Studies of diboson production at LHC

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On behalf of the CMS and ATLAS Collaborations

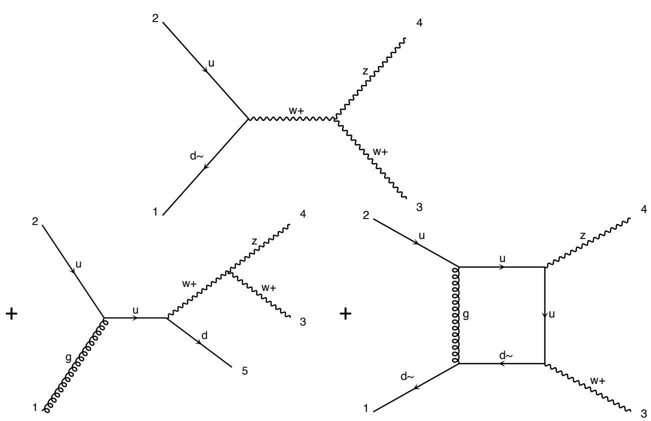
Importance of diboson measurements

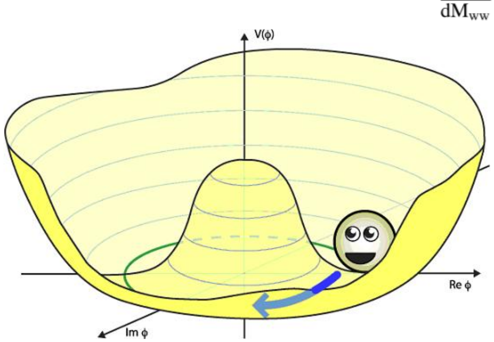
So far New Physics has not been directly seen at the LHC

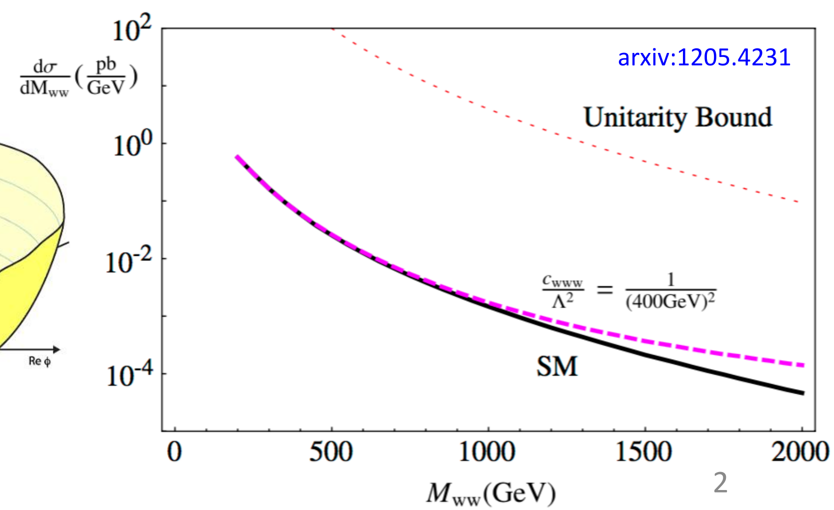
→ Precision measurements are more important then ever !

- Need to understand the perturbative higher order corrections
- Understand the nature of electroweak symmetry breaking (EWSB)
- Looking for indirect signatures of New Physics above directly reachable energy

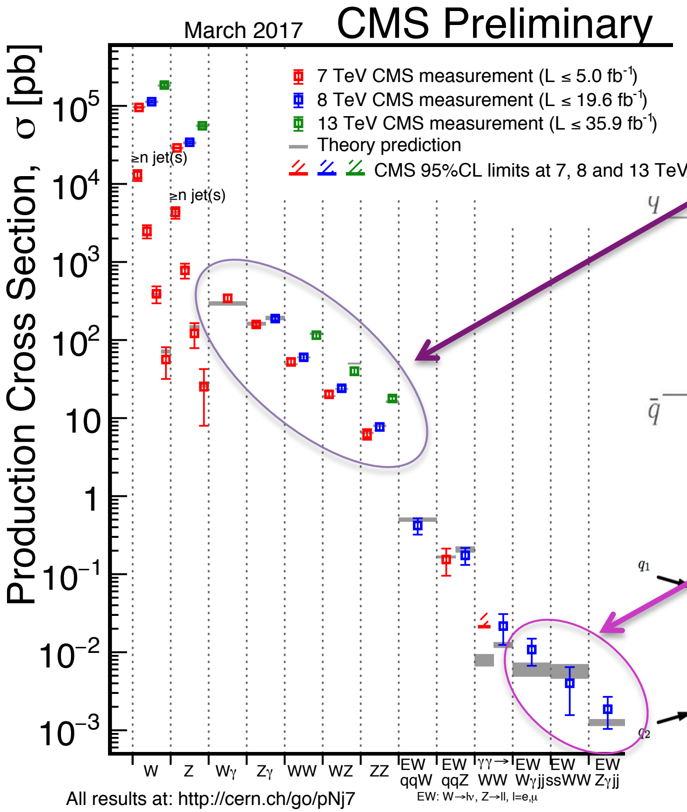
Diboson measurements





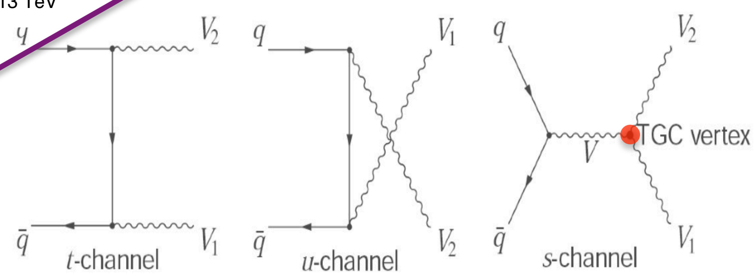


Diboson cross section at LHC



Diboson production cross section: 5 orders of magnitude

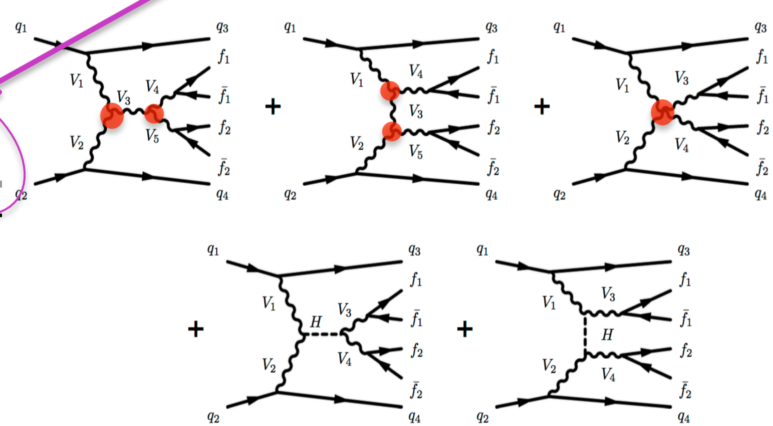
- **5-300 pb: Inclusive (QCD) diboson production**



Probing:

- higher order QCD (and QED) perturbative corrections
- SM gauge structure: triple gauge couplings (TGC)

- **< 0.01 pb: Electroweak (QED) diboson production**



Probing:

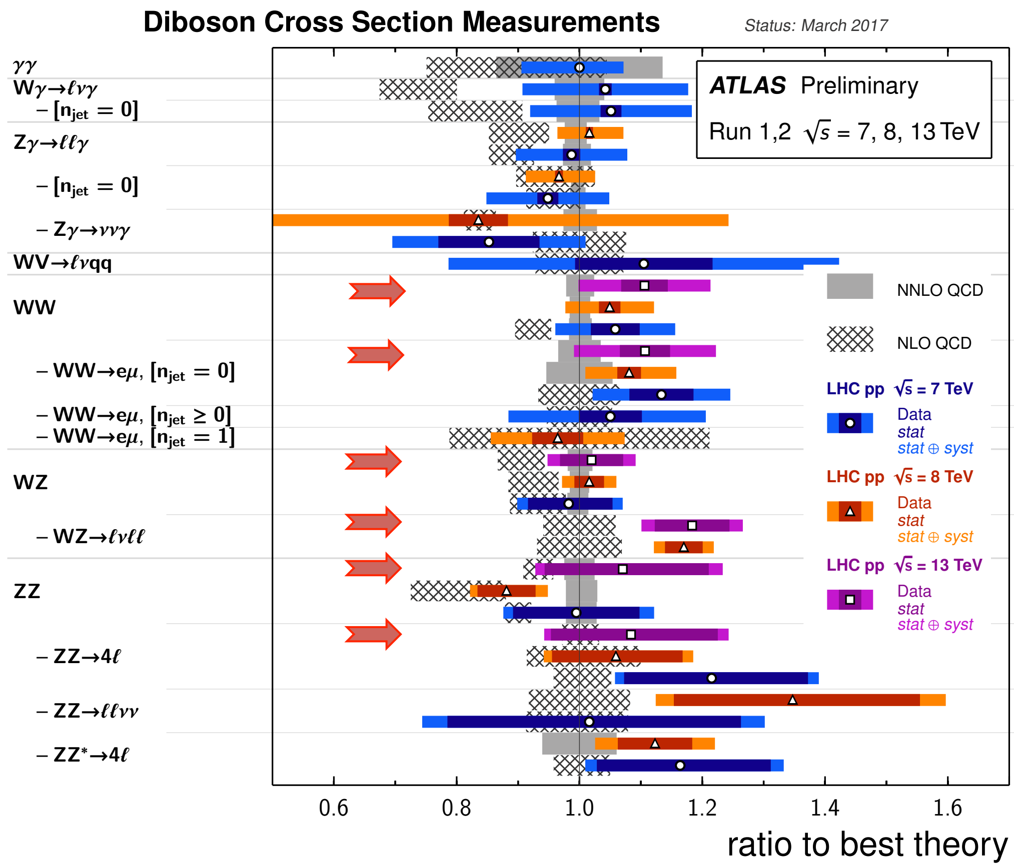
- higher order QED perturbative corrections
- the nature of EWSB via EWK vector boson scattering production
- SM gauge structure: triple and quartic gauge couplings (TGC and QGC)

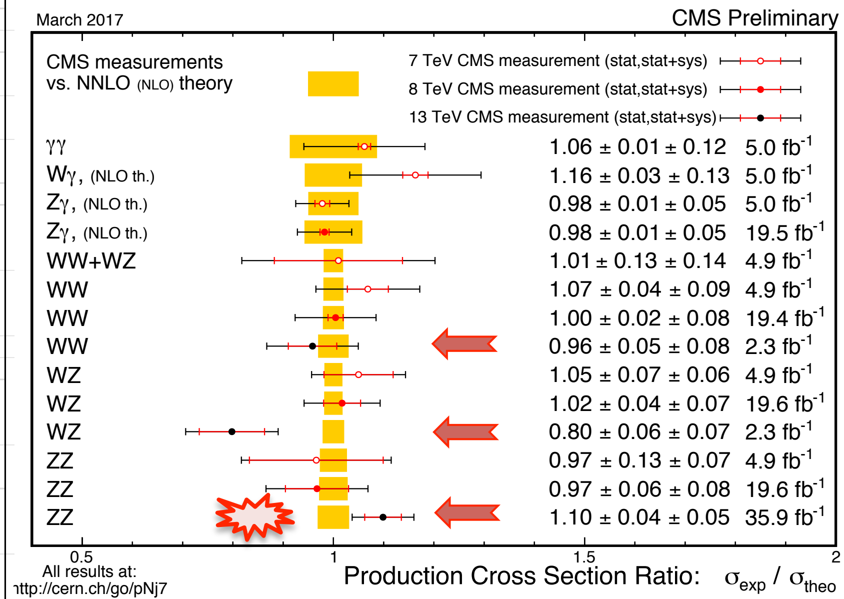
One of the consequences of non-Abelian gauge theories are the self-interactions of gauge bosons

- Diboson measurements are probing weak boson self-interactions

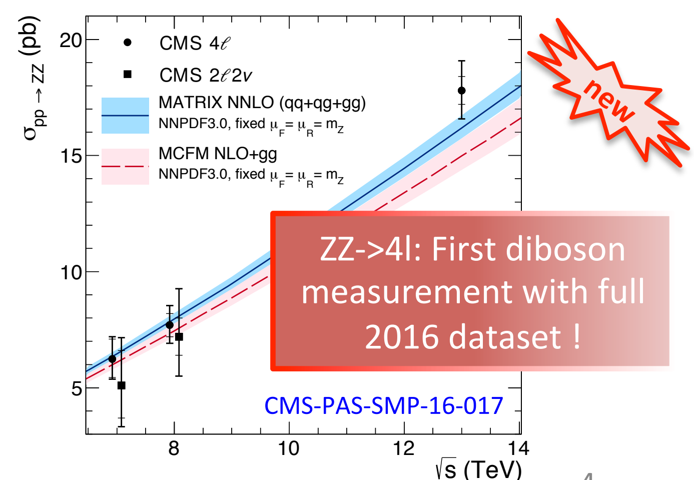
Inclusive diboson cross section measurement summary

Several measurements with 13 TeV data already available !





All diboson inclusive cross section measurements are already systematics dominated !



ZZ->4l: First diboson measurement with full 2016 dataset !

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

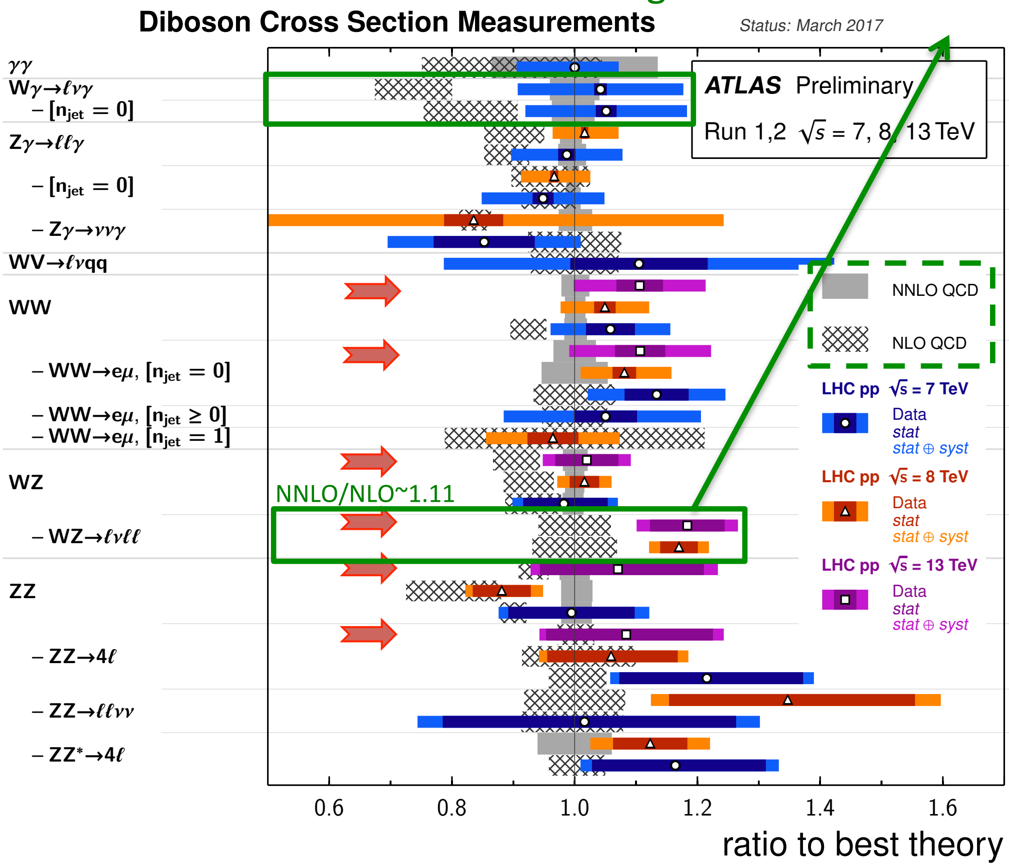
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

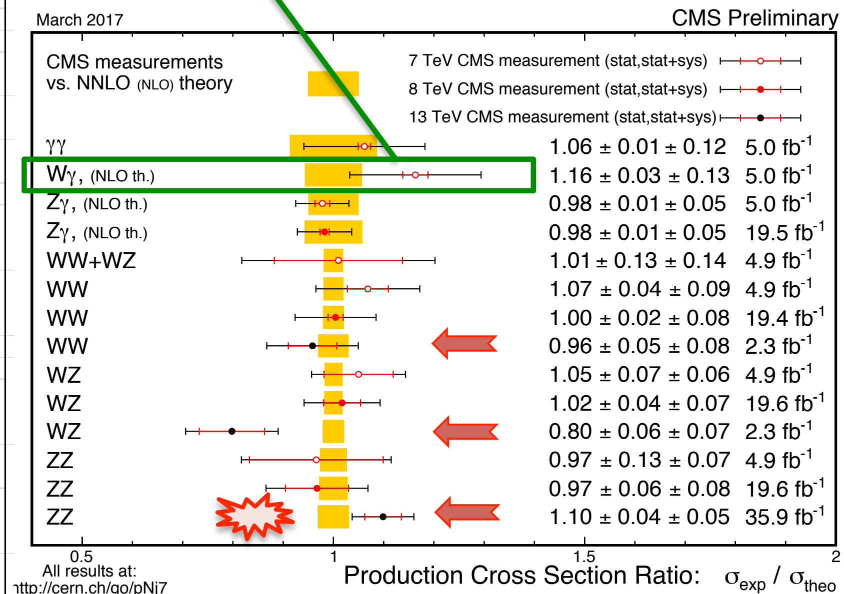
Inclusive diboson cross section measurement summary

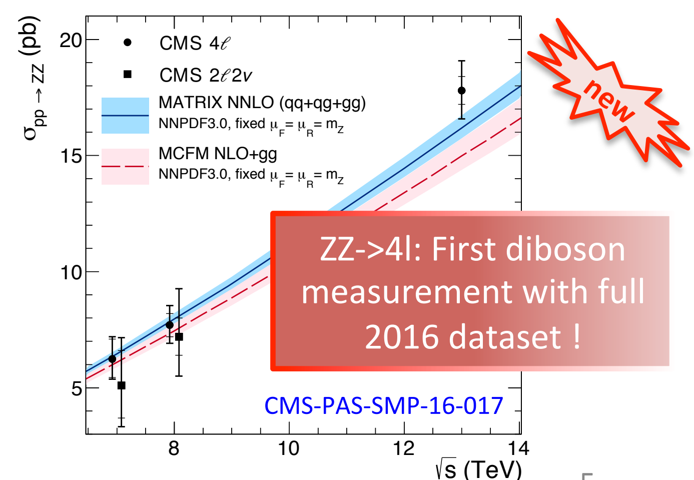
arXiv.1504.01330, arXiv: 1604.08576

In agreement with NNLO QCD calculation

Several measurements with 13 TeV data already available !







ZZ->4l: First diboson measurement with full 2016 dataset !

Good agreement with best theory calculation (NNLO or NLO QCD, LO QED) for both ATLAS and CMS!

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

Inclusive diboson cross section measurement summary

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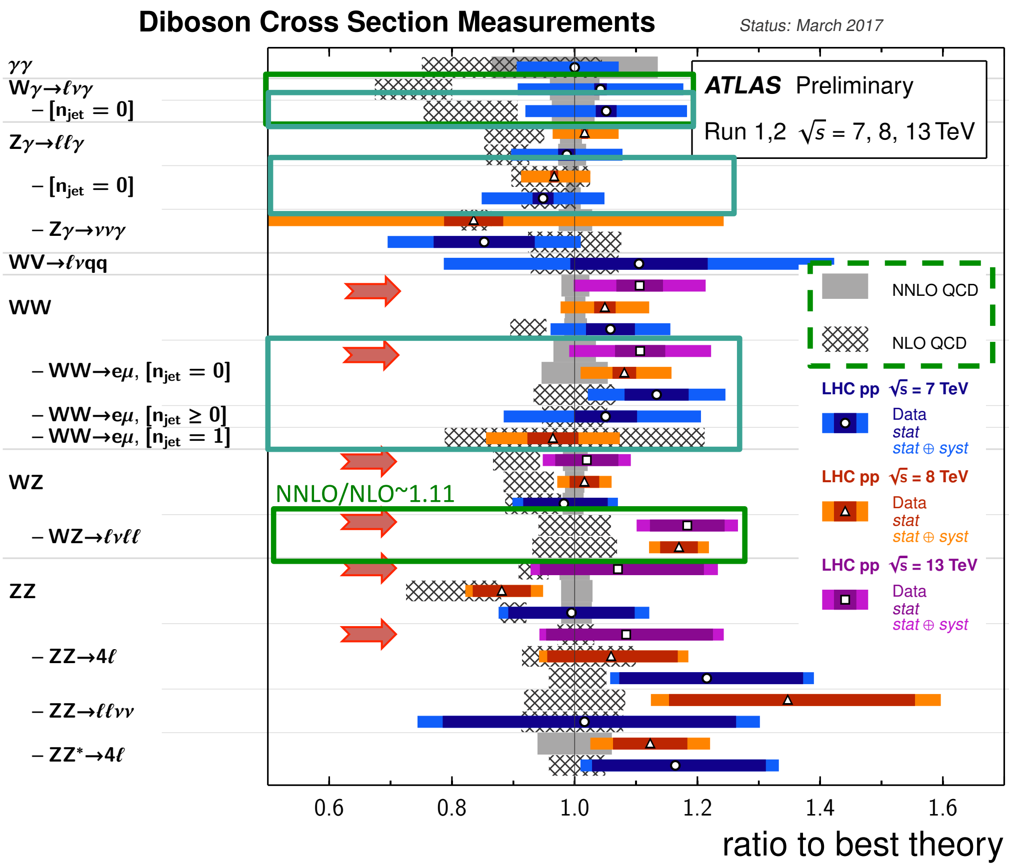
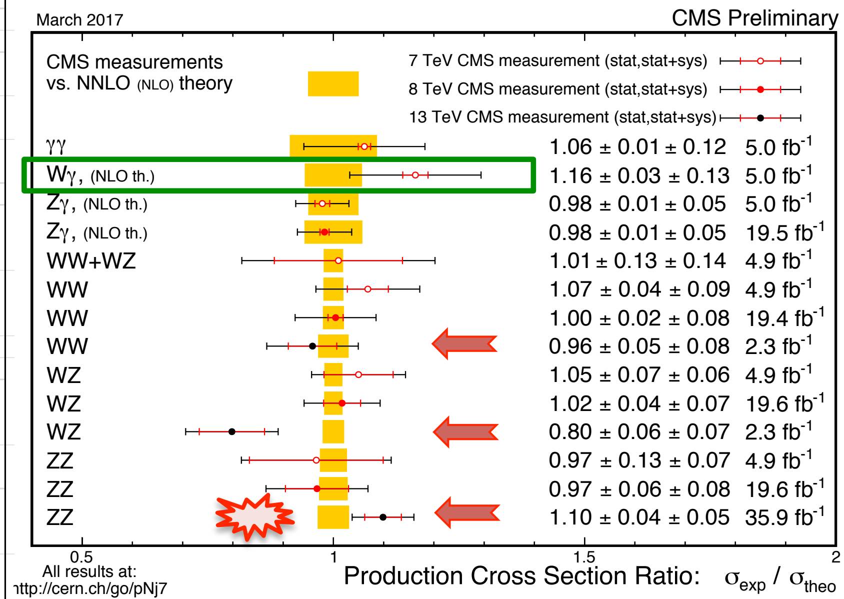
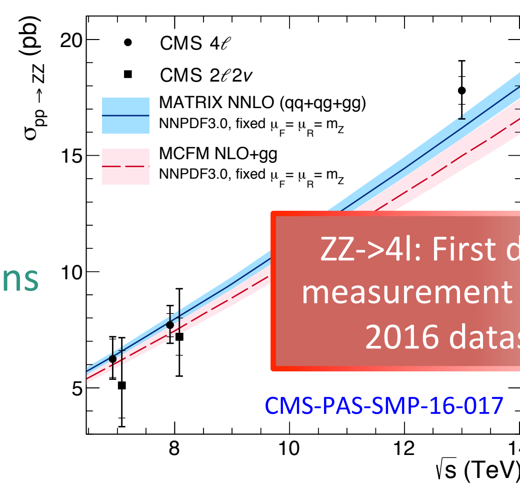




Jet related observables allow direct probe of higher order corrections

- Measurements of cross section in jet bins (exclusive)

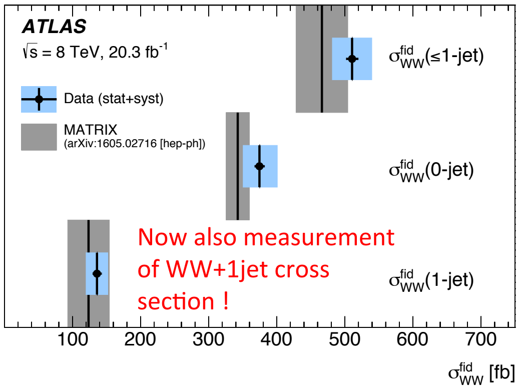


ZZ->4l: First diboson measurement with full 2016 dataset !

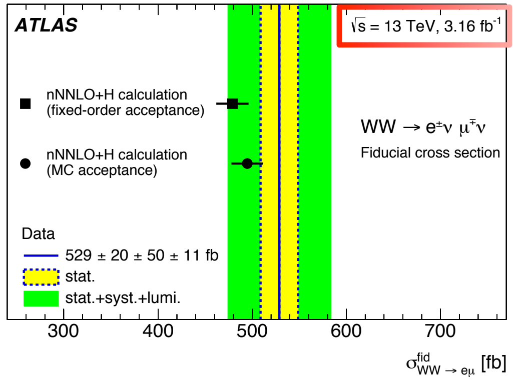
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

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

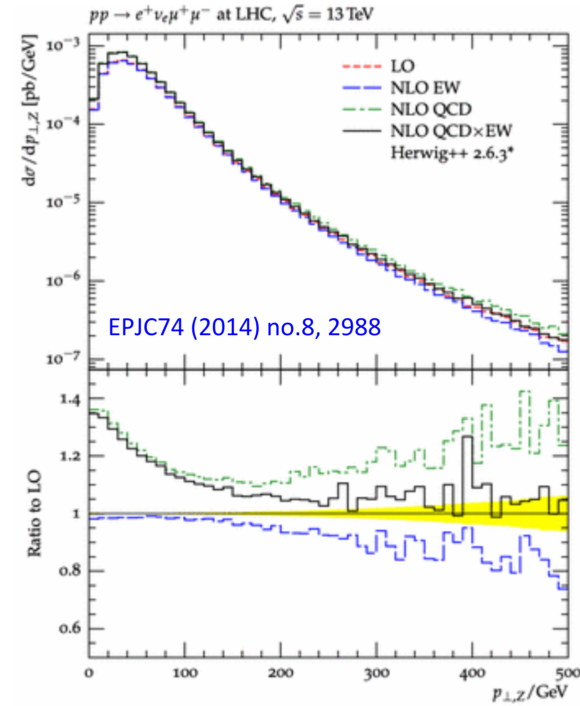
Diboson measurements:
importance of higher order corrections



PLB 763 (2016) 114



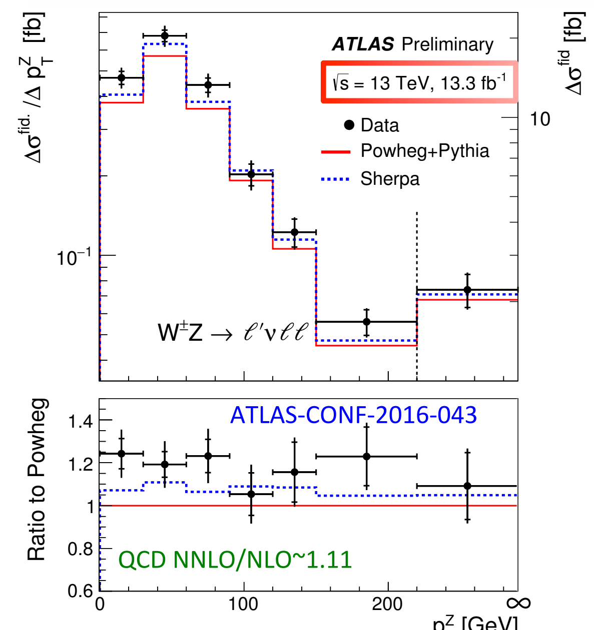
arXiv:1702.04519



Due to large ttbar background WW measurement is performed applying a jet veto (0- or 1-jet events only)

- Veto enhances the contribution of the soft gluons to the pT(WW) distribution
- Jet veto efficiency is sensitive to higher-order QCD corrections
  → Large theoretical uncertainty!

Expecting sizable effect from NNLO QCD and NLO QED in high pT/ mass of the diboson system



Jet related observables allow direct probe of higher order corrections

- Measurements of cross section in jet bins (exclusive)
- Differential measurements

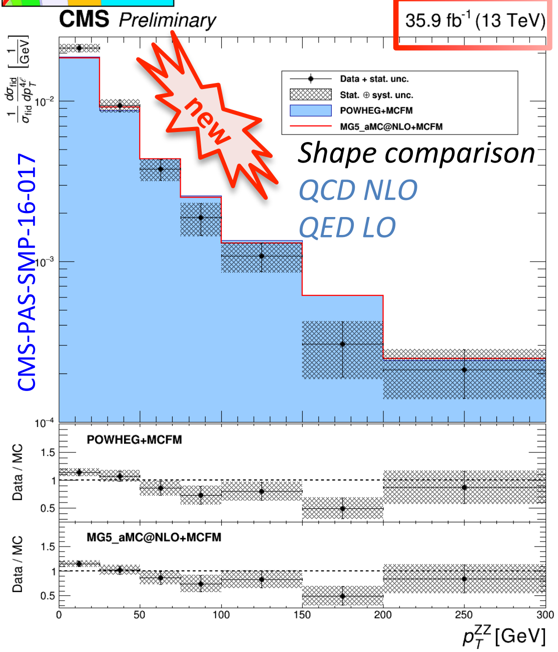
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

New differential measurements: ZZ

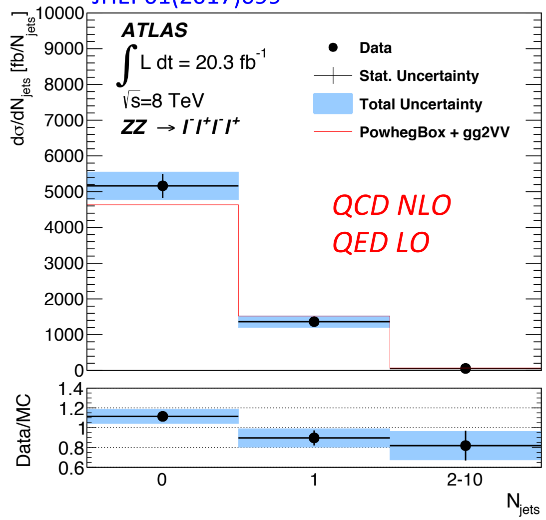
ZZ->4l: First diboson measurement with full 2016 dataset !

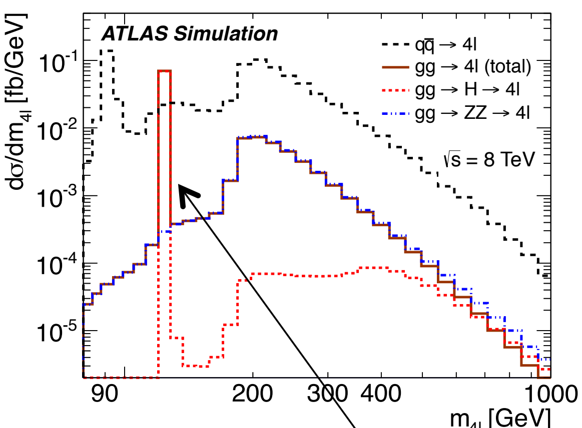
- possible indication of softer p_T^{4l} then predicted by NLO QCD
- m_{4l} differential distribution is essential for the study of the different production mechanisms !

CMS-PAS-SMP-16-017

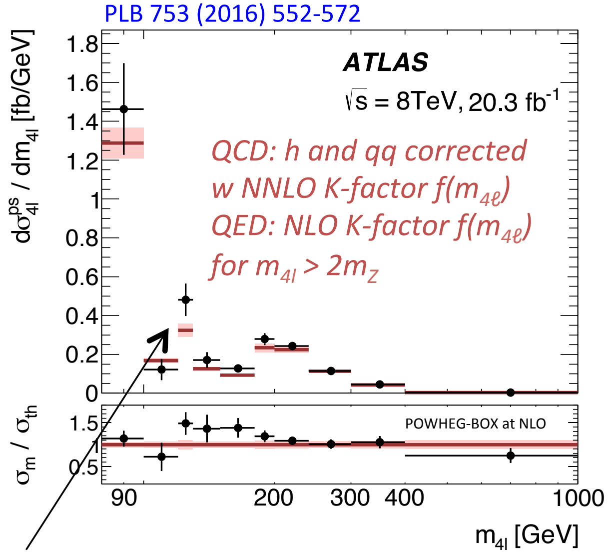


JHEP01(2017)099

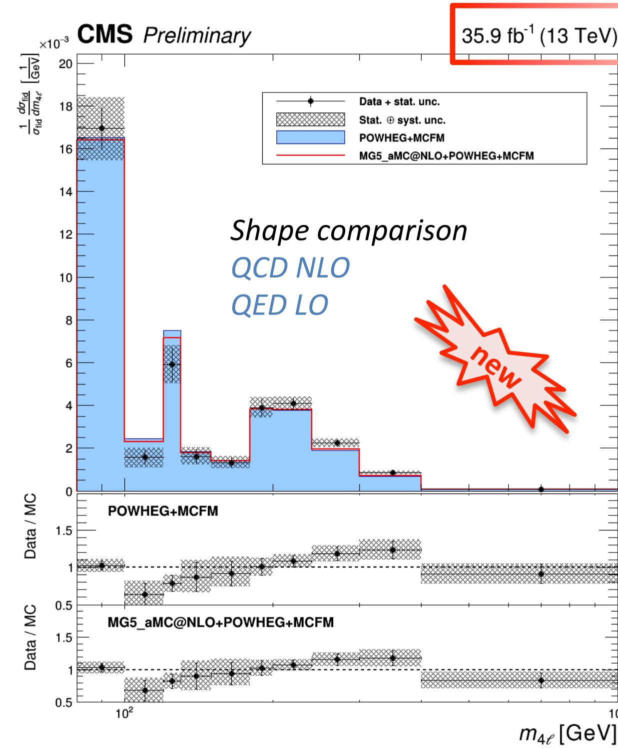




PLB 753 (2016) 552-572

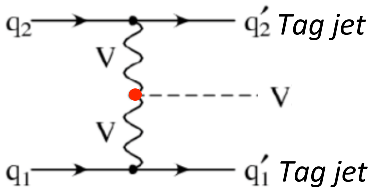


dominated by the resonant Higgs boson contribution

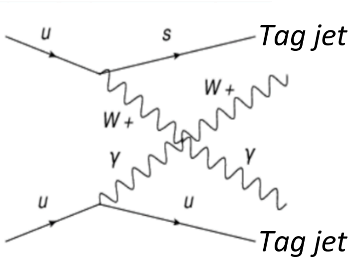


EWK production: Vector boson scattering

VBF process:



VBS process:



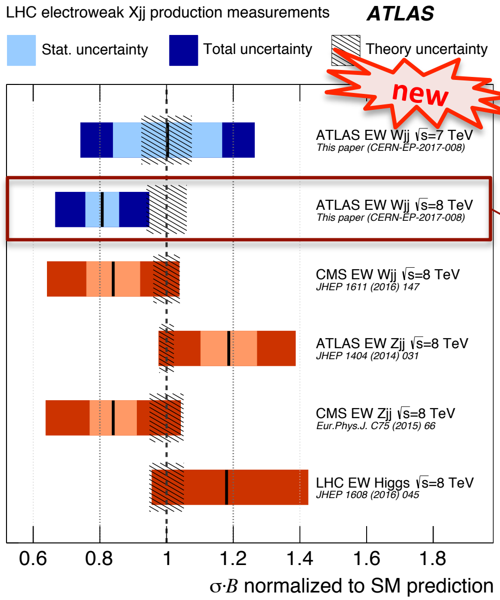
- **V(V)+2jets production is dominated** by $O(\alpha_S^2)$ QCD processes
  - evaluated from data in control region or from simultaneous fit
- **EWK V(V)+2jets production** is essential to probe the nature of the EWSB
  - **$V_L V_L$ scattering** linked to the mechanism responsible for the EWSB
  - characteristic signature: two high p_T jets in the forward-backward region with large rapidity separation and low hadronic activity in-between

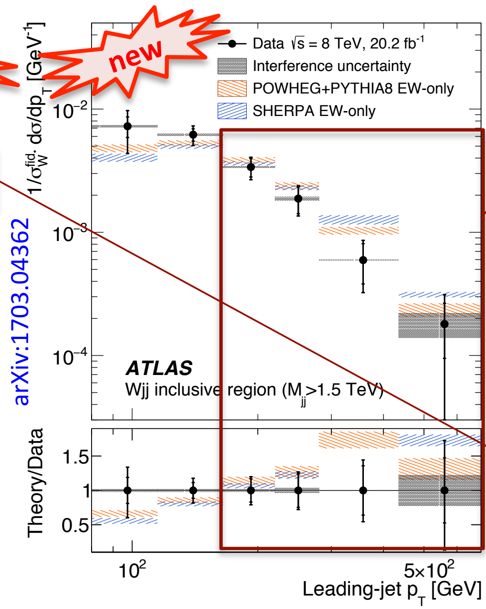
- First observation (evidance) of EWK V(V) production with 8 TeV data
- First observation of EWK VV right around the corner (with 13 TeV data) ?

EWK measurements: V(V)+2jets		ATLAS (8 TeV)	CMS (8 TeV)
Diboson *(statistic dominated)*	**W±(lν)W±(lν)**	PRL 113, 141803, arxiv:1611.02428 **Evidence**: EWK signal significance 3.6σ (exp 2.8σ)	PRL 114 (2015) 051801 EWK signal significance 1.9σ (exp 2.9σ)
	W(lν)γ	-	CMS-PAS-SMP-14-011 EWK signal significance 2.7σ (exp 1.5σ)
	Z(ll)γ	STDM-2015-21 EWK signal significance 2.0σ (exp 1.8σ)	CMS-PAS-SMP-14-018 **Evidence**: EWK signal significance 3.0σ (exp 2.1σ)
Single boson *(systematic dominated)*	**Z(ll)**	JHEP 04 (2014) 031 **Observation**: EWK signal significance ~5σ	EPJC 75 (2015) 66 **Observation**: EWK signal significance ~5σ
	W(lν)	arXiv:1703.04362 **Observation**: EWK signal significance >5σ	JHEP 11 (2016) 147 **Evidence**: EWK signal significance ~4σ

New EWK production measurements: W, Zγ

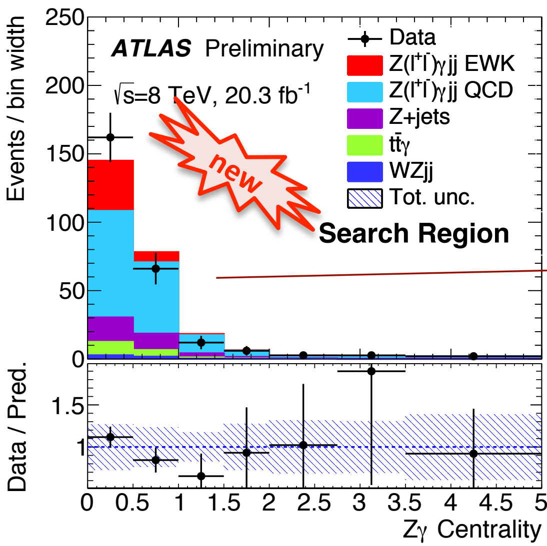
EWK measurements are also going differential!

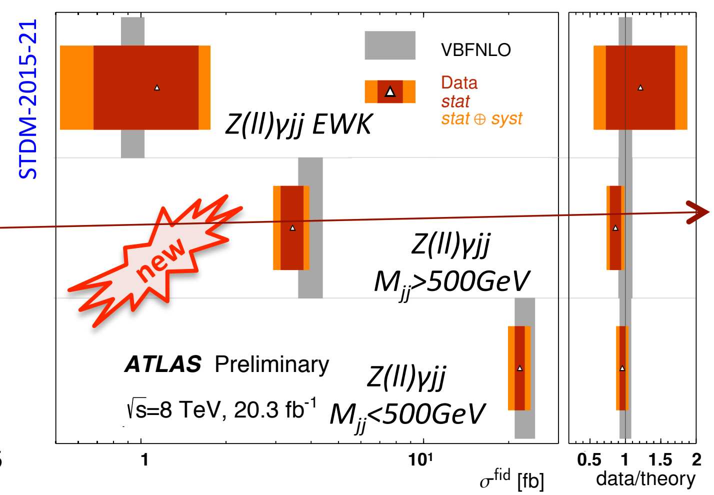




EWK(+QCD) W+2j measurement:

- Unlike QCD+EWK production for EWK production higher masses (M_{jj} > 1.5 TeV) predictions give a harder spectrum than observed in the data
    - Signature of NLO electroweak corrections ?
- Dominant uncertainty is systematic: jet energy scale and resolution, PDF





EWK Zγ+2j measurement:

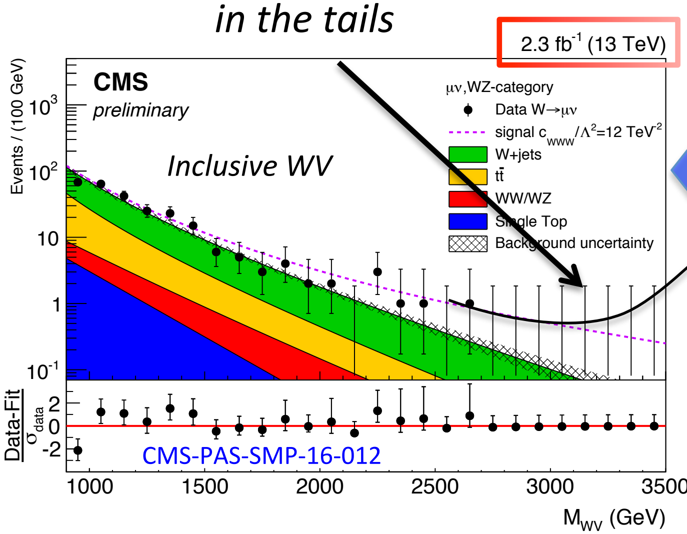
- Z(ll) and Z(νν) channels included
- Cross section is extracted using a likelihood fit over the centrality of the Zγ two-body system ($\zeta_{Z\gamma}$)
- Measurement statistics dominated

Anomalous couplings as a search for New Physics?

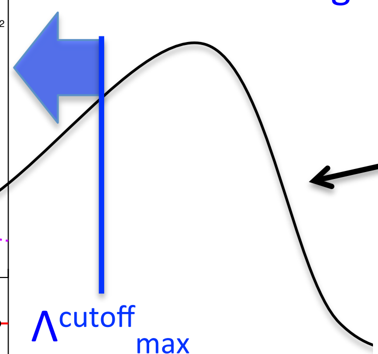
SM precision measurements ⟵ ***Anomalous coupling parameters (EFT,...)*** ⟶ *Specific BSM model*

Mostly probing strongly coupled BSM (weakly coupled needs resonant enhancement)

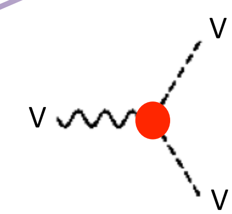
Search for deviation in the tails



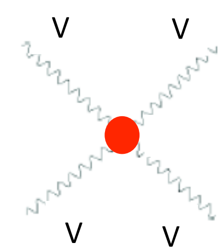
Breaking the SM relations (gauge invariance) leads to a theory with effective range of validity



New Physics signal at energy beyond direct experimental reach



Anomalous Triple gauge couplings (aTGC)



Anomalous Quartic gauge couplings (aQGC)

Parametrization: **extend SM Lagrangian** (effective Lagrangian or effective field theory) **with additional operators and anomalous parameters, measure parameters:**

EFT: $$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_{i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

Anomalous couplings: variety of measurements

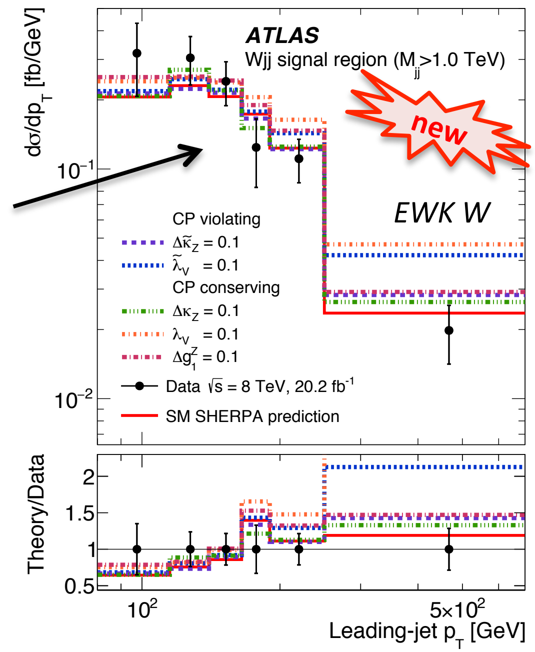
Measurements performed in numerous production channels:

- inclusive diboson measurements
- EWK production offers a complementary test of anomalous couplings

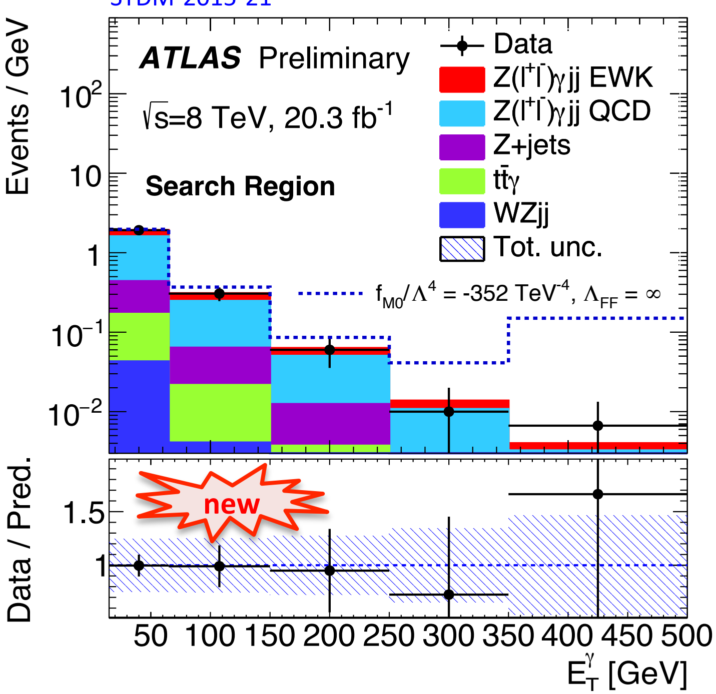
Limiting factor: observed statistics in the tail (primary), systematic and statistical uncertainty on the signal/bkg model (secondary)

No significant deviation of data from SM expectation is observed

arXiv:1703.04362



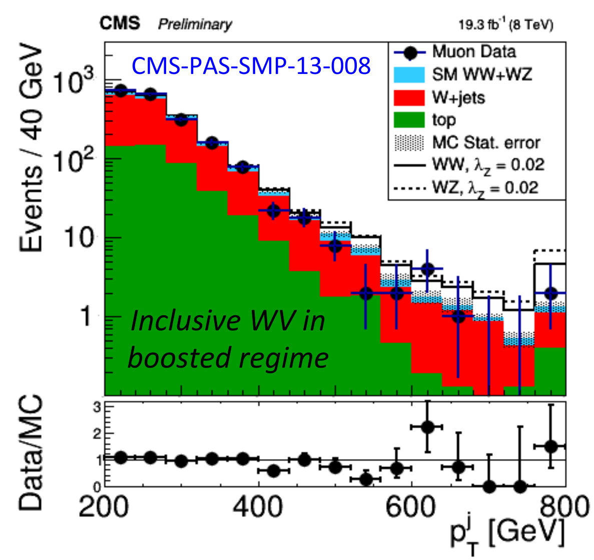
STDM-2015-21



Anomalous couplings result in an **increase of cross section at high energies**

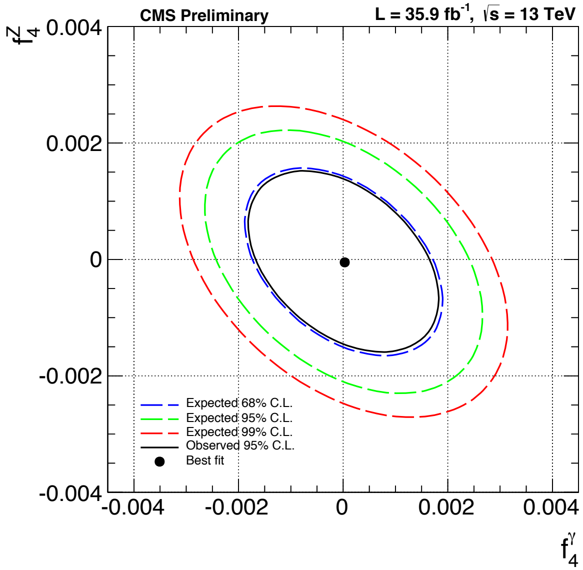
➢ invariant mass of the diboson system and the boson p_T are particularly sensitive

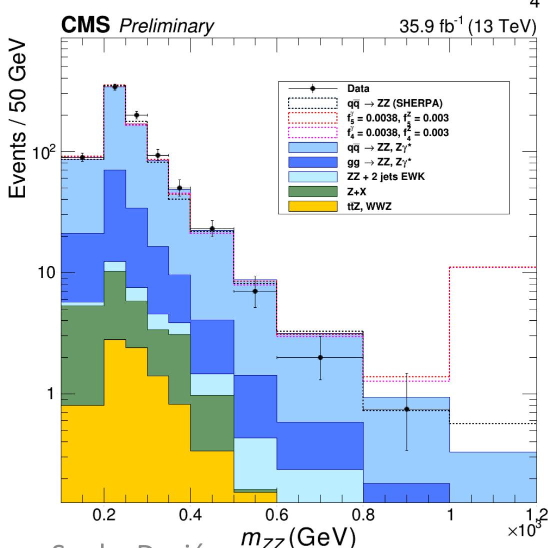
CMS-PAS-SMP-13-008



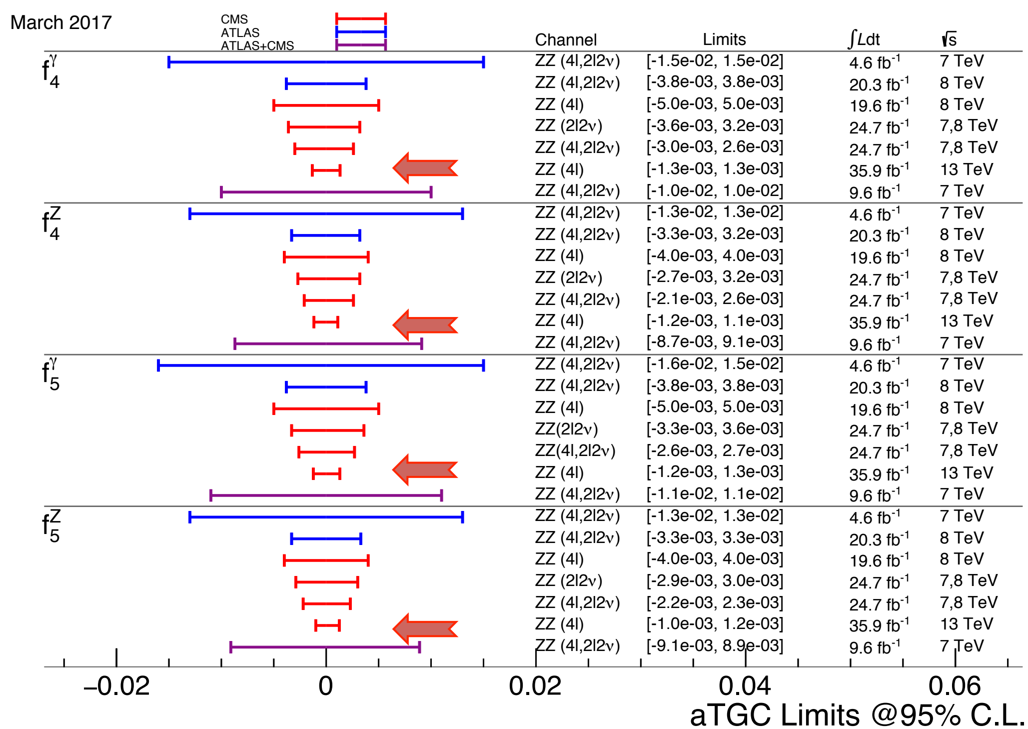
Anomalous couplings: results

LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) comparable to LEP results.





- Anomalous coupling sensitivity depends on the diboson channel
- Sensitivity is defined by the reach of diboson system invariant mass
  - → Best sensitivity from channels with larger BR (semileptonic decays in boosted topology)
  - → Large gain in sensitivity with increase of √s



Recent measurement with 13 TeV data!

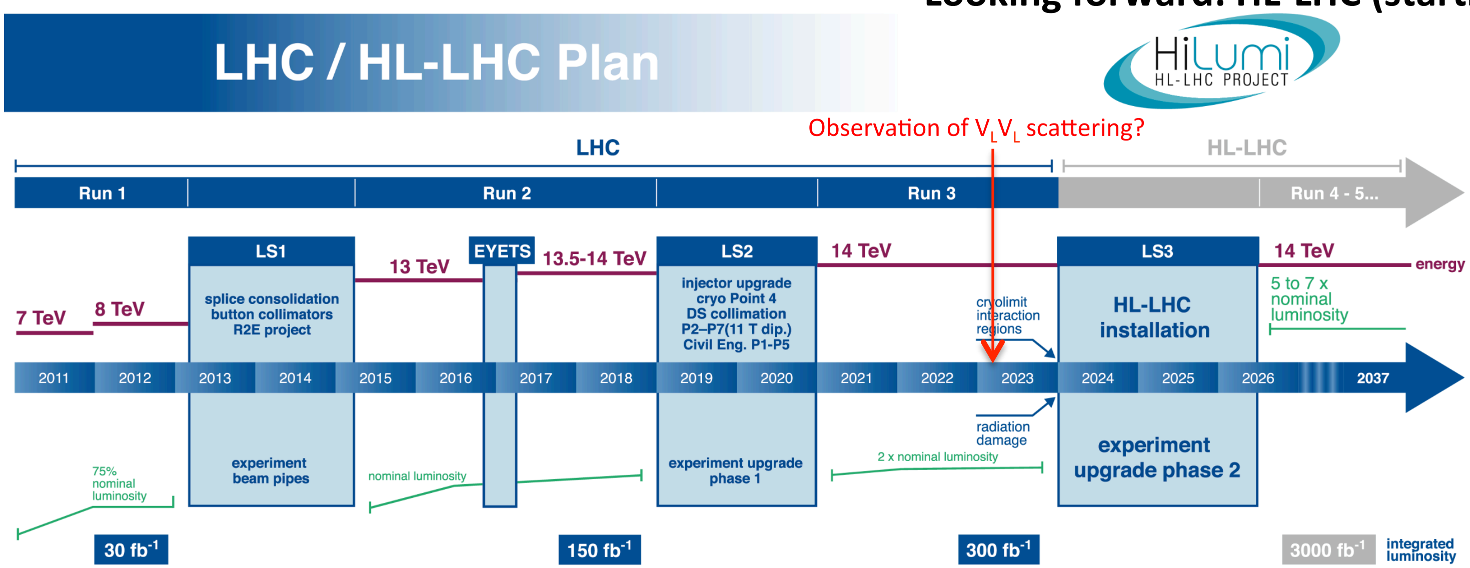
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

The present and the future of diboson physics

LHC Run2 is ongoing, so far ~40 fb^{-1} of data collected by ATLAS and CMS experiments

- All inclusive (differential) diboson measurements are already systematics (statistics) dominated
  - Work is ongoing to decrease experimental uncertainties
  - Measurements are pushing for more precise theoretical calculations (NNLO or 3NLO QCD, NLO EWK, …)
- We expect to have the sensitivity for first observation of the diboson EWK production with 2016/2017 data
- Significant increase of sensitivity for indirect search for New Physics (aTGC, aQGC)
- ➢ Await for vast of new diboson results in next few months!
- Continue to probe the nature of EWSB !

Looking forward: HL-LHC (starting 2023)



http://hilumilhc.web.cern.ch/about/hl-lhc-project

The present and the future of diboson physics

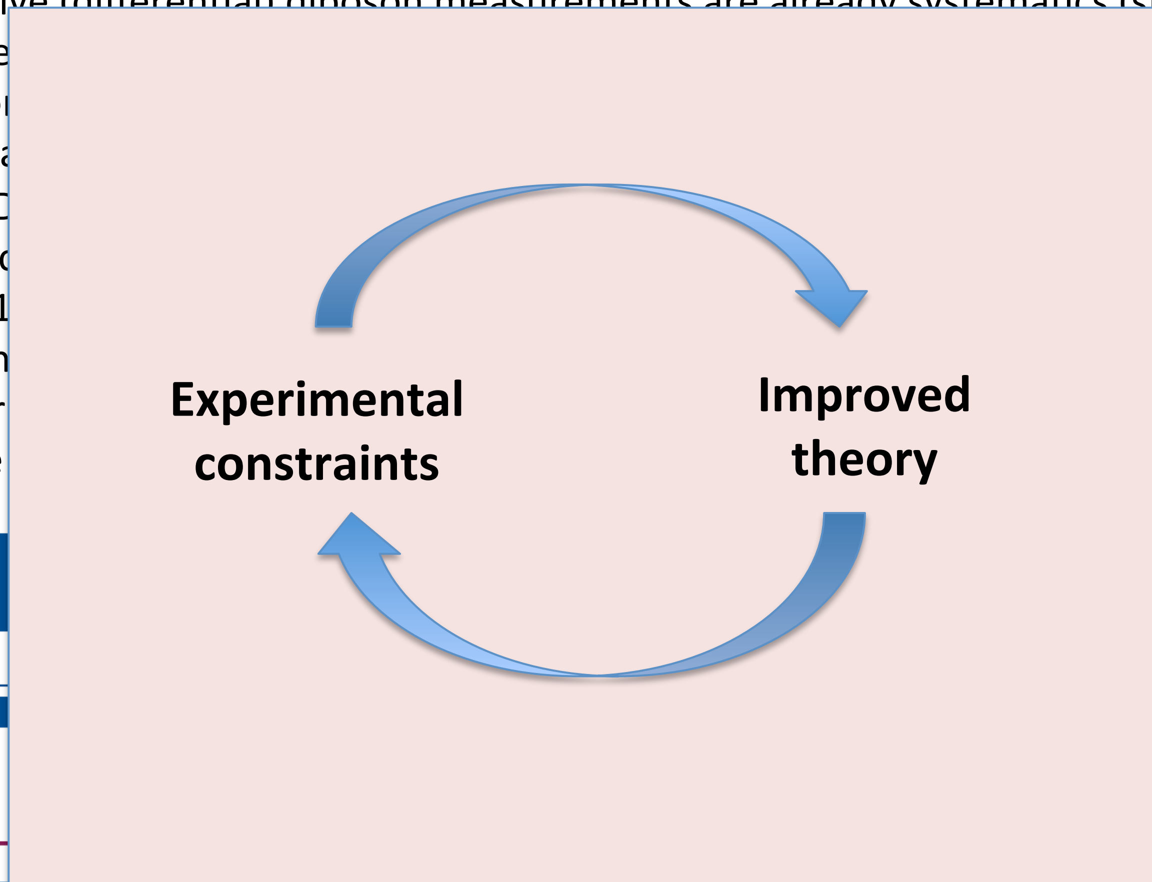
LHC Run2 is ongoing, so far ~40 fb^{-1} of data collected by ATLAS and CMS experiments

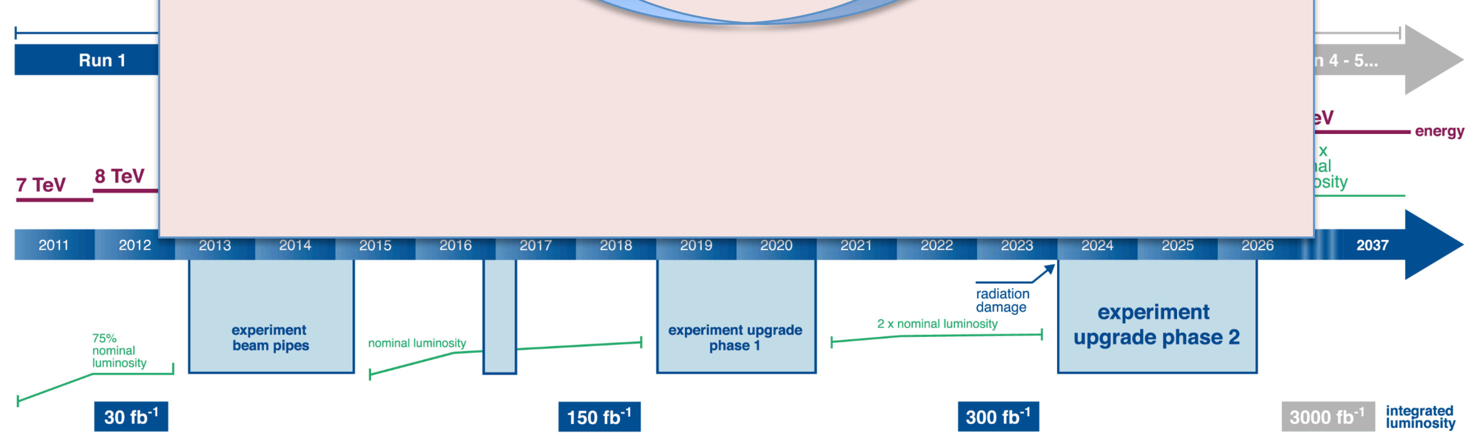
- All inclusive (differential) diboson measurements are already systematics (statistics) dominate
  - Wo
  - Mea ... NNLO or 3NLO QCD
- We expec ... roduction with 2016/201
- Significan ... aQGC)

➢ Await for

- Continue

... HC (starting 2023)





http://hilumilhc.web.cern.ch/about/hl-lhc-project

Backup

Diboson inclusive measurements: overview

	ATLAS		CMS	
	8 TeV	13 TeV	8 TeV	13 TeV
Z->4l	PRL 112, 231806 (2014)	-	-	PLB 763 (2016) 280, CMS-PAS-SMP-16-017 Cross section, differential and aTGC
ZZ->4l	PLB 753 (2016) 552-572, JHEP01 099 (2017) Cross section, differential, aTGC	PRL 116, 101801 (2016) Cross section	PLB 740 (2015) 250, CMS-PAS-SMP-15-012 Cross section, differential and aTGC measurement	
ZZ->2l2ν	JHEP01, 099 (2017) Cross section, differential, aTGC	-	EPJC 75 (2015) 511 Cross section and aTGC measurement	-
Zγ->llγ	PRD 93, 112002 (2016) Cross section, differential and aTGC measurement	-	JHEP 04 (2015) 164 Cross section and aTGC measurement	-
Zγ->ννγ			PLB 760 (2016) 448 Cross section and aTGC measurement	CMS-PAS-SMP-16-004 Cross section
WW->lνlν	JHEP 09 (2016) 029 (WW+0jet) Cross section, differential and aTGC measurement PLB 763 (2016) 114 (WW+1jet) Cross section measurement	arXiv:1702.04519 Cross section	EPJC 76 (2016) 401 (WW+0- or 1-jet) Cross section, differential and aTGC measurement	CMS-PAS-SMP-16-006 Cross section
WZ->3lν	PRD 93, 092004 (2016) Cross section, differential, upper limit on EWK WZ, aTGC, aQGC measurement	PLB 762 (2016) 1 (3.2 fb-1) Cross section, differential (Njets) ATLAS-CONF-2016-043 (13.3 fb-1) Cross section, differential and aTGC!	CMS-SMP-14-014, arXiv:1609.05721	arXiv:1607.06943 (CMS-PAS-SMP-16-002) (2.3 fb-1) Cross section
WV->lνjj	-	-	-	CMS-PAS-SMP-16-012 aTGC measurement

- Large cross section of multiboson production at LHC in pp collisions
- Clean signature and small branching ratio for vector bosons decaying leptonicaly
- Not clean signature but large branching ratio for hadronic decays

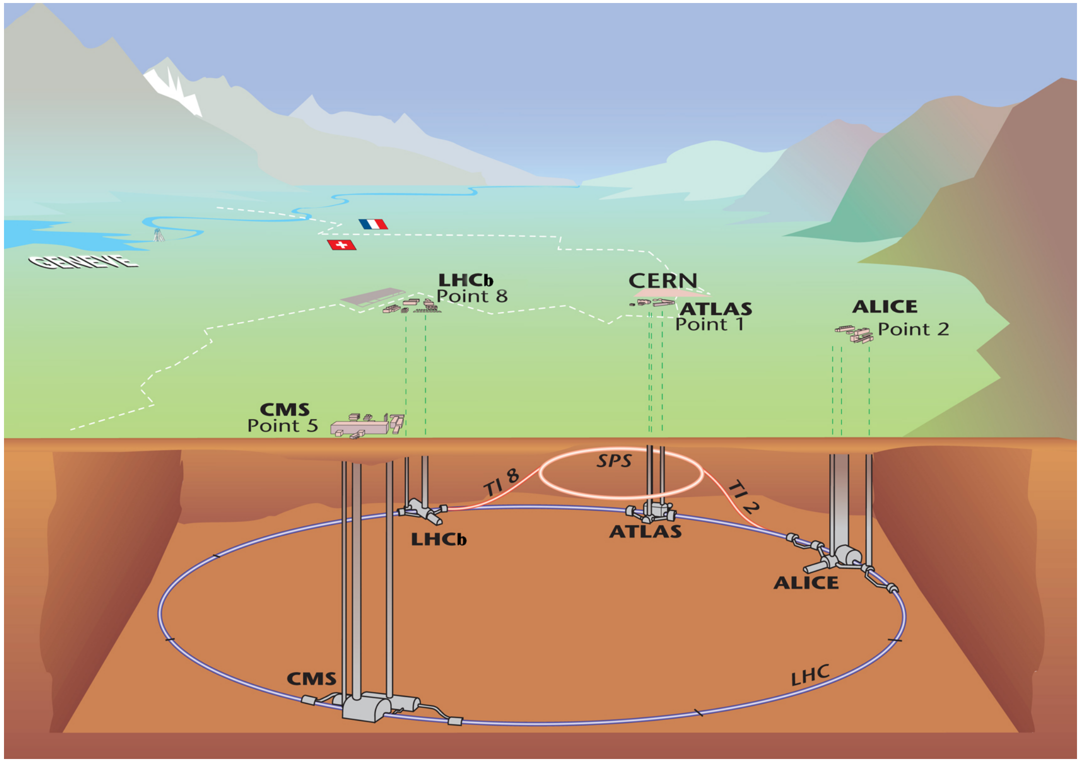
EWK results: overview

VBS measurements (VV+2jets)		ATLAS	CMS
8 TeV	**EWK W±W± ->lvlv**	PRL 113, 141803 Cross section (EWK, EWK+QCD) and aQGC measurement **Evidence**: EWK signal significance 3.6σ (exp 2.8σ) arxiv:1611.02428 Updated aQGC limits	PRL 114 (2015) 051801 Cross section (EWK+QCD) and aQGC measurement EWK signal significance 1.9σ (exp 2.9σ)
	EWK Wγ ->lvγ	-	CMS-PAS-SMP-14-011 Cross section (EWK, EWK+QCD) and aQGC measurement EWK signal significance 2.7σ (exp 1.5σ)
	EWK Zγ ->llγ	STDM-2015-21 Cross section (EWK, EWK+QCD), aQGC measurement EWK signal significance 2.0σ (exp 1.8σ)	CMS-PAS-SMP-14-018 Cross section (EWK, EWK+QCD) and aQGC measurement **Evidence**: EWK signal significance 3.0σ (exp 2.1σ)
	EWK WZ ->lvll	Phys. Rev. D 93, 092004 (2016) Cross section (EWK, EWK+QCD) measurement	PRL 114 (2015) 051801 Cross section (EWK+QCD) measurement
	EWK WV->lvjj	PRD 95 (2017) 032001 aQGC measurement	-

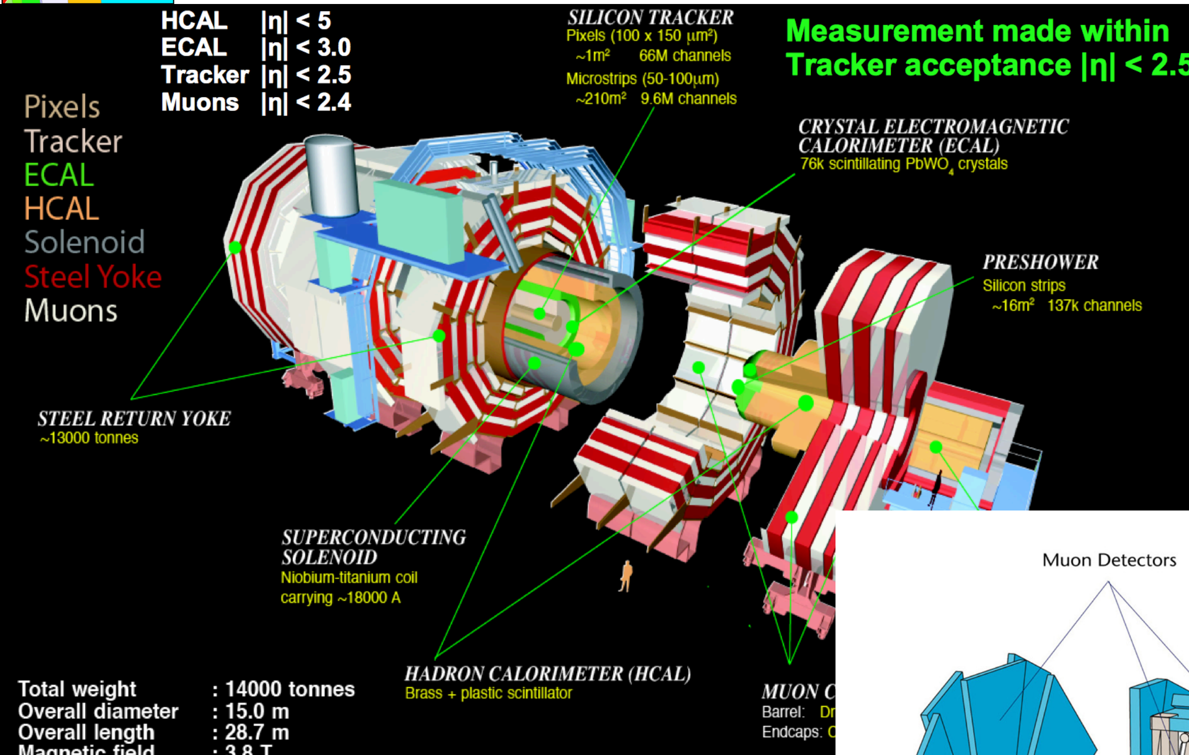
VBF measurements (V+2jets)		ATLAS	CMS
8 TeV	**EWK Z(ll)**	JHEP 04 (2014) 031 Cross section (EWK) and aTGC measurement **Observation**: EWK signal significance ~5σ ()	EPJC 75 (2015) 66 Cross section (EWK) measurement **Observation**: EWK signal significance ~5σ
	EWK W(lv)	arXiv:1703.04362 Cross section (EWK, EWK+QCD), differential (EWK, EWK+QCD), aTGC measurement **Observation**: EWK signal significance >5σ	CMS-PAS-SMP-13-012, arXiv:1607.06975 Cross section (EWK) measurement **Evidence**: EWK signal significance ~4σ

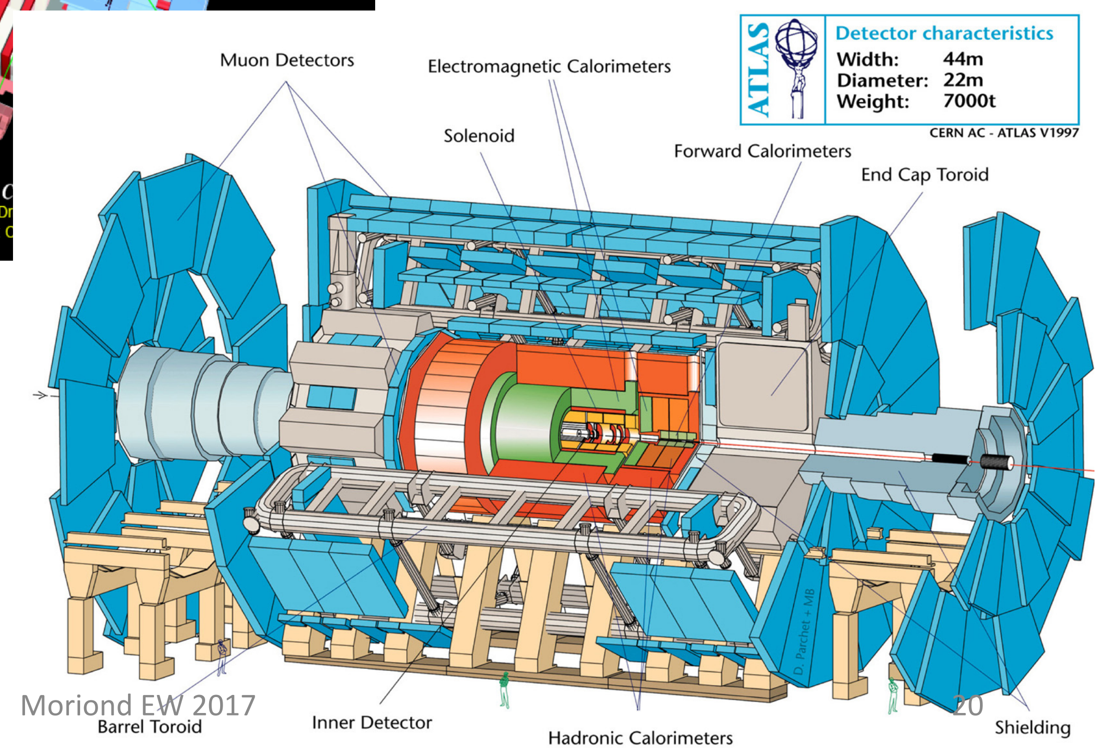
+ some measurements also with 7 TeV !

CMS and ATLAS experiments

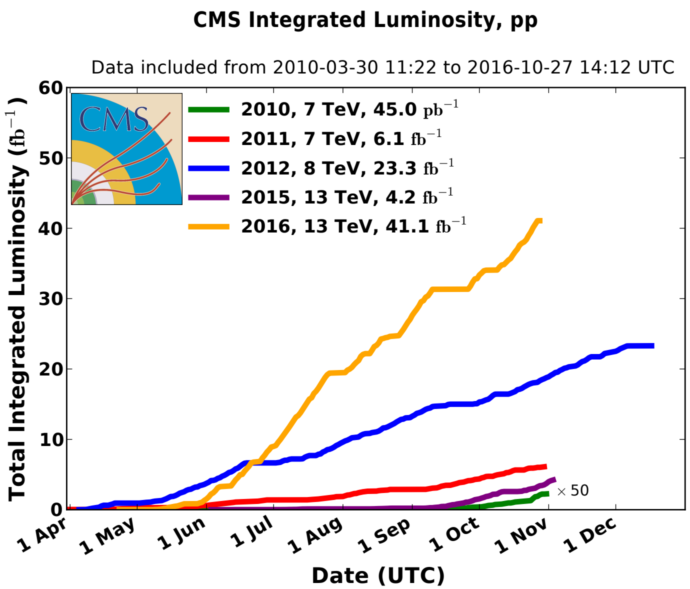


CMS and ATLAS experiments

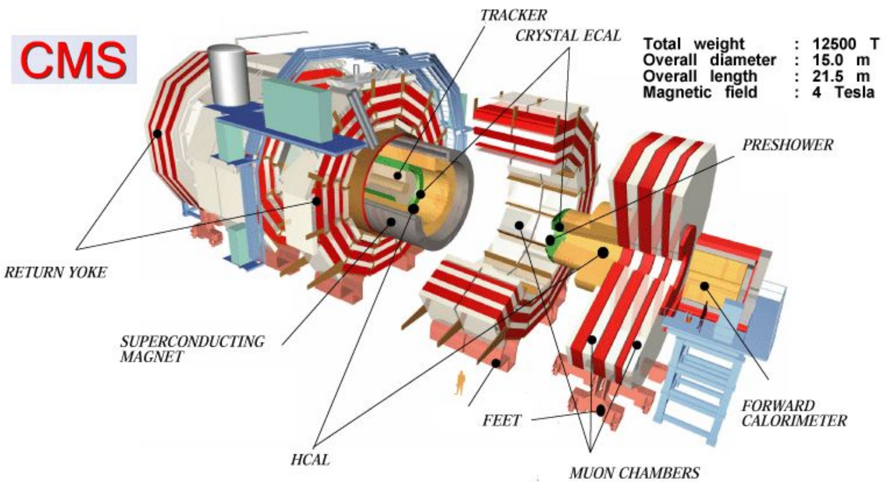


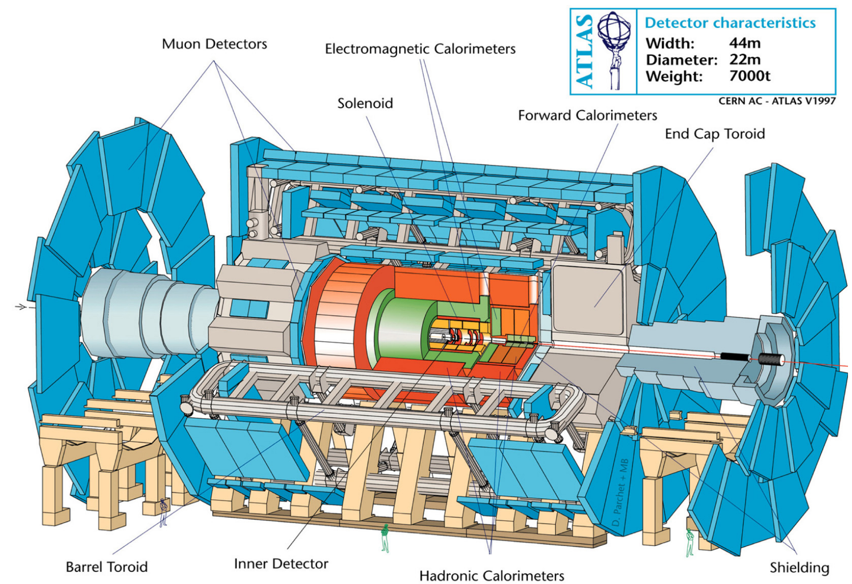


LHC performance

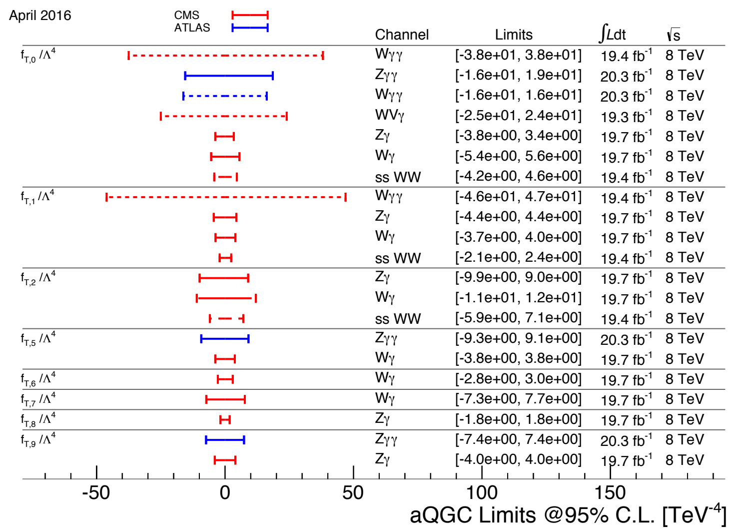


- **Wonderful performance of LHC accelerator in past years**
  - Large amount of data collected **by ATLAS and CMS experiments** of proton-proton collisions at a center-of-mass energies of $\sqrt{s}$ = 7, 8 and 13 TeV
  - Huge amount of measurements performed, including milestone discovery of Higgs boson !



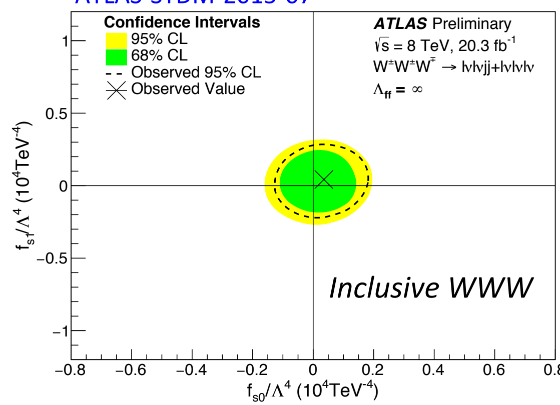


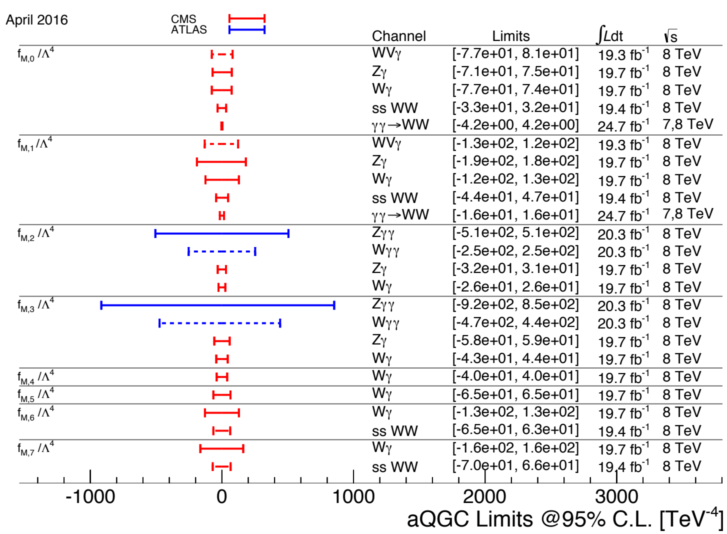
aQGC couplings: variety of measurements



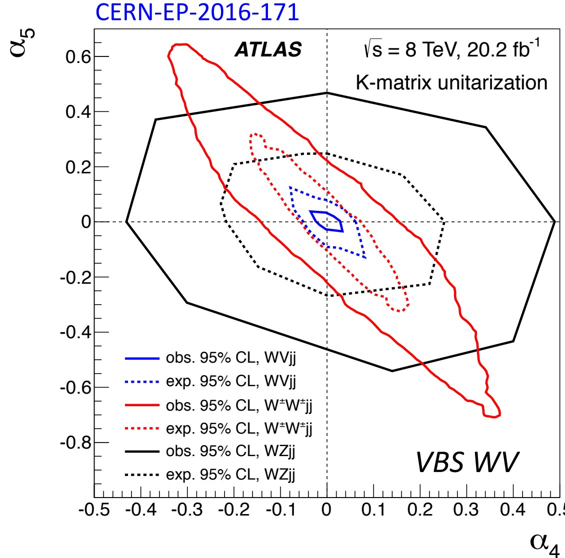
VBS channels have better sensitivity than triboson production.

ATLAS-STDM-2015-07





CERN-EP-2016-171

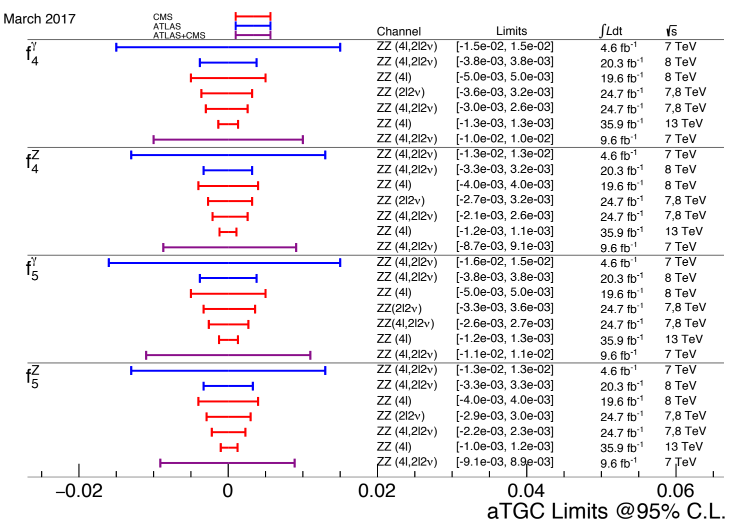


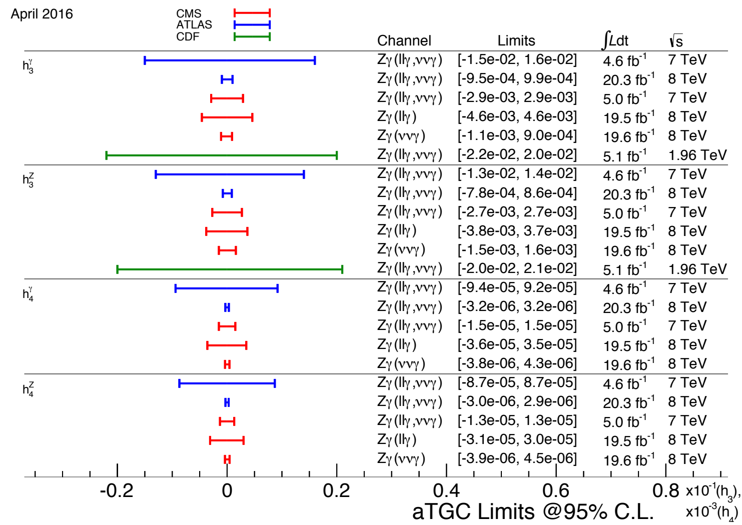
Semileptonic channel WV shows best sensitivity.

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

aTGC couplings: variety of measurements

LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) comparable to LEP results.

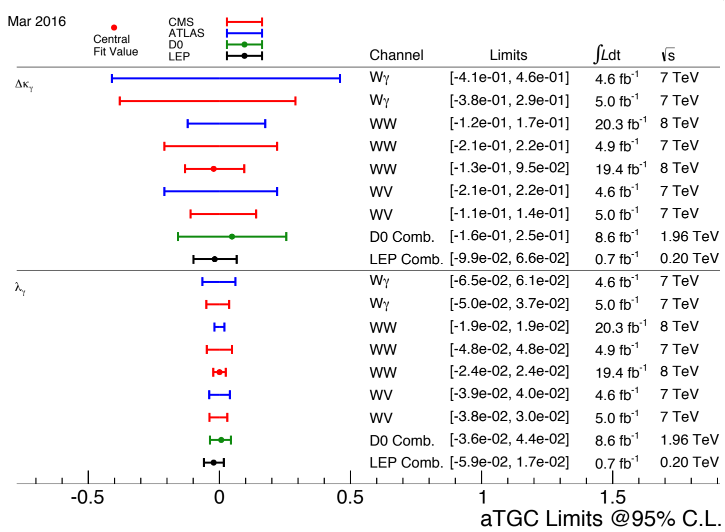


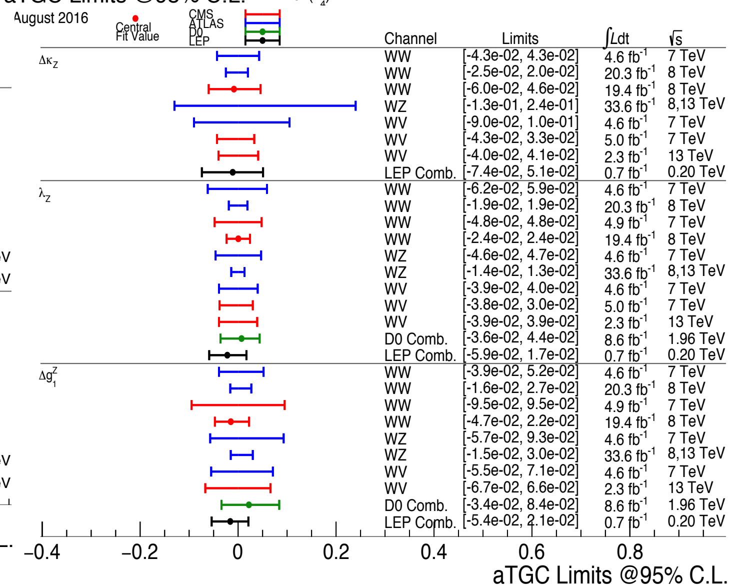


Best sensitivity from Zγ->ννγ channel (larger BR then Zγ->llγ)

Best sensitivity from WV->lνjj channel (larger BR)

Increase of collision energy -> increase in sensitivity

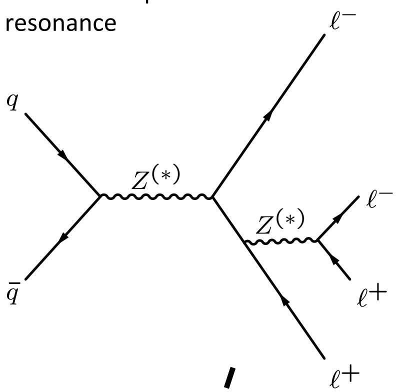




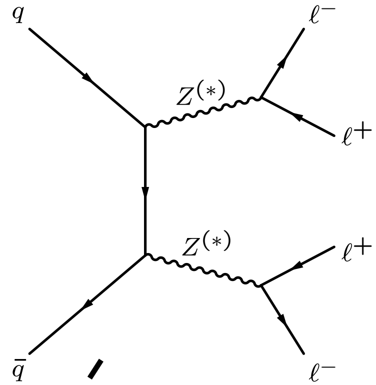
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

ZZ production modes

Dominant 4l production at Z resonance



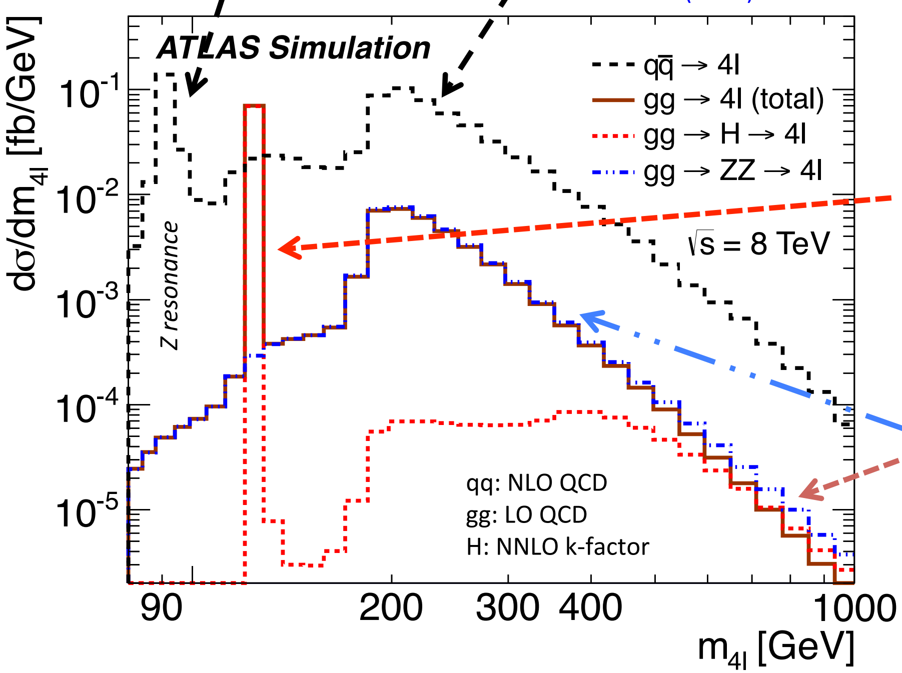
Dominant 4l production above the Z resonance

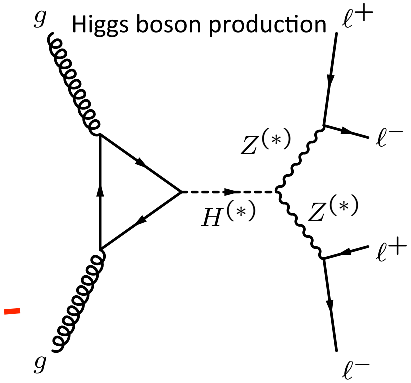


+ small contribution from qq VBS production

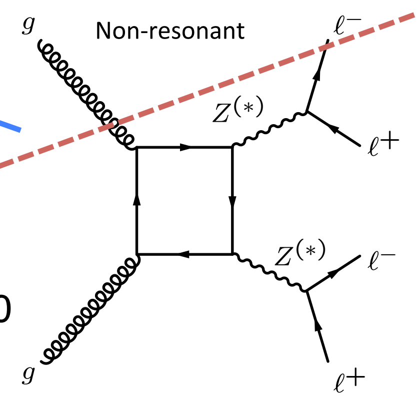
M_{4l} spectrum is essential for the study of the different production mechanisms !

PLB 753 (2016) 552-572





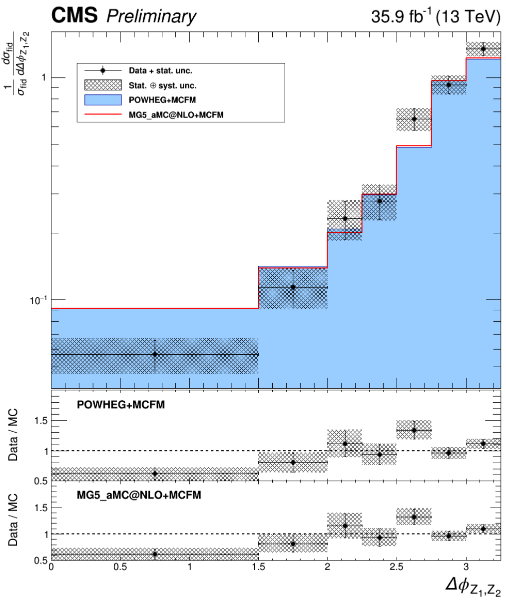
+ VBF, VH, ttH higgs production (<15% to higgs production)

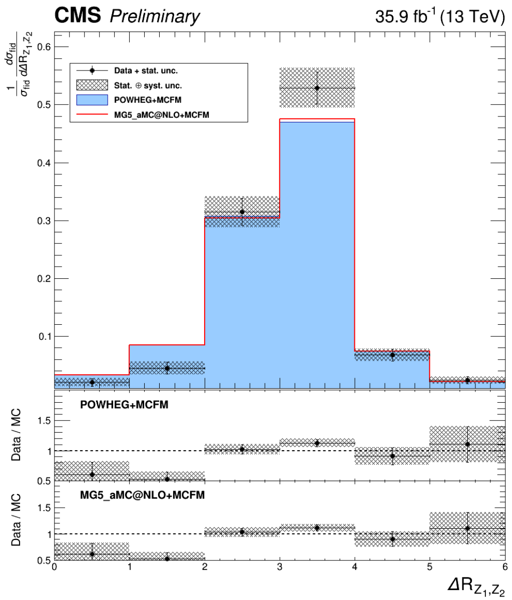


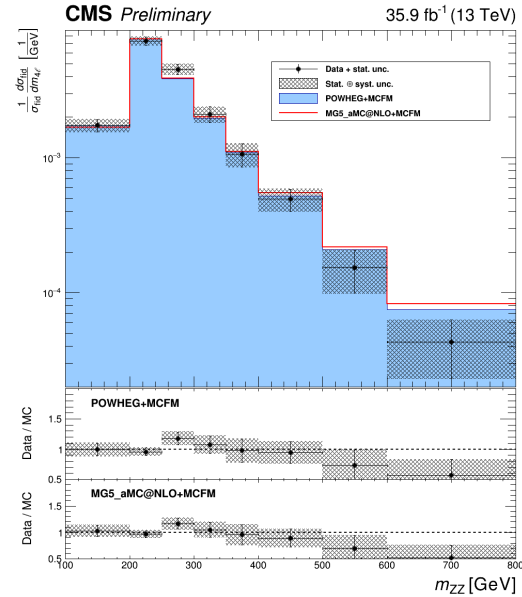
large destructive interference of ggH with ggF processes (high mass m_{4l})

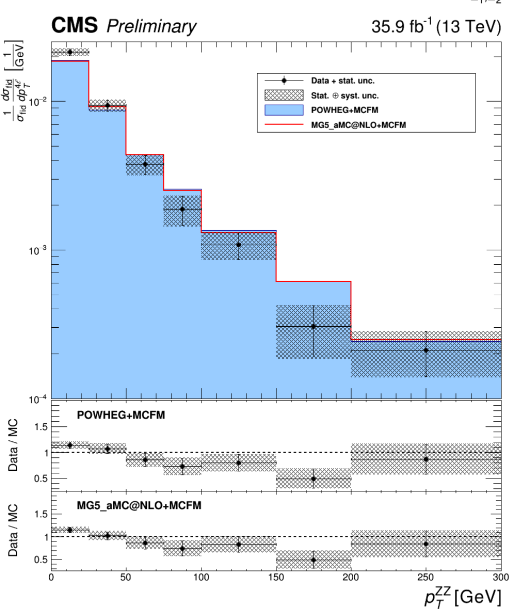
ZZ normalized differential with full 2016 data

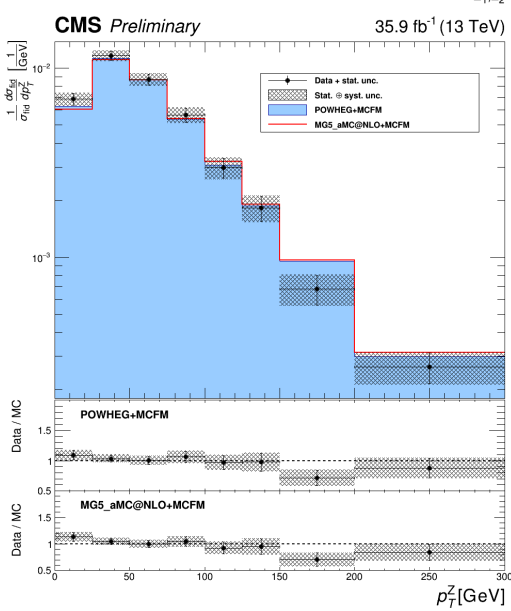
CMS-PAS-SMP-16-017

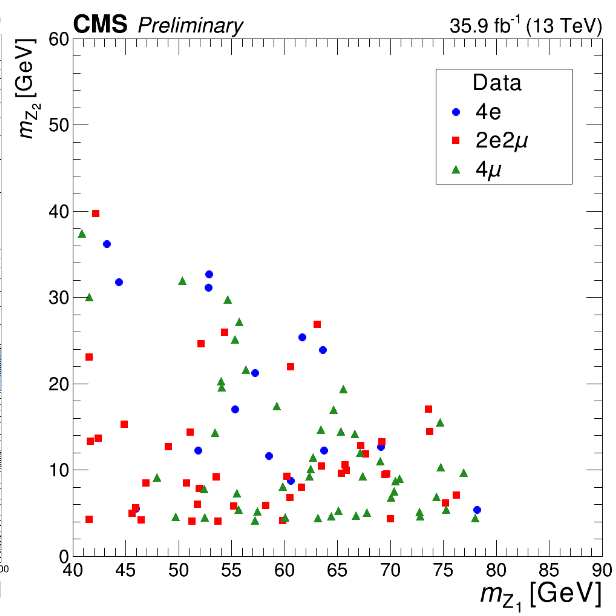








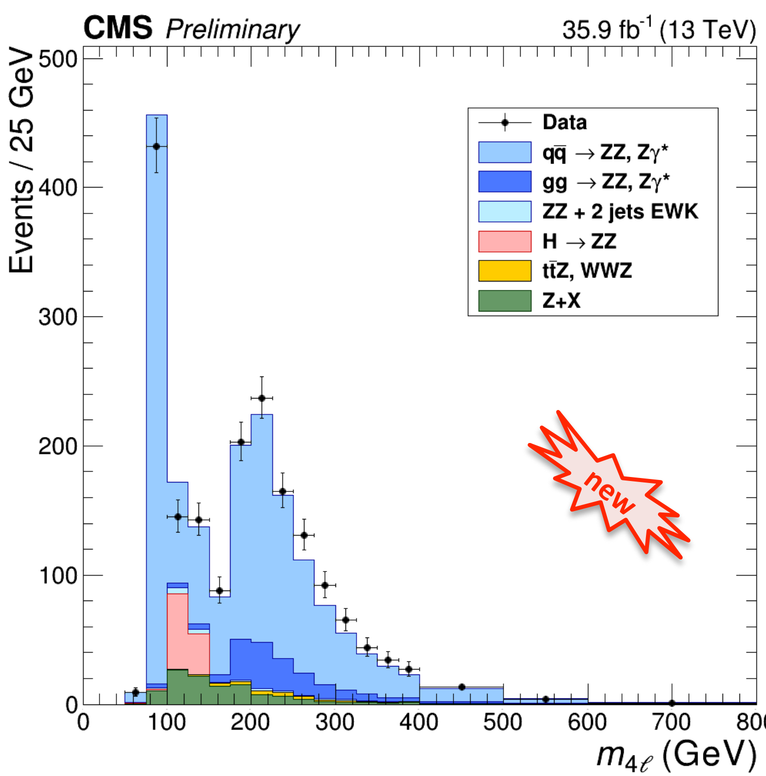


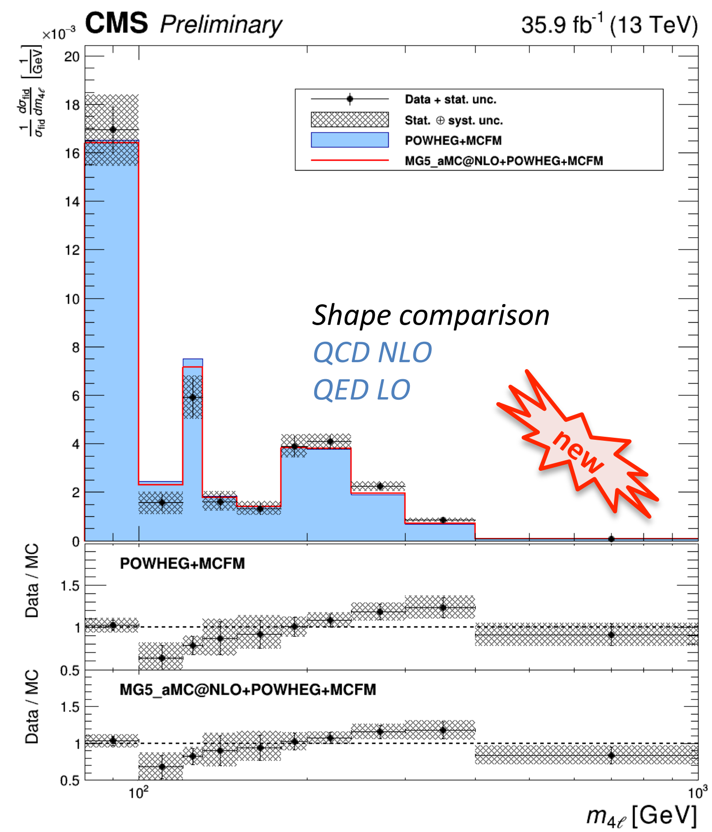


New differential measurements: ZZ

CMS-PAS-SMP-16-017

qq->4l: NLO in QCD with Powheg/aMC@NLO_MG5 scaled to NNLO (k-factor=1.1)
qg->4l: LO
gg->ZZ: LO with MCFM scaled to NLO (k-factor=1.7)
EWK ZZ production in association with two jets is generated with PHANTOM
gg->H->ZZ: NLO with POWHEG 2.0 scaled to NNLO (k-factor=1.7)





ZZ normalized differential with full 2016 data

CMS-PAS-SMP-16-017

Table 4: Fiducial definitions for the reported cross sections. The common requirements are applied for both measurements.

Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20\,\text{GeV}$, $p_T^{\ell_2} > 10\,\text{GeV}$, $p_T^{\ell_{3,4}} > 5\,\text{GeV}$, $\lvert\eta^\ell\rvert < 2.5$, $m_{\ell^+\ell^-} > 4\,\text{GeV}$ (any opposite-sign same-flavor pair)
$Z \to 4\ell$	$m_{Z_1} > 40\,\text{GeV}$ $80 < m_{4\ell} < 100\,\text{GeV}$
$ZZ \to 4\ell$	$60 < m_{Z_1}, m_{Z_2} < 120\,\text{GeV}$

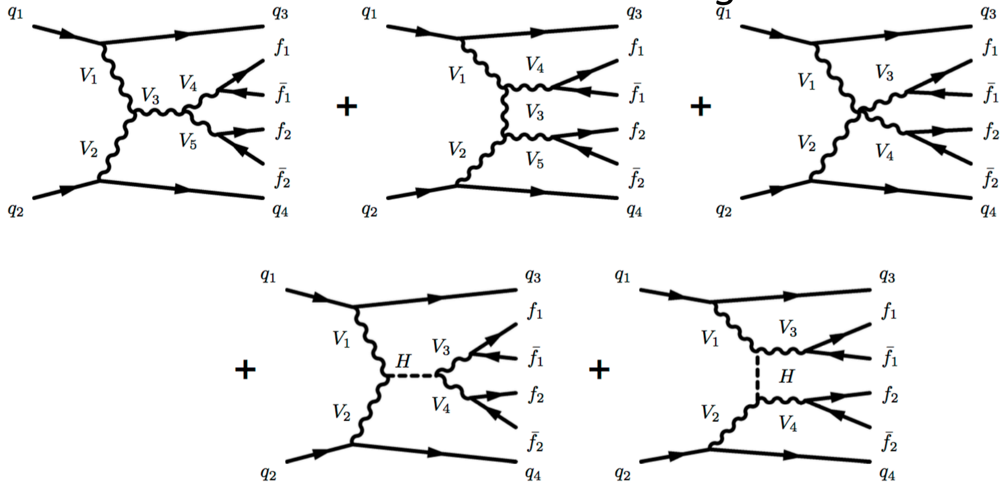
Uncertainty	$Z \to 4\ell$	$ZZ \to 4\ell$
Lepton efficiency	6–10%	2–6%
Trigger efficiency	2–4%	2%
MC statistics	1–2%	0.5%
Background	0.6–1.3%	0.5–1%
Pileup	1–2%	1%
PDF	1%	1%
QCD Scales	1%	1%
Integrated luminosity	2.6%	2.6%

$$\sigma_{\text{fid}}(pp \to Z \to 4\ell) = 29.7 \pm 1.4\,(\text{stat})^{+2.0}_{-1.8}\,(\text{syst}) \pm 0.8\,(\text{lumi})\,\text{fb},$$

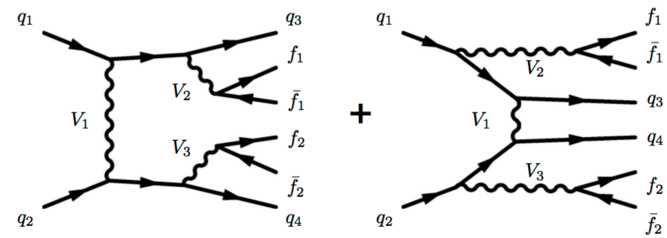
$$\sigma_{\text{fid}}(pp \to ZZ \to 4\ell) = 42.2 \pm 1.4\,(\text{stat})^{+1.6}_{-1.5}\,(\text{syst}) \pm 1.1\,(\text{lumi})\,\text{fb}.$$

$$\sigma(pp \to ZZ) = 17.8 \pm 0.6\,(\text{stat})^{+0.7}_{-0.6}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.5\,(\text{lumi})\,\text{pb}.$$

VV EWK with scattering

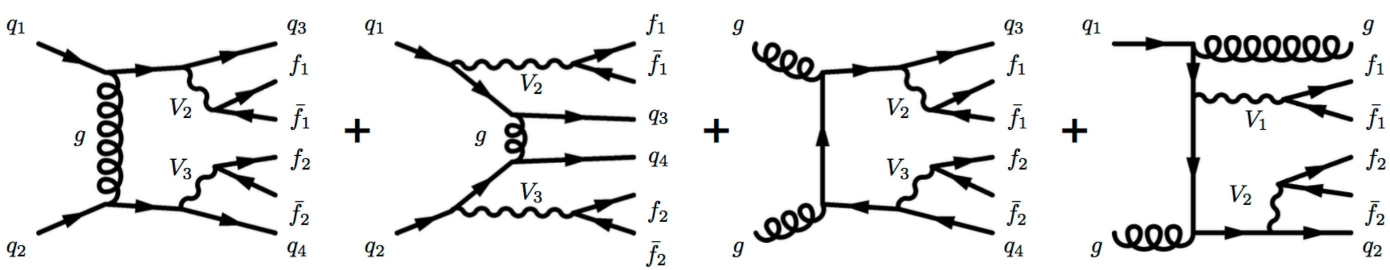


VV EWK w/o scattering



EWK production via vector boson scattering

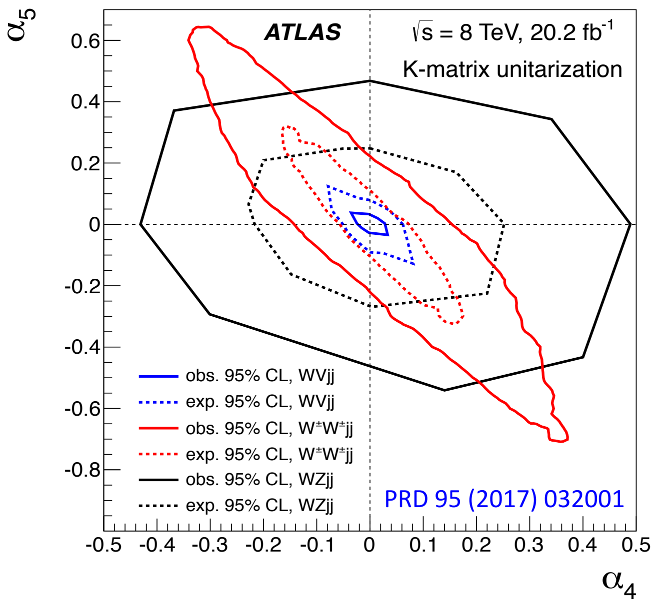
VV QCD



Probing the nature of the Electroweak Symmetry Breaking (EWSB)!

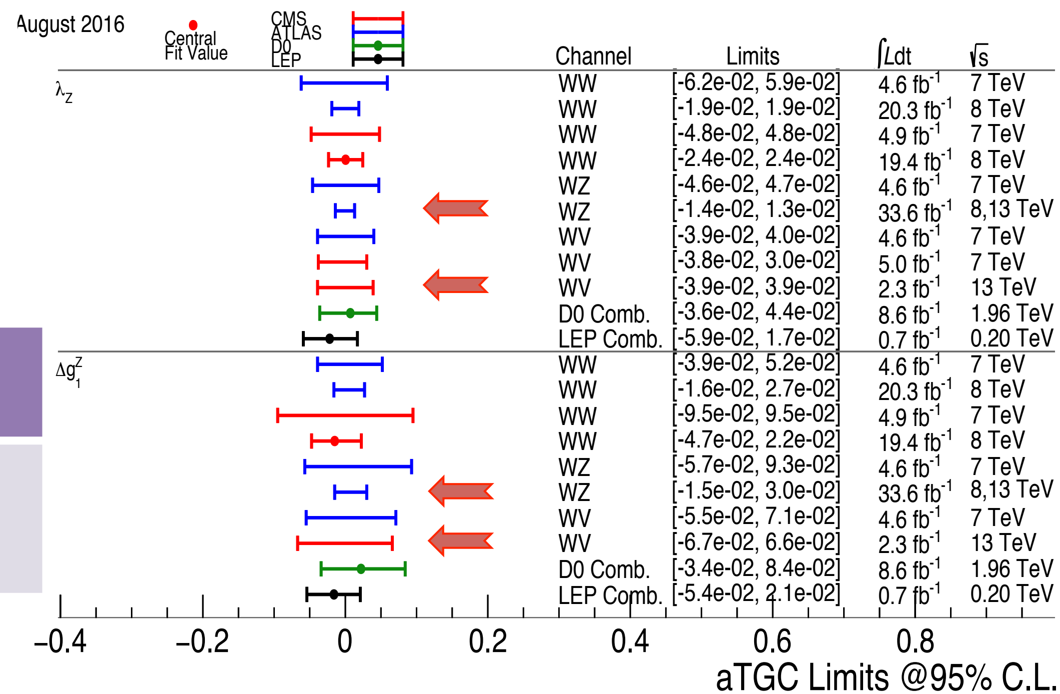
Anomalous couplings: results

LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) comparable to LEP results.



- Anomalous coupling sensitivity depends on the diboson channel
- Sensitivity is defined by the reach of diboson system invariant mass
  - → Best sensitivity from channels with larger BR (semileptonic decays in boosted topology)
  - → Large gain in sensitivity with increase of √s

limits are set on $c_i^{(n)}/\Lambda^n$	→	Probing scales of $\Lambda^n = c_i^{(n)}/\text{limit}$
in the limit of strong coupling ($c_i = 4\pi$) for dim6 (n=2)	→	limit on Λ up to 2 TeV !



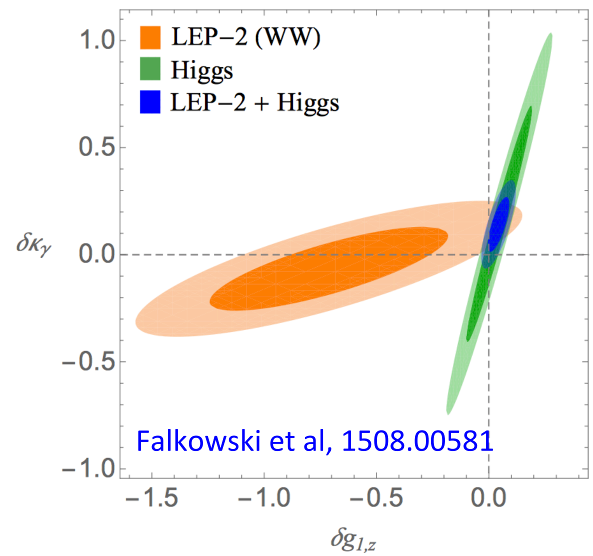
Recent measurement with 13 TeV data!

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

aTGC couplings: variety of measurements

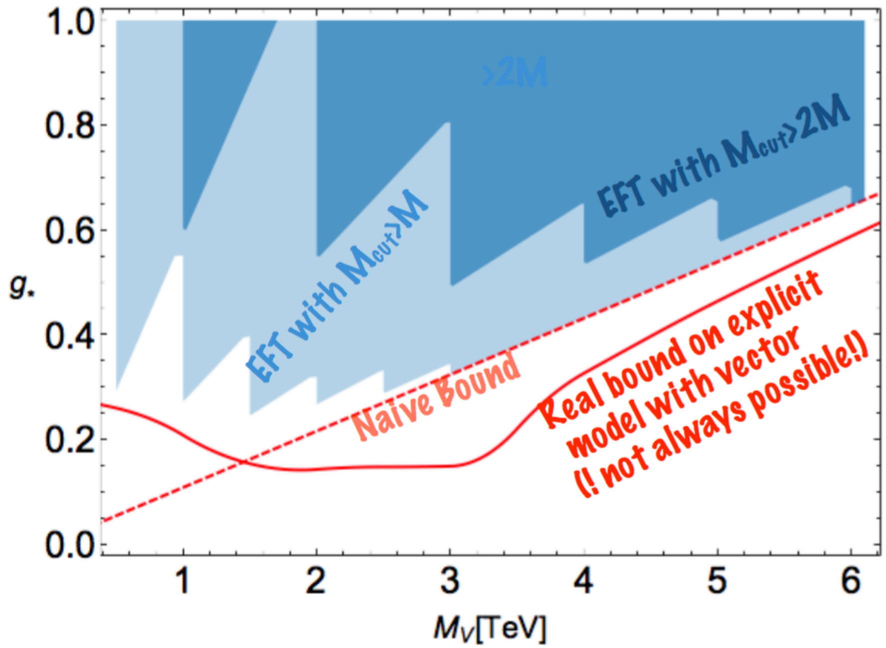
Future Prospects

- Full 2016 data will provide significantly stronger limits than our 8 TeV results
- Combination of anomalous coupling limits using inclusive diboson measurements and Higgs measurements (and ATLAS and CMS combination)
  - ✧ Improvement in sensitivity



Anomalous couplings: results

LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) comparable to LEP results.



Future prospects under discussion:

Self-Consistency Check

- perturbativity of physical expansion
- deriving limits with extra cut on $\sqrt{s} < M_{cutoff}$

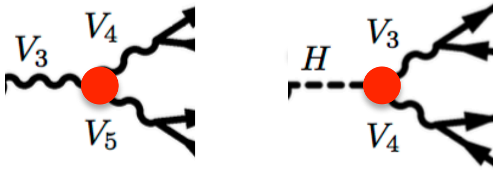
→ limits in the (c,M) plane

Combination of anomalous coupling limits with Higgs measurements

→ Improvement in sensitivity

Limits are set on $c_i^{(n)}/\Lambda^n$ → probing energies of $\Lambda^n = c_i^{(n)}/\text{limit}$

In the limit of strong coupling ($c_i = 4\pi$) → limit on Λ up to 2 TeV !



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

Zγ VBS

STDM-2015-21

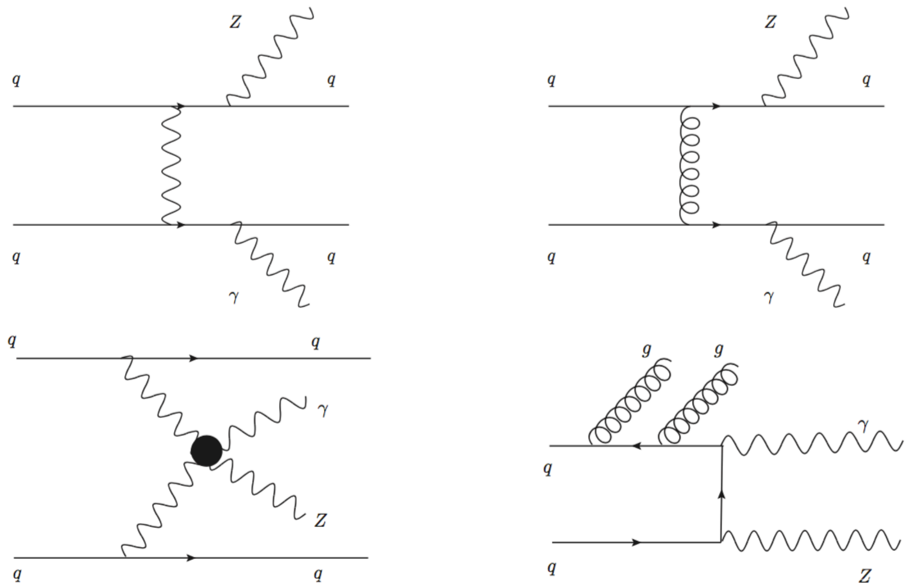
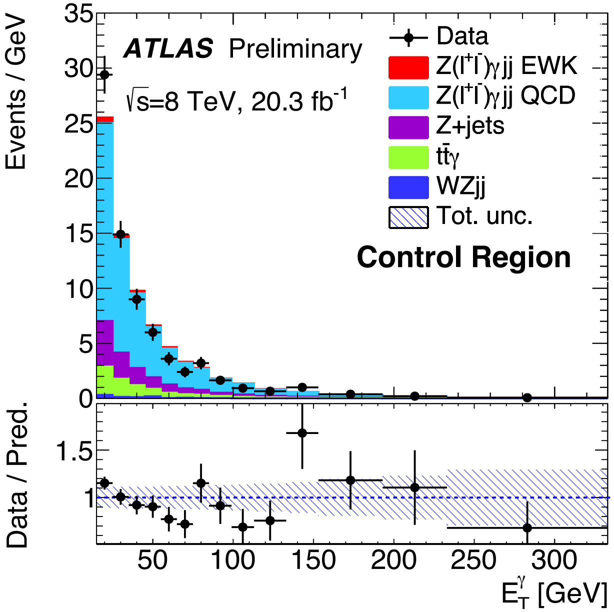


Figure 1: Feynman diagrams of Electroweak $Z\gamma jj$ production involving VBS subprocesses (bottom left) or non-VBS subprocesses (top left) and of QCD $Z\gamma jj$ production with gluon exchange (top right) or radiation (bottom right).

- small constructive interference occurs between QCD and EWK quark scattering productions
- interference contribution is predicted from Sherpa to be less than 10% of the EWK cross-section in the search region (m_{jj}> greater than 500 GeV) with a decreasing trend as a function of m_{jj}
- interference is treated as an uncertainty in the measurements

Zγ VBS

STDM-2015-21



main background for Z(ll)γ is Z+jets (jet misidentified as a photon)

- Estimated using the fake rate method (based on control regions populated by events passing all selection criteria but with the candidate photon failing some of the identification criteria and/or the isolation requirement)
  - uncertainty is dominated by the systematic uncertainty due to the correlation between photon identification and isolation requirements

dominant background for Z(νν)γ is *W*(lν)γ+jets production (lepton is neither reconstructed nor detected)

- estimated using the Sherpa MC samples with normalization determined with data

Zγ VBS

STDM-2015-21

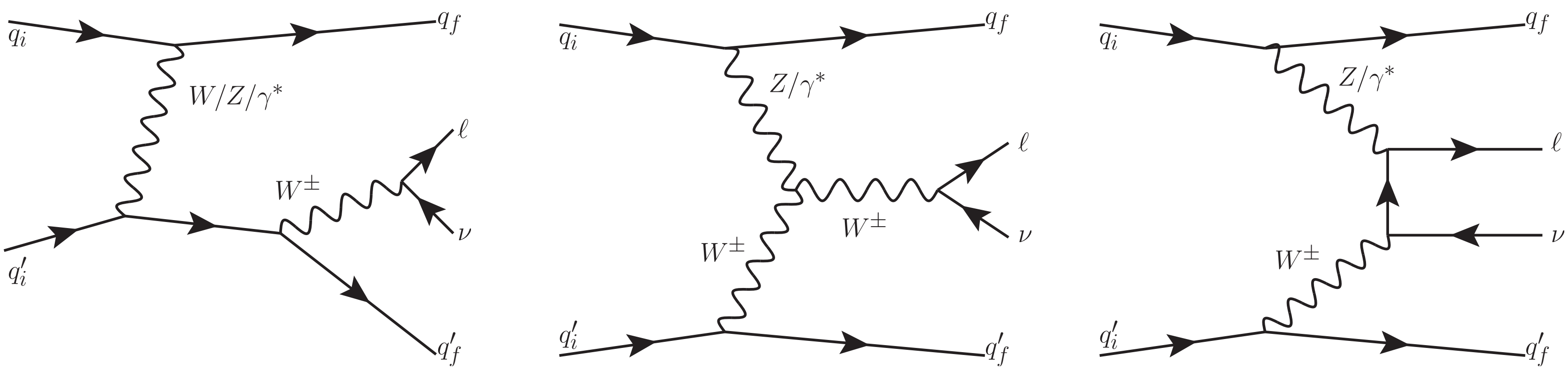
A centrality observable ζ is defined to quantify the relative position in pseudo-rapidity of a physics object with respect to the two leading jets (j_1 and j_2):

$$\zeta \equiv \left| \frac{\eta - \bar{\eta}_{jj}}{\Delta\eta_{jj}} \right| \quad \text{with} \quad \bar{\eta}_{jj} = \frac{\eta_{j_1} + \eta_{j_2}}{2}, \quad \Delta\eta_{jj} = \eta_{j_1} - \eta_{j_2}, \tag{1}$$

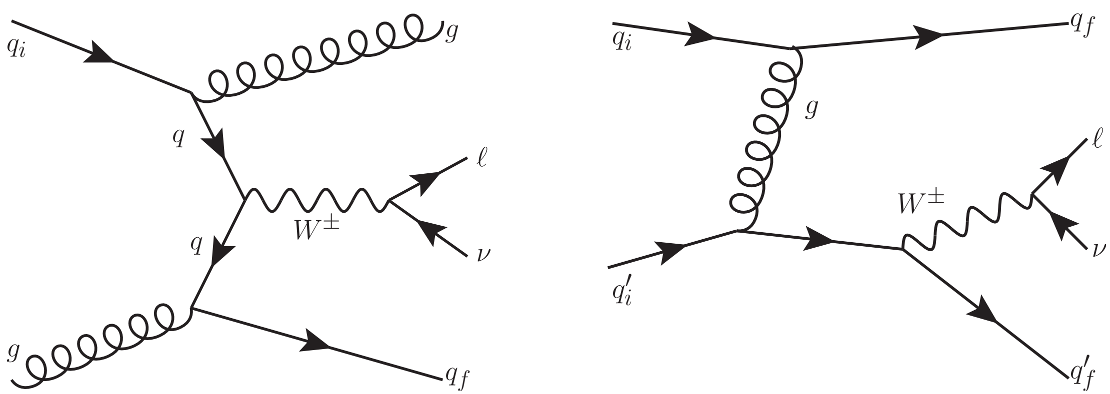
W VBF

arXiv:1703.04362

EWK Wjj production at the LHC:



QCD Wjj production at the LHC:

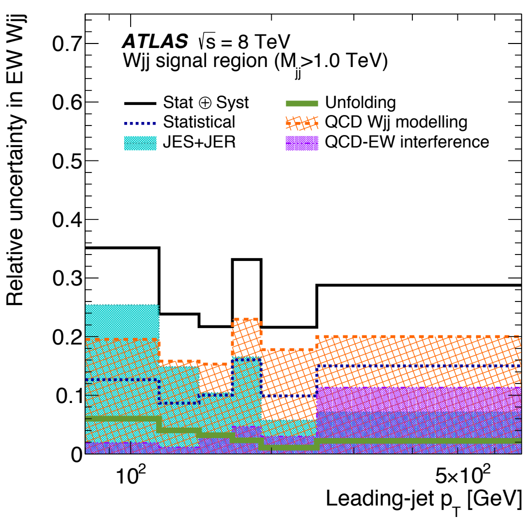


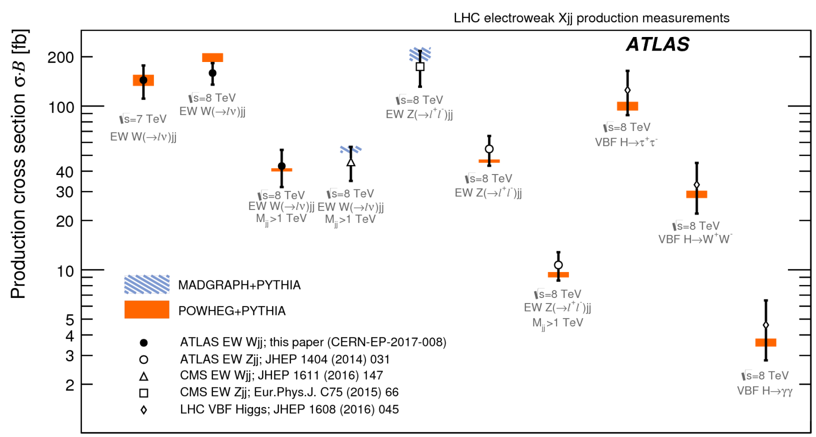
W VBF

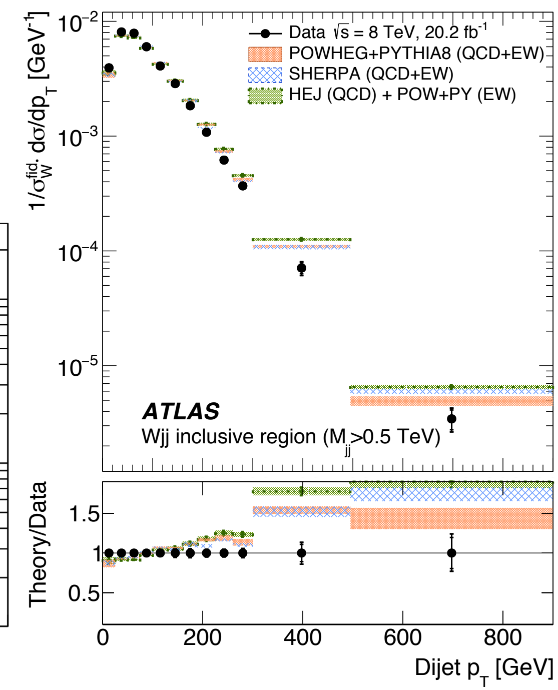
arXiv:1703.04362

Source	Uncertainty in μ_{EW} 7 TeV	8 TeV
Statistical		
Signal region	0.094	0.028
Control region	0.127	0.044
Experimental		
Jet energy scale (η intercalibration)	0.124	0.053
Jet energy scale and resolution (other)	0.096	0.059
Luminosity	0.018	0.019
Lepton and E_{T}^{miss} reconstruction	0.021	0.012
Multijet background	0.064	0.019
Theoretical		
MC statistics (signal region)	0.027	0.026
MC statistics (control region)	0.029	0.019
EW Wjj (scale and parton shower)	0.012	0.031
QCD Wjj (scale and parton shower)	0.043	0.018
Interference (EW and QCD Wjj)	0.037	0.032
Parton distribution functions	0.053	0.052
Other background cross sections	0.002	0.002
EW Wjj cross section	0.076	0.061
Total	0.26	0.14

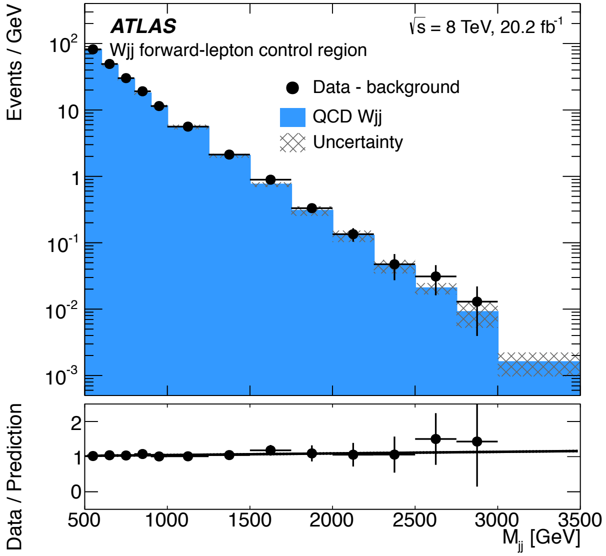
- W+2j renormalization and factorization scale variations and parton-shower modelling
  - affect the acceptance of the jet centrality requirement
- The interference uncertainty is estimated by including the Sherpa leading-order interference model as part of the background W+2j process
- a 0.076 (0.061) uncertainty in the signal cross section at 7 (8) TeV due to higher-order QCD corrections and non-perturbative modelling is estimated using scale and parton-shower variations
  - affecting the measurement of μEW but not the extracted cross sections



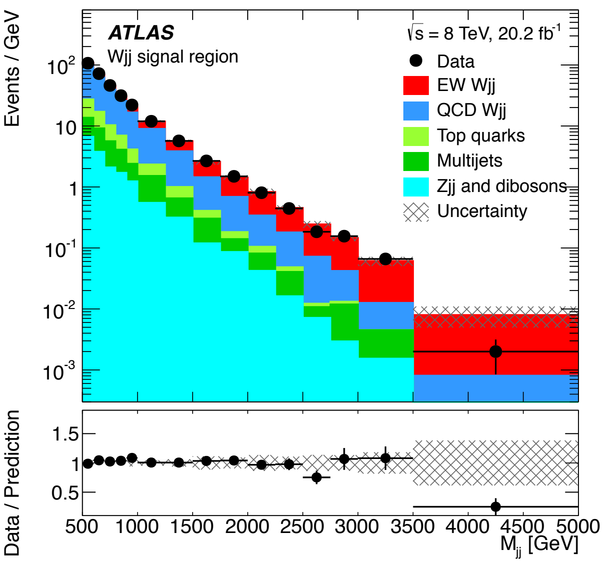




W VBF



- SM prediction of the dijet mass distribution receives significant uncertainties from the experimental jet energy scale and resolution
- These uncertainties are constrained with a correction to the predicted distribution derived using data in a control region where the signal contribution is suppressed



- measurement is performed with an extended joint binned likelihood fit of the M_{jj} distribution for the normalization factors of the QCD and EWK W+2j Powheg +Pythia8 predictions
- The interference between the processes is not included in the fit, and is instead taken as an uncertainty based on SM predictions.
- uncertainty in the shape of the QCD W+2j distribution dominates the measurement, but is reduced by using the forward-lepton control region to correct the modelling of the Mjj shape

WW CMS 8TeV

EPJC 76 (2016) 401

Source	Uncertainty (%)
Statistical uncertainty	1.5
Lepton efficiency	3.8
Lepton momentum scale	0.5
Jet energy scale	1.7
E_T^{miss} resolution	0.7
$t\bar{t}$+tW normalization	2.2
W +jets normalization	1.3
$Z/\gamma^* \to \ell^+\ell^-$ normalization	0.6
$Z/\gamma^* \to \tau^+\tau^-$ normalization	0.2
Wγ normalization	0.3
Wγ^* normalization	0.4
VV normalization	3.0
$H \to W^+W^-$ normalization	0.8
Jet counting theory model	4.3
PDFs	1.2
MC statistical uncertainty	0.9
Integrated luminosity	2.6
Total uncertainty	7.9

- jet counting model uncertainty includes the renormalization and factorization scales, and underlying event uncertainties

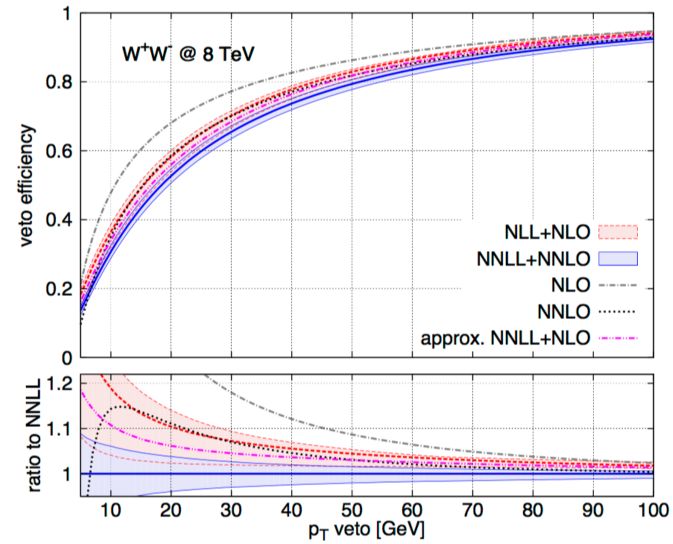
Process	zero-jet category		one-jet category	
	Different-flavor	Same-flavor	Different-flavor	Same-flavor
$q\bar{q} \to W^+W^-$	3516 ± 271	1390 ± 109	1113 ± 137	386 ± 49
$gg \to W^+W^-$	162 ± 50	91 ± 28	62 ± 19	27 ± 9
W^+W^-	3678 ± 276	1481 ± 113	1174 ± 139	413 ± 50
ZZ + WZ	84 ± 10	89 ± 11	86 ± 4	42 ± 2
VVV	33 ± 17	17 ± 9	28 ± 14	14 ± 7
top quark ($B_{t\text{-}tag}$)	522 ± 83	248 ± 26	1398 ± 156	562 ± 128
$Z/\gamma^* \to \ell^+\ell^-$	38 ± 4	141 ± 63	136 ± 14	65 ± 33
Wγ^*	54 ± 22	12 ± 5	18 ± 8	3 ± 2
Wγ	54 ± 20	20 ± 8	36 ± 14	9 ± 6
W + jets(e)	189 ± 68	46 ± 17	114 ± 41	16 ± 6
W + jets(μ)	81 ± 40	19 ± 9	63 ± 30	17 ± 8
Higgs boson	125 ± 25	53 ± 11	75 ± 22	22 ± 7
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

WW CMS 13TeV

EPJC 76 (2016) 401

arXiv:1507.02565

Uncertainty source	Propagation to cross section (%)
Experimental uncertainties	4.9
QCD scales and higher order effects	3.2
PDFs	0.4
Underlying event and parton shower	3.7
Non-prompt normalization	3.0
Top-quark normalization	2.0
$W\gamma^*$ normalization	0.3
Simulation and data control regions sample size	1.4
Total systematic uncertainty	7.4
Total statistical uncertainty	5.0
Luminosity	3.0
Total uncertainty	9.5

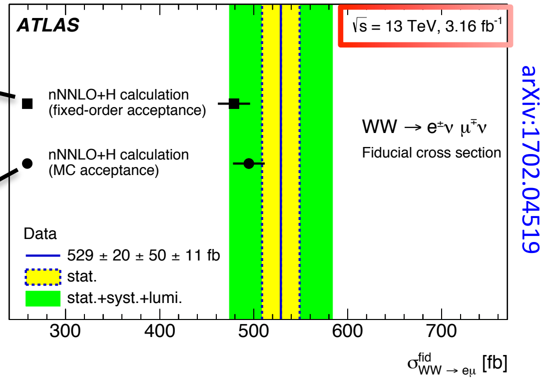


- reweghting the spectrum obtained using POWHEG to the analytical prediction obtained using the pT-resummation at next-to-next-to-leading logarithm precision
  - uncertainties in the theoretical modeling of the signal efficiency are estimated by varying indepedently the resummation, the factorization, and the renormalization scales in the analytical calculation of the *pT*WW spectrum
  - The uncertainty in the efficiency of the gg → W W component is determined by the variation of the renormalization and factorization scales in the theoretical calculation of this process. The propagation of these uncertainties in the signal acceptance, together with the effect of scale variations in the background simulations, yield an uncertainty of 3.2% in the measurement of the W+W− cross section.
- Experimental uncertainties: lepton reconstruction and identification efficiencies, efficiency to discriminate jets from b-quarks and jets from light quarks, uncertainties in the electron and muon energy scales, jet energy scale, and *E*miss energy scale and resolution

WW

NNLO (qq), NLO (gg), Powheg NLO(H)

Powheg NLO(qq,H), SherpaLO (ggWW)



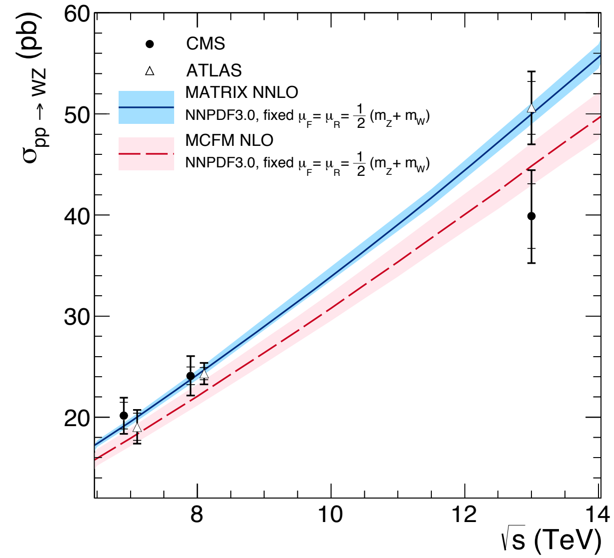
- The $q\bar{q} \rightarrow WW$ production cross section is known to O(α2s) (NNLO), the non-resonant gg sub-process is known to O(α3s) (NLO), and the resonant gg → $H \rightarrow W\,W$ cross section is calculated to O(α5s) (N3LO) taking into account the $H \rightarrow W\,W$ branching fraction (nNNLO+H)
- alternative prediction, the calculation for the nNNLO+H combination corrected by the acceptance A calculated using the MC event generator POWHEG-BOX v2 + PYTHIA v8.210 for the $q\bar{q}$ and resonant gg → H → WW processes, and SHERPA v2.1.1 for the non-resonant gg process. In this calculation the acceptance factor is estimated to be A = (16.4 ± 0.9) % where the uncertainty includes the parton shower modelling (taken as the difference between PYTHIA v8.210 and HERWIG++ showers), PDF uncertainty (estimated as the largest difference between the CT10 NLO eigenvector uncertainty band and the MSTW2008nlo and NNPDF3.0 PDF central values), scale uncertainty associated with the jet veto requirement and the residual renormalisation and factorisation scale uncertainty (estimated by varying the two scales independently by factors of 2 and 0.5)

- The nNNLO+H prediction agrees within uncertainties with the experimental cross-section measurement in the fiducial phase space.

WZ CMS

CMS-SMP-14-014, arXiv:1609.05721

Source	$\sqrt{s} = 7$ TeV				$\sqrt{s} = 8$ TeV			
	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Renorm. and fact. scales	1.3	1.3	1.3	1.3	3.0	3.0	3.0	3.0
PDFs	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Pileup	0.3	0.5	1.0	0.6	0.2	0.4	0.3	0.2
Lepton and trigger efficiency	2.9	2.7	2.0	1.4	3.4	2.5	2.5	3.2
Muon momentum scale	—	0.6	0.4	1.1	—	0.5	0.8	1.3
Electron energy scale	1.9	0.8	1.2	—	1.4	0.8	0.8	—
E_T^{miss}	3.7	3.4	4.3	3.7	1.5	1.5	1.6	1.2
ZZ cross section	0.5	0.9	0.6	0.9	0.1	0.1	0.1	0.1
Zγ cross section	0.0	0.0	0.1	0.0	0.2	0.0	0.2	0.0
$t\bar{t}$ and Z+jets	2.7	6.5	6.3	6.0	4.6	7.2	6.1	7.7
Other simulated backgrounds	0.2	0.2	0.9	0.2	1.0	1.1	1.1	1.0
Total systematic uncertainty	6.1	7.8	8.1	7.2	7.0	8.6	7.7	9.2
Statistical uncertainty	13.5	13.9	13.1	11.0	7.7	7.2	6.4	5.2
Integrated luminosity uncertainty	2.2	2.2	2.2	2.2	2.6	2.6	2.6	2.6



Sample	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	Total
$\sqrt{s} = 8$ TeV; $\mathcal{L} = 19.6$ fb^{-1}					
Non-prompt leptons	18.4 ± 12.7	32.0 ± 21.0	54.4 ± 33.0	62.4 ± 37.7	167.1 ± 55.8
ZZ	2.1 ± 0.3	2.4 ± 0.4	3.2 ± 0.5	4.7 ± 0.7	12.3 ± 1.0
Zγ	3.4 ± 1.3	0.4 ± 0.4	5.2 ± 1.8	0	9.1 ± 2.2
Wγ^*	0	0	0	2.8 ± 1.0	2.8 ± 1.0
VVV	6.7 ± 2.2	8.7 ± 2.8	11.6 ± 3.8	14.8 ± 5.1	41.9 ± 7.3
Total background (N_{bkg})	30.6 ± 13.0	43.5 ± 21.2	74.4 ± 33.3	84.7 ± 38.1	233.2 ± 56.3
WZ	211.1 ± 1.6	262.1 ± 1.8	346.7 ± 2.1	447.8 ± 2.4	1267.7 ± 4.0
Total expected	241.6 ± 13.1	305.7 ± 21.3	421.0 ± 33.3	532.4 ± 38.2	1500.8 ± 56.5
Data (N_{obs})	258	298	435	568	1559