Vector-Boson Fusion and Scattering

Michael Rauch | 12 Dec 2017

Institute for Theoretical Physics

Theory Motivation

Standard Model:
gauge theory $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$\mathcal{L}_{\text{SM}} \supset -\frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu}$$

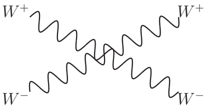
with

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - ig\epsilon^{abc} W^b_\mu W^c_\nu$$

$\Rightarrow$ vertices with 3 and 4 gauge bosons

e.g. $W^+ W^- \rightarrow W^+ W^-$

- build W^+ - W^- – collider



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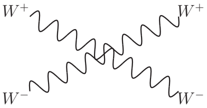

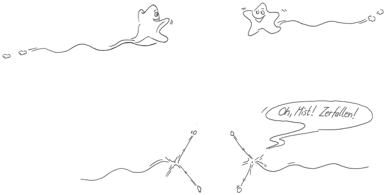

life time W: $\frac{\hbar}{2 \cdot 2.5\text{ GeV}} \simeq 10^{-25}$ s
$\rightarrow$ not practicable

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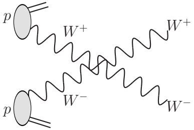
- produce W as parton of the proton [Cahn, Dawson; ...]



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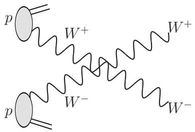

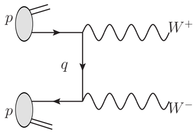

$\leftrightarrow$ large background of other processes with same final state
$\leftrightarrow$ not a good approximation

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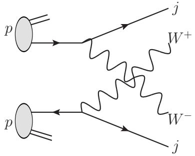
$\Rightarrow$ vertices with 3 and 4 gauge bosons

e.g. $W^+W^- \rightarrow W^+W^-$

- produce WW from proton-proton scattering

[Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; . . .]

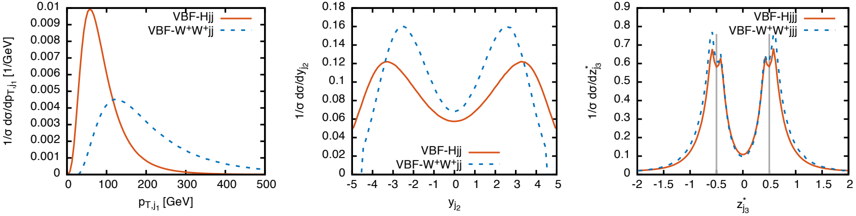


Event Topology

topology of VBF (vector-boson fusion)/VBS (vector-boson scattering) shows distinct signature

- two so-called tagging jets in forward direction
- reduced jet activity in central direction
- leptonic decay products typically between the tagging jets

→ two-sided deep-inelastic scattering



$$z^*_{j3} = \left(y_{j3} - \frac{y_{j1} + y_{j2}}{2} \right) / \left| y_{j1} - y_{j2} \right|$$

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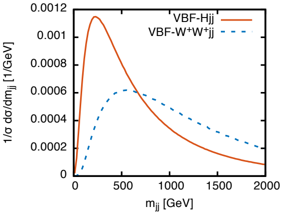
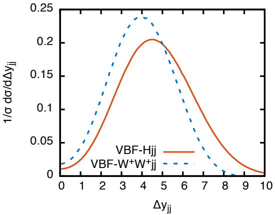
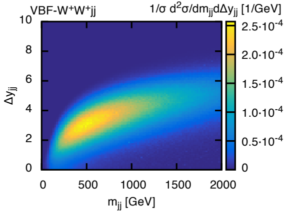
$\rightarrow$ two-sided deep-inelastic scattering







Diboson-VBF production

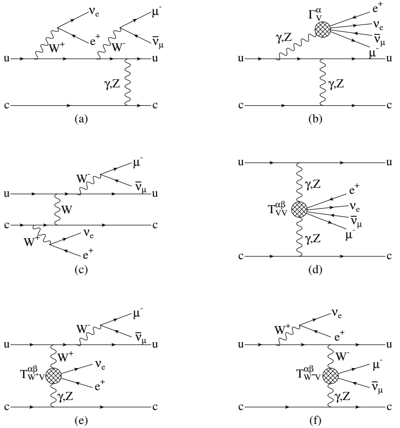
Karlsruhe Institute of Technology

[Bozzi, Jäger, Oleari, Zeppenfeld (VV); Campanario, Kaiser, Kerner, Zeppenfeld (Vγ)]
[Denner, Hosekova, Kallweit (W^+W^+)]

- Important process for LHC run-II and beyond
- Part of the NLO wish list [Les Houches 2005]
- background to Higgs searches
- access to anomalous triple and quartic gauge couplings

Available tools:

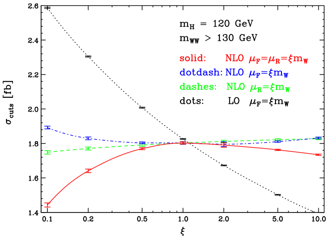
- VBFNLO [Zeppenfeld, MR et al.]
  NLO QCD, VBF approximation
- Phantom [Ballestrero et al.]
  LO, $pp \to 6f$
- automated tools, e.g.
  GoSam [Cullen et al.]
  MadGraph5_aMC@NLO [Artoisenet et al.]



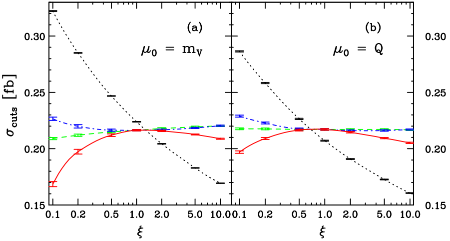
Scale dependence

Dependence on factorization and renormalization scale [Bozzi, Jäger, Oleari, Zeppenfeld]

$pp \to W^+W^-jj$



$pp \to W^+Zjj$



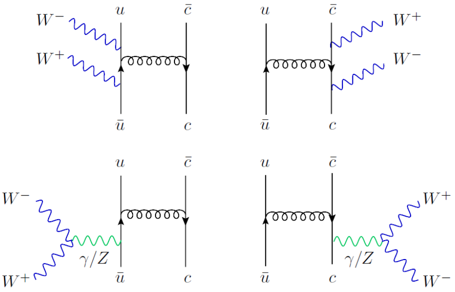
- sizable scale dependence at LO: $\sim \pm$ 10%
- strongly reduced at NLO: $\sim \pm$ 2% (up to 6% in distributions)
- K-factor around 0.98 for $\mu = m_V$, 1.04 for $\mu = Q$ (momentum transfer)

QCD-Diboson production

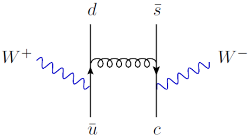
Most important background: QCD-Diboson Production
All combinations available at NLO QCD:

[Melia, Melnikov, Röntsch, Zanderighi; Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]
[Campanario, Kerner, Ninh, Zeppenfeld; Gehrmann, Greiner, Heinrich]

W^+W^-jj



W^+W^-jj & W^+W^+jj
(latter after changing quark flavors appropriately)



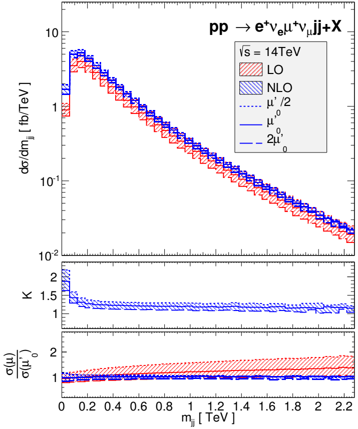
+ diagrams where quark line without attached vector bosons is replaced by gluons

QCD-Diboson production

$pp \to e^+ \nu_e \mu^+ \nu_\mu$

[Campanario, Kerner, Ninh, Zeppenfeld]

Impact of NLO QCD corrections



- K factors typically between 1 and 1.5
- corrections $< 20\%$ for invariant mass of two leading jets > 200 GeV
- huge correction for small m_{jj} due to new phase-space region (almost collinear quark-gluon splitting)
- good scale choice (interpolates between different regions):

$$\mu'_0 = \frac{1}{2}\Big(\sum_{\text{jets}} p_{T,i} \exp |y_i - y_{12}| + \sum_{W} \sqrt{p_{T,i}^2 + m_{W,i}^2} \Big)$$

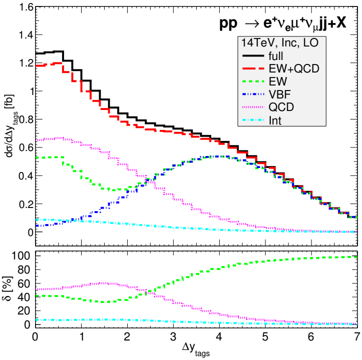
$$(y_{12} = (y_1 + y_2)/2)$$

QCD-EW interference

$pp \to e^+\nu_e\mu^+\nu_\mu$

[Campanario, Kerner, Ninh, Zeppenfeld]

Comparing contributions at LO



EW: full $\mathcal{O}(\alpha^6)$ calculation
VBF: VBF approximation
(only t-/u-channel diagrams)

- QCD and EW contributions of similar size
  (destructive interference for QCD, no gluon-initiated contributions)
- QCD-EW interference largest for large $p_{T,j}$, small Δy_{tags}
  up to 20% reducing to 10% (3%) for loose (tight) VBF cuts
- VBF contribution by far dominant in VBF region (96%)
  $\to$ good approximation

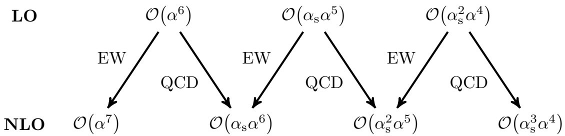
Definition of VBF region:

- $m_{jj} > 500$ GeV
- $\Delta y_{\text{tags}} > 4$
- $y_{j_1} \times y_{j_2} < 0$

NLO Electroweak Corrections

Including EW corrections mixes orders

[Biedermann, Denner, Pellen]



LO fiducial cross sections

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	Sum
σ_{LO} [fb]	1.4178(2)	0.004815(2)	0.17229(2)	1.6383(2)

NLO fiducial cross sections

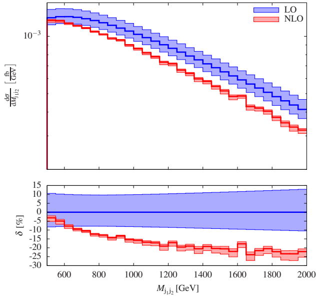
Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{NLO}$ [fb]	-0.2169(3)	-0.0568(5)	-0.00032(3)	-0.0063(4)	-0.2804(7)
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

- large EW corrections at $\mathcal{O}(\alpha^7)$
- negative corrections at $\mathcal{O}(\alpha_s\alpha^6)$ mostly also present in VBF approximation (remaining difference: 0.6%)
- photon PDF contribution (not included above) small (+1.5% – +2.7%)

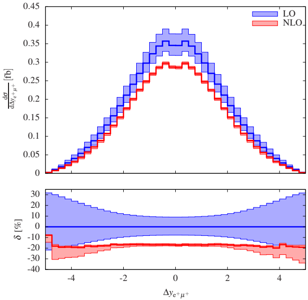
NLO EW Differential Distributions

[Biedermann, Denner, Pellen]

invariant mass of the two tagging jets



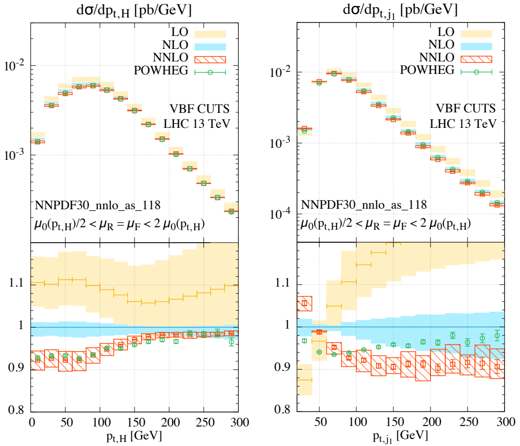
rapidity difference of the two leptons



- large Sudakov logarithms from bosonic part
- larger effects than e.g. in diboson production
  $\rightarrow$ Casimir C^{ew} larger for bosons than for fermions $\rightarrow$ $\langle m_{4\ell} \rangle$ larger for VBS
- $\rightarrow$ intrinsic feature

NNLO QCD corrections to VBF-Higgs

VBF-Higgs production in NNLO QCD [Cacciari, Dreyer, Karlberg, Salam, Zanderighi]



	$\sigma^{\text{(no cuts)}}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$4.032\,^{+0.057}_{-0.069}$	1.026
NLO	$3.929\,^{+0.024}_{-0.023}$	1
NNLO	$3.888\,^{+0.016}_{-0.012}$	0.990

	$\sigma^{\text{(VBF cuts)}}$ [pb]	$\sigma/\sigma^{\text{NLO}}$
LO	$0.957\,^{+0.066}_{-0.059}$	1.092
NLO	$0.876\,^{+0.008}_{-0.018}$	1
NNLO	$0.826\,^{+0.013}_{-0.014}$	0.943

central scale:

$$\mu_0^2(p_{T,H}) = \frac{M_H}{2}\sqrt{\left(\frac{M_H}{2}\right)^2 + p_{T,H}^2}$$

jets: anti-k_T, $R = 0.4$,
$p_{T,j} > 25$ GeV, $|y_j| < 4.5$

VBF cuts: $m_{jj} > 600$ GeV,
$\Delta y_{jj} > 4.5$, $y_{j1} \cdot y_{j2} < 0$

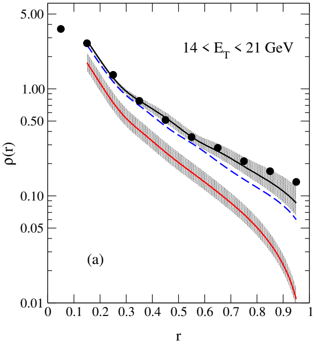
- tiny corrections to inclusive cross section
- significant ($\mathcal{O}(-10\%)$) corrections in VBF region

Jet-Clustering Dependence

- in NNLO calculation fixed choice of jet-clustering parameters (R, n)
- $\leftrightarrow$ no dependence at LO
  $\Rightarrow$ can use VBF-H+3jets NLO QCD calculation, [MR, Zeppenfeld]
  to convert between different values

$$\mathrm{d}\sigma^{\mathrm{NNLO}}_{Hjj}(R,n) = \mathrm{d}\sigma^{\mathrm{NNLO}}_{Hjj}(R{=}0.4, n{=}-1) \underbrace{-\mathrm{d}\sigma^{\mathrm{NLO}}_{H3+}(R{=}0.4, n{=}-1) + \mathrm{d}\sigma^{\mathrm{NLO}}_{H3+}(R,n)}_{=\Delta(R,n)}$$

- energy flow in DIS jets at HERA [Kauer, Reina, Repond, Zeppenfeld]

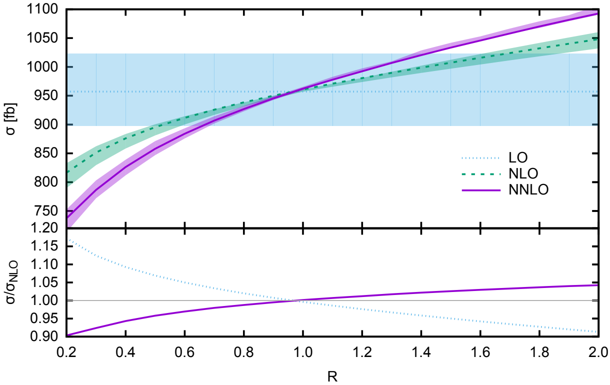


- differential E_T-distribution inside jet cone
  (ZEUS: black dots)
- Energy flow significantly smaller for NLO (max. 2 partons, red) than for NNLO (up to 3 partons, blue)

Integrated Cross Section

VBF-Hjj, $\sqrt{S} = 13$ TeV, $m_{jj} > 600$ GeV, $\Delta y_{jj} > 4.5$

[MR, Zeppenfeld]

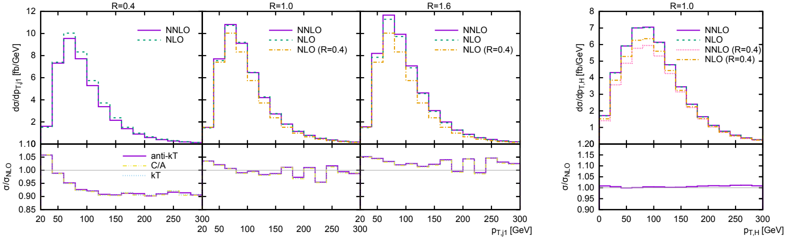


- band: uncertainty from scale variation
- small cone misses part of the jet energy
  $\Rightarrow$ smaller m_{jj}
  $\Rightarrow$ less events with $m_{jj} > 600$ GeV

Differential Cross Sections

VBF-Hjj, $\sqrt{S} = 13$ TeV, $m_{jj} > 600$ GeV, $\Delta y_{jj} > 4.5$

[MR, Zeppenfeld]



- good agreement between NLO and NNLO result also in distributions
- remaining effects in some phase-space regions
  possible explanations: 2-loop effects,
  suppressed radiation between tagging jets
- disclaimer:
  nothing special about $R = 1.0$ for VBF-Higgs production
  $\leftrightarrow$ possible large corrections by other effects
  (underlying event, pile-up, ...)

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]

VBFNLO

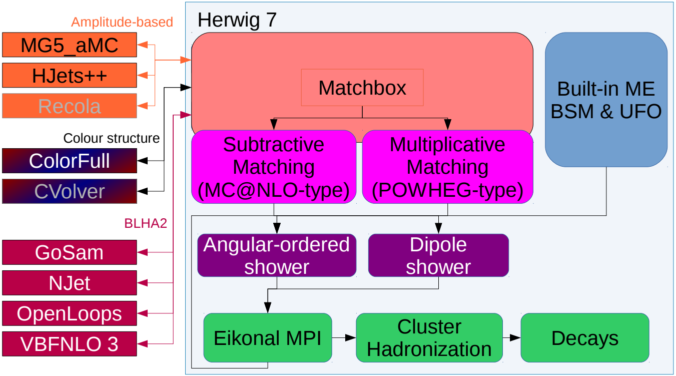
F
~~Ph~~ysics
Vector-Boson-~~Fusion~~ at Next-to-Leading Order

- Fully flexible parton-level Monte Carlo for processes with electroweak bosons
- Process list
  - VBF/VBS production at NLO QCD of
    - Higgs
    - 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, $W\gamma$, $Z\gamma$)
  - diboson production (all combinations)
  - triboson production (all combinations)
    (semi-leptonic decay mode contributes to VBS final state)
  - ...
- new physics models
  - anomalous Higgs, triple and quartic gauge couplings
  - ...
- BLHA interface to Monte-Carlo event generators
  $\rightarrow$ NLO event output

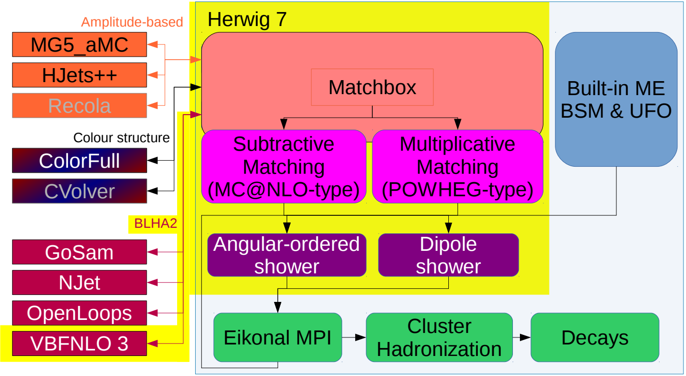
Herwig 7

- fully automated matching of NLO to parton showers through Matchbox module
  [work led by S. Plätzer with substantial contributions by J. Bellm, A. Wilcock, MR, 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



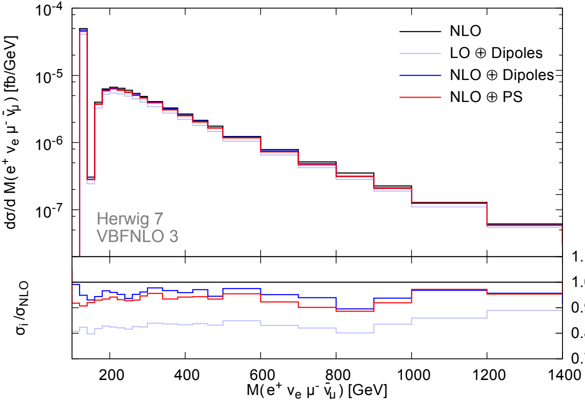
VBFNLO 3 & Herwig 7 – this talk

- 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



Distributions

Process as example: $pp \to ((Hjj \to) W^+ W^- jj \to) e^+ \nu_e \mu^- \bar{\nu}_\mu jj$ via VBF
Four-lepton invariant mass



- Higgs peak at 125 GeV
- *WW* continuum production above 180 GeV
- significant cancellation between diagrams at high invariant masses
- $\Rightarrow$ ideal test for anomalous couplings

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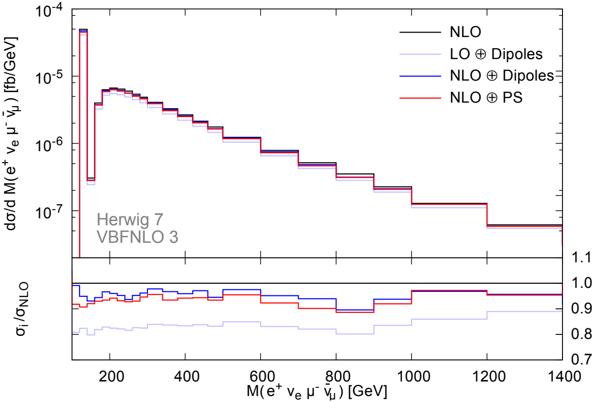
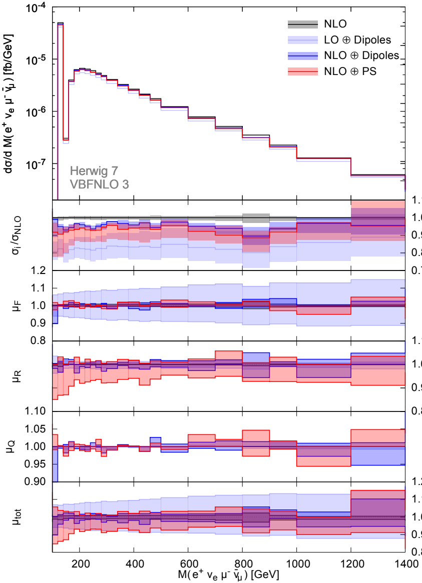


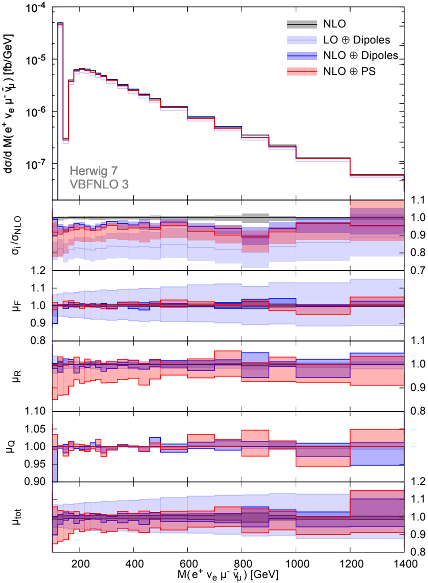
- all parton-shower results smaller than NLO cross section
- additional K-factor effect for LO $\oplus$ Dipoles result ($K = 1.077$)
- no relevant shape changes
  (as expected: insensitive to QCD effects)

Four-lepton Invariant Mass



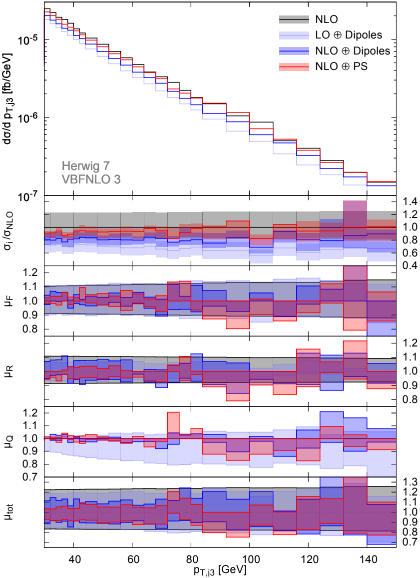
- ← central scale $\mu_0 = p_{T,j1}$ transverse momentum of leading jet
- ← band: scale variation $\{\mu_F, \mu_R, \mu_Q\}/\mu_0 \in [\frac{1}{2}; 2]$ $\mu_i/\mu_j \in [\frac{1}{2}; 2]$
- ← factorization scale $\mu_F/\mu_0 \in [\frac{1}{2}; 2]$
- ← renormalization scale $\mu_R/\mu_0 \in [\frac{1}{2}; 2]$
- ← shower scale $\mu_Q/\mu_0 \in [\frac{1}{2}; 2]$
- ← 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 $\alpha_s \rightarrow$ more splittings
  $\rightarrow$ bigger migration effects
- small variations from shower-scale changes
- modest remaining overall uncertainty

Transverse Momentum Third Jet

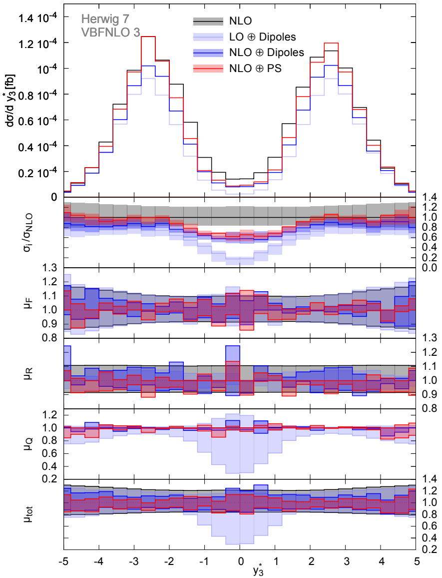


- large scale variation bands for
  - shower scale in LO⊕Dipoles

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

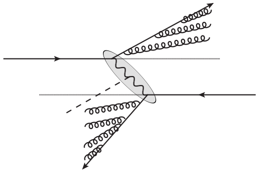
    → LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10 - 20\%)$
- → call for multi-jet merging

Rapidity of third jet



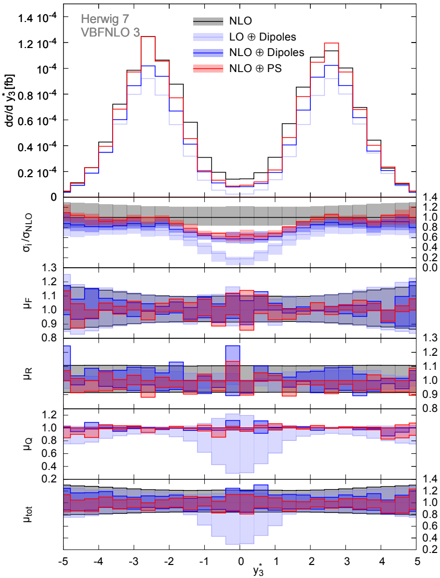
Rapidity of third jet relative to two tagging jets

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



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

Rapidity of third jet

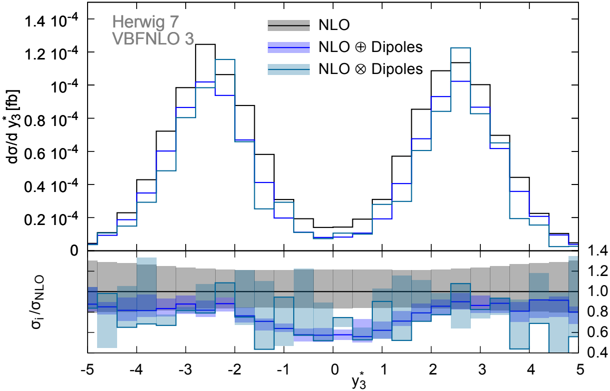


Rapidity of third jet relative to two tagging jets

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

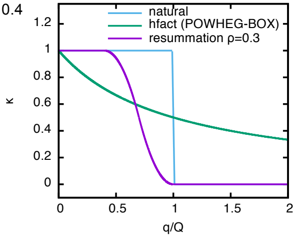
- impact of parton showers (+LO) long unclear
- Herwig predicts very low radiation in central region
- large shower-scale unc.
- stabilised when combining with NLO
- still reduction present
- scale variation bands not overlapping
- only small effects in forward region (mostly global normalization)

Rapidity of third jet – POWHEG

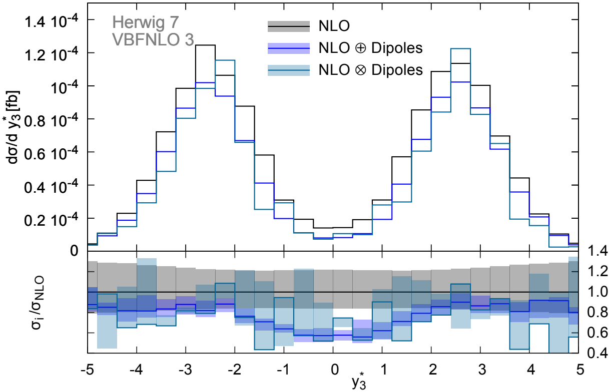


- POWHEG-like (⊗) using resummation scheme [Plätzer]:

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



Rapidity of third jet – POWHEG

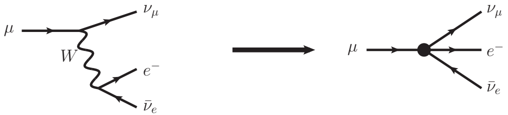


- band: joint variation $\mu_F = \mu_R = \mu_Q \in [\frac{1}{2}, 2]\ \mu_0$
- similar predictions from MC@NLO-like (⊕) and POWHEG-like (⊗) matching
- also holds for other distributions

Effective Field Theory

Assumption: new physics is heavy

Classic example: μ decay $\rightarrow$ Fermi theory



$$G_F = \frac{\sqrt{2}}{8} \frac{g^2}{M_W^2}$$

Integrate out W boson propagator:

$$\frac{i}{q^2 - M_W^2} \rightarrow \frac{i}{-M_W^2} + \mathcal{O}\left(\frac{M_W}{E}\right)$$

valid if $q^2 \ll M_W^2$

$\Rightarrow$ Effective Lagrangian

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

Effective Field Theory

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

- operators $\mathcal{O}$ contain SM fields only
- respect SM gauge symmetries
- suppressed by $1/\Lambda^{d-4}$ (Λ: scale of new physics)
  $\rightarrow$ keep only leading order(s) (lowest dimension $d = 6$)
- building blocks:
  - Higgs field Φ
  - (covariant) derivative ∂^μ, D^μ
  - field strength tensors $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$
  - fermion fields ψ
- $d = 6$ constrained from diboson production
  $\rightarrow$ probe next order $d = 8$
- Motivation:
  - $d = 6$ from loop contribution to vertex $\rightarrow$ might be suppressed
  - $d = 8$ from integrating out tree-level propagator

Linear Lagrangian

- linear realization of the EFT
- D6: 59 operators when assuming
  - baryon/lepton-number conservation
  - flavour universality

[Buchmüller, Wyler; Hagiwara et al; Grzadkowski et al; . . .]

List of Operators (only gauge and Higgs couplings)

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger\, \widehat{W}^{\mu\nu}\, (D_\nu\Phi) \qquad \mathcal{O}_B = (D_\mu\Phi)^\dagger\, \widehat{B}^{\mu\nu}\, (D_\nu\Phi)$$

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{BB} = \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}^\mu{}_\nu \widehat{W}^\nu{}_\rho \widehat{W}^\rho{}_\mu\right] \qquad \mathcal{O}_{\phi,2} = \partial_\mu \left(\Phi^\dagger\Phi\right) \partial^\mu \left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{\widetilde{W}} = (D_\mu\Phi)^\dagger\, \widetilde{W}^{\mu\nu}\, (D_\nu\Phi) \qquad \mathcal{O}_{\widetilde{B}} = (D_\mu\Phi)^\dagger\, \widetilde{B}^{\mu\nu}\, (D_\nu\Phi)$$

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger \widetilde{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{\widetilde{B}B} = \Phi^\dagger \widetilde{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}\left[\widetilde{W}^\mu{}_\nu \widehat{W}^\nu{}_\rho \widehat{W}^\rho{}_\mu\right]$$

One constraint on CP-odd operators

$$\mathcal{O}_{\widetilde{W}} + \frac{1}{2}\mathcal{O}_{\widetilde{W}W} = \mathcal{O}_{\widetilde{B}} + \frac{1}{2}\mathcal{O}_{\widetilde{B}B}$$

Additional CP-even operator

$$\mathcal{O}_{\phi W} = \mathrm{Tr}\left[W^{\mu\nu} W_{\mu\nu}\right] \Phi^\dagger\Phi \equiv 2\mathcal{O}_{WW}$$

Vertex Contributions

List of Operators (only gauge and Higgs couplings)

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \widehat{W}^{\mu\nu} \, (D_\nu \Phi) \qquad \mathcal{O}_B = (D_\mu \Phi)^\dagger \, \widehat{B}^{\mu\nu} \, (D_\nu \Phi)$$

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{BB} = \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}^\mu{}_\nu \widehat{W}^\nu{}_\rho \widehat{W}^\rho{}_\mu\right] \qquad \mathcal{O}_{\phi,2} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$$

$$\mathcal{O}_{\widetilde{W}} = (D_\mu \Phi)^\dagger \, \widetilde{W}^{\mu\nu} \, (D_\nu \Phi) \qquad \mathcal{O}_{\widetilde{B}} = (D_\mu \Phi)^\dagger \, \widetilde{B}^{\mu\nu} \, (D_\nu \Phi)$$

$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger \widetilde{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{\widetilde{B}B} = \Phi^\dagger \widetilde{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{\widetilde{W}WW} = \mathrm{Tr}\left[\widetilde{W}^\mu{}_\nu \widehat{W}^\nu{}_\rho \widehat{W}^\rho{}_\mu\right]$$

Modification of corresponding triple-gauge-coupling vertices:

	$\mathcal{O}_{WWW}$	$\mathcal{O}_W$	$\mathcal{O}_B$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{\phi,2}$	$\mathcal{O}_{\widetilde{W}WW}$	$\mathcal{O}_{\widetilde{W}}$	$\mathcal{O}_{\widetilde{B}}$	$\mathcal{O}_{\widetilde{W}W}$	$\mathcal{O}_{\widetilde{B}B}$
WWZ	X	X	X				X	X	X		
$WW\gamma$	X	X	X				X	X	X		
HWW		X		X		X		X		X	
HZZ		X	X	X	X	X		X	X	X	X
$HZ\gamma$		X	X	X	X	(X)		X	X	X	X
$H\gamma\gamma$				X	X	(X)				X	X
$WWWW$	X	X					X				
$WWZZ$	X	X					X				
$WWZ\gamma$	X	X					X				
$WW\gamma\gamma$	X						X				

Dimension-8

Bosonic dimension-8 operators [Eboli, Gonzalez-Garcia]
(D6 could be loop-induced → D8 effects can become sizable [Arzt, Einhorn, Wudka])

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

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,2} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{O}_{M,3} = \left[\widehat{B}_{\mu\nu}\widehat{B}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}D^\mu\Phi\right] \times \widehat{B}^{\beta\nu}$$
$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}D^\nu\Phi\right] \times \widehat{B}^{\beta\mu}$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger\widehat{W}_{\beta\nu}\widehat{W}^{\beta\mu}D^\nu\Phi\right]$$

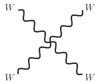
$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\widehat{W}_{\alpha\beta}\widehat{W}^{\alpha\beta}\right]$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\mu\beta}\widehat{W}^{\alpha\nu}\right]$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\widehat{W}_{\beta\nu}\widehat{W}^{\nu\alpha}\right]$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\right] \times \widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[\widehat{W}_{\alpha\nu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\mu\beta}\widehat{B}^{\alpha\nu}$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[\widehat{W}_{\alpha\mu}\widehat{W}^{\mu\beta}\right] \times \widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$$
$$\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$$
$$\mathcal{O}_{T,9} = \widehat{B}_{\alpha\mu}\widehat{B}^{\mu\beta}\widehat{B}_{\beta\nu}\widehat{B}^{\nu\alpha}$$

→ each operators contains at least four bosons
⇒ leading contribution to quartic gauge coupling

Unitarity Violation

Important gauge cancellations between different diagram types

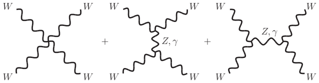
- longitudinal W scattering through quartic gauge boson vertex



high energy limit: centre-of-mass energy $\sqrt{s} \to \infty$

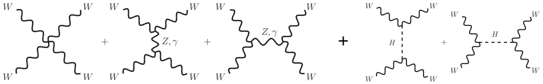
$\mathcal{M}_{\text{quartic vertex}} \propto s^2 \quad \to$ cross section diverges $\quad \sigma \propto s^4/s = s^3 \to \infty$

- add triple gauge boson vertices



$\mathcal{M}_{\text{quartic+triple vertices}} \propto s \to$ still divergent

- additional Higgs diagrams



remove divergence exactly $\quad \sigma \propto 1/s \to 0$

Anomalous gauge couplings spoil cancellation $\to$ stringent tests

Unitarization

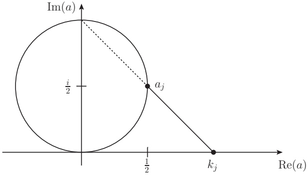
Anomalous gauge couplings spoil cancellation
$\leftrightarrow$ effects can become large $\rightarrow$ unitarity violation

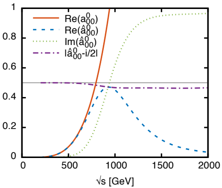
Several solutions:

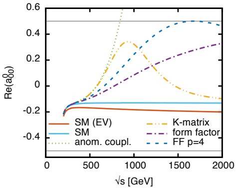
- consider only unitarity-conserving phase-space regions
  throws away information $\rightarrow$ reduced sensitivity
- (dipole) form factor multiplying amplitudes

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

- K-matrix unitarization [Alboteanu, Kilian, Reuter, Sekulla]
  based on partial-wave analysis [Jacob, Wick]
  project amplitude back onto Argand circle

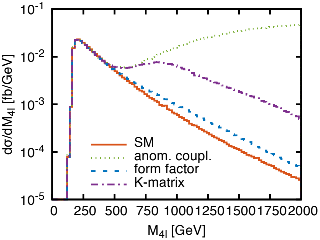


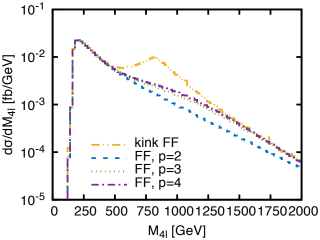




Cross Section Results

Example Process: $pp\ (\rightarrow W^+W^+jj) \rightarrow e^+\nu_e\mu^+\nu_\mu jj$ at NLO QCD accuracy





- kink form factor (simplified projection for comparison):

$$F_{\text{kink}}(E) = \begin{cases} 1 & \text{for } E \leq \Lambda_{\text{FF,kink}}\,, \\ \left(\frac{\Lambda_{\text{FF,kink}}}{E}\right)^4 & \text{for } E > \Lambda_{\text{FF,kink}}\,, \end{cases}$$

- huge effects for un-unitarized result $\leftrightarrow$ unphysical
- K-matrix method maximising contribution while staying in physical region
- $\rightarrow$ study parton-shower and hadronization impact

Impact of Current Limits

Investigate impact of D6 vs D8 operators on VBS

D6 input: Global Higgs and Gauge analysis of run-I data

[Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, MR]

Take results and apply to vector-boson scattering

$\Rightarrow$ No contribution from $\mathcal{O}_{GG}$ and fermionic operators

$f_x/\Lambda^2[\text{TeV}^{-2}]$	LHC–Higgs + LHC–TGV + LEP–TGV Best fit	95% CL interval
f_{WW}	-0.1	$(-3.1, 3.7)$
f_{BB}	0.9	$(-3.3, 6.1)$
f_W	1.7	$(-0.98, 5.0)$
f_B	1.7	$(-11.8, 8.8)$
f_{WWW}	-0.06	$(-2.6, 2.6)$
$f_{\phi,2}$	1.3	$(-7.2, 7.5)$

For simplicity: use pos. and neg. 95% CL bound with other parameters set to zero
$\rightarrow$ slightly larger effect than true 95% CL bound

Additionally:

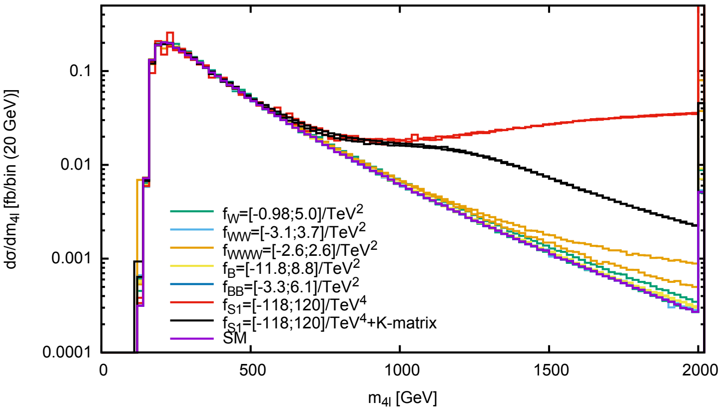
effect from dimension-8 operator $\mathcal{O}_{S,1}$

using CMS, $W^\pm W^\pm jj$, $\sqrt{S} = 8$ TeV, no unitarization [arXiv:1410.6315]

$$f_{S,1}/\Lambda^4 \in (-118, 120)\text{TeV}^{-4} \qquad (\text{for } f_{S,0}/\Lambda^4 = 0)$$

Results

Process: $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$, $\sqrt{S} = 13$ TeV, VBF cuts, NLO QCD

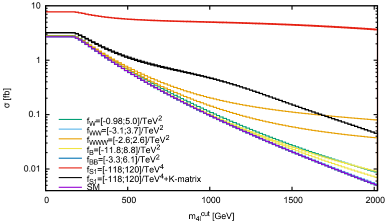


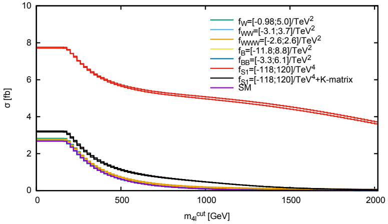
- last bin: overflow bin, $m_{4\ell} > 2000$ GeV
- effect of D6 contributions in general small; largest one by $\mathcal{O}_{WWW}$
- D8 operator clearly dominating

Results

Process: $pp \to W^+W^+jj \to \ell^+\nu\ell^+\nu jj$, $\sqrt{S} = 13$ TeV, VBF cuts, NLO QCD

cross section when requiring $m_{4\ell} > m_{4\ell}^{\text{cut}}$





- $\mathcal{O}_{WWW}$ contribution large only for very high $m_{4\ell} \leftrightarrow$ low event counts

  excess of 10 events for $m_{4\ell} > 1$ TeV, $\mathcal{L} = 100$ fb^{-1}, SM contrib. of 10 events
  other D6 operators below 1 event

  $\leftrightarrow$ unitarity violating contributions (?)

- $\mathcal{O}_{S1}$ yielding large excess even without cuts on $m_{4\ell}$

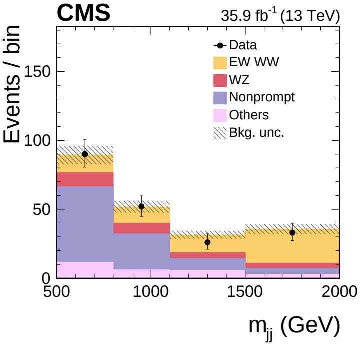
  excess of almost 500 events for $m_{4\ell} > 1$ TeV, $\mathcal{L} = 100$ fb^{-1}
  even after unitarization excess of 37 events

Experimental Results

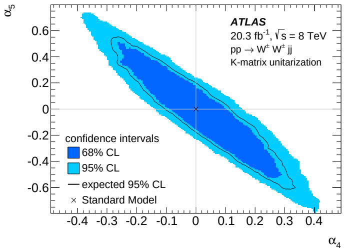
VBF / VBS processes also measured by ATLAS and CMS

- VBF-H production well established: $\frac{\sigma}{\sigma_{SM}} = 1.18^{+0.25}_{-0.23}$ [ATLAS&CMS Higgs combination]
- VBS:

Observation of EW same-sign *WW* production



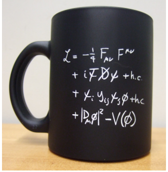
limits on D8 operators



Conclusions

Vector-boson fusion and scattering

- characteristic signature: two tagging jets in forward regions
- enhance over irred. QCD background by VBF cuts
- state-of-the-art:
  NLO EW, NNLO QCD, NLO QCD + parton shower
- modest higher-order corrections
  $\leftrightarrow$ need to consider not only scale variation,
  but also e.g. jet definition as uncertainty
- parton-shower 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
  - presence of central rapidity gap stabilised
  - $\rightarrow$ multi-jet merging to further reduce uncertainties
- testing anomalous (triple and) quartic gauge couplings
  $\rightarrow$ (fairly) model-independent constraints on new-physics effects



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KIT
Karlsruhe Institute of Technology

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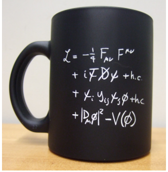

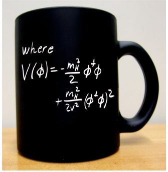

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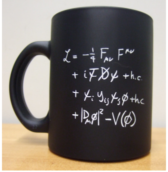
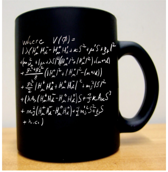




BLHA Interface

Defined standardized interface between Monte Carlo tools and one-loop programs

→Binoth Les Houches Accord (BLHA) [arXiv:1001.1307, arXiv:1308.3462]

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

Distribution of tasks:

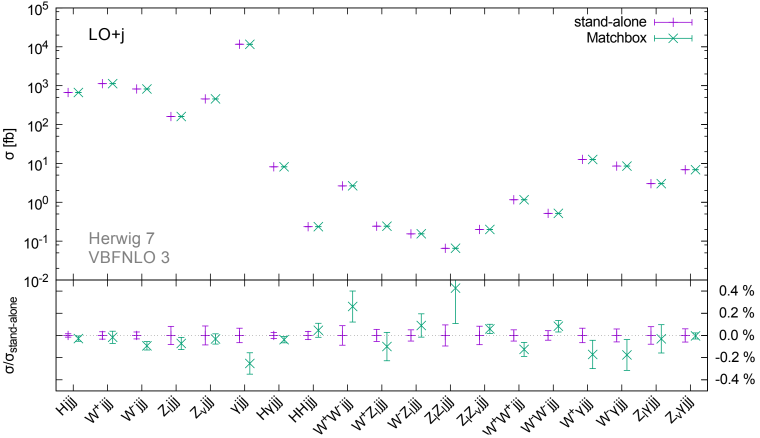
- MC tool:
  - cuts, histograms, parameters
  - Monte Carlo integration
  - phasespace (→ VBFNLO)
  - IR subtraction
  - Born, colour- and spin-correlated Born (only BLHA1)
- One-loop provider (OLP):
  - one-loop matrix elements $2\Re(\mathcal{M}_{\text{LO}}^{\dagger}\mathcal{M}_{\text{virt}})$ (coefficients of ϵ^{-2}, ϵ^{-1}, ϵ^{0}; $|\mathcal{M}_{\text{LO}}|^2$)
  - Born, colour- and spin-correlated Born (only BLHA2)

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

Validation

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

Karlsruhe Institute of Technology

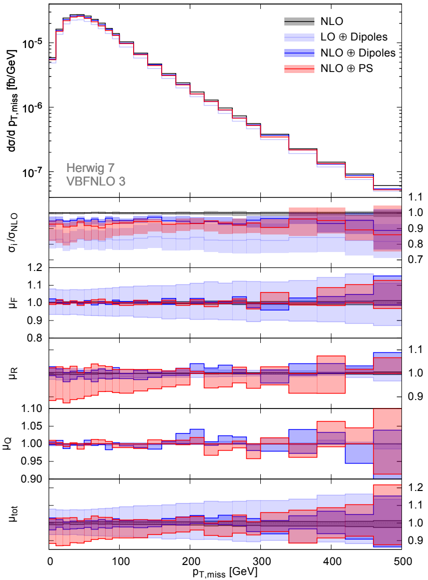
Generation-level cuts:

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

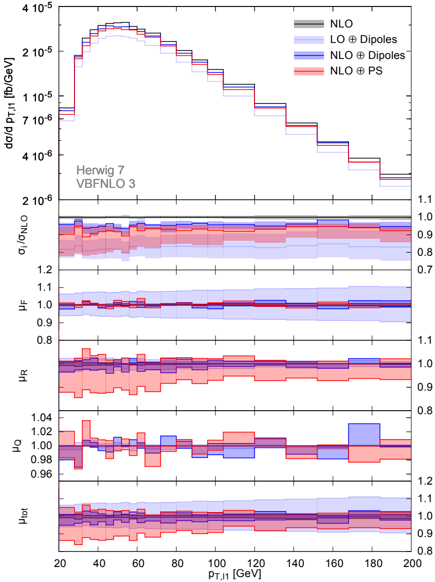
Analysis-level cuts:

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

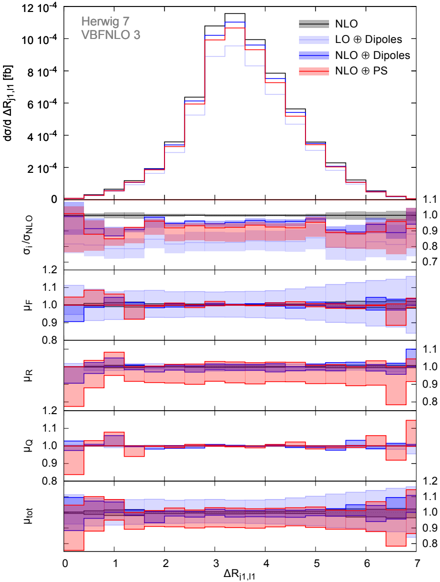
Missing Transverse Momentum



Transverse Momentum of Leading Lepton



R Separation of Leading Jet and Leading Lepton



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

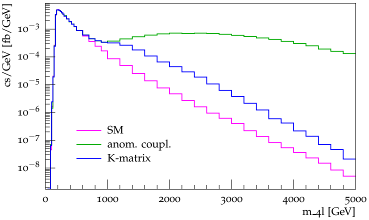
Jacobian peak at $\Delta R_{j1\ell1} = \pi$

Combination EFT with Parton Shower

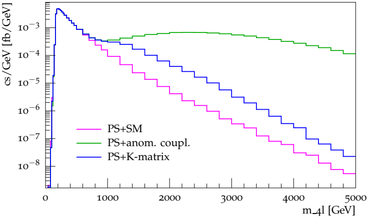
Can also combine K-matrix in setup with parton shower [VBFNLO 3 & Herwig 7]

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)



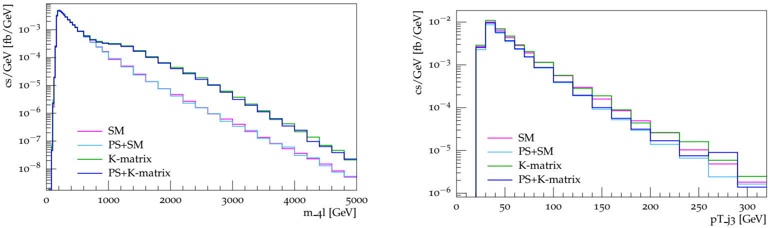
No significant shape changes in $m_{4\ell}$ when switching on PS
(integrated c.s. PS/NLO: -3.0% (SM) / -3.8% (K-matrix))

Combination EFT with Parton Shower

Can also combine K-matrix in setup with parton shower [VBFNLO 3 & Herwig 7]

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

$m_{4\ell}$ – Comparison $\qquad$ $p^T_{j,3}$ – 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