Vector boson scattering in the channel $pp \to W^{\pm}W^{\pm}jj$ with the ATLAS detector

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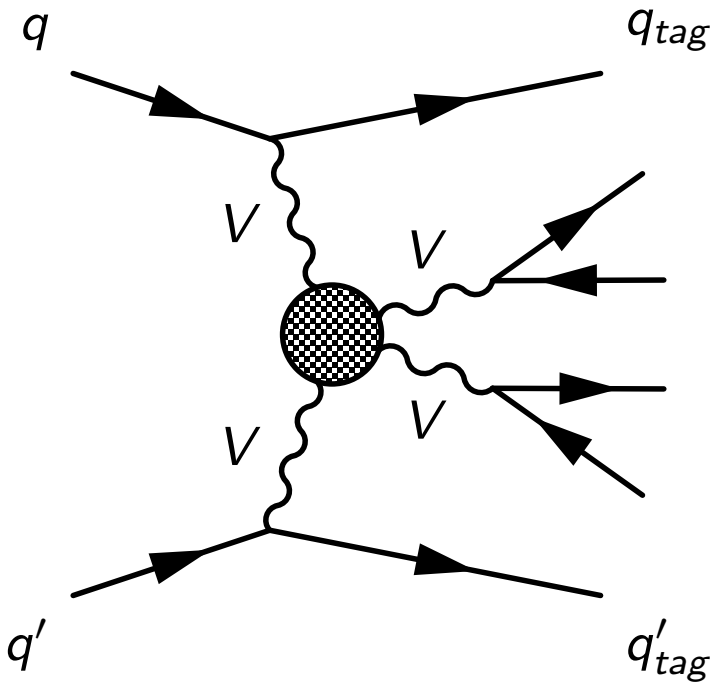
Vector Boson Scattering (VBS)

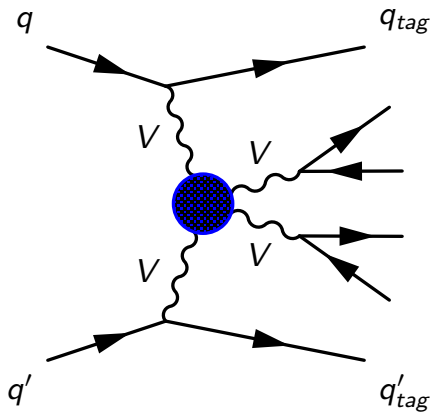


Scattering of two weak gauge bosons

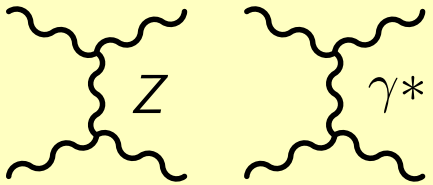
- Never measured before!
  ⇒ First observation of a process containing VVVV vertex (predicted by the SM)
- Contains scattering of longitudinal components of the gauge bosons
  ⇒ Probe electroweak symmetry breaking mechanism

$W^{\pm}W^{\pm}$ scattering analysis at 8 TeV published in Phys. Rev. Lett. 113, 141803

Scattering of same-sign W bosons



Same-sign WW channel
$(V, V = W^{\pm}W^{\pm})$
$\Rightarrow$ ● contains:



Diagrams with triple gauge couplings

(TGC better constrained by other channels)

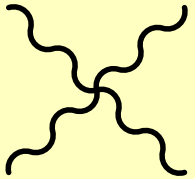
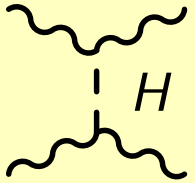


Diagram with WWWW vertex **NEW!**

(No process including VVVV vertex observed before)



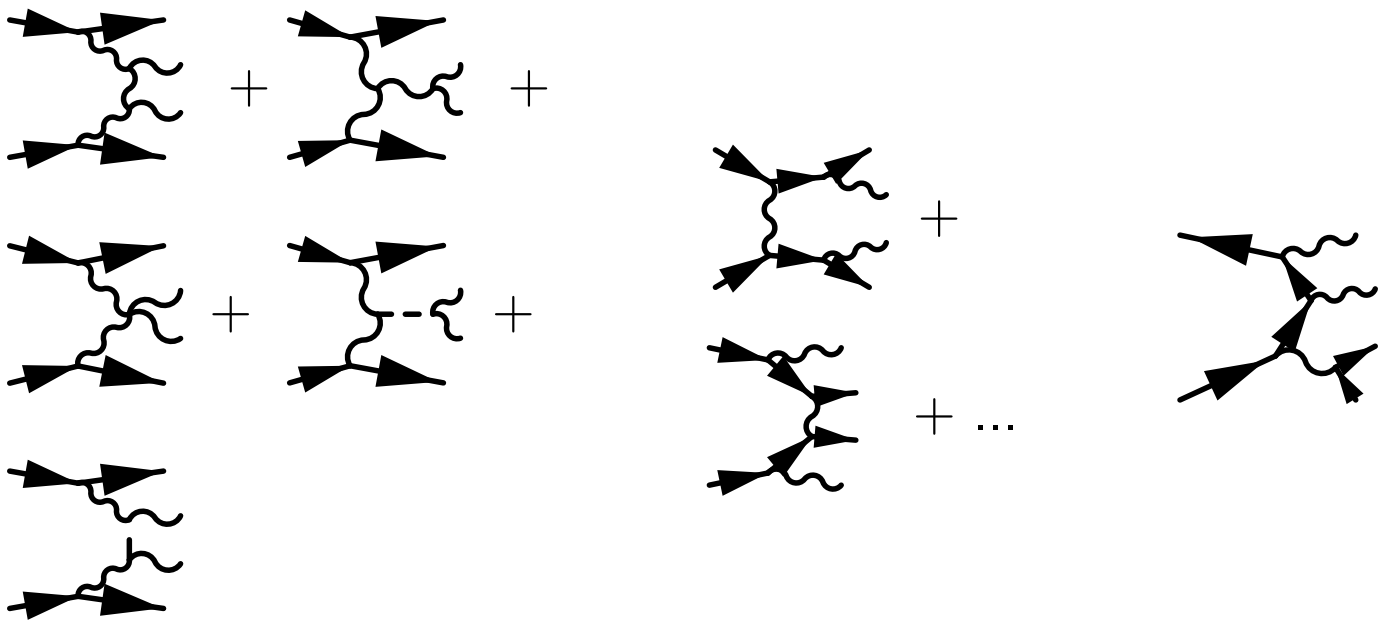
Higgs in t-channel

(SM $\Rightarrow$ H unitarizes VBS)

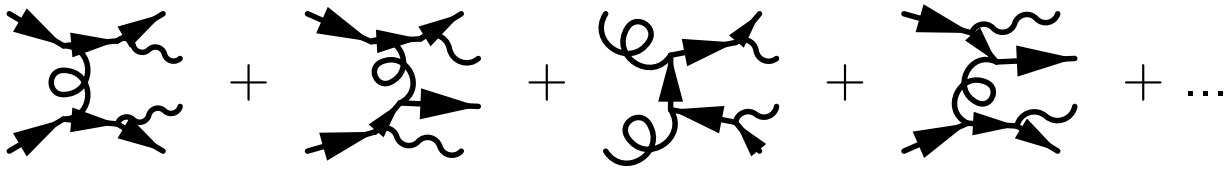
VBS signal definition

VVjj-EW: $\mathcal{O}(EW) = 6$

VBS **irreducible EW** **VVV**



VVjj-QCD: $\mathcal{O}(EW) = 4$, $\mathcal{O}(QCD) = 2$



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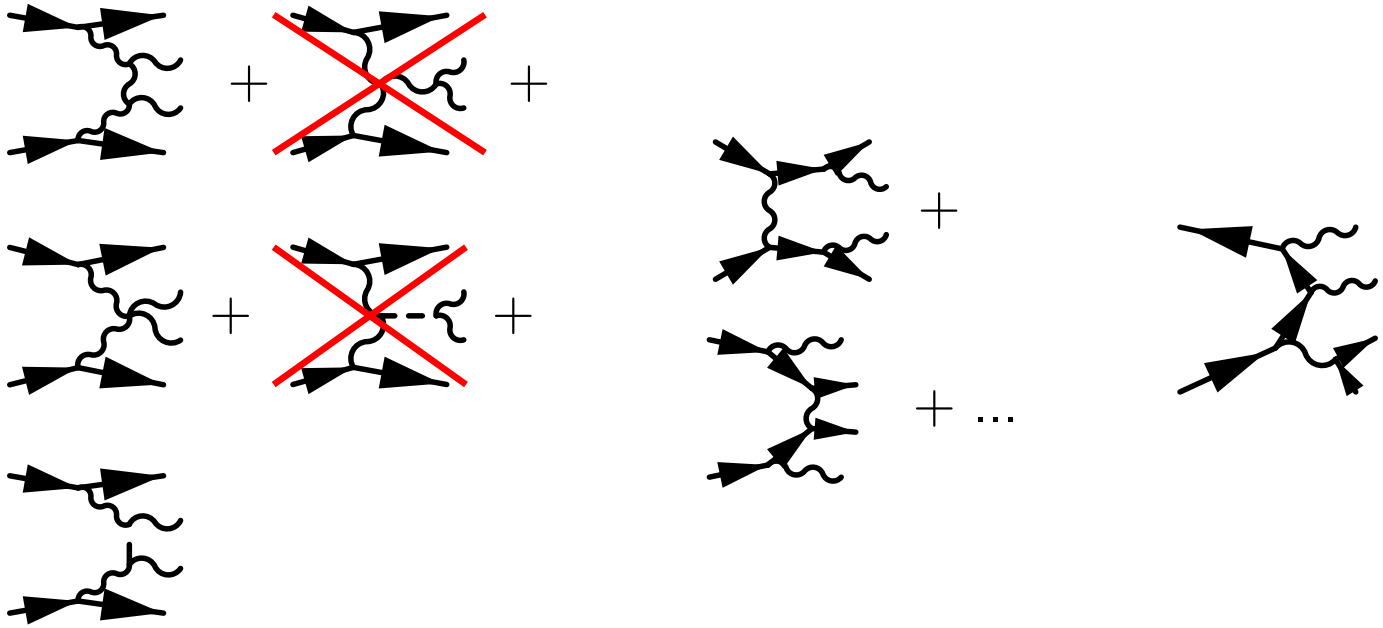

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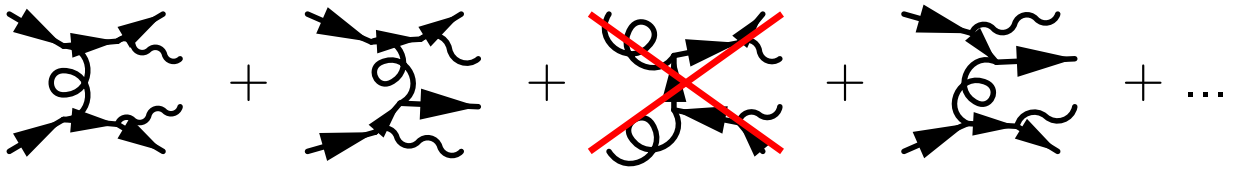


x... not included in $W^{\pm}W^{\pm}jj$

VBS in $W^{\pm}W^{\pm}jj$ channel

Cross sections in various VV channels at 8 TeV:

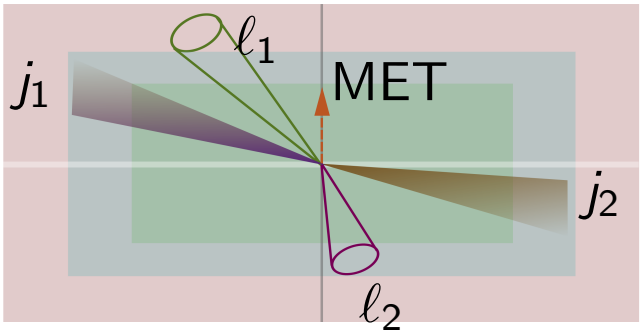
Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb	1:1
$\ell^{\pm}\nu\ell^{\mp}\nu jj$	$W^{\pm}W^{\mp} + ZZ$	93.7 fb	3192 fb	1:30
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb	1:20
$\ell\ell\ell\ell jj$	ZZ	1.5 fb	106 fb	1:70

(cuts: 2 leptons: $p_{\mathrm{T}} > 5$ GeV, $m_{\ell\ell} > 4$ GeV, 2 jets: $p_{\mathrm{T}} > 10$ GeV)

VBS by channel

- $W^{\pm}W^{\pm}jj$ most promising: high EW/QCD ratio (no gluons in initial state)
- $W^{\pm}Zjj$ has larger QCD contribution, but profits from clean 3 lepton signature
- $W^{\pm}W^{\mp}$overwhelmed by ttbar background $\rightarrow$ use MVA methods

VBS topology



- two forward energetic tagging jets (initial quarks radiating off Ws)
- two central leptons (decay products of Ws)
- Missing E_{T} from Ws

Inclusive analysis phase space

- 2 same-sign high-p_{T} leptons
- at least 2 high-p_{T} jets
- $E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$
- leading jets: $m_{jj} > 500\,\mathrm{GeV}$

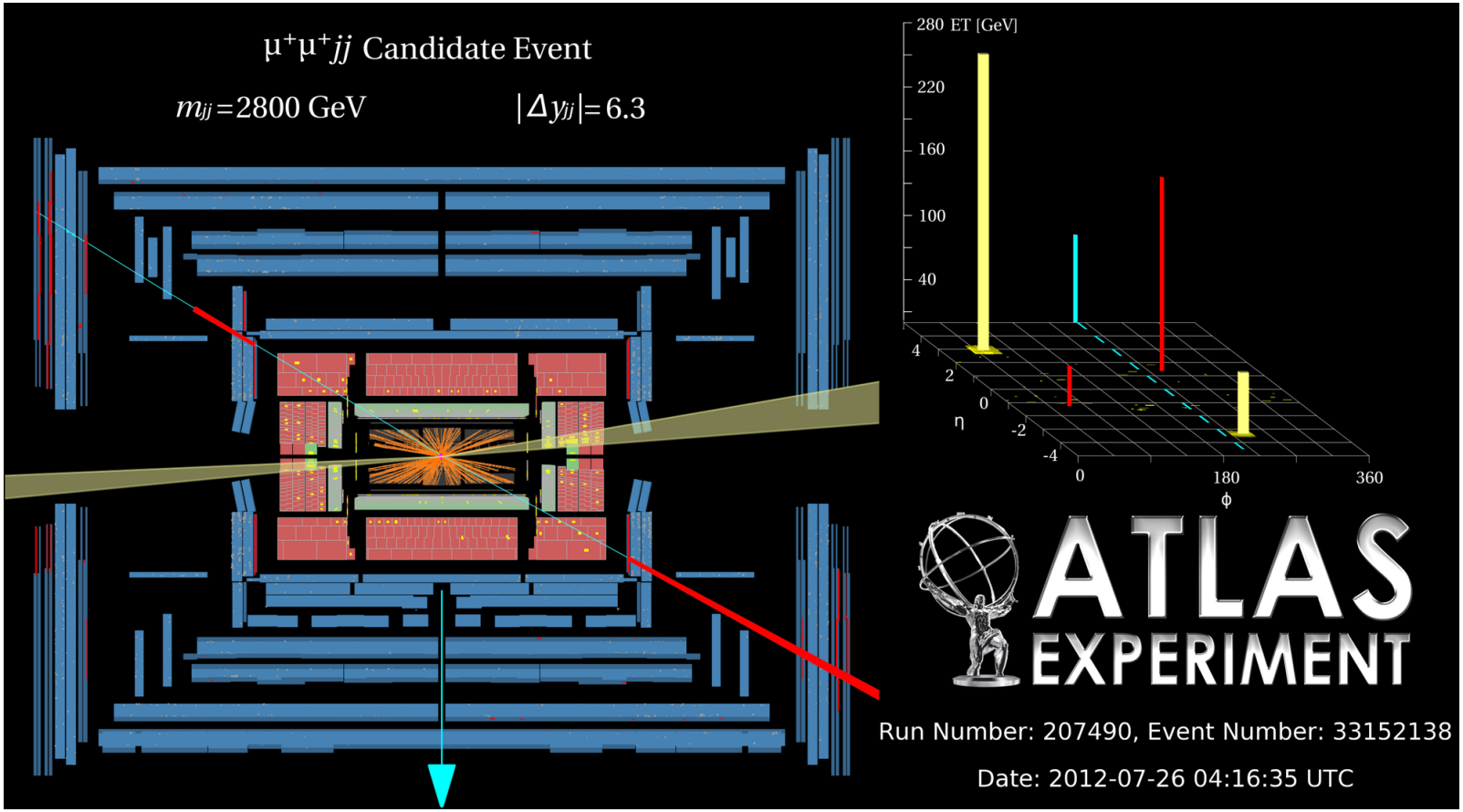
Measure $W^{\pm}W^{\pm}jj$ (incl. EW, QCD)

VBS analysis phase space

inclusive analysis phase space +

- $|\Delta y(jj)| > 2.4$

Measure $W^{\pm}W^{\pm}jj$ EW and set aQGC limits



$$p_{\mathrm{T}}(\mathrm{lep1}) = 180.2\,\mathrm{GeV}$$
$$p_{\mathrm{T}}(\mathrm{lep2}) = 37.5\,\mathrm{GeV}$$
$$E_{\mathrm{T}}^{\mathrm{miss}} = 74.8\,\mathrm{GeV}$$

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Backgrounds to $W^{\pm}W^{\pm}$jj-EW

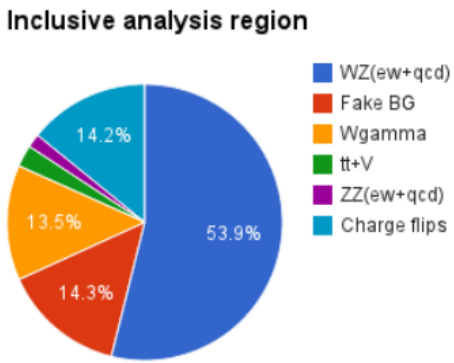
Prompt background — Real prompt leptons

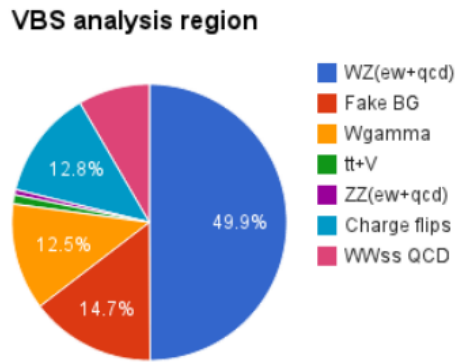
- WZ/γ^{*}+jets
- ZZ+jets
- $t\bar{t}+W/Z$, tZj

Conversions

- prompt photon conversion — $W\gamma$
- charge mis-ID due to bremsstrahlung with conversion — $Z/\gamma*$+jets or $t\bar{t}$

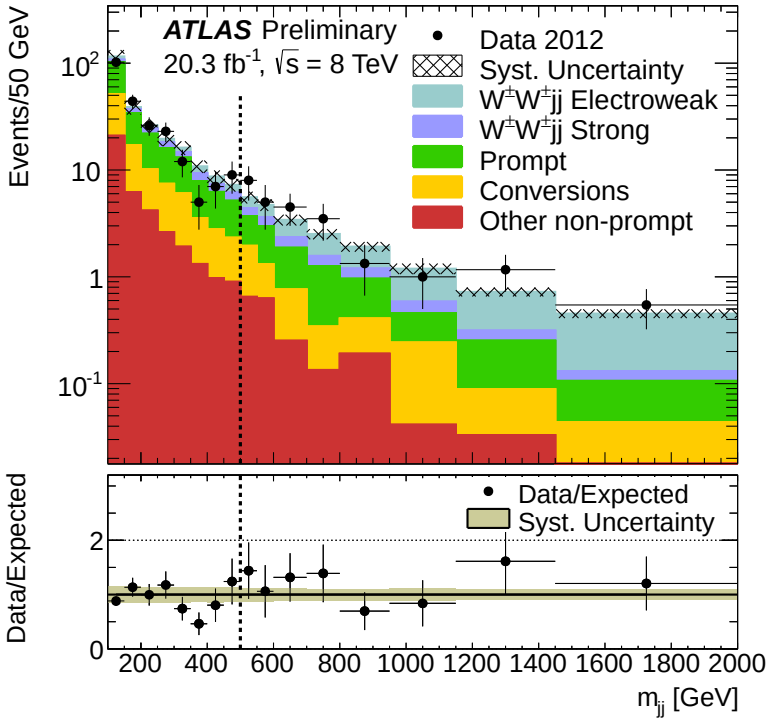
Fake leptons — leptons from hadron decays in jets — W+jets





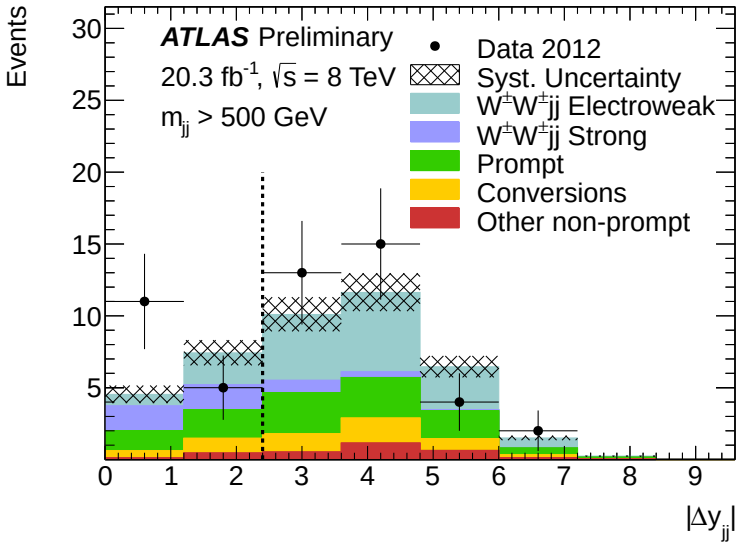
Kinematics of jets

Tagging jets invariant mass



(Inclusive region before m_{jj} cut)

Rapidity difference



(VBS signal region before Δy_{jj} cut)

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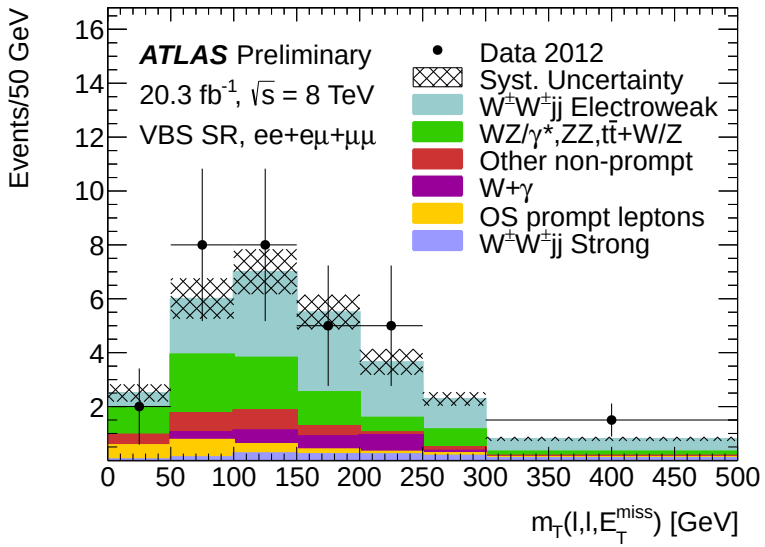
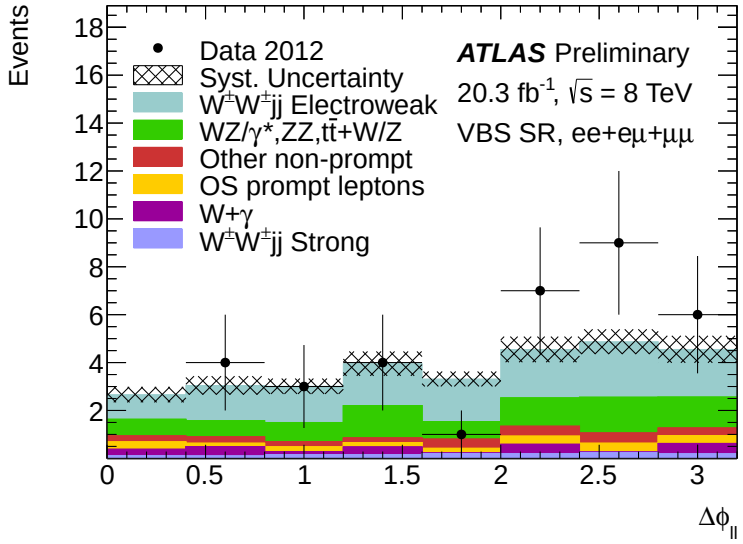
Kinematics of leptons

Transverse mass of leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$



(VBS signal region)

Lepton $\Delta\phi$



(VBS signal region)

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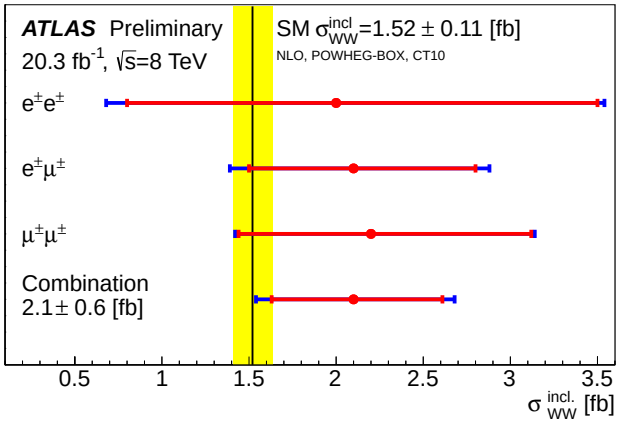
Results

Extract cross section by fitting a likelihood function to the observed data

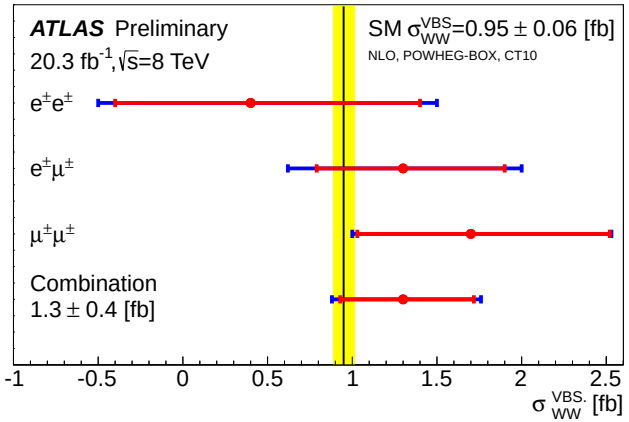
Total cross sections

	Observed	Significance
EWQCD (incl. Region)	2.1 ± 0.5 (stat.) ± 0.3 (syst.) fb	$4.5\,\sigma$
EW (VBS Region)	1.3 ± 0.4 (stat.) ± 0.2 (syst.) fb	$3.6\,\sigma$

Comparison to theory prediction:



$\sigma_{WW}^{\mathrm{incl}}$ [fb]



$\sigma_{WW}^{\mathrm{VBS}}$ [fb]

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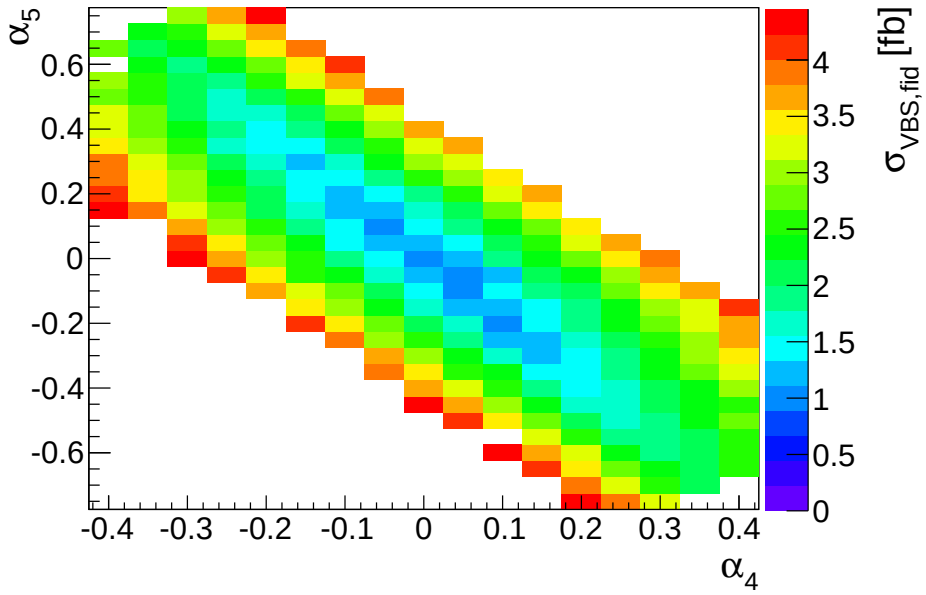
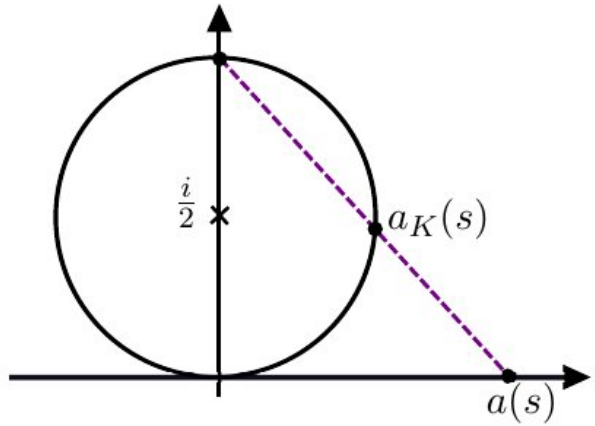
Anomalous quartic gauge couplings

Effective field theory

Model effects of new physics via higher-order operators
$\rightarrow$ Using electroweak chiral Lagrangian with parameters α_4, α_5 defined as
$\mathcal{L}_4 = \alpha_4(\mathrm{tr}[\mathbf{V}_\mu \mathbf{V}_\nu])^2$ and $\mathcal{L}_5 = \alpha_5(\mathrm{tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2$

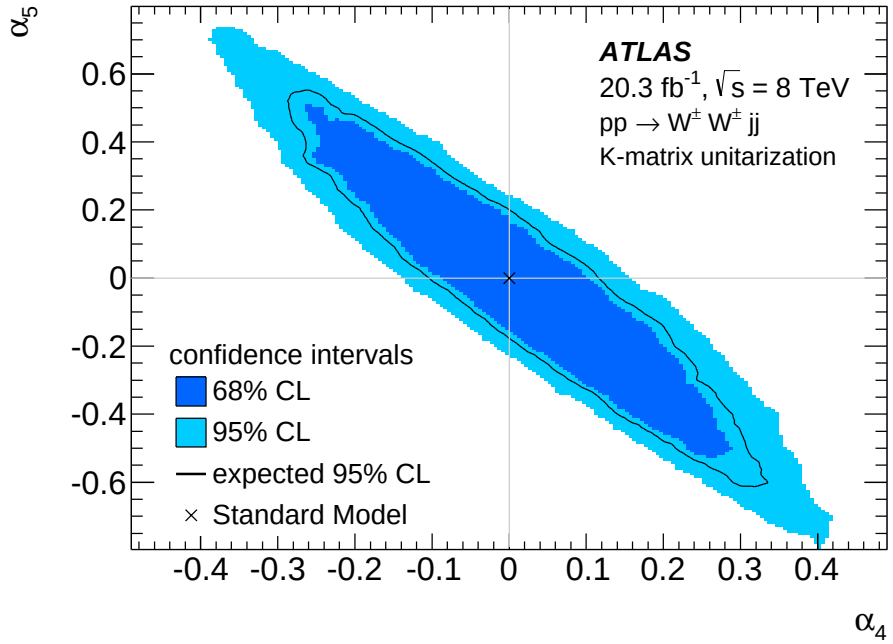




unitarization with K-matrix method
(WHIZARD generator)

Anomalous quartic gauge couplings

Set limits on α_4, α_5 in the VBS analysis region



One-dimensional limits at 95 % C.L. :

$$\alpha_4 \in [-0.14, 0.16]$$

$$\alpha_5 \in [-0.23, 0.24]$$

$\Rightarrow$ First limits on aQGC with massive electroweak vector bosons

Conclusions

- First evidence of $W^{\pm}W^{\pm}$ scattering and $W^{\pm}W^{\pm}jj$ production
  $\Rightarrow$ Measurements in good agreement with the SM prediction
- First limits on anomalous couplings of massive electroweak gauge bosons of parameters α_4, α_5

Backup

Available experimental constraints on 4 electroweak gauge boson couplings

- No observation of processes with quartic gauge boson vertex before today
- No constraints on massive gauge boson quartic couplings
- Constraints on anomalous quartic gauge couplings with photons exist:

Experiment	channel	Publication	year
CMS	WWγ, WZγ	CMS-PAS-SMP-13-009	2013
CMS	WW$\rightarrow \gamma\gamma$	JHEP07 (2013) 116	2013
D0	$\gamma\gamma \rightarrow WW$	Phys Rev D **88** 012005	2013
L3	$WW\gamma$	Phys. Lett. B 527:29-38, 2002	2002
OPAL	$WW\gamma$	Phys. Lett. B580:17-36, 2004	2004
DELPHI	$WW\gamma$	Eur. Phys. J C31:139-147, 2003	2003

Theory predictions

Calculations in the inclusive/VBS analysis phase spaces

$W^{\pm}W^{\pm}jj$-EW

Cross section from PowhegBox + Pythia8

Uncertainties
- Comparison to VbfNLO 5/3%
- Parton shower influence and models 2/4%
- scale and pdf: 2%, 2/3%

$W^{\pm}W^{\pm}jj$-QCD

Cross section from PowhegBox + Pythia8

Uncertainties
- Generator systematic (from EW) 5%
- Parton shower influence and models: 3/7%
- scale and pdf 12/13%; 2%

Analysis event selection

Leptons	• exactly 2 • well isolated, tight quality cuts • $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$ • $m_{\ell\ell} > 20\,\mathrm{GeV}$
Jets	• at least 2 • $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.5$
$E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$	
Veto	• events with additional softer and less isolated leptons • events with b-tagged jets
VBS cuts	• $m_{jj} > 500\,\mathrm{GeV}$ • $\lvert\Delta y_{jj}\rvert > 2.4$ (in VBS region)