Diboson production at the LHC

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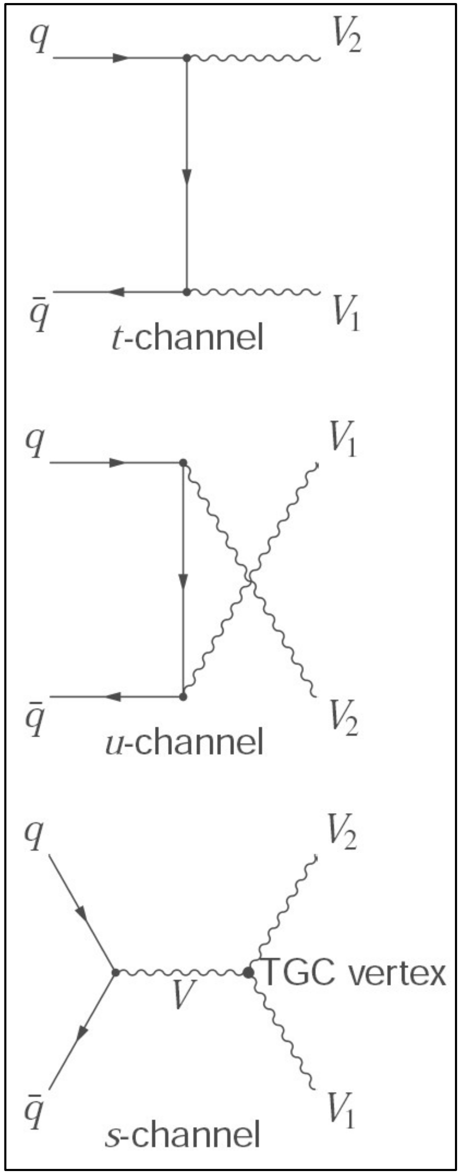
LHCP2016, Lund

Diboson production



- Production dominated by **qq annihilation** and small contribution from gluon-gluon interaction.
- **Diboson measurements are an important test of the Standard Model and perturbative QCD at TeV scale**
- **Confirm irreducible background** for Higgs analysis **(WW, ZZ, Zγ)**
- Diboson processes are the backgrounds for **New Physics**
- Measurement of anomalous triple and quartic gauge boson couplings (aTGC and aQGC) is an **indirect search for New Physics**

Cross Section Measurement

The cross-section is calculated using essentially **σ= N / L** but:

- With corrections for background contamination
- Event selection efficiency

$$\sigma \times BR = \frac{N_{obs} - N_{bkg}}{A \times C \times \mathcal{L}_{int}}$$

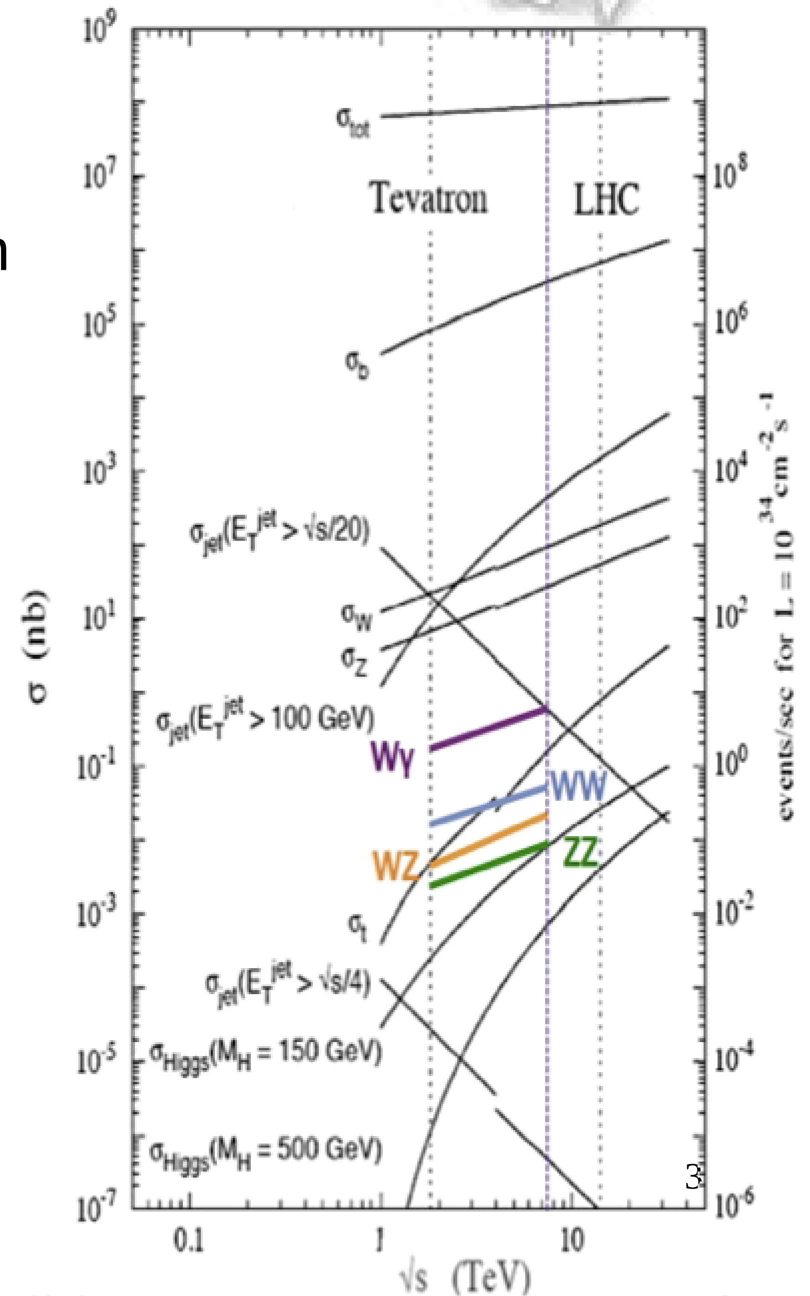
We measure events within an analysis-specific fiducial region

- **A** is the efficiency for events to fall in the fiducial region relative to the full phase space

$$A = \frac{N_{\mathrm{MC}}^{\mathrm{gen,\ fiducial}}}{N_{\mathrm{MC}}^{\mathrm{gen,\ total}}}$$

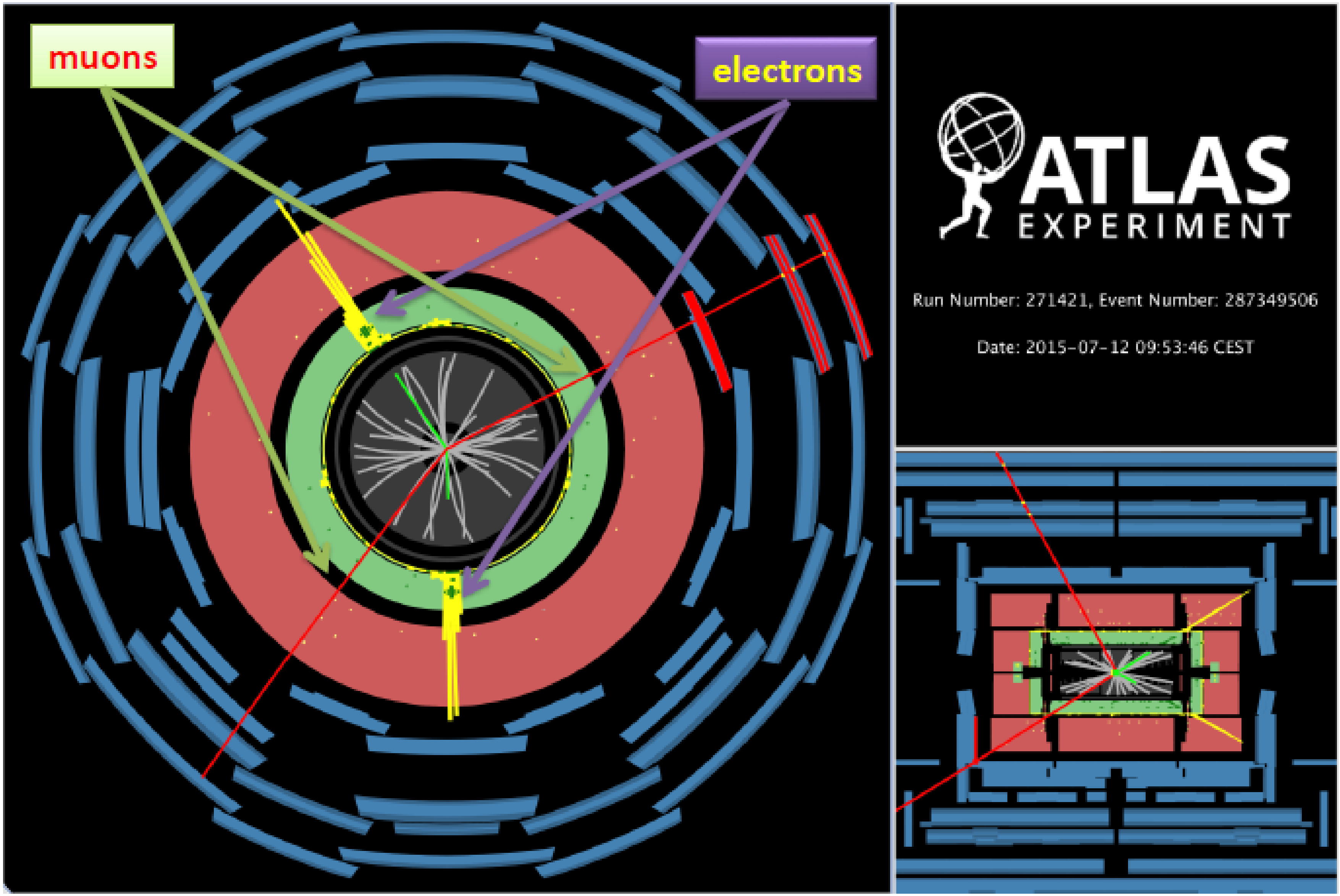
- **C** is the reconstruction efficiency relative to the fiducial region

$$C = \frac{N_{\mathrm{MC}}^{\mathrm{reco.}}}{N_{\mathrm{MC}}^{\mathrm{gen,\ fiducial}}} \times \frac{\epsilon^{\mathrm{data}}}{\epsilon^{\mathrm{MC}}}$$

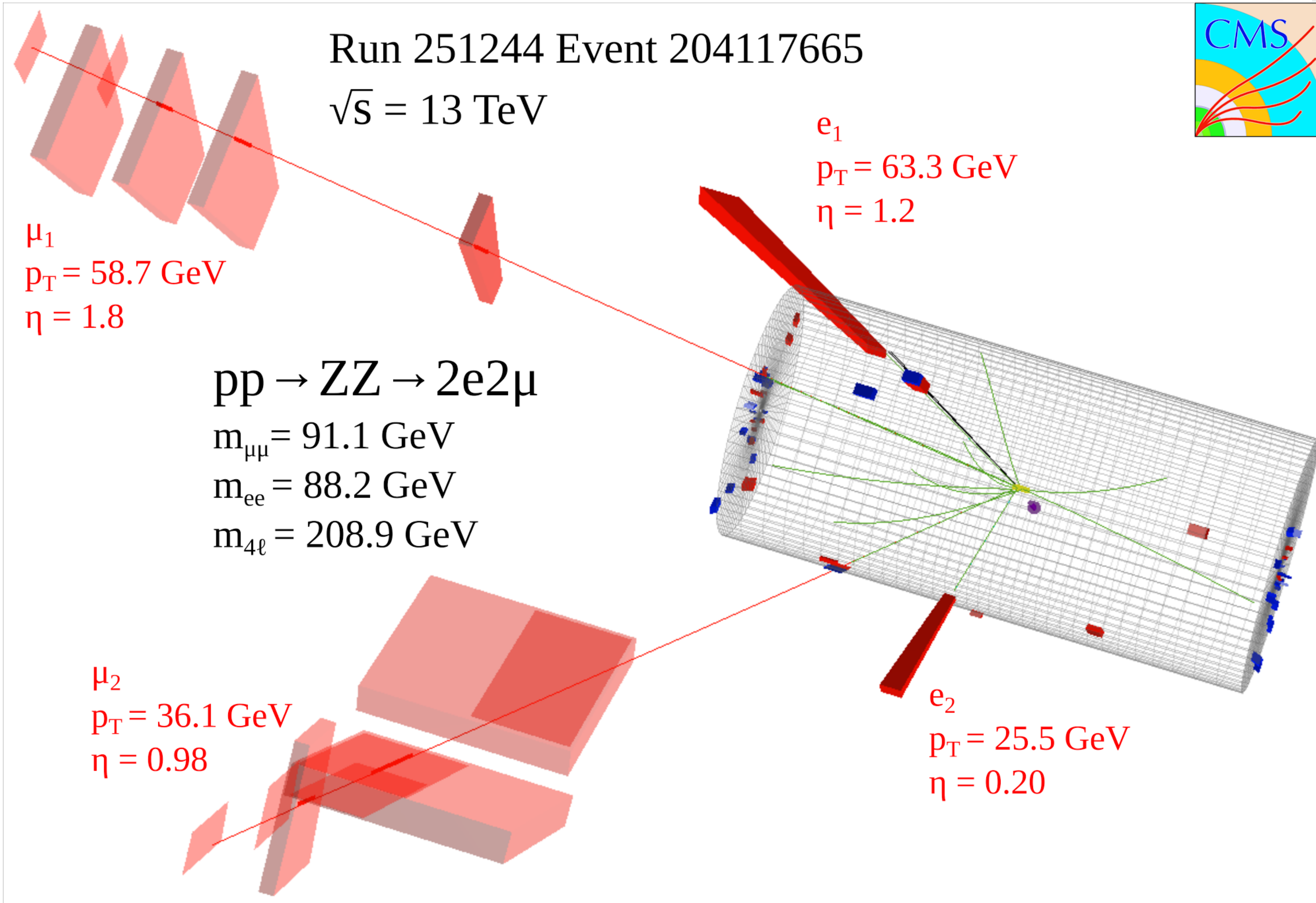


ATLAS event display

Event display for the ZZ-> ee+ μμ candidate event



CMS event display

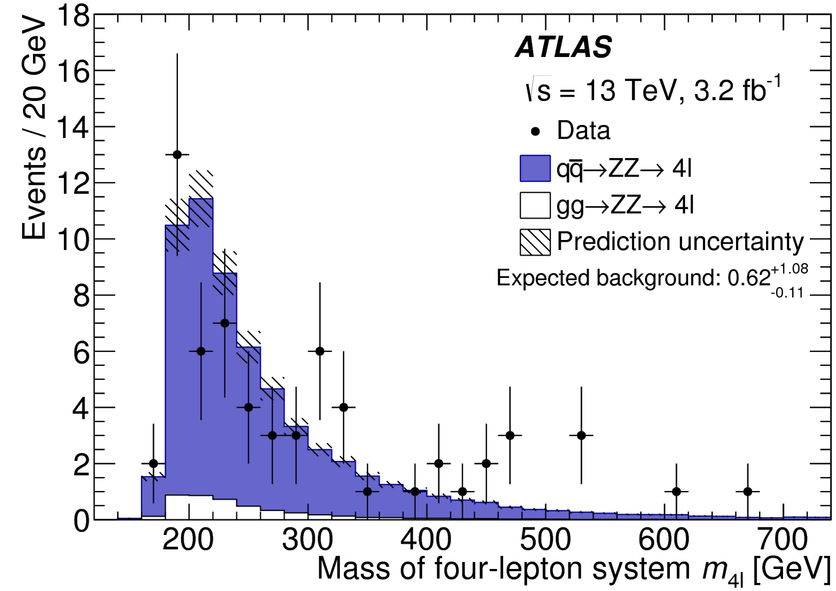


Phys. Rev. Lett. 116, 101801 (2016)

ZZ at 13 TeV (ATLAS)

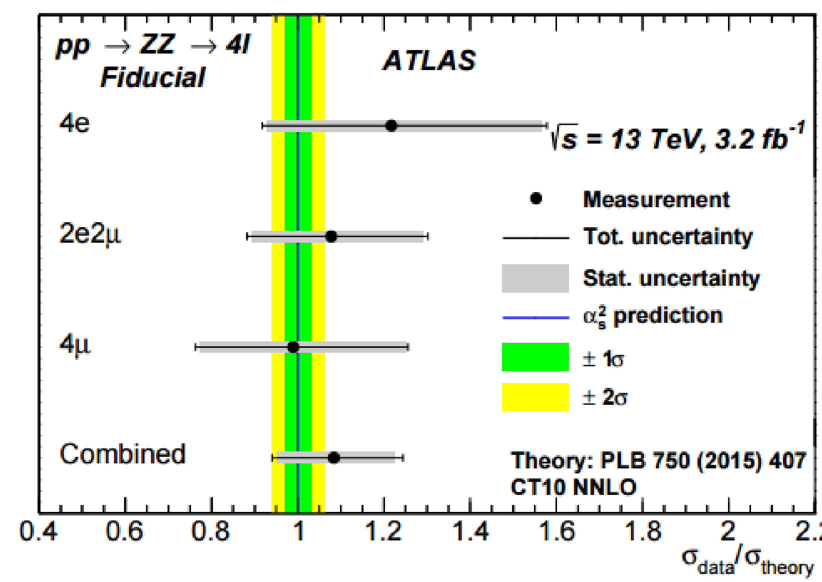
- ZZ → 4 leptons (eeee,eeμμ,μμμμ) channel
- Small BR but **very clean signal**
- Event selection:
  - p_T > 20 GeV, 4 leptons, opposite charge – same flavour pair
  - On-shell Z mass selection

    66 GeV < mll < 116 GeV



- Background with < 4 leptons from Data
- Observed 63 events - Expected bckg 0.62 events
- Systematic uncertainty dominated by statistics in the control samples

Fiducial xs calculated in a phase space close to experimental acceptance



Prediction [O(αs2)] $15.6^{+0.4}_{-0.4}$ pb

$$16.7\ ^{+2.2}_{-2.0}(\text{stat.})\ ^{+0.9}_{-0.7}(\text{syst.})\ ^{+1.0}_{-0.7}(\text{lumi.})\ \text{pb}$$

ZZ at 13 TeV (CMS)

CMS-PAS-SMP-16-001

Same final state but using less luminosity : 2.6 fb^{-1}

- Event selection

  4 high p_T leptons

  At least 1 lepton pT> 20 GeV,

  other 3 leptons pT> 10 GeV

- On-shell Z mass selection

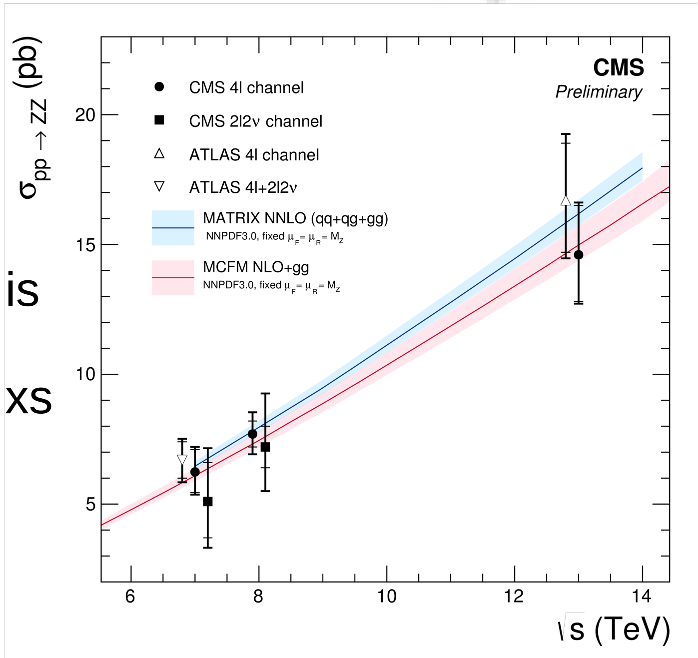
  60 GeV < mll < 120 GeV

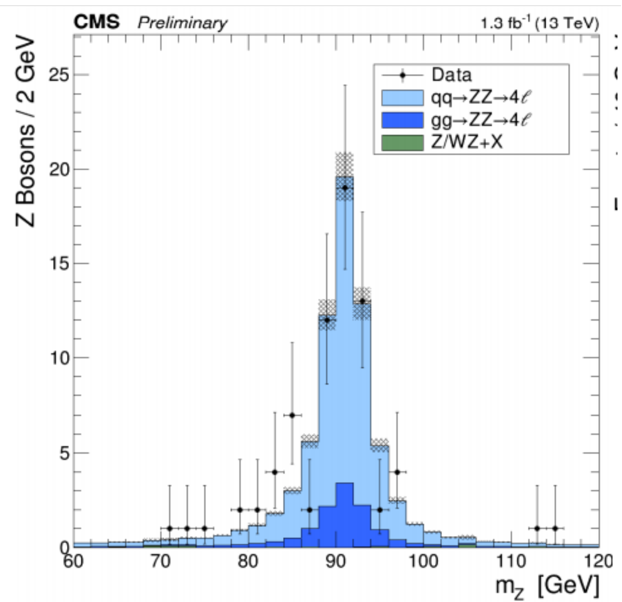
- Observed 39 events – expected background 0.89
- Main background: Z and WZ + jets

  Z+l'l' → misidentification probability

- Statistics are the dominant uncertainty
  - Prediction [NNLO]: $16.5^{+0.7}_{-0.5}$ pb

Smaller mass window is estimated to give 1.6% diff in measured xs





$$\sigma(pp \to ZZ) = 14.6^{+1.9}_{-1.8}\,(\text{stat})^{+0.5}_{-0.3}\,(\text{syst}) \pm 0.2\,(\text{theo}) \pm 0.4\,(\text{lum})\ \text{pb}$$

CMS-PAS-SMP-16-002

WZ at 13 TeV (CMS)

WZ → lν ll channel (eee,eeμ,μμe,μμμ)

W selection

- Lepton > 20, MET > 30 GeV

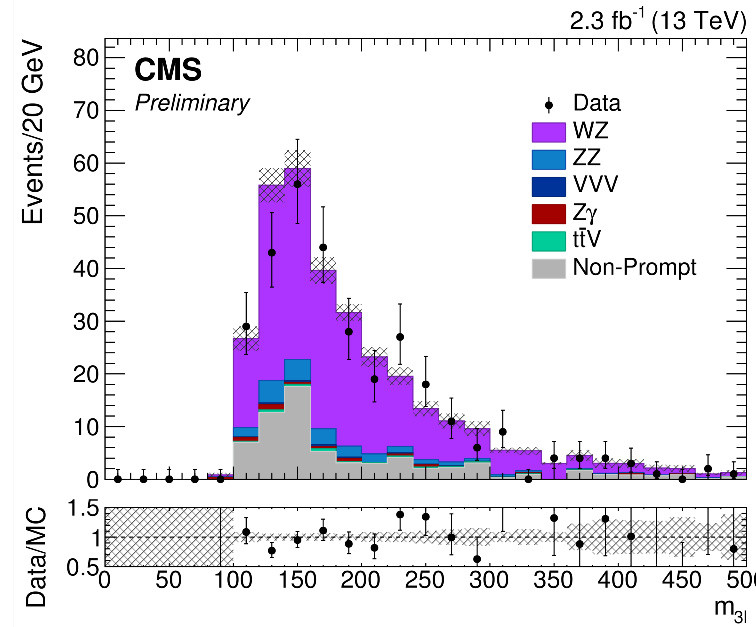
Z selection

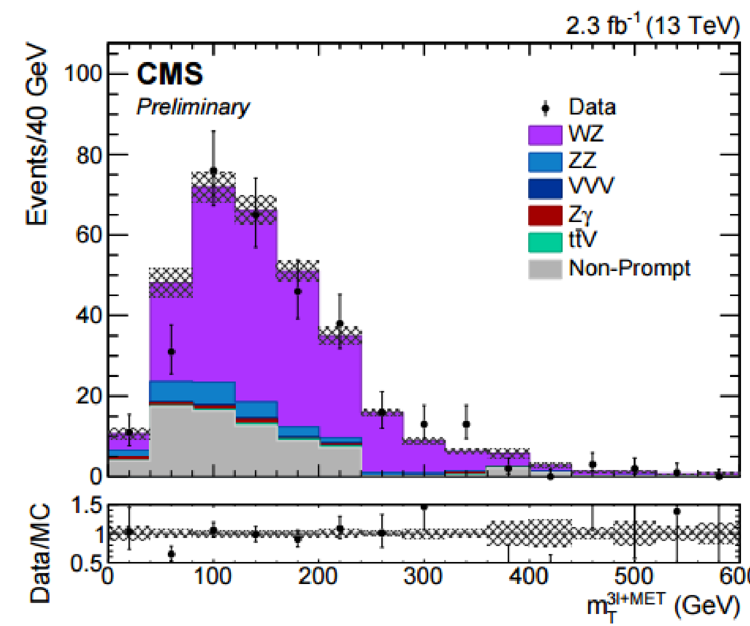
- OS SF 2 leptons > 20, 10 GeV
- 60 GeV < mll < 120 GeV

- **M_{3l} > 100 GeV**
- Background: processes with **prompt leptons** are estimated from **MC**. The processes with at least one **misidentified jet** are estimated from **data → tight-to-loose method:**

  Estimating the probability fake rate (in dijet events) and applying this probability to control regions with loose candidates (1,2 or 3) to estimate the contribution to the signal region

- Main background **lepton miss-ID** Z+jets, ttbar





WZ at 13 TeV (CMS)

CMS-PAS-SMP-16-002

Decay channel	N_{WZ}^{exp}	Background Non-prompt	Background Prompt	Total expected	Observed
eee	$35.88 \pm 0.63^{+1.84}_{-1.78}$	$10.64 \pm 1.73^{+3.19}_{-2.46}$	$6.08 \pm 0.59^{+0.73}_{-0.66}$	$52.60 \pm 1.93^{+3.91}_{-3.29}$	49
$ee\mu$	$50.23 \pm 0.77^{+2.41}_{-2.35}$	$14.83 \pm 3.56^{+3.88}_{-2.98}$	$7.57 \pm 0.47^{+1.00}_{-0.87}$	$72.63 \pm 3.67^{+4.89}_{-4.14}$	78
$\mu\mu e$	$56.02 \pm 0.80^{+2.47}_{-2.42}$	$21.56 \pm 3.21^{+5.01}_{-3.86}$	$8.43 \pm 0.55^{+1.17}_{-1.04}$	$86.01 \pm 3.35^{+5.90}_{-4.89}$	83
$\mu\mu\mu$	$83.96 \pm 0.99^{+3.35}_{-3.27}$	$20.16 \pm 4.91^{+6.05}_{-4.65}$	$11.13 \pm 0.49^{+1.47}_{-1.28}$	$115.25 \pm 5.03^{+7.30}_{-6.09}$	108
Total	$226.09 \pm 1.61^{+9.46}_{-9.25}$	$67.19 \pm 7.08^{+14.43}_{-11.10}$	$33.21 \pm 1.05^{+4.32}_{-3.80}$	$326.50 \pm 7.33^{+18.66}_{-15.90}$	318

Prediction (NLO) 274^{+11}_{-10} fb

$$\sigma_{\text{fid}}(\text{pp} \to \text{WZ} \to \ell\nu\ell'\ell') = 265 \pm 22\,(\text{stat})^{+20}_{-22}\,(\text{syst}) \pm 9\,(\text{lum})\text{ fb},$$

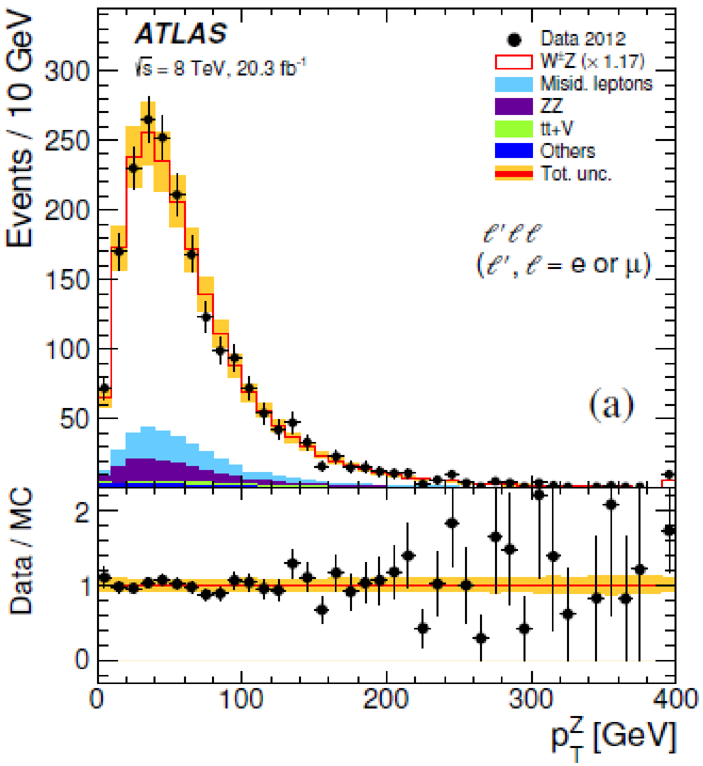
Main systematic coming from misidentification probability (5-6% in final xs)

Prediction (NLO) $42.6^{+1.6}_{-0.8}$ pb

$$\sigma(\text{pp} \to \text{WZ}) = 40.9 \pm 3.4\,(\text{stat})^{+3.1}_{-3.3}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 1.3\,(\text{lum})\text{ pb}.$$

WZ at 8 TeV (ATLAS)

Phys. Rev. D 93, 092004 (2016)



Total expected	1824.8±7.0
Observed events	2091

- 2 opposite charge same flavor leptons in m_Z region
- Additional lepton $p_T > 20$ GeV , $E_T^{miss} > 30$ GeV
- Background sources: events where at least one of the candidate leptons is not a prompt lepton **(reducible background)** and events where all candidates are prompt leptons or are produced in the decay of a τ **(irreducible background).**

Main reducible background: Z+jets, Zγ
Main irreducible background: ZZ

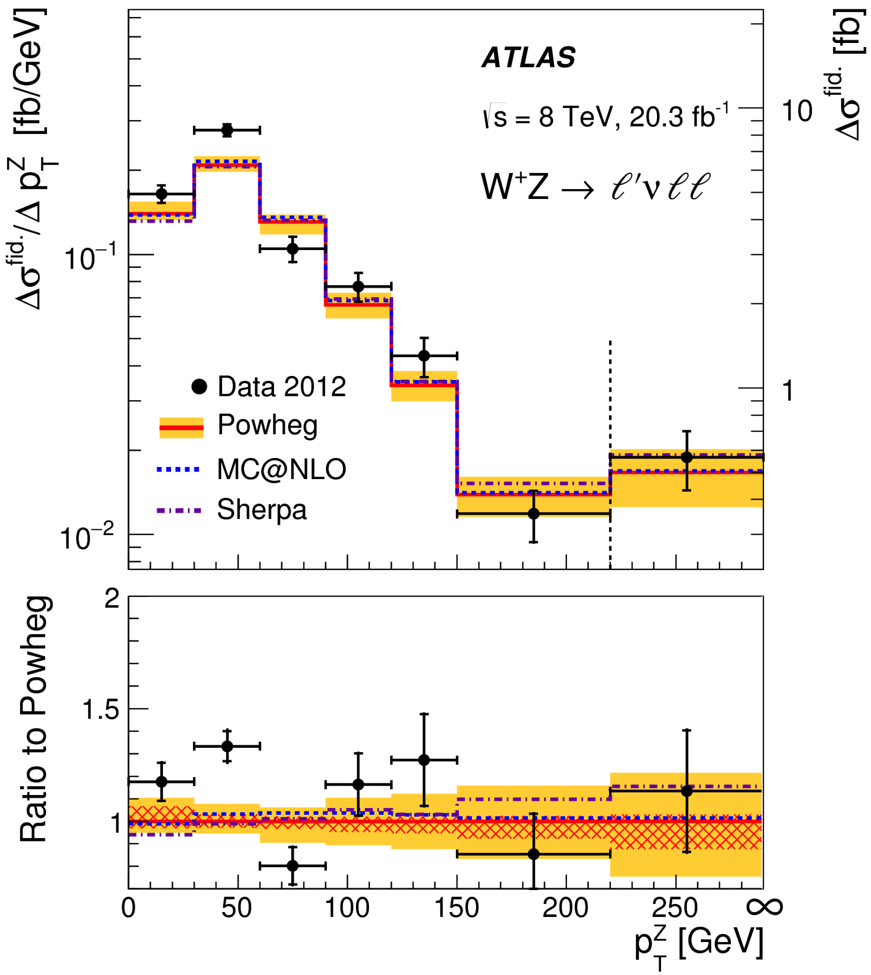
- **Reducible background:** data-driven method based on the **inversion of a global matrix** containing the efficiencies and the misidentification probabilities for prompt and fake leptons
- Main systematics are fake lepton and electron ID efficiency

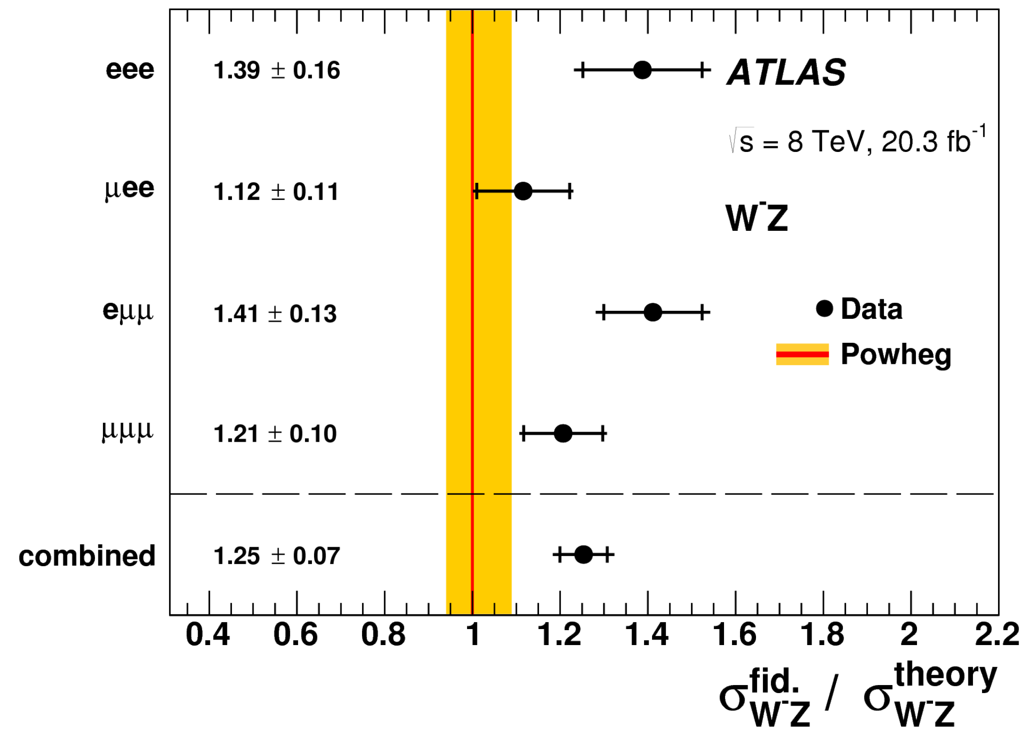
Prediction (NLO) 21.0 ± 1.6 pb.

$$\sigma^{\text{tot.}}_{W^\pm Z} = 24.3 \pm 0.6\,(\text{stat.}) \pm 0.6\,(\text{sys.}) \pm 0.4\,(\text{th.}) \pm 0.5\,(\text{lumi.})\quad \text{pb}$$

WZ at 8 TeV (ATLAS)

Phys. Rev. D 93, 092004 (2016)



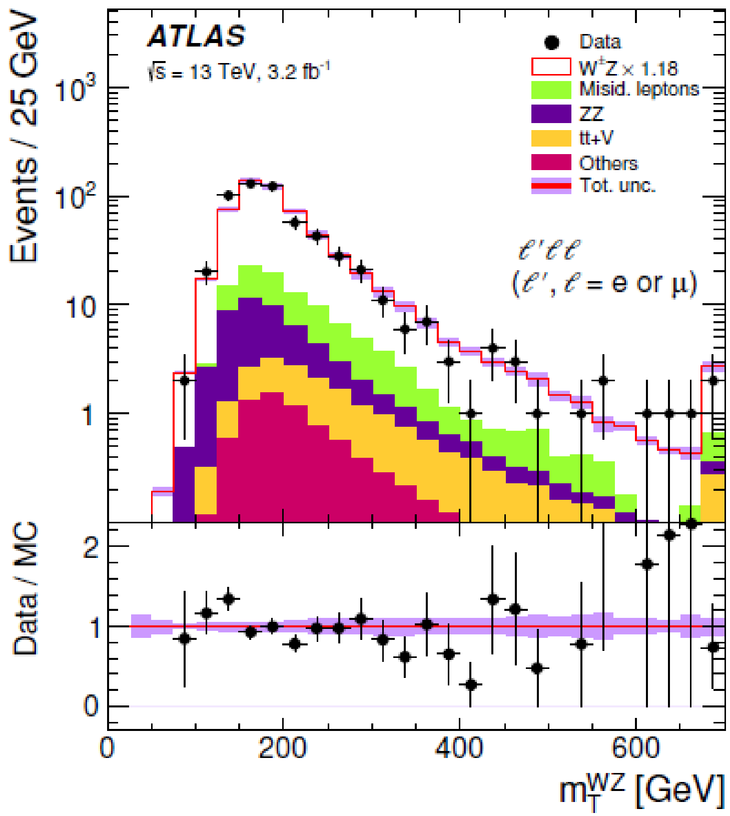


Comparison with NLO

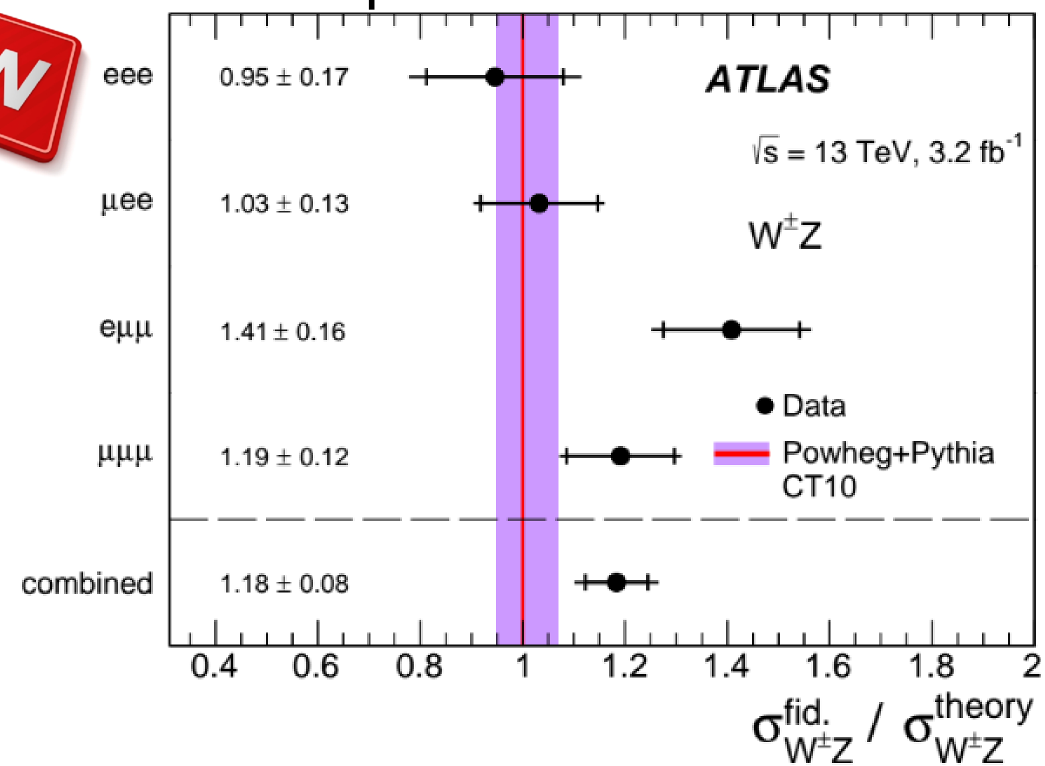
WZ at 13 TeV (ATLAS)

arXiv:1606.04017

- The Z+jets and Zγ background : scaling the observed number of events in a Z control sample by a fake factor.
- tt, Wt and WW + jets (“top-like”) : exploiting the different-flavour decay channels of these processes.



Comparison with NLO



$$\sigma^{tot.}_{W^{\pm}Z} = 50.6 \pm 2.6\,(\text{stat.}) \pm 2.0\,(\text{sys.}) \pm 0.9\,(\text{th.}) \pm 1.2\,(\text{lumi.})\ \text{pb}$$

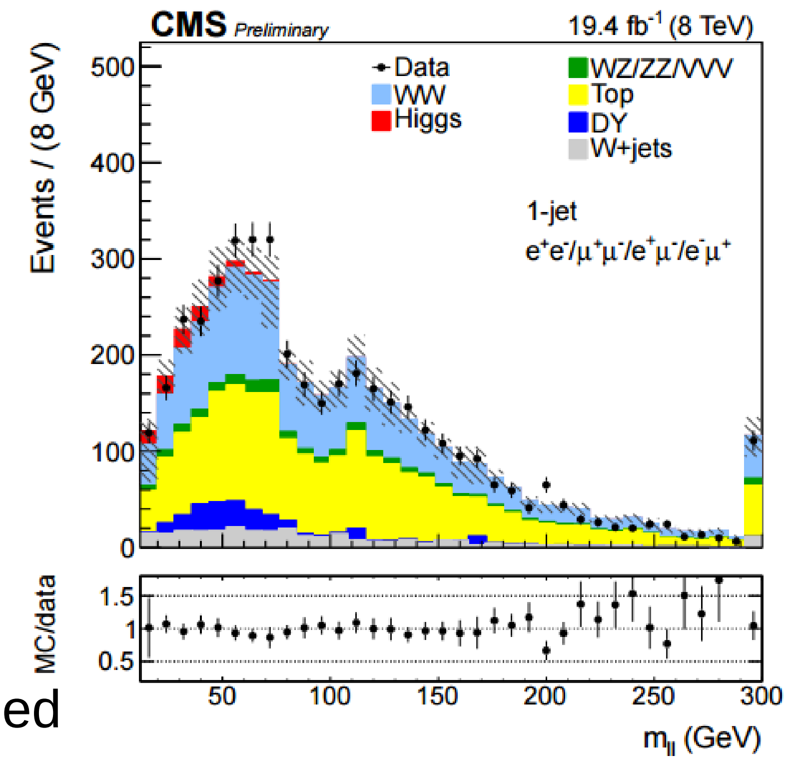
Prediction (NNLO) $48.2^{+1.1}_{-1.0}$ pb.

arXiv:1507.03268 submitted to EPJC

WW at 8 TeV (CMS)

Event Selection (19.4 fb^{-1}):

- 2 opposite sign high p_T leptons
- High E_t^{miss}
- 0 or 1 jet bin
- Additional lepton veto, top veto, Z veto…
- Higgs portion is not considered as signal



Main backgrounds estimated in data:

- Top quark production (mainly ttbar and tW)
- Instrumental backgrounds arising from misidentified leptons in W+jets production → tight-to-loose
- Mismeasurement of ~E_T^{miss} in Z/γ +jets events

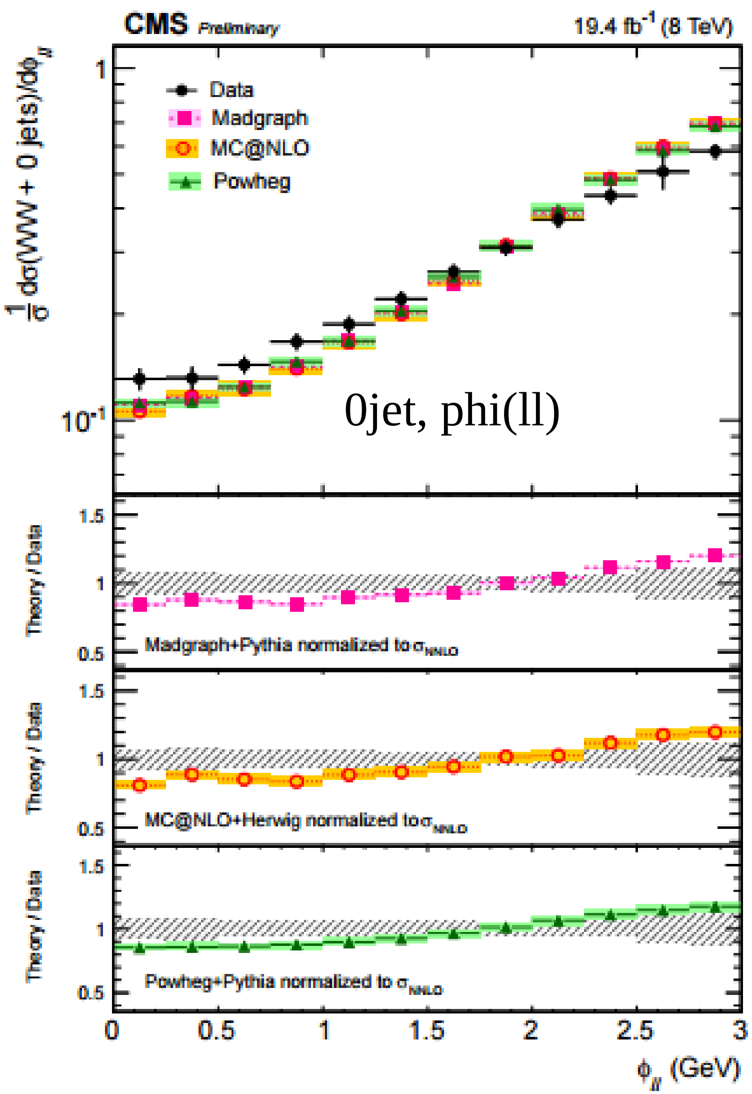
Prediction (NNLO):

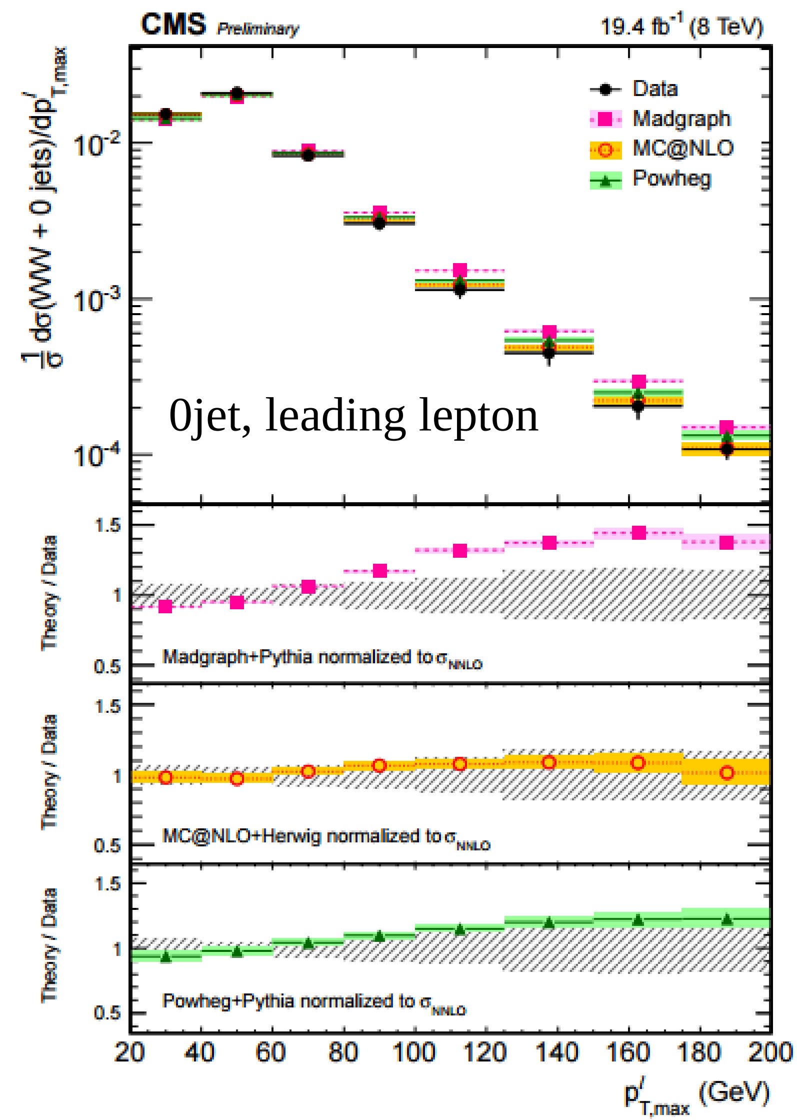
$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\text{stat.}) \pm 3.2\,(\text{exp.}) \pm 3.1\,(\text{th.}) \pm 1.6\,(\text{lum.})\,\text{pb} \qquad 59.8^{+1.3}_{-1.1}\,\text{pb}$$

xs in fiducial regions defined by zero jets at particle level varying jet p_T threshold:

p_T^{jet} threshold (GeV)	σ_{0jet} measured (pb)	σ_{0jet} predicted (pb)
20	36.2 ± 0.6 (stat.) ± 2.1 (exp.) ± 1.1 (th.) ± 0.9 (lum.)	36.7 ± 0.1 (stat.)
25	40.8 ± 0.7 (stat.) ± 2.3 (exp.) ± 1.3 (th.) ± 1.1 (lum.)	40.9 ± 0.1 (stat.)
30	44.0 ± 0.7 (stat.) ± 2.5 (exp.) ± 1.4 (th.) ± 1.1 (lum.)	43.9 ± 0.1 (stat.)

WW at 8 TeV (CMS)

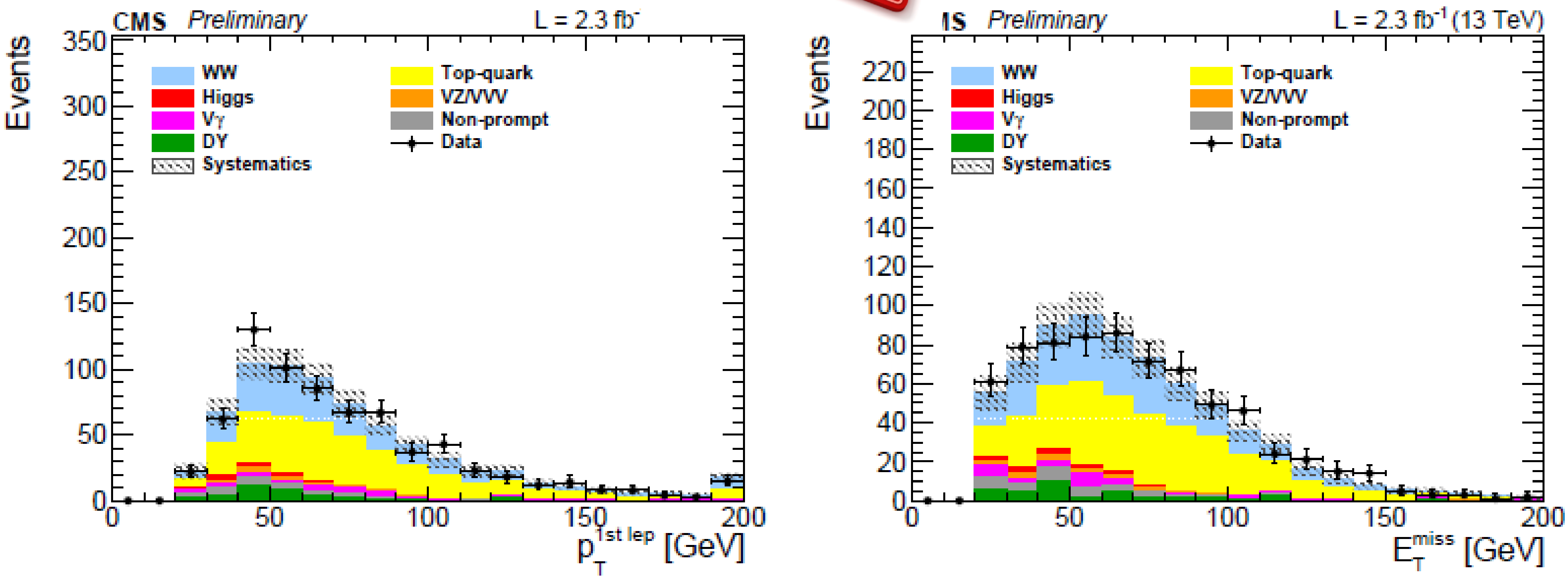




WW at 13 TeV (CMS)

CMS-PAS-SMP-16-006

- **Luminosity: 2.3 fb^{-1}**



Combination of the 0-jet and 1-jet categories:

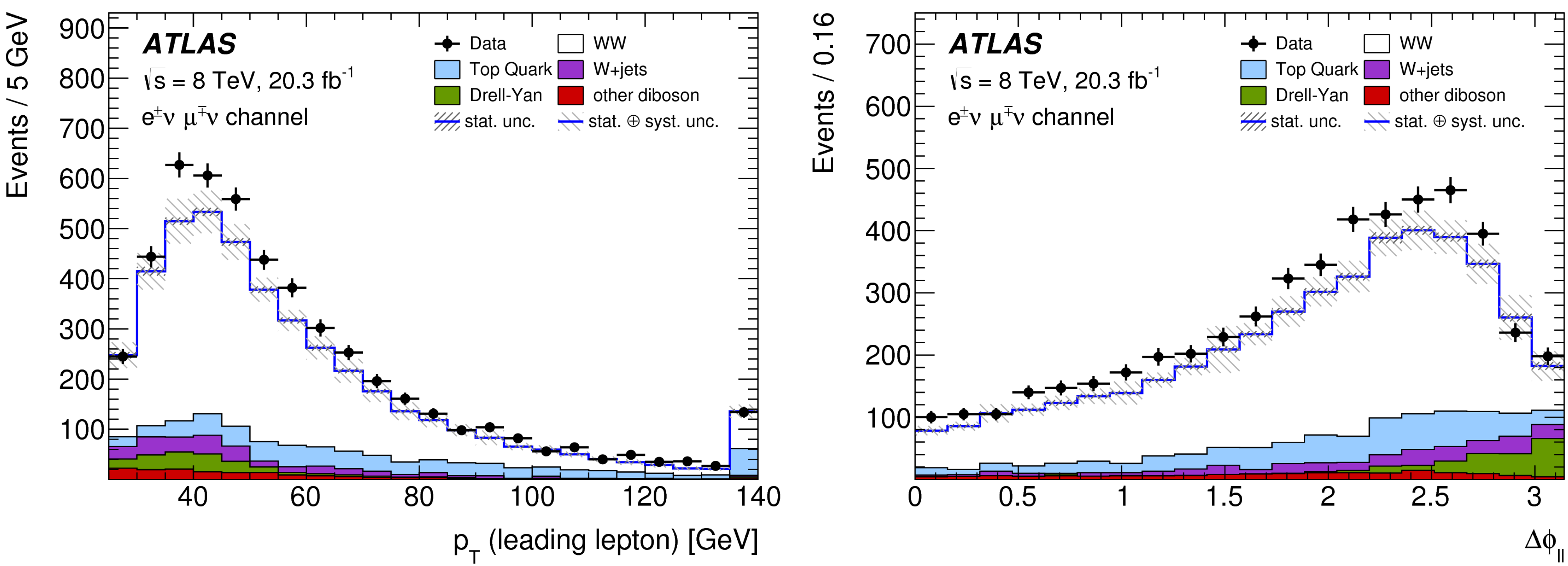
$$115.3 \pm 10.3\ (\text{stat.} + \text{syst.}) \pm 3.6\ (\text{lumi.})\ \text{pb}$$

$$\sigma^{\text{NNLO}}(pp \to W^+W^-) = 120.3 \pm 3.6\ \text{pb}$$

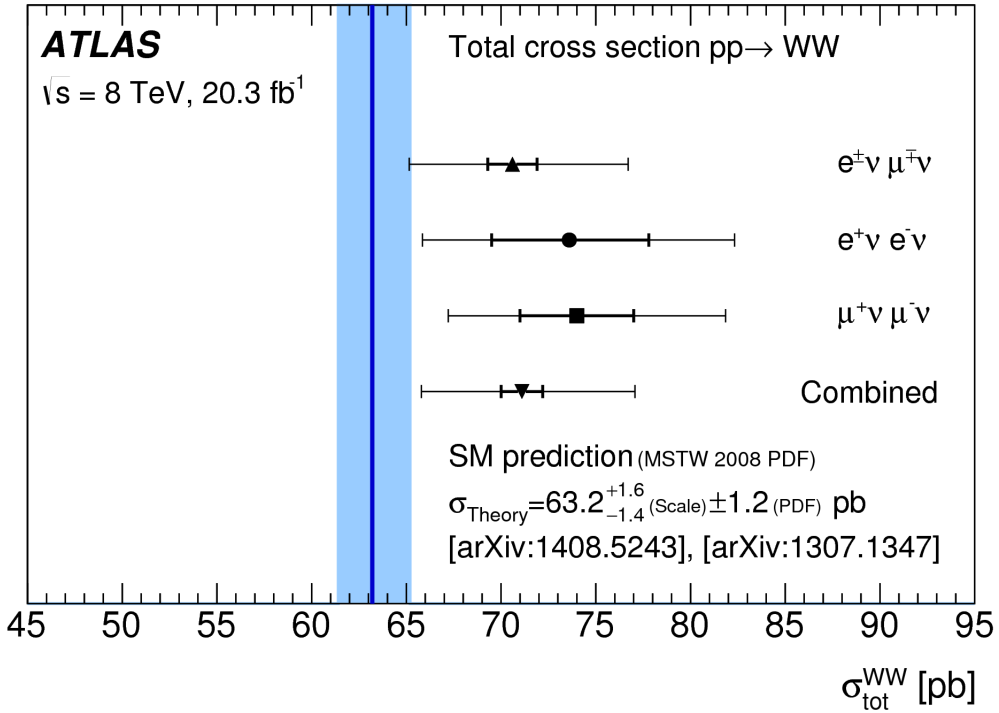
WW at 8 TeV (ATLAS)

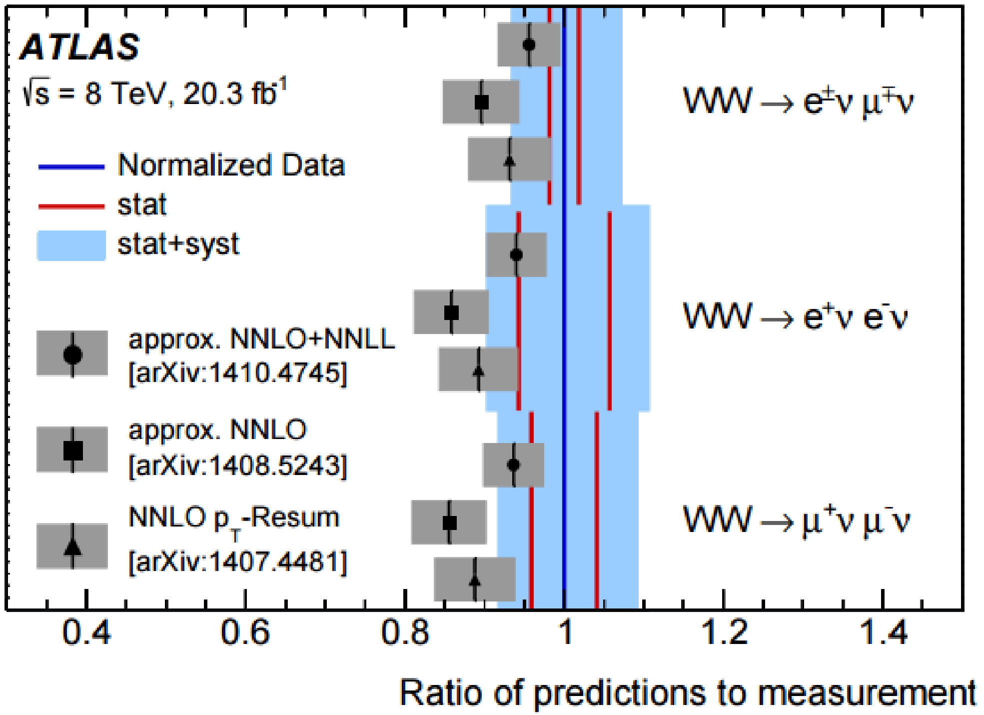
Event Selection:

- 2 opposite sign high pT leptons
- High Missing E_T
- Additional lepton veto, top veto, jet veto, Z veto, etc
- DY contribution extracted from a fit ($\Delta(\phi$ (missing p_T, missing E_T))
- Systematic dominant from modeling of signal efficiency (Jets)



WW at 8 TeV (ATLAS)





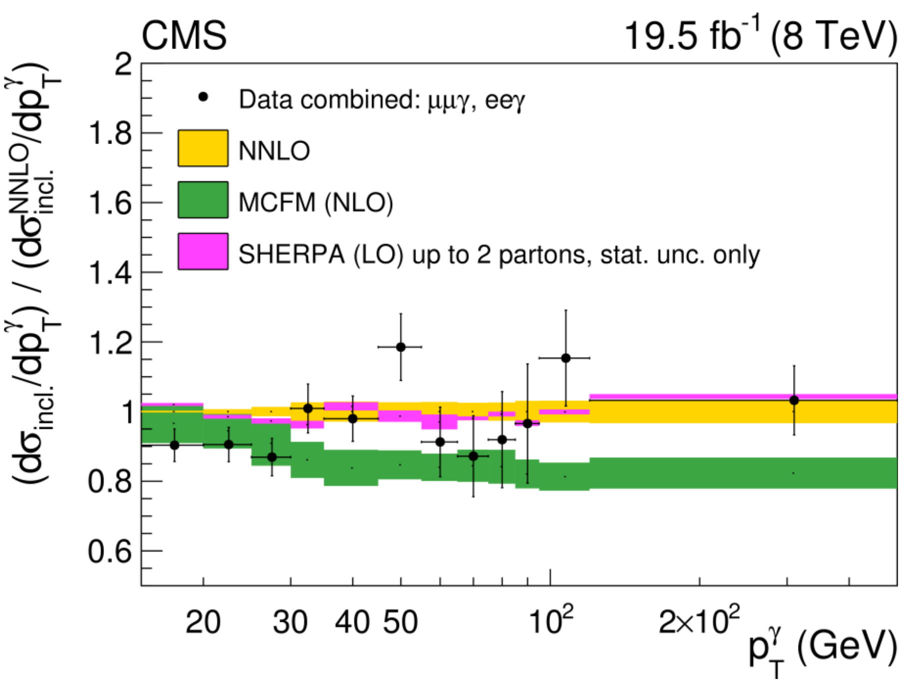
Consistent within 1.4 standard deviations wrt NNLO $63.2^{+1.6}_{-1.4}(\text{scale})\pm1.2(\text{PDF})$ pb.

$$71.1\pm1.1(\text{stat})\ ^{+5.7}_{-5.0}(\text{syst})\ \pm1.4(\text{lumi})\ \text{pb}.$$

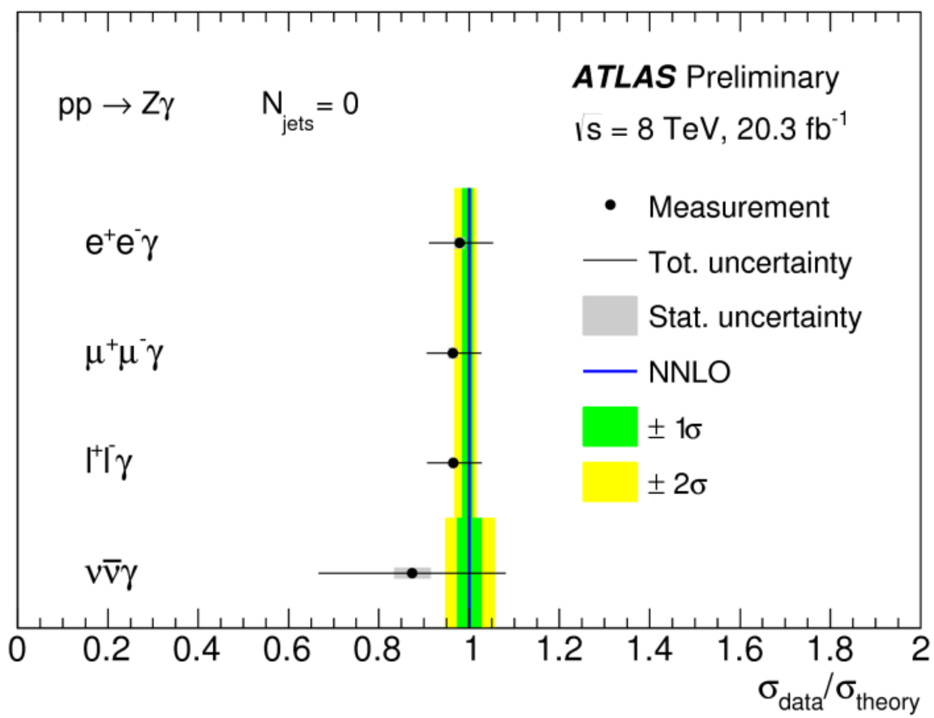
Z(ll)γ at 8 TeV

Two good leptons with pT > 20 GeV (CMS) and 25 GeV (ATLAS)

- Dilepton mass > 50 GeV (CMS) and 40 GeV (ATLAS)
- One good photon with ET > 15 GeV and ΔR(*l*, γ) > 0.7

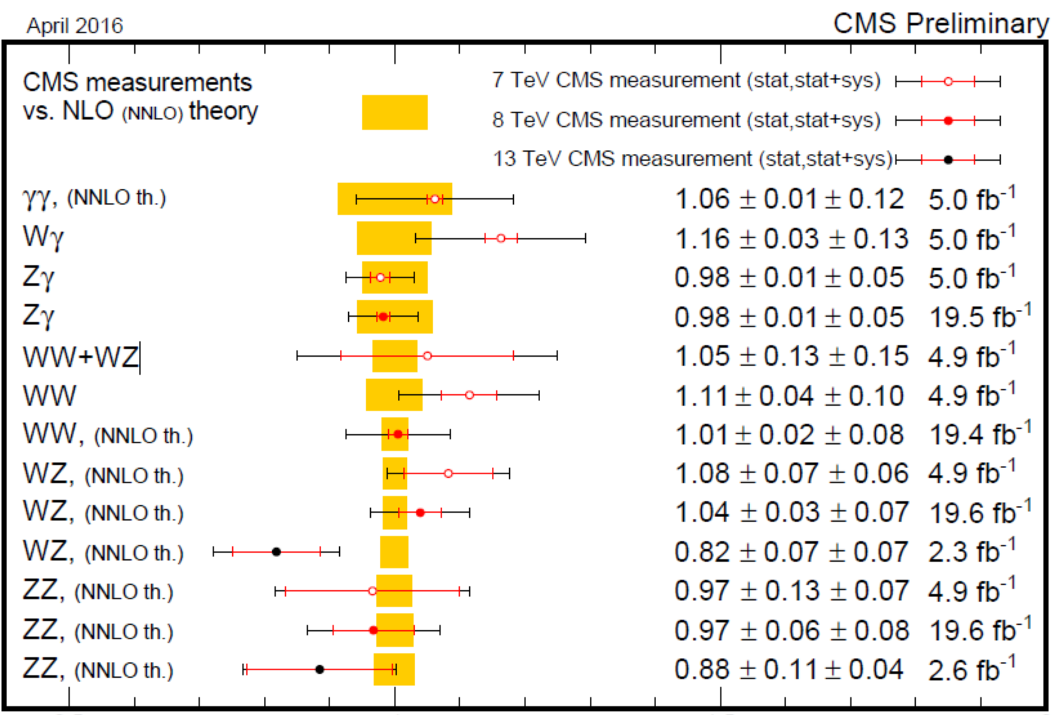


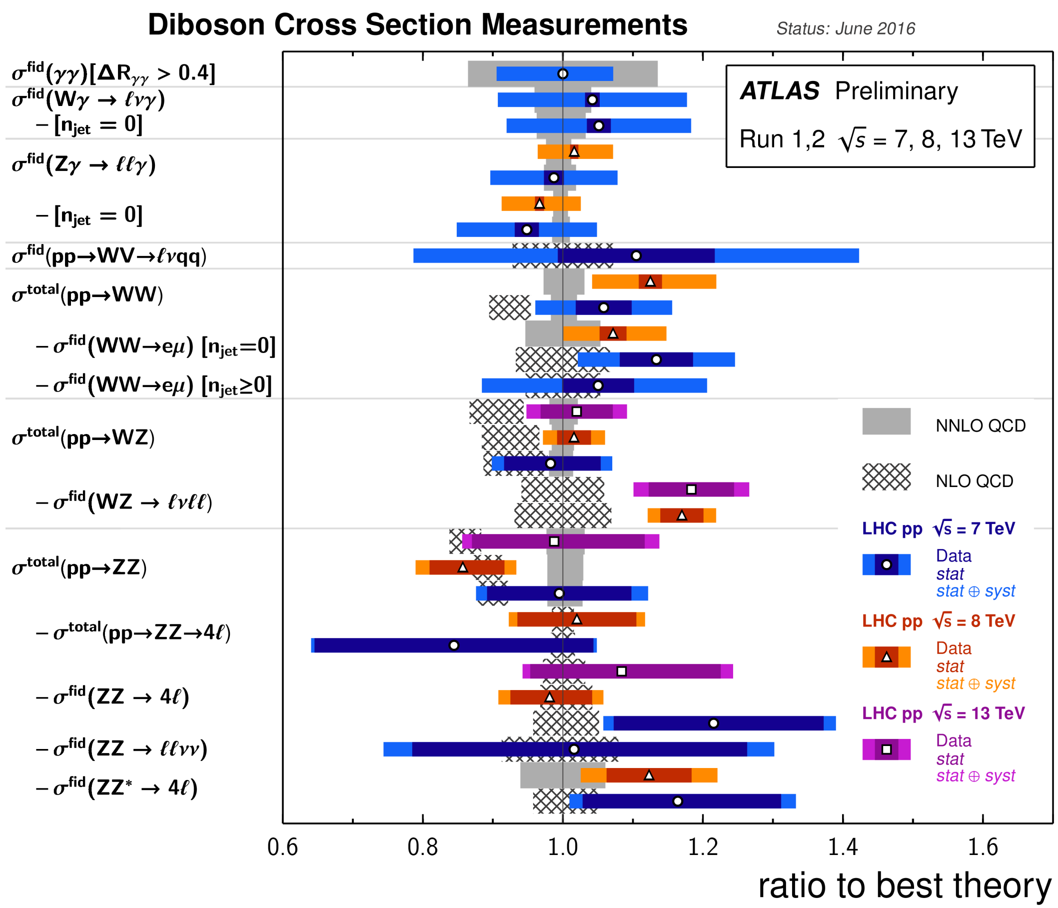
J. High Energy Phys. 04 (2015) 164



Phys. Rev. D 93, 112002 (2016)

Summary Tables: ATLAS & CMS





ATLAS: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

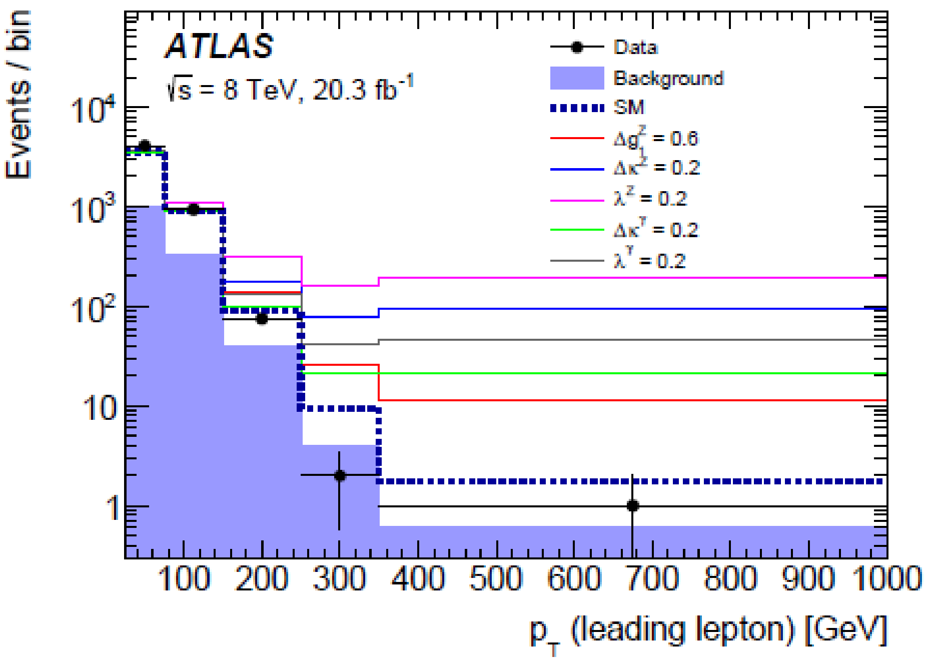
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

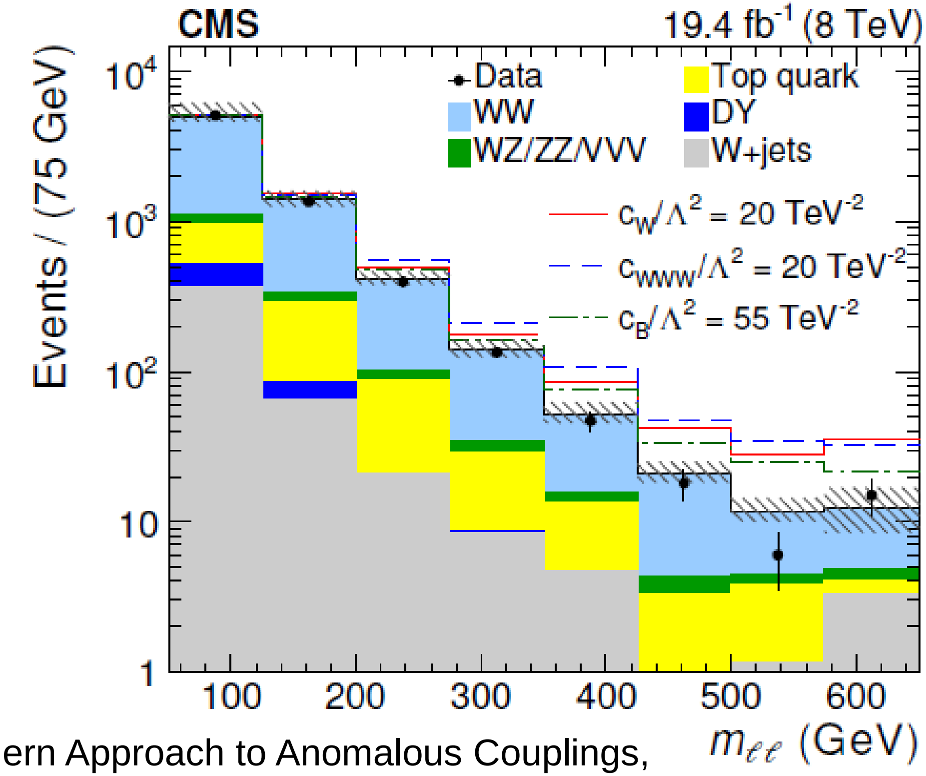
Anomalous Gauge Couplings

- **Anomalous couplings** result in an **increase of diboson cross section** at high energies:
  - Observables proportional to the **invariant mass of the diboson system** and the **boson p_T** are particularly sensitive (mVV, mV, p_TV …)
- Couplings are measured (or limits are set) by performing **binned fit** in single sensitive observable :
  - Sensitivity mostly in highest bins
- Limiting factors: **observed statistics in the tail** (primary) and **systematic and statistical uncertainty on the signal model** (secondary)
- Sensitivity depends on absolute size of **anomalous coupling signal**, absolute size of **expected background and uncertainties**
  - Binning is optimized to reach highest expected sensitivity
  - Fit is usually performed simultaneously on electron and muon channel
  - 95% CL limits are set

ATGC limit at WW channel

ATLAS: arXiv:1603.01702, submitted to JHEP, **CMS**: arXiv: arXiv:1507.03268 submitted to EPJC





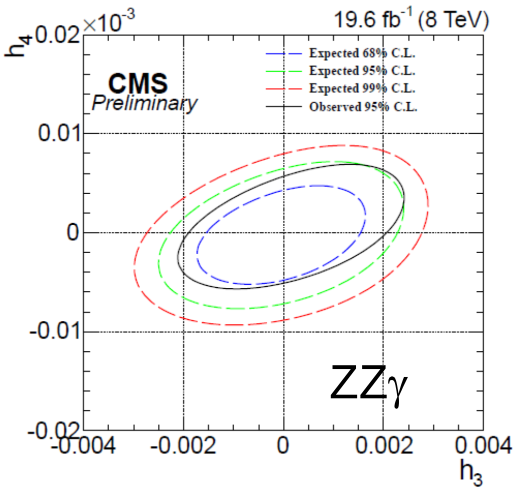
EFT Scenario (C. Degrandeet al., Effective Field Theory: A Modern Approach to Anomalous Couplings, Annals Phys. 335 (2013) 21–32, arXiv:1205.4231 [hep-ph]).

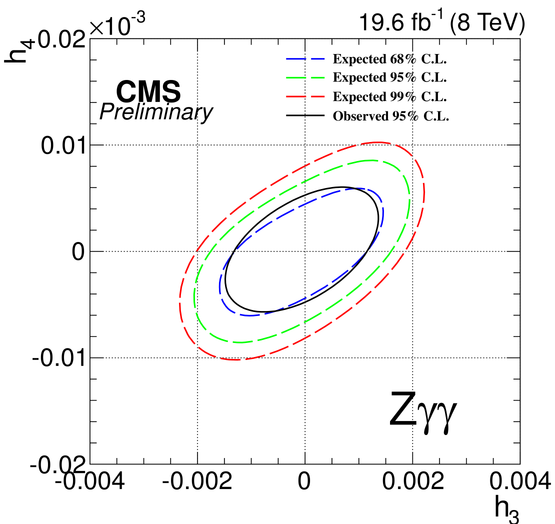
Parameter	ATLAS 95% CL interval	CMS 95% CL interval
C_{WWW}/Λ^2	[-4.61/4.60]	[-5.7, 5.9]
C_B/Λ^2	[-20.9, 26.3]	[-29.2, 23.9]
C_W/Λ^2	[-5.87, 10.54]	[-11.4, 5.4]

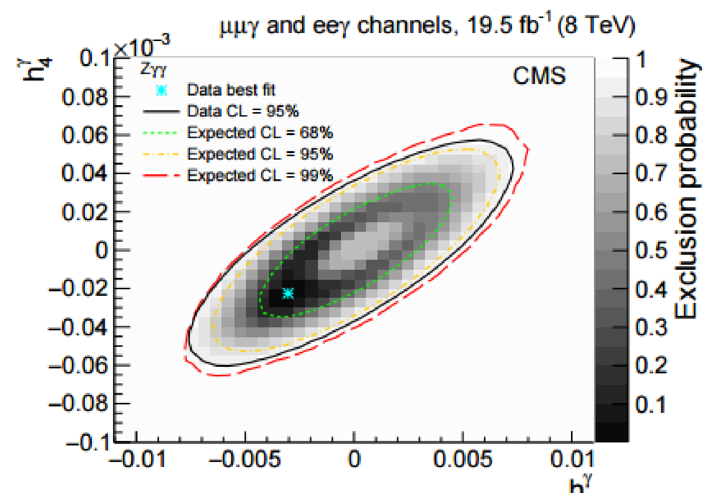
Limits ZZγ/Zγγ couplings (CMS)

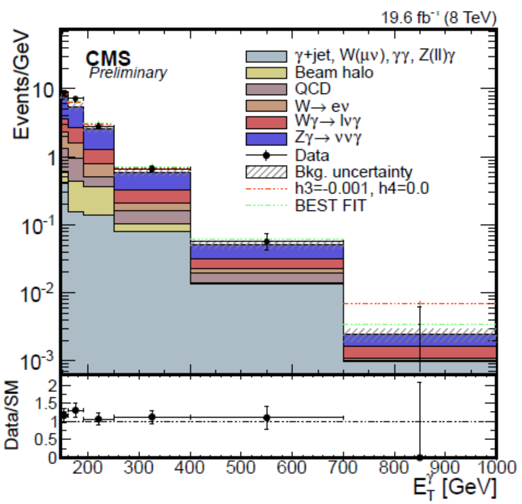
- Zγ → ννγ channel
- Zγ → llγ channel

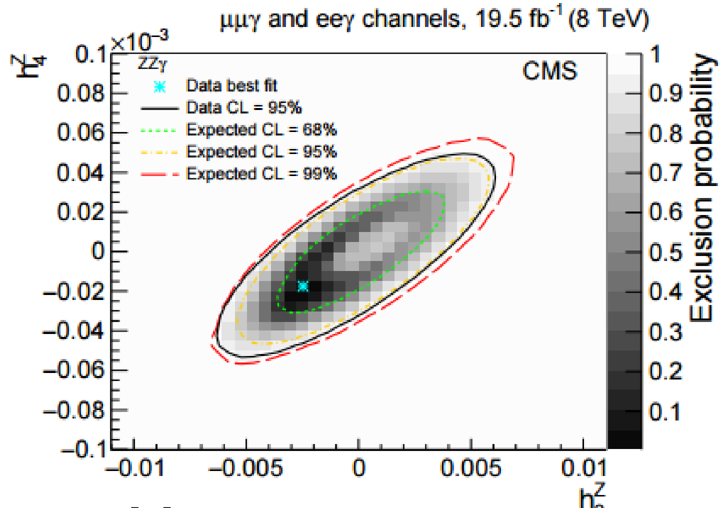
Best fit of the combined muon and electron





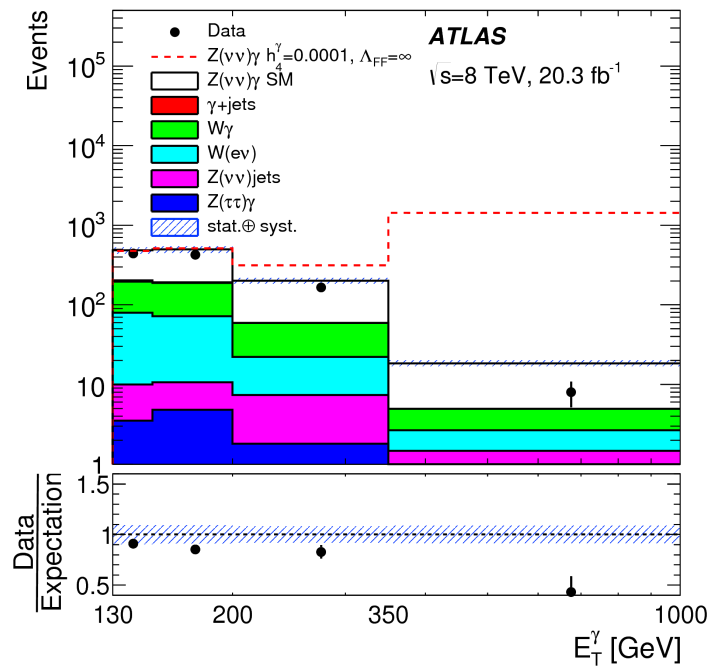


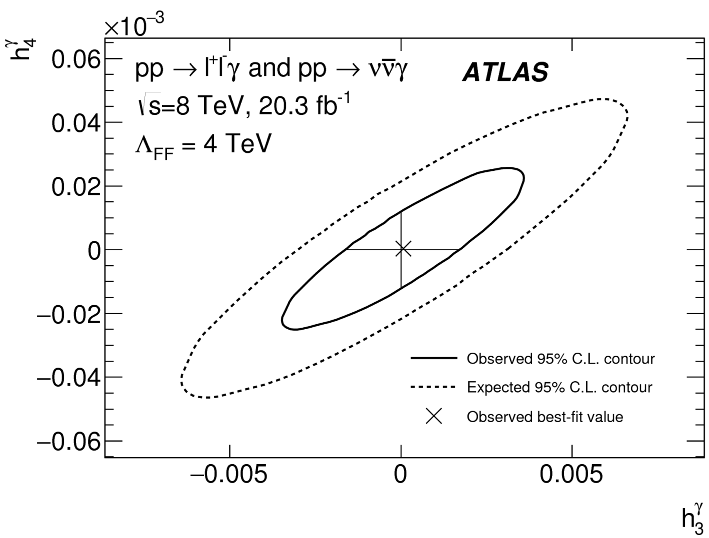


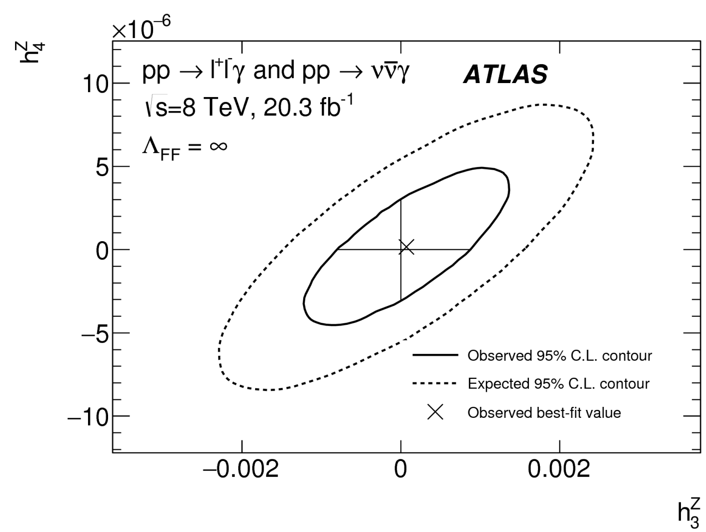


aTGC is consistent with 0

Limits ZZγ/Zγγ couplings (ATLAS)



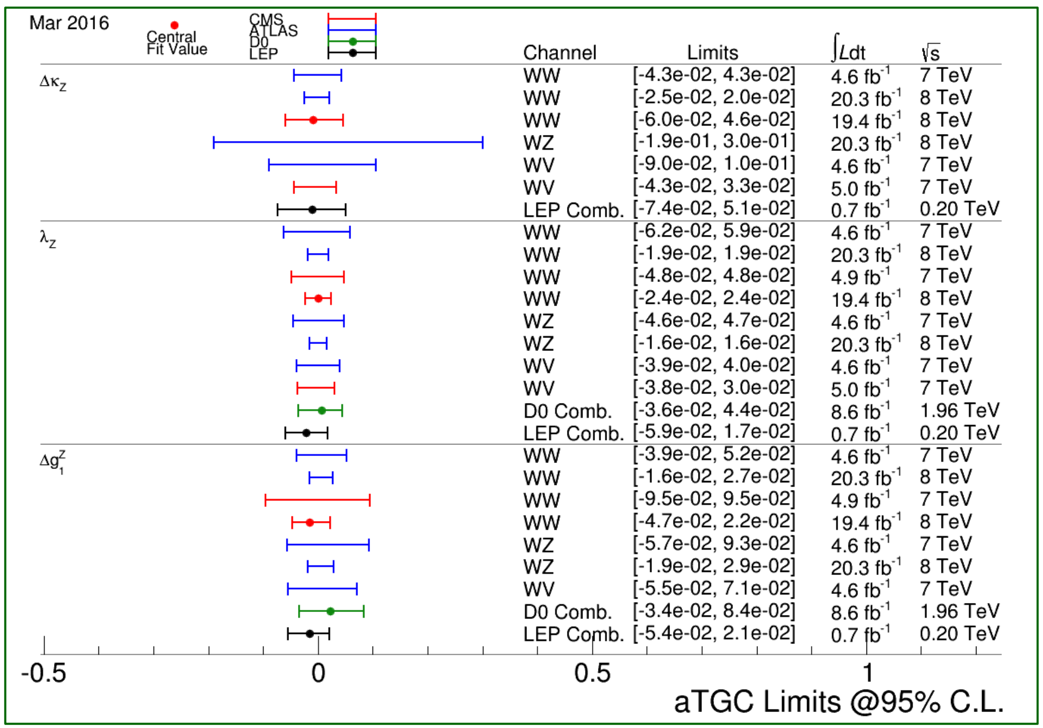




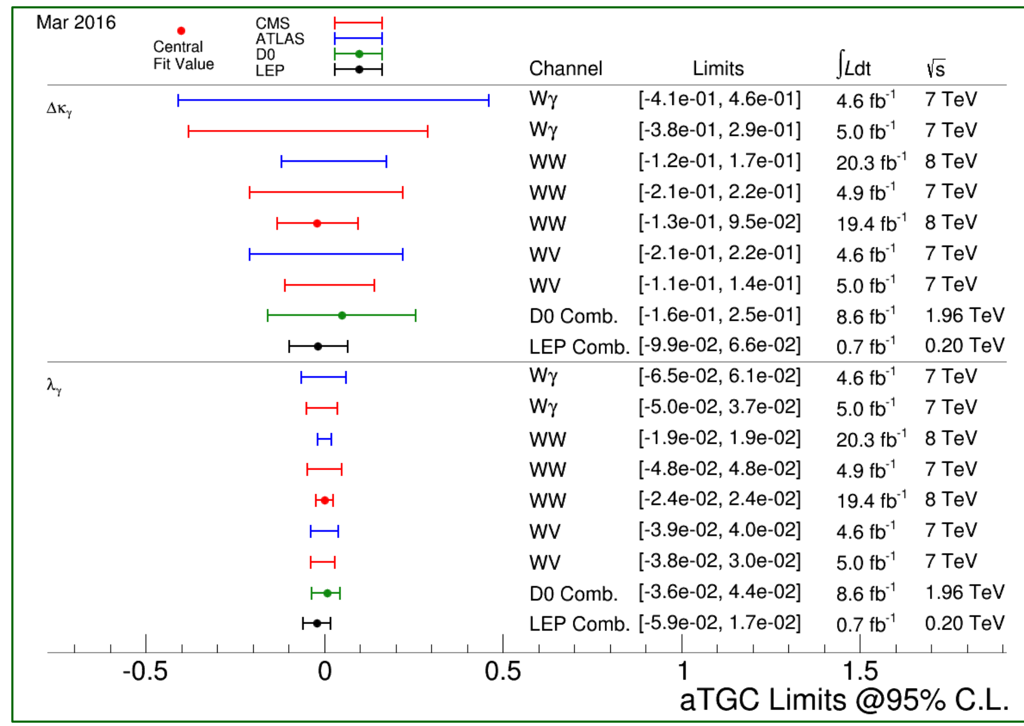
aTGC is consistent with 0

ATGC overview

WWZ



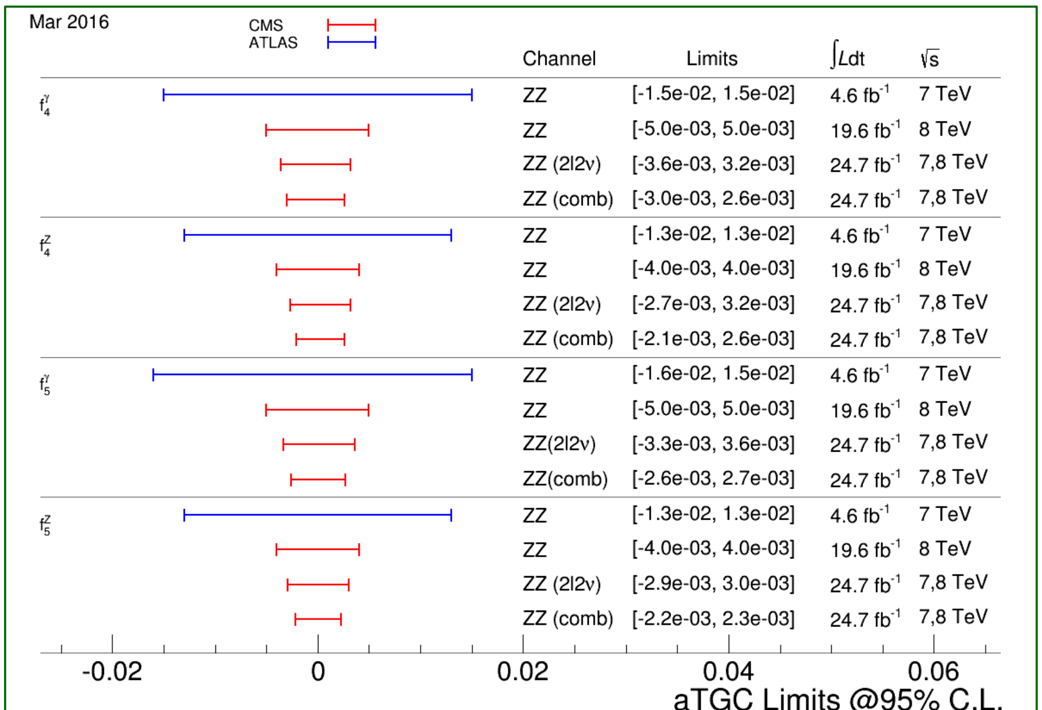
WWγ



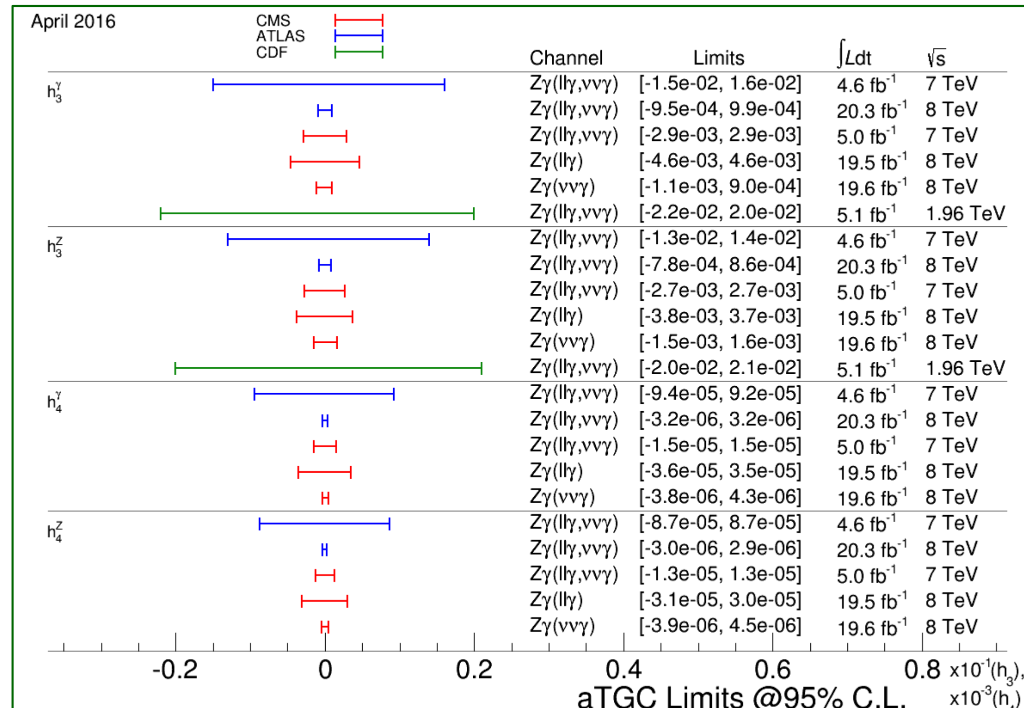
Neutral aTGC overview

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

aTGC ZZZ and ZγZ



aTGC Zγγ and ZZγ



Summary

- Very good performance of the LHC has provided good data for both Run I and Run II

- Several full analysis results from Run I at 8 TeV haven been published

- Some diboson cross sections have already been measured in Run II

  Differences when comparing with NLO predictions but good agreement with NNLO predictions.

- Anomalous couplings search shows no deviation from the SM

Thanks for your attention!

Backup

ZZ at 13 TeV (CMS)

- Systematic uncertainties

Uncertainty	$Z \to 4\ell$	$ZZ \to 4\ell$
ID efficiency	2–6%	0.4–0.9%
Isolation efficiency	1–6%	0.3–1.1%
Trigger efficiency	2–4%	2%
MC statistics	1–2%	1%
Background	0.7–1.4%	0.7–2%
Pileup	0.4–0.8%	0.2%
PDF	1%	1%
Scale	1%	1%
Luminosity	2.7%	2.7%

ZZ at 13 TeV (CMS)

- Fiducial xs:
-
-

Cross section measurement	Fiducial cuts
Common requirements	$p_T^{\ell_1} > 20$ GeV, $p_T^{\ell_2} > 10$ GeV, $p_T^{\ell_{3,4}} > 5$ GeV, $\left|\eta^\ell\right| < 2.5$ GeV, $m_{\ell^+\ell^-} > 4$ GeV (any $\ell\ell$ pair)
$Z \to \ell\ell\ell'\ell'$	$m_{Z_1} > 40$ GeV $80 < m_{\ell\ell\ell'\ell'} < 100$ GeV
$ZZ \to \ell\ell\ell'\ell'$	$60 < m_{Z_1}, m_{Z_2} < 120$ GeV

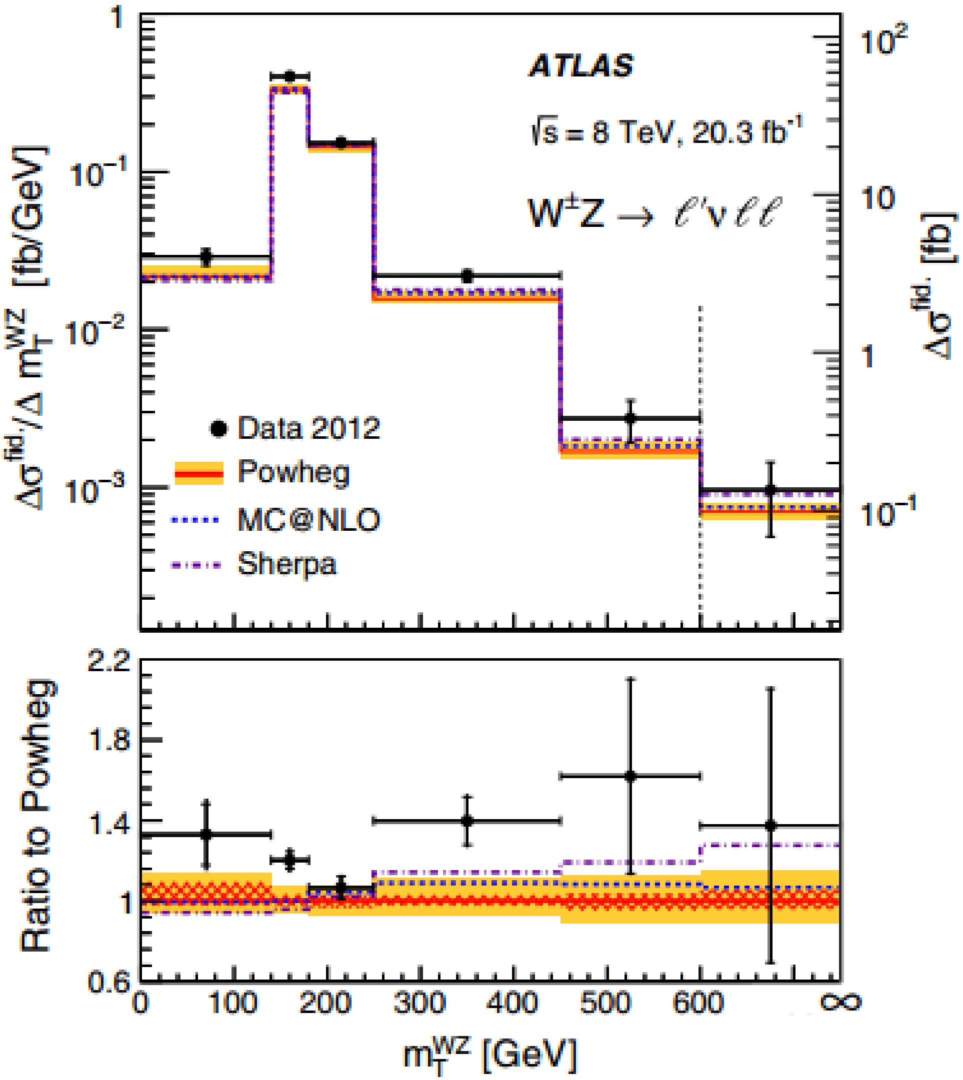
$$\sigma_{\text{fid}}(\text{pp} \to \text{Z} \to \ell\ell\ell'\ell') = 30.5^{+5.2}_{-4.7}\,(\text{stat})^{+1.8}_{-1.4}\,(\text{syst}) \pm 0.8\,(\text{lum})\text{ fb},$$

$$\sigma_{\text{fid}}(\text{pp} \to \text{ZZ} \to \ell\ell\ell'\ell') = 34.8^{+4.6}_{-4.2}\,(\text{stat})^{+1.2}_{-0.8}\,(\text{syst}) \pm 0.9\,(\text{lum})\text{ fb}.$$

WZ at 8 TeV (ATLAS)

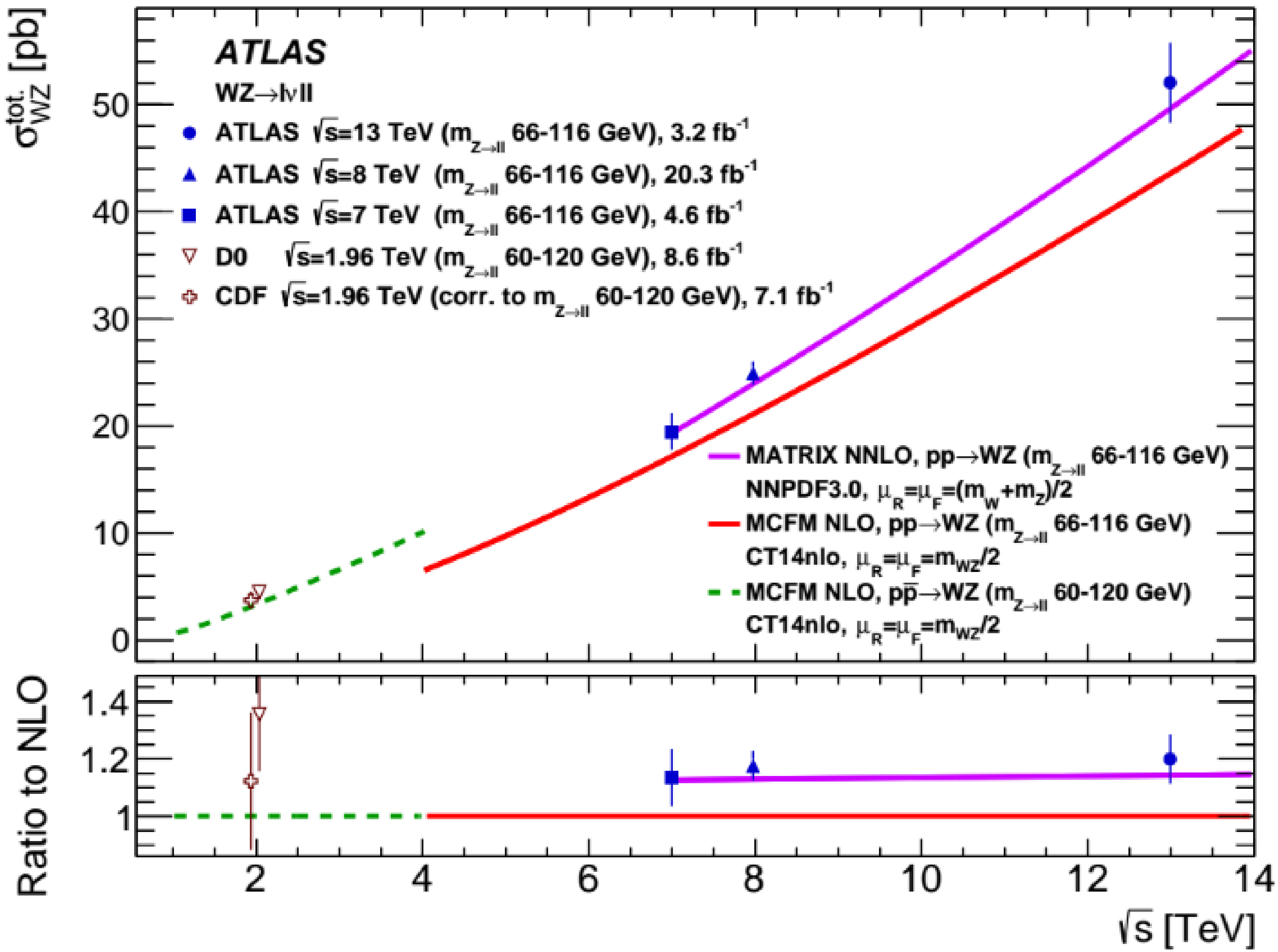
Source	eee	μee	$e\mu\mu$	$\mu\mu\mu$	Combined
	Relative uncertainties [%]				
e energy scale	0.8	0.4	0.4	0.0	0.3
e id. efficiency	2.9	1.8	1.0	0.0	1.0
μ momentum scale	0.0	0.1	0.1	0.1	0.1
μ id. efficiency	0.0	0.7	1.3	2.0	1.4
E_T^{miss} and jets	0.3	0.2	0.2	0.1	0.3
Trigger	0.1	0.1	0.2	0.3	0.2
Pileup	0.3	0.2	0.2	0.1	0.2
Misid. leptons background	2.9	0.9	3.1	0.9	1.3
ZZ background	0.6	0.5	0.6	0.5	0.5
Other backgrounds	0.7	0.7	0.7	0.7	0.7
Uncorrelated	0.7	0.6	0.5	0.5	0.3
Total systematics	4.5	2.6	3.7	2.5	2.4
Luminosity	2.2	2.2	2.2	2.2	2.2
Statistics	6.2	5.4	5.3	4.7	2.7
Total	8.0	6.3	6.8	5.7	4.2

WZ at 8 TeV (ATLAS)

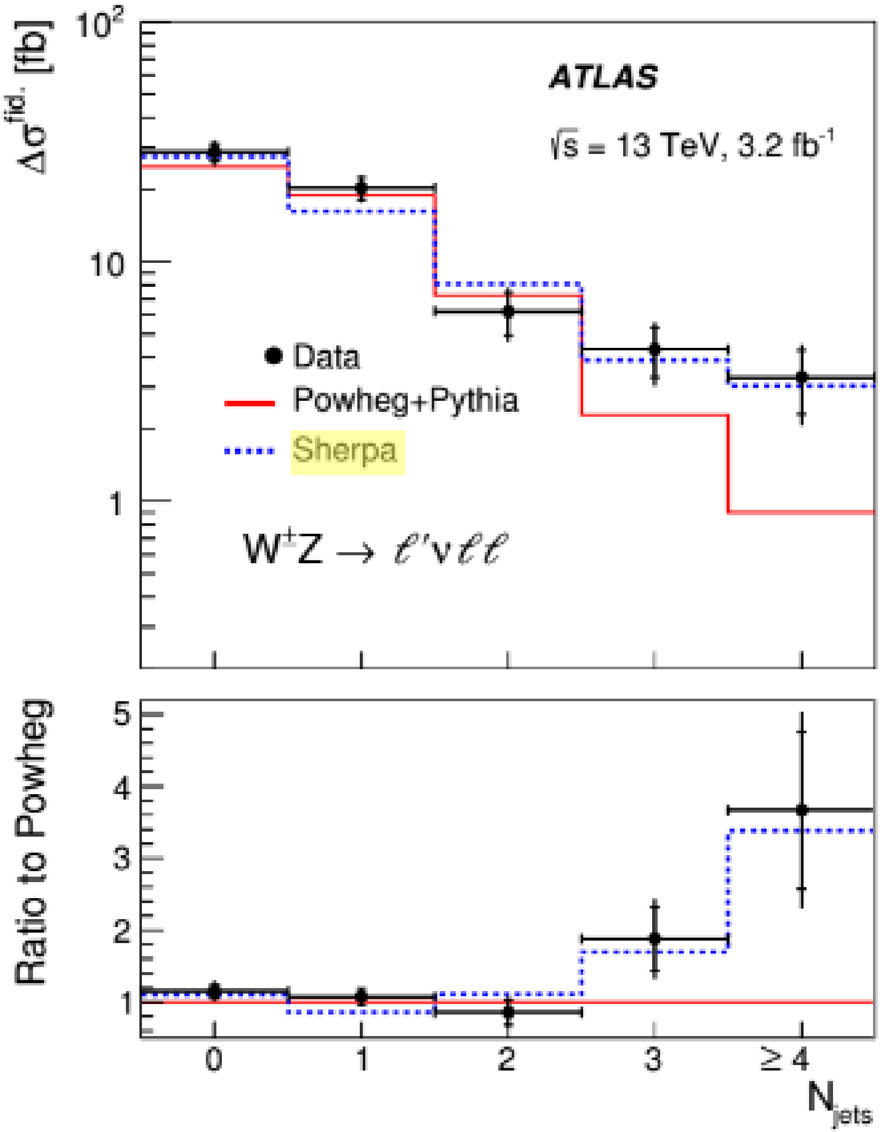


WZ at 13 TeV (ATLAS)

Comparison of W±Z cross section measurements at various centre-of-mass energies with Standard Model expectations.



WZ at 13 TeV (ATLAS)



13 TeV WZ at CMS

Decay channel	N_{WZ}^{exp}	Background Non-prompt	Background Prompt	Total expected	Observed
eee	$35.88 \pm 0.63^{+1.84}_{-1.78}$	$10.64 \pm 1.73^{+3.19}_{-2.46}$	$6.08 \pm 0.59^{+0.73}_{-0.66}$	$52.60 \pm 1.93^{+3.91}_{-3.29}$	49
eeμ	$50.23 \pm 0.77^{+2.41}_{-2.35}$	$14.83 \pm 3.56^{+3.88}_{-2.98}$	$7.57 \pm 0.47^{+1.00}_{-0.87}$	$72.63 \pm 3.67^{+4.89}_{-4.14}$	78
$\mu\mu$e	$56.02 \pm 0.80^{+2.47}_{-2.42}$	$21.56 \pm 3.21^{+5.01}_{-3.86}$	$8.43 \pm 0.55^{+1.17}_{-1.04}$	$86.01 \pm 3.35^{+5.90}_{-4.89}$	83
$\mu\mu\mu$	$83.96 \pm 0.99^{+3.35}_{-3.27}$	$20.16 \pm 4.91^{+6.05}_{-4.65}$	$11.13 \pm 0.49^{+1.47}_{-1.28}$	$115.25 \pm 5.03^{+7.30}_{-6.09}$	108
Total	$226.09 \pm 1.61^{+9.46}_{-9.25}$	$67.19 \pm 7.08^{+14.43}_{-11.10}$	$33.21 \pm 1.05^{+4.32}_{-3.80}$	$326.50 \pm 7.33^{+18.66}_{-15.90}$	318

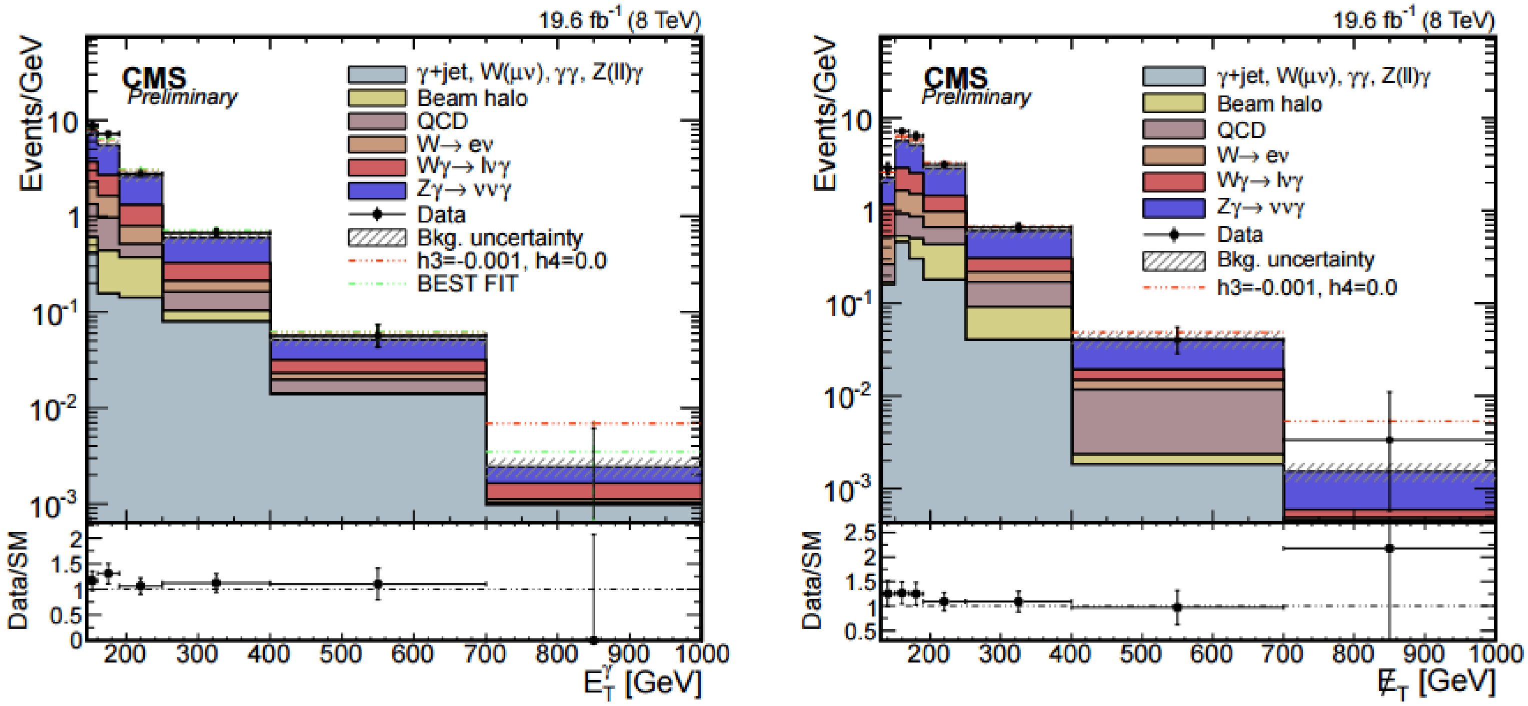
Zγ at 8 TeV CMS

Zγ → ννγ selection:

- 1central (|*η*|<*1.44*) high *pT*(>*145* GeV) photon
- *ETmiss>140* GeV
- Large W(**ℓνγ**) BKG from MC but checked in CR.

- Measurements in good agreement with NNLO predictions (50.0 + 2.4 − 2.2 fb.):

$$52.7 \pm 2.1(\text{stat.}) \pm 6.4(\text{syst.}) \pm 1.4(\text{lumi.})\ \text{fb}$$



8 TeV WW CMS

Process	0-jet category		1-jet category	
	Different-flavor	Same-flavor	Different-flavor	Same-flavor
Total bkg.	1179 ± 123	643 ± 73	1954 ± 168	749 ± 133
W^+W^- + Total bkg.	4857 ± 302	2124 ± 134	3128 ± 217	1162 ± 142
Data	4847	2233	3114	1198