Karlsruhe Institute of Technology

VBFNLO

Michael Rauch | MBI 2015, Sep 2015

INSTITUTE FOR THEORETICAL PHYSICS

Introduction

VBFNLO

Vector-Boson-Fusion at Next-to-Leading Order

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Vector-Boson-~~Fusion~~ Physics at Next-to-Leading Order

Introduction

VBFNLO

F
~~Ph~~ysics
Vector-Boson-~~Fusion~~ at Next-to-Leading Order

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons
  - accurate predictions needed for LHC
    (both signal and background)
  - MC efficient solution for high number of final-state particles
    (decays of electroweak bosons included)
- general cuts and distributions of final-state particles
- various choices for renormalization and factorization scales
- any pdf set available from LHAPDF
  (or hard-wired CTEQ6L1, CT10, MRST2004qed, MSTW2008)
- event files in Les Houches Accord (LHA) or HepMC format (LO only)
- BLHA interface to Monte-Carlo event generators
  $\rightarrow$ NLO event output

Process overview

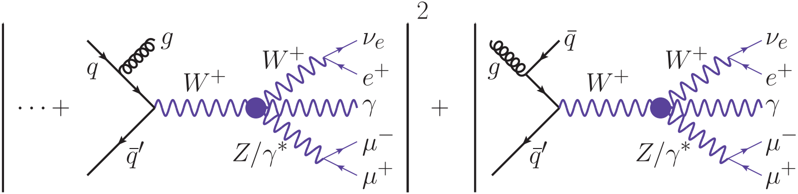
List of implemented processes

(New in VBFNLO 2.7.1/3.0.0β1)

- vector-boson fusion production at NLO QCD of
  - Higgs (+NLO EW, NLO SUSY) } (including Higgs decays)
  - Higgs plus third hard jet } (including Higgs decays)
  - Higgs plus photon } (including Higgs decays)
  - Higgs pair
  - vector boson (W, Z, γ)
  - two vector bosons (W^+W^-, $W^\pm W^\pm$, WZ, ZZ, Wγ, Zγ)
- diboson production
  - diboson (WW, WZ, ZZ, Wγ, Zγ, $\gamma\gamma$) (NLO QCD)
  - diboson via gluon fusion (WW, ZZ, Zγ, $\gamma\gamma$) (part of NNLO QCD contribution to diboson)
  - diboson (WW, WZ, ZZ, Wγ) plus hard jet (NLO QCD)
  - diboson ($W^\pm W^\pm$, WZ, Wγ, ZZ, Zγ) plus two hard jets (NLO QCD)
- triboson production (NLO QCD)
  - triboson (all combinations of W, Z, γ)
  - triboson (W$\gamma\gamma$) plus hard jet
- Higgs plus vector boson (NLO QCD) (including Higgs decays)
  - Higgs plus vector boson (WH)
  - Higgs plus vector boson plus hard jet (WH)
- Higgs plus two jets via gluon fusion (one-loop LO) (including Higgs decays)
- new physics models
  - anomalous Higgs, triple and quartic gauge couplings
  - K-matrix unitarization for selected couplings
  - Higgsless and spin-2 models
  - Two-Higgs model
- BLHA interface for VBF processes

Implementation Details

- Helicity amplitude method [Hagiwara, Zeppenfeld]
- Same building blocks for different Feynman graphs
  $\Rightarrow$ Compute only once per phase-space point and reuse (”leptonic tensors”)
  $\rightarrow$ Significantly faster than generated code (up to factor 10)



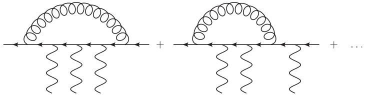
- Catani-Seymour dipole subtraction scheme

$$\sigma_{\text{NLO}} = \underbrace{\int_{m+1} [\mathrm{d}\sigma^R|_{\epsilon=0} - \mathrm{d}\sigma^A|_{\epsilon=0}]}_{\text{real emission}} + \underbrace{\int_m [\mathrm{d}\sigma^V + \int_1 \mathrm{d}\sigma^A]_{\epsilon=0}}_{\text{virtual contributions}} + \underbrace{\int_m \mathrm{d}\sigma^C}_{\text{finite collinear term}}$$

Gauge Test

Tensor reduction of loop integrals using (-4: [Passarino, Veltman]; 5+: [Denner, Dittmaier])
→ numerical precision limited due to possibly small Gram determinants

- Identify → gauge test

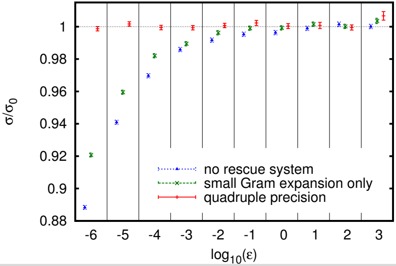


replace one vector boson by corresponding momentum (cache system for loop integrals → no reevaluation needed)

$$p_i^\mu \mathcal{M}_\mu^n(\{p\}; p_{i-1}, p_i, p_{i+1}) = \mathcal{M}^{n-1}(\{p\}; p_{i-1}, p_i + p_{i+1}) - \mathcal{M}^{n-1}(\{p\}; p_{i-1} + p_i, p_{i+1})$$

- Repair [Impl: Campanario]
  → rescue system (small Gram det. expansion) → quad precision → discard

  Example: $gg \to ZZg$ [Campanario, Li, MR, Spira]



ϵ: go to next step if $\dfrac{\Delta(p_i^\mu \mathcal{M}_\mu^n)}{\varepsilon_i^\mu \mathcal{M}_\mu^n} > \epsilon$

strong and efficient test of accuracy of building blocks

number of unstable points reduced to 10^{-6} level
additional CPU cost $\sim$ 10%

BLHA Interface

Interface NLO program with parton-shower MC [Arnold, Plätzer, MR et al.]
well-defined standard: Binoth Les Houches Accord (BLHA)

Motivation:
Combine advantages of NLO calculations and parton shower

NLO calculation

- normalization correct to NLO
- additional jet at high-p_T accurately described
- theoretical uncertainty reduced

Parton shower

- Sudakov suppression at small p_T
- events at hadron level possible

$\Rightarrow$ Interface VBFNLO with parton shower $\rightarrow$ BLHA interface
$\rightarrow$ First tests: Herwig 7 package Matchbox as MC program [Gieseke, Plätzer]

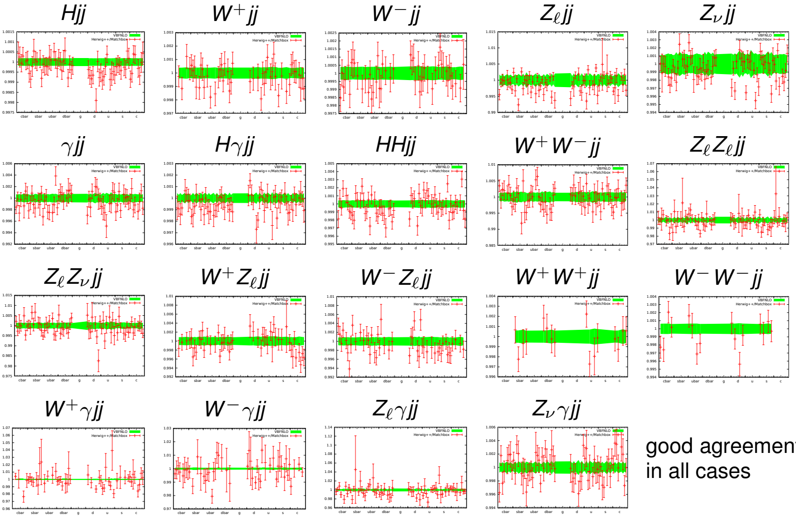
Two parton showers: angular-ordered and Catani-Seymour dipoles

Matching methods: MC@NLO and POWHEG

$\rightarrow$ particular focus of VBFNLO: Vector Boson Fusion/Scattering
$\Rightarrow$ start with this process group [see also Jäger et al. for POWHEG-BOX implementation]

Cross checks

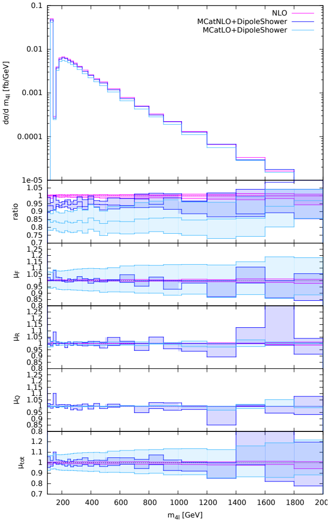
Check all VBF processes → lots of validation plots



good agreement in all cases

VBF-W^+W^- + parton shower

Example: VBF-W^+W^-, VBF cuts, central scale: $\mu_0 = p^T_{j,1}$



Comparison of:

- pure NLO
- NLO+PS (MC@NLO+dipole shower)
- LO+PS (dipole shower)

Panels:

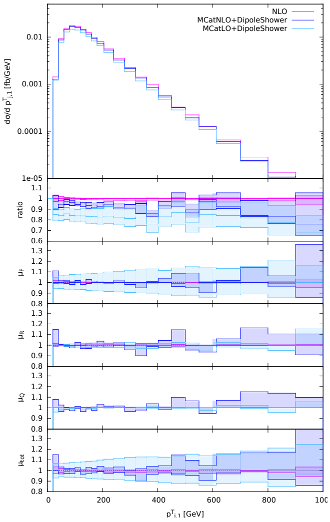
- differential c.s.
- ratio of c.s. and total scale variation
- individual variation of μ_F, μ_R, μ_Q (shower scale)
- total variation $\mu_i/\mu_0 \in [\frac{1}{2}; 2]$ with $\mu_i/\mu_j \in [\frac{1}{2}; 2]$

Inclusion of parton shower:

- smaller c.s. (additional splittings)
- larger uncertainties (additional shower scale unc.)

VBF-W^+W^- + parton shower

Example: VBF-W^+W^-, VBF cuts, central scale: $\mu_0 = p^T_{j,1}$



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VBF-W^+W^- + parton shower

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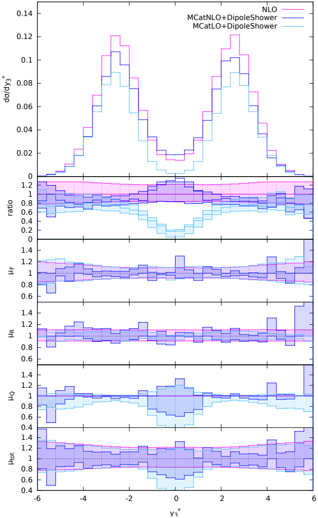
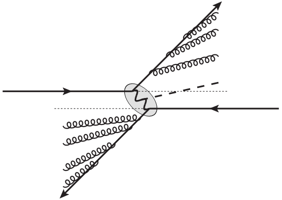
Example: VBF-W^+W^-, VBF cuts, central scale: $\mu_0 = p^T_{j,1}$



$$y_3^* = y_3 - \frac{y_1+y_2}{2}$$

- almost no radiation generated in central region by LO+PS
- additional radiation by shower created mainly between jets and beam axis (color connections)
- $\rightarrow$ central region corrected at NLO by W^+W^-jjj ME
- dipole shower “interpolates” between NLO behavior in central region and shower behavior at small angles



NLO Event Output

Additional features:

- events at NLO

```
HepMC::Version 2.06.08
HepMC::IO_GenEvent-START_EVENT_LISTING
E 1 -1 1.0000000000000000e+02 1.1426144356896106e-01 8.0545791941901580e-03 0 -1 5 10003 10006 0 1 9.65741
N 1 "0"
U GEV MM
C 1.2003526218804084e+00 1.2429340593057579e+04
F 2 -2 1.9944966561722052e-01 5.4752809081600089e-03 1.0000000000000000e+02 4.8837107666330770e-01 7.07735
V -1 0 0 0 0 0 0 2 0
P 10001 24 -4.5106124574613865e+01 2.1914561871288999e+01 4.8707785224913533e+02 4.8305712963914090e+02 -8
[...]
```

- anomalous couplings including available unitarization schemes
- BLHA interface completely following Les Houches standard
  $\rightarrow$ also working with other MC generators (e.g. Sherpa)
  $\leftrightarrow$ when using BLHA v1 with VBF processes, care needs to be taken to use the VBF approximation also in the MC generator
- other process classes will follow (e.g. QCD-VVjj)

Anomalous quartic gauge couplings

Vector-boson scattering ideal process to test anomalous quartic gauge couplings

[Feigl, Schlimpert; Löschner, Perez]

$\Rightarrow$ Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- operators $\mathcal{O}$ contain SM fields only
- respect SM gauge symmetries
- suppressed by $1/\Lambda^{d-4}$ (Λ: scale of new physics)
- building blocks:
  - Higgs field Φ
  - (covariant) derivative ∂^μ, D^μ
  - fermion fields ψ
  - field strength tensors $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$

Redefine field strength tensors

$$\widehat{W}_{\mu\nu} = igT^a W^a_{\mu\nu} \,, \qquad \widehat{B}_{\mu\nu} = ig' Y B_{\mu\nu} \qquad \text{such that} \qquad [D_\mu, D_\nu] = \widehat{W}_{\mu\nu} + \widehat{B}_{\mu\nu}$$

$\rightarrow$ commonly adapted for dimension-6 operators

Anomalous quartic gauge couplings

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$\rightarrow$ commonly adapted for dimension-6 operators

Dimension-8 operators in Lagrangian [Eboli, Gonzalez-Garcia, Mizukoshi]

$$\mathcal{L}_{S,0} \propto \left[(D_\mu\Phi)^\dagger (D_\nu\Phi)\right] \times \left[(D^\mu\Phi)^\dagger (D^\nu\Phi)\right]$$

$$\mathcal{L}_{M,2} \propto \left[\widehat{B}^{\mu\nu}\widehat{B}_{\mu\nu}\right] \times \left[\left(D^\beta\Phi\right)^\dagger (D_\beta\Phi)\right]$$

$$\mathcal{L}_{T,1} \propto \left[\widehat{W}^{\alpha\nu}\widehat{W}_{\mu\beta}\right] \times \left[\widehat{W}^{\mu\beta}\widehat{W}_{\alpha\nu}\right]$$

$$\ldots$$

(at least) four gauge fields in each term $\rightarrow$ modify quartic gauge couplings

paper defines $\widehat{W}^{\mu\nu}$, $\widehat{B}^{\mu\nu}$ without coupling constants ig, $ig'Y$

$\rightarrow$ UFO file by Eboli, Gonzalez-Garcia follows this convention $\rightarrow$ MadGraph

$\rightarrow$ VBFNLO implementation follows dim-6 convention

$\Rightarrow$ simple constant relations between the two, e.g. $f_{M,2}^{\text{VBFNLO}} = -\frac{4}{g'^2} \cdot f_{M,2}^{\text{Eboli}}$

Form factor tool

Contribution of higher-dimensional operators can violate unitarity above certain energy scale $\rightarrow$ unphysical

- Determine energy scale of unitarity violation $\rightarrow$ Partial-wave analysis
  - Consider amplitudes for on-shell $VV \rightarrow VV$ scattering ($V \in W, Z, \gamma$)
  - Decompose into series of partial waves with coefficients a_i, $i = 0, 1, 2, \ldots$
  - $\rightarrow$ Condition for unitarity conservation: $|\mathrm{Re}(a_i)| < \frac{1}{2}$
  - Strongest bound typically from $i = 0 \rightarrow$ check only this contribution

  $\Rightarrow$ maximal energy scale Λ_{max}
- Ensure unitarity at higher energies by applying form factor
  - Unitarity preserved by new-physics contributions entering at or before Λ_{max} $\rightarrow$ acts as cut-off
  - effective implementation in low-energy theory $\Rightarrow$ form factor
  - explicit form model-dependent $\rightarrow$ choice arbitrary
  - VBFNLO: dipole form factor

$$\mathcal{F}(s) = \frac{1}{\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^n} \qquad \Lambda_{FF}^2,\ n\text{: free parameters}$$

- Determine maximal Λ_{FF} from given anomalous couplings, n and maximum energy considered

$\rightarrow$ implemented in form factor tool available from VBFNLO web site
`http://www.itp.kit.edu/~vbfnloweb/wiki/doku.php?id=download:formfactor`

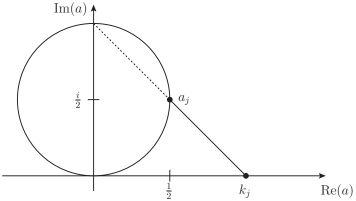
Example output

```
[...]
 Reading in anomalous couplings parameter:
   SQRT_S                 =  14000.
   FFEXP                  =  2.0000
   FS0                    = 0.10000E-09
   FS1                    = 0.10000E-09
[...]
 Checking tree-level unitarity violation with on-shell W+W- -> W+W- scattering
 using the largest helicity combination of the zeroth partial wave...
[...]
 Checking tree-level unitarity violation with on-shell VV->VV scattering
 including all Q=0 channels involving W and Z bosons using the largest
 helicity combination of the zeroth partial wave...
[...]
 Results for each channel, taking only the helicity combination with the largest
 contribution to the zeroth partial wave into account:

 FFscale_WWWW =     688. GeV    ( without FF: |Re(pwave_0)| > 0.5 at   0.8 TeV )
[...]
 No tree-level unitarity violation in W+W- -> AA scattering found.
[...]
 Results for each channel, taking contributions from all helicity combinations to
 the zeroth partial wave into account by diagonalizing the T-matrix:

 FFscale_WWWW_diag =     688. GeV    ( without FF: |Re(pwave_0)| > 0.5 at   0.8 TeV )
[...]
 FFscale_VVVV_Q_0 =     622. GeV    ( without FF: |Re(pwave_0)| > 0.5 at   0.7 TeV )
[...]
```

K matrix unitarization



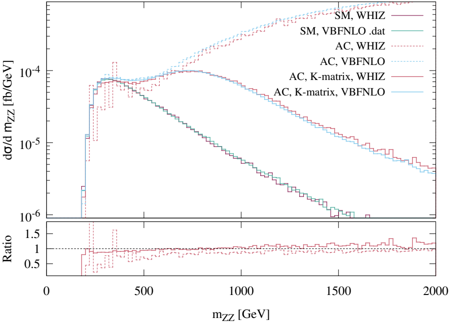
Project amplitude k_j,
which exceeds (tree-level) unitarity,
back onto Argand circle
$\rightarrow$ K matrix unitarization
$\rightarrow$ a_j

[$\rightarrow$ Marco's talk]

[VBFNLO implementation: Löschner, Perez; following: Alboteanu, Kilian, Reuter]

Comparison with Whizard, which has this method already implemented:

[Kilian, Ohl, Reuter, Sekulla, et al.]



Example: VBF-ZZ ($e^+e^-\mu^+\mu^-$)

good agreement between both codes for longitudinal ops. at LO
$\rightarrow$ can now generate distributions also at NLO via VBFNLO

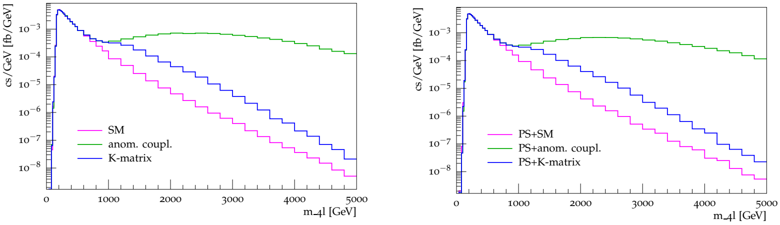
Extension to mixed and transverse operators not straight-forward
$\rightarrow$ work ongoing

Combination with Parton Shower

Can also combine K-matrix in setup with parton shower [VBFNLO3&Herwig7]

Example: VBF-W^+W^+ ($pp \to e^+\nu_e\,\mu^+\nu_\mu\,jj$)
anom. coupl.: $f_{S,1} = 100$ TeV^{-4}

fixed-order NLO | NLO+PS (MC@NLO + dipole shower)



No significant shape changes in $m_{4\ell}$ when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

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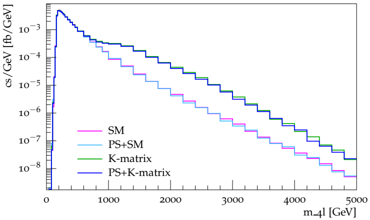
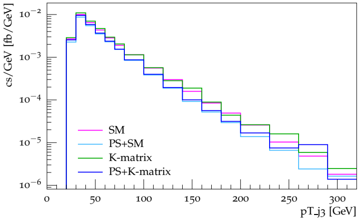
$m_{4\ell}$ – Comparison



$p^T_{j,3}$ – Comparison



No significant shape changes in $m_{4\ell}$ when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

$\leftrightarrow$ $p^T_{j,3}$ mostly sensitive to parton-shower effects

Reweighting events (REPOLO)

[F. Schissler, available on request]

Generating events at detector-level time-consuming (shower, detector simulation, . . .)

→ Reuse SM Higgs events and reweight for different BSM scenarios

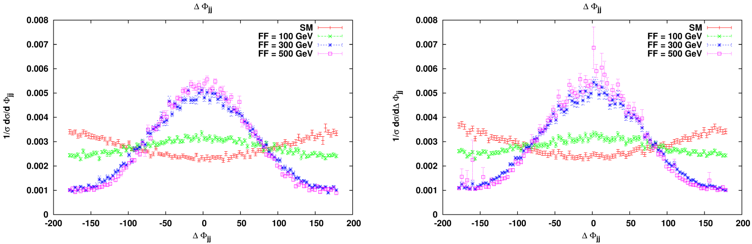
→ REPOLO (REweighting POwheg events at Leading Order)

uses VBFNLO framework to multiply each event by a factor $\frac{|\mathcal{M}_{\mathrm{BSM}}|^2}{|\mathcal{M}_{\mathrm{SM}}|^2}$

Limitation:

event with high reweighting factor ($|\mathcal{M}_{\mathrm{SM}}|^2 \ll |\mathcal{M}_{\mathrm{BSM}}|^2$) can destroy distributions
→ only SM-like distributions can be safely reweighted

Example: VBF-$H \to \gamma\gamma$, SM → anomalous Higgs couplings ($+HW_+^{\mu\nu}W_{\mu\nu}^-$, $HZ^{\mu\nu}Z_{\mu\nu}$)
left: direct generation; right: reweighting



⇒ distributions correctly reproduced, larger errors in SM-suppressed regions

Diboson production beyond NLO

→ need precise predictions for LHC

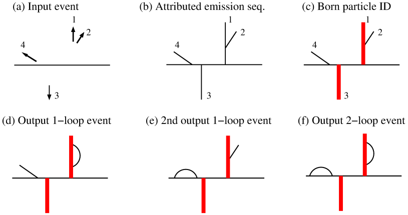
↔ need (reasonably) fast predictions for LHC

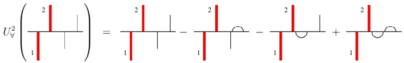
→ Merging of NLO calculations with different jet multiplicities

LoopSim approach

[Rubin, Salam, Sapeta]

- based on unitarity
- assign angular-ordered branching structure to each event (C/A algorithm with radius R_{LS}) until number of particles identical to Born number
- hard structure of event determined → remaining particles marked as “Born”
- construct virtual “loop” events: recombine particles j not marked as “Born”:





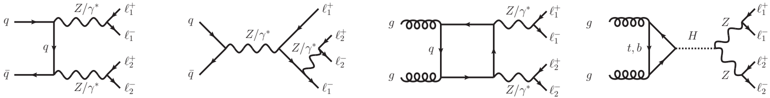
⇒ Exact tree-level and one-loop parts, singular part of two-loop diagrams

↔ constant term of two-loop diagrams missing

ZZ production

$pp \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$, 8 TeV

[Campanario, MR, Sapeta]



Integrated cross sections and scale variation (setup as in [1], inclusive on-shell ZZ):

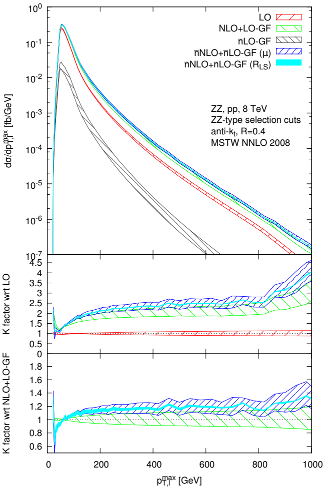
σ_{LO} [pb]	$5.0673(4)\ ^{+1.6\%}_{-2.7\%}$	(*Ref. [1]*: $5.060\ ^{+1.6\%}_{-2.7\%}$)
σ_{NLO} [pb]	$7.3788(10)\ ^{+2.8\%}_{-2.3\%}$	(*Ref. [1]*: $7.369\ ^{+2.8\%}_{-2.3\%}$)
$\sigma_{\text{NLO+LO-GF}}$ [pb]	$7.946(3)\ ^{+4.2\%}_{-3.2\%}$	
σ_{NNLO} [pb]		(*Ref. [1]*: $8.284\ ^{+3.0\%}_{-2.3\%}$)
$\sigma_{\bar{n}\text{NLO}}$ [pb]	$8.103(5)\ ^{+4.7\%}_{-2.6\%}\ (\mu)\quad ^{+0.8\%}_{-0.6\%}\ (R_{LS})$	
$\sigma_{\bar{n}\text{NLO}+\bar{n}\text{LO-GF}}$ [pb]	$8.118(5)\ ^{+4.7\%}_{-2.6\%}\ (\mu)\quad ^{+0.8\%}_{-0.6\%}\ (R_{LS})$	

good agreement between $\bar{n}$NLO and NNLO $\to$ 2% difference only
uncertainty due to LoopSim parameter R_{LS} small

[1]: [Cascioli, Rathlev et al.]

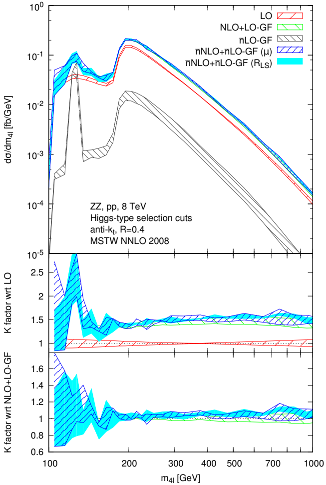
ZZ production

$p_{T,\ell}^{max}$, inclusive cuts



significant $\bar{n}$NLO corrections at high p_T

$m_{4\ell}$, Higgs cuts



distribution stable when adding $\bar{n}$NLO

Conclusions

- particular focus on speed and stability
- New features in latest VBFNLO release:
  - BLHA interface to MC generators
    $\rightarrow$ parton-shower (and hadronization) effects
  - K-matrix unitarization for selected couplings
- studying merged NLO samples with LoopSim

VBFNLO is a flexible parton-level Monte Carlo for processes with electro-weak bosons

Code available at `http://www.itp.kit.edu/vbfnlo`

VBFNLO is collaborative effort:

K. Arnold, J. Baglio, J. Bellm, G. Bozzi, M. Brieg, F. Campanario, C. Englert, B. Feigl, J. Frank, T. Figy, F. Geyer, N. Greiner, C. Hackstein, V. Hankele, B. Jäger, N. Kaiser, M. Kerner, G. Klämke, M. Kubocz, M. Löschner, L.D. Ninh, C. Oleari, S. Palmer, S. Plätzer, S. Prestel, MR, R. Roth, H. Rzehak, F. Schissler, O. Schlimpert, M. Spannowsky, M. Worek, D. Zeppenfeld

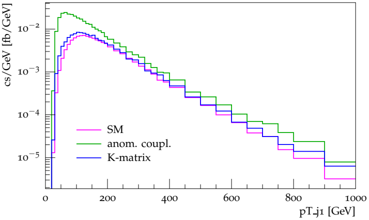
Contact: `vbfnlo@itp.kit.edu`

K-matrix + Parton Shower

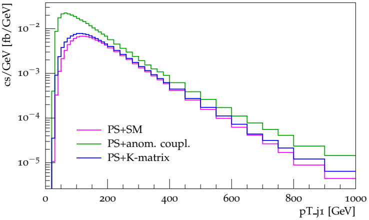
Combine K-matrix setup with parton shower [VBFNLO3&Herwig7]

Example: VBF-W^+W^+ ($pp \to e^+\nu_e\,\mu^+\nu_\mu\,jj$)
anom. coupl.: $f_{S,1} = 100\ \text{TeV}^{-4}$

fixed-order NLO



NLO+PS (MC@NLO + dipole shower)



Strong enhancement of leading jet at low transverse momenta without unitarization

small dependence on parton-shower effects