WG3 Multibosons : Activities report and outlook

The LHC-EWWG Multiboson subgroup conveners

ATLAS: Shu Li, Heather Russell; previous: Joany Manjarres
CMS: Yacine Haddad, Lorenzo Viliani; previous: Philip Chang, Roberto Covarelli
Theory: Jonas Lindert, Céline Degrande

LHC EWWG General Meeting - 17th Nov 2022

YR status

git@github.com:LHCEWWG-MB/YellowReport.git

CERN Yellow Reports: Monographs CERN-2022-XXX-M
Volume X/2022

Multibosons Physics at the LHC

Report of the EW Working Group

Editors: P. Azzurri
C. Degrande
D. Gillberg
L. Helary
S. Li
M. Liu
J.M. Lindert
K. Lohwasser
P. Vischia

Contents

1. Measurements of Multibosons: current status → best practice for inter-experiment consistency
2. Predictions for Multibosons: state-of-the-art and best-practise
3. Predictions for Multibosons: MC/phenomenological studies
4. Fiducial cross-section and BSM

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Contents

New structure: ordered by process classes

1. Diboson production
2. Vector-boson fusion
3. Vector-boson scattering
4. Triboson
5. MC/Pheno Studies
6. Fiducial cross-sections and BSM

Status: 69 pages
For every section: Theory + Exp editors assigned

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Contents

- Significant progress earlier this year
- Progress stalled over the last few months
  - problem: man-power / focus / changing editorship in experimental sections

Measurements of Multibosons: current results and outlook

What's there

- Diboson
  - Zγ
  - Wγ
  - γγ
- VBF
  - Z-jj
  - W-jj
- VBS
  - WW-ss-jj
  - W+W–jj
  - WZ-jj
  - ZZ-jj
  - Semi-leptonic-jj
  - Wγ-jj
  - Zγ-Wγ-jjjj
  - Polarised measurements
- Tribosons
  - γγγ
  - Wγγ
  - Zγγ
  - WWγ & WZγ

What's missing

- Diboson
  - ZZ (already existing text was outdated)
  - WW (already existing text was outdated)
- Triboson
  - WWW
  - WWZ
  - WZZ

TBD: common phase-space definitions

Predictions for Multibosons: state-of-the-art and best-practise

What's there

- Diboson
  - Reference cross sections at NNLO QCD + NLOgg + NLO EW + NLOγ/qγ for WW/ZZ/WZ (all relevant leptonic channels)
  - Theory review in progress

process	$pp \to e^-\mu^-e^+\mu^+$	$pp \to e^-e^-e^+e^+$	$pp \to e^-e^+\nu_\mu\bar{\nu}_\mu$	$pp \to e^-\mu^+\nu_\mu\bar{\nu}_e$	$pp \to e^-e^+\nu_e\bar{\nu}_e$
$\sigma^{q\bar{q}}_{\mathrm{LO}}$	$16.04(0)^{+5.0\%}_{-6.1\%}$ fb	$9.164(0)^{+4.9\%}_{-6.0\%}$ fb	$3.948(0)^{+2.0\%}_{-2.9\%}$ fb	$272.8(0)^{+5.6\%}_{-6.7\%}$ fb	$4.551(0)^{+2.1\%}_{-3.0\%}$ fb
$\sigma^{q\bar{q}}_{\mathrm{NLO\ QCD}}$	$21.46(0)^{+3.0\%}_{-2.4\%}$ fb	$12.27(0)^{+3.0\%}_{-2.4\%}$ fb	$2.866(0)^{+5.2\%}_{-5.2\%}$ fb	$255.9(0)^{+2.4\%}_{-2.1\%}$ fb	$3.512(1)^{+4.3\%}_{-4.3\%}$ fb
$\sigma^{q\bar{q}}_{\mathrm{NLO\ EW}}$	$14.85(0)^{+5.1\%}_{-6.2\%}$ fb	$8.506(0)^{+5.0\%}_{-6.1\%}$ fb	$3.495(0)^{+2.2\%}_{-3.1\%}$ fb	$264.4(0)^{+5.7\%}_{-6.8\%}$ fb	$4.057(0)^{+2.3\%}_{-3.1\%}$ fb
$\sigma^{q\bar{q}}_{\mathrm{NNLO\ QCD}}$	$22.71(1)^{+1.4\%}_{-1.3\%}$ fb	$12.97(1)^{+1.4\%}_{-1.3\%}$ fb	$2.844(1)^{+0.68\%}_{-0.28\%}$ fb	$249.8(1)^{+0.90\%}_{-0.58\%}$ fb	$3.446(11)^{+0.92\%}_{-0.30\%}$ fb
$\sigma^{gg}_{\mathrm{LO}}$	$2.214(0)^{+25\%}_{-19\%}$ fb	$1.219(0)^{+25\%}_{-19\%}$ fb	$0.5783(0)^{+29\%}_{-21\%}$ fb	$26.85(0)^{+27\%}_{-19\%}$ fb	$0.7391(2)^{+28\%}_{-21\%}$ fb
$\sigma^{gg}_{\mathrm{NLO\ QCD}}$	$3.598(2)^{+13\%}_{-12\%}$ fb	$1.935(1)^{+13\%}_{-12\%}$ fb	$0.3124(1)^{+21\%}_{-53\%}$ fb	$31.23(11)^{+4.0\%}_{-7.0\%}$ fb	$0.4366(29)^{+17\%}_{-43\%}$ fb
$\sigma^{\gamma\gamma}_{\mathrm{LO}}$	$0.01037(0)^{+18\%}_{-16\%}$ fb	$0.01554(0)^{+18\%}_{-17\%}$ fb	$0.00009607(1)^{+17\%}_{-16\%}$ fb	$3.178(0)^{+18\%}_{-16\%}$ fb	$0.02213(1)^{+18\%}_{-16\%}$ fb
$\sigma^{\gamma\gamma/q\gamma}_{\mathrm{NLO\ EW}}$	$0.01148(1)^{+7.7\%}_{-11\%}$ fb	$0.01365(1)^{+5.0\%}_{-7.2\%}$ fb	$-0.0002370(1)^{+112\%}_{-130\%}$ fb	$2.648(0)^{+1.7\%}_{-2.7\%}$ fb	$0.01768(4)^{+2.6\%}_{-3.8\%}$ fb
σ_{LO}	$16.05(0)^{+5.0\%}_{-6.1\%}$ fb	$9.179(0)^{+4.9\%}_{-6.0\%}$ fb	$3.949(0)^{+2.0\%}_{-2.9\%}$ fb	$276.0(0)^{+5.7\%}_{-6.8\%}$ fb	$4.573(0)^{+2.2\%}_{-3.0\%}$ fb
$\sigma_{\mathrm{NLO\ QCD}}$	$21.48(0)^{+3.0\%}_{-2.4\%}$ fb	$12.28(0)^{+3.0\%}_{-2.4\%}$ fb	$2.866(0)^{+5.2\%}_{-5.2\%}$ fb	$259.1(0)^{+2.6\%}_{-2.2\%}$ fb	$3.534(1)^{+4.3\%}_{-4.4\%}$ fb
$\sigma_{\mathrm{NLO\ EW}}$	$14.87(0)^{+5.1\%}_{-6.2\%}$ fb	$8.519(0)^{+5.0\%}_{-6.1\%}$ fb	$3.495(0)^{+2.2\%}_{-3.1\%}$ fb	$267.1(0)^{+5.6\%}_{-6.8\%}$ fb	$4.075(0)^{+2.2\%}_{-3.1\%}$ fb
$\sigma_{\mathrm{NLO\ QCD+EW}}$	$20.29(0)^{+3.1\%}_{-2.5\%}$ fb	$11.62(0)^{+3.1\%}_{-2.5\%}$ fb	$2.412(0)^{+6.0\%}_{-5.9\%}$ fb	$250.2(0)^{+2.4\%}_{-2.0\%}$ fb	$3.036(1)^{+4.8\%}_{-4.8\%}$ fb
$\sigma_{\mathrm{NLO\ QCD\times EW}}$	$19.89(0)^{+3.0\%}_{-2.4\%}$ fb	$11.40(0)^{+3.0\%}_{-2.4\%}$ fb	$2.536(0)^{+5.4\%}_{-5.4\%}$ fb	$250.8(0)^{+2.5\%}_{-2.2\%}$ fb	$3.149(1)^{+4.4\%}_{-4.5\%}$ fb
$\sigma_{\mathrm{NLO\ QCD\times EW_{qq}}}$	$19.89(0)^{+3.0\%}_{-2.4\%}$ fb	$11.40(0)^{+3.0\%}_{-2.4\%}$ fb	$2.536(0)^{+5.4\%}_{-5.4\%}$ fb	$250.7(0)^{+2.5\%}_{-2.2\%}$ fb	$3.149(1)^{+4.4\%}_{-4.5\%}$ fb
$\sigma_{\mathrm{NNLO\ QCD}}$	$24.93(1)^{+3.5\%}_{-2.8\%}$ fb	$14.21(1)^{+3.4\%}_{-2.7\%}$ fb	$3.423(1)^{+5.3\%}_{-3.0\%}$ fb	$279.8(1)^{+2.1\%}_{-1.3\%}$ fb	$4.207(11)^{+4.8\%}_{-2.8\%}$ fb
$\sigma_{\mathrm{nNNLO\ QCD}}$	$26.32(1)^{+3.0\%}_{-2.7\%}$ fb	$14.92(1)^{+2.9\%}_{-2.6\%}$ fb	$3.157(1)^{+2.7\%}_{-4.8\%}$ fb	$284.2(2)^{+0.64\%}_{-0.91\%}$ fb	$3.904(12)^{+2.8\%}_{-5.0\%}$ fb
$\sigma_{\mathrm{(n)NNLO\ QCD+EW}}$	$25.14(1)^{+3.4\%}_{-2.9\%}$ fb	$14.26(1)^{+3.2\%}_{-2.7\%}$ fb	$2.703(1)^{+3.0\%}_{-5.3\%}$ fb	$275.3(2)^{+0.40\%}_{-0.65\%}$ fb	$3.406(12)^{+3.0\%}_{-5.4\%}$ fb
$\sigma_{\mathrm{(n)NNLO\ QCD\times EW}}$	$24.38(1)^{+2.9\%}_{-2.7\%}$ fb	$13.85(1)^{+2.8\%}_{-2.6\%}$ fb	$2.794(1)^{+2.9\%}_{-5.0\%}$ fb	$275.1(2)^{+0.57\%}_{-0.84\%}$ fb	$3.479(10)^{+2.9\%}_{-5.1\%}$ fb
$\sigma_{\mathrm{NNLO\ QCD\times EW}+gg\mathrm{NLO}}$	$24.65(1)^{+3.0\%}_{-2.8\%}$ fb	$13.99(1)^{+2.9\%}_{-2.7\%}$ fb	$2.830(1)^{+3.1\%}_{-5.6\%}$ fb	$276.1(2)^{+0.59\%}_{-0.86\%}$ fb	$3.526(10)^{+3.0\%}_{-5.6\%}$ fb
$\sigma_{\mathrm{nNNLO\ QCD\times EW_{qq}}}$	$24.65(1)^{+3.0\%}_{-2.8\%}$ fb	$13.99(1)^{+2.9\%}_{-2.7\%}$ fb	$2.830(1)^{+3.1\%}_{-5.6\%}$ fb	$275.5(2)^{+0.36\%}_{-0.66\%}$ fb	$3.523(10)^{+2.9\%}_{-5.5\%}$ fb

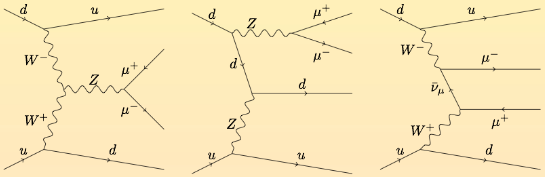
Predictions for Multibosons: state-of-the-art and best-practise

What's there

- Diboson
  - Reference cross sections at NNLO QCD + NLOgg + NLO EW + NLOγ/qγ for WW/ZZ/WZ (all relevant leptonic channels)
  - Theory review in progress
- VBF-V
  - Theory review: draft available / work in progress
- VBS-VV
  - Theory review: draft available

What's missing

- Triboson



(a) vector boson fusion **(b)** bremsstrahlung-like **(c)** non-resonant

Fig. 2.1: Representative Feynman diagrams for the production of two charged leptons in association with two jets at order α^4. This process is also referred to as EW Zjj in this section, or more inclusively EW Vjj that also includes the $\ell\nu jj$ final states (i.e. EW Wjj). Semileptonic diboson final states also contribute at order α^4, but are not shown as their contribution is very small in the VBF kinematic region ($m_{jj} \gg m_W$).

Recommendations and good practice

– Present results of the measurements for the full process (EW+int+QCD) as well for the contributions separately. On the theory side, beyond LO one should specify how the EW component is defined as it is ill defined from the theory point of view in the full computation.

– Keep in mind that while the VBS approximation is currently perfectly valid and has an effect of few per cent (in typical PSP), this might not hold for future measurements as these will be much more precise and maybe in other PSP.

– In this respect, it is very important to ensure sound PSP definition. In the sense that they should make sense also beyond LO. For example ZZ measurement of CMS which goes down to mjj > 100 GeV and suppress triboson contributions in this way. At NLO QCD, this is not sufficient to suppress these contributions due to extra real radiations.

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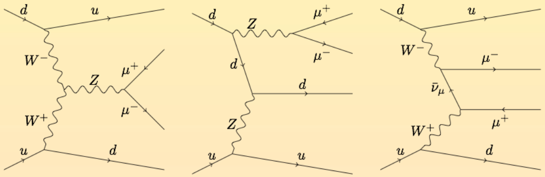

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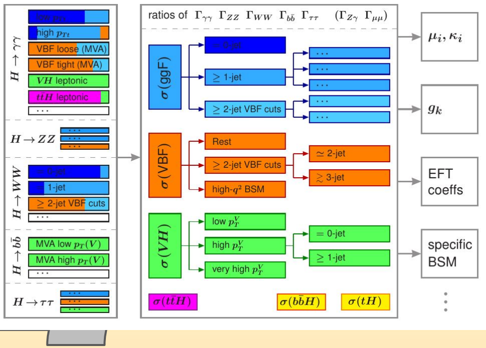
What's missing

- Triboson

Question: is there motivation for reference cross sections beyond Dibosons
(VBF-V and VBS-VV xsections strongly depend on precise fiducial phase-space)



Inspired by Higgs STXS: Useful benchmarks!

LHC EWWG Working group proposal

Step towards making

global fits easier ?

→ and basis to start EFT investigations

- ***Common differential cross section definitions in BSM phase-space***
- Advantage:
  - **Benchmarking**
  - **Combinations**

Multiboson Production

Final state	Object	Selection requirements
WW	**leptons**	p_T >25 GeV, $\lvert\eta\rvert < 2.5$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	jets	no jets with p_T >30 GeV and within $\lvert\eta\rvert < 5.0$
	final BSM region	$m_{\ell\ell}$: 380-600 GeV, >600 GeV
WZ	**leptons**	$p_{T,\text{lead}}$ >25 GeV, p_T >15 GeV, $\lvert\eta\rvert < 2.5$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	jets	no b-jets with p_T >30 GeV and within $\lvert\eta\rvert < 5.0$
	bosons	$m_{T,W}$ >30 GeV (see Eq. **??**), $\Delta(m_Z, m_{\ell\ell})$ <15 GeV
	final BSM region	$m_{T,WZ}$: 380-600 GeV, >600 GeV (see Eq. **??**)
ZZ	**leptons**	p_T >25 / 15 / 10 GeV (leading leptons), $\lvert\eta\rvert < 2.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV
$W\gamma$	**leptons**	p_T >35, $\lvert\eta\rvert < 2.5$
	photons	E_T >25, $\lvert\eta\rvert < 2.5$, $\Delta R(\ell, \gamma) > 0.7$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	bosons	$m_{T,W}$ >50 GeV
	final BSM region	$p_{T,\gamma}$: 25-60 GeV, 60-90 GeV, 90-150 GeV, >150 GeV
$Z(\to \ell\ell)\gamma$	**leptons**	p_T >35, $\lvert\eta\rvert < 2.5$
	photons	E_T >25, $\lvert\eta\rvert < 2.5$, $\Delta R(\ell, \gamma) > 0.4$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	final BSM region	$p_{T,\gamma}$: 100-250 GeV, >250 GeV
$Z(\to \nu\nu)\gamma$	**photons**	E_T >25, $\lvert\eta\rvert < 2.5$, $\Delta R(\ell, \gamma) > 0.4$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	final BSM region	$p_{T,\gamma}$: 100-250 GeV, >250 GeV

Vectorboson Fusion

Final state	Object	Selection requirements
Z VBF / Zjj	**leptons**	$p_{T,\text{lead}}$ >25 GeV, $\lvert\eta\rvert < 2.5$
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\lvert\eta\rvert < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	further jets	p_T >25 GeV, none in interval between leptons
	event	p_T^{balance} <0.15 (see Eq. **??**)
	final BSM region	m_{jj}: 0.8-1.2 TeV, >1.2 TeV

Vectorboson Scattering

Final state	Object	Selection requirements
WW VBS / $WWjj$ same-sign	**leptons**	p_T >20 GeV, $\lvert\eta\rvert < 2.5$, same-sign
	jets	$p_{T,j1}$ >30 GeV, $p_{T,j1}$ >30 GeV, $\lvert\eta\rvert < 4.5$, $\Delta\eta_{jj}$ >2.5
	final BSM region	m_{jj}: 0.25-0.5 TeV, >0.5 TeV
$Z\gamma$ VBS / $Z\gamma jj$	**leptons**	p_T >35, $\lvert\eta\rvert < 2.5$
	photons	E_T >75, $\lvert\eta\rvert < 2.5$, $\Delta R(\ell/j, \gamma) > 0.4$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	jets	$p_{T,j1}$ >30 GeV, $p_{T,j1}$ >30 GeV, $\lvert\eta\rvert < 4.5$, $\Delta\eta_{jj}$ >3.0
	final BSM region	m_{jj}>0.5 TeV
WZ VBS /	**leptons**	$p_{T,\text{lead}}$ >25 GeV, p_T >15 GeV, $\lvert\eta\rvert < 2.5$
	neutrinos	$(\sum \vec{p}_\nu) > 30$ GeV
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\lvert\eta\rvert < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	further jets	p_T >25 GeV, none in interval between leptons
	event	p_T^{balance} <0.15 (see Eq. **??**)
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV
ZZ VBS / $ZZjj$	**leptons**	p_T >25 / 15 / 10 GeV (leading leptons), $\lvert\eta\rvert < 2.5$
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\lvert\eta\rvert < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <25 GeV
	further jets	p_T >25 GeV, none in interval between leptons
	event	p_T^{balance} <0.15 (see Eq. **??**)
	final BSM region	m_{WZ}: 0.8-1.0 TeV, >1.0 TeV

Is there support for for universal STFX-like approach also for (inclusive) MB measurements?

Outlook

- Meeting amongst YR editors on 23/11 at 3:30pm (CERN time) in order to touch base and realign focus

- Additional input for YR
  - Formalise STXS approach
  - Unified framework for theory uncertainty estimates

- Next public meeting planned for: 7th Dec 2022

- Goal: final draft until next General Meeting (June?) - cut out what’s not in until then!