Measurement of the ZZ^(*) and the inclusive four lepton production cross sections at 7, 8 and 13 TeV and limits on anomalous triple gauge couplings with the ATLAS detector

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on behalf of ATLAS

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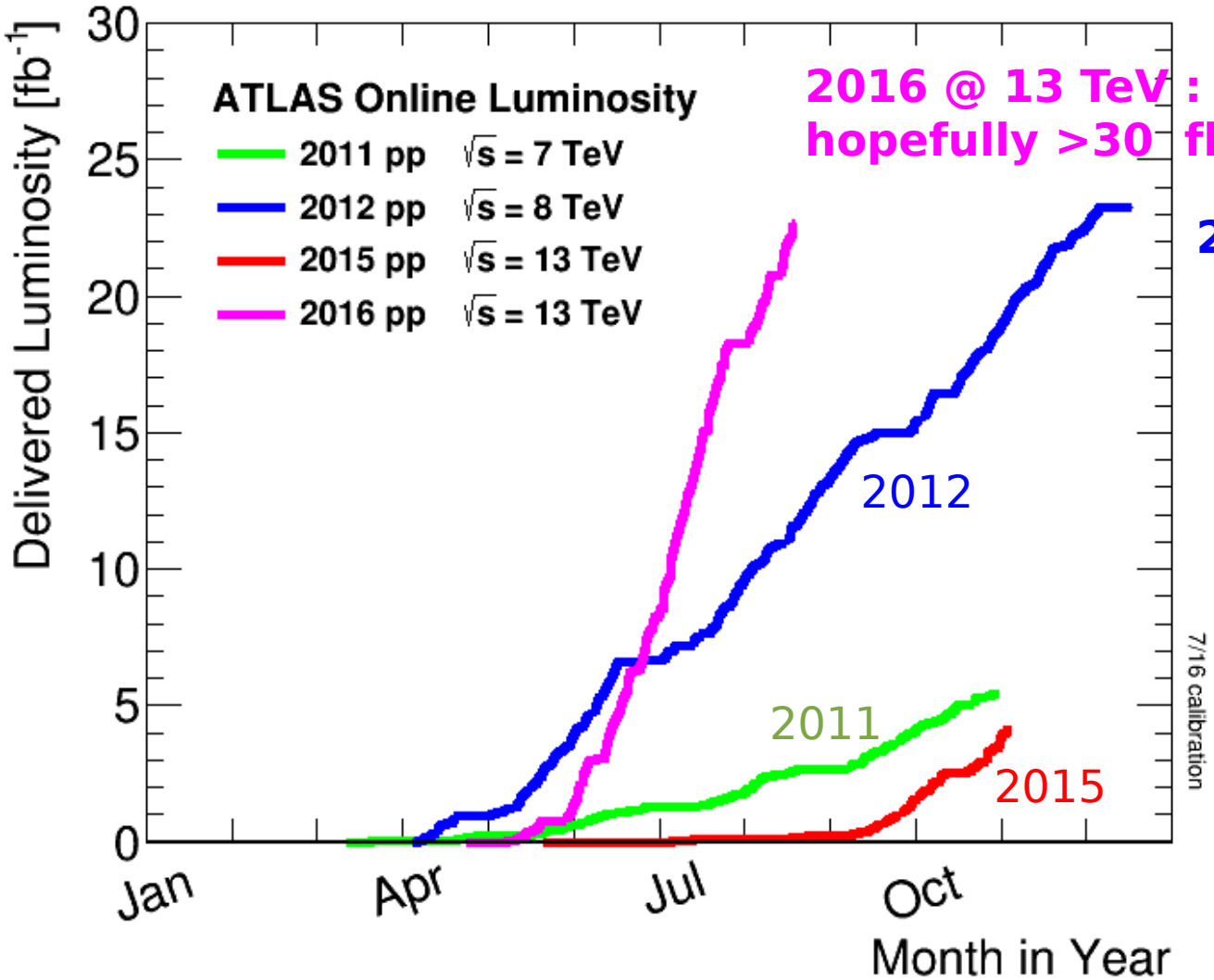
Overview

- **ZZ cross sections at various pp collision energies**
  - @ $\sqrt{s}$ = 13 TeV : current collision energy
    - First diboson measurement from ATLAS @ 13 TeV
      Phys. Rev. Lett. 116 101801 (2016)
  - @ 8 TeV :
    - total ZZ cross section ATLAS-CONF-2013-02
    - Differential 4 lepton mass Phys. Lett. B, 753 (2016) 552
  - 7 TeV : total & differential cross section JHEP03(2013)128

- **Search for Anomalous Triple Gauge Couplings (aTGCs)**
  - Event counting to probe presence of aTGCs
  - Current results: ATLAS 7 TeV JHEP03(2013)128
    & combination ATLAS+CMS 7 TeV ATLAS-CONF-2016-036

Increasing pp collision energy and increasing data sets



2016 @ 13 TeV : hopefully >30 fb^{-1} for analysis

2012 @ 8 TeV: 20.3 fb^{-1}

2011 @ 7 TeV: 4.6 fb^{-1}

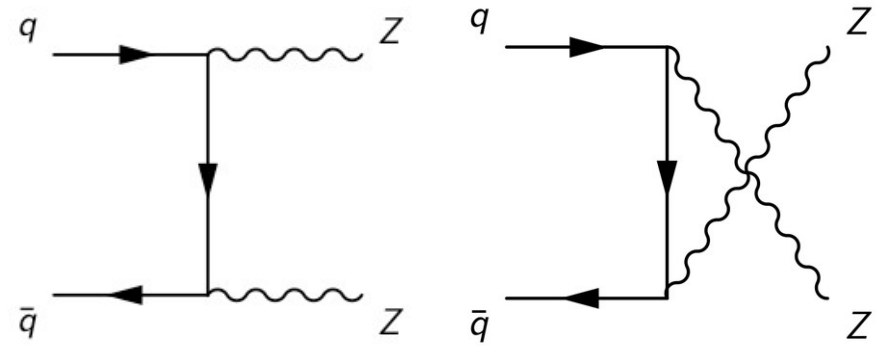
2015 @ 13 TeV: 3.2 fb^{-1}

1. total ZZ production

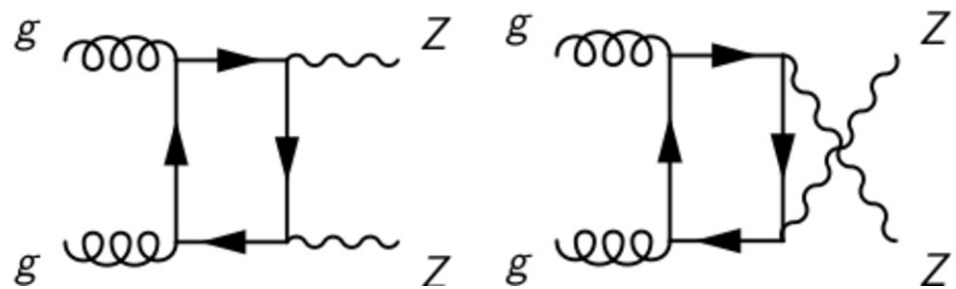
@ 13 TeV: Phys. Rev. Lett. 116 101801 (2016)
@ 8 TeV: ATLAS-CONF-2013-02

ZZ production at pp

- **u,t channels: SM**
  - Mostly $q\bar{q}$:



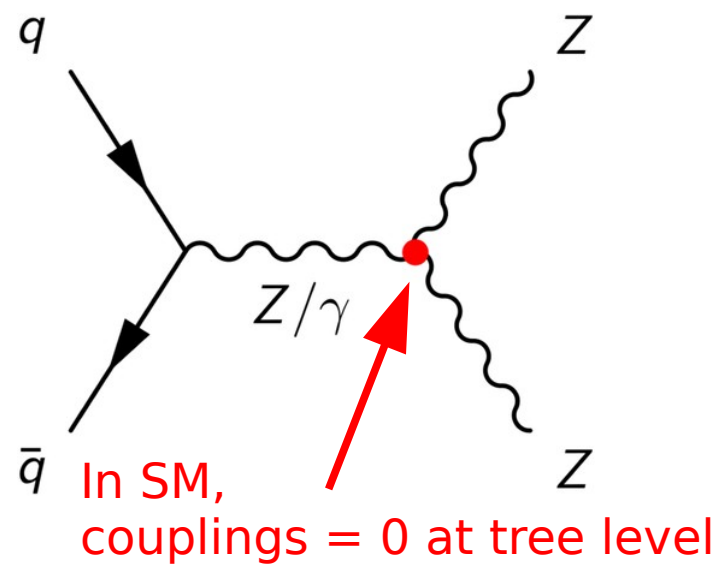
  - ~6% from gg :



- **s-channel: beyond SM:**

  production via anomalous

  Triple Gauge Couplings (aTGCs)



ZZ production cross section

$$N_{sigal}(pp \to ZZ \to 4l) = L \cdot \sigma^{tot}(pp \to ZZ) \cdot BR(ZZ \to 4l) \cdot A \cdot C$$

Total cross section for ZZ production

Measured in a reduced phase-space (geometrical & kinematic requirements on the decay products)
4l = {4e or 4μ or 2e2μ}

$$A = \frac{Fiducial\ events}{Total\ events}$$

Acceptance correction for the geometrical & kinematic criteria

$$C = \frac{Reconstructed\ events}{Generated\ fiducial\ events}$$

Efficiency correction for detector ability to reconstruct these objects

1. We measure a "fiducial cross section", which corresponds to the reduced phase-space of the actual measurement,
* This is a fraction of the total:

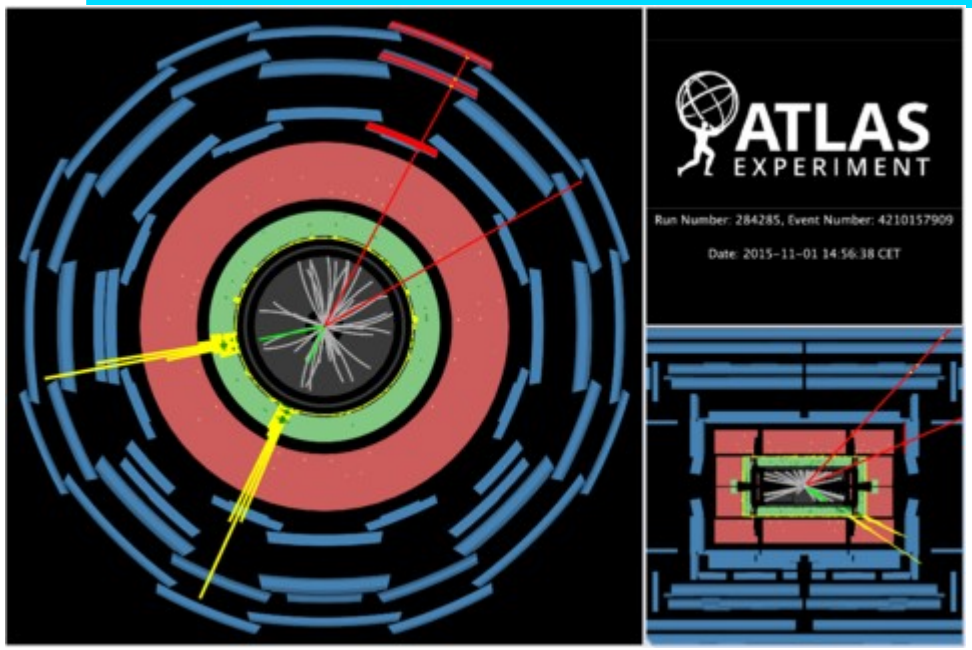
$$\sigma^{fiducial}(pp \to ZZ \to 4l) = \frac{N_{obs} - N_{bkg}}{L \cdot C}$$

$$\sigma^{fiducial}(pp \to ZZ \to 4l) = \sigma^{tot}(pp \to ZZ) \cdot BR(ZZ \to 4l) \cdot A$$

2. We then extrapolate to the "total cross section" for ZZ production by extrapolating the leptons to the full phase-space,
and correcting for the BR(ZZ → 4l) ~ 4 * (3.4% * 3.4%) for 4e, 4μ and 2e2μ together

$$\sigma^{tot}(pp \to ZZ \to 4l) = \frac{N_{obs} - N_{bkg}}{L \cdot BR(ZZ \to 4l) \cdot A \cdot C}$$

ZZ production at 13 TeV - selection



- Exactly four isolated, $\Delta R(l,l) > 0.2$, prompt final state leptons (e or μ only)
- All four leptons must have $p_T > 20$ GeV
- Electrons must satisfy $|\eta| < 2.47$
- At least one muon with $|\eta| < 2.4$, the remaining with $|\eta| < 2.7$
- Dilepton masses m(e+ e-) and m(μ+ μ-): in the rage 66 - 116 GeV
- When 4 leptons with the same flavor (4e or 4μ case): select the pairing which minimize $|m_{1,2} - m_Z| + |m_{3,4} - m_Z|$

Observed events:

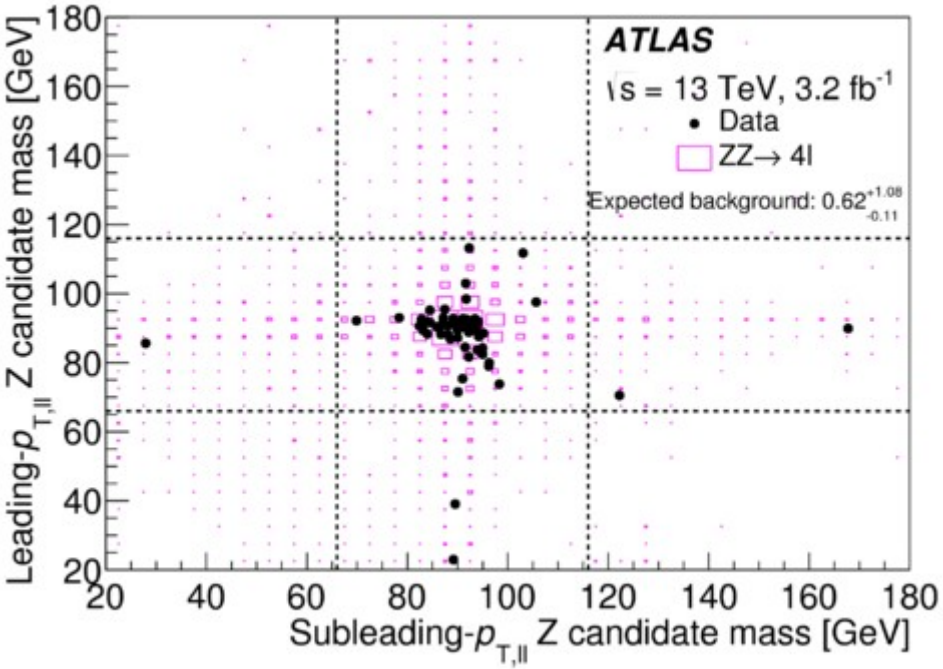
Channel	Events
4e	15
2e2μ	30
4μ	18
Total	63

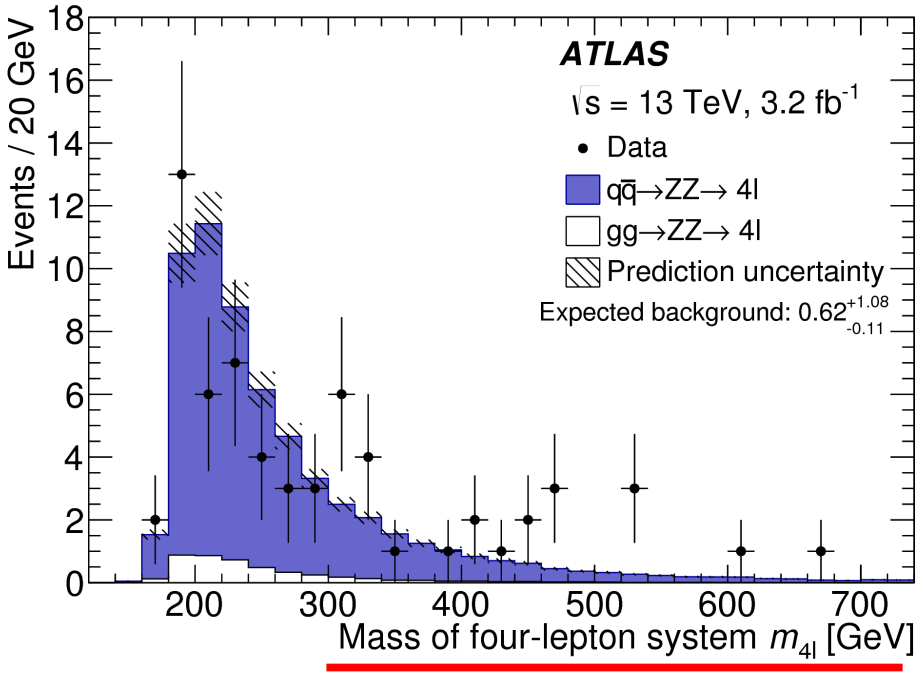
Total expected background:

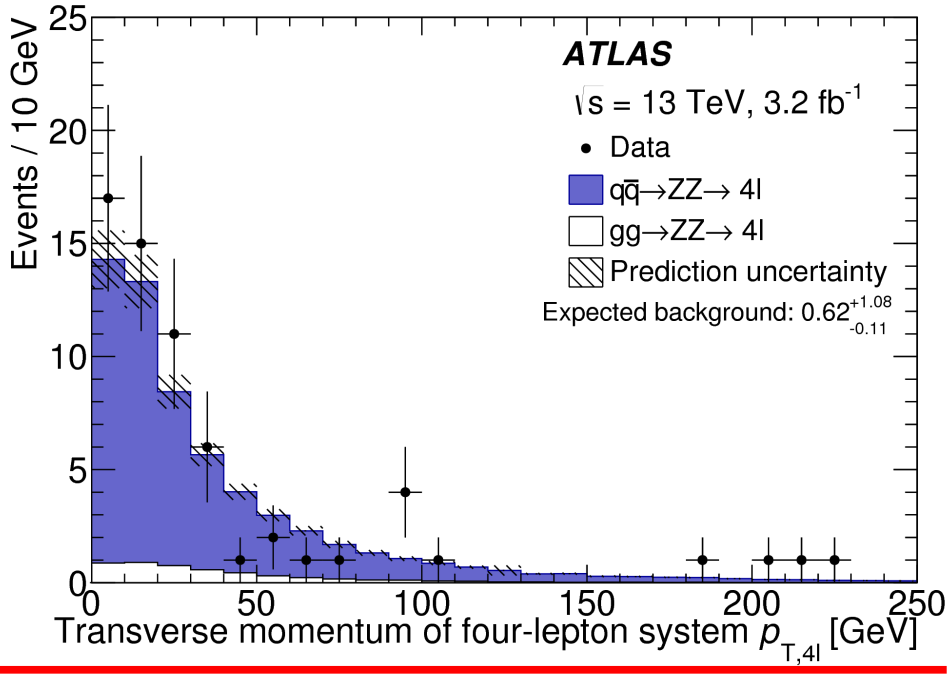
$0.62^{+1.08}_{-0.11}$ events

$L = 3.2\ fb^{-1}$ @ 13 TeV

ZZ production at 13 TeV - kinematics







* 63 observed events

* expected background:

$0.62^{+1.08}_{-0.11}$ events

ZZ production at 13 TeV – cross section

- DOI: 10.1103/PhysRevLett.116.101801 L = 3.2 fb^{-1} @ 13 TeV

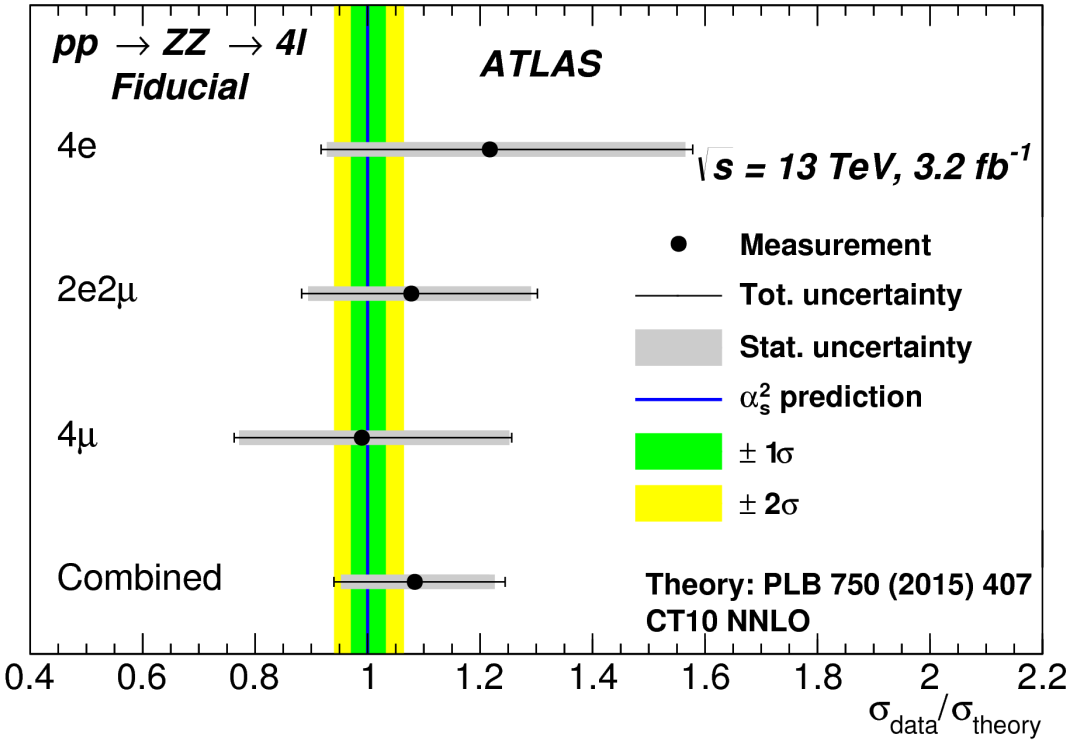
	Measurement	$\mathcal{O}(\alpha_s^2)$ prediction
$\sigma^{fid}_{ZZ\to e^+e^-e^+e^-}$	$8.4\ ^{+2.4}_{-2.0}(stat.)\ ^{+0.4}_{-0.2}(syst.)\ ^{+0.5}_{-0.3}(lumi.)$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{fid}_{ZZ\to e^+e^-\mu^+\mu^-}$	$14.7\ ^{+2.9}_{-2.5}(stat.)\ ^{+0.6}_{-0.4}(syst.)\ ^{+0.9}_{-0.6}(lumi.)$ fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{fid}_{ZZ\to \mu^+\mu^-\mu^+\mu^-}$	$6.8\ ^{+1.8}_{-1.5}(stat.)\ ^{+0.3}_{-0.3}(syst.)\ ^{+0.4}_{-0.3}(lumi.)$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{fid}_{ZZ\to \ell^+\ell^-\ell'^+\ell'^-}$	$29.7\ ^{+3.9}_{-3.6}(stat.)\ ^{+1.0}_{-0.8}(syst.)\ ^{+1.7}_{-1.3}(lumi.)$ fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	$16.7\ ^{+2.2}_{-2.0}(stat.)\ ^{+0.9}_{-0.7}(syst.)\ ^{+1.0}_{-0.7}(lumi.)$ pb	$15.6^{+0.4}_{-0.4}$ pb

* Acceptance of geometric and kinematic criteria on the leptons:

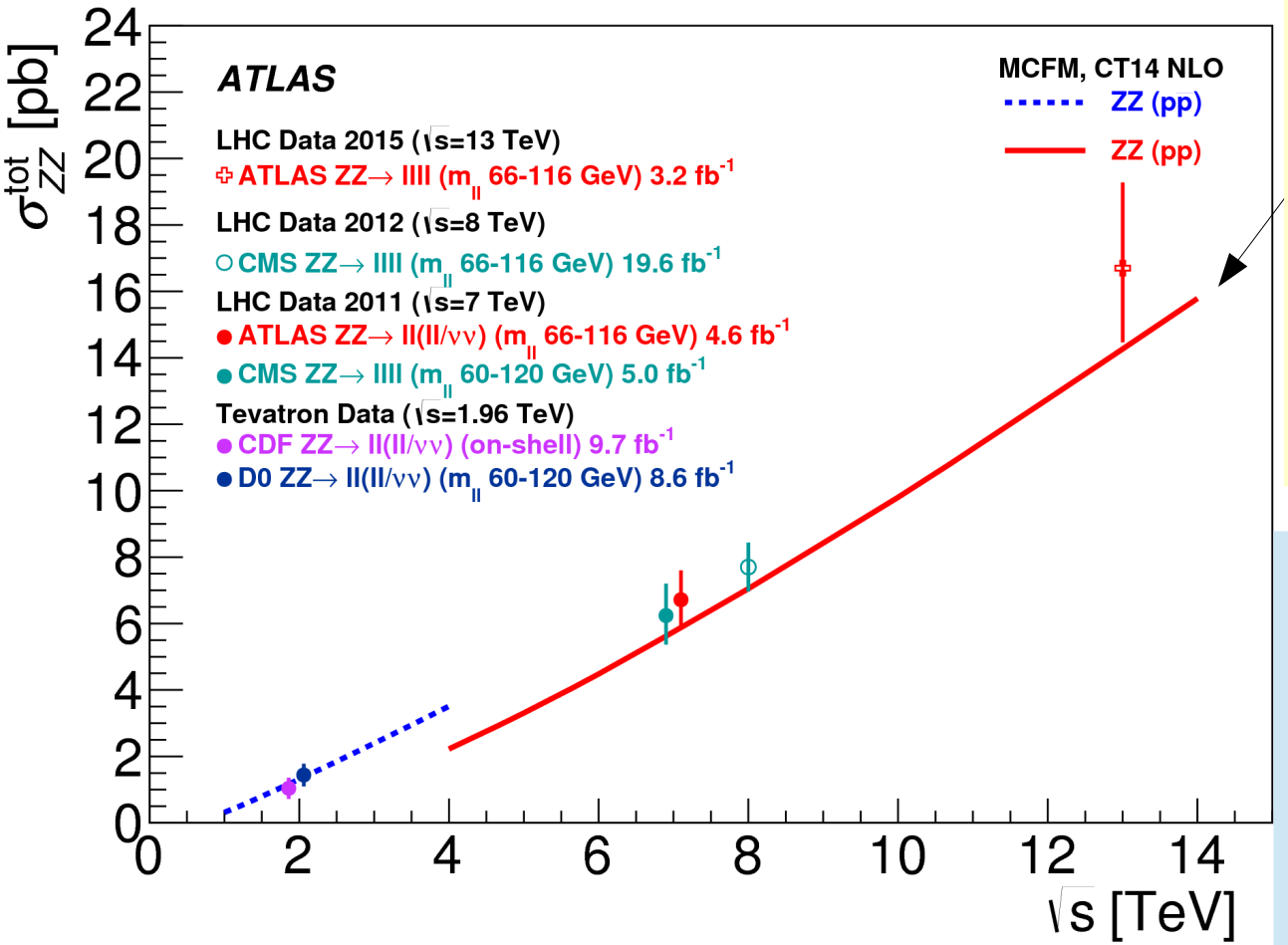
$$A = 0.39 \pm 0.02$$

* Detector efficiency in measuring these leptons:

$$C = \begin{array}{l} 0.55 \pm 0.02\,(4e) \\ 0.63 \pm 0.02\,(2e2\mu) \\ 0.81 \pm 0.03\,(4\mu) \end{array}$$



ZZ production cross section



Theory (MCFM) in this plot:
~14pb @ 13 TeV, but it is
NLO in qq → ZZ and
LO in gg → ZZ:
(unlike the 15.6pb @ 13 TeV
in previous page table:
with one more QCD order and
EW corrections,
it is ~10% higher)

Previous ATLAS result @ 8TeV:
[ATLAS-CONF-2013-020]

Nobs: 305, Nbkg: 20.4 evnts

→ $\sigma_{tot} = 7.1^{+0.5}_{-0.4} \pm 0.3 \pm 0.2\ pb$

w.r.t theory: $\sigma_{tot} = 7.2^{+0.3}_{-0.2}\ pb$

Note: no latest EW corct'ns,
no extra QCD order

2. Differential ZZ production measurements

@ 7 TeV, full ZZ: JHEP03(2013)128
@ 8 TeV: inclusive 4l: Phys Lett B, 753 (2016) 552

2a.
@ 7 TeV, ZZ → 4l total & differential

JHEP03(2013)128

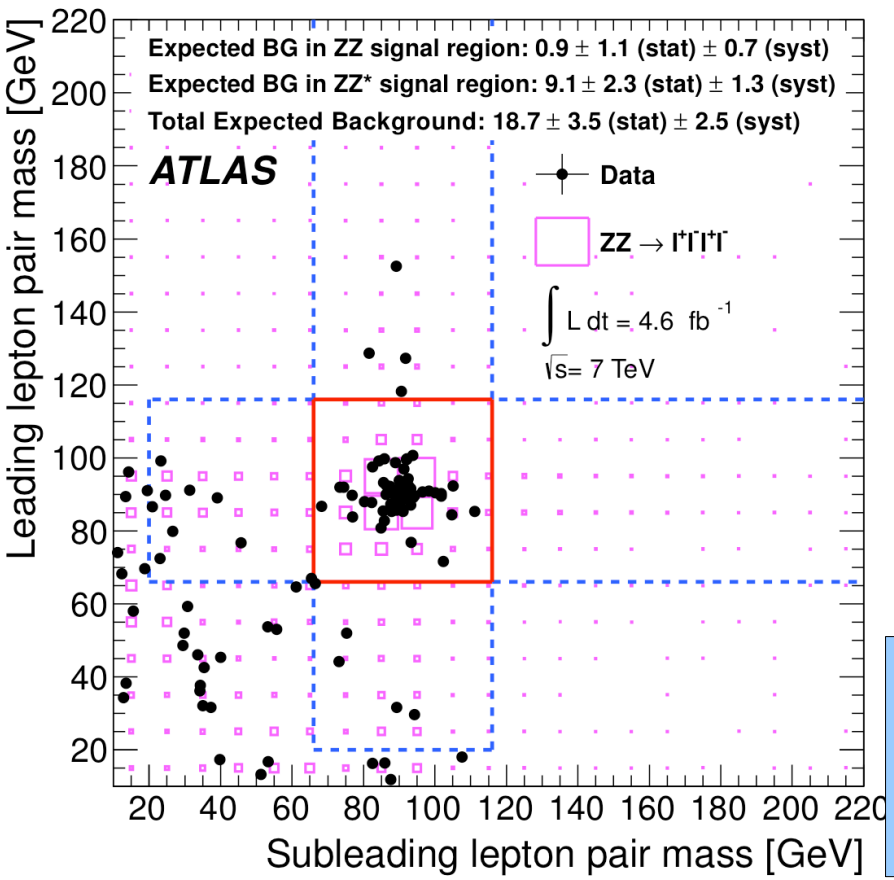
4.6 fb^{-1} @ 7 TeV : ZZ production cross section

$ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
Observed ZZ	16	23	27	66
Expected ZZ background	$0.5 \pm 0.6 \pm 0.3$	< 0.6	$0.7 \pm 0.7 \pm 0.6$	$0.9 \pm 1.1 \pm 0.7$

ZZ → 4l

$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	$e^+e^- E_T^{miss}$	$\mu^+\mu^- E_T^{miss}$	$\ell^+\ell^- E_T^{miss}$
Observed ZZ	35	52	87
Expected ZZ background	$20.8 \pm 2.3 \pm 1.2$	$26.1 \pm 2.8 \pm 1.4$	$46.9 \pm 4.8 \pm 1.9$

ZZ → 2l 2v



Acceptance;

Selection	A_{ZZ}
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$0.804 \pm 0.001 \pm 0.010$
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	$0.081 \pm 0.001 \pm 0.004$

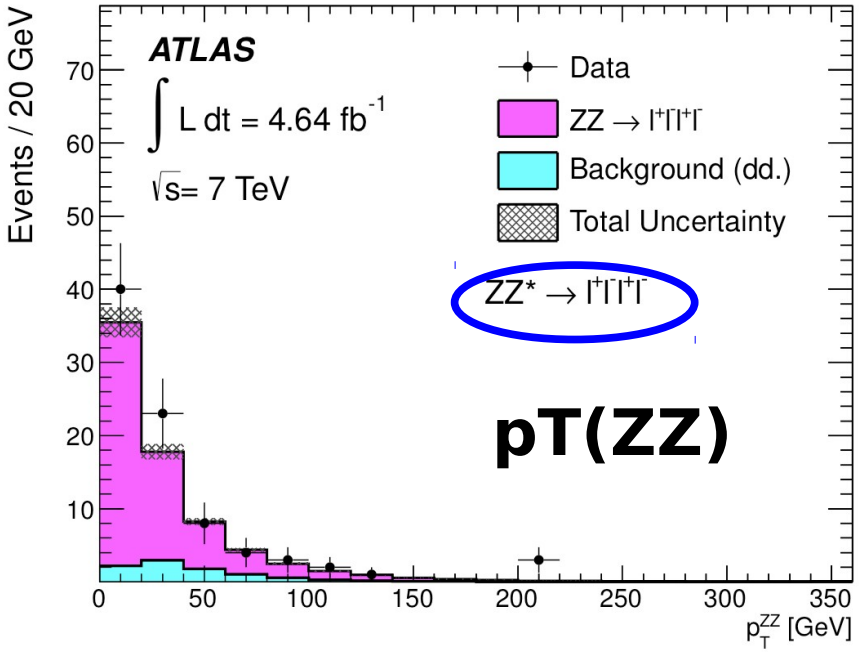
Efficiency;

Selection	C_{ZZ}
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$0.552 \pm 0.002 \pm 0.021$
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	$0.679 \pm 0.004 \pm 0.014$

$$\sigma_{ZZ}^{tot} = 6.7 \pm 0.7\ (\text{stat.})\ ^{+0.4}_{-0.3}\ (\text{syst.}) \pm 0.3\ (\text{lumi.})\ \text{pb}$$

Theory: $5.89^{+0.22}_{-0.18}\ pb$
(NLO in qq → ZZ, LO in gg → ZZ, no EW corctns)

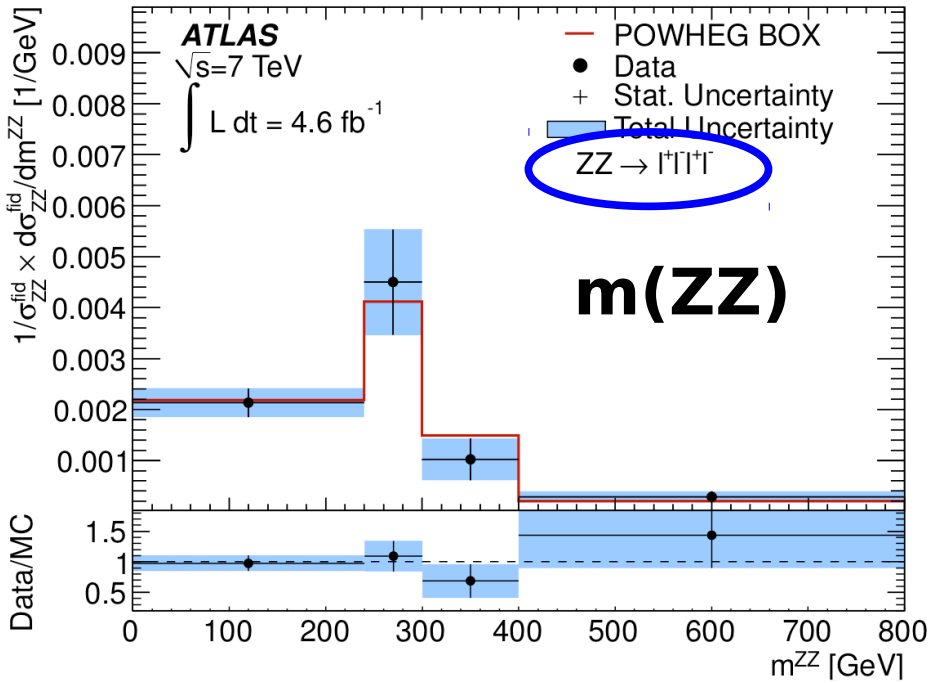
Unfolded quantities and differential cross sections in the fiducial volume

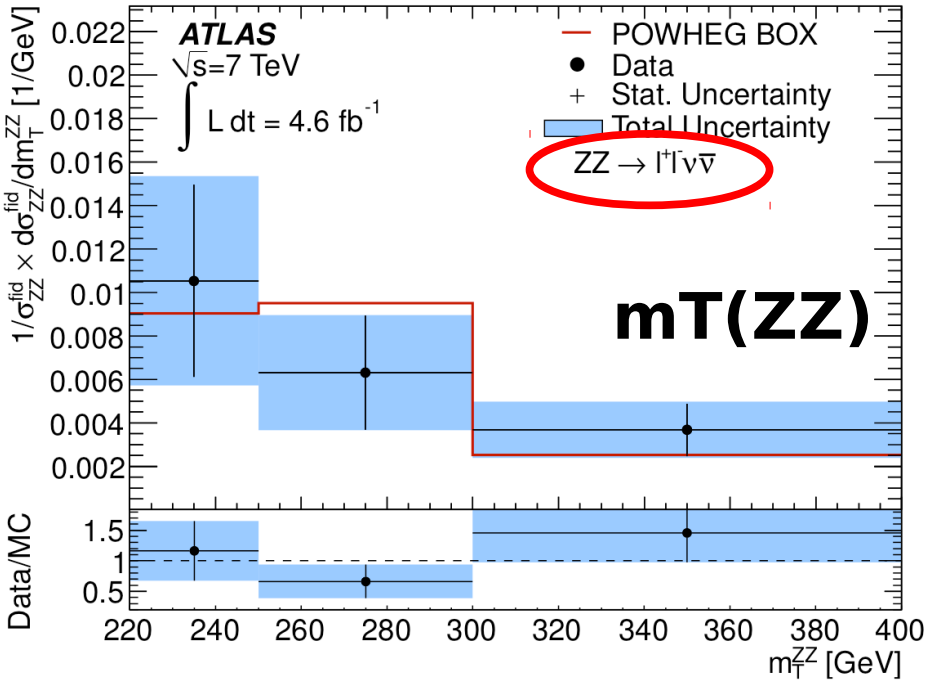


Binned distribution of events in various kinematical variables & knowledge of efficiency corrections with the correlations among the bins, allows to:

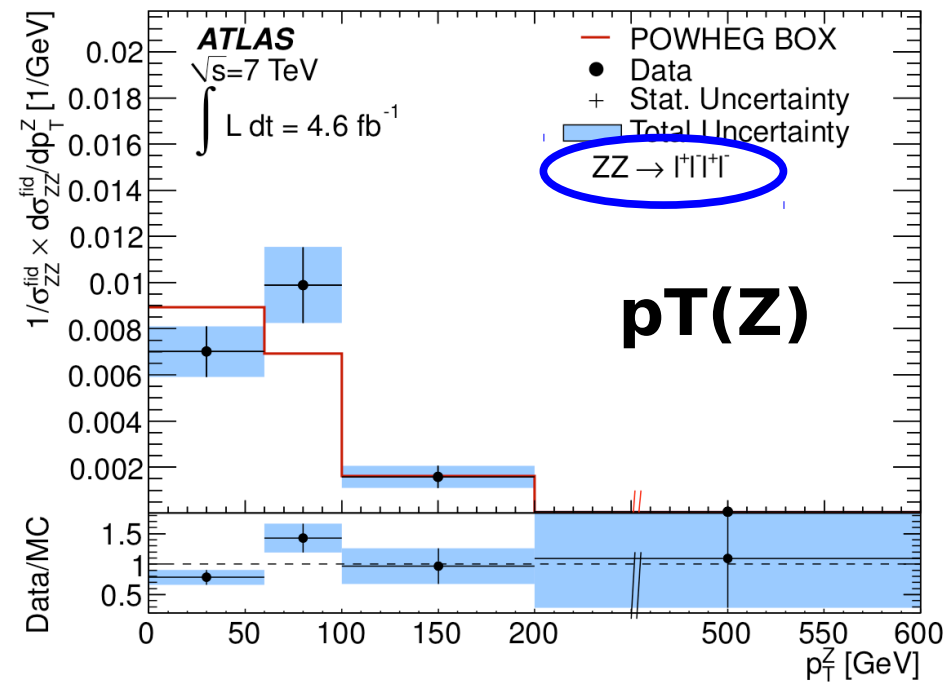
"unfold" the distributions of the reconstructed kinematics to the generated kinematics

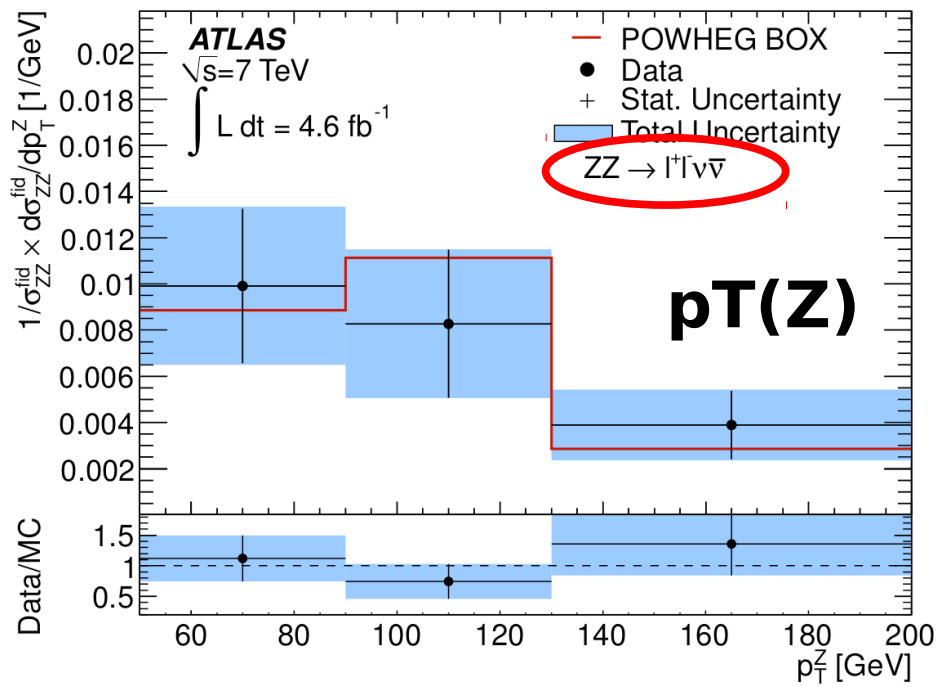
and derive differential cross sections

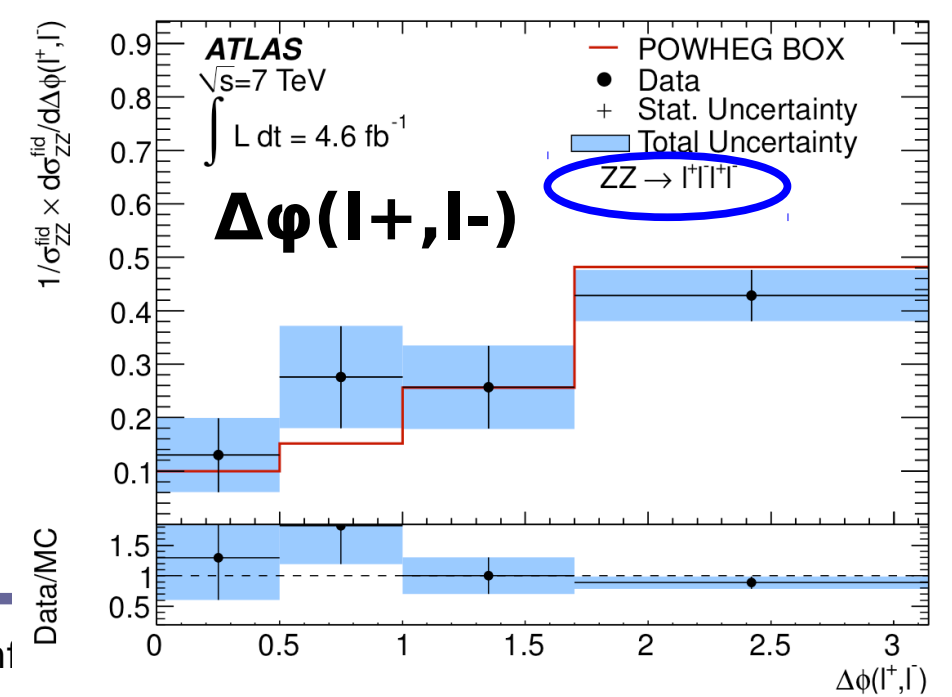


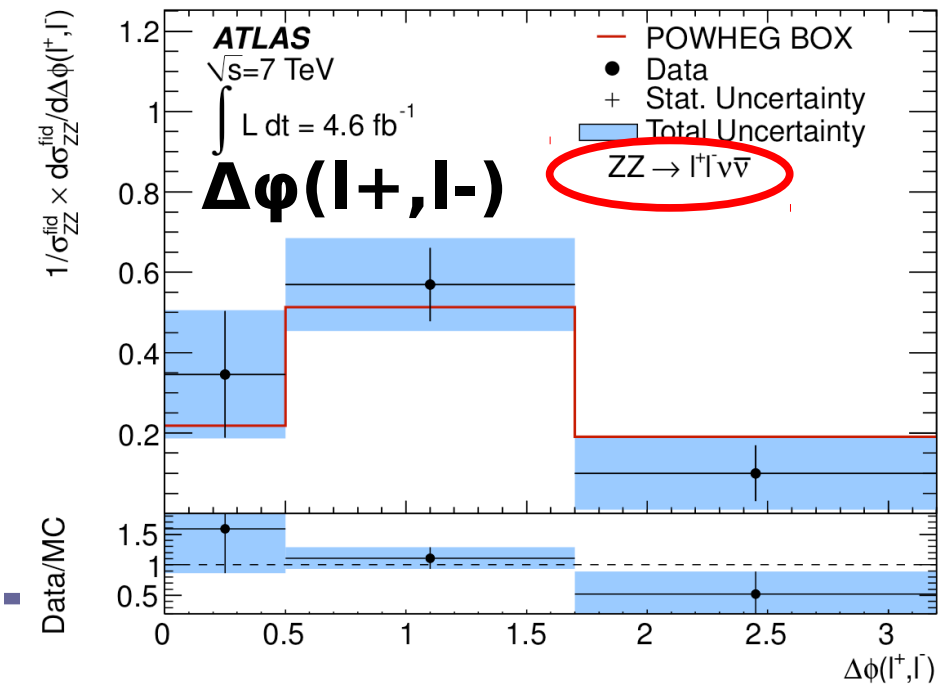


Unfolded quantities: differential cross sections







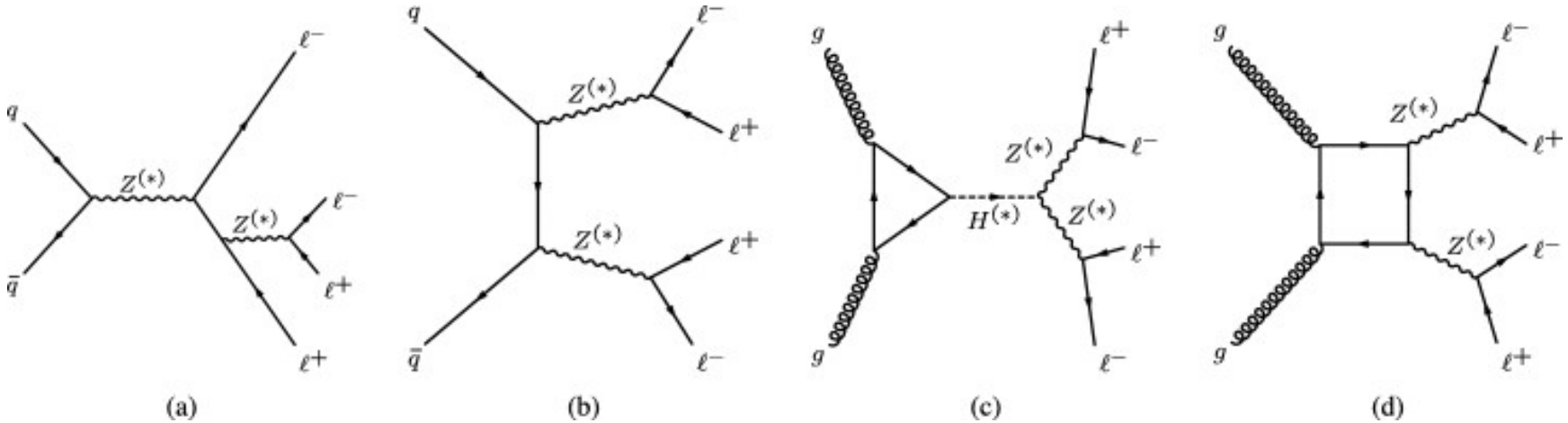


2b.
@ 8 TeV: inclusive 4l

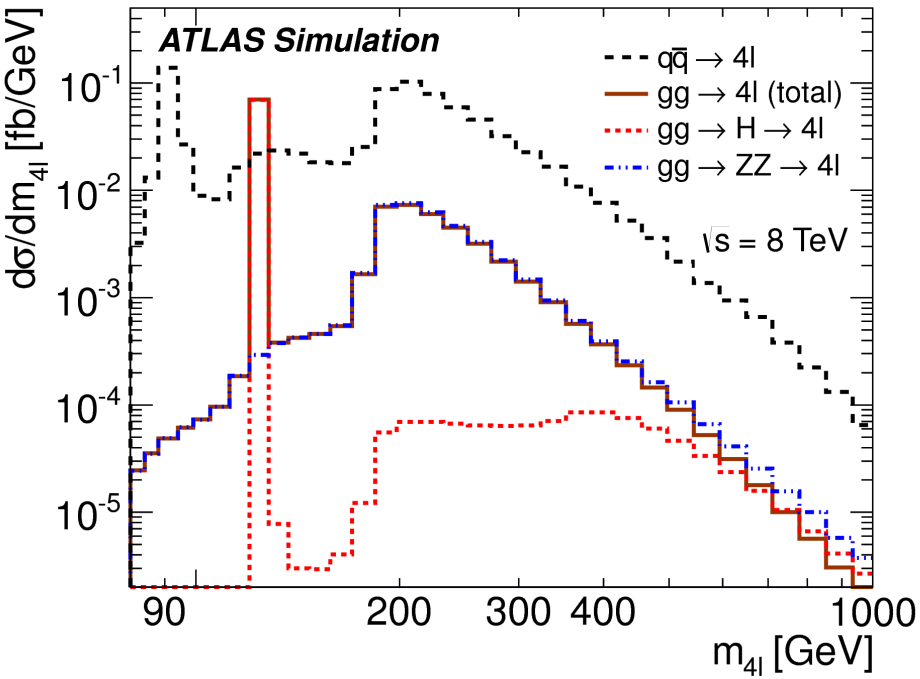
Phys Lett B, 753 (2016) 552

4l @ 8TeV (20.3 fb^{-1}): Production

- Production of 4l by $Z^{(*)}$, $Z^{(*)}Z^{(*)}$, and Higgs



- Studied mass of 4 lepton system → Interference of ZZ with Higgs at high masses

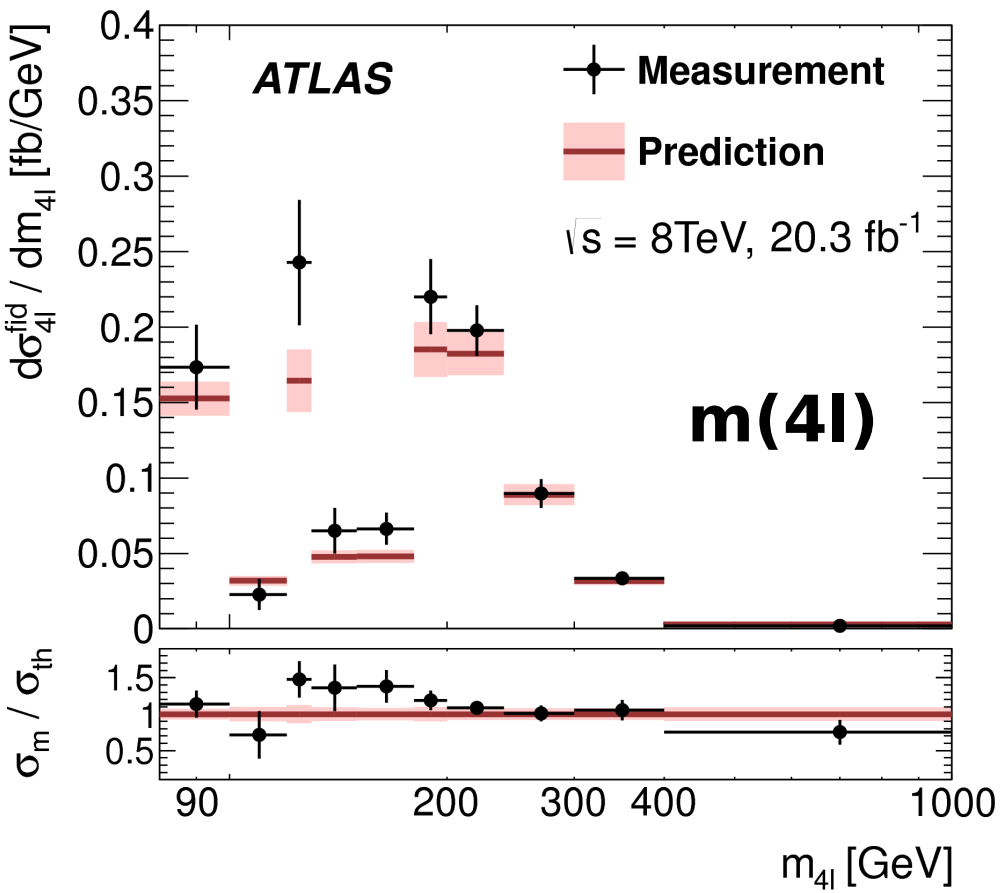


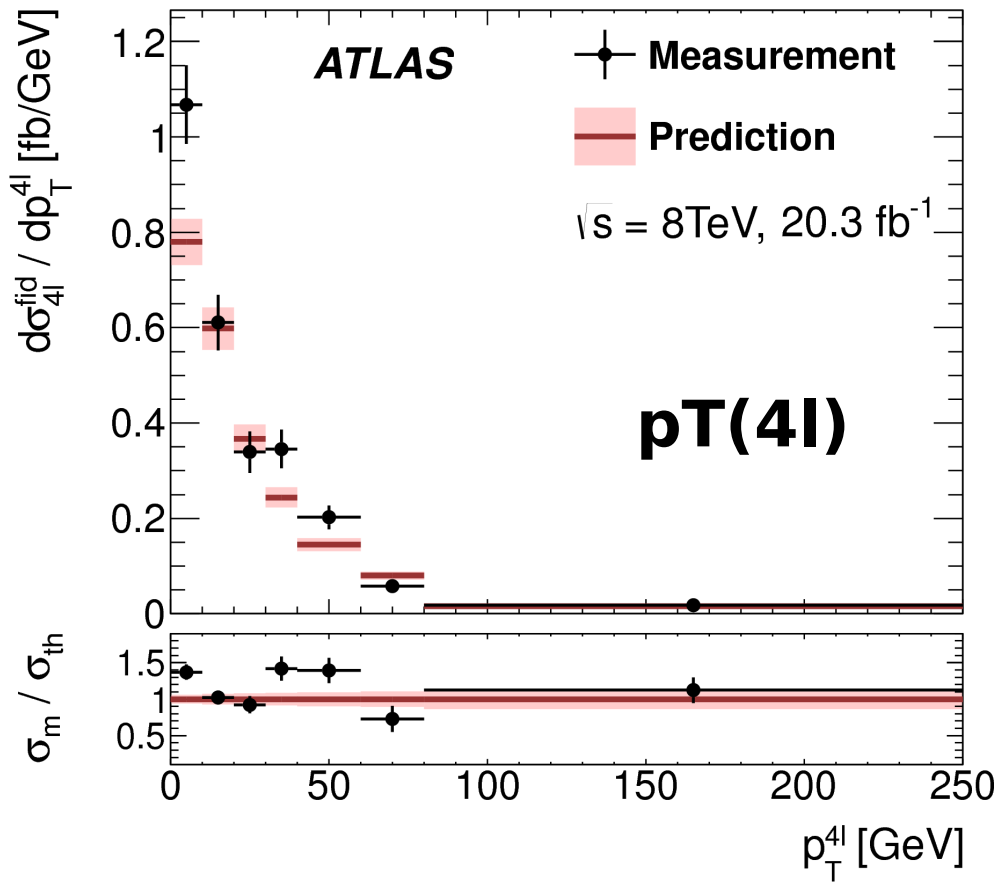
4l @ 8TeV (20.3 fb^{-1}): cross-sections

- **Total:**

4ℓ	Measured σ^{fid} [fb]	SM σ^{fid} [fb]	Measured σ^{ext} [fb]	SM σ^{ext} [fb]
$4e$	$7.4^{+0.9}_{-0.8}$ (stat) $^{+0.4}_{-0.3}$ (syst) $^{+0.2}_{-0.2}$ (lumi)	6.9 ± 0.4	$17.8^{+2.1}_{-2.0}$ (stat) $^{+1.5}_{-1.1}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.0
4μ	$8.7^{+0.8}_{-0.7}$ (stat) $^{+0.2}_{-0.2}$ (syst) $^{+0.3}_{-0.2}$ (lumi)	8.3 ± 0.5	$17.3^{+1.5}_{-1.4}$ (stat) $^{+0.9}_{-0.7}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.0
$2e2\mu$	$15.9^{+1.1}_{-1.1}$ (stat) $^{+0.5}_{-0.4}$ (syst) $^{+0.5}_{-0.4}$ (lumi)	13.7 ± 0.9	$37.7^{+2.7}_{-2.6}$ (stat) $^{+2.5}_{-2.0}$ (syst) $^{+1.1}_{-1.1}$ (lumi)	32.1 ± 2.0
Total			73^{+4}_{-4} (stat) $^{+4}_{-4}$ (syst) $^{+2}_{-2}$ (lumi)	65 ± 4

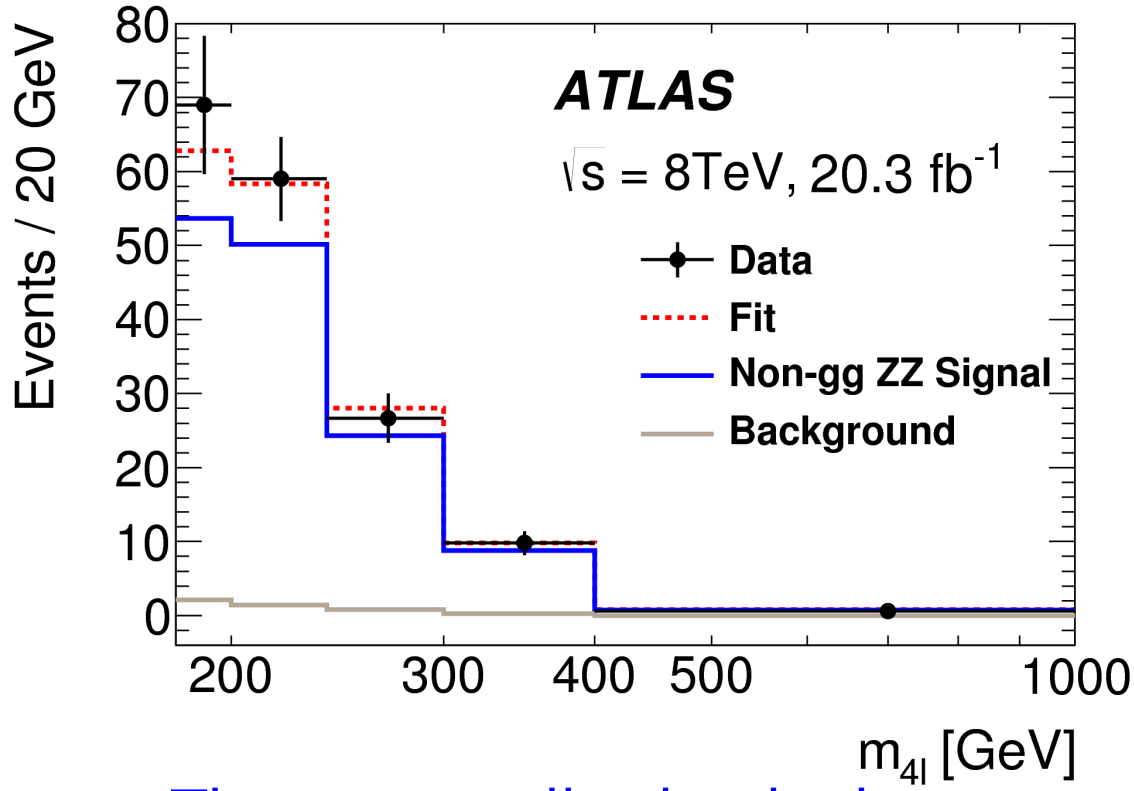
- **Differential**: - in fiducial phase space, iterative Bayesian unfolding





4l @ 8TeV (20.3 fb^{-1}): gg → 4l @m4l>180 GeV

- Above m_{4l} > 180 GeV, dominated by ZZ production.
- m_{4l} used as the discriminant w.r.t. LO gg → ZZ prediction
- Extracted from likelihood fit using reconstructed m_{4l} distributions
- Uncertainties treated as fully correlated between gg and qq processes.



The gg contribution is the difference between data and non-gg signal and background

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

μ_{gg} = 2.4±1.0(stat.)±0.5(syst.)±0.8(theory)

→ we probably need another order in QCD for gg → ZZ (prelim. calculations show enhancement by up to x2 in gg → ZZ
Note though that: gg → ZZ is small (~6%) compared to qq → ZZ

3. ZZ production at 7 TeV and anomalous Triple Gauge Couplings (aTGCs)

JHEP03(2013)128

Contribution of aTGCs to the cross section

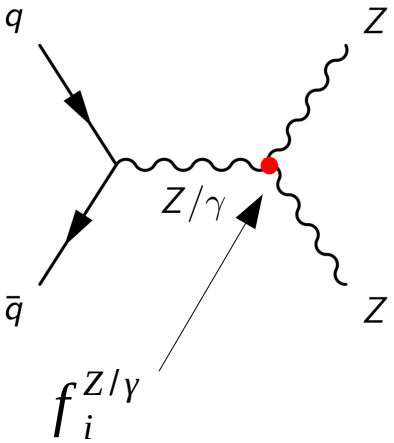
- Traditionally, effective Lagrangian used to include effect of aTGCs: e.g., PRD 62, 113011 (Bauer - Reinwater)

Effective Lagrangian

$$L = \frac{e}{m_Z^2}\left[f_4^V \left(\partial_\mu V^{\mu\beta}\right) Z_\alpha \left(\partial^\alpha Z_\beta\right) + f_5^V \left(\partial^\sigma V_{\sigma\mu} \tilde{Z}^{\mu\beta} Z_\beta\right)\right], V = Z, \gamma$$

SM values:

$f_4^\gamma = f_4^Z = f_5^\gamma = f_5^Z = 0$



- ZZ cross section enhanced by aTGCs with ~quadratic dependence on them

With one aTGC active:

$$d\sigma_{SM+TGC} = F_0 + fF_1 + f^2 F_2$$

$$d\sigma_{SM+TGC} = \overbrace{F_{00}}^{\text{SM contribution}} + f_4^\gamma F_{01} + f_4^Z F_{02} + f_5^\gamma F_{03} + f_5^Z F_{04}$$
$$+ \left(f_4^\gamma\right)^2 F_{11} + f_4^\gamma f_4^Z F_{12} + f_4^\gamma f_5^\gamma F_{13} + f_4^\gamma f_5^Z F_{14}$$
$$+ \left(f_4^Z\right)^2 F_{22} + f_4^Z f_5^\gamma F_{23} + f_4^Z f_5^Z F_{24}$$
$$+ \left(f_5^\gamma\right)^2 F_{33} + f_5^\gamma f_5^Z F_{34}$$
$$+ \left(f_5^Z\right)^2 F_{44}$$

aTGCs and differential event yields

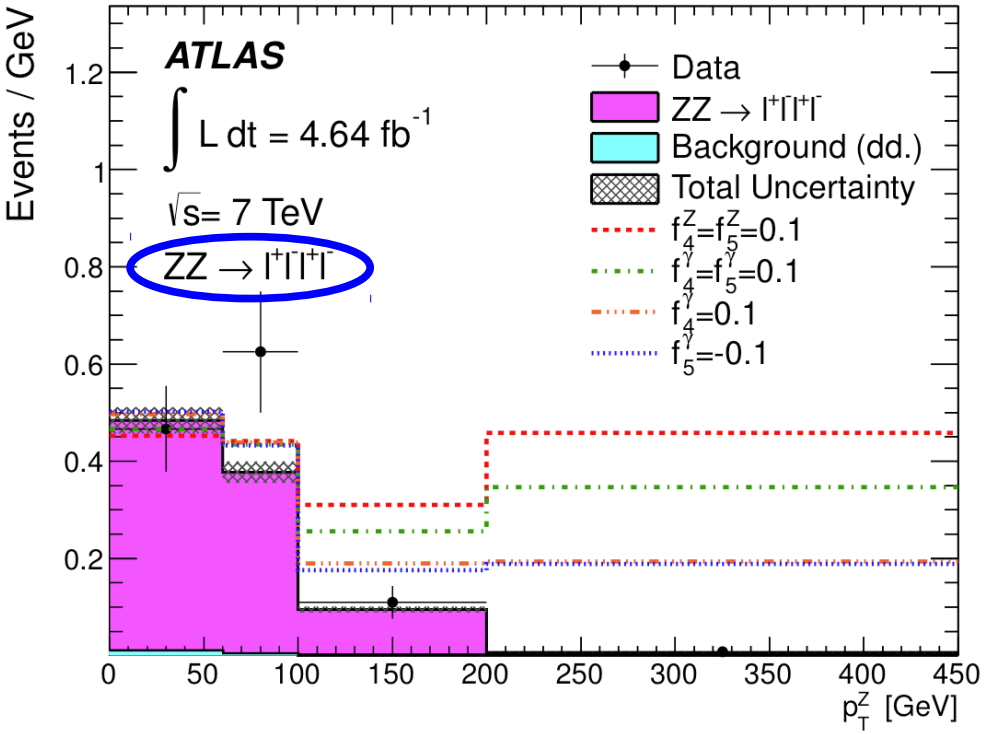
- **aTGC contribution not the same across phase-space**

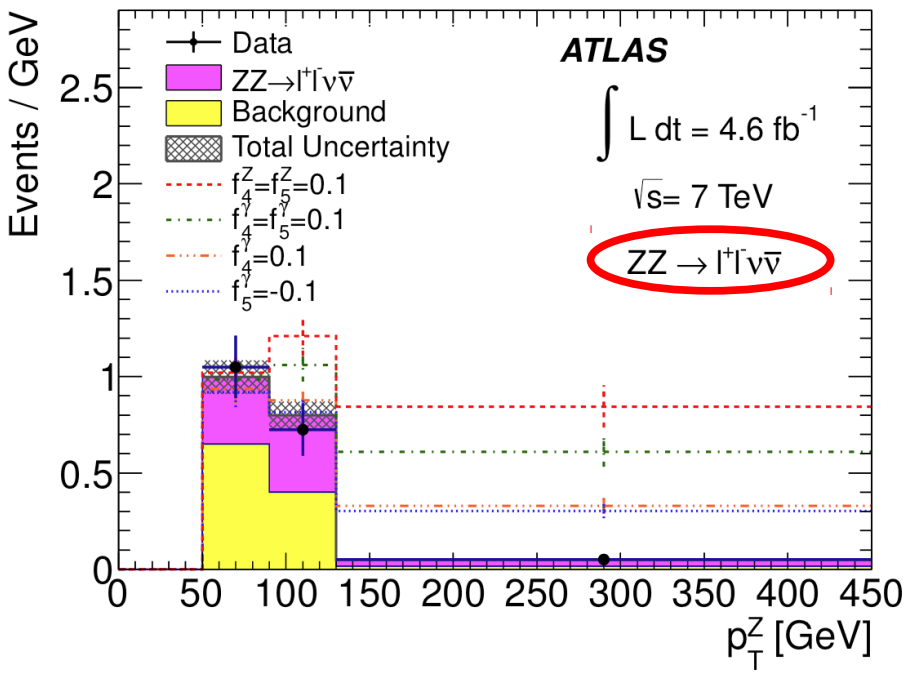
  → use event yield as function of single kinematical variables and compare to expectation from SM.

- Typically use pT(Z), m(ZZ) system

- Effect of aTGCs most significant in high pT & high mass

  For result use **pT(Z)** from both ZZ → 4l and ZZ → 2l2v



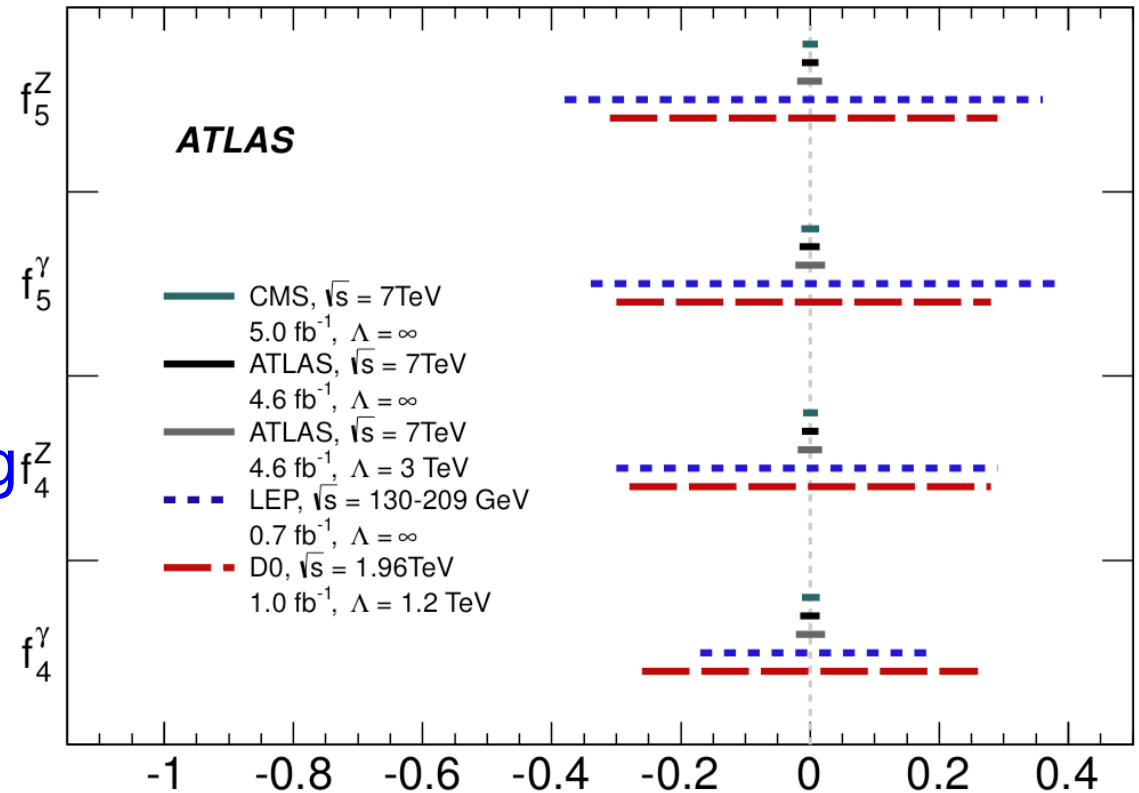


Limits on aTGCs from 4.6 fb^{-1} at 7 TeV

- Using both ZZ → 4l and ZZ → 2l 2v events

f_{40}^{γ}	f_{40}^{Z}	f_{50}^{γ}	f_{50}^{Z}
$[-0.015, 0.015]$	$[-0.013, 0.013]$	$[-0.016, 0.015]$	$[-0.013, 0.013]$

Recall:
SM has all these couplings = 0



With the increasing statistics and by looking at a proper kinematic regime, instead of using total event yield:

→ aTGC limits improved

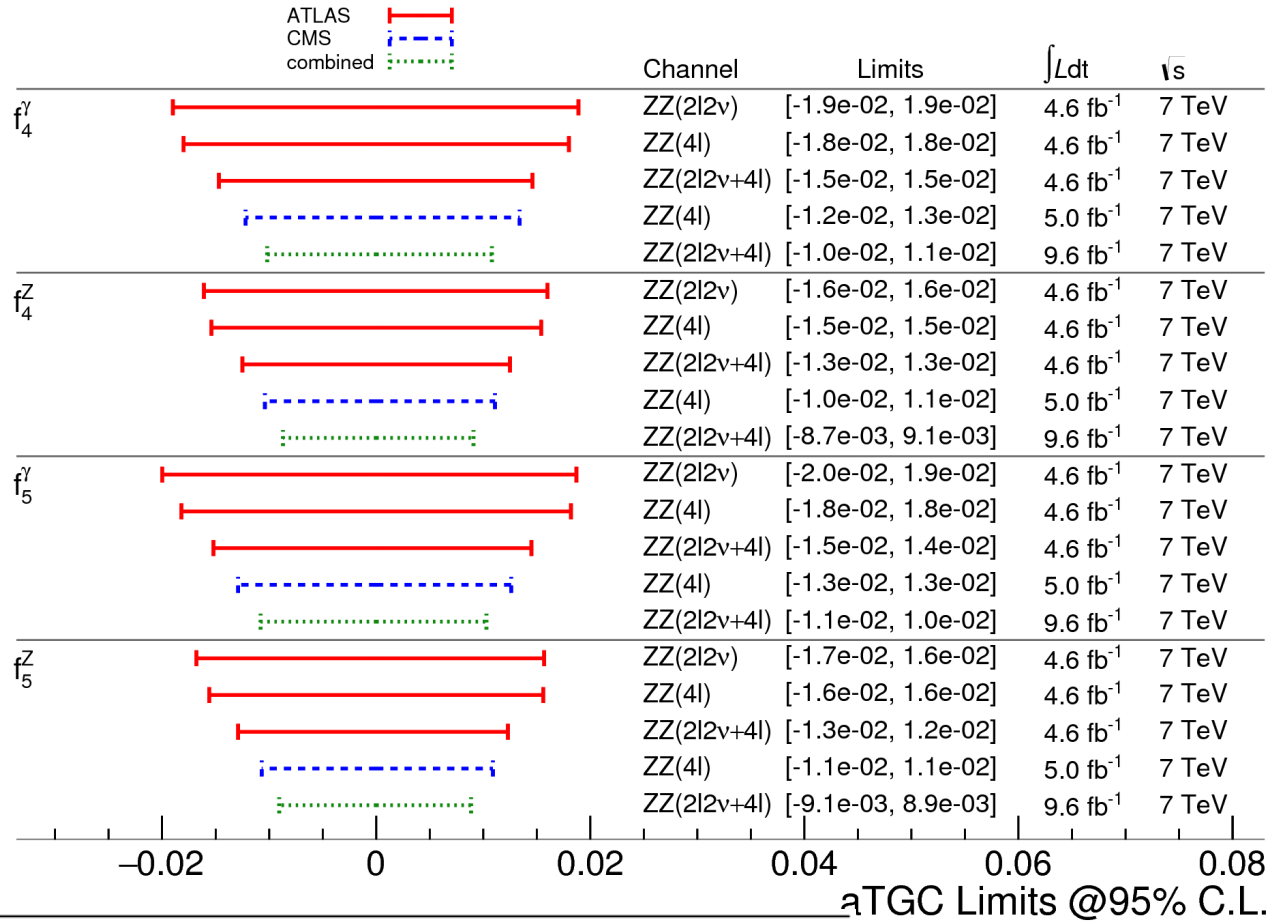
from: $f^{\gamma,Z}_{4,5} < 0.1$ @ 90 C.L (12 events, total counting)

to: $f^{\gamma,Z}_{4,5} < 0.015$ @ 90 C.L (66 events, binned counting)

ATLAS+CMS combination of 7 TeV results

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-036/

- Combination across channels and across experiments improves limits: ATLAS-CONF-2016-036



Observed limit	f_4^γ	f_4^Z	f_5^γ	f_5^Z
deltaNLL ATLAS	[-0.015, 0.015]	[-0.013, 0.013]	[-0.015, 0.015]	[-0.013, 0.012]
deltaNLL CMS	[-0.012, 0.013]	[-0.010, 0.011]	[-0.013, 0.013]	[-0.011, 0.011]
deltaNLL combined	[-0.010, 0.011]	[-0.0087, 0.0091]	[-0.011, 0.010]	[-0.0091, 0.0089]
F-C combined	[-0.010, 0.011]	[-0.0089, 0.0092]	[-0.011, 0.010]	[-0.0092, 0.0089]

There is also limits on two aTGCs at a time (see CONF note)

Summary & Conclusions

- **13 and 8 TeV measurements in ATLAS is the total σ^{tot}_{ZZ}**
  - consistent with theory; better with NNLO in pQCD corr'ns

- **Differential cross sections and search for new physics:**
  - 8 TeV : mass(4l) used to constrain gg → ZZ production
  - 7 TeV: both ZZ → 4l and ZZ → 2l2v are used
    - Differences from SM prediction in differential event yields are interpreted as contribution of anomalous Triple Gauge Couplings (aTGCs):
      - Results consistent with TGC couplings = 0, i.e., the SM value

        → no evidence for new physics

- **Note: Interpreting discrepancies as contribution from New Physics?**
  increased precision of SM calculations (here next order in QCD) & bigger data samples are very important!

References

- ATLAS 7 TeV (xsec & aTGCs): JHEP03(2013)128
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2012-02/
- ATLAS 8 TeV (total ZZ xsec): ATLAS-CONF-2013-02
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-020/
- ATLAS 8 TeV (inclusive 4l): Phys. Lett. B, 753 (2016) 552

  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-15/
- ATLAS 13 TeV, total xsec: DOI: 10.1103/PhysRevLett.116.101801 (2016)
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-13/
- ATLAS summary plots from SM:
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/
- ATLAS and CMS combination for aTGC limits (7 TeV):
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-036/

Thank you

ZZ production at 8 TeV

- Currently available 8 TeV result from ATLAS (ATLAS-CONF-2013-020):

@ 8 TeV: $\sigma_{ZZ}^{tot} = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.2(\text{lumi.})\ \text{pb}$

vs. 7.2 pb theory then (no latest EW corrections, no extra QCD order)

* Leptons: pT>7 GeV , |η| < 2.5

* Nobs: 305 events , <Nbkg>: 20.4 ± 2.9(stat) ± 5.0(syst.) events

* Detector efficiency similar to 13 TeV analysis: <C>= 0.68±0.02

but +64% in acceptance $A = 0.64 \pm 0.01$ [due to lower pT: 7 vs. 20 GeV]

7 TeV analysis with 4.6 fb^{-1} : complete

- Bigger fiducial region in ZZ → 4l than the first 13 TeV result shown before (A = 0.39 → 0.80)

ZZ → 4l

- Electrons: pT > 7 GeV , |η| < 2.47
  - Up to one electron can be in 2.5 < |η| < 3.16 , with pT > 20 GeV
- Muons : pT > 7 GeV , |η| < 2.5
  - Up to one muon can be in: 2.5 < |η| < 2.7, with pT > 10 GeV
- 66 < m(ll) < 116 GeV , DR(ll) > 0.2

- Includes ZZ → 2l 2v channel: tight cuts to reduce the higher background : A = 0.08 [but BR(ZZ → 2l2v) x3 higher than 4l]

ZZ → 2l 2v

- Electrons: pT > 20 GeV , |η| < 2.47
- Muons: pT > 20 GeV , |η| < 2.5
- 76 < m(ll) < 106 GeV , DR(ll) > 0.3

- High Missing Tranverse Energy (MET) projected on pT(Z): > 75 GeV
- pT ~balanced: MET – pT(Z) / pT(Z) < 0.4
- No jets with pT> 25 GeV, |η|< 4.5

7 TeV ZZ: limits on pairs of aTGC paramters as well