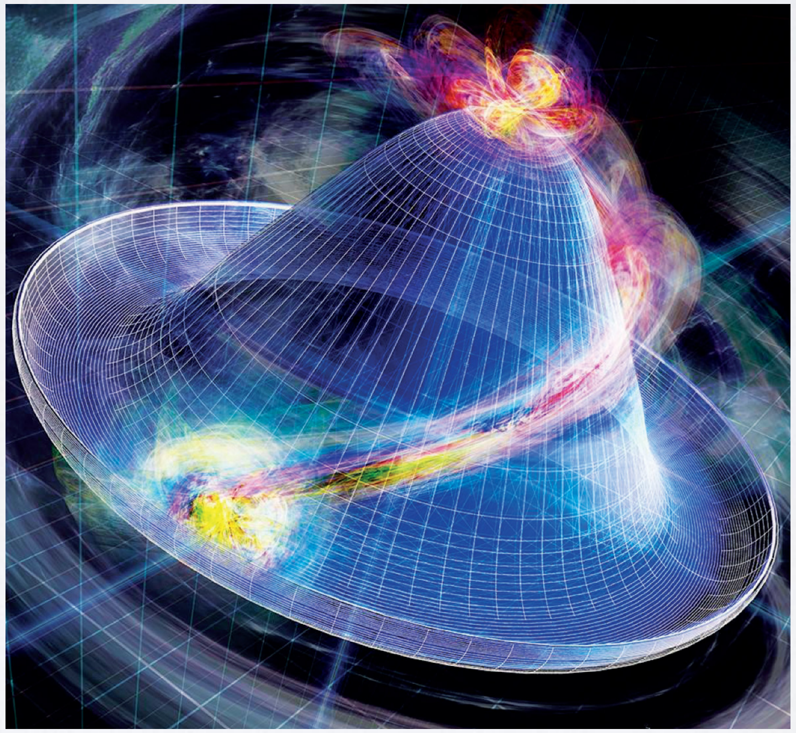
The WHIZARD Generator, Status, Projects & Plans



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Universität Hamburg
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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

BASED UPON: hep-ph/9607454 ; hep-ph/9806432 ; hep-ph/0102195 ; 0708.4241 ; 1112.1039 ; 1206.3700 ; 1411.3834; 1510.02739 ; 1609.03390 ; 1811.09711

WHIZARD: Overview & Technicalities

WHIZARD v3.0.1 (08.07.2021)

http://whizard.hepforge.org

http://launchpad.net/whizard

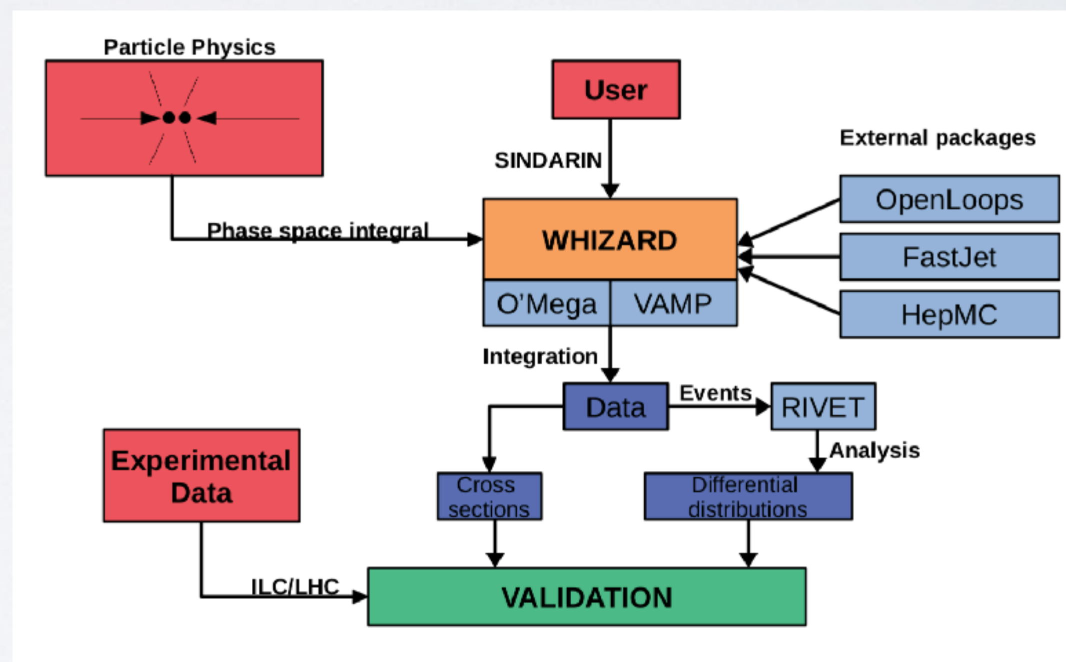
<whizard@desy.de>

WHIZARD Team: W. Kilian, T. Ohl, JRR; S. Braß / P. Bredt / N. Kreher / P. Stienemeier / T. Striegl

☑ Event generator for lepton-lepton, hadron and lepton-hadron colliders (SM & BSM)

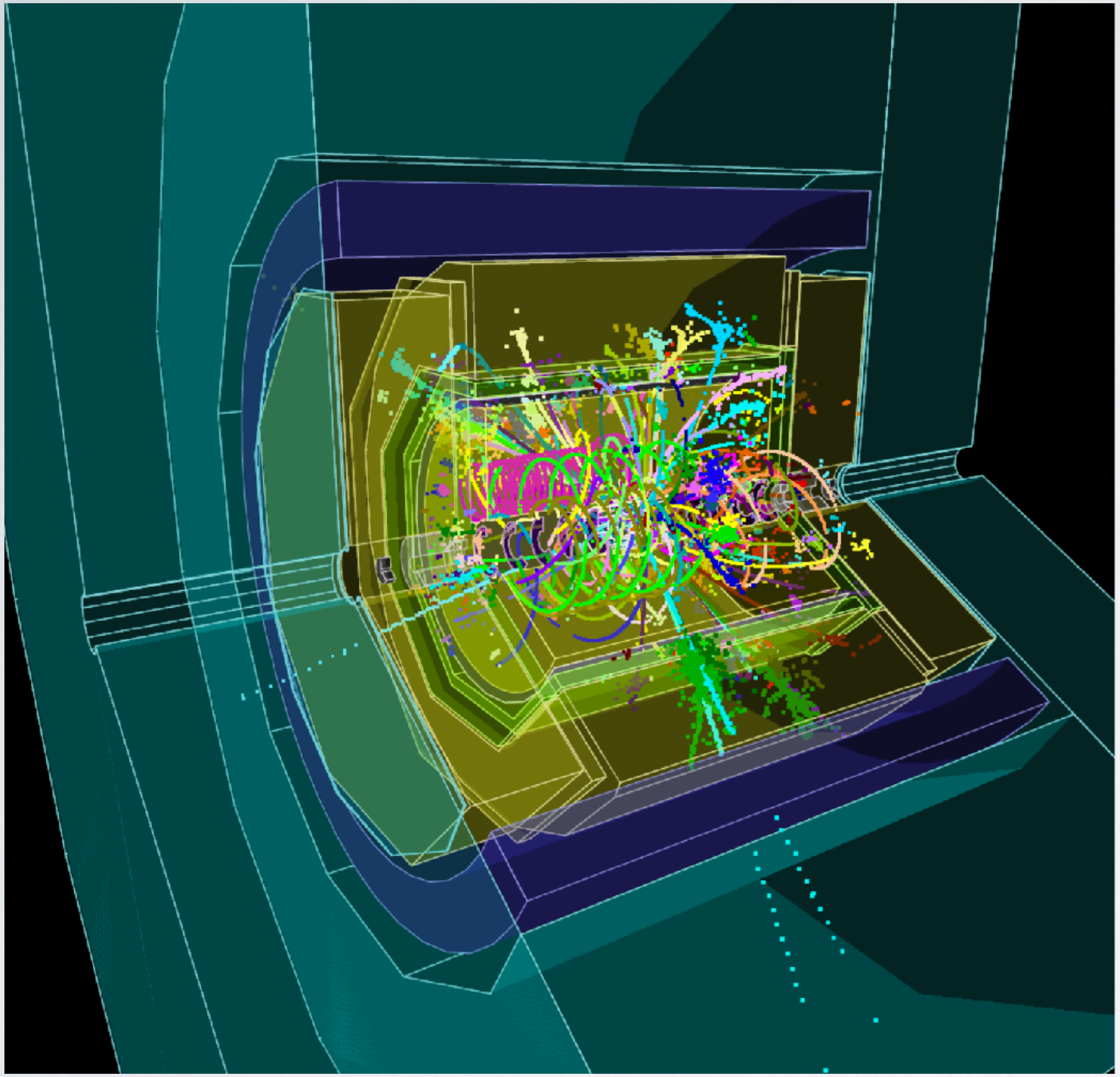
- Programming Languanges: `Fortran2018 (gfortran ≥7.5.0),OCaml (≥4.05.0)`
- Large self test suite, unit tests [module tests], regression testing
- Continous integration system (`gitlab CI` @ Siegen)
- Integrated fully in ILCDirac/DD4Hep software chain

  cf. Talk by Mikael Berggren



- Installed centrally, physics runs in workspaces
- Standard installation: `configure`
- `make, [ make check ], make install`
- Working directory: run `whizard <input>.sin`

Lepton simulations in WHIZARD



SLAC Bereiche

Linear Collider

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Standard Model Data Samples

Angelegt von Timothy Barklow, zuletzt geändert am Okt 12, 2018

Lumi_linker number	Ecm(GeV)	General Description	Machine Configuration
2	500	RDR (Jul 2005)	rdr
3	350	RDR (Aug 2005)	rdr
4	250	RDR (Aug 2008) but do_isr=T (ISR turned on by mistake)	rdr_isr_on
5	250	RDR (May 2009) (note: beams 1 & 2 are swapped, see user.f90)	rdr_beams_swapped
6	350	SB2009_350_nTF_extbunches	sb2009_ntf
7	500	SB2009_500_nTF_extbunches	sb2009_ntf
8	350	SB2009_350_TF_extbunches	sb2009_tf
9	500	SB2009_500_TF_extbunches	sb2009_tf
10	3000	CLIC_July_2010_C++	clic_cplus
11	3000	CLIC_Aug_2010_C_Schulte	clic_schulte_aug2010
12	1000	ILC_1000_with_TF_Aug_2010	ilc_tf_aug2010
13	500	CLIC_500_Feb_2011_Schulte	clic_shulte_feb2011
14	1000	ILC_1000_5pcBS_no_TF_Sep_2011	5pcBS_notf
15	1000	ILC_1000_10pcBS_no_TF_Sep_2011	10pcBS_notf
16	1000	ILC_1000_B1b_with_TF_Nov_2011	B1b_tf
17	1500	CLIC_1500_Nov_2011	clic_1500_nov2011
18	1000	ILC_1000_Waisty_opt_Jan_2012	B1b_ws
19	1400	CLIC_1400_Jan_2012	clic_1400_jan2012
20	350	CLIC_350_Apr_2012	clic_350_apr2012
21	500	ilc_500_waisty_250_jan_2012	TDR_ws
22	250	ilc_250_waisty_250_jan_2012	TDR_ws
23	350	ilc_350_waisty_250_jan_2012	TDR_ws

$e^+ e^- \to tth$ @ 1 TeV in 8 jets

"SLAC DBD samples" and 250 GeV ILC: full SM !

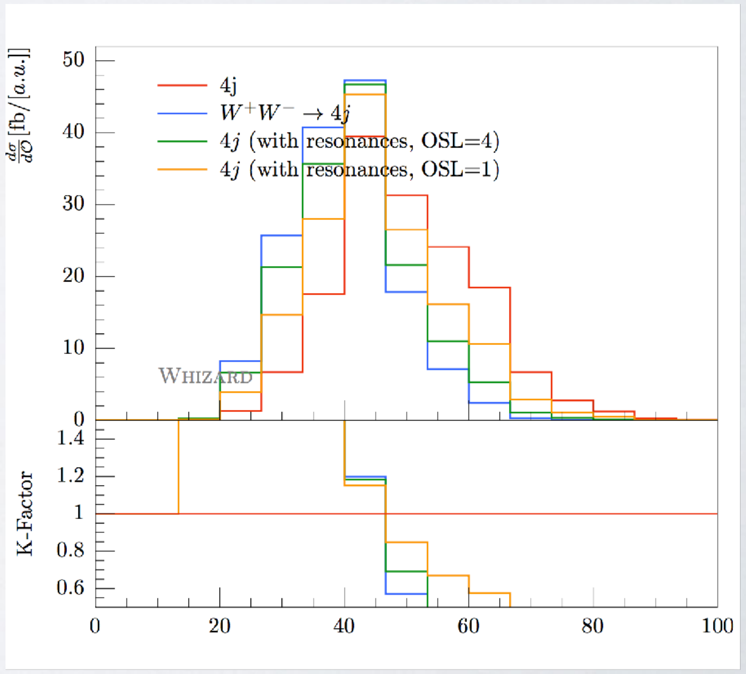
cf. the ILC Snowmass tutorials and Mikael Berggren's talk

WHIZARD: Features

- ☑ Tree-level ME generator O'Mega (fully recursive, compiled code and virtual machine)
- ☑ Interfaces to external packages:
  FastJet, GoSam, GuineaPig(++),HepMC2/3,HOPPET, LCIO, LHAPDF(5/6), LoopTools, OpenLoops, PYTHIA6 [internal], PYTHIA8, Recola, StdHep [internal], Tauola/PHOTOS [internal]
- Gridpack functionality for packing and unpacking
- ☑ Event formats: ASCII, LHA, LHEF (v1-3), StdHEP/LCIO/HepMC2/HepMC3
- WHIZARD API: callable as a library from any C/C++/Fortran/Python program / Jupyter
- Scattering processes (2→10 etc.) and [auto-] decays, factorized processes, preset BRs
- Scripting language for the steering: SINDARIN

```
cuts = let subevt @cljets = cluster [jet] in
       select if Pt > 30 GeV [@cljets] in
```

- ⟹ arbitrary cut expressions, subevents & clustering, scales
- Parton shower/hadronization: direct interfaces to PYTHIA6/8
  (HERWIG/Sherpa via LHE/HepMC events)
- Insertion of resonance histories, e.g. $e^+e^- \to WW/ZZ \to (jj)(jj)$
- ☑ Rescanning/-weighting of event files, multiple observables
  (with concatenated structure functions & resonance histories)



WHIZARD: Manual & Tutorials

https://whizard.hepforge.org/manual/

whizard is hosted by Hepforge, IPPP Durham

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WHIZARD 3.0
A generic
Monte-Carlo integration and event generation package
for multi-particle processes
MANUAL [1]

Wolfgang Kilian, Thorsten Ohl, Jürgen Reuter, with contributions from Fabian Bach, Simon Braß, Pia Bredt, Bijan Chokoufé Nejad, Christian Fleper, Vincent Rothe, Sebastian Schmidt, Marco Sekulla, Christian Speckner, So Young Shim, Florian Staub, Pascal Stienemeier, Christian Weiss

WHIZARD Manual @

https://whizard.hepforge.org/

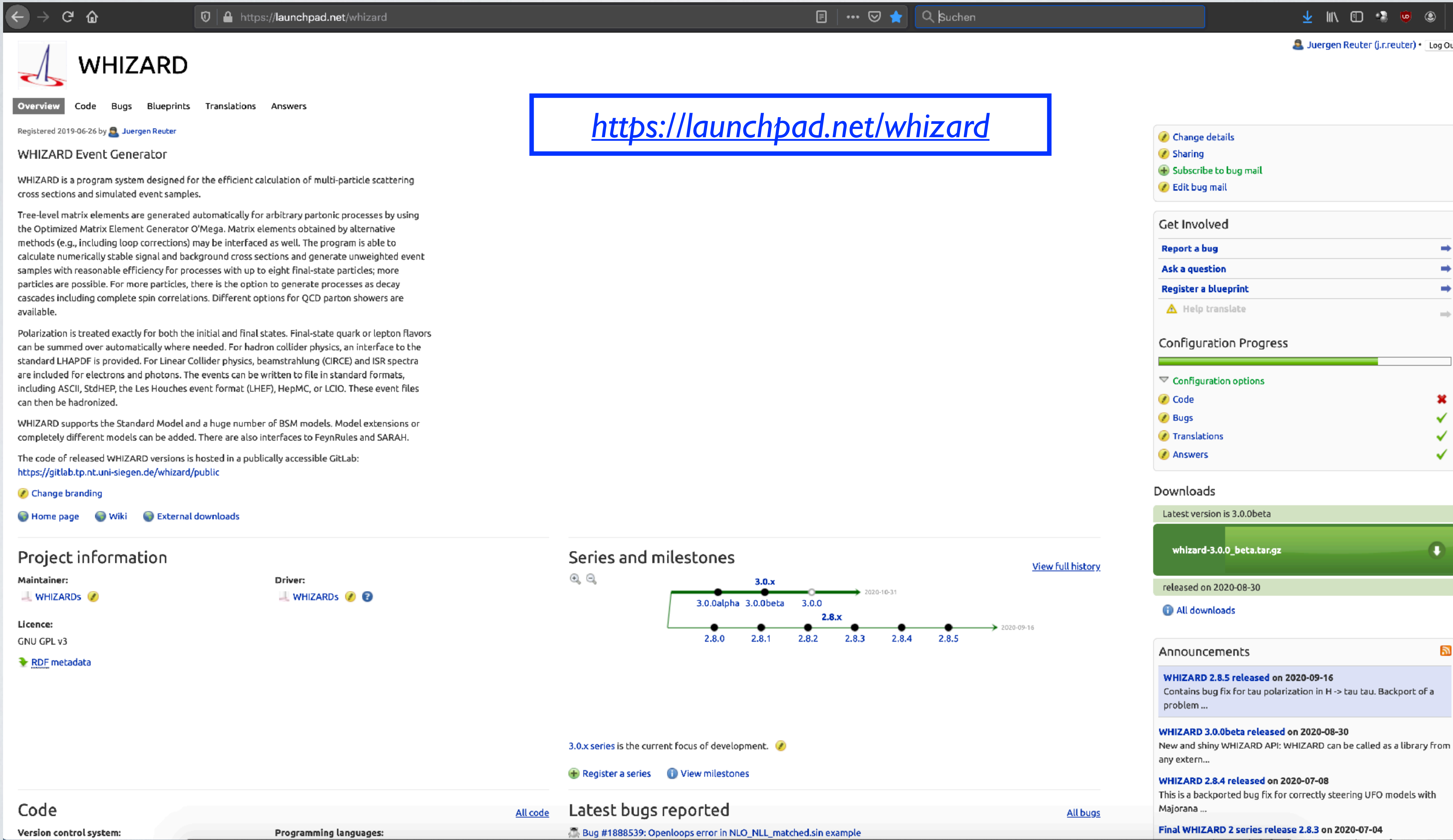
available as PDF and web pages

WHIZARD Tutorial

e.g. for Snowmass, 20.9.2020: https://indico.fnal.gov/event/45413/

WHIZARD: User support / bug tracker

WHIZARD v3.0.1 (08.07.2021) https://launchpad.net/whizard



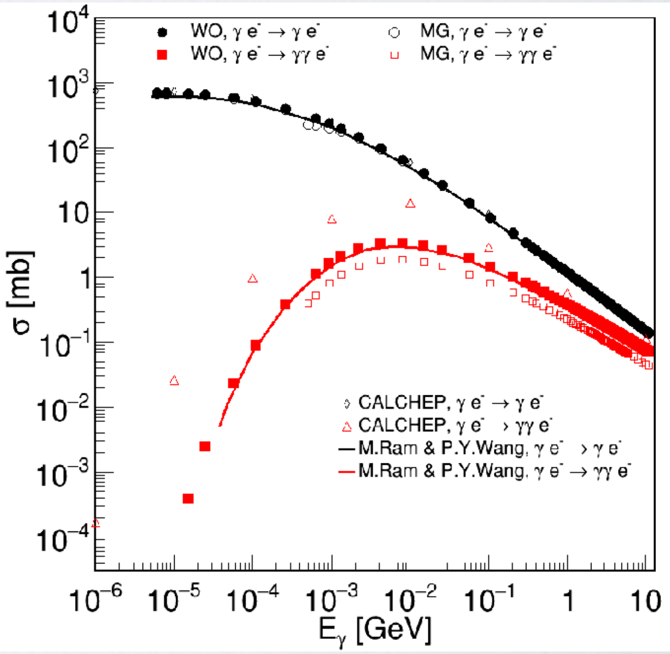
Beam simulations in WHIZARD

1. Unpolarized simulation with unpol. spectra
2. Pol. simulation: unpol. spectra + pol. beams
3. Polarized spectrum with helicity luminosities
4. W.i.p.: simulate z dependence [cf. talk T. Ohl]

- ☑ Beamstrahlung for lepton colliders CIRCE1/2
- ☑ Photon collisions (Compton backscatt.) CIRCE2
- ☑ Effective Photon and Effective W/Z approximation
- ☑ Beam events from file
- ☑ Gaussian beam spread (in energy, plans for spread in angles)
- ☑ Proton collisions (LHAPDF & internal)
- ☑ Lepton-hadron collisions
- ☑ asymmetric beams, crossing angle, fixed-target mode
- ☑ Polarized beams: completely general (density matrix), polar. fractions
- ☑ Electron PDFs: LL available, NLL in implementation
- ☑ ISR/EPA handler generates physical p_T distributions
- ☑ All options also for decays: particle beams, polarized decays etc.

```
beams_pol_density = @([<spin entries>]), @([<spin entries>])
beams_pol_fraction = <degree beam 1>, <degree beam 2>
```

```
beams_momentum = 250 GeV, 250 GeV
beams_theta = 0, 10 degree
```



Lepton Collider Beam Spectra

from: https://whizard.hepforge.org/circe_files/

Index of /circe_files/CEPC

Name	Last modified	Size	Description
Parent Directory		-	
cepc240.circe	29-Jul-2016 13:20	252K	
cepc250.circe	29-Jul-2016 13:20	252K	

Index of /circe_files/ILC

Name	Last modified	Size	De
Parent Directory		-	
250_SetA_ee024.circe	2019-11-04 02:41	5.2M	
250_SetA_eg024.circe	2019-11-04 02:41	3.6M	
250_SetA_ge024.circe	2019-11-04 02:41	3.6M	
250_SetA_gg024.circe	2019-11-04 02:41	2.6M	
500_TDR_ws_ee021.circe	2019-11-18 16:59	9.4M	
500_TDR_ws_eg021.circe	2019-11-18 16:59	3.6M	
500_TDR_ws_ge021.circe	2019-11-18 16:59	3.6M	
500_TDR_ws_gg021.circe	2019-11-18 16:59	2.6M	
1000_B1b_ws_ee018.circe	2019-11-18 16:59	34M	
ilc200ee_nobeamsprea..>	2016-07-29 13:20	1.0M	
ilc230ee_nobeamsprea..>	2016-07-29 13:20	1.0M	
ilc250ee_nobeamsprea..>	2016-07-29 13:20	1.0M	
ilc350ee_nobeamsprea..>	2016-07-29 13:20	1.0M	
ilc500ee_nobeamsprea..>	2016-07-29 13:20	1.0M	

FCC-ee-365 in simulation, cf. talk by Thorsten Ohl

Index of /circe_files/TESLA

Name	Last modified	Size	Description
Parent Directory		-	
teslagg_500.circe	29-Jul-2016 13:20	1.1M	
teslagg_500_polavg.circe	29-Jul-2016 13:20	270K	

Index of /circe_files/CLIC

Name	Last modified	Size	De
Parent Directory		-	
0.5TeVeeMapPB0.67E0.0Mi0.30.circe	06-Jul-2016 17:03	6.0M	
0.5TeVegMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	6.0M	
0.5TeVgeMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	6.0M	
0.5TeVggMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	3.9M	
0.35TeVeeMapPB0.67E0.0Mi0.30.circe	06-Jul-2016 17:02	6.0M	
0.35TeVegMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:02	6.0M	
0.35TeVgeMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	6.0M	
0.35TeVggMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	3.9M	
0.38TeVeeMapPB0.67E0.0Mi0.30.circe	23-Jun-2017 16:02	14M	
0.38TeVegMapPB0.67E0.0Mi0.0.circe	23-Jun-2017 16:02	9.0M	
0.38TeVgeMapPB0.67E0.0Mi0.0.circe	23-Jun-2017 16:02	9.0M	
0.38TeVggMapPB0.67E0.0Mi0.0.circe	23-Jun-2017 16:02	3.9M	
1.4TeVeeMapPB0.67E0.0Mi0.15.circe	06-Jul-2016 17:03	35M	
1.4TeVegMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:03	15M	
1.4TeVgeMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:04	7.8M	
1.4TeVggMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:04	15M	
3TeVeeMapN100.circe	06-Jul-2016 17:04	1.0M	
3TeVeeMapPB0.67E0.0Mi0.15.circe	06-Jul-2016 17:04	24M	
3TeVegMapN100.circe	06-Jul-2016 17:04	521K	
3TeVegMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:04	12M	
3TeVgeMapN100.circe	06-Jul-2016 17:04	1.0M	
3TeVgeMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:04	24M	
3TeVggMapN100.circe	06-Jul-2016 17:05	273K	
3TeVggMapPB0.67E0.0Mi0.0.circe	06-Jul-2016 17:05	6.1M	

Efficient Phase Space Integration & Simulation

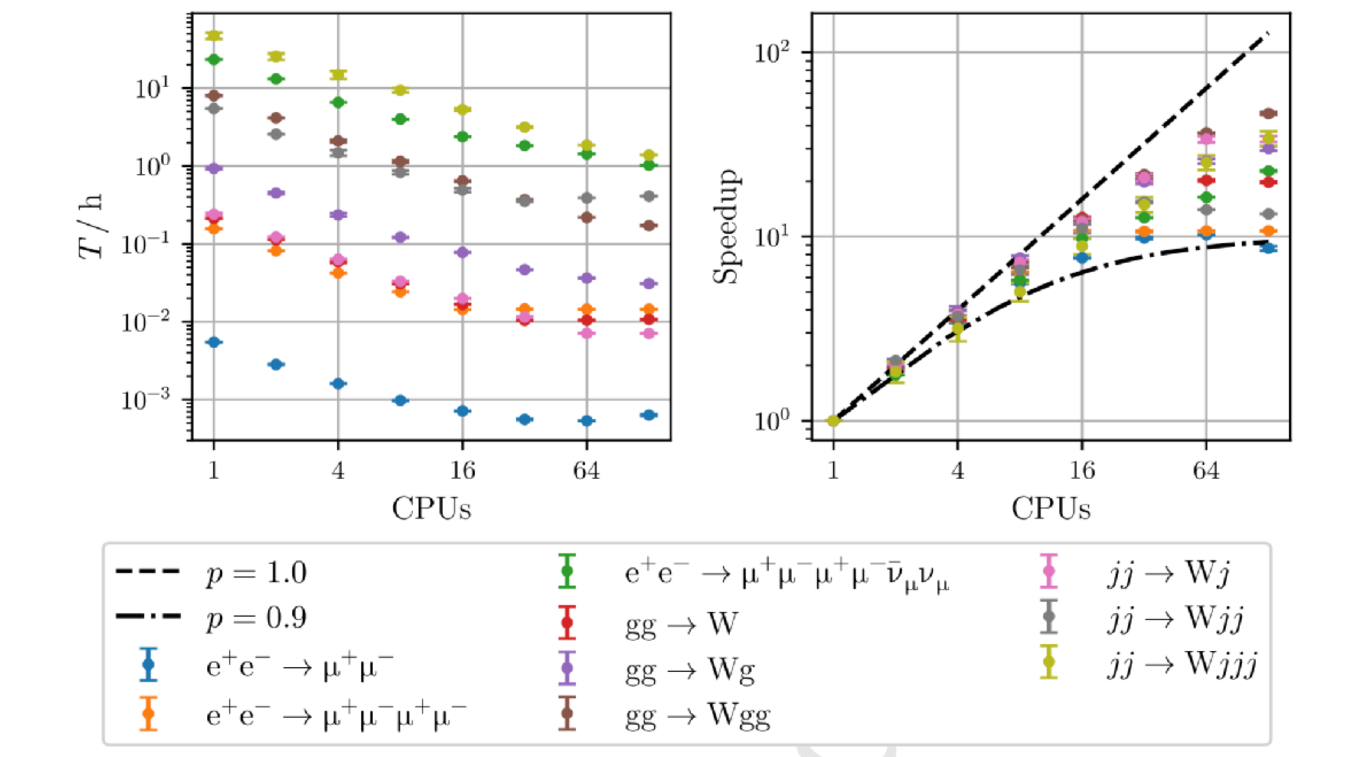
- `VAMP`: adaptive multi-channel Monte Carlo integrator
- `VAMP2`: fully MPI-parallelized version, using RNG stream generator

`WHIZARD` algorithm: heuristics to classify phase-space topology, adaptive multi-channel mapping $\Longrightarrow$ optimized for EW resonances

Complicated processes:
factorization into production and decay
with `unstable` option

Cascade decay, factorize production and decay

```
unstable “W+” { decay_helicity = 0 }
```



- Parallelization of integration: OMP multi-threading for different helicities
- MPI parallelization (using OpenMPI or MPICH)
- Distributes workers over multiple cores, grid adaption needs non-trivial communication
- Speedups of 10 to 30, saturation at O(100) tasks
- Integration times go down from weeks to hours! [can do also parallel event generation]
- Load balancer / non-blocking communication [v3.0.0]

Braß/Kilian/JRR, 1811.09711 [EPJC]

BSM Models in WHIZARD

Hard-coded models:

MODEL TYPE	with CKM matrix	trivial CKM
Yukawa test model	---	Test
QED with e, μ, τ, γ	---	QED
QCD with d, u, s, c, b, t, g	---	QCD
Standard Model	SM_CKM	SM
SM with anomalous gauge couplings	SM_ac_CKM	SM_ac
SM with Hgg, $H\gamma\gamma$, $H\mu\mu$, He^+e^-	SM_Higgs_CKM	SM_Higgs
SM with bosonic dim-6 operators	---	SM_dim6
SM with charge 4/3 top	---	SM_top
SM with anomalous top couplings	---	SM_top_anom
SM with anomalous Higgs couplings	---	SM_rx/NoH_rx/SM_ul
SM extensions for VV scattering	---	SSC/AltH/SSC_2/SSC_AltT
SM with Z'	---	Zprime
Two-Higgs Doublet Model	THDM_CKM	THDM
Higgs Singlet Extension	---	HSExt
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	---	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	---	PSSSM
Littlest Higgs	---	Littlest
Littlest Higgs with ungauged $U(1)$	---	Littlest_Eta
Littlest Higgs with T parity	---	Littlest_Tpar
Simplest Little Higgs (anomaly-free)	---	Simplest
Simplest Little Higgs (universal)	---	Simplest_univ
SM with graviton	---	Xdim
UED	---	UED
"SQED" with gravitino	---	GravTest
Augmentable SM template	---	Template

(external) UFO models:

- ☑ WHIZARD 3.0.1: Full UFO support
- ☑ LO externals UFO models
- ☑ Complete support for SMEFTsim 3.0
- ☑ Spin 0, 1/2, 1, 3/2, 2 supported
- ☑ Arbitrary Lorentz structures supported
- ☑ Support for customized propagators
- ☑ 5-, 6-, 7-, 8-point vertices
- ☑ Majorana and Dirac statistics
- ☑ Resonance histories with UFO
- ☑ BSM SLHA input files

Old FeynRules / SARAH interface **is deprecated**

backwards validation possible via v3.0.0

NLO SM support in in WHIZARD

- NLO QCD automation completed, NLO EW *pp* completed, mixed corrections in validation
- FKS subtraction, NLO matrix elements from OpenLoops/Recola
- also: resonance-aware FKS subtraction [Ježo/Nason, 1509.09071]
- Differential fixed-order results automatically available
- POWHEG matching for arbitrary processes (QCD validation, EW implementation)
- Photon isolation, photon recombination, light-, b-, c-jet selection

1 TeV

Process	WHIZARD+OpenLoops $\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	K
$e^+e^- \to jj$	622.737(8)	639.39(5)	1.03
$e^+e^- \to jjj$	340.6(5)	317.8(5)	0.93
$e^+e^- \to jjjj$	105.0(3)	104.2(4)	0.99
$e^+e^- \to jjjjj$	22.33(5)	24.57(7)	1.10
$e^+e^- \to t\bar{t}$	166.37(12)	174.55(20)	1.05
$e^+e^- \to t\bar{t}j$	48.12(5)	53.41(7)	1.11
$e^+e^- \to t\bar{t}jj$	8.592(19)	10.526(21)	1.23
$e^+e^- \to t\bar{t}jjj$	1.035(4)	1.405(5)	1.36
$e^+e^- \to t\bar{t}t\bar{t}$	$0.6388(8) \cdot 10^{-3}$	$1.1922(11) \cdot 10^{-3}$	1.87
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.673(7) \cdot 10^{-5}$	$5.251(11) \cdot 10^{-5}$	1.96
$e^+e^- \to t\bar{t}H$	2.020(3)	1.912(3)	0.95
$e^+e^- \to t\bar{t}Hj$	$2.536(4) \cdot 10^{-1}$	$2.657(4) \cdot 10^{-1}$	1.05
$e^+e^- \to t\bar{t}Hjj$	$2.646(8) \cdot 10^{-2}$	$3.123(9) \cdot 10^{-2}$	1.18
$e^+e^- \to t\bar{t}Z$	4.638(3)	4.937(3)	1.06
$e^+e^- \to t\bar{t}Zj$	$6.027(9) \cdot 10^{-1}$	$6.921(11) \cdot 10^{-1}$	1.15
$e^+e^- \to t\bar{t}Zjj$	$6.436(21) \cdot 10^{-2}$	$8.241(29) \cdot 10^{-2}$	1.28
$e^+e^- \to t\bar{t}W^\pm jj$	$2.387(8) \cdot 10^{-4}$	$3.716(10) \cdot 10^{-4}$	1.56
$e^+e^- \to t\bar{t}HZ$	$3.623(19) \cdot 10^{-2}$	$3.584(19) \cdot 10^{-2}$	0.99
$e^+e^- \to t\bar{t}ZZ$	$3.788(6) \cdot 10^{-2}$	$4.032(7) \cdot 10^{-2}$	1.06
$e^+e^- \to t\bar{t}HH$	$1.3650(15) \cdot 10^{-2}$	$1.2168(16) \cdot 10^{-2}$	0.89
$e^+e^- \to t\bar{t}W^+W^-$	$1.3672(21) \cdot 10^{-1}$	$1.5385(22) \cdot 10^{-1}$	1.13

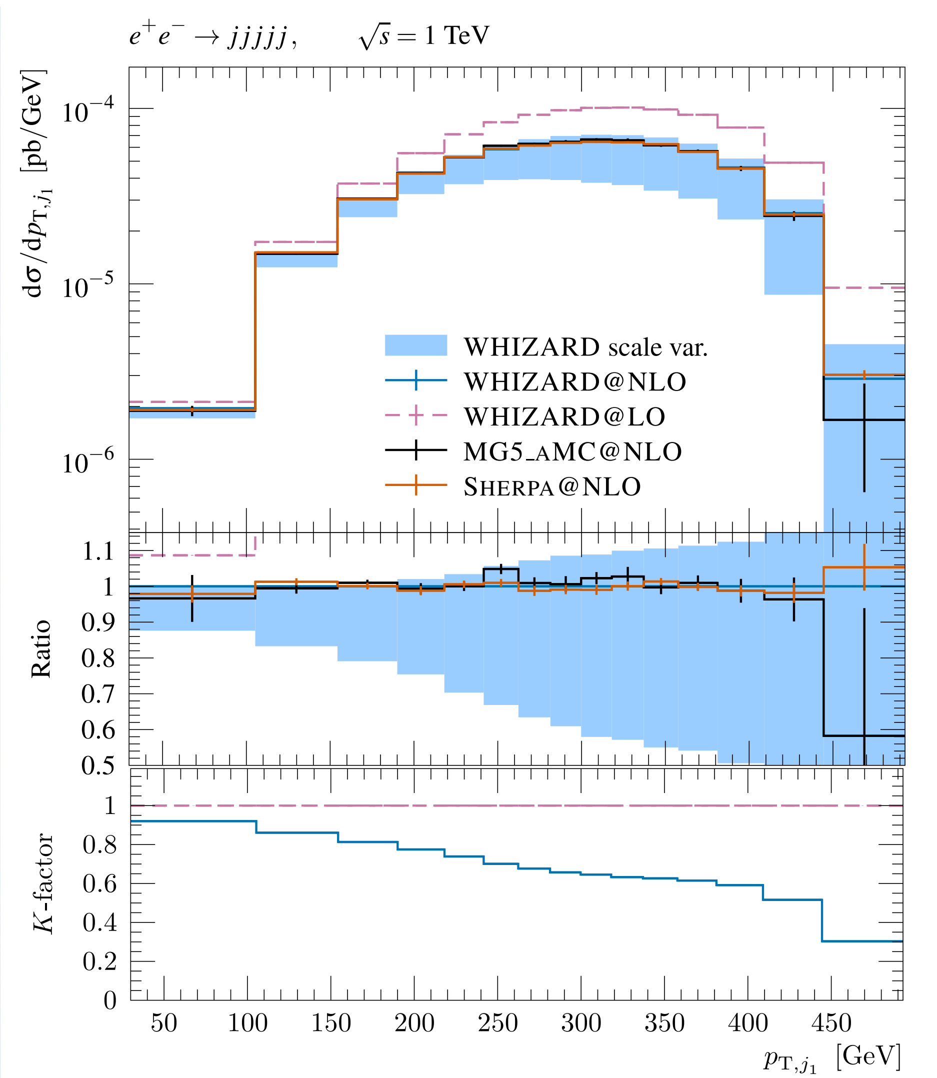
13 TeV

Process	WHIZARD+OpenLoops $\sigma_{\rm LO}$[fb]	$\sigma_{\rm NLO}$[fb]	K
$pp \to jj$	$1.162(4) \cdot 10^9$	$1.601(5) \cdot 10^9$	1.38
$pp \to jjj$	$9.01(4) \cdot 10^7$	$7.46(9) \cdot 10^7$	0.83
$pp \to t\bar{t}$	$4.589(9) \cdot 10^5$	$6.740(10) \cdot 10^5$	1.47
$pp \to t\bar{t}j$	$3.123(6) \cdot 10^5$	$4.087(9) \cdot 10^5$	1.31
$pp \to t\bar{t}jj$	$1.360(4) \cdot 10^5$	$1.775(7) \cdot 10^5$	1.31
$pp \to t\bar{t}t\bar{t}$	4.485(6)	9.070(9)	2.02
$pp \to W^\pm$	$1.3749(8) \cdot 10^8$	$1.7696(10) \cdot 10^8$	1.29
$pp \to W^\pm j$	$2.046(3) \cdot 10^7$	$2.854(5) \cdot 10^7$	1.39
$pp \to W^\pm jj$	$6.856(12) \cdot 10^6$	$7.814(27) \cdot 10^6$	1.14
$pp \to W^\pm jjj$	$1.840(5) \cdot 10^6$	$1.978(7) \cdot 10^6$	1.07
$pp \to Z$	$4.2541(3) \cdot 10^7$	$5.4086(16) \cdot 10^7$	1.27
$pp \to Zj$	$7.215(4) \cdot 10^6$	$9.733(10) \cdot 10^6$	1.35
$pp \to Zjj$	$2.364(5) \cdot 10^6$	$2.676(7) \cdot 10^6$	1.13
$pp \to Zjjj$	$6.381(23) \cdot 10^5$	$6.85(3) \cdot 10^5$	1.07
$pp \to W^+W^+jj$	$1.506(5) \cdot 10^2$	$2.235(7) \cdot 10^2$	1.48
$pp \to W^-W^-jj$	$6.772(24) \cdot 10^1$	$9.982(28) \cdot 10^1$	1.47
$pp \to ZW^\pm$	$2.780(5) \cdot 10^4$	$4.488(4) \cdot 10^4$	1.61
$pp \to ZW^\pm j$	$1.609(4) \cdot 10^4$	$2.0940(28) \cdot 10^4$	1.30
$pp \to ZW^\pm jj$	$8.06(3) \cdot 10^3$	$9.02(4) \cdot 10^3$	1.12
$pp \to ZZ$	$1.0969(10) \cdot 10^4$	$1.4183(11) \cdot 10^4$	1.29
$pp \to ZZj$	$3.667(9) \cdot 10^3$	$4.807(8) \cdot 10^3$	1.31
$pp \to ZZjj$	$1.356(6) \cdot 10^3$	$1.684(8) \cdot 10^3$	1.24

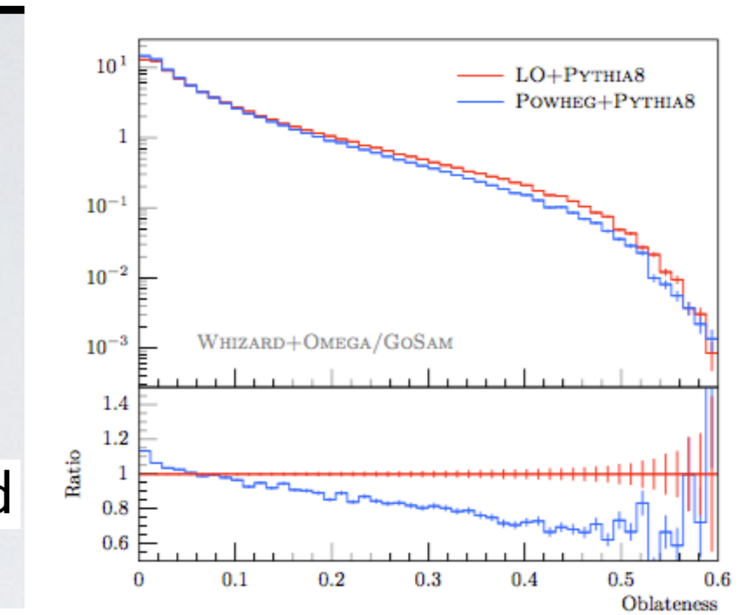
Some sample NLO QCD + EW results

QCD corrections:

Process	WHIZARD+OpenLoops σ_{LO} [fb]	WHIZARD+OpenLoops σ_{NLO} [fb]
$e^+e^- \to jj$	$622.737(8)$	$639.39(5)$
$e^+e^- \to jjj$	$340.6(5)$	$317.8(5)$
$e^+e^- \to jjjj$	$105.0(3)$	$104.2(4)$
$e^+e^- \to jjjjj$	$22.33(5)$	$24.57(7)$
$e^+e^- \to jjjjjj$	$3.583(17)$	$4.46(4)$



POWHEG matching:



EW corrections:

Cross-validation of WHIZARD and MUNICH orig. ref. [Kallweit et. al.: 1412.5157]

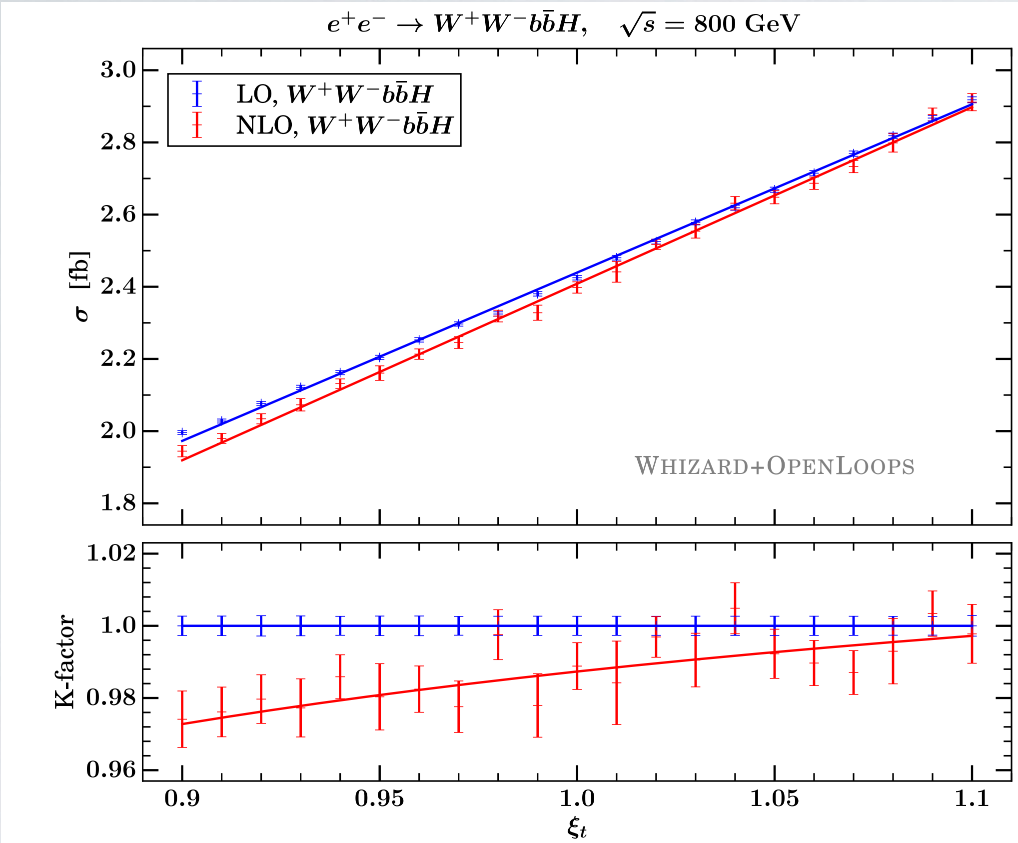
process $pp \to$	α^n	MUNICH+OpenLoops $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	WHIZARD+OpenLoops $\sigma^{\text{tot}}_{\text{NLO}}$ [fb]	δ [%]	dev [%]	$\sigma^{\text{sig}}_{\text{NLO}}$
ZZ	α^2	$1.05729(1) \cdot 10^4$	$1.05729(11) \cdot 10^4$	-4.20	0.0001	0.01
W^+Z	α^2	$1.71505(2) \cdot 10^4$	$1.71507(2) \cdot 10^4$	-0.15	0.001	0.88
W^-Z	α^2	$1.08576(1) \cdot 10^4$	$1.08574(1) \cdot 10^4$	$+0.07$	0.001	0.90
W^+W^-	α^2	$7.93106(7) \cdot 10^4$	$7.93087(21) \cdot 10^4$	$+4.55$	0.002	0.89
ZH	α^2	$6.18523(6) \cdot 10^2$	$6.18533(6) \cdot 10^2$	-5.29	0.002	1.17
W^+H	α^2	$7.18070(7) \cdot 10^2$	$7.18072(9) \cdot 10^2$	-2.31	0.0003	0.18
W^-H	α^2	$4.59289(4) \cdot 10^2$	$4.59299(5) \cdot 10^2$	-2.15	0.002	1.62
ZZZ	α^3	$9.7429(2) \cdot 10^0$	$9.7417(11) \cdot 10^0$	-9.47	0.012	1.01
W^+W^-Z	α^3	$1.08288(2) \cdot 10^2$	$1.08293(10) \cdot 10^2$	$+7.67$	0.004	0.45
W^+ZZ	α^3	$2.0188(4) \cdot 10^1$	$2.0188(23) \cdot 10^1$	$+1.58$	0.0001	0.01
W^-ZZ	α^3	$1.09844(2) \cdot 10^1$	$1.09838(12) \cdot 10^1$	$+3.09$	0.006	0.51
$W^+W^-W^+$	α^3	$8.7979(2) \cdot 10^1$	$8.7991(15) \cdot 10^1$	$+6.18$	0.014	0.79
$W^+W^-W^-$	α^3	$4.9447(1) \cdot 10^1$	$4.9441(2) \cdot 10^1$	$+7.13$	0.013	2.52
ZZH	α^3	$1.91607(2) \cdot 10^0$	$1.91614(18) \cdot 10^0$	-8.78	0.004	0.39
W^+ZH	α^3	$2.48068(2) \cdot 10^0$	$2.48095(28) \cdot 10^0$	$+1.64$	0.011	0.96
W^-ZH	α^3	$1.34001(1) \cdot 10^0$	$1.34016(15) \cdot 10^0$	$+2.51$	0.011	1.02
ZHH	α^3	$2.39350(2) \cdot 10^{-1}$	$2.39337(32) \cdot 10^{-1}$	-11.06	0.005	0.41
W^+HH	α^3	$2.44794(2) \cdot 10^{-1}$	$2.44776(24) \cdot 10^{-1}$	-12.04	0.007	0.74
W^-HH	α^3	$1.33525(1) \cdot 10^{-1}$	$1.33471(19) \cdot 10^{-1}$	-11.53	0.041	2.80

$$\delta \equiv \frac{\sigma^{\text{tot}}_{\text{NLO}} - \sigma^{\text{tot}}_{\text{LO}}}{\sigma^{\text{tot}}_{\text{LO}}} \qquad \text{dev} \equiv \frac{|\sigma^{\text{tot}}_{\text{WHIZARD}} - \sigma^{\text{tot}}_{\text{MUNICH}}|}{\sigma^{\text{tot}}_{\text{WHIZARD}}} \qquad \sigma^{\text{sig}} \equiv \frac{|\sigma^{\text{tot}}_{\text{WHIZARD}} - \sigma^{\text{tot}}_{\text{MUNICH}}|}{\sqrt{\Delta^2_{\text{err,WHIZARD}} + \Delta^2_{\text{err,MUNICH}}}}$$

process $pp \to$	$\alpha^n \alpha_s^m$	MG5_aMC@NLO $\sigma^{\text{tot}}_{\text{NLO}}$ [pb] [1804.10017]	WHIZARD $\sigma^{\text{tot}}_{\text{NLO}}$ [pb]	δ [%]	dev [%]	$\sigma^{\text{sig}}_{\text{NLO}}$
W^+j	$\alpha\alpha_s$	11552.(4)	11545.(4)	-0.37	0.07	1.26
Zj	$\alpha\alpha_s$	7062.(1)	7064.(3)	-0.80	0.03	0.77
$t\bar{t}$	α_s^2	432.90(6)	432.99(5)	-1.15	0.02	1.16
$t\bar{t}W^+$	$\alpha\alpha_s^2$	0.23025(3)	0.23017(5)	-4.53	0.03	1.28
$t\bar{t}Z$	$\alpha\alpha_s^2$	0.50033(7)	0.50041(10)	-0.84	0.02	0.67

Determination of Top-Yukawa coupling

Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

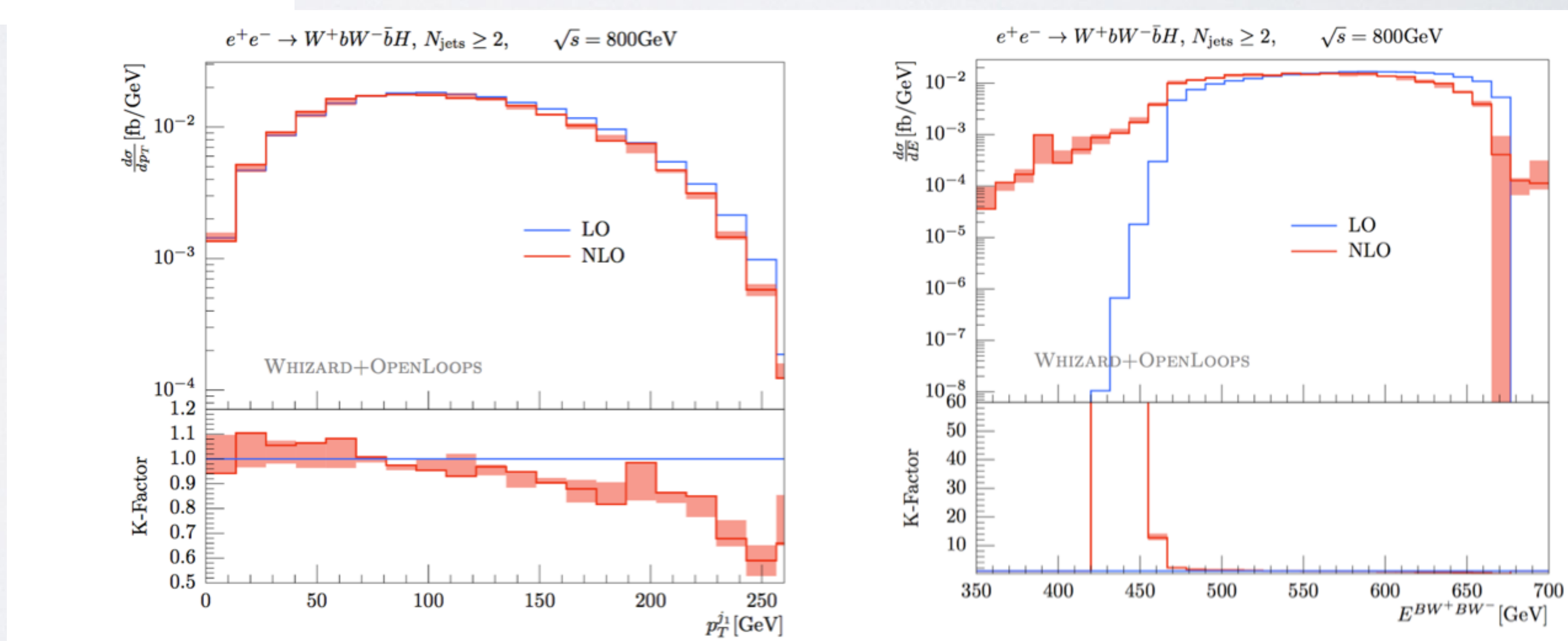


SM signal-strength / coupling modifier:

$$\lim_{\xi_t \to 1} \sigma(\xi_t) \left[\frac{d\sigma(\xi_t)}{d\xi_t}\right]^{-1} = \frac{S+I+B}{2S+I} = \frac{1}{2} + \frac{I/2+B}{2S+I}$$

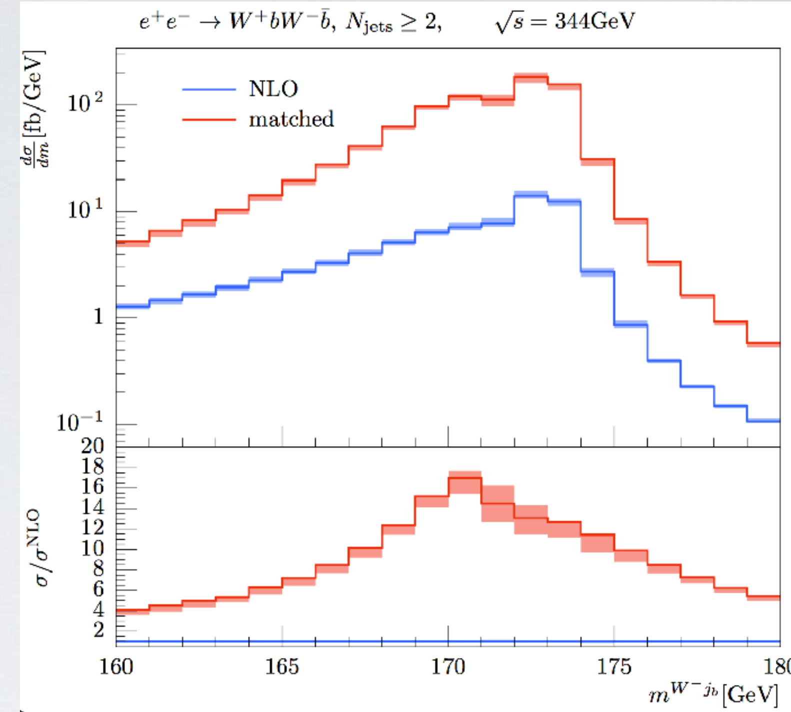
	ttH	$W^+W^-b\bar{b}H$
LO	0.514 ± 0.0002	0.520 ± 0.001
NLO	0.485 ± 0.0002	0.497 ± 0.002

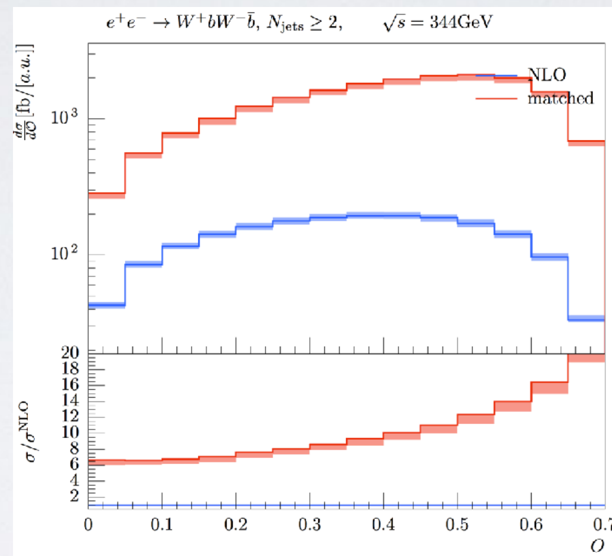
cf. also CLIC Top Report, 1807.02441

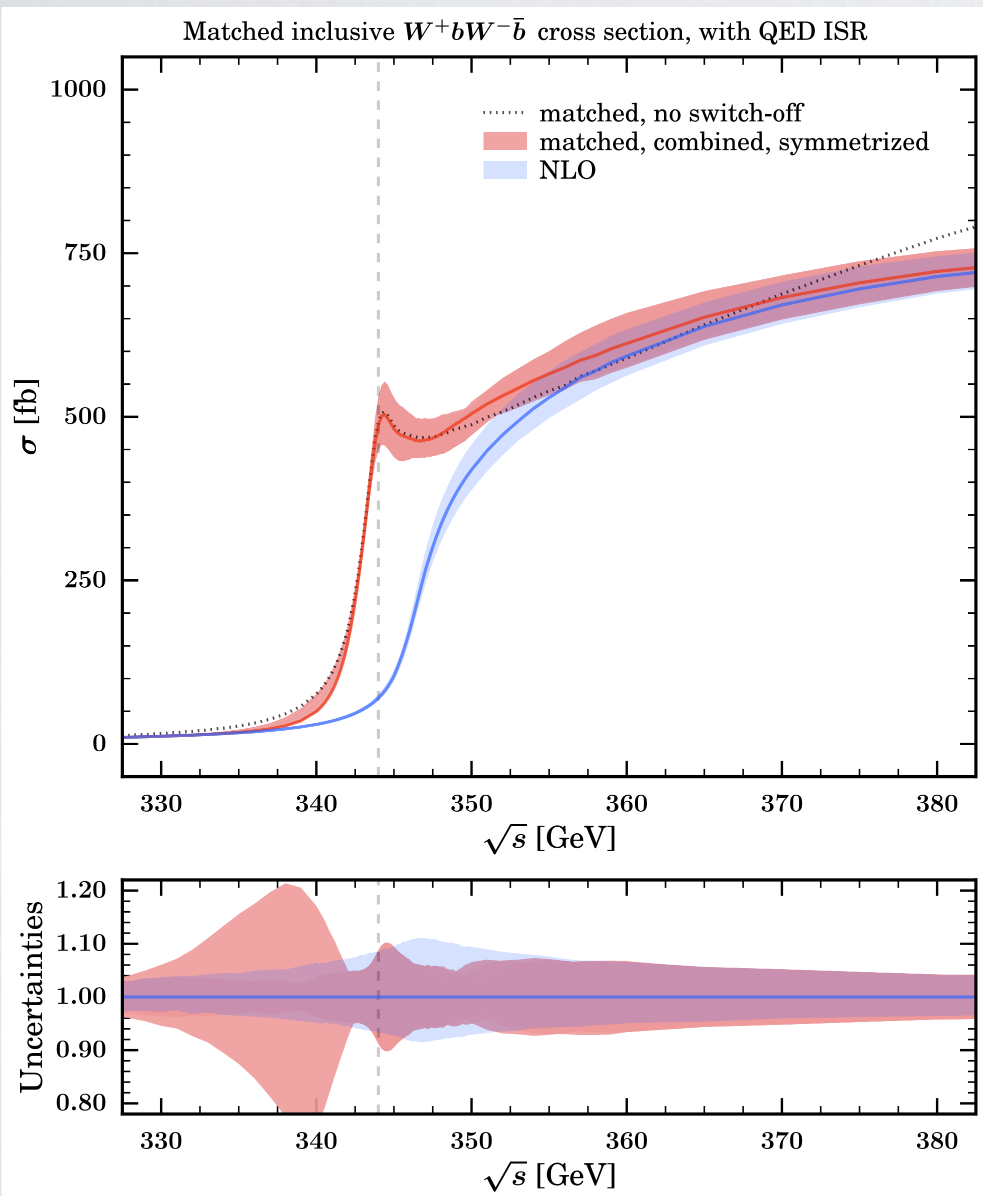


Advanced support for top threshold

- Exclusive Top threshold NLL-NLO QCD matched available
- Implemented for v2.5.1, revalidated in v3.0 parallelized
- Recent improvement in axial form factor matching








```
model = SM_tt_threshold

nrqcd_order = 1
FF = 1    ! NLL resummed
mpole_fixed = 1
Vtb = 1
m1S = 172 GeV
scale = m1S

$method = "threshold"
process eett_threshold = E1, e1 => Wp, Wm, b, B {
  $restrictions = "3+5~t && 4+6~tbar" nlo_calculation = real }

sqrts = 350 GeV
integrate (eett_threshold)
```

Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

Ongoing Projects & Plans for WHIZARD

- WHIZARD 3.0.1 generator: status on LO, NLO, BSM/UFO, beams, performance

Ongoing projects / short-to-midterm plans:

- Integration into Key4HEP software framework planned (similar to DD4HEP)
- YFS photon resummation for arbitrary processes
- NLO EW for massless lepton collider beams
- Initial state photon shower, together with improved matching
- Special setup for WW threshold (similar to top threshold)
- Specific processes at (massive) NNLO QED (e.g. Bhabha scattering)

https://whizard.hepforge.org
https://launchpad.net/whizard