The MC generator Whizard for future collider studies

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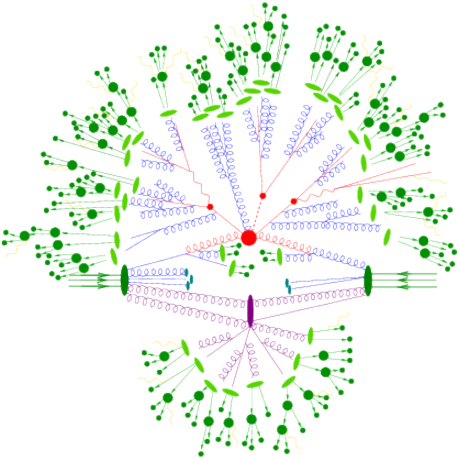
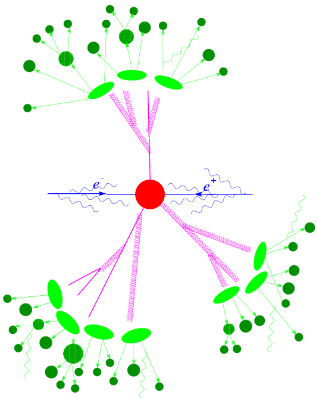
11.07.2025

Monte Carlo generators: *pp* collisions



Credits: SHERPA

Monte Carlo generators: e^+e^- collisions



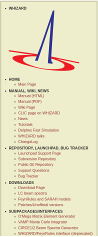
Credits: SHERPA

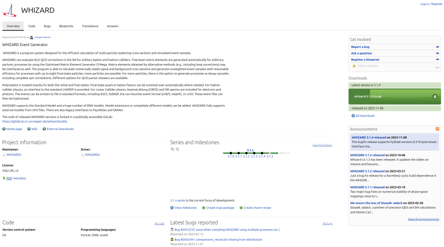
WHIZARD: overview

- WHIZARD 3: released on 27.04.2021
- complete MC tool for high-energy colliders (LHC, FCC, LCF, MuC...)
- hard interactions at LO internal: O'Mega
- hard interactions at NLO external: OpenLoops, Recola, GoSam...
- parton shower internal (QCD only) or external (Pythia6/8)
- external hadronisation
- lepton collider beam setups
  - Gaussian spread/beam spectra
  - beam polarisation (any combination)
  - ISR, EPA, EVA
  - crossing angle, asymmetric beams
- BSM via internal models and UFO interface

WHIZARD: User support

- manual: `https://whizard.hepforge.org/manual.pdf`
- LaunchPad: `https://launchpad.net/whizard`
- contact: whizard@desy.de





BSM support

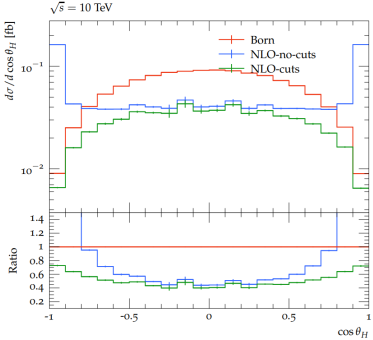
- a variety of internal models (SM, MSSM, THDM, Littlest Higgs, ...); full support for UFO models (LO)
- spin 0, 1/2, 1, 3/2 and 2 supported
- Majorana-fermion statistics available
- arbitrary Lorentz structure supported
- 5-, 6-, 7-, 8-, ... point vertices (optimisation pending)
- arbitrary SU(N) supported, complicated colour structures (sextets, decuplets, ...) available

  [1206.3700], [2403.04685]
- Suggestions from users taken into account

NLO SM automation

- NLO SM automation for lepton/hadron colliders completed in 2022
- FKS subtraction (also resonance-aware), NLO matrix elements from external providers
- setup for automatic differential fixed-order results
- loop-induced processes supported

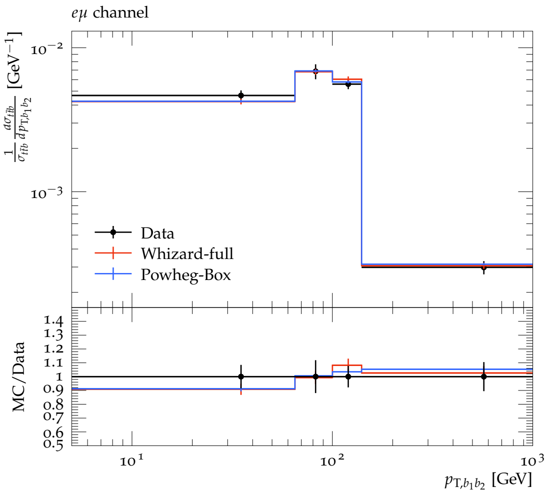
$\mu^+\mu^- \to X, \sqrt{s} = 3$ TeV	$\sigma^{\rm incl}_{\rm LO}$ [fb]	$\sigma^{\rm incl}_{\rm NLO}$ [fb]	$\delta_{\rm EW}$ [%]
W^+W^-	$4.6591(2) \cdot 10^2$	$4.847(7) \cdot 10^2$	$+4.0(2)$
ZZ	$2.5988(1) \cdot 10^1$	$2.656(2) \cdot 10^1$	$+2.19(6)$
HZ	$1.3719(1) \cdot 10^0$	$1.3512(5) \cdot 10^0$	$-1.51(4)$
HH	$1.60216(7) \cdot 10^{-7}$	$5.66(1) \cdot 10^{-7}$ *	
W^+W^-Z	$3.330(2) \cdot 10^1$	$2.568(8) \cdot 10^1$	$-22.9(2)$
W^+W^-H	$1.1253(5) \cdot 10^0$	$0.895(2) \cdot 10^0$	$-20.5(2)$
ZZZ	$3.598(2) \cdot 10^{-1}$	$2.68(1) \cdot 10^{-1}$	$-25.5(3)$
HZZ	$8.199(4) \cdot 10^{-2}$	$6.60(3) \cdot 10^{-2}$	$-19.6(3)$
HHZ	$3.277(1) \cdot 10^{-2}$	$2.451(5) \cdot 10^{-2}$	$-25.2(1)$
HHH	$2.9699(6) \cdot 10^{-8}$	$0.86(7) \cdot 10^{-8}$ *	
$W^+W^-W^+W^-$	$1.484(1) \cdot 10^0$	$0.993(6) \cdot 10^0$	$-33.1(4)$
W^+W^-ZZ	$1.209(1) \cdot 10^0$	$0.699(7) \cdot 10^0$	$-42.2(6)$
W^+W^-HZ	$8.754(8) \cdot 10^{-2}$	$6.05(4) \cdot 10^{-2}$	$-30.9(5)$
W^+W^-HH	$1.058(1) \cdot 10^{-2}$	$0.655(5) \cdot 10^{-2}$	$-38.1(4)$
$ZZZZ$	$3.114(2) \cdot 10^{-3}$	$1.799(7) \cdot 10^{-3}$	$-42.2(2)$
$HZZZ$	$2.693(2) \cdot 10^{-3}$	$1.766(6) \cdot 10^{-3}$	$-34.4(2)$
$HHZZ$	$9.828(7) \cdot 10^{-4}$	$6.24(2) \cdot 10^{-4}$	$-36.5(2)$
$HHHZ$	$1.568(1) \cdot 10^{-4}$	$1.165(4) \cdot 10^{-4}$	$-25.7(2)$



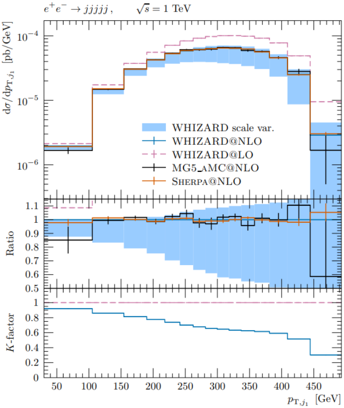
[2208.09438]

NLO SM automation

Validation: p_{T,b_1b_2} in $pp \to e\mu\nu\nu bb$ compared to ATLAS Run-2 data from 2018 [NLO QCD]



NLO SM automation



[2104.11141]

NLO BSM automation

- NLO QCD available for BSM with GoSam
- e.g. $pp \to jjHH$ NLO QCD in HEFT [2502.09132]

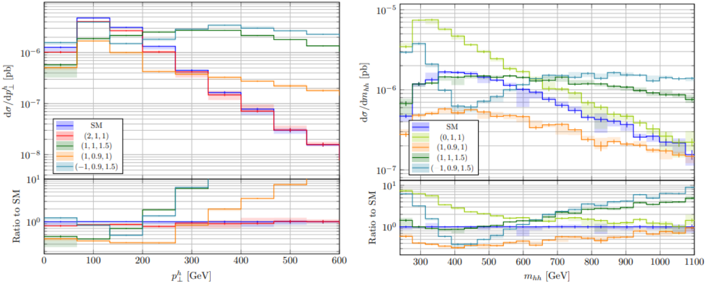
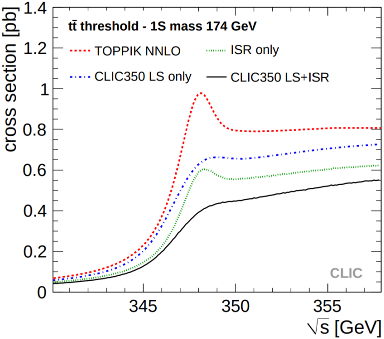


Figure 5: Transverse momentum distribution of (any of) the Higgs bosons (left) and invariant-mass distribution of the di-Higgs system (right) for selected benchmark points in (c_λ, c_V, c_{2V})-space of table 1 at NLO.

Beam spectra

- To achieve high luminosity, bunches are squeezed strongly which creates strong electromagnetic fields.
- Each beam feels the electromagnetic field of the opposite beam.
- Deflected beams emit beamstrahlung, in addition to the ISR from the hard scattering process.
- As a result, beam energies are smeared; the effect is non-negligible.



[1303.3758]

CIRCE2

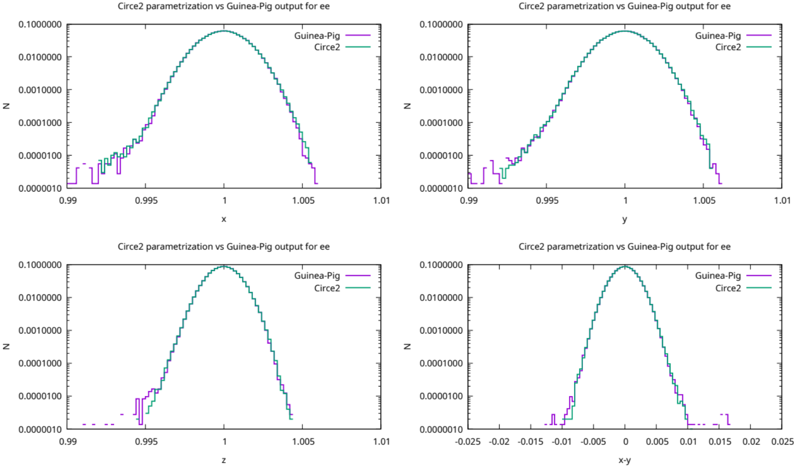
- CIRCE2 acts as a bridge between beam simulation and event generation.
- It is available as a part of WHIZARD and as a separate package, also for generating smooth distributions from your own Guinea-Pig and CAIN outputs.

Index of /circe_files

Name	Last modified	Size	Description
Parent Directory		-	
C3/	2025-04-15 11:16	-	
CEPC/	2016-07-29 13:22	-	
CLIC/	2017-06-23 16:04	-	
FCCee/	2025-06-17 09:48	-	
ILC/	2019-11-18 17:07	-	
TESLA/	2016-07-29 13:22	-	
XCC/	2025-04-15 15:37	-	

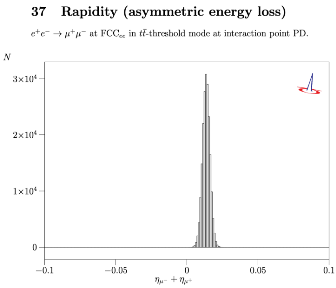
Example: FCC-ee beams

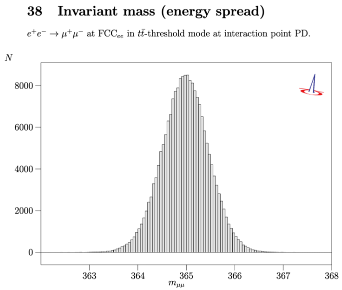
Fitting e^+e^- spectrum at tt [Thorsten Ohl, 2024/25]



FCC-ee beam spectrum

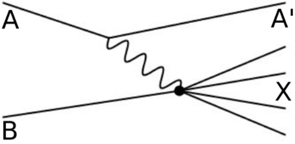
- New development: FCC-ee beam spectra based on the most recent 2025 machine design
- Five different interaction regions: PA, PJ, PD, PG and a fictitious symmetric interaction point, PB
- Four different energy runs: Z pole (91 GeV), WW threshold (161 GeV), ZH threshold (240 GeV), tt threshold (365 GeV)



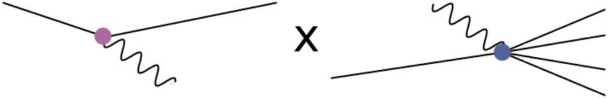


Electroweak factorisation

- At multi-TeV lepton colliders, vector-boson-fusion processes are often significant, compared to *s*-channel annihilation, as VBF is enhanced by soft/collinear logs.
- Let us consider a certain vector-boson-initiated process:



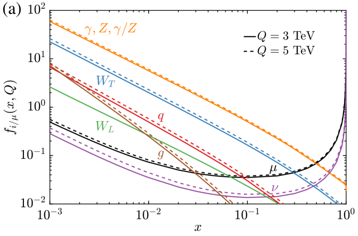
- Ideally, we would like to *factorise* the process into a universal structure function describing the boson emission and a hard-process cross section:



$$\sigma(f_A f_B \to f'_A X) = \sum_{\lambda_V} \int_{x_{min}}^{1} \mathrm{d}x F_{\lambda_V}(x, \mu_F) \times \hat{\sigma}(f_B V_{\lambda_V} \to X)$$

EW PDFs

- The structure function $F_{\lambda_V}(x, \mu_F)$ can be computed analytically in the collinear limit at leading order (*Effective W/Z Approximation*).
- At very high energies, collinear logs are large. They can be resummed in a PDF-like way (*Electroweak PDFs*).
- Above the electroweak scale, multiple emissions can occur and all SM particles have to be taken into account in the PDF.
- Polarisation effects become important even for unpolarised beams!
- First LHAPDF-like EW PDF sets available → [LePDF]
- Implementation far from trivial: multiple scales, lower cut-off scale, polarisation, interference, beam remnants...

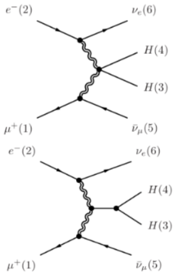


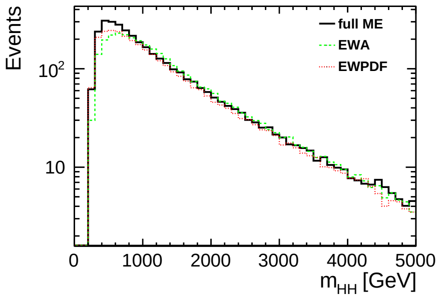
[2007.14300]

Double Higgs production

Both EWA and EW PDFs (with some limitations) implemented in Whizard; *soon* to become public

PRELIMINARY





$$e^- \mu^+ \rightarrow HH + X$$

Conclusions and Outlook

- Whizard is an efficient tool for physics studies and analyses at HEP experiments: LHC, Belle II, ILC/CLIC/FCC/CEPC, MuC, ...
- Any SM (NLO) and a vast set of BSM processes can be handled, limited mainly by external programs and CPU time.
- Specific support for future colliders is one of the highest priorities of our collaboration.

The WHIZARD 3 Team

U. Siegen: Wolfgang Kilian, Pia Bredt, Nils Kreher, Tobias Striegl

DESY: Jürgen Reuter, Krzysztof Mękała

U. Würzburg: Thorsten Ohl

U. Warsaw (exp.): Filip Żarnecki

KIT: Marius Höfer

Links

- Reference: Kilian/Ohl/Reuter, EPJ C71 (2011) 1742
- WHIZARD Portal: `https://whizard.hepforge.org/`
- Launchpad Page: `https://launchpad.net/whizard`
- gitlab repo: `https://gitlab.tp.nt.uni-siegen.de/whizard/public`

BACKUP

Technical Remarks

- **Language:** `Fortran` (2018, object-oriented/modular) with `O'Caml`
- **Development:** `gitlab` with automated test suite and CI
- **Installation:** `configure && make && make install`
- **Numerics:** Support for extended and quadruple precision (if needed)
- **Running:** Options
  1. Stand-alone with input script: `whizard` ⟨*input*⟩`.sin` (optional workspace transfer for cluster operation)
  2. As a library, callable from: `Fortran`, `C`, `C++`, `Python`
- **BSM:** Predefined (many models) and UFO (everything else)
- **Script:** SINDARIN (input, parameters, cuts, workflow, result aggregation, output control, ...)
- **Parallel:** OpenMP (multi-core), MPI (HPC cluster)