Studies of ZZ production in leptonic final states with ATLAS

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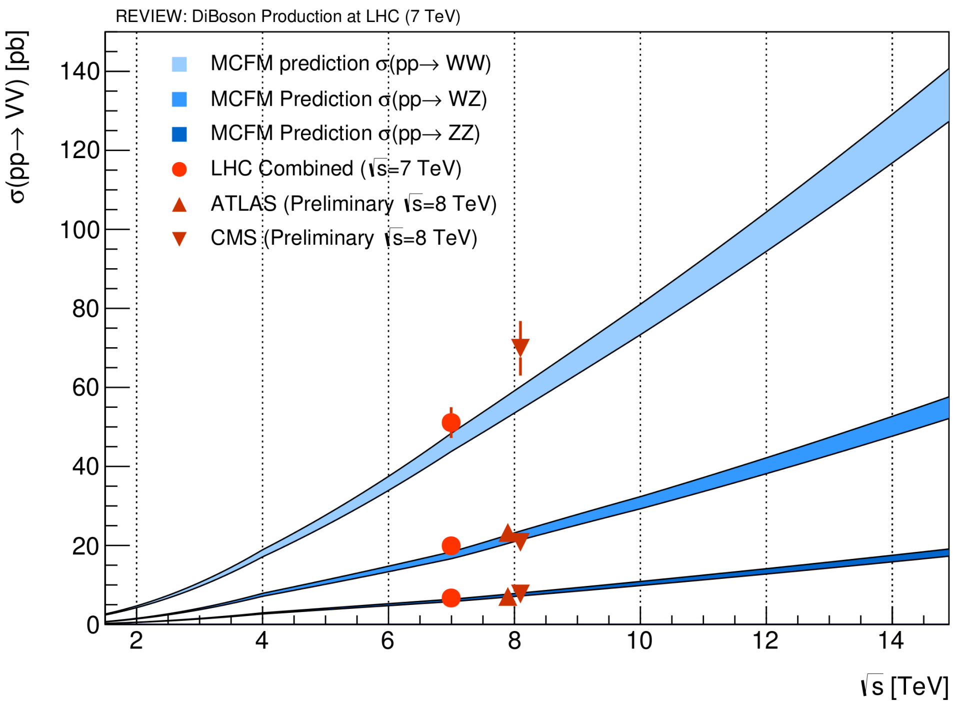
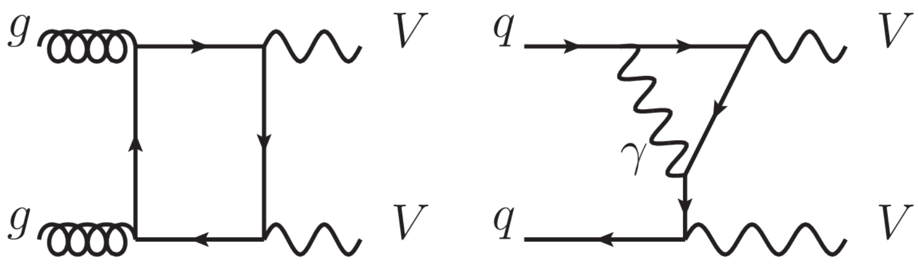
measurements of total and differential cross sections to …

… 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



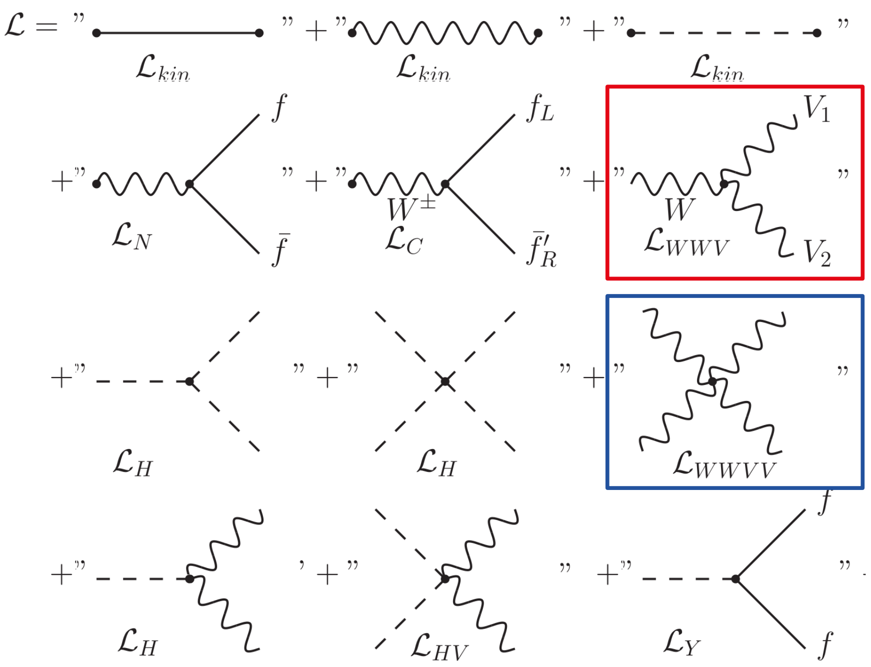


exploration of self-coupling structure of gauge bosons will …

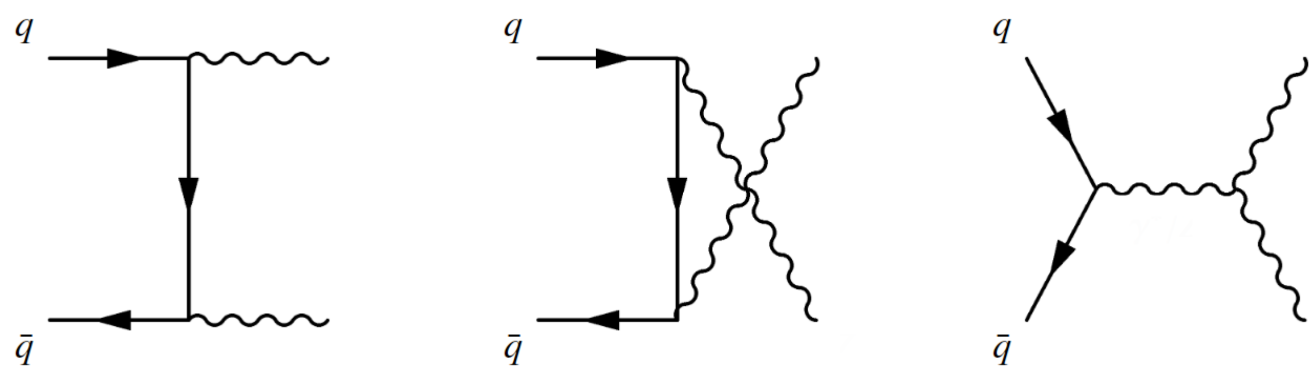
… improve understanding of electroweak symmetry breaking and unitarity

… intersect with determination of Higgs couplings

… indicate new physics if anomalous **triple**/**quartic** couplings are present

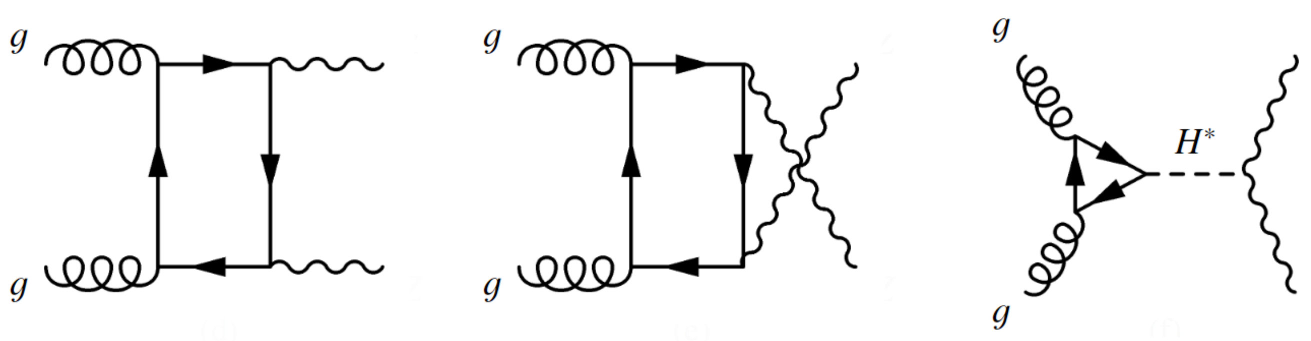


- quark-antiquark initial state without additional jets in the final state:



→ access to triple gauge couplings

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



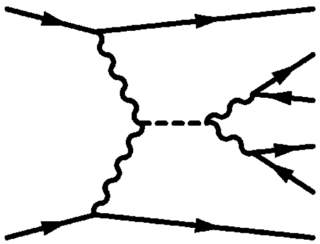
→ interference effects can be utilized to learn more about s-channel resonance

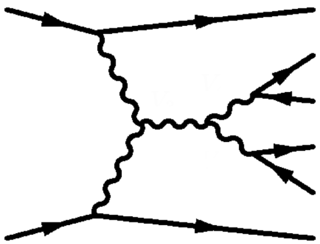
Diboson Production Modes At LHC

- quark-antiquark initial state with final state jets (*VVjj*)
  - vector boson fusion (VBF) give access to …

    … triple gauge couplings

    … properties of s-channel particle



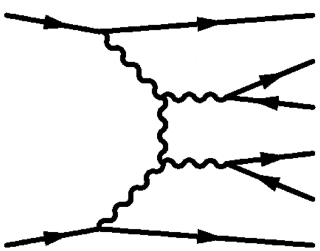


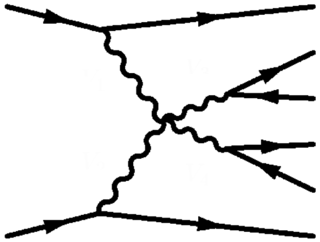
  - vector boson scattering (VBS) gives access to …

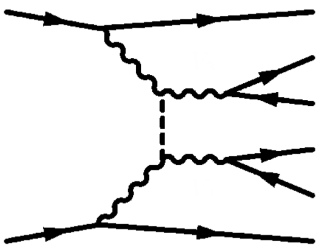
    … triple gauge couplings

    … quartic gauge couplings

    … properties of t-channel particle



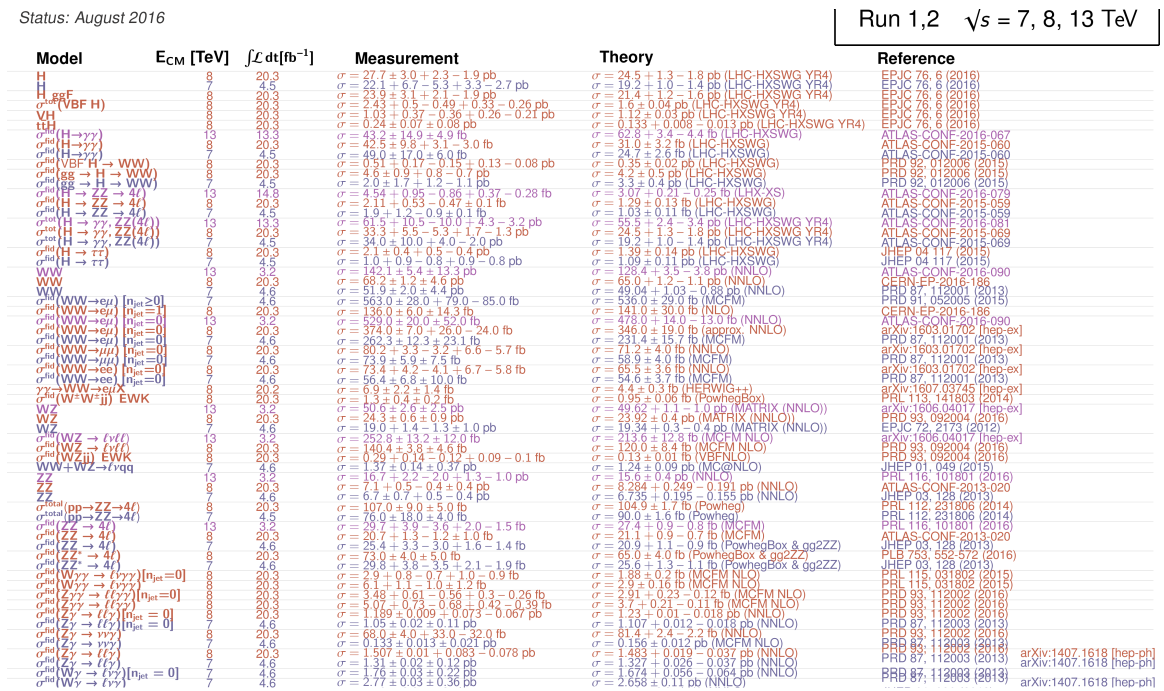




  - *VVjj*-electroweak and *VVjj*-QCD

    ➡ 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

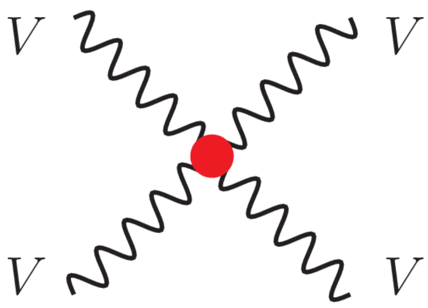


- dedicated analyses in Higgs groups
  - cross section, properties (spin, couplings, …), high mass searches, ...
- exotics groups look mainly for resonances

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

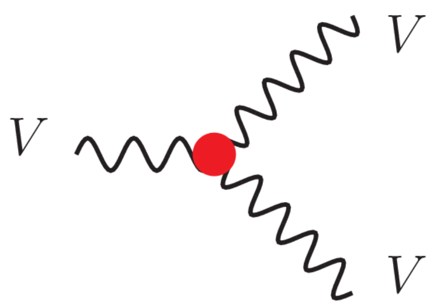
What makes it particularly interesting to look at *ZZ*?

- neither triple nor quartic gauge couplings with only *Z*s 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?

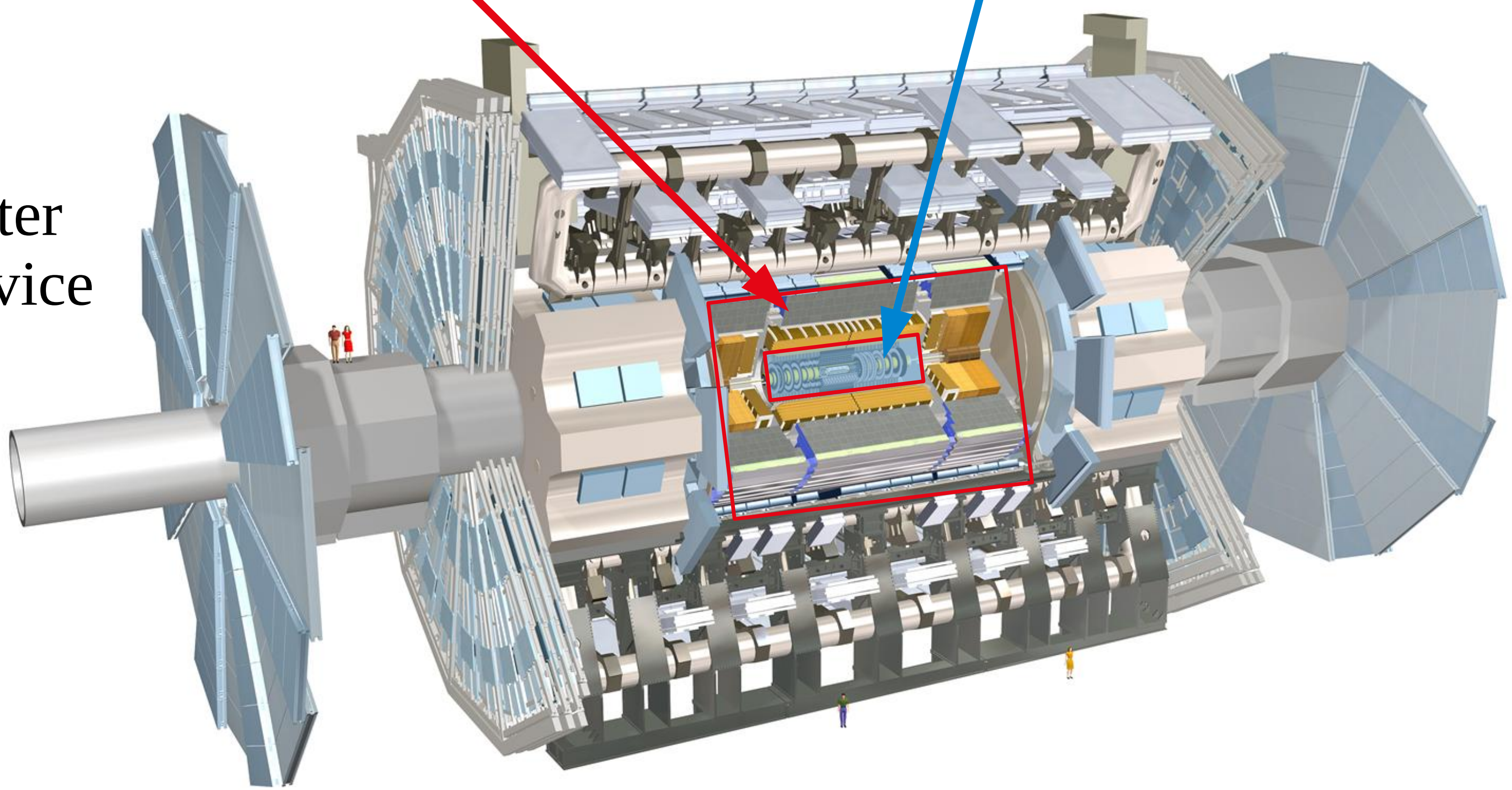
- lower cross sections compared to other diboson processes
- lower branching fraction compared to other final states

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

inner detector for precision tracking

electromagnetic and hadronic calorimeter

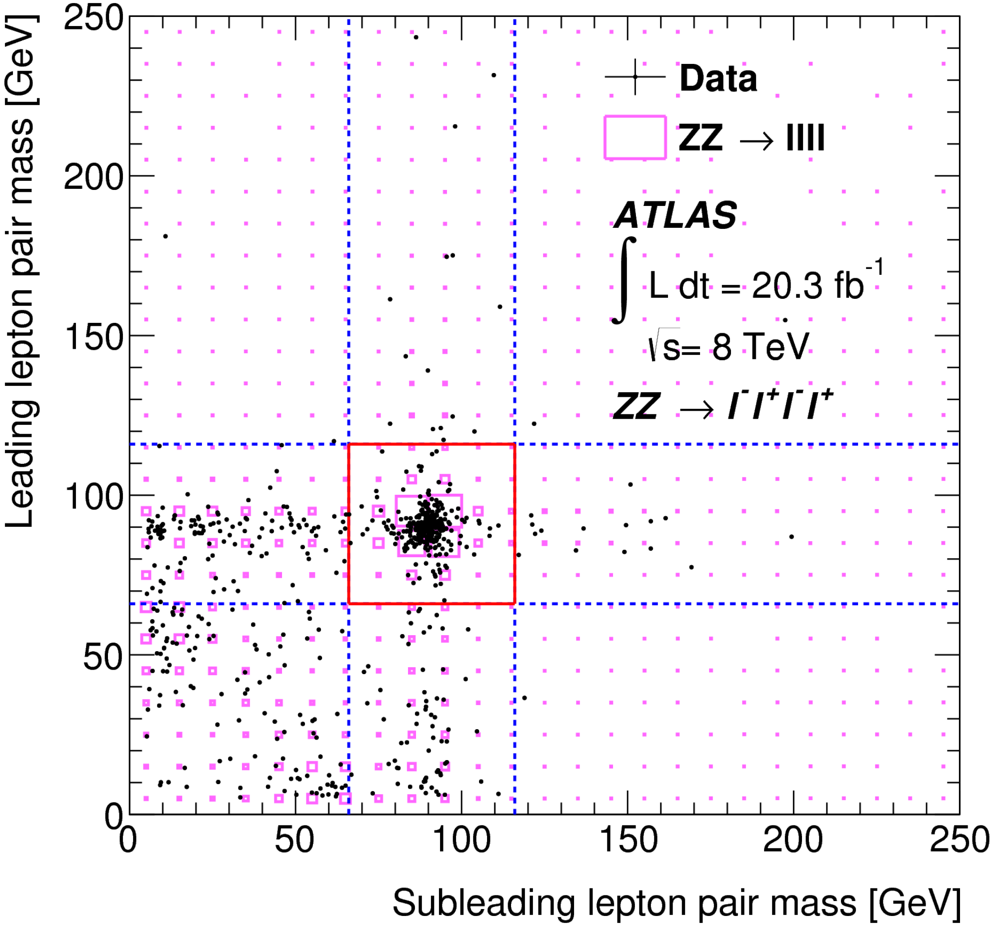
muon spectrometer as outer most device



- 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

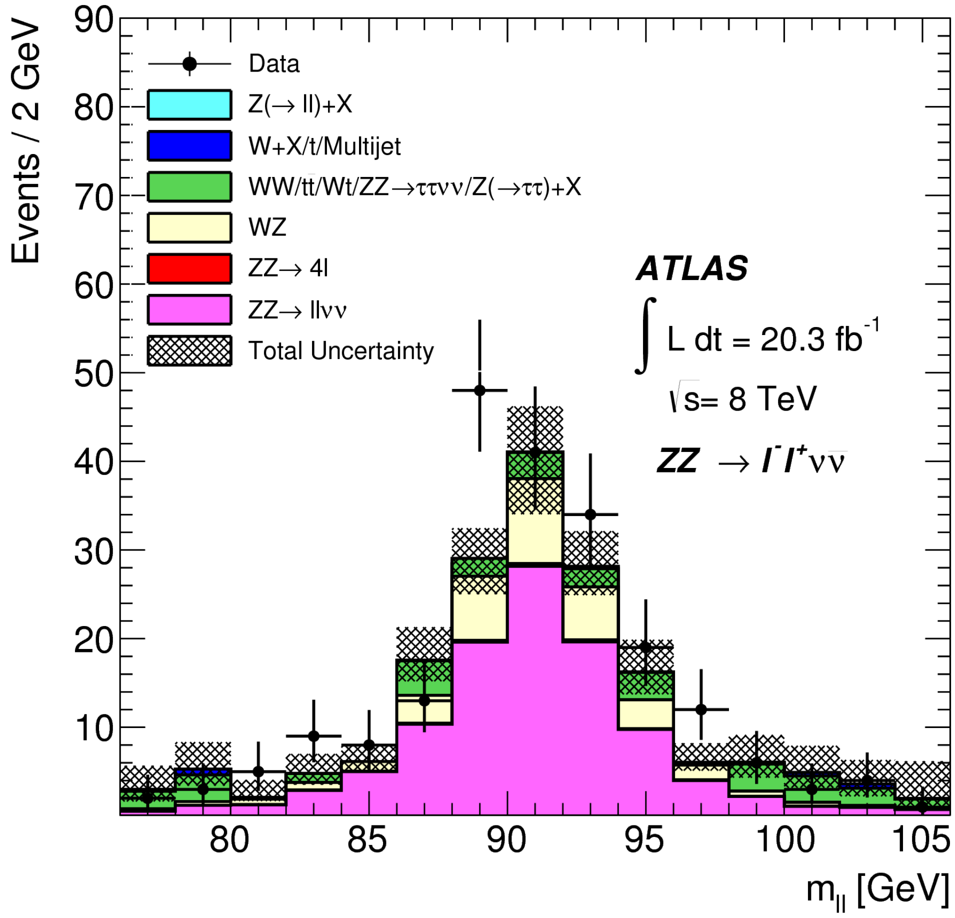
four charged lepton final state selection:

- quite loose lepton requirements to maximize efficiency
- events with two opposite-charged, same-flavor lepton pairs (ℓℓ)
- invariant mass requirement of 66 < m(ℓℓ)/GeV < 116
- signal over background ratio of ~17
- high reconstruction efficiency (C_{ZZ}):
  - ~50% in four electron channel
  - ~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

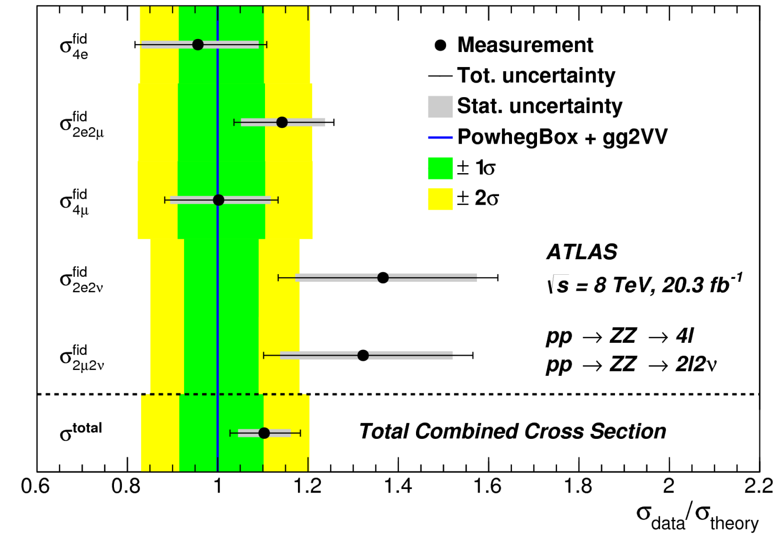


- reconstruction efficiency (C_{ZZ}) in electron (muon) amounts 68% (75%)
- main systematics arise from jet and missing energy reconstruction

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

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

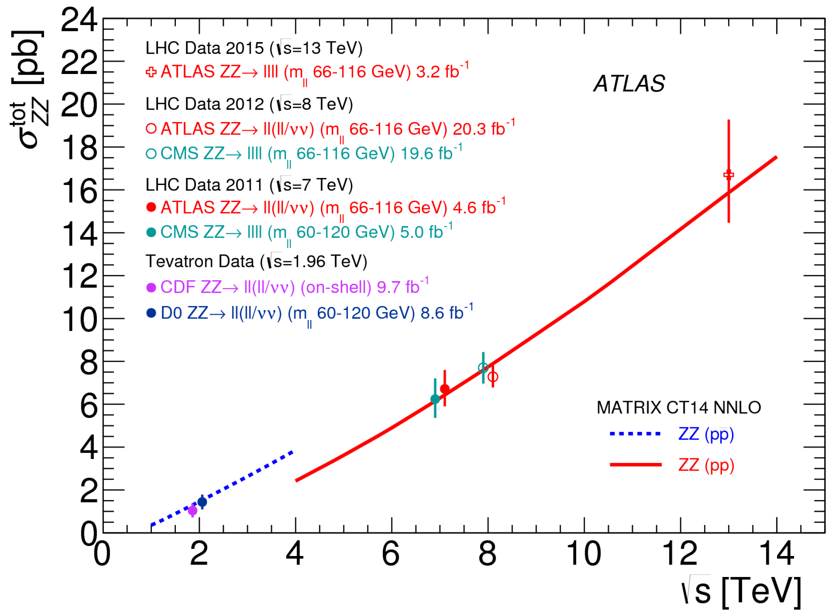
with luminosity $\mathcal{L}$ and efficiency correction factor C_{ZZ}



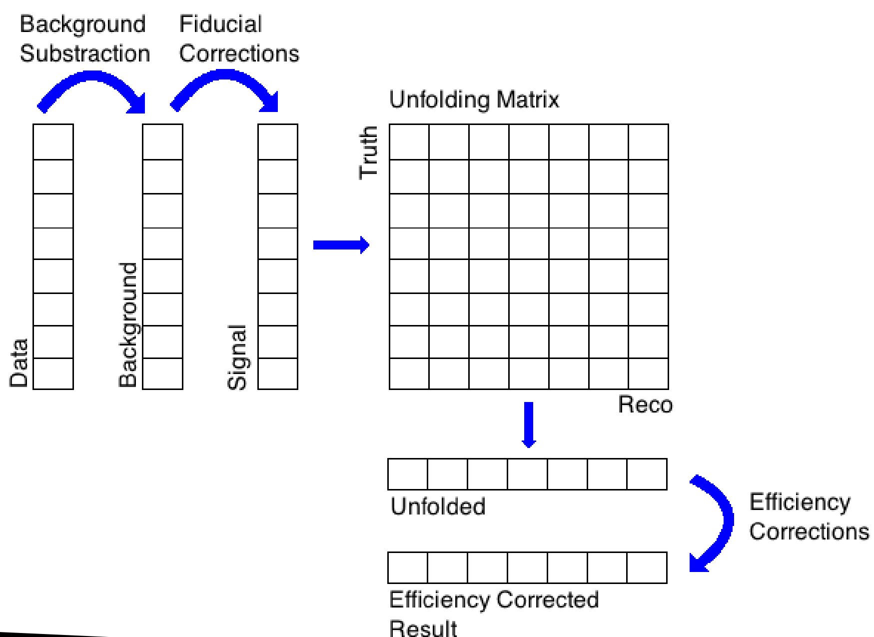
- total *ZZ* production cross section extrapolated from fiducial volume

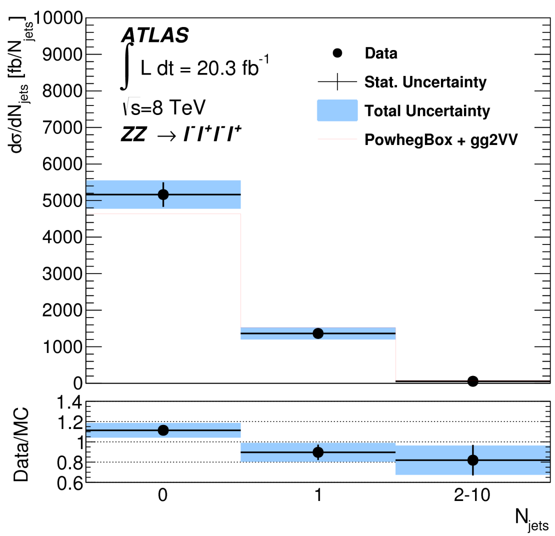
$$\sigma_{ZZ}^{\text{total}} = \frac{N^{\text{obs}} - N^{\text{background}}}{\mathcal{L} \cdot BR(ZZ \to 4\ell/2\ell2\nu) \cdot A_{ZZ} \cdot C_{ZZ}}$$

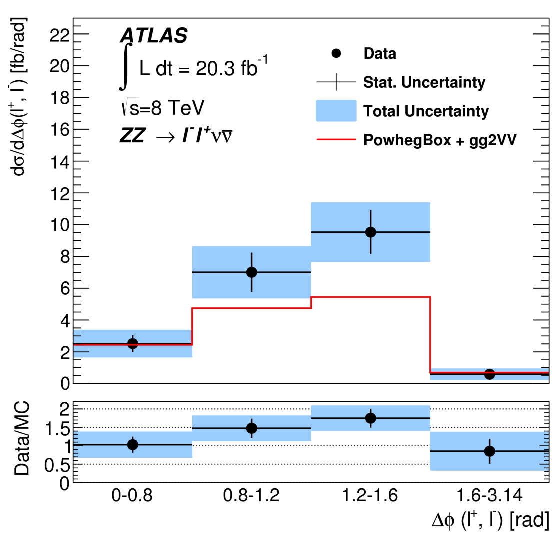
with branching fraction $BR(ZZ \to X)$ and acceptance correction factor A_{ZZ}

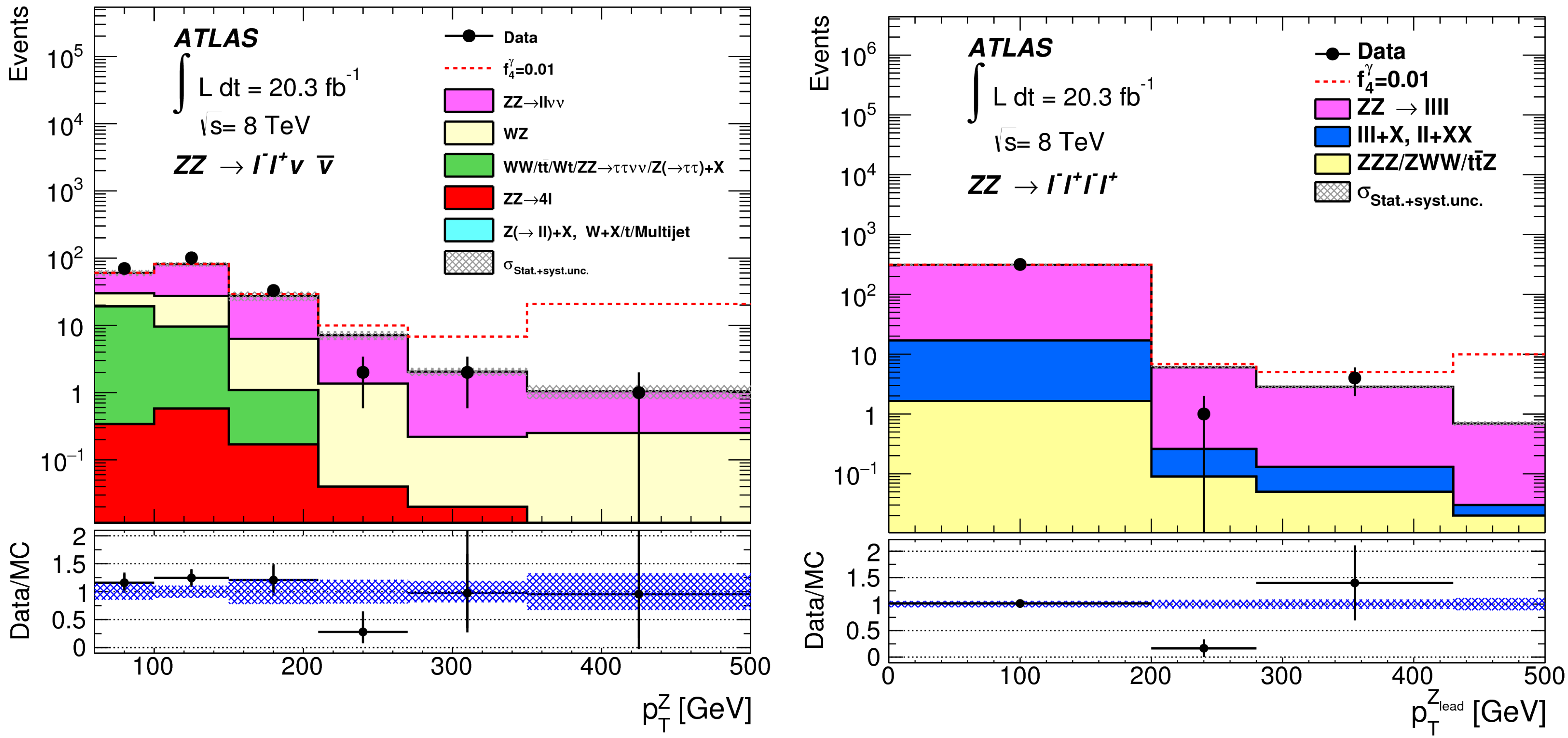


- Bayesian iterative unfolding to account for detector resolution, efficiency and acceptance:
  - ➡ input is simulation and output is used as next input
  - ➡ unfolding algorithm takes response matrix and measured spectrum to form a likelihood
- 4ℓ is unfolded in total phase space while it is fiducial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







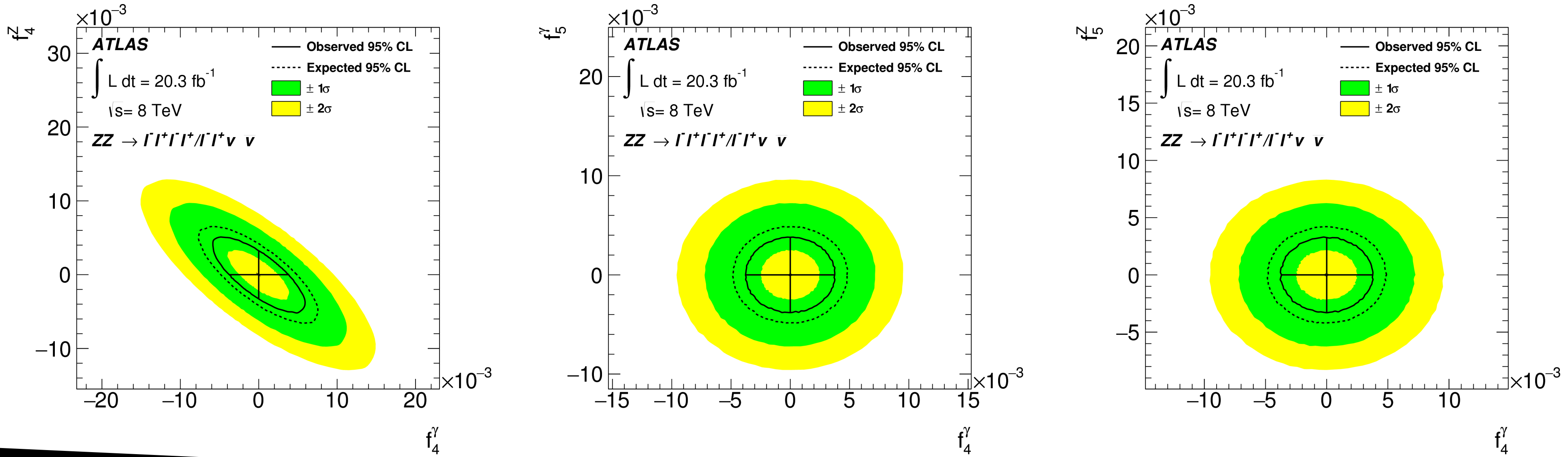


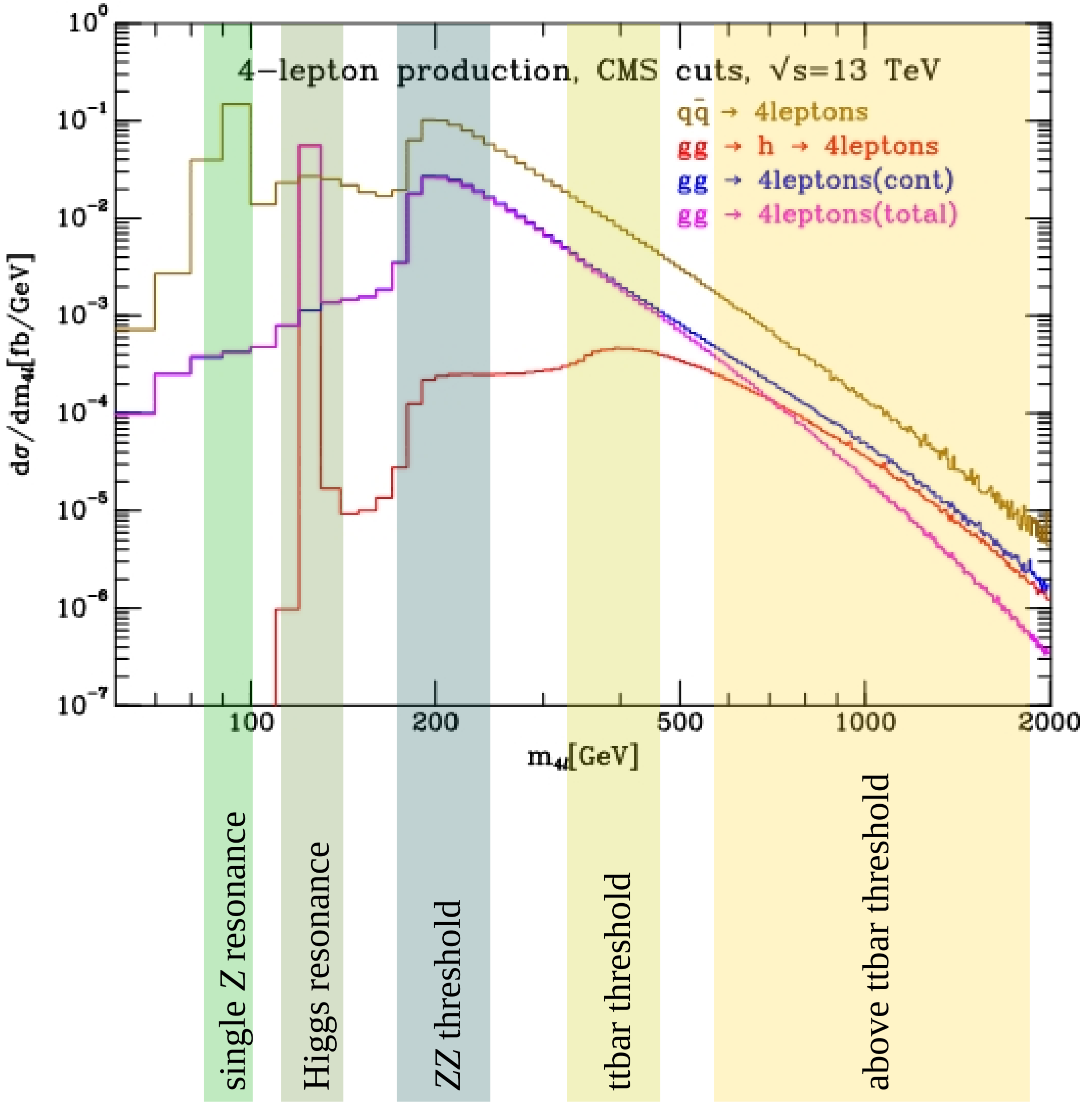
- transverse momentum (p_T) of leading/reconstructed Z boson are found to be sensitive to triple gauge couplings
- profile-likelihood-ratio test statistic used to assess compatibility between predictions with aTGCs and data in two highest p_T bins

- 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, γ):

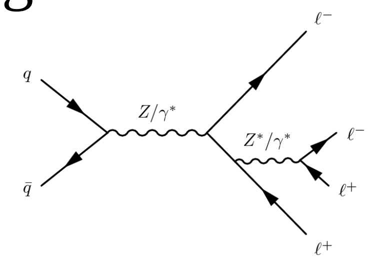
$$g_{ZZV}\Gamma^{\alpha\beta\mu}_{ZZV} = e\,\frac{P^2 - M_V^2}{M_Z^2}\left[i f_4^V\left(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}\right) + i f_5^V \epsilon^{\mu\alpha\beta\rho}\left(q_1 - q_2\right)_\rho\right]$$

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

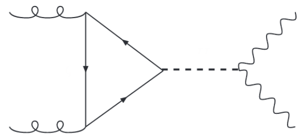


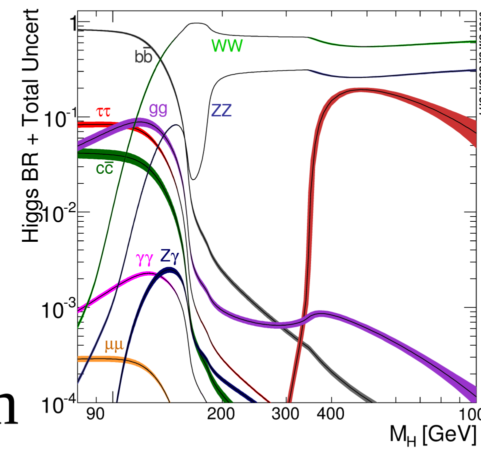


- single Z boson resonance:

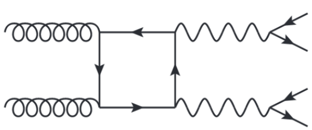


- Higgs resonance





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



→ interference gets strong

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

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

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

  ➡ not negligible uncertainties

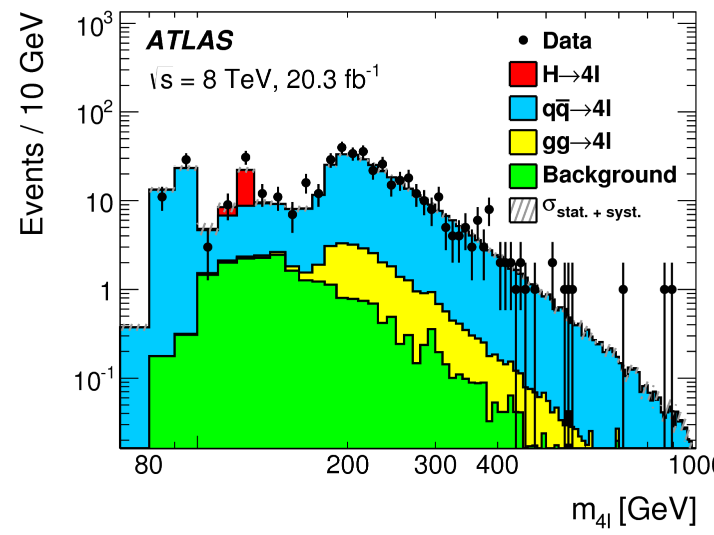
- measurement of differential 4ℓ gives important feedback regarding sanity of calculations

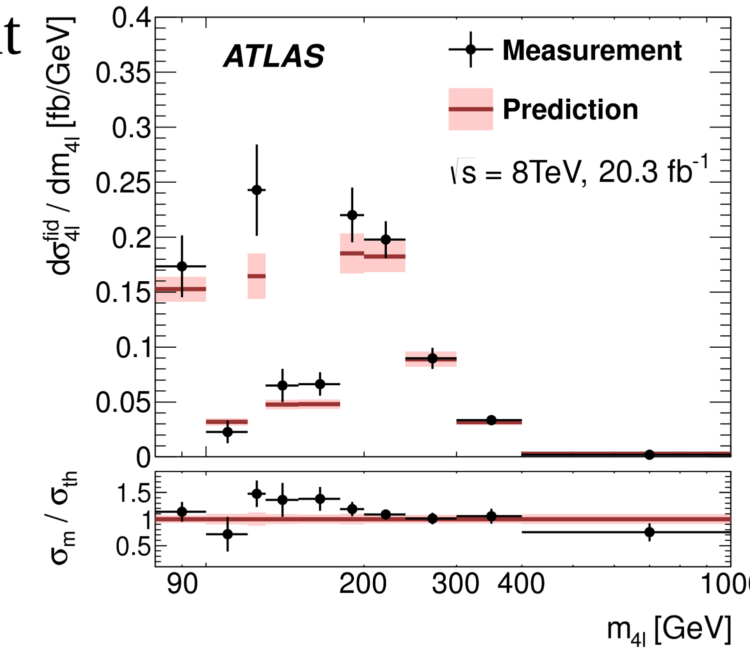
  ➡ determination of gluon initial state signal strength above 180 GeV to

  $\mu_{gg} = \sigma(\text{data}) / \sigma(\text{LO})$

  $= 2.4 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.8(\text{theory})$

  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

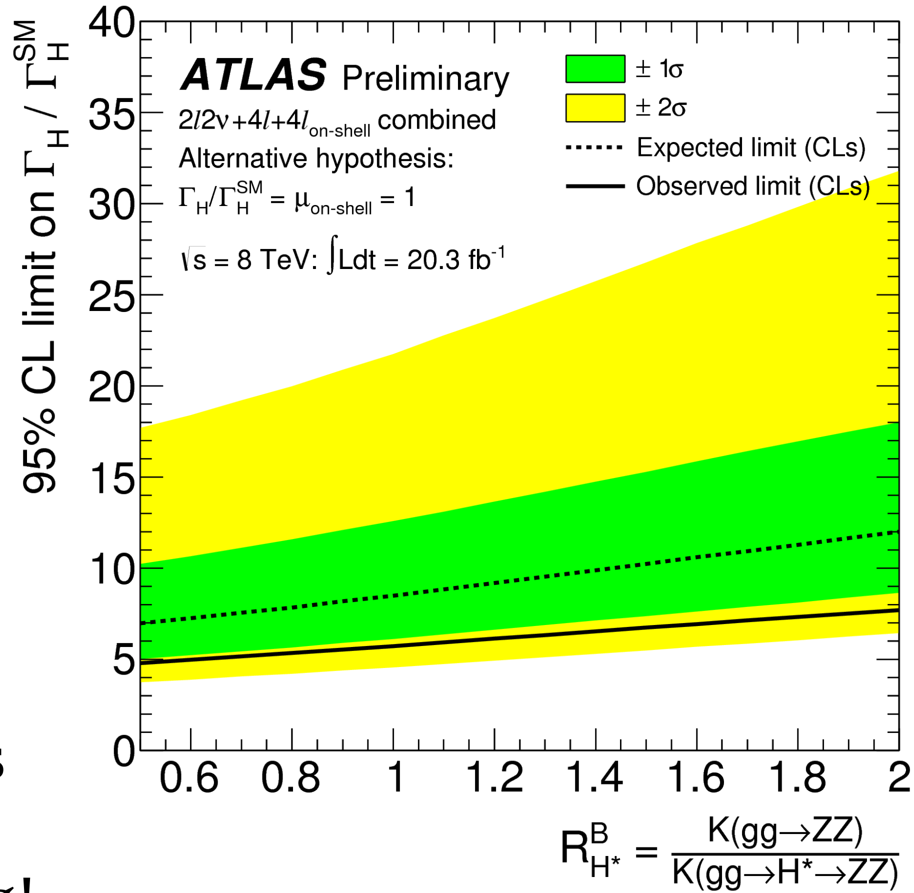
→ fixed μ_H makes on-peak cross section independent of Γ_H

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

→ off-peak cross section becomes dependent on width Γ_H

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

→ 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, …)

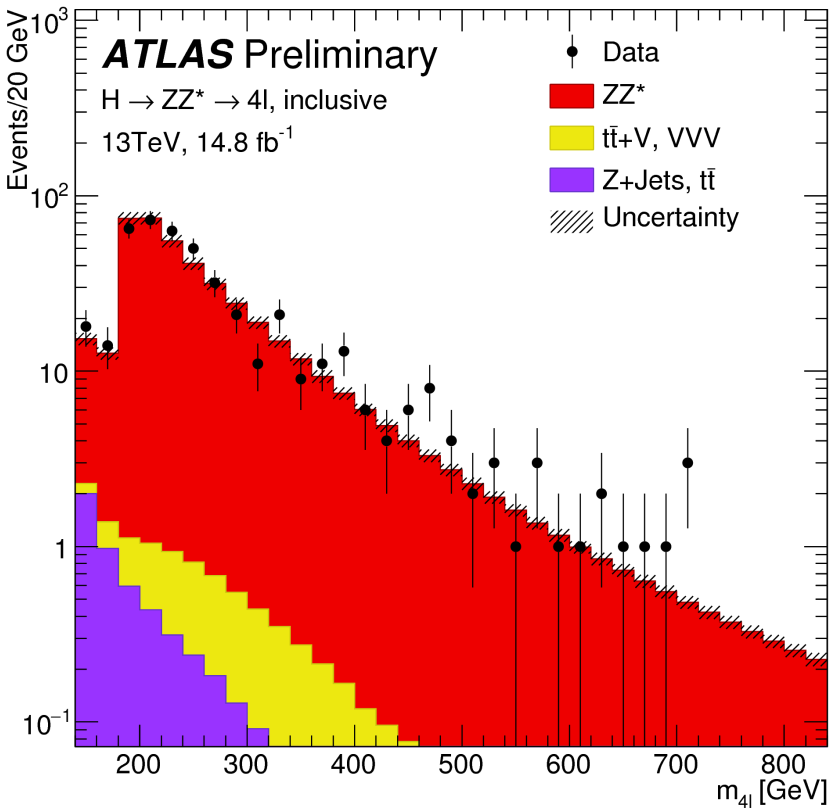
  ➡ many extensions have an extended Higgs sector with further heavier particles for which we should search

- selection of events with two same-flavor, opposite-charge leptons pairs ($4e$, 4μ, $2e2\mu$) consistent with on-shell Z bosons

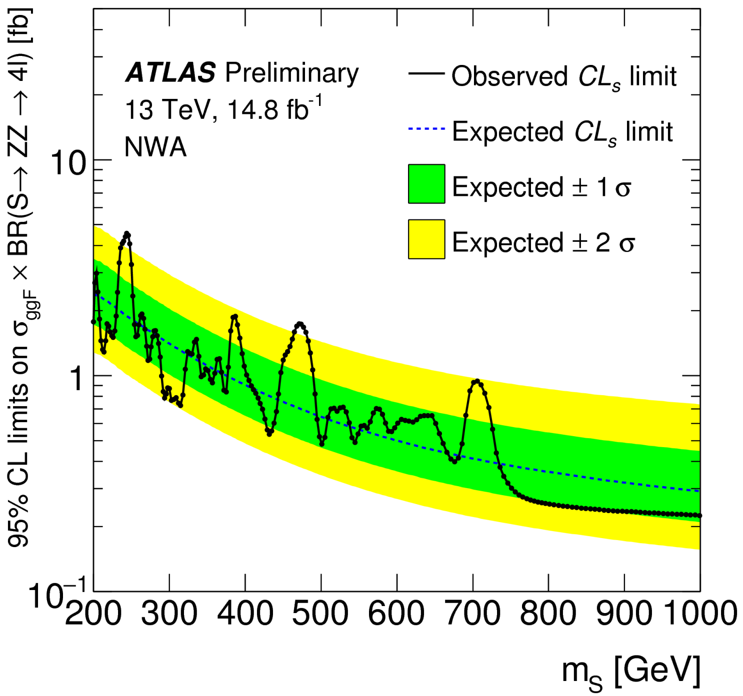
- SM ZZ production with identical final state is dominant irreducible background

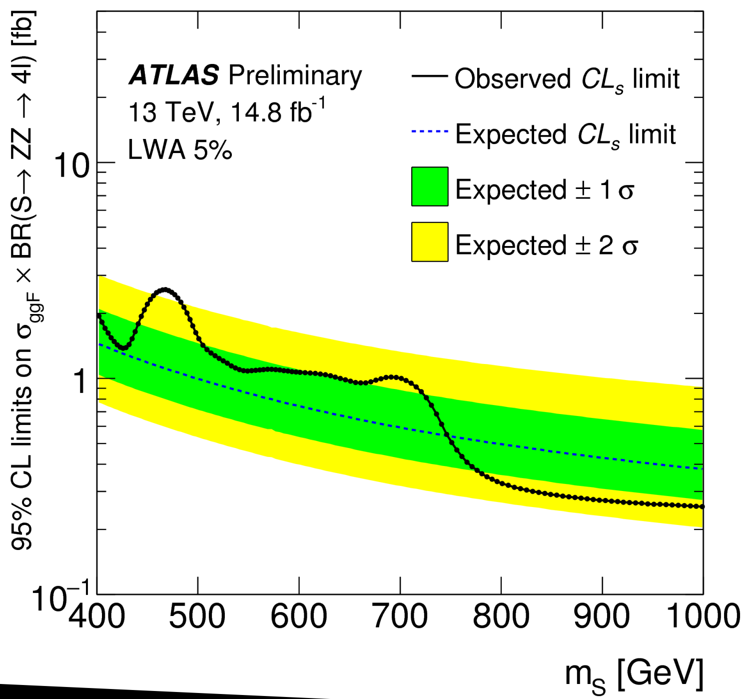
  ➡ any control region would overlaps with a signal region

  ➡ 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

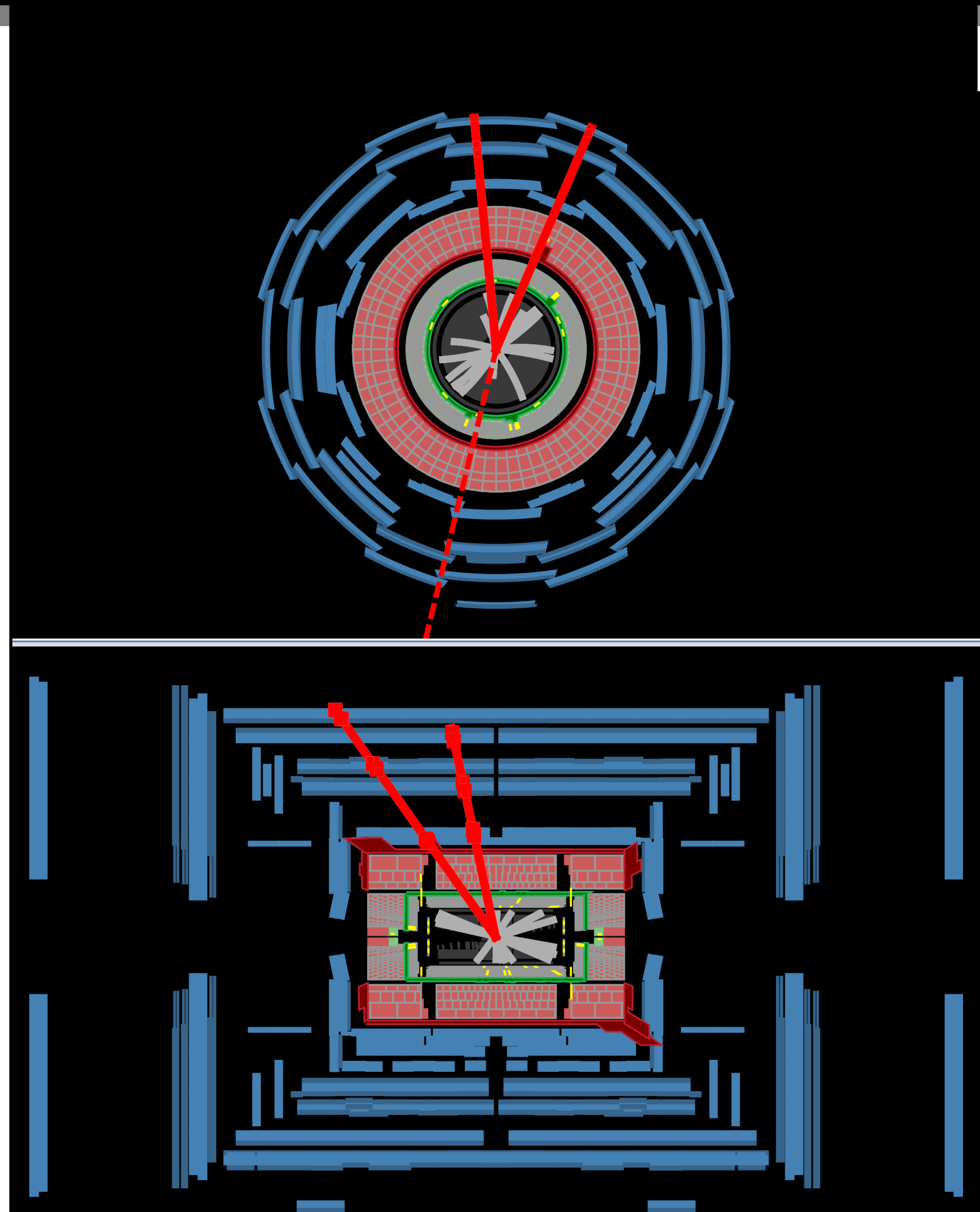
From 4ℓ To 2ℓ2ν Final State

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

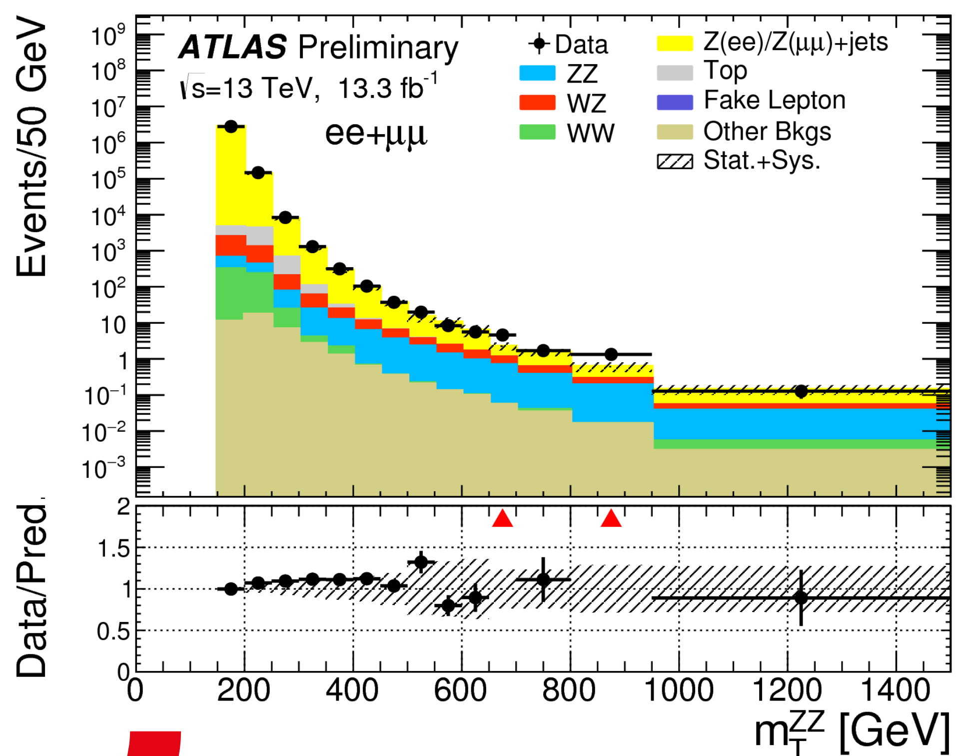
➡ determination of E_T^{miss} through p_T balance

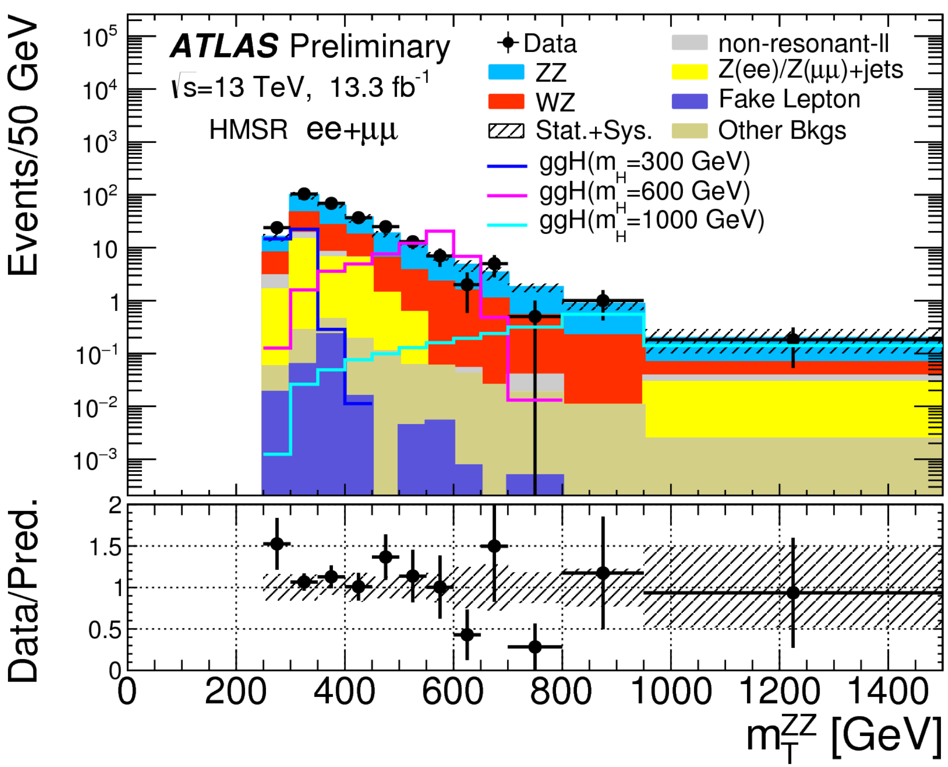
➡ transverse mass m_T^{ZZ} is observable closest to $m_{4\ell}$ which cannot be reconstructed

$$(m_{\mathrm{T}}^{ZZ})^2 \equiv \left(\sqrt{m_Z^2 + \left|p_{\mathrm{T}}^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|E_{\mathrm{T}}^{\mathrm{miss}}\right|^2} \right)^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2$$



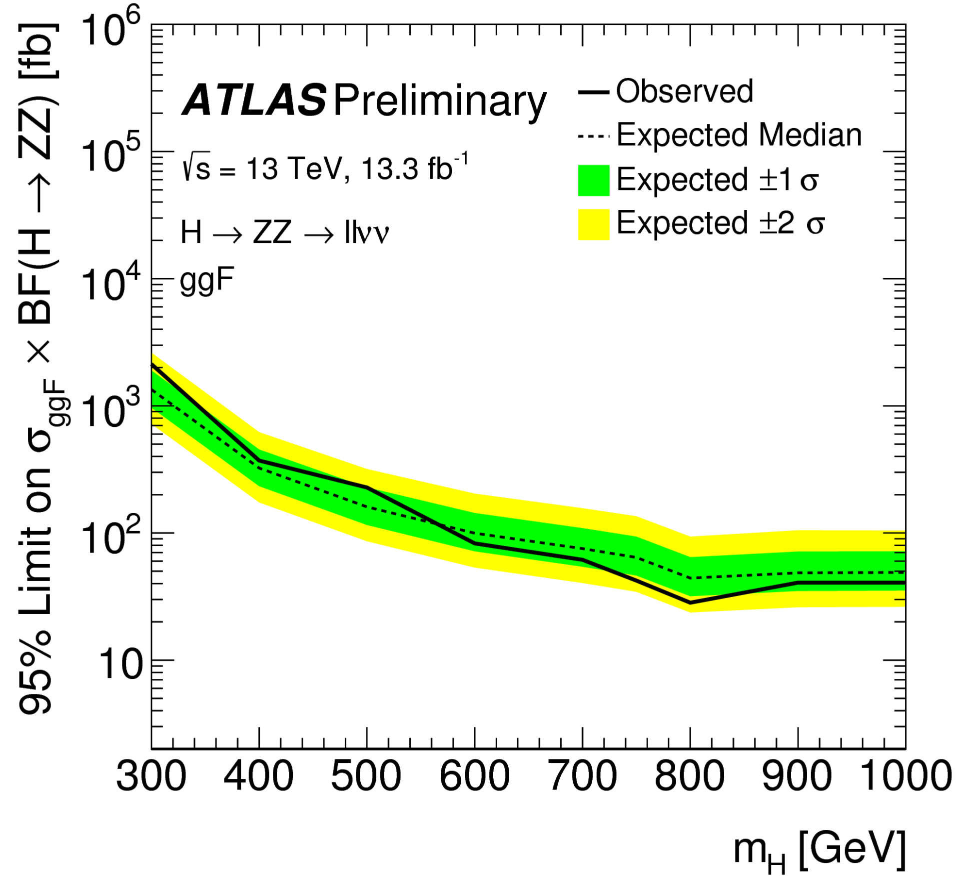
- events with exactly two same-flavor, opposite-charged leptons with high transverse momentum
- m(ℓℓ) compatible with *Z* boson mass within 15 GeV

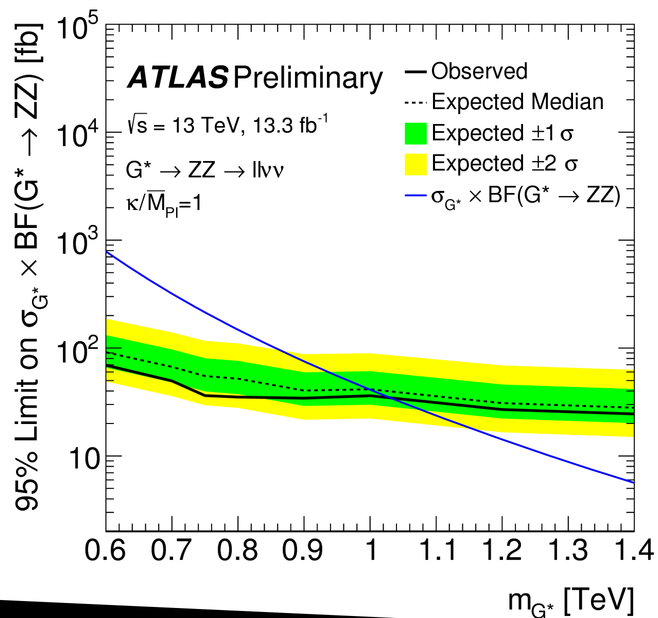




- more than 120 GeV for E_T^{miss}
- elaborated cuts on kinematic correlations

- 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

Summary

- 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