Vector boson scattering and fusion results from ATLAS and CMS

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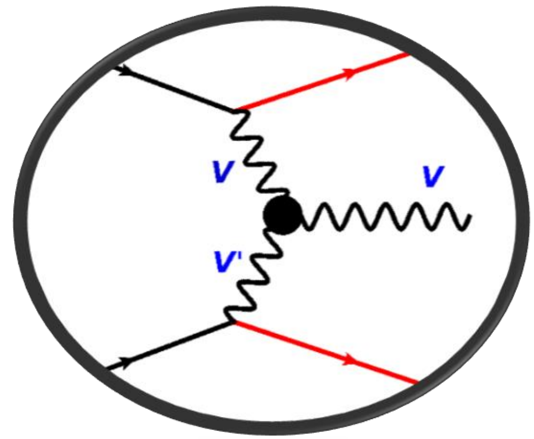
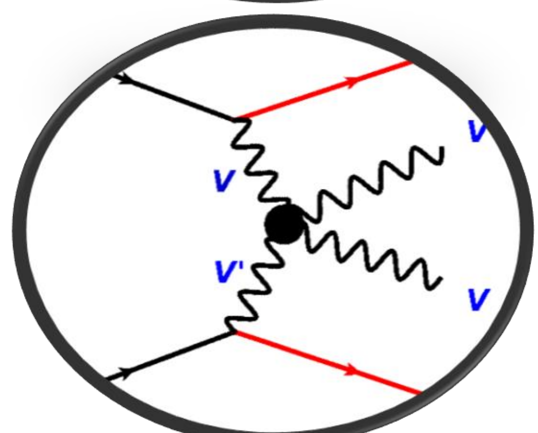




Preview

- **Vector Boson Fusion**

  Zjj ATLAS JHEP04 (2014) 031; CMS JHEP10 (2013) 062, EPJC 75 (2015) 66

  Wjj CMS PAS-SMP-13-012

- **Vector Boson Scattering**

  $W^{\mp}W^{\mp}jj$ ATLAS PRL113,141803(2015); CMS PRL114, 051801(2015)

  $WZjj$ ATLAS PRD93, 092004 (2016)

  $W\gamma jj$ CMS PAS-SMP-14-011

  $Z\gamma jj$ CMS PAS-SMP-14-018

- **Exclusive WW**

  $\gamma\gamma \to WW$ CMS arXiv:1604.04464; **ATLAS NEW!**

- **Future Prospect**

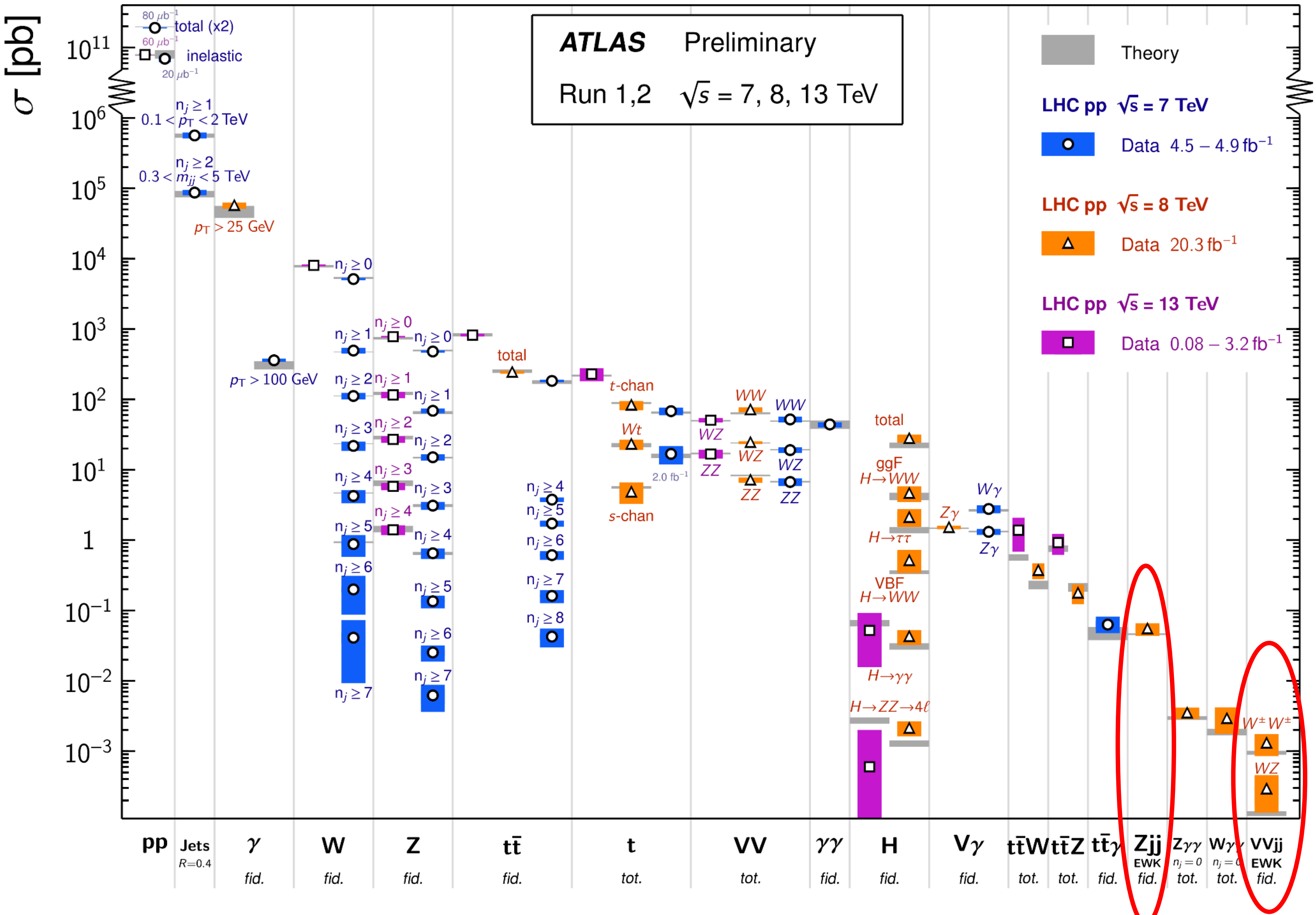
  VBS $W^{\mp}W^{\mp}jj$, $WZjj$, $ZZjj$

  ATLAS-PHYS-PUB-2013-006; CMS-PAS-FTR-13-006;
  CERN-LHCC-2015-010

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

Standard Model Production Cross Section Measurements

Status: June 2016



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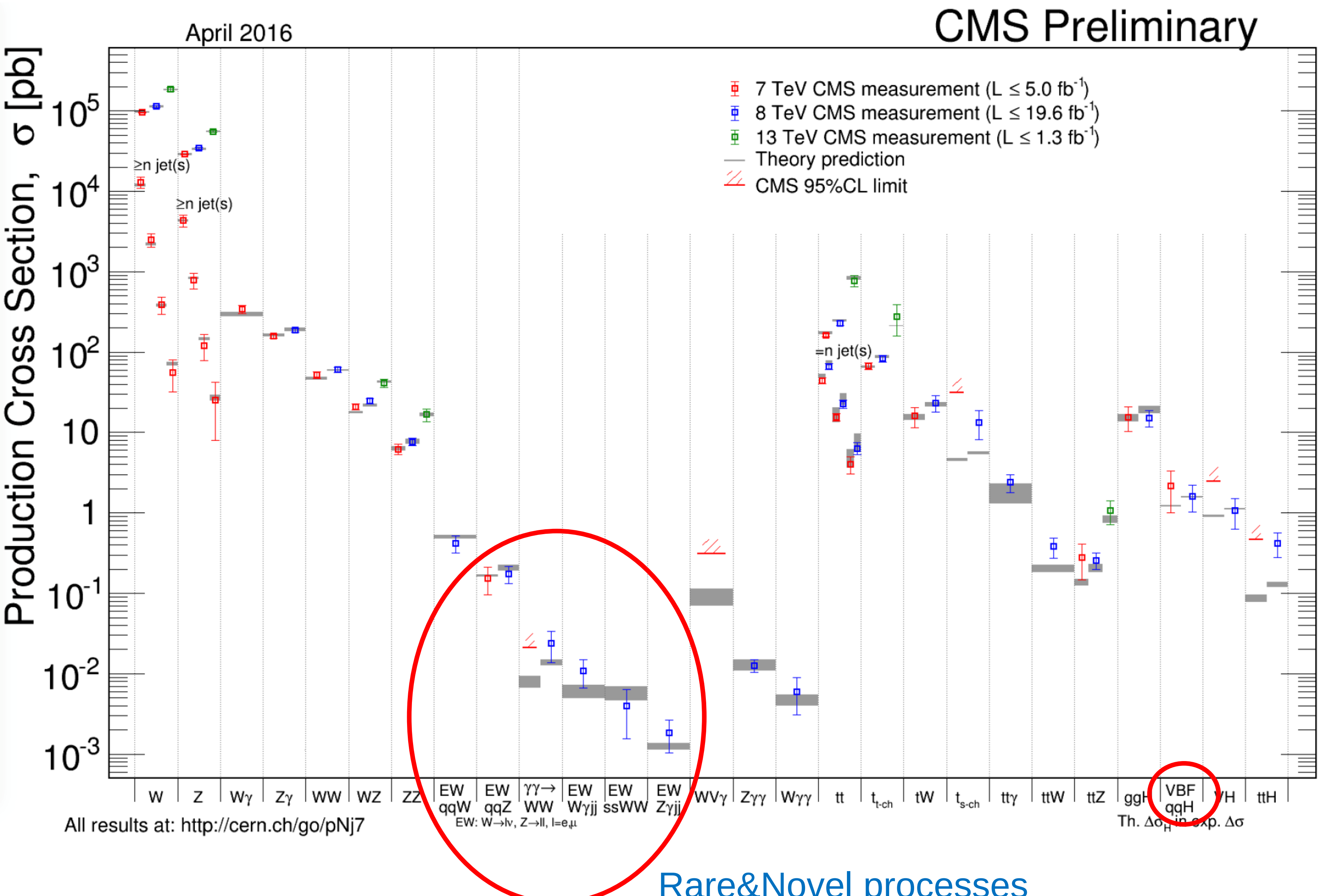
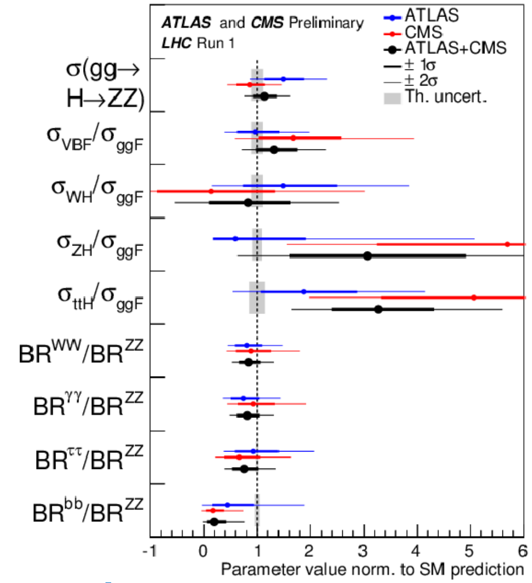


Rare&Novel processes

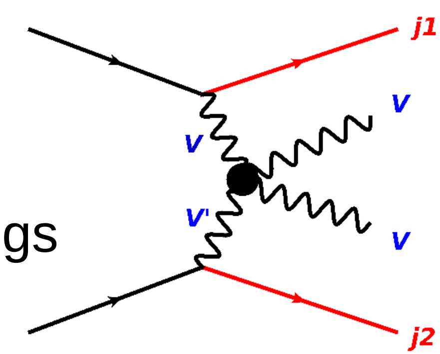
VBF/VBS: Motivation



- VBF Higgs established at >5σ
  - ATLAS-CONF-2015-044
  - CMS-PAS-HIG-15-002

- VBF/VBS SM processes

1. Rare&Novel processes to be discovered
2. Clean environment with less QCD activity,
   VBFJets property measurement;
3. VV scattering sensitive to UV completeness
4. High Tail enhancements:
   to probe anomalous Triple (Quartic) Gauge Couplings

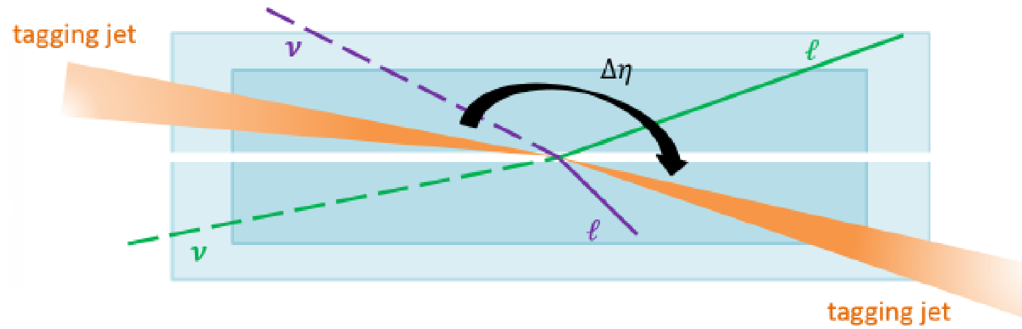


aQGCs *WWWW/WWγγ/WWZγ/ZZZγ/ZZγγ/Zγγγ*

Dimension 6 LEP style a_0^c, a_0^W; Whizard Parametrization α_4, α_5
or Dimension 8 operators $\boldsymbol{L_{S0,S1}}$, $\boldsymbol{L_{M0-7}}$, $\boldsymbol{L_{T0-9}}$

VBF/VBS: characteristics

- **Two VBF Tagged Jets:**
  Large M_{jj} and $|\Delta\eta_{jj}|$
  More quark-like



- **Lower central hadronic activity:**
  More balanced between
  VBF and Central systems

$$p_{\mathrm{T}}^{\mathrm{balance}} = \frac{\left|\vec{p}_{\mathrm{T}}^{\ell_1} + \vec{p}_{\mathrm{T}}^{\ell_2} + \vec{p}_{\mathrm{T}}^{j_1} + \vec{p}_{\mathrm{T}}^{j_2}\right|}{\left|\vec{p}_{\mathrm{T}}^{\ell_1}\right| + \left|\vec{p}_{\mathrm{T}}^{\ell_2}\right| + \left|\vec{p}_{\mathrm{T}}^{j_1}\right| + \left|\vec{p}_{\mathrm{T}}^{j_2}\right|}$$

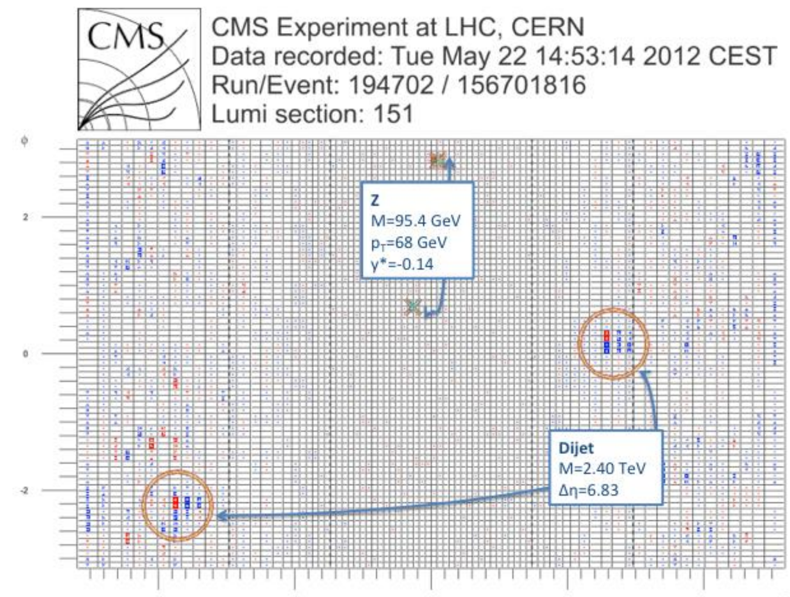
$$Rp_{\mathrm{T}}^{\mathrm{hard}} = \frac{|\mathbf{p}_{\mathrm{Tj_1}} + \mathbf{p}_{\mathrm{Tj_2}} + \mathbf{p}_{\mathrm{TZ}}|}{|\mathbf{p}_{\mathrm{Tj_1}}| + |\mathbf{p}_{\mathrm{Tj_2}}| + |\mathbf{p}_{\mathrm{TZ}}|}$$

$$y^* = y_{\mathrm{Z}} - \frac{1}{2}(y_{\mathrm{j_1}} + y_{\mathrm{j_2}})$$

Zeppenfeld Variable

$$|y_{W\gamma} - (y_{j1} + y_{j2})/2.0|$$

$$|\Delta\phi_{W\gamma,dijet}|$$



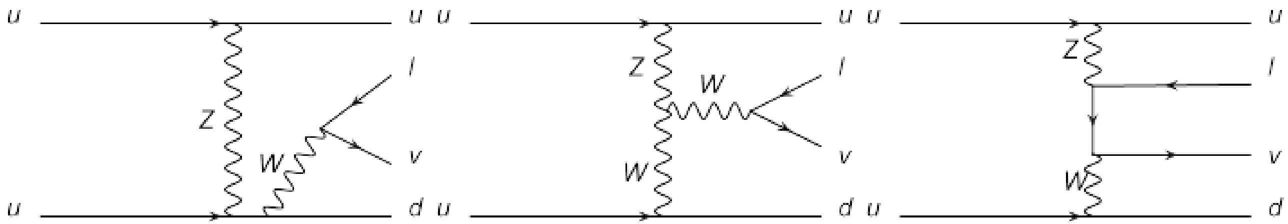
CMS VBF Z+2jets

M_{jj}=2.4TeV, $|\Delta\eta_{jj}|$=6.83

Theoretical Inputs

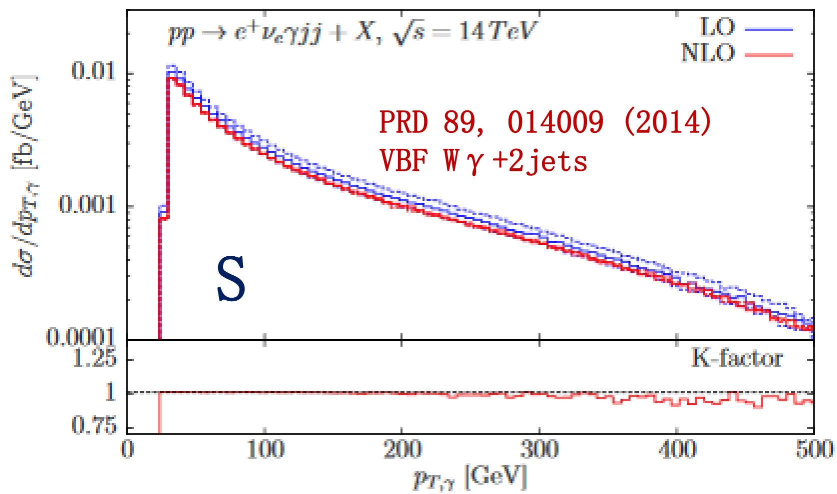
- **Diagrams other than VBF/VBS-like (not in VBF Higgs case)**

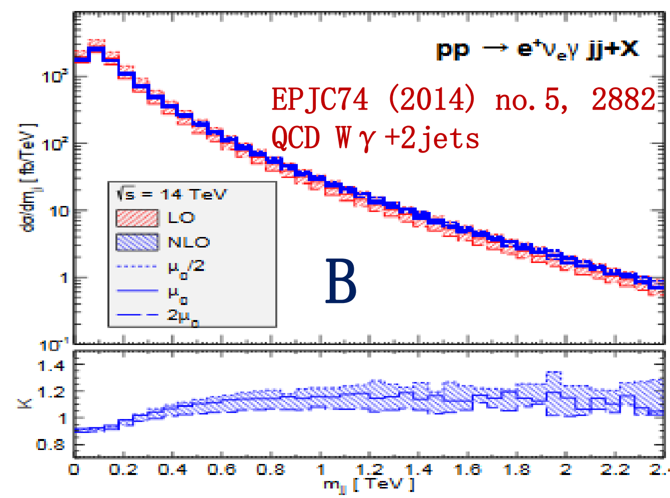
  Suppressed in VBF selection region



(a) Bremsstrahlung (b) VBF (c) Multiperipheral

- **K Factors: MCFM/POWHEG/VBFNLO, usually flat and near unity in VBF region**





- **Interference:**

  Between EWK and QCD, modelled by MadGraph or Sherpa;
  Included inside nominal result or for systematics

Zjj

ATLAS, 8TeV

> 5σ

JHEP04(2014)031;

- **EWK/QCD Zjj simulated by Sherpa with CKKW matching; Xsec from POWHEG NLO**
- **Interference effects as systematic, studied with Sherpa, ~6%.**

Object selections:
- two electron/muon
- two high-p_T forward jets

Kinematic selections:
- $81 < m_{ll} < 101$ GeV
- $p_T^{ll} > 20$ GeV
- $p_T^{balance} < 0.15$
- $N_{jet}^{gap} = 0$
- $m_{jj} > 250$ GeV

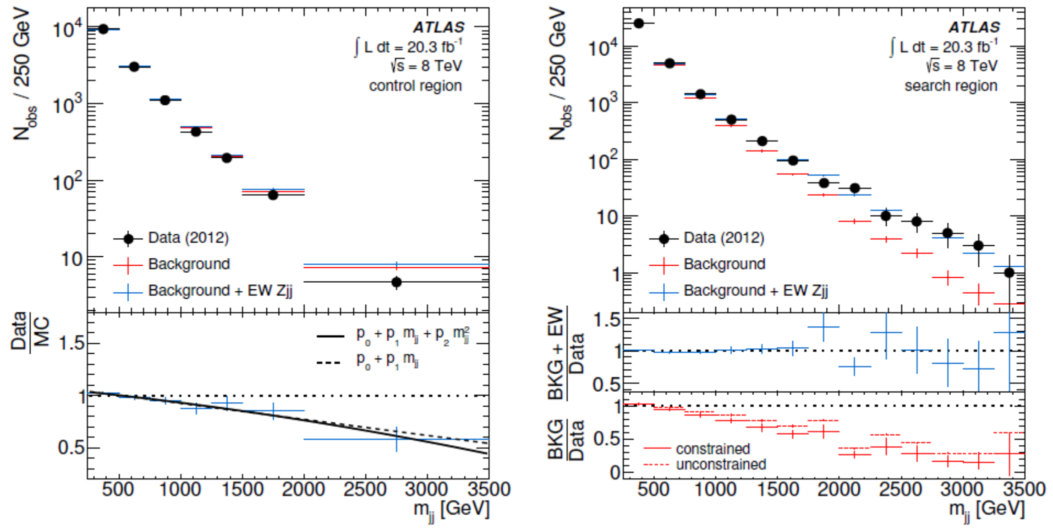
Search Region

- **Xsec Measured for both inclusive and VBF Zjj, in various regions**
- **Data-Driven Bkg estimation verified with POWHEG/Sherpa particle-level ratio, and checked with various control regions**

Source	ΔN_{EW}		ΔC_{EW}	
	Electrons	Muons	Electrons	Muons
Lepton systematics	—	—	±3.2 %	±2.5%
Control region statistics	±8.9 %	±11.2 %	—	—
JES	±5.6 %		$^{+2.7}_{-3.4}$ %	
JER	±0.4 %		±0.8 %	
Pileup jet modelling	±0.3 %		±0.3 %	
JVF	±1.1 %		$^{+0.4}_{-1.0}$ %	
Signal modelling	±8.9 %		$^{+0.6}_{-1.0}$ %	
Background modelling	±7.5 %		—	
Signal/background interference	±6.2 %		—	
PDF	$^{+1.5}_{-3.9}$ %		±0.1 %	

Scales, Matching, MPI variations

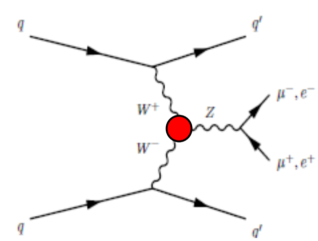
(left) Control region → Bkg Reweighting
(right) Signal extracted from Mjj fit



$$\sigma_{EW}\,(m_{jj} > 1\ \mathrm{TeV}) = 10.7 \pm 0.9\,(\mathrm{stat}) \pm 1.9\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\ \mathrm{fb},$$

POWHEG NLO

$$9.38 \pm 0.05\,(\mathrm{stat})\ ^{+0.15}_{-0.24}\,(\mathrm{scale}) \pm 0.24\,(\mathrm{PDF}) \pm 0.09\,(\mathrm{model})\ \mathrm{fb}$$



Event number in the search region with m_{jj} >1TeV → Set limit on aTGC

aTGC	Λ = 6 TeV (obs)	Λ = 6 TeV (exp)	Λ = ∞ (obs)	Λ = ∞ (exp)
$\Delta g_{1,Z}$	[−0.65, 0.33]	[−0.58, 0.27]	[−0.50, 0.26]	[−0.45, 0.22]
λ_Z	[−0.22, 0.19]	[−0.19, 0.16]	[−0.15, 0.13]	[−0.14, 0.11]

Zjj

CMS, 7&8 TeV

JHEP10(2013)062; EPJC75(2015)66

- **EWK Zjj simulated by MG at LO, QCD Zjets from MG MLM matching**
- **For MC-based QCD ZJJ, MCFM/(MG LO) effect <10% for |y*|<1.2; w/o reweighting to evaluate syst.**
- **Signal extracted with MVA or Mjj fit with CLs method, in both signal and control regions**

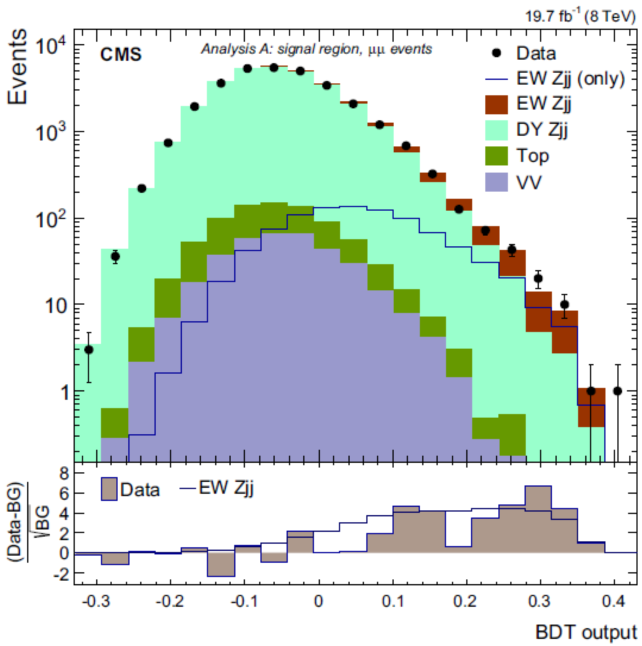
$$\hat{N}^{\ell\ell jj}(\mu, \upsilon) = \mu N_{\mathrm{EW\ Zjj}} + \sqrt{\mu\upsilon} N_{\mathrm{I}} + \upsilon N_{\mathrm{DY\ Zjj}},$$

- **Diff w/o Interference as syst.**
- **q-g discriminator (~5% gain to reduce uncertainty)**

Nominal

Analysis	A	B	C
Channels	ee, $\mu\mu$	$\mu\mu$	ee, $\mu\mu$ binned in M_{jj}
Selection	$p_{T j1,j2} > 50, 30$ GeV		
	$Rp_T^{hard} < 0.14$		$p_{TZ} > 50$ GeV
	$\lvert y^* \rvert < 1.2$		$\lvert y_Z \rvert < 1.4442$
	$M_{jj} > 200$ GeV		$M_{jj} > 450$ GeV
Jets	PF	JPT	PF
Variables used			
M_{jj}	•	•	•
p_{Tj_1}, p_{Tj_2}		•	•
η_{j_1}, η_{j_2}			•
$\Delta_{rel}(jj) = \frac{\lvert \mathbf{p}_{Tj_1} + \mathbf{p}_{Tj_2} \rvert}{p_{Tj_1} + p_{Tj_2}}$			•
$\Delta\eta_{jj}$		•	
$\lvert\eta_{j_1}\rvert + \lvert\eta_{j_2}\rvert$	•	•	•
$\Delta\phi_{jj}$		•	•
$\Delta\phi_{Z,j_1}$		•	
y_Z	•	•	
z_Z^*	•		
p_{TZ}	•	•	
Rp_T^{hard}		•	
q/g discriminator	•		•
DY Zjj model	MC-based	MC-based	From data

Photon+Jets



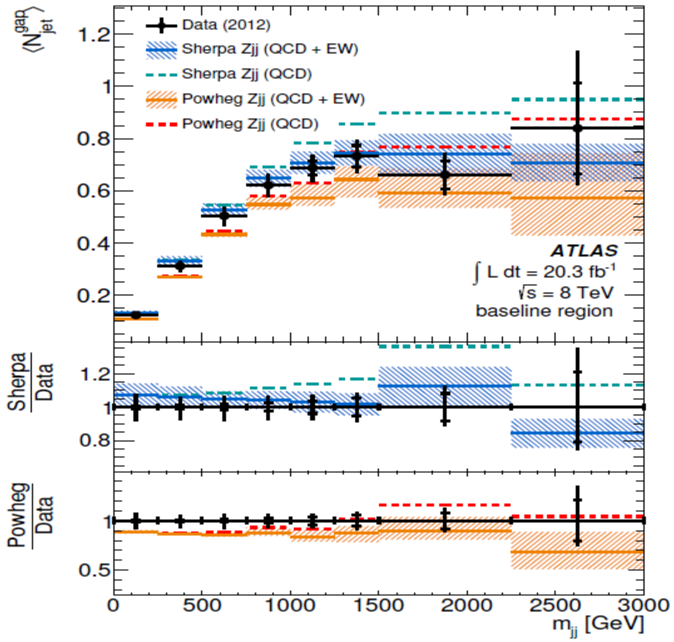
$$\mu = 0.84 \pm 0.07\,(\text{stat}) \pm 0.19\,(\text{syst}) = 0.84 \pm 0.20\,(\text{total}),$$

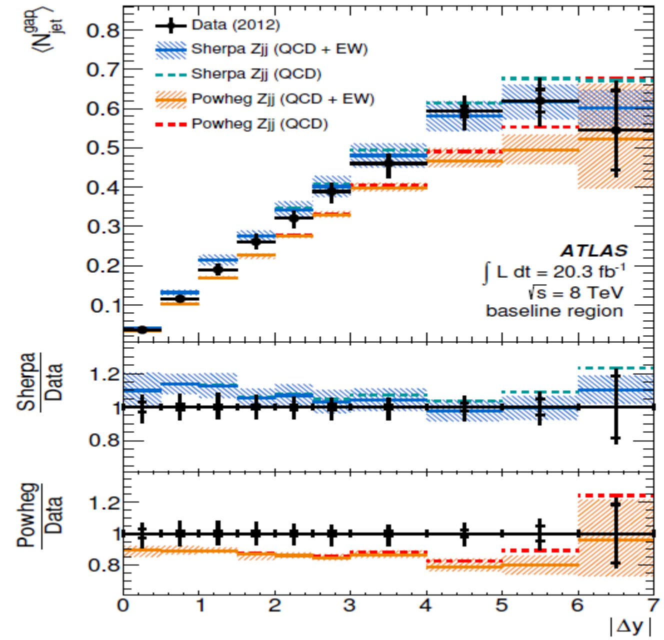
$> 5\sigma$

Zjj VBF Pattern

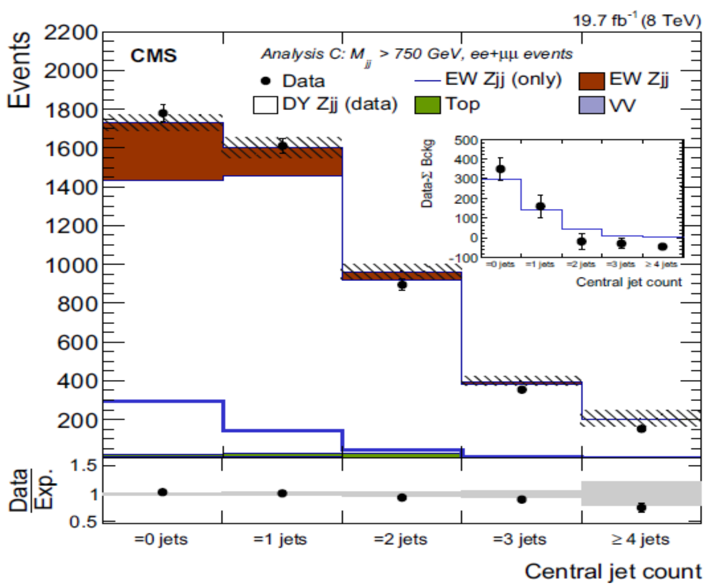
ATLAS, 8TeV
CMS, 7&8 TeV

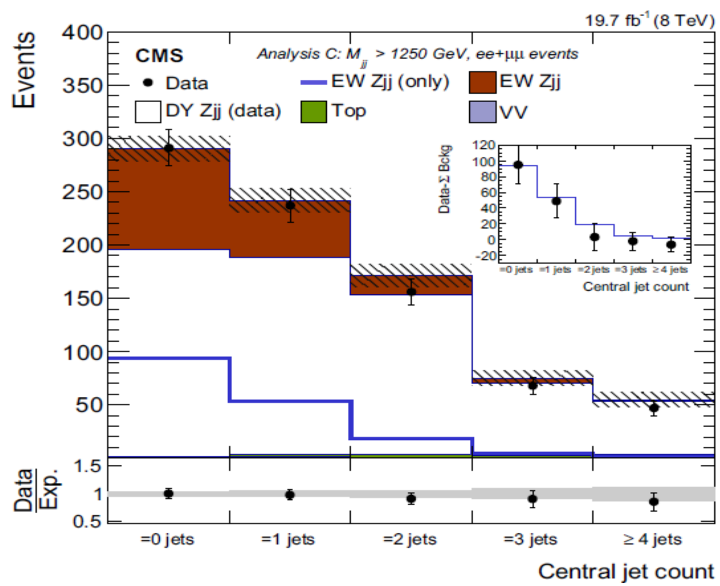
JHEP04(2014)031; JHEP10(2013)062; EPJC75(2015)66





PT>25GeV, eta within two tagged jets





PT>15GeV, eta within two tagged jets

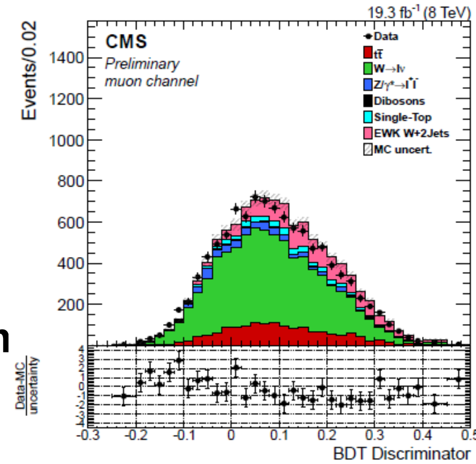
Wjj

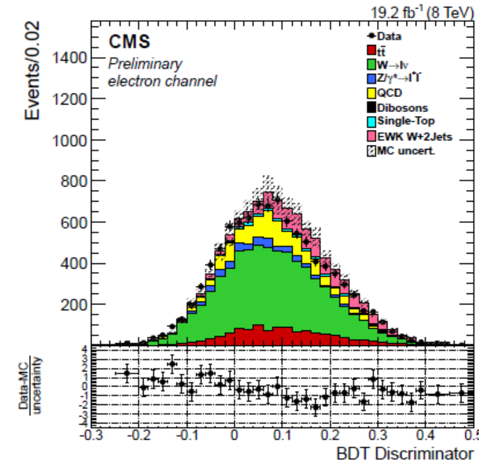
CMS, 8TeV

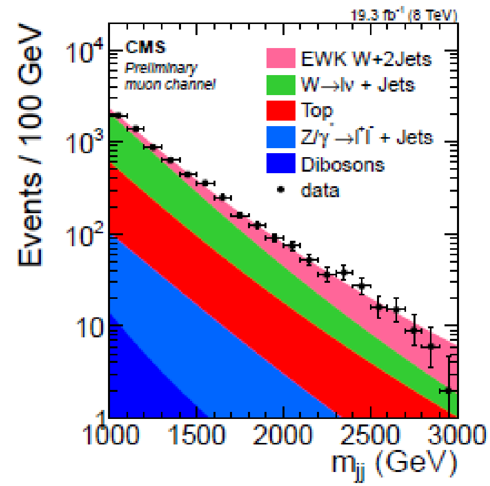
- **EWK Wjj simulated by MG at LO, QCD Wjets from MG MLM matching**
- **DATA-driven QCD Wjets normalization from BDT control region**
- **Signal extracted from unbinned maximum likelihood fit to Mjj**
- **Floating QCD Wjets shape**

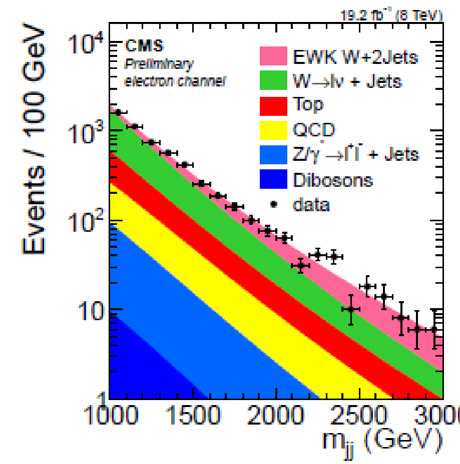
$$\mathcal{F} = \frac{1.0}{m_{jj}^{a_0 + a_1 log(m_{jj}/8000)}}$$

- **Diff w/o Interference as syst.**









Event category	Measured cross section
μjj	0.43 ± 0.04 (stat.) ± 0.10 (syst.) ± 0.01 (lumi.) pb
ejj	0.41 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb
combined μjj and ejj	0.42 ± 0.04 (stat.) ± 0.09 (syst.) ± 0.01 (lumi.) pb

in agreement with the SM prediction of $0.50 \pm 0.02(\mathrm{Scale}) \pm 0.02(\mathrm{PDF})$ pb

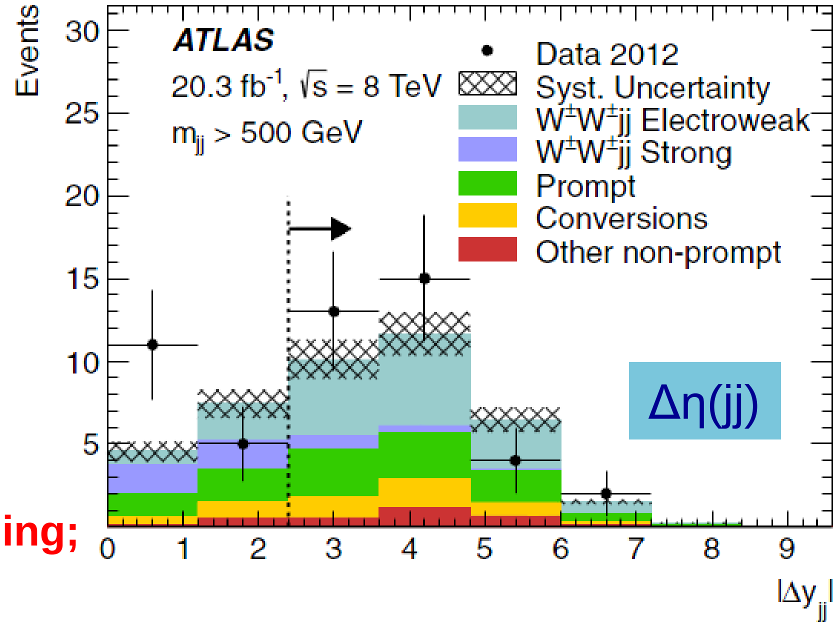
With p_T^{jet1}> 60 GeV p_T^{jet2}> 50 GeV $|\eta^{jet}|$< 4.7 m_{jj} > 1 TeV

$W^{\mp} W^{\mp} jj$

ATLAS, 8TeV

PRL 113 (2014) 141803

- **Event Selection:**
  2 SS leptons with p_T>25 GeV
  b-veto, m_{ll}>20 GeV
  3rd lepton veto: pT>7/6 GeV
  $|m_{ll}-m_Z|$> 10 GeV, E_T^{miss} > 40 GeV
  $m_{jj} > 500$GeV, (inclusive)
  $m_{jj} > 500$GeV +$|\Delta\eta_{jj}|$>2.4 (VBS)



- **Signal simulated by Sherpa with CKKW matching; Xsec from POWHEG NLO**

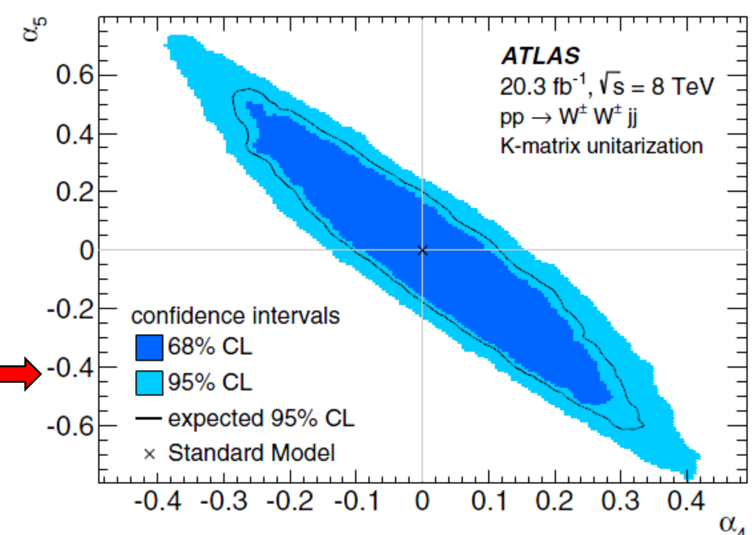
4.5(3.4)σ for EWK+QCD
3.6(2.8)σ for EWK

- **Background:**
  Dominated by WZ/γ^* and γ conversions

- **Measured significance and cross section:**

EWK+QCD $\sigma^{fid.}$ = 2.1 ± 0.5(stat) ± 0.3(syst) fb.
$\sigma^{theo.}$ = 1.52 ± 0.11 fb
1.00 (EWK)+0.35(QCD)+Intf

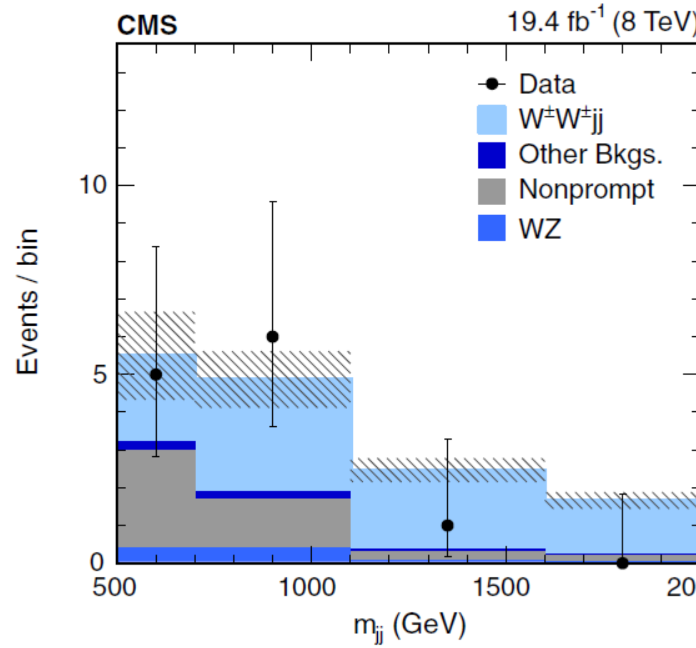
EWK(+intf) $\sigma^{fid.}$ = 1.3 ± 0.4(stat) ± 0.2(syst) fb.
$\sigma^{theo.}$ = 0.95 ± 0.06 fb
0.88 ±0.05 fb wo intf
QCD=0.098fb



$W^{\mp}W^{\mp}jj$

CMS, 8TeV

PRL 114 (2015) 051801



- **Event selection:**
  Two same-sign lepton with P_T>20 GeV
  3rd lepton veto: pT>10 GeV
  M_{ll}>50 GeV, $|m_{ll}-m_Z|$> 15 GeV, E_T^{miss} > 40 GeV
  mjj>500 GeV, $|\Delta\eta_{jj}|$>2.5 (VBS topology)

- **Background:**
  Largest background from non-prompt leptons (including γ conversion)

- **Signal simulated by MadGraph at LO;**
  Xsec from VBFNLO
  Interference included in Signal

2.0(3.1) σ for EWK+QCD
1.9(2.9) σ for EWK

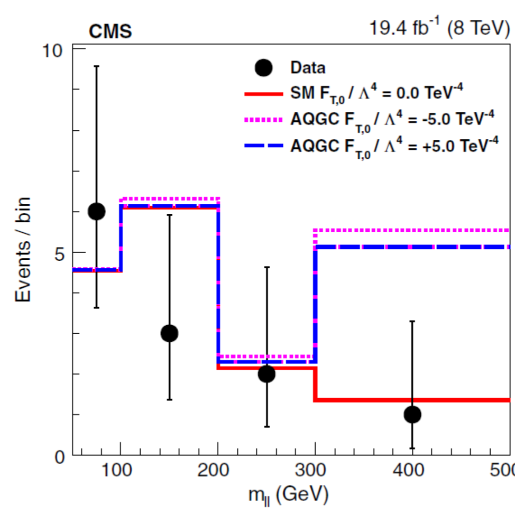
- Measured cross section:

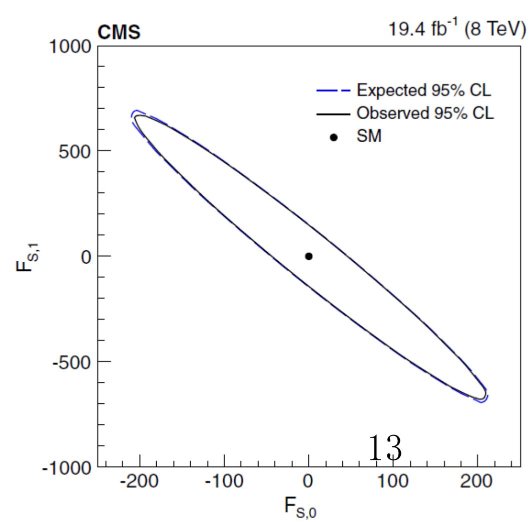
$$\sigma^{fid.} = 4.0^{+2.4}_{-2.0}(\text{stat})^{+1.1}_{-1.0}(\text{syst})\ \text{fb}$$

$$\sigma^{theo.} = 5.8 \pm 1.2\ \text{fb}$$

The cross section is extracted for a fiducial signal region. The fiducial region is defined by requiring two same-sign leptons with $p_T{}^{\ell} > 10$ GeV and $|\eta_\ell| < 2.5$, two jets with $p_T{}^j > 20$ GeV and $|\eta^j| < 5.0$, $m_{jj} > 300$ GeV, and $|\Delta\eta_{jj}| > 2.5$ and is less stringent than the event selection

- Use m_{ll} to set limits on aQGCs
  Also put limits on a H^{++} model.



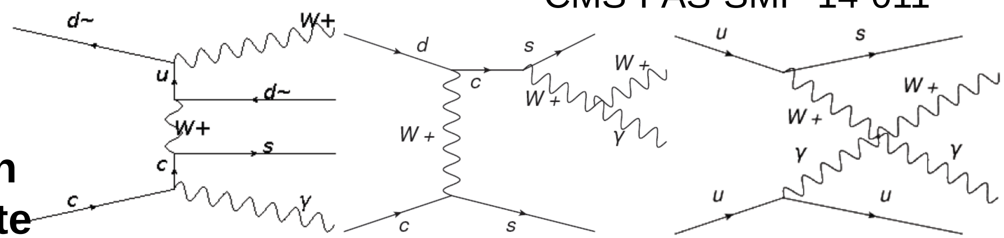


$W\gamma jj$

CMS, 8TeV

CMS-PAS-SMP-14-011

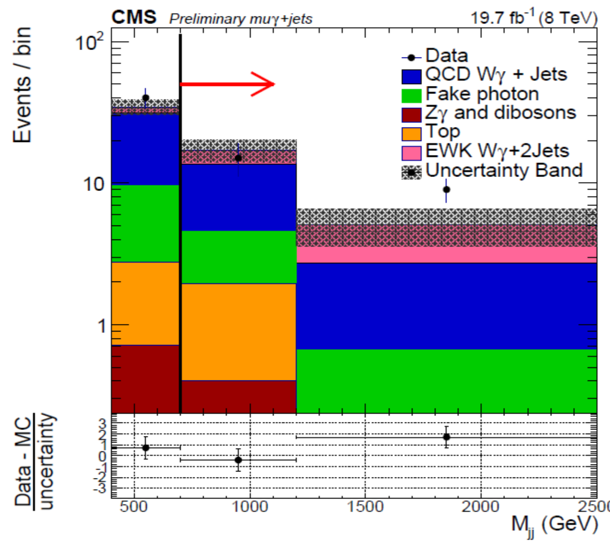
- **QCD $W\gamma jj$: MC Shape + DD Normalization**
- **Jet/Electron Fake Photon: Ratio/Template**
- **Jet fake Electron: MET Template**



(a) Bremsstrahlung (b) With TGC (c) With QGC

Single lepton trigger	$\lvert M_{e\gamma} - M_Z \rvert > 10$ GeV (electron channel)
Lepton, photon ID and isolation	$p_T^{j1} > 40$, $p_T^{j2} > 30$ GeV
Second lepton veto	$\lvert\eta^{j1}\rvert < 4.7$, $\lvert\eta^{j2}\rvert < 4.7$
Muon (electron) $p_T > 25(30)$ GeV, $\lvert\eta\rvert < 2.1(2.4)$	$\lvert\Delta\phi_{j1,\not E_T}\rvert > 0.4$, $\lvert\Delta\phi_{j2,\not E_T}\rvert > 0.4$
Photon $p_T^\gamma > 22$ GeV, $\lvert\eta\rvert < 1.44$	B quark jet veto for tag jets
W transverse mass > 30 GeV	Dijet pair invariant mass $M_{jj} > 200$ Ge
$\not E_T > 35$ GeV	$\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{jl}, \Delta R_{l\gamma} > 0.5$

- **Signal Extracted from binned Mjj fit**



- **Dominate Systematics:**
  - **JES & JER**
  - **Jet Fake Photon**
  - **QCD $W\gamma jj$ prediction**

- $\lvert y_{W\gamma} - (y_{j1} + y_{j2})/2.0\rvert < 0.6$,
- $\lvert\Delta\phi_{W\gamma,dijet}\rvert > 2.6$,
- $M_{jj} > 700$ GeV,
- $\lvert\Delta\eta(j1, j2)\rvert > 2.4$.

Items	EWK measurement	EWK+QCD measurement
$\hat{\mu}$	$1.78^{+0.99}_{-0.76}$	$0.99^{+0.21}_{-0.19}$
EWK fraction (search region)	100%	27.1%
EWK fraction (fiducial region)	100%	25.8%
Observed (Expected) significance	2.67(1.52) σ	7.69(7.49) σ
Theory cross section (fb)	6.1 ± 1.2 (scale) ± 0.2 (PDF)	23.5 ± 6.6 (scale) ± 0.8 (PDF)
Measured cross section (fb)	10.8 ± 4.1 (stat.) ± 3.4 (syst.) ± 0.3 (lumi.)	23.2 ± 4.3 (stat.) ± 1.7 (syst.) ± 0.6 (lumi.)

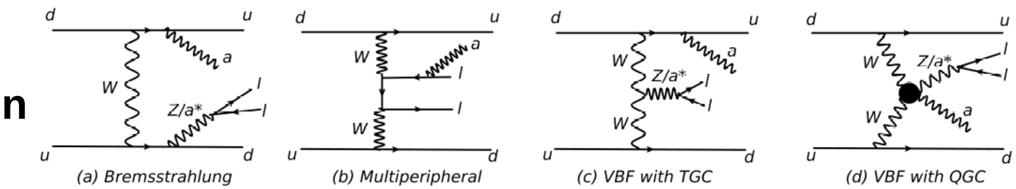
aQGC limit set based on p_T^W

$\lvert y_{W\gamma} - (y_{j1} + y_{j2})/2.0\rvert < 1.2$,
$\lvert\Delta\eta(j1, j2)\rvert > 2.4$,
$p_T^\gamma > 200$ GeV

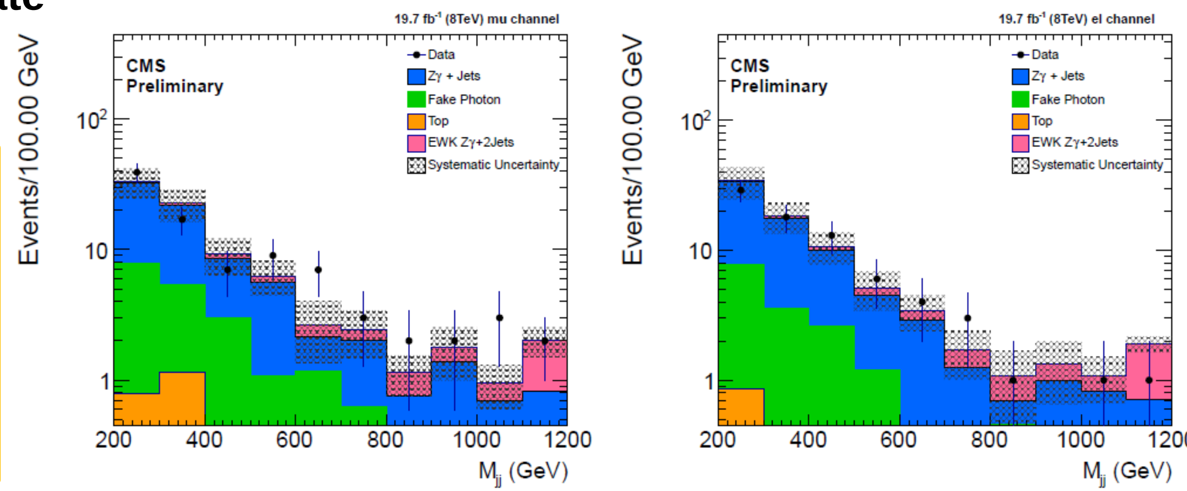
$Z\gamma jj$

CMS, 8TeV

CMS-PAS-SMP-14-018



- **QCD $Z\gamma jj$: MC Shape + DD Normalization**
- **Jet/Electron Fake Photon**
- **Jet fake Electron: MET Template**
- **Signal Extracted from binned**
  Mjj fit [400-800], [800-] GeV



Two Opposite Sign Leptons with PT>20GeV
Photon PT>25GeV
Two Jets with PT>30GeV
70GeV<mll<110GeV

$\Delta\eta_{jj} > 1.6$, $M_{jj} > 400$ GeV,

$\Delta\phi_{Z\gamma,jj} > 2.0$,

$|y_{Z\gamma} - (y_{j1} + y_{j2})/2.0| < 1.2$

$3.0(2.1)\sigma$ **First Evidence!**

fiduciał cross section of EWK

$1.86^{+0.89}_{-0.75}(stat.)^{+0.41}_{-0.27}(sys.) \pm 0.05(lumi.)$ fb

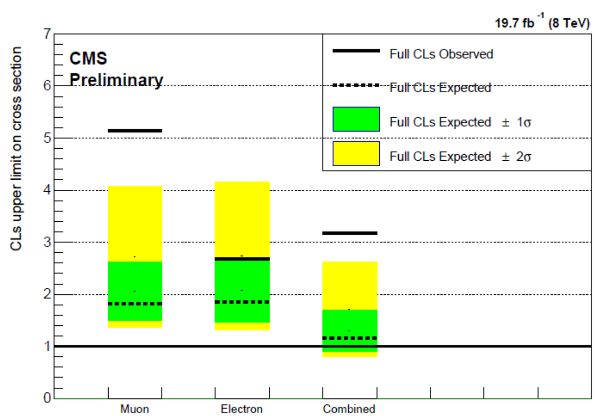
MADGRAPH $1.26 \pm 0.11(scale) \pm 0.05(PDF)$ fb

$M_{jj} > 800$ GeV: $4.3/4.5\ \sigma$ expected/observed

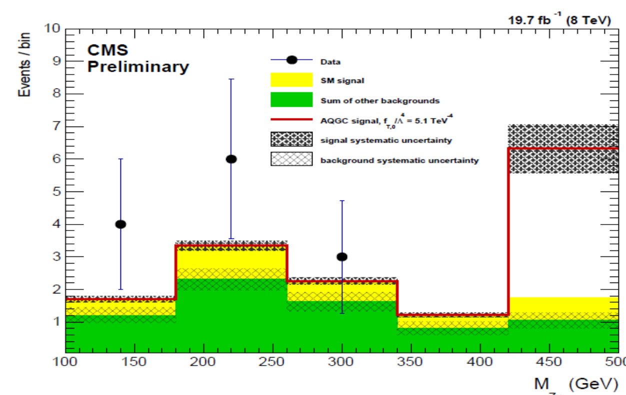
EWK and QCD $Z\gamma$+two jets

$1.00 \pm 0.43(stat.) \pm 0.26(syst.) \pm 0.03(lumi.)$ fb,

MADGRAPH: $0.78 \pm 0.09(scale) \pm 0.02(PDF)$ fb,



aQGC limit set based on $M_{Z\gamma}$

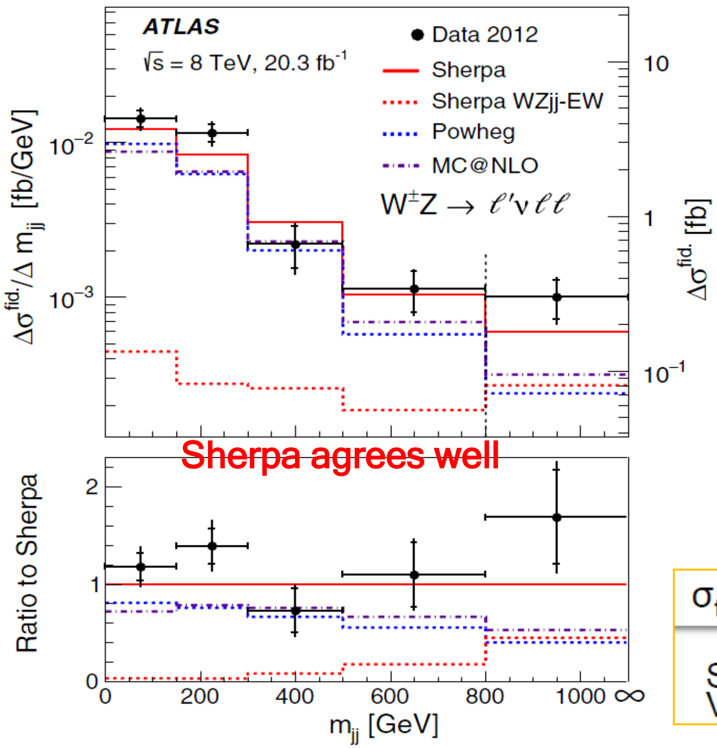


WZjj

ATLAS, 8TeV

PRD93, 092004 (2016)

Variable	Total	Fiducial and aTGC	VBS	aQGC
Lepton $\|\eta\|$	...	< 2.5	< 2.5	< 2.5
p_T of ℓ_Z, p_T of ℓ_W [GeV]	...	$> 15, > 20$	$> 15, > 20$	$> 15, > 20$
m_Z range [GeV]	66–116	$\|m_Z - m_Z^{PDG}\| < 10$	$\|m_Z - m_Z^{PDG}\| < 10$	$\|m_Z - m_Z^{PDG}\| < 10$
m_T^W [GeV]	...	> 30	> 30	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	...	$> 0.2, > 0.3$	$> 0.2, > 0.3$	$> 0.2, > 0.3$
p_T two leading jets [GeV]	...	...	> 30	> 30
$\|\eta_j\|$ two leading jets	...	...	< 4.5	< 4.5
Jet multiplicity	...	...	≥ 2	≥ 2
m_{jj} [GeV]	...	...	> 500	> 500
$\Delta R(j, \ell)$	...	...	> 0.3	> 0.3
$\|\Delta\phi(W, Z)\|$	...	...	...	> 2
$\sum \|p_T^\ell\|$ [GeV]	...	...	...	> 250



Selection	VBS	aQGC
Data	45	9
Total expected	37.2 ± 1.1	4.9 ± 0.3
WZjj-EW	7.4 ± 0.2	1.1 ± 0.1
WZjj-QCD	20.8 ± 0.8	2.8 ± 0.3
tZ	3.0 ± 0.1	0.3 ± 0.0
Misid. leptons	2.5 ± 0.6	0.1 ± 0.1
ZZ	1.9 ± 0.3	0.2 ± 0.1
$t\bar{t} + V$	1.6 ± 0.1	0.3 ± 0.0

95% CL upper limit is 0.63fb

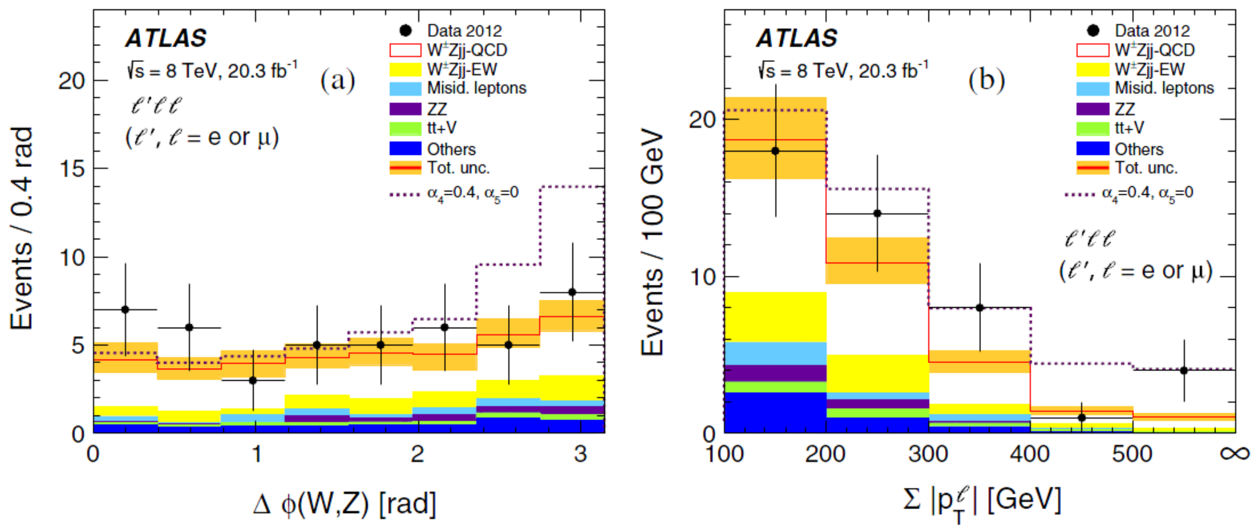
σ_{fid} (WZjj-EW) = $0.29^{+0.14}_{-0.12}(stat)^{+0.09}_{-0.1}$(syst) fb

SM expectation 0.13 ± 0.01 fb from VBFNLO.

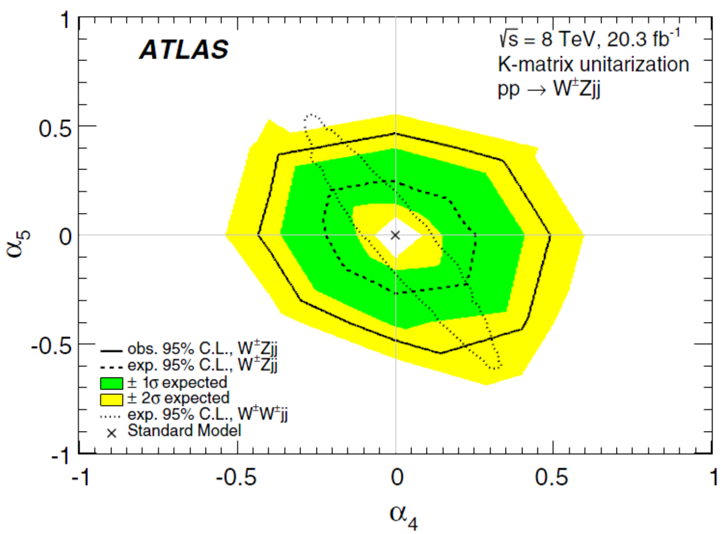
WZjj

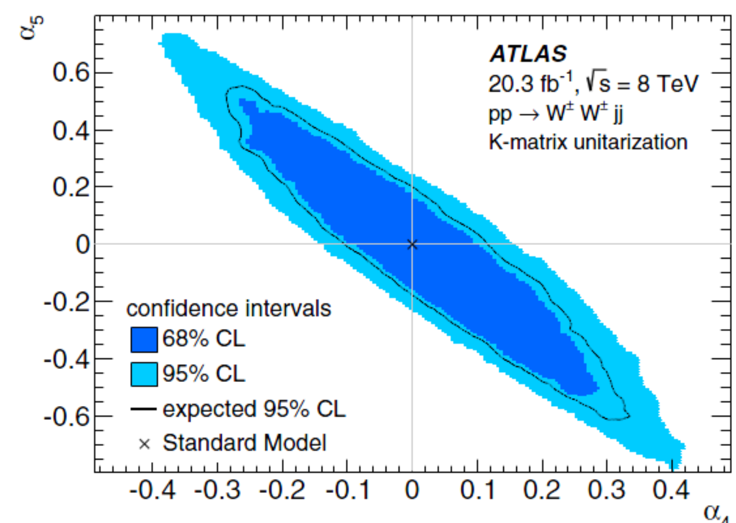
ATLAS, 8TeV

PRD93, 092004 (2016)



Mesured fiducial xsec is used to set limits on aQGC





Assuming $\Lambda = 1$ TeV and K-matrix unitarization

$\alpha_{4(5)} = 0.5$ corresponds to $f_{S,0(1)} = 2177$

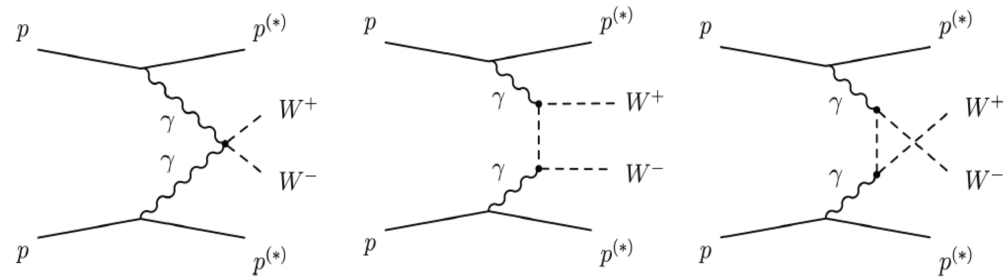
ATLAS SS WW

$\gamma\gamma \rightarrow WW$

CMS, 7&8TeV

arXiv:1604.04464

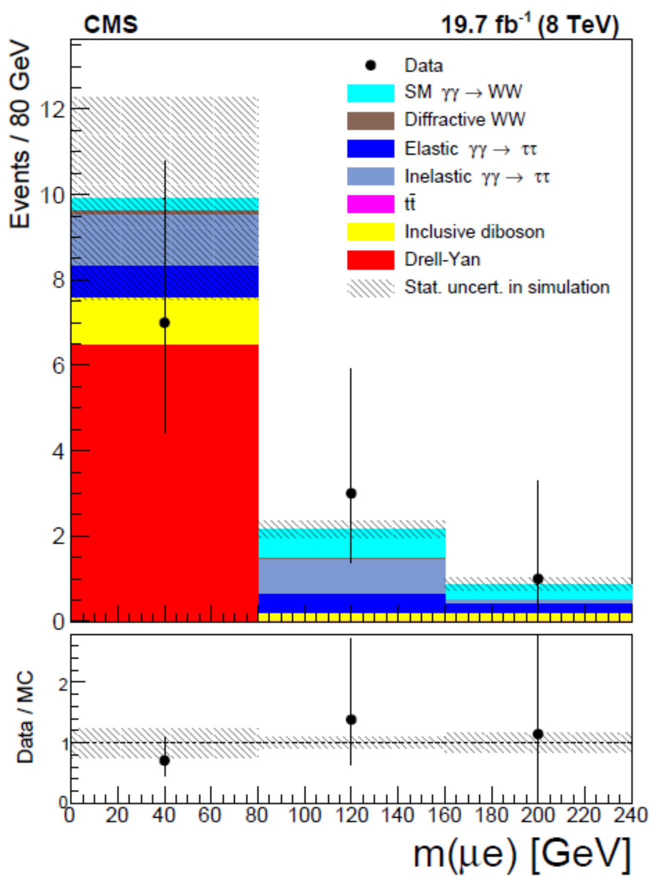
$$pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}$$

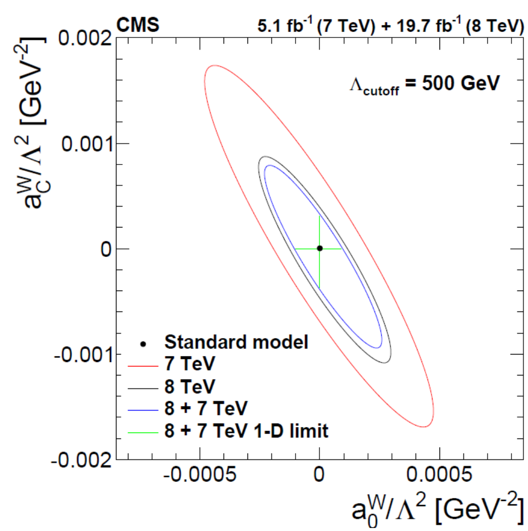


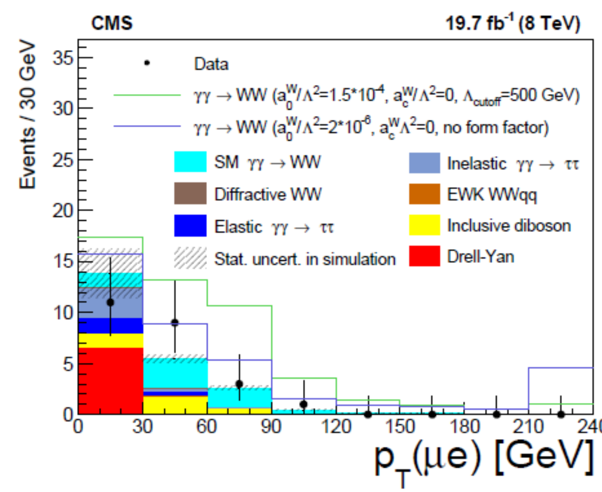
- **High Energy Photon interactions**
- **e, μ pair with PT($e\mu$)>30GeV**
- **No associated charged particle from the same vertex**
- **3.4 $(2.8)\sigma$ observed (expected)**

$$\sigma(pp \rightarrow p^{(*)}W^+W^-p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}) = 11.9^{+5.6}_{-4.5}\ \text{fb}.$$

SM prediction is 6.9 ± 0.6 fb







$$\frac{a_0^W}{\Lambda^2} = -\frac{4M_W^2}{e^2}\frac{f_{M,0}}{\Lambda^4},$$
$$\frac{a_C^W}{\Lambda^2} = \frac{4M_W^2}{e^2}\frac{f_{M,1}}{\Lambda^4},$$

$$a_{0,C}^W(W_{\gamma\gamma}^2) = \frac{a_{0,C}^W}{\left(1 + \frac{W_{\gamma\gamma}^2}{\Lambda_{\text{cutoff}}^2}\right)^2}$$

$\gamma\gamma \to WW$

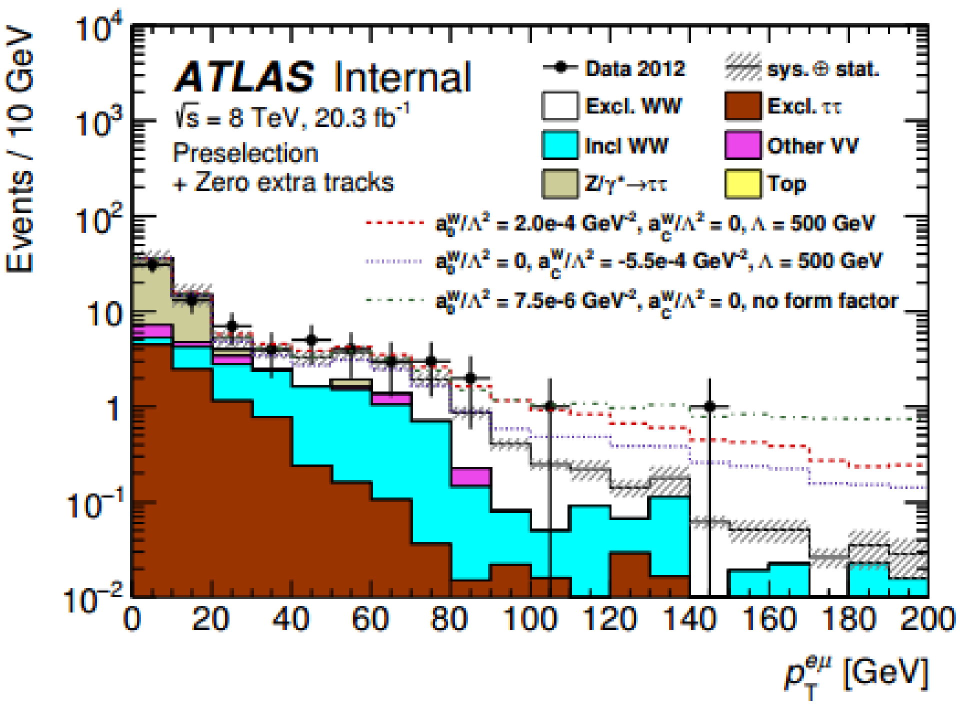
ATLAS, 8TeV

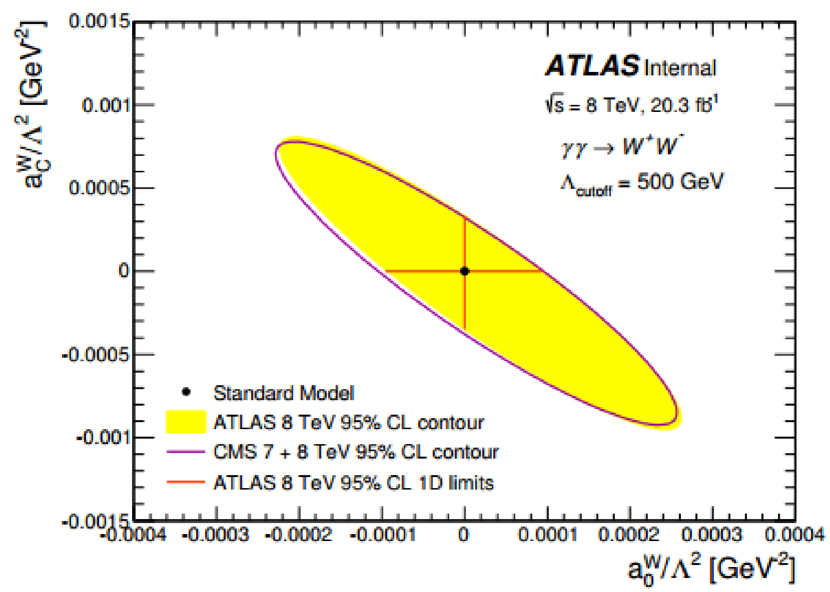
NEW!

	Expected Signal	Data	Total Bkg	Incl W^+W^-	Excl. $\tau\tau$	Other-VV	Other Bkg	MC/Data	$\epsilon \times A$ (Signal)
Preselection	22.6 ± 1.9	99424	97877	11443	21.4	1385	85029	0.98	0.254
$p_T^{\ell\ell} > 30$ GeV	17.6 ± 1.5	63329	63023	8072	4.30	896.3	54051	1.00	0.198
Δz_0^{iso} requirement	9.3 ± 1.2	23	8.3 ± 2.6	6.6 ± 2.5	1.4 ± 0.3	0.3 ± 0.2	–	0.77	0.105 ± 0.012
aQGC signal region									
$p_T^{\ell\ell} > 120$ GeV	0.37 ± 0.04	1	0.37 ± 0.13	0.32 ± 0.12	0.05 ± 0.03	0	–	0.74	0.0042 ± 0.0005

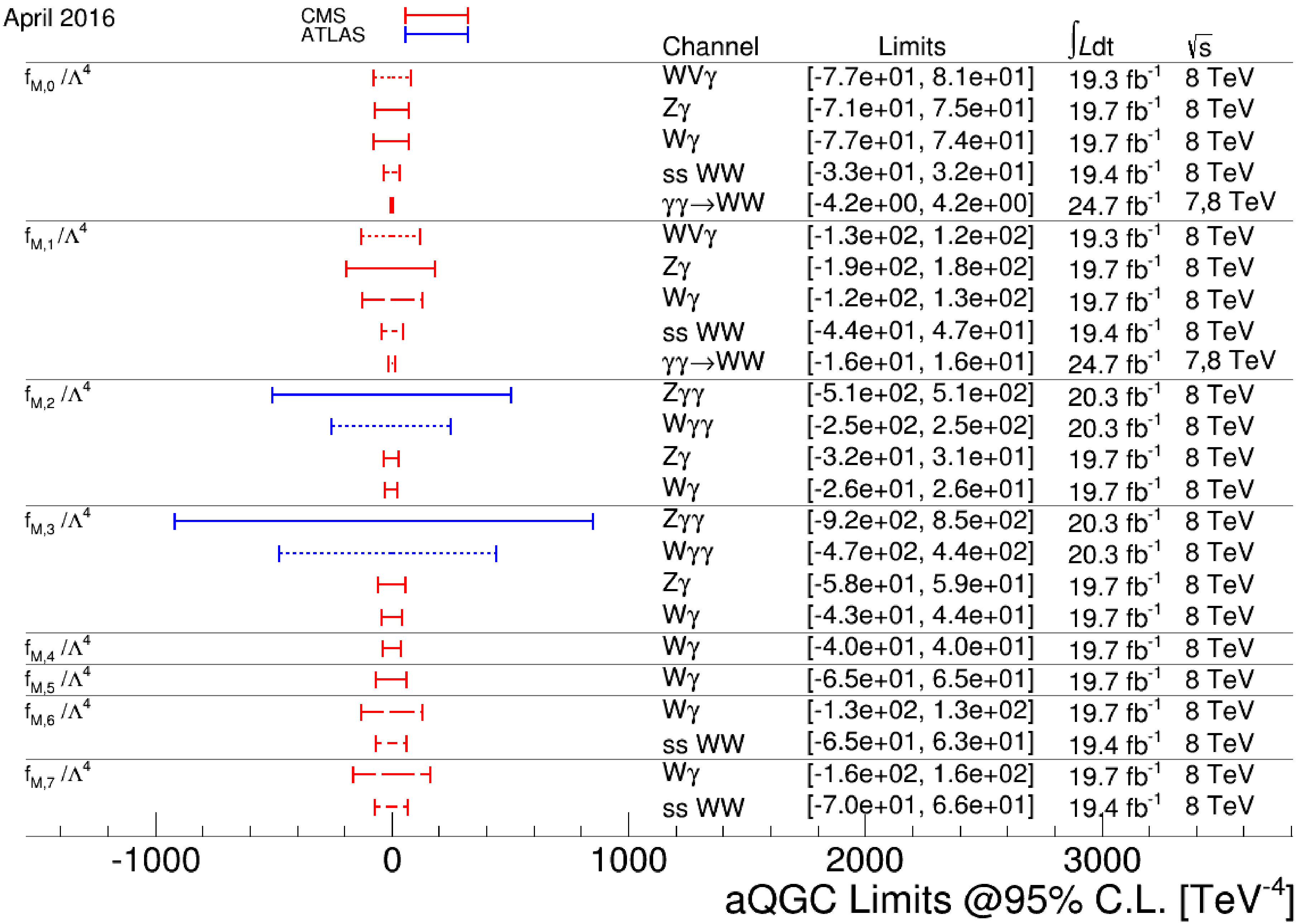
$$(\sigma \cdot BR)^{\text{Measured}}_{\gamma\gamma\to W^+W^-\to e^\pm\mu^\mp X} = 6.9 \pm 2.2\,(\text{stat.}) \pm 1.4\,(\text{syst.})\ \text{fb}$$

3.0 σ

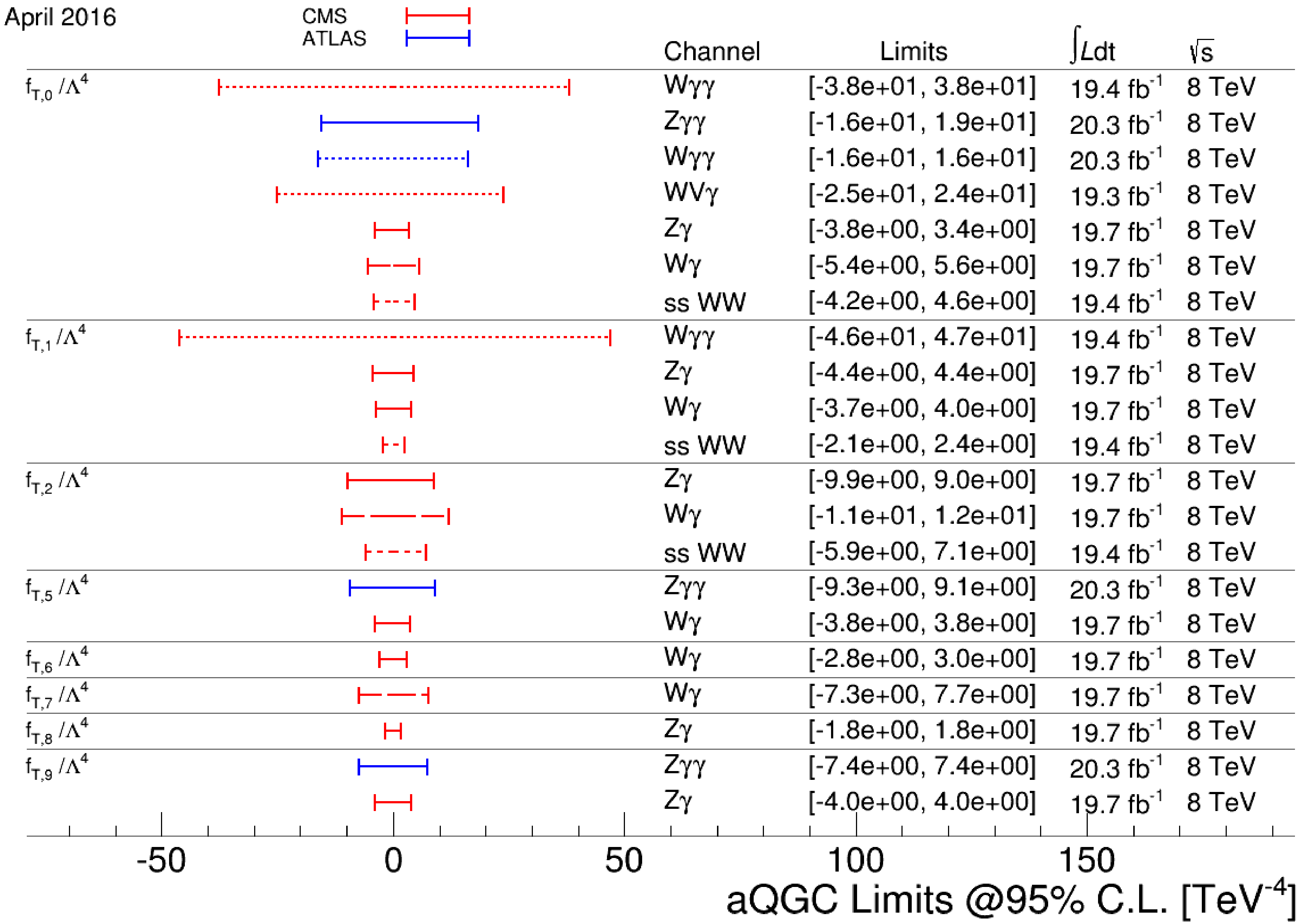




aQGC limit on fM parameters

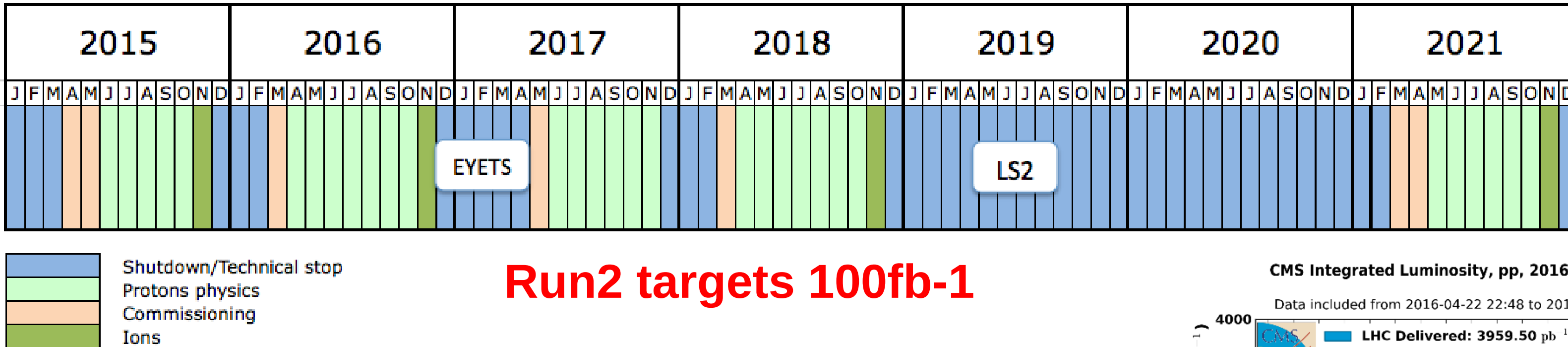


aQGC limit on fT parameters

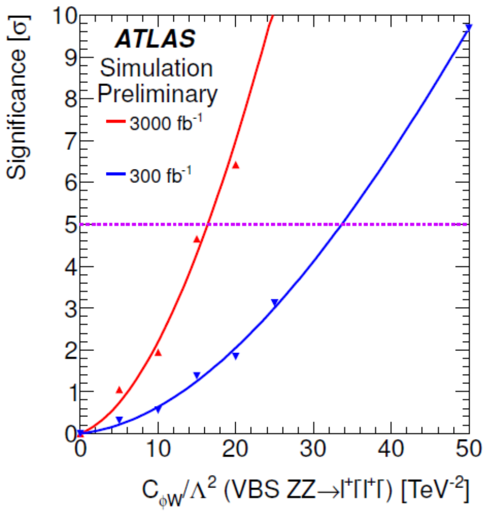


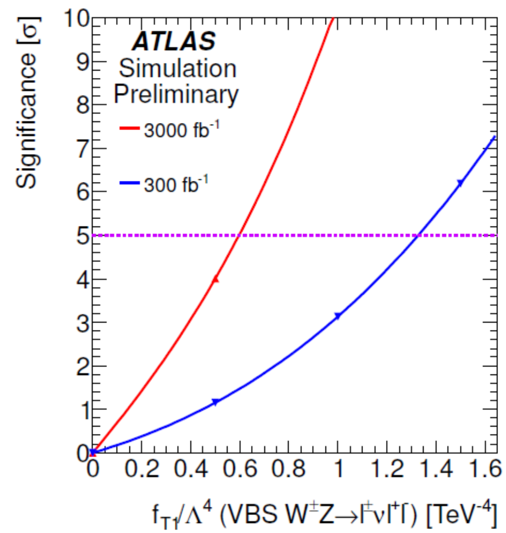
Run2 and future

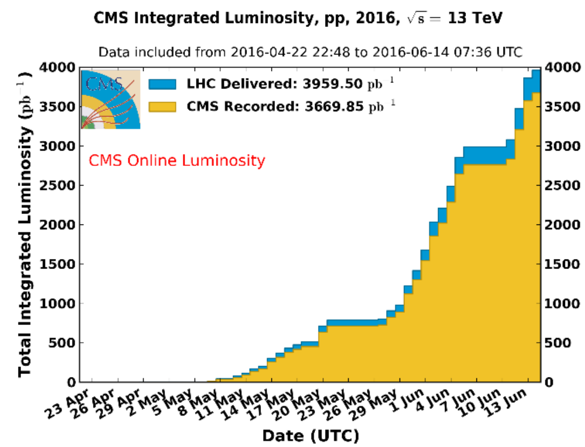
ATLAS-PHYS-PUB-2013-006; CMS-PAS-FTR-13-006; CERN-LHCC-2015-010

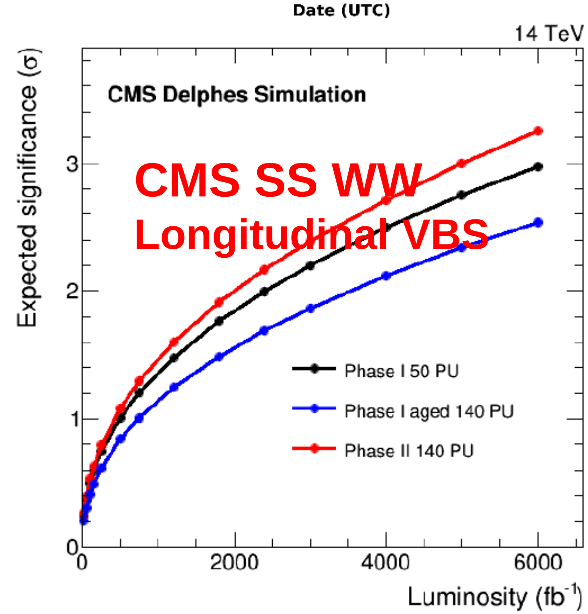


Run2 targets 100fb-1









CMS SS WW
Longitudinal VBS

CMS VBS WZjj

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1} f_{T1}/Λ^4 at 3000 fb^{-1}	0.8 TeV^{-4} 0.45 TeV^{-4}	1.0 TeV^{-4} 0.55 TeV^{-4}

Summary

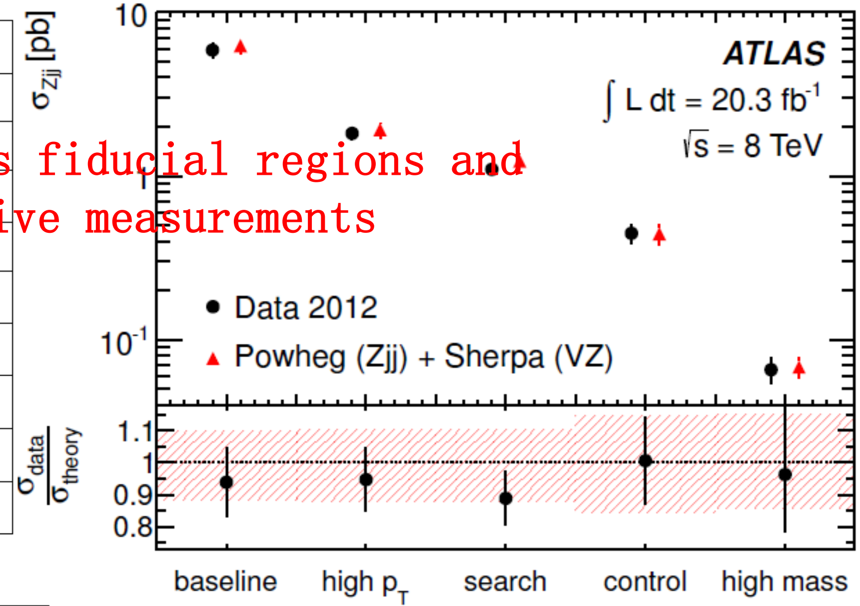
- Extensive Studies on VBF/VBS from LHC Run1
- VBF ZJJ has been established at 5σ!
- With limited statistics, VBF topology has been studied
- Rich results for VBS, evidence for SS WW and VBS $Z\gamma jj$
- Stringent limits on aQGC from the LHC
- With O(100fb-1) data of Run2, a new era of VBF/VBS is coming:
  SM as discovery and for discovery

Thank you!

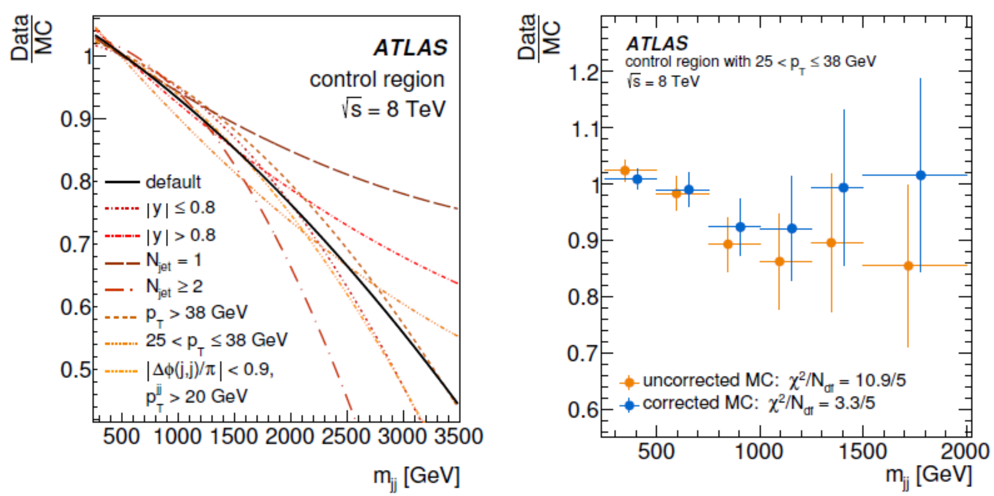
Backup

ATLAS Zjj, 8TeV

Object	*baseline*	*high-mass*	*search*	*control*	*high-p_T*
Leptons	$\lvert\eta^\ell\rvert < 2.47$, $p_T^\ell > 25$ GeV				
Dilepton pair	$81 \le m_{\ell\ell} \le 101$ GeV				
	—		$p_T^{\ell\ell} > 20$ GeV		
Jets	$\lvert y^j\rvert < 4.4$, $\Delta R_{j,\ell} \ge 0.3$				
	$p_T^{j_1} > 55$ GeV				$p_T^{j_1} > 85$ GeV
	$p_T^{j_2} > 45$ GeV				$p_T^{j_2} > 75$ GeV
Dijet system	—	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV		—
Interval jets	—		$N_{\rm jet}^{\rm gap} = 0$	$N_{\rm jet}^{\rm gap} \ge 1$	—
Zjj system	—		$p_T^{\rm balance} < 0.15$	$p_T^{\rm balance,3} < 0.15$	—



Various fiducial regions and inclusive measurements



(a) (b)

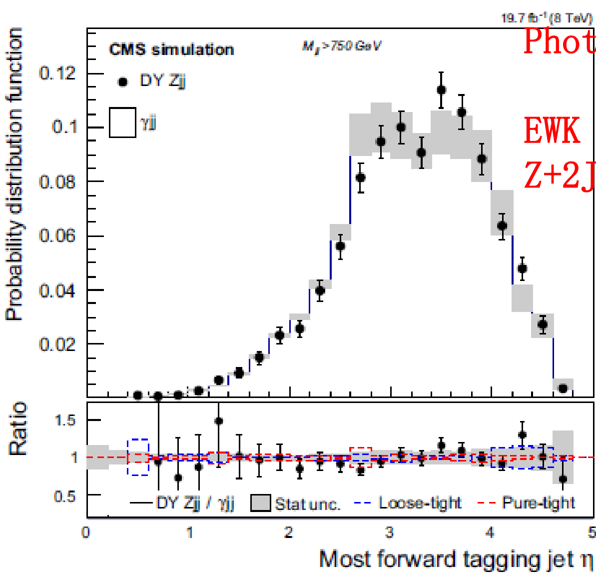
Figure 12. (a) Background reweighting functions obtained for different choices of *control* region. (b) The agreement between data and simulation in the $25 < p_T \le 38$ GeV subregion both before and after applying a background reweighting function derived in the $p_T > 38$ GeV subregion.

Checking DATA-Driven Bkg estimations in various Control regions

CMS Zjj, 8TeV

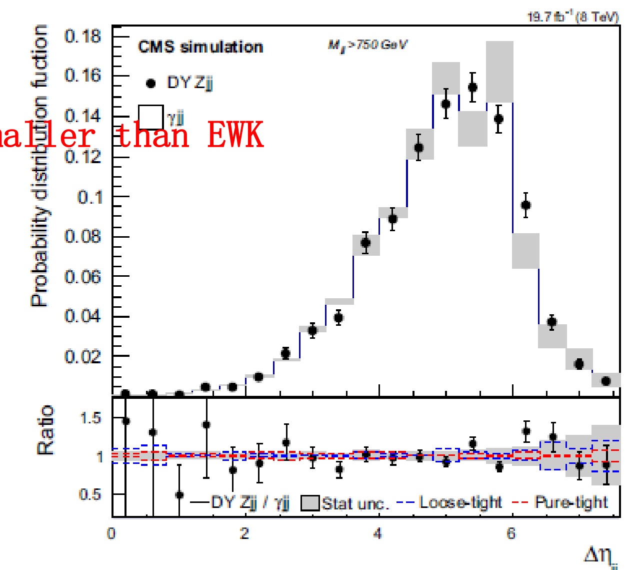
Table 5 Fitted signal strengths in the different analyses and channels including the statistical and systematic uncertainties. For method C, only events with $M_{jj} > 450$ GeV are used. The breakup of the systematic components of the uncertainty is given in detail in the listings

	Analysis A			Analysis B	Analysis C		
	ee	$\mu\mu$	ee + $\mu\mu$	$\mu\mu$	ee	$\mu\mu$	ee + $\mu\mu$
Luminosity	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Trigger/lepton selection	0.04	0.04	0.04	0.04	0.04	0.04	0.04
JES+residual response	0.06	0.05	0.05	0.04	0.06	0.05	0.05
JER	0.02	0.02	0.02	0.02	0.04	0.04	0.03
Pileup	0.01	0.02	0.02	0.01	0.01	0.01	0.01
DY Zjj	0.07	0.05	0.07	0.08	0.14	0.12	0.13
q/g discriminator	<0.01	<0.01	<0.01	–	<0.01	<0.01	<0.01
Top, dibosons	0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01
Signal acceptance	0.03	0.04	0.04	0.04	0.06	0.06	0.06
DY/EW Zjj interference	0.14	0.14	0.14	0.13	0.06	0.08	0.08
Systematic uncertainty	0.19	0.18	0.19	0.17	0.17	0.17	0.18
Statistical uncertainty	0.11	0.10	0.07	0.09	0.24	0.21	0.16
$\mu = \sigma/\sigma_{th}$	0.82	0.86	0.84	0.89	0.91	0.85	0.88

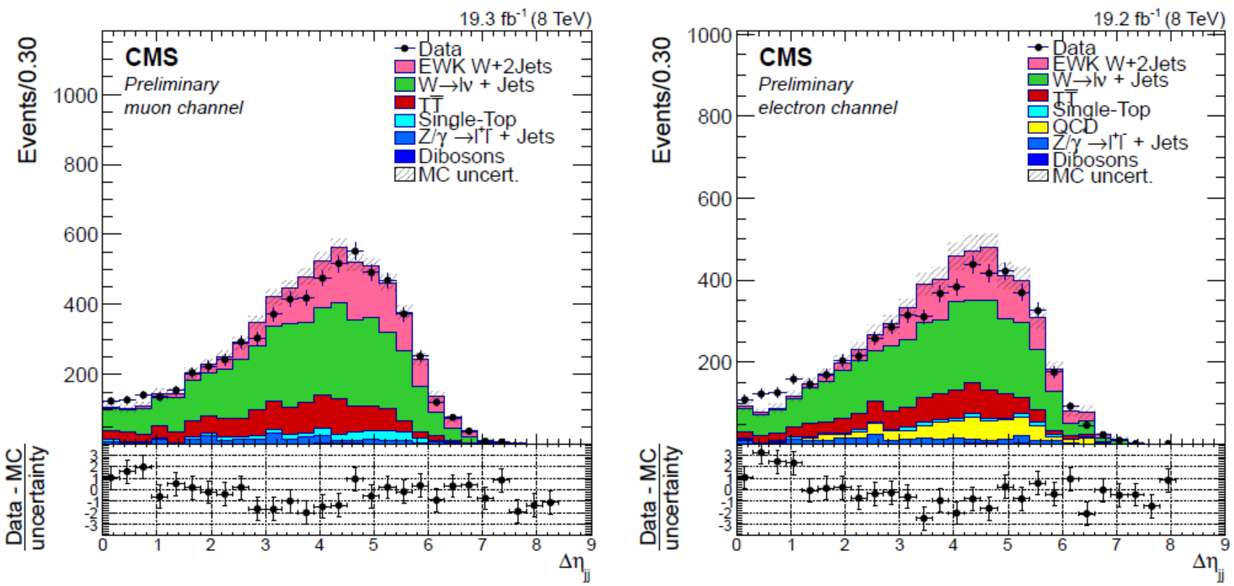


Photon+jets vs Z+Jets

EWK Photon+2Jets is much smaller than EWK Z+2Jets



CMS Wjj, 8TeV



Source of uncertainty	Muons	Electrons
Luminosity	2.6%	2.6%
Jet energy scale	7.3%	5.4%
Jet energy resolution	3.7%	2.2%
W+jets shape and normalization	16.7%	13.0%
Top-quark shape and normalization	6.0%	5.5%
Interference effect	13.8%	14.4%
QCD fraction prediction (electron channel)	—	4.4%
Lepton trigger efficiency	1.0%	0.9%
Lepton selection efficiency	2.0%	1.8%
Pileup	$< 1\%$	$< 1\%$
Fiducial acceptance	1.7%	1.7%
total (without luminosity)	24.1%	21.6%

$W^{\mp} W^{\mp} jj$

TABLE II. Estimated background yields, observed number of data events, and predicted signal yields for the three channels are shown with their systematic uncertainty. Contributions due to interference are included in the $W^{\pm}W^{\pm}jj$ electroweak prediction.

	Inclusive region			VBS region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	...	2.1 ± 0.5	1.9 ± 0.7	...
Other nonprompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10

ATLAS

TABLE I. Signal and background yields after the full selection. Only statistical uncertainties are reported. The signal, $W^{\pm}W^{\pm}jj$, includes EW and QCD processes and their interference.

	Nonprompt	WZ	VVV	Wrong sign	WW DPS	Total bkg.	$W^{\pm}W^{\pm}jj$	Data
$W^{+}W^{+}$	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	3.1 ± 0.6	7.1 ± 0.1	10
$W^{-}W^{-}$	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	...	...	2.6 ± 0.5	1.8 ± 0.1	2
$W^{\pm}W^{\pm}$	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	5.7 ± 0.8	8.9 ± 0.1	12

CMS

In addition to vetoing loosely identified leptons, we also veto the following cases:

- **Events with a loosely isolated, reconstructed muon or electron.**
- **Events with a fully identified lepton and another opposite-charge, same-flavor, lepton-reconstructed lepton (without an isolation requirement), such that their invariant mass is compatible with a Z boson.**
- **Events with a fully identified lepton and an isolated hadron-reconstructed lepton, such that their invariant mass is compatible with a Z boson.**

Those additional requirements reduce by ~60% the WZ background with a tiny effect on the dilepton events. The mll cut is pretty much irrelevant after all, but it was actually applied to reduce the non-prompt lepton background at preselection level.

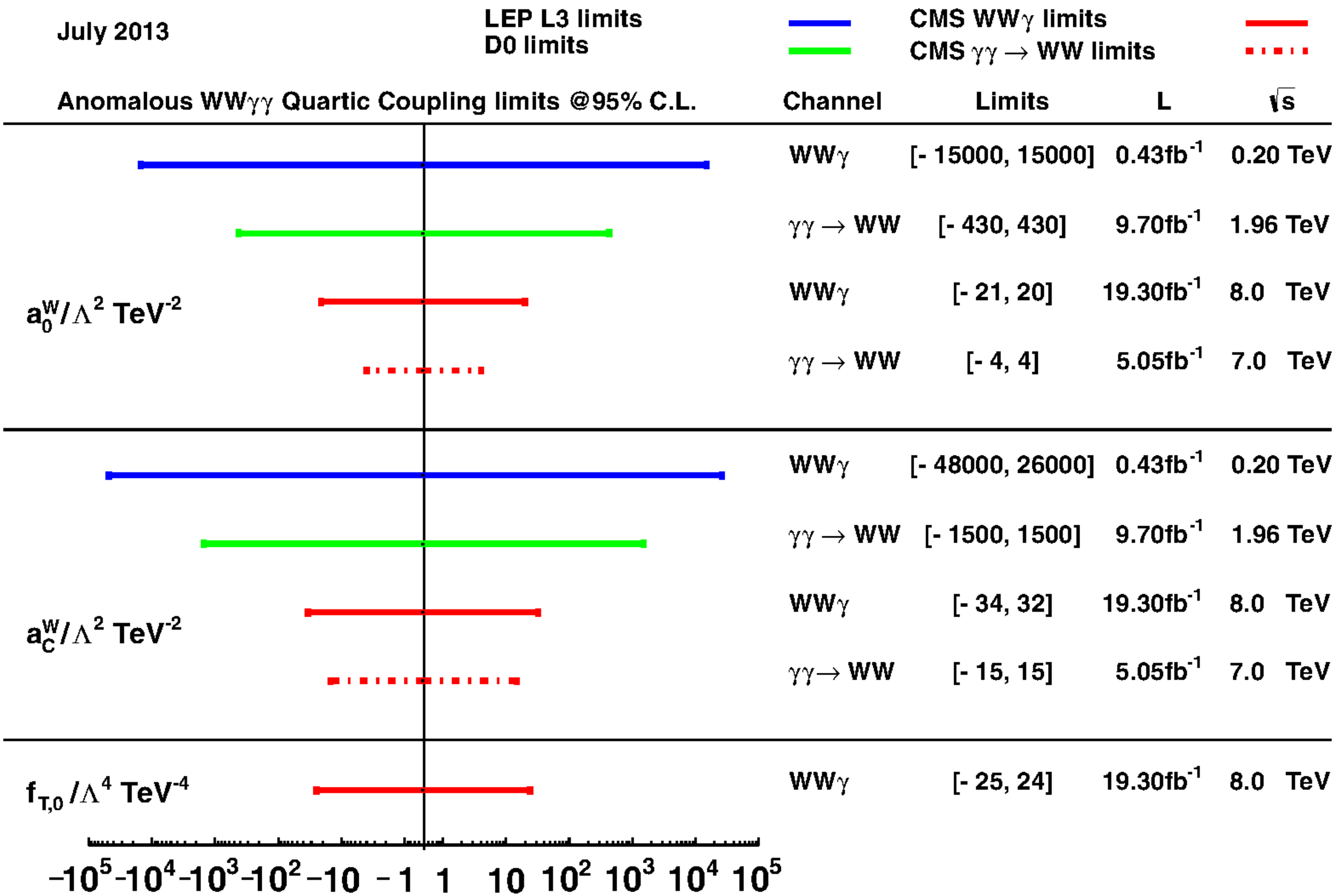
https://indico.cern.ch/event/338764/contributions/1734455/attachments/663828/912493/VBS_5_September_2014.pdf

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

Phys. Rev. D74:073005, 2006


July 2013
LEP L3 limits
D0 limits
CMS WWγ limits
CMS γγ → WW limits
Anomalous WWγγ Quartic Coupling limits @95% C.L.
Channel
Limits
L
√s
WWγ [- 15000, 15000] 0.43fb-1 0.20 TeV
γγ → WW [- 430, 430] 9.70fb-1 1.96 TeV
WWγ [- 21, 20] 19.30fb-1 8.0 TeV
γγ → WW [- 4, 4] 5.05fb-1 7.0 TeV
a0W/Λ2 TeV-2
WWγ [- 48000, 26000] 0.43fb-1 0.20 TeV
γγ → WW [- 1500, 1500] 9.70fb-1 1.96 TeV
WWγ [- 34, 32] 19.30fb-1 8.0 TeV
γγ→ WW [- 15, 15] 5.05fb-1 7.0 TeV
aCW/Λ2 TeV-2
fT,0 /Λ4 TeV-4
WWγ [- 25, 24] 19.30fb-1 8.0 TeV
-105 -104 -103 -102 -10 - 1 1 10 102 103 104 105