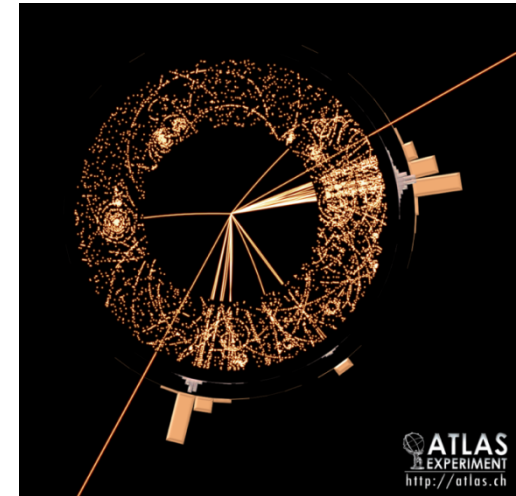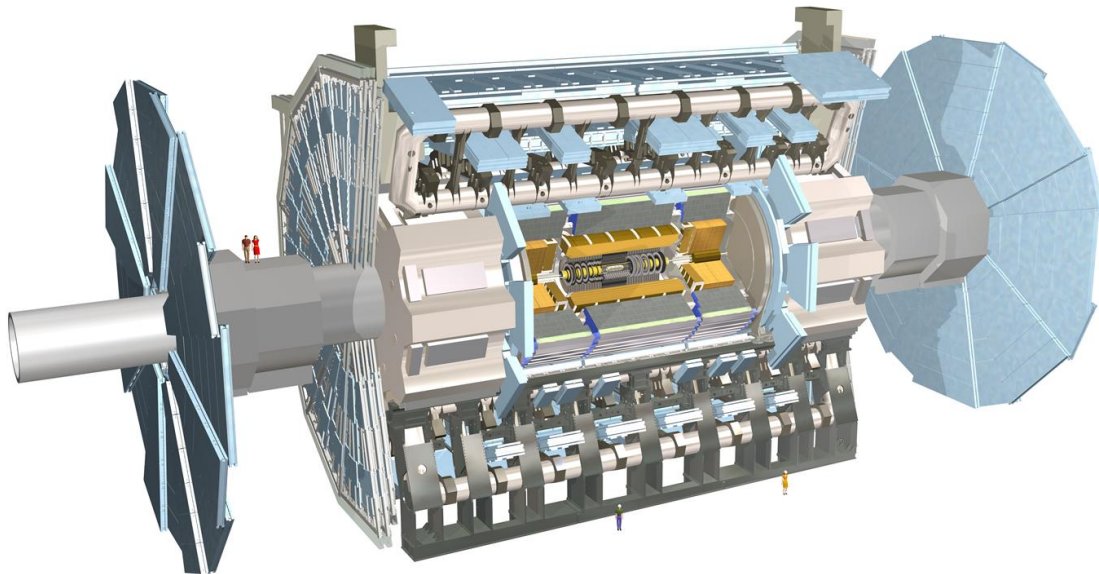# Measurements of ZZ and Z γ production at the LHC with ATLAS

Outline:
- The ATLAS Detector
- Zγ Production
- ZZ Production
- Limits on aTGCs

Joshua Moss

The Ohio State University

15 August 2013

The ATLAS Experiment

Muon Spectrometer

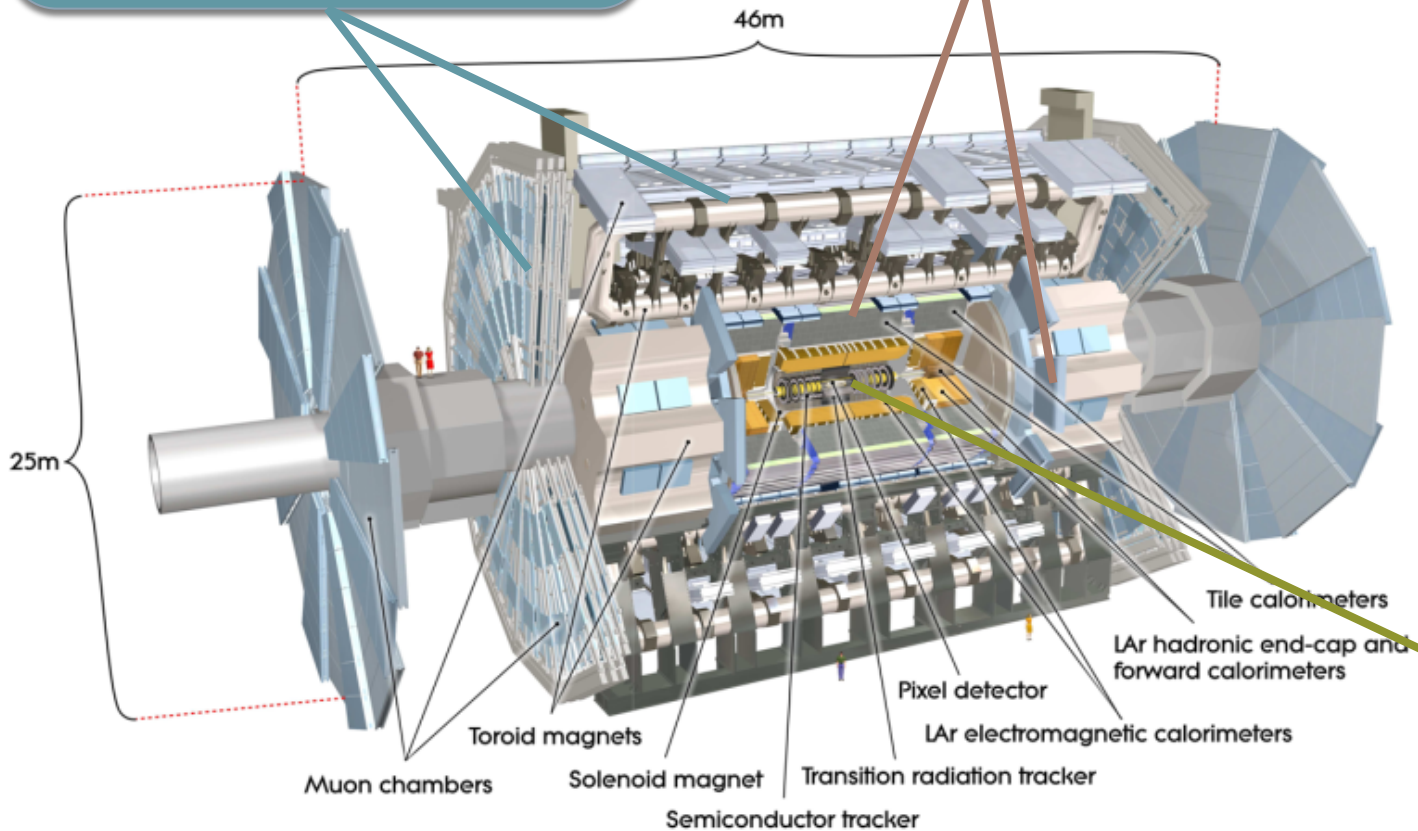3-layer gas-based muon chambers

$|\eta| < 2.7$ coverage

Air-core toroidal magnets, up to 4 T

Calorimeters

EM : Pb-LAr Had: Fe-Scint,

E-Resolution: $\sigma/E \sim 10\%/\sqrt{E}$

e, μ — tracks in ID/MS

γ — EM Shower Shape

ν - missing transverse energy

46m

25m

12 m radius

~7000 tons

3000 km of Cables

~100M channels

Tile calorimeters

LAr hadronic end-cap and forward calorimeters

Pixel detector

LAr electromagnetic calorimeters

Transition radiation tracker

Semiconductor tracker

Solenoid magnet

Toroid magnets

Muon chambers

Inner Detector

$|\eta| < 2.5$

2 T Solenoid Magnet

Tracking and Vertexing

Measurements of ZZ and Z γ and Z γ γ production at the LHC with ATLAS

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# Motivation for Zγ and ZZ studies

Diboson Production cross-section measurements

- Precision tests of EW theory and perturbative QCD at TeV scale

- Generally provide clean signatures in channels decaying to leptons

- Irreducible backgrounds to Higgs Searches (H→Zγ, H→ZZ)

Anomalous Triple Gauge Couplings (aTGC)

- Non-zero coupling strength for the neutral vertices is an indication of new physics

- Enhances cross-sections for Zγ and ZZ and modifies the event kinematics

coupling	parameters	channel
$WW\gamma$	$\lambda_\gamma,\ \Delta\kappa_\gamma$	WW, Wγ
WWZ	$\lambda_Z,\ \Delta\kappa_Z, \Delta g_1^Z$	WW, WZ
$ZZ\gamma$	$h_3^Z,\ h_4^Z$	Zγ
$Z\gamma\gamma$	$h_3^\gamma,\ h_4^\gamma$	Zγ
$Z\gamma Z$	$f_{40}^Z,\ f_{50}^Z$	ZZ
ZZZ	$f_{40}^\gamma,\ f_{50}^\gamma$	ZZ
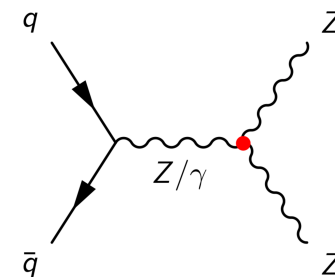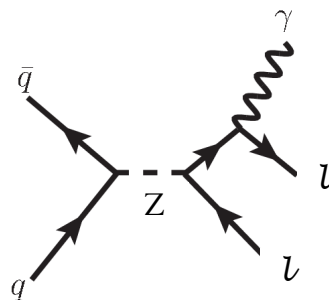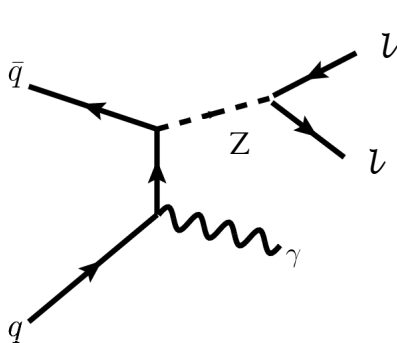
Forbidden SM s-channel TGC diagram

Measurements of ZZ and Z γ and Z γ γ production at the LHC with ATLAS

Zγ in the Standard Model

- Look at final states with electrons, muons ($\ell\ell\gamma$) and neutrinos ($\nu\nu\gamma$)

- Make inclusive ($N_{jets}\geq0$) and exclusive ($N_{jets}=0$) fiducial cross-section measurements

- Uses full 2011 dataset corresponding to a luminosity of 4.6 fb-1

- Measurement limited by systematics → γ ID (6.0%)

Zγ → $\ell\ell\gamma$ Selection:
Isolated, well-reconstructed charged leptons
$p_T>25$ GeV, $|\eta|<\sim2.5$
Isolated photons with $E_T>15$ GeV
Require $M(\ell^+,\ell^-)>40$ GeV

Background: Z+jet (jet fakes a photon)

Zγ → $\nu\nu\gamma$ Selection:
Isolated photons with $E_T>100$ GeV
For neutrinos, Missing $E_T>90$ GeV
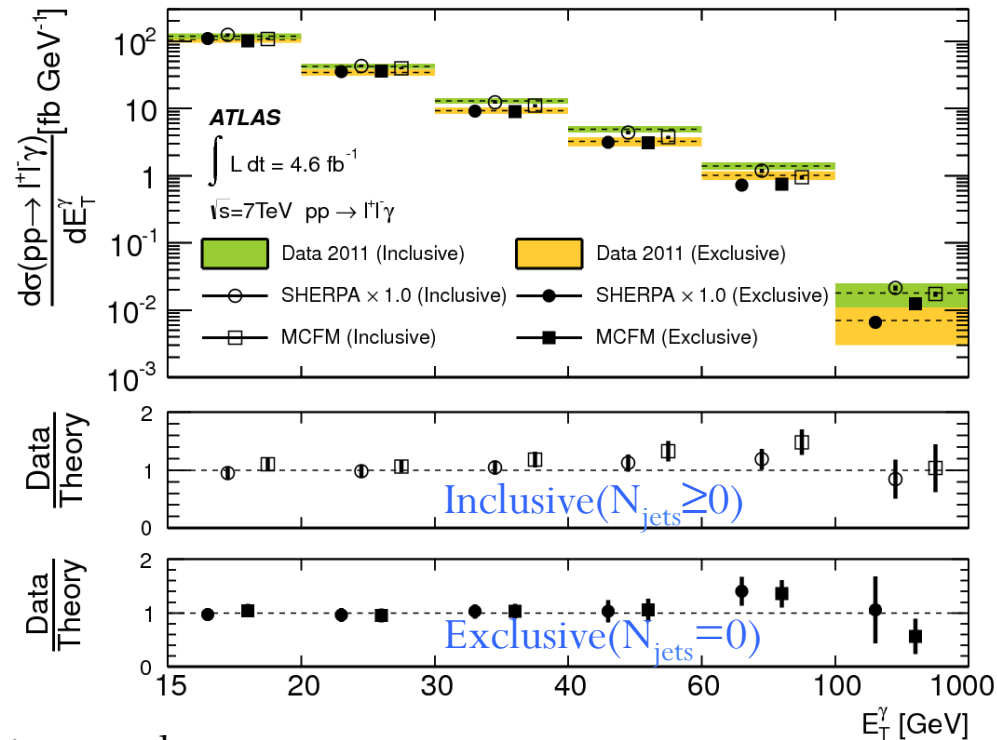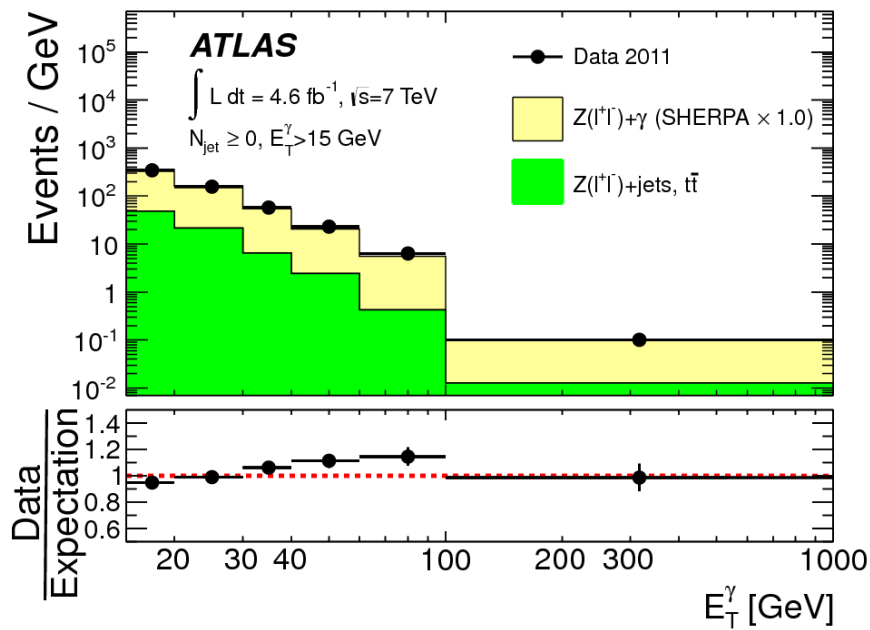Veto events with selected leptons

Backgrounds: : W+jet , Wγ

Backgrounds are estimated using a combination of data-driven techniques and monte-carlo

Zγ with the $\ell\ell\gamma$ final state

- First ATLAS Zγ differential measurements:

  E_t^γ, jet multiplicity, Zγ mass

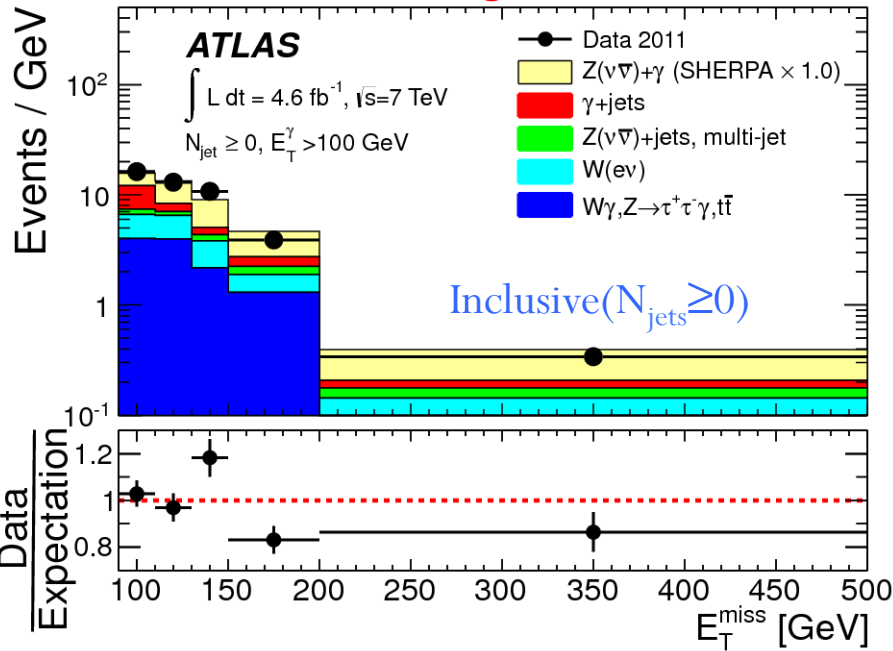Integrated fiducial cross-section using the inclusive sample:

$\sqrt{s}$	Int. lumi	Theory (MCFM)	Experiment (inclusive, fiducial)
7 TeV	4.6 fb-1	1.18 ± 0.05 pb	1.31 ± 0.02 (stat) ± 0.11 (syst) ± 0.05 (lumi) pb

Zγ with the ννγ final state
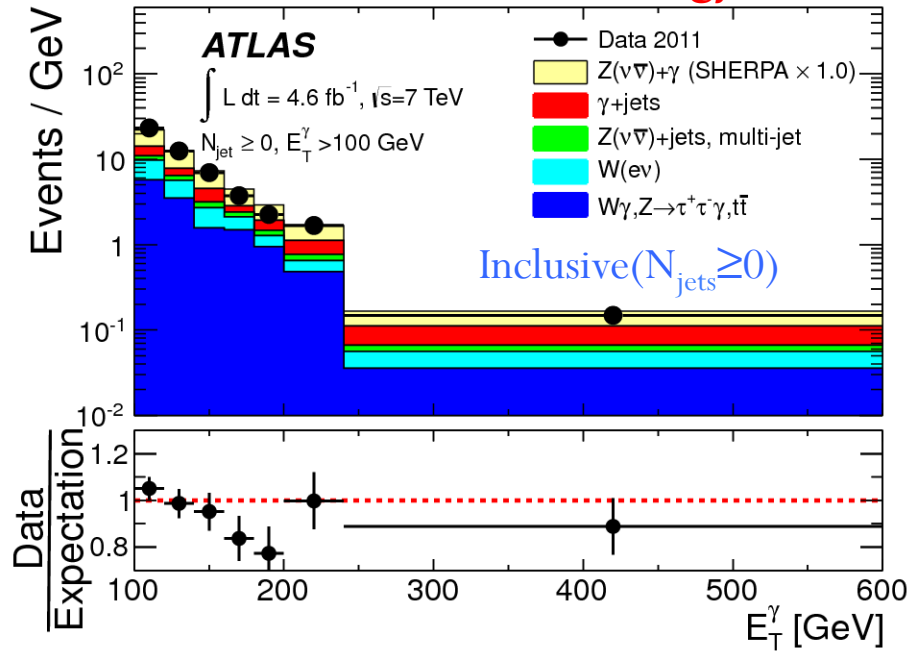
First ATLAS measurement in this channel

Higher background than for the charged lepton channel
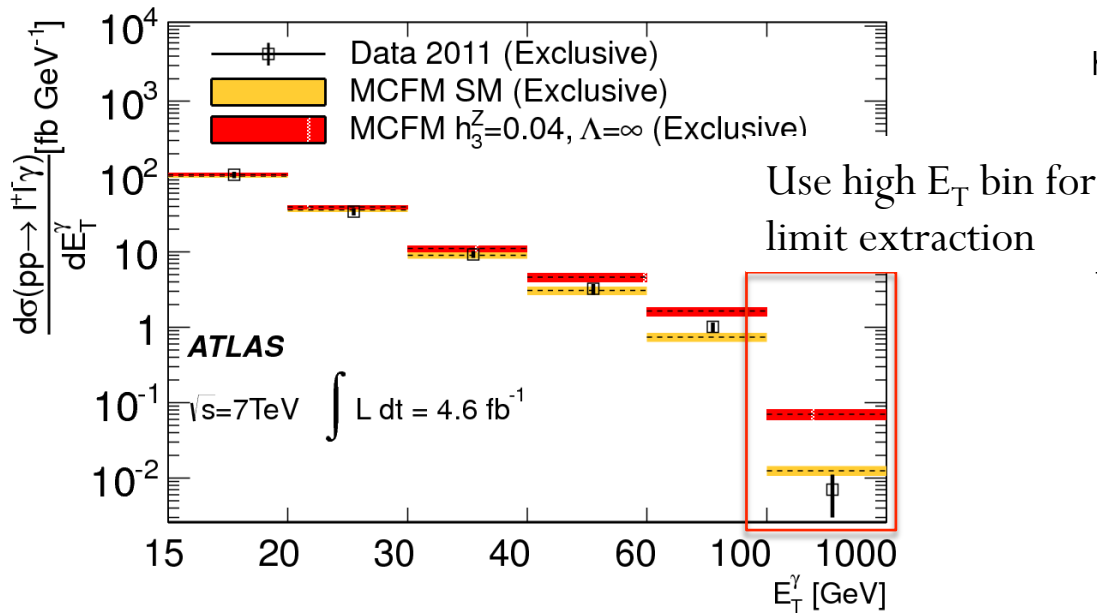
Phys. Rev. D 87, 112003 (2013)

Missing ET

Photon transverse energy

Selection	Theory (MCFM)	Experiment
Inclusive (7 TeV)	0.156 ± 0.012 pb	0.133 ± 0.013 (stat) ± 0.020 (syst) ± 0.005 (lumi) pb
Exclusive (7 TeV)	0.115 ± 0.009 pb	0.116 ± 0.010 (stat) ± 0.013 (syst) ± 0.004 (lumi) pb

aTGC limits in Zγ final states

Use high E_T bin for limit extraction

- Use the exclusive measurements for limit setting
- Expect enhancement for events with high photon E_T
- No sign of deviation from SM predictions
- Expect improvement with higher $\sqrt{s}$ and improved systematics
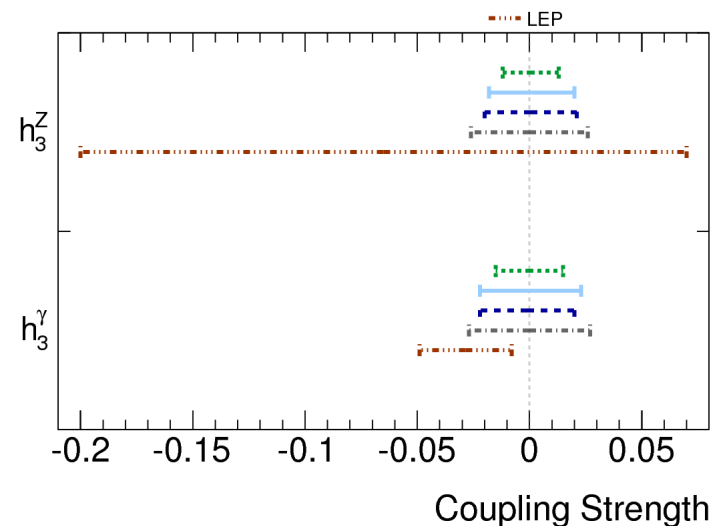
Phys. Rev. D 87, 112003 (2013)

Coupling Strength

ATLAS
$pp \rightarrow l^+l^-\gamma, pp \rightarrow \nu\bar{\nu}\gamma$
95% CL
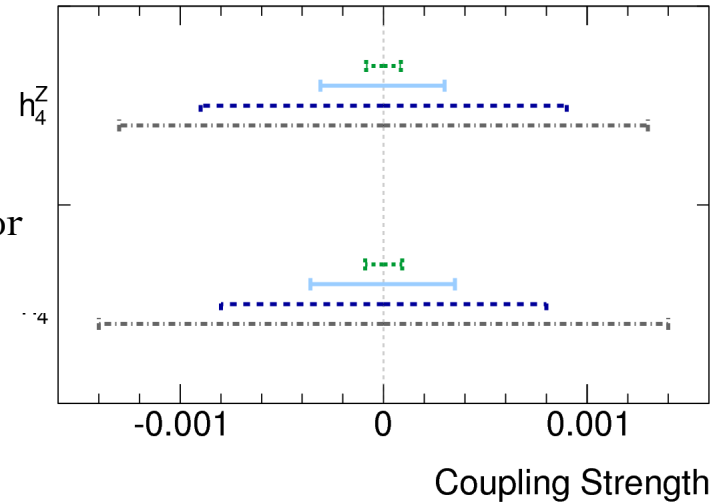
ATLAS, $\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}, $\Lambda = \infty$
ATLAS, $\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}, $\Lambda = 3$ TeV
CDF, $\sqrt{s}$ = 1.96 TeV, 5.1 fb^{-1}, $\Lambda = 1.5$ TeV
D0, $\sqrt{s}$ = 1.96 TeV, 7.2 fb^{-1}, $\Lambda = 1.5$ TeV
LEP

Coupling Strength

ZZ to Four-lepton Final State
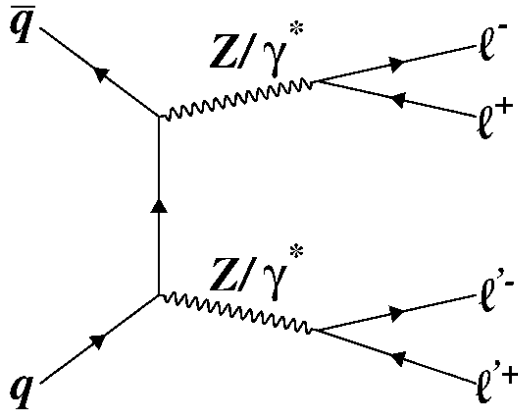
- 3 distinct final states:

  $e^-e^+e^-e^+$, $e^-e^+\mu^-\mu^+$, $\mu^-\mu^+\mu^-\mu^+$

- Clean signature with limited background

- Use the full 2012 dataset, 20 fb^{-1} for the cross-section measurement

Theoretical prediction: MCFM, $66 < M_Z < 116$ GeV

$$\sigma^{\text{Theory}}_{SM} \quad = \quad 7.2^{+0.3}_{-0.2} \text{ pb}$$

Require:

1. 4 isolated, well reconstructed charged leptons
   $p_T > 7$ GeV $|\eta| < 2.7$ muons
   $p_T > 7$ GeV $|\eta| < 2.47$ electrons

2. Must be able to make 2 oppositely charged, same-flavor pairs → 2 candidate Z-bosons

3. Lepton pairs must have an invariant mass within 25 GeV of the PDG Z-boson mass

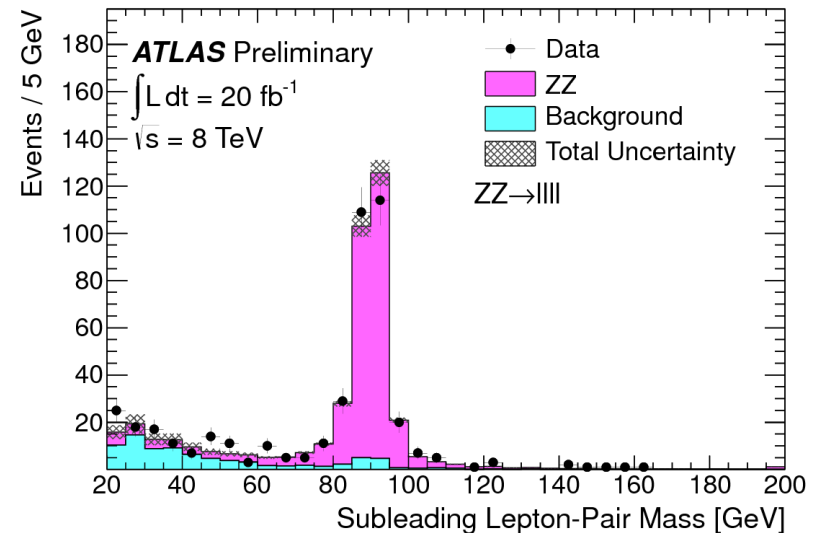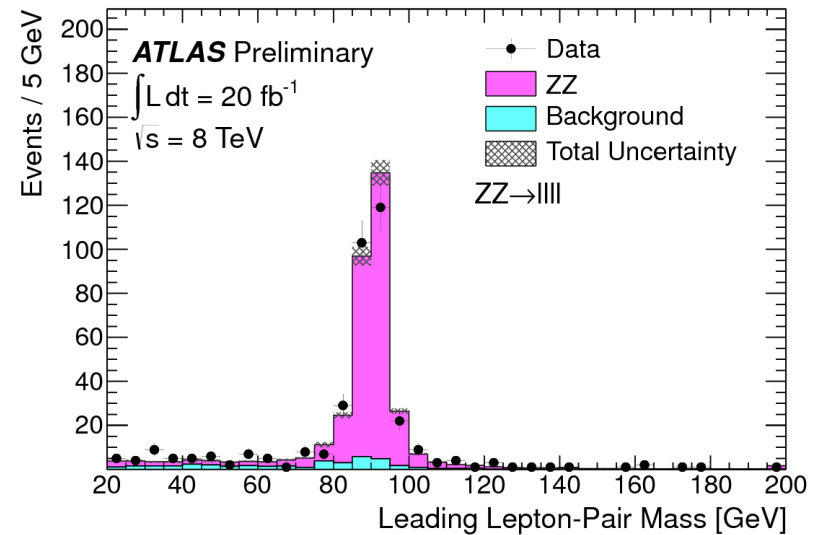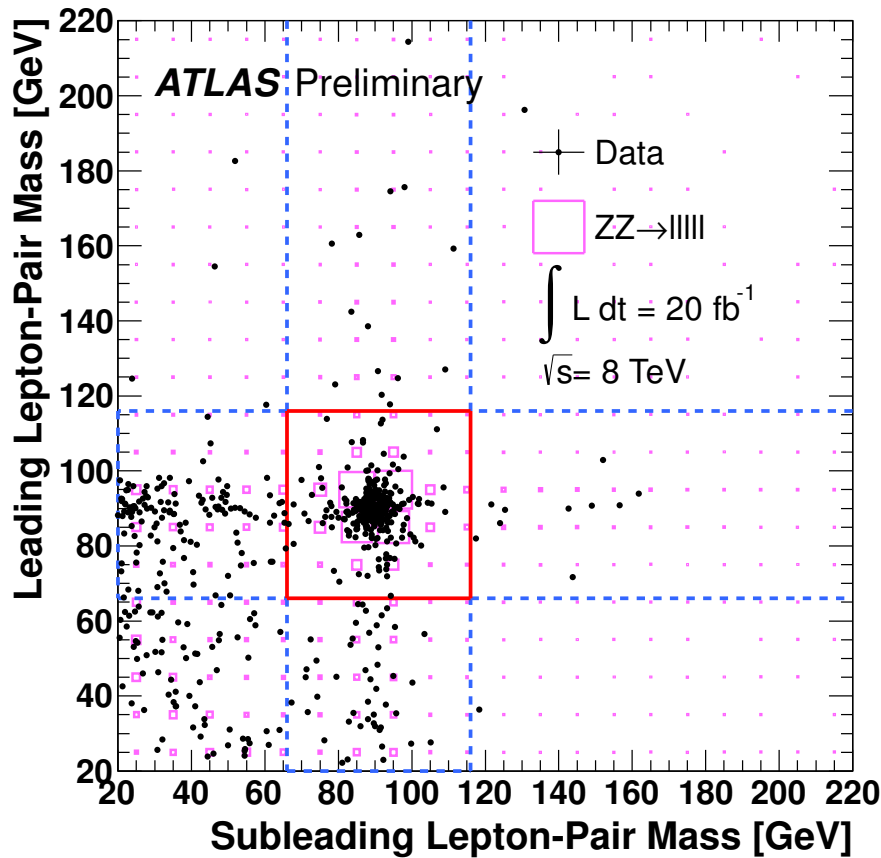**ATLAS Results: ZZ**
7 TeV: JHEP03 (2013) 128
8 TeV: ATLAS-CONF-2013-020
   cds.cern.ch/record/1525555

ZZ Candidate Events

628 Events with 4 opposite sign, same flavor lepton pairs
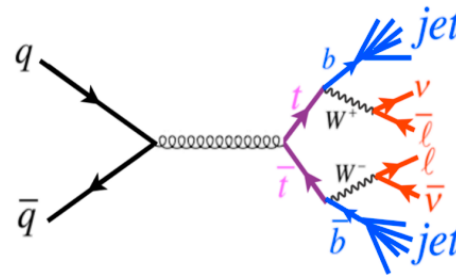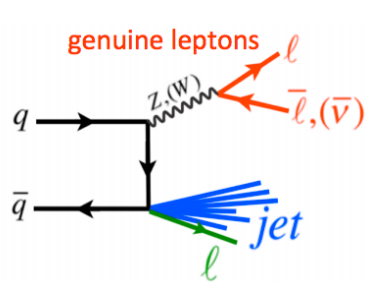
305 Candidate Events in the signal region

Measurements of ZZ and Z γ and Z γ γ production at the LHC with ATLAS

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ZZ Backgrounds

Signal to background ~ 14

Four leptons in the final state has few backgrounds: "golden channel"

Two categories of background:

- Events with "fake" leptons: object mimics signature of either 1 or 2 leptons

- Dominant background
- Estimated using data-driven techniques

- Events with 4 "real" leptons but not from ZZ: irreducible background
  - ZZZ, ttZ, higher order processes → rarer, less probable events
  → Estimate Contribution from Monte Carlo Simulation

Final state	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
Background, $N_{4\ell}^{fake}$	$9.6 \pm 1.8 \pm 1.4$	$0.6 \pm 1.4 \pm 0.5$	$8.5 \pm 2.1 \pm 3.1$	$18.7 \pm 2.9 \pm 5.0$
MC, irreducible	0.4 ± 0.1	0.5 ± 0.1	0.7 ± 0.1	1.6 ± 0.1
Total background	$10.0 \pm 1.8 \pm 1.4$	$1.1 \pm 1.4 \pm 0.5$	$9.3 \pm 2.1 \pm 3.1$	$20.4 \pm 2.9 \pm 5.0$

Kinematic distributions for ZZ→4l

- Events follow the SM predicted distributions

- Leading lepton-pair transverse momentum is most sensitive to triple gauge couplings

- Invariant mass of the four-lepton system useful for new physics searches

ATLAS Preliminary
$\int L\,dt = 20\ fb^{-1}$
$\sqrt{s} = 8$ TeV
ZZ→llll

- Data
- ZZ
- Background
- Total Uncertainty

Four-Lepton Mass [GeV]
Events / 20 GeV

ATLAS Preliminary
$\int L\,dt = 20\ fb^{-1}$
$\sqrt{s} = 8$ TeV
ZZ→llll

Sensitive to aTGCs

- Data
- ZZ
- Background
- Total Uncertainty

Leading Lepton-Pair Transverse Momentum [GeV]
Events / 20 GeV

ATLAS Preliminary
$\int L\,dt = 20\ fb^{-1}$
$\sqrt{s} = 8$ TeV
ZZ→llll

- Data
- ZZ
- Background
- Total Uncertainty

Four-Lepton Transverse Momentum [GeV]
Events / 20 GeV

Measured SM ZZ cross-section

- Results compatible with the Standard Model predictions

- Largest number of ZZ events observed

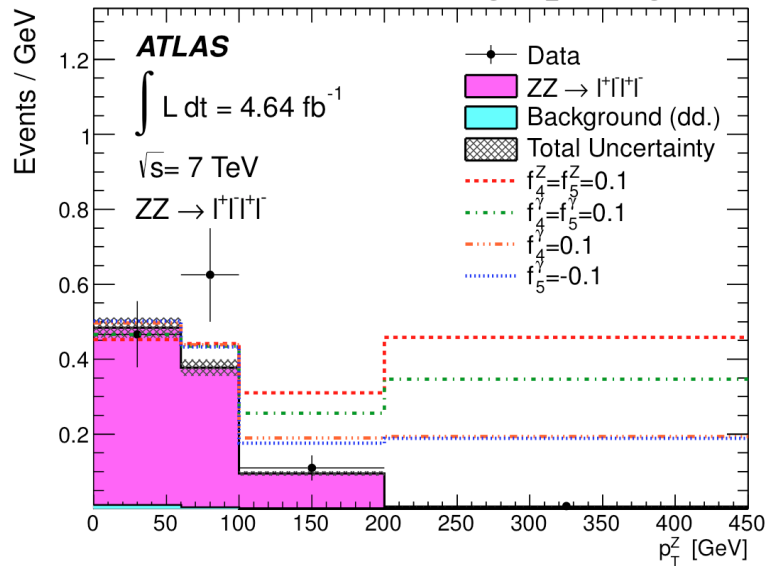- Measurement is still statistically limited but not for long!

March 2013:
ATLAS-CONF-2013-020
cds.cern.ch/record/1525555
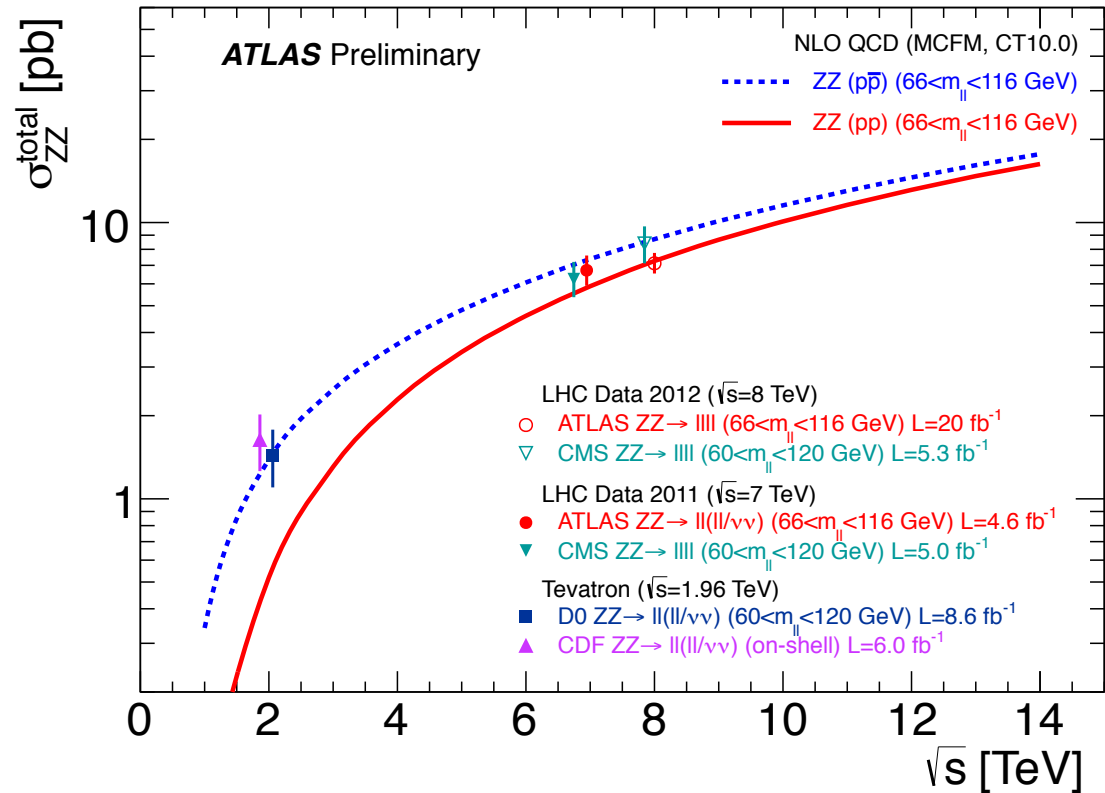
$\sqrt{s} = 8\,\text{TeV}$	Int. lumi	Events	Theory	Experiment
ATLAS	20.4 fb-1	305	$7.2^{+0.3}_{-0.2}$ pb	$7.1^{+0.5}_{-0.4}(stat) \pm 0.3(syst) \pm 0.2(lumi)$ pb
CMS	19.6 fb-1	324	7.7 ± 0.6 pb	$7.7 \pm 0.5(stat)^{+0.5}_{-0.4}(syst) \pm 0.4(theory) \pm 0.3(lumi)$ pb

Measurements of ZZ and Z γ and Z γ γ production at the LHC with ATLAS

15 August 2013

Enhancement in high p_T region

Current Limits on TGC Coupling parameters
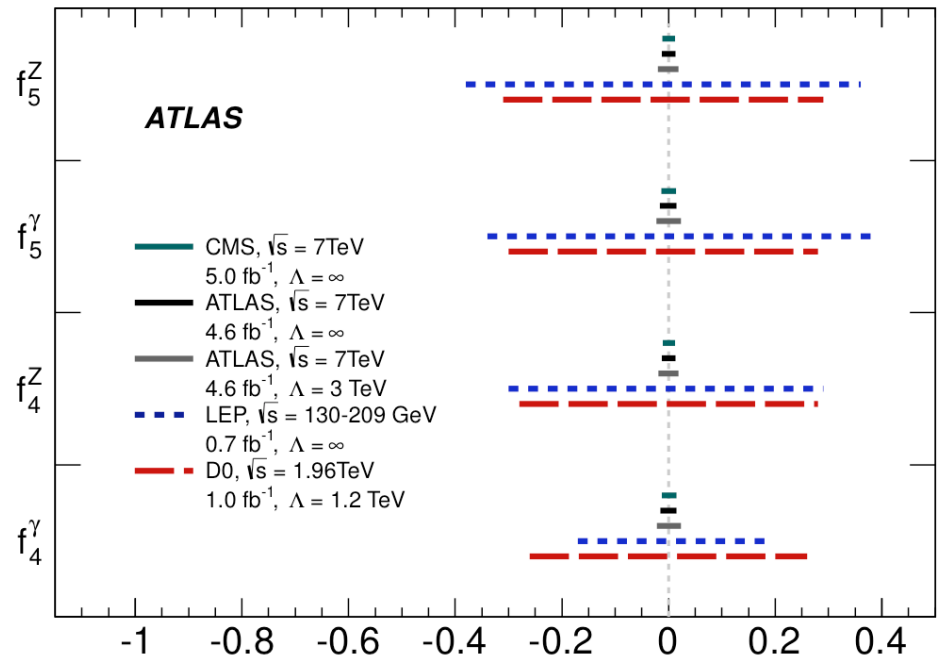
- Use a profile likelihood function and the leading Z transverse momentum spectrum
- Limits set from analysis at CM energy of 7TeV consistent with zero for all couplings
  → Consistent with the Standard Model prediction
- Analysis of the 2012 dataset at 8TeV ongoing and expect public result in fall of 2013
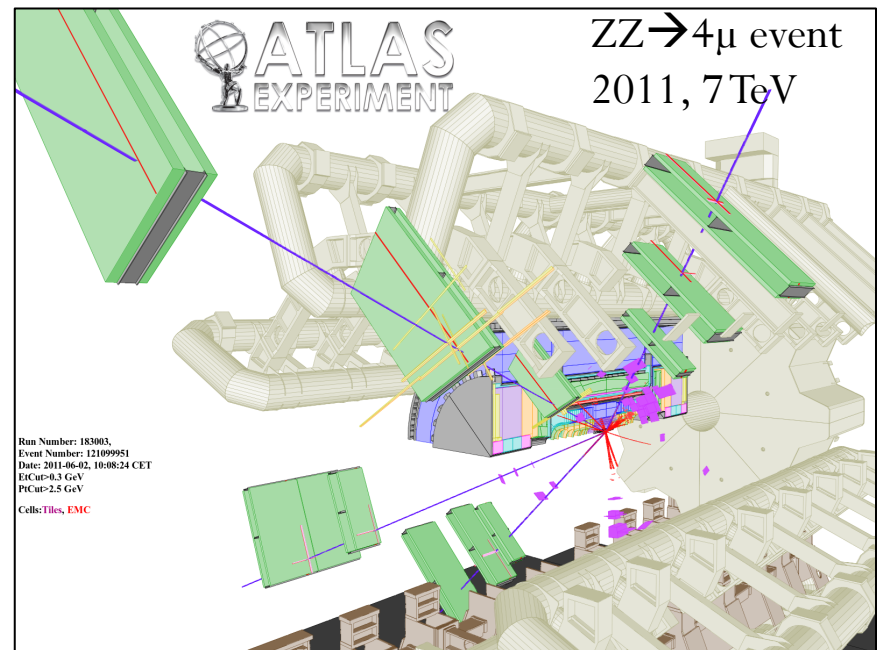
Summary

- Results for neutral diboson cross-section measurements were presented for Zγ and ZZ in the final states where the Z decays to leptons

  Good greement between predictions from MCFM and the measured cross-sections

- No evidence for aTGC couplings which would be an indication for physics beyond the standard model.

  Limits set using the 2011 dataset ➔ work on 2012 dataset ongoing

More measurements using diboson and triboson final states in ATLAS will be shown next by Duong Hai Nguyen

ZZ➔4μ event
2011, 7 TeV

Run Number: 183003,
Event Number: 121099951
Date: 2011-06-02, 10:08:24 CET
EtCut>0.3 GeV
PtCut>2.5 GeV
Cells: Tiles, EMC

Measurements of ZZ and Zγ and Zγγ production at the LHC with ATLAS

15 August 2013

Extra Slides

ATLAS Experiment

For the most up to date ATLAS information, go to ATLAS home page at www.atlas.ch

For the latest ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Measurements of ZZ and Z γ and Z γ γ production at the LHC with ATLAS

15 August 2013

The LHC at CERN

- 27 km long ring previously housing LEP
- 1232 superconducting dipole magnets
- 7 TeV nominal beam energy
- 10^{34} cm^{-2} s^{-1} nominal Luminosity
- 2808 proton bunches per beam
- 25 ns bunch spacing (40Mhz)

Physics program for the LHC

- Test the Standard Model & Measure its properties precisely
- Find/Measure the Higgs Boson
- Search for physics beyond the standard Model: Supersymmetry, extra-dimensions, gravitons, matter-antimatter asymmetry
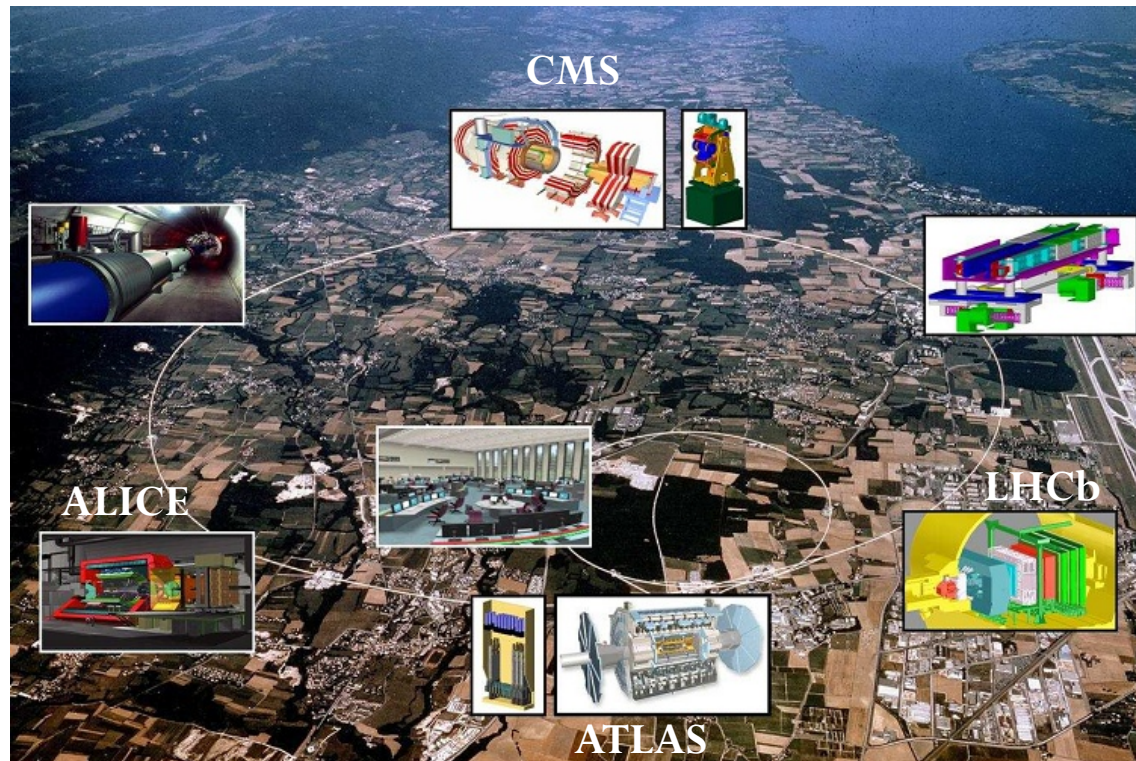
Current operating parameters: Beam Energy= 4 TeV   Luminosity~8 x10^{33}cm^{-2} s^{-1}

The ATLAS Collaboration

3000 Scientists
38 Countries
174 Institutes and Labs

Argentina	Morocco
Armenia	Netherlands
Australia	Norway
Austria	Poland
Azerbaijan	Portugal
Belarus	Romania
Brazil	Russia
Canada	Serbia
Chile	Slovakia
China	Slovenia
Colombia	South Africa
Czech Republic	Spain
Denmark	Sweden
France	Switzerland
Georgia	Taiwan
Germany	Turkey
Greece	UK
Israel	USA
Italy	CERN
Japan	JINR

ATLAS
Collaboration

U.S. Participation:
~700 physicists, engineers and
graduate students from 44 institutions

Measurements of ZZ and Zγ and Zγ γ production at the LHC with ATLAS

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