QCD effects in vector-boson-fusion processes

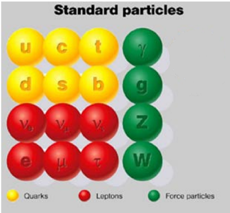
Michael Rauch | April 25, 2016

INSTITUTE FOR THEORETICAL PHYSICS

Standard Model of Particle Physics

Status of a few years ago:

- matter particles: quarks, leptons
- force particles: photon, W/Z boson, gluon



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

$$\mathcal{L} = \sum_L \bar{\psi}_L i \not{D}_L \psi_L + \sum_R \bar{\psi}_R i \not{D}_R \psi_R - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

where

$$D^\mu_L = \partial^\mu + i g_s t^a G^{a,\mu} + i g' \frac{Y}{2} B^\mu - i g t^a W^{a,\mu}$$

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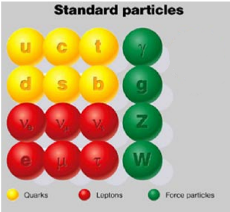

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left-handed fermions right-handed fermions

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gluon elektro-weak gauge bosons

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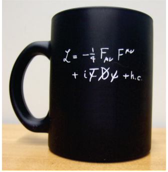
weak interaction
maximally parity-violating [Wu]



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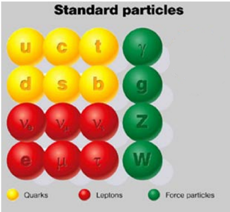

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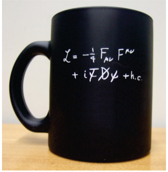

no mass terms   fermion: $\mathcal{L}_{\mathrm{mass},f} = -m_f (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

gauge boson: $\mathcal{L}_{\mathrm{mass},V} = -\frac{m_V^2}{2} V_\mu V^\mu$

$\rightarrow$ violate gauge invariance

Spontaneous Symmetry Breaking

Solution: spontaneous symmetry breaking

idea: additional field Φ such that $\mathcal{L}$ invariant under gauge transformations
but ground state not invariant
$\Rightarrow$ non-vanishing vacuum expectation value of Φ

Ex. ferro-magnetism:
$T > T_c$: no magnetisation $\rightarrow$ rotational symmetry
$T < T_c$: spontaneous magnetisation $\rightarrow$ preferred direction, symmetry broken

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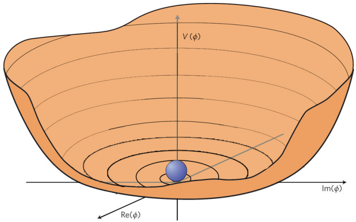
field theory:

- global continuous symmetry:
  massless Goldstone boson
  for every broken generator
- local gauge symmetry:
  eliminated by gauge transformations
  (*would-be goldstone bosons*)
  longitudinal modes of gauge bosons

$$\mathcal{L} \propto -\mu^2(\Phi^\dagger\Phi) - \lambda(\Phi^\dagger\Phi)^2$$

$\mu^2 > 0$



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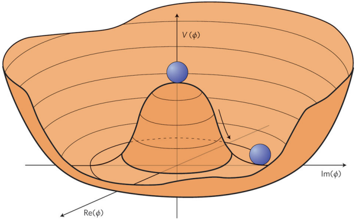
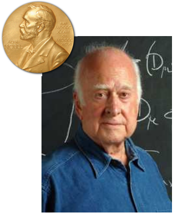


Higgs Mechanism in the Standard Model

Standard Model: Higgs Mechanism [Englert, Brout; Higgs; Guralnik, Hagen, Kibble 1964]

(based on similar ideas in solid state physics) [Anderson 1963]

$\rightarrow$ Nobel prize 2013



- Add Higgs field as $SU(2)$ doublet with hypercharge $+1$:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + H + iG^0) \end{pmatrix}$$

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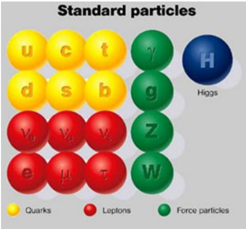

- Breaks $SU(2)_L \otimes U(1)_Y \to U(1)_{\text{em}}$ ($\to$ photon massless)
- $G^\pm$, G^0 $\to$ longitudinal modes of $W^\pm$, Z
- H real scalar field $\to$ Higgs boson
- $v = \frac{2M_W}{e\sqrt{1-\frac{M_W^2}{M_Z^2}}} \simeq 246\,\mathrm{GeV}$ vacuum expectation value
- Contribution to Lagrangian:

$$\mathcal{L}_H = (D_{L,\mu}\Phi)^\dagger (D_L^\mu \Phi) \qquad \text{kinetic term}$$

$$+ \frac{m_H^2}{2}\Phi^\dagger\Phi - \frac{m_H^2}{2v^2}(\Phi^\dagger\Phi)^2 \qquad \text{Higgs potential}$$

$$- (\lambda_\ell \bar{L}\Phi e_R + \lambda_u \bar{Q}\Phi^c u_R + \lambda_d \bar{Q}\Phi d_R + h.c.) \qquad \text{Yukawa coupling to fermions}$$

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Karlsruher Institut für Technologie

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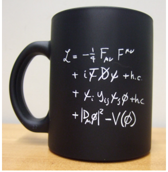
- Contribution to Lagrangian:

$$\begin{aligned}
\mathcal{L}_H &= (D_{L,\mu}\Phi)^\dagger (D_L^\mu \Phi) \\
&\quad + \frac{m_H^2}{2}\Phi^\dagger\Phi - \frac{m_H^2}{2v^2}(\Phi^\dagger\Phi)^2 \\
&\quad - (\lambda_\ell \bar{L}\Phi e_R + \lambda_u \bar{Q}\Phi^c u_R + \lambda_d \bar{Q}\Phi d_R + h.c.) \\
&\overset{\text{SSB}}{=} \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - \frac{m_H^2}{2}H^2 - \frac{m_H^2}{2v}H^3 - \frac{m_H^2}{8v^2}H^4 \\
&\quad - (\text{mass and interaction terms with gauge bosons}) \\
&\quad - \sum_{\text{fermions}} \frac{\lambda_f}{\sqrt{2}}(\,\text{v} + \text{H}\,)\bar{\psi}_f \psi_f
\end{aligned}$$

mass term ($m_f = \frac{\lambda_f v}{\sqrt{2}}$) — fermion-Higgs coupling



From Theory to Experiment

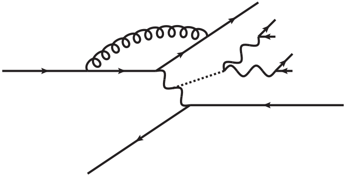
- Lagrangian defines all fundamental fields and interactions
- Seven particle types hit (LHC) detector elements:
  p, n, π, K, e, μ, γ
- $\leftrightarrow$ direct calculation practically not possible
  final-state multiplicity, non-perturbative effects, ...
- $\rightarrow$ Monte Carlo Event Generators

  evolution from hard process down to hadron level

  Major generators:
  - Pythia [Sjöstrand]
  - Sherpa [Krauss et al.]
  - Herwig [Bellm, Gieseke, Grellscheid, Plätzer, MR, Reuschle, Richardson, Schichtel, Seymour, Siodmok, Wilcock, Fischer, Harrendorf, Nail, Papaefstathiou, D. Rauch]
  - ...

Monte Carlo Event (1)

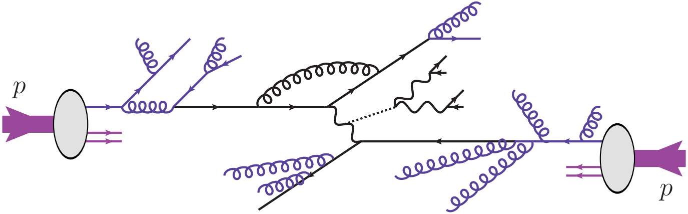
Hard Process



- calculable by perturbation theory
- LO / NLO QCD / NLO QCD+EW accuracy
- typical scale $\mathcal{O}(100\text{ GeV})$

Monte Carlo Event (2)

Parton Shower



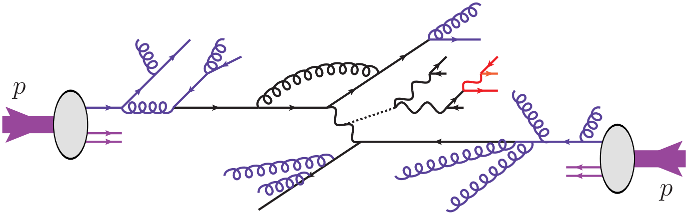
- initial- and final-state parton shower
- based on unitarity and collinear factorization
- adds additional radiation according to DGLAP splitting kernels P
- evolution governed by Sudakov factor
  (non-emission probability between hard scale θ_{max} and probed scale θ)

$$\Delta(\theta_{\text{max}}, \theta) = \exp\left(- \sum_j \int_{\theta^2}^{\theta^2_{\text{max}}} \frac{\mathrm{d}\tilde{\theta}^2}{\tilde{\theta}^2} \int_{z_-(\tilde{\theta})}^{z_+(\tilde{\theta})} \mathrm{d}z \, \frac{\alpha_s}{2\pi} P_{ij}(z) \right)$$

- resums leading logs and in large-N limit also next-to-leading logs
- evolution stops at $\mathcal{O}(1~\text{GeV})$
  $\to \alpha_S$ large, perturbative expansion breaks down

Monte Carlo Event (3)

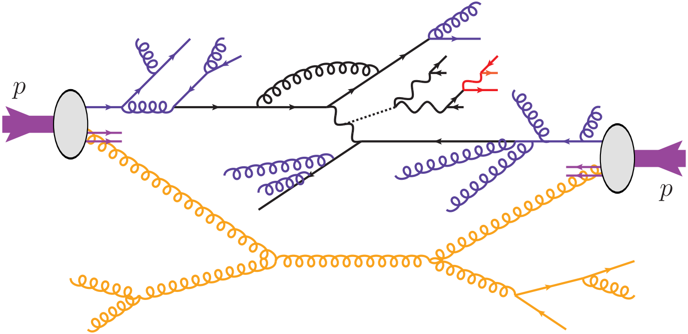
Perturbative Decays of Heavy Particles



- simulate decays of any remaining heavy particles, e.g. *t*, *W*, *Z*, *H*

Monte Carlo Event (4)

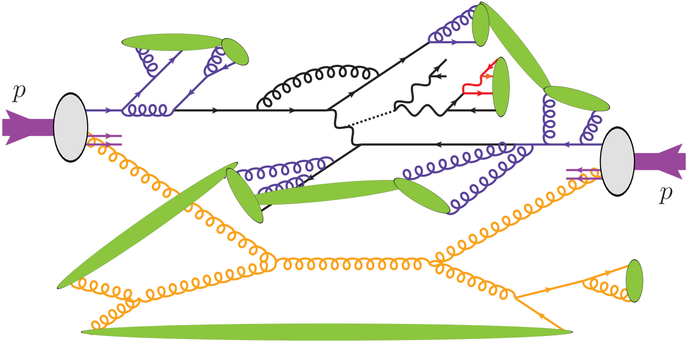
Secondary Hard Processes



- proton remnants can scatter again
  → multi-parton interactions (MPI)
- another proton from bunch can scatter as well
  → pile-up
- Poisson statistics
- mostly QCD 2 → 2 processes, dominated by t-channel gluon exchange

Monte Carlo Event (5)

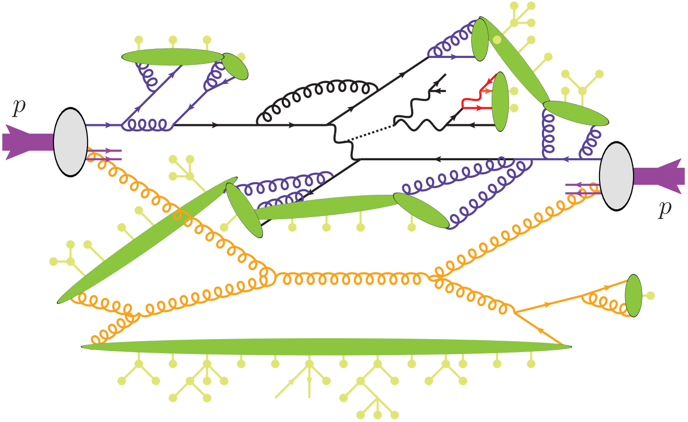
Hadronization



- re-group partons into (colourless) hadrons
- phenomenological model
- parameters fitted from experimental data

Monte Carlo Event (6)

Hadron Decays

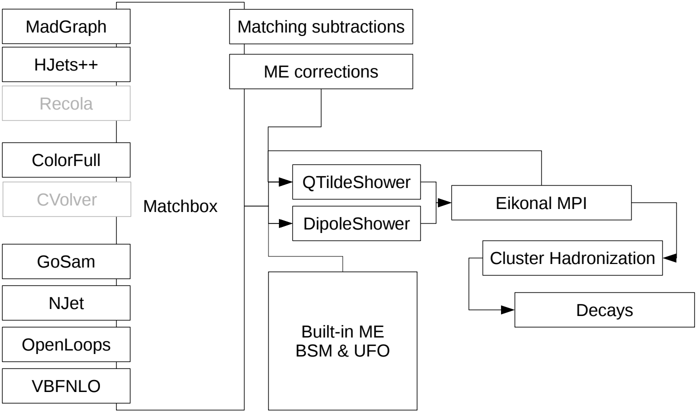


- Decay unstable hadrons to final set

Herwig 7

- fully automated matching of NLO to parton showers through Matchbox module

  [J. Bellm, S. Plätzer, MR, C. Reuschle, A. Wilcock]
- subtractive (MC@NLO-type, ⊕) and multiplicative (POWHEG-type, ⊗) matching
- angular-ordered (QTilde, PS) and dipole (Dipoles) shower
- matrix elements through binary interface, no event files



VBF event topology

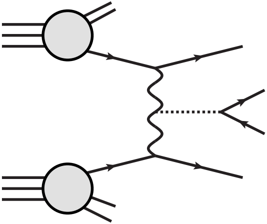
VBF (vector-boson fusion) topology shows distinct signature

- 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.*]
- advantageous scale choice:
  momentum transfer q^2
  of intermediate vector bosons



Diboson-VBF production

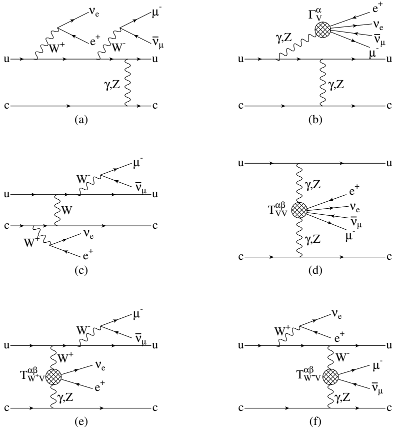
[Bozzi, Jäger, Oleari, Zeppenfeld (VV); Campanario, Kaiser, Zeppenfeld ($W^{\pm}\gamma$)]
[Denner, Hosekova, Kallweit ($W^{+}W^{+}$)]

- 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

→ VBFNLO [MR, Zeppenfeld et al.]



NLO plus Parton Shower

Combine advantages of NLO calculations and parton shower

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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

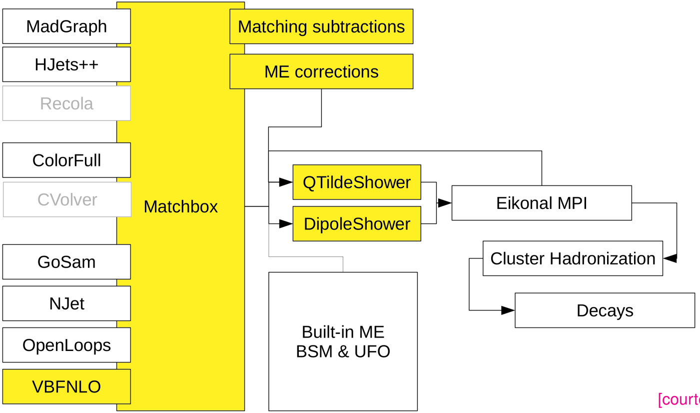
Implementations for specific VBF processses

- 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]

$\rightarrow$ process-by-process implementation $\rightarrow$ slow progress on availability

VBFNLO 3 & Herwig 7 – this talk

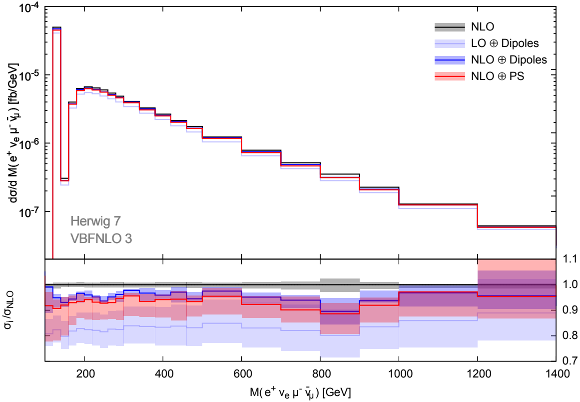
- matrix elements from VBFNLO via BLHA2 interface [Binoth et al., Alioli et al.]
  $\rightarrow$ all combinations including leptonic gauge-boson decays
- extensions to make accessible
  - phase-space sampling
  - (electroweak) random helicity summation
  - anomalous couplings



[courtesy of S. Plätzer]

Distributions

Process as example: $pp \rightarrow ((Hjj \rightarrow) W^+ W^- jj \rightarrow) e^+ \nu_e \mu^- \bar{\nu}_\mu jj$ 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
- ⇒ ideal test for anomalous couplings

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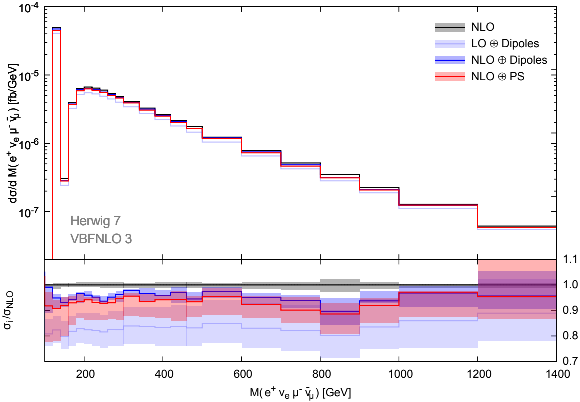
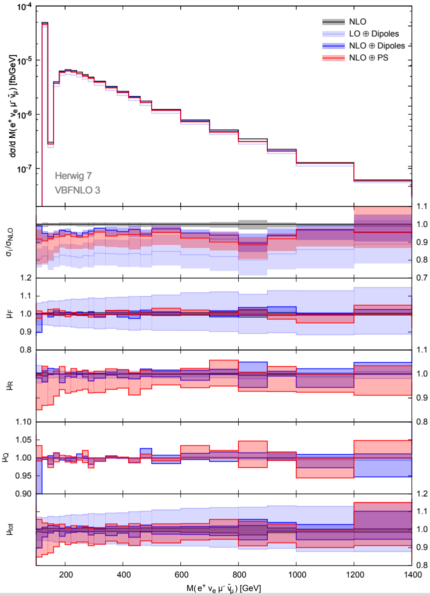


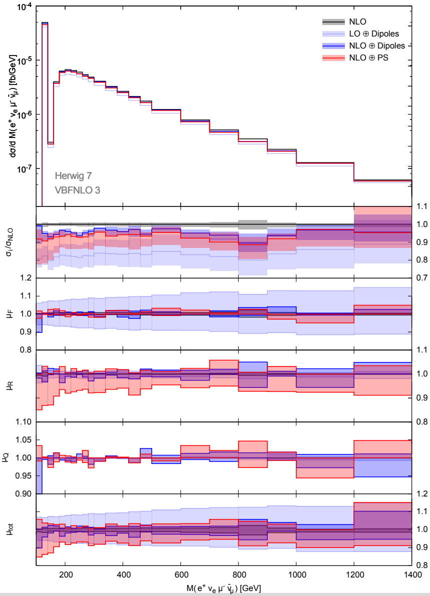
- all parton-shower results smaller than NLO cross section
- additional parton splittings hard, wide-angle $\to$ separate jet
- $\leftrightarrow$ VBF cut $m_{jj} > 600$ GeV
- no relevant shape changes (as expected: insensitive to QCD effects)

Four-lepton Invariant Mass



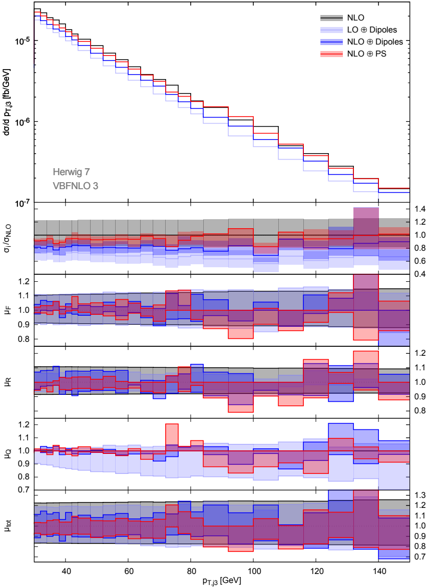
- ← central scale $\mu_0 = p_{T,j1}$ transverse momentum of leading jet
- ← band: scale variation $\{\mu_F, \mu_R, \mu_Q\}/\mu_0 \in [\frac{1}{2}; 2]$ $\mu_i/\mu_j \in [\frac{1}{2}; 2]$
- ← factorization scale $\mu_F \in [\frac{1}{2}; 2]$
- ← renormalization scale $\mu_R \in [\frac{1}{2}; 2]$
- ← shower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

Transverse Momentum Third Jet

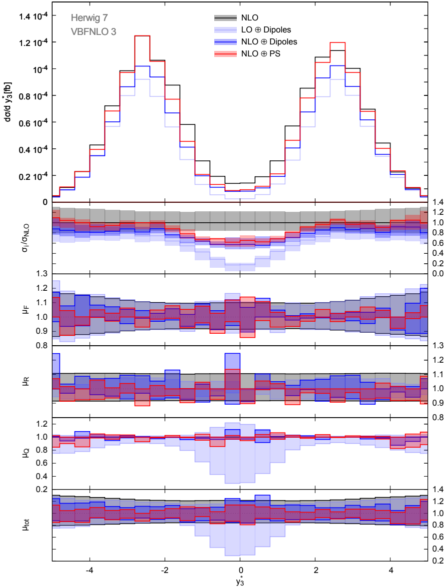


- large scale variation bands for
  - shower scale in LO$\oplus$Dipoles

    $\rightarrow$ pure parton-shower effect
  - fact./ren. scale in “NLO”

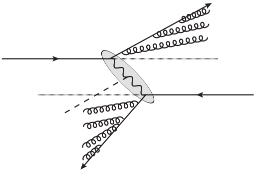
    $\rightarrow$ LO accuracy of observable
- reduced for both NLO + parton-shower curves
- still significant remaining uncertainty $\mathcal{O}(10 - 20\%)$
- $\rightarrow$ call for multi-jet merging

Rapidity of third jet



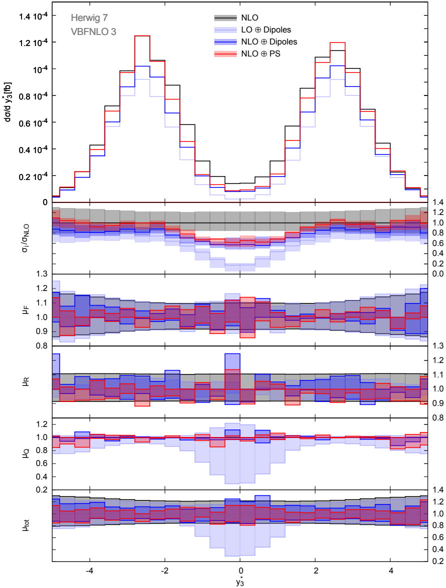
Rapidity of third jet
relative to two tagging jets

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



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

Rapidity of third jet

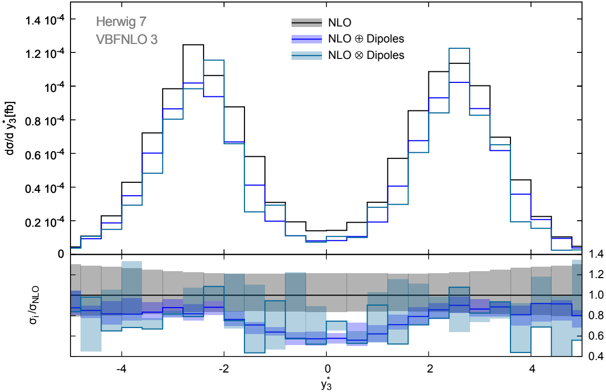


Rapidity of third jet relative to two tagging jets

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

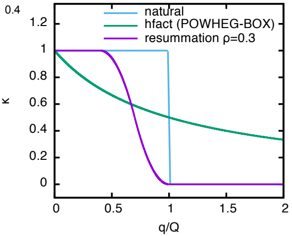
- impact of parton showers (+LO) long unclear
- Herwig predicts very low radiation in central region
- large shower-scale unc.
- stabilised when combining with NLO
- still reduction present
- scale variation bands not overlapping
- only small effects in forward region (mostly global normalization)

Rapidity of third jet – POWHEG

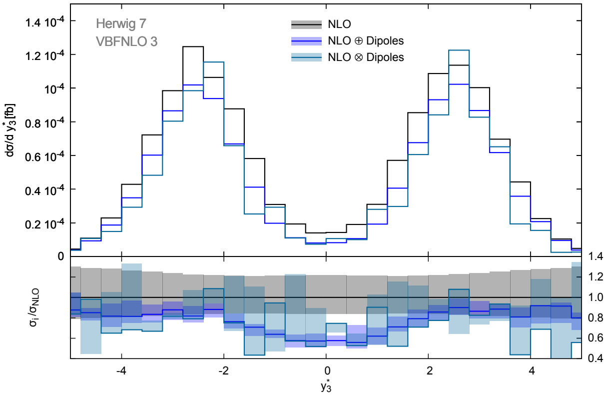


- POWHEG-like (⊗) using resummation scheme [Plätzer]:

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



Rapidity of third jet – POWHEG



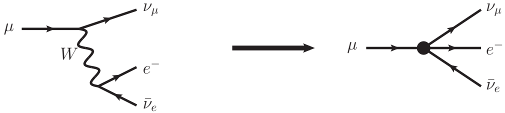
- band: joint variation $\mu_F = \mu_R = \mu_Q \in [\frac{1}{2}, 2]\ \mu_0$
- similar predictions from MC@NLO-like (⊕) and POWHEG-like (⊗) matching
- also holds for other distributions

Effective Field Theory

Karlsruher Institut für Technologie

Assumption: new physics is heavy

Classic example: μ decay $\rightarrow$ Fermi theory (t-channel W integrated out)



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

$\Rightarrow$ Effective Lagrangian

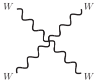
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4}\sum_{i}\frac{f_i^{(d)}}{\Lambda^{d-4}}\mathcal{O}_i^{(d)}$$

- 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 (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

Unitarity Violation

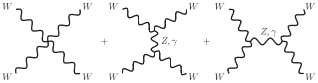
Important gauge cancellations between different diagram types

- longitudinal W scattering through quartic gauge boson vertex



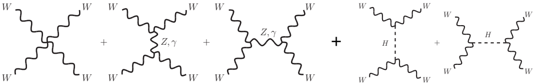
high energy limit: centre-of-mass energy $\sqrt{s} \to \infty$
$\mathcal{M}_{\text{quartic vertex}} \propto s^2 \quad \to$ cross section diverges $\quad \sigma \propto s^4 \to \infty$

- add triple gauge boson vertices



$\mathcal{M}_{\text{quartic vertex}} \propto s \to$ still divergent

- additional Higgs diagrams



remove divergence exactly $\qquad \sigma \propto 1/S \to 0$

Anomalous gauge couplings spoil cancellation $\to$ stringent tests

Unitarization

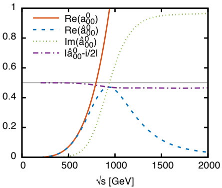
Anomalous gauge couplings spoil cancellation
$\leftrightarrow$ effects can become large $\rightarrow$ unitarity violation

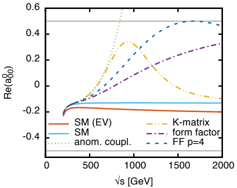
Several solutions:

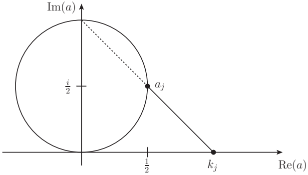
- consider only unitarity-conserving phase-space regions
  throws away information $\rightarrow$ reduced sensitivity
- (dipole) form factor multiplying amplitudes

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

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

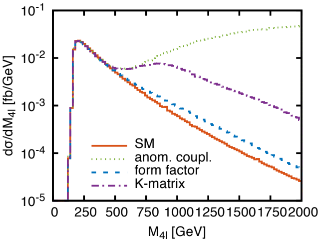






Cross Section Results

Example Process: $pp(\to W^+W^+jj) \to e^+\nu_e\mu^+\nu_\mu jj$ 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
- $\to$ study parton-shower and hadronization impact

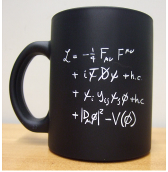
Conclusions

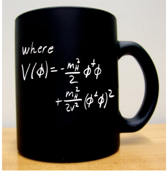
Parton-shower and scale variation effects in

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
- $\rightarrow$ study hadronization impact





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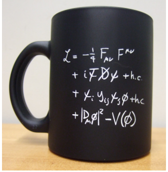
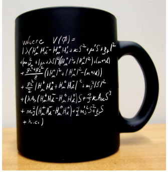




Setup

Cuts:

$$p_{T,j} > 30 \text{ GeV}\,, \qquad |y_j| < 4.5\,,$$
$$p_{T,\ell} > 20 \text{ GeV}\,, \qquad |y_\ell| < 2.5\,,$$
$$m_{j1,j2} > 600 \text{ GeV}\,, \qquad |y_{j1} - y_{j2}| > 3.6\,,$$

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

BLHA Interface

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

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

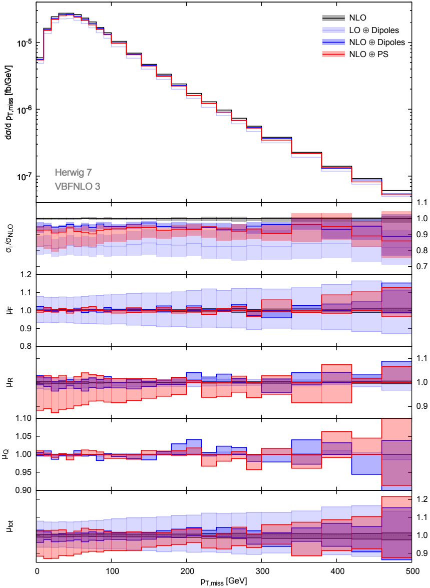
- tree-level evaluation of matrix elements well under control
- modular structure of NLO calculations
- algorithms for treatment of infrared singularities (Catani-Seymour, FKS, . . .)
- → incorporate one-loop matrix element information into MC tools

Distribution of tasks:

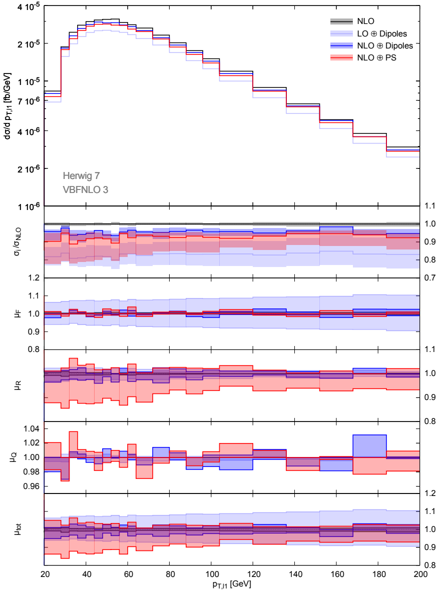
- MC tool:
  - cuts, histograms, parameters
  - Monte Carlo integration
  - phasespace (→ VBFNLO)
  - IR subtraction
  - Born, colour- and spin-correlated Born (only BLHA1)
- One-loop provider (OLP):
  - one-loop matrix elements $2\Re(\mathcal{M}_{\text{LO}}^{\dagger}\mathcal{M}_{\text{virt}})$ (coefficients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

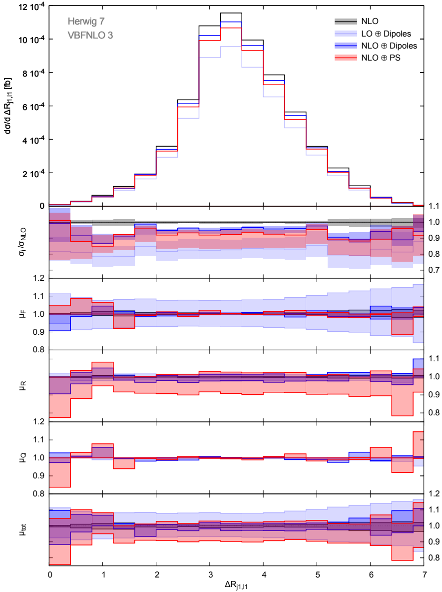
Missing Transverse Momentum



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 $\Delta R_{j1\ell1} = \pi$