Latest VBS measurements in ATLAS

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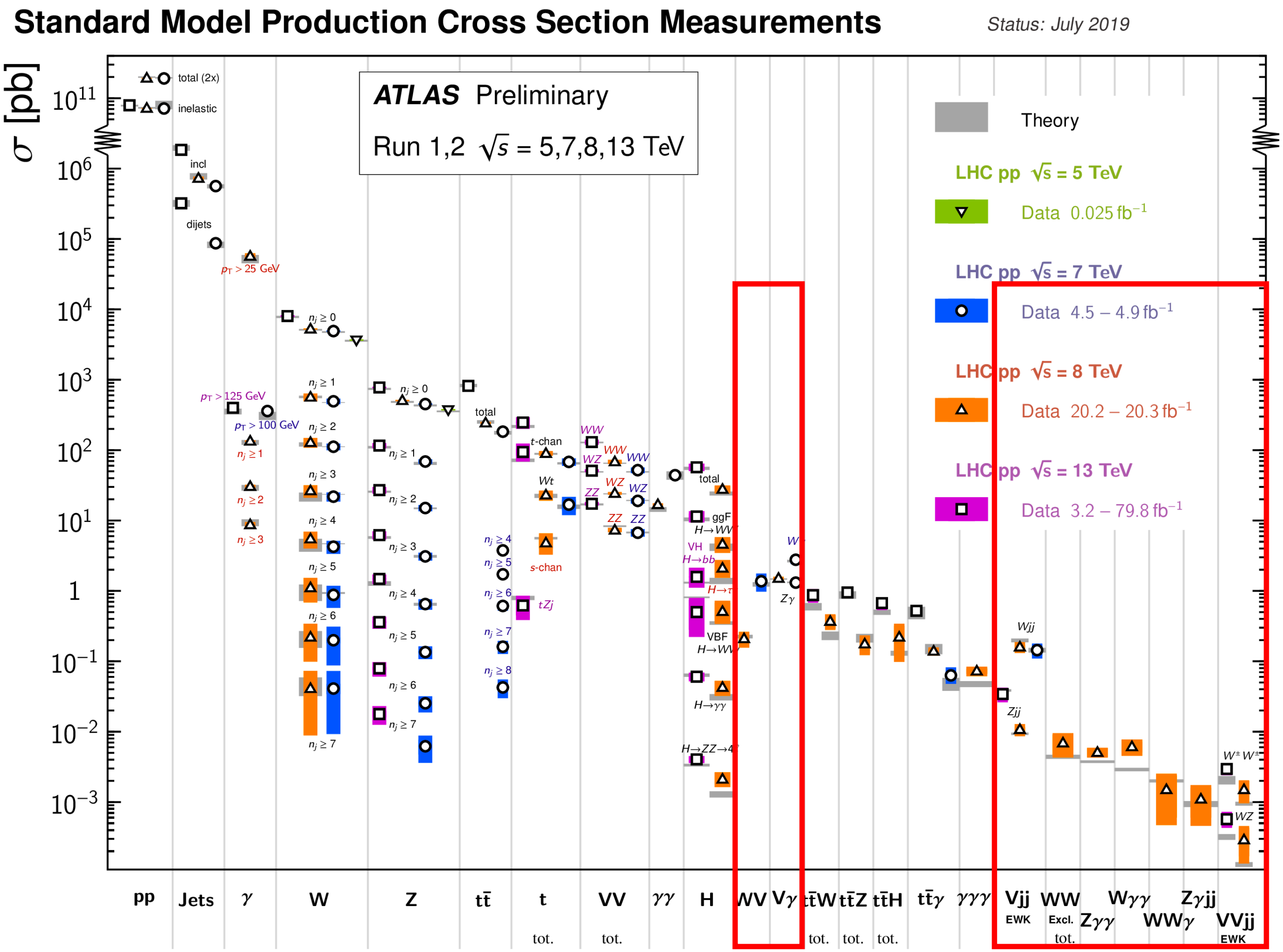
SM measurements in a nutshell

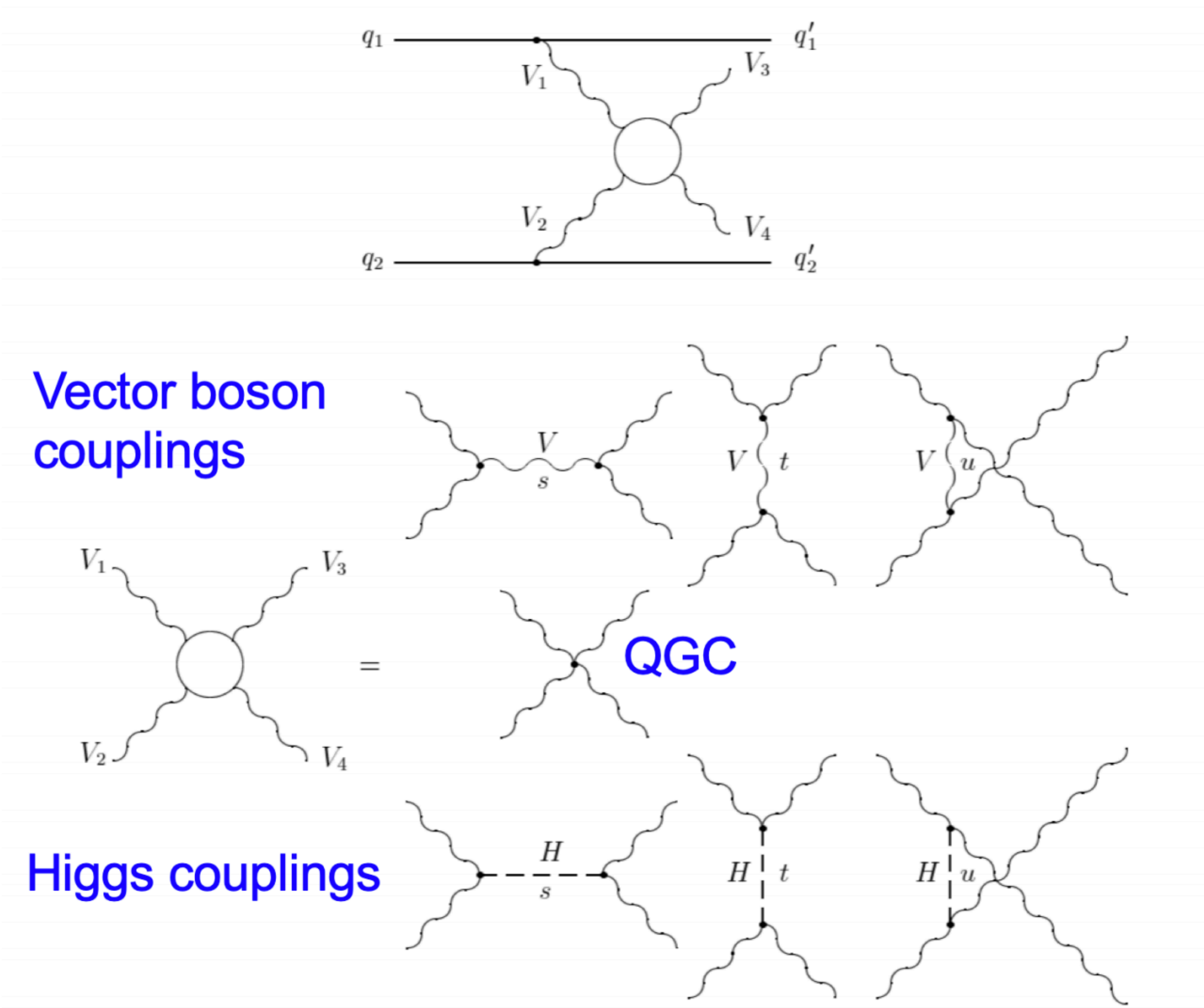


Measurements of Multi-Boson Production processes:

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

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

Vector Boson Scattering topology in a nutshell

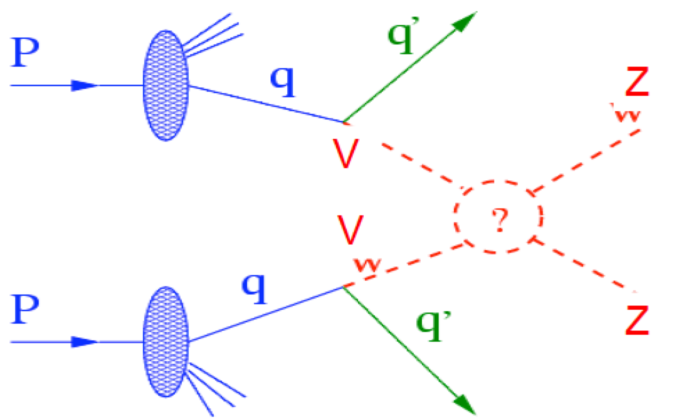


Vector Boson Scattering (VBS) is a key process
to probe the mechanism of electroweak symmetry breaking.

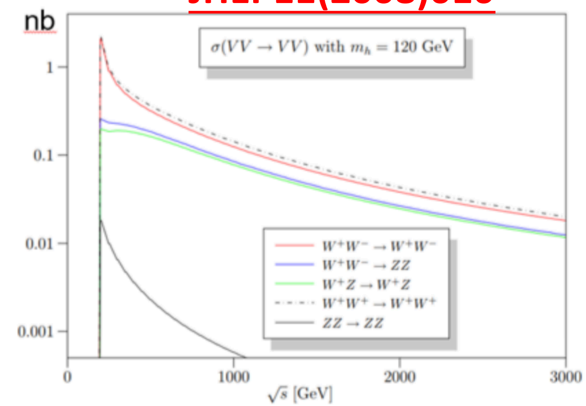
Main interest of VV scattering

Unitarity violation of Vector Boson Scattering

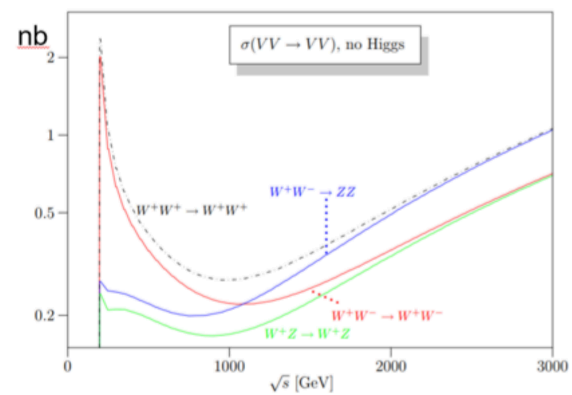
$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) \sim \frac{s}{M_W^2}$$



JHEP11(2008)010



w/ Higgs

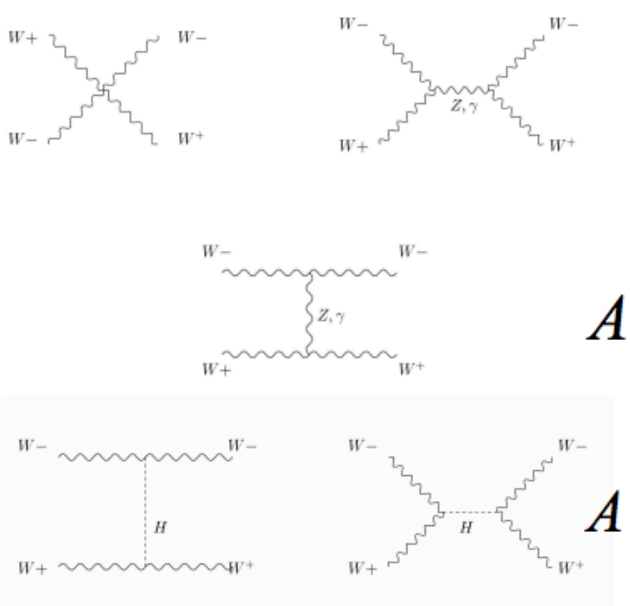


w/o Higgs

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

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

VV scattering topology SM review



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

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

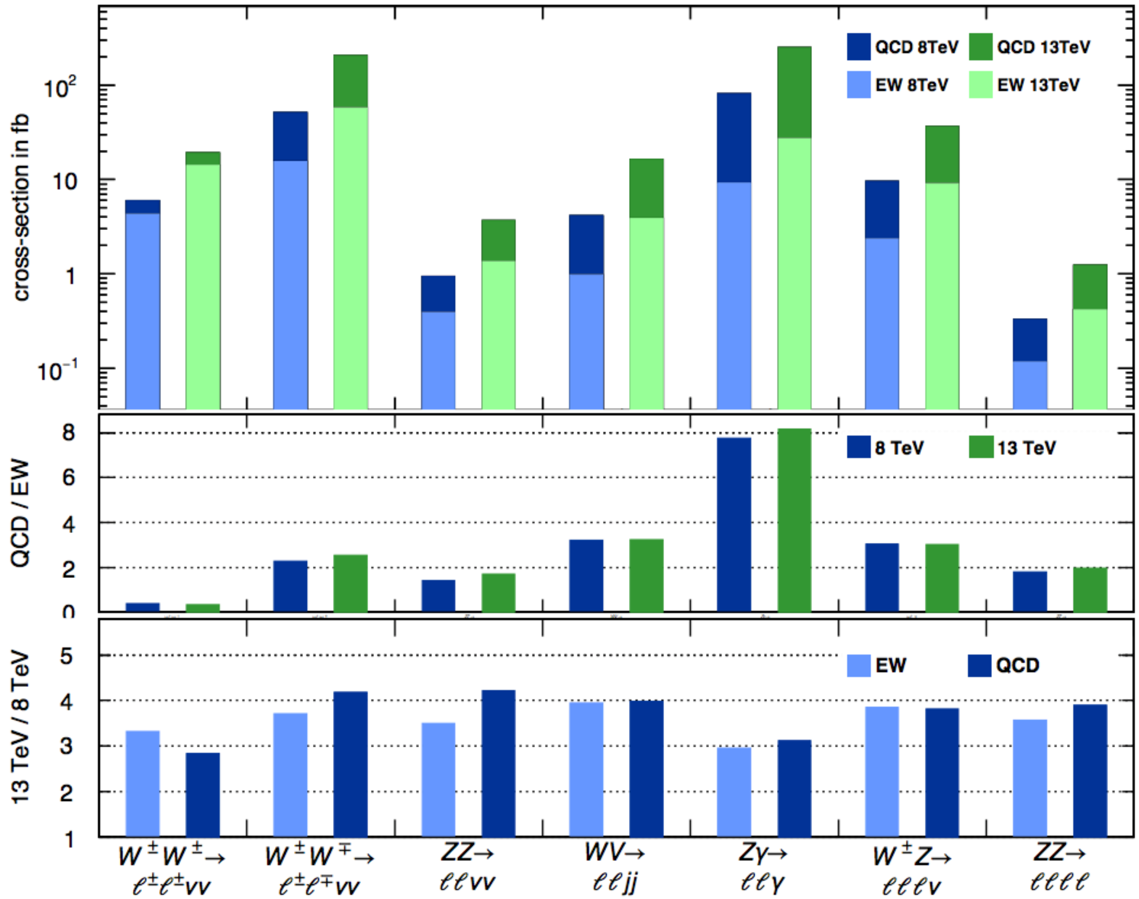
E^4 terms cancel between TGC and QGC

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

VBS measurement sensitivity prospect at 8TeV vs 13TeV



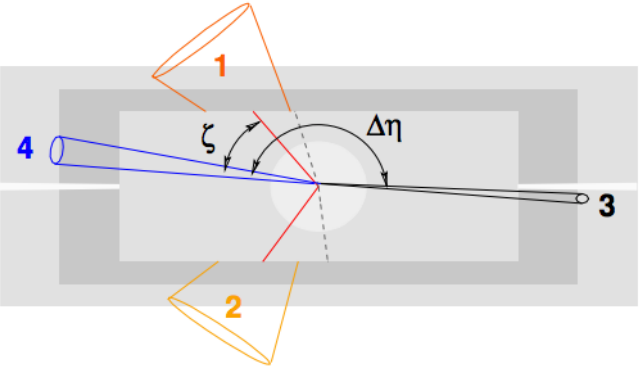
[CERN-THESIS-2014-105]

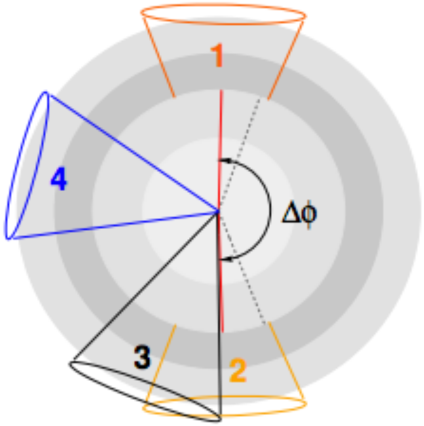
How much the jump in energy buy us

- 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

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: $\max\left(\left|\frac{y_i - 0.5(y(j_1)+y(j_2))}{y(j_1)-y(j_2)}\right|\right)$
  - pT balance: $\frac{\sum_i \vec{p_T}_i}{\sum_i |\vec{p_T}_i|}$
    - All hard process decay products and jets

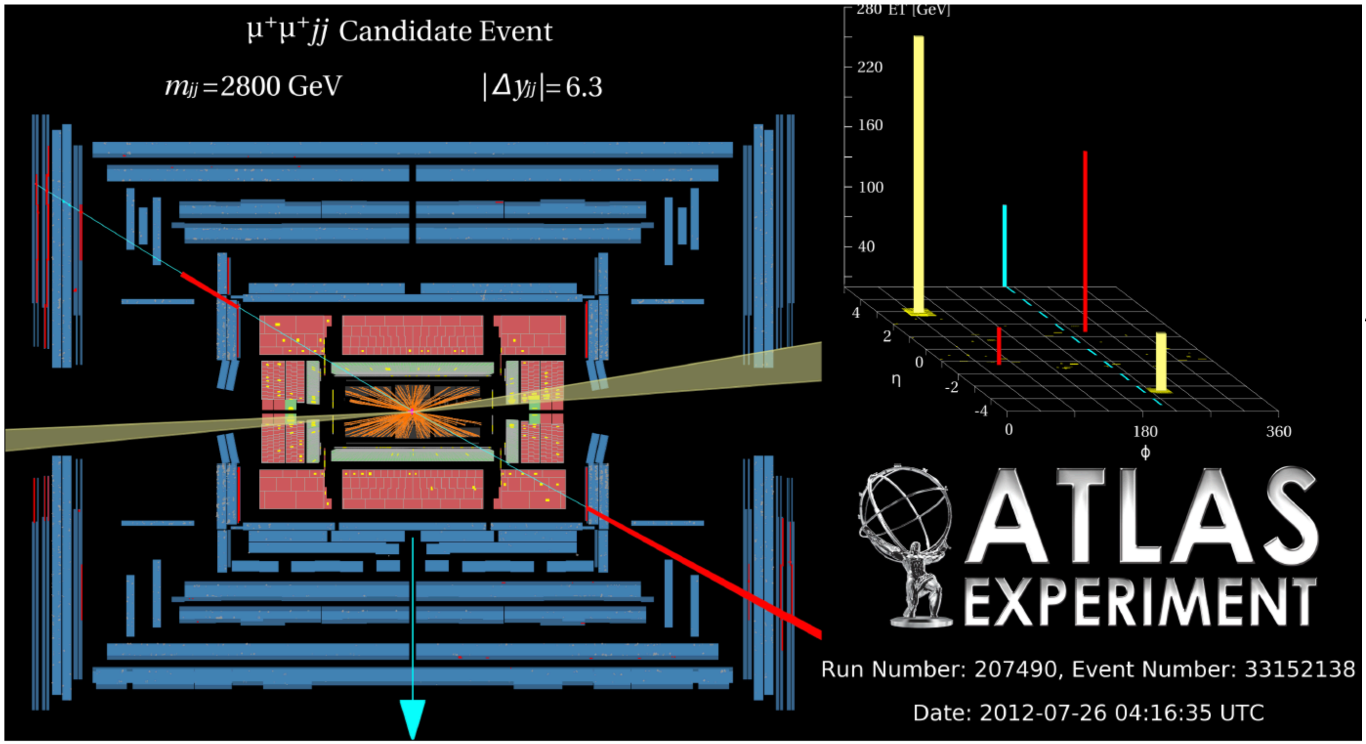




Experimental challenges per final states

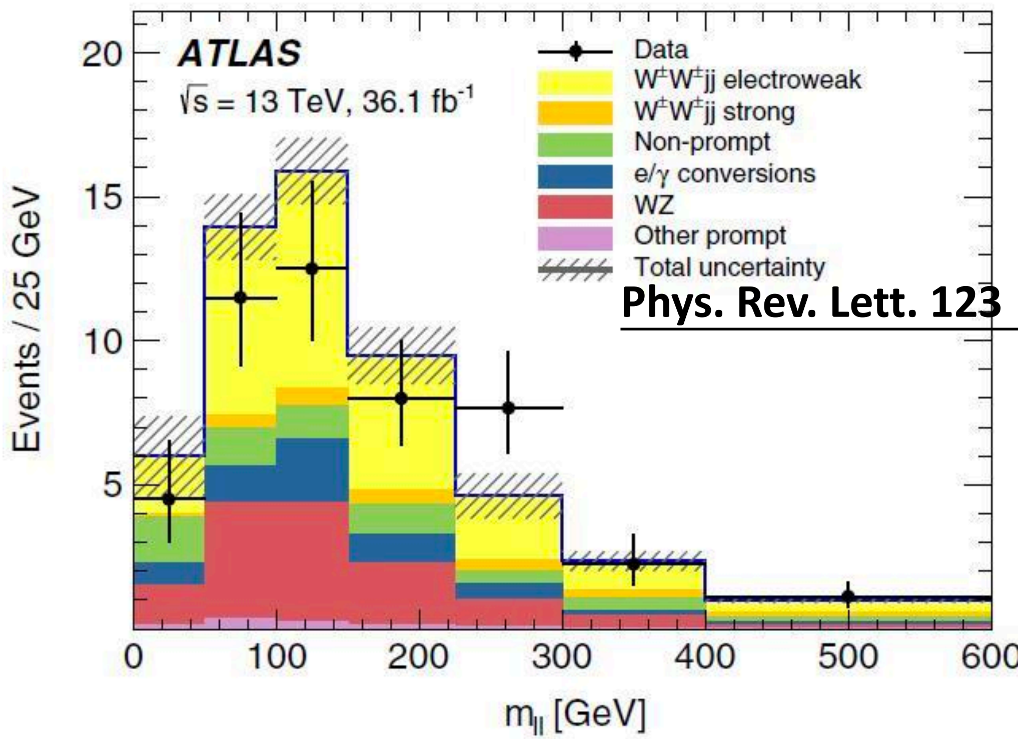
	channel	final state	comment *
Observed!	VBF W	ℓν jj	statistics is not a problem, good modelling of W+jets needed
Observed!	VBF Z	ℓℓ jj	statistics is not a problem, good modelling of Z+jets needed
Observed!	VBS $W^{\pm}W^{\pm}$	$\ell^{\pm}\nu\ell'^{\pm}\nu$ jj	"golden channel": very good EW/QCD ratio, 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	ℓℓℓ'ν jj	similar cross section as ssWW, but larger QCD background, fair reconstructibility of fs
Evidence	VBS Wγ/Zγ	ℓνγ jj / ℓℓγ jj	photon brings higher stat. (and different experimental systematics), lacks sensitivity to BSM in Higgs sector
	VBS WV	ℓνjj jj	large backgrounds (W+jets, ttbar), but promising boosted regime when looking for NP effects
	VBS ZV	ℓℓjj jj	large backgrounds (Z+jets, ttbar), but promising boosted regime when looking for NP effects, no neutrinos in final state
New Observed!	VBS ZZ	ℓℓℓ'ℓ' jj	very clean channel, very good reconstructibility of final state and low background contamination, but small cross-section
	VBS ZZ	ℓℓνν jj	challenging to measure invisible Z decay, combination with leptonic decay might help to suppress dileptonic ttbar background

	ssWW	WZ	ZZ	Zγ	VBF Z/W
ATLAS	Observation	Observation	Observation (5.5 σ)	4.1 σ	Observation
CMS	Observation	<3 σ	<3 σ	4.7 σ	Observation



A clean signature of VBS like-sign WW pair production event display, observed by ATLAS (2018) and CMS (2017) at >5σ significance

Former accomplishments: 1st observation of same-sign WW VBS processes at ATLAS



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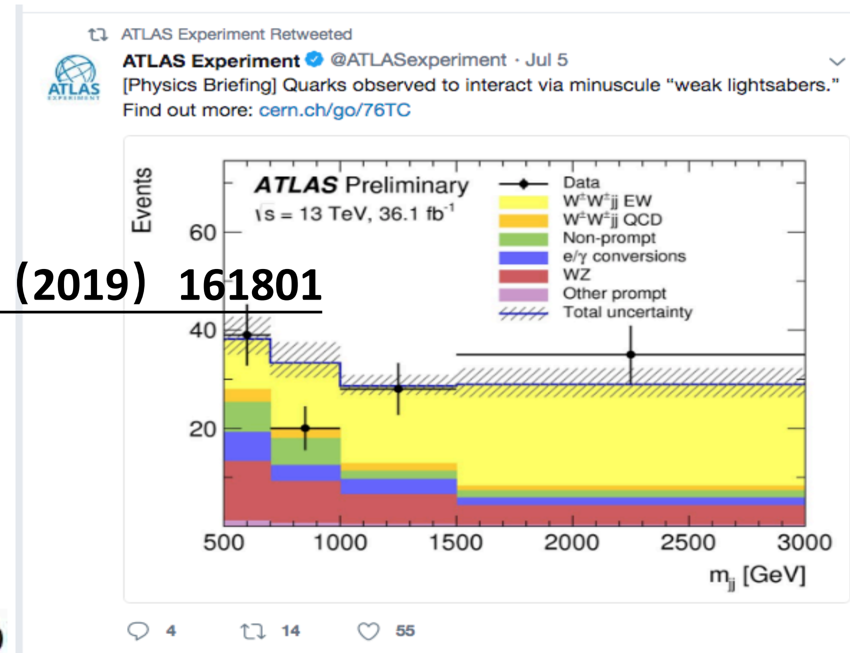
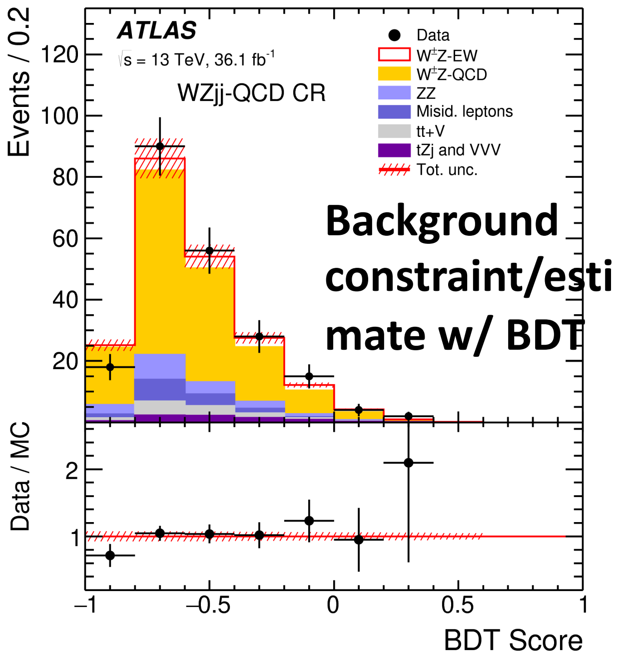
ATLAS on twitter:

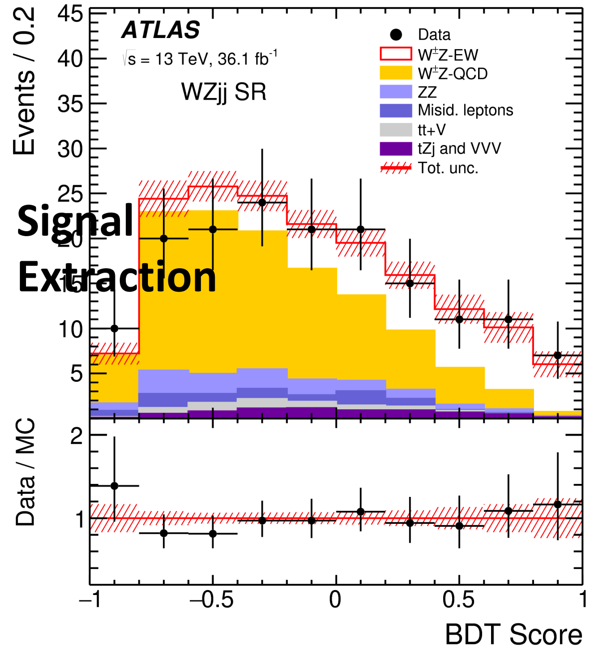


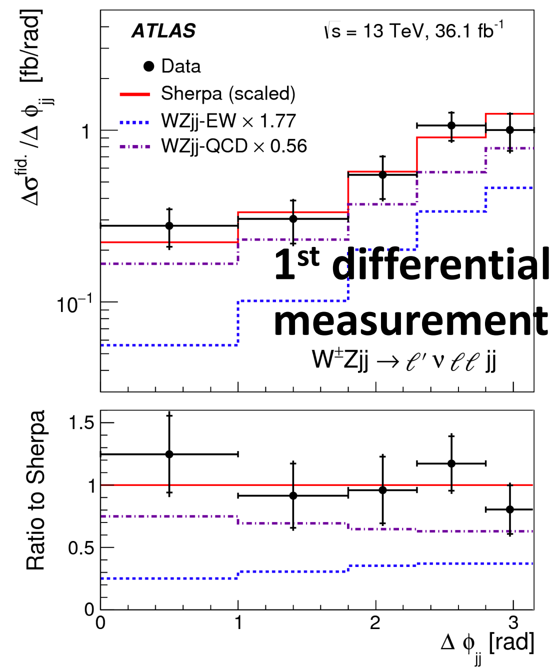
ATLAS Collaboration Physics Briefing highlights for ssWW 5-σ observation:
http://atlas.cern/updates/physics-briefing/weak-lightsabers
ICHEP2018 highlights: Conf notes, Plenary talk, Parallel talk

Former accomplishments: 1st observation of WZ VBS processes at LHC

Phys. Lett. B 793 (2019) 469







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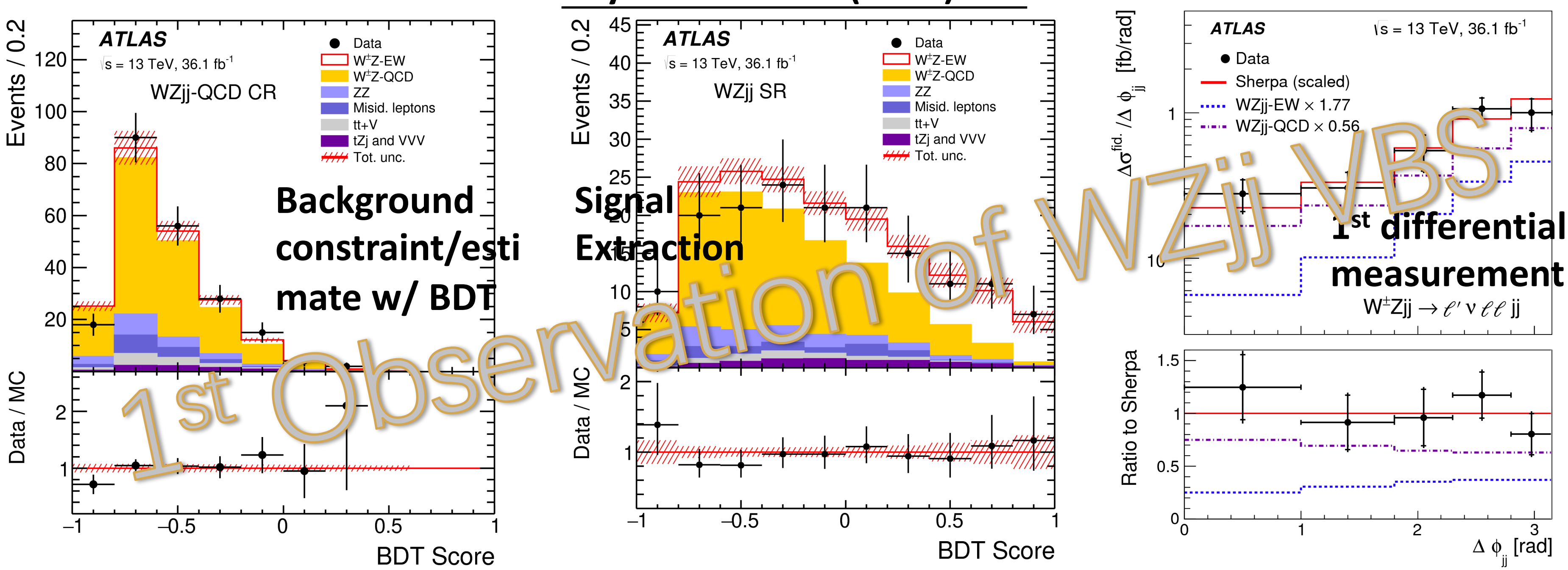

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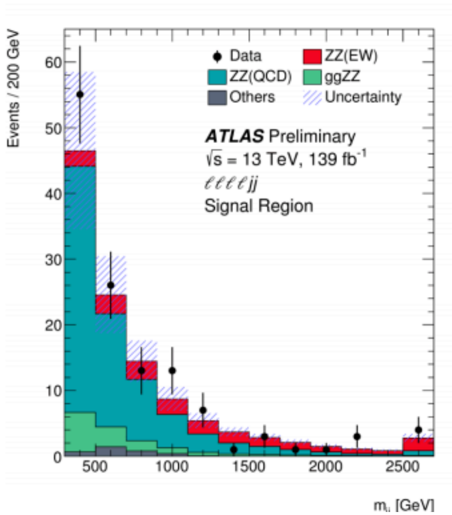
Recent highlights: 1st observation of ZZ VBS process at LHC

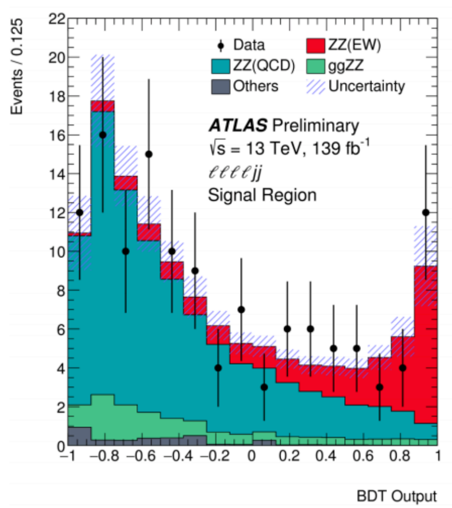
Utilizing 139 fb^{-1} full Run-2 data

***EPS-HEP conf note* ATLAS-CONF-2019-033**

Paper under submission

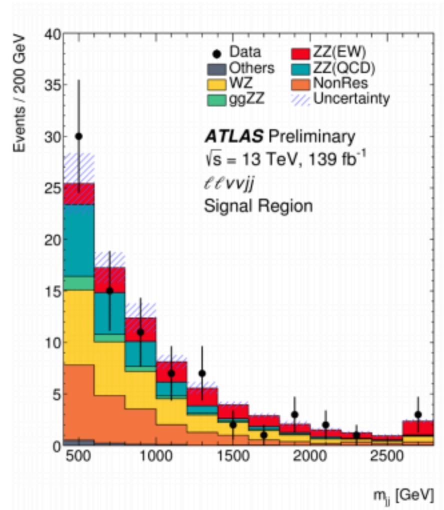
m_{jj} distribution in the 4l signal region





Obs. 5.5 σ
Exp. 4.3 σ

m_{jj} distribution in the 2l2v signal region



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

Recent highlights: 1st observation of ZZ VBS process at LHC

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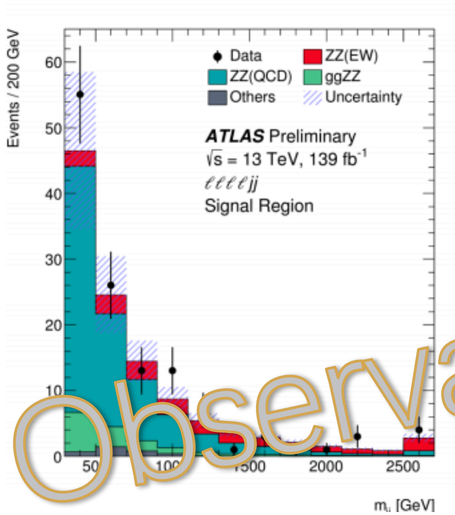

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Exp. 4.3 σ

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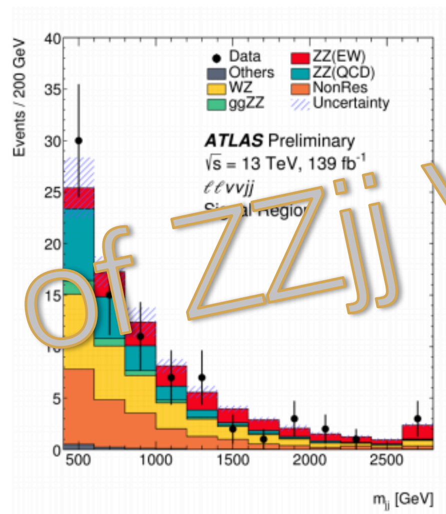
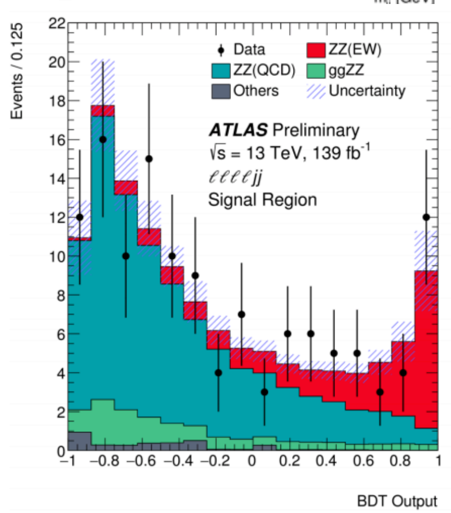


1st Observation of ZZjj VBS



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  - MET, MET significance
  - Δη(l,l), Δϕ(l,l), ΔR(l,l), m_{ll}
  - $p_T^{l_1}$, $p_T^{l_2}$

ZZ VBS analysis strategy overview

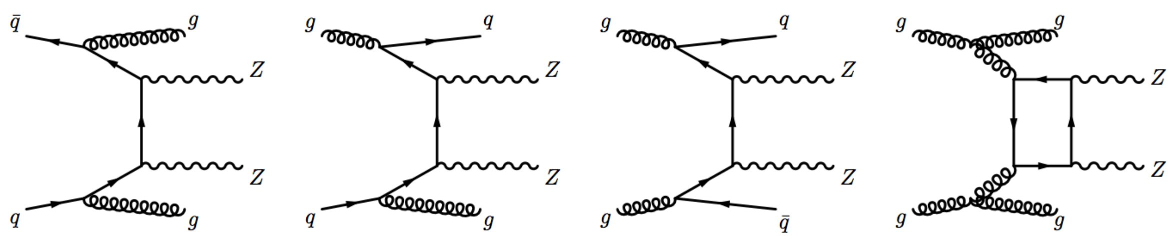
- VBS in a further extrapolated phasespace after inclusive ZZ selection plus VBS-enriched dijet cut
- MVA (BDTG)-based analysis is used then to extract the EW VBS ZZ signal from background
- Interference between EW and QCD as systematic on the EW VBS ZZ production measurement
- Combining ZZ→4l and ZZ→2l2v 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

ZZ VBS object and event selections overview

<table>
<tr><th></th><th>$\ell\ell\ell\ell jj$</th><th>$\ell\ell\nu\nu jj$</th></tr>
<tr><td>Electrons</td><td colspan="2">$p_{\mathrm{T}} > 7$ GeV, $|\eta| < 2.47$
$|d_0/\sigma_{d_0}| < 5$ and $|z_0 \times \sin\theta| < 0.5$ mm</td></tr>
<tr><td rowspan="2">Muons</td><td>$p_{\mathrm{T}} > 7$ GeV, $|\eta| < 2.7$</td><td>$p_{\mathrm{T}} > 7$ GeV, $|\eta| < 2.5$</td></tr>
<tr><td colspan="2">$|d_0/\sigma_{d_0}| < 3$ and $|z_0 \times \sin\theta| < 0.5$ mm</td></tr>
<tr><td>Jets</td><td>$p_{\mathrm{T}} > 30$ (40) GeV for $|\eta| < 2.4$ ($2.4 < |\eta| < 4.5$)</td><td>$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet</td></tr>
<tr><td>ZZ selection</td><td>$p_{\mathrm{T}} > 20, 20, 10$ GeV for the leading, sub-leading and third leptons
Two OSSF lepton pairs with smallest $|m_{\ell^+\ell^-} - m_Z| + |m_{\ell'^+\ell'^-} - m_Z|$
$m_{\ell^+\ell^-} > 10$ GeV for lepton pairs
$\Delta R(\ell, \ell') > 0.2$
$66 < m_{\ell^+\ell^-} < 116$ GeV</td><td>$p_{\mathrm{T}} > 30$ (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
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 12</td></tr>
<tr><td rowspan="2">Dijet selection</td><td colspan="2">Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$</td></tr>
<tr><td>$m_{jj} > 300$ GeV and $\Delta y(jj) > 2$</td><td>$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$</td></tr>
</table>

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

QCD ZZjj:

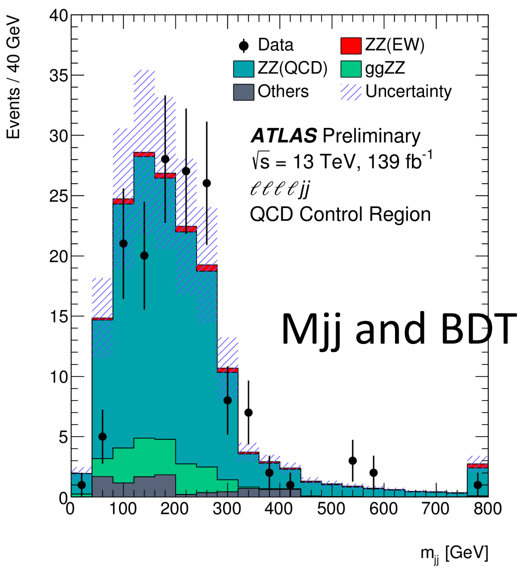


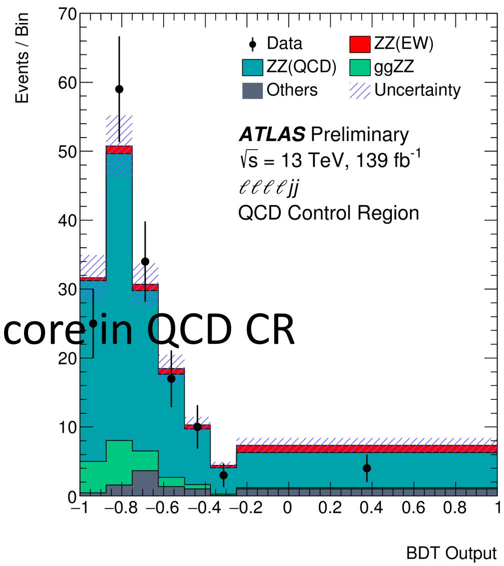
BDT MVA analysis in ZZ VBS

Gradient BDT in both channels:

- 4l: EW vs QCD
- 2l2v: EW vs All except Zjets (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}	$p_T(ZZjj)/H_T(ZZjj)$
$E_T^{miss} significance$	$Y(j1)\times Y(j2)$
$\Delta Y(jj)$	$\|\Delta Y(jj)\|$
$Y(j1)\times Y(j2)$	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	-

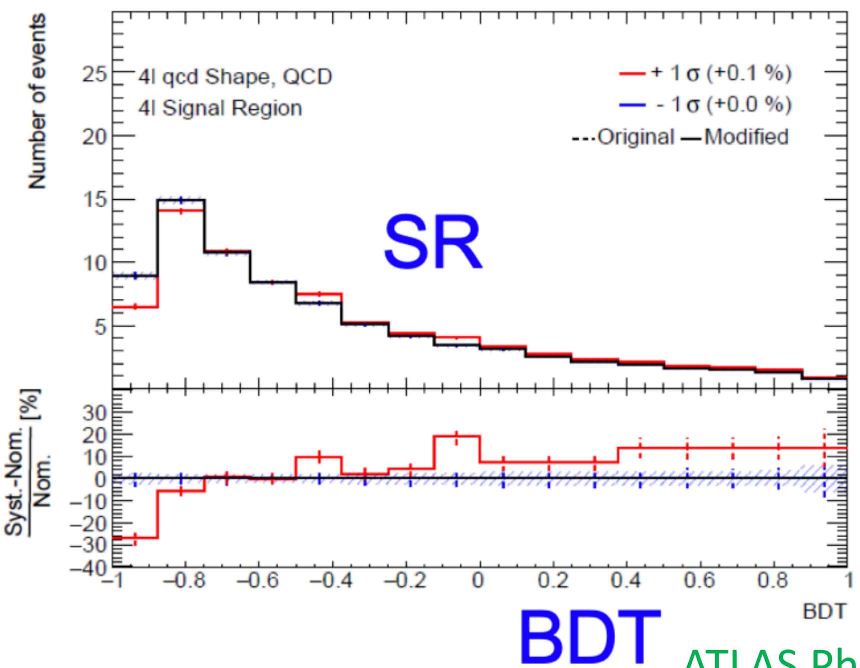


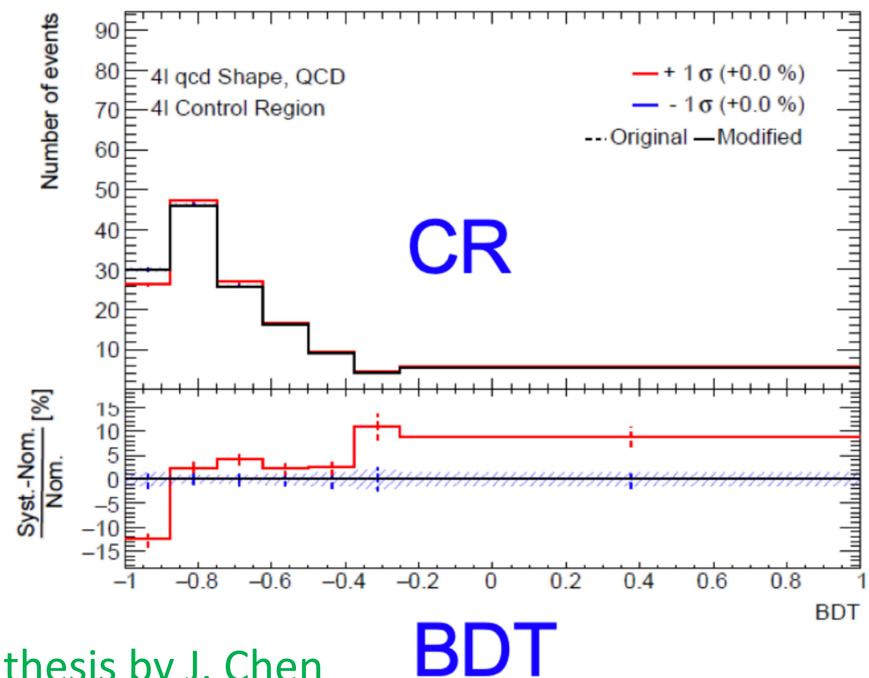


Mjj and BDT score in QCD CR

QCD ZZjj modeling uncertainties in ZZ VBS

- The theoretical uncertainties commonly estimated by varying certain physics parameters (QCD scale choice, PDF tuning, couplings …).
- The shape differences of different generators cannot be covered by QCD up/down variations
- Two different generators (Sherpa and MG) are used to compare the modelling of the QCD processes at matrix element level





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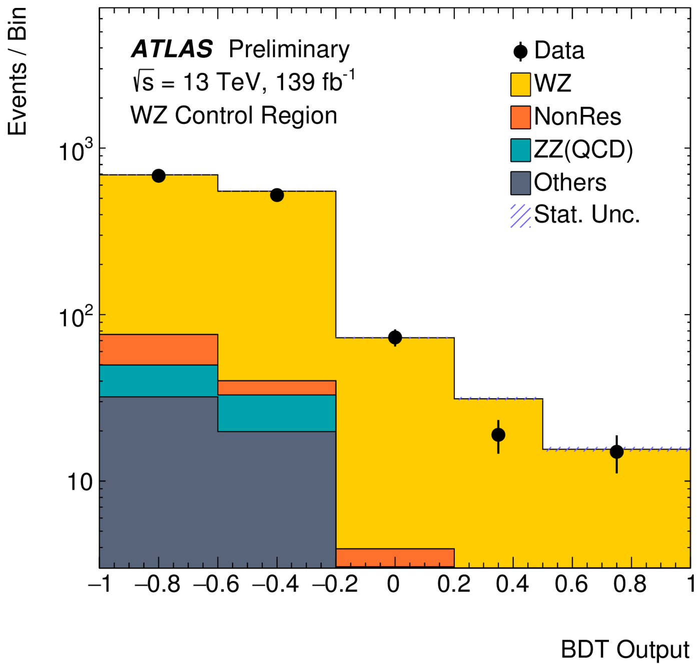
Other background treatments in 2l2v channel



WZ dominant CR:

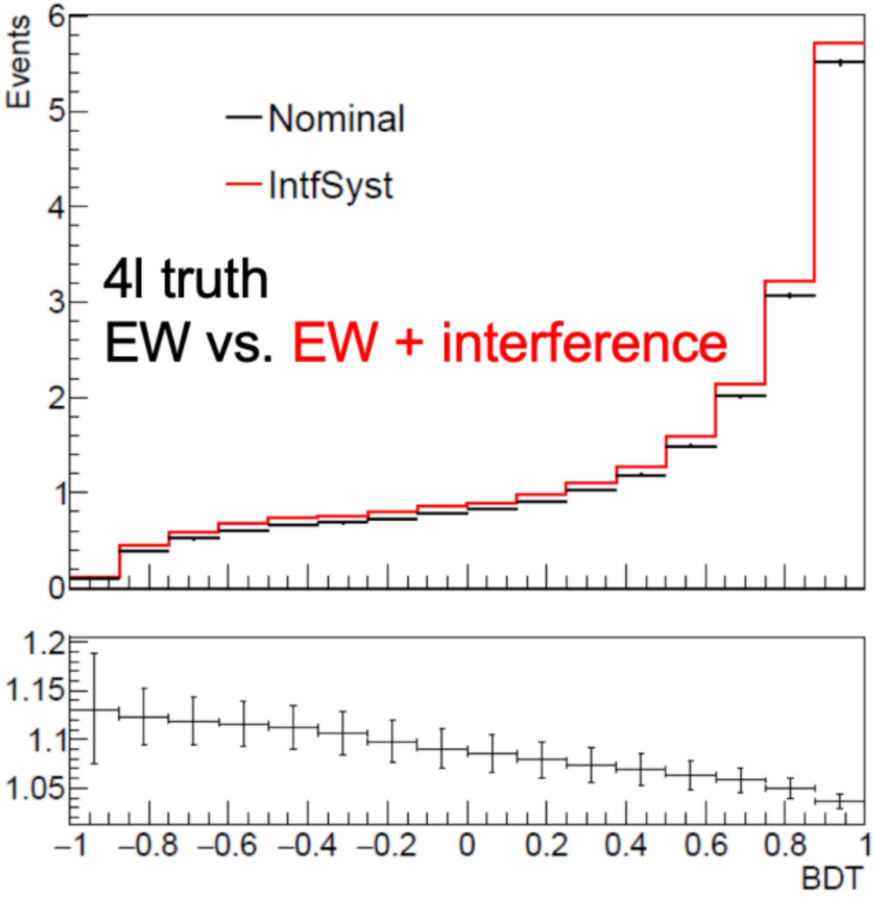
- $80 < M_{\ell\ell} < 100\text{GeV}$
- $P_T^{\ell_1} > 30\text{GeV}$, $P_T^{\ell_2} > 20\text{GeV}$, $|\eta_\ell| < 2.5$, medium
- $p_T^{\ell 3rd} > 20\text{GeV}$, $|(\eta^{\ell 3rd})| < 2.5$, medium
- Transverse mass $m_T^W > 40\text{GeV}$
- B-jet veto: 85% working point
- $n_{jets} \geq 2$
- $P_T^{J_1} > 60\text{GeV}$, $P_T^{J_2} > 40\text{GeV}$
- MET Significance > 3

Non-resonant 2l control region:

- two different-flavour opposite-charge leptons
- veto events with any additional lepton with Loose ID and $P_T > 7\text{GeV}$
- $80 < M_{\ell\ell} < 100\text{GeV}$
- $P_T^{\ell_1} > 30\text{GeV}$, $P_T^{\ell_2} > 20\text{GeV}$, $|\eta_\ell| < 2.5$
- $n_{jets} \geq 2$, $P_T^{j_1} > 60\text{GeV}$, $P_T^{j_2} > 40\text{GeV}$, $|\eta_j| < 4.5$
- $M_{jj} > 400\text{GeV}$, $\Delta Y_{JJ} > 2$, $Y_{j1} \times Y_{j2} < 0$
- B-jet veto
- MET Significance > 12

ZZjj EWK/QCD interference treatment

- EWK-QCD interference is neglected. The estimated size of interference is treated as an additional uncertainty, studied in truth level then convert to reconstruction level.
- The size of interference over EW contribution reduces when entering more EW-signal like regions → treatment of interference is not critical to the results.
- Uncertainty due to interference:7(2)% in 4l (2l2v) channel. Difference mostly due to different mjj cut between two channels.



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Summary of ZZ VBS measurements

Signal/Bgd yield estimations:

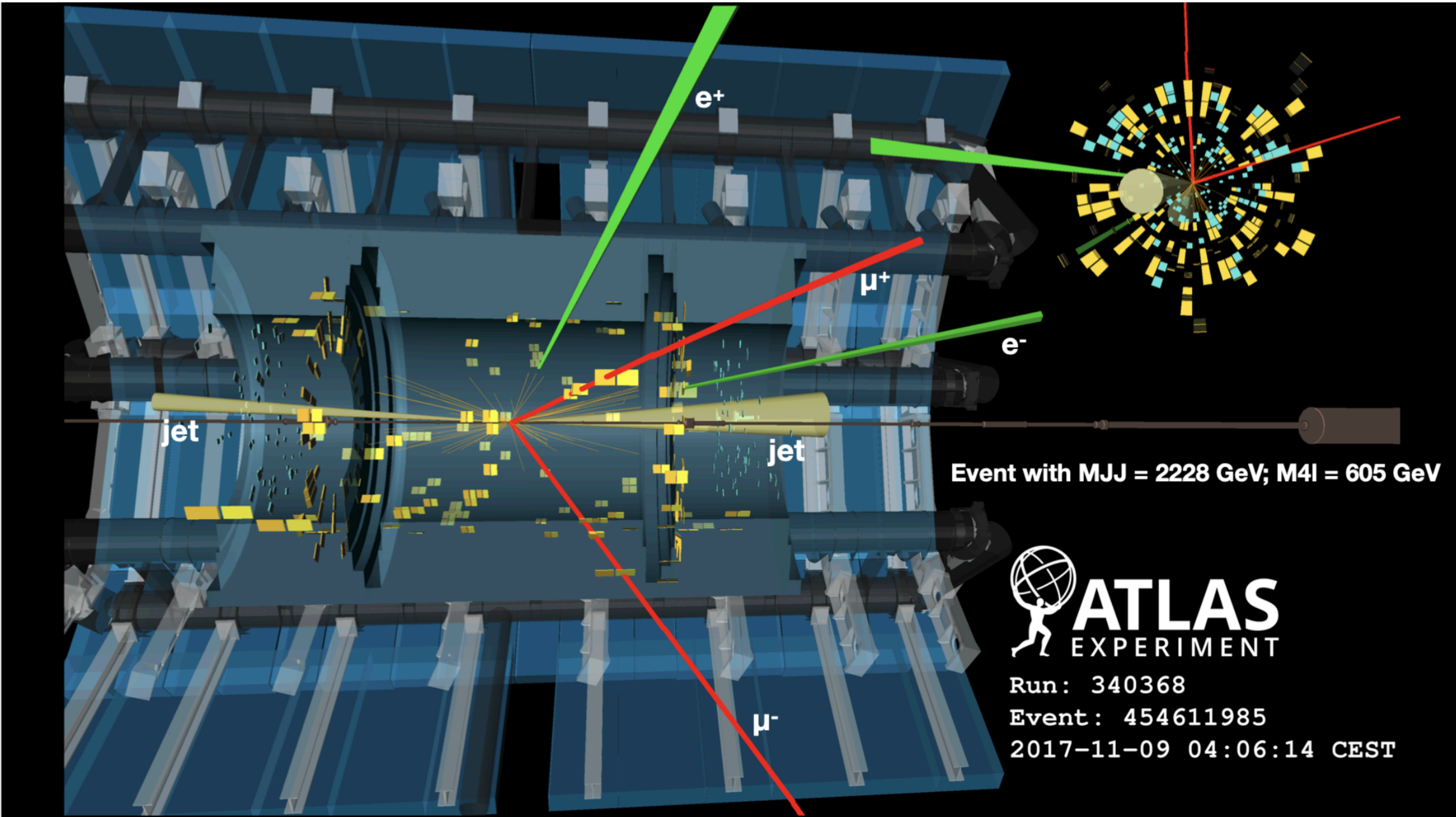
Process	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
EW $ZZjj$	20.6 ± 2.5	12.3 ± 0.7
QCD $ZZjj$	77.4 ± 25.0	17.2 ± 3.5
QCD $ggZZjj$	13.1 ± 4.4	3.5 ± 1.1
Non-resonant-$\ell\ell$	-	21.4 ± 4.8
WZ	-	22.8 ± 1.1
Others	3.2 ± 2.1	1.2 ± 0.9
Total	114.3 ± 25.6	78.4 ± 6.2
Data	127	82

	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:

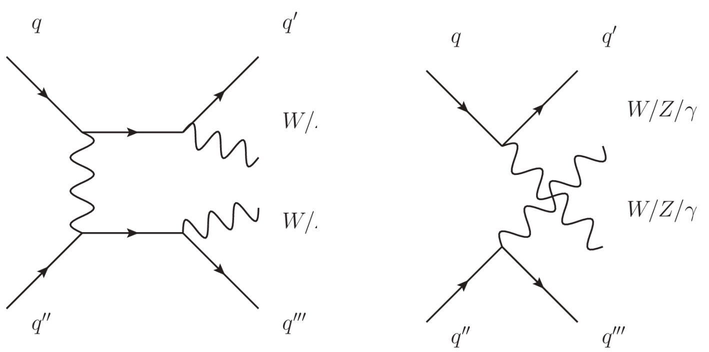
	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.54 ± 0.42	0.95 ± 0.22	5.48 (3.90) σ
$\ell\ell\nu\nu jj$	0.73 ± 0.65	-	1.15 (1.80) σ
Combined	1.35 ± 0.34	0.96 ± 0.22	5.52 (4.30) σ

Event display of the ZZ VBS process

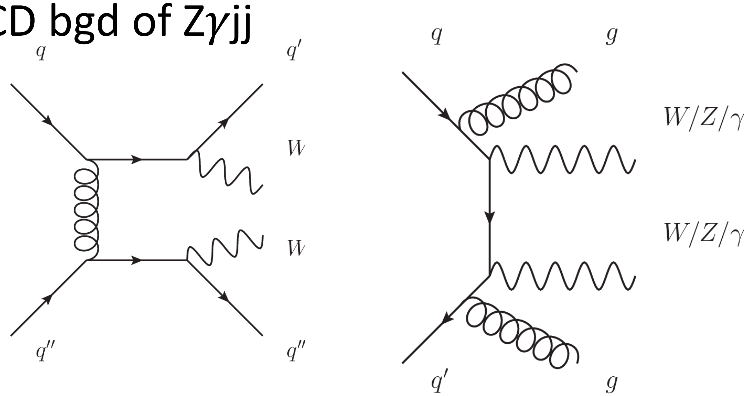


Recent highlights: 1st evidence of Zγ VBS process at ATLAS

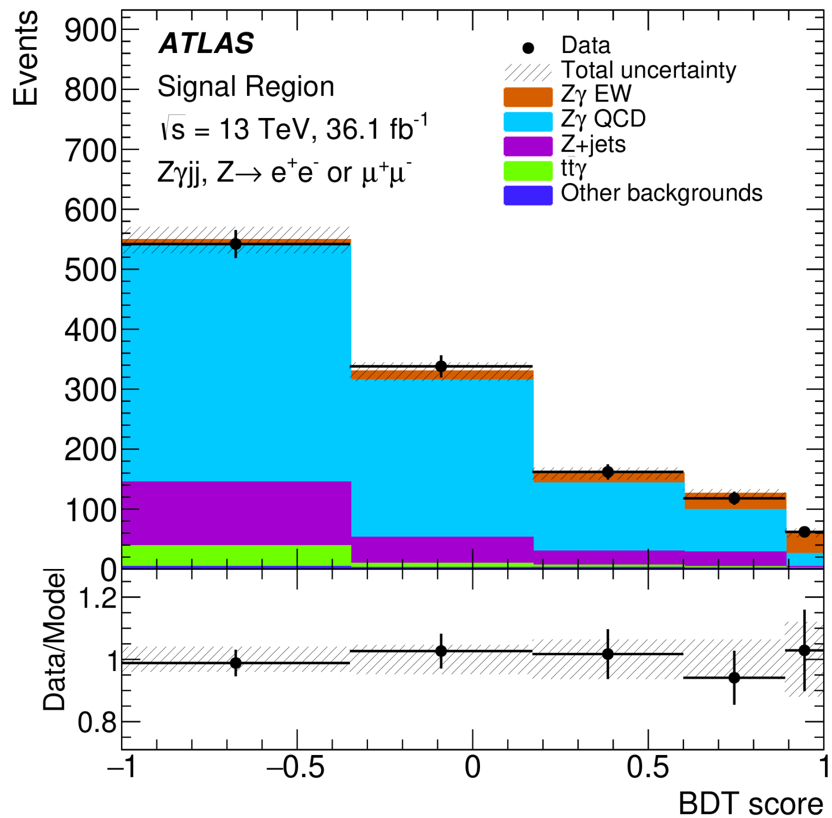
EWK signal of Zγjj



QCD bgd of Zγjj



arXiv:1910.09503



Utilizing 36fb^{-1} data of 2015+2016

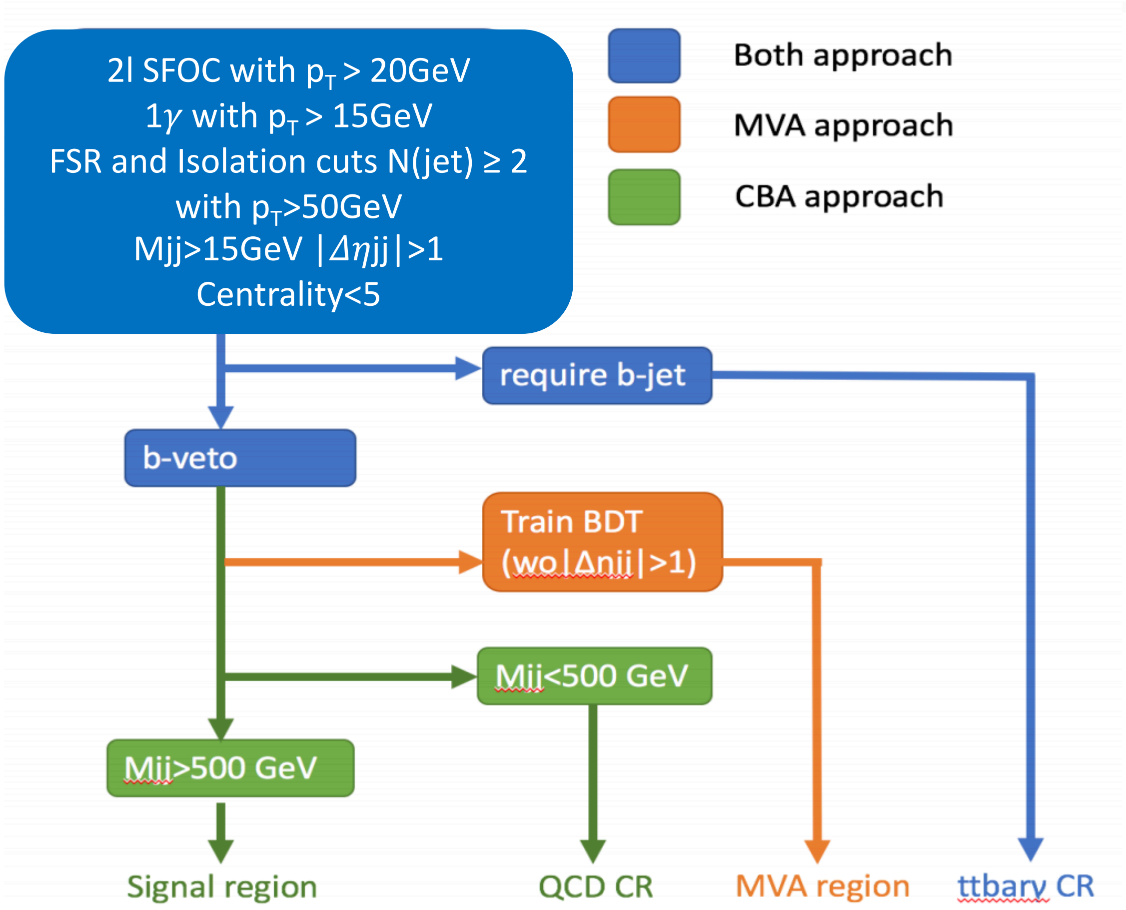
MVA analysis with BDT

Exp./Obs. Signif. = 4.1$\boldsymbol{\sigma}$

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

	$\ell^+\ell^-\gamma jj$ preselection
Lepton	$p_T^\ell > 20$ GeV $\lvert\eta_\ell\rvert < 2.5$ remove e if $\Delta R(e,\mu) < 0.1$ $N_\ell \geq 2$
Boson	$m_{\ell^+\ell^-} > 40$ GeV $m_{\ell^+\ell^-} + m_{\ell^+\ell^-\gamma} > 182$ GeV
Photon	$E_T^\gamma > 15$ GeV $\lvert\eta_\gamma\rvert < 2.37$ remove γ if $\Delta R(\ell,\gamma) < 0.4$ $N_\gamma \geq 1$
Jet	$p_T^{\text{jet}} > 50$ GeV , $\lvert\eta_{\text{jet}}\rvert < 4.5$ $N_{\text{Jets}} \geq 2$ remove jets if $\Delta R(\ell,\text{jet}) < 0.3$ OR $\Delta R(\gamma,\text{jet}) < 0.4$ $\lvert\Delta\eta_{jj}\rvert > 1.0$ $m_{jj} > 150$ GeV
Signal Region	$\ell^+\ell^-\gamma jj$ preselection $\zeta(\ell\ell\gamma) < 5$

Analysis scheme: BDT MVA analysis w/ Cut-Based x-check



MVA:

- Baseline selection splitting into BDT region and b-tagged control region for ttbar+photon
- Fit BDT output in BDT region to extract signal

Cut-based:

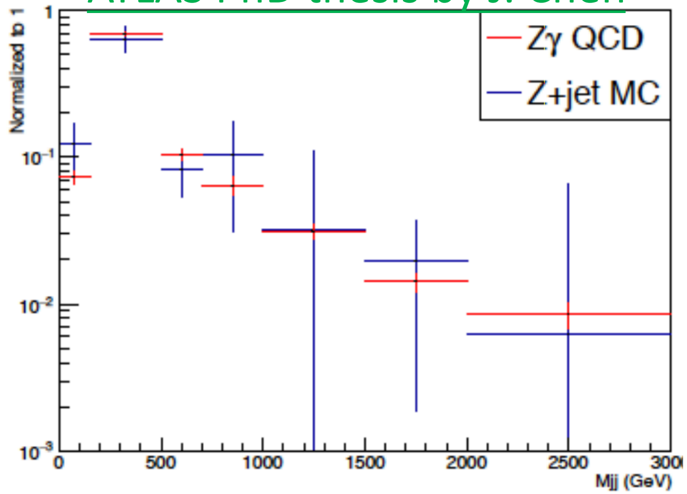
- BDT region splitting into low and high Mjj (500GeV edge)
- Fit Centrality of Z+photon

Background estimation strategy (pre-fit)

Z+jets

- estimated in relaxed region (pt jets>30 GeV, but excluding the SR) using ABCD method (isolation vs anti-ID).
- Extrapolated to the BDT region given the Zγ to Z+jet event shape consistency

ATLAS PhD thesis by J. Chen



tt+γ

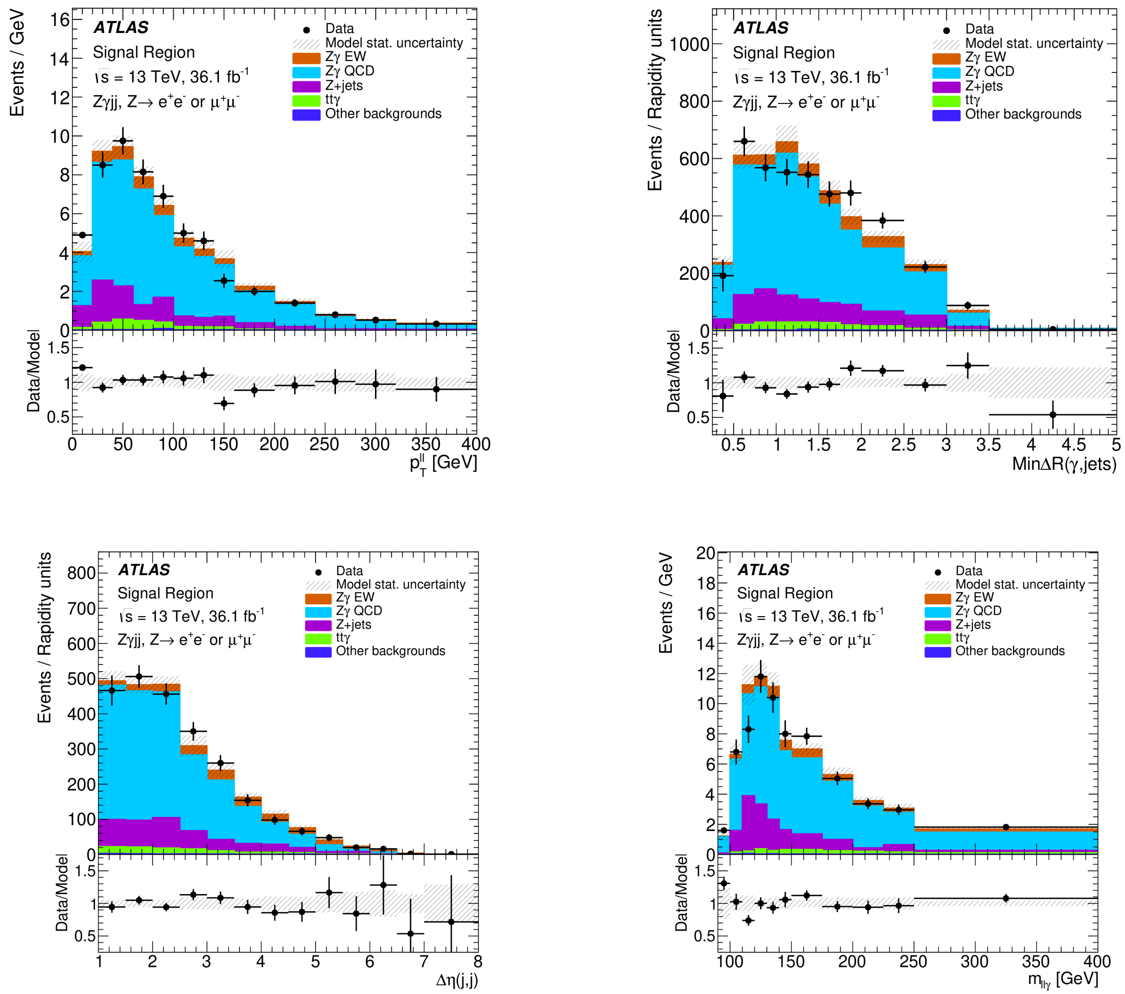
- Estimated by constructing b-CR: # of b-jets >0
- Normalization factor derived using MG5_aMC@NLO MC

Other Backgrounds

- Based on MC prediction
- Small contribution of the order of 0.5% in the SR and 1% in the b-CR.
- Largest contributions:
  - WZjj (QCD and EWK)
  - Single top, mostly tW

BDT inputs for $Z\gamma$ VBS

Variable used in the BDT
m_{jj}
$\Delta\eta_{jj}$
$\zeta(\ell\ell\gamma)$
$m_{\ell\ell\gamma}$
$p_T^{\ell\ell\gamma}$
$m_{\ell\ell}$
$p_T^{\ell\ell}$
$p_T^{\text{lead lep}}$
$p_T^{\text{lead jet}}$
$\eta^{\text{lead jet}}$
$min\Delta R(\gamma, j)$
$\Delta\phi(\ell\ell\gamma, jj)$
$\Delta R(\ell\ell\gamma, jj)$



Systematic uncertainties

Source	Uncertainty [%]
Statistical	$^{+19}_{-18}$
$Z\gamma jj$–EW theory modelling	$^{+10}_{-6}$
$Z\gamma jj$–QCD theory modelling	±6
$t\bar{t}+\gamma$ theory modelling	±2
$Z\gamma jj$–EW and $Z\gamma jj$–QCD interference	$^{+3}_{-2}$
Jets	±8
Pile-up	$^{+6}_{-4}$
Electrons	±1
Muons	$^{+3}_{-2}$
Photons	±1
Electrons/photons scale	±1
b-tagging	±2
MC statistics	±8
Backgrounds normalisation	$^{+9}_{-8}$
Luminosity	±2
Total uncertainty	$^{+27}_{-25}$

Summary of Zγ VBS measurements

Zγjj EWK fid.

$$\sigma^{\text{fid.}}_{Z\gamma jj-\text{EW}} = 7.8 \pm 1.5\,(\text{stat.}) \pm 1.0\,(\text{syst.})\,{}^{+1.0}_{-0.8}\,(\text{mod.})\ \text{fb}$$

$$\sigma^{\text{fid., MadGraph}}_{Z\gamma jj-\text{EW}} = 7.75 \pm 0.03\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.40\,(\text{scale})\ \text{fb}$$

$$\sigma^{\text{fid., Sherpa}}_{Z\gamma jj-\text{EW}} = 8.94 \pm 0.08\,(\text{stat.}) \pm 0.20\,(\text{PDF} + \alpha_S) \pm 0.50\,(\text{scale})\ \text{fb}$$

Zγjj QCD+EWK fid.

$$\sigma^{\text{fid.}}_{Z\gamma jj} = 71 \pm 2\,(\text{stat.})\,{}^{+9}_{-7}\,(\text{syst.})\,{}^{+21}_{-17}\,(\text{mod.})\ \text{fb}$$

$$\sigma^{\text{fid., MadGraph+Sherpa}}_{Z\gamma jj} = 88.4 \pm 2.4\,(\text{stat.}) \pm 2.3\,(\text{PDF} + \alpha_S)^{+29.4}_{-19.1}\,(\text{scale})\ \text{fb.}$$

Signal and Bgd yields:

	SR		b-CR	
Data	1222		388	
Total expected	1222	±35	389	±19
$Z\gamma jj$–EW (signal)	104	±26	5	± 1
$Z\gamma jj$–QCD	864	±60	82	± 9
Z+jets	200	±40	19	± 4
$t\bar{t} + \gamma$	48	±10	280	±21
Other backgrounds	7	± 1	4	± 1

Summary of the measured significance:

Result	μ_{EWK}	μ_{QCD}	Signifance
Cut-based (obs)	0.96 ±0.23(stat) ±0.16(sys) ± 0.06 (theo)	0.87±0.26	2.8 σ
BDT (obs)	1 ±0.19 (stat) ±0.13(sys) + 0.13 -0.10 (theo)	0.86±0.25	4.1 σ

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(**NEW Observation!**)
  - Upcoming channels w.i.p.: ZZ, W/Z+γ(**evidence!**), semileptonic WV(jj)/ZV(jj)
  - Important test of EWSB and higgs mechanism in the unitarization of VV→VV scattering
  - Next steps: differential measurements, 1st extraction of $V_L V_L$ polarization components

- 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, MSSM, aQGCs