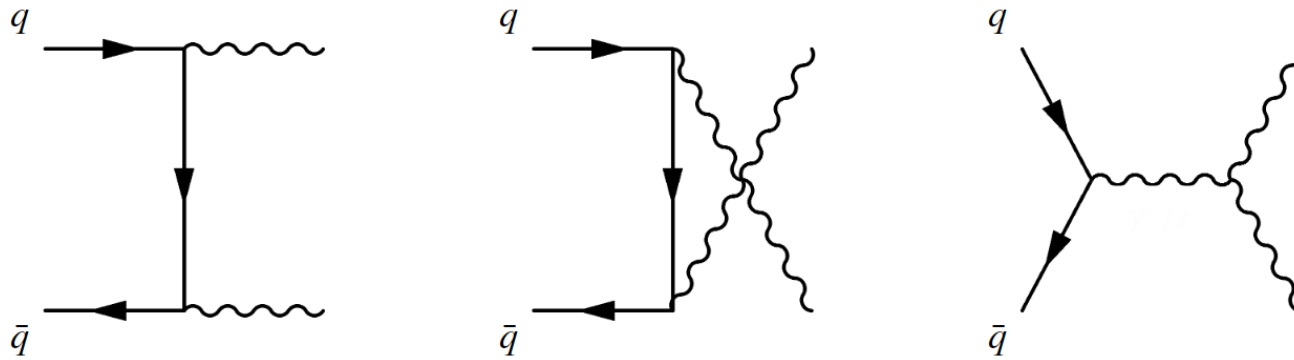


exploration of self-coupling structure of gauge bosons will ...

- ... improve understanding of electroweak symmetry breaking and unitarity
- ... intersect with determination of Higgs couplings
- ... indicate new physics if anomalous **triple/quartic** couplings are present

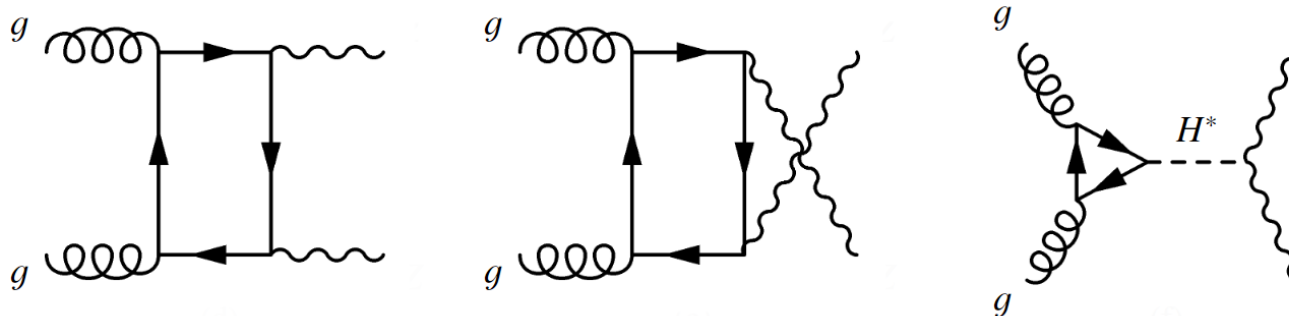


- quark-antiquark initial state without additional jets in the final state:



→ access to triple gauge couplings

- gluon induced production of ZZ or W^+W^-



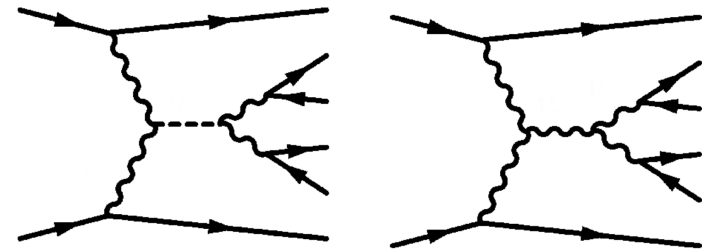
→ interference effects can be utilized to learn more about s-channel resonance

- quark-antiquark initial state with final state jets ($VVjj$)

- vector boson fusion (VBF) give access to ...

... triple gauge couplings

... properties of s-channel particle

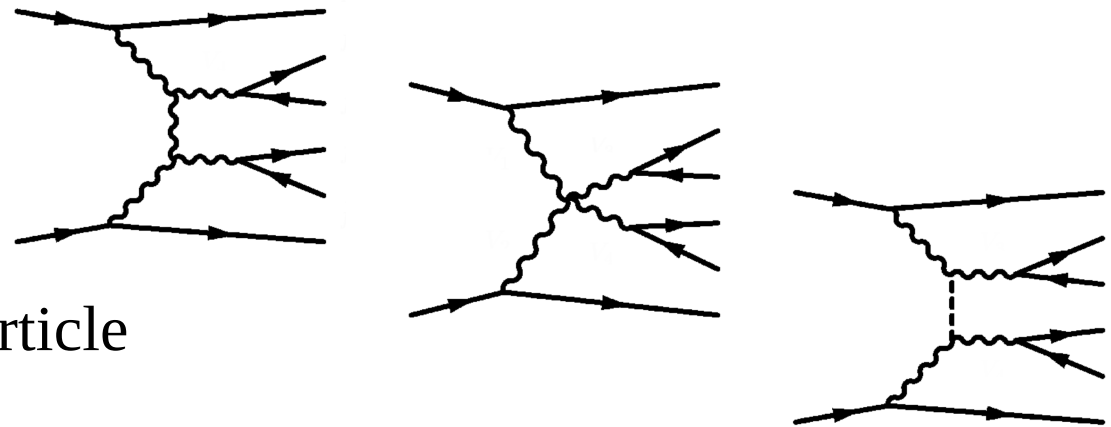


- vector boson scattering (VBS) gives access to ...

... triple gauge couplings

... quartic gauge couplings

... properties of t-channel particle



- $VVjj$ -electroweak and $VVjj$ -QCD

→ gauge bosons origination from final state/initial state radiation

- many studies at various center-of-mass energies performed in Standard Model group:

- total/differential cross section measurements
- limits on triple/quartic gauge couplings
- evidence for VBF, VBS
- dedicated analyses in Higgs groups

Status: August 2016

Run 1,2 $\sqrt{s} = 7, 8, 13$ TeV

Model	E_{CM} [TeV]	$\int \mathcal{L} dt$ [fb $^{-1}$]	Measurement	Theory	Reference
H	8	20.3	$\sigma = 27.7 \pm 3.0 \pm 2.3 \pm 1.9$ pb	$\sigma = 24.5 \pm 1.3 \pm 1.8$ pb (LHC-HXSWG YR4)	EPJCF 76, 6 (2016)
H \rightarrow BF	8	20.3	$\sigma = 25.1 \pm 6.7 \pm 5.3 \pm 3.3 \pm 2.7$ pb	$\sigma = 19.2 \pm 1.0 \pm 1.4$ pb (LHC-HXSWG YR4)	EPJCF 76, 6 (2016)
H \rightarrow BF (VBF H)	8	20.3	$\sigma = 23.4 \pm 3.1 \pm 1.9 \pm 1.9$ pb	$\sigma = 21.4 \pm 2.1 \pm 1.6$ pb (LHC-HXSWG YR4)	EPJCF 76, 6 (2016)
VH	8	20.3	$\sigma = 2.43 \pm 0.5 \pm 0.49 \pm 0.53 \pm 0.26$ pb	$\sigma = 1.6 \pm 0.04$ pb (LHC-HXSWG YR4)	EPJCF 76, 6 (2016)
tH	8	20.3	$\sigma = 1.03 \pm 0.37 \pm 0.36 \pm 0.26 \pm 0.21$ pb	$\sigma = 1.12 \pm 0.03$ pb (LHC-HXSWG YR4)	EPJCF 76, 6 (2016)
tH (H \rightarrow ZZ)	13	13.3	$\sigma = 0.24 \pm 0.07 \pm 0.08$ pb	$\sigma = 0.133 \pm 0.008 \pm 0.013$ pb (LHC-HXSWG YR4)	EPJCF 76, 6 (2016)
tH (H \rightarrow ZZ)	8	20.3	$\sigma = 43.2 \pm 14.9 \pm 4.9$ pb	$\sigma = 62.8 \pm 34.4$ fb (LHC-HXSWG)	ATLAS CONF-2016-067
tH (H \rightarrow ZZ)	8	20.3	$\sigma = 42.5 \pm 9.8 \pm 3.1 \pm 3.0$ fb	$\sigma = 31.0 \pm 3.2$ fb (LHC-HXSWG)	ATLAS CONF-2015-060
tH (H \rightarrow ZZ)	7	4.5	$\sigma = 49.0 \pm 7.0 \pm 6.0$ fb	$\sigma = 24.7 \pm 2.6$ fb (LHC-HXSWG)	ATLAS CONF-2015-060
tH (VBF H \rightarrow WW)	8	20.3	$\sigma = 0.51 \pm 0.17 \pm 0.18 \pm 0.13 \pm 0.08$ pb	$\sigma = 0.35 \pm 0.02$ pb (LHC-HXSWG)	PRD 92, 012008 (2015)
tH (gg \rightarrow H \rightarrow WW)	8	20.3	$\sigma = 4.6 \pm 0.9 \pm 0.8 \pm 0.7$ pb	$\sigma = 4.2 \pm 0.5$ pb (LHC-HXSWG)	PRD 92, 012006 (2015)
tH (gg \rightarrow H \rightarrow WW)	13	13.3	$\sigma = 2.11 \pm 0.3 \pm 1.5 \pm 1.1$ pb	$\sigma = 3.2 \pm 0.4$ pb (LHC-HXSWG)	PRD 92, 012006 (2015)
tH (H \rightarrow ZZ \rightarrow 4 ℓ)	8	20.3	$\sigma = 4.54 \pm 0.95 \pm 0.86 \pm 0.37 \pm 0.28$ fb	$\sigma = 3.07 \pm 0.21 \pm 0.25$ fb (LHC-XS)	ATLAS CONF-2016-029
tH (H \rightarrow ZZ \rightarrow 4 ℓ)	8	20.3	$\sigma = 1.9 \pm 1.0 \pm 0.9 \pm 0.1$ fb	$\sigma = 1.03 \pm 0.11$ fb (LHC-HXSWG)	ATLAS CONF-2015-059
tH (H \rightarrow ZZ \rightarrow ZZ(4 ℓ))	13	13.3	$\sigma = 61.5 \pm 10.5 \pm 10.0 \pm 4.3 \pm 3.2$ pb	$\sigma = 52.5 \pm 2.4 \pm 3.4$ pb (LHC-HXSWG YR4)	ATLAS CONF-2016-081
tH (H \rightarrow ZZ \rightarrow ZZ(4 ℓ))	8	20.3	$\sigma = 33.2 \pm 5.5 \pm 5.3 \pm 1.7 \pm 1.3$ pb	$\sigma = 35.5 \pm 1.1 \pm 1.8$ pb (LHC-HXSWG YR4)	ATLAS CONF-2015-069
tH (H \rightarrow ZZ \rightarrow ZZ(4 ℓ))	7	4.5	$\sigma = 34.0 \pm 10.0 \pm 4.0 \pm 2.0$ pb	$\sigma = 19.2 \pm 1.0 \pm 1.4$ pb (LHC-HXSWG YR4)	ATLAS CONF-2015-069
tH (H \rightarrow ZZ \rightarrow ZZ(4 ℓ))	8	20.3	$\sigma = 2.1 \pm 0.4 \pm 0.5 \pm 0.4$ pb	$\sigma = 1.39 \pm 0.14$ pb (LHC-HXSWG)	ATLAS CONF-2015-069
tH (H \rightarrow ZZ \rightarrow ZZ(4 ℓ))	7	4.5	$\sigma = 1.0 \pm 0.9 \pm 0.8 \pm 0.9 \pm 0.8$ pb	$\sigma = 1.09 \pm 0.11$ pb (LHC-HXSWG)	JHEP 04, 117 (2015)
WW	13	3.2	$\sigma = 142.1 \pm 5.4 \pm 13.3$ pb	$\sigma = 128.4 \pm 3.5 \pm 3.8$ pb (NNLO)	ATLAS CONF-2016-090
WW	8	20.3	$\sigma = 68.2 \pm 1.2 \pm 4.6$ pb	$\sigma = 65.0 \pm 1.2 \pm 1.1$ pb (NNLO)	CERN-EP-2016-186
WW	7	4.6	$\sigma = 51.9 \pm 2.0 \pm 4.4$ pb	$\sigma = 49.04 \pm 1.03 \pm 0.88$ pb (NNLO)	PRD 87, 112001 (2013)
WW \rightarrow eu ℓ	8	4.6	$\sigma = 563.0 \pm 28.0 \pm 79.0 \pm 85.0$ fb	$\sigma = 536.0 \pm 29.0$ fb (MC-FM)	PRD 87, 052005 (2015)
WW \rightarrow eu ℓ [$\eta_{jet} \geq 0$]	8	20.3	$\sigma = 136.0 \pm 6.0 \pm 14.3$ fb	$\sigma = 141.0 \pm 30.0$ fb (NLO)	CERN-EP-2016-186
WW \rightarrow eu ℓ [$\eta_{jet} \geq 0$]	13	3.2	$\sigma = 620.0 \pm 30.0 \pm 52.0$ fb	$\sigma = 478.0 \pm 14.0 \pm 13.0$ fb (NNLO)	ATLAS CONF-2016-090
WW \rightarrow eu ℓ [$\eta_{jet} \geq 0$]	8	20.3	$\sigma = 374.0 \pm 7.0 \pm 26.0 \pm 24.0$ fb	$\sigma = 346.0 \pm 19.0$ fb (approx. NNLO)	arXiv:1603.01702 [hep-ex]
WW \rightarrow eu ℓ [$\eta_{jet} = 0$]	8	4.6	$\sigma = 26.3 \pm 12.3 \pm 23.1$ fb	$\sigma = 231.4 \pm 15.7$ fb (MC-FM)	PRD 87, 112001 (2013)
WW \rightarrow uu ℓ [$\eta_{jet} = 0$]	8	20.3	$\sigma = 80.2 \pm 3.3 \pm 3.2 \pm 6.6 \pm 5.7$ fb	$\sigma = 71.2 \pm 4.0$ fb (NNLO)	arXiv:1603.01702 [hep-ex]
WW \rightarrow uu ℓ [$\eta_{jet} = 0$]	7	4.6	$\sigma = 73.9 \pm 5.9 \pm 7.5$ fb	$\sigma = 58.9 \pm 4.0$ fb (MC-FM)	PRD 87, 112001 (2013)
WW \rightarrow ee ℓ [$\eta_{jet} = 0$]	8	20.3	$\sigma = 73.4 \pm 4.2 \pm 4.3 \pm 6.7 \pm 5.8$ fb	$\sigma = 65.5 \pm 3.6$ fb (NNLO)	arXiv:1603.01702 [hep-ex]
WW \rightarrow ee ℓ [$\eta_{jet} = 0$]	7	4.6	$\sigma = 56.4 \pm 6.8 \pm 10.0$ fb	$\sigma = 54.6 \pm 3.7$ fb (MC-FM)	PRD 87, 112001 (2013)
WW \rightarrow ee ℓ [$\eta_{jet} = 0$]	8	4.6	$\sigma = 9.3 \pm 2.2 \pm 4.4$ fb	$\sigma = 4.4 \pm 0.3$ fb (HERWIG++)	arXiv:1607.03745 [hep-ex]
WW \rightarrow ee ℓ [$\eta_{jet} = 0$]	8	20.3	$\sigma = 1.3 \pm 0.4 \pm 0.2$ fb	$\sigma = 0.95 \pm 0.06$ fb (PowhegBox)	PRD 93, 092004 (2016)
WW \rightarrow ee ℓ [$\eta_{jet} = 0$]	13	3.2	$\sigma = 9.3 \pm 2.2 \pm 4.4$ fb	$\sigma = 49.92 \pm 1.1 \pm 1.0$ pb (MATRIX (NNLO))	arXiv:1606.04017 [hep-ex]
WZ	8	20.3	$\sigma = 24.3 \pm 0.6 \pm 0.9$ pb	$\sigma = 23.92 \pm 0.4$ pb (MATRIX (NNLO))	PRD 93, 092004 (2016)
WZ	7	4.6	$\sigma = 19.0 \pm 1.4 \pm 1.3 \pm 1.0$ pb	$\sigma = 19.34 \pm 0.3 \pm 0.4$ pb (MATRIX (NNLO))	EPJCF 72, 2173 (2012)
WZ (WZ \rightarrow $\nu\ell\ell$)	13	3.2	$\sigma = 26.2 \pm 13.2 \pm 12.0$ fb	$\sigma = 23.6 \pm 12.3$ fb (MC-FM NLO)	arXiv:1605.04017 [hep-ex]
WZ (WZ \rightarrow $\nu\ell\ell$)	8	20.3	$\sigma = 140.4 \pm 3.8 \pm 4.6$ fb	$\sigma = 120.0 \pm 8.4$ fb (MC-FM NLO)	PRD 93, 092004 (2016)
WZ (WZ \rightarrow EWK)	8	20.3	$\sigma = 0.39 \pm 0.14 \pm 0.12 \pm 0.09 \pm 0.1$ fb	$\sigma = 0.13 \pm 0.01$ fb (VBF NLO)	PRD 93, 092004 (2016)
WW+WZ \rightarrow $\nu\ell\ell$	7	4.6	$\sigma = 1.37 \pm 0.14 \pm 0.37$ pb	$\sigma = 1.24 \pm 0.09$ pb (MC@NLO)	JHEP 01, 049 (2015)
ZZ	13	3.2	$\sigma = 16.7 \pm 2.2 \pm 2.0 \pm 1.3 \pm 1.0$ pb	$\sigma = 15.6 \pm 0.4$ pb (NNLO)	ATLAS CONF-2015-020
ZZ	8	20.3	$\sigma = 7.1 \pm 0.5 \pm 0.4 \pm 0.4$ pb	$\sigma = 8.294 \pm 0.299 \pm 0.191$ pb (NNLO)	ATLAS CONF-2015-020
ZZ	7	4.6	$\sigma = 6.7 \pm 0.7 \pm 0.5 \pm 0.4$ pb	$\sigma = 6.735 \pm 0.195 \pm 0.155$ pb (NNLO)	JHEP 03, 128 (2013)
ZZ (pp \rightarrow ZZ \rightarrow 4 ℓ)	8	20.3	$\sigma = 107.0 \pm 9.0 \pm 5.0$ fb	$\sigma = 104.9 \pm 1.7$ fb (Powheg)	JHEP 03, 128 (2013)
ZZ (pp \rightarrow ZZ \rightarrow 4 ℓ)	7	4.6	$\sigma = 76.0 \pm 16.0 \pm 4.0$ fb	$\sigma = 90.0 \pm 1.6$ fb (Powheg)	JHEP 03, 128 (2013)
ZZ (ZZ \rightarrow 4 ℓ)	13	3.2	$\sigma = 39.7 \pm 3.9 \pm 3.6 \pm 2.0 \pm 1.5$ fb	$\sigma = 27.4 \pm 0.9 \pm 0.8$ fb (MC-FM)	PRD 112, 231808 (2014)
ZZ (ZZ \rightarrow 4 ℓ)	8	20.3	$\sigma = 25.4 \pm 3.3 \pm 3.0 \pm 1.6 \pm 1.4$ fb	$\sigma = 21.1 \pm 0.9 \pm 0.7$ fb (MC-FM)	PRD 112, 231808 (2014)
ZZ (ZZ \rightarrow 4 ℓ)	7	4.6	$\sigma = 25.4 \pm 3.3 \pm 3.0 \pm 1.6 \pm 1.4$ fb	$\sigma = 20.9 \pm 1.1 \pm 0.9$ fb (PowhegBox & gg2ZZ)	ATLAS CONF-2013-020
ZZ (ZZ \rightarrow 4 ℓ)	8	20.3	$\sigma = 73.0 \pm 4.0 \pm 5.0$ fb	$\sigma = 65.0 \pm 4.0$ fb (PowhegBox & gg2ZZ)	PLB 753, 552-572 (2016)
ZZ (ZZ \rightarrow 4 ℓ)	13	3.2	$\sigma = 29.9 \pm 0.8 \pm 0.7 \pm 1.1 \pm 0.9$ fb	$\sigma = 1.16 \pm 0.13 \pm 1.1$ fb (PowhegBox & gg2ZZ)	JHEP 03, 128 (2013)
ZZ (WZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	8	20.3	$\sigma = 2.9 \pm 0.8 \pm 0.7 \pm 1.0 \pm 0.9$ fb	$\sigma = 1.38 \pm 0.2$ fb (MC-FM NLO)	PRD 112, 031802 (2015)
ZZ (WZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	7	4.6	$\sigma = 3.48 \pm 0.91 \pm 0.88 \pm 1.3 \pm 0.26$ fb	$\sigma = 2.91 \pm 0.6$ fb (MC-FM NLO)	PRD 93, 092004 (2016)
ZZ (WZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	8	20.3	$\sigma = 1.89 \pm 0.09 \pm 0.68 \pm 0.42 \pm 0.39$ pb	$\sigma = 3.7 \pm 0.21 \pm 0.11$ pb (MC-FM NLO)	PRD 93, 112002 (2018)
ZZ (WZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	8	20.3	$\sigma = 1.05 \pm 0.02 \pm 0.11$ pb	$\sigma = 1.23 \pm 0.01 \pm 0.018$ pb (NNLO)	PRD 93, 112002 (2018)
ZZ (ZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	7	4.6	$\sigma = 68.0 \pm 4.0 \pm 33.0 \pm 32.0$ fb	$\sigma = 81.4 \pm 2.4 \pm 2.6$ fb (NNLO)	PRD 87, 112003 (2013)
ZZ (ZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	8	20.3	$\sigma = 0.133 \pm 0.013 \pm 0.024$ pb	$\sigma = 0.156 \pm 0.012$ pb (MC-FM NLO)	PRD 87, 112003 (2013)
ZZ (ZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	7	4.6	$\sigma = 1.507 \pm 0.01 \pm 0.083 \pm 0.078$ pb	$\sigma = 1.483 \pm 0.019 \pm 0.037$ pb (NNLO)	PRD 87, 112003 (2013)
ZZ (ZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	8	20.3	$\sigma = 1.26 \pm 0.03 \pm 0.32$ pb	$\sigma = 1.327 \pm 0.026 \pm 0.037$ pb (NNLO)	PRD 87, 112003 (2013)
ZZ (ZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	7	4.6	$\sigma = 2.77 \pm 0.03 \pm 0.36$ pb	$\sigma = 1.674 \pm 0.056 \pm 0.064$ pb (NNLO)	PRD 87, 112003 (2013)
ZZ (ZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	8	20.3	$\sigma = 1.507 \pm 0.01 \pm 0.083 \pm 0.078$ pb	$\sigma = 1.483 \pm 0.019 \pm 0.037$ pb (NNLO)	PRD 87, 112003 (2013)
ZZ (ZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	7	4.6	$\sigma = 1.26 \pm 0.03 \pm 0.32$ pb	$\sigma = 1.327 \pm 0.026 \pm 0.037$ pb (NNLO)	PRD 87, 112003 (2013)
ZZ (ZZ \rightarrow $\nu\ell\ell$) [$\eta_{jet} = 0$]	8	20.3	$\sigma = 2.77 \pm 0.03 \pm 0.36$ pb	$\sigma = 1.674 \pm 0.056 \pm 0.064$ pb (NNLO)	PRD 87, 112003 (2013)

- cross section, properties (spin, couplings, ...), high mass searches, ...

- exotics groups look mainly for resonances

➔ all kind of subsequent decay modes of diboson system are considered

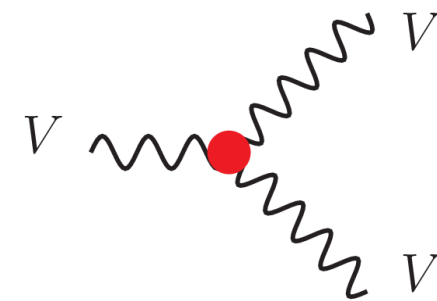
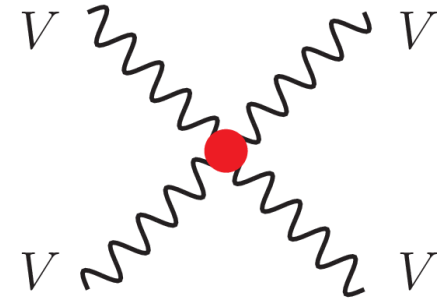
Motivation For ZZ In Leptonic Final States

What makes it particularly interesting to look at ZZ?

- neither triple nor quartic gauge couplings with only Zs allowed on tree level in SM
- in most cases very little backgrounds
- very clean signature for both $2\ell 2\nu$ and 4ℓ
 - ➔ full detector capability can be exploited
- possibility to reconstruct full event kinematics in case of 4ℓ

... and what are the disadvantages?

- lower cross sections compared to other diboson processes
- lower branching fraction compared to other final states

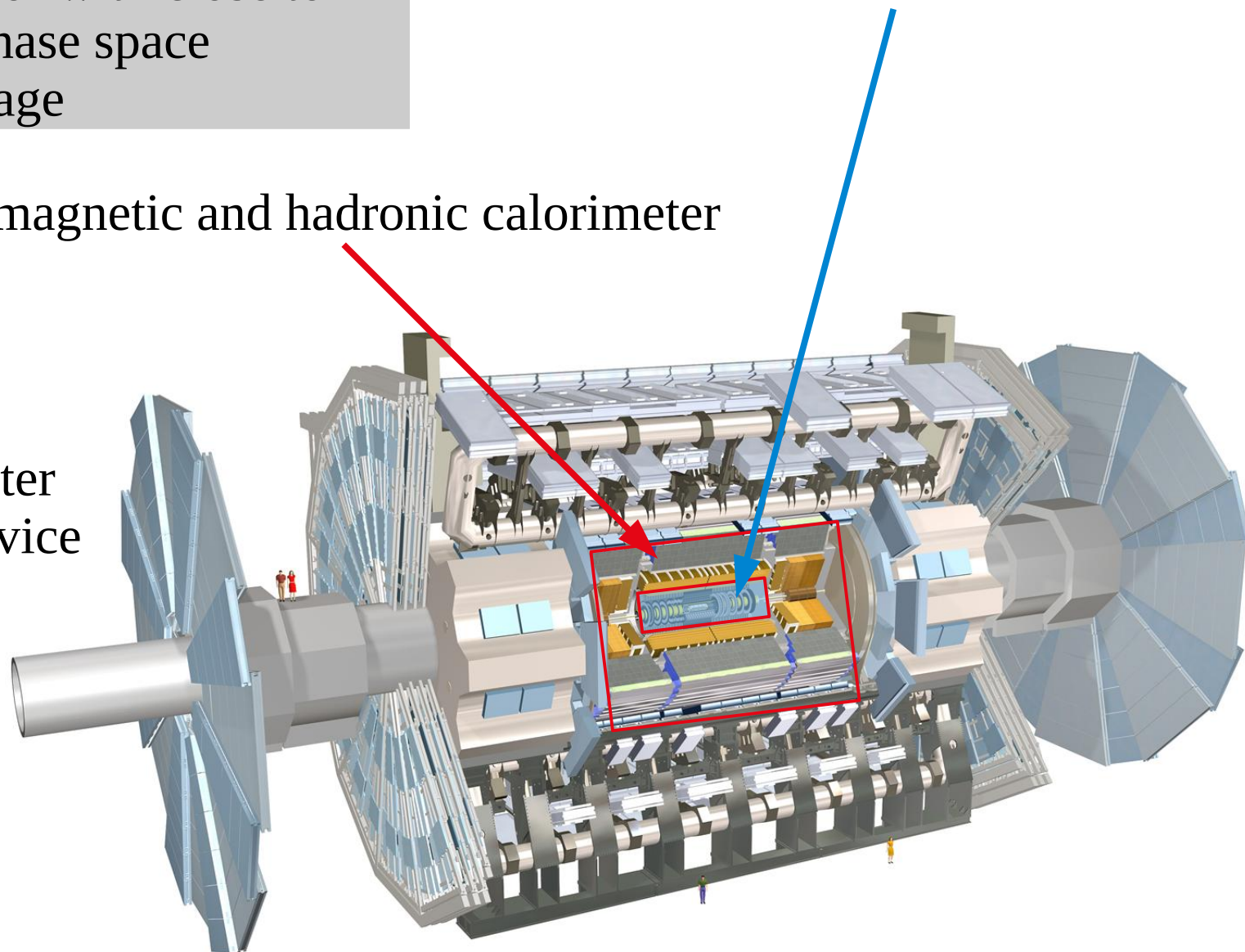


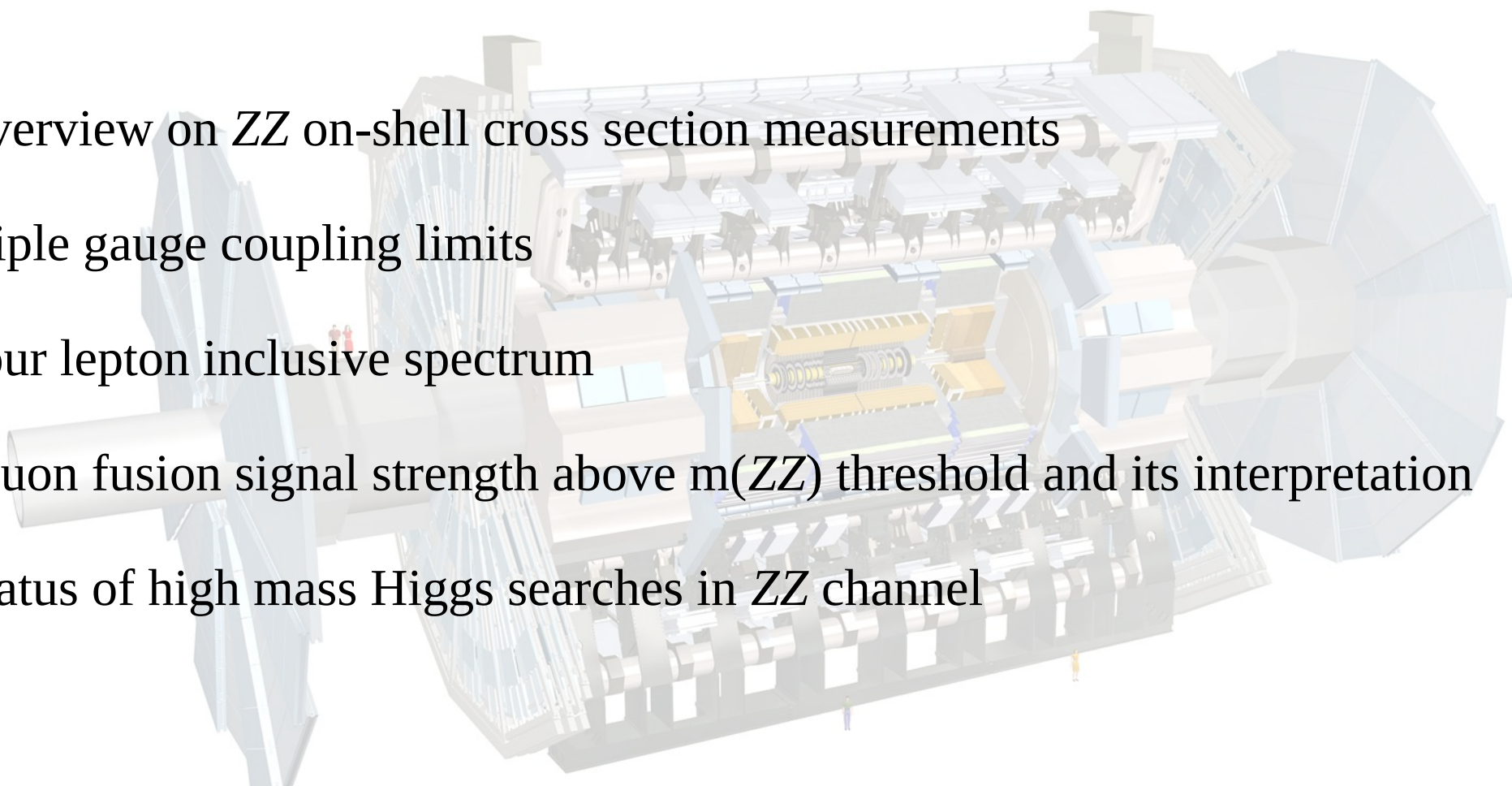
ATLAS : multipurpose particle detector with close to full phase space coverage

inner detector for precision tracking

electromagnetic and hadronic calorimeter

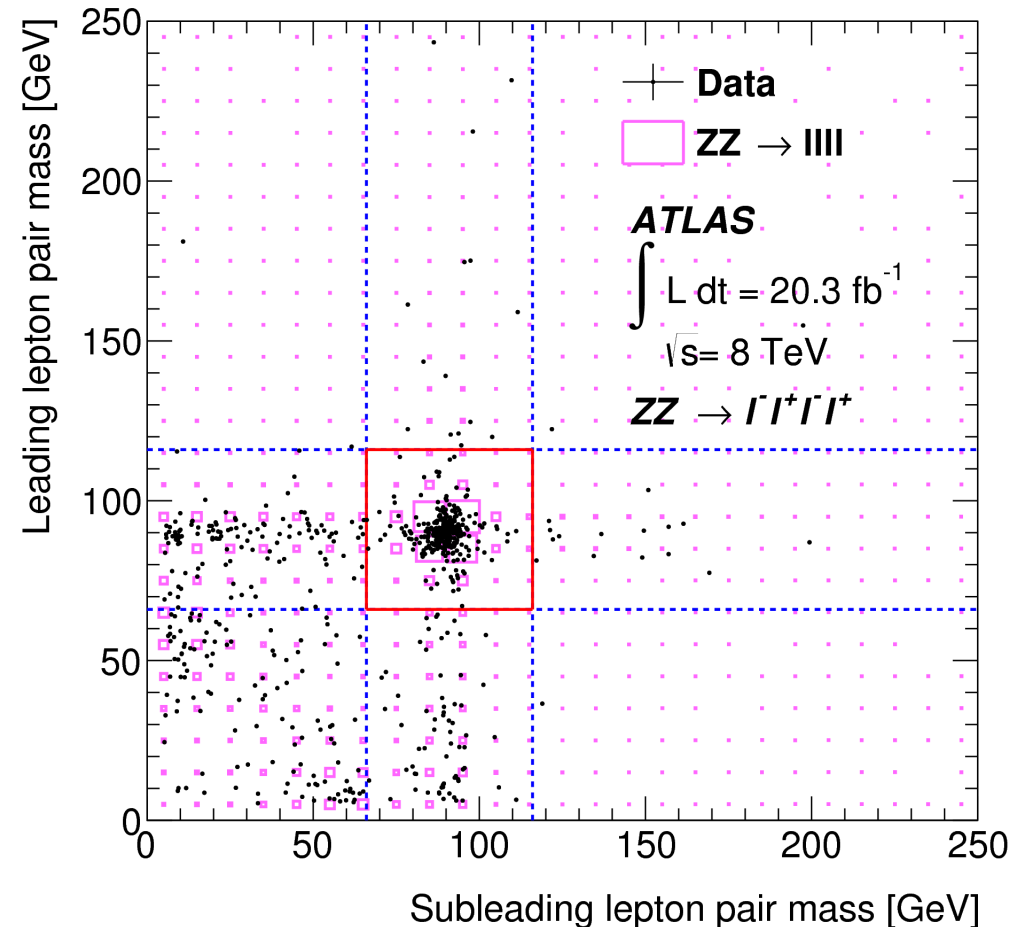
muon spectrometer as outer most device



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- overview on ZZ on-shell cross section measurements
 - triple gauge coupling limits
 - four lepton inclusive spectrum
 - gluon fusion signal strength above $m(ZZ)$ threshold and its interpretation
 - status of high mass Higgs searches in ZZ channel

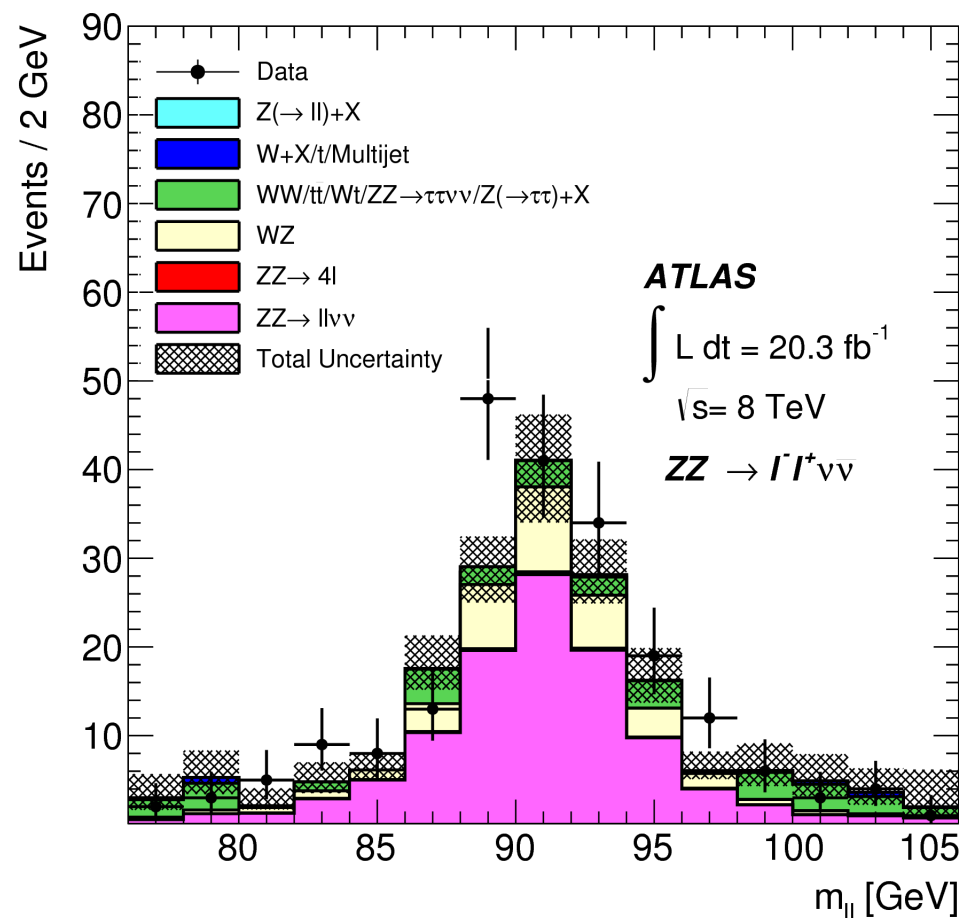
four charged lepton final state selection:

- quite loose lepton requirements to maximize efficiency
- events with two opposite-charged, same-flavor lepton pairs ($\ell\ell$)
- invariant mass requirement of $66 < m(\ell\ell)/\text{GeV} < 116$
- signal over background ratio of ~ 17
- high reconstruction efficiency (C_{ZZ}):
 - $\sim 50\%$ in four electron channel
 - $\sim 85\%$ in four muon channel
- main systematics are lepton identification and efficiency



two charged lepton and missing energy final state:

- selection of two same-flavor opposite-charged leptons ($\ell\ell$)
- invariant mass requirement of $76 < m(\ell\ell)/\text{GeV} < 106$
- more than 90 GeV missing transverse energy (E_T^{miss}) recoiling to reconstructed Z boson
- jet veto and further elaborated event requirements
- signal over background ratio of ~ 1.6
- reconstruction efficiency (C_{ZZ}) in electron (muon) amounts 68% (75%)
- main systematics arise from jet and missing energy reconstruction



- cross section measurement in an fiducial phase space close to detector acceptance for minimal theoretical dependencies

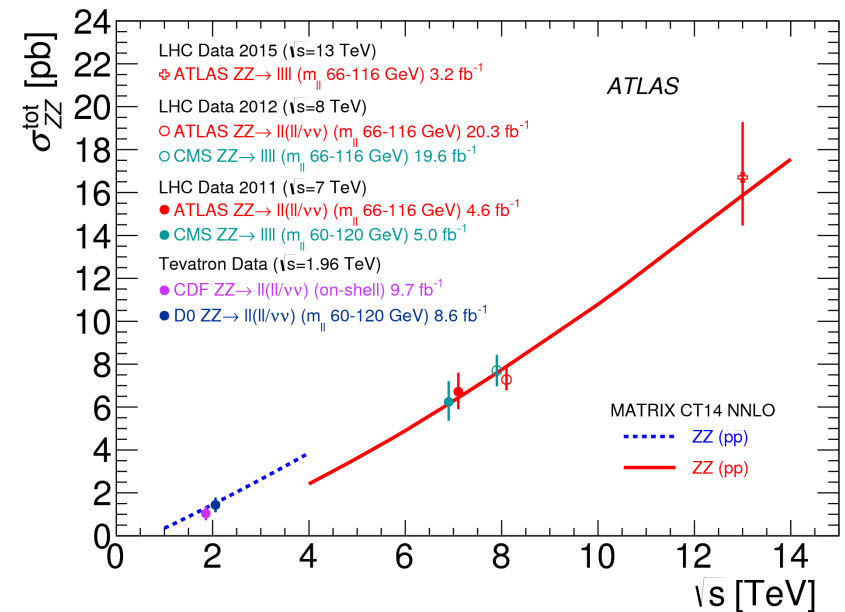
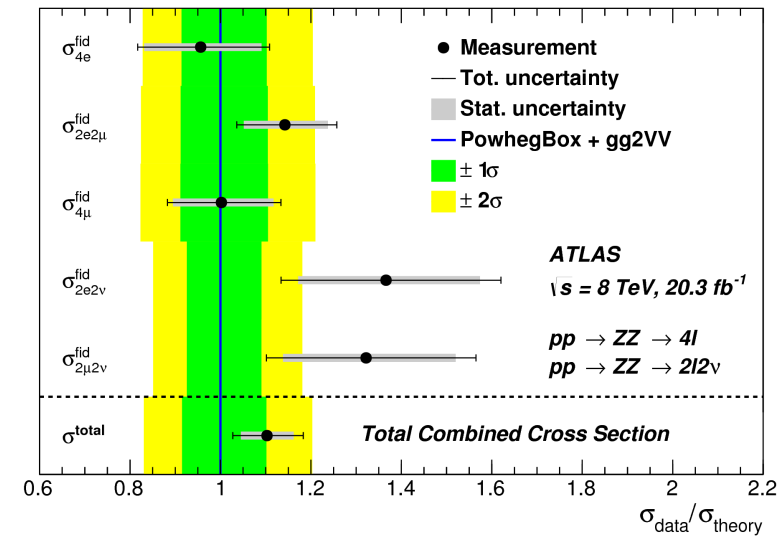
$$\sigma_{ZZ}^{\text{fiducial}} = \frac{N^{\text{obs}} - N^{\text{background}}}{\mathcal{L} \cdot C_{ZZ}}$$

with luminosity \mathcal{L} and efficiency correction factor C_{ZZ}

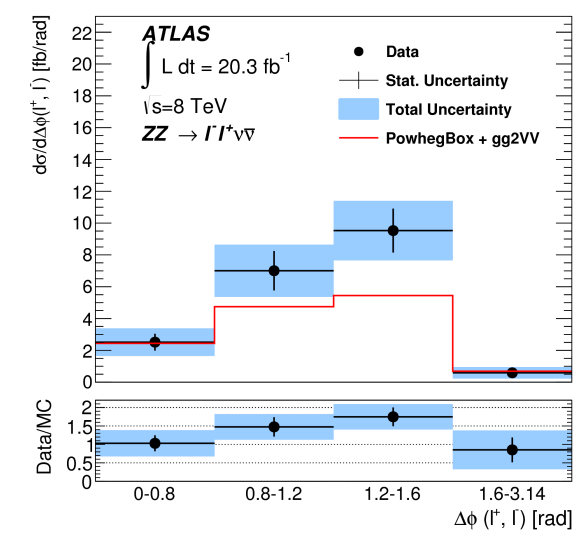
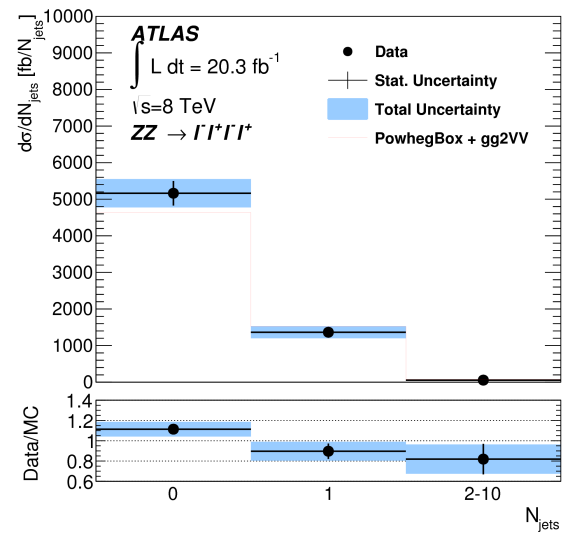
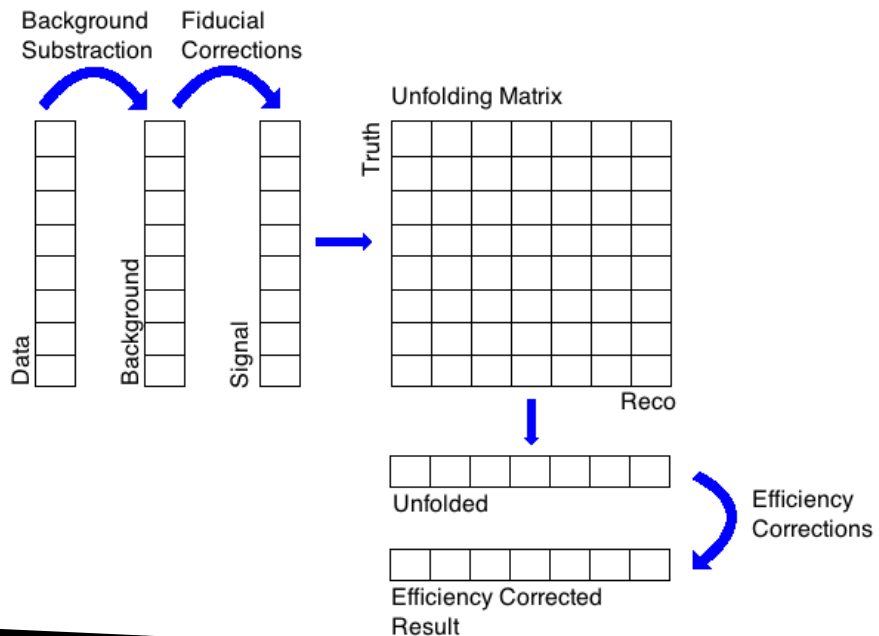
- total ZZ production cross section extrapolated from fiducial volume

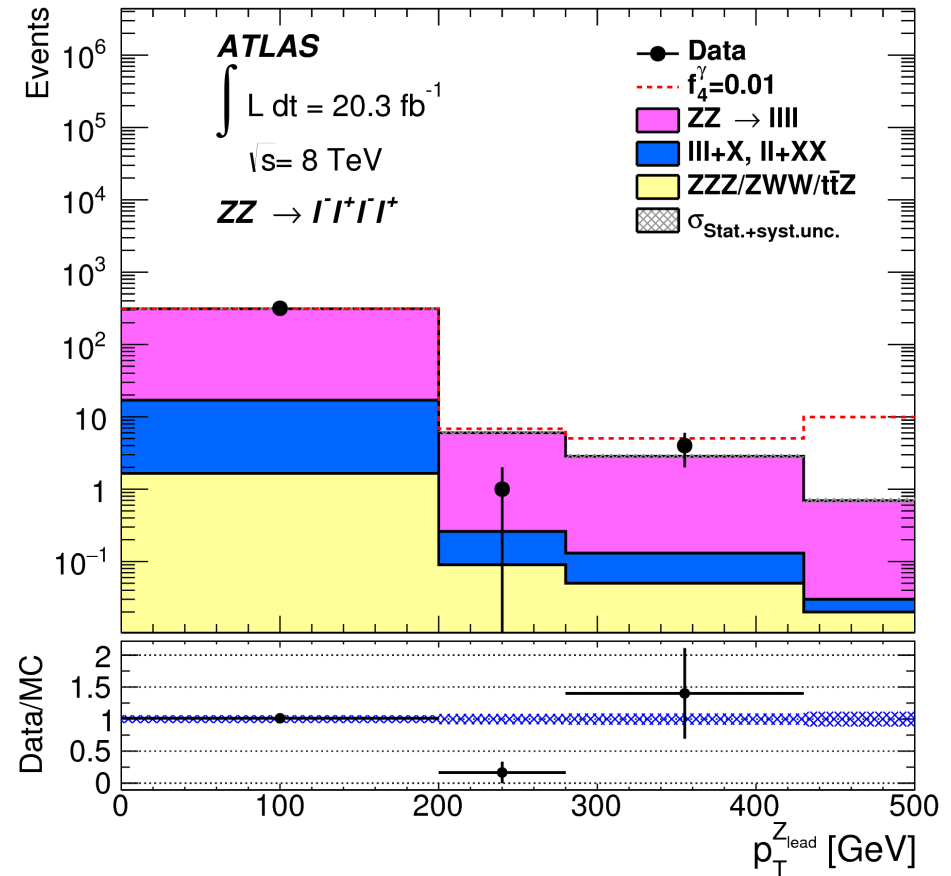
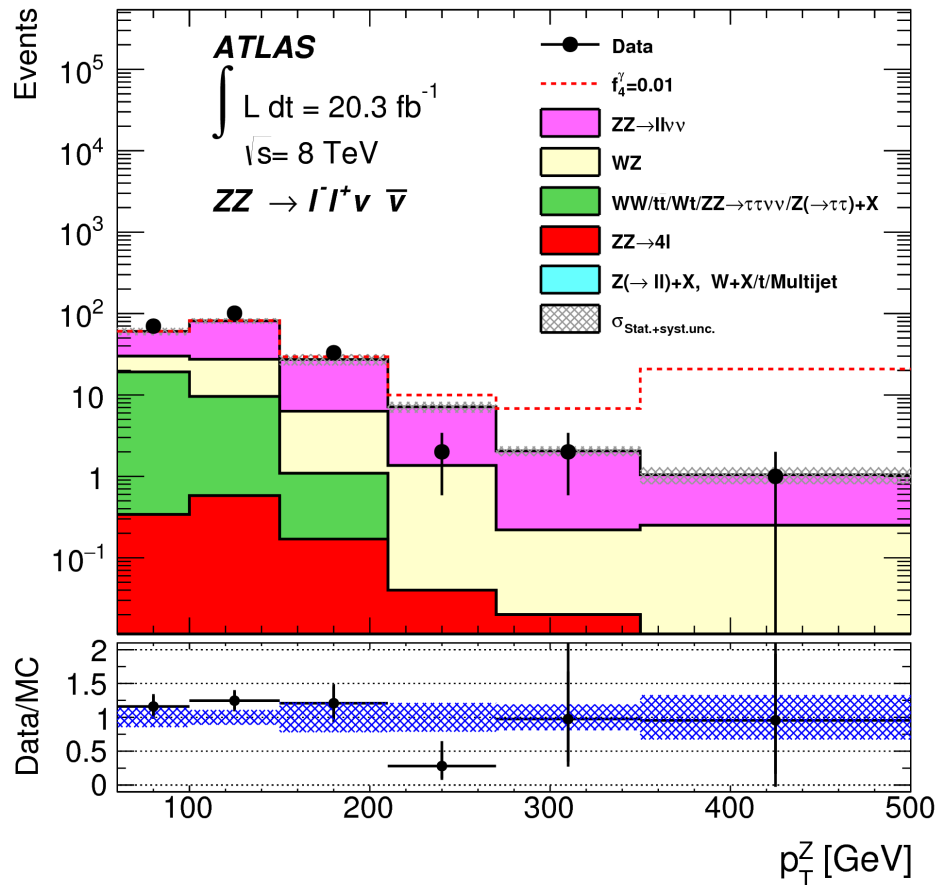
$$\sigma_{ZZ}^{\text{total}} = \frac{N^{\text{obs}} - N^{\text{background}}}{\mathcal{L} \cdot \text{BR}(ZZ \rightarrow 4\ell/2\ell 2\nu) \cdot A_{ZZ} \cdot C_{ZZ}}$$

with branching fraction $\text{BR}(ZZ \rightarrow X)$ and acceptance correction factor A_{ZZ}



- Bayesian iterative unfolding to account for detector resolution, efficiency and acceptance:
 - ➔ input is simulation and output is used as next input
 - ➔ unfolding algorithm takes response matrix and measured spectrum to form a likelihood
- 4ℓ is unfolded in total phase space while it is fiducial one for $2\ell 2\nu$
 - ➔ most appropriate measurement to compare theory with



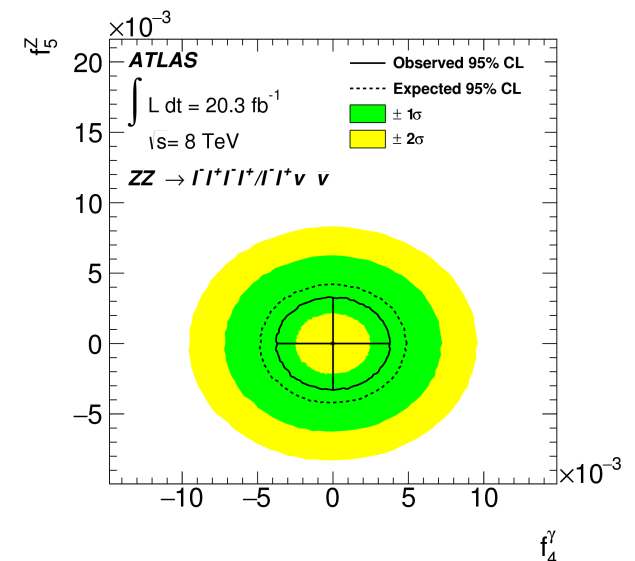
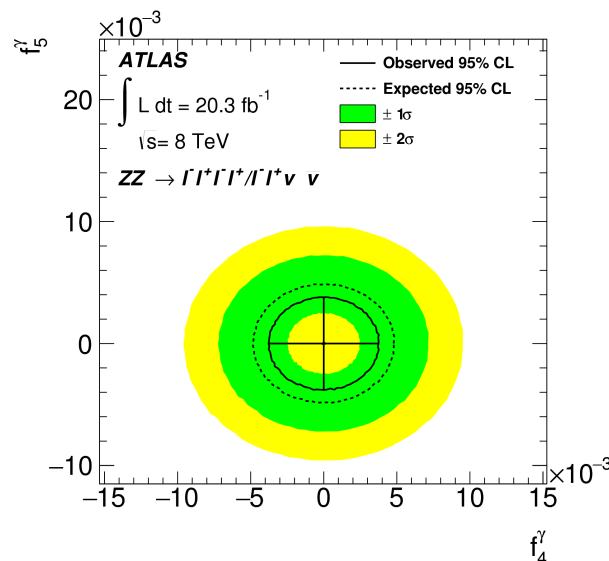
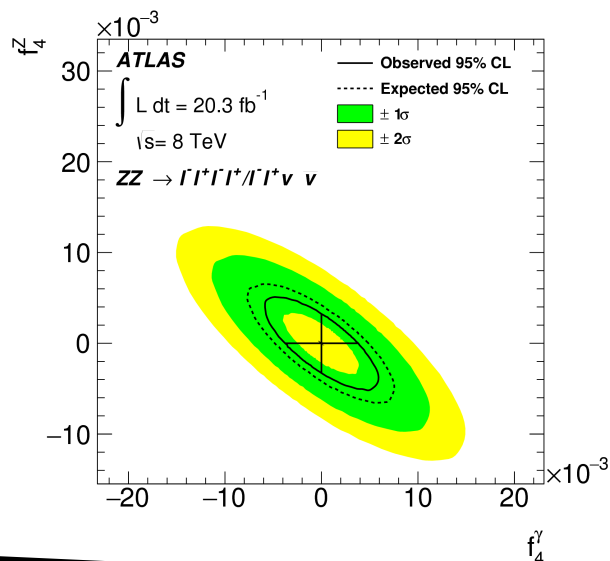


- transverse momentum (p_T) of leading/reconstructed Z boson are found to be sensitive to triple gauge couplings
- profile-likelihood-ratio test statistic used to assess compatibility between predictions with aTGCs and data in two highest p_T bins

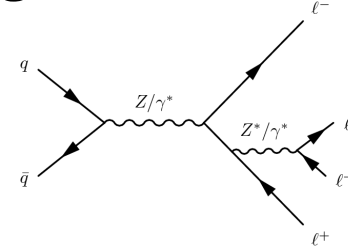
- vertex function with triple gauge couplings f_4^V (forbidden by CP invariance) and f_5^V (required to be 0 due to parity conservation) ($V=Z, \gamma$):

$$g_{ZZV}\Gamma_{ZZV}^{\alpha\beta\mu} = e \frac{P^2 - M_V^2}{M_Z^2} \left[i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho \right]$$

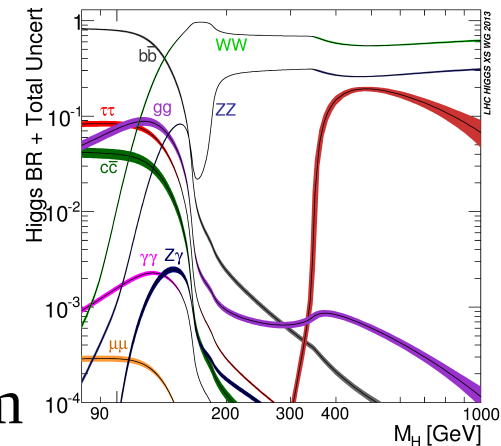
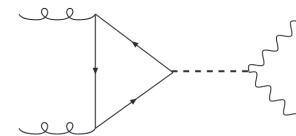
- current sensitivity well within the unitarization constraints and therefore no need for a cut-off form factor
- 95% confidence intervals derived with frequentist method



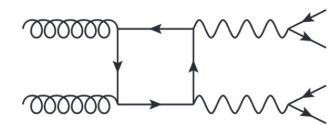
- single Z boson resonance:



- Higgs resonance

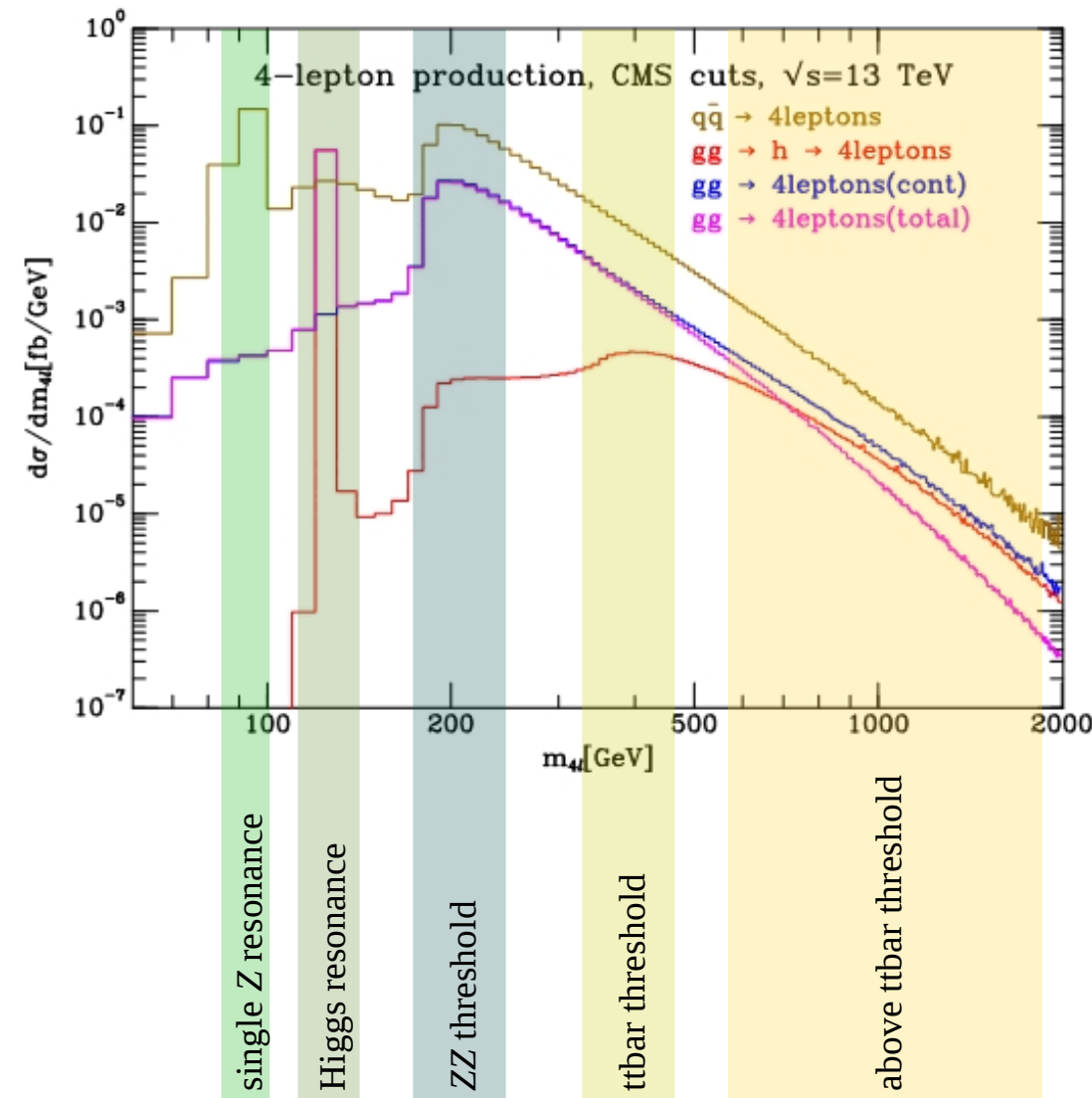


- SM ZZ continuum production of an on-shell Z boson pair



➔ interference gets strong

- heavy top limit invalid for gluon initial state above ttbar threshold



Cross Section Measurement And Signal Strength

- accuracy of theory predictions of ZZ production via gluon initial state improved recently significantly

- approximations of higher order QCD effects available but no full NLO calculation

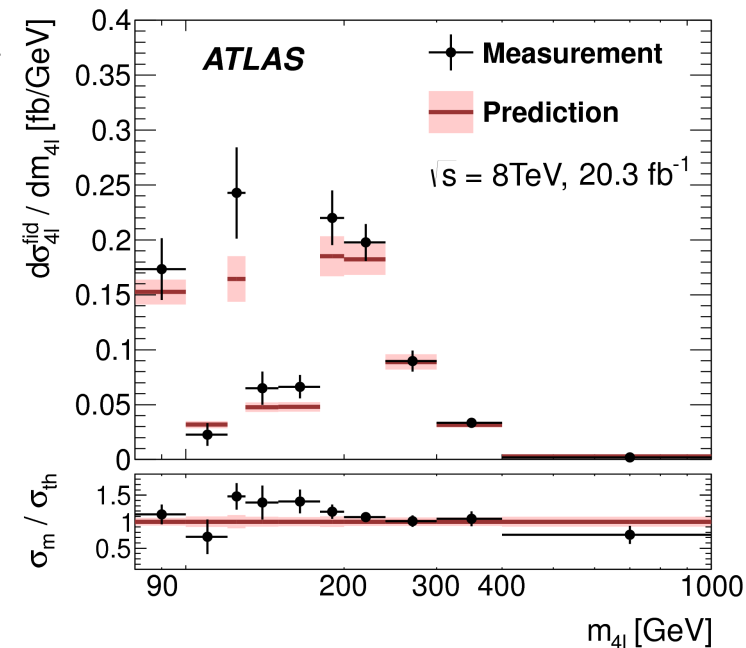
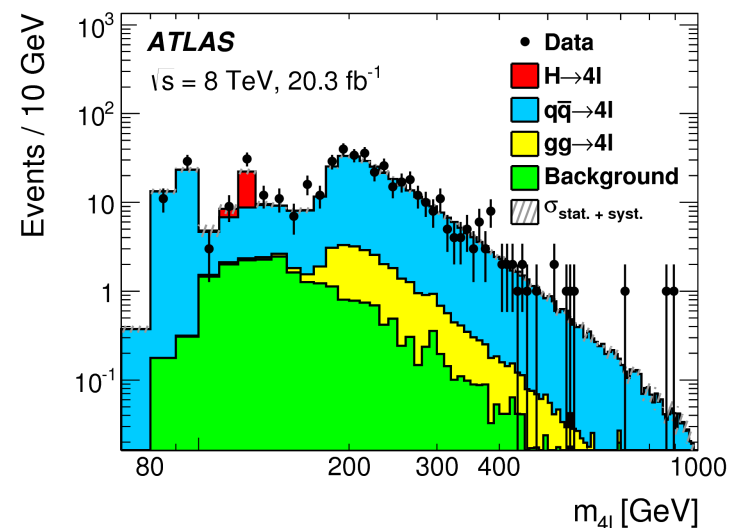
➔ not negligible uncertainties

- measurement of differential 4 ℓ gives important feedback regarding sanity of calculations

➔ determination of gluon initial state signal strength above 180 GeV to

$$\begin{aligned} \mu_{gg} &= \sigma(\text{data}) / \sigma(\text{LO}) \\ &= 2.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.8(\text{theory}) \end{aligned}$$

agrees with predicted k-factor of ~ 2



- with on-shell Higgs signal strength μ_H it is possible to interpret gluon signal strength μ_{gg} as Standard Model Higgs width Γ_H inside κ -framework

→ fixed μ_H makes on-peak cross section independent of Γ_H

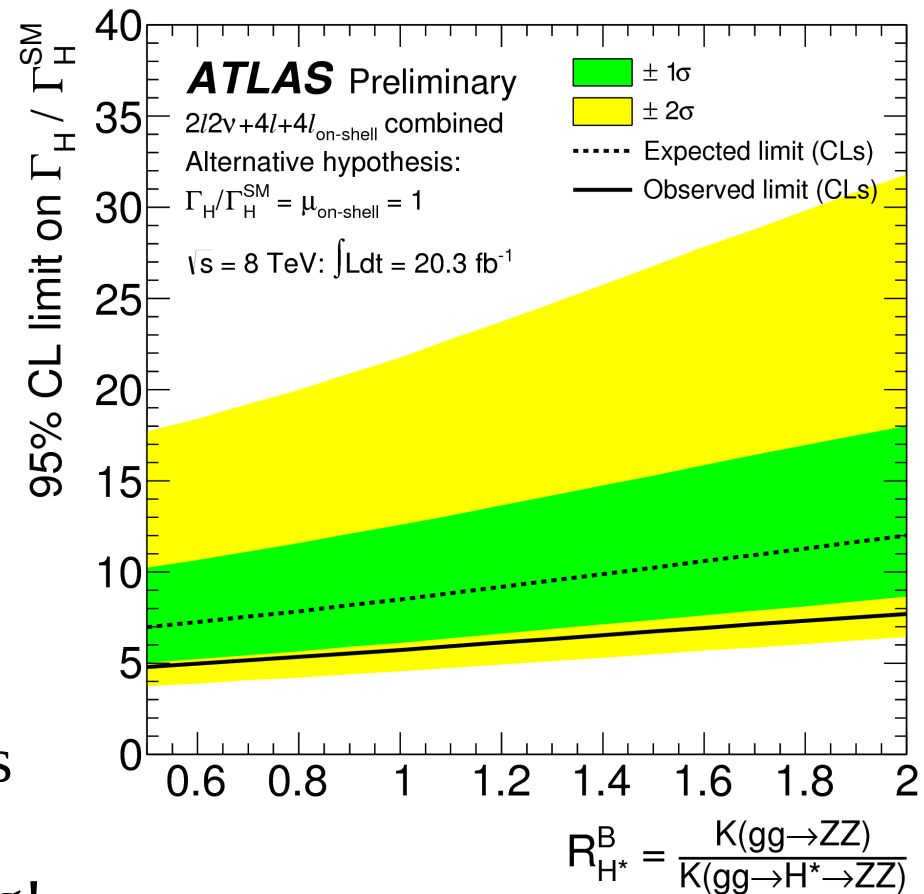
$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-peak}} = \mu_H \sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-peak, SM}}$$

→ off-peak cross section becomes dependent on width Γ_H

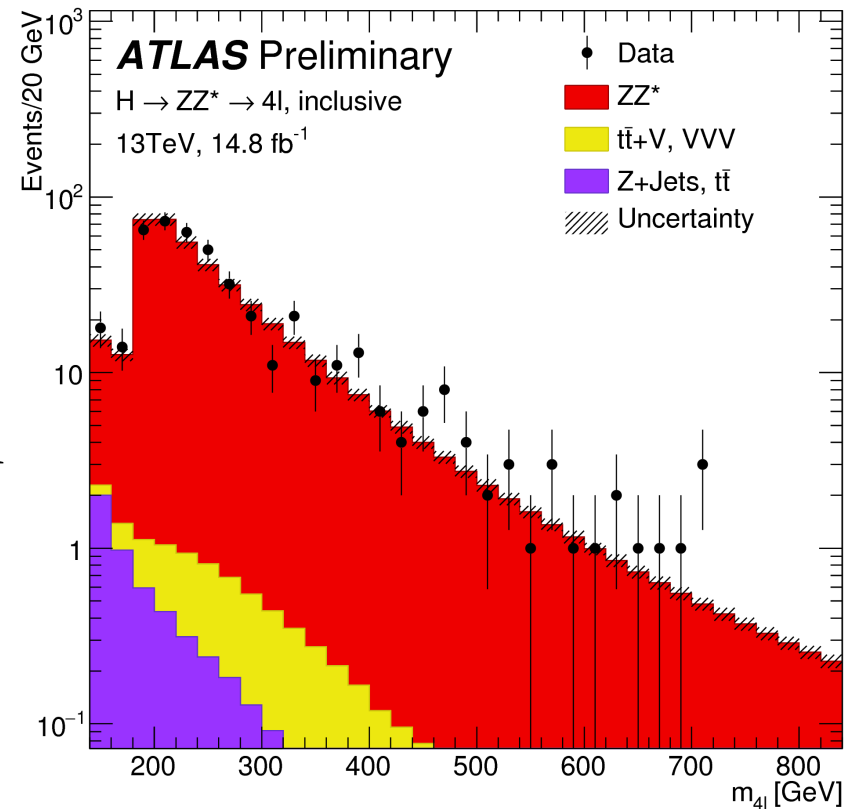
$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-peak}}}{dm_{ZZ}} = \mu_H \cdot \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} \cdot \frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-peak, SM}}}{dm_{ZZ}}$$

→ limits can be set

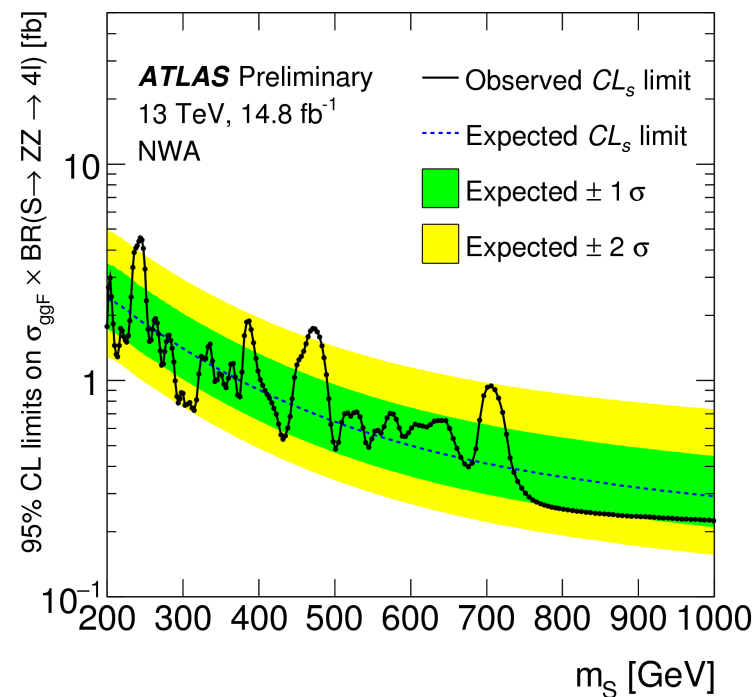
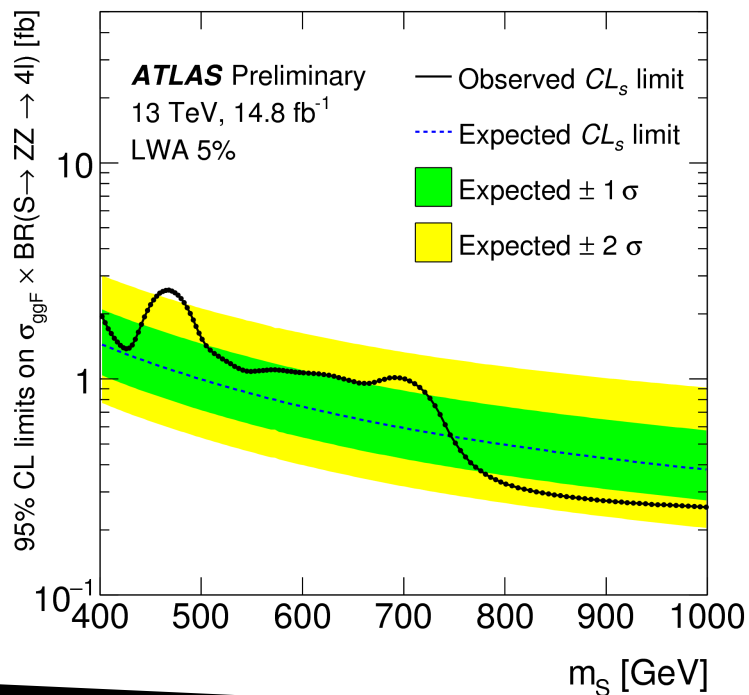
- besides missing higher order corrections for gluon initial state ZZ production there are **MANY** assumptions entering!



- bare SM does not hold explanations for all observations (dark matter, dark energy, neutrino masses, ...)
- ➔ many extensions have an extended Higgs sector with further heavier particles for which we should search
- selection of events with two same-flavor, opposite-charge leptons pairs ($4e, 4\mu, 2e2\mu$) consistent with on-shell Z bosons
- SM ZZ production with identical final state is dominant irreducible background
- ➔ any control region would overlaps with a signal region
- ➔ precise modeling of predictions considering latest theory results



- expected and observed exclusion cross sections for Higgs-like scalar production
- search for resonance dominated by detector resolution using narrow width approximation (NWA) for scalar
- large width approximation to search for broader bump (fluctuations are blurred)



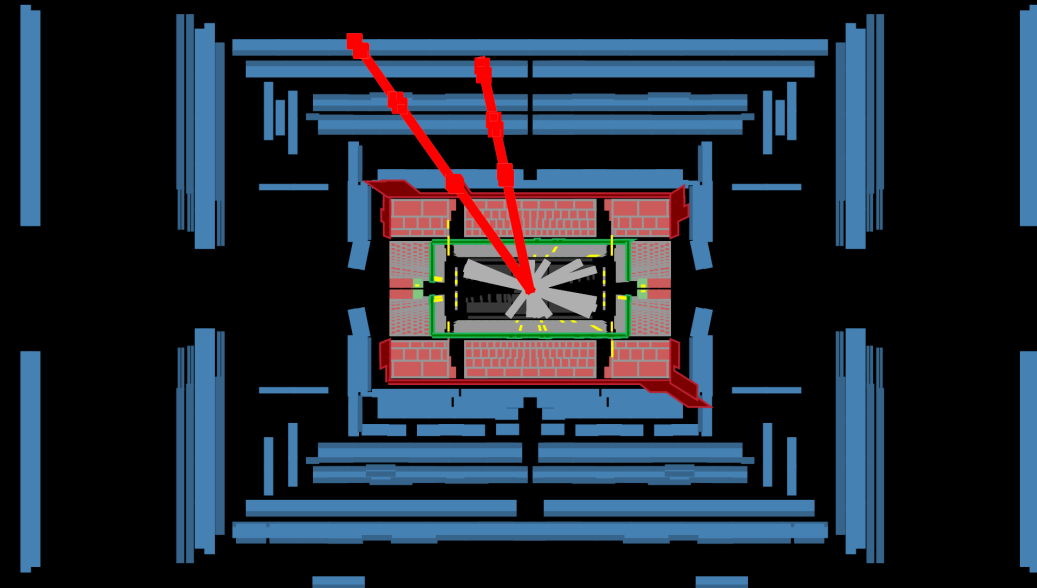
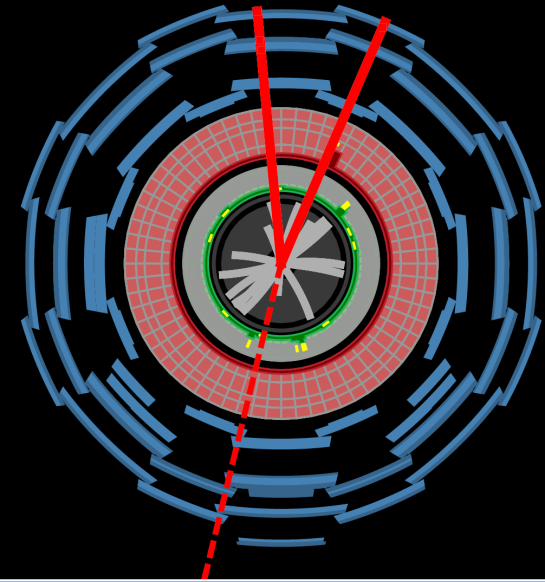
- interference effects between SM $pp \rightarrow ZZ$ (main background) and $pp \rightarrow H \rightarrow ZZ$ found to be small at current sensitivities
- no relevant excess found in run 2 data analyzed up to ICHEP

- final state with higher statistics compared to for charged leptons
- neutrinos escape ATLAS undetected

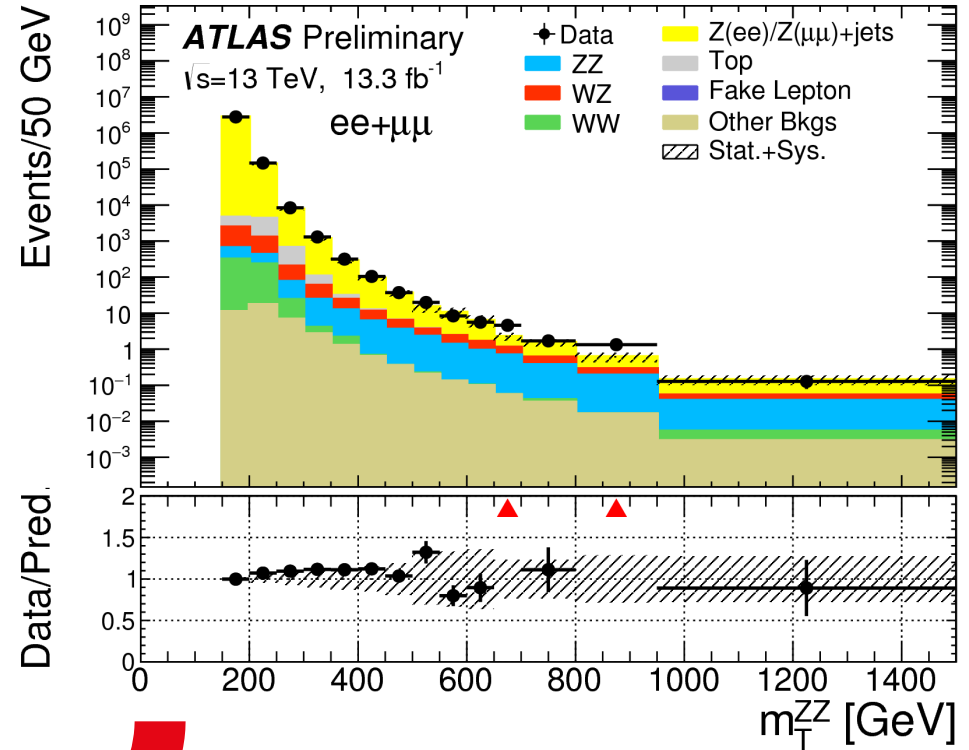
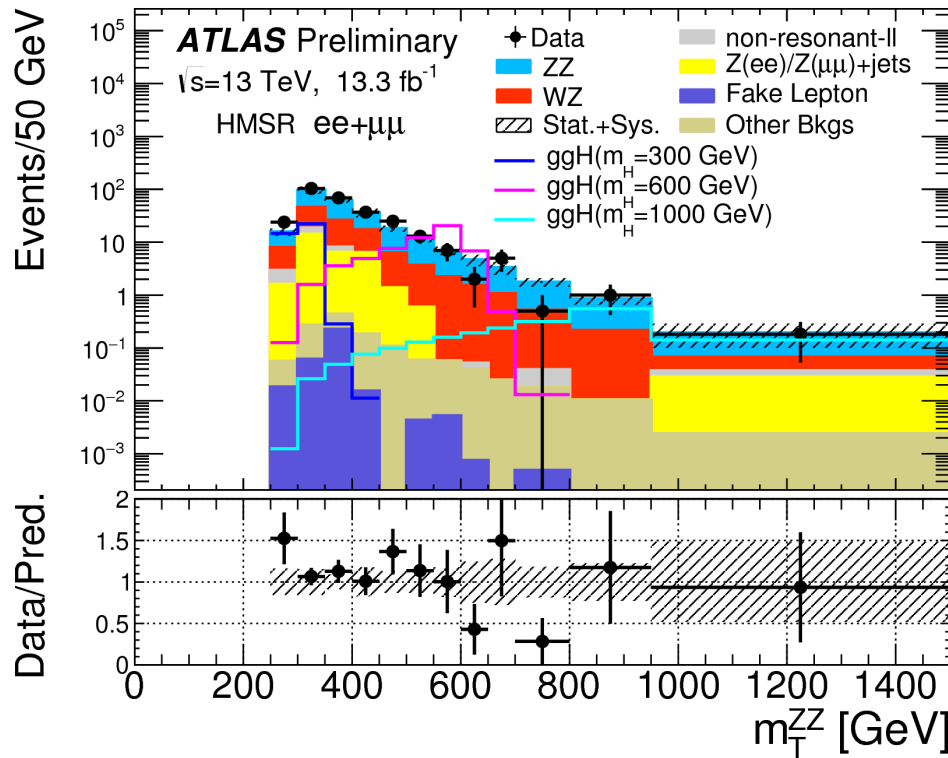
→ determination of E_T^{miss} through p_T balance

→ transverse mass m_T^{ZZ} is observable closest to $m_{4\ell}$ which cannot be reconstructed

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

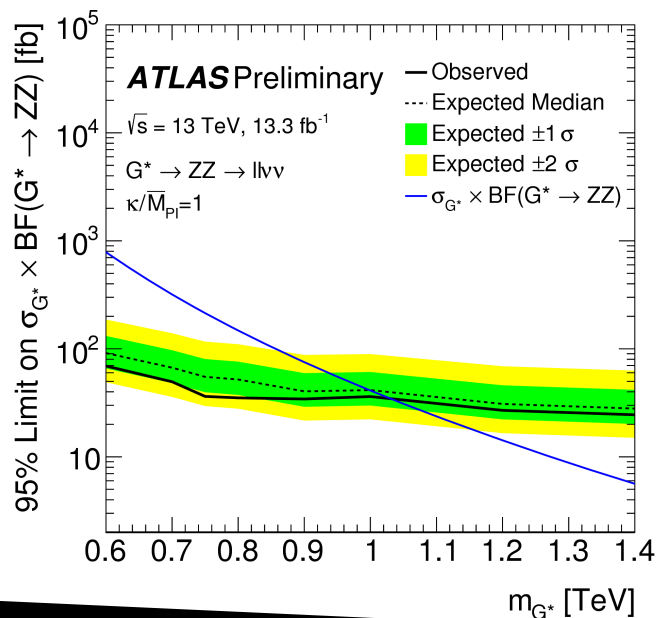
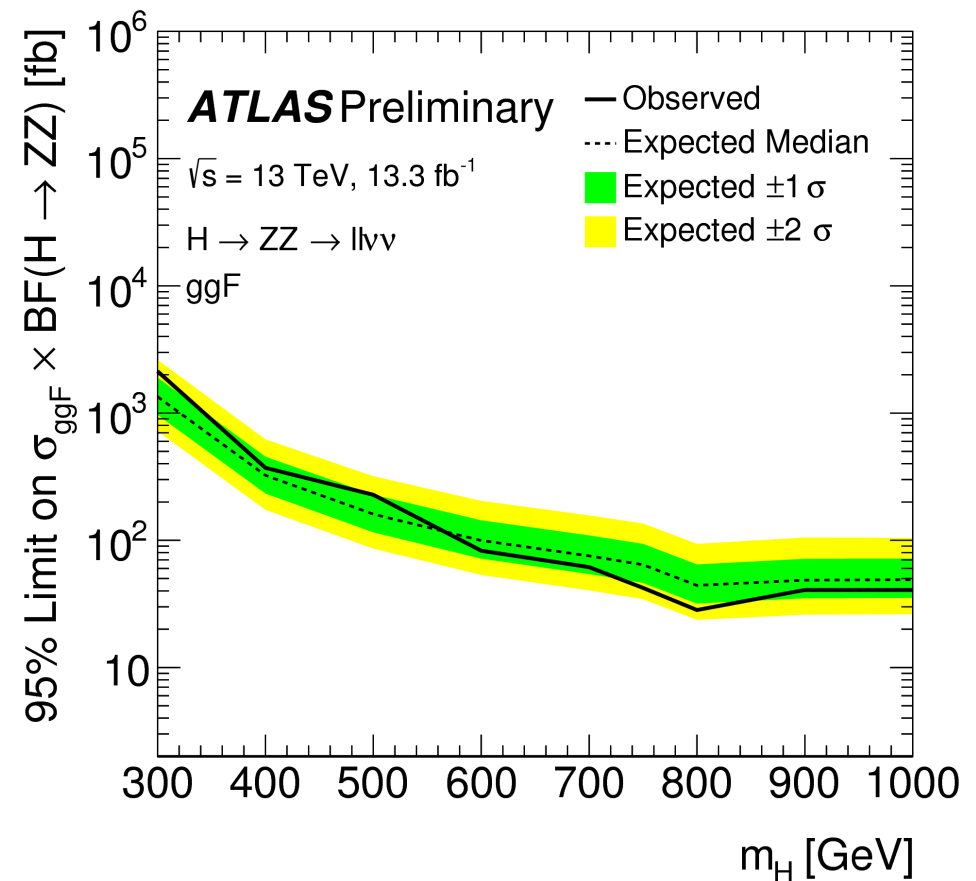


- events with exactly two same-flavor, opposite-charged leptons with high transverse momentum
- $m(\ell\ell)$ compatible with Z boson mass within 15 GeV



- more than 120 GeV for E_T^{miss}
- elaborated cuts on kinematic correlations

- complementary sensitivity to other searches in $H \rightarrow ZZ$ channel particular above 500 GeV :
 - more statistics than 4ℓ channel due to higher branching fraction
 - less background than $2\ell 2q$ or $2\nu 2q$ because of cleaner event topology
- search for resonance dominated by detector resolution using NWA



- results can also be interpreted in different context, i.e. as search for a spin-2 Kaluza-Klein graviton in a specific model
- no excess over expected exclusion up to now

- diboson physics in general is contributing to our understanding of SM electroweak sector
 - ➔ run 1 triple gauge coupling limits one order of magnitude more stringent than LEP and run 2 improves run 1 by similar amount
- various processes, production modes and final states can give complementary results
 - ➔ different kinematic regions can be accessed
 - ➔ trade of between efficiency and resolution
- latest theory predictions need to be incorporated properly in all analyses and related uncertainties need to be estimated carefully
 - ➔ particularly going from LO to NLO for fully gluon initiated processes introduces big k-factor to be considered by searches
- run 2 data analyses just started and there is much more possible than current default studies