Snowmass MC Tutorial on the WHIZARD Generator

SnowMass2021

Simon Braß, DESY

Jürgen R. Reuter, DESY

Outline of the tutorial

1) Introduction: Installation and running (review)

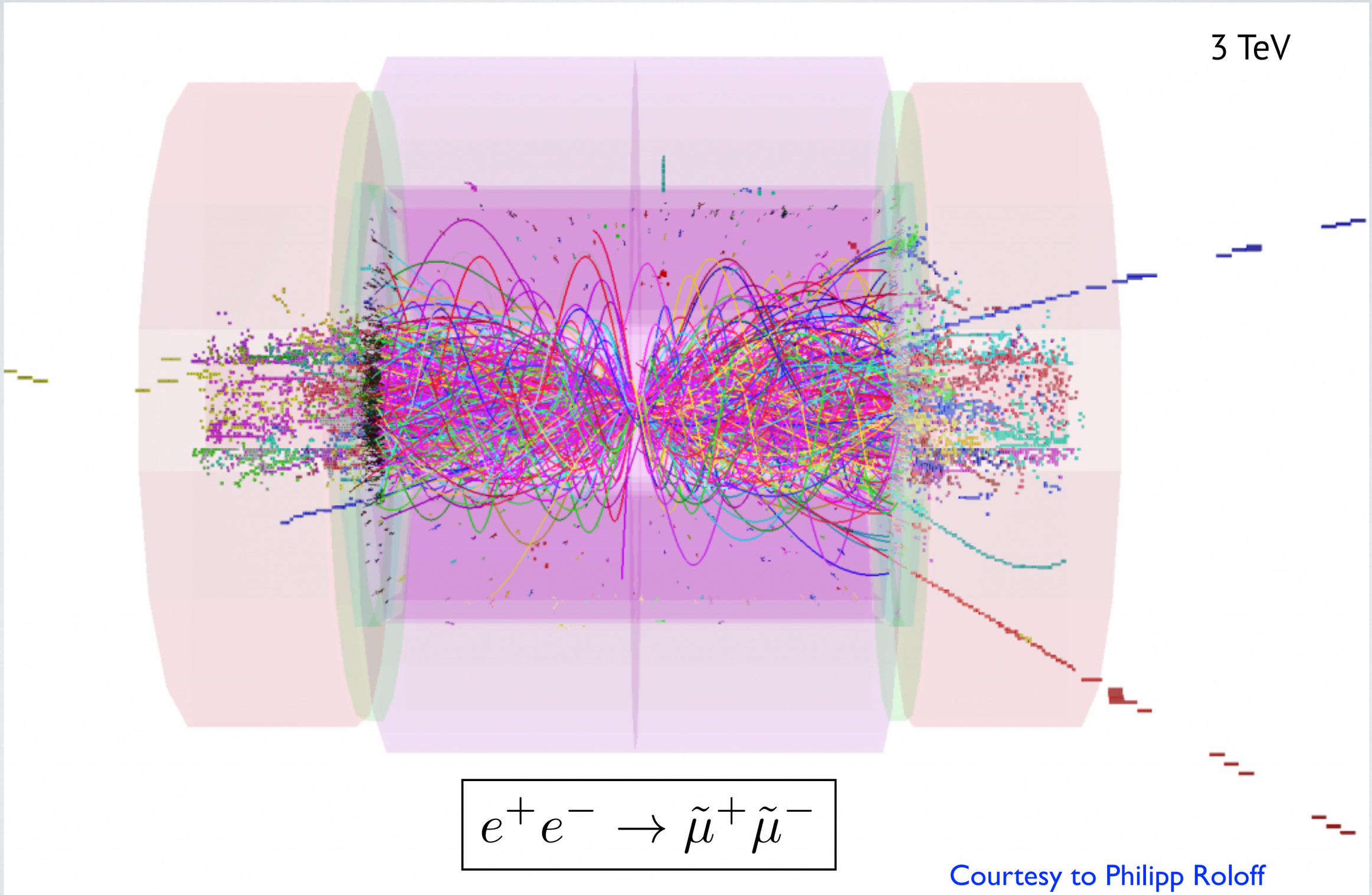
2) Beam spectra (review)

3) Processes, structure functions, selections, resonances (active)

4) Dedicated examples (active)

5) Event formats (active)

Events at lepton colliders … Experiment



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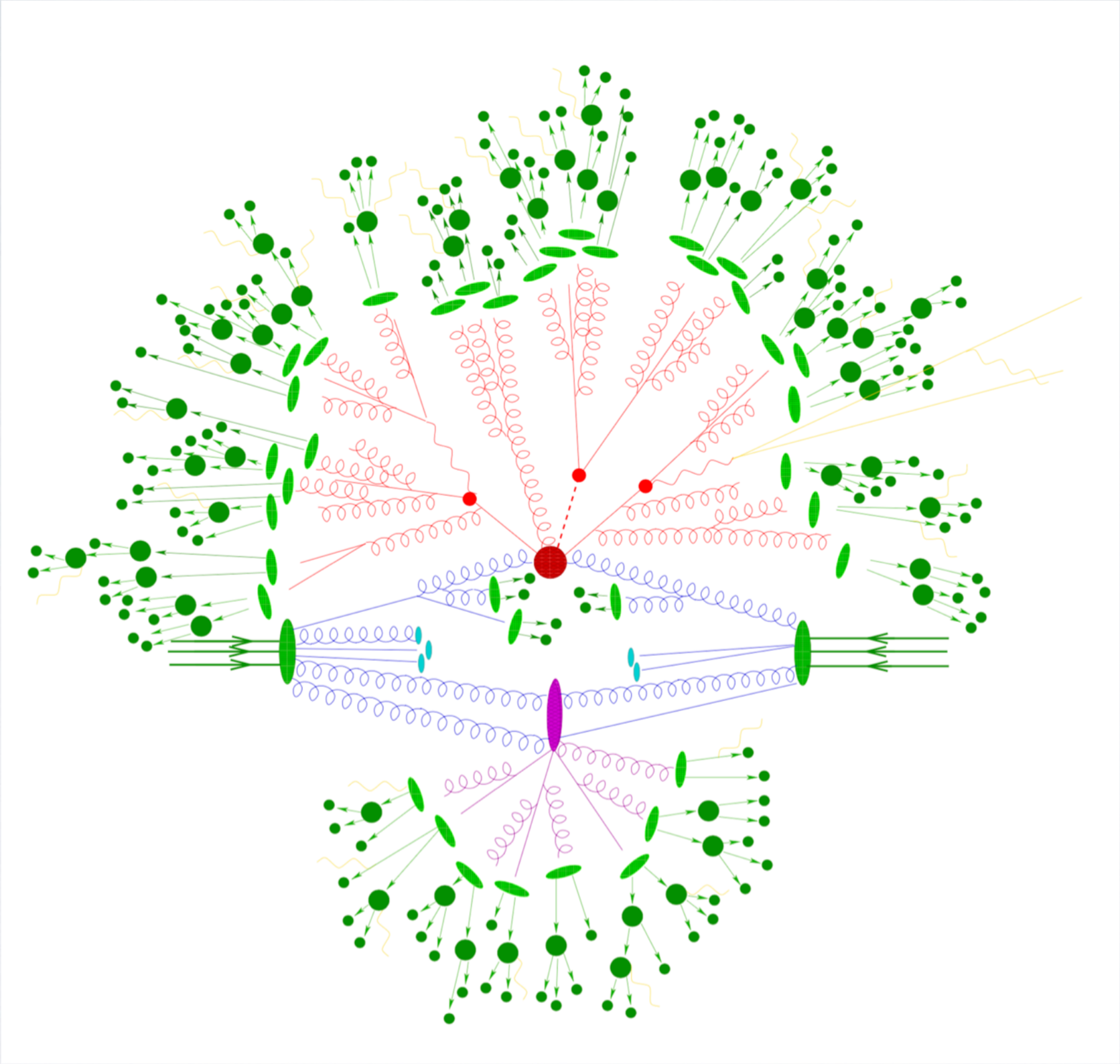

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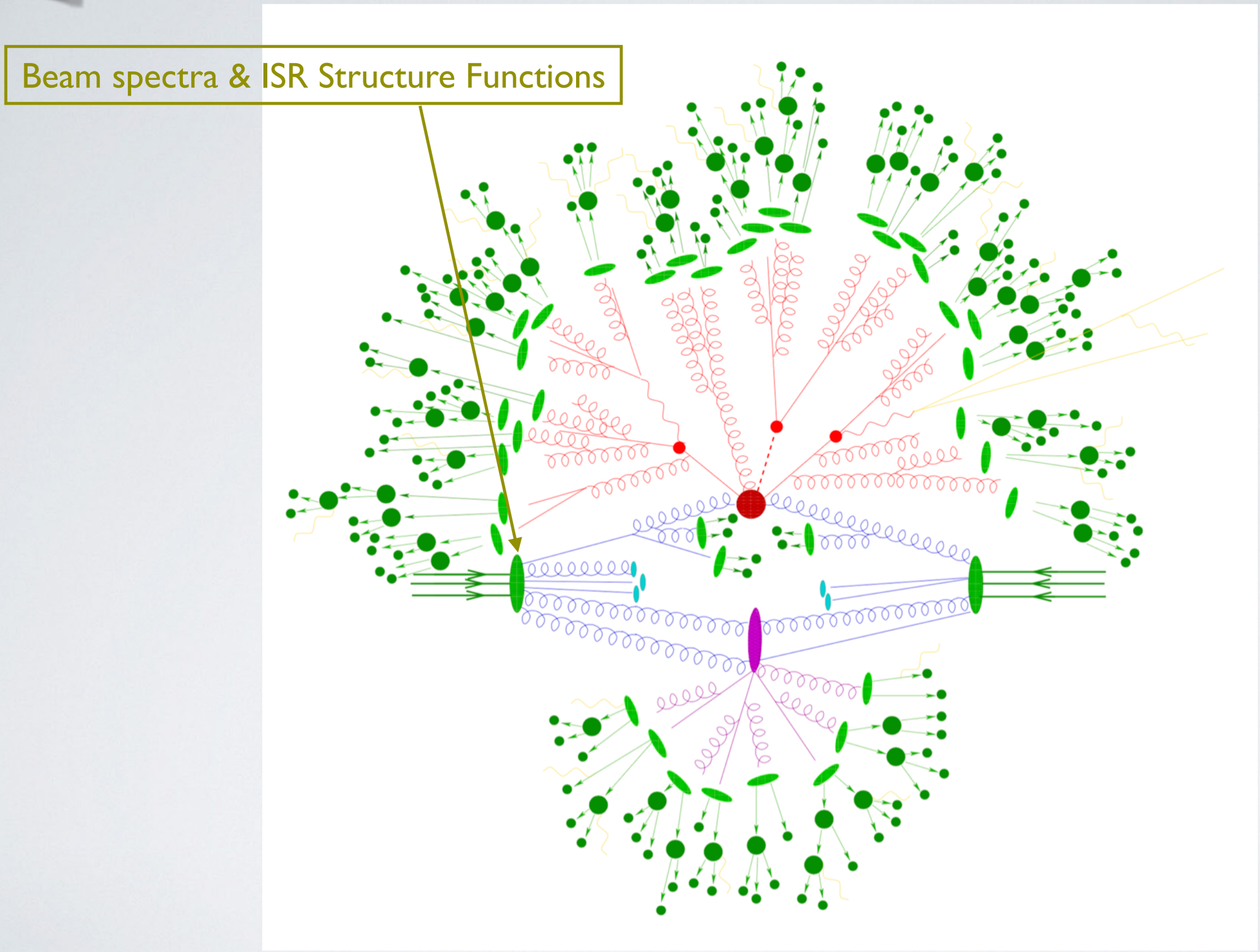

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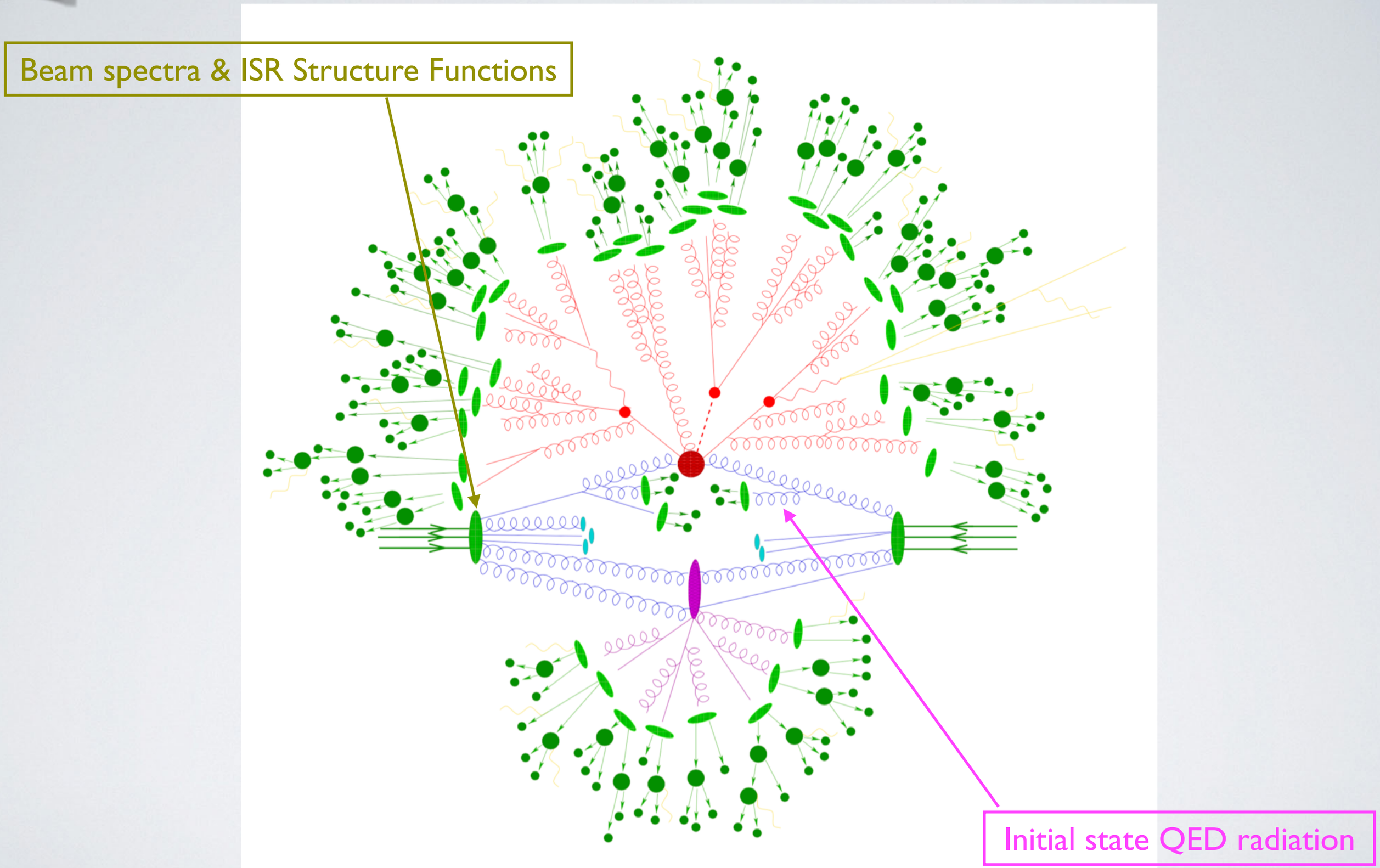

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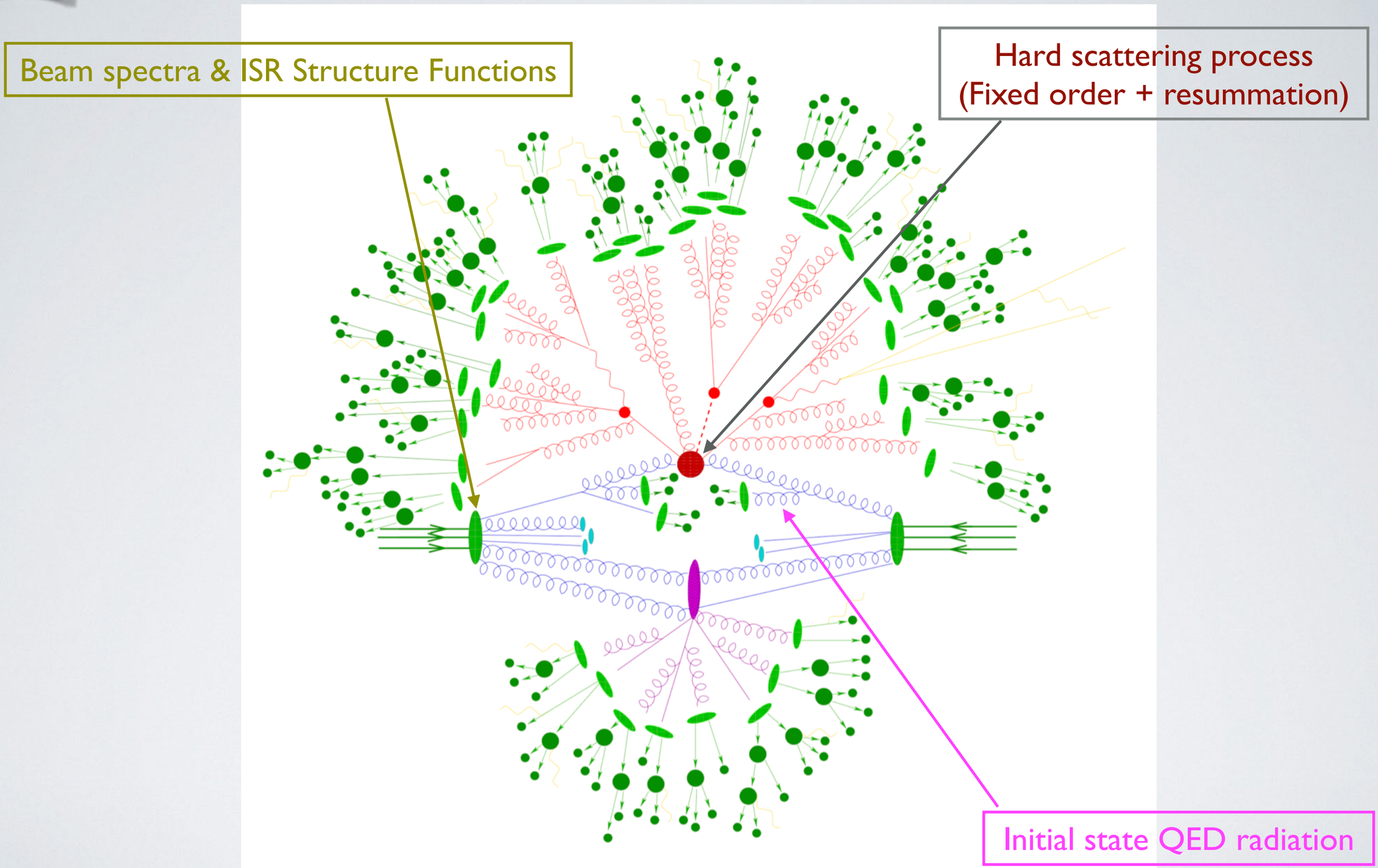

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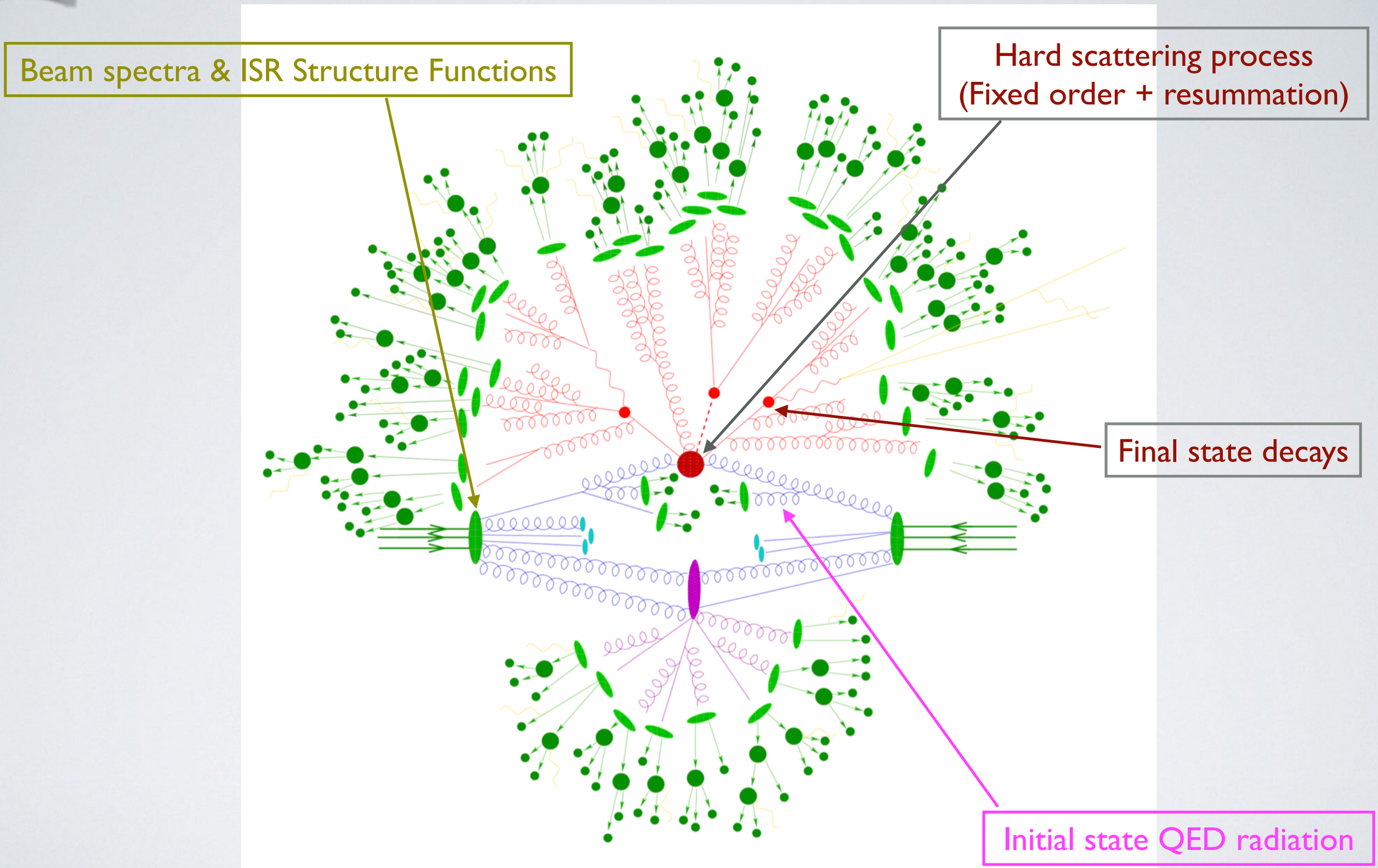

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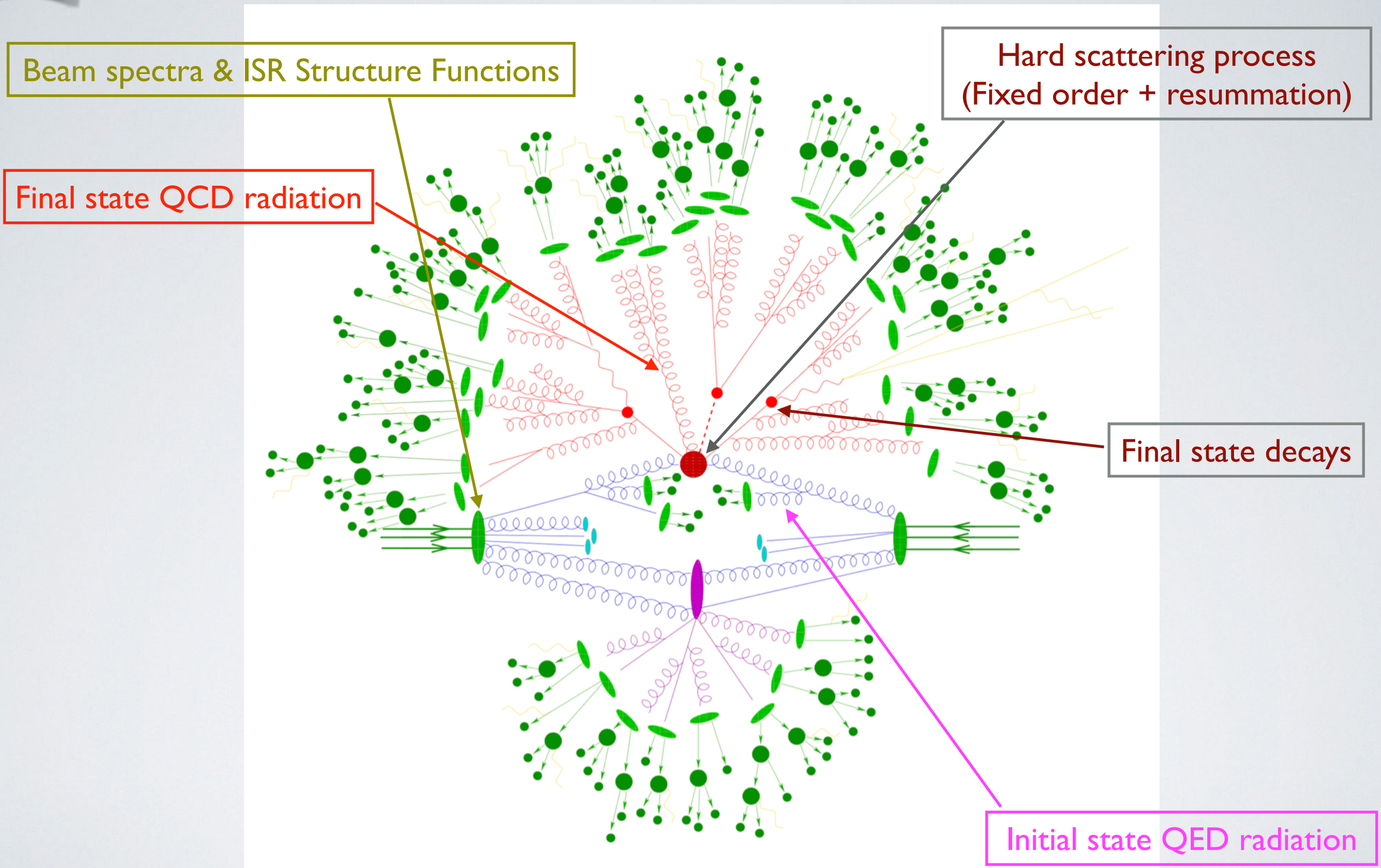

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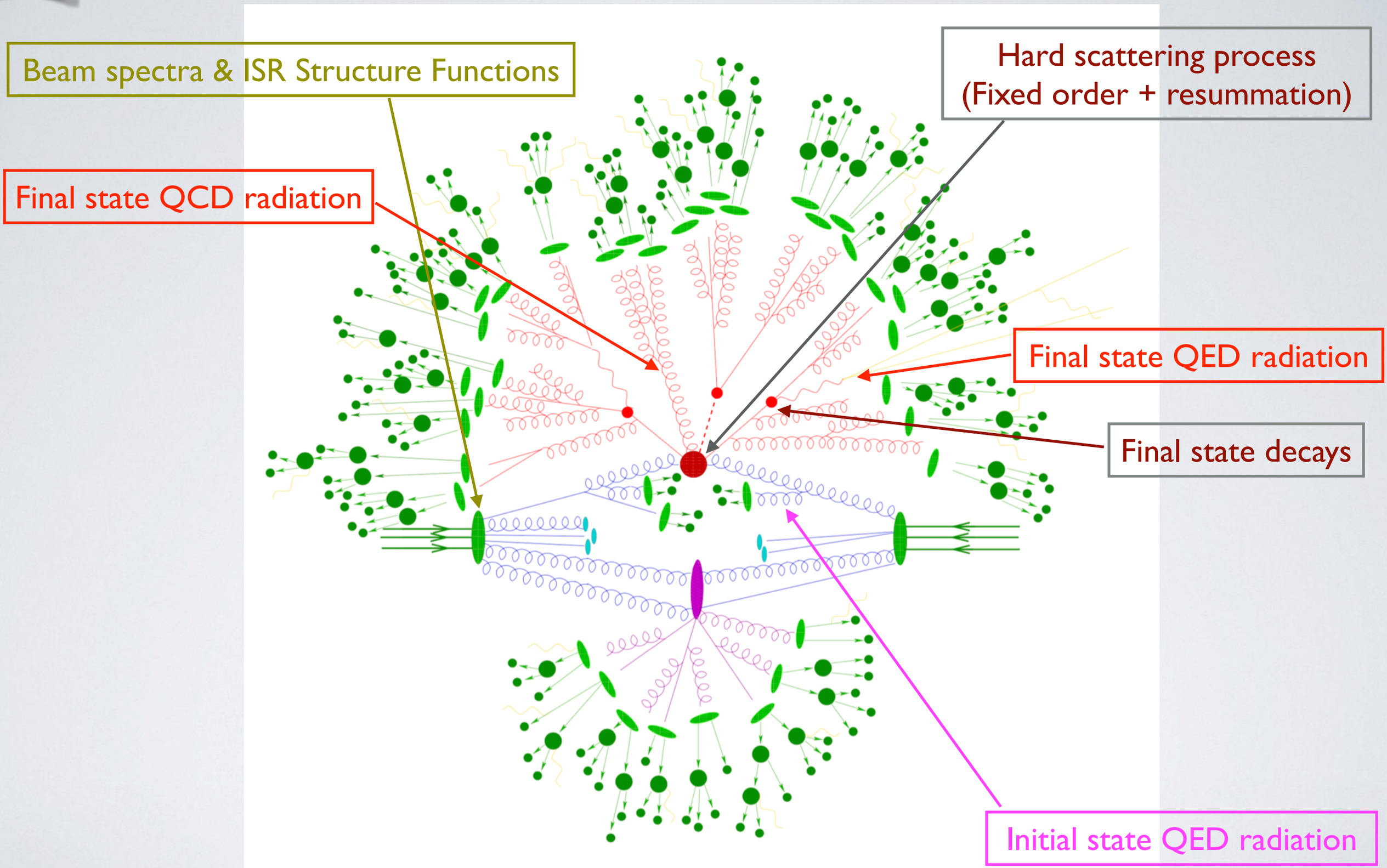

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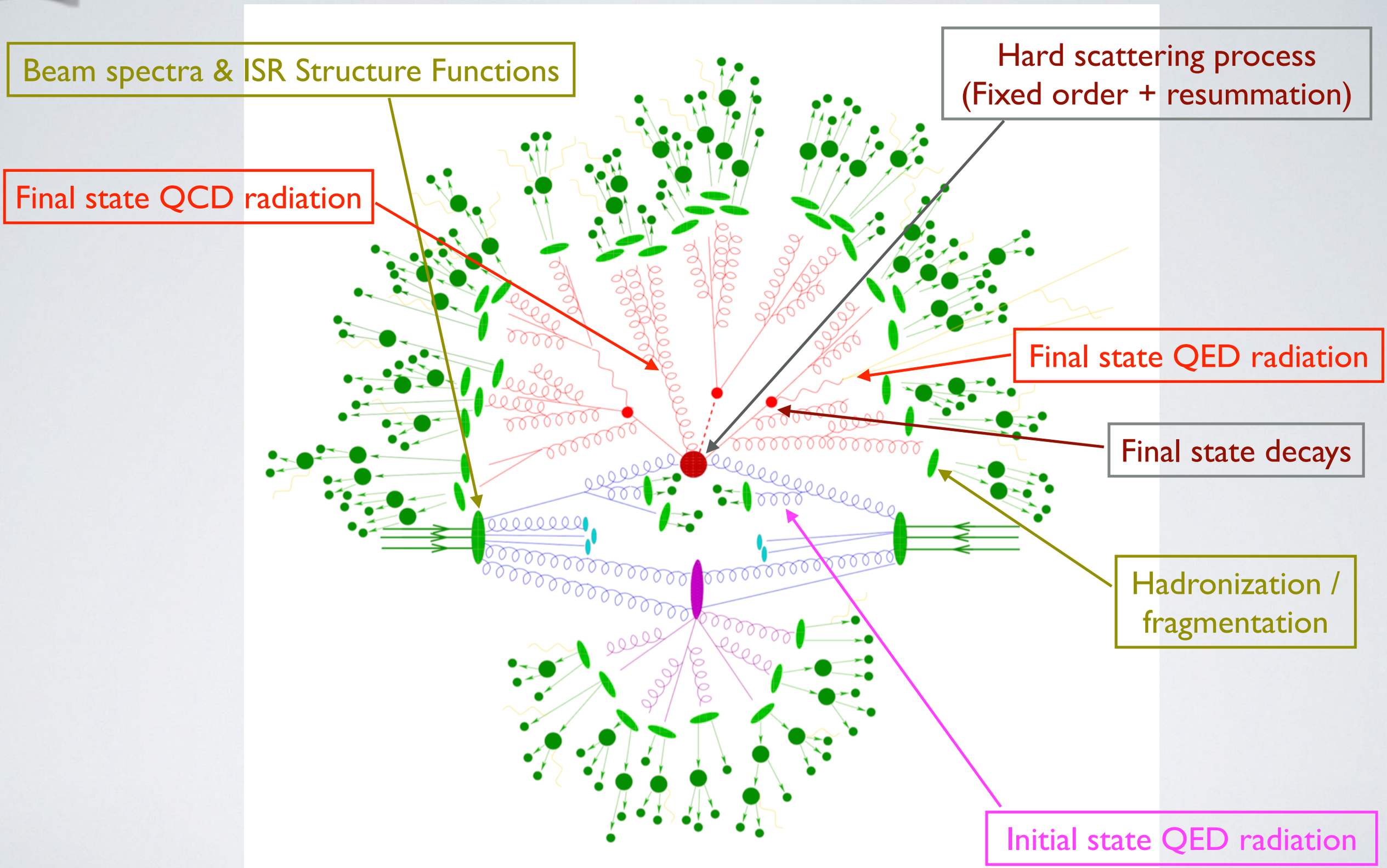

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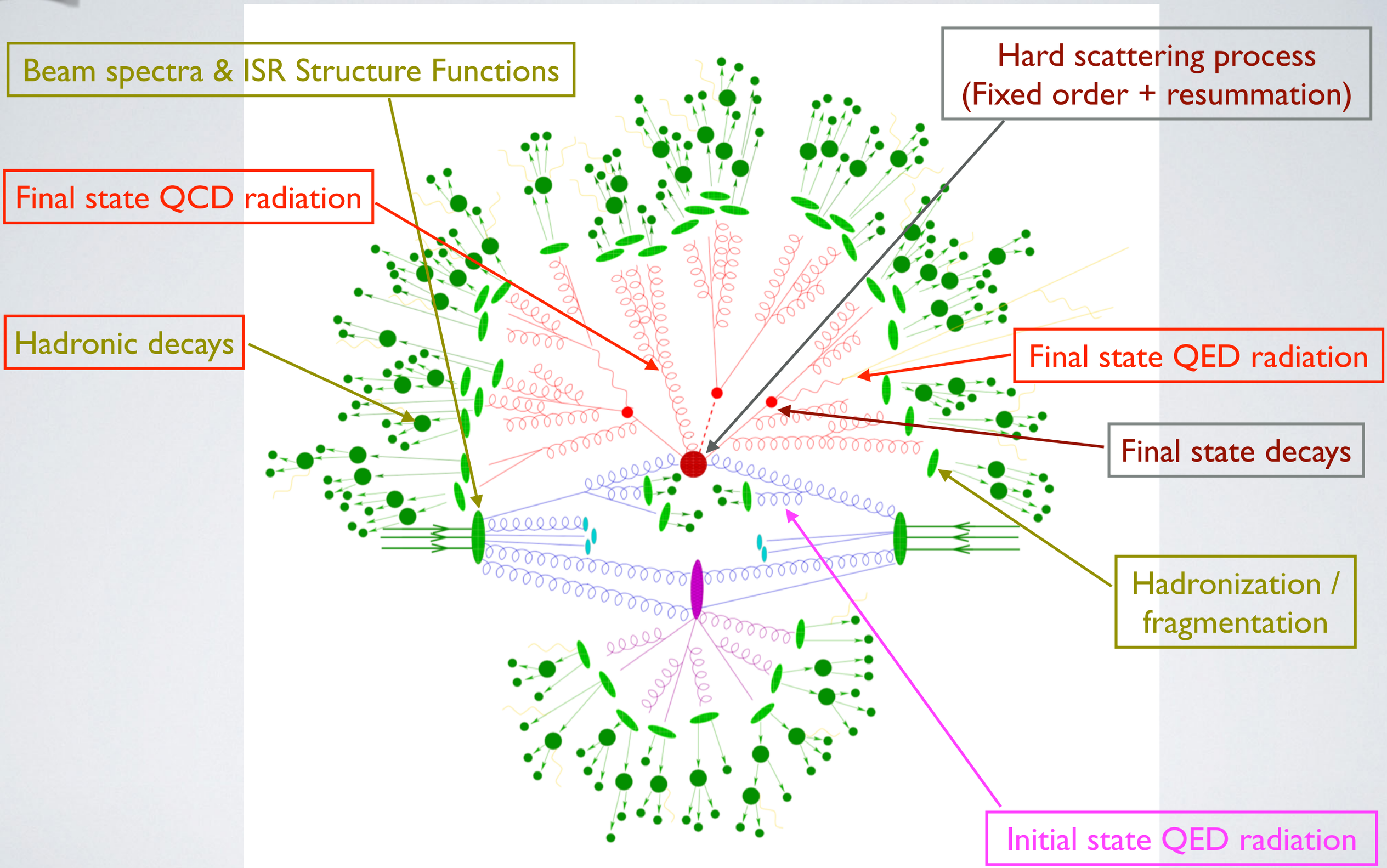

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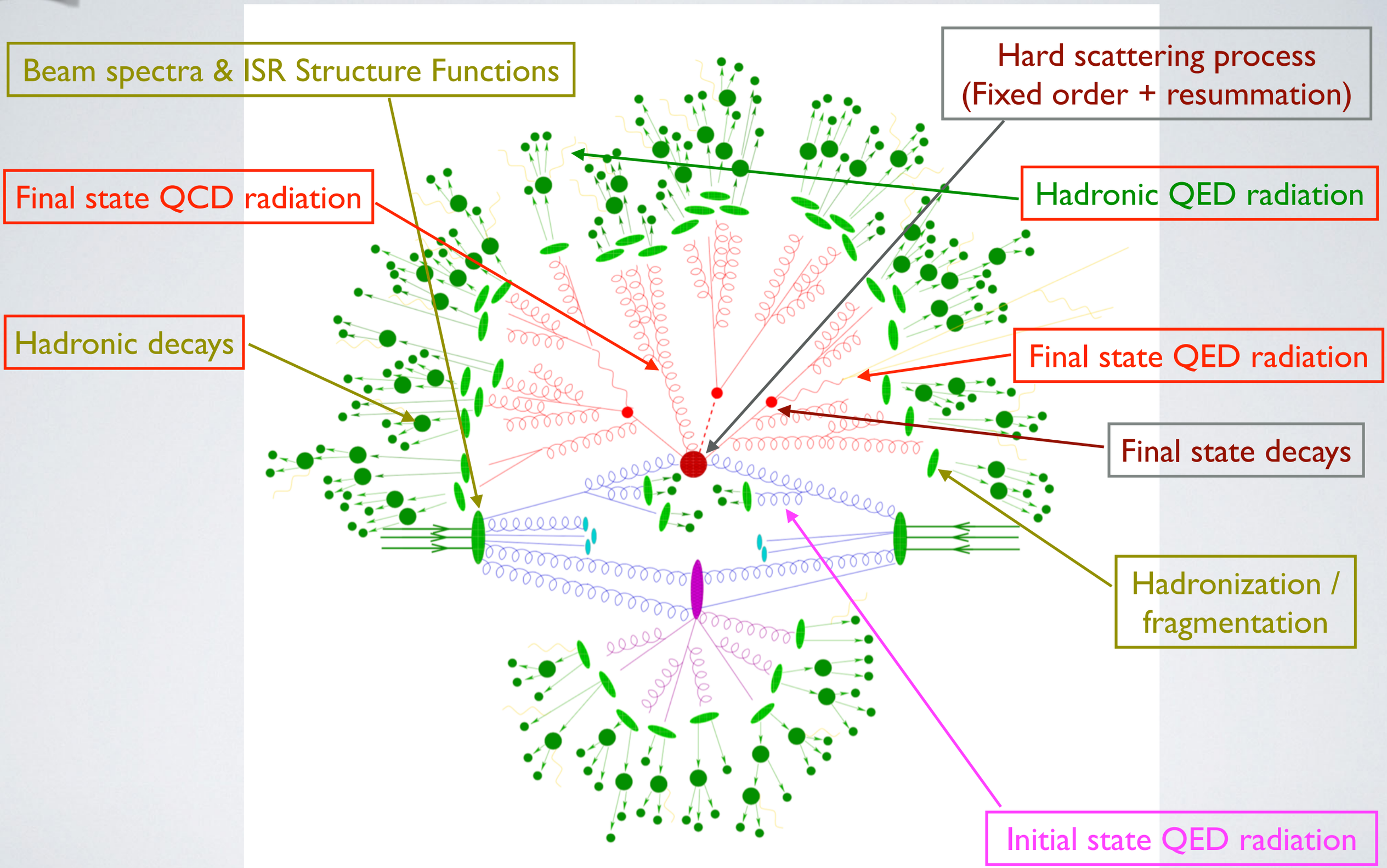

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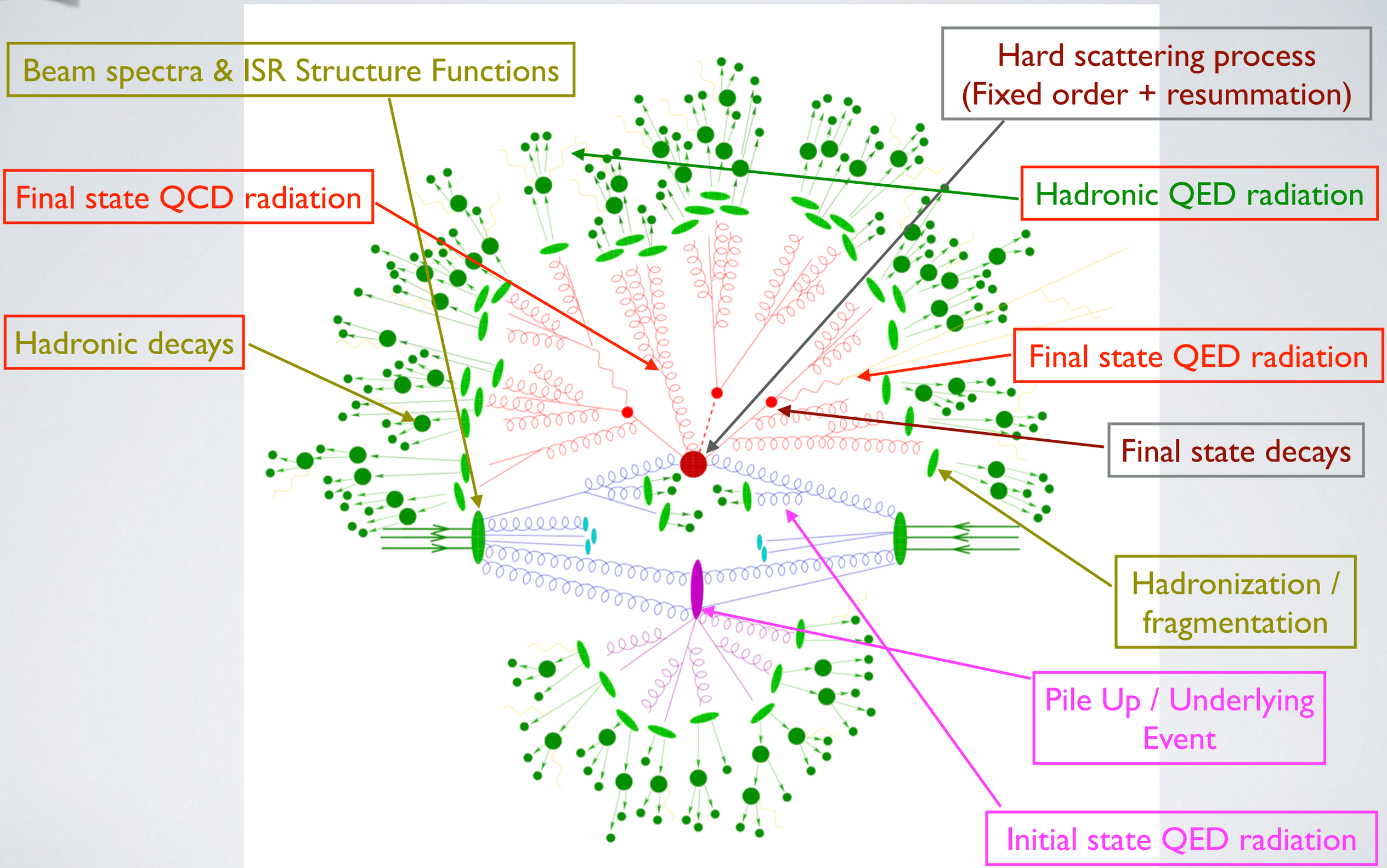

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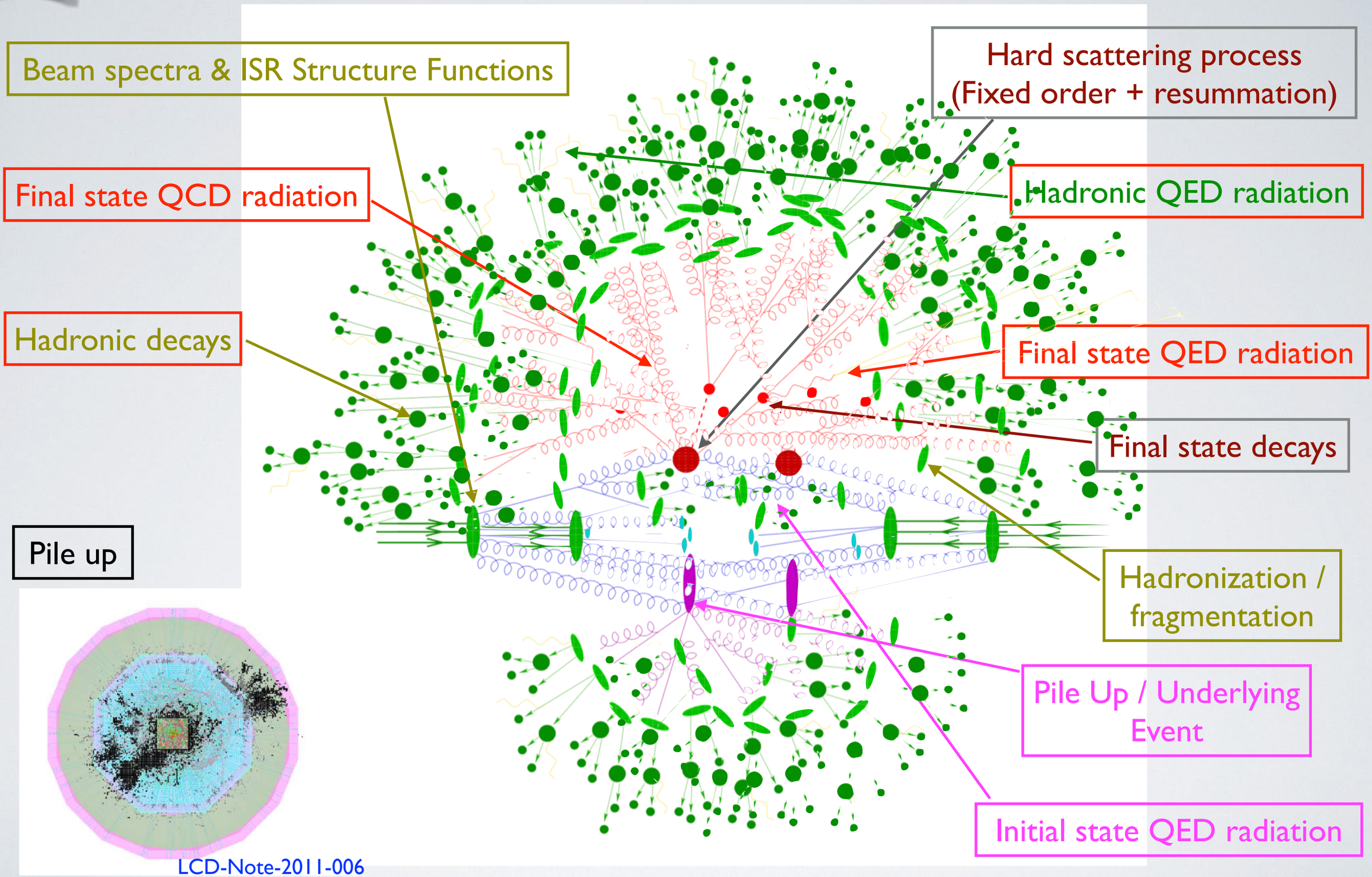


WHIZARD: Introduction / Technical Facts

WHIZARD v2.8.5 (16.09.2020)

WHIZARD v3.0.0β (30.08.2020)

<*whizard@desy.de*>

http://whizard.hepforge.org

WHIZARD Team:

Wolfgang Kilian, Thorsten Ohl, JRR

SB / Pia Bredt / Nils Kreher / Allan Price / Vincent Rothe / Pascal Stienemeier / Tobias Striegl

PUBLICATIONS

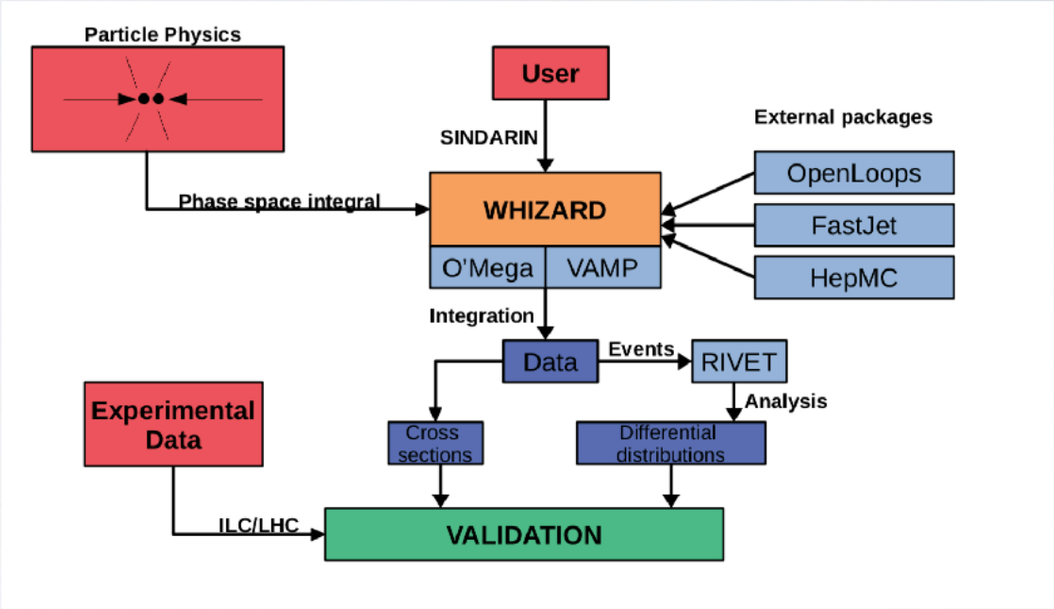
General WHIZARD reference:	EPJ C71 (2011) 1742, arXiv:0708.4241
O'Mega (ME generator):	LC-TOOL (2001) 040; arXiv:hep-ph/0102195
VAMP (MC integrator):	CPC 120 (1999) 13; arXiv:hep-ph/9806432
VAMP2 (MC integrator):	EPJ C79 (2019) 4.344; arXiv:1811.09711
CIRCE (beamstrahlung):	CPC 101 (1997) 269; arXiv:hep-ph/9607454
Parton shower:	JHEP 1204 (2012) 013; arXiv:1112.1039
Color flow formalism:	JHEP 1210 (2012) 022; arXiv:1206.3700
NLO capabilities:	JHEP 1612 (2016) 075; arXiv: 1609.03390
Parallelization of MEs:	CPC 196 (2015) 58; arXiv:1411.3834
POWHEG matching:	EPS-HEP (2015) 317; arXiv: 1510.02739

- Programming Languanges: `Fortran2008 (gfortran ≥5.1.0), OCaml (≥4.02.3)`
- Standard installation: `configure <FLAGS>, make, [make check], make install`
- 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, preset BRs
- Scripting language for the steering: SINDARIN
- Beam structure: polarization, asymmetric beams, crossing angle, structured beams, decays

WHIZARD: Installation and Run

- Installed centrally, production runs in specific workspaces
- Download: http://whizard.hepforge.org/whizard-2.8.5.tar.gz
- Unpack it, intended to be installed in `/usr/local` (or locally)
- Create `build` directory and do `../configure`
- Options: `../configure --prefix=<dir> --enable-lcio –with-XXX`
- `make`, `[ make check ]`, `make install`
- Working directory: create `SINDARIN` steering file `<input>.sin`
- Working directory: run `whizard <input>.sin`

WHIZARD: User support / bug tracker

WHIZARD v2.8.5 (24.09.2020) https://launchpad.net/whizard

https://launchpad.net/whizard

https://launchpad.net/whizard

Juergen Reuter (j.r.reuter) • Log Out

WHIZARD

Overview | Code | Bugs | Blueprints | Translations | Answers

Registered 2019-06-26 by Juergen Reuter

WHIZARD Event Generator

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

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

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

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

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

Change branding

Home page | Wiki | External downloads

Project information

Maintainer: WHIZARDs

Driver: WHIZARDs

Licence: GNU GPL v3

RDF metadata

Series and milestones

View full history

3.0.x: 3.0.0alpha, 3.0.0beta, 3.0.0 (2020-10-31)

2.8.x: 2.8.0, 2.8.1, 2.8.2, 2.8.3, 2.8.4, 2.8.5 (2020-09-16)

3.0.x series is the current focus of development.

Register a series | View milestones

Code

All code

Version control system:

Programming languages:

Latest bugs reported

All bugs

Bug #1888539: Openloops error in NLO_NLL_matched.sin example

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Configuration Progress

Configuration options
Code ✖
Bugs ✓
Translations ✓
Answers ✓

Downloads

Latest version is 3.0.0beta

whizard-3.0.0_beta.tar.gz

released on 2020-08-30

All downloads

Announcements

WHIZARD 2.8.5 released on 2020-09-16
Contains bug fix for tau polarization in H -> tau tau. Backport of a problem ...

WHIZARD 3.0.0beta released on 2020-08-30
New and shiny WHIZARD API: WHIZARD can be called as a library from any extern...

WHIZARD 2.8.4 released on 2020-07-08
This is a backported bug fix for correctly steering UFO models with Majorana ...

Final WHIZARD 2 series release 2.8.3 on 2020-07-04

WHIZARD: Manual

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

whizard is hosted by Hepforge, IPPP Durham

- WHIZARD
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  - CLIC page on WHIZARD
  - News
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  - Delphes Fast Simulation
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  - ChangeLog
- REPOSITORY, LAUNCHPAD, BUG TRACKER
  - Launchpad Support Page
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  - Public Git Repository
  - Support Questions
  - Bug Tracker
- DOWNLOADS
  - Download Page
  - LC beam spectra
  - FeynRules and SARAH models
  - Patches/Unofficial versions
- SUBPACKAGES/INTERFACES
  - O'Mega Matrix Element Generator
  - VAMP Monte Carlo Integrator
  - CIRCE1/2 Beam Spectra Generator
  - WHIZARD/FeynRules interface (deprecated)
- CONTACT
  - Launchpad Support Page
  - Contact us

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

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

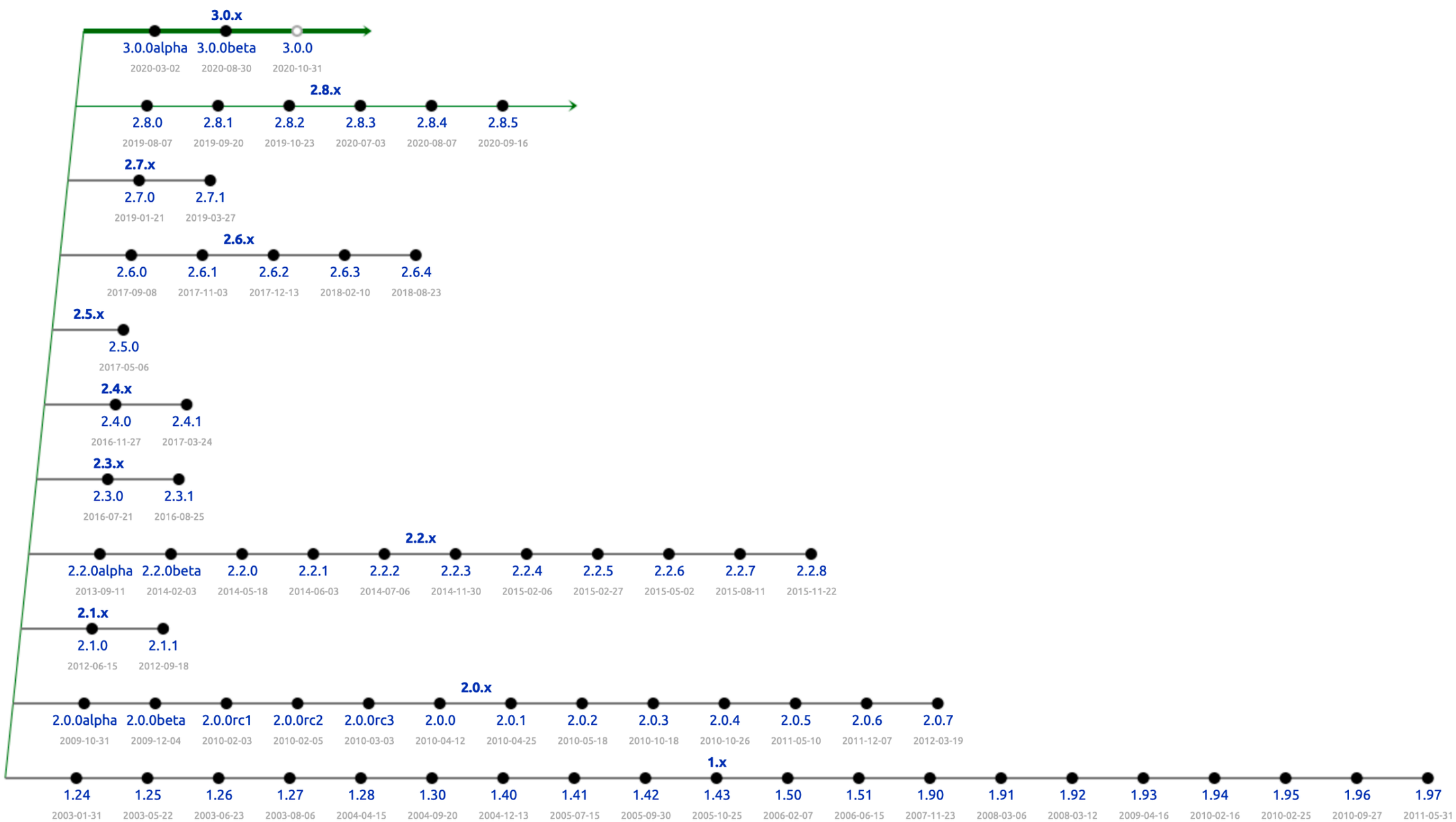
WHIZARD Manual @ HepForge

https://whizard.hepforge.org/manual

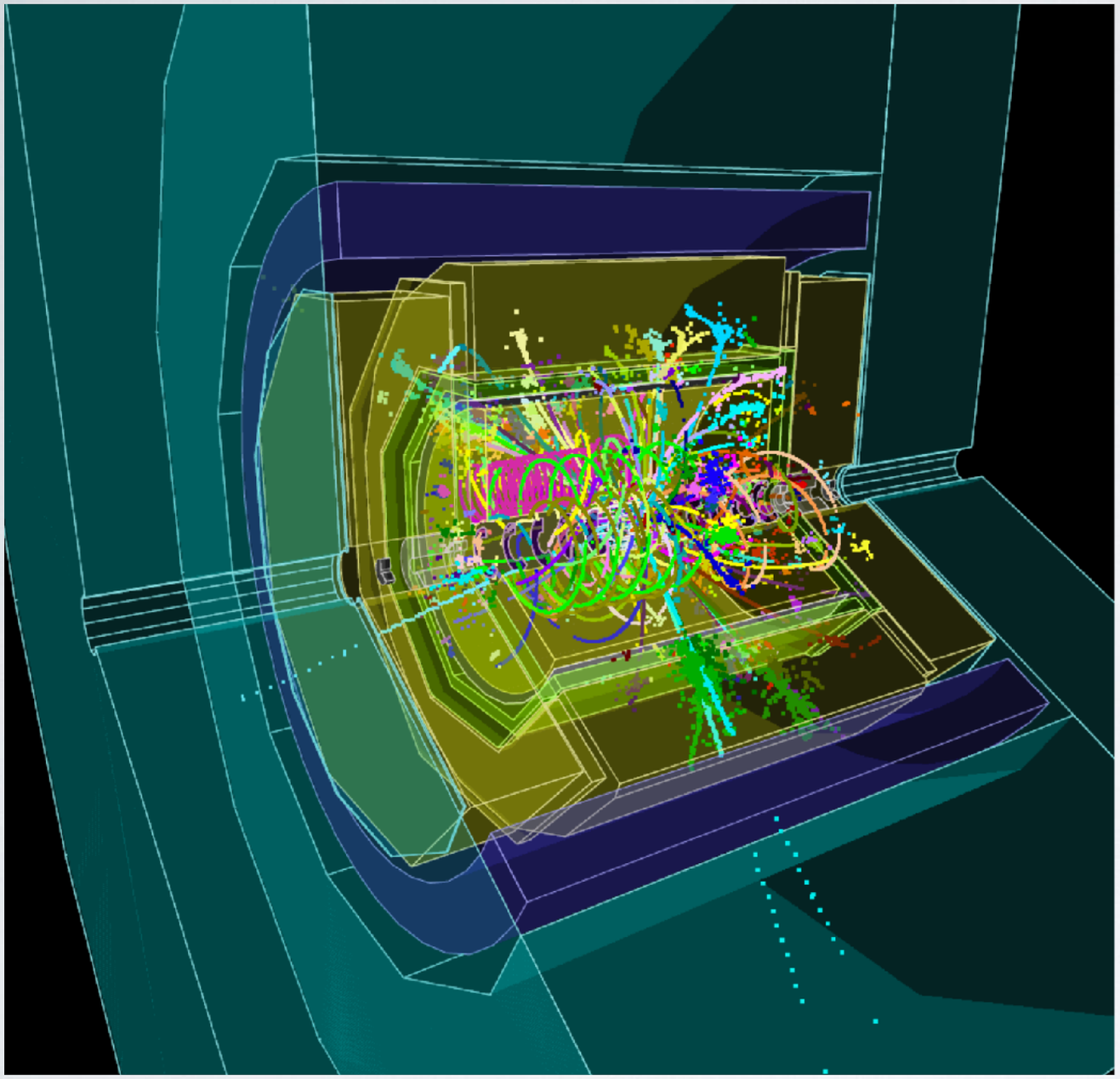
WHIZARD: Timeline

Overview Code Bugs Blueprints Translations Answers

timeline



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 !

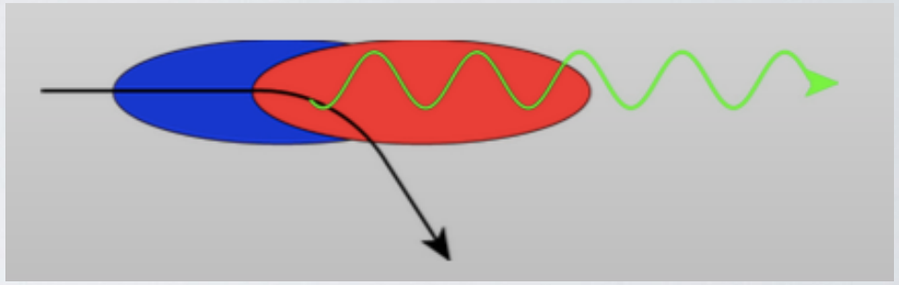
cf. the ILC tutorial

Lepton Collider Beam Simulation

- 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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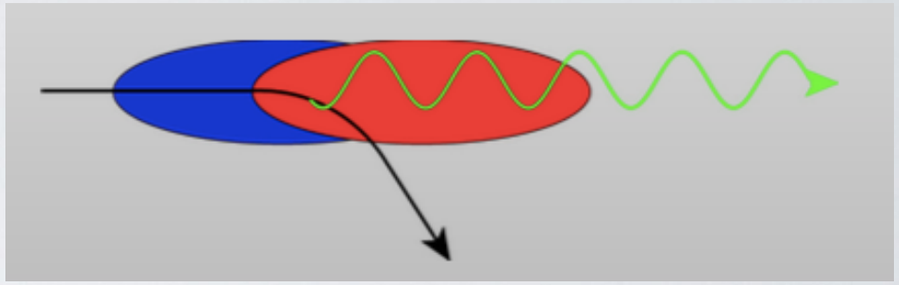
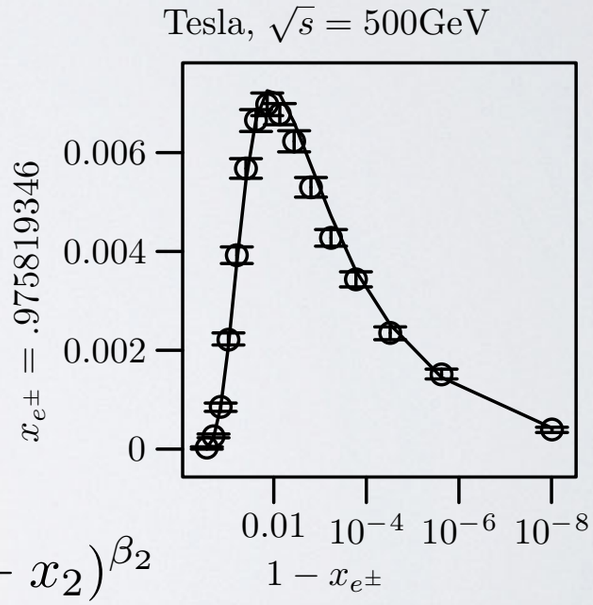


- Depends on the machine: damping rings, final focus magnet, crossing angle etc.
- Simulation tool for beam spectrum: `GuineaPig` [D. Schulte, 1998+]
- Very limited statistics: O(100k) vs. Simulations need O(many G)
- Can we use simple parameterizations?
- TESLA/SLC/NLC/JLC spectra were rather simple
- Fits with 6 or 7 parameters possible [`WHIZARD–CIRCE1`]
- ILC/CLIC: Beams not factorizable: $D_{B_1B_2}(x_1,x_2) \neq D_{B_1}(x_1)\cdot D_{B_2}(x_2)$
- No simple power law: $D_{B_1B_2}(x_1,x_2) \neq x_1^{\alpha_1}(1-x_1)^{\beta_1}x_2^{\alpha_2}(1-x_2)^{\beta_2}$



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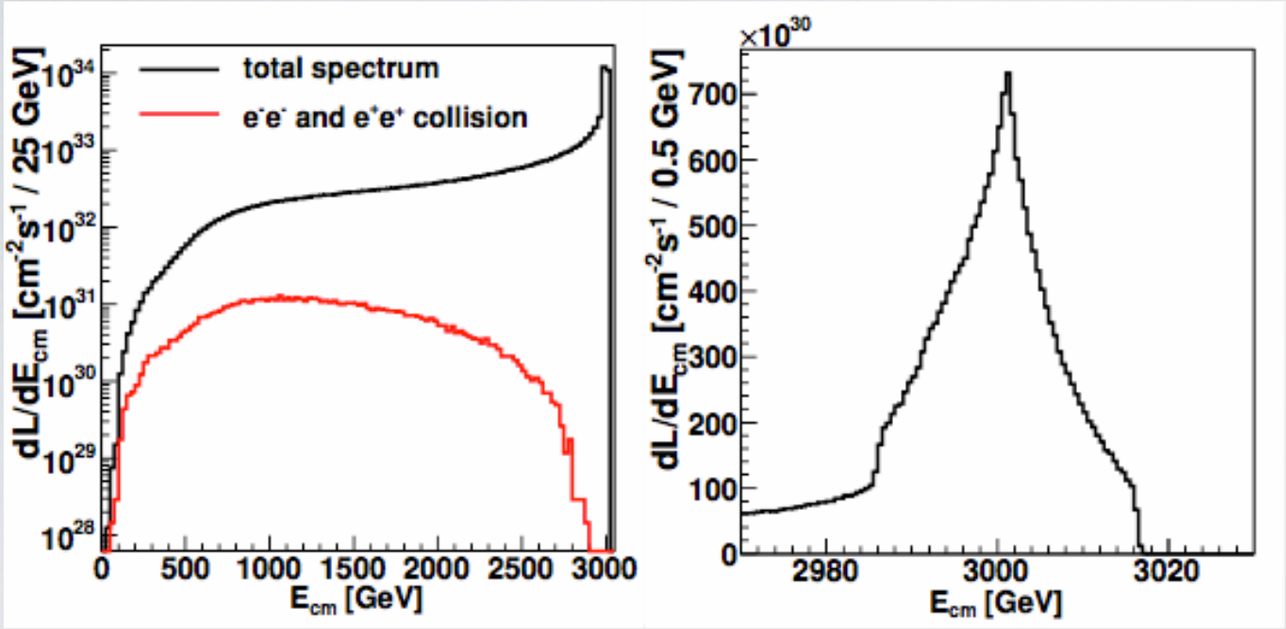

Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)

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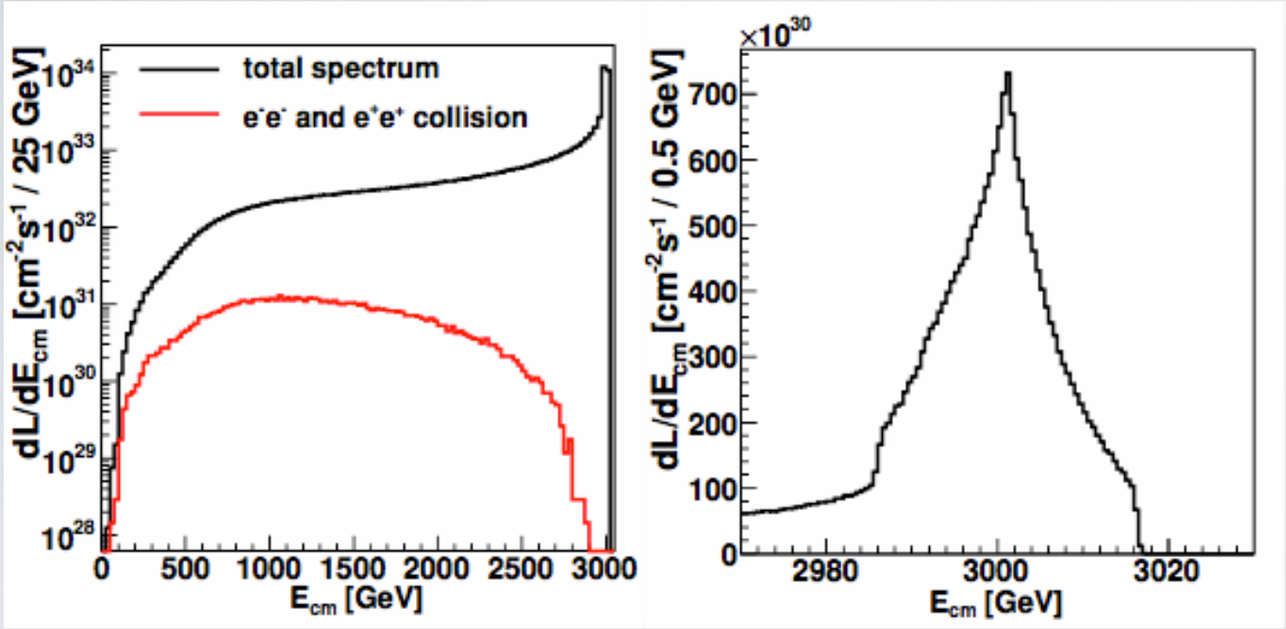

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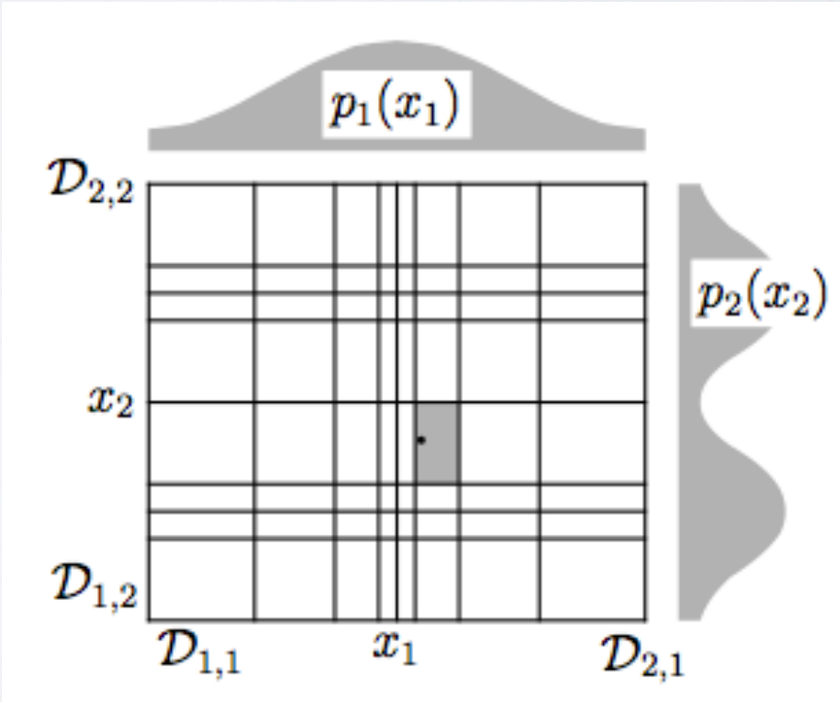
CIRCE2 algorithm (WHIZARD 2.2.5, 02/15)

- 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]



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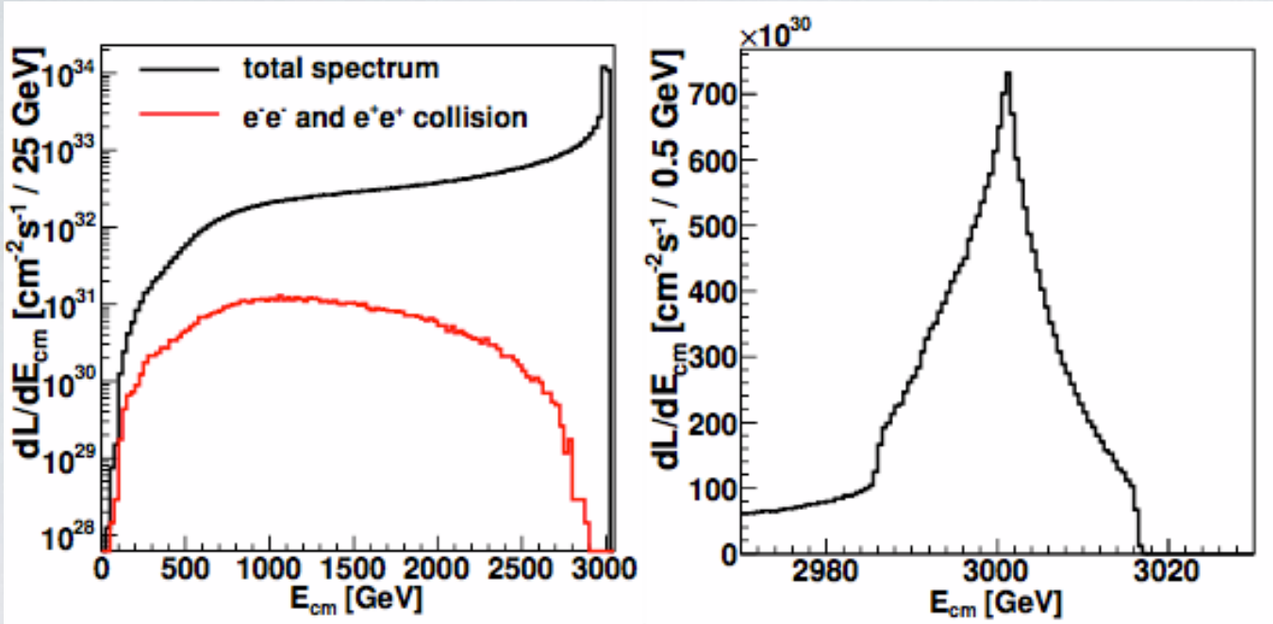

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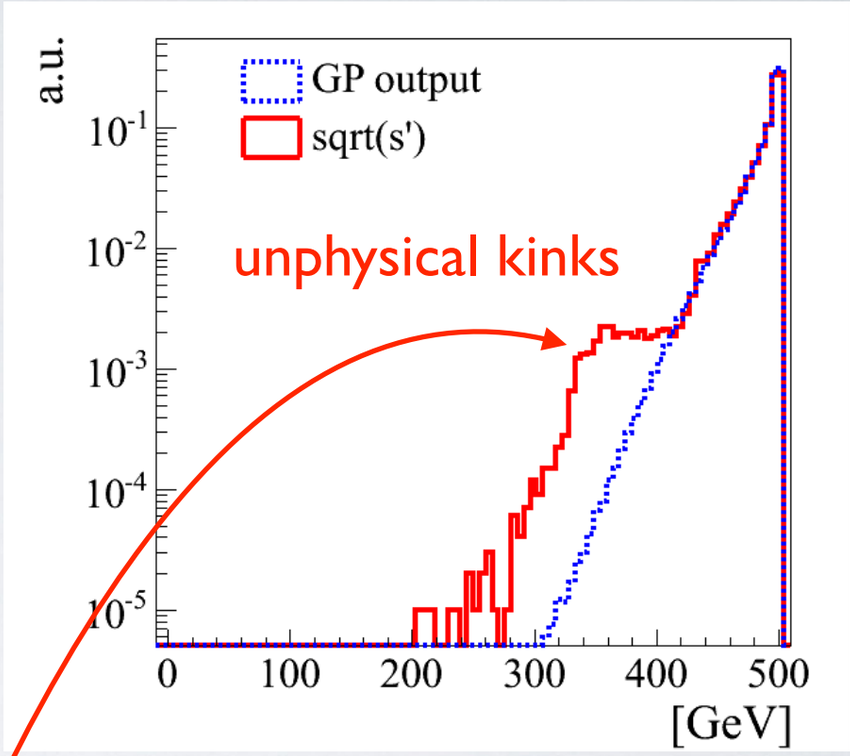

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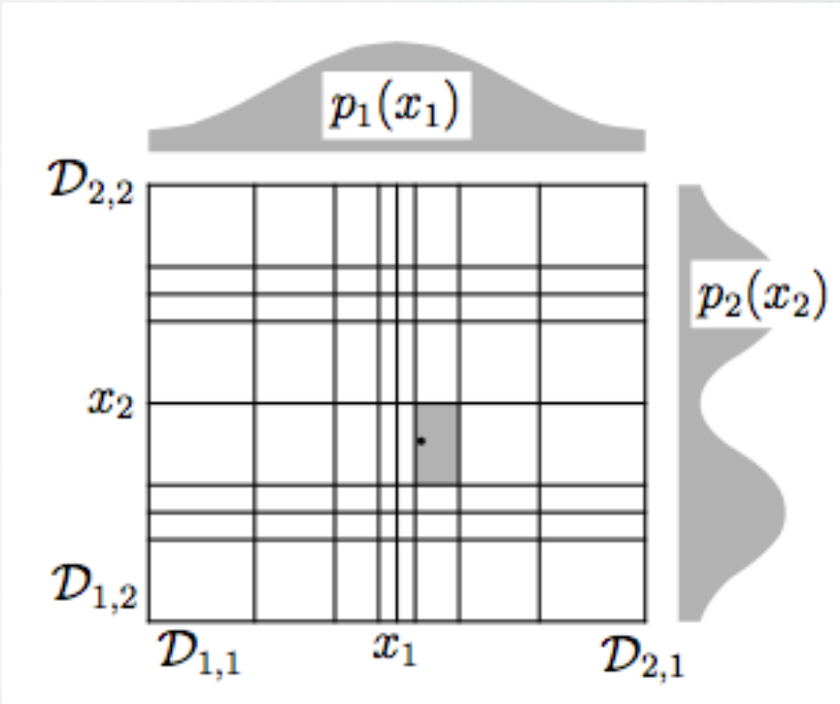

Lepton Collider Beam Spectra

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

Index of /circe_files/CEPC

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

Index of /circe_files/ILC

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

Index of /circe_files/TESLA

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

Index of /circe_files/CLIC

Name	Last modified	Size	De
Parent Directory		-	
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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	

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

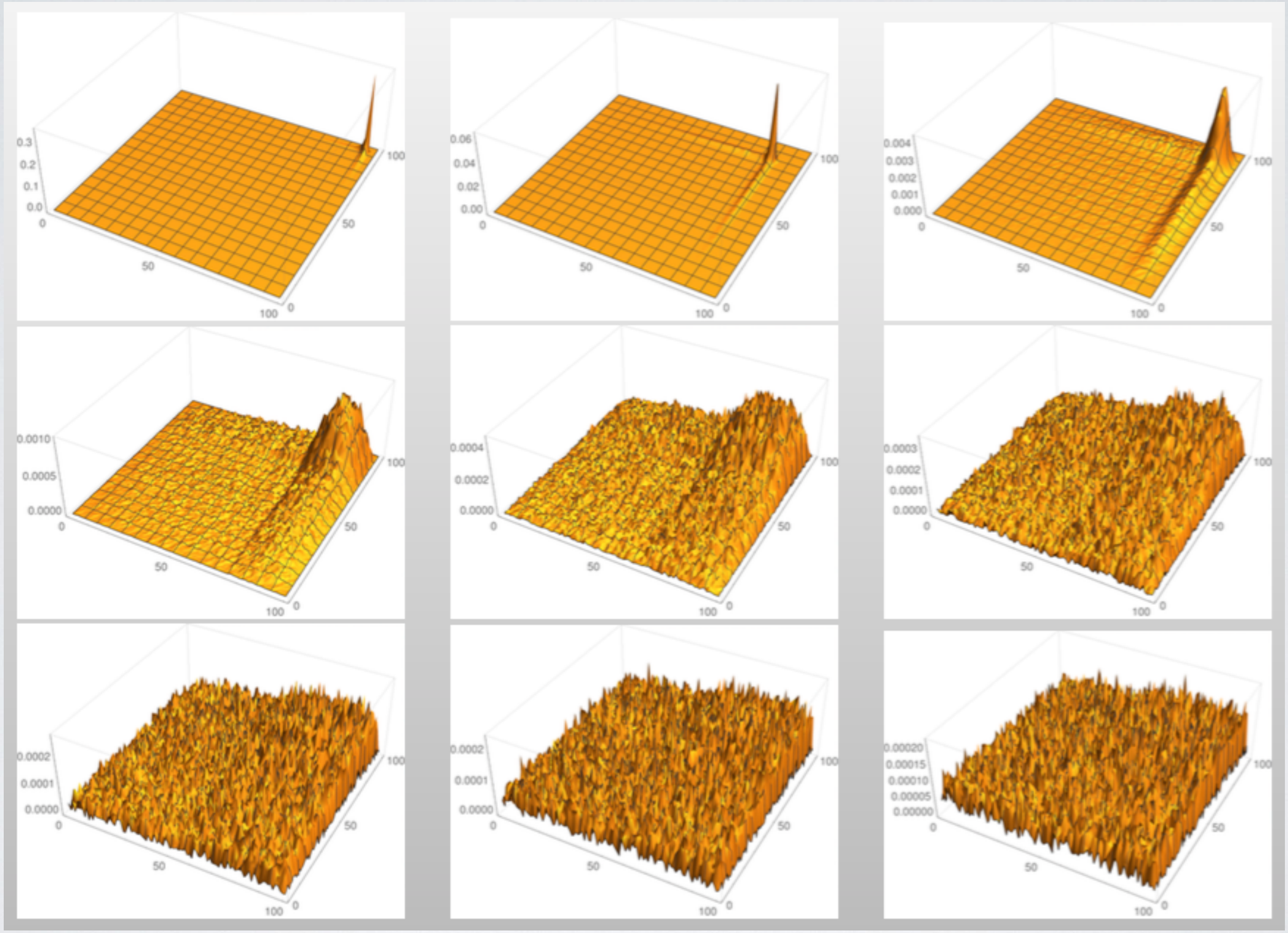
3. Run WHIZARD with SINDARIN input:

```
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

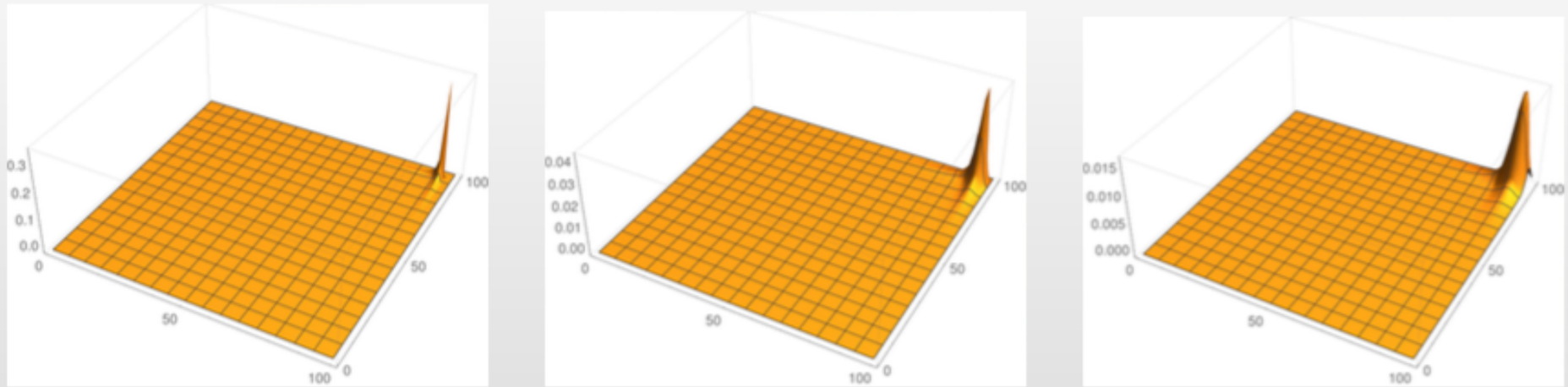
Iterations of Beam Spectrum



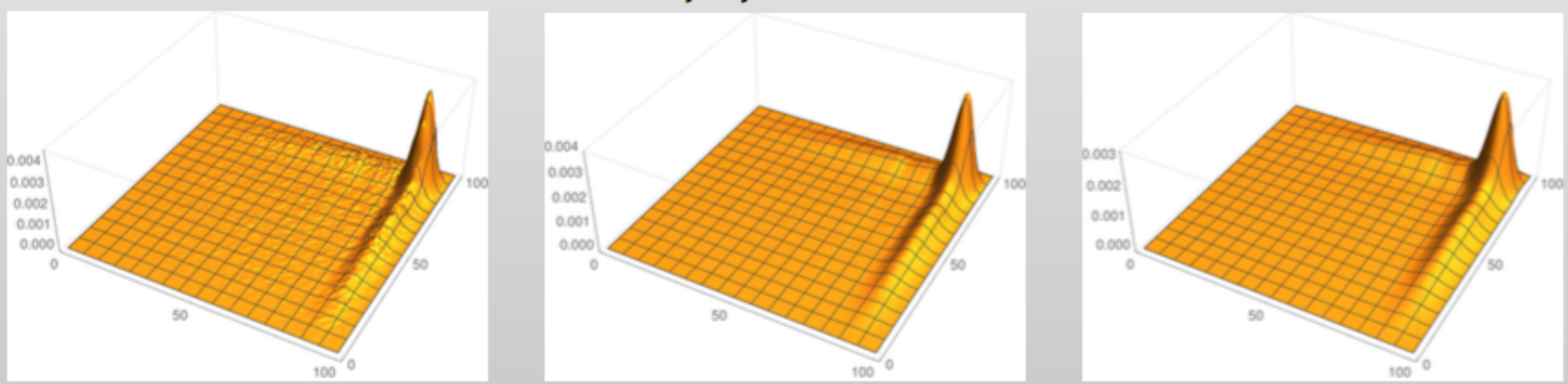
(171,306 GuineaPig events in 10,000 bins)

Iterations of Beam Spectrum

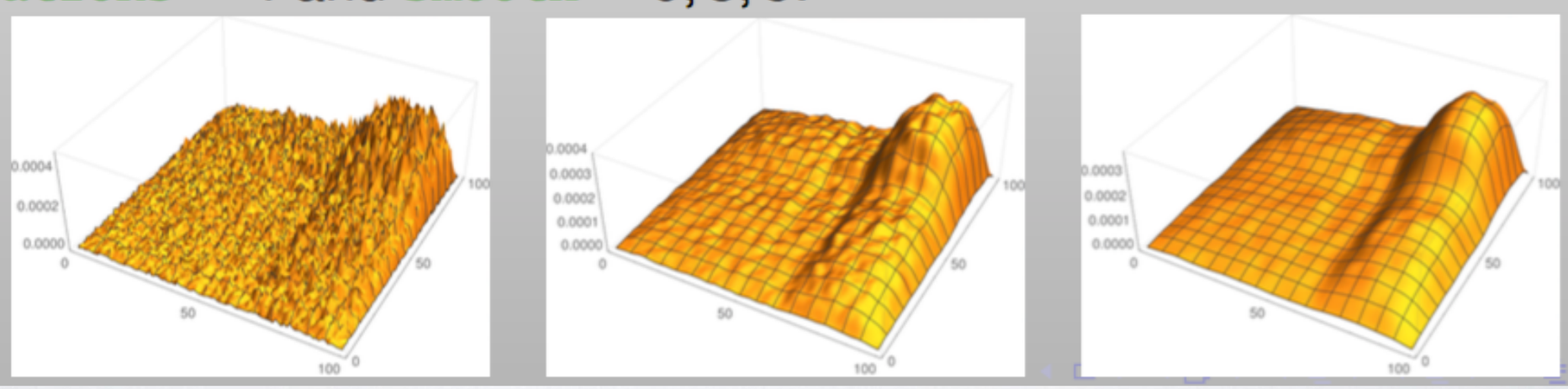
- `iterations` $= 0$ and `smooth` $= 0, 3, 5$:



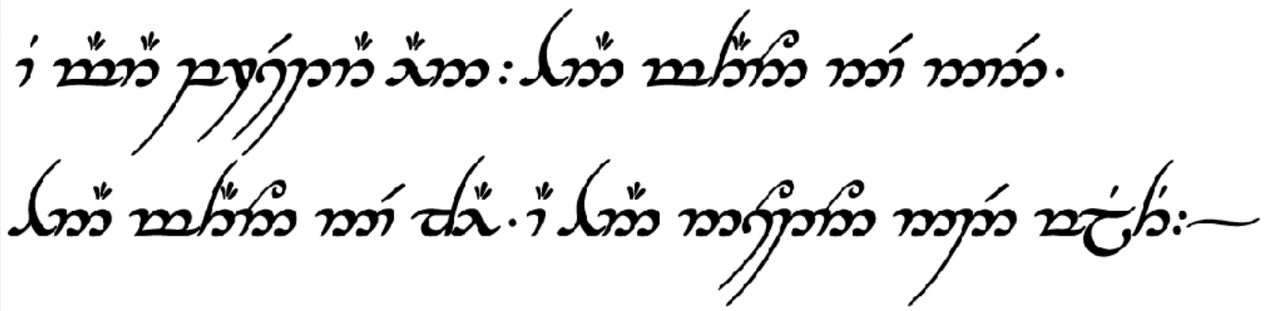
- `iterations` $= 2$ and `smooth` $= 0, 3, 5$:



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



WHIZARD input files: SINDARIN



```
model = NMSSM

alias ll = e1:E1:e2:E2
alias parton = u:U:d:D:s:S:g
alias jet = parton
alias stop = st1:st2:ST1:ST2

process susyprod = parton, parton =>
    stop,stop + gg,gg + gg,stop


sqrts = 13000 GeV
beams = p, p => lhapdf

integrate (susyprod)
     { iterations = 15:500000, 5:1000000 }

n_events = 10000

sample_format = lhef, stdhep, hepmc
sample = “susydata”

simulate (susyprod)
```

integer variables

```
int i = 3
```

real variables

```
real a = 2.78
real foo = -7.8%
real coeff = 20.1 TeV^(-2)
```

complex variables

```
complex ca = 2 + I
```

string variables

```
string $str = “foo”
```

logical variables

```
logical ?ok = false
```

printing

```
printf “abc”
printf “%i” (12345)
```

conditionals

```
if i == 1 then
  printf “one = %1” (i)
elsif i == 2 then
  printf “two”
endif
```

aliases

```
alias lepton = e1,e2,e3
```

scanning

```
scan mW = (75 GeV,
           (80 GeV => 82 GeV /+ 0.5 GeV),
           (83 GeV => 90 GeV /*/ 5)) {
  <scan body>
}
```

Beam structure: polarization & special beams

Beam polarization: enhances signal-to-background ratios, more model-independent studies

```
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

$|m| = 2$ 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

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

Scan over polarizations

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

Beam structure: polarization & special beams

Beam polarization: enhances signal-to-background ratios, more model-independent studies

```
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

$|m| = 2$ 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

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

Beam polarization, CLIC-like setup

```
beams = e1, E1
beams_pol_density = @(-1), @()
beams_pol_fraction = 80%, 0%
```

Scan over polarizations

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

Beam structure: polarization & special beams

Beam polarization: enhances signal-to-background ratios, more model-independent studies

```
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

$|m| = 2$ 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

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

Beam polarization, CLIC-like setup

```
beams = e1, E1
beams_pol_density = @(-1), @()
beams_pol_fraction = 80%, 0%
```

Scan over polarizations

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

Polarized decays: longitudinal Z

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

Beam structure: polarization & special beams

Beam polarization: enhances signal-to-background ratios, more model-independent studies

```
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

$|m| = 2$ 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

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

Beam polarization, CLIC-like setup

```
beams = e1, E1
beams_pol_density = @(-1), @()
beams_pol_fraction = 80%, 0%
```

Beam polarization, ILC-like setup

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

Scan over polarizations

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

Polarized decays: longitudinal Z

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

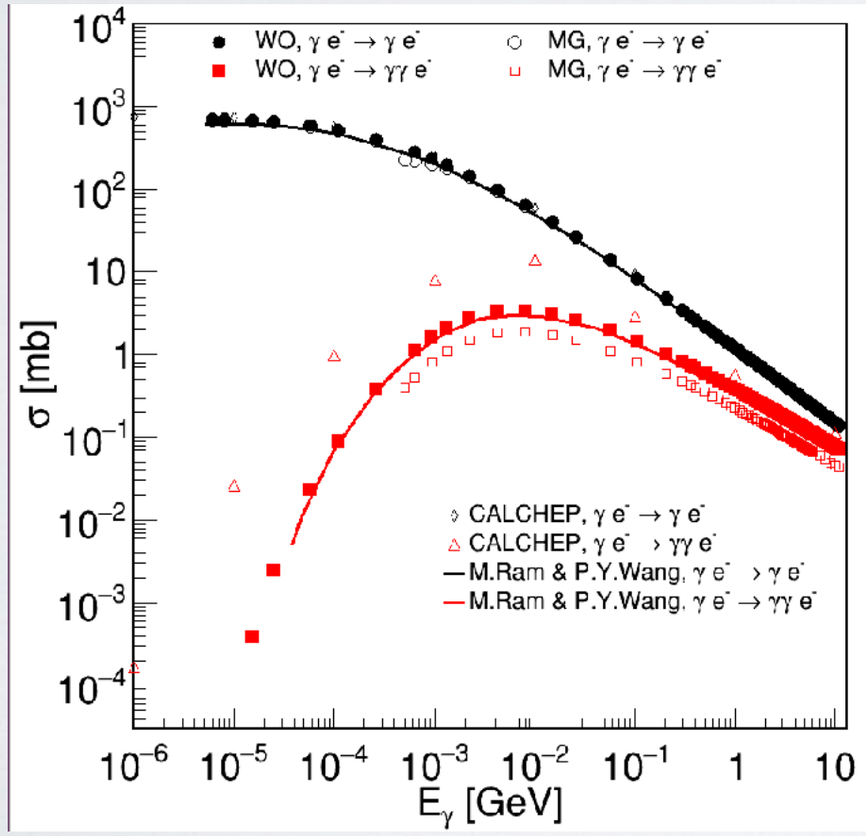
Beam structure: special beams

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"
```

Asymmetric beams

```
beams = e1, E1
beams_momentum = 7 GeV, 3 GeV
```

Inclusive Lepton Collider ISR included

Soft exponentiation to all orders

Gribov/Lipatov, 1971

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

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

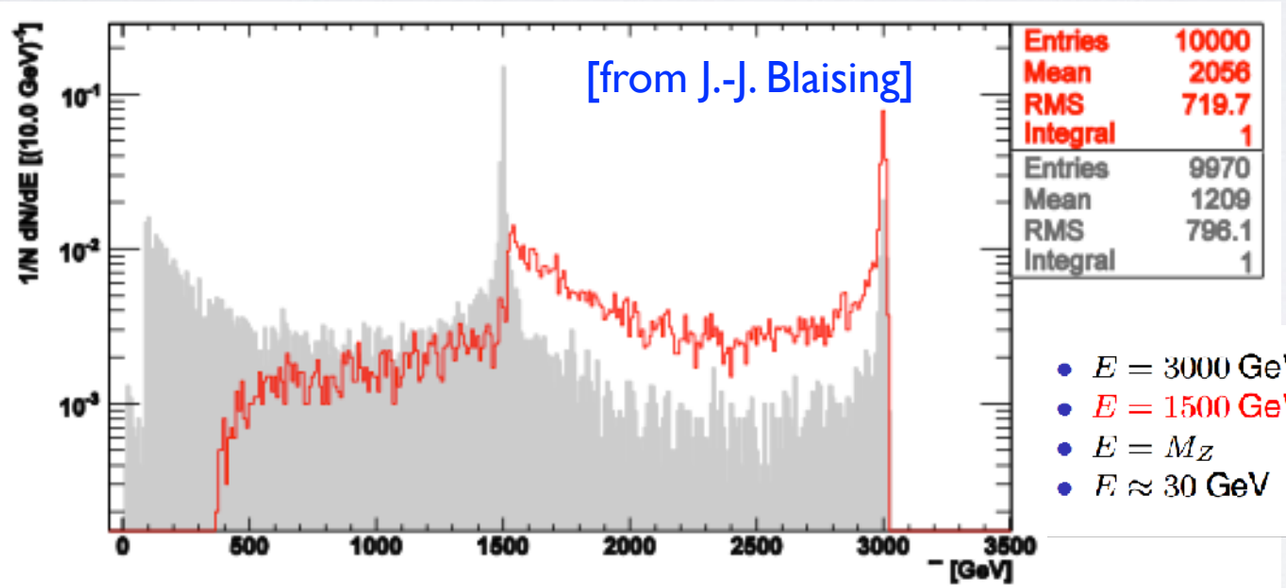
Hard-collinear photons up to 3rd QED order

Kuraev/Fadin, 1983; Skrzypek/Jadach, 1991

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

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

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



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

```
beams = e, E => isr
```

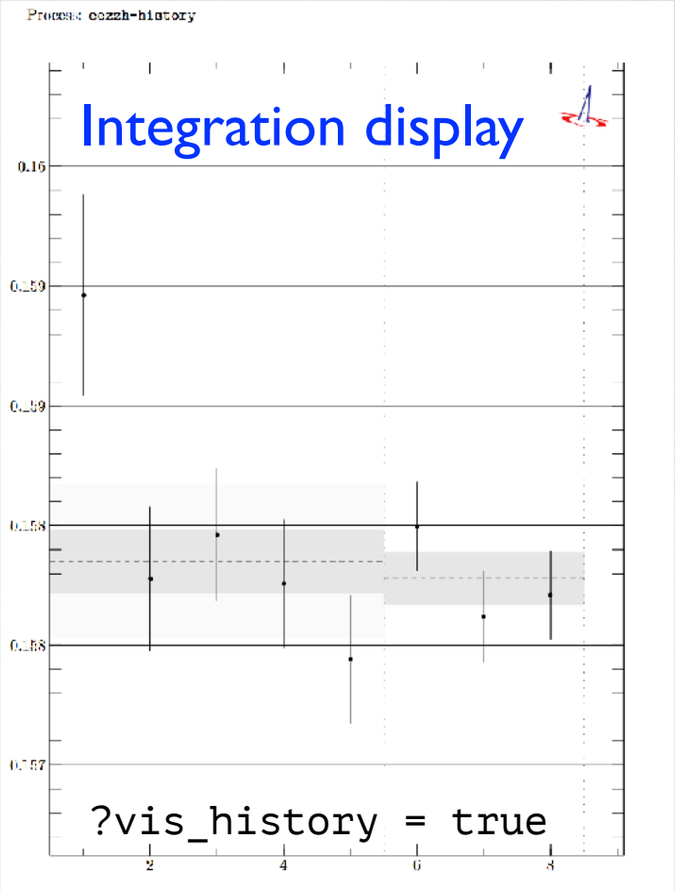
```
?isr_handler = true
$isr_handler_mode = "recoil"
```

- ❑ 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: implementation started, details

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`



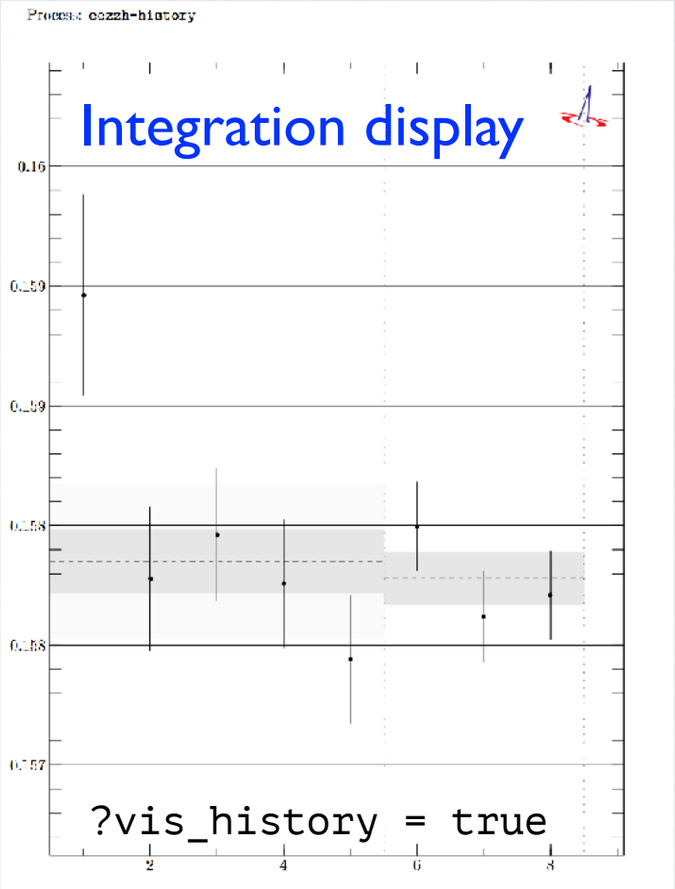
Complicated processes:
factorization into production and decay
with `unstable` option

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`

```
| Beam structure: [any particles]
| Beam data (collision):
|   e-  (mass = 5.1099700E-04 GeV)
|   e+  (mass = 5.1099700E-04 GeV)
|   sqrts = 5.000000000000E+02 GeV
| Phase space: generating configuration ...
| Phase space: ... success.
| Phase space: writing configuration file 'tt.i1.phs'
| ---------------------------------------------------------------------------
| Process [scattering]: 'tt'
|   Library name  = 'default_lib'
|   Process index = 1
|   Process components:
|     1: 'tt_i1':   e-, e+ => t, tbar [omega]
| ---------------------------------------------------------------------------
| Phase space: 1 channels, 2 dimensions
| Phase space: found 1 channel, collected in 1 grove.
| Phase space: wood
| Starting integration for process 'tt'
| Integrate: iterations = 5:50000:"gw", 3:100000
| Integrator: 50000 initial calls, 20 bins, stratified = T
| Integrator: VAMP
|===============================================================================|
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]   Chi2 N[It] |
|===============================================================================|
   1      41472  5.4836513E+02  9.95E-03    0.00    0.00*  48.24
   2      41472  5.4835310E+02  8.87E-03    0.00    0.00*  80.14
   3      41472  5.4836529E+02  8.63E-03    0.00    0.00*  58.76
   4      41472  5.4836077E+02  8.42E-03    0.00    0.00*  74.84
   5      41472  5.4836205E+02  8.43E-03    0.00    0.00   62.48
|-------------------------------------------------------------------------------|
   5     207360  5.4836117E+02  3.94E-03    0.00    0.00   62.48    0.31   5
|-------------------------------------------------------------------------------|
   6      99792  5.4836230E+02  3.61E-03    0.00    0.00*  62.48
   7      99792  5.4836321E+02  3.61E-03    0.00    0.00   62.48
   8      99792  5.4837075E+02  3.62E-03    0.00    0.00   62.48
|-------------------------------------------------------------------------------|
   8     299376  5.4836541E+02  2.09E-03    0.00    0.00   62.48    1.65   3
|===============================================================================|
```

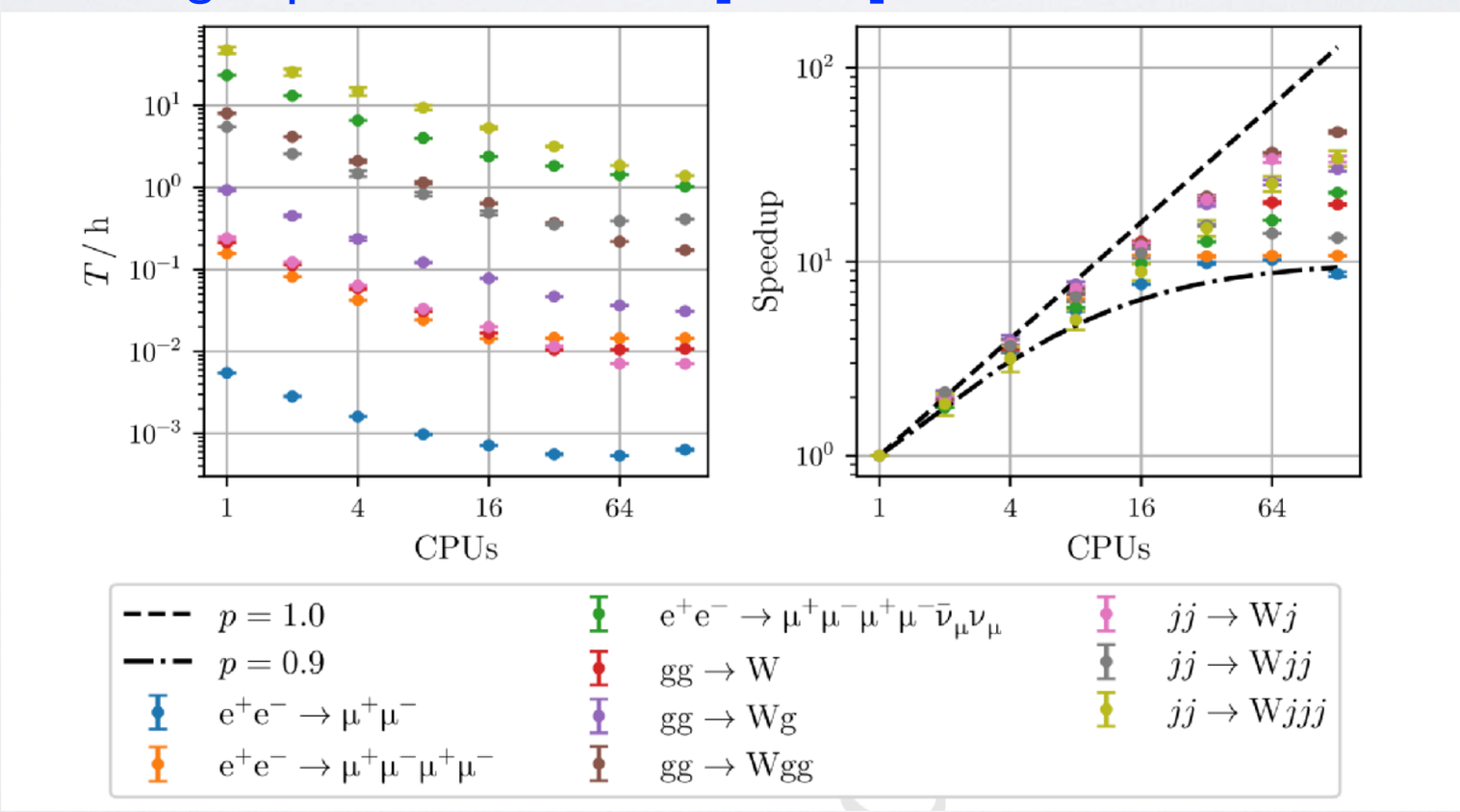


Complicated processes:
factorization into production and decay
with `unstable` option

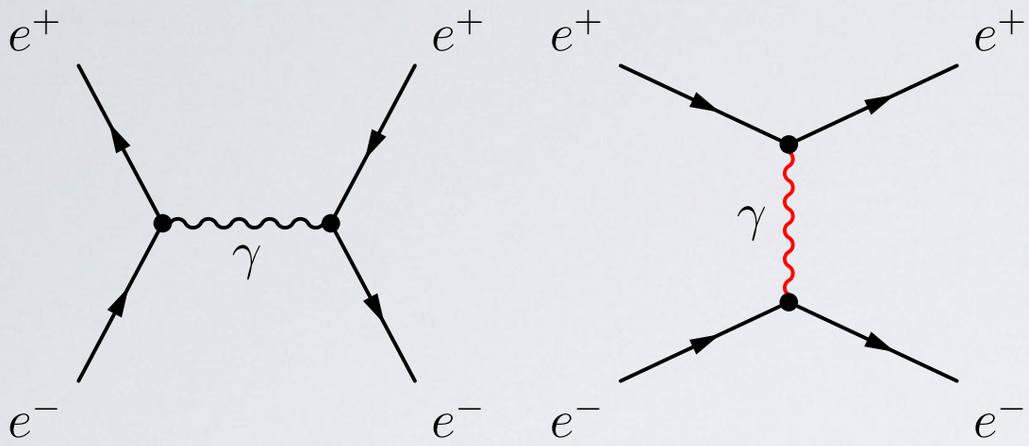
MPI Parallelization

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 [v3.0.0]

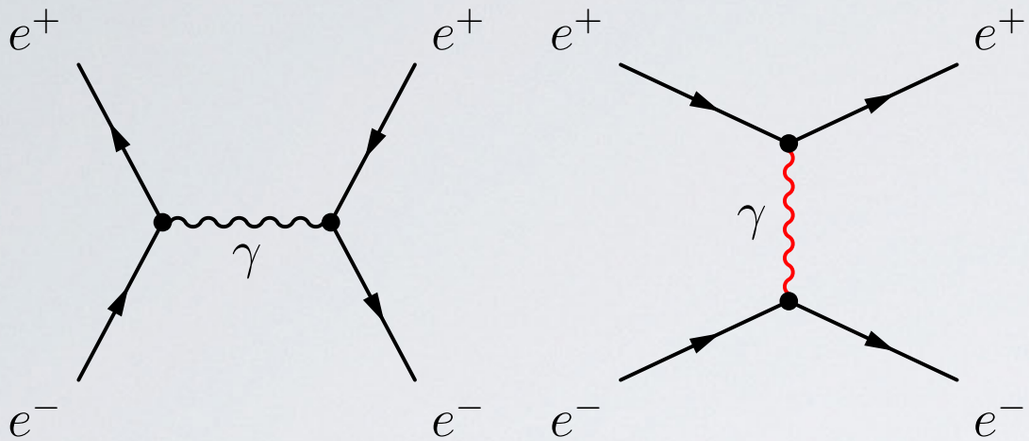


“Fiducial Volumes”: Example Bhabha scattering




```
process bhabha = e1, E1 => e1, E1

sqrts = 40 GeV

integrate (bhabha)
```

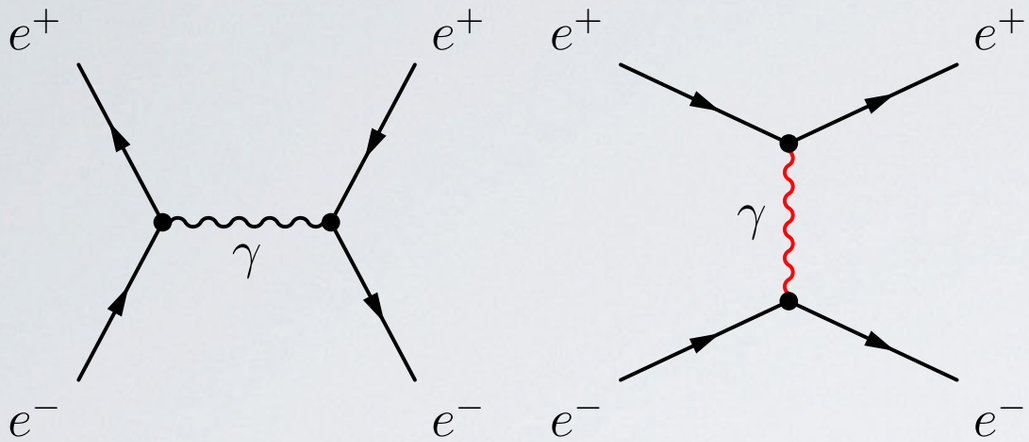
"Fiducial Volumes": Example Bhabha scattering




```
process bhabha = e1, E1 => e1, E1

sqrts = 40 GeV

integrate (bhabha)
```

```
| Beam structure: [any particles]
| Beam data (collision):
|   e-  (mass = 5.1099700E-04 GeV)
|   e+  (mass = 5.1099700E-04 GeV)
|   sqrts = 4.000000000000E+01 GeV
| Phase space: generating configuration ...
| Phase space: ... success.
| Phase space: writing configuration file 'bhabha.i1.phs'
| ------------------------------------------------------------------
| Process [scattering]: 'bhabha'
|   Library name  = 'default_lib'
|   Process index = 1
|   Process components:
|     1: 'bhabha_i1':   e-, e+ => e-, e+ [omega]
| ------------------------------------------------------------------
| Phase space: 3 channels, 2 dimensions
| Phase space: found 3 channels, collected in 2 groves.
| Phase space: Using 3 equivalences between channels.
| Phase space: wood
 Beam structure: [any particles]
Warning: No cuts have been defined.
| Starting integration for process 'bhabha'
| Integrate: iterations = 5:50000:"gw", 3:100000
| Integrator: 2 chains, 3 channels, 2 dimensions
| Integrator: Using VAMP channel equivalences
| Integrator: 50000 initial calls, 20 bins, stratified = T
| Integrator: VAMP
|==================================================================
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]
|==================================================================
   1      48600  5.9946241E+10  4.43E+10   73.91  162.94*   0.01
   2      42696  9.2062615E+13  8.44E+13   91.63  189.34    0.01
   3      47168  3.2144700E+12  1.96E+12   60.83  132.12*   0.01
   4      46856  2.4037833E+13  1.32E+13   54.80  118.63*   0.01
   5      46665  3.5100618E+15  2.21E+15   63.08  136.27    0.01
|------------------------------------------------------------------
   5     231985  6.1862900E+10  4.43E+10   71.60  344.88    0.01
|------------------------------------------------------------------
   6      99956  7.8036957E+15  3.65E+15   46.78  147.91    0.00
   7      99956  6.1589334E+15  4.11E+15   66.67  210.80    0.00
   8      99956  8.4374589E+14  3.42E+14   40.56  128.23*   0.00
|------------------------------------------------------------------
   8     299868  9.4028760E+14  3.40E+14   36.11  197.75    0.00
|==================================================================
| Time estimate for generating 10000 events: 1d:08h:56m:54s
```

“Fiducial Volumes”: Example Bhabha scattering

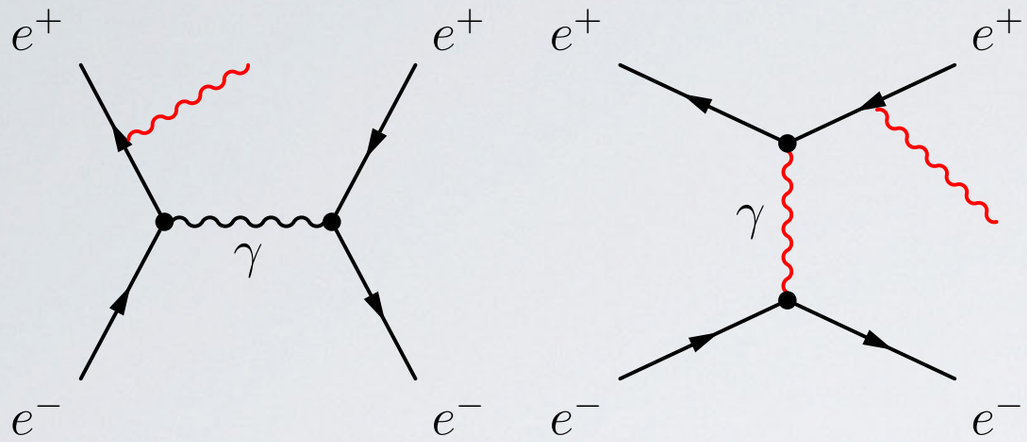



```
process bhabha = e1, E1 => e1, E1

sqrts = 40 GeV

integrate (bhabha)
```

```
cuts = all 175 degree >
            Theta > 5 degree [e1:E1]
```

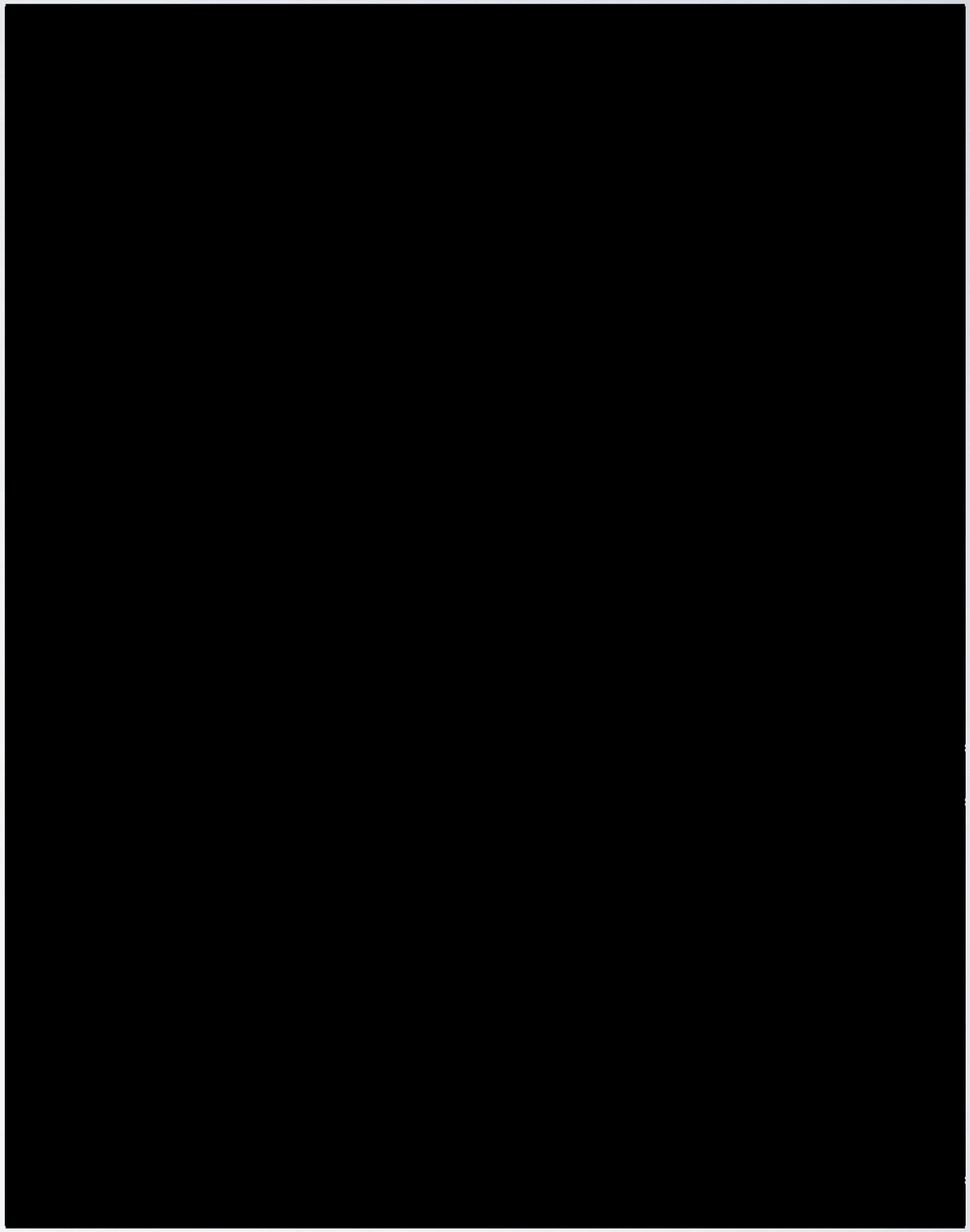
```
| Beam structure: [any particles]
| Beam data (collision):
|   e-  (mass = 5.1099700E-04 GeV)
|   e+  (mass = 5.1099700E-04 GeV)
|   sqrts = 4.000000000000E+01 GeV
| Phase space: generating configuration ...
| Phase space: ... success.
| Phase space: writing configuration file 'bhabha.i1.phs'
| ------------------------------------------------------------------
| Process [scattering]: 'bhabha'
|   Library name  = 'default_lib'
|   Process index = 1
|   Process components:
|     1: 'bhabha_i1':   e-, e+ => e-, e+ [omega]
| ------------------------------------------------------------------
| Phase space: 3 channels, 2 dimensions
| Phase space: found 3 channels, collected in 2 groves.
| Phase space: Using 3 equivalences between channels.
| Phase space: wood
 Beam structure: [any particles]
| Applying user-defined cuts.
| Starting integration for process 'bhabha'
| Integrate: iterations = 5:50000:"gw", 3:100000
| Integrator: 2 chains, 3 channels, 2 dimensions
| Integrator: Using VAMP channel equivalences
| Integrator: 50000 initial calls, 20 bins, stratified = T
| Integrator: VAMP
|==================================================================
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]
|==================================================================
   1      48600  9.0221672E+07  1.65E+06    1.83    4.03*   0.73
   2      42768  8.9209077E+07  2.75E+05    0.31    0.64*   7.02
   3      45056  8.9672290E+07  7.88E+04    0.09    0.19*  27.73
   4      42768  8.9657200E+07  4.35E+04    0.05    0.10*  33.72
   5      45200  8.9702761E+07  3.10E+04    0.03    0.07*  46.83
|------------------------------------------------------------------
   5     224392  8.9682534E+07  2.39E+04    0.03    0.13   46.83
|------------------------------------------------------------------
   6      99792  8.9651332E+07  1.90E+04    0.02    0.07*  46.23
   7      99792  8.9672596E+07  1.89E+04    0.02    0.07*  46.23
   8      99792  8.9655053E+07  1.87E+04    0.02    0.07*  46.22
|------------------------------------------------------------------
   8     299376  8.9659627E+07  1.09E+04    0.01    0.07   46.22
|==================================================================
| Time estimate for generating 10000 events: 0d:00h:00m:01s
```

“Fiducial Volumes”: Example Bhabha scattering

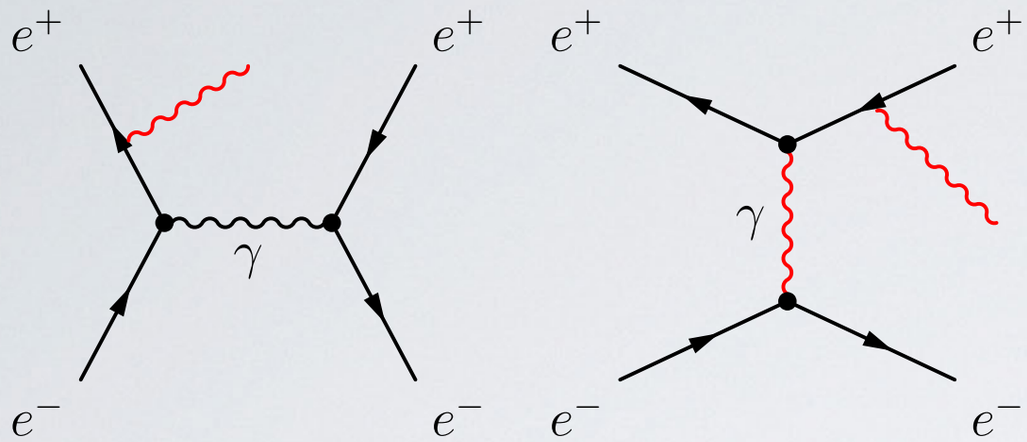



```
process rad_bha = e1, E1 => e1, E1, A

sqrts = 40 GeV

integrate (rad_bha)
```

```
cuts = all 175 degree >
            Theta > 5 degree [e1:E1]
```



"Fiducial Volumes": Example Bhabha scattering

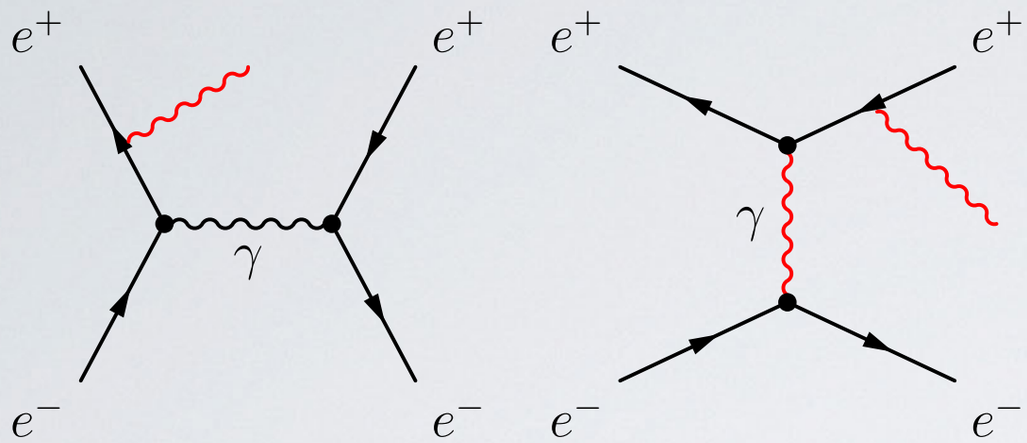



```
process rad_bha = e1, E1 => e1, E1, A

sqrts = 40 GeV

integrate (rad_bha)
```

```
cuts = all 175 degree >
            Theta > 5 degree [e1:E1]
```

```
| Beam structure: e-, e+
| Beam data (collision):
|   e-  (mass = 5.1099700E-04 GeV)
|   e+  (mass = 5.1099700E-04 GeV)
|   sqrts = 4.000000000000E+01 GeV
| Phase space: generating configuration ...
| Phase space: ... success.
| Phase space: writing configuration file 'rad_bha.i1.phs'
| ------------------------------------------------------------------------
| Process [scattering]: 'rad_bha'
|   Library name  = 'default_lib'
|   Process index = 1
|   Process components:
|     1: 'rad_bha_i1':   e-, e+ => e-, e+, A [omega]
| ------------------------------------------------------------------------
| Phase space: 18 channels, 5 dimensions
| Phase space: found 18 channels, collected in 5 groves.
| Phase space: Using 26 equivalences between channels.
| Phase space: wood
 Beam structure: e-, e+
| Applying user-defined cuts.
| Starting integration for process 'rad_bha'
| Integrate: iterations = 5:50000:"gw", 3:100000
| Integrator: 5 chains, 18 channels, 5 dimensions
| Integrator: Using VAMP channel equivalences
| Integrator: 50000 initial calls, 20 bins, stratified = T
| Integrator: VAMP
|========================================================================
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]
|========================================================================
   1      49986  5.0203316E+07  1.66E+07   33.15   74.11*   0.06
   2      49978  1.1812064E+08  5.18E+07   43.87   98.08    0.03
   3      49968  1.1729365E+09  6.26E+08   53.38  119.31    0.03
   4      49956  2.7297462E+08  5.78E+07   21.17   47.33*   0.04
   5      49944  6.0477456E+08  1.50E+08   24.85   55.53    0.03
|------------------------------------------------------------------------
   5     249832  7.7782386E+07  1.52E+07   19.54   97.66    0.03
|------------------------------------------------------------------------
   6      99996  5.2449924E+08  6.01E+07   11.47   36.26*   0.04
   7      99996  5.2196986E+08  8.00E+07   15.32   48.44    0.02
   8      99996  6.9502777E+08  1.33E+08   19.07   60.30    0.02
|------------------------------------------------------------------------
   8     299988  5.4350814E+08  4.52E+07    8.31   45.53    0.02
|========================================================================
| Time estimate for generating 10000 events: 0d:00h:53m:31s
```

“Fiducial Volumes”: Example Bhabha scattering

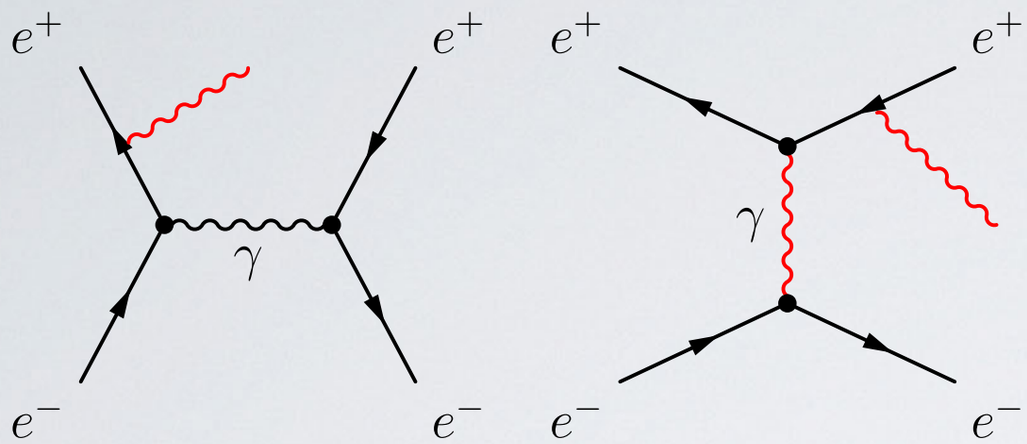



```
process rad_bha = e1, E1 => e1, E1, A

sqrts = 40 GeV

integrate (rad_bha)
```

```
cuts = all 175 degree >
            Theta > 5 degree [e1:E1:A]
   and all M > 3 GeV [A,e1:E1]
```

```
| Beam structure: e-, e+
| Beam data (collision):
|   e-  (mass = 5.1099700E-04 GeV)
|   e+  (mass = 5.1099700E-04 GeV)
|   sqrts = 4.000000000000E+01 GeV
| Phase space: generating configuration ...
| Phase space: ... success.
| Phase space: writing configuration file 'rad_bha.i1.phs'
| ------------------------------------------------------------------------
| Process [scattering]: 'rad_bha'
|   Library name  = 'default_lib'
|   Process index = 1
|   Process components:
|     1: 'rad_bha_i1':   e-, e+ => e-, e+, A [omega]
| ------------------------------------------------------------------------
| Phase space: 18 channels, 5 dimensions
| Phase space: found 18 channels, collected in 5 groves.
| Phase space: Using 26 equivalences between channels.
| Phase space: wood
 Beam structure: e-, e+
| Applying user-defined cuts.
| Starting integration for process 'rad_bha'
| Integrate: iterations = 5:50000:"gw", 3:100000
| Integrator: 5 chains, 18 channels, 5 dimensions
| Integrator: Using VAMP channel equivalences
| Integrator: 50000 initial calls, 20 bins, stratified = T
| Integrator: VAMP
|========================================================================
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]
|========================================================================
   1      49986  7.1434640E+05  3.21E+04    4.50   10.06*   0.28
   2      49976  7.0403816E+05  8.62E+03    1.22    2.74*   1.93
   3      49968  7.0892929E+05  6.04E+03    0.85    1.90*   3.26
   4      49962  7.1708222E+05  5.09E+03    0.71    1.59*   4.17
   5      49950  6.9928103E+05  4.33E+03    0.62    1.38*   5.63
|------------------------------------------------------------------------
   5     249842  7.0698352E+05  2.73E+03    0.39    1.93    5.63
|------------------------------------------------------------------------
   6      99990  7.0707619E+05  3.14E+03    0.44    1.40    4.48
   7      99990  7.1310651E+05  4.96E+03    0.70    2.20    1.62
   8      99990  7.0891943E+05  3.00E+03    0.42    1.34*   1.59
|------------------------------------------------------------------------
   8     299970  7.0885111E+05  1.99E+03    0.28    1.54    1.59
|========================================================================
| Time estimate for generating 10000 events: 0d:00h:00m:41s
```

"Fiducial Volumes": Example Bhabha scattering




```
process rad_bha = e1, E1 => e1, E1, A

sqrts = 40 GeV

integrate (rad_bha)
```

```
cuts = all 175 degree >
            Theta > 5 degree [e1:E1:A]
   and all M > 3 GeV [A,e1:E1]
```

```
cuts = any M > 100 GeV [lepton,neutrino]
```

```
cuts = all M2 < -(50 GeV)^2
     [combine [incoming lepton, lepton]]
```

```
cuts = all Dist > 2 [e1:E1, e2:E2]
```

```
cuts = any E > 2*mW [extract index 2
                 [sort by -Pt [lepton]]
```

```
| Beam structure: e-, e+
| Beam data (collision):
|   e-  (mass = 5.1099700E-04 GeV)
|   e+  (mass = 5.1099700E-04 GeV)
|   sqrts = 4.000000000000E+01 GeV
| Phase space: generating configuration ...
| Phase space: ... success.
| Phase space: writing configuration file 'rad_bha.i1.phs'
| ------------------------------------------------------------
| Process [scattering]: 'rad_bha'
|   Librar
|   Proces
|   Proces
|     1: '
| --------
| Phase sp
| Phase sp
| Phase sp
| Phase sp
 Beam stru
| Applying
| Starting
| Integrat
| Integrat
| Integrat
| Integrat
| Integrat
|==========
| It                                                    Eff[%]
|==========
|   1                                                    0.28
|   2                                                    1.93
|   3                                                    3.26
|   4                                                    4.17
|   5                                                    5.63
|------------------------------------------------------------
|   5     249842  7.0698352E+05  2.73E+03    0.39    1.93    5.63
|------------------------------------------------------------
|   6      99990  7.0707619E+05  3.14E+03    0.44    1.40    4.48
|   7      99990  7.1310651E+05  4.96E+03    0.70    2.20    1.62
|   8      99990  7.0891943E+05  3.00E+03    0.42    1.34*   1.59
|------------------------------------------------------------
|   8     299970  7.0885111E+05  1.99E+03    0.28    1.54    1.59
|==========================================================
| Time estimate for generating 10000 events: 0d:00h:00m:41s
```

- ☑ Standard cut expressions
- ☑ Combine cuts
- ☑ Cut window
- ☑ Cuts on particle containers
- ☑ Selection cuts
- ☑ Space-like cuts
- ☑ Cuts on tensor products
- ☑ Sorting and selecting

Cuts, subevent expressions and selections

Standard cut expression:

```
cuts = all Pt > 100 GeV [lepton]
```

Combine two cuts:

```
cuts = all Pt > 100 GeV [lepton]
    and all M > 10 GeV [lepton, lepton]
```

Selection cuts:

```
cuts = any M > 100 GeV [combine if cos(Theta) > 0.5
                        [lepton,neutrino]
```

Space-like cuts (incoming particles):

```
cuts = all M2 < -(50 GeV)^2
    [combine [incoming lepton, lepton]]
```

Cut window on a selection:

```
real eta_cut = 5
cuts = any 5 degree < Theta < 175 degree
    [select of abs(Eta) < eta_cut [lepton]]
```

Cut window on a selection:

```
cuts = E <= 200 GeV [collect [neutrino]]
```

Cuts on tensor products:

```
cuts = all Dist > 2 [e1:E1, e2:E2]
```

Sorting and selecting:

```
cuts = any E > 2*mW [extract index 2
                     [sort by -Pt [lepton]]
```

Clustering: [FastJet: Cacciari/Salam/Soyez]

```
jet_algorithm = antikt_algorithm
jet_r = 0.7
?keep_flavors_when_clustering = true
```

Subevents and jet counts:

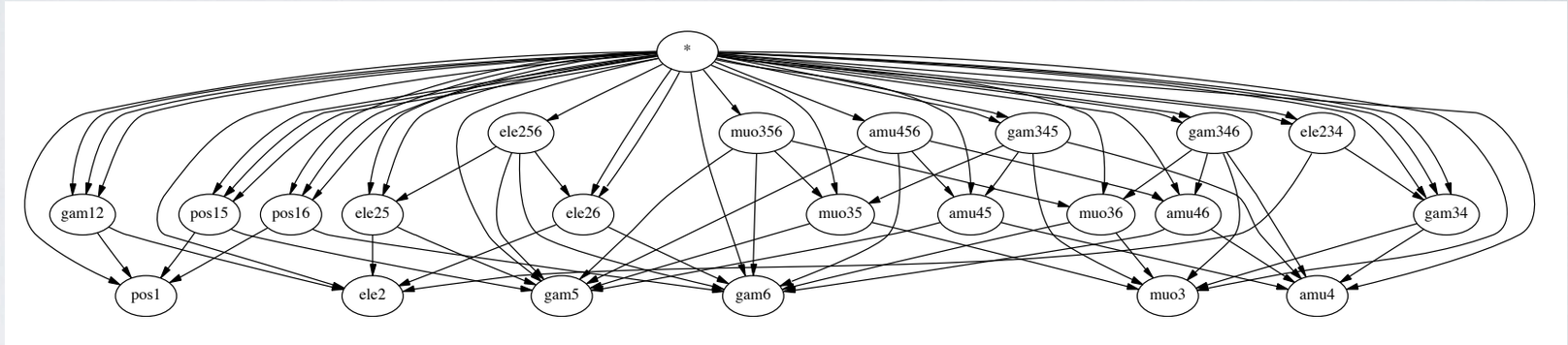
```
cuts = let subevt @clustered_jets = cluster [jet] in
       let subevt @pt_selected =
          select if Pt > 30 GeV [@clustered_jets] in
       let subevt @eta_selected =
          select if abs(Eta) < 4 [@pt_selected] in
       count [@eta_selected] >= 1
```

MLM matching:

```
mlm_ptmin = 5 GeV; mlm_etamax = 2.5
mlm_Rmin = 1
mlm_nmaxMEjets = 1
```

The matrix element generator: O'Mega

- Built-in matrix element generator `O'Mega` (recursiveness via Directed Acyclical Graphs)

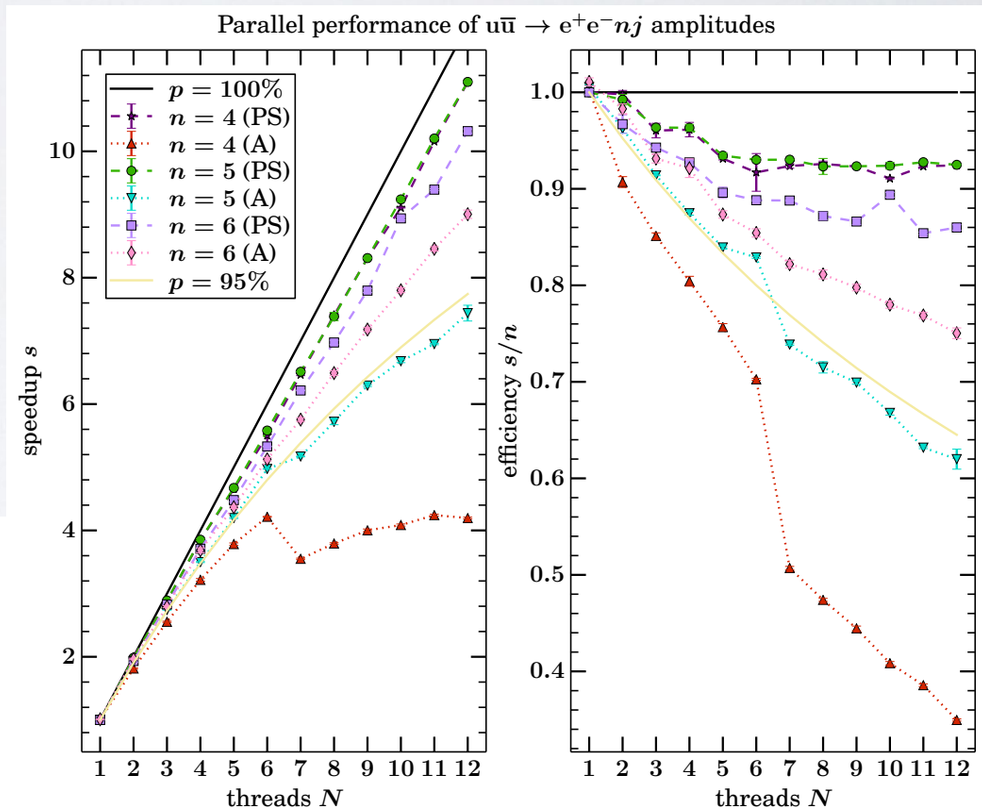


- `O'Mega Virtual Machine (OVM):` matrix elements not as compiled code, but bytecode instructions:

```
process <proc> = in1, in2 => <out>  { $method = "ovm" }
```

```
Flavor states table
2 -2 11 -11
Color flows table: [ (i, j) (k, l) -> (m, n) ...]
1 0 0 -1 0 0 0 0
Color ghost flags table:
0 0 0 0
Color factors table: [ i, j: num den power], i, j are indexed color flows
        1        1        1        1        1
Flavor color combination is allowed:
1
OVM instructions for momenta addition, fusions and brakets start here:
0 0 0 0 0 0 0 0
1 0 0 5 1 2 0 0
11 2 0 2 1 0 0 1
13 2 0 2 2 0 0 1
14 11 0 1 3 0 0 1
12 11 0 1 4 0 0 1
0 0 0 0 0 0 0 0
60 22 2 1 5 0 0 1
-1 2 1 1 2 2 0 0
58 23 2 2 5 0 0 1
-4 3 1 2 2 2 0 0
0 0 0 0 0 0 0 0
2 -1 0 1 1 0 0 0
-4 2 1 2 1 1 0 0
-1 1 1 1 1 1 0 0
```

process	BC size	Fortran size	t_{compile}
$gg \to gggggg$	428 MiB	4.0 GiB	-
$gg \to ggggg$	9.4 MiB	85 MiB	483(18) s
$gg \to q\bar{q}q'\bar{q}'q''\bar{q}''g$	3.2 MiB	27 MiB	166(15) s
$e^+e^- \to 5\,(e^+e^-)$	0.7 MiB	1.9 MiB	32.46(13) s



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"}
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sample_format = ascii,debug,mokka,lha
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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: (ASCII transcription from binary)

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

Event header information as agreed upon with LC Gen Group

Event Formats

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]

HepMC3 Format: modern implementation

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

```
HepMC::Version 2.06.09
HepMC::IO_GenEvent-START_EVENT_LISTING
E 1 -1 1.0000000000000000e+02 1.1625848297740160e-01 -1.000000
U GEV MM
V -1 0 0 0 0 0 1 2 0
P 10001 2212 0 0 4.0000000000000000e+03 4.0000000000000000e+03
P 10003 21 0 0 1.1391076920243 13e+01 1.1391076920243 13e+01 0
P 10005 93 0 0 3.9888608923079760e+03 3.9888608923079760e+03 0
V -2 0 0 0 0 0 1 2 0
P 10002 2212 0 0 -4.0000000000000000e+03 4.0000000000000000e+03
P 10004 21 0 0 -3.2685024745934277e+02 3.2685024745934277e+02 0
P 10006 93 0 0 -3.6731497525406571e+03 3.6731497525406571e+03 0
V -3 0 0 0 0 0 0 2 0
P 10007 2 -5.0143659198302345e+01 -6.8695604145339697e+00 -2.49
P 10008 -2 5.0143659198302345e+01 6.8695604145339697e+00 -6.584
HepMC::IO_GenEvent-END_EVENT_LISTING
```

NEW in WHIZARD v2.8.1

Reweighting 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
}
```

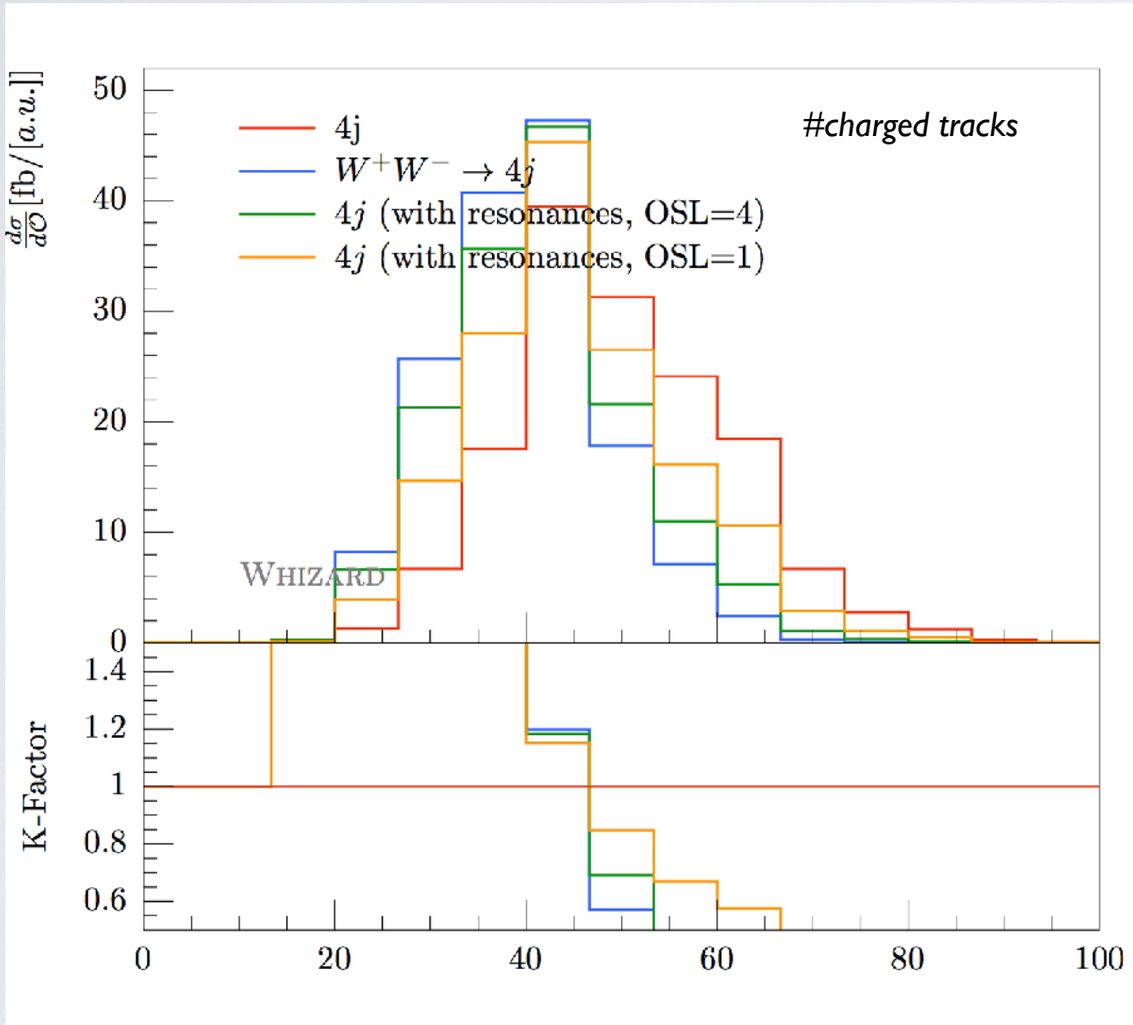
```
simulate (lcio_10_p) {
  alt_setup =
  {alphas = 0.125},
  {alphas = 0.25},
  {alphas = 0.5},
  {alphas = 1},
  {alphas = 2},
  {alphas = 4},
  {alphas = 8},
  {alphas = 16},
  {alphas = 32},
  {alphas = 64}
  ?keep_beams = true
}
```

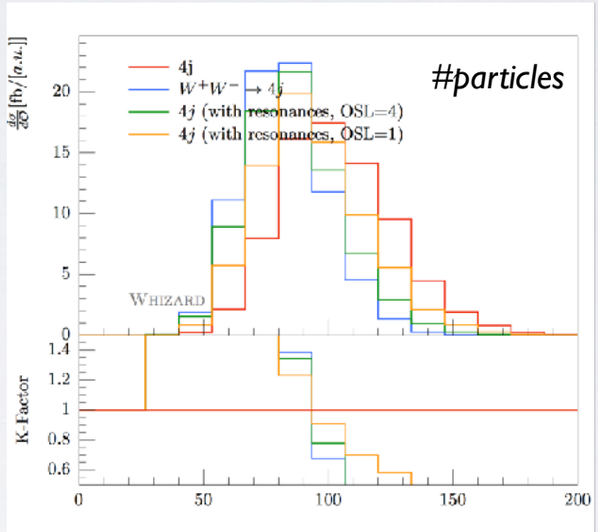
- Scanning parameter space of BSM models (or SM templates)
- Major bottleneck: MC samples have to be produced over and over again
- Feature: rescanning of event files with different setup / alternate setups
- Assumption: phase space is identical, sampling can be done in the same way
- NEW v2.7.0: works also w/ differently concatenated structure functions (e.g. ISR + beamstr.)

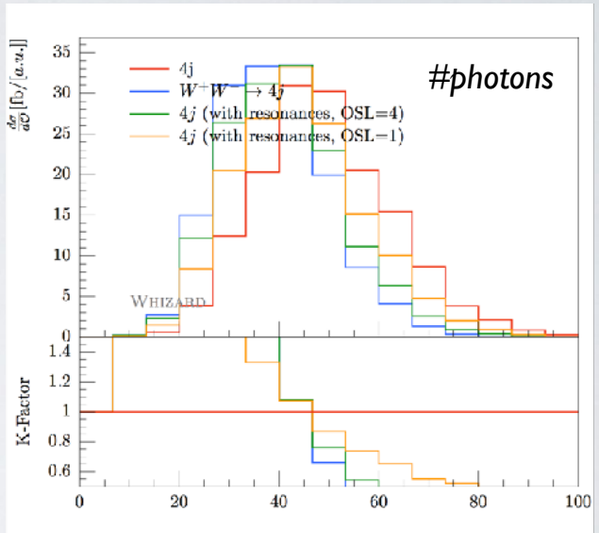
Keep resonances in ME-PS merging

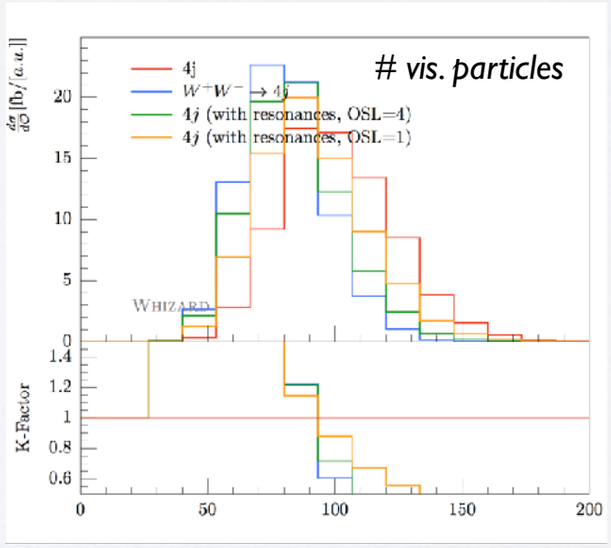
```
?resonance_history = true
resonance_on_shell_limit = 4
resonance_on_shell_turnoff = 1
resonance_background_factor = 1e-10
```

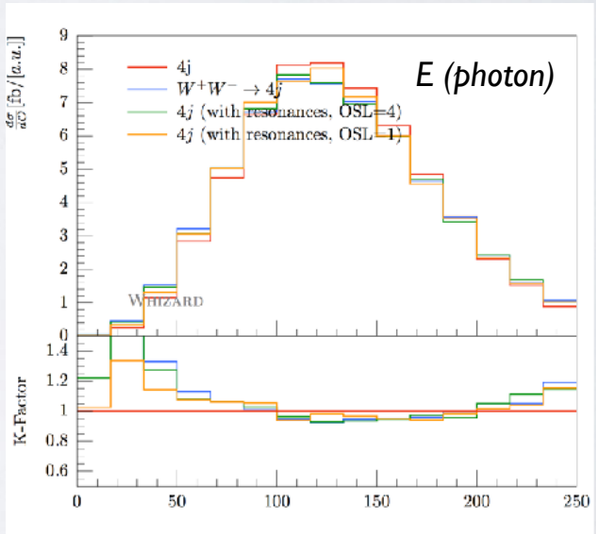
- Problem: $e^+e^- \to jjjj$ not dominated by highest α_s power, but by resonances $e^+e^- \to WW/ZZ \to (jj)(jj)$
- Solution: proper merging resonant subprocesses w/ resonance histories
- `WHIZARD v2.6.0:` option to set resonance histories











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

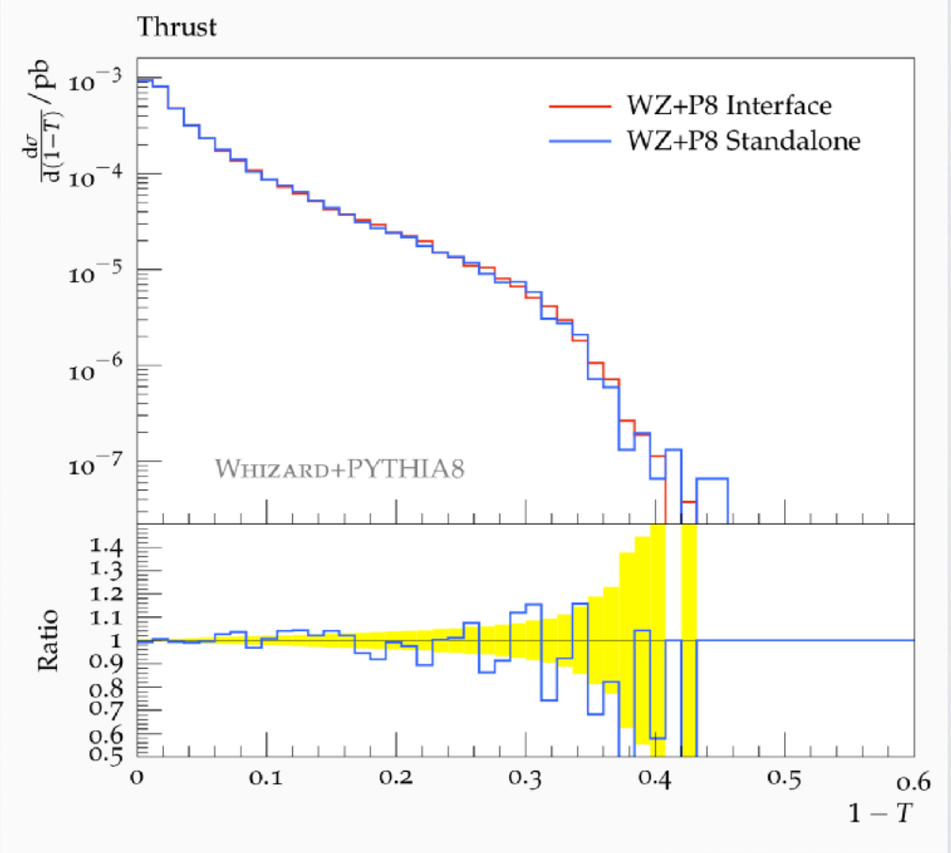
Interface between WHIZARD – PYTHIA8

- 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

```
| ==================================================================
| 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      0.000    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

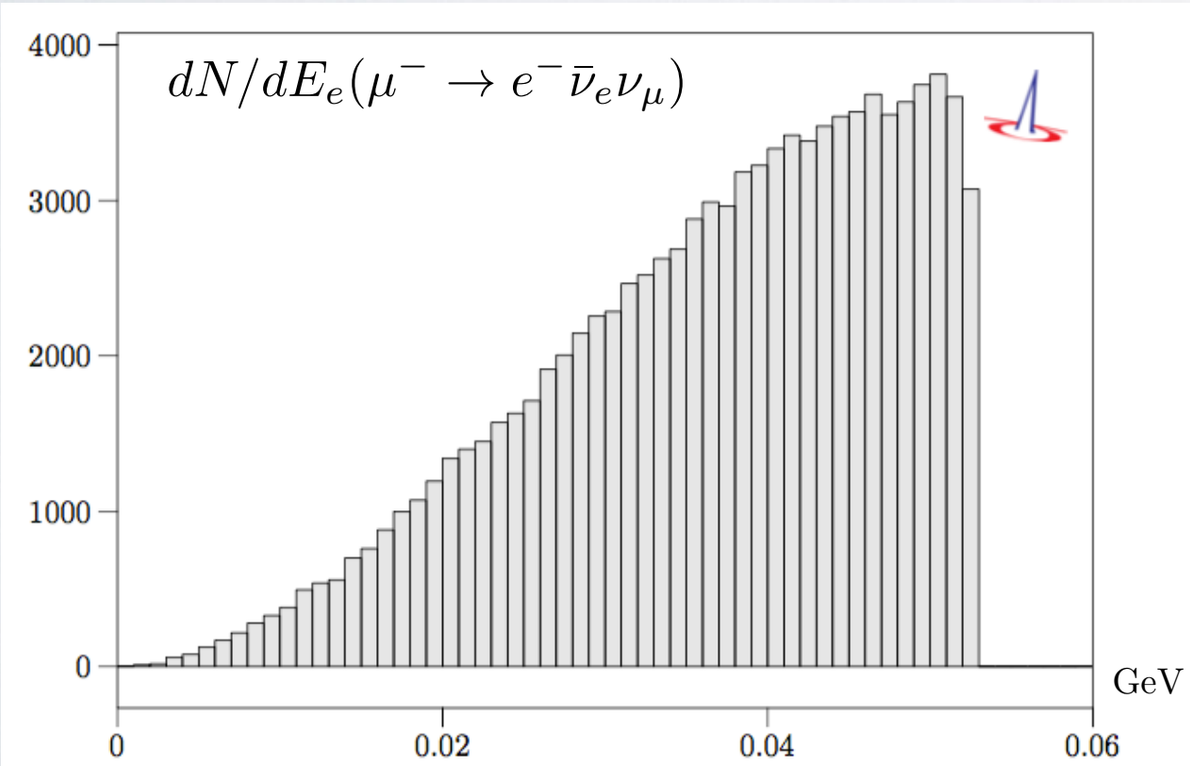


Decay processes / auto decays

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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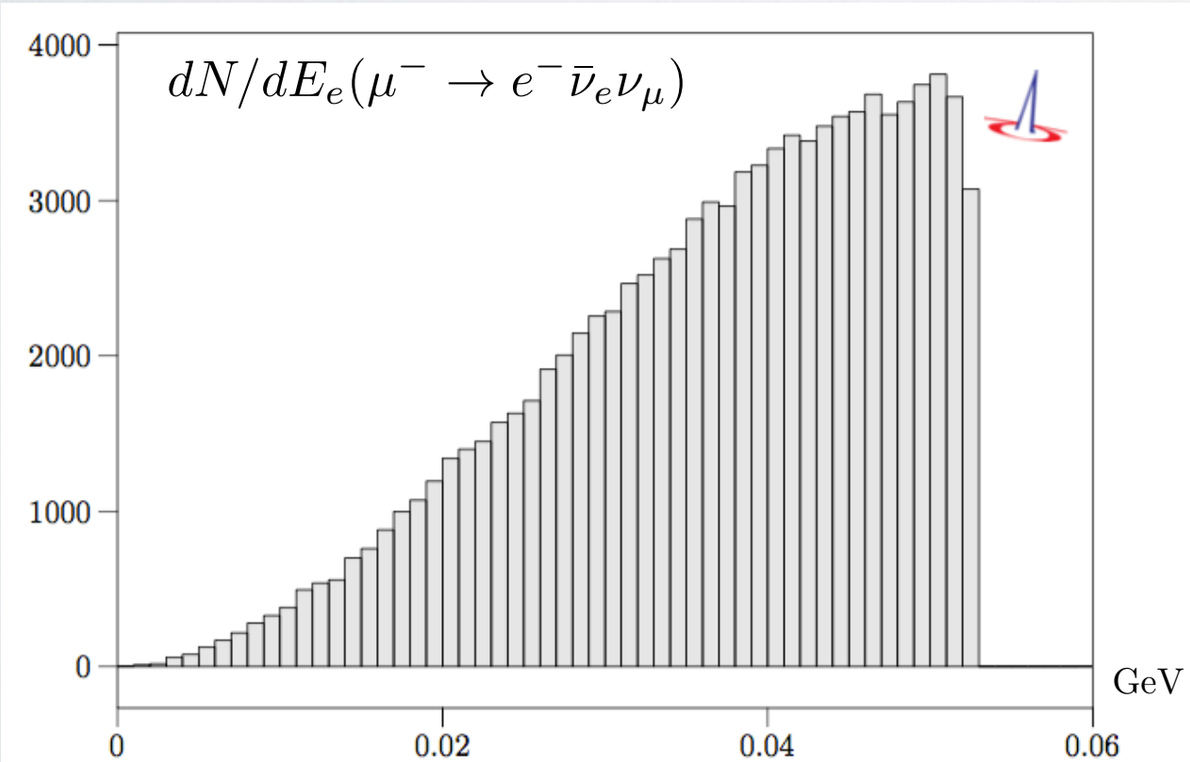


Automatic integration of particle decays

```
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
```

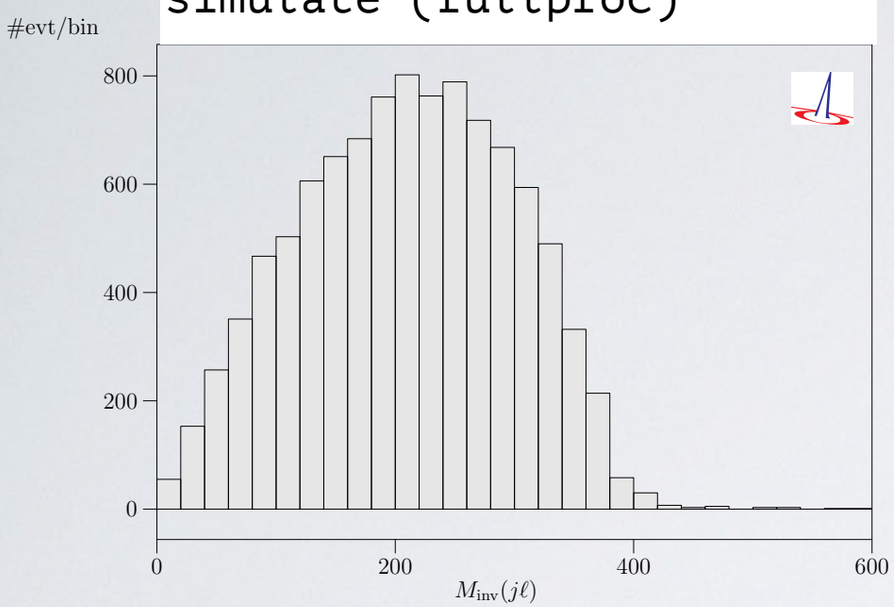
Preset branching ratios possible:

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

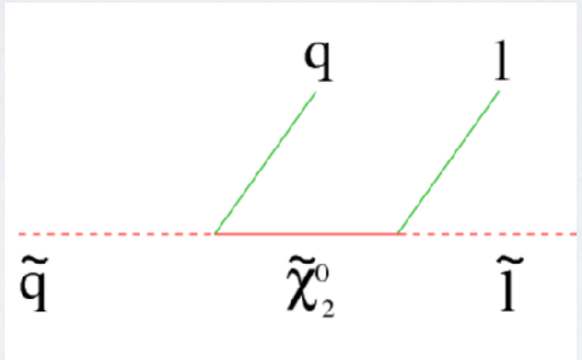
Spin Correlation and Polarization in Cascades

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

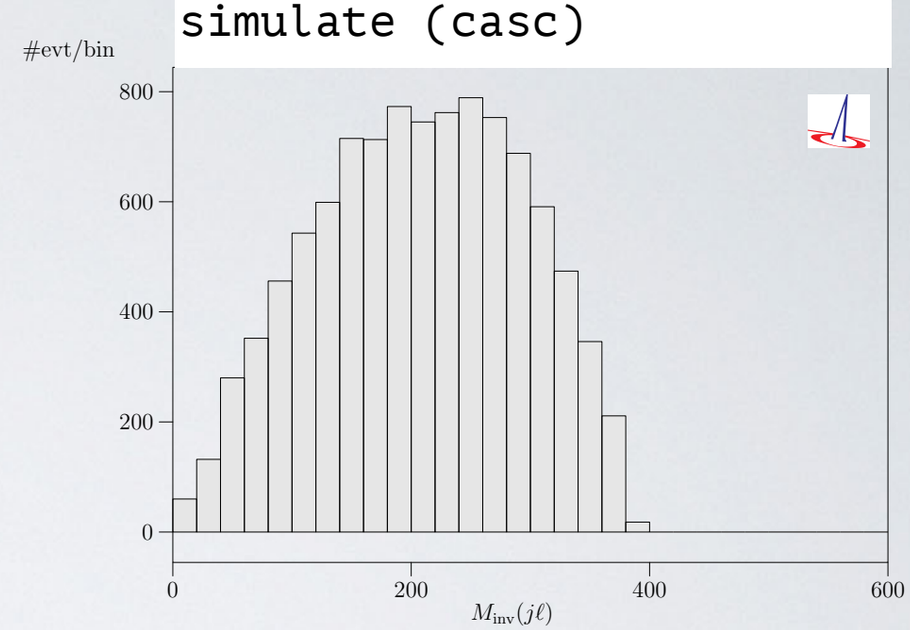
```
simulate (fullproc)
```



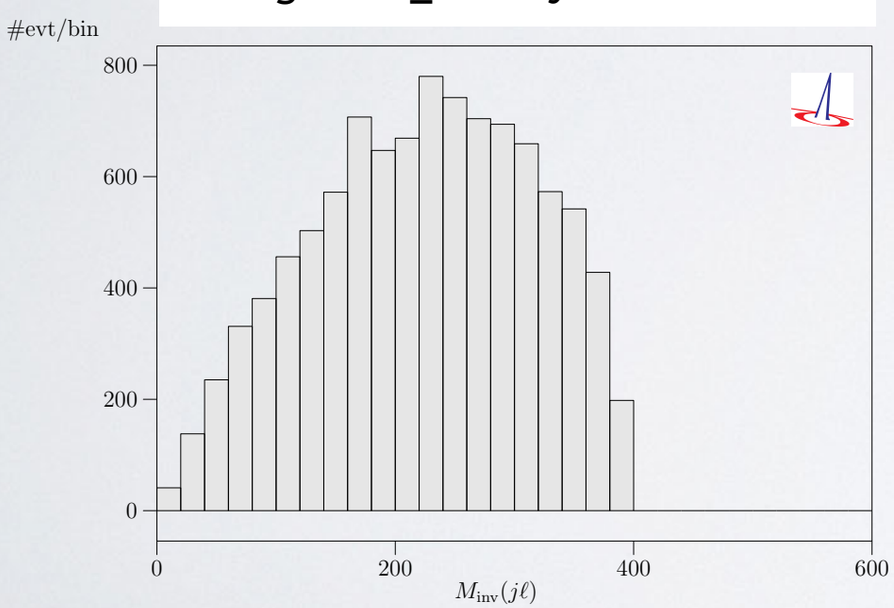

```
unstable su1
unstable neu2
```



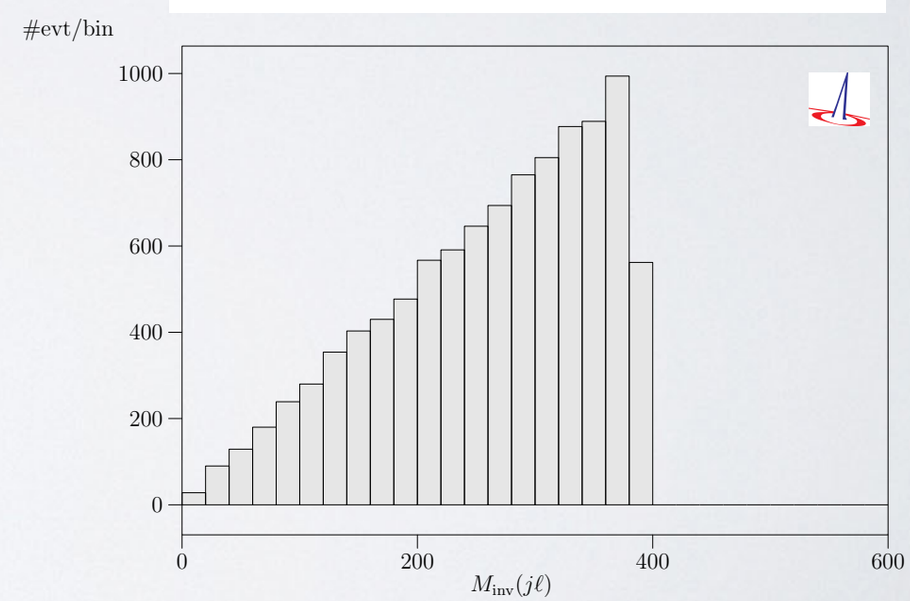

```
simulate (casc)
```




```
?diagonal_decay = true
```



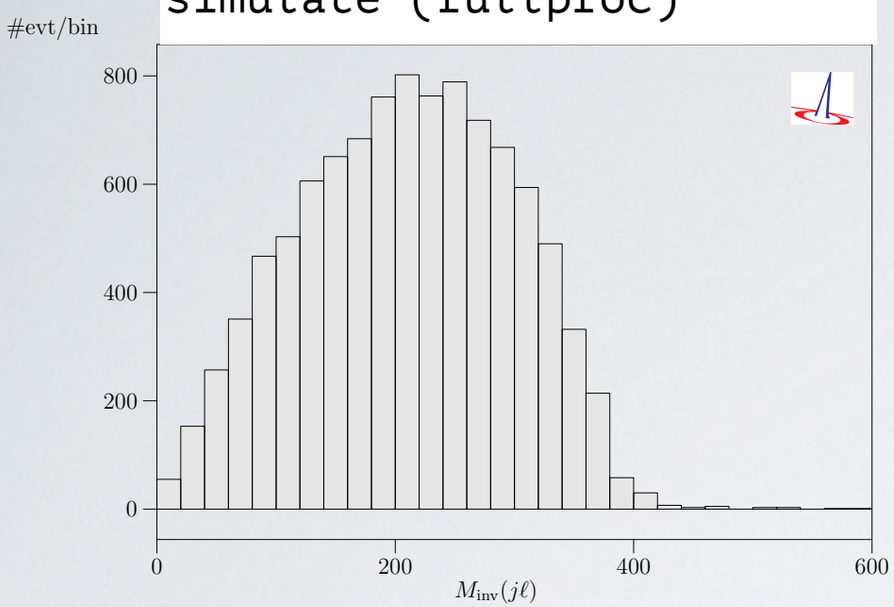

```
?isotropic_decay = true
```



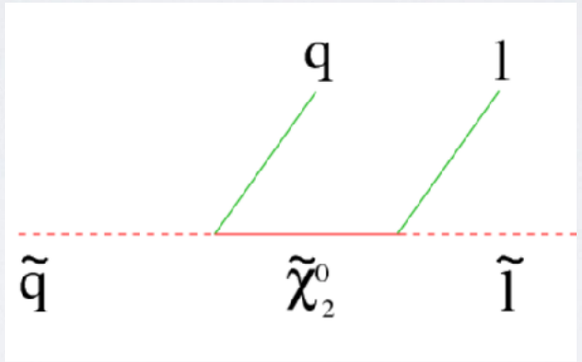
Spin Correlation and Polarization in Cascades

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

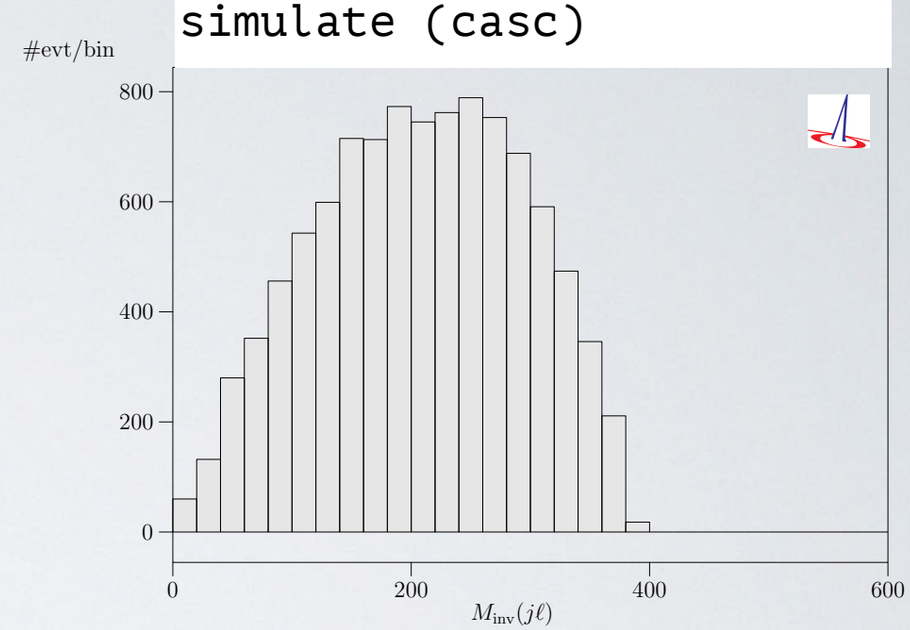
```
simulate (fullproc)
```



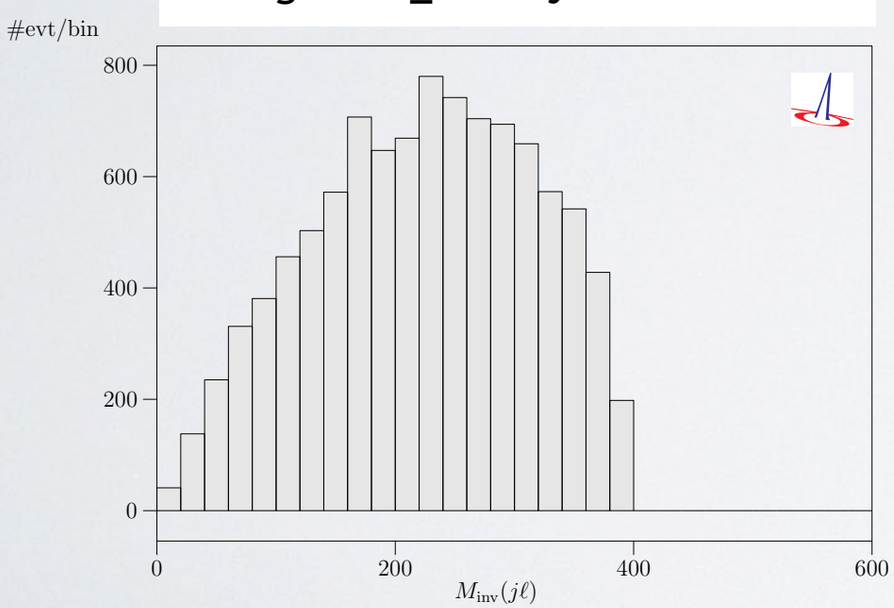

```
unstable su1
unstable neu2
```



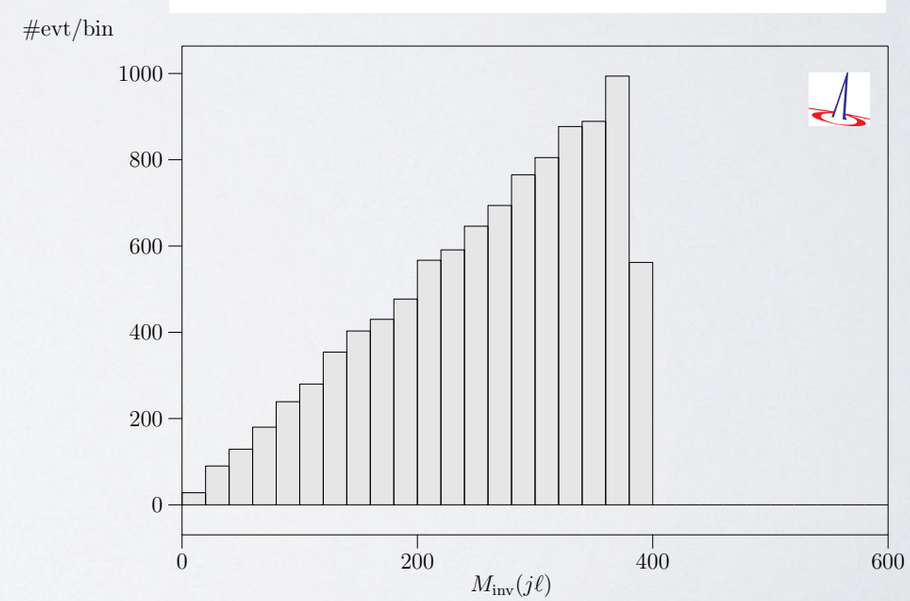

```
simulate (casc)
```




```
?diagonal_decay = true
```




```
?isotropic_decay = true
```



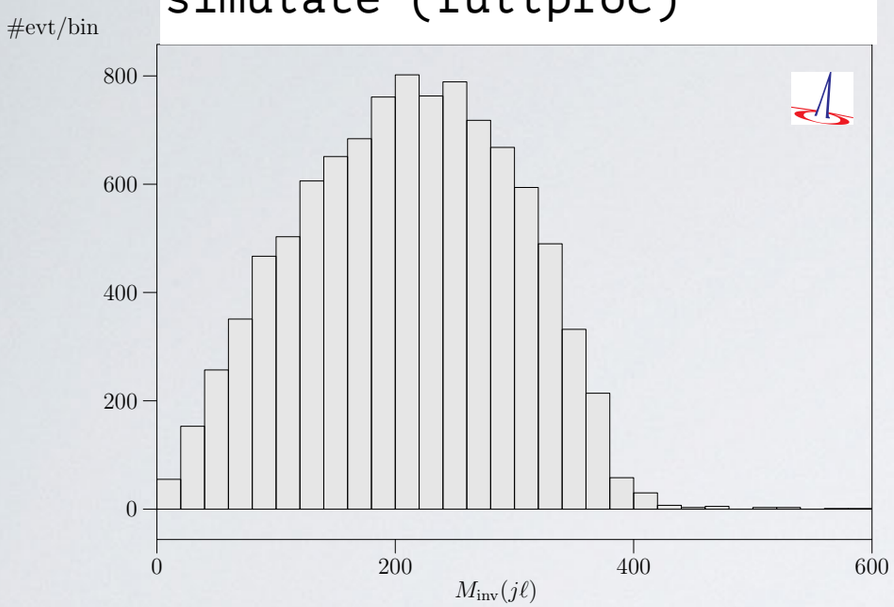
Possibility to select specific helicity in decays!

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

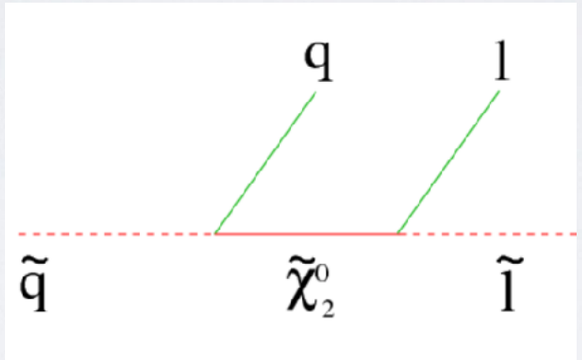
Spin Correlation and Polarization in Cascades

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

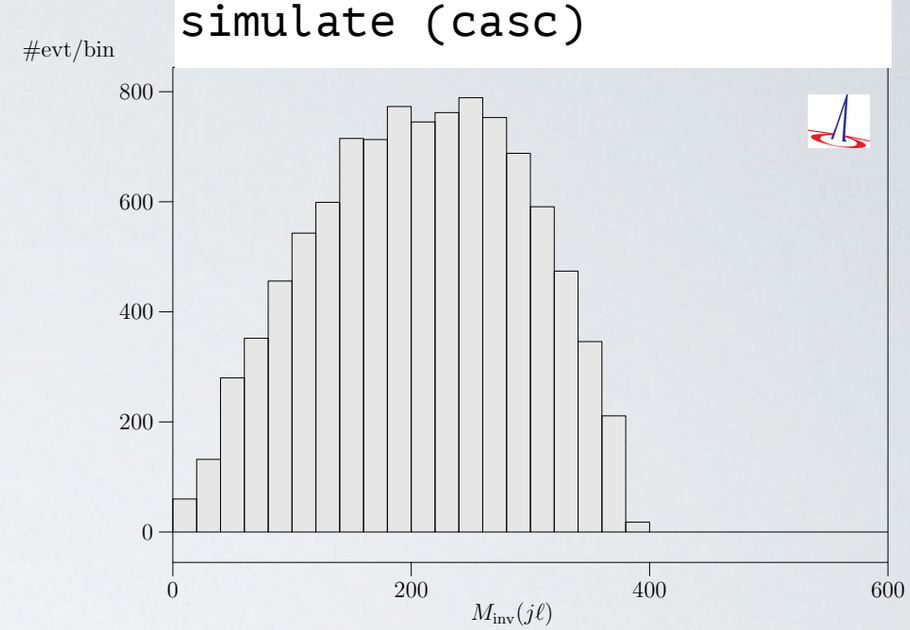
```
simulate (fullproc)
```



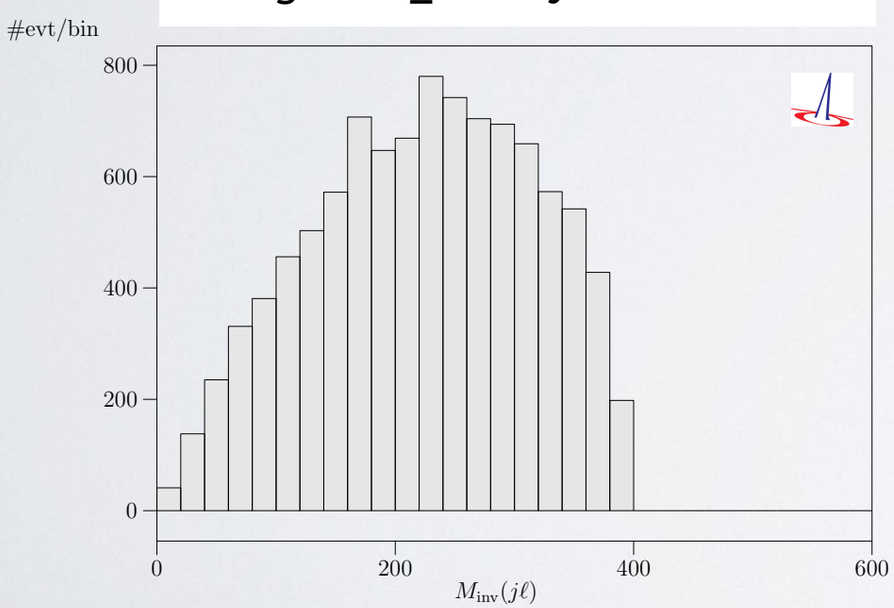

```
unstable su1
unstable neu2
```




```
simulate (casc)
```




```
?diagonal_decay = true
```



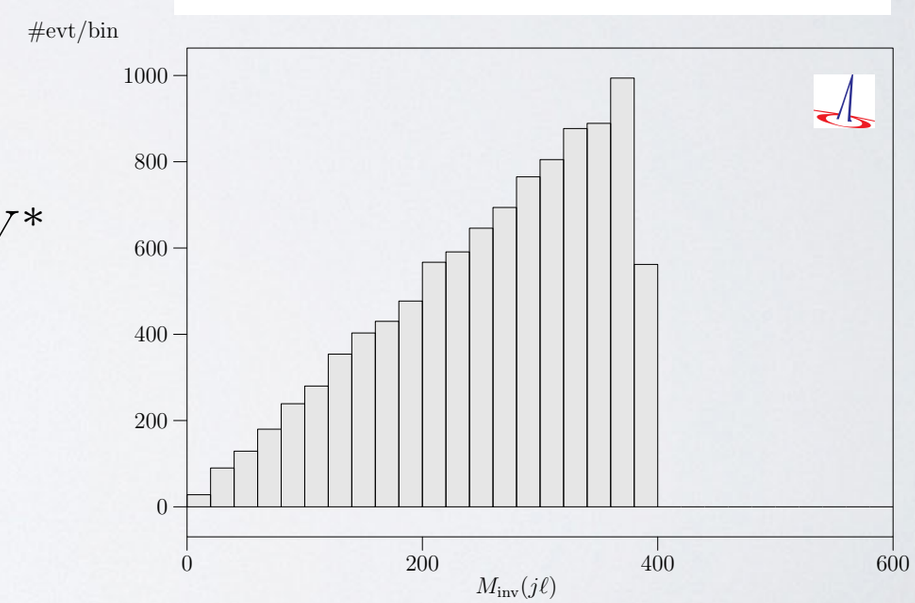
Factorized example:

ILC TDR / CLIC CDR

$$e^+e^- \to t\bar{t}H \to t\bar{t}WW^*$$

$$\to b\bar{b}\ell\nu_\ell jjjjjj$$

```
?isotropic_decay = true
```



Possibility to select specific helicity in decays!

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

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
```

BSM physics in WHIZARD

BSM Models in WHIZARD

Hard-coded models:

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

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SM with Hgg, $H\gamma\gamma$, $H\mu\mu$, He^+e^-	SM_Higgs_CKM	SM_Higgs
SM with bosonic dim-6 operators	---	SM_dim6
SM with charge 4/3 top	---	SM_top
SM with anomalous top couplings	---	SM_top_anom
SM with anomalous Higgs couplings	---	SM_rx/NoH_rx/SM_ul
SM extensions for VV scattering	---	SSC/AltH/SSC_2/SSC_AltT
SM with Z'	---	Zprime
Two-Higgs Doublet Model	THDM_CKM	THDM
Higgs Singlet Extension	---	HSExt
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	---	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	---	PSSSM
Littlest Higgs	---	Littlest
Littlest Higgs with ungauged $U(1)$	---	Littlest_Eta
Littlest Higgs with T parity	---	Littlest_Tpar
Simplest Little Higgs (anomaly-free)	---	Simplest
Simplest Little Higgs (universal)	---	Simplest_univ
SM with graviton	---	Xdim
UED	---	UED
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Augmentable SM template	---	Template

(external) UFO models:

- ☑ WHIZARD 2.8.3: Full UFO support
- ☑ New version demands OCaml ⩾4.02.3
- ☑ LO externals UFO models
- ☑ Spin 0, 1/2, 1, 3/2, 2, 3, 4, 5 supported
- ☑ Arbitrary Lorentz structures supported
- ☑ 5-, 6-point vertices (and even higher)
- ☑ Majorana statistics (3.0.0)
- ☑ BSM SLHA input (2.8.3)
- ☑ Crazy color structures (as internal particles)

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Littlest Higgs with T parity	---	Littlest_Tpar
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- ☑ Majorana statistics (3.0.0)
- ☑ BSM SLHA input (2.8.3)
- ☑ Crazy color structures (as internal particles)

Old FeynRules / SARAH interface **is deprecated**

kept at the moment for user backwards compatibility

Models from UFO Files in WHIZARD

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

UFO file is assumed to be in working directory OR

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

UFO file is in user-specified directory

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

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

All the setup works the same as for intrinsic models

```
show (model)
```

- shows names of particles of the UFO model
- displays names of available parameters

Models from UFO Files in WHIZARD

```
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```

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

```
show (model)
```

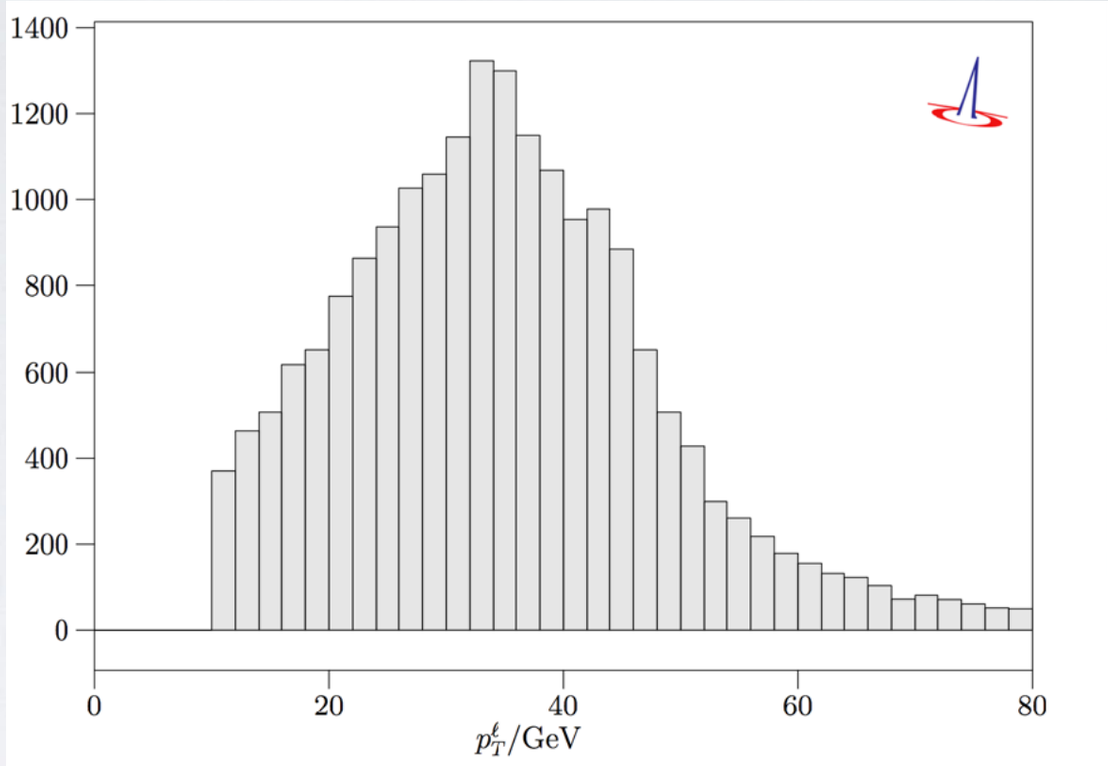
- shows names of particles of the UFO model
- displays names of available parameters

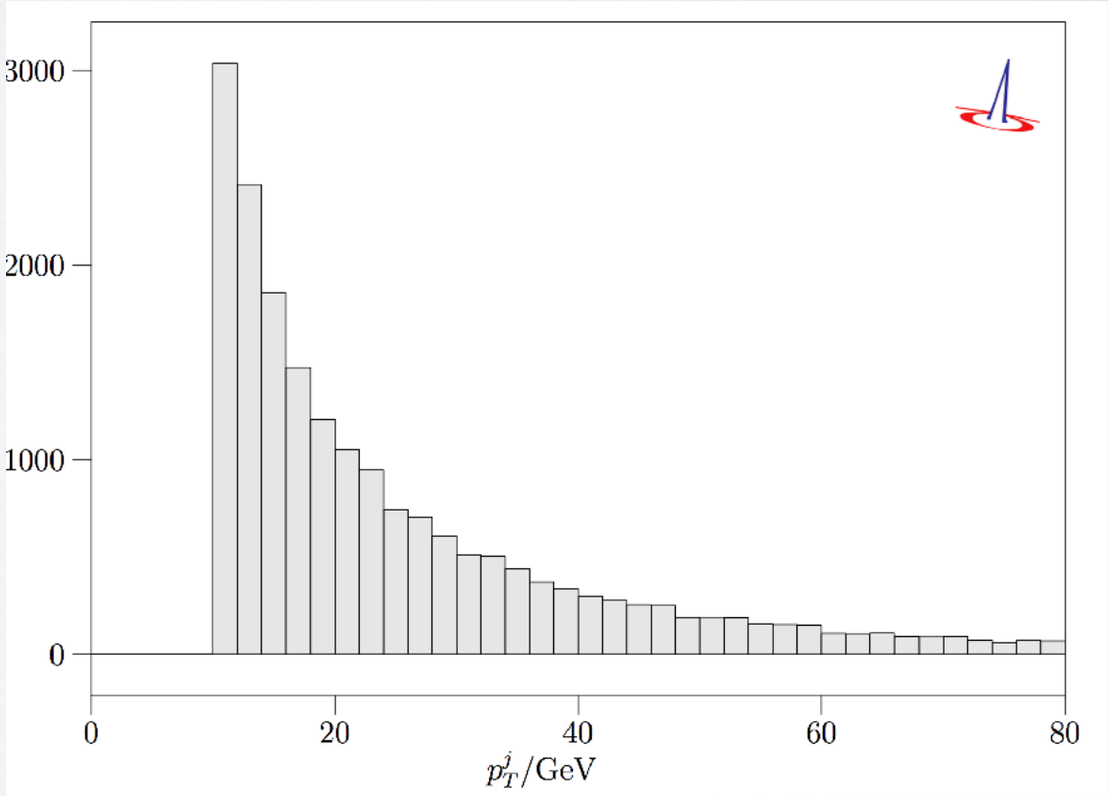
WHIZARD Examples

W-endpoint at the LHC

```
model = SM

alias parton = u:U:d:D:g
alias jet = parton
alias lepton = e1:e2
alias neutrino = n1:N1:n2:N2

process enj = parton, parton => lepton, neutrino, jet

sqrts = 14 TeV
beams = p, p => pdf_builtin
$pdf_builtin_set = "cteq6l"

me = 0  mmu = 0  ms = 0   mc = 0

cuts = all Pt >= 10 GeV [jet:lepton]
integrate (enj)  { iterations = 5:20000:"gw", 3:10000 }

n_events = 20000

histogram pt_lepton (0 GeV, 80 GeV, 2 GeV)
histogram pt_jet (0 GeV, 80 GeV, 2 GeV)

analysis = record pt_lepton (eval Pt
             [extract index 1 [sort by -Pt [lepton]]]);
           record pt_jet (eval Pt
             [extract index 1 [sort by -Pt [jet]]])

checkpoint = 1000

simulate (enj)

compile_analysis { $out_file = "W-endpoint.dat" }
```

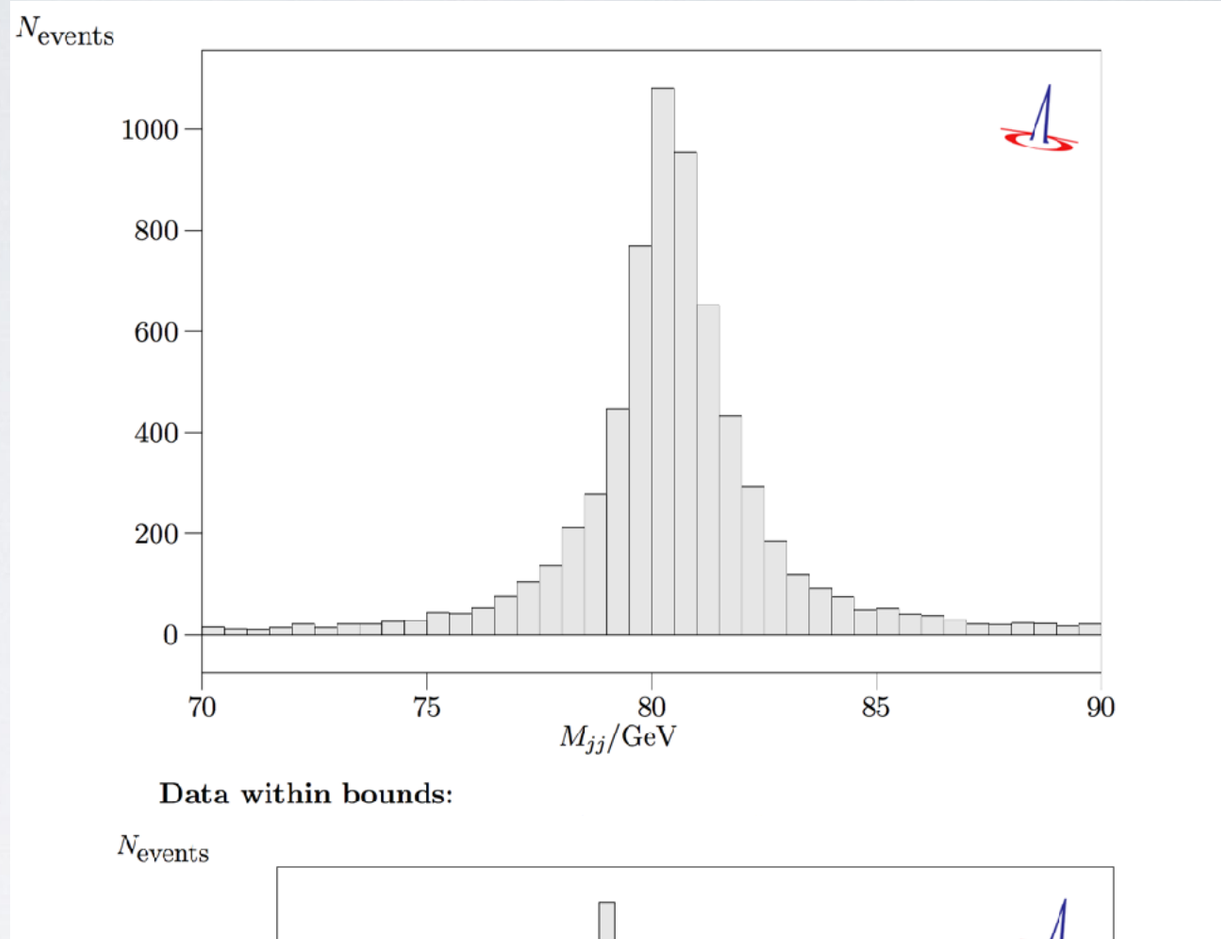
```
| |=================================================================|
| | % complete | events generated | events remaining | time remaining
| |=================================================================|
|      0.0              0              20000              ???
|      5.0           1000              19000              0m:31s
|     10.0           2000              18000              0m:29s
|     15.0           3000              17000              0m:28s
|     20.0           4000              16000              0m:26s
|     25.0           5000              15000              0m:25s
|     30.0           6000              14000              0m:23s
|     35.0           7000              13000              0m:21s
|     40.0           8000              12000              0m:20s
```

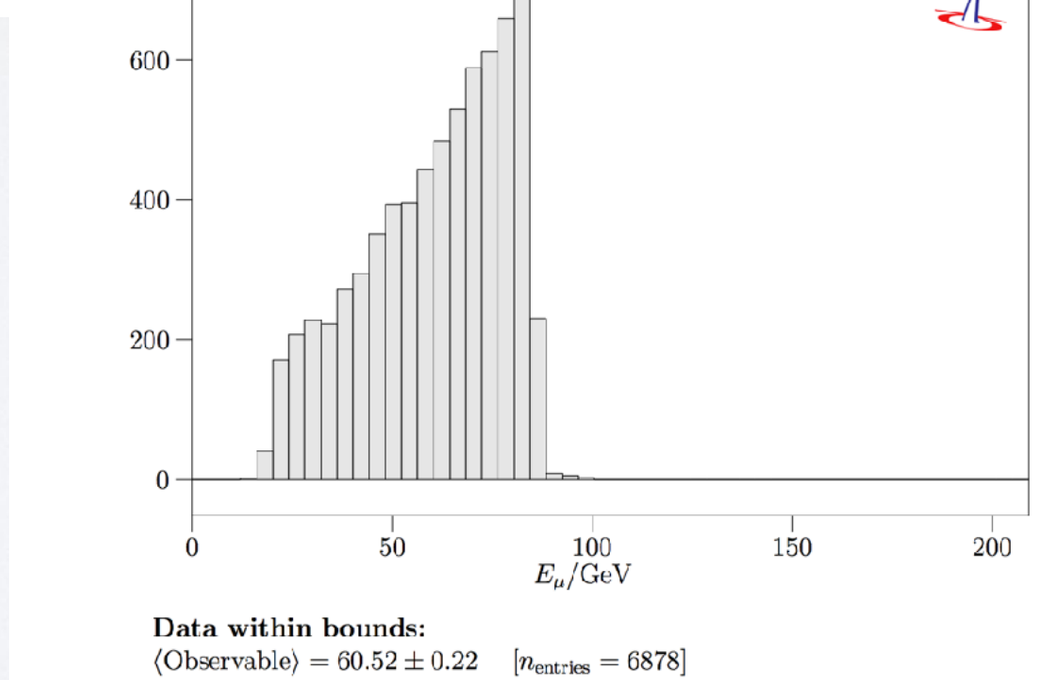




WW production in e^+e^- — CC10 process

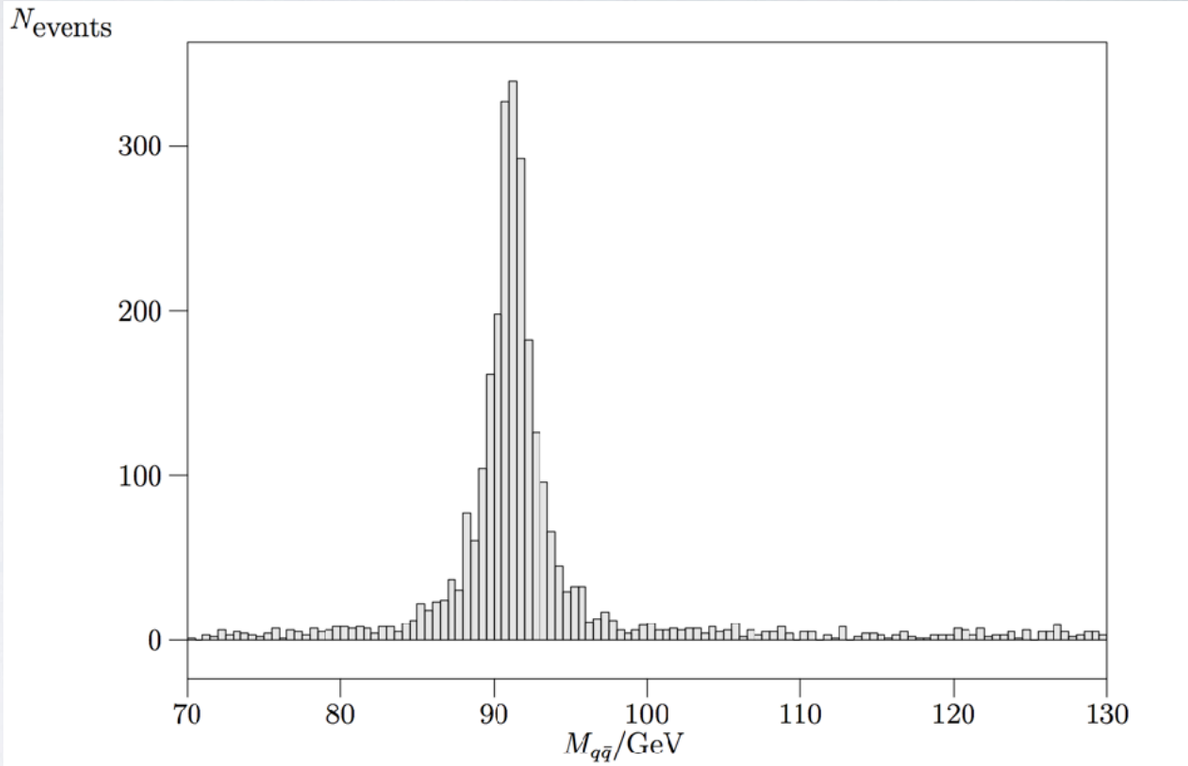
```
model = SM

process cc10 = e1, E1 => e2, N2, u, D

sqrts = 209 GeV

integrate (cc10)
     { iterations = 15:500000, 5:1000000 }

# For better statistics: 100 times LEP
luminosity = 10 / fb

histogram m_jets (70 GeV, 90 GeV, 0.5 GeV)
histogram e_muon (0 GeV, 209 GeV, 4)

analysis = record m_jets (eval M [u, D]);
           record e_muon (eval E [e2])

simulate (cc10)

compile_analysis ( “out_file” = cc10.dat)
```

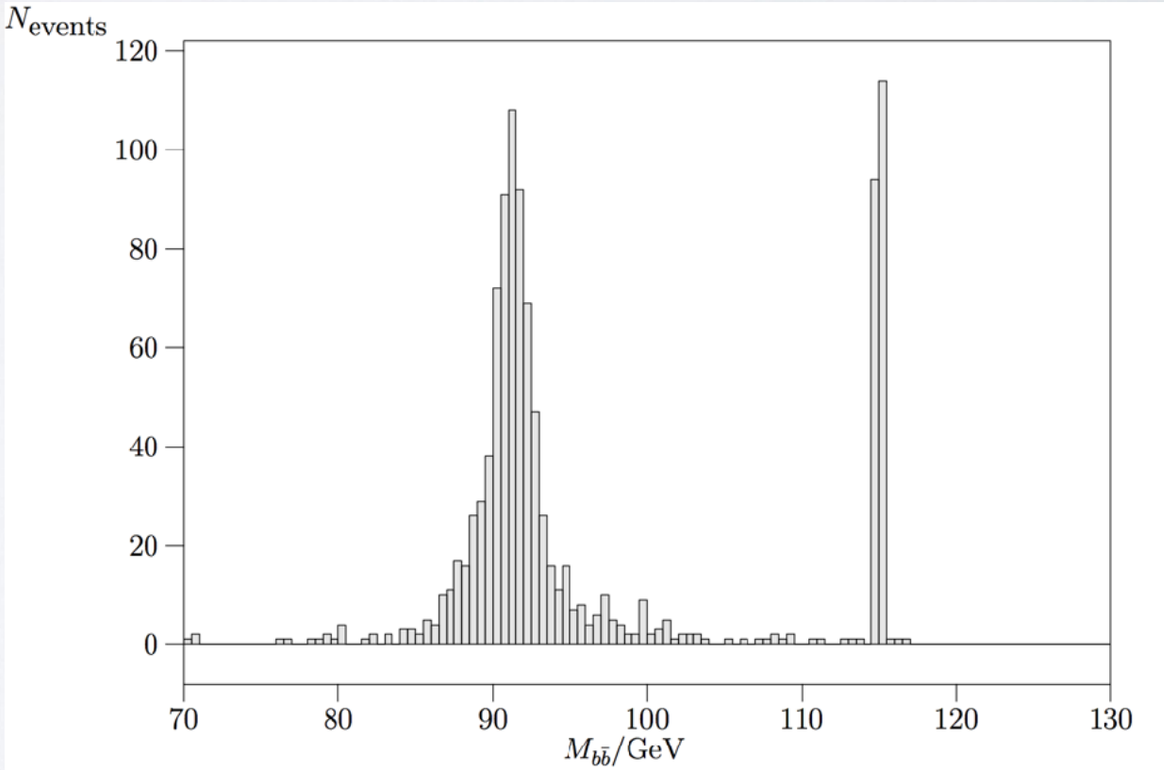




LEP Higgs Search

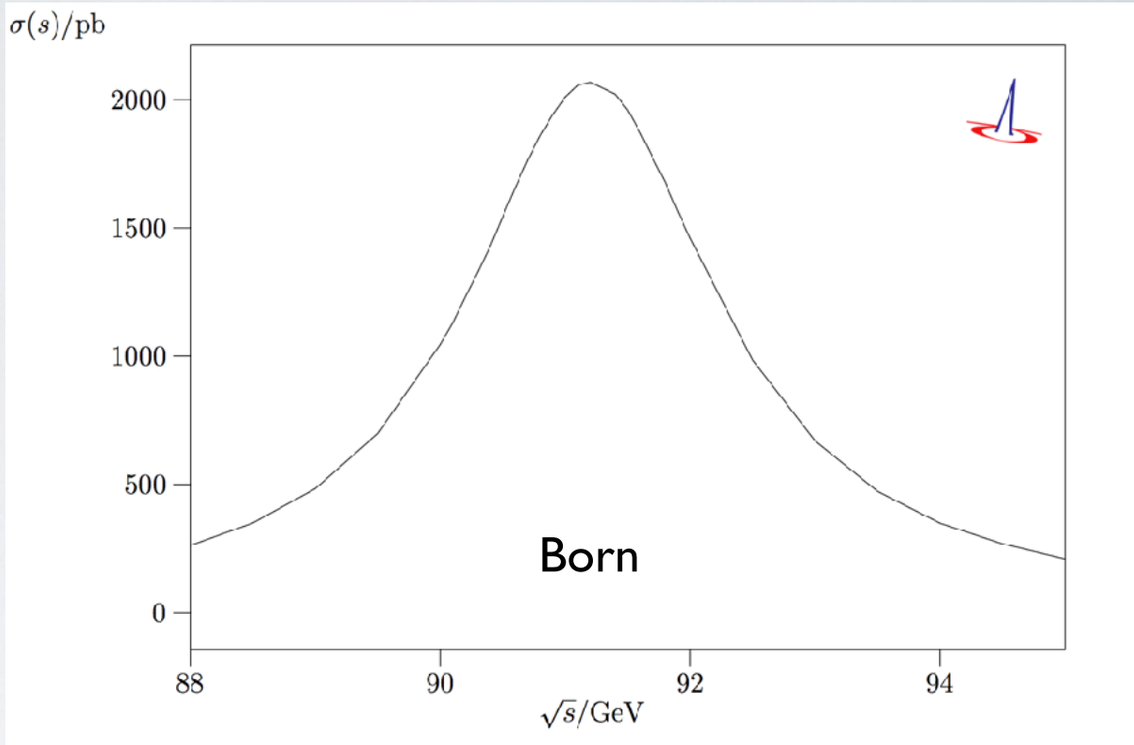
```
model = SM

alias n = n1:n2:n3
alias N = N1:N2:N3
alias q = u:d:s:c
alias Q = U:D:S:C

# Higgsstrahlung's process
process zh = e1, E1 => Z, h
# Missing energy channel
process nnbb = e1, E1 => n, N, b, B
# 4-jet channels
process qqbb = e1, E1 => q, Q, b, B
process bbbb = e1, E1 => b, B, b, B
process eebb = e1, E1 => e1, E1, b, B
process qqtt = e1, E1 => q, Q, e3, E3
process bbtt = e1, E1 => b, B, e3, E3

sqrts = 209 GeV

# would-be Higgs mass at LEP
mH = 115 GeV
wH = 3.228 MeV
mb = 2.9 GeV
me = 0  ms = 0  mc = 0

cuts = all M >= 10 GeV [q, Q]
# For better statistics: 100 times LEP
luminosity = 10 / fb

integrate (nnbb,qqbb,eebb,qqtt,bbtt)
     { iterations = 12:20000, 1:30000 }

analysis = record m_invisible (eval M [n, N]);
           record m_bb (eval M [b, B])

histogram m_invisible (70 GeV, 130 GeV, 0.5 GeV)
histogram m_bb (70 GeV, 130 GeV, 0.5 GeV)
histogram m_jj (70 GeV, 130 GeV, 0.5 GeV)
simulate (nnbb)
simulate (qqbb) { analysis = record m_jj (eval M / 1 GeV
                    [combine [q,Q]]) }
```

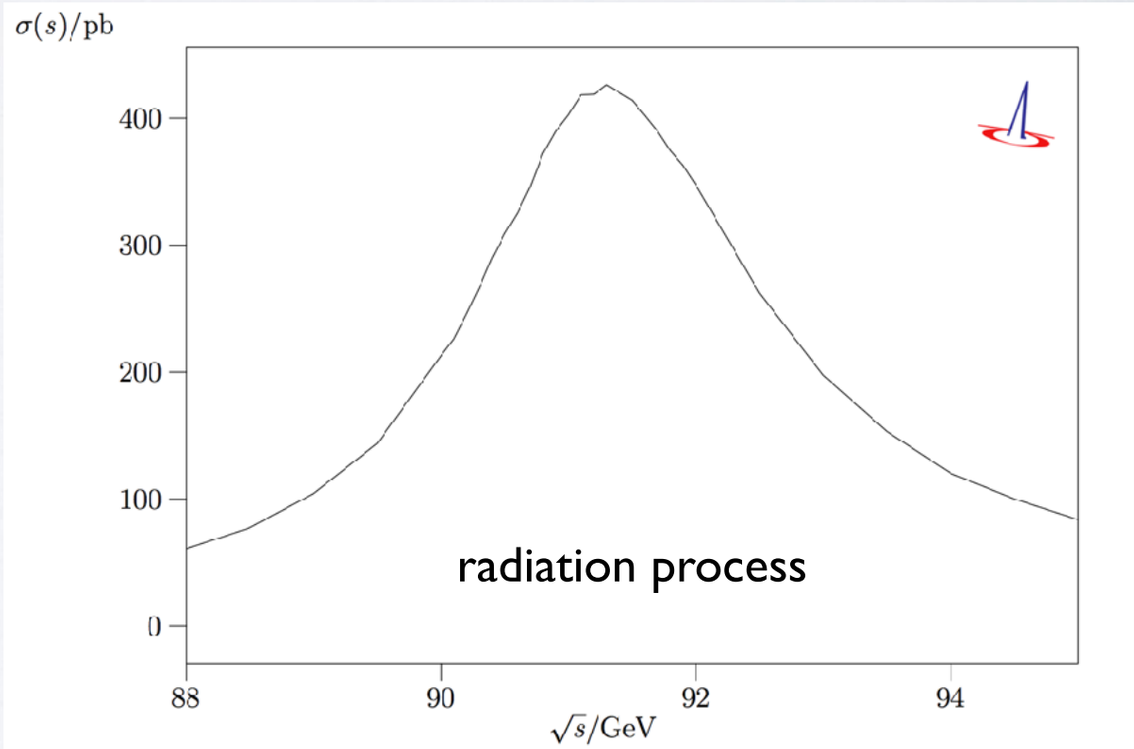




Z-lineshape at SLC/LEP I

```
model = SM

alias lep = e1:E1:e2:E2
alias prt = lep:A

process born = e1, E1 => e2, E2
process rc = e1, E1 => e2, E2, A

cuts = all E >= 100 MeV [prt]
   and all abs (cos(Theta)) <= 0.99 [prt]
   and all M2 >= (1 GeV)^2 [prt, prt]

integrate (enj)  { iterations = 5:20000:"gw", 3:10000 }


plot lineshape_born { x_min=88 GeV  x_max= 95 GeV }
plot lineshape_rc { x_min=88 GeV  x_max= 95 GeV }

scan sqrts = ((88.0 GeV => 90.0 GeV /+ 0.5 GeV),
              (90.1 GeV => 91.9 GeV /+ 0.1 GeV),
              (92.0 GeV => 95.0 GeV /+ 0.5 GeV)) {
   beams = e1, E1
   integrate (born) { iterations = 2:1000:"gw", 1:2000 }
   record lineshape_born (sqrts, integral (born) / 1000)
   integrate (rc)  { iterations = 5:3000:"gw", 2:5000 }
   record lineshape_rc (sqrts, integral (rc) / 1000)
}

compile_analysis { $out_file = "Z-lineshape.dat" }
```





MLM-matched samples / OPAL tune


```
model = SM

alias j = u:d:s:c:U:D:S:C:g

process eeuu = e1, E1 => u, U
process eeuuj = e1, E1 => u, U, j
process eeuujj = e1, E1 => u, U, j, j
process eeuujjj = e1, E1 => u, U, j, j, j

sqrts = 91 GeV
beams = e1, E1

me = 0  mmu = 0  ms = 0   mc = 0

?ps_fsr_active = true
?hadronization_active = false
$shower_method = "PYTHIA6"

?mlm_matching = true
mlm_nmaxMEjets = 5
mlm_Rmin = 1
mlm_ETclusminE = 10 GeV
real ycut = mlm_ETclusminE**2

cuts = all kT > ycut [j, j]
integrate (eeuu, eeuuj, eeuujj, eeuujjj)

n_events = 20000

histogram pt_lepton (0 GeV, 80 GeV, 2 GeV)
histogram pt_jet (0 GeV, 80 GeV, 2 GeV)

?rebuild_events = true
$sample = "EEMatching5"
sample_format = lhef

checkpoint = 2500

simulate (eeuu, eeuuj, eeuujj, eeuujjj)
```

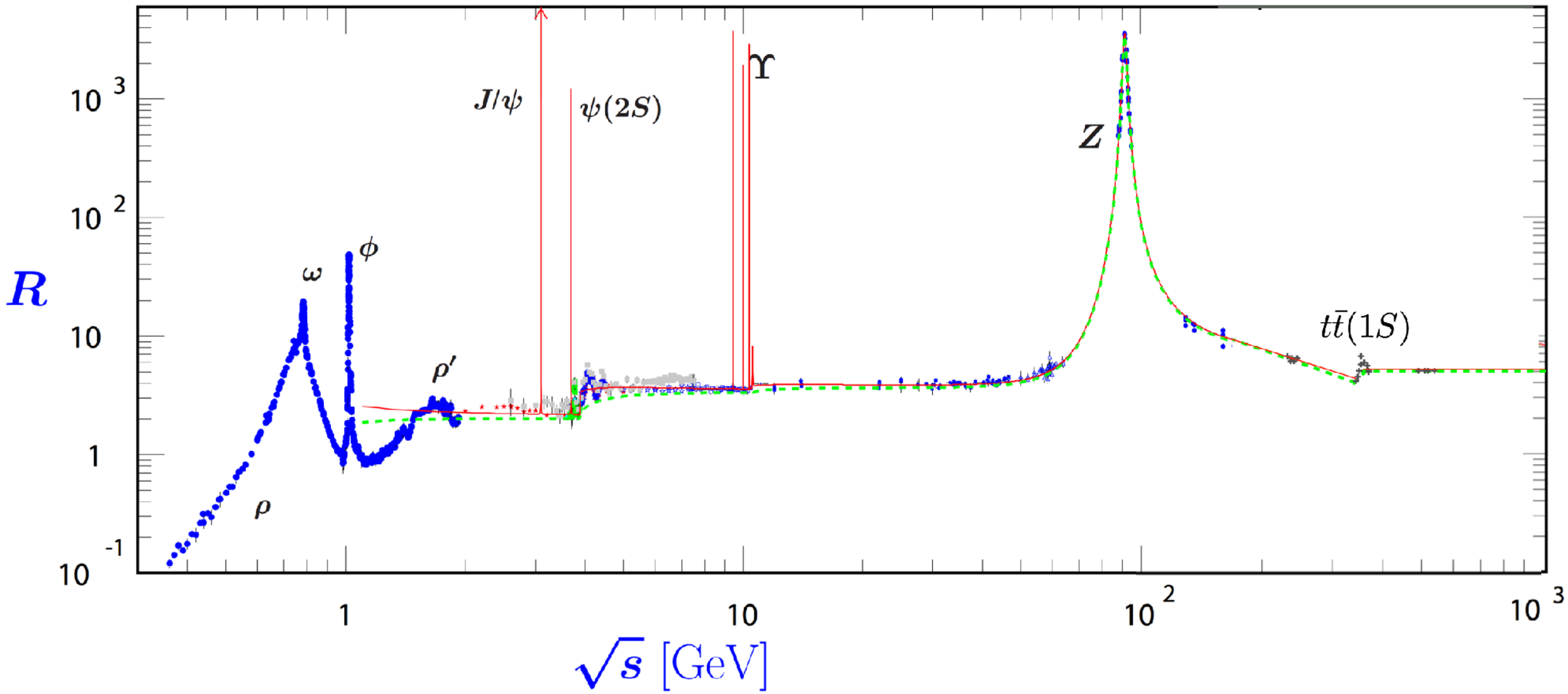
```
model = SM

alias j = u:d:s:c:U:D:S:C:g

beams = e1, E1  => circe2 => isr

?isr_handler = true
$isr_handler_mode = "recoil"
isr_alpha = 0.0072993
isr_mass = 511 keV

process eejj = e1, E1 => j, j

sqrts = 91 GeV

me = 0  ms = 0   mc = 0

?ps_fsr_active = true
?hadronization_active = true
$shower_method = "PYTHIA6"

$ps_PYTHIA_PYGIVE = "MSTJ(28)=0; PMAS(25,1)=120.;
 PMAS(25,2)=0.3605E-02; MSTJ(41)=2; MSTU(22)=2000;
 PARJ(21)=0.40000; PARJ(41)=0.11000;
 PARJ(42)=0.52000; PARJ(81)=0.25000;
 PARJ(82)=1.90000; MSTJ(11)=3; PARJ(54)=-0.03100;
 PARJ(55)=-0.00200; PARJ(1)=0.08500;
 PARJ(3)=0.45000; PARJ(4)=0.02500;
 PARJ(2)=0.31000; PARJ(11)=0.60000;
 PARJ(12)=0.40000; PARJ(13)=0.72000;
 PARJ(14)=0.43000; PARJ(15)=0.08000;
 PARJ(16)=0.08000; PARJ(17)=0.17000;
 MSTP(3)=1;MSTP(71)=1"

integrate (eejj)

n_events = 20000

simulate (eejj)
```

Summary & Outlook

- `WHIZARD 2.8.5` event generator for lepton collider physics [not only]
- ee physics: beamspectra, polarization, ISR, LCIO, LC top threshold
- Full-fledged parallel MPI integration *[Load balancer* `WHIZARD 3.0.0`*]*
- All SM backgrounds: *[ILC-TDR ("DBD") samples, new ILC samples]*
- BSM: UFO interface *[of course many, many hard-coded models]*
- NLO QCD done (`WHIZARD 3.0.0β`) *[NLO EW: first results]*
- Dedicated setup for NLO/NLL (NR)QCD top threshold matching
- BEWARE OF BLACK BOXES: always understand basics of physics

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

Outlook to PDG 20xx:



BACKUP

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)

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

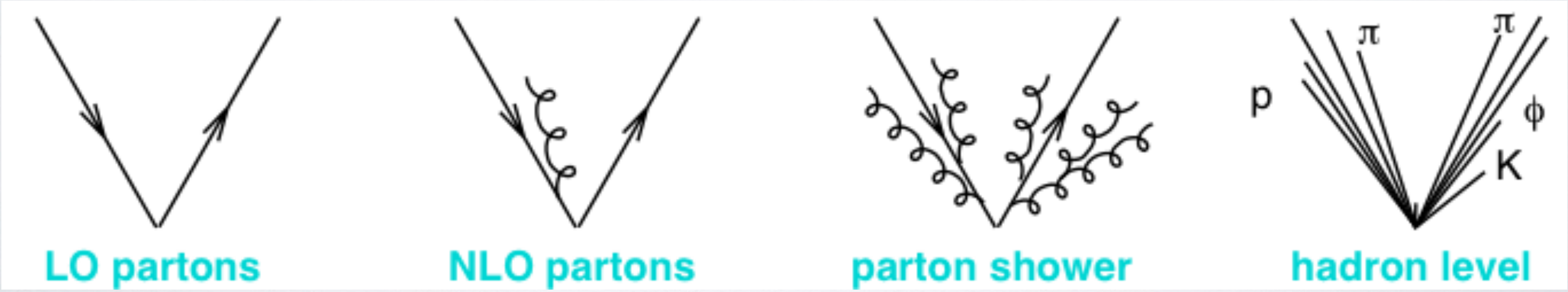
```
beams_pol_density = @(j:j:h_j, j-1:j-1:h_{j-1}, ..., -j:-j:h_{-j})
```

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

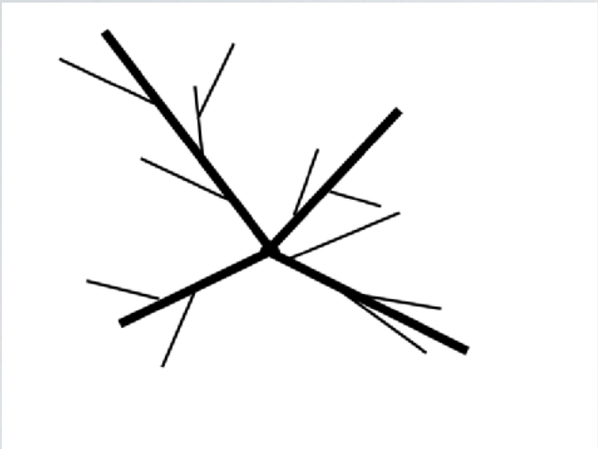
Diagonal / arbitrary density matrices

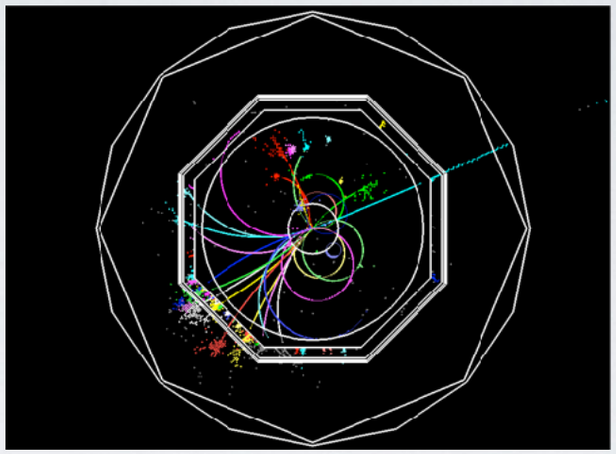
Old Etruscan wisdom: Loops and legs …

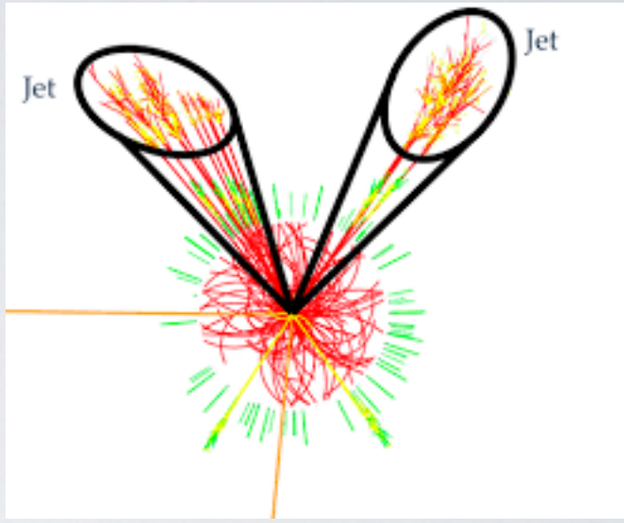
Old Etruscan wisdom: Loops and legs …



Infrared Safety, Cuts & Selections: Jet Finders

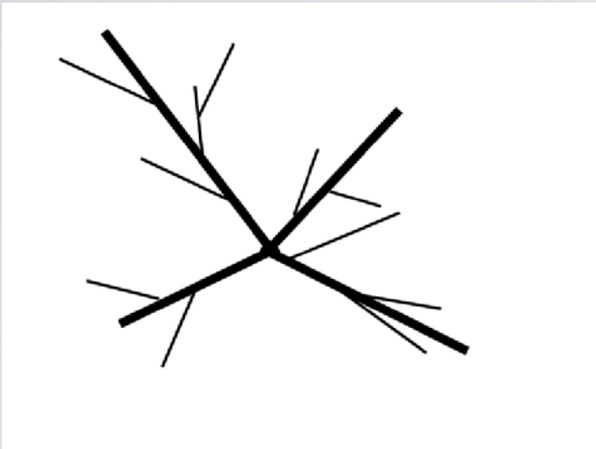


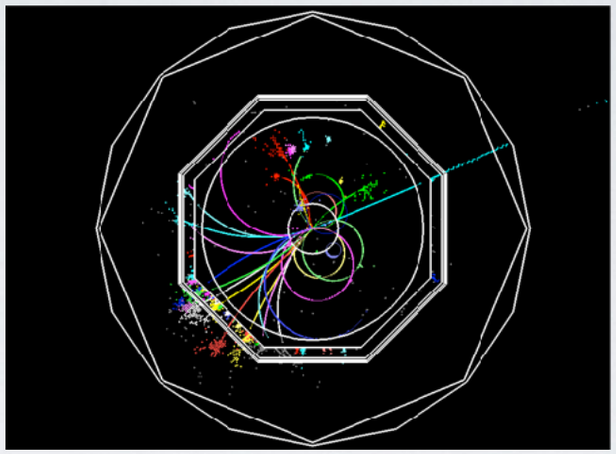


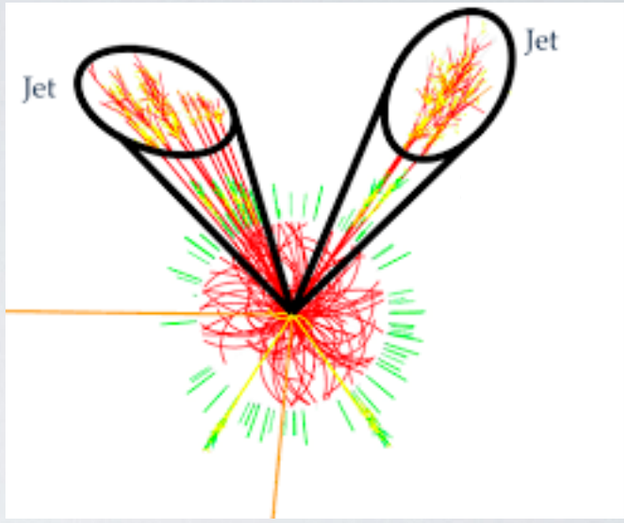


- **Jet cluster algorithms** map parton momenta to jet objects
- Jet resolution measure to decide whether to recombine jets
- Typically a distance measure:

Infrared Safety, Cuts & Selections: Jet Finders







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- Jet resolution measure to decide whether to recombine jets
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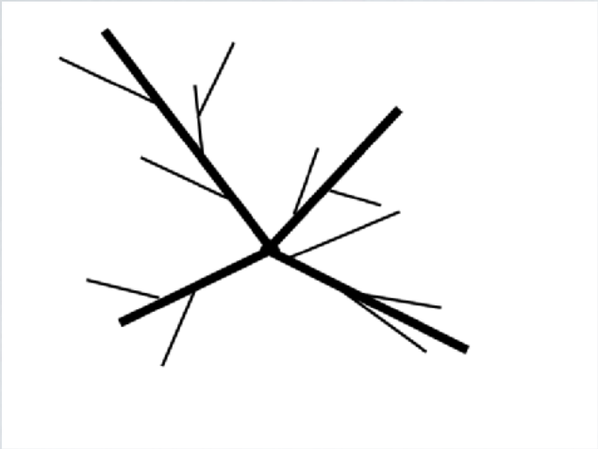
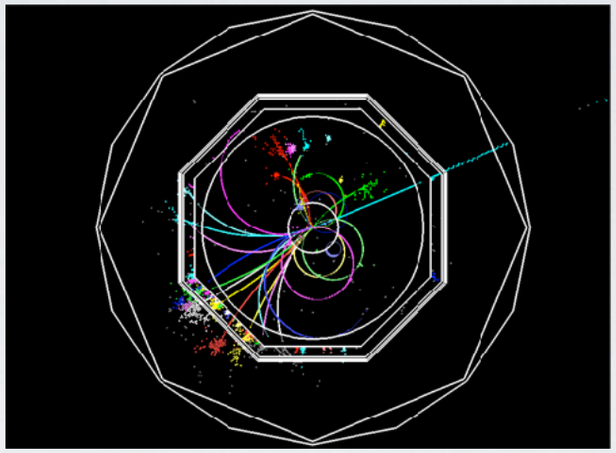
$$d_{ij} = \min\left(k_{\perp i}^{2p}, k_{\perp j}^{2p}\right) \frac{\Delta y^2 + \Delta\phi^2}{\hat{R}^2}$$

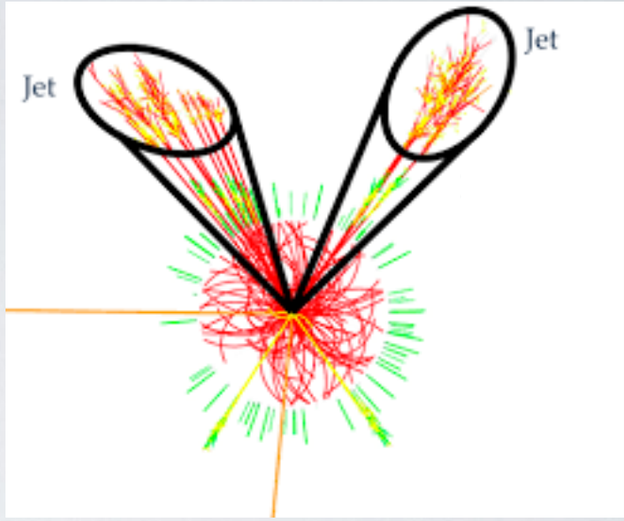
soft particles: $k_\perp \to 0$

collinear particles: $\Delta y^2 + \Delta\phi^2 \to 0$

Infrared Safety, Cuts & Selections: Jet Finders







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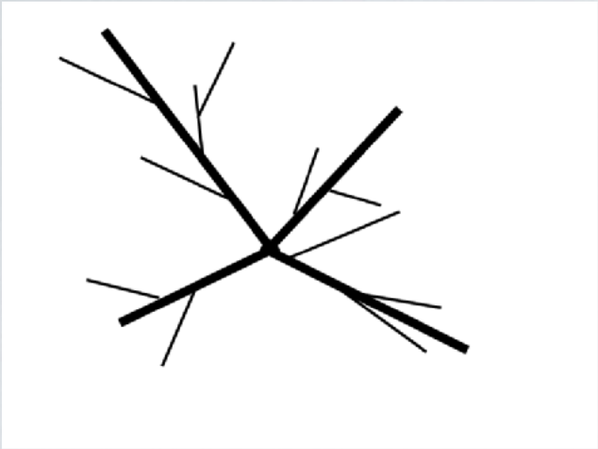
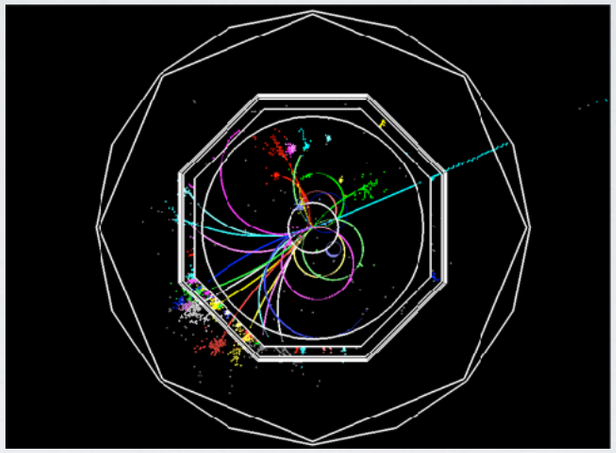
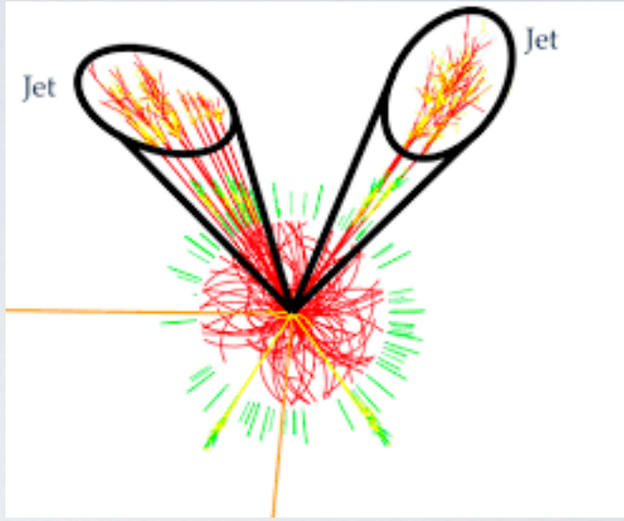
`FastJet` Cacciari/Salam/Soyez, '08

- $p = +1$ *k_T — algorithm*
- $p = 0$ *Cambridge-Aachen — algorithm*
- $p = -1$ *anti-k_T — algorithm*

Infrared Safety, Cuts & Selections: Jet Finders







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`FastJet` Cacciari/Salam/Soyez, '08

- $p = +1$ k_T — *algorithm*
- $p = 0$ *Cambridge-Aachen — algorithm*
- $p = -1$ *anti-k_T — algorithm*

Clustering:

```
jet_algorithm = antikt_algorithm
jet_r = 0.7
?keep_flavors_when_clustering = true
```

Subevents and jet counts:

```
cuts = let subevt @clustered_jets = cluster [jet] in
       let subevt @pt_selected =
          select if Pt > 30 GeV [@clustered_jets] in
       let subevt @eta_selected =
          select if abs(Eta) < 4 [@pt_selected] in
       count [@eta_selected] >= 1
```

NLO Automation in WHIZARD

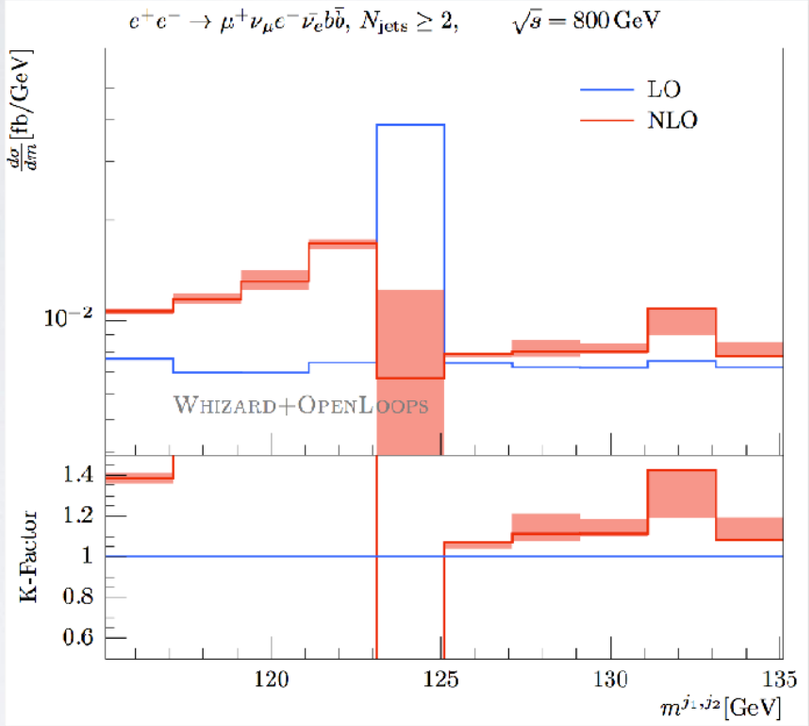
Working NLO interfaces to:

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

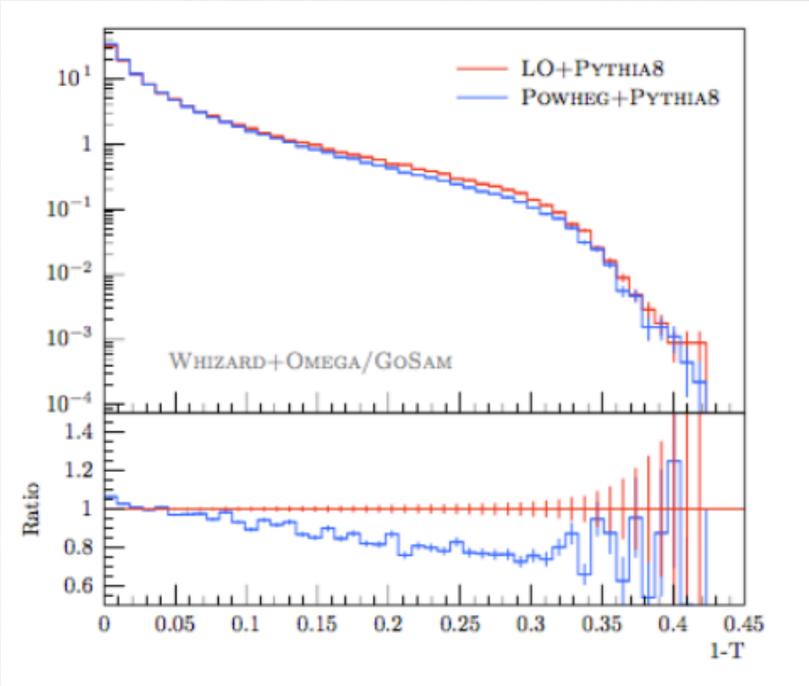
NLO QCD (massless & massive) fully supported

```
alpha_power = 2
alphas_power = 1

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



- FKS subtraction [Frixione/Kunszt/Signer, hep-ph/9512328]
- Resonance-aware treatment [Ježo/Nason, 1509.09071]
- Virtual MEs external
- Real and virtual subtraction terms internal
- NLO decays available for the NLO processes
- Fixed order events for plotting (weighted)
- Automated POWHEG damping and matching
- NLO QCD: final clean-up NLO EW first results
- Release WHIZARD 3.0.0β (August 2020)



FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

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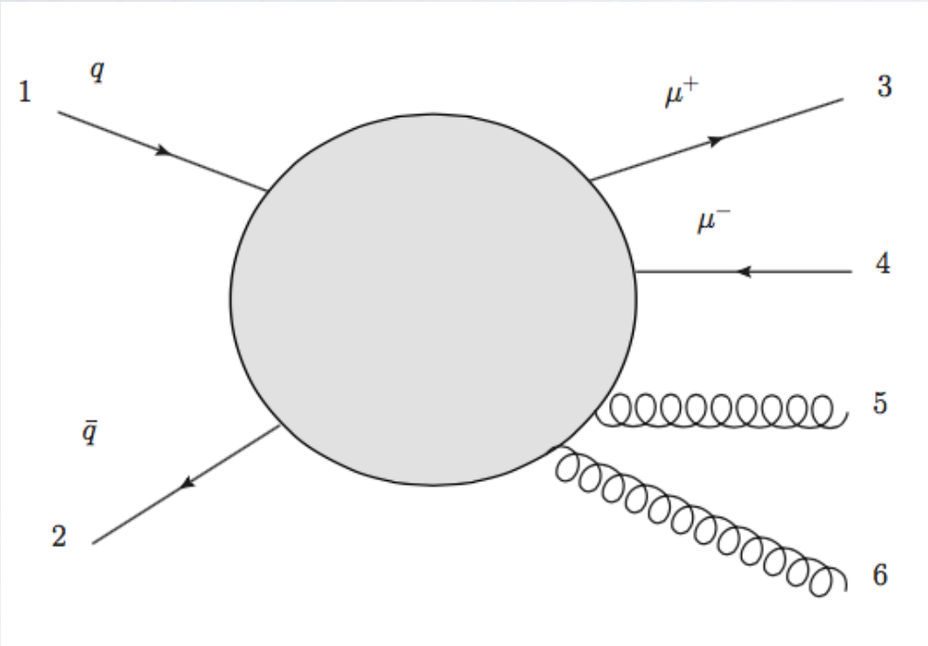

Automated subtraction terms in `WHIZARD`, algorithm:

- Find all singular pairs

$$\mathcal{I} = \{(1,5),(1,6),(2,5),(2,6),(5,6)\}$$

- Partition phase space according to singular regions

$$\mathbb{1} = \sum_{\alpha\in\mathcal{I}} S_\alpha(\Phi)$$

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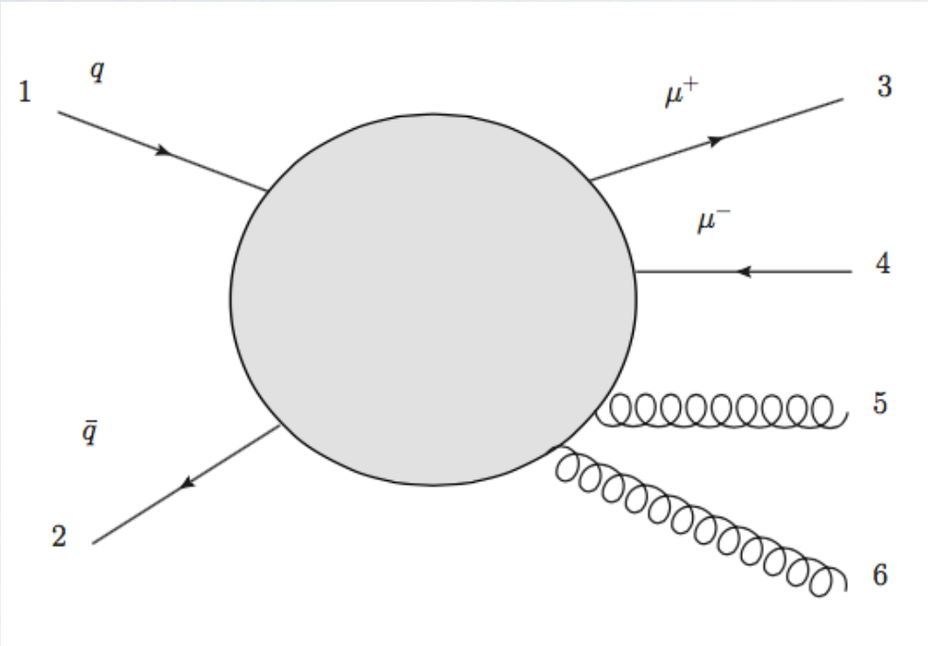

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Soft subtraction involves color-correlated matrix elements:

$$\mathcal{B}_{kl} \sim -\sum_{\substack{\text{color}\\ \text{spin}}} \mathcal{A}^{(n)} \vec{\mathcal{Q}}(\mathcal{I}_k)\cdot\vec{\mathcal{Q}}(\mathcal{I}_l)\mathcal{A}^{(n)*},$$

Collinear subtraction involves spin-correlated matrix elements:

$$\mathcal{B}_{+-} \sim Re\left\{\frac{\langle k_{\mathrm{em}} k_{\mathrm{rad}}\rangle}{[k_{\mathrm{em}} k_{\mathrm{rad}}]} \sum_{\substack{\text{color}\\ \text{spin}}} \mathcal{A}_+^{(n)} \mathcal{A}_-^{(n)*}\right\}$$

Resonance mappings for NLO processes

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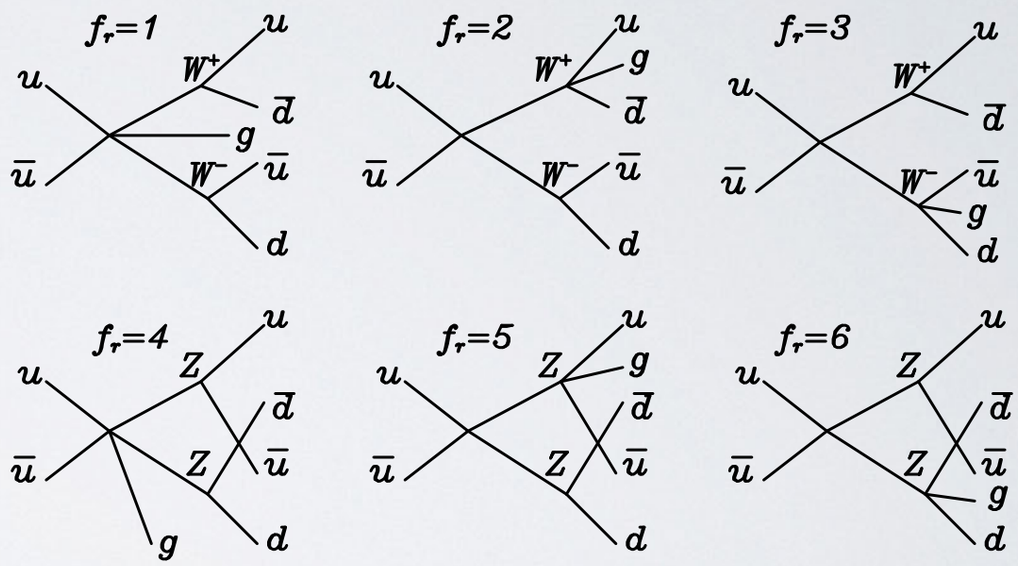

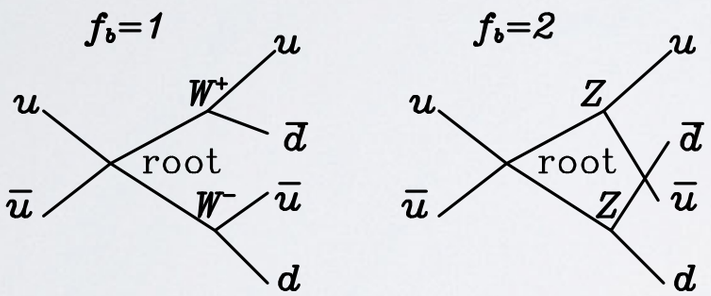

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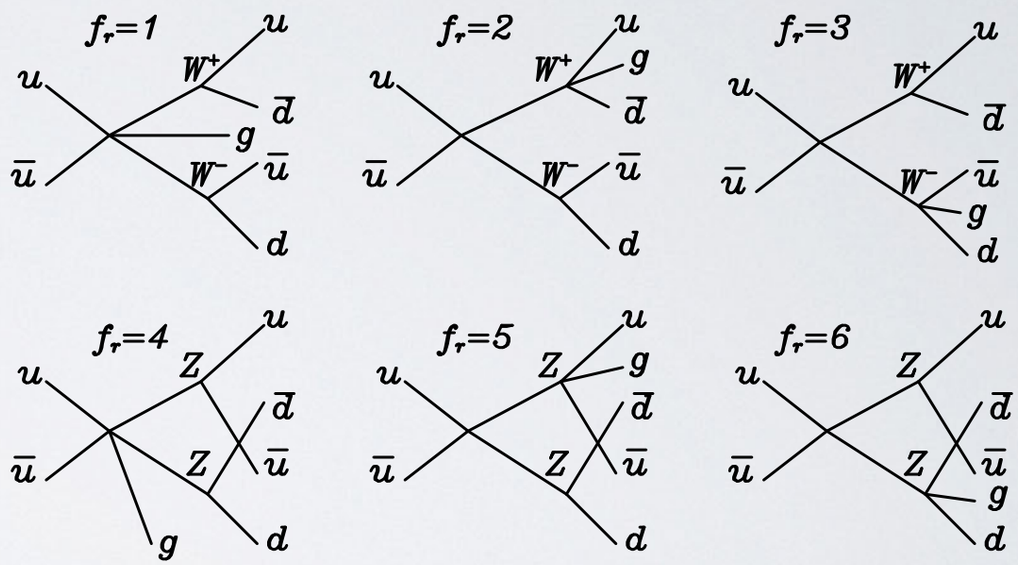

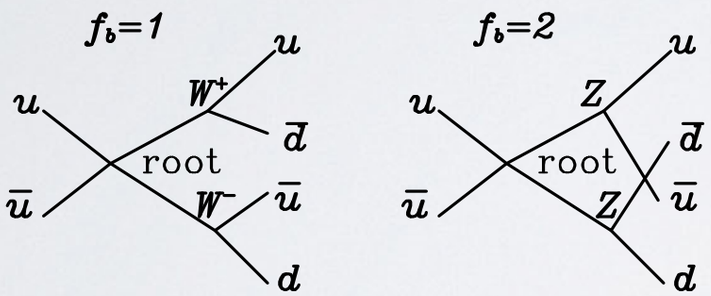

- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (ZZ, ZH histories)

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		
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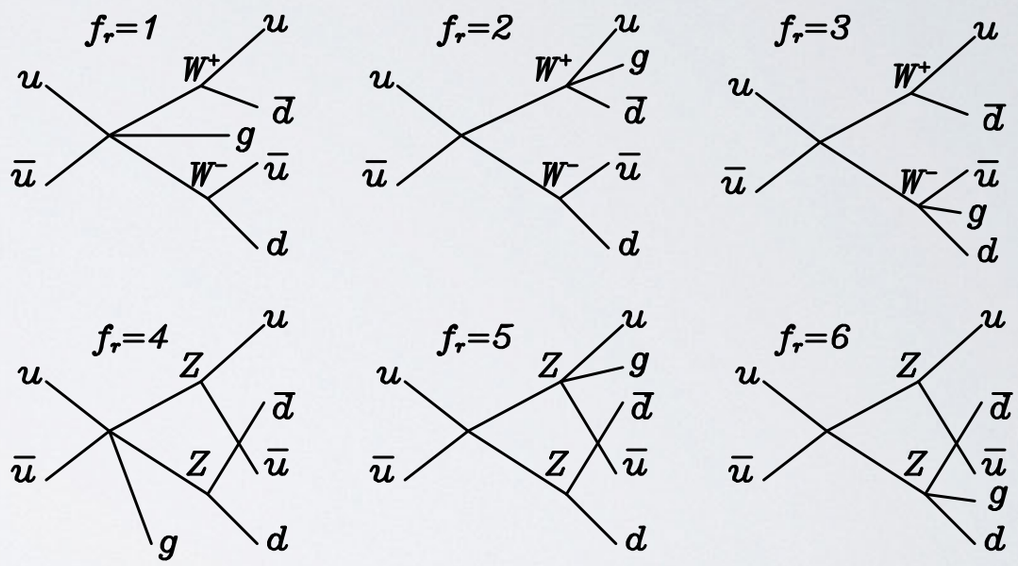

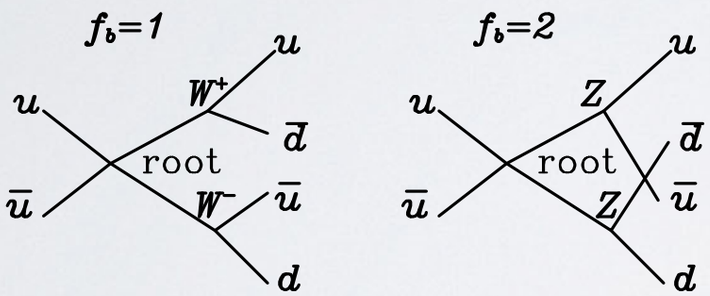

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2	11962	2.8591952E+00	5.20E-02	1.82	1.99*	10.91		
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	5

FKS with resonance mappings

NLO Fixed-Order Events

$$\mathrm{d}\sigma_n^{\mathrm{NLO}} = \mathrm{d}\Phi_n \left[\mathcal{B}_n + \mathcal{V}_n + \mathcal{B}_n \otimes S \right] + \mathrm{d}\Phi_{n+1} \left[\mathcal{R}_{n+1} - \mathcal{B}_n \otimes \mathrm{d}S \right]$$

each of these can become negative!

- Add weights of real emission events to weight of Born kinematics using the FKS mapping
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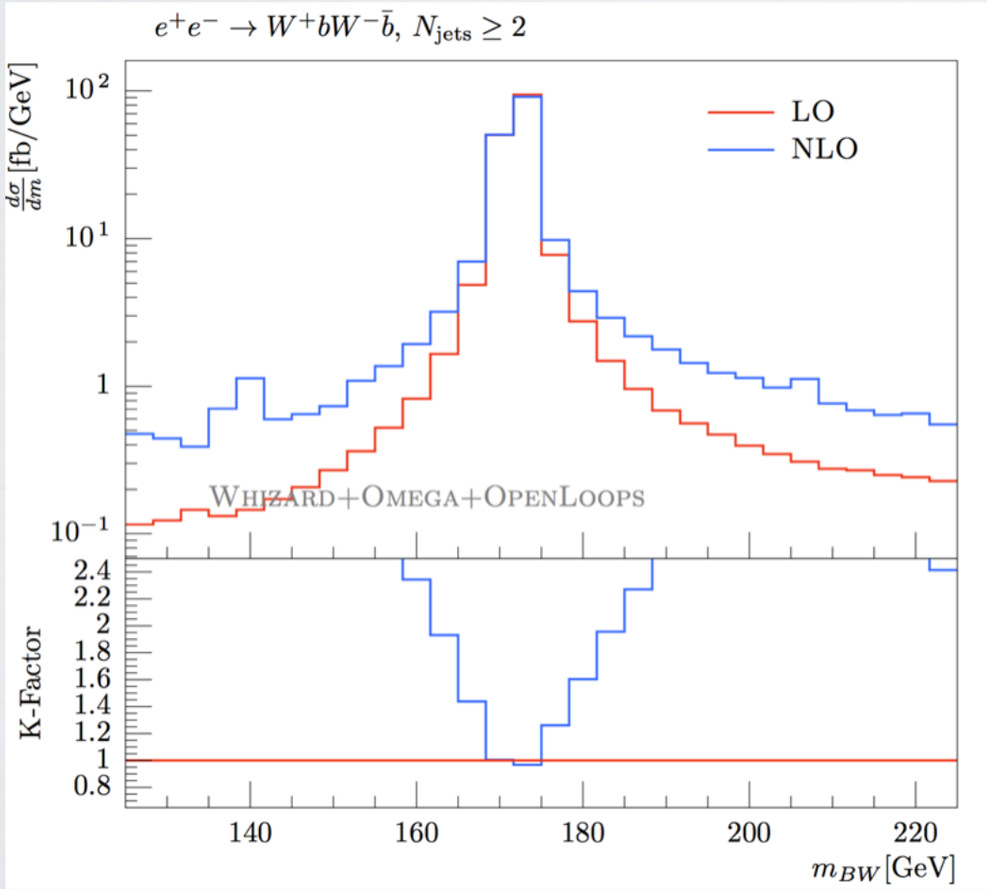

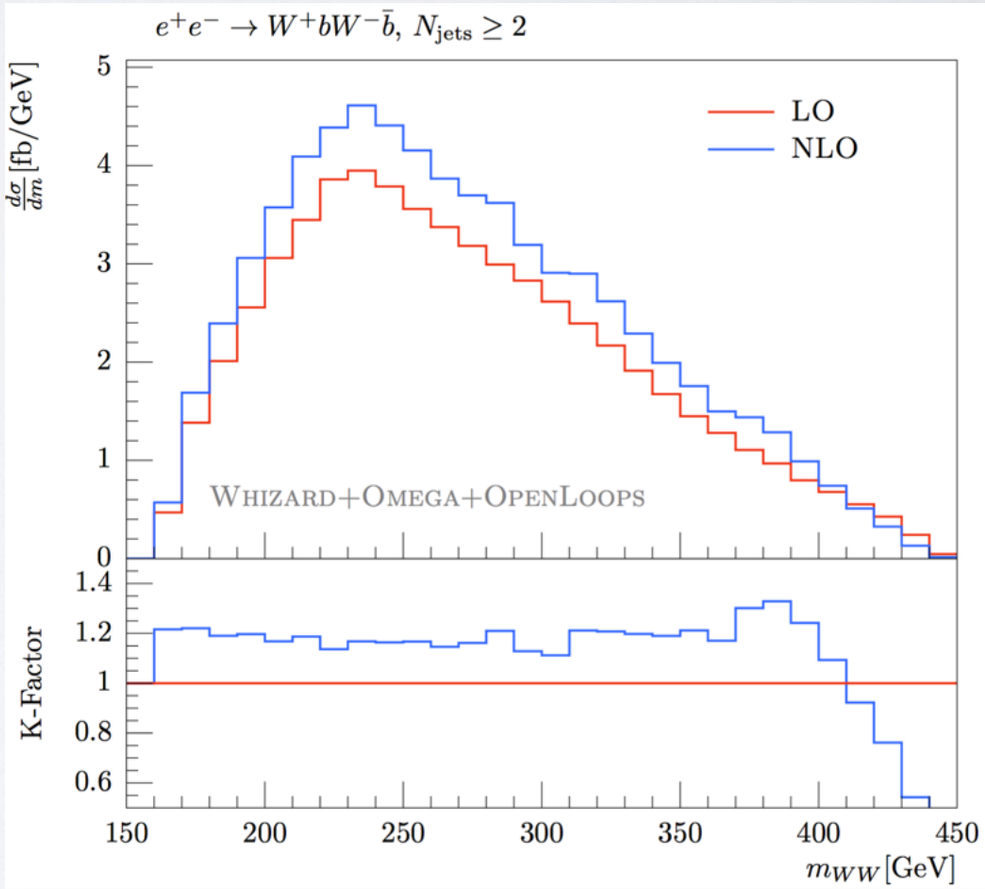

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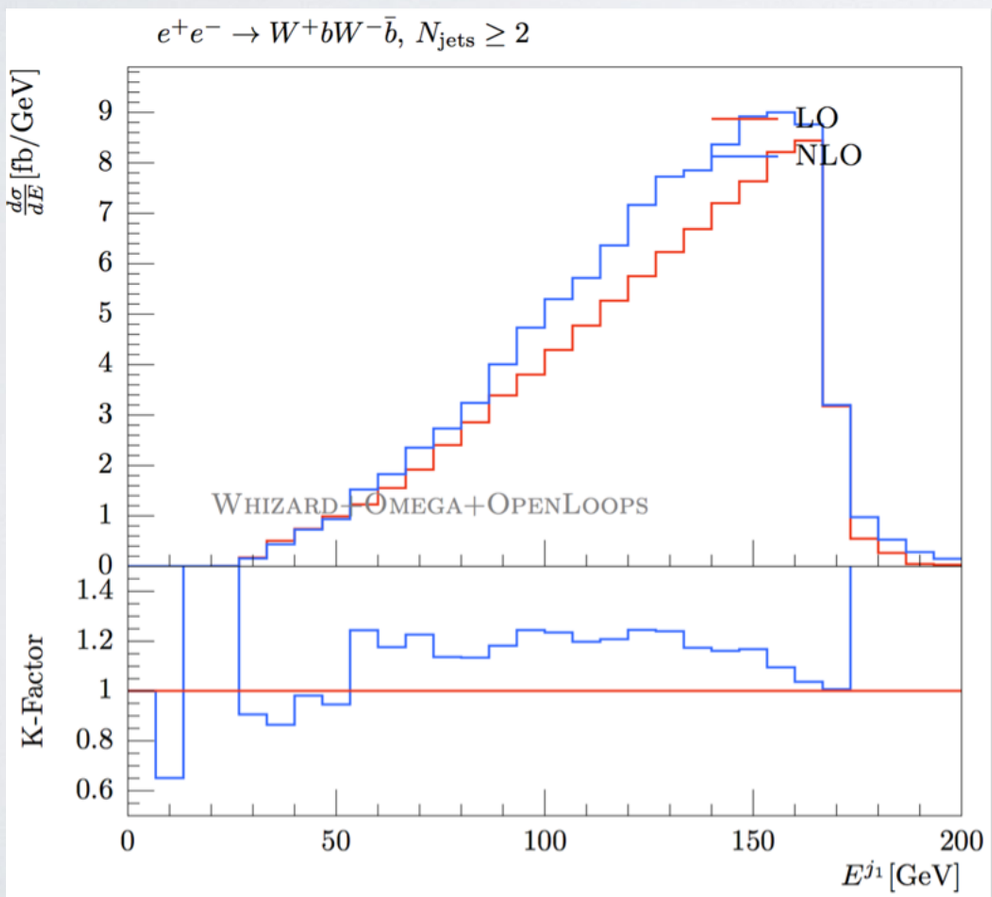
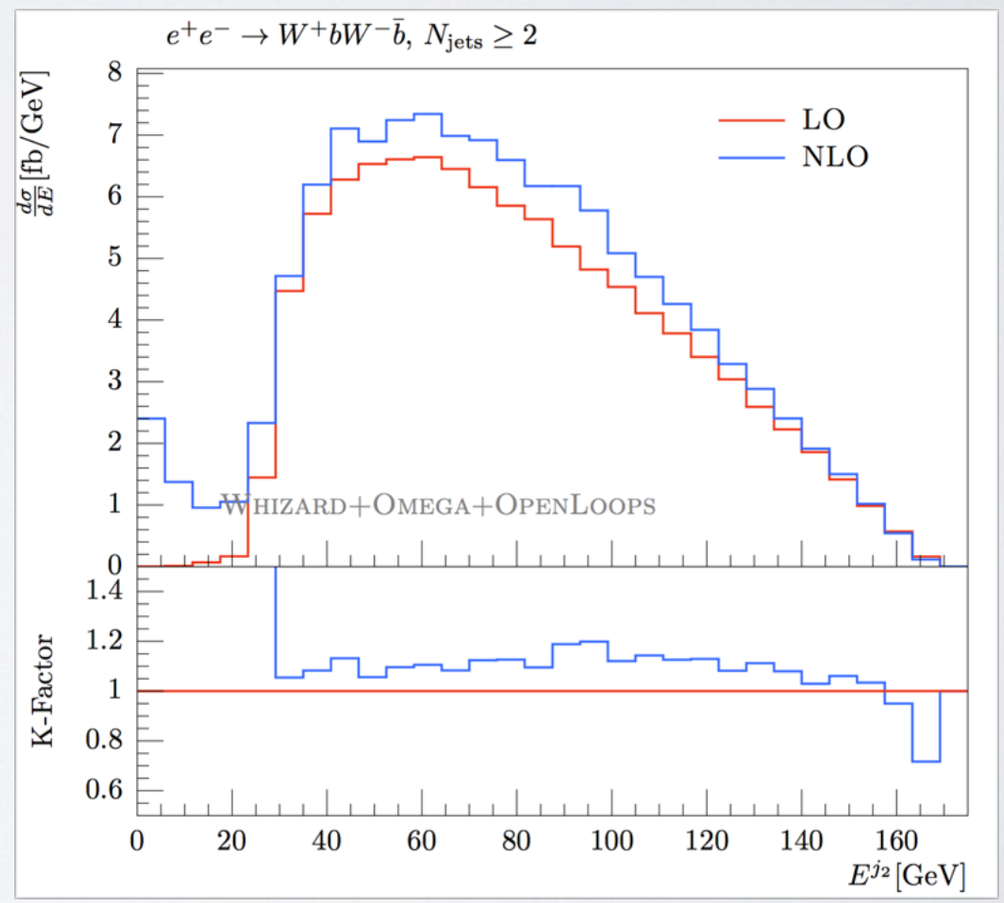




Validation of NLO QCD for e^+e^- Collisions

1 TeV

Process	MG5_aMC σ^{LO}[fb]	MG5_aMC σ^{NLO}[fb]	MG5_aMC K	WHIZARD σ^{LO}[fb]	WHIZARD σ^{NLO}[fb]	WHIZARD K
$e^+e^- \to jj$	622.3(5)	639.3(1)	1.02733	622.73(4)	639.41(9)	1.02678
$e^+e^- \to jjj$	340.1(2)	317.3(8)	0.93297	342.4(5)	318.6(7)	0.9305
$e^+e^- \to jjjj$	104.7(1)	103.7(3)	0.99045	105.1(4)	103.0(6)	0.98003
$e^+e^- \to jjjjj$	22.11(6)	24.65(4)	1.11488	22.80(2)	24.35(15)	1.06798
$e^+e^- \to jjjjjj$	N/A	N/A	N/A	3.62(2)	0.0(0)	0.0
$e^+e^- \to b\bar{b}$	92.37(6)	94.89(1)	1.02728	92.32(1)	94.78(7)	1.02664
$e^+e^- \to b\bar{b}b\bar{b}$	$1.644(3) \cdot 10^{-1}$	$3.60(1) \cdot 10^{-1}$	2.1897	$1.64(2) \cdot 10^{-1}$	$3.67(4) \cdot 10^{-1}$	2.2378
$e^+e^- \to t\bar{t}$	166.2(2)	174.5(3)	1.04994	166.4(1)	174.53(6)	1.04886
$e^+e^- \to t\bar{t}j$	48.13(5)	53.36(1)	1.10867	48.3(2)	53.25(6)	1.10248
$e^+e^- \to t\bar{t}jj$	8.614(9)	10.49(3)	1.21777	8.612(8)	10.46(6)	1.21458
$e^+e^- \to t\bar{t}jjj$	1.044(2)	1.420(4)	1.3601	1.040(1)	1.414(10)	1.3595
$e^+e^- \to t\bar{t}t\bar{t}$	$6.45(1) \cdot 10^{-4}$	$11.94(2) \cdot 10^{-4}$	1.85117	$6.463(2) \cdot 10^{-4}$	$11.91(2) \cdot 10^{-4}$	1.8428
$e^+e^- \to t\bar{t}t\bar{t}j$	$2.719(5) \cdot 10^{-5}$	$5.264(8) \cdot 10^{-5}$	1.93602	$2.722(1) \cdot 10^{-5}$	$5.250(14) \cdot 10^{-5}$	1.92873
$e^+e^- \to t\bar{t}b\bar{b}$	0.1819(3)	0.292(1)	1.60533	0.186(1)	0.293(2)	1.57527
$e^+e^- \to t\bar{t}H$	2.018(3)	1.909(3)	0.94601	2.022(3)	1.912(3)	0.9456
$e^+e^- \to t\bar{t}Hj$	$0.2533(3) \cdot 10^{-0}$	$0.2665(6) \cdot 10^{-0}$	1.05212	0.2540(9)	0.2664(5)	1.04889
$e^+e^- \to t\bar{t}Hjj$	$2.663(4) \cdot 10^{-2}$	$3.141(9) \cdot 10^{-2}$	1.1795	$2.666(4) \cdot 10^{-2}$	$3.144(9) \cdot 10^{-2}$	1.17928
$e^+e^- \to t\bar{t}\gamma$	12.7(2)	13.3(4)	1.04726	12.71(4)	13.78(4)	1.08418
$e^+e^- \to t\bar{t}Z$	4.642(6)	4.95(1)	1.06636	4.64(1)	4.94(1)	1.06467
$e^+e^- \to t\bar{t}Zj$	0.6059(6)	0.6917(24)	1.14168	0.610(4)	0.6927(14)	1.13565
$e^+e^- \to t\bar{t}Zjj$	$6.251(28) \cdot 10^{-2}$	$8.181(21) \cdot 10^{-2}$	1.30875	$6.233(8) \cdot 10^{-2}$	$8.201(14) \cdot 10^{-2}$	1.31573
$e^+e^- \to t\bar{t}W^{\pm}jj$	$2.400(4) \cdot 10^{-4}$	$3.714(8) \cdot 10^{-4}$	1.54747	$2.41(1) \cdot 10^{-4}$	$3.695(9) \cdot 10^{-4}$	1.5332
$e^+e^- \to t\bar{t}\gamma\gamma$	0.383(5)	0.416(2)	1.08618	0.382(3)	0.420(3)	1.09952
$e^+e^- \to t\bar{t}\gamma Z$	0.2212(3)	0.2364(6)	1.06873	0.220(1)	0.240(2)	1.09094
$e^+e^- \to t\bar{t}\gamma H$	$9.75(1) \cdot 10^{-2}$	$9.42(3) \cdot 10^{-2}$	0.96614	$9.748(6) \cdot 10^{-2}$	$9.58(7) \cdot 10^{-2}$	0.98277
$e^+e^- \to t\bar{t}ZZ$	$3.788(4) \cdot 10^{-2}$	$4.00(1) \cdot 10^{-2}$	1.05597	$3.756(4) \cdot 10^{-2}$	$4.005(2) \cdot 10^{-2}$	1.0663
$e^+e^- \to t\bar{t}W^+W^-$	0.1372(3)	0.1540(6)	1.1225	0.1370(4)	0.1538(4)	1.12257
$e^+e^- \to t\bar{t}HH$	$1.358(1) \cdot 10^{-2}$	$1.206(3) \cdot 10^{-2}$	0.888	$1.367(1) \cdot 10^{-2}$	$1.218(1) \cdot 10^{-2}$	0.8909
$e^+e^- \to t\bar{t}HZ$	$3.600(6) \cdot 10^{-2}$	$3.58(1) \cdot 10^{-2}$	0.99445	$3.596(1) \cdot 10^{-2}$	$3.581(2) \cdot 10^{-2}$	0.9958

Validation of NLO QCD for *pp* Collisions

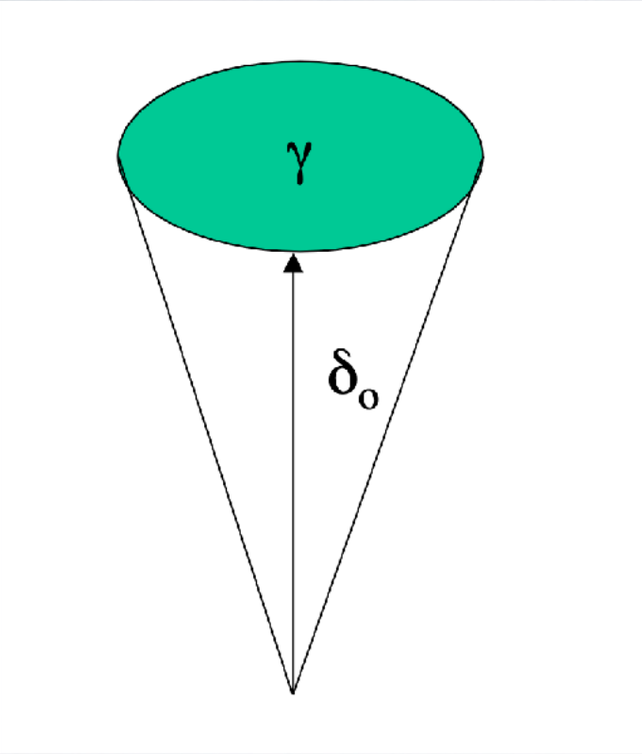
13 TeV

Process	MG5_aMC σ^{LO}[pb]	MG5_aMC σ^{NLO}[pb]	MG5_aMC K	WHIZARD σ^{LO}[pb]	WHIZARD σ^{NLO}[pb]	WHIZARD K
$pp \to jj$	$1.162(1) \cdot 10^6$	$1.580(7) \cdot 10^6$	1.36	$1.157(2) \cdot 10^6$	$1.604(7) \cdot 10^6$	1.39
$pp \to jjj$	$8.940(21) \cdot 10^4$	$7.62(2) \cdot 10^4$	0.85	$8.921(47) \cdot 10^4$	$7.46(9) \cdot 10^4$	0.84
$pp \to Z$	$4.248(5) \cdot 10^4$	$5.410(22) \cdot 10^4$	1.27	$4.2536(3) \cdot 10^4$	$5.4067(2) \cdot 10^4$	1.27
$pp \to Zj$	$7.209(5) \cdot 10^3$	$9.745(32) \cdot 10^3$	1.35	$7.207(2) \cdot 10^3$	$9.720(17) \cdot 10^3$	1.35
$pp \to Zjj$	$2.348(6) \cdot 10^3$	$2.684(5) \cdot 10^3$	1.14	$2.352(8) \cdot 10^3$	$2.735(9) \cdot 10^3$	1.16
$pp \to W^\pm$	$1.375(2) \cdot 10^5$	$1.773(7) \cdot 10^5$	1.29	$1.3750(5) \cdot 10^5$	$1.7696(9) \cdot 10^5$	1.29
$pp \to W^\pm j$	$2.045(1) \cdot 10^4$	$2.839(9) \cdot 10^4$	1.39	$2.043(1) \cdot 10^4$	$2.845(6) \cdot 10^4$	1.39
$pp \to W^\pm jj$	$6.805(15) \cdot 10^3$	$7.780(13) \cdot 10^3$	1.14	$6.798(7) \cdot 10^3$	$7.93(3) \cdot 10^3$	1.17
$pp \to HZ$	$6.646(8) \cdot 10^{-1}$	$7.69(2) \cdot 10^{-1}$	1.16	$6.47(1) \cdot 10^{-1}$	$7.68(1) \cdot 10^{-1}$	1.19
$pp \to ZZ$	$1.097(3) \cdot 10^1$	$1.4190(25) \cdot 10^1$	1.29	$1.094(2) \cdot 10^1$	$1.4192(32) \cdot 10^1$	1.3
$pp \to ZZj$	$3.662(3) \cdot 10^0$	$4.830(16) \cdot 10^0$	1.32	$3.659(2) \cdot 10^0$	$4.820(11) \cdot 10^0$	1.32
$pp \to ZZjj$	$1.344(2) \cdot 10^0$	$1.678(3) \cdot 10^0$	1.25	$1.356(5) \cdot 10^0$	$1.684(8) \cdot 10^0$	1.24
$pp \to ZW^\pm$	$2.777(3) \cdot 10^1$	$4.485(12) \cdot 10^1$	1.62	$2.775(2) \cdot 10^1$	$4.488(4) \cdot 10^1$	1.62
$pp \to ZW^\pm j$	$1.605(5) \cdot 10^1$	$2.100(5) \cdot 10^1$	1.31	$1.604(6) \cdot 10^1$	$2.103(4) \cdot 10^1$	1.31
$pp \to W^+W^{-*}$	$0.7355(5) \cdot 10^2$	$1.028(3) \cdot 10^2$	1.4	$0.7349(7) \cdot 10^2$	$1.027(1) \cdot 10^2$	1.4
$pp \to W^+W^-j^*$	$2.865(3) \cdot 10^1$	$3.730(13) \cdot 10^1$	1.3	$2.868(1) \cdot 10^1$	$3.733(8) \cdot 10^1$	1.3
$pp \to W^+W^-jj^*$	$1.144(2) \cdot 10^1$	$1.387(2) \cdot 10^1$	1.21	$1.139(5) \cdot 10^1$	$1.372(6) \cdot 10^1$	1.2
$pp \to W^+W^+jj$	$1.484(3) \cdot 10^{-1}$	$2.251(11) \cdot 10^{-1}$	1.52	$1.483(4) \cdot 10^{-1}$	$2.238(6) \cdot 10^{-1}$	1.51
$pp \to W^-W^-jj$	$6.752(7) \cdot 10^{-2}$	$9.99(1) \cdot 10^{-2}$	1.48	$6.755(4) \cdot 10^{-1}$	$9.97(3) \cdot 10^{-1}$	1.48
$pp \to W^+W^-W^{\pm *}$	$1.307(3) \cdot 10^{-1}$	$2.111(4) \cdot 10^{-1}$	1.62	$1.309(1) \cdot 10^{-1}$	$2.117(2) \cdot 10^{-1}$	1.62
$pp \to W^+W^-W^\pm j^*$	$9.17(1) \cdot 10^{-2}$	$1.200(4) \cdot 10^{-2}$	0.13	$9.18(3) \cdot 10^{-2}$	$1.198(3) \cdot 10^{-2}$	0.13
$pp \to ZW^+W^{-*}$	$0.966(7) \cdot 10^{-1}$	$1.679(5) \cdot 10^{-1}$	1.74	$0.966(2) \cdot 10^{-1}$	$1.682(2) \cdot 10^{-1}$	1.74
$pp \to ZZW^\pm$	$2.996(16) \cdot 10^{-2}$	$5.63(1) \cdot 10^{-2}$	1.88	$3.062(6) \cdot 10^{-2}$	$5.615(6) \cdot 10^{-2}$	1.83
$pp \to ZZZ$	$1.085(2) \cdot 10^{-2}$	$1.431(5) \cdot 10^{-2}$	1.32	$1.084(2) \cdot 10^{-2}$	$1.430(2) \cdot 10^{-2}$	1.32
$pp \to W^+W^-W^\pm Z^*$	$0.639(8) \cdot 10^{-3}$	$1.230(3) \cdot 10^{-3}$	1.92	$0.642(2) \cdot 10^{-3}$	$1.240(2) \cdot 10^{-3}$	1.93
$pp \to W^\pm ZZZ$	$0.586(1) \cdot 10^{-5}$	$1.240(4) \cdot 10^{-5}$	2.12	$0.588(2) \cdot 10^{-5}$	$1.229(2) \cdot 10^{-5}$	2.09
$pp \to t\bar{t}$	$4.584(3) \cdot 10^2$	$6.746(14) \cdot 10^2$	1.47	$4.588(2) \cdot 10^2$	$6.740(9) \cdot 10^2$	1.47
$pp \to t\bar{t}j$	$3.135(2) \cdot 10^2$	$4.095(8) \cdot 10^2$	1.31	$3.131(3) \cdot 10^2$	$4.194(9) \cdot 10^2$	1.34
$pp \to t\bar{t}jj$	$1.361(1) \cdot 10^2$	$1.784(3) \cdot 10^2$	1.31	$1.360(4) \cdot 10^2$	$1.775(7) \cdot 10^2$	1.31
$pp \to t\bar{t}t\bar{t}$	$4.505(5) \cdot 10^{-3}$	$9.076(13) \cdot 10^{-3}$	2.01	$4.511(2) \cdot 10^{-3}$	$9.070(9) \cdot 10^{-3}$	2.01
$pp \to t\bar{t}Z$	$5.273(4) \cdot 10^{-1}$	$7.625(25) \cdot 10^{-1}$	1.45	$5.281(8) \cdot 10^{-1}$	$7.639(9) \cdot 10^{-1}$	1.45
$pp \to t\bar{t}Zj$	$3.953(4) \cdot 10^{-1}$	$5.08(1) \cdot 10^{-1}$	1.29	$3.95(1) \cdot 10^{-1}$	$5.07(2) \cdot 10^{-1}$	1.28
$pp \to t\bar{t}W^\pm$	$3.777(3) \cdot 10^{-1}$	$5.67(2) \cdot 10^{-1}$	1.5	$3.775(5) \cdot 10^{-1}$	$5.674(5) \cdot 10^{-1}$	1.5
$pp \to t\bar{t}W^\pm j$	$2.352(2) \cdot 10^{-1}$	$3.434(8) \cdot 10^{-1}$	1.46	$2.356(7) \cdot 10^{-1}$	$3.436(7) \cdot 10^{-1}$	1.46
$pp \to t\bar{t}ZZ$	$1.349(14) \cdot 10^{-3}$	$1.843(4) \cdot 10^{-3}$	1.37	$1.359(3) \cdot 10^{-3}$	$1.842(3) \cdot 10^{-3}$	1.36

Photon isolation in WHIZARD

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

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



R distance (photon-parton): $R_{i\gamma} = \sqrt{\Delta\eta_{i\gamma}^2 + \Delta\phi_{i\gamma}^2}$

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

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

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

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

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

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

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

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

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

b and *c* jet clustering

b-jet selection
c-jet selection

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

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

jet_algorithm = antikt_algorithm
jet_r = 0.5

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

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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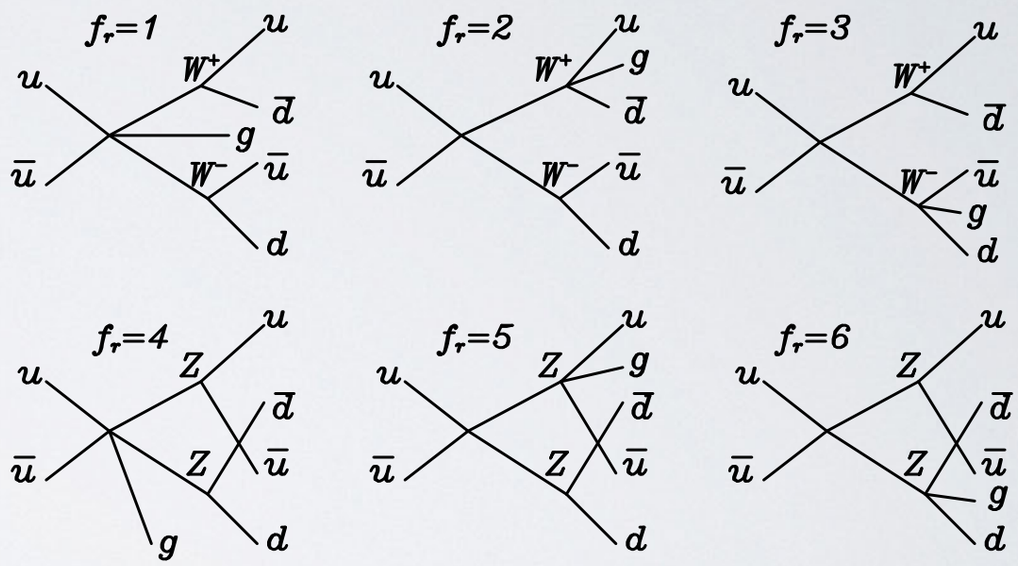

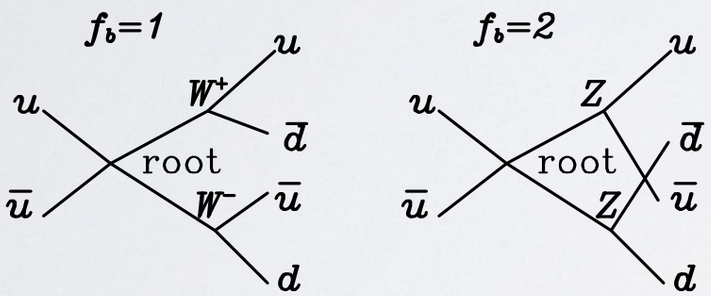

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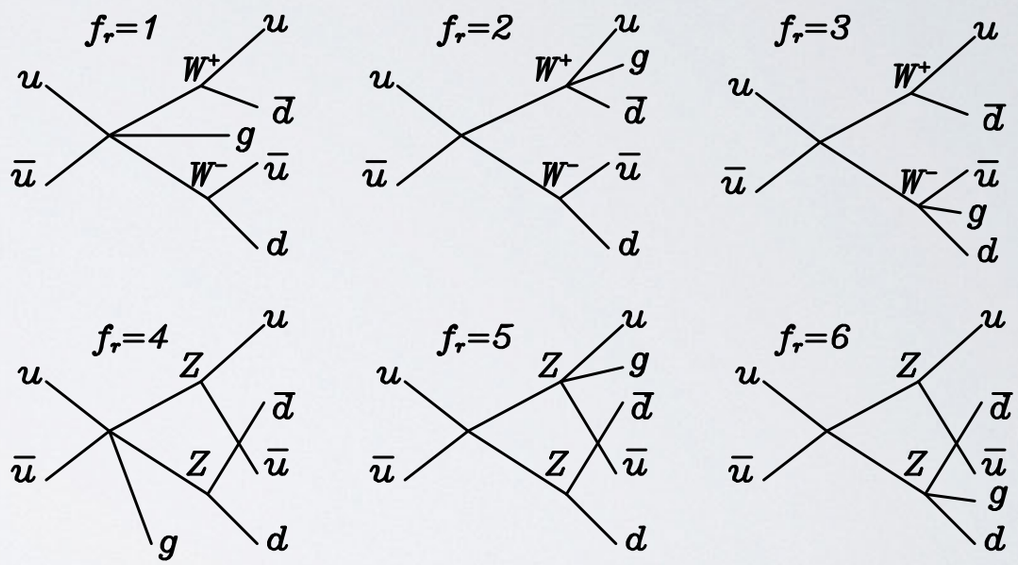

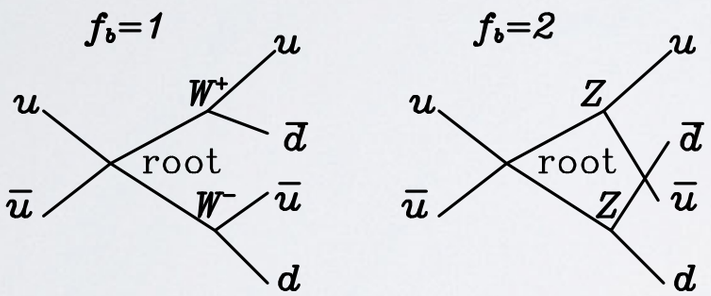

- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (ZZ, ZH histories)

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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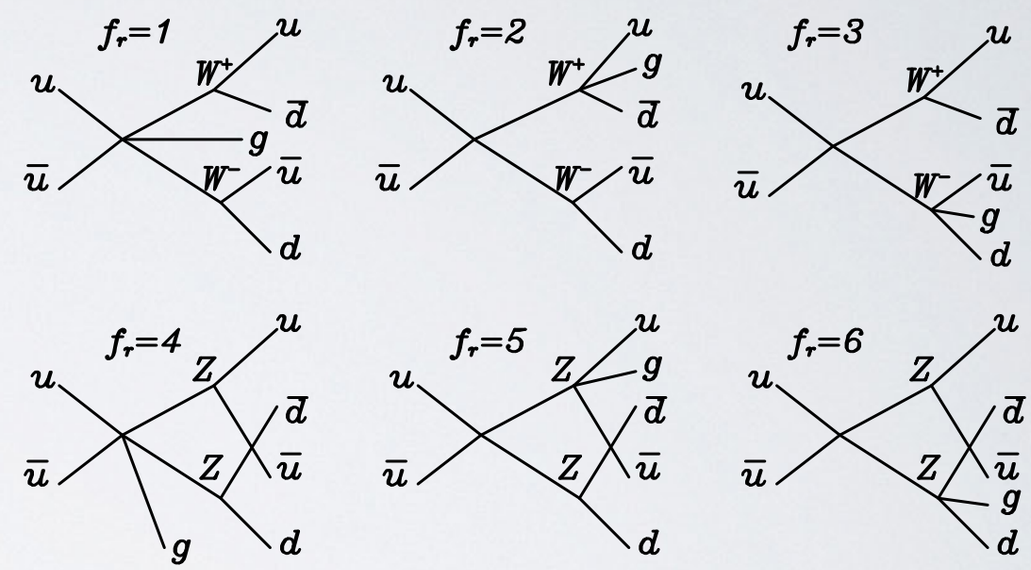

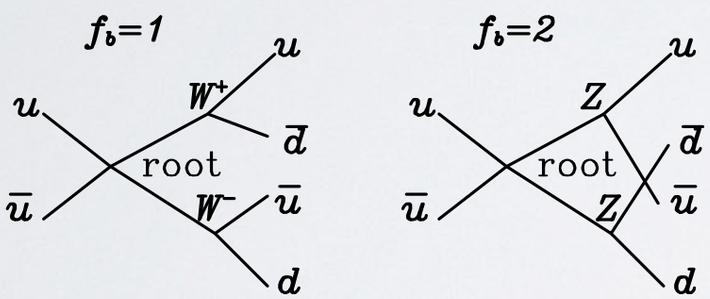

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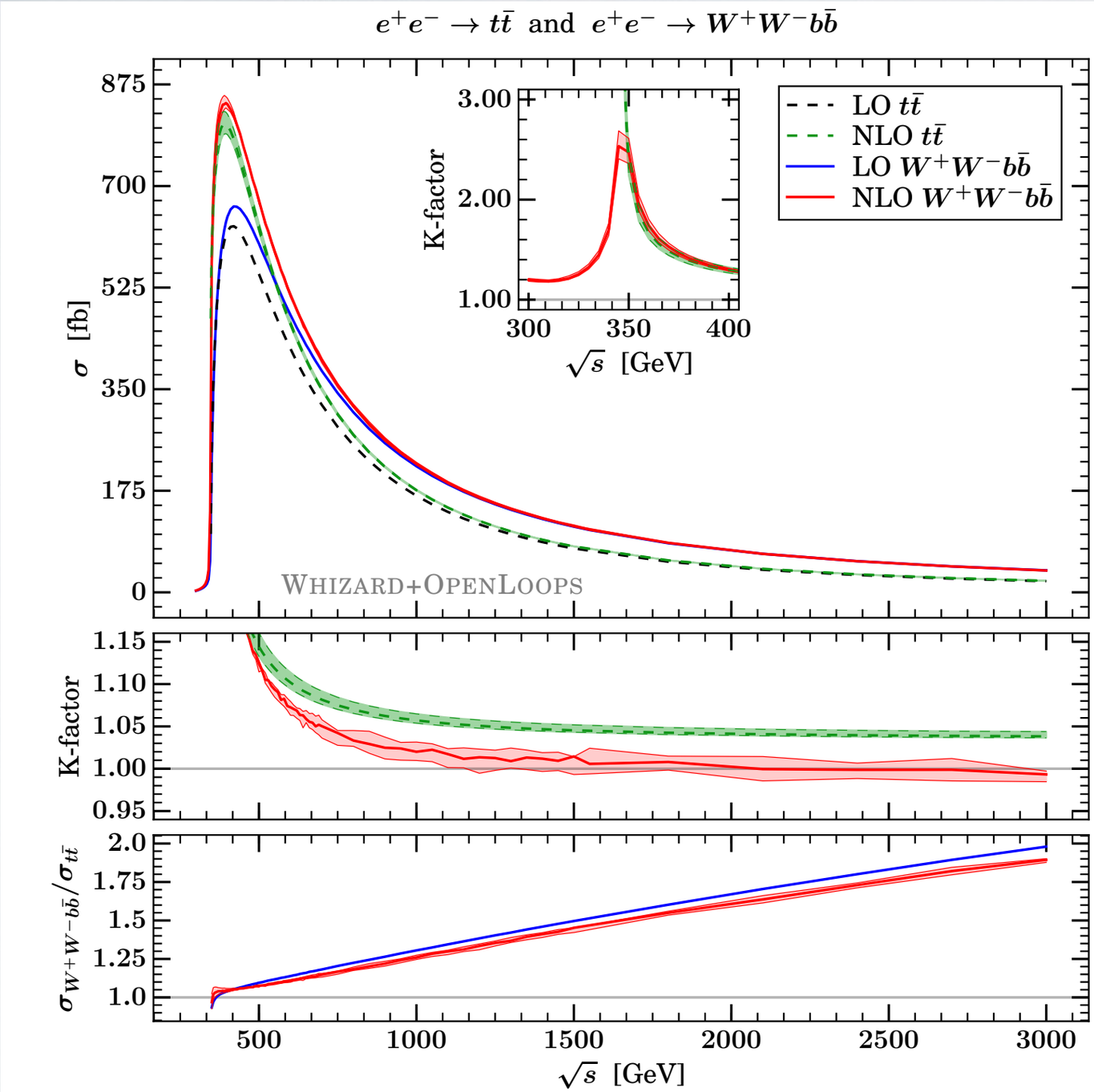
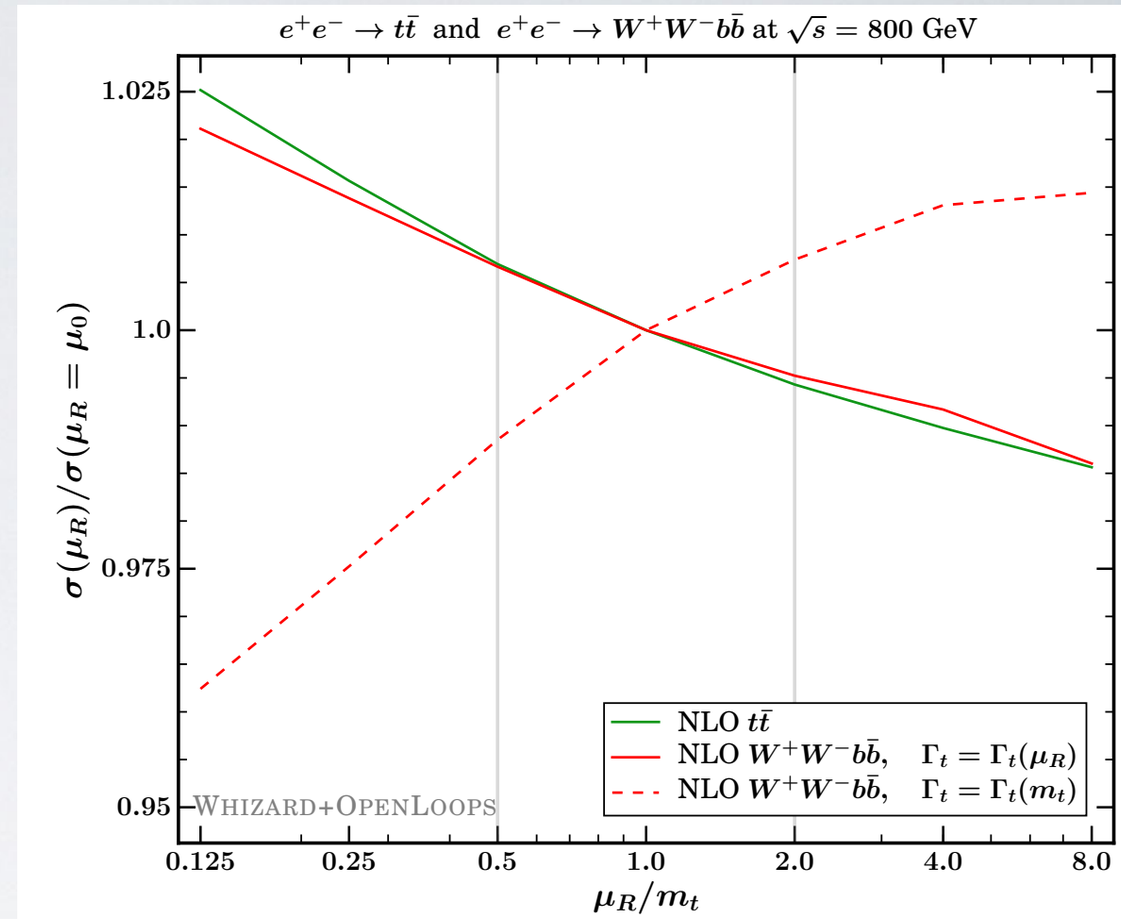
1	11988	2.9057032E+00	8.35E-02	2.87	3.15*	7.90		
2	11962	2.8591952E+00	5.20E-02	1.82	1.99*	10.91		
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	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
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Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

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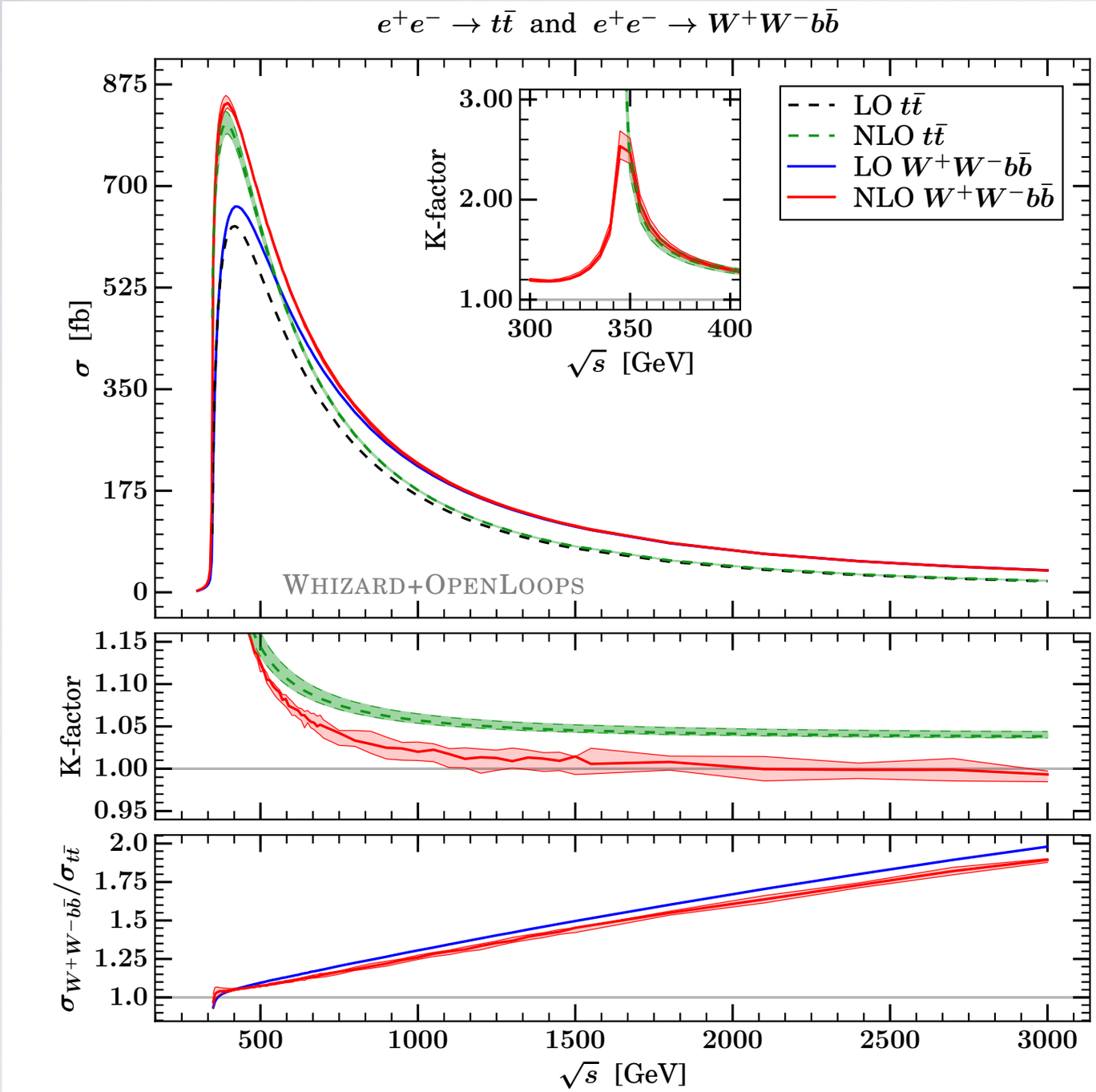

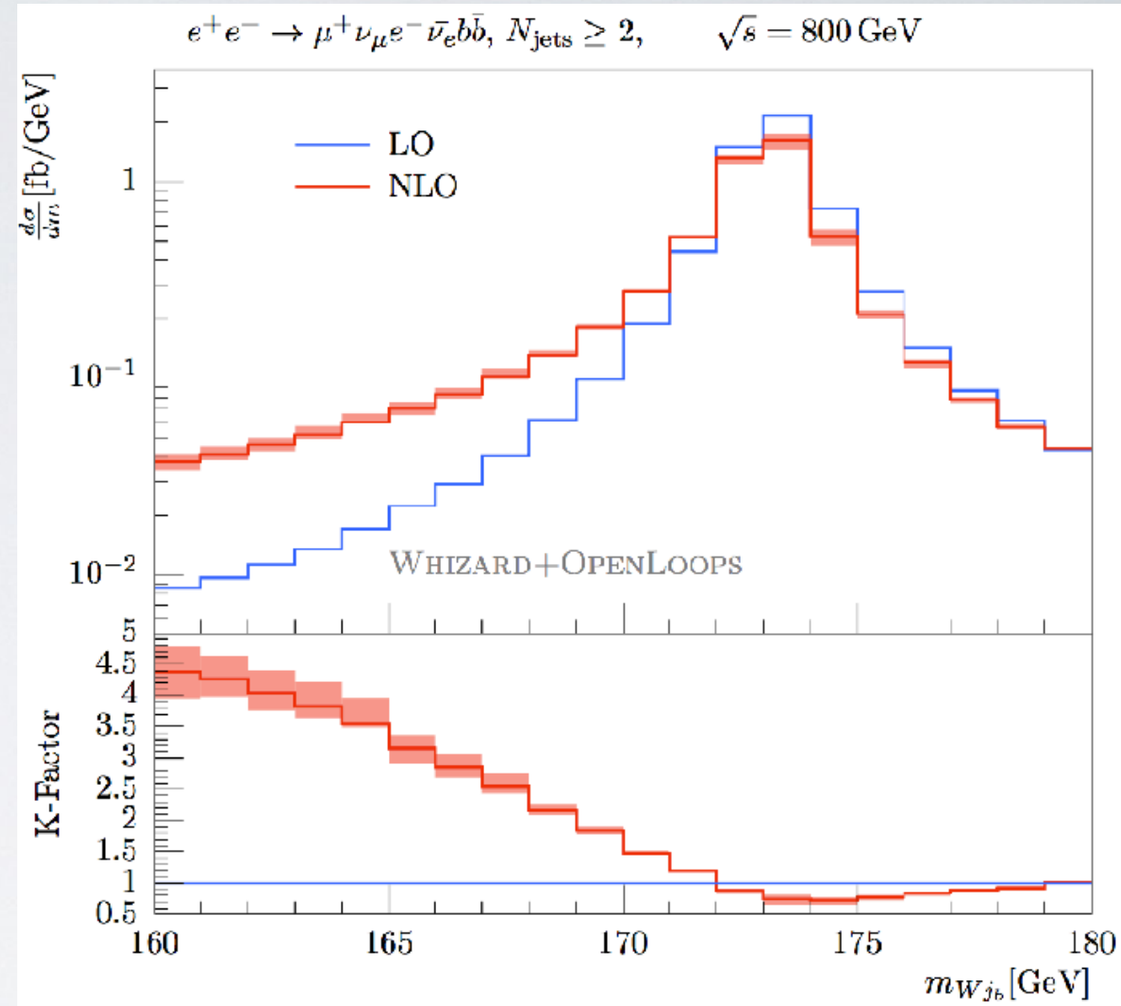

	$e^+e^- \to t\bar{t}$			$e^+e^- \to W^+W^-b\bar{b}$		
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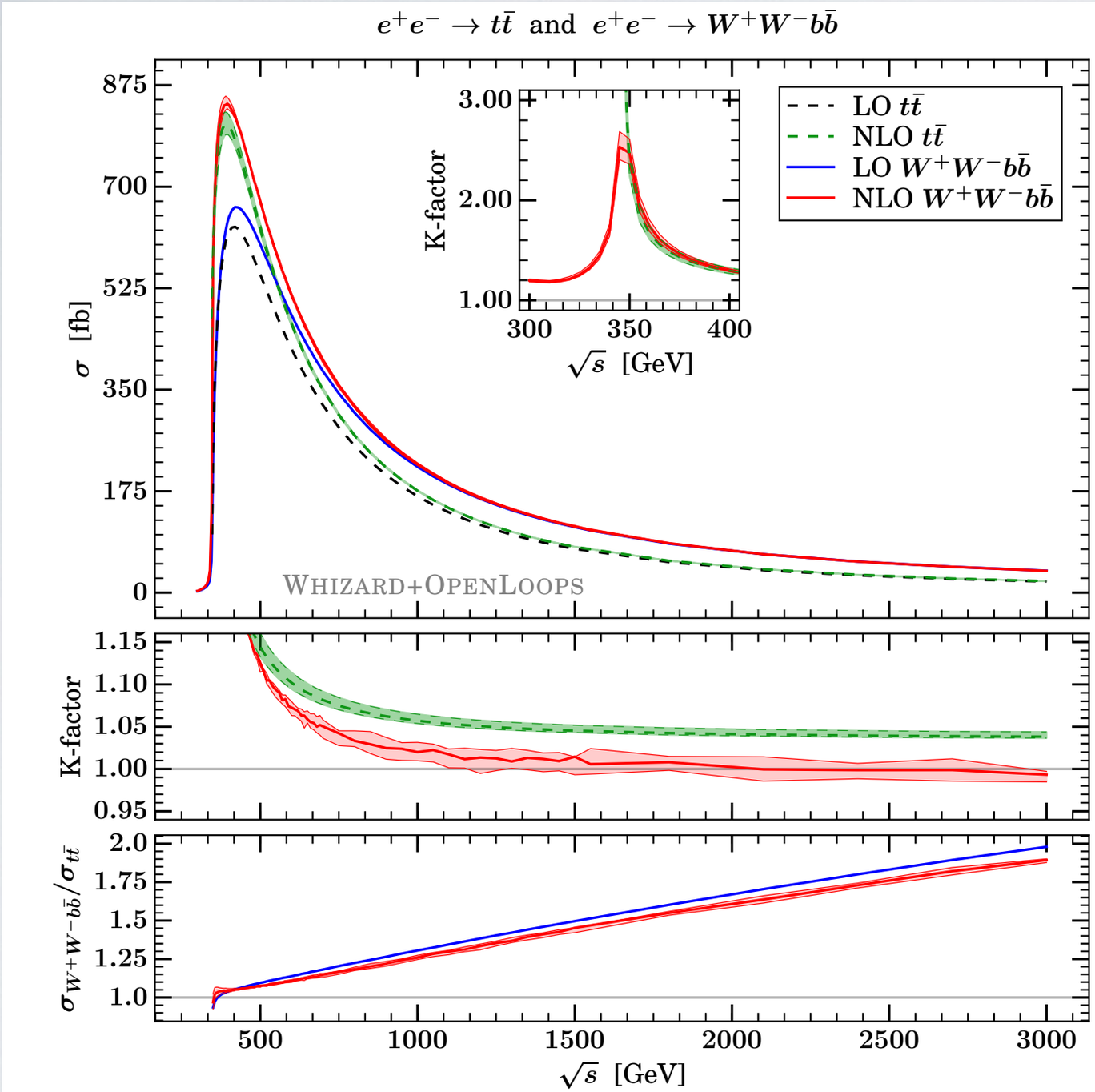

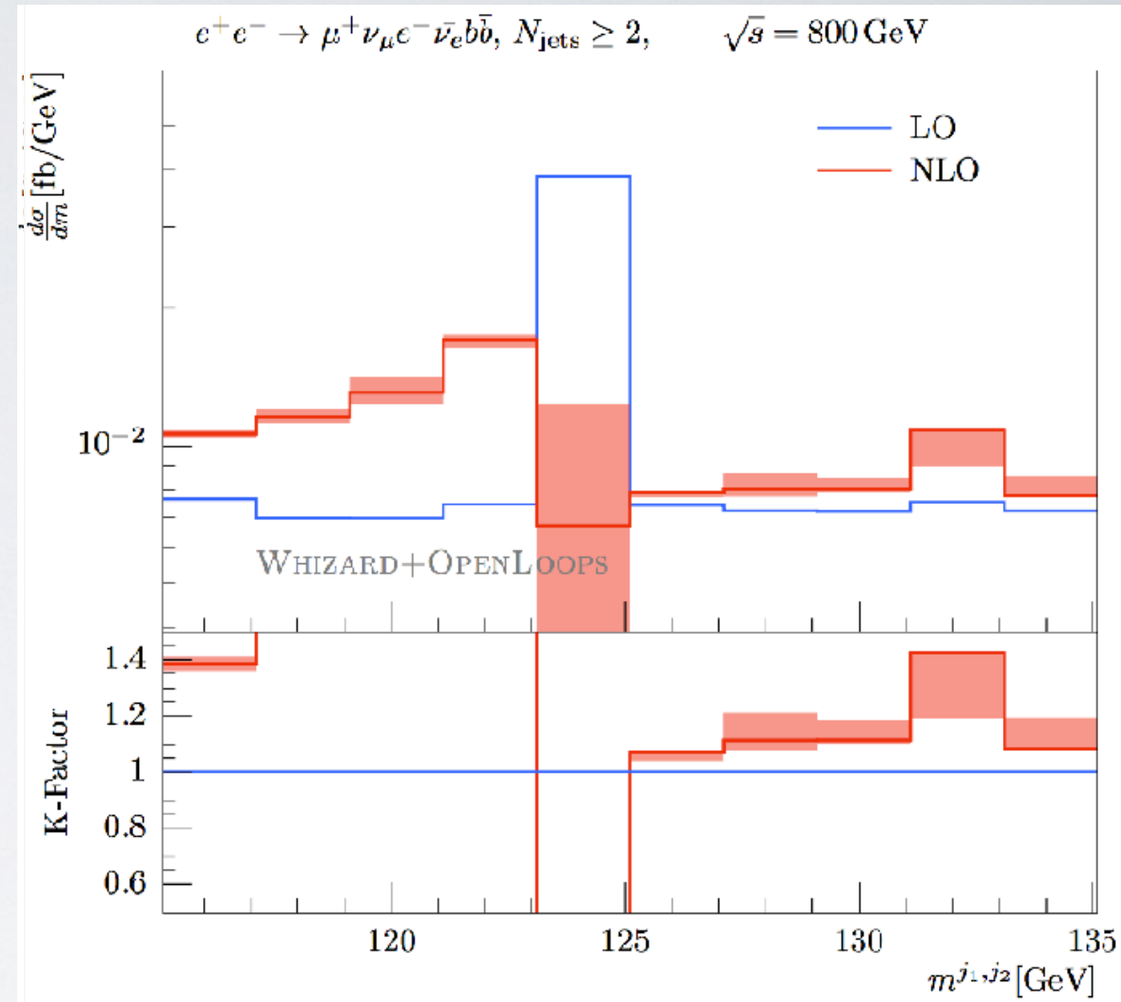

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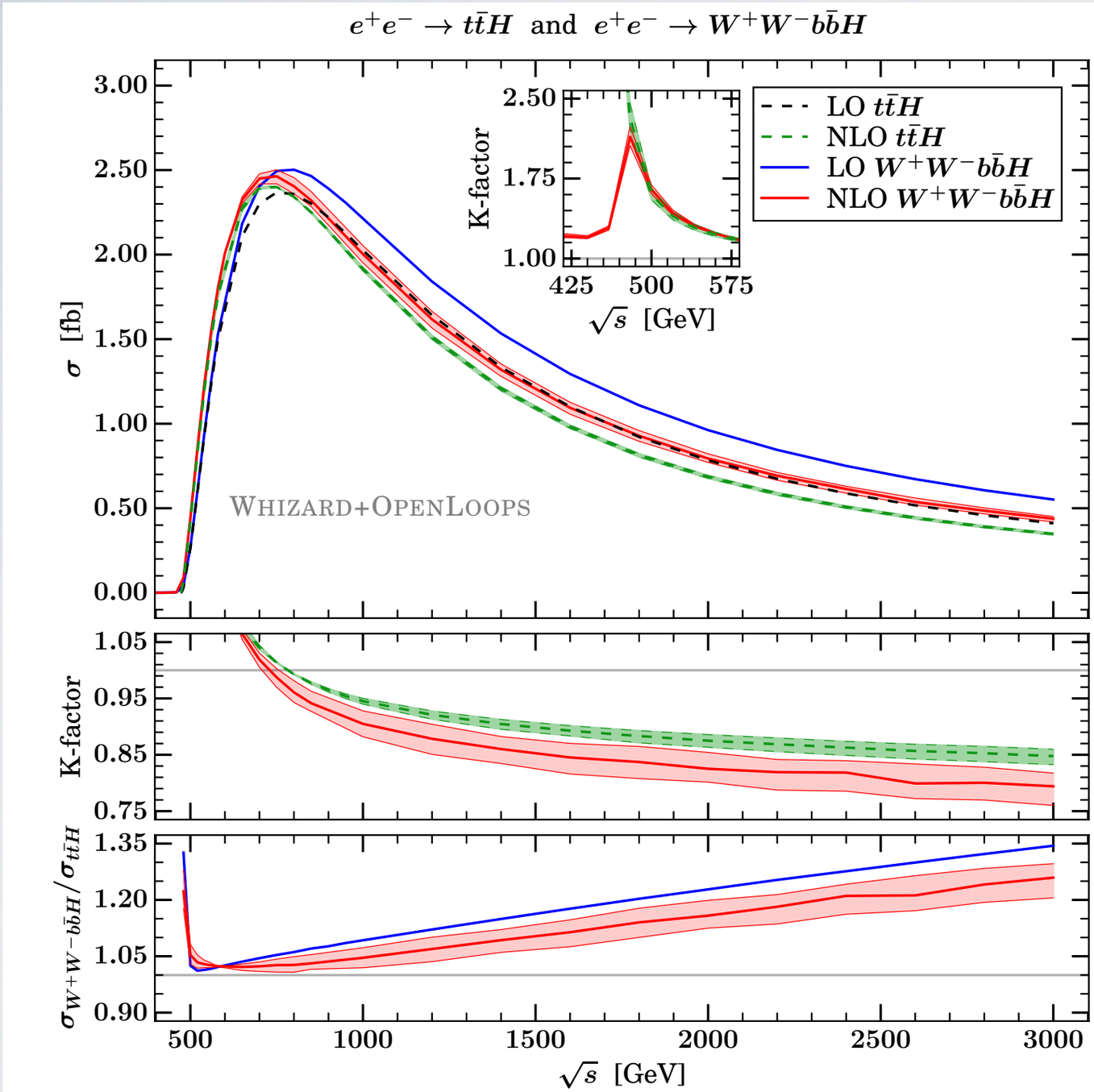
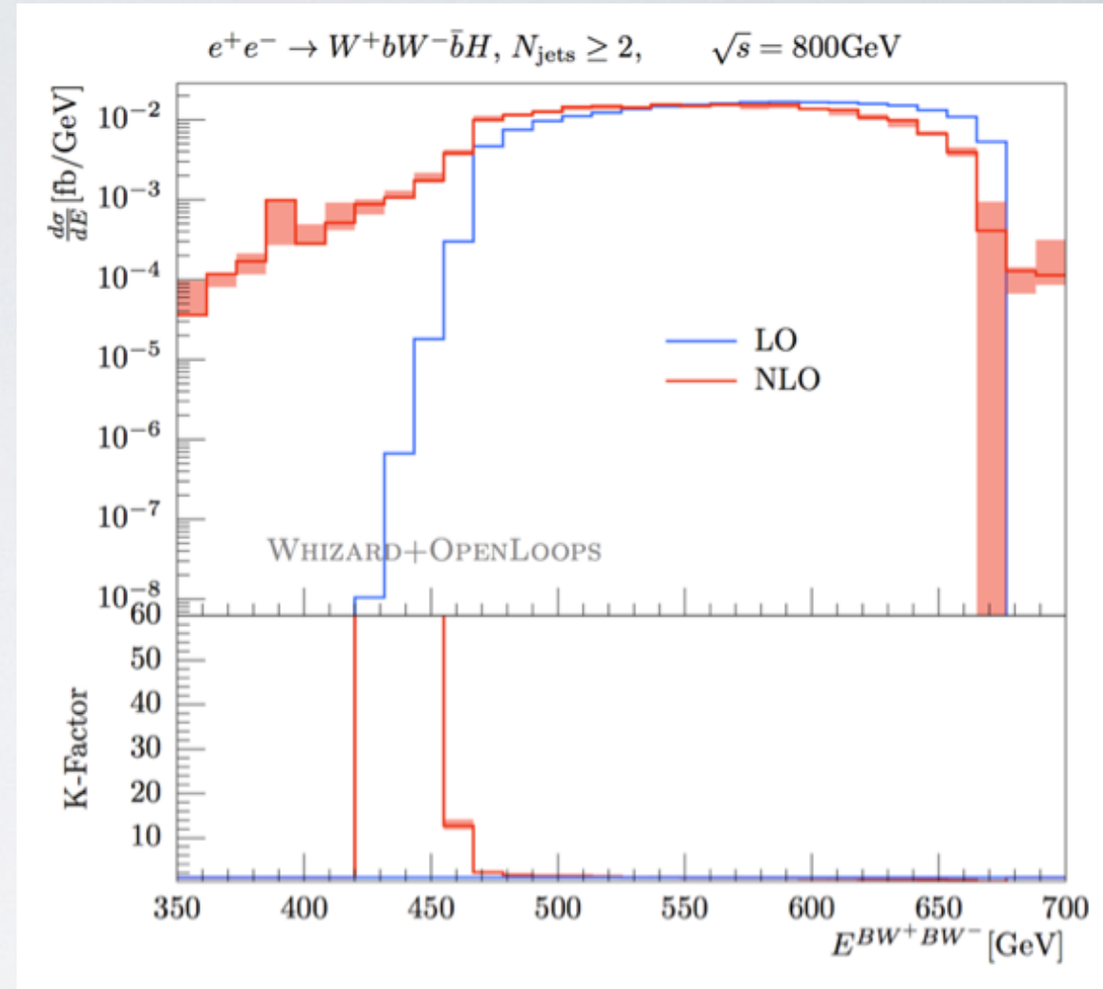
NLO QCD Results for off-shell $e^+e^- \to ttH$





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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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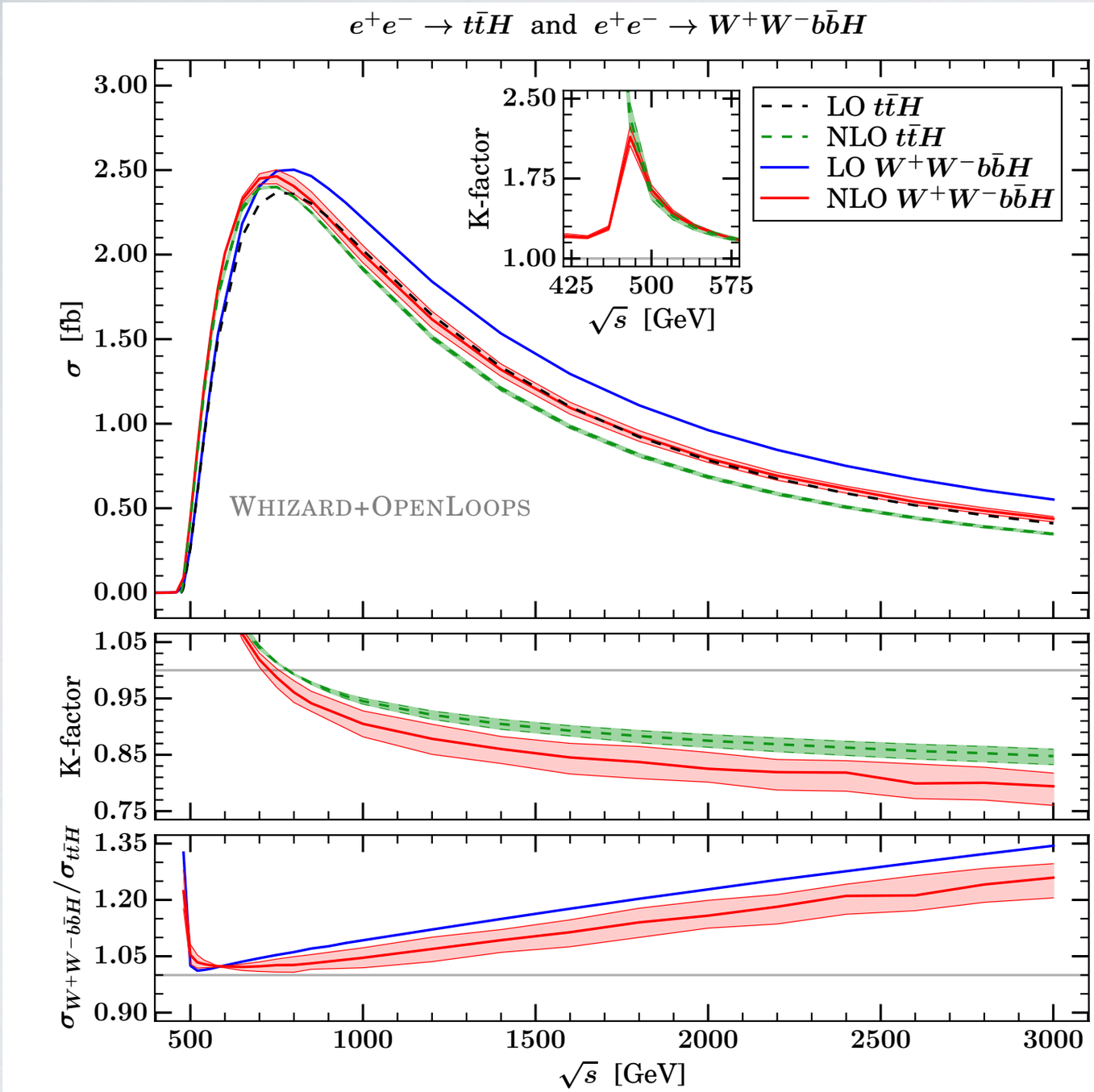

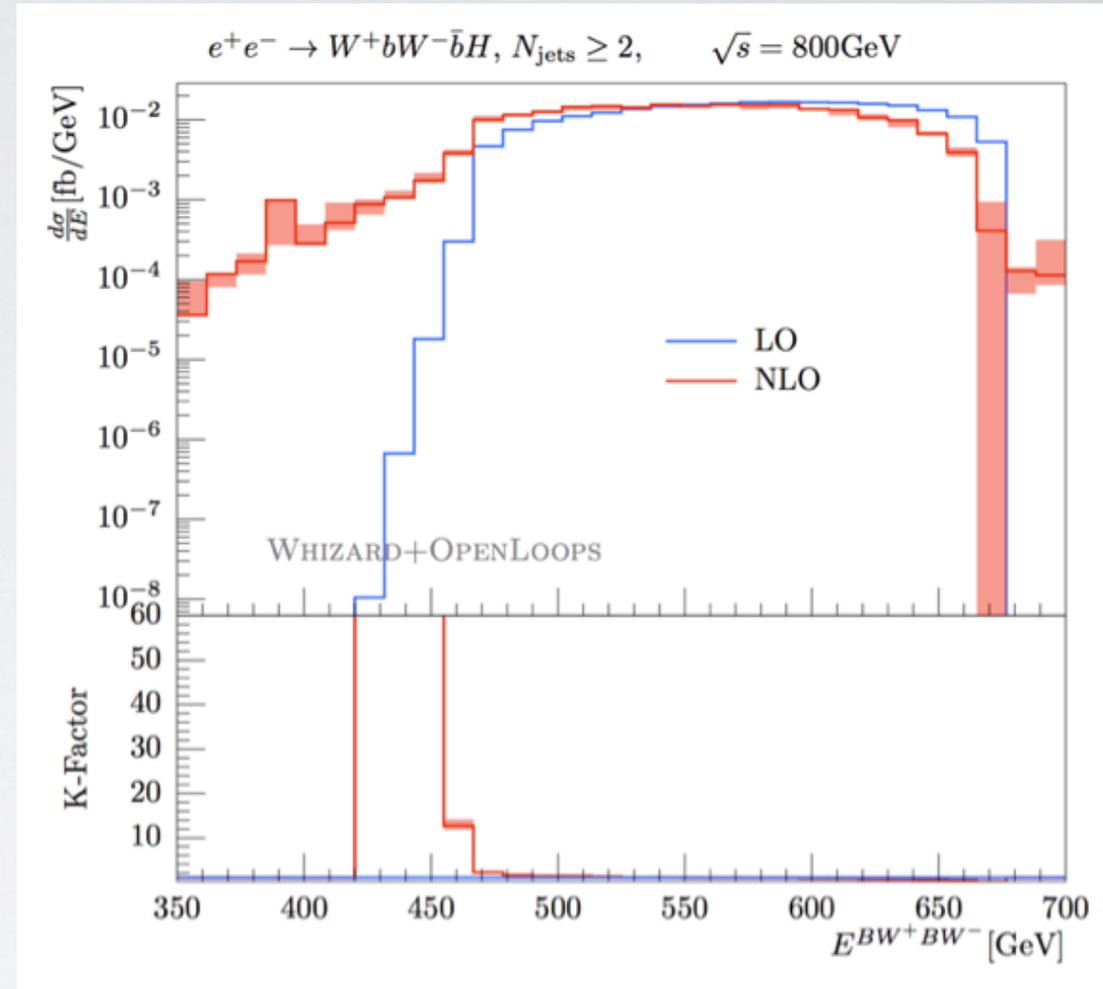

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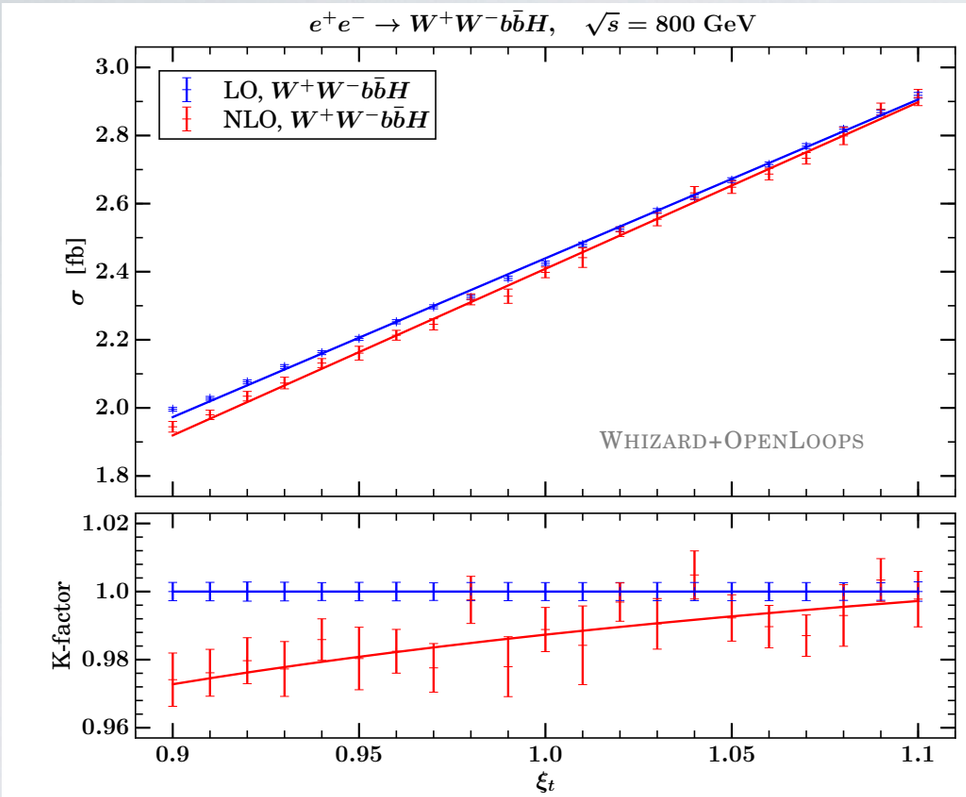
Chokoufé/Kilian/Lindert/Pozzorini/JRR/Weiss, 1609.03390

Determination of Top-Yukawa coupling

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

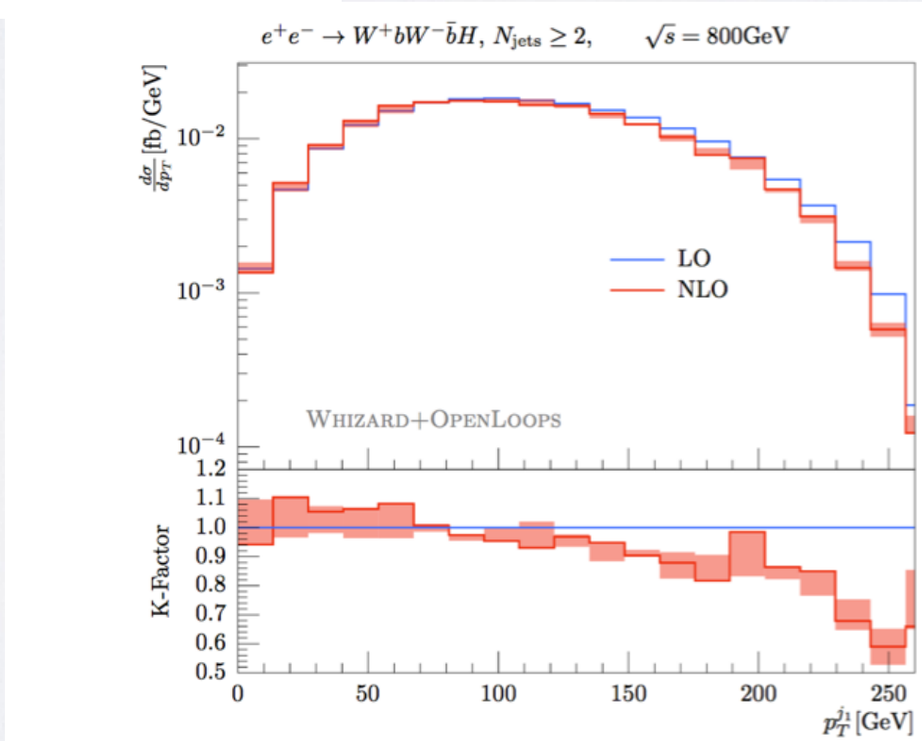


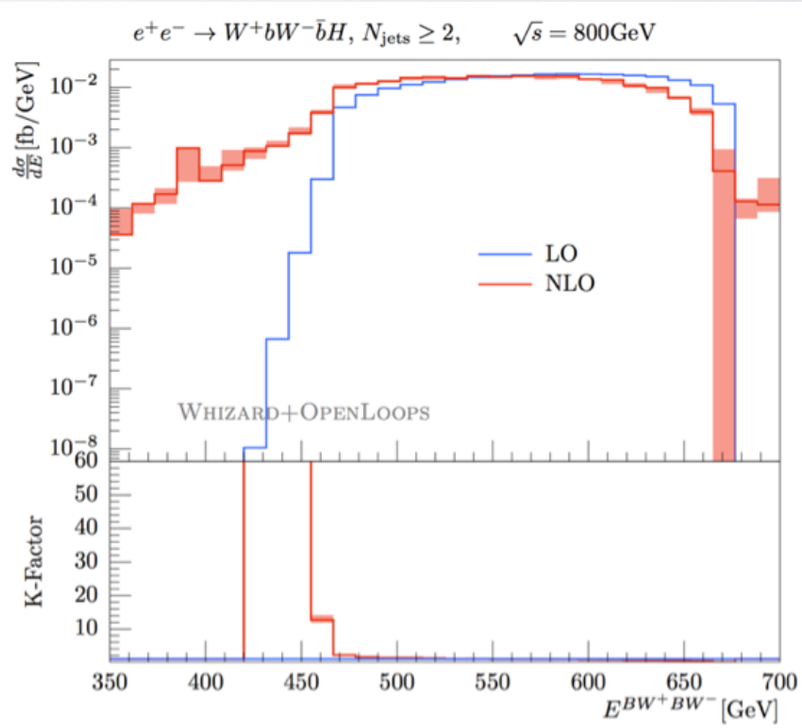
SM signal-strength / coupling modifier:

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

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

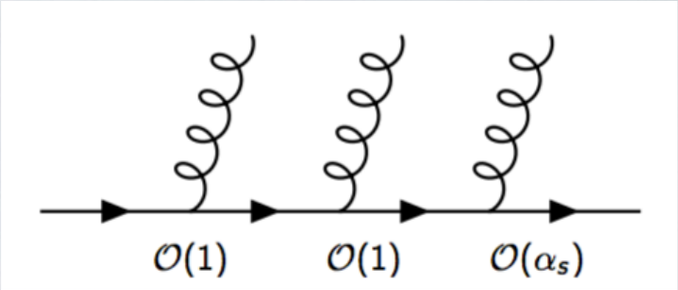
cf. also CLIC Top Report, 1807.02441





Automated POWHEG Matching in WHIZARD

- Soft gluon emissions before hard emission generate large logs
- Consistent matching of NLO matrix element with shower
- POWHEG method: hardest emission first [Nason et al.]



- Complete NLO events

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\rm rad} R(\Phi_{n+1})$$

- POWHEG generate events according to the formula:

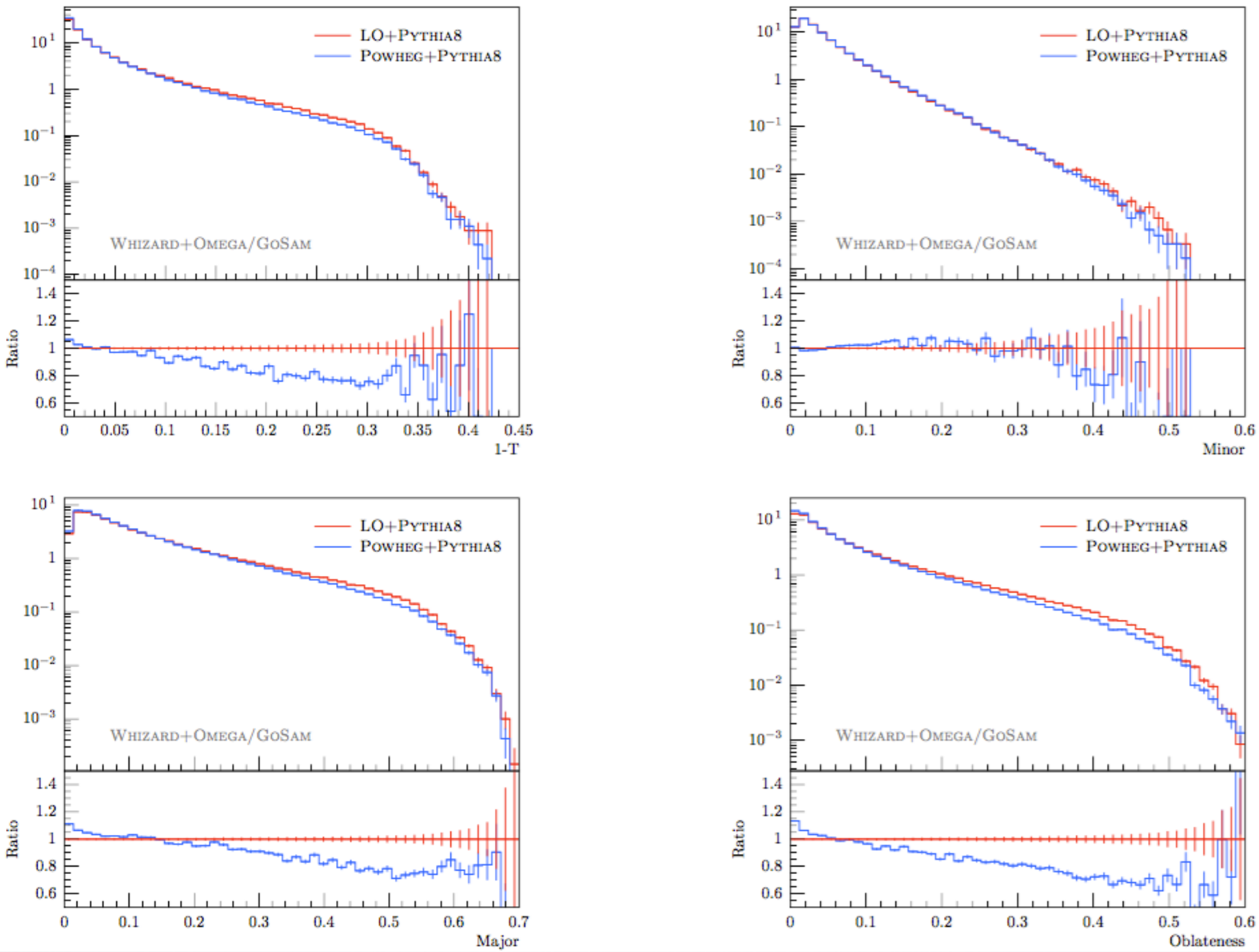
$$d\sigma = \overline{B}(\Phi_n)\left[\Delta_R^{\rm NLO}(k_T^{\rm min}) + \Delta_R^{\rm NLO}(k_T)\frac{R(\Phi_{n+1})}{B(\Phi_n)}d\Phi_{\rm rad}\right]$$

- Uses the modified Sudakov form factor

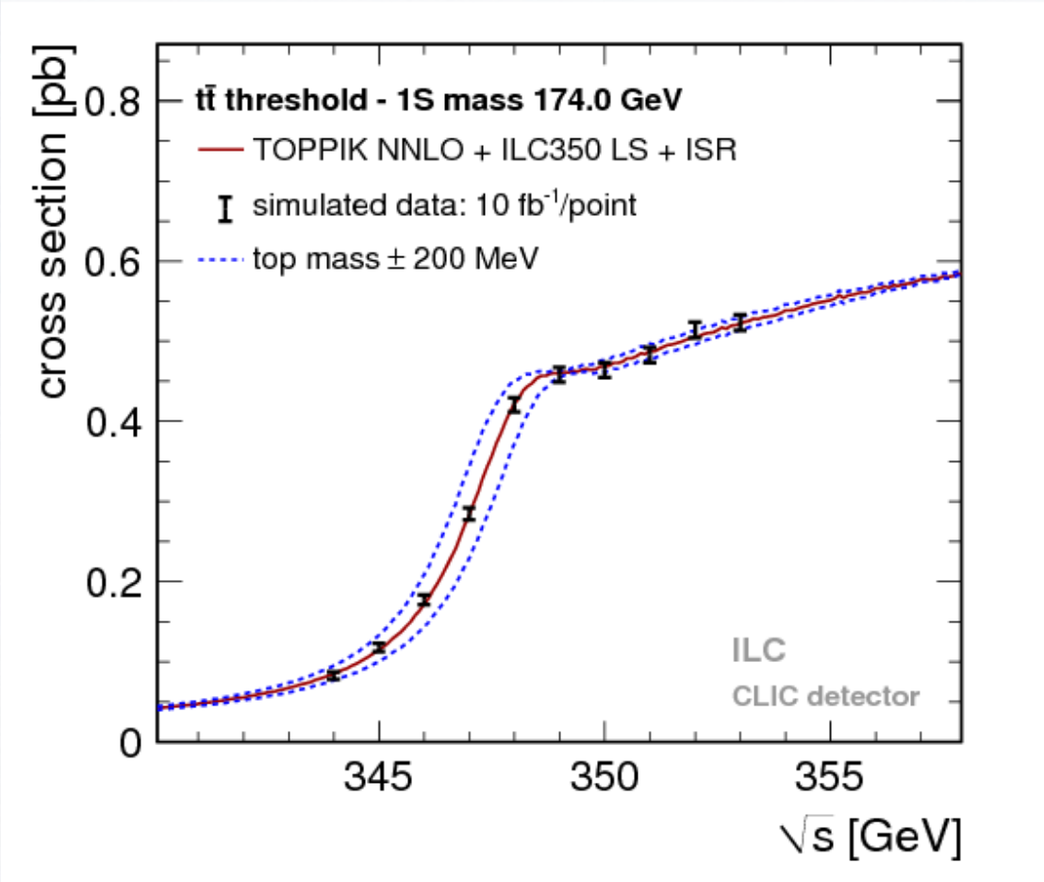
```
$loop_me_method = "openloops"
?alphas_is_fixed = false
?alphas_from_mz = true
?alphas_from_lambda_qcd = false

alpha_power = 2
alphas_power = 0

?combined_nlo_integration = true

?powheg_matching = true
powheg_grid_size_xi = 5
powheg_grid_size_y = 5
powheg_grid_sampling_points = 1000000
powheg_pt_min = 1
?powheg_use_singular_jacobian = false

scale = 2 * mtop

jet_algorithm = antikt_algorithm
jet_r = 1
```

```
process nlo_tt_powheg = E1, e1 => t, T { nlo_calculation = full }

sqrts = 500 GeV

integrate (nlo_tt_powheg)  {iterations = 5:50000:"gw", 5:50000:""}

y_min = 1
y_max = n_events
histogram Pt_j1 (0 GeV, 200 GeV, 10 GeV)
histogram E_g (0 GeV, 30 GeV, 1 GeV)

analysis = let subevt @clustered_jets = cluster [colored] in
           let subevt @Eselected_jets = select if (E > 1 GeV)
                   [@clustered_jets] in
           let subevt @jetsbypt = sort by -Pt [@Eselected_jets] in
           record Pt_j1 (eval Pt [extract index 1 [@jetsbypt]])
      and  record E_g (eval E [g])

$sample = "nlo_tt_powheg"

simulate (nlo_tt_powheg)   {  n_events = 20000 }
```

POWHEG Matching, example: e^+e^- to dijets



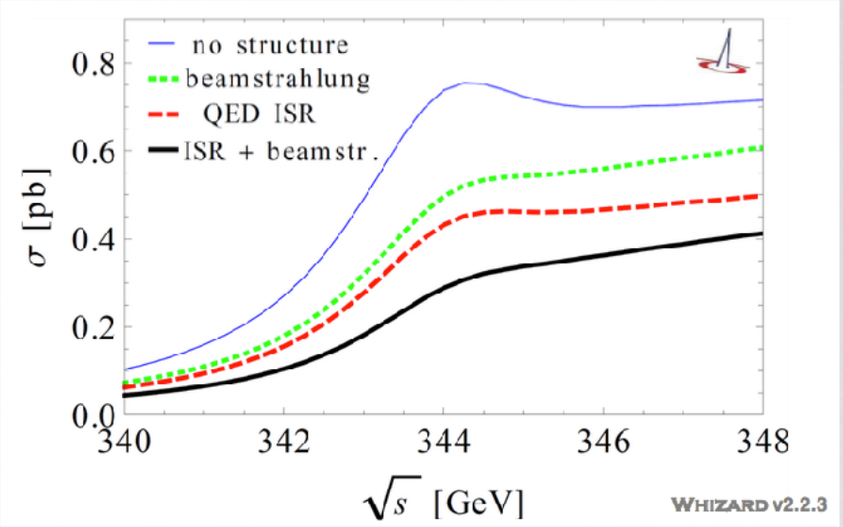
4) Top threshold in WHIZARD



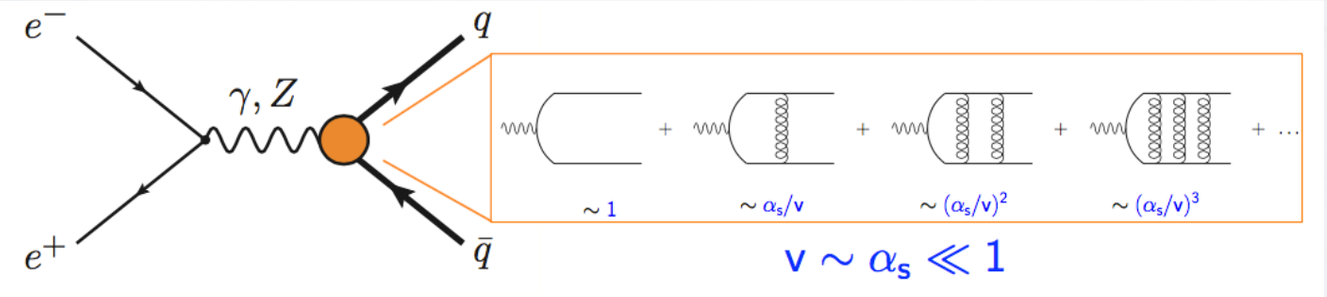
Top Threshold in WHIZARD

- Why include LL/NLL in a Monte Carlo event generator?
- Important effects: beamstrahlung; ISR; LO EW terms
- More exclusive observables accessible

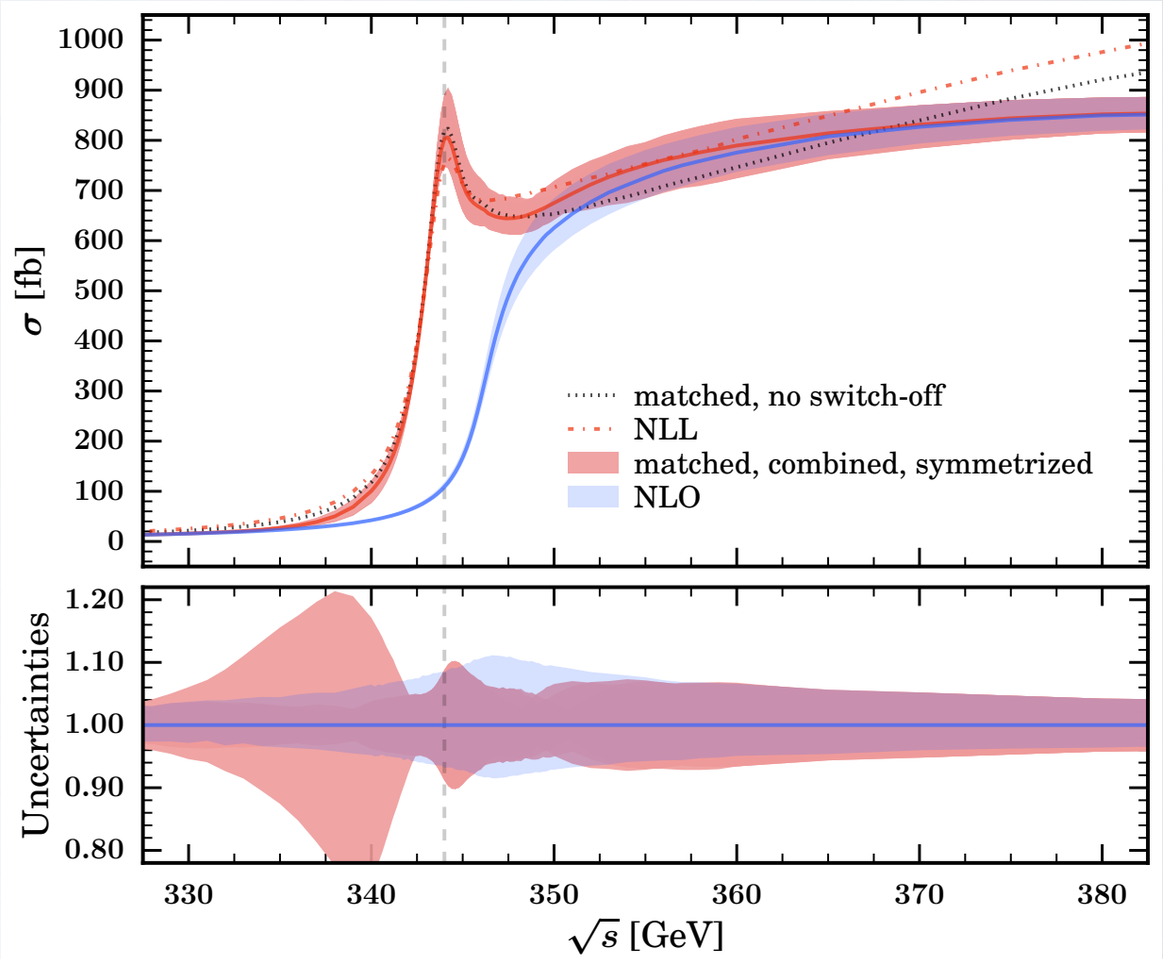
- Resummed threshold effects as vertex form factor
- TOPPIK code [Jezabek/Teubner], included in WHIZARD



Threshold region: top velocity $v \sim \alpha_s \ll 1$




```
model = SM_tt_threshold

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

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

sqrts = 350 GeV
integrate (eett_threshold)
```

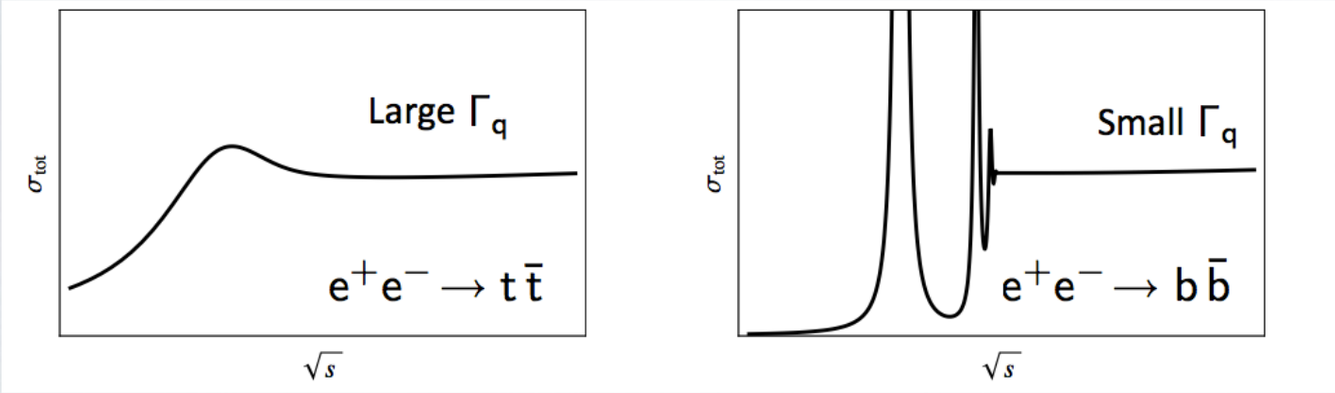


Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 1712.02220

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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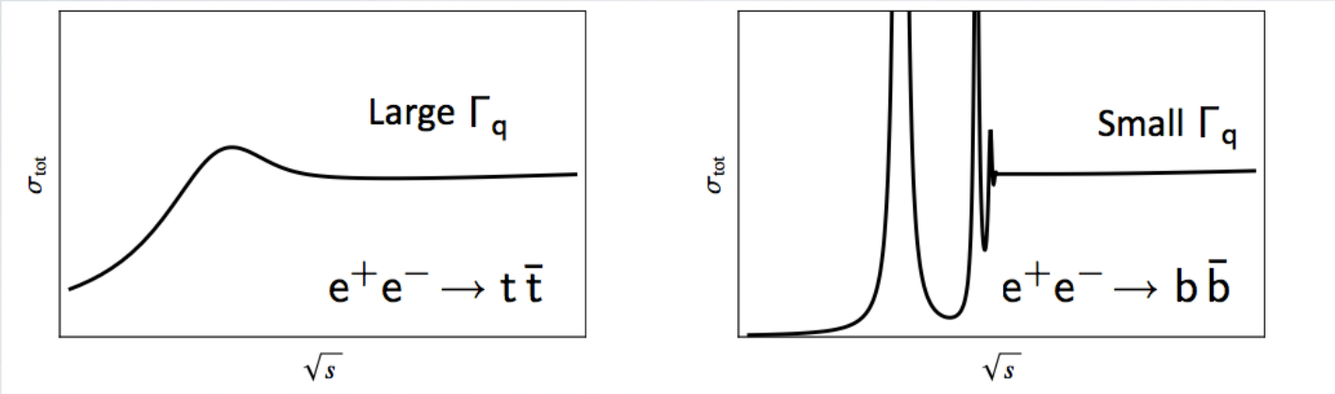

error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty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

from 1702.05333

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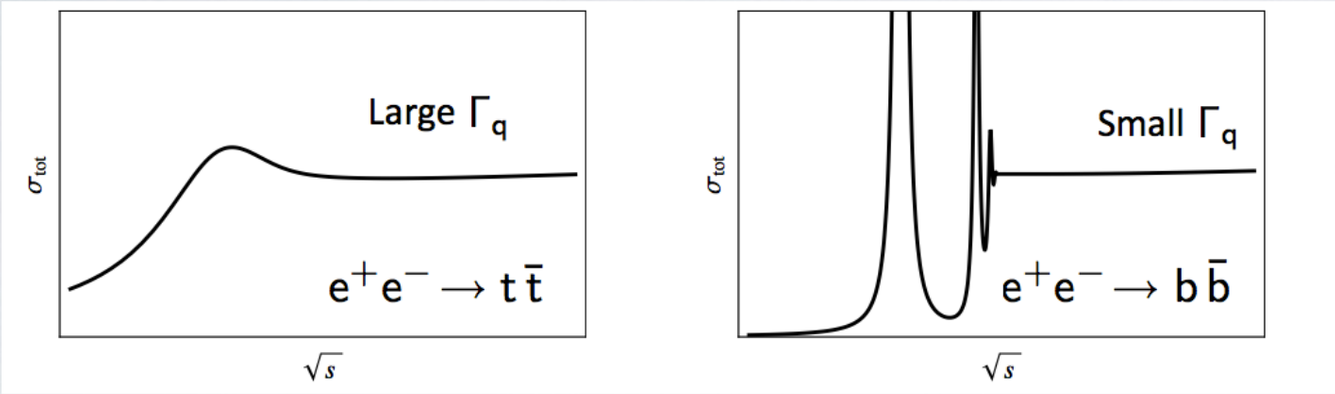

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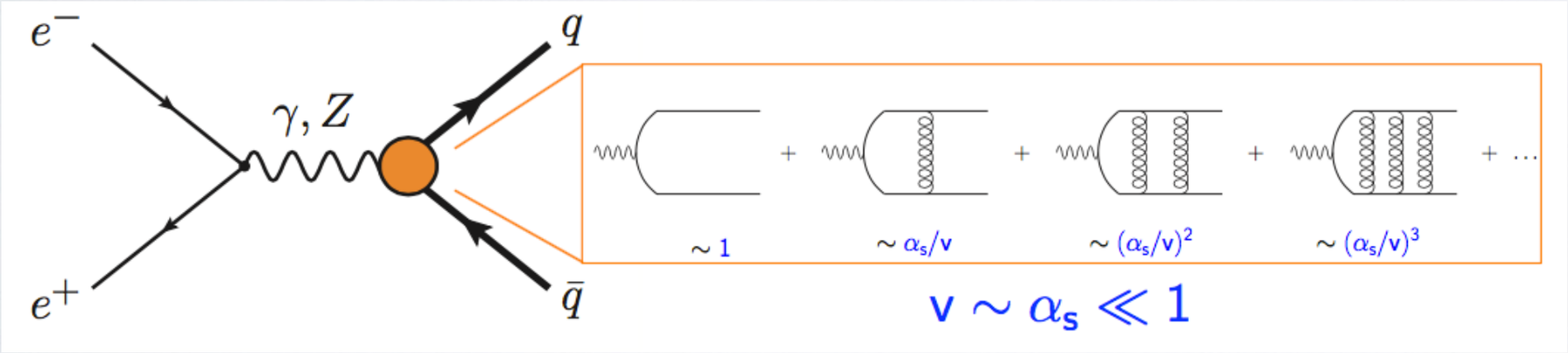
Threshold region: top velocity $v \sim \alpha_s \ll 1$ non-relativistic EFT: (v)NRQCD



Continuum region: "standard" fixed-order QCD

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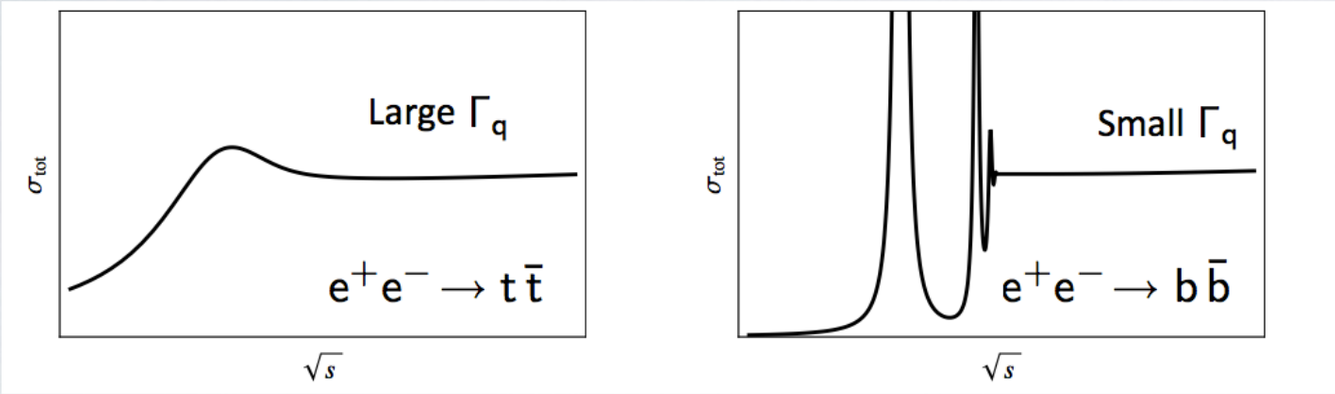

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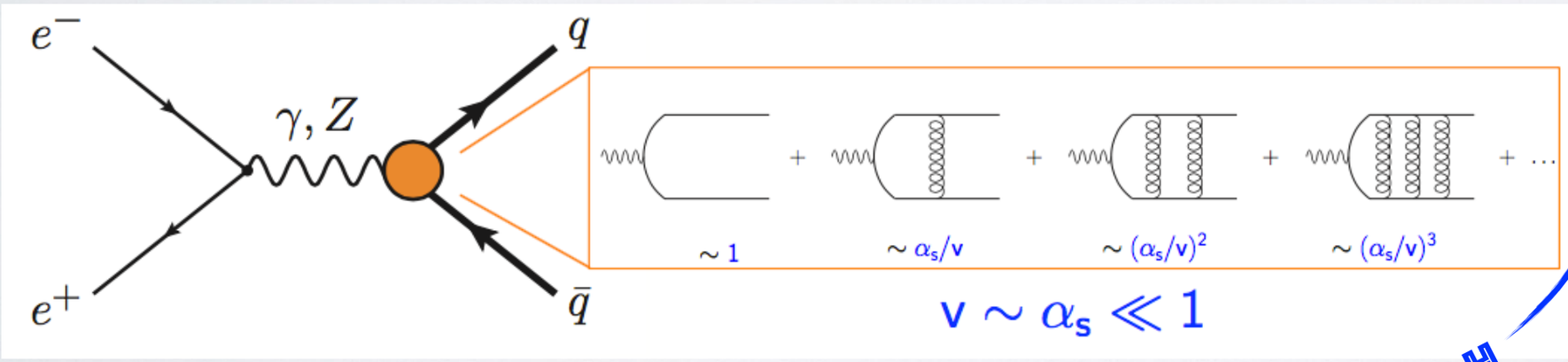
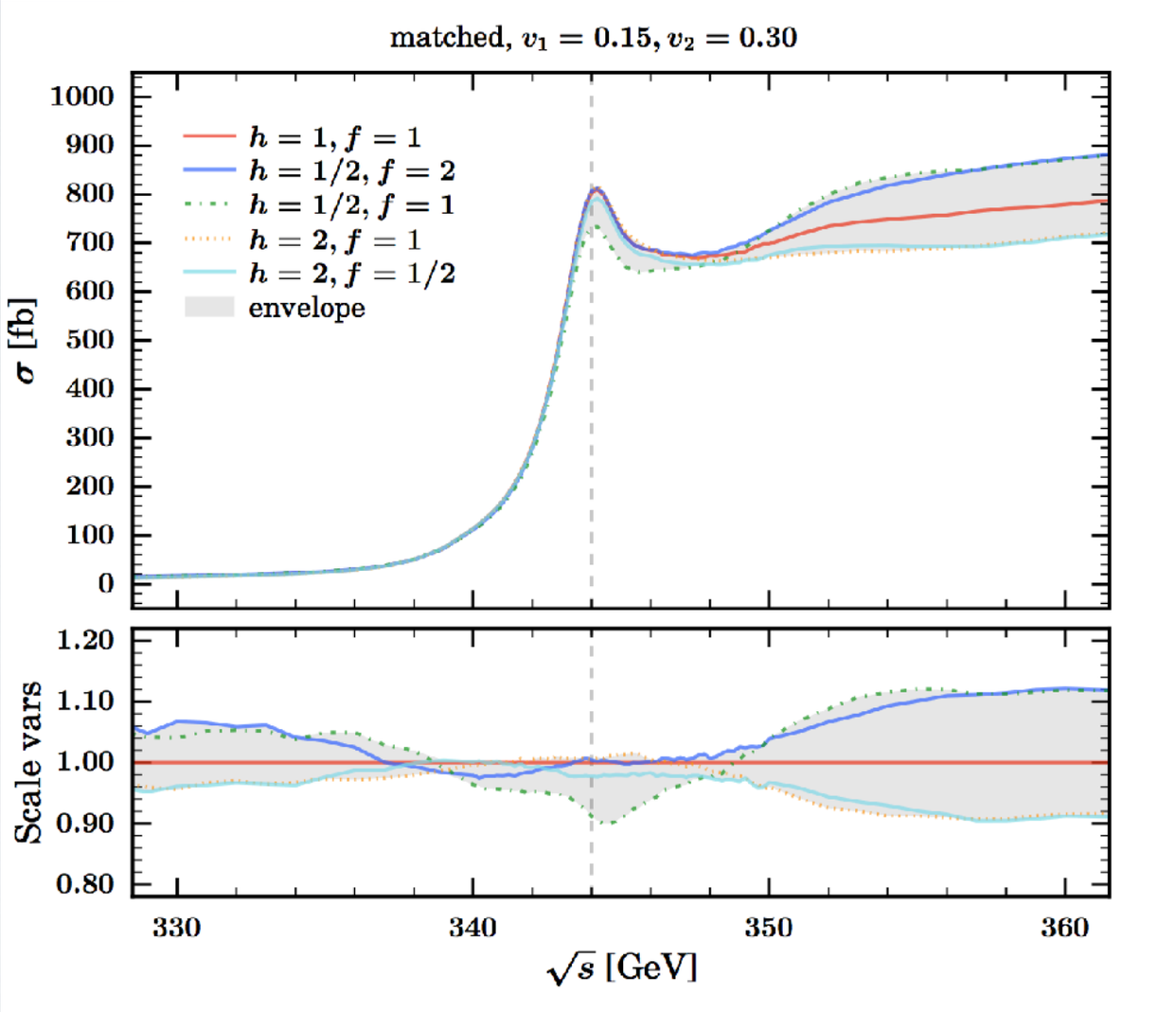
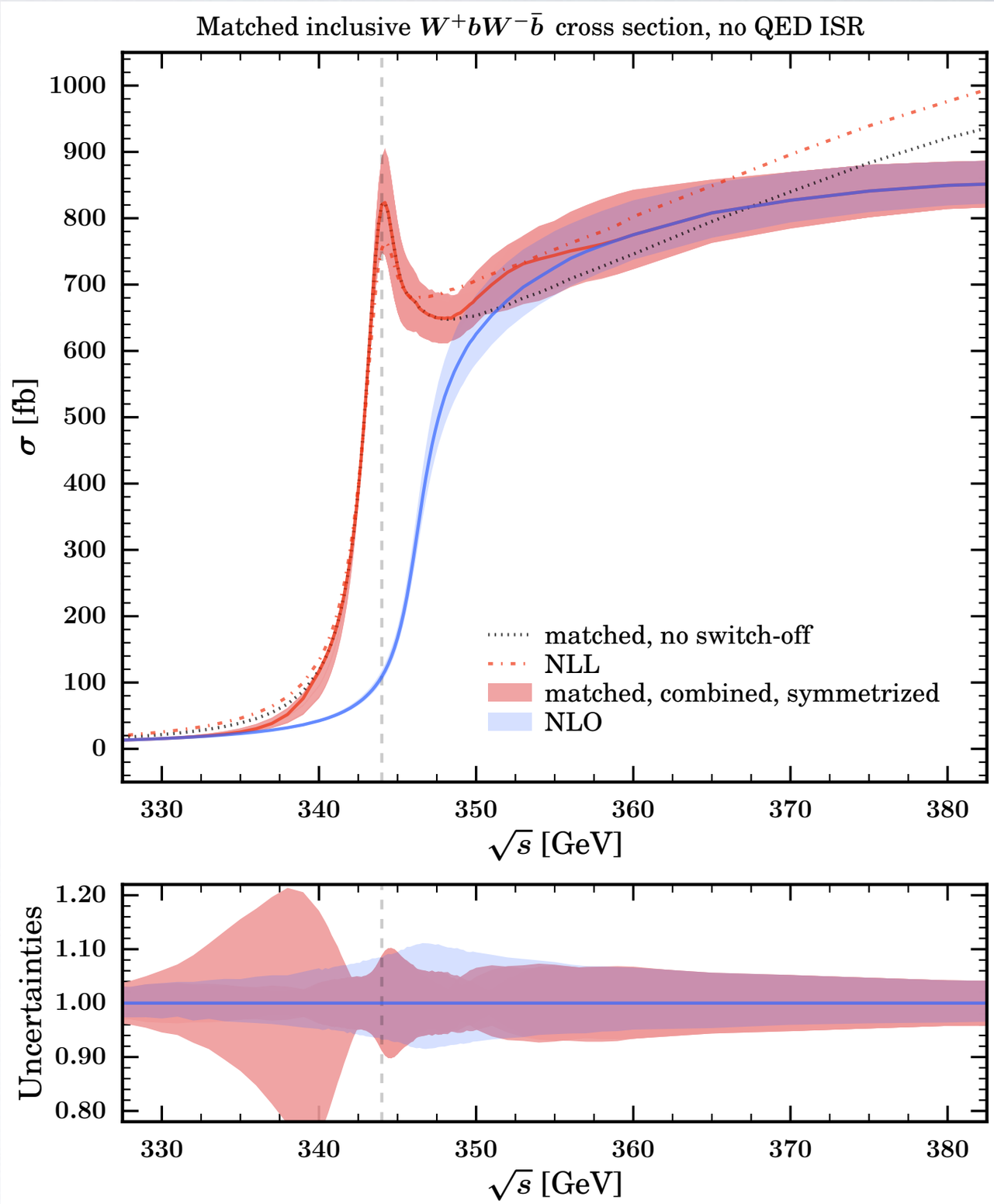


MATCH

Continuum region: "standard" fixed-order QCD

Matching threshold NLL to continuum NLO





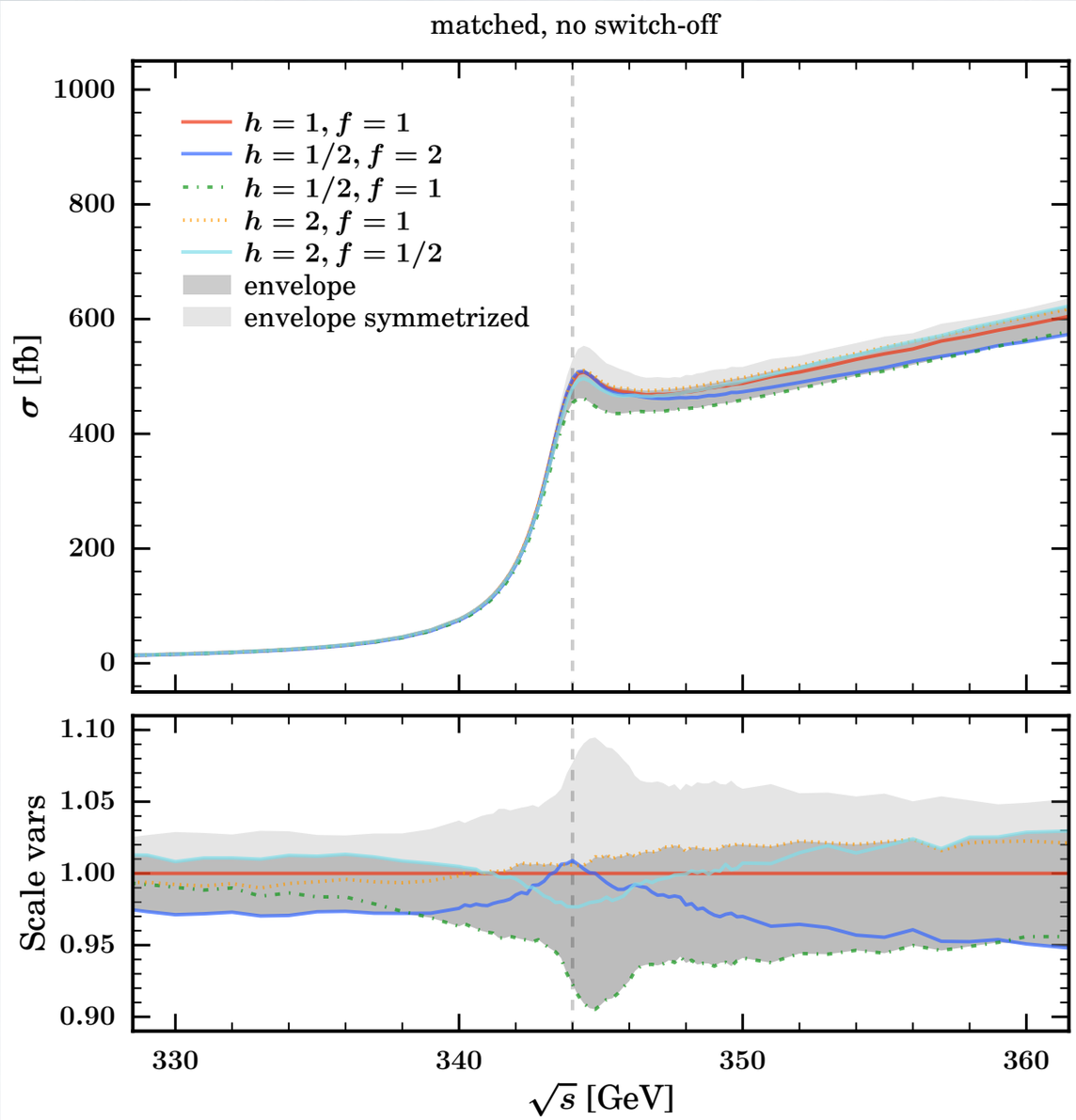
Total uncertainty: *h-f* variation band and matching [switch-off function]

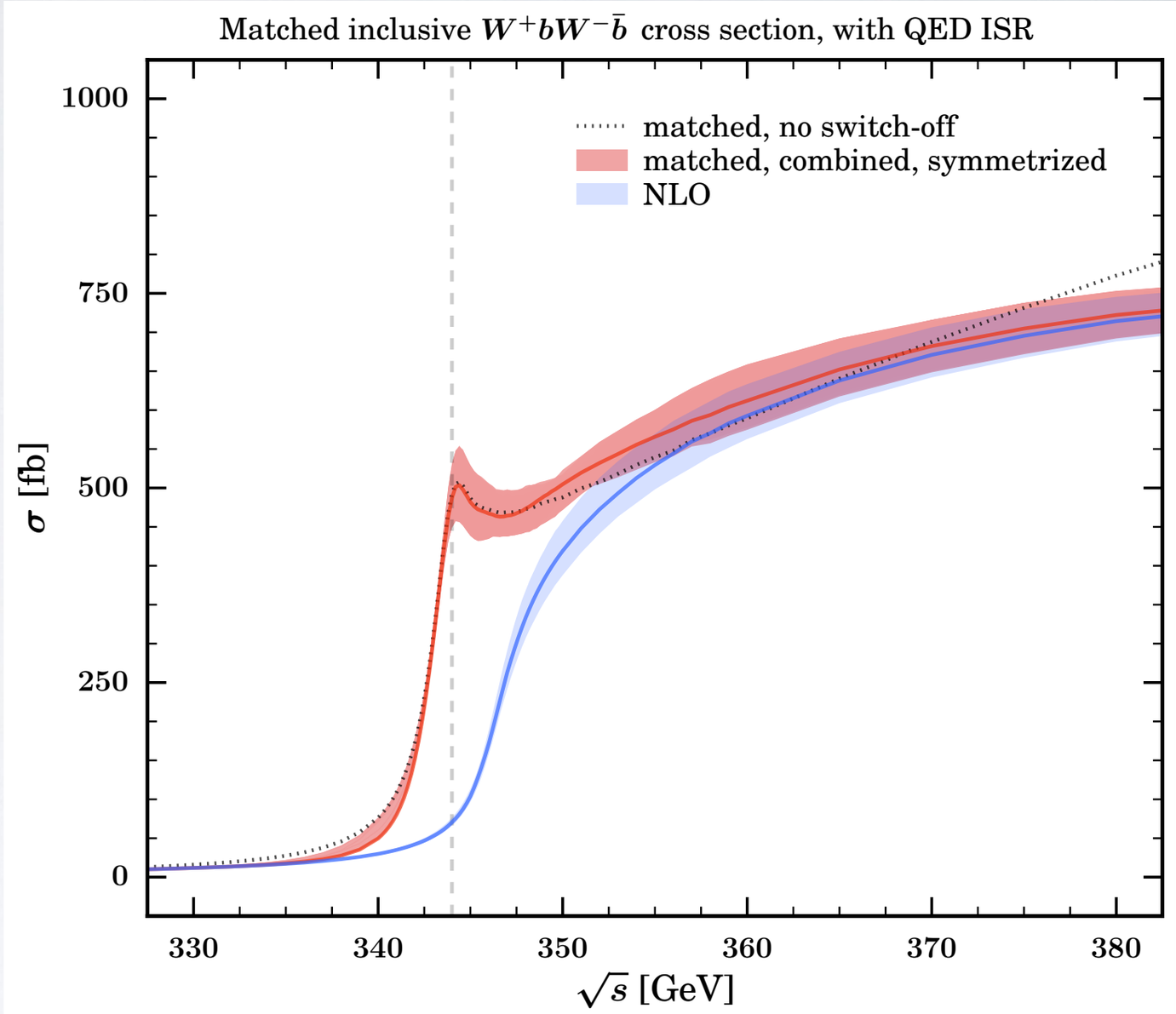
Symmetrization of error bands:

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

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

Threshold matching with QED ISR





Matched threshold differential distributions