Semi-leptonic VBS measurements

VBS Polarization Workshop LLR
October, 2018

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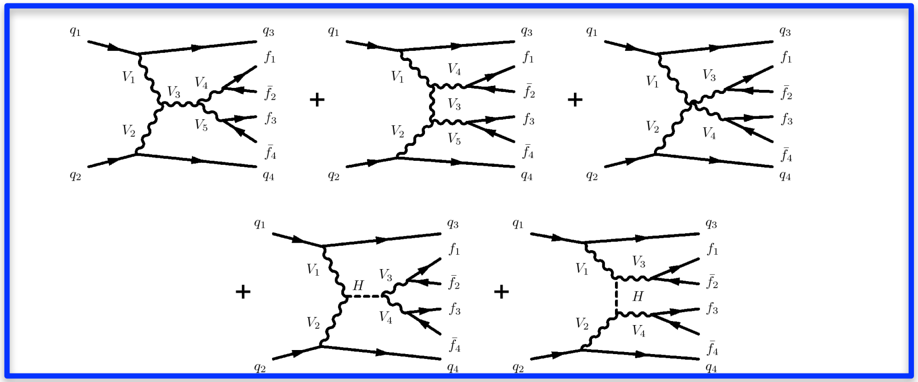
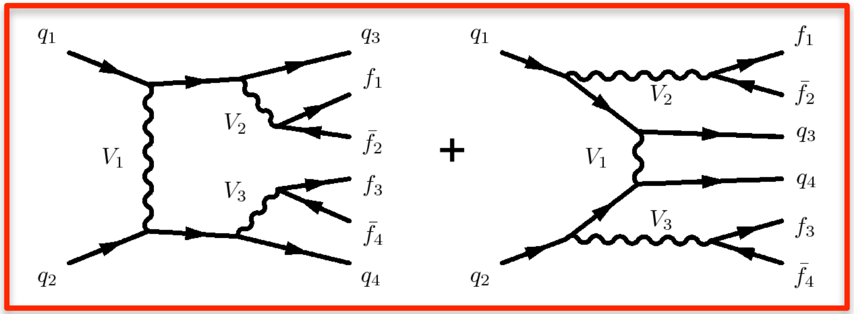
Recent LHC results

- Recent Run 2 ATLAS and CMS VBS results at $\sqrt{s}$ of 13 TeV
- Using datasets with integrated luminosity of 36 fb^{-1}
  - Measurements of EW production of $W^{\pm}W^{\pm}$ by ATLAS and CMS
    - ATLAS-CONF-2018-030, PRL. 120, 081801 (2018)
    - Evidence by ATLAS and CMS in Run-2
    - Events with two same sign leptons in association with two jets
  - Measurements of EW production of $W^{\pm}Z$ by ATLAS and CMS
    - ATLAS-CONF-2018-033, CMS-PAS-SMP-18-001
    - Events with three leptons in association with two jets
  - Measurement of EW ZZ production by CMS
    - Phys. Lett. B 774 (2017) 682
    - Events with four leptons in association with two jets

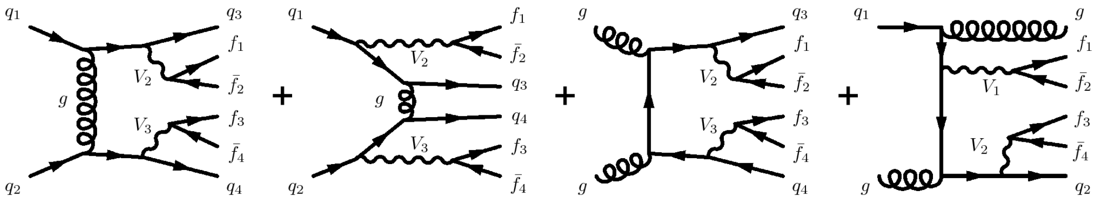
Vector boson scattering

- VVjj process cross section at leading-order (LO):
  - Pure EW contribution at $O(\alpha^6)$
    - VBS and irreducible EW (separately not gauge-invariant)





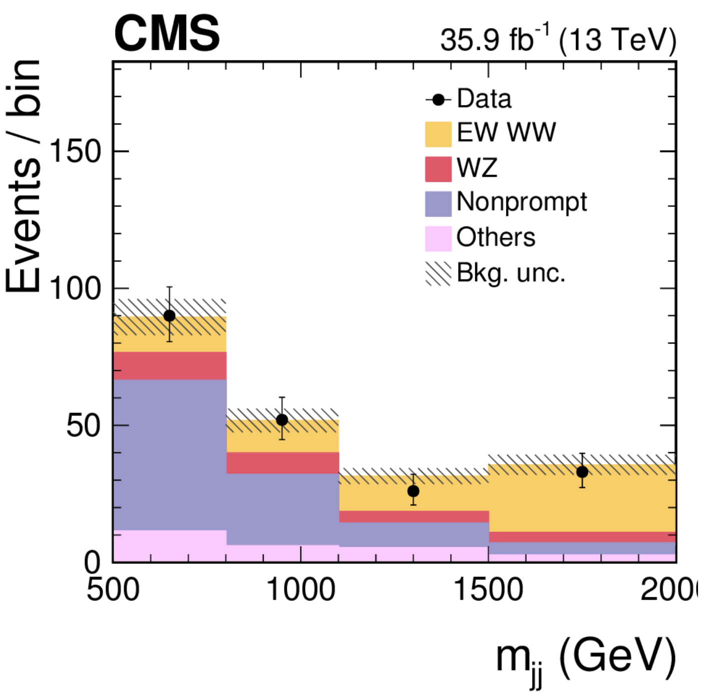
  - QCD induced contribution at $O(\alpha^4\alpha_s^2)$

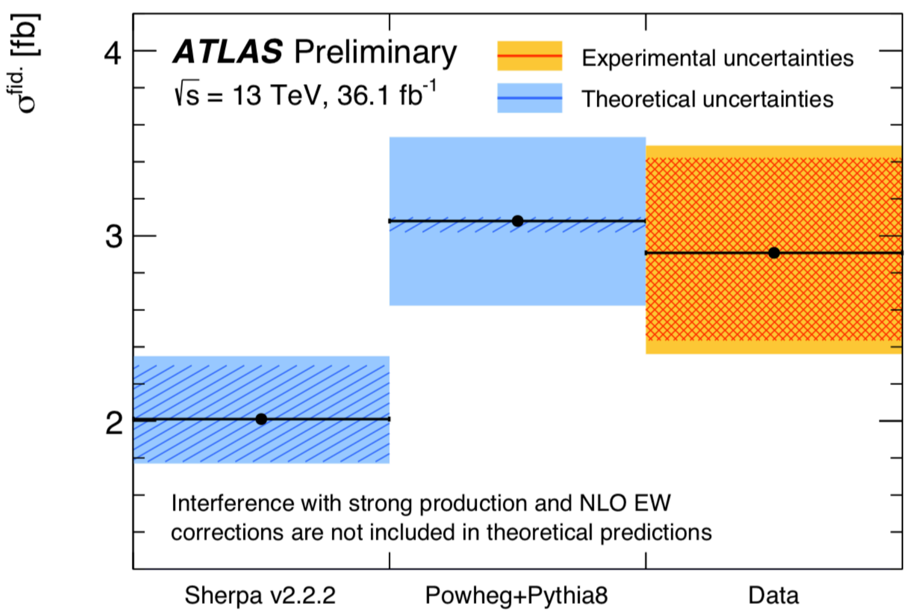


  - Interference of the EW and QCD amplitudes contributes at $O(\alpha^5\alpha_s)$
    - O(+1%) in typical fiducial region

Recent LHC results

- Recent Run 2 ATLAS and CMS VBS results at $\sqrt{s}$ of 13 TeV
- Measurements of $W^{\pm}W^{\pm}$ and WZ SM EW production fiducial cross sections
    - Need for reliable predictions: higher orders, parton showers, approximations, etc.

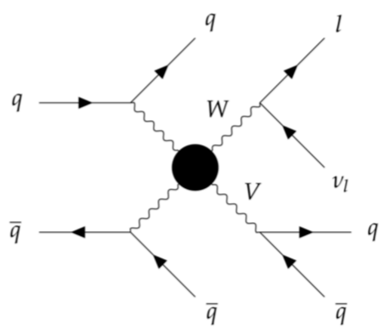




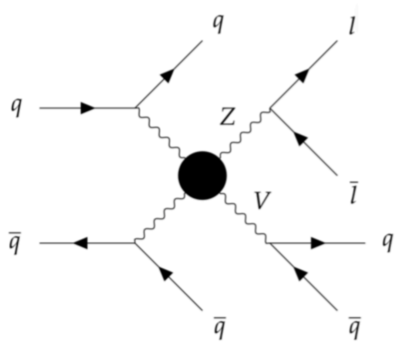
Semileptonic final states

- Study of the semileptonic WV and ZV VBS processes
  - Benefit from the large hadronic branching fraction of W or Z boson
  - Ability to fully reconstruct the WV mass
    - Up to quadratic ambiguity
    - See previous talk

- $W^{\pm}Vjj$ includes contributions from:
  - $W^{\pm}W^{\pm}jj$, $W^{\pm}Wjj$, and $W^{\pm}Zjj$ VBS processes
- ZVjj also includes contributions from ZZjj
- W/Z in VBS events can be highly boosted



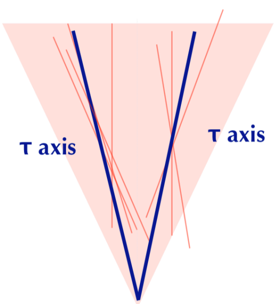
- Main challenges of the WVjj channel:
  - Large backgrounds from W+jets and top
  - Difficult to separate WW and WZ production

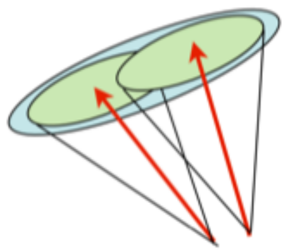


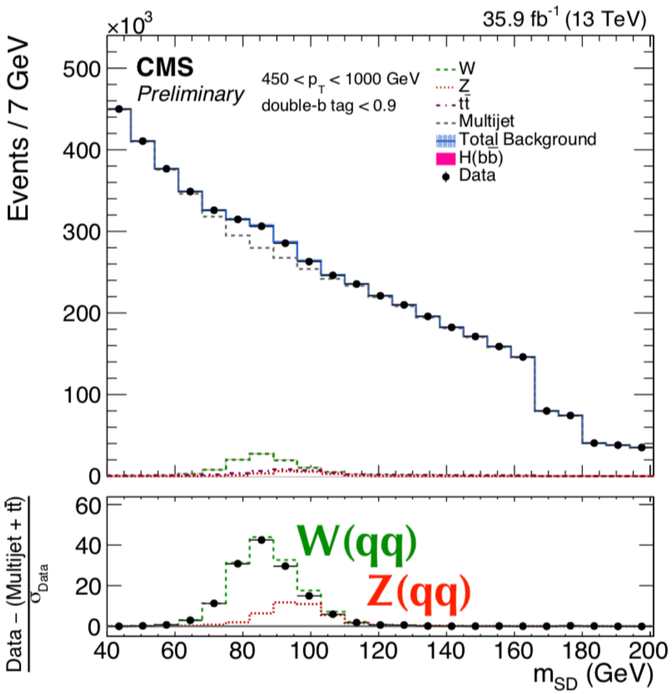
Boosted W/Z

- W/Z in VBS events can be highly boosted
- Particular interest for anomalous couplings
- Influence of higher order operators most prominent at:
    - Large boson pT
    - Large di-boson invariant mass
- Large radius V-jets
- V-jet tagging via substructure techniques

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







PRL 120 (2018) 071802

- Before computing the mass
    - Remove pileup and soft wide angle radiation

Experimental challenge: boost

- Boosted V-tagging techniques still rapidly advancing
  - Active advances with deep neutral networks and boosted decision trees
  - Large factors in background suppression appear within reach

ECF ratio D2

at p_T~500 GeV: ~30% W signal at ~1% mistag

$$D_2^1 = \frac{e_2^1}{(e_2^1)^3}$$

n-subjetiness ratio τ_{21}

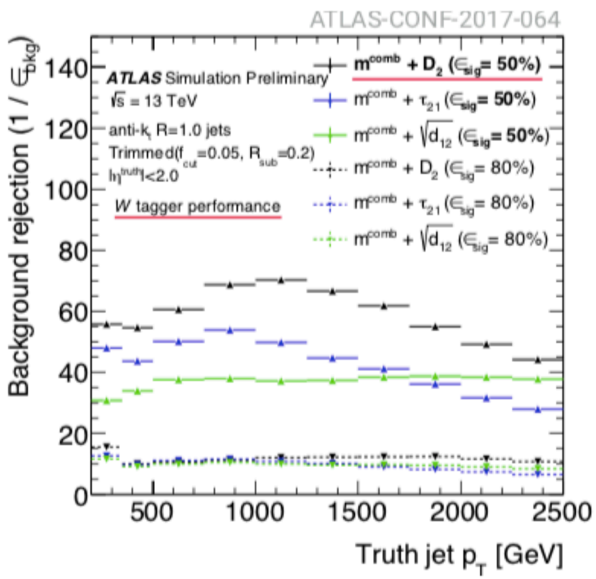
at p_T~500 GeV: ~55% W signal at ~2% mistag

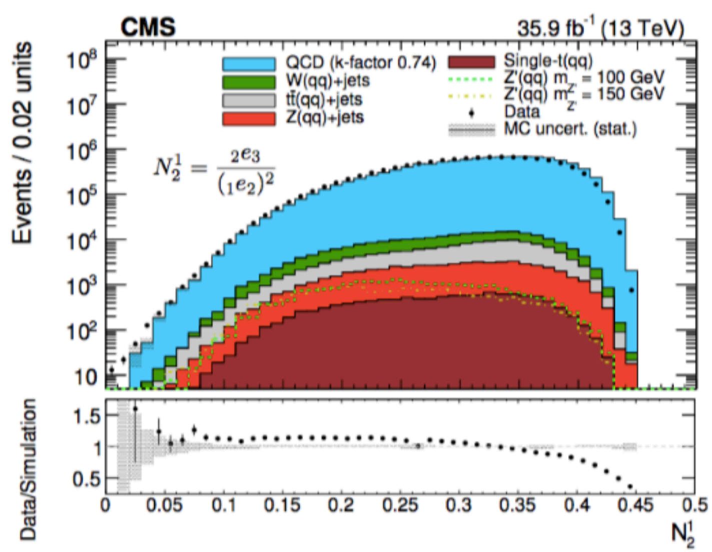
ECF ratio N_2^1

at p_T~500 GeV: ~15% W signal at ~5% mistag

$$N_2^1 = \frac{{}_2e_3}{({}_1e_2)^2}$$

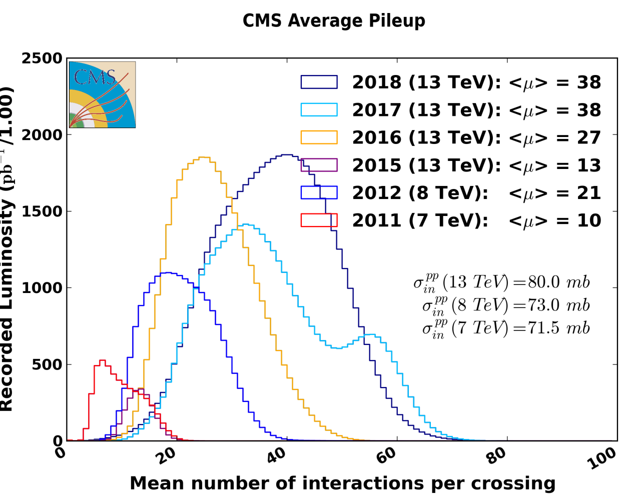
Ian Moult: BOOST16

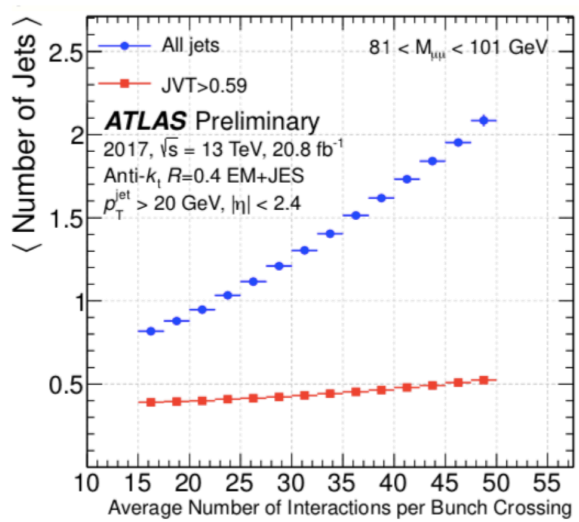


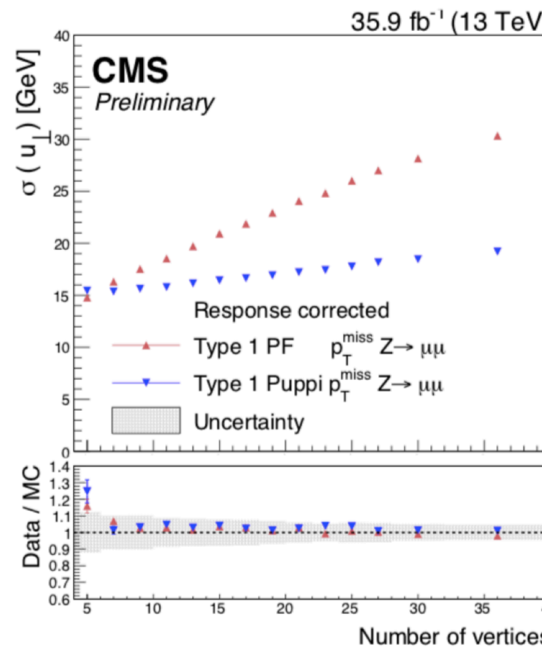


Pileup mitigation

- LHC during 2015-2018: on average 15-40 pileup
- Pileup affects missing energy, jet substructure, lepton isolation, etc.
    - Different techniques to mitigate the effect of pileup in ATLAS and CMS
    - Examples: Jet vertex tagger in ATLAS and Puppi in CMS



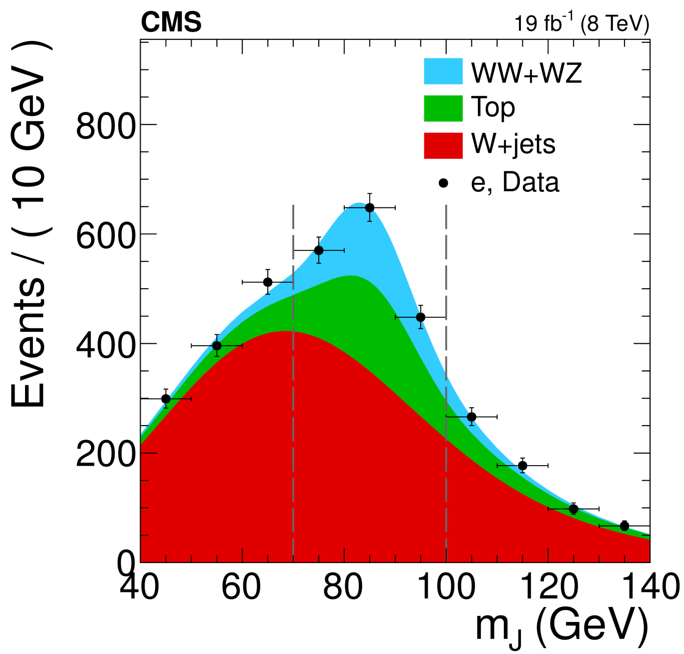




- HL-LHC

Background estimation

- Large backgrounds from W+jets
  - Determine ratio fo simulated to data distributions in sideband
  - Extrapolate to signal region using transfer function (from simulation)
  - Accounts for data-MC differences in shape and normalization



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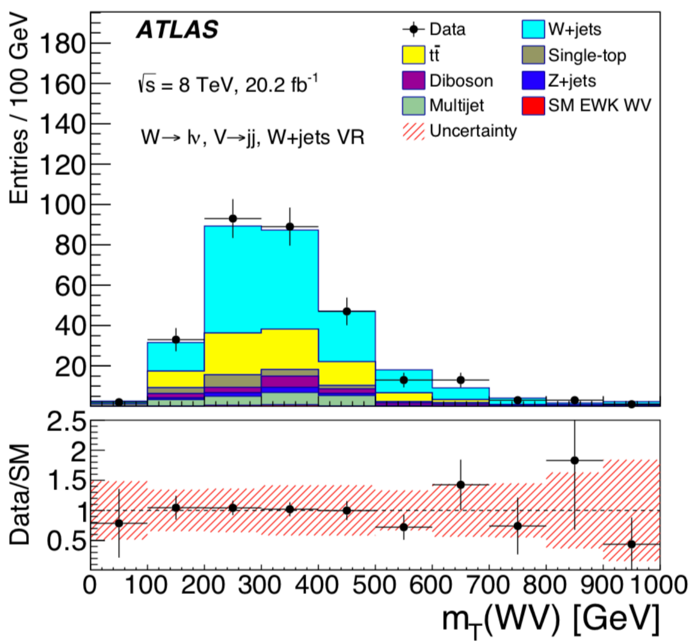
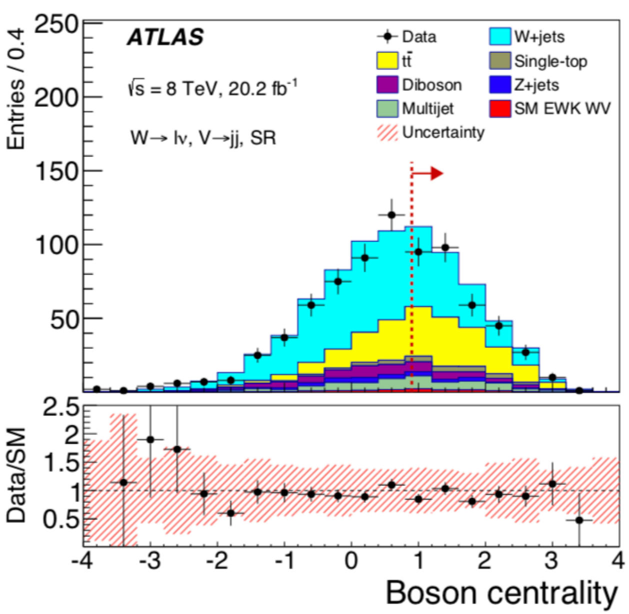


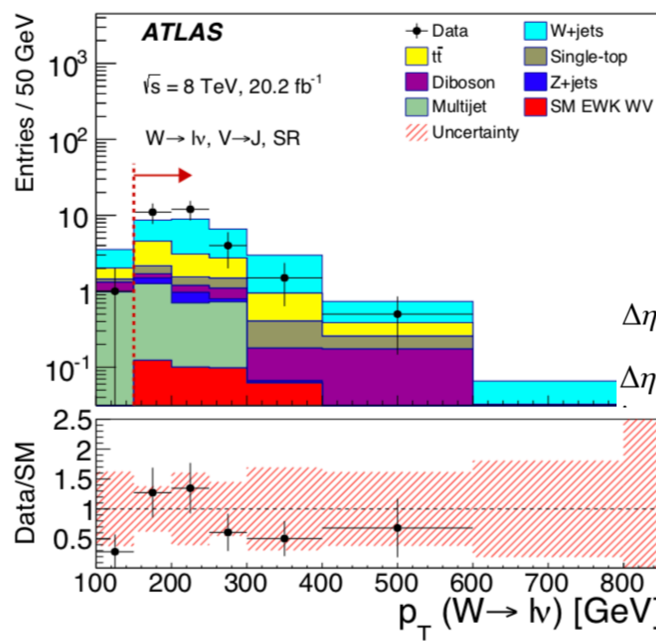
Phys. Rev. D 95 032001 (2017)

ATLAS 8 TeV measurement

- ATLAS measurement of WVjj at 8 TeV
  - Resolved and merged V-jets considered
- Leptonic W reconstructed from the neutrino solution
- Optimized for AQGC sensitivity
  - mjj>800 GeV, boson centrality, pT balance, etc. requirements
- Leptonic W reconstructed from the neutrino solution

Phys. Rev. D 95 032001 (2017)





$$A_{WV} = \frac{|\vec{p}_{\rm T}(V_{\rm had}) + \vec{p}_{\rm T}(W_{\rm lep})|}{p_{\rm T}(V_{\rm had}) + p_{\rm T}(W_{\rm lep})} .$$

$$\zeta_V = \min\{\Delta\eta_-, \Delta\eta_+\} ,$$

$$\Delta\eta_- = \min\{\eta(V_{\rm had}), \eta(W_{\rm lep})\} - \min\{\eta_{\rm jtag1}, \eta_{\rm jtag2}\}$$

$$\Delta\eta_+ = \max\{\eta_{\rm jtag1}, \eta_{\rm jtag2}\} - \max\{\eta(V_{\rm had}), \eta(W_{\rm lep})\}$$

ATLAS 8 TeV measurement

- Use transverse mass of the WV system to search for AQGC signal

$$m_T(WV) = \sqrt{(E_T(V_{had}) + E_T(W_{lep}))^2 - (p_x(V_{had}) + p_x(W_{lep}))^2 - (p_y(V_{had}) + p_y(W_{lep}))^2}$$

	Resolved channel		Merged channel
	e^+ and μ^+	e^- and μ^-	e and μ
W + jets	92 ± 37	51 ± 29	19.4 ± 9.9
$t\bar{t}$	59 ± 18	63 ± 35	6.8 ± 2.8
Single-top	10.0 ± 5.6	5.5 ± 3.2	2.2 ± 1.2
Diboson	8.6 ± 5.7	10.8 ± 6.4	1.6 ± 1.2
Z + jets	4.5 ± 1.5	3.4 ± 2.4	0.58 ± 0.64
Multijet	16 ± 16	12 ± 12	1.8 ± 1.9
Total background	190 ± 53	145 ± 54	32 ± 12
EWK WV (SM)	3.66 ± 0.82	2.34 ± 0.56	0.54 ± 0.22
EWK WV ($\alpha_4 = 0.1, \alpha_5 = 0$)	21.0 ± 4.2	9.2 ± 1.9	15.1 ± 4.4
Data	173	131	32

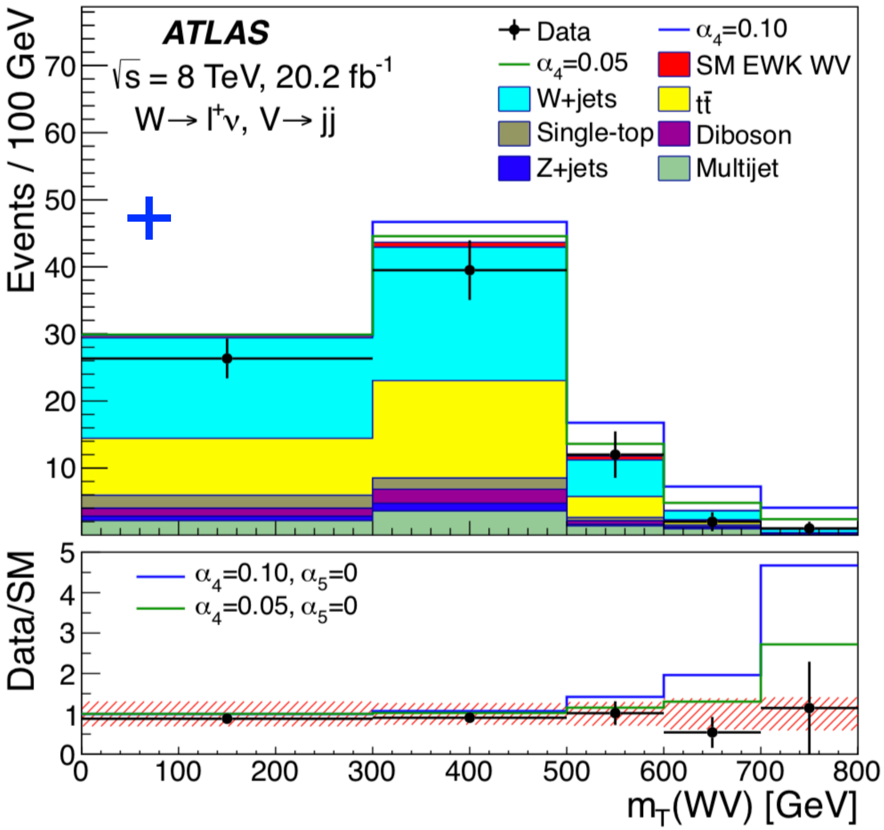
	Fractional uncertainty	
Source	*Resolved*	*Merged*
W/Z + jets modeling	0.13	0.29
$t\bar{t}$ modeling	0.14	0.07
Multijet yield	0.06	0.05
Minor background yields	0.04	0.05
Jet reconstruction	0.21	0.17
Other detector/luminosity	0.04	0.03
Limited stats in MC or CR	0.02	0.06
Total	0.29	0.36

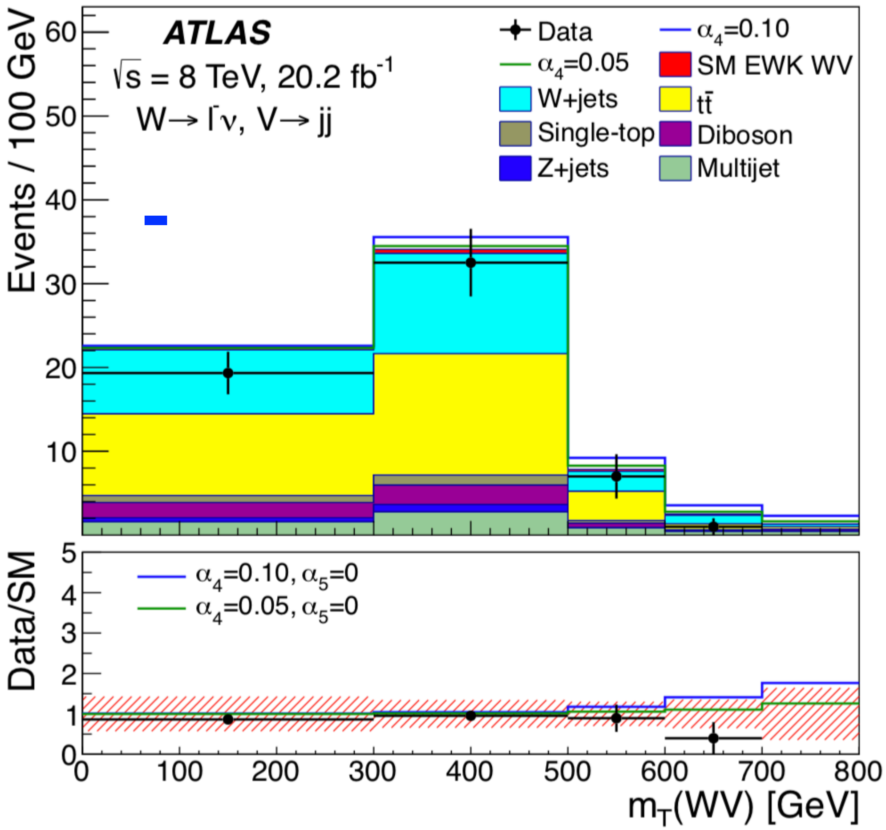
$$\alpha_4 \mathcal{L}_4 = \alpha_4 \, \mathrm{tr}[\mathbf{V}_\mu \mathbf{V}_\nu] \, \mathrm{tr}[\mathbf{V}^\mu \mathbf{V}^\nu] ,$$
$$\alpha_5 \mathcal{L}_5 = \alpha_5 \, \mathrm{tr}[\mathbf{V}_\mu \mathbf{V}^\mu] \, \mathrm{tr}[\mathbf{V}_\nu \mathbf{V}^\nu] ,$$

- Resolved category is split by charge

ATLAS 8 TeV measurement

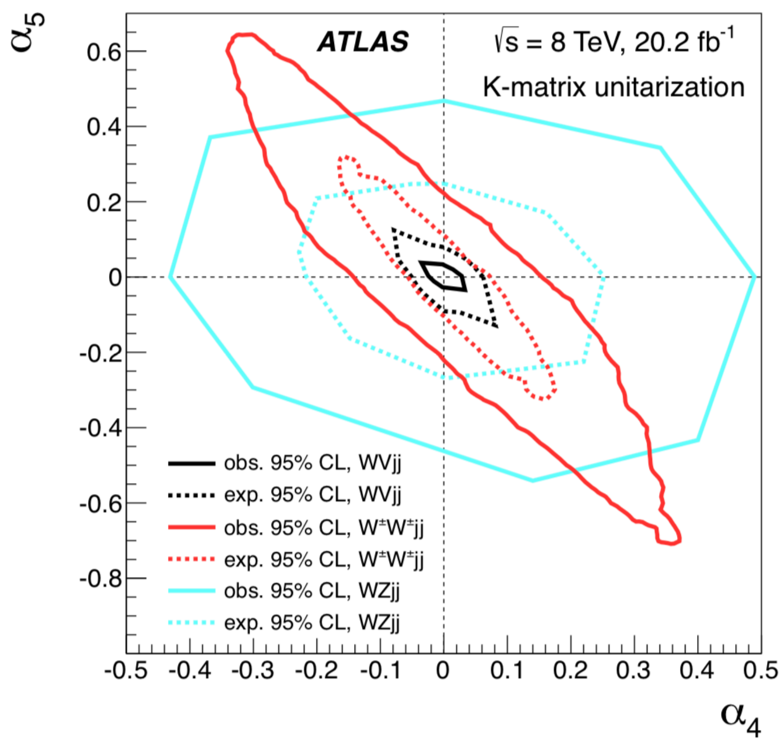
- Resolved category
  - No excess seen

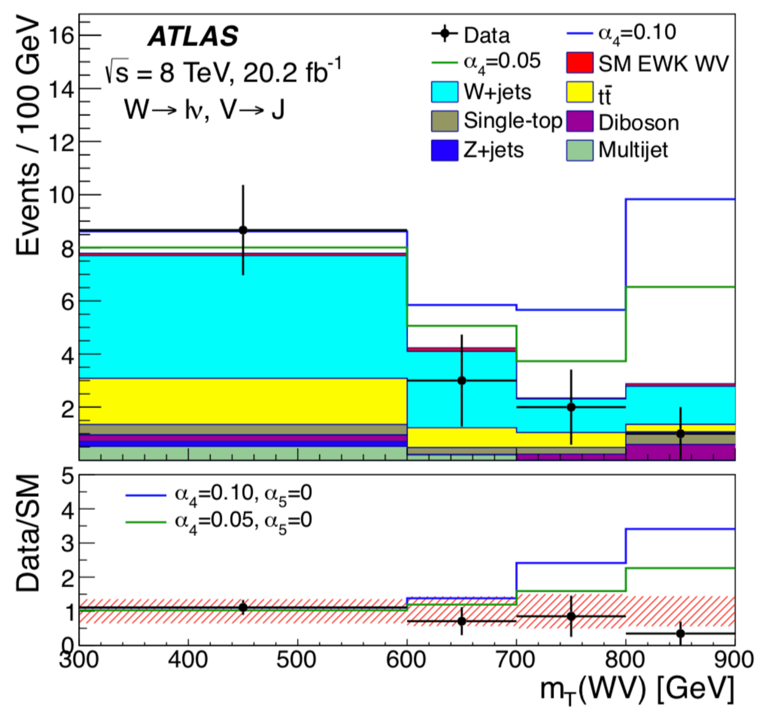




ATLAS 8 TeV measurement

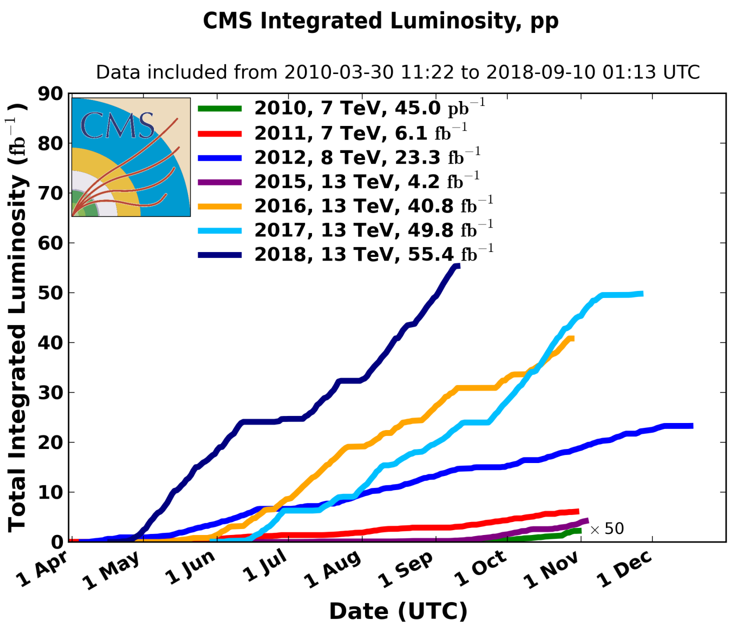
- More stringent limits than the corresponding $W^{\pm}W^{\pm}$ and WZ leptonic channels
  - Boosted category improves the limits by 40%

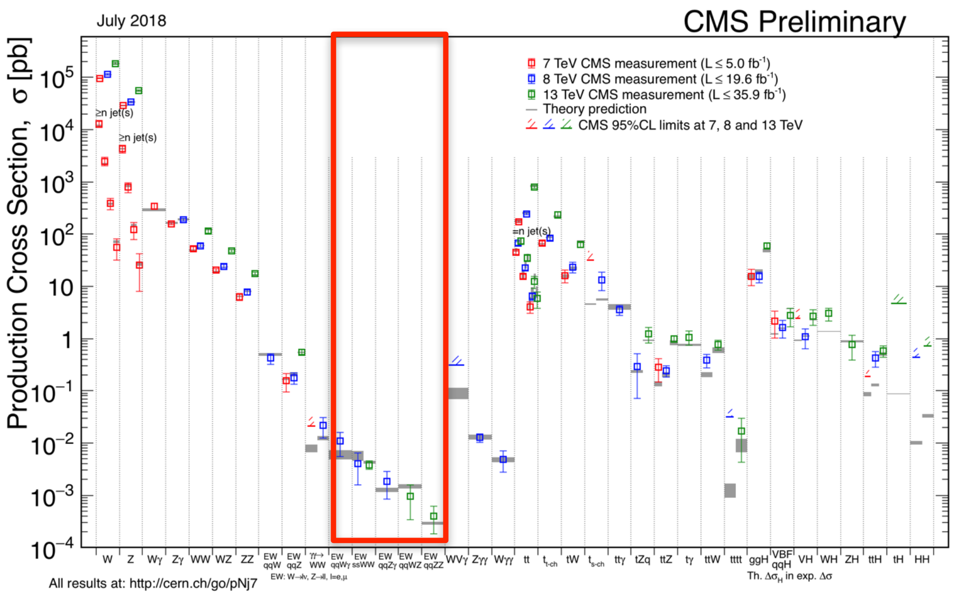




LHC Run 2

- Measurements of VBS cross sections of *O*(1fb) in leptonic channels
  - Measurements are statistically limited
  - Current 13 TeV results using dataset of 36 fb^{-1}
- ATLAS and CMS have accumulated ~30 fb^{-1} at $\sqrt{s}$ of 7/8 TeV and ~150 fb^{-1} at $\sqrt{s}$ of 13 TeV
  - Semileptonic measurements at 13 TeV to come





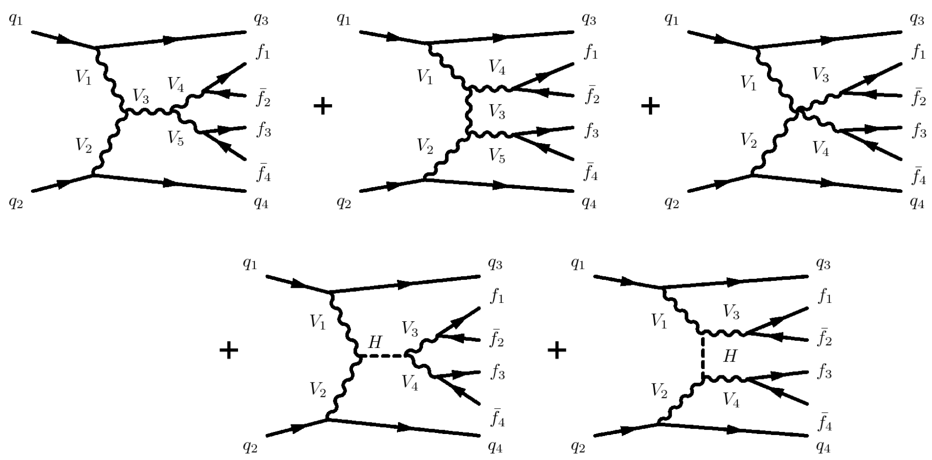
Summary

- First measurements of the VBS processes by ATLAS and CMS
  - In leptonic channels
- Many measurements yet to come with full run-2 data sample
  - Including semileptonic channels
  - Expect more than 150 fb^{-1} by the end of the year
- Semileptonic channels not sensitive to SM EW production yet
  - But give stringent limits on AQGC
- Use of boosted jets in anomalous coupling studies

ADDITIONAL MATERIAL

Vector boson scattering

- Vector boson scattering (VBS) at the LHC
  - Interaction of massive vector bosons (W, Z) radiated by partons of the incoming protons
  - Probe the non-Abelian gauge structure of the EW interactions
- Key process to investigate electroweak symmetry breaking



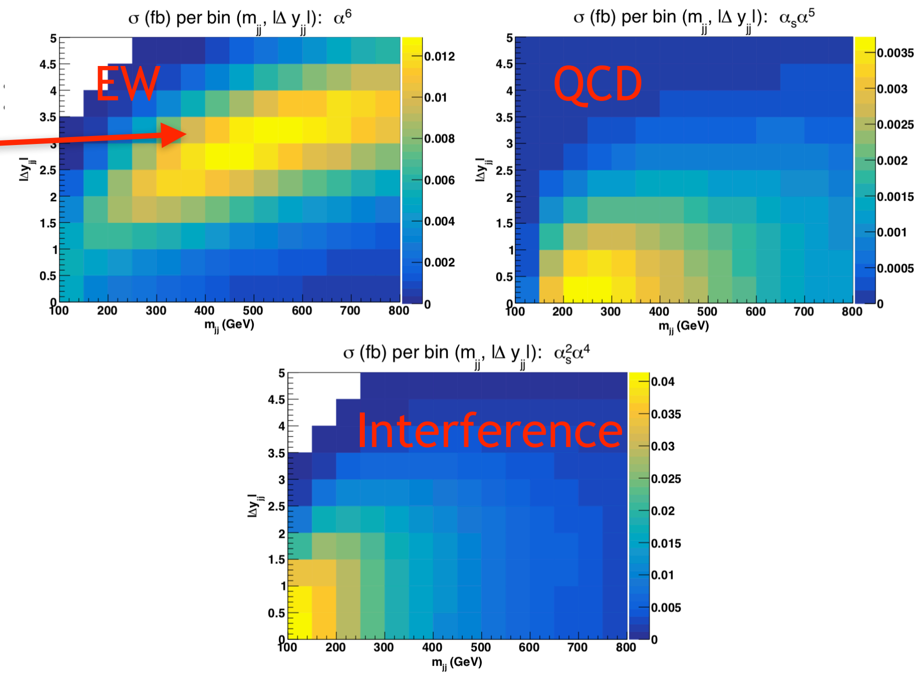
- Typical signature of VBS events: 2 energetic jets and four fermions
- The scattering diagram can be mediated by Higgs boson
  - Interaction of longitudinally polarized bosons is of particular interest

Experimental signature

- VBS events at LHC have distinct event topology
  - Two energetic jets with large di-jet mass (m_{jj}) and pseudorapidity separation $|\Delta y_{jj}|$
  - "Centrality" of the diboson system with respect to the two forward jets
- Common feature of all VBS signatures
  - Example of W^+W^+
- Cuts to enhance the EW contribution
  - m_{jj} and $|\Delta y_{jj}|$ requirements
  - 'Centrality' requirements

$$z_i = \frac{1}{\Delta\eta_{jj}}\left(\eta_i - \frac{\eta_1+\eta_2}{2}\right)$$

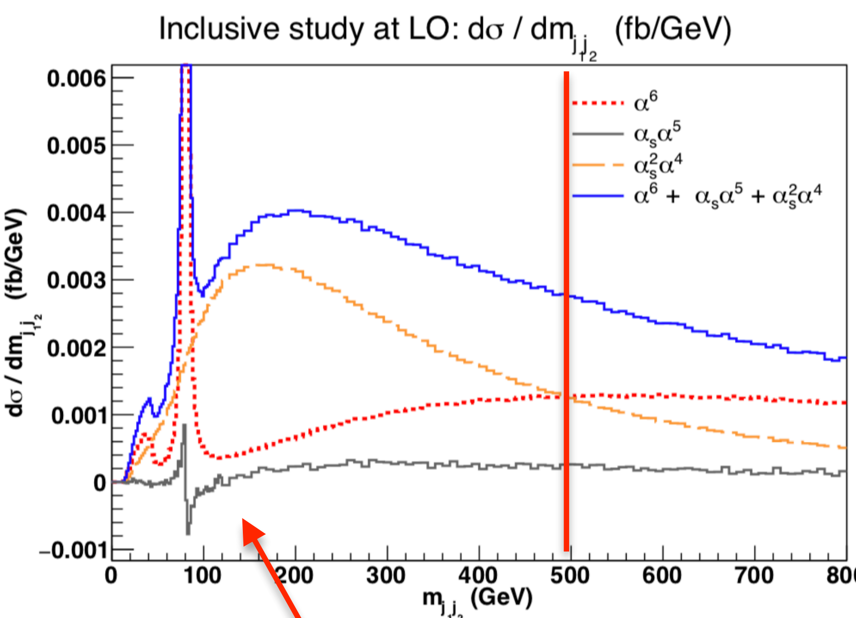
Phys. Rev. D 54 (1996) 6680

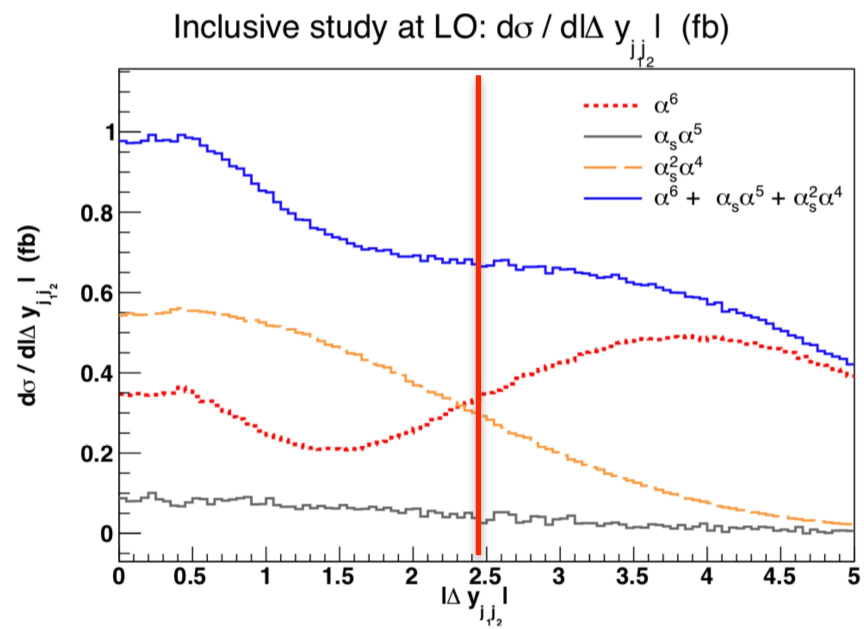


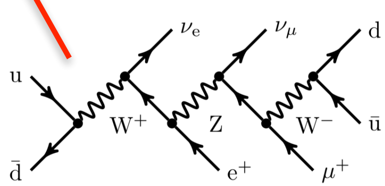
Ballestrero, et al.; 1803.07943

Same-sign WW

- $W^{\pm}W^{\pm}$ has the largest ratio of EW production to QCD initiated production
  - Double charge structure of the leptonic final state
  - QCD consists of diagrams with a gluon connecting the quark lines (no diagrams with gluon-gluon or quark-gluon)



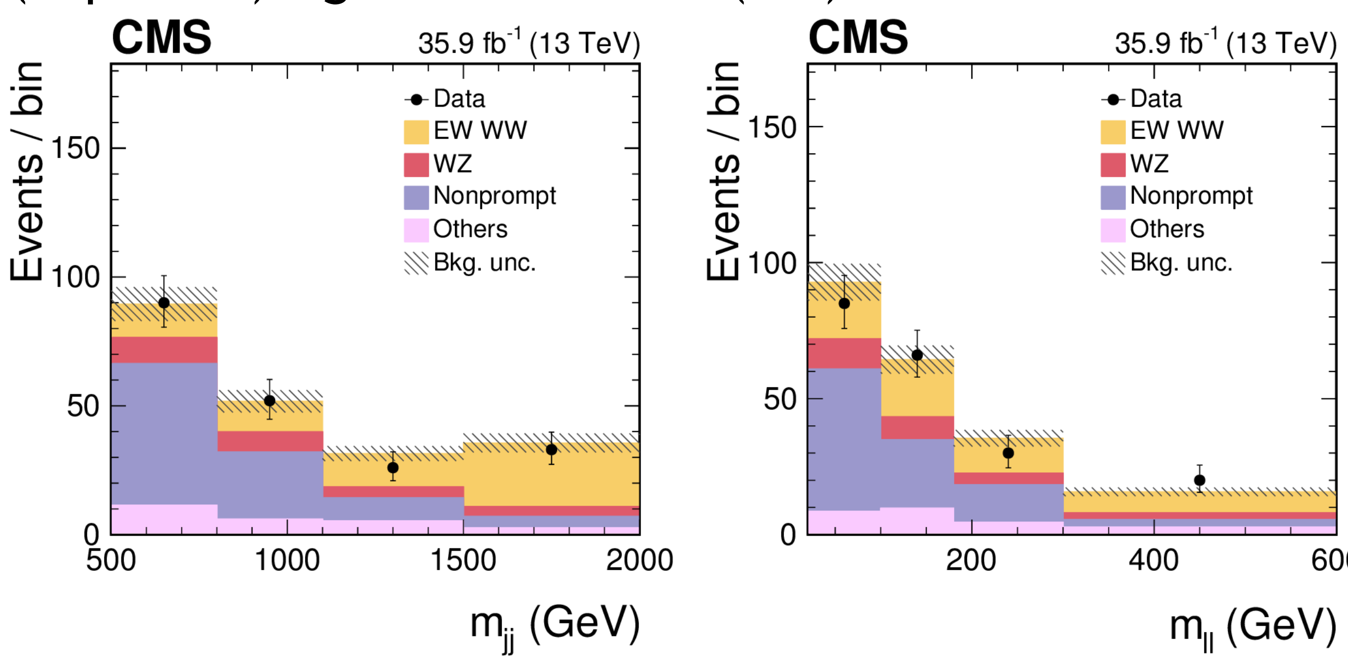




Ballestrero, et al.; 1803.07943

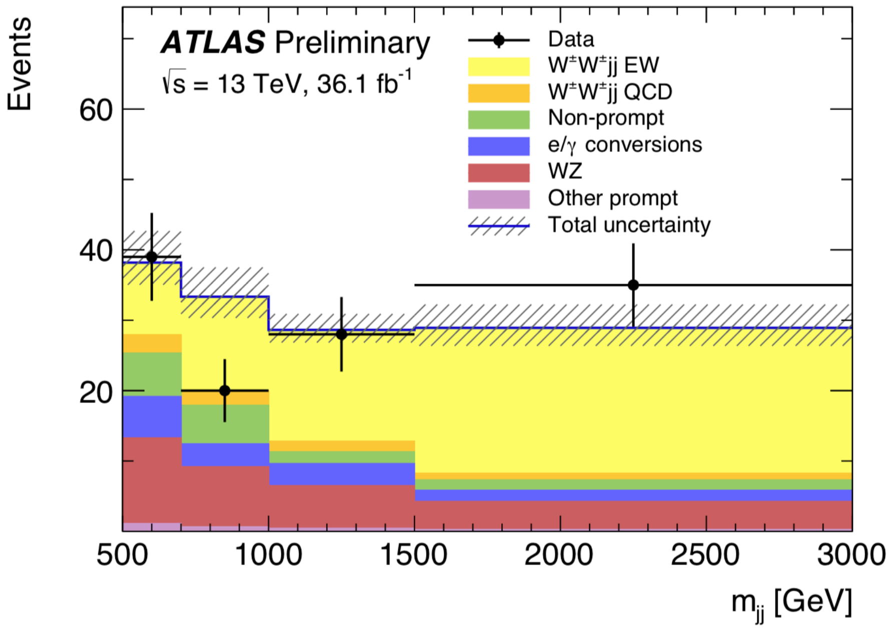
CMS same-sign WW

- Measurement performed in ee, μμ, and eμ final states
  - Major backgrounds (non-prompt leptons and QCD+EW WZ) estimated from data (use low m_{jj} for the WWjj QCD enhanced control region)
  - Signal extracted from a fit to m_{jj} and m_{ll} distributions (and control region)
  - Major uncertainties: jet energy scale/resolution, background modeling
- Observed (expected) significance is 5.5 (5.7) standard deviations



ATLAS same-sign WW

- Measurement performed in ee, μμ, and eμ final states
  - Major backgrounds (non-prompt leptons and QCD+EW WZ) estimated from data (use low m_{jj} for the WWjj QCD enhanced control region)
  - Signal extracted from a fit to m_{jj} distribution in signal and control region
  - Major uncertainties: jet energy scale/resolution, background modeling
- Observed (expected) significance is 6.9 (4.6) standard deviations



Cross section measurement

- ATLAS and CMS fiducial definitions
- Main differences from jet pT and MET requirements

Requirement	CMS	ATLAS
$p_T^j >$ [GeV]	30/30	65/35
$\lvert\eta^j\rvert <$	5.0	4.5
$\lvert\Delta\eta_{jj}\rvert >$	2.5	2.0
E_T^{miss} [GeV]	N/A	30
$m_{\ell\ell} >$ [GeV]	N/A	20

- CMS cross section:
  - The predicted cross section calculated at LO using Madgraph

$$\sigma_{pred} = 4.25 \pm 0.27\text{fb}$$

$$\sigma_{meas} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})\text{fb}$$

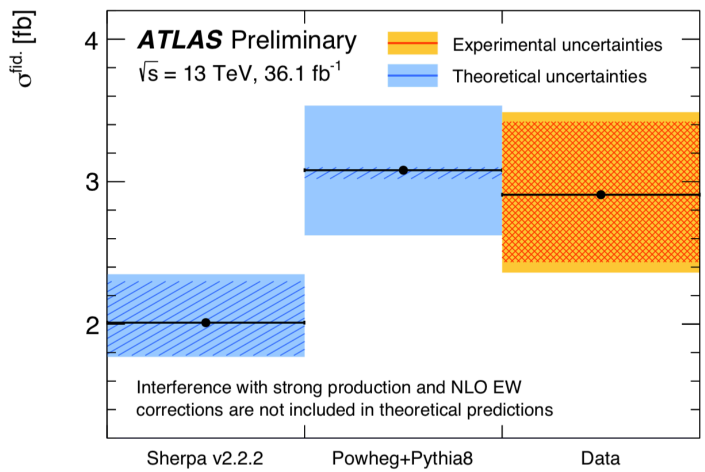
- ATLAS cross section:
  - The predicted cross section calculated at LO using Sherpa

$$\sigma_{pred} = 2.01 \pm 0.28\text{fb}$$

$$\sigma_{meas} = 2.91 \pm 0.50(\text{stat}) \pm 0.27(\text{syst})\text{fb}$$

Theory predictions

- What about theory predictions? How consistent are different theory predictions?
- CMS uses Madgraph, ATLAS uses SHERPA
    - The interference contribution is not included (O(1%))

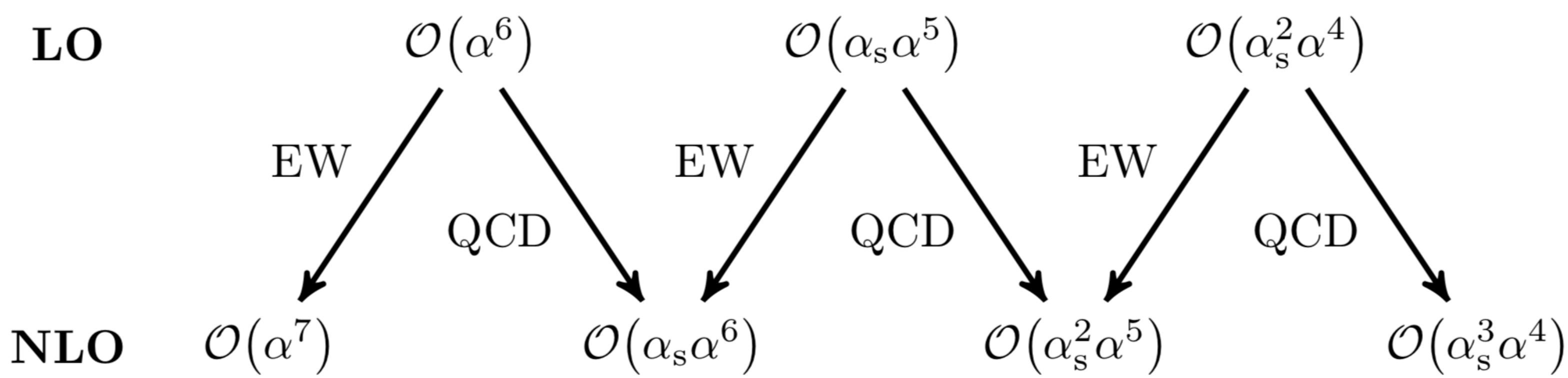


- Powheg includes NLO QCD corrections. What about NLO EW corrections?
- Need for reliable predictions: higher orders, parton showers, approximations, etc.

NLO corrections

- Same sign WW is the only diboson process with full NLO computation (EW and QCD)

B. Biedermann, A. Denner, and M. Pellen

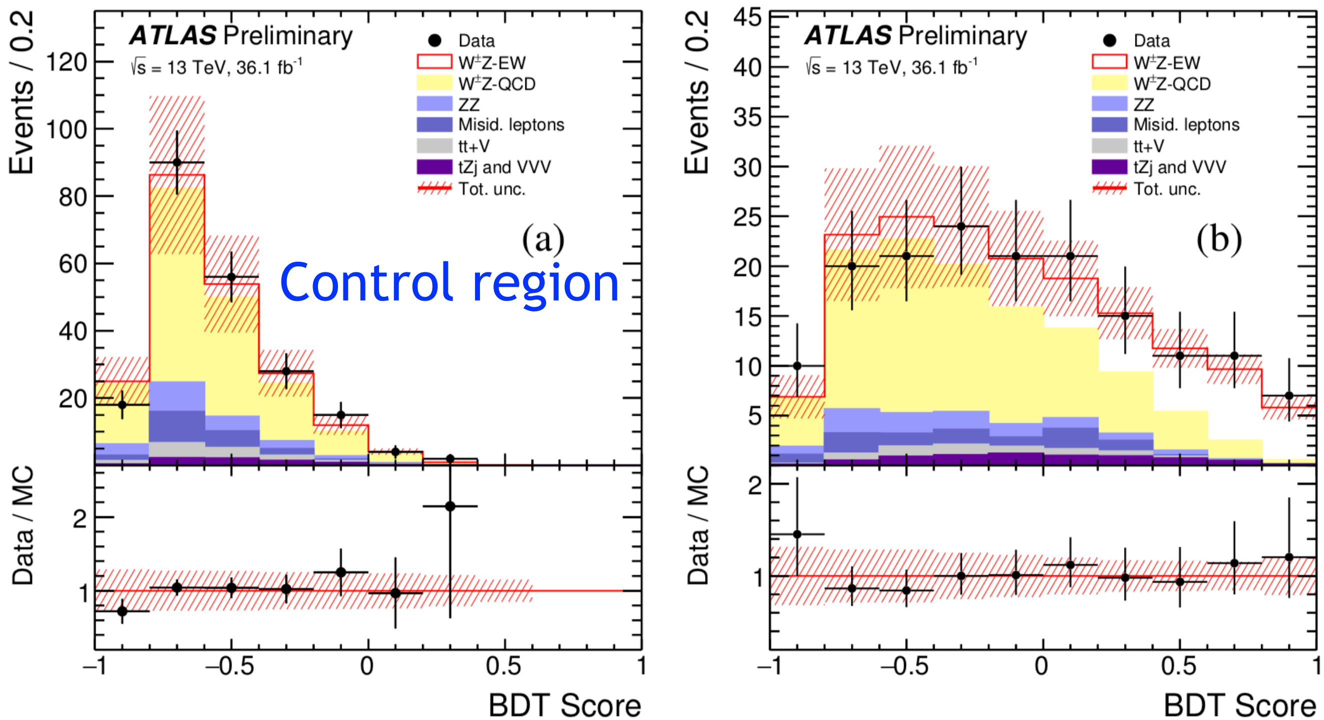


Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

- EW corrections are large and negative (~-15%) in the fiducial region
  - Common feature for the VBS at LHC?
- Meaningless distinction between EW signal and QCD background at NLO

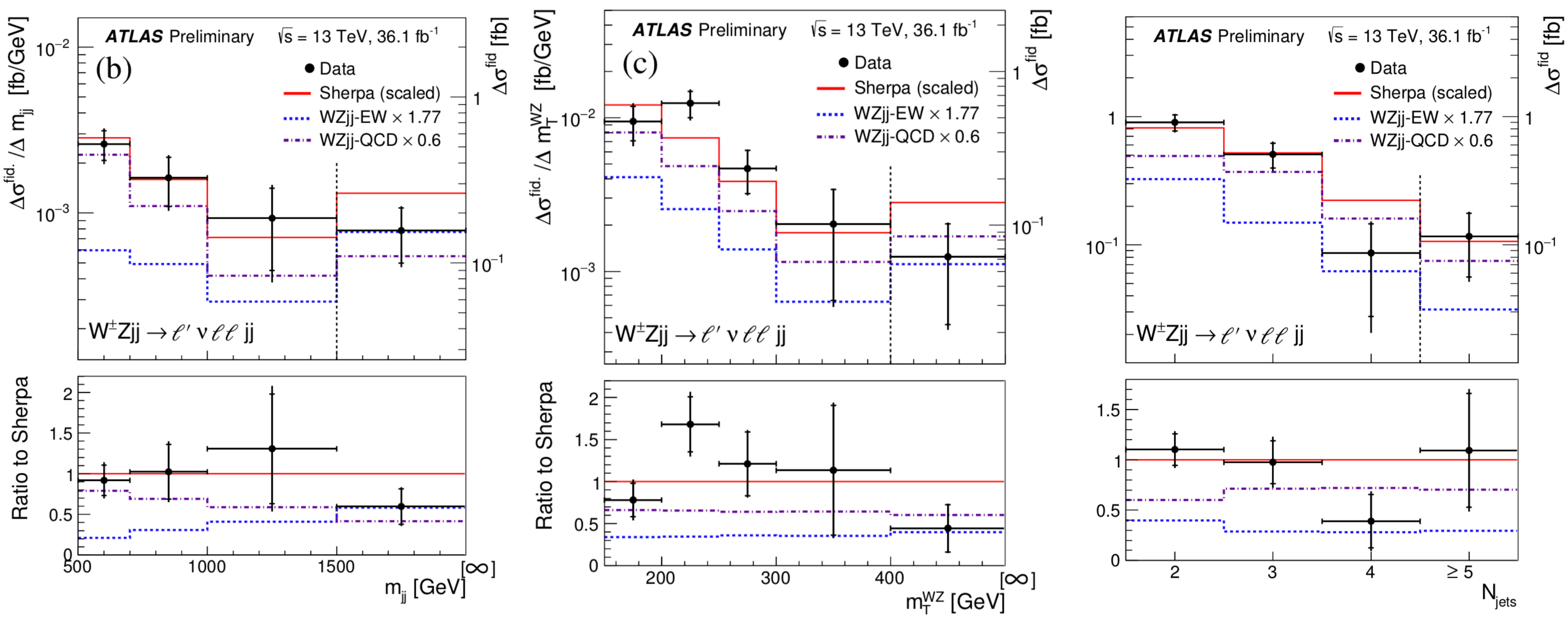
ATLAS WZ

- Measurement performed in three lepton final states
  - Major background (QCD WZ) estimated from data (use low m_{jj} for the WWjj QCD enhanced control region)
  - BDT trained to separate WZ EW signal from other processes
- Observed (expected) significance is 5.6 (3.3) standard deviations



ATLAS WZ

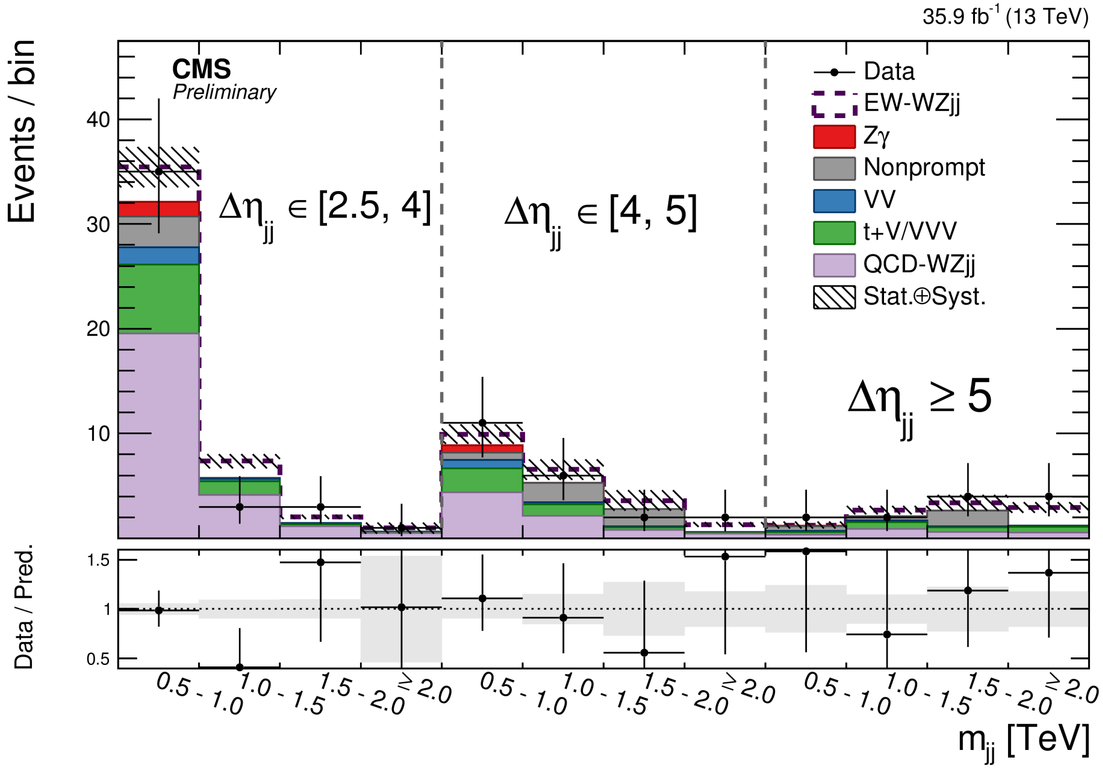
- Fiducial cross section: $\sigma_{\text{meas}} = 0.57 \pm 0.14(\text{stat}) \pm 0.05(\text{syst}) \pm 0.04(\text{th.})\text{fb}$
- Sherpa $\sigma_{\text{pred}} = 0.32 \pm 0.03\text{fb}$
- Madgraph $\sigma_{\text{pred}} = 0.37 \pm 0.01(\text{stat})\text{fb}$
- Differential cross sections in the VBS fiducial phase space



m_jj m_T N_jets

CMS WZ

- Measurement performed in three lepton final states
  - Major background (QCD WZ) estimated from data (use low m_{jj} for the WWjj QCD enhanced control region)
  - Signal extraction using 2D m_{jj} and $|\Delta y_{jj}|$ distributions
- Observed (expected) significance is 1.9 (2.7) standard deviations



CMS WZ

- Measured WZjj QCD+EW cross section in VBS enhanced phase space

$$\sigma^{\text{fid}}_{\text{WZjj}} = 2.91^{+0.53}_{-0.49}\,(\text{stat})\;{}^{+0.41}_{-0.34}\,(\text{syst})$$

$$\sigma_{\text{fid,MG}} = 3.27\,{}^{+0.39}_{-0.32}(\text{scale}) \pm 0.15\,(\text{PDF})$$

- Theory prediction computed using Madgraph at LO

	Tight Fiducial	Loose Fiducial
$p_{\text{T}}(\ell_{\text{Z},1})$ [GeV]	> 25	> 20
$p_{\text{T}}(\ell_{\text{Z},2})$ [GeV]	> 15	> 20
$p_{\text{T}}(\ell_{\text{W}})$ [GeV]	> 20	> 20
$\lvert\eta(\mu)\rvert$	< 2.5	< 2.5
$\lvert\eta(e)\rvert$	< 2.5	< 2.5
$\lvert m_{\text{Z}} - m_{\text{Z}}^{\text{PDG}}\rvert$ [GeV]	< 15	< 15
$m_{3\ell}$ [GeV]	> 100	> 100
$m_{\ell\ell}$ [GeV]	> 4	> 4
p_{T}^{miss} [GeV]	-	-
$\lvert\eta(\text{j})\rvert$	< 4.7	< 4.7
$p_{\text{T}}(\text{j})$ [GeV]	> 50	> 30
$\lvert\Delta R(\text{j},\ell)\rvert$	> 0.4	> 0.4
n_{j}	≥ 2	≥ 2
$p_{\text{T}}(\text{b})$ [GeV]	-	-
$n_{\text{b-jet}}$	-	-
m_{jj}	> 500	> 500
$\lvert\Delta\eta(\text{j}_1,\text{j}_2)\rvert$	> 2.5	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$	< 2.5	-

- What about NLO corrections for WZ?

→ Cross section:

LO $\mathcal{O}(\alpha^6)$ [fb]	NLO EW $\mathcal{O}(\alpha^7)$ [fb]	Corrections [%]
0.2362	0.1899	−19.6%

[Denner, Dittmaier, Maierhöfer, MP, Schwan] **Preliminary**

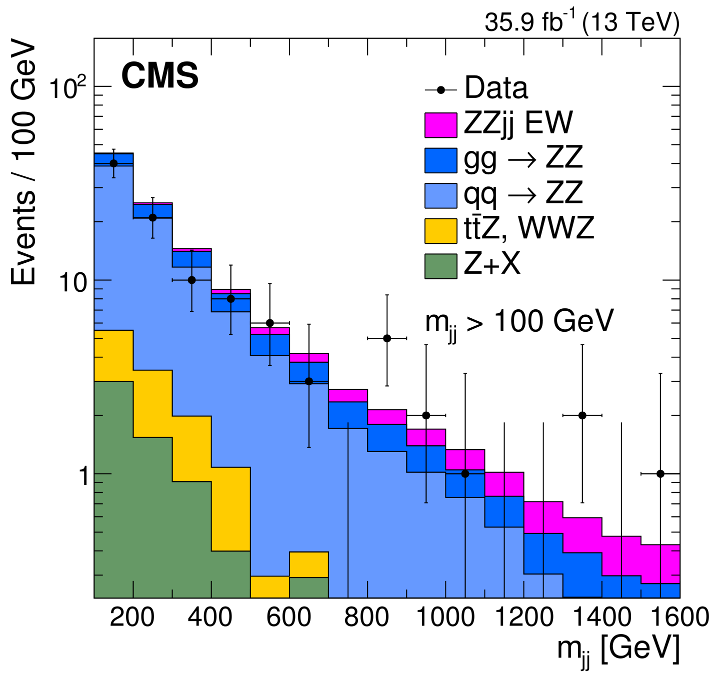
- Talk by Matthieu Pellen at QCD@LHC 2018
- Large corrections (similar to W±W±)!

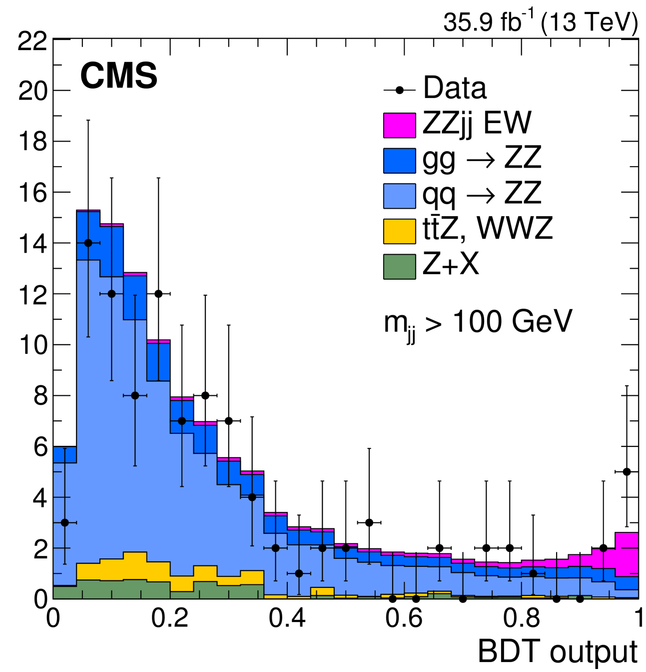
CMS ZZ

- ZZjj measurement in fully leptonic final state
  - Small cross section but clean signature
- Exploit BDT to enhance the sensitivity

  m_{jj}, $\Delta\eta_{jj}$, $z^*(Z_1)$, $z^*(Z_2)$, $R(p_T)$, dijet p_T balance, $m_{4\ell}$

  Use all events with m_{jj} > 100 GeV
- Observed (expected) significance is 2.7 (1.6) standard deviations

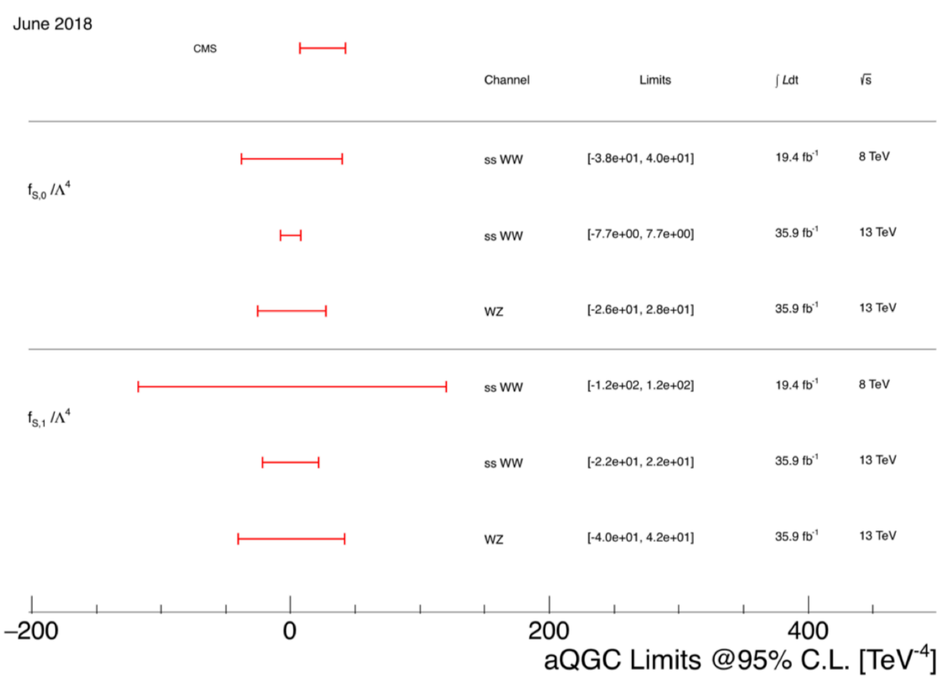


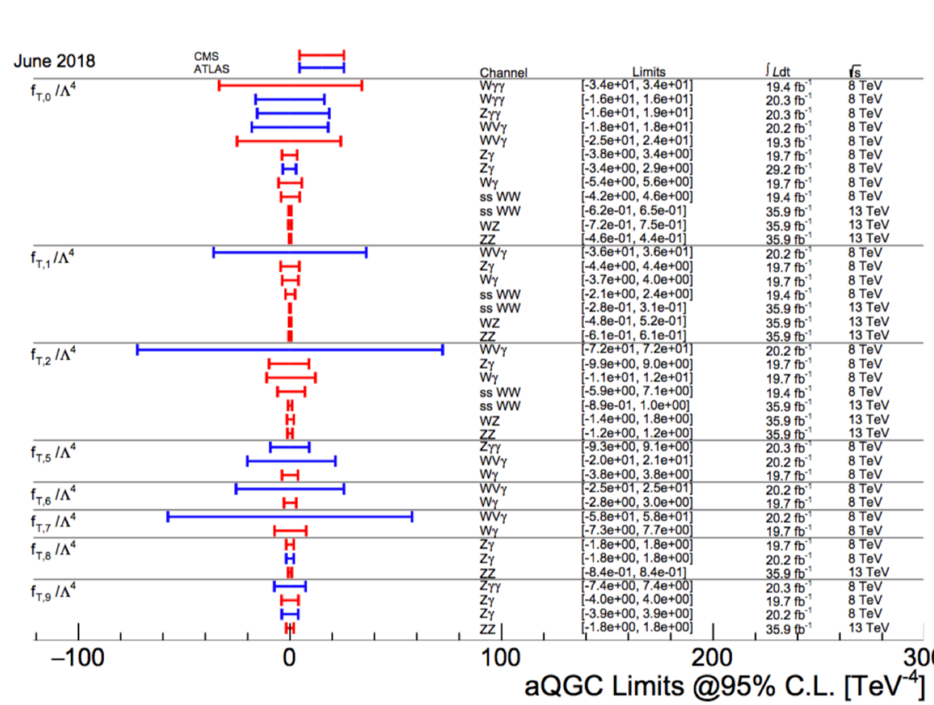


Anomalous couplings

- Search for anomalous quartic gauge couplings
  - Enhancement of cross section at large diboson mass
- Use effective field theory (presented without unitarity bounds):

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





Same-sign WW yields

CMS

	e^+e^+	$e^+\mu^+$	$\mu^+\mu^+$	e^-e^-	$e^-\mu^-$	$\mu^-\mu^-$	Total
Data	14	63	40	10	48	26	201
Signal + total bkg.	19.0 ± 1.9	67.6 ± 3.8	44.1 ± 3.4	11.8 ± 1.8	38.9 ± 3.3	23.9 ± 2.8	205 ± 13
Signal	6.2 ± 0.2	24.7 ± 0.4	18.3 ± 0.4	2.5 ± 0.1	8.7 ± 0.2	6.5 ± 0.2	66.9 ± 2.4
Total bkg.	12.8 ± 1.9	42.9 ± 3.8	25.7 ± 3.4	9.4 ± 1.8	30.2 ± 3.3	17.4 ± 2.8	138 ± 13
Nonprompt	5.6 ± 1.7	24.9 ± 3.6	18.4 ± 3.3	5.0 ± 1.6	19.9 ± 3.2	14.2 ± 2.8	88 ± 13
WZ	3.0 ± 0.2	8.5 ± 0.3	4.4 ± 0.2	1.9 ± 0.2	5.2 ± 0.3	2.2 ± 0.1	25.1 ± 1.1
QCD WW	0.6 ± 0.1	1.7 ± 0.1	1.3 ± 0.1	0.2 ± 0.1	0.6 ± 0.1	0.4 ± 0.1	4.8 ± 0.4
$W\gamma$	1.4 ± 0.5	3.6 ± 0.9	0.2 ± 0.2	0.8 ± 0.4	2.3 ± 0.7	—	8.3 ± 1.6
Triboson	0.8 ± 0.2	2.2 ± 0.4	1.2 ± 0.3	0.3 ± 0.1	0.9 ± 0.3	0.5 ± 0.2	5.8 ± 0.8
Wrong sign	1.5 ± 0.6	1.4 ± 0.4	—	1.1 ± 0.5	1.2 ± 0.4	—	5.2 ± 1.1

ATLAS

	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	combined
WZ	1.7 ± 0.6	1.2 ± 0.4	13 ± 4	8.1 ± 2.5	5.0 ± 1.6	3.3 ± 1.1	32 ± 9
Non-prompt	4.1 ± 2.4	2.3 ± 1.8	9 ± 6	6 ± 4	0.57 ± 0.16	0.67 ± 0.26	23 ± 12
e/γ conversions	1.74 ± 0.31	1.8 ± 0.4	6.1 ± 2.4	3.7 ± 1.0	-	-	13.4 ± 3.5
Other prompt	0.17 ± 0.06	0.14 ± 0.05	0.90 ± 0.24	0.60 ± 0.25	0.36 ± 0.12	0.19 ± 0.07	2.4 ± 0.5
$W^\pm W^\pm jj$ strong	0.38 ± 0.13	0.16 ± 0.06	3.0 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.26	7.3 ± 2.5
Expected background	8.1 ± 2.4	5.6 ± 1.9	32 ± 7	20 ± 5	7.7 ± 1.7	4.9 ± 1.1	78 ± 15
$W^\pm W^\pm jj$ electroweak	3.80 ± 0.30	1.49 ± 0.13	16.5 ± 1.2	6.5 ± 0.5	9.1 ± 0.7	3.50 ± 0.29	40.9 ± 2.9
Data	10	4	44	28	25	11	122

ATLAS and CMS WZ

CMS

	Electroweak Signal
$p_{\mathrm{T}}(\ell_{\mathrm{Z},1})$ [GeV]	> 25
$p_{\mathrm{T}}(\ell_{\mathrm{Z},2})$ [GeV]	> 15
$p_{\mathrm{T}}(\ell_{\mathrm{W}})$ [GeV]	> 20
$\lvert\eta(\mu)\rvert$	< 2.4
$\lvert\eta(e)\rvert$	< 2.5
$\lvert m_{\mathrm{Z}} - m_{\mathrm{Z}}^{\mathrm{PDG}}\rvert$ [GeV]	< 15
$m_{3\ell}$ [GeV]	> 100
$m_{\ell\ell}$ [GeV]	> 4
p_{T}^{miss} [GeV]	> 30
$\lvert\eta(\mathrm{j})\rvert$	< 4.7
$p_{\mathrm{T}}(\mathrm{j})$ [GeV]	> 50
$\lvert\Delta R(\mathrm{j},\ell)\rvert$	> 0.4
n_{j}	≥ 2
$p_{\mathrm{T}}(\mathrm{b})$ [GeV]	> 30
$n_{\mathrm{b-jet}}$	$= 0$
m_{jj}	> 500
$\lvert\Delta\eta(\mathrm{j}_1,\mathrm{j}_2)\rvert$	> 2.5
$\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1}+\eta_{j_2})\rvert$	< 2.5

ATLAS

- $p_T(\ell_{lead}) > 27$ GeV
- $p_T(\ell_Z) > 15$ GeV
- $p_T(\ell_W) > 20$ GeV
- $\eta(\mu, e) < 2.5, 2.47$
  - e: exclude [1.37, 1.52]
- $m_T(W) > 30$ GeV
- $p_T(j) > 40$ GeV

ATLAS WZ

	SR	QCD-CR	b-CR	ZZ-CR
Data	161	213	141	52
Total MC	199.2 ± 1.4	289.4 ± 1.9	159.2 ± 1.8	44.7 ± 6.4
$WZjj$-EW (signal)	24.93 ± 0.18	8.46 ± 0.10	1.36 ± 0.05	0.21 ± 0.12
$WZjj$-QCD	144.17 ± 0.85	231.2 ± 1.1	24.44 ± 0.29	1.43 ± 0.69
Misid. leptons	9.2 ± 1.1	17.7 ± 1.5	29.7 ± 1.6	0.50 ± 0.32
ZZ-QCD	8.10 ± 0.19	14.98 ± 0.34	1.96 ± 0.08	35.0 ± 5.9
tZ	6.46 ± 0.18	6.56 ± 0.19	36.19 ± 0.45	0.18 ± 0.09
$t\bar{t} + V$	4.21 ± 0.18	9.11 ± 0.23	65.36 ± 0.64	2.8 ± 1.3
ZZ-EW	1.50 ± 0.10	0.44 ± 0.05	0.10 ± 0.08	3.4 ± 1.6
VVV	0.59 ± 0.03	0.93 ± 0.04	0.13 ± 0.01	1.0 ± 1.0

Source	Uncertainty [%]
$WZjj$-EW theory modelling	5.0
$WZjj$-QCD theory modelling	2.3
$WZjj$-EW and $WZjj$-QCD interference	1.9
Jets	6.7
Pileup	2.2
Electrons	1.6
Muons	0.7
b-tagging	0.3
MC statistics	2.1
Misid. lepton background	1.0
Other backgrounds	0.1
Luminosity	2.1

CMS WZ

Process	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	Total Yield
QCD WZ	14.1 ± 0.9	9.4 ± 0.5	7.1 ± 0.4	4.8 ± 0.3	35.4 ± 1.1
t+V/VVV	6.0 ± 0.4	3.4 ± 0.2	2.6 ± 0.2	1.8 ± 0.1	13.7 ± 0.5
Nonprompt	5.1 ± 2.1	2.3 ± 1.0	1.4 ± 0.6	0.7 ± 0.3	9.5 ± 2.4
VV	0.9 ± 0.1	1.7 ± 0.2	$0.5 \pm < 0.1$	0.7 ± 0.1	3.7 ± 0.2
$Z\gamma$	< 0.1	2.2 ± 0.8	< 0.1	< 0.1	2.2 ± 0.9
Pred. Background	26.0 ± 2.2	18.9 ± 1.6	11.6 ± 0.8	8.0 ± 0.5	64.5 ± 2.9
EW WZ	5.1 ± 1.1	3.6 ± 0.8	2.5 ± 0.5	1.8 ± 0.4	13.0 ± 1.5
Data	38	15	12	10	75

Source of systematic uncertainty	Relative systematic uncertainty [%]	
	σ_{WZjj}	EW WZ Significance
Jet energy scale	+9.8/-9.2	7.5
Jet energy resolution	+1.1/-1.9	< 0.1
QCD WZ modeling	-	0.9
Other background theory	+2.5/-2.2	0.2
Nonprompt normalization	+2.1/-2.4	1.1
Nonprompt stat.	+6.1/-5.8	6.2
Lepton energy scale and eff.	+3.5/-2.7	< 0.1
b-tagging	+1.7/-1.9	< 0.1
Luminosity	+3.1/-3.4	< 0.1