Karlsruhe Institute of Technology

VBFNLO

Robin Roth | 25.08.2016

Multi-Boson Interactions 2016, Madison

Institute for Theoretical Physics

Motivation

Goal

- test the Standard Model (SM) at the LHC with the highest possible precision
- look for deviations from the SM in a model independent way
- focus on processes with electroweak bosons

Methods

- more precise SM prediction, reduced theory error $\Rightarrow$ NLO, $\bar{n}$NLO, NLO+PS
- parametrize beyond-SM effects $\Rightarrow$ Anomalous Couplings (AC) / EFT
- improve analyses $\Rightarrow$ better cuts and observables, dynamical jet veto

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$\Rightarrow$ VBFNLO

Overview

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VBFNLO

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

VBFNLO

Scattering, Diboson, Triboson, additional Jets

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

VBFNLO

F

~~Ph~~ysics

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

VBFNLO

F
~~Ph~~ysics
Vector-Boson-~~Fusion~~ at Next-to-Leading Order [0811.4559, 1107.4038, 1404.3940]

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons
  - accurate predictions for LHC physics
    (both signal and background)
  - efficient for large number of final-state particles
    (decays/off-shell effects of electroweak bosons included)
- anomalous couplings for many processes
- general cuts and distributions of final-state particles
- various choices for (dynamical) renormalization and factorization scales
- pdf set via LHAPDF
  (or CTEQ6L1, CT10, MRST2004qed, MSTW2008 shipped with release)
- event files in Les Houches Accord (LHA) or HepMC format (LO only)
- BLHA interface to Monte-Carlo event generators
  $\rightarrow$ NLO event output

Overview of implemented processes

(New in VBFNLO 2.7.1/3.0.0β2)

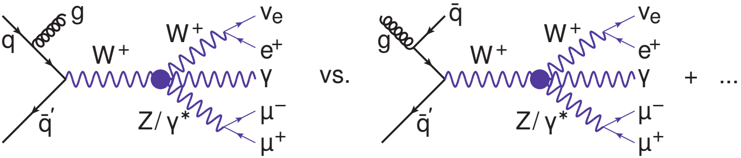
- vector-boson fusion production at NLO QCD of
  - Higgs (+NLO EW, NLO SUSY)
  - Higgs plus third hard jet
  - Higgs plus photon
  - Higgs pair

  } (including Higgs decays)

  - 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
  ⇒ Compute only once per phase-space point and reuse (”leptonic tensors”)
  → Significantly faster than generated code (up to factor 10)
  → Easy extension for anomalous couplings



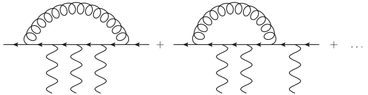
- Catani-Seymour dipole subtraction scheme

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

Gauge Test

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

- Identify $\rightarrow$ gauge test

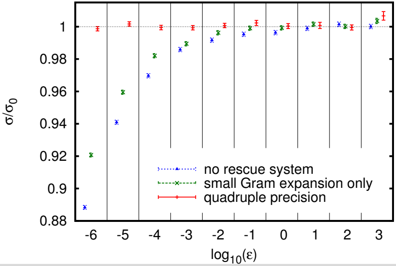


replace one vector boson by corresponding momentum (cache system for loop integrals $\rightarrow$ no reevaluation needed)

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

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

Example: $gg \rightarrow ZZg$ [Campanario, Li, Rauch, Spira]



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

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

Standardized interface between Monte Carlo tools and one-loop programs
$\rightarrow$ Binoth Les Houches Accord (BLHA)

[1001.1307, 1308.3462]

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

$\Rightarrow$ Combine advantages of NLO calculations and parton shower

- tree-level evaluation of matrix elements well under control
- modular structure of NLO calculations
- algorithms for treatment of infrared singularities (Catani-Seymour, FKS, . . .)
- $\rightarrow$ incorporate one-loop matrix element information into MC tools

$\Rightarrow$ Matchbox module in Herwig7

[work led by S. Plätzer with substantial contributions by J. Bellm, A. Wilcock, M. Rauch, C. Reuschle]

BLHA Interface – Distribution of Tasks

One-loop provider (OLP)

- one-loop matrix elements $2\Re(\mathcal{M}_{\text{LO}}^{\dagger}\mathcal{M}_{\text{virt}})$ (coefficients of $\epsilon^{-2}, \epsilon^{-1}, \epsilon^{0}; |\mathcal{M}_{\text{LO}}|^2$)
- Born, colour- and spin-correlated Born (only BLHA2)

Monte Carlo Tool

- cuts, histograms, parameters
- Monte Carlo integration
- phase space ($\rightarrow$ VBFNLO)
- IR subtraction
- Born, colour- and spin-correlated Born (only BLHA1)

VBFNLO

- VBF/VBS processes at NLO QCD [see also Jäger et al. (POWHEG-BOX VBF)] $\rightarrow$ other processes in preparation
- Anomalous Couplings

Herwig7

- **Two parton showers**: angular-ordered Catani-Seymour dipoles
- **Two matching methods**: MC@NLO and POWHEG

- Setup stage via “contract” file (needed for tools which generate code on the fly)
- Run-time stage via binary interface (function calls) $\rightarrow$ fast

NLO Event Output

- events at NLO

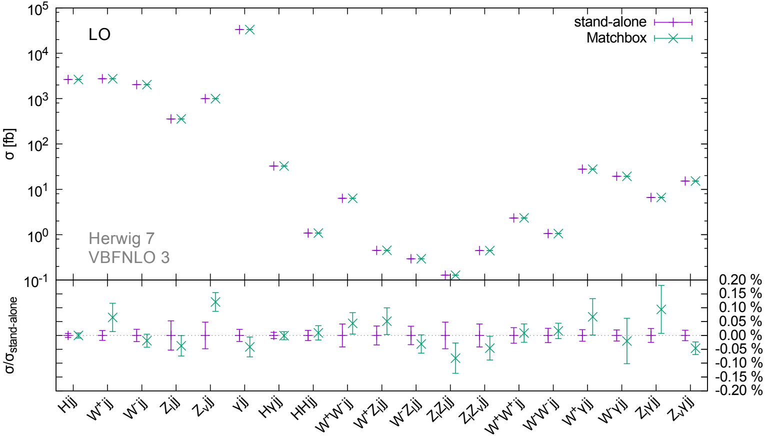
```
HepMC::Version 2.06.08
HepMC::IO_GenEvent-START_EVENT_LISTING
E 1 -1 1.0000000000000000e+02 1.1426144356896106e-01 8.0545791941901580e-03 0 -1 5 10003 10006 0
      1 9.6574119350375395e-05
N 1 "0"
U GEV MM
C 1.2003526218804084e+00 1.2429340593057579e+04
F 2 -2 1.9944966561722052e-01 5.4752809081600089e-03 1.0000000000000000e+02 4.8837107666330770e
      -01 7.0773553098927189e-01 0 0
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 -8.0096530215583300e+01 11 0 0 -5 0
[...]
```

- 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-VV + 0,1,2 jets)

Validation

Compare LO results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox

(inclusive cuts, with leptonic gauge boson decays into single different-flavour combination, Higgs non-decaying)



→ good agreement at or below permill level

Validation

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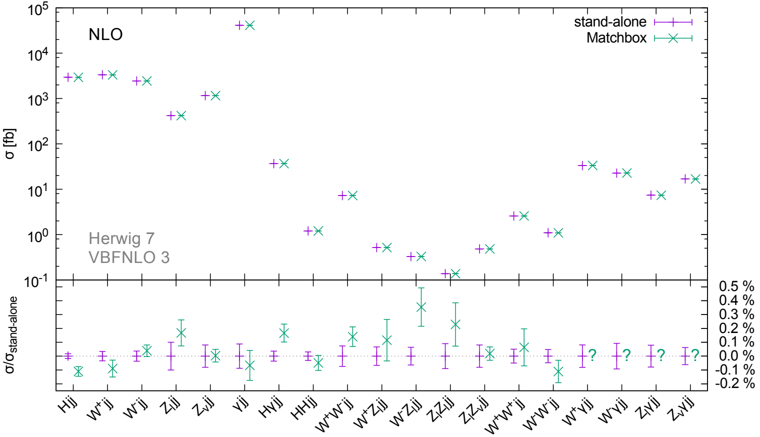


→ good agreement
discrepancy in $V\gamma$ processes: $\pm 0.7\%$ deviation → under investigation

VBF event topology

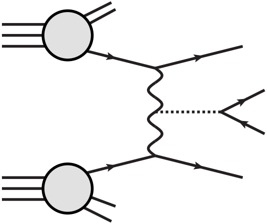
VBF (vector-boson fusion) topology shows distinct signature

- two tagging jets in forward region
- reduced jet activity in central region
- leptonic decay products typically between tagging jets

$\rightarrow$ two-sided DIS

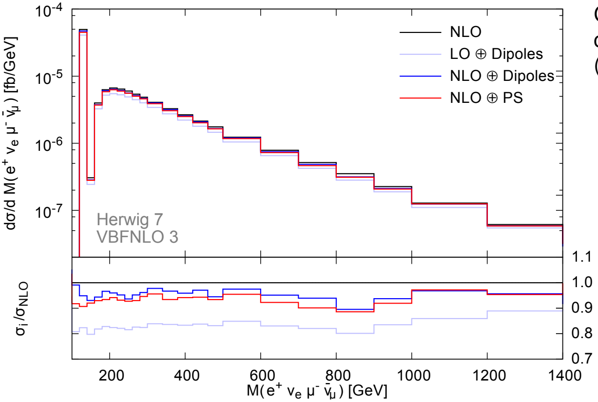
First studied in context of Higgs searches [Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; . . .]

- $\sim$ 10% compared to main production mode gluon fusion
- NLO QCD corrections moderate ($\mathcal{O}(\lesssim 10\%)$)
- NLO EW same size, opposite sign as QCD for $M_H \sim 126$ GeV [Ciccolini *et al.* , Figy *et al.*]
- NNLO QCD known for subsets: no significant contributions for integrated c.s. [Harlander *et al.* , Bolzoni *et al.*] corrections up to 10% in distributions [Cacciari *et al.*]
- incl. NNNLO QCD: tiny effects [Dreyer, Karlberg]
- advantageous scale choice: momentum transfer q^2 of intermediate vector bosons



VBF-H NLO+PS Distributions

$pp \to ((Hjj \to) W^+ W^- jj \to) e^+ \nu_e \mu^- \bar{\nu}_\mu jj$ via VBF
comparing Dipole shower and angular ordered matched to NLO parton shower



Cuts inspired from ATLAS VBF category in $H \to WW$ (CMS similar)

$p_{T,j} > 30$ GeV,
$|y_j| < 4.5$,
anti-k_T $R = 0.4$, b veto

$p_{T,\ell} > 20$ GeV,
$|y_\ell| < 2.5$,
$m_{e^+,\mu^-} > 15$ GeV

$m_{j1,j2} > 600$ GeV,
$|y_{j1} - y_{j2}| > 3.6$

PDF: MMHT2014 $\mu_0 = p_{T,j1}$

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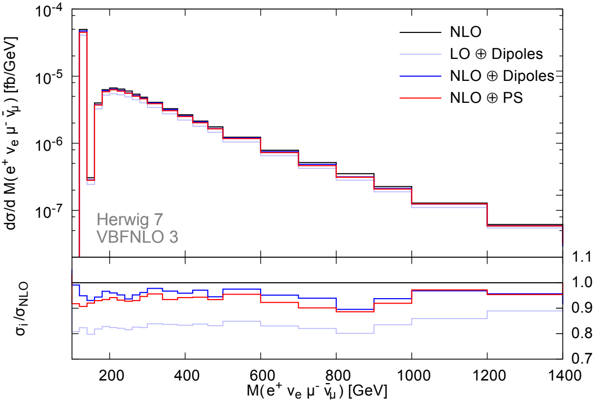

- Higgs peak at 125 GeV
- *WW* continuum production above 180 GeV
- significant cancellation between diagrams at high invariant masses
- $\mathcal{M}_{\text{4-vertex only}} \propto M_{4\ell}^4$
- $\mathcal{M}_{\text{Higgs}} \propto M_{4\ell}^2$
- $\mathcal{M}_{\text{tot}} \propto$ const.

$\Rightarrow$ ideal test for anomalous couplings

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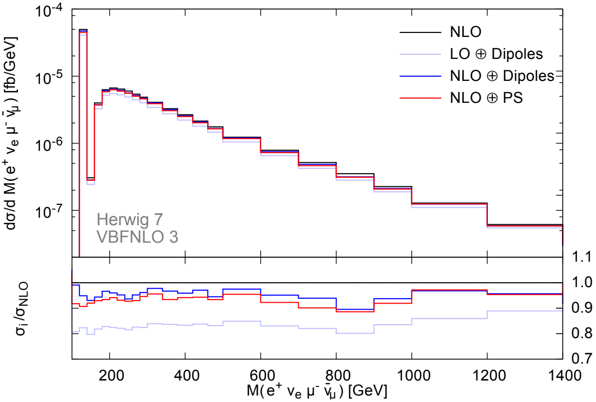
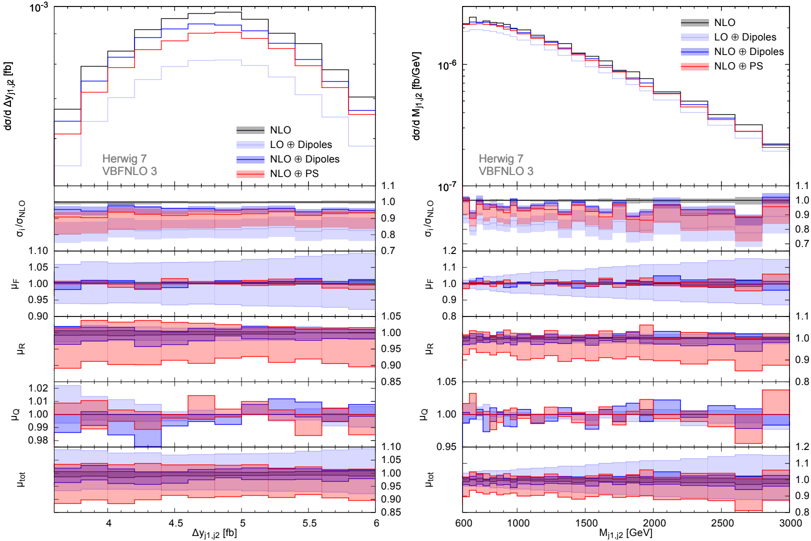


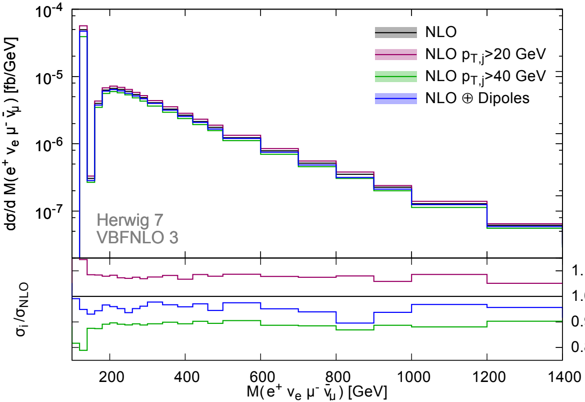
- all parton-shower results smaller than NLO cross section
- additional K-factor effect for LO $\oplus$ Dipoles result ($K = 1.077$)
- no relevant shape changes (as expected: insensitive to QCD effects)

VBF Distributions



Migration Effects

Vary transverse momentum cut of jets (default: $p_{T,j} > 30$ GeV)



- same effect when slightly raising $p_{T,j}$ cut
- additional parton splittings: if hard & wide-angle emission $\rightarrow$ separate jet
- $\rightarrow$ reduces energy and transverse momentum of emitting parton
- $\leftrightarrow$ $p_{T,j}$ cut, VBF cut $m_{jj} > 600$ GeV

Migration Effects

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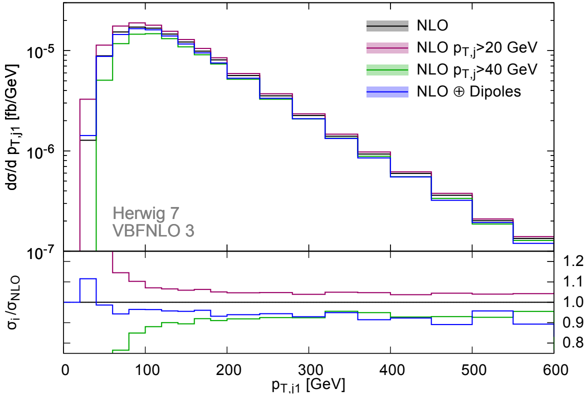


- less pronounced for small $p_{T,j1}$
  $\rightarrow$ VBF cut main source
- $\rightarrow$ migration of events across cut boundary
- $\leftrightarrow$ generation-level vs. analysis-level cuts
- $\Rightarrow$ no tuning of acceptance criteria required
- generation-level cuts nevertheless chosen slightly weaker

Anomalous couplings

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

- 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

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

- includes couplings factors appearing naturally from New Physics Loops
- commonly adapted for dimension-6 operators

Operator dimensions

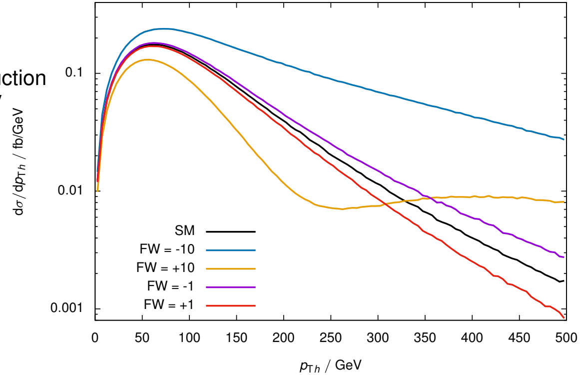
- $d = 6$: triple gauge couplings, higgs couplings
- $d = 8$: quartic gauge couplings, neutral triple gauge couplings

Anomalous Couplings – Example

Example operator: $\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \hat{W}^{\mu\nu} \, (D_\nu \Phi), \quad \mathcal{L} = \mathcal{L}_{SM} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \ldots$

WWH vertex: $\underbrace{i g m_W g^{\mu\nu}}_{\text{SM}} \underbrace{- \frac{1}{2} i \frac{f_W}{\Lambda^2} g m_W \left(-g^{\mu\nu} \left(p_h \cdot p_- + p_h \cdot p_+ \right) + p_h^\nu p_-^\mu + p_h^\mu p_+^\nu \right)}_{\mathcal{O}_W}$

WH production
$\Lambda = 1$ TeV



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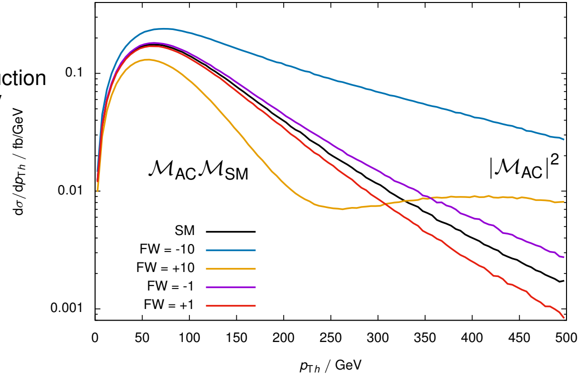

Validity of EFT approach

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EFT assumptions

- all NP scales well above observables, no resonances at measurable scales
- f/Λ^2 "small", depends on coupling: $\mathcal{O}(1)$ or $\mathcal{O}(\alpha_{\text{QED}})$

Power counting in Λ

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \underbrace{\mathcal{M}_{\text{AC}}^{d=6}}_{1/\Lambda^2} + \underbrace{\mathcal{M}_{\text{AC}}^{d=8}}_{1/\Lambda^4}$$

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\text{SM}}|^2}_{1/\Lambda^0} + \underbrace{2\text{Re}\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=6}}_{1/\Lambda^2} + \underbrace{\left|\mathcal{M}_{\text{AC}}^{d=6}\right|^2}_{1/\Lambda^4} + \underbrace{2\text{Re}\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=8}}_{1/\Lambda^4} + \underbrace{\left|\mathcal{M}_{\text{AC}}^{d=8}\right|^2}_{1/\Lambda^8}$$

- power-counting Λ^{-4}: $\left|\mathcal{M}_{\text{AC}}^{d=6}\right|^2$, $\mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}^{d=8}$?
- conservative: experimental fit only in range where $|\mathcal{M}_{\text{AC}}|^2 \ll \mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{SM}}$
- but: $\mathcal{M}_{\text{SM}}$ accidentally small (weak coupling compared to $\mathcal{M}_{\text{AC}}$, radiation zero)
  $\Rightarrow \mathcal{M}_{\text{SM}}^*\mathcal{M}_{\text{AC}}$ suppressed, $\left|\mathcal{M}_{\text{AC}}^{d=6}\right|^2$ leading $1/\Lambda^4$ term

Anomalous Quartic Gauge Couplings

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

[Feigl, Schlimpert; Löschner, Perez]

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 → modify quartic gauge couplings

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

→ UFO file by Eboli, Gonzalez-Garcia follows this convention → MadGraph

→ VBFNLO implementation follows dim-6 convention

⇒ 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

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

- 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`

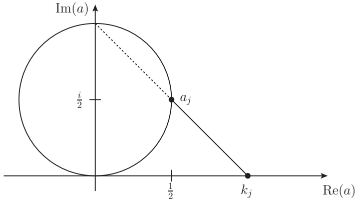
Example output

```
[...]
 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



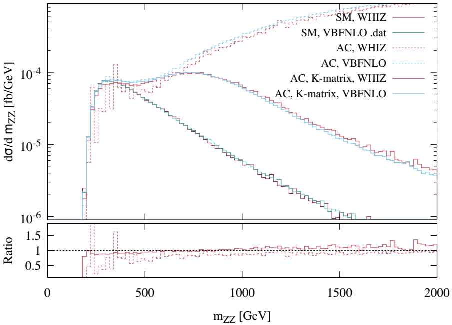
Project amplitude k_j,
which exceeds (tree-level) unitarity,
back onto Argand circle
$\rightarrow$ K matrix unitarization
$\rightarrow$ a_j

[$\rightarrow$ 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

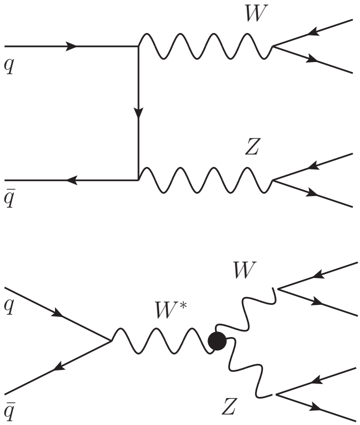
Diboson production at the LHC

Why Diboson

- leptonic decays: “easy” to tag, precise knowledge of final state
- access to triple gauge couplings, deviations in EW sector

Observables

- new resonances
- enhanced production at high energy $\Rightarrow$ AC
- $m_T, p_{\mathrm{T}\,V}, p_{\mathrm{T}\,l}$
- decay angles, spin information



LoopSim

Idea

- "Giant QCD K-factors beyond NLO"
  [Rubin, Salam, Sapeta, 1006.2144]
- merge different multiplicity final states
  X@NLO + Xj@NLO = X@$\bar{n}$NLO
- parton level ($\rightarrow$ fast)
- use NLO events, interface to existing Monte Carlos programs

Properties

- preserve NLO total cross section
- exact tree-level and one-loop
- only singular two-loop contributions
- include dominant contributions from extra emissions, $\mathcal{O}(\alpha_s \ln^2 p_{\mathrm{Tjet}}/m_Z)$
- nearly NNLO in high-p_T tails

l (loops)					
2	$\sigma_0^{(2)}$	$\sigma_1^{(2)}$	$\dots$		
1	$\sigma_0^{(1)}$	$\sigma_1^{(1)}$	$\sigma_2^{(1)}$	$\dots$	
0	$\sigma_0^{(0)}$	$\sigma_1^{(0)}$	$\sigma_2^{(0)}$	$\sigma_3^{(0)}$	$\dots$
	0	1	2	3	$\dots$

k (legs)

LoopSim

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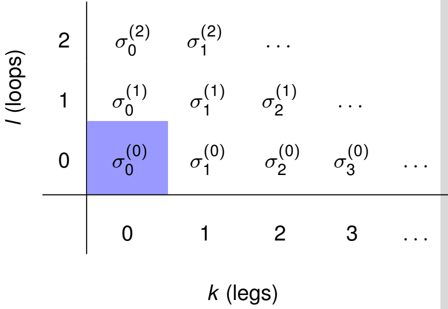

X@LO

LoopSim

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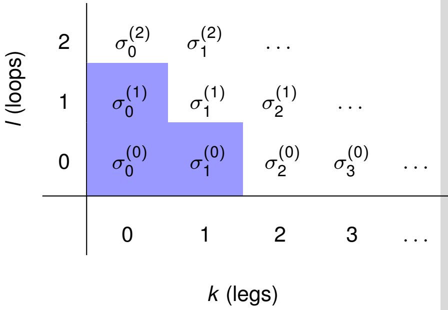

X@NLO

LoopSim

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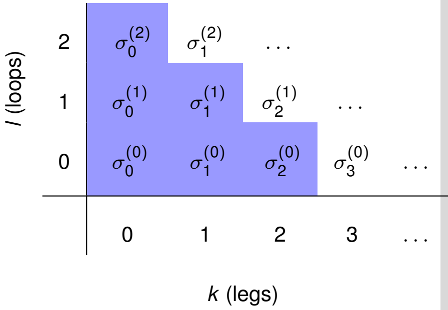

X@NNLO

LoopSim

Idea

- "Giant QCD K-factors beyond NLO"
  [Rubin, Salam, Sapeta, 1006.2144]
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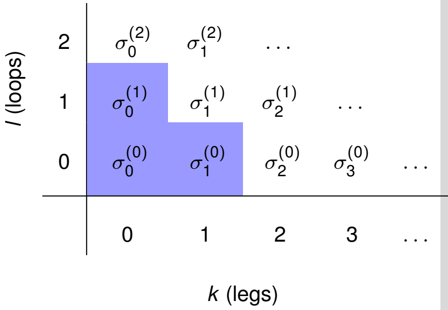

X@NLO

LoopSim

Idea

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  X@NLO + Xj@NLO = X@$\bar{n}$NLO
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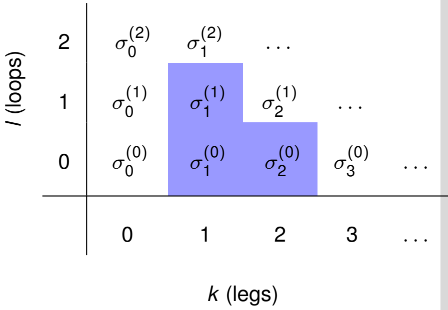

X+jet@NLO

LoopSim

Idea

- “Giant QCD K-factors beyond NLO”
  [Rubin, Salam, Sapeta, 1006.2144]
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  X@NLO + Xj@NLO = X@$\bar{n}$NLO
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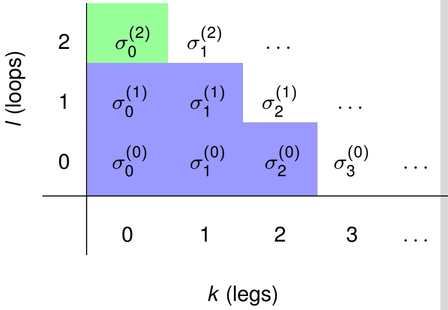
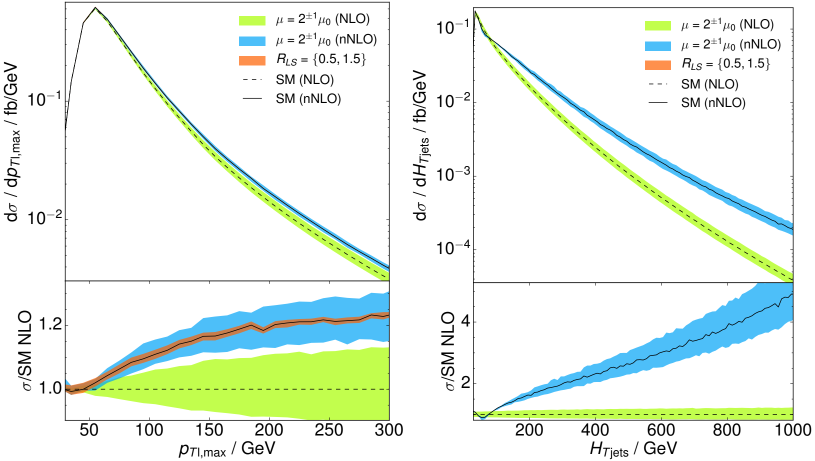


X@$\bar{n}$NLO

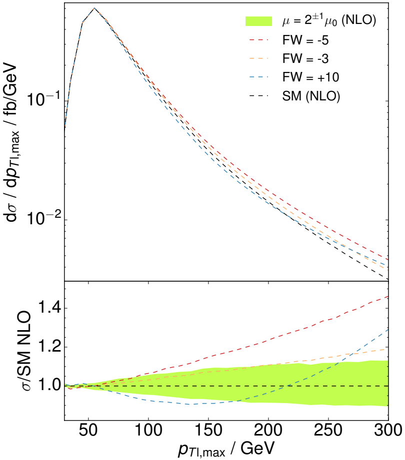
$\bar{n}$NLO for WZ production

Karlsruhe Institute of Technology

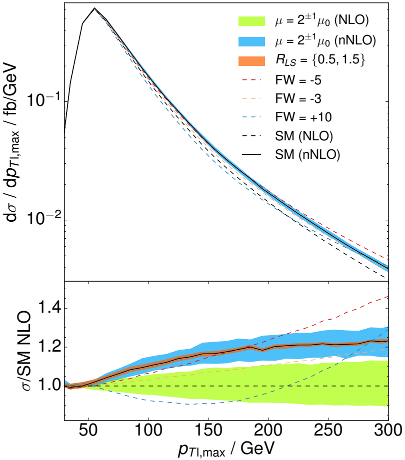
$e^+\nu_e\ \mu^+\mu^-$ + X, LHC@13 TeV, inclusive cuts



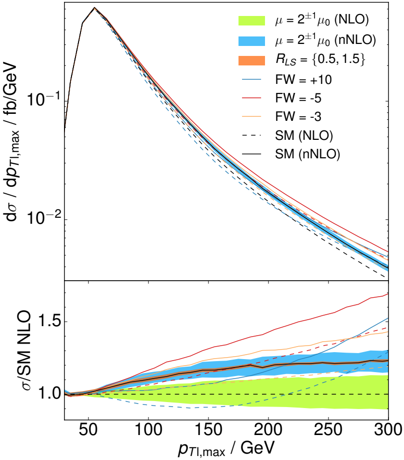
AC for diboson production



AC for diboson production

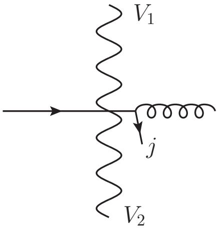


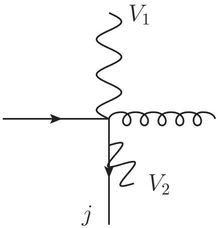
AC for diboson production



Jet vetos

want VV + jets, not Vj + V





Traditional (fixed) jet veto

- don't allow any jets above a fixed p_T threshold
- introduces large logs $\log p_{T\,\text{veto}}/m_{VV}$
- cuts away relevant phase space: $m_{VV} \approx 1$ TeV $\leftrightarrow$ $p_{T\,\text{jet}} = 50/300$ GeV

Dynamical veto

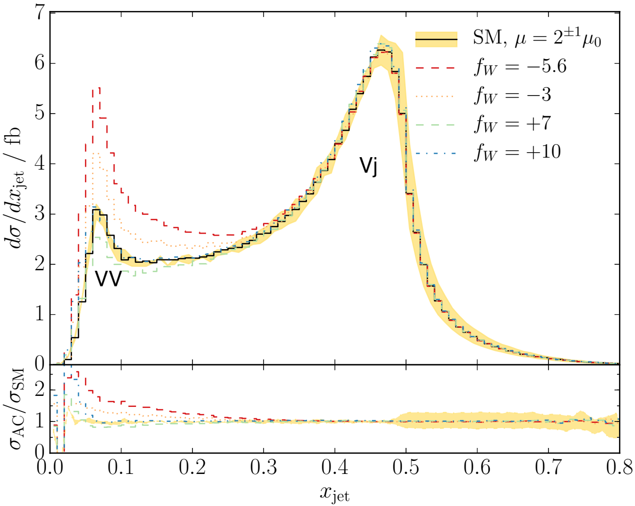
[Campanario, RR, Zeppenfeld, 1410.4840]

- veto scaled depending on overall scale $\Rightarrow$ smaller logs
- allow more QCD radiation in tails of EW distributions

$$x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}$$

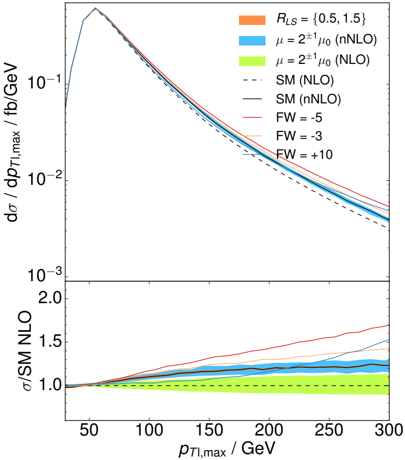
$$E_T = E\,\frac{|\vec{p}_T|}{|\vec{p}|}$$

Observable $x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}$



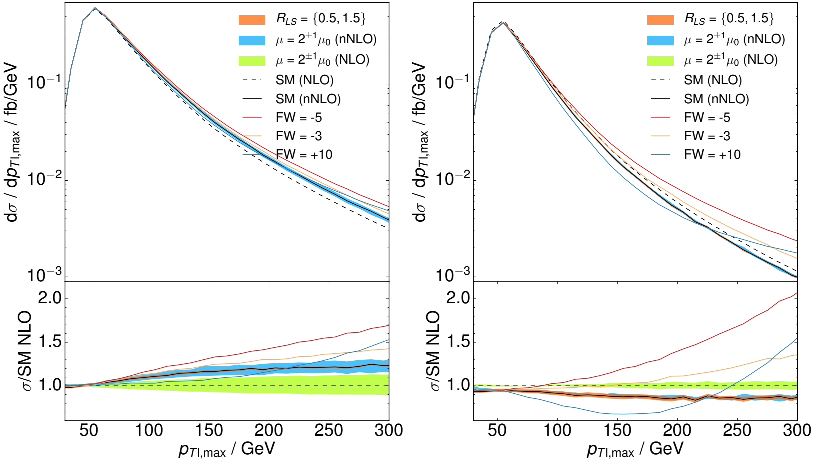
$p_{TZ} > 200$ GeV

Dynamical veto to improve AC sensitivity



inclusive

Dynamical veto to improve AC sensitivity



inclusive

$x_{\text{jet}} < 0.2$

Conclusions I

Beyond NLO: Loopsim

- method to combine multiplicities consistently at parton level
  X@NLO + Xj@NLO = X@$\bar{n}$NLO
- captures log enhanced terms of real emission
- nearly NNLO in high-p_T region

Anomalous couplings

- diboson production interesting channel to study triple gauge couplings
- validity depends on coupling and phase space region
- increase sensitive $\Rightarrow$ dynamical jet veto

$$x_{\text{jet}} = \frac{\sum_{\text{jets}} E_{T,i}}{\sum_{\text{jets}} E_{T,i} + E_{T,W} + E_{T,Z}}$$

Conclusions II

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

- 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
- study merged NLO samples with LoopSim

VBFNLO is collaborative effort: [0811.4559, 1107.4038, 1404.3940]

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, M. Rauch, R. Roth, H. Rzehak, F. Schissler, O. Schlimpert, M. Spannowsky, M. Worek, D. Zeppenfeld

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

Contact: `vbfnlo@itp.kit.edu`

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

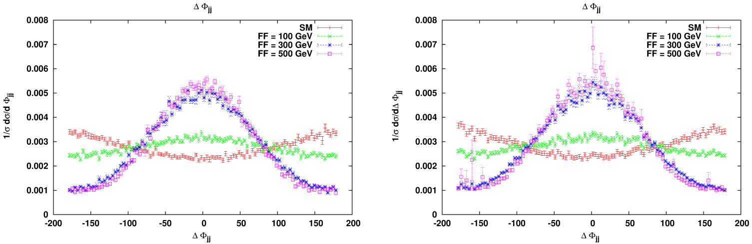
→ REPOLO (REweighting POwheg events at Leading Order)

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

Limitation:

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

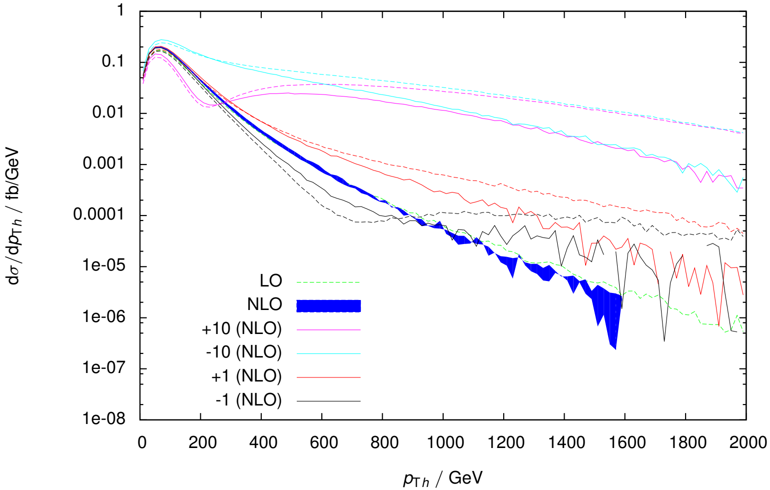
Example: VBF-$H \to \gamma\gamma$, SM → anomalous Higgs couplings ($+HW_+^{\mu\nu} W^-_{\mu\nu}$, $HZ^{\mu\nu} Z_{\mu\nu}$)
left: direct generation; right: reweighting



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

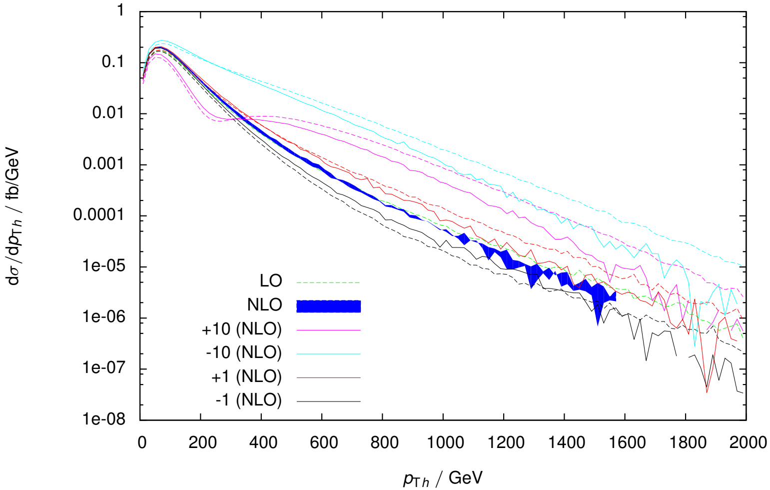
Anomalous Couplings – Formfactor effects

WHj with inclusive cuts and several values of f_W/Λ^2 in TeV^{-2} and no form factor



Anomalous Couplings – Formfactor effects

with form factor $\left(\frac{\Lambda^2}{\Lambda^2+m_{WH}^2}\right)^2$, $\Lambda = 2\,\text{TeV}$

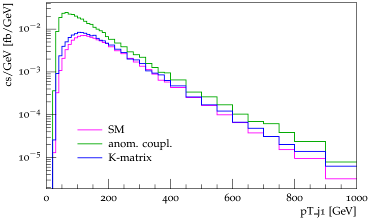


K-matrix + Parton Shower

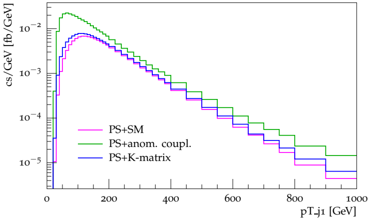
Combine K-matrix setup with parton shower [VBFNLO3&Herwig7]

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

Combination with Parton Shower

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

Example: VBF-W^+W^+ ($pp \to e^+\nu_e\,\mu^+\nu_\mu\,jj$)
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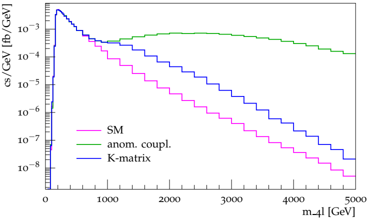

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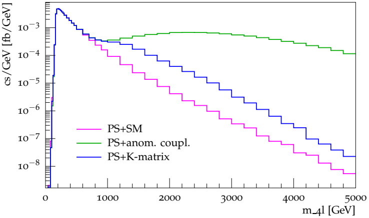

No significant shape changes in $m_{4\ell}$ when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

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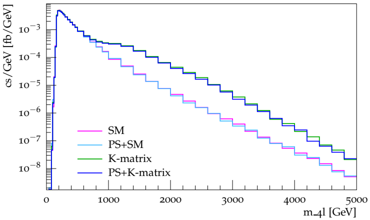
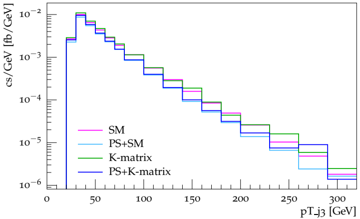
$m_{4\ell}$ – Comparison



$p^T_{j,3}$ – Comparison

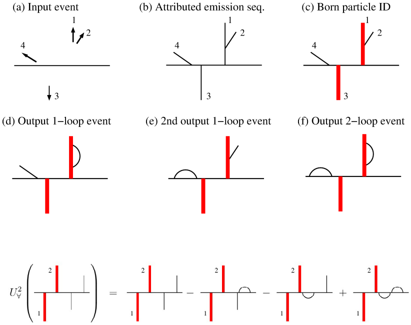


No significant shape changes in $m_{4\ell}$ when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

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

The Loopsim Method – “Looping”

- based on unitarity
- per-event: assign angular-ordered branching structure (C/A algorithm with radius R_{LS})
- hard structure of event determined $\rightarrow$ remaining particles: “Born”
- construct virtual “loop” events: recombine non-“Born” particles $\Rightarrow$ subtraction events
- Clustering radius R_{LS} gives estimate of dependence on merging
- Scale dependence preserved for additional emissions, overestimates the NNLO scale dependence



LoopSim with VBFNLO

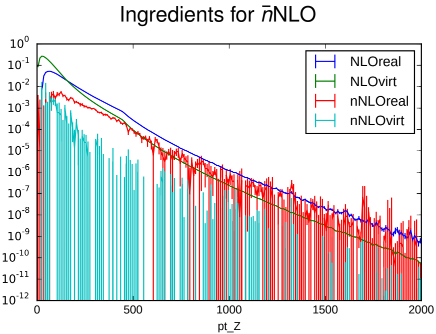
Interfacing with LoopSim

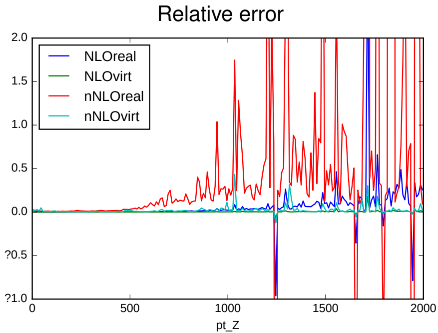
- VBFNLO produces event sample
- LoopSim generates looped events from sample
- run analysis on those final events

Issues

- no flavour information from VBFNLO (summed over)
- need very inclusive sample (no jet cut) to fill all of phase space
- Consistent scale choice over all samples needed

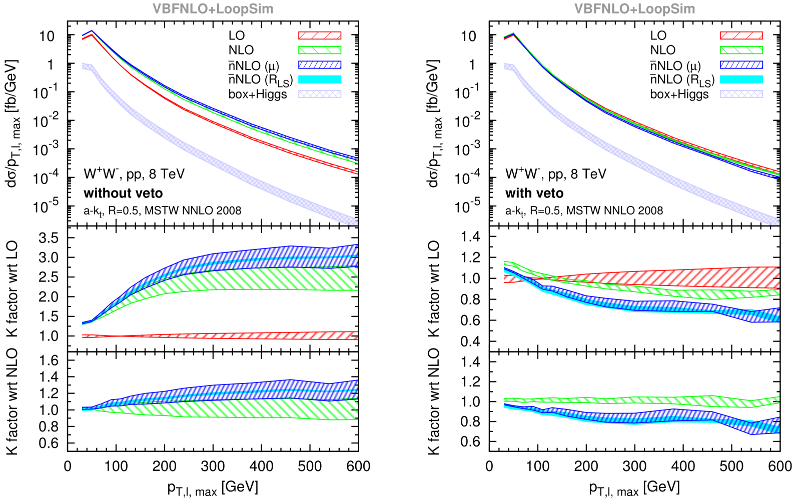
practical LoopSim





- LoopSim slower than bare `VBFNLO` run by a factor 8
- interest not in phase space region with highest cross section but tails

Previous LoopSim results

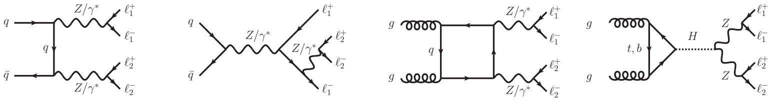


[Campanario, Rauch, Sapeta, 1309.7293]

ZZ production

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

[Campanario, Rauch, 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]	$8.118(5)\ ^{+4.7\%}_{-2.6\%}\ (\mu)\quad ^{+0.8\%}_{-0.6\%}\ (R_{LS})$	

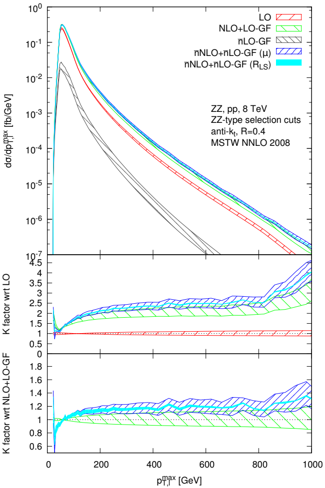
good agreement between $\bar{n}$NLO and NNLO $\to$ 2% difference only

uncertainty due to LoopSim parameter R_{LS} small

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

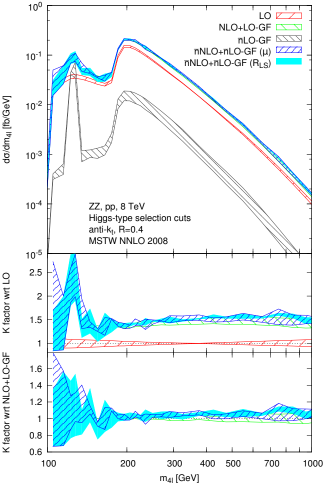
ZZ production

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



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

$m_{4\ell}$, Higgs cuts



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

Event Selection for WZ AC at $\bar{n}$NLO

Karlsruhe Institute of Technology

Cuts

$$p_{\mathrm{T}\,j} > 30\,\mathrm{GeV} \qquad p_{\mathrm{T}\,l} > 15\,\mathrm{GeV} \qquad \not{p}_{\mathrm{T}} > 30\,\mathrm{GeV}$$

$$|\eta_j| < 4.5 \qquad |\eta_l| < 2.5 \qquad R_{l,j} > 0.4$$

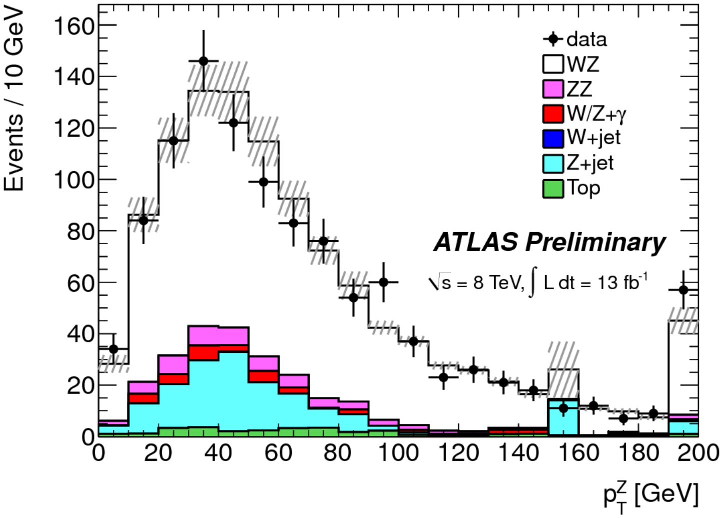
$$60\,\mathrm{GeV} < m_{ll} < 120\,\mathrm{GeV}$$

boosted: $p_{\mathrm{T}\,Z} > 200\,\mathrm{GeV}$

Input values

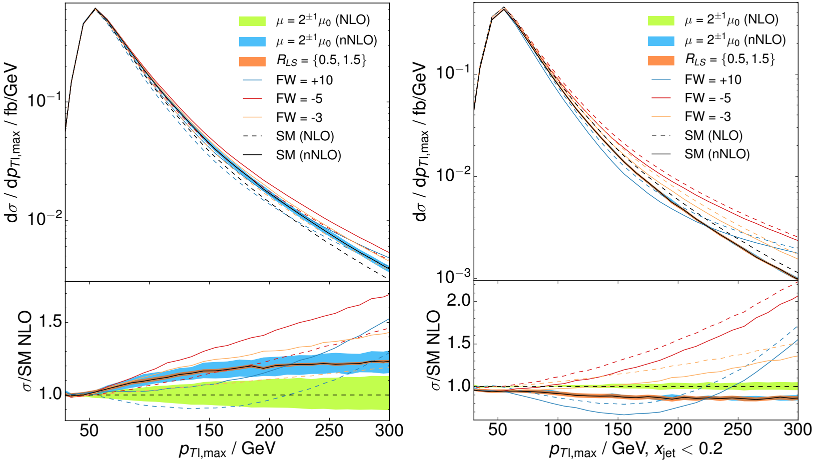
- EW constants: VBFNLO default
- PDF: NNPDF23

ATLAS WZ p_{TZ}

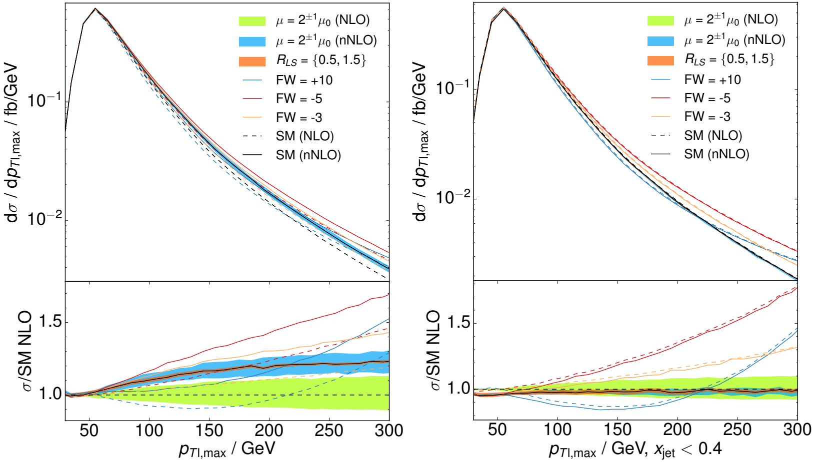


Events / 10 GeV
0
20
40
60
80
100
120
140
160
0
20
40
60
80
100
120
140
160
180
200
p_T^Z [GeV]
data
WZ
ZZ
W/Z+γ
W+jet
Z+jet
Top
ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ L dt = 13 fb^{-1}

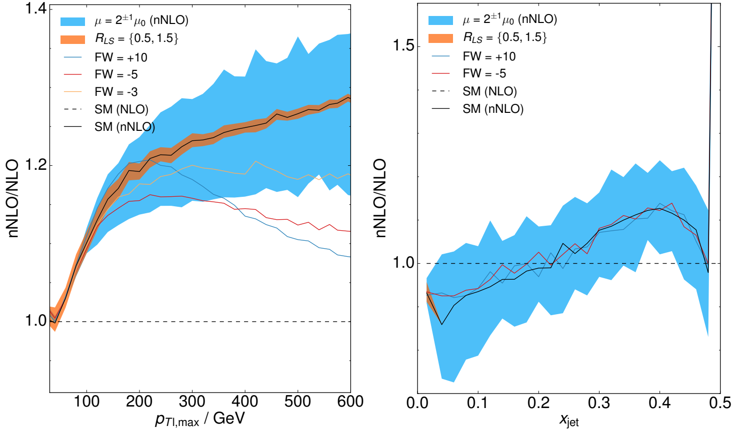
Different x_{jet} cuts



Different x_{jet} cuts



x_{jet} $\bar{n}$NLO corrections



Observable: x_{jet}, x_Z

Motivation

- 3 particle final state (WZj)
- the transverse momenta can be parametrized using only two variables
  6 d.o.f. ($p_{\mathrm{TW}}, p_{\mathrm{TZ}}, p_{\mathrm{Tjet}}$)- 2 (total $p_{\mathrm{T}} = 0$) - 1 (no ϕ dependence) - 1 (rescaling at high p_{T})
- dalitz-like construction

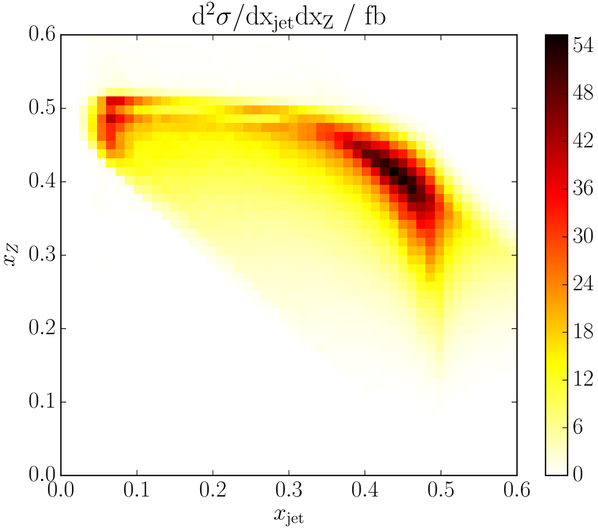
$$x_{\mathrm{jet}} = \frac{\sum_{\mathrm{jets}} \mathrm{E}_{\mathrm{T},i}}{\sum_{\mathrm{jets}} \mathrm{E}_{\mathrm{T},i} + \mathrm{E}_{\mathrm{T},W} + \mathrm{E}_{\mathrm{T},Z}}, \quad x_V = \frac{E_{TV}}{\sum_{\mathrm{jets}} \mathrm{E}_{\mathrm{T},i} + \mathrm{E}_{\mathrm{T},W} + \mathrm{E}_{\mathrm{T},Z}}$$

$$x_{\mathrm{jet}} + x_{\mathrm{W}} + x_{\mathrm{Z}} = 1$$

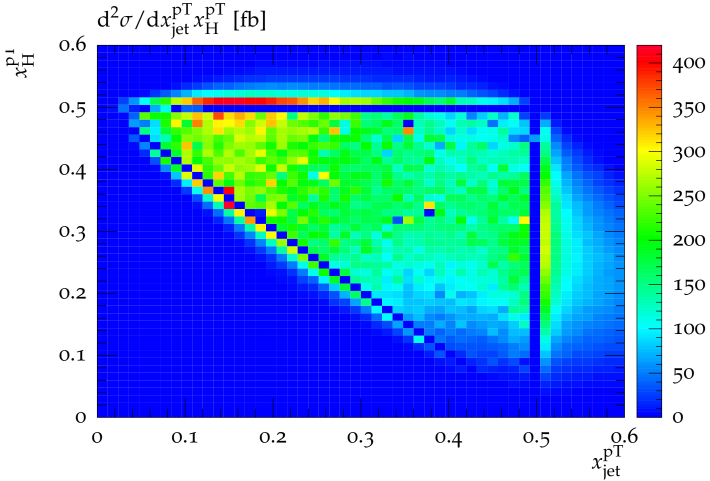
$$x_i \leq 0.5 \quad \text{(at LO only)}$$

other choices: p_{T} instead of E_{T}, partons instead of jets, ...
Careful not to be (too) infrared-sensitive

Observable: x_{jet}, x_Z



PS effects on x_{jet}



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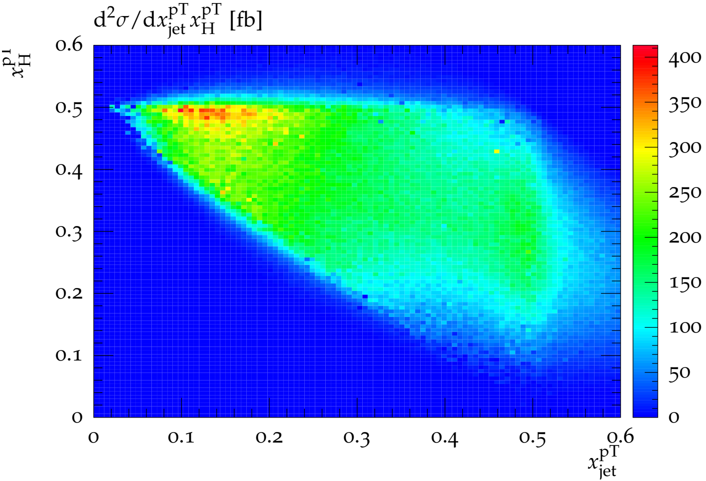
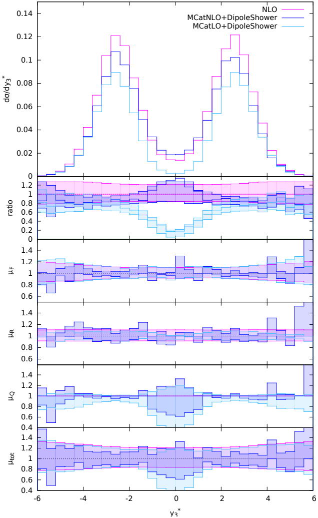


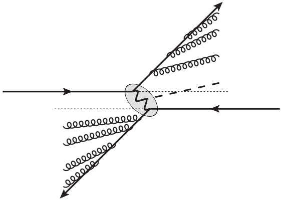
VBF-W^+W^- + parton shower

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



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

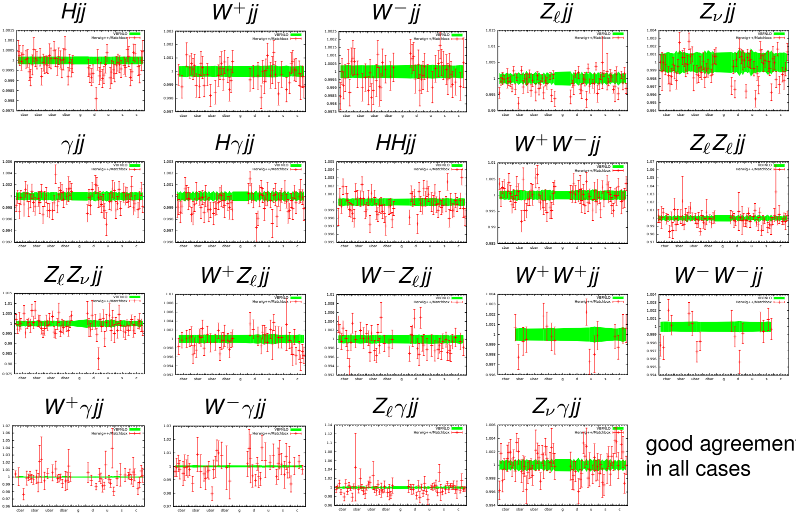
- almost no radiation generated in central region by LO+PS
- additional radiation by shower created mainly between jets and beam axis (color connections)
- → central region corrected at NLO by $W^+W^- jjj$ ME
- dipole shower "interpolates" between NLO behavior in central region and shower behavior at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



Cross checks

Compare standalone VBFNLO and Herwig7/Matchbox+VBFNLO

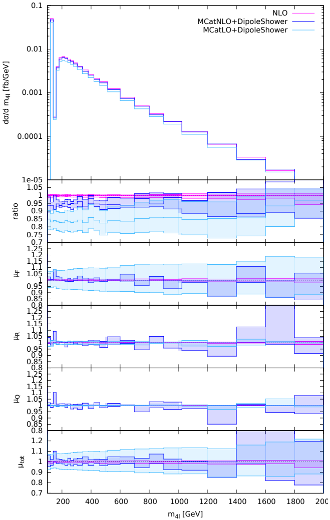
VBF/VBS processes split by initial state flavours:



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:

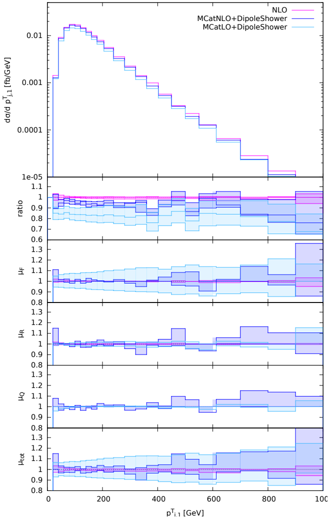
- differential c.s.
- ratio of c.s. and total scale variation
- individual variation of μ_F, μ_R, μ_Q (shower scale)
- total variation $\mu_i/\mu_0 \in [\frac{1}{2}; 2]$ with $\mu_i/\mu_j \in [\frac{1}{2}; 2]$

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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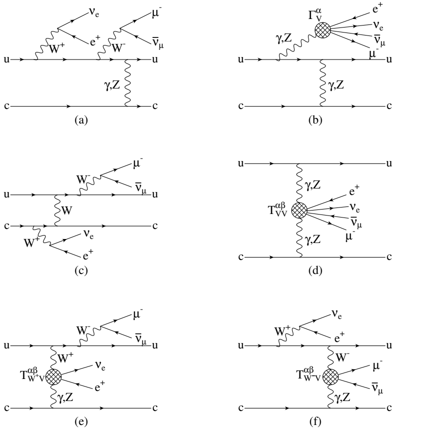
Diboson-VBF production

[Bozzi, Jäger, Oleari, Zeppenfeld (VV); Campanario, Kaiser, Zeppenfeld ($W^\pm \gamma$)]
[Denner, Hosekova, Kallweit (W^+W^+)]

- Important process for LHC run-II
- Part of the NLO wish list
  [Les Houches 2005]
- background to Higgs searches
- access to anomalous triple and quartic gauge couplings
- NLO QCD implementation of
  - all boson combinations
  - leptonic and semi-leptonic decays
  - including off-shell and non-resonant contributions
  - VBF approximation

$\rightarrow$ VBFNLO [Rauch, Zeppenfeld et al.]



NLO plus Parton Shower

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

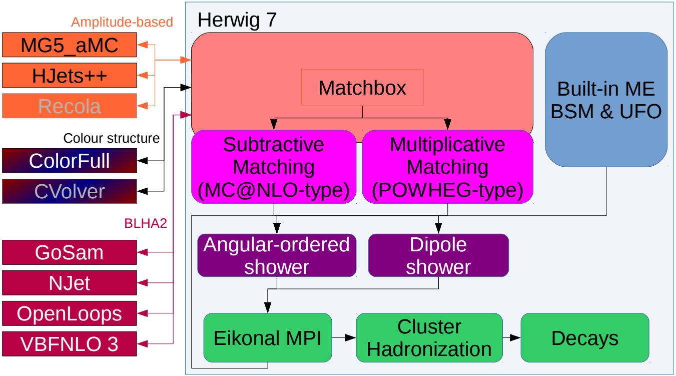
State of the Art

Implementations for specific VBF processses

- POWHEG-BOX [Alioli, Hamilton, Nason, Oleari, Re]
  currently available VBF implementations:
  - Z [Jäger, Schneider, Zanderighi]
  - $W^\pm, Z$ [Schissler, Zeppenfeld]
  - $W^\pm W^\pm$, $W^\pm W^\mp$ [Jäger, Zanderighi]
  - ZZ [Jäger, Karlberg, Zanderighi]
- VBF-H with POWHEG method [D'Errico, Richardson]
- HJets++ [Campanario, Figy, Plätzer, Sjödahl]

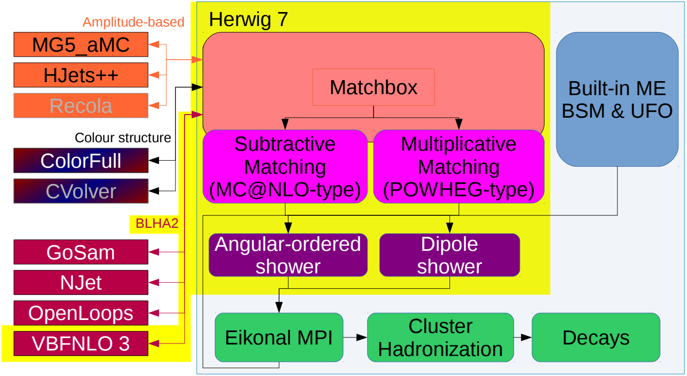
Herwig 7

- fully automated matching of NLO to parton showers through Matchbox module
  [work led by S. Plätzer with substantial contributions by J. Bellm, A. Wilcock, M. Rauch, C. Reuschle]
- subtractive (MC@NLO-type, $\oplus$) and multiplicative (POWHEG-type, $\otimes$) matching
- angular-ordered (QTilde, PS) and dipole (Dipoles) shower
- matrix elements through binary interface, no event files

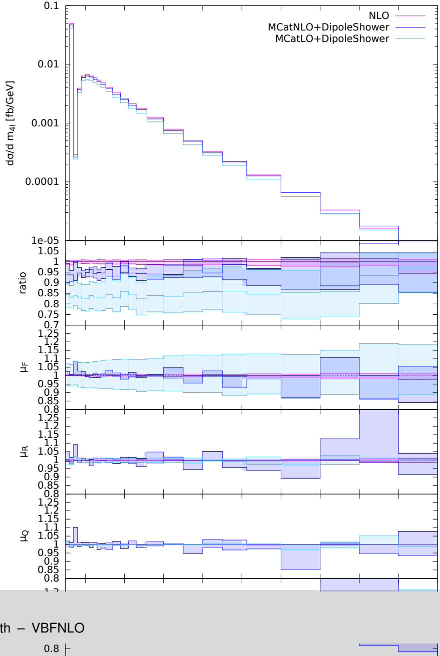


VBFNLO 3 & Herwig 7

- matrix elements from VBFNLO via BLHA2 interface [Binoth et al., Alioli et al.]
- extensions to make accessible
  - phase-space sampling
  - (electroweak) random helicity summation
  - anomalous couplings

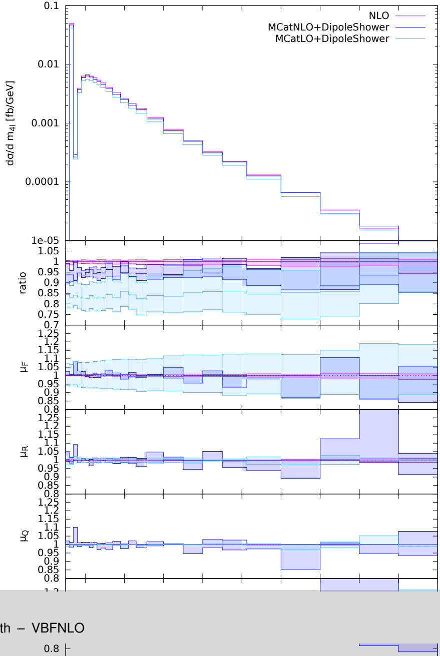


Four-lepton Invariant Mass



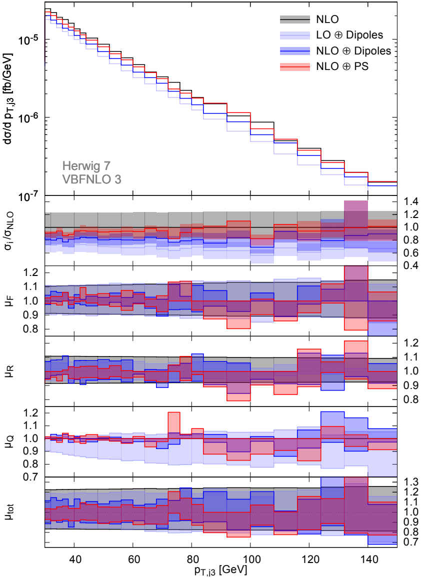
- ← central scale $\mu_0 = p_{T,j1}$ transverse momentum of leading jet
- ← band: scale variation $\{\mu_F, \mu_R, \mu_Q\} / \mu_0 \in [\frac{1}{2}; 2]$ $\mu_i/\mu_j \in [\frac{1}{2}; 2]$
- ← factorization scale $\mu_F \in [\frac{1}{2}; 2]$
- ← renormalization scale $\mu_R \in [\frac{1}{2}; 2]$
- ← shower scale $\mu_Q \in [\frac{1}{2}; 2]$
- ← all three scales

Four-lepton Invariant Mass



- consistent variation of scales between hard process and parton shower
- large factorization scale dependence for LO result
- larger dependence for down variation of renormalization scale in angular-ordered shower:
  larger $\alpha_s \to$ more splittings
  $\to$ bigger migration effects
- small variations from shower-scale changes
- modest remaining overall uncertainty

Transverse Momentum Third Jet

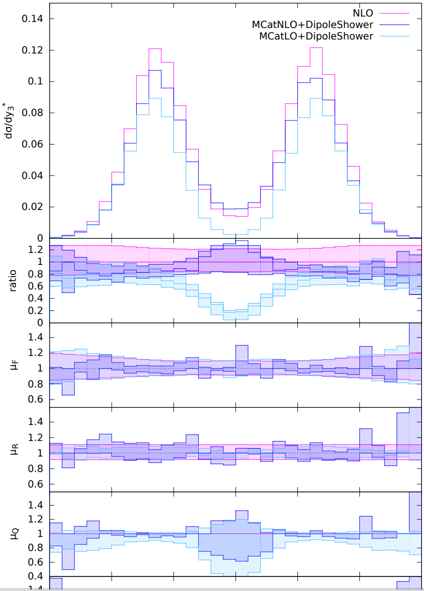


- large scale variation bands for
  - shower scale in LO⊕Dipoles

    → pure parton-shower effect
  - fact./ren. scale in "NLO"

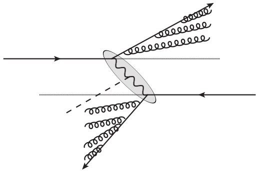
    → LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10-20\%)$
- → call for multi-jet merging

Rapidity of third jet



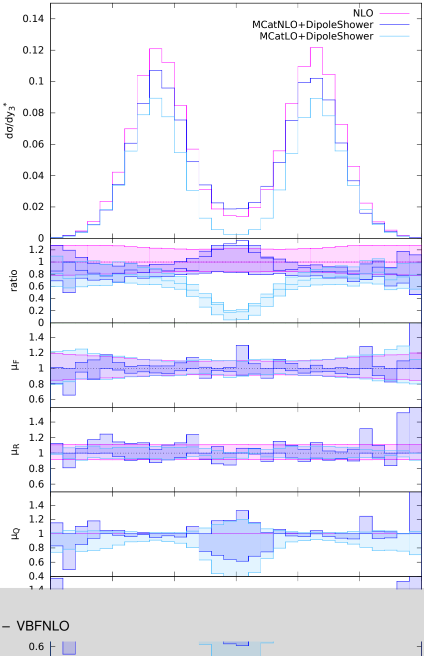
Rapidity of third jet
relative to two tagging jets

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



- VBF colour structure suppresses additional central jet radiation
- colour connection between tagging jet and remnant
- $\leftrightarrow$ distinction from QCD-induced production

Rapidity of third jet



Rapidity of third jet relative to two tagging jets

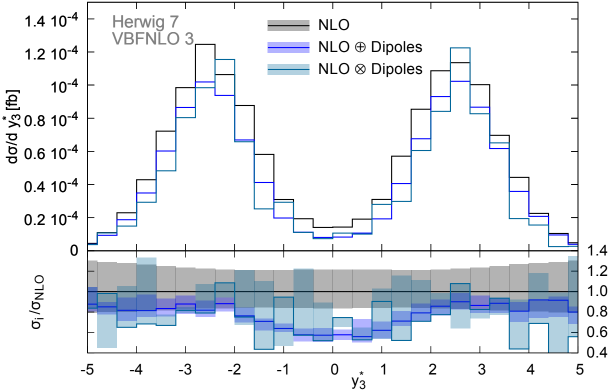
$$y_3^* = y_3 - \frac{y_1+y_2}{2}$$

- impact of parton showers (+LO) long unclear
- Herwig predicts very low radiation in central region
- large shower-scale unc.

- stabilised when combining with NLO
- still reduction present
- scale variation bands not overlapping

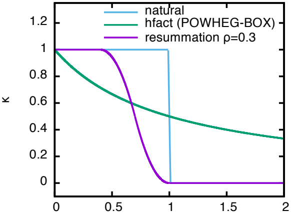
- only small effects in forward region (mostly global normalization)

Rapidity of third jet – POWHEG

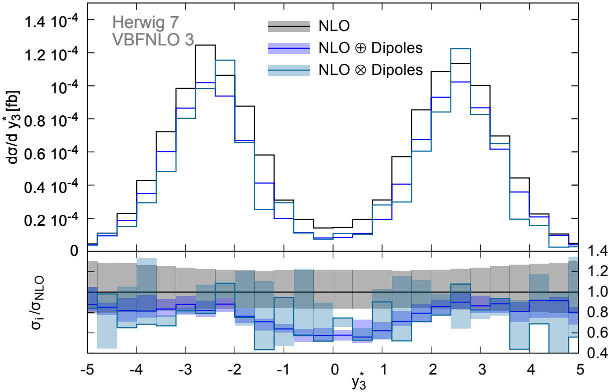


- POWHEG-like (⊗) using resummation scheme [Plätzer]:

$$\kappa(Q,q;\rho) = \begin{cases} 1 & \text{for } q < (1-2\rho)Q \\ 1 - \frac{(1-2\rho-\frac{q}{Q})^2}{2\rho^2} & \text{for } (1-2\rho)Q < q < (1-\rho)Q \\ \frac{(1-\frac{q}{Q})^2}{2\rho^2} & \text{for } (1-\rho)Q < q < Q \\ 0 & \text{for } q > Q \end{cases}$$



Rapidity of third jet – POWHEG



- band: joint variation $\mu_F = \mu_R = \mu_Q \in [\frac{1}{2}, 2]\ \mu_0$
- similar predictions from MC@NLO-like ($\oplus$) and POWHEG-like ($\otimes$) matching
- also holds for other distributions

Conclusions

Karlsruhe Institute of Technology

Parton-shower and scale variation effects in

W^+W^-jj production via vector-boson-fusion

- important process for the LHC
  - Higgs properties – unitarity in WW scattering
  - testing anomalous (triple and) quartic gauge couplings
- study performed with Herwig 7 & VBFNLO 3
- compatible behavior of both parton showers and matching schemes
- small parton-shower effects for distributions of variables already present at LO

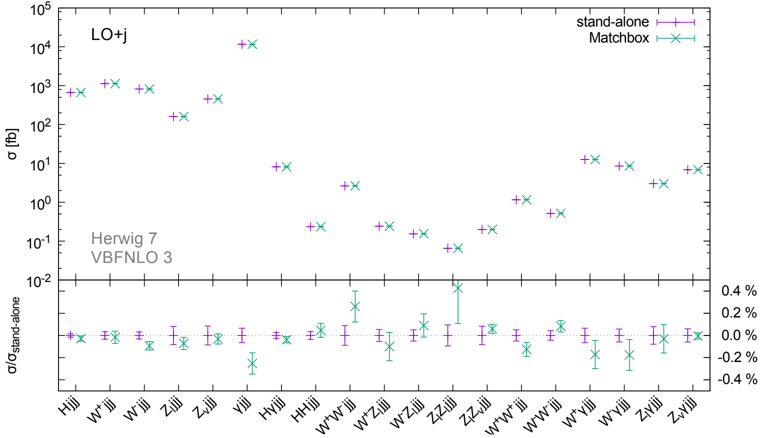
  mostly reduction of inclusive cross section due to additional jet radiation
- presence of central rapidity gap stabilised
- $\rightarrow$ multi-jet merging to further reduce uncertainties

Validation

Karlsruhe Institute of Technology

Compare LO+j results between VBFNLO stand-alone run and interfaced to Herwig 7 via Matchbox

(inclusive cuts, with leptonic gauge boson decays into single different-flavour combination, Higgs non-decaying)



→ good agreement

Setup

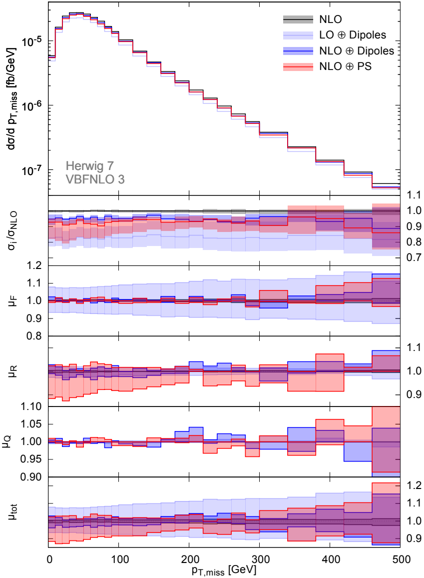
Generation-level cuts:

$$p_{T,j} > 20 \text{ GeV}\,, \qquad |y_j| < 5.0\,,$$
$$\text{anti-}k_T \text{ jets with } R = 0.4\,, \qquad b\text{-quark veto}$$
$$p_{T,\ell} > 15 \text{ GeV}\,, \qquad |y_\ell| < 3.0\,,$$
$$m_{e^+,\mu^-} > 15 \text{ GeV}\,,$$
$$m_{j1,j2} > 400 \text{ GeV}\,, \qquad |y_{j1} - y_{j2}| > 3.0$$

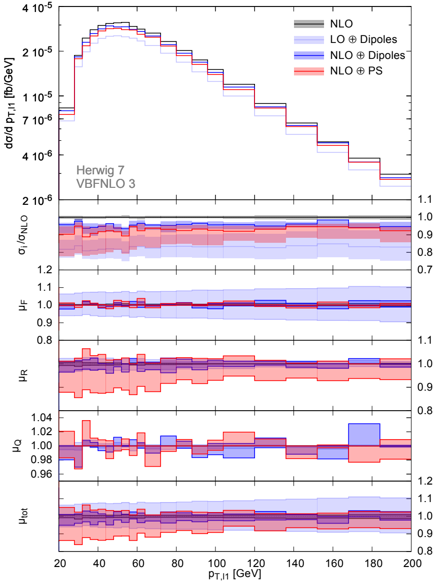
Analysis-level cuts:

$$p_{T,j} > 30 \text{ GeV}\,, \qquad |y_j| < 4.5\,,$$
$$\text{anti-}k_T \text{ jets with } R = 0.4\,, \qquad b\text{-quark veto}$$
$$p_{T,\ell} > 20 \text{ GeV}\,, \qquad |y_\ell| < 2.5\,,$$
$$m_{e^+,\mu^-} > 15 \text{ GeV}\,,$$
$$m_{j1,j2} > 600 \text{ GeV}\,, \qquad |y_{j1} - y_{j2}| > 3.6$$

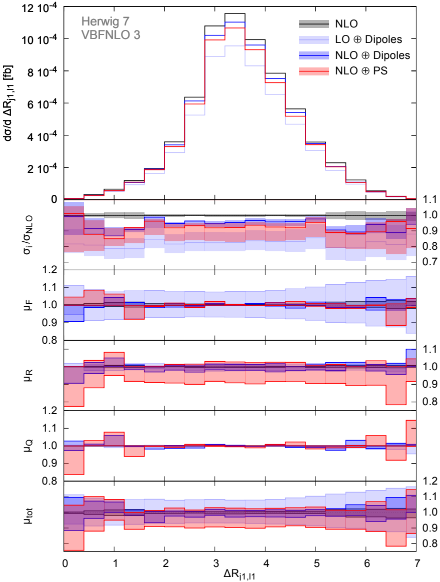
Missing Transverse Momentum



Transverse Momentum of Leading Lepton



R Separation of Leading Jet and Leading Lepton



$$\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$$

Jacobian peak at $\Delta R_{j1\ell1} = \pi$