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Recent Theory Developments in Vector Boson Fusion/Scattering

Alexander Karlberg

9th Edition of the Large Hadron Collider Physics Conference
Online (Paris)

Outline

- This talk is not a review of Vector Boson Fusion/Scattering theory. *Way* too much to cover in $\sim$ 15 minutes.
- But in one line: "Theory predictions for VBF and VBS very advanced due to many novel results in the past few years."
- In this talk I will highlight a few results from the past year
  - VBF and Parton Showers: 2003.12435
  - VBF at high $p_{t,H}$: 2105.11399
  - Non-factorisable QCD corrections to VBF: 1906.10899 + 2005.11334
  - Full NLO for VBS-ZZ: 2009.00411
- Given experimental audience I will try and focus on results and phenomenology rather than theoretical details.
- For a full review of Vector Boson Scattering Theory (and experiment) see 2102.10991 and very recently 2106.01393 from VBSCAN...

Vector-Boson Scattering at the LHC: unravelling the Electroweak sector

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Abstract

Vector-boson scattering (VBS) processes probe the innermost structure of electroweak interactions in the Standard Model, and provide a unique sensitivity for new physics phenomena affecting the gauge sector. In this review, we report on the salient aspects of this class of processes, both from the theory and experimental point of view. We start by discussing recent achievements relevant for their theoretical description, some of which have set important milestones in improving the precision and accuracy of the corresponding simulations. We continue by covering the development of experimental techniques aimed at detecting these rare processes and improving the signal sensitivity over large backgrounds. We then summarise the details of the most relevant VBS signatures and review the related measurements available to date, along with their comparison with Standard-Model predictions. We conclude by discussing the perspective at the upcoming Large Hadron Collider runs and at future hadron facilities.

Vector Boson Scattering Processes: Status and Prospects

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Abstract

Insight into the electroweak (EW) and Higgs sectors can be achieved through measurements of vector boson scattering (VBS) processes. The scattering of EW bosons are rare processes that are precisely predicted in the Standard Model (SM) and are closely related to the Higgs mechanism. Modifications to VBS processes are also predicted in models of physics beyond the SM (BSM), for example through changes to the Higgs boson couplings to gauge bosons and the resonant production of new particles. In this review, experimental results and theoretical developments of VBS at the Large Hadron Collider, its high luminosity upgrade, and future colliders are presented.

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THE EUROPEAN PHYSICAL JOURNAL C

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Special Article - Tools for Experiment and Theory

Parton-shower effects in Higgs production via vector-boson fusion

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Abstract We present a systematic investigation of parton-shower and matching uncertainties of perturbative origin for Higgs-boson production via vector-boson fusion. To this end we employ different generators at next-to-leading order QCD accuracy matched with shower Monte Carlo programs, `PYTHIA8`, and `HERWIG7`, and a next-to-next-to-leading order QCD calculation. We thoroughly analyse the intrinsic sources of uncertainty within each generator, and then compare predictions among the different tools using the respective recommended setups. Within typical vector-boson fusion

in the experimentally accessible domain. The precise determination of the Higgs boson's couplings to other elementary particles, spin, and CP properties is thus of paramount importance.

A particularly clean environment for the necessary measurements at the LHC is provided by the vector-boson fusion (VBF) production mode where the Higgs boson is produced by two scattering partons in association with two hard jets (often referred to as tagging jets) in the forward and backward regions of the detector via the exchange of weak mas-

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From 1909.02845 (ATLAS)

Uncertainty source	$\frac{\Delta\sigma_{ggF}}{\sigma_{ggF}}$ [%]	$\frac{\Delta\sigma_{VBF}}{\sigma_{VBF}}$ [%]	$\frac{\Delta\sigma_{WH}}{\sigma_{WH}}$ [%]	$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}}$ [%]	$\frac{\Delta\sigma_{t\bar{t}H+tH}}{\sigma_{t\bar{t}H+tH}}$ [%]
Statistical uncertainties	6.4	15	21	23	14
Systematic uncertainties	6.2	12	22	17	15
Theory uncertainties	3.4	9.2	14	14	12
Signal	2.0	8.7	5.8	6.7	6.3
Background	2.7	3.0	13	12	10
Experimental uncertainties (excl. MC stat.)	5.0	6.5	9.9	9.6	9.2
Luminosity	2.1	1.8	1.8	1.8	3.1
Background modeling	2.5	2.2	4.7	2.9	5.7
Jets, E_T^{miss}	0.9	5.4	3.0	3.3	4.0
Flavor tagging	0.9	1.3	7.9	8.0	1.8
Electrons, photons	2.5	1.7	1.8	1.5	3.8
Muons	0.4	0.3	0.1	0.2	0.5
τ-lepton	0.2	1.3	0.3	0.1	2.4
Other	2.5	1.2	0.3	1.1	0.8
MC statistical uncertainties	1.6	4.8	8.8	7.9	4.4
Total uncertainties	8.9	19	30	29	21

Recent Higgs combination study shows that theory uncertainties are dominating in the VBF channel despite "good" theoretical understanding of the process.

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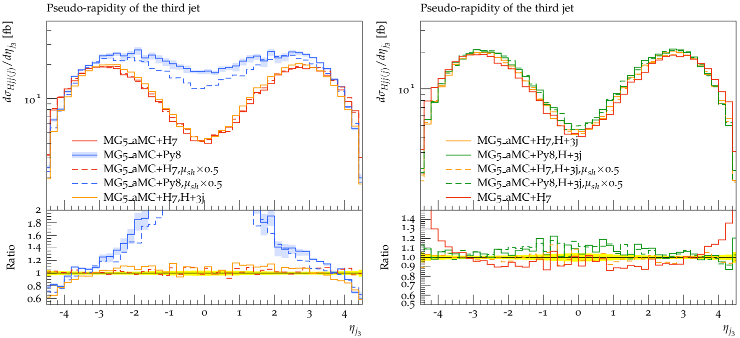
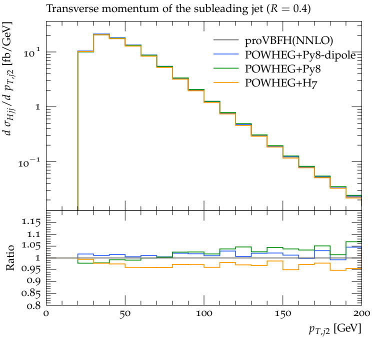
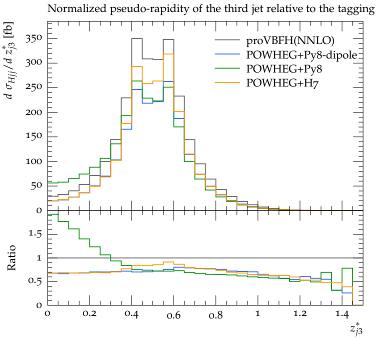
Intrinsic uncertainties in MG5



- When considering third jet observables very large discrepancies outside of the scale variation can be observed
- If one includes NLO corrections this discrepancy disappears and very good agreement is found with the lower order prediction matched to H7
- PY8 mathcing clearly leads to unphysical predictions

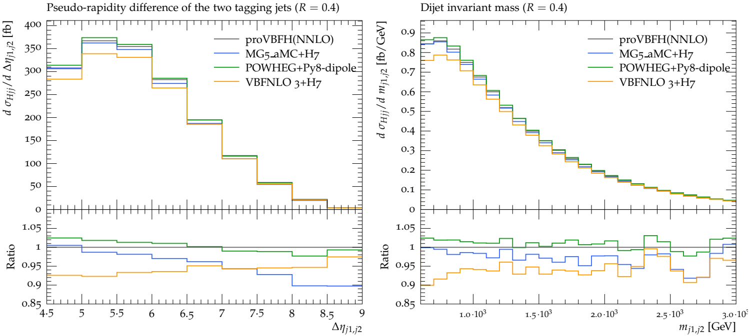
Intrinsic uncertainties in POWHEG





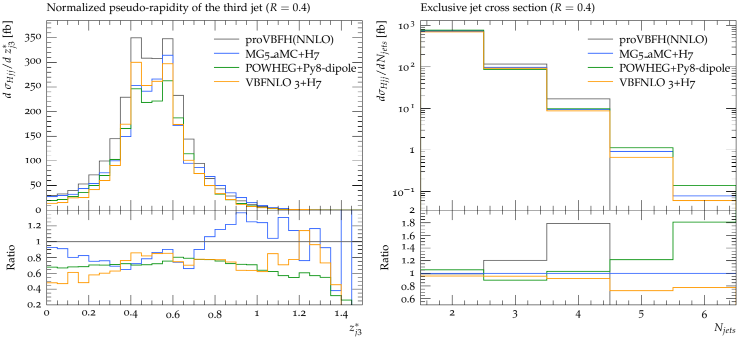
- POWHEG can be matched to H7 and PY8. Here we pick angular ordered H7 and PY8 with both its default recoil and a local initial-final recoil
- Only small differences for hard observables
- For the third jet we see the same "unphysical" behaviour of PY8 with its default recoil scheme, although the effect is smaller than in MG5_aMC due to POWHEG handling the first emission itself

Comparing all generators



- Comparing all generators we see a clear picture
- For hard observables we find some shape differences, typically at the $\mathcal{O}(10\%)$
- However, this effect shrinks if one were to compare normalised distributions

Comparing all generators



- When considering higher jet multiplicities the discrepancies increase a lot
- Not surpising given less robust hard perturbative input
- In particular the Monte Carlos predict significantly fewer jets than the fixed order calculation

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Conclusions

- Large effort in studying Parton Shower effects in VBF
- VBF insensitive to NLO matching prescription but very sensitive to recoil scheme inside PY8

→ Default recoil scheme unphysical for VBF/VBS processes. Local recoil can currently only be used with POWHEG.

- For H7 this does not seem to be the case
- Not one "best" prediction but a number of physically sound predictions
- The uncertainties are typically below 10%, and are dominated by differences in normalisation rather than shapes for most observables

A comparative study of Higgs boson production from vector-boson fusion

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The data taken in Run II at the Large Hadron Collider have started to probe Higgs boson production at high transverse momentum. Future data will provide a large sample of events with boosted Higgs boson topologies, allowing for a detailed understanding of electroweak Higgs boson plus two-jet production, and in particular the vector-boson fusion mode (VBF). We perform a detailed comparison of precision calculations for Higgs boson production in this channel, with particular emphasis on large Higgs boson transverse momenta, and on the jet radius dependence of the cross section. We study fixed-order predictions at next-to-leading order and next-to-next-to-leading order QCD, and compare the results to NLO plus parton shower (NLOPS) matched calculations. The impact of the NNLO corrections on the central predictions is mild, with inclusive scale uncertainties of the order of a few percent, which can increase with the imposition of kinematic cuts. We find good agreement between the fixed-order and matched calculations in non-Sudakov regions, and the various NLOPS predictions also agree well in the Sudakov regime. We analyze backgrounds to VBF Higgs boson production stemming from associated production, and from gluon-gluon fusion. At high Higgs boson transverse momenta, the Δy_{jj} and/or m_{jj} cuts typically used to enhance the VBF signal over background lead to a reduced efficiency. We examine this effect as a function of the jet radius and using different definitions of the tagging jets. QCD radiative corrections increase for all Higgs production modes with increasing Higgs boson p_T, but the proportionately larger increase in the gluon fusion channel results in a decrease of the gluon-gluon fusion background to electroweak Higgs plus two jet production upon requiring exclusive two-jet topologies. We study this effect in detail and contrast in particular a central jet veto with a global jet multiplicity requirement.

From Silvia Ferrario's PSR21 talk!

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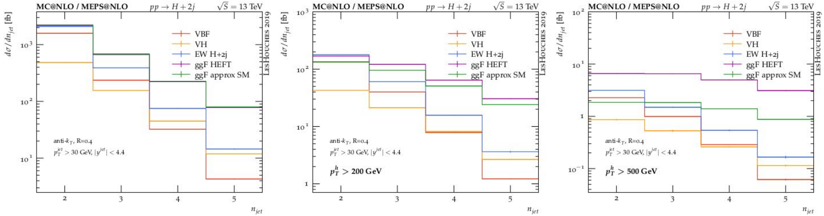
Disentangling VBF using jet multiplicity

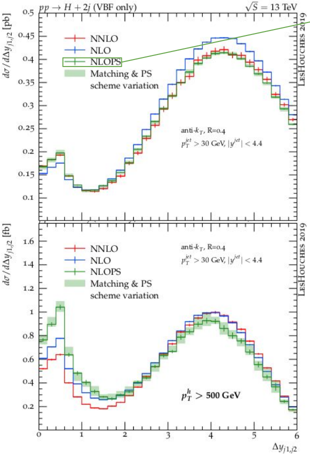
Sherpa CSS
[cross-checked with (PWG+)HW7]



Process σ [fb]	pTH ≥ 0 GeV 2j incl	2j excl	pTH ≥ 200 GeV 2j incl	2j excl	pTH ≥ 500 GeV 2j incl	2j excl
EW H+2j	**2565**	**2087**	**259**	**179**	**5.34**	**3.15**
VBF+VH	**2555**	**2069**	**258**	**177**	**5.38**	**3.14**
VBF	**1859**	**1586**	**183**	**134**	**3.61**	**2.27**
VH	**696**	**483**	**74.8**	**42.7**	**1.77**	**0.87**
ggF (SM)	**3219**	**2227**	**305**	**154**	**5.96**	**1.85**

- ➔ **ggF** is dominant for high multiplicities and slightly reduces at high pTH
- ➔ jet veto ($n_{jet} = 2$) very effective in reducing **ggF**, partially effective for **VH**
- ➔ At very large pTH disentangling **VH** from **VBF** becomes more difficult
- ➔ Full **EW Hjj** ≈ **VBF** + **VH**

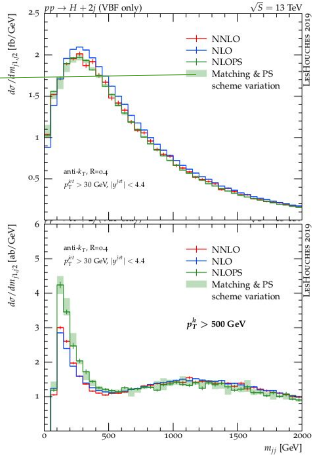
m_{jj} and Δy_{jj} for VBF



Hw7, dipole shower

envelope obtained from 6 NLOPS
HW7 dipole and **AO** showers
PWG+PY8, **PWG+HW7**(AO)
Sherpa CSS and **Dire** showers

For large pTH, **NLOPS** is quite different from **NNLO**; adding the PS to the **NLO** enhances the differences instead of reducing them! All the NLOPS predictions are consistent.



Nonfactorizable QCD Effects in Higgs Boson Production via Vector Boson Fusion

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(Received 23 July 2019; published 17 September 2019)

We discuss nonfactorizable QCD corrections to Higgs boson production in vector boson fusion at the Large Hadron Collider. We point out that these corrections can be computed in the eikonal approximation retaining all the terms that are not suppressed by the ratio of the transverse momenta of the tagging jets to the total center-of-mass energy. Our analysis shows that in certain kinematic distributions the non-factorizable corrections can be as large as a percent making them quite comparable to their factorizable counterparts.

On the impact of non-factorisable corrections in VBF single and double Higgs production

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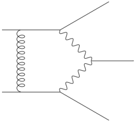
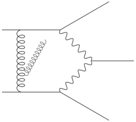
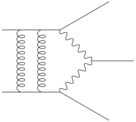
Non-factorisable corrections pre June 2019



→ Identically zero due to colour conservation



→ Contributes to the three jet cross section [Campanario et al. (2013)], but is known to be kinematically suppressed in the VBF phase space [Bolzoni et al. (2011)]



→ "Impossible" to compute exactly but estimated to contribute at the permille level based on colour suppression ($1/N_c^2$) and lower order Abelian calculation [Bolzoni et al. (2011)]

Non-factorisable QCD [1906.10899]

- Recently the non-factorisable QCD corrections were estimated in the eikonal approximation [Liu, Melnikov, Penin (2019)]
- Result expressed as an expansion in $p_{t,j}/\sqrt{s}$, which is argued to be small due to large m_{jj} requirement in typical VBF analyses
- Only leading power available, but argued to have an uncertainty of a few percent in most regions of phase space
- Result proportional to Born cross section, as real emission diagrams show up at higher power

$$\mathrm{d}\sigma_{\mathrm{nf}}^{\mathrm{NNLO}} = \left(\frac{N_c^2-1}{4N_c^2}\right)\alpha_s^2\chi_{\mathrm{nf}}\left(q_{\perp,1},q_{\perp,2}\right)\mathrm{d}\sigma^{\mathrm{LO}}$$

! Colour suppressed but π^2-enhanced (Glauber phase)

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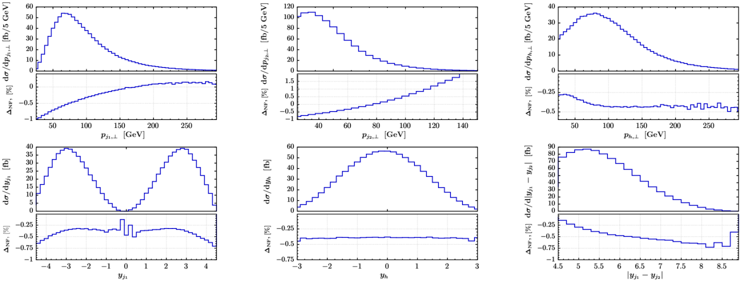
Non-factorisable QCD [1906.10899]

VBF cuts: $m_{jj} > 600$ GeV, $\Delta y_{jj} > 4.5$, $y_{j_1} y_{j_2} < 0$

$$d\sigma^{\text{LO}} = 957 \text{ fb}, \qquad d\sigma^{\text{NNLO}}_{\text{nf}} = -3.73 \text{ fb}, \qquad d\sigma^{\text{NNLO}}_{\text{f}} = -32 \text{ fb}$$

Although non-factorisable corrections are of the order of several permille, they are clearly suppressed compared to their factorisable counterparts.

Fiducially they can grow to the percent level:



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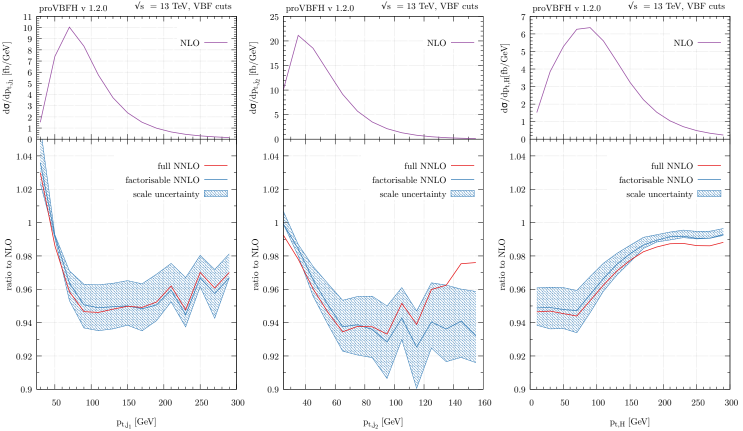
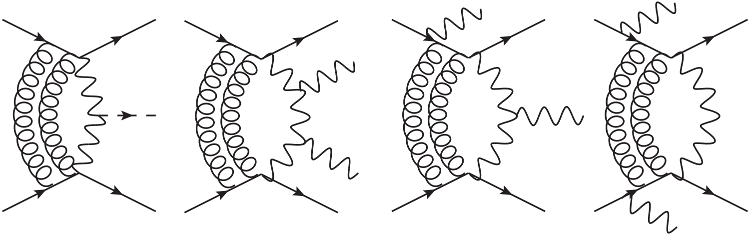
Factorisable vs non-factorisable



- Non-factorisable corrections mostly contained within scale uncertainty band, but can become important in some regions of phase space.

What about VBS?

- VBS usually done in VBS approximation, which neglects non-factorisable corrections
- At NLO this is exact as for VBF, so no urgency in computing them
- However, the non-factorisable corrections computed in the eikonal approximation are finite on their own and only depend on the topology



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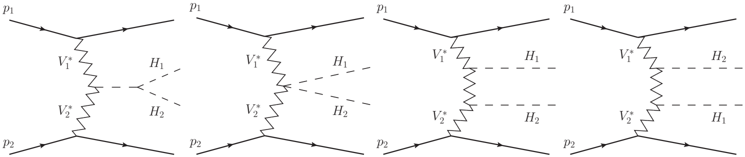
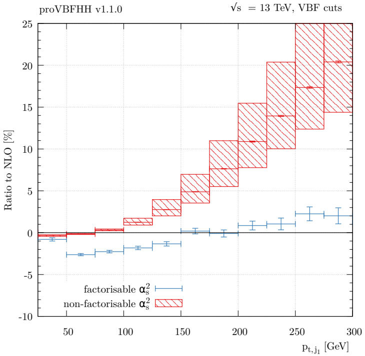
Di-Higgs → VBS

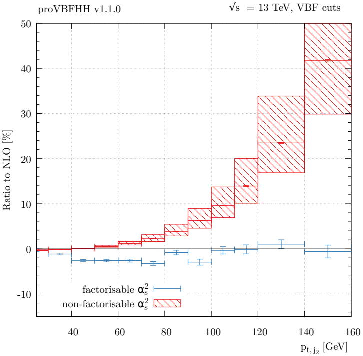


- Di-Higgs production offer most complicated topologies for VBS
- Very delicate unitarity cancellations lead to enhanced non-factorisable corrections!
- Should be kept in mind when thinking of NF corrections in VBS

$\lambda = M_V$	σ_{TT}	σ_{BB}	σ_{TB}	Σ
Born	10.393 fb	14.172 fb	–23.904 fb	0.662 fb
1-loop NF	0.339%	0.518%	0.399%	2.03%
2-loop NF	–0.667%	–0.658%	–0.666%	–0.50%
Full NF	–0.327%	–0.139%	–0.267%	1.52%

Differential distributions





- The enhancement is particularly striking when looking at the two hardest jets
- In magnitude the corrections can quickly become larger than the factorisable (N)NLO corrections reaching almost 50% in phase space accessible to the HL-LHC.
- In most other distributions they are contained to around 5%, but still larger than factorisable NNLO-QCD

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NLO QCD and EW corrections to vector-boson scattering into ZZ at the LHC

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Abstract: We present the first calculation of the full next-to-leading-order electroweak and QCD corrections for vector-boson scattering (VBS) into a pair of Z bosons at the LHC. We consider specifically the process $pp \to e^+e^-\mu^+\mu^-jj + X$ at orders $\mathcal{O}(\alpha^7)$ and $\mathcal{O}(\alpha_s\alpha^6)$ and take all off-shell and interference contributions into account. Owing to the presence of enhanced Sudakov logarithms, the electroweak corrections amount to −16% of the leading-order electroweak fiducial cross section and induce significant shape distortions

JHEP11(2020)110

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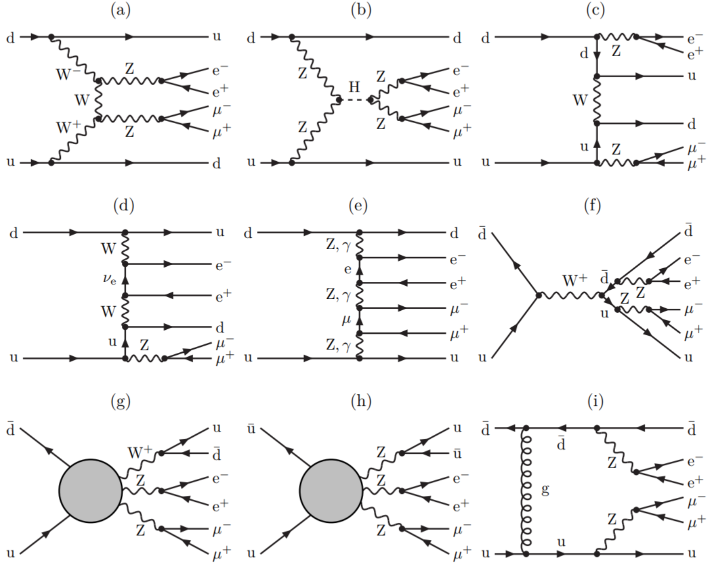
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Z
Z
μ−
μ+
u
u
(c)
d
Z
e−
e+
d
u
W
d
u
Z
μ−
μ+
u
(d)
d
u
W
e−
νe
e+
W
d
u
Z
μ−
μ+
u
(e)
d
d
Z, γ
e−
e
e+
Z, γ
μ−
μ
μ+
Z, γ
u
u
(f)
d̄
d̄
W+
d̄
e−
e+
Z
Z
u
μ−
μ+
u
u
(g)
d̄
u
W+
d̄
Z
e−
e+
Z
μ−
μ+
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(h)
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Z
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Z
e−
e+
Z
μ−
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d̄
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Z
e−
e+
g
μ−
Z
μ+
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u
u

NLO corrections to $\mathcal{O}(\alpha^6)$

NLO contributions:

Order	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha^6)+\mathcal{O}(\alpha^7)+\mathcal{O}(\alpha_s\alpha^6)$
$M_{j_1j_2} > 100\,\text{GeV}$			
$\sigma_{\text{NLO}}[\text{fb}]$	0.08211(4)	0.12078(11)	0.10521(11)
$\sigma^{\max}_{\text{NLO}}[\text{fb}]$	0.08728(5) [+6.3%]	0.12540(13) [+3.8%]	0.10838(14) [+3.0%]
$\sigma^{\min}_{\text{NLO}}[\text{fb}]$	0.07749(4) [−5.6%]	0.11656(9) [−3.5%]	0.10225(9) [−2.8%]
$\delta[\%]$	−15.9	23.6	7.7
$M_{j_1j_2} > 500\,\text{GeV}$			
$\sigma_{\text{NLO}}[\text{fb}]$	0.06069(4)	0.07375(25)	0.06077(25)
$\sigma^{\max}_{\text{NLO}}[\text{fb}]$	0.06568(5) [+8.2%]	0.07466(26) [+1.2%]	0.06149(24) [+1.2%]
$\sigma^{\min}_{\text{NLO}}[\text{fb}]$	0.05636(4) [−7.1%]	0.07282(21) [−1.3%]	0.05977(30) [−1.6%]
$\delta[\%]$	−17.6	0.1	−17.5

The large EW correction can mostly be explained through the usual LL EW Sudakov logs

$$d\sigma_{\text{LL}} = d\sigma_{\text{LO}}(1+\delta_{\text{EW,LL}})$$

$$\delta_{\text{EW,LL}} = \frac{\alpha}{4\pi}\left\{-4C_W^{\text{EW}}\log^2\left(\frac{Q^2}{M_W^2}\right) + 2b_W^{\text{EW}}\log\left(\frac{Q^2}{M_W^2}\right)\right\} \approx -16.4\%$$

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Large NLO-QCD corrections

Contribution	σ_{α^6} [ab]	$\Delta\sigma_{\alpha^7}$ [ab]	$\Delta\sigma_{\alpha^7}/\sigma_{\alpha^6}$ [%]	$\Delta\sigma_{\alpha_s\alpha^6}$ [ab]	$\Delta\sigma_{\alpha_s\alpha^6}/\sigma_{\alpha^6}$ [%]
$M_{j_1j_2} > 100$ GeV					
all	97.683(2)	−15.55(5)	−15.9	23.10(11)	23.6
VBS-WW	95.237(2)	−15.28(5)	−16.0	1.33(11)	1.4
VBS-ZZ	1.9463(2)	−0.1979(6)	−10.2	3.892(4)	200
WZZ	0.1361(1)	−0.0142(1)	−10.5	13.850(4)	10174
ZZZ	0.3629(1)	−0.0542(6)	−14.9	4.029(3)	1110
$M_{j_1j_2} > 500$ GeV					
all	73.679(2)	−13.01(4)	−17.7	0.07(25)	0.10
VBS-WW	72.846(2)	−12.91(4)	−17.7	−2.73(25)	−3.7
VBS-ZZ	0.8096(2)	−0.0986(3)	−12.2	0.486(6)	60.1
WZZ	0.00471(2)	−0.00085(1)	−18.1	1.849(5)	39258
ZZZ	0.01887(1)	−0.00529(2)	−28.0	0.470(1)	2488

- Extremely large NLO-QCD corrections to tri-boson channels
- This is due to diagrams with three resonant bosons opening up at this level
- It leads to significant NLO-QCD corrections when M_{jj} is small

→ Must include tri-boson state for meaningful VBS measurement

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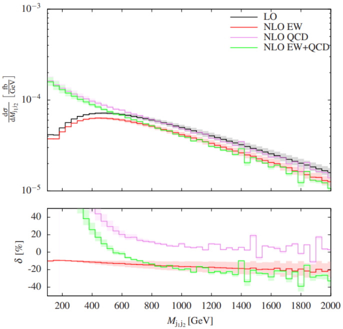
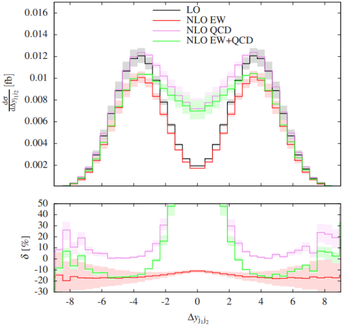
NLO distributions





- Even more pronounced differentially
- Clear that one can only talk about VBS for very tight M_{jj} and Δy_{jj} cuts
- Otherwise all channels and in particular tri-boson channels need to be included

Conclusions

- Many exciting theory advances in both VBF and VBS in recent years.
- Many detailed studies ongoing in VBF to pin down the process.
- Full NLO corrections known to all VBS processes $\rightarrow$ large EW corrections.
- Most important take-home messages:
  - Default recoil scheme of Pythia8 unphysical for VBF/VBS processes. Local recoil can currently only be used with POWHEG.
  - Not possible to talk about VBS approximation outside of very tight selection cuts (and even then still theoretically problematic). Future generators need to take all contributions into account.