Vector Boson Scattering
ATLAS-CMS comparison
Introduction to the discussion session

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ATLAS/CMS comparison: channels and integrated luminosity

Channel	Final state	ATLAS	CMS
ssWW	$\ell\ell$+2j	36 fb^{-1}	137 fb^{-1}
VV+2j	ZZ$\rightarrow 4\ell$	139 fb^{-1}	137 fb^{-1}
	WZ$\rightarrow 3\ell$	36 fb^{-1}	137 fb^{-1}
	ZZ$\rightarrow \ell\ell\nu\nu$	139 fb^{-1}	-
	ZV$\rightarrow \nu\nu$qq	35 fb^{-1}	-
	WV$\rightarrow \ell\nu$qq	35 fb^{-1}	137 fb^{-1}
	ZV$\rightarrow \ell\ell$qq	35 fb^{-1}	-
Zγ	$\ell\ell\gamma$+2j	139 fb^{-1}	137 fb^{-1}
	$\nu\nu\gamma$+2j	139 fb^{-1}	-
Wγ	$\ell\ell\gamma$+2j	-	35.9 fb^{-1}

ATLAS/CMS comparison: fiducial requirements

Channel	FS	ATLAS	CMS
ssWW	$\ell\ell$+2j	$p_T^\ell > 27$ GeV, $m_{ll} > 40$ GeV $p_T^j > 65, 35$ GeV, $M_{jj} > 500$ GeV, $\Delta y_{jj} > 2$	$p_T^\ell > 25, 20$ GeV, $m_{ll} > 20$ GeV $p_T^j > 50$ GeV, $M_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$, $z_\ell^* < 0.75$
VV+2j	WZ$\rightarrow 3\ell$	$p_T^\ell > 15, 15(Z), 20(W)$ GeV, $\lvert m_{ll} - m_Z \rvert < 10$ GeV, $m_T^W > 30$ GeV $p_T^j > 40$ GeV, $\eta^{j1}.\eta^{j2} < 0$, $M_{jj} > 500$ GeV	$p_T^\ell > 25, 10(Z), 20(W)$ GeV, $\lvert m_{ll} - m_Z \rvert < 15$ GeV, $m_{\ell\ell\ell} > 100$ GeV, MET$>$ 30 GeV, $\max(z_\ell^*) < 1$ $p_T^j > 50$ GeV, $M_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$
	ZZ$\rightarrow 4\ell$	$p_T^\ell > 20, 20, 10, 7$ GeV, $66 < m_{ll} < 116$ GeV, $\Delta R_{ll} > 0.2$ $p_T^j > 30(40$ if $2.4 < \lvert\eta\rvert < 4.5)$ GeV, $\eta^{j1}.\eta^{j2} < 0$, $M_{jj} > 300$ GeV, $\Delta y_{jj} > 2$	$p_T^\ell > 20, 10, 5, 5$ GeV, $60 < m_{ll} < 120$ GeV, $M_{4\ell} > 180$ GeV $p_T^j > 30$ GeV, $M_{jj} > 100, 400, 1k$ GeV, $\Delta\eta_{jj} > 2.4$
	WV$\rightarrow \ell\nu qq$	Boosted (J $\Delta R = 0.8$) and Resolved (jj $\Delta R = 0.4$) V(qq) topologies. $p_T^\ell > 27$(veto 7) GeV, MET$>$ 80 GeV V-tag $p_T^j > 20(30$ if $2.4 < \lvert\eta\rvert < 4.5)$ GeV, $p_T^J > 200$ GeV, $\lvert\eta^J\rvert < 2$ $p_T^j > 30$ GeV, $\eta^{j1}.\eta^{j2} < 0$, $M_{jj} > 400$ GeV	$p_T^\ell > 30(\mu), 35(e)$(veto 10) GeV, MET$>$ 30 GeV, $m_T(W) < 185$ GeV V-tag $p_T^j > 30$ GeV, $p_T^J > 200$ GeV $p_T^j > 30$ GeV, $M_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$
$Z\gamma$	$\ell\ell\gamma$+2j	$p_T^\ell > 30, 20$ GeV, $m_{ll} > 40$ GeV, $E_T^\gamma > 25$ GeV, ΔR(l,γ)$>$ 0.4 $M_{ll} + M_{ll\gamma} > 182$ GeV, $\zeta_{ll\gamma} < 0.4$ $p_T^j > 50$ GeV, $M_{jj} > 150$ GeV, $\Delta y_{jj} > 1$, $\Delta R(\gamma, j) > 0.4$, $\Delta R(\ell, j) > 0.3$, $Njets^{Gap} = 0$	$p_T^\ell > 25(ee), 20(\mu\mu)$ GeV, $70 < m_{ll} < 110$ GeV, $E_T^\gamma > 20$ GeV, ΔR(l,γ)$>$ 0.7 $M_{ll\gamma} > 100$ GeV, $\eta^* < 2.4$ $p_T^j > 30$ GeV, $M_{jj} > 500$ GeV, $\Delta\eta_{jj} > 2.5$, $\Delta R(\gamma, j) > 0.5$, $\Delta R(\ell, j) > 0.5$, $\Delta\Phi(Z\gamma, jj) > 1.9$

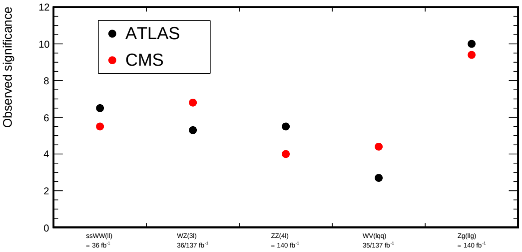
ATLAS/CMS comparison: experimental methods

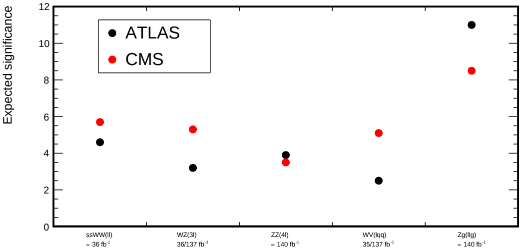
Channel	FS	ATLAS	CMS
ssWW	$\ell\ell$+2j	36 fb^{-1} fit with 30 bins (5 Mjj $\times$ 6 lep-lep) + WZ CR	137 fb^{-1} 2D fit M$_{jj}$-M$_{\ell\ell}$, diff. in M$_{jj}$, M$_{ll}$,p$_T^{\ell 1}$ polarisation meas. with 2 BDTs
VV+2j	WZ$\rightarrow$ 3ℓ	36 fb^{-1} BDT (15 vars) in SR, combined fit SR+b-CR+QCD-CR+ZZ-CR, diff xs in m$_T$(WZ),Σp_T^{ℓ}, $\Delta\Phi$(W,Z), N$_{jets}$, M$_{jj}$, $\Delta\Phi_{jj}$, Δy_{jj}	137 fb^{-1} BDT (13 vars), diff xs in M$_{jj}$
	ZZ$\rightarrow$ 4ℓ	139 fb^{-1} Multivariate discriminant, CR+SR combined fit	137 fb^{-1} Matrix Element analysis
	WV$\rightarrow$ $\ell\nu$qq	35 fb^{-1} Fit of BDT in 9 SR, M$_{jj}$ in 12 CR	137 fb^{-1} DNN
Zγ	$\ell\ell\gamma$+2j	139 fb^{-1} Fit of M$_{jj}$ CR+SR	137 fb^{-1} 2D fit M$_{jj}$-M$_{\ell\ell}$, diff. in M$_{jj}$, p$_T^{\ell}$, p$_T^{\gamma}$, p$_T^{j1}$

ATLAS/CMS comparison: systematics

Channel	FS	ATLAS	CMS
ssWW	$\ell\ell$+2j	36 fb^{-1} Bkg non-prompt l $\simeq$ 50%, e charge misid $\simeq$ 15%, bkg theo model $\simeq$ 25%	137 fb^{-1} Bkg non-prompt l $\simeq$ 3.5%, lep id $\simeq$ 2%, bkg theo model $\simeq$ 2%, MC stat 2.6%
VV+2j	WZ$\rightarrow$ 3ℓ	36 fb^{-1} Jets 6.6%, QCD model 5.2%, EWK model 4.8%	137 fb^{-1} Jets 4.3%, theo model 3.8%, MC stat 3.7%, lep 2.9%
	ZZ$\rightarrow$ 4ℓ	139 fb^{-1} Exp 10%, Bkg CR 15%, EWK theo model 10%, QCD theo model 30%	137 fb^{-1} Jets-Bkg 5-15%, trig+lep 2-9%, MC stat 2-4%, Bkg theo model 12-20%, EWK theo model 10-18%
	WV$\rightarrow$ $\ell\nu$qq	35 fb^{-1} jets 20%, Bkg norm. 30%, EWK model 10%, discri modeling 5-30%	137 fb^{-1} jets 4%, Bkg norm. 12%, EWK model 9%, btag 5%, MC syst 10%
Zγ	$\ell\ell\gamma$+2j	139 fb^{-1} EWK model 6%, QCD model 5%, Jets 5%	137 fb^{-1} theo model 5%, Jets 8%, MC stat 5%, PU 5%, eγ 4.5%

ATLAS/CMS comparison: significance

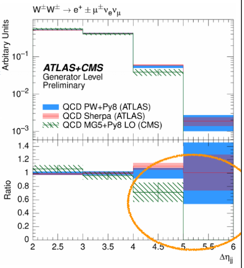


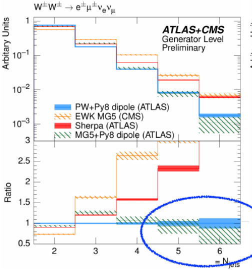


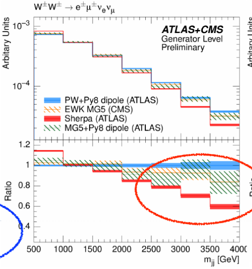
ATLAS/CMS comparison: MC modeling and systematics

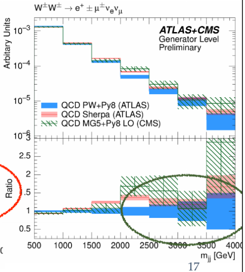
Comparisons

- **EWK samples**
  - Samples with new dipole-recoil scheme have **significantly smaller jet multiplicity**
  - The ***mjj* and Δηjj distribution are softer for Sherpa** (ATLAS) sample
- **QCD samples:**
  - **mjj much softer for the QCD PW+Py8** (ATLAS) samples
  - **$\Delta\eta_{jj}$ much more central for the QCD MG5+Py8** (CMS) sample









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ATLAS/CMS comparison: HL-LHC projections

Prospects for High-Luminosity LHC

- Cross sections at LO and NLO EW for W^+W^- scattering at **√s=14,27,100 TeV**
  - **σ increase** with **√s** while **EW corrections** become negatively **larger**
  - typical **scale** in the **Sudakov logarithms** is increasing

$\sqrt{s}$	$\sigma^{\mathrm{LO}}[\mathrm{fb}]$	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}[\mathrm{fb}]$	$\delta_{\mathrm{EW}}[\%]$
14 TeV	1.4282(2)	1.213(5)	−15.1
27 TeV	4.7848(5)	3.881(7)	−18.9
100 TeV	25.485(9)	19.07(6)	−25.2

arXiv:2102.10991

- Simulations of **upgraded detectors** at √s=14 and total luminosity 3000 fb^{-1}
  - VBS **$W^\pm W^\pm$** - **expected** total uncertainty on cross section is **4.5 (5-6)%** for **CMS(ATLAS)**
  - VBS **$W_L^\pm W_L^\pm$** - **CMS+ATLAS combination** should yield **3σ discovery**
  - VBS **$W^\pm Z$** - overall expected uncertainty **5.5 (5)%** for **CMS(ATLAS)**
  - VBS **$W^\pm Z_L$** - expect **evidence** of **1.3-1.4σ** for CMS and **1.5-2.5σ** for ATLAS

Remember...

G. Altarelli, EPS-HEP 2011

LHC scenarios

Catastrophic: No Higgs, no new physics

Can only occur if the LHC is not enough to fully probe the EW scale: unitarity violations impose one or the other (eg new vector bosons) or both

Theorist projection: non standard Higgs and new physics

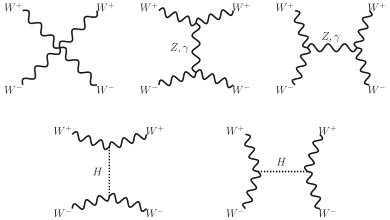
A lot of model building in this direction

Pure SM: A light scalar Higgs, no new physics at the EW scale

If so, nature does not abhor fine tuning at all

This is the paradigm that experiment must try to falsify

VBS is back on the front line...
...towards the end goal of a more complete theory



- VBS as a test of the exact nature of EWSB and of the Higgs potential
- Right now: "Bottom-Up" approach with EFT.
- Still iterating on the "correct" EFT ...
- Full theoretical model probably still a long way...

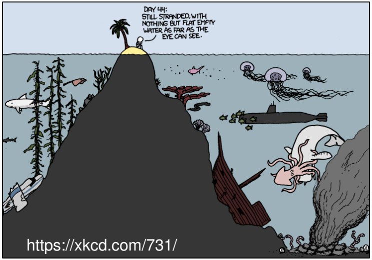
Feature

Tags:
vector bosons,
W boson

Unraveling Nature's secrets: vector boson scattering at the LHC

22nd September 2020 | By Lucia Di Ciaccio, Simone Pagan Griso

"It would be a sensation if more precise measurements indicated that such new terms are necessary to describe the data. It would be a sign of physics beyond the Standard Model and indication of the direction to take in order to develop a more complete theory, depending on which kinds of terms are needed. The interplay between experimental observations and models in the quest for a complete theory would continue."



A few open items...

Ruiz *et al.* arXiv:2106.01393

Theory side

- VBS approx vs full NLO (EW+QCD) corrections: Pellen *et al* arXiv:1803.07943
- EFT definition
- NLO EFT ?
- For future colliders: behaviour in the massless limit, EW PDF ?

Experimental side

- More stat.
- Add final states with tau leptons, hadronic decays.
- Improve acceptance: triggering on VBF jets, quark-gluon discrimination.
- Reduce systs: MC modeling, JES.

Common to both

- Data to publish to allow for theoretical re-interpretation in several years time.
- Central jet activity (MC modeling).
- Polarisation: theoretical definitions and measurements.

Backups

BACKUPS

ATL-PHYS-PUB-2020-026

Comparison of ATLAS and CMS VBS MCs

- Ability to use VBS to constrain BSM models depends on reliable theoretical predictions with well understood systematic uncertainties

- Comparison of several MCs from ATLAS, CMS and VBScan COST (particle level)

Sample name	Generator	μ-scale	Shower	Tune	PDF	further settings
Sherpa (ATLAS)	SHERPA v2.2.2 *Bug in colour flow*	dynamic scale, m_{WW}	internal	internal	NNPDF3.0-NNLO	multileg-LO, exactly six EW vertices with one additional parton at LO accuracy in QCD
PW+Py8 (ATLAS)	POWHEG v2, VBS approx.	fixed scale, m_W	PYTHIA 8.212	AZNLO	NNPDF3.0-NLO	NLO
PW+Py8 dipole-recoil (ATLAS)	POWHEG v2	fixed scale, m_W	PYTHIA 8.235	AZNLO	NNPDF3.0-NLO	Dipole Recoil [6]
MG5+Py8 dipole-recoil (ATLAS)	MG5_AMCNLO v2.6.2	dynamic scale, $\sqrt{p_T^{jet1} p_T^{jet1}}$	PYTHIA 8.235	A14	NNPDF3.0-NLO	LO, Dipole Recoil [6]
MG5+Py8 (CMS)	MG5_AMCNLO v2.3.3	dynamic scale, using a 2→2 topology from the clustered external state	PYTHIA 8.212	CUETP8M1 [7]	NNPDF3.0-LO	LO, exactly six EW vertices
PW+Py8 (VBScan)	POWHEG v2	dynamic scale, $\sqrt{p_T^{jet1} p_T^{jet2}}$	PYTHIA 8.230	Monash	NNPDF3.0-NLO	NLO

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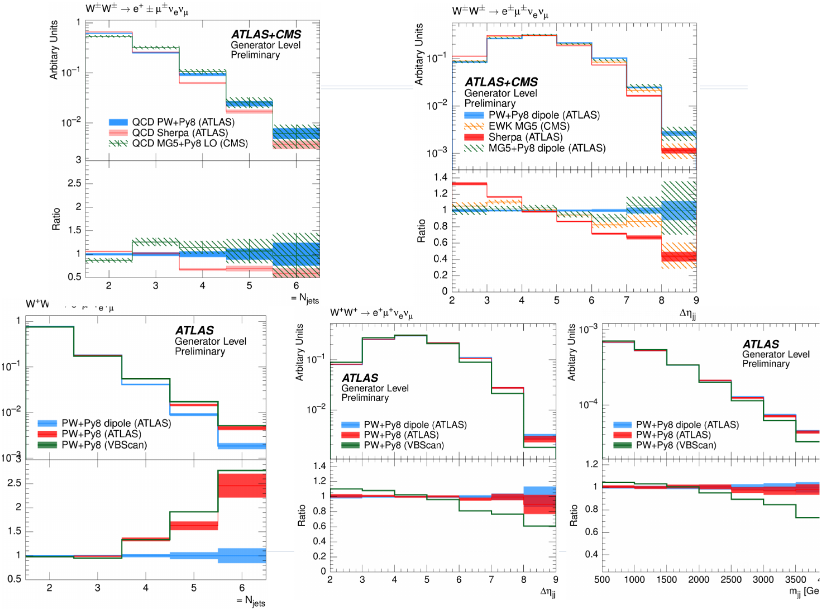
ATLAS/CMS MC comparison details

Selection requirement	Selection value
dressed leptons with dressing cone of $\Delta R = 0.1$ and minimum p_{T}^{ℓ}	> 20 GeV
η_ℓ	$\lvert\eta_\ell\rvert \leq 2.5$
Charge of leading electron and muon	$c_e \times c_\mu > 0$
minimum ΔR between any of the leptons	$\Delta R \geq 0.3$
Jets, anti-k_t with $R = 0.4$, excluding leptons and neutrinos	$p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 4.5$
Minimum jet distance to lepton, otherwise jet is removed	$\Delta R \geq 0.3$
Minimum number of jets with above criteria	2
distance in pseudo-rapidity of the jets	$\Delta\eta_{jj} \geq 2.5$
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 40 GeV
Signal region: invariant mass of jet system	$m_{jj} \geq 500$ GeV
Control region: invariant mass of jet system	200 GeV $< m_{jj} <$ 500 GeV

Sample name	Fiducial cross section [fb] $\mathrm{W^+W^+} \to e^+\mu^+\nu_e\nu_\mu$	Fiducial cross section [fb] $\mathrm{W^\pm W^\pm} \to e^\pm\mu^\pm\nu_e\nu_\mu$
Sherpa (ATLAS)	0.968 ± 0.005	1.136 ± 0.005
PW+Py8 (ATLAS)	1.320 ± 0.009	1.768 ± 0.009
PW+Py8 dipole-recoil (ATLAS)	1.322 ± 0.009	1.769 ±0.009
MG5+Py8 dipole-recoil (ATLAS)	1.313 ± 0.028	1.734 ± 0.028
MG5+Py8 (CMS)	1.281 ± 0.018	1.707 ± 0.021
PW+Py8 (VBScan)	1.364 ± 0.0004	n/a


$W^{\pm}W^{\pm} \to e^{+} \pm \mu^{\pm} \nu_e \nu_\mu$
ATLAS+CMS
Generator Level
Preliminary
QCD PW+Py8 (ATLAS)
QCD Sherpa (ATLAS)
QCD MG5+Py8 LO (CMS)
Arbitary Units
Ratio
= N_{jets}
$W^{\pm}W^{\pm} \to e^{\pm}\mu^{\pm}\nu_e\nu_\mu$
ATLAS+CMS
Generator Level
Preliminary
PW+Py8 dipole (ATLAS)
EWK MG5 (CMS)
Sherpa (ATLAS)
MG5+Py8 dipole (ATLAS)
Arbitary Units
Ratio
$\Delta\eta_{jj}$
ATLAS
Generator Level
Preliminary
PW+Py8 dipole (ATLAS)
PW+Py8 (ATLAS)
PW+Py8 (VBScan)
= N_{jets}
$W^{+}W^{+} \to e^{+}\mu^{+}\nu_e\nu_\mu$
ATLAS
Generator Level
Preliminary
PW+Py8 dipole (ATLAS)
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PW+Py8 (VBScan)
Arbitary Units
Ratio
$\Delta\eta_{jj}$
ATLAS
Generator Level
Preliminary
PW+Py8 dipole (ATLAS)
PW+Py8 (ATLAS)
PW+Py8 (VBScan)
Arbitary Units
Ratio
m_{jj} [Ge