



Multiboson measurements from CMS

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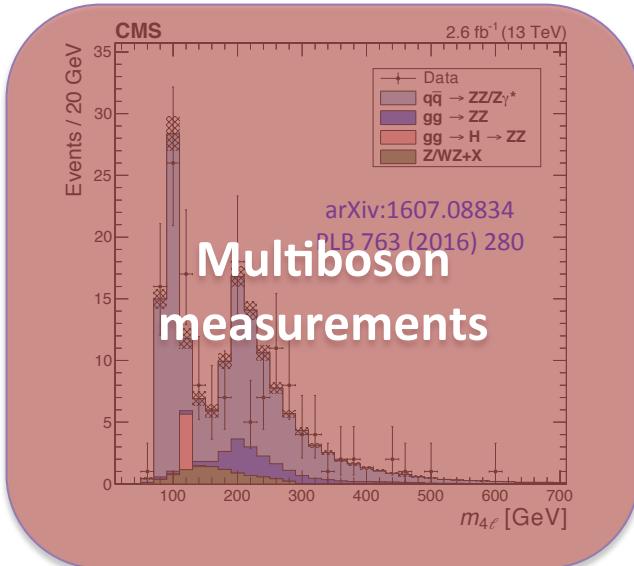
On behalf of the CMS Collaboration



Importance of multiboson measurements

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

→ Precision measurements are more important than ever !



Higher order perturbative corrections?

- Inclusive and differential cross section measurements

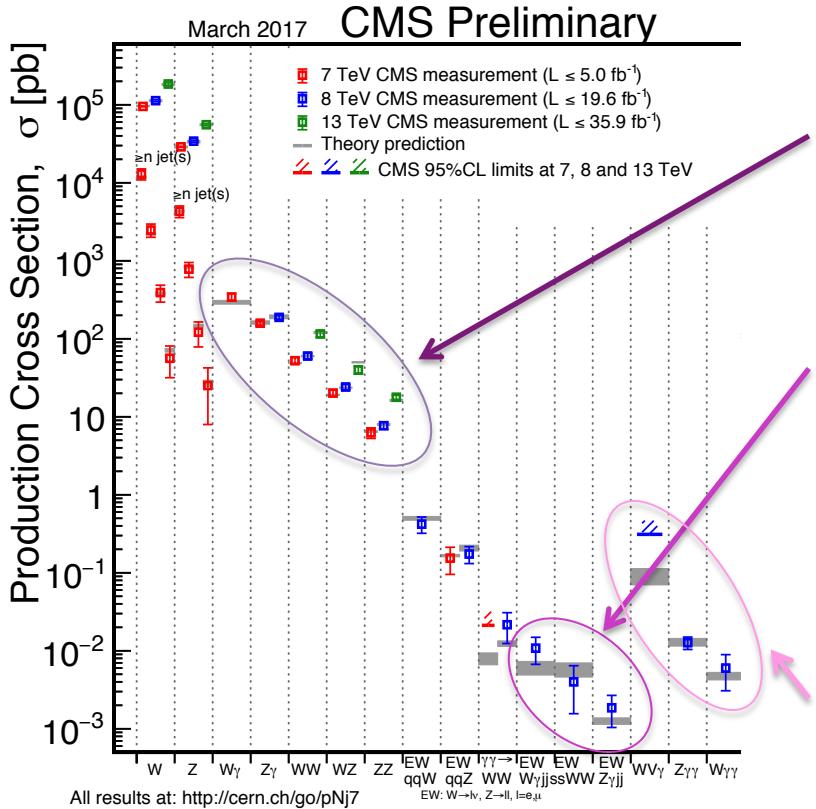
Nature of electroweak symmetry breaking?

- Electroweak diboson production via vector boson scattering

Signature of physics beyond SM above directly reachable energy?

- Search for accesses in high energy/mass tails of diboson production

Multiboson cross section at LHC



Inclusive (QCD) diboson production

Probing:

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

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)

Inclusive (QCD) triboson production

Probing:

- higher order QCD (and QED) perturbative corrections
- SM gauge structure: quartic gauge couplings (QGC)

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

- Multiboson measurements are probing weak boson self-interactions

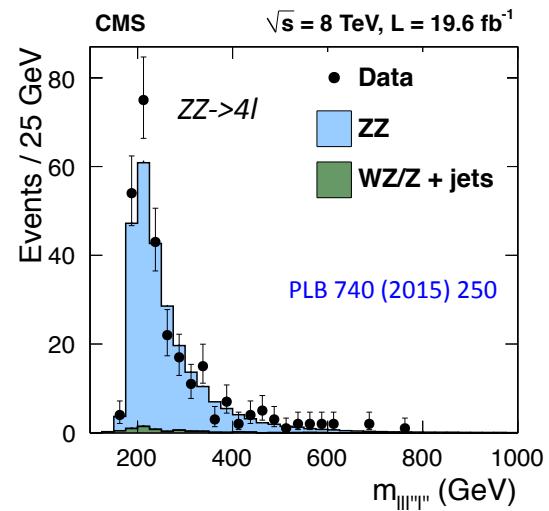
Multiboson decay channels

Fully leptonic channels:

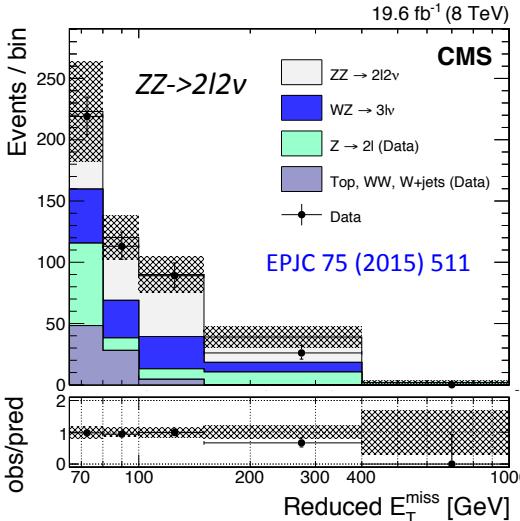
- Most precise measurements of the bulk of multiboson signal
- Total and differential cross section measurements

ZZ->4l:

- ✓ Clean signal signature
- ✓ Low background
- Small BR



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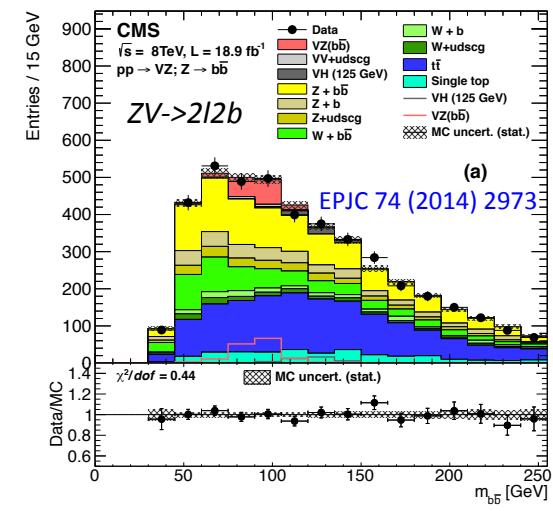
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Z->2v and V->jj channels:

- Access to higher pT/mass of the multiboson system
- Valuable for cross section measurement in high pT phase space and NP searches

ZZ->2l2v and ZZ->2l2j:

- Not clean signal signature
 - Large experimental systematic uncertainties
- Low signal to background except at high energy
- ✓ Larger BR



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Inclusive diboson cross section measurement summary (I/II)

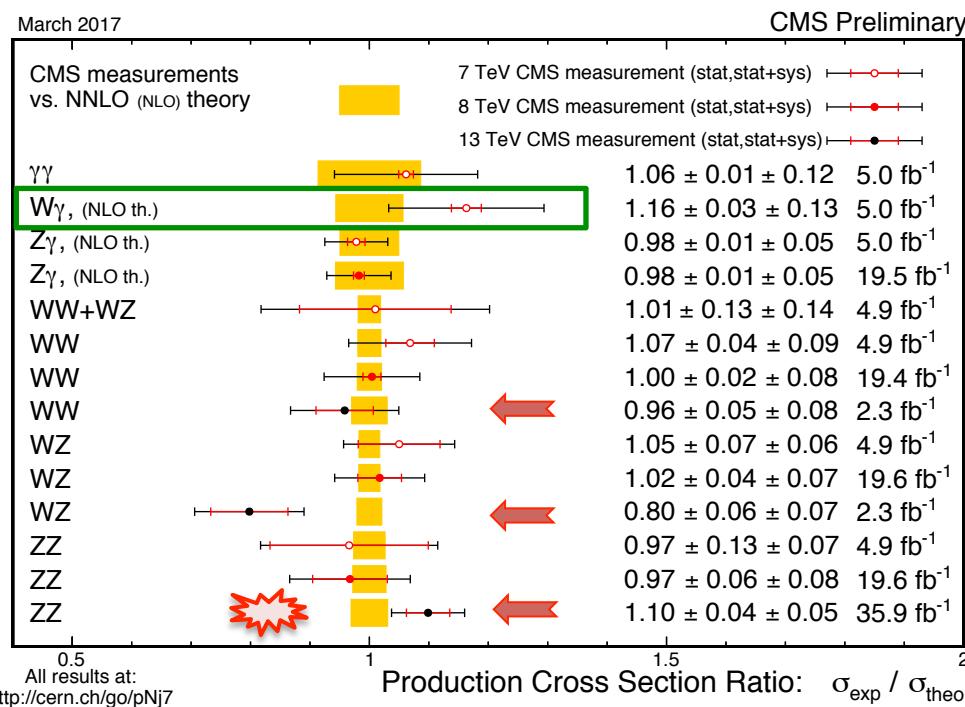


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arXiv.1504.01330

NNLO/NLO QCD k-factor ~ 1.2

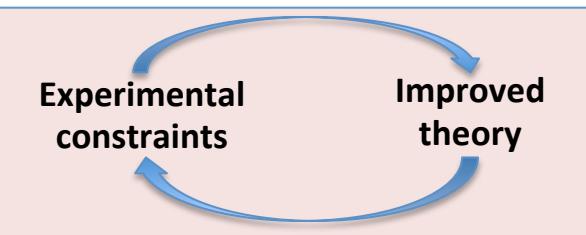
ZZ $\rightarrow 4l$: First diboson measurement with full 2016 dataset !



Several measurements available with 13 TeV data already available !

ZZ $\rightarrow 4l$ measurement statistical uncertainty: 6.5% (8 TeV) \rightarrow 3.3% (13 TeV)

Now, all diboson inclusive cross section measurements are already systematics dominated !

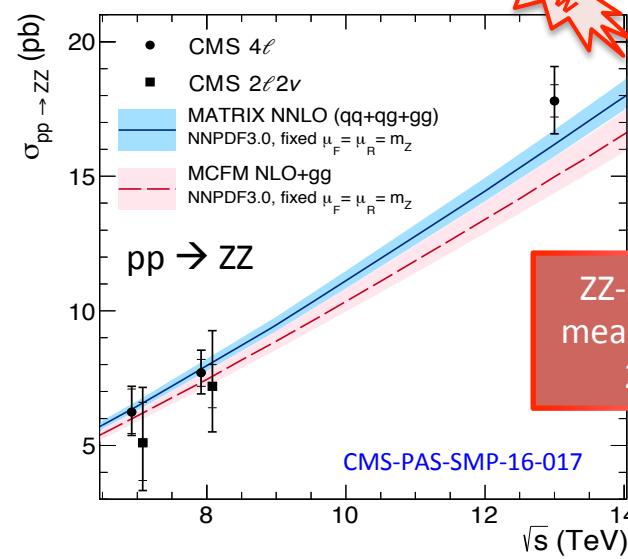
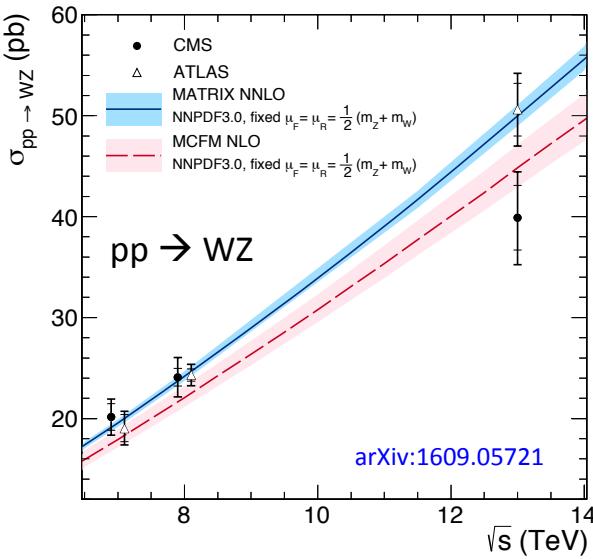


From theory side: NNLO QCD calculations now available for all diboson processes, including differential calculations !

Inclusive diboson cross section measurement summary (II/II)



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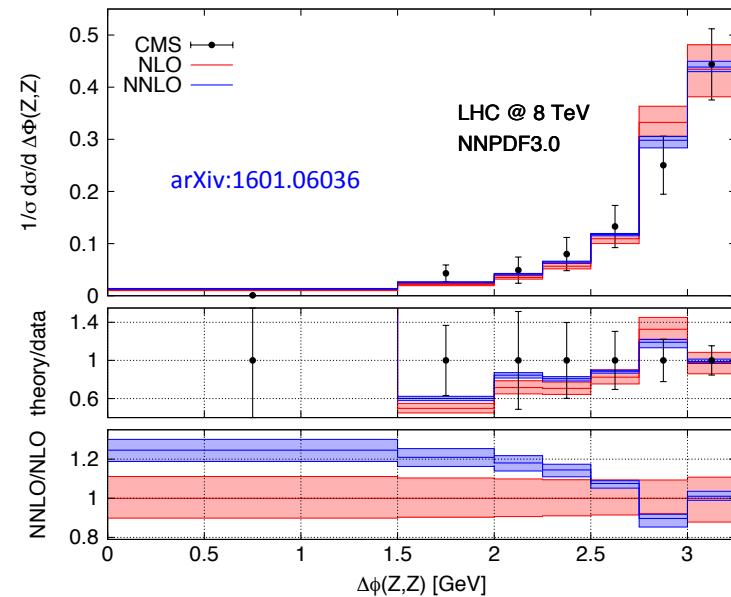
Uncertainties in inclusive diboson measurements:

Channel (fully leptonic)	\sqrt{s}	Dominant systematic uncertainty source	Syst/stat uncertainty w/o lumi (%)
WZ	8 TeV	uncertainty on background estimate	6.7 / 3.6
ZZ	13 TeV	lepton/trigger efficiency	3.6 / 3.3
WW	8 TeV	higher order corrections, UE, lepton efficiency	5.3 (exp) + 5.2 (theory) / 1.5
Wγ	7 TeV	uncertainty on background estimate	10.8 / 2.2
Zγ	8 TeV	uncertainty on background estimate	4.8 / 1.0

Importance of differential cross section measurements

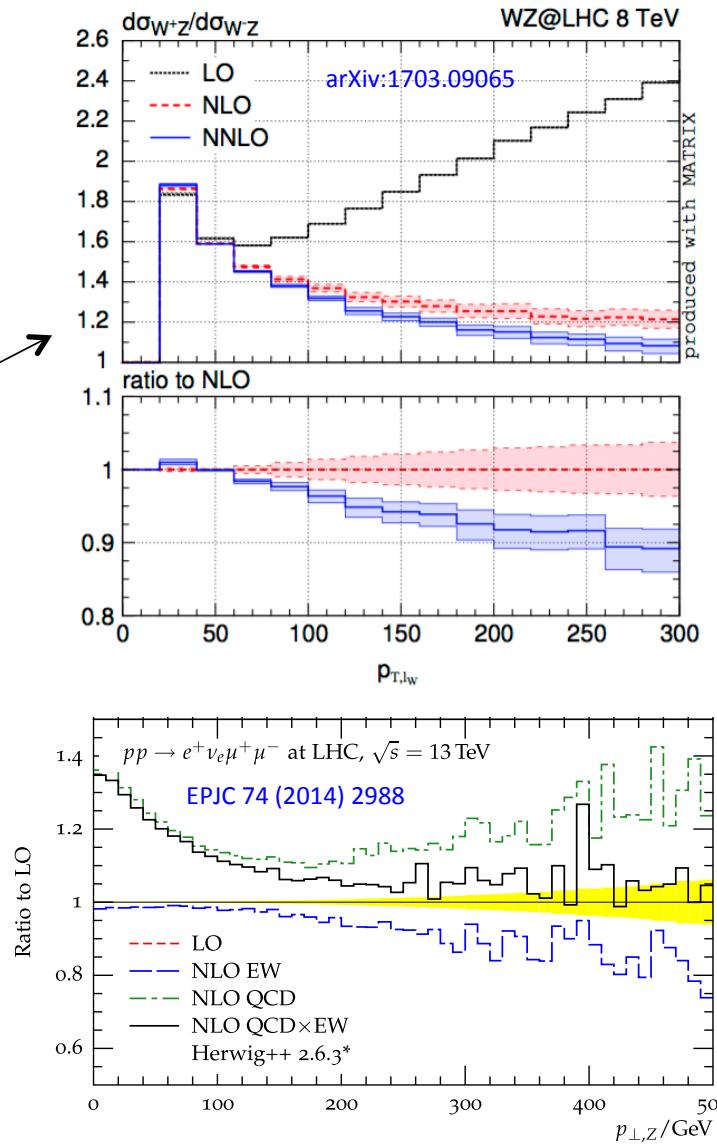
Jet related observables allow direct probe of higher order corrections \longleftrightarrow **Differential measurements**

- **Look for differences of shape in sensitive observables**
- Absolute measurement: measurement of absolute cross section per bin
- Normalized measurement: measurement of shape (significant cancellation of systematic uncertainties)
- More possibilities with larger statistics: ratios of production processes



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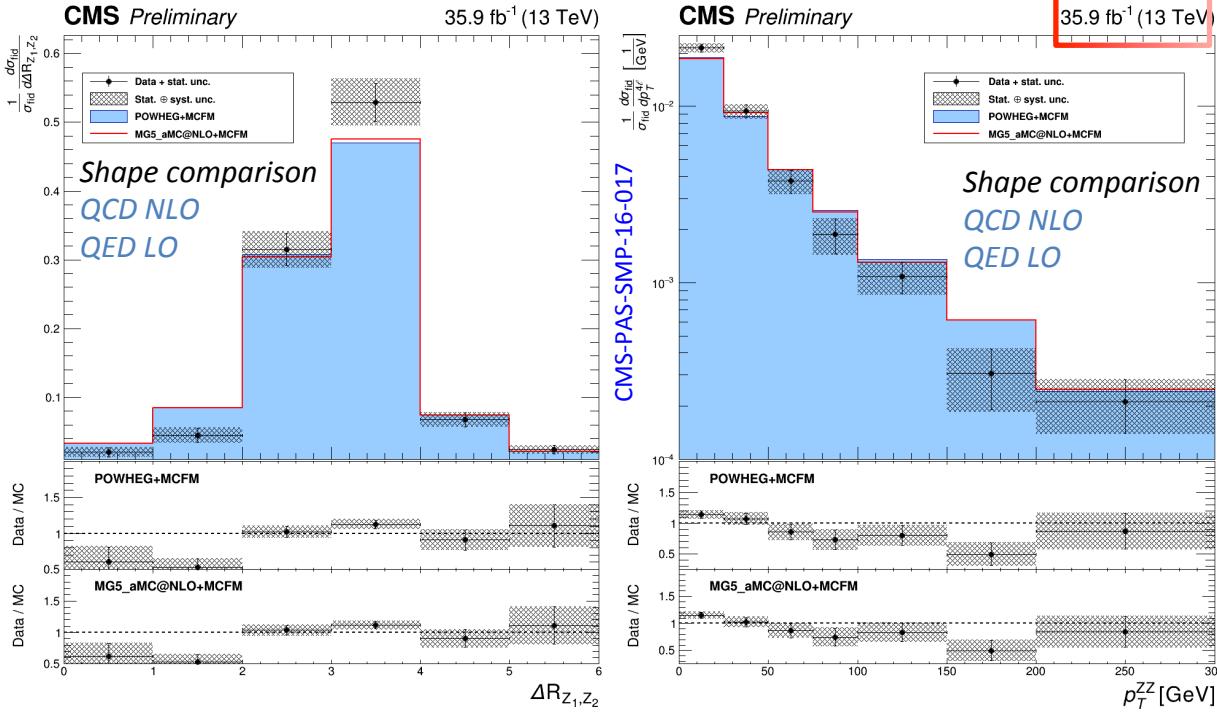
Expecting sizable effect from NNLO QCD and NLO QED in high pT and angular distributions of the diboson system

New differential measurements: ZZ->4l



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

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



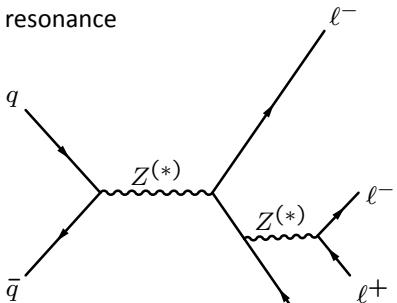
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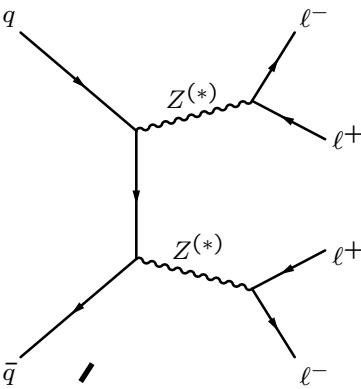
- Possible indication of softer p_T^{4l} than predicted by NLO QCD
- Data elsewhere are well reproduced by the simulation

ZZ production modes

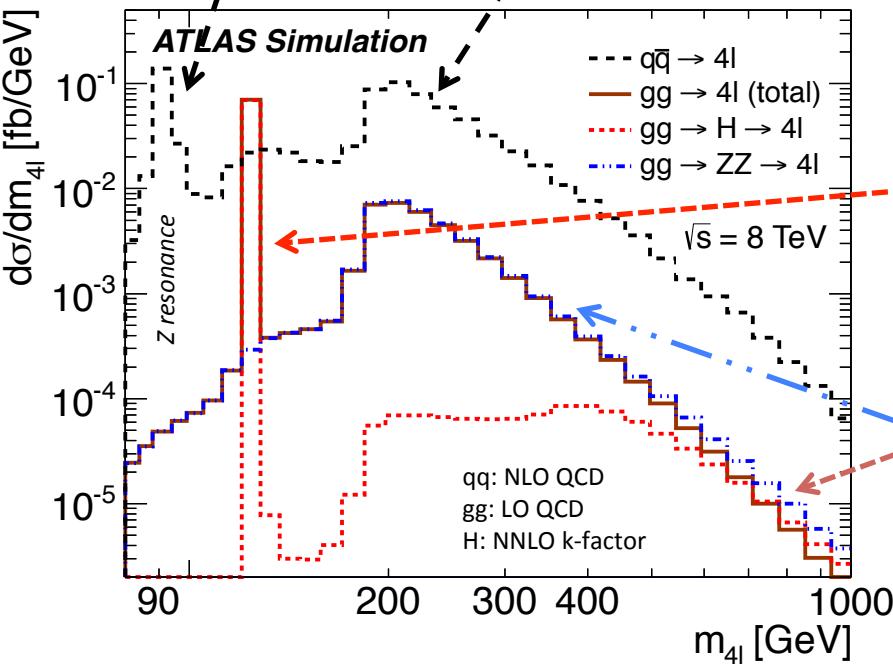
Dominant 4l production at Z resonance



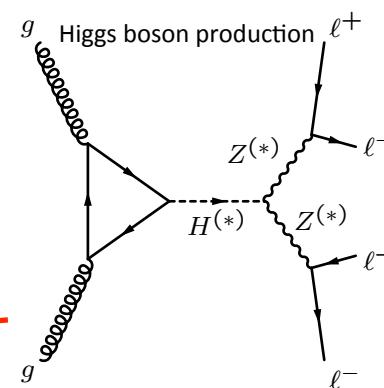
Dominant 4l production above the Z resonance



+ small contribution from qq VBS production

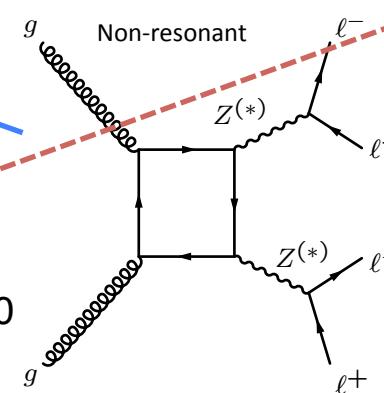


M_{4l} spectrum is essential for the study of the different production mechanisms !



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

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

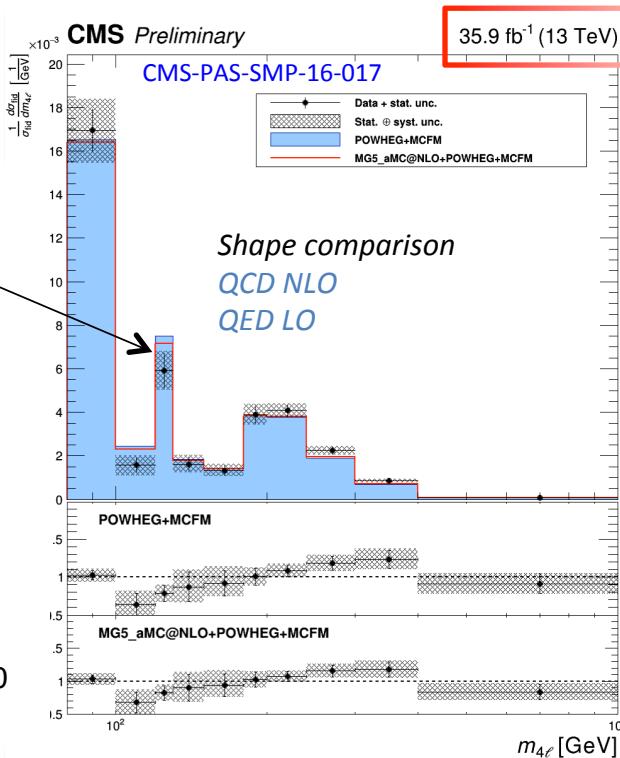
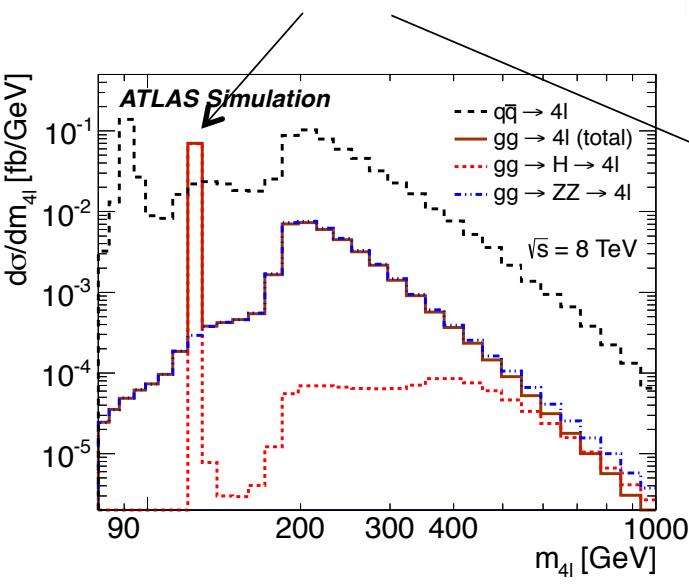


New differential measurements: ZZ->4l

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

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$\text{ZZ} \rightarrow 4\ell$	$60 < m_{Z_1}, m_{Z_2} < 120 \text{ GeV}$

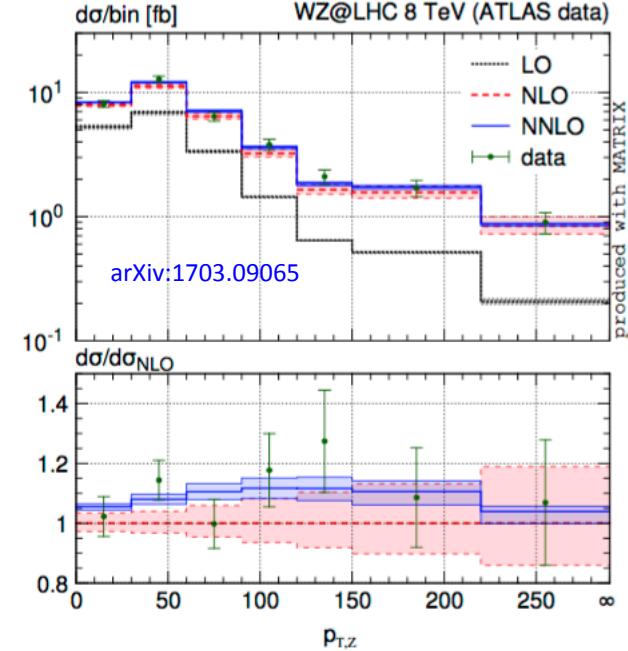
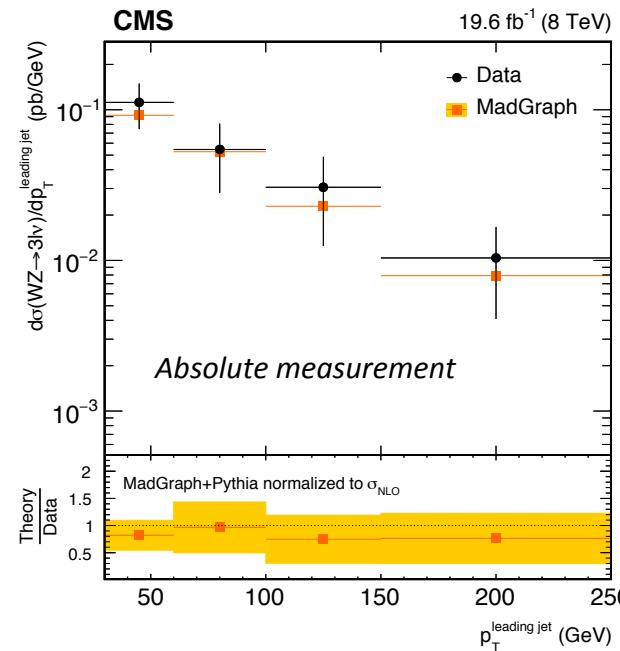
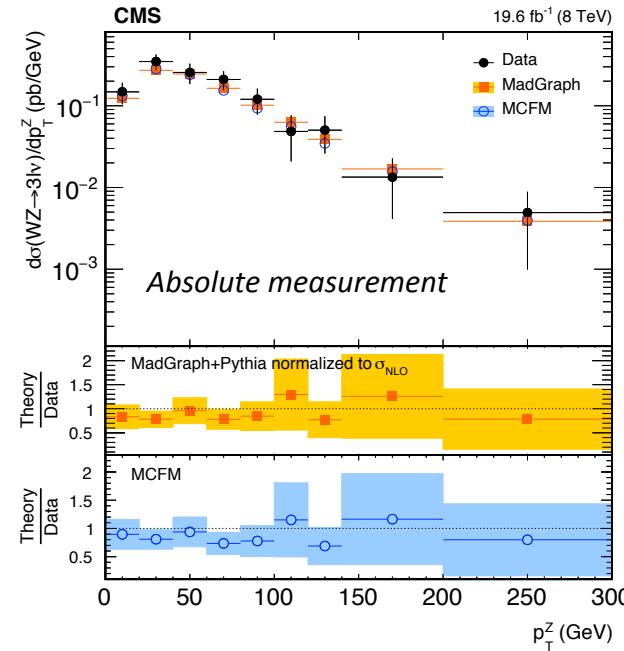
dominated by the resonant
Higgs boson contribution



- Other then ZZ on-shell, including contributions from the Z and Higgs boson resonances and continuum ZZ production
- With full 2016 dataset starting to be sensitive to differences in shape

New differential measurements: WZ \rightarrow 3l ν (8 TeV)

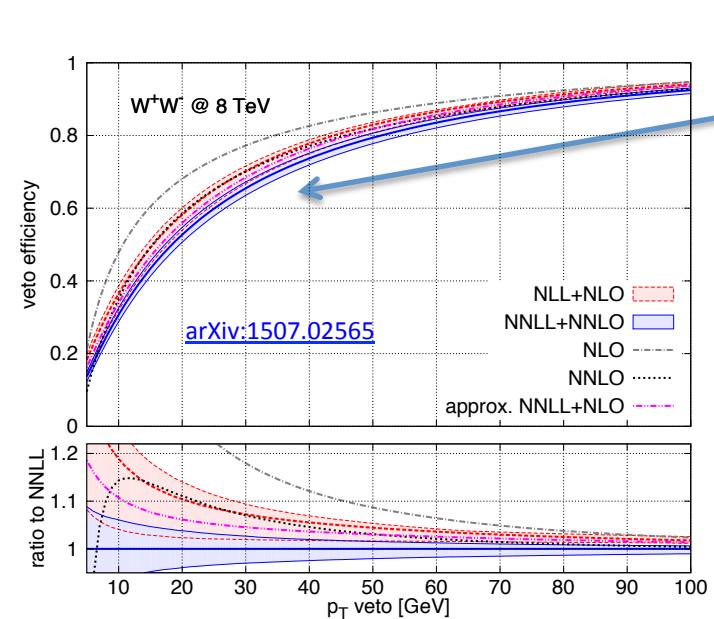
- Overall (non significant) higher yield in agreement with expected NNLO QCD corrections ($\sim 11\%$) is observed
- Decrease in uncertainties needed to probe differences in shape



Differential measurements: WW (8 TeV) importance of higher order corrections



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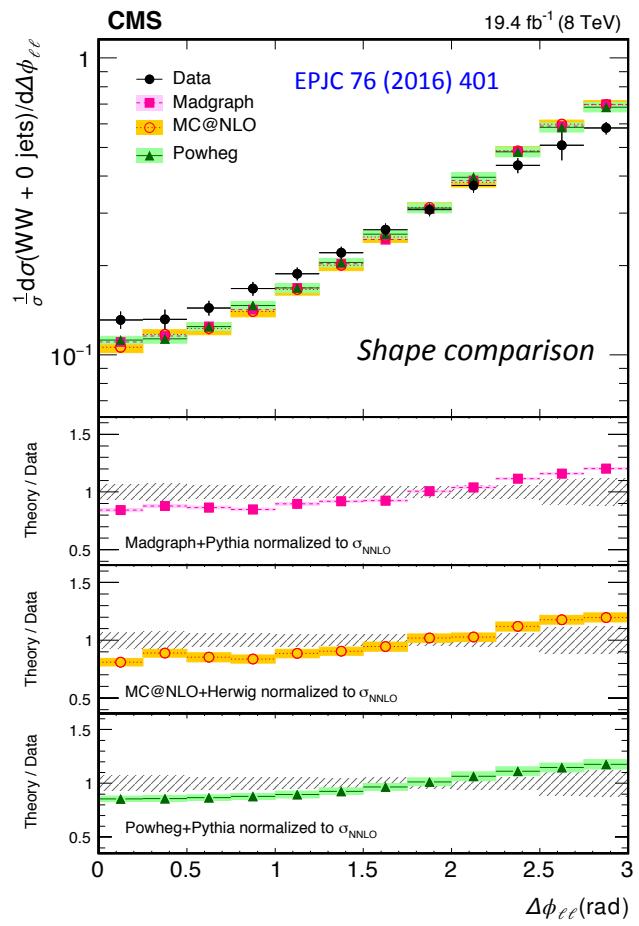


p_T^{jet} (GeV)	$\sigma_{\text{zero-jet}} \text{ measured (pb)}$	$\sigma_{\text{zero-jet}} \text{ predicted (pb)}$
>20	$36.2 \pm 0.6 \text{ (stat)} \pm 2.1 \text{ (exp)} \pm 1.1 \text{ (theo)} \pm 0.9 \text{ (lumi)}$	$36.7 \pm 0.1 \text{ (stat)}$
>25	$40.8 \pm 0.7 \text{ (stat)} \pm 2.3 \text{ (exp)} \pm 1.3 \text{ (theo)} \pm 1.1 \text{ (lumi)}$	$40.9 \pm 0.1 \text{ (stat)}$
>30	$44.0 \pm 0.7 \text{ (stat)} \pm 2.5 \text{ (exp)} \pm 1.4 \text{ (theo)} \pm 1.1 \text{ (lumi)}$	$43.9 \pm 0.1 \text{ (stat)}$

Differential distributions show good agreement with several predictions from NLO perturbative QCD calculations. Some differences observed in $\Delta\phi_{\parallel}$ distributions.

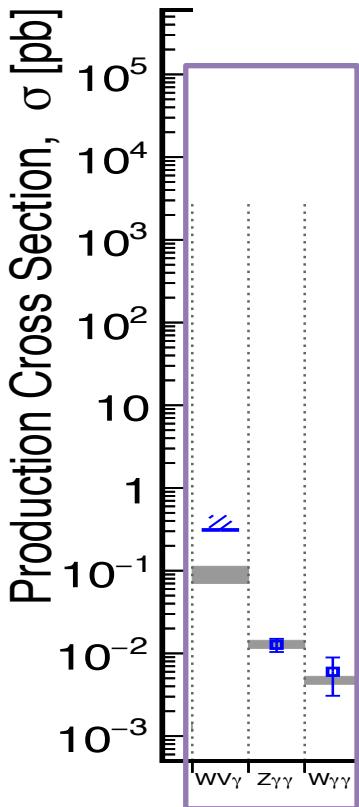
Due to large $t\bar{t}$ background **WW measurement is performed applying a jet veto (0- or 1-jet events only)**

- 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!**



Rare processes: Triboson measurements

- 7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
- 13 TeV CMS measurement ($L \leq 2.7 \text{ fb}^{-1}$)
- Theory prediction
- ✗ CMS 95%CL limit



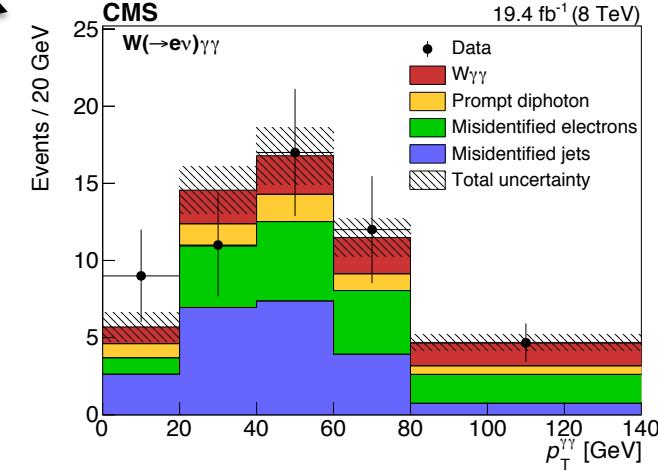
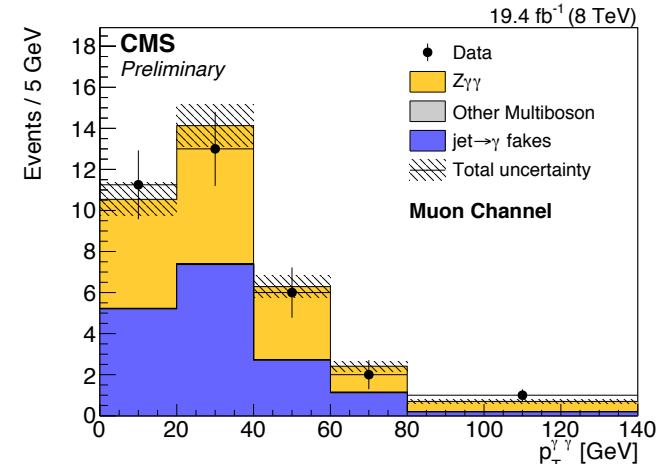
W $\gamma\gamma$ and Z $\gamma\gamma$:

- Measurements dominated by systematic uncertainty on background (jets misidentified as photons)

New in W $\gamma\gamma$: added electron channel

Triboson measurements	CMS (8 TeV)
W $\gamma\gamma \rightarrow l\nu jj\gamma$	PRD 90 (2014) 032008 Upper limit on cross section and aQGC measurement
W $\gamma\gamma \rightarrow l\nu\gamma\gamma$	CMS-PAS-SMP-15-008, arxiv:1704.00366 Cross section and aQGC measurement signal significance 2.6σ
Z $\gamma\gamma \rightarrow ll\gamma\gamma$	CMS-PAS-SMP-15-008 <u>Observation:</u> signal significance 5.9σ

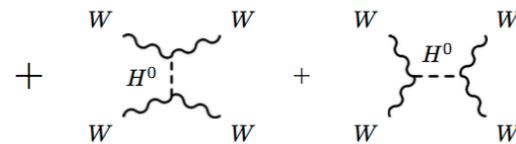
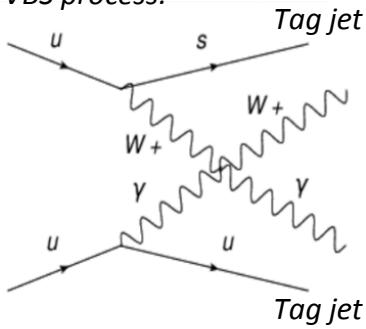
First observation of triboson production: Z $\gamma\gamma$!



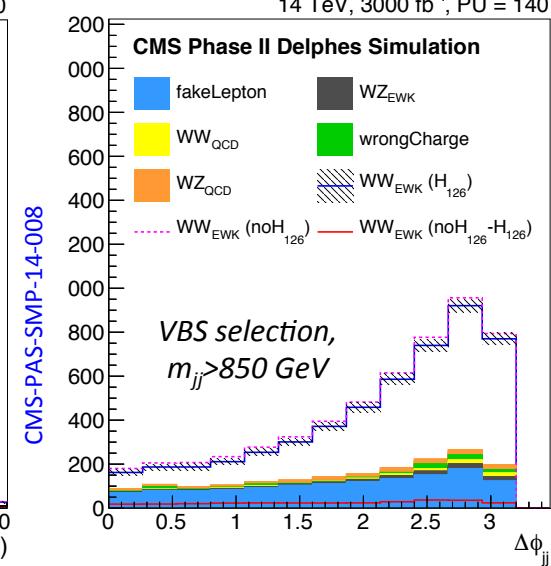
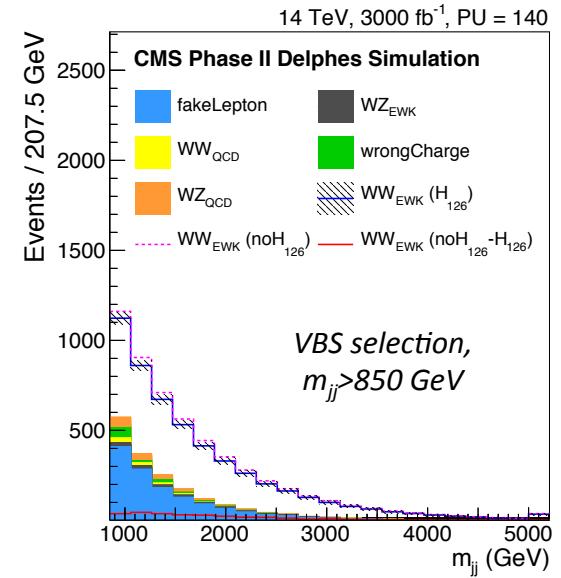
EWK (QED) diboson production

- **VV+2jets production is dominated by $O(\alpha_s^2)$ QCD processes**
- **EWK VV+2jets production is essential to probe the nature of the EWSB**
 - **$V_L V_L$ scattering** linked to the mechanism responsible for the EWSB

VBS process:



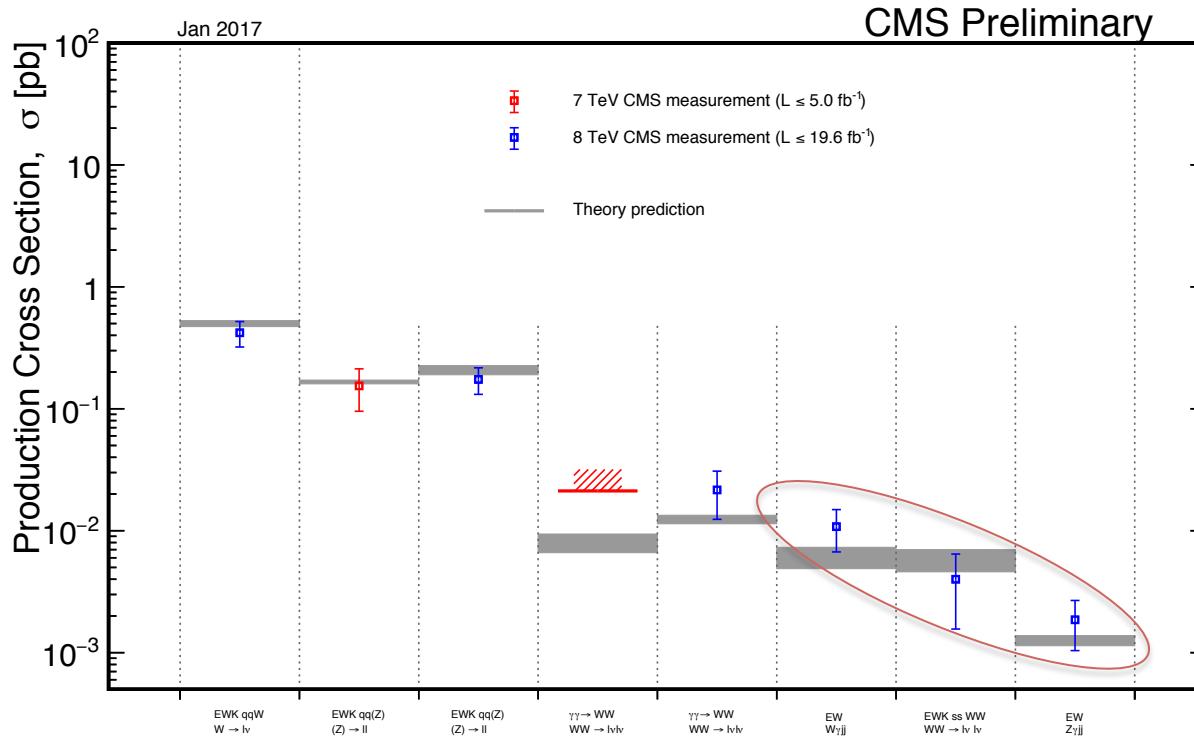
HL-LHC prospects:



VBS characteristic signature:

- Two high p_T jets in the forward-backward region
- Large rapidity separation between jets ($\Delta\eta_{jj}$)
 - low hadronic activity in-between
- Large di-jet invariant mass (M_{jj})

EWK (QED) diboson production: results



EWK measurements: VV+2jets	CMS (8 TeV)
$W^\pm W^\pm \rightarrow l\nu l\nu$	PRL 114 (2015) 051801 EWK signal significance 1.9σ (exp 2.9σ)
$W\gamma \rightarrow l\nu\gamma$	CMS-PAS-SMP-14-011 EWK signal significance 2.7σ (exp 1.5σ)
$Z\gamma \rightarrow ll\gamma$	CMS-PAS-SMP-14-018 Evidence: EWK signal significance 3.0σ (exp 2.1σ)

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

Anomalous couplings as a search for New Physics?

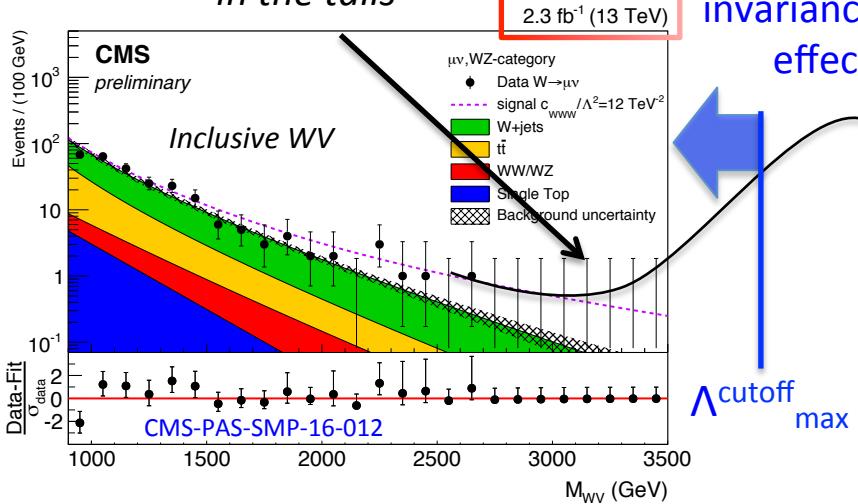
SM precision measurements

Anomalous coupling parameters (EFT,...)

Specific BSM model

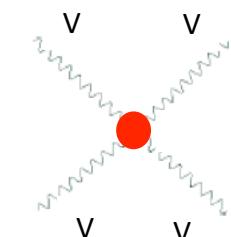
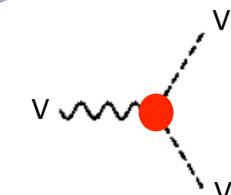
Mostly probing strongly coupled BSM (weakly coupled needs resonant enhancement)

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



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

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

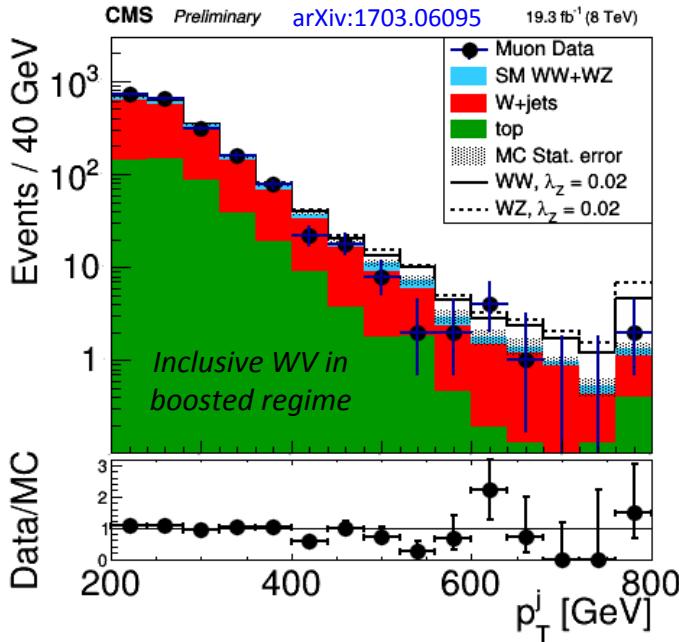
Anomalous couplings: variety of measurements

Measurements performed in numerous production channels:

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

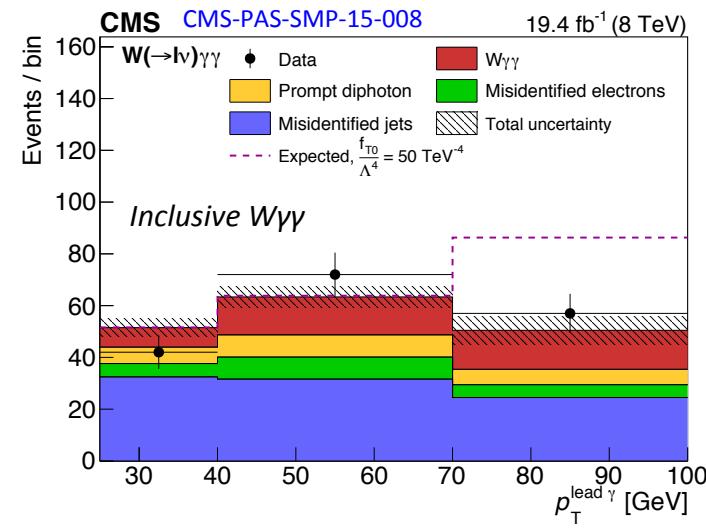
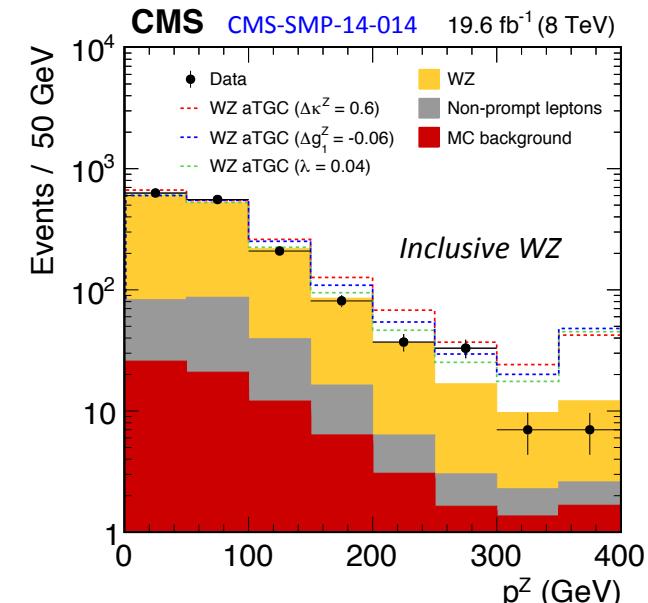
Limiting factor: observed statistics in the tail (primary), systematic and statistical uncertainty on the signal/bkg model (secondary)

No significant deviation of data from SM expectation is observed



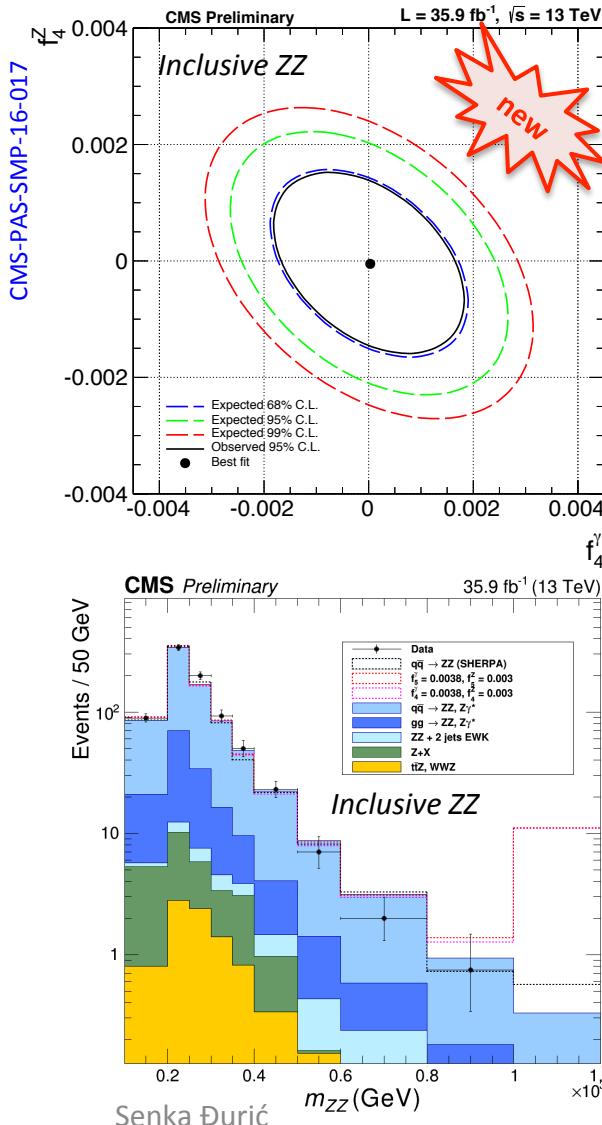
Anomalous couplings result in an **increase of cross section at high energies**

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

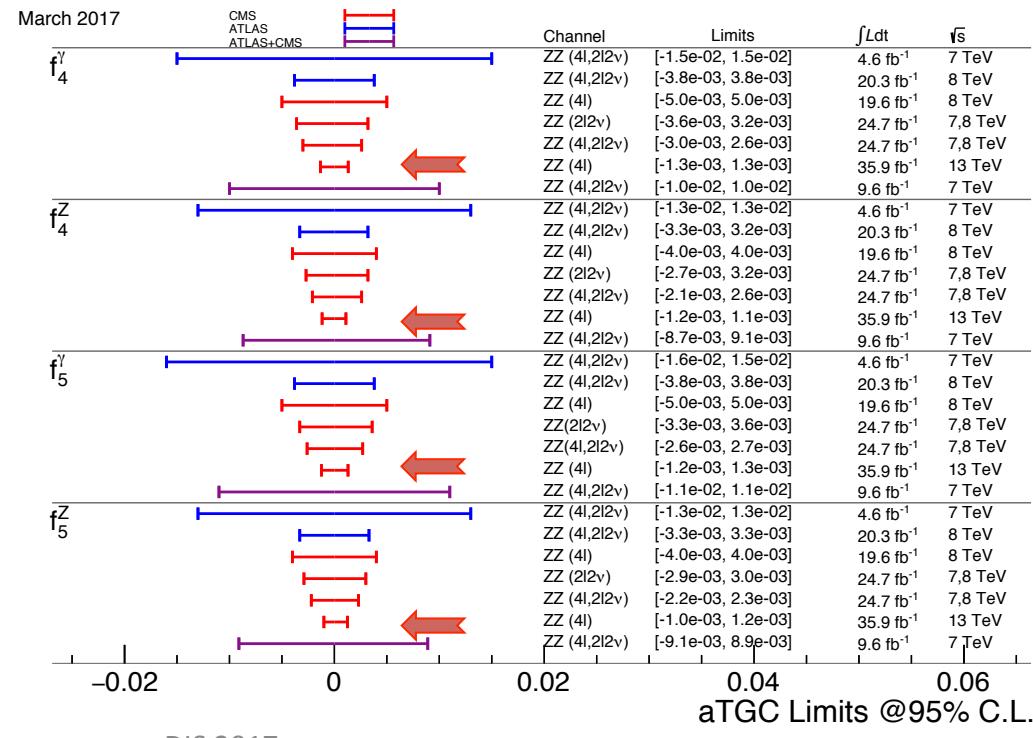


Anomalous couplings: results

LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) tighter than 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 \sqrt{s}



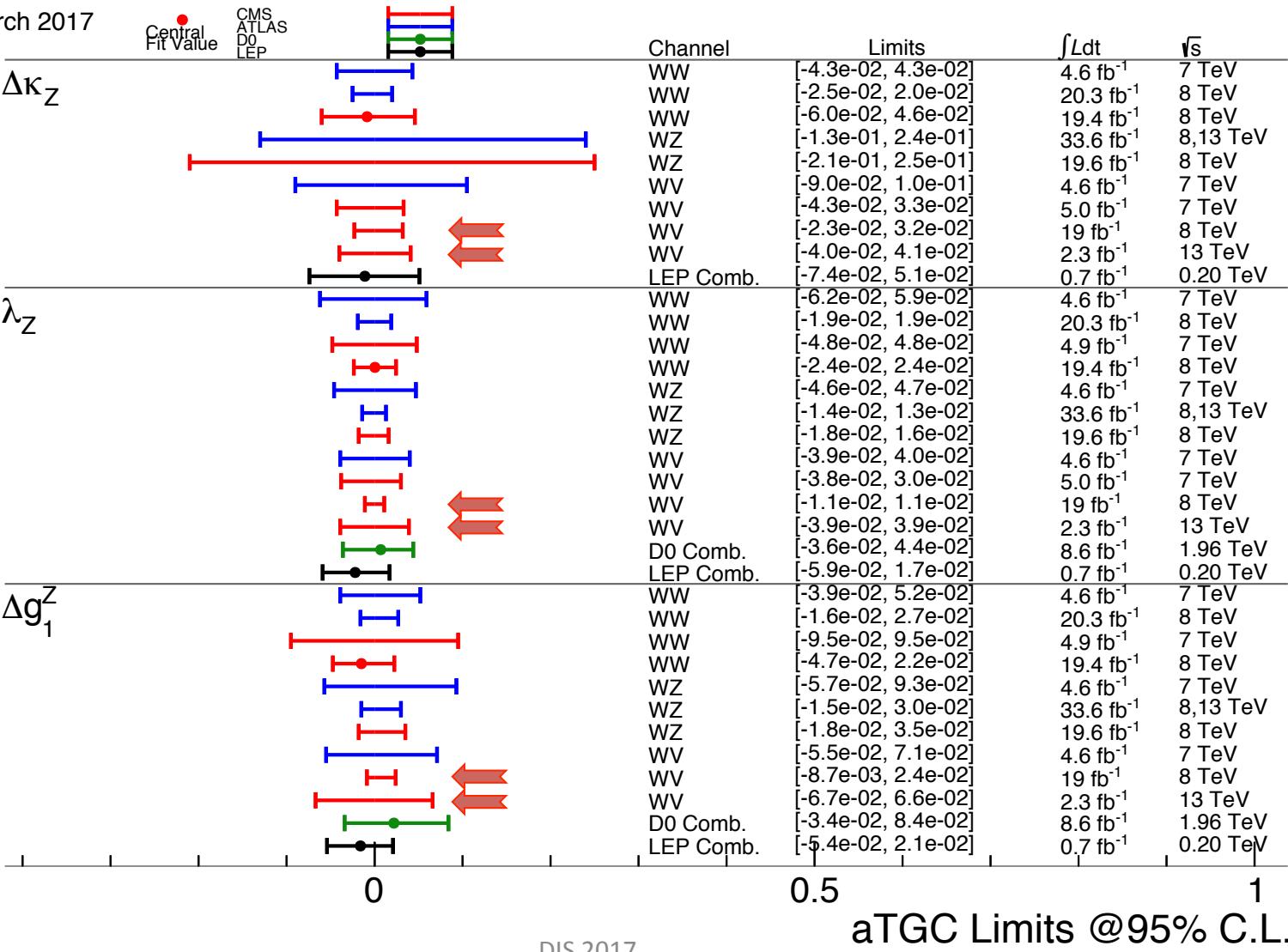
Recent measurement
with 13 TeV data!

Anomalous couplings: results

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

March 2017

Central Fit Value
CMS
ATLAS
D0
LEP



Recent measurement
with 8 and 13 TeV data!

Probing scales
of $\Lambda^n = c_i^{(n)} / \Lambda^n$
limits are set
in the limit of strong coupling
($c_i = 4\pi$) for dim6 ($n=2$)

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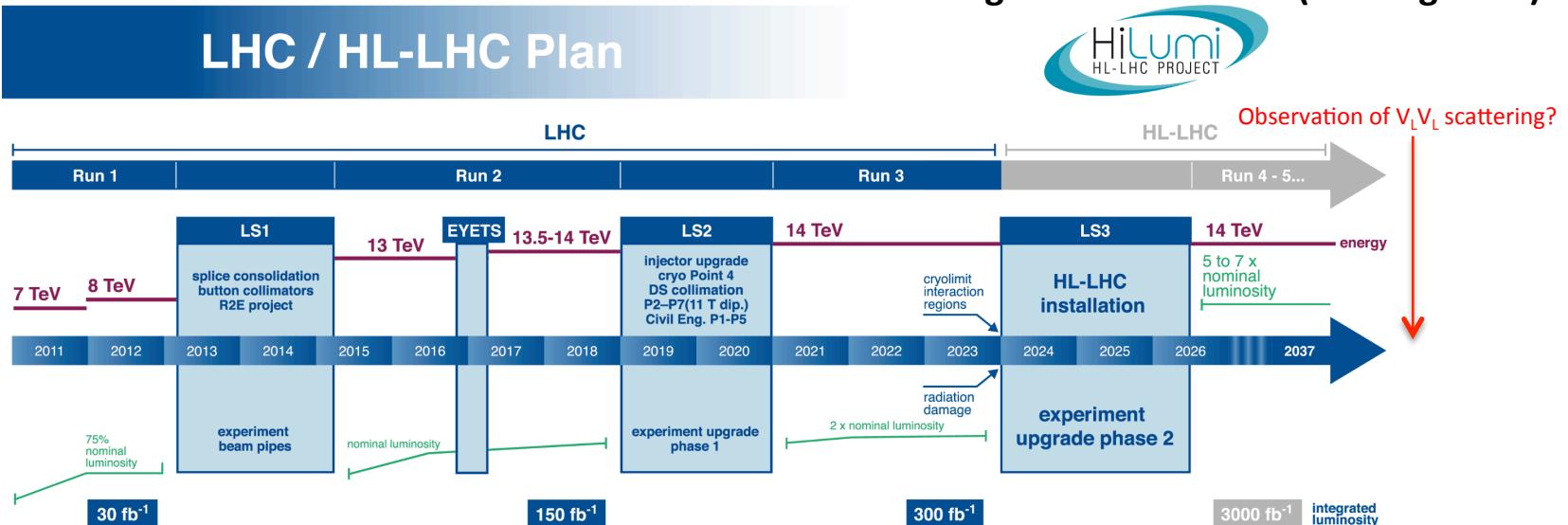
aTGC Limits @ 95% C.L.
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The present and the future of multiboson physics

LHC Run2 is ongoing, so far $\sim 40 \text{ fb}^{-1}$ of data collected by CMS experiments

- Variety of multiboson measurements performed: inclusive and differential cross sections
 - Measurements are pushing for more precise theoretical calculations (NNLO or 3NLO QCD, NLO EWK, ...)
 - Future prospects: increase in sensitivity to higher order perturbative corrections and different production mechanisms, self-consistency check and combinations for anomalous couplings
- Expect 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)





Backup



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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
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	Cross section, differential and aTGC
ZZ->2l2v	JHEP01, 099 (2017) Cross section, differential, aTGC	-	EPJC 75 (2015) 511 Cross section and aTGC measurement	-
Zγ->lly	PRD 93, 112002 (2016) Cross section, differential and aTGC measurement	-	JHEP 04 (2015) 164 Cross section and aTGC measurement	-
Zγ->vvγ		-	PLB 760 (2016) 448 Cross section and aTGC measurement	CMS-PAS-SMP-16-004 Cross section
WW->lvlv	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->3lv	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 Cross section, differential and aTGC measurement	arXiv:1607.06943 (CMS-PAS-SMP-16-002) (2.3 fb-1) Cross section
WV->lvjj	-	-	arXiv:1703.06095 aTGC measurement	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 leptonically
- Not clean signature but large branching ratio for hadronic decays



Triboson and rare processes measurements: overview



Triboson measurements		ATLAS	CMS
8 TeV	$W\gamma\gamma \rightarrow l\nu jj\gamma$	-	PRD 90 (2014) 032008 Upper limit on cross section and aQGC measurement
	$W\gamma\gamma \rightarrow l\nu\gamma\gamma$	PRL 115, 031802 (2015) Cross section (inclusive and exclusive) and aQGC measurement Evidence: signal significance $>3\sigma$	CMS-PAS-SMP-15-008, arxiv:1704.00366 Cross section and aQGC measurement signal significance 2.6σ
	$Z\gamma\gamma \rightarrow ll\gamma\gamma$	PRD 93, 112002 (2016) Observation: signal significance 6.3σ	CMS-PAS-SMP-15-008 Observation: signal significance 5.9σ
	$WW\gamma \rightarrow l\nu l\nu jj, l\nu l\nu l\nu$	ATLAS-STDM-2015-07 Upper limit on cross section and aQGC measurement	-

Rare processes		ATLAS	CMS
7 TeV	$W^+W^- \rightarrow \gamma\gamma \rightarrow l\nu l\nu$ exclusive	-	JHEP 08 (2016) 119 Evidence: signal significance 3.4σ (exp 2.8σ) aQGC measurement
8 TeV		PRD 94 (2016) 032011 Evidence: signal significance 3σ aQGC measurement, search for exclusive Higg production	

For the first time, evidence and observations of triboson and exclusive WW production!

EWK results: overview

VBS measurements (VV+2jets)		ATLAS	CMS
8 TeV	EWK $W^\pm W^\pm \rightarrow l\bar{v}l\bar{v}$	<p>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</p>	<p>PRL 114 (2015) 051801 Cross section (EWK+QCD) and aQGC measurement EWK signal significance 1.9σ (exp 2.9σ)</p>
	EWK $W\gamma \rightarrow l\bar{v}\gamma$	-	<p>CMS-PAS-SMP-14-011 Cross section (EWK, EWK+QCD) and aQGC measurement EWK signal significance 2.7σ (exp 1.5σ)</p>
	EWK $Z\gamma \rightarrow l\bar{l}\gamma$	<p>STDM-2015-21 Cross section (EWK, EWK+QCD), aQGC measurement EWK signal significance 2.0σ (exp 1.8σ)</p>	<p>CMS-PAS-SMP-14-018 Cross section (EWK, EWK+QCD) and aQGC measurement Evidence: EWK signal significance 3.0σ (exp 2.1σ)</p>
	EWK $WZ \rightarrow l\bar{l}ll$	<p>Phys. Rev. D 93, 092004 (2016) Cross section (EWK, EWK+QCD) measurement</p>	<p>PRL 114 (2015) 051801 Cross section (EWK+QCD) measurement</p>
	EWK $WW \rightarrow l\bar{v}jj$	<p>PRD 95 (2017) 032001 aQGC measurement</p>	-
VBF measurements (V+2jets)		ATLAS	CMS
8 TeV	EWK $Z(l\bar{l})$	<p>JHEP 04 (2014) 031 Cross section (EWK) and aTGC measurement Observation: EWK signal significance $\sim 5\sigma$ ()</p>	<p>EPJC 75 (2015) 66 Cross section (EWK) measurement Observation: EWK signal significance $\sim 5\sigma$</p>
	EWK $W(l\bar{v})$	<p>arXiv:1703.04362 Cross section (EWK, EWK+QCD), differential (EWK, EWK+QCD), aTGC measurement Observation: EWK signal significance $> 5\sigma$</p>	<p>CMS-PAS-SMP-13-012, arXiv:1607.06975 Cross section (EWK) measurement Evidence: EWK signal significance $\sim 4\sigma$</p>

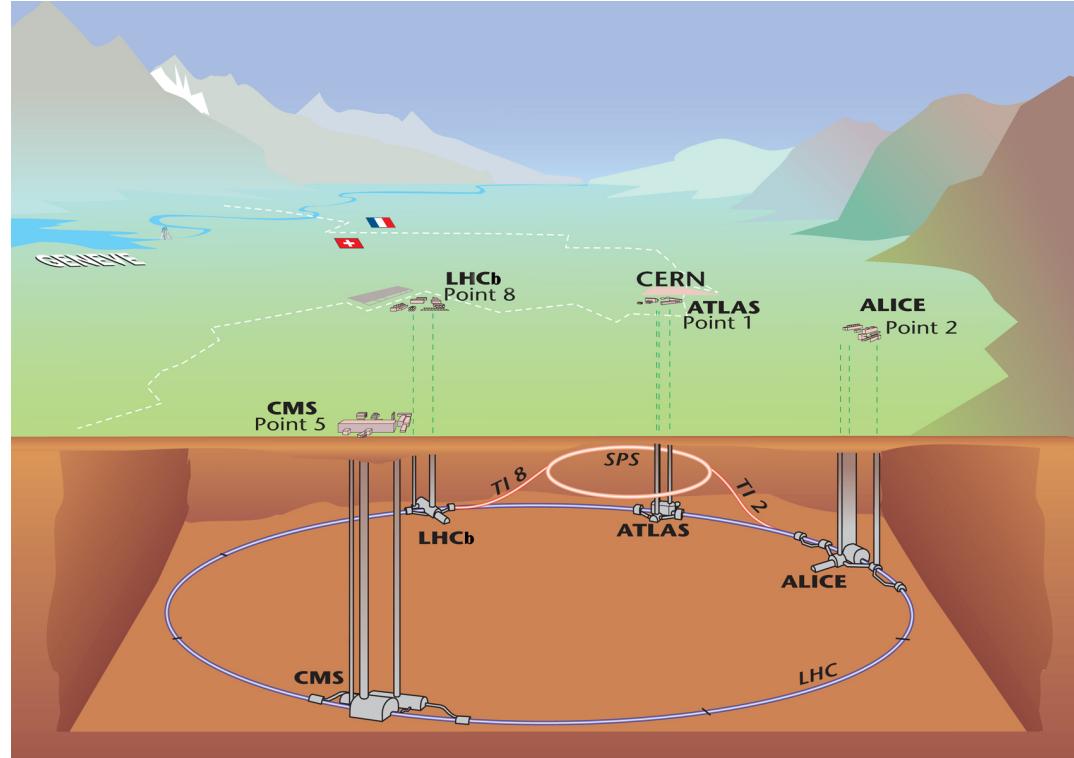
+ some measurements also with 7 TeV !



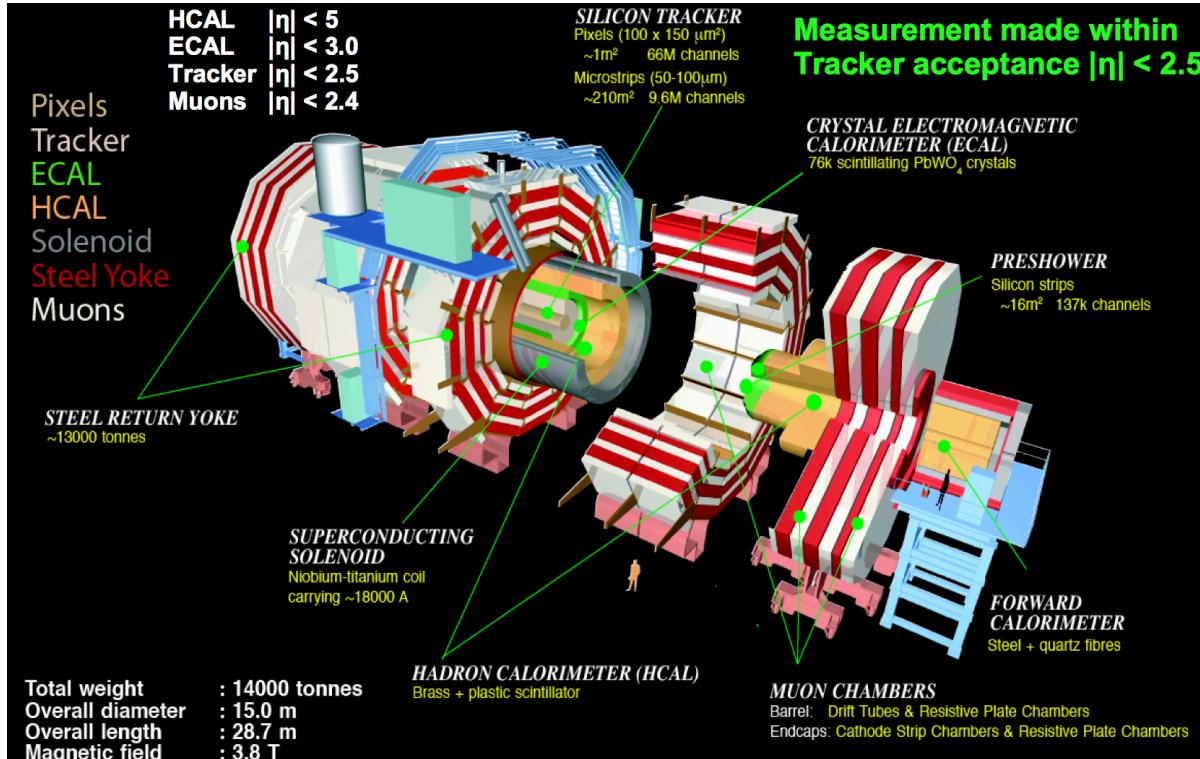
LHC experiments



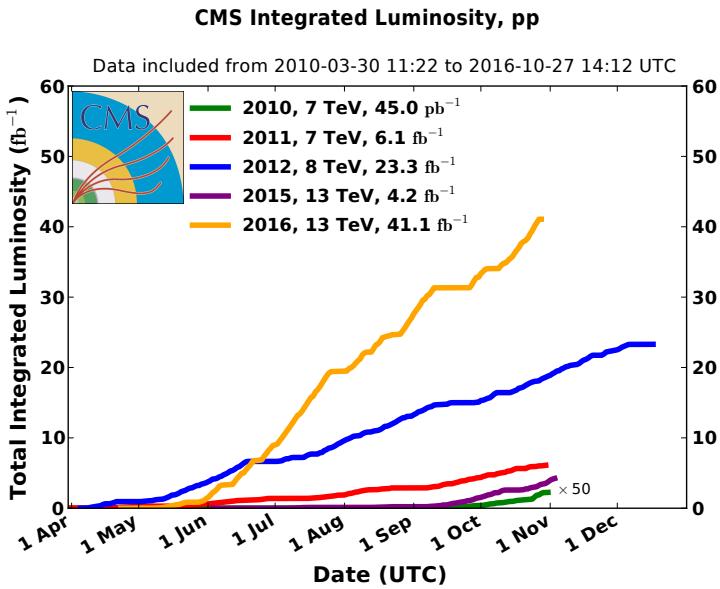
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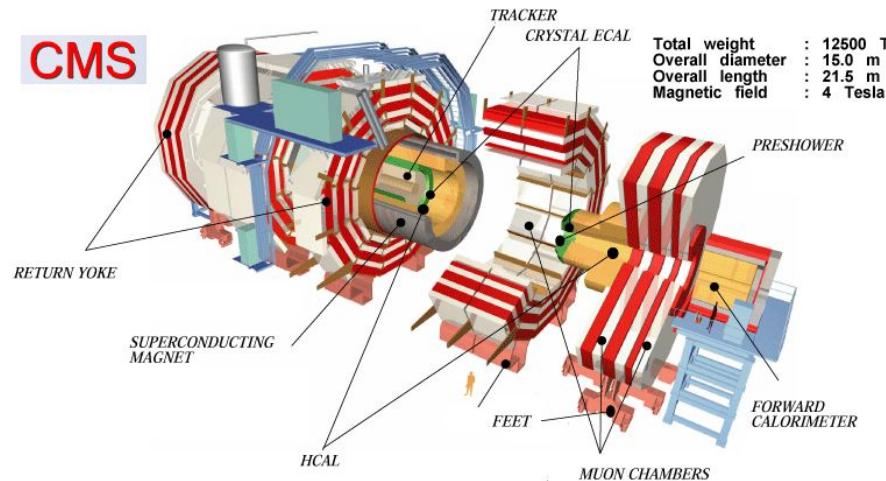
CMS experiment



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 !





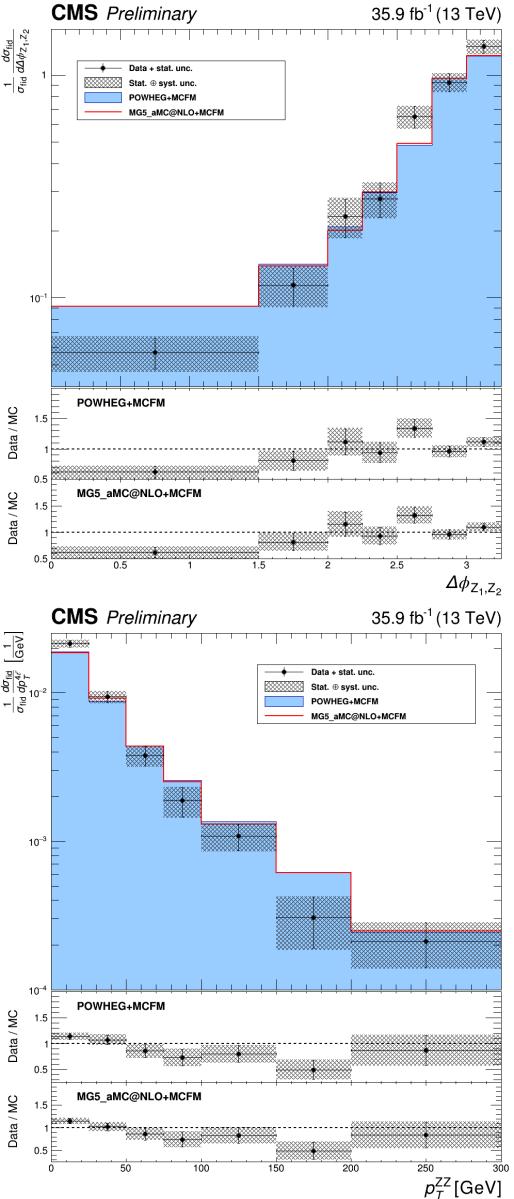
ZZ normalized differential with full 2016 data



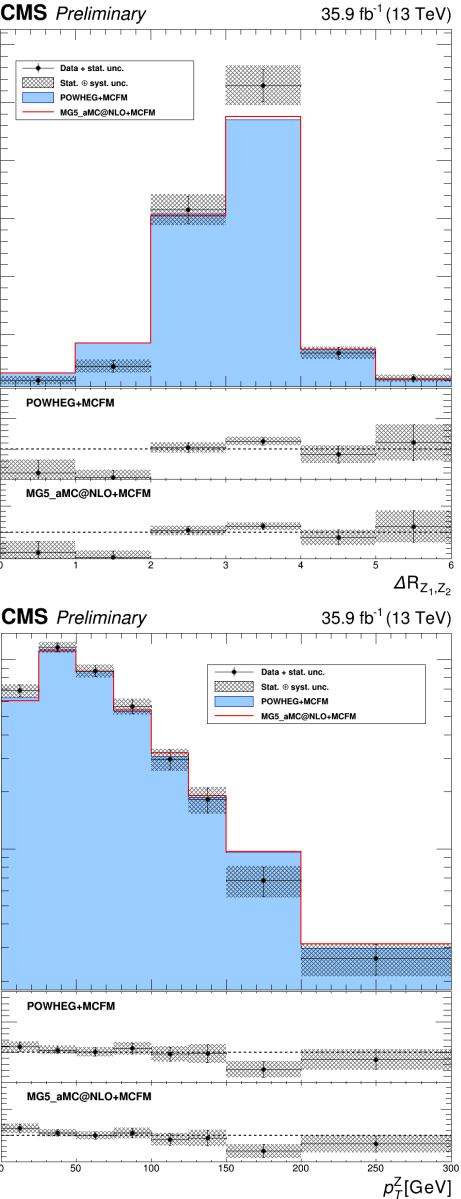
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CMS-PAS-SMP-16-017

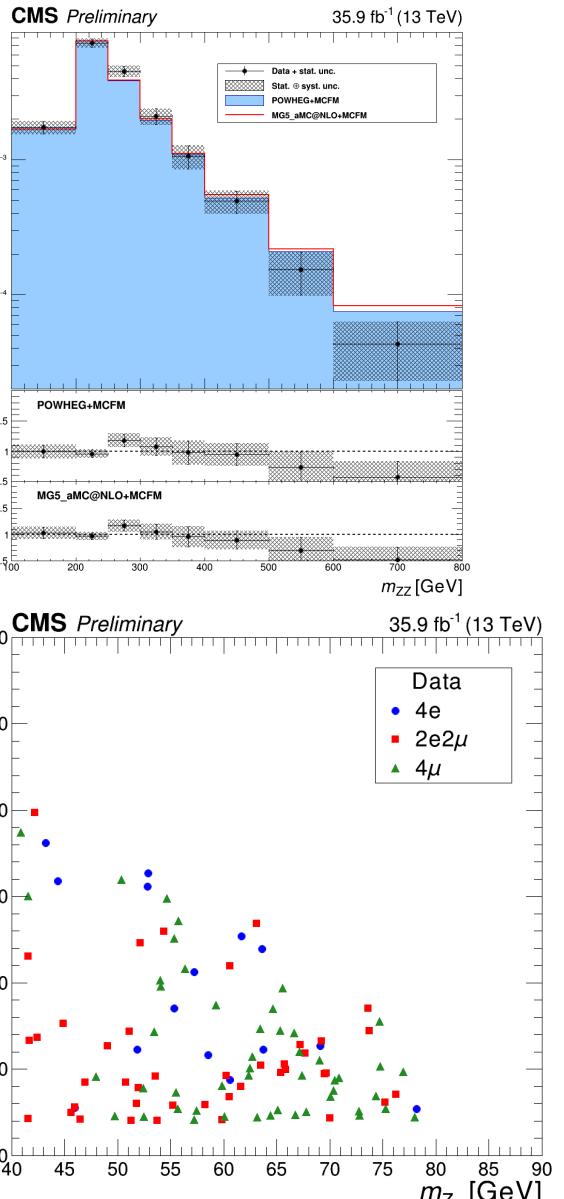
CMS Preliminary



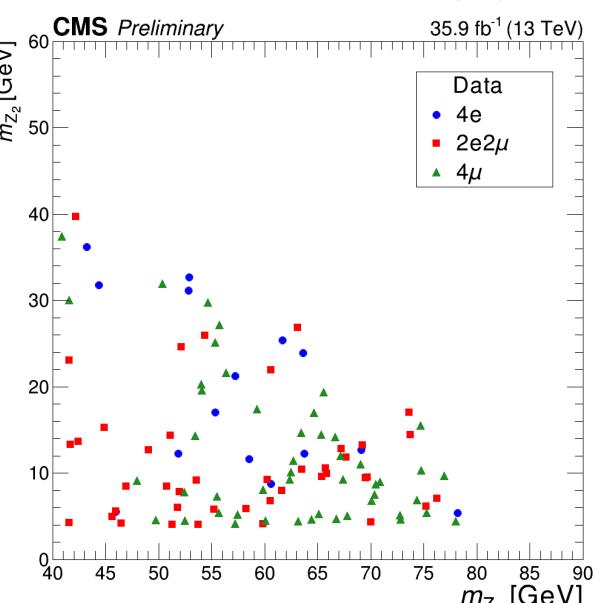
CMS Preliminary



CMS Preliminary



CMS Preliminary



New differential measurements: ZZ

qq->4l: NLO in QCD with Powheg/aMC@NLO_MG5

qg->4l: LO

gg->ZZ: LO with MCFM

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=1.1)

scaled to NLO (k-factor=1.7)

scaled to NNLO (k-factor=1.7)

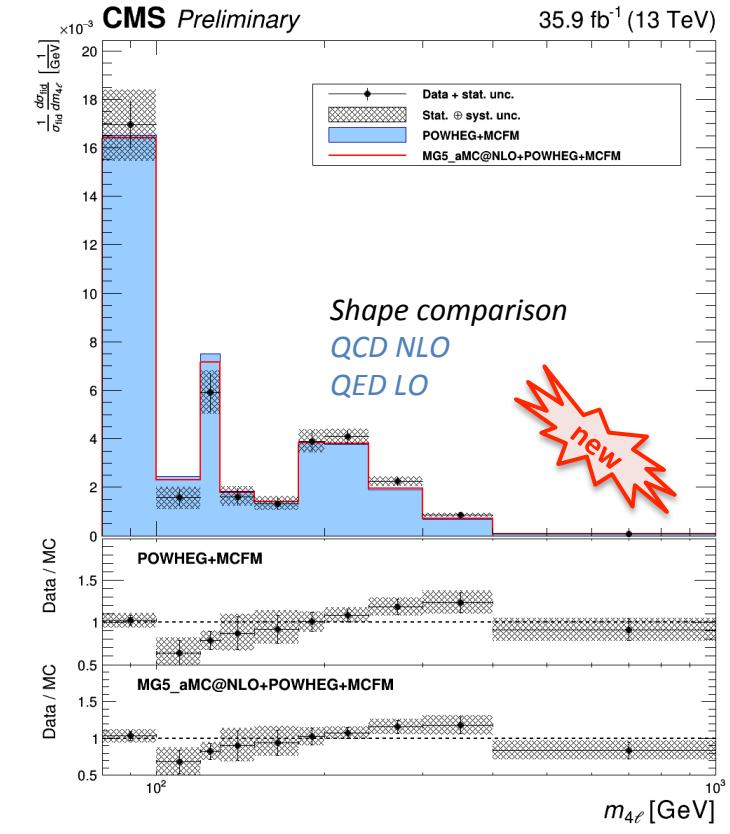
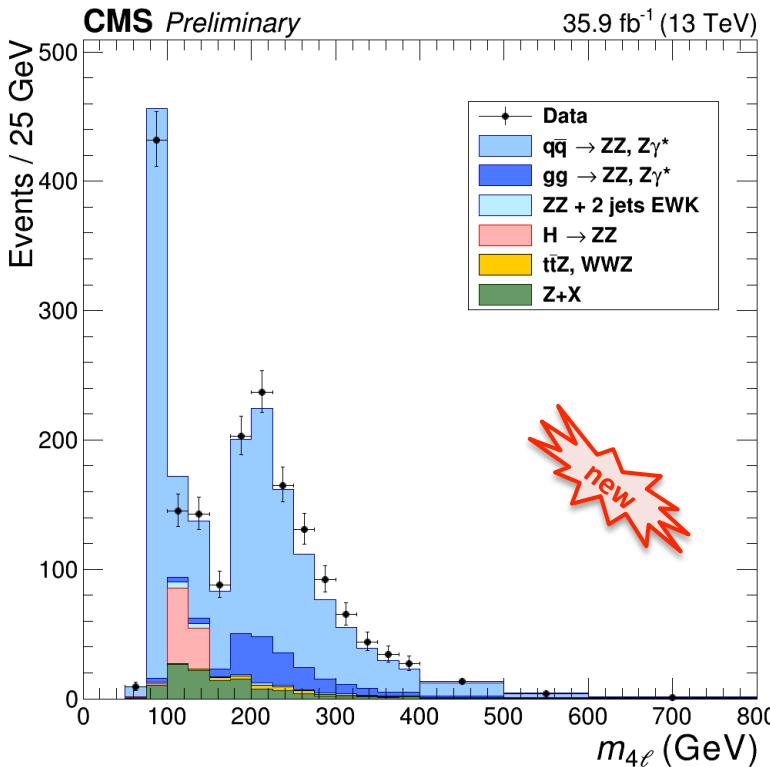


Table 4: Fiducial definitions for the reported cross sections. The common requirements are applied for both measurements.

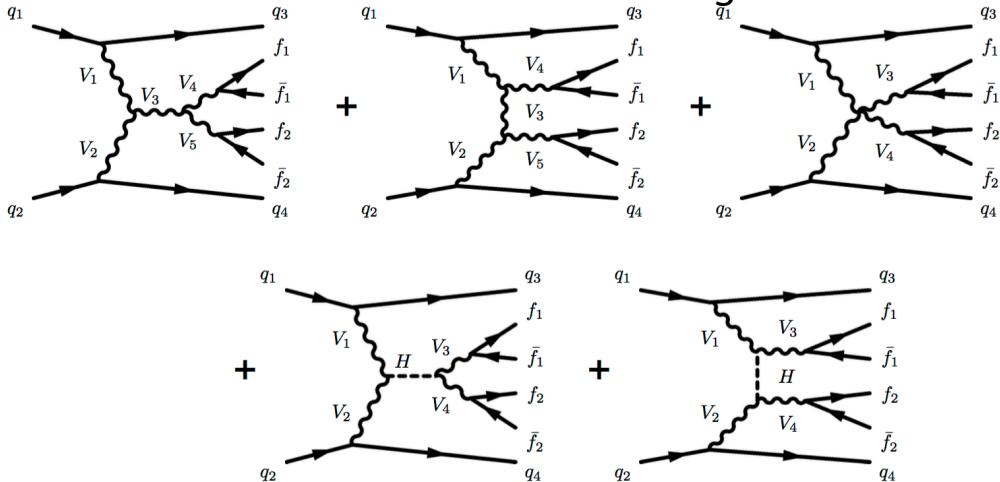
Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20 \text{ GeV}$, $p_T^{\ell_2} > 10 \text{ GeV}$, $p_T^{\ell_{3,4}} > 5 \text{ GeV}$, $ \eta^\ell < 2.5$, $m_{\ell^+\ell^-} > 4 \text{ GeV}$ (any opposite-sign same-flavor pair)
$Z \rightarrow 4\ell$	$m_{Z_1} > 40 \text{ GeV}$ $80 < m_{4\ell} < 100 \text{ GeV}$
$ZZ \rightarrow 4\ell$	$60 < m_{Z_1}, m_{Z_2} < 120 \text{ GeV}$
Uncertainty	
Lepton efficiency	6–10%
Trigger efficiency	2–4%
MC statistics	1–2%
Background	0.6–1.3%
Pileup	1–2%
PDF	1%
QCD Scales	1%
Integrated luminosity	2.6%
$Z \rightarrow 4\ell$	$ZZ \rightarrow 4\ell$
	2–6%
	2%
	0.5%
	0.5–1%
	1%
	1%
	2.6%

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

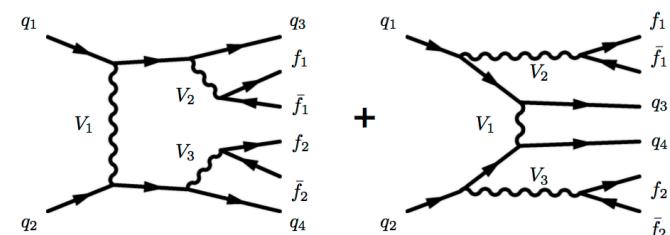
$$\sigma_{\text{fid}}(\text{pp} \rightarrow ZZ \rightarrow 4\ell) = 42.2 \pm 1.4 \text{ (stat)}^{+1.6}_{-1.5} \text{ (syst)} \pm 1.1 \text{ (lumi)} \text{ fb}.$$

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

VV EWK with scattering



VV EWK w/o scattering

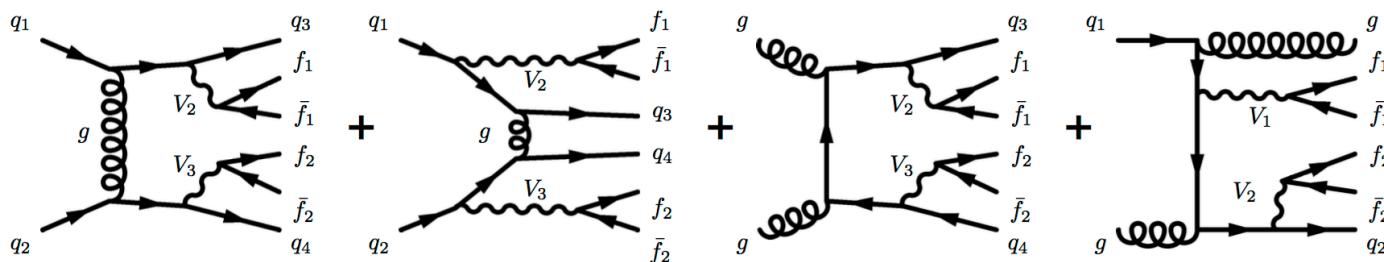


EWK production via vector boson scattering



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VV QCD

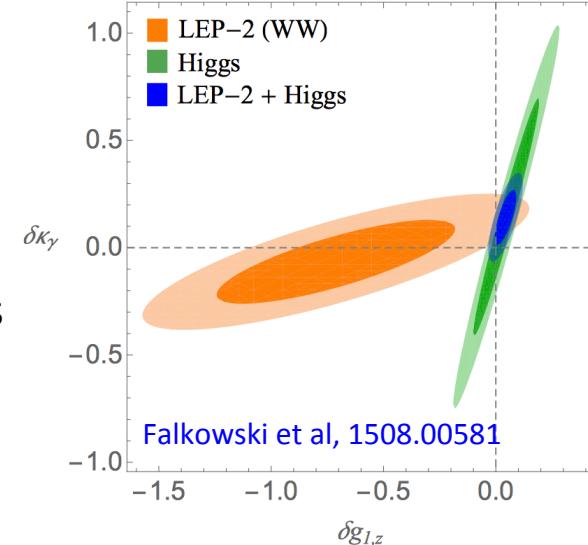


Probing the nature of the Electroweak Symmetry Breaking (EWSB)!

aTGC couplings: variety of measurements

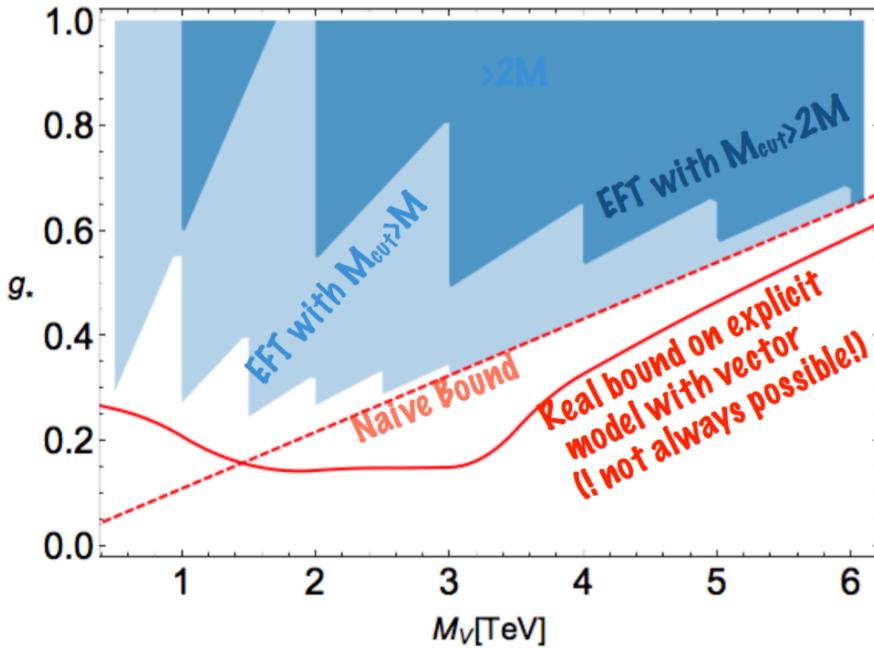
Future Prospects

- 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:

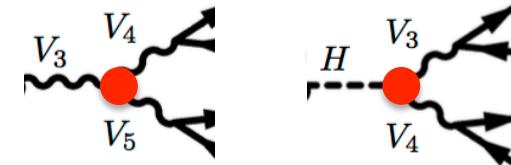
Self-Consistency Check

- perturbativity of physical expansion
- deriving limits with extra cut on $\sqrt{s} < M_{\text{cutoff}}$
→ limits in the (c, M) plane

Combination of anomalous coupling limits with Higgs measurements

→ Improvement in sensitivity

Limits are set on $c_i^{(n)}/\Lambda^n \rightarrow$ 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 !



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
t̄t+tW normalization	2.2
W+jets normalization	1.3
Z/ γ^* $\rightarrow \ell^+ \ell^-$ normalization	0.6
Z/ γ^* $\rightarrow \tau^+ \tau^-$ normalization	0.2
W γ normalization	0.3
W γ^* normalization	0.4
VV normalization	3.0
H $\rightarrow W^+ W^-$ 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

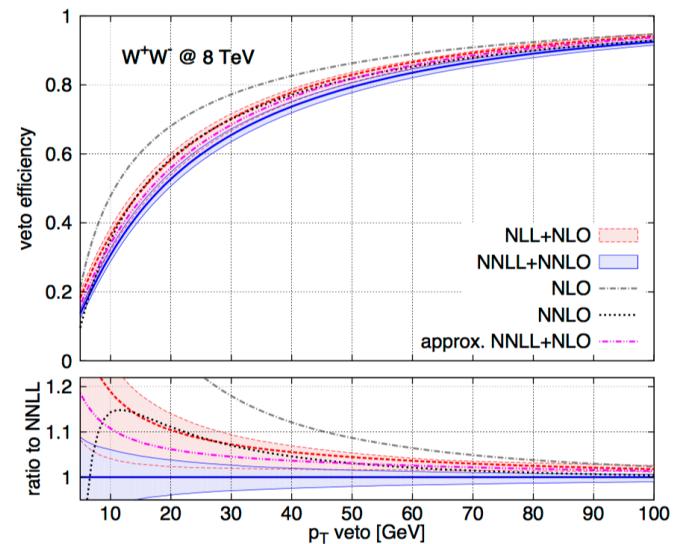
- jet counting model uncertainty includes the renormalization and factorization scales, and underlying event uncertainties

Process	zero-jet category		one-jet category	
	Different-flavor	Same-flavor	Different-flavor	Same-flavor
q̄q $\rightarrow W^+ W^-$	3516 \pm 271	1390 \pm 109	1113 \pm 137	386 \pm 49
gg $\rightarrow W^+ W^-$	162 \pm 50	91 \pm 28	62 \pm 19	27 \pm 9
W $^+ W^-$	3678 \pm 276	1481 \pm 113	1174 \pm 139	413 \pm 50
ZZ + WZ	84 \pm 10	89 \pm 11	86 \pm 4	42 \pm 2
VVV	33 \pm 17	17 \pm 9	28 \pm 14	14 \pm 7
top quark (B _{t-tag})	522 \pm 83	248 \pm 26	1398 \pm 156	562 \pm 128
Z/ γ^* $\rightarrow \ell^+ \ell^-$	38 \pm 4	141 \pm 63	136 \pm 14	65 \pm 33
W γ^*	54 \pm 22	12 \pm 5	18 \pm 8	3 \pm 2
W γ	54 \pm 20	20 \pm 8	36 \pm 14	9 \pm 6
W + jets(e)	189 \pm 68	46 \pm 17	114 \pm 41	16 \pm 6
W + jets(μ)	81 \pm 40	19 \pm 9	63 \pm 30	17 \pm 8
Higgs boson	125 \pm 25	53 \pm 11	75 \pm 22	22 \pm 7
Total bkg.	1179 \pm 123	643 \pm 73	1954 \pm 168	749 \pm 133
W $^+ W^-$ + total bkg.	4857 \pm 302	2124 \pm 134	3128 \pm 217	1162 \pm 142
Data	4847	2233	3114	1198

WW CMS 13TeV

CMS-PAS-SMP-16-006

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



- reweighting 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 independently the resummation, the factorization, and the renormalization scales in the analytical calculation of the pT WW spectrum
 - The uncertainty in the efficiency of the $gg \rightarrow W W$ 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 Emiss energy scale and resolution

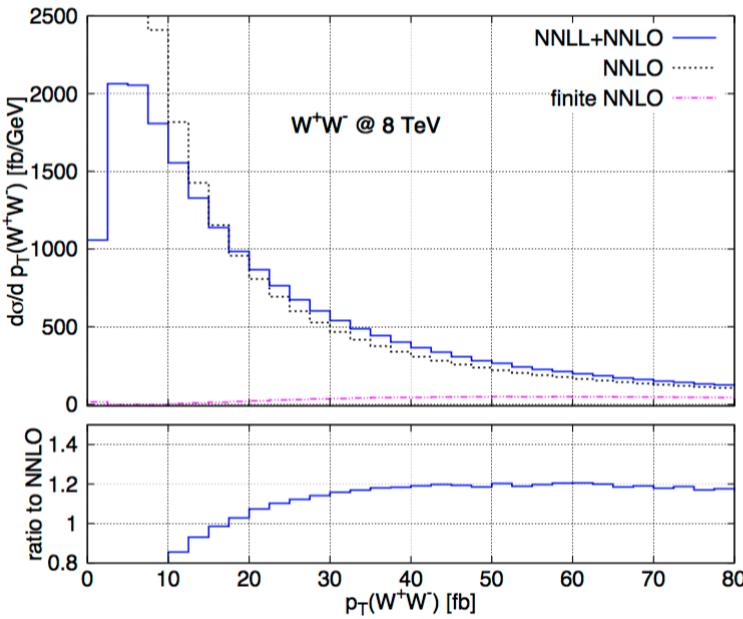


CMS-PAS-SMP-16-006

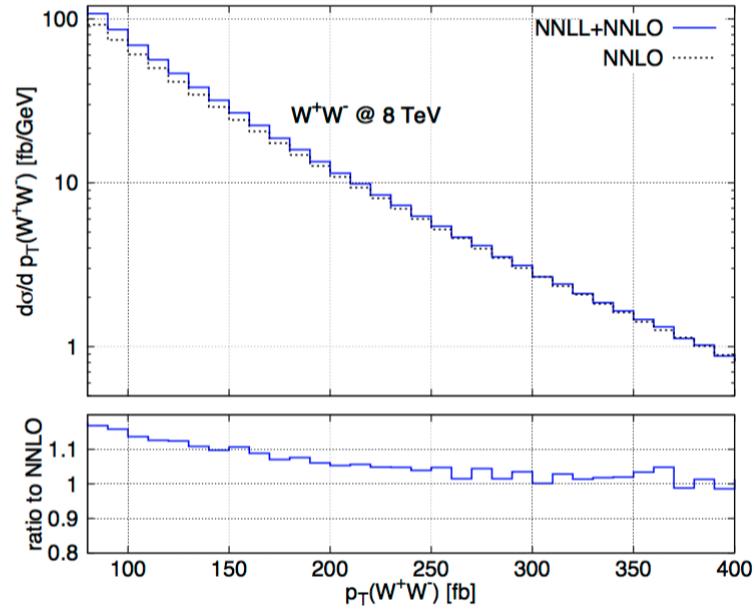
WW CMS 13TeV



- This measurement is performed at relatively low WW pT.
- This region cannot be properly simulated by a fixed-order MC because of the importance of large $\log(p_{\text{TWW}}/m_{\text{WW}})$ terms. There are analytical calculations available that resum these logs: arXiv:1507.02565 (NNLL + NNLO), arXiv:1407.4481 (NLL + approx NNLO).
- We use the WW pT as a proxy for these corrections and reweight the POWHEG events comparing the out-of-the-box distribution with the result of the most precise (NNLL + NNLO) analytical calculation.



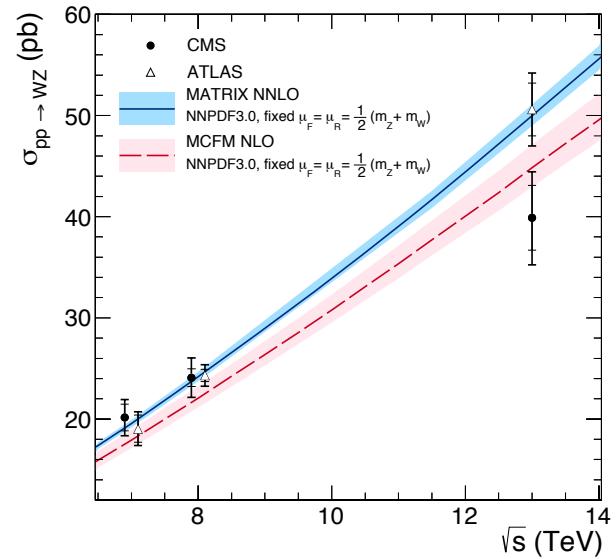
(a)



(b)

Figure 5: The transverse-momentum spectrum of the W^+W^- pair at NNLL+NNLO (a) in the low- p_T region and (b) at high transverse momenta. The NNLL+NNLO result (red, dashed) is compared to the fixed-order NNLO prediction (grey, dash-dotted) and to the finite component of Eq. (4) (magenta, dash-double dotted). The lower insets show the NNLL+NNLO result normalized to NNLO.

Source	$\sqrt{s} = 7 \text{ TeV}$				$\sqrt{s} = 8 \text{ TeV}$			
	eee	ee μ	$\mu\mu e$	$\mu\mu\mu$	eee	ee μ	$\mu\mu e$	$\mu\mu\mu$
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
Z γ 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	ee μ	$\mu\mu e$	$\mu\mu\mu$	Total
$\sqrt{s} = 8 \text{ TeV}; \mathcal{L} = 19.6 \text{ fb}^{-1}$					
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
Z γ	3.4 ± 1.3	0.4 ± 0.4	5.2 ± 1.8	0	9.1 ± 2.2
W γ^*	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



Triboson and rare processes measurements: overview



Triboson measurements		ATLAS	CMS
8 TeV	$W\gamma\gamma \rightarrow l\nu jj\gamma$	-	PRD 90 (2014) 032008 Upper limit on cross section and aQGC measurement
	$W\gamma\gamma \rightarrow l\nu\gamma\gamma$	PRL 115, 031802 (2015) Cross section (inclusive and exclusive) and aQGC measurement Evidence: signal significance $>3\sigma$	CMS-PAS-SMP-15-008 Cross section and aQGC measurement signal significance 2.4σ
	$Z\gamma\gamma \rightarrow ll\gamma\gamma$	PRD 93, 112002 (2016) Observation: signal significance 6.3σ	CMS-PAS-SMP-15-008 Observation: signal significance 5.9σ
	$WW\gamma \rightarrow l\nu l\nu jj, l\nu l\nu l\nu$	ATLAS-STDM-2015-07 Upper limit on cross section and aQGC measurement	-

Rare processes		ATLAS	CMS
7 TeV	$W^+W^- \rightarrow \gamma\gamma \rightarrow l\nu l\nu$ exclusive	-	JHEP 08 (2016) 119 Evidence: signal significance 3.4σ (exp 2.8σ) aQGC measurement
8 TeV		PRD 94 (2016) 032011 Evidence: signal significance 3σ aQGC measurement, search for exclusive Higg production	

For the first time, evidence and observations of triboson and exclusive WW production!

$W\gamma$ (7 TeV)

Phys. Rev. D 89 (2014) 092005

Table 7: Summary of systematic uncertainties in the measurement of $W\gamma$ cross section, separated into the main groups of sources for the $e\nu\gamma$ and $\mu\nu\gamma$ channels. “n/a” stands for “not applicable”.

	Uncertainties	$e\nu\gamma$	$\mu\nu\gamma$
Source (Group 1)		Effect from N_{sig}	
e/γ energy scale	(e: 0.5%; γ : 1% (EB), 3% (EE))	2.9%	n/a
γ energy scale	(1% (EB), 3% (EE))	n/a	2.9%
μp_T scale	(0.2%)	n/a	0.6%
Total uncertainty in N_{sig}		2.9%	3.0%
Source (Group 2)	Uncertainties	Effect from $\mathcal{F}_S = A_S \cdot \epsilon_S$	
e/γ energy resolution	(1% (EB), 3% (EE))	0.3%	n/a
γ energy resolution	(1% (EB), 3% (EE))	n/a	0.1%
μp_T resolution	(0.6%)	n/a	0.1%
Pileup	(Shift pileup distribution by $\pm 5\%$)	2.4%	0.8%
PDF		0.9%	0.9%
Modeling of signal		5.0%	5.0%
Total uncertainty in $\mathcal{F}_S = A_S \cdot \epsilon_S$		5.6%	5.1%
Source (Group 3)	Uncertainties	Effect from ρ_{eff}	
Lepton reconstruction		0.4%	1.5%
Lepton trigger		0.1%	0.9%
Lepton ID and isolation		2.5%	0.9%
E_T selection		1.4%	1.5%
γ identification and isolation	(0.5% (EB), 1.0% (EE))	0.5%	0.5%
Total uncertainty in ρ_{eff}		2.9%	2.5%
Source (Group 4)		Effect from background yield	
Template method		9.3%	10.2%
Electron misidentification		1.5%	0.1%
MC prediction		0.8%	0.5%
Total uncertainty due to background		9.5%	10.2%
Source (Group 5)			
Luminosity		2.2%	2.2%

The uncertainty in the modeling of the signal is taken from the difference in acceptance between MCFM and MADGRAPH predictions.