Electroweak Physics at the LHC

Les Recontres de Physique de la Vallée d'Aoste, La Thuile

The University Of Sheffield.

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ATLAS, CMS and LHCb Collaborations

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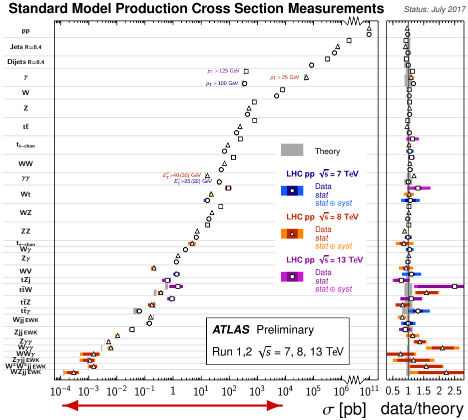
25.02.2018 - 03.03.2018

Introduction

- Cross sections of electroweak processes at the LHC span eight orders of magnitude
- High precision measurements using events with single W and Z bosons
- Precise measurement of diboson processes
- First measurements of rare processes

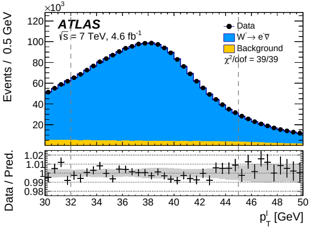


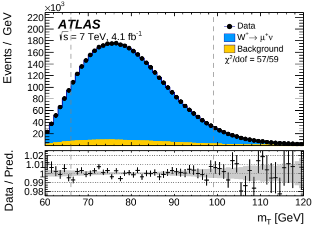
- Summary of recent results in the electroweak sector from ATLAS, CMS and LHCb

Measurement of m_W

arXiv:1701.07240

- **First measurement** of m_W at the LHC
- Performed in 2011 data at $\sqrt{s} = 7$ TeV, using 7.8M $W \to \mu\nu$ and 5.9M $W \to e\nu$ events
- Extensive re-weighting approach to describe all relevant kinematic distributions ($y \times p_{\mathrm{T}} \times A_i$)
- The largest sources of uncertainties are theoretical!
  - QCD modelling (parton-shower and angular coefficients)
  - PDF uncertainty from CT10 (+ CT14 and MMHT2014)

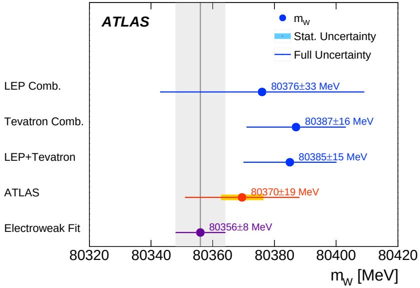


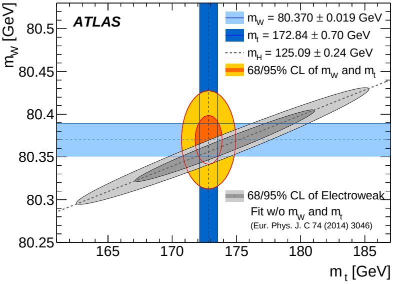


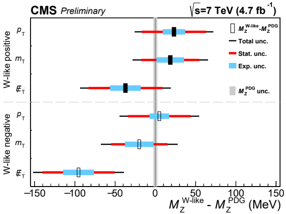
Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T, W^+, e-μ	80370.0	12.3	8.3	6.7	14.5	9.7	9.4	3.4	16.9	30.9	2/6
m_T, W^-, e-μ	80381.1	13.9	8.8	6.6	11.8	10.2	9.7	3.4	16.2	30.5	7/6
m_T, $W^\pm$, e-μ	80375.7	9.6	7.8	5.5	13.0	8.3	9.6	3.4	10.2	25.1	11/13
p_T^ℓ, W^+, e-μ	80352.0	9.6	6.5	8.4	2.5	5.2	8.3	5.7	14.5	23.5	5/6
p_T^ℓ, W^-, e-μ	80383.4	10.8	7.0	8.1	2.5	6.1	8.1	5.7	13.5	23.6	10/6
p_T^ℓ, $W^\pm$, e-μ	80369.4	7.2	6.3	6.7	2.5	4.6	8.3	5.7	9.0	18.7	19/13
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Measurement of m_W

arXiv:1701.07240







CMS-PAS-SMP-14-007

- The measurement of m_W is compatible with previous measurements and as precise as CDF and D0 individually:

$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp. syst.}) \pm 14(\text{mod. syst.})\ \text{MeV}$$

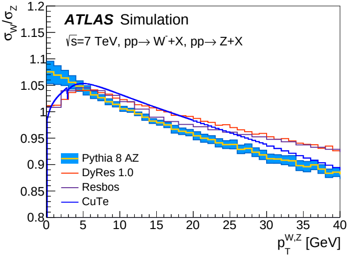
- It is compatible with the global electroweak fit

$$m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F m_Z^2}\,(1+\Delta r)}\right)$$

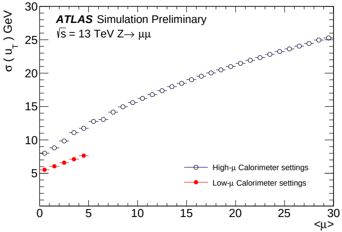
- W-like measurement of m_Z from CMS hints at a more precise recoil calibration with larger uncertainties on the lepton calibration

Prospects for low-μ run

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9



- Further improvements in QCD modelling needed
  - measurements of angular coefficients A_i (or using higher order predictions)
  - using PDFs that include LHC data
  - improve knowledge of p_T^W
- aim to replace the extrapolation from p_T^Z with direct measurement



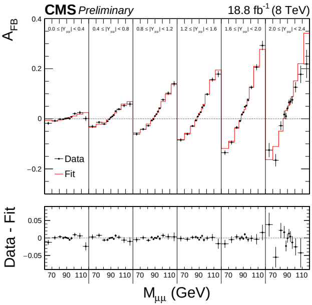
- low-μ data at 13 TeV could allow for a measurement of p_T^W with 1% precision
- the LHC delivered 160 fb^{-1} of $\langle\mu\rangle \sim 2$ data in the end of 2016

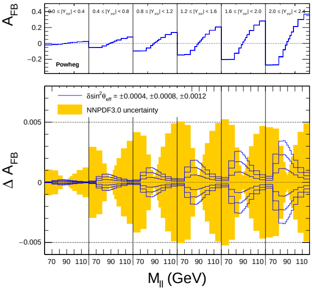
Measurement of $\sin^2\theta_{\text{eff}}$

CMS-PAS-SMP-16-007

- Measurement of $\sin^2\theta_{\text{eff}}^{\text{lep}}$ from the forward-backward asymmetry A_{FB} using 2012 data at $\sqrt{s} = 8$ TeV

$$A_{\text{FB}} = \frac{\sigma(\cos\theta^* > 0) - \sigma(\cos\theta^* < 0)}{\sigma(\cos\theta^* > 0) + \sigma(\cos\theta^* < 0)}$$





- Ambiguity in quark direction dilutes A_{FB} and causes a large sensitivity to PDFs
- Variations of $\sin^2\theta_{\text{eff}}^{\text{lep}}$ and variations of PDF uncertainties show different shape dependence

→ PDF uncertainties are constrained by the fit

Channel	without constraining PDFs	with constraining PDFs
Muon	0.23125 ± 0.00054	0.23125 ± 0.00032
Electron	0.23054 ± 0.00064	0.23056 ± 0.00045
Combined	0.23102 ± 0.00057	0.23101 ± 0.00030

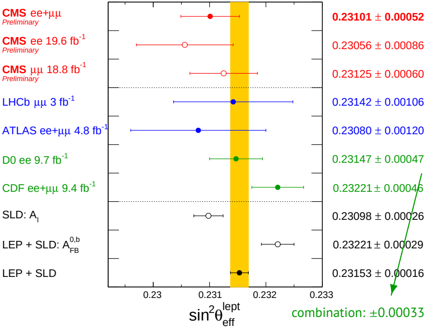
Measurement of $\sin^2\theta_{\text{eff}}$

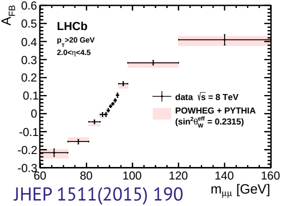
CMS-PAS-SMP-16-007

- The measured value of $\sin^2\theta_{\text{eff}}$ is:

$$\sin^2\theta_{\text{eff}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$

- In agreement with previous measurements at LEP, SLC, Tevatron and LHC
- **Most precise** measurement at the **LHC**





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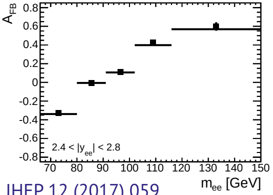
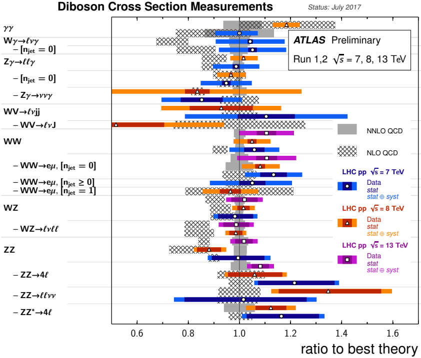
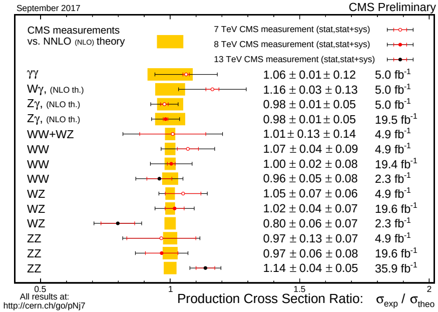


JHEP 12 (2017) 059

- LHCb can probe larger values of $y_{\ell\ell}$ but statistically limited
- Recent measurement of A_{FB} by ATLAS without a measurement of $\sin^2\theta_{\text{eff}}$

Diboson Measurements





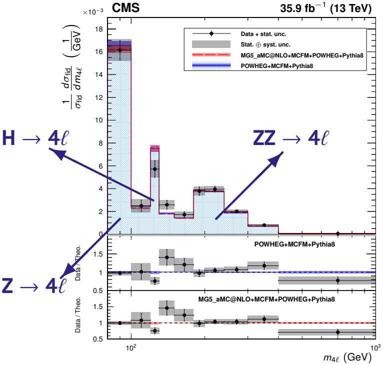
Recent diboson measurements reach a precision of 10% or better

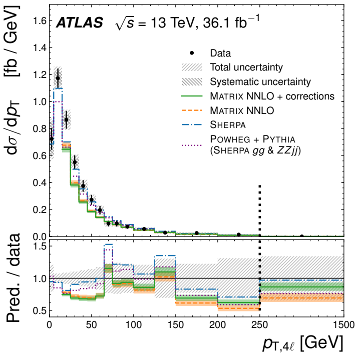
- Many of them are already systematically limited
- Agreement with theory improves substantially using NNLO calculations

$ZZ \rightarrow 4\ell$ production

arXiv:1709.08601 and arXiv:1709.07703

- Updated results on $pp \rightarrow ZZ \rightarrow 4\ell$ cross sections from ATLAS and CMS, and $pp \rightarrow Z \rightarrow 4\ell$ from CMS
- Fiducial cross section measurement **systematically limited** for the first time

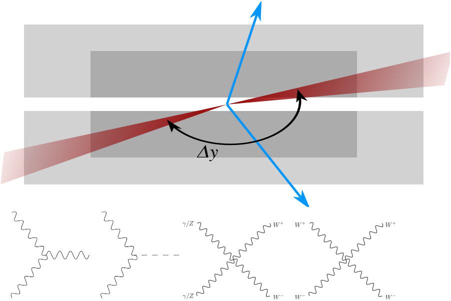


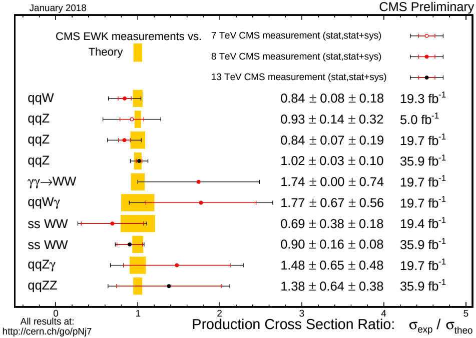


- Large dataset and clean final state allows for an increasing number of differential measurements
- Limits on anomalous neutral TGCs improved by ~ 2

$$-0.0012 < f_4^Z < 0.0010, \quad -0.0010 < f_5^Z < 0.0013,$$
$$-0.0012 < f_4^\gamma < 0.0013, \quad -0.0012 < f_5^\gamma < 0.0013.$$

Vector Boson Scattering / Vector Boson Fusion



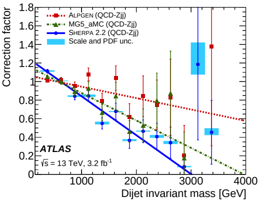


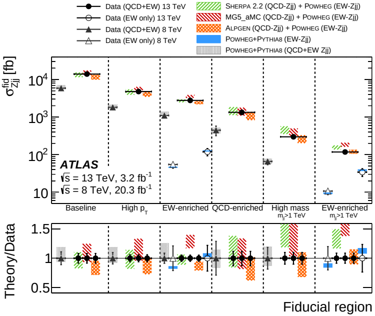
- LHC dataset allows studies of the EW prod. of single ($\mathcal{O}(\alpha^4_{EW})$) and diboson ($\mathcal{O}(\alpha^6_{EW})$) final states
- Access to quartic EW couplings in $VV \rightarrow VV$ signatures with sensitivity to EWSB
- VBS and VBF topology is:
  - two forward jets with high invariant mass
  - and a large rapidity gap

Electroweak *Zjj* production

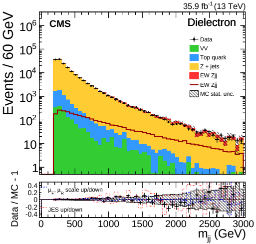
arXiv:1712.09814 and arXiv:1709.10264

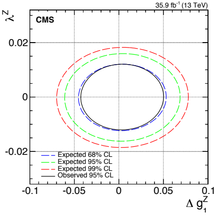
- Electroweak *Zjj* production measured by ATLAS and CMS
- **ATLAS highlights**: analysis in EW- and QCD-enriched regions, data-driven correction factors to QCD





- **CMS highlights**: full 2015+2016 dataset, higher precision, *studies on had. activity*, limits on aTGCs

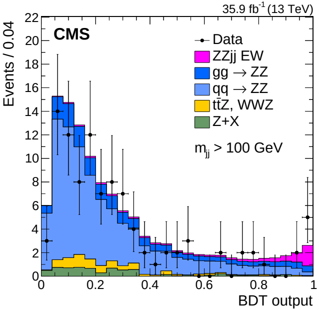




- **Comparison** of ATLAS and CMS results:

$$\sigma_{EW}(\text{ATLAS}) = 119 \pm 16 \pm 20 \quad \text{fb for } m_{jj} > 250 \text{ GeV}$$

$$\sigma_{EW}(\text{CMS}) = 552 \pm 19 \pm 55 \quad \text{fb for } m_{jj} > 120 \text{ GeV}$$



- **First study** of electroweak *ZZjj* production
- A fit to a BDT discriminant is used to separate the EW signal (5%) from the QCD induced production (83%)
- The significance of the signal is 2.7σ (1.6σ expected)

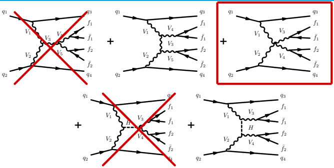
- The fiducial cross section is measured to be:

$$\sigma^{\text{fid.}} = 0.40^{+0.21}_{-0.16}(\text{stat})^{+0.13}_{-0.09}(\text{syst})\ \text{fb}$$

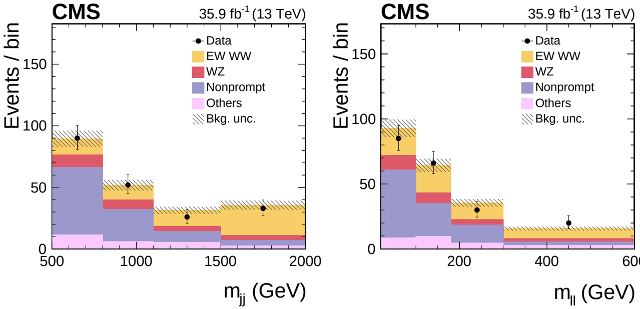
compared to the theoretical prediction at LO of $\sigma^{\text{fid.}} = 0.29^{+0.02}_{-0.03}$ fb

Observation of Vector Boson Scattering

arXiv:1709.05822



- Electroweak $W^{\pm}W^{\pm}jj$ production is an ideal probe for vector boson scattering
- QCD production suppressed using leptons with same charge
- **First observation** with 5.5σ (5.7σ expected)



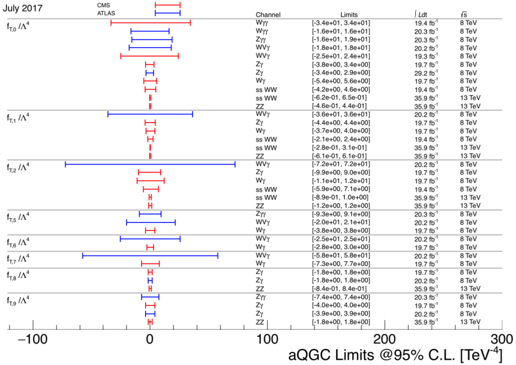
- The fiducial cross section is measured to be:

$$\sigma^{\text{fid.}} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst}) \text{ fb}$$

in agreement with the theoretical prediction at LO of $\sigma^{\text{fid.}} = 4.25 \pm 0.27$ fb

BSM Limits on Quartic Couplings

- Measurements of VBS are used to set model independent limits on BSM physics
- Here shown are limits on EFT dim-8 transverse parameters



- New limits from $W^{\pm}W^{\pm}jj$ and $ZZjj$ constrain the transverse parameters to $\mathcal{O}(10^0)/\text{TeV}^4$ ($f_{T,0}, f_{T,1}, f_{T,2}$ from $\text{SU}_L(2)$, $f_{T,9}, f_{T,9}$ from $\text{U}_Y(1)$)
- Limits on mixed longitudinal and transverse parameters set to $\mathcal{O}(10^1)/\text{TeV}^4$ - $\mathcal{O}(10^0)/\text{TeV}^4$

Conclusions

- The **electroweak precision measurements** at the LHC become increasingly precise
  - for the measurements of m_W and $\sin^2\theta_{\text{eff}}$ the precision of Tevatron is in reach
  - improvements in the theoretical description of the W and Z DY processes are needed
- Measurements of **diboson production** reach the precision era
  - with uncertainties of typically a few percent they are sensitive to NNLO effects
  - limits on anomalous triple gauge couplings improve on those derived at LEP
- The large datasets recorded by the experiments render **rare processes** accessible
  - access to quartic gauge couplings in triboson and VBS signatures
  - first observation of a VBS process

Backup