NLO QCD & BSM with WHIZARD

Jürgen R. Reuter, DESY

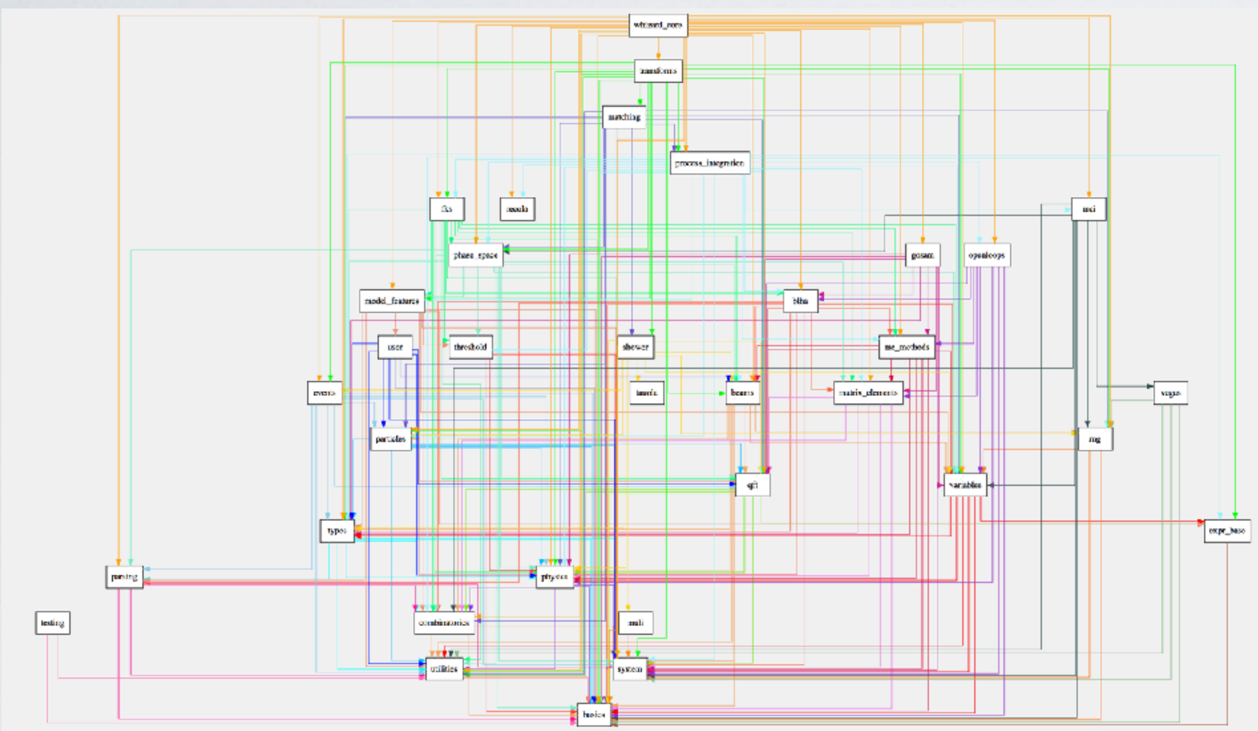
HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

WHIZARD: Introduction / Technical Facts

WHIZARD v2.8.2 (24.10.2019) http://whizard.hepforge.org <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR*

Simon Braß / Pia Bredt / Nils Kreher / Vincent Rothe / So Young Shim / Pascal Stienemeier



PUBLICATIONS

General WHIZARD reference: EPJ C71 (2011) 1742, arXiv:0708.4241

O'Mega (ME generator): LC-TOOL (2001) 040; arXiv:hep-ph/0102195

VAMP (MC integrator): CPC 120 (1999) 13; arXiv:hep-ph/9806432

CIRCE (beamstrahlung): CPC 101 (1997) 269; arXiv:hep-ph/9607454

Parton shower: JHEP 1204 (2012) 013; arXiv:1112.1039

Color flow formalism: JHEP 1210 (2012) 022; arXiv:1206.3700

NLO capabilities: JHEP 1612 (2016) 075; arXiv: 1609.03390

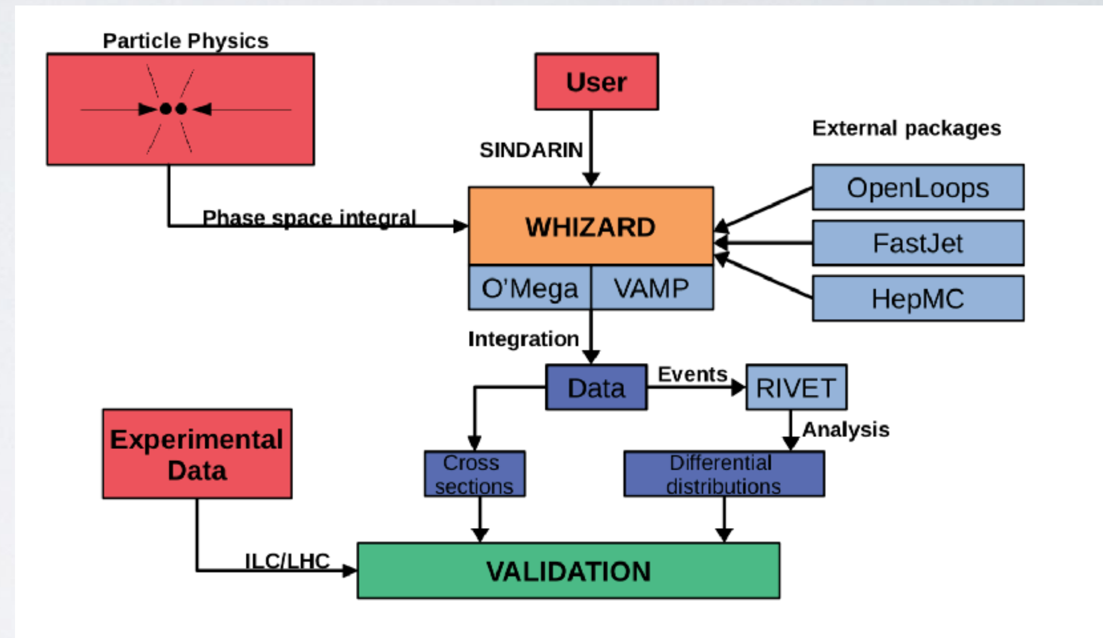
Parallelization of MEs: CPC 196 (2015) 58; arXiv:1411.3834

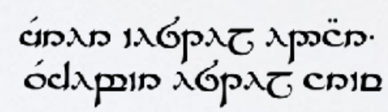
POWHEG matching: EPS-HEP (2015) 317; arXiv: 1510.02739

- Programming Languanges: `Fortran2008 (gfortran ≥5.1.0), OCaml (≥4.02.3)`
- Standard installation: `configure <FLAGS>, make, [make check], make install`
- Installed centrally, production runs in specific workspaces
- Large self test suite, unit tests [module tests], regression testing
- Continous integration system (`gitlab CI` @ Siegen)

WHIZARD: Introduction / Technical Facts

- Universal event generator for lepton and hadron colliders (SM and BSM physics)
- Tree ME generator `O'Mega` optimized ME generator Ω
- Generator/simulation tool for lepton collider beam spectra: `CIRCE1/2`
- Two different parton shower implementations
- Interfaces to external packages:
  `FastJet, GoSam, GuineaPig(++), HepMC2/3, HOPPET, LCIO, LHAPDF(5/6), LoopTools, OpenLoops, PYTHIA6 [internal], PYTHIA8, Recola, StdHep [internal], Tauola [internal]`



- Scattering processes (2→10 etc.) and [auto-] decays, factorized processes
- Scripting language for the steering: `SINDARIN` 
- Beam structure: polarization, asymmetric beams, crossing angle, structured beams, decays

```
beams = e1, E1
beams_pol_density = @(-1), @(+1)
beams_pol_fraction = 80%, 30%
```

```
beams = p, p => lhapdf
$lhapdf = "NNPDF3"
```

```
beams = e1, E1 => circe2 => isr => ewa
```

WHIZARD: Introduction / Technical Facts

WHIZARD v2.8.2 (24.10.2019) http://launchpad.net/whizard

Juergen Reuter (j.r.reuter) • Log Out

WHIZARD

http://launchpad.net/whizard

Overview Code Bugs Blueprints Translations Answers

Registered 2019-06-26 by Juergen Reuter

WHIZARD Event Generator

WHIZARD is a program system designed for the efficient calculation of multi-particle scattering cross sections and simulated event samples.

Tree-level matrix elements are generated automatically for arbitrary partonic processes by using the Optimized Matrix Element Generator O'Mega. Matrix elements obtained by alternative methods (e.g., including loop corrections) may be interfaced as well. The program is able to calculate numerically stable signal and background cross sections and generate unweighted event samples with reasonable efficiency for processes with up to eight final-state particles; more particles are possible. For more particles, there is the option to generate processes as decay cascades including complete spin correlations. Different options for QCD parton showers are available.

Polarization is treated exactly for both the initial and final states. Final-state quark or lepton flavors can be summed over automatically where needed. For hadron collider physics, an interface to the standard LHAPDF is provided. For Linear Collider physics, beamstrahlung (CIRCE) and ISR spectra are included for electrons and photons. The events can be written to file in standard formats, including ASCII, StdHEP, the Les Houches event format (LHEF), HepMC, or LCIO. These event files can then be hadronized.

WHIZARD supports the Standard Model and a huge number of BSM models. Model extensions or completely different models can be added. There are also interfaces to FeynRules and SARAH.

The code of released WHIZARD versions is hosted in a publically accessible GitLab: https://gitlab.tp.nt.uni-siegen.de/whizard/public

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Help translate

Configuration Progress

Configuration options
- Code ✗
- Bugs ✓
- Translations ✓
- Answers ✓

Downloads

Latest version is 2.8.2

whizard-2.8.2.tar.gz

released 9 hours ago

All downloads

Announcements

WHIZARD 2.8.2 a moment ago
New minor release: Rescans with LCIO event files and LCIO alternative weights...

WHIZARD 2.8.1 on 2019-09-24
New minor release 2.8.1: some bug fixes on the UFO implementation, whose par...

WHIZARD Launchpad started on 2019-06-26
The WHIZARD project has joined Launchpad and will start to manage bug report ...

Read all announcements

Make announcement

Project information

Maintainer: WHIZARDs

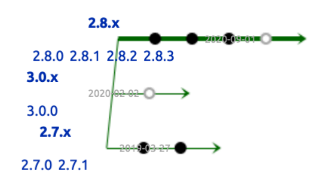
Driver: WHIZARDs

Licence: GNU GPL v3

RDF metadata

Series and milestones

View full history



2.8.x series is the current focus of development.

Register a series View milestones

Code

All code

Version control system: Git

Programming languages: Fortran 2008, ocaml

Latest bugs reported

All bugs

Bug #1844988: Circe2 does not compile with ocaml >= 4.08.0
Reported on 2019-09-23

Bug #1840632: Error after loading UFO file
Reported on 2019-08-19

Bug #1839654: Cross section of the SM double Compton process
Reported on 2019-08-09

Bug #1839475: Reading UFO model containing "\r" line endings
Reported on 2019-08-08

Bug #1834355: No unit tests for 4-fermion couplings
Reported on 2019-06-26

Latest questions

All questions

radiative Bhabha scattering
Posted on 2019-10-15

EPA dependence on epa_mass
Posted on 2019-10-01

How to make a UFO model calculates the width of particle without making it de...
Posted on 2019-09-30

How to make a UFO model calculates the width of particle without making it de...
Posted on 2019-09-30

Latest blueprints

All blueprints

Inclusive Lepton Collider ISR included

Soft exponentiation to all orders

$$\epsilon = \frac{\alpha}{\pi} q_e^2 \ln\left(\frac{s}{m^2}\right)$$

Gribov/Lipatov, 1971

$$f_0(x) = \epsilon \cdot (1-x)^{-1+\epsilon}$$

Hard-collinear photons up to 3rd QED order

Kuraev/Fadin, 1983; Skrzypek/Jadach, 1991

$$g_3(\epsilon) = 1 + \frac{3}{4}\epsilon + \frac{27-8\pi^2}{96}\epsilon^2 + \frac{27-24\pi^2+128\zeta(3)}{384}\epsilon^3$$

$$\begin{aligned} f_3(x) = {} & g_3(\epsilon)\, f_0(x) - \frac{\epsilon}{2}(1+x) \\ & - \frac{\epsilon^2}{8}\left(\frac{1+3x^2}{1-x}\ln x + 4(1+x)\ln(1-x) + 5 + x\right) \\ & - \frac{\epsilon^3}{48}\Bigg((1+x)\left[6\,\mathrm{Li}_2(x) + 12\ln^2(1-x) - 3\pi^2\right] + 6(x+5)\ln(1-x) \\ & + \frac{1}{1-x}\left[\frac{3}{2}(1+8x+3x^2)\ln x + 12(1+x^2)\ln x \ln(1-x) \right. \\ & \left. - \frac{1}{2}(1+7x^2)\ln^2 x + \frac{1}{4}(39-24x-15x^2)\right]\Bigg) \end{aligned}$$

$$\zeta(3) = 1.202056903159594285399738161511\ldots$$

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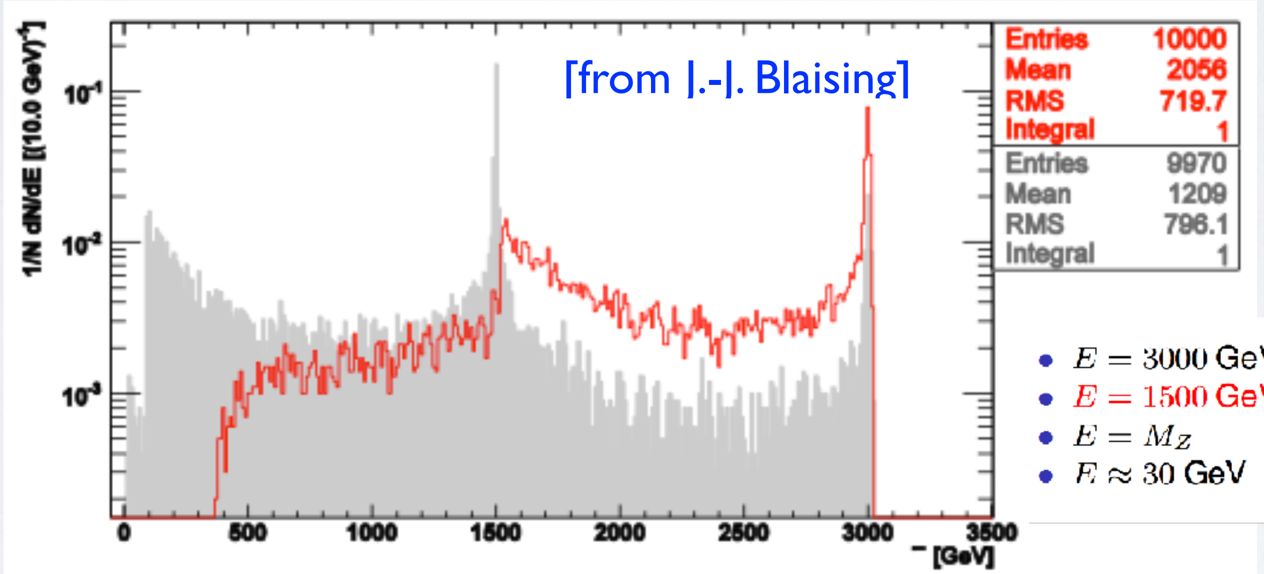

- $E = 3000$ GeV (luminosity spectrum peak)
- $E = 1500$ GeV (Z peak and lumi spectrum)
- $E = M_Z$ (Z resonance)
- $E \approx 30$ GeV (due to $e^+e^- \to \gamma^* \to b\bar{b}$)

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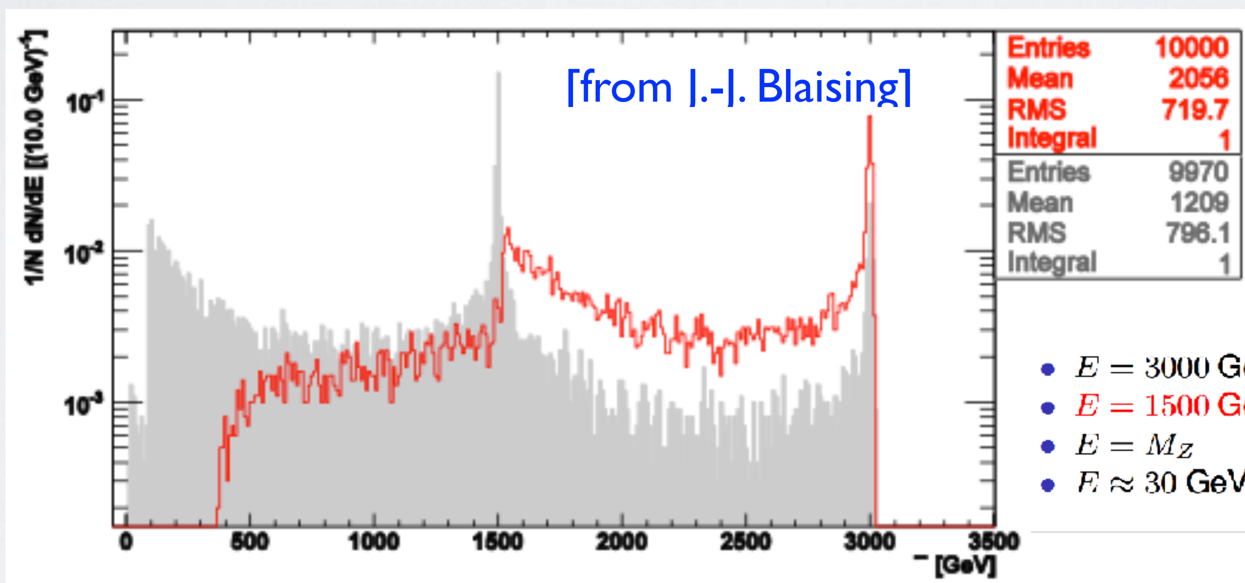

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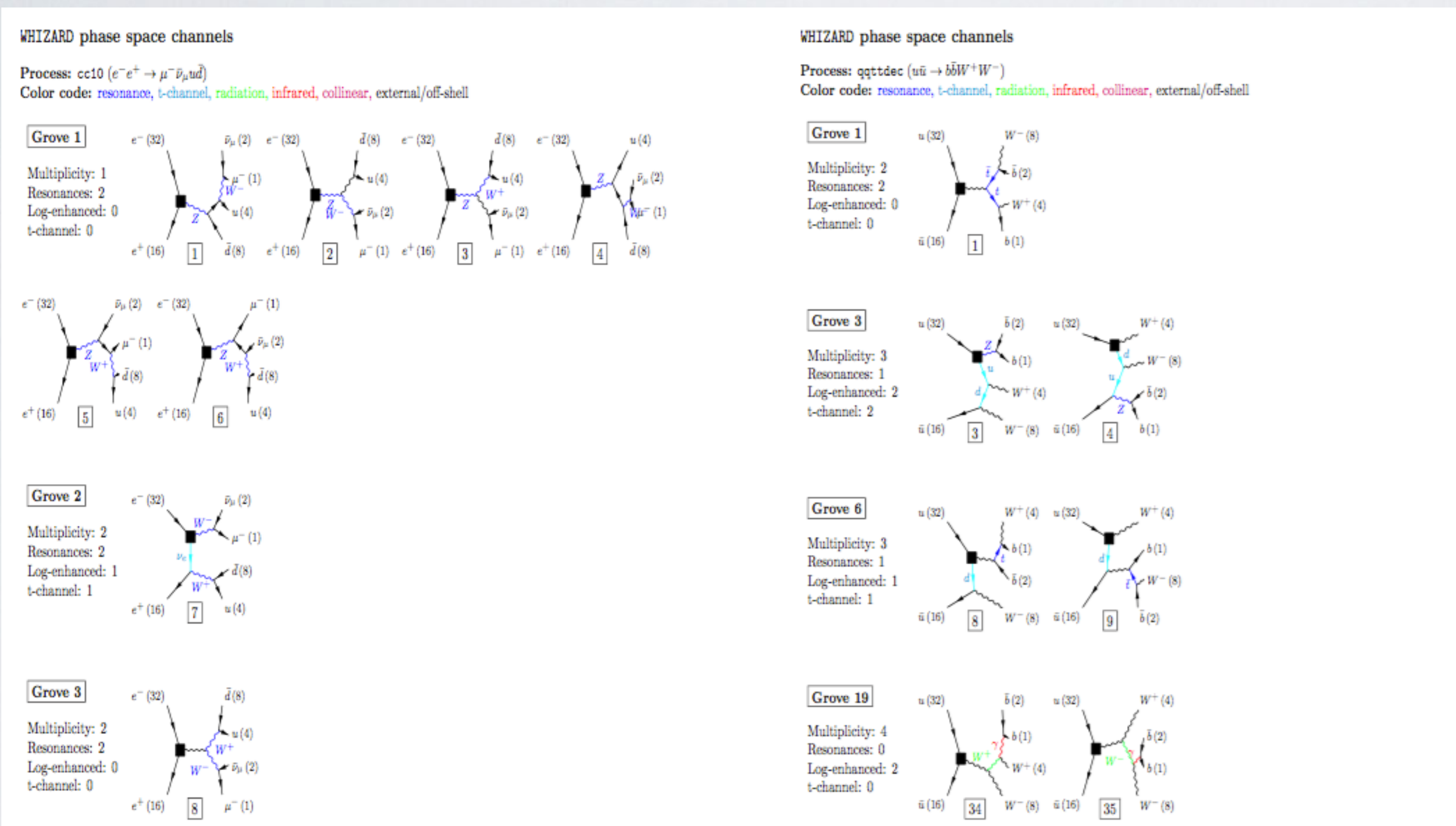
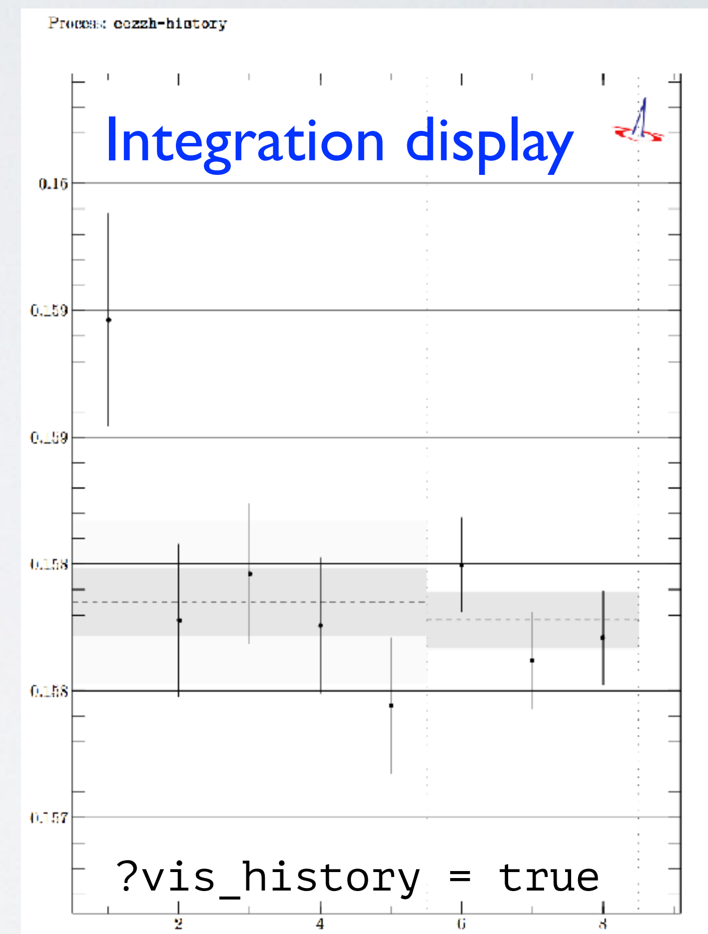
- ❑ One explicit ISR photon / beam: ISR/EPA handler generates physical p_T distributions
- ❑ Collinear factorizarton, explicit matching: heuristic procedures LO — *tbd* for NLO !
- ❑ Preparation for EW corrections w. NLO structure functions [Frixione, 1909.03886; Bertone/Cacciari/Frixione/Stagnitto, *in prep.*]
- ❑ Plans for YFS / different schemes

Phase Space Integration

- 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 $\Longrightarrow$ `resonant, t-channel, radiation, infrared, collinear, off-shell`



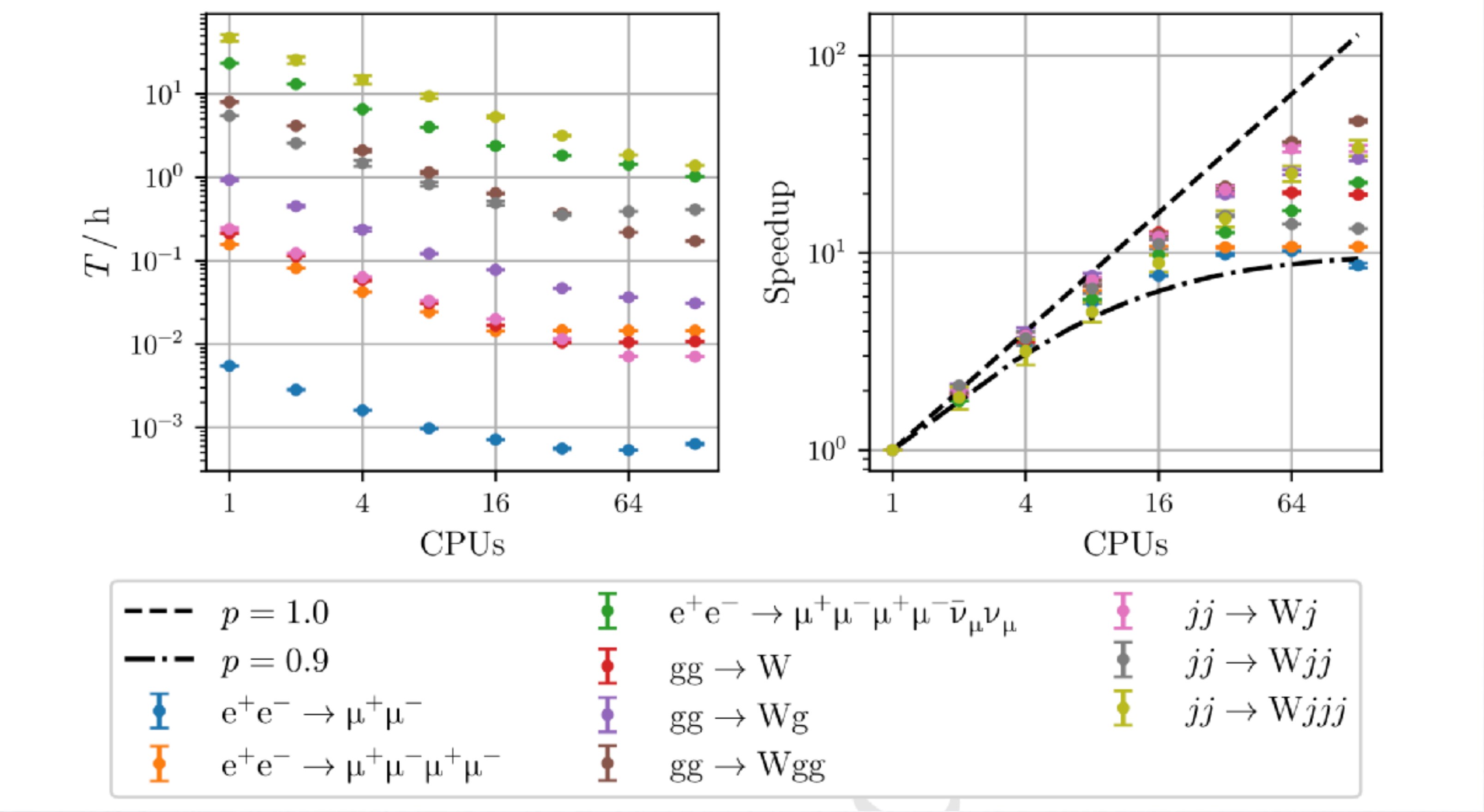


Complicated processes: factorization into production/decay with `unstable` option (also polarized)

Resonance-aware factorization for NLO processes and parton showers (e.g. $e^+e^- \to jjjj$)

MPI Parallelization

- Event generation trivially parallelizable — Braß/Kilian/JRR, 1811.09711 [EPJC]
- Major bottleneck: adaptive phase space integration (generation of grids)
- Parallelization of integration: OMP multi-threading for different helicities since long
- `v2.5.0/2.6.4/2.7.1`: MPI parallelization (using OpenMPI or MPICH)
- Distributes workers over multiple cores, grid adaption needs non-trivial communication
- Amdahl's law: $s = \frac{1}{1-p+\frac{p}{N}}$
- 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 is being implemented [expected for `v2.8.3`]



Event Formats

Event formats: conventions for outputting details of the events

```
sample_format = hepmc
sample_format = lhef  {$lhef_version = "3.0"}
sample_format = stdhep, stdhep_up, stdhep_ev4
sample_format = ascii,debug,mokka,lha
sample_format = lcio
simulate (<process>)
```

- External format, ASCII: HepMC [Dobbs/Hansen, 2001]
- External format, binary: LCIO [Gaede, 2003]
- Internal formats, binary: StdHEP [Lebrun, 1990]
- Internal formats, ASCII: LHA, LHEF [Alwall et al. , 2006]

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LCIO Format: (ASCII transcription from binary)

```
============================================================================
        Event  : 1 - run:  0 -  timestamp [...]
============================================================================
 date: [...]
 detector : unknown
 event parameters:
 parameter Event Number [int]: 1,
 parameter ProcessID [int]: 1,
 parameter Run ID [int]: 0,
 parameter beamPDG0 [int]: 11,
 parameter beamPDG1 [int]: -11,
 parameter Energy [float]: 500,
 parameter Pol0 [float]: 0,
 parameter Pol1 [float]: 0,
 parameter _weight [float]: 1,
 parameter alphaQCD [float]: 0.1178,
 parameter crossSection [float]: 338.482,
 parameter crossSectionError [float]: 7.2328,
 parameter scale [float]: 500,
 parameter BeamSpectrum [string]: ,
 parameter processName [string]: lcio_5_p,
 collection name : MCParticle
 parameters:
--------------- print out of MCParticle collection ---------------
  flag:  0x0
  simulator status bits: [sbvtcls]  s: created in simulation b: backscatter v: vertex is not endpoint of parent t: decayed in tracker c: decayed in
calorimeter l: has left detector s: stopped o: overlay
[   id   ]index| PDG |    px,     py,        pz    | energy  |gen|[simstat]| vertex x,y,z |    mass |  charge |      spin      | colorflow | [par] - [dau]
[00000004]    0|   11| 0.00e+00, 0.00e+00, 2.50e+02| 2.50e+02| 3 |[    0  ]| 0.0, 0.0, 0.0| 5.11e-04|-1.00e+00| 0.0, 0.0, 0.0|  (0, 0)    | [] - [2,3]
[00000005]    1|  -11| 0.00e+00, 0.00e+00,-2.50e+02| 2.50e+02| 3 |[    0  ]| 0.0, 0.0, 0.0| 5.11e-04| 1.00e+00| 0.0, 0.0, 0.0|  (0, 0)    | [] - [2,3]
[00000006]    2|   13| 1.42e+02, 1.99e+02,-5.22e+01| 2.50e+02| 1 |[    0  ]| 0.0, 0.0, 0.0| 1.06e-01|-1.00e+00| 0.0, 0.0, 1.0|  (0, 0)    | [0,1] - []
[00000007]    3|  -13|-1.42e+02,-1.99e+02, 5.22e+01| 2.50e+02| 1 |[    0  ]| 0.0, 0.0, 0.0| 1.06e-01| 1.00e+00| 0.0, 0.0,-1.0|  (0, 0)    | [0,1] - []
```

Event header information as agreed upon with LC Gen Group

Event Formats

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sample_format = lcio
simulate (<process>)
```

- External format, ASCII: HepMC [Dobbs/Hansen, 2001]
- External format, binary: LCIO [Gaede, 2003]
- Internal formats, binary: StdHEP [Lebrun, 1990]
- Internal formats, ASCII: LHA, LHEF [Alwall et al., 2006]

HepMC3 Format: modern implementation

```
HepMC::Version 3.01.01
HepMC::Asciiv3-START_EVENT_LISTING
E 1 3 8
U GEV MM
A 0 alphaQCD 0.116258482977402
A 0 alphaQED -1
A 0 event_scale 100
A 3 flow1 1
A 4 flow1 3
A 5 flow1 2
A 6 flow1 1
A 7 flow1 3
A 3 flow2 2
A 4 flow2 1
A 5 flow2 1
A 6 flow2 3
A 8 flow2 2
A 0 signal_process_id 1
P 1 0 2212 0.0000000000000000e+00 0.000000000
P 2 0 2212 0.0000000000000000e+00 0.000000000
P 3 1 21 0.0000000000000000e+00 0.00000000000
P 4 2 21 0.0000000000000000e+00 0.00000000000
P 5 1 93 0.0000000000000000e+00 0.00000000000
P 6 2 93 0.0000000000000000e+00 0.00000000000
V -3 0 [3,4]
P 7 -3 2 -5.0143659198302345e+01 -6.869560414
P 8 -3 -2 5.0143659198302345e+01 6.8695604145
HepMC::Asciiv3-END_EVENT_LISTING
```

```
HepMC::Version 2.06.09
HepMC::IO_GenEvent-START_EVENT_LISTING
E 1 -1 1.0000000000000000e+02 1.1625848297740160e-01 -1.0000000
U GEV MM
V -1 0 0 0 0 0 1 2 0
P 10001 2212 0 0 4.0000000000000000e+03 4.0000000000000000e+03
P 10003 21 0 0 1.1139107692024313e+01 1.1139107692024313e+01 0
P 10005 93 0 0 3.9888608923079760e+03 3.9888608923079760e+03 0
V -2 0 0 0 0 0 1 2 0
P 10002 2212 0 0 -4.0000000000000000e+03 4.0000000000000000e+03
P 10004 21 0 0 -3.2685024745934277e+02 3.2685024745934277e+02 0
P 10006 93 0 0 -3.6731497525406571e+03 3.6731497525406571e+03 0
V -3 0 0 0 0 0 0 2 0
P 10007 2 -5.0143659198302345e+01 -6.8695604145339697e+00 -2.49
P 10008 -2 5.0143659198302345e+01 6.8695604145339697e+00 -6.584
HepMC::IO_GenEvent-END_EVENT_LISTING
```

NEW in WHIZARD v2.8.1

Rescanning of Event Files

- Scanning parameter space of BSM models (or SM templates)
- Major bottleneck: MC samples have to be produced over and over again
- Feature: rescanning of event files with different setup
- Assumption: phase space is identical, sampling can be done in the same way
- works also w/ differently concatenated structure functions (e.g. ISR + beamstr.)
- Open issues: rescanning with resonance matching in showered events

```
process reweight_8_p1 = e1, E1 => e2, E2

sqrts = 1000
n_events = 10000

?unweighted = false
sample_format = weight_stream

simulate (reweight_8_p1) {
  $sample = "reweight_8a"
  iterations = 1:1000
}

?update_sqme = true
rescan "reweight_8a" (reweight_8_p1) {
  $sample = "reweight_8c"
  ee = 3 * ee     ! should update sqme
}
?update_weight = true
rescan "reweight_8a" (reweight_8_p1) {
  $sample = "reweight_8d"
  ee = 3 * ee     ! should update sqme and event
weight
```

WHIZARD v2.8.2

- Rescan now also works with LCIO
- Alternative weights/ cross sections can be written to LCIO

Rescanning of Event Files

```
------------------------------------------------------------------------
       Event  : 1 - run:  0 - timestamp 1569613753000000000 - weight 1
========================================================================
 date:      27.09.2019  19:49:13.000000000
 detector : unknown
 event parameters:
 parameter Event Number [int]: 1,
 parameter ProcessID [int]: 1,
 parameter Run ID [int]: 0,
 parameter beamPDG0 [int]: 2212,
 parameter beamPDG1 [int]: 2212,
 parameter Energy [float]: 8000,
 parameter Pol0 [float]: 0,
 parameter Pol1 [float]: 0,
 parameter _weight [float]: 1,
 parameter alphaQCD [float]: 0.1178,
 parameter alternateSqme1 [float]: 135.189,
 parameter alternateSqme10 [float]: 3.54389e+07,
 parameter alternateSqme2 [float]: 540.754,
 parameter alternateSqme3 [float]: 2163.02,
 parameter alternateSqme4 [float]: 8652.07,
 parameter alternateSqme5 [float]: 34608.3,
 parameter alternateSqme6 [float]: 138433,
 parameter alternateSqme7 [float]: 553732,
 parameter alternateSqme8 [float]: 2.21493e+06,
 parameter alternateSqme9 [float]: 8.85972e+06,
 parameter alternateWeight1 [float]: 1.12598,
 parameter alternateWeight10 [float]: 295168,
 parameter alternateWeight2 [float]: 4.50391,
 parameter alternateWeight3 [float]: 18.0156,
 parameter alternateWeight4 [float]: 72.0625,
 parameter alternateWeight5 [float]: 288.25,
 parameter alternateWeight6 [float]: 1153,
 parameter alternateWeight7 [float]: 4612,
 parameter alternateWeight8 [float]: 18448,
 parameter alternateWeight9 [float]: 73792,
 parameter crossSection [float]: 97927.9,
 parameter crossSectionError [float]: 20802.6,
 parameter scale [float]: 488.791,
 parameter BeamSpectrum [string]: ,
 parameter processName [string]: lcio_10_p,

 collection name : MCParticle
 parameters:

--------------- print out of MCParticle collection ---------------

  flag:  0x0
  simulator status bits: [sbvtcls]  s: created in simulation b: backscatter v: vertex is not endpoint of parent t: decayed in tracker c: decayed in calorimeter l: has left de


[   id   ]index|      PDG |    px,      py,         pz    | px_ep,   py_ep , pz_ep      | energy  |gen|[simstat ]| vertex x,     y   ,   z     | endpoint x,    y  ,   z     |

[00000004]    0|      2212| 0.00e+00, 0.00e+00, 4.00e+03| 0.00e+00, 0.00e+00, 0.00e+00| 4.00e+03| 4 |[    0   ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 0
[00000005]    1|      2212| 0.00e+00, 0.00e+00,-4.00e+03| 0.00e+00, 0.00e+00, 0.00e+00| 4.00e+03| 4 |[    0   ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 0
[00000006]    2|        21| 0.00e+00, 0.00e+00, 7.22e+01| 0.00e+00, 0.00e+00, 0.00e+00| 7.22e+01| 3 |[    0   ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 0
[00000007]    3|        21| 0.00e+00, 0.00e+00,-8.27e+02| 0.00e+00, 0.00e+00, 0.00e+00| 8.27e+02| 3 |[    0   ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 0
[00000008]    4|        93| 0.00e+00, 0.00e+00, 3.93e+03| 0.00e+00, 0.00e+00, 0.00e+00| 3.93e+03| 1 |[    0   ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 0
[00000009]    5|        93| 0.00e+00, 0.00e+00,-3.17e+03| 0.00e+00, 0.00e+00, 0.00e+00| 3.17e+03| 1 |[    0   ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 0
[00000010]    6|         6| 1.60e+02,-2.33e+01,-4.88e+02| 0.00e+00, 0.00e+00, 0.00e+00| 5.42e+02| 1 |[    0   ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 1
[00000011]    7|        -6|-1.60e+02, 2.33e+01,-2.67e+02| 0.00e+00, 0.00e+00, 0.00e+00| 3.57e+02| 1 |[    0   ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 1
```

Alternative weights / cross sections entries in the LCIO event header

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

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 2.8.2 Full UFO support
- ☑ well, *almost full* ....
- ☑ New version demands OCaml ≥4.02.3
- ☑ LO externals UFO models
- ☑ Spin 0, 1/2, 1, 2 supported, 3/2 in 2.8.3
- ☑ Arbitrary Lorentz structures supported
- ☑ 5-, 6-point vertices (and even higher)
- ☑ Missing: Majorana statistics (2.8.3)
  - BSM SLHA input (2.8.4)
  - crazy color structures (parsing works)

BSM Models in WHIZARD

Hard-coded models:

MODEL TYPE	with CKM matrix	trivial CKM
Yukawa test model	---	Test
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QCD with d, u, s, c, b, t, g	---	QCD
Standard Model	SM_CKM	SM
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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:

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- ☑ Arbitrary Lorentz structures supported
- ☑ 5-, 6-point vertices (and even higher)
- ☑ Missing: Majorana statistics (2.8.3)
  BSM SLHA input (2.8.4)
  crazy color structures (parsing works)

Old FeynRules / SARAH interface **is deprecated**

kept at the moment for user backwards compatibility

Models from UFO Files in WHIZARD


```
model = SM  (ufo)
```

UFO file is assumed to be in working directory OR

```
model = SM  (ufo (“<my UFO path>”))
```

UFO file is in user-specified directory

```
|                                WHIZARD 2.5.1
|==============================================================================|
| Reading model file '/Users/reuter/local/share/whizard/models/SM.mdl'
| Preloaded model: SM
| Process library 'default_lib': initialized
| Preloaded library: default_lib
| Reading model file '/Users/reuter/local/share/whizard/models/SM_hadrons.mdl'
| Reading commands from file 'ufo_2.sin'
| Model: Generating model 'SM' from UFO sources
| Model: Searching for UFO sources in working directory
| Model: Found UFO sources for model 'SM'
| Model: Model file 'SM.ufo.mdl' generated
| Reading model file 'SM.ufo.mdl'
```

```
| Switching to model 'SM' (generated from UFO source)
```

All the setup works the same as for intrinsic models

Models from UFO Files in WHIZARD

```
model = SM  (ufo)
```

UFO file is assumed to be in working directory OR

```
model = SM  (ufo ("<my UFO path>"))
```

UFO file is in user-specified directory

```
pure function VVVV4_p0123 (g, a2, k2, a3, k3, a4, k4) result (a1)
  type(vector) :: a1
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: a2
  type(vector), intent(in) :: a3
  type(vector), intent(in) :: a4
  type(momentum), intent(in) :: k2, k3, k4
  ! -----------------------------------------------------------------
  ! 1 *  * Metric(2,4) * Metric(1,3) + -1 *  * Metric(3,4) * Metric(1,2)
  ! -----------------------------------------------------------------
  complex(kind=default), dimension(0:3) :: a1a
  complex(kind=default), dimension(0:3) :: a2a
  complex(kind=default), dimension(0:3) :: a3a
  complex(kind=default), dimension(0:3) :: a4a
  real(kind=default), dimension(0:3) :: p1, p2, p3, p4
  integer :: nu1
  integer :: nu2
  integer :: nu3
  integer :: nu4
  ! -----------------------------------------------------------------
  a2a(0) = a2%t
  a2a(1:3) = a2%x
  a3a(0) = a3%t
  a3a(1:3) = a3%x
  a4a(0) = a4%t
  a4a(1:3) = a4%x
  p2(0) = k2%t
  p2(1:3) = k2%x
  p3(0) = k3%t
  p3(1:3) = k3%x
  p4(0) = k4%t
  p4(1:3) = k4%x
  p1 = - p2 - p3 - p4
```

```
pure function FFS4_p012 (g, psibar2, k2, phi3, k3) result (psi1)
  type(conjspinor) :: psi1
  complex(kind=default), intent(in) :: g
  type(conjspinor), intent(in) :: psibar2
  complex(kind=default), intent(in) :: phi3
  type(momentum), intent(in) :: k2, k3
  ! -----------------------------------------------------------------
  ! 1 * <2|(1-g5)/2|1> *  + 1 * <2|(1+g5)/2|1> *
  ! -----------------------------------------------------------------
  real(kind=default), dimension(0:3) :: p1, p2, p3
  complex(kind=default), dimension(1:4) :: bra01
  complex(kind=default), dimension(1:4) :: bra02
  integer :: alpha
  ! -----------------------------------------------------------------
  p2(0) = k2%t
  p2(1:3) = k2%x
  p3(0) = k3%t
  p3(1:3) = k3%x
  p1 = - p2 - p3
  ! -----------------------------------------------------------------
  ! <2|(1-g5)/2|1>
  bra01(1) = 0 + psibar2%a(1)
  bra01(2) = 0 + psibar2%a(2)
  bra01(3) = 0
  bra01(4) = 0
  ! -----------------------------------------------------------------
  ! <2|(1+g5)/2|1>
  bra02(1) = 0
  bra02(2) = 0
  bra02(3) = 0 + psibar2%a(3)
  bra02(4) = 0 + psibar2%a(4)
  ! -----------------------------------------------------------------
```

Models from UFO Files in WHIZARD

```
model = SM  (ufo)
```

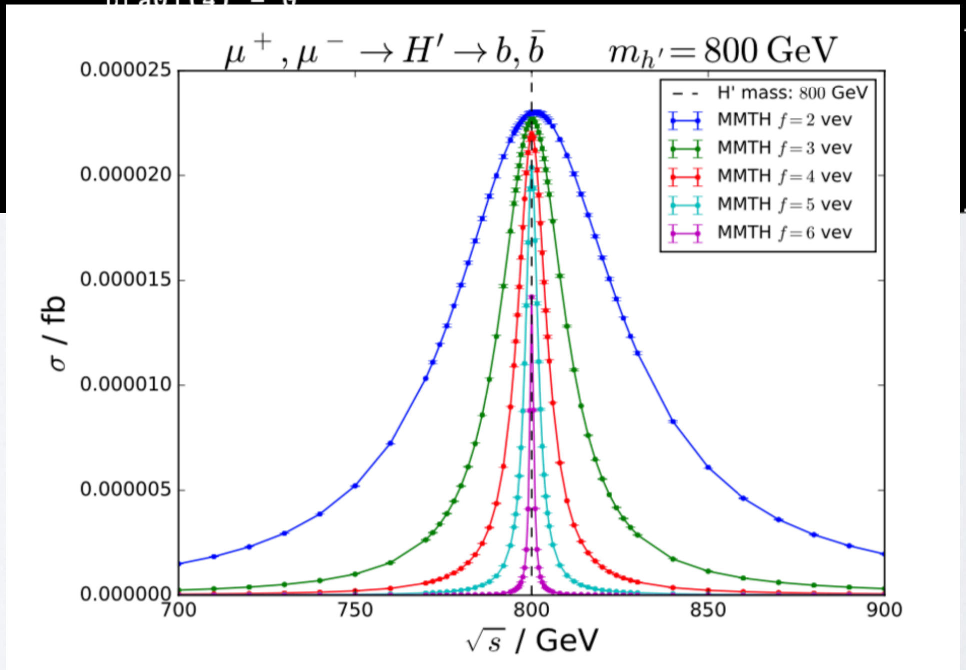
UFO file is assumed to be in working directory   OR

```
model = SM  (ufo ("<my UFO path>"))
```

UFO file is in user-specified directory

```
pure function VVVV4_p0123 (g, a2, k2, a3, k3, a4, k4) result (a1)
  type(vector) :: a1
  complex(kind=default), intent(in) :: g
  type(vector), intent(in) :: a2
  type(vector), intent(in) :: a3
  type(vector), intent(in) :: a4
  type(momentum), intent(in) :: k2, k3, k4
  ! ----------------------------------------------------------------
  ! 1 *  * Metric(2,4) * Metric(1,3) + -1 *  * Metric(3,4) * Metric(1,2)
  ! ----------------------------------------------------------------
  complex(kind=default), dimension(0:3) :: a1a
  complex(kind=default), dimension(0:3) :: a2a
  complex(kind=default), dimension(0:3) :: a3a
  complex(kind=default), dimension(0:3) :: a4a
  real(kind=default), dimension(0:3) :: p1, p2, p3, p4
  integer :: nu1
  integer :: nu2
  integer :: nu3
  integer :: nu4
  ! ----------------------------------------------------------------
  a2a(0) = a2%t
  a2a(1:3) = a2%x
  a3a(0) = a3%t
  a3a(1:3) = a3%x
  a4a(0) = a4%t
  a4a(1:3) = a4%x
  p2(0) = k2%t
  p2(1:3) = k2%x
  p3(0) = k3%t
  p3(1:3) = k3%x
  p4(0) = k4%t
  p4(1:3) = k4%x
  p1 = - p2 - p3 - p4
```

```
pure function FFS4_p012 (g, psibar2, k2, phi3, k3) result (psi1)
  type(conjspinor) :: psi1
  complex(kind=default), intent(in) :: g
  type(conjspinor), intent(in) :: psibar2
  complex(kind=default), intent(in) :: phi3
  type(momentum), intent(in) :: k2, k3
  ! ----------------------------------------------------------------
  ! 1 * <2|(1-g5)/2|1> *  + 1 * <2|(1+g5)/2|1> *
  ! ----------------------------------------------------------------
  real(kind=default), dimension(0:3) :: p1, p2, p3
  complex(kind=default), dimension(1:4) :: bra01
  complex(kind=default), dimension(1:4) :: bra02
  integer :: alpha
  ! ----------------------------------------------------------------
  p2(0) = k2%t
  p2(1:3) = k2%x
  p3(0) = k3%t
  p3(1:3) = k3%x
  p1 = - p2 - p3
  ! ----------------------------------------------------------------
  ! <2|(1-g5)/2|1>
  bra01(1) = 0 + psibar2%a(1)
  bra01(2) = 0 + psibar2%a(2)
  bra01(3) = 0
  bra01(4) = 0
```



Minimal Mirror Twin Higgs: Lipp / JRR , *in preparation*

NLO Automation in WHIZARD

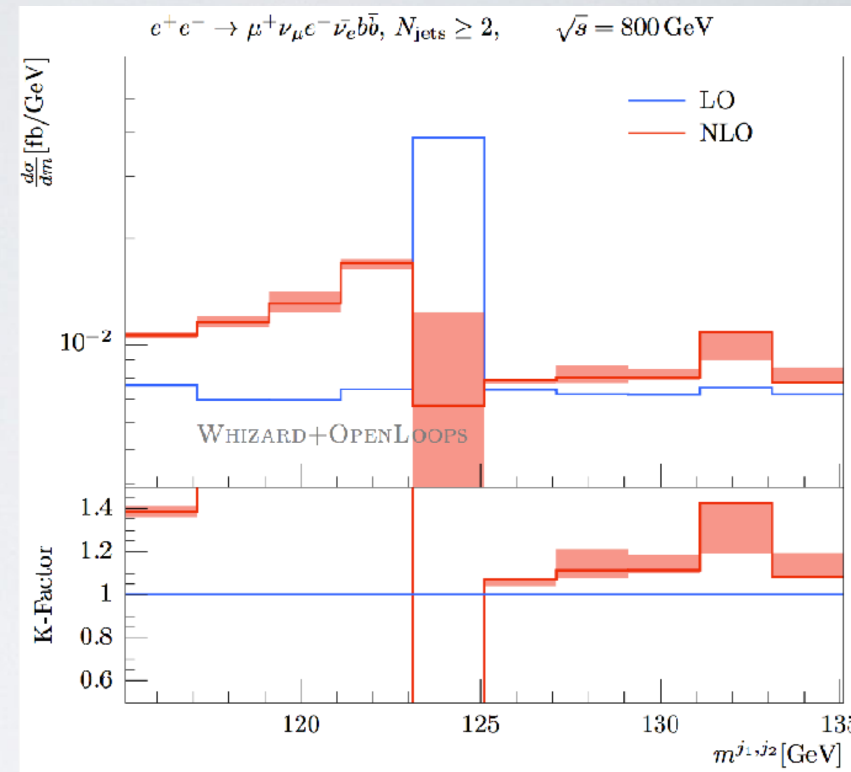
Working NLO interfaces to:

- ★ GoSam [N. Greiner, G. Heinrich, J. v. Soden-Fraunhofen et al.]
- ★ OpenLoops [F. Cascioli, J. Lindert, P. Maierhöfer, S. Pozzorini]
- ★ Recola [A. Denner, L. Hofer, J.-N. Lang, S. Uccirati]

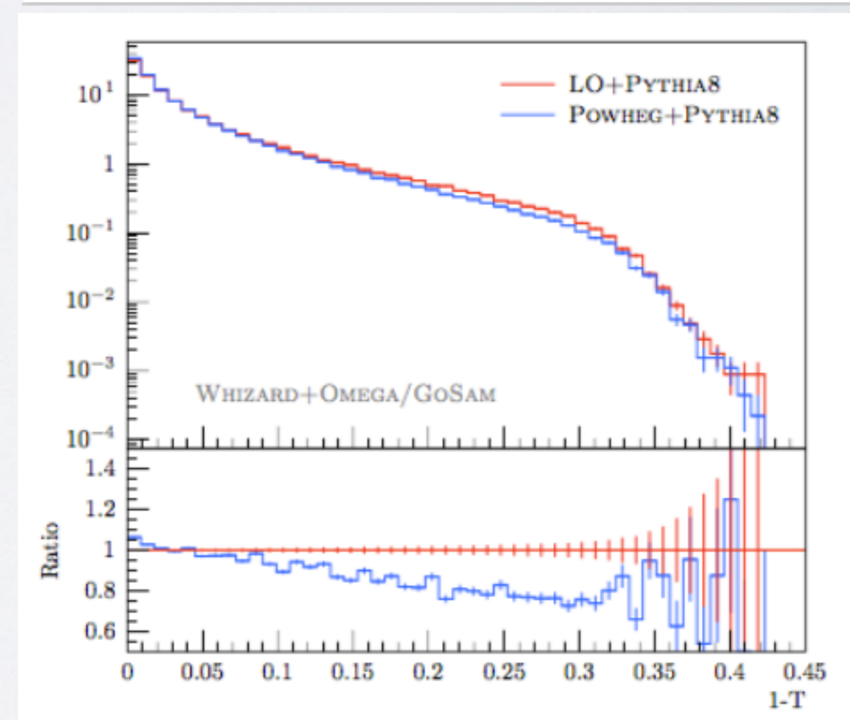
NLO QCD (massless & massive) fully supported

```
alpha_power = 2
alphas_power = 1

process eejjj = e1,E1 => j, j, j { nlo_calculation = full }
```



- FKS subtraction [Frixione/Kunszt/Signer, hep-ph/9512328]
- Resonance-aware treatment [Ježo/Nason, 1509.09071]
- Virtual MEs external
- Real and virtual subtraction terms internal
- NLO decays available for the NLO processes
- Fixed order events for plotting (weighted)
- Automated POWHEG damping and matching
- Exclusive matched NLO/NLL top threshold [talk JRR, today]
- NLO QCD: final clean-up NLO EW started
- Approaching WHIZARD 3.0.0α (ca. end 2019)



Validation of NLO QCD for ee Collisions

1 TeV

Process	MG5_aMC σ^{LO}[fb]	MG5_aMC σ^{NLO}[fb]	MG5_aMC K	WHIZARD σ^{LO}[fb]	WHIZARD σ^{NLO}[fb]	WHIZARD K
$e^+e^- \to jj$	622.3(5)	639.3(1)	1.02733	622.73(4)	639.41(9)	1.02678
$e^+e^- \to jjj$	340.1(2)	317.3(8)	0.93297	342.4(5)	318.6(7)	0.9305
$e^+e^- \to jjjj$	104.7(1)	103.7(3)	0.99045	105.1(4)	103.0(6)	0.98003
$e^+e^- \to jjjjj$	22.11(6)	24.65(4)	1.11488	22.80(2)	24.35(15)	1.06798
$e^+e^- \to jjjjjj$	N/A	N/A	N/A	6.0(2)	0.0(0)	0.0
$e^+e^- \to b\bar{b}$	92.37(6)	94.89(1)	1.02728	92.32(1)	94.78(7)	1.02664
$e^+e^- \to b\bar{b}b\bar{b}$	$1.644(3) \cdot 10^{-1}$	$3.60(1) \cdot 10^{-1}$	2.1897	$1.64(2) \cdot 10^{-1}$	$3.67(4) \cdot 10^{-1}$	2.2378
$e^+e^- \to t\bar{t}$	166.2(2)	174.5(3)	1.04994	166.4(1)	174.53(6)	1.04886
$e^+e^- \to t\bar{t}j$	48.13(5)	53.36(1)	1.10867	48.3(2)	53.25(6)	1.10248
$e^+e^- \to t\bar{t}jj$	8.614(9)	10.49(3)	1.21777	8.612(8)	10.46(6)	1.21458
$e^+e^- \to t\bar{t}jjj$	1.044(2)	1.420(4)	1.3601	1.040(1)	1.414(10)	1.3595
$e^+e^- \to t\bar{t}t\bar{t}$	$6.45(1) \cdot 10^{-4}$	$11.94(2) \cdot 10^{-4}$	1.85117	$6.463(2) \cdot 10^{-4}$	$11.91(2) \cdot 10^{-4}$	1.8428
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.719(5) \cdot 10^{-5}$	$5.264(8) \cdot 10^{-5}$	1.93602	$2.722(1) \cdot 10^{-5}$	$5.250(14) \cdot 10^{-5}$	1.92873
$e^+e^- \to t\bar{t}b\bar{b}$	0.1819(3)	0.292(1)	1.60533	0.186(1)	0.293(2)	1.57527
$e^+e^- \to t\bar{t}H$	2.018(3)	1.909(3)	0.94601	2.022(3)	1.912(3)	0.9456
$e^+e^- \to t\bar{t}Hj$	$0.2533(3) \cdot 10^{-0}$	$0.2665(6) \cdot 10^{-0}$	1.05212	0.2540(9)	0.2664(5)	1.04889
$e^+e^- \to t\bar{t}Hjj$	$2.663(4) \cdot 10^{-2}$	$3.141(9) \cdot 10^{-2}$	1.1795	$2.666(4) \cdot 10^{-2}$	$3.144(9) \cdot 10^{-2}$	1.17928
$e^+e^- \to t\bar{t}\gamma$	12.7(2)	13.3(4)	1.04726	12.71(4)	13.78(4)	1.08418
$e^+e^- \to t\bar{t}Z$	4.642(6)	4.95(1)	1.06636	4.64(1)	4.94(1)	1.06467
$e^+e^- \to t\bar{t}Zj$	0.6059(6)	0.6917(24)	1.14168	0.610(4)	0.6927(14)	1.13565
$e^+e^- \to t\bar{t}Zjj$	$6.251(28) \cdot 10^{-2}$	$8.181(21) \cdot 10^{-2}$	1.30875	$6.233(8) \cdot 10^{-2}$	$8.201(14) \cdot 10^{-2}$	1.31573
$e^+e^- \to t\bar{t}W^{\pm}jj$	$2.400(4) \cdot 10^{-4}$	$3.714(8) \cdot 10^{-4}$	1.54747	$2.41(1) \cdot 10^{-4}$	$3.695(9) \cdot 10^{-4}$	1.5332
$e^+e^- \to t\bar{t}\gamma\gamma$	0.383(5)	0.416(2)	1.08618	0.382(3)	0.420(3)	1.09952
$e^+e^- \to t\bar{t}\gamma Z$	0.2212(3)	0.2364(6)	1.06873	0.220(1)	0.240(2)	1.09094
$e^+e^- \to t\bar{t}\gamma H$	$9.75(1) \cdot 10^{-2}$	$9.42(3) \cdot 10^{-2}$	0.96614	$9.748(6) \cdot 10^{-2}$	$9.58(7) \cdot 10^{-2}$	0.98277
$e^+e^- \to t\bar{t}ZZ$	$3.788(4) \cdot 10^{-2}$	$4.00(1) \cdot 10^{-2}$	1.05597	$3.756(4) \cdot 10^{-2}$	$4.005(2) \cdot 10^{-2}$	1.0663
$e^+e^- \to t\bar{t}W^+W^-$	0.1372(3)	0.1540(6)	1.1225	0.1370(4)	0.1538(4)	1.12257
$e^+e^- \to t\bar{t}HH$	$1.358(1) \cdot 10^{-2}$	$1.206(3) \cdot 10^{-2}$	0.888	$1.367(1) \cdot 10^{-2}$	$1.218(1) \cdot 10^{-2}$	0.8909
$e^+e^- \to t\bar{t}HZ$	$3.600(6) \cdot 10^{-2}$	$3.58(1) \cdot 10^{-2}$	0.99445	$3.596(1) \cdot 10^{-2}$	$3.581(2) \cdot 10^{-2}$	0.9958

Validation of NLO QCD for *pp* Collisions

13 TeV

Process	POWHEG σ^{LO}[nb]	POWHEG σ^{NLO}[nb]	POWHEG K	WHIZARD σ^{LO}[nb]	WHIZARD σ^{NLO}[nb]	WHIZARD K
$pp \to e^+e^-$	0.9629(3)	1.0961(3)	1.13829	0.9637(1)	1.0962(2)	1.13742
$pp \to e^+\nu_e$	5.808(1)	6.657(1)	1.14616	5.808(1)	6.649(1)	1.1448
$pp \to e^+e^-j$	1.824(3)	2.210(2)	1.2116	1.823(2)	2.920(5)	1.6017

Process	MG5_AMC σ^{LO}[pb]	MG5_AMC σ^{NLO}[pb]	MG5_AMC K	WHIZARD σ^{LO}[pb]	WHIZARD σ^{NLO}[pb]	WHIZARD K
$pp \to jj$	$1.162(1) \cdot 10^6$	$1.580(7) \cdot 10^6$	1.3596	$1.157(2) \cdot 10^6$	$1.604(7) \cdot 10^6$	1.3863
$pp \to Zj$	$7.209(5) \cdot 10^3$	$9.745(32) \cdot 10^3$	1.35178	$7.207(2) \cdot 10^3$	$9.720(17) \cdot 10^3$	1.3487
$pp \to Zjj$	$2.348(6) \cdot 10^3$	$2.684(5) \cdot 10^3$	1.14307	$2.352(8) \cdot 10^3$	$2.735(9) \cdot 10^3$	1.16286
$pp \to W^\pm j$	$2.045(1) \cdot 10^4$	$2.839(9) \cdot 10^4$	1.3882	$2.043(1) \cdot 10^4$	$2.845(6) \cdot 10^4$	1.3925
$pp \to W^\pm jj$	$6.805(15) \cdot 10^3$	$7.780(13) \cdot 10^3$	1.14326	$6.798(7) \cdot 10^3$	$7.93(3) \cdot 10^3$	1.1665
$pp \to ZZ$	$1.097(3) \cdot 10^1$	$1.4190(25) \cdot 10^1$	1.2935	$1.094(2) \cdot 10^1$	$1.4192(32) \cdot 10^1$	1.2972
$pp \to ZW^\pm$	$2.777(3) \cdot 10^1$	$4.485(12) \cdot 10^1$	1.61507	$2.775(2) \cdot 10^1$	$4.488(4) \cdot 10^1$	1.6173
$pp \to ZW^\pm j$	$1.605(5) \cdot 10^5$	$2.100(2) \cdot 10^5$	1.3084	$1.604(6) \cdot 10^1$	$2.103(4) \cdot 10^1$	1.3111
$pp \to t\bar{t}$	$4.584(3) \cdot 10^2$	$6.746(14) \cdot 10^2$	1.47163	$4.588(2) \cdot 10^2$	$6.740(9) \cdot 10^2$	1.46902
$pp \to t\bar{t}j$	$3.135(2) \cdot 10^2$	$4.095(8) \cdot 10^2$	1.30621	$3.131(3) \cdot 10^2$	$4.194(9) \cdot 10^2$	1.33951
$pp \to t\bar{t}t\bar{t}$	$4.505(5) \cdot 10^{-3}$	$9.076(13) \cdot 10^{-3}$	2.01466	$4.511(2) \cdot 10^{-3}$	$9.070(9) \cdot 10^{-3}$	2.01064
$pp \to t\bar{t}Z$	$5.273(4) \cdot 10^{-1}$	$7.625(25) \cdot 10^{-1}$	1.44604	$5.281(8) \cdot 10^{-1}$	$7.639(9) \cdot 10^{-1}$	1.4465

Validation of NLO QCD for *pp* Collisions

13 TeV

Process	POWHEG σ^{LO}[nb]	POWHEG σ^{NLO}[nb]	POWHEG K	WHIZARD σ^{LO}[nb]	WHIZARD σ^{NLO}[nb]	WHIZARD K
$pp \to e^+e^-$	0.9629(3)	1.0961(3)	1.13829	0.9637(1)	1.0962(2)	1.13742
$pp \to e^+\nu_e$	5.808(1)	6.657(1)	1.14616	5.808(1)	6.649(1)	1.1448
$pp \to e^+e^-j$	1.824(3)	2.210(2)	1.2116	1.823(2)	2.920(5)	1.6017

Process	MG5_AMC σ^{LO}[pb]	MG5_AMC σ^{NLO}[pb]	MG5_AMC K	WHIZARD σ^{LO}[pb]	WHIZARD σ^{NLO}[pb]	WHIZARD K
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b-jet selection
c-jet selection

```
alias ljet = u:U:d:D:s:S:gl
alias jet = ljet:c:C

process charm_selec = e1, E1 => c, C, ljet, ljet, ljet, ljet

jet_algorithm = antikt_algorithm
jet_r = 0.5

cuts = let subevt @clustered = cluster [jet] in
       let subevt @cjets = select_c_jet if Pt > 30 GeV [@clustered] in
       count [@selected] >= 4 and count [@cjets] == 2
```

Photon isolation in WHIZARD

Frixione, hep-ph/9706545; hep-ph/9801442; hep-ph/9809397

- Isolate perturbative and fragmentation contributions to photons
- Partons must be allowed inside isolation cone (IR-safe observables!)
- Otherwise: soft-collinear IR cancellations would be spoiled
- Define isolation cone around each photon: Radius δ (η–Φ space)

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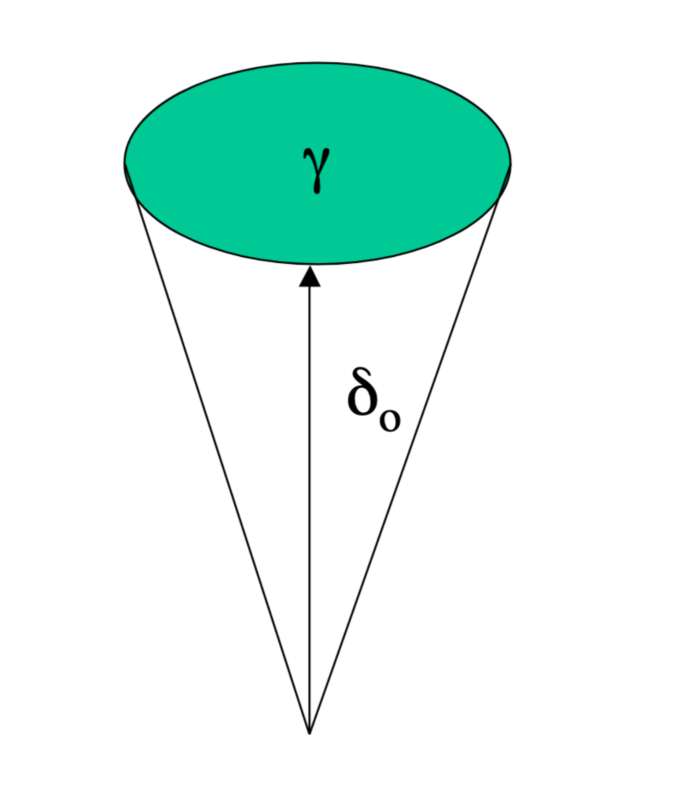

R distance (photon-parton):

$$R_{i\gamma} = \sqrt{\Delta\eta_{i\gamma}^2 + \Delta\phi_{i\gamma}^2}$$

Reject event if partons inside δ_0 -cone don't fulfill jet isolation criterion:

$$\sum_{i\in\text{partons}} E_i\theta(\delta - R_{i\gamma}) \;\leq\; \mathcal{X}(\delta) \quad \text{for all} \quad \delta \leq \delta_0$$

$$\mathcal{X}(\delta) = E_\gamma \epsilon_\gamma \left(\frac{1-\cos\delta}{1-\cos\delta_0}\right)^n \qquad \lim_{\delta\to\infty} \mathcal{X}(\delta) = 0$$

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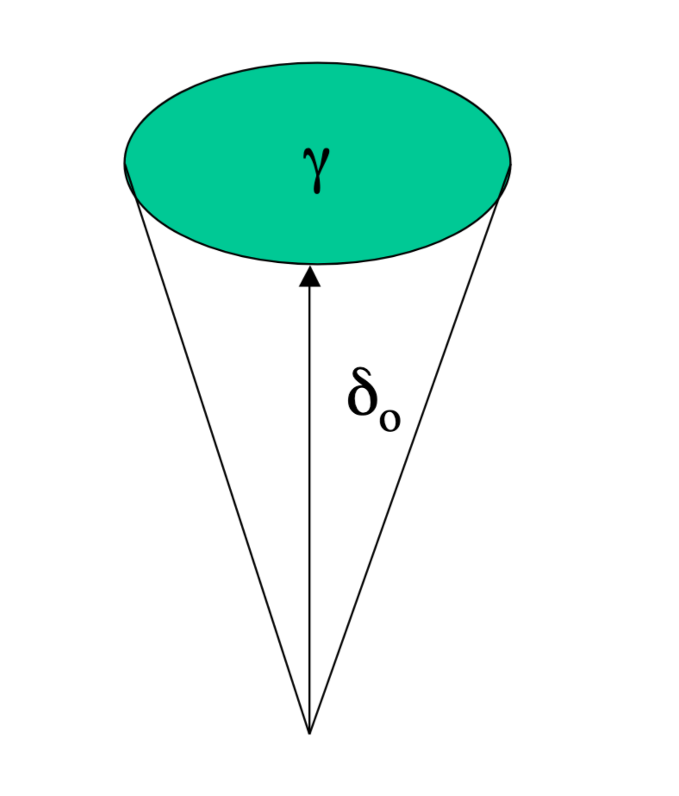

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```
photon_iso_eps = 1.0
photon_iso_n = 1
photon_iso_r0 = 0.4
```

```
alias ljet = u:U:d:D:s:S:gl
jet_algorithm = antikt_algorithm
jet_r = 0.5

process ee_aajj = e1, E1 => A, A, ljet, ljet

cuts = let subevt @clustered = cluster [jet] in
       photon_isolation [A, @clustered]

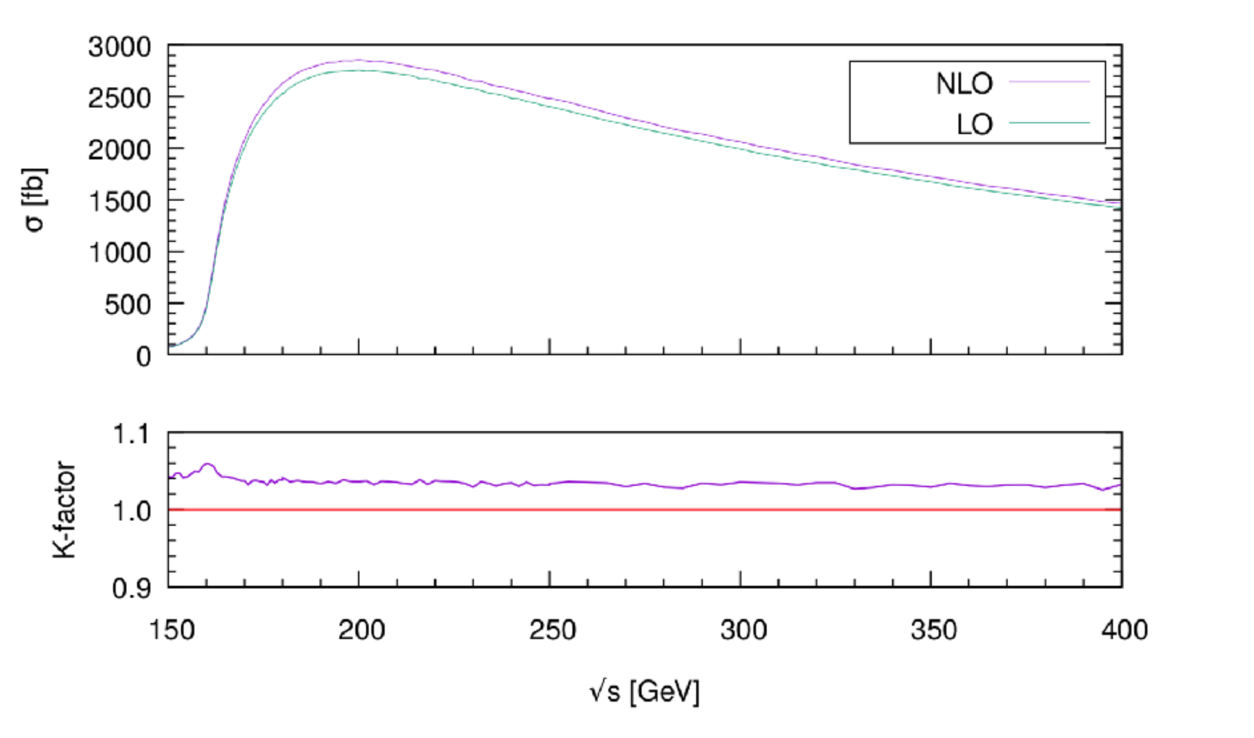
process ee_mmaa = e1, E1 => e2, E2, A, A

cuts = photon_isolation if Pt > 5 GeV [A, e2:E2:A]
```

NLO QCD for semi-leptonic $e^+e^- \to WW$

Bredt/Niedermeier/JRR/Rothe/Stienemeier, *work in progress*

$e^+e^- \to \mu\nu jj$



$\sqrt{s}$	σ_{LO}[pb]	σ_{NLO}[pb]	*K-factor*
160	0.4446	$0.4711^{+0.36\%}_{-0.62\%}$	$1.060^{+0.28\%}_{-0.66\%}$
200	2.755	$2.854^{+0.21\%}_{-0.81\%}$	$1.036^{+0.19\%}_{-0.77\%}$
250	2.405	$2.481^{+0.64\%}_{-0.12\%}$	$1.032^{+0.58\%}_{-0.19\%}$
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K factor mostly $\frac{\alpha_s}{\pi}$

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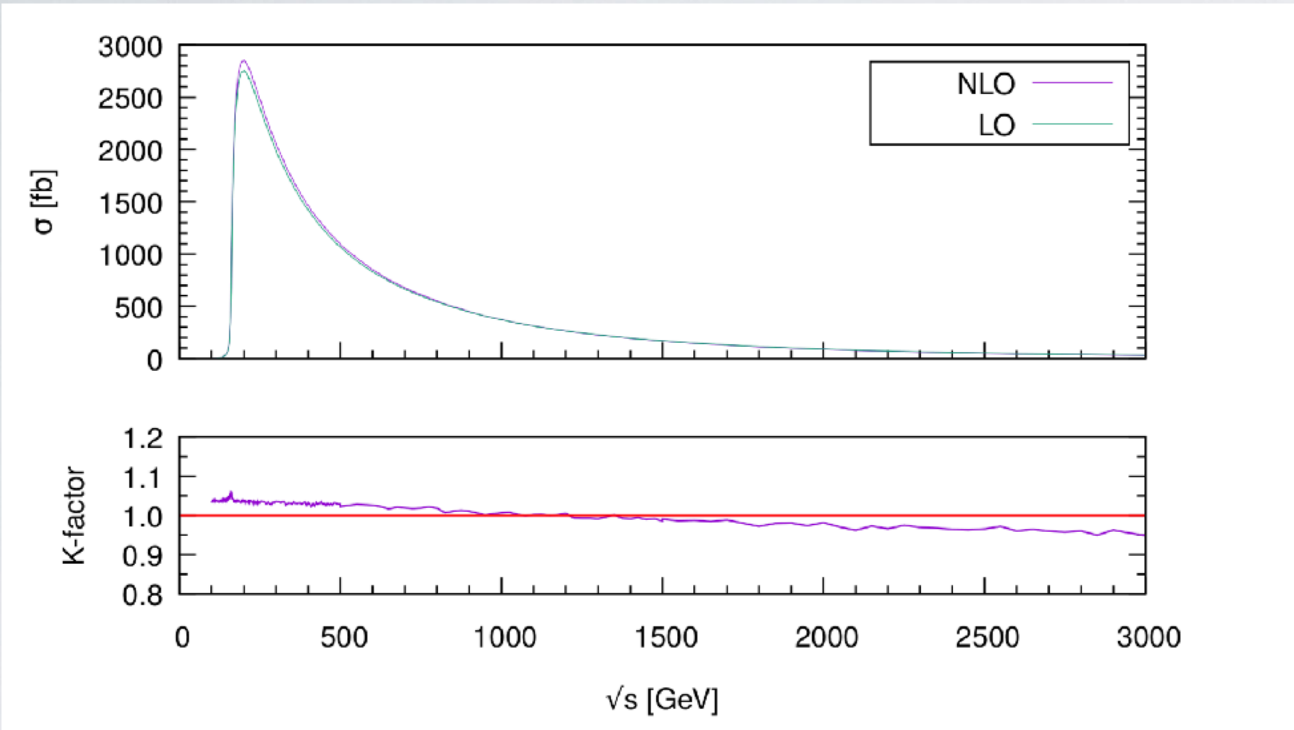

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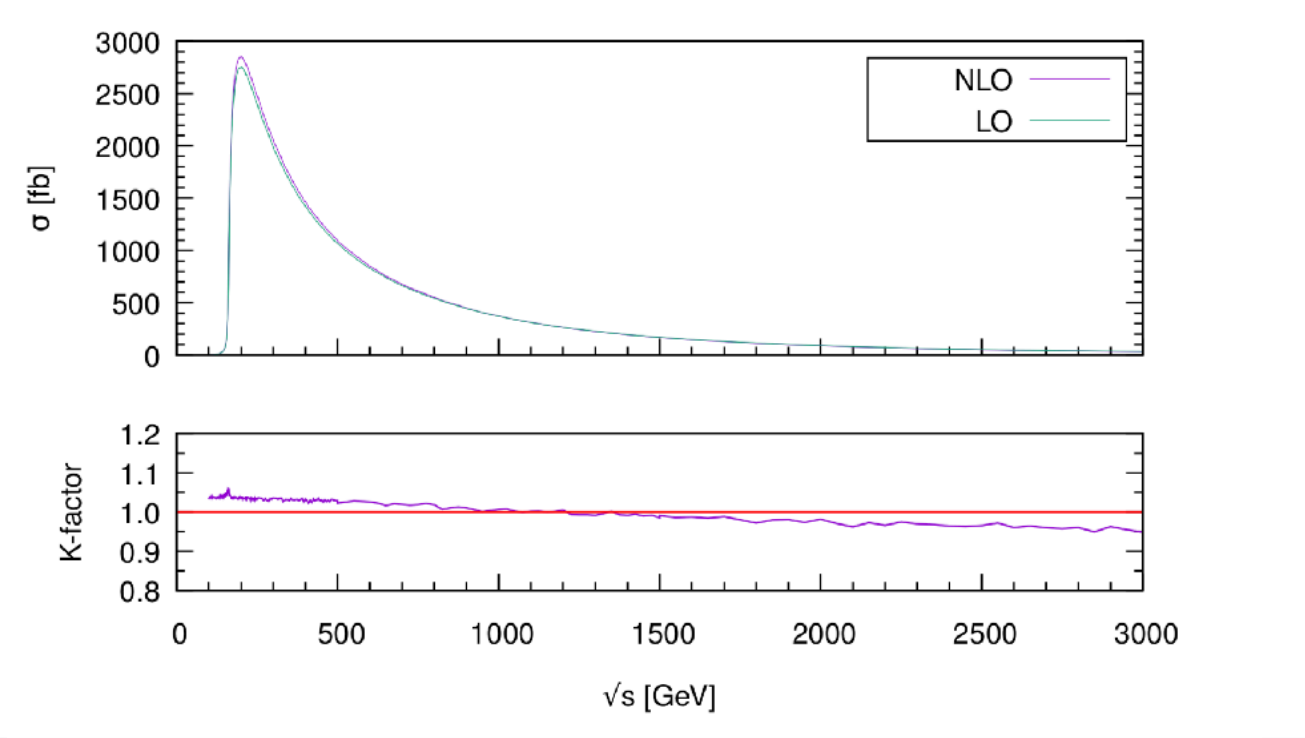

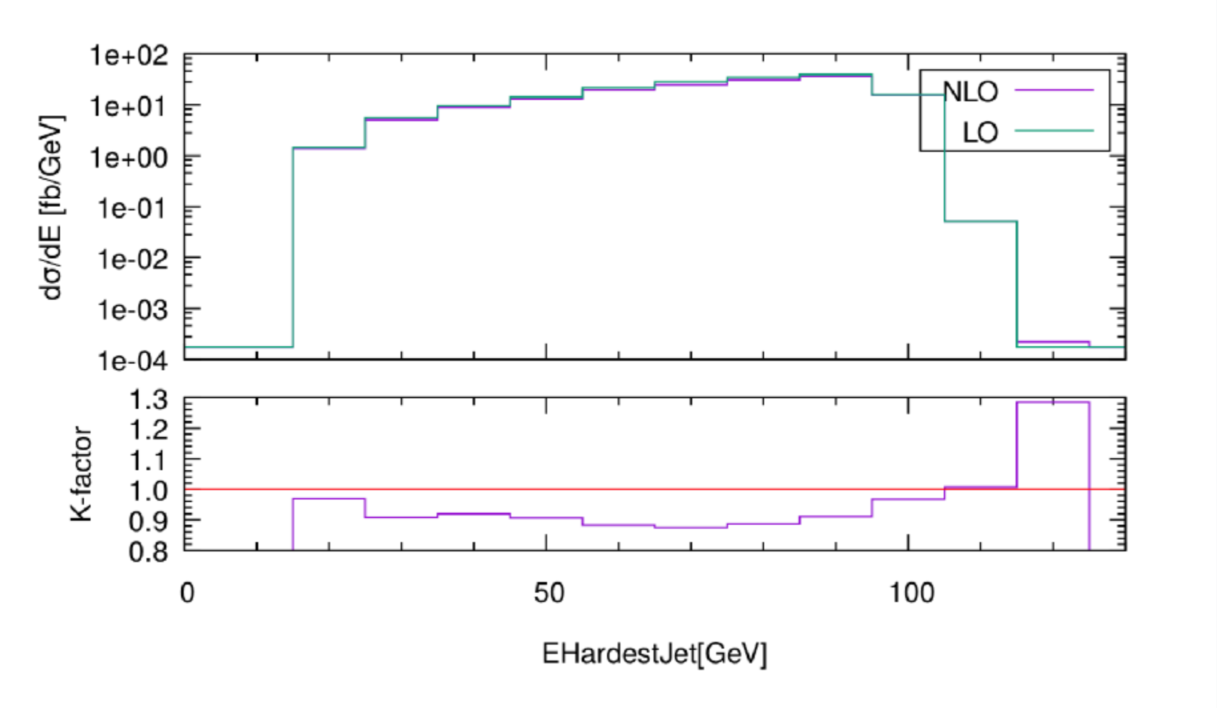

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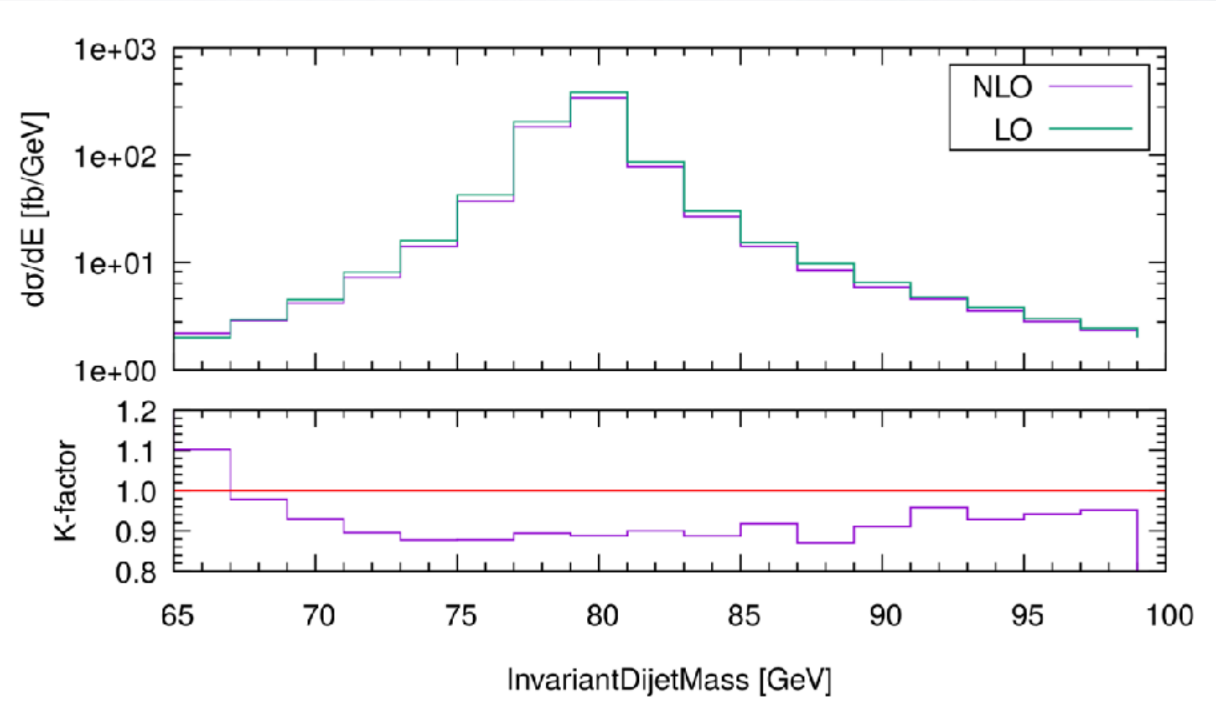

Interface between WHIZARD – PYTHIA8

- Intention: directly communicate between event records of WHIZARD and PYTHIA8
- No intermediate files: direct communication between event records
- Allows for using all the machinery for matching and merging from PYTHIA8

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```
| ==========================================================================
| Running self-test: whizard_lha
| --------------------------------------------------------------------------
Running test: whizard_lha_1
 --------  LHA initialization information  ------------

  beam    kind      energy  pdfgrp  pdfset
     A    2212    6500.000      -1      -1
     B    2212    6500.000      -1      -1

  Event weighting strategy = -3

  Processes, with strategy-dependent cross section info
  number      xsec (pb)      xerr (pb)      xmax (pb)
      1     1.0000e+00     5.0000e-02     1.0000e+00
      2     1.2000e+00     6.0000e-02     1.0000e+00
      3     1.4000e+00     7.0000e-02     1.0000e+00
      4     1.6000e+00     8.0000e-02     1.0000e+00
      5     1.8000e+00     9.0000e-02     1.0000e+00

 --------  End LHA initialization information  --------
 ... success.
Running test: whizard_lha_2
 --------  LHA initialization information  ------------

  beam    kind      energy  pdfgrp  pdfset
     A    2212    6500.000      -1      -1
     B    2212    6500.000      -1      -1

  Event weighting strategy = -3

  Processes, with strategy-dependent cross section info
  number      xsec (pb)      xerr (pb)      xmax (pb)
      1     1.0000e+00     5.0000e-02     1.0000e+00

 --------  End LHA initialization information  --------

 --------  LHA event information and listing  ---------------------------------------------------------------

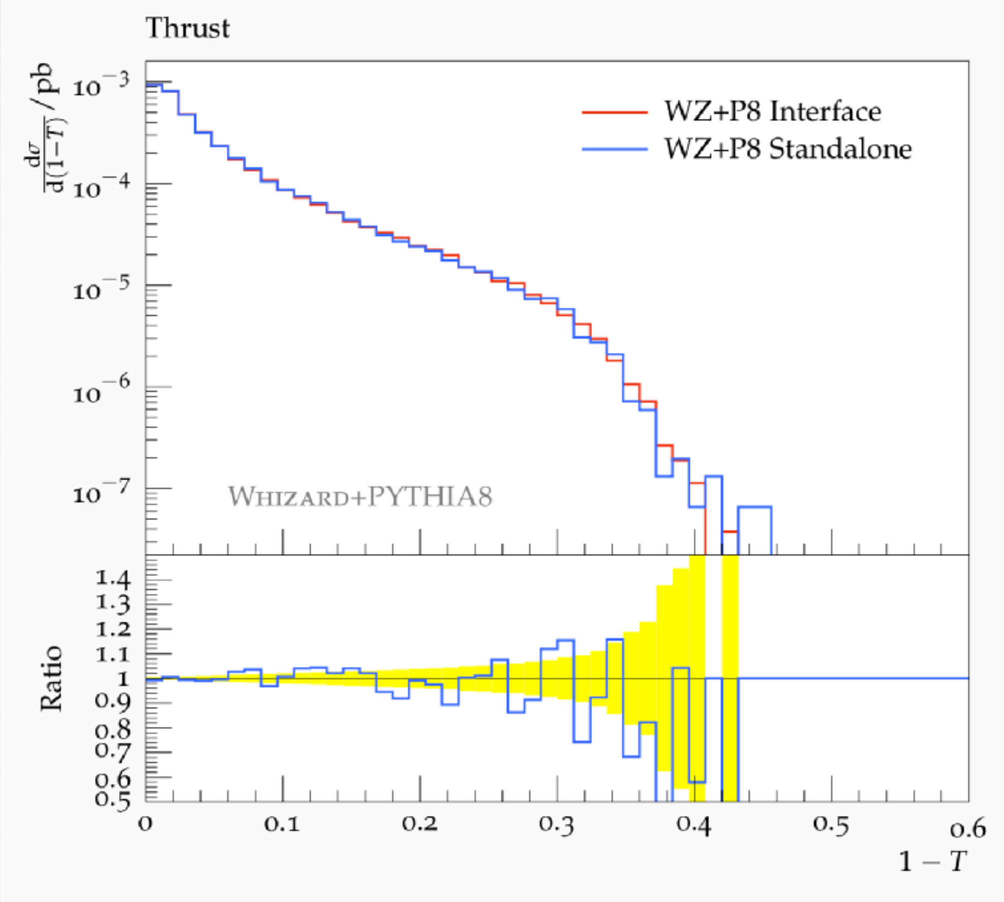
    process =        1    weight =   1.0000e+00     scale =   1.0000e+03 (GeV)
                       alpha_em =   7.8740e-03    alpha_strong =   1.0000e-01

    Participating Particles
    no        id stat     mothers     colours      p_x        p_y        p_z         e          m        tau      spin
     1      2011   -9     0     0     0     0     0.000      0.000      0.000      1.000      1.000    0.000    0.000
     2      2012   -9     0     0     0     0     0.000      0.000      0.000      2.000      2.000    0.000    0.000
     3        11   -1     1     0     0     0     0.000      0.000      0.000      4.000      4.000    0.000    0.000
     4        12   -1     2     0     0     0     0.000      0.000      0.000      6.000      6.000    0.000    0.000
     5        91    3     1     0     0     0     0.000      0.000      0.000      3.000      3.000    0.000    0.000
     6        92    3     2     0     0     0     0.000      0.000      0.000      5.000      5.000    0.000    0.000
     7         3    1     3     4     0     0     0.000      0.000      0.000      7.000      7.000    0.000    0.000
     8         4    1     3     4     0     0     0.000      0.000      0.000      8.000      8.000    0.000    0.000
     9         5    1     3     4     0     0     0.000      0.000      0.000      9.000      9.000    0.000    0.000

 --------  End LHA event information and listing  ---------------------------------------------------------
```

```
$shower_method = “PYTHIA8”
$hadronization_method = “PYTHIA8”
```

Allows to use the PYTHIA8 toolbox for matching



Gridpack functionality in WHIZARD

- Workspace subdirectory for GRID communication: job ID
- Pack and unpack features: transfers whole directories, relies on `tar`

```
./whizard --job_id "42"
```

or

```
./whizard -J "42"
```

[actually for the integration grids!]

```
$grid_path = "&lt;afs/.../...&gt;"
```

```
./whizard script1_tar.sin --pack my_workspace
```

`script1_tar.sin` contains `$compile_workspace = "my_workspace"`

On the remote machine, you can run this with

```
./whizard script2_tar.sin --unpack my_workspace.tgz
```

Summary & Outlook

- WHIZARD 2.8.2 brings many new features
- Full-fledged parallel MPI integration *[Load balancer* WHIZARD 2.8.3*]*
- Full-fledged UFO interface *[Majorana fermions & SLHA* WHIZARD 2.8.3*]*
- Old goodies of e^+e^- physics: beam spectra, e^+e^- ISR, LCIO, polarizations
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WHIZARD STRATEGY

WE'RE HAPPY TO ACCOMODATE WELL-POSED USER REQUESTS
PLEASE USE: *http://launchpad.net/whizard*

BACKUP

Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances (Z, W, H, t)
- In general: resonance masses *not* respected by modified kinematics of subtraction terms
- Collinear (and soft) radiation can lead to mismatch between Born and subtraction terms
- Algorithm to include resonance histories [Ježo/Nason, 1509.09071]
- Avoids double logarithms in the resonances' width
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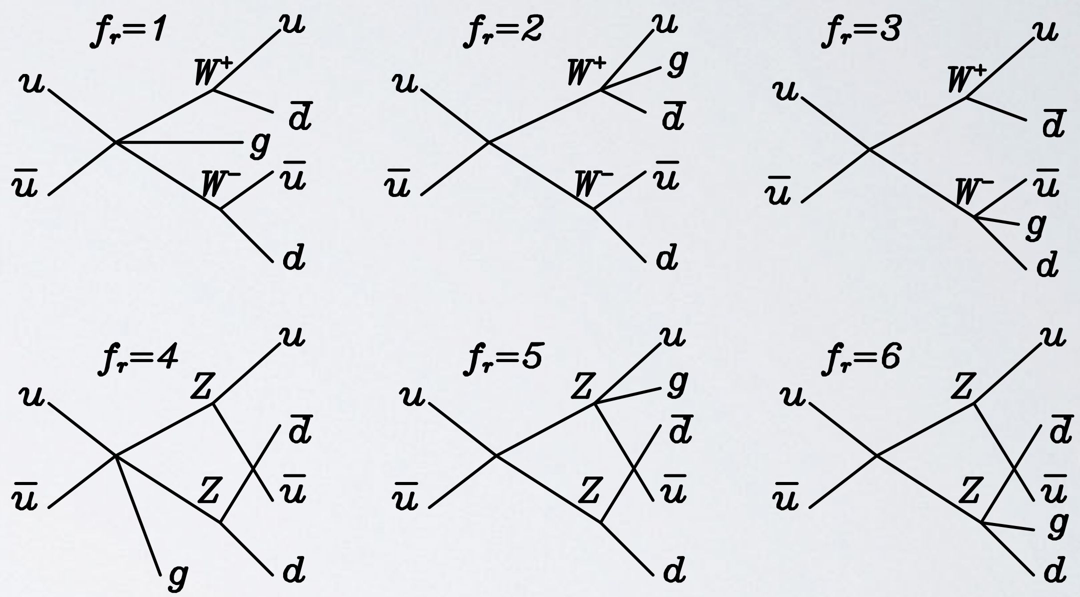

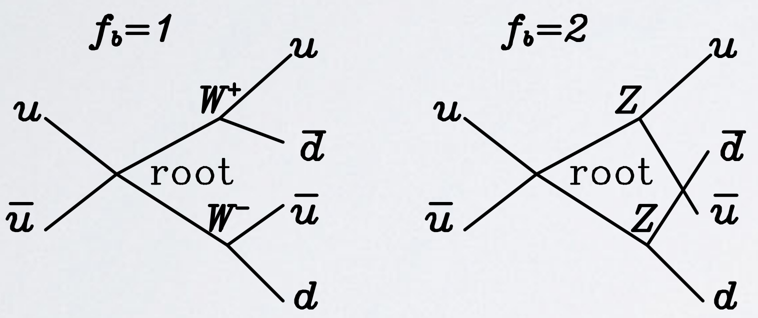

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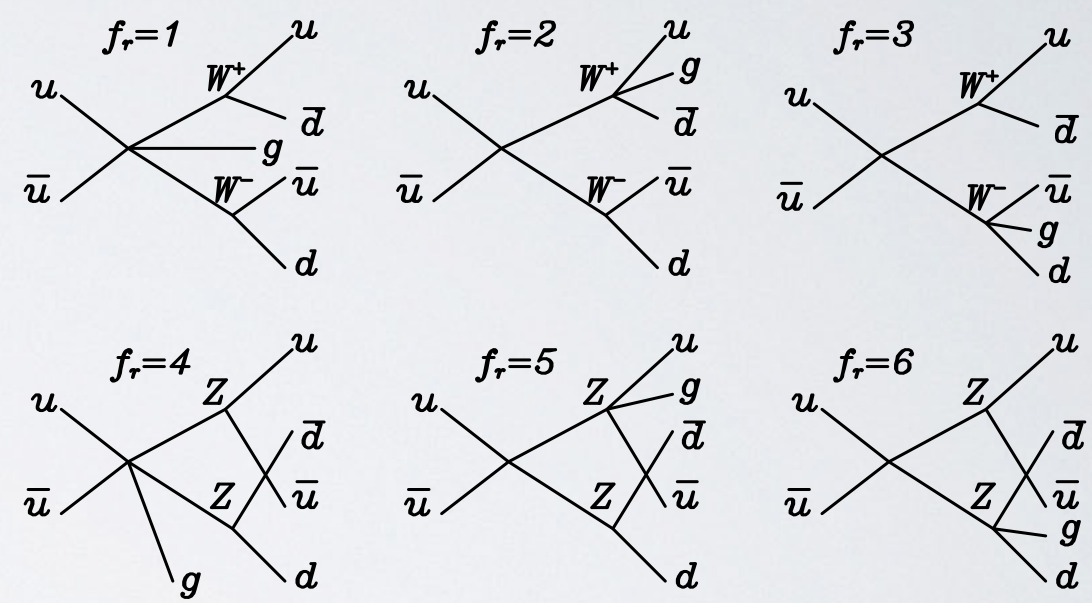

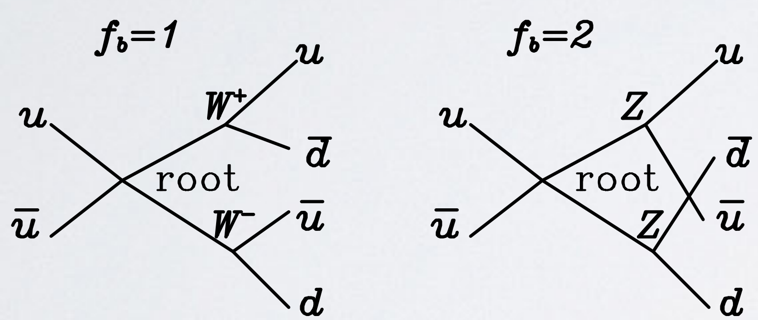

- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (*ZZ, ZH* histories)

It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	9.6811847E+00	6.42E+00	66.30	72.60*	0.65		
2	11959	2.8539703E+00	2.35E-01	8.25	9.02*	0.69		
3	11936	2.4907574E+00	6.54E-01	26.25	28.68	0.35		
4	11908	2.7695559E+00	9.67E-01	34.91	38.09	0.30		
5	11874	2.4346151E+00	4.82E-01	19.80	21.57*	0.74		
5	59665	2.7539078E+00	1.97E-01	7.15	17.47	0.74	0.49	5

standard FKS

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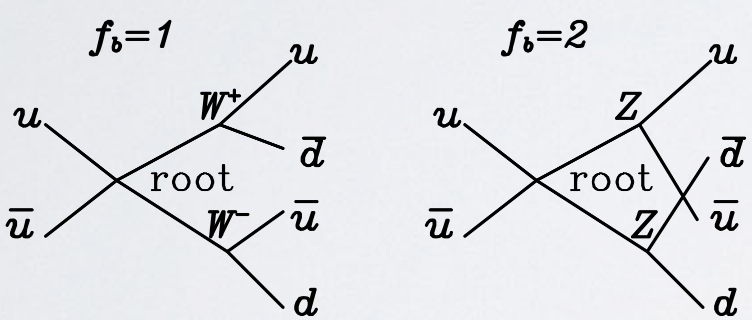
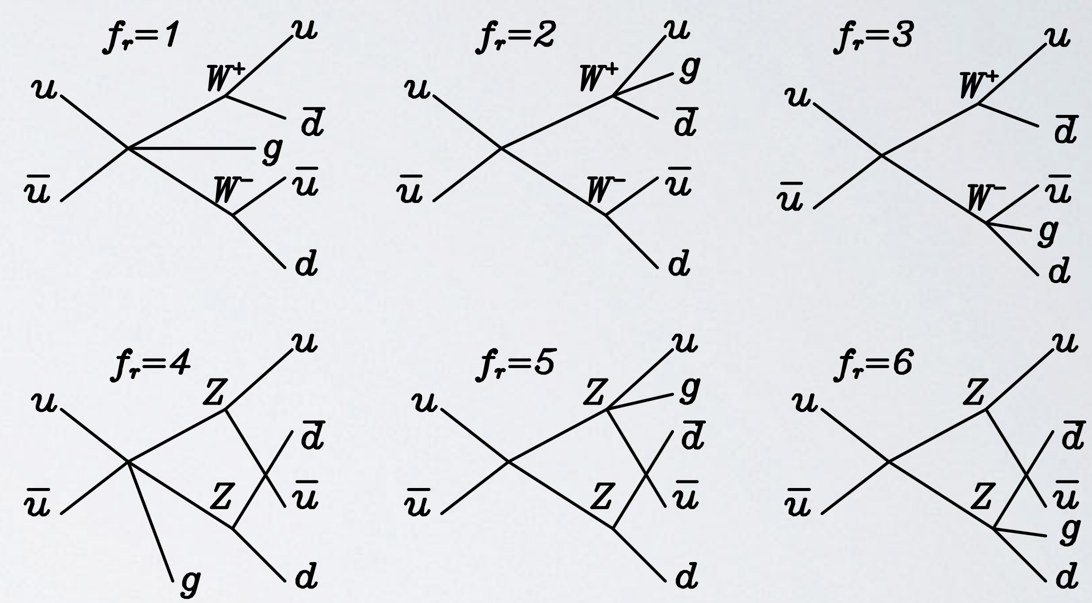
- Collinear (and soft) radiation can lead to mismatch between Born and subtraction terms

- Algorithm to include resonance histories [Ježo/Nason, 1509.09071]
- Avoids double logarithms in the resonances' width
- Most important for narrow resonances $(H \to bb)$
- Separate treatment of Born and real terms,
  soft mismatch [, collinear mismatch]





- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ *(ZZ, ZH* histories)

It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	9.6811847E+00	6.42E+00	66.30	72.60*	0.65		
2	11959	2.8539703E+00	2.35E-01	8.25	9.02*	0.69		
3	11936	2.4907574E+00	6.54E-01	26.25	28.68	0.35		
4	11908	2.7695559E+00	9.67E-01	34.91	38.09	0.30		
5	11874	2.4346151E+00	4.82E-01	19.80	21.57*	0.74		
5	59665	2.7539078E+00	1.97E-01	7.15	17.47	0.74	0.49	5

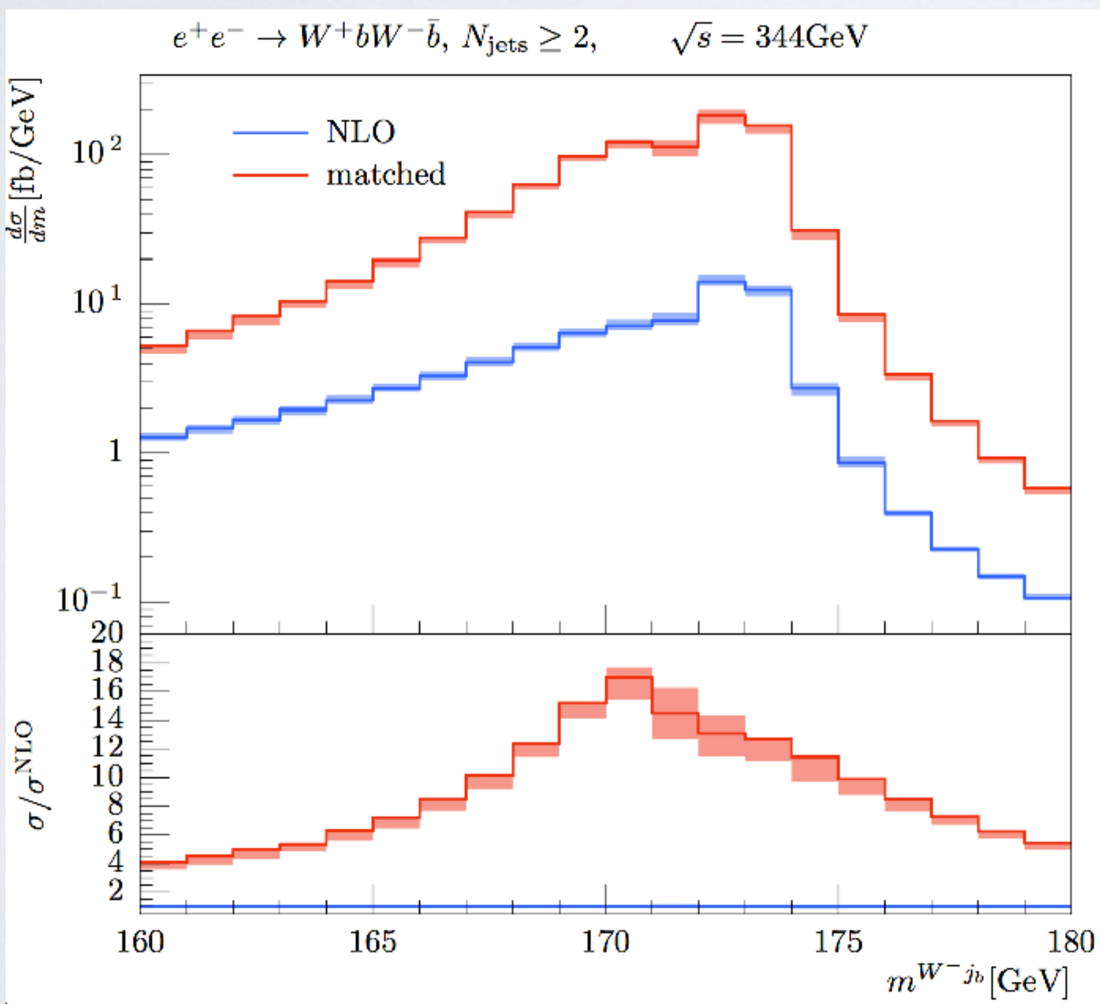
standard FKS

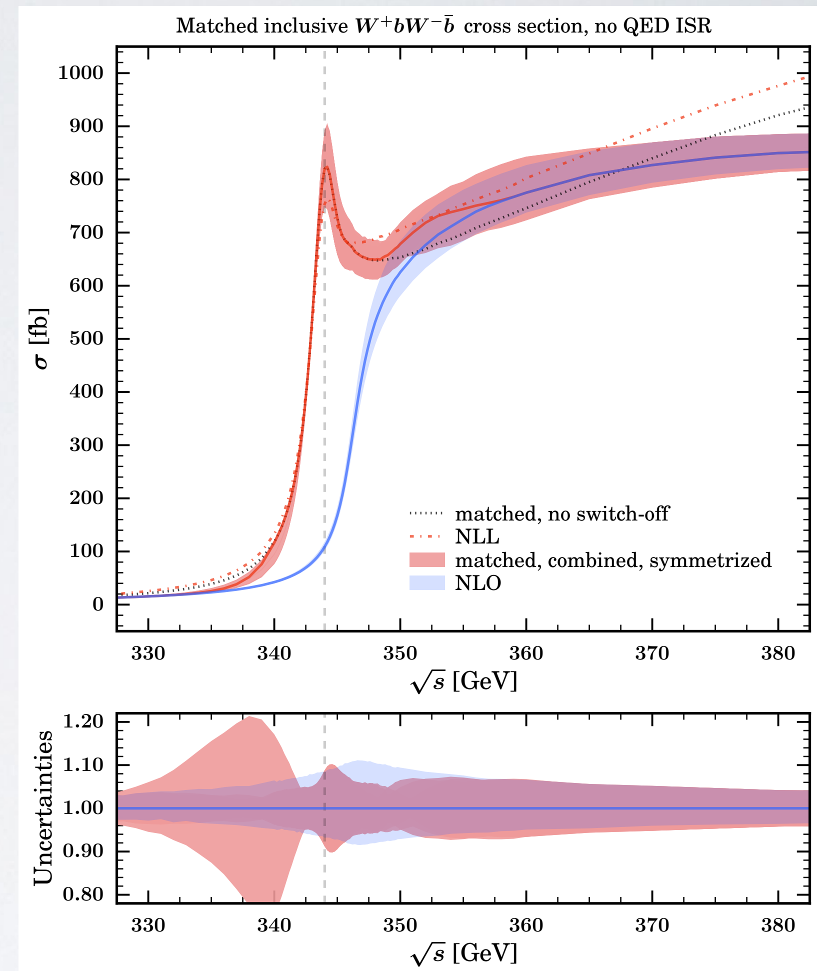
It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	2.9057032E+00	8.35E-02	2.87	3.15*	7.90		
2	11962	2.8591952E+00	5.20E-02	1.82	1.99*	10.91		
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	5

FKS with resonance mappings

Top Threshold/Continuum in WHIZARD

- Top threshold scan best-known method to measure top quark mass, ΔM ~ 30-70 MeV
- Continuum top production best-known method to measure top couplings
- WHIZARD provides special model for top threshold
- Matches threshold resummation with NLO QCD
- Allows for (almost) fully exclusive final states

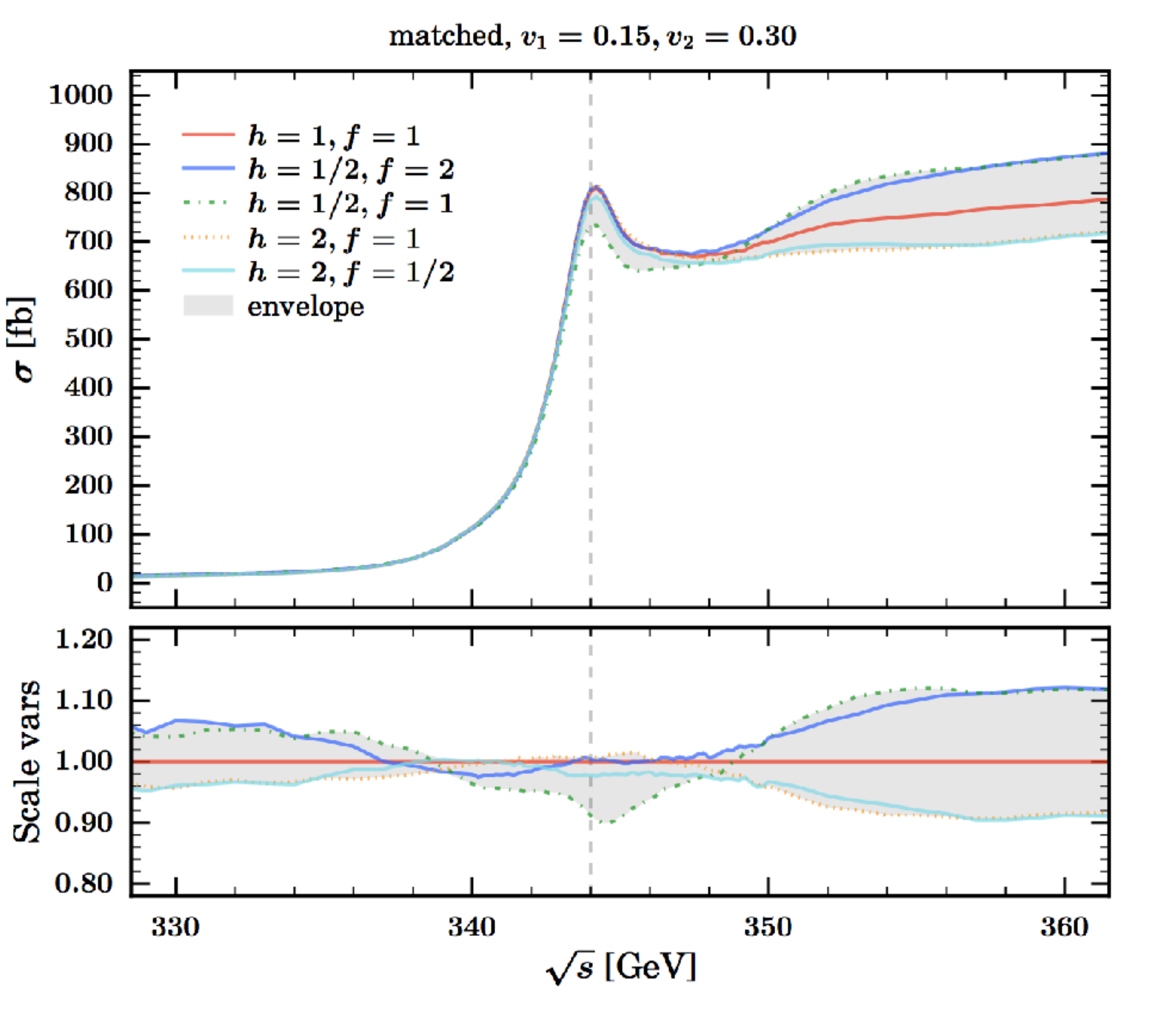


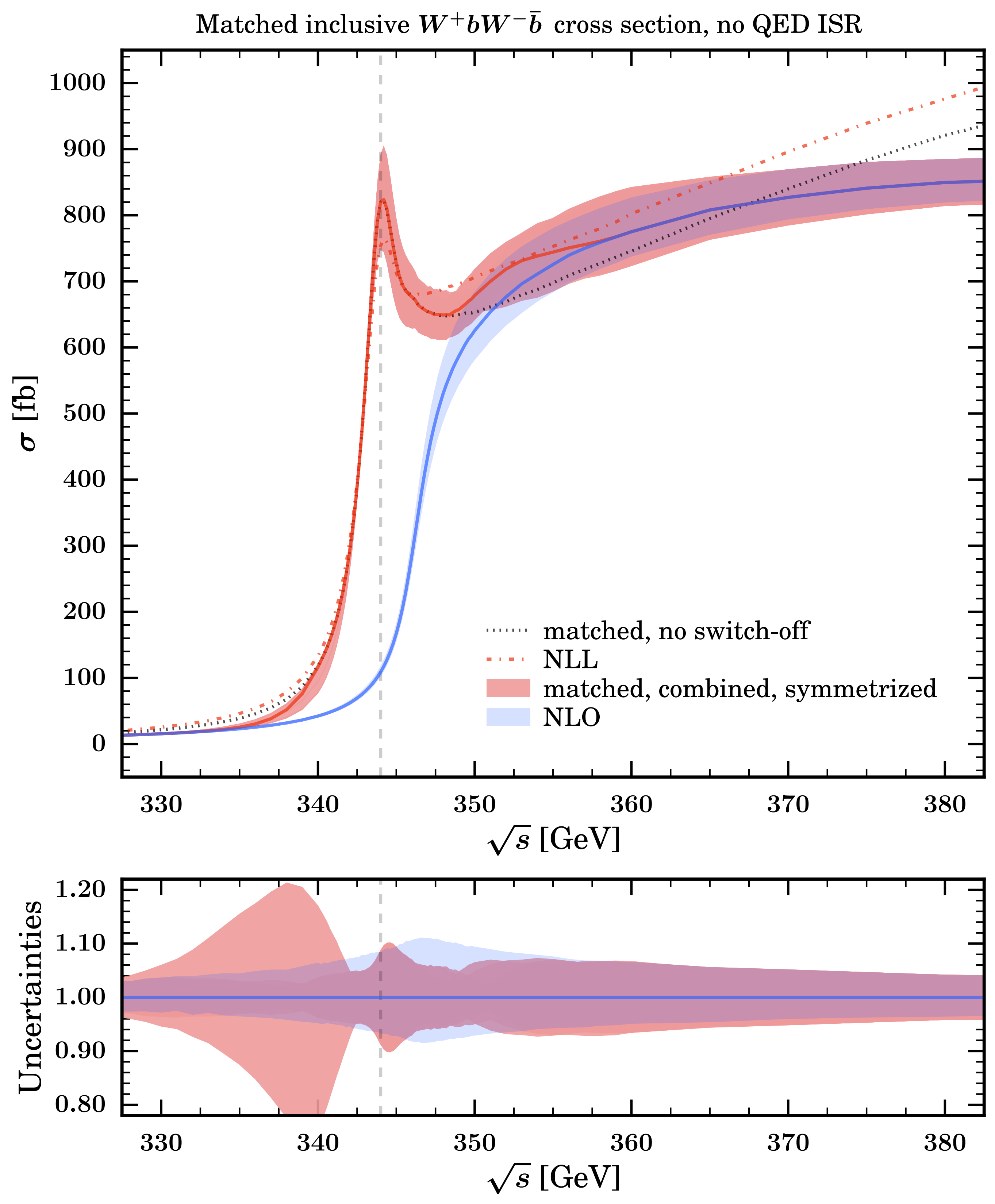


Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220 [JHEP 1803(2018)184]

Allows to study top mass dependence of differential distributions at threshold

Matching threshold NLL to continuum NLO





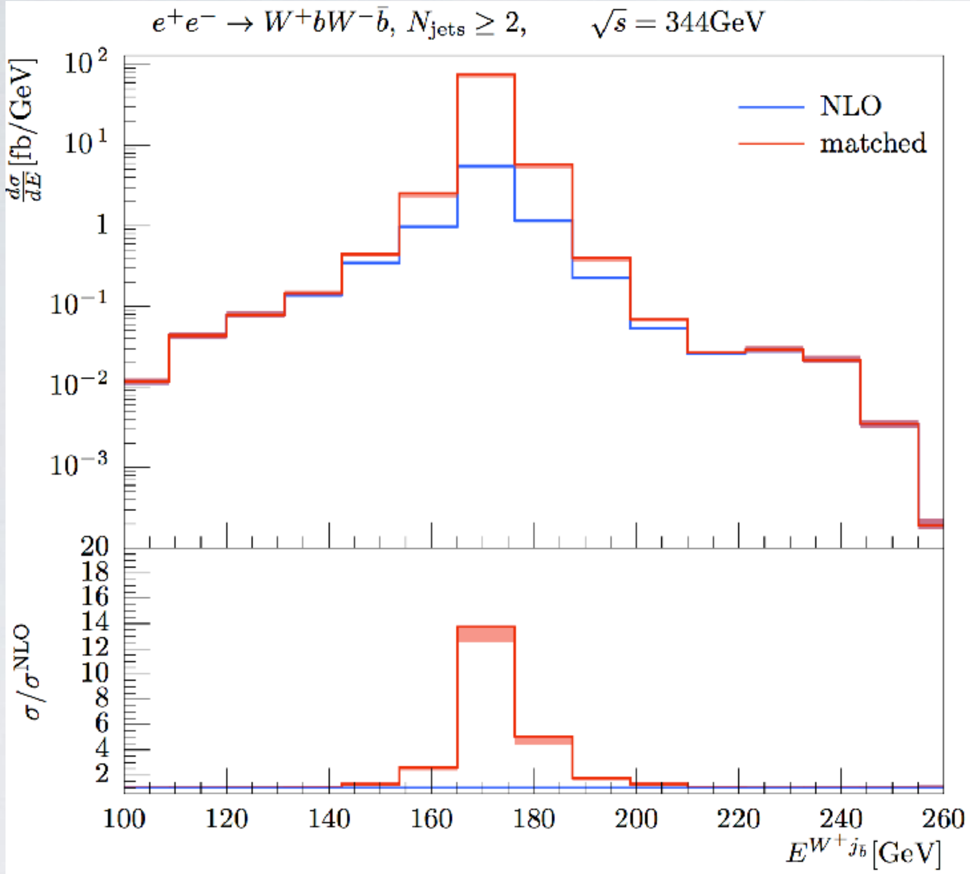
Total uncertainty: *h-f* variation band and matching [switch-off function]

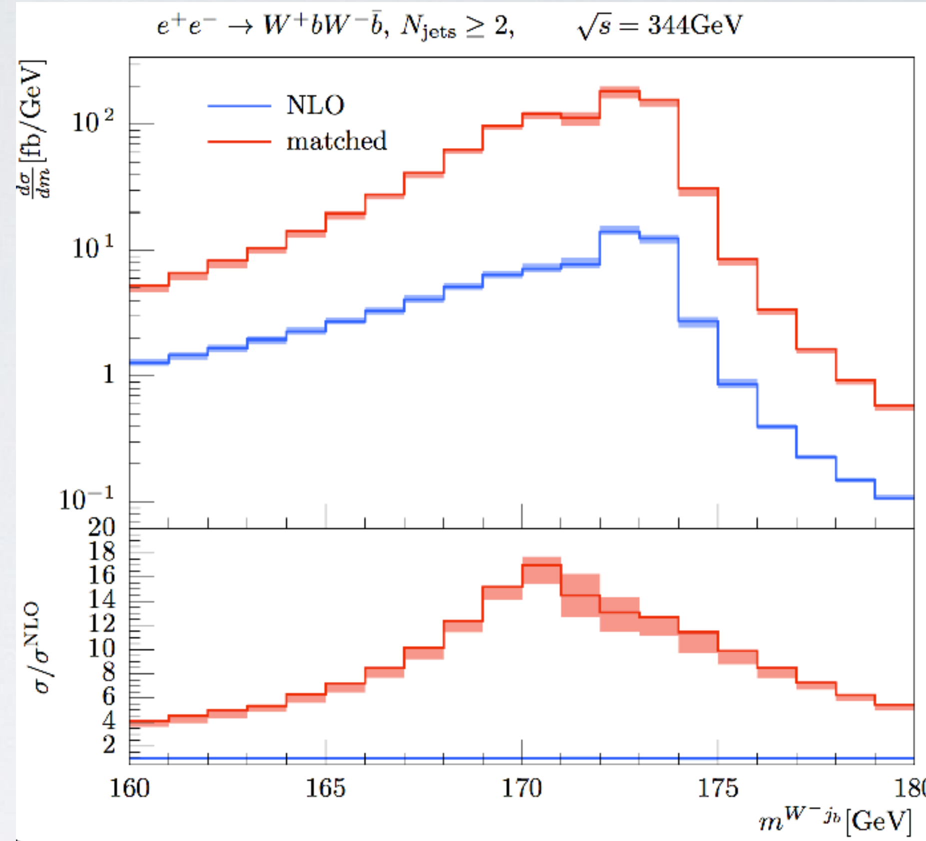
Symmetrization of error bands:

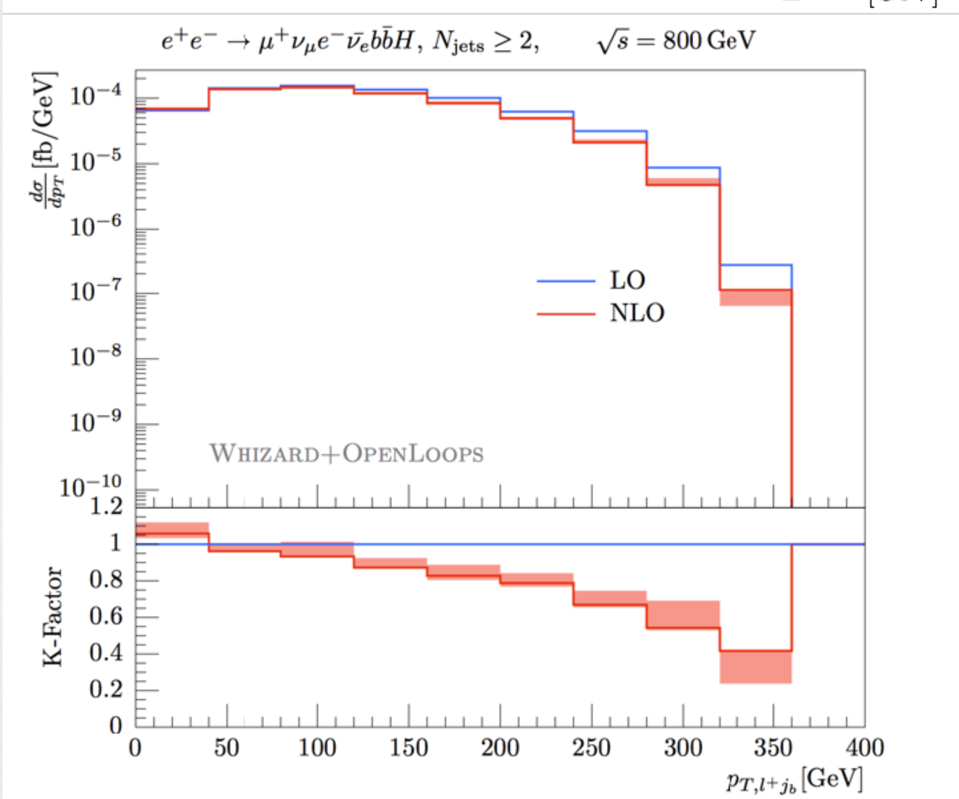
$$\sigma_{\max} = \max\left[\max_{i\in\mathrm{HF}} \sigma_i \ , \ \sigma_0 + (\sigma_0 - \min_{i\in\mathrm{HF}} \sigma_i)\right]$$

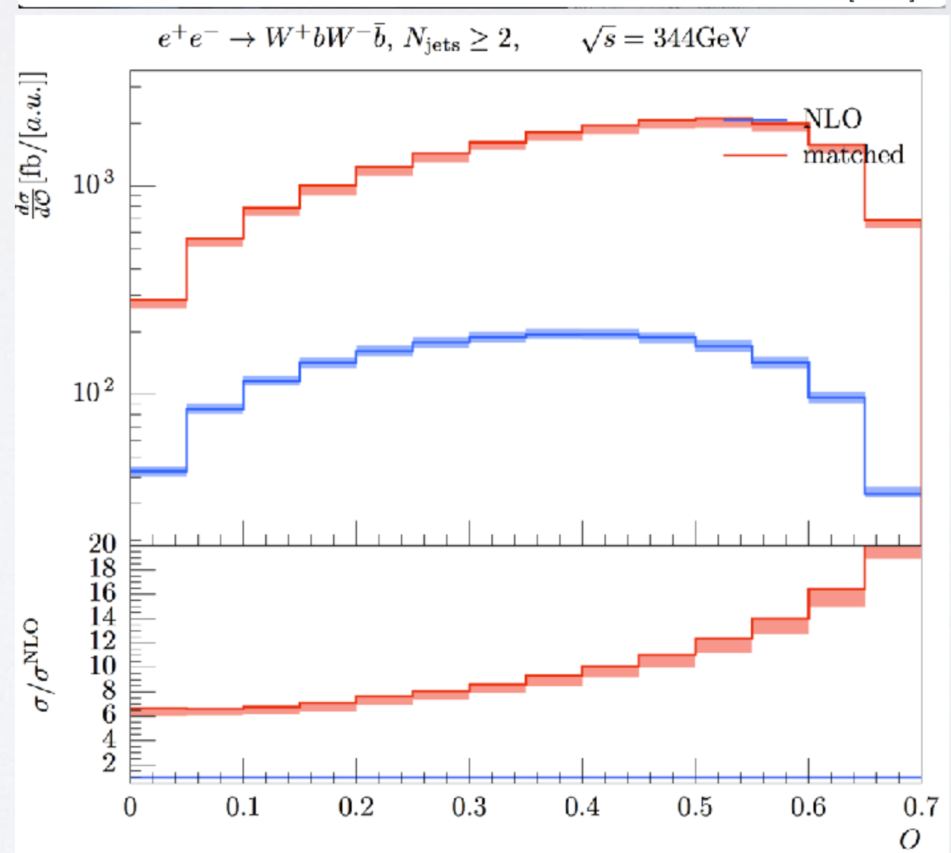
$$\sigma_{\min} = \min\left[\min_{i\in\mathrm{HF}} \sigma_i \ , \ \sigma_0 - (\max_{i\in\mathrm{HF}} \sigma_i - \sigma_0)\right]$$

Matched threshold differential distributions

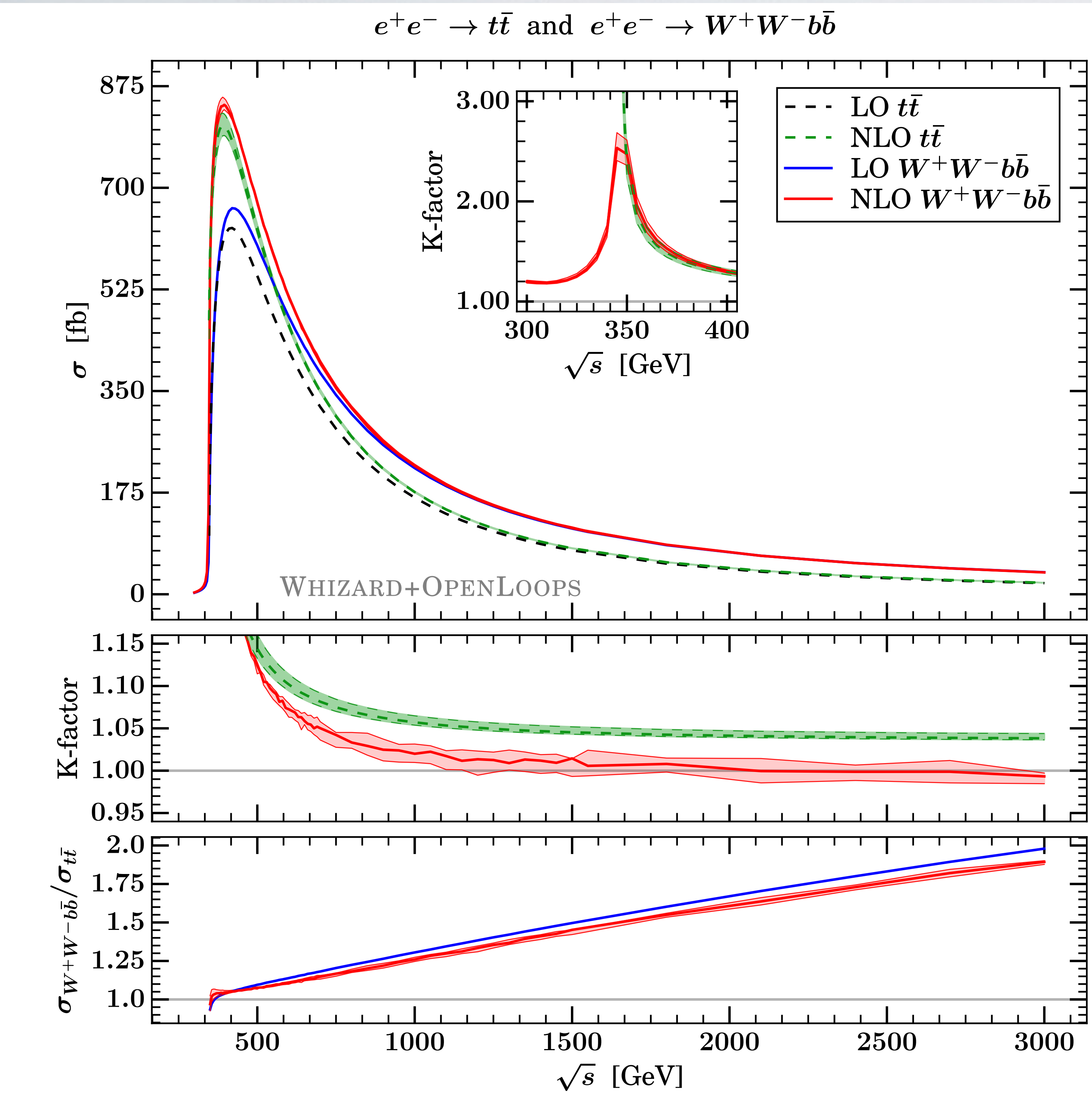


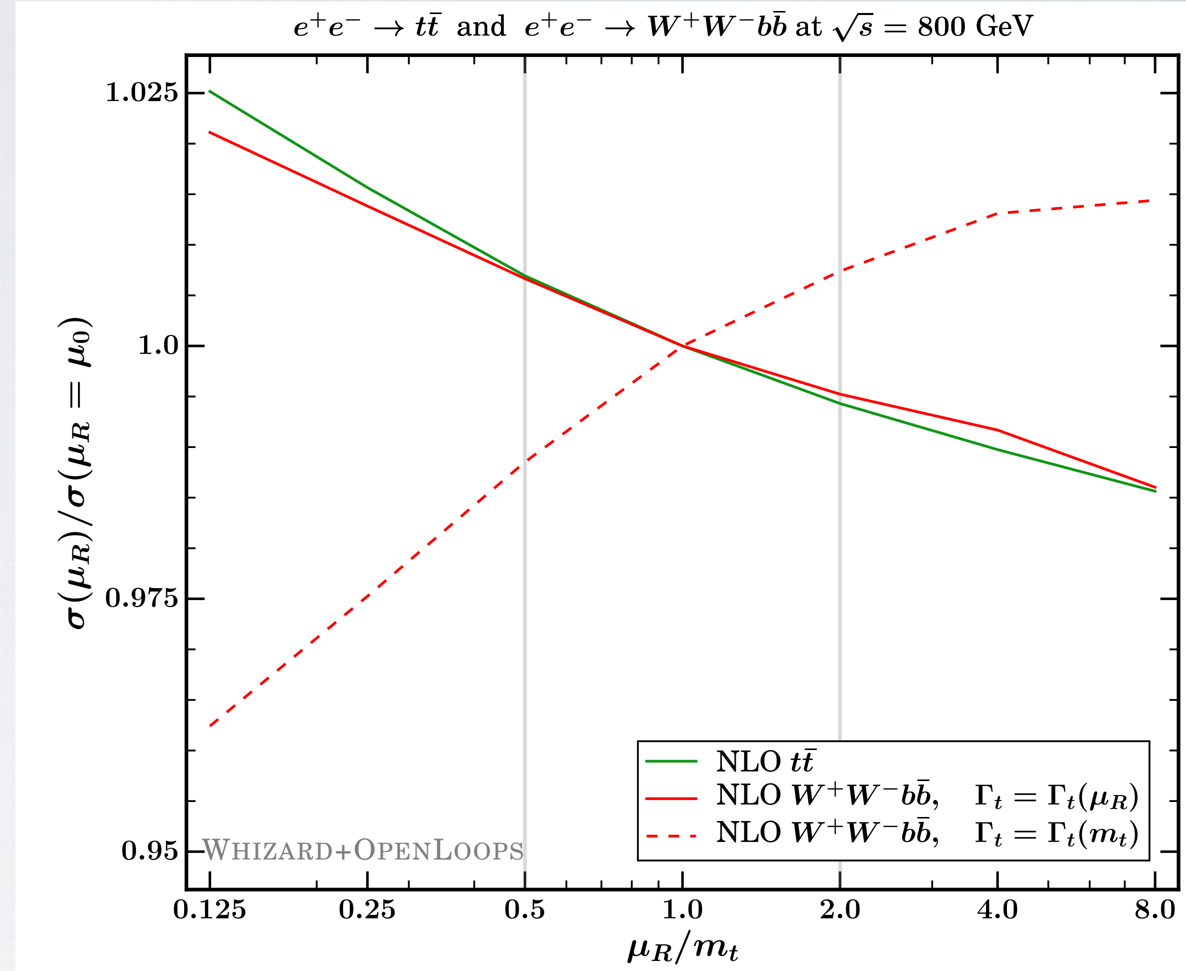






NLO QCD Results for off-shell $e^+e^- \to tt$

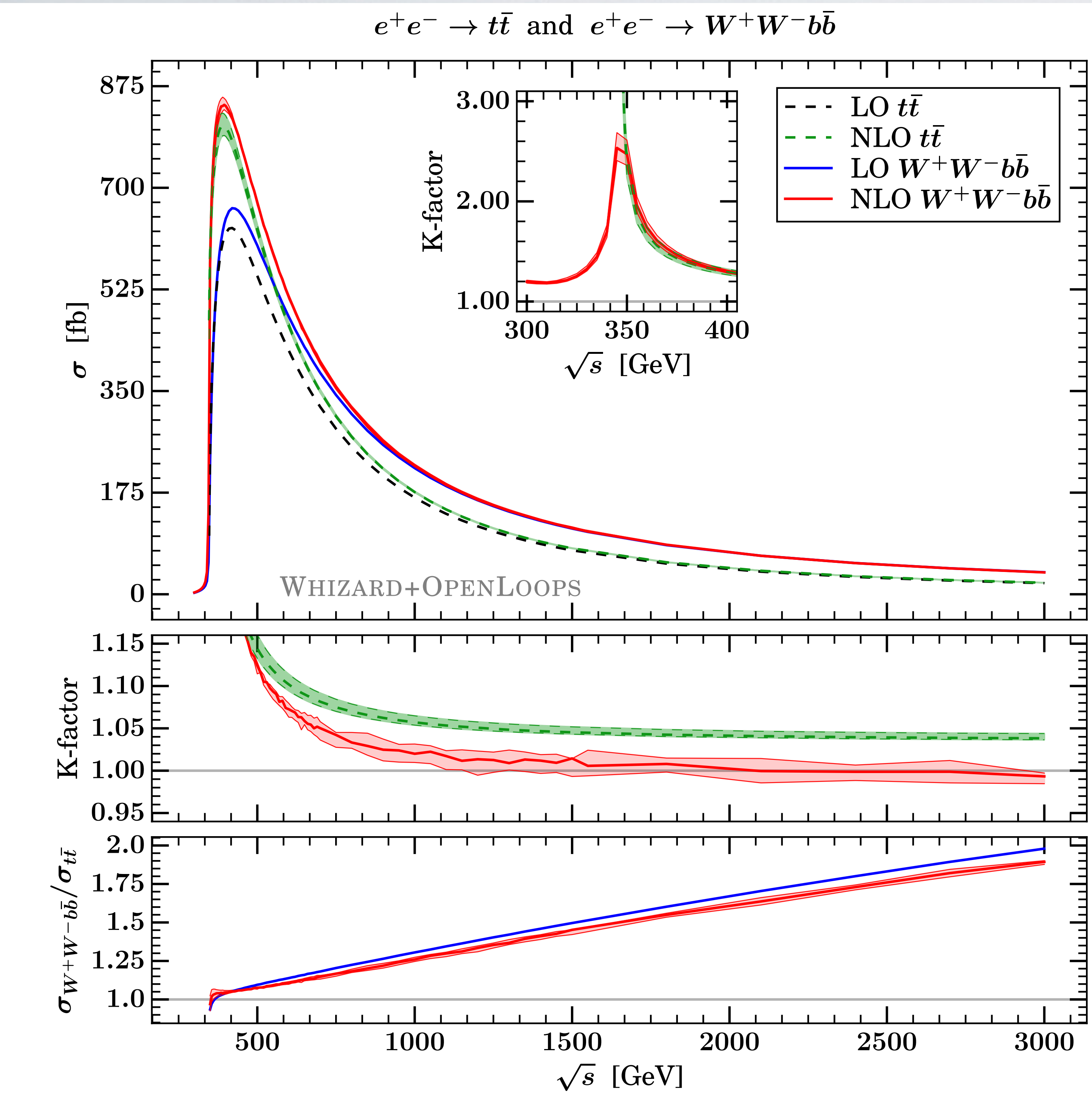


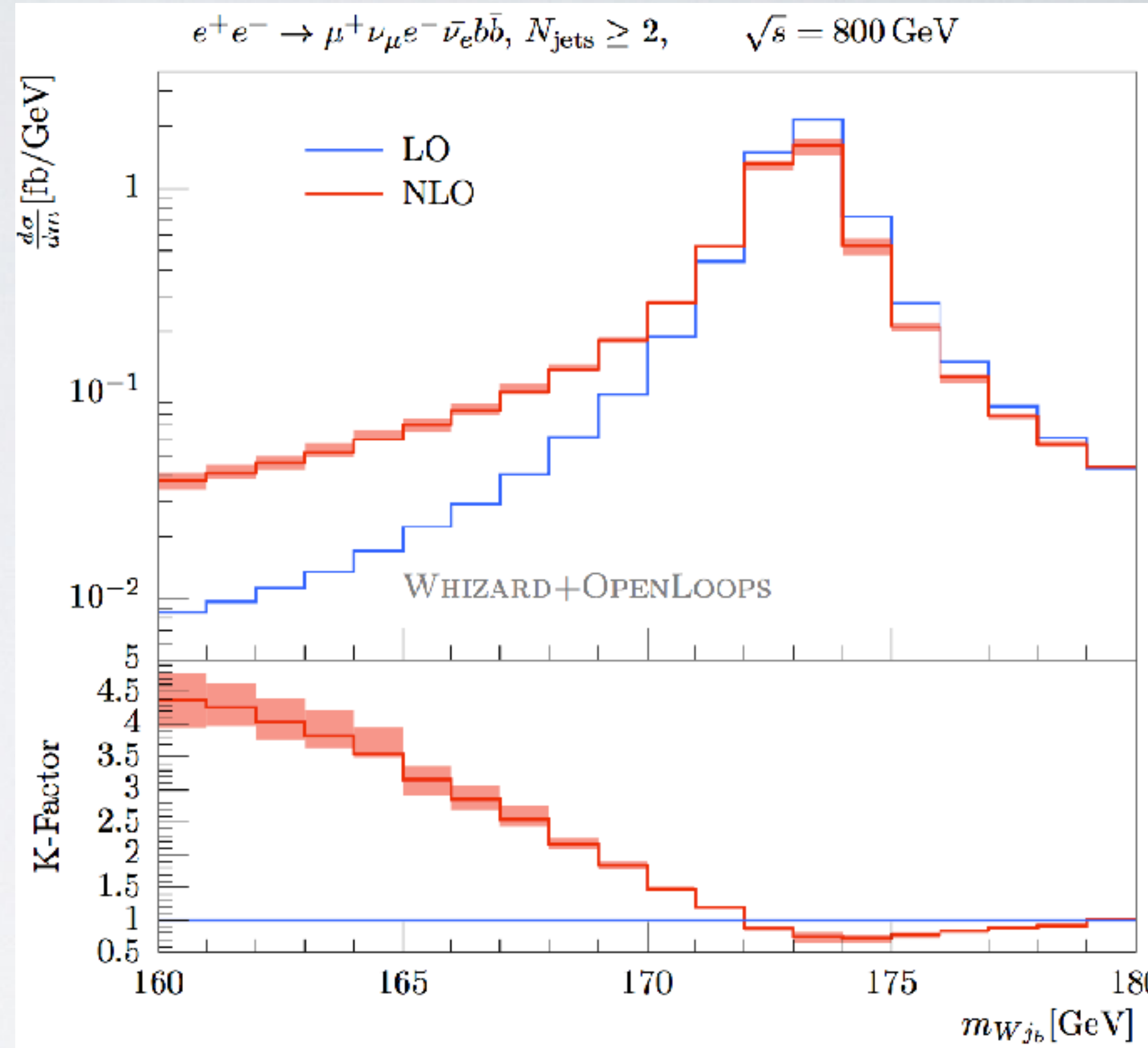


	$e^+e^- \to t\bar{t}$			$e^+e^- \to W^+W^-b\bar{b}$		
$\sqrt{s}$ [GeV]	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor
500	548.4	$627.4^{+1.4\%}_{-0.9\%}$	1.14	600.7	$675.1^{+0.4\%}_{-0.8\%}$	1.12
800	253.1	$270.9^{+0.8\%}_{-0.4\%}$	1.07	310.2	$320.7^{+1.1\%}_{-0.7\%}$	1.03
1000	166.4	$175.9^{+0.7\%}_{-0.3\%}$	1.06	217.2	$221.6^{+1.1\%}_{-1.0\%}$	1.02
1400	86.62	$90.66^{+0.6\%}_{-0.2\%}$	1.05	126.4	$127.9^{+0.7\%}_{-1.5\%}$	1.01
3000	19.14	$19.87^{+0.5\%}_{-0.2\%}$	1.04	37.89	$37.63^{+0.4\%}_{-0.9\%}$	0.993

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

NLO QCD Results for off-shell $e^+e^- \to tt$





$\sqrt{s}$ [GeV]	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor
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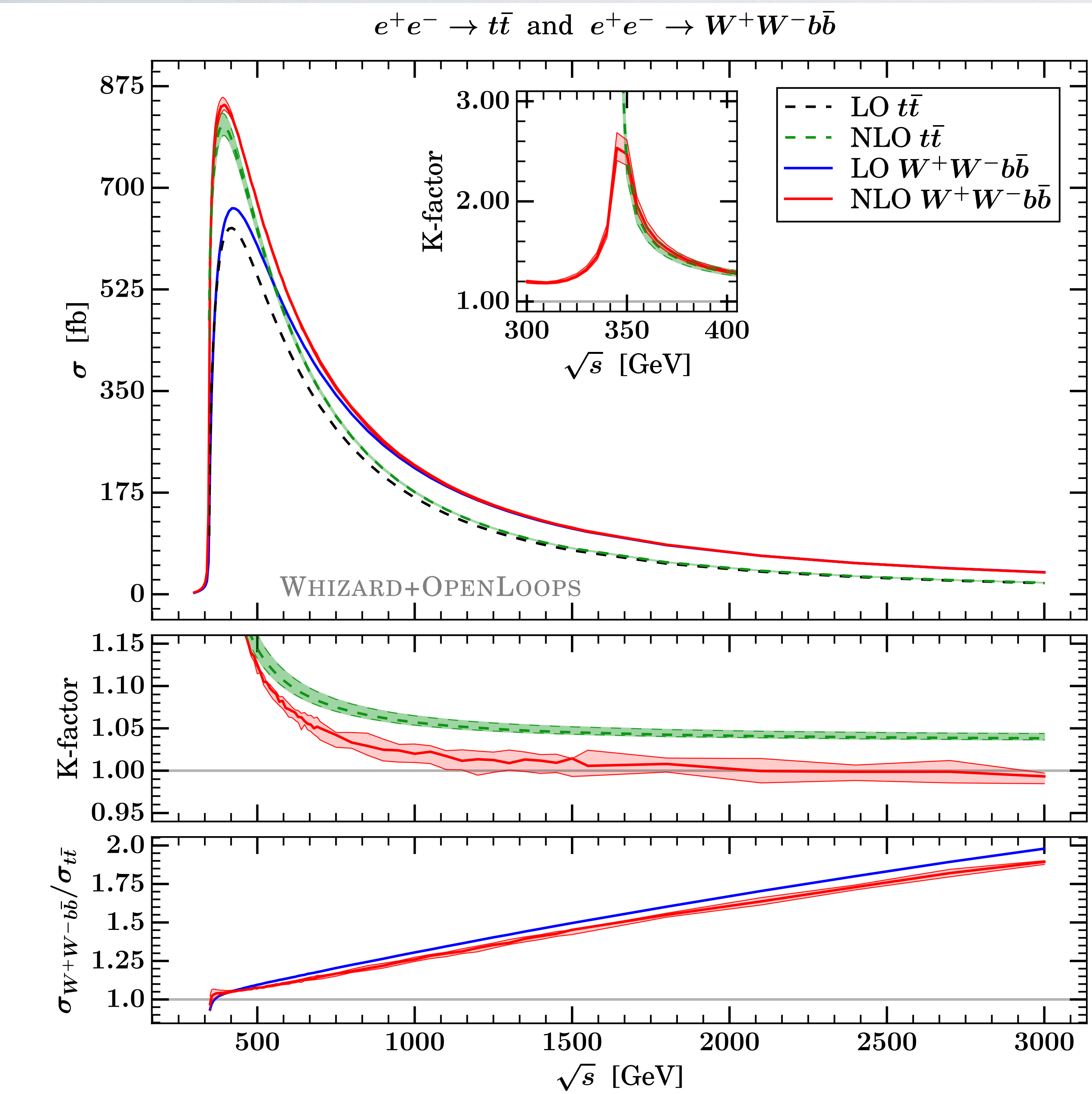

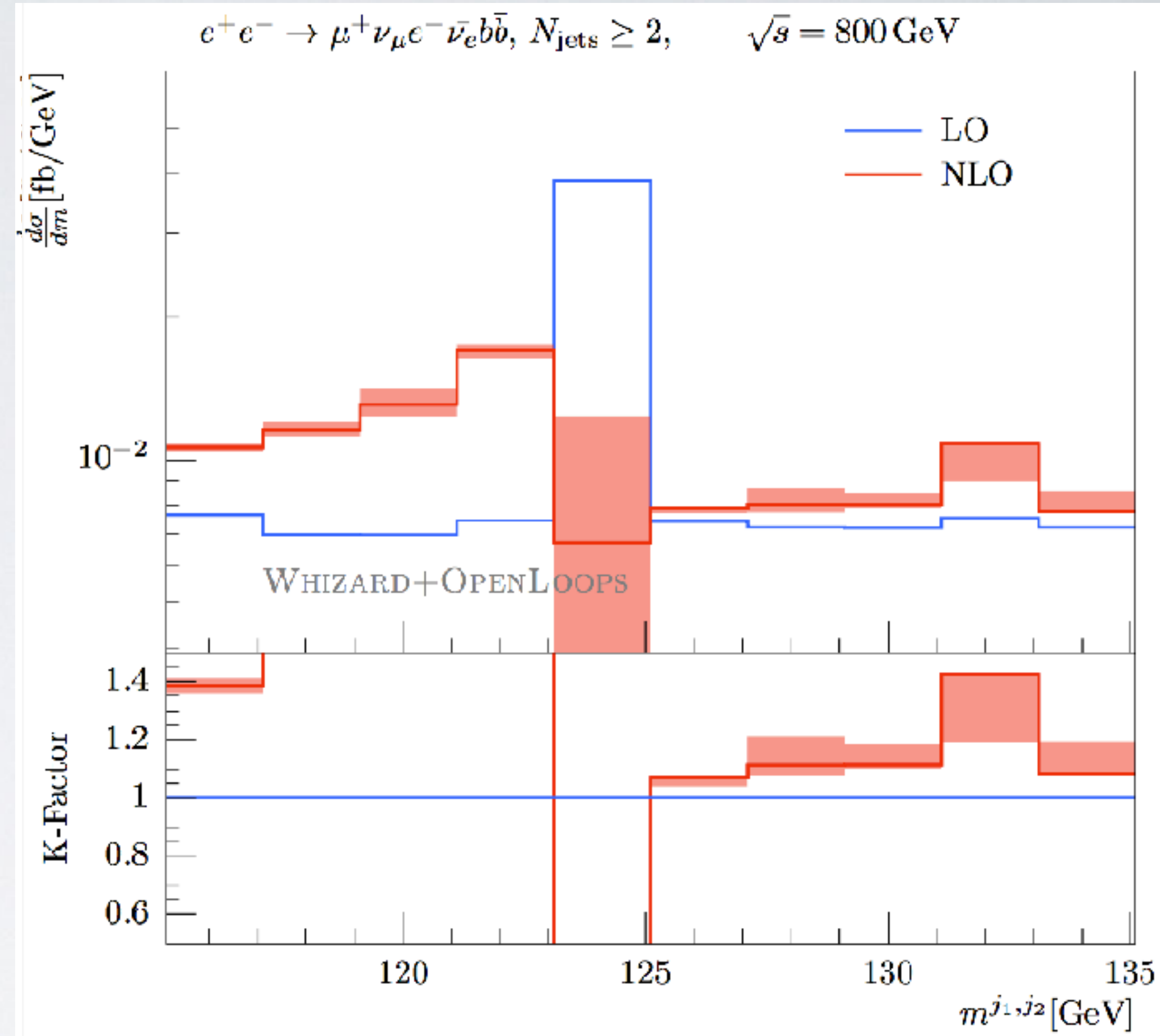

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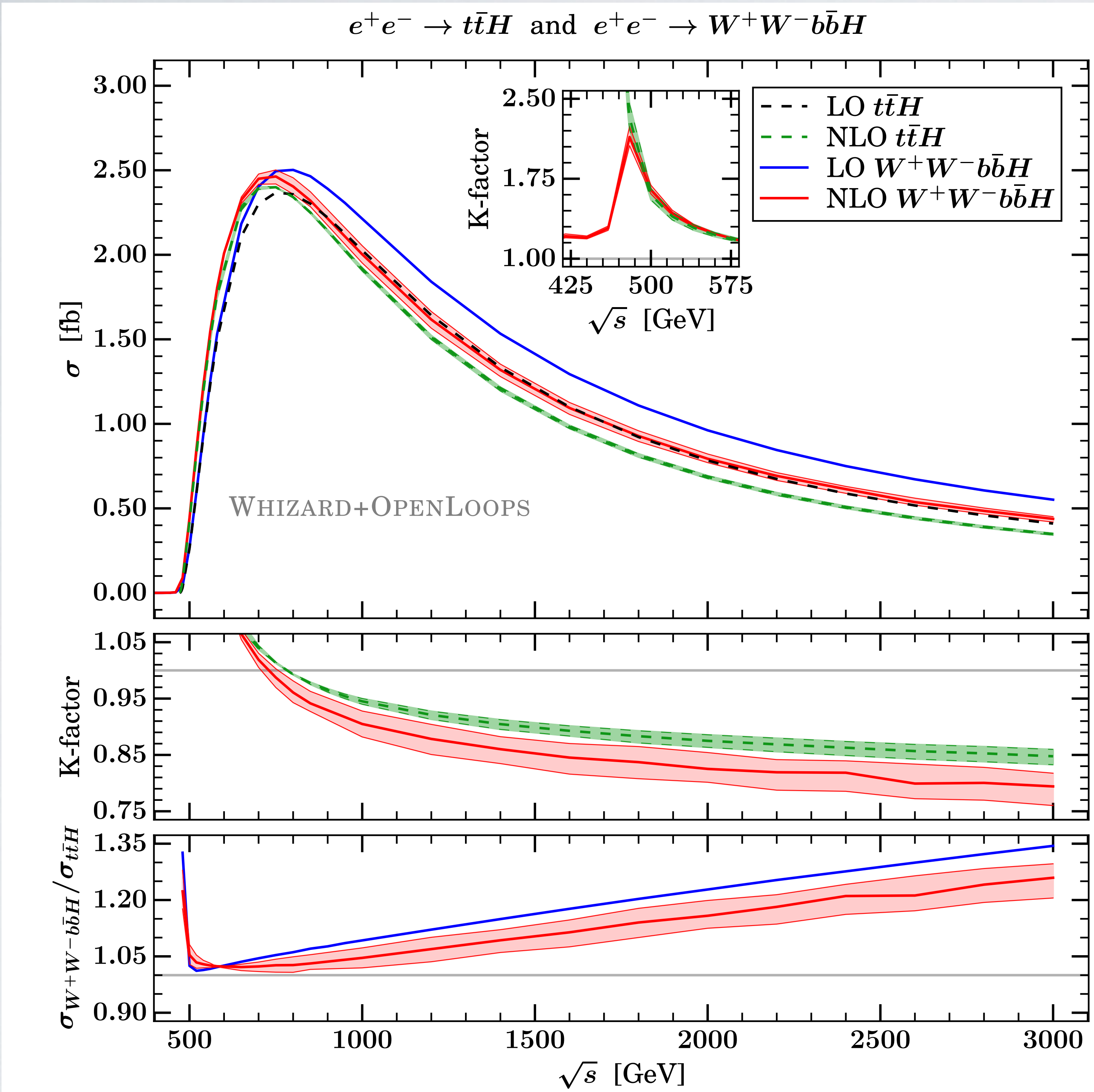
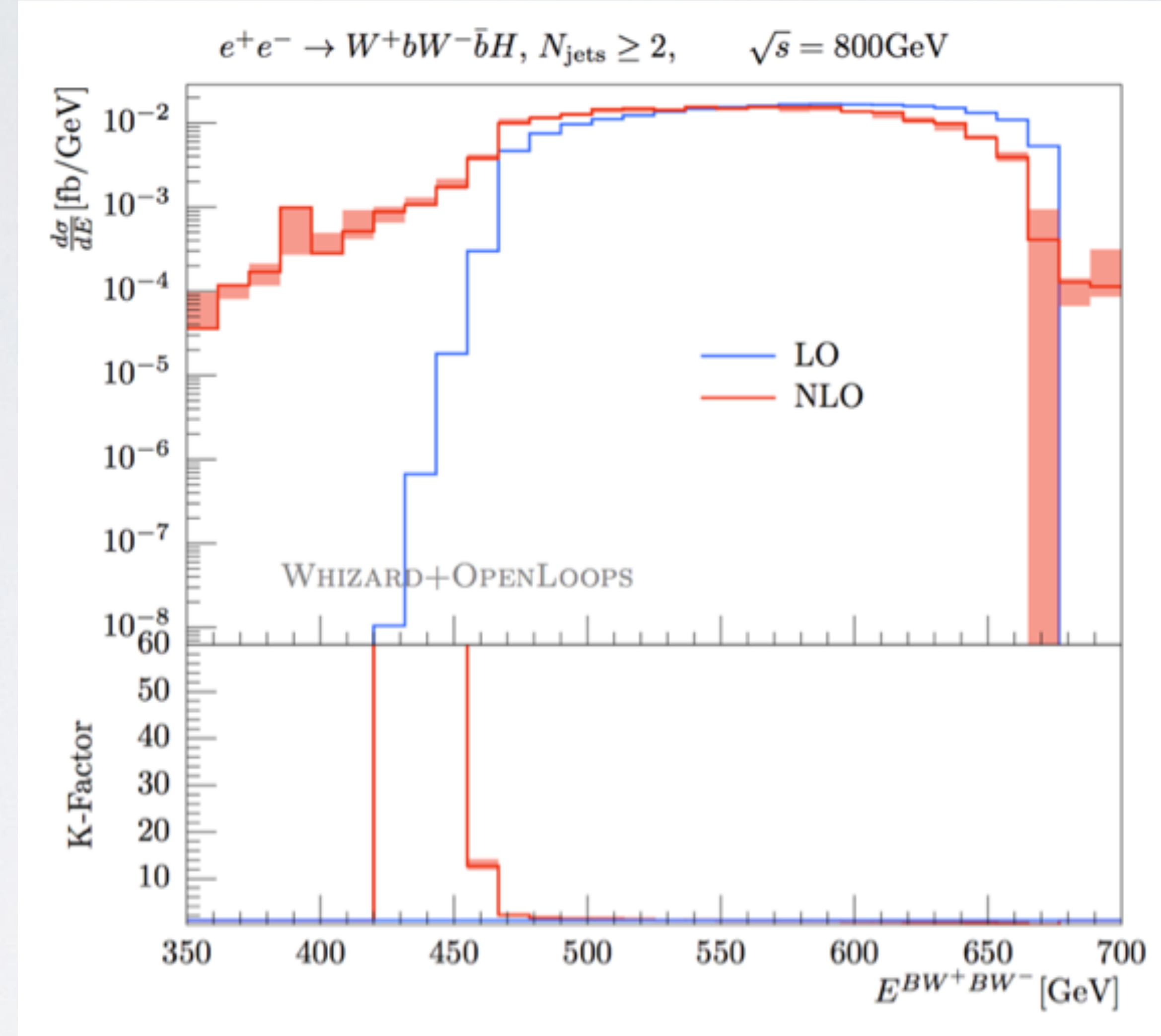
Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

NLO QCD Results for off-shell $e^+e^- \to ttH$

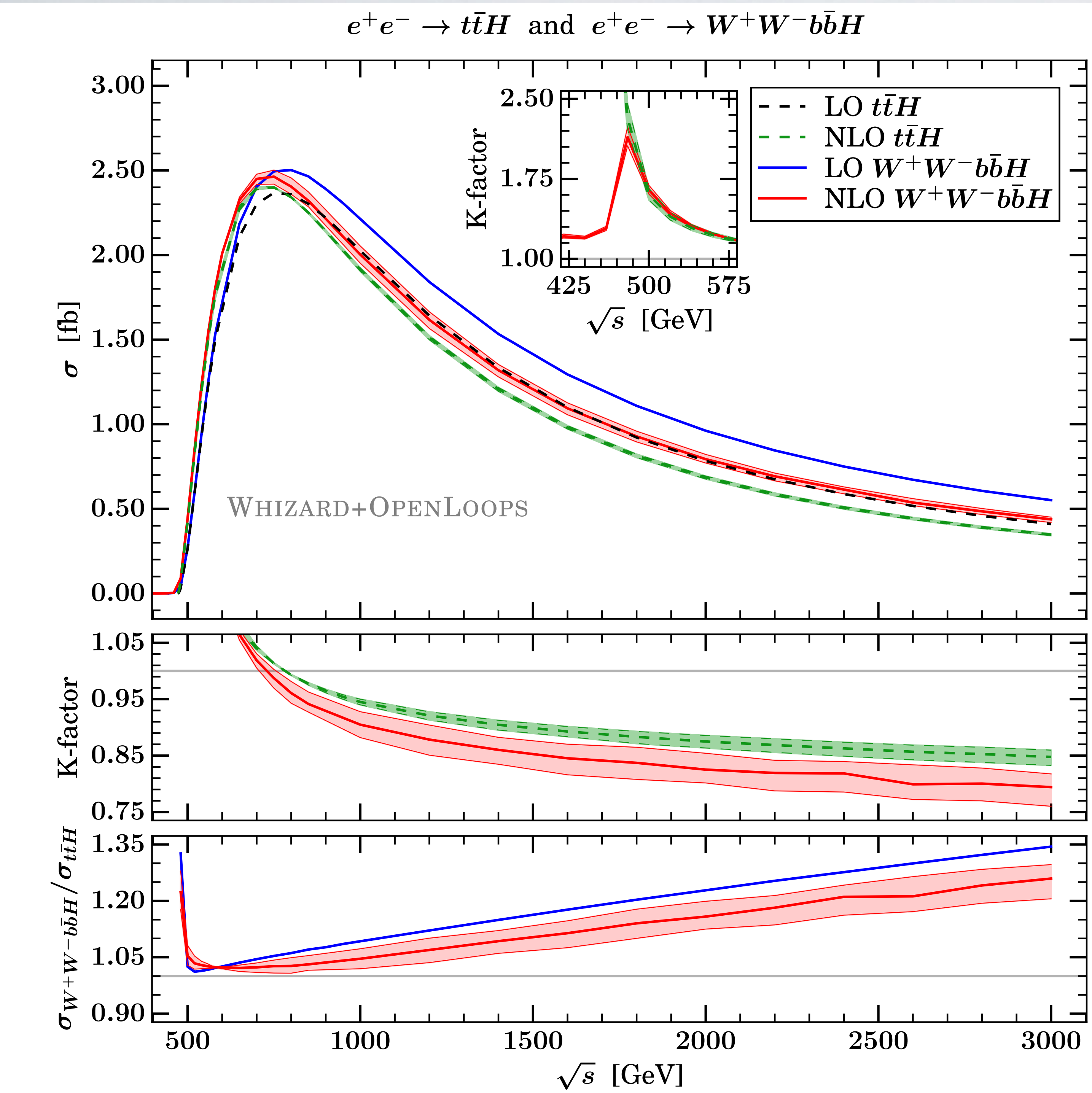


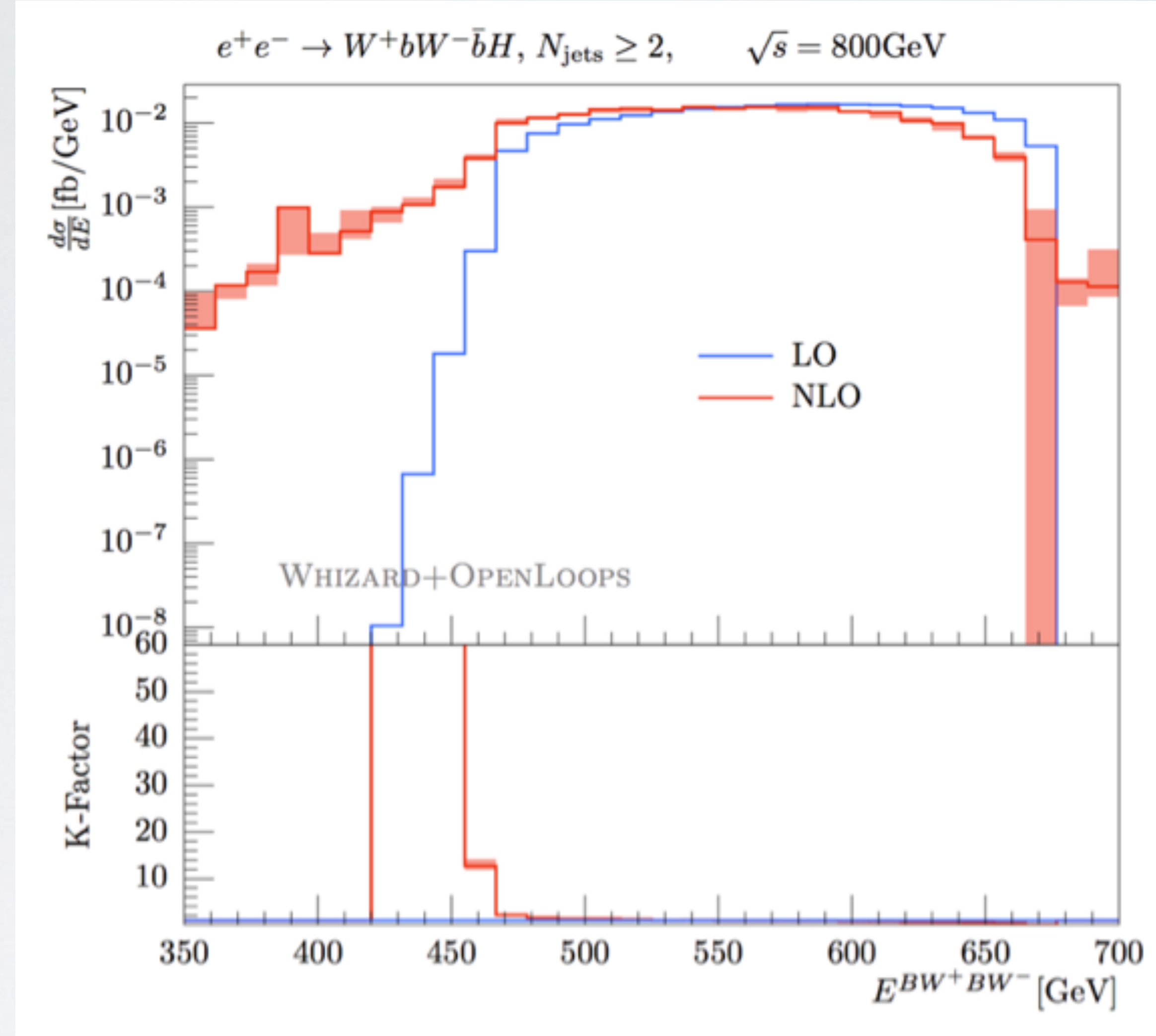


	$e^+e^- \to t\bar{t}H$			$e^+e^- \to W^+W^-b\bar{b}H$		
$\sqrt{s}$ [GeV]	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor
500	0.26	$0.42^{+3.6\%}_{-3.1\%}$	1.60	0.27	$0.44^{+2.6\%}_{-2.4\%}$	1.63
800	2.36	$2.34^{+0.1\%}_{-0.1\%}$	0.99	2.50	$2.40^{+2.1\%}_{-1.9\%}$	0.96
1000	2.02	$1.91^{+0.5\%}_{-0.5\%}$	0.95	2.21	$2.00^{+2.5\%}_{-2.5\%}$	0.90
1400	1.33	$1.21^{+0.9\%}_{-1.0\%}$	0.90	1.53	$1.32^{+2.6\%}_{-3.0\%}$	0.86
3000	0.41	$0.35^{+1.4\%}_{-1.8\%}$	0.84	0.55	$0.44^{+2.9\%}_{-4.3\%}$	0.79

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

NLO QCD Results for off-shell $e^+e^- \to ttH$





	$e^+e^- \to t\bar{t}H$			$e^+e^- \to W^+W^-b\bar{b}H$		
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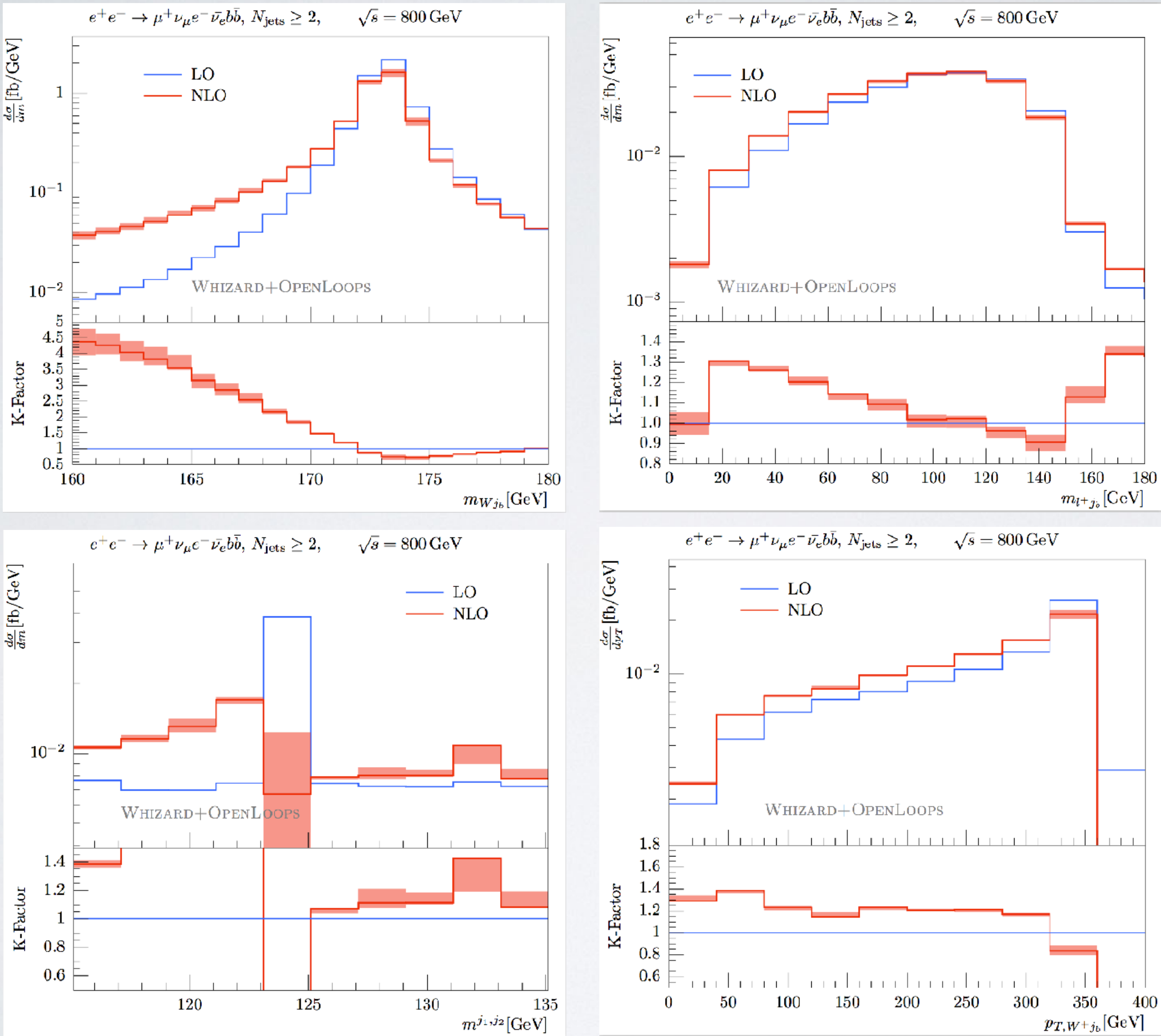
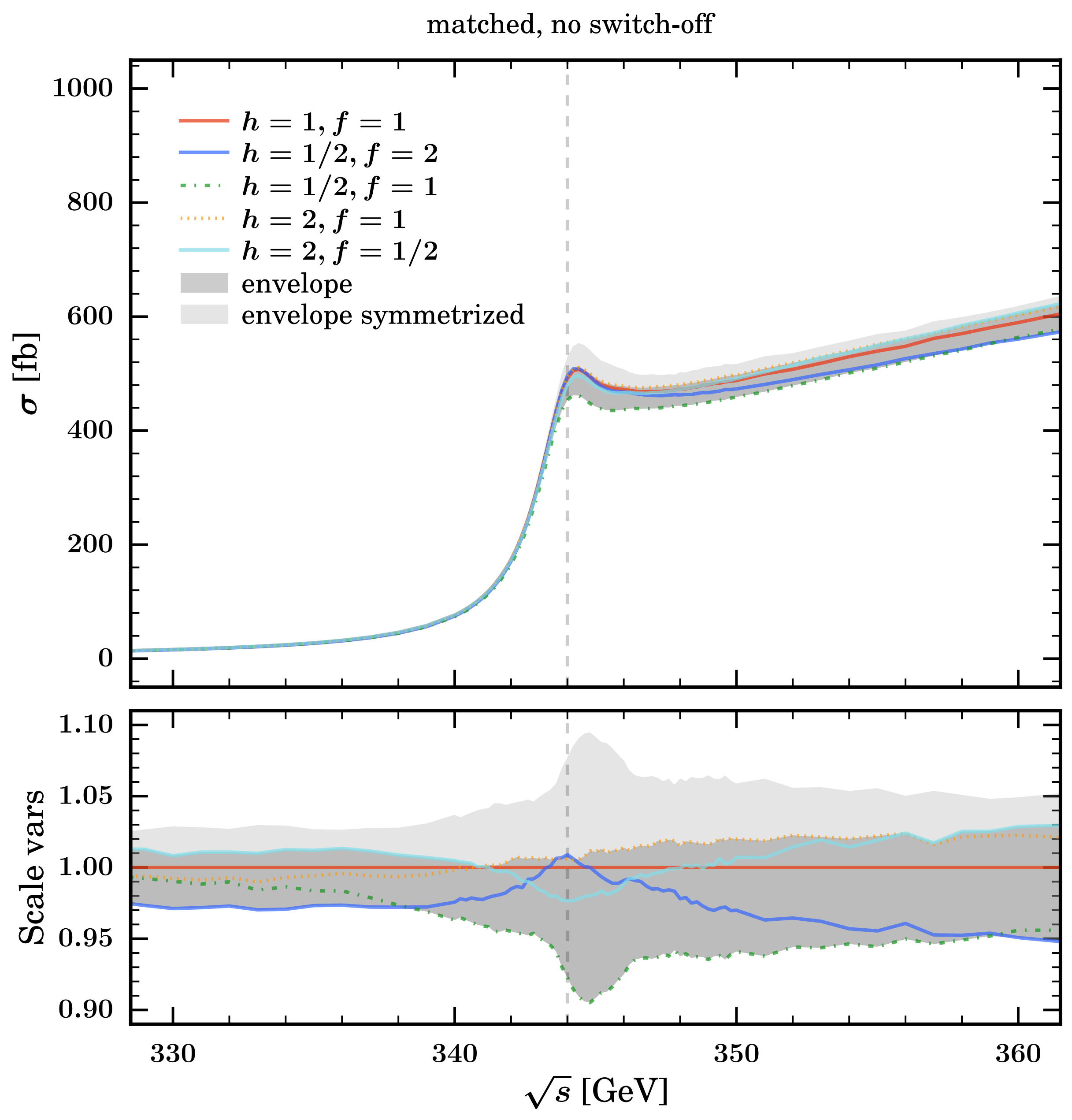
Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

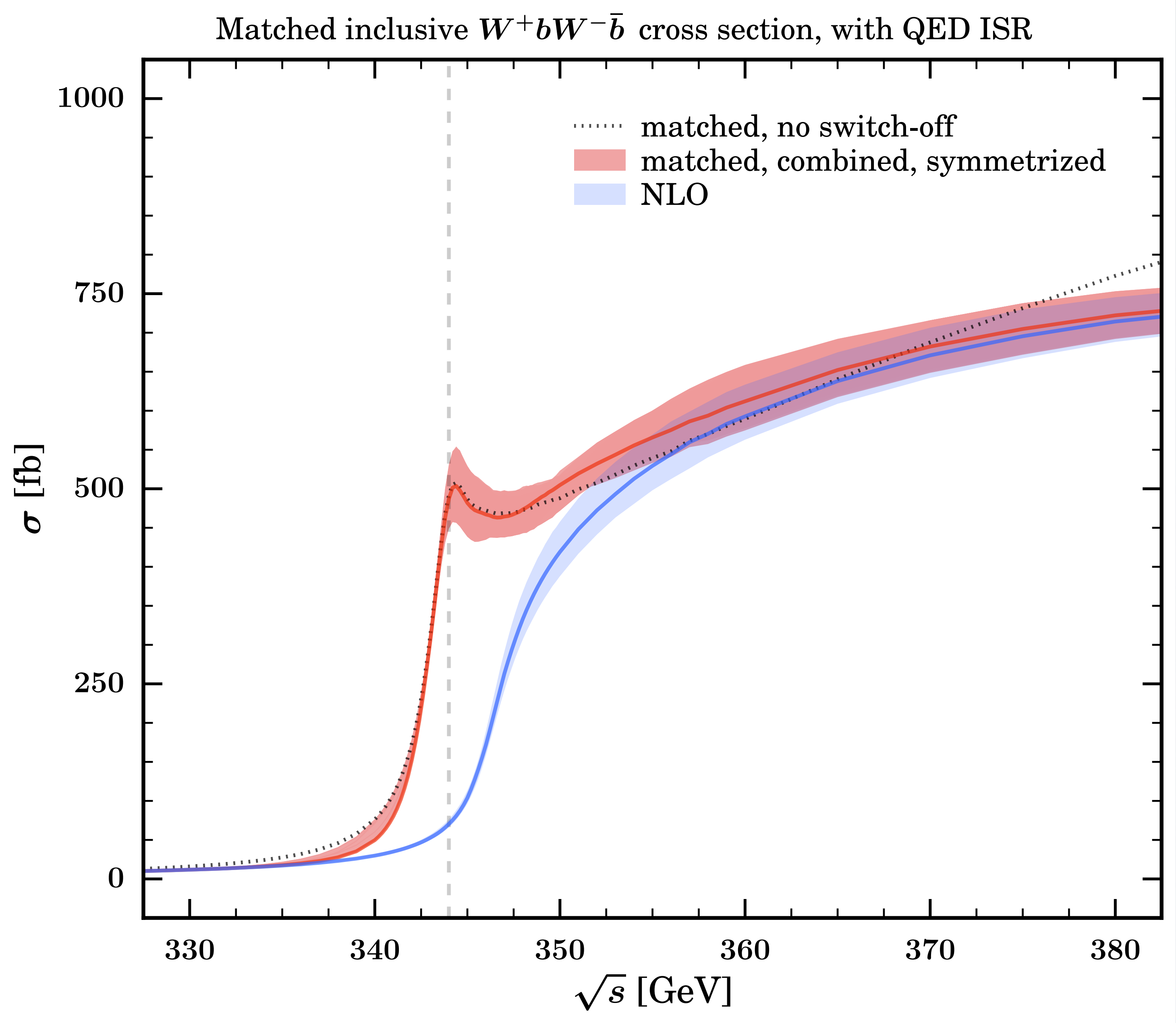
Differential Results for off-shell $e^+e^- \to tt$

$$m_t^2 = m_W^2 + \frac{2\langle m_{\ell j_b}^2 \rangle}{1 - \langle \cos\theta_{\ell j_b} \rangle}$$



Threshold matching with QED ISR



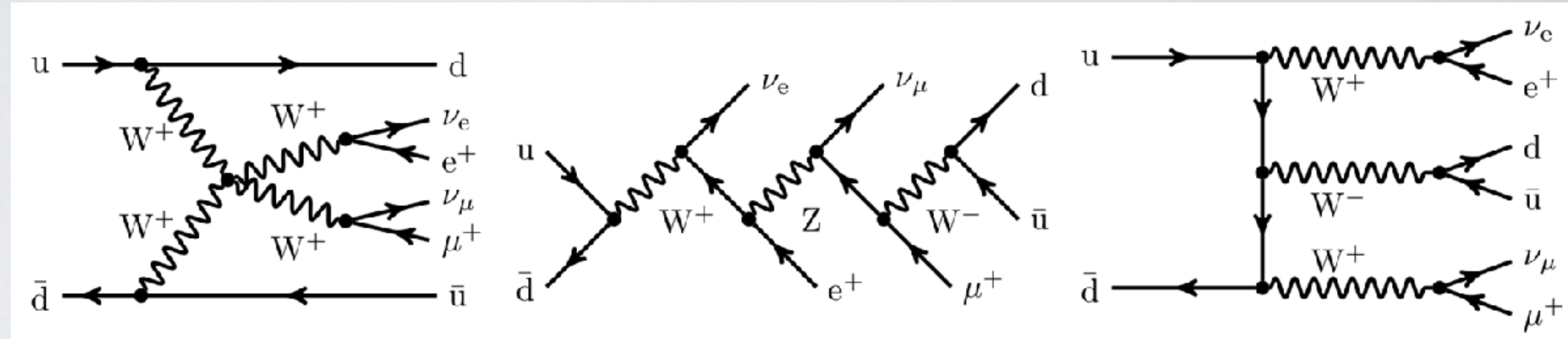


Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 2017

LHC VBS: Comparison LO & LO+PS

Ballestrero *et al.*, 1803.07943

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	$\mathcal{O}(\alpha_s\alpha^5)$
σ[fb]	2.292 ± 0.002	1.477 ± 0.001	0.223 ± 0.003



Code	σ[fb]
BONSAY	1.43636 ± 0.00002
MG5_aMC	1.4304 ± 0.0007
MoCaNLO+Recola	1.43476 ± 0.00009
PHANTOM	1.4374 ± 0.0006
Powheg-Box	1.44092 ± 0.00009
VBFNLO	1.43796 ± 0.00005
Whizard	1.4381 ± 0.0002

LO

$p_{T,\ell} > 20$ GeV $\quad |y_\ell| < 2.5 \quad \Delta R_{\ell\ell} > 0.3$

$p_{T,\mathrm{miss}} > 40$ GeV

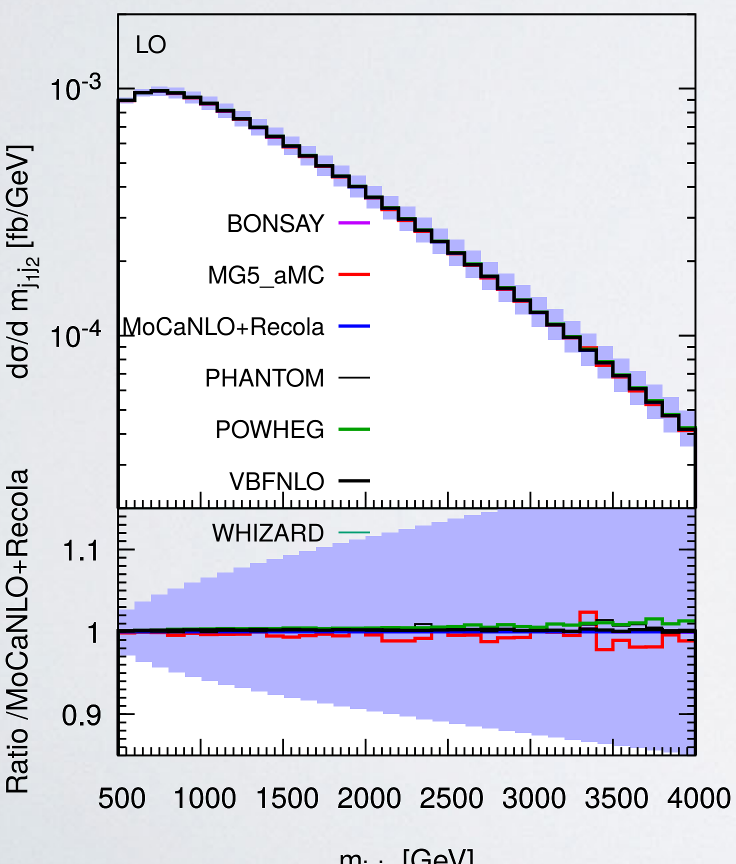
Anti-k_T jets with $R = 0.4$:

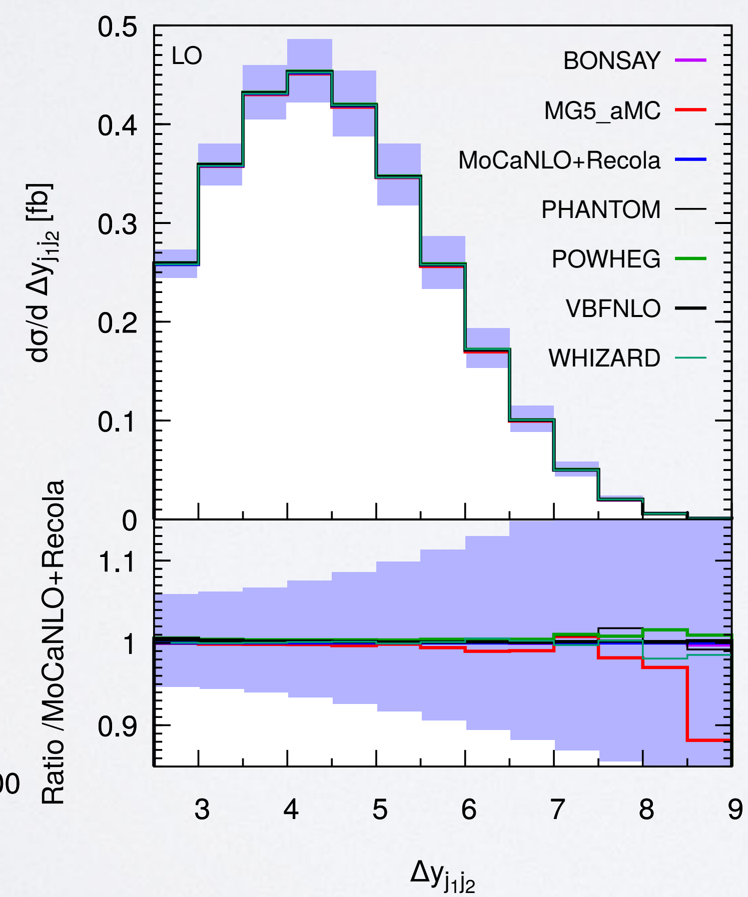
$p_{T,j} > 30$ GeV $\quad |y_j| < 4.5 \quad \Delta R_{\ell j} > 0.3$

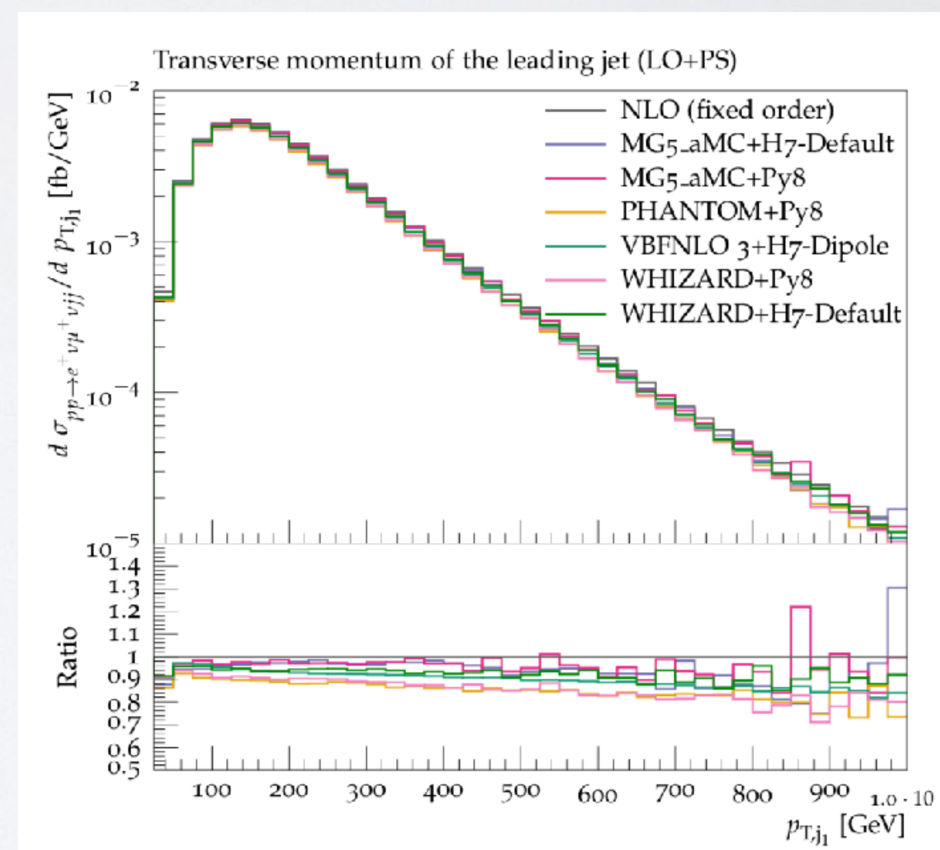
$m_{jj} > 500$ GeV $\quad |\Delta y_{jj}| > 2.5$

Code	σ[fb]
MG5_aMC+Pythia8	1.352 ± 0.003
MG5_aMC+Herwig7	1.342 ± 0.003
MG5_aMC+Pythia8, Γ_{resc}	1.275 ± 0.003
MG5_aMC+Herwig7, Γ_{resc}	1.266 ± 0.003
PHANTOM+Pythia8	1.235 ± 0.001
PHANTOM+Herwig7	1.258 ± 0.001
VBFNLO+Herwig7-Dipole	1.3001 ± 0.0002
WHIZARD+Pythia8	1.229 ± 0.001

LO+PS







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Ballestrero *et al.*, 1803.07943

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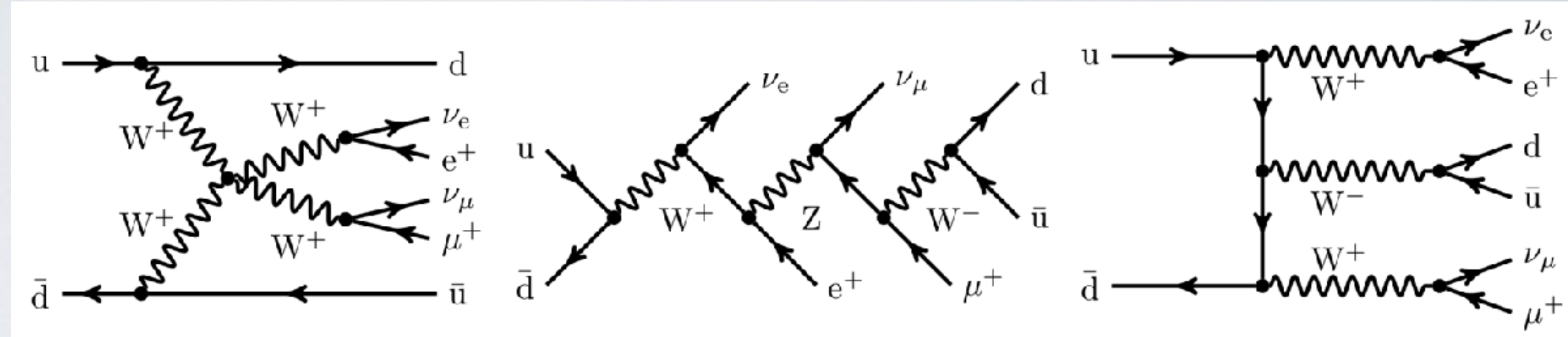

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LO+PS

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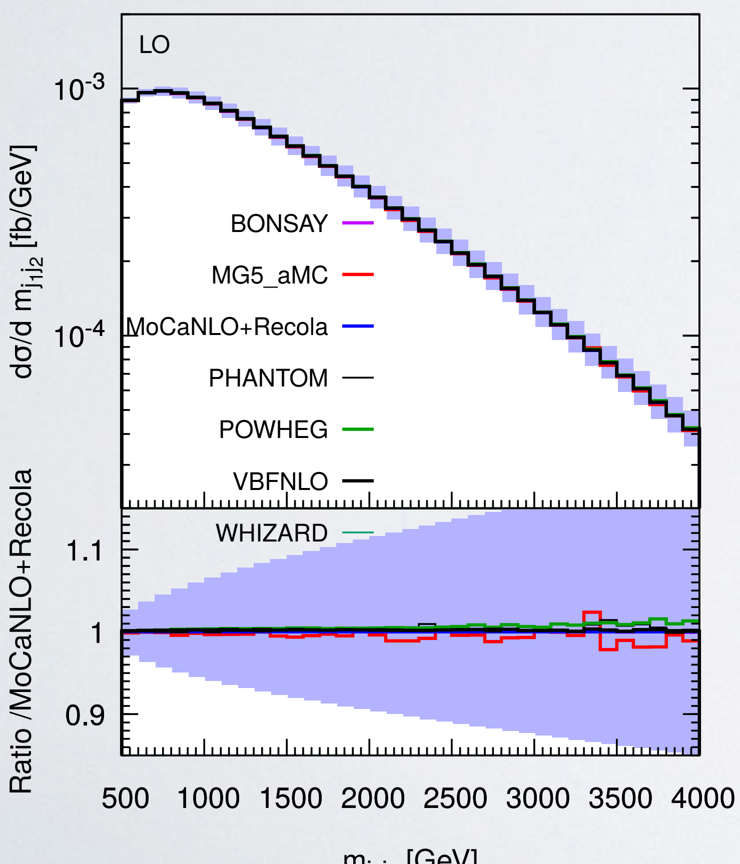

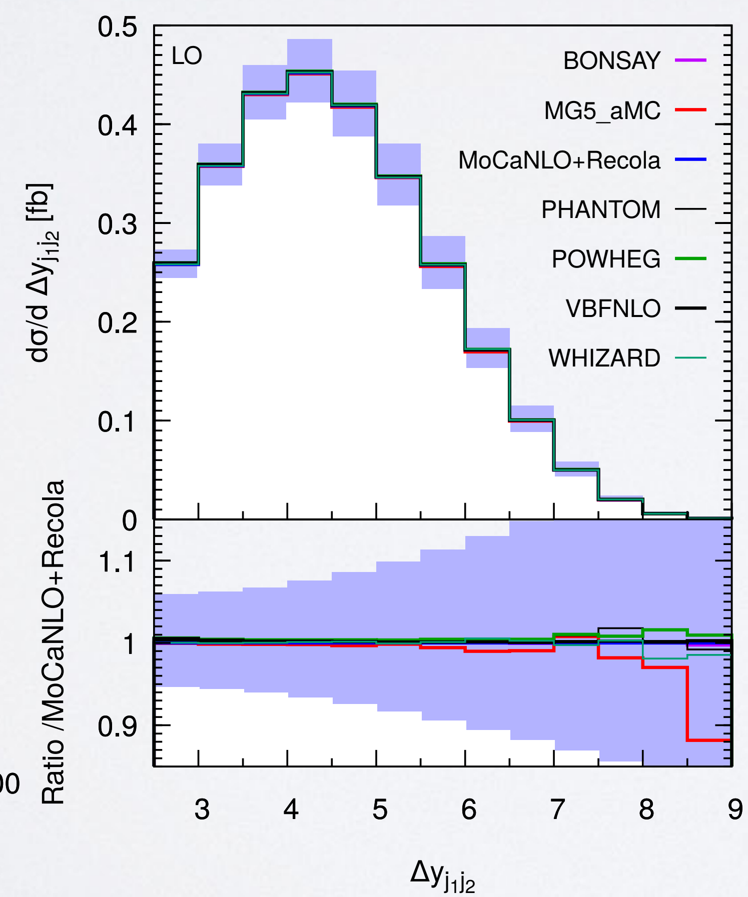

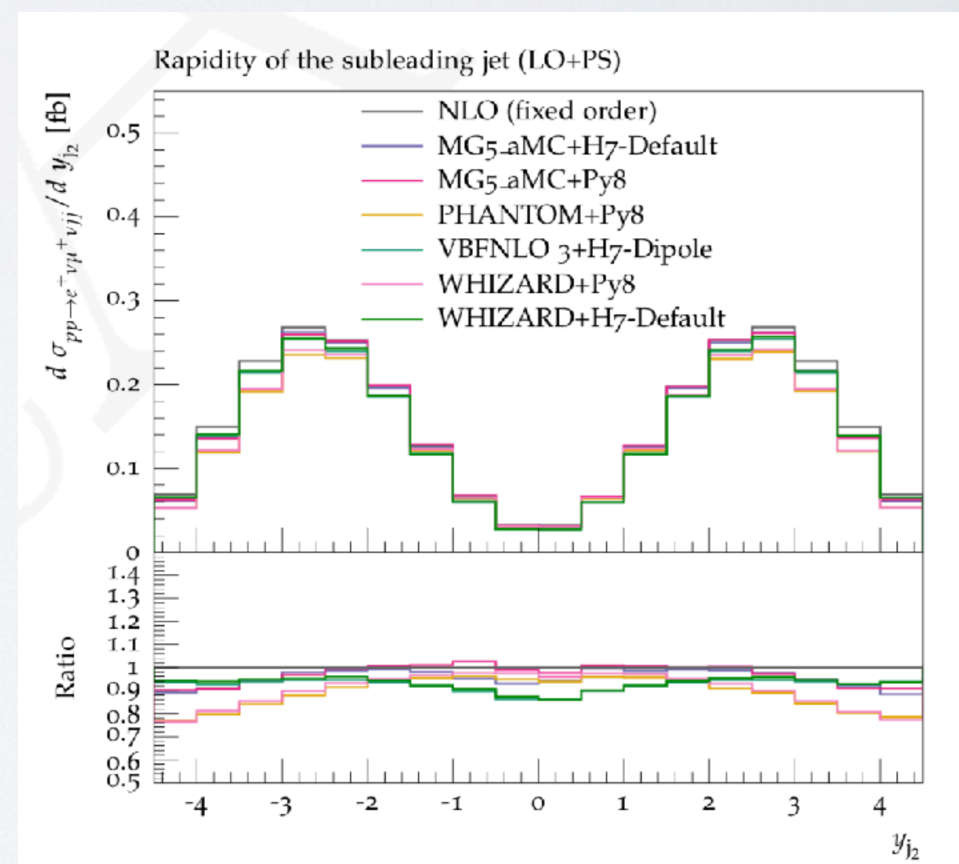

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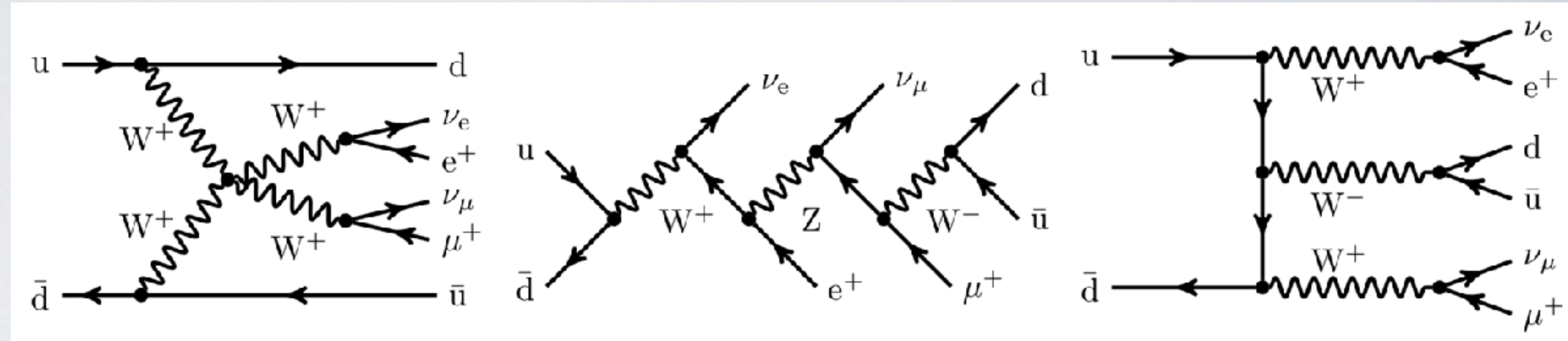

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PHANTOM	[illegible]
POWHE[illegible]	[illegible]
VBF[illegible]	[illegible]
WHIZ[illegible]	[illegible]

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Anti-k_T jets with $R = 0.4$: [illegible]

LO+PS

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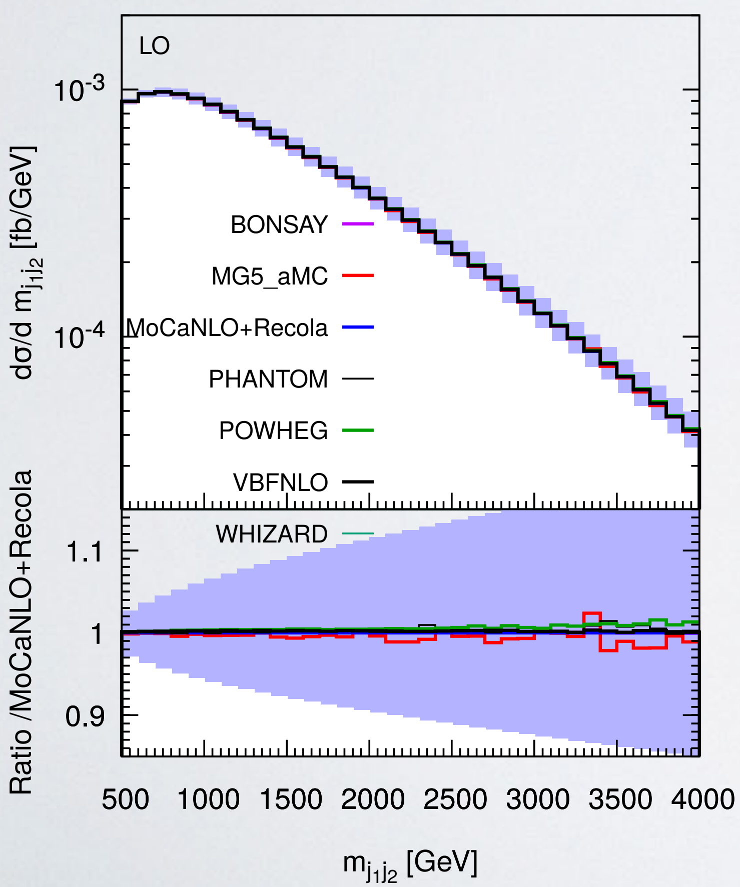
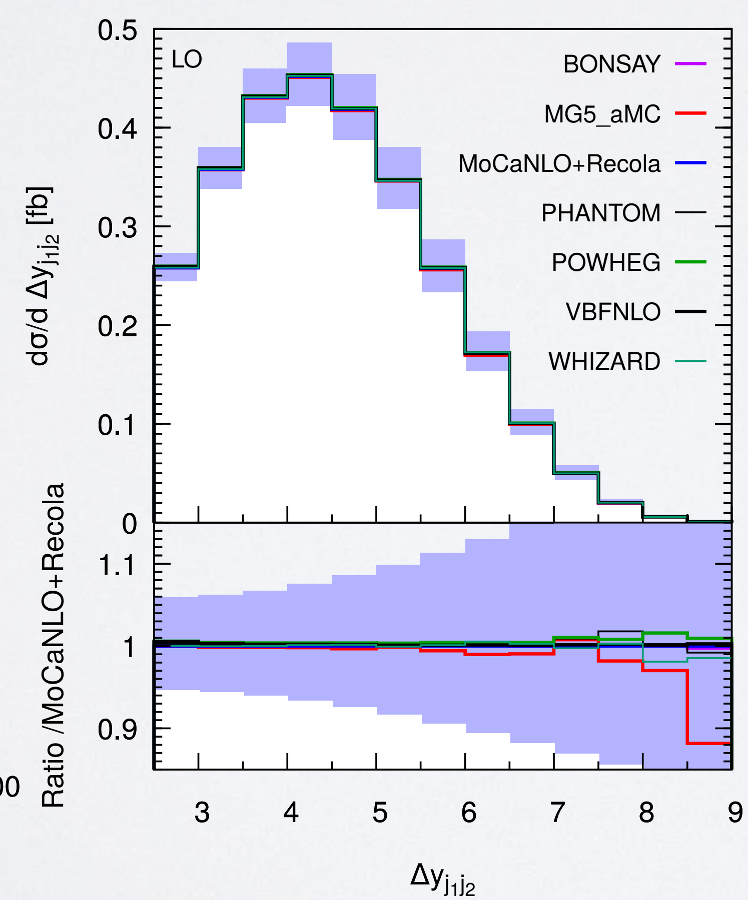
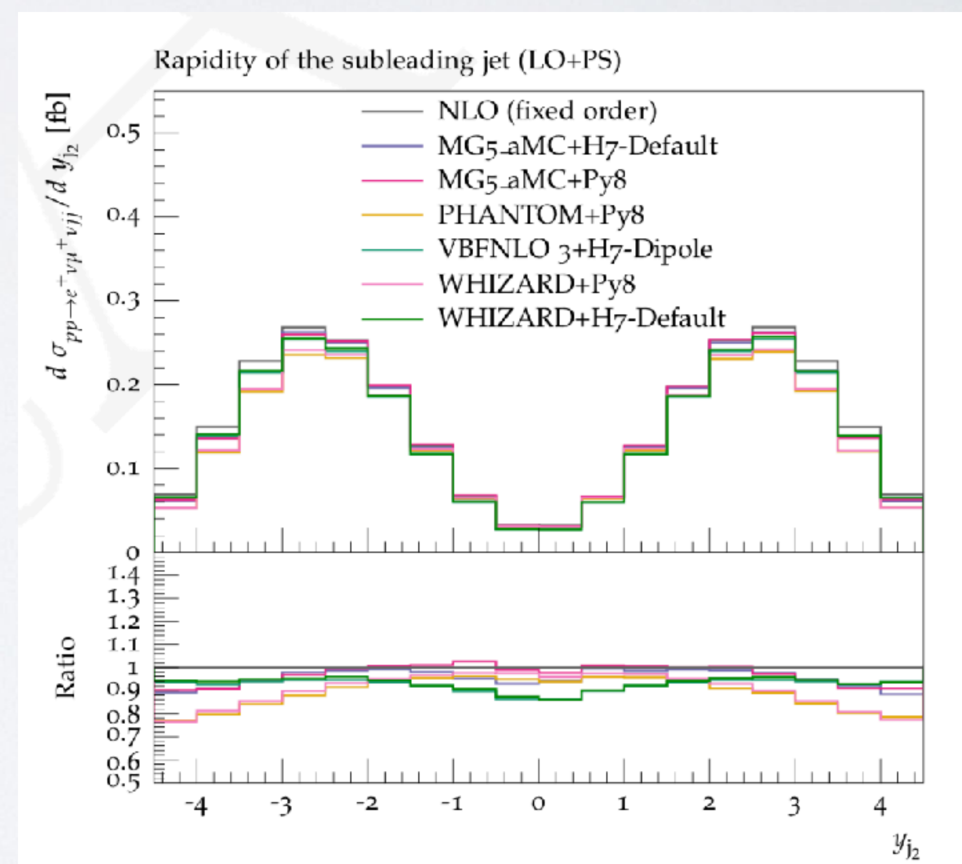
MG5_aMC+Pythia8, Γ_{resc}	1.275 ± 0.003
MG5_aMC+Herwig7, Γ[illegible]	[illegible] ± 0.003
[illegible]	[illegible] ± 0.001
[illegible]	[illegible] ± 0.001
[illegible]	[illegible] ± 0.0002
[illegible]	[illegible] ± 0.001

First official use of MPI-parallelized phase space
& first published application of WHIZARD & HERWIG showering







Keep resonances in ME-PS merging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resonance_on_shell_turnoff = 1
resonance_background_factor = 1e-10
```

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- Solution: proper merging with resonant subprocesses by means of resonance histories
- `WHIZARD v2.6.0`: option to set resonance histories

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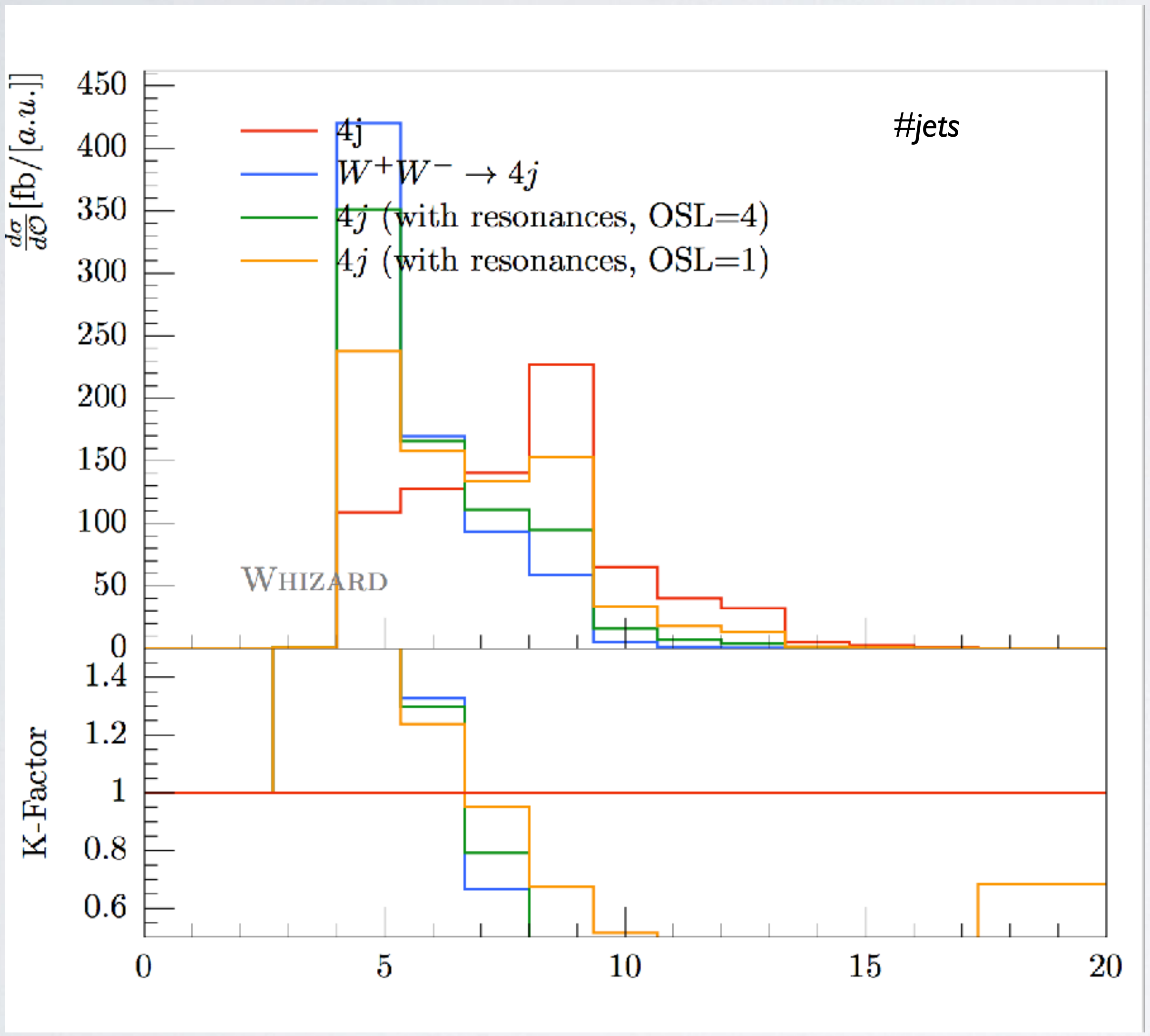

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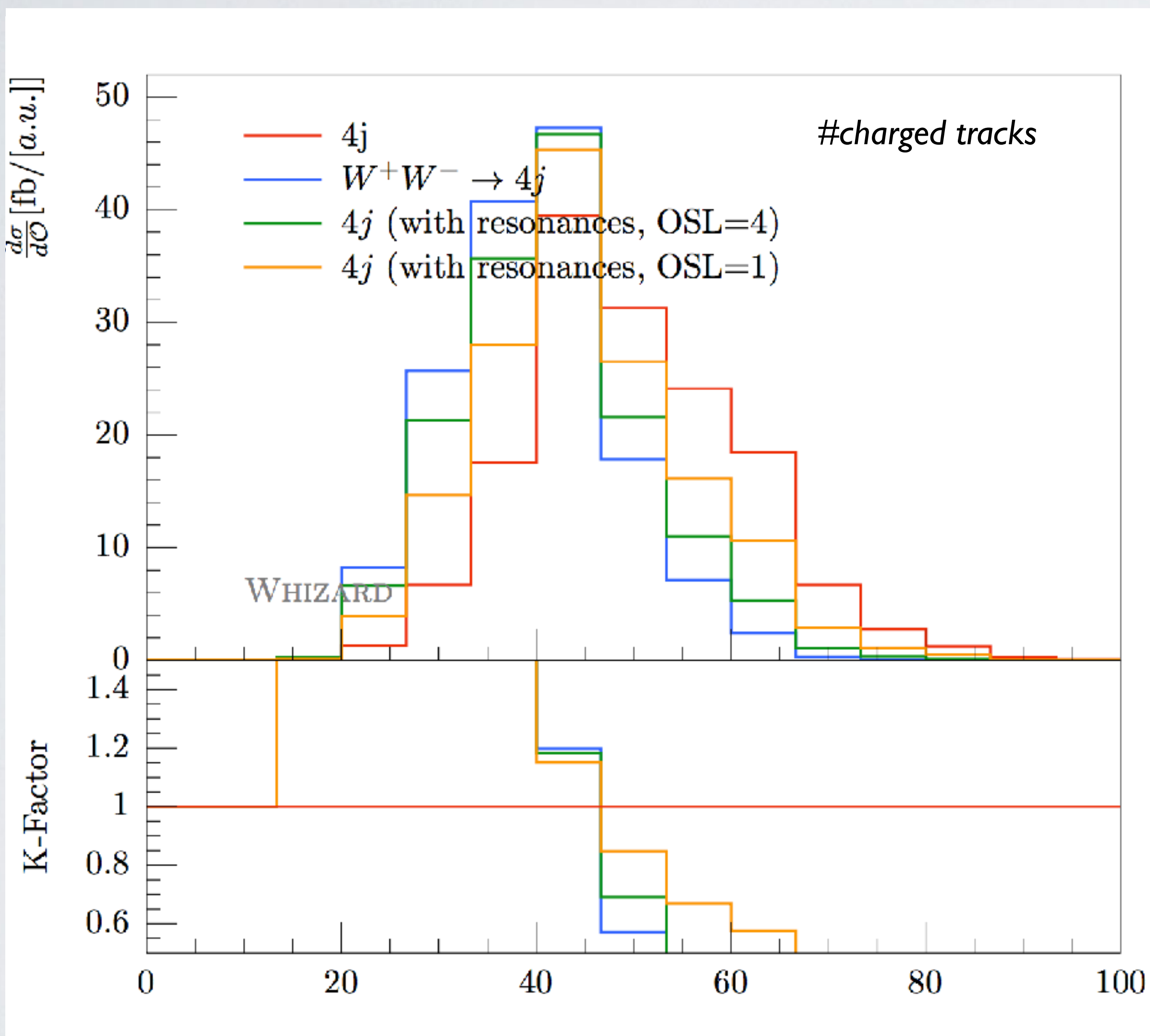

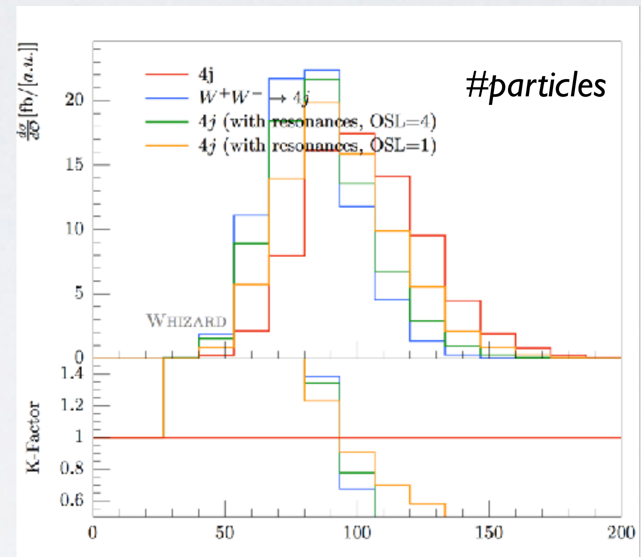

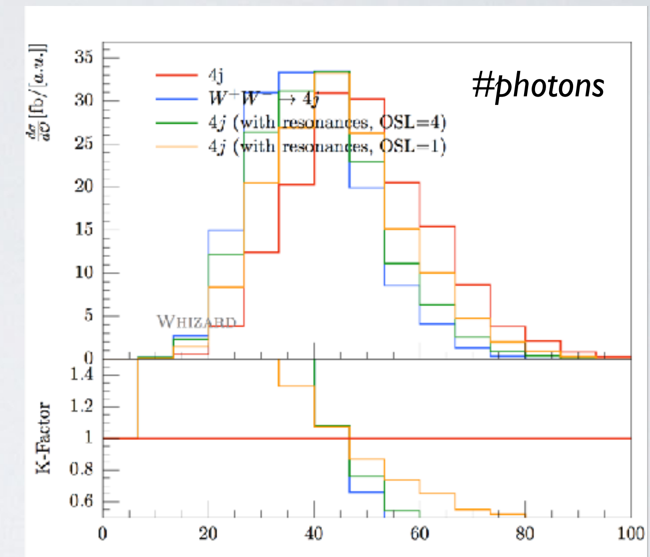

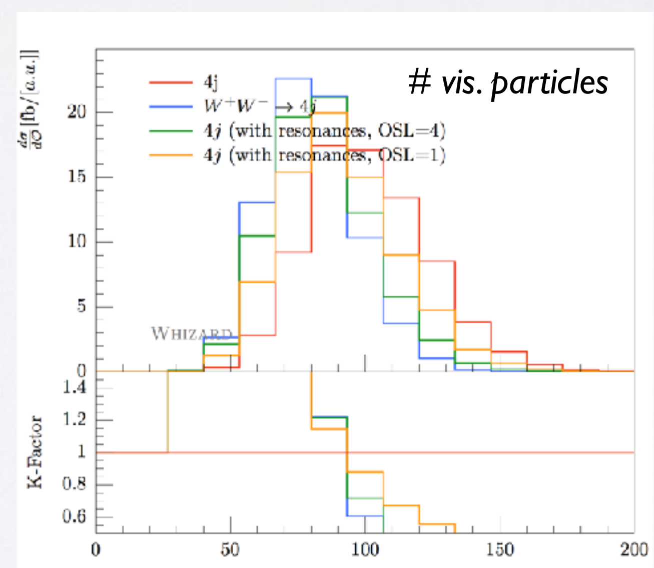

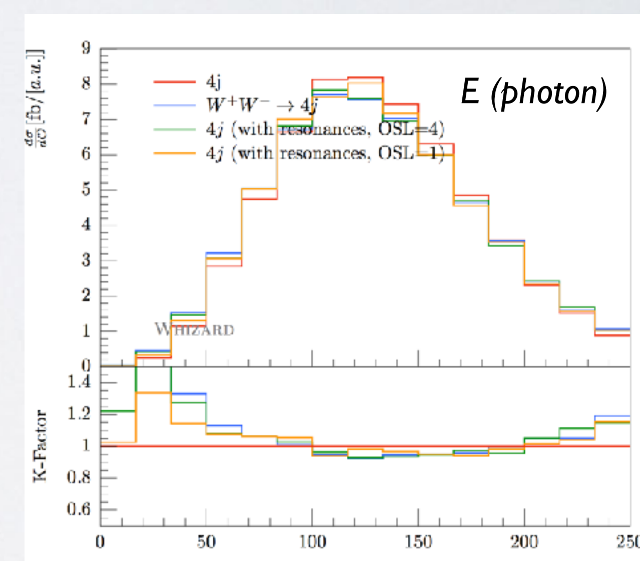

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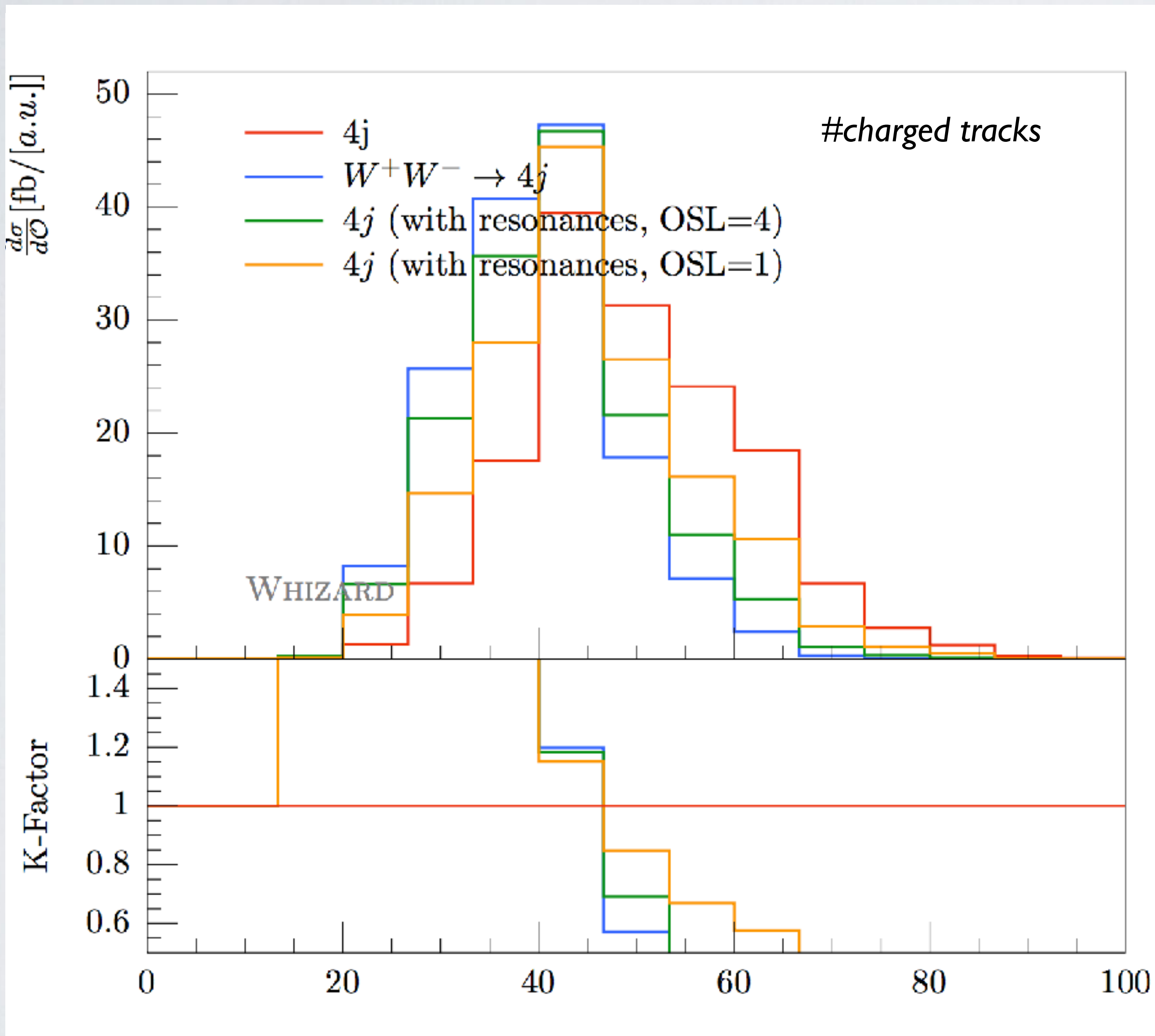

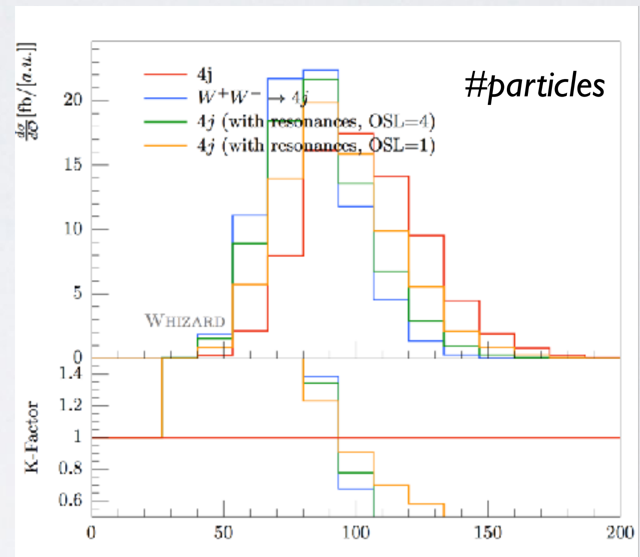

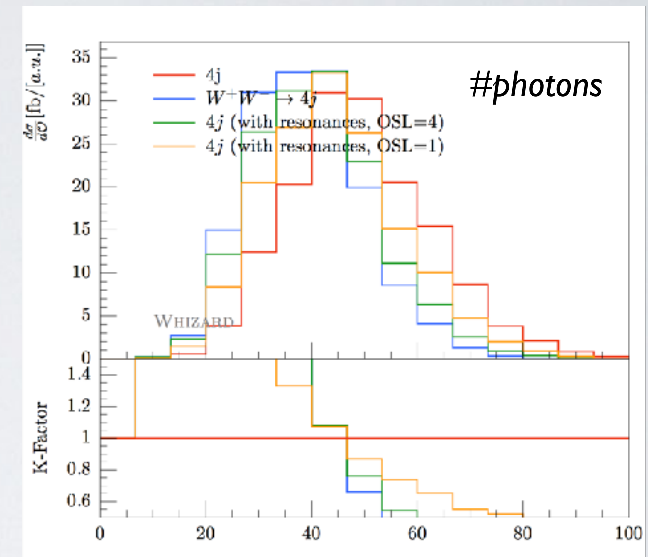

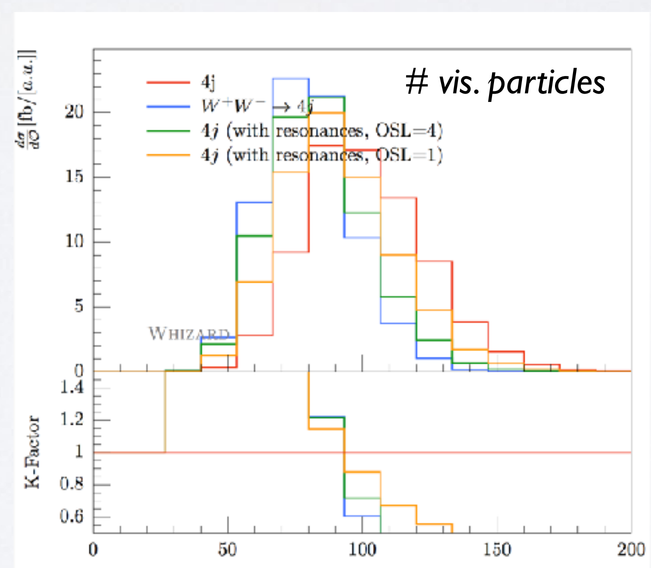

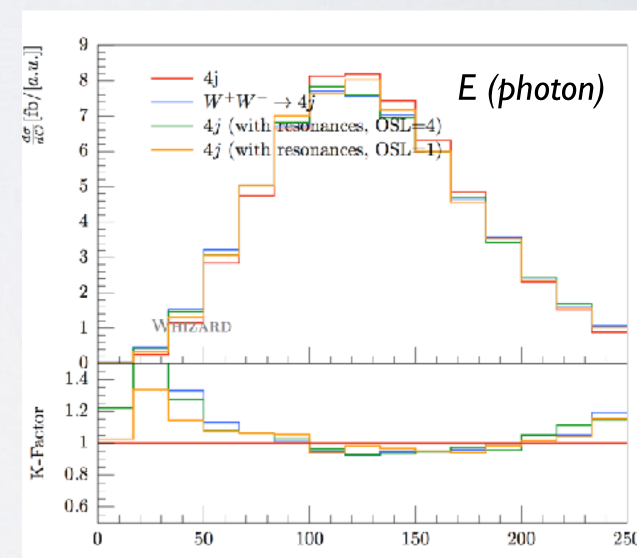

- LC Generator Group first successful tests on $e^+e^- \to 6j$; includes tests w/ resonant $H \to bb$