# Precision tools for the simulation of double-Higgs production via vector-boson fusion

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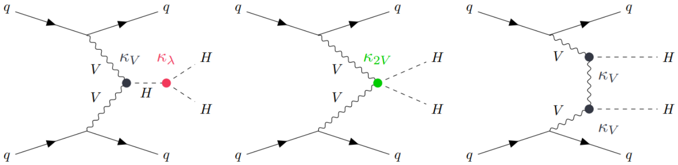
# Main Sources

- B. Jäger, A. Karlberg and S. Reinhardt, *Precision tools for the simulation of double-Higgs production via vector-boson fusion*, JHEP 06 (2025) 022, [arXiv:2502.09112]
- J. Braun, P. Bredt, G. Heinrich and M. Höfer, *Double Higgs production in vector boson fusion at NLO QCD in HEFT*, [arXiv:2502.09132]

# VBF-HH process

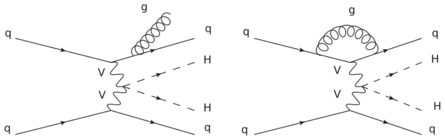
# Electroweak HHjj Production

- VBF-HH: EW production process ($\mathcal{O}(\alpha^4)$) of Higgs pair in association with 2 jets
- VBF-approximation: neglect s-channel, interference u- and t-channel diagrams
- Born diagrams with anomalous couplings (*kappa framework*):




Source: Jäger, Karlberg and Reinhardt, [arXiv:2502.09112]

- NLO-QCD corrections:



# Tools

# Summary slide for tools

| | |
|---|---|
| VBFNLO:<br>NLO-QCD (VBF-approx) | Baglio et al. [2405.06990] |
| MadGraph5_aMC@NLO (+ SMEFTsim):<br>NLO-QCD+PS (+ EFT) | Frederix et al. [1401.7340], Alwall et al. [1405.0301]<br>Brivio, Jiang, Trott [1709.06492], Brivio [2012.11343] |
| MoCaNLO:<br>NLO-EW and NLO-QCD (full) | Dreyer, Karlberg, Lang, Pellen [2005.13341] |
| proVBFHH:<br>NNLO/$\mathrm{N}^3\mathrm{LO}$-QCD (VBF-approx),<br>non-factorizable contributions, $(\kappa_{2V}, \kappa_V, \kappa_\lambda)$ | Dreyer, Karlberg [1811.07918], [1811.07906]<br>Dreyer, Karlberg, Tancredi [2005.11334] |
| VBF_HH_HEFT (WHIZARD+GoSam):<br>NLO-QCD, HEFT (full) | Braun, Bredt, Heinrich, Höfer [2502.09132] |
| POWHEG-BOX/VBF_HH:<br>NLO-QCD+PS (VBF-approx), $(\kappa_{2V}, \kappa_V, \kappa_\lambda)$ | Karlberg, Jäger, Reinhardt [2502.09112] |

# POWHEG-BOX * (VBF_HH)

'Positive Weight Hardest Emission Generator':

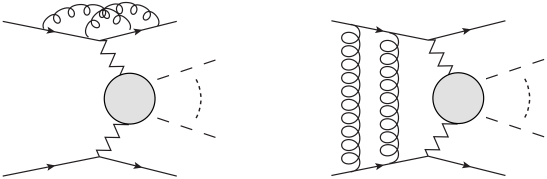
Monte-Carlo-Event Generator combining NLO calculations with parton shower programs

- POWHEG-method: Hardest emission with NLO accuracy $\rightarrow$ softer emissions by parton shower
- New process in the POWHEG-BOX-V2:
  $\rightarrow$ Process independent components: POWHEG-BOX
  $\rightarrow$ Process dependent components: User
- Based on method of splitting diagrams into building blocks ('bosonic tensors')
- Choose SM/anomalous coupling amplitudes in kappa-framework via input-file

* Nason [hep-ph/0409146], Frixione, Nason and Oleari [0709.2092], Alioli, Nason, Oleari and Re [1002.2581]

# ProVBFHH*

- QCD corrections to VBF-HH in VBF-approximation:
  $\rightarrow$ NNLO: fully differential $\rightarrow$ $\mathrm{N^3LO}$: inclusive in jet kinematics, fully differential in Higgs momenta
- Matrix elements expressed in terms of DIS structure functions
- Non-factorizable corrections in eikonal approximation, NNLO:



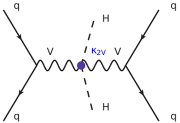
Source: Jäger, Karlberg and Reinhardt, [2502.09112]

- Updated to include anomalous couplings in kappa-framework
- Independent cross check of `POWHEG/VBF_HH` with `proVBFHH`

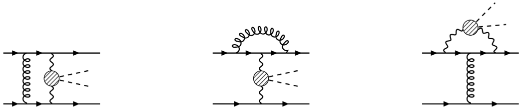
* Dreyer, Karlberg [1811.07918], [1811.07906]

# VBF_HH_HEFT (WHIZARD*+GoSam†)

- Higgs Effective Field Theory (HEFT)
- Event generator WHIZARD combined with one-loop-amplitude provider GoSam
- No VBF-approximation
  → include s-channel:




→ One-loop corrections:



Source: Braun, Bredt, Heinrich and Höfer, [2502.09132]

- Anomalous interactions for VBF-HH in HEFT:

$$\mathcal{L}_{eff} \supset \left(2c_V\frac{h}{v} + c_{2V}\frac{h^2}{v^2}\right)\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right) + c_\lambda \frac{m_h^2}{2v}h^3$$

* Moretti, Ohl, Reuter [hep-ph/0102195], Kilian, Ohl, Reuter [0708.4233]

† GoSam collaboration [1111.2034],[1404.7096], Braun et al. [GoSam-3.0 to appear]

# Phenomenological Results

# Settings

General settings:

- Proton-proton collision with $\sqrt{s} = 13\,\mathrm{TeV}$
- PDF: `NNPDF40MC_nnlo_as_01180` *, $\alpha_s(M_Z) = 0.118$
- $G_\mu$ scheme: $\alpha$ from $G_\mu = 1.16637x10^{-5}\,\mathrm{GeV}^{-2}$, $m_W$ and $m_Z$
- Masses and widths:

$$\begin{aligned} m_W &= 80.3692\,\mathrm{GeV}, & \Gamma_W &= 2.085\,\mathrm{GeV} \\ m_Z &= 91.1880\,\mathrm{GeV}, & \Gamma_Z &= 2.4955\,\mathrm{GeV} \\ m_H &= 125.2\,\mathrm{GeV}, & \Gamma_H &= 3.7x10^{-3}\,\mathrm{GeV} \end{aligned}$$

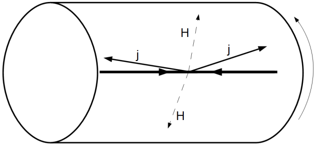
- Assuming diagonal CKM-matrix
- Factorization and renormalization scale (7-point scale variation):

$$\mu_R^2 = \mu_F^2 = \frac{m_H}{2}\sqrt{\left(\frac{m_H}{2}\right)^2 + p_{T,HH}^2}$$

* Cruz-Martinez, Forte, Laurenti, Rabemananjara and Rojo [2406.12961]

# Settings

VBF analysis setup:




- Jets: anti-$k_T$ algorithm with R=0.4. Require 2 tagging jets with

$$p_{T,j} > 25 \ \mathrm{GeV}, \ \ |y_j| < 4.5, \ \ m_{jj} > 600 \ \mathrm{GeV}, \ \ \Delta y_{jj} > 4.5, \ \ y_{j_1} \cdot y_{j_2} < 0$$

- Requirements for subleading jets:

$$p_{T,j_3} > 25\,\mathrm{GeV}, \qquad |y_{j_3}| < 4.5$$

Parton shower settings:

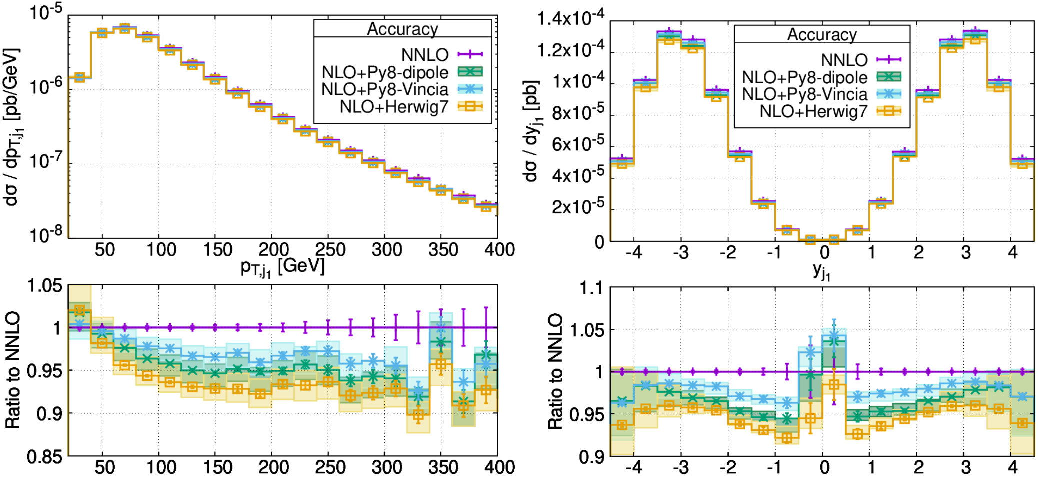
- `PYTHIA` version 8.312 * with `Monash 2013` tune †, global- and dipole-recoil scheme, `VINCIA` antenna shower
- `HERWIG7` version 7.3.0 ‡
- Underlying event, hadronization and MPI turned off but discussed in [2502.09112] and appendix

*Bierlich et al. [2203.11601]

†Skands, Carrazza and Rojo [1404.5630]

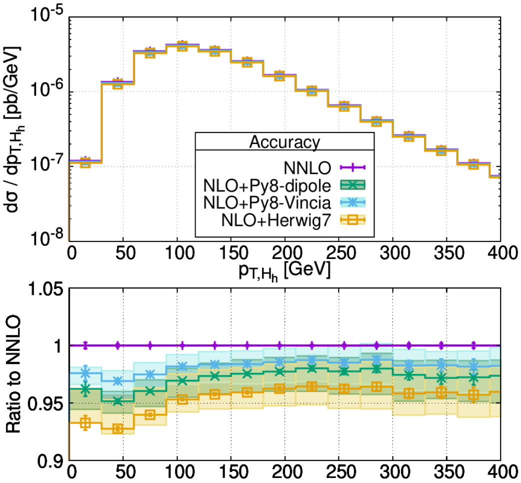
‡Bewick et al. [2312.05175]

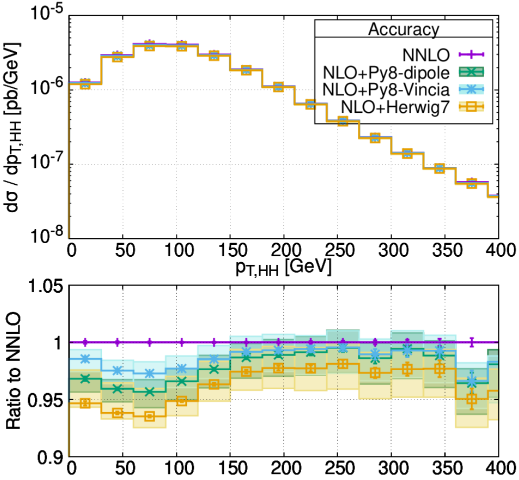
# Comparison NNLO (proVBFHH) and NLO+PS (POWHEG)




Source: Jäger, Karlberg and Reinhardt, [2502.09112]

# Comparison NNLO (proVBFHH) and NLO+PS (POWHEG)

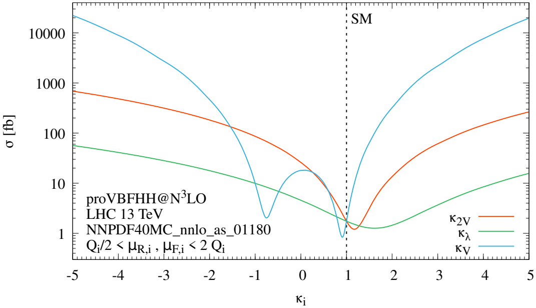


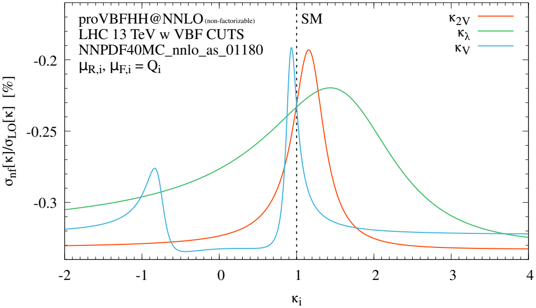




Source: Jäger, Karlberg and Reinhardt, [2502.09112]

# Anomalous Couplings

- Bounds for anomalous couplings used: $(0.6 < \kappa_{2V} < 1.5)$ *, $(0.98 < \kappa_V < 1.1)$ †, $(-1.2 < \kappa_\lambda < 7.2)$‡
- Cross section dependence at $\mathrm{N^3LO}$ and impact on non-factorizable corrections at NNLO (`proVBFHH`):




Source: Jäger, Karlberg and Reinhardt, [2502.09112]

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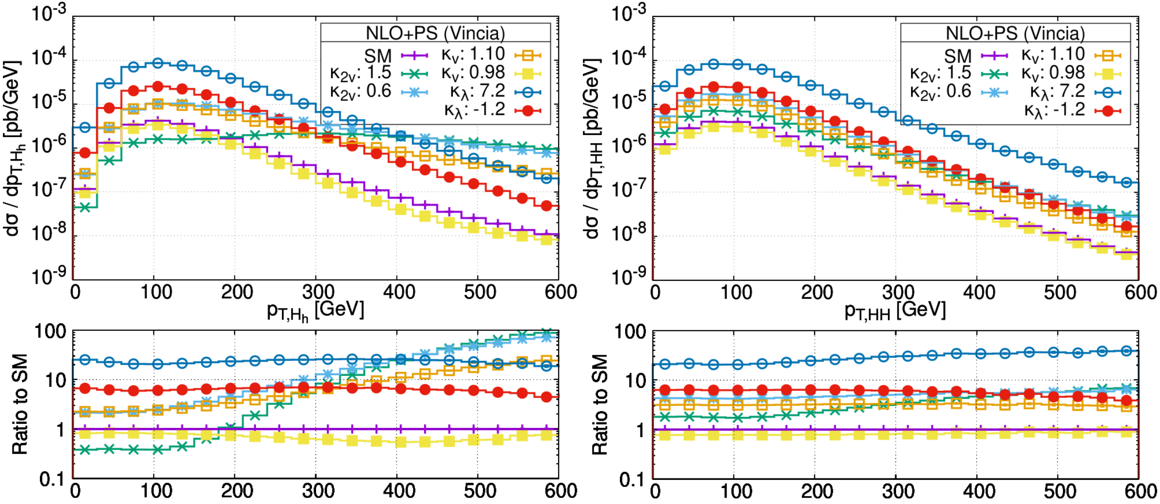
*ATLAS Collaboration [2406.09971]

†CMS Collaboration [2407.13554] (Fig. 6)

‡ATLAS Collaboration [2406.09971]

# Anomalous Couplings




Source: Jäger, Karlberg and Reinhardt, [2502.09112]

# Settings VBF_HH_HEFT

- Proton-proton collision with $\sqrt{s} = 13.6\,\mathrm{TeV}$
- PDF: PDF4LHC21_mc*, $\alpha_s(M_Z) = 0.118$
- EW scheme: $\alpha^{-1}(m_Z) = 127.9$, $G_\mu = 1.16637x10^{-5}\,\mathrm{GeV}^{-2}$ and $m_Z$
- Masses and widths:

$$\begin{aligned} m_W &= 79.8244\,\mathrm{GeV}, & \Gamma_W &= 2.085\,\mathrm{GeV} \\ m_Z &= 91.1876\,\mathrm{GeV}, & \Gamma_Z &= 2.4952\,\mathrm{GeV} \\ m_H &= 125.0\,\mathrm{GeV}, & \Gamma_H &= 4.07x10^{-3}\,\mathrm{GeV} \end{aligned}$$

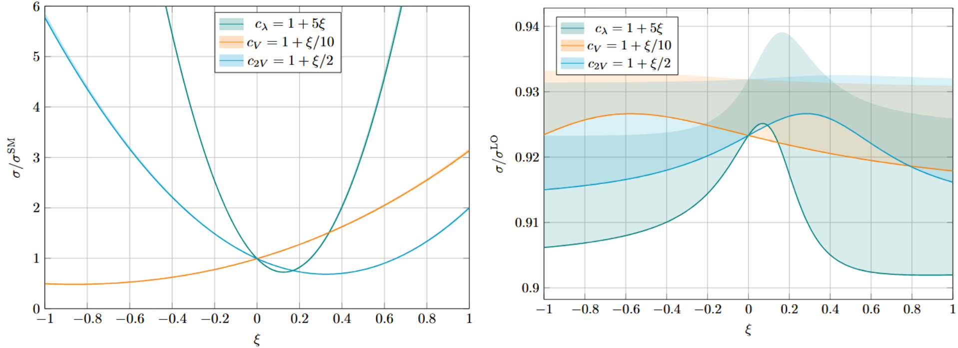
- Require 2 tagging jets with

$$p_{T,j} > 20\ \mathrm{GeV},\ \ |y_j| < 4.5,\ \ m_{jj} > 600\ \mathrm{GeV},\ \ |\eta_{j_1} - \eta_{j_2}| > 4.0$$

*Ball et al. [2203.05506]

# Results VBF_HH_HEFT

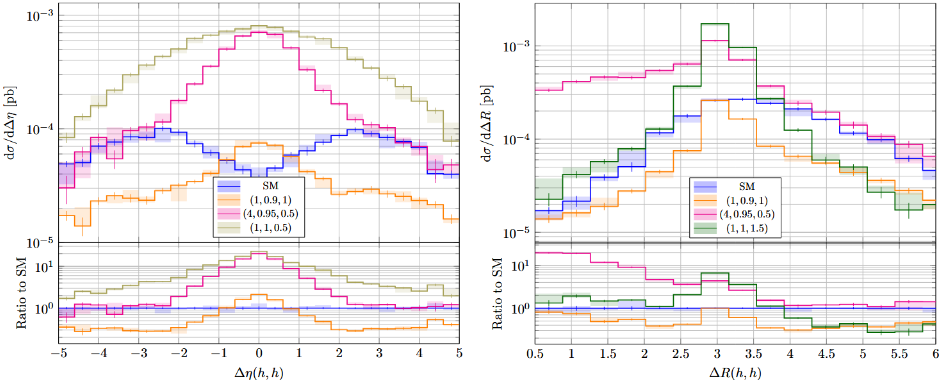
- Ratio of NLO to SM and LO:




Source: Braun, Bredt, Heinrich and Höfer, [2502.09132]

# Results VBF_HH_HEFT

- Distributions for $\Delta\eta_{HH}$ and $\Delta R_{HH}$:




Source: Braun, Bredt, Heinrich and Höfer, [2502.09132]

# Summary and Outlook

# Summary and Outlook

- Presented different implementations of VBF-HH
- Presented phenomenological results for a typical VBF cut setup
- Compared SM-NNLO results from `proVBFHH` and NLO+PS from `POWHEG` results for different parton shower settings
- Discussed results with HEFT by `VBF_HH_HEFT`
- Shape of distributions for different observables and total cross section dependent anomalous couplings
- Non-factorizable corrections and K-factor also influenced by anomalous couplings
- Work in progress: Detailed comparison of `POWHEG`/`proVBFHH` and `VBF_HH_HEFT`

Thanks for Listening!

Any Questions?

# Extra Slides

# Cross Section Values

SM results:

| accuracy | $\sigma$ [fb] | ratio to NLO |
|---|---|---|
| LO | 0.668 | 1.087 |
| NLO | 0.614 | 1 |
| NNLO | 0.603 | 0.982 |
| NLO+PYTHIA8 | $0.585^{+0.007}_{-0.009}$ | 0.953 |
| NLO+VINCIA | $0.592^{+0.007}_{-0.010}$ | 0.964 |
| NLO+HERWIG7 | $0.575^{+0.013}_{-0.007}$ | 0.936 |

Source: Jäger, Karlberg and Reinhardt, [2502.09112]

Anomalous couplings results (PY+Vincia):

| Coupling factor | $\sigma$ [fb] | ratio to SM |
|---|---|---|
| SM | 0.592 | 1 |
| $\kappa_{2V} = 1.5$ | 1.14 | 1.93 |
| $\kappa_{2V} = 0.6$ | 2.57 | 4.34 |
| $\kappa_V = 1.1$ | 1.86 | 3.15 |
| $\kappa_V = 0.98$ | 0.463 | 0.781 |
| $\kappa_\lambda = 7.2$ | 13.0 | 21.9 |
| $\kappa_\lambda = -1.2$ | 3.71 | 6.27 |

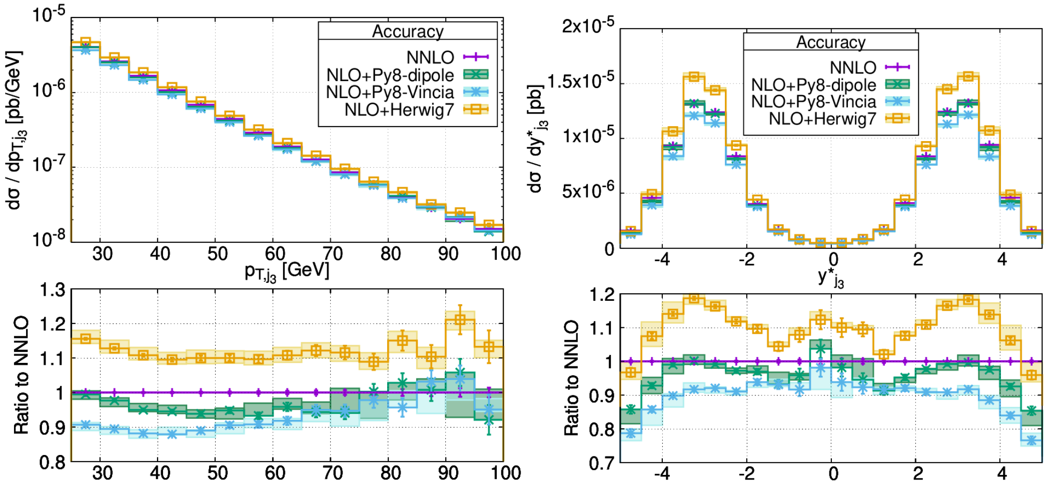
Source: Jäger, Karlberg and Reinhardt, [2502.09112]

VBF_HH_HEFT results:

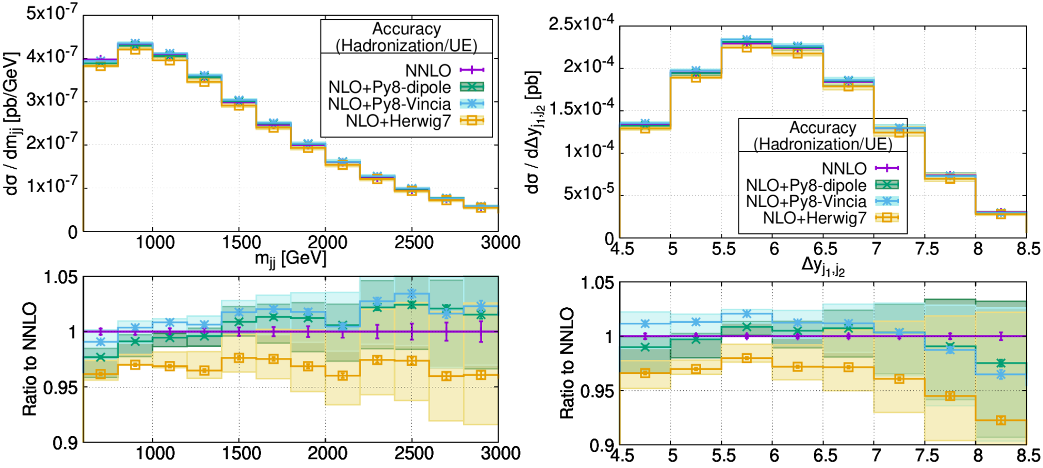
| No. | $c_\lambda$ | $c_V$ | $c_{2V}$ | $\sigma_{\text{NLO}}$ in fb | $\sigma_{\text{LO}}$ in fb | $\sigma_{\text{NLO}}/\sigma_{\text{LO}}$ | $\sigma_{\text{NLO}}/\sigma_{\text{NLO}}^{\text{SM}}$ |
|---|---|---|---|---|---|---|---|
| SM | 1 | 1 | 1 | $0.760^{+0.00}_{-0.029} \pm 0.006$ | $0.814^{+0.096}_{-0.068} \pm 0.003$ | 0.933(8) | 1.000(8) |
| 1 | -1 | 0.9 | 1.5 | $2.11^{+0.00}_{-0.07} \pm 0.01$ | $2.290^{+0.308}_{-0.245} \pm 0.004$ | 0.920(4) | 2.779(12) |
| 2 | -1 | 1.05 | 1.3 | $3.37^{+0.00}_{-0.07} \pm 0.02$ | $3.70^{+0.34}_{-0.29} \pm 0.01$ | 0.910(6) | 4.430(26) |
| 3 | 0 | 1 | 1 | $1.91^{+0.00}_{-0.03} \pm 0.01$ | $2.10^{+0.19}_{-0.17} \pm 0.01$ | 0.909(6) | 2.519(16) |
| 4 | 1 | 0.9 | 1 | $0.376^{+0.00}_{-0.011} \pm 0.003$ | $0.408^{+0.050}_{-0.039} \pm 0.001$ | 0.923(8) | 0.495(4) |
| 5 | 1 | 1 | 0.5 | $4.39^{+0.00}_{-0.018} \pm 0.02$ | $4.80^{+0.54}_{-0.46} \pm 0.01$ | 0.915(5) | 5.776(26) |
| 6 | 1 | 1 | 1.5 | $1.51^{+0.01}_{-0.05} \pm 0.01$ | $1.660^{+0.218}_{-0.177} \pm 0.003$ | 0.913(5) | 1.993(9) |
| 7 | 2 | 0.9 | 1.4 | $3.86^{+0.02}_{-0.12} \pm 0.02$ | $4.23^{+0.48}_{-0.40} \pm 0.01$ | 0.913(4) | 5.078(19) |
| 8 | 2 | 1 | 1 | $0.624^{+0.008}_{-0.029} \pm 0.005$ | $0.683^{+0.069}_{-0.059} \pm 0.003$ | 0.914(8) | 0.821(6) |
| 9 | 3 | 1.1 | 0.5 | $4.35^{+0.02}_{-0.13} \pm 0.02$ | $4.74^{+0.59}_{-0.49} \pm 0.01$ | 0.917(5) | 5.729(28) |
| 10 | 4 | 0.95 | 0.5 | $2.38^{+0.03}_{-0.05} \pm 0.01$ | $2.62^{+0.28}_{-0.23} \pm 0.01$ | 0.909(6) | 3.134(19) |
| 11 | 6 | 1.1 | 1 | $9.82^{+0.05}_{-0.17} \pm 0.05$ | $10.90^{+0.94}_{-0.84} \pm 0.03$ | 0.903(5) | 12.93(7) |

Source: Braun, Bredt, Heinrich and Höfer, [2502.09132]

# Comparison NNLO (proVBFHH) and NLO+PS (POWHEG)




Source: Jäger, Karlberg and Reinhardt, [2502.09112]

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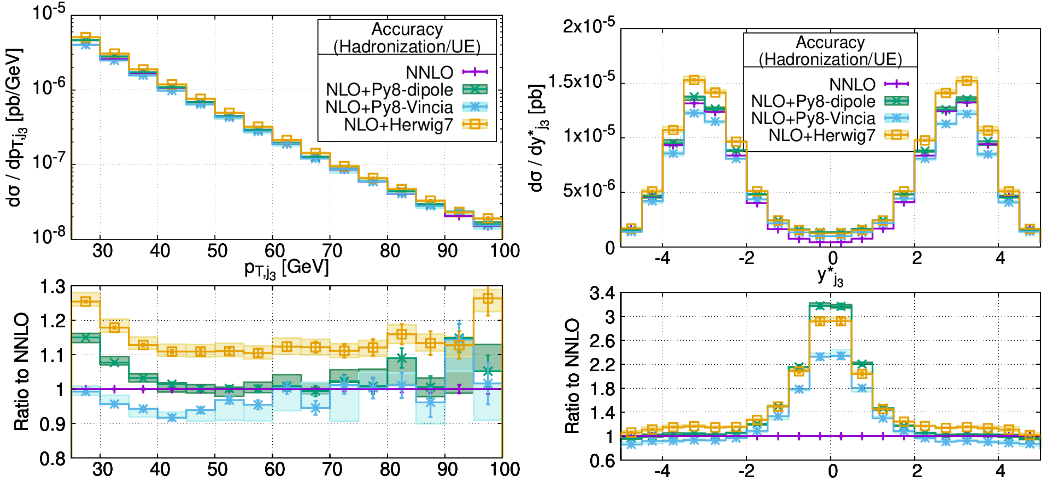
# Comparison NNLO (`proVBFHH`) and NLO+PS (`POWHEG`)

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