Electroweak physics in CMS and ATLAS

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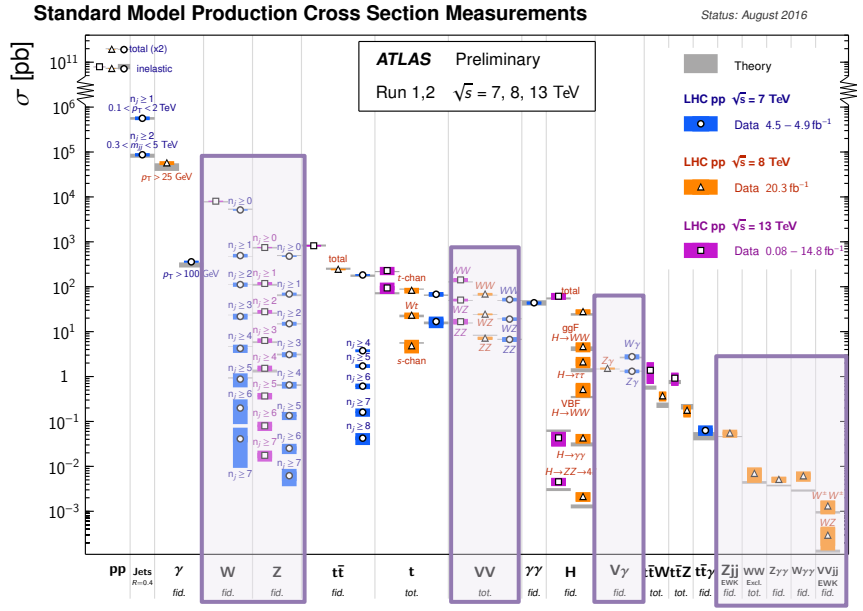
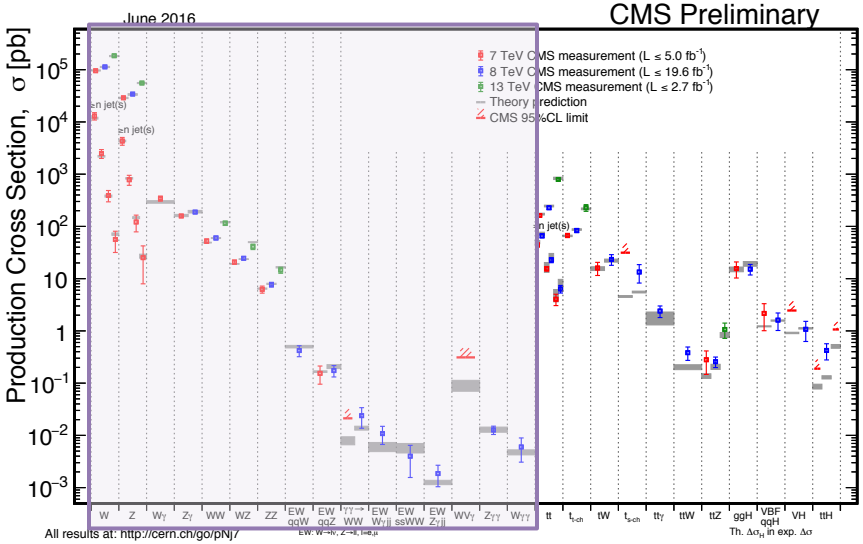
On behalf of the CMS and ATLAS Collaborations

EWK physics at LHC: overview



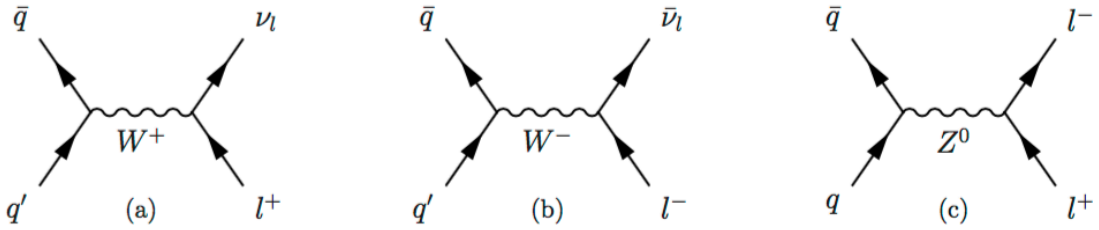


Importance of EWK measurements:

- Precision measurements of EWK properties
  - Single boson and diboson production
- Probe of higher order calculations (EWK and QCD)
  - Associated production of bosons and jets
- Study of rare processes
  - Triboson and exclusive WW production
- Vector boson fusion and vector boson scattering production
- Search for New Physics in the high pt/mass tails

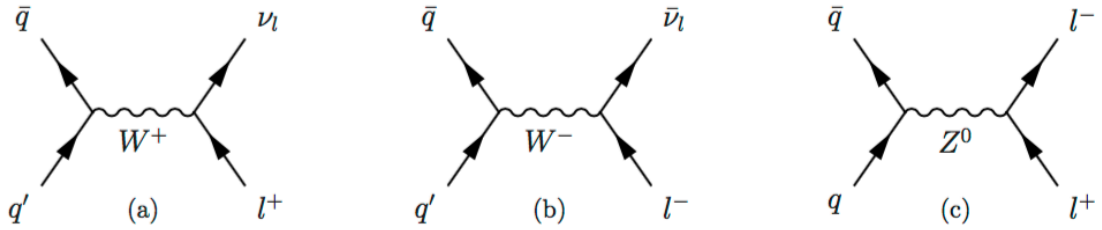
Numerous ATLAS and CMS EWK results are available

- **In the talk focusing only on recent results !**



Single boson production at LHC

Single boson measurements (W, Z): overview

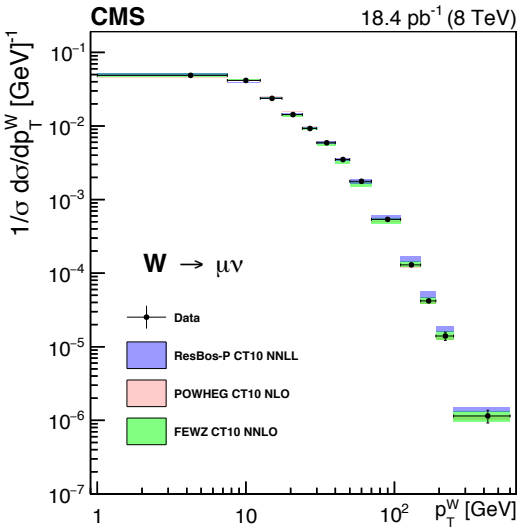


W, Z measurements		ATLAS	CMS
13 TeV	Z(+jets)->μμ(+jets)	ATLAS-CONF-2016-046, PLB 759 (2016) 601 Z+jets, differential cross section	CMS-PAS-SMP-15-011, CMS-PAS-SMP-15-010 Differential cross section (2.8fb^{-1})
	DY->μμ	-	CMS-PAS-SMP-16-009 Differential cross section (2.8fb^{-1})
	W(+jets)->μν(+jets)	PLB 759 (2016) 601	CMS-PAS-SMP-16-005 Differential cross section (2.5fb^{-1})

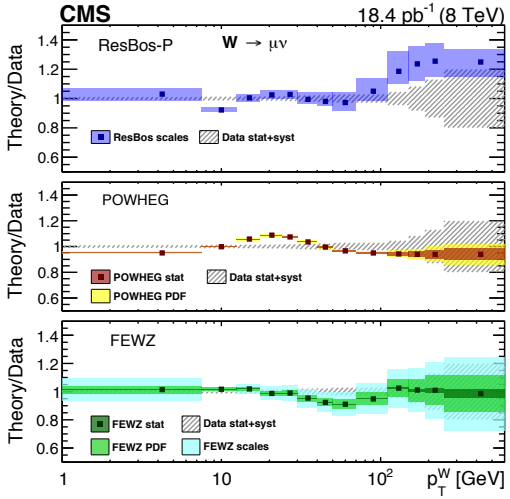
W, Z measurements		ATLAS	CMS
8 TeV	Z->ll	JHEP08(2016)159	CMS-SMP-14-012, arXiv:1606.05864, PLB 750 (2015) 154, CMS-PAS-SMP-14-009
	DY	JHEP 08 (2016) 009, EPJC 76(5), 1-61 (2016)	CMS-PAS-SMP-15-002, EPJC 76 (2016) 325, EPJC 75 (2015) 147
	W(+jets)	ATLAS-STDM-2015-16	CMS-SMP-14-012, arXiv:1606.05864 CMS-PAS-SMP-14-023, CMS-PAS-SMP-14-020, arXiv:1608.07561

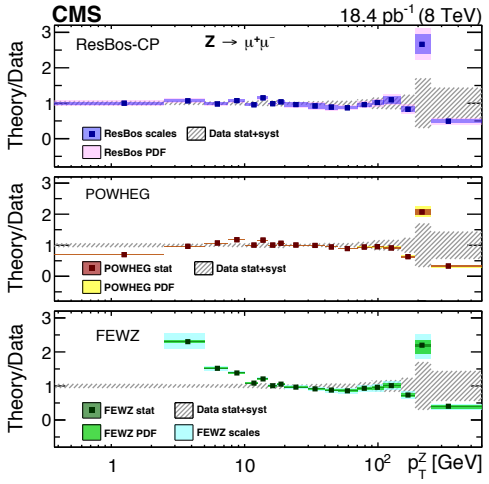
+ more legacy measurements with 7 and 8 TeV data !

Single boson measurements (W, Z)

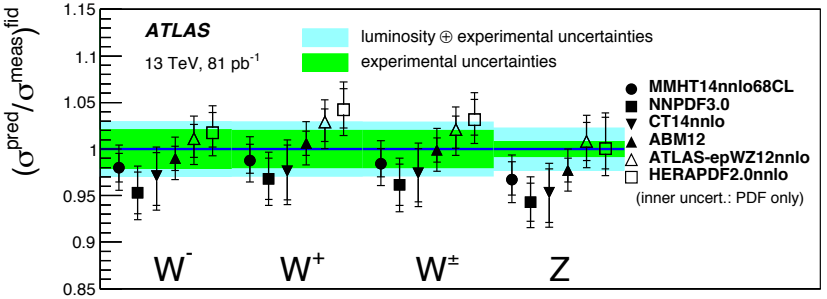


CMS-SMP-14-012, arXiv:1606.05864





PLB 759 (2016) 601



- The predictions are able to describe data well on the total, exclusive and inclusive jet multiplicities within the uncertainties
- Studies of wide range of differential distributions with extensive comparisons with MCs
- Precision test on theoretical predictions
- In general, NNLO shows better agreement with data than NLO

Prospects: W mass measurement at LHC ?

J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012)

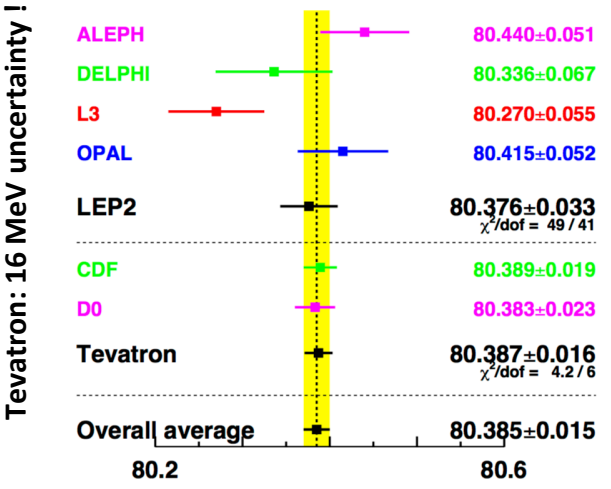
W-like measurement of the Z boson mass using Z->μμ events

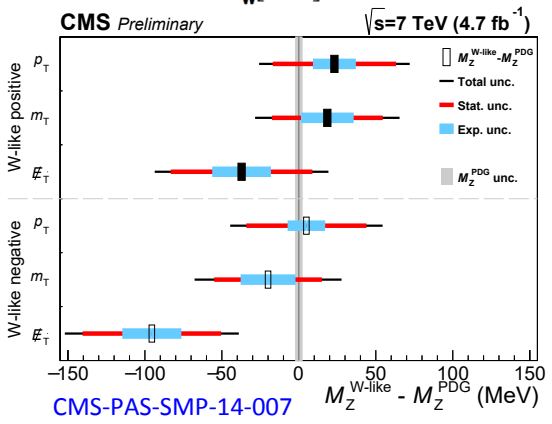
- One μ removed to form W-like candidate
- Proof of principle of W mass measurement procedure
- Validated critical issues
  - Muon p_T calibration
  - Hadronic recoil in presence of high pileup
  - ✓ **Precision suitable to pursue an accurate measurement of the W mass at the LHC**

CMS systematic uncertainty: ~20 MeV (experimental)
+ ~30 MeV (theoretical: QED radiation dominant) !
Theoretical uncertainty is larger then at Tevatron!

→ **A fundamental step towards the W mass measurement !**

- Detector calibration is at the level required for a first competitive measurement with LHC !



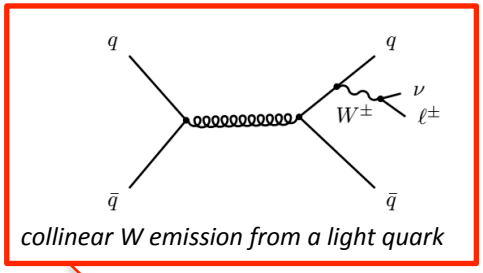


CMS-PAS-SMP-14-007

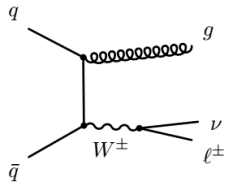
The Z mass is extracted through the W-like lepton p_T, M_T and MET distributions

Real W emission process

Relevant QCD and EW corrections to both processes !



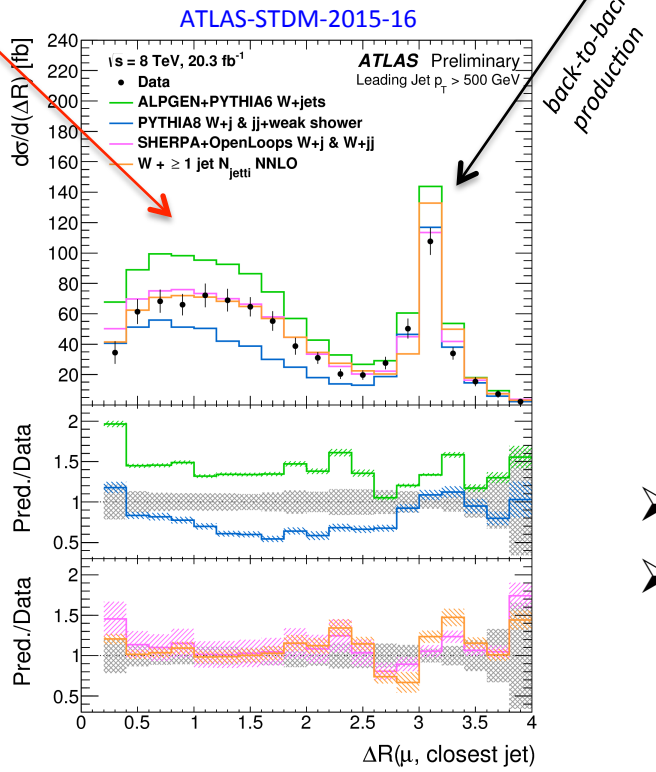
collinear W emission from a light quark



W boson is balanced by a hadronic recoil

collinear

back-to-back production



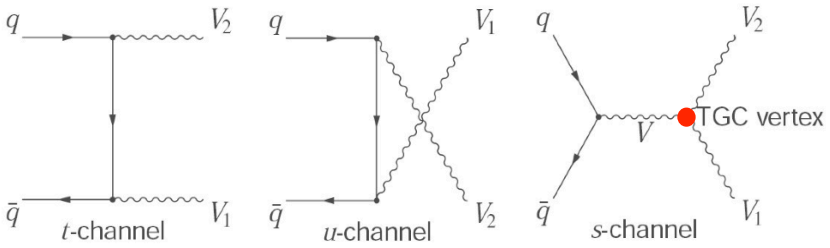
W boson angular distribution and cross section in events with high transverse momentum jets

- Events with μ and a jet with p_T > 500 GeV
  - enhanced contributions from real W boson emission in the region of small ΔR(μ, closest jet)

➢ Measurement has implications for MC

➢ **Real W emission process is only just now being probed directly at the energy of the LHC**

LO production diagrams (pp->VV)



Diboson production at LHC

- Important test of the Standard Model
- Backgrounds for New Physics and Higgs measurements

Sensitive to theoretical calculation

- Large NLO QCD corrections at high √s
- Non-negligible NNLO QCD and NLO QED corrections

Diboson measurements: overview

	ATLAS		CMS	
	8 TeV	**13 TeV**	**8 TeV**	**13 TeV**
Z->4l	PRL 112, 231806 (2014)	-	-	arXiv:1607.08834 (CMS-SMP-16-001) Cross section
ZZ->4l	PLB 753 (2016) 552-572 (4l) Differential and total cross section	PRL 116, 101801 (2016) Cross section	PLB 740 (2015) 250, CMS-PAS-SMP-15-012 Cross section, differential and aTGC measurement	
ZZ->2l2v	ATLAS-CONF-2013-020 Cross section	-	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->vvγ			PLB 760 (2016) 448 Cross section and aTGC measurement	CMS-PAS-SMP-16-004 Cross section
WW->lvlv	arXiv:1603.01702 (WW+0jet) Cross section, differential and aTGC measurement arXiv:1608.03086 (WW+1jet) Cross section measurement	ATLAS-CONF-2016-090 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	arXiv:1606.04017 (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->lvjj	-	-	-	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

Diboson measurements:
importance of higher order corrections (WW, Wγ)

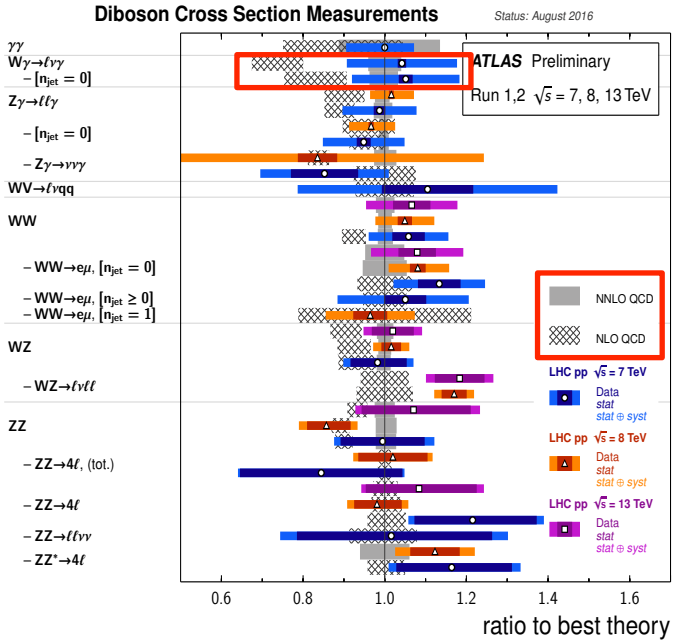
Diboson cross section is sensitive to higher order corrections.
In some cases this is more visible (Wγ, WW).

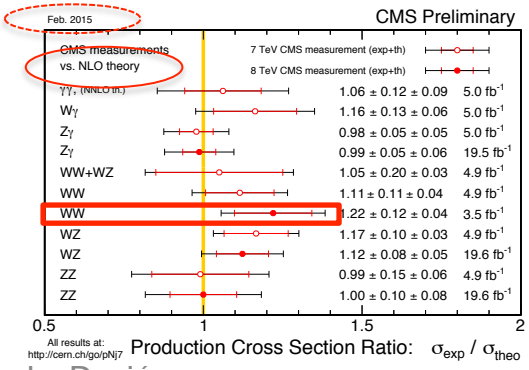
Wγ:

- LO cross section exhibits radiation amplitude zero
  - Significant contribution from NLO correction

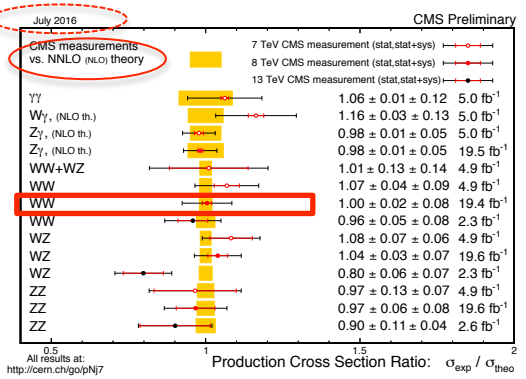
WW:

- Due to large background from ttbar measurement in performed applying a jet veto (0- or 1-jet events only)
  - Jet veto efficiency is sensitive to higher-order QCD corrections
  - Veto enhances the contribution of the soft gluons to the pT(WW) distribution



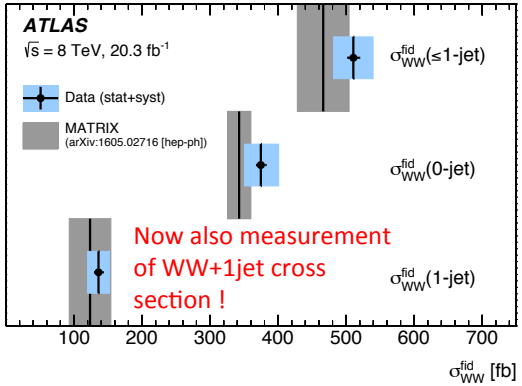


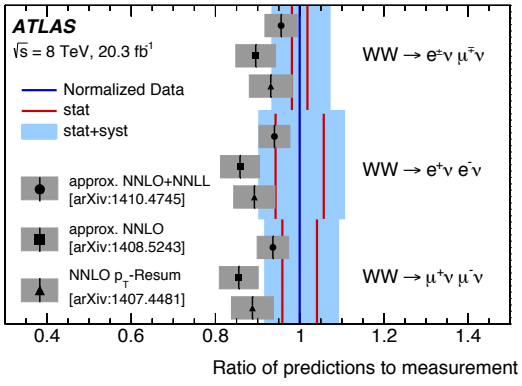
Also few other changes made effect: more data, change of MC generator for acceptance estimate!



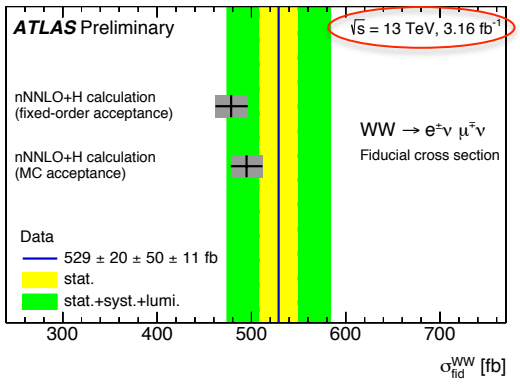
Diboson measurements:
importance of higher order corrections (WW)

arXiv:1603.01702, arXiv:1608.03086





ATLAS-CONF-2016-090



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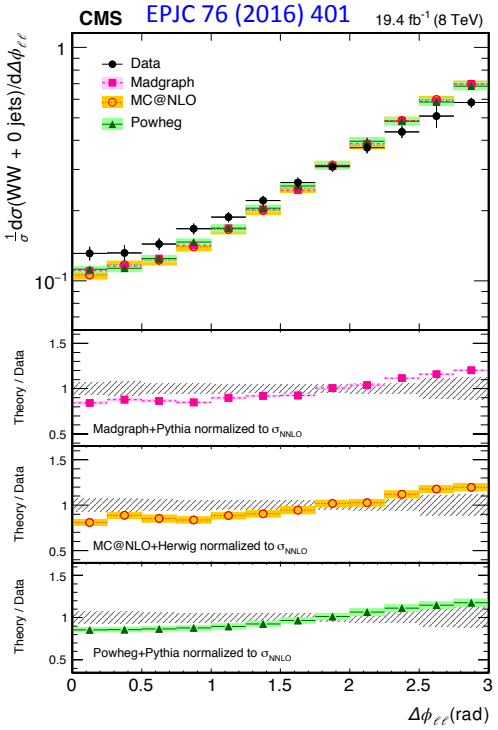
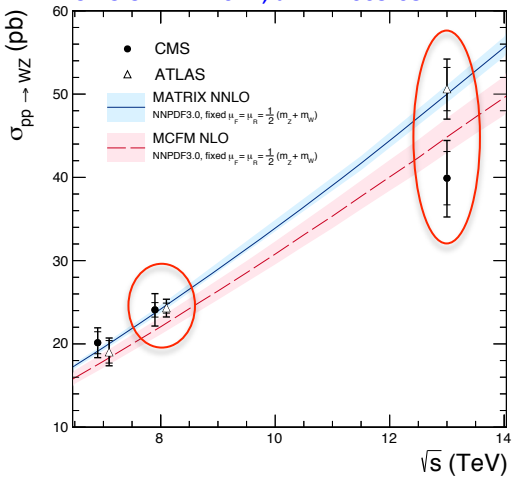


Differential distributions show good agreement with several predictions from perturbative QCD calculations. Some differences observed in $\Delta\phi_{ll}$ distributions.

Recent diboson measurements: WZ and ZZ

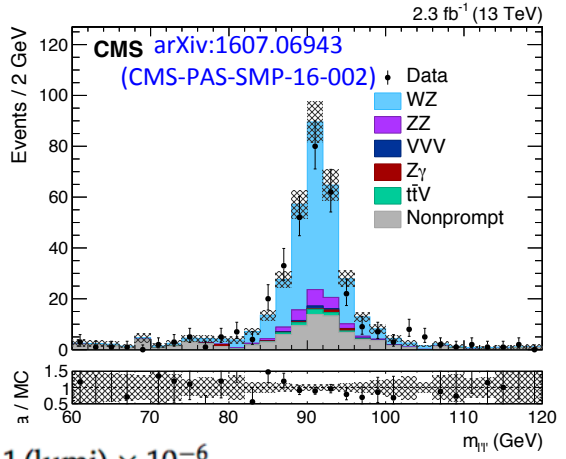
CMS-SMP-14-014, arXiv:1609.05721



Good agreement with SM expectation!

Run2 measurement strategy and techniques similar to Run1

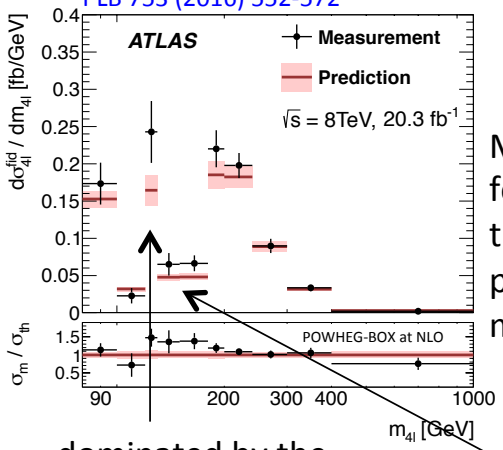
- ZZ->4l is still statistics dominated measurement !
- Measurement of BR(Z->4l):



$$\mathcal{B}(Z \to \ell^+\ell^-\ell'^+\ell'^-) = 4.9^{+0.8}_{-0.7}\,(\text{stat})^{+0.3}_{-0.2}\,(\text{syst})^{+0.2}_{-0.1}\,(\text{theo}) \pm 0.1\,(\text{lumi}) \times 10^{-6}$$

Expected (MG5_aMC@NLO) = 4.6×10^{-6}

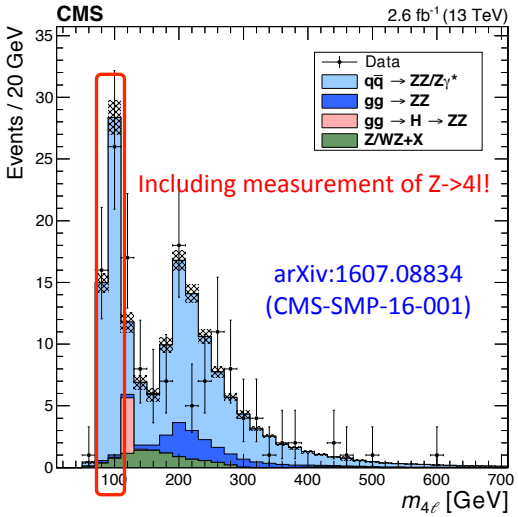
PLB 753 (2016) 552-572



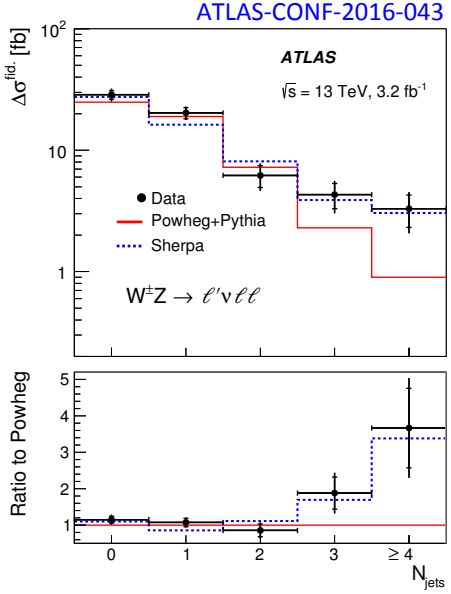
M_{4l} is essential for the study of the different production mechanisms !

dominated by the resonant Higgs-boson contribution

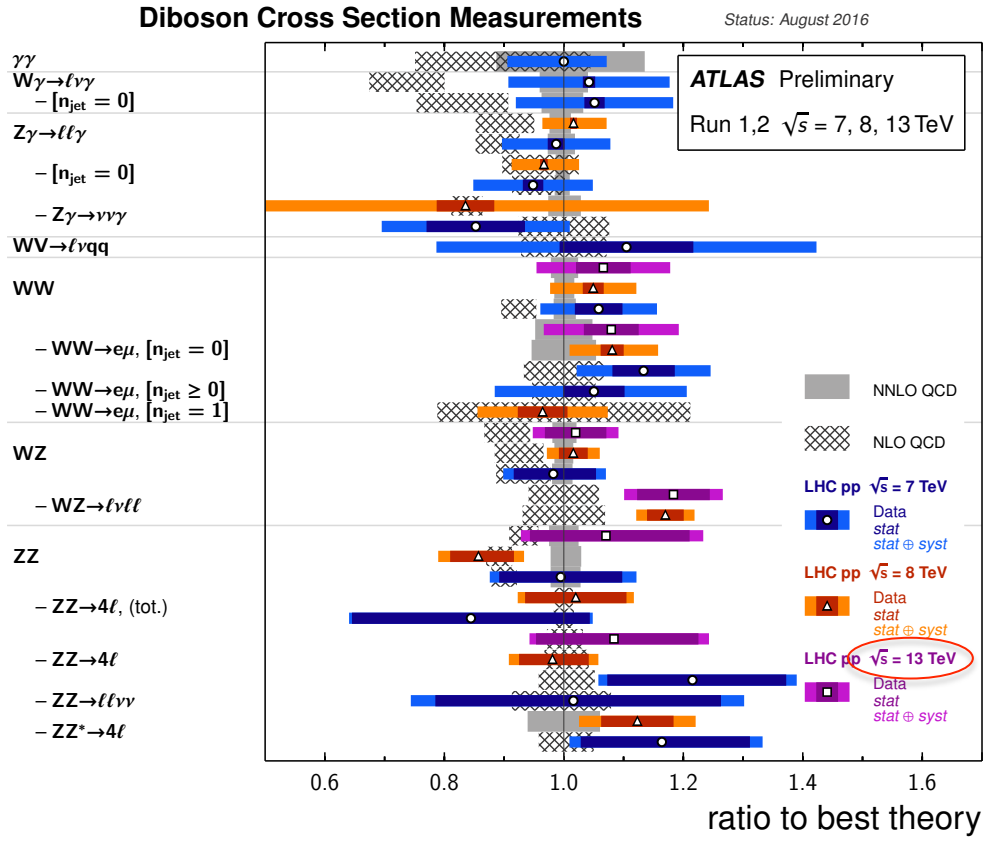
NLO EW K-factors not available for $M_{4l} < 2 \times M_Z$

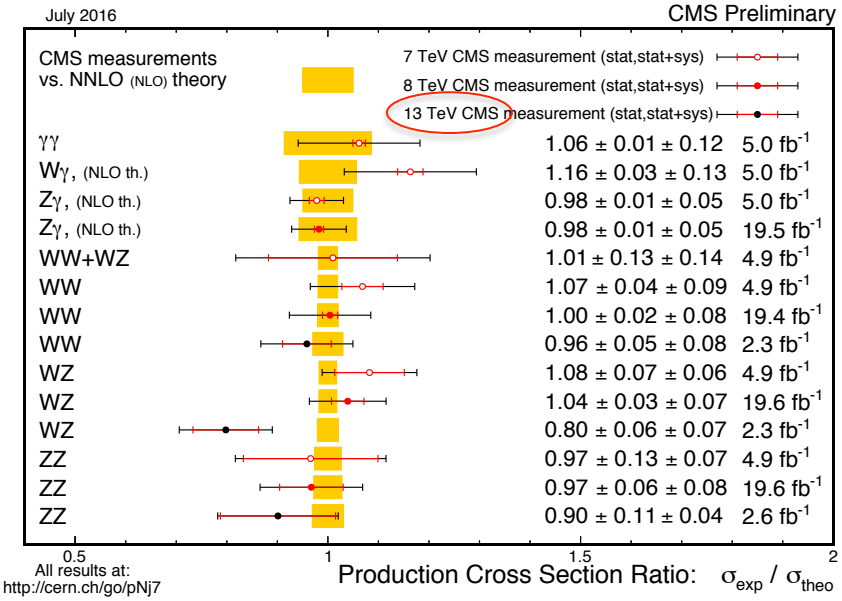


ATLAS-CONF-2016-043

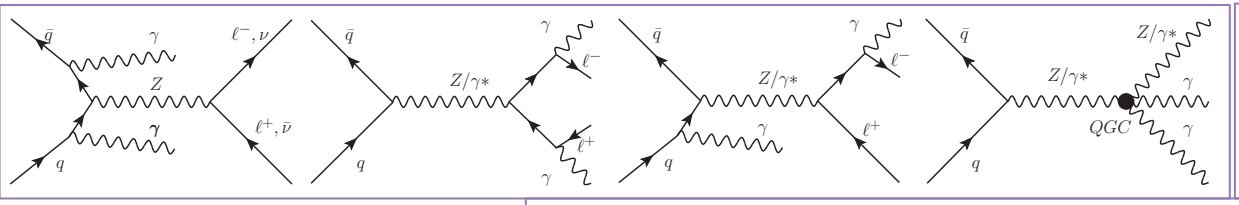


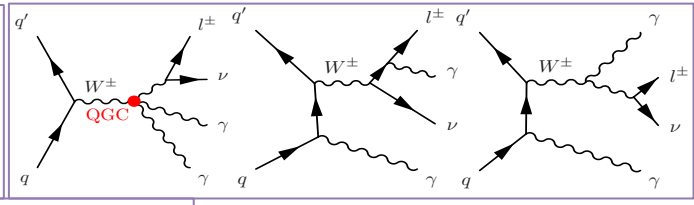
Diboson measurements: cross section results

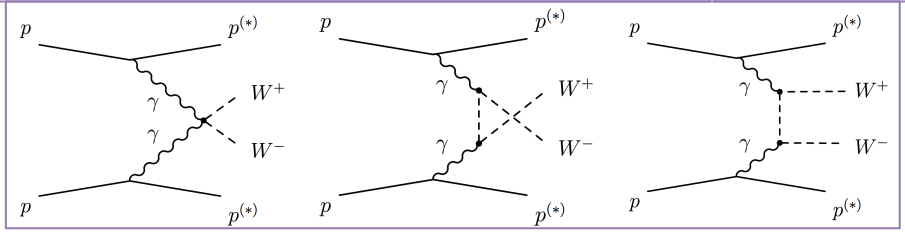




Good agreement with best theory calculation in both ATLAS and CMS!







Triboson and rare process production at LHC

Statistics dominated measurements but high physics relevance!

Triboson and rare processes measurements: overview

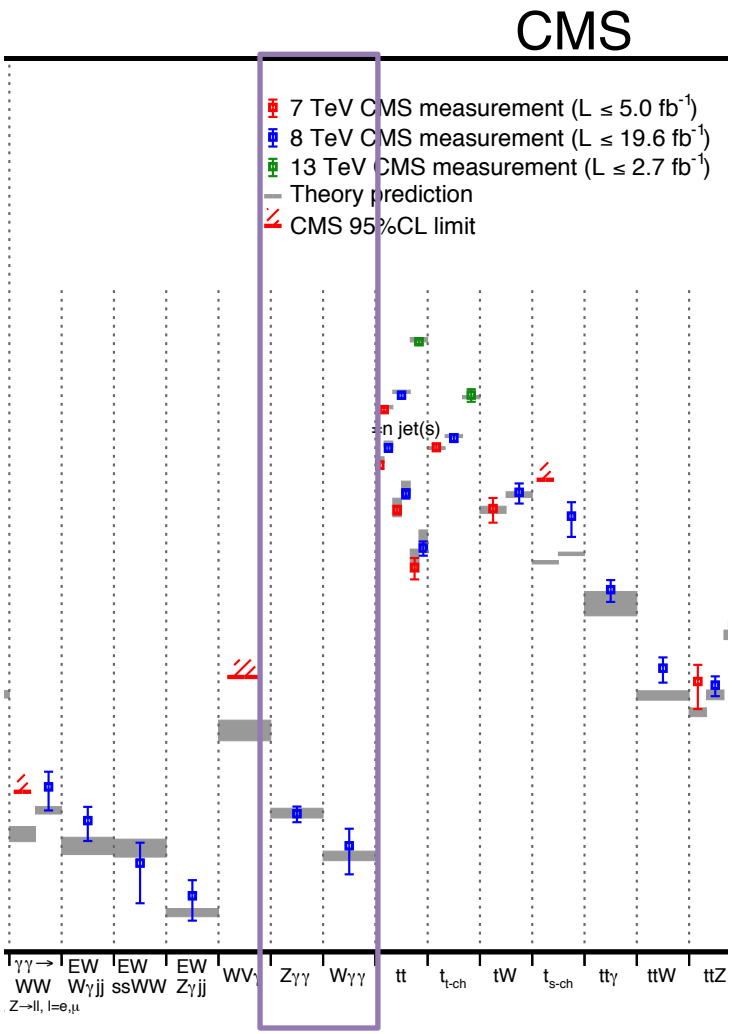
Triboson measurements		ATLAS	CMS
8 TeV	WVγ->lνjjγ	-	PRD 90 (2014) 032008 Upper limit on cross section and aQGC measurement
	Wγγ->lνγγ	PRL 115, 031802 (2015) Cross section (inclusive and exclusive) and aQGC measurement **Evidence**: signal significance >3σ	CMS-PAS-SMP-15-008 Cross section and aQGC measurement signal significance 2.4σ
	Zγγ->llγγ	PRD 93, 112002 (2016) **Observation**: signal significance 6.3σ	CMS-PAS-SMP-15-008 **Observation**: signal significance 5.9σ
	WWW->lνlνjj, lνlνlν	ATLAS-STDM-2015-07 Upper limit on cross section and aQGC measurement	-

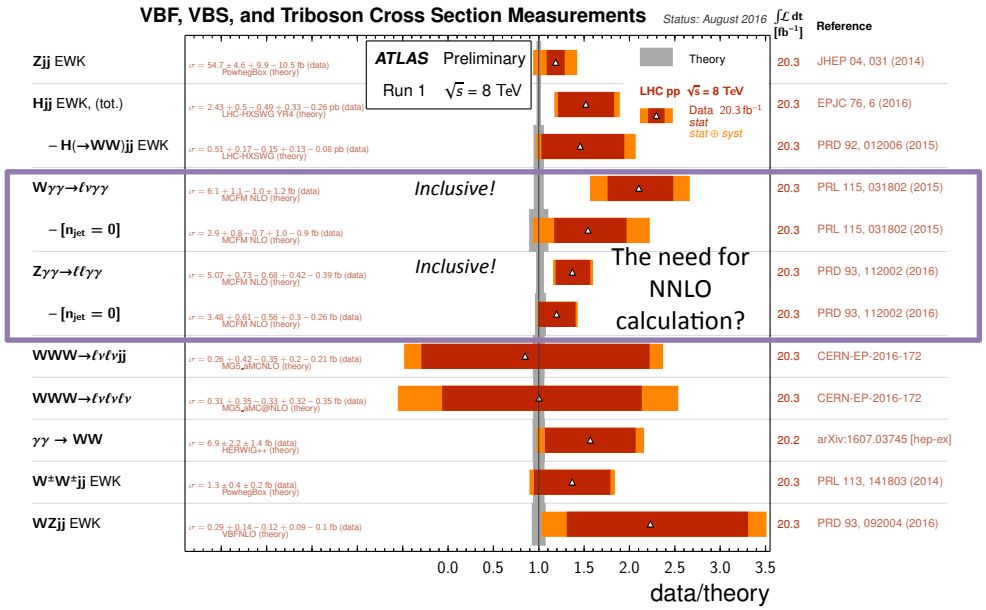
Rare processes		ATLAS	CMS
7 TeV	W^+W^-->γγ->lνlν exclusive	-	JHEP 08 (2016) 119 **Evidence**: signal significance 3.4σ (exp 2.8σ) aQGC measurement
8 TeV		PRD 94 (2016) 032011 **Evidence**: signal significance 3σ aQGC measurement, search for exclusive Higg production	

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

Triboson measurements (Zγγ and Wγγ)

Signal Observation/Evidence (>5/3σ significance) of Zγγ/Wγγ !



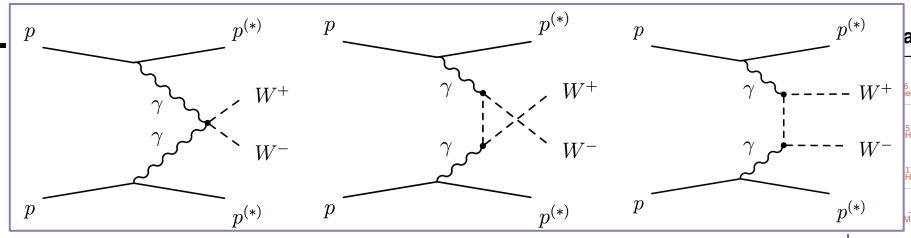


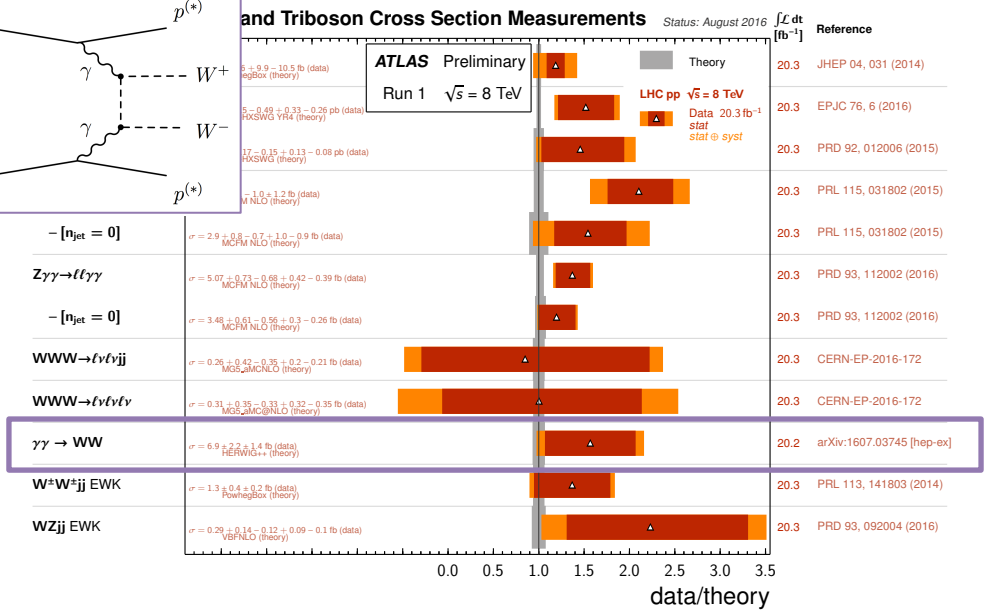
Wγγ and Zγγ:

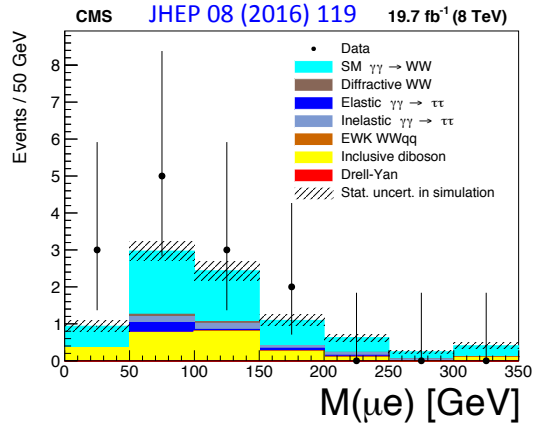
- Measurements dominated by systematic uncertainty on background (jets misidentified as photons)
- ATLAS and CMS measurements are consistent
  - Measured Zγγ cross sections in different phase space
  - Different measurement sensitivity for Wγγ (CMS using muon channel only)

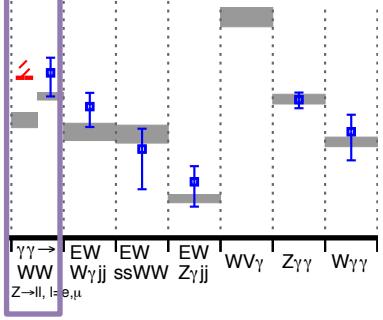
Exclusive WW measurement

Signal Evidence (>3σ significance) by both Collaborations



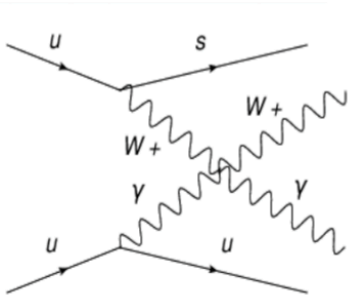


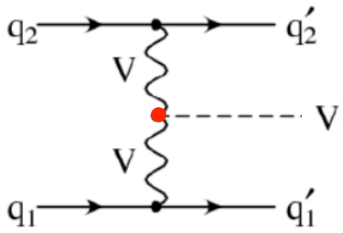




Search for exclusive or quasi-exclusive γγ → W^+W^- production

- Measurement with opposite sign different flavor selection
  - significantly smaller background than same flavor (DY, γγ→l^+l^-) channel
- Requiring no additional charged tracks from the same primary vertex





Vector boson scattering (VBS) and vector boson fusion (VBF) production

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

VBS and VBF results: overview

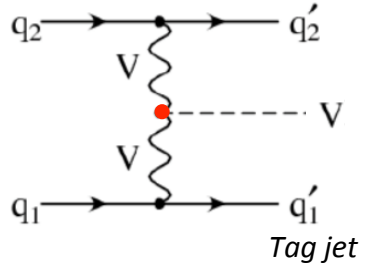
VBS measurements (VV+2jets)		ATLAS	CMS
8 TeV	**EWK $W^{\pm}W^{\pm}$ ->lvlv**	PRL 113, 141803 Cross section (EWK, EWK+QCD) and aQGC measurement **Evidence**: EWK signal significance 3.6σ (exp 2.8σ)	PRL 114 (2015) 051801 Cross section (EWK+QCD) and aQGC measurement EWK signal significance 1.9σ (exp 2.9σ)
	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	-	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	ATLAS-STDM-2014-02 Cross section (EWK, EWK+QCD) measurement	PRL 114 (2015) 051801 Cross section (EWK+QCD) measurement
	EWK WV->lvjj	CERN-EP-2016-171, arXiv:1609.05122 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)	-	CMS-PAS-SMP-13-012, arXiv:1607.06975 Cross section (EWK) measurement **Evidence**: EWK signal significance ~4σ

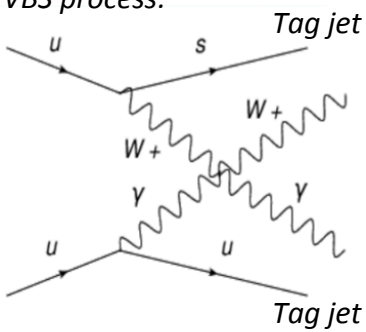
+ some measurements also with 7 TeV !

EWK production: VBF/VBS

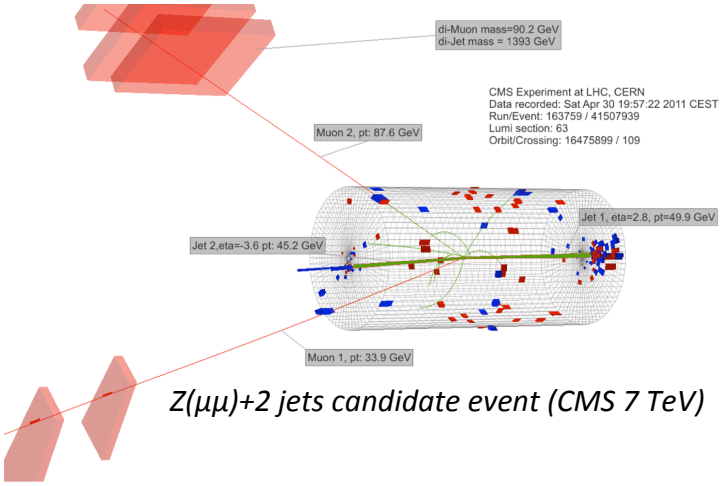
VBF process:



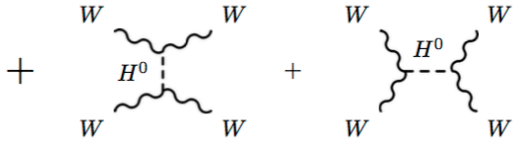
VBS process:



- **V(V)+2jets production is dominated** by $O(\alpha_S^2)$ QCD processes
- **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

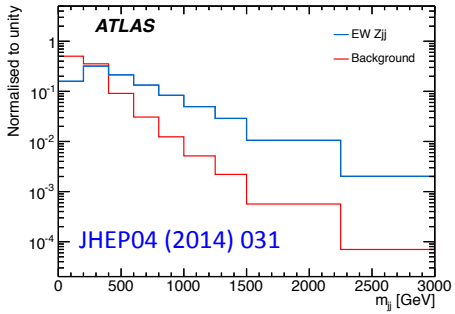


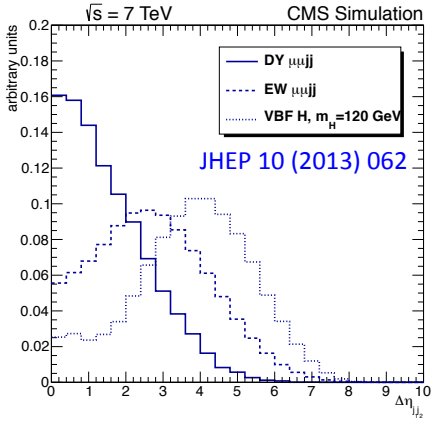
Z(μμ)+2 jets candidate event (CMS 7 TeV)



VBF/VBS characteristic signature:

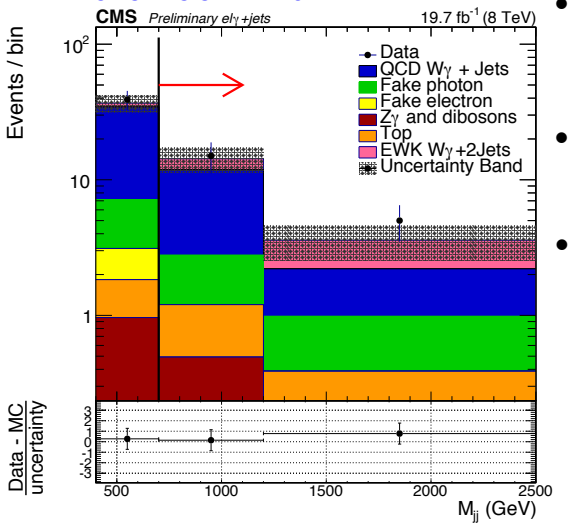
- Two high p_T jets in the forward-backward region
- Large rapidity separation between jets ($\Delta\eta_{jj}$)
  - low hadronic activity in-between
- Large di-jet invariant mass (M_{jj})





New VBS results: Wγ, Zγ, WV

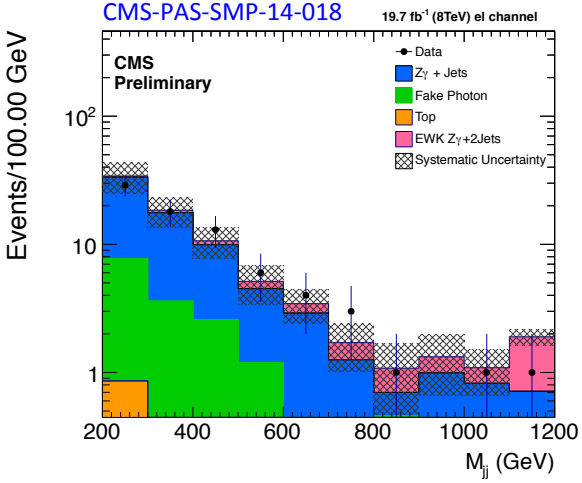
CMS-PAS-SMP-14-011



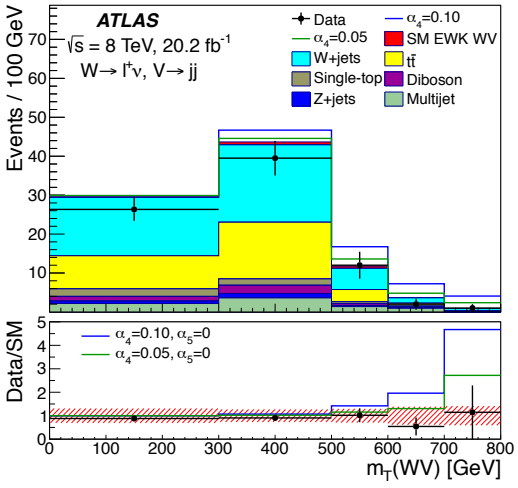
- **Vγ+2jets production is dominated** by $O(\alpha_S^2)$ QCD processes
  - Bkg normalisation is evaluated from data in a low Mjj control region
- Statistics dominated measurement

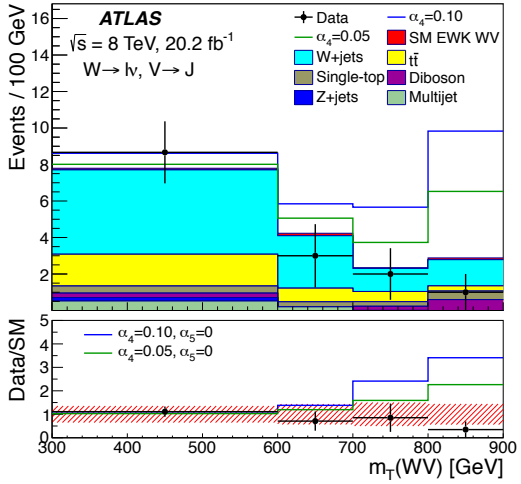
- **W(W/Z)+2jets production**
  - Bkg dominated with W+jets events, estimated in the control region
  - W/Z reconstructed as two small-radius jets or one large-radius jet using jet substructure techniques

CMS-PAS-SMP-14-018

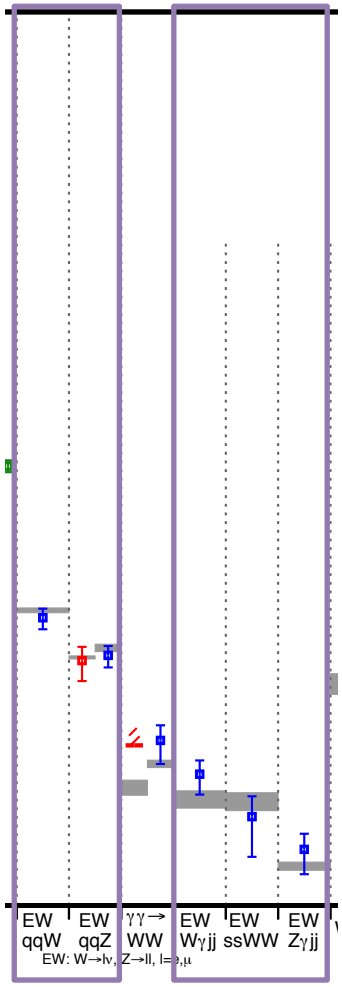


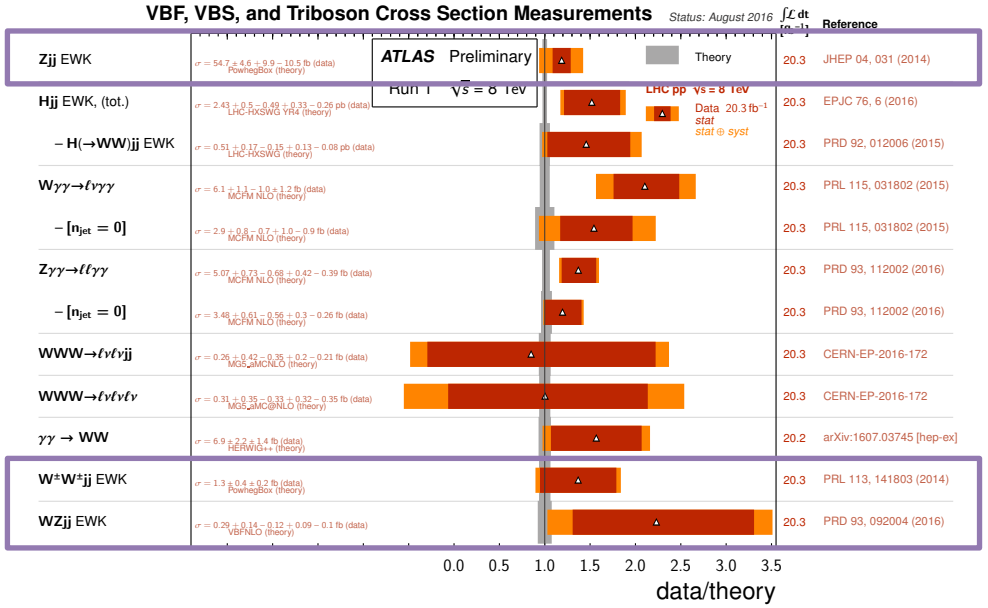
CERN-EP-2016-171

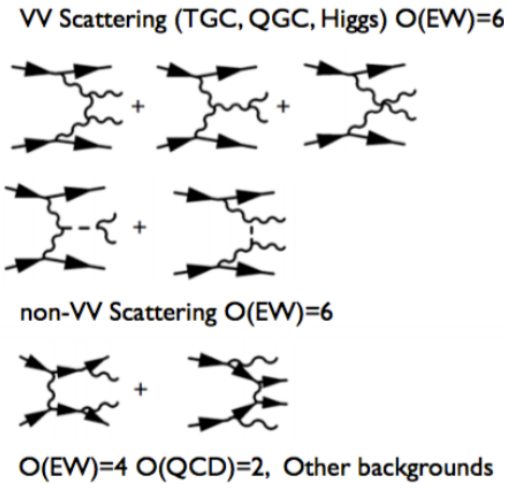




EWK cross section measurements: summary







LHC performed first observations/evidence of EWK VBF/VBS production processes.

Good agreement with SM predictions.

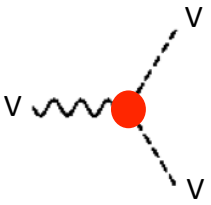
New Physics search: anomalous vector boson couplings

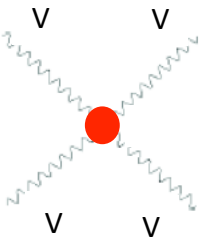
(Multi)boson production is sensitive to New Physics

- New particles decaying to vector bosons: W', Z', …
- Anomalies in vector boson scattering/fusion

Triple and quartic vector boson couplings

- Fundamental prediction of Standard Model (SM)
- Consequence of the non-Abelian nature of the SU(2)xU(1) gauge theory
- **Have exact values in SM!**





Anomalous couplings as search for New Physics?

Two general ways to look for deviations from the SM:

a) Assume a specific model of New Physics: SUSY scenario, dark matter, …

b) Look for model independent deviations and measure "the deviation from SM" (deviations still have to be parametrized)

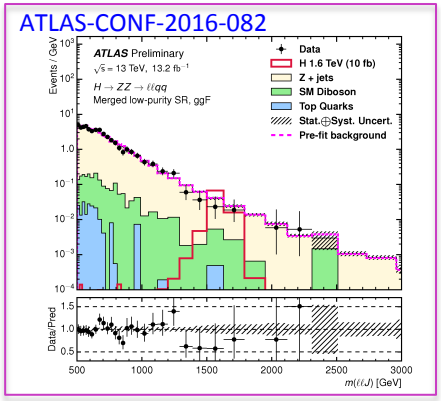
And also choose between:

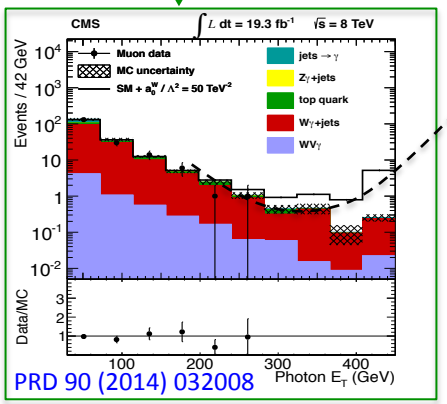
Anomalous coupling measurement

1. Looking for a peak in observed distribution

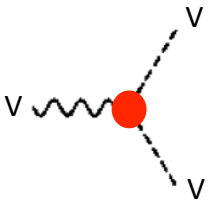
Anomalous coupling measurement

2. Looking for a deviation in the tails of observed distribution (broad deviation)

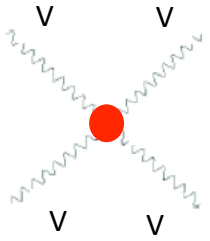




Deviation in the tails due to NP signal at energy beyond direct experimental reach



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:

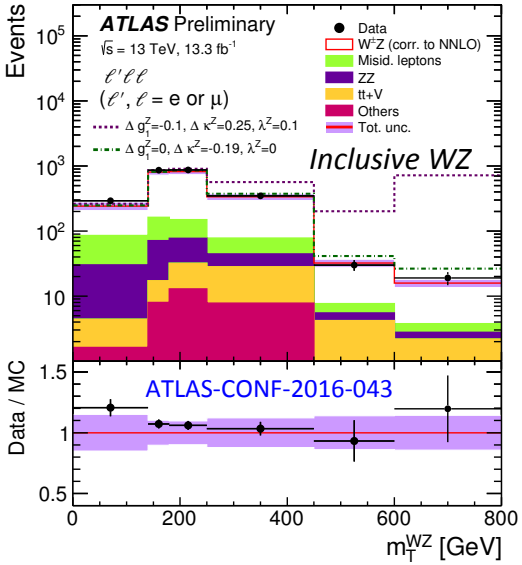
EFT: $\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$

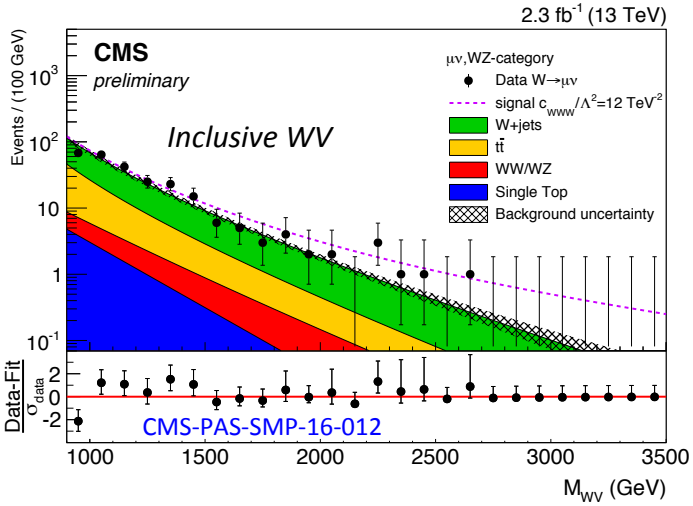
Anomalous couplings: variety of measurements

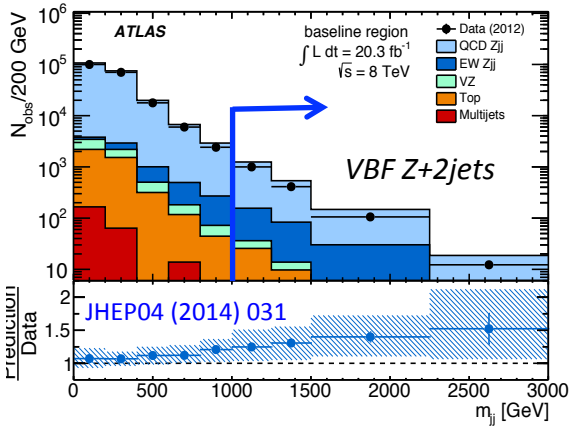
Measurements performed in numerous production channels:

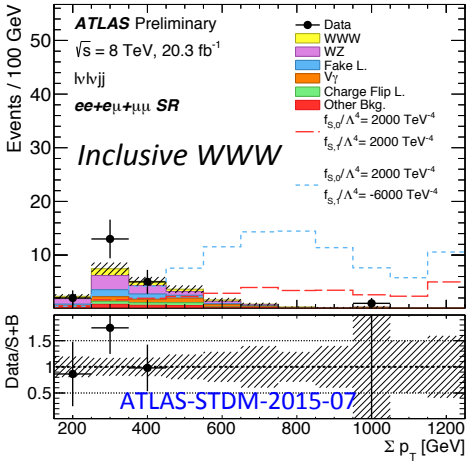
- inclusive diboson and triboson measurements
- EWK production (VBF/VBS) offers a complementary test of anomalous couplings

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





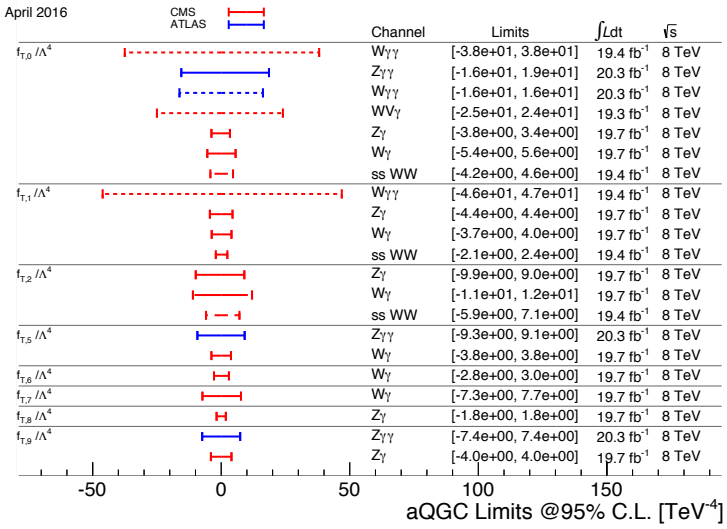


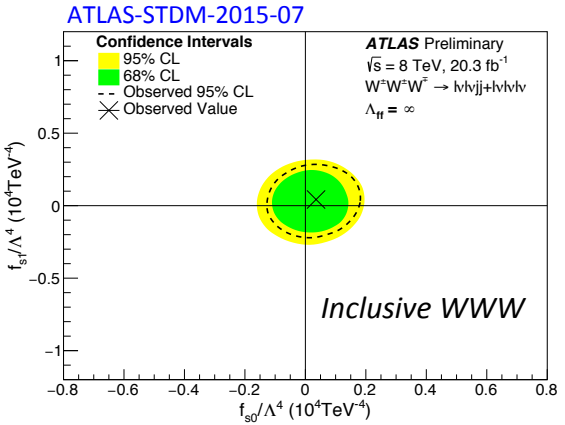


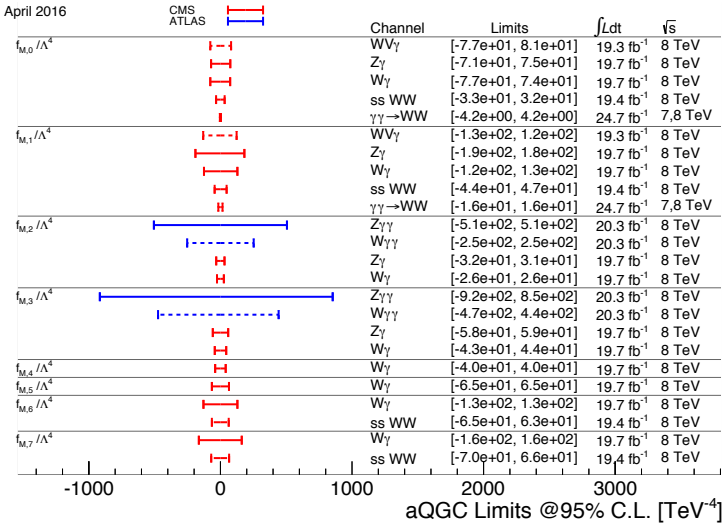
Anomalous couplings result in an **increase of cross section at high energies** -> invariant mass of the diboson system and the boson p_T are particularly sensitive

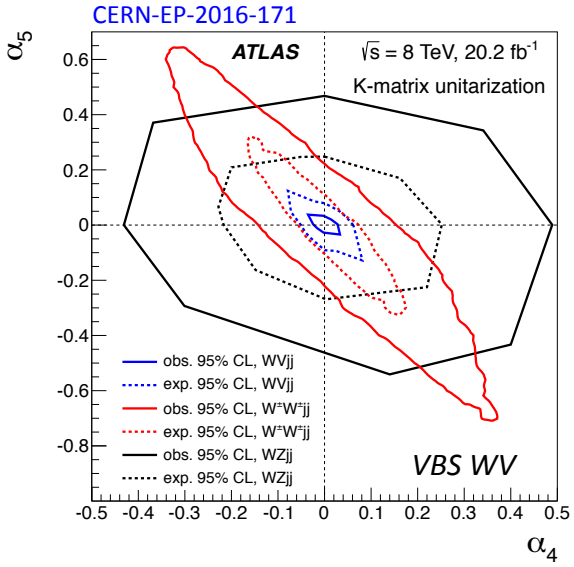
aQGC couplings: variety of measurements

VBS channels have better sensitivity than triboson production.







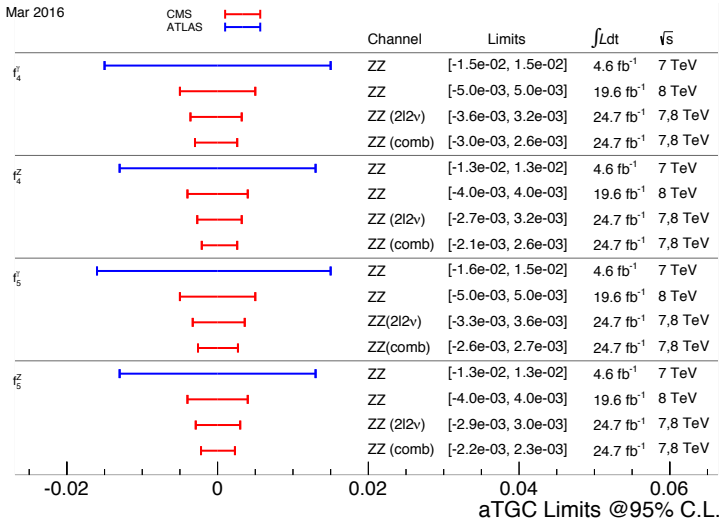


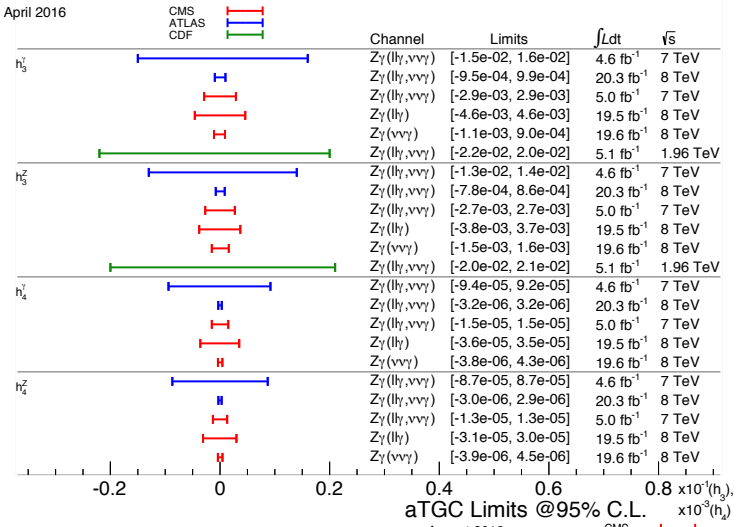
Semileptonic channel WV shows best sensitivity.

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

aTGC couplings: variety of measurements

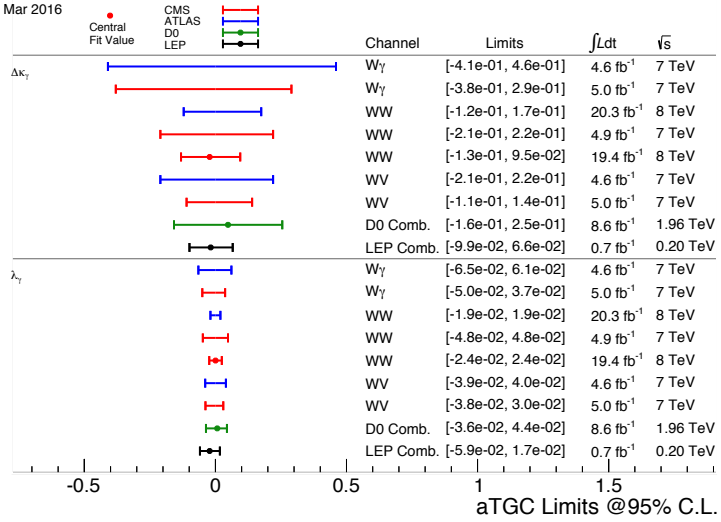
LHC and LEP probing at different energies. Limits on parameters (without the use of form factors) comparable to LEP results.

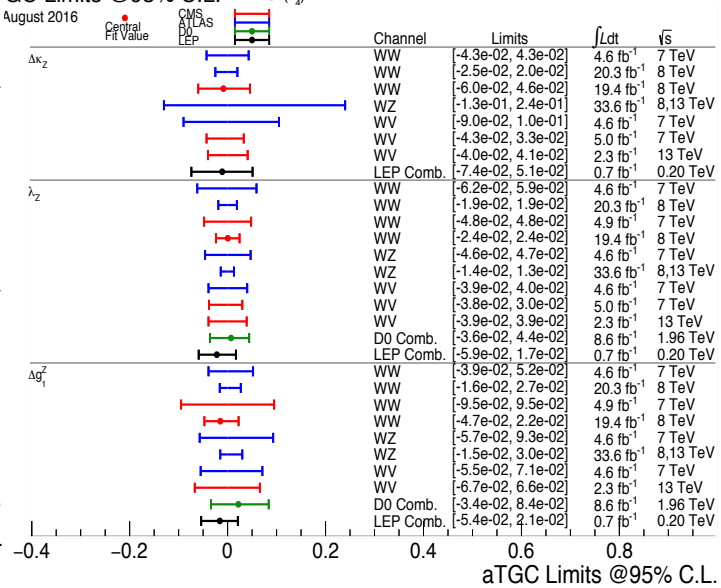




Best sensitivity from Zγ->νvγ channel (larger BR then Zγ->llγ)

Best sensitivity from WV->lνjj channel (larger BR) Increase of collision energy -> increase in sensitivity



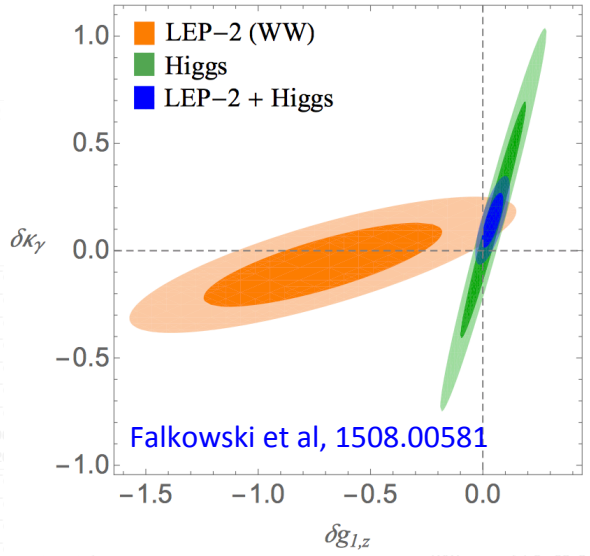


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

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



The future of EWK physics

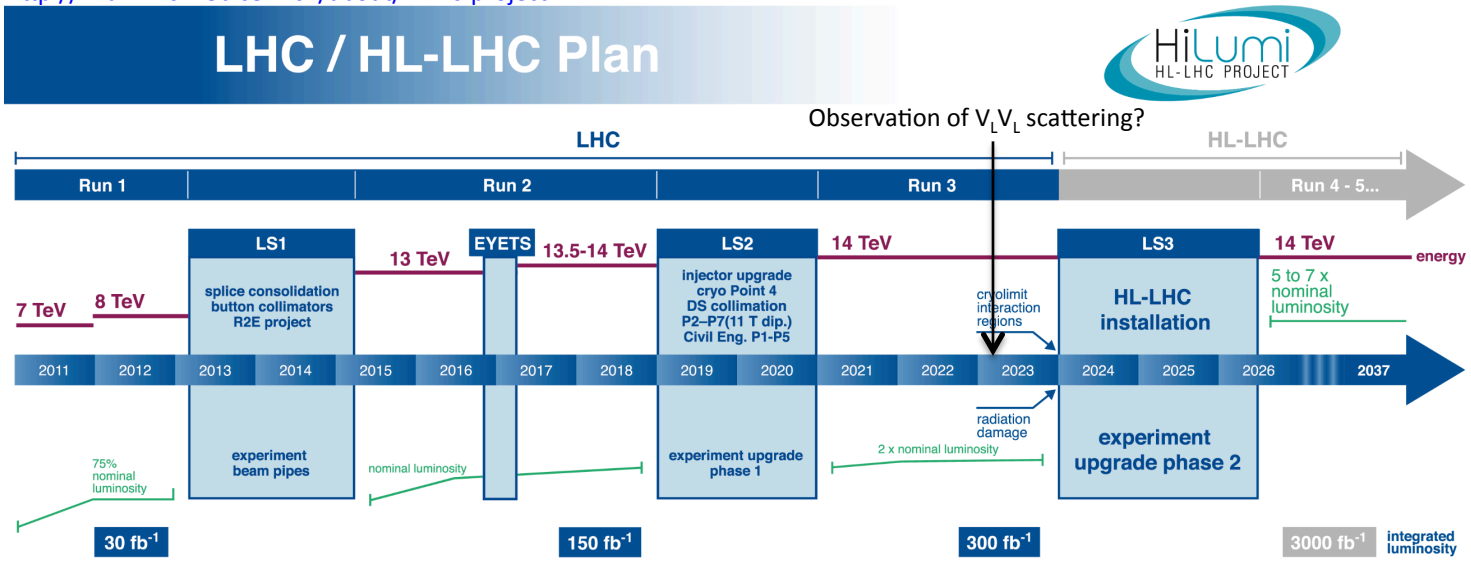
LHC Run2 is ongoing, expecting ~30 fb^{-1} by the end of this year

- We expect to have first observation of VBS production (same-sign WW)
- First evidence/observations of triboson production
- Precision measurements pushing for more precise theoretical calculations (NNLO QCD, 3NLO QCD, NLO EWK,…)
- Significant increase of sensitivity to anomalous vector boson couplings

➢ Await for vast of new EWK results in spring 2017!

Looking forward: HL-LHC (starting 2023)

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



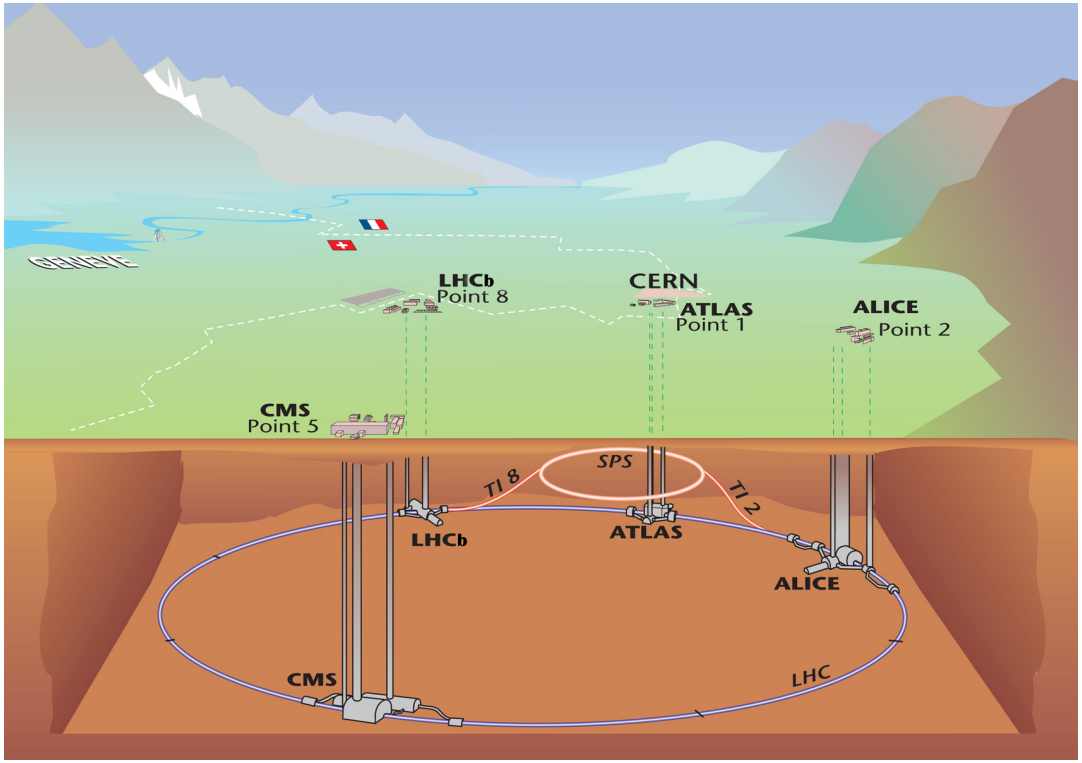

CMS
Compact Muon Solenoid

ATLAS

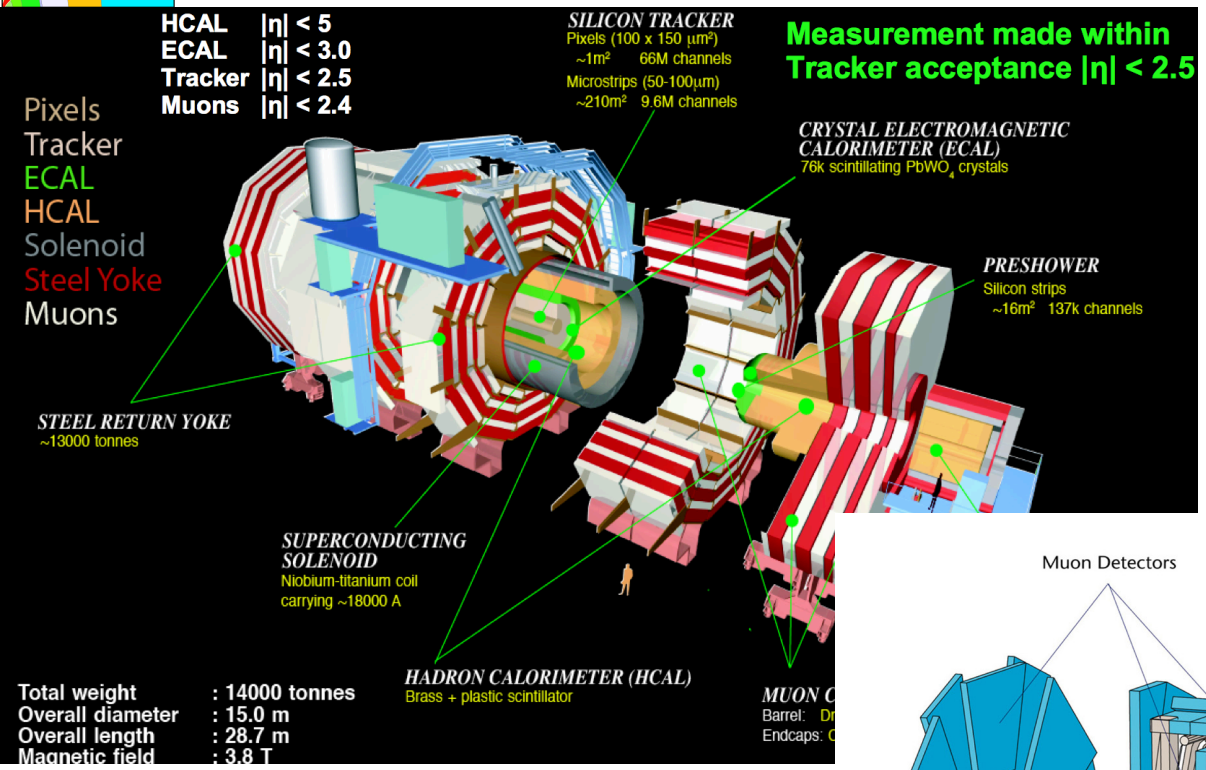
Backup

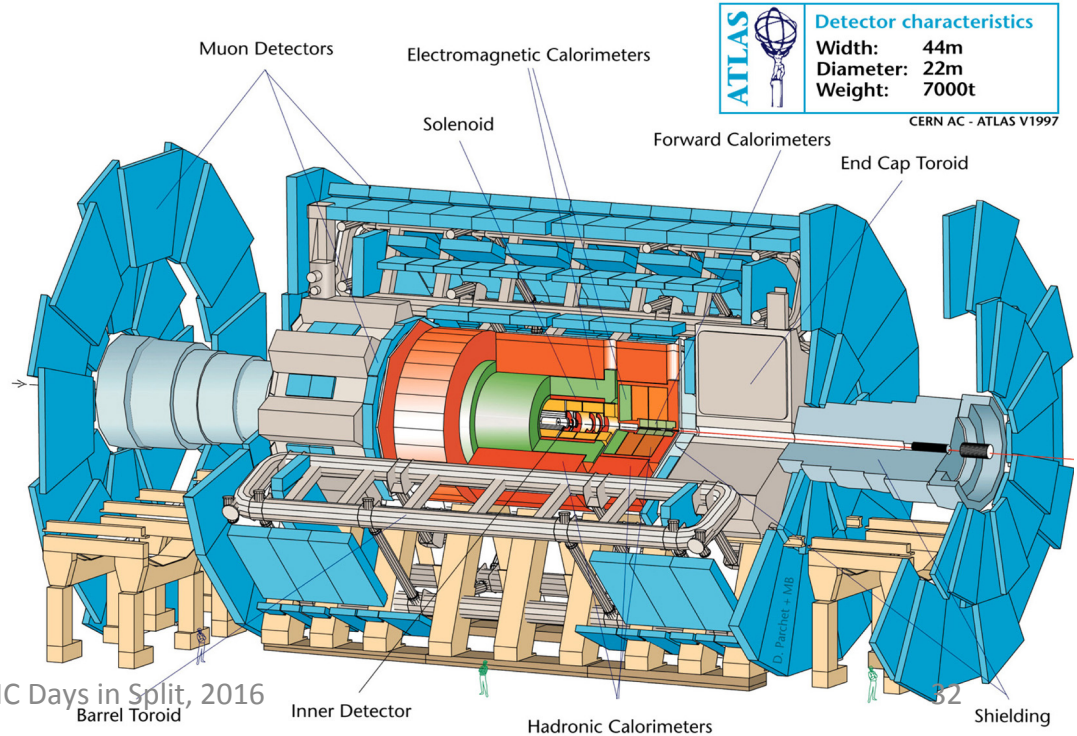

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

CMS and ATLAS experiments

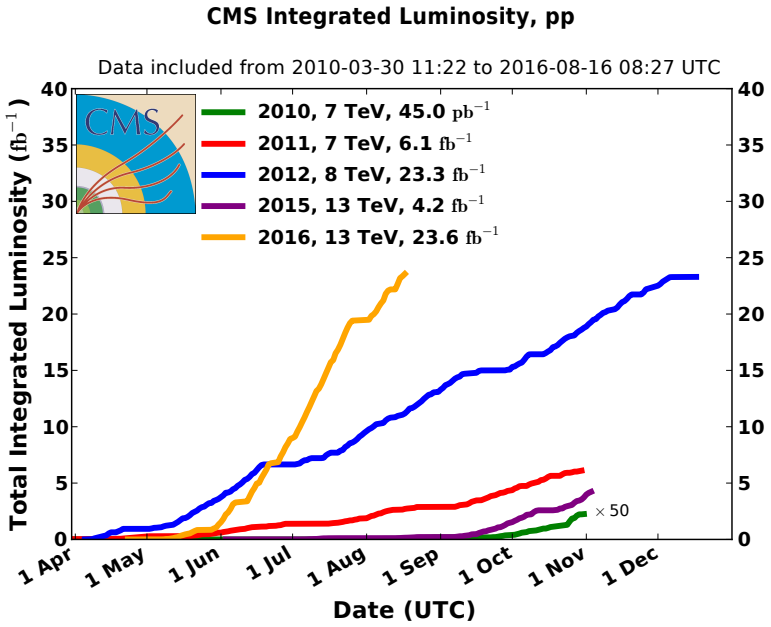


CMS and ATLAS experiments





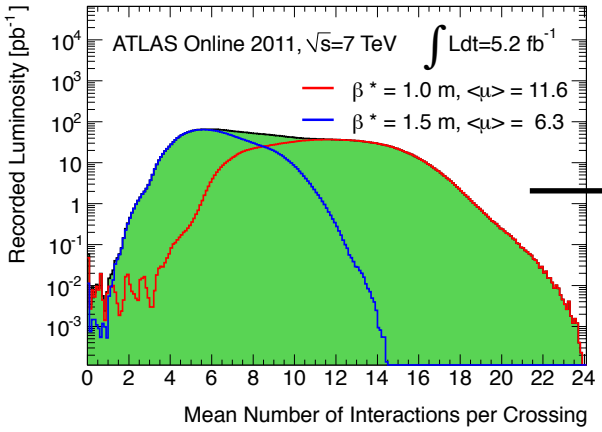
LHC performance

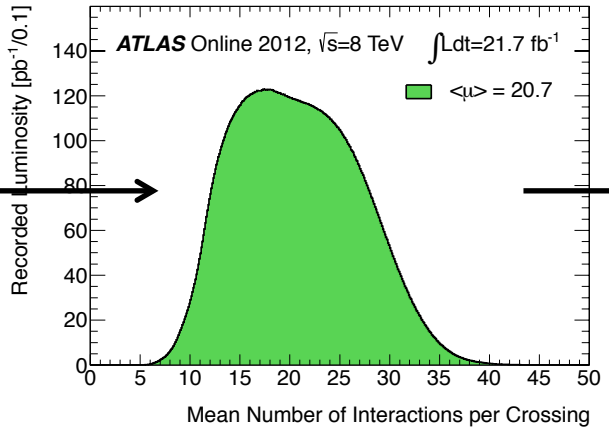


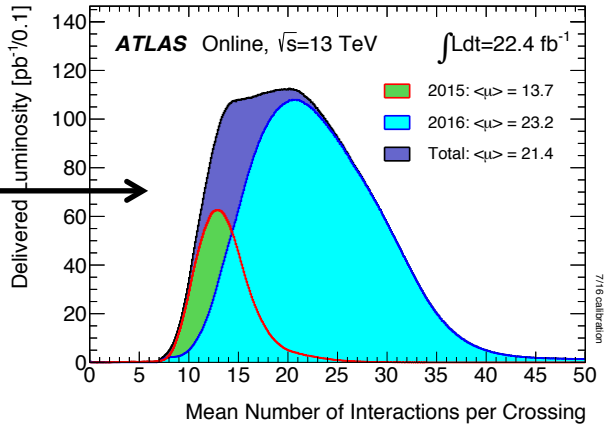
- **Wonderful performance of LHC accelerator in past years**

➢ Large amount of data collected by ATLAS and CMS experiments of proton-proton collisions at a center-of-mass energies of √s = 7, 8 and 13 TeV

➢ Huge amount of measurements performed, including milestone discovery of Higgs boson !



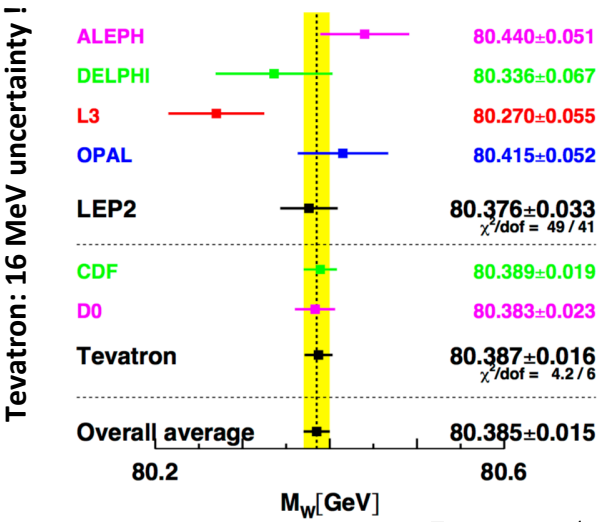


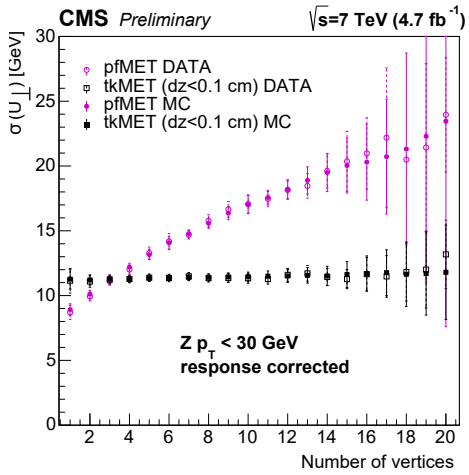


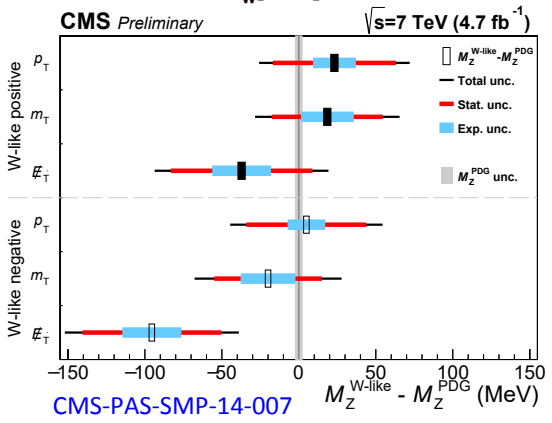
Prospects: W mass measurement at LHC ?

Sources of uncertainty	$M_Z^{W_{like}+}$ p_T	m_T	$\not{E}_T$	$M_Z^{W_{like}-}$ p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

J. Beringer et al. (Particle Data Group), PR D86, 010001 (2012)







CMS-PAS-SMP-14-007

The Z mass is extracted through the W-like lepton p_T, M_T and MET distributions

Exclusive WW measurement

The signal topology considered is pp → p(*)W+W−p(*), where the p(*) indicates that the final state protons either remain intact (“exclusive” or “elastic” production), or dissociate into an undetected system (“quasi-exclusive” or “proton dissociation” production).

The zero-additional-tracks requirement

- motivated by the lack of underlying event activity expected for exclusive and quasi-exclusive γγ → W+W− production
- the beam protons remain intact or dissociate into an undetected forward system respectively