# Status of the WHIZARD Generator


Jürgen R. Reuter, DESY

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

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*In Wizard's Isle still lay forgot,*
*enmeshed and tortured in that grot*
*cold, evil, doorless, without light,*
*and blank-eyed stared at endless night*
*two comrades. Now alone they were.*
*The others lived no more, but bare*
*their broken bones would lie and tell*
*how ten had served their master well.*

J.R.R. Tolkien, *Lay of Leithian, Canto 9*

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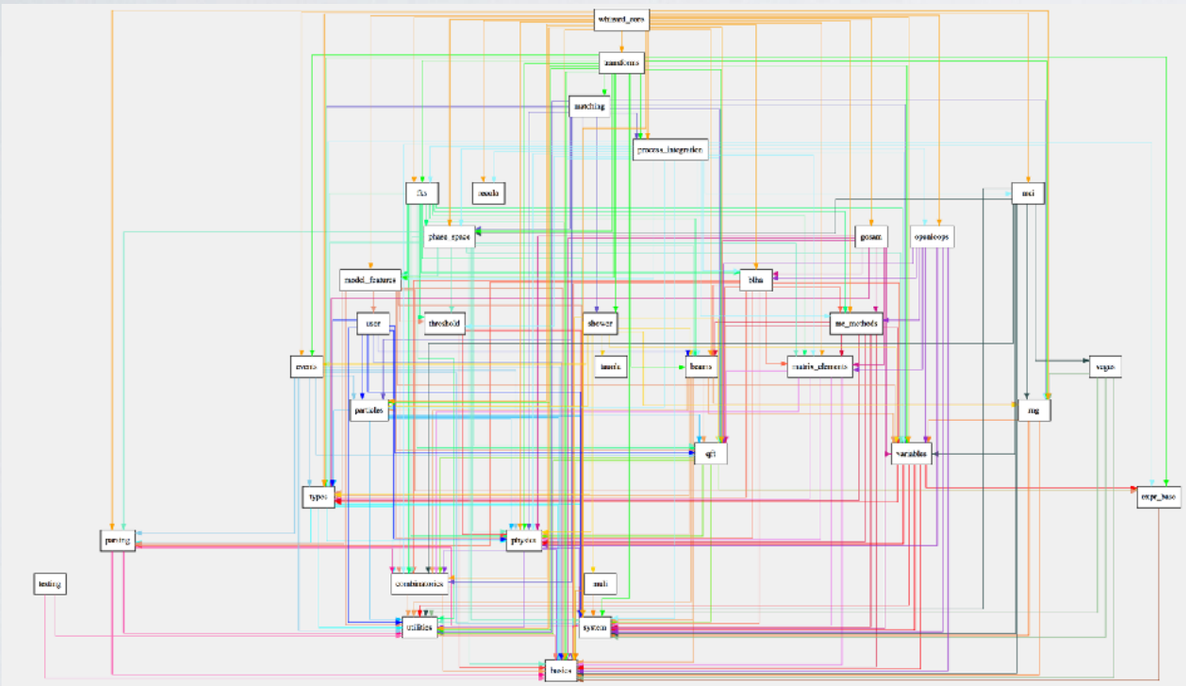
# WHIZARD: Introduction / Technical Facts

WHIZARD v2.7.1 (27.03.2019) http://whizard.hepforge.org <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR*
*Simon Braß / Nils Kreher / Vincent Rothe / So Young Shim / Pascal Stienemeier*



**PUBLICATIONS**

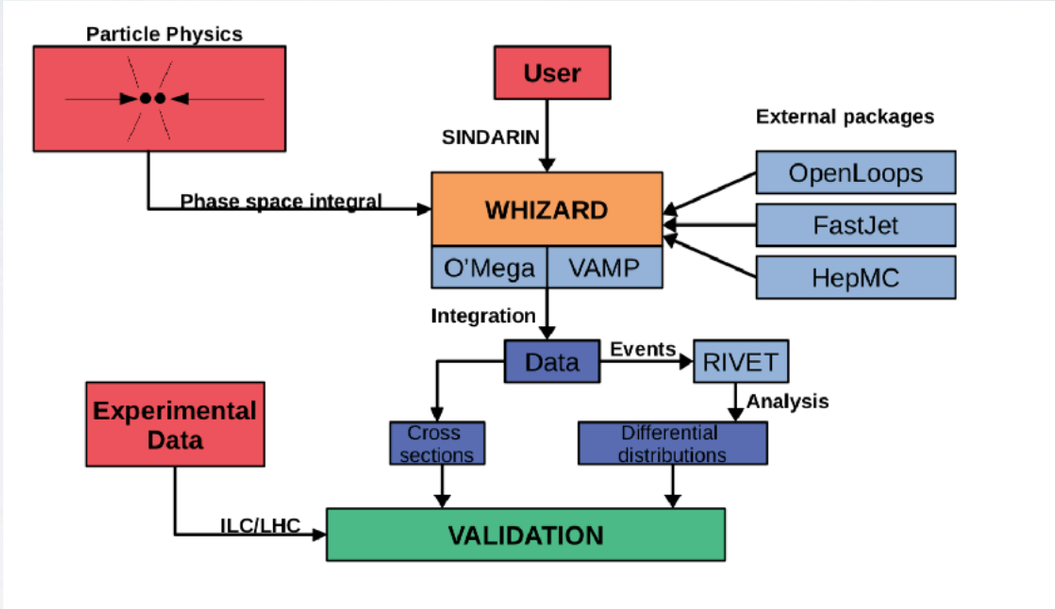
| | |
|---|---|
| General WHIZARD reference: | EPJ C71 (2011) 1742, arXiv:0708.4241 |
| O'Mega (ME generator): | LC-TOOL (2001) 040; arXiv:hep-ph/0102195 |
| VAMP (MC integrator): | CPC 120 (1999) 13; arXiv:hep-ph/9806432 |
| CIRCE (beamstrahlung): | CPC 101 (1997) 269; arXiv:hep-ph/9607454 |
| Parton 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 (≥3.12.0)`
- 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

- Interfaces to external packages:
  FastJet, GoSam, GuineaPig(++), HepMC, 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: Past and recent timeline (I)

- Original scope: electroweak (multi-fermion) studies at 1.6 TeV TESLA [≈ 1998–2000]
- Milestone: first-ever multi-leg implementation of MSSM v1.25 [2003]
- Color flow formalism [≈2005]
- Used for many TESLA studies and most ILC CDR and TDR, CLIC CDR and detector LoI studies (versions v1.24, v1.50, v1.95) [≈ 2002–2013]
- **Major refactoring phase I**: LHC physics → v2.0.0 [≈ 2007–2010; **38 months**]

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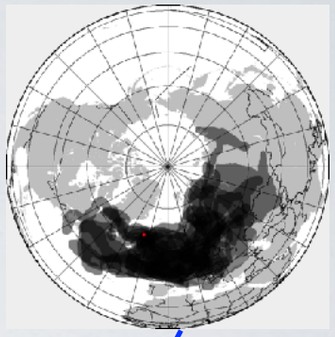
Eyjafjallajökull



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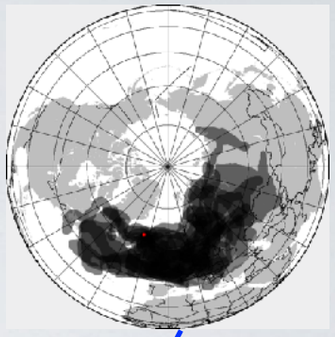
- **Major refactoring phase I**: LHC physics → v2.0.0 [≈ 2007–2010; **38 months**]
- Validation inside ATLAS and CMS [≈2011–2014]
- **Refactoring phase II**: NLO automation / maintainability → v2.2.0 [≈ 2012–2014; **18 months**]
- Strong interest of CEPC group for CEPC simulations [≈ 2013 — now]
- 04/2015, ALCW'15 Tokyo: LC generator group endorsed v2.2 for new mass productions
- FCC-ee interest in simulations: [ca. spring 2016]
- **Refactoring phase III:** first NLO implementation overhaul [2016; **3 months**]

Eyjafjallajökull



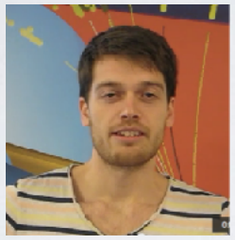
# WHIZARD: Past and recent timeline (II)

- Final validation for $e^+e^-$ physics between v1.95 & v2 [until end of 2017, partially mid 2018]

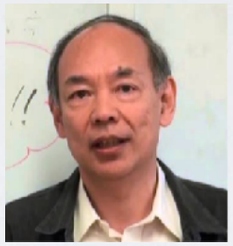
Special thanks to: [beam spectra, photon background, event formats, shower/hadronization, tau decays]


Mikael Berggren

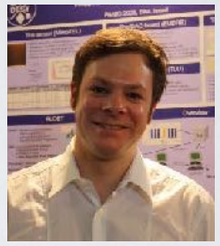

Jean-Jacques Blaising


Moritz Habermehl


Mo Xin


Akiya Miyamoto


Tim Barklow


Philipp Roloff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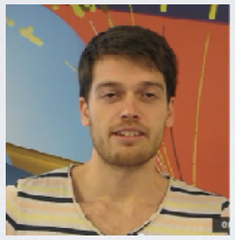
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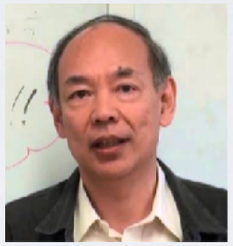
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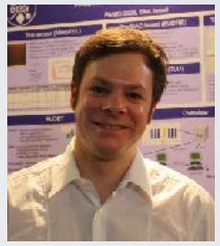

Philipp Roloff


Junping Tian

- 01/2018, CERN, LC generator meeting: only trivial minor, ready for mass production
- **Refactoring phase IV:** core data structure overhaul: NLO [fall 2018; **ca. 2-3months**]

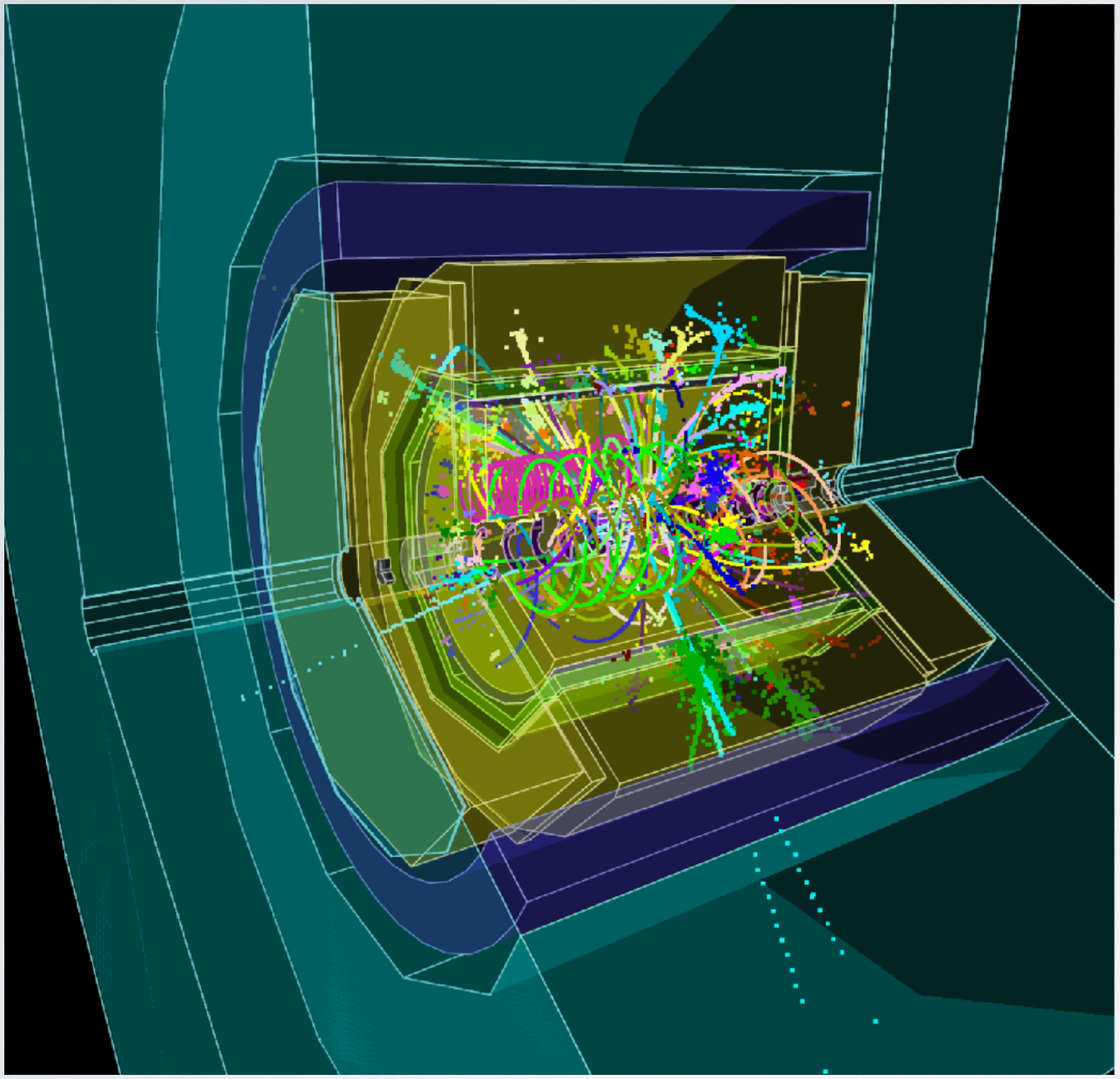
  [dust-layer buried students, total-code-no-man-wasteland alarm]
- Preparation for `WHIZARD 3.0.0α` started: *… PARALLEL TO ….*

  Work on: [NLO QCD final validation; structure functions; NLO EW; shower and matching/merging]
- **(Technical) refactoring phase V:** code modernization (submodules etc: `gfortran 6.1+` )

  [fall / winter of 2019; when NAG debugging compiler support ready]

# Examples for $e^+e^-$ simulation





SLAC Bereiche

Linear Collider

Seiten

Seiten / Home / Data Samples

## 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

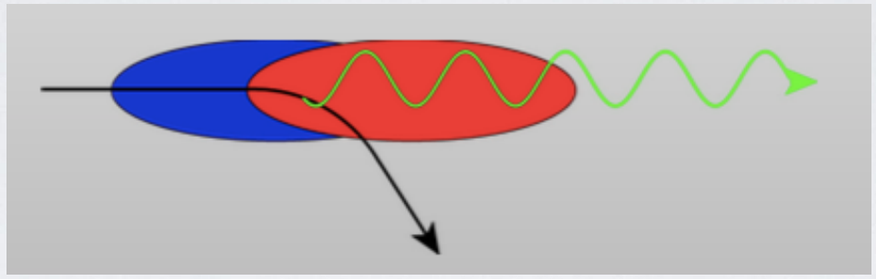
"SLAC DBD samples" and more: full SM !

# $e^+e^-$ Beamspectra

# $e^+e^-$ Beamspectra

- High-energy e+e- colliders need to achieve extreme luminosities
- Price for limited AC power: high bunch charges and tiny bunch cross sections
- Dense beams generate strong EM fields: deflect particles in other bunch (beamstrahlung)

$$L \approx \frac{N}{4\pi\sigma_x\sigma_y}\frac{\eta P_{AC}}{E_{CM}}$$



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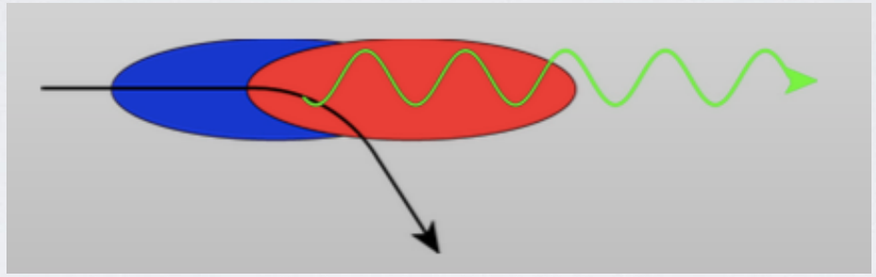

**Index of /circe_files/CLIC**

| Name | Last modified | Size | Des |
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| 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 | |

**Index of /circe_files/TESLA**

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| teslagg_500_polavg.circe | 29-Jul-2016 13:20 | 270K | |

**Index of /circe_files/ILC**

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| ilc200ee_nobeamspread.circe | 29-Jul-2016 13:20 | 1.0M | |
| ilc230ee_nobeamspread.circe | 29-Jul-2016 13:20 | 1.0M | |
| ilc250ee_nobeamspread.circe | 29-Jul-2016 13:20 | 1.0M | |
| ilc350ee_nobeamspread.circe | 29-Jul-2016 13:20 | 1.0M | |
| ilc500ee_nobeamspread.circe | 29-Jul-2016 13:20 | 1.0M | |

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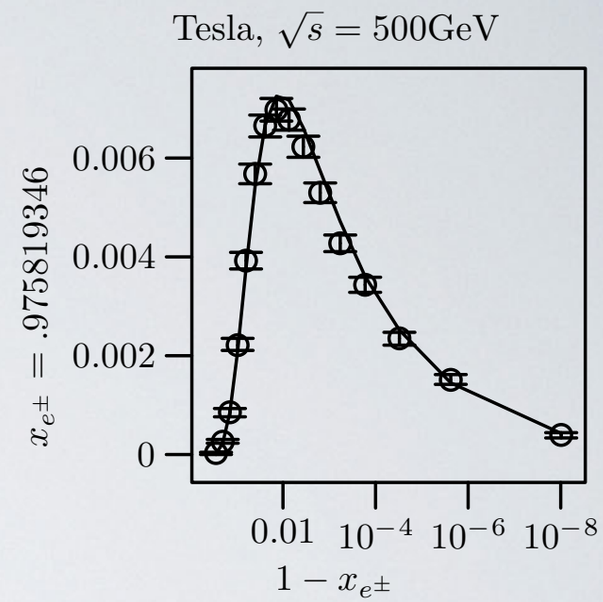
| cepc250.circe | 29-Jul-2016 13:20 | 252K | |

# Lepton Collider Beam Simulation

- Adapt `GuineaPig` beam spectra for `WHIZARD v2`
- For `WHIZARD v1.95` simulations done by `Lumilinker` [T. Barklow]
- TESLA/SLC spectra were rather simple
- Fits with 6 or 7 parameters possible [`CIRCE1`]
- Beams not factorizable: $D_{B_1 B_2}(x_1, x_2) \neq D_{B_1}(x_1) \cdot D_{B_2}(x_2)$
- No simple power law: $D_{B_1 B_2}(x_1, x_2) \neq x_1^{\alpha_1}(1-x_1)^{\beta_1} x_2^{\alpha_2}(1-x_2)^{\beta_2}$



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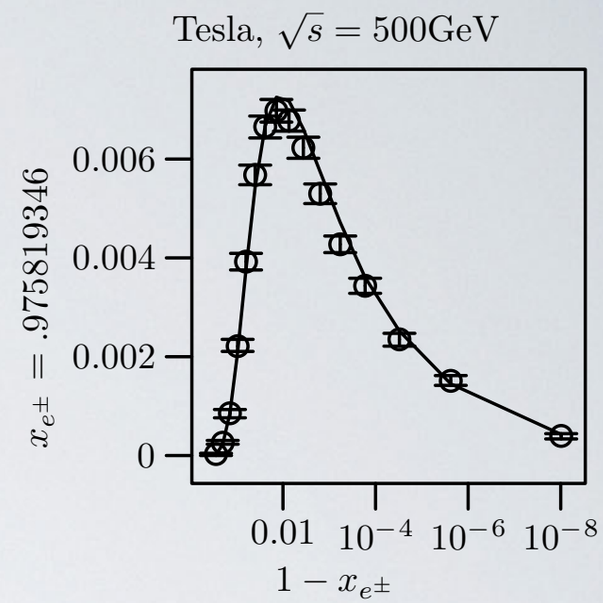


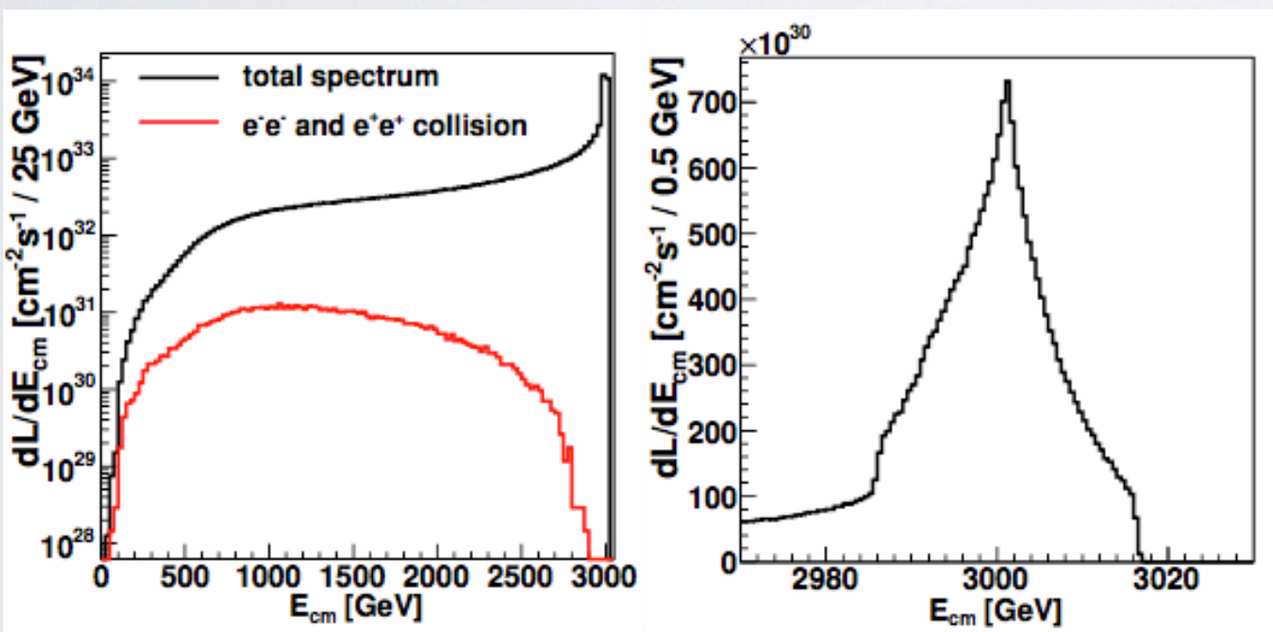


Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)

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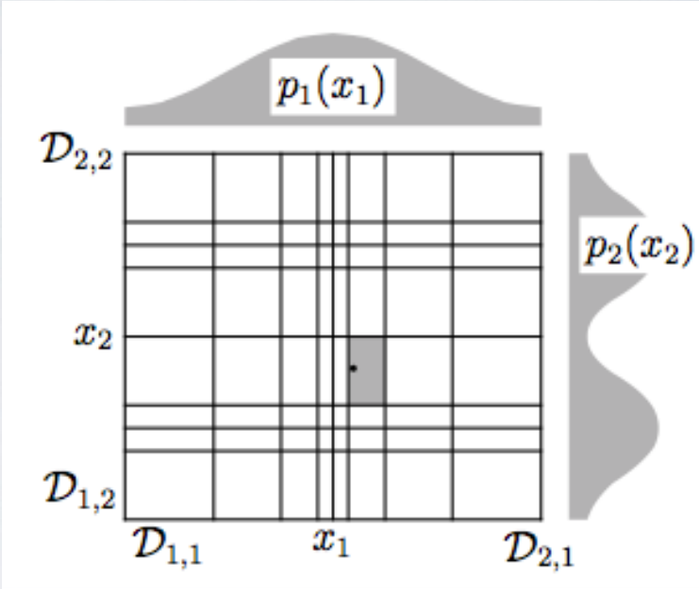
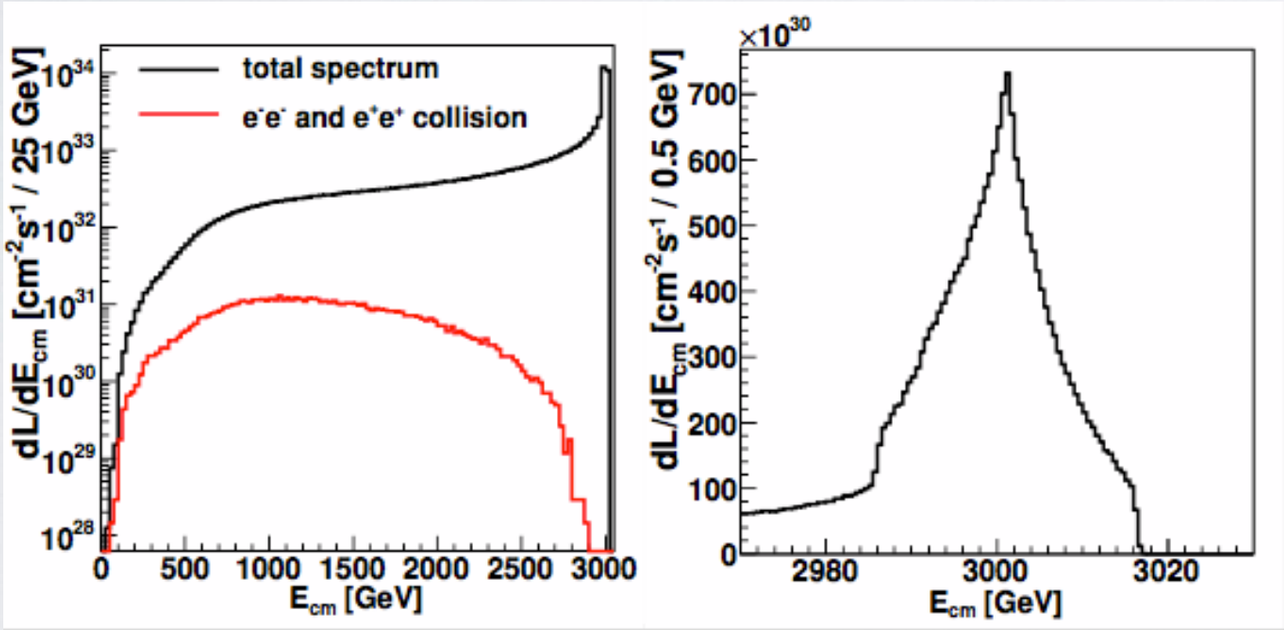


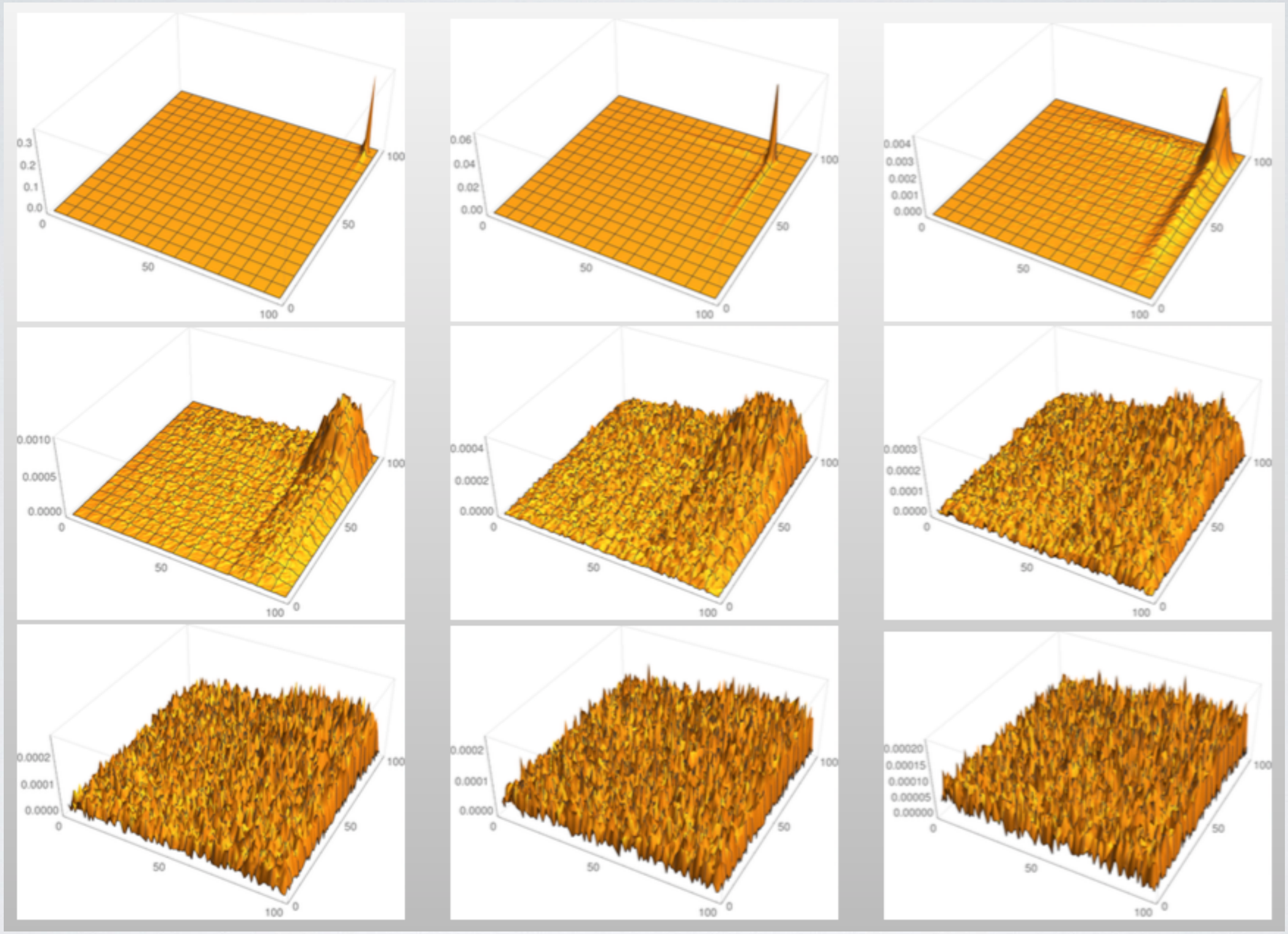

Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)

`CIRCE2` algorithm (`WHIZARD 2.2.5`, 02/15)

- Adapt 2D factorized variable width histogram to steep part of distribution
- Smooth correlated fluctuations with moderate Gaussian filter [suppresses artifacts from limited GuineaPig statistics
- Smooth continuum/boundary bins separately [avoid artificial beam energy spread]

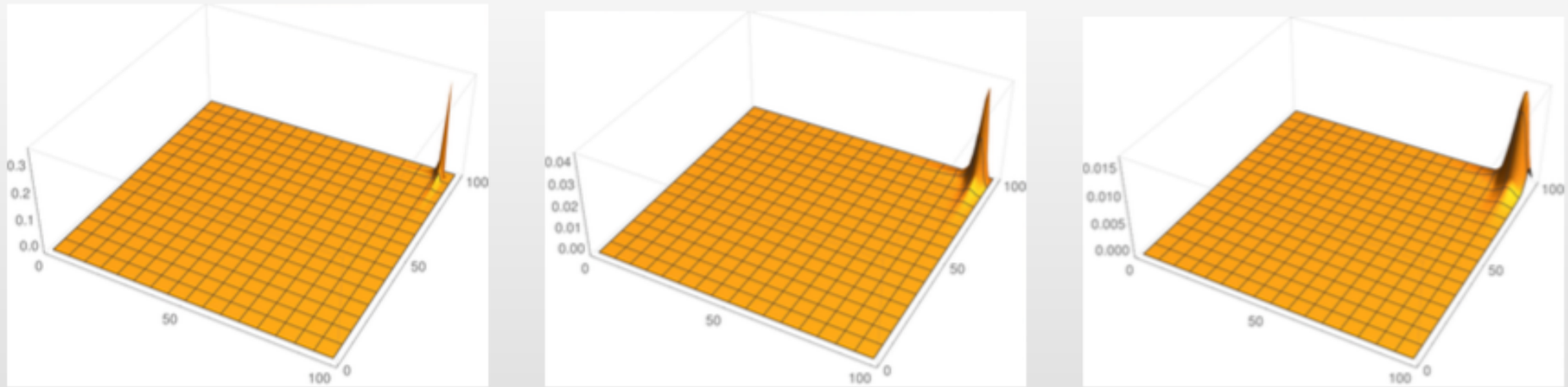
# Iterations of Beam Spectrum



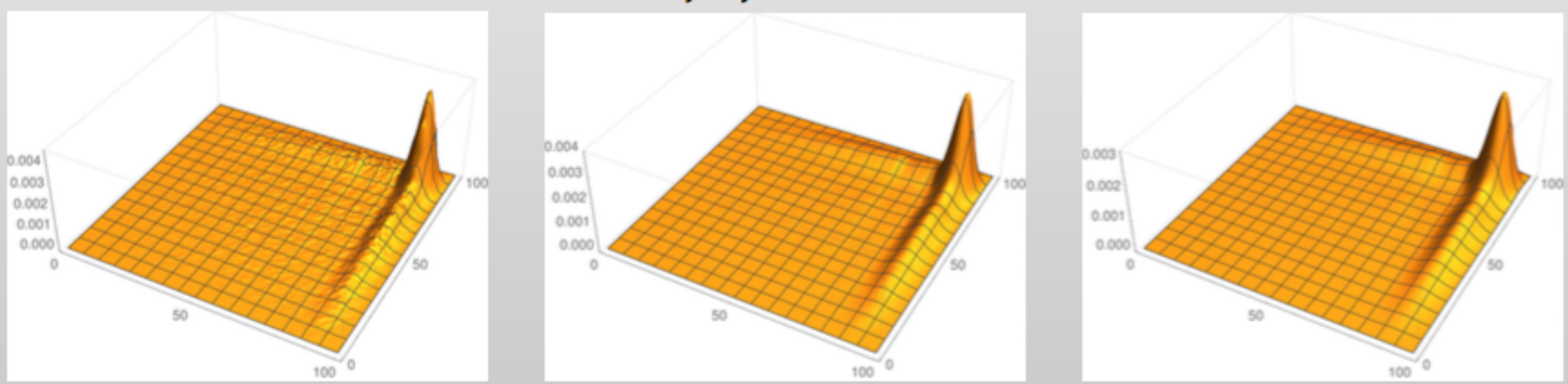
(171,306 GuineaPig events in 10,000 bins)

# Iterations of Beam Spectrum

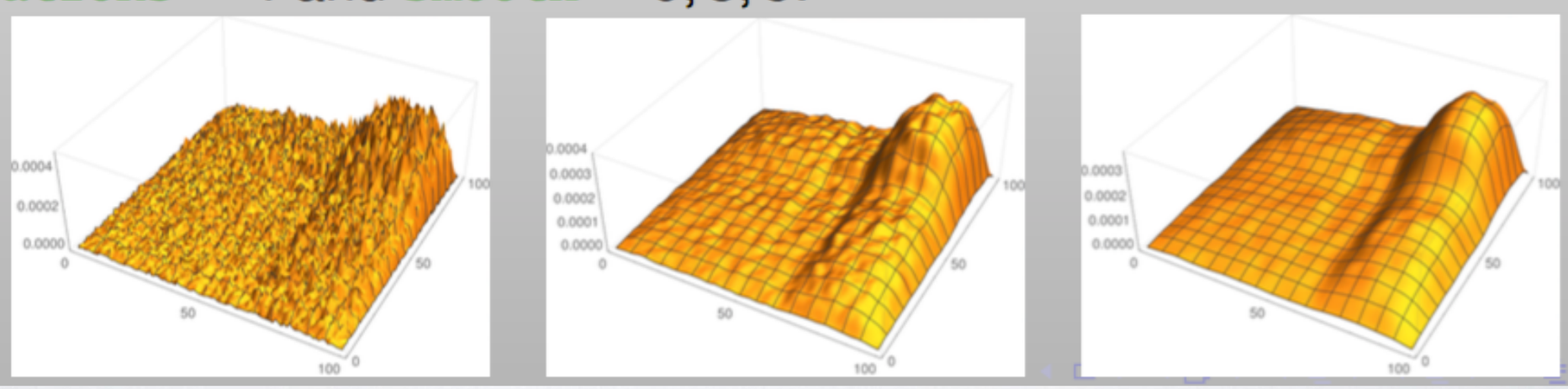
- `iterations` = 0 and `smooth` = 0, 3, 5:



- `iterations` = 2 and `smooth` = 0, 3, 5:



- `iterations` = 4 and `smooth` = 0, 3, 5:



# 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

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

Hard-collinear photons up to 3rd QED order

Kuraev/Fadin, 1983; Skrzypek/Jadach, 1991

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

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

$$\zeta(3) = 1.202056903159594285399738161 51\ldots$$

# Inclusive Lepton Collider ISR included

Soft exponentiation to all orders

Gribov/Lipatov, 1971

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

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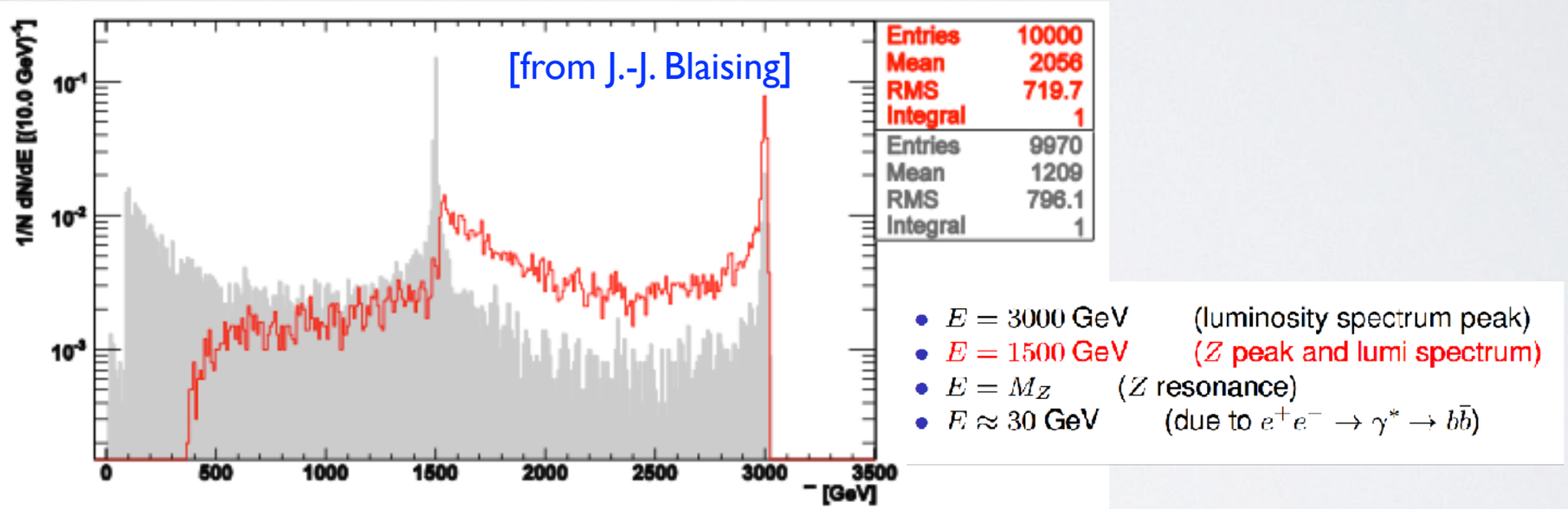

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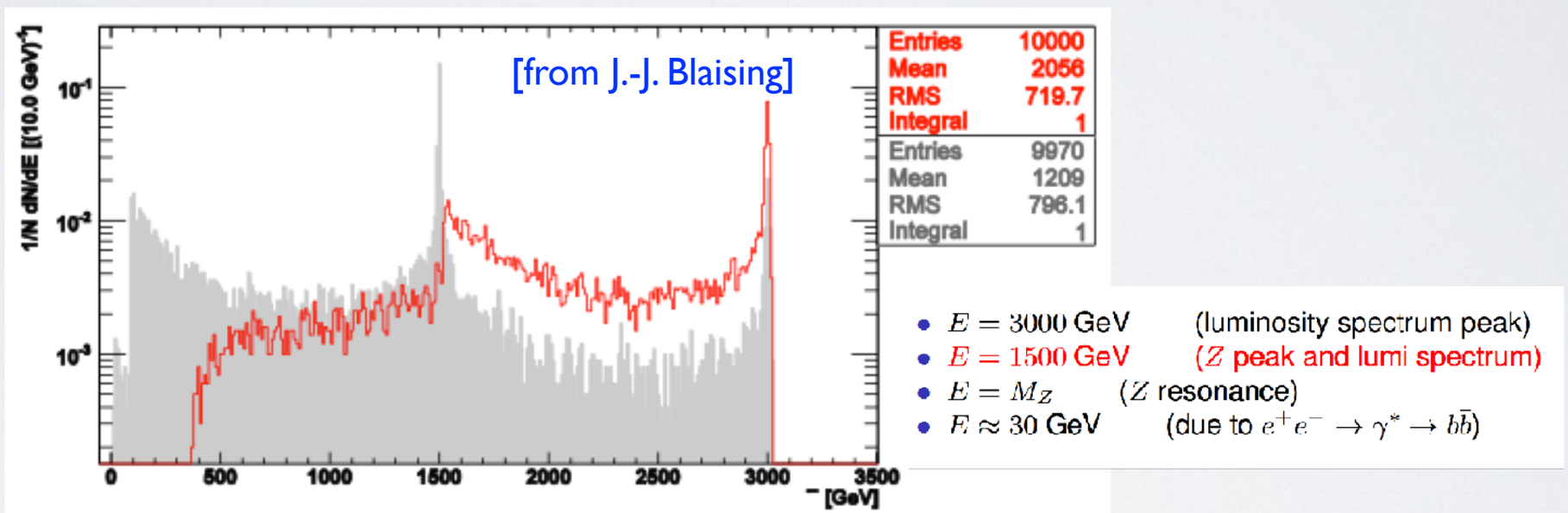
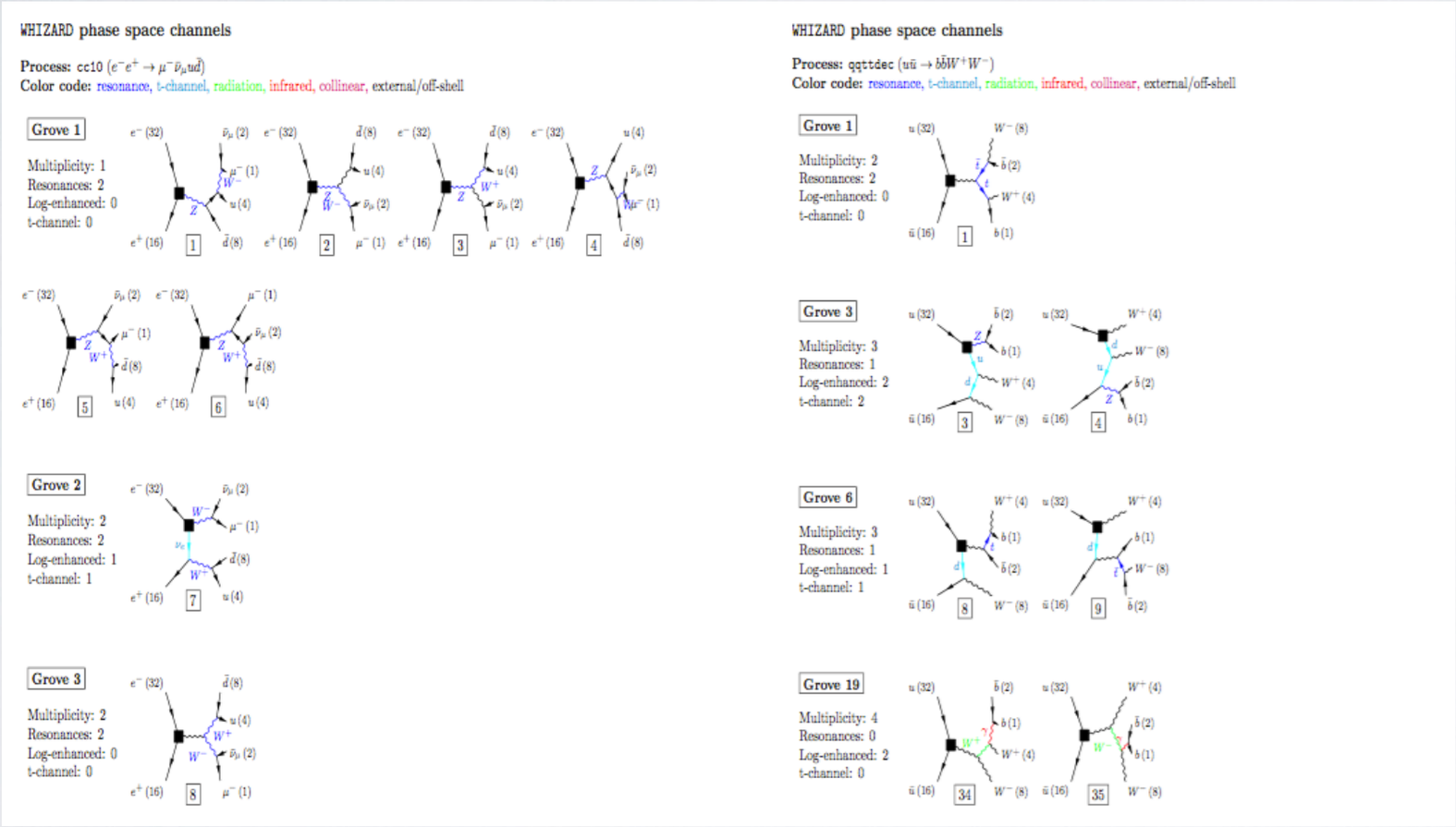


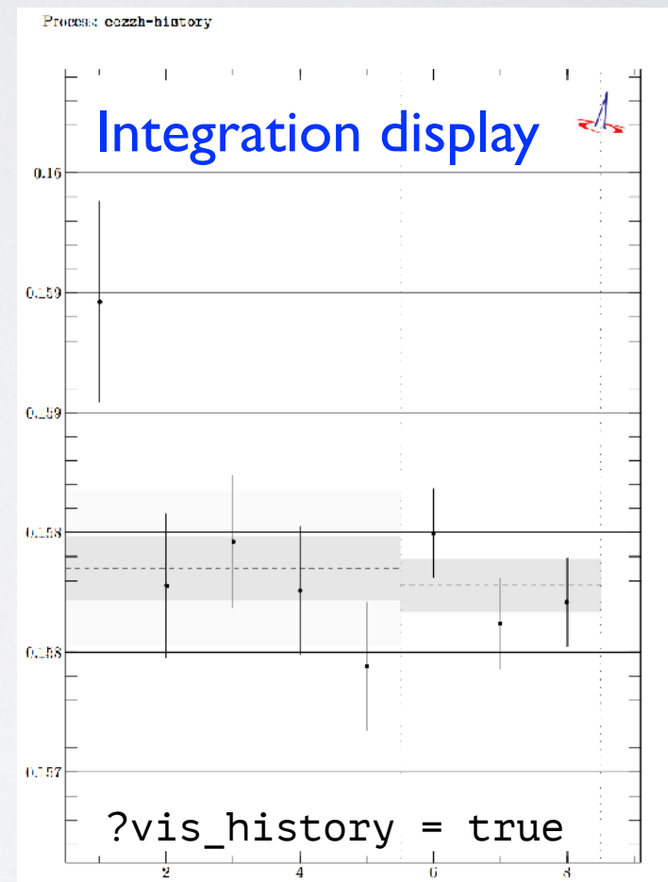

- ☐ One explicit ISR photon / beam: ISR/EPA handler generates physical $p_T$ distributions
- ☐ Explicit matching needed: heuristic procedures LO — *tbd* for NLO !
- ☐ Collinear structure functions: plans for implementations of YFS / different schemes

# 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`



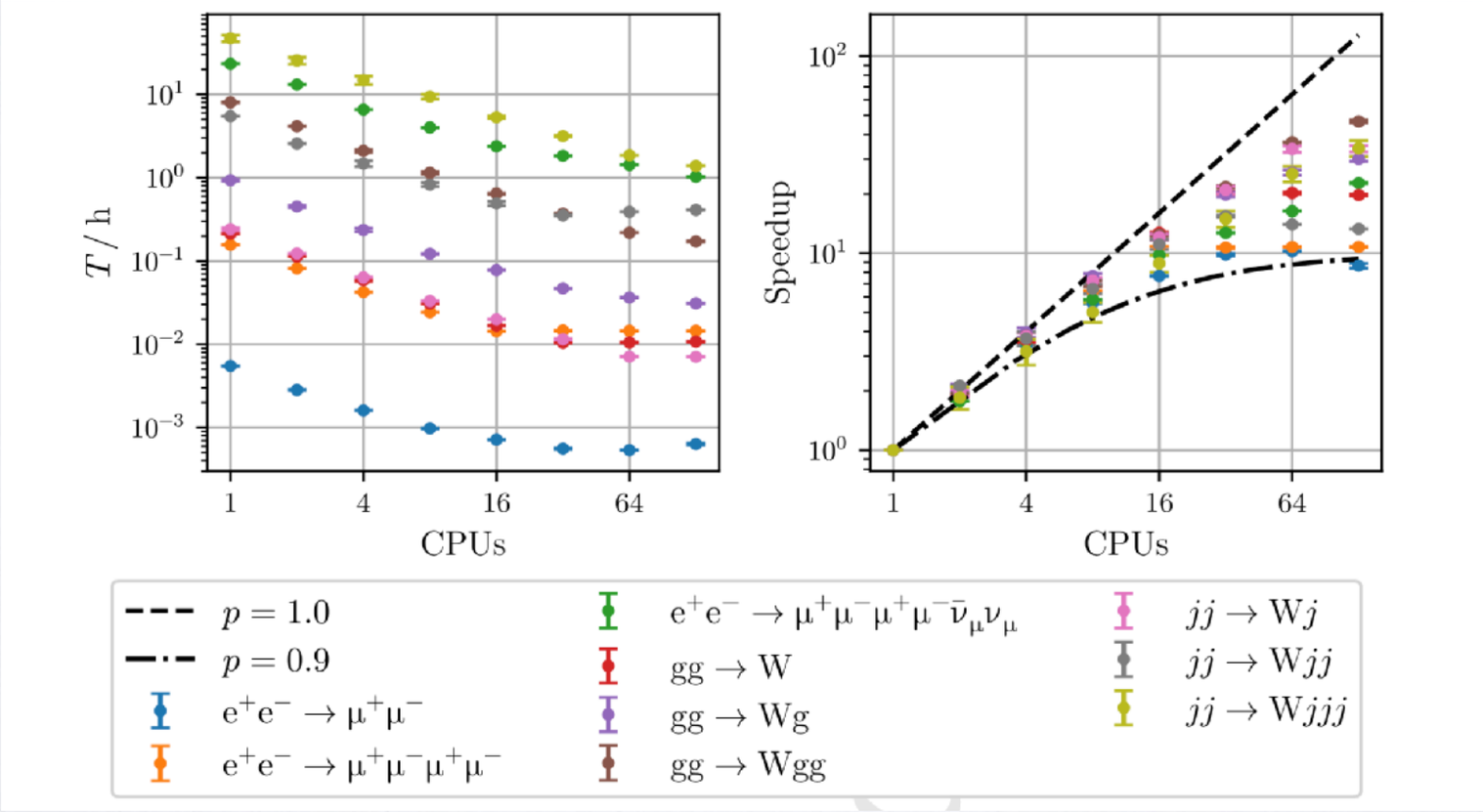

Complicated processes: factorization into production and decay with the `unstable` option

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

# MPI Parallelization

Braß/Kilian/JRR, 1811.09711 [EPJC]

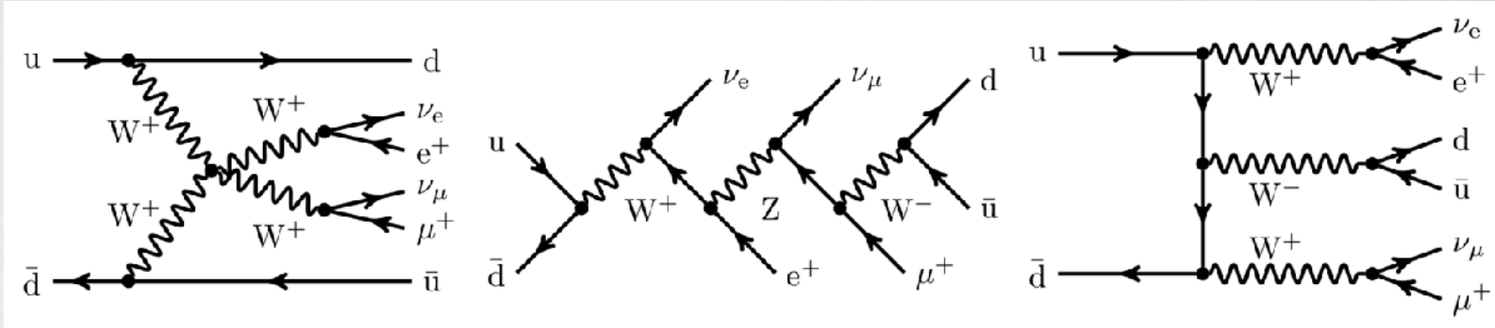
- Event generation trivially parallelizable
- Major bottleneck: adaptive phase space integration (generation of grids)
- Parallelization of integration: OMP multi-threading for different helicities since long
- NEW (after v2.5.0/2.6.4/2.7.1): MPI parallelization (using OpenMPI or MPICH)
- Distributes 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 v2.8.0]



# LHC VBS: Comparison LO & LO+PS

Ballestrero *et al.*, 1803.07943

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




| Code | $\sigma$[fb] |
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| MoCaNLO+Recola | $1.43476 \pm 0.00009$ |
| PHANTOM | $1.4374 \pm 0.0006$ |
| Powheg-Box | $1.44092 \pm 0.00009$ |
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| Whizard | $1.4381 \pm 0.0002$ |

LO

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

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

Anti-$k_T$ jets with $R = 0.4$:

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

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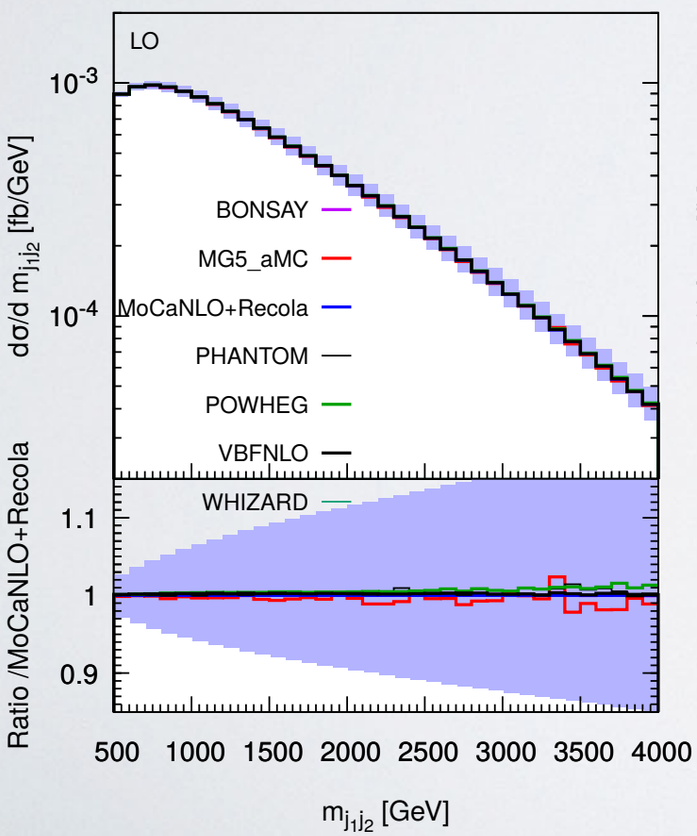
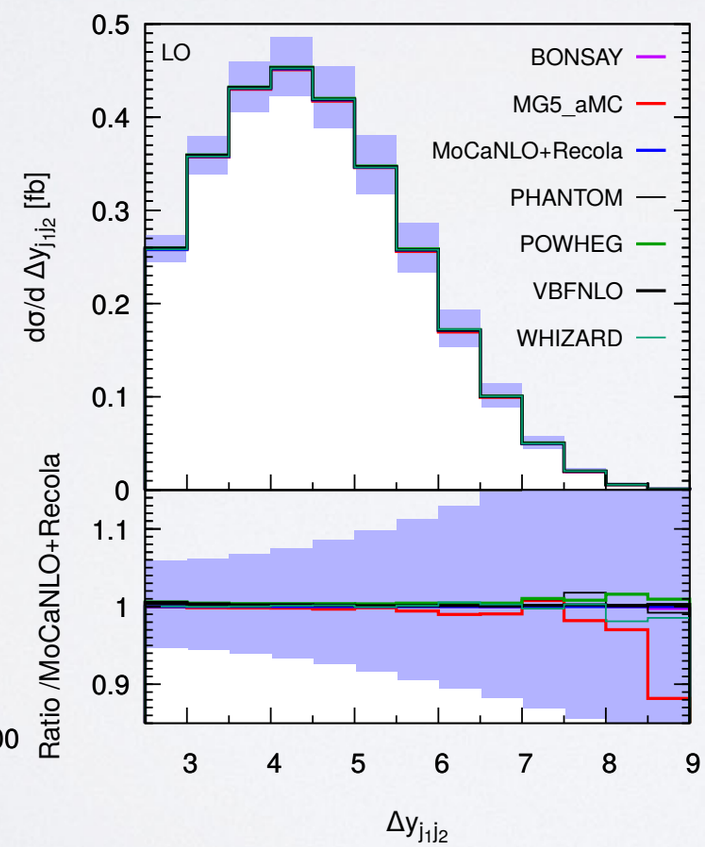
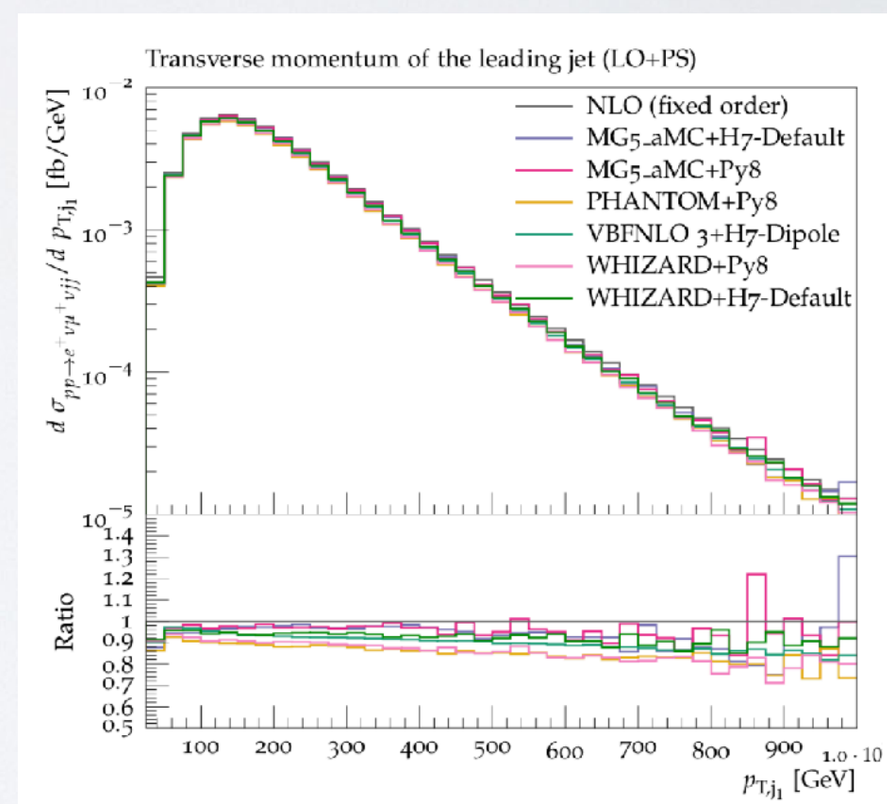
LO+PS



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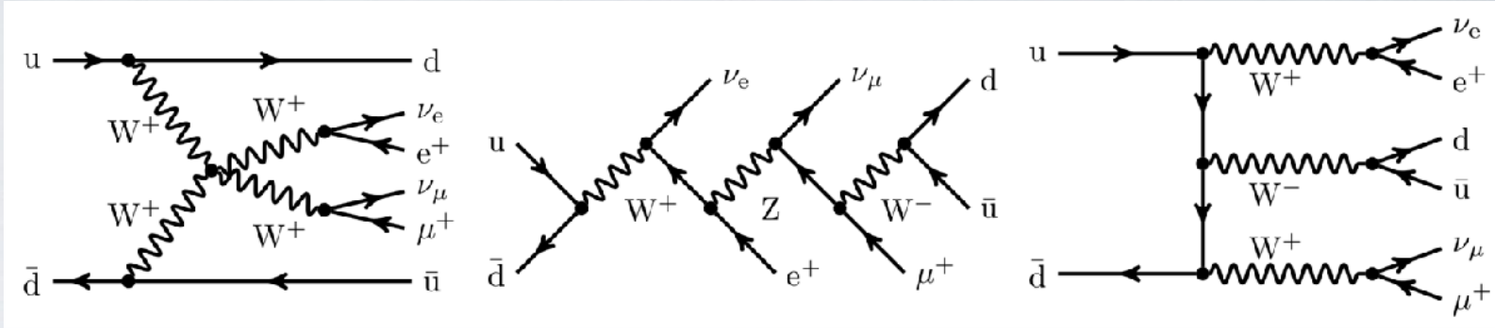


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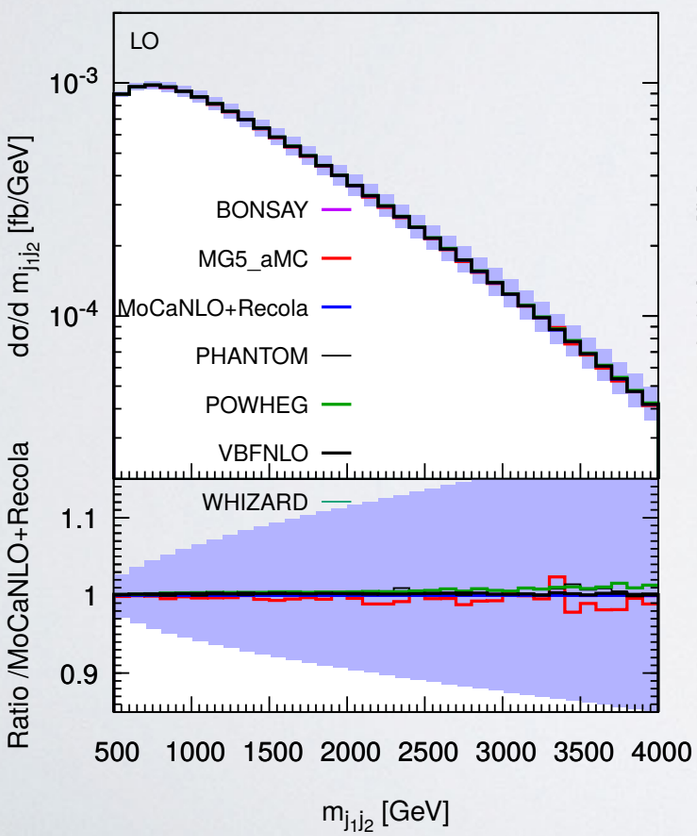


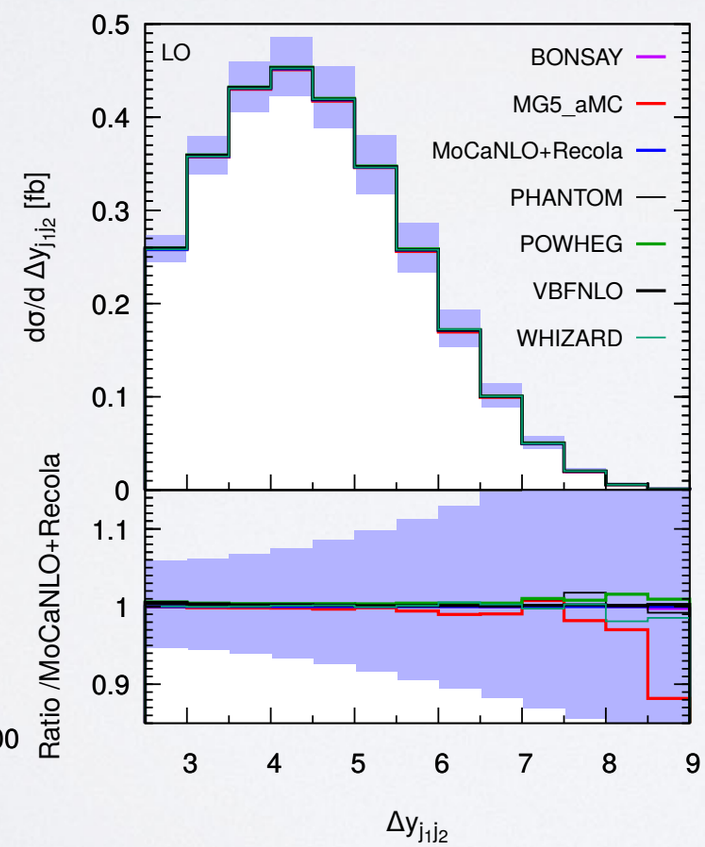


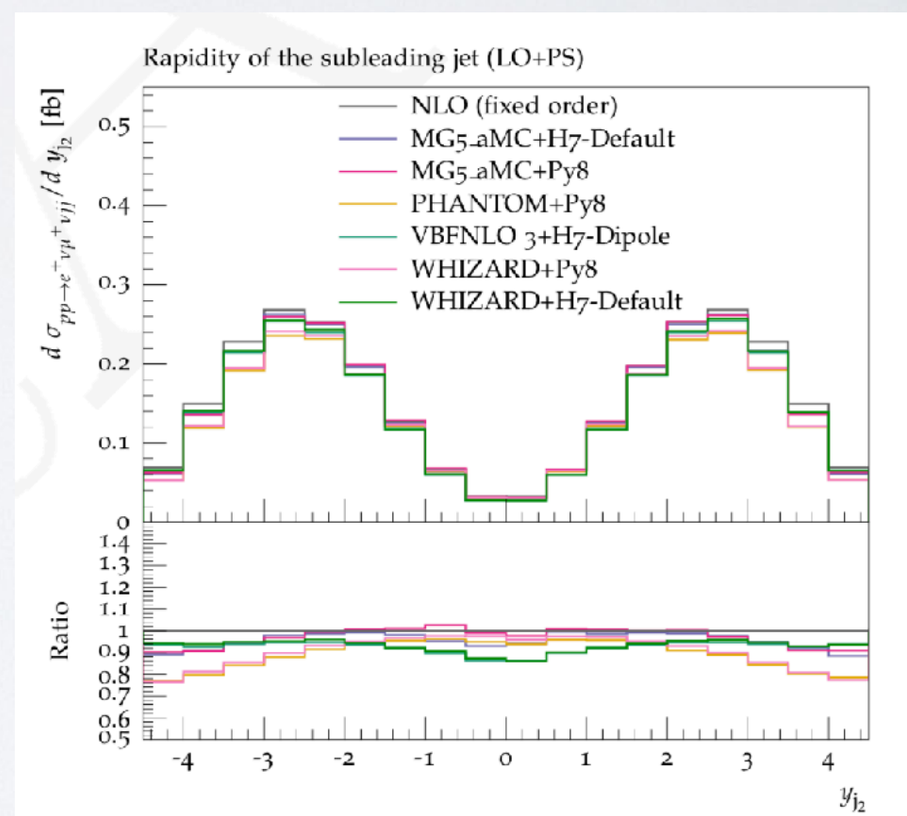

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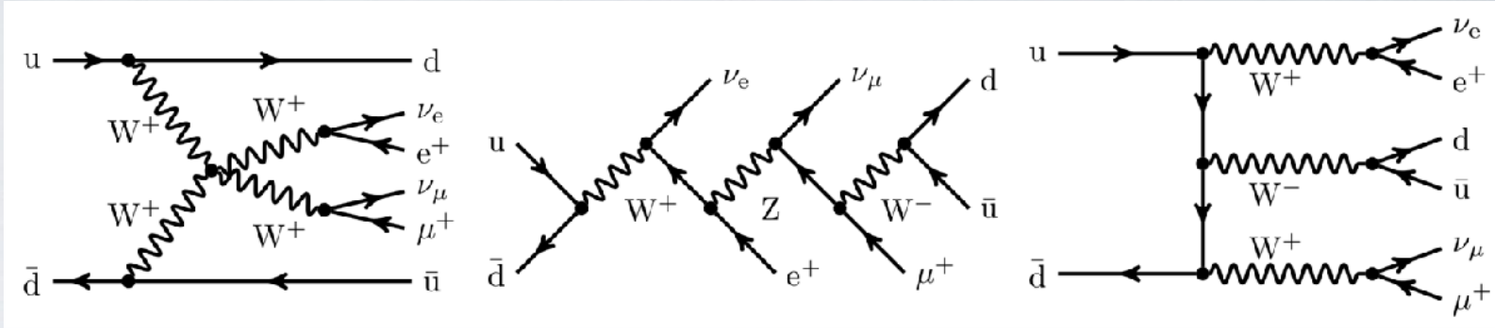


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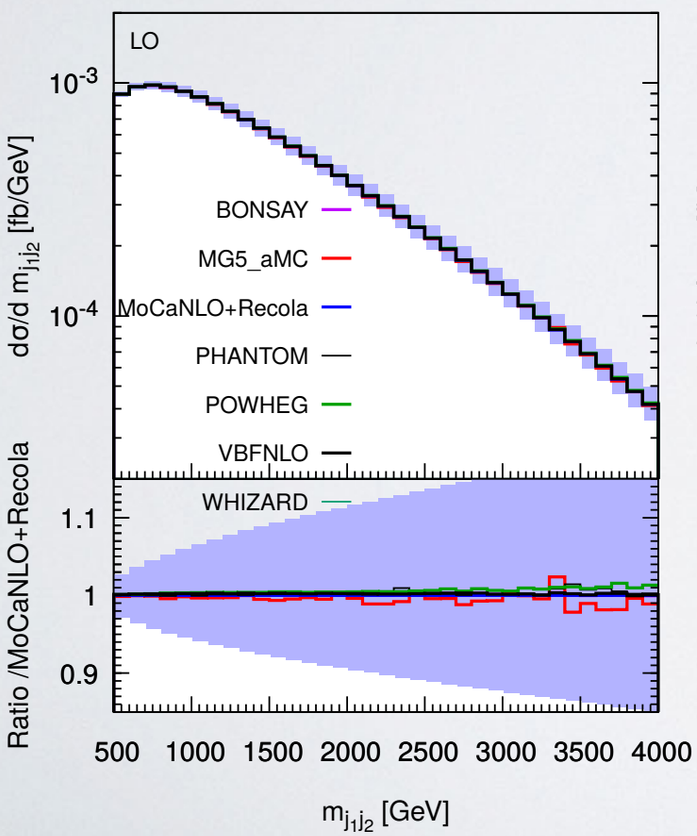
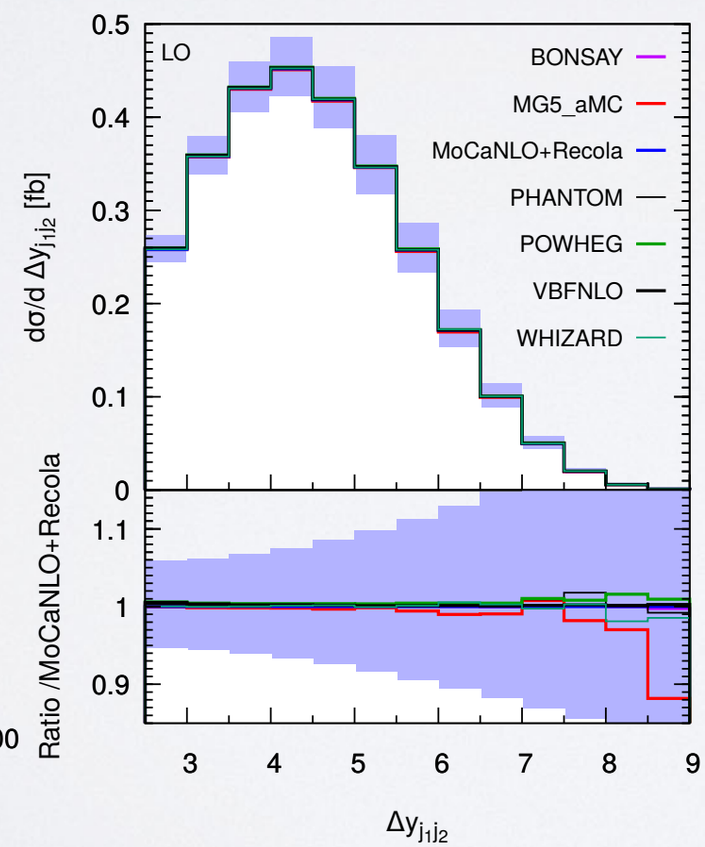
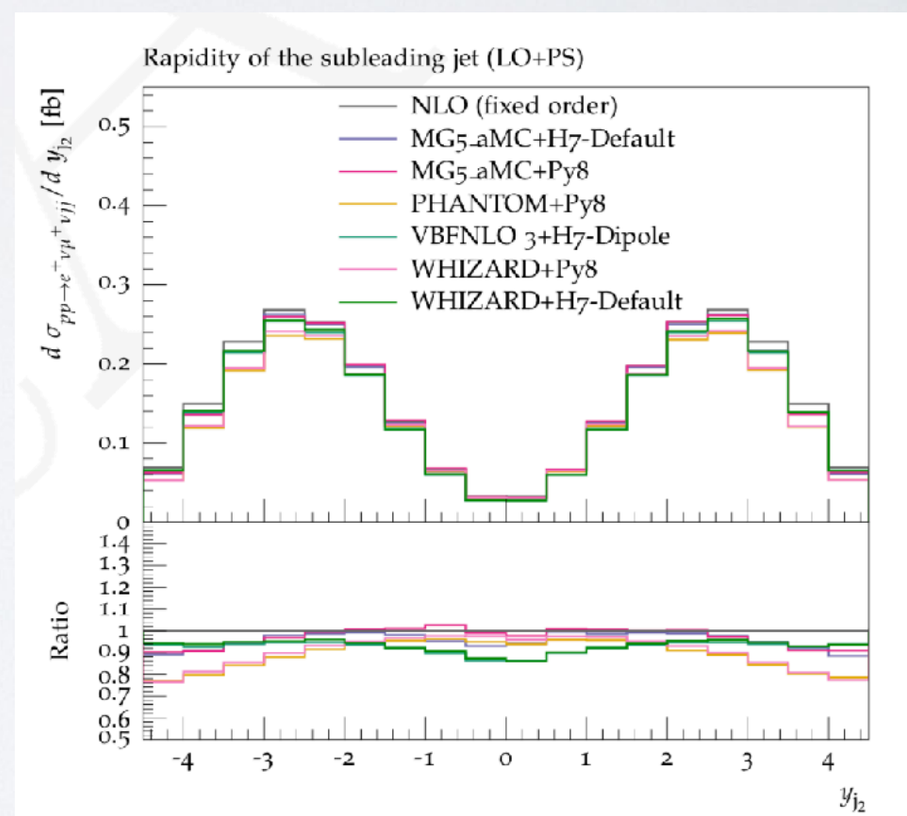
| | $\pm 0.001$ |
| | $\pm 0.0002$ |
| | $\pm 0.001$ |

LO+PS

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



# Keep resonances in ME-PS merging



```
?resonance_history = true
resonance_on_shell_limit = 4
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```

- Problem: $e^+e^- \to jjjj$ not dominated by highest $\alpha_s$ power,
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- `WHIZARD v2.6.0:` option to set resonance histories

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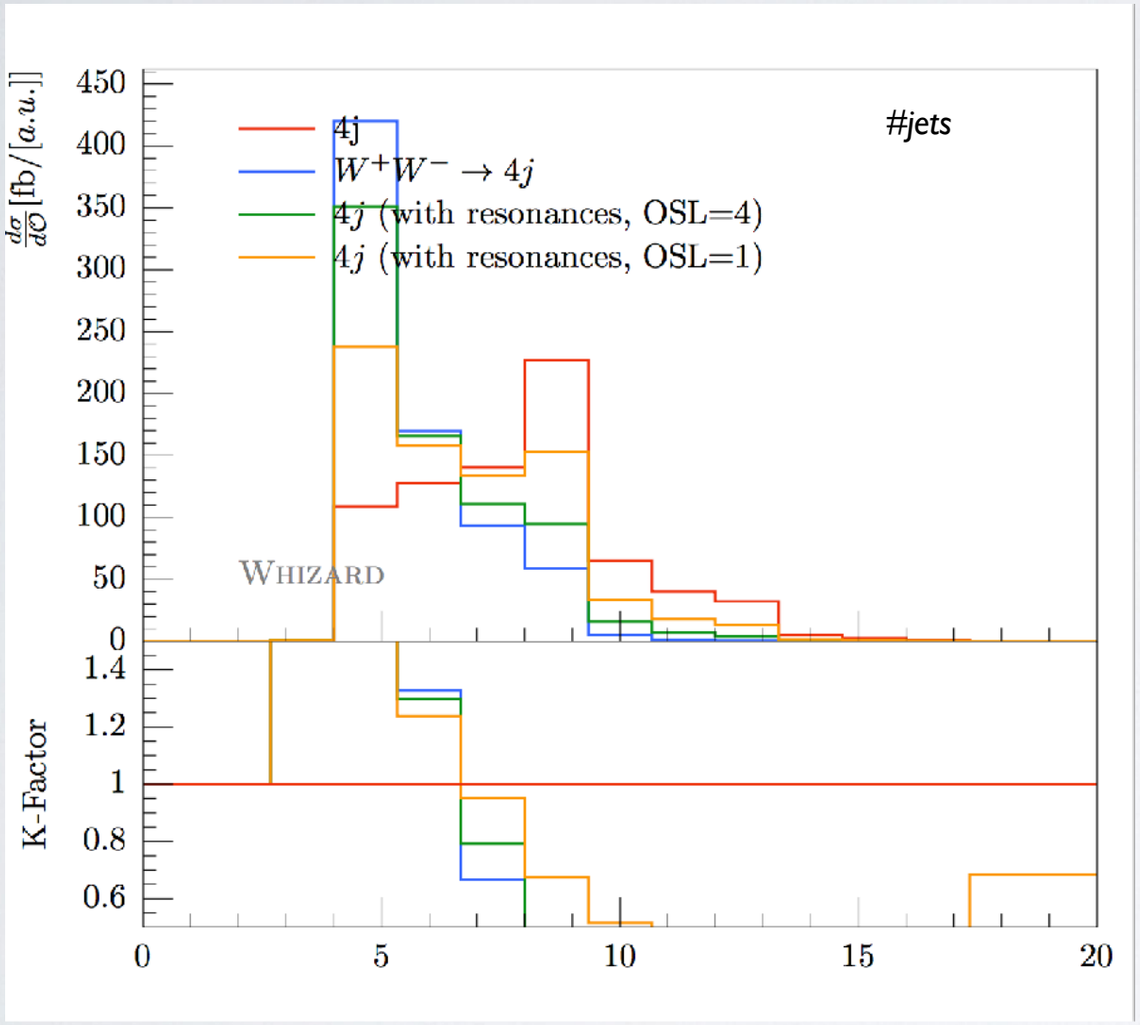

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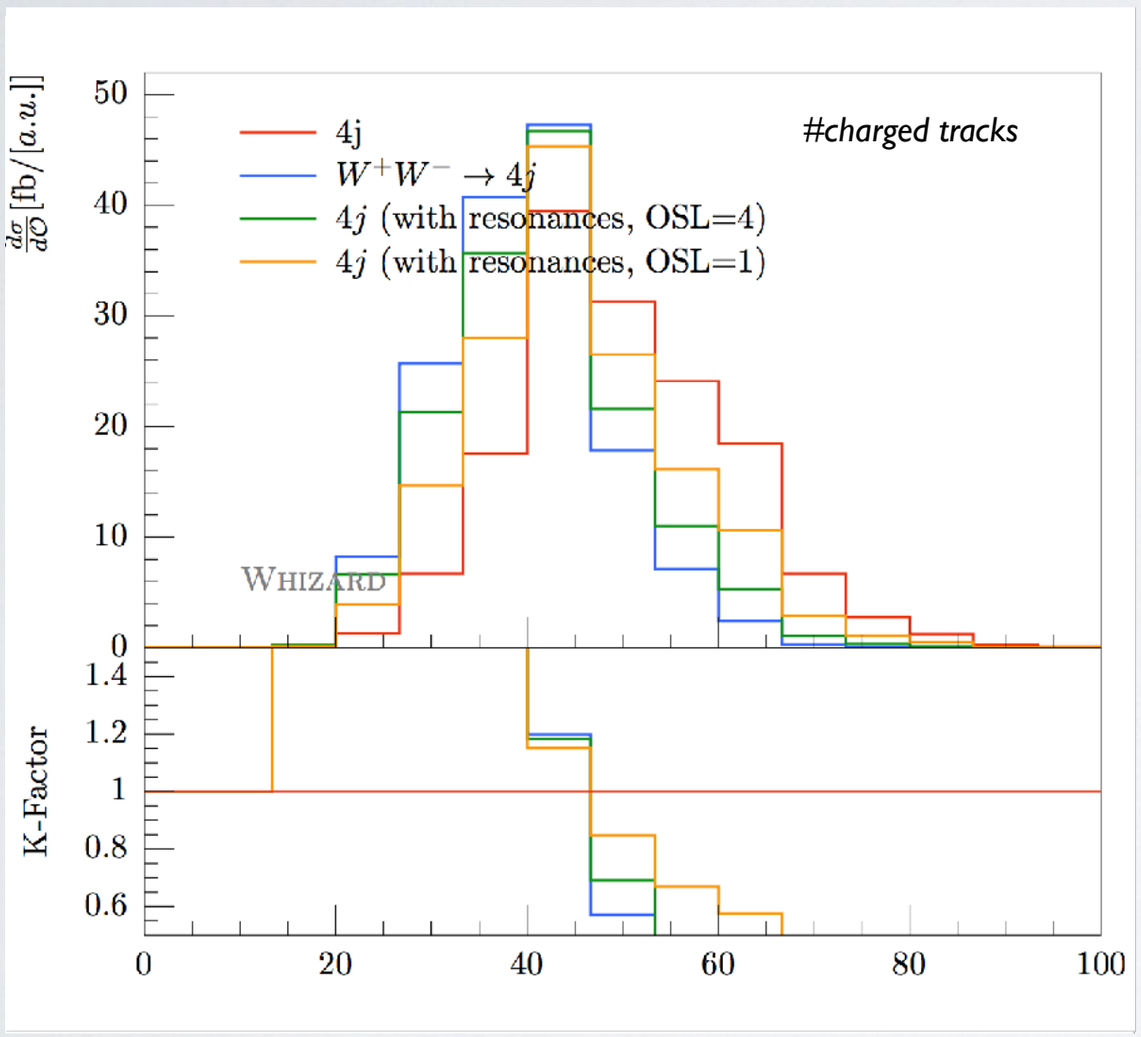


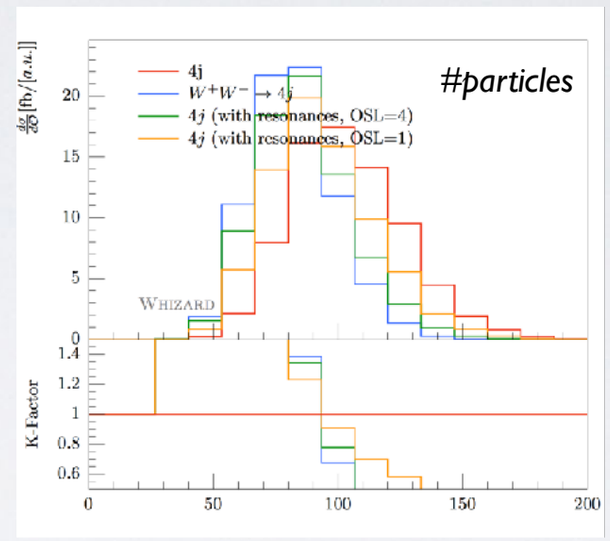


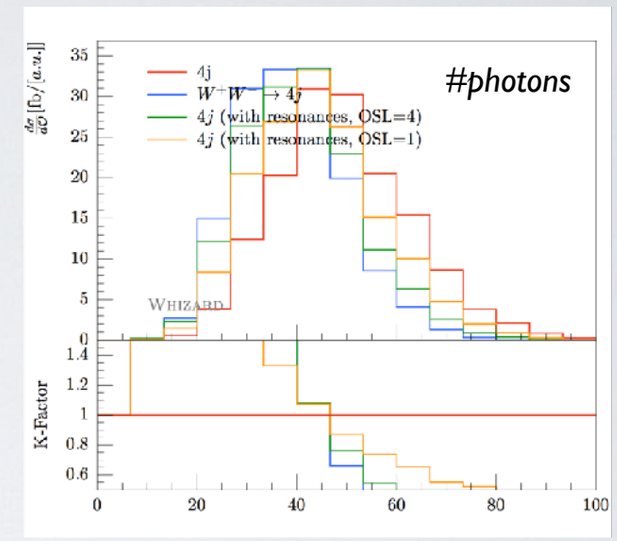


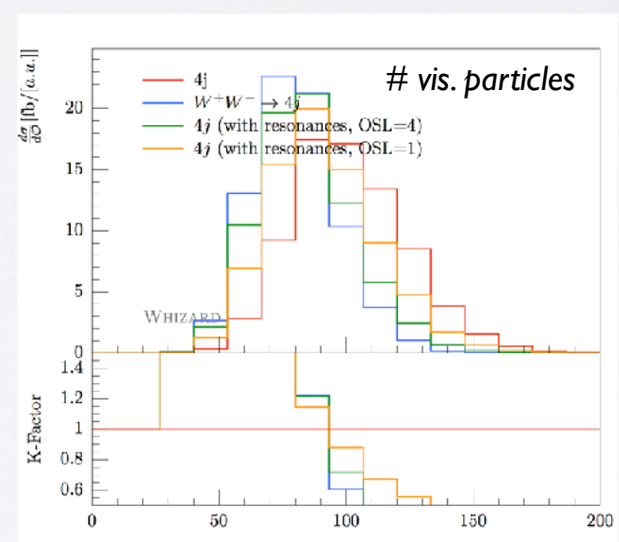


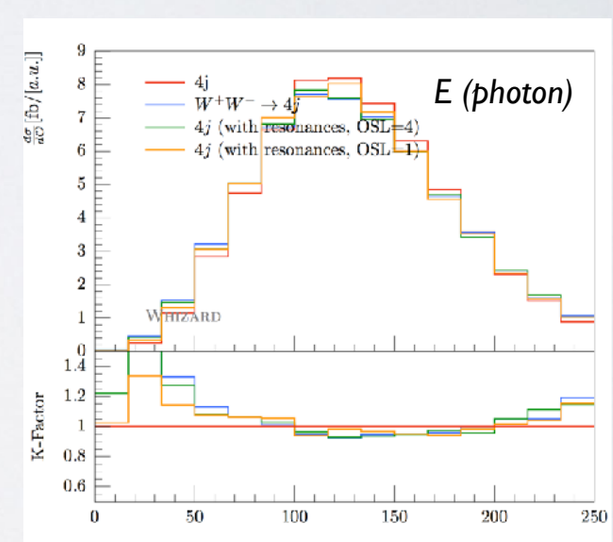

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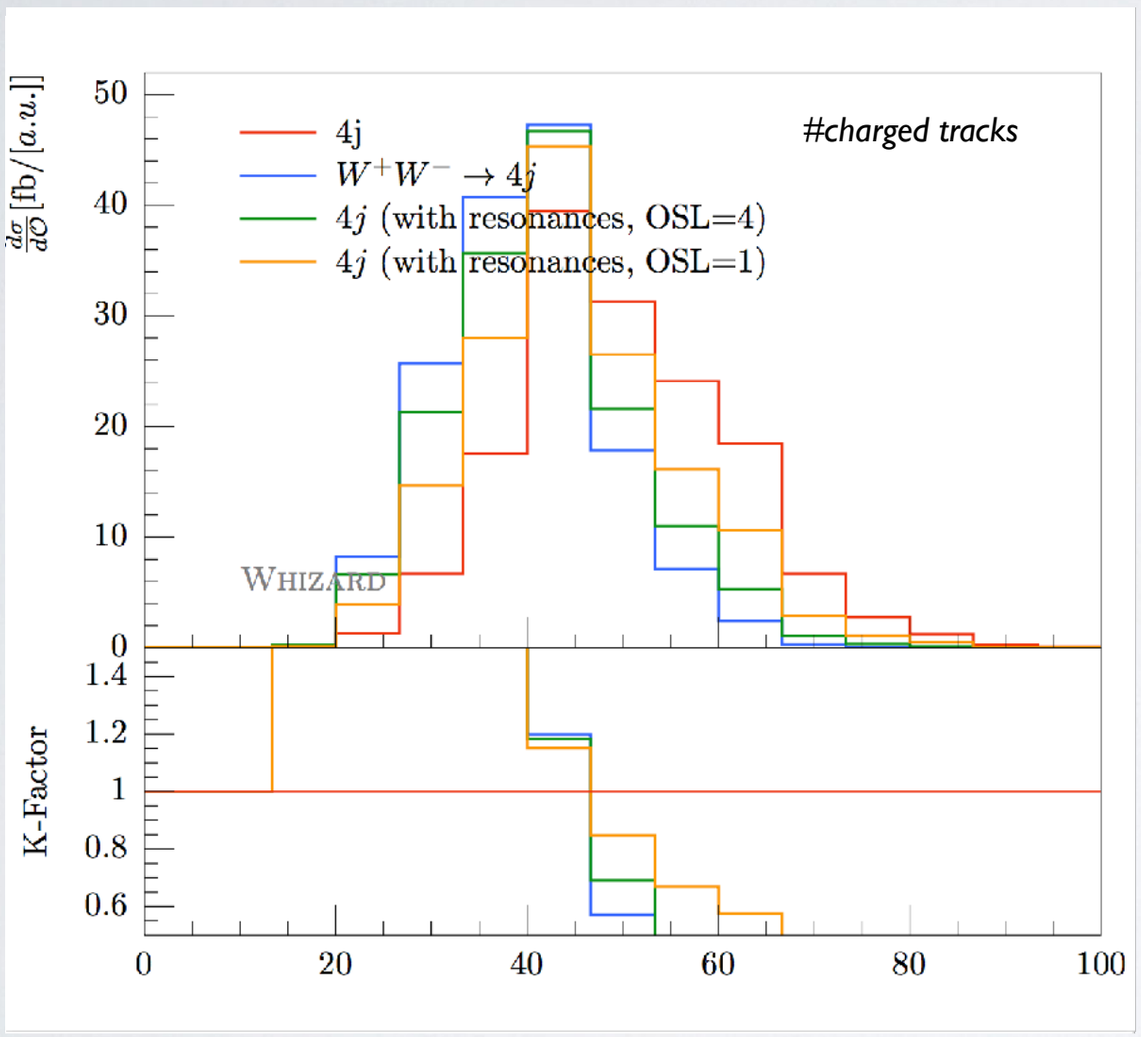


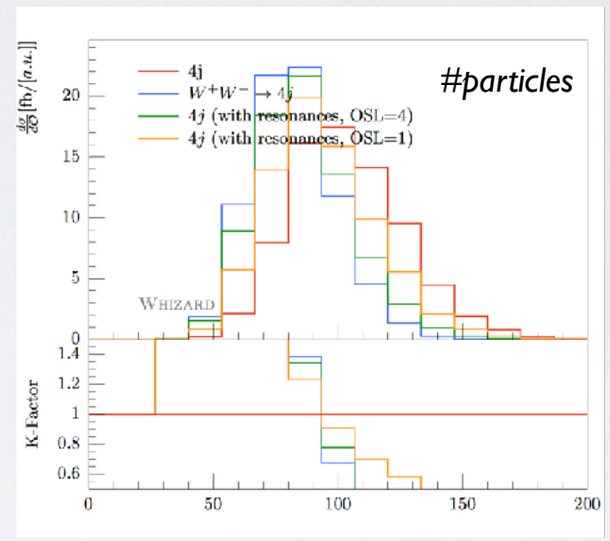


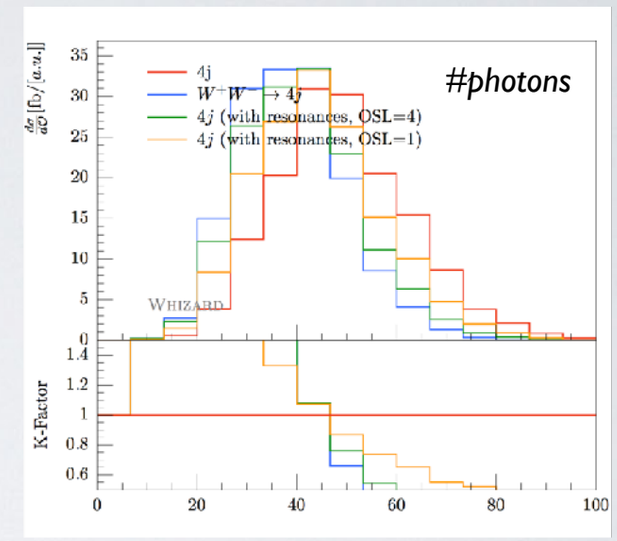


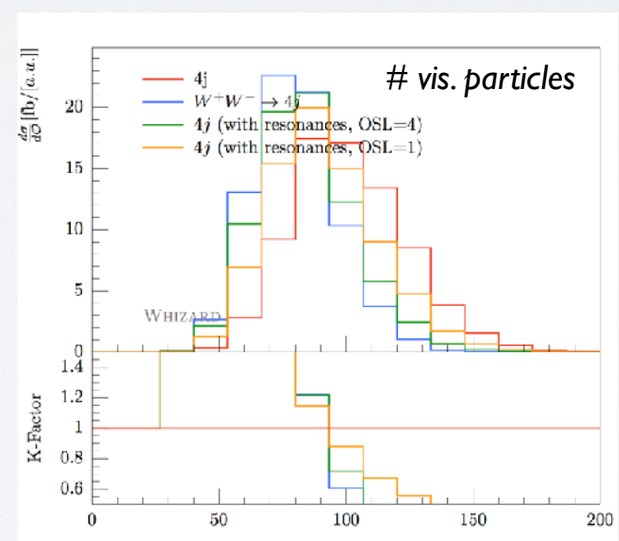


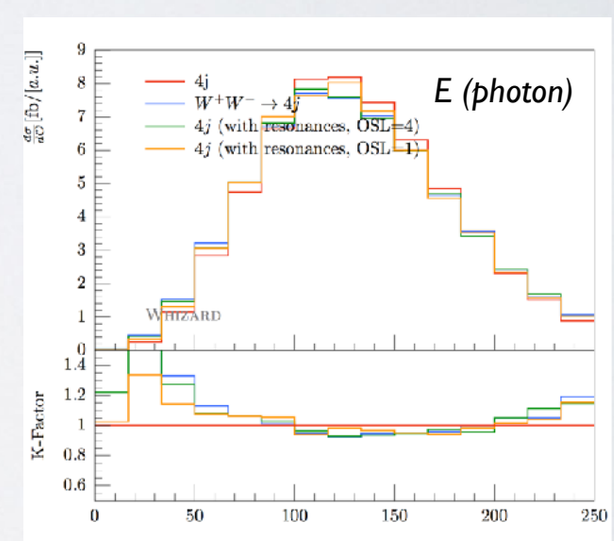


- LC Generator Group first successful tests on $e^+e^- \to 6j$ ; includes tests w/ resonant $H \to bb$

# Rescanning of Event Files



```
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
}
```

- 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
- NEW v2.7.0: works also w/ differently concatenated structure functions (e.g. ISR + beamstr.)
- Open issues: rescanning with resonance matching in showered events

# 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]

# 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]

**LCIO Format (LC I/O, particle-flow motivated):** (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

# BSM Models in WHIZARD

| MODEL TYPE | with CKM matrix | trivial CKM |
|---|---|---|
| Yukawa test model | --- | Test |
| QED with $e, \mu, \tau, \gamma$ | --- | 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 |

- Automated models: interface to SARAH/BSM Toolbox Staub, 0909.2863; Ohl/Porod/Staub/Speckner, 1109.5147
- Automated models: interface to FeynRules Christensen/Duhr; Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251

# BSM Models in WHIZARD

| MODEL TYPE | with CKM matrix | trivial CKM |
|---|---|---|
| Yukawa test model | --- | Test |
| QED with $e, \mu, \tau, \gamma$ | --- | 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 |
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| Simplest Little Higgs (anomaly-free) | --- | Simplest |
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| SM with graviton | --- | Xdim |
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| Augmentable SM template | --- | Template |

- Automated models: interface to SARAH/BSM Toolbox Staub, 0909.2863; Ohl/Porod/Staub/Speckner, 1109.5147
- Automated models: interface to FeynRules Christensen/Duhr; Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251
- Automated models: UFO interface [new WHIZARD/O'Mega model format]

# BSM Models in WHIZARD



| MODEL TYPE | with CKM matrix | trivial CKM |
|---|---|---|
| Yukawa test model | --- | Test |
| QED with $e, \mu, \tau, \gamma$ | --- | 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 |

by So Young Shim
heavily used
for CLIC
Yellow Report
multi-boson
studies
(VVV + VBS)

- Automated models: interface to SARAH/BSM Toolbox Staub, 0909.2863; Ohl/Porod/Staub/Speckner, 1109.5147
- Automated models: interface to FeynRules Christensen/Duhr; Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251
- Automated models: UFO interface [new WHIZARD/O'Mega model format]

# 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

NEW

Old FeynRules / SARAH interface will get 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

```
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)
  ! ------------------------------------------------------------------
```

NEW

Old FeynRules / SARAH interface will get deprecated

kept at the moment for user backwards compatibility

☑ WHIZARD 2.8.0 Release will contain full UFO support (Mid/end June 2019)

New version will demand OCaml ≥4.02.3

# NLO Automation in WHIZARD

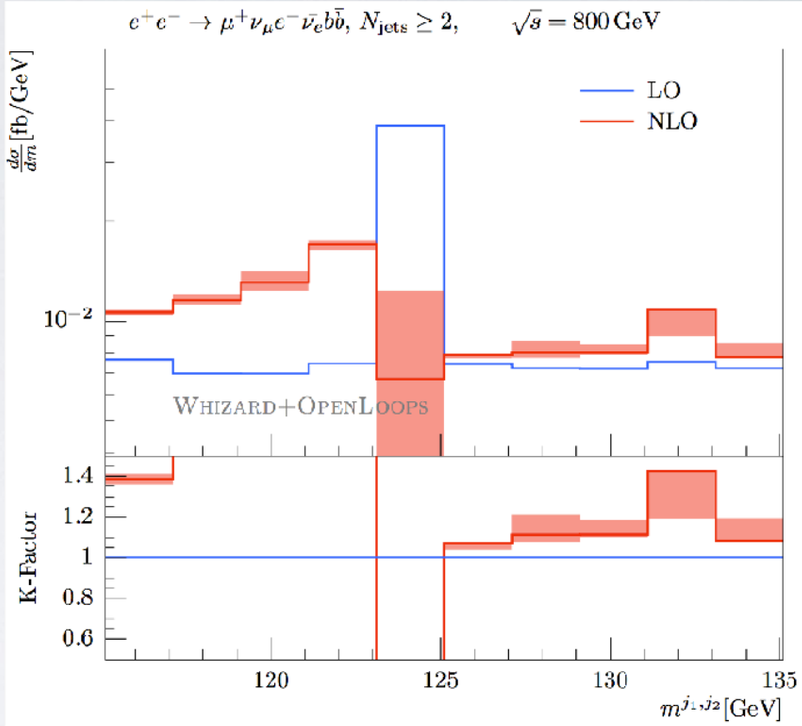
Working NLO interfaces to:

- ★ 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]

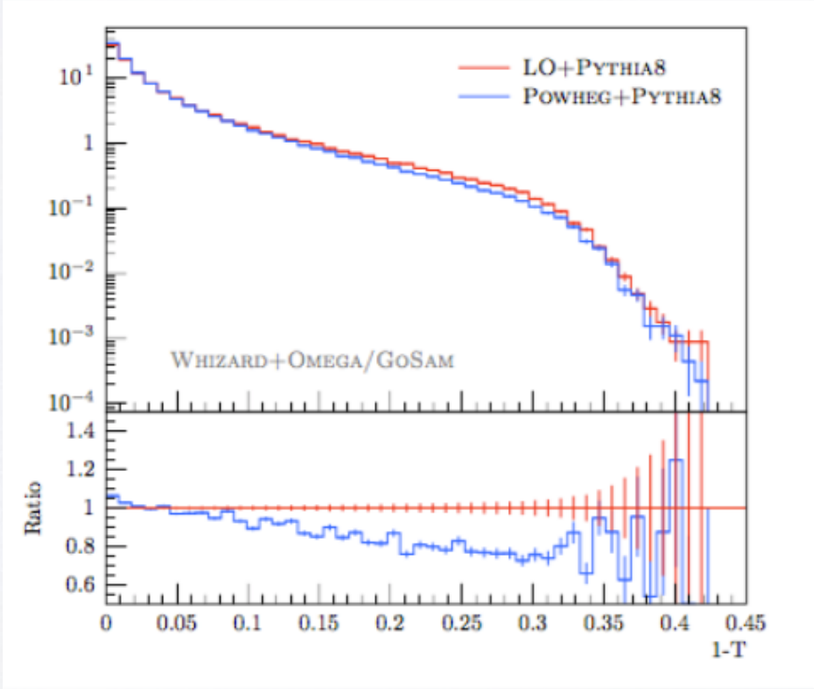
NLO QCD (massless & massive) fully supported

```
alpha_power = 2
alphas_power = 0

process eett = 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
- NLO QCD: final validation NLO EW started NEW
- Approaching WHIZARD 3.0.0α (ca. end 2019)



# Validation of NLO QCD for ee/pp Collisions

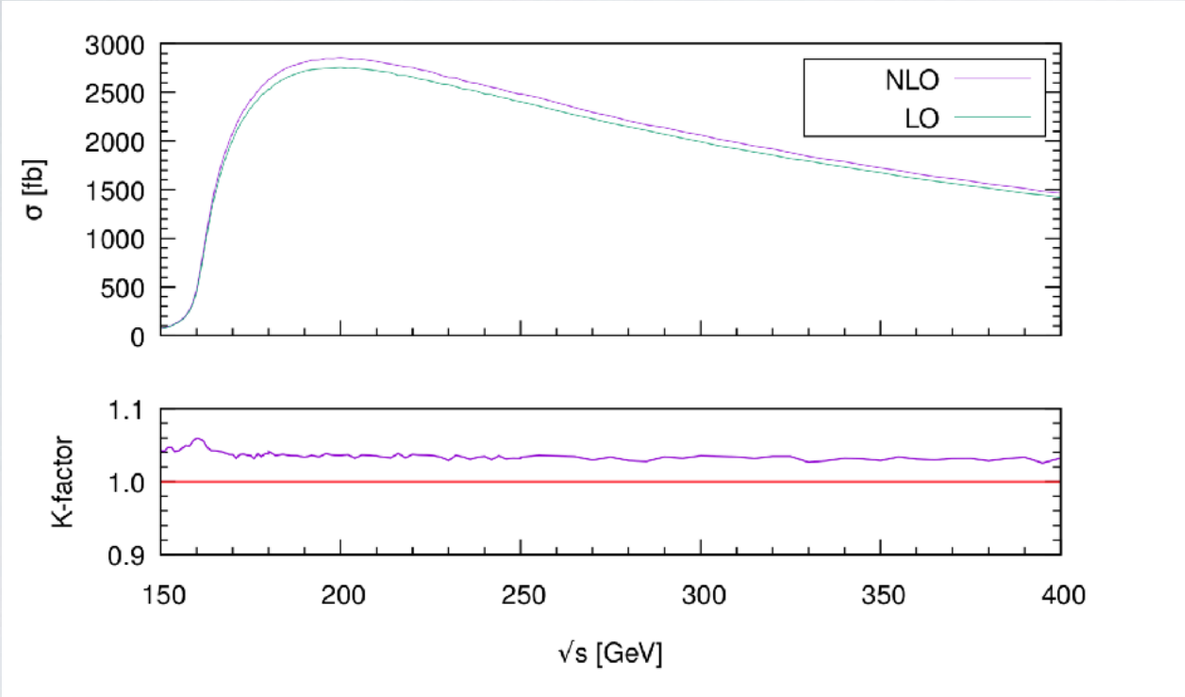
| Process | MG5_AMC $\sigma^{\mathrm{LO}}$[fb] | MG5_AMC $\sigma^{\mathrm{NLO}}$[fb] | MG5_AMC $K$ | WHIZARD $\sigma^{\mathrm{LO}}$[fb] | WHIZARD $\sigma^{\mathrm{NLO}}$[fb] | WHIZARD $K$ |
|---|---|---|---|---|---|---|
| $e^+e^- \to jj$ | 622.3(5) | 639(1) | 1.02684 | 622.73(4) | 639.7(2) | 1.02725 |
| $e^+e^- \to jjj$ | 340.1(2) | 317.3(8) | 0.93297 | 342.4(5) | 318.6(7) | 0.9305 |
| $e^+e^- \to jjjj$ | 104.7(1) | 103.5(2) | 0.98854 | 105.1(4) | 104.4(6) | 0.99335 |
| $e^+e^- \to jjjjj$ | 22.11(6) | 24.36(35) | 1.10176 | 22.80(2) | 24.72(59) | 1.08421 |
| $e^+e^- \to b\bar{b}$ | 92.37(6) | 94.89(1) | 1.02728 | 92.32(1) | 94.78(7) | 1.02664 |
| $e^+e^- \to t\bar{t}$ | 166.2(2) | 174.5(6) | 1.04994 | 166.4(1) | 175.1(1) | 1.05228 |
| $e^+e^- \to t\bar{t}j$ | 48.13(5) | 53.43(1) | 1.11012 | 48.3(2) | 53.66(9) | 1.11098 |
| $e^+e^- \to t\bar{t}jj$ | 8.614(9) | 10.49(3) | 1.21777 | 8.612(8) | 10.46(6) | 1.21458 |
| $e^+e^- \to t\bar{t}t\bar{t}$ | $6.45(1) \cdot 10^{-4}$ | $12.21(5) \cdot 10^{-4}$ | 1.89302 | $6.463(2) \cdot 10^{-4}$ | $12.16(2) \cdot 10^{-4}$ | 1.88147 |
| $e^+e^- \to b\bar{b}b\bar{b}$ | $1.644(3) \cdot 10^{-1}$ | $3.60(1) \cdot 10^{-1}$ | 2.1897 | $1.64(2) \cdot 10^{-1}$ | $3.67(4) \cdot 10^{-1}$ | 2.2378 |
| $e^+e^- \to t\bar{t}b\bar{b}$ | $1.819(3) \cdot 10^{-1}$ | $2.92(1) \cdot 10^{-1}$ | 1.6052 | $1.86(1) \cdot 10^{-1}$ | $2.93(2) \cdot 10^{-1}$ | 1.5752 |
| $e^+e^- \to tth$ | 2.018(3) | 1.911(6) | 0.947 | 2.022(3) | 1.913(3) | 0.9461 |
| $e^+e^- \to t\bar{t}\gamma$ | 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 |
| $e^+e^- \to t\bar{t}HZ$ | $3.600(6) \cdot 10^{-2}$ | $3.58(1) \cdot 10^{-2}$ | 0.99445 | $3.596(1) \cdot 10^{-2}$ | $3.581(2) \cdot 10^{-2}$ | 0.9958 |
| $e^+e^- \to t\bar{t}\gamma Z$ | 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 |
| $e^+e^- \to t\bar{t}\gamma\gamma$ | 0.383(5) | 0.416(2) | 1.08618 | 0.382(3) | 0.420(3) | 1.09952 |
| $e^+e^- \to t\bar{t}ZZ$ | $3.788(4) \cdot 10^{-2}$ | $4.00(1) \cdot 10^{-2}$ | 1.05597 | $3.756(4) \cdot 10^{-2}$ | $4.005(2) \cdot 10^{-2}$ | 1.0663 |
| $e^+e^- \to t\bar{t}HH$ | $1.358(1) \cdot 10^{-2}$ | $1.206(3) \cdot 10^{-2}$ | 0.888 | $1.367(1) \cdot 10^{-2}$ | $1.218(1) \cdot 10^{-2}$ | 0.8909 |
| $e^+e^- \to t\bar{t}W^+W^-$ | 0.1372(3) | 0.1540(6) | 1.1225 | 0.1370(4) | 0.1538(4) | 1.12257 |
| $e^+e^- \to t\bar{t}W^\pm jj$ | $2.400(4) \cdot 10^{-4}$ | $3.72(1) \cdot 10^{-4}$ | 1.54999 | $2.41(1) \cdot 10^{-4}$ | $3.74(2) \cdot 10^{-4}$ | 1.55186 |

| Process | POWHEG $\sigma^{\mathrm{LO}}$[nb] | POWHEG $\sigma^{\mathrm{NLO}}$[nb] | POWHEG $K$ | WHIZARD $\sigma^{\mathrm{LO}}$[nb] | WHIZARD $\sigma^{\mathrm{NLO}}$[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 |
| $pp \to jj$ | $397.3(1.5) \cdot 10^4$ | $639.0(1.3) \cdot 10^4$ | 1.60835 | $401.2(0.9) \cdot 10^4$ | $3656(150) \cdot 10^4$ | 9.11266 |

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

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

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



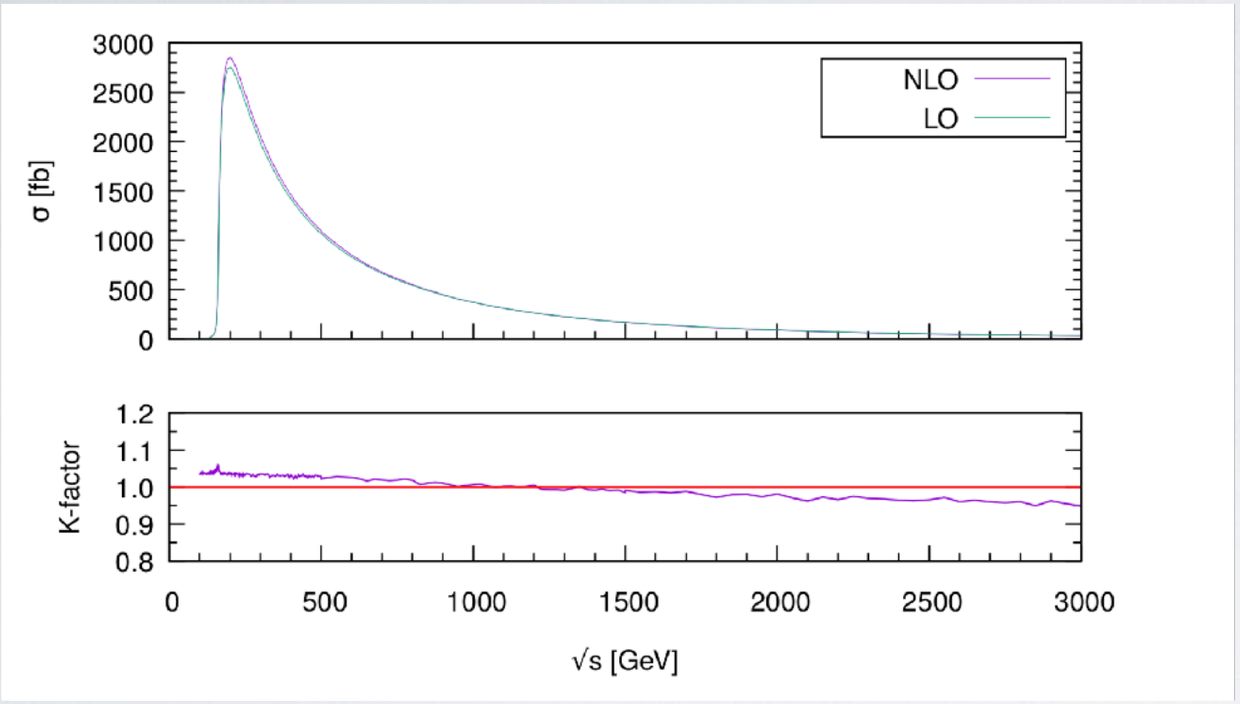

| $\sqrt{s}$ | $\sigma_{LO}$[pb] | $\sigma_{NLO}$[pb] | *K-factor* |
|---|---|---|---|
| 160 | 0.4446 | $0.4711^{+0.36\%}_{-0.62\%}$ | $1.060^{+0.28\%}_{-0.66\%}$ |
| 200 | 2.755 | $2.854^{+0.21\%}_{-0.81\%}$ | $1.036^{+0.19\%}_{-0.77\%}$ |
| 250 | 2.405 | $2.481^{+0.64\%}_{-0.12\%}$ | $1.032^{+0.58\%}_{-0.19\%}$ |
| 500 | 1.070 | $1.101^{+0.45\%}_{-0.73\%}$ | $1.028^{+0.58\%}_{-0.69\%}$ |
| 1000 | 0.3710 | $0.3734^{+0.00\%}_{-0.73\%}$ | $1.006^{+0.00\%}_{-0.70\%}$ |
| 1500 | 0.1694 | $0.1670^{+0.47\%}_{-0.05\%}$ | $0.9860^{+0.50\%}_{-0.10\%}$ |

K factor mostly $\frac{\alpha_s}{\pi}$

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

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

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



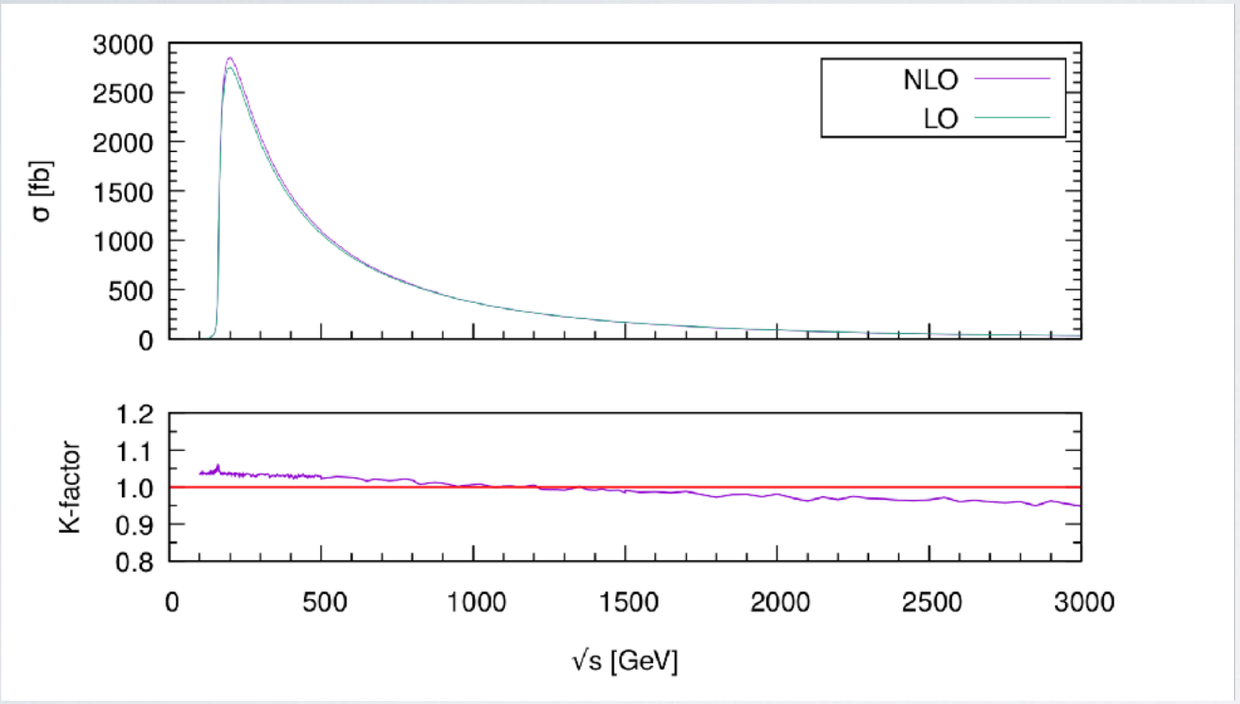

| $\sqrt{s}$ | $\sigma_{LO}$[pb] | $\sigma_{NLO}$[pb] | *K-factor* |
|---|---|---|---|
| 160 | 0.4446 | $0.4711^{+0.36\%}_{-0.62\%}$ | $1.060^{+0.28\%}_{-0.66\%}$ |
| 200 | 2.755 | $2.854^{+0.21\%}_{-0.81\%}$ | $1.036^{+0.19\%}_{-0.77\%}$ |
| 250 | 2.405 | $2.481^{+0.64\%}_{-0.12\%}$ | $1.032^{+0.58\%}_{-0.19\%}$ |
| 500 | 1.070 | $1.101^{+0.45\%}_{-0.73\%}$ | $1.028^{+0.58\%}_{-0.69\%}$ |
| 1000 | 0.3710 | $0.3734^{+0.00\%}_{-0.73\%}$ | $1.006^{+0.00\%}_{-0.70\%}$ |
| 1500 | 0.1694 | $0.1670^{+0.47\%}_{-0.05\%}$ | $0.9860^{+0.50\%}_{-0.10\%}$ |

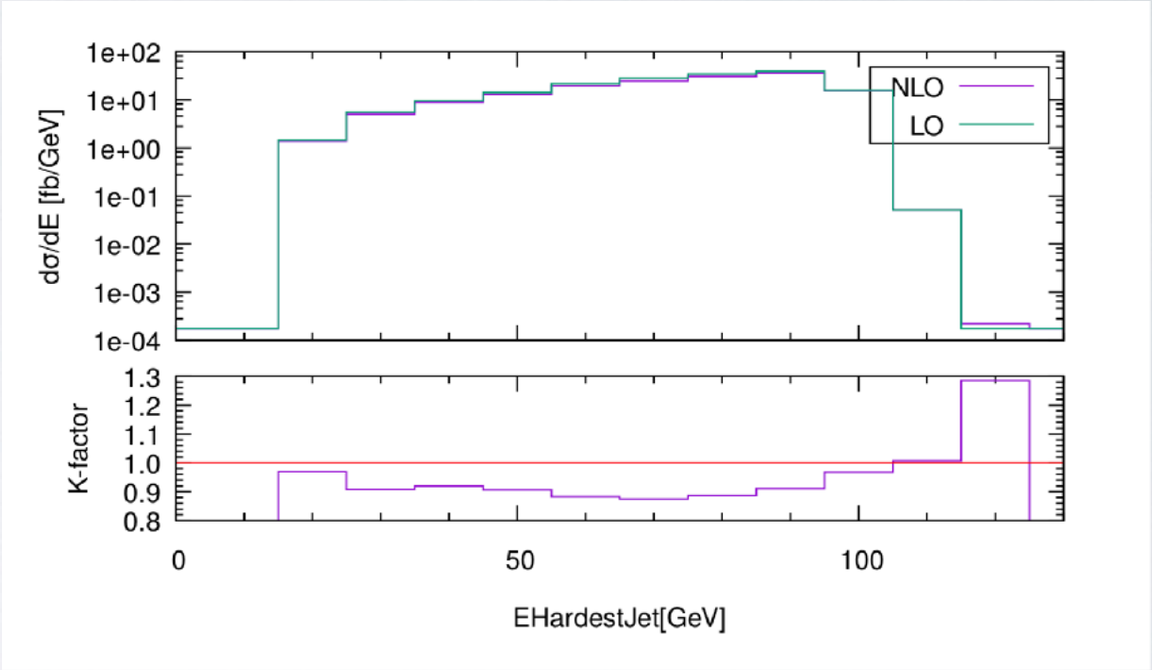
K factor mostly $\frac{\alpha_s}{\pi}$

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

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

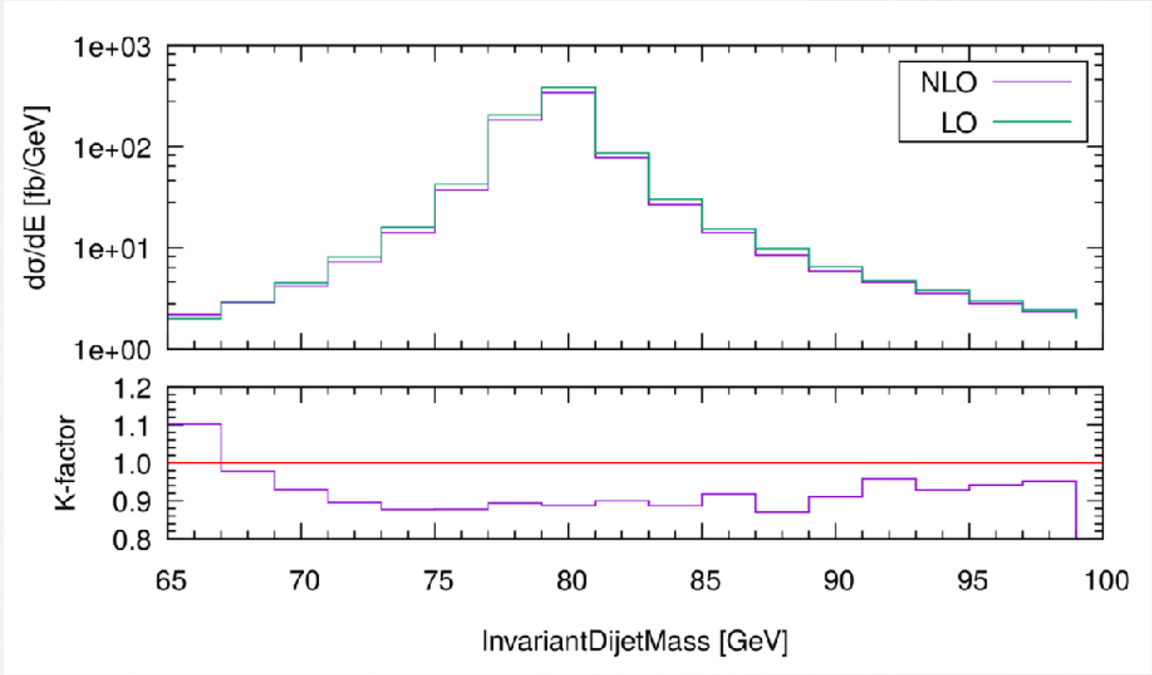
$e^+e^- \to \mu\nu jj$



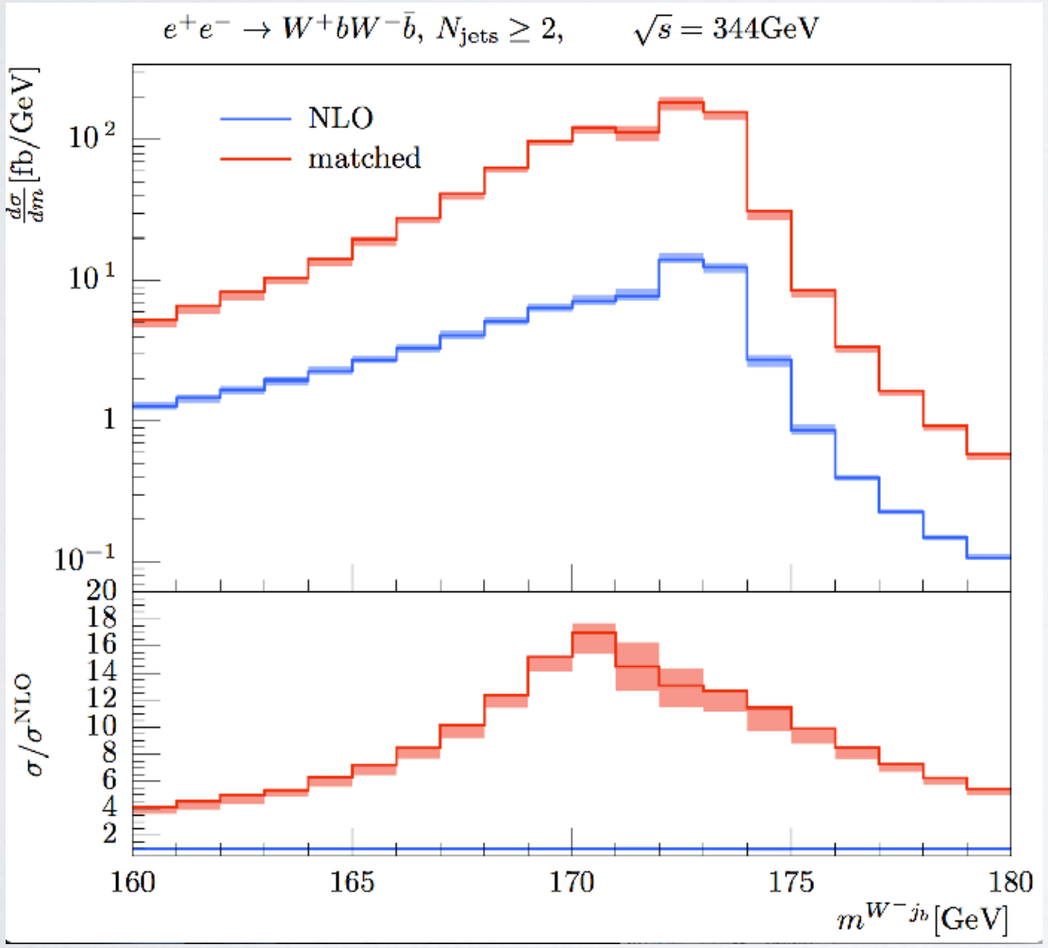

| $\sqrt{s}$ | $\sigma_{LO}$[pb] | $\sigma_{NLO}$[pb] | *K-factor* |
|---|---|---|---|
| 160 | 0.4446 | $0.4711^{+0.36\%}_{-0.62\%}$ | $1.060^{+0.28\%}_{-0.66\%}$ |
| 200 | 2.755 | $2.854^{+0.21\%}_{-0.81\%}$ | $1.036^{+0.19\%}_{-0.77\%}$ |
| 250 | 2.405 | $2.481^{+0.64\%}_{-0.12\%}$ | $1.032^{+0.58\%}_{-0.19\%}$ |
| 500 | 1.070 | $1.101^{+0.45\%}_{-0.73\%}$ | $1.028^{+0.58\%}_{-0.69\%}$ |
| 1000 | 0.3710 | $0.3734^{+0.00\%}_{-0.73\%}$ | $1.006^{+0.00\%}_{-0.70\%}$ |
| 1500 | 0.1694 | $0.1670^{+0.47\%}_{-0.05\%}$ | $0.9860^{+0.50\%}_{-0.10\%}$ |

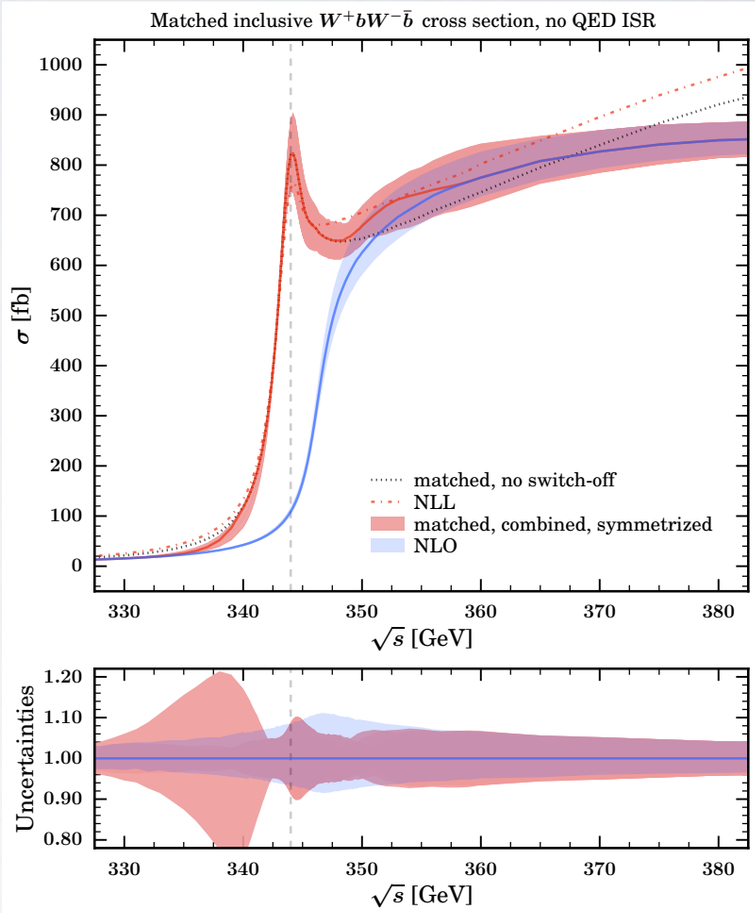
K factor mostly $\frac{\alpha_s}{\pi}$



# 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

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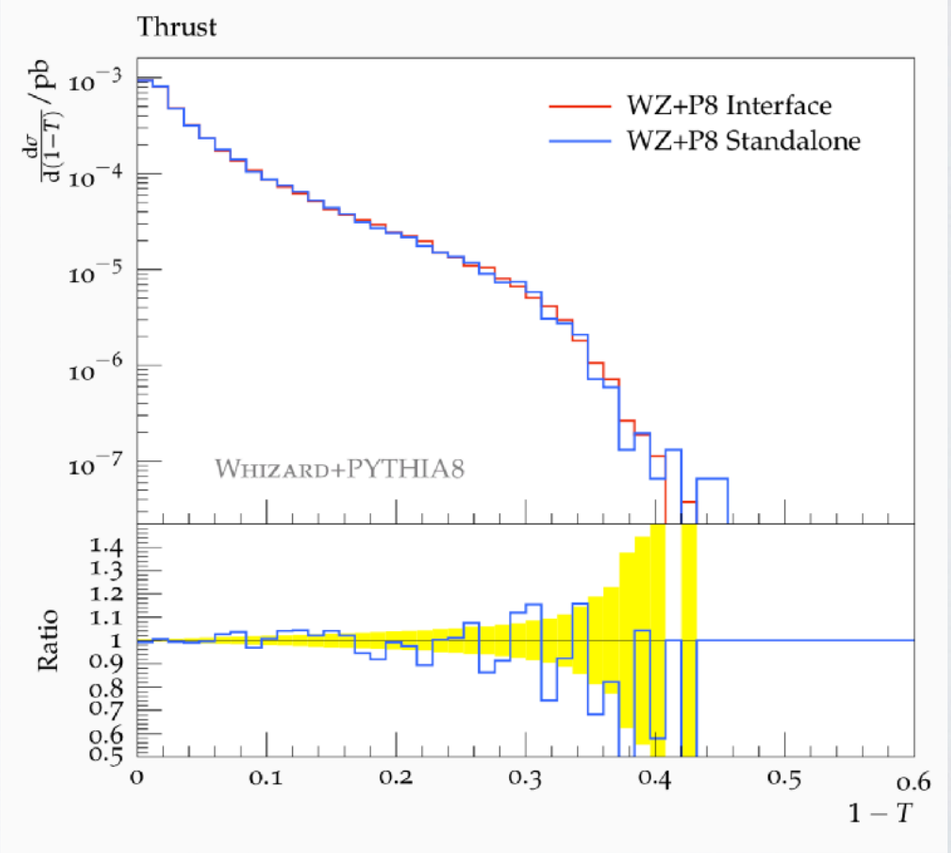
```
| ==================================================================
| Running self-test: whizard_lha
| ------------------------------------------------------------------
Running test: whizard_lha_1
 --------  LHA initialization information  ------------

  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

 --------  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 = "<afs/.../...>"
```

```
./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 2.7.1` event generator for collider physics (ee, pp, ep)
- High-multiplicity SM hard processes (2→10 etc.)
- Allows to simulate all possible BSM models
- Strong focus on $e^+e^-$ physics: beam spectra, $e^+e^-$ ISR, LCIO, polarizations
- NLO QCD (almost) done → `WHIZARD 3.0.0α` [EW validation started]
- NEW:
  - ☑ UFO models: *[general Lorentz structures* `WHIZARD 2.8.0`*]*
  - ☑ MPI parallel integration
  - ☑ Possibility to pre-set branching ratios for factorized processes
  - ☑ Resonance matching to parton shower
  - ☑ Fully integrated `PYTHIA8` interface
  - ☑ Batch mode / gridpack functionality
  - ☑ Dedicated work on *WW* threshold (match NLO + NLL)

    w/ C. Schwinn

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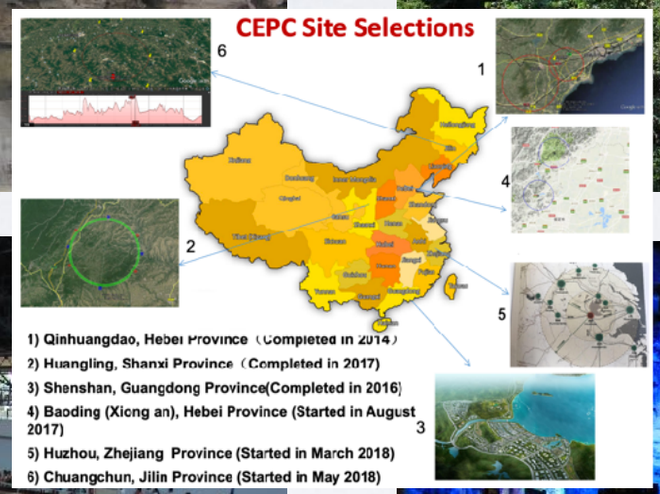
    w/ C. Schwinn

WHIZARD STRATEGY

**WE'RE HAPPY TO ACCOMODATE SPECIFIC DEMANDS OF THE CEPC COMMUNITY**

# Looking forward to CEPC




# BACKUP

# Decay processes / auto decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

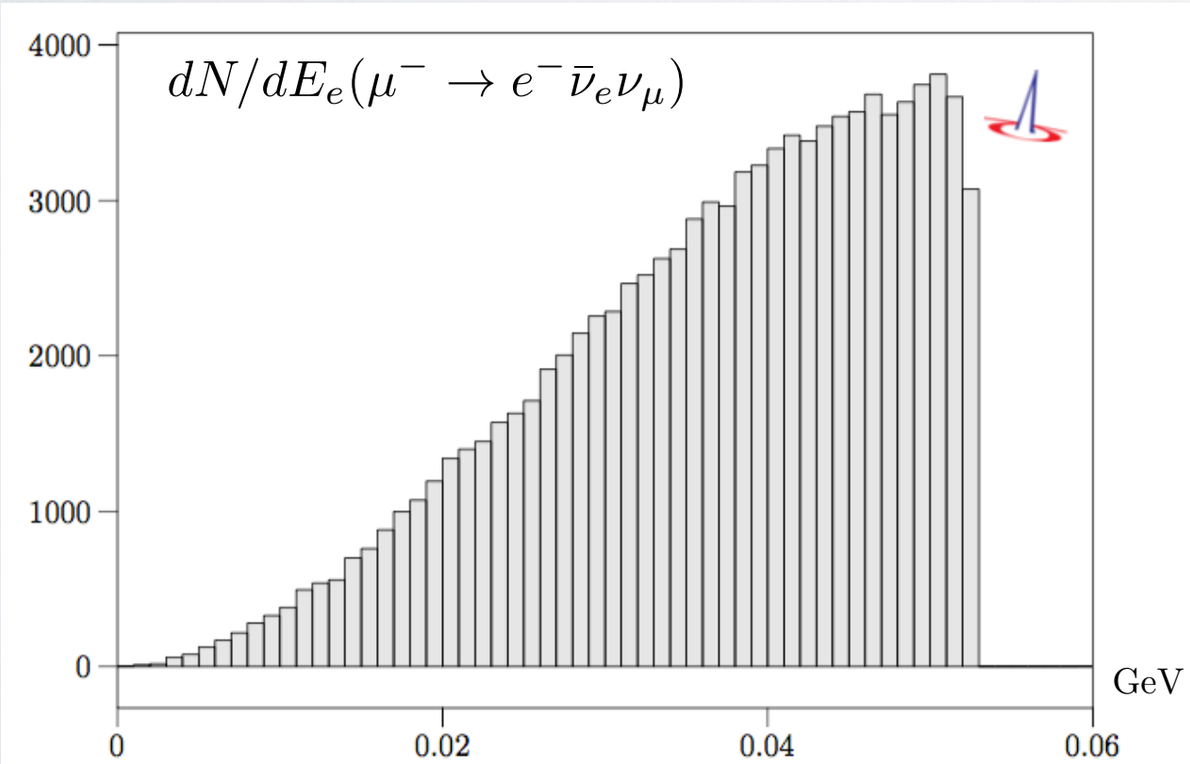
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

histogram e_e1 (0, 60 MeV, 1 MeV)
analysis = record e_e1 (eval E [e1])

n_events = 100000

simulate (mudec)

compile_analysis { $out_file = "test.dat" }
```



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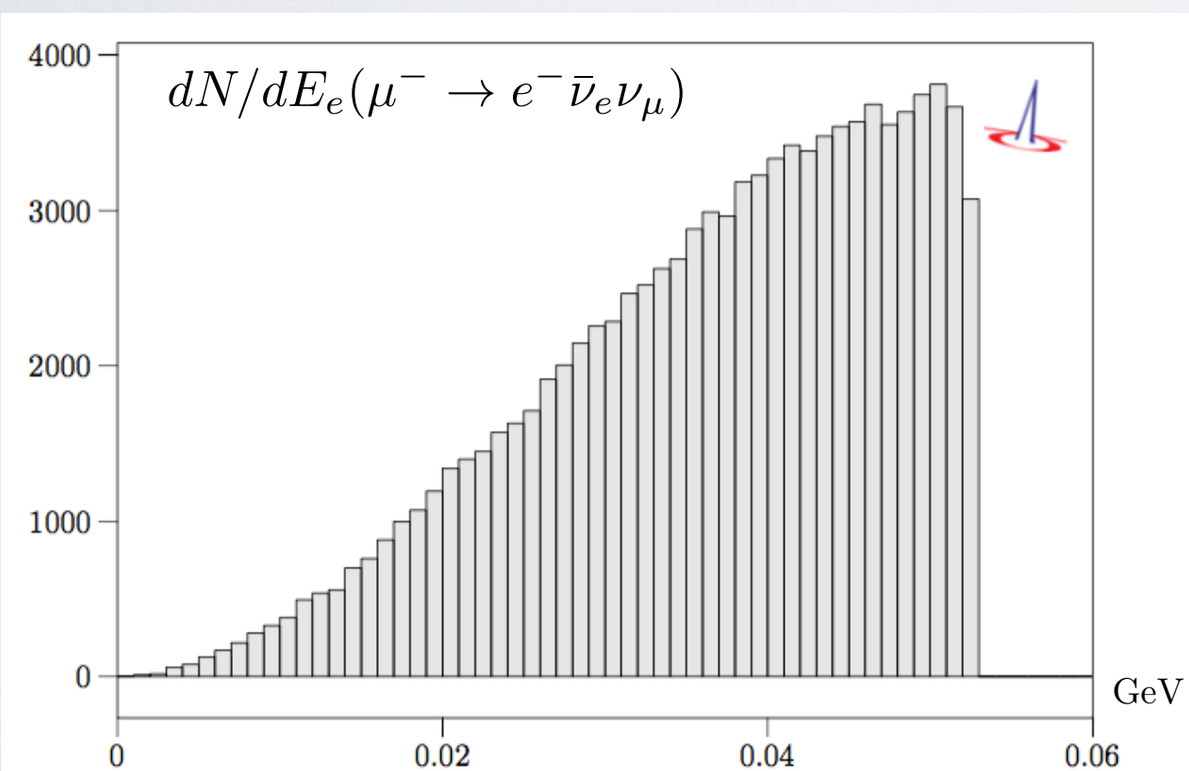



## Automatic integration of particle decays

```
auto_decays_multiplicity = 2
?auto_decays_radiative = false

unstable Wp () { ?auto_decays = true }
```

```
|=================================================================
| It      Calls  Integral[GeV] Error[GeV]  Err[%]    Acc  Eff[%]
|=================================================================
  1       100  2.2756406E-01  0.00E+00    0.00    0.00* 100.00
|-----------------------------------------------------------------
  1       100  2.2756406E-01  0.00E+00    0.00    0.00  100.00
|=================================================================
| Unstable particle W+: computed branching ratios:
|   decay_p24_1: 3.3337068E-01   dbar, u
|   decay_p24_2: 3.3325864E-01   sbar, c
|   decay_p24_3: 1.1112356E-01   e+, nue
|   decay_p24_4: 1.1112356E-01   mu+, numu
|   decay_p24_5: 1.1112356E-01   tau+, nutau
|   Total width = 2.0478471E+00 GeV (computed)
|               = 2.0490000E+00 GeV (preset)
|   Decay options: helicity treated exactly
```

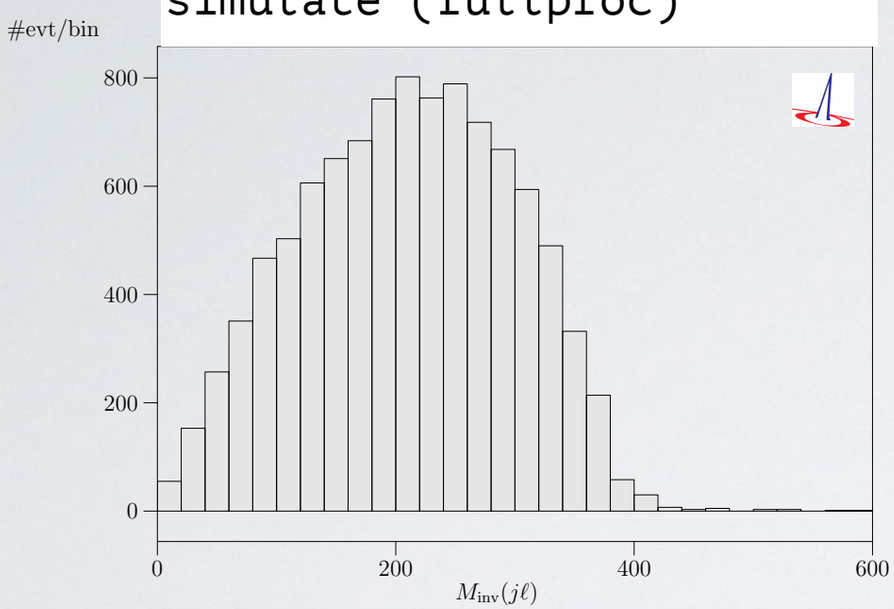
## Preset branching ratios possible:

```
integral (br_hZA_redef) = 200 keV
```

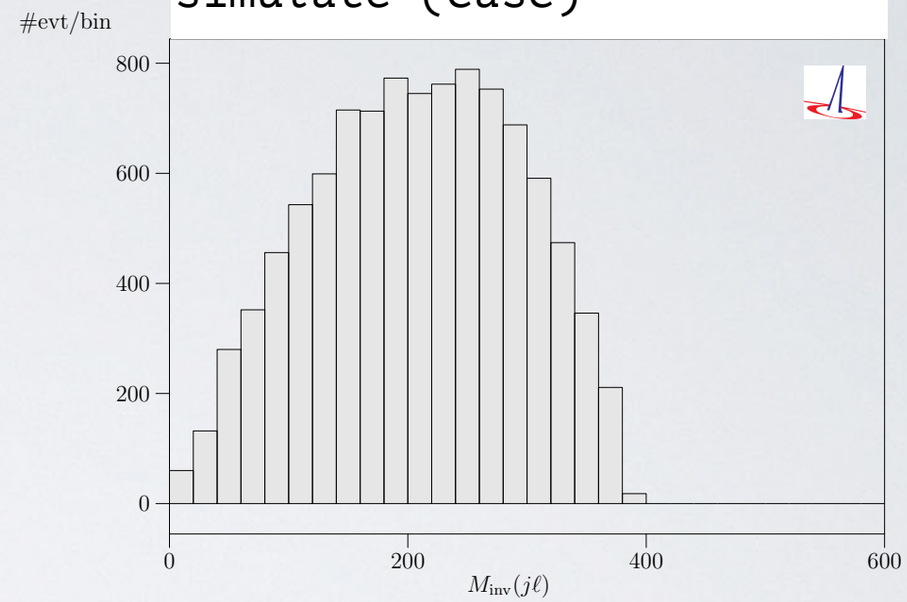
# Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay $p + p \to \tilde{u}^* + \tilde{u} \to \tilde{u}^* + u + \tilde{e}^+ + e^-$

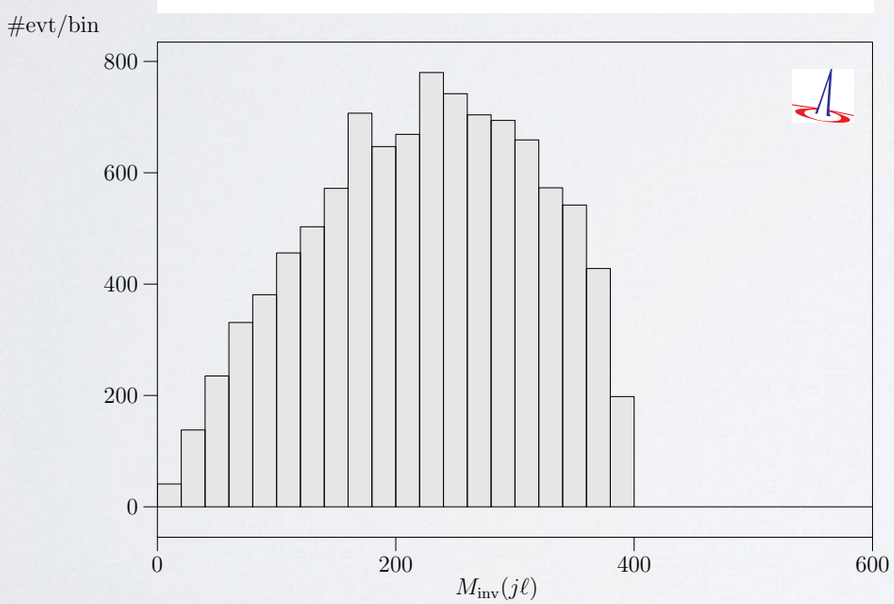
```
simulate (fullproc)
```



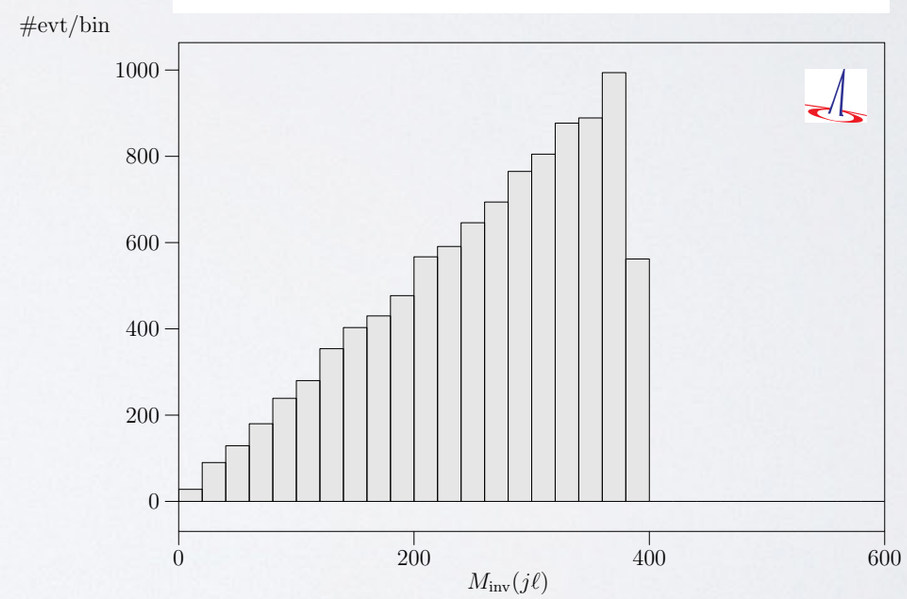

```
simulate (casc)
```




```
?diagonal_decay = true
```




```
?isotropic_decay = true
```

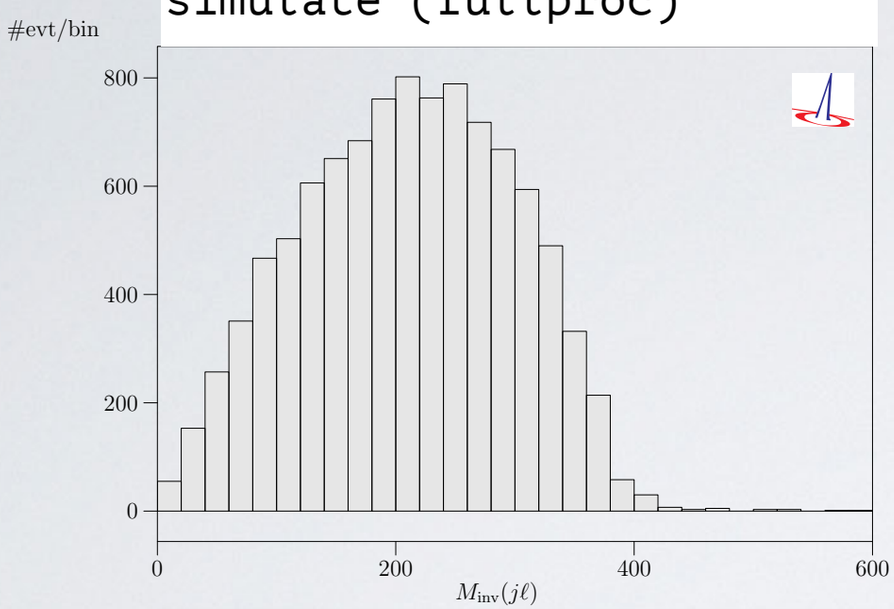


# Spin Correlation and Polarization in Cascades

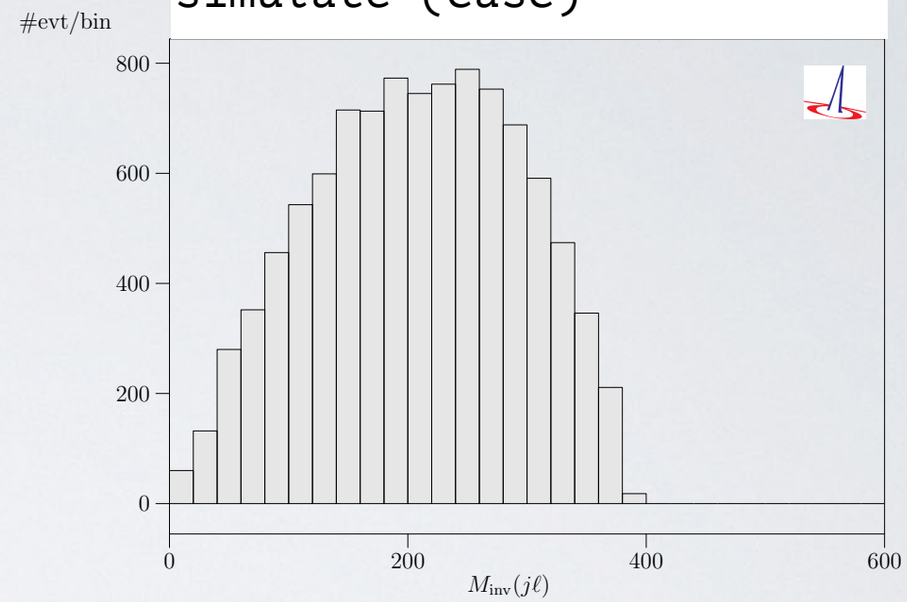
Cascade decay, factorize production and decay

$$p + p \to \tilde{u}^* + \tilde{u} \to \tilde{u}^* + u + \tilde{e}^+ + e^-$$

```
simulate (fullproc)
```




```
simulate (casc)
```

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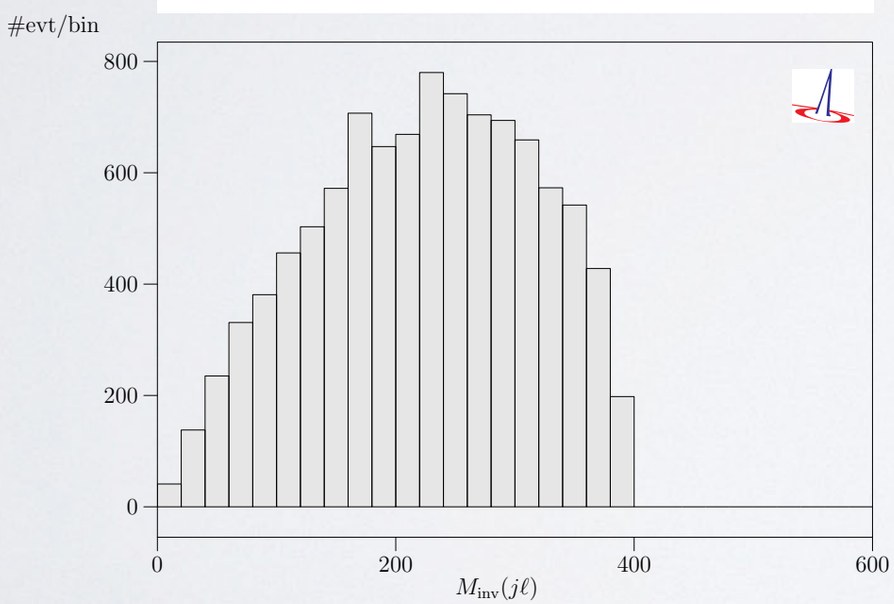


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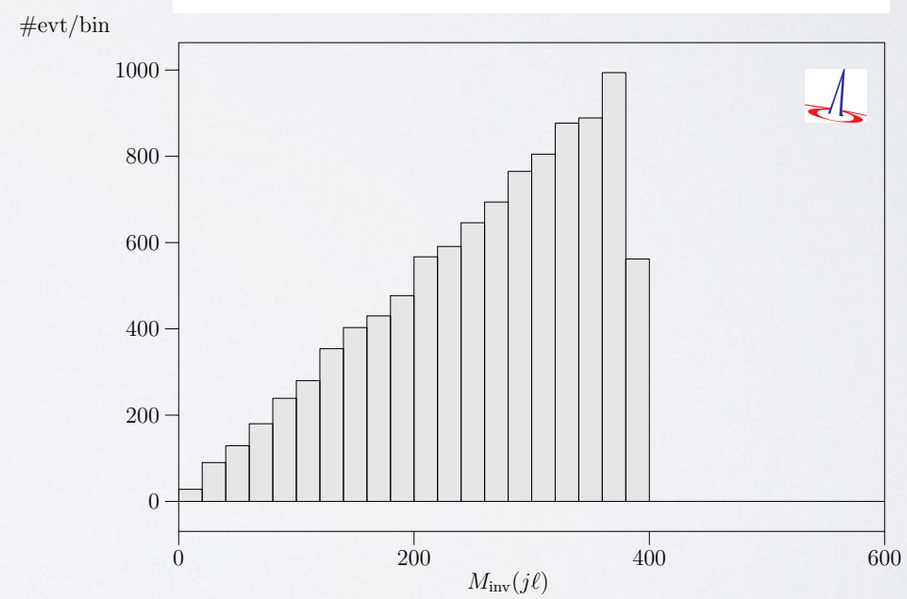


Possibility to select specific helicity in decays!

```
unstable "W+" { decay_helicity = 0 }
```

# Workflow GuineaPig/CIRCE2/WHIZARD

1. Run Guinea-Pig++ with

```
do_lumi=7;num_lumi=100000000;num_lumi_eg=100000000;num_lumi_gg=100000000;
```

to produce lumi.[eg][eg].out with $(E_1, E_2)$ pairs.

[Large event numbers, as Guinea-Pig++ will produce only a small fraction!]

2. Run circe2_tool.opt with steering file

```
{ file="ilc500/beams.circe"                          # to be loaded by WHIZARD
  { design="ILC" roots=500 bins=100 scale=250 # E in [0,1]
    { pid/1=electron pid/2=positron pol=0      # unpolarized e-/e+
      events="ilc500/lumi.ee.out" columns=2    # <= Guinea-Pig
      lumi = 1564.763360                       # <= Guinea-Pig
      iterations = 10                          # adapting bins
      smooth = 5 [0,1) [0,1)                   # Gaussian filter 5 bins
      smooth = 5 [1] [0,1) smooth = 5 [0,1) [1] } } }
```

to produce correlated beam description

3. Run WHIZARD with SINDARIN input:

```
beams = e1, E1 => circe2
$circe2_file = "ilc500.circe"
$circe2_design = "ILC"
?circe_polarized = false
```

3 simulation options

1. Unpolarized simulation with unpol. spectra
2. Pol. simulation: unpol. spectra + pol. beams
3. Polarized spectrum with helicity luminosities

# Beam structure: special beams

## Beam polarization, ILC-like setup

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

## Polarized decays: longitudinal Z

```
process zee = Z => e1, E1
beams = Z
beams_pol_density = @(0)
```

## Scan over polarizations

```
scan int h1 = (-1,1) {
  scan int h2 = (-1,1) {
    beams_pol_density = @(h1), @(h2)
    integrate (proc)
  }
}
```

## Asymmetric beams

```
beams = e1, E1
beams_momentum = 100 GeV, 900 GeV
```

## Beams with crossing angle

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

## Beams with rotated crossing angle

```
beams_momentum = 250 GeV, 250 GeV
beams_theta = 0, 10 degree
beams_phi   = 0, 45 degree
```

## Structure functions (also concatenated)

```
beams = p, p => pdf_builtin
$pdf_builtin_set = “mmht2014lo”
```

```
beams = p, pbar => lhapdf
```

```
beams = e, p => none, pdf_builtin
```

```
beams = e1, E1 => circe1
$circe1_acc = “TESLA”
?circe1_generate = false
circe1_mapping_slope = 2
```

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

```
beams = e1, E1 => beam_events
$beam_events_file = “uniform_spread_2.5%.dat”
```

# Beam structure: beam polarization



## Beam polarization

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

| Spin $j$ | Particle type | possible $m$ values |
|---|---|---|
| 0 | Scalar boson | 0 |
| 1/2 | Spinor | +1, -1 |
| 1 | (Massive) Vector boson | +1, (0), -1 |
| 3/2 | (Massive) Vectorspinor | +2, (+1), (-1), -2 |
| 2 | (Massive) Tensor | +2, (+1), (0), (-1), -2 |

## Different density matrices

$|m| = 2$ massless

$|m| = 2j + 1$ massive

```
beams_pol_density = @()
```

Unpolarized beams

$$\rho = \frac{1}{|m|}\mathbb{I}$$

```
beams_pol_density = @(±j)
beams_pol_fraction = f
```

Circular polarization

$$\rho = \mathrm{diag}\left(\frac{1 \pm f}{2}\,,\,0\,,\,\ldots\,,\,0\,,\frac{1 \mp f}{2}\right)$$

```
beams_pol_density = @(0)
beams_pol_fraction = f
```

Longitudinal polarization (massive)

$$\rho = \mathrm{diag}\left(\frac{1-f}{|m|}\,,\,\ldots\,,\,\frac{1-f}{|m|}\,,\,\frac{1+f\,(|m|-1)}{|m|}\,,\,\frac{1-f}{|m|}\,,\,\ldots\,,\,\frac{1-f}{|m|}\right)$$

```
beams_pol_density = @(j, -j, j:-j:exp(-I*phi))
beams_pol_fraction = f
```

Transversal polarization (along an axis)

$$\rho = \begin{pmatrix} 1 & 0 & \cdots & \cdots & \frac{f}{2}\,e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ \frac{f}{2}\,e^{i\phi} & \cdots & \cdots & 0 & 1 \end{pmatrix}$$

```
beams_pol_density = @(j:j:1-cos(theta),
          j:-j:sin(theta)*exp(-I*phi), -j:-j:1+cos(theta))
beams_pol_fraction = f
```

Polarization along arbitrary axis (θ,Φ)

$$\rho = \frac{1}{2}\cdot\begin{pmatrix} 1-f\cos\theta & 0 & \cdots & \cdots & f\sin\theta\,e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ f\sin\theta\,e^{i\phi} & \cdots & \cdots & 0 & 1+f\cos\theta \end{pmatrix}$$

```
beams_pol_density = @(j:j:h_j, j-1:j-1:h_{j-1}, ..., -j:-j:h_{-j})
```

```
beams_pol_density = @({m:m':x_{m,m'}})
```

Diagonal / arbitrary density matrices

# 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
- Most important for narrow resonances ($H \to bb$)
- Separate treatment of Born and real terms,

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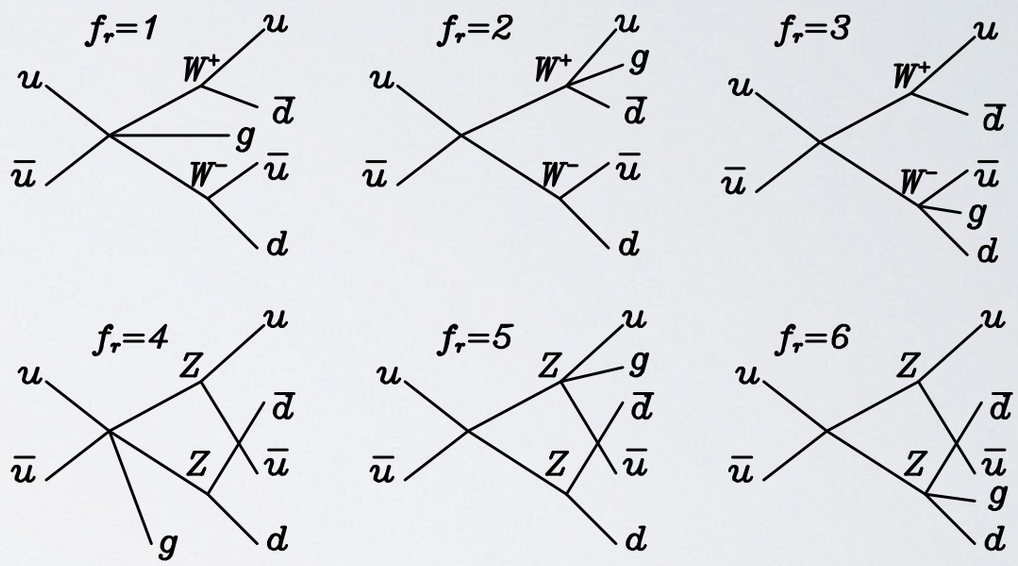


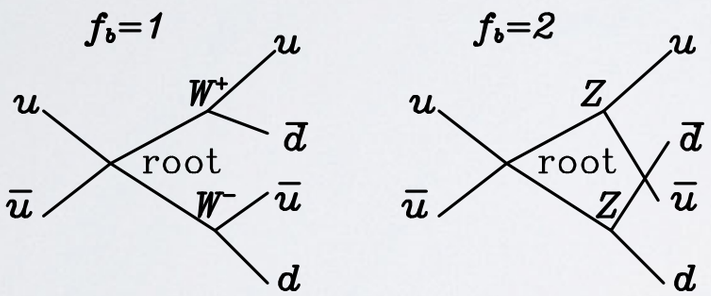

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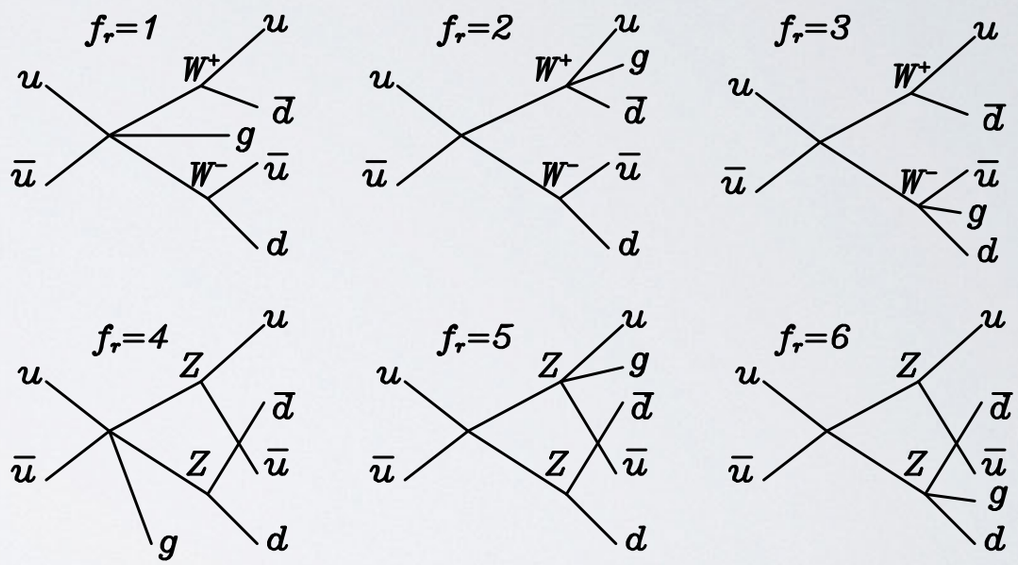
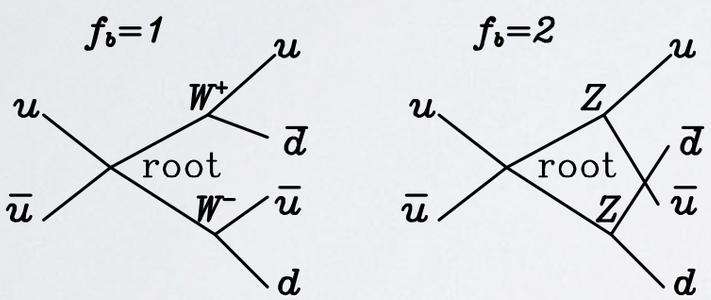



- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ ($ZZ$, $ZH$ histories)

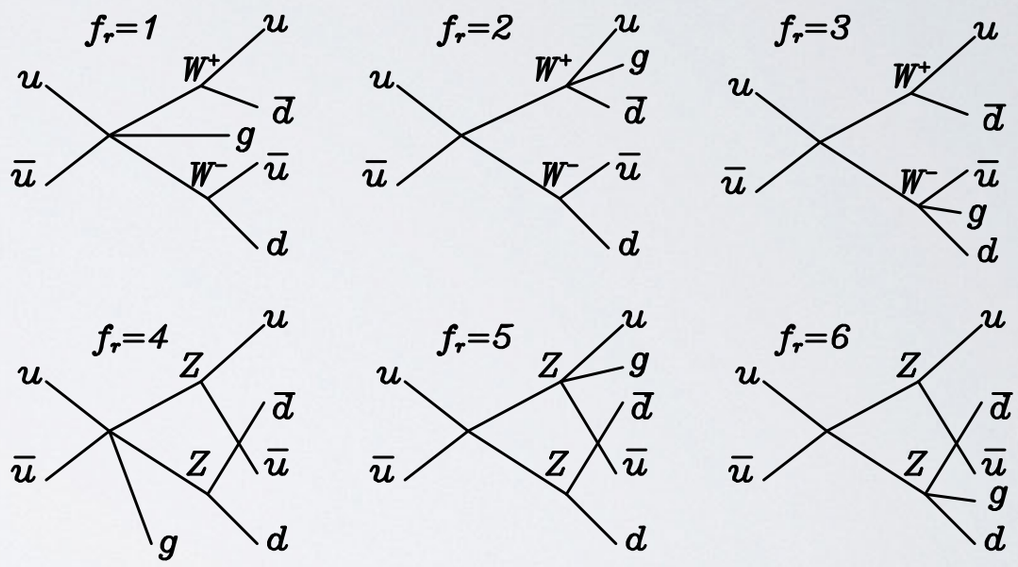
| It | Calls | Integral[fb] | Error[fb] | Err[%] | Acc | Eff[%] | Chi2 | N[It] |
|---|---|---|---|---|---|---|---|---|
| 1 | 11988 | 9.6811847E+00 | 6.42E+00 | 66.30 | 72.60* | 0.65 | | |
| 2 | 11959 | 2.8539703E+00 | 2.35E-01 | 8.25 | 9.02* | 0.69 | | |
| 3 | 11936 | 2.4907574E+00 | 6.54E-01 | 26.25 | 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 |

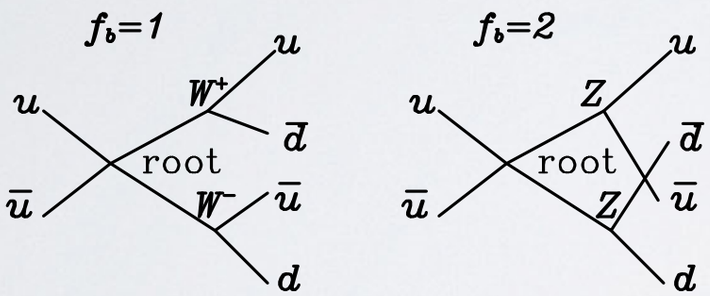
standard FKS

# 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
- Most important for narrow resonances ($H \to bb$)
- Separate treatment of Born and real terms,
  soft mismatch [, collinear mismatch]

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| 2 | 11959 | 2.8539703E+00 | 2.35E-01 | 8.25 | 9.02* | 0.69 | | |
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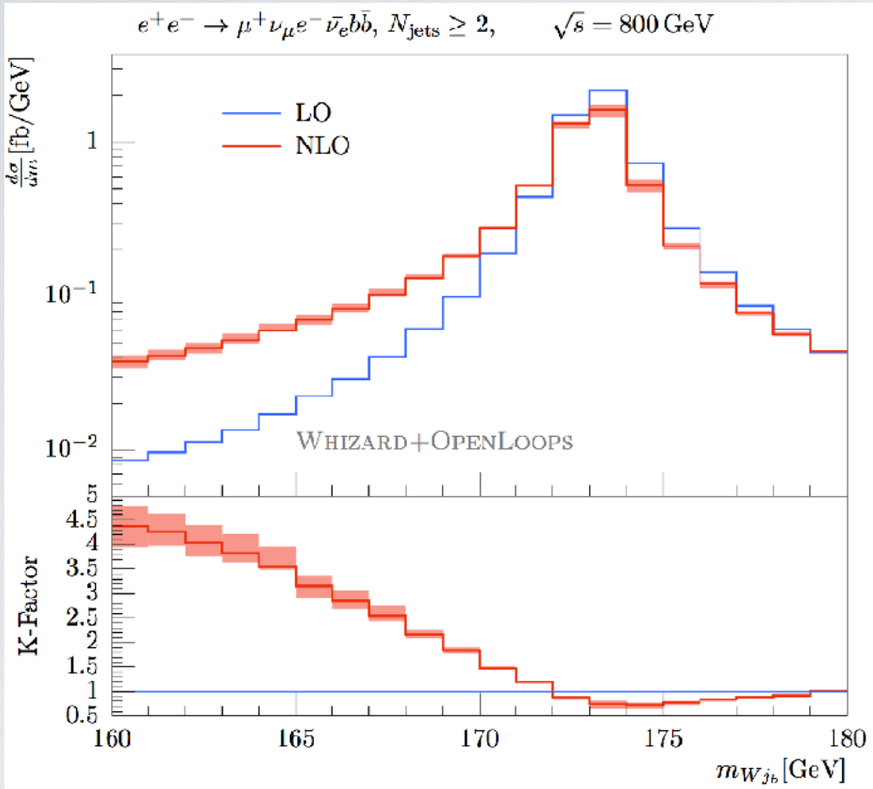
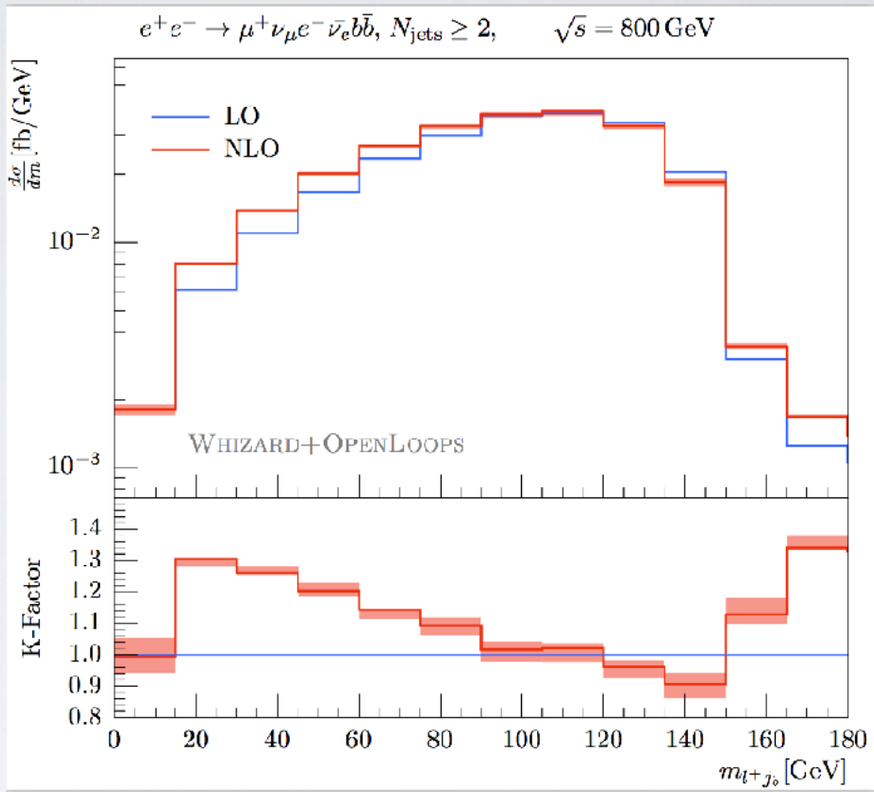
standard FKS

| 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 |

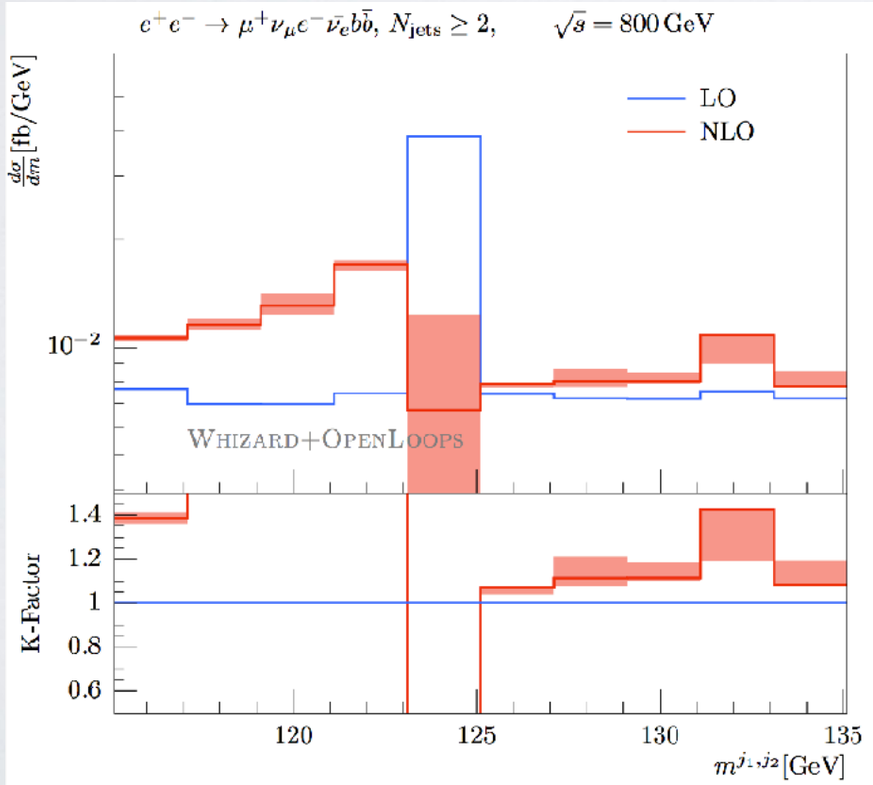
FKS with resonance mappings

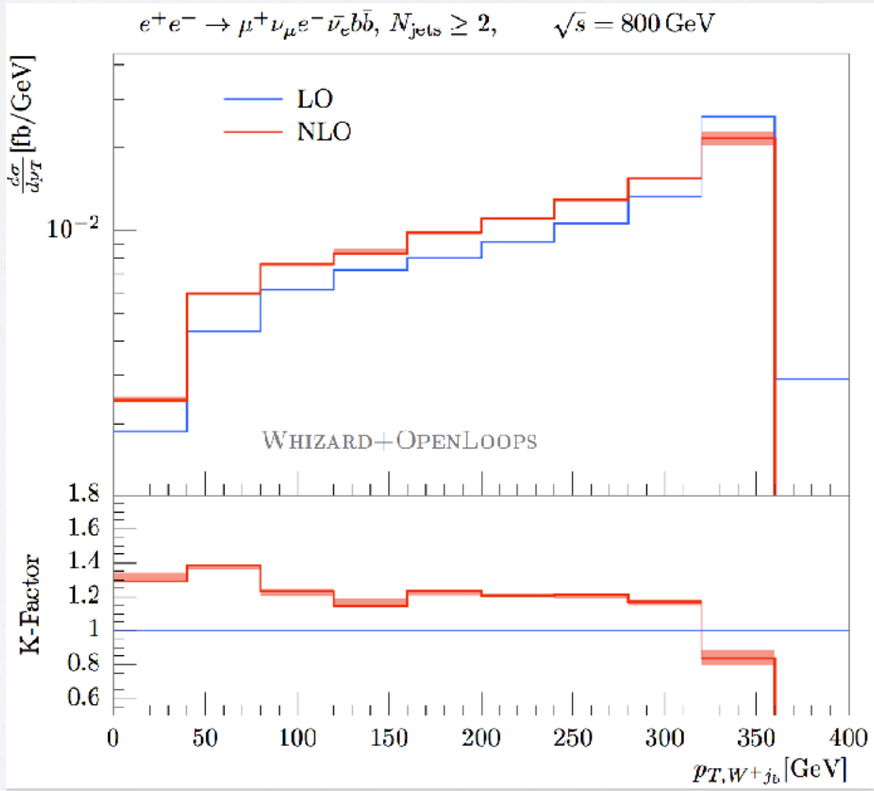
# Differential Results for off-shell $e^+e^- \to tt$



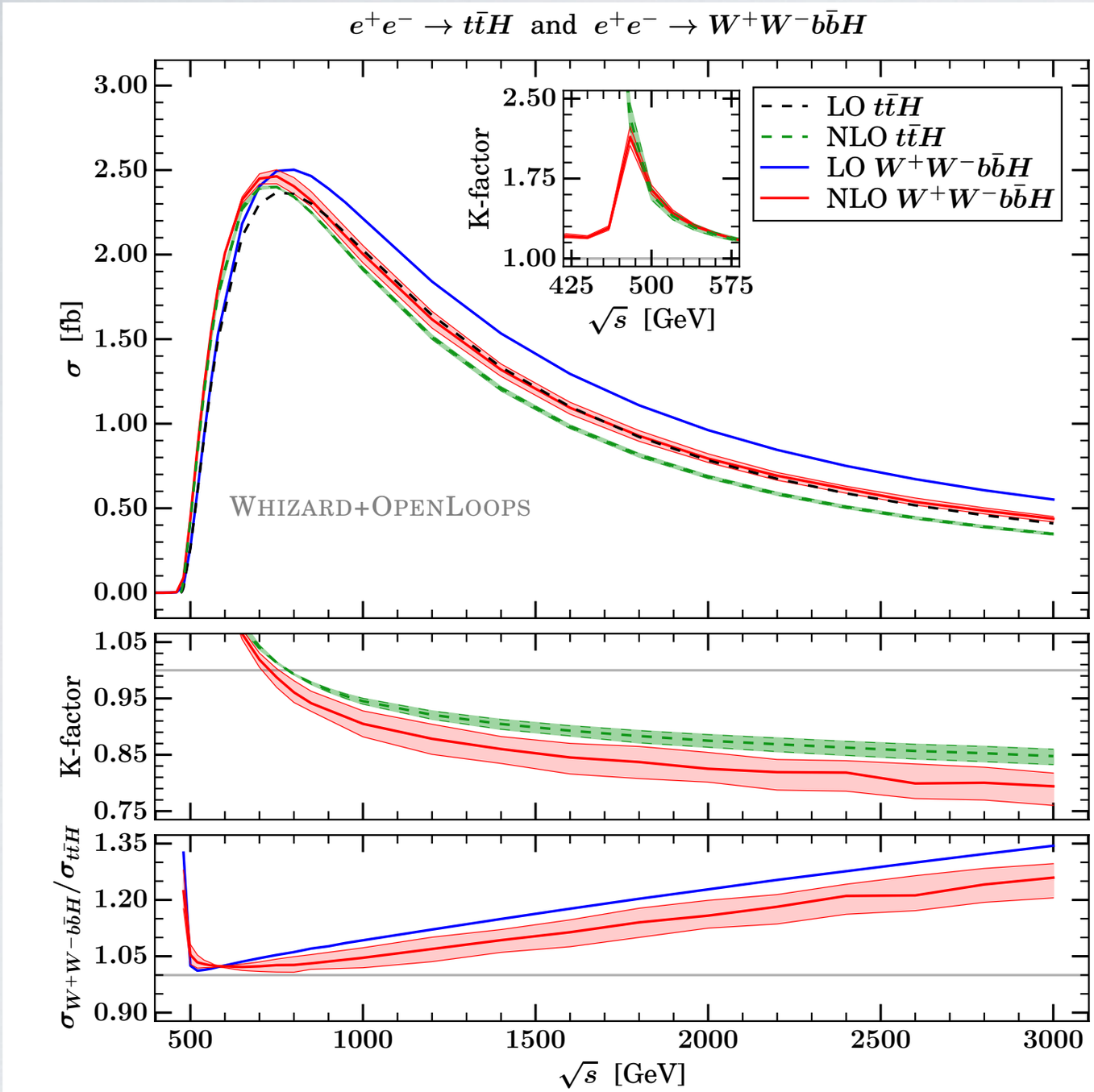



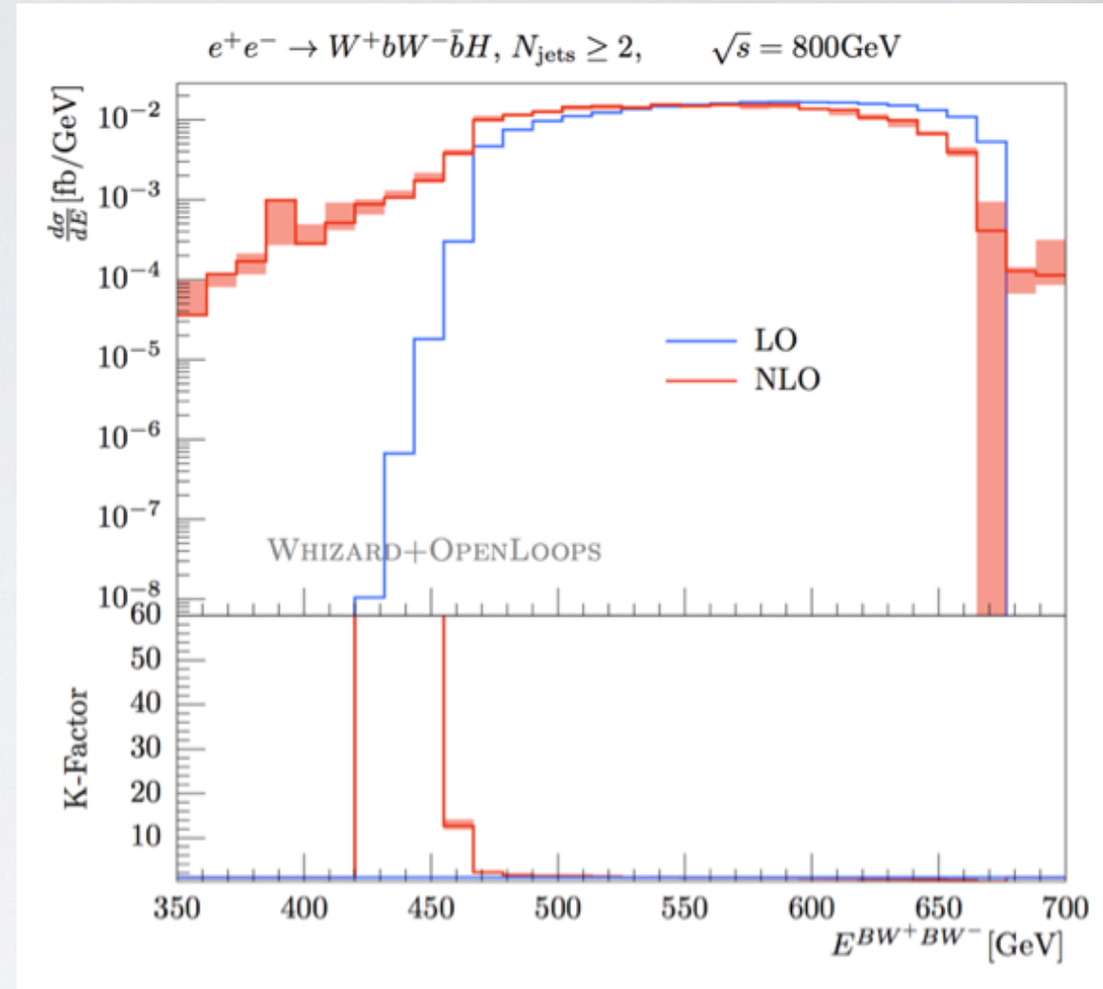

$$m_t^2 = m_W^2 + \frac{2\langle m_{\ell j_b}^2 \rangle}{1 - \langle \cos\theta_{\ell j_b} \rangle}$$



# 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] | $\sigma^{\text{LO}}$[fb] | $\sigma^{\text{NLO}}$[fb] | K-factor | $\sigma^{\text{LO}}$[fb] | $\sigma^{\text{NLO}}$[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

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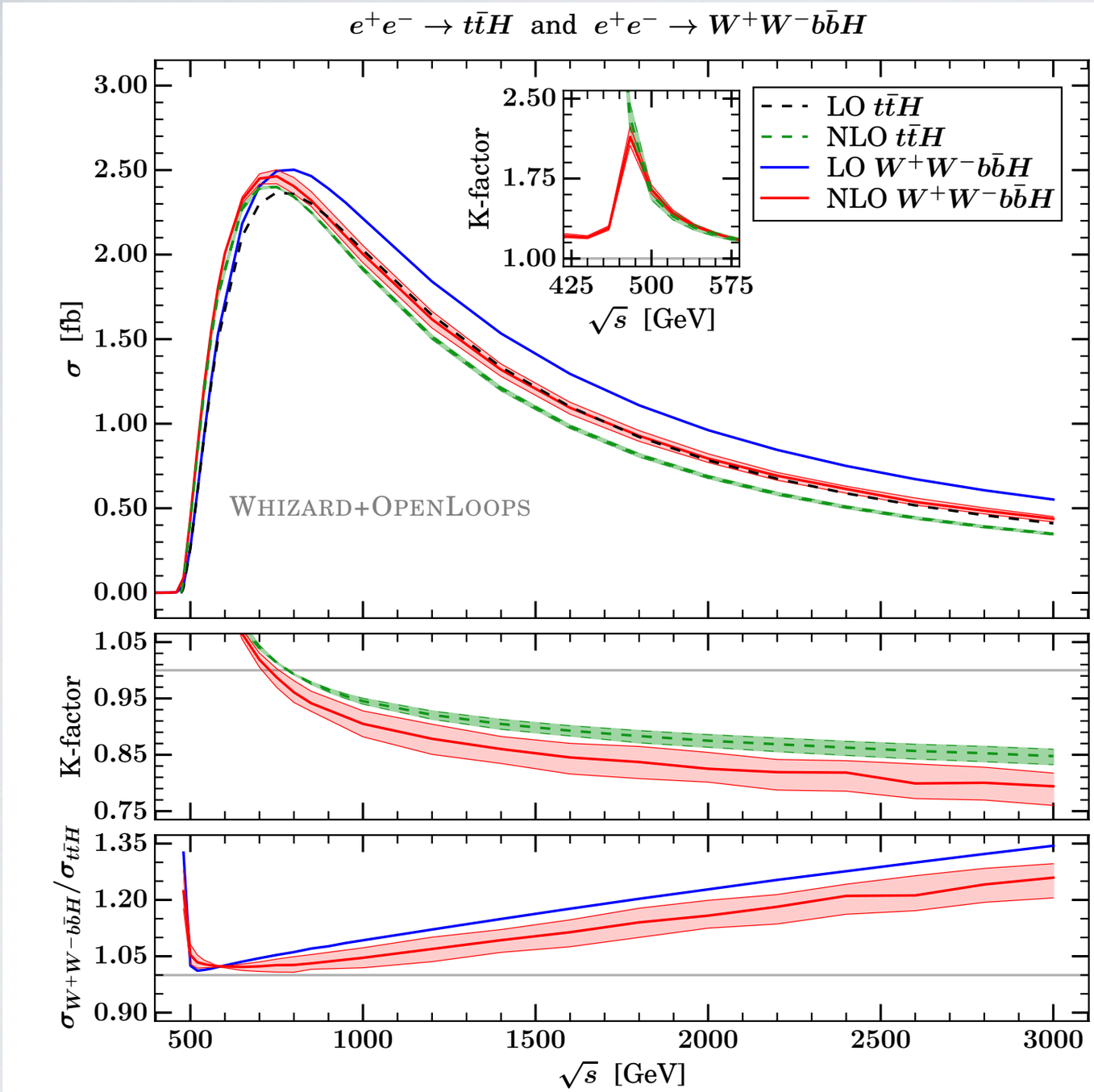


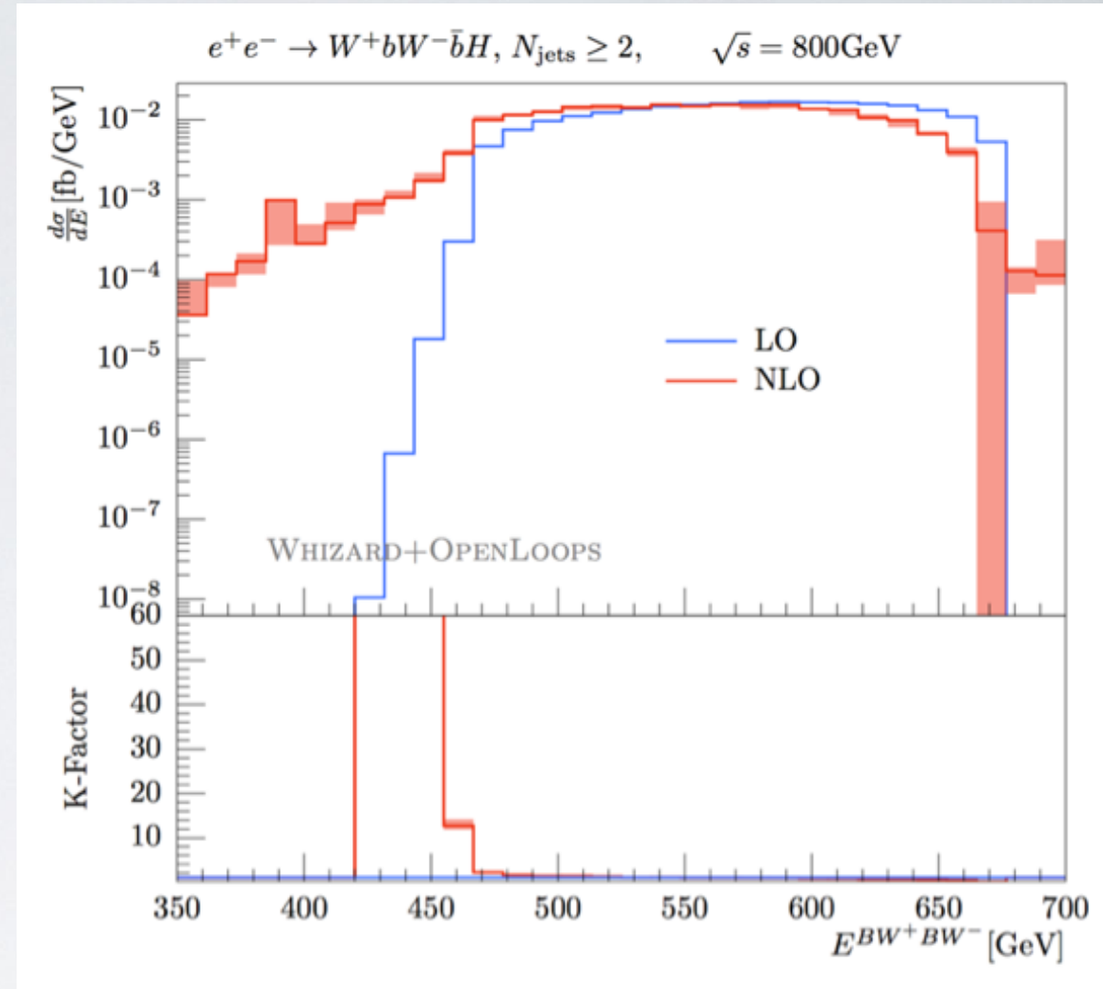


| | $e^+e^- \to t\bar{t}H$ | | | $e^+e^- \to W^+W^-b\bar{b}H$ | | |
|---|---|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | $\sigma^{\text{LO}}$[fb] | $\sigma^{\text{NLO}}$[fb] | K-factor | $\sigma^{\text{LO}}$[fb] | $\sigma^{\text{NLO}}$[fb] | K-factor |
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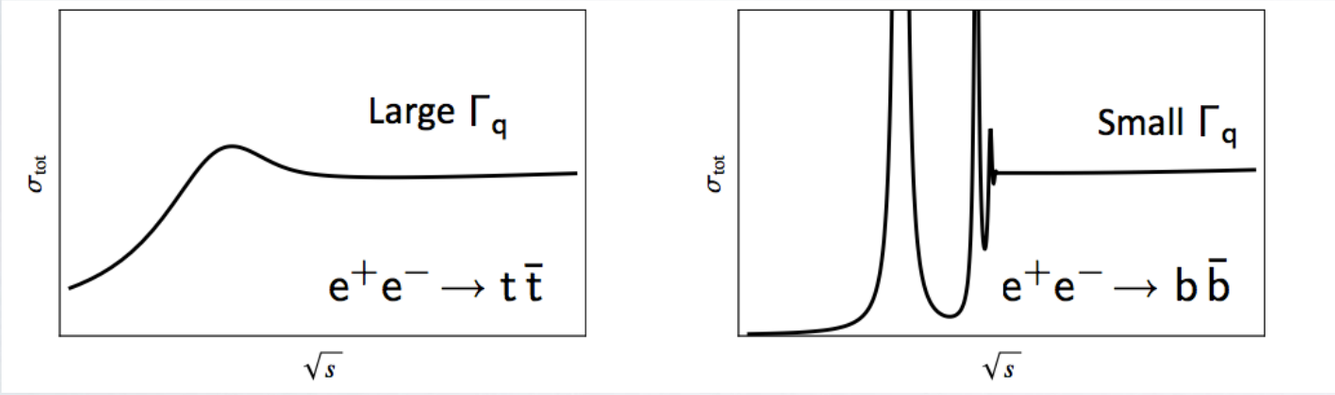
Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

# Top Threshold/Continuum at lepton colliders



- Top threshold scan best-known method to measure top quark mass, $\Delta M \sim 30\text{-}70$ MeV
- Continuum top production best-known method to measure top couplings

Heavy quark production at lepton colliders, qualitatively:



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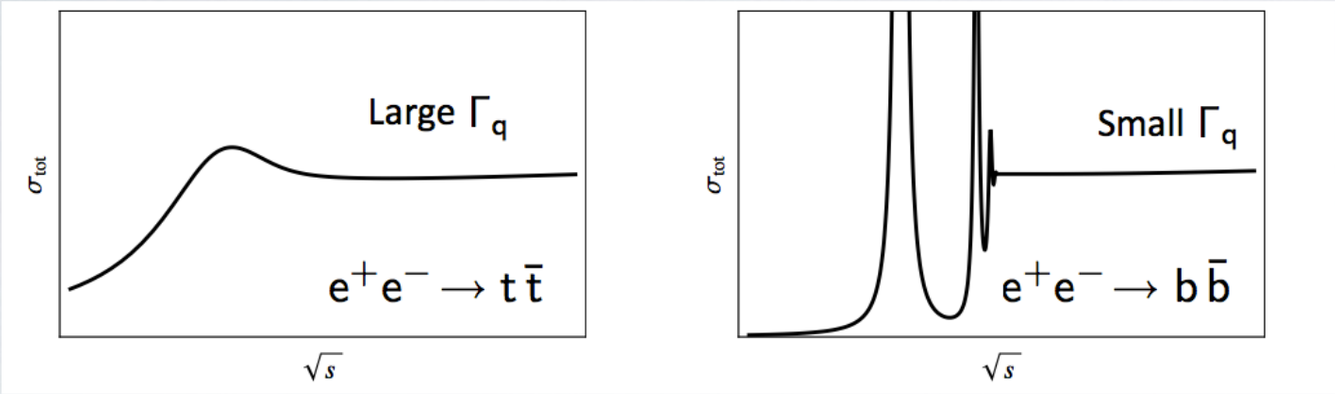


| error source | $\Delta m_t^{PS}$ [MeV] |
|---|---|
| stat. error (200 fb$^{-1}$) | 13 |
| theory (NNNLO scale variations, PS scheme) | 40 |
| parametric ($\alpha_s$, current WA) | 35 |
| non-resonant contributions (such as single top) | < 40 |
| residual background / selection efficiency | 10 – 20 |
| luminosity spectrum uncertainty | < 10 |
| beam energy uncertainty | < 17 |
| combined theory & parametric | 30 – 50 |
| combined experimental & backgrounds | 25 - 50 |
| total (stat. + syst.) | 40 – 75 |

from 1702.05333

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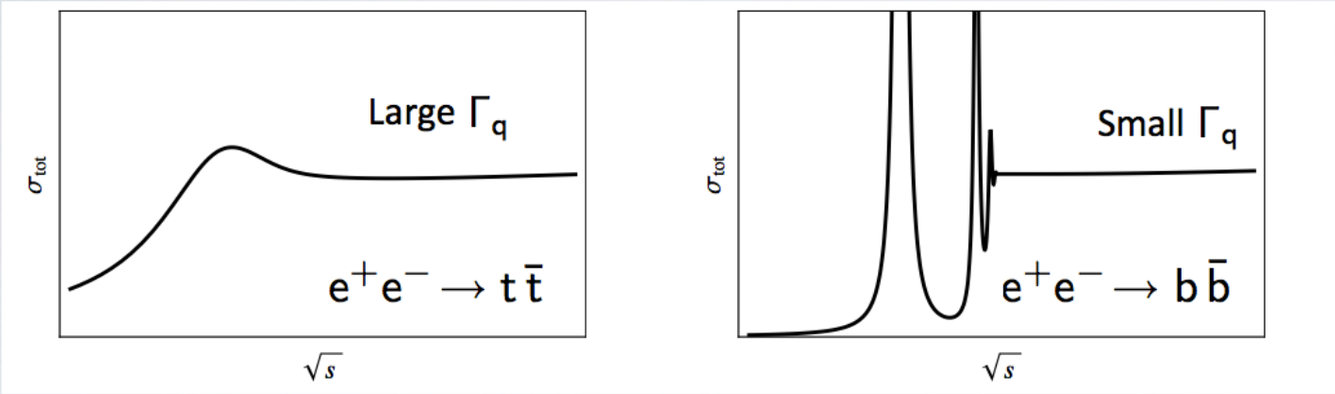


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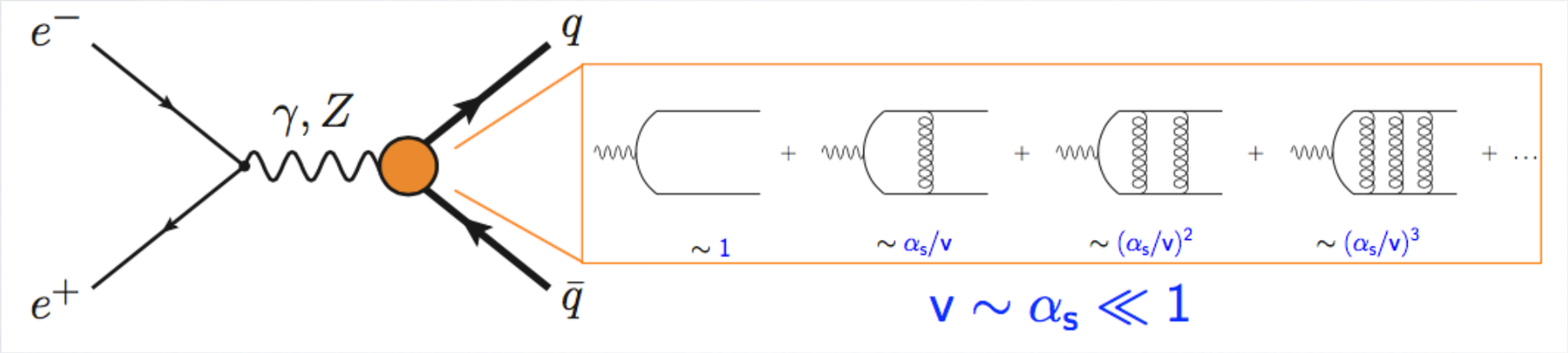
from 1702.05333

Threshold region: top velocity $v \sim \alpha_s \ll 1$ non-relativistic EFT: (v)NRQCD




Continuum region: "standard" fixed-order QCD

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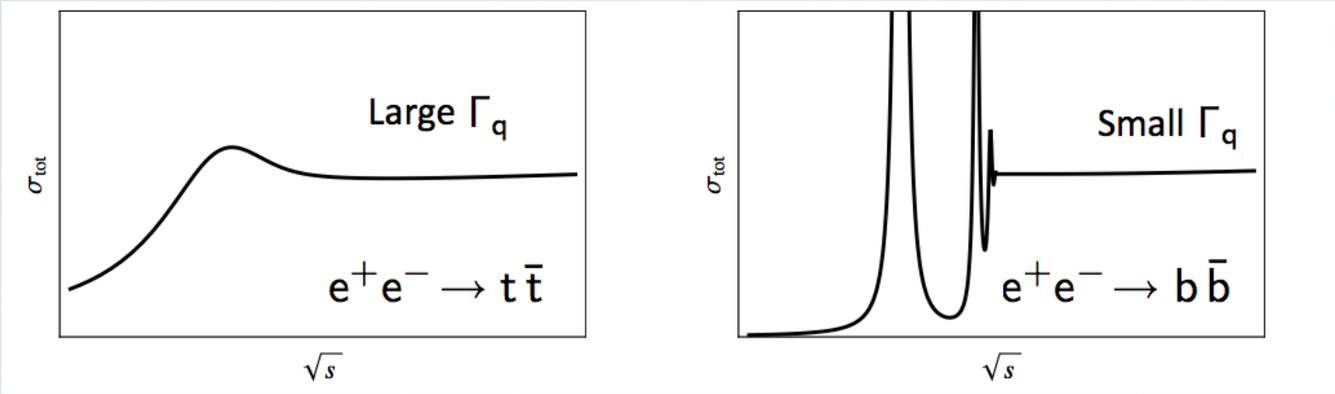


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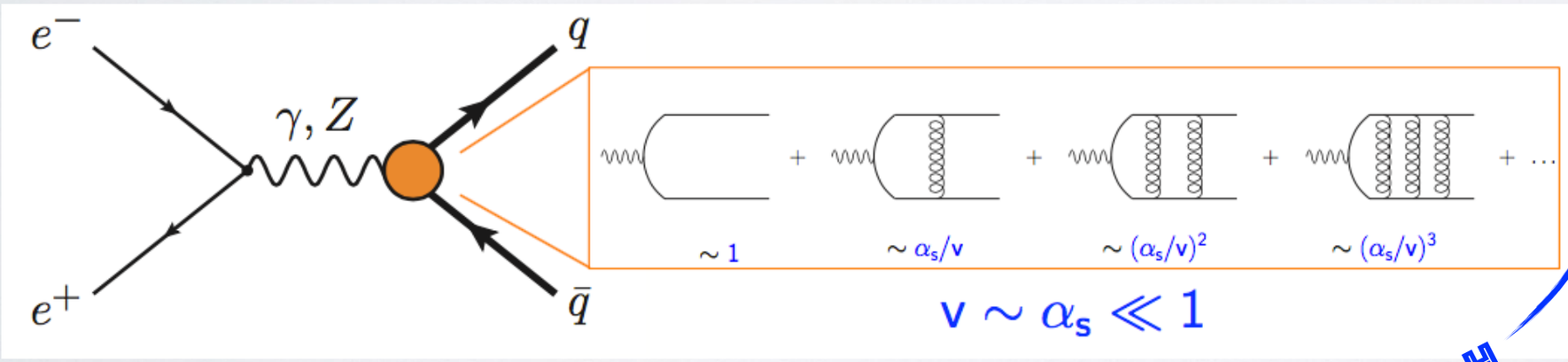


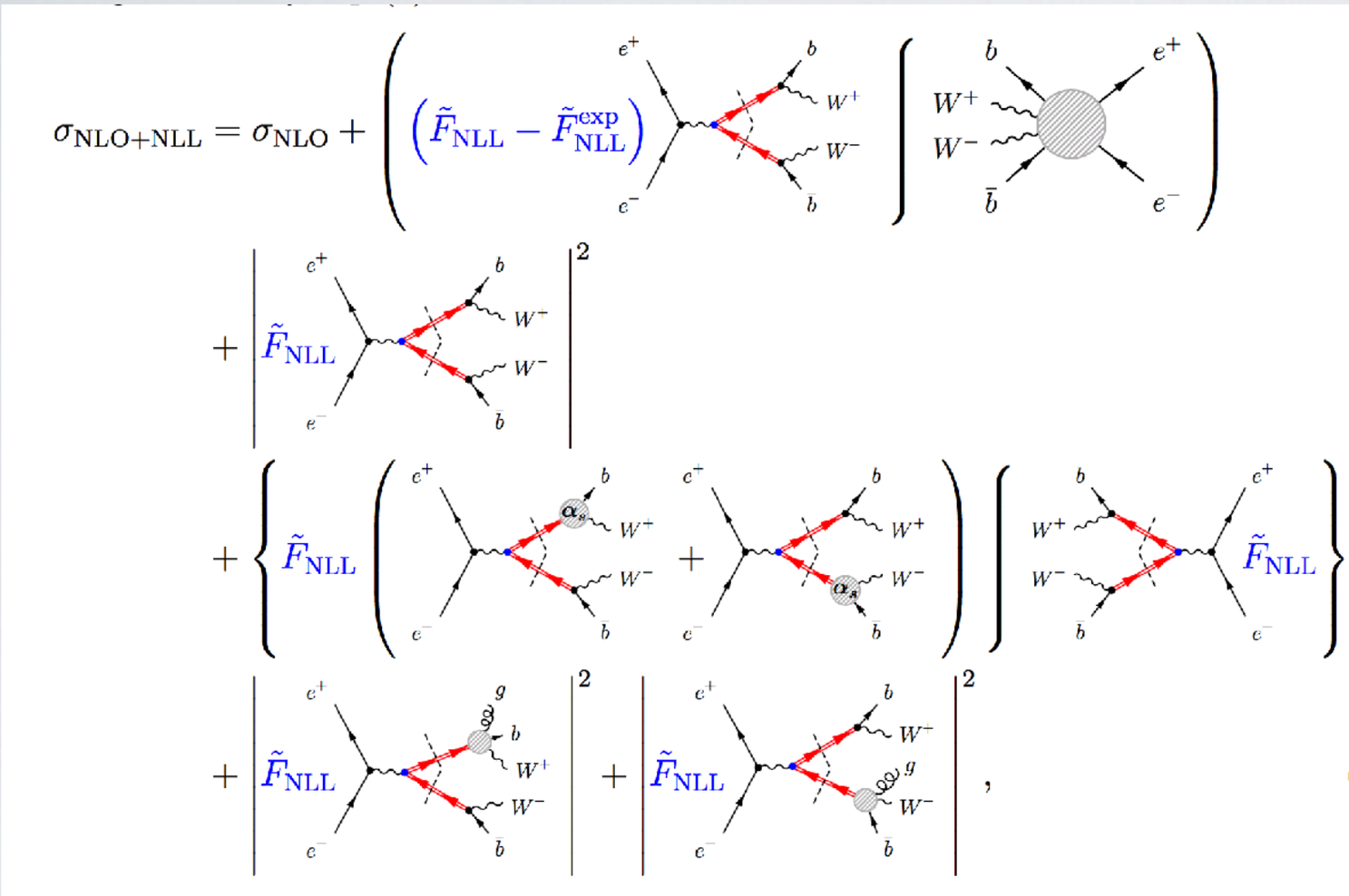


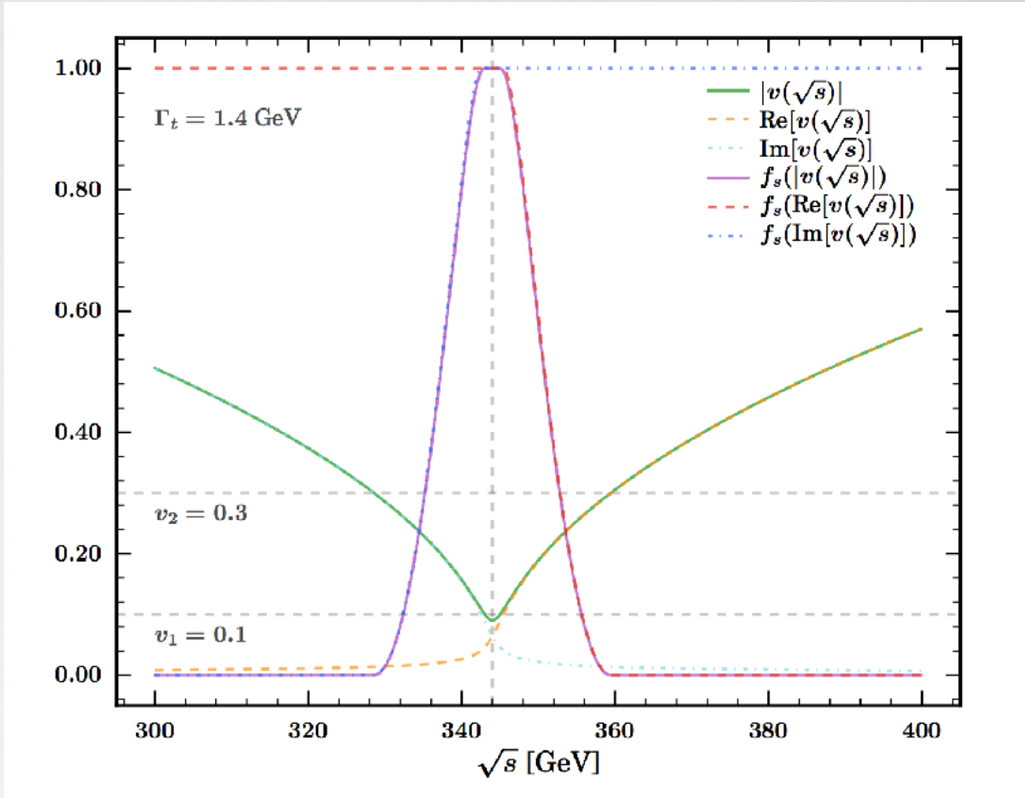
MATCH

Continuum region: "standard" fixed-order QCD

# Top threshold: validation and matching

- Transition region between relativistic and resummation effects




$$\sigma_{\rm matched} = \sigma_{\rm FO}\left[\alpha_{\rm H}\right] + \sigma^{\rm full}_{\rm NRQCD}\left[f_s\,\alpha_{\rm H},\; f_s\,\alpha_{\rm S},\; f_s\,\alpha_{\rm US}\right] - \sigma^{\rm expanded}_{\rm NRQCD}\left[f_s\,\alpha_{\rm H},\; f_s\,\alpha_{\rm H}\right] ,$$

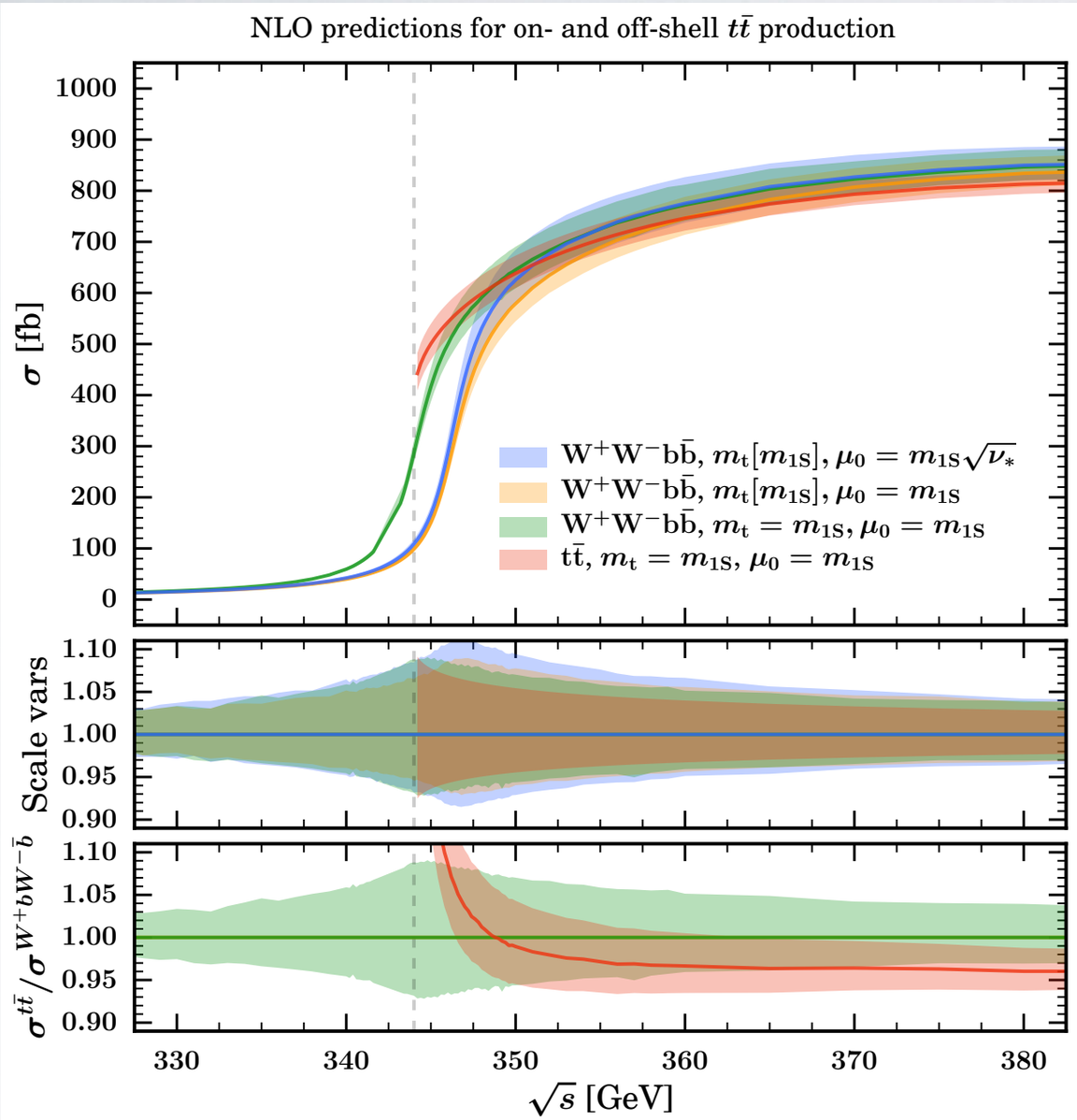
Smoothstep matching function:

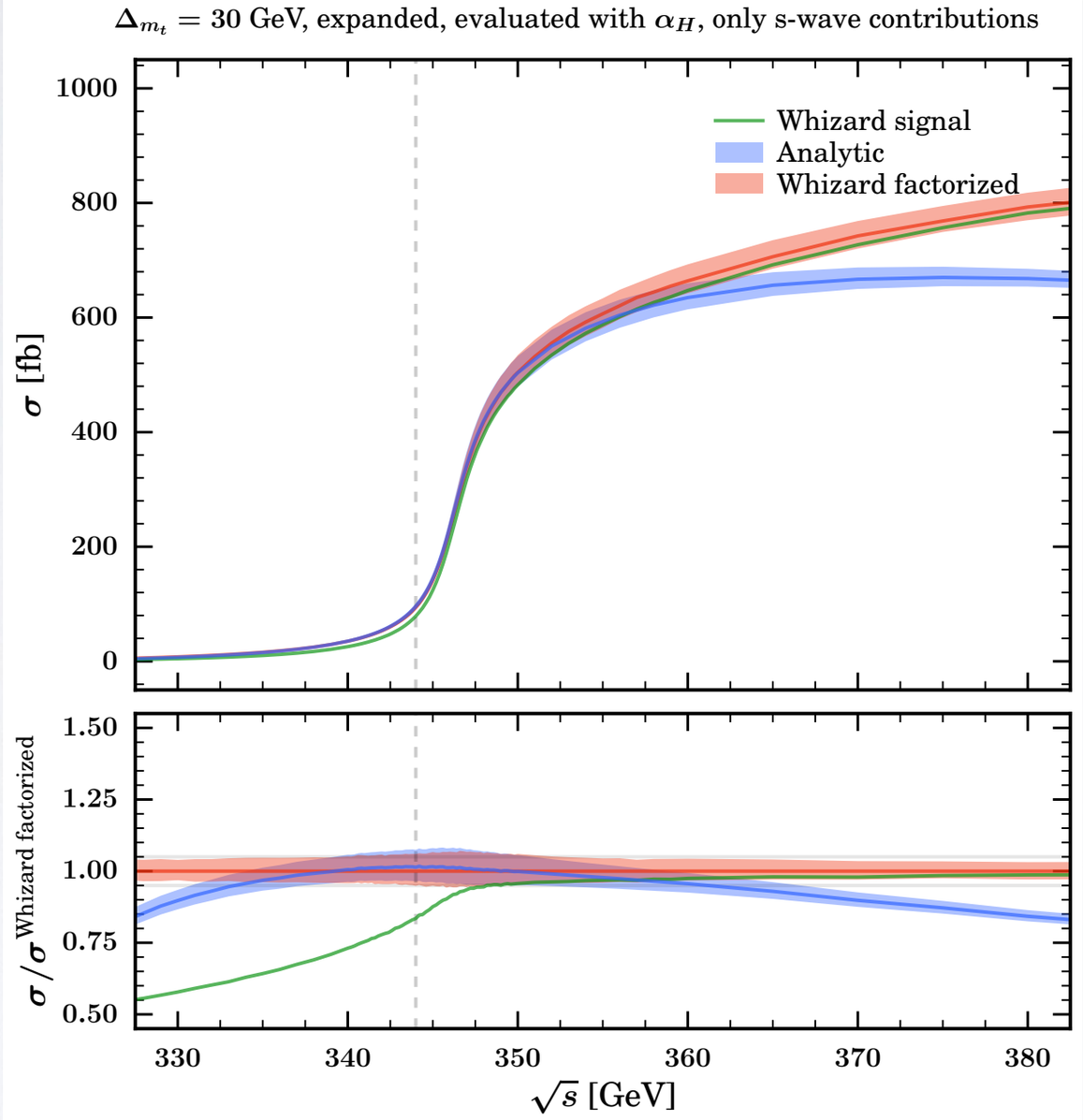
$$f_s(v) = \begin{cases} 1 & v < v_1 \\ 1 - 3\left(\frac{v-v_1}{v_2-v_1}\right)^2 - 2\left(\frac{v-v_1}{v_2-v_1}\right)^3 & v_1 \le v \le v_2 \\ 0 & v > v_2 \end{cases}$$

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

# Top threshold: validation and matching






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

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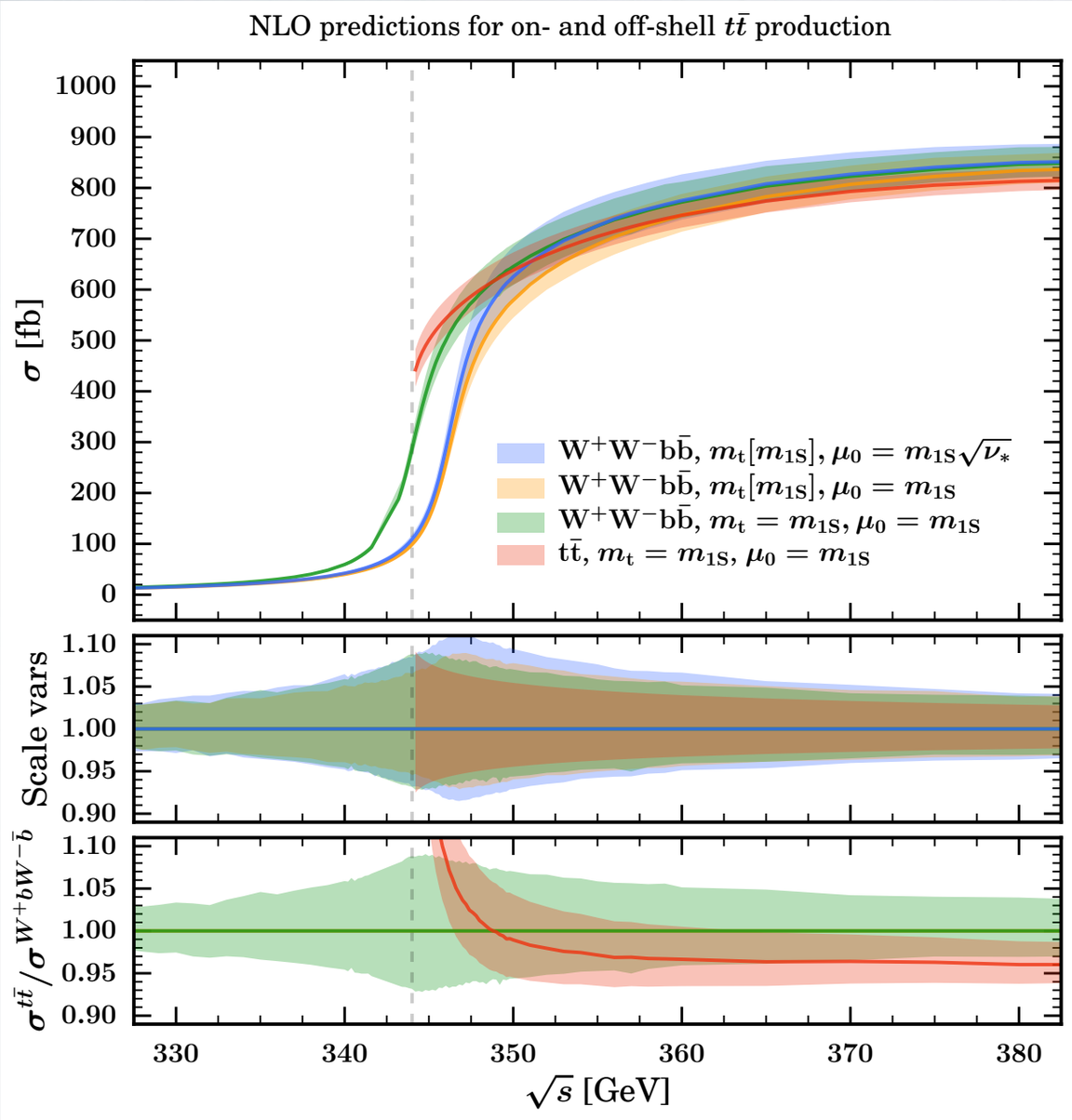
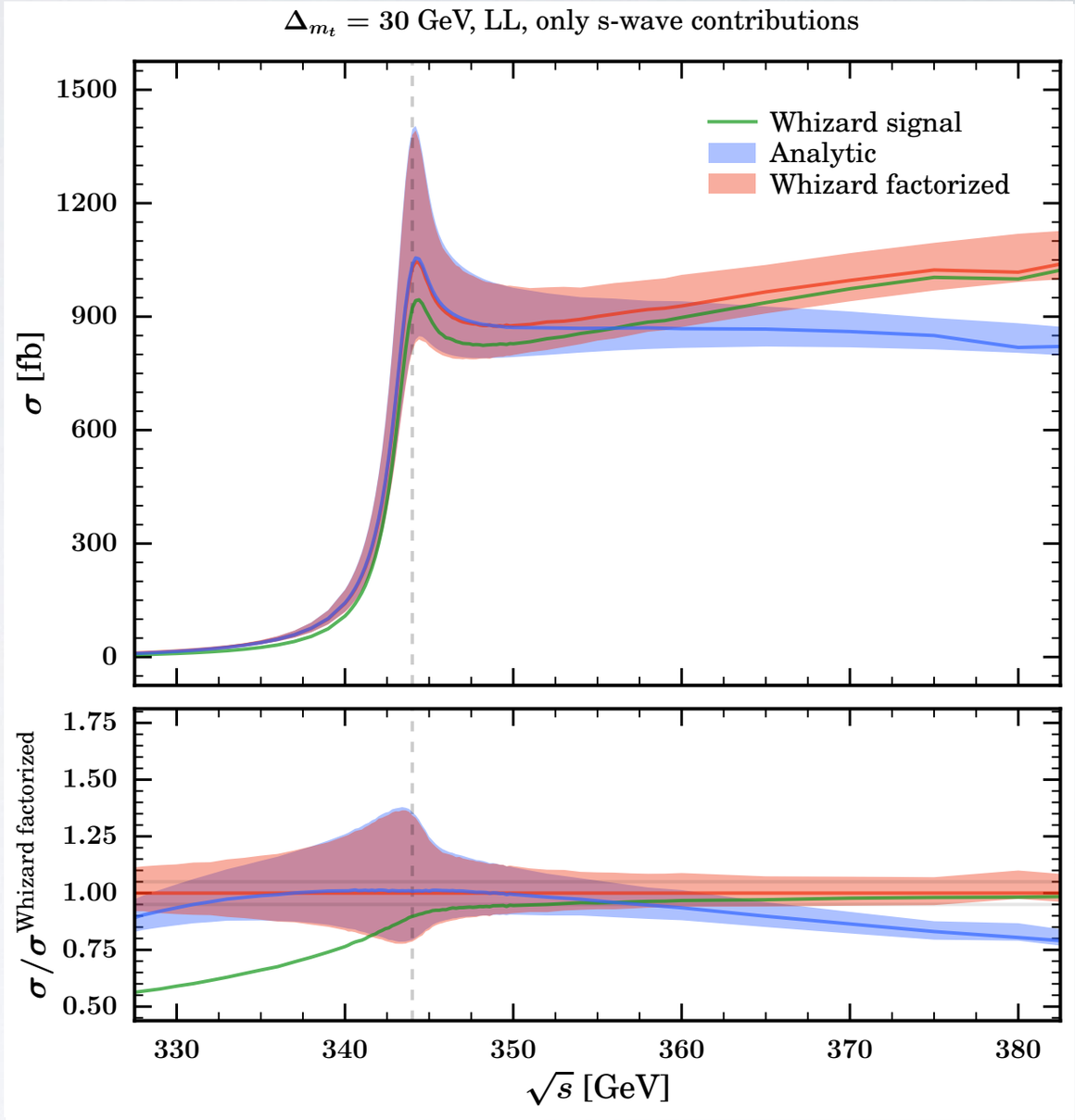
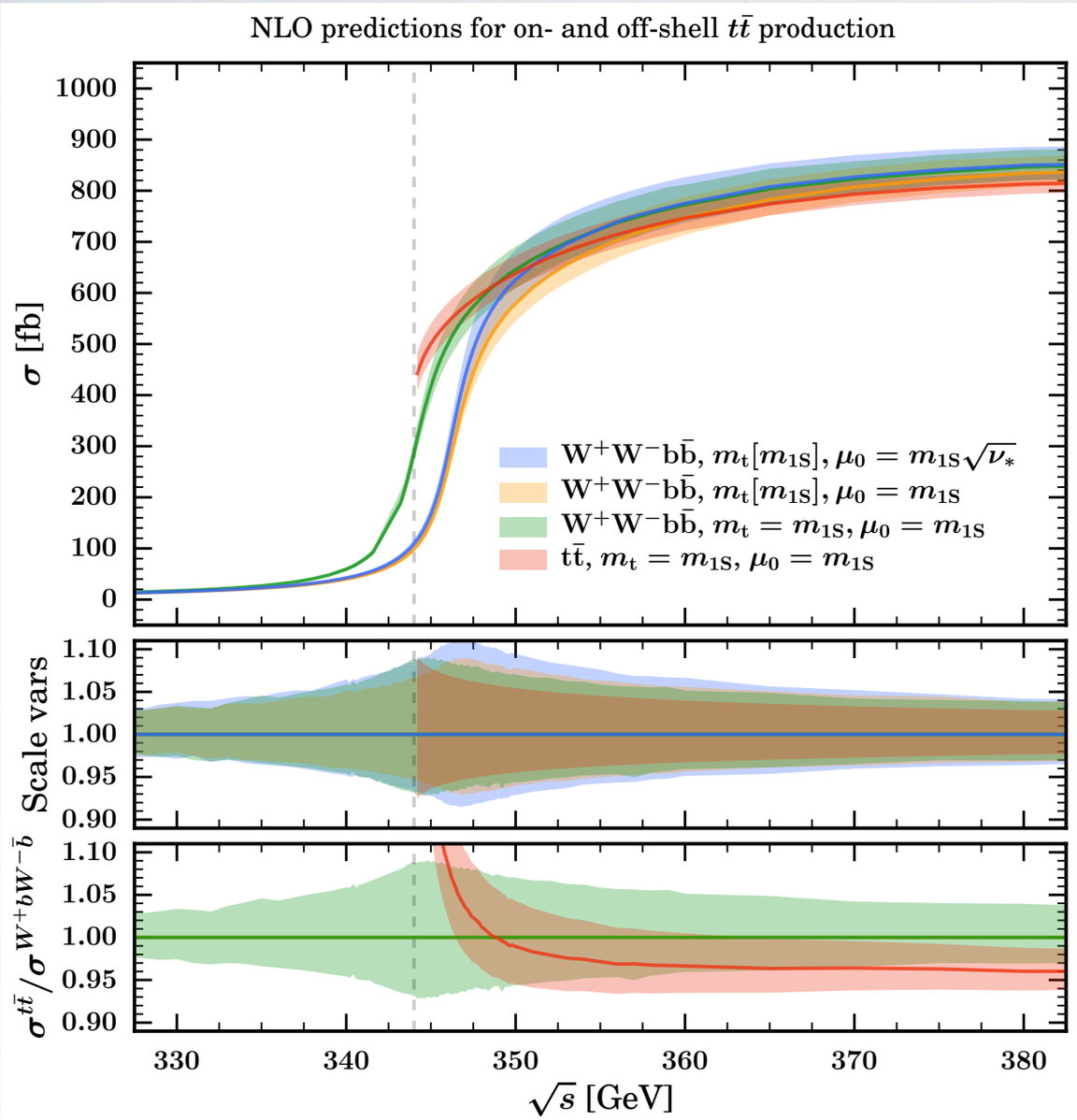


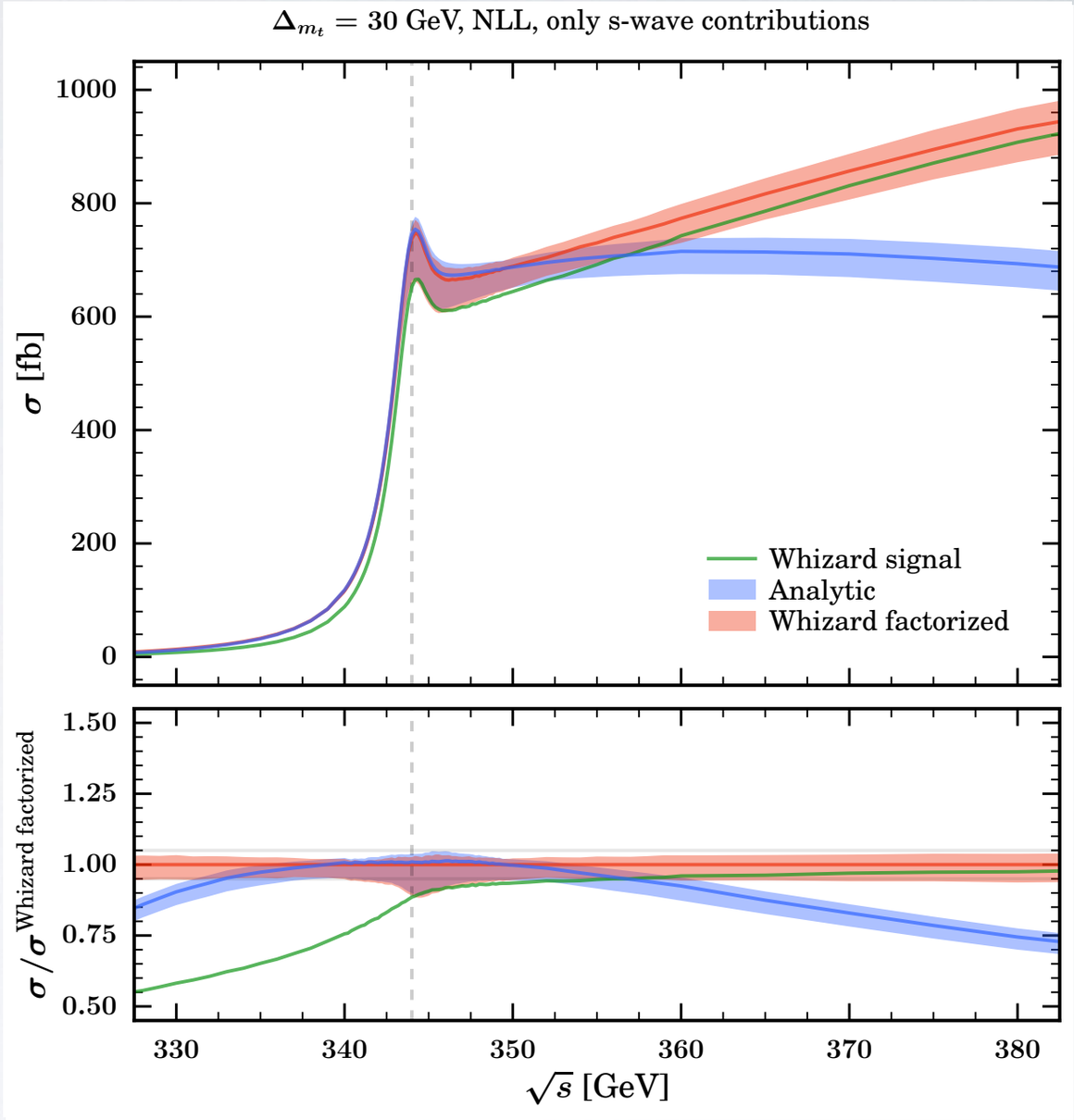




Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

# Top threshold: validation and matching



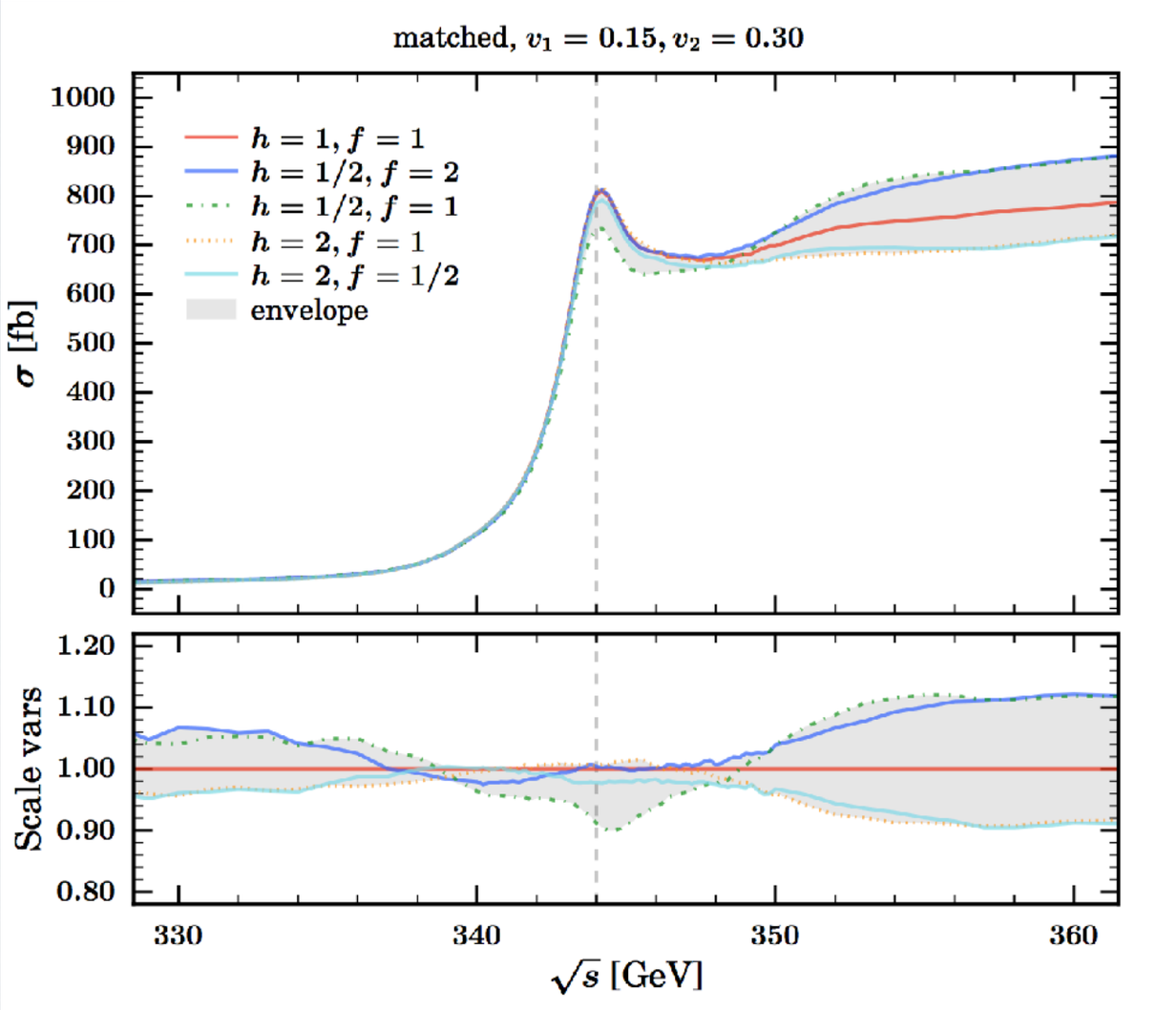


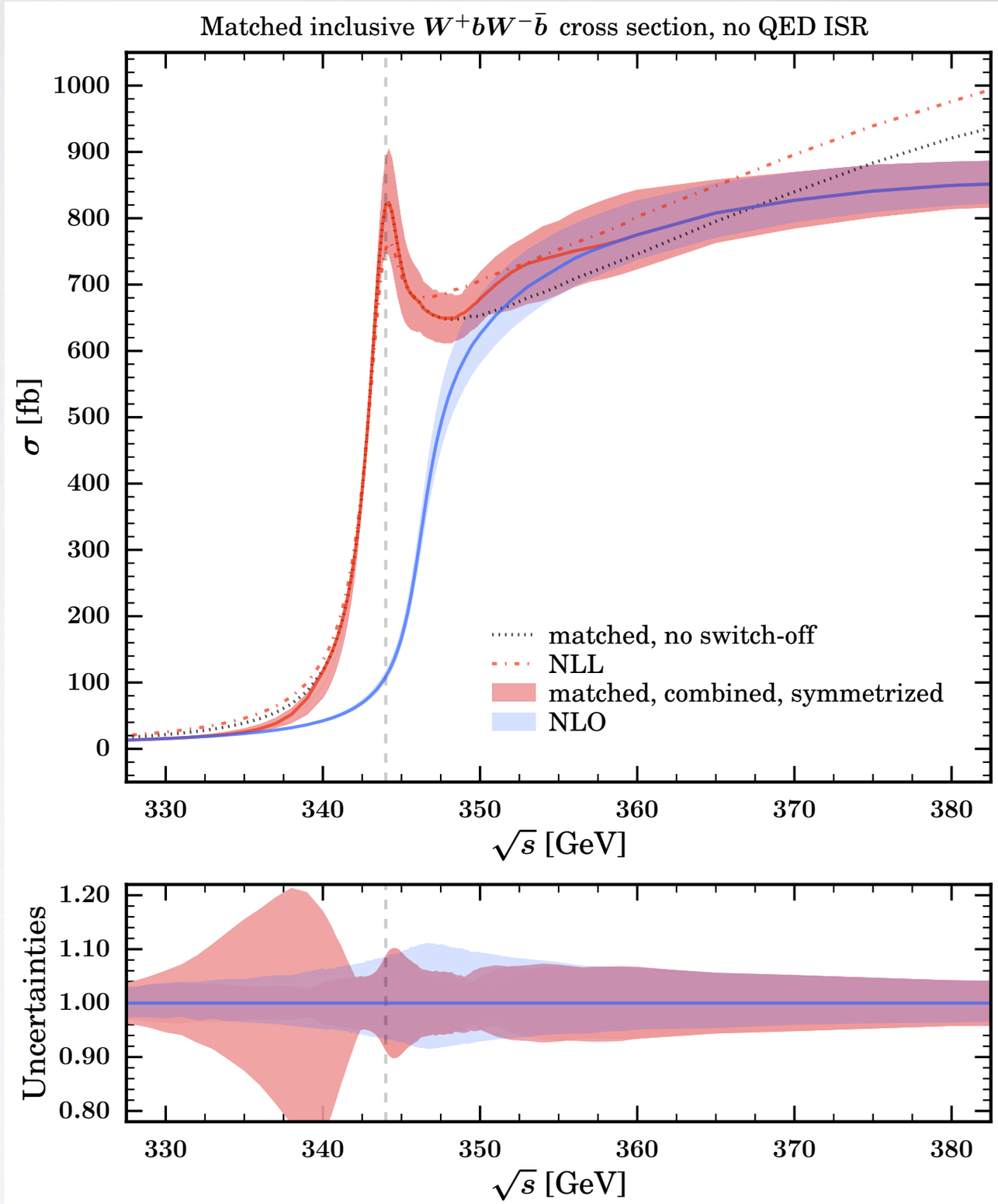




Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

# Matching threshold NLL to continuum NLO





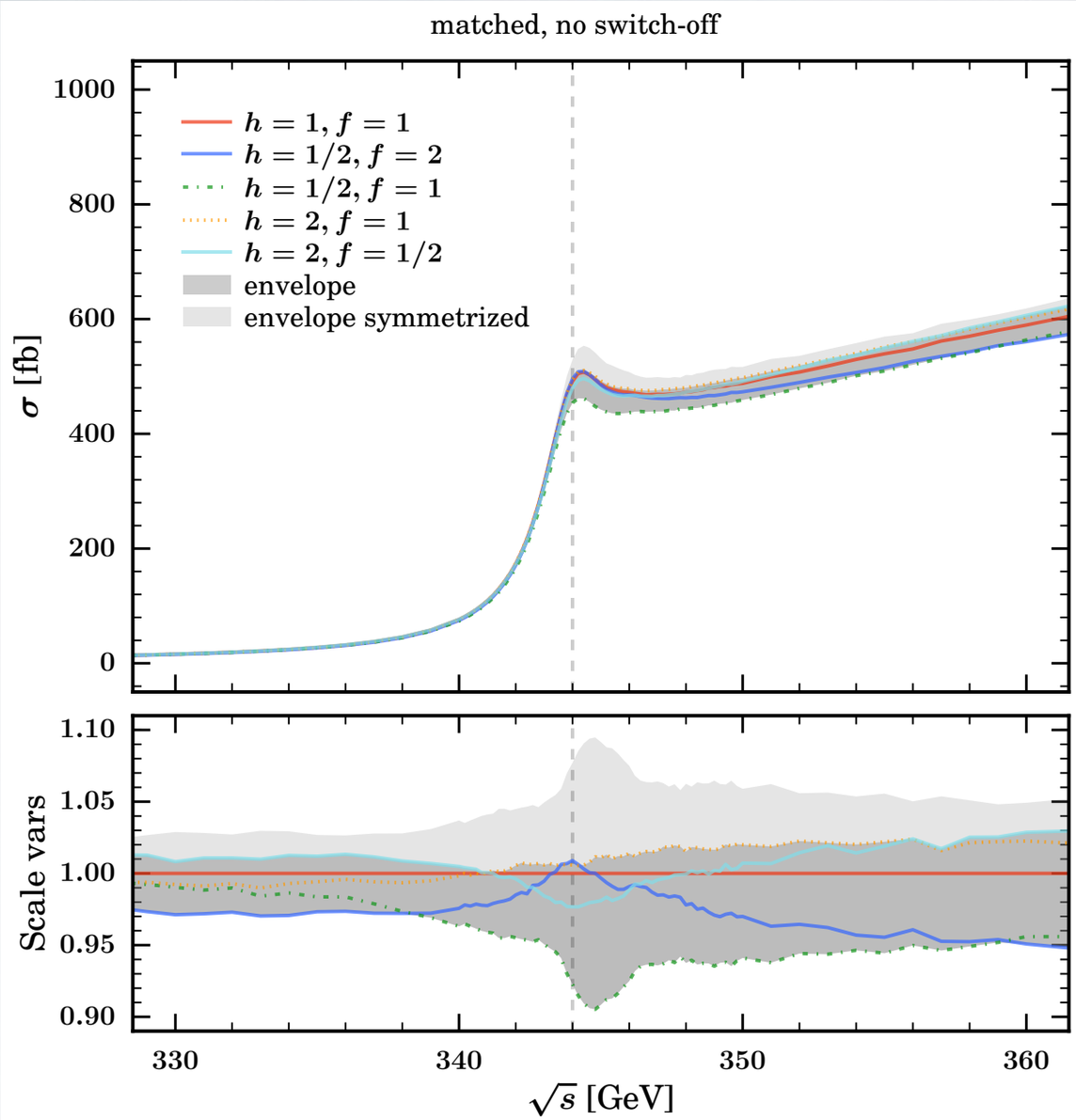

**Total uncertainty: *h-f* variation band and matching [switch-off function]**

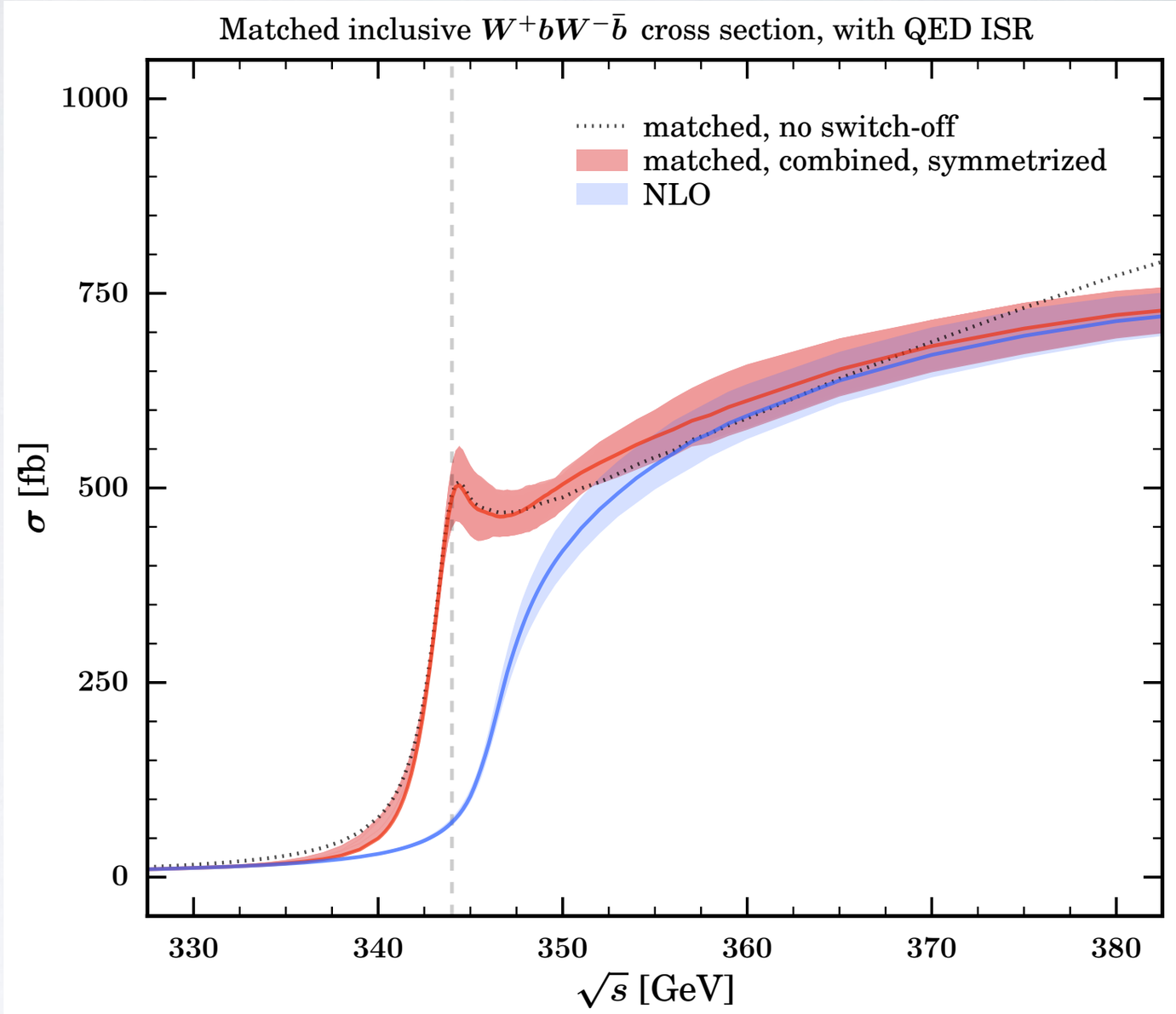
Symmetrization of error bands:

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

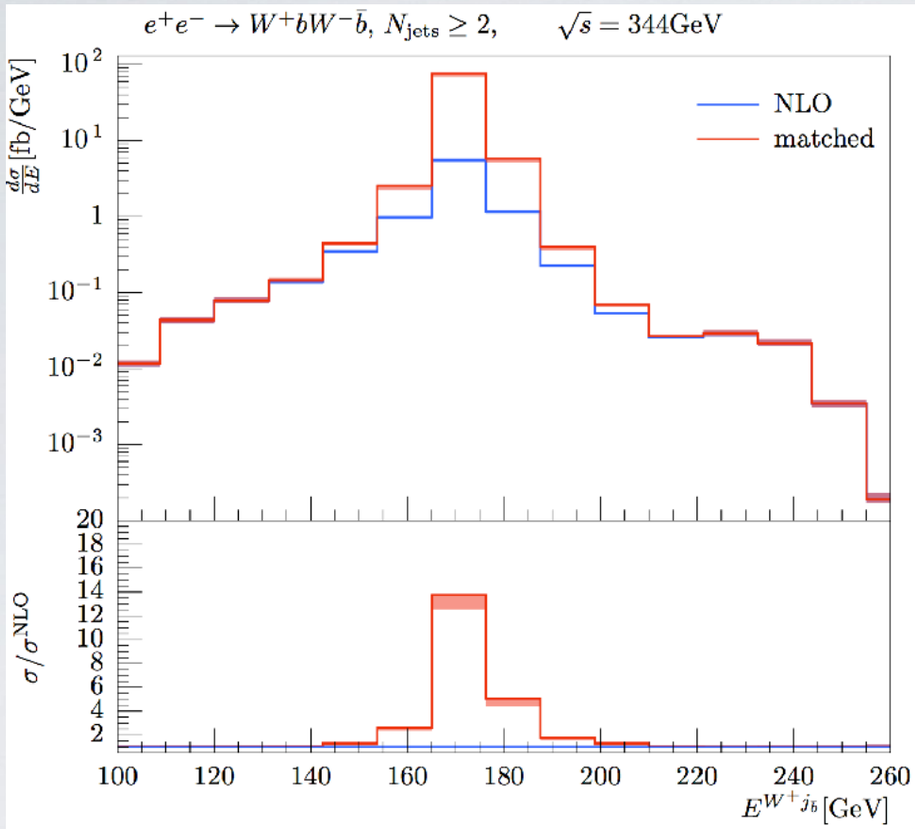
$$\sigma_{\min} = \min\left[\min_{i\in\mathrm{HF}} \sigma_i \ , \ \sigma_0 - (\max_{i\in\mathrm{HF}} \sigma_i - \sigma_0)\right]$$

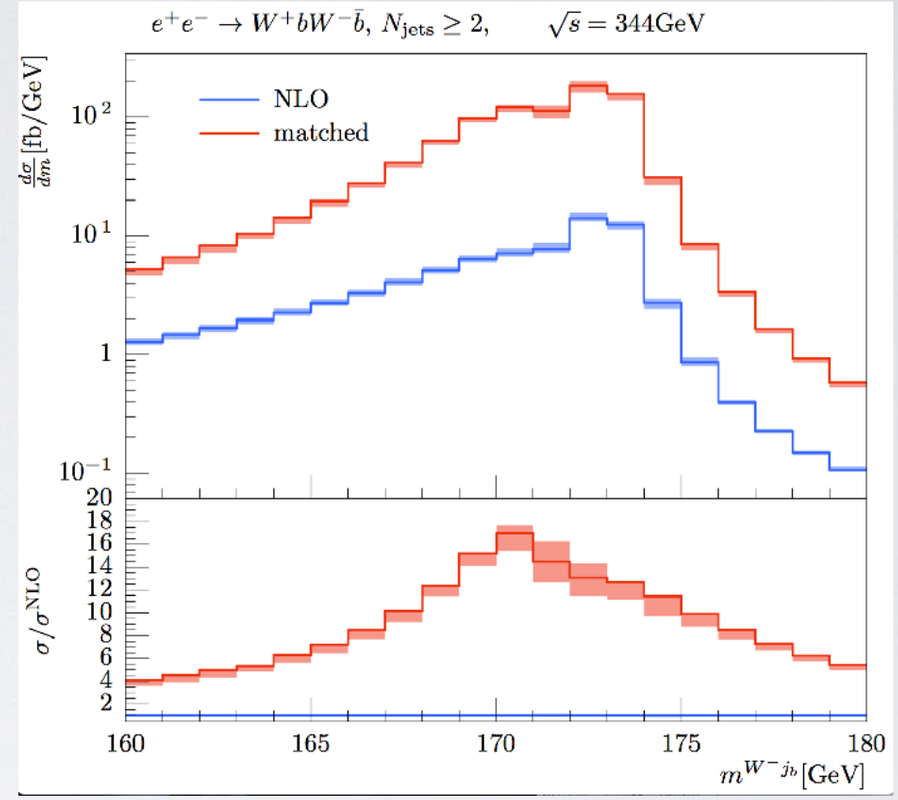
# Threshold matching with QED ISR

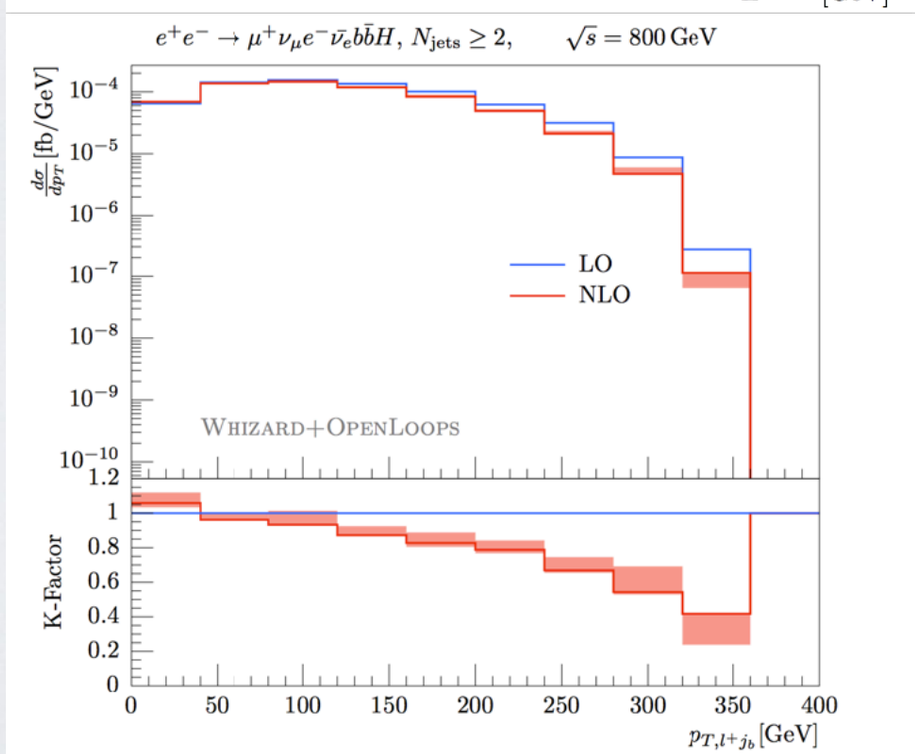


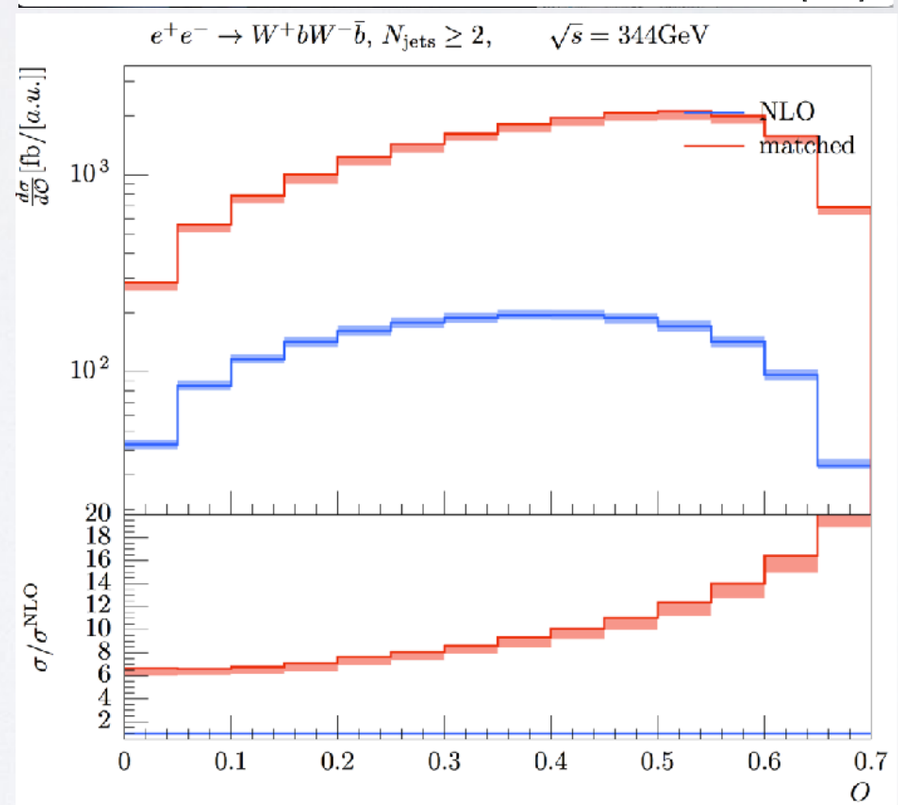



# Matched threshold differential distributions



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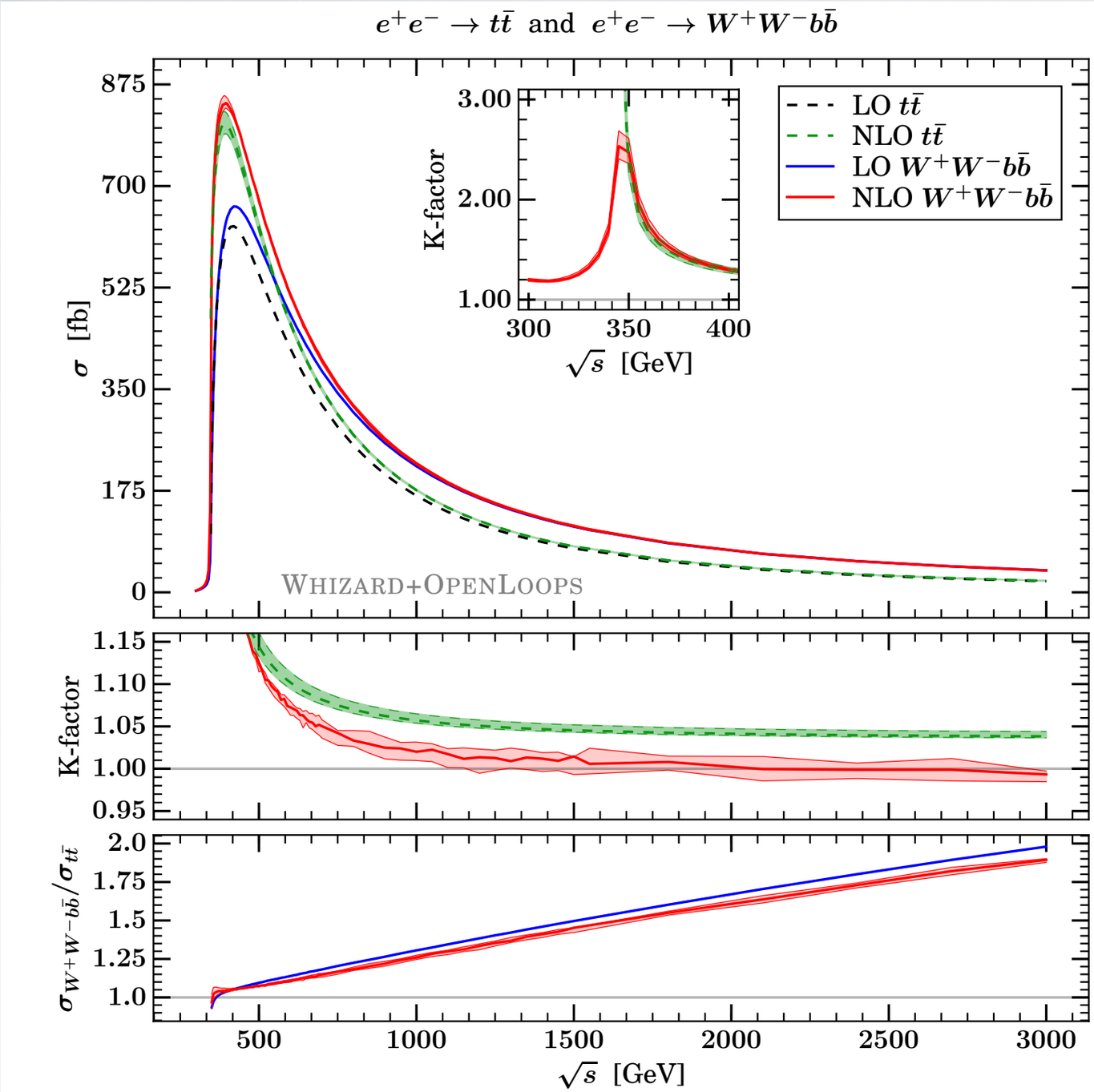


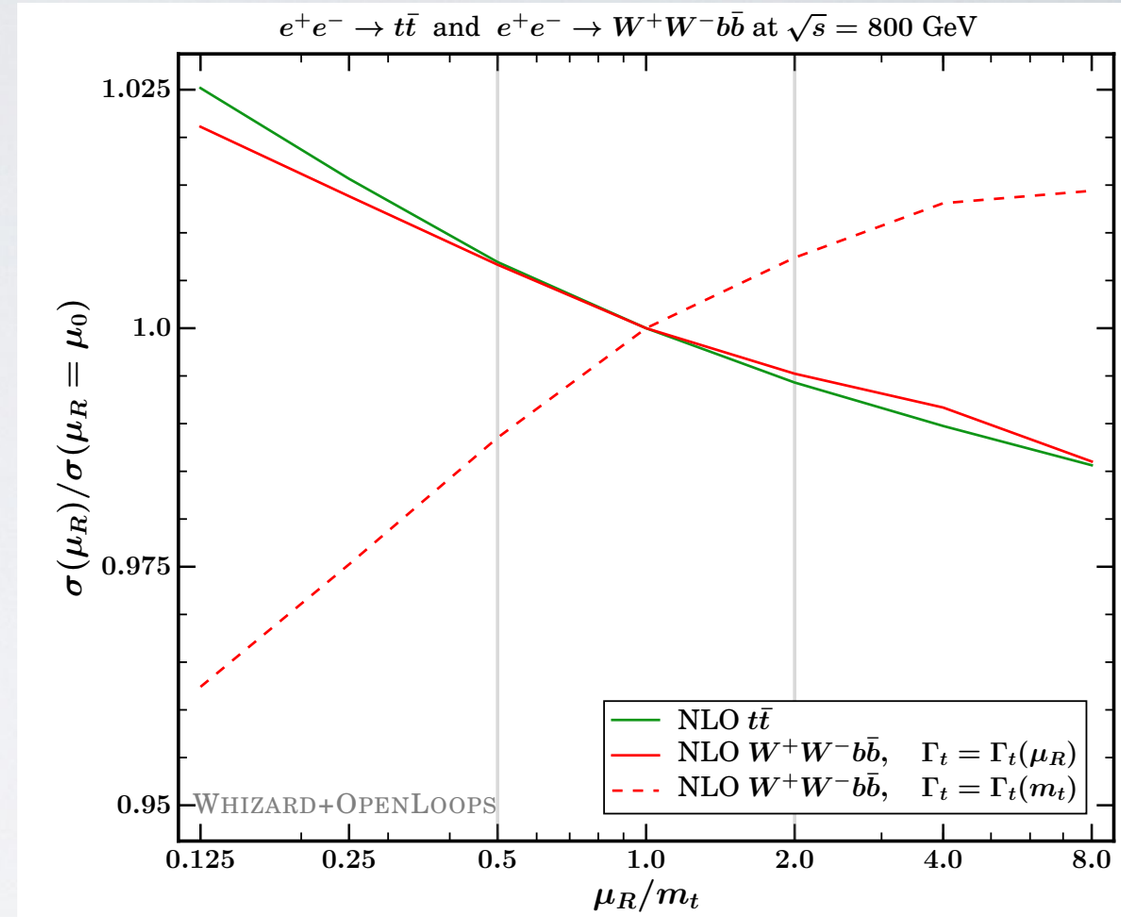


| | $e^+e^- \to t\bar{t}$ | | | $e^+e^- \to W^+W^-b\bar{b}$ | | |
|---|---|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | $\sigma^{\rm LO}$[fb] | $\sigma^{\rm NLO}$[fb] | K-factor | $\sigma^{\rm LO}$[fb] | $\sigma^{\rm NLO}$[fb] | K-factor |
| 500 | 548.4 | $627.4^{+1.4\%}_{-0.9\%}$ | 1.14 | 600.7 | $675.1^{+0.4\%}_{-0.8\%}$ | 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 |

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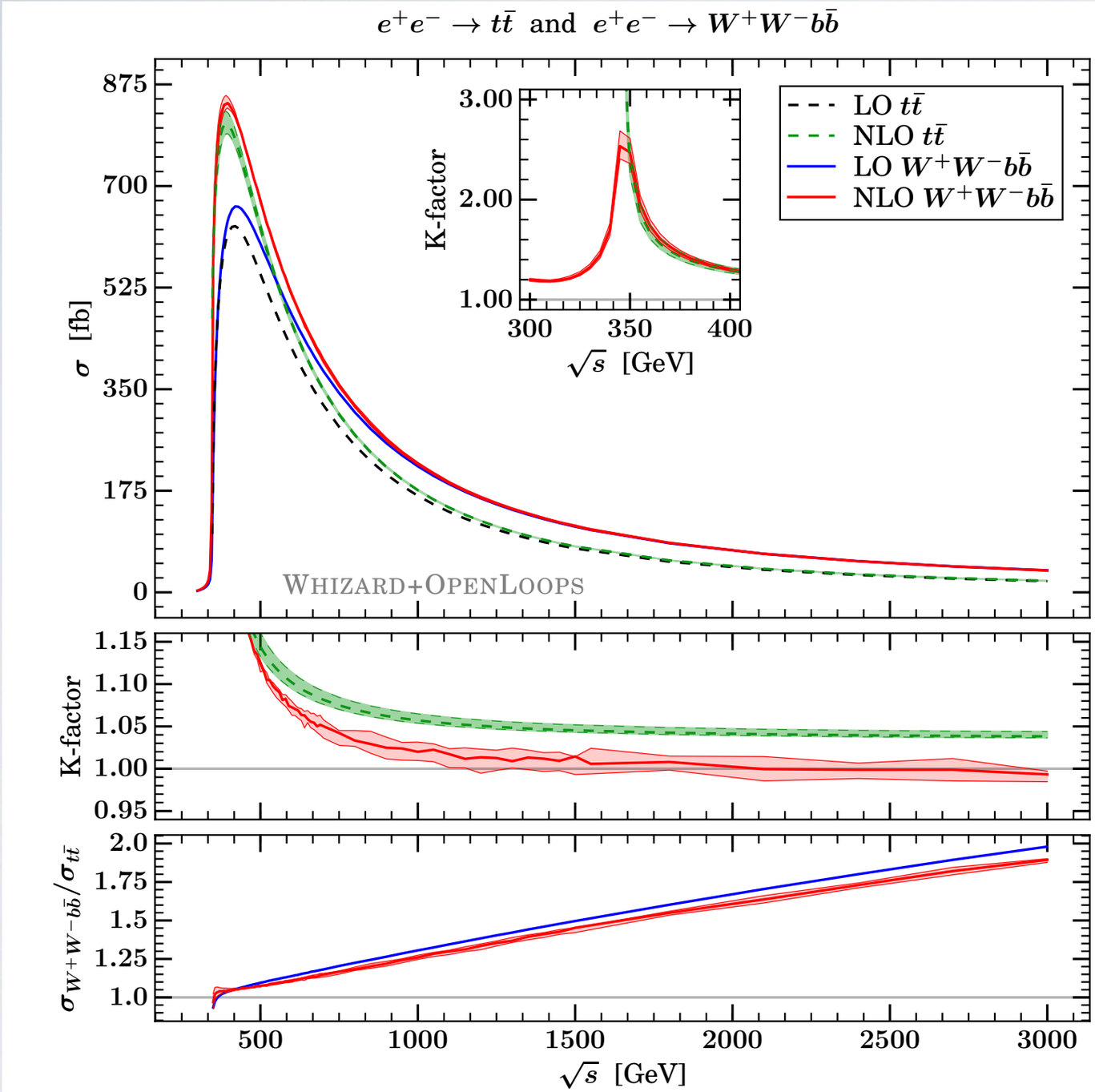
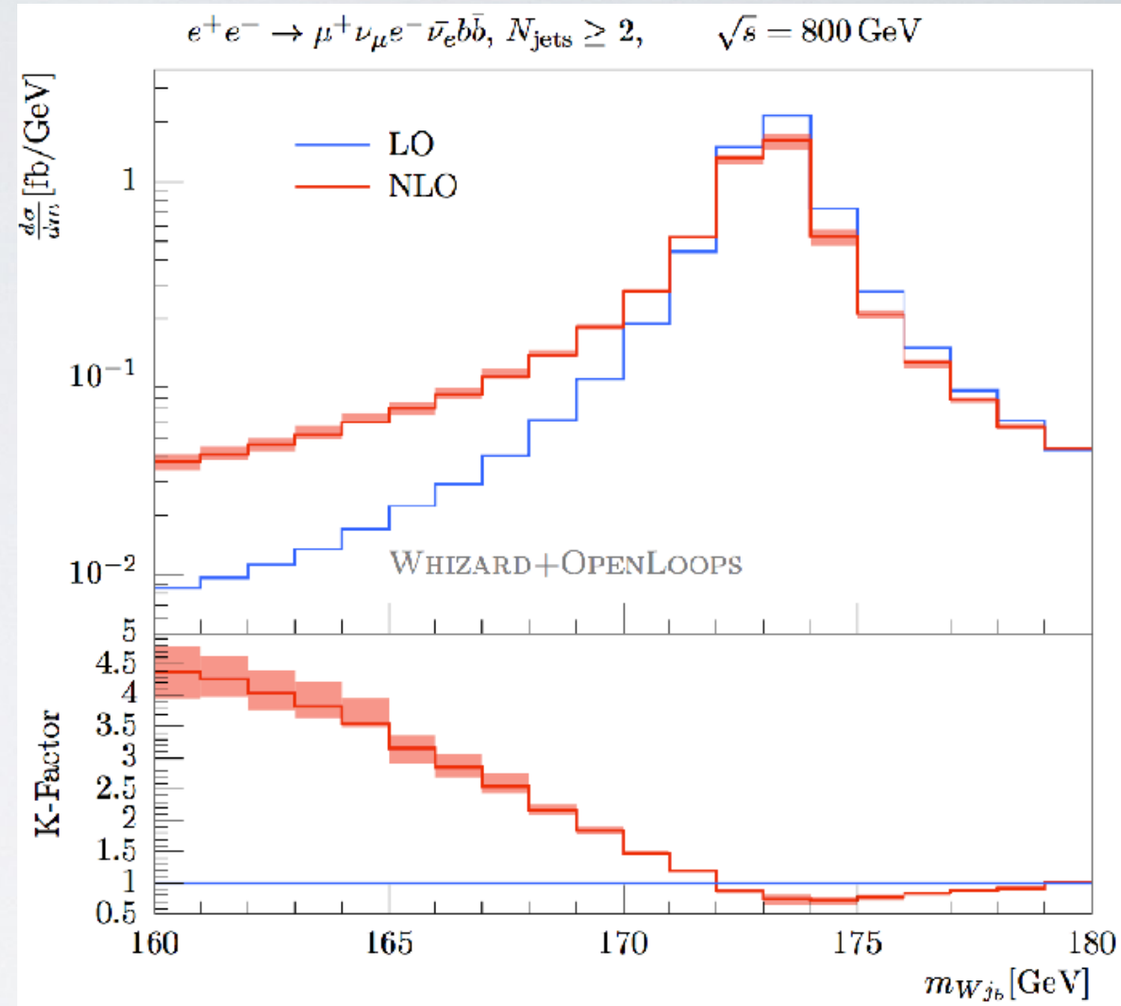
# NLO QCD Results for off-shell $e^+e^- \to tt$




| | $e^+e^- \to t\bar{t}$ | | | $e^+e^- \to W^+W^-b\bar{b}$ | | |
|---|---|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | $\sigma^{\text{LO}}$[fb] | $\sigma^{\text{NLO}}$[fb] | K-factor | $\sigma^{\text{LO}}$[fb] | $\sigma^{\text{NLO}}$[fb] | K-factor |
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| 800 | 253.1 | $270.9^{+0.8\%}_{-0.4\%}$ | 1.07 | 310.2 | $320.7^{+1.1\%}_{-0.7\%}$ | 1.03 |
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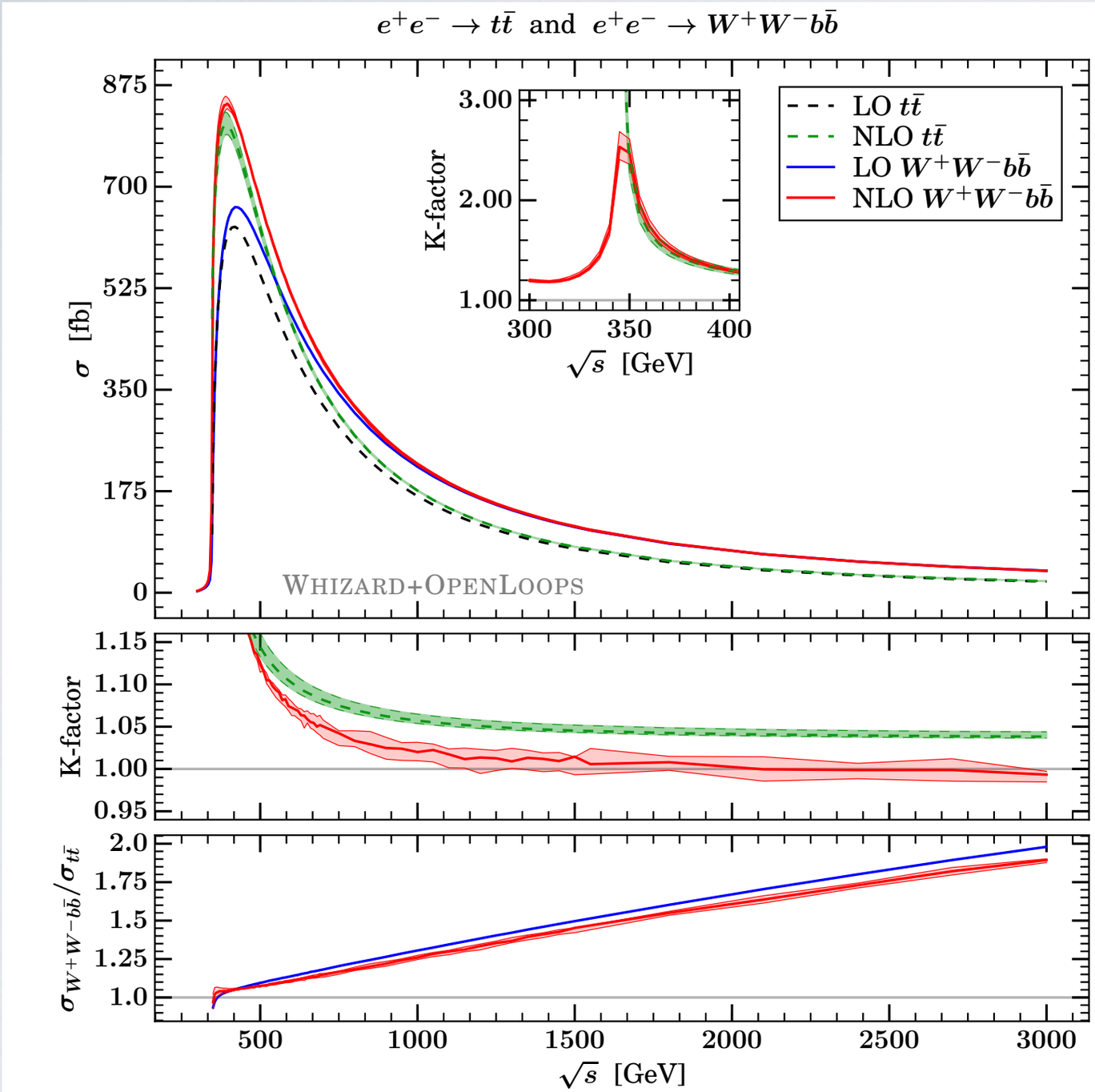
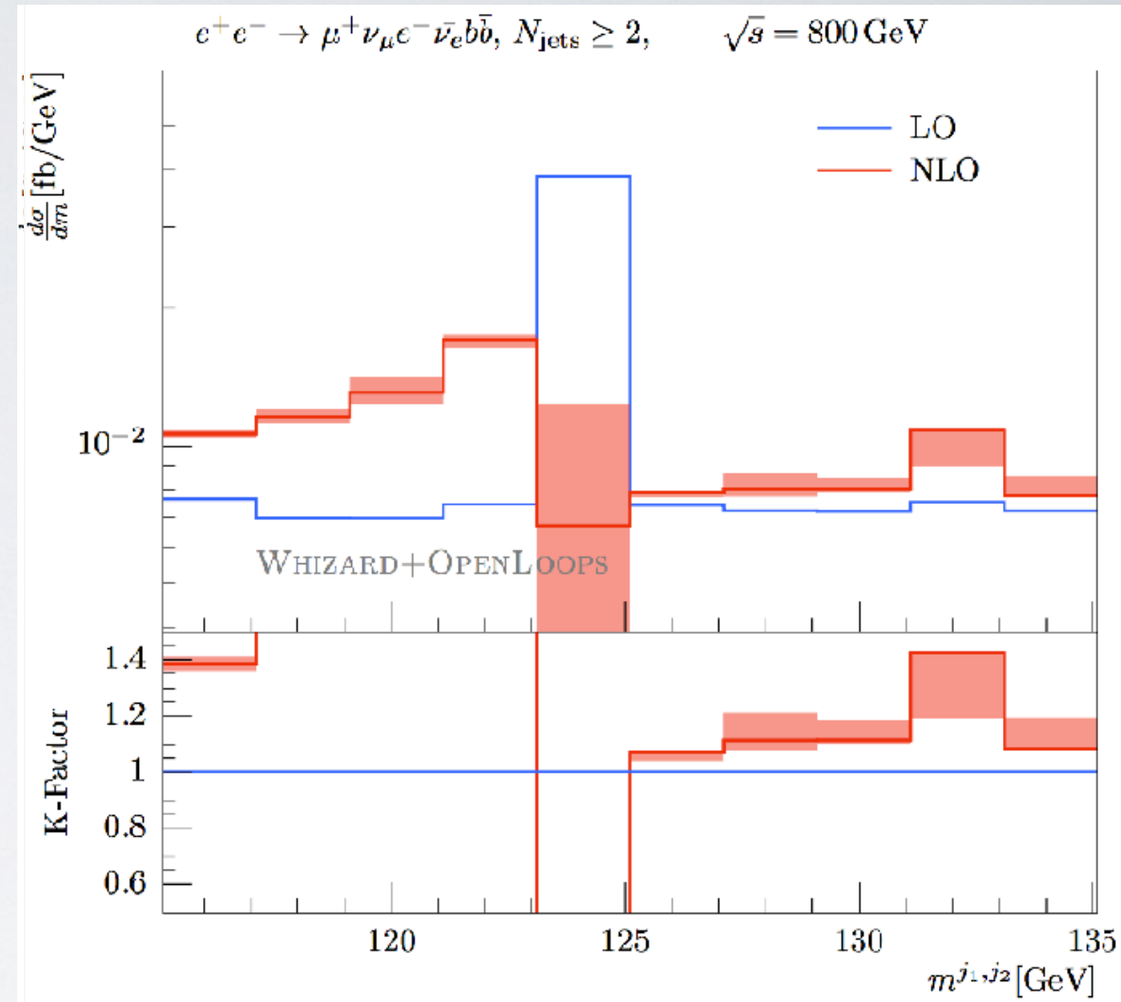
| 3000 | 19.14 | $19.87^{+0.5\%}_{-0.2\%}$ | 1.04 | 37.89 | $37.63^{+0.4\%}_{-0.9\%}$ | 0.993 |

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

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




| | $e^+e^- \to t\bar{t}$ | | | $e^+e^- \to W^+W^-b\bar{b}$ | | |
|---|---|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | $\sigma^{\text{LO}}$[fb] | $\sigma^{\text{NLO}}$[fb] | K-factor | $\sigma^{\text{LO}}$[fb] | $\sigma^{\text{NLO}}$[fb] | K-factor |
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Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390