Status of VBS measurements at the LHC

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On behalf of ATLAS+CMS collaborations

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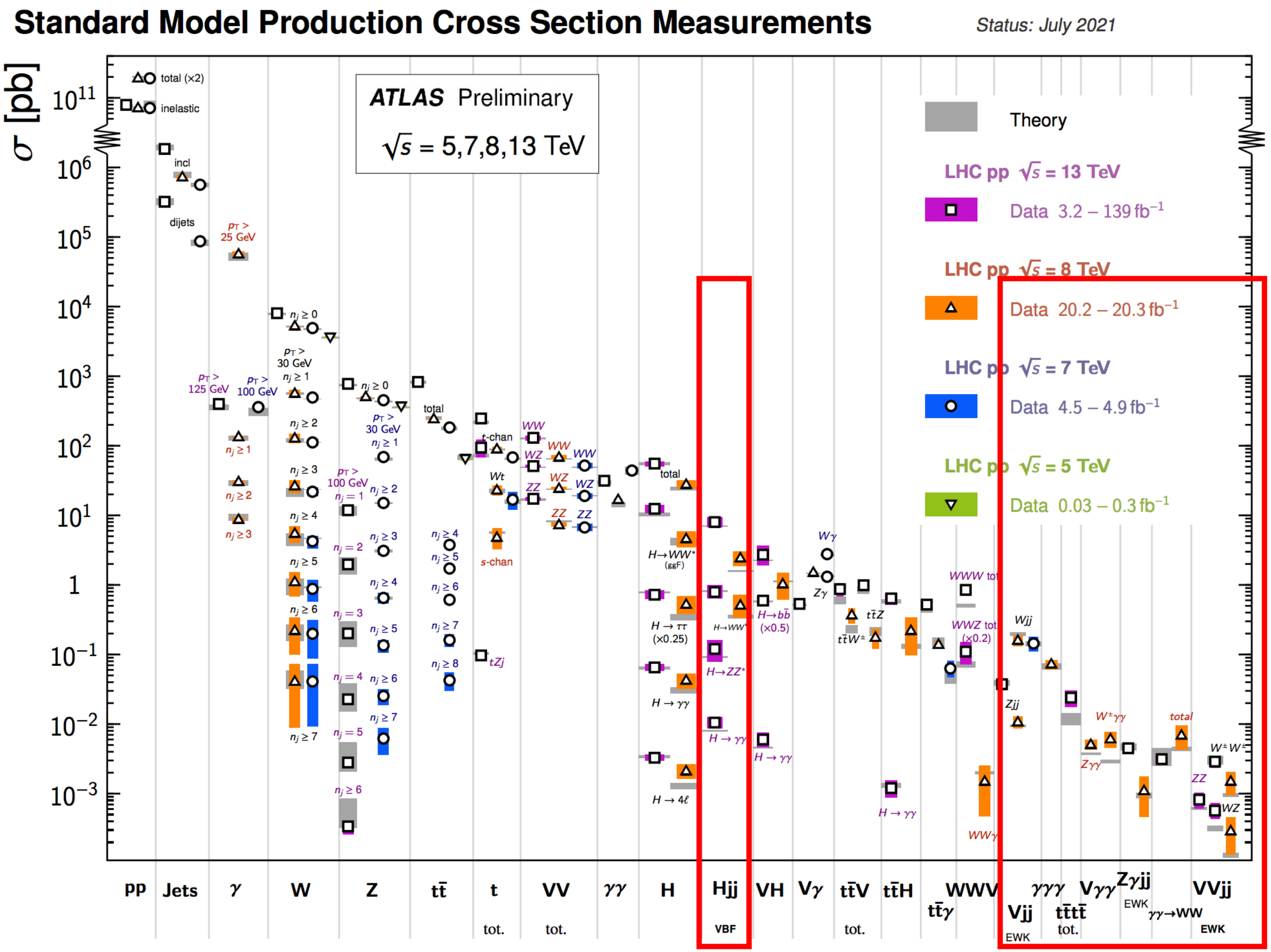
Tsung-Dao Lee Institute

ATLAS EXPERIMENT

CMS Compact Muon Solenoid

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

SM measurements in a nutshell

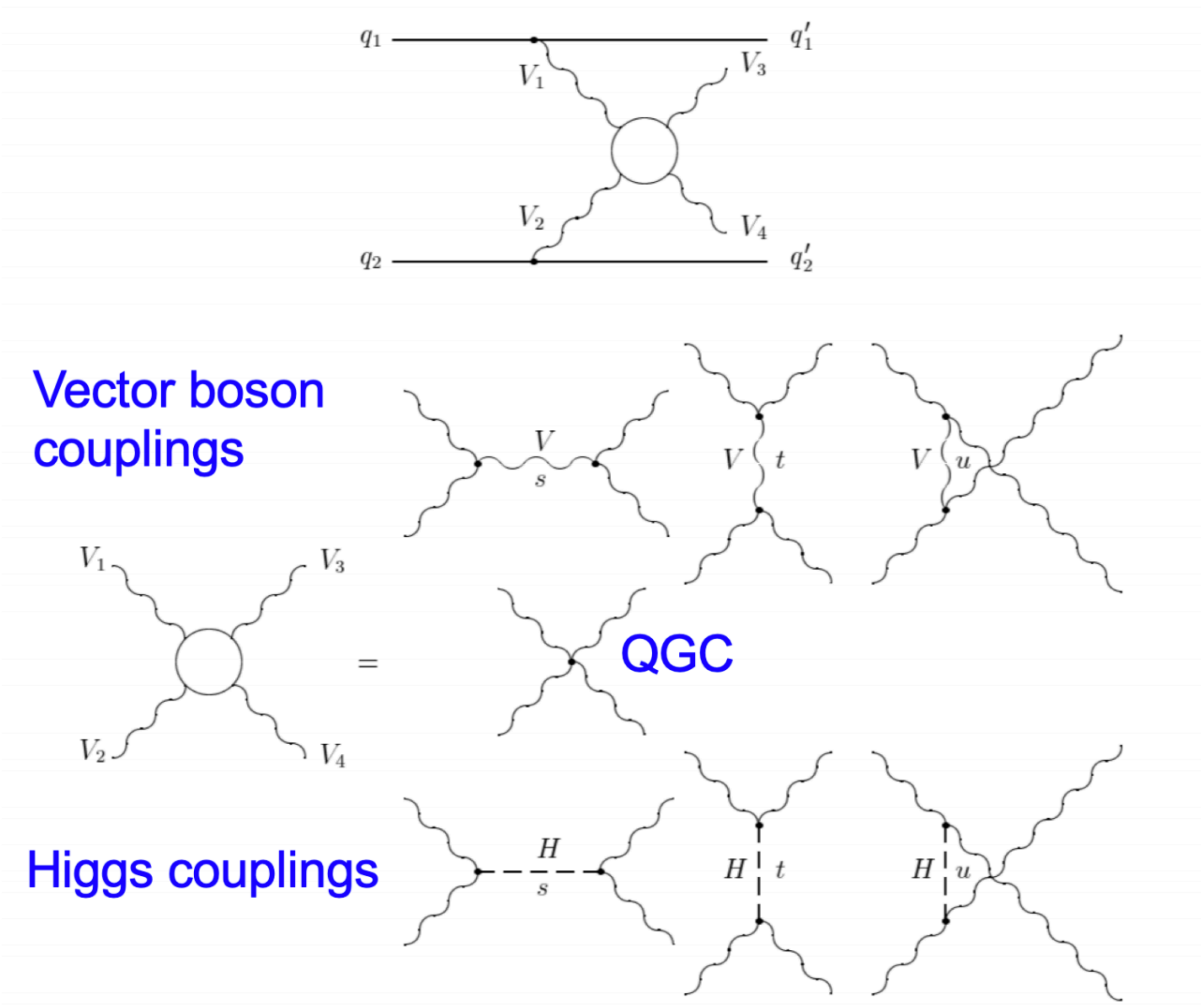


Measurements of Multi-Boson Production processes:

At the moment including diboson/triboson/ ***VBS***/VBF/… (Vγ/Vγγ/VVγ but not γγ/γγγ)

VBS, being the rare processes in SM at LHC, desire a good discrimination against enormous backgrounds.

Vector Boson Scattering topology in a nutshell

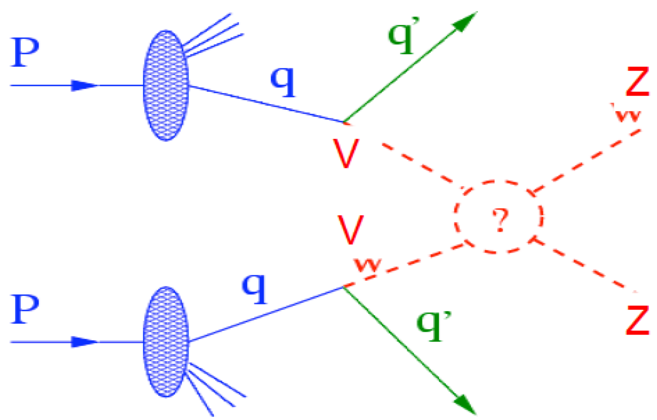


Vector Boson Scattering (VBS) is a key process
to probe the mechanism of electroweak symmetry breaking.

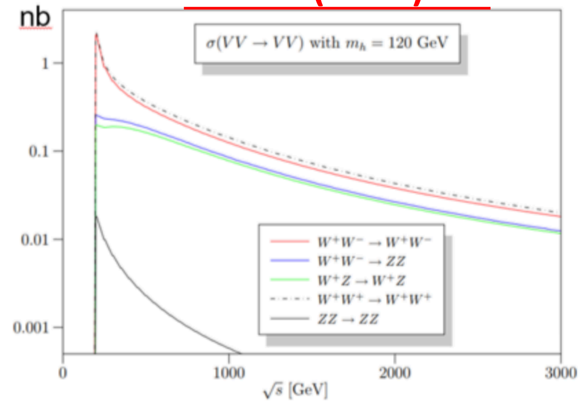
Main interest of VV scattering

Unitarity violation of Vector Boson Scattering

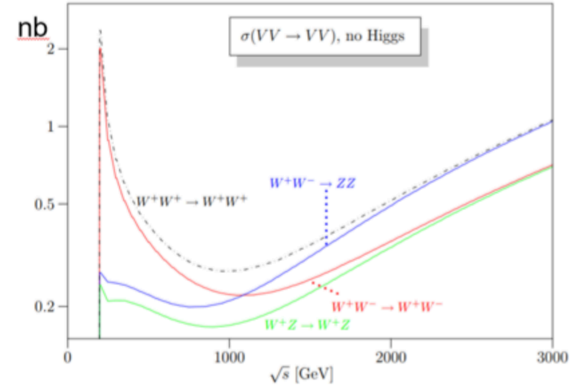
$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) \sim \frac{s}{M_W^2}$$



JHEP11(2008)010



w/ Higgs



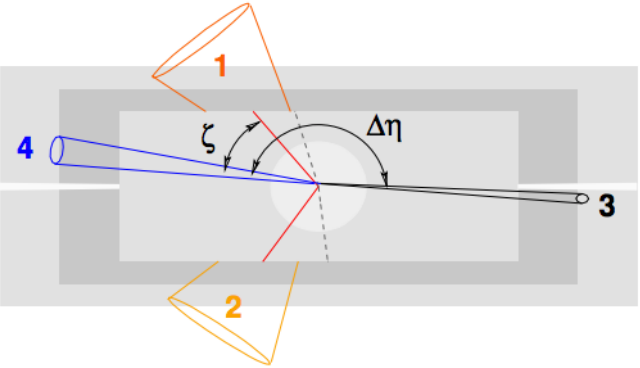
w/o Higgs

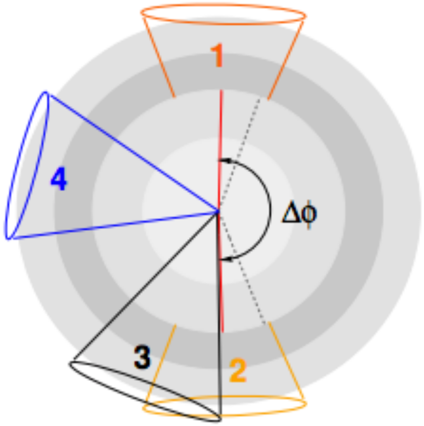
The m_h = 125 GeV Higgs will unitarize VV→VV scattering provided it has SM hVV couplings. This can be carefully examined by either

- Precise measurements of the hVV couplings at the light Higgs resonance
- Measurement of VV→VV differential cross sections at high p_T and invariant mass

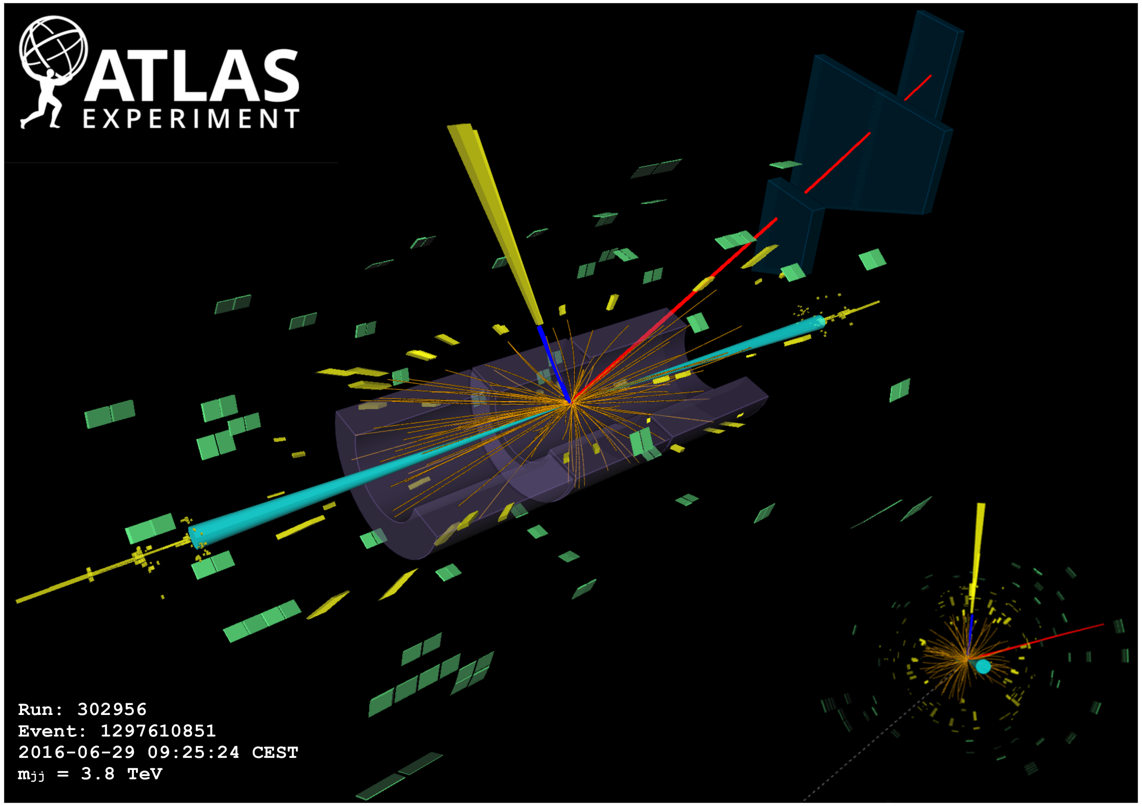
VBS signature in short

- Typical VBS topology
  - tagging jets:
    - transverse momenta: pT(j1), pT(j2)
    - invariant mass: M(jj)
    - rapidity difference: ΔY(jj)
  - central jet veto
  - centrality: $\max\left(\left|\frac{y_i - 0.5(y(j_1)+y(j_2))}{y(j_1)-y(j_2)}\right|\right)$
  - p_T balance: $\frac{\sum_i \vec{p_{T}}_i}{\sum_i |\vec{p_{T}}_i|}$
    - All hard process decay products and jets





An example event display of VBS signatures



- A clean signature of VBS like-sign WW pair production w/ forward-backward jets and central like-sign leptons
- Observed by CMS (2017) and ATLAS (2018) at >5σ significance

Experimental challenges per final states

channel	final state	comment *
Observed! VBF W	$\ell\nu$ jj	statistics is not a problem, good modelling of W+jets needed
Observed! VBF Z	$\ell\ell$ jj	statistics is not a problem, good modelling of Z+jets needed
Observed! VBS $W^{\pm}W^{\pm}$	$\ell^{\pm}\nu\ell'^{\pm}\nu$ jj	"golden channel": very good EW/QCD ratio, mainly experimental (charge misID) background, good statistics
VBS $W^{\pm}W^{\mp}$	$\ell^{\pm}\nu\ell'^{\mp}\nu$ jj	hard to investigate due to dileptonic ttbar background, Higgs group does also use this final state
Observed! VBS WZ	$\ell\ell\ell'\nu$ jj	similar cross section as ssWW, but larger QCD background, fair reconstructibility of fs
Observed! VBS $W\gamma/Z\gamma$	$\ell\nu\gamma$ jj / $\ell\ell\gamma$ jj	photon brings higher stat. (and different experimental systematics), lacks sensitivity to BSM in Higgs sector
VBS WV	$\ell\nu$jj jj	large backgrounds (W+jets, ttbar), but promising boosted regime when looking for NP effects
VBS ZV	$\ell\ell$jj jj	large backgrounds (Z+jets, ttbar), but promising boosted regime when looking for NP effects, no neutrinos in final state
VBS ZZ	$\ell\ell\ell'\ell'$ jj	very clean channel, very good reconstructibility of final state and low background contamination, but small cross-section
Observed! VBS ZZ	$\ell\ell\nu\nu$ jj	challenging to measure invisible Z decay, combination with leptonic decay might help to suppress dileptonic ttbar background

https://indico.desy.de/event/7512/contributions/82684/attachments/55321/67389/aQGCWS.pdf P. Anger

Summary of VBS Observations at LHC

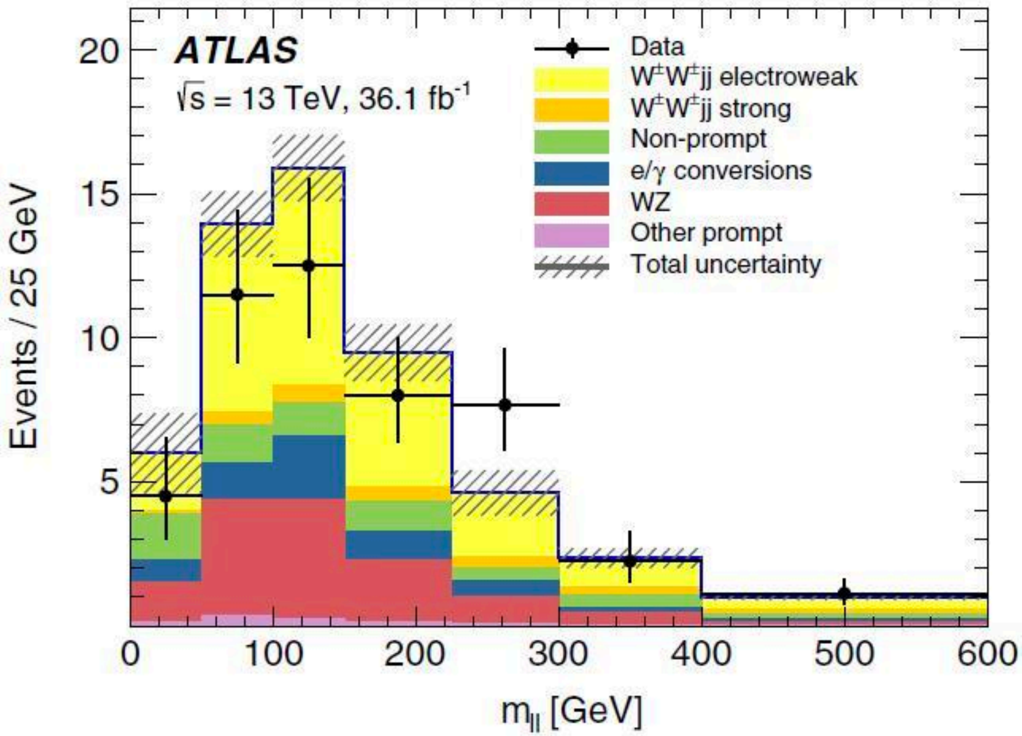
Today's MAIN COURSE…

	$W^{\pm}W^{\pm}jj$	WZjj	ZZjj	$W\gamma jj$	$Z\gamma jj$	$\gamma\gamma \rightarrow WW$
CMS 13TeV	5.5σ	6.8σ	4.0σ	5.3σ	9.4σ	x
ATLAS 13TeV	6.5σ	5.3σ	5.5σ	x	10σ	8.4σ

- Quite a large topic with many different channels
- Fruitful accomplishments at LHC on VBS observations
- Will go through the complete list of these channels with a bit more details on more recent observations.

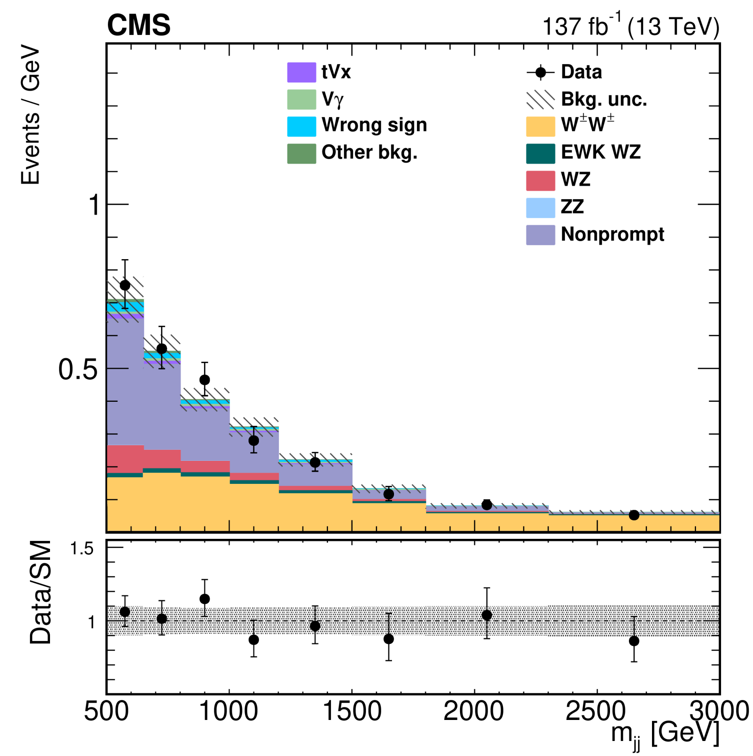
Former Highlights: observation of same-sign WW VBS processes at CMS/ATLAS

Phys. Rev. Lett. 123 （2019） 161801



Phys. Rev. Lett. 120 (2018) 081801

Phys. Lett. B 809 (2020) 135710



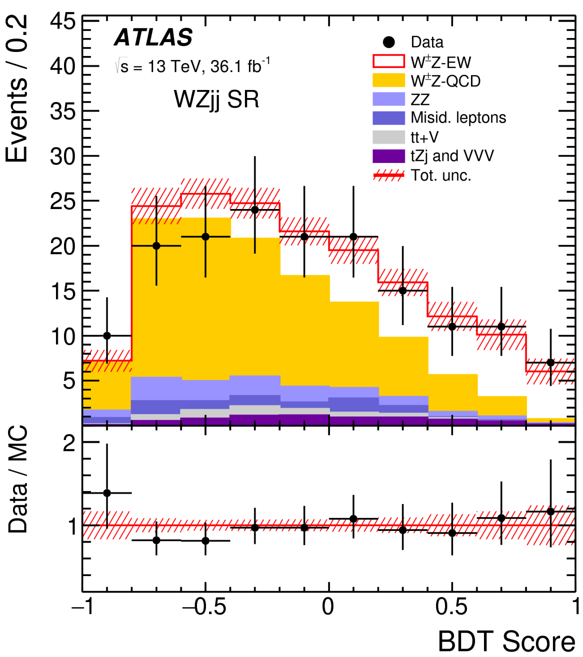
1st evidence (>3σ) by ATLAS (2014)

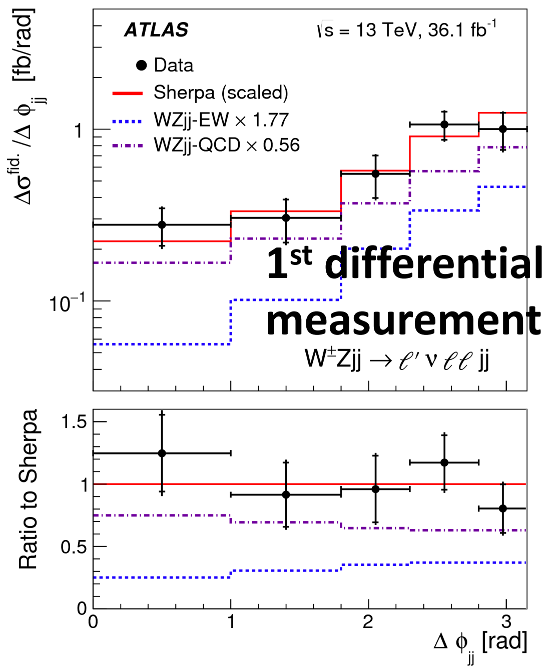
1st observation (>5σ) by CMS in 2017 (published in 2018) followed by ATLAS observation (published in 2019)

http://atlas.cern/updates/physics-briefing/weak-lightsabers

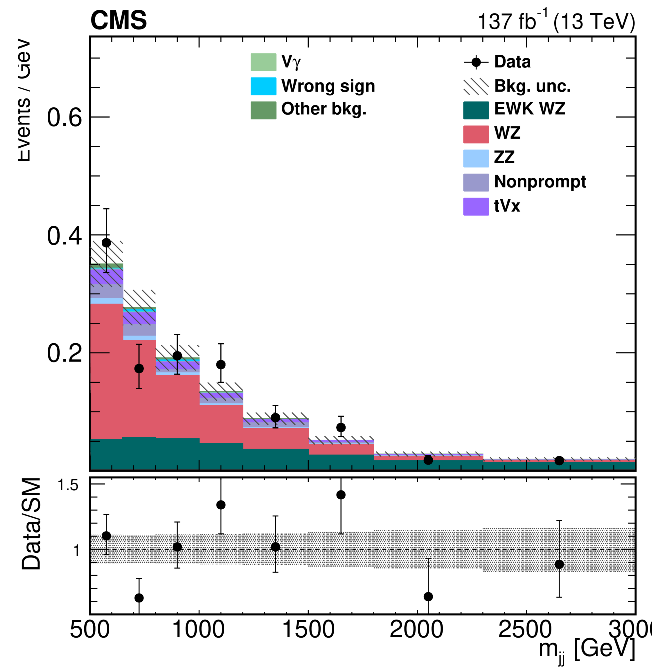
Former Highlights: 1st observation of WZ VBS processes by ATLAS at LHC

Phys. Lett. B 793 (2019) 469





Phys. Lett. B 809 (2020) 135710



1st observation (>5σ) by ATLAS in ICHEP2018 highlight (published in 2019) followed by CMS observation (published in 2020)

http://atlas.cern/updates/physics-briefing/weak-lightsabers

Former Highlights: 1^{st} observation of ZZ VBS process at LHC

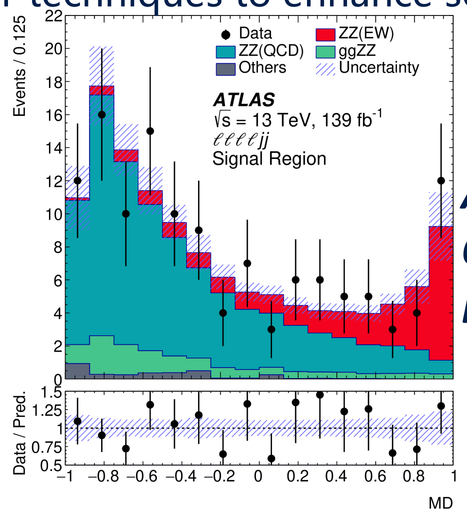
Combine 4l and 2l2v results
BDT techniques to enhance sensitivity

Discriminant based on a matrix element likelihood approach (MELA) for EW and EW+QCD measurements

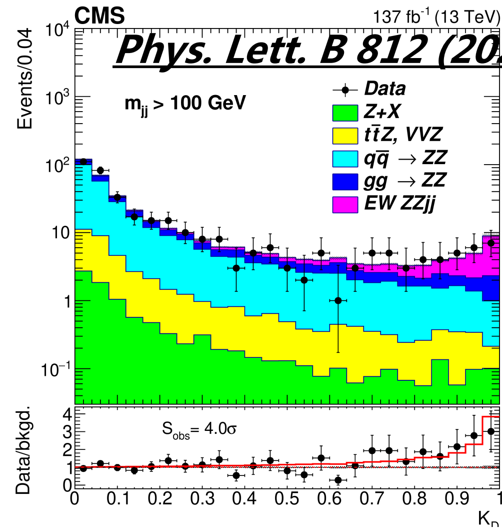
1st Observation
Utilizing 139 fb^{-1} full Run-2 data

EPS-HEP2019 Highlight:
ATLAS-CONF-2019-033

arXiv:2004.10612 under Nature Physics Review

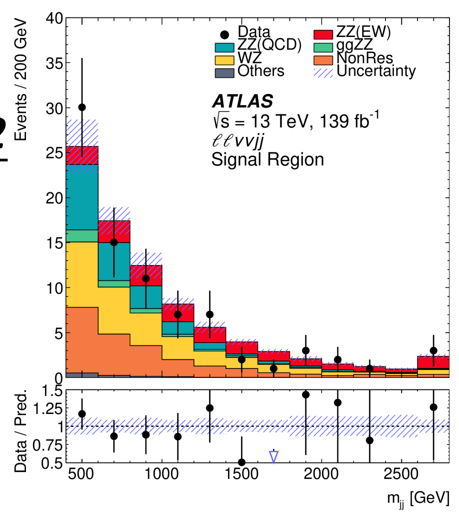


ATLAS
Obs. 5.5 σ
Exp. 4.3 σ



Phys. Lett. B 812 (2020) 135992

CMS
Obs. 4.0 σ
Exp. 3.5 σ



- BDT input variables, 4l BDT
  - m_{jj}, $\Delta y(j,j)$
  - $p_T^{j_1}$, $p_T^{j_2}$
  - y_{Z1}, y_{Z2}
  - $y_{j1} \times y_{Z2}$
  - m_{4l}, p_T^{4l}
  - p_T of the third lepton
  - p_T of the Z boson with mass closer to the nominal Z boson mass
  - $p_T^{ZZjj}/(p_T^{j_1} + p_T^{j_2} + p_T^{Z1} + p_T^{Z2})$

BDT inputs for ATLAS

- BDT input variables, 2l2v BDT
  - m_{jj}, $\Delta y(j,j)$
  - $p_T^{j_2}$
  - $y_{j1} \times y_{Z2}$
  - $p_T^{ZZjj}/(p_T^{j_1} + p_T^{j_2} + p_T^{Z1} + p_T^{Z2})$
  - MET, MET significance
  - $\Delta\eta(l,l)$, $\Delta\phi(l,l)$, $\Delta R(l,l)$, m_{ll}
  - $p_T^{l_1}$, $p_T^{l_2}$

https://atlas.cern/updates/briefing/milestone-electroweak-symmetry-breaking

arXiv:2106.11082 Submitted to PRD

1^{st} observation of EWK Z(ll)γjj process w/ CMS full Run2

Basic event selection
- Two same-flavor opposite-sign tight leptons ★
- Double muon/electron HLT paths
- Third lepton veto
- 70 GeV $< M_{ll} <$ 110 GeV ★
- One good photon in barrel/endcap ★
- Two jets with $p_T > 30$ GeV, $|\eta|<4.7$ ★

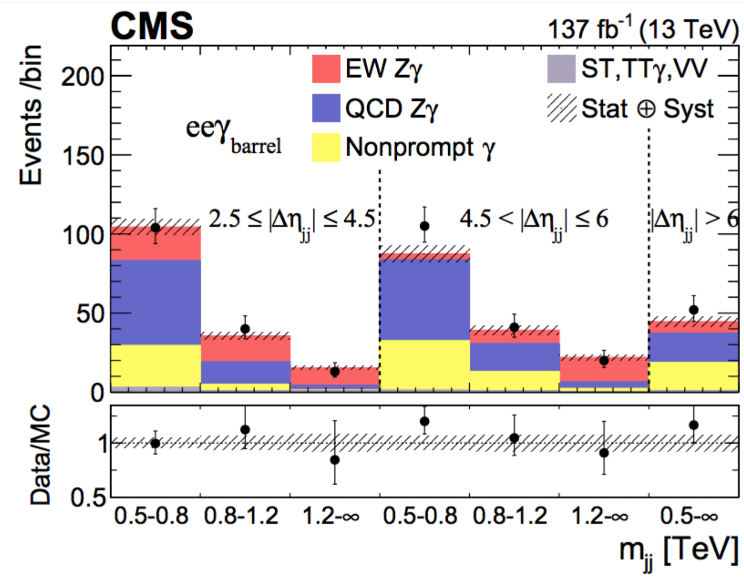
Suppress FSR
- $M_{ll\gamma} > 100$ GeV

Low mjj control region
- 150 GeV $< M_{jj} <$ 500 GeV

VBS Signal region
- $M_{jj} > 500$ GeV ★
- $\Delta\eta_{jj} > 2.5$ ★

For aQGC
- $p_T^{\gamma} > 120$ GeV

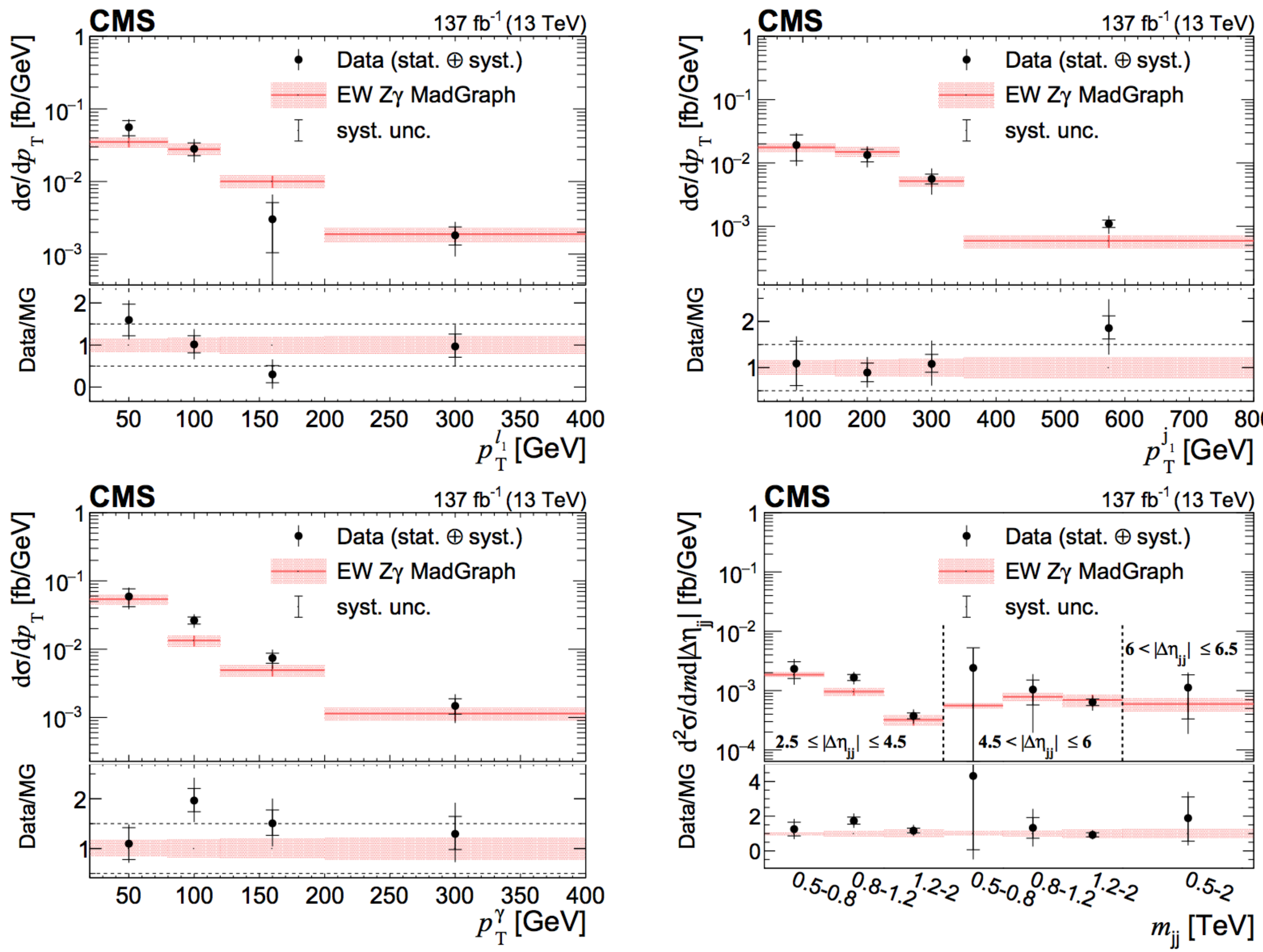
signal extraction
- zepp $= |\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2| < 2.4$
- dphi $= |\phi_{Z\gamma} - (\phi_{j1} + \phi_{j2})| > 1.9$



- The significance calculated w/ simul. fit in the signal region with 2D m_{jj}-$\Delta\eta_{jj}$ binning and the control region with 1D m_{jj} binning in 4 categories for μ/e and barrel/endcap photon
- Obs. (Exp.) significance: 9.4 σ (8.5 σ).

arXiv:2106.11082 Submitted to PRD

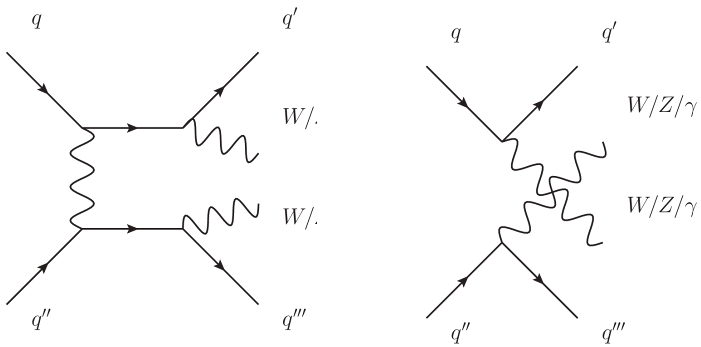
Differentially measured EWK Z(ll)γjj process w/ CMS full Run2



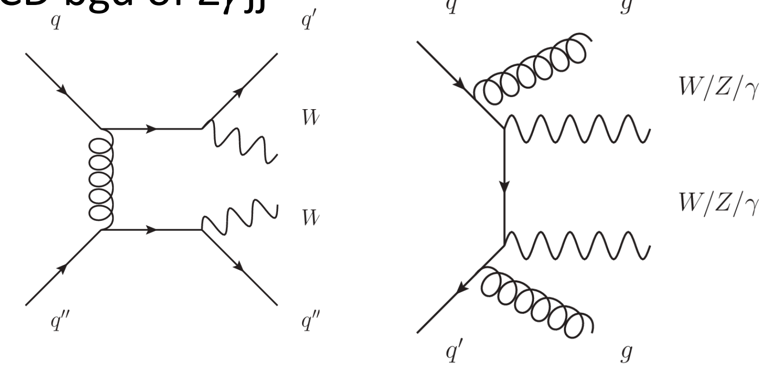
ATLAS-CONF-2021-38

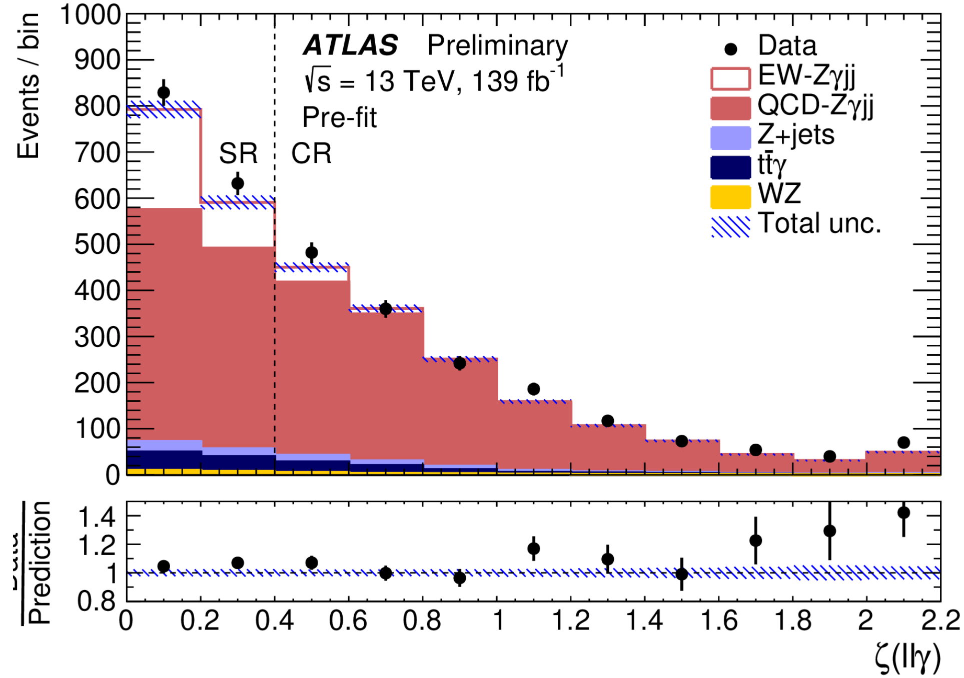
NEW: Observation of $Z\gamma$ VBS process in $ee/\mu\mu$ at ATLAS

EWK signal of $Z\gamma jj$



QCD bgd of $Z\gamma jj$





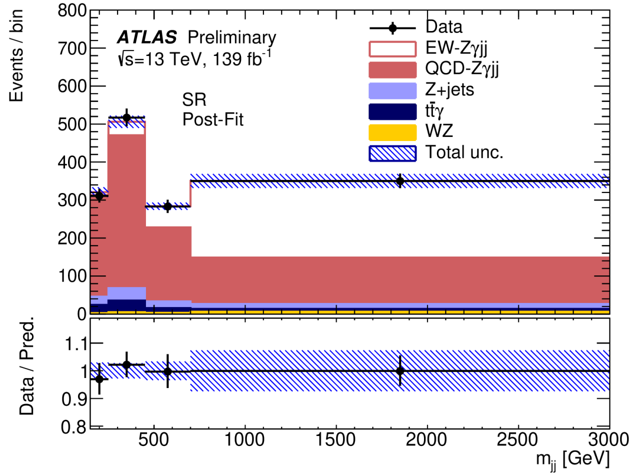
- Utilizing 139 fb^{-1} data of full Run-2
- EWK $Z\gamma$ signal is extracted with a maximum likelihood fit to the m_{jj} distributions in DATA simultaneously for SR and CR, relying on template MC distributions.
- Obs. Signif. ~10 **σ**

ATLAS-CONF-2021-38

Overview of the measured fiducial phasespace of $Z\gamma$ VBS

Lepton	$p_T^\ell > 20, 30$(leading) GeV, $\lvert\eta_\ell\rvert < 2.47$ $N_\ell \geq 2$
Photon	$E_T^\gamma > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_T^{cone20} < 0.07 E_T^\gamma$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_T^{jet} > 50$ GeV, $\lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150$ GeV remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40$ GeV $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$

Smart FSR rejection cut ($m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV)



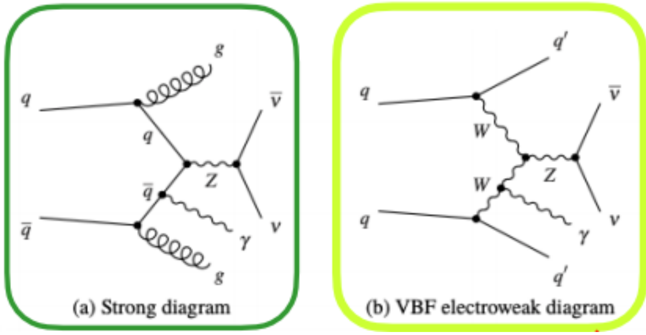
σ$_{EW}$(obs.) =
4.49 ± 0.40 (stat.) ± 0.42(syst.) fb

σ$_{EW}$(exp.) =
4.73 ± 0.01 (stat.) ± 0.15 (PDF)+0.23−0.22 (scale) fb

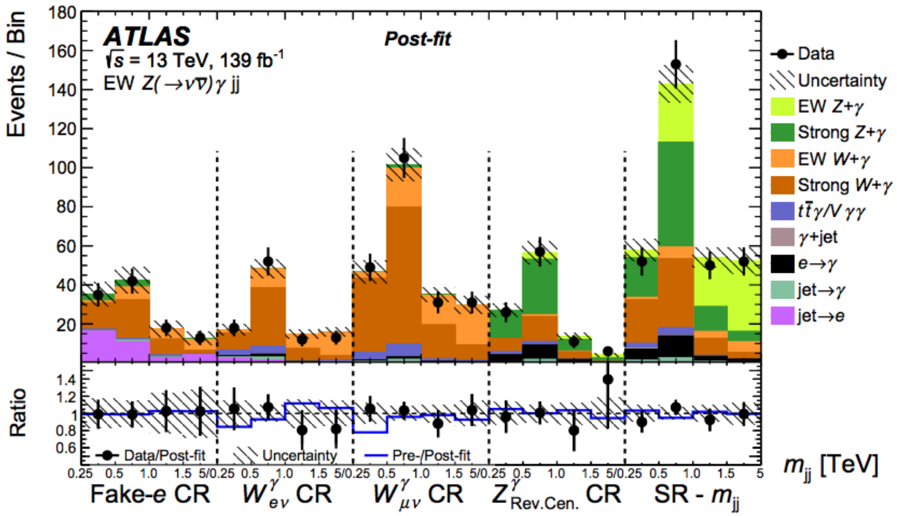
	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	±9	±1	±1	±5	$^{+6}_{-5}$	$^{+5}_{-4}$	±13

ATLAS-CONF-2021-004 **arXiv:2109.00925 [submitted to EPJC]**

NEW: 1st Observation of $Z\gamma$ VBS process in neutrino channels at ATLAS

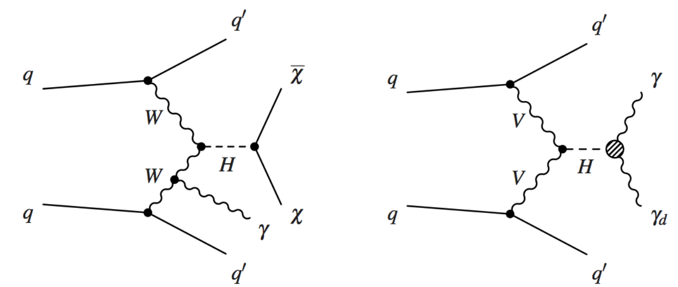


QCD Z($\nu\nu$)γjj **EWK Z($\nu\nu$)γjj**

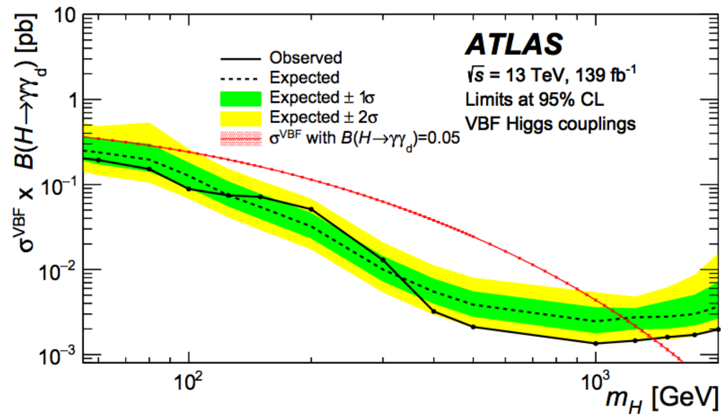


$\mu_{Z\gamma_{\rm EW}}$	$\beta_{Z\gamma_{\rm QCD}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

Obs.(Exp.) Significance: 5.2σ(5.1σ)



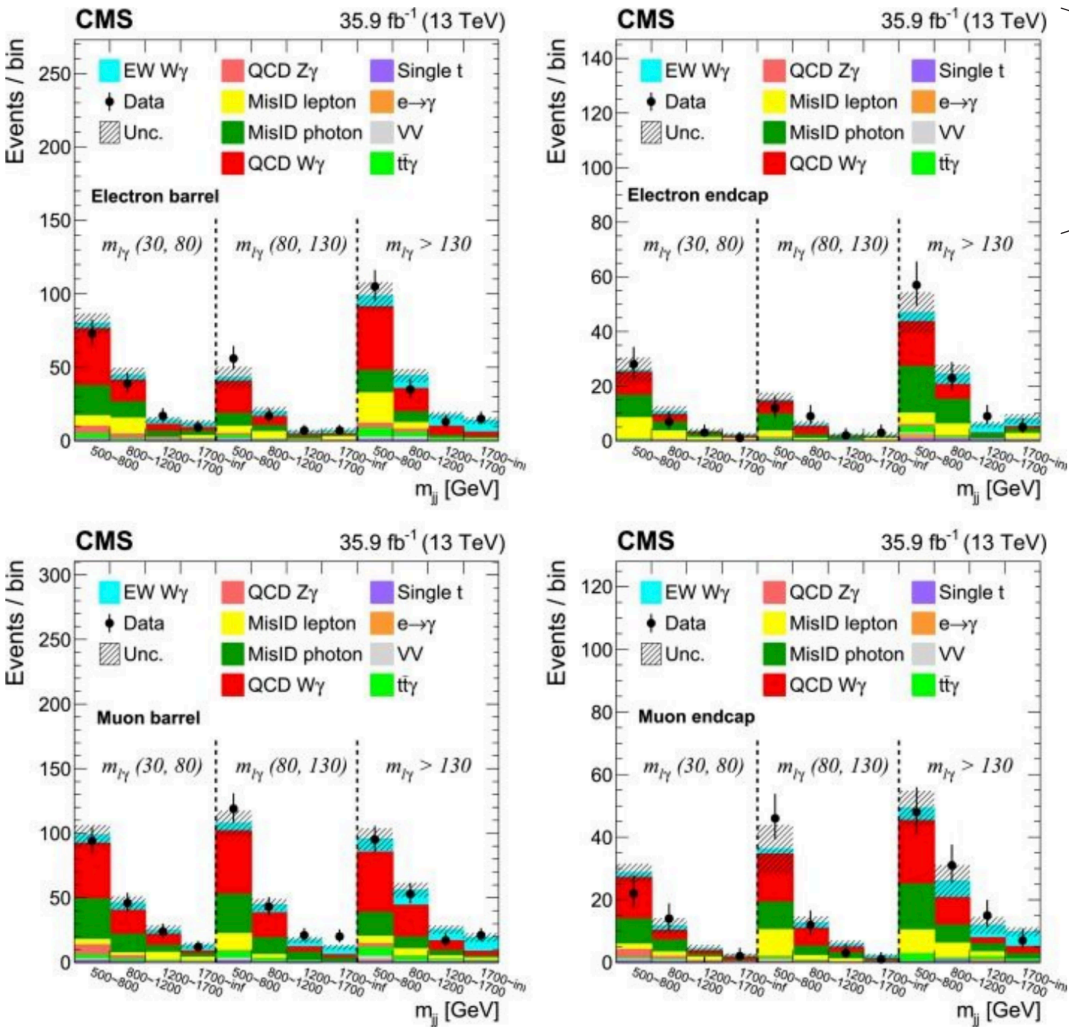
(a) Invisible Higgs boson signal (b) Dark-photon signal

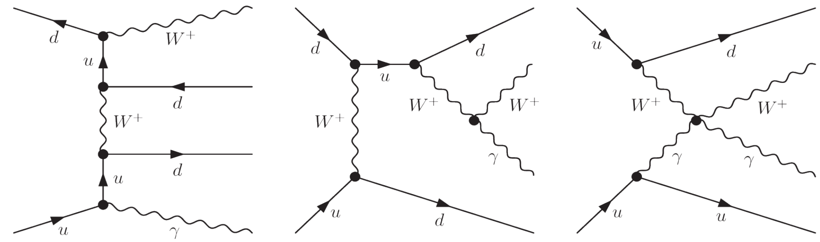


- Similar signatures used to provide strong constraints for:
- **invisible Higgs decay in VBF model with additional photon (0.37 (0.34+0.15−0.10) at 95% CL)**
- **VBF Higgs to dark photons: H→$\gamma\gamma$d(0.018 (0.017+0.007 −0.005) at 95% CL)**

Phys. Lett. B 811 (2020) 135988

1st observation of EWK Wγjj process by CMS





- First observation of the VBS Wγ production with leptonic final states
- Signal events are extracted from 2D m_{jj}-$m_{l\gamma}$ distribution
  - ☑ Simultaneous fit in the CR and SR

Obs. (Exp.) significance: 5.3σ (4.8σ)
1st observation at LHC by combining CMS 13TeV+8TeV

$$\sigma_{EW}^{theory} = 17.0 \pm 4.1 \text{ fb}$$

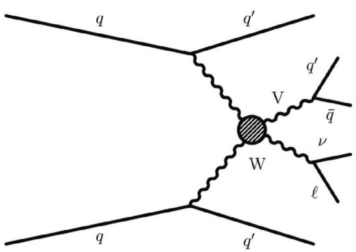
$$\sigma_{EW+QCD}^{theory} = 89.7 \pm 13.9 \text{ fb}$$

$$\sigma_{EW} = 20.4 \pm 4.5 \text{ fb}$$

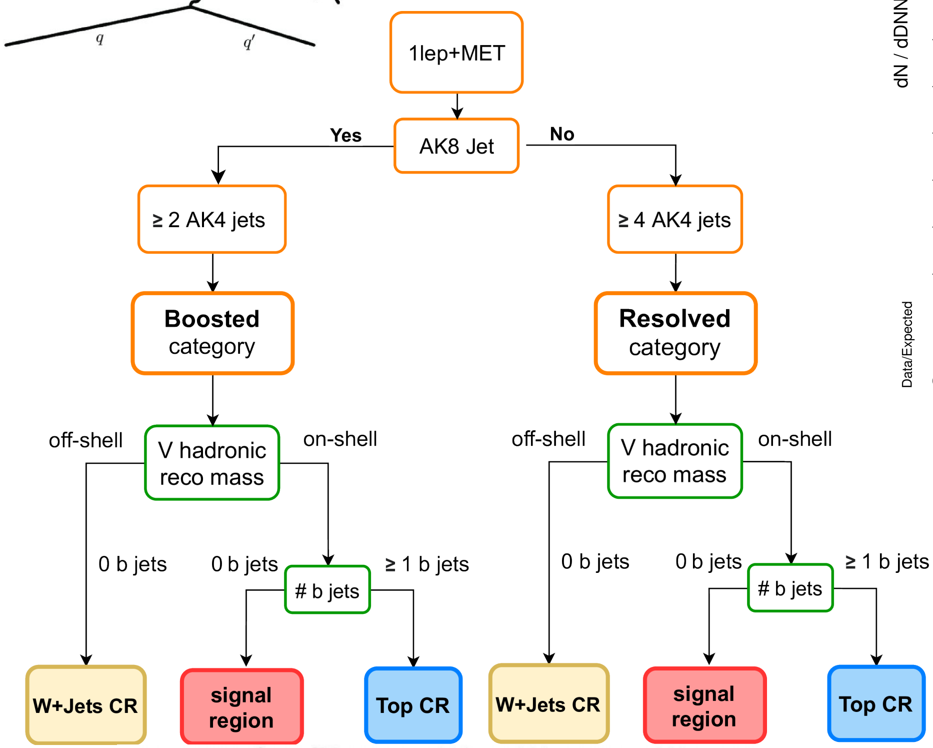
$$\sigma_{EW+QCD} = 108 \pm 16 \text{ fb}$$

[CMS-PAS-SMP-20-013]

Dive into complex final states: semi-leptonic VBS channels



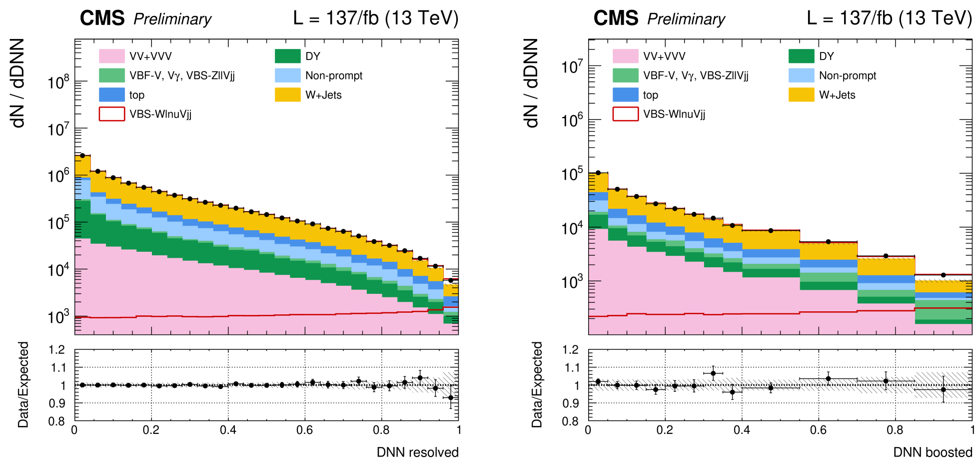
- Exploring challenging channels: VW->l+jets
- Larger XS than fully leptonic VBS channels

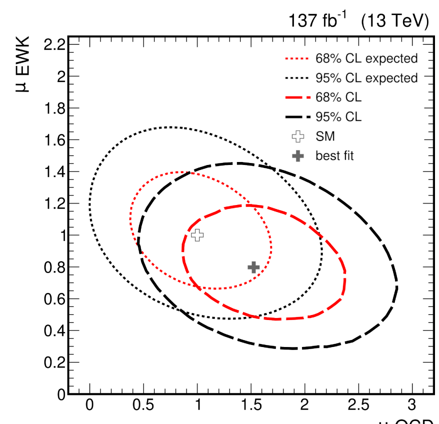


$$\mu_{EW} = \sigma^{\rm obs}/\sigma^{\rm SM} = 0.85^{+0.24}_{-0.20} = ^{+0.21}_{-0.17}\,(\text{syst.})\ ^{+0.12}_{-0.12}(\text{stat.})$$

$$\mu_{EW+QCD} = \sigma^{\rm obs}/\sigma^{\rm SM} = 0.98^{+0.20}_{-0.17} = ^{+0.19}_{-0.16}\,(\text{syst.})\ ^{+0.07}_{-0.07}(\text{stat.})$$

DNN trained in SR for signal and bgd separation. Different DNNs are used for resolved and boosted categories.



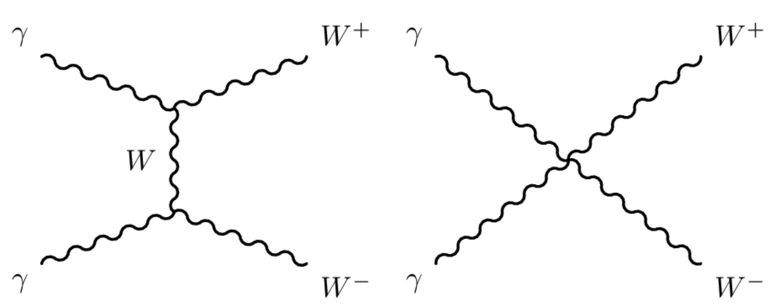


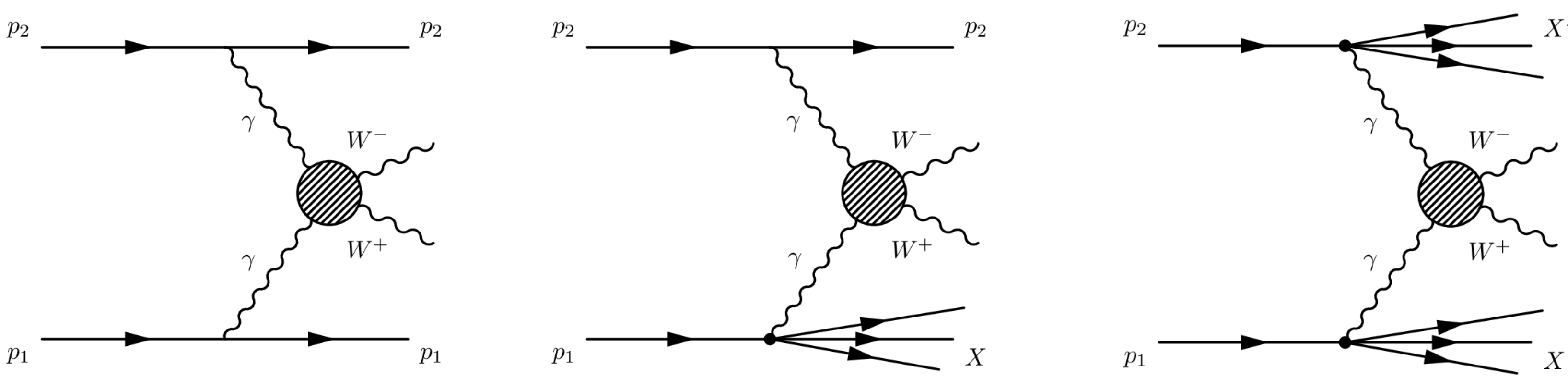
- Good agreements between data and MC prediction in both Boosted and Resolved.
- Obs./Exp. 4.4(5.1)σ

1st Observation of photon scattering into W boson pairs at ATLAS

- Photon-induced $W^{\pm}W^{\mp}$ via trilinear and quartic gauge-boson self-interactions
- probe the gauge structure of the electroweak
- $\gamma\gamma \rightarrow W^{\pm}W^{\mp}$ unique property among VBS-like diboson processes
  - NO diagrams NOT involving gauge-boson self-interactions are present at Born level

Phys. Lett. B 816 (2021) 136190

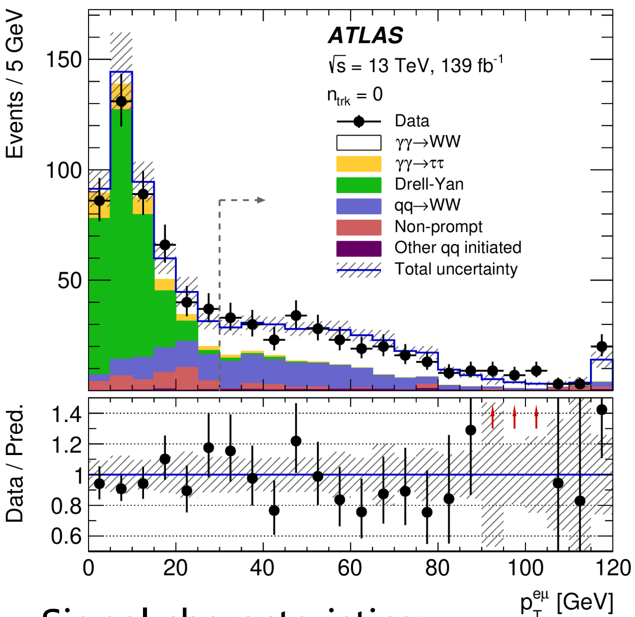


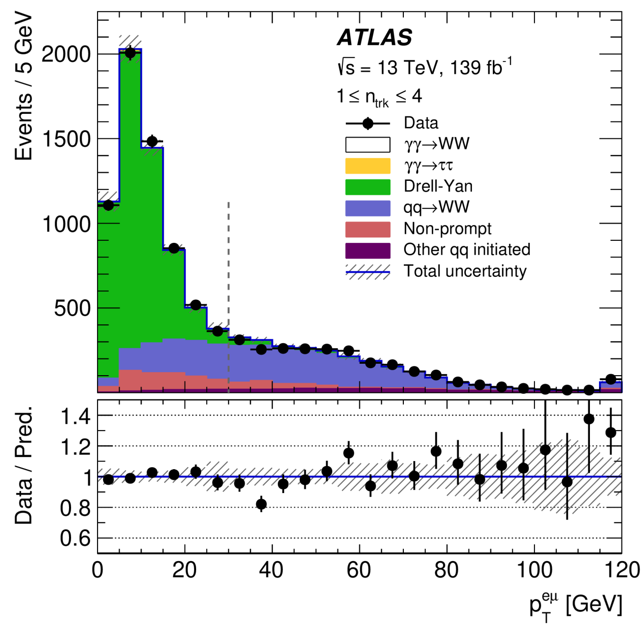


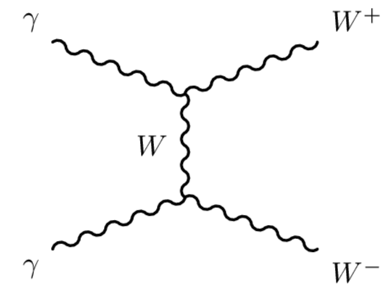
- Evidence for $\gamma\gamma \rightarrow W^{\pm}W^{\mp}$ production from Run-1: ATLAS, 3.0σ, CMS, 3.4σ
- w/ full Run2, ATLAS now obtain the **first observation at LHC**
- Signal process of $p\ p(\gamma\gamma) \rightarrow p\ (*)W+W-\ p\ (*)$ with **three contribution categories**: final-state proton either stays intact or fragments after emitting a photon, i.e. **elastic, single-dissociated and double-dissociated** WW production

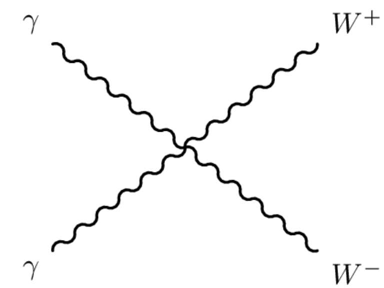
1st Observation of photon scattering into W boson pairs at ATLAS

Phys. Lett. B 816 (2021) 136190



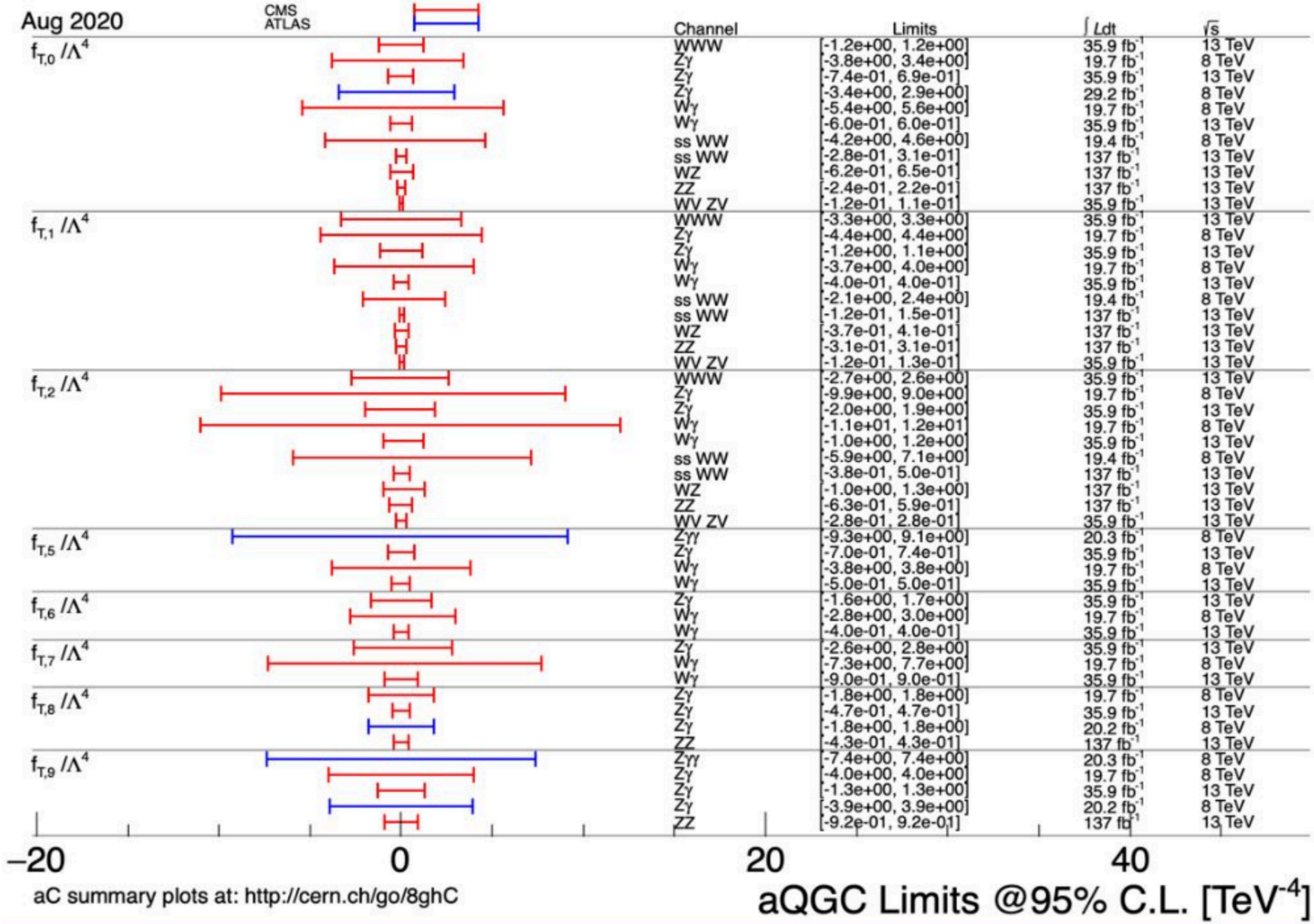






- Signal characteristics:
  - Charged leptonic decays of the W, no additional charged-particle activity.
  - $W^+W^- \rightarrow e^{\pm}\nu\mu^{\mp}$ to further enhance purity.
- Obs. (Exp.) signif. = 8.4 (6.7) σ
- Measured fiducial x-sec: 3.13 ± 0.31 (stat.) ± 0.28 (syst.) fb
- Predicted fiducial x-sec: 3.5±1.0 fb
  - w/ MG5_aMC@NLO+Pythia8 using the appropriate elastic or inelastic MMHT2015qed PDF sets. Extra survival factor introduced (for re-scattering effects, helicity structure of the hard scatterings…)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC



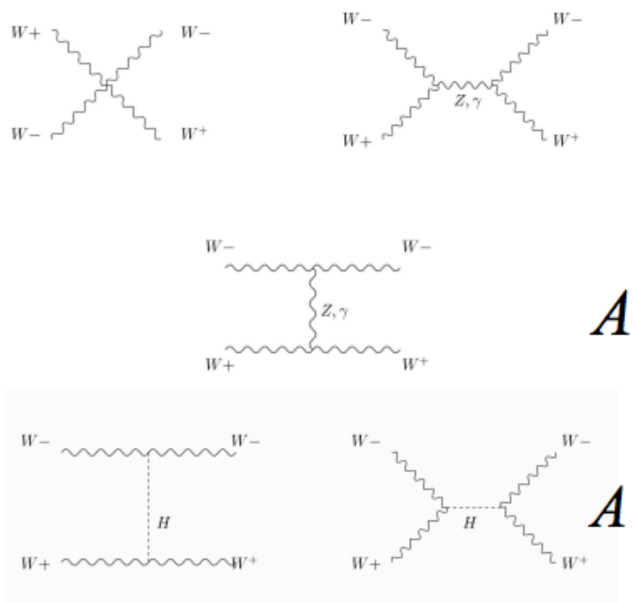
Summary and prospects

- LHC Run2 provides large amount of pp collision data at a higher center-of-mass energy, giving rise to VBS observation sensitivity
  - **Observed** VBS-VV channels: like-sign WW, WZ, ZZ, W/Z+γ (**NEW!**), Exclusive γγ→WW (**NEW!**)
  - **More adventurous channels to explore at LHC:** semileptonic WV(jj)/ZV(jj), Oppo-sign WW, …
  - Important test of EWSB and higgs mechanism in the unitarization of VV→VV scattering
  - First differential measurements and polarization extraction attempts are being tried out
  - Next steps: more differential measurements, 1st extraction of $V_L V_L$ polarization components, BSM constraints

- Potential showstoppers and improvements
  - Quark/Gluon induced jet separation using jet substructure technique to distinguish "color-charge" (tracking info, multiplicities, track jet width, calo topo cluster width, etc.)
  - Forward tracking improvement in future LHC upgrade
  - Pileup jet suppression in forward region
  - Theoretical uncertainties: improvement of high order precision in QCD irreducible background modelings, high order EWK effect predictions, interference modeling
  - Experimental challenges: Charge flips, soft-leptons
  - New physics probing: (doubly-)charged higgs, other heavy resonances, MSSM, aQGCs

Backup

VV scattering topology SM review



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

E^4 terms cancel between TGC and QGC

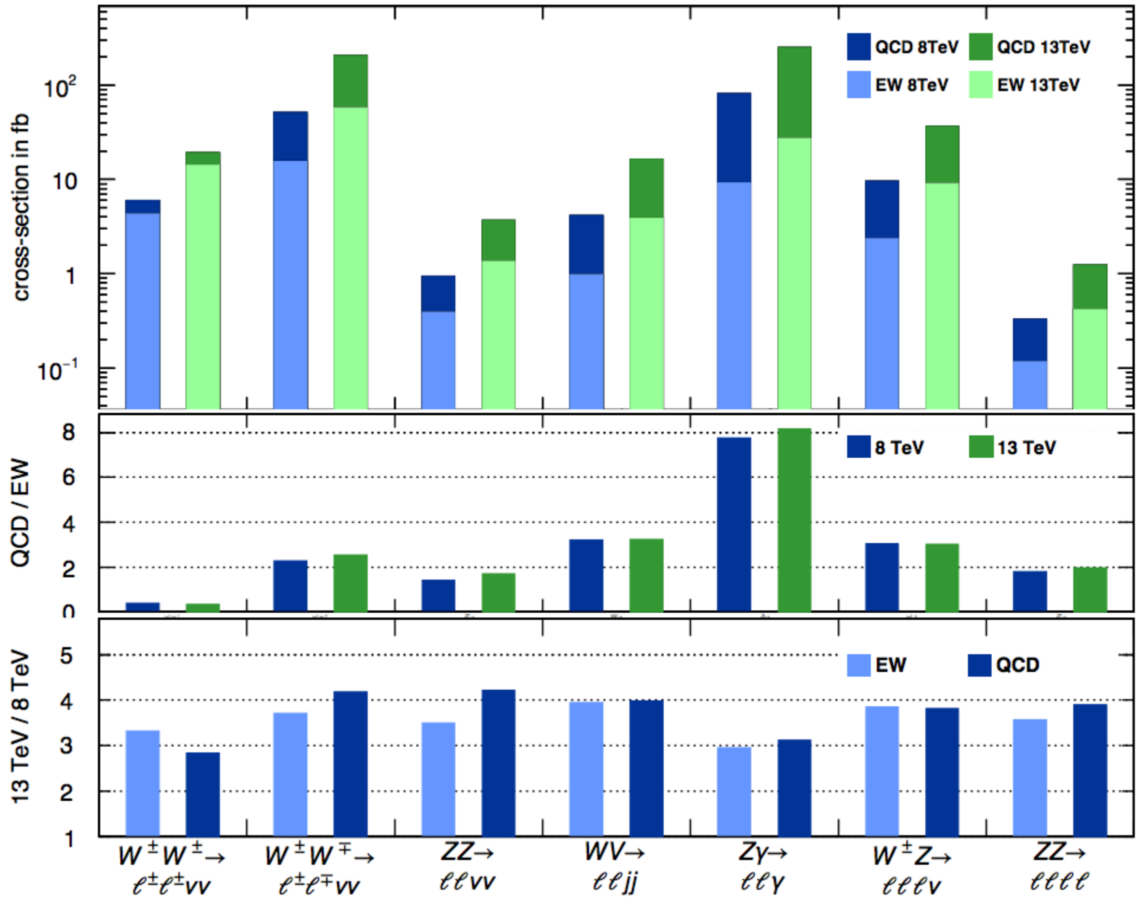
Terms which grow with energy cancel for $E >> M_H$

This cancellation requires $M_H < 800$ GeV

SM particles have just the right couplings so amplitudes don't grow with energy

S. Dawson

VBS measurement sensitivity prospect at 8TeV vs 13TeV



[CERN-THESIS-2014-105] (P. Anger)

How much the jump in energy buy us

- Measurements mostly stat. limited
- Signals mostly qq initiated→no huge jumps in inclusive x-sec
- Still EWK production tends to raise slightly faster than QCD at high m(jj), being the most interesting part sensitive to high √s of the bosons scattering

ZZ VBS analysis strategy overview

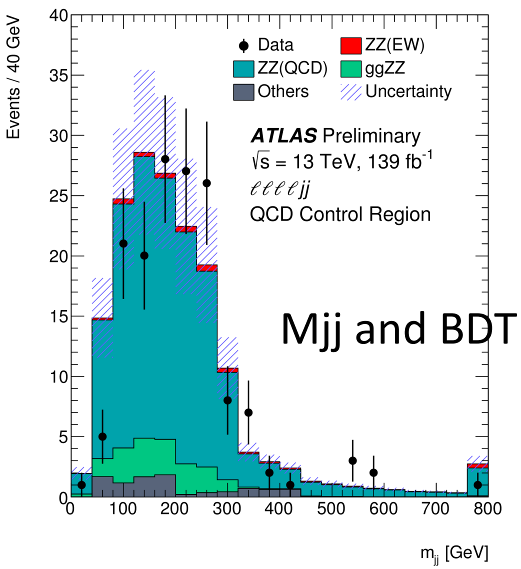
- VBS in a further extrapolated phasespace after inclusive ZZ selection plus VBS-enriched dijet cut
- MVA (BDTG)-based analysis is used then to extract the EW VBS ZZ signal from background
- Interference between EW and QCD as systematic on the EW VBS ZZ production measurement
- Combining ZZ→4l and ZZ→2l2v final states to gain enough sensitivity:
  - ZZ→4l channel:
    - Clean experimental signature except QCD induced ZZjj, small “other” background contribution (~3%): fake leptons from Z+jets, ttbar, WZ; irreducible backgrounds from other rare processes such as ttV and VVV.
    - The QCD 4l+jj being the major background. EW/QCD is around 20% level overall, MVA discriminant is adopted.
  - ZZ→2l2v channel:
    - Much larger backgrounds: WZ, WW + ttbar, +irreducible QCD ZZjj (when looking for EW)
    - Z+jets w/ fake MET largely suppressed while tightening MET-significance cut
    - EW/background ~15%, MVA becomes essential but more complicated than 4l channel

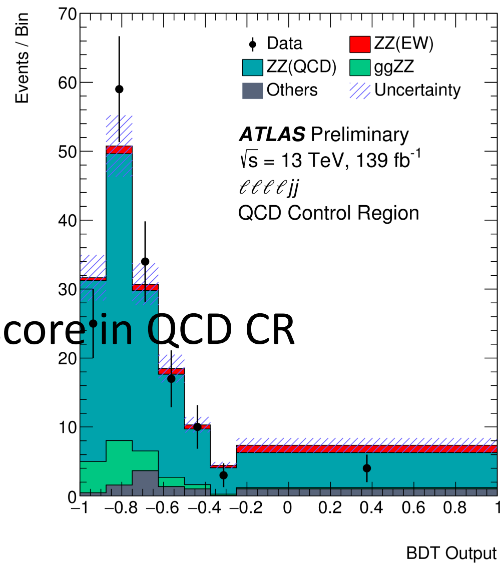
BDT MVA analysis in ZZ VBS

Gradient BDT in both channels:

- 4l: EW vs QCD
- 2l2v: EW vs All except Z+j (b/c of large negative weights)
- All likely discriminating variables taken into account, except those badly modeled (e.g. Centrality) and lowest ranked ones

$\ell\ell\nu\nu$ variables	$\ell\ell\ell\ell$ variables
$\Delta\eta(ll)$	m_{jj}
m_{ll}	leading p_T^j
$\Delta\phi(ll)$	subleading p_T^j
m_{jj}	$p_T(ZZjj)/H_T(ZZjj)$
$E_T^{miss}\,significance$	$Y(j1)\times Y(j2)$
$\Delta Y(jj)$	$\lvert\Delta Y(jj)\rvert$
$Y(j1)\times Y(j2)$	Y^*_{Z2}
HT	Y^*_{Z1}
$\Delta R(ll)$	p_T^{ZZ}
subleading p_T^j	m_{ZZ}
E_T^{miss}	p_T^{Z1}
subleading p_T^l	$p_T^{\ell 3}$
leading p_T^l	-





Mjj and BDT score in QCD CR

arXiv:2004.10612 (submitted to Nature Physics)

Summary of ZZ VBS measurements

Signal/Bgd yield estimations:

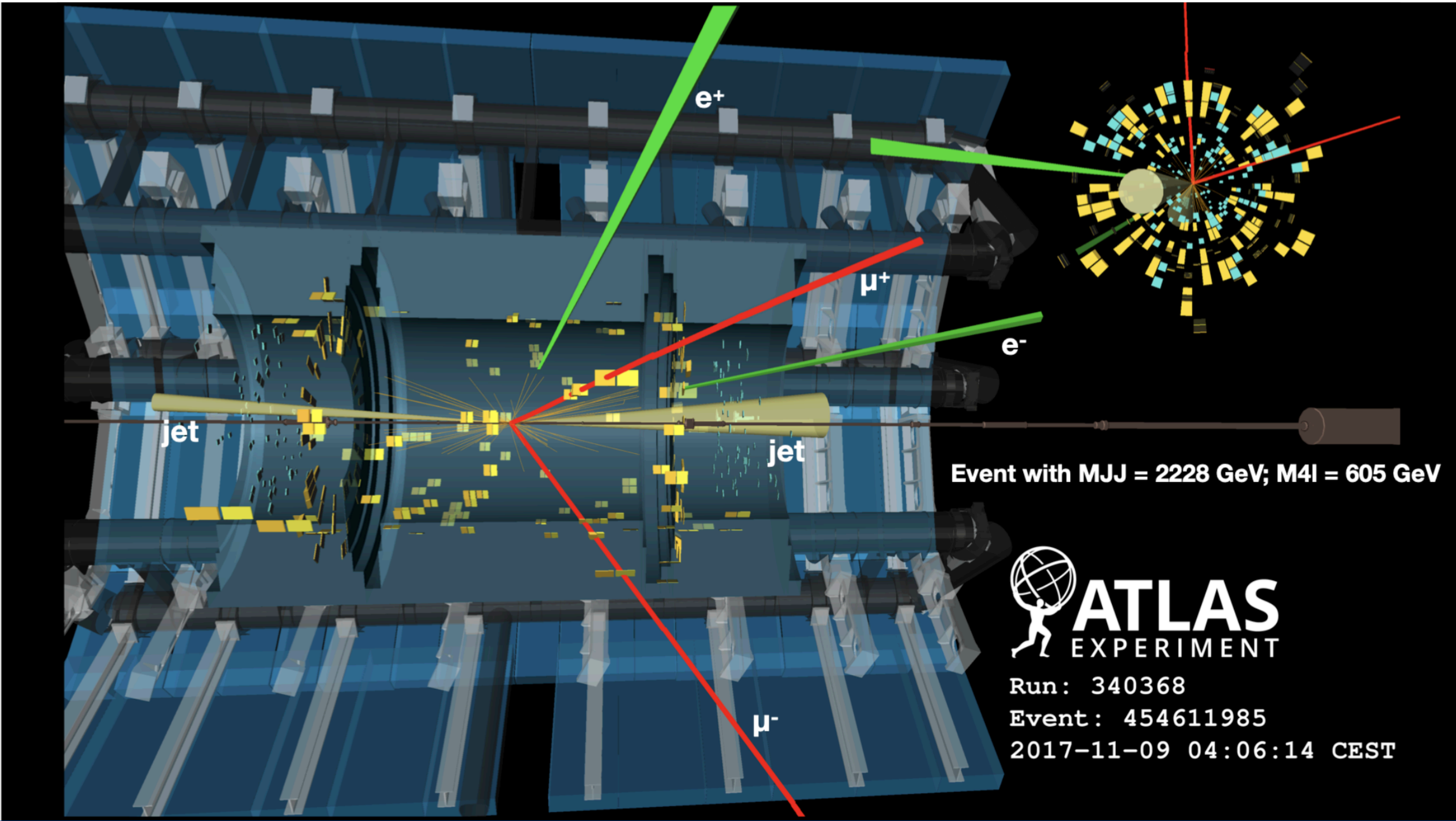
Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77.4 ± 25.0	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114.3 ± 25.6	78.4 ± 6.2
Data	127	82

	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$	$1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$

Observation:

	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.54 ± 0.42	0.95 ± 0.22	5.48 (3.90) σ
$\ell\ell\nu\nu jj$	0.73 ± 0.65	-	1.15 (1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52 (4.30) σ

Event display of the ZZ VBS process

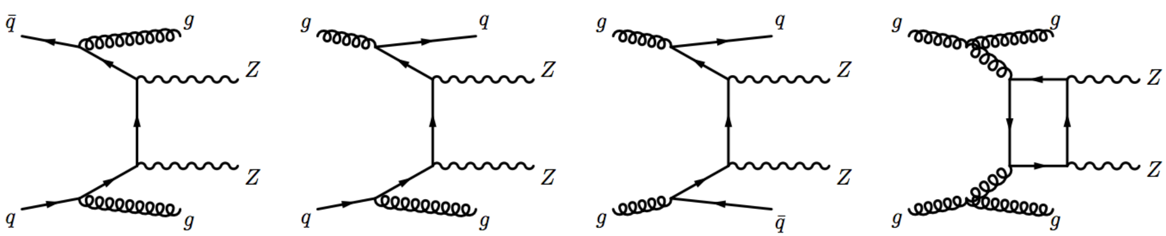


ZZ VBS object and event selections overview

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.47$ $\lvert d_0/\sigma_{d_0}\rvert < 5$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	
Muons	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.7$ $\lvert d_0/\sigma_{d_0}\rvert < 3$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	$p_T > 7$ GeV, $\lvert\eta\rvert < 2.5$
Jets	$p_T > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_T > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_T > 20, 20, 10$ GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\lvert m_{\ell^+\ell^-} - m_Z\rvert + \lvert m_{\ell'^+\ell'^-} - m_Z\rvert$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_T > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets E_T^{miss} significance > 12
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

Generally tighter selections in llvv channel due to more backgrounds
Going into VBS-rich region after dijet selection

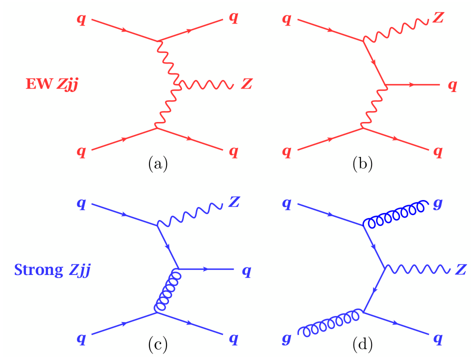
QCD ZZjj:

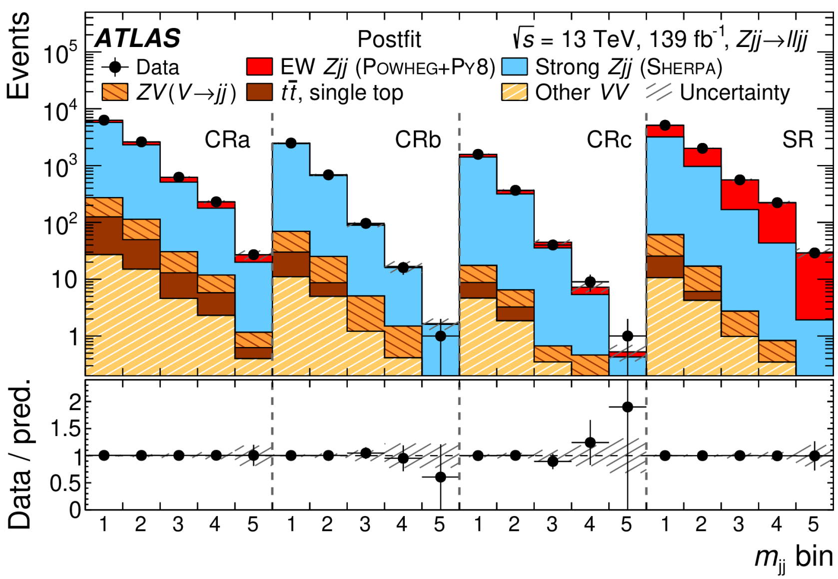


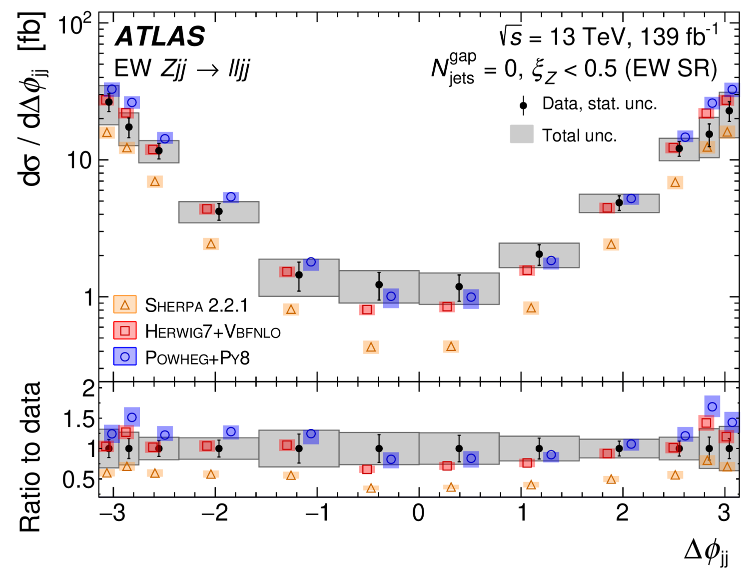
Eur. Phys. J. C 81 (2021) 163

Differential measurements of VBF Zjj process

- 2→1 fusion process of Zjj 1st observed by ATLAS in Run1
- Challenging bgd separation between strong and EWK Zjj
- CR for strong Zjj constraint and Likelihood fit to measure EWK Zjj bin-by-bin
- differential XS are measured: m_{jj}, Δyjj, $\Delta\phi_{jj}$, $p_{T,\ell\ell}$
  - signed azimuthal angle between the two jets found sensitive to the interference between SM and dim6 scattering amplitudes, providing direct test of charge-conjugation and parity invariance in boson self-interactions.





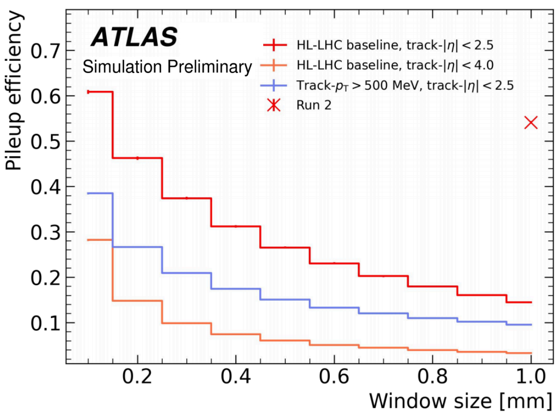


ATLAS-PHYS-PUB-2021-11

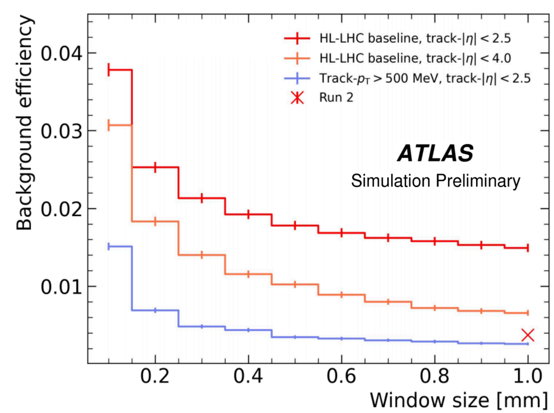
Photon scattering into W boson pairs at HL-LHC

1. HL-LHC baseline, track-|η| < 2.5 - nominal analysis
2. HL-LHC baseline, track-|η| < 4.0 - forward tracking with the ITk
3. Track-pT > 500 MeV, track-|η| < 2.5 - dedicated low-pT reconstruction

- Require dilepton vertex plus zero additional tracks within a window of size Δz around that vertex
  - rejects events with underlying event activity (backgrounds)
- Signal and background efficiency is impacted by pile-up
  - depends on μ and Δz



We want this efficiency to be as high as possible



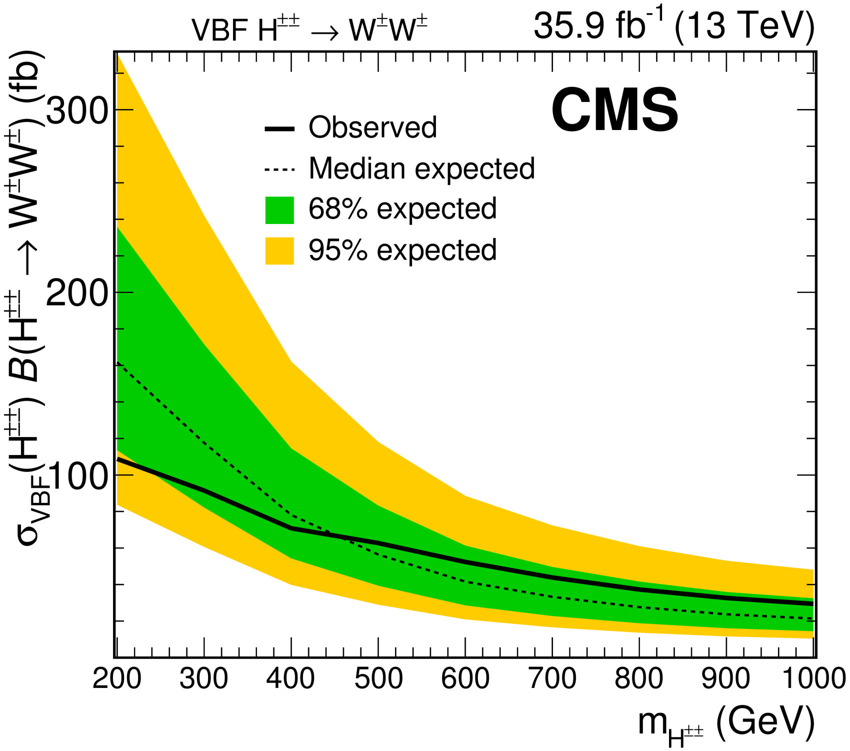
We want this efficiency to be as low as possible

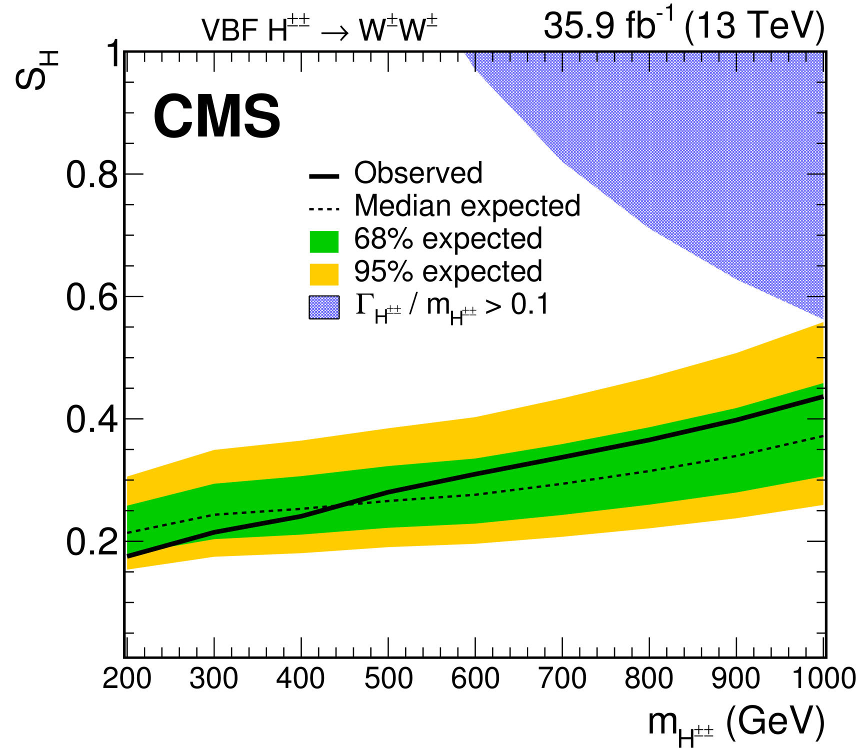
- **Smaller window** size reduces chance of pileup track falling in window ⇒ **higher efficiency**
- **Lower reconstructed track-pT** means more pileup tracks ⇒ **lower efficiency**
- **Extended η range** means more pileup tracks (and with worse resolution) ⇒ **lower efficiency**

- **Smaller window** size loses UE tracks due to finite resolution ⇒ **higher efficiency**
- **Extended η range** means higher tracking acceptance ⇒ **lower efficiency**
- **Lower reconstructed track-pT** means more UE tracks reconstructed ⇒ **lower efficiency**

VBS/VBF signature for New Physics Searches: Doubly charged Higgs

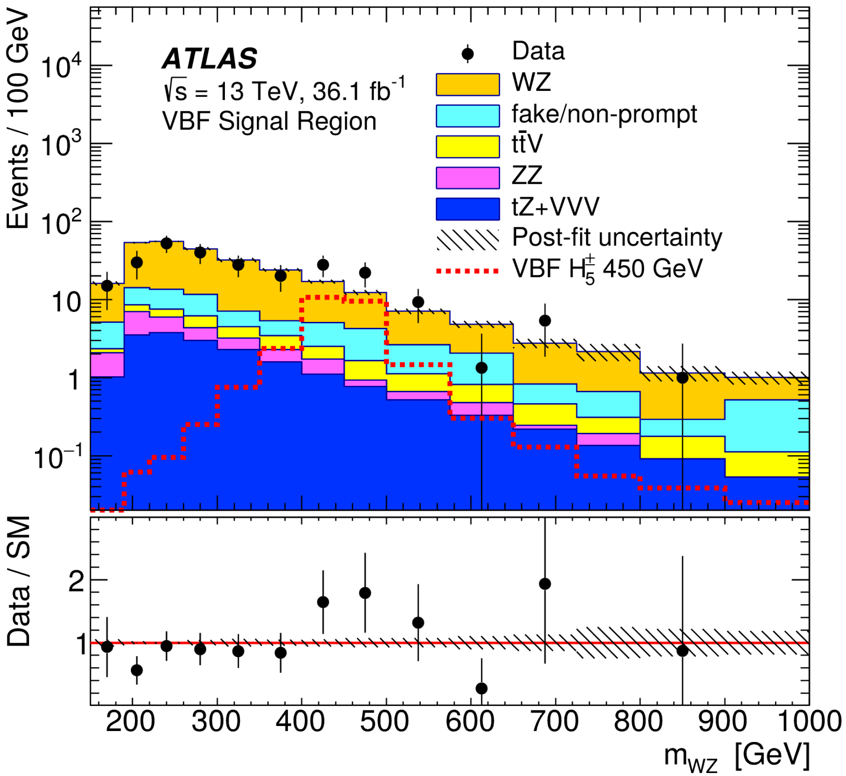
Phys. Rev. Lett. 120 (2018) 081801



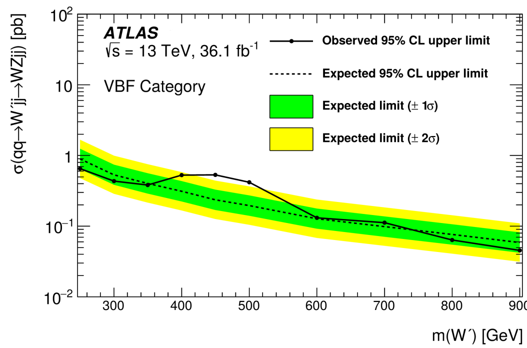


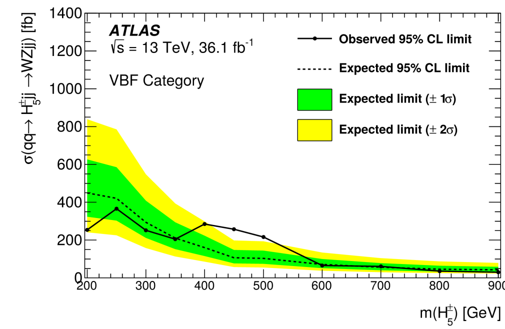
- Expected and observed 95% CL upper limits on the x-sec times BR, $\sigma_{VBF}(H^{\pm\pm})$ $(H^{\pm\pm} \to W^{\pm}W^{\pm})$ (left) and on s_H in the Georgi-Machacek model (right) as a function of doubly charged Higgs boson mass.
- The blue area in the upper-right corner covers the region where GM model is not applicable

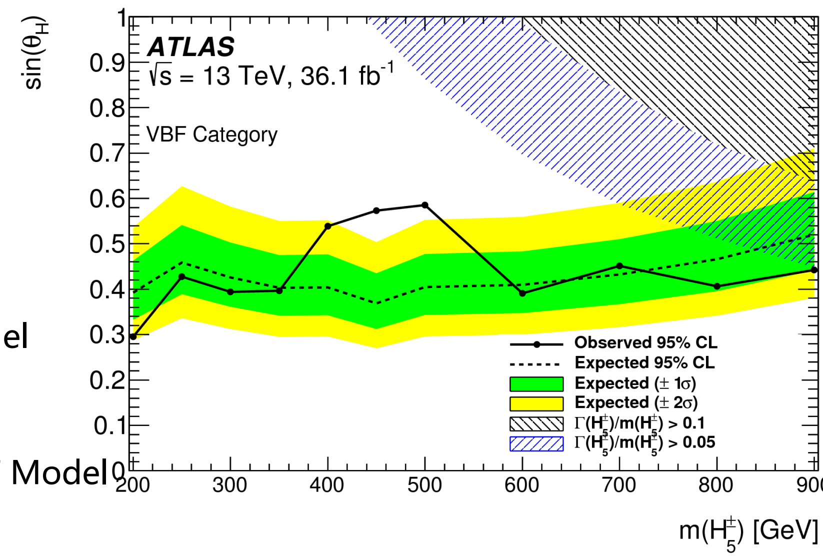
VBS/VBF signature for New Physics Searches: Charged Higgs



Phys. Lett. B 787 (2018) 68



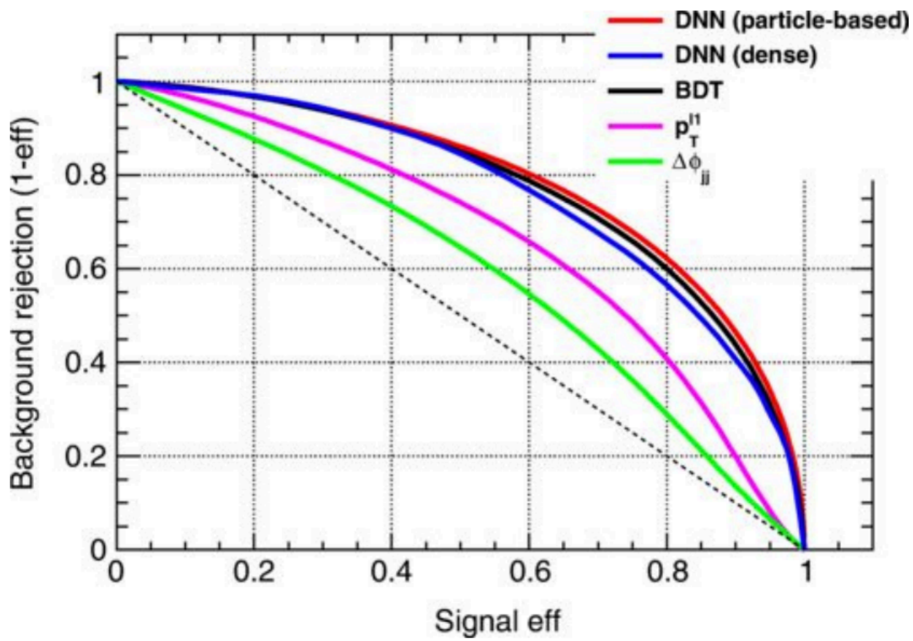




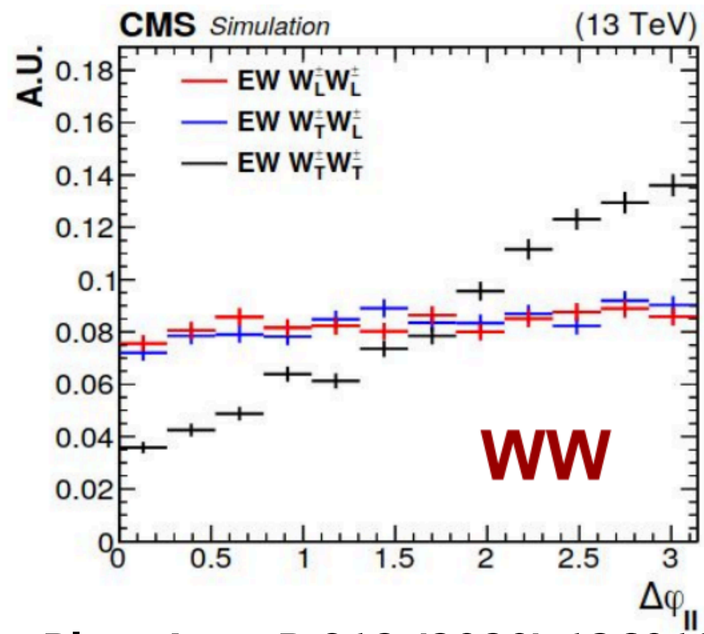
- VBF category of WZ production constrains charged resonance model
- Observed and expected 95% CL upper limits on:
- $\sigma \times B(W' \rightarrow W^{\pm}Z)$ for the VBF production of a W' boson in the HVT Model
- $\sigma \times B(H5^{\pm} \rightarrow W^{\pm}Z)$ as a function of $mH5^{\pm}$ in the GM model

Future of VBS diboson physics: polarized VBS attempt

Small Signal, <10% of VBS
Junho Lee… Q.Li... et.al.,
PRD 99, 033004 (2019) ; PRD 100, 116010 (2019)



BDT and DNN can help improve the sensitivity. **Although it still needs 3000/fb to reach 4-5 standard deviations.**



Phys. Lett. B 812 (2020) 136018

Observed (expected) significance
for LL and LT+LL: **0.88 (1.17)σ; 2.3 (3.1)σ**

Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W_L^\pm W_L^\pm$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W_X^\pm W_T^\pm$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W_L^\pm W_X^\pm$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W_T^\pm W_T^\pm$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21