Measurements of VBS
(and other diboson processes)

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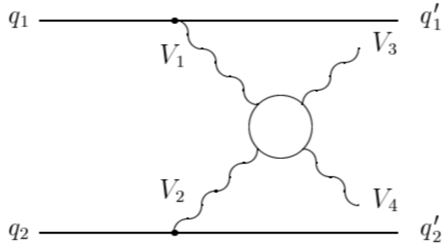
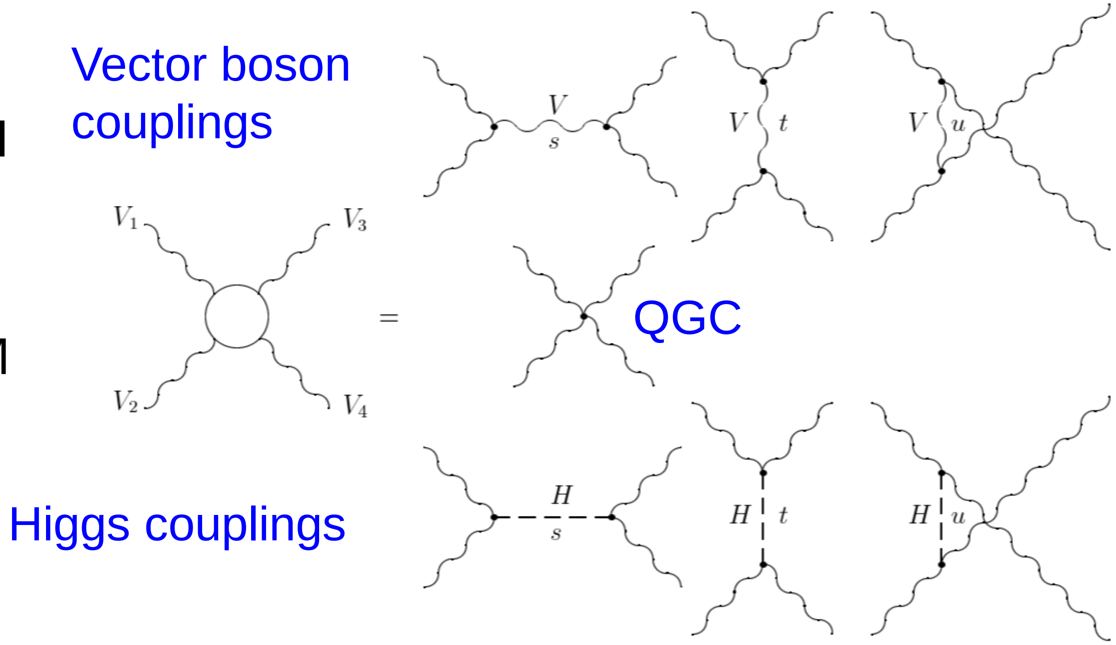
The VBS Processes at LHC

- Vector Boson Scattering (VBS) is a key process to probe the mechanism of electroweak symmetry breaking (EWSB)
- Involving Quartic Gauge Couplings (QGCs) which is sensitive to new physics
  - Only charged QGCs allowed at Standard Model (SM) tree-level (WWWW, WWZZ, WWZγ, WWγγ)
  - Constraint on anomalous QGCs (aQGCs)
  - Probe new physics through deviations from SM

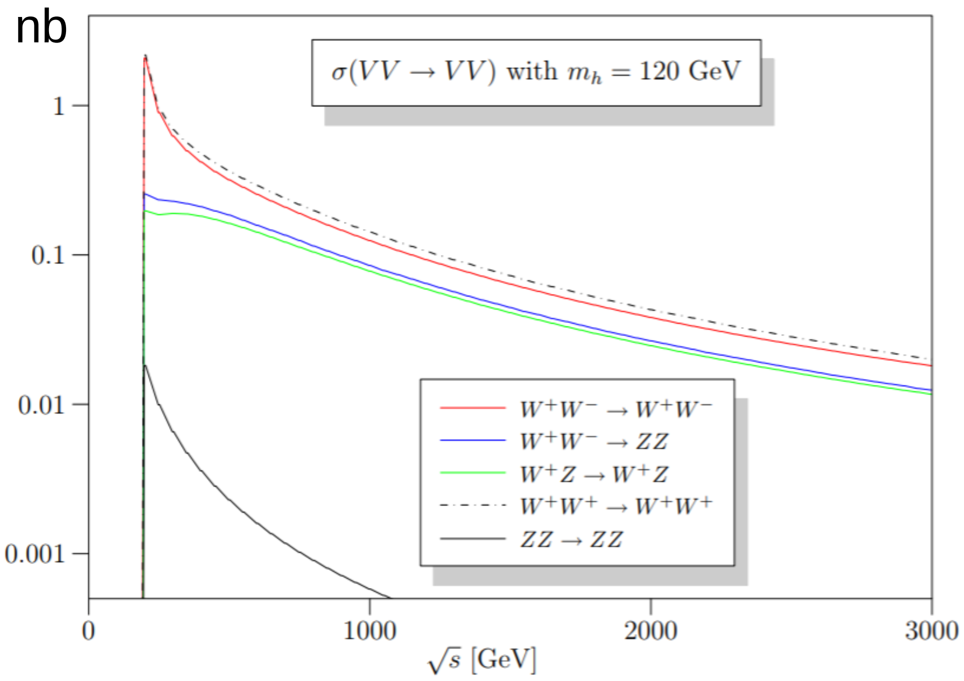
Phys. Rev. D **55**, 7165 – Published 1 June 1997



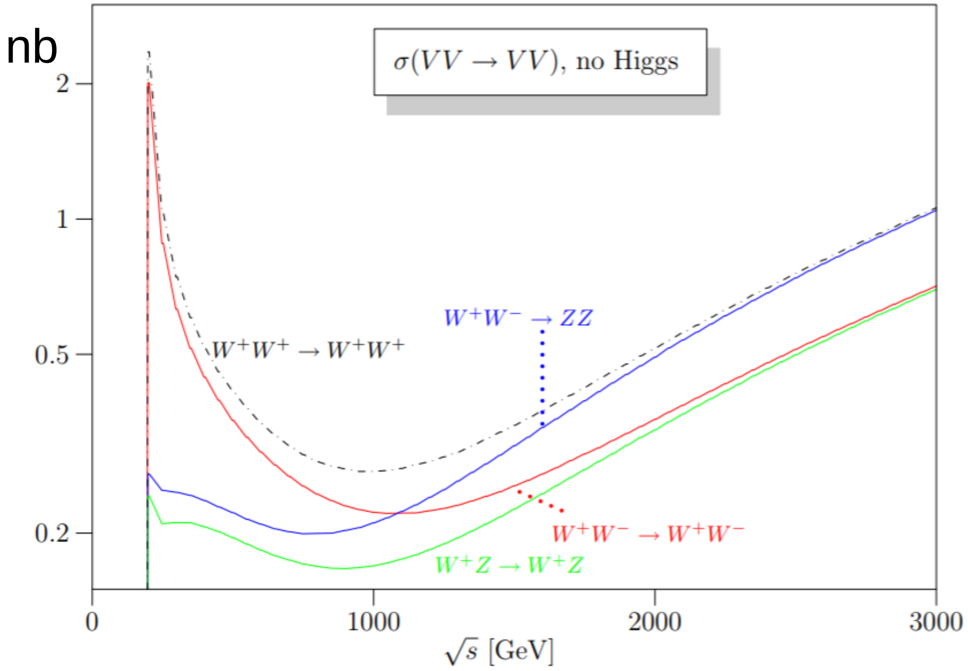


The VBS Unitarity Violation Issue

SM VV scattering processes with low mass Higgs (120 GeV)



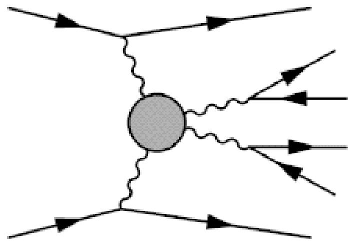
SM VV scattering processes w/o a Higgs boson



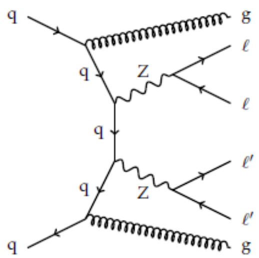
JHEP11(2008)010

- Close connection with Higgs physics
- The VBS cross sections will go diverge without Higgs or other similar underlying new unitarization mechanisms

Experimental Signatures of VBS

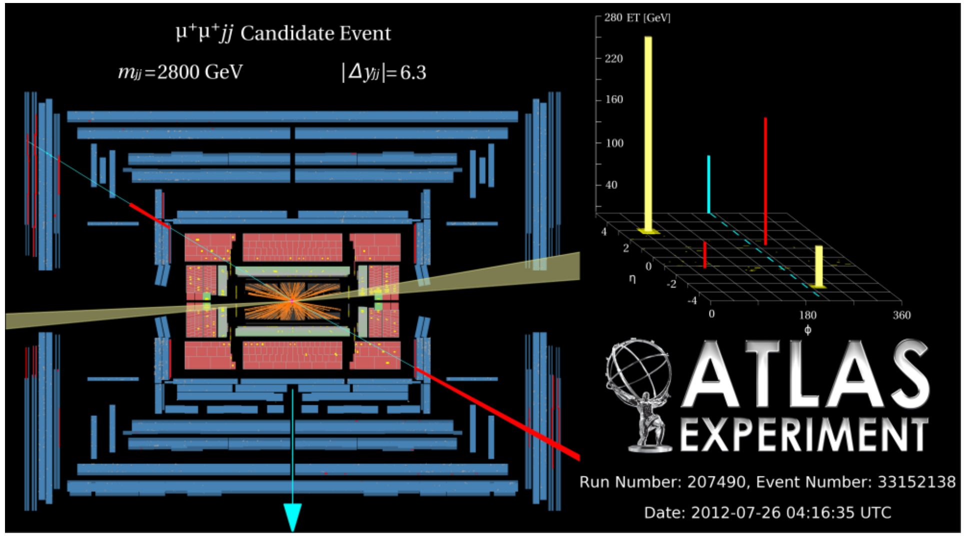


- Two intermediate vector bosons radiated from two incoming quarks
- Final state with two vector bosons plus two outgoing jets
- In general, two “tag” jets in forward region with large rapidity separation and large invariant mass
- Suffer from pile-up (PU) jets, especially in the forward region when go to HL/HE
- EW VBS has relatively smaller cross-sections, suffer from irreducible QCD VV + 2jets events

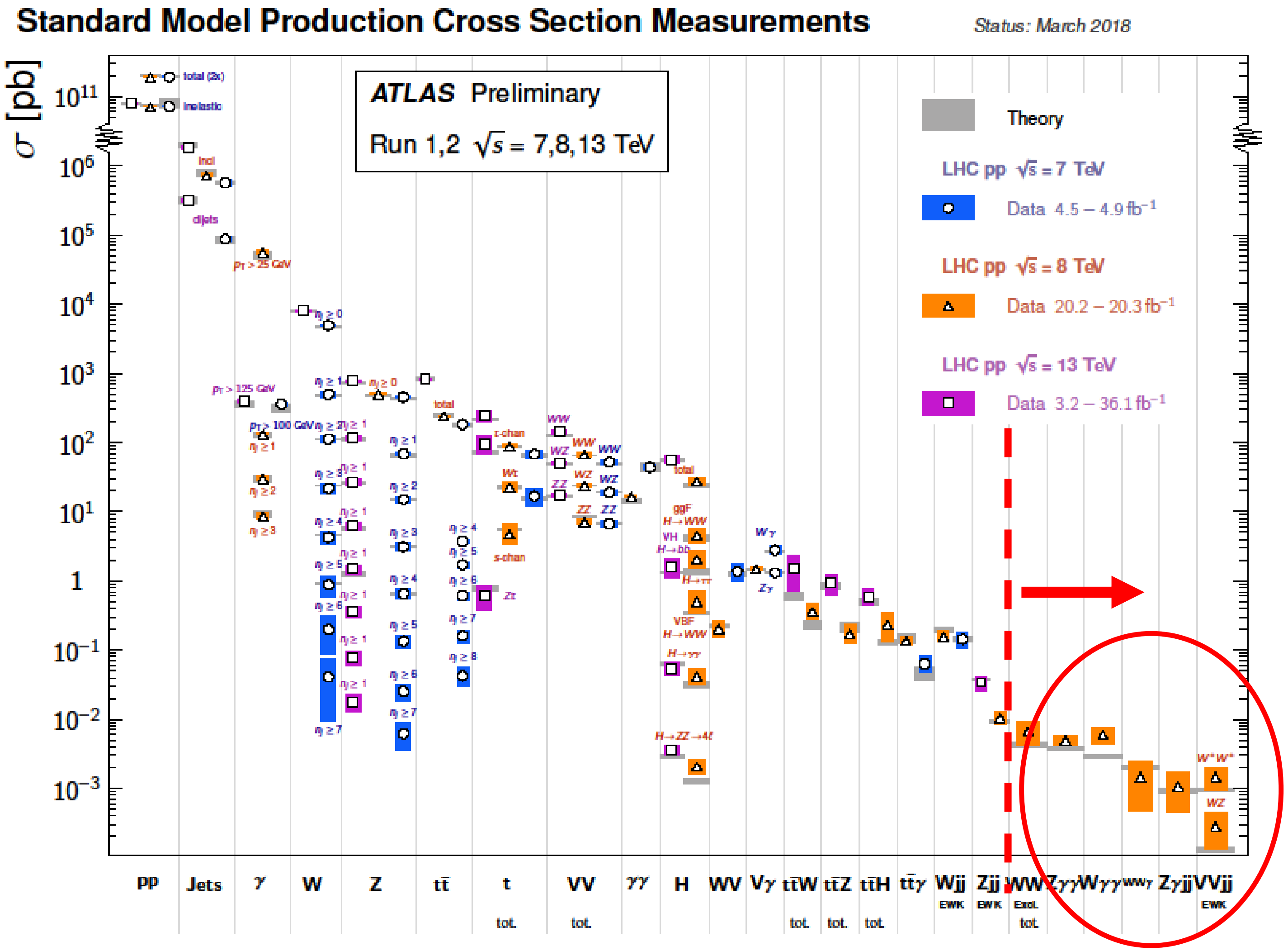


→ A HL-LHC project with extended detector η coverage will be crucial and ideal general VBS measurements, as of signal sensitivity and background rejection, etc.

Candidate VBS event from ssWW
[Phys. Rev. Lett. **113**, 141803]



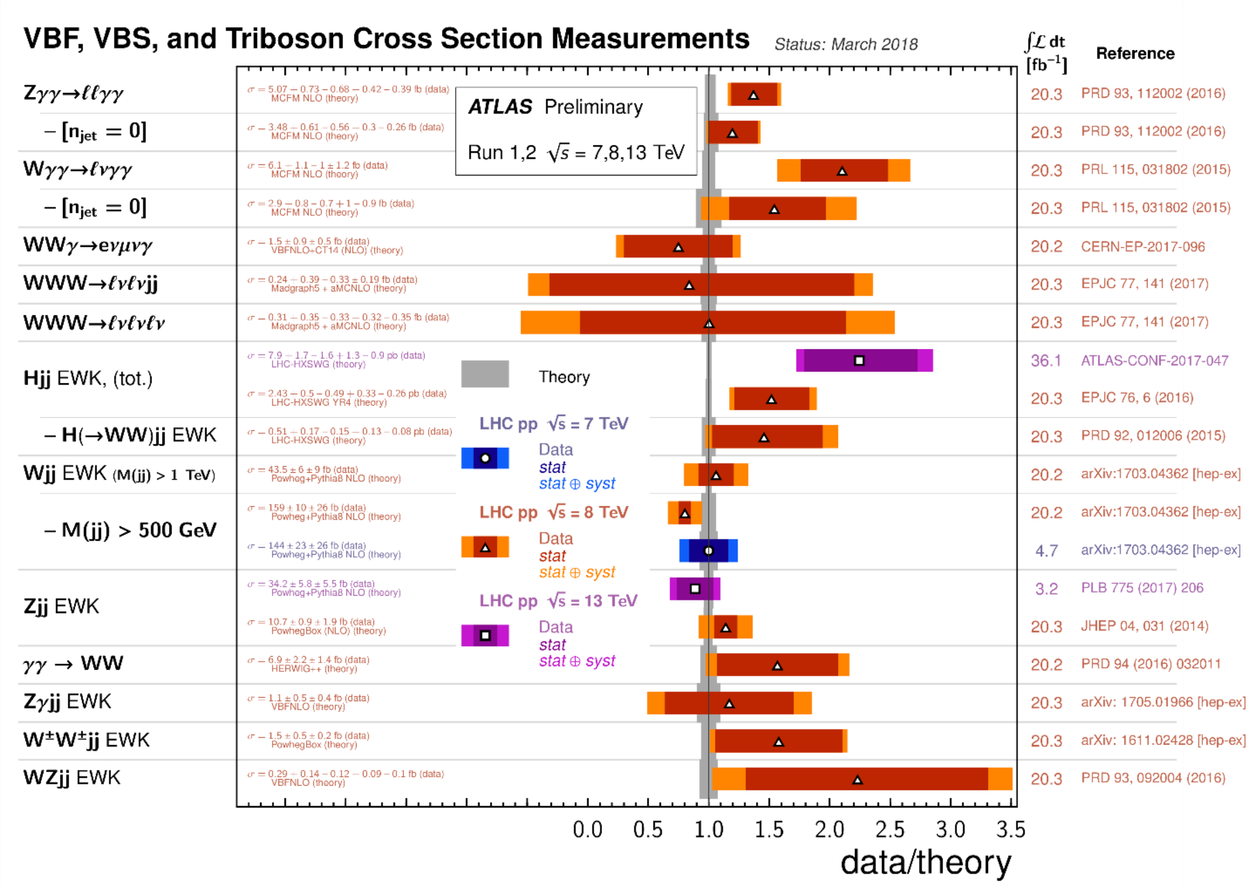
Where Are the MultiBoson Processes



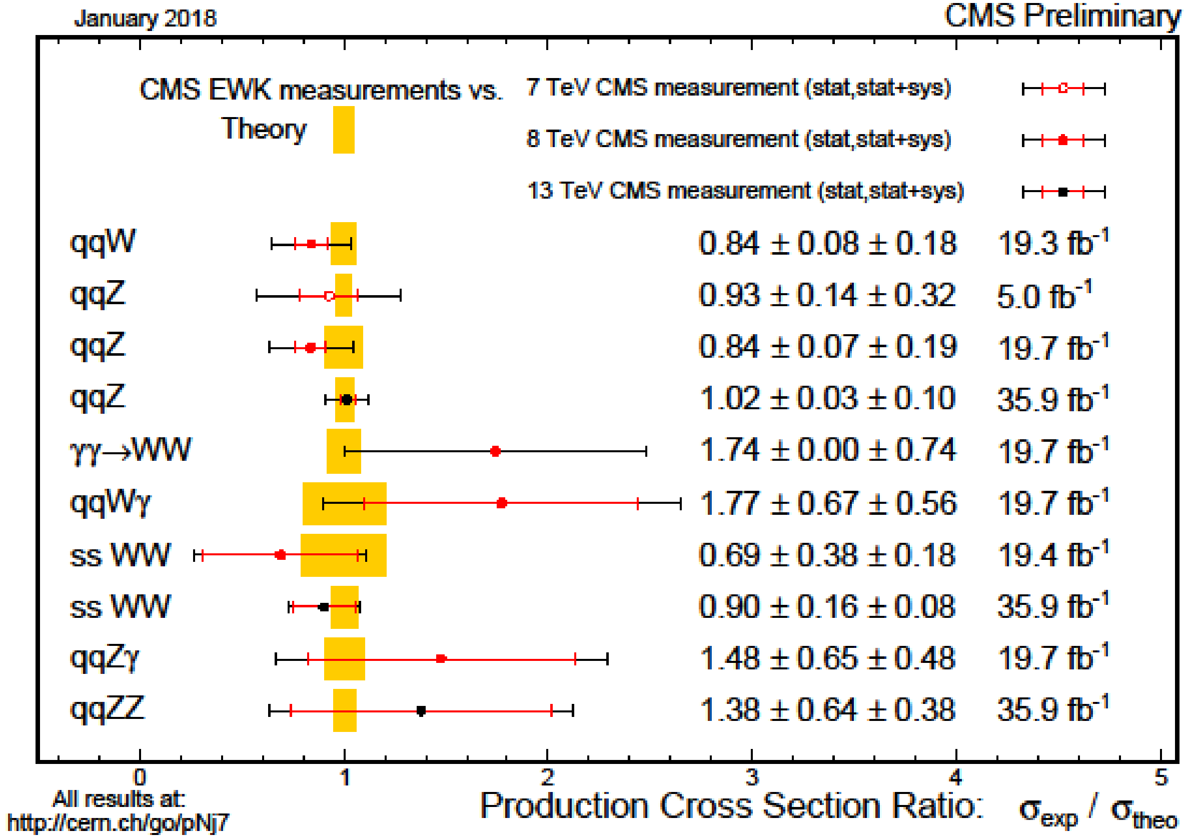
- ✓ We have been able to have many precision measurements of VV final states with current luminosity
- ✓ With additional two jets, cross sections go below 10^{-2} pb level

Current VBS Measurements at the LHC

ATLAS measurements



CMS measurements



Statistic limited in the VV + 2jets measurements

Looking Forward for More Luminosity

* Differential cross section measurements instead of an overall significance
* Longitudinal VV scattering part
* Try to include semi-leptonic channels as well
* Much improved limit on aQGCs
* …

Expected VBS Measurements with 3000 fb^{-1} @14 TeV

Studies with HL-LHC on VBF/VBS processes
This talk will focus on VBS part

VBF Higgs	SM diboson VBS
VBF H(125) to WW	ssWW
VBF H(125) to ZZ to 4l	VBS ZZ to 4l
VBF H(125) to YY	VBS WZ to lvll
VBF H(125) to ττ	

More luminosity and higher energy gives the possibility to

- ✓ Precision measurements of electroweak scattering processes
- ✓ Probe to new physics through anomalous vector boson couplings or any deviations from SM prediction
- ✓ One disadvantage we have to suffer is the higher pileup, especially pileup jets in forward region

The (a)QGCs in VV Final States

Michael Rauch, arxiv:1610.08420
O. J. P. Eboli, M. C. Gonzalez-Garcia, arXiv:1604.03555

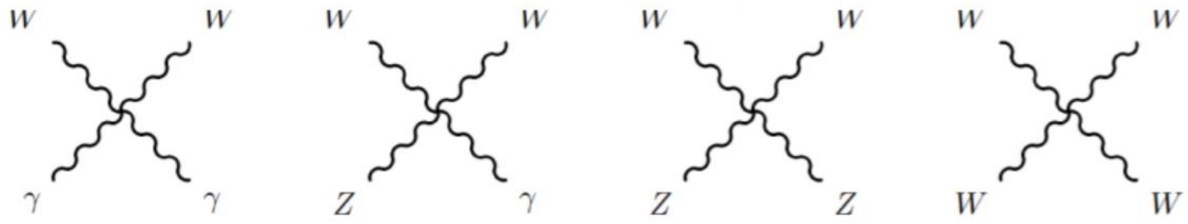
- Effective operators approach

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4} \sum_{i} \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- Three types of dimension-8 operators
  - Scalar: S0, S1, S2
  - Tensor: T0 – T9
  - Mixed: M0 – M7

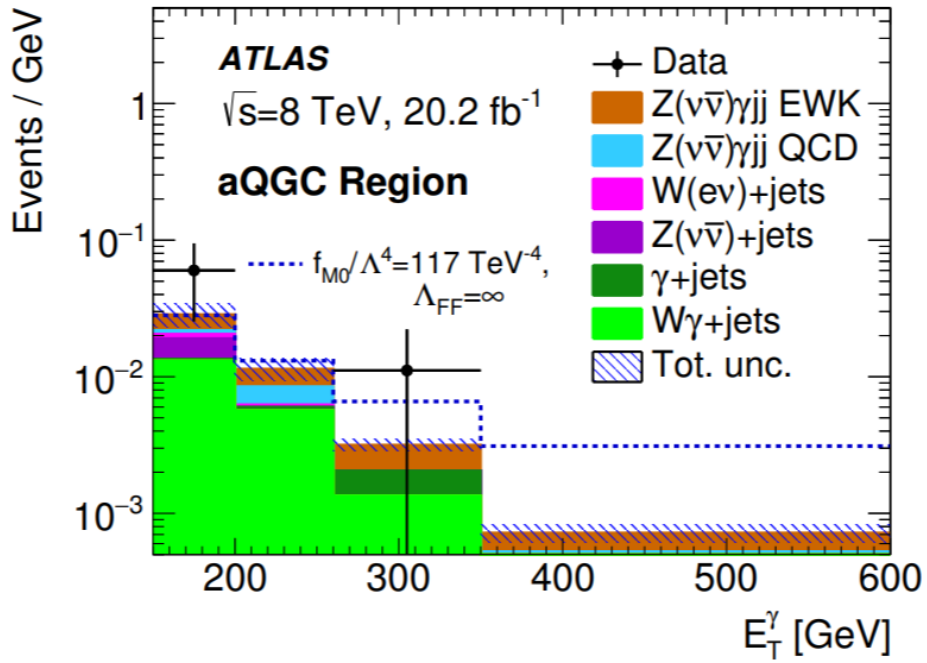
	$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,2}$	$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,7}$	$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$	$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$	$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$
$WWWW$	X	X		X		
$WWZZ$	X	X	X	X	X	
$ZZZZ$	X	X	X	X	X	X
$WWZ\gamma$		X	X	X	X	
$WW\gamma\gamma$		X	X	X	X	
$ZZZ\gamma$		X	X	X	X	X
$ZZ\gamma\gamma$		X	X	X	X	X
$Z\gamma\gamma\gamma$				X	X	X
$\gamma\gamma\gamma\gamma$				X	X	X

SM allowed ones



General Signatures from aQGCs

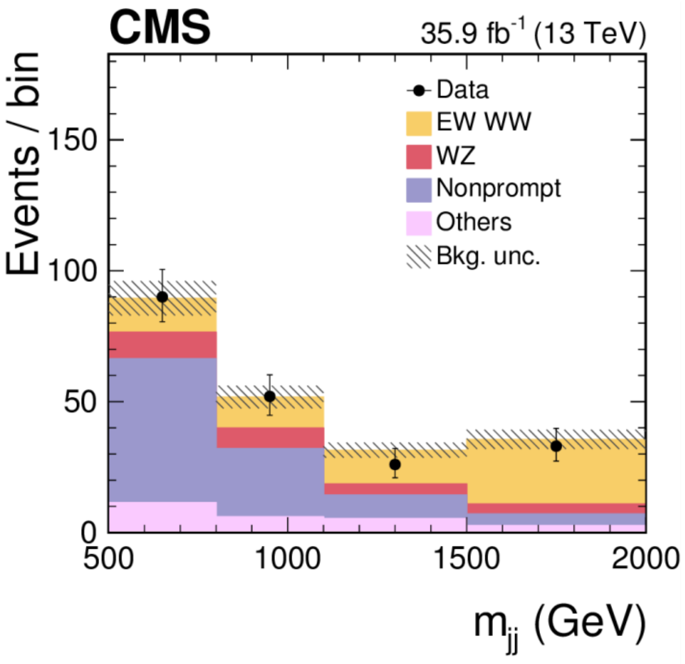
- Enhanced cross sections in the high energy/mass tail region
- Usually powerful observables
  - Mass, pT, mT, etc. depending on final states
  - In most cases we are looking at the highest few bins → Higher luminosity and higher energy will help a lot
  - Will benefit from a more accurate high-order calculation as well in the tail region

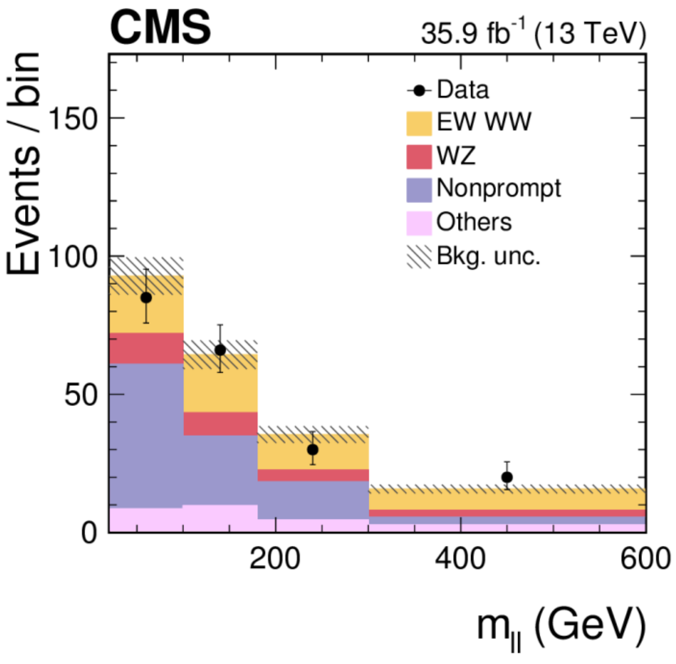


JHEP 07 (2017) 107

Current Same-sign WW Scattering @13 TeV

Phys. Rev. Lett. 120, 081801 – Published 22 February 2018





Data	201
Signal + total background	205 ± 13
Signal	66.9 ± 2.4
Total background	138 ± 13
Nonprompt	88 ± 13
WZ	25.1 ± 1.1
QCD WW	4.8 ± 0.4
$W\gamma$	8.3 ± 1.6
Triboson	5.8 ± 0.8
Wrong sign	5.2 ± 1.1

General event selections

- ✓ Two isolated same-sign leptons
- ✓ Two jets with high mass and large η separation
- ✓ Centrality cuts

- ✓ Profile likelihood ratio test statistic based on 2D (m_{jj}, m_{ll}) distributions
- ✓ Observed (expected) significance of 5.5 (5.7) σ

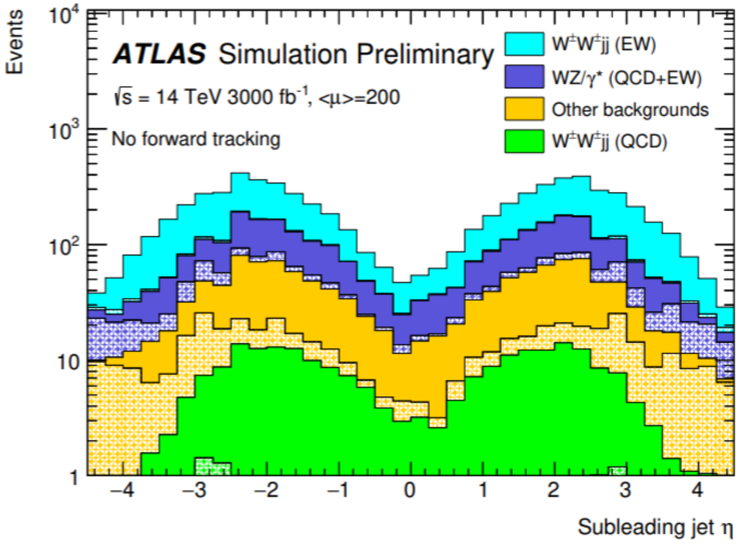
One of the VBS channels with best S/B

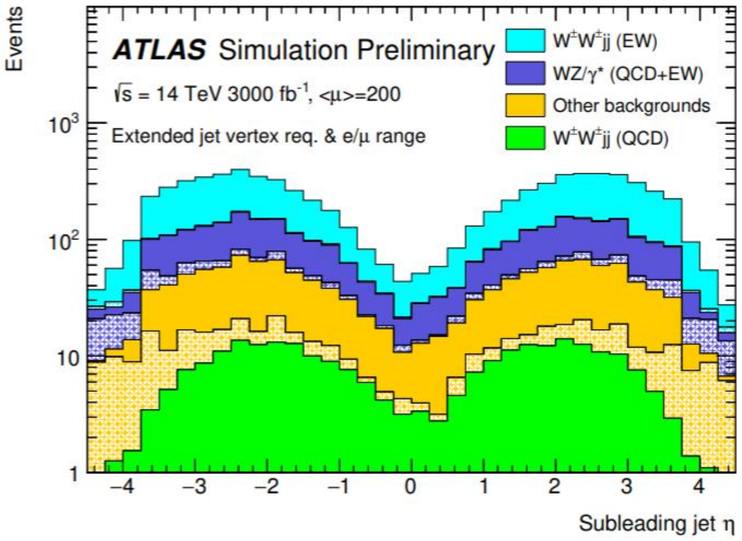
~50% of prompt backgrounds come from WZ process

Same-sign VBS WW→lνlν in the Future

ATL-PHYS-PUB-2017-023

- Studies on the impact of ITk and forward muon tagger from ATLAS
- Particle-level analysis, with smearing functions to estimate the detector effect





η coverage	Applied range for jet vertex requirement	Lepton η range
No forward tracking	$\lvert\eta_{\text{jet}}\rvert \leq 2.5$	$\lvert\eta_{e,\mu}\rvert \leq 2.7$
Forward tracking for jets only	$\lvert\eta_{\text{jet}}\rvert \leq 3.8$	$\lvert\eta_{e,\mu}\rvert \leq 2.7$
Forward tracking for jets and electrons	$\lvert\eta_{\text{jet}}\rvert \leq 3.8$	$\lvert\eta_{e}\rvert \leq 4.0$, $\lvert\eta_{\mu}\rvert \leq 2.7$
Forward tracking for jets, electrons and muons	$\lvert\eta_{\text{jet}}\rvert \leq 3.8$	$\lvert\eta_{e,\mu}\rvert \leq 4.0$

Expected sensitivity (stat. + 15% syst.)	Z_σ				Z_σ
	ee	$e\mu$	μe	$\mu\mu$	Combined
No forward tracking	3.9	6.3	7.1	13	17
Forward tracking for jets only	3.8	6.1	7.0	13	16
Forward tracking for jets and electrons	3.9	6.2	7.1	13	16
Forward tracking for jets, electrons and muons	3.9	6.7	7.8	16	19

Improved signal acceptance and WZ background rejection	Signal variation	Background variation	Z_σ variation	$\frac{\Delta\mu}{\mu}$ variation
Extending jet vertex requirement range	+12%	+14%	-1.9%	+1.9%
Extending lepton range	+3.0%	-7.7%	+17%	-14%
Combination	+14%	+7.3%	+15%	-13%

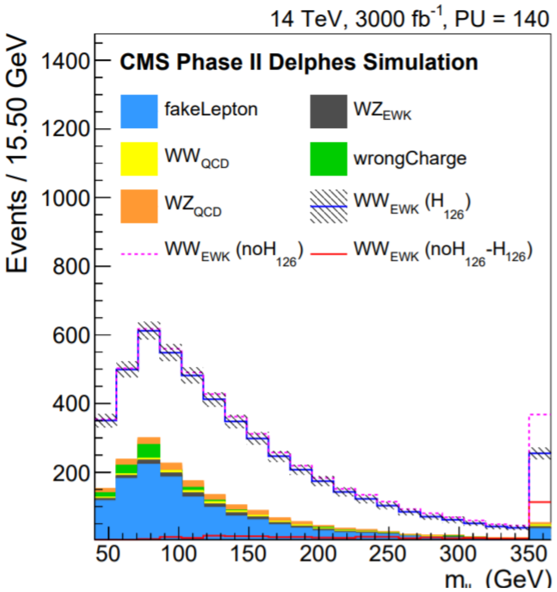
w/ only forward jet, significance actually goes down due to larger increase from background (WZ and QCD WW)

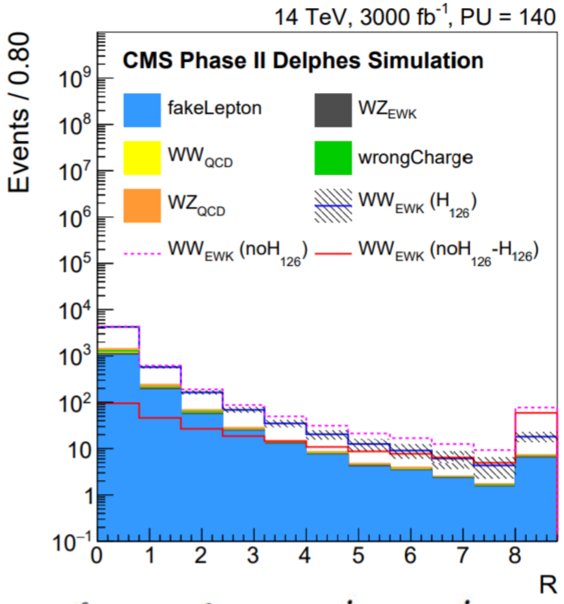
General event selections
- ✓ Two isolated same-sign leptons
- ✓ Two jets with high mass and large η separation
- ✓ Centrality cuts + E_T^{miss} + Z veto
- ✓ Largest prompt background from WZ

Same-sign VBS WW→lvlv in the Future

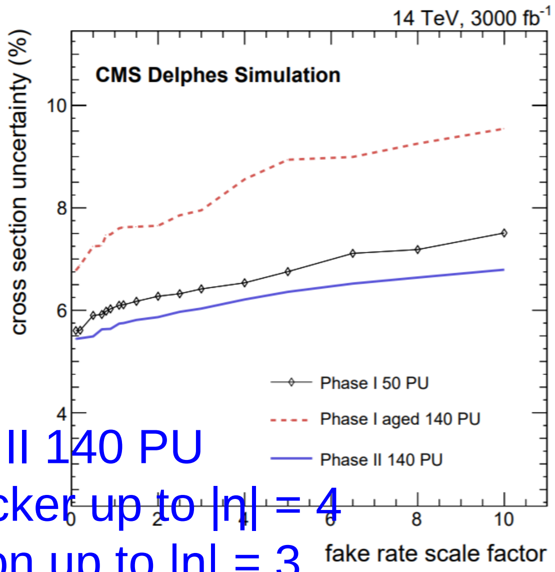
CMS-PAS-SMP-14-008

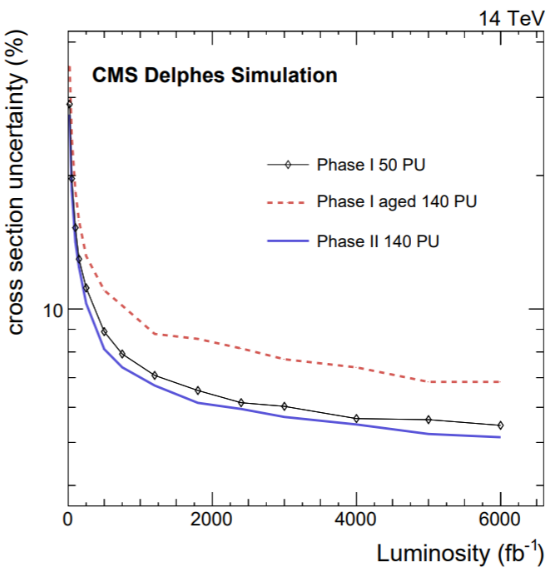
- Studies based on 3 different scenarios with different PU and detector aging and coverage configurations from CMS
- Studies with CMS DELPHES simulation
- 2D template fit (m_{ll}, R) for the VBS results
- Total uncertainty around 6% (jet/lepton energy and efficiency, fake rate, lumi. and theoretical)





$$R = p_{\mathrm{T}}^{\ell_1} \cdot p_{\mathrm{T}}^{\ell_2} / (p_{\mathrm{T}}^{j_1} \cdot p_{\mathrm{T}}^{j_2})$$





Phase II 140 PU
- ✓ Tracker up to |η| = 4
- ✓ Muon up to |η| = 3

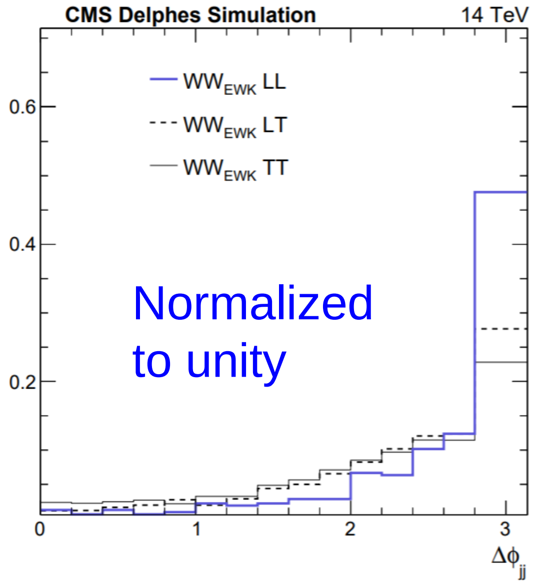
Fake background included

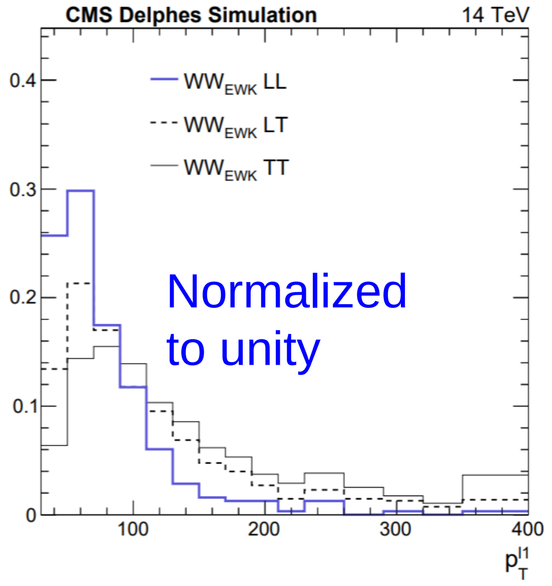
Final results also given as a function of fake rate scale factor

Same-sign VBS WW→lνlν the Future

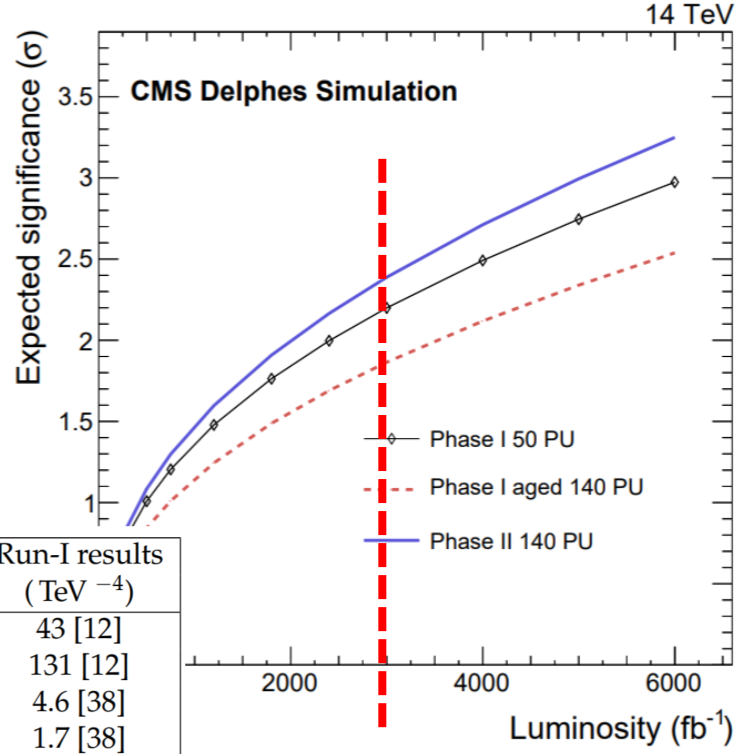
CMS-PAS-SMP-14-008

- More detailed studies based on different component of the VBS processes based on polarization of V bosons
  - Both longitudinal (LL), both transverse (TT), mixed (LT)
- Also a much improved limit on QGC couplings





Phase II 140 PU
✓ Tracker up to |η| = 4
✓ Muon up to |η| = 3



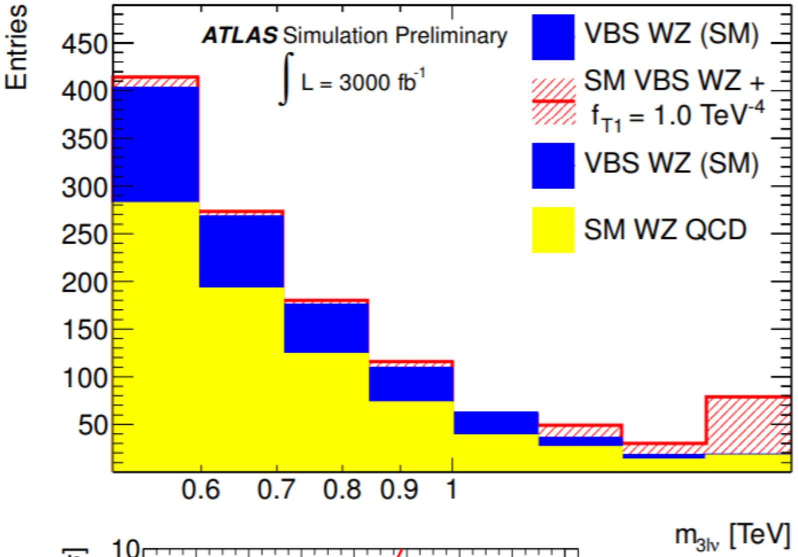
	Phase I (TeV^{-4})	Phase II (TeV^{-4})	Phase I aged (TeV^{-4})	Run-I results (TeV^{-4})
S_0	2.47	2.49	2.85	43 [12]
S_1	8.19	8.25	9.45	131 [12]
M_0	1.88	1.76	2.03	4.6 [38]
M_1	2.54	2.38	2.72	1.7 [38]
M_6	3.78	3.54	4.05	69 [12]
M_7	3.42	3.24	3.75	73 [12]
T_0	0.17	0.17	0.19	3.4 [39]
T_1	0.078	0.070	0.080	2.4 [12]
T_2	0.25	0.23	0.25	7.1 [12]

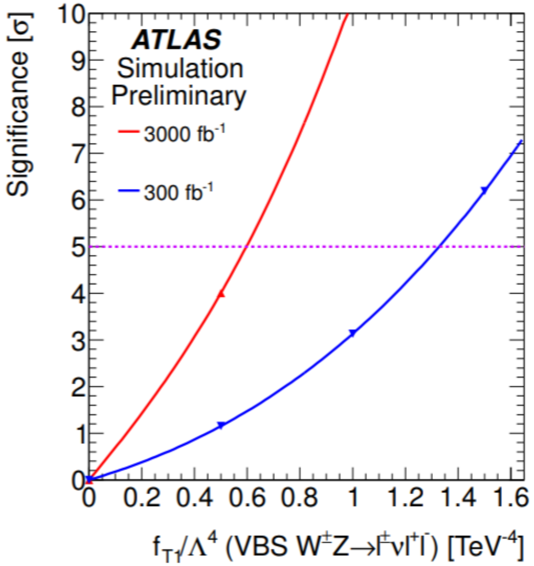
2.4 sigma for 3000 fb^{-1} for the LL part

VBS WZ→lvll

ATL-PHYS-PUB-2013-006

- Fully leptonic channel comes with a larger cross section comparing to VBS ZZ→4l
- m_{VV} can still be reconstructed by solving for the neutrino p_z using the W boson mass constraint
- Event selections
  - Exactly 3 leptons with pT > 25 GeV
  - One same-flavor, opposite-sign (SFOS) pair and one additional lepton
  - At least two jets with pT > 50 GeV
  - m_{jj} > 1 TeV (from two leading jets)
- Rather clean channel. Only irreducible QCD background considered





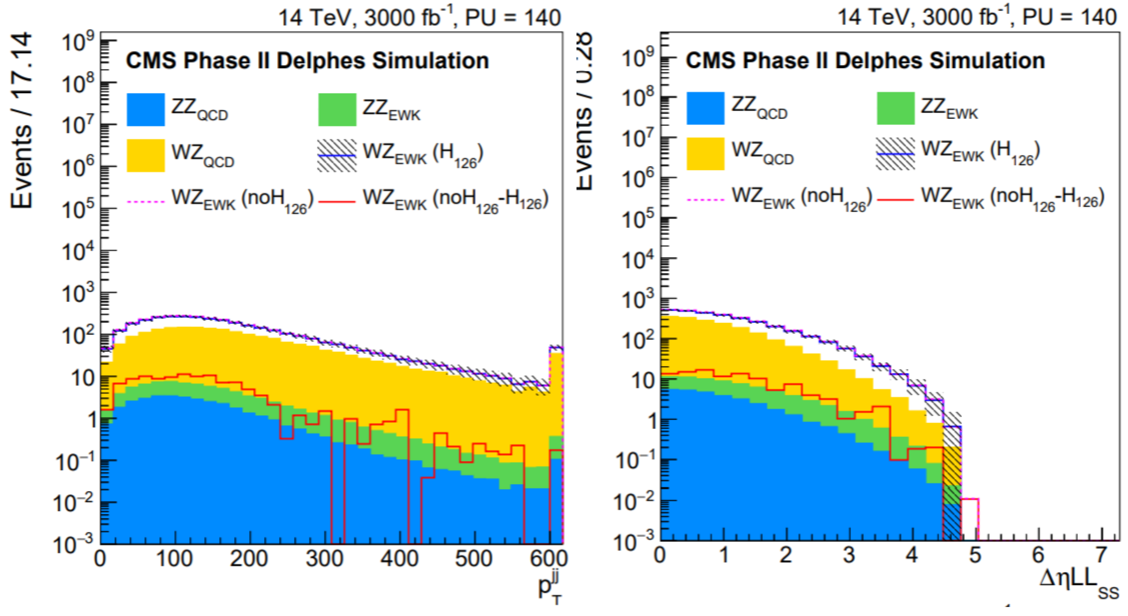
f_{T1} value for a 5 sigma discovery

	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
f_{T1}/Λ^4	$1.3\ \mathrm{TeV}^{-4}$	$0.6\ \mathrm{TeV}^{-4}$

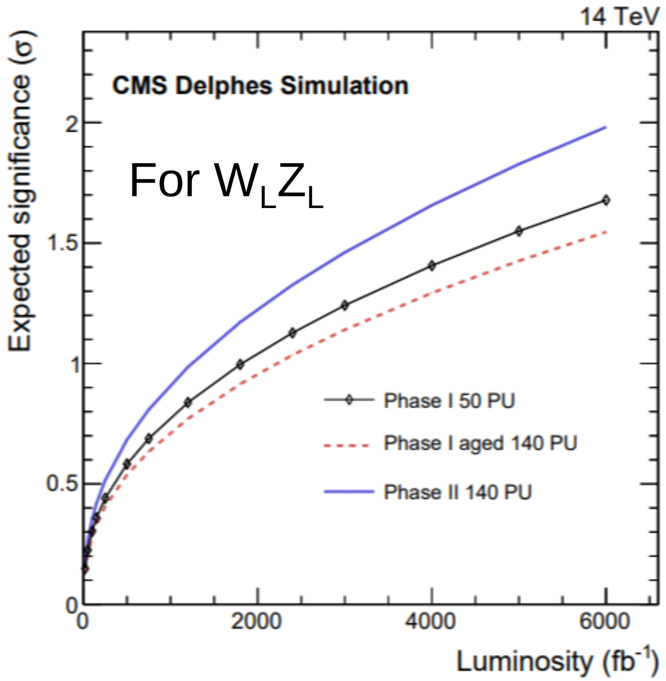
VBS WZ→lvll

[CMS-PAS-SMP-14-008](#)

- Event selections
  - Exactly 3 good leptons with pT > 20 GeV
  - One SFOS pair within 10 GeV Z mass
  - Two leading jets with pT > 30 GeV, invariant mass 600 GeV and pseudo-rapidity difference greater than 4
  - E_T^{miss} cuts and m_{ll} > 20 GeV for all SFOS pairs
- Considered background
  - QCD production of WZ and ZZ
  - EWK production of ZZ
- Similar 2D methods as ssWW for VBS results, with different observables



Phase II 140 PU
✓ Tracker up to |η| = 4
✓ Muon up to |η| = 3



VBS WZ/WW Combined (Leptonic Channels)

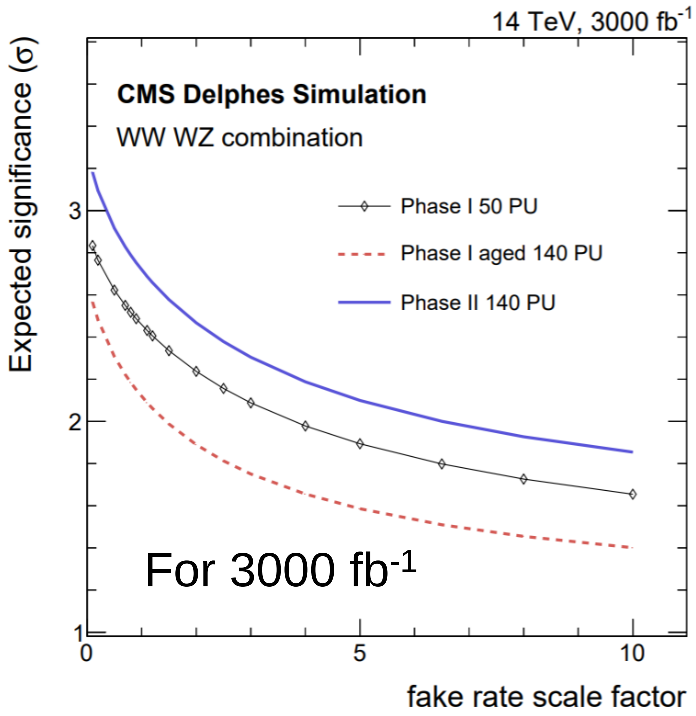
CMS-PAS-SMP-14-008

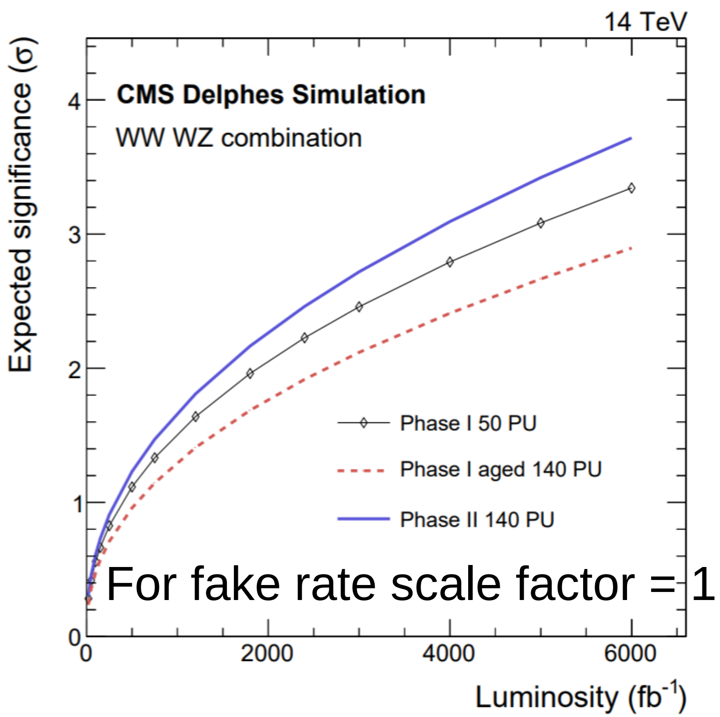
- Combined to determine the significance of the longitudinal part of VV scattering and the 95% CL limit on deviations from the SM due to partial unitarization schemes
- Correlations accounted between two analyses

	Phase I	Phase II	Phase I aged
noH 95% CL exclusion	0.14	0.14	0.20
LL scattering discovery significance	2.50	2.75	2.14

Promising from fully leptonic channel WW/WZ

Phase II 140 PU
- ✓ Tracker up to $|\eta| = 4$
- ✓ Muon up to $|\eta| = 3$



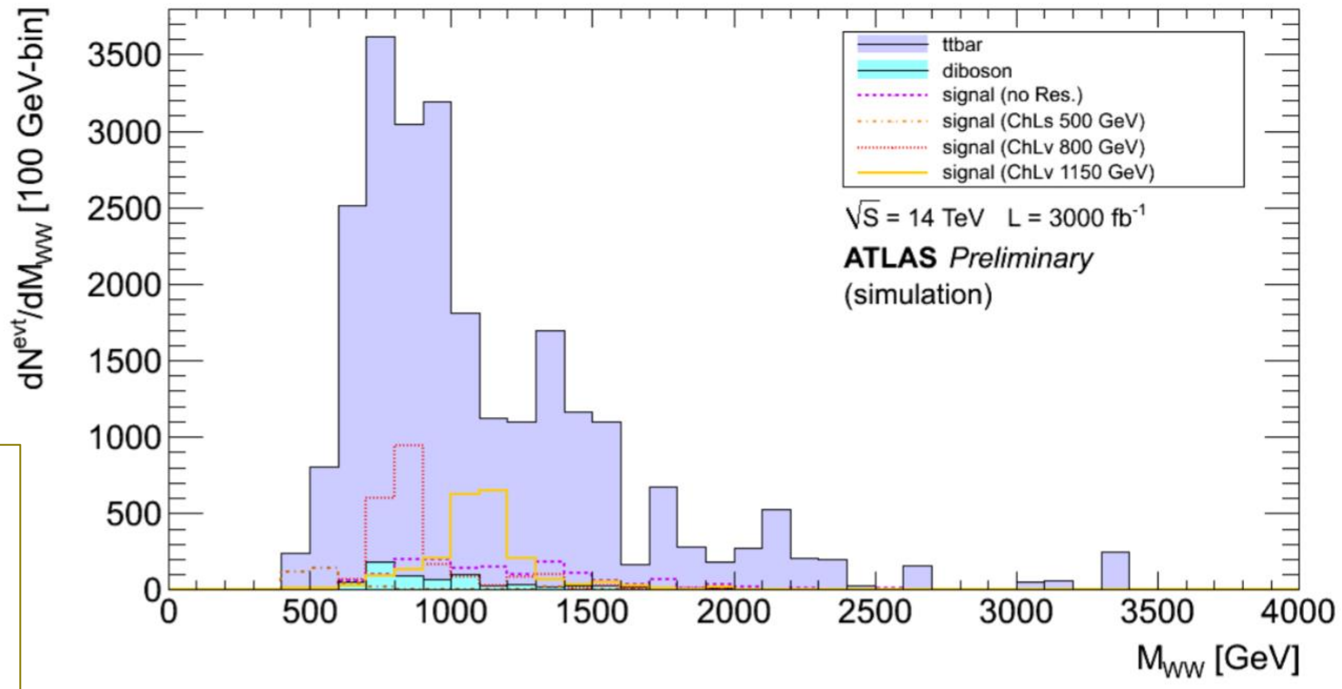


VBS WW→lvJ

[ATL-PHYS-PUB-2012-005](#)
[ATL-PHYS-PUB-2012-001](#)

- Larger branching ratio
- Only one neutrino there, better reconstructible
- Higher reconstruction efficiency for jet (merged jet especially in the boosted case) than leptons at high pT
- Disadvantage is also clear: large ttbar background

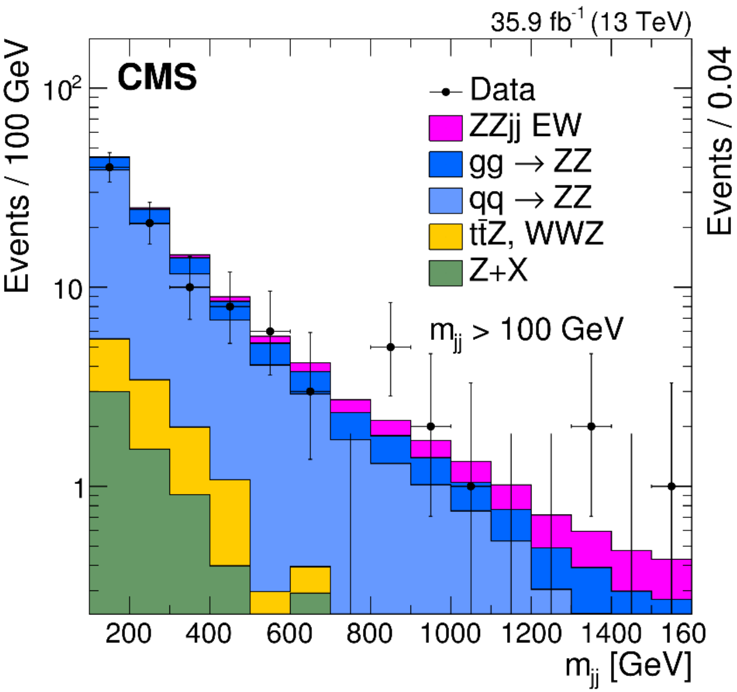
model	SM
(a_4, a_5)	$(0, 0)$
S/B	$(3.3 \pm 0.3)\%$
$S/\sqrt{B}\ (L = 300\text{fb}^{-1})$	2.3 ± 0.3
$S/\sqrt{B}\ (L = 3000\,\text{fb}^{-1})$	7.2 ± 0.1

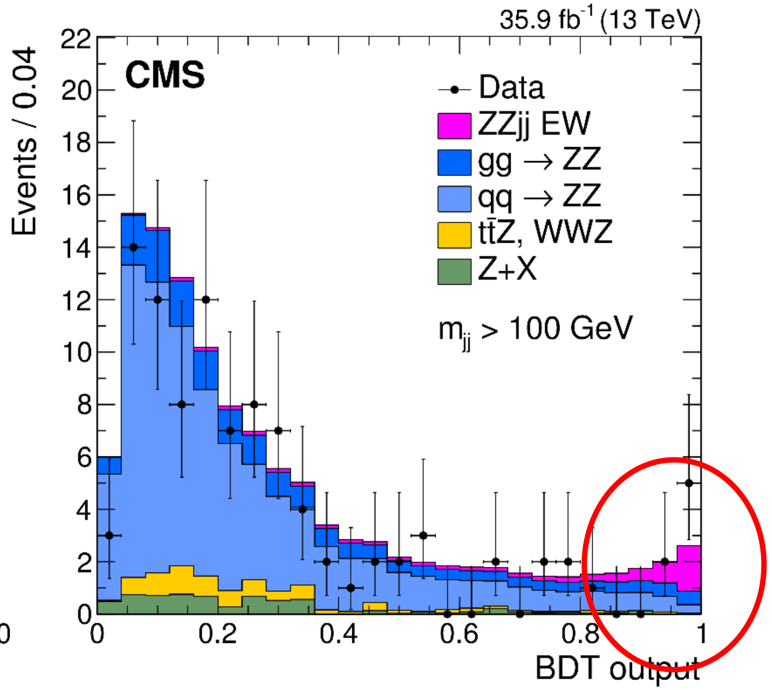


- ✓ One lepton with pT > 60 GeV, E_T^{miss} > 25 GeV
- ✓ Two AntiKt0.4 tag jets with pT > 40 GeV and η separation greater than 5, and m_{jj} > 250 GeV
- ✓ One AntiKt0.6 W-jet with pT > 300 GeV and mass around W boson

Current VBS ZZ→4l @13 TeV

Phys. Lett. B 774 (2017) 682





Observed (expected) significance of 2.7 (1.6) sigma from EWK processes

$$\mu = 1.39^{+0.72}_{-0.57}\,(\text{stat})\,^{+0.46}_{-0.31}\,(\text{syst}) = 1.39^{+0.86}_{-0.65}$$

- ✓ gg→ZZ plus two jets diagrams have large contribution, in the EWK sensitive region.
- ✓ Even more important than the QCD qq→ZZ processes at the high m_{jj} region

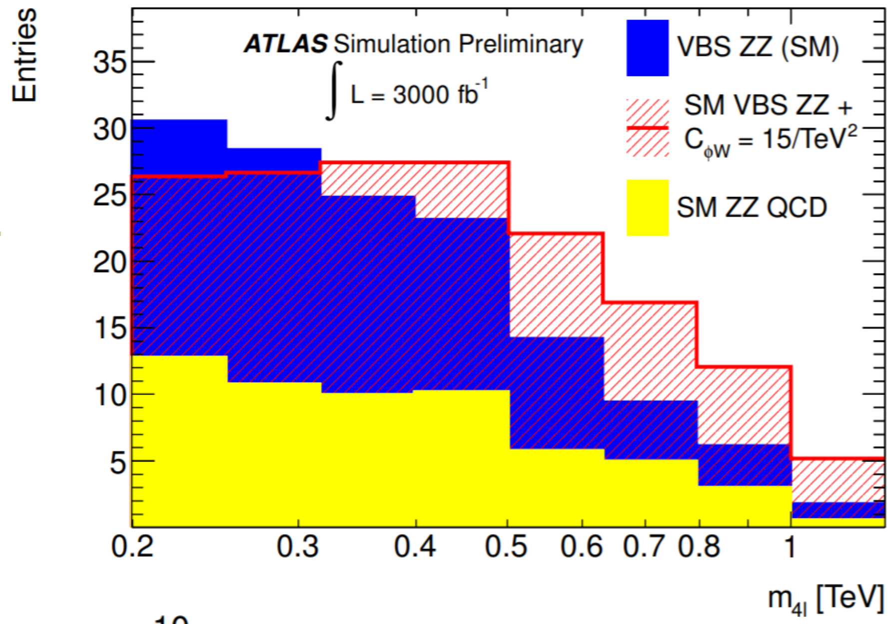
General event selections

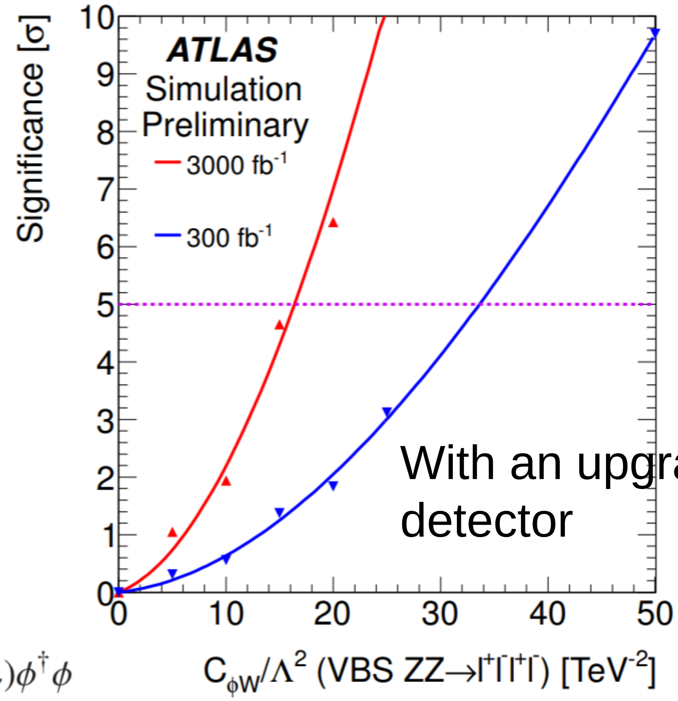
- ✓ 4 isolated leptons forming two SFOS pair around Z mass
- ✓ Two jets with m_{jj} > 100 GeV
- ✓ BDT method to extract the EWK VBS component

Future VBS ZZ→4l

ATL-PHYS-PUB-2013-006

- Cleanest channel with fully reconstructible ZZ final state
- Small cross section
- → Benefits a lot from the HL-LHC and hopefully not suffers too much from the high PU
- Event selections
  - Exactly 4 good leptons with pT > 25 GeV
  - Two SFOS pairs
  - m_{jj} > 1 TeV with two leading jets, with pT > 50 GeV
- Only considered SM QCD ZZ background





With an upgraded ATLAS detector

$$\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2}\mathrm{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$$

Summary

- VBS measurements will be a key part of the HL-LHC program, and benefit a lot from the higher luminosity and larger detector coverage in forward region
- Evidence of longitudinal VV scattering being possible
- Suffer from higher PU especially for tagging forward jets
  - How to pick up the correct two tag jets
  - Jets related uncertainties
- Background component depends on final states, but the irreducible QCD VV + 2jets processes have large contribution in many channels
- gg box diagrams give also large contribution for ZZ→4l channel
- Much improved limit on aQGCs

backup

Same-sign VBS WW→lvlv in Future

ATL-PHYS-PUB-2017-023

	Applied range for jet vertex requirement	Lepton η range
No forward tracking	$\lvert\eta_{\mathrm{jet}}\rvert \leq 2.5$	$\lvert\eta_{e,\mu}\rvert \leq 2.7$
Forward tracking for jets only	$\lvert\eta_{\mathrm{jet}}\rvert \leq 3.8$	$\lvert\eta_{e,\mu}\rvert \leq 2.7$
Forward tracking for jets and electrons	$\lvert\eta_{\mathrm{jet}}\rvert \leq 3.8$	$\lvert\eta_{e}\rvert \leq 4.0$, $\lvert\eta_{\mu}\rvert \leq 2.7$
Forward tracking for jets, electrons and muons	$\lvert\eta_{\mathrm{jet}}\rvert \leq 3.8$	$\lvert\eta_{e,\mu}\rvert \leq 4.0$

CMS Upgrade Scenarios

Phase I: the CMS detector in the Phase-I configuration [26], which will allow to collect 300 fb^{-1} of integrated luminosity, assuming no degradations due to radiation, and 50 pile-up events per collision on average.

Phase I aged: the CMS detector in the Phase-I configuration [26], in which detector upgrades are assumed not to degrade with radiation, while an intermediate aging after 1 ab^{-1} of integrated luminiosity with 140 pile-up events on average is considered for the barrel calorimetric system.

Phase II: the fully upgraded Phase-II CMS detector, with 140 pile-up events per collision on average. The upgrades are a new radiation-tolerant tracker, with granularity increased by a factor four with respect to the current one, and coverage extended until $|\eta| = 4$; new endcap calorimeters with high granularity and fine longitudinal segmentation; muon detectors improved in redundancy for $1.5 < |\eta| < 2.5$ and extended until $|\eta| = 3$.