Karlsruhe Institute of Technology

VBFNLO

Michael Rauch | Higgs (N)NLO MC and Tools Workshop for LHC Run-2, Dec 2014

INSTITUTE FOR THEORETICAL PHYSICS

Introduction

VBFNLO

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

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

Process overview

List of implemented processes

(New in VBFNLO 2.7.0)

- 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)
- 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 (WZ, Wγ) plus hard jet (NLO QCD)
  - diboson ($W^\pm W^\pm$, WZ, Wγ) 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 couplings
  - anomalous triple and quartic gauge couplings
  - Higgsless and spin-2 models
  - Two-Higgs model

Intermediate state Higgs boson in all processes included where applicable

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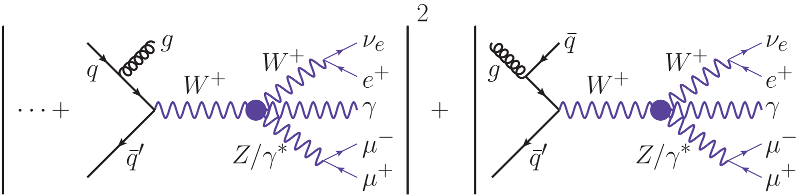
Implementation Details

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



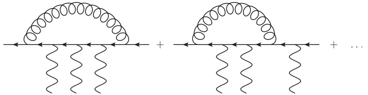
- Catani-Seymour dipole subtraction scheme

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

Gauge Test

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

- Identify → gauge test



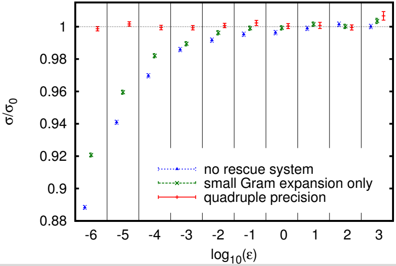
replace one vector boson by corresponding momentum (cache system for loop integrals → no reevaluation needed)

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

- Repair [Impl: Campanario]

→ rescue system (small Gram det. expansion) → quad precision → discard

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



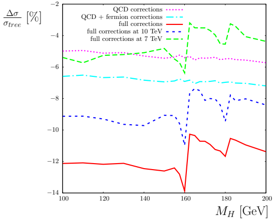
ϵ: go to next step if $\dfrac{\Delta(p_i^\mu \mathcal{M}_\mu^n)}{\varepsilon_i^\mu \mathcal{M}_\mu^n} > \epsilon$

strong and efficient test of accuracy of building blocks

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

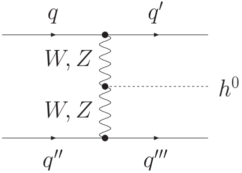
Vector-boson-fusion Higgs

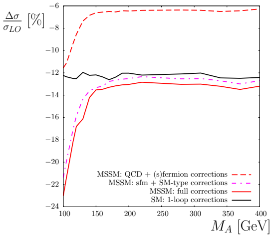
[Han, Valencia, Willenbrock; Figy, Oleari, Zeppenfeld; Campbell, Ellis, Berger]



- Clear signature due to two tagging jets
- QCD corrections relatively small $\sim 5\%$
- EW corrections of same size

  [Ciccolinni, Denner, Dittmaier; Figy, Palmer, Weiglein]





- SM (QCD+EW) corrections
- SUSY (QCD+EW) corrections

  [Hollik, Plehn, MR, Rzehak; Figy, Palmer, Weiglein]

- available for all Higgs bosons (h^0, H^0, A^0)
- CP-conserving and -violating scenario
- Higgs boson decays in narrow-width approximation
- For $H \to WW/ZZ \to 4\ell$ full spin information and off-shell effects included

Two-Higgs Model

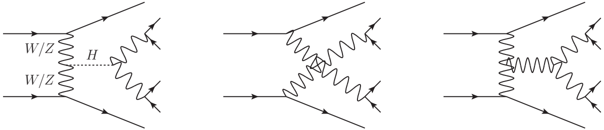
Two Higgs model for VBF processes [MR]

Search for heavy Higgs bosons: [more physics $\to$ talk by Nikolas Kauer]

- width becomes large (Γ_H^{OS} =123 (304, 647) GeV at $m_H = 600$ (800, 1000) GeV)
- significant signal-background interference
- What defines “background”?

  $B = \int d\Phi |\mathcal{M}_B|^2$ or
  $S = \int d\Phi \left[|\mathcal{M}_H|^2 + 2\mathrm{Re}\mathcal{M}_H\mathcal{M}_B^* \right]$ violate unitarity at large s

  Notation: $\mathcal{M}_H \sim \frac{s}{v^2}$ Signal amplitude for s-, t- and u-channel exchange of H
  $\mathcal{M}_B \sim \frac{-s}{v^2}$ continuum electroweak background amplitude

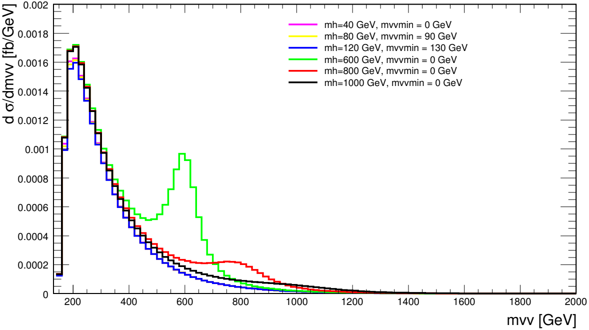


- $\leftrightarrow$ 125 GeV Higgs well established

Continuum-Higgs interference

$\Rightarrow$ Compare to SM light Higgs scenario

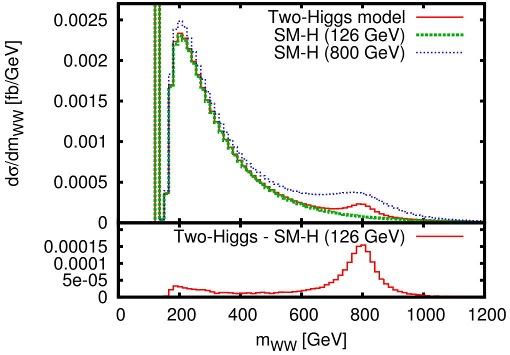
- Define $S = \int d\Phi |\mathcal{M}_B + \mathcal{M}_H(m_H)|^2 - B$ with $B = \int d\Phi |\mathcal{M}_B + \mathcal{M}_h(m_h)|^2$
- Integrate over suitable mass range $[m_H - \Gamma_1, m_H + \Gamma_2]$
- $\Rightarrow$ S and B well defined and do not violate unitarity



$\rightarrow$ light-Higgs curves indistinguishable at large m_{VV}

Two-Higgs Model

→ Model with two Higgs resonances



Example:

- h_0: M_{h_0}=126 GeV, $g^2_{h_0 VV}/g^2_{HVV,SM} = 0.7$
- H_0: M_{H_0}=800 GeV, $g^2_{H_0 VV}/g^2_{HVV,SM} = 0.3$

→ Consistent definition possible

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]
(Φ Higgs doublet, $W^{\mu\nu}/B^{\mu\nu}$: SU(2)/U(1) field strength tensors):

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

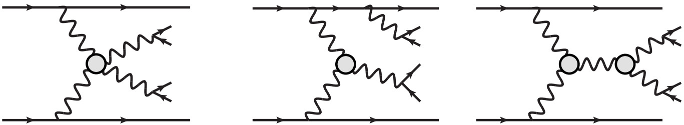
$$\mathcal{L}_{M,2} \propto [B^{\mu\nu} B_{\mu\nu}] \times \left[\left(D^\beta\Phi\right)^\dagger (D_\beta\Phi)\right]$$

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

$$\ldots$$

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

triple gauge couplings contribute as well



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

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

- 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`

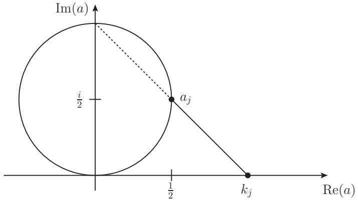
Example output

```
[...]
 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 )
[...]
```

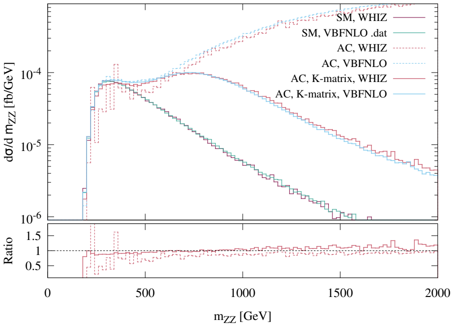
K matrix unitarization



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

[VBFNLO implementation: Löschner, Perez]

Comparison with Whizard, which has this method already implemented: [Kilian, Ohl, Reuter]



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

Reweighting events (REPOLO)

[F. Schissler, available on request]

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

$\rightarrow$ Reuse SM Higgs events and reweight for different BSM scenarios

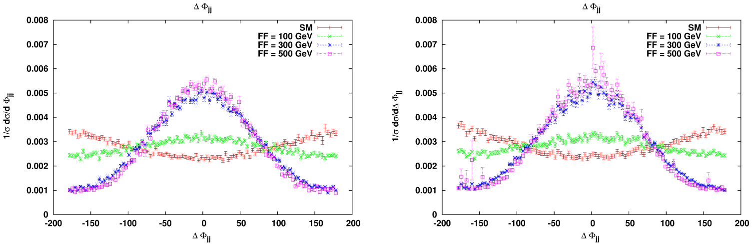
$\rightarrow$ REPOLO (REweighting POwheg events at Leading Order)

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
$\rightarrow$ only SM-like distributions can be safely reweighted

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



$\Rightarrow$ distributions correctly reproduced, larger errors in SM-suppressed regions

BLHA Interface

[Arnold, Plätzer, MR et al.; see also Jäger et al. for POWHEG-BOX implementation]

Interface NLO program with parton-shower MC
well-defined standard: Binoth Les Houches Accord (BLHA)
→ implemented in VBFNLO (BLHA2)
work in progress: VBF processes checked, others to follow

- Events at NLO

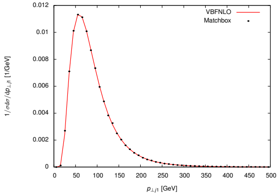
```
HepMC::Version 2.06.08
HepMC::IO_GenEvent-START_EVENT_LISTING
E 1 -1 1.0000000000000000e+02 1.1426144356896106e-01 8.0545791941901580e-03 0 -1 5 10003 10006 0 1 9.65741
N 1 "0"
U GEV MM
C 1.2003526218804084e+00 1.2429340593057579e+04
F 2 -2 1.9944966561722052e-01 5.4752809081600089e-03 1.0000000000000000e+02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

- Anomalous couplings including available unitarization schemes

⇒ Herwig++ package Matchbox [Gieseke, Plätzer]

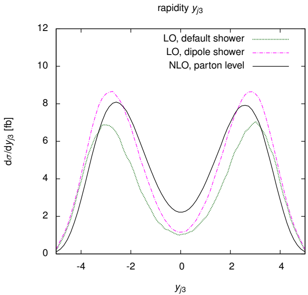
Parton shower based on Catani-Seymour dipoles as well as angular-ordered shower

Matching methods: MC@NLO and POWHEG

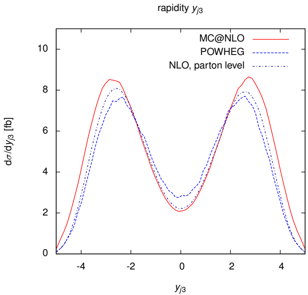


NLO validation plot

VBF-*H* + parton shower



Rapidity of third hardest jet



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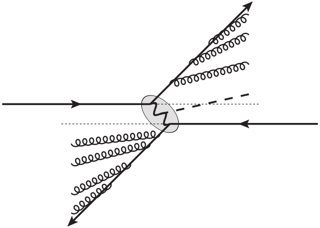

- additional radiation by shower created mainly between jets and beam axis (color connections)
- dipole shower “interpolates” between NLO behavior in central region and shower behavior at small angles

WH(*j*) production at NLO QCD

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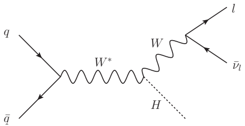
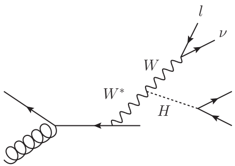
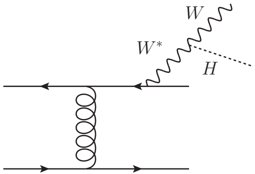
Implementation of *WH* and *WH*(*j*) at NLO QCD

[Campanario, Roth, Zeppenfeld; see also Ji-Juan et al.; Luisoni et al.]

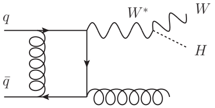


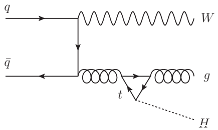




two types of virtual contributions:

- Drell-Yan-like diagrams ($W^* \to WH$)
- Higgs coupling to heavy quark (top) loop (2-3% effect)



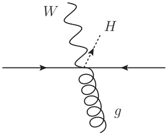


- including leptonic decays of *W* boson and off-shell effects
- allows including decay of Higgs boson
- anomalous *WWH* couplings from dimension-6 operators implemented

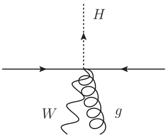
Boosted Higgs

- experimental analyses require high p_T to reduce background
- $p_{T,W} = p_{T,H}$ for WH (LO), but deviates with additional radiation
- large NLO effects on distributions in boosted phase space region

Inclusive cuts

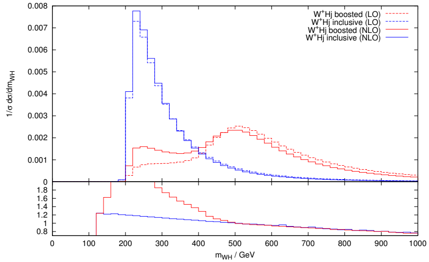


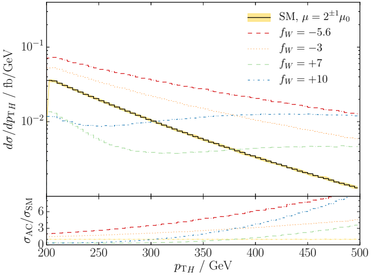
Boosted Higgs



Cuts	Cross Section (fb) LO	NLO	K
inclusive	25	28	1.11
$p_{T,H} > 200$ GeV	3.5	3.7	1.08

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \, \hat{W}^{\mu\nu} \, (D_\nu \Phi)$$

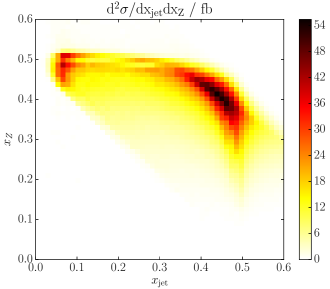




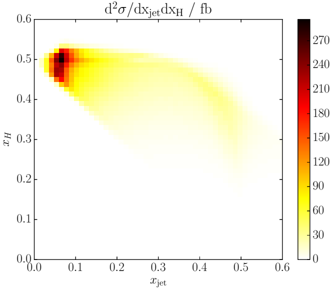
QCD Patterns in WZj vs. WHj

[Campanario, Roth, Zeppenfeld]

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



WZj



WHj

- *WHj* has mainly soft jets, while *WZj* also has a phase space region with hard *Vj* and a soft second vector boson

Conclusions

- VBF-H available at NLO QCD+EW in SM and MSSM (h^0, H^0, A^0)
- WH and WHj available at NLO QCD in SM and with D6 anomalous couplings
- Two-Higgs model for diboson-VBF processes
  $\rightarrow$ allows for consistent definition of signal+interference in heavy-Higgs scenarios
- Reweighting of VBF-H events to account for BSM effects
- BLHA2 interface forthcoming
- particular focus on speed and stability

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

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

VBFNLO is collaborative effort:

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

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