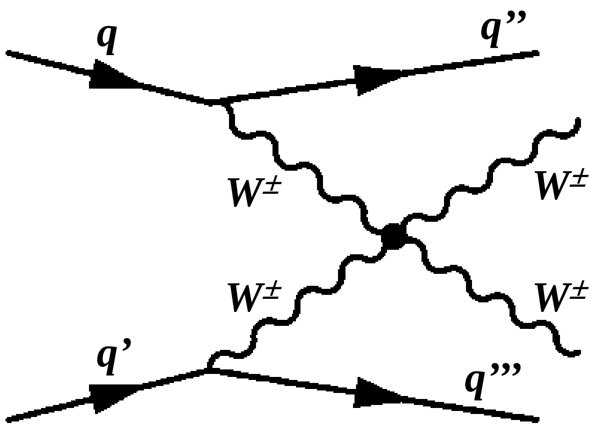
First Evidence of Same-sign WW Vector Boson Scattering Process at ATLAS



Junjie Zhu

University of Michigan

Fermilab Wine Cheese Seminar

May 23, 2014

Outline

- Introduction to Quartic Gauge Coupling and Vector Boson Scattering
- Previous studies with QGC and VBS
- Same-sign WW VBS studies at ATLAS using 20.3 fb^{-1} of data (ATLAS-CONF-2014-013)
  - First evidence for $W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$ scattering process
  - First set of limits on WWWW aQGCs
- Summary

Introduction

- SM is based on SU(3)×SU(2)×U(1) gauge symmetry
- The SM Lagrangian for the EW sector can be written as:

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\mathcal{L}_{\mathrm{EW}} = \; & \mathcal{L}_{\mathrm{K}} + \\
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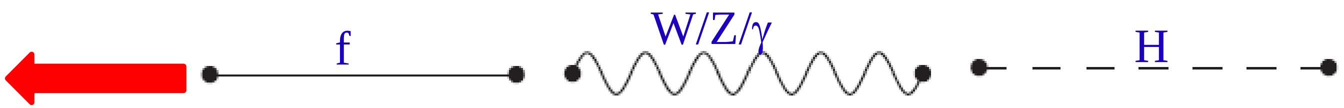

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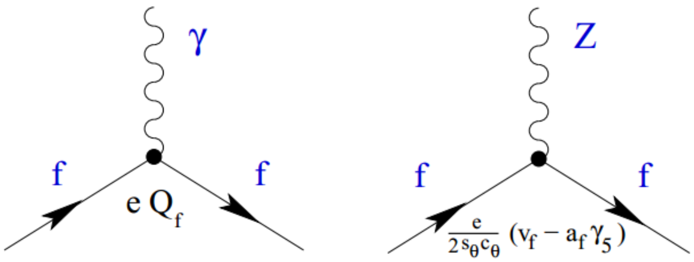

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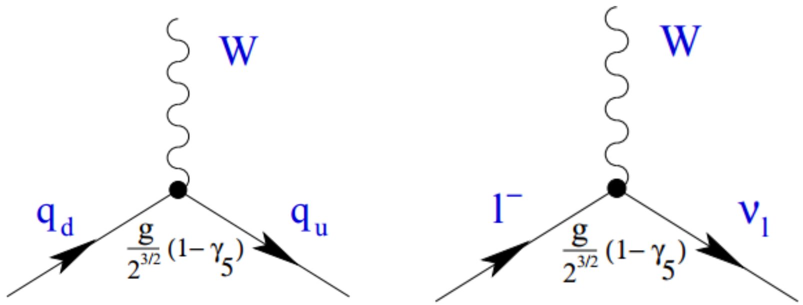

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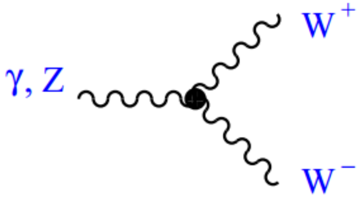

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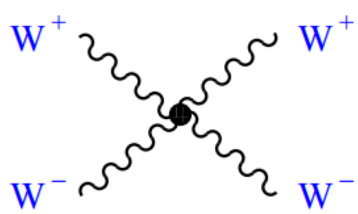

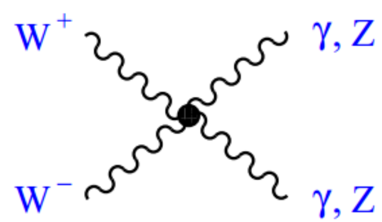

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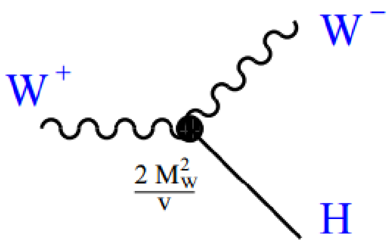

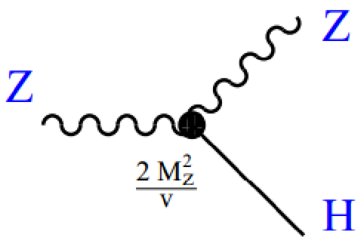

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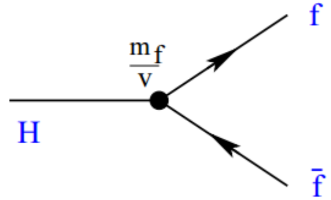

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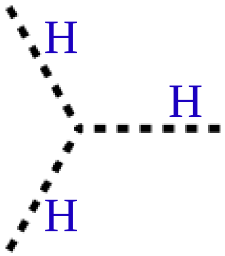

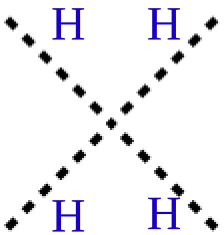

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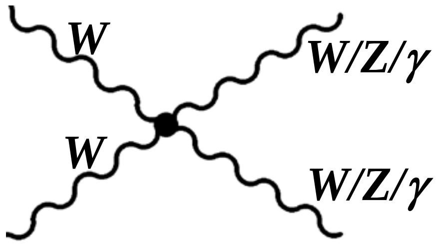
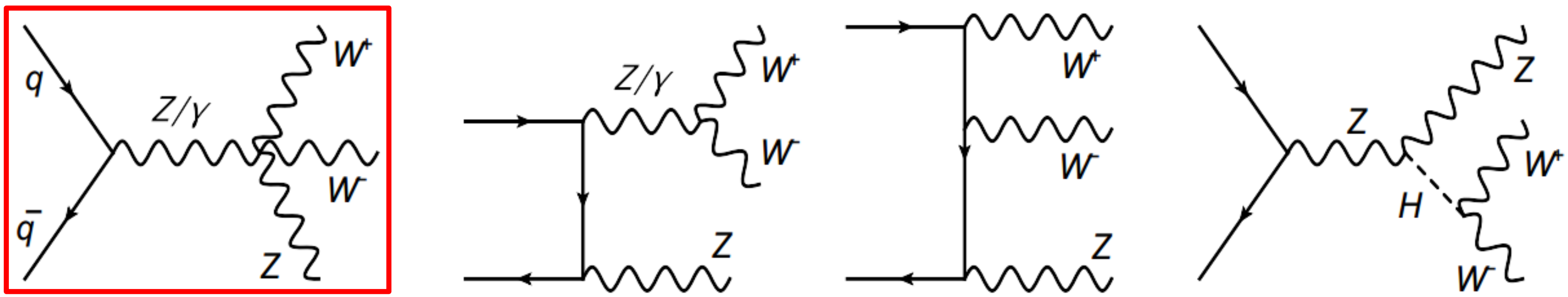
- $\mathcal{L}_K$: Well known mass terms
- $\mathcal{L}_N$, $\mathcal{L}_C$, $\mathcal{L}_{WWV}$: Precise measurements from LEP, SLD, Tevatron and LHC experiments
- $\mathcal{L}_{WWVV}$: Related to today's topics
- $\mathcal{L}_{HVV}$, $\mathcal{L}_Y$: Recently observations at the LHC, H→WW, H→ZZ*, H→ττ (H→tt), H→bb from the Tevatron
- $\mathcal{L}_{HHH/H}$: Not yet seen, waiting for sLHC or ILC



Four QGC couplings: WWWW, WWγγ, WWZγ, WWZZ

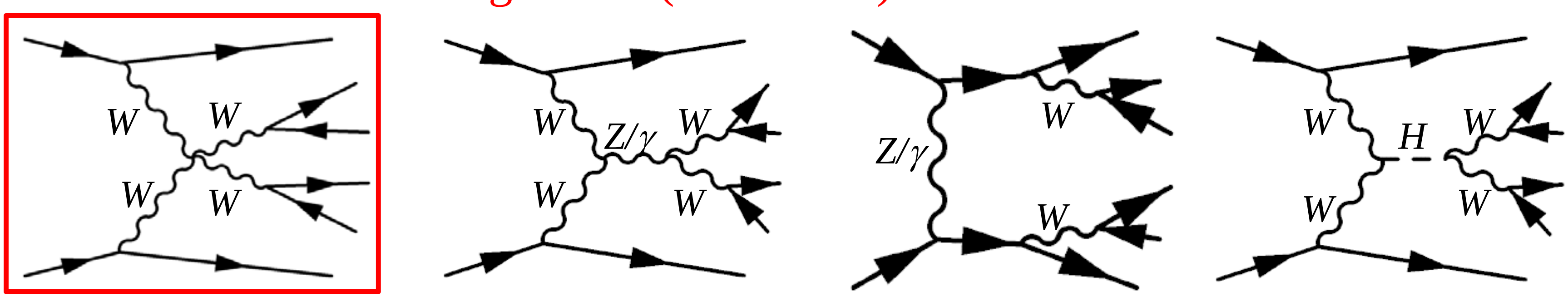
Processes with Quartic Gauge Couplings

- QGC process: process where a QGC vertex contributes
  - No reaction is ever mediated by a QGC vertex alone
  - Even a gauge-invariant definition of the QGC-alone contribution is not possible!
- Two classes of QGC processes are measurable:
  - Triboson production (WWZ as one example)



QGC **TGC** **Fermion-mediated** **Higgs-mediated**

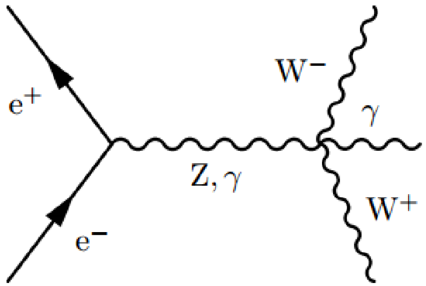
  - Vector boson scattering/fusion (VBS/VBF)



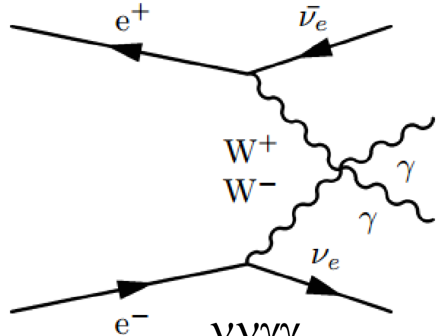
QGC **TGC** **Fermion-mediated** **Higgs-mediated**

QGC Studies at the LEP

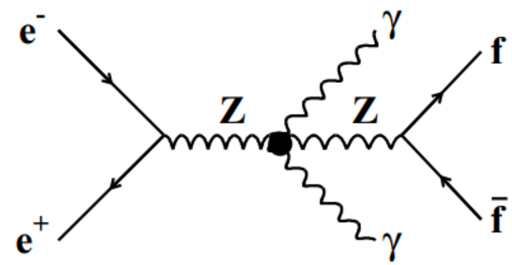
- Searches for WWγγ and WWZγ processes with $e^+e^- \rightarrow \nu\nu\gamma\gamma$, WWγ, or qqγγ



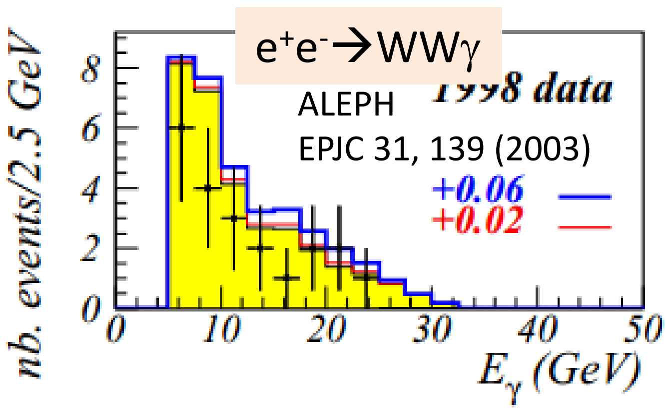
qqeνγ, qqμνγ, qqqqγ

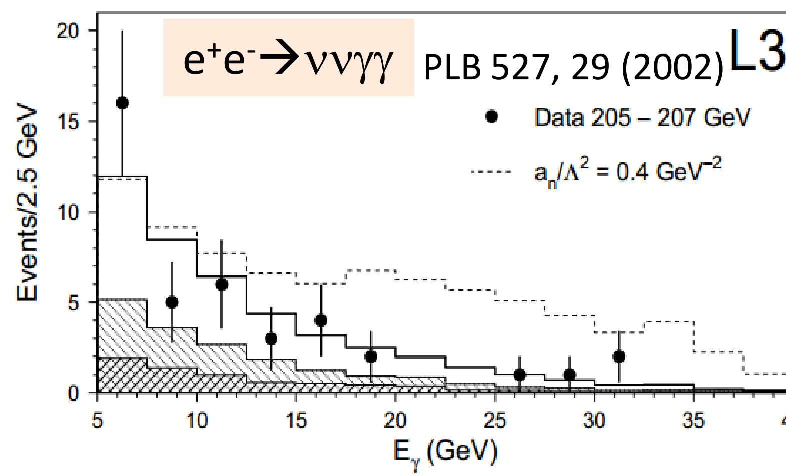


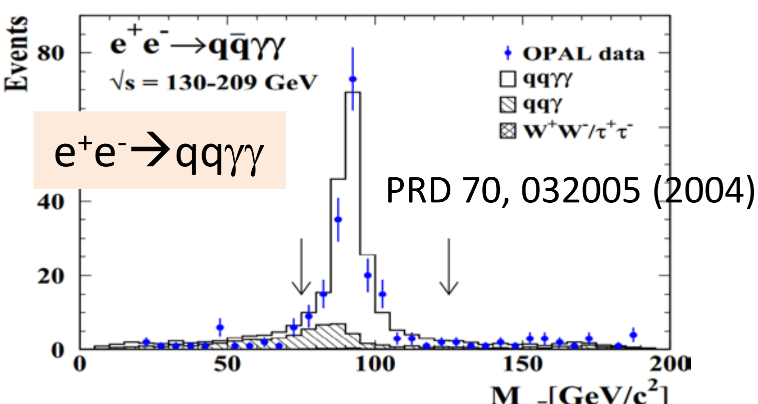
ννγγ



qqγγ



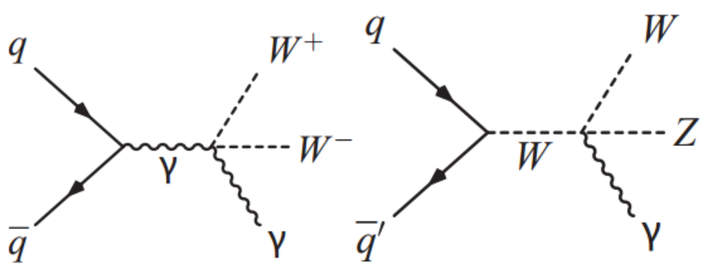




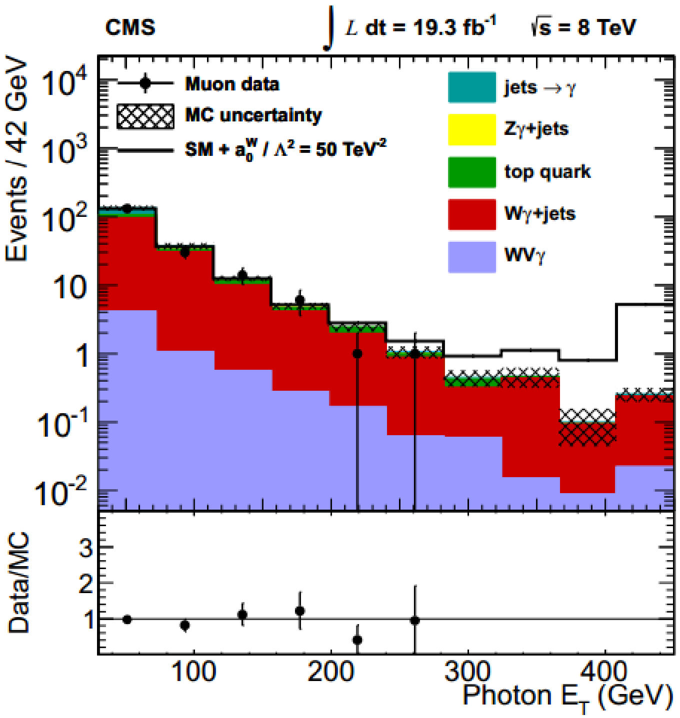
Data are found to be consistent with SM background predictions with ISR/FSR

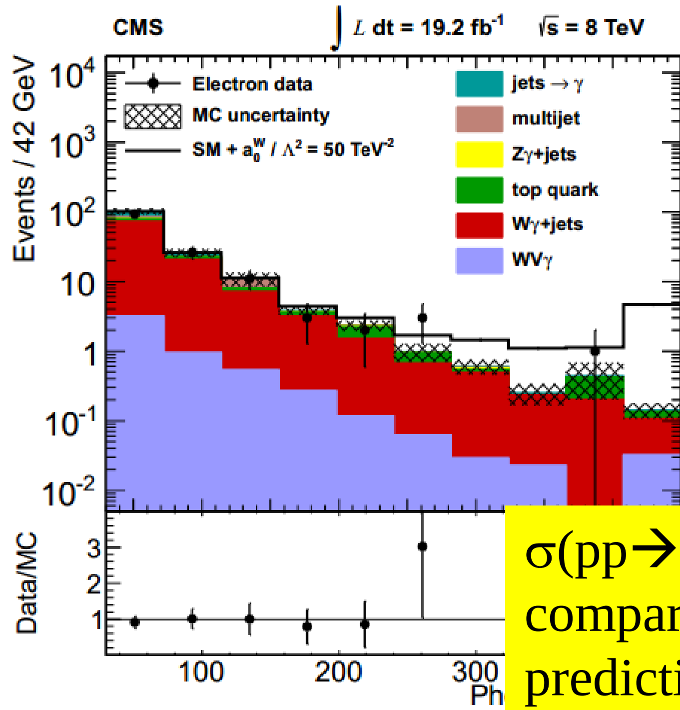
QGC Studies at the LHC

- CMS: pp → W(→ℓν)V(→jj)γ



Process	Muon channel number of events	Electron channel number of events
SM WWγ	6.6 ± 1.5	5.0 ± 1.1
SM WZγ	0.6 ± 0.1	0.5 ± 0.1
Wγ + jets	136.9 ± 10.5	101.6 ± 8.5
WV + jet, jet → γ	33.1 ± 4.8	21.3 ± 3.3
MC tt̄γ	12.5 ± 3.0	9.1 ± 2.2
MC single top quark	2.8 ± 0.8	1.7 ± 0.6
MC Zγ + jets	1.7 ± 0.1	1.5 ± 0.1
Multijets	—	7.2 ± 5.1
Total prediction	194.2 ± 11.5	147.9 ± 10.7
Data	183	139



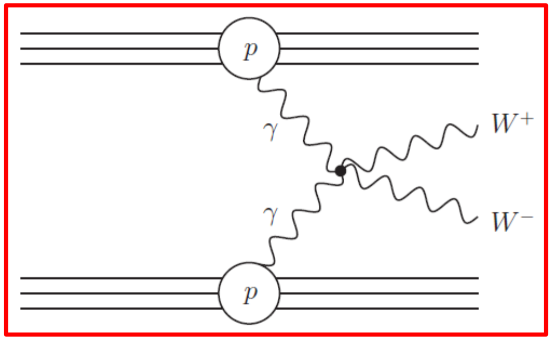


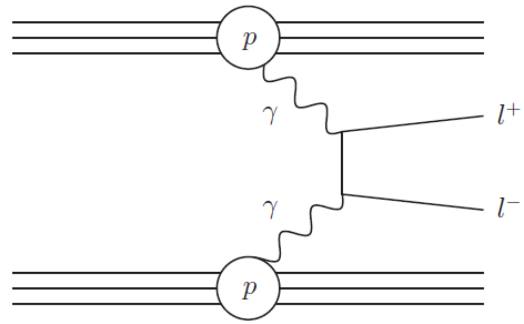
arXiv:1404.4619

σ(pp→WVγ)<311 fb compared to the SM prediction of 91.6 ± 21.7 fb

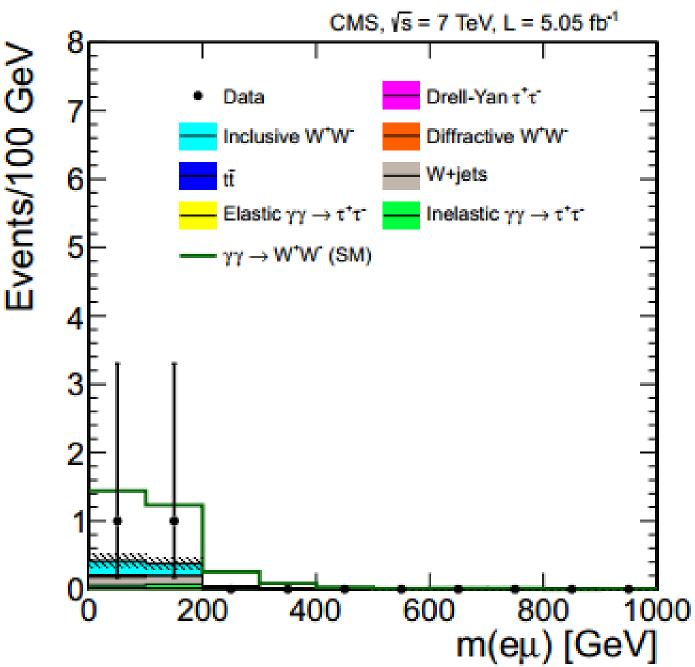
QGC Studies at the LHC

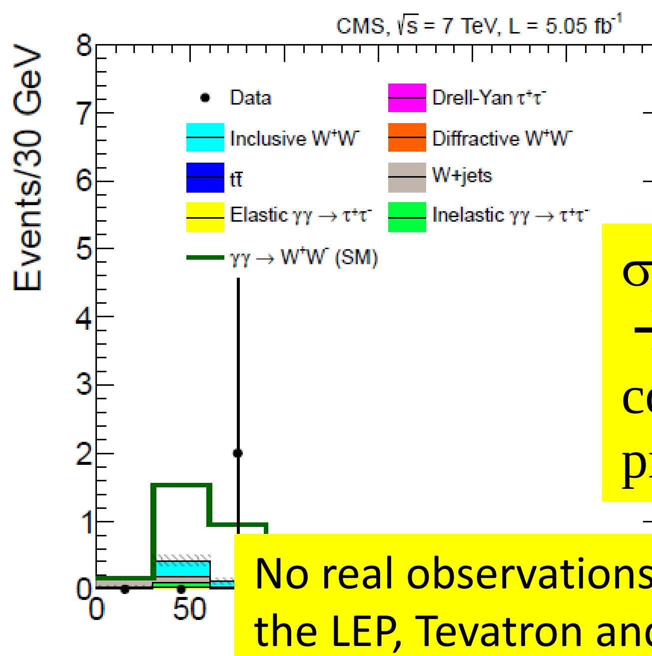
- CMS: $pp \rightarrow p^{(*)}WWp^{(*)} \rightarrow p^{(*)}e\nu\mu\nu p^{(*)}$





- High-p_T dilepton ($e\mu$) and two forward scattered protons not detected, no other tracks associated with the PV, large $p_T(e\mu)$ and $m(e\mu)$





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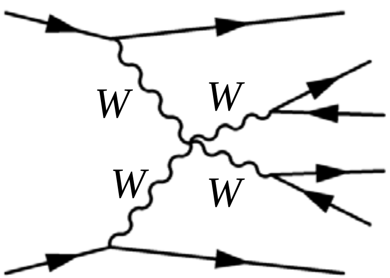
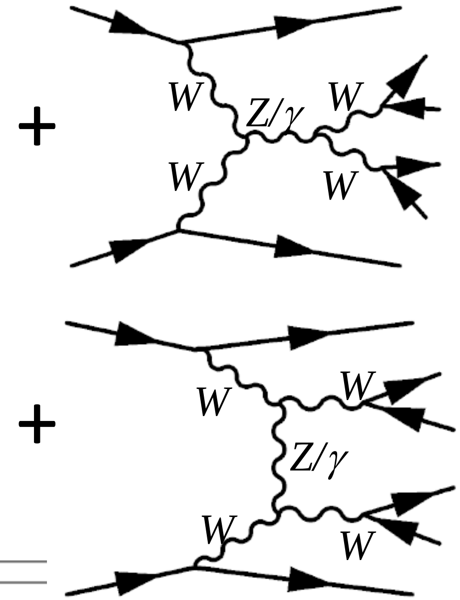
$\sigma(pp \rightarrow p^{(*)}WWp^{(*)} \rightarrow p^{(*)}e\nu\mu\nu p^{(*)}) < 10.6$ fb compared to the SM prediction of 4.0 ± 0.7 fb

No real observations of any QGC processes at the LEP, Tevatron and LHC so far

Vector Boson Scattering (VV → VV)

W^+W^- scattering/fusion without a SM Higgs

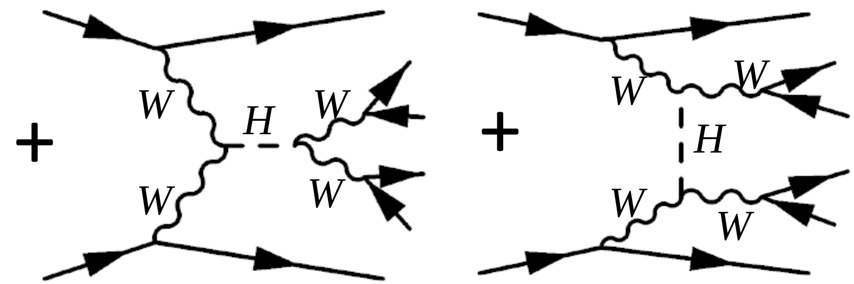




M ∝ s

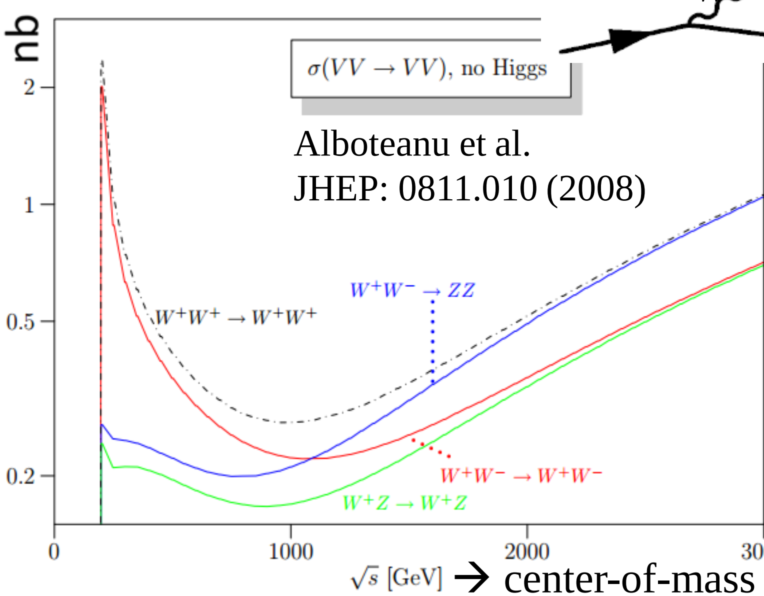
Unitarity violation

The unitarity can be restored by adding a Higgs scalar with exactly the SM HWW coupling

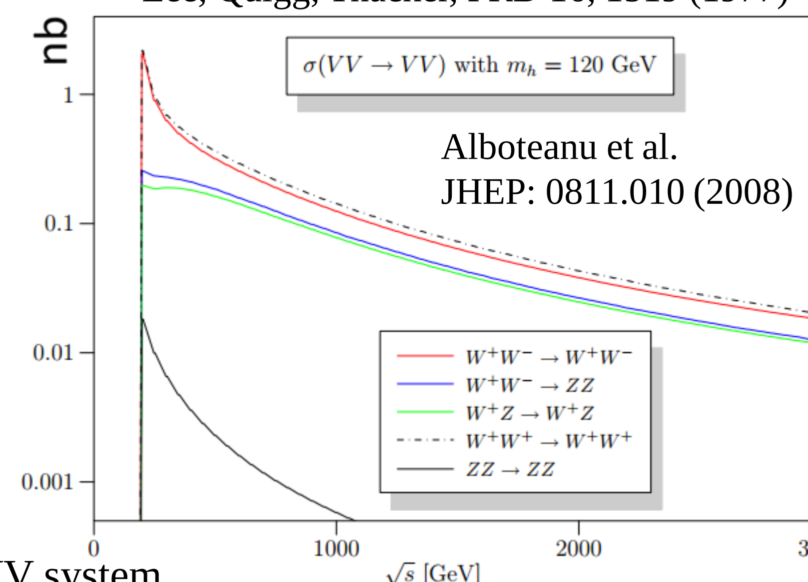


$$M \propto M_H^2\left(\frac{s}{s-M_H^2}+\frac{t}{t-M_H^2}\right)$$

Lee, Quigg, Thacker, PRD 16, 1519 (1977)



Alboteanu et al.
JHEP: 0811.010 (2008)

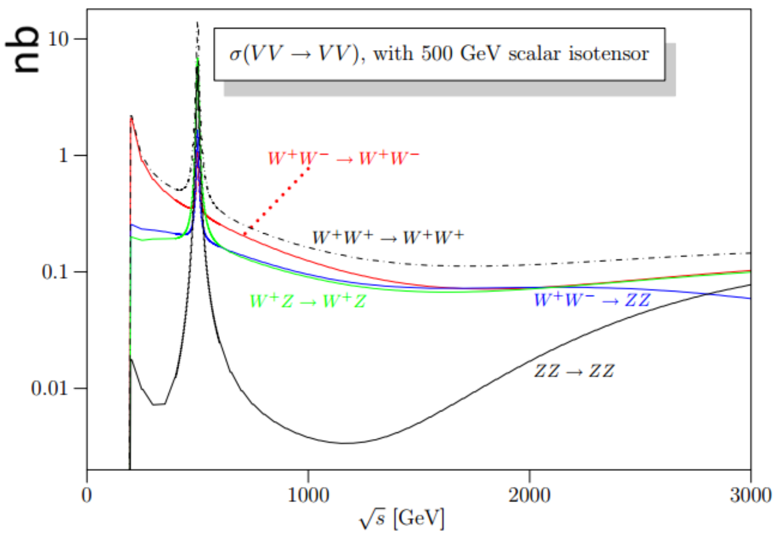


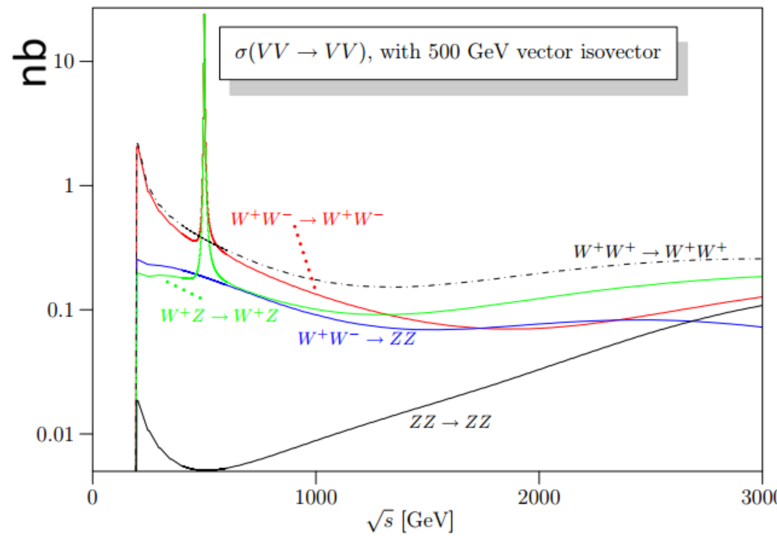
Alboteanu et al.
JHEP: 0811.010 (2008)

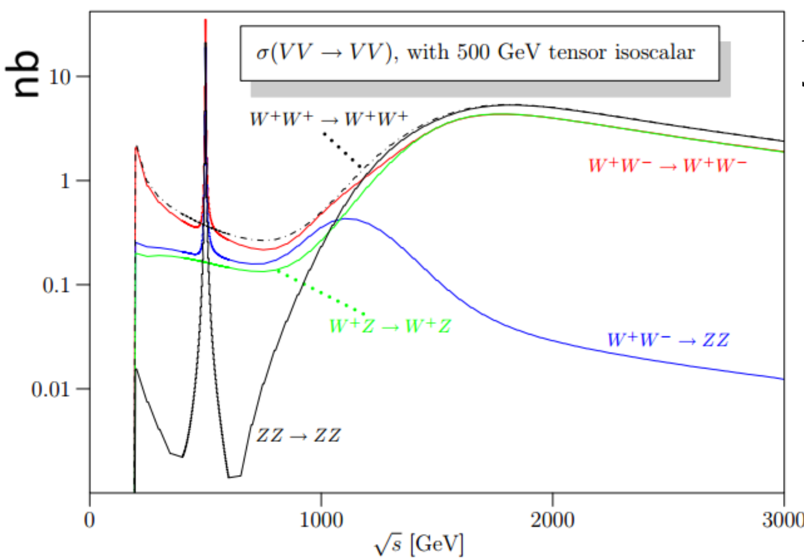
√s [GeV] → center-of-mass energy for VV system

High Mass Resonances

- The Higgs boson is the most economic solution to restore the unitarity, but it is not the only choice (new physics, or new physics + Higgs)



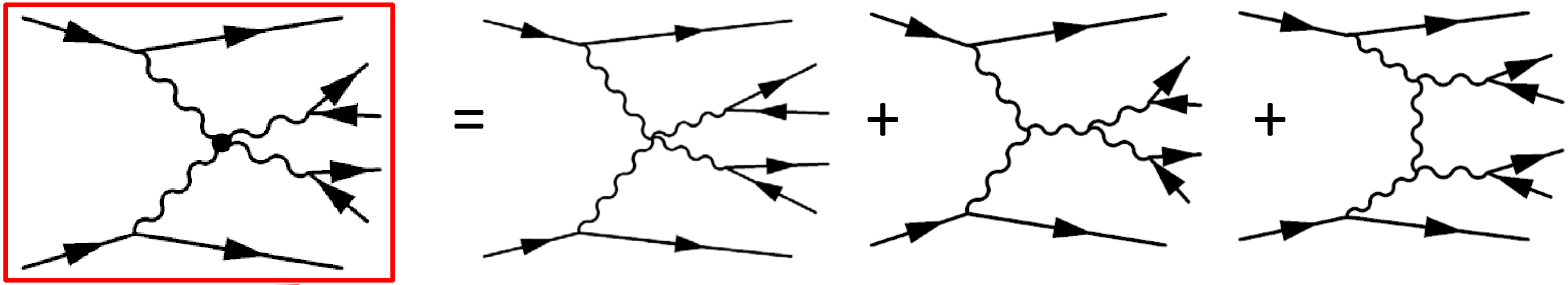


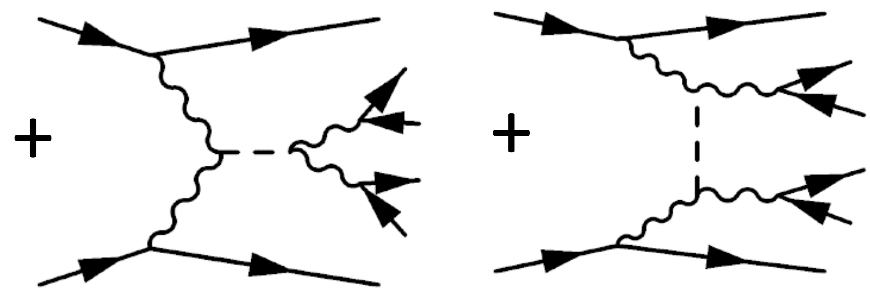


Alboteanu et al.
JHEP: 0811.010 (2008)

- With the discovery of a SM-like Higgs boson, we need to know if this boson is fully or only partially responsible for the EWSB in the whole energy regime (SM vs non-SM Higgs)
- Observe or exclude strong VV scattering
- Measure HVV couplings and determine the dynamics of EWSB

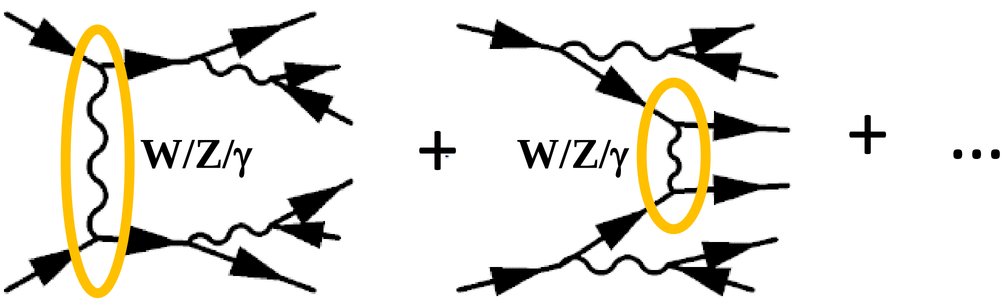
Electroweak Production (EW VVjj)





VBS processes

No QCD vertices involved



Non-VBS processes
Not gauge invariantly separable from VBS

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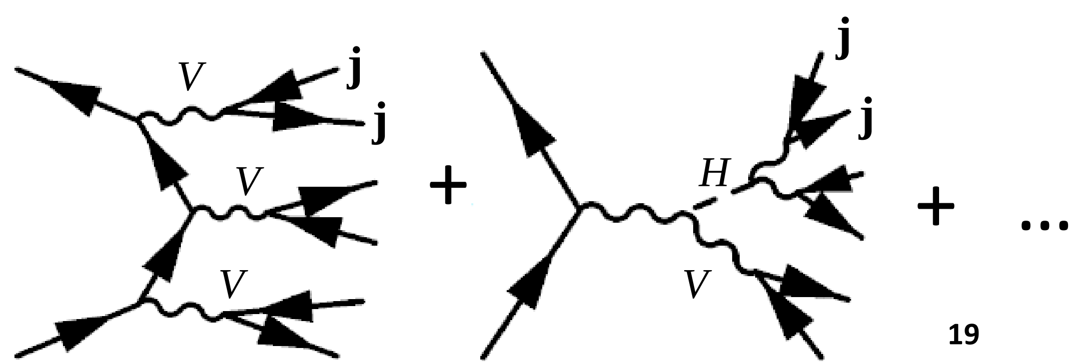
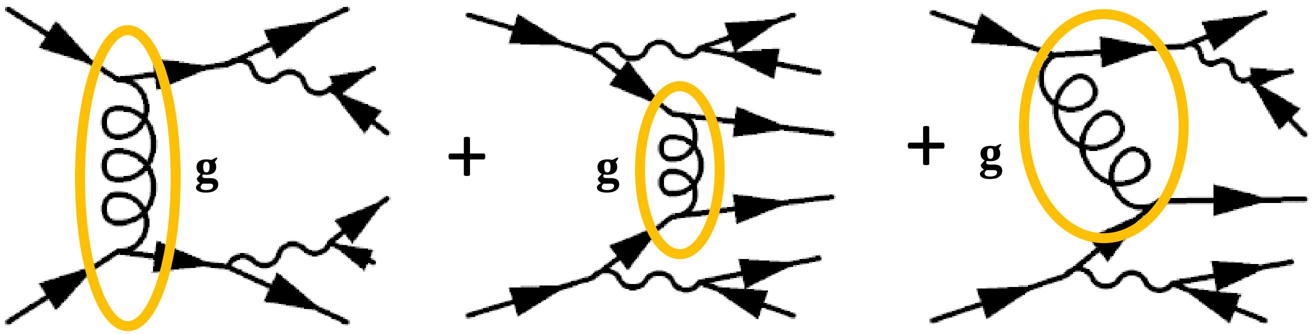
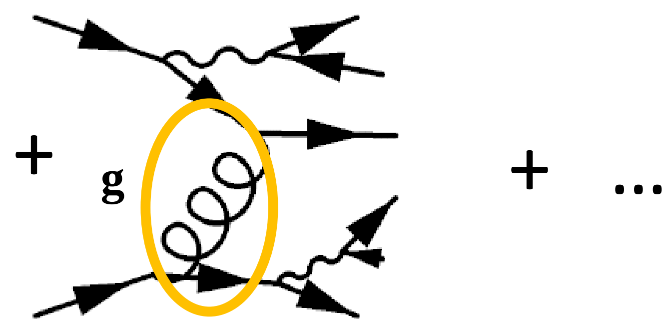
Gauge invariantly separable from VBS



Strong Production (QCD/strong VVjj)



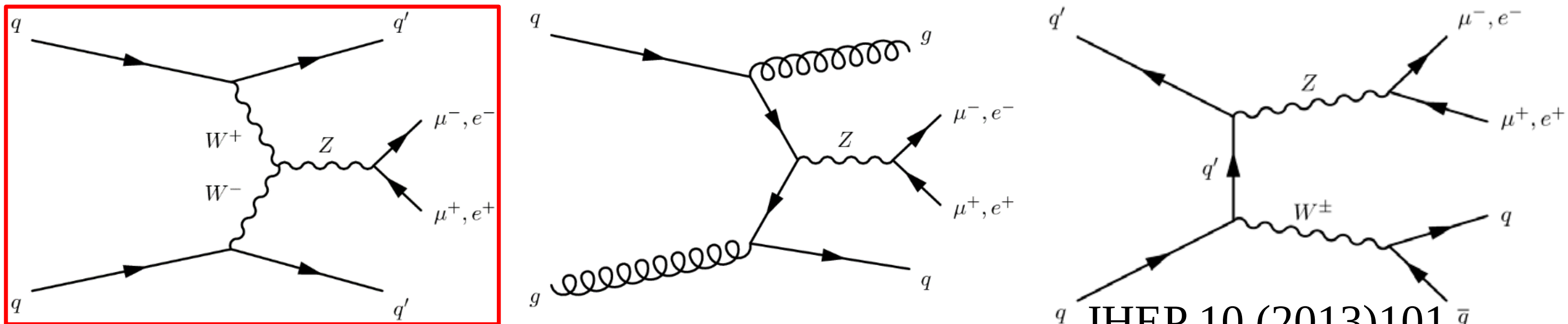
QCD vertices involved



VBS processes are interesting processes to study
Investigate different selection criteria (forward jets, large m_{jj}, Δy_{jj}, central-jet veto etc) to reduce the contributions from strong production and non-VBS production

VBS Studies at the LHC

- CMS: EW production of Zjj final state
- Tight cuts on $p_T(j_1)$, $p_T(j_2)$, m_{jj}, $\Delta\eta_{jj}$ to increase the signal-to-background ratio



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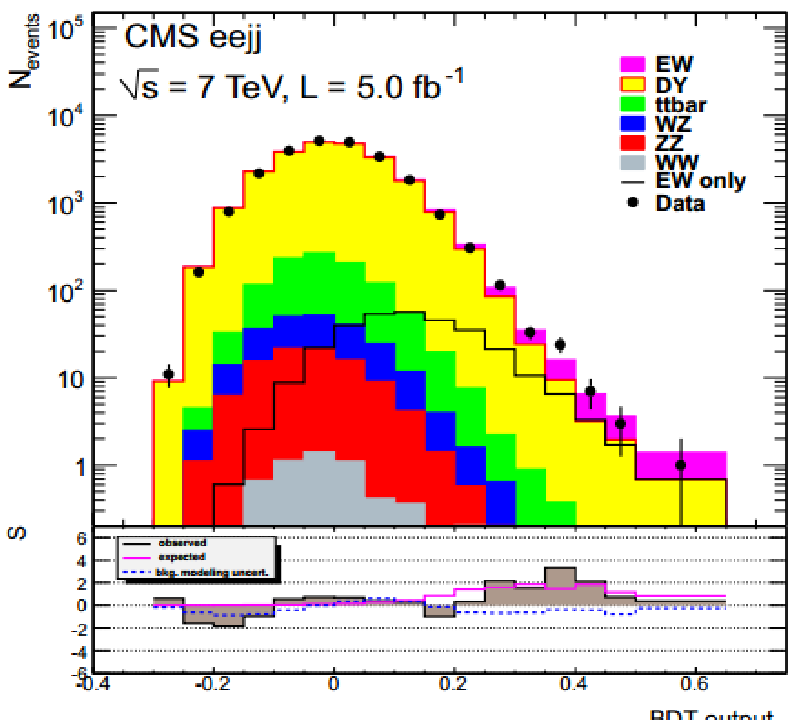
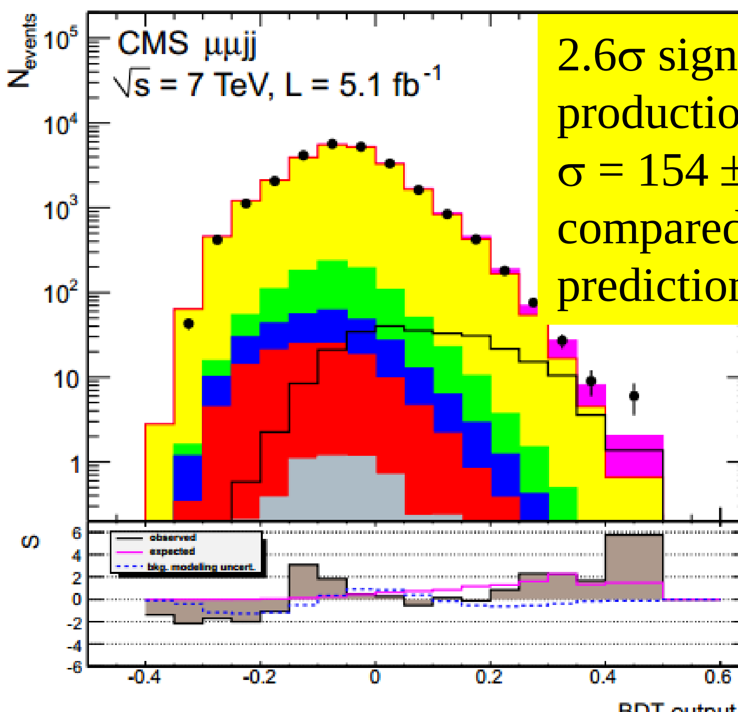
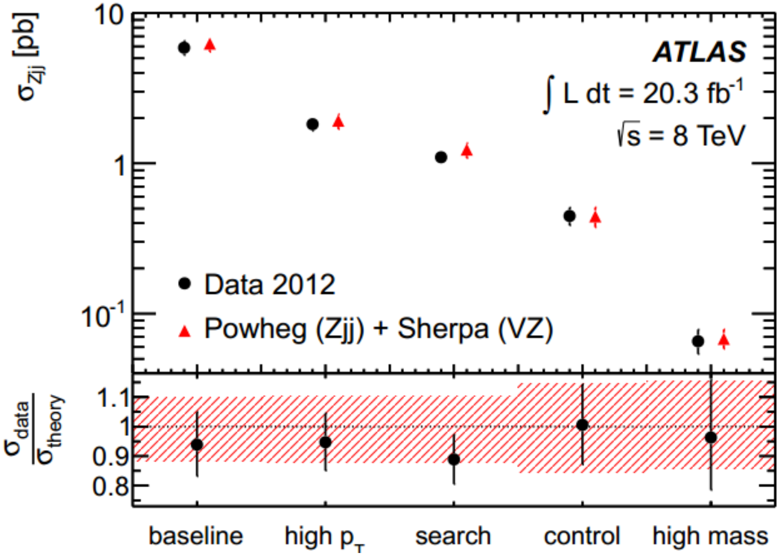




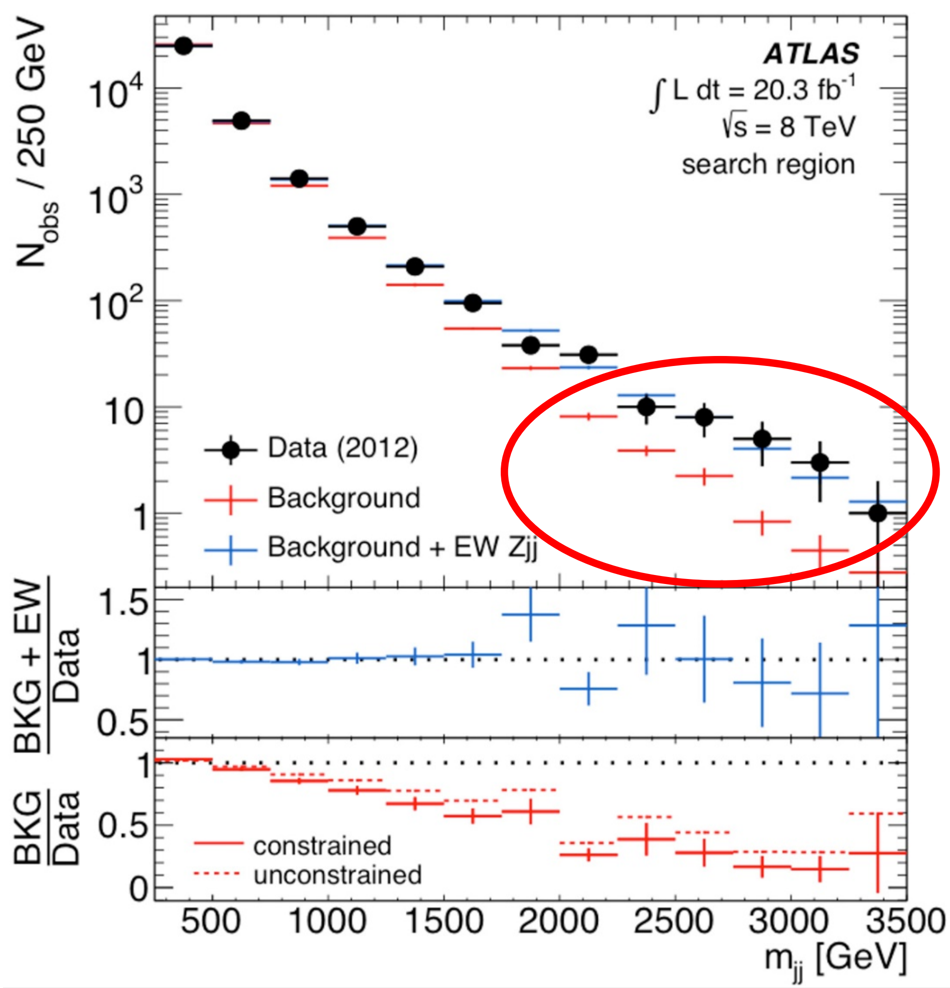
2.6σ significance for EW production of Zjj
σ = 154 ± 24 ± 53 fb compared to the SM prediction of 166 fb

VBS Studies at the LHC

- ATLAS performed similar studies for EW production of Zjj final state



JHEP 04 (2014)031

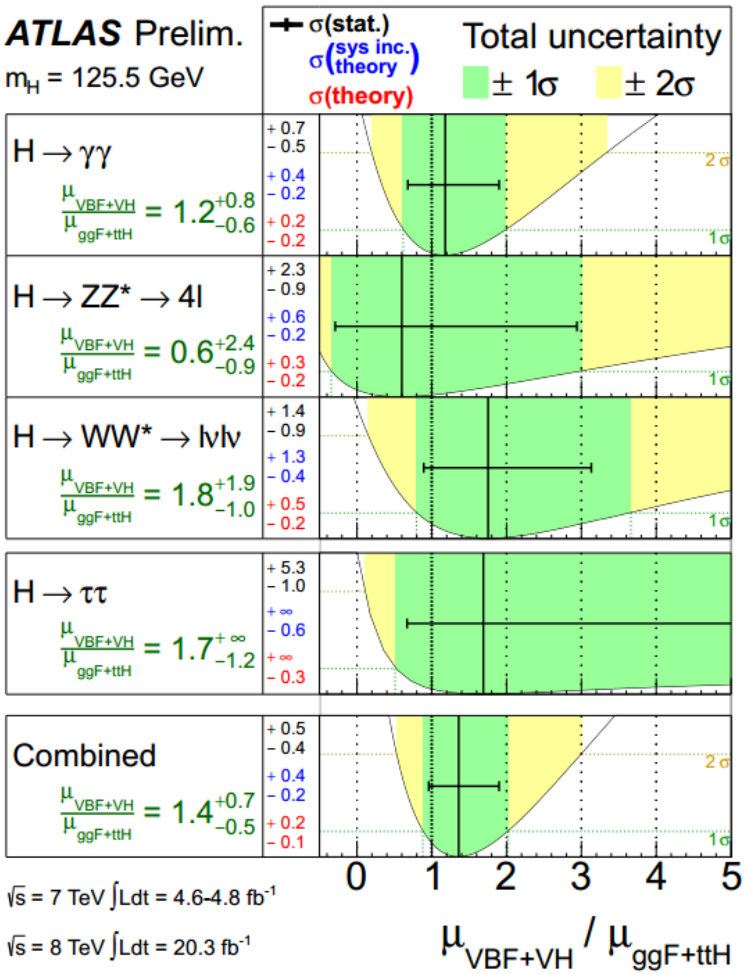


5σ significance for EW production of Zjj
$\sigma_{fid} = 54.7 \pm 4.6 \pm 10.5$ fb
compared to the SM prediction of 46.1 fb

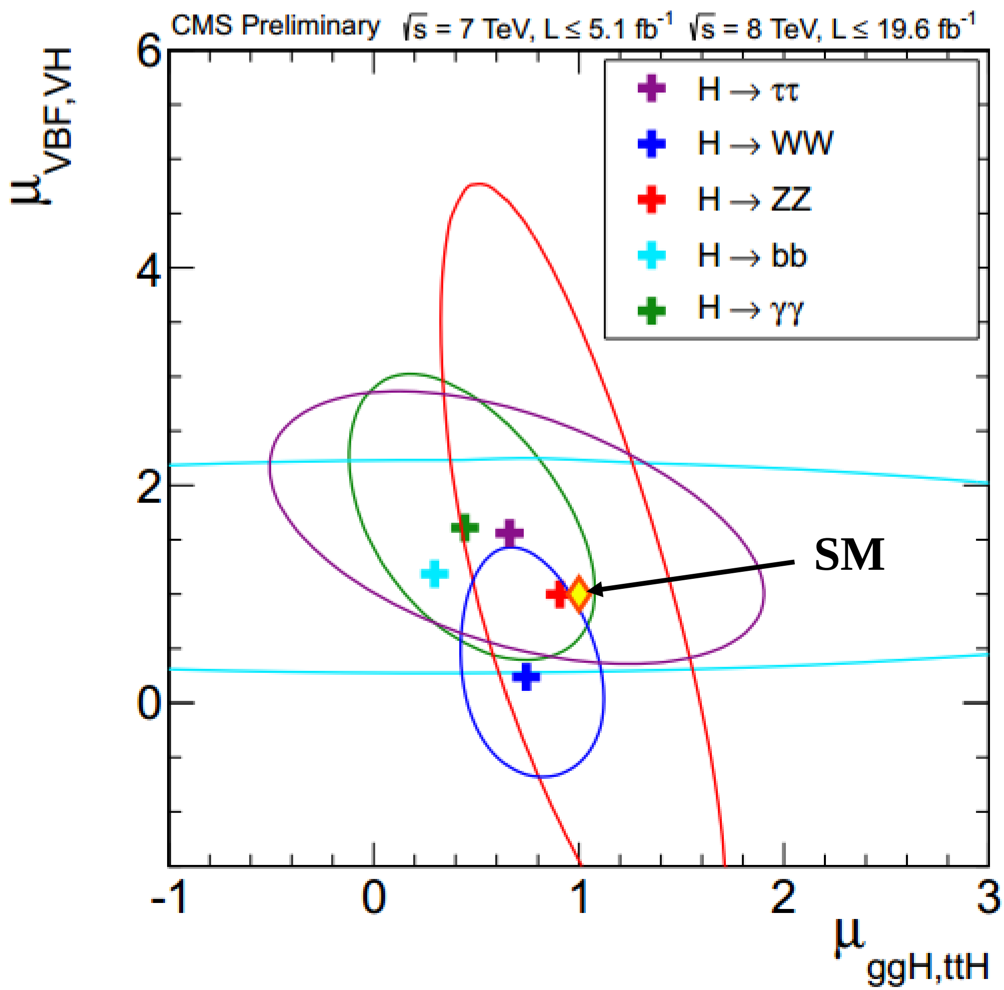
VBS Studies at the LHC

- Both ATLAS and CMS have searched for H→γγ, ZZ*, WW*, ττ, bb production in VBF modes
- No 3σ evidence observed in each individual channel yet

ATLAS-CONF-2014-009



CMS-PAS-HIG-13-005



Vector Boson Scattering

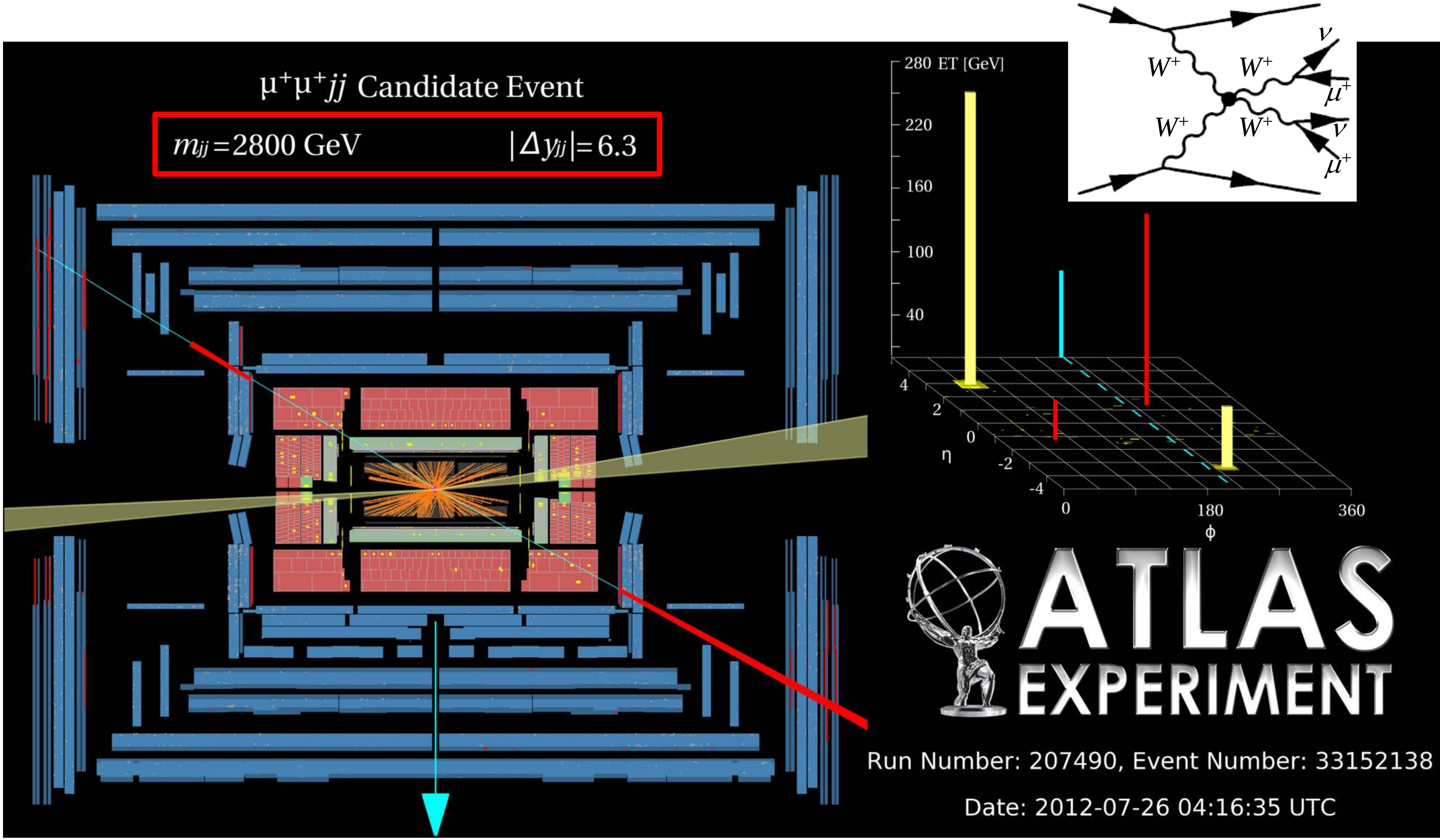
- No evidences for QGC processes (no studies with VV→VV, V=W,Z) so far
- Only observed the Zjj VBS process with WW→Z (TGC) at the LHC
- Not an easy task to observe VBS process with QGCs:
  - We do not have W/Z beams
  - Large reducible and irreducible SM backgrounds
  - Often could not fully reconstruct the final states W and/or Z bosons
  - Hard to do with photons due to ISR and FSR

Final state	Process	VVjj-EW	VVjj-QCD	Ratio
$\ell^{\pm}\nu\ell'^{\pm}\nu' jj$ (same sign, arbitrary flavor)	$W^{\pm}W^{\pm}$	19.5 fb	18.8 fb	1.04
$\ell^{\pm}\nu\ell'^{\mp}\nu' jj$ (opposite sign)	$W^{\pm}W^{\mp}$	91.3 fb	3030 fb	0.03
$\ell^{+}\ell^{-}\nu'\nu' jj$	ZZ	2.4 fb	162 fb	0.015
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\nu' jj$	$W^{\pm}Z$	30.2 fb	687 fb	0.04
$\ell^{\pm}\ell^{\mp}\ell'^{\pm}\ell'^{\mp} jj$	ZZ	1.5 fb	106 fb	0.014

Sherpa prediction (8 TeV) with two leptons $p_T > 5$ GeV, $M_{ll} > 4$ GeV and at least two jets with $p_T > 10$ GeV

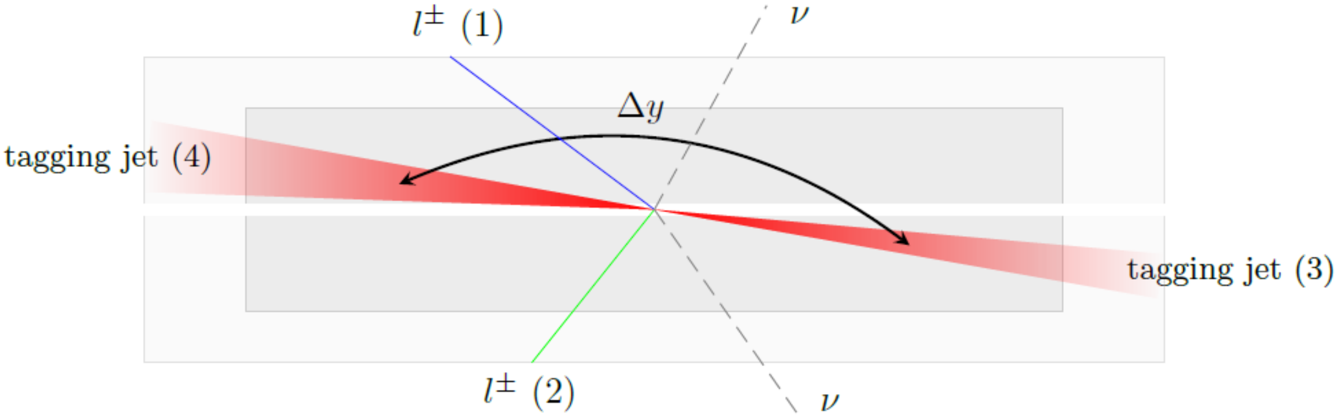
Two same-sign leptons in the final state will also greatly reduce other SM backgrounds (even though only t-channel Higgs exchange is allowed for same-sign WW VBS)

ss WW VBS Event Display



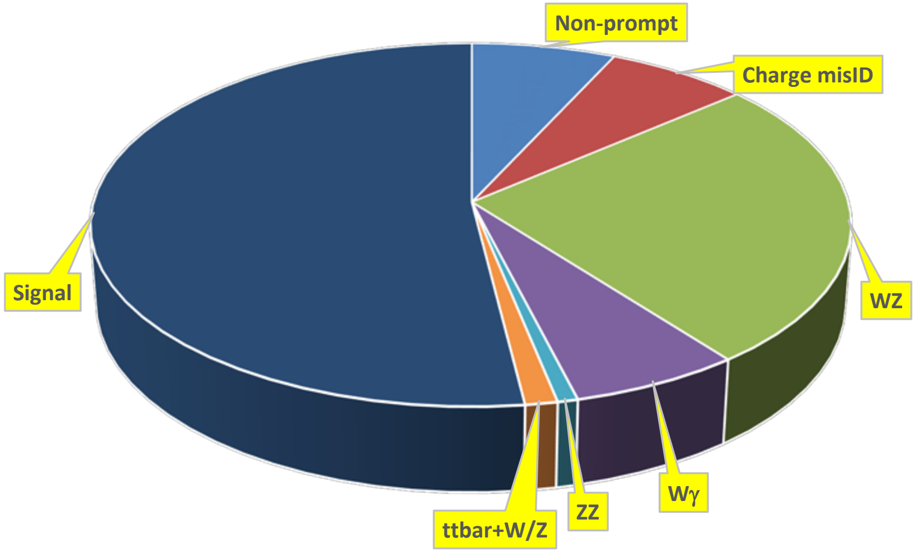
Event Selection

- Exactly two SS isolated leptons with p_T>25 GeV and $|\eta|$<2.5
- MET > 40 GeV
- At least two jets with p_T>30 GeV and $|\eta|$<4.5
- WZ veto: veto a third lepton with lower p_T and looser quality requirements
- Z veto: $|m_{ee} - m_Z| > 10$ GeV to suppress the Z→ee contribution with the charge of one electron misidentified
- ttbar veto: no b-tagged jets in each event
- $m_{jj} > 500$ GeV (inclusive region)
- $m_{jj} > 500$ GeV and $|\Delta y_{jj}| > 2.4$ (VBS region) → enhance the contribution from electroweak production

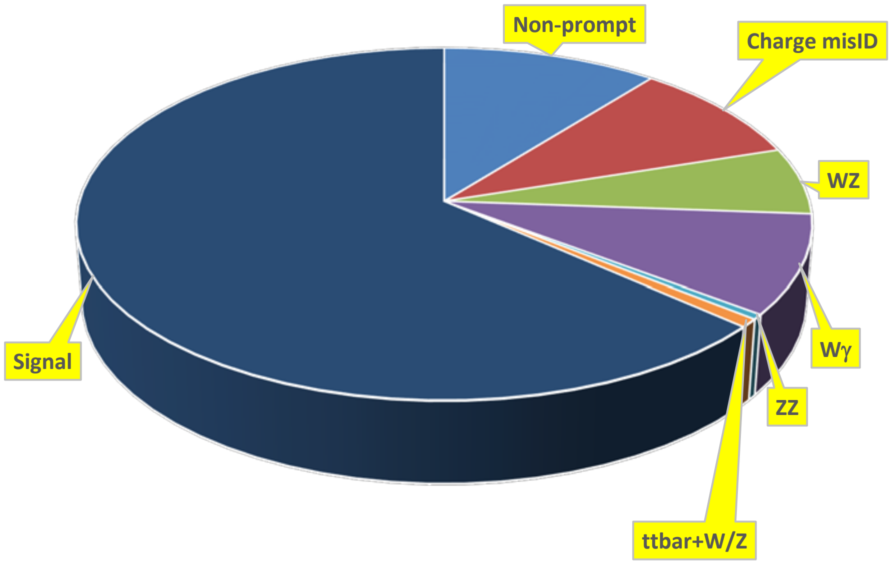


Backgrounds

- MC-based estimation:
  - WZ + jets (Sherpa)
  - Wγjj, tt+W/Z, ZZ (Alpgen+Sherpa/Madgraph/Sherpa)
  - Double parton scattering (negligible)
- Data-driven estimation:
  - Z + jets for ee and eμ channels (charge misID bkg)
  - Background with one or two jets reconstructed as isolated leptons (non-prompt bkg)



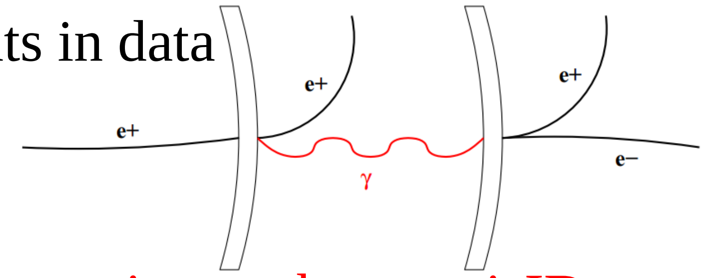
Inclusive region



VBS region

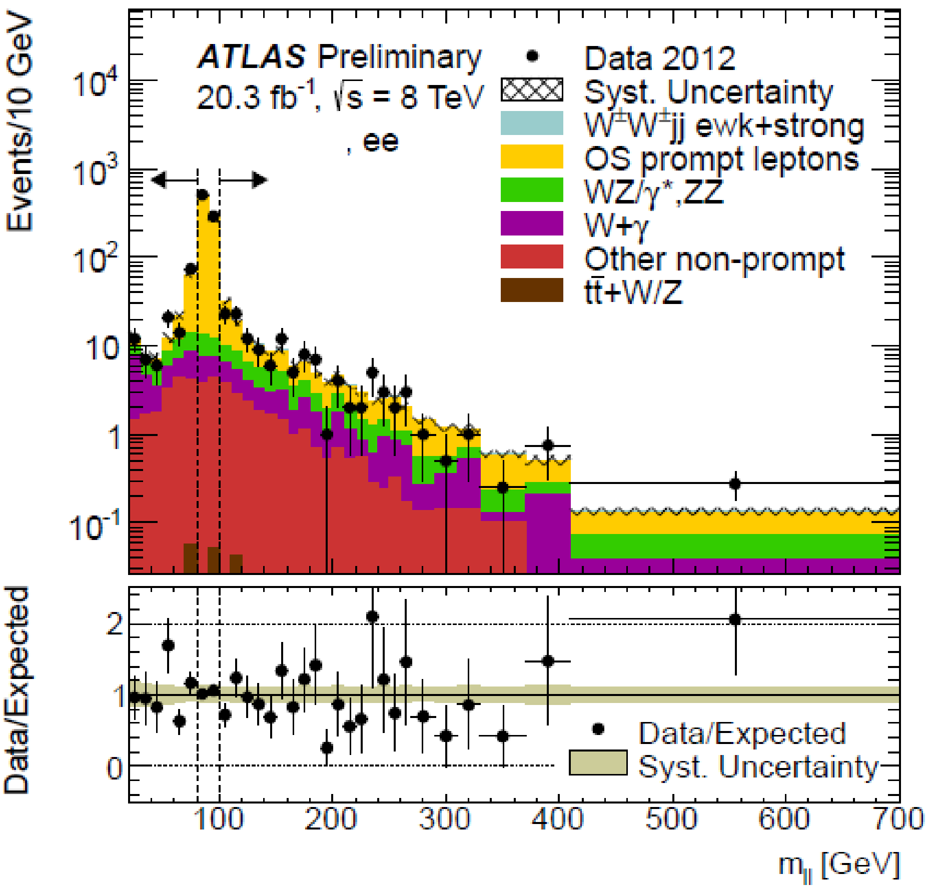
Charge misID Background

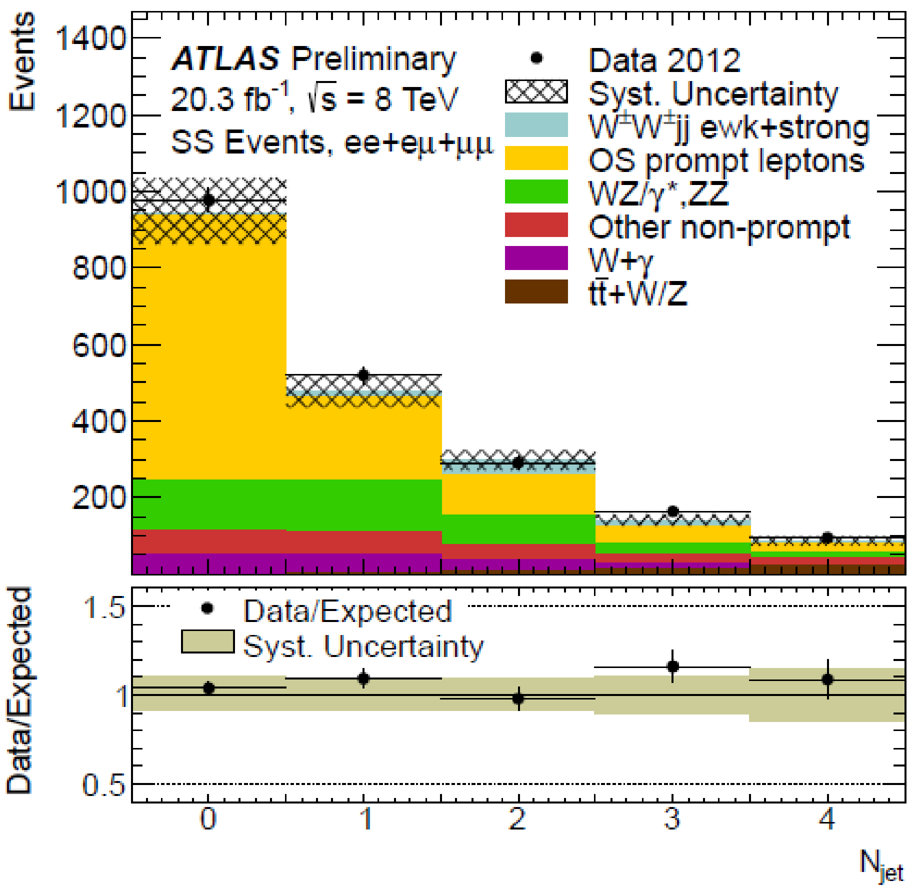
- Muon charge misID rate is negligible
- Charge misID rate measured using Z→ee events in data
- Likelihood and tag-and-probe methods used
- Excellent MC closure test for both methods
- OS events are scaled by the charge misID rate to estimate charge misID background in the SS signal region
- Electrons that suffer charge misID tend to have a lower reconstructed energy due to bremsstrahlung, average electron energy loss corrected based on MC studies
- Several CRs defined to check charge misID rate and bkg estimation method



Region name	Charge misID (OS-scaled)	Other backgrounds	Observed	Expected / Observed
SS Z	11419 ± 12 (stat.)	108 ± 16	11820	0.98 ± 0.01
Low N_{jet} CF	1924.5 ± 5.0 (stat.)	301 ± 56	2370	0.94 ± 0.03
VBF-like SS Z	313.4 ± 2.4	12.1 ± 1.8	348	0.94 ± 0.05
SS Incl.	1021.7 ± 3.7	261 ± 41	1318	0.97 ± 0.04
Top	21.5 ± 0.5	20.2 ± 4.6	46	0.91 ± 0.17 (0.5σ)

Charge misID Background

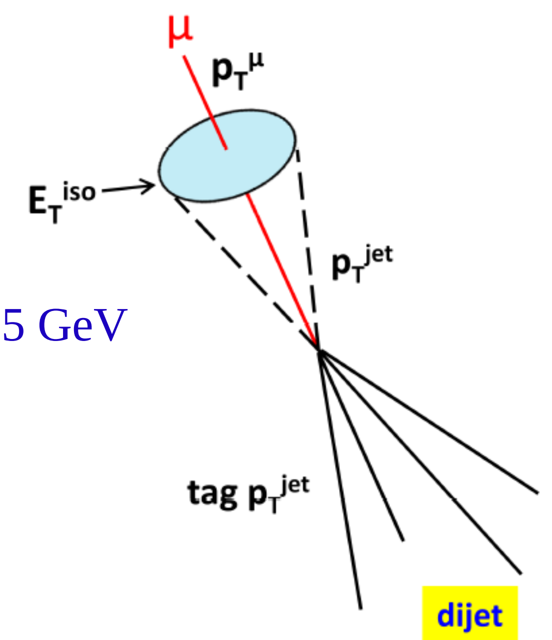


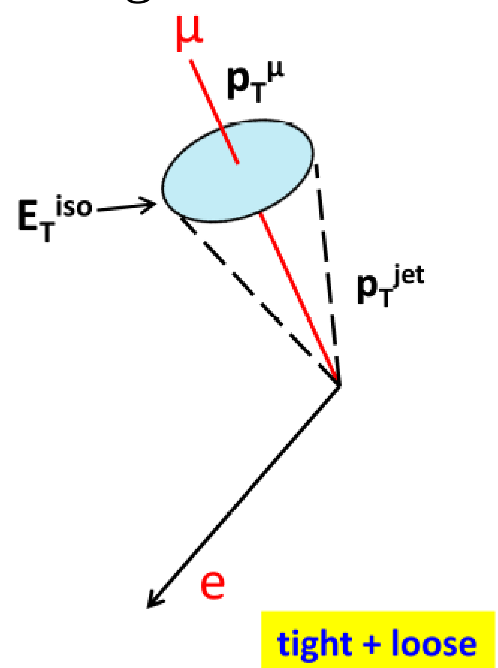


Non-prompt Background

- Fake factor method:
  - Measure a correction factor based on two definitions of leptons
    - Tight: normal lepton definition
    - Loose: failing isolation cuts and passing looser quality criteria
  - $f = N_{tight} / N_{loose}$ determined from a dijet sample
  - Scale the tight+loose data sample by the fake factor to estimate the non-prompt background in the signal region

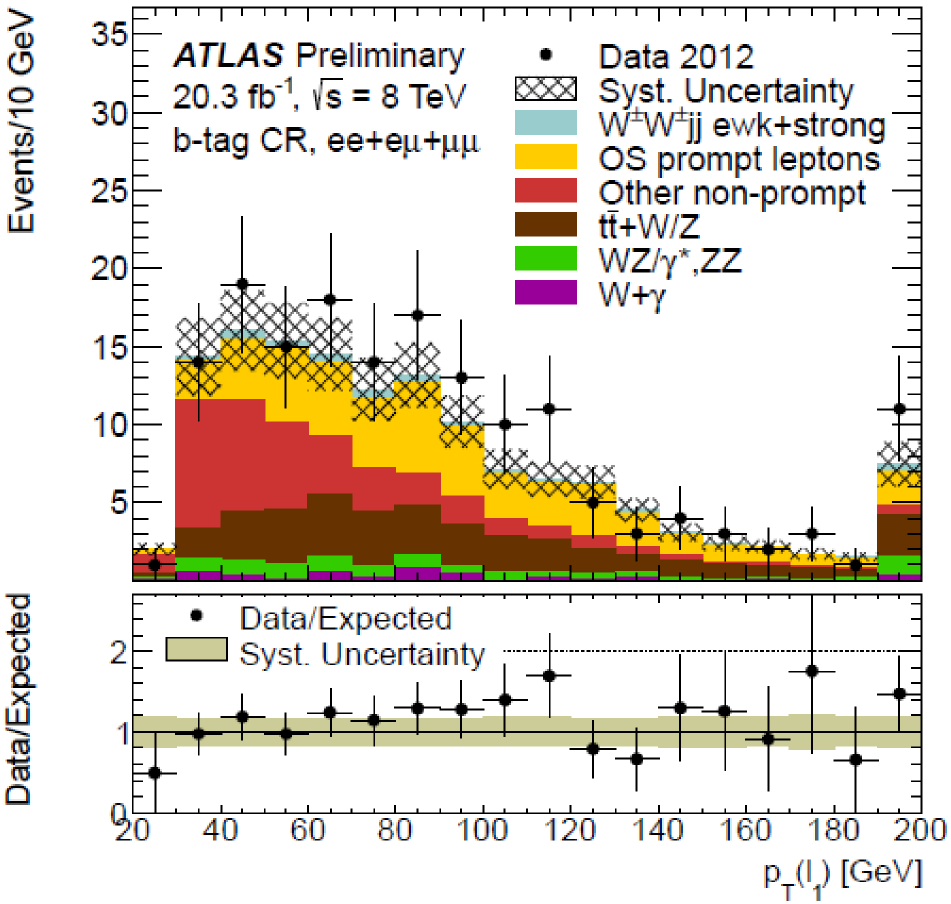
Lepton, jet $p_T > 25$ GeV
$\Delta\phi(l, j) > 2.8$
$M_T < 40$ GeV

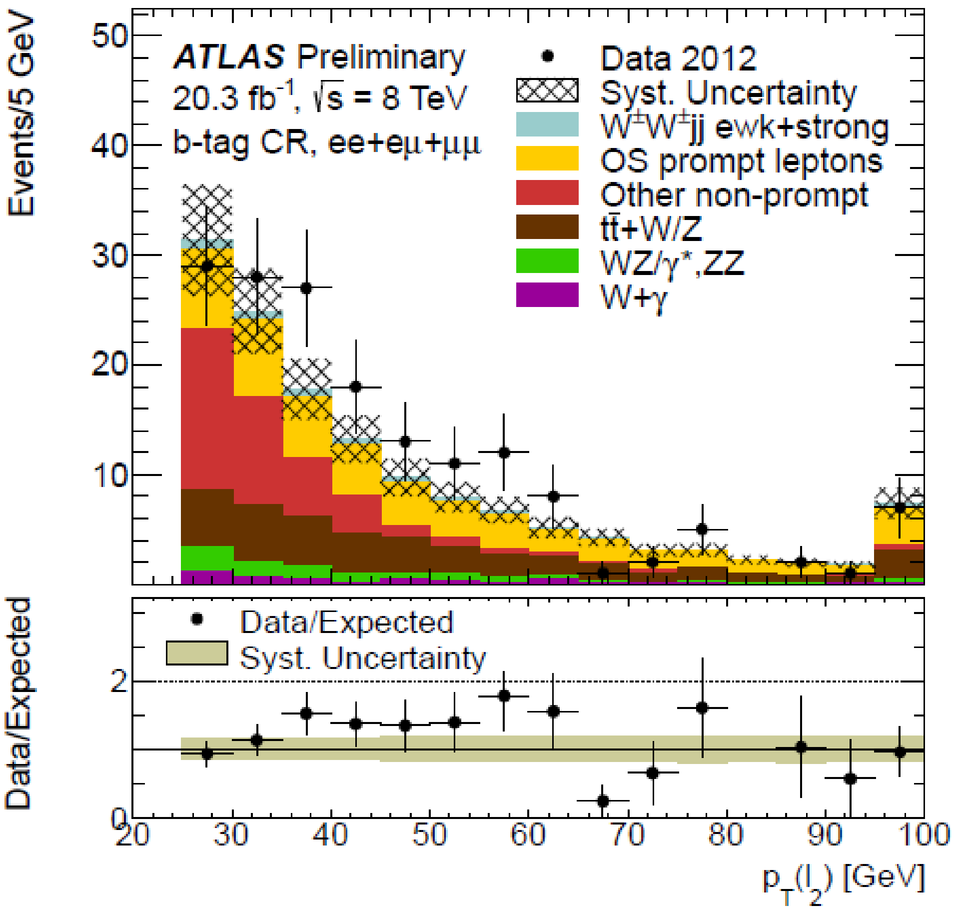




Non-prompt Background

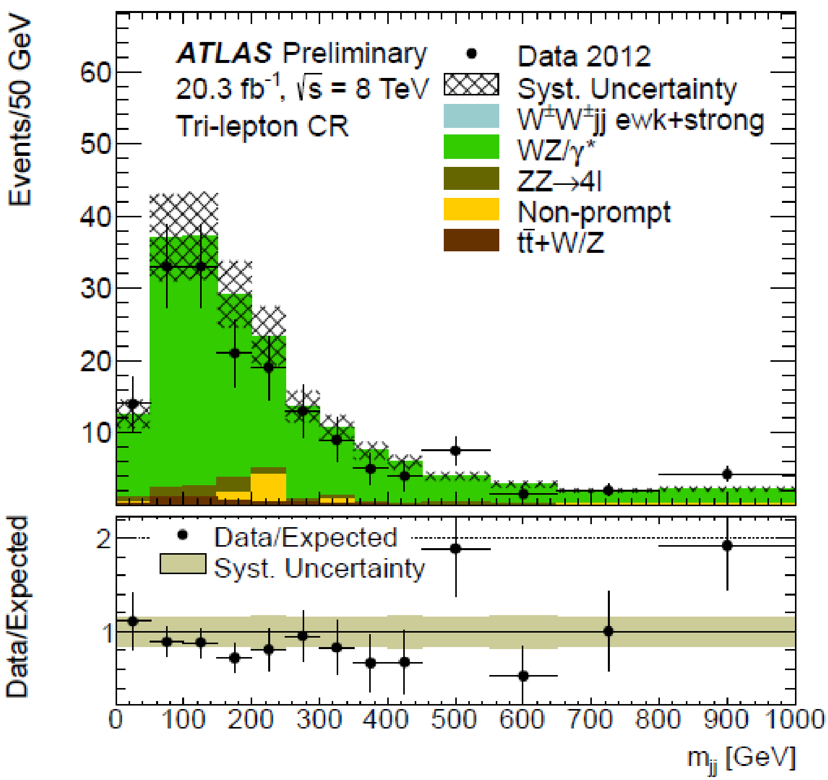
- Due to tight lepton definition used, not easy to find a region dominated by non-prompt background
- Use same-sign ttbar events with at least one tagged b-jet

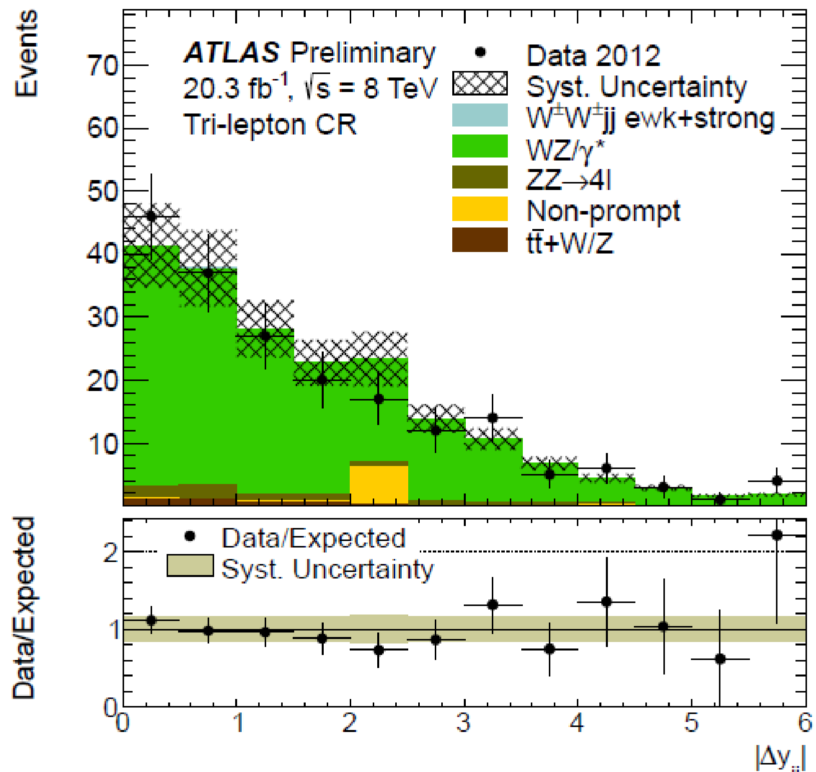




WZ+jets Background

- Dominant backgrounds for the two signal regions
- The generator-level Z/γ^* mass is required to be greater than 1 GeV(30% off-shell contribution to the total after the final selection)
- Normalized to QCD NLO calculation using VBFNLO
- Sherpa MC simulation checked using events with three leptons and m_{jj} and Δy_{jj} cuts removed





Signal Simulation

- Several MC event generators available to produce $W^{\pm}W^{\pm}jj$ events (Sherpa, VBFNLO, Powheg-box, WHIZARD etc)
- Sherpa sample normalized to Powheg-box predicted cross sections
- Inclusive and VBS fiducial regions defined at the generator level using similar cuts applied at the reconstruction level

Process	Inclusive SR	VBS SR	Dominant uncertainty sources
EW $W^{\pm}W^{\pm}jj$	1.00 ± 0.06 fb	0.88 ± 0.05 fb	Generator/PDF/parton shower/scale uncertainties
Strong $W^{\pm}W^{\pm}jj$	0.35 ± 0.05 fb	0.098 ± 0.018 fb	Scale dependence/Generator/parton shower MC statistics

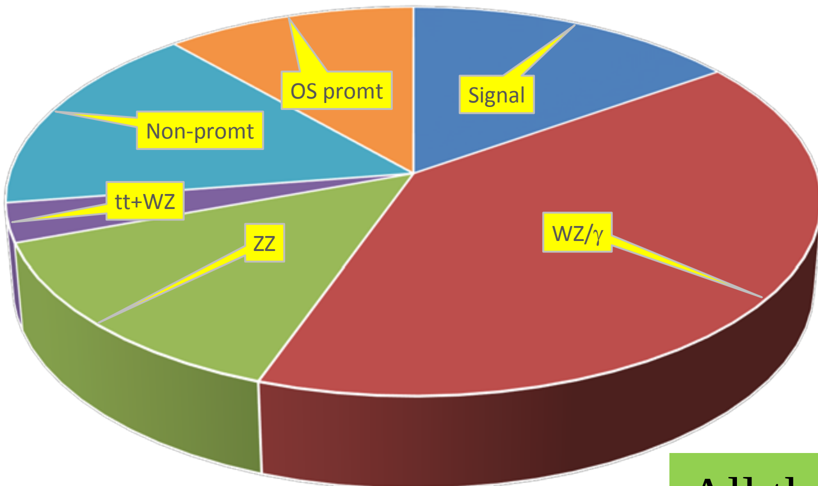
- Interference effects between EW and strong production studied using Sherpa, increase the inclusive SR cross section by (12±6)% and the VBS SR cross section by (7±4)%
- Inclusive: EW+strong+interference as the signal
- VBS: EW+interference as the signal

Control Regions

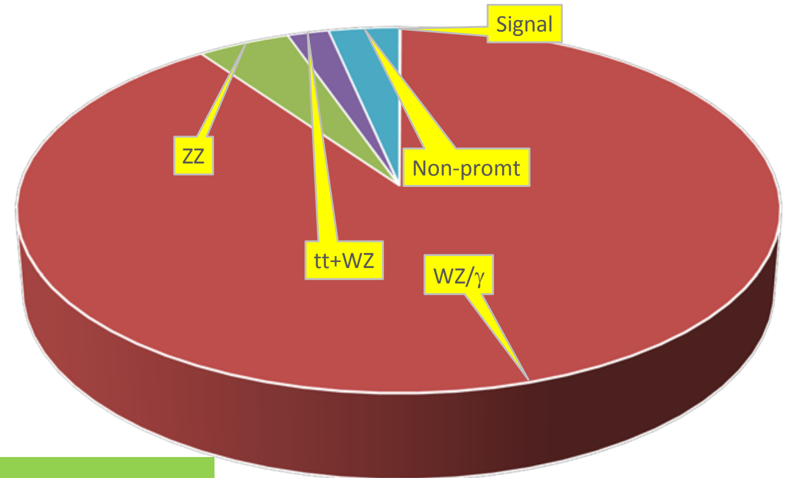
- Background modellings are checked in several background-dominated control regions with similar phase space as the two SRs
  - Low m_{jj} CR: $m_{jj} < 500$ GeV
  - Trilepton CR: events with three leptons, m_{jj} and Δy_{jj} cuts removed
  - b-tag CR: at least one b-tagged jet
  - ≤ 1 jet CR: events with ≤ 1 jet and Z-veto cut removed
- Check both event yields and shape distributions in these CRs

Background Compositions in CRs

Low m_{jj} CR

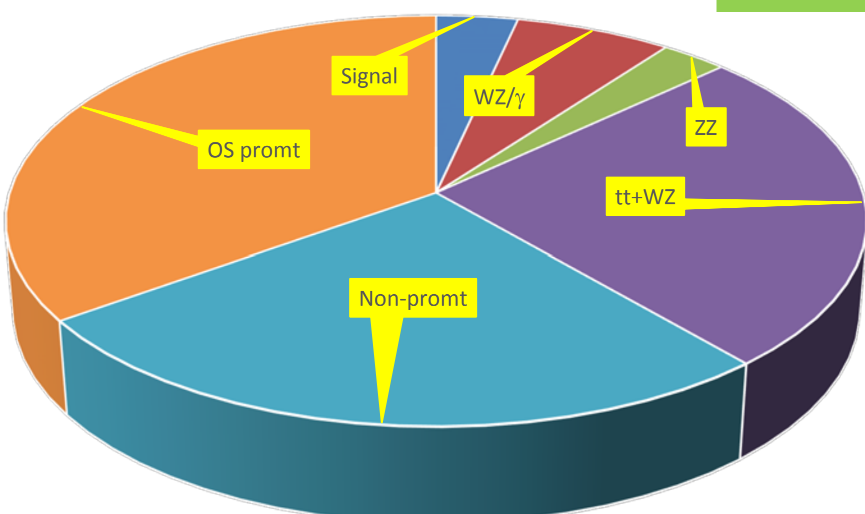


Trilepton CR

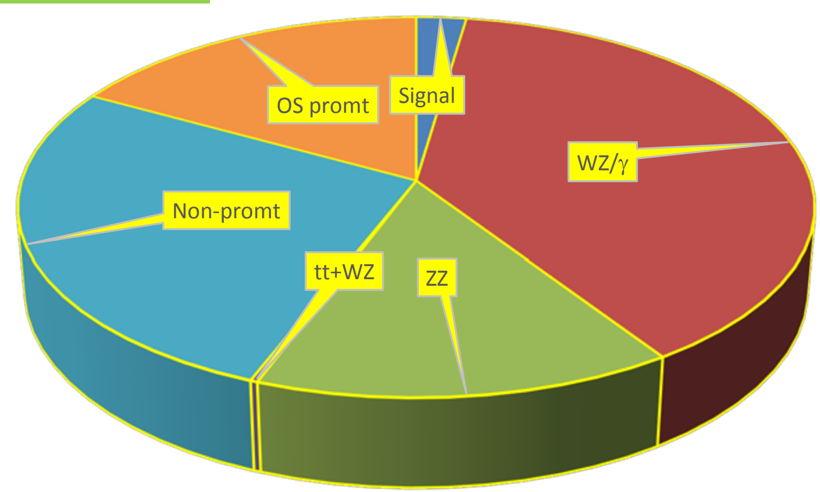


All three channels combined together

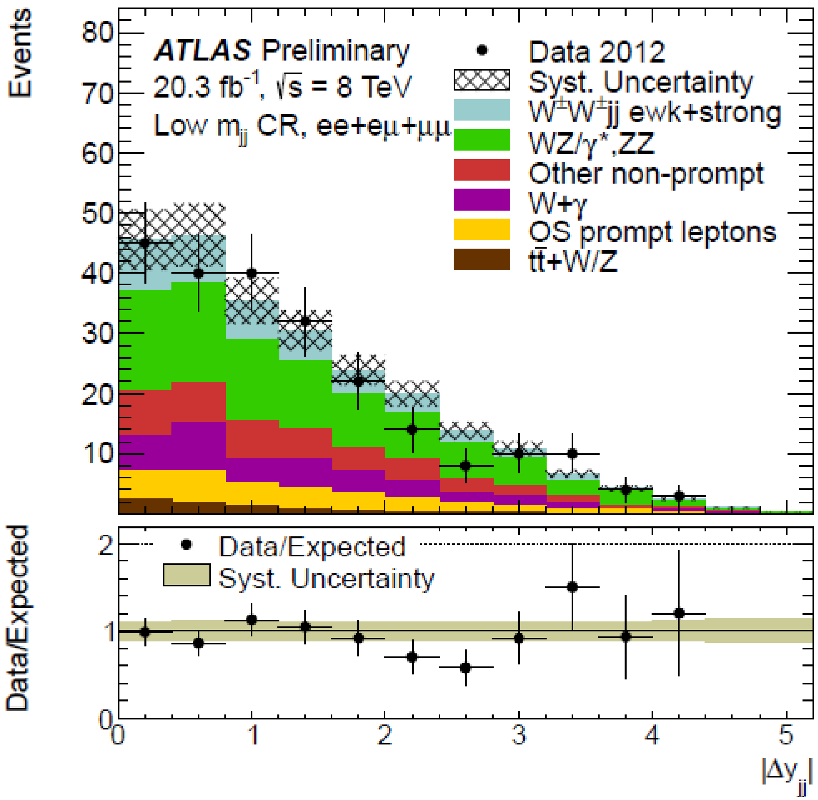
b-tag CR

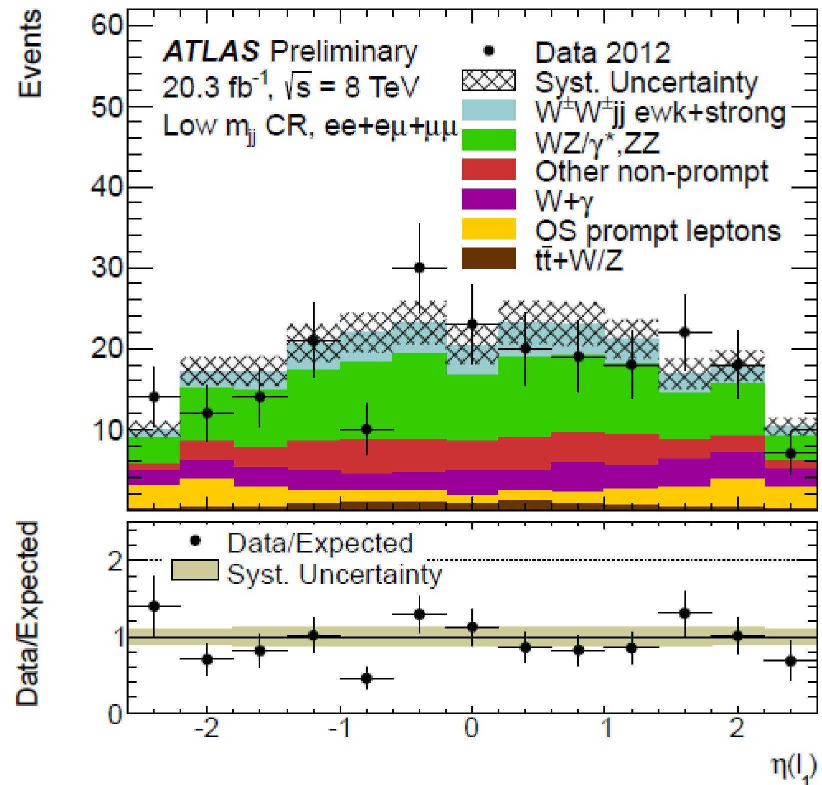


≤ 1 jet CR



Low m_{jj} Control Region

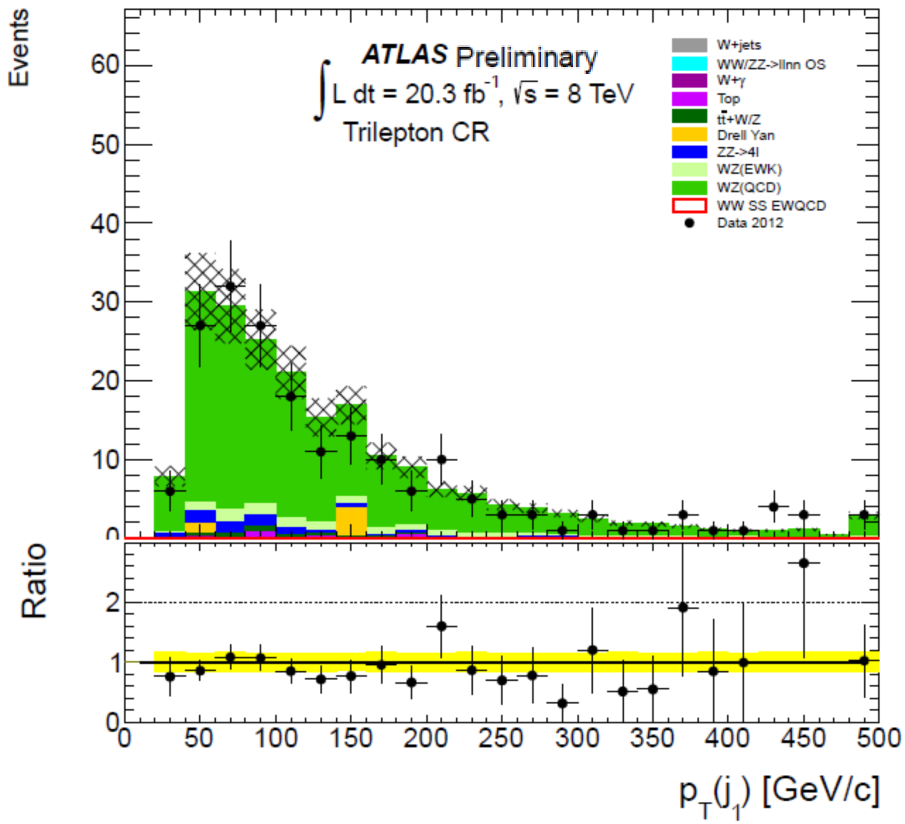


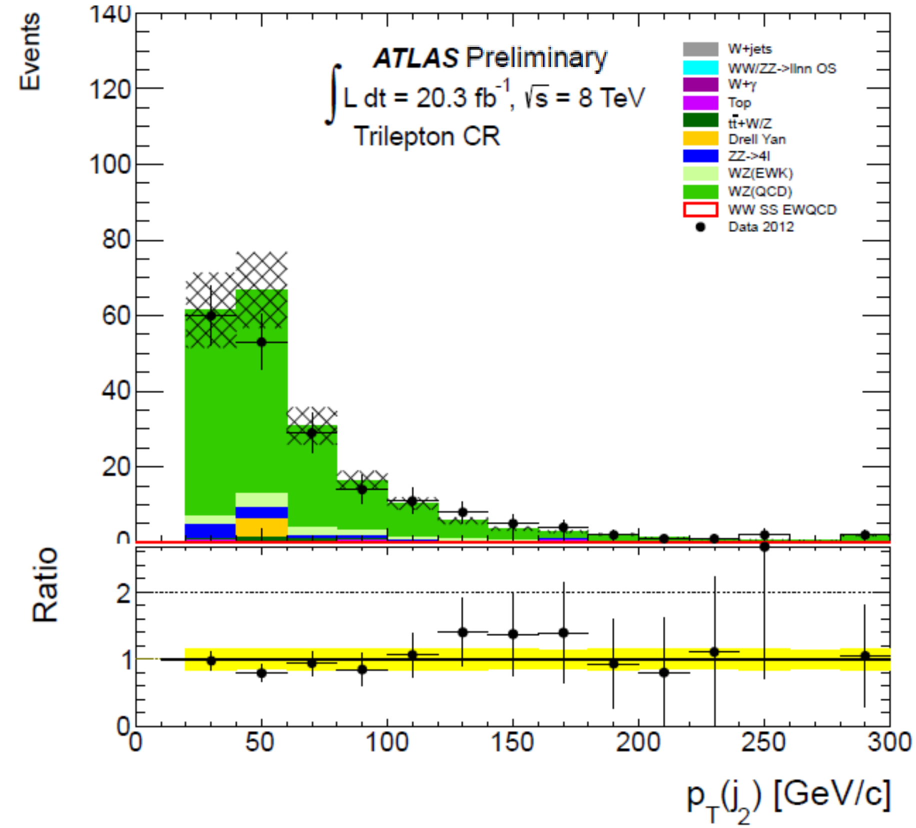


Low m_{jj} Control Region

	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj ewk+strong	6.5 ± 0.7	18.8 ± 1.9	11.4 ± 1.2	37 ± 4
WZ/γ^{*},ZZ	25 ± 4	54 ± 9	18.4 ± 3.1	98 ± 16
$W + \gamma$	14 ± 4	20 ± 6	–	34 ± 10
$t\bar{t} + W/Z$	1.7 ± 0.7	3.8 ± 1.6	2.4 ± 1.0	7.9 ± 3.4
OS prompt leptons	19.4 ± 2.3	8.4 ± 1.4	–	27.8 ± 3.4
Other non-prompt	9 ± 4	21 ± 8	8 ± 4	39 ± 10
Total Predicted	76 ± 9	127 ± 16	40 ± 6	243 ± 27
Data	78	120	30	228

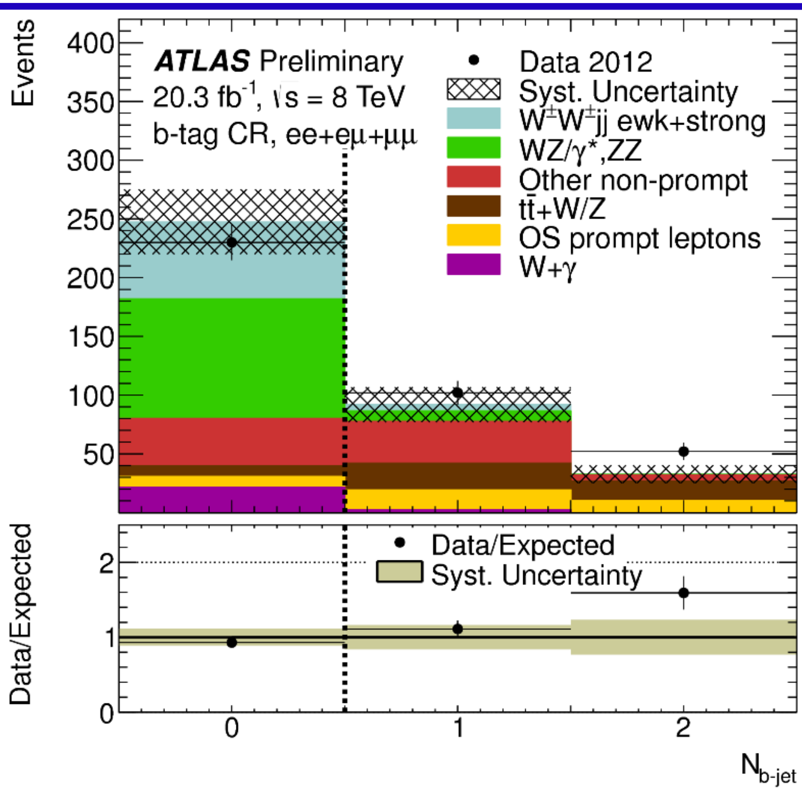
Trilepton Control Region

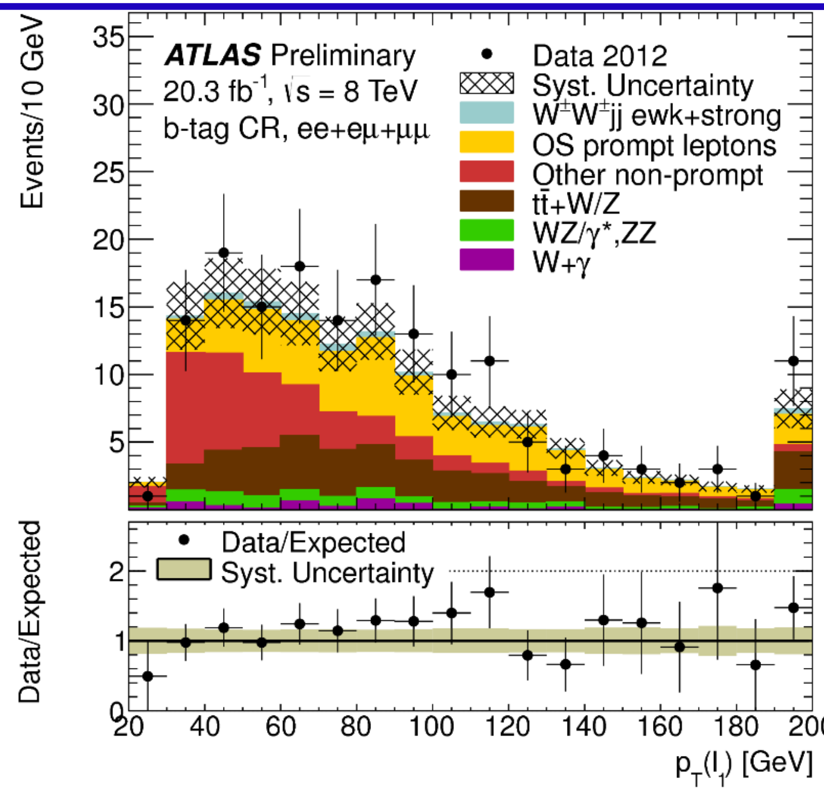




Trilepton Control Region				
	$e^{\pm}e^{\pm}\ell^{\mp}$	$e^{\pm}\mu^{\pm}\ell^{\mp}$	$\mu^{\pm}\mu^{\pm}\ell^{\mp}$	Total
$W^{\pm}W^{\pm}$jj ewk+strong	0.01 ± 0.01	0.11 ± 0.02	0.00 ± 0.00	0.12 ± 0.02
WZ/γ^*	32 ± 5	96 ± 16	57 ± 10	186 ± 31
$ZZ \to$4l	2.2 ± 0.6	5.3 ± 1.3	1.8 ± 0.5	9.2 ± 2.1
$t\bar{t} + W/Z$	0.65 ± 0.28	2.4 ± 1.0	1.0 ± 0.5	4.1 ± 1.7
Non-prompt	0.48 ± 0.32	6 ± 5	0.00 ± 0.00	7 ± 5
Total Predicted	36 ± 6	110 ± 18	60 ± 10	206 ± 33
Data	40	104	48	192

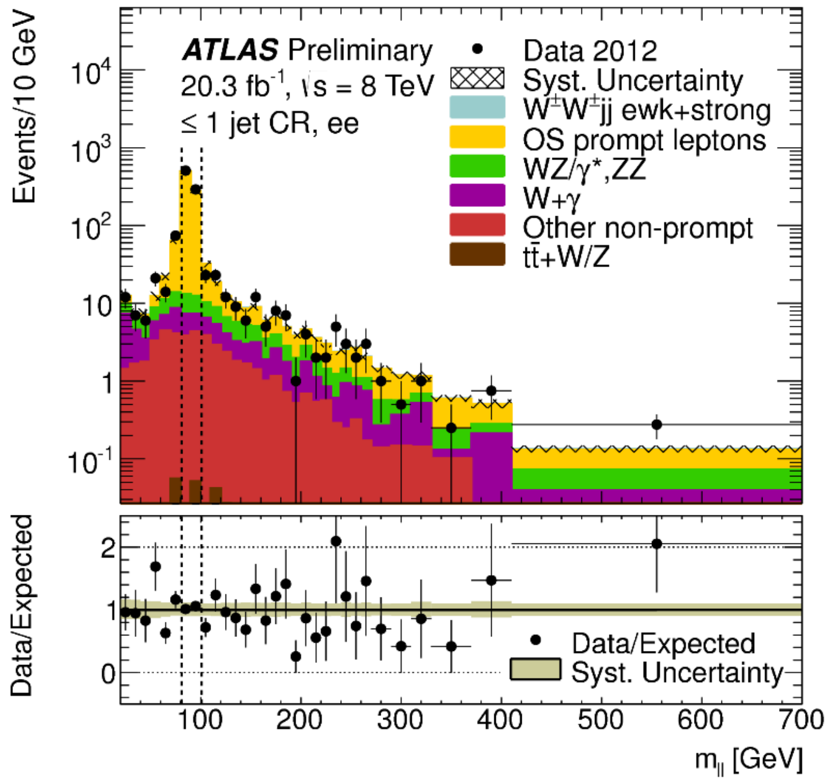
b-tag Control Region

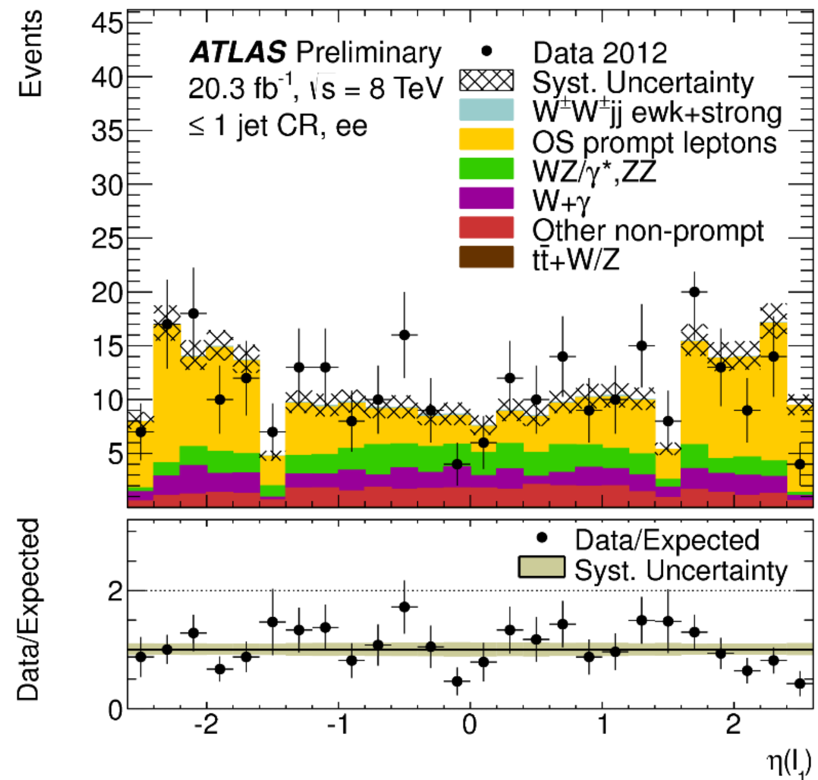




b-tag Control Region				
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	Total
$W^\pm W^\pm$jj ewk+strong	0.81 ± 0.10	2.57 ± 0.28	1.55 ± 0.18	4.9 ± 0.5
$WZ\gamma^*,ZZ$	2.3 ± 0.5	4.9 ± 0.9	2.2 ± 0.4	9.4 ± 1.6
$W + \gamma$	1.7 ± 0.7	2.3 ± 0.9	–	4.0 ± 1.4
$t\bar{t} + W/Z$	7.1 ± 3.1	18 ± 8	11 ± 4	36 ± 15
OS prompt leptons	22 ± 5	27 ± 6	–	49 ± 11
Other non-prompt	6.7 ± 2.5	20 ± 8	10 ± 5	37 ± 10
Total Predicted	40 ± 6	75 ± 13	25 ± 7	141 ± 22
Data	46	82	36	164

≤1 jet Control Region

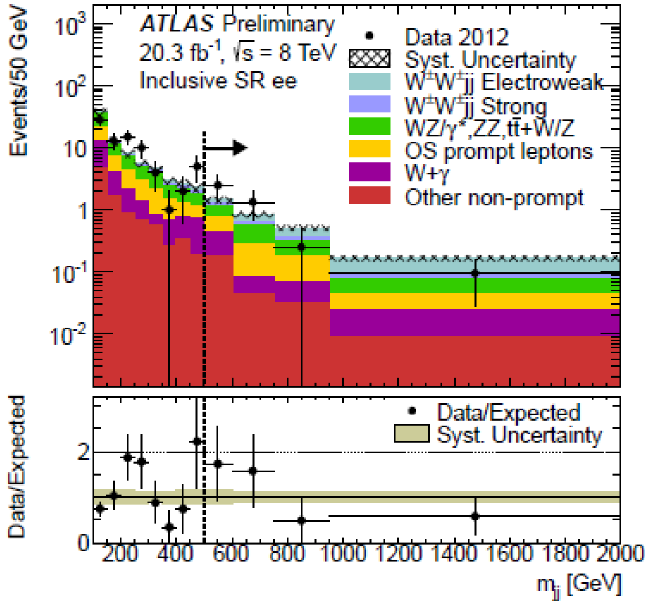


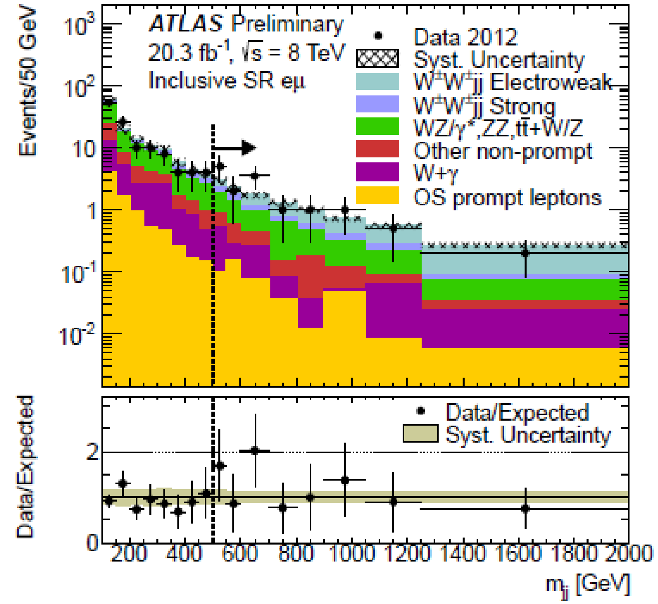


$\leq$ 1 jet Control Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj ewk+strong	2.72 ± 0.30	8.2 ± 0.8	4.2 ± 0.4	15.1 ± 1.5
WZ/γ^*,ZZ	46 ± 8	130 ± 23	75 ± 13	250 ± 40
$W+\gamma$	39 ± 11	59 ± 17	–	98 ± 29
$t\bar{t}+W/Z$	0.34 ± 0.15	0.8 ± 0.4	0.56 ± 0.25	1.7 ± 0.7
OS prompt leptons	152 ± 17	24 ± 4	–	177 ± 21
Other non-prompt	38 ± 15	65 ± 26	8 ± 5	111 ± 30
Total Predicted	278 ± 28	290 ± 40	88 ± 14	650 ± 70
Data	288	328	101	717

Inclusive Signal Region

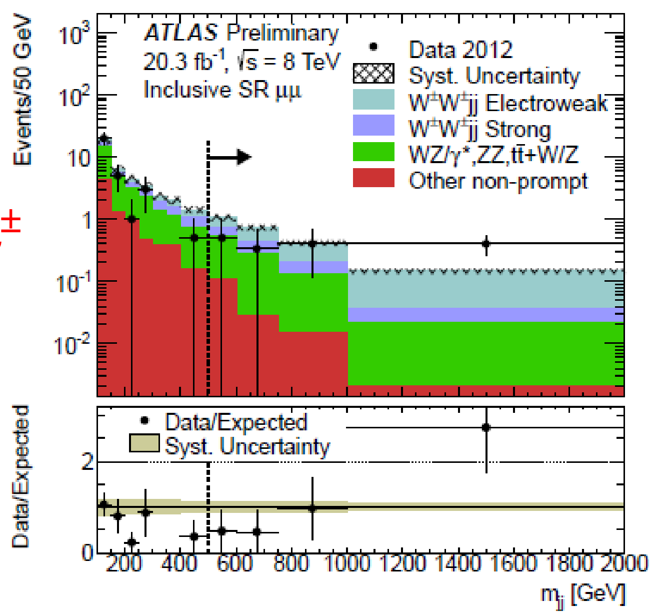
$e^{\pm}e^{\pm}$

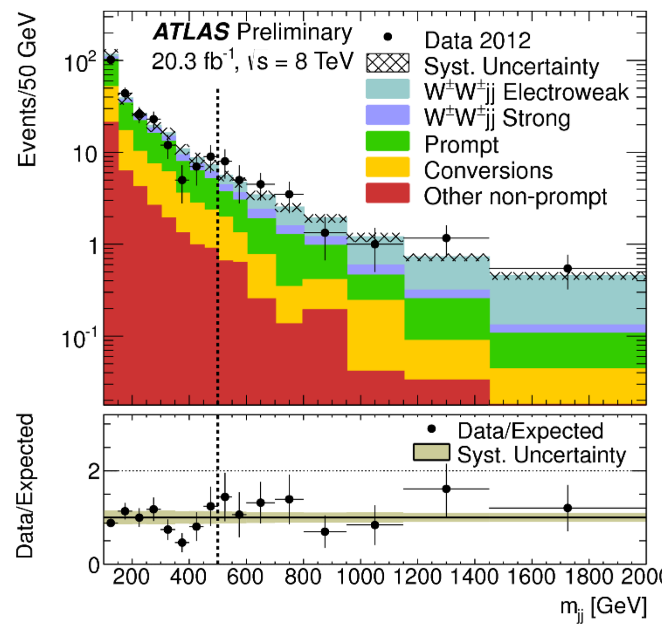




$e^{\pm}\mu^{\pm}$

$\mu^{\pm}\mu^{\pm}$

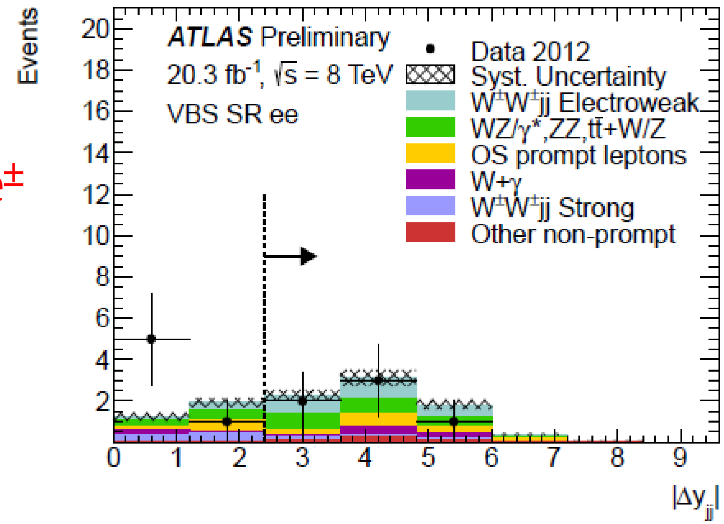




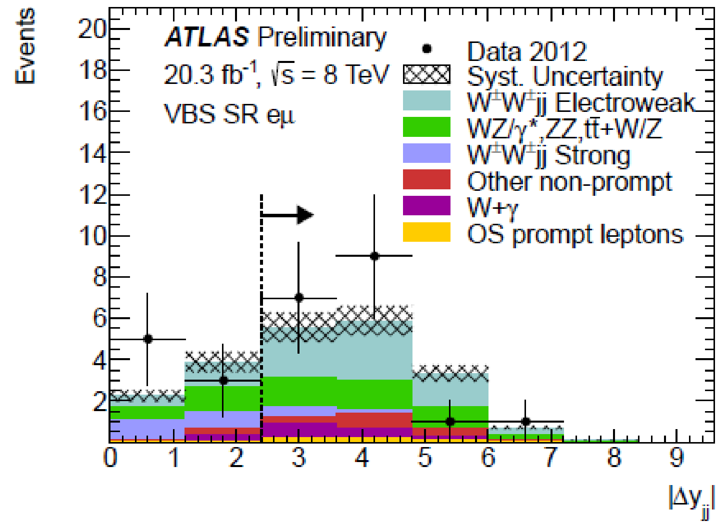
Combined

VBS Signal Region

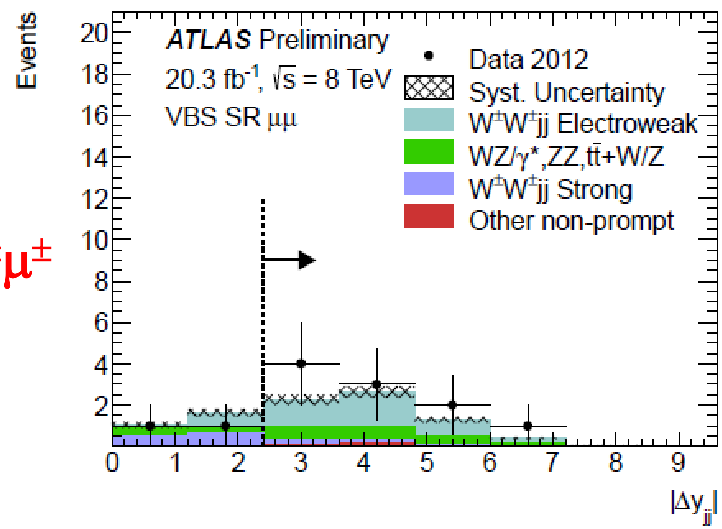
$e^{\pm}e^{\pm}$



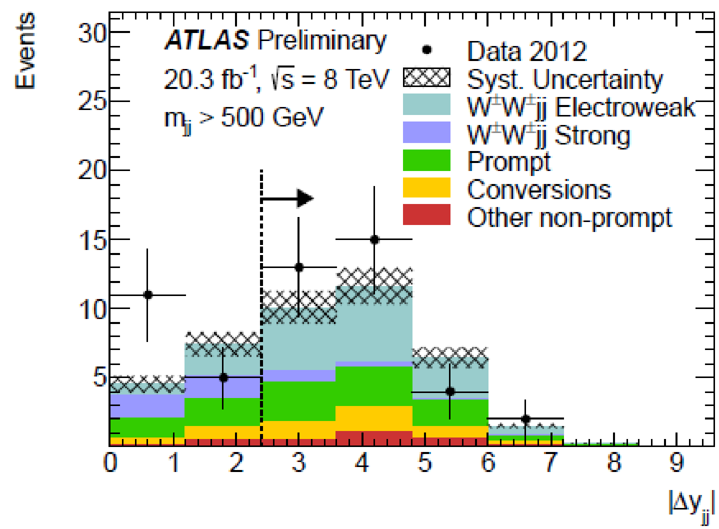
$e^{\pm}\mu^{\pm}$



$\mu^{\pm}\mu^{\pm}$



Combined



Signal Region Numbers

Inclusive Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	16.9 ± 1.5
$W^{\pm}W^{\pm}$jj Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	4.8 ± 0.8
WZ/γ^*,ZZ,$t\bar{t}+W/Z$	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	11.6 ± 2.5
$W+\gamma$	1.1 ± 0.6	1.6 ± 0.8	–	2.7 ± 1.2
OS prompt leptons	2.1 ± 0.4	0.77 ± 0.27	–	2.8 ± 0.6
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	2.9 ± 0.8
Total Predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	42 ± 5
Data	12	26	12	50

VBS Signal Region				
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	Total
$W^{\pm}W^{\pm}$jj Electroweak	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4	13.9 ± 1.2
$W^{\pm}W^{\pm}$jj Strong	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08	1.34 ± 0.26
WZ/γ^*,ZZ,$t\bar{t}+W/Z$	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5	8.2 ± 1.9
$W+\gamma$	0.7 ± 0.4	1.3 ± 0.7	–	2.0 ± 1.0
OS prompt leptons	1.39 ± 0.27	0.64 ± 0.24	–	2.0 ± 0.5
Other non-prompt	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19	2.3 ± 0.7
Total Predicted	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8	29.8 ± 3.5
Data	6	18	10	34

Inclusive SR Systematic Uncertainties

Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - Inclusive SR			
Background	ee/eμ/μμ	Signal	ee/eμ/μμ
Jet uncertainties	11/13/13	Jet uncertainties	5.7
Theory WZ/γ^*	5.6/7.7/11	Theory $W^\pm W^\pm jj$-ewk	4.7
MC statistics	8.2/5.9/8.4	Theory $W^\pm W^\pm jj$-strong	3.1
Fake rate	3.5/7.1/7.2	Luminosity	2.8
OS lepton bkg/ Conversion rate	5.9/4.2/–	MC statistics	3.5/2.1/2.8
Theory $W+\gamma$	2.8/2.6/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.2/2.4/1.8	Lepton reconstruction	1.9/1.0/0.7
Luminosity	1.7/2.1/2.4	b-tagging efficiency	0.6
Lepton reconstruction	1.6/1.2/1.2	trigger efficiency	0.1/0.3/0.5
b-tagging efficiency	1.0/1.1/1.0		
Trigger efficiency	0.1/0.2/0.4		

VBS SR Systematic Uncertainties

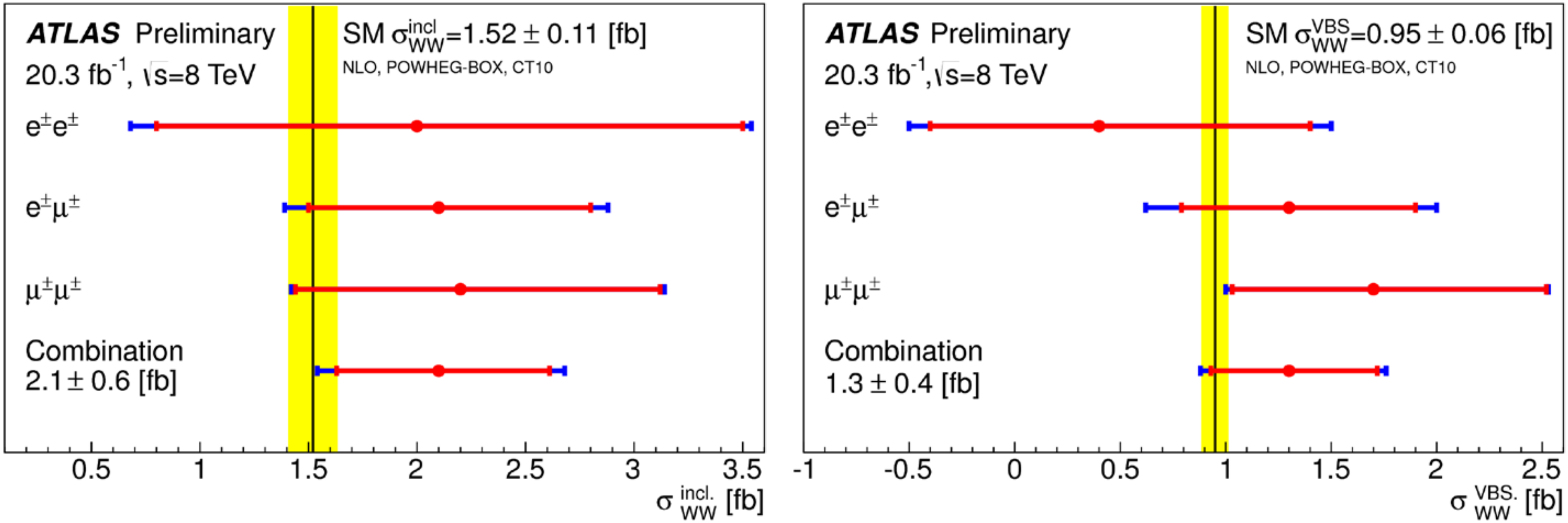
Systematic Uncertainties $ee/e\mu/\mu\mu$ (%) - VBS SR			
Background	ee/eμ/μμ	Signal	ee/eμ/μμ
Jet uncertainties	13/15/15	Theory $W^{\pm}W^{\pm}jj$-ewk	6.0
Theory WZ/γ^*	4.5/5.4/7.8	Jet uncertainties	5.1
MC statistics	8.9/6.4/8.4	Luminosity	2.8
Fake rate	4.0/7.2/6.8	MC statistics	4.5/2.7/3.7
OS lepton bkg/ Conversion rate	5.5/4.4/–	E_T^{miss} reconstruction	1.1
E_T^{miss} reconstruction	2.9/3.2/1.4	Lepton reconstruction	1.9/1.0/0.7
Theory $W+\gamma$	3.1/2.6/–	b-tagging efficiency	0.6
Luminosity	1.7/2.1/2.4	trigger efficiency	0.1/0.3/0.5
Theory $W^{\pm}W^{\pm}jj$-strong	0.9/1.5/2.6		
Lepton reconstruction	1.7/1.1/1.1		
b-tagging efficiency	0.8/0.9/0.7		
Trigger efficiency	0.1/0.2/0.4		

Cross Section Extraction

- Profile likelihood ratio method used to extract the final cross sections from all three channels taken into account correlated systematics

$$L(\sigma_{W^\pm W^\pm jj}, \mathcal{L}, \alpha_j) = \mathrm{Gaus}(\mathcal{L}_0|\mathcal{L}, \sigma_{\mathcal{L}}) \prod_{i\in\{ee,\mu\mu,e\mu\}} \mathrm{Pois}(N_i^{\mathrm{obs}}|N_{i,\mathrm{tot}}^{\mathrm{exp}}) \prod_{j\in\mathrm{syst}} \mathrm{Gaus}(\alpha_j^0|\alpha_j, 1)$$

  - Inclusive SR: σ = 2.1 ± 0.5 (stat) ± 0.3 (syst) fb, 4.5σ obs. (3.4σ exp.)
  - VBS SR: σ = 1.3 ± 0.4 (stat) ± 0.2 (syst) fb, 3.6σ obs. (2.8σ exp.)
- First ever evidence for EWK VV → VV scattering at the LHC



Anomalous QGCs

- Set limits on possible new physics using the measured cross sections
- Use the effective Lagrangian:

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_d \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

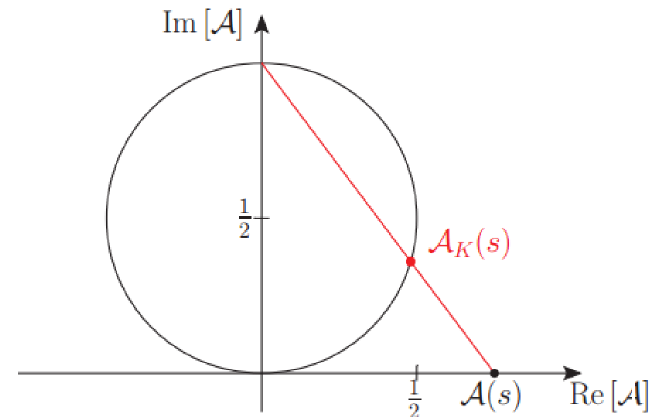
- Consider the chiral Lagrangian approach as implemented in WHIZARD (JHEP 11(2008) 010):
  - The terms that affect WWVV QGCs are α_4 and α_5
- Indirect constraints from electroweak precision data (Eboli et al, PRD 74, 073005 (2006), 99% CL bounds):

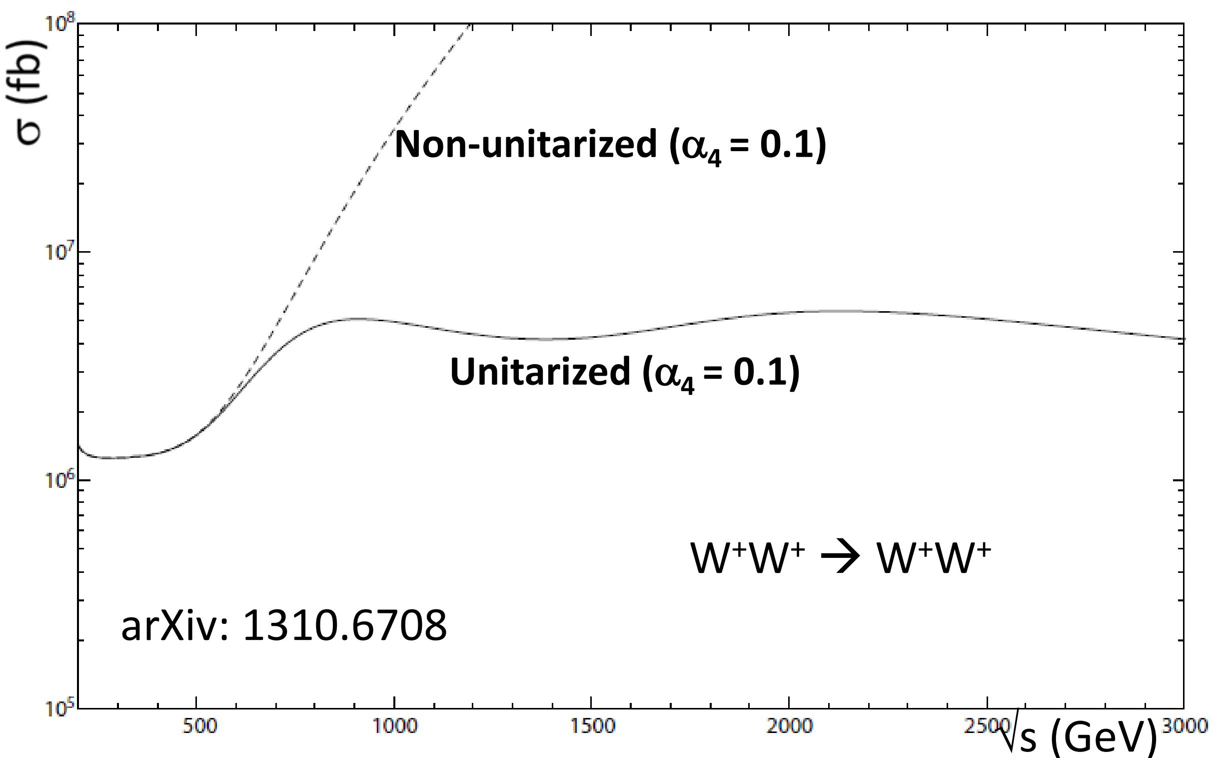
$$-0.35 < \alpha_4 < 0.06 \text{ and } -0.87 < \alpha_5 < 0.15$$

Unitarization Scheme

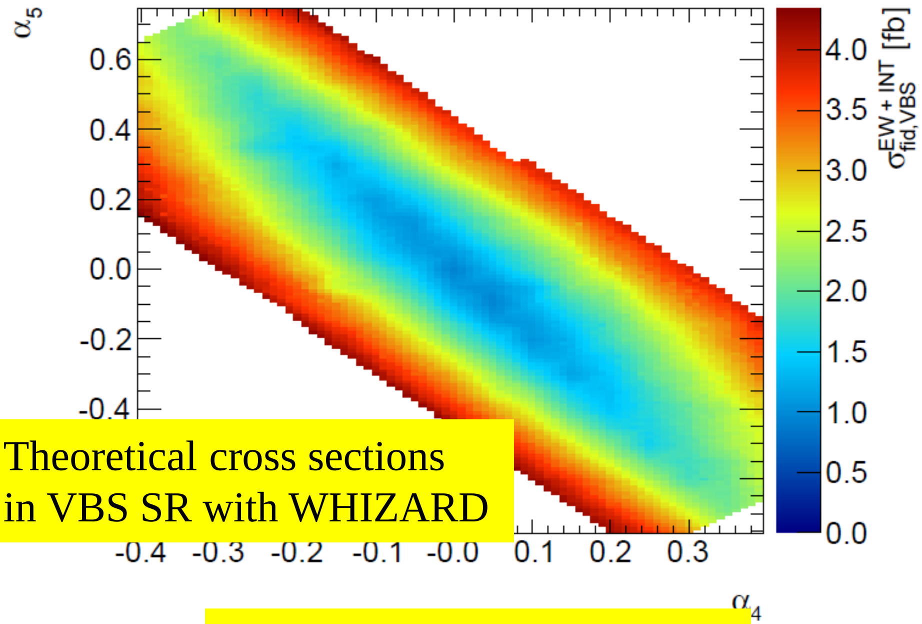
- Unitarization: cut-off, form factor, K-matrix, inverse-amplitude method
- We use the K-matrix method as implemented in WHIZARD
  - ❖ Projecting the scattering amplitude $\mathcal{A}(s)$ onto the Argand circle → Saturation of the amplitude to achieve unitarity
  - ❖ Amplitudes satisfying unitarity are invariant under K-matrix unitarization

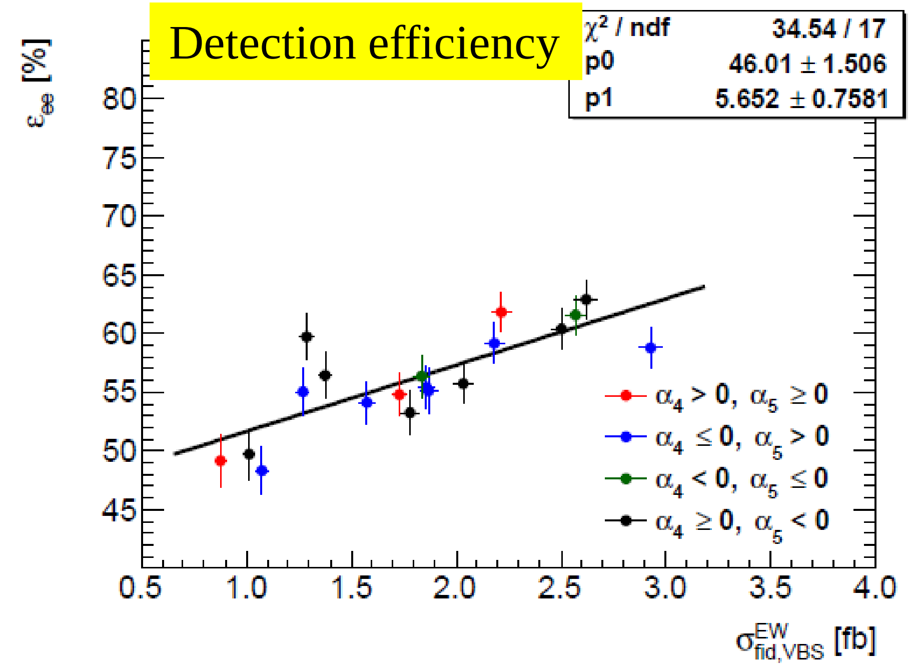
$$\mathcal{A}_K(s) = \frac{1}{Re\left(\frac{1}{\mathcal{A}(s)}\right) - i} = \frac{\mathcal{A}(s)}{1 - i\mathcal{A}(s)}$$

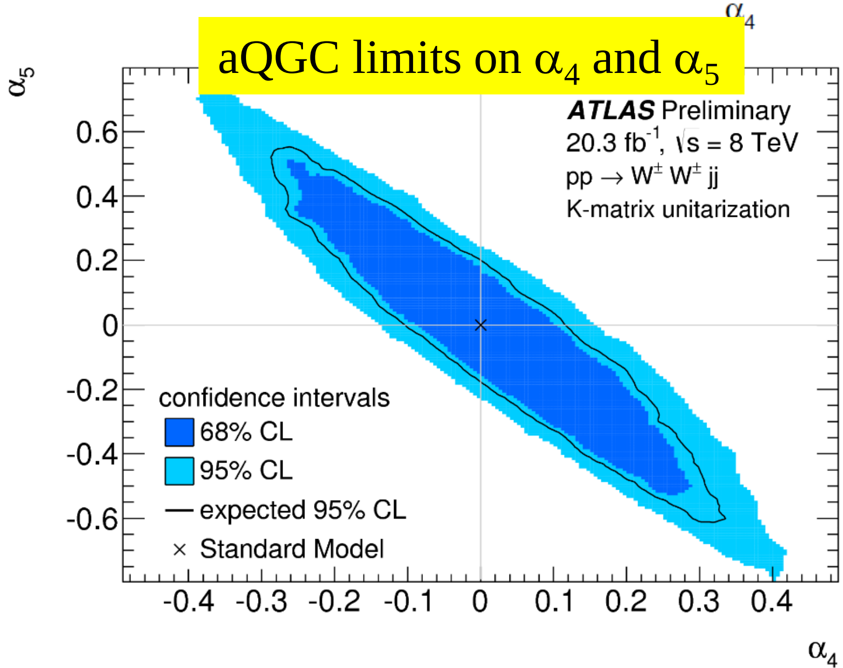




aQGC Measurement







1D aQGC limits:

$\alpha_4 \propto$ [-0.139, 0.157] obs. [-0.104, 0.116] exp.

$\alpha_5 \propto$ [-0.229, 0.244] obs. [-0.180, 0.199] exp.

Summary

- VV→VV scattering processes are important processes to understand the dynamics of EWSB
- QGCs predicted in the SM due to non-Abelian nature of the EW theory
- Presented a search for the same-sign WW VBS process using 20.3 fb^{-1} of data collected by the ATLAS detector
  - Provided a first evidence for the EW production of of $W^{\pm}W^{\pm} \rightarrow W^{\pm}W^{\pm}$ at the LHC (4.5 σ obs. for the inclusive SR, 3.6 σ obs. for the VBS SR)
  - Provided a first set of aQGC limits on WWWW interactions
  - Opened a new section in the SM to experimentally study quartic W/Z interactions
- Studies with 13/14 TeV data will increase our understanding of WWVV and VV→VV scattering