SUMMARY OF WG2 ACTIVITIES

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VBSCAN FINAL EVENT, 27 AUG 2021

WG2: ANALYSIS TECHNIQUES

- Conveners:
  - R.C., Madgalena Slawinska
  - Formerly: Matthias Mozer and Joany Manjarres

- Mandate:
  1. Determination of the best observable quantities for VBS data analysis
  2. Implementation of advanced techniques in the signal characterization
  3. Experimental results publication guidelines and combination

WG2 IN NUMBERS

- Workshops organized within the WG:
  - Jet reconstruction techniques → Oct. 2018, Krakow
  - Combination and EFT → Mar. 2019, CERN
  - WITH WG1: VBS polarization workshop → Oct. 2018 Palaiseau
- 14 periodic meetings over 4 years
  - 2 jointly with WG1, many jointly with WG3
- 17 STSMs
  - 2 Thessaloniki → Dresden
  - 2 Krakow → CERN
  - 2 NIKHEF → CERN
  - 3 Thessaloniki → CERN
  - 1 Budapest → Antwerpen
  - 1 Milano → CERN
  - 2 Thessaloniki → Sheffield
  - 3 Pavia → Zurich
  - 1 Thessaloniki → Annecy

1. OBSERVABLES - BSM FIDUCIAL REGIONS

Jointly With WG1

- Effort to define common BSM-enriched fiducial measurements for experiments (Run3)
- Will either become a separate «recommendation» note or be part of the LHC-EWWG YR

Lohwasser, Gomez-Ambrosio et al.

Table 4.4: Suggestions for common fiducial BSM regions

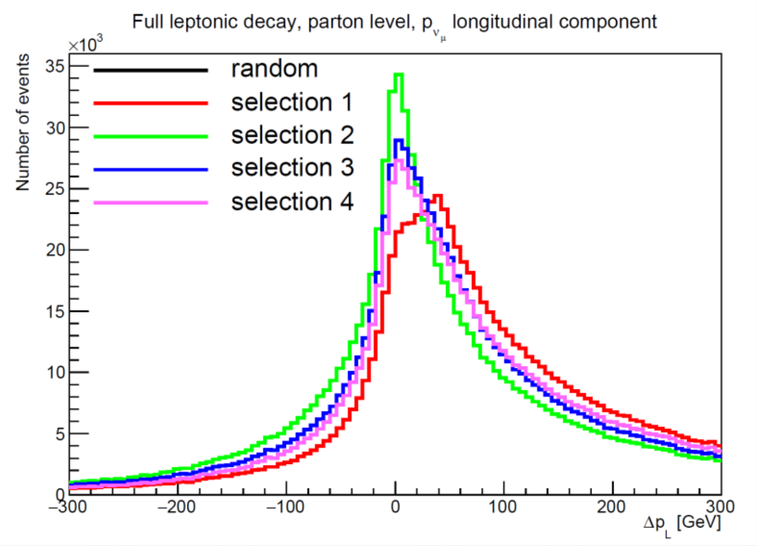
Final state	Object	Selection requirements
Vectorboson Fusion		
Final state	Object	Selection requirements
Z VBF / Zjj	**leptons**	$p_{T,\text{lead}}$ >25 GeV, $\lvert\eta\rvert < 2.5$
	jets	$p_{T,j1}$ >55 GeV, $p_{T,j1}$ >40 GeV, $\lvert\eta\rvert < 4.5$
	bosons	$\Delta(m_Z, m_{\ell\ell})$ <10 GeV
	further 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

1. OBSERVABLES - POLARIZATION

- A complete study to extrapolate neutrino momenta in final states with 1 or 2 W-boson leptonic decays
  - Analytical approach to extracting polarization information
  - First section of arxiv:2008.05316.pdf

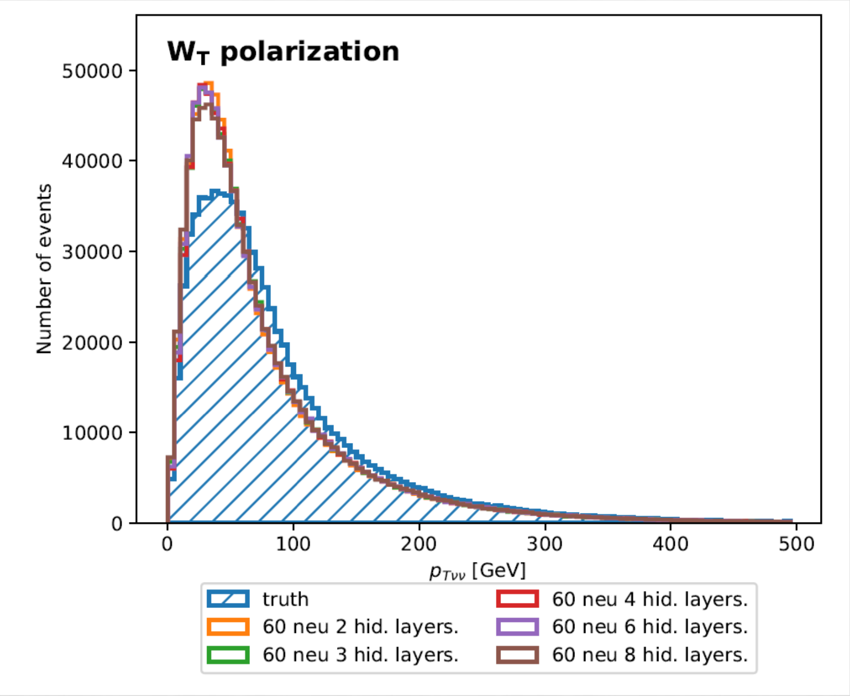
Novak, Grossi et al.
Eur.Phys.J.C 80 (2020) 12, 1144

$$\underbrace{(p_{lL}^2 - E_l^2)}_{a} p_{\nu L}^2 + \underbrace{(m_{\mathrm{W}}^2 p_{lL} + 2p_{lL}\vec{p}_{lT}\vec{p}_{\nu T})}_{b} p_{\nu L} + \underbrace{\frac{m_{\mathrm{W}}^4}{4} + (\vec{p}_{lT}\vec{p}_{\nu T})^2 + m_{\mathrm{W}}^2\vec{p}_{lT}\vec{p}_{\nu T} - E_l^2\vec{p}_{\nu T}^2)}_{c} = 0;$$



2. TECHNIQUES - POLARIZATION

- A complete study to extrapolate neutrino momenta in final states with 1 or 2 W-boson leptonic decays
  - ML approach extracting polarization information (Deep Neural Networks)
  - Second section of arxiv:2008.05316.pdf



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2. TECHNIQUES - JETS

- A dedicated workshop to cover all jet techniques relevant to VBS
  - Theory/experiment cross-inputs
- Main topics
  - Central- and b-jet vetoes
  - Quark-gluon discrimination
  - Boosted-V tagging
  - Pileup suppression
  - New endcap detectors (timing, high-granularity calorimeters)
- Workshop conclusion paves the way for new techniques to be used in Run3 and future VBS analysis

New techniques in particle reconstruction for VBS

22 Oct 2018, 10:00 → 24 Oct 2018, 14:20 Europe/Zurich

Krakow

Henning Kirschenmann (Helsinki Institute of Physics (FI)), Lucrezia Stella Bruni (Nikhef National institute for subatomic physics (NL)), Magdalena Slawinska (Polish Academy of Sciences (PL)), Pietro Govoni (Universita & INFN, Milano-Bicocca (IT)), Senka Duric (Kansas State University (US)), Steven Schramm (Universite de Geneve (CH))

Description: This workshop is intended to review the state of the art for the physics object reconstruction in the ATLAS and CMS experiments, identify areas where improvements could benefit VBS analyses and what new techniques may be used and start the work to get them done.

The programme will cover modern jet reconstruction, use of machine learning, high-energy leptons reconstruction, VBS final state description.

Supported by the EU Framework Programme Horizon 2020

q/g tagging

quark jets are well described with MC due to LEP constraints

gluon jets need to be additionally tuned in MC (no strong LEP constraints)

- LHC experiments should provide measurements of theoretically well defined quantities to perform tuning <= new Les Houches observables were proposed
- lower uncertainty from MC can result in lower theoretical uncertainties in measurements
  - q/g differences are the origin of the limiting uncertainty for many results using jets

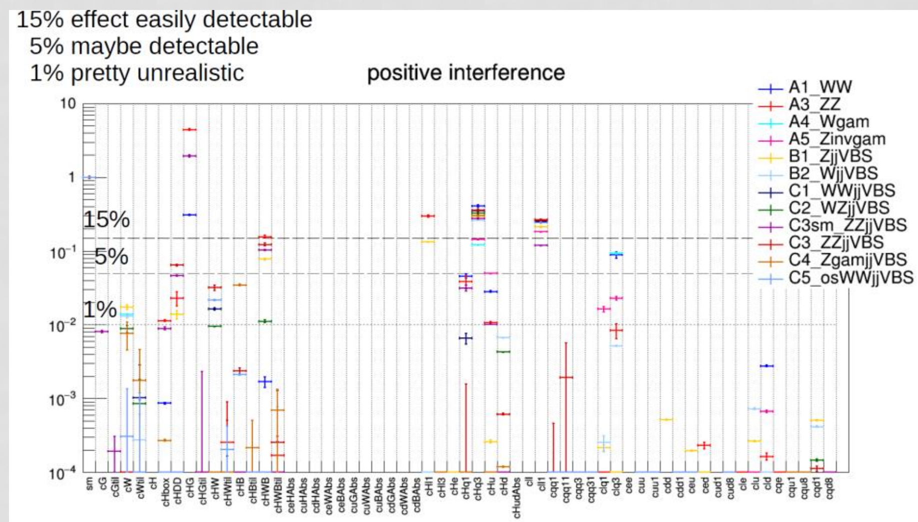
3. COMBINATION - SMEFT

Jointly With WG1

- Large effort in the Action to parametrize possible deviations from SM in VBS in terms of dimension-6 (SMEFT) operators
- Enables inclusion of VBS in SMEFT global fits
- Enables direct comparison with constraints from other LHC processes (e.s. inclusive dibosons)

- 2017-2018:
  - Operator «surveys»

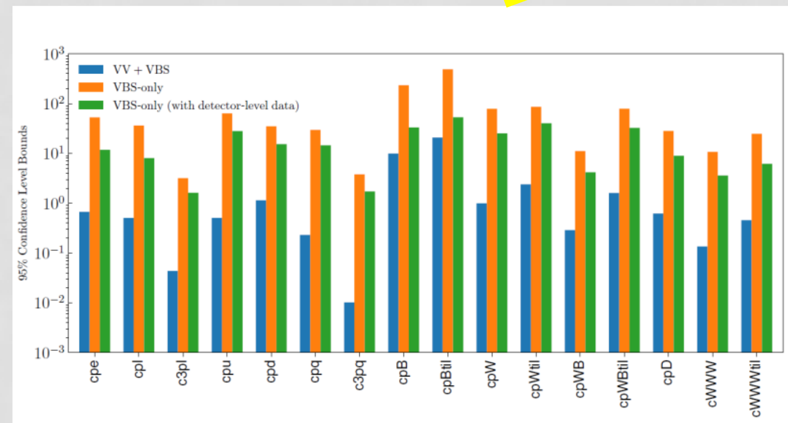
Lohwasser, Gomez-Ambrosio et al.

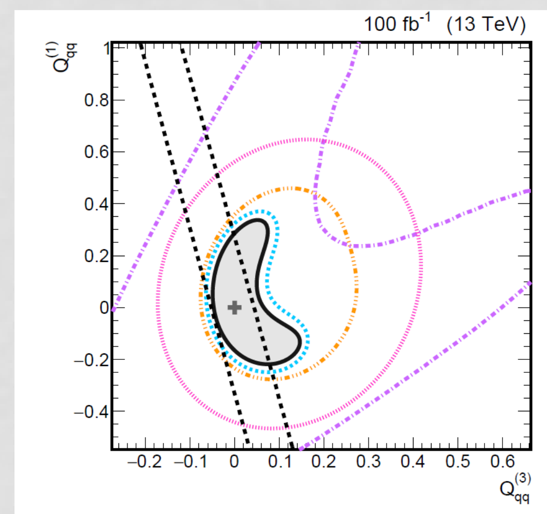


3. COMBINATION - SMEFT

Jointly With WG1

- 2019-2021: The papers:
  - Phys. Rev. D 104, 013003 (2021): **Dedes et al.**
    - focusing on ssWW
  - arxiv:2101.03180: **Gomez-Ambrosio et al.**
    - determination of dim-6 VBS limits from existing LHC measurements, compared to dibosons
    - based on earlier VBSCan works: arxiv:1807.09634, arxiv:1809.04189
  - arxiv:2108.03199 **Boldrini et al.**
    - comprehensive sensitivity estimate including dim-6 quadratic effects, marginalized limits and 2D constraints





3. COMBINATION – DIM-8

Jointly With WG3

- Most experimental VBS studies extract limits on dimension-8 EFT operators (genuine-aQGC generating basis, by O. Eboli et al.)
  - At the moment only existing as single limits per final states
- Large effort in WG2 to provide ATLAS/CMS combinations of dim-8 limits using different final states
  1. Using public CMS-fitting package
  2. Using internal ATLAS combination tools
  3. Other possibilities investigated (gFitter, HEPFit…)

3. COMBINATION – DIM-8

Jointly With WG3

- With CMS fitting package
  - Public data from HEPData
    - Reasonable assumptions on systematic correlations
  - MadGraph reweighting tool to obtain many Wilson coefficient values with few samples
  - Parton-shower level

Neukum et al.

reconstructed limits	CMS ssWW (TeV^{-4})	CMS ZZ (TeV^{-4})	combined (TeV^{-4})
f_{S0}/Λ^4	[-7.20, 7.21]	[-62.1, 63.1]	[-7.22, 7.71]
f_{S1}/Λ^4	[-21.5, 23.3]	[-66.3, 66.6]	[-21.7, 23.4]
f_{M0}/Λ^4	[-5.41, 5.51]	[-10.1, 10.5]	[-5.34, 5.59]
f_{M1}/Λ^4	[-7.89, 8.14]	[-33.6, 32.1]	[-7.76, 8.02]
f_{M7}/Λ^4	[-12.00, 11.90]	[-62.5, 65.7]	[-12.1, 12.0]
f_{T0}/Λ^4	[-0.506, 0.529]	[-0.41, 0.39]	[-0.369, 0.361]
f_{T1}/Λ^4	[-0.252, 0.271]	[-0.64, 0.64]	[-0.241, 0.257]
f_{T2}/Λ^4	[-0.805, 0.925]	[-1.19, 1.14]	[-0.711, 0.784]

No significant change (f_S, f_M rows)

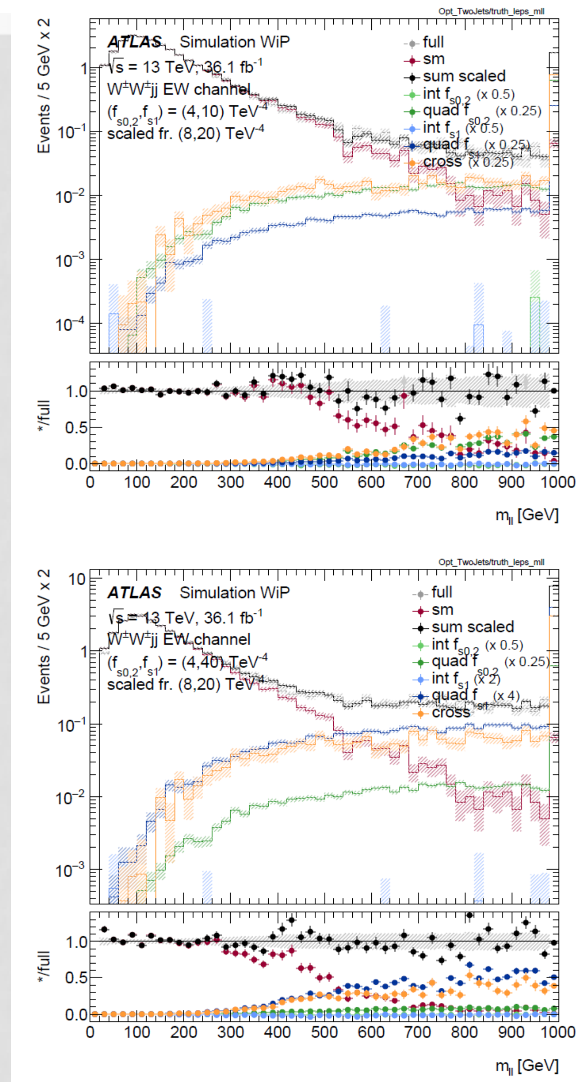
combination useful ☺ (f_T rows)

3. COMBINATION – DIM-8

Jointly With WG3

- With ATLAS tools
  - Use both MadGraph reweighting and split-component generation to cross-check results
  - Unitarity restoration with «clipping» method
  - Thorough validation of MC templates
  - Ready for ATLAS ssWW and WZ combination (new 13 TeV analyses?)

Todt, Sampsonidou et al.



3. COMBINATION - SUMMARY

- WG2 has introduced important concepts in general in EFT combinaton techniques:
  - Split MC generation (SM, interference, quadratic, mixed) as an alternative to reweighting allows limit extraction with a limited number of samples

$$f_{\mathrm{EFT}}(v) = f_{\mathrm{SM}}(v) + \sum_i \frac{c_i}{\Lambda^2} f_{\mathrm{Lin}_i}(v) + \sum_i \frac{c_i^2}{\Lambda^4} f_{\mathrm{Quad}_i}(v) + \sum_{i \neq j} \frac{c_i c_j}{\Lambda^4} f_{\mathrm{Mix}_{ij}}(v)$$

  - Highlighting the non-negligible impact of EFT^2 terms (bringing the question of interplay with dim-8 effects)
  - Establishing clearly a hierarchy of process sensitivity to dim-6 and dim-8 effects, providing a pathway to experimental analyses

CONCLUSIONS - OUTLOOK

- VBSCan WG2 gave a fundamental contribution (especially) to establish cross-experiment standards in terms of:
  - Observables
  - Reconstruction techniques
  - EFT combination methods

  useful for Run3 and future LHC analyses
- Future areas of work (for a possible new COST?)
  - Bring to conclusion ATLAS-CMS dim-8 fits
    - Needs a unique prescription to avoid unitarity violation (clipping vs. smooth cut-offs vs. …)
  - Fit VBS with all other LHC inputs in a global SMEFT fit
  - Fully exploit new ML-based techniques for jet reconstruction and extraction of VBS longitudinal polarization