The WHIZARD Generator for Lepton Colliders

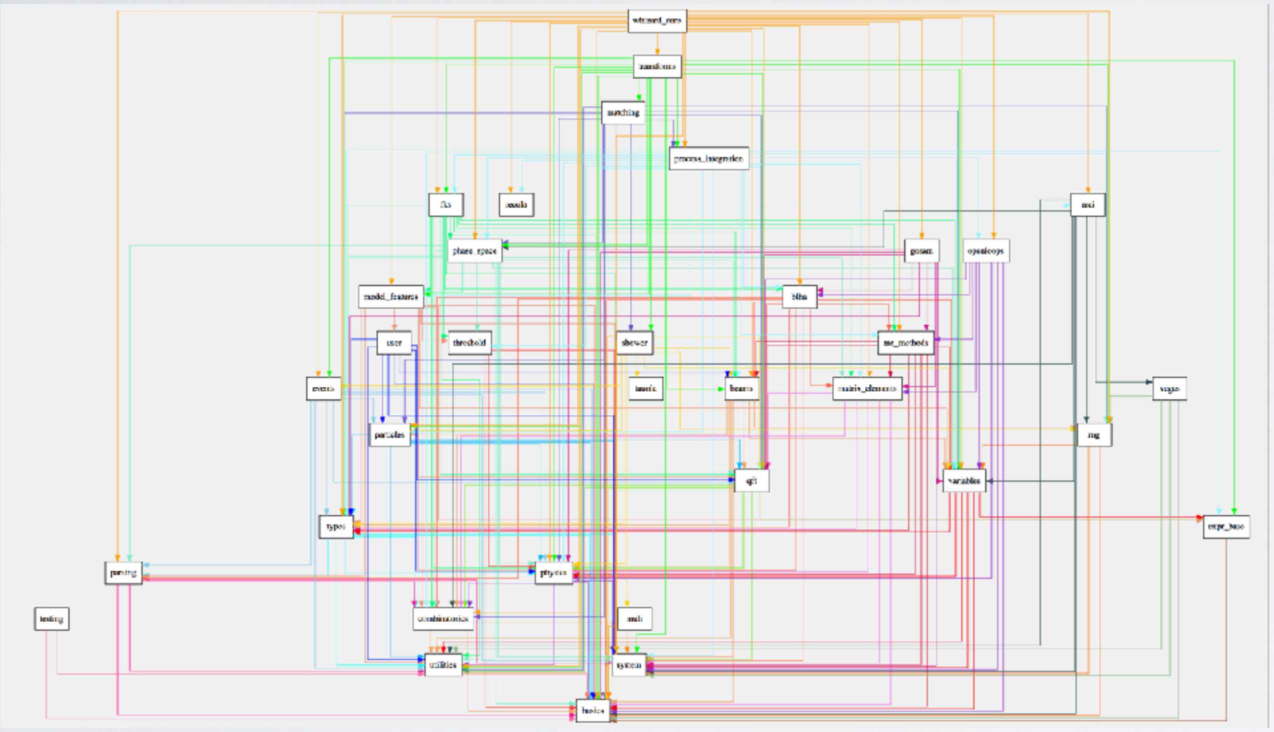
Jürgen R. Reuter, DESY

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

WHIZARD: Introduction / Technical Facts

WHIZARD v2.6.4 (23.08.2018) 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/Zhijie Zhao



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

WHIZARD v2.7.0 (21.01.2019) http://whizard.hepforge.org <whizard@desy.de>

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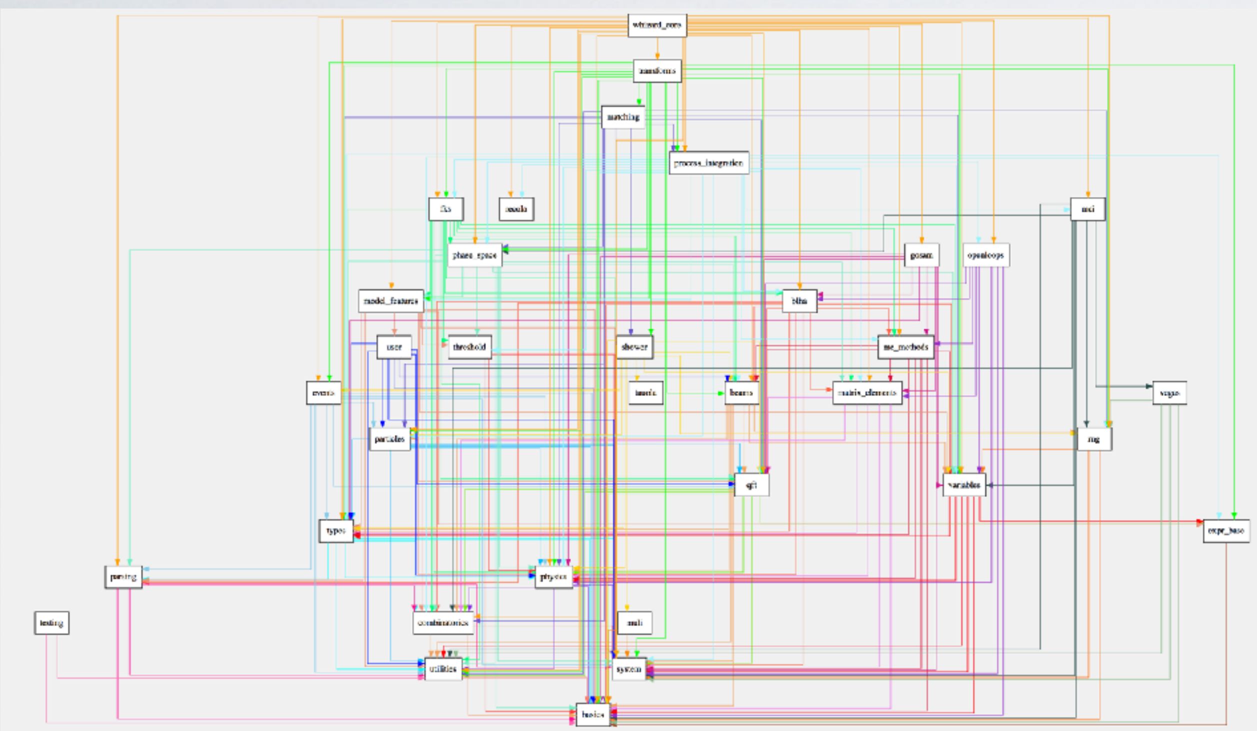

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WHIZARD: Past and recent timeline (I)

- 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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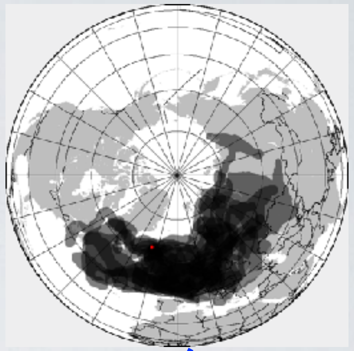
Eyjafjallajökull



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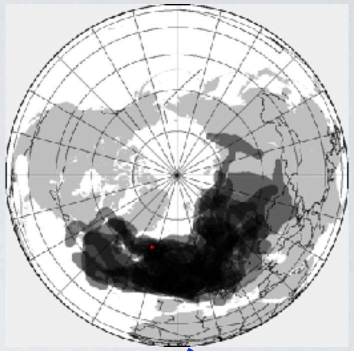


- Validation inside ATLAS and CMS [≈2011–2014]
- **Refactoring phase II**: NLO automation / maintainability → v2.2.0 [≈ 2012–2014; **18 months**]
- Strong interest of CEPC group for CEPC simulations [≈ 2013 — now] Talk by Manqi Ruan
- 04/2015, ALCW'15 Tokyo: LC generator group endorsed v2.2 for new mass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

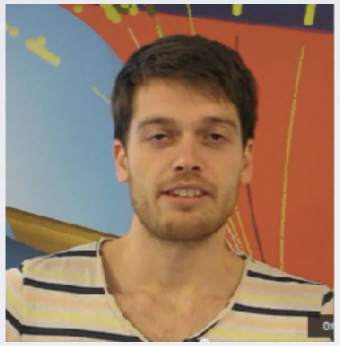
WHIZARD: Past and recent timeline (II)

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

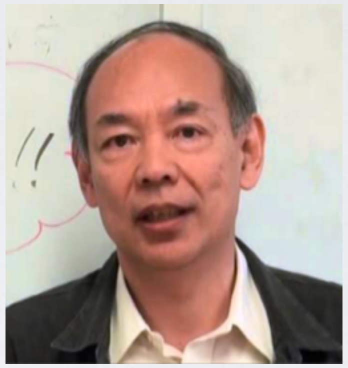
  Special thanks to: [beam spectra, photon background, event formats, shower/hadronization, tau decays]


Mikael Berggren

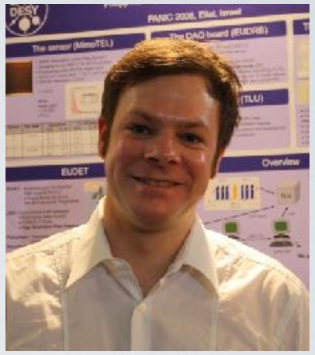

Jean-Jacques Blaising


Moritz Habermehl


Mo Xin


Akiya Miyamoto


Tim Barklow


Philipp Roloff

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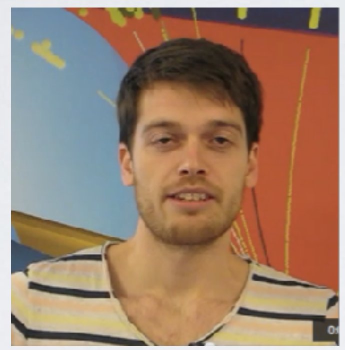

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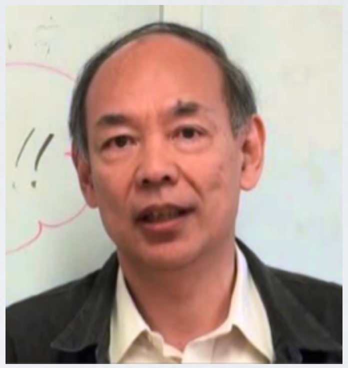

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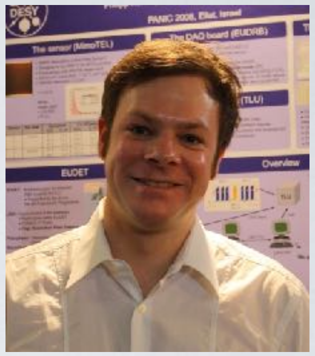


Philipp Roloff

- 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 phase for `WHIZARD 3.0.0` 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+`)

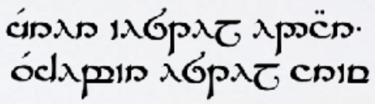
  [mid / end of 2019; when NAG debugging compiler support ready]

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]`
- Event formats: LHE, StdHEP, HepMC, LCIO + several ASCII
  - Scattering processes and [auto-] decays

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

  - Factorized processes with spin correlations [variants: no correlations, definite helicity, predefined branching ratios]
  - Scripting language for the steering: `SINDARIN`



  - Beam structure: polarization, asymmetric beams, crossing angle, structured beams, decays

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

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

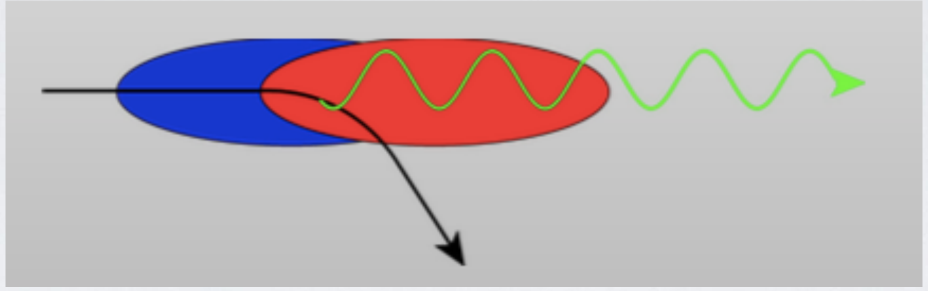
```
beams = e1, E1 => circe2 => isr => ewa
```

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 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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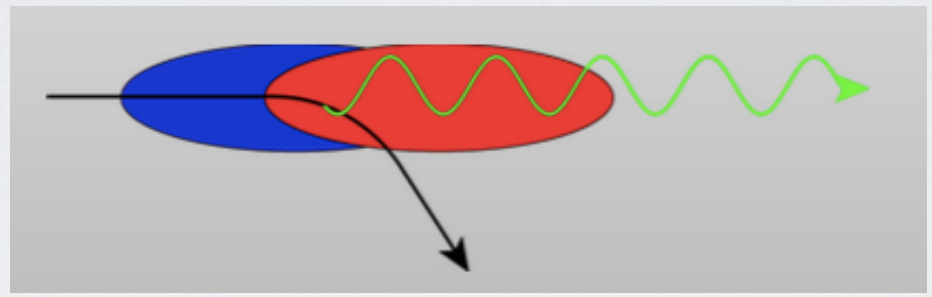

Index of /circe_files/CLIC

Name	Last modified	Size	Des
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

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

Index of /circe_files/ILC

Name	Last modified	Size	Description
Parent Directory		-	
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	

Index of /circe_files/CEPC

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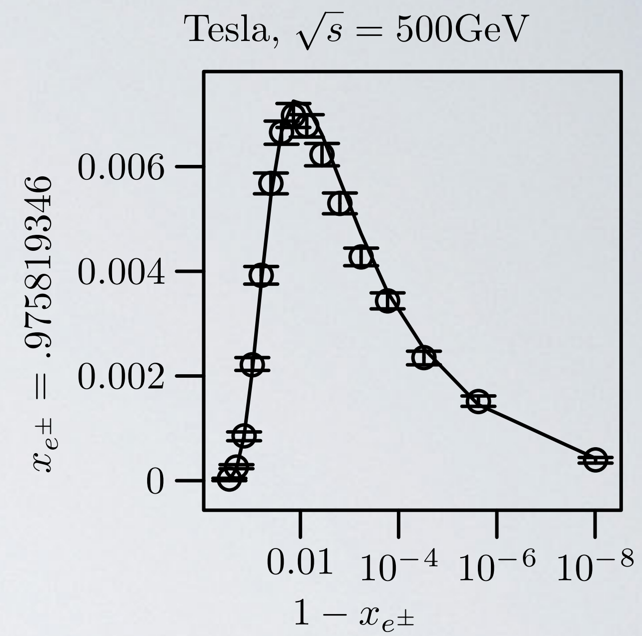
cepc240.circe	29-Jul-2016 13:20	252K	
cepc250.circe	29-Jul-2016 13:20	252K	

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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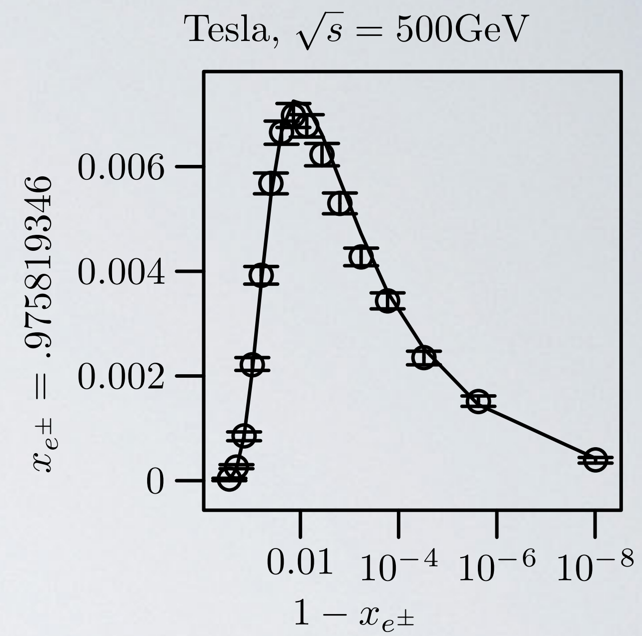

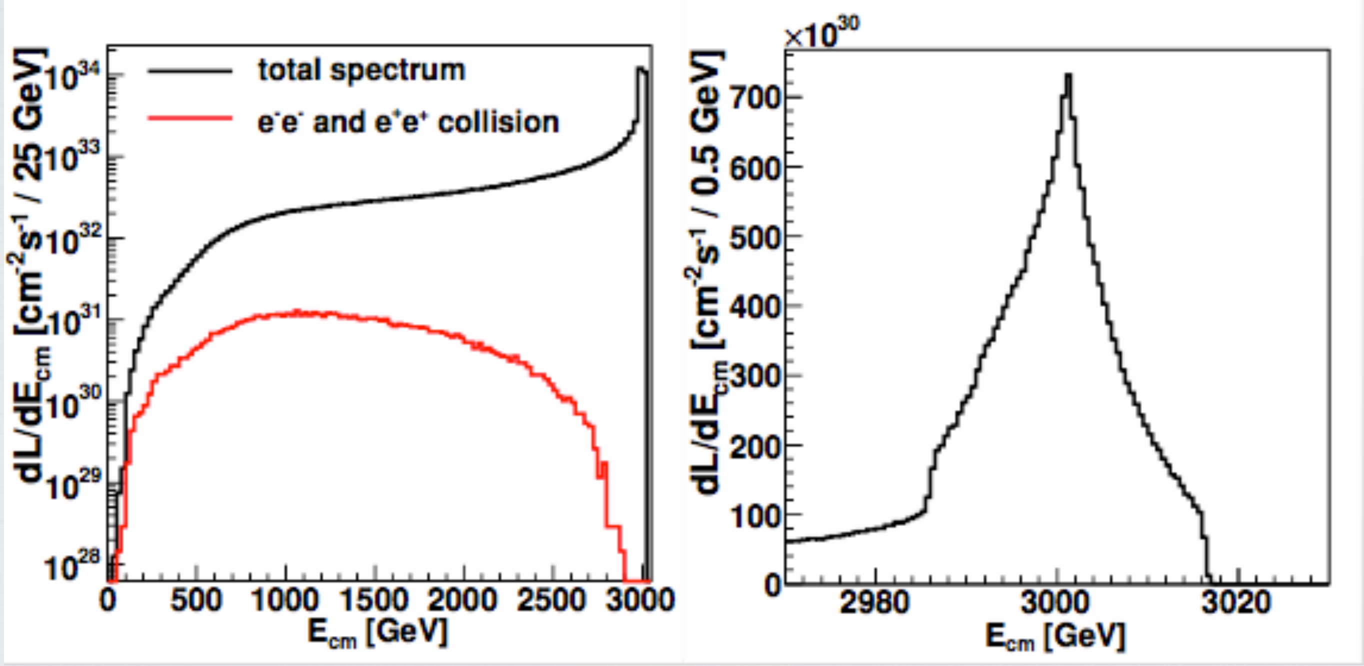

Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)

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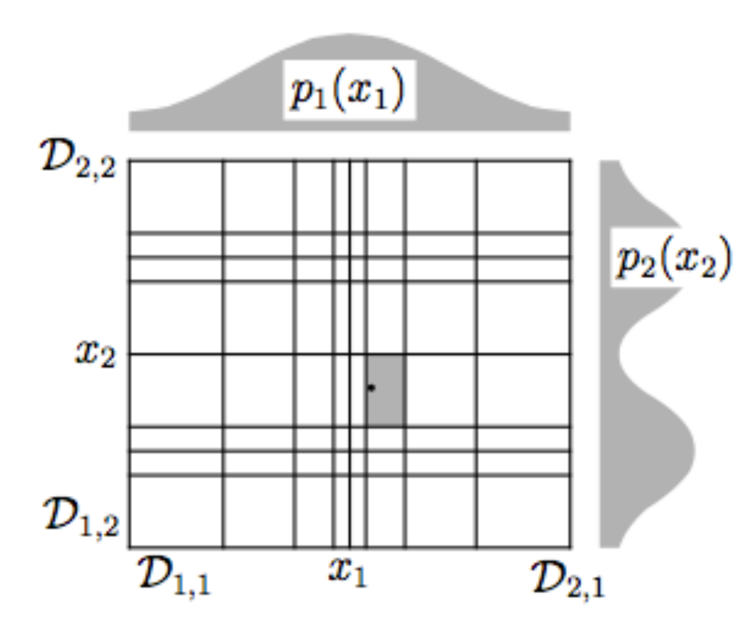

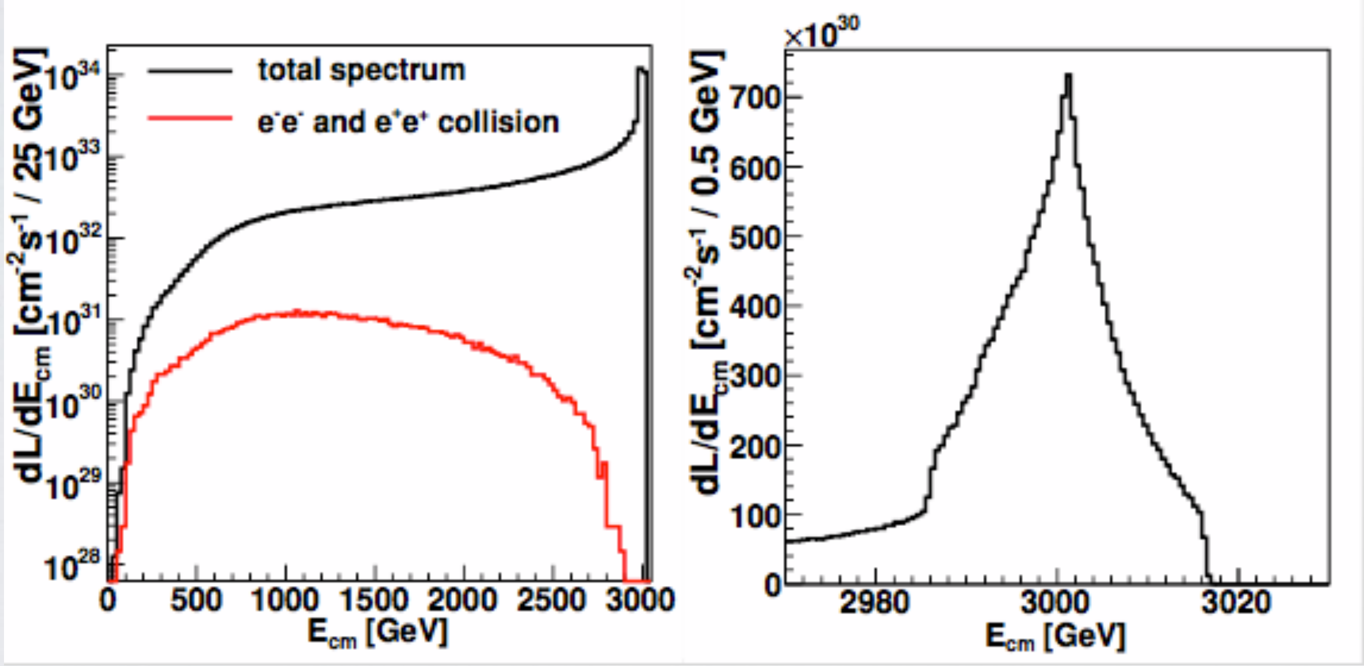

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Tails @ CLIC much more complicated (wakefields)

`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]

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

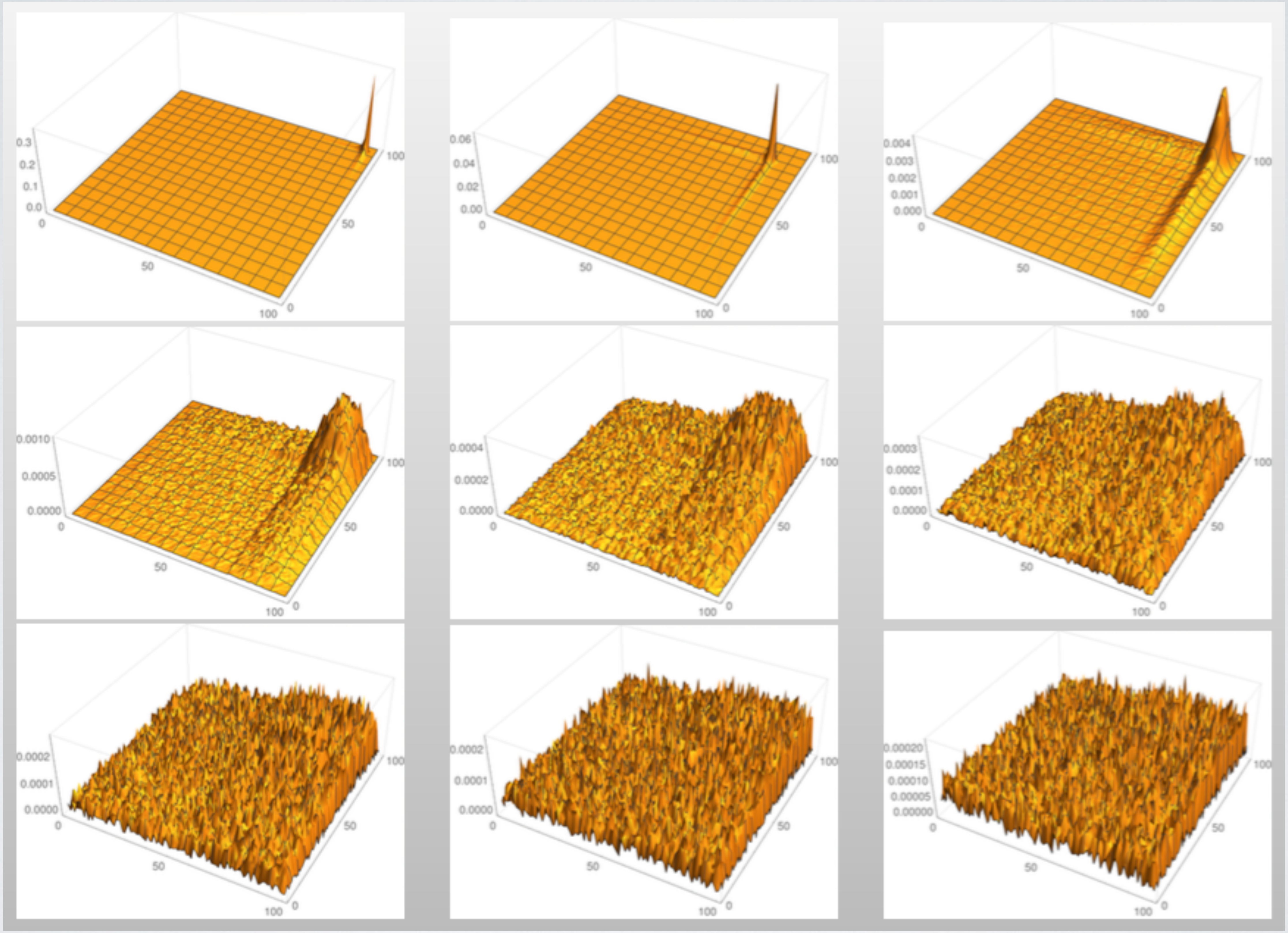
3. Run `WHIZARD` with `SINDARIN` input:

```
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

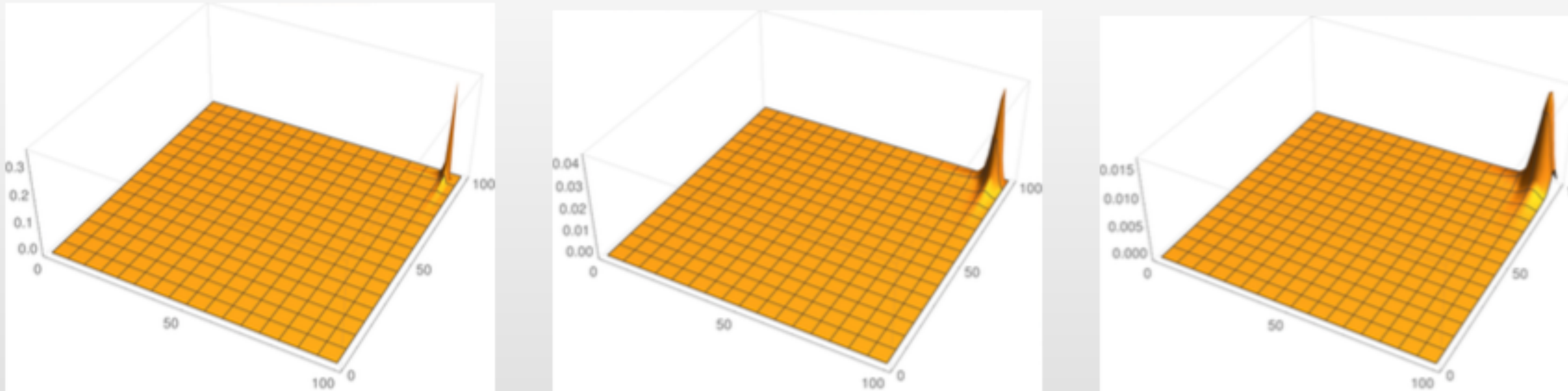
Iterations of Beam Spectrum



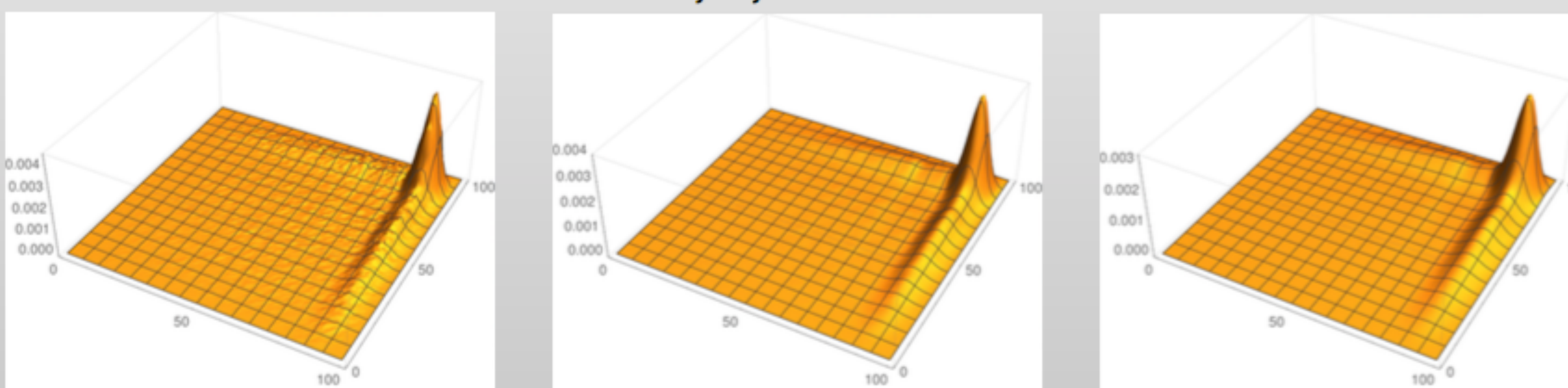
(171,306 GuineaPig events in 10,000 bins)

Iterations of Beam Spectrum

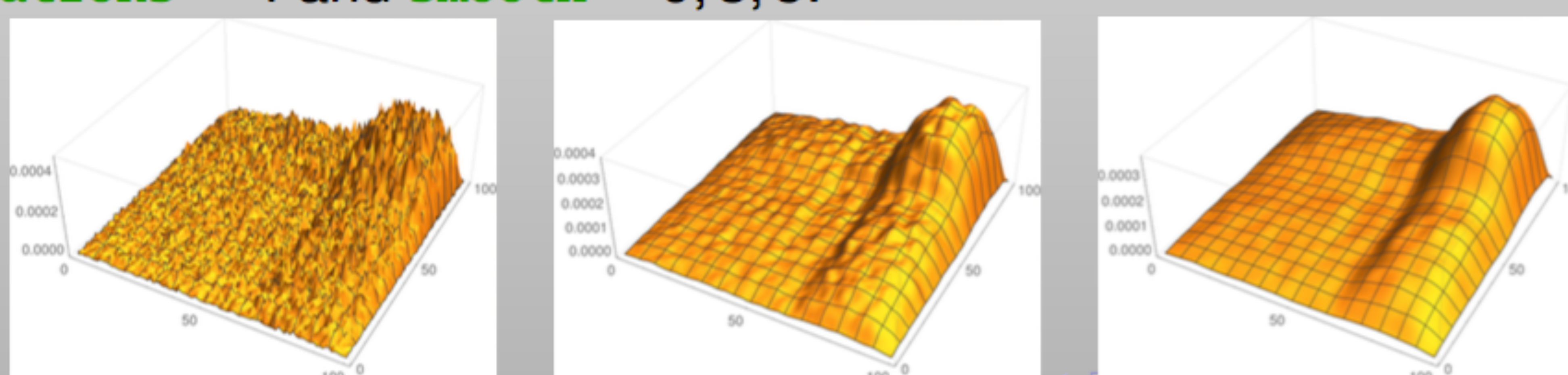
- iterations = 0 and smooth = 0, 3, 5:



- 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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Hard-collinear photons up to 3rd QED order

Kuraev/Fadin, 1983; Skrzypek/Jadach, 1991

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

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

$$\zeta(3) = 1.2020569031595942853997381615 1\ldots$$

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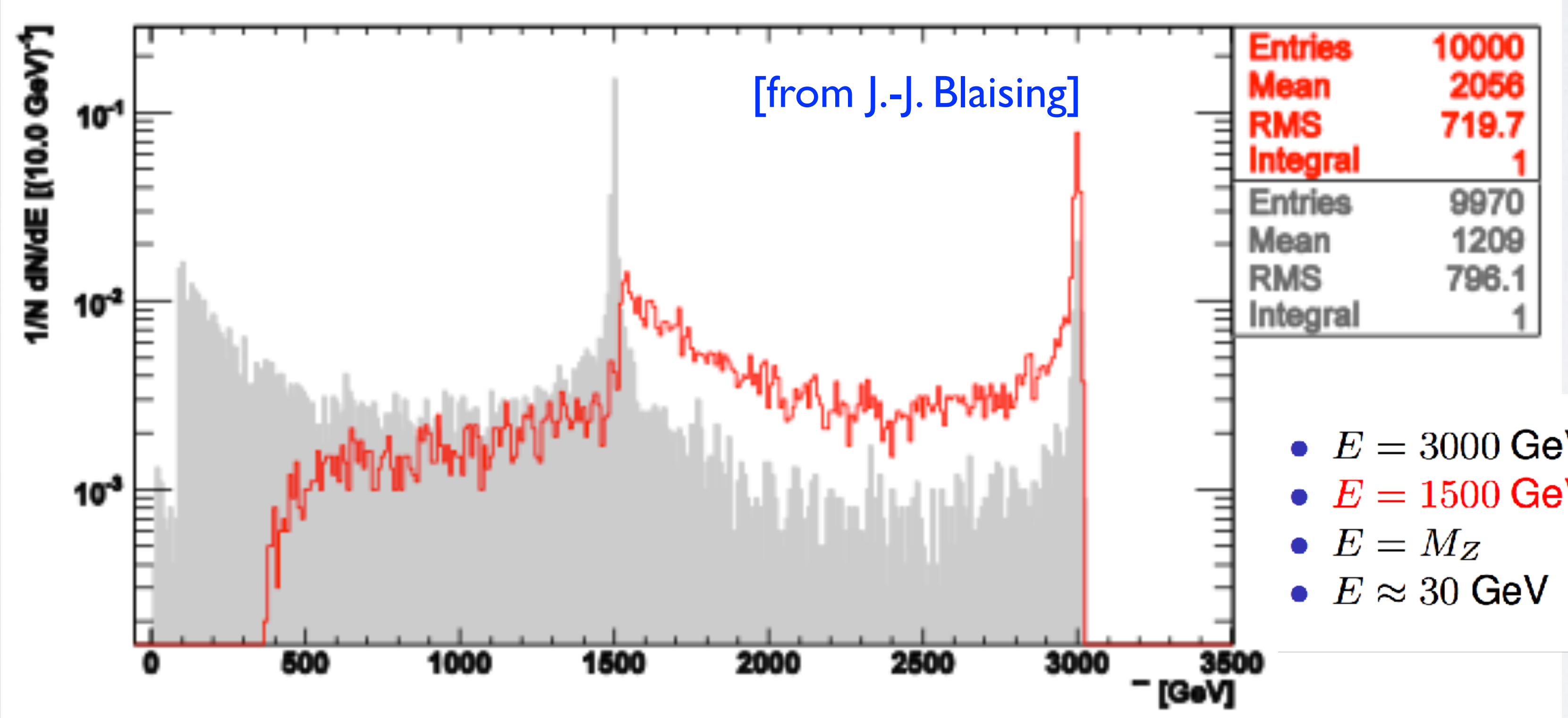
$$\begin{aligned} f_3(x) = {} & g_3(\epsilon)\, f_0(x) - \frac{\epsilon}{2}(1+x) \\ & - \frac{\epsilon^2}{8}\left(\frac{1+3x^2}{1-x}\ln x + 4(1+x)\ln(1-x) + 5 + x\right) \\ & - \frac{\epsilon^3}{48}\Bigg((1+x)\left[6\,\mathrm{Li}_2(x) + 12\ln^2(1-x) - 3\pi^2\right] + 6(x+5)\ln(1-x) \\ & \qquad + \frac{1}{1-x}\left[\frac{3}{2}(1+8x+3x^2)\ln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

$$\zeta(3) = 1.2020569031595942853997381615 1\ldots$$



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

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

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

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

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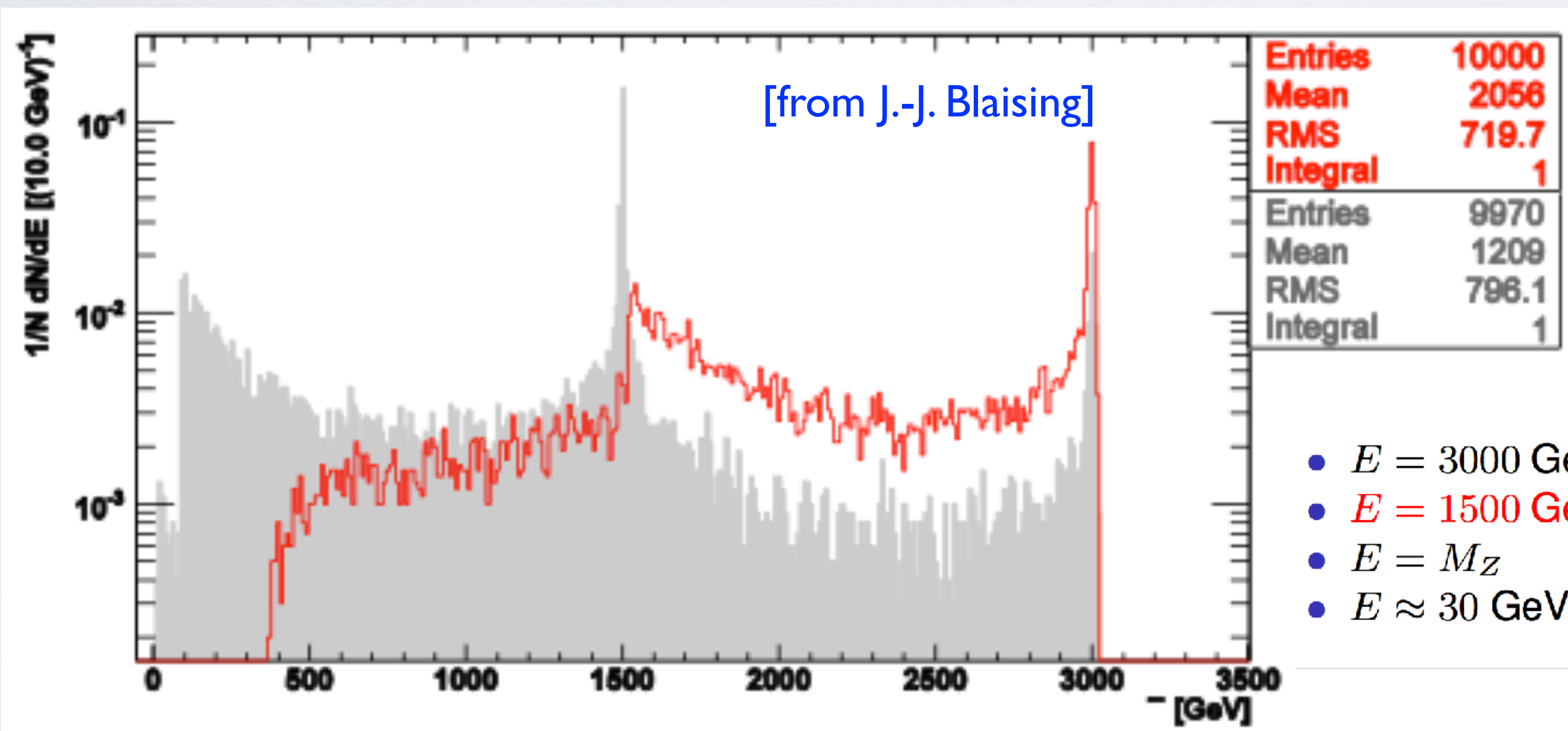

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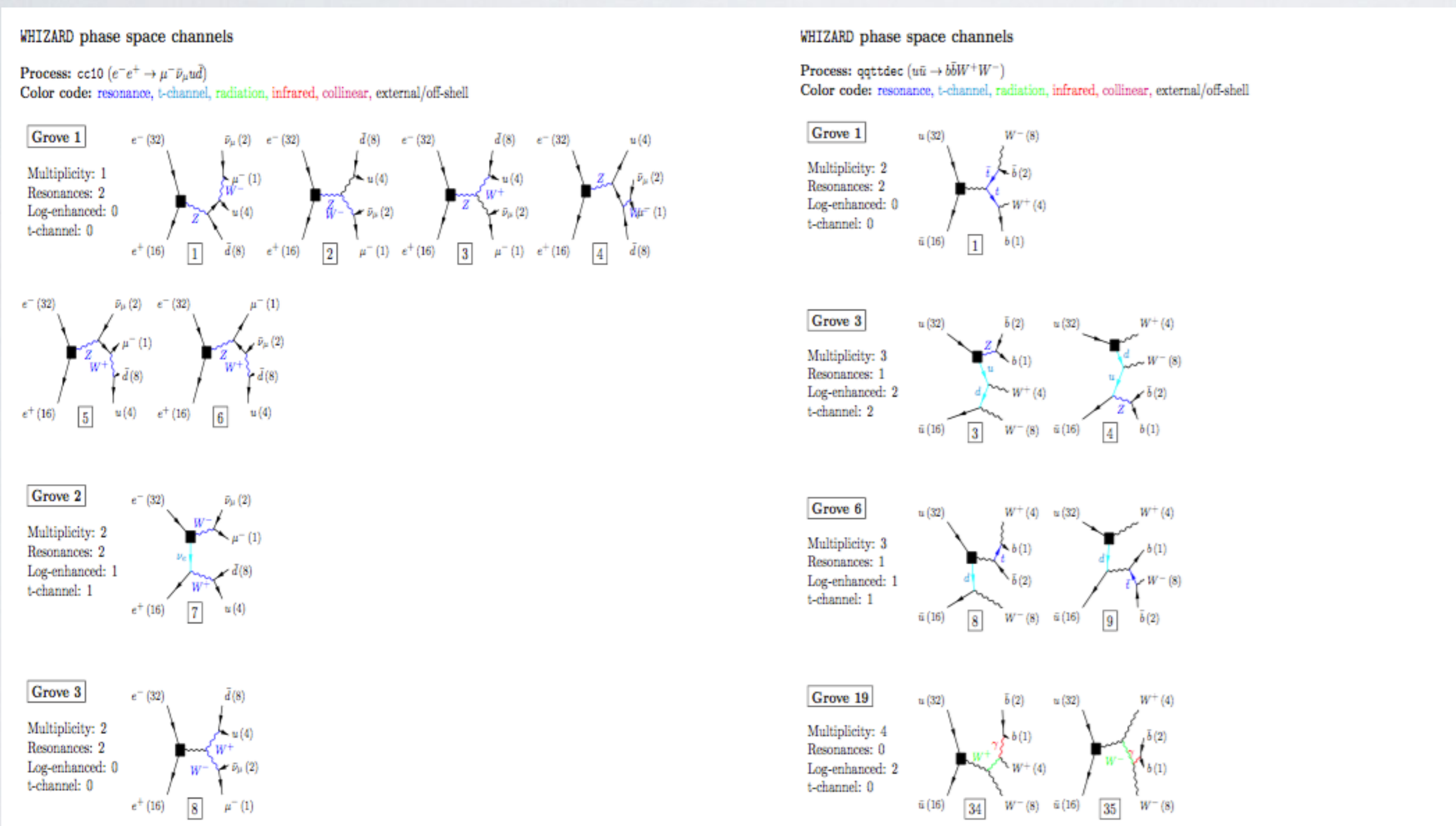
- $E = 1500$ GeV (Z peak and lumi spectrum)
- $E = M_Z$ (Z resonance)
- $E \approx 30$ GeV (due to $e^+e^- \to \gamma^* \to b\bar{b}$)

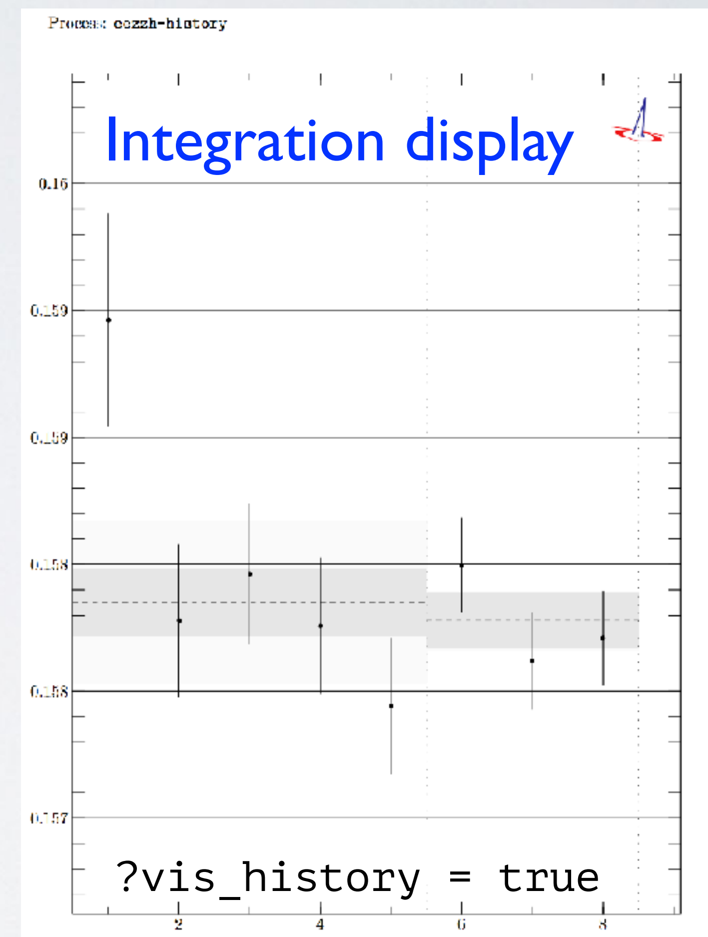
- ☐ One explicit ISR photon / beam: ISR/EPA handler generates physical p_T distributions
- ☐ Explicit matching needed: heuristic procedures LO — *tbd* for NLO !

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`





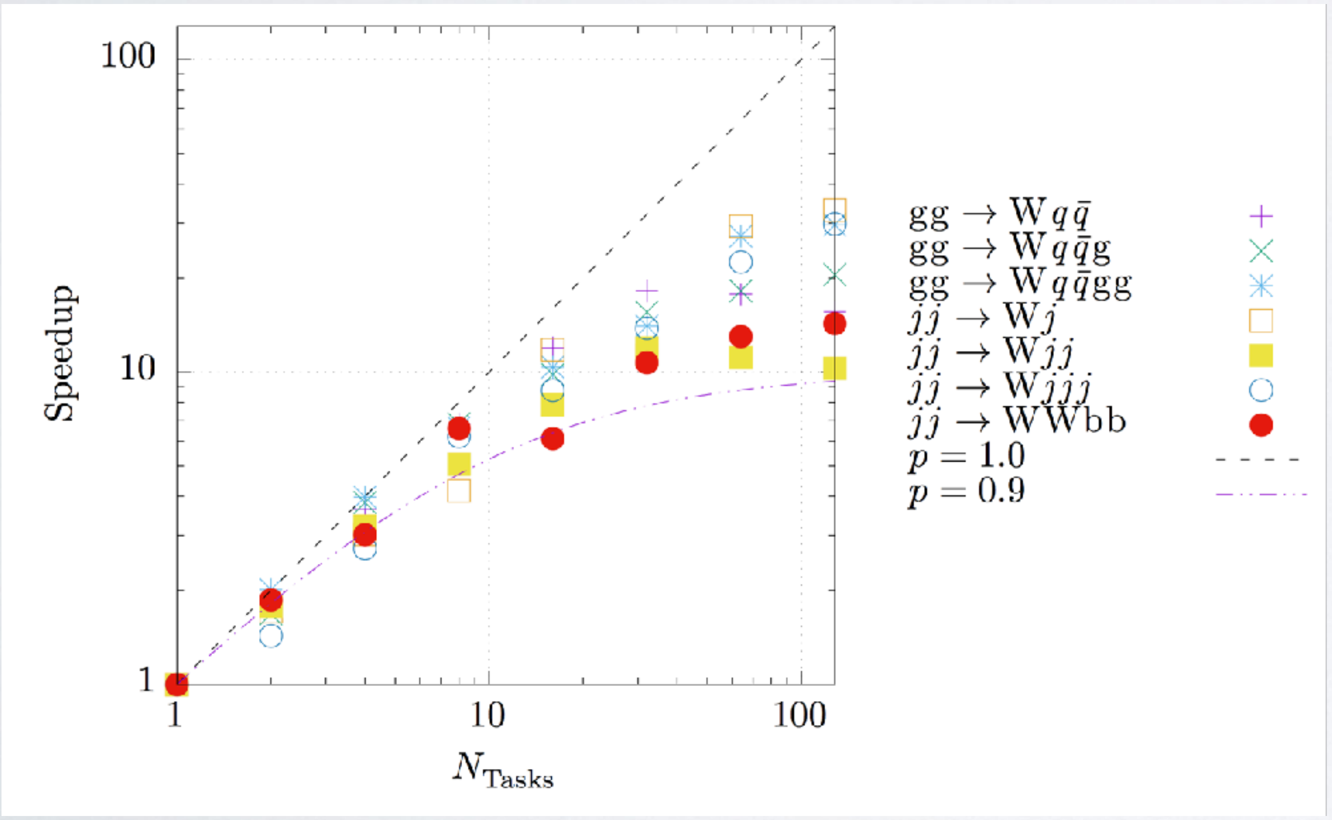
Complicated processes: factorization into production and decay with the `unstable` option

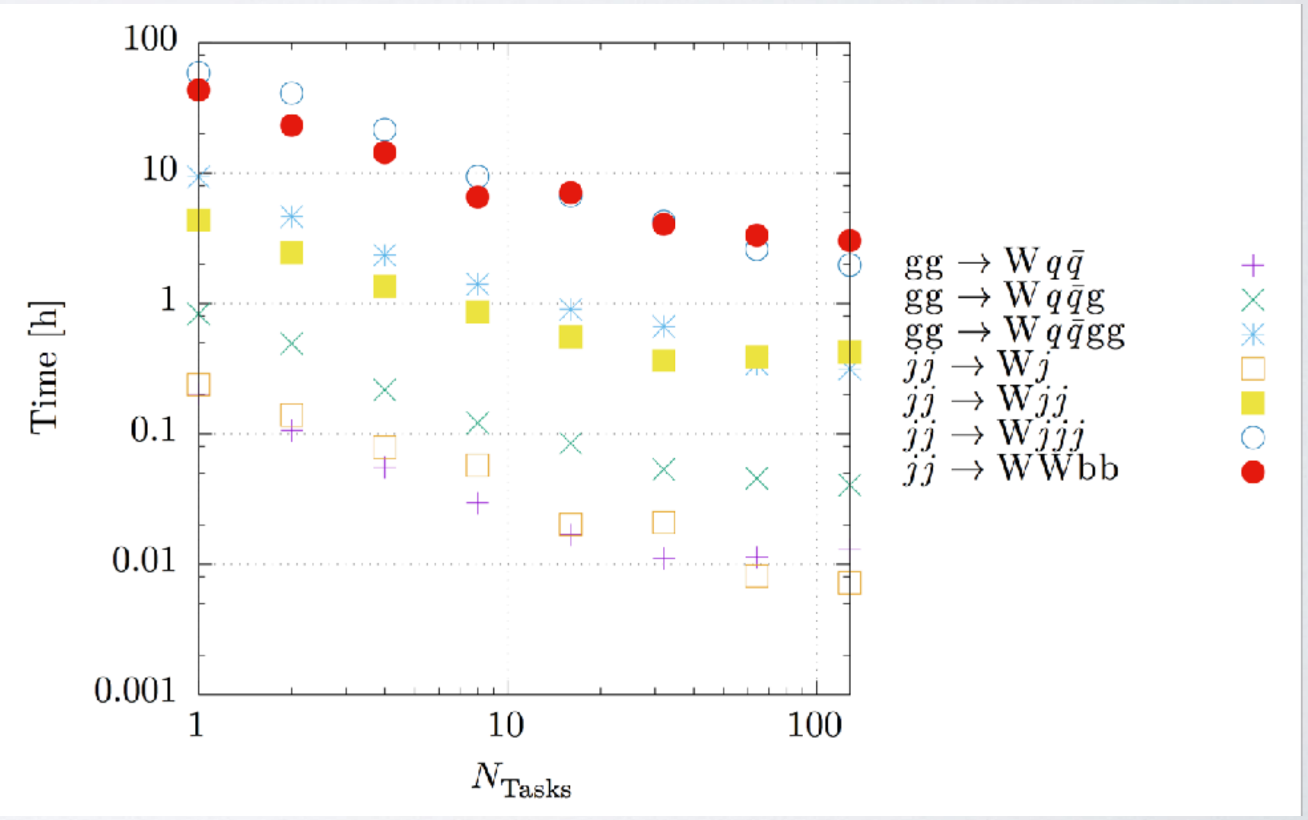
Resonance-aware factorization for NLO processes and parton showers (e.g. $e^+e^- \to jjjj$)

MPI Parallelization

Braß/Kilian/JRR, 1811.09711

- 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): 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]

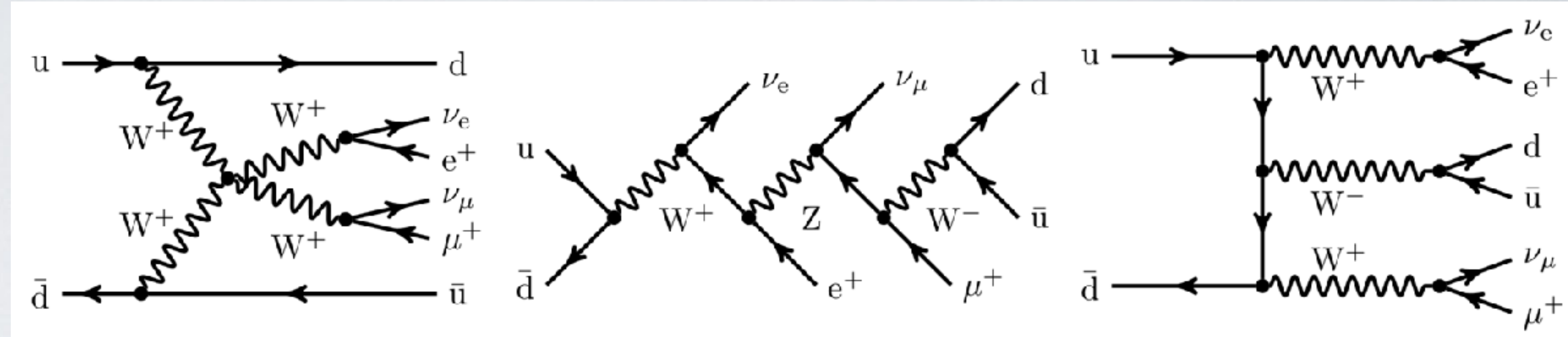




LHC VBS: Comparison LO & LO+PS

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



LO

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

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

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

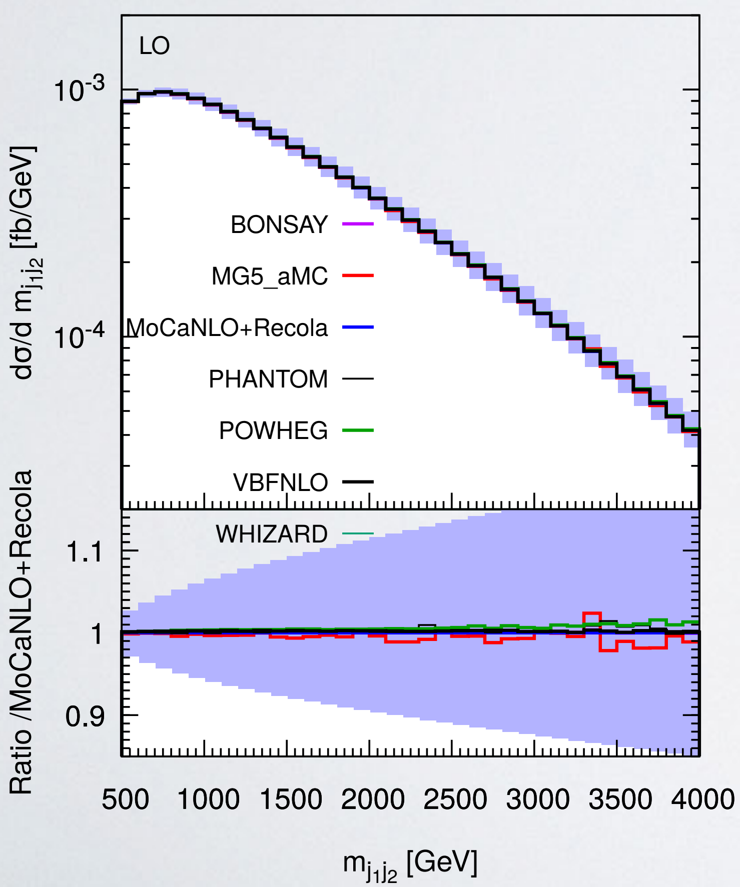
Anti-k_T jets with $R = 0.4$:

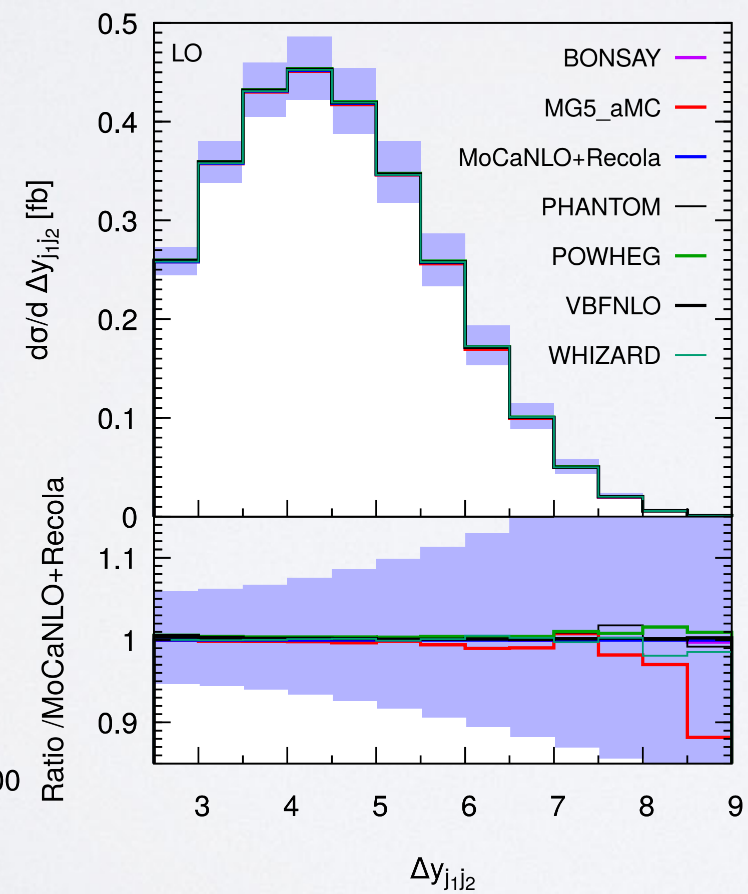
$p_{T,j} > 30$ GeV $\quad |y_j| < 4.5 \quad \Delta R_{\ell j} > 0.3$

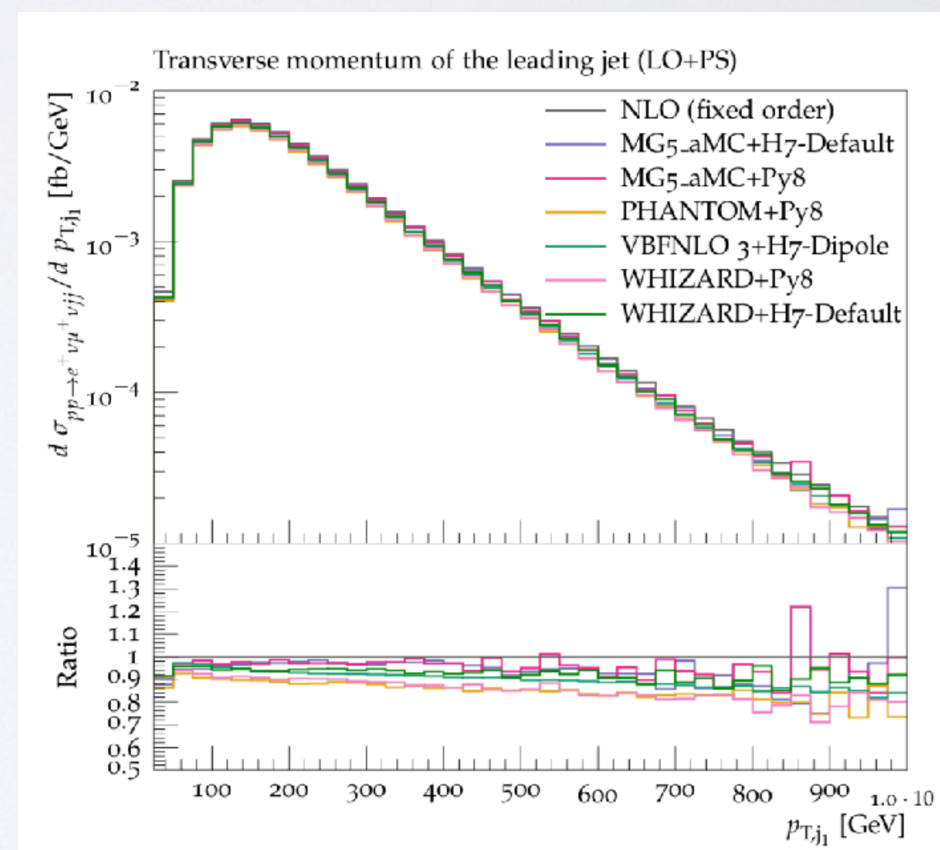
$m_{jj} > 500$ GeV $\quad |\Delta y_{jj}| > 2.5$

LO+PS

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







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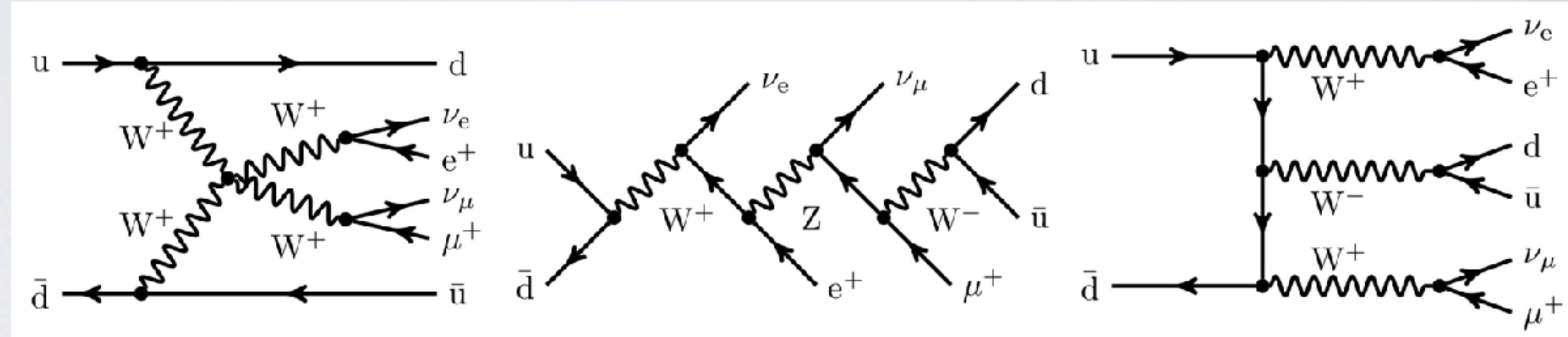

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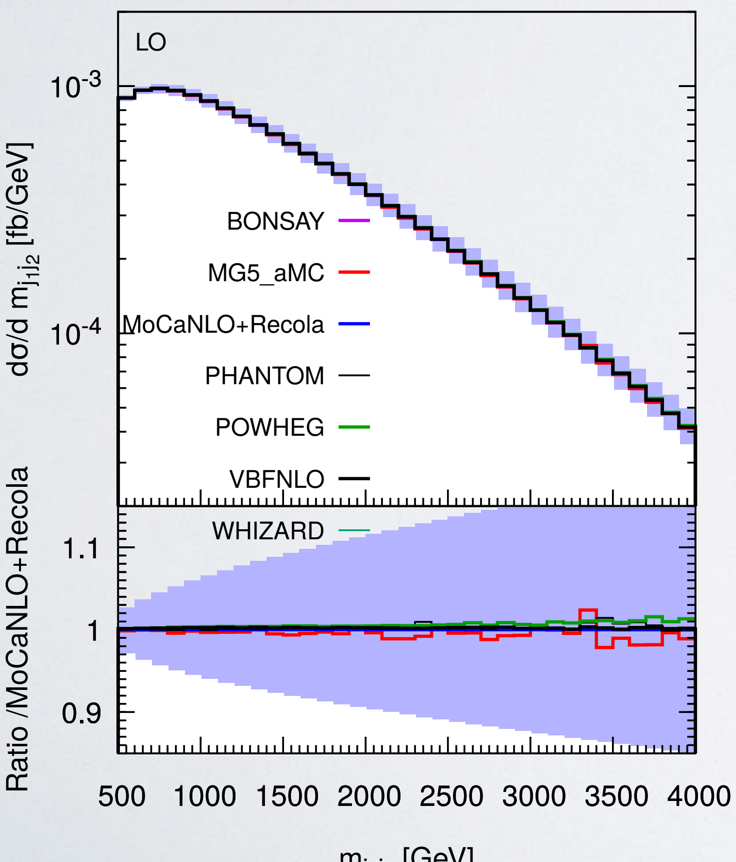
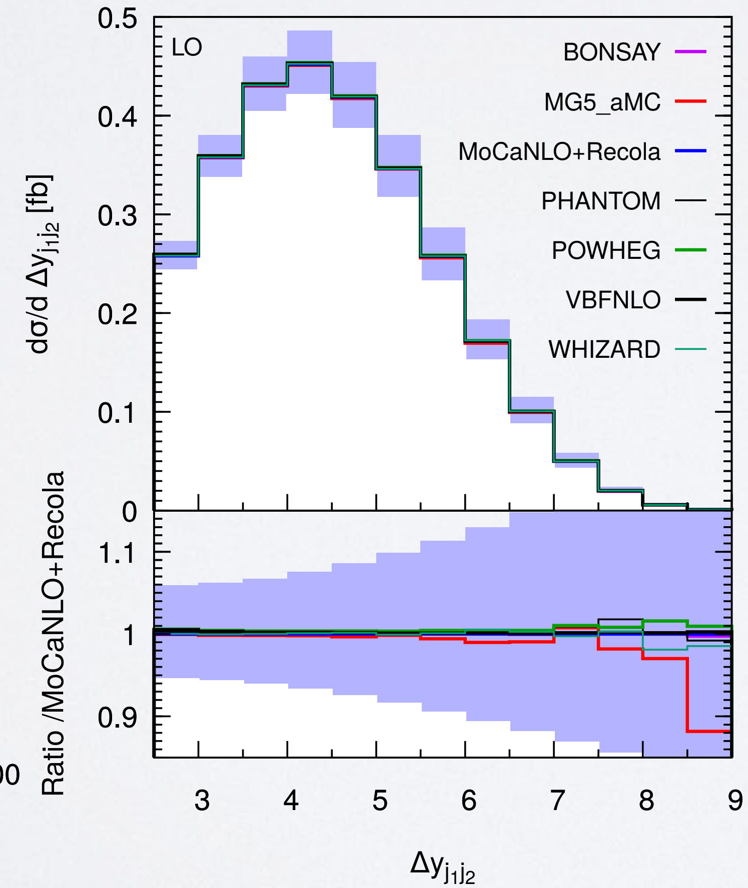
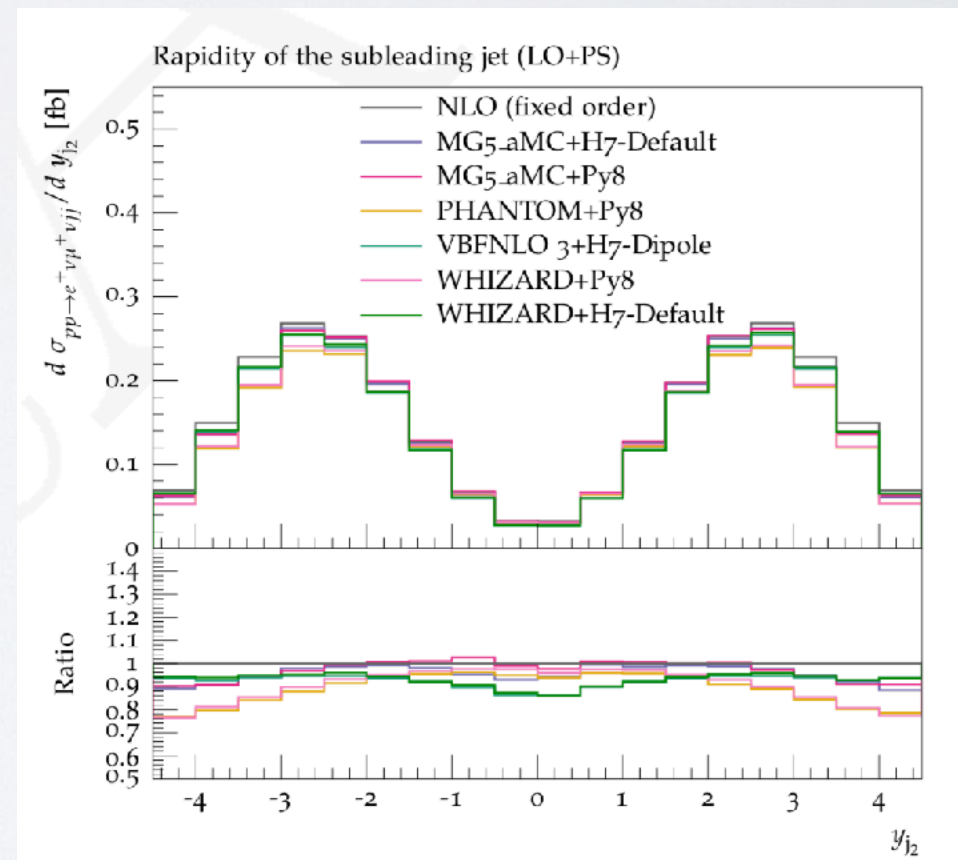
LO+PS







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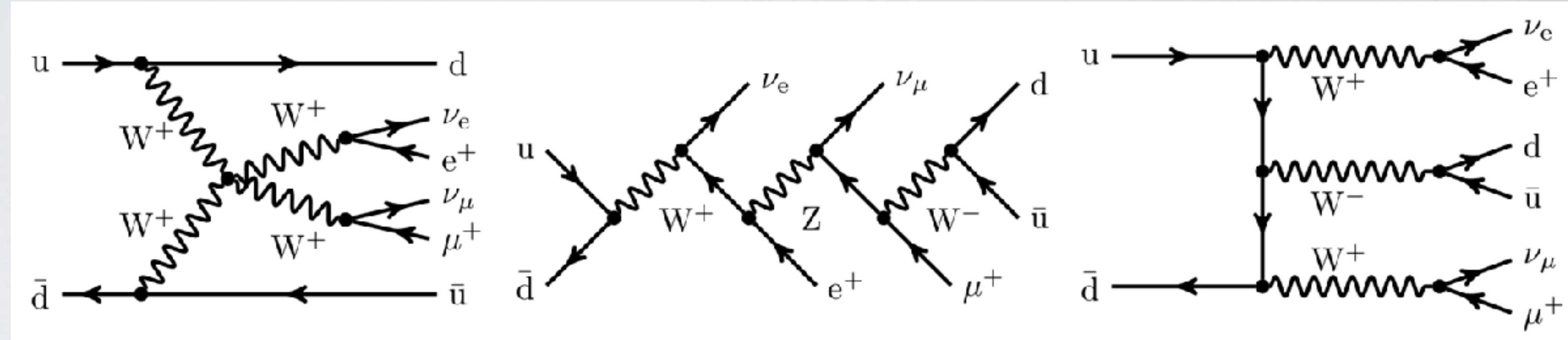

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PHANTOM	[illegible]
POWHEG	[illegible]
VBFNLO	[illegible]
WHIZARD	[illegible]

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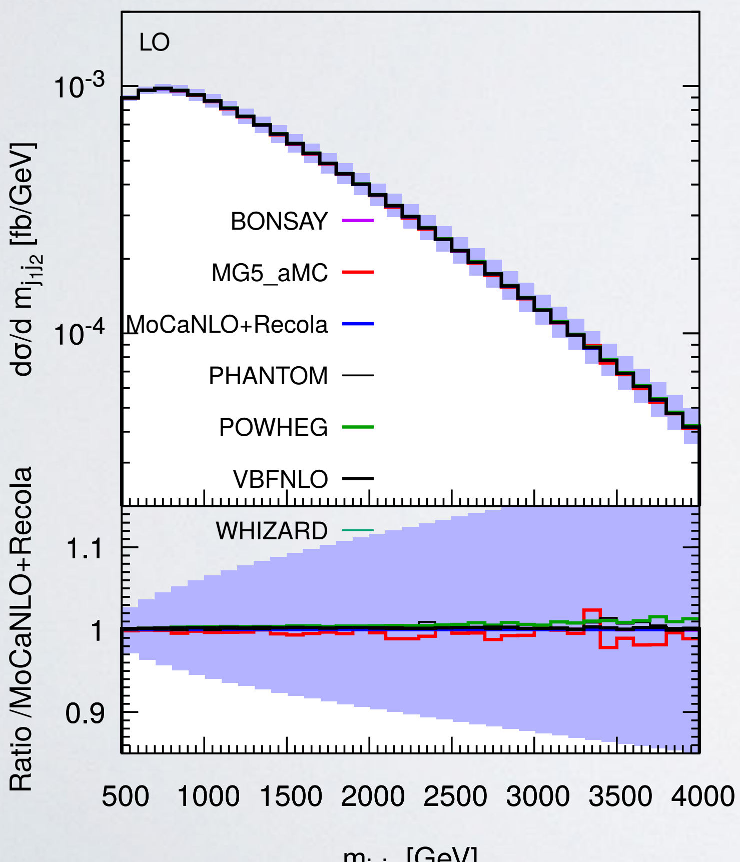
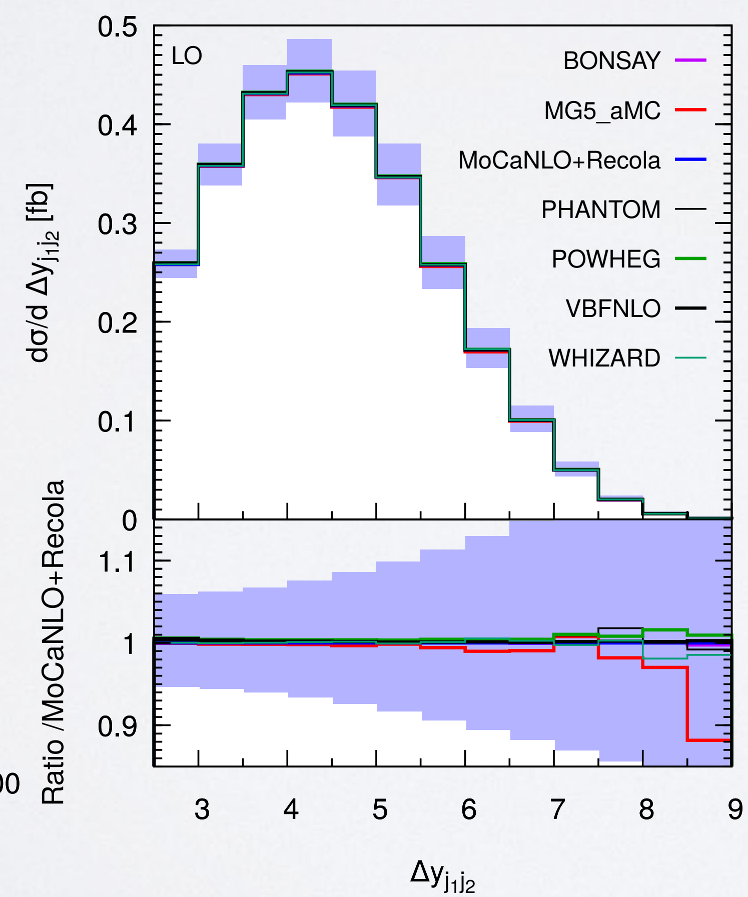
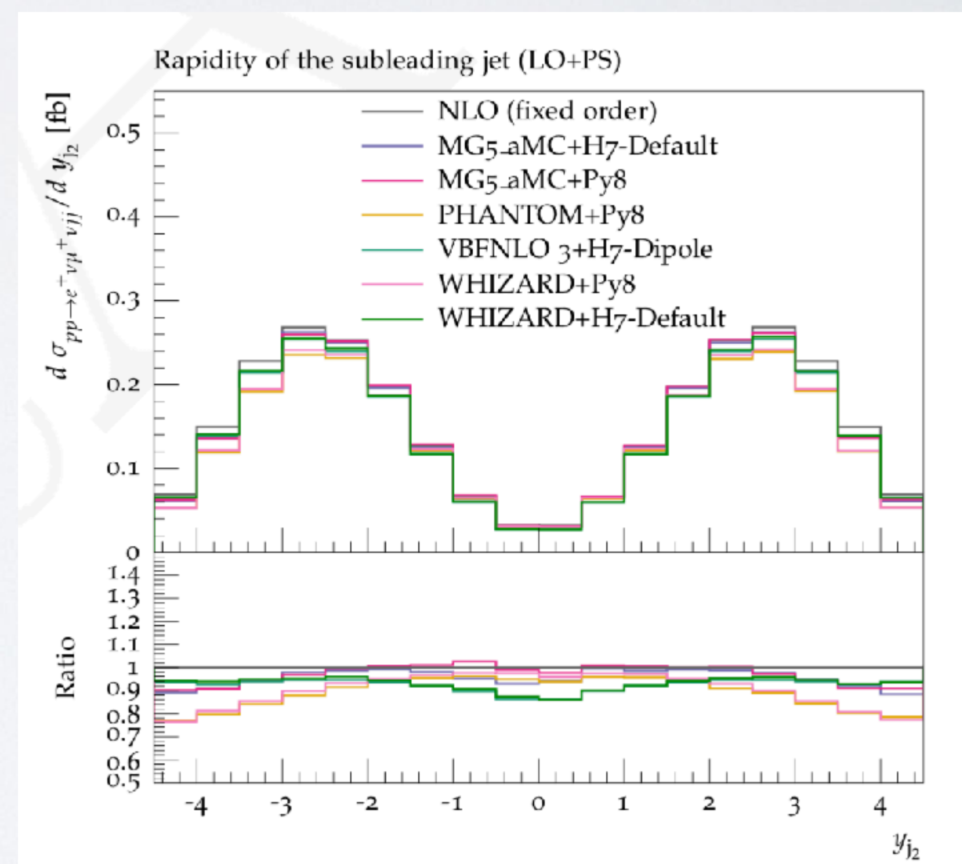
[illegible]	± 0.001
[illegible]	± 0.001
[illegible]	± 0.0002
[illegible]	± 0.001

LO+PS

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







Decay processes / auto decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

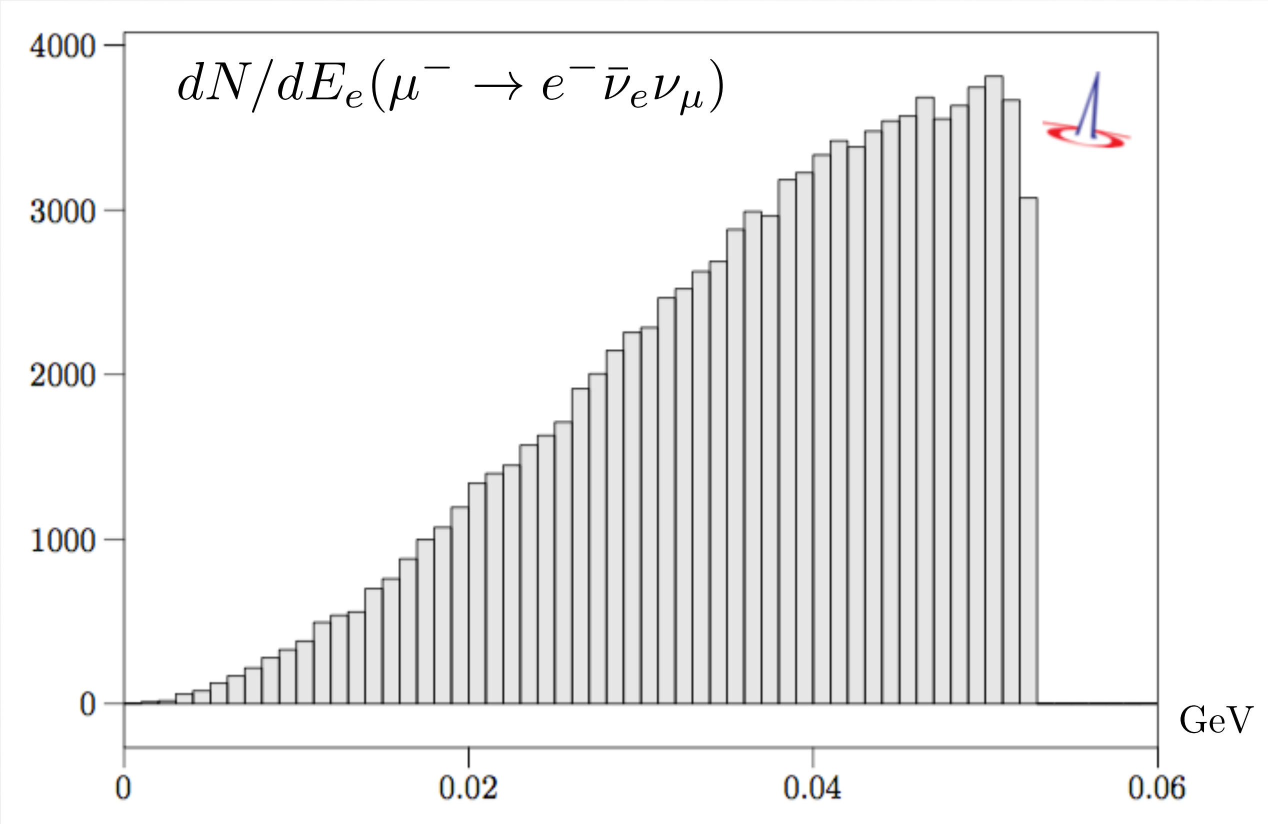
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

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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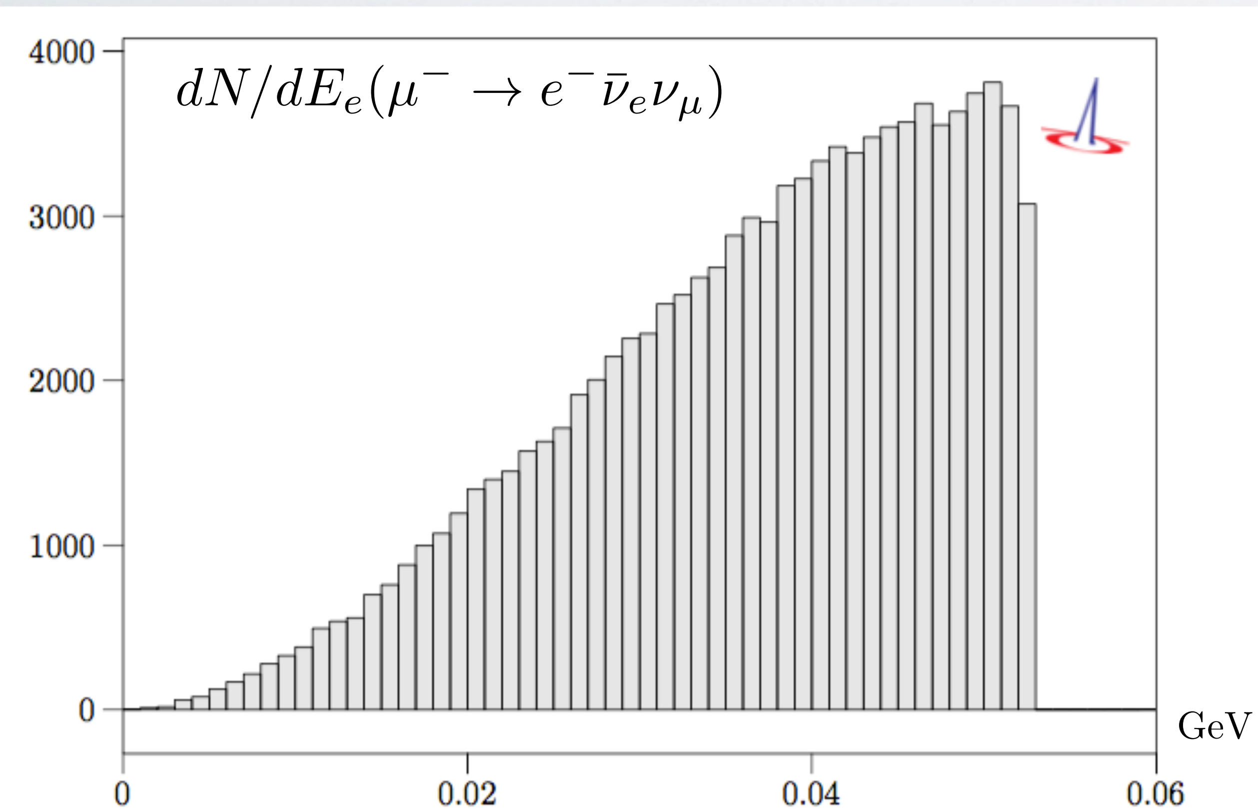

Automatic integration of particle decays

```
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
```

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 (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] - []
```

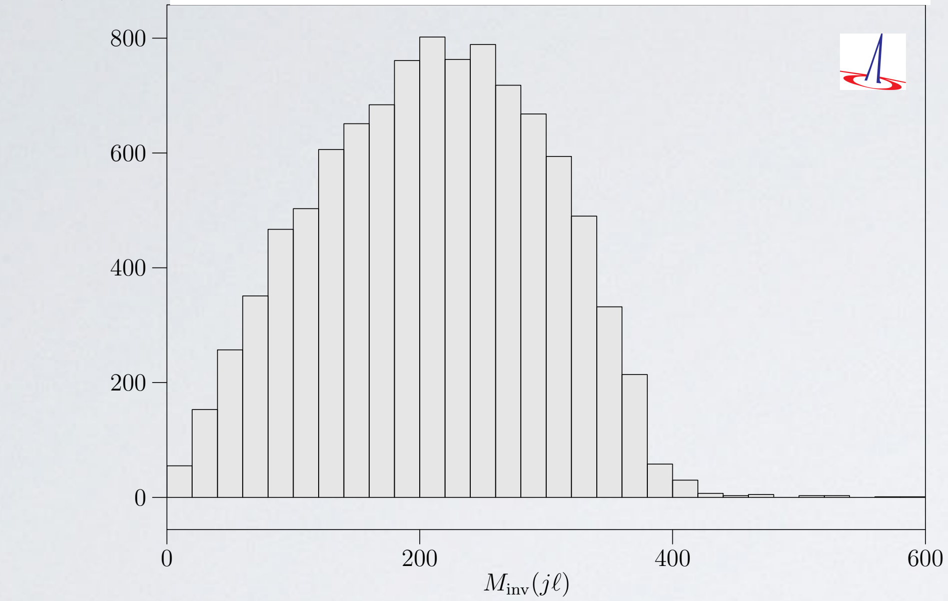
Event header information as agreed upon with LC Gen Group

Spin Correlation and Polarization in Cascades

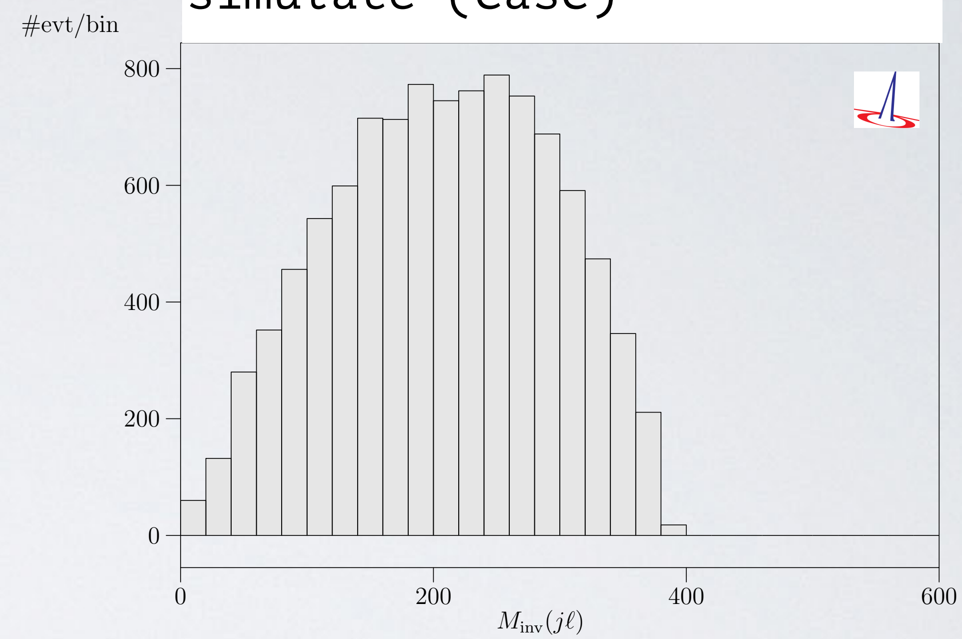
Cascade decay, factorize production and decay

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

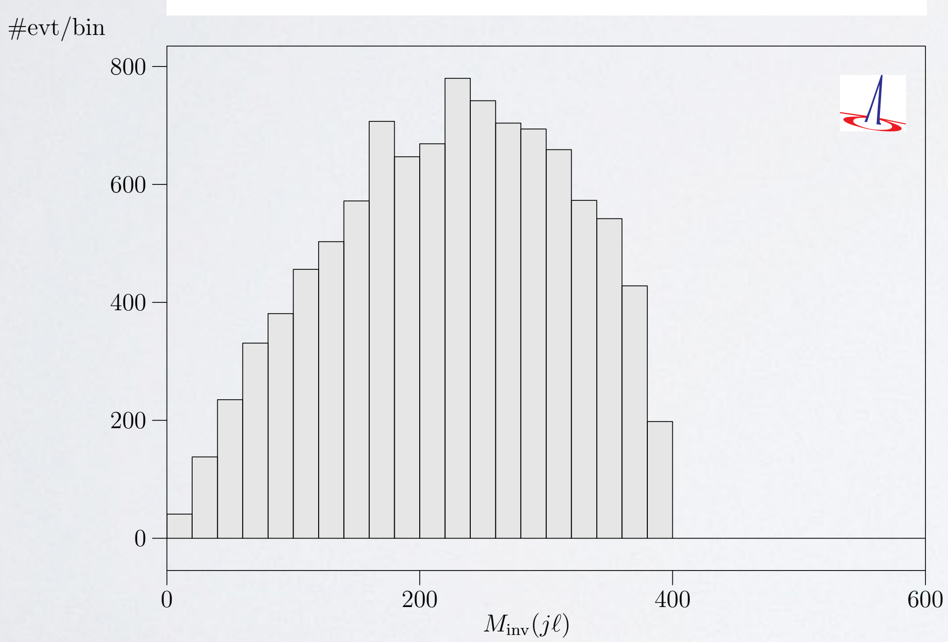
`simulate (fullproc)`



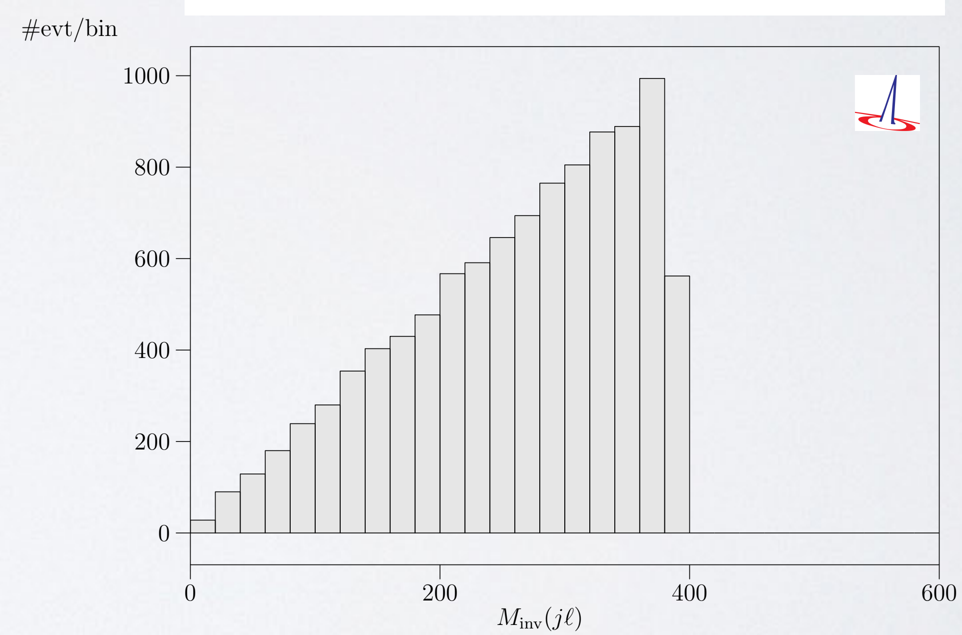
`simulate (casc)`



`?diagonal_decay = true`



`?isotropic_decay = true`



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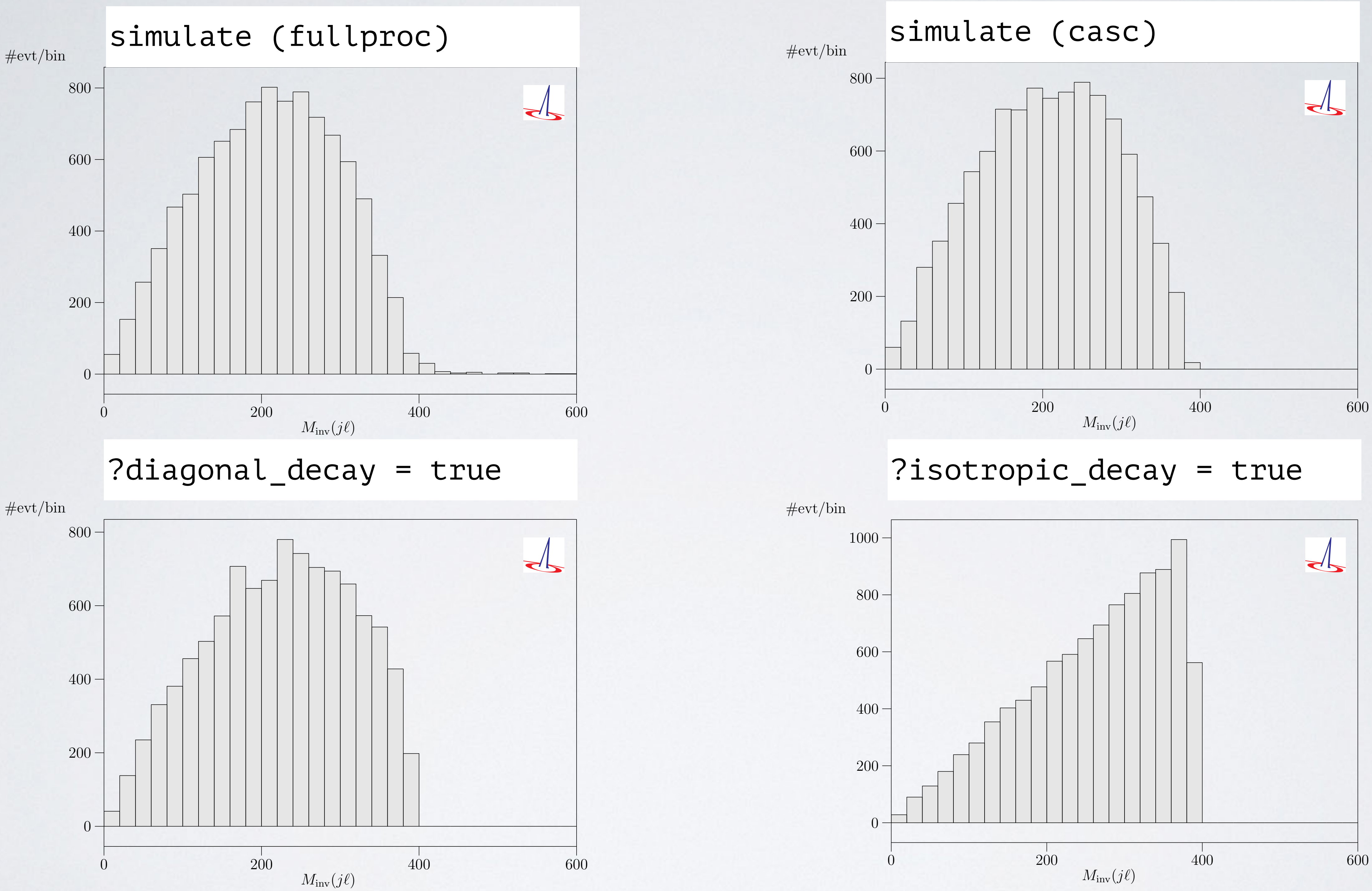

Possibility to select specific helicity in decays!

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

Keep resonances in ME-PS merging


```
?resonance_history = true
resonance_on_shell_limit = 4
resonance_on_shell_turnoff = 1
resonance_background_factor = 1e-10
```

- Problem: $e^+e^- \to jjjj$ not dominated by highest α_s power,
  but by resonances $e^+e^- \to WW/ZZ \to (jj)(jj)$
- Solution: proper merging with resonant subprocesses by means of resonance histories
- `WHIZARD v2.6.0`: option to set resonance histories

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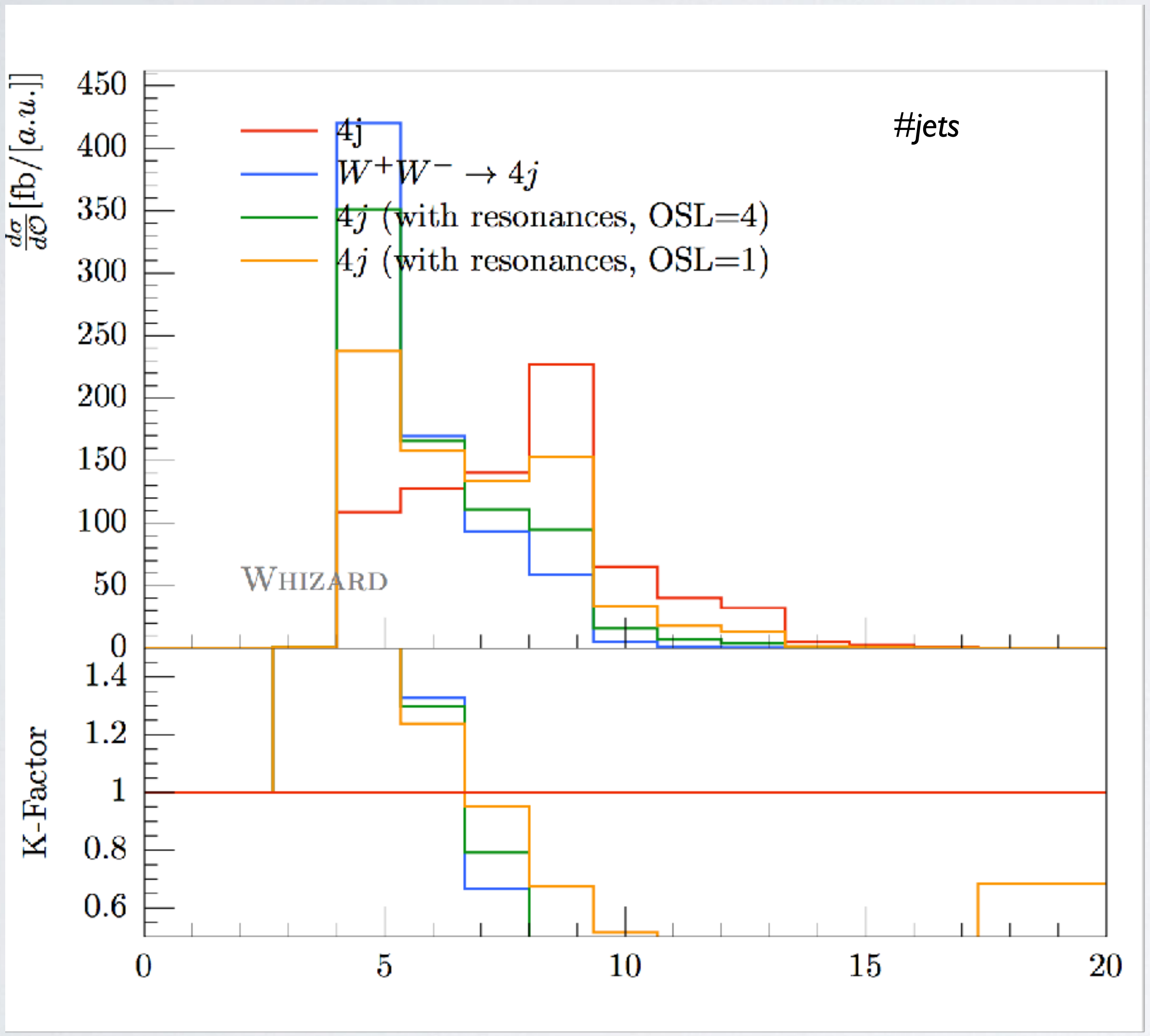

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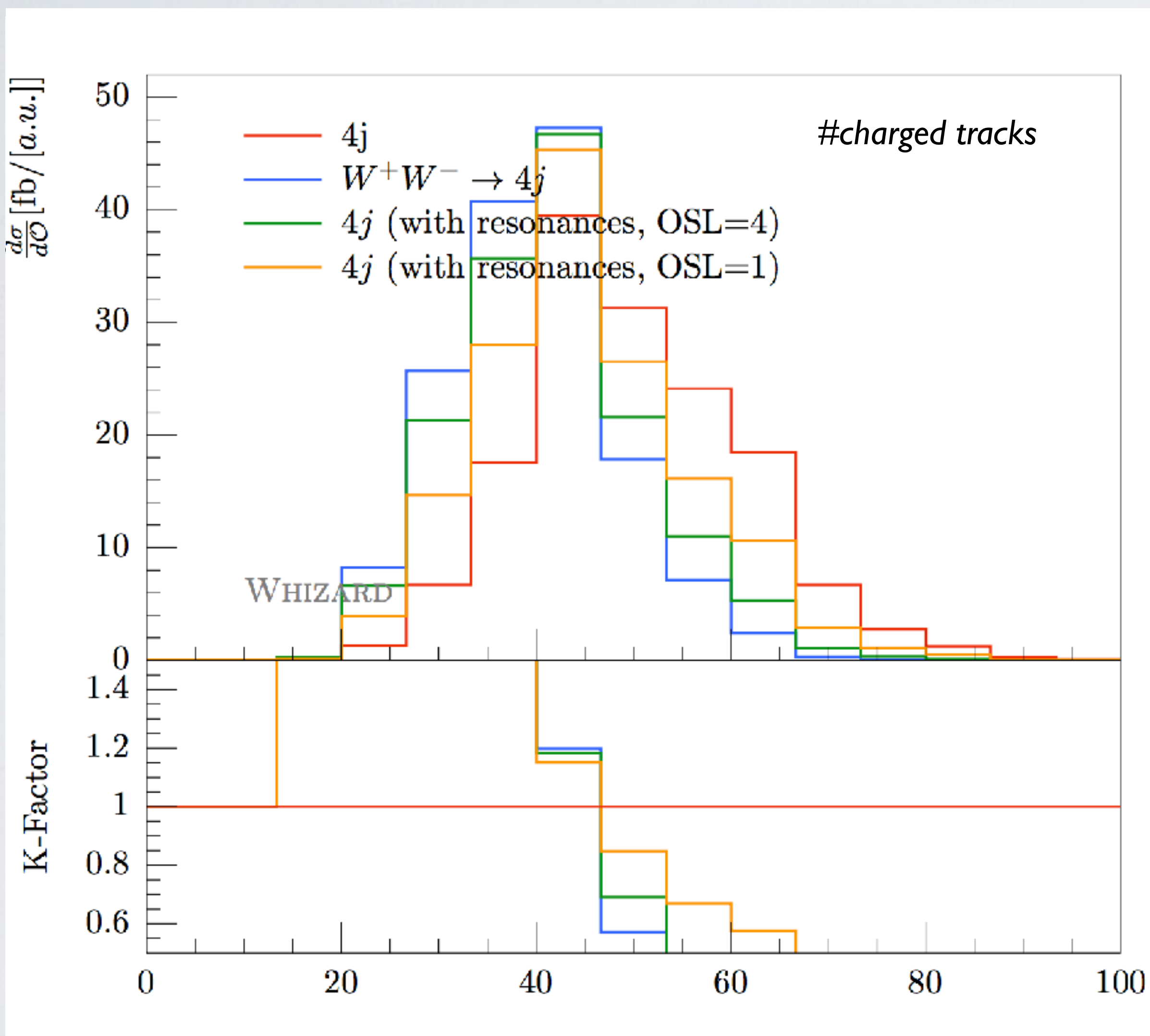
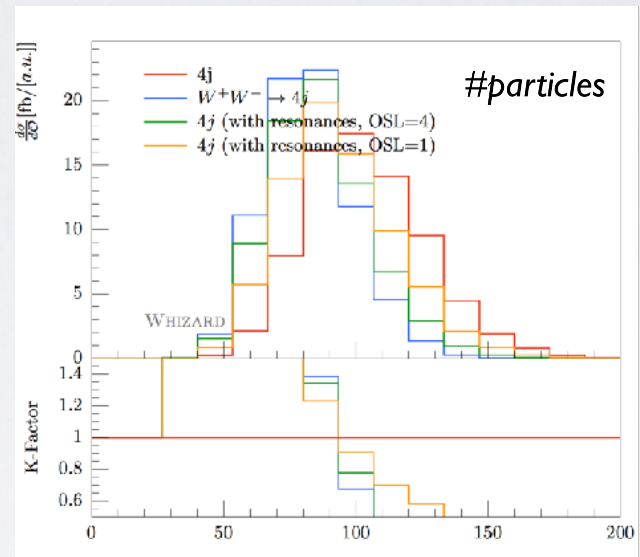
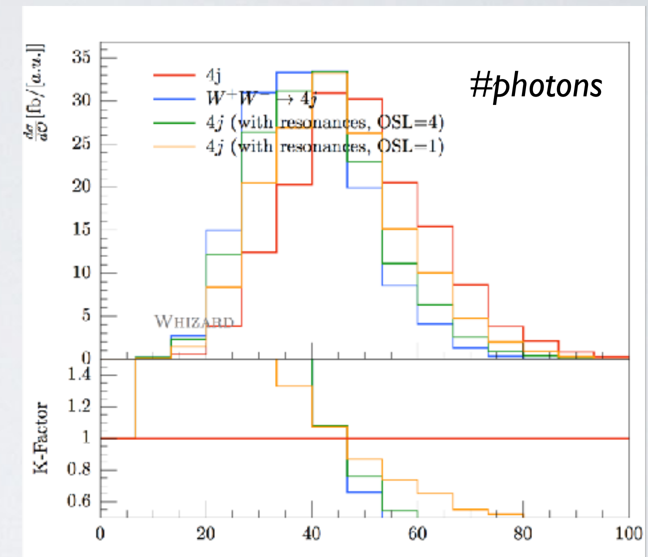
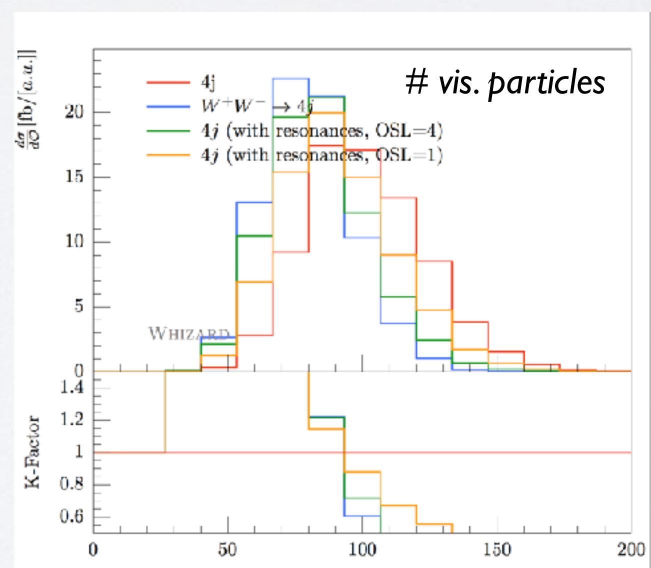
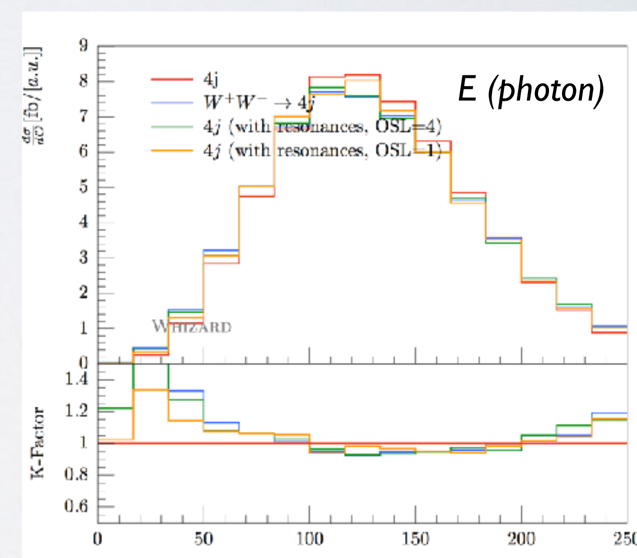






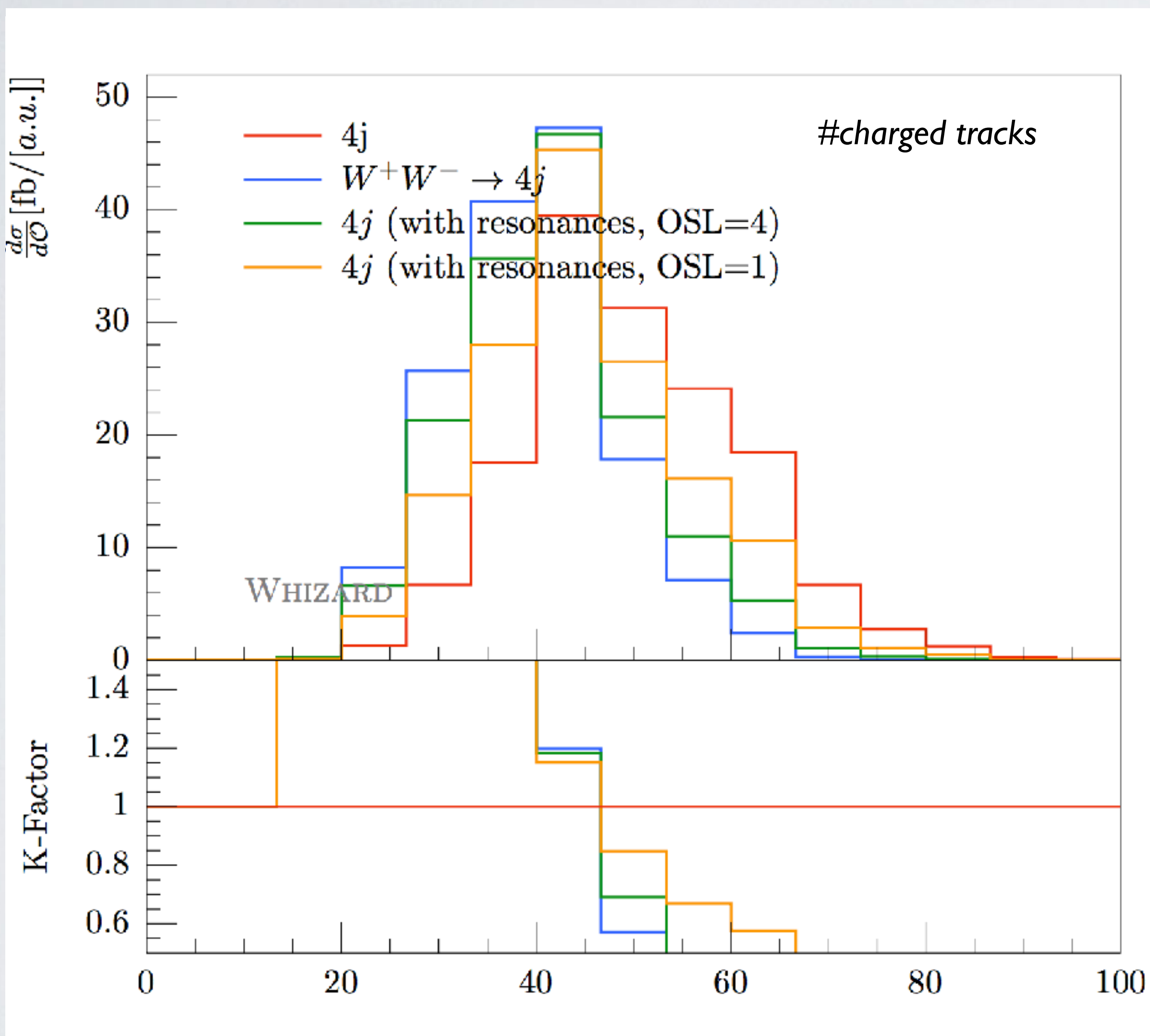


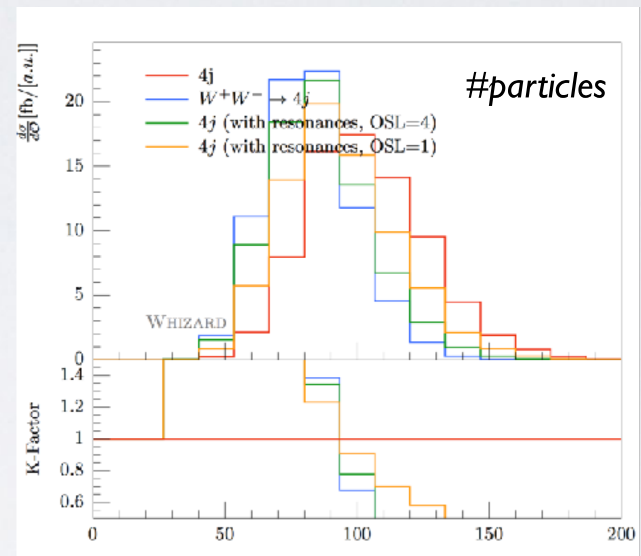


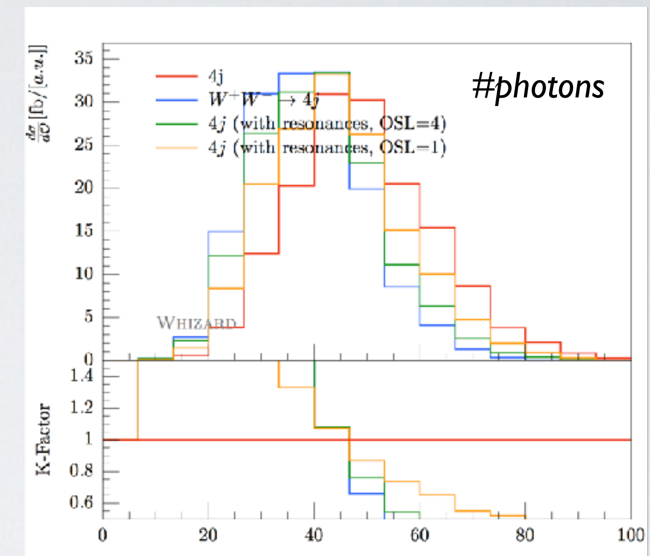
Keep resonances in ME-PS merging

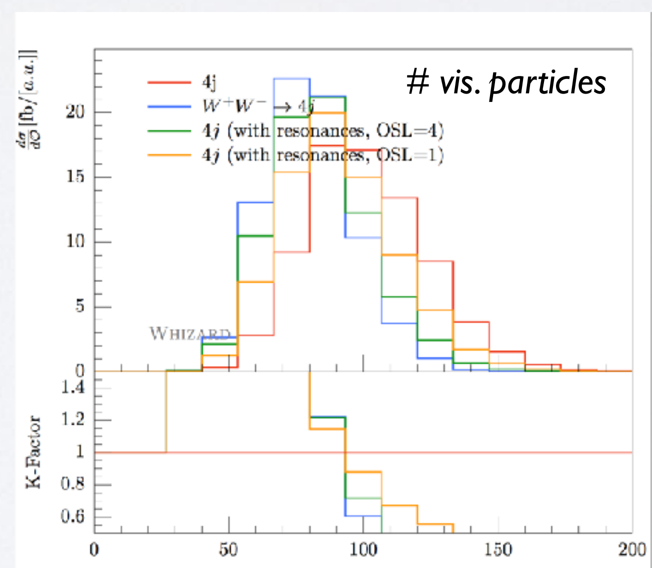

```
?resonance_history = true
resonance_on_shell_limit = 4
resonance_on_shell_turnoff = 1
resonance_background_factor = 1e-10
```

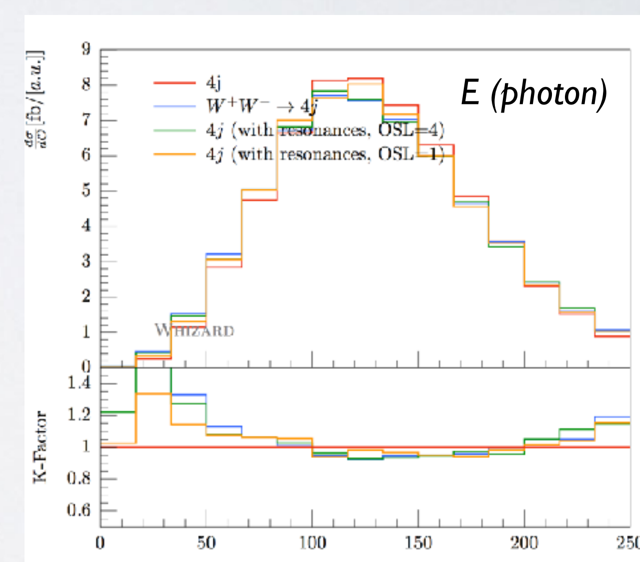
- **Problem:** $e^+e^- \to jjjj$ not dominated by highest α_s power, but by resonances $e^+e^- \to WW/ZZ \to (jj)(jj)$
- **Solution:** proper merging with resonant subprocesses by means of resonance histories
- `WHIZARD v2.6.0:` option to set resonance histories











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

BSM Models in WHIZARD

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

- 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

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- Automated models: UFO interface [new WHIZARD/O'Mega model format]

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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
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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

Old FeynRules / SARAH interface will get deprecated

kept at the moment for user backwards compatibility

All SM-like models/scalar extensions already supported
Higher-dim. operators, general Lorentz/color structures is work in progress

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

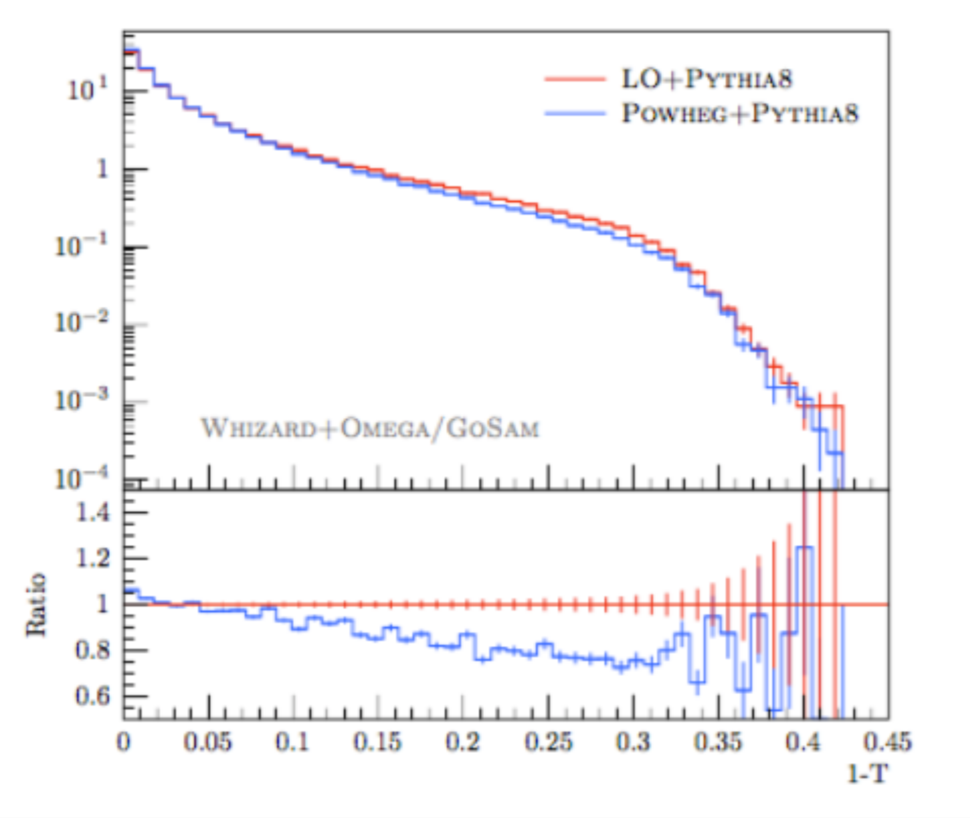
```
alpha_power = 2
alphas_power = 0

process eett = e1,E1 => t, tbar
     { nlo_calculation = “full” }
```

List of validated NLO QCD processes

- $e^+e^- \to jj$
- $e^+e^- \to jjj$
- $e^+e^- \to \ell^+\ell^- jj$
- $e^+e^- \to \ell^+\nu_\ell jj$
- $e^+e^- \to t\bar{t}$
- $e^+e^- \to t\bar{t}t\bar{t}$
- $e^+e^- \to t\bar{t}W^+jj$
- $e^+e^- \to tW^-b$
- $e^+e^- \to W^+W^-b\bar{b}, \quad \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}$
- $e^+e^- \to b\bar{b}\ell^+\ell^-$
- $e^+e^- \to t\bar{t}H$
- $e^+e^- \to W^+W^-b\bar{b}H, \quad \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}H$
- $pp \to \ell^+\ell^-$
- $pp \to \ell\nu$
- $pp \to ZZ$

- 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 refactoring phase (3rd + 4th NLO refactoring)



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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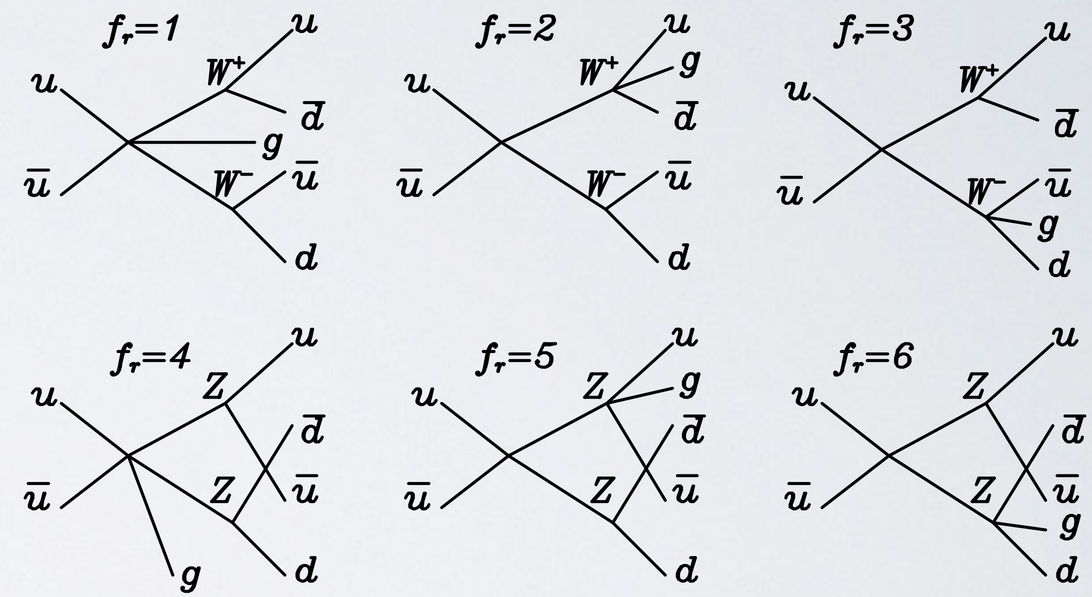

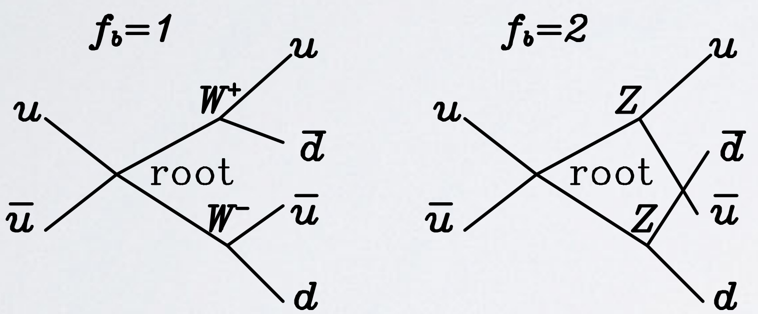

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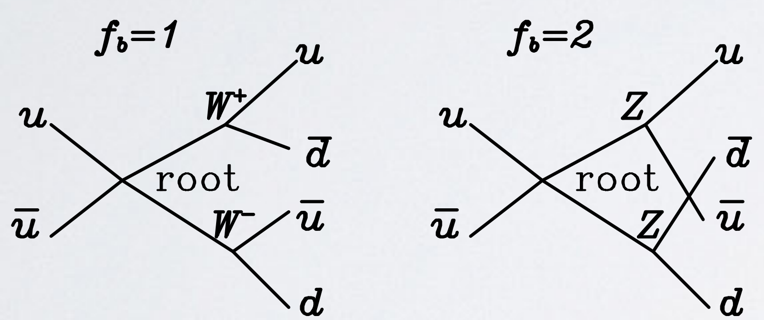

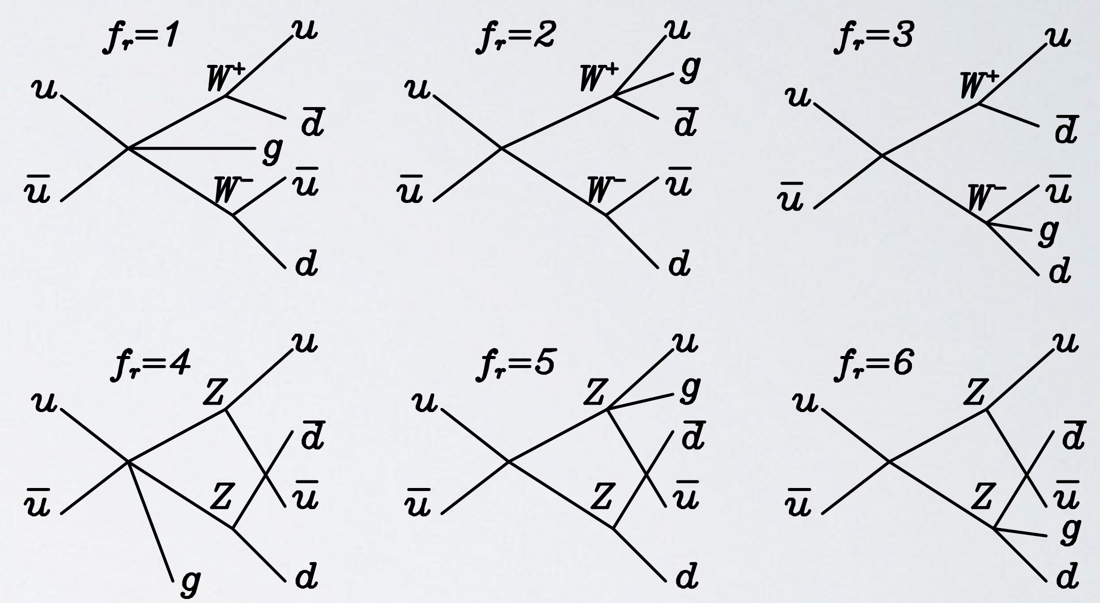

- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (ZZ, ZH histories)

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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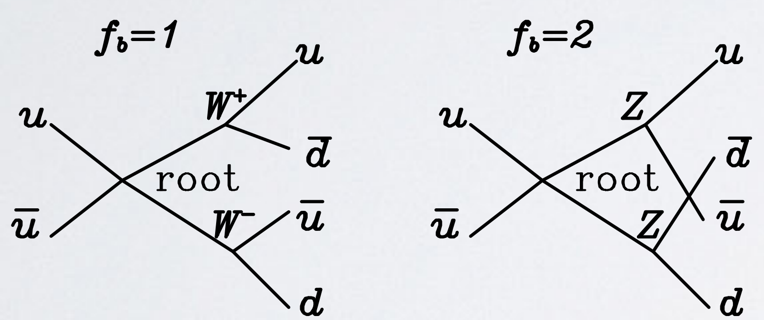

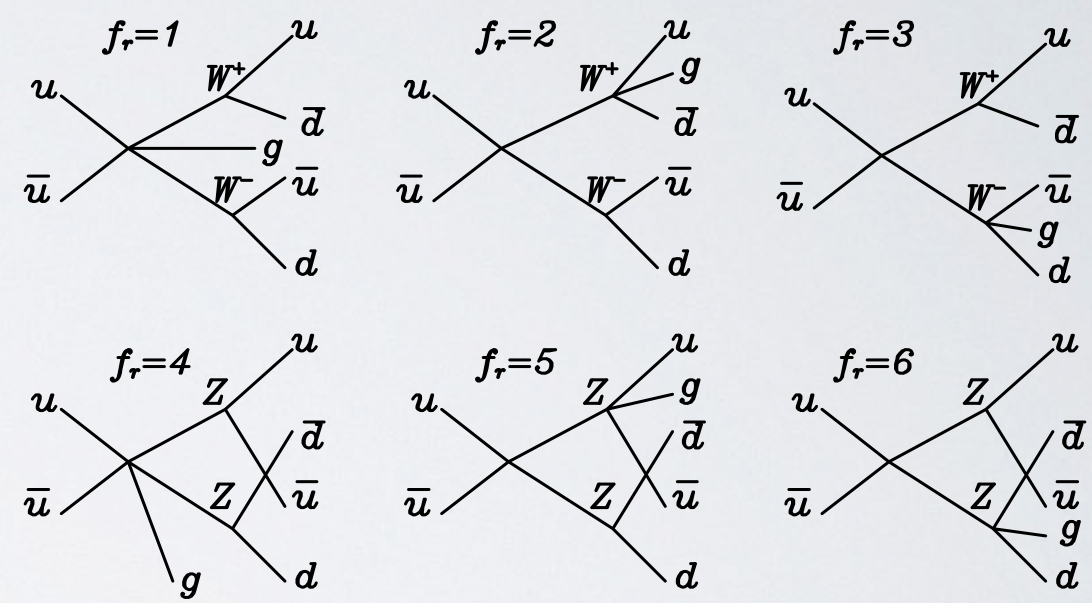

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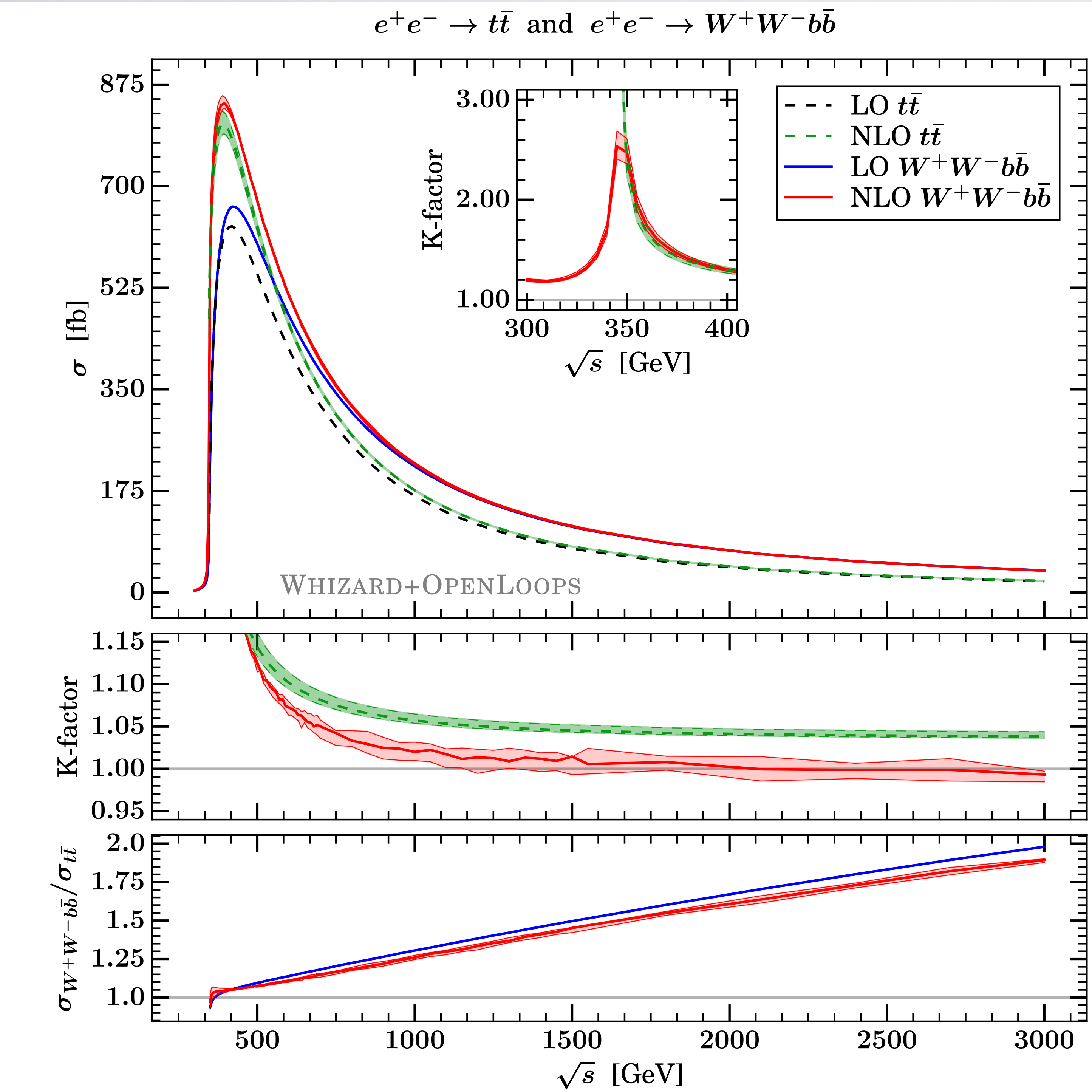
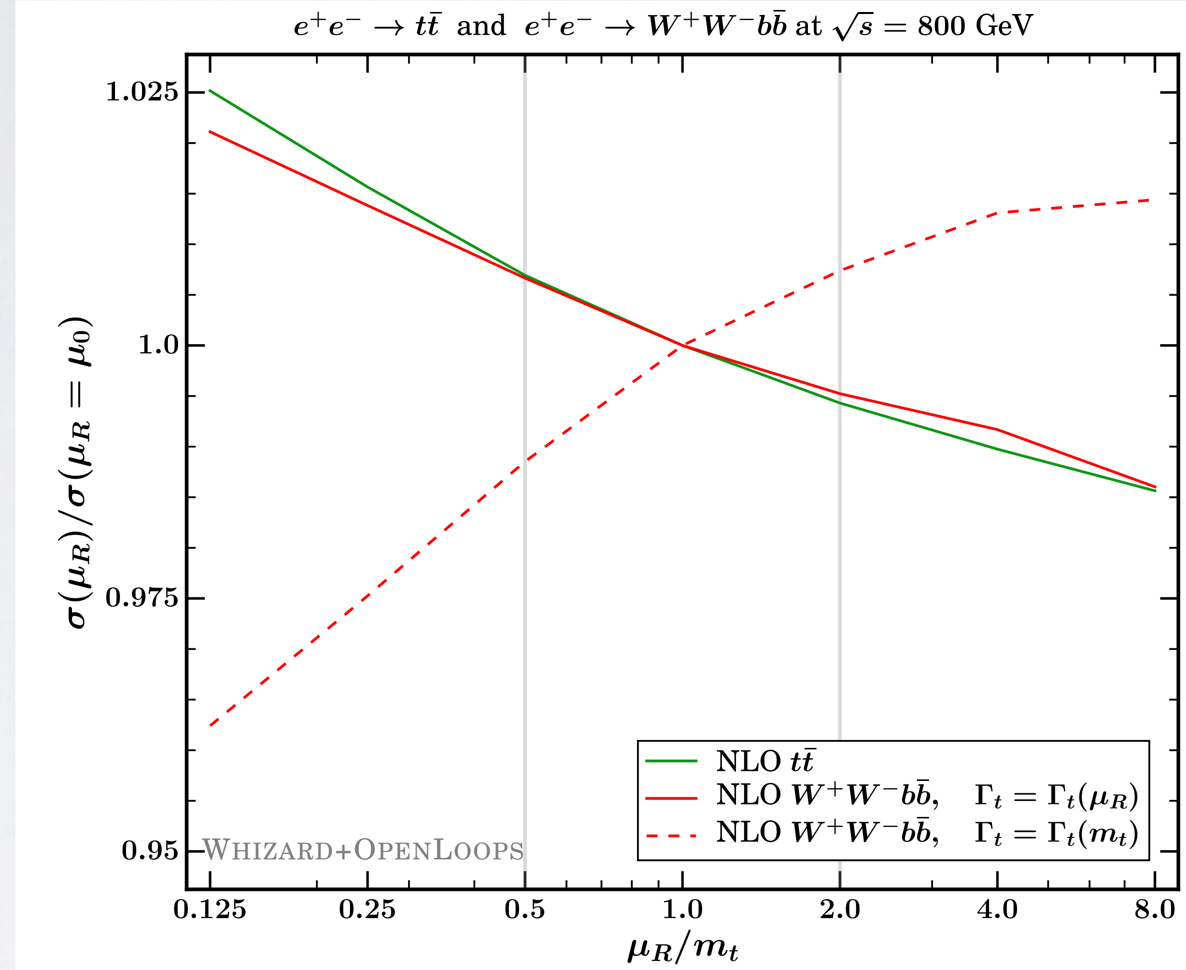
standard FKS

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

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

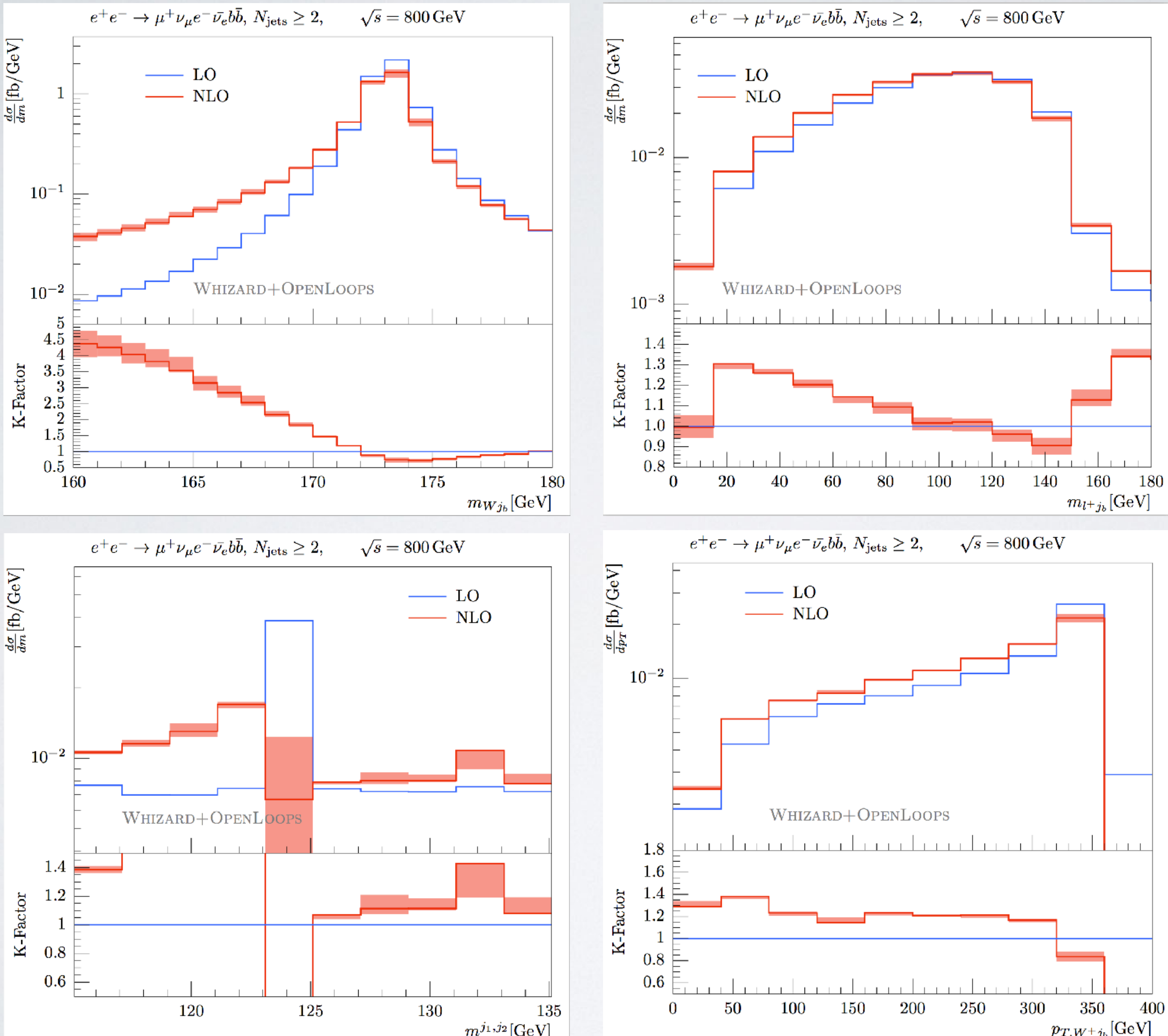




	$e^+e^- \to t\bar{t}$			$e^+e^- \to W^+W^-b\bar{b}$		
$\sqrt{s}$ [GeV]	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor
500	548.4	$627.4^{+1.4\%}_{-0.9\%}$	1.14	600.7	$675.1^{+0.4\%}_{-0.8\%}$	1.12
800	253.1	$270.9^{+0.8\%}_{-0.4\%}$	1.07	310.2	$320.7^{+1.1\%}_{-0.7\%}$	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

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

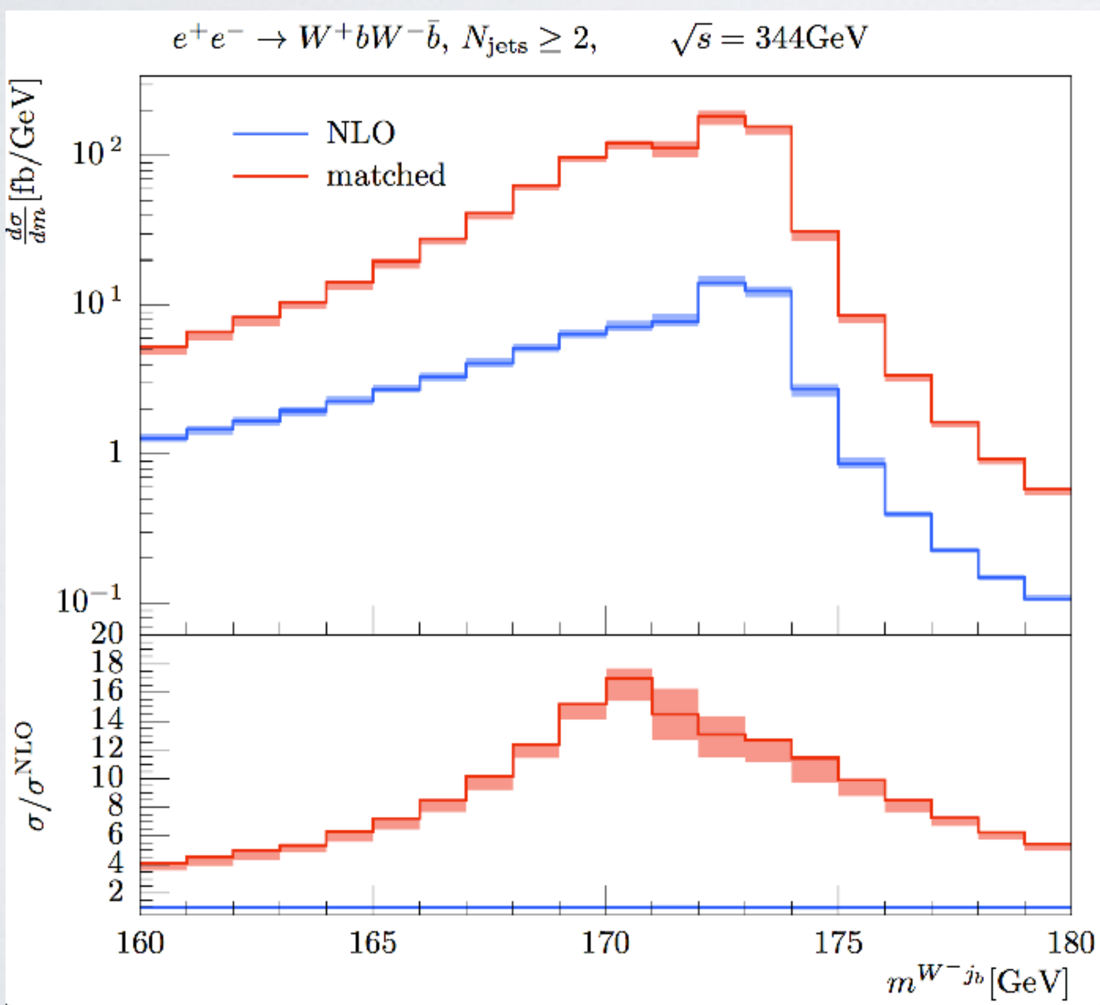
Differential Results for off-shell $e^+e^- \to tt$

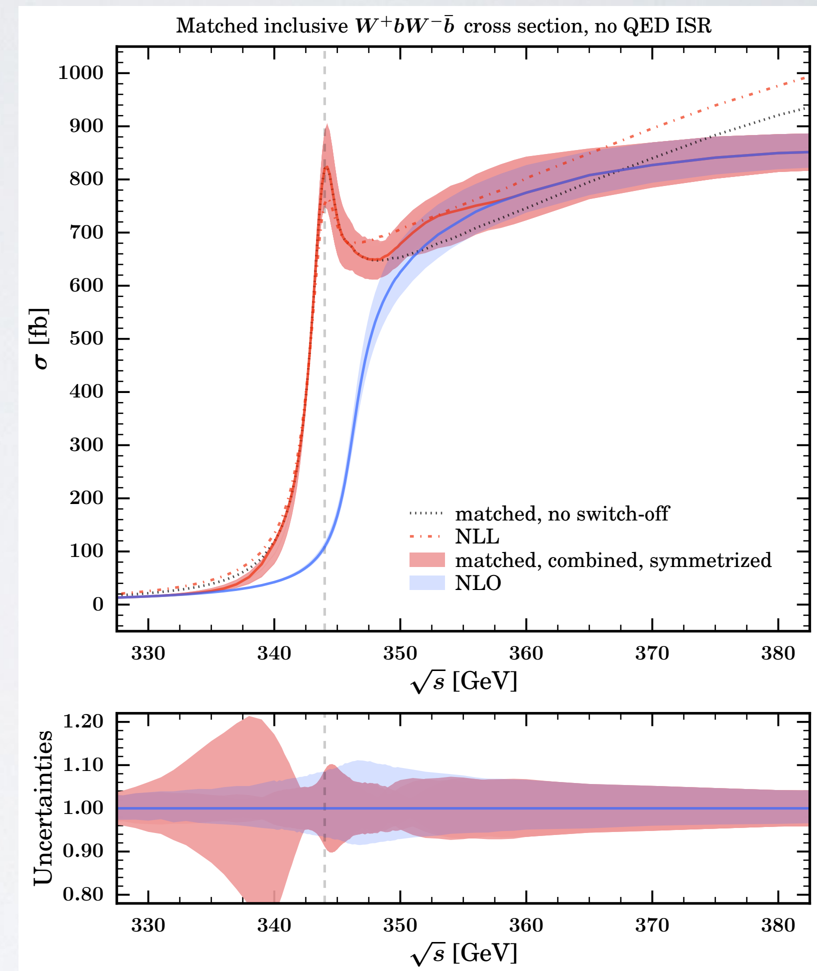


$$m_t^2 = m_W^2 + \frac{2\langle m_{\ell j_b}^2 \rangle}{1 - \langle \cos\theta_{\ell j_b} \rangle}$$

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





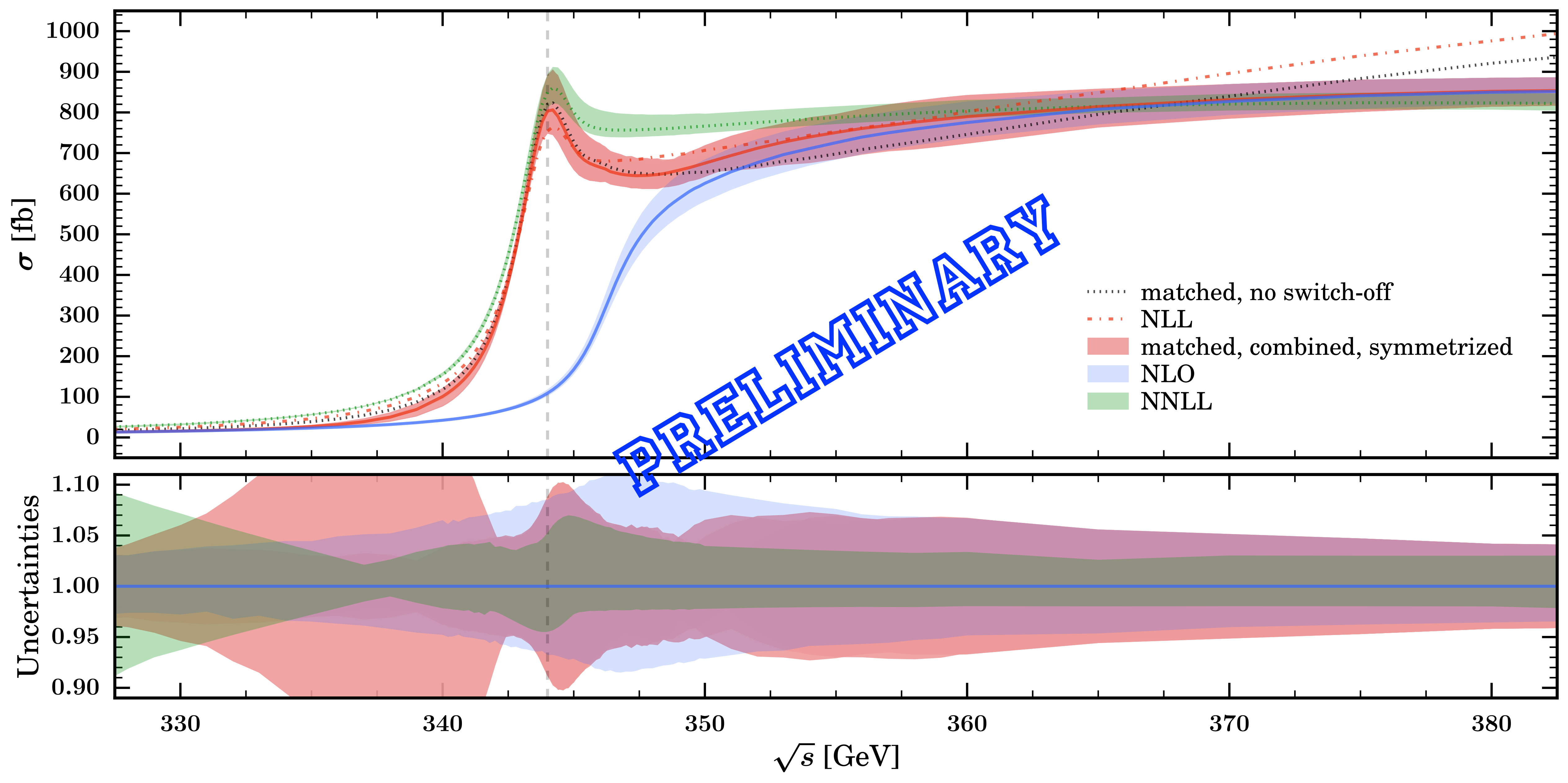
Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss,
1712.02220 [JHEP 1803(2018)184]

Allows to study top mass dependence of differential distributions at threshold

Future Work …

Next steps: higher QCD order, EW corrections (ISR matching!!), soft gluons … … …

$$e^+e^- \to W^+bW^-\bar{b}$$



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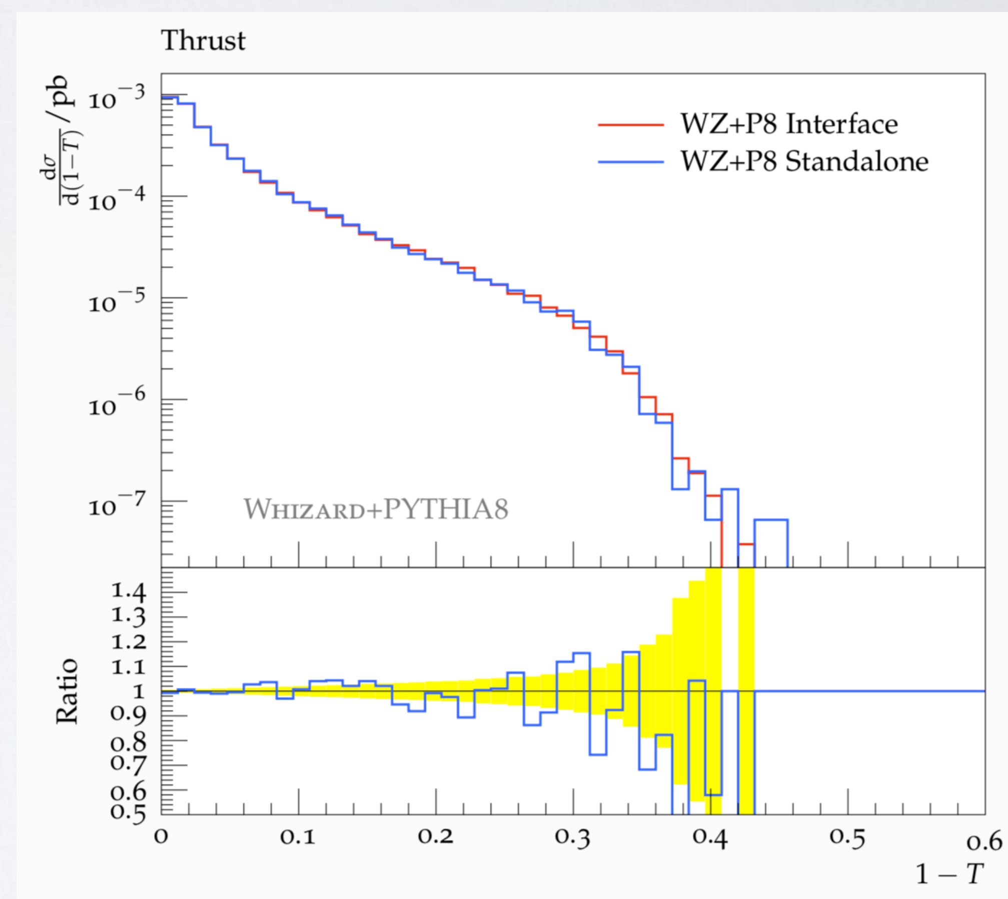
```
| ==========================================================================
| Running self-test: whizard_lha
| --------------------------------------------------------------------------
Running test: whizard_lha_1
 --------  LHA initialization information  ------------

  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

- Implemented by Wolfgang Kilian [on sabbatical at CERN w. CLICdp 03/2018-08/2018]
- 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 2.7.0 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 [EW validation started]
- NEW:
  - ☑ UFO models: *[WIP: still waiting for general Lorentz structures]*
  - ☑ 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

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WE'RE HAPPY TO ACCOMODATE SPECIFIC DEMANDS OF FCC-EE COMMUNITY

BACKUP

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

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

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

Longitudinal polarization (massive)

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

```
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)

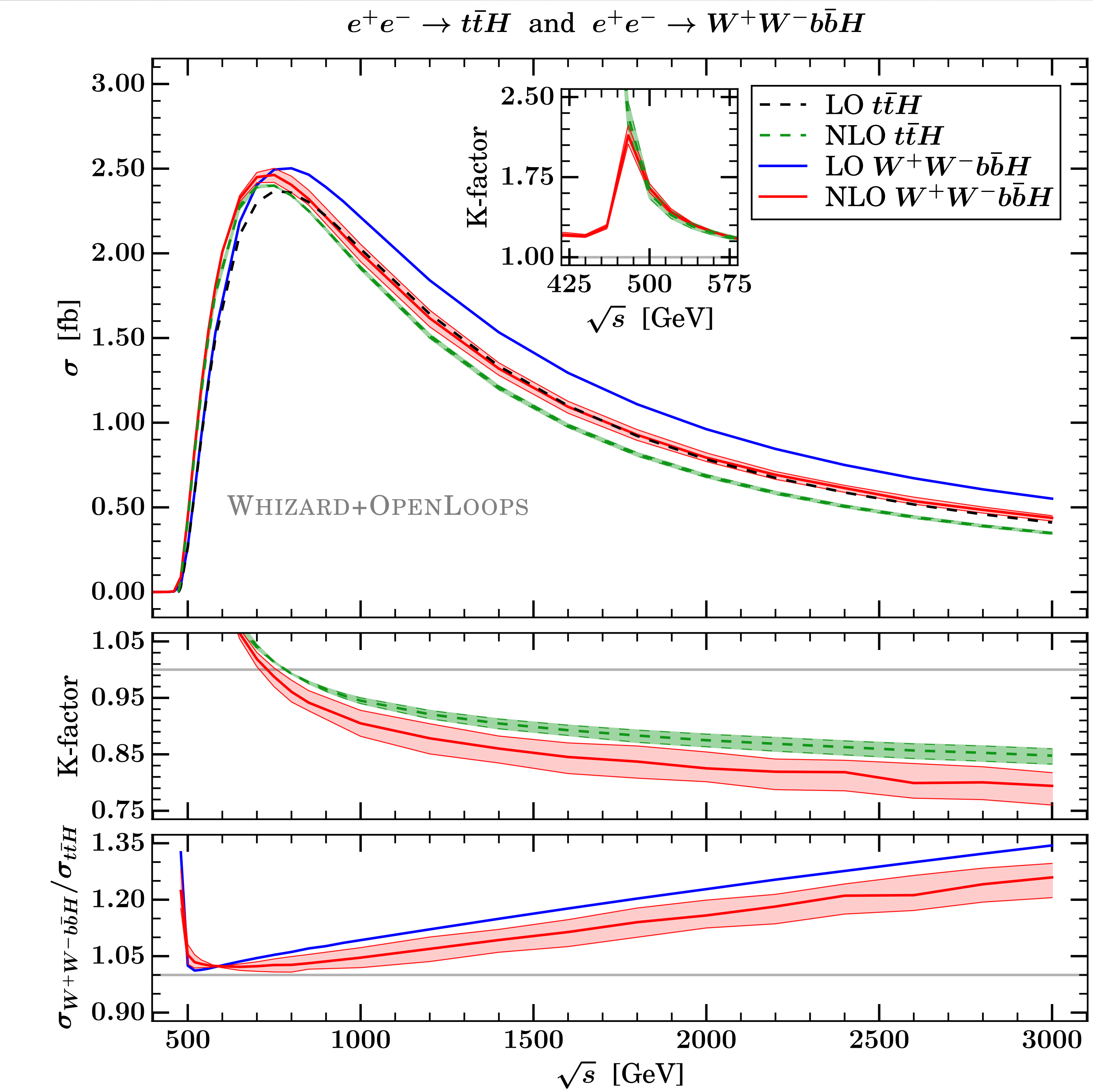
$$\rho = \frac{1}{2}\cdot\begin{pmatrix} 1-f\cos\theta & 0 & \cdots & \cdots & f\sin\theta\,e^{-i\phi} \\ 0 & 0 & \ddots & & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & & \ddots & 0 & 0 \\ f\sin\theta\,e^{i\phi} & \cdots & \cdots & 0 & 1+f\cos\theta \end{pmatrix}$$

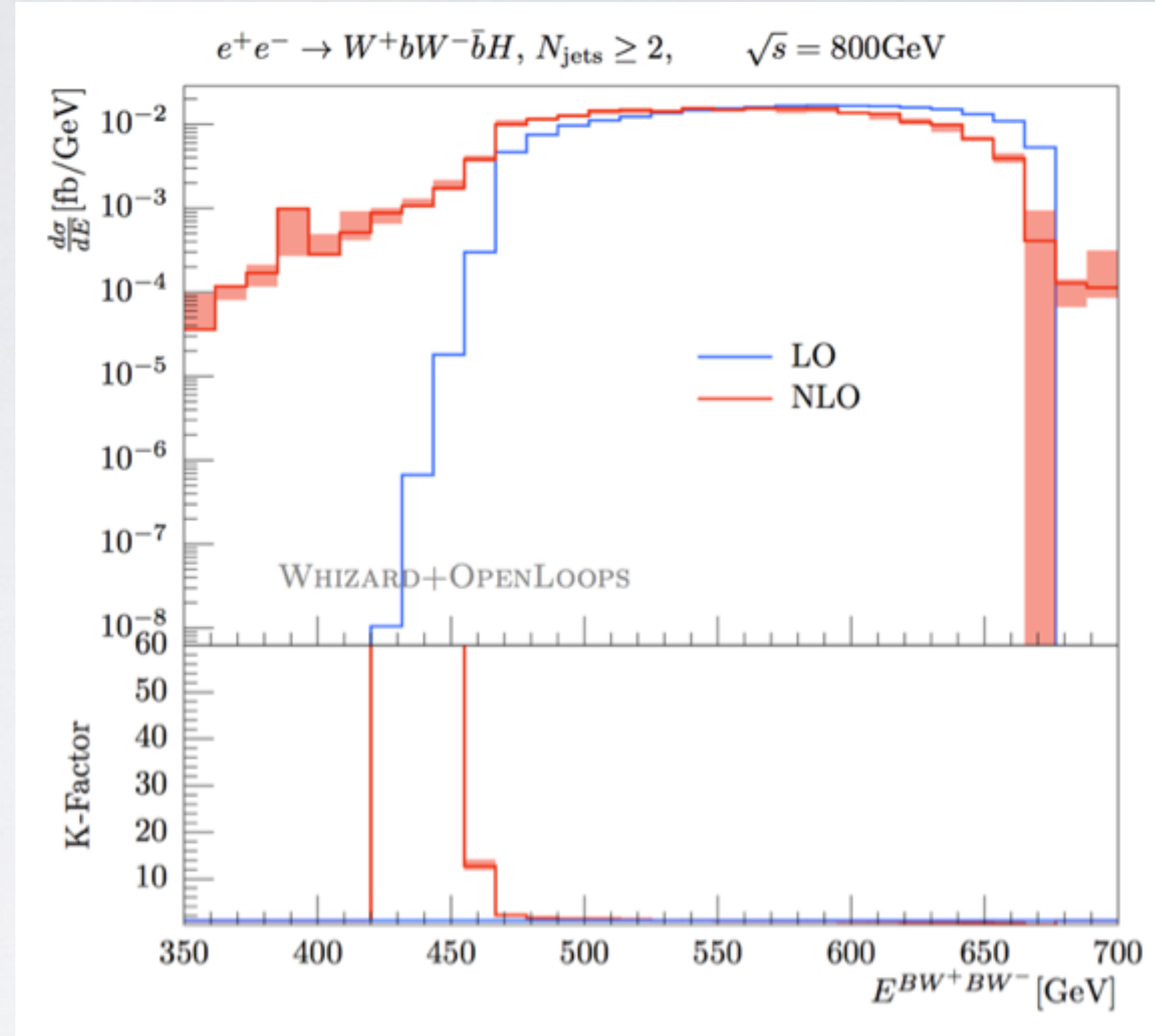
```
beams_pol_density = @(j:j:h_j, j-1:j-1:h_j-1, …, -j:-j:h_-j)
```

```
beams_pol_density = @({m:m′:x_m,m′})
```

Diagonal / arbitrary density matrices

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





$\sqrt{s}$ [GeV]	$e^+e^- \to t\bar{t}H$ σ^{LO}[fb]	$e^+e^- \to t\bar{t}H$ σ^{NLO}[fb]	$e^+e^- \to t\bar{t}H$ K-factor	$e^+e^- \to W^+W^-b\bar{b}H$ σ^{LO}[fb]	$e^+e^- \to W^+W^-b\bar{b}H$ σ^{NLO}[fb]	$e^+e^- \to W^+W^-b\bar{b}H$ 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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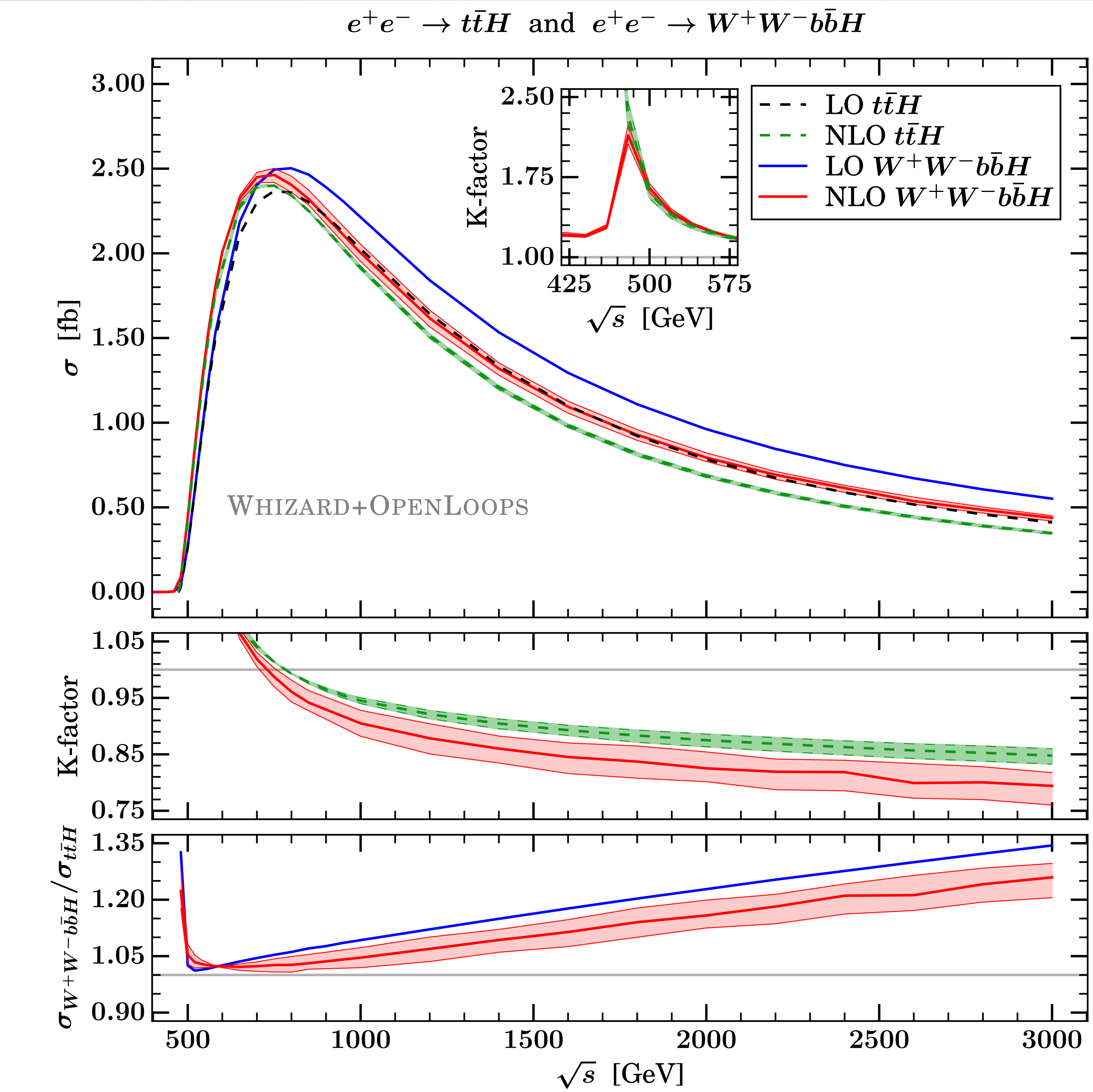

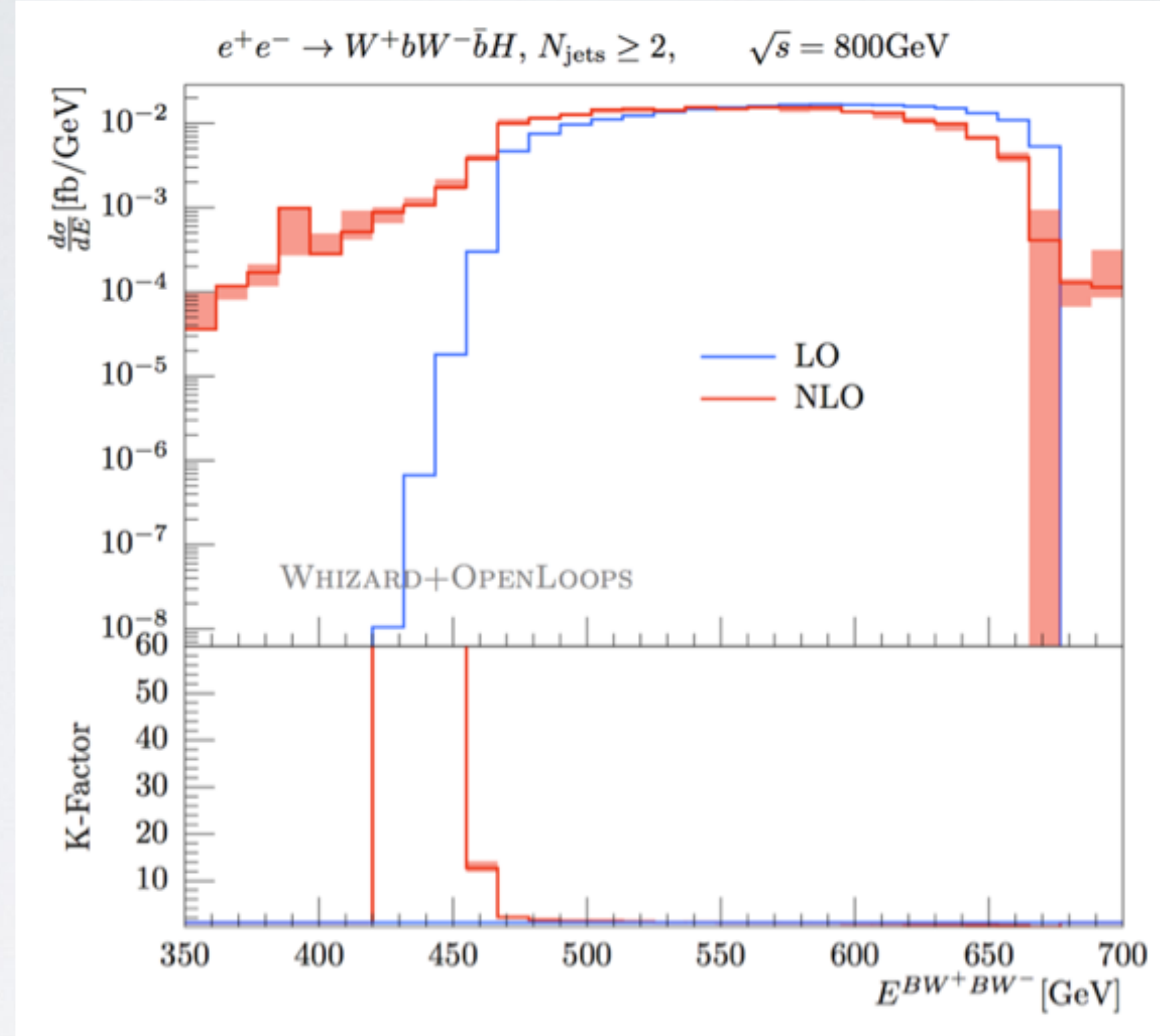

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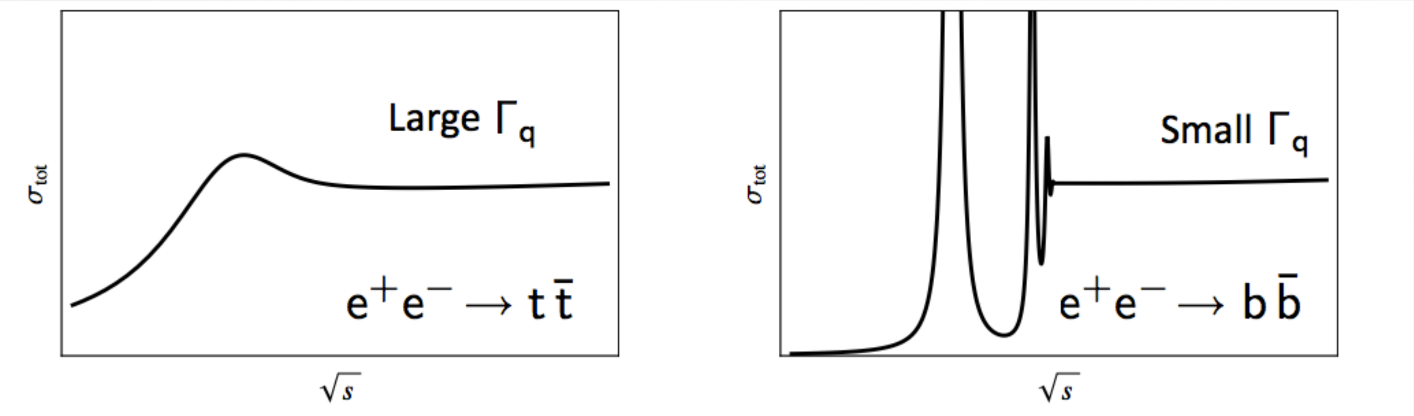
Top Threshold/Continuum at lepton colliders

- 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

Heavy quark production at lepton colliders, qualitatively:



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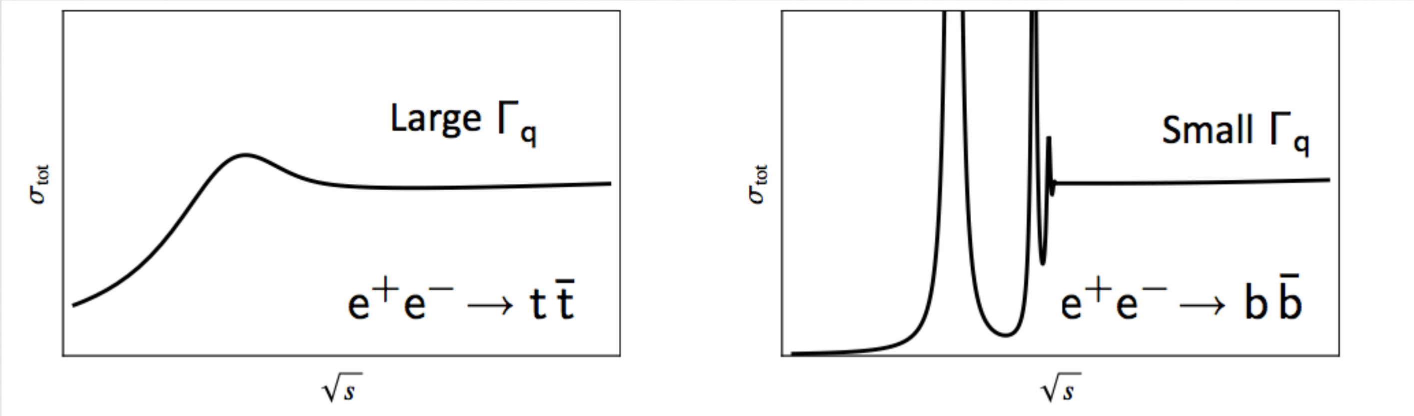

error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty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

from 1702.05333

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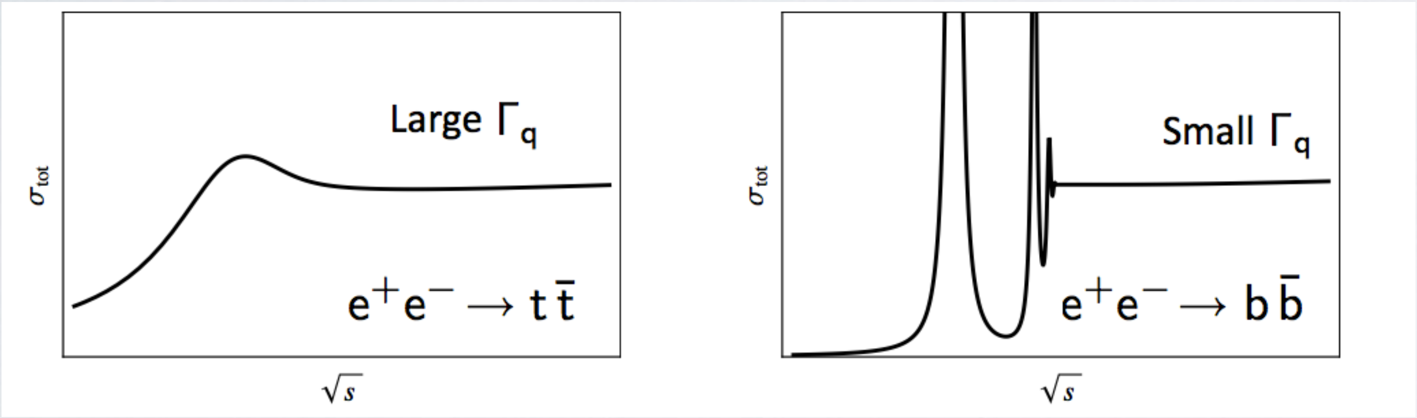

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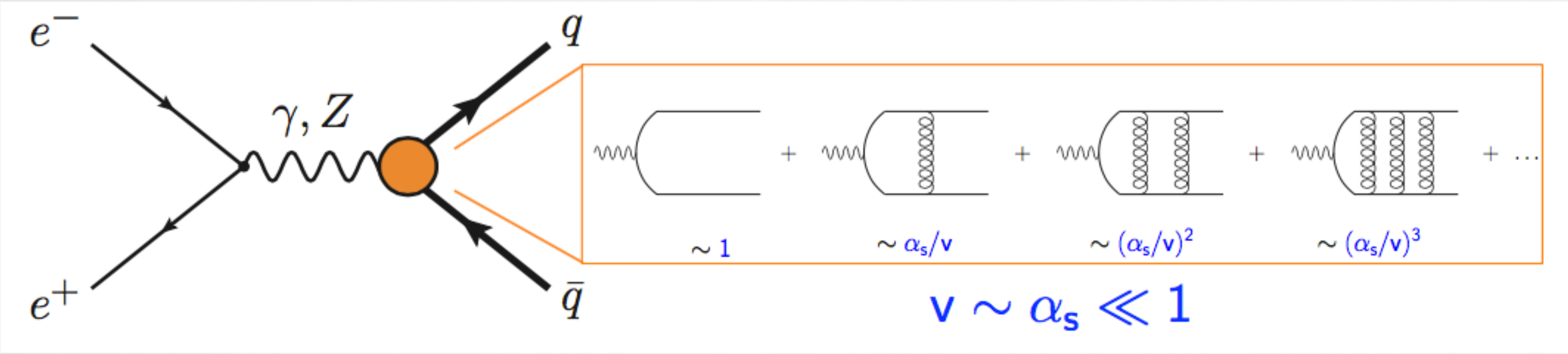
from 1702.05333

Threshold region: top velocity v ~ α_s ≪ 1 non-relativistic EFT: (v)NRQCD



Continuum region: "standard" fixed-order QCD

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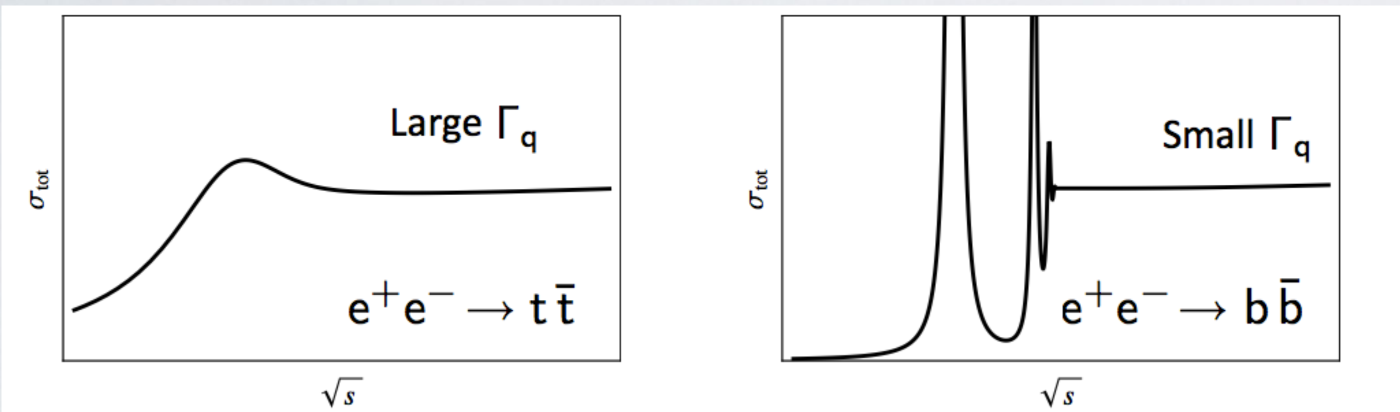

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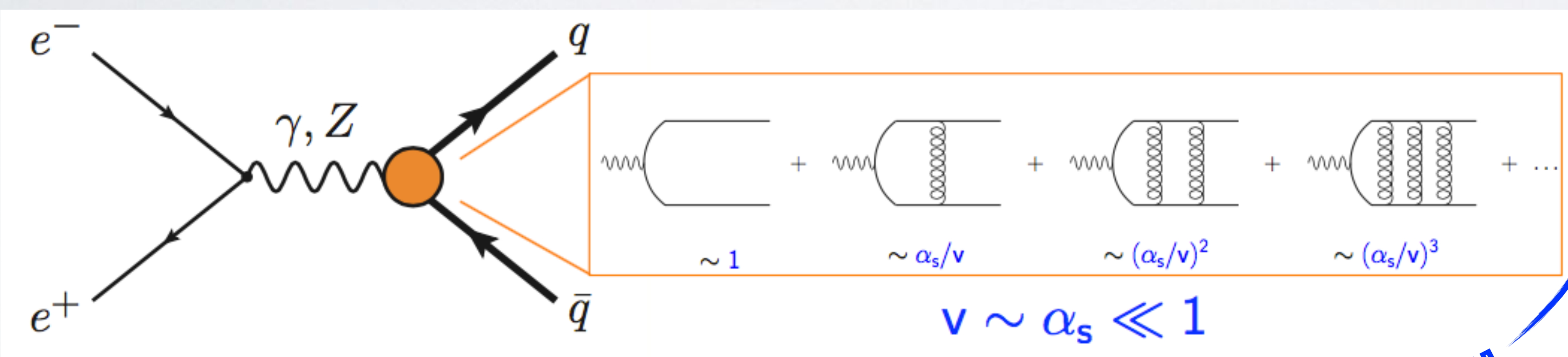
Threshold region: top velocity $v \sim \alpha_s \ll 1$ non-relativistic EFT: (v)NRQCD

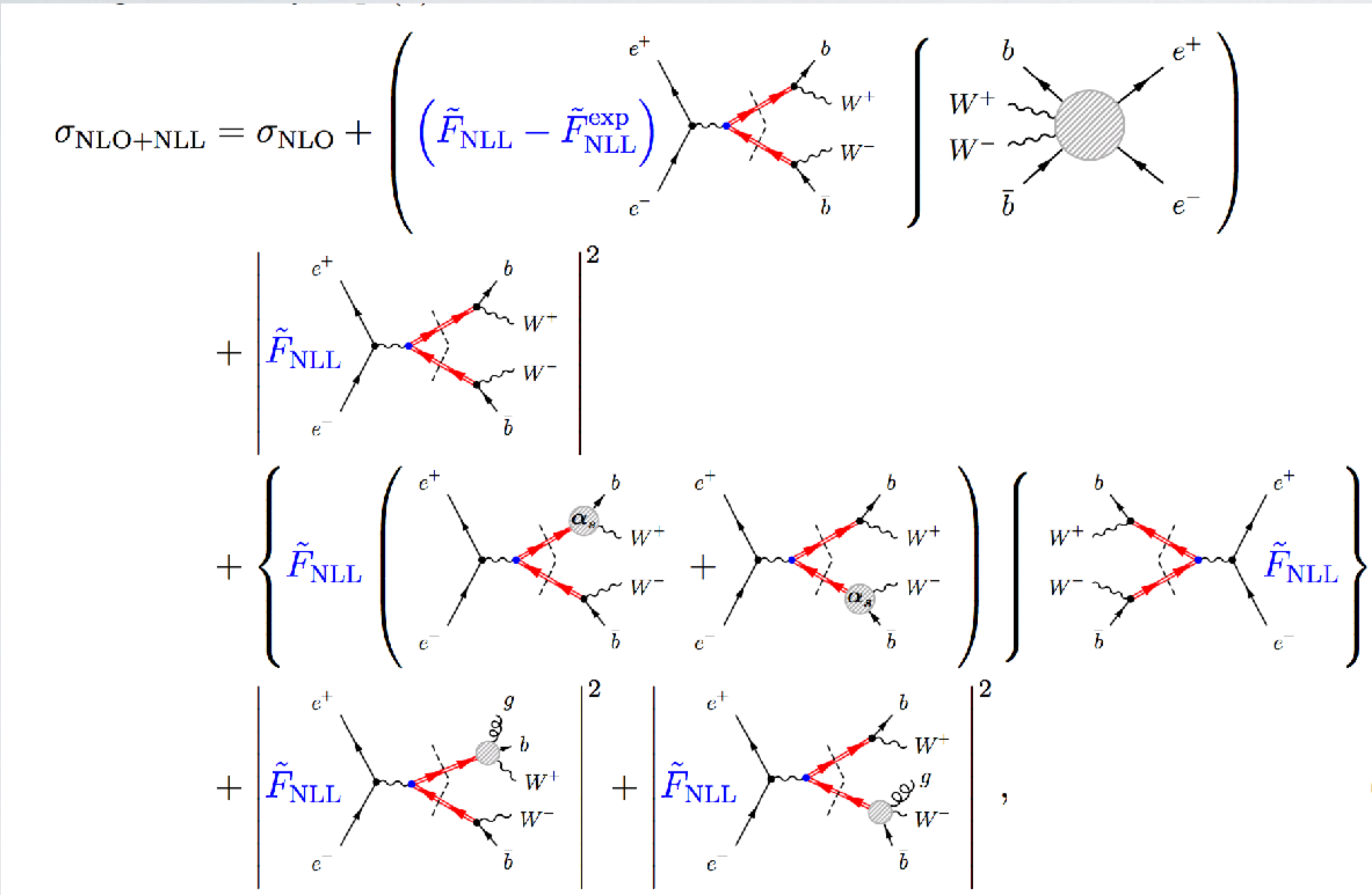


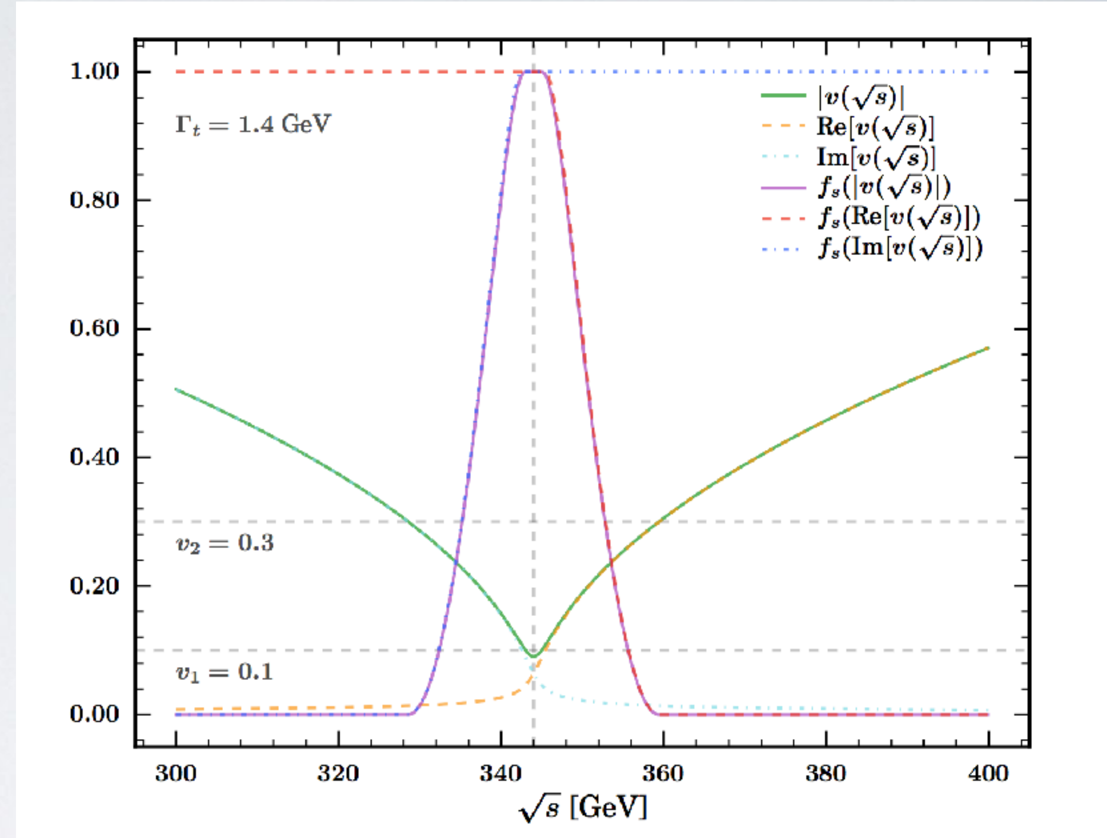
MATCH

Continuum region: “standard” fixed-order QCD

Top threshold: validation and matching

- Transition region between relativistic and resummation effects





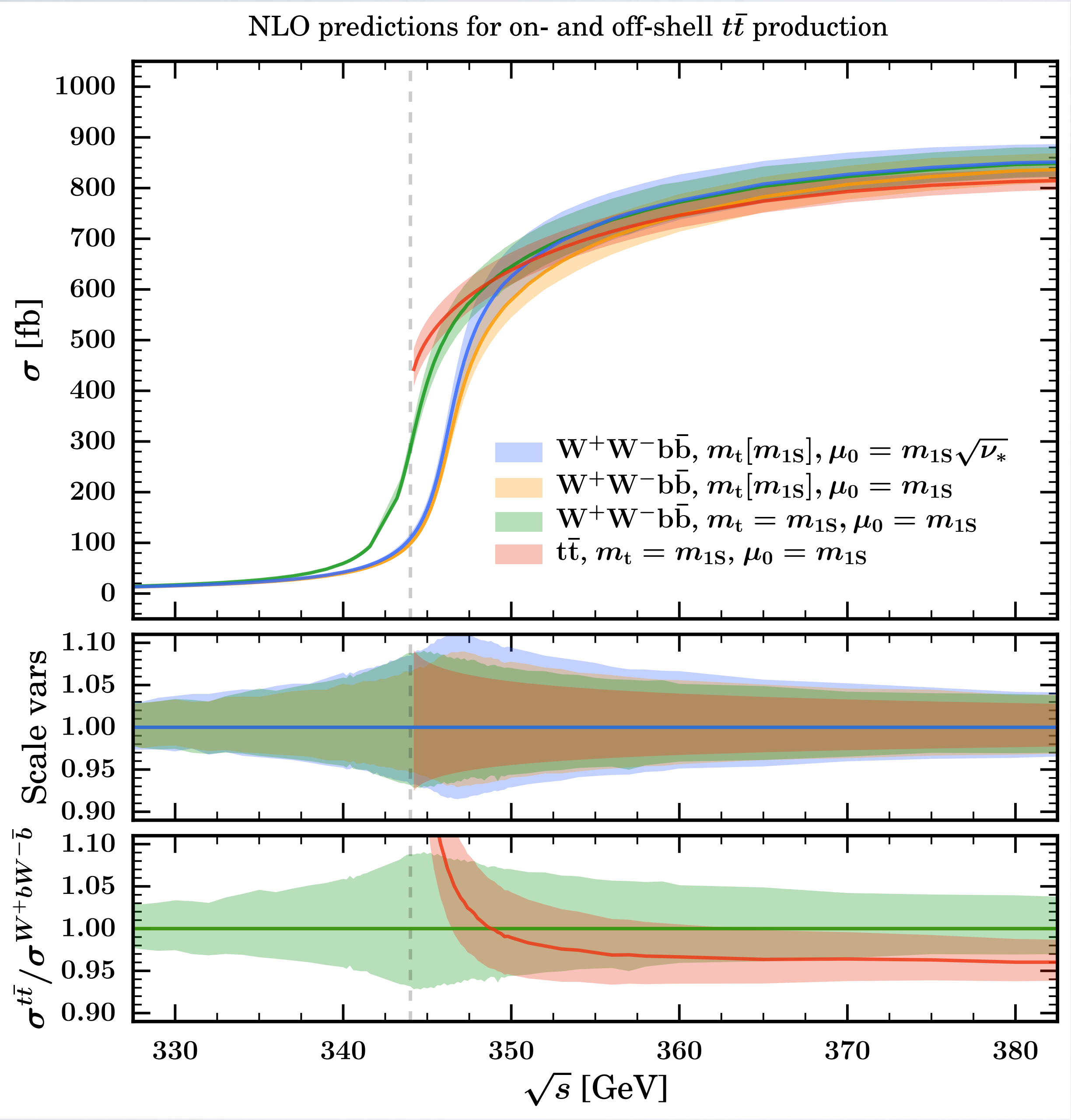
$$\sigma_{\rm matched} = \sigma_{\rm FO}\,[\alpha_{\rm H}] + \sigma^{\rm full}_{\rm NRQCD}\,[f_s\,\alpha_{\rm H},\ f_s\,\alpha_{\rm S},\ f_s\,\alpha_{\rm US}] - \sigma^{\rm expanded}_{\rm NRQCD}\,[f_s\,\alpha_{\rm H},\ f_s\,\alpha_{\rm H}]\ ,$$

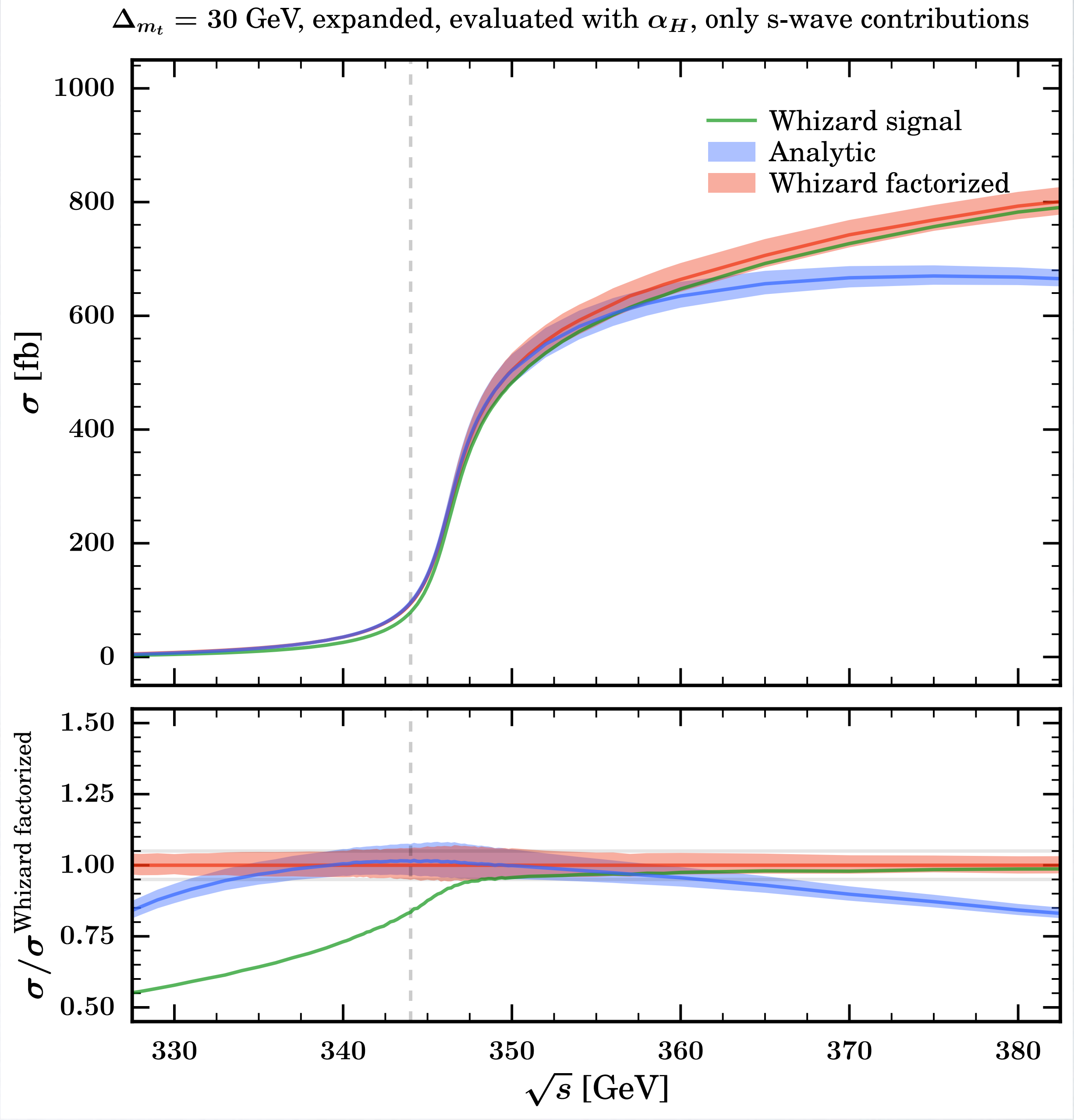
Smoothstep matching function:

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

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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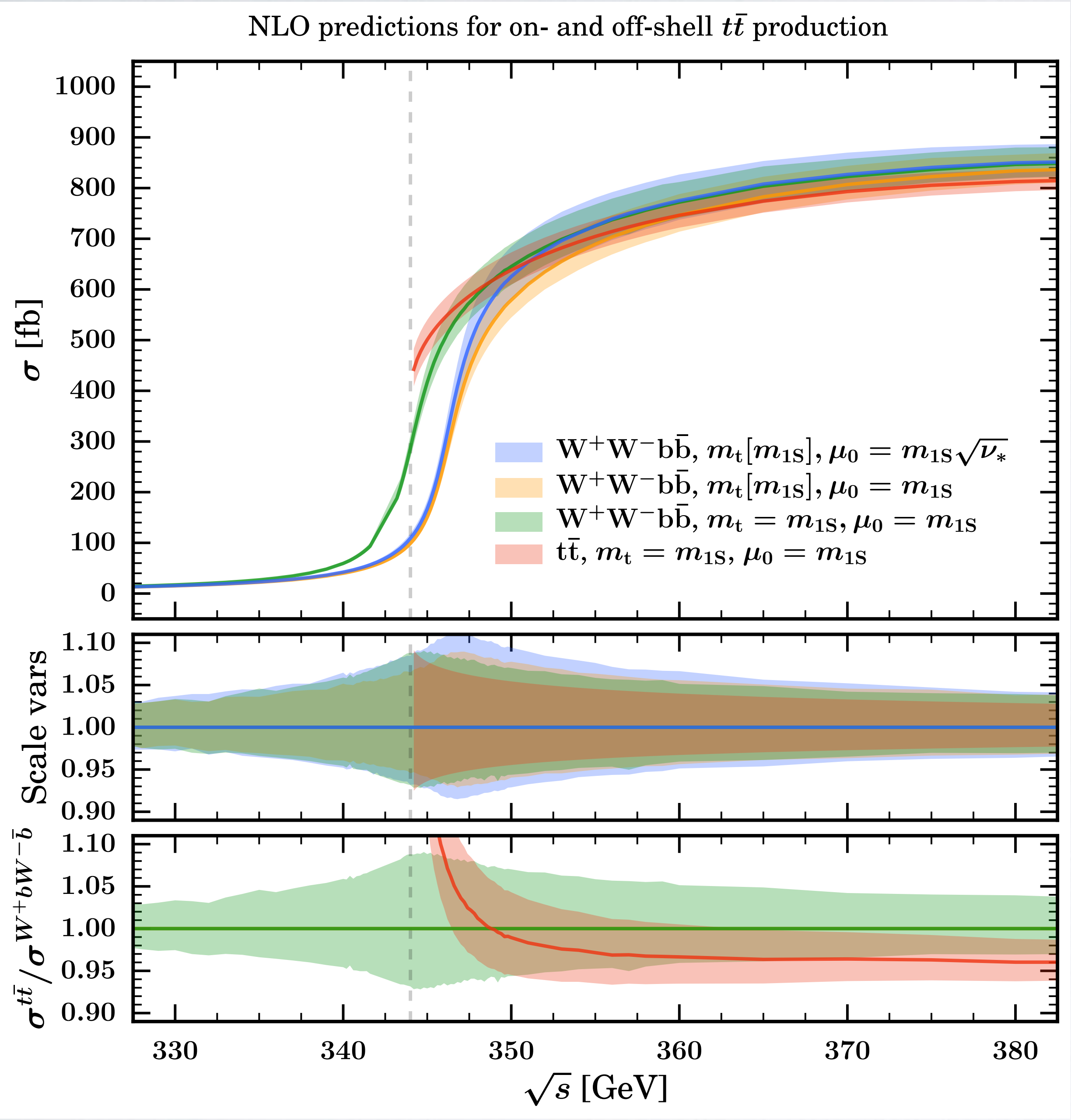

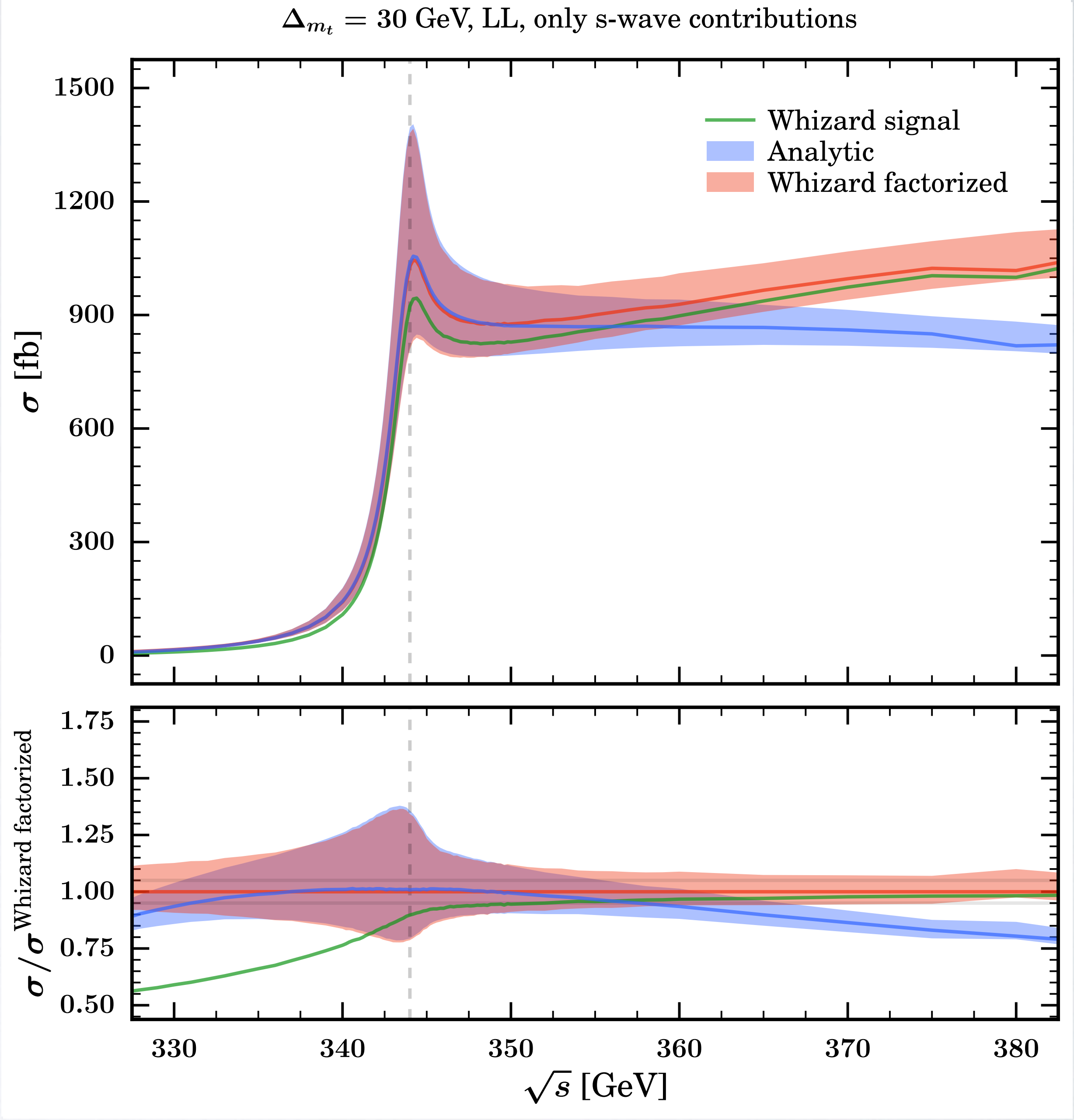

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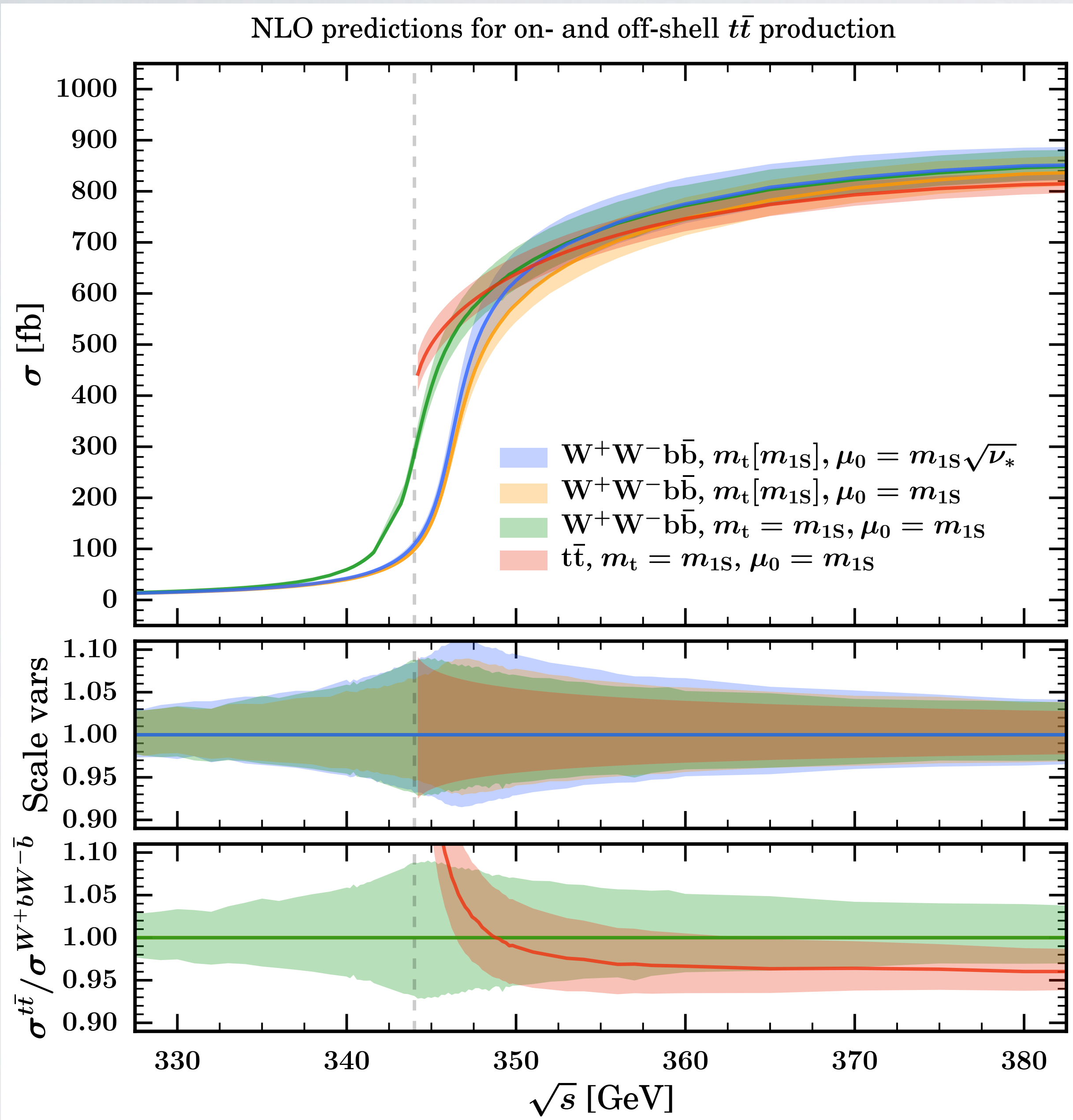
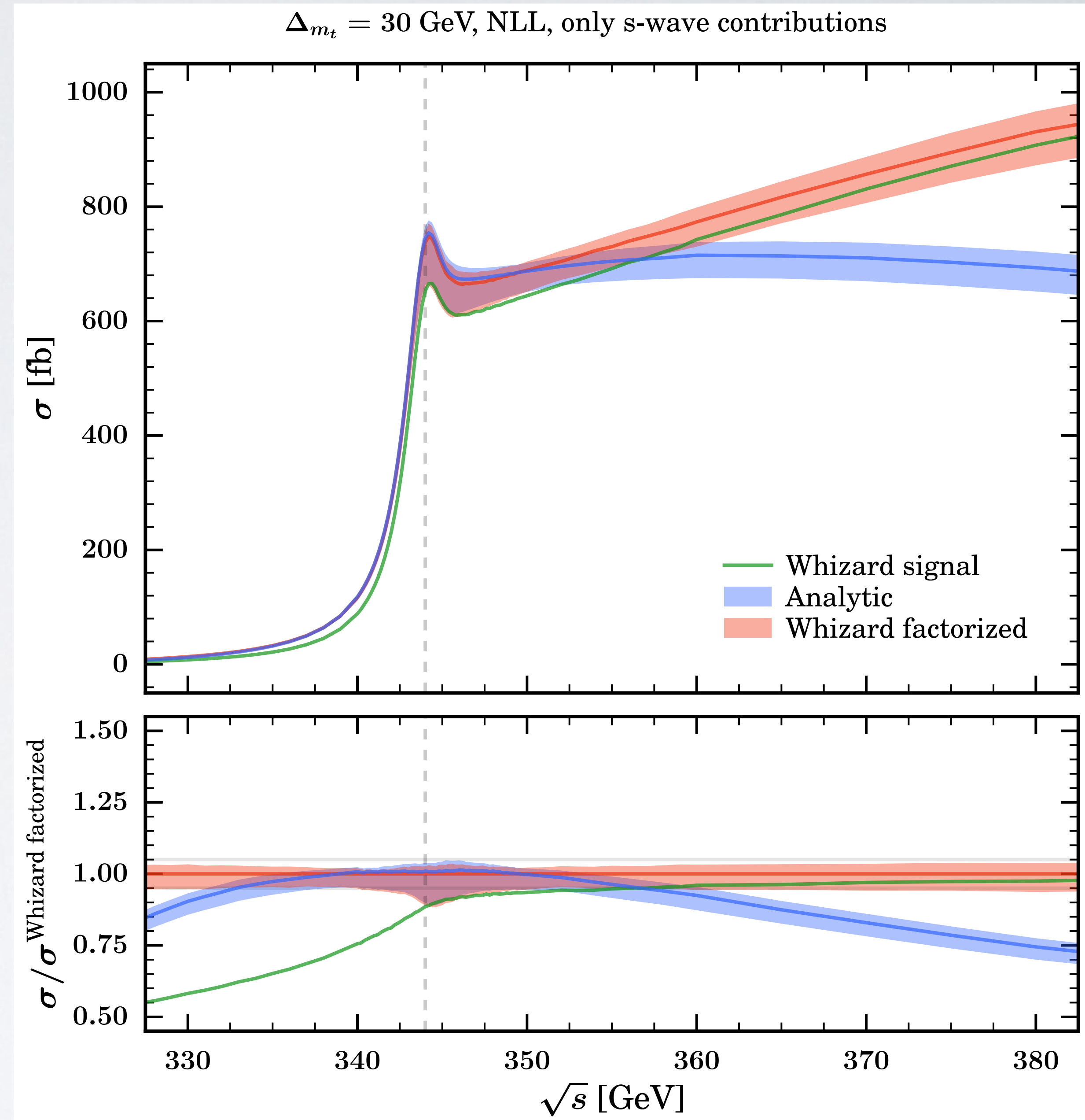
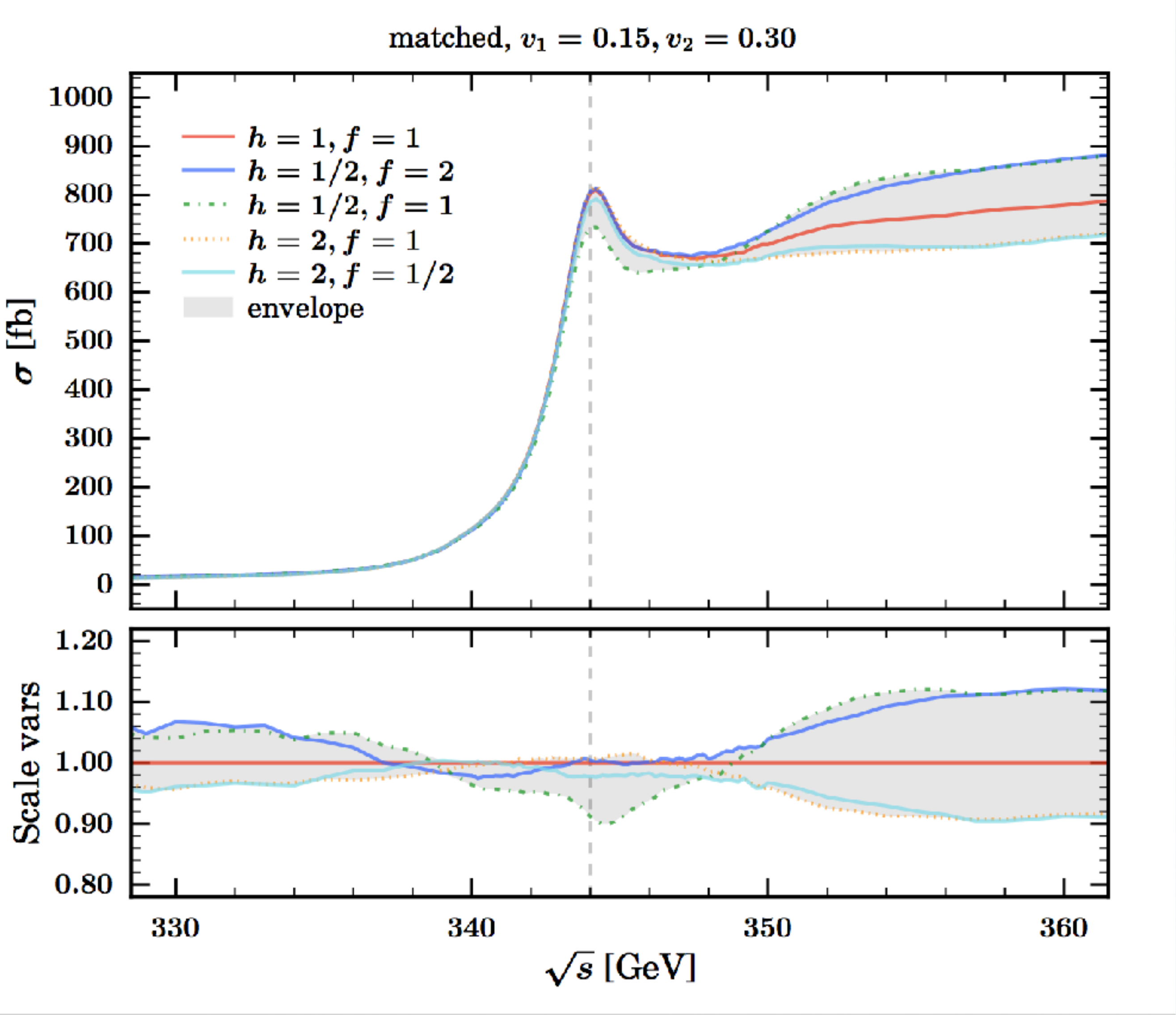
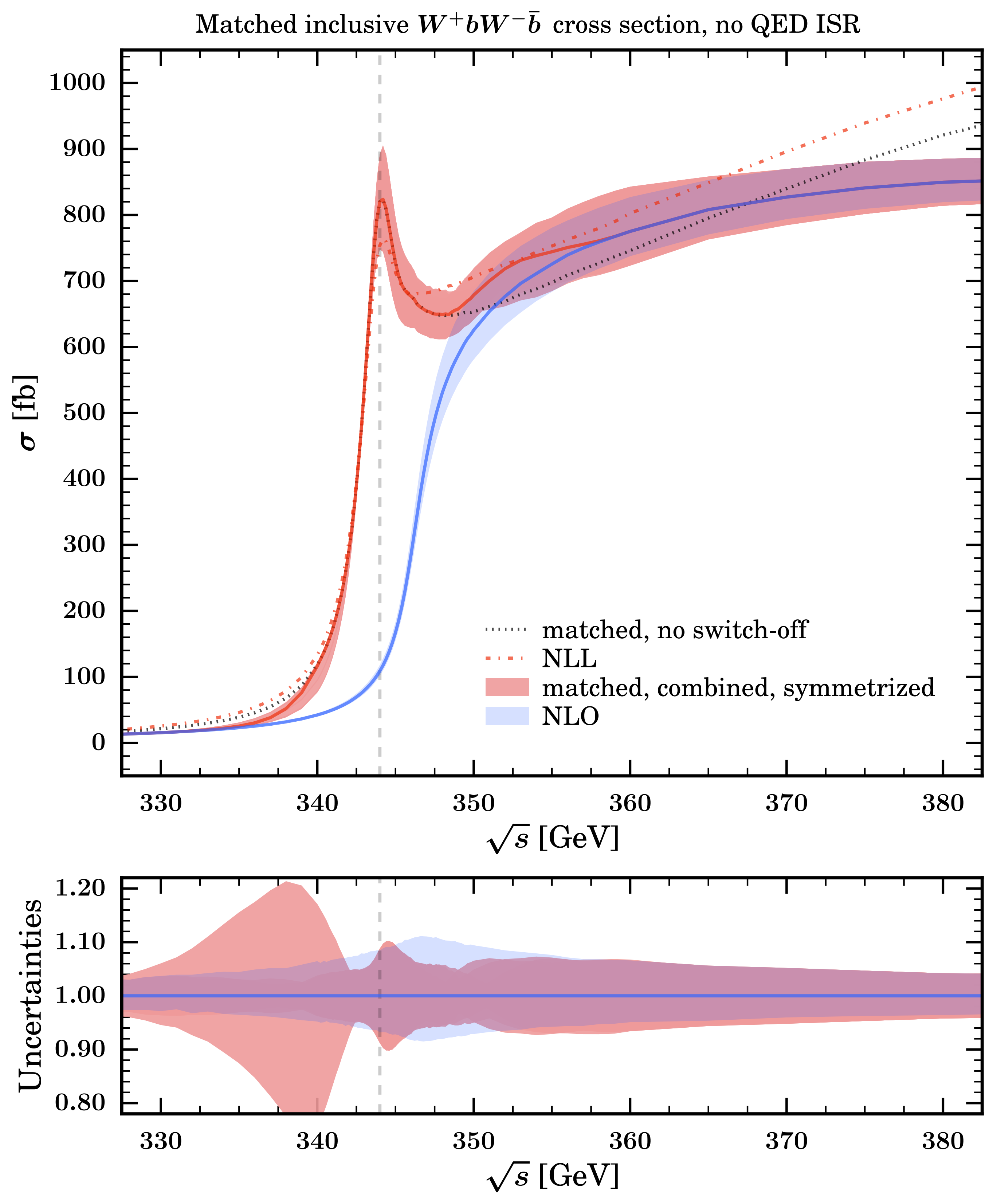




Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

Matching threshold NLL to continuum NLO





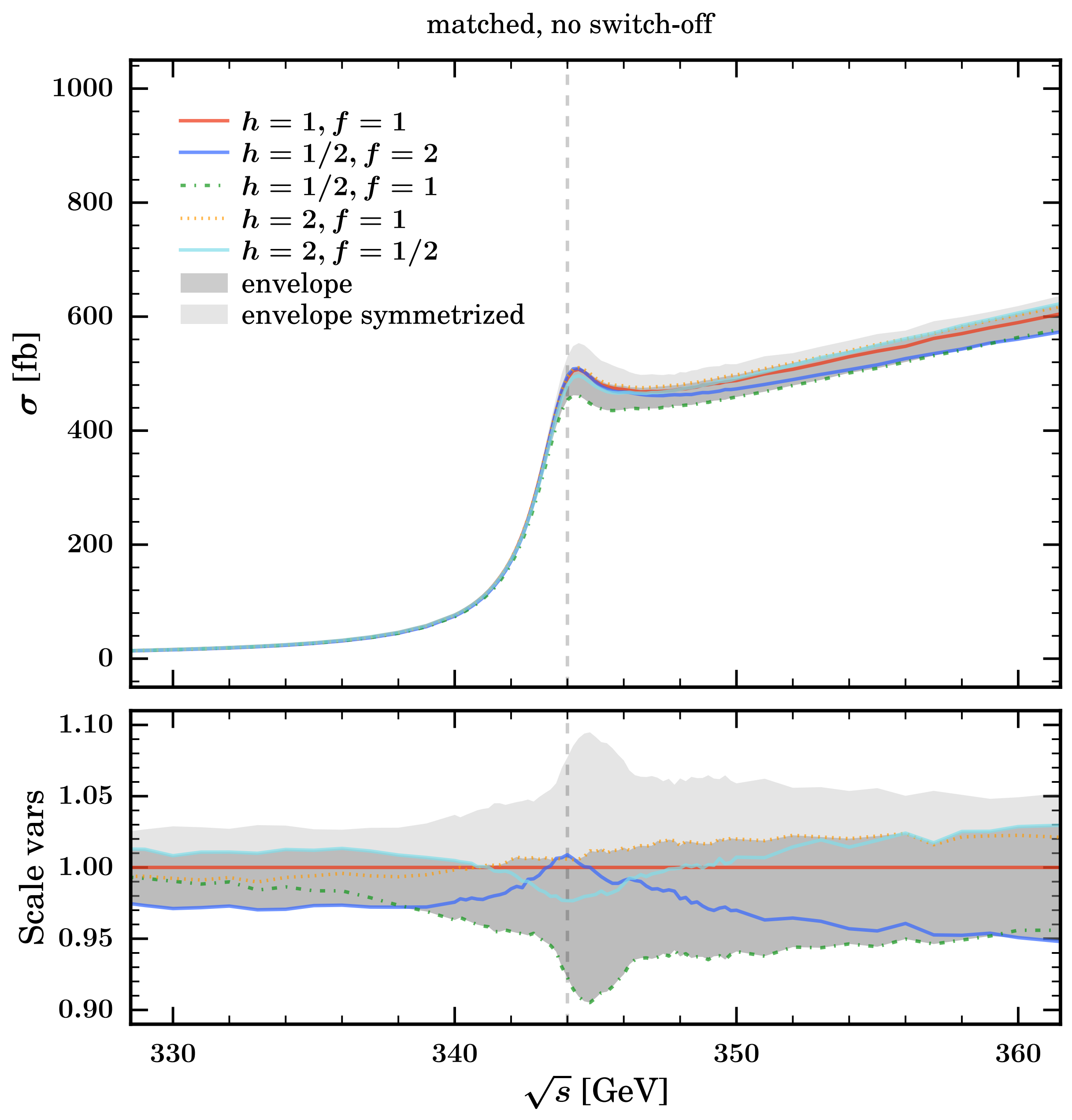
Total uncertainty: *h-f* variation band and matching [switch-off function]

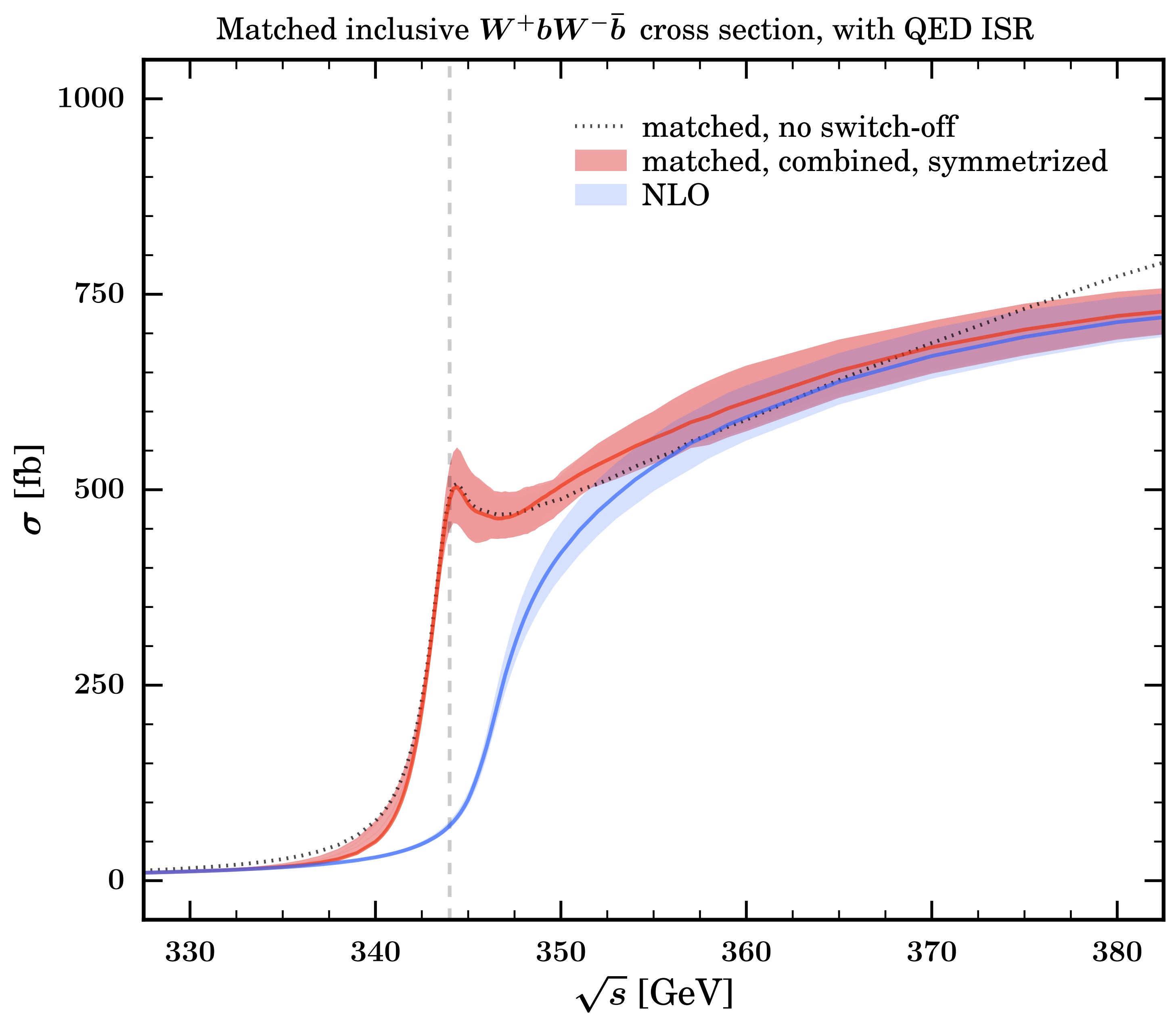
Symmetrization of error bands:

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

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

Threshold matching with QED ISR





Matched threshold differential distributions