Release: VBFNLO 3.0

A Parton Level Monte Carlo for Processes with Electroweak Bosons

VBFNLO collaboration

Jornadas científicas IFIC: Origin of mass. L1 Higgs Force.

Ivan Rosario

VBFNLO Collaboration

- **Members**

  - Julien Baglio, Francisco Campanario, Tinghua Chen, Heiko Dietrich-Siebert, Terrance Figy, Matthias Kerner, Michael Kubocz, Maximilian Löschner, Le Duc Ninh, Simon Plätzer, Michael Racuh, Robin Roth, Ivan Rosario, Dieter Zeppenfeld.

- **Former Members**

  - Ken Arnold, Manuel Bähr, Johannes Bellm, Giuseppe Bozzi, Martin Brieg, Christoph Englert, Bastian Feigl, Jessica Frank, Florian Geyer, Nicolas Greiner, Christoph Hackstein, Vera Hankele, Barbara Jäger, Nicolas Kaiser, Gunnar Klämke, Carlo Oleari, Sophy Palmer, Stefan Prestel, Heidi Rzehak, Franziska Schissler, Oliver Schlimpert, Michael Spannowsky, Malgorzata Worek.

Outline

VBFNLO overview

Update features

Conclusions

VBFNLO Overview

- **Monte Carlo integration**
  - Partonic collisions
  - Next-to-leading order in QCD
- **Stablished software**
- **Fast**
  - Phase-space optimization
  - Leptonic tensors

VBFNLO Overview

$$\sigma = \sigma^{LO} + \sigma^{NLO} = \int_m d\sigma^B + \int_{\mathrm{m+1}} d\sigma^R + \int_{\mathrm{m}} d\sigma^V$$

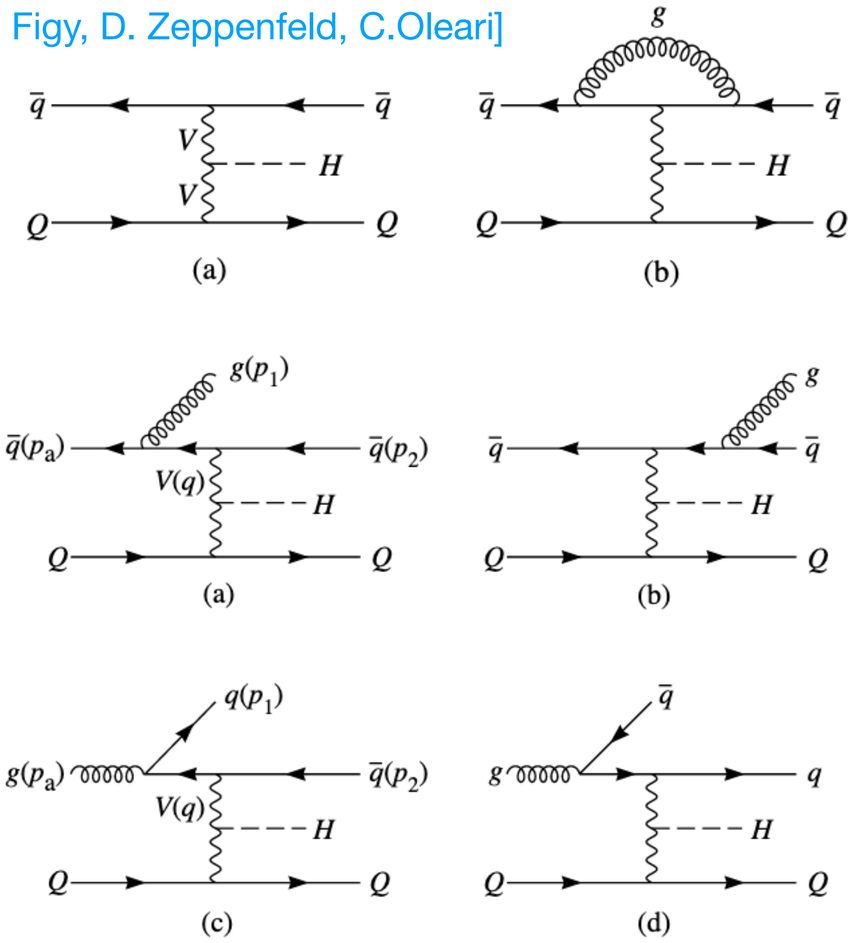
- **Implementation details**
  - Helicity amplitudes

    [K. Hagiwara, D.Zeppenfeld]
  - Infrared divergence substraction
    - Catani-Seymour

      [S. Catani, MH. Seymour]

$$\sigma^{NLO} = \int_{m+1} \left[d\sigma^R - d\sigma^A \right] + \int_{m+1} d\sigma^A + \int_m d\sigma^V$$

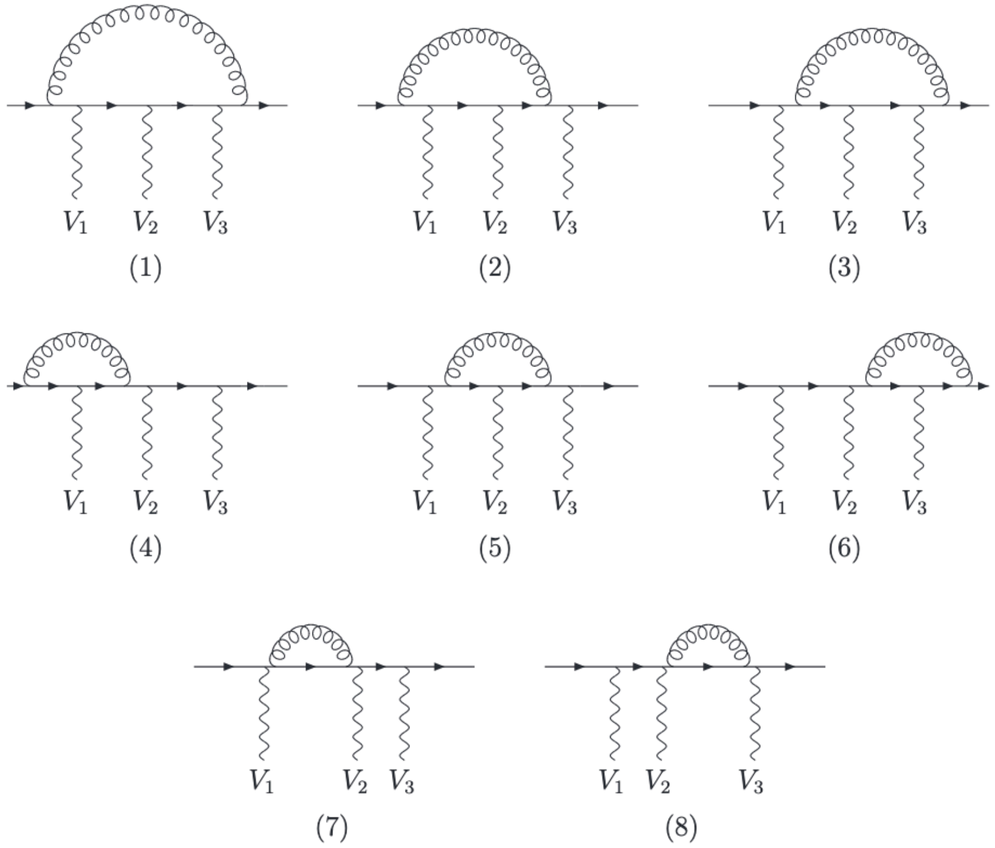
[T. Figy, D. Zeppenfeld, C.Oleari]



VBFNLO Overview

- **Implementation details**
  - Virtual contributions
    - Passarino-Veltman up to boxes [G. Passarino, M. Veltman]
    - Denner-Dittmaier for pentagons and hexagons [A. Denner, S. Dittmaier]

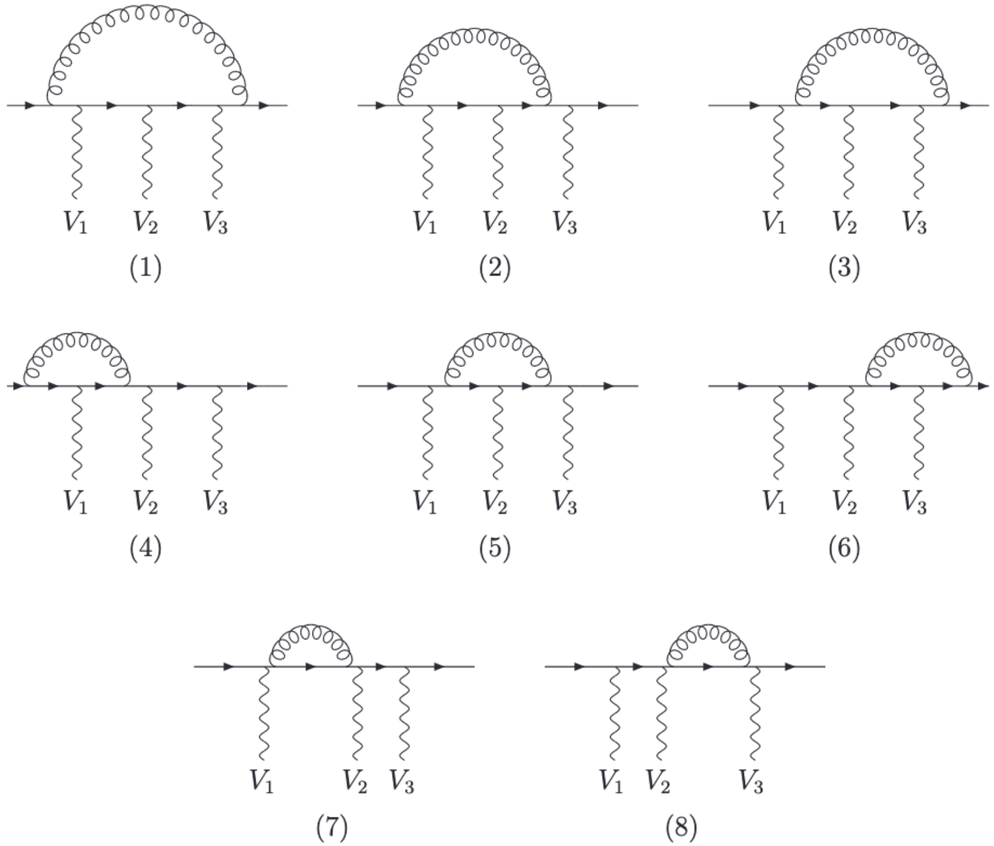
[F.Campanario]



VBFNLO Overview

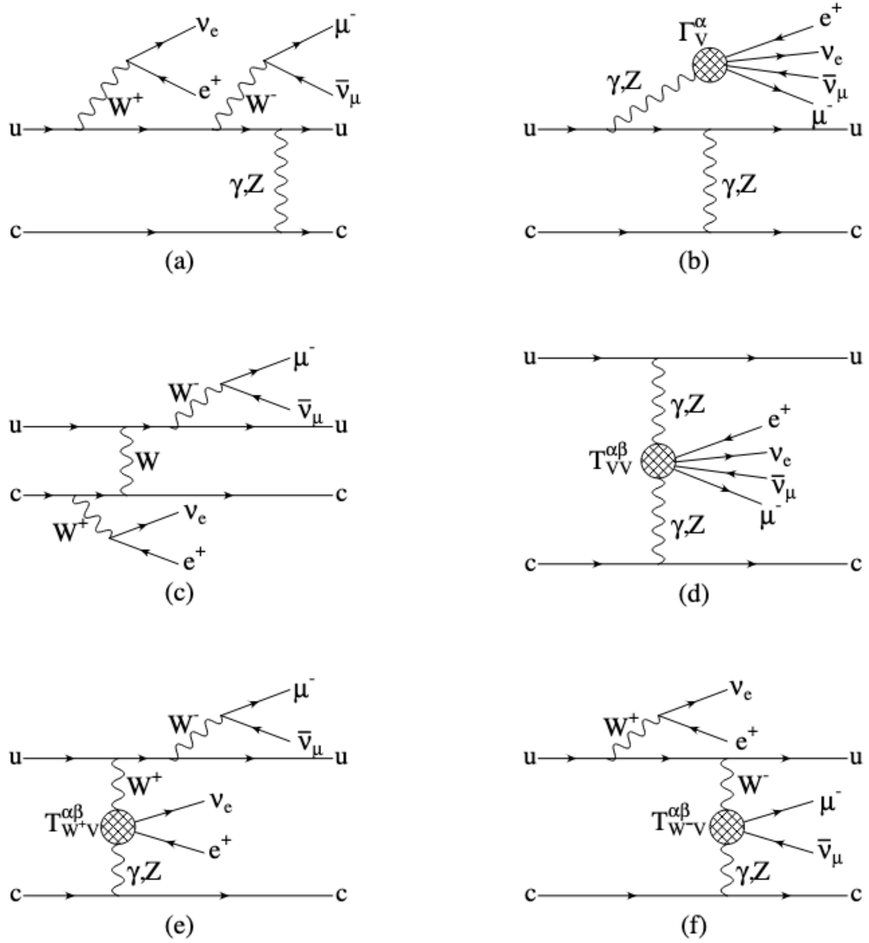
- **Unstable points (due to small Gram or Cailey determinants)**
  - Sets of Gauge invariant sub-amplitudes
  - Ward-Takahashi identities
  - Rescue system in quadruple precision [F.Campanario]

[F.Campanario]

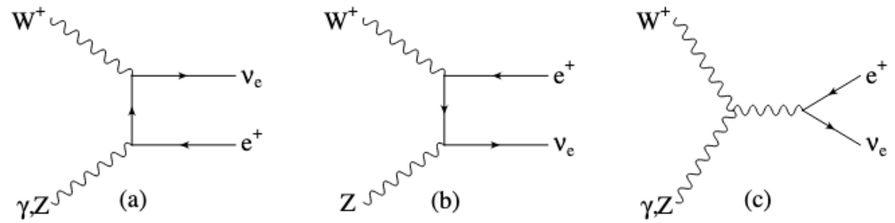


VBFNLO Overview

[B. Jäger, C. Oleari, D. Zeppenfeld]



- $T^{\alpha\beta}_{W^+V}$



- **Optimisations**
  - Leptonic tensors
    - Only computed once
  - Dedicated phase-space for different topologies

VBFNLO Overview

- **Processes:**
  - Vector Boson Scattering ($Hjj, Vjj, VVjj$) (VBS)
  - Higgs production via VBS (NLO QCD+EW)
  - $VV(j)$ and $VVV(j)$
  - HW and HWj
  - QCD-induced $Vjj, VVjj$
  - Gluon fusion $Hjj, Hjjj$
- **A complete list of processes can be found in the Manual**

VBFNLO Overview

- **Effective Field Theory**

$$\mathscr{L}_{\text{EFT}} = \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots$$

$$\begin{aligned}
\widehat{W}_{\mu\nu} &= igT^a W^a_{\mu\nu} \\
\widehat{B}_{\mu\nu} &= ig'Y B_{\mu\nu} \\
D_\mu &= \partial_\mu + igT^a W^a_\mu + ig'Y B_\mu,
\end{aligned}$$

- **Unitarization**
  - Form factors (all)
  - K-matrix (VBS, $\mathcal{O}_{S,1}$, $\mathcal{O}_{S,0} \equiv \mathcal{O}_{S,2}$)
  - T_u-matrix (VBS, dim-8)

- **Example of operators in VBFNLO**

[Banglio et al]

1. Operators using $D_\mu\Phi$:

$$\begin{aligned}
\mathcal{O}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{O}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \\
\mathcal{O}_{S,2} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]
\end{aligned} \tag{36}$$

2. Operators using $D_\mu\Phi$, $\hat{W}_{\mu\nu}$ and $\hat{B}_{\mu\nu}$:

$$\begin{aligned}
\mathcal{O}_{M,0} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{O}_{M,1} &= \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{O}_{M,2} &= \left[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{O}_{M,3} &= \left[\hat{B}_{\mu\nu}\hat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{O}_{M,4} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times \hat{B}^{\beta\nu} \\
\mathcal{O}_{M,5} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times \hat{B}^{\beta\mu} \\
\mathcal{O}_{M,5hc} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\mu} D^\nu\Phi\right] \times \hat{B}^{\beta\nu} \\
\mathcal{O}_{M,6} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right] \\
\mathcal{O}_{M,7} &= \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]
\end{aligned} \tag{37}$$

- **A complete list of processes can be found in the Manual**

VBFNLO Overview

- **Higgs boson production via VBF in the MSSM (NLO QCD + EW)**
- **Two Higgsless extra dimension models**
  - Warped Higgsless scenario
  - Three-Site Higgsless model
- $VVjj$ **via VBF**
  - Spin-2 model
  - two-Higgs doublet model
- **CP-even and CP-odd Higgs in gluon fusion up to** $3j$ **in gluon fusion**

Availability

- **New wepage**
  - https://ific.uv.es/vbfnlo/
- **Repository**
  - https://igit.ific.uv.es/vbfnlo/vbfnlo
  - https://github.com/vbfnlo/vbfnlo
- **Contact**
  - vbfnlo@ific.uv.es
  - ivan.rosario@ific.uv.es

Availability

https://ific.uv.es/vbfnlo/

Downloads

Here you can find the latest releases, manuals, and tools for VBFNLO.

VBFNLO

Release version of VBFNLO.

Manual

The VBFNLO user manual.

Form factor tool for aGC

Tool to compute form factors for anomalous gauge coupling calculations.

Parallel

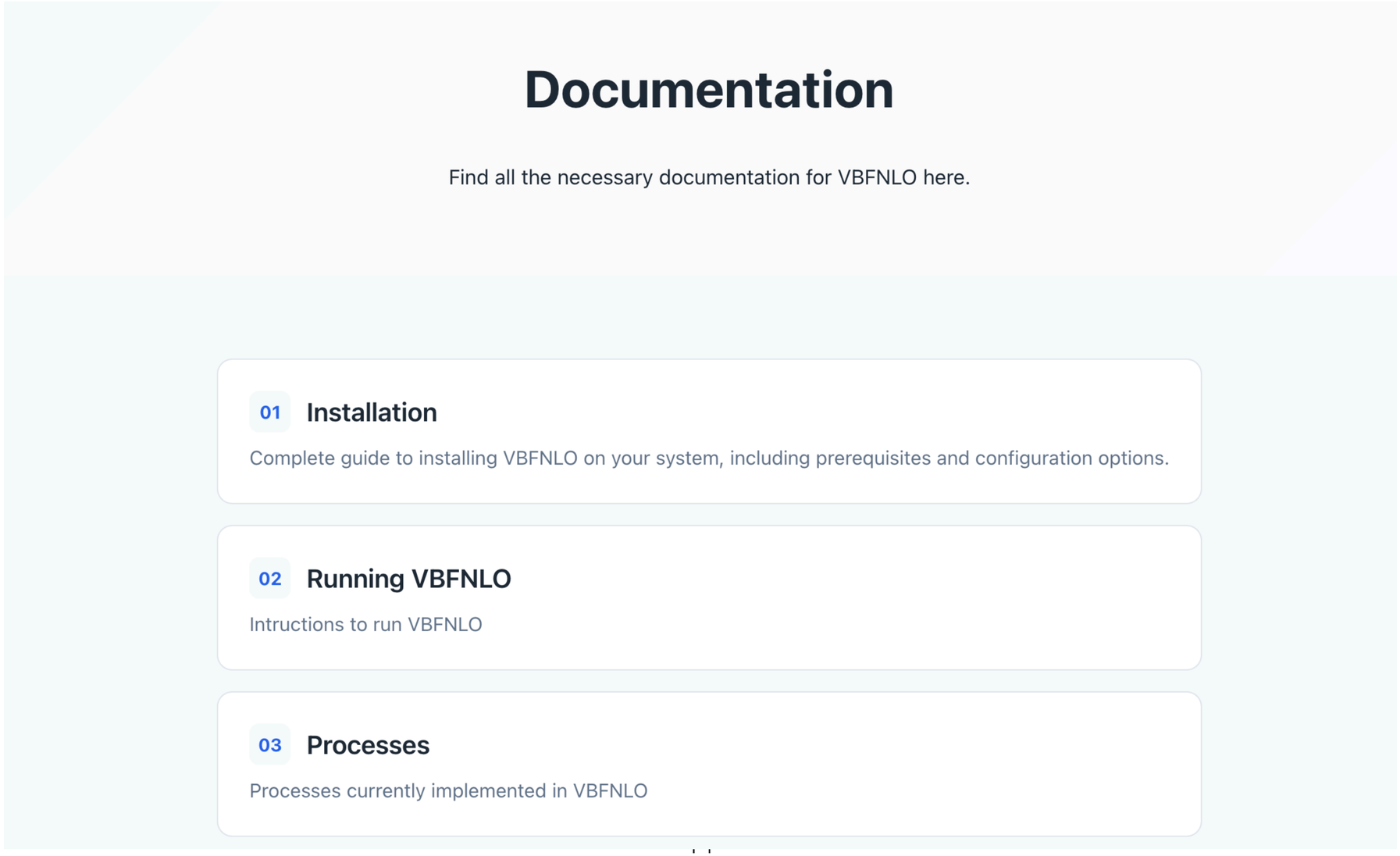
Tool to combine multiple independent runs in VBFNLO.

Archive

Previous versions of VBFNLO and its manual.

Availability

https://ific.uv.es/vbfnlo/



VBFNLO 3.0 updates

- **New processes**
- **OpenMPI**
- **T_u-matrix unitarization**
- **BLHA Interface:**
  - All VBF
  - VV and VVV with fully leptonic decays
- **LHAPDF v6**
- **Other minor updates and enhancements**

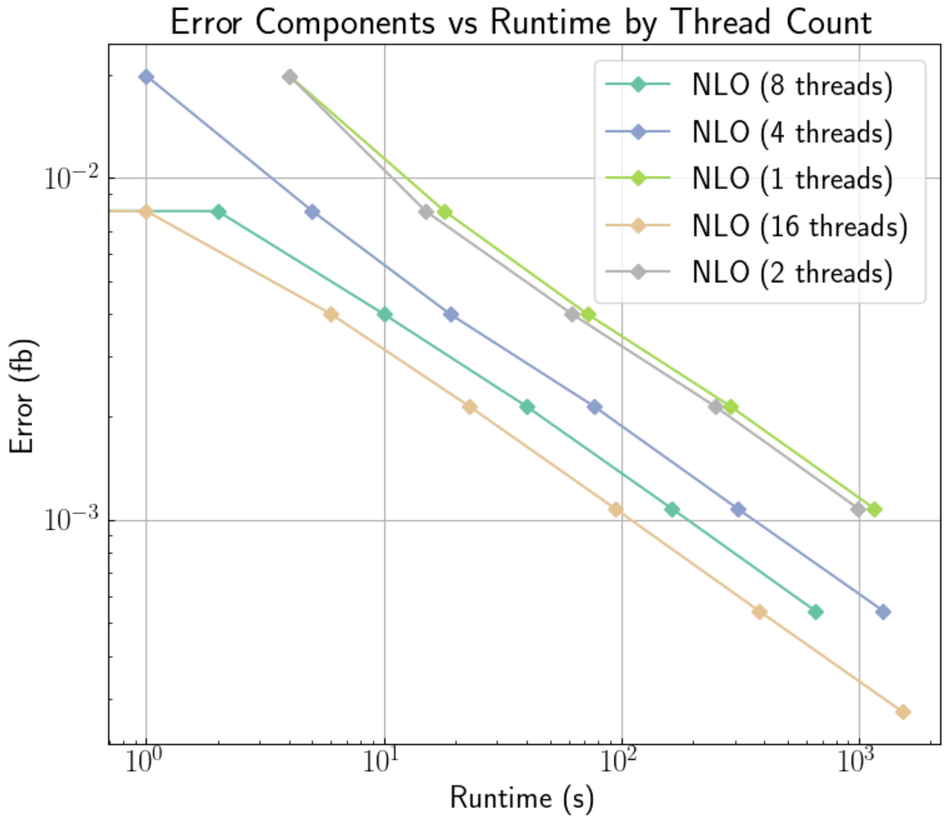
New processes

- **QCD and VBS**
  - QCD-induced: $ZZjj, Z\gamma jj, \gamma\gamma jj$
  - VBS: $Z\gamma jj, \gamma\gamma jj$
- VVj
  - W^+W^-j
  - ZZj
- **Gluon fusion at LO**
  - WWj
  - ZZj
  - Φjjj
- **Decays for HHjj in VBS**
  - $b\bar{b}\gamma\gamma$
  - $b\bar{b}\tau^+\tau^-$

Code Parallelization

- **Code parallelization using OpenMPI**
  - Widely used in HPC
  - Grid integration
  - Histogram generation
- **Easy to use:**
  - Configure with:
    - —enable-MPI
    - FC=mpifort
  - `mpirun -np 16 ./vbfnlo`

VBS cuts | $pp \to HHjj$ (VBS)



AMD Ryzen Threadripper 1950X 16-Core Processor

This example is only for demonstration purposes.

T_u unitarization

- **Motivation for unitarization**

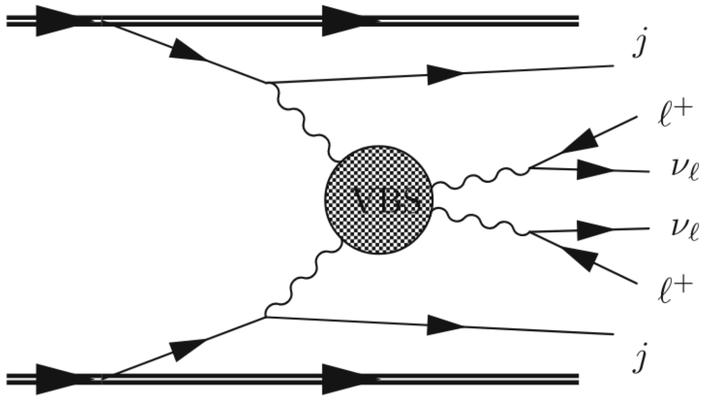
[G. Perez, M. Sekulla, D. Zeppenfeld]

Measurement Normalization	CMS, 13 TeV[6] Éboli	CMS, 13 TeV VBFNLO	ATLAS, 8 TeV[8] VBFNLO (T-matrix)	CMS, 8 TeV[7] Éboli
f_{S_0}/Λ^4	[−7.7,7.7]	[−7.7,7.7]		[−38,40]
f_{S_1}/Λ^4	[−21.6,21.8]	[−21.6,21.8]	[−960,960]	[−118,120]
f_{M_0}/Λ^4	[−6.0,5.9]	[−14,15]		[−33,32]
f_{M_1}/Λ^4	[−8.7,9.1]	[−22,21]		[−44,47]
f_{M_6}/Λ^4	[−11.9,11.8]	[−28.7,28.9]		[−65,63]
f_{M_7}/Λ^4	[−13.3,12.9]	[−31.4,32.3]		[−70,66]
f_{T_0}/Λ^4	[−0.62,0.65]	[−3.7,3.8]		[−4.2,4.6]
f_{T_1}/Λ^4	[−0.28,0.31]	[−1.7,1.8]		[−1.9,2.2]
f_{T_2}/Λ^4	[−0.89,1.02]	[−5.3,6.0]		[−5.2,6.4]

- **Large discrepancy between ATLAS and CMS**

T_u unitarization

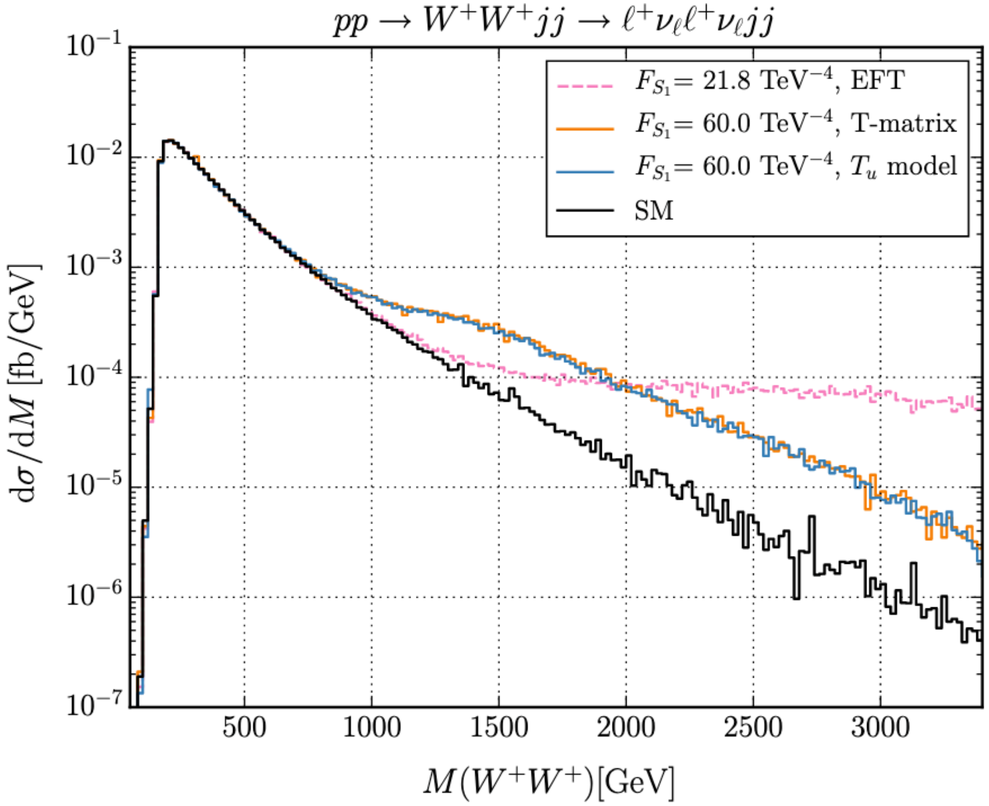
- **The $V_L V_L \to V_L V_L$ amplitude grows with energy**
- **SM Higgs unitarizes it**
- **EFTs spoil it**



[G. Perez, M. Sekulla, D. Zeppenfeld]

$$\mathcal{S}_1 = \frac{f_{S_1}}{\Lambda^4}\left[(D_\mu\phi)^\dagger D^\mu\phi\right]\left[(D_\nu\phi)^\dagger D^\nu\phi\right]$$

[G. Perez, M. Sekulla, D. Zeppenfeld]



T_u unitarization

- VBS $WWjj$

  [G. Perez, M. Sekulla, D. Zeppenfeld]

- Rest of VBS

  [H. Schäfer-Siebert, M. Sekulla, D. Zeppenfeld]

[G. Perez, M. Sekulla, D. Zeppenfeld]

Measurement Normalization	CMS, 13 TeV Éboli	Corresponding T_u Éboli	CMS, 13 TeV VBFNLO	Corresponding T_u VBFNLO
f_{S_0}/Λ^4	[−7.7,7.7]	[−22,22]	[−7.7,7.7]	[−22,22]
f_{S_1}/Λ^4	[−21.6,21.8]	[−50,60]	[−21.6,21.8]	[−50,60]
f_{M_0}/Λ^4	[−6.0,5.9]	[−20.0,14.5]	[−14,15]	[−35,49]
f_{M_1}/Λ^4	[−8.7,9.1]	[−29,23]	[−22,21]	[−56,71]
f_{M_6}/Λ^4	[−11.9,11.8]	[−39,30]	[−29,29]	[−72,94]
f_{M_7}/Λ^4	[−13.3,12.9]	[−44,33]	[−31,32]	[−79,107]
f_{T_0}/Λ^4	[−0.62,0.65]	[−1.35,1.60]	[−3.7,3.8]	[−8.0, 9.5]
f_{T_1}/Λ^4	[−0.28,0.31]	[−0.61,0.85]	[−1.7,1.8]	[−3.6, 5.0]
f_{T_2}/Λ^4	[−0.89,1.02]	[−2.1, 2.6]	[−5.3,6.0]	[−12, 15]

BLHA interface

What is BLHA

Motivation

Validation

Examples

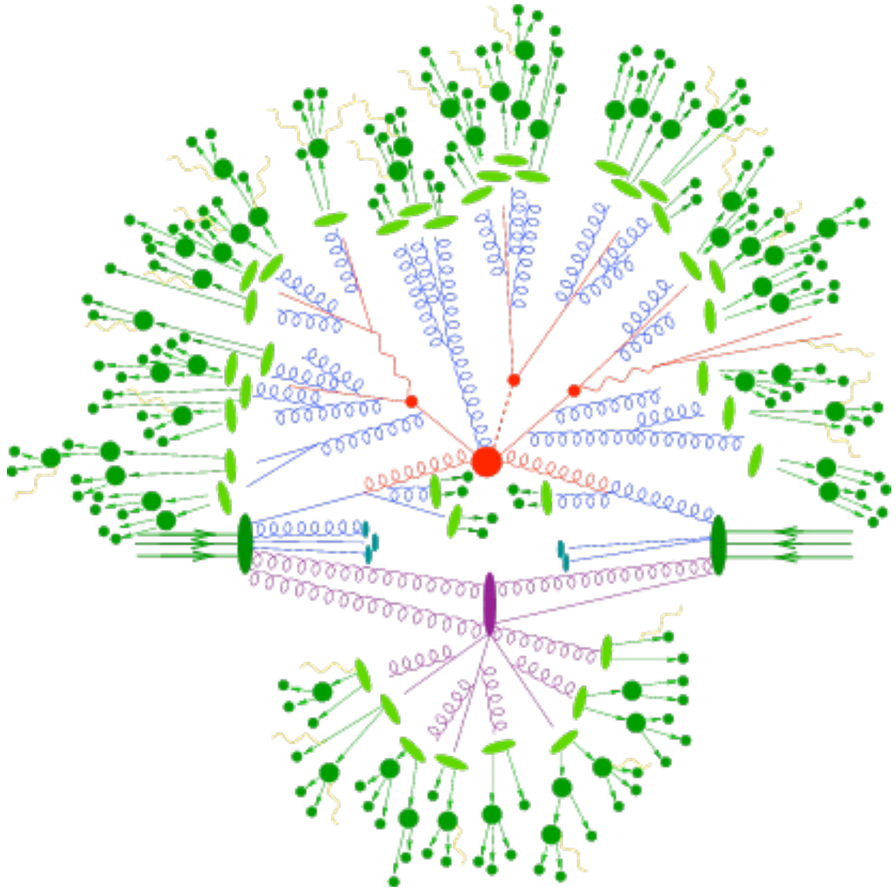
BLHA interface

- **Stands for Binoth Les Houches Accord (BLHA)**
- **Convention:**
  - **How** HEP software must communicate

BLHA interface

- **Protons (PDFs)** One-loop providers
- **Hard collision (Perturbatively)**
- **Parton Shower**
- **Hadronization**

Event generators

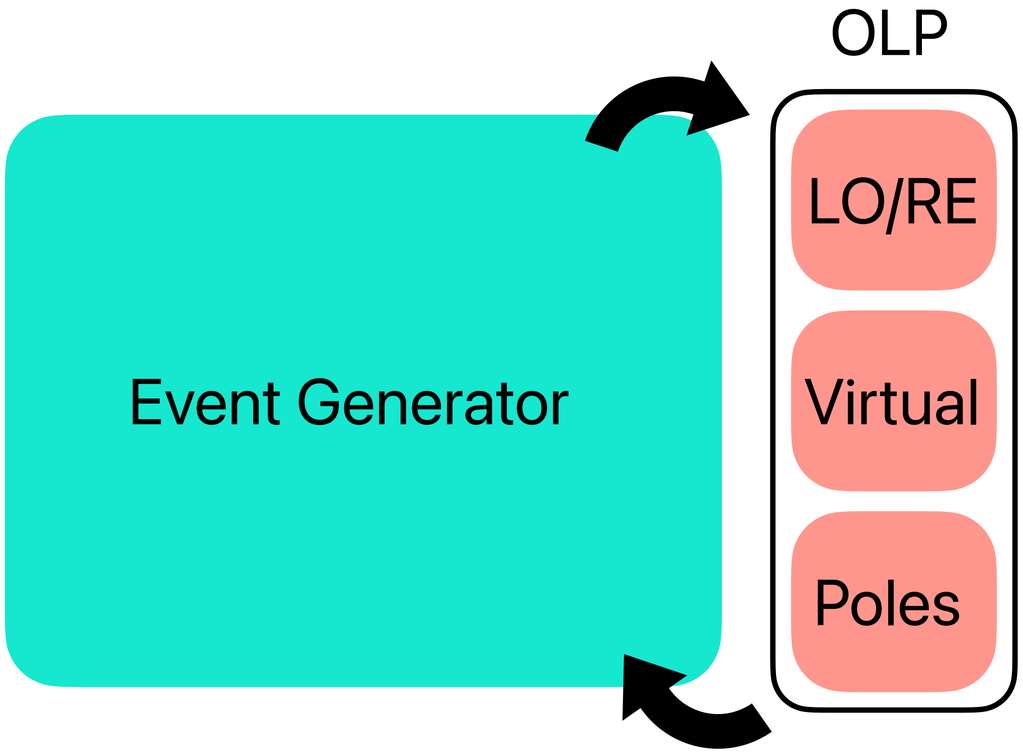


[sherpa-team.gitlab.io]

BLHA interface

- **Protons (PDFs)**
- **Hard collision (Perturbatively)**
  One-loop providers
- **Parton Shower**
- **Hadronization**

Event generators

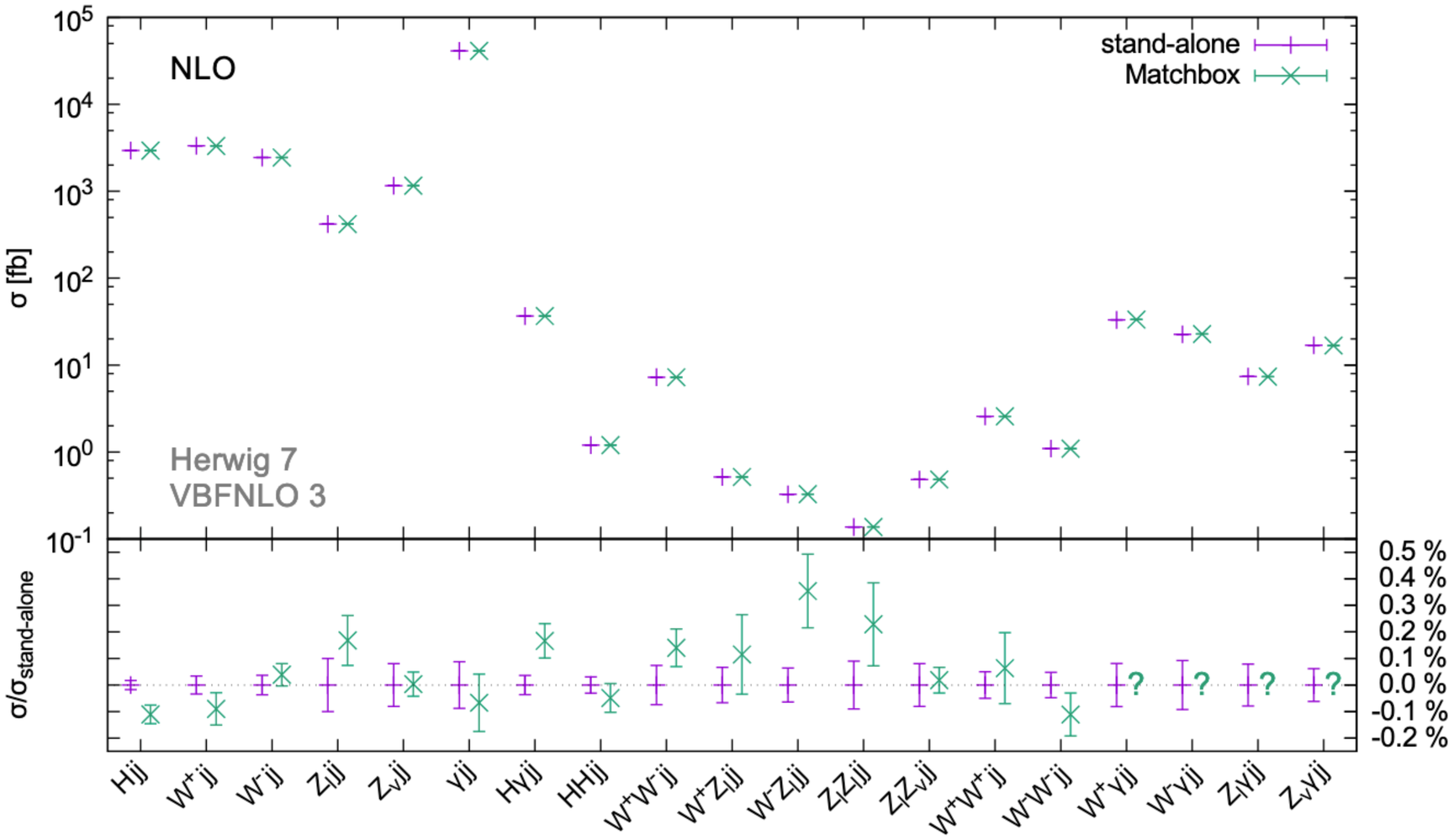


BLHA interface

- **Implementation process specific**
- **Processes**
  - VBS
    [M. Rauch, S. Plätzer]
  - VV and VVV with fully leptonic decays
  - Semi-leptonic decays and other processes in the future
- **Extended interface**
  - VBFNLO phasespace
  - Custom BLHA for Herwig
    - Multiple OLPs in the same run

BLHA interface

[M. Rauch]



BLHA interface

- Diboson

		Herwig + VBFNLO		Herwig + MadGraph		
Process	Component	σ [pb]	ϵ/σ [%]	σ [pb]	ϵ/σ [%]	RD [%]
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$	Born	0.3055(4)	0.14	0.3048(4)	0.13	0.25
	Reals	0.05564(15)	0.28	0.0554(3)	0.45	0.47
	Virtual	0.08933(17)	0.2	0.08934(16)	0.18	0.016
$pp \to e^+\nu_e\mu^-\mu^+$	Born	0.01873(4)	0.2	0.01866(3)	0.16	0.36
	Reals	0.00803(4)	0.53	0.008010(16)	0.19	0.26
	Virtual	0.006332(18)	0.28	0.006336(12)	0.19	0.066
$pp \to e^-\bar{\nu}_e\mu^-\mu^+$	Born	0.01136(2)	0.18	0.011335(16)	0.14	0.19
	Reals	0.005833(6)	0.11	0.005840(8)	0.14	0.12
	Virtual	0.003663(10)	0.28	0.003667(7)	0.20	0.11
$pp \to e^-e^+\mu^-\mu^+$	Born	0.006915(12)	0.18	0.006937(9)	0.12	0.31
	Reals	0.000592(2)	0.38	0.000589(2)	0.39	0.44
	Virtual	0.001846(4)	0.23	0.001840(3)	0.16	0.33
$pp \to e^+\nu_e\gamma$	Born	1.739(8)	0.44	1.742(6)	0.37	0.20
	Reals	1.893(9)	0.50	1.883(2)	0.12	0.48
	Virtual	0.2730(12)	0.45	0.2736(6)	0.21	0.23
$pp \to e^-\bar{\nu}_e\gamma$	Born	1.316(5)	0.41	1.32(5)	0.36	0.49
	Reals	1.585(7)	0.46	1.5858(19)	0.12	0.074
	Virtual	0.195776(8)	0.43	0.1951(4)	0.22	0.35
$pp \to e^-e^+\gamma$	Born	1.227(4)	0.34	1.225(3)	0.26	0.10
	Reals	0.380(3)	0.16	0.3843(6)	0.9	1.0
	Virtual	0.1436(6)	0.38	0.1443(4)	0.29	0.51
$pp \to \gamma\gamma$	Born	35.04(3)	0.092	35.00(3)	0.092	0.11
	Reals	17.81(3)	0.19	17.78(3)	0.19	0.17
	Virtual	-0.054(11)	20.75	-0.049(11)	22.52	11.12

- Triboson

	Herwig + VBFNLO		VBFNLO standalone		
Process	σ [pb]	ϵ/σ [%]	σ [pb]	ϵ/σ [%]	RD [%]
$pp \to \gamma\gamma\gamma$	60.07(4)	0.06	60.03(3)	0.05	0.07
$pp \to e^+\bar{\nu}_e\gamma\gamma$	7.98(3)	0.39	7.9809(7)	0.009	0.04
$pp \to e^-\nu_e\gamma\gamma$	6.79(2)	0.35	6.8080(7)	0.010	0.28
$pp \to e^-\bar{\nu}_e\mu^+\nu_\mu\gamma$	2.902(10)	0.35	2.9139(3)	0.010	0.42
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu\tau^+\nu_\tau$	0.2623(6)	0.23	0.2621(2)	0.08	0.05
$pp \to e^-\bar{\nu}_e\mu^+\nu_\mu\tau^-\bar{\nu}_\tau$	0.1626(3)	0.16	0.16261(16)	0.10	0.010
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu\tau^-\tau^+$	0.04174(8)	0.20	0.041750(10)	0.02	0.03
$pp \to e^+\nu_e\mu^+\mu^-\gamma$	0.3142(15)	0.47	0.31283(4)	0.012	0.44
$pp \to e^-e^+\mu^-\mu^+\tau^+\nu_\tau$	0.003549(10)	0.28	0.0035499(9)	0.03	0.04
$pp \to e^-e^+\mu^-\mu^+\tau^-\bar{\nu}_\tau$	0.002135(4)	0.18	0.0021311(6)	0.03	0.16
$pp \to e^-e^+\gamma\gamma$	4.764(16)	0.33	4.7708(6)	0.012	0.14
$pp \to \nu_e\bar{\nu}_e\gamma\gamma$	4.498(10)	0.23	4.4939(6)	0.013	0.09
$pp \to e^-e^+\mu^-\mu^+\gamma$	0.1133(4)	0.36	0.11349(2)	0.02	0.19
$pp \to e^-e^+\mu^-\mu^+\tau^-\tau^+$	0.001214(6)	0.46	0.001219(3)	0.24	0.42

BLHA interface

- **Matching with Herwig Matchbox module**
  - MC@NLO
    [S. Frixione, B. R. Webber]
  - POWHEG
    [S. Frixione, P. Nason, C. Oleari]
- **(N)LO multi-jet merging**

- **Showers in Herwig**
  - Angular ordered shower
  - Dipole shower

BLHA interface

- **Applications:**
  - Study of Parton Shower uncertainties in VBS

    [M. Rauch, S.Plätzer]
  - Anomalous Higgs boson couplings in VBS

    [T. Chen Ph.D. thesis]
  - NLO multijet merging for Higgs production

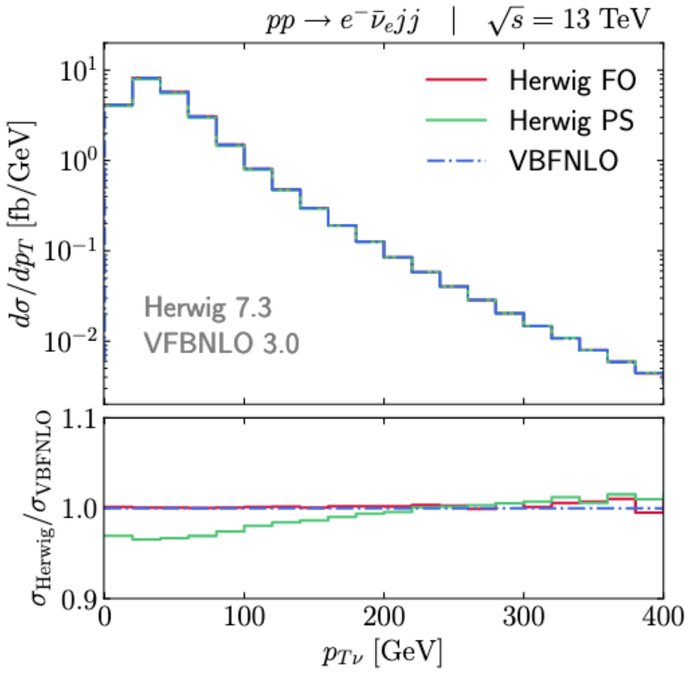
    [T. Chen, T.M. Figy, S. Plätzer]
  - Soft QCD effects in VBS/VBF topologies

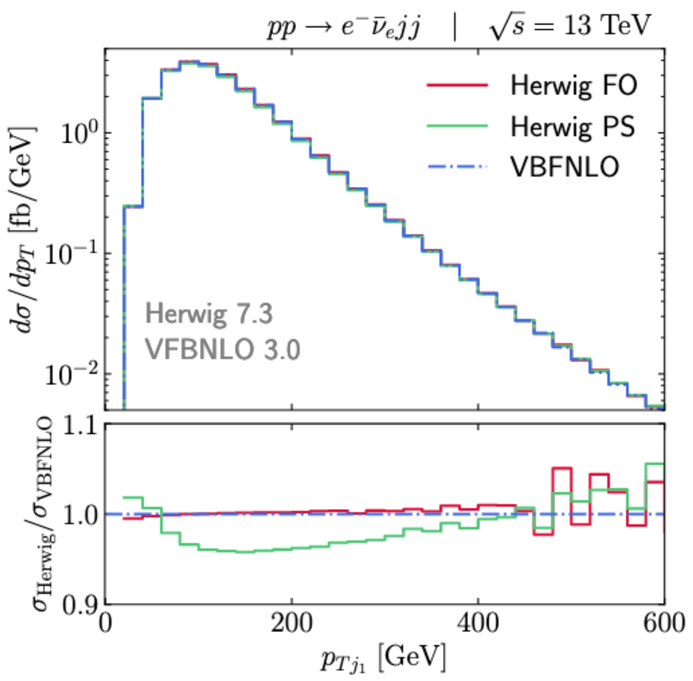
    [C. Bittrich, P. Kirchgaeßer, A. Papaefstathiou, S. Plätzer, S. Todt]
  - Study of Parton Shower uncertainties in tri-boson

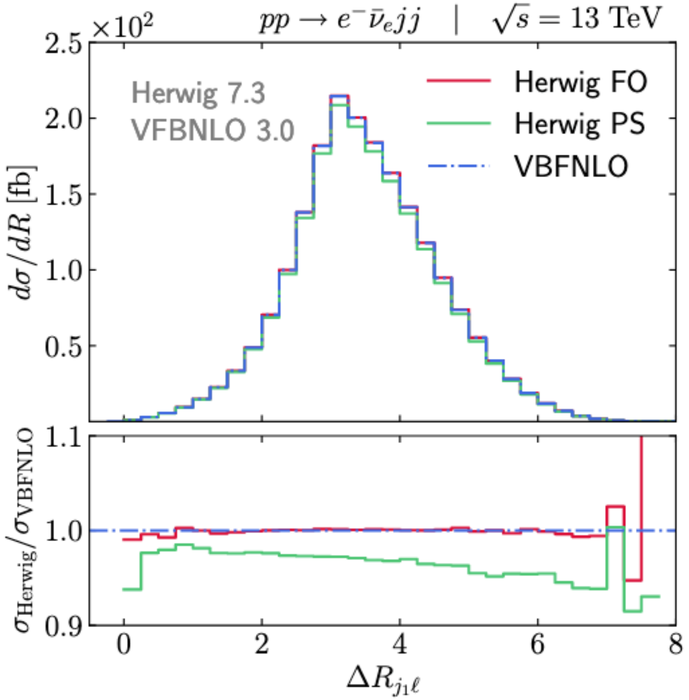
    To be published: [I. Rosario, F. Campanario, S. Plätzer]

BLHA interface

- **Results using the BLHA interface:**







Summary and Outlook

- **VBFNLO 3.0 is out with some interesting enhancements**
  - New processes
  - Parallelization through OpenMPI
  - T_u unitarization
  - BLHA interface
- **New website: ific.uv.es/vbfnlo**
- **Public repository: https://github.com/vbfnlo/vbfnlo**

- **Bugs, suggestions or comments:**
  - Email: vbfnlo@ific.uv.es
  - Issues or pull requests on GitHub

Thank you very much!