The Event Generator WHIZARD

Jürgen R. Reuter, DESY

in memoriam: Maria Callas

Μαρία Καλογεροπούλου ✻ 2.12.1923 — † 16.9.1977

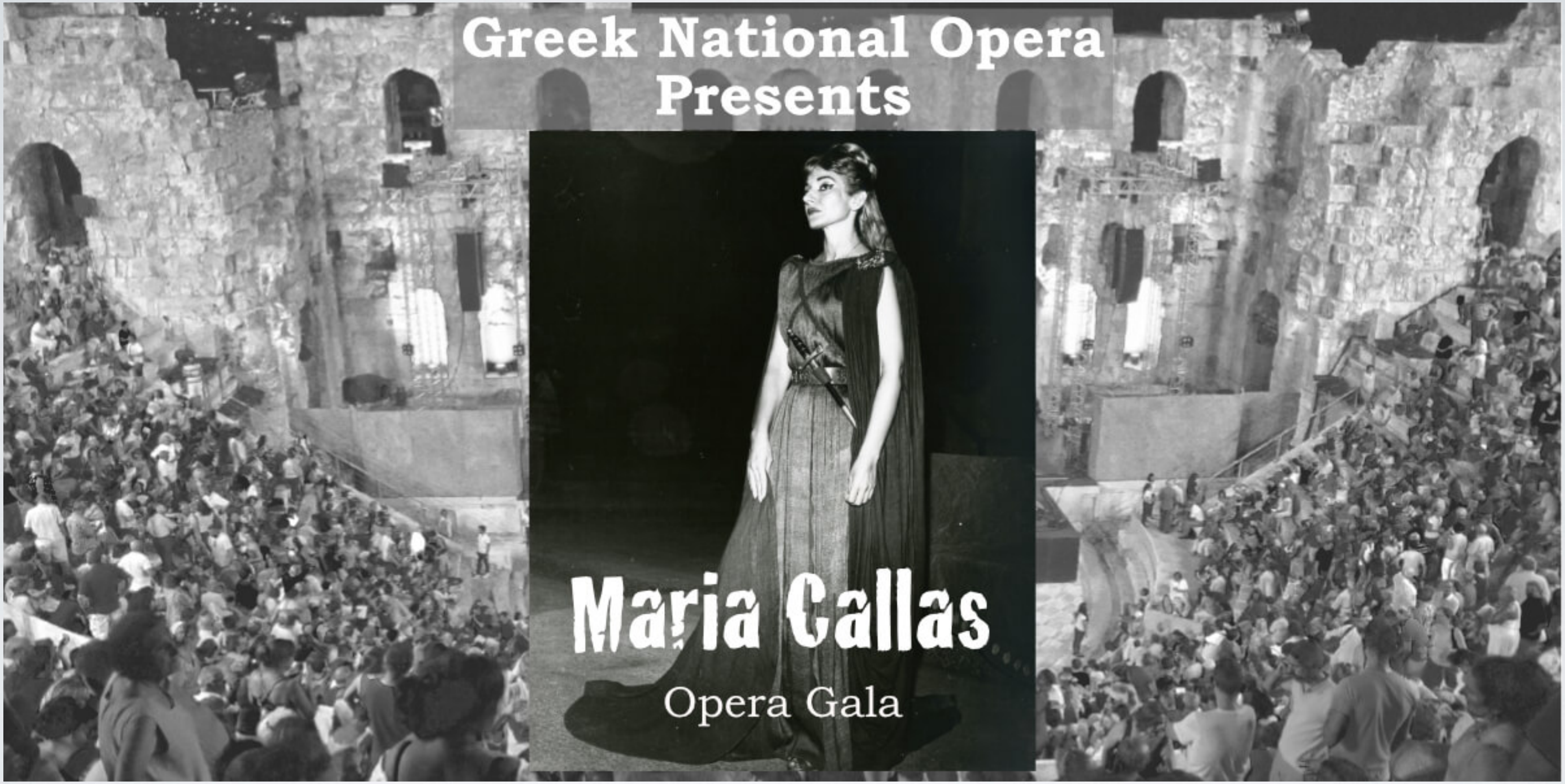
La Traviata

Lucia di Lammermoor

Medea

in memoriam: Maria Callas

Μαρία Καλογεροπούλου ✻ 2.12.1923 — † 16.9.1977



WHIZARD: Some (technical) facts

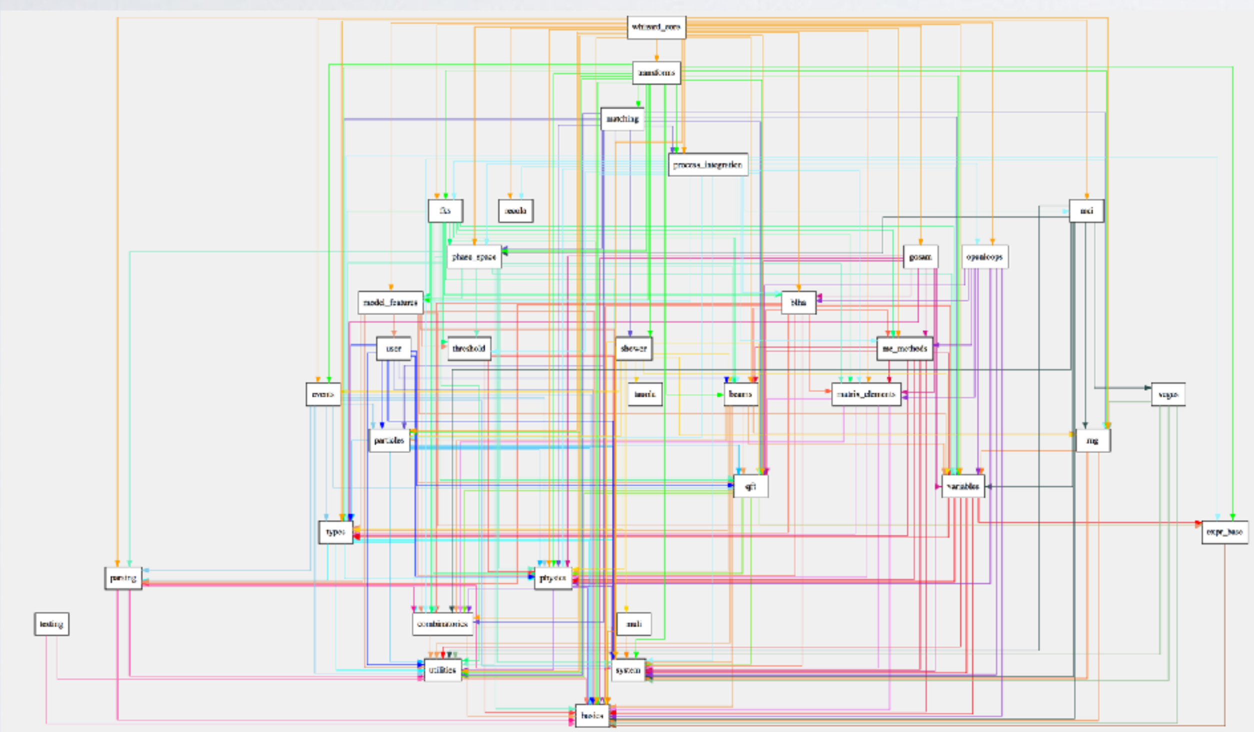
WHIZARD v2.6.0 (08.09.2017) http://whizard.hepforge.org

<whizard@desy.de>

Ancient acronym: ***W**, **Hi**ggs, **Z**, and **R**espective **D**ecays*

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

Simon Braß/Vincent Rothe/Christian Schwinn/Marco Sekulla/So Young Shim/Florian Staub/Pascal Stienemeier/ Zhijie Zhao + 2 Master



PUBLICATIONS

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

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

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

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

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

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

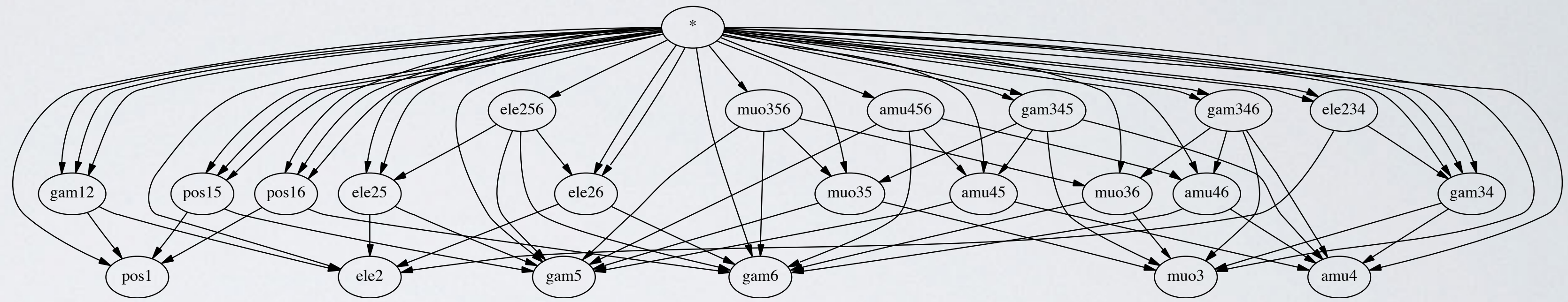
NLO capabilities: JHEP 1612 (2016) 075; arXiv: 1609.03390

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

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

WHIZARD: Introduction / Technical Facts

- Universal event generator for lepton and hadron colliders
- Tree ME generator `O'Mega` optimized ME generator (recursive via Directed Acyclical Graphs)



- Generator/simulation tool for lepton collider beam spectra: `CIRCE1/2`
- Parton showering internal: analytic + k_T-ordered, hadronization: external
- Interfaces to external packages for Feynman rules, hadronization, tau decays, event formats, analysis, jet clustering etc.: `FastJet, GoSam, GuineaPig(++), HepMC, HOPPET, LCIO, LHAPDF(4/5/6), LoopTools, OpenLoops, PYTHIA6 [internal], [PYTHIA8], Recola, StdHep [internal], Tauola [internal]`
- Event formats: LHE, StdHEP, HepMC, LCIO + several ASCII
- Programming Languanges: `Fortran2003/2008 (gfortran ≥4.8.4), OCaml (≥3.12.0)`
- 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: Past and recent timeline

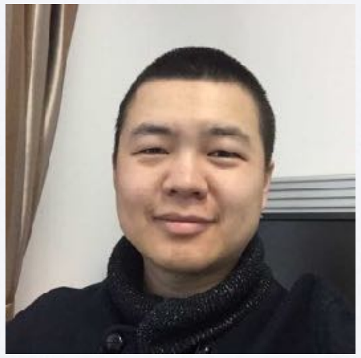
- Original scope: electroweak (multi-fermion) studies at 1.6 TeV TESLA [≈ 1998–2000]
- Milestone: first-ever multi-leg implementation of MSSM v1.25 [2003]
- Color flow formalism [≈2005]
- Used for many TESLA studies and most ILC CDR and TDR, CLIC CDR and detector LoI studies (versions v1.24, v1.50, v1.95) [≈ 2002–2013]
- Major refactoring phase I: LHC physics → v2.0.0 [≈ 2007–2010]
- Validation inside ATLAS and CMS [≈2011–2014]
- 2nd refactoring phase II: NLO automation / maintainability → v2.2.0 [≈ 2012–2014]
- Strong interest of CEPC/FCC-ee study group(s) for simulations [≈ 2013/14 — now]
- 04/2015, ALCW'15 Tokyo: LC generator group endorsed v2.2 for new mass productions
- Final validation for LC [ee] physics between v1.95 and v2 [finalized until November]

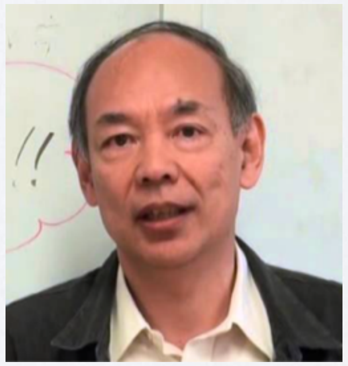
Special thanks to: [beam spectra, photon background, event formats, shower/hadronization, tau decays]


Mikael Berggren

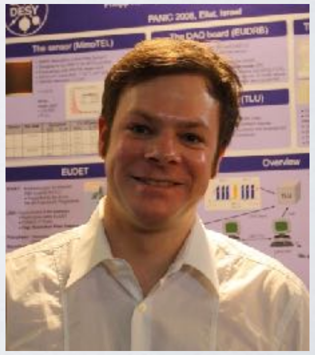

Jean-Jacques Blaising


Moritz Habermehl

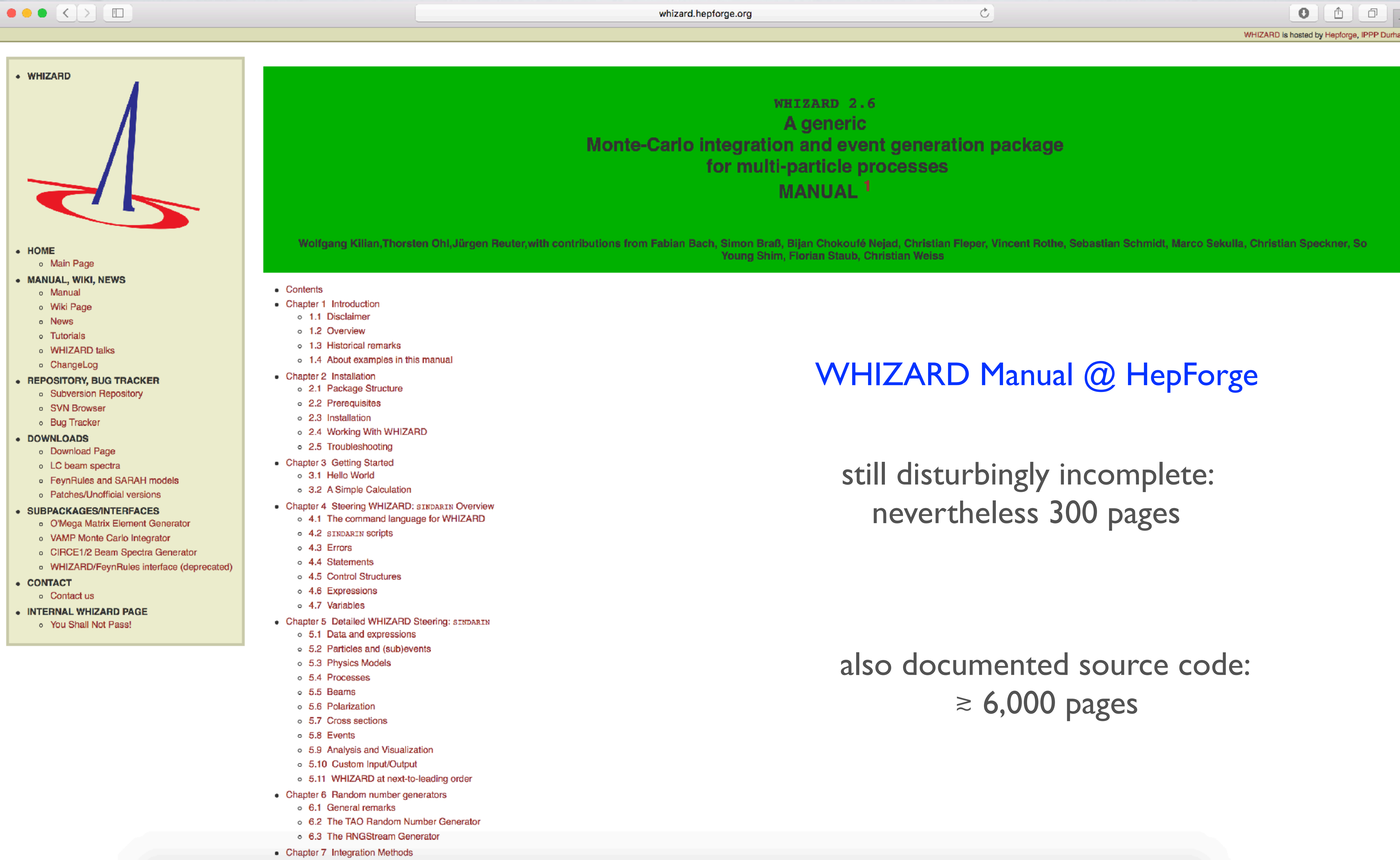

Mo Xin


Akiya Miyamoto


Tim Barklow


Philipp Roloff

WHIZARD: Manual

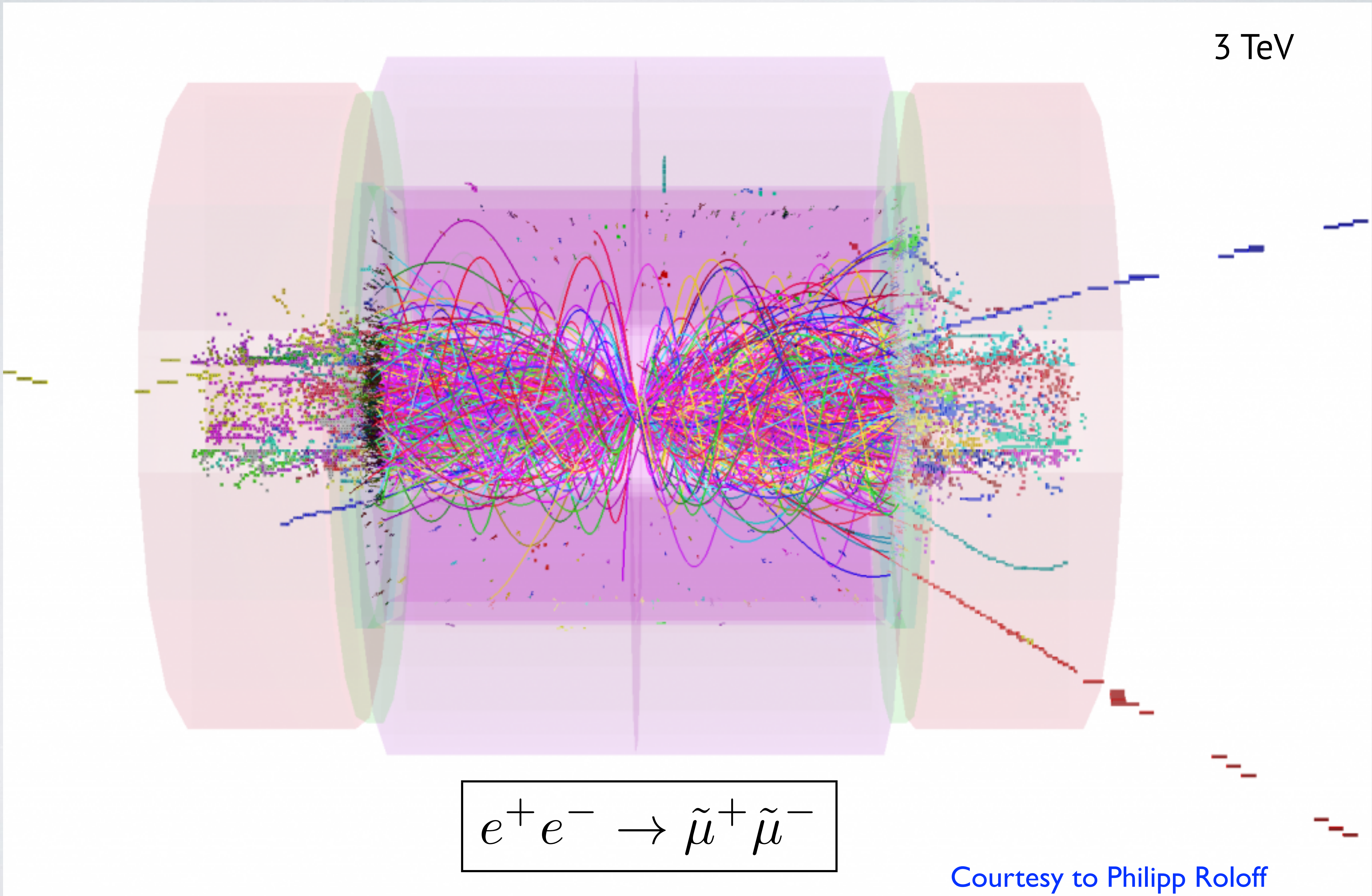


WHIZARD Manual @ HepForge

still disturbingly incomplete:
nevertheless 300 pages

also documented source code:
$\gtrsim$ 6,000 pages

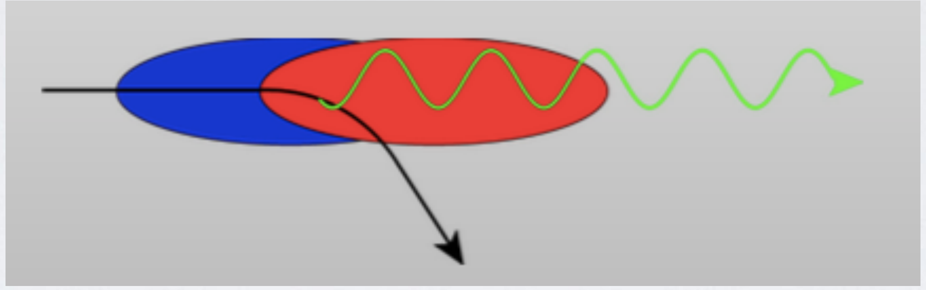
e^+e^- Beamspectra



e^+e^- Beamspectra

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

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



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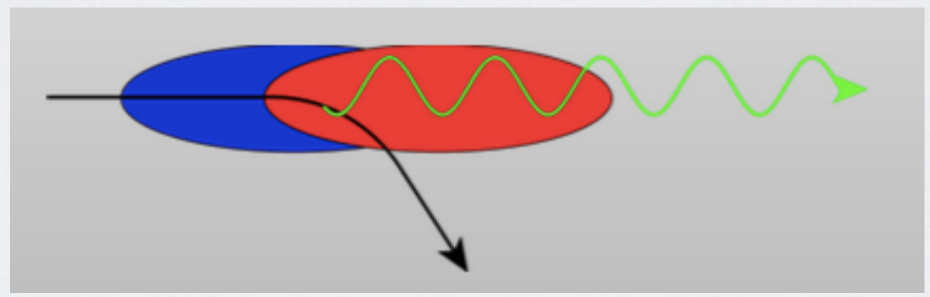

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ilc250ee_nobeamspread.circe	29-Jul-2016 13:20	1.0M	
ilc350ee_nobeamspread.circe	29-Jul-2016 13:20	1.0M	
ilc500ee_nobeamspread.circe	29-Jul-2016 13:20	1.0M	

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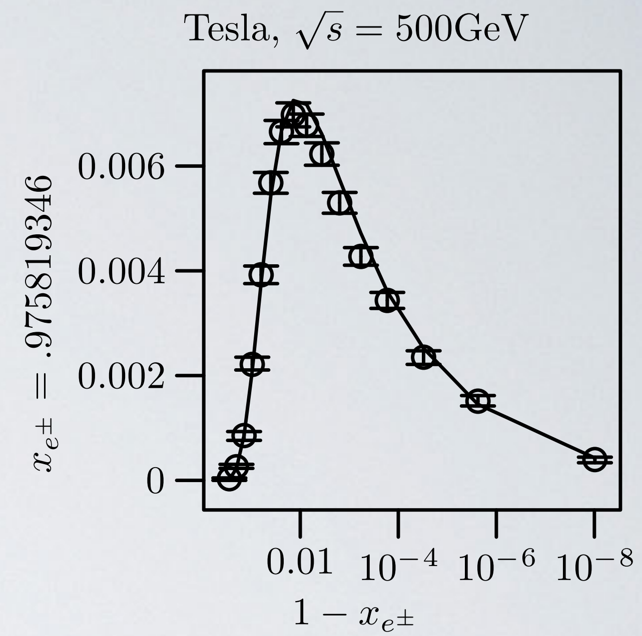
Lepton Collider Beam Simulation

- Another demand: adapt `GuineaPig` beam spectra for `WHIZARD v2`
- For `WHIZARD v1.95` simulations done by `Lumilinker` [T. Barklow]
- TESLA/SLC spectra were rather simple
- Fits with 6 or 7 parameters possible [`CIRCE1`]
- Beams not factorizable: $D_{B_1B_2}(x_1, x_2) \neq D_{B_1}(x_1) \cdot D_{B_2}(x_2)$
- 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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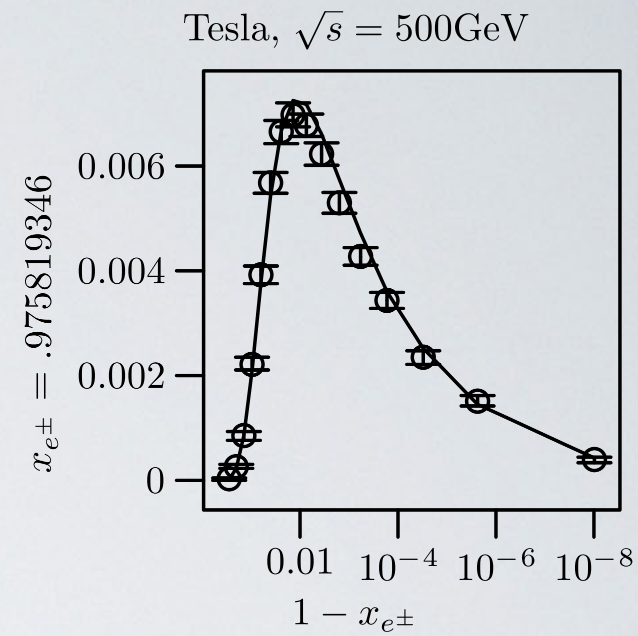

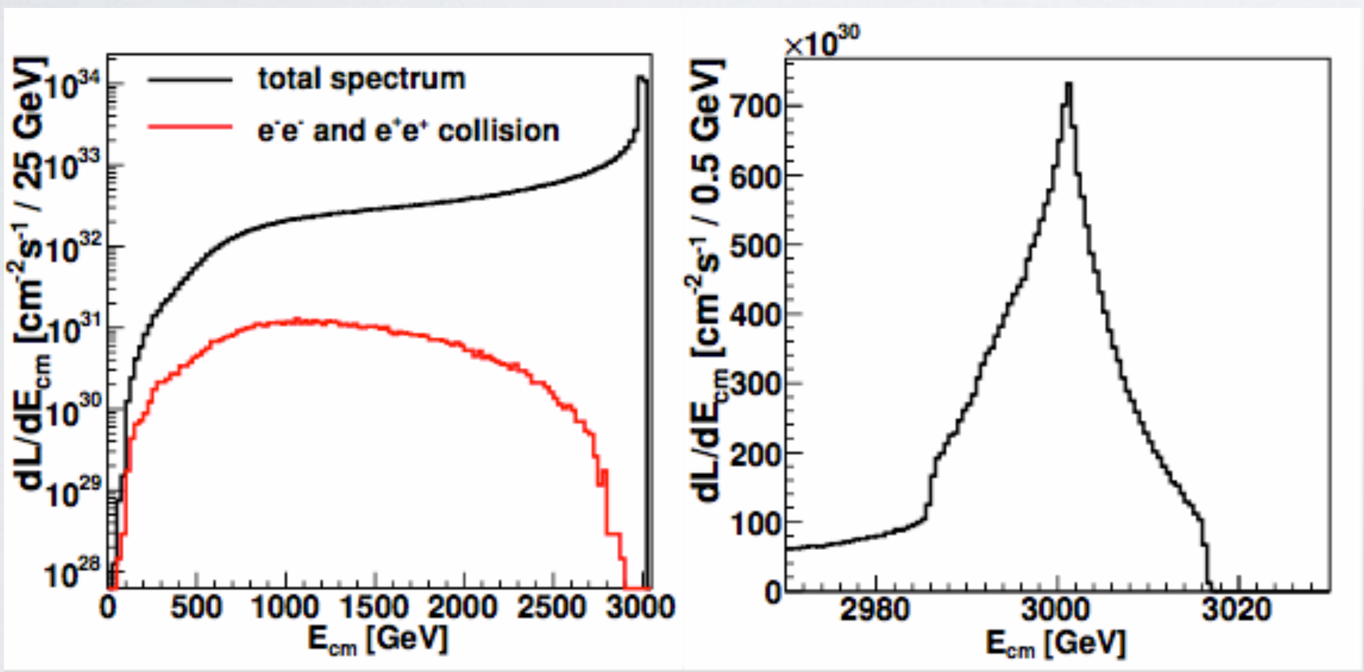

Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)

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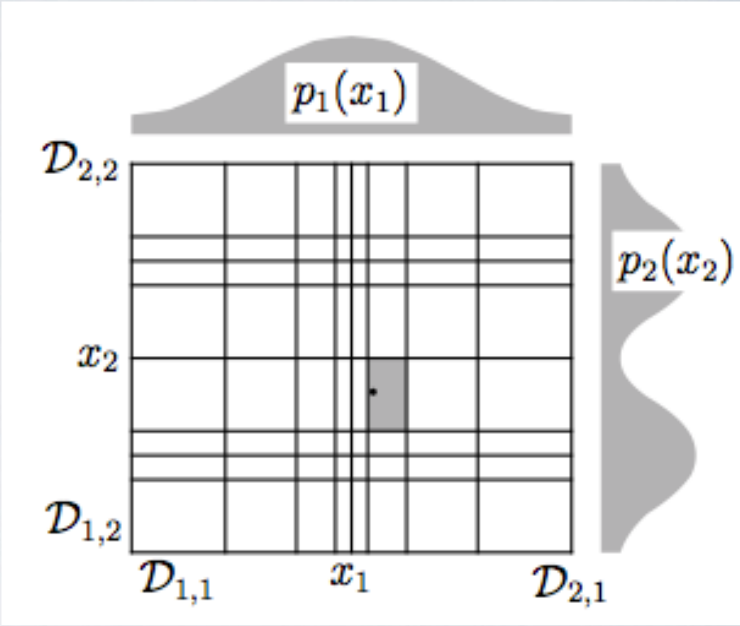
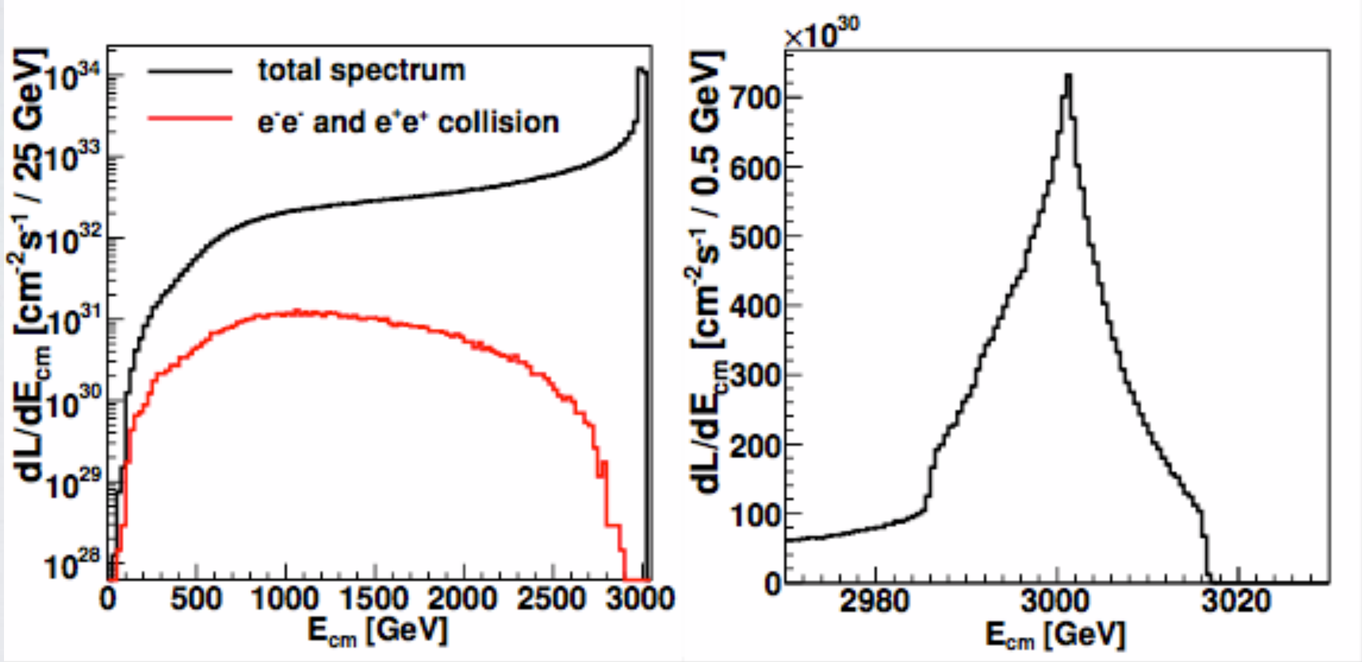




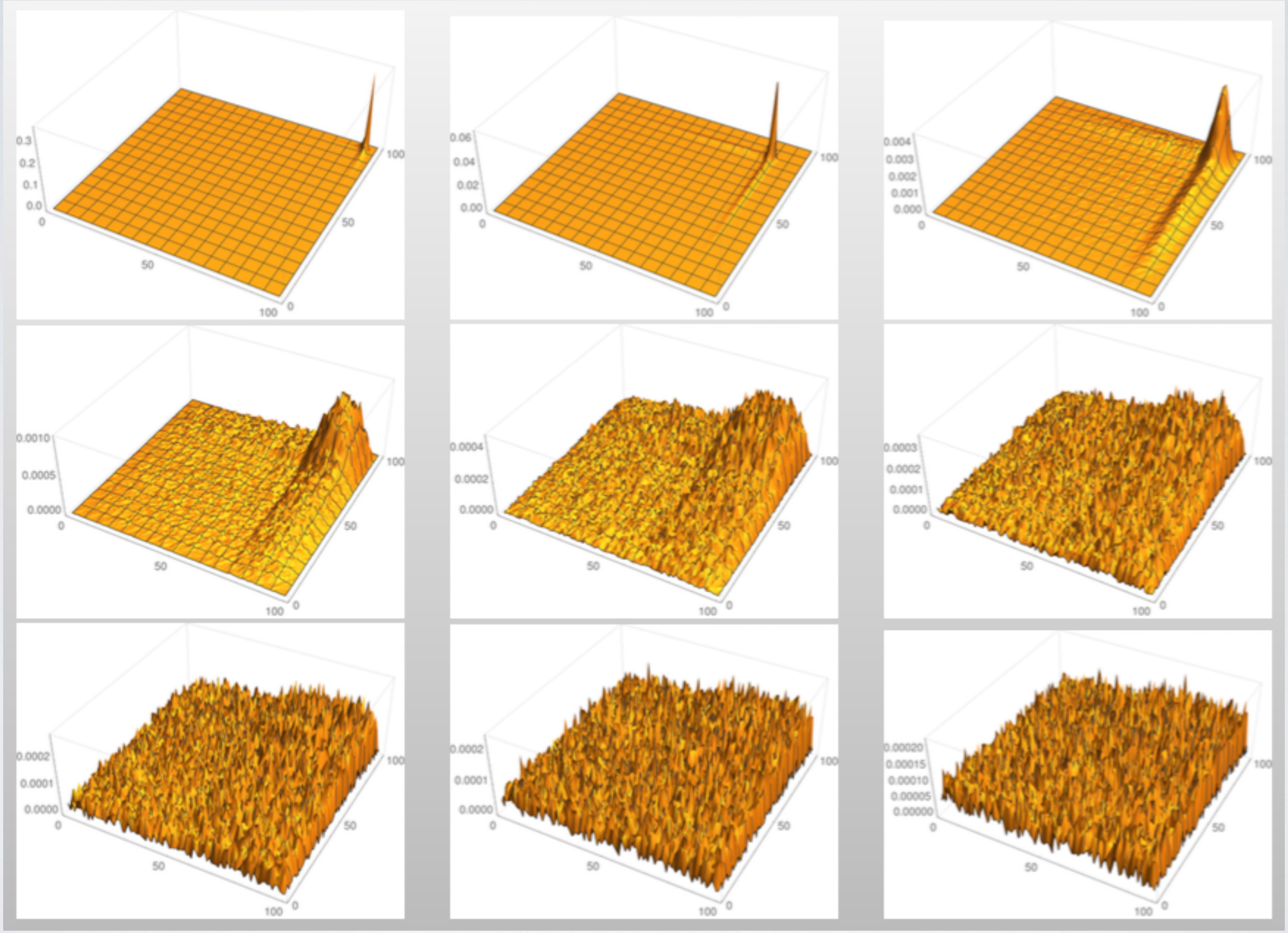
Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)

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

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

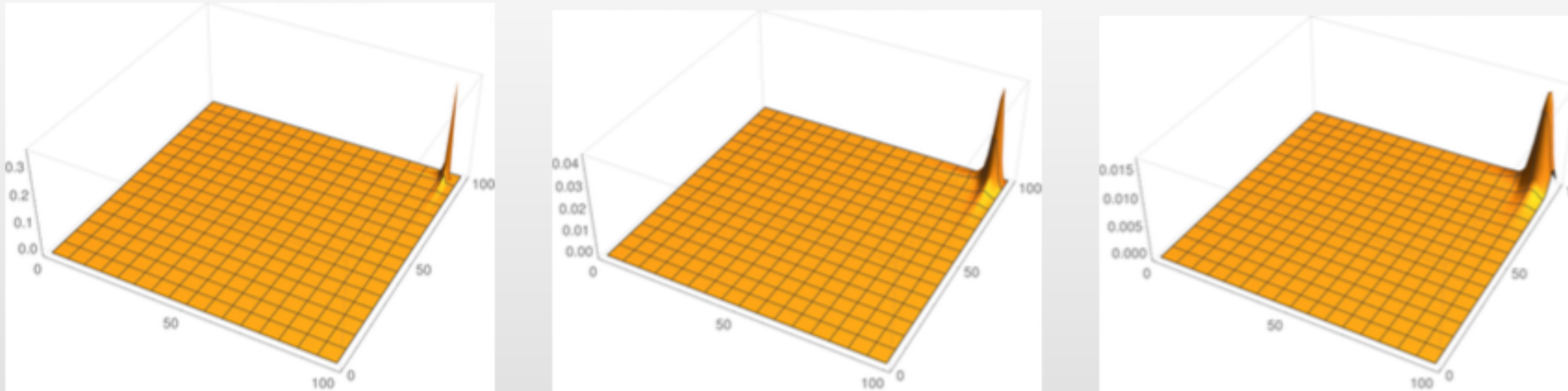
Iterations of Beam Spectrum



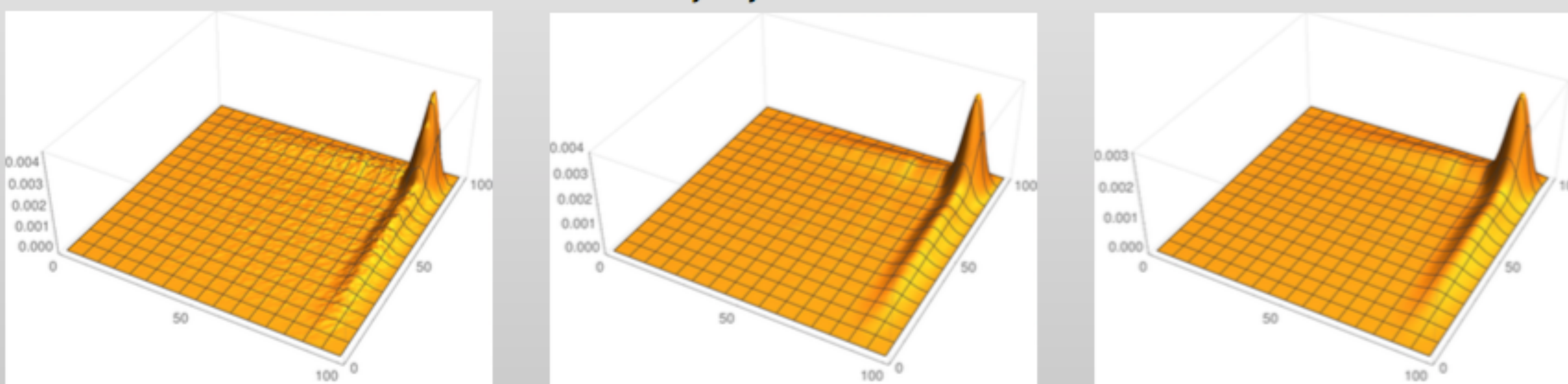
(171,306 GuineaPig events in 10,000 bins)

Iterations of Beam Spectrum

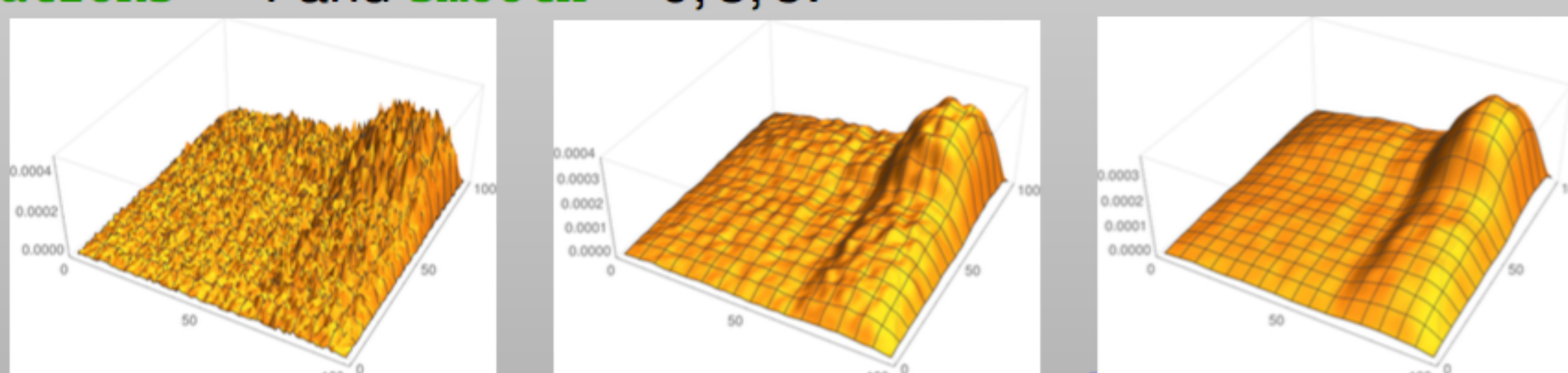
- `iterations` = 0 and `smooth` = 0, 3, 5:



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



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



Inclusive Lepton Collider ISR included

Soft exponentiation to all orders

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

Gribov/Lipatov, 1971

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

Hard-collinear photons up to 3rd QED order

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Hard-collinear photons up to 3rd QED order

Kuraev/Fadin, 1983; Skrzypek/Jadach, 1991

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

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

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

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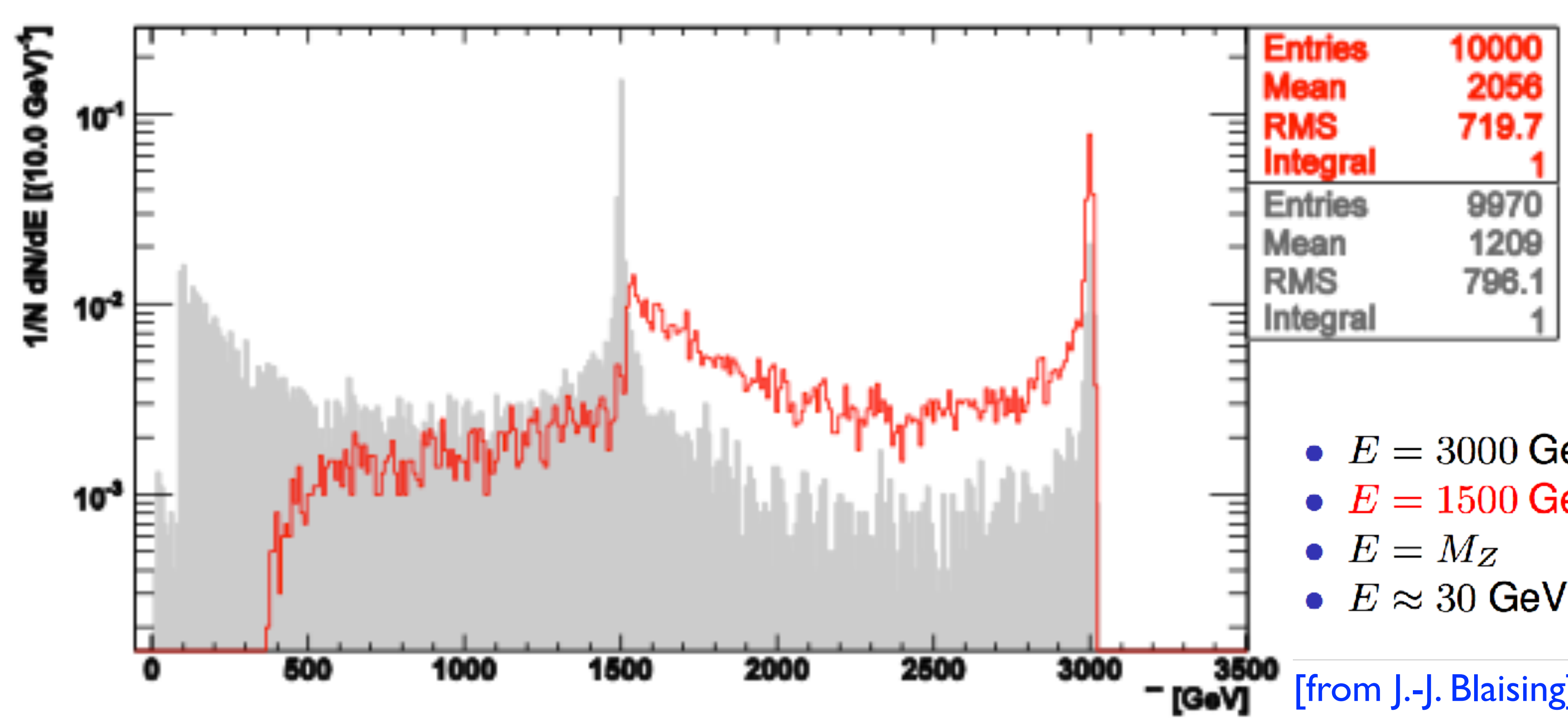
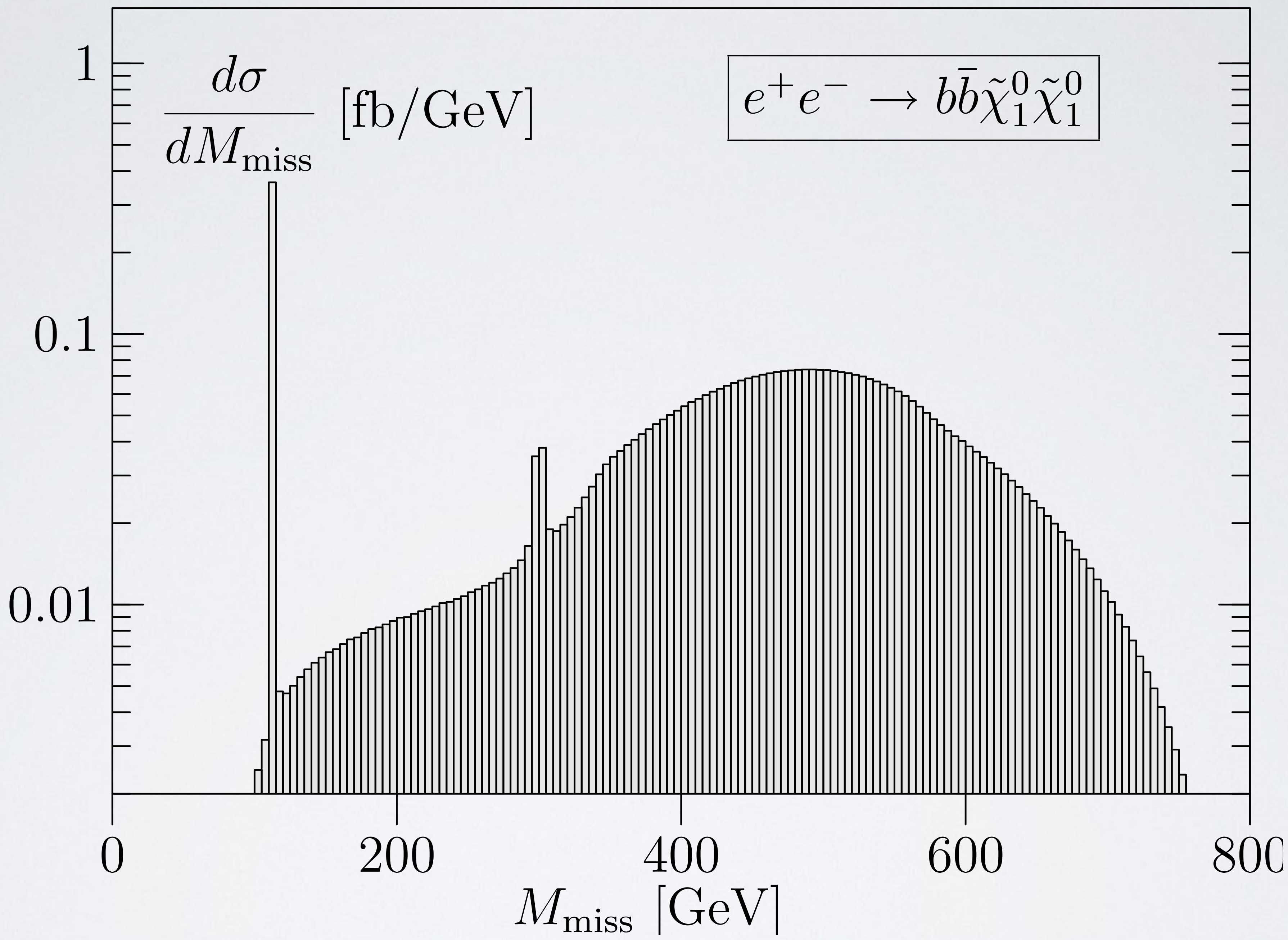


- $E = 3000$ GeV (luminosity spectrum peak)
- $E = 1500$ GeV (Z peak and lumi spectrum)
- $E = M_Z$ (Z resonance)
- $E \approx 30$ GeV (due to $e^+e^- \to \gamma^* \to b\bar{b}$)

[from J.-J. Blaising]

Beamstrahlung / ISR for high-energy searches



Hagiwara/Kilian/Krauss/Ohl/Plehn/Rainwater/JRR/Schumann [CATPISS collaboration], hep-ph/0512260

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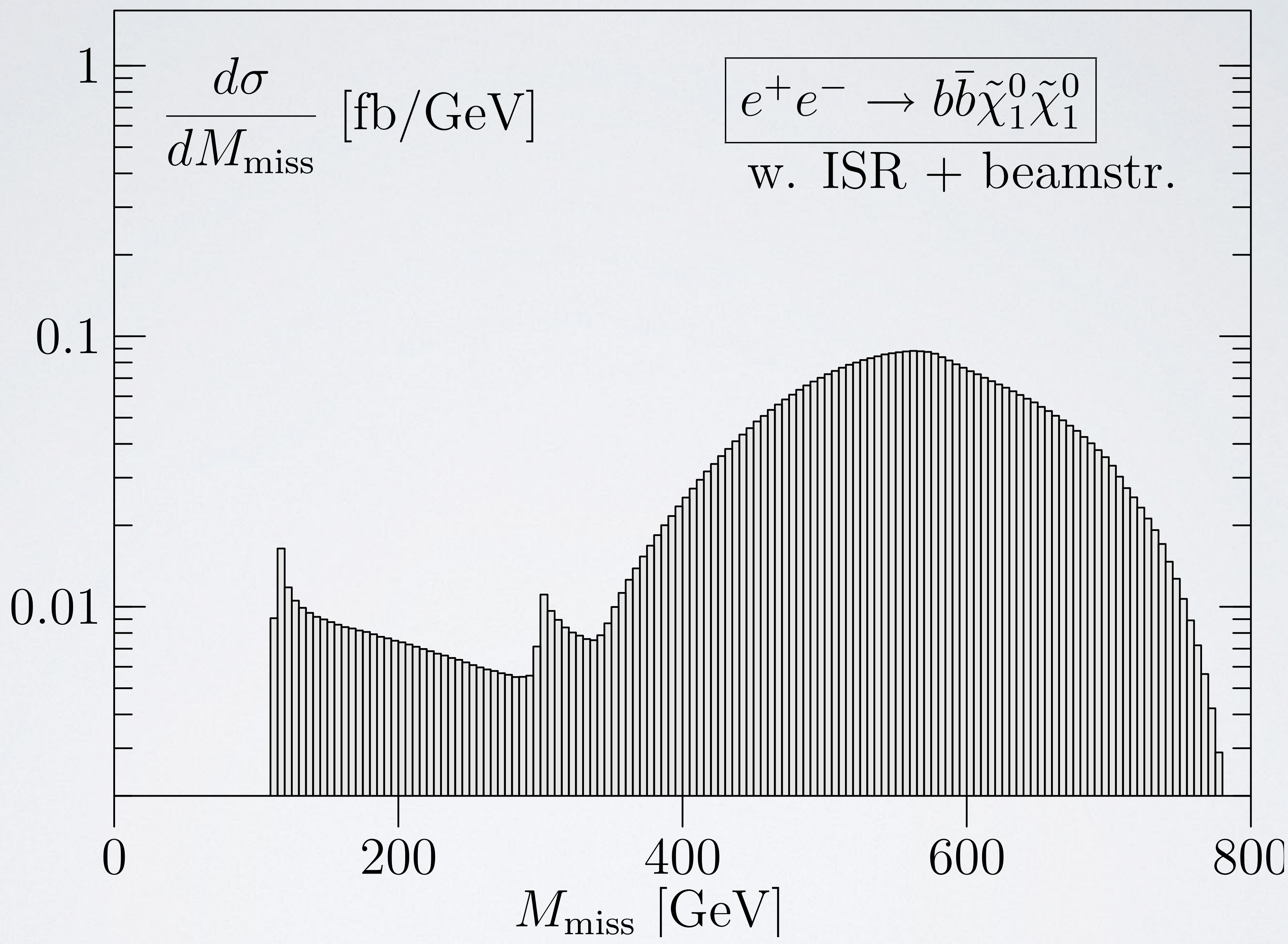
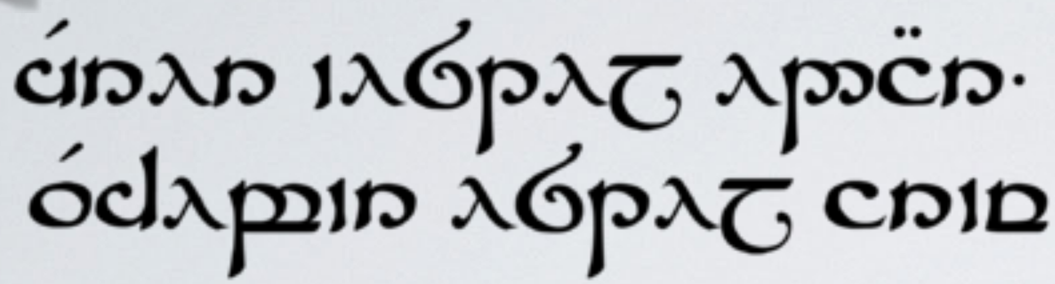


Hagiwara/Kilian/Krauss/Ohl/Plehn/Rainwater/JRR/Schumann [CATPISS collaboration], hep-ph/0512260

General structure of SINDARIN input



```
model = NMSSM

alias ll = “e-“:”e+”:”mu+”:”mu-“
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)
```

Standard cut expression:

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

Cuts on tensor products:

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

Selection cuts:

```
cuts = any PDG == 13 [lepton]
```

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

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
```

Decay processes / auto decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

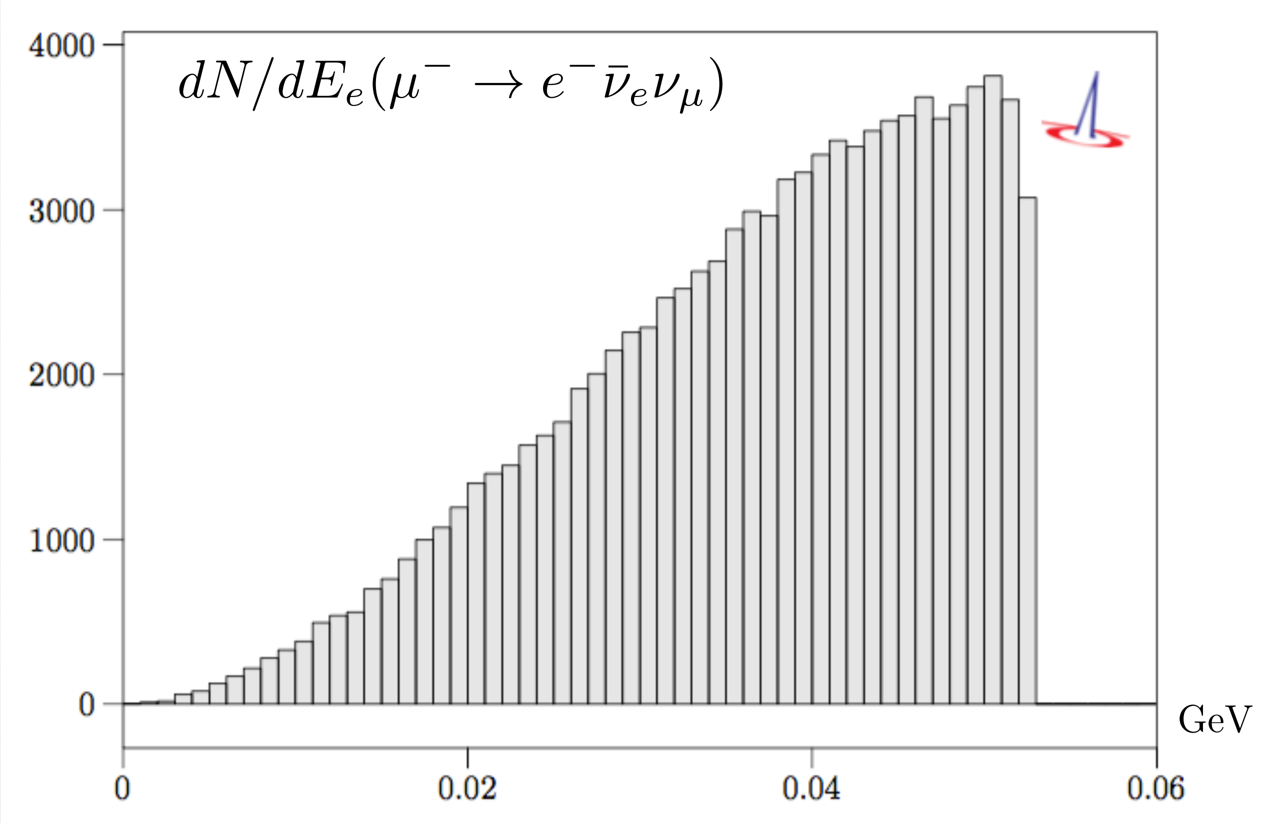
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

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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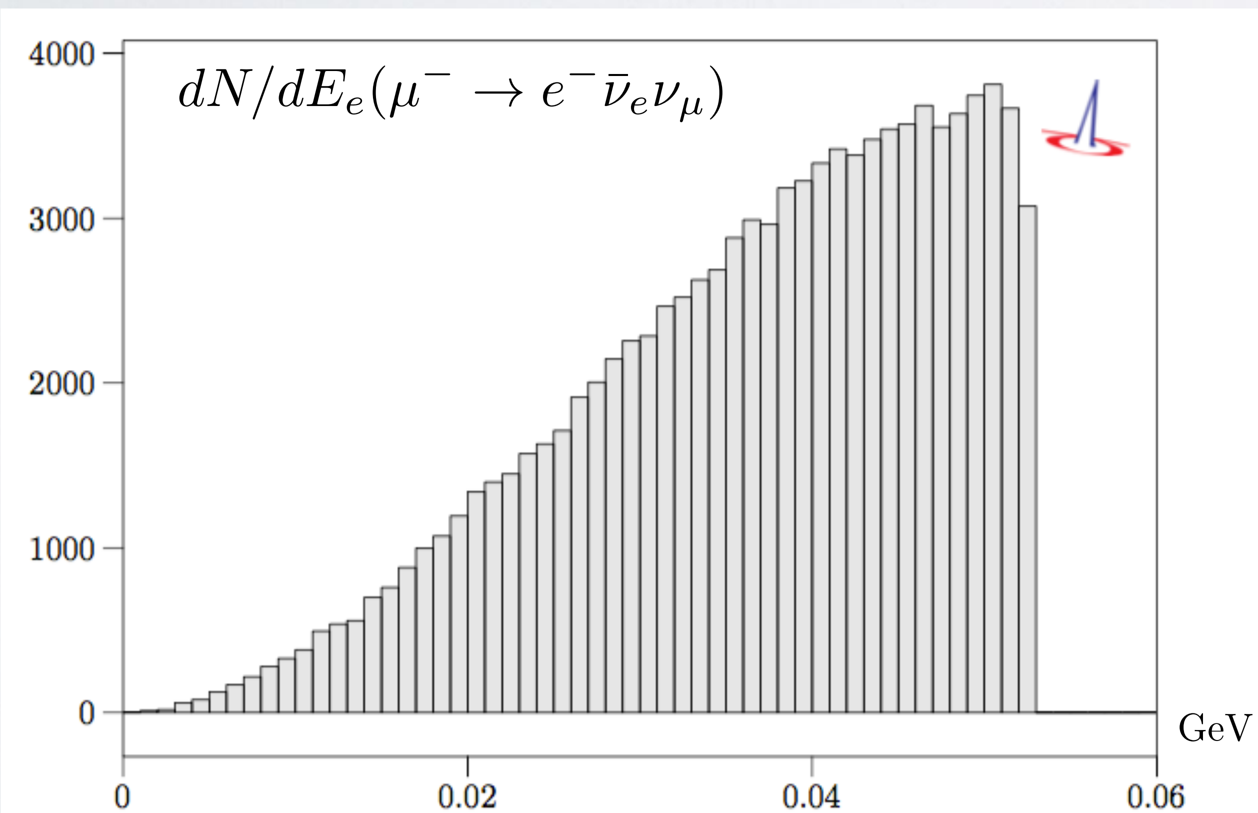


Automatic integration of particle decays

```
auto_decays_multiplicity = 2
?auto_decays_radiative = false

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

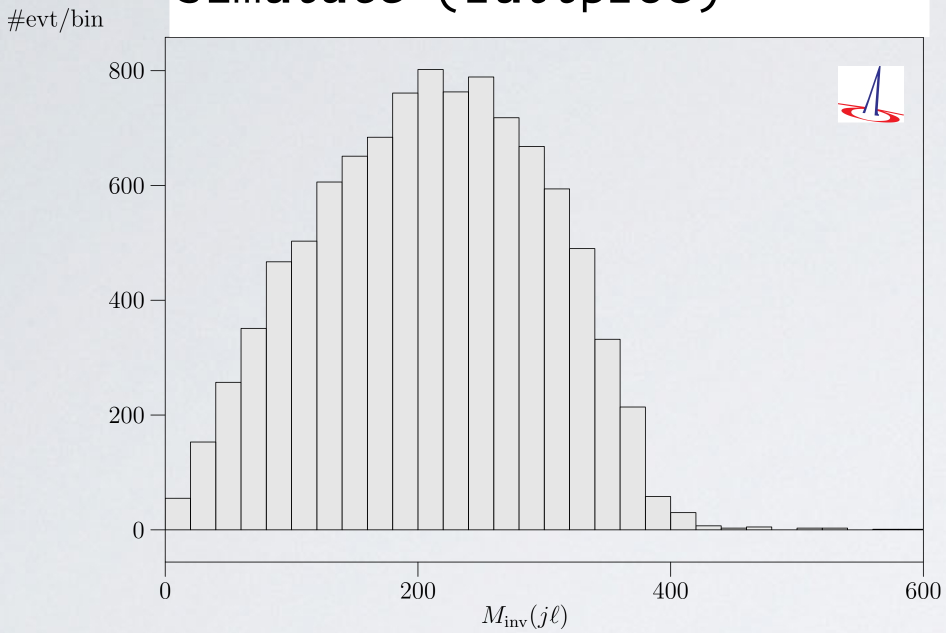
```
|=====================================================================
| It      Calls  Integral[GeV] Error[GeV]  Err[%]    Acc
|=====================================================================
   1        100  2.2756406E-01  0.00E+00    0.00    0.00*
|---------------------------------------------------------------------
   1        100  2.2756406E-01  0.00E+00    0.00    0.00
|=====================================================================
| 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
```

Spin Correlation and Polarization in Cascades

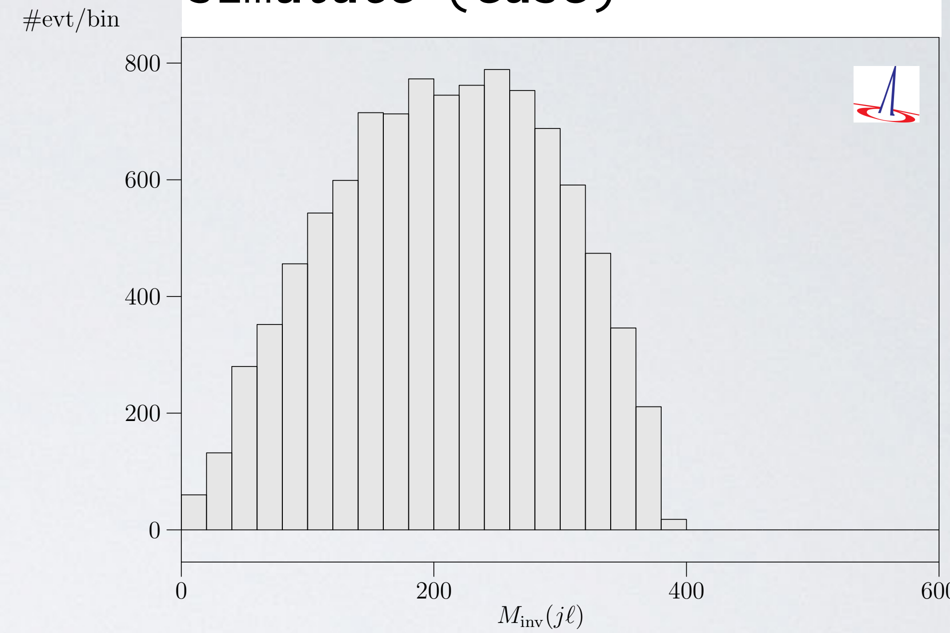
Cascade decay, factorize production and decay

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

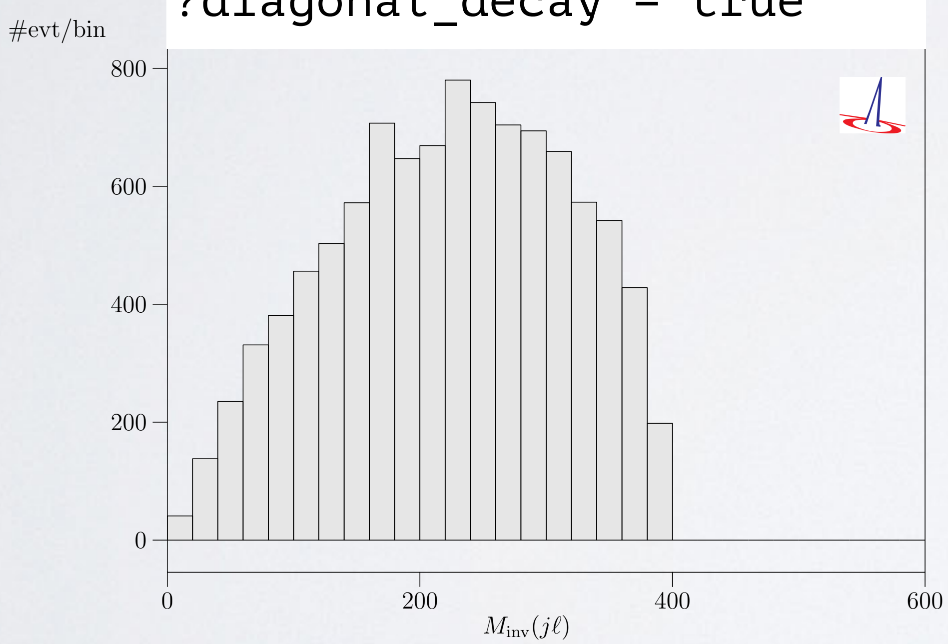
`simulate (fullproc)`



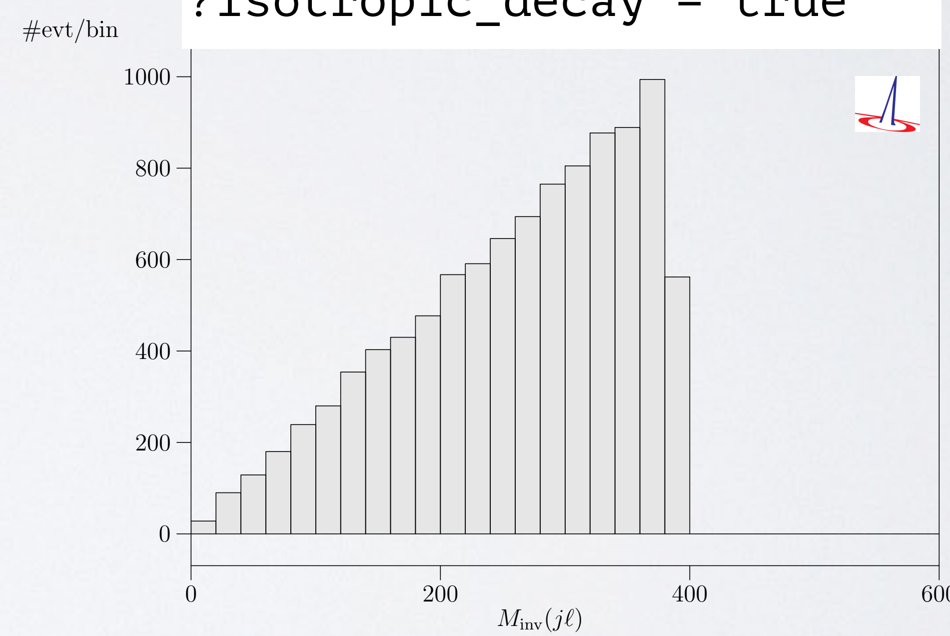
`simulate (casc)`



`?diagonal_decay = true`



`?isotropic_decay = true`



Spin Correlation and Polarization in Cascades

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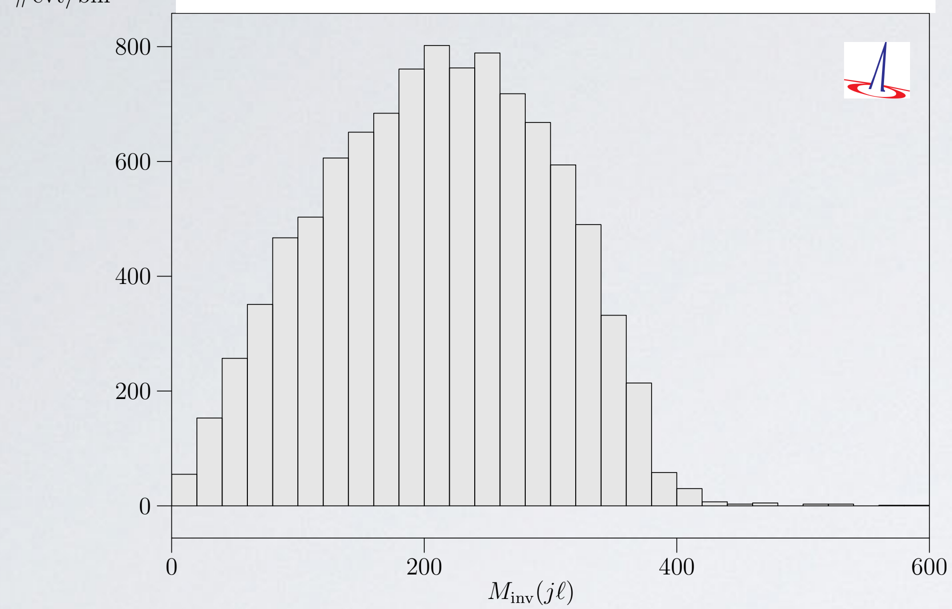
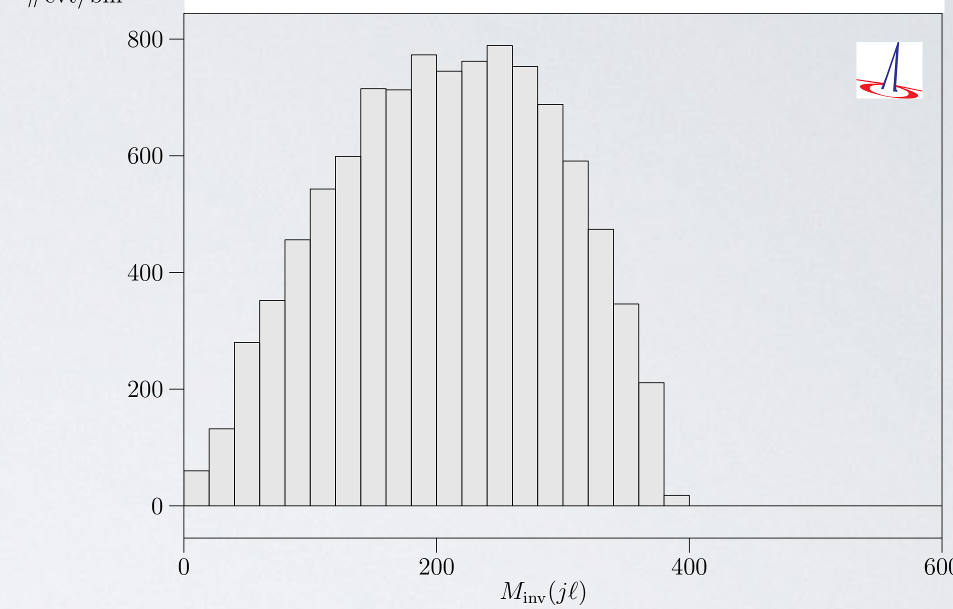
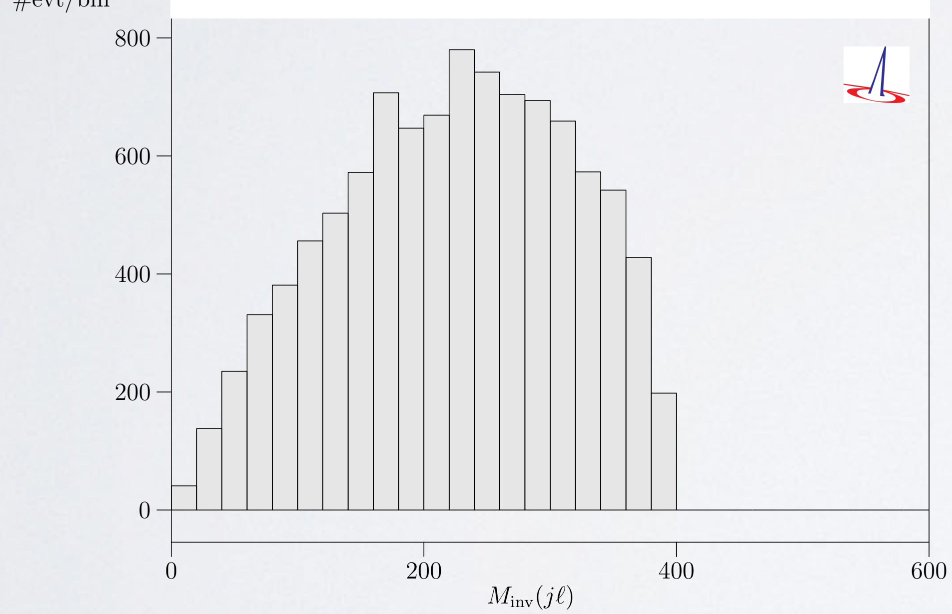
`simulate (fullproc)`



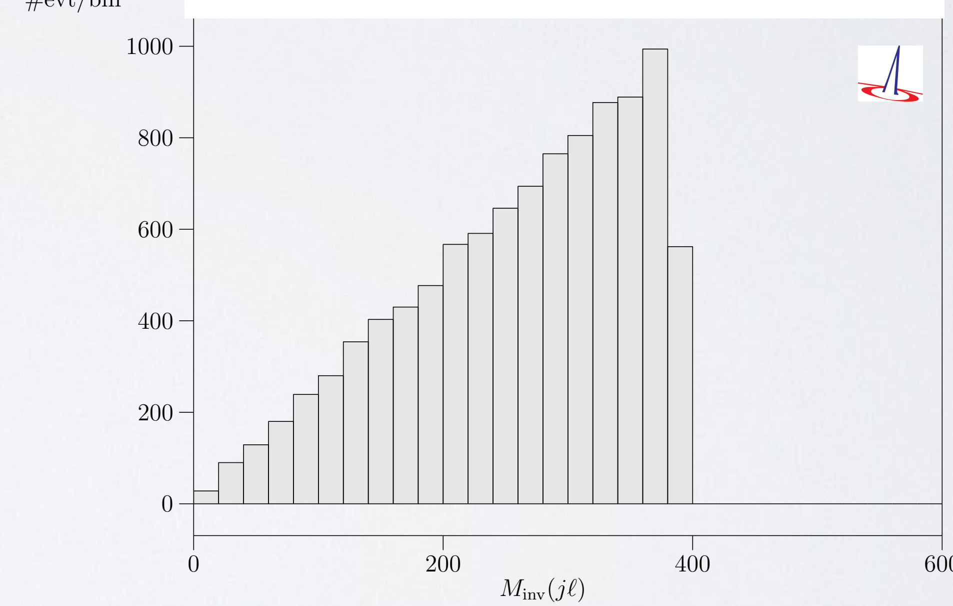
`simulate (casc)`



`?diagonal_decay = true`



`?isotropic_decay = true`



Possibility to select specific helicity in decays!

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

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

Beam structure: special beams

Beam polarization, ILC-like setup

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

Polarized decays: longitudinal *Z*

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

Scan over polarizations

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

Asymmetric beams

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

Beams with crossing angle

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

Beams with rotated crossing angle

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

Structure functions (also concatenated)

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

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

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

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

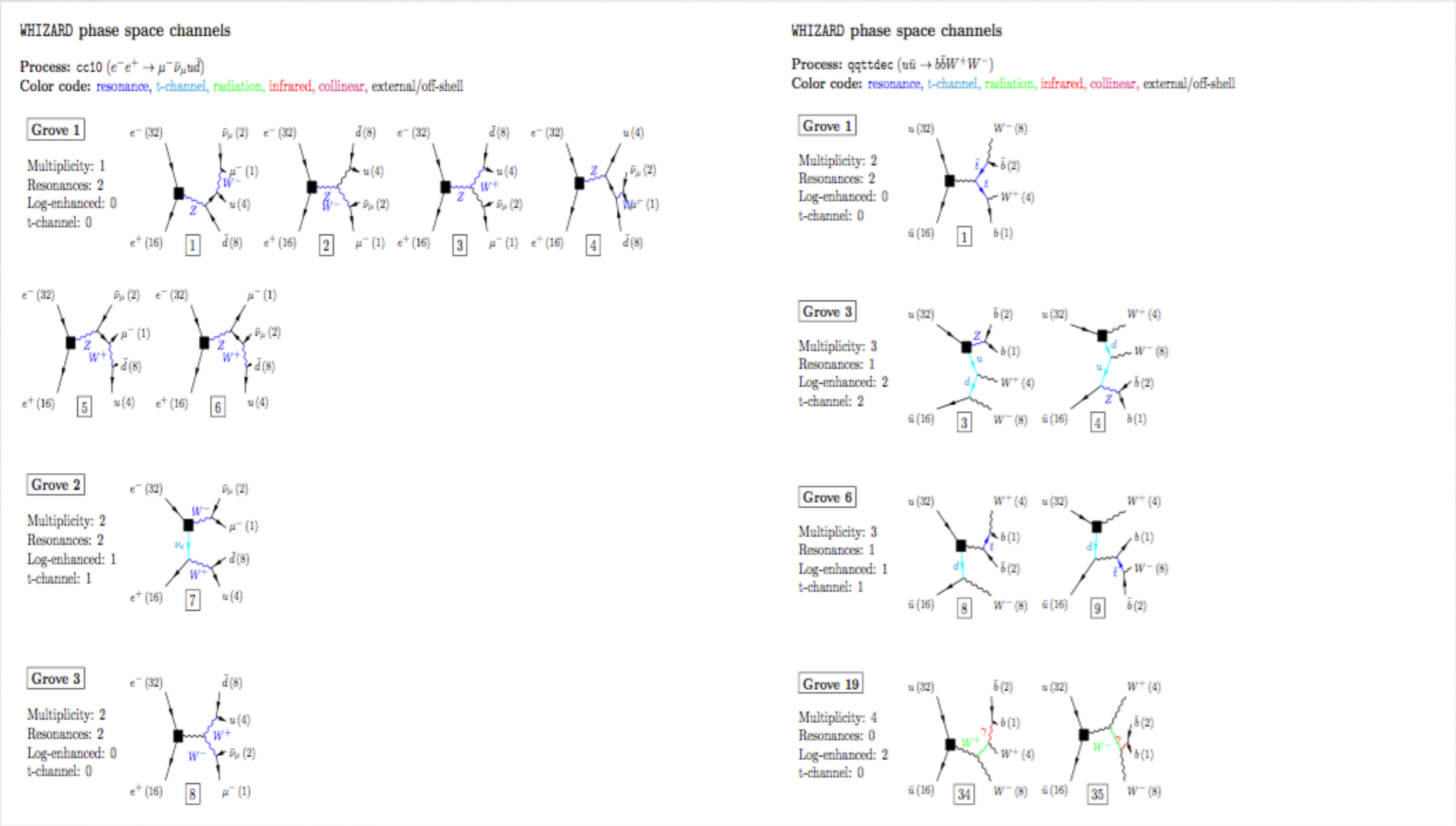
```
beams = e, E => circe2 => isr => ewa
```

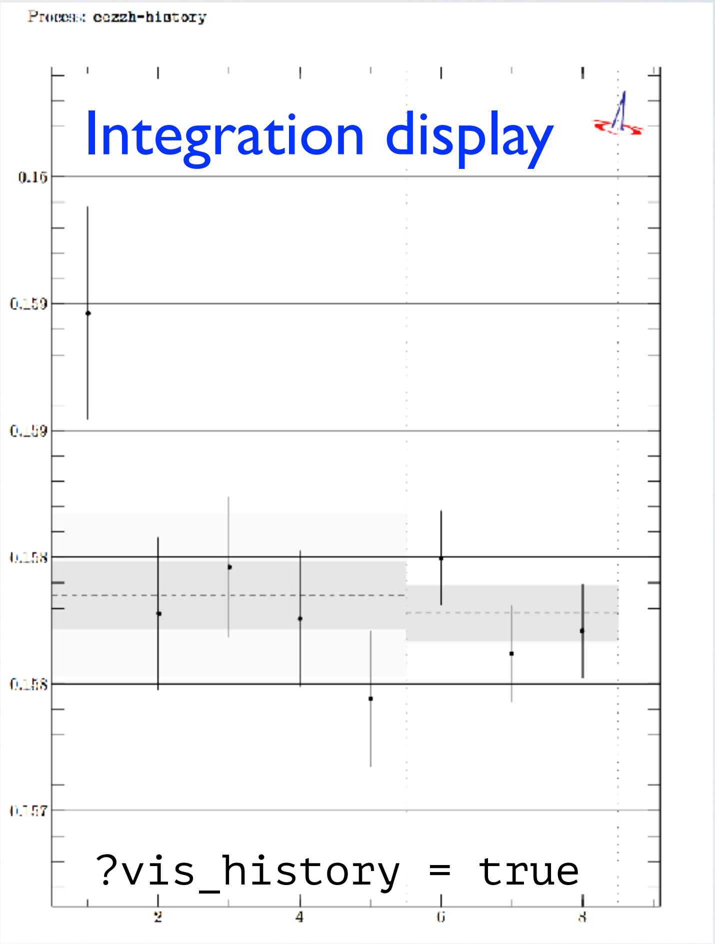
```
beams = e1, E1 => beam_events
$beam_events_file = “uniform_spread_2.5%.dat”
```

Phase Space Integration

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

WHIZARD algorithm: heuristics to classify phase-space topology, adaptive multi-channel mapping $\Longrightarrow$ resonant, t-channel, radiation, infrared, collinear, off-shell





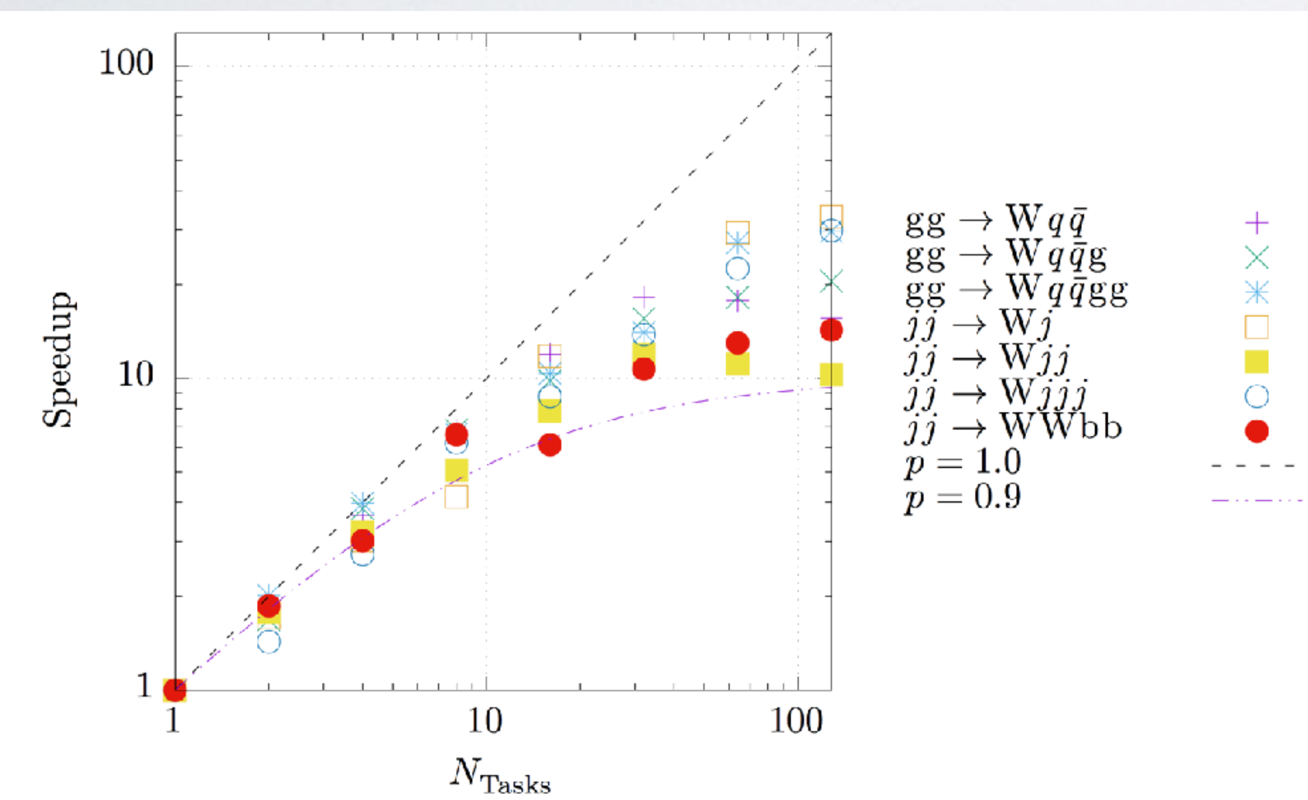
Complicated processes: factorization into production and decay with the unstable option

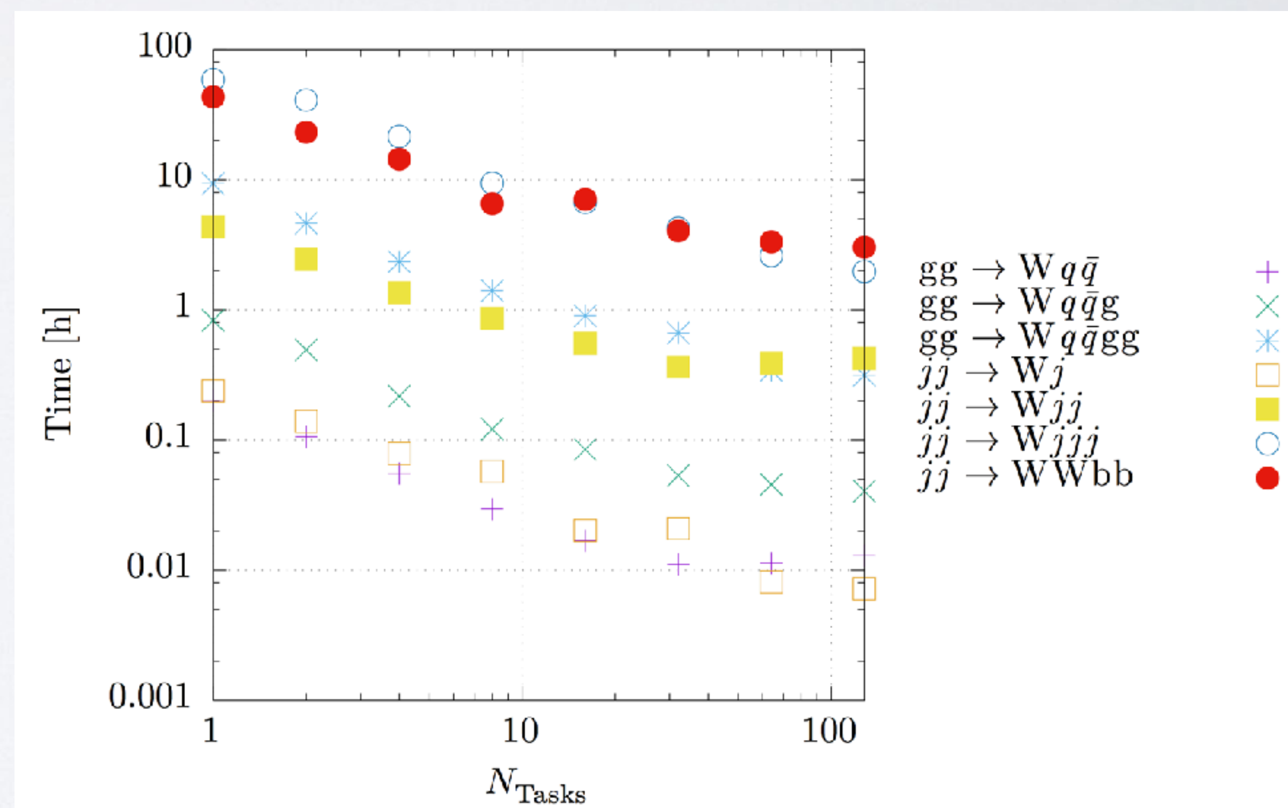
Resonance-aware factorization for NLO processes and parton showers (e.g. $e^+e^- \to jjjj$)

MPI Parallelization

NEW

- Event generation trivially parallelizable
- Major bottleneck: phase space integration (generation of grids)
- Parallelization of integration: OMP multi-threading for different helicities since long
- NEW (after v2.5.0): MPI parallelisation (using OpenMPI)
- 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!





Keep resonances in ME-PS merging

NEW

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

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

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  but by resonances $e^+e^- \to WW/ZZ \to (jj)(jj)$
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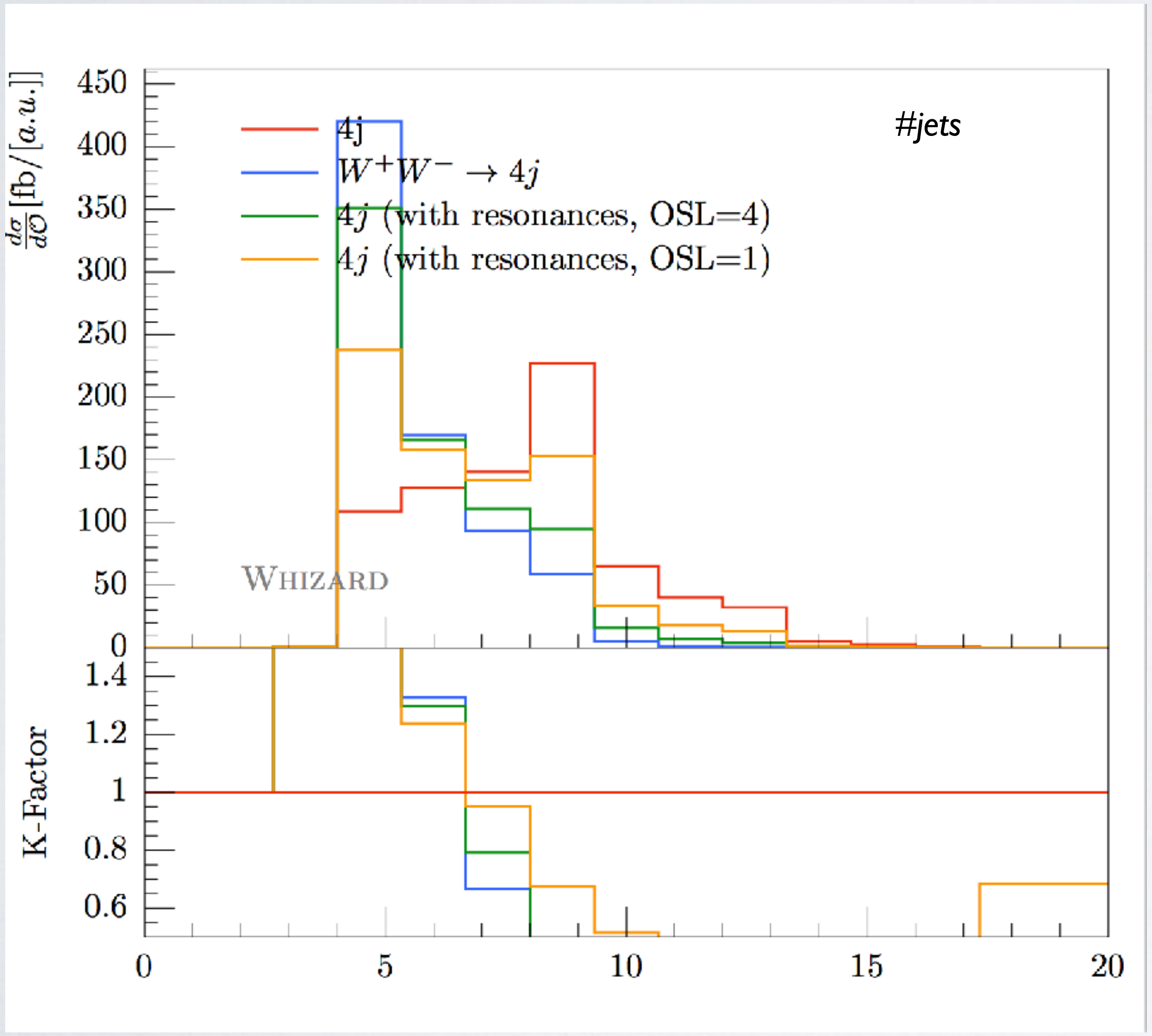

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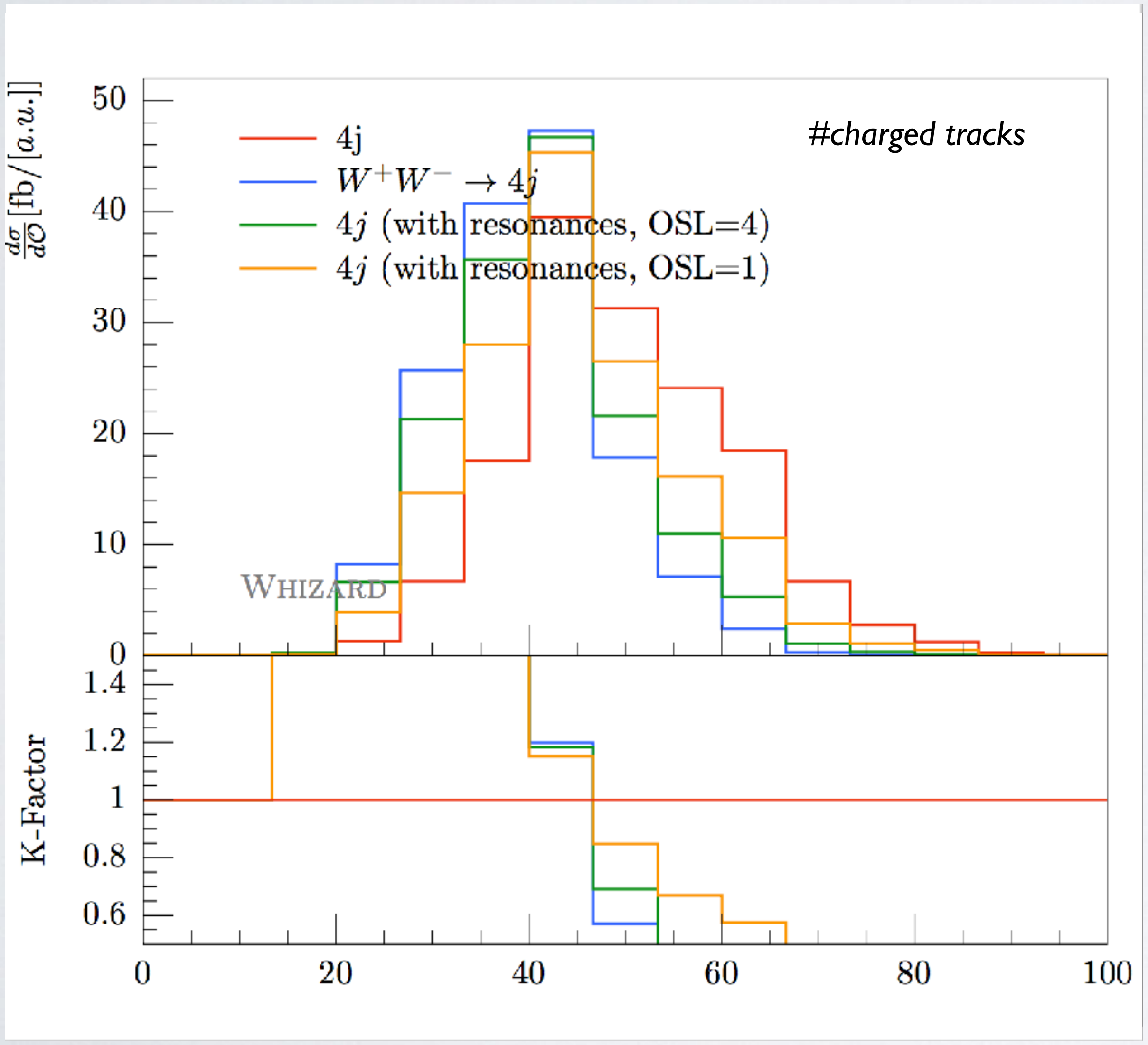
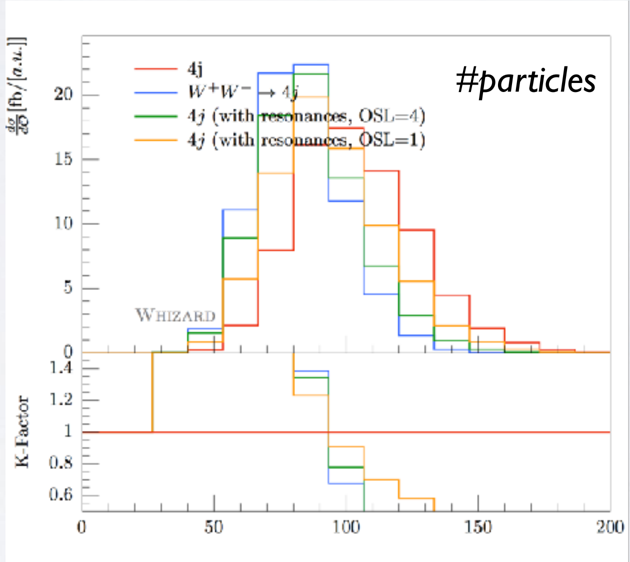
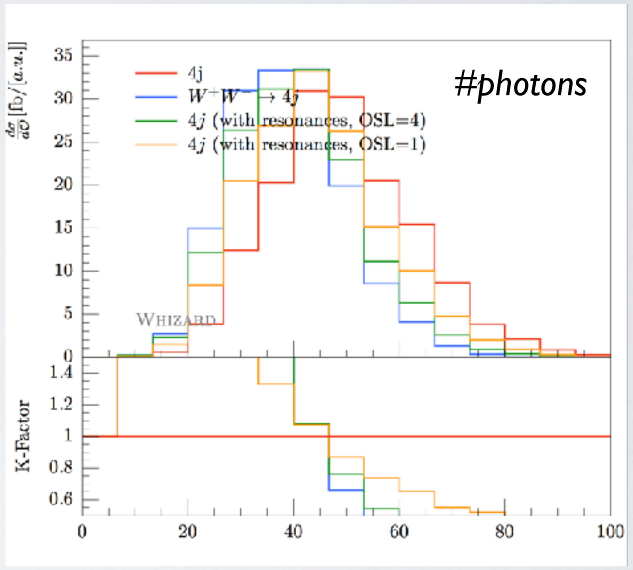
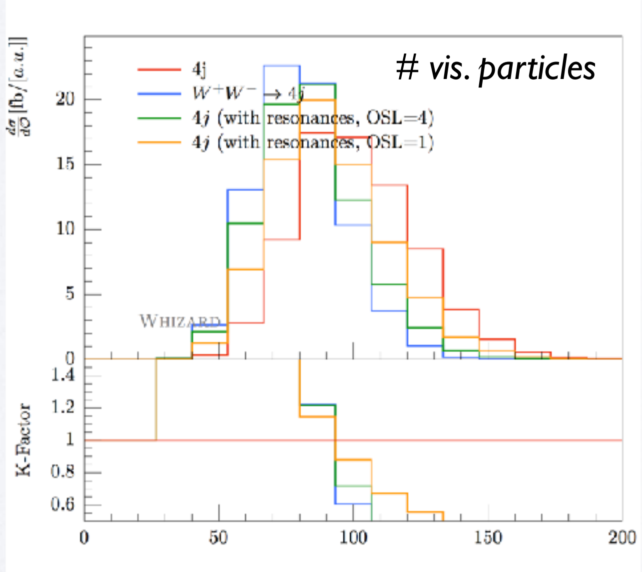
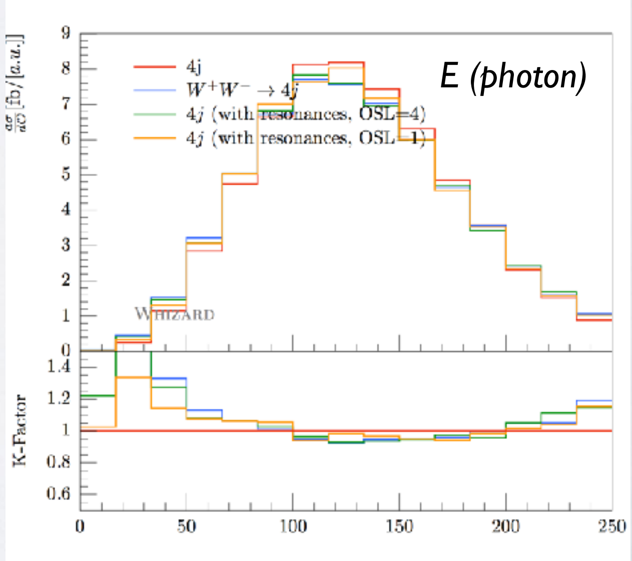
```











BSM Models in WHIZARD

MODEL TYPE	with CKM matrix	trivial CKM
Yukawa test model	---	Test
QED with e, μ, τ, γ	---	QED
QCD with d, u, s, c, b, t, g	---	QCD
Standard Model	SM_CKM	SM
SM with anomalous gauge couplings	SM_ac_CKM	SM_ac
SM with Hgg, $H\gamma\gamma$, $H\mu\mu$	---	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	2HDM_CKM	2HDM
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	---	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	---	PSSSM
Littlest Higgs	---	Littlest
Littlest Higgs with ungauged $U(1)$	---	Littlest_Eta
Littlest Higgs with T parity	---	Littlest_Tpar
Simplest Little Higgs (anomaly-free)	---	Simplest
Simplest Little Higgs (universal)	---	Simplest_univ
SM with graviton	---	Xdim
UED	---	UED
"SQED" with gravitino	---	GravTest
Augmentable SM template	---	Template

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

BSM Models in WHIZARD

MODEL TYPE	with CKM matrix	trivial CKM
Yukawa test model	---	Test
QED with e, 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, $H\gamma\gamma$, $H\mu\mu$	---	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	2HDM_CKM	2HDM
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	---	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	---	PSSSM
Littlest Higgs	---	Littlest
Littlest Higgs with ungauged $U(1)$	---	Littlest_Eta
Littlest Higgs with T parity	---	Littlest_Tpar
Simplest Little Higgs (anomaly-free)	---	Simplest
Simplest Little Higgs (universal)	---	Simplest_univ
SM with graviton	---	Xdim
UED	---	UED
"SQED" with gravitino	---	GravTest
Augmentable SM template	---	Template

- Automated models: interface to SARAH/BSM Toolbox Staub, 0909.2863; Ohl/Porod/Staub/Speckner, 1109.5147
- Automated models: interface to FeynRules Christensen/Duhr; Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251
- Automated models: UFO interface [new WHIZARD/O'Mega model format] **NEW in v2.5.0**

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)
```

NEW

All the setup works the same as for intrinsic models

Old FeynRules / SARAH interface might get deprecated

kept at the moment for user backwards compatibility

All SM-like models/scalar extensions already supported

Higher-dim. operators, general Lorentz/color structures is work in progress (scheduled end of 2017)

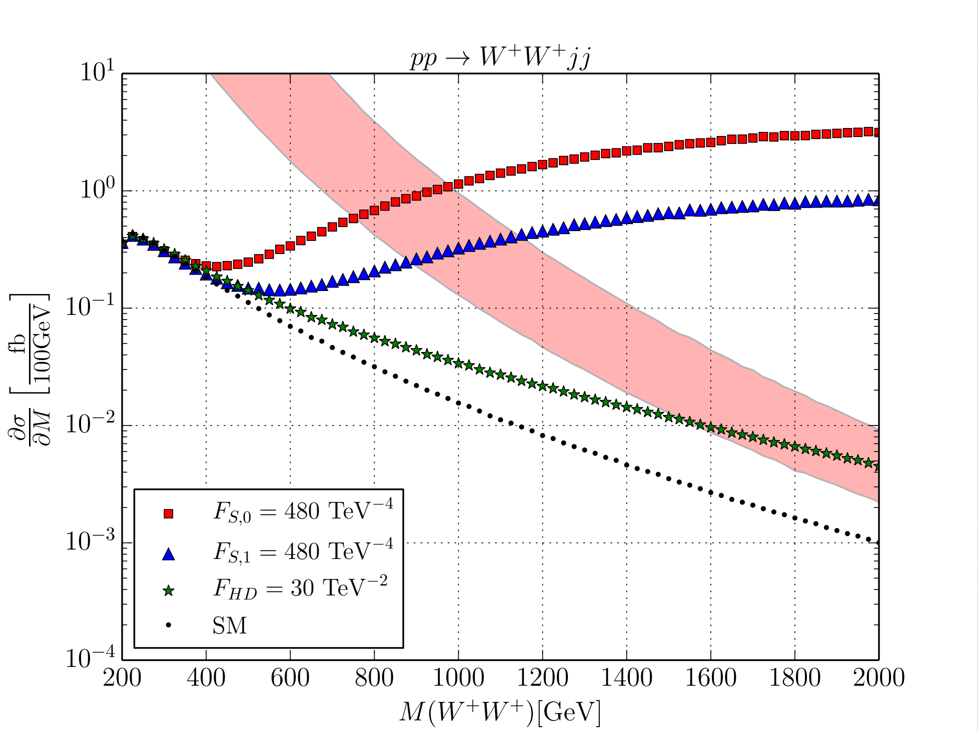
New Physics in Vector Boson Scattering: LHC

- Vector Boson Scattering (VBS) major measurement of LHC runs II/III Gianotti, 01/2014
- Light Higgs suppression makes VBS prime candidate for BSM searches
- Model-independent EFT descriptions not so useful: either weakly-coupled resonances in reach or strongly-coupled sectors Alboteanu/Kilian/JRR, 0806.4145; Kilian/Ohl/JRR/Sekulla, 1408.6207
- Parameterize new physics by dim 6/dim 8 operators, calculate unitarity limits
- Dimension-8 operators for longitudinal/mixed/transverse modes Fleper/Kilian/JRR/Sekulla, 2017
- T-matrix unitarization implemented in `WHIZARD` (both for operators and resonances)

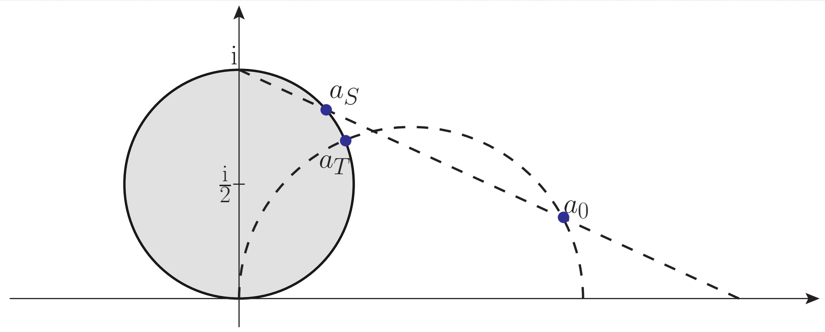
$$\mathcal{L}_{S,0} = F_{S,0}\mathrm{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}_\nu\mathbf{H})]\,\mathrm{Tr}[(\mathbf{D}^\mu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})]$$
$$\mathcal{L}_{S,1} = F_{S,1}\mathrm{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})]\,\mathrm{Tr}[(\mathbf{D}_\nu\mathbf{H})^\dagger(\mathbf{D}^\nu\mathbf{H})]$$

$$\mathcal{L}_{M,0} = -g^2 F_{M,0}\mathrm{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})]\,\mathrm{Tr}[\mathbf{W}_{\nu\rho}\mathbf{W}^{\nu\rho}]$$
$$\mathcal{L}_{M,1} = -g^2 F_{M,1}\mathrm{Tr}[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\rho\mathbf{H})]\,\mathrm{Tr}[\mathbf{W}_{\nu\rho}\mathbf{W}^{\nu\mu}]$$

$$\mathcal{L}_{T,0} = g^4 F_{T,0}\mathrm{Tr}[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}]\,\mathrm{Tr}[\mathbf{W}_{\alpha\beta}\mathbf{W}^{\alpha\beta}]$$
$$\mathcal{L}_{T,1} = g^4 F_{T,1}\mathrm{Tr}[\mathbf{W}_{\alpha\nu}\mathbf{W}^{\mu\beta}]\,\mathrm{Tr}[\mathbf{W}_{\mu\beta}\mathbf{W}^{\alpha\nu}]$$
$$\mathcal{L}_{T,2} = g^4 F_{T,2}\mathrm{Tr}[\mathbf{W}_{\alpha\mu}\mathbf{W}^{\mu\beta}]\,\mathrm{Tr}[\mathbf{W}_{\beta\nu}\mathbf{W}^{\nu\alpha}]$$

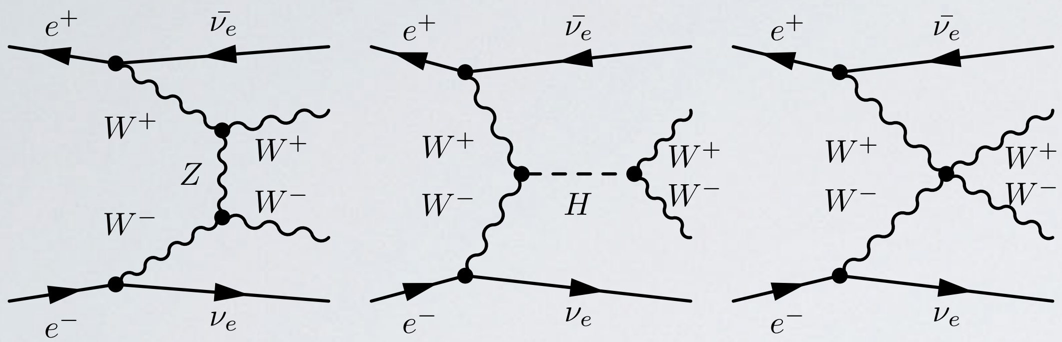


T-matrix unitarization

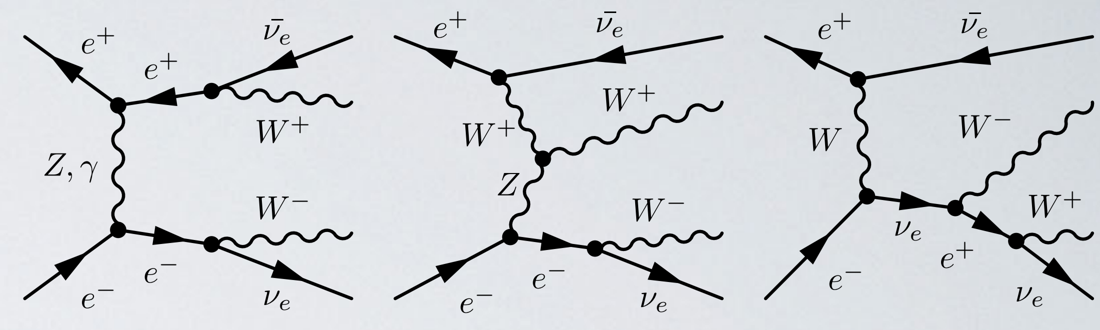


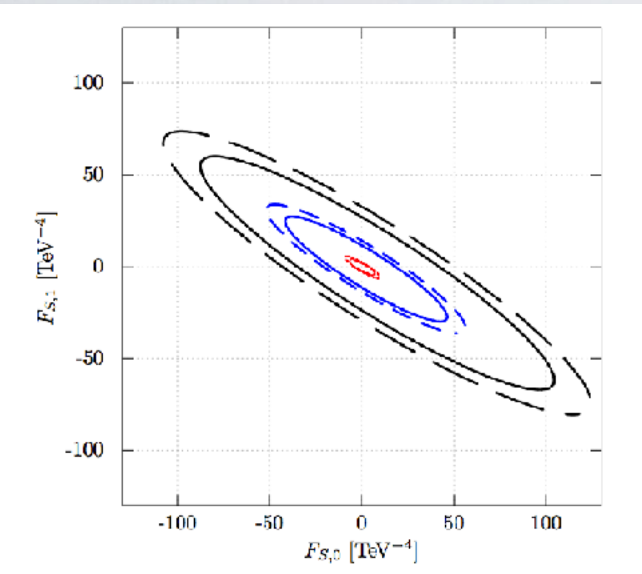
New Physics in VBS: LHC & Lepton Colliders

Signal

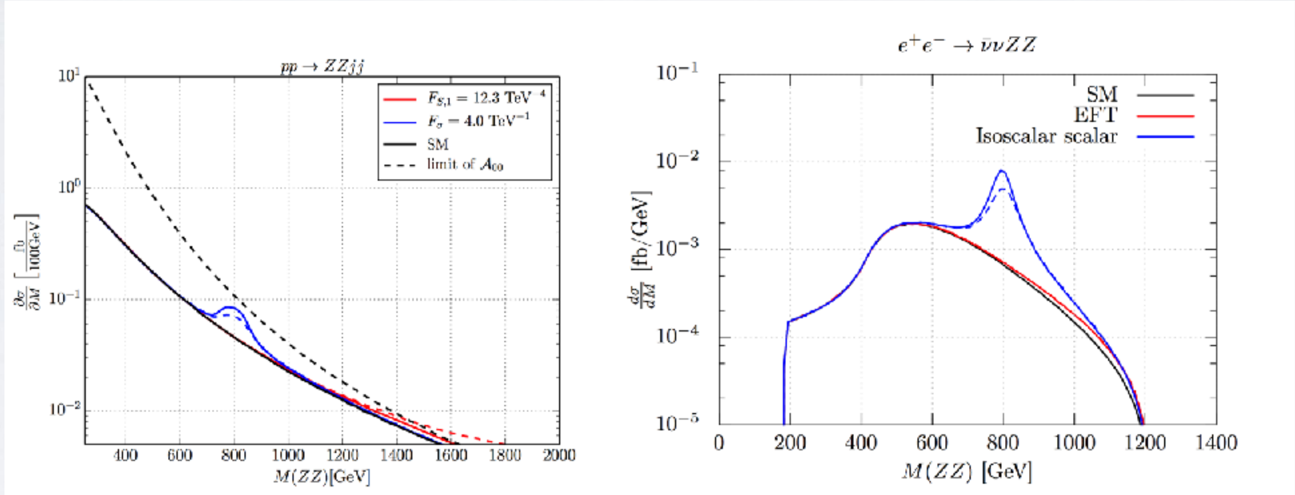


Bkgd.

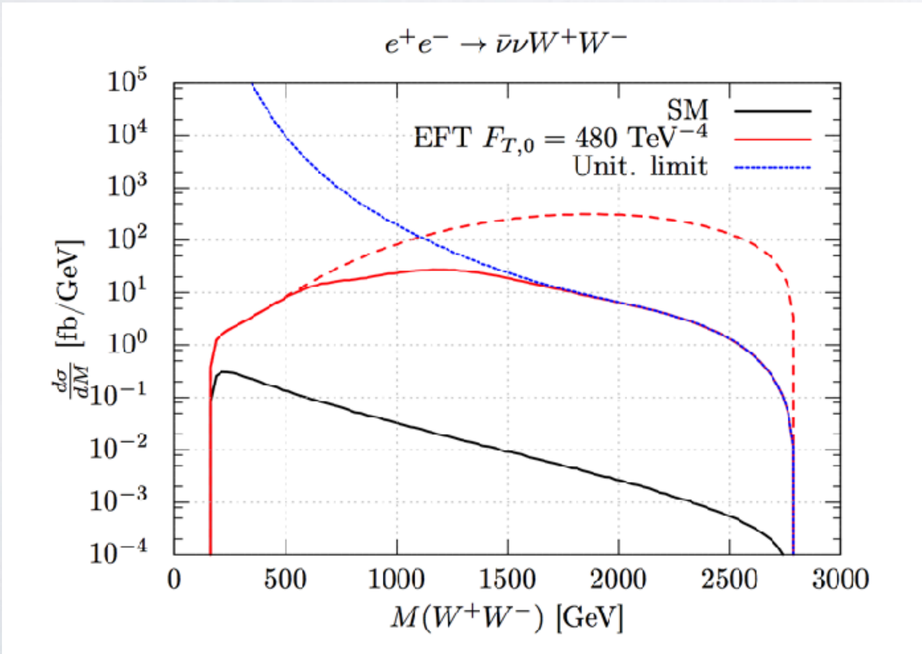


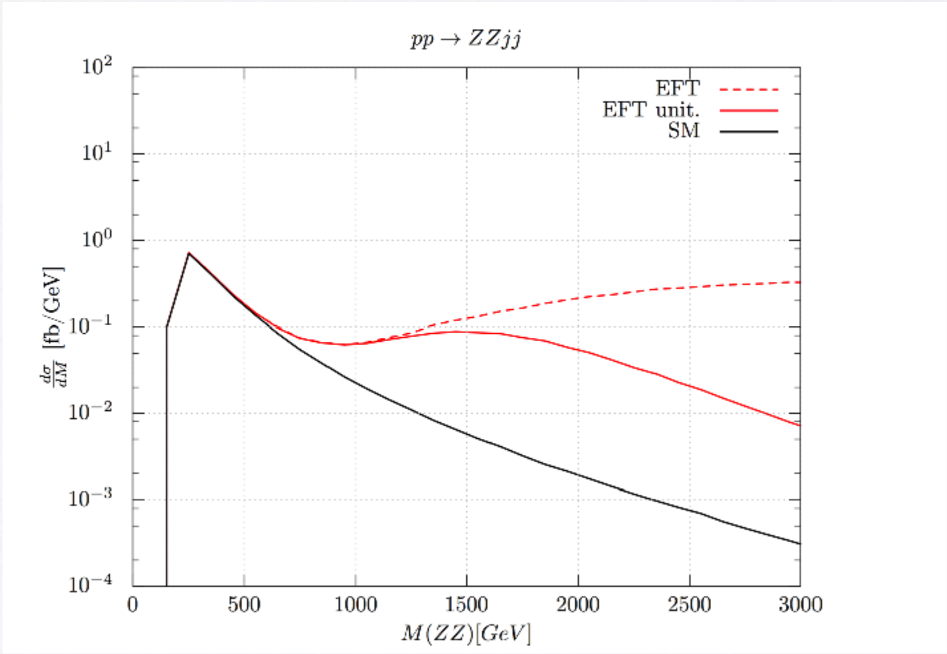


Fleper/Kilian/JRR/Sekulla: Eur.Phys.J. C77 (2017) no.2, 120



LHC (14 TeV) CLIC (1.4 TeV)





Fleper/Kilian/JRR/Sekulla: *to appear soon*

WIP:

Unitarity limits for $pp \to VVV$

Kilian/JRR/Sekulla

VBS SM: Comparison VBScan COST network

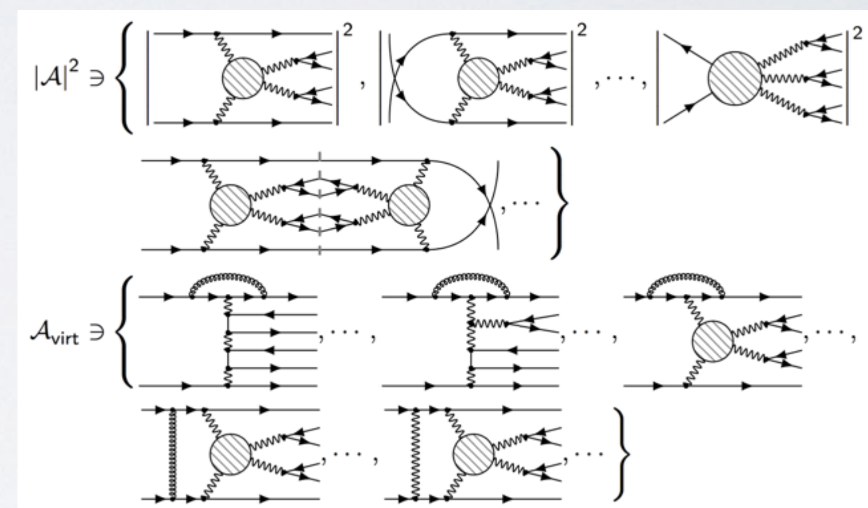
A. Karlberg/M. Pellen/M. Rauch/JRR/V. Rothe/C. Schwan/P. Stienemeier/M. Zaro

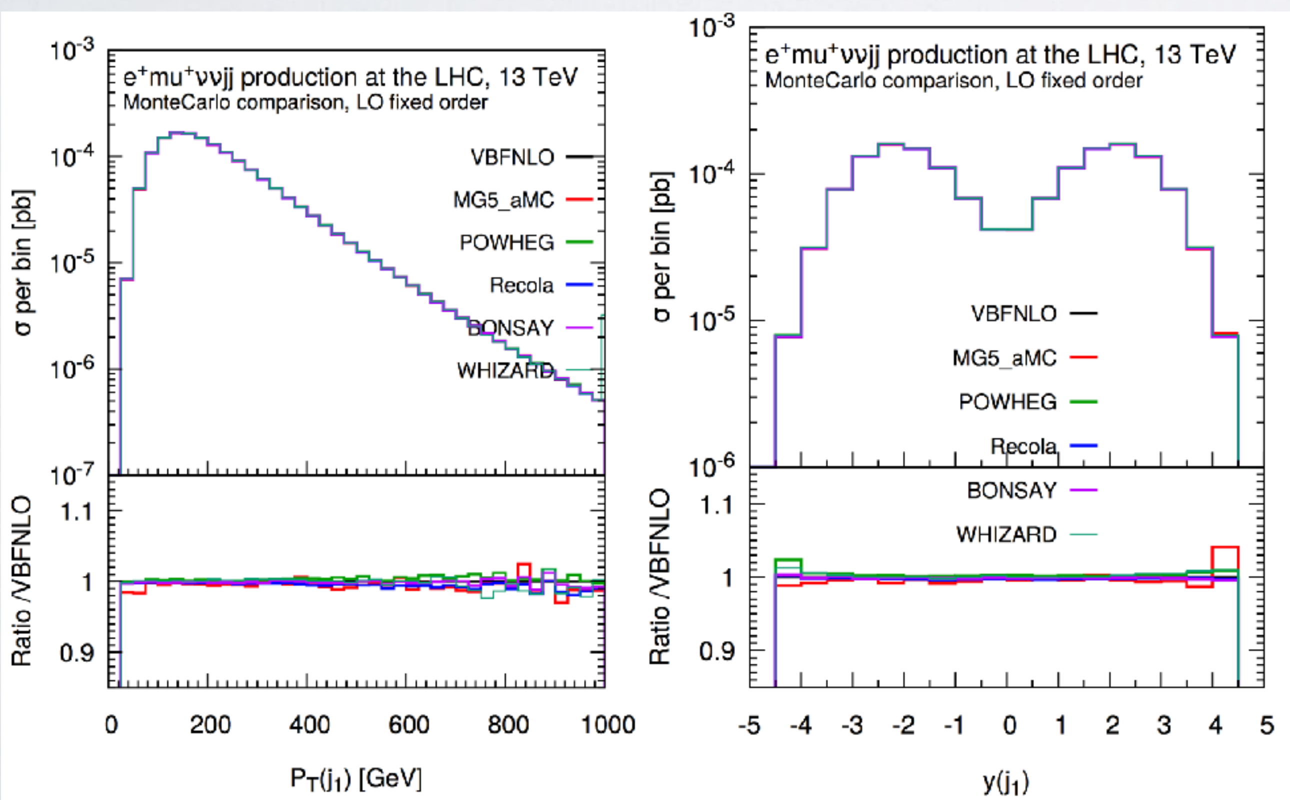
$\mathcal{O}(\alpha^6)$ Integrated Cross Sections for pp $\to e^+ \nu_e \mu^+ \nu_\mu jj + X$

NLO comparison still under way

Code	LO σ [fb]
BONSAY	1.5524 ± 0.0002
MG5_aMC	1.547 ± 0.001
POWHEG	1.5573 ± 0.0003
RECOLA+MOCANLO	1.5503 ± 0.0003
VBFNLO	1.5538 ± 0.0002
WHIZARD	1.5539 ± 0.0004

Contact person	Code	Squares	Interf.	Off-shell	NF QCD	EW Corr.
A. Karlberg	POWHEG	t/u	No	Yes	No	No
M. Pellen	RECOLA+MOCANLO	Yes	Yes	Yes	Yes	Yes
M. Rauch	VBFNLO	Yes	No	Yes	No	No
C. Schwan	BONSAY	t/u	No	V+l PA	No	No
M. Zaro	MG5_aMC	Yes	Yes	Yes	No	No
V. Rothe	WHIZARD	Yes	Yes	Yes	Yes	Yes





Code	LO σ [fb]	NLO σ [fb]
BONSAY	1.5524 ± 0.0002	1.3469 ± 0.0008
MG5_aMC	1.547 ± 0.001	1.318 ± 0.003
POWHEG	1.5573 ± 0.0003	1.334 ± 0.003
RECOLA+MOCANLO	1.5503 ± 0.0003	1.317 ± 0.004
VBFNLO	1.5538 ± 0.0002	1.3531 ± 0.0003
WHIZARD	1.5539 ± 0.0004	

NLO Automation in WHIZARD

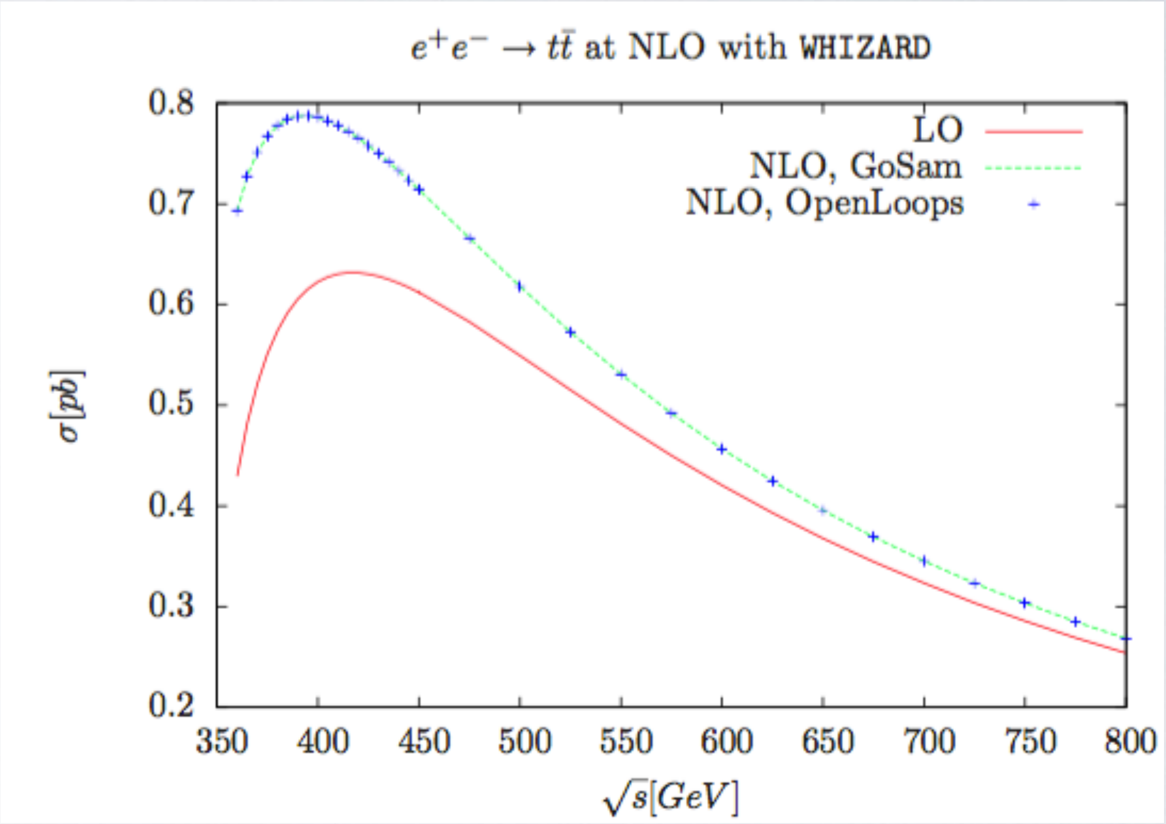
Working NLO interfaces to:

- ★ 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]

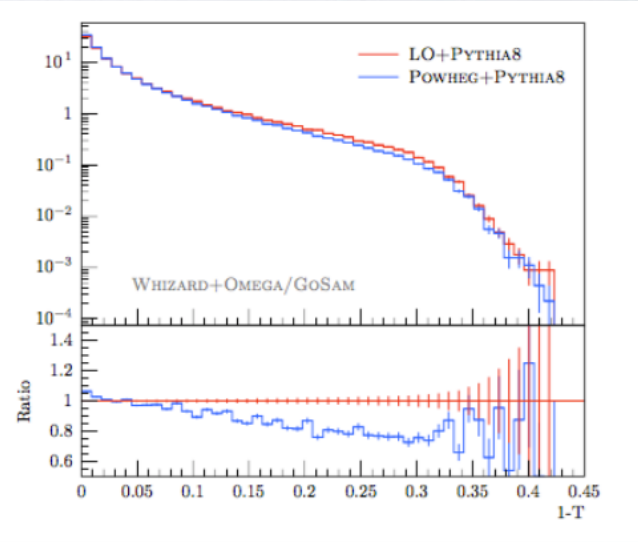
NLO QCD (massless & massive emitters) fully supported

```
alpha_power = 2
alphas_power = 0

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



- FKS subtraction [Frixione/Kunszt/Signer,
- 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, either LHEF or HepMC)
- Automated POWHEG damping and matching



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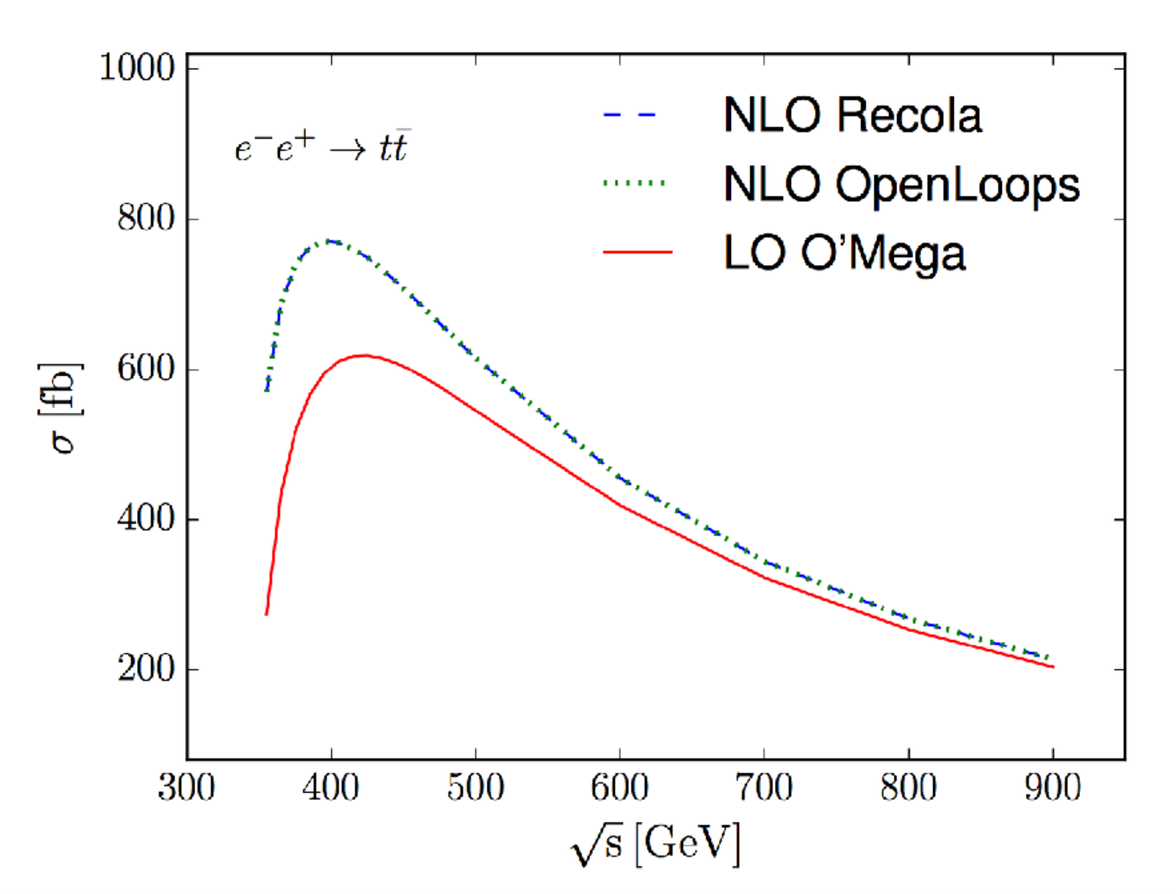

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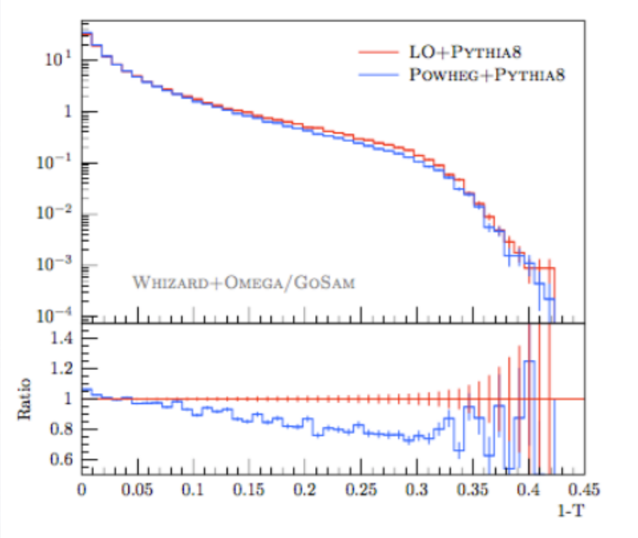


Examples and Validation

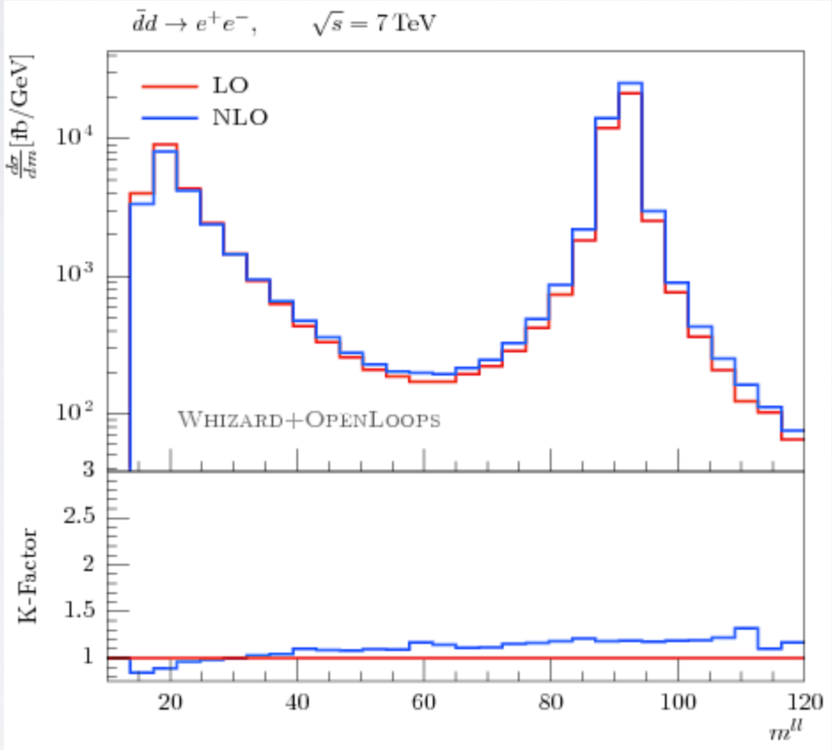
List of validated NLO QCD processes

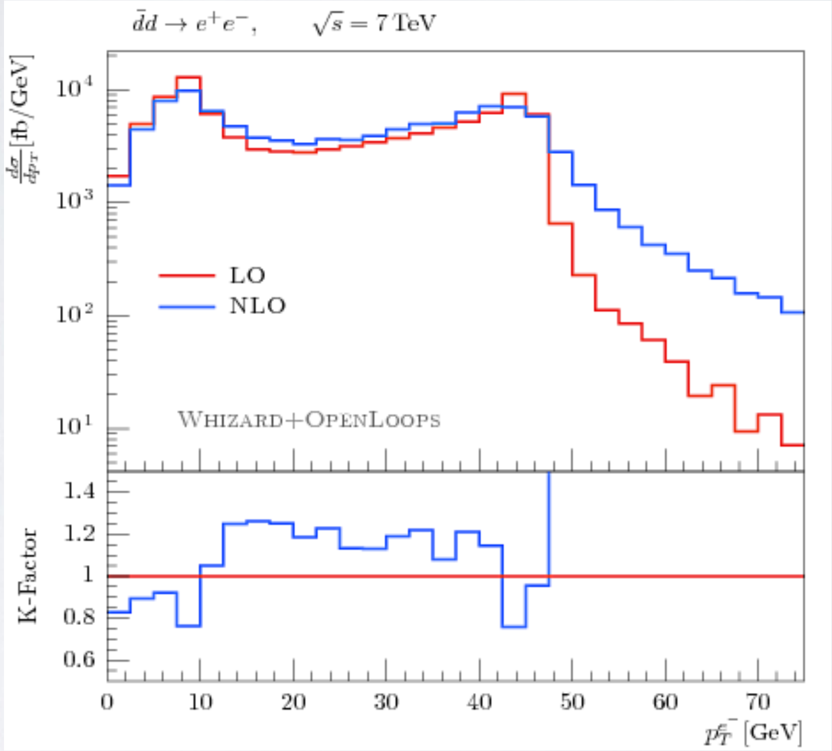
- $e^+e^- \to jj$
- $e^+e^- \to jjj$
- $e^+e^- \to \ell^+\ell^- jj$
- $e^+e^- \to \ell^+\nu_\ell jj$
- $e^+e^- \to t\bar{t}$
- $e^+e^- \to t\bar{t}t\bar{t}$
- $e^+e^- \to t\bar{t}W^+ jj$
- $e^+e^- \to tW^- b$
- $e^+e^- \to W^+W^- b\bar{b}, \quad \ell^+\ell^-\nu_\ell\bar{\nu}_\ell b\bar{b}$
- $e^+e^-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

NEW

- Simplest hadron collider processes validated:

$pp \to (Z \to ll) + X, \quad pp \to (W \to l\nu) + X, \quad pp \to ZZ + X$



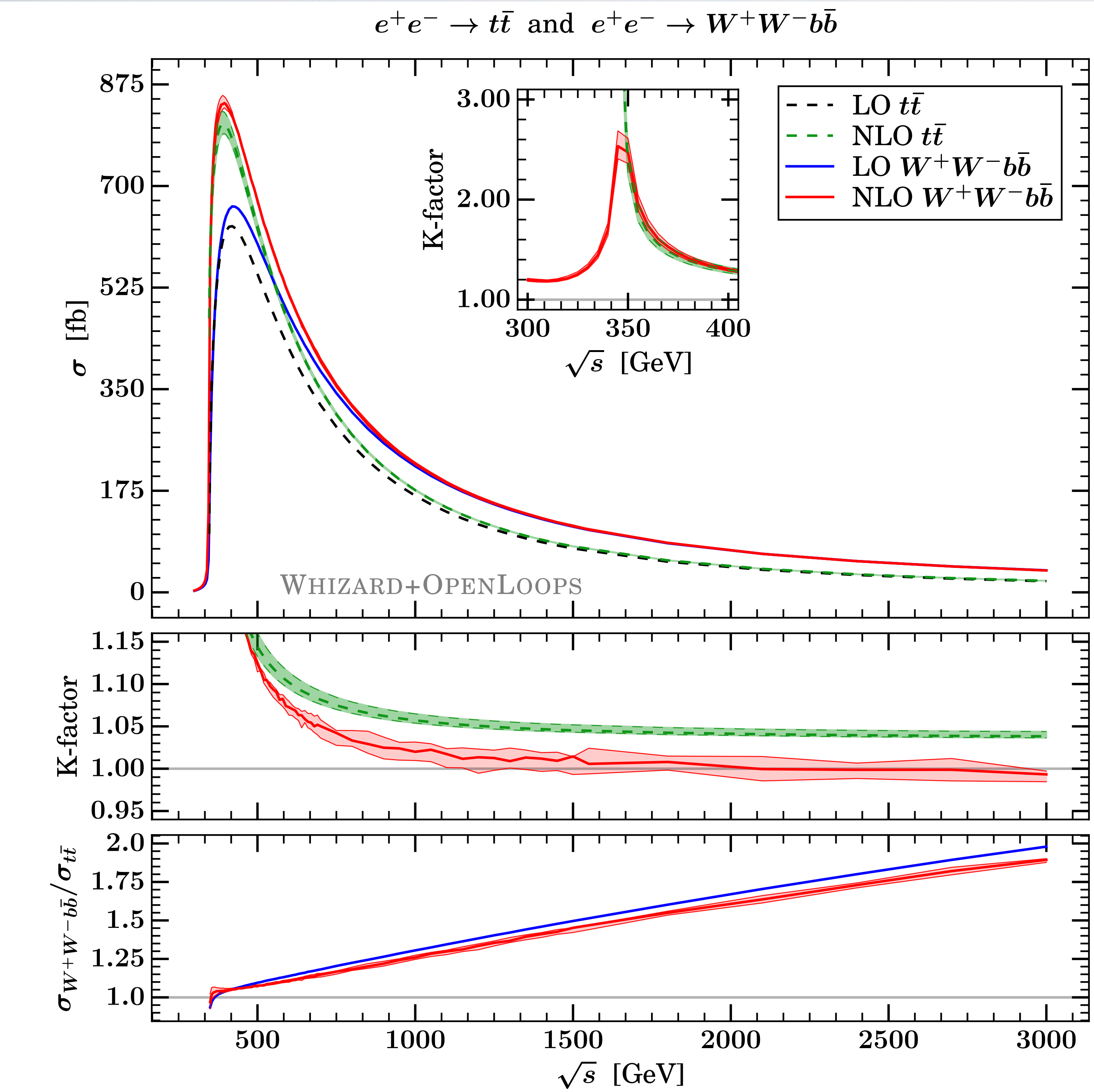


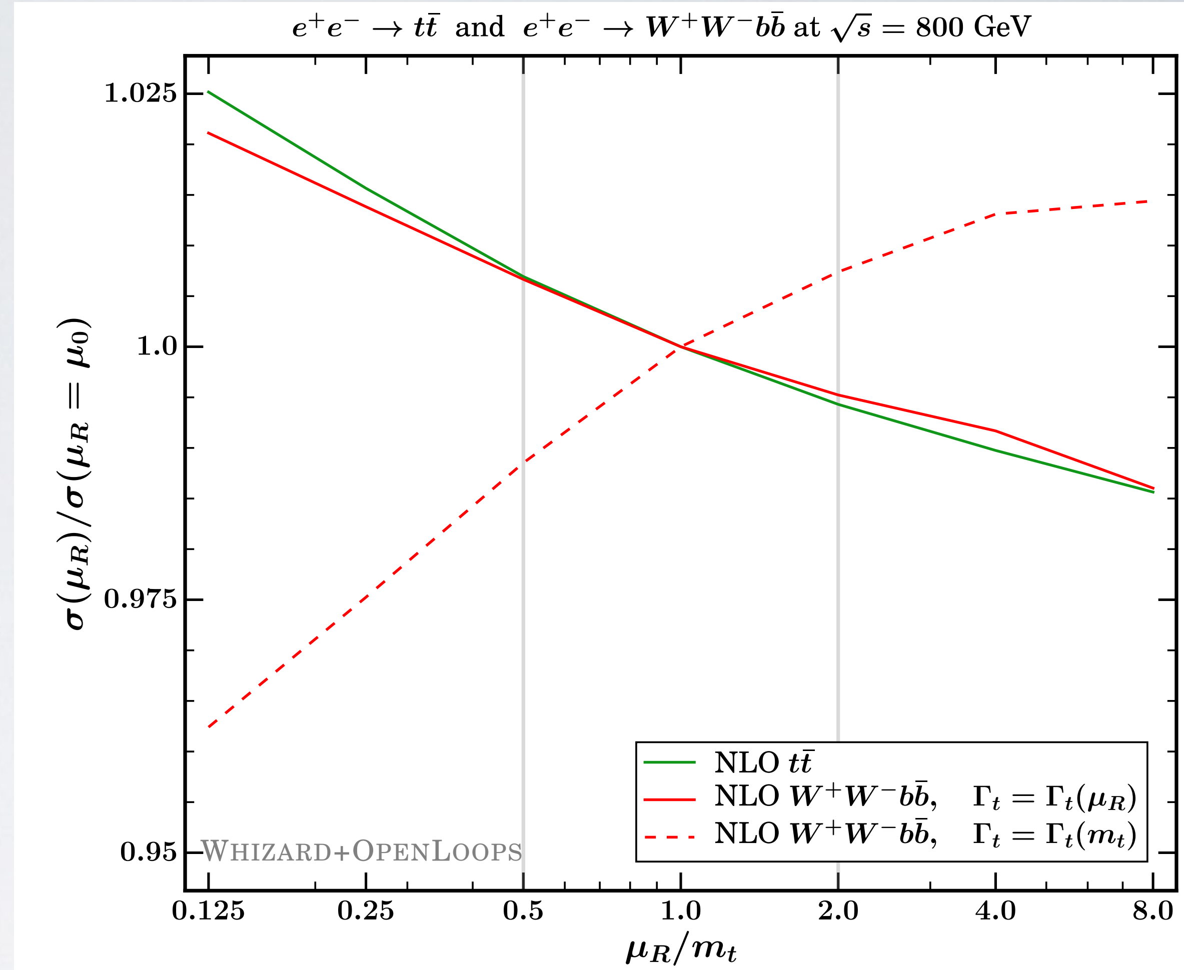
- ✦ QCD NLO infrastructure in pp close to complete
- ✦ After complete NLO QCD validation: WHIZARD v3.0.0
- ✦ Status of EW corrections: all parts technically completed, validation phase started [Rothe et al.]

Validation of NLO QCD for Lepton Collisions

Final state	MG5_aMC σ^{LO}[fb]	MG5_aMC σ^{NLO}[fb]	MG5_aMC K	WHIZARD σ^{LO}[fb]	WHIZARD σ^{NLO}[fb]	WHIZARD K
jj	622.3(5)	639(1)	1.02684	622.73(4)	639.7(2)	1.0272
$b\bar{b}$	92.37(6)	94.89(1)	1.02728	92.32(1)	94.78(7)	1.0266
$t\bar{t}$	166.2(2)	174.5(6)	1.04994	166.4(1)	175.1(1)	1.0522
$t\bar{t}t\bar{t}$	$6.45(1)\cdot 10^{-4}$	$12.21(5)\cdot 10^{-4}$	1.89302	$6.463(2)\cdot 10^{-4}$	$12.16(2)\cdot 10^{-4}$	1.8814
$b\bar{b}b\bar{b}$	$1.644(3)\cdot 10^{-1}$	$3.60(1)\cdot 10^{-1}$	2.1897	$1.64(2)\cdot 10^{-1}$	$3.67(4)\cdot 10^{-1}$	2.2378
$t\bar{t}b\bar{b}$	$1.819(3)\cdot 10^{-1}$	$2.92(1)\cdot 10^{-1}$	1.6052	$1.86(1)\cdot 10^{-1}$	$2.93(2)\cdot 10^{-1}$	1.5752
$t\bar{t}j$	48.13(5)	53.43(1)	1.11012	48.3(2)	53.66(9)	1.1109
$t\bar{t}H$	2.018(3)	1.911(6)	0.947	2.022(3)	1.913(3)	0.9461
$t\bar{t}\gamma$	12.7(2)	13.3(4)	1.04726	12.71(4)	13.78(4)	1.0841
$t\bar{t}Z$	4.642(6)	4.95(1)	1.06636	4.64(1)	4.94(1)	1.0646
$t\bar{t}HZ$	$3.600(6)\cdot 10^{-2}$	$3.58(1)\cdot 10^{-2}$	0.99445	$3.596(1)\cdot 10^{-2}$	$3.581(2)\cdot 10^{-2}$	0.9958
$t\bar{t}\gamma Z$	0.2212(3)	0.2364(6)	1.06873	0.220(1)	0.240(2)	1.0909
$t\bar{t}\gamma H$	$9.75(1)\cdot 10^{-2}$	$9.42(3)\cdot 10^{-2}$	0.96614	$9.748(6)\cdot 10^{-2}$	$9.58(7)\cdot 10^{-2}$	0.9827
$t\bar{t}\gamma\gamma$	0.383(5)	0.416(2)	1.08618	0.382(3)	0.420(3)	1.0995
$t\bar{t}ZZ$	$3.788(4)\cdot 10^{-2}$	$4.00(1)\cdot 10^{-2}$	1.05597	$3.756(4)\cdot 10^{-2}$	$4.005(2)\cdot 10^{-2}$	1.0663
$t\bar{t}HH$	$1.358(1)\cdot 10^{-2}$	$1.206(3)\cdot 10^{-2}$	0.888	$1.367(1)\cdot 10^{-2}$	$1.218(1)\cdot 10^{-2}$	0.8909
$t\bar{t}W^+W^-$	0.1372(3)	0.1540(6)	1.1225	0.1370(4)	0.1538(4)	1.1225
$t\bar{t}W^\pm jj$	$2.400(4)\cdot 10^{-4}$	$3.72(1)\cdot 10^{-4}$	1.54999	$2.41(1)\cdot 10^{-4}$	$3.74(2)\cdot 10^{-4}$	1.5518
jjj	340.1(2)	316(2)	0.92914	342.4(5)	319(1)	0.9316
$jjjj$	104.7(1)	109.0(6)	1.04106	105.1(4)	118(1)	1.1227
$t\bar{t}t\bar{t}j$	$2.719(5)\cdot 10^{-5}$	$5.34(3)\cdot 10^{-5}$	1.96394	$2.722(1)\cdot 10^{-5}$	$4.471(5)\cdot 10^{-5}$	1.6425
$t\bar{t}Hj$	0.2533(3)	0.2658(9)	1.04935	0.254(1)	0.307(1)	1.2087
$t\bar{t}\gamma j$	2.355(2)	2.62(1)	1.11253	2.47(1)	3.14(2)	1.2712
$t\bar{t}Zj$	0.6059(6)	0.694(3)	1.14548	0.610(4)	0.666(5)	1.0918

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

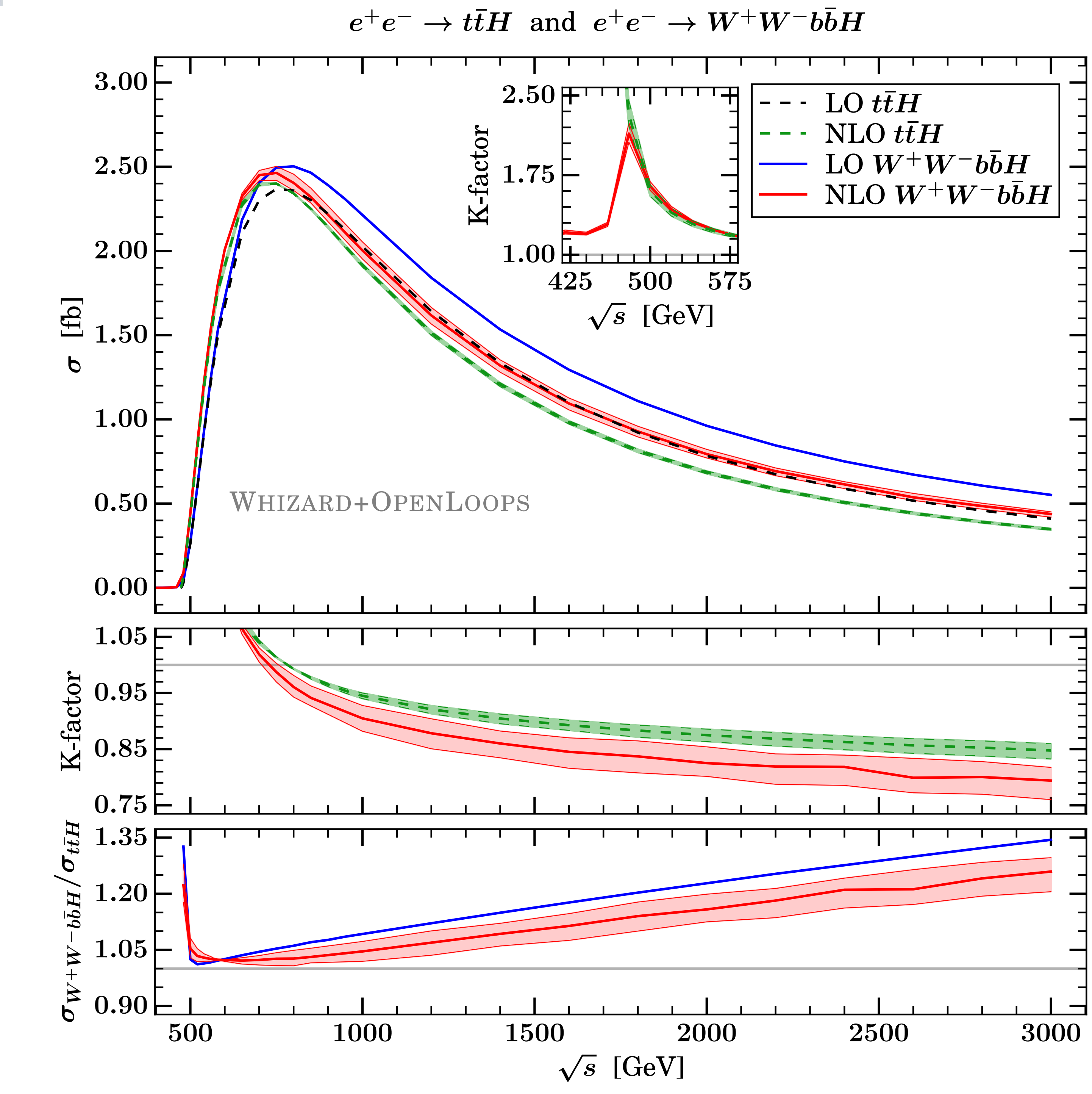


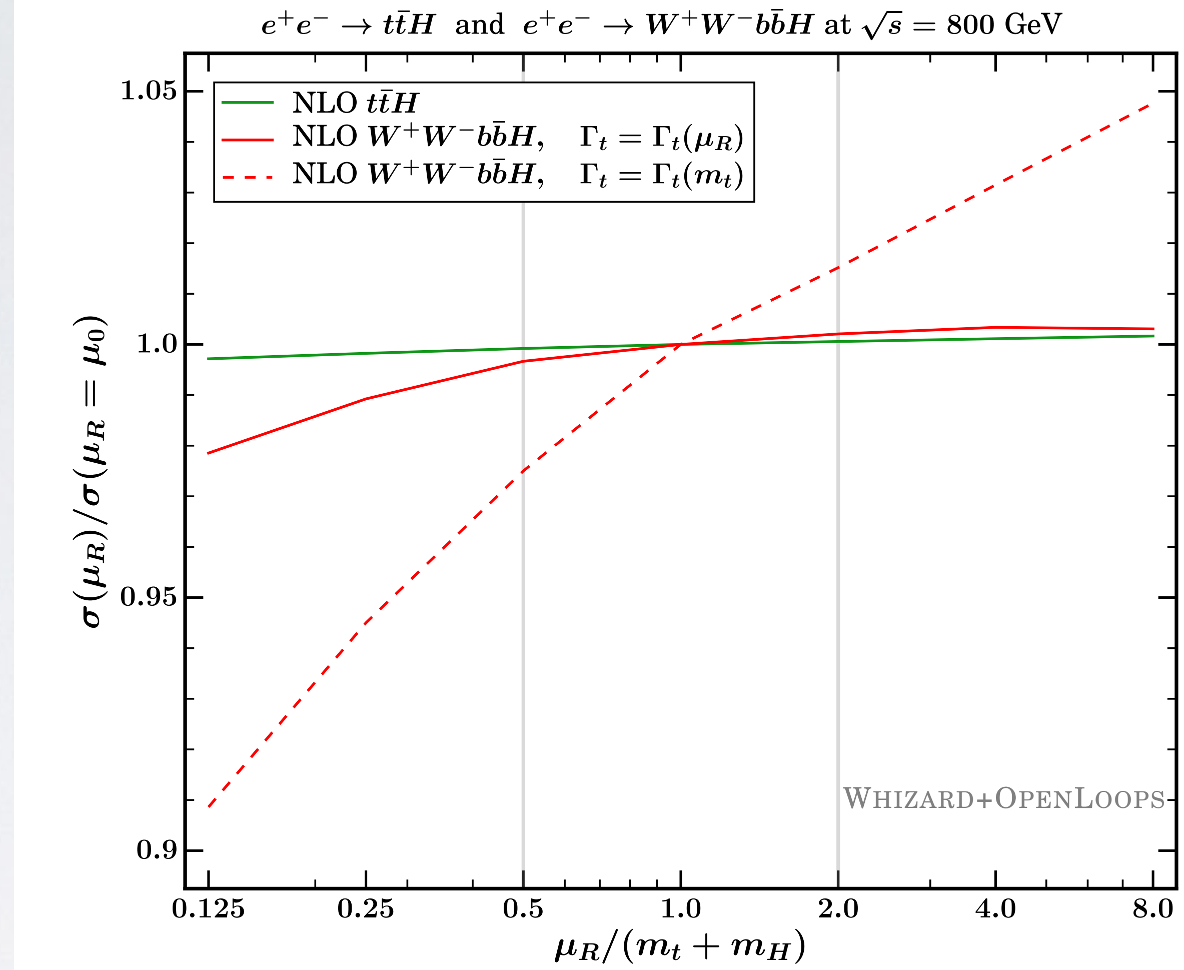


	$e^+e^- \to t\bar{t}$			$e^+e^- \to W^+W^-b\bar{b}$		
$\sqrt{s}$ [GeV]	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor	$\sigma^{\rm LO}$[fb]	$\sigma^{\rm NLO}$[fb]	K-factor
500	548.4	$627.4^{+1.4\%}_{-0.9\%}$	1.14	600.7	$675.1^{+0.4\%}_{-0.8\%}$	1.12
800	253.1	$270.9^{+0.8\%}_{-0.4\%}$	1.07	310.2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

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

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

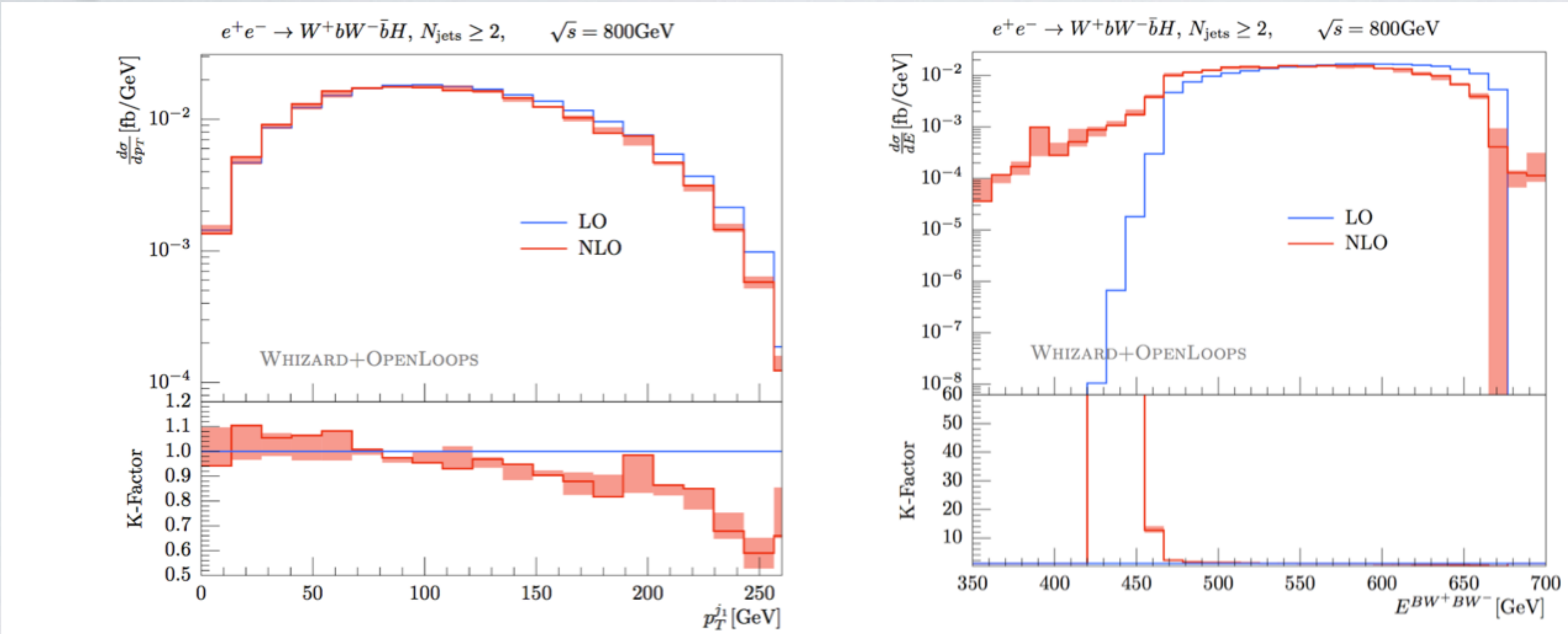


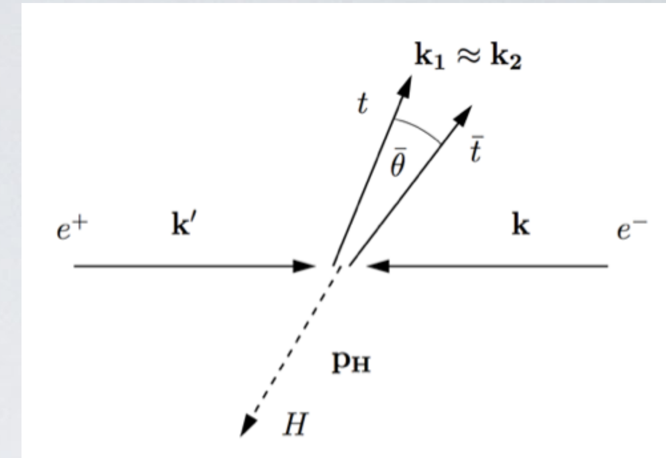


	$e^+e^- \to t\bar{t}H$			$e^+e^- \to W^+W^-b\bar{b}H$		
$\sqrt{s}$ [GeV]	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor
500	0.26	$0.42^{+3.6\%}_{-3.1\%}$	1.60	0.27	$0.44^{+2.6\%}_{-2.4\%}$	1.63
800	2.36	$2.34^{+0.1\%}_{-0.1\%}$	0.99	2.50	$2.40^{+2.1\%}_{-1.9\%}$	0.96
1000	2.02	$1.91^{+0.5\%}_{-0.5\%}$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

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

Differential Results for off-shell *ttH*

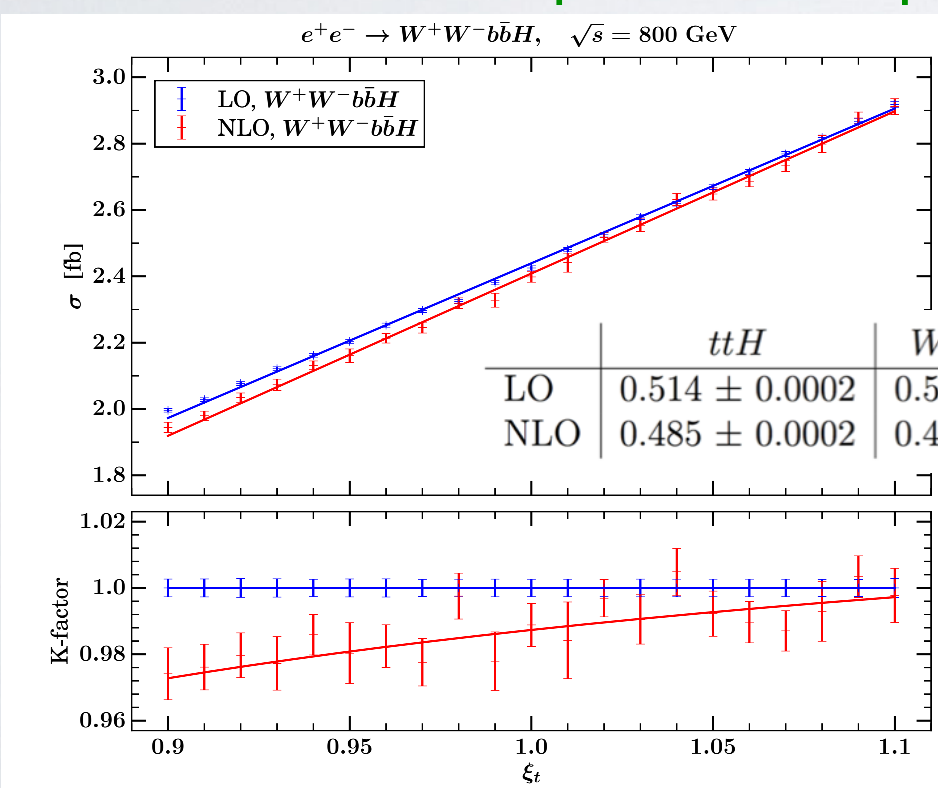




$$E_h = \frac{1}{2\sqrt{s}}\left[s + M_h^2 - (k_1 + k_2)^2\right]$$

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

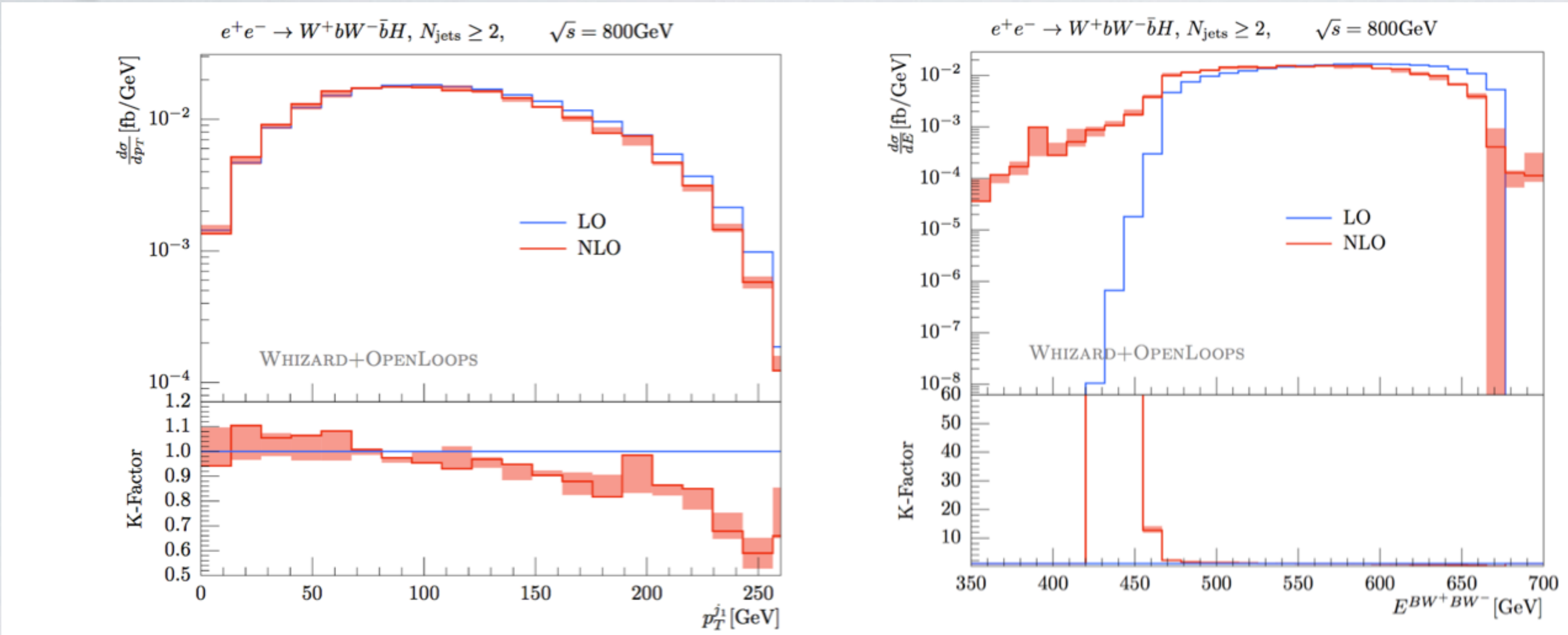
Determination of top Yukawa coupling (*ttH*)

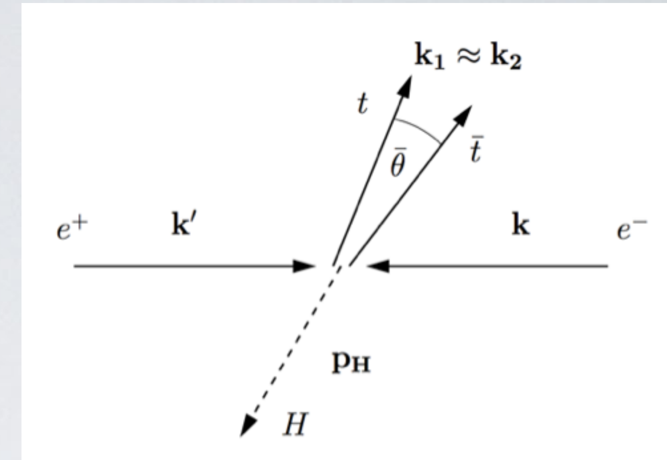


	ttH	$W^+W^-b\bar{b}H$
LO	0.514 ± 0.0002	0.520 ± 0.001
NLO	0.485 ± 0.0002	0.497 ± 0.002

cf. Talk by Alexander Mitov

Differential Results for off-shell ttH





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

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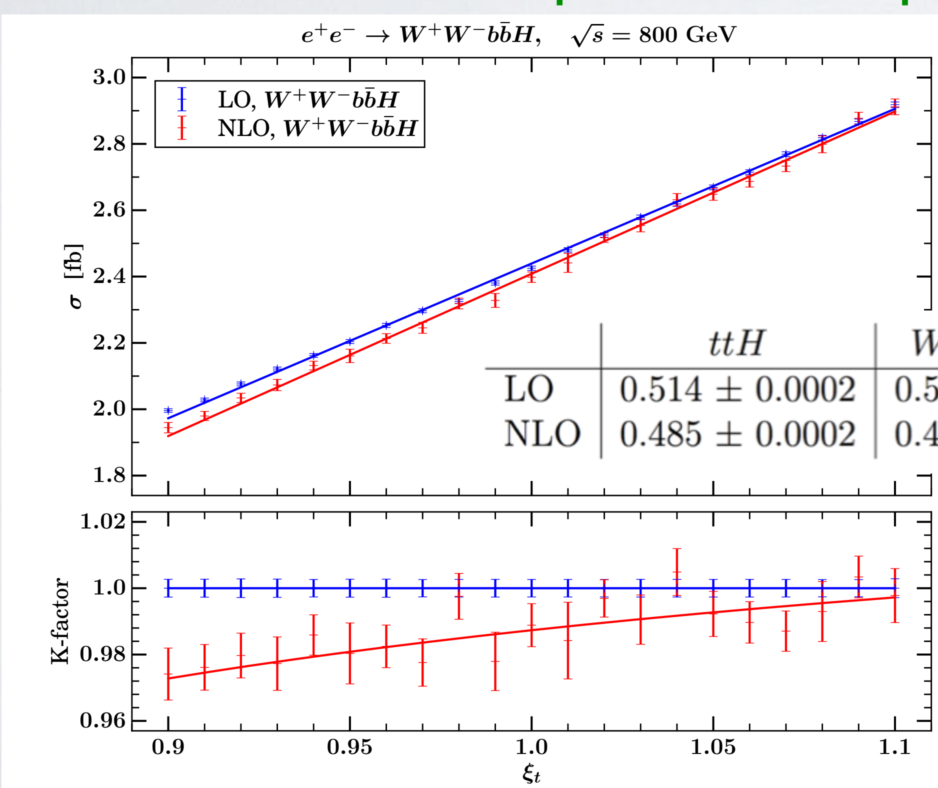

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Polarized Results (tt)

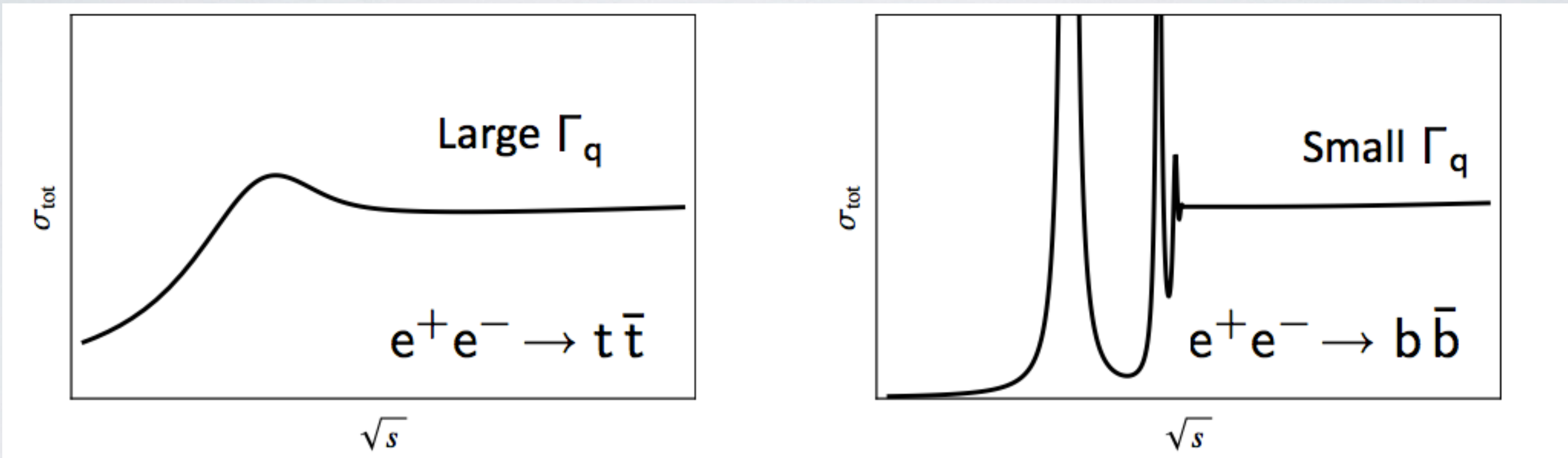
- ILC will always run polarized
- Polarized 1-loop amplitudes beyond BLHA

		$\sqrt{s} = 800$ GeV			$\sqrt{s} = 1500$ GeV		
$P(e^-)$	$P(e^+)$	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor
0%	0%	253.7	272.8	1.075	75.8	79.4	1.049
-80%	0%	176.5	190.0	1.077	98.3	103.1	1.049
+80%	0%	176.5	190.0	1.077	53.2	55.9	1.049
-80%	30%	420.8	452.2	1.074	124.9	131.0	1.048
-80%	60%	510.7	548.7	1.074	151.6	158.9	1.048
80%	-30%	208.4	224.5	1.077	63.0	66.1	1.049
80%	-60%	240.3	258.9	1.077	72.7	76.3	1.049

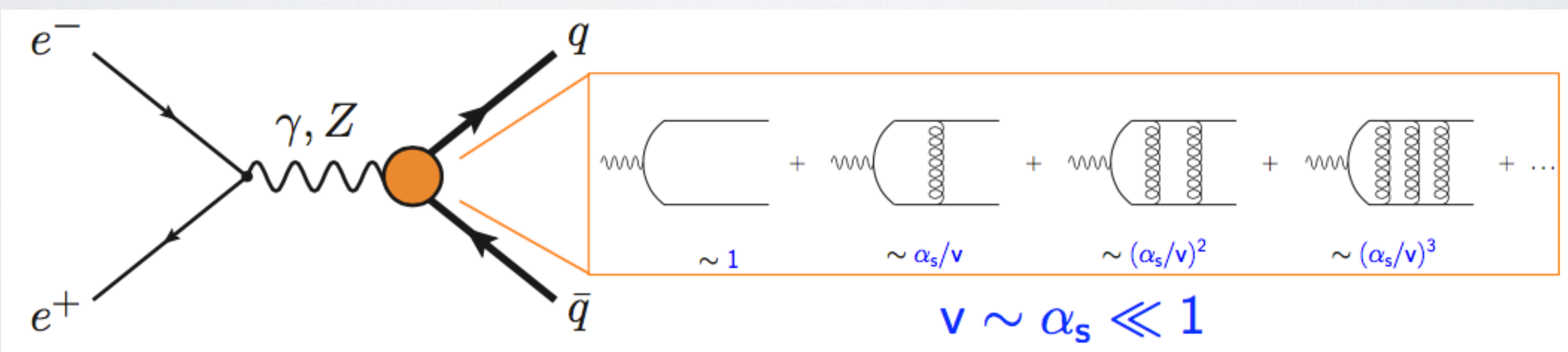
Top Threshold at lepton colliders

ILC top threshold scan best-known method to measure top quark mass, ΔM ~ 30-70 MeV

Heavy quark production at lepton colliders, qualitatively:

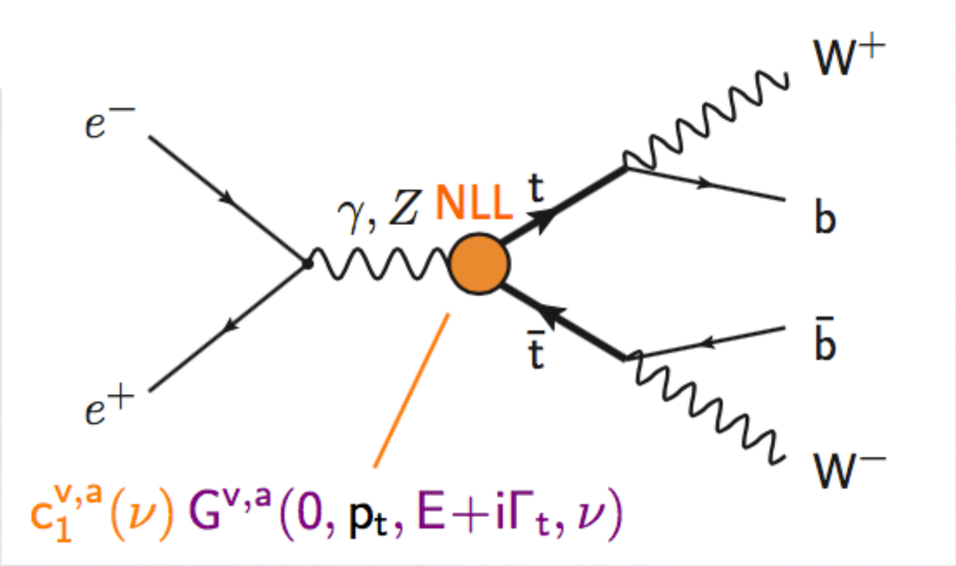


Threshold region: top velocity $v \sim \alpha_s \ll 1$



Top Threshold in WHIZARD

- Implement resummed threshold effects as effective vertex [form factor] in WHIZARD
- $G^{v,a}(0, p_t, E + i\Gamma_t, \nu)$ from TOPPIK code [Jezabek/Teubner], included in WHIZARD

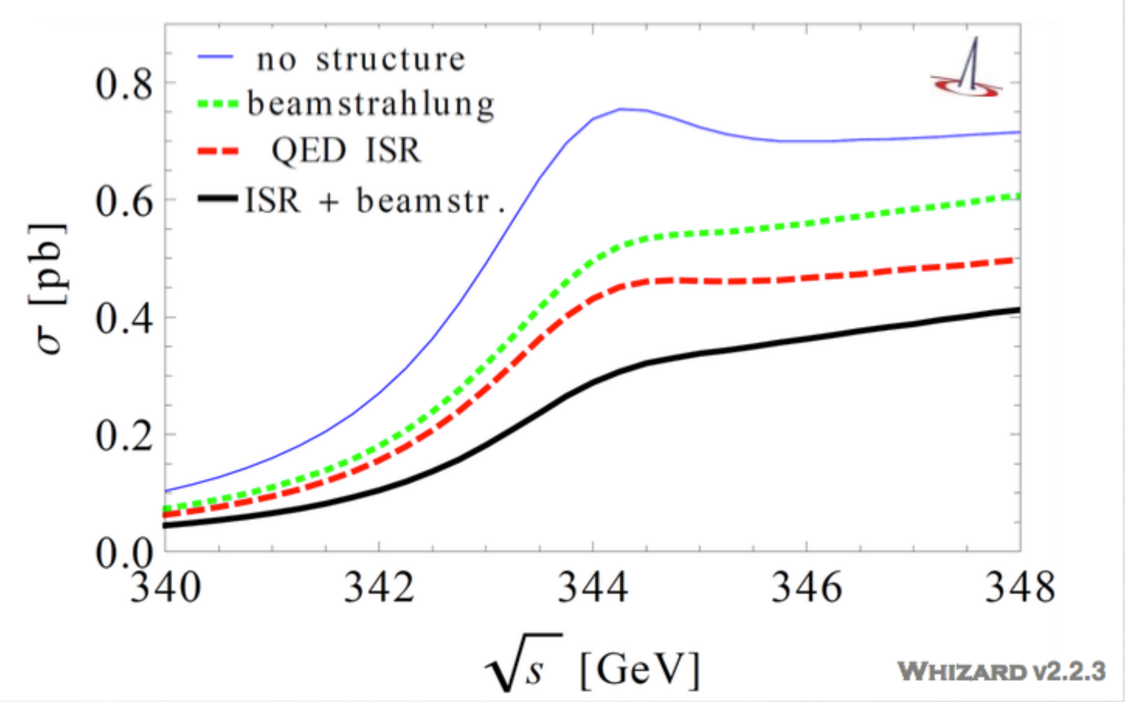


- Default parameters:

$$\mathbf{M^{1S} = 172\,GeV},\ \Gamma_t = 1.54\,\mathrm{GeV},\quad \alpha_s(M_Z) = 0.118$$

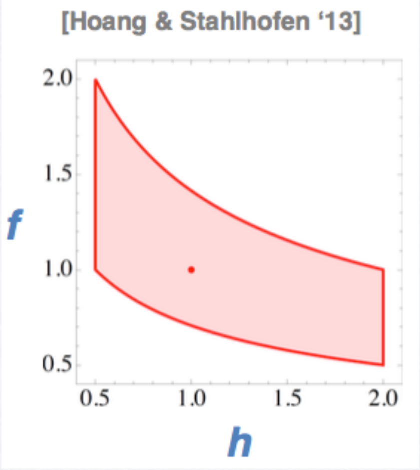
$$M^{1S} = M_t^{pole}(1 - \Delta^{LL/NLL}_{(Coul.)})$$

- Important effects: beamstrahlung; ISR; LO EW terms
- Exclusive observables accessible



Theory uncertainties from scale variations: hard and soft scale

$\mu_h = h \cdot m_t \qquad \mu_s = f \cdot m_t v$



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error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNLO 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

- Default parameters:

$$\mathbf{M^{1S}} = \mathbf{172\,GeV}, \; \Gamma_t = 1.54\,\mathrm{GeV}, \quad \alpha_s(M_Z) = 0.118$$

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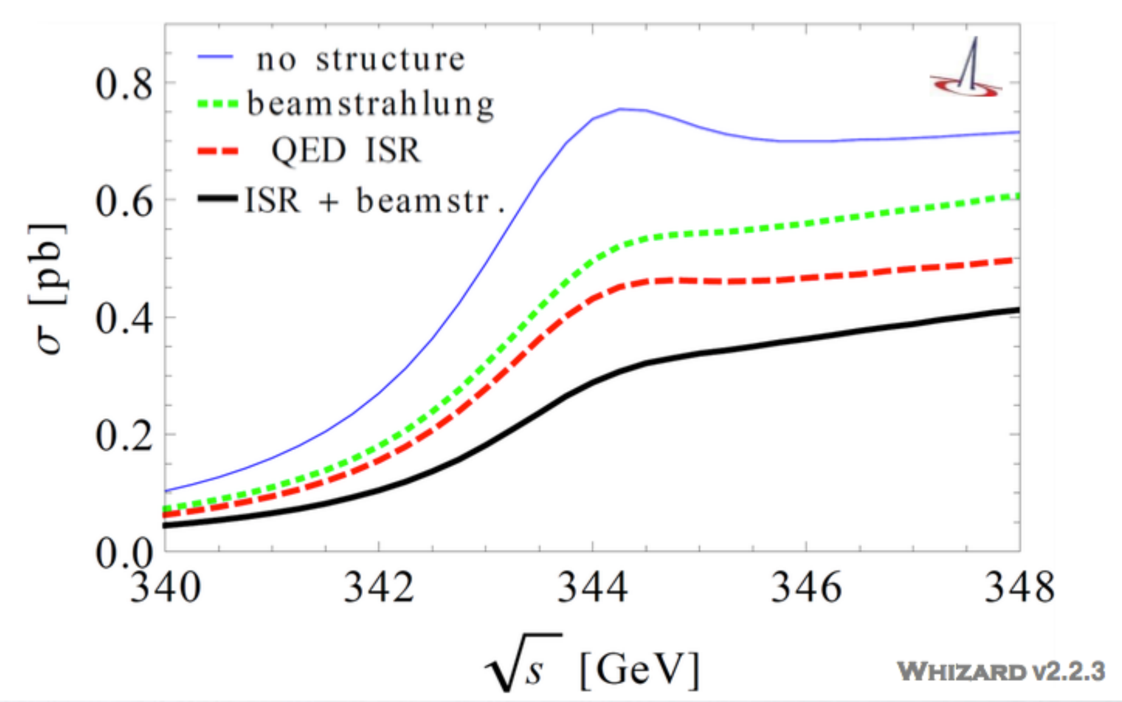

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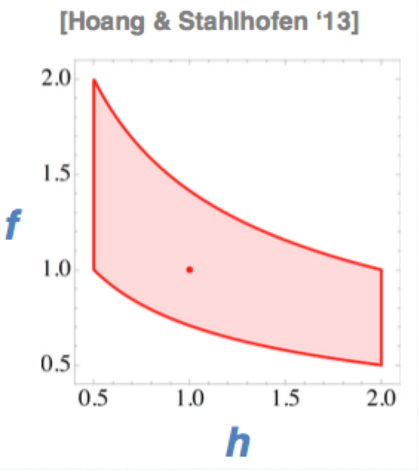
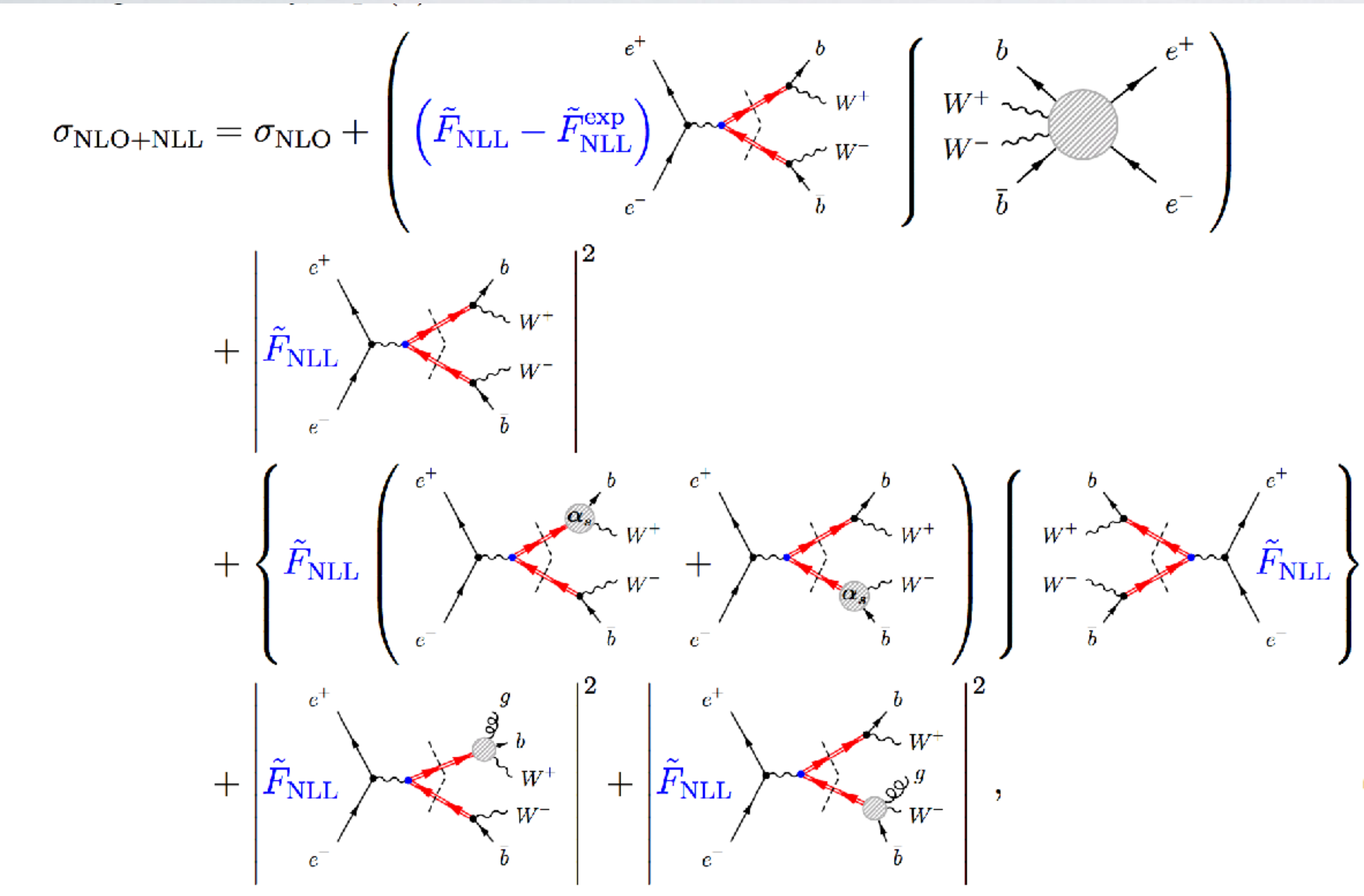
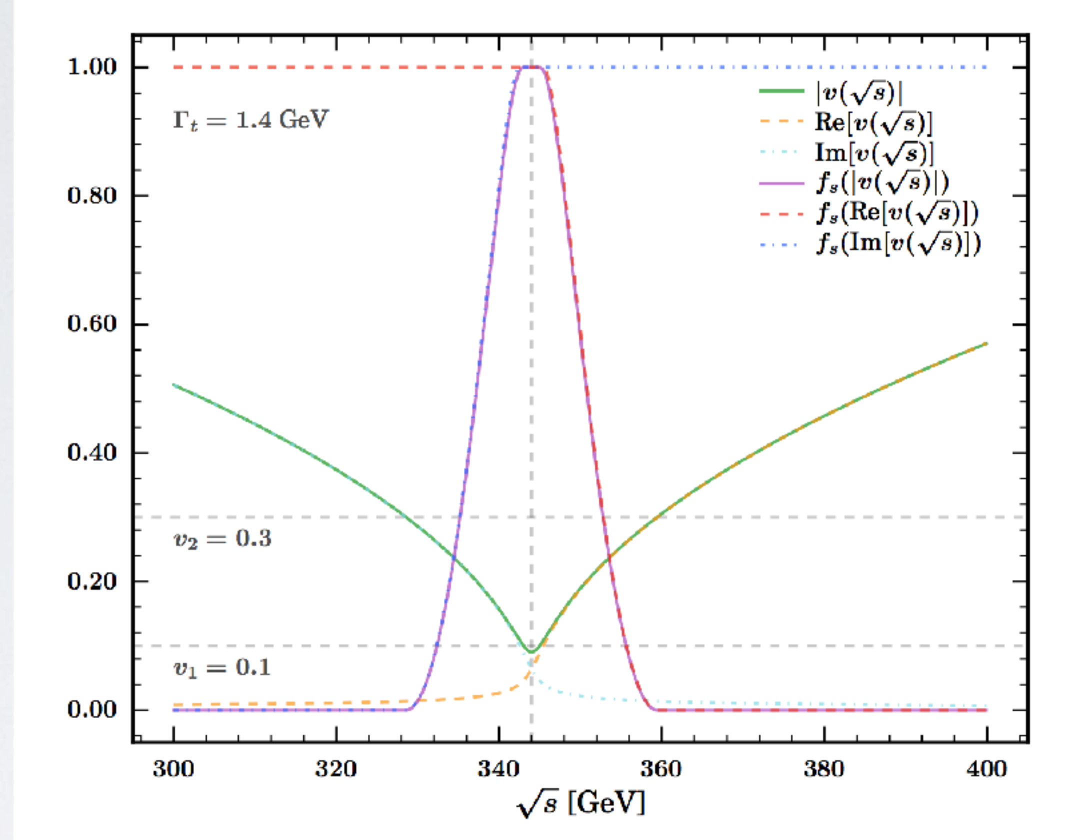


Top threshold: validation and matching

- Transition region between relativistic and resummation effects





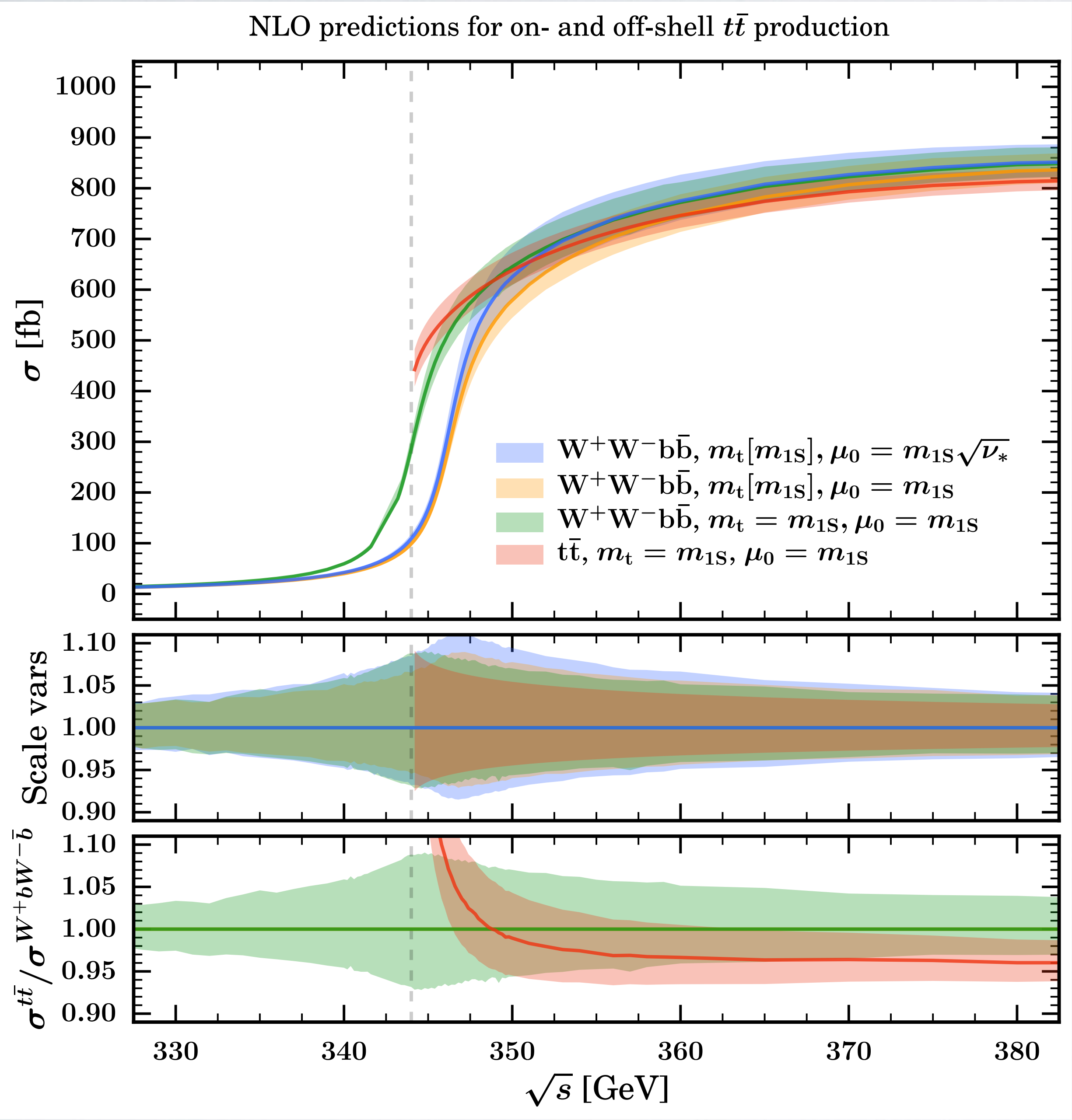
$$\sigma_{\text{matched}} = \sigma_{\text{FO}}\left[\alpha_{\text{H}}\right] + \sigma^{\text{full}}_{\text{NRQCD}}\left[f_s\,\alpha_{\text{H}},\ f_s\,\alpha_{\text{S}},\ f_s\,\alpha_{\text{US}}\right] - \sigma^{\text{expanded}}_{\text{NRQCD}}\left[f_s\,\alpha_{\text{H}},\ f_s\,\alpha_{\text{H}}\right]\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

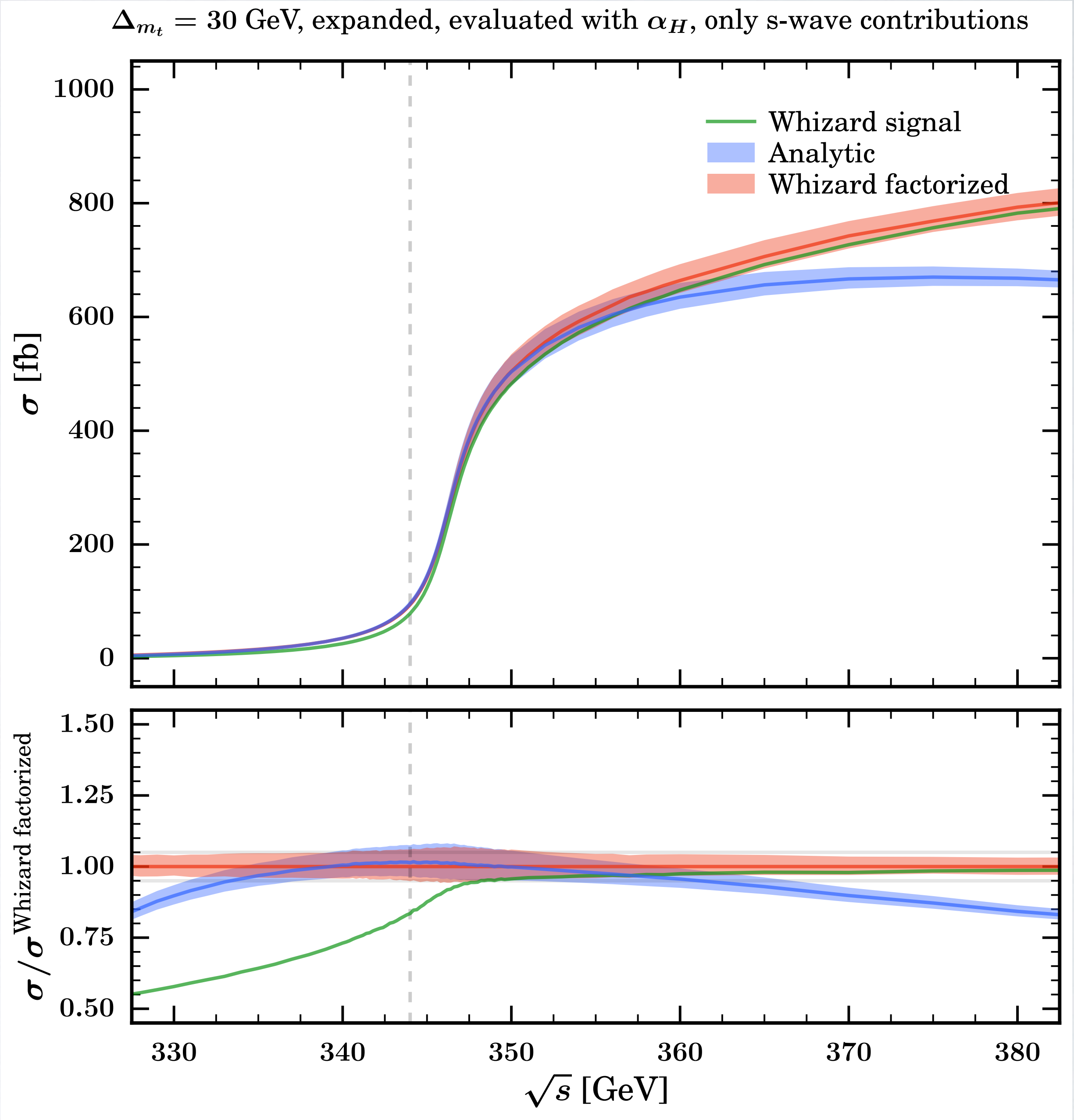
Smoothstep matching function:

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

Chokoufé/Hoang/Kilian/JRR/
StahlhofenTeubner/Weiss,
to appear very soon

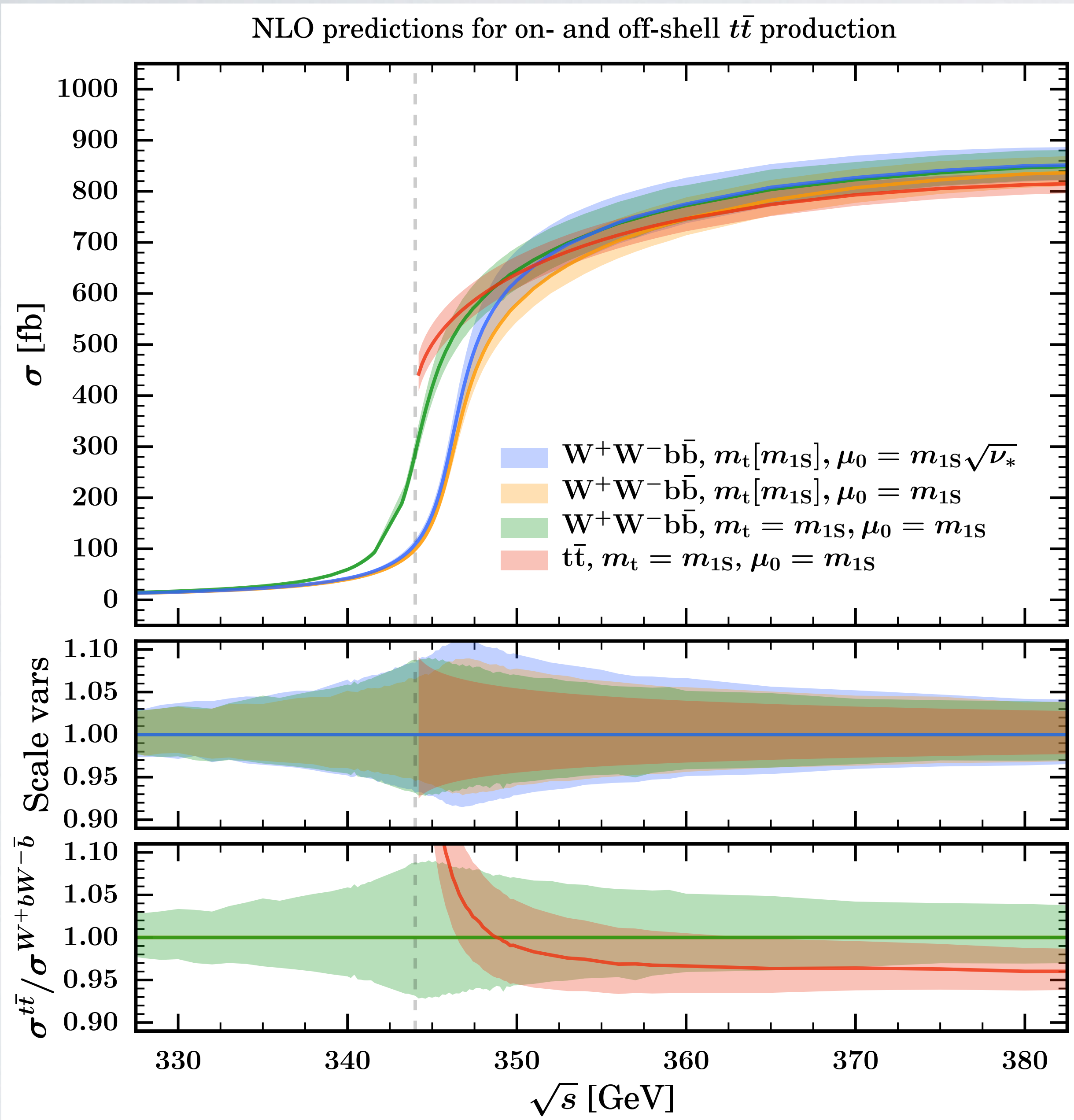
Top threshold: validation and matching

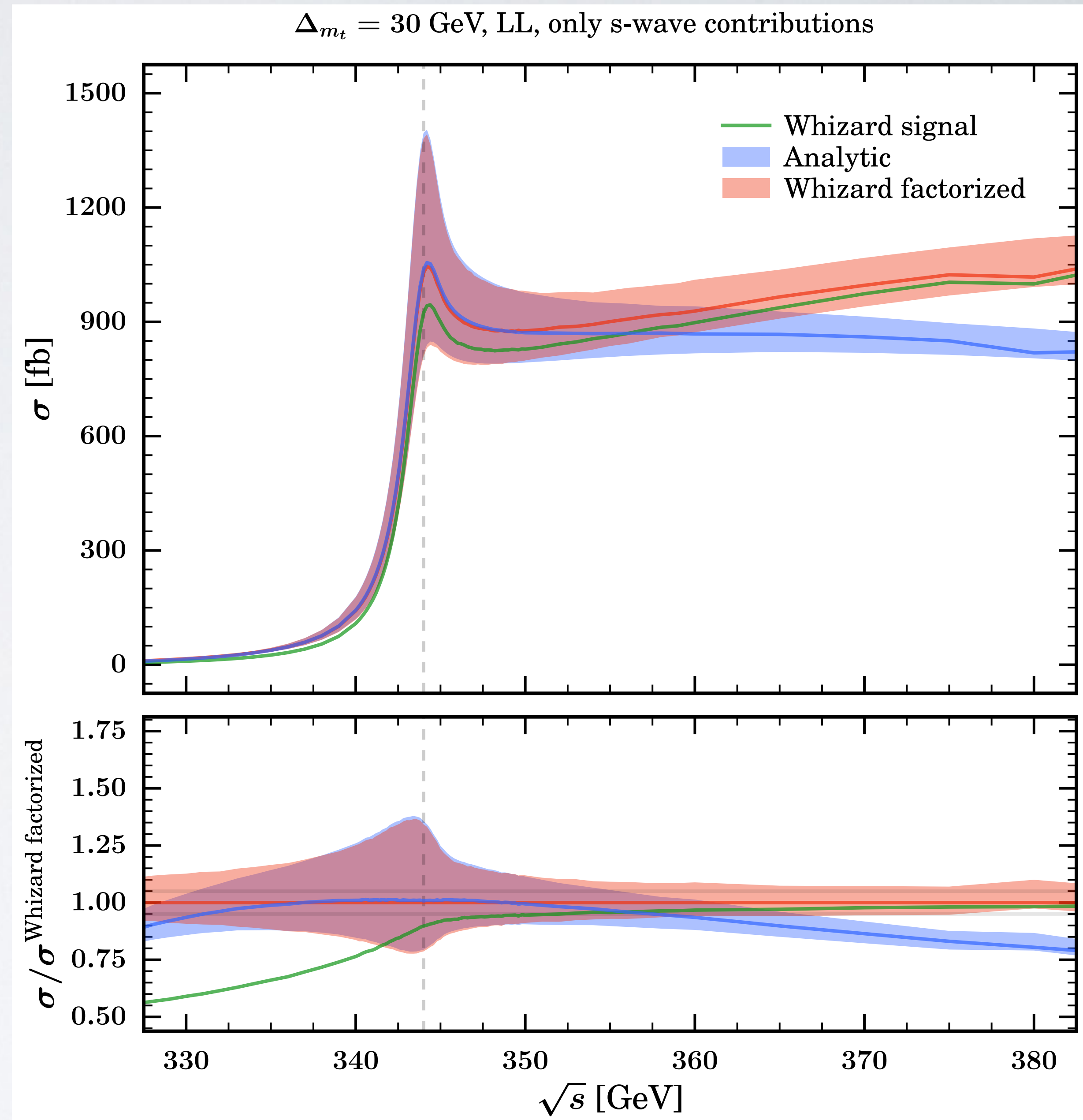




Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, *to appear very soon*

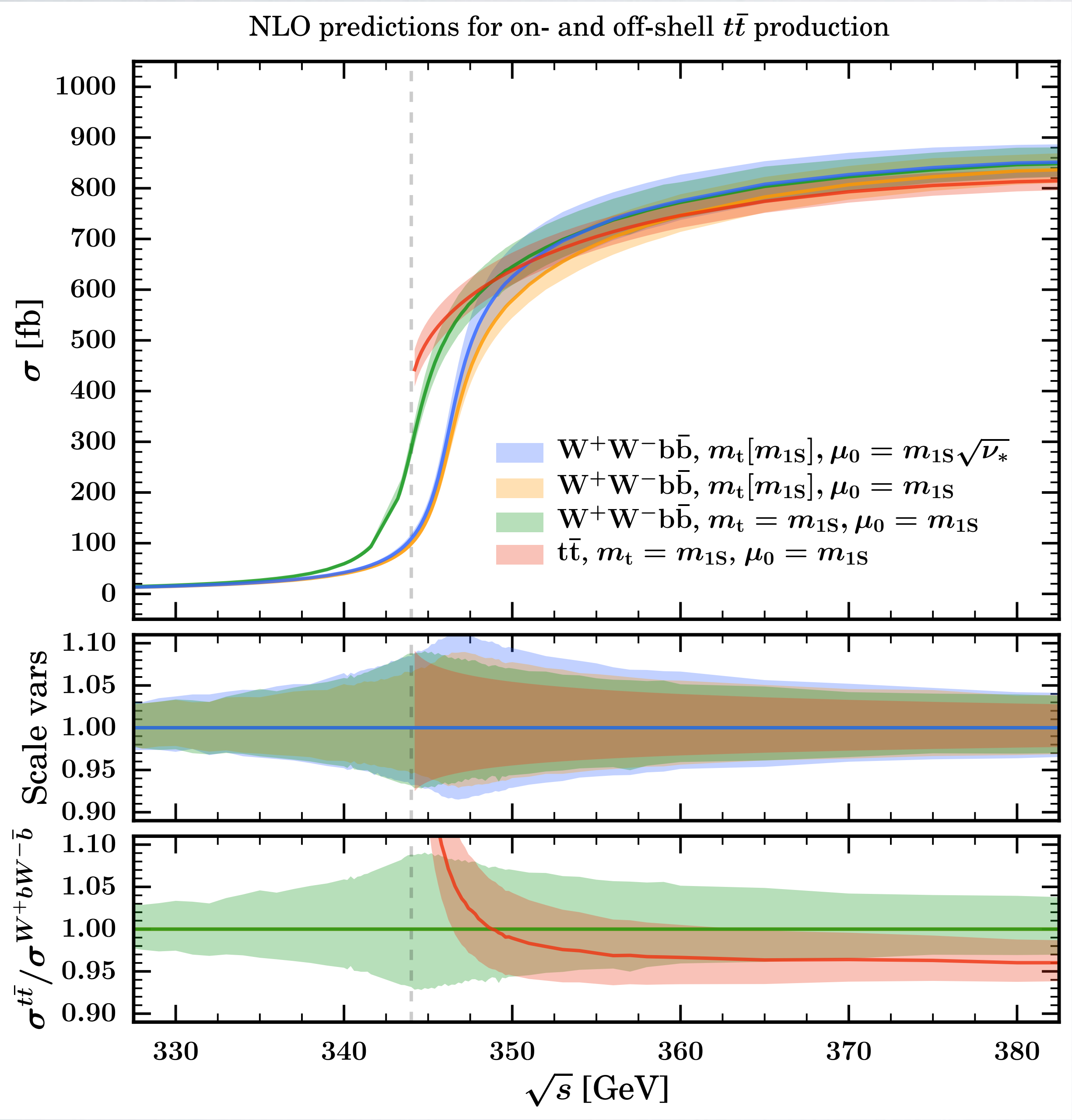
Top threshold: validation and matching

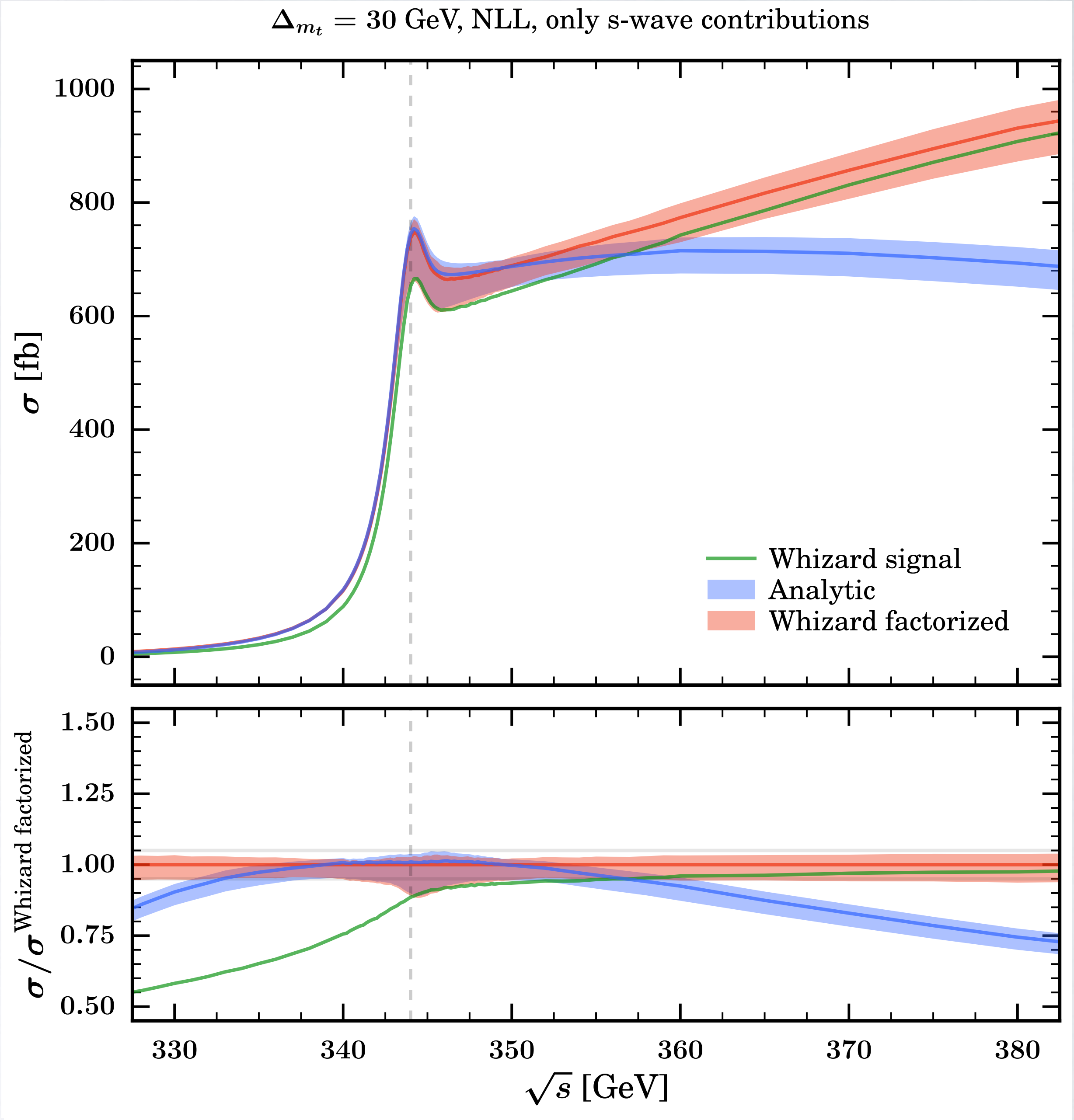




Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, *to appear very soon*

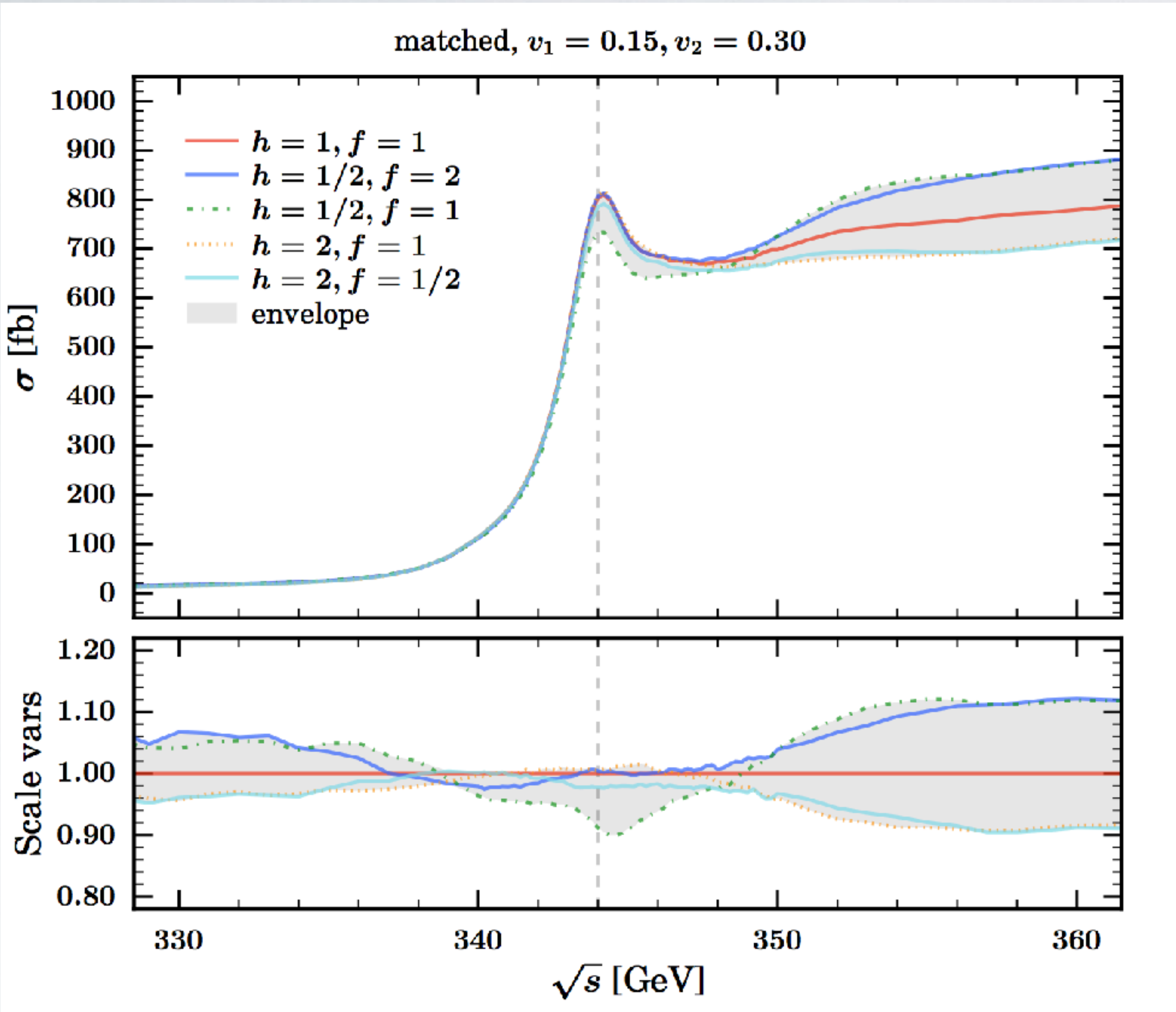
Top threshold: validation and matching

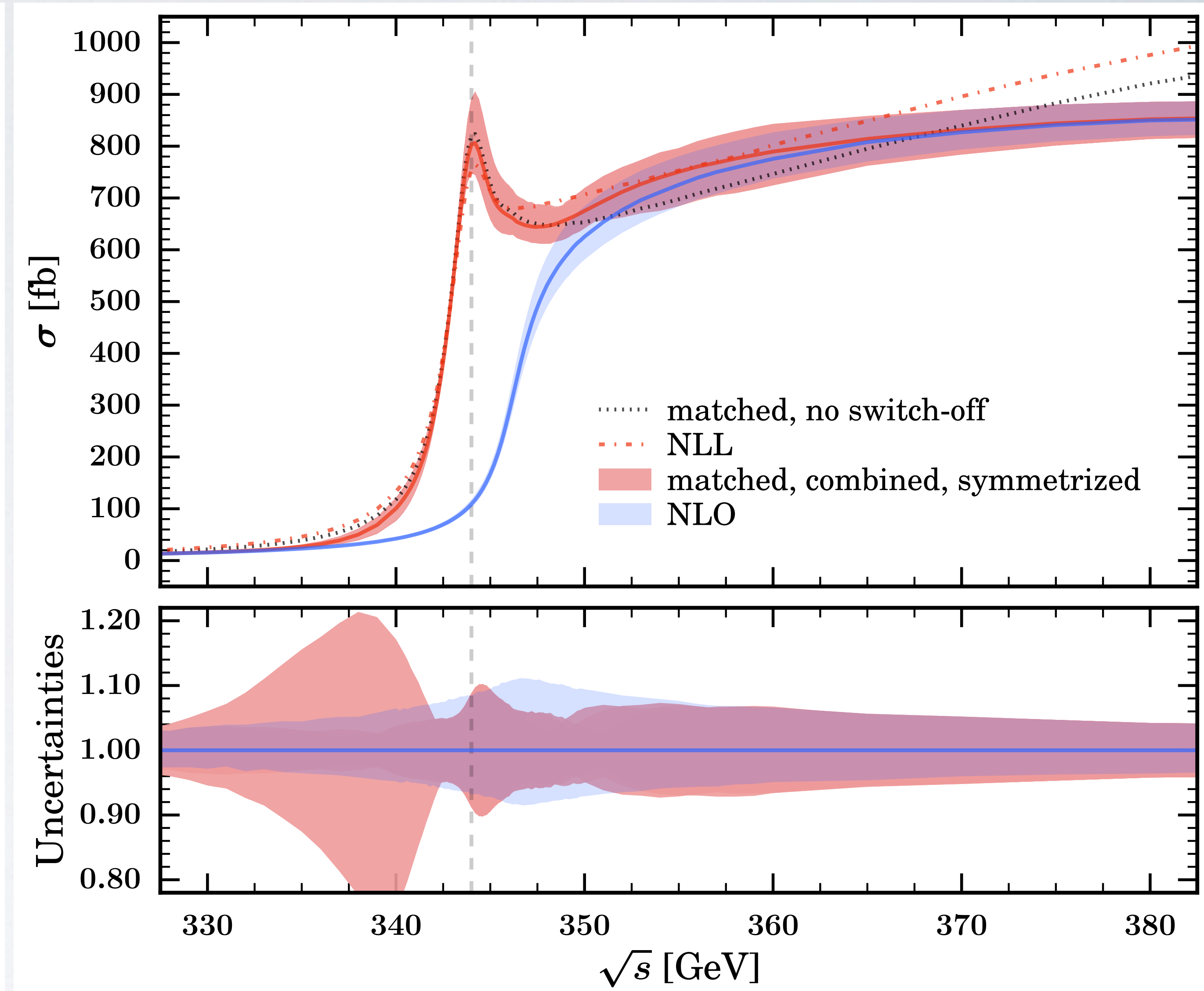




Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, *to appear very soon*

Matching threshold NLL to continuum NLO

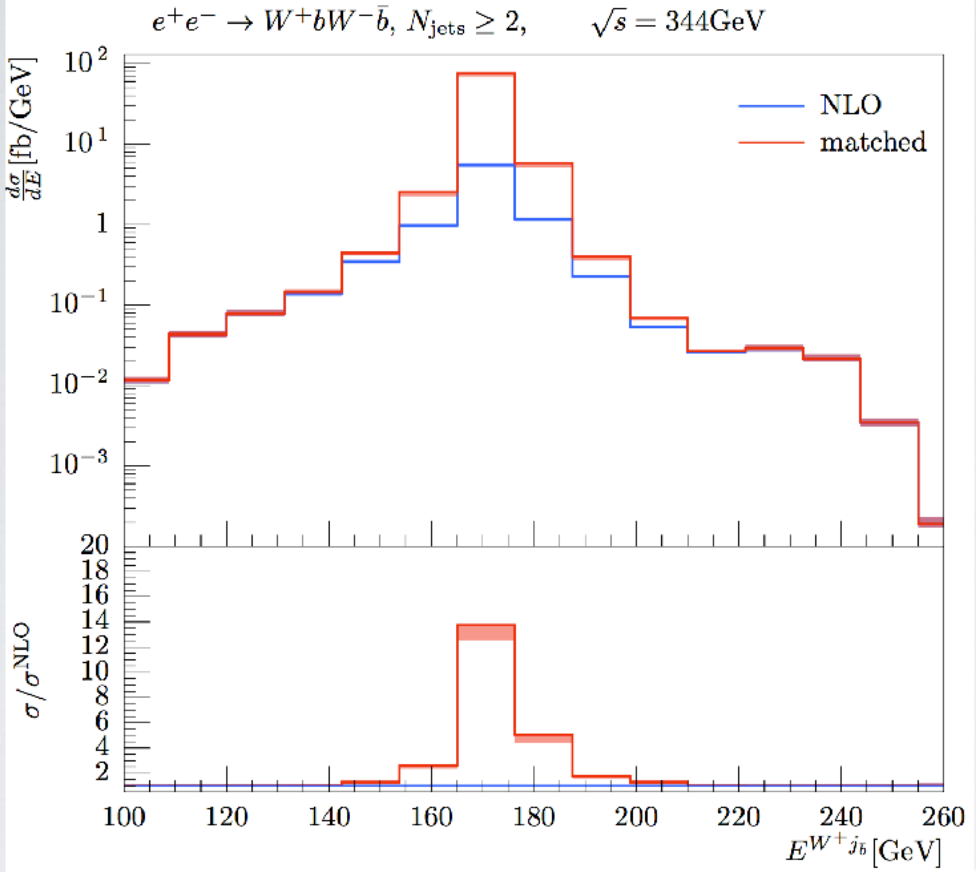


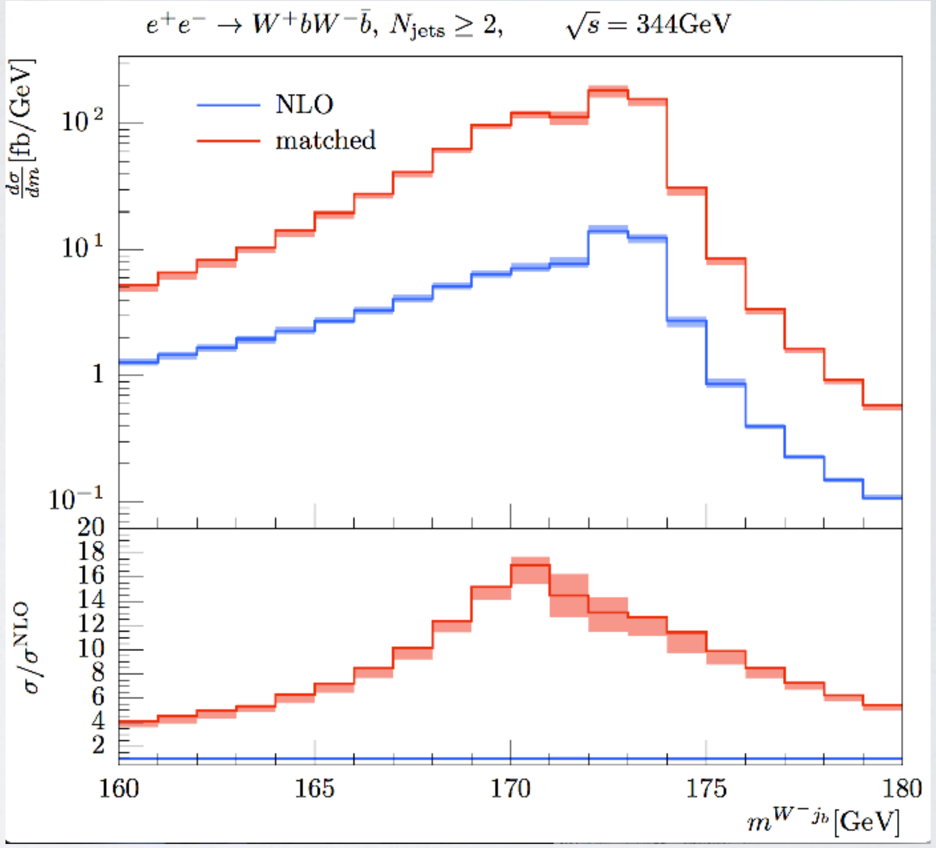


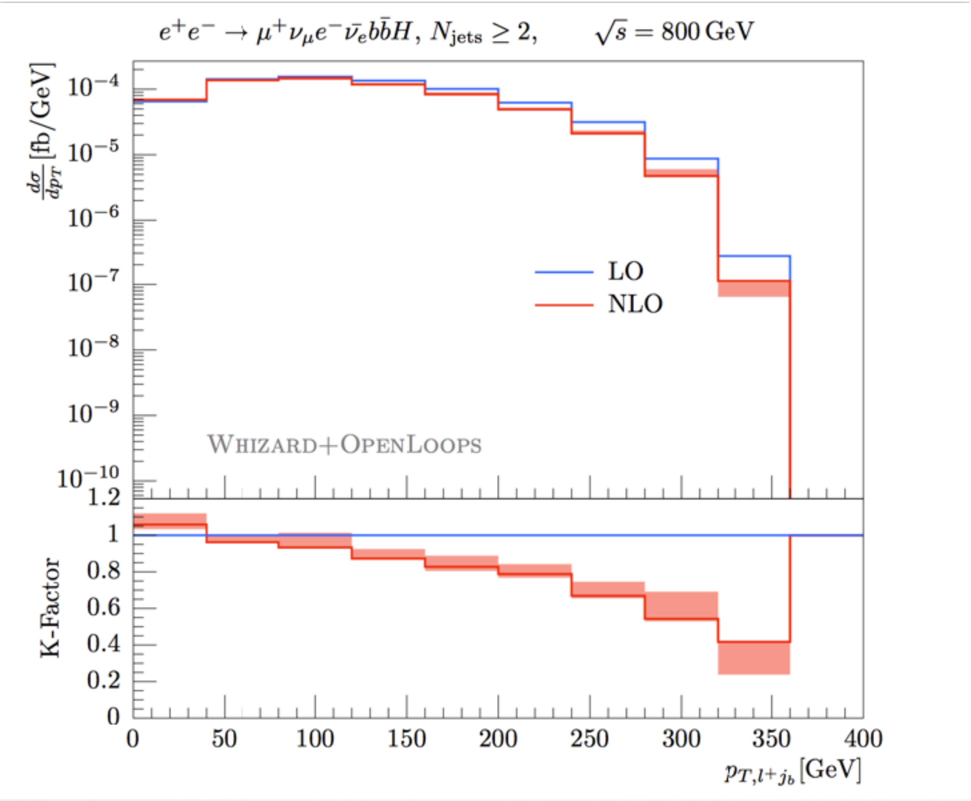
Total uncertainty: **matching and *h-f* variation band**

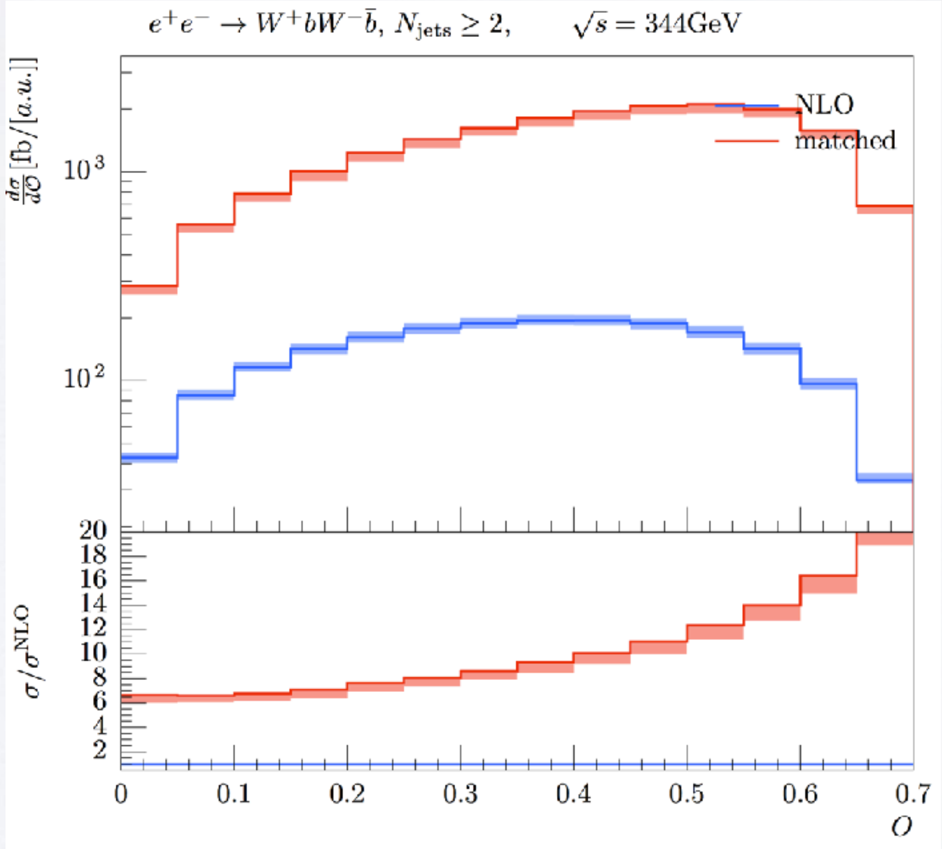
Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, *to appear very soon*

Matched threshold differential distributions









Conclusions & Outlook

- `WHIZARD 2.6` event generator for collider physics (ee, pp, ep)
- Allows to simulate all possible BSM models
- High-multiplicity SM processes ($2 \to 10$ etc.)
- e^+e^- physics: beam spectra, e^+e^- ISR, LCIO, polarizations
- NLO automation: reals and subtraction terms (FKS) [+ virtuals externally],
- NLO QCD (almost) done → `WHIZARD 3.0` [EW in validation]
- Automated POWHEG matching
- Top threshold in e^+e^-: NLL NRQCD threshold / NLO continuum matching
- NEW: UFO models, MPI parallel integration, Resonance matching to shower

BACKUP

More SINDARIN references

```
int i =3
```
integer variables

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

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

```
string $str = “foo”
```
string variables

```
logical ?ok = false
```
logical variables

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

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

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

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

Space-like cuts (incoming particles):

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

Combine two cuts:

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

Collecting particles:

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

Cut window on a selection:

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

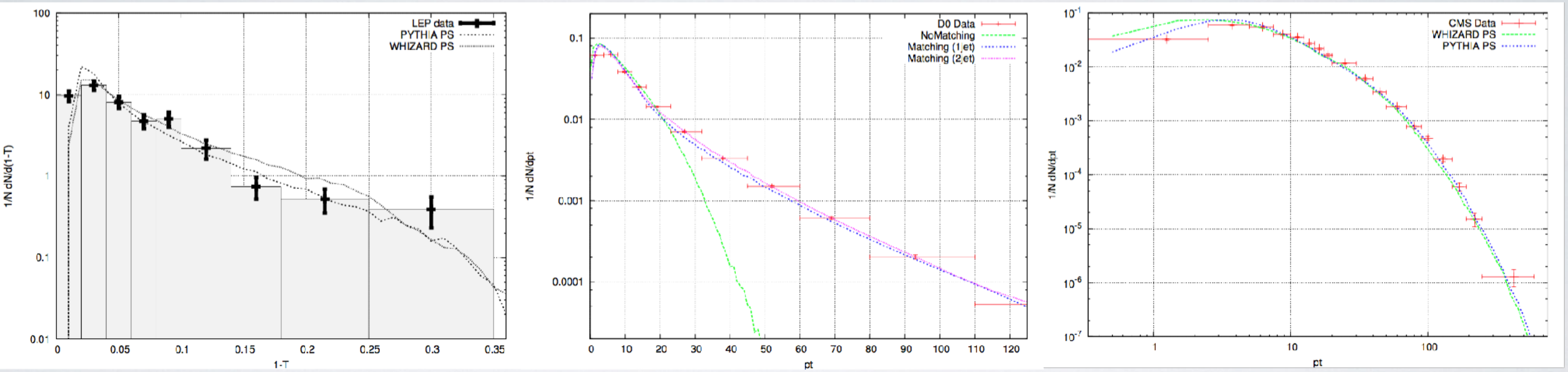
MLM matching:

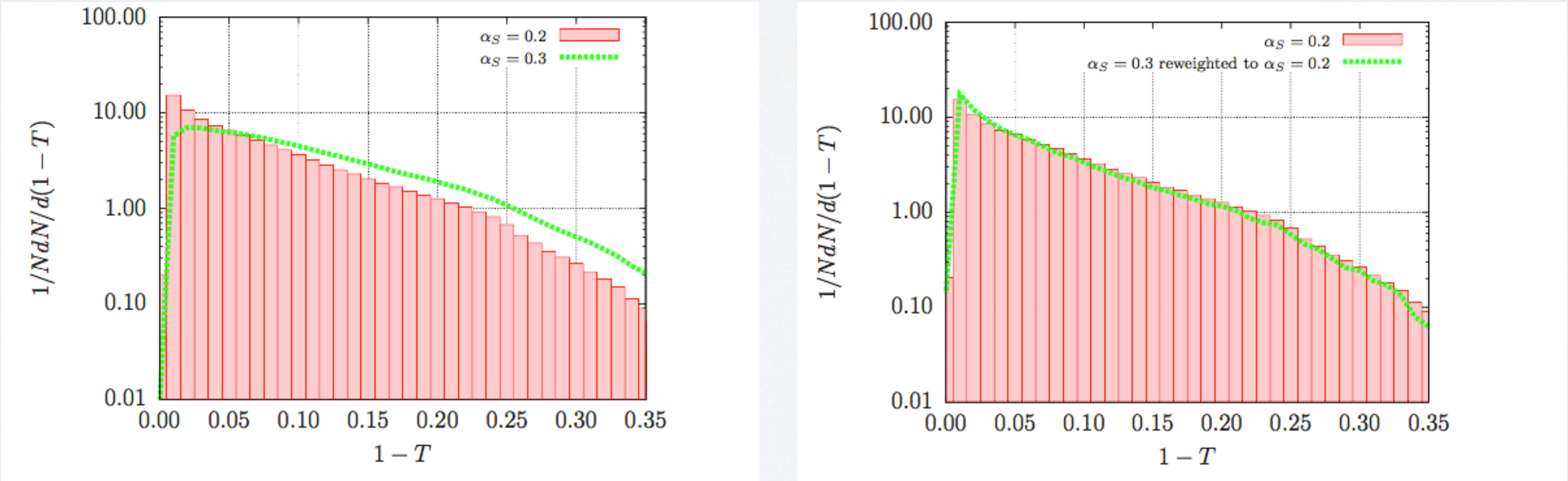
```
mlm_ptmin = 5 GeV; mlm_etamax = 2.5
mlm_Rmin = 1
mlm_nmaxMEjets = 1
```

WHIZARD Parton Shower

- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)

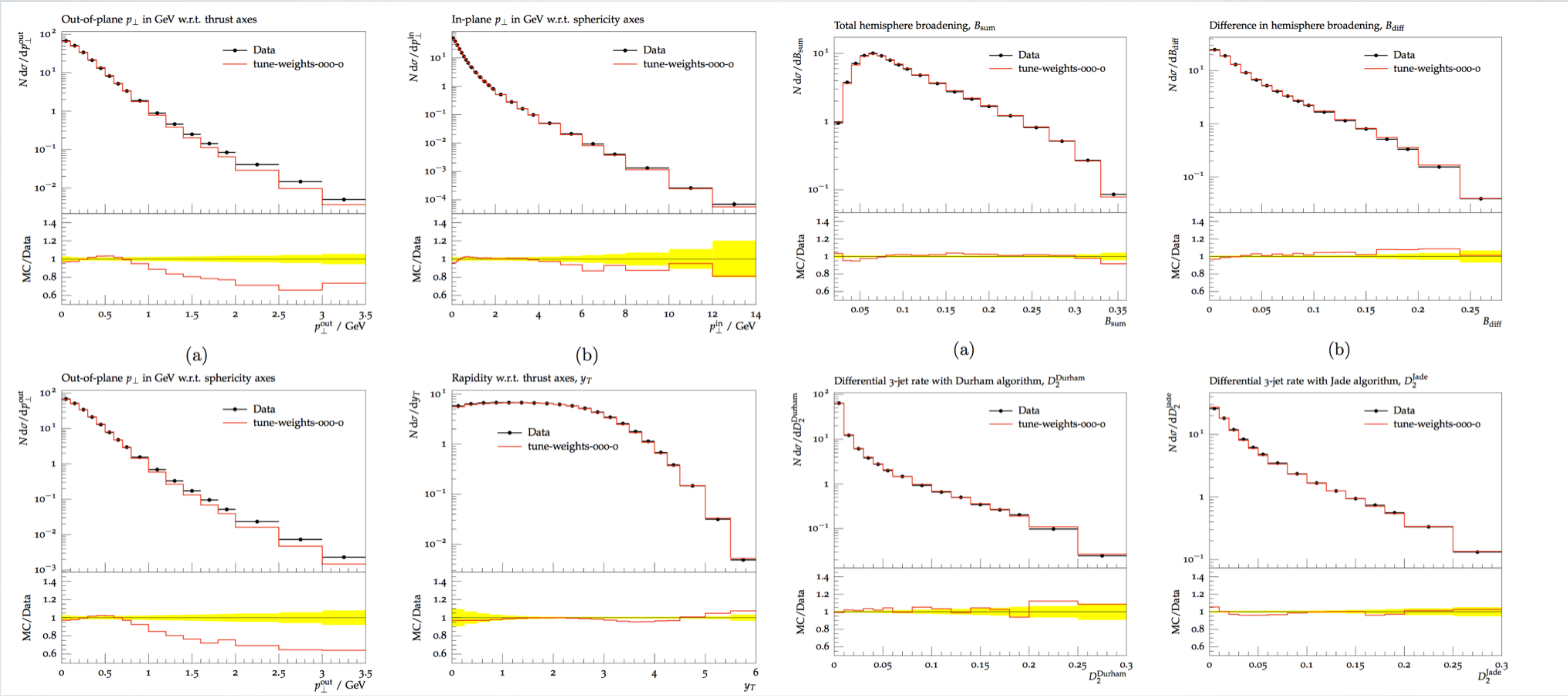




- Technical overhaul of the shower / merging part
- Plans: implement GKS matching, QED shower (also interleaved, infrastructure ready)

Tuning of the WHIZARD Parton Shower

- First tunes of both kT-ordered QCD and Analytic QCD shower Chokoufe/Englert/JRR, 2015
- Di- and Multijet data from LEP as given in RIVET analysis
- Usage of the PROFESSOR tool for determining the best fit Buckley et al., 2009



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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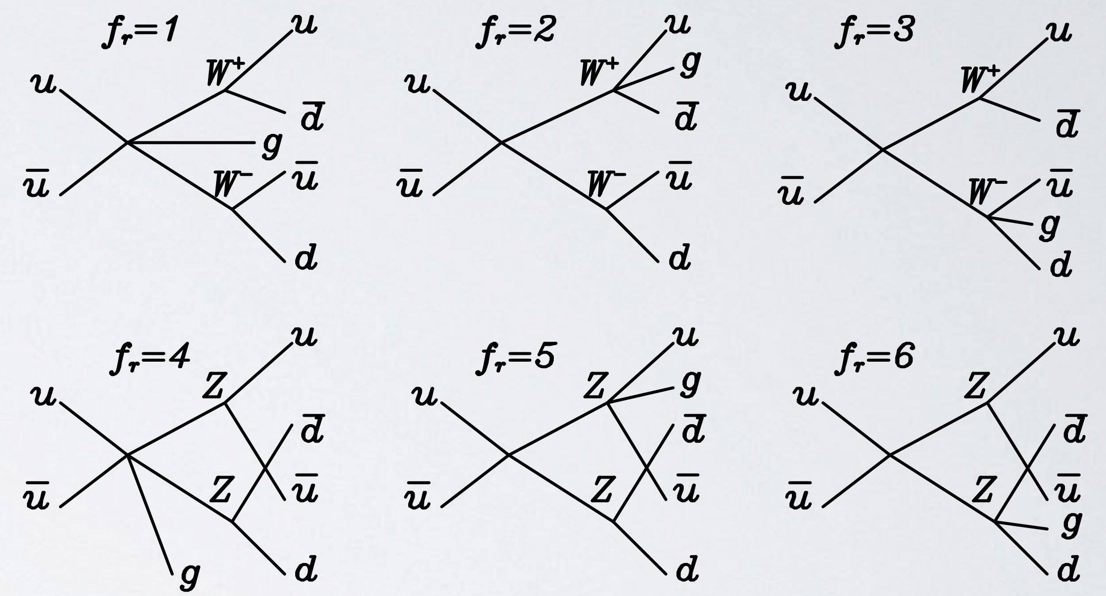

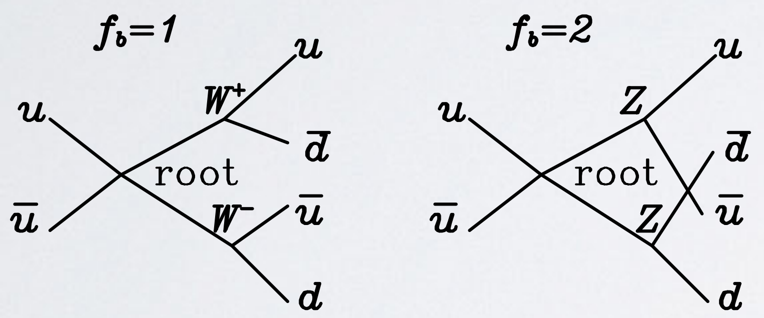

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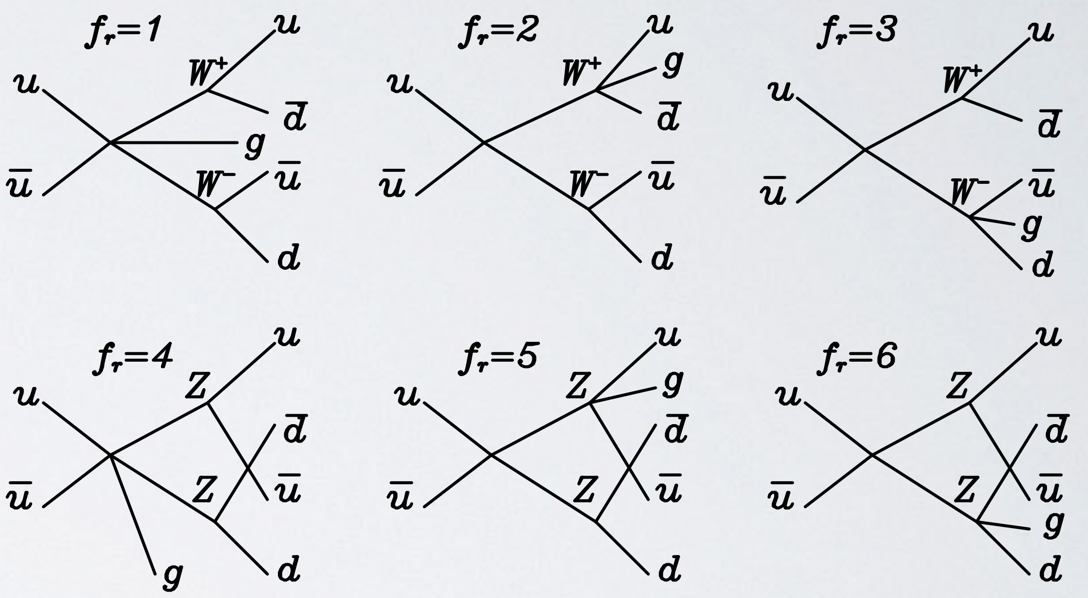

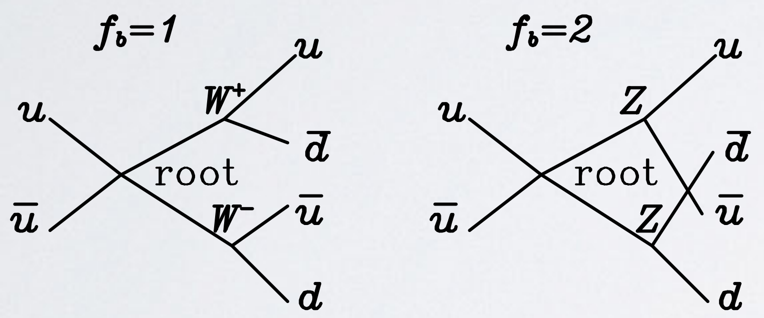

- `WHIZARD` complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (ZZ, ZH histories)

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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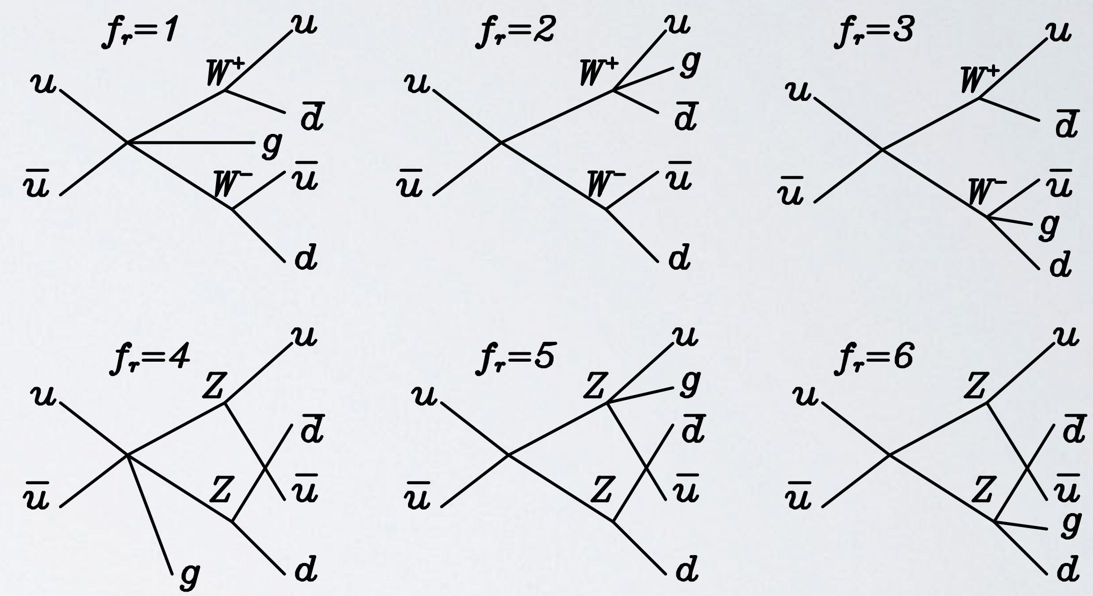

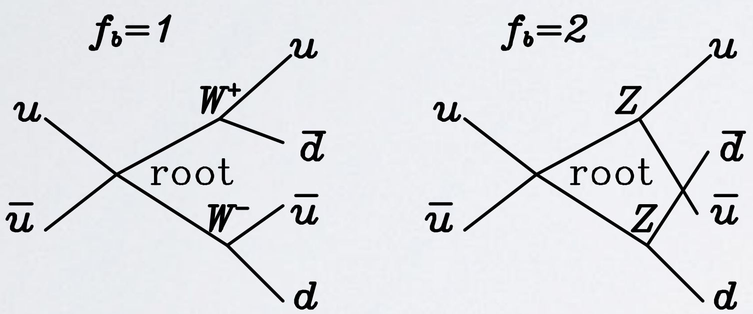

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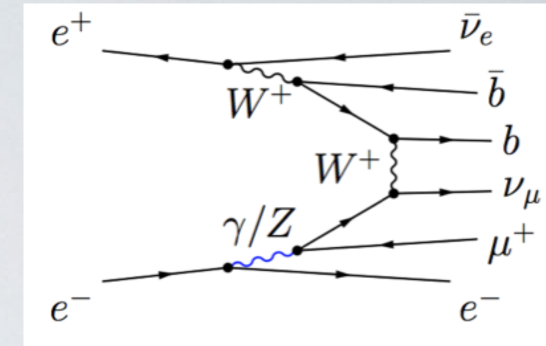
2	11962	2.8591952E+00	5.20E-02	1.82	1.99*	10.91		
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	5

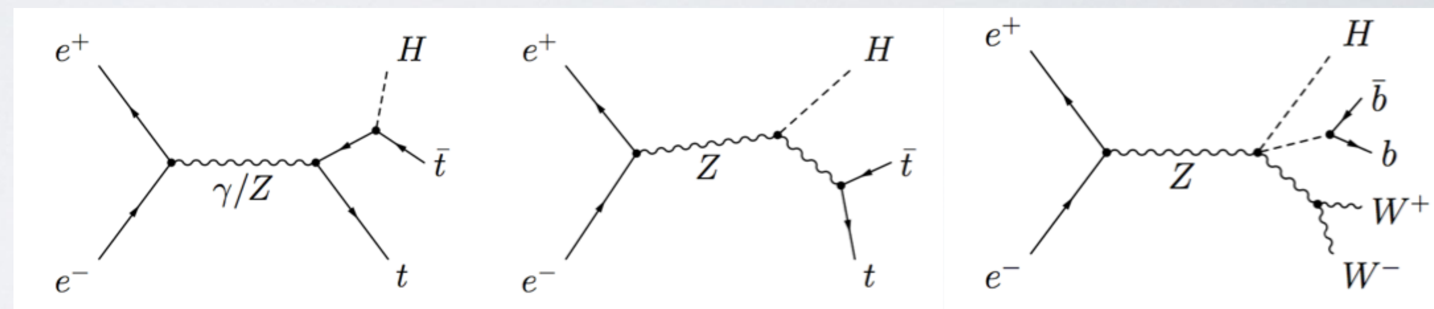
FKS with resonance mappings

Lepton colliders: *tt* and *ttH* (on- & off-shell)

- Cross checks for 2 → 2 and 2 → 4 processes with `Sherpa` and `Munich`
- Using massive *b* quarks: no cuts necessary for $e^+e^- \to W^+W^-bb$
- Full process $e^+e^- \to \mu^+\nu_\mu e^-\nu_e bb$ exhibits Coulomb singularity:



- *ttH* production: 8% contamination from Higgsstrahlung
- Contribution from quartic SM vertices



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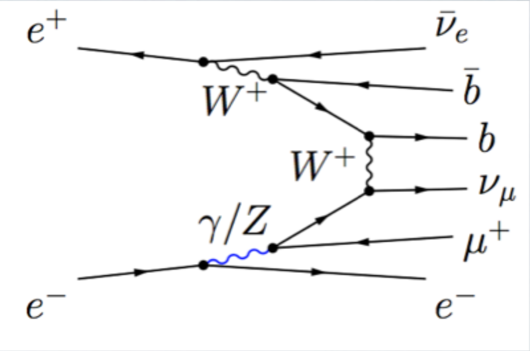

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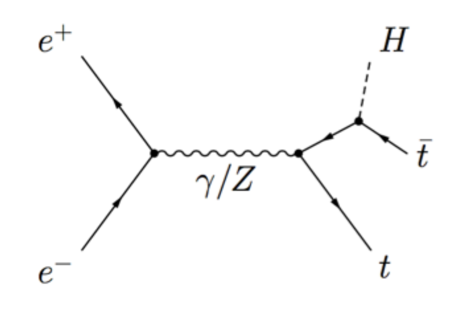

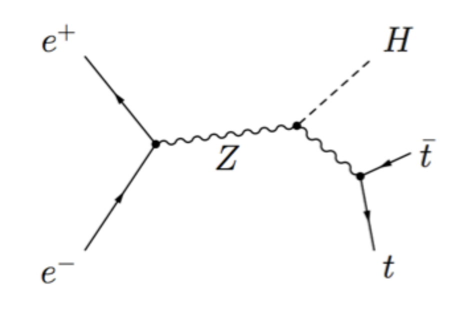

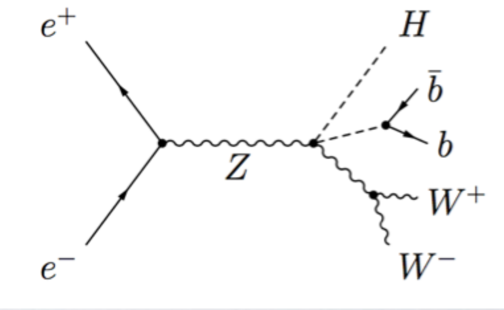

INPUT PARAMETERS:

$$m_Z = 91.1876\,\mathrm{GeV}, \qquad m_W = 80.385\,\mathrm{GeV}$$
$$m_b = 4.2\,\mathrm{GeV}, \qquad m_t = 173.2\,\mathrm{GeV}.$$

$$\Gamma^{\mathrm{LO}}_{t\to Wb} = 1.4986\,\mathrm{GeV}, \qquad \Gamma^{\mathrm{NLO}}_{t\to Wb} = 1.3681\,\mathrm{GeV},$$
$$\Gamma^{\mathrm{LO}}_{t\to f\bar{f}b} = 1.4757\,\mathrm{GeV}, \qquad \Gamma^{\mathrm{NLO}}_{t\to f\bar{f}b} = 1.3475\,\mathrm{GeV}.$$

$$m_H = 125\ \mathrm{GeV} \qquad \Gamma_H = 0.000431\ \mathrm{GeV}$$

$$\Gamma^{\mathrm{LO}}_Z = 2.4409\,\mathrm{GeV}, \qquad \Gamma^{\mathrm{NLO}}_Z = 2.5060\,\mathrm{GeV},$$
$$\Gamma^{\mathrm{LO}}_W = 2.0454\,\mathrm{GeV}, \qquad \Gamma^{\mathrm{NLO}}_W = 2.0978\,\mathrm{GeV}.$$

complex mass scheme:

$$\mu_i^2 = M_i^2 - \mathrm{i}\Gamma_i M_i \qquad \text{for } i = \mathrm{W, Z, t, H}$$

$$s_w^2 = 1 - c_w^2 = 1 - \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$$

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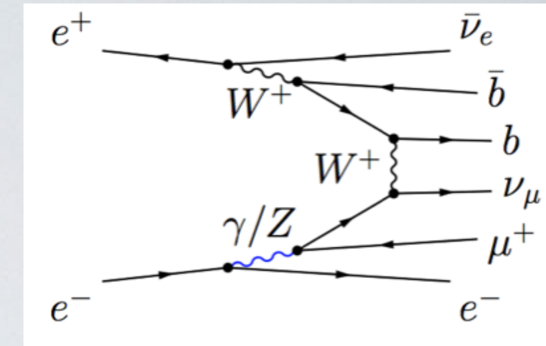

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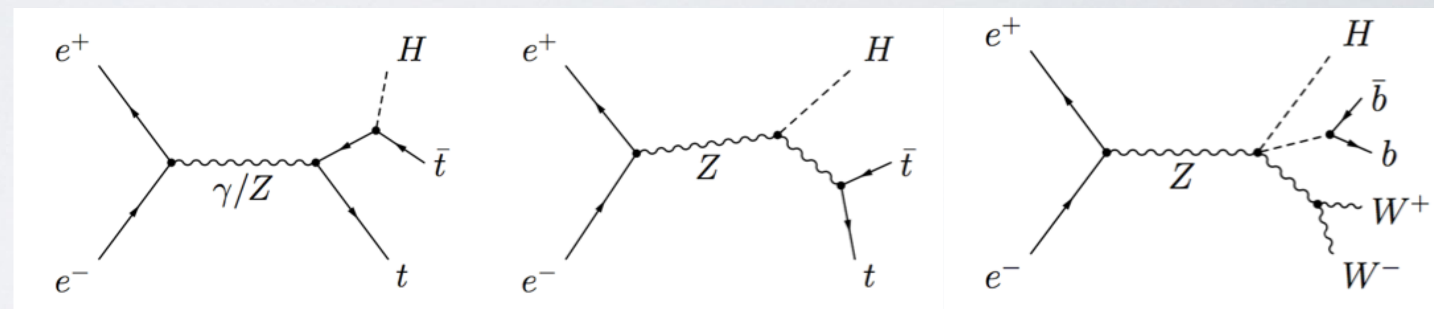

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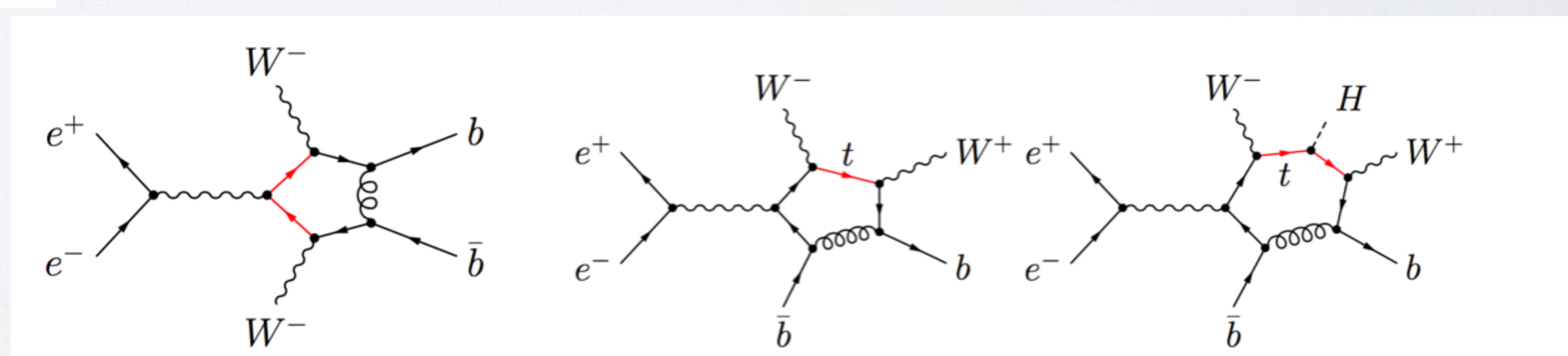
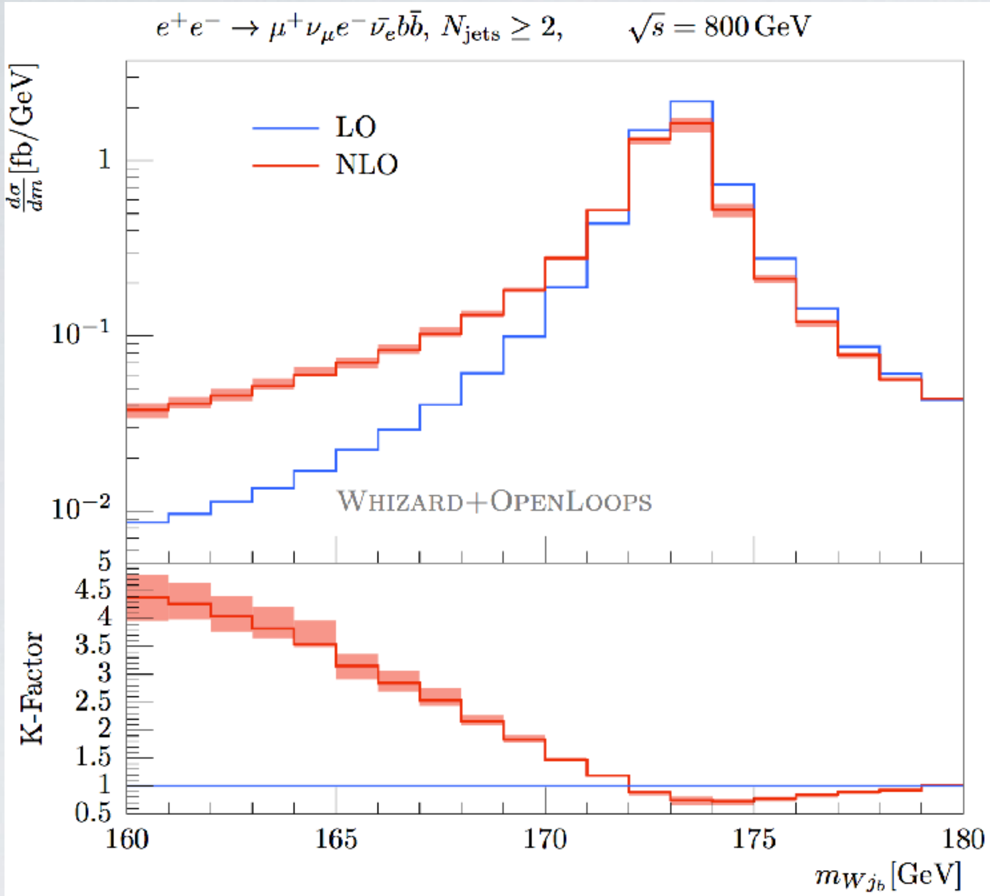
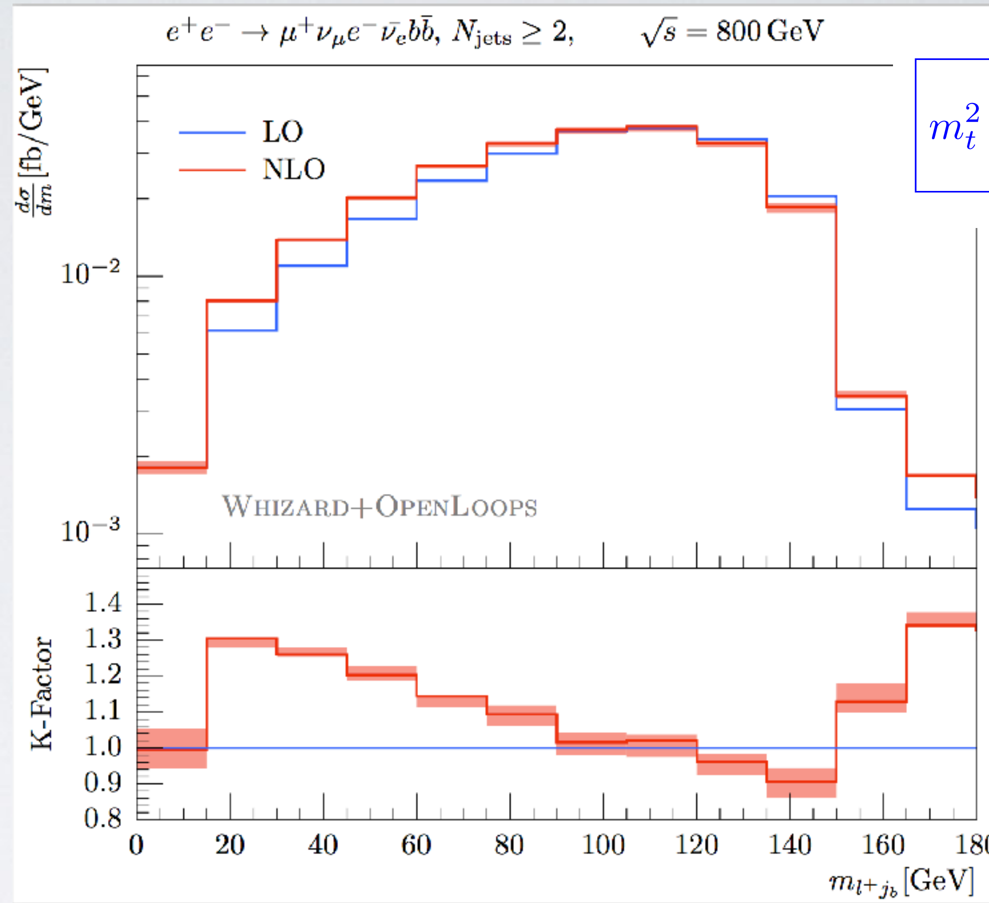
- Typical pentagons/hexagons:

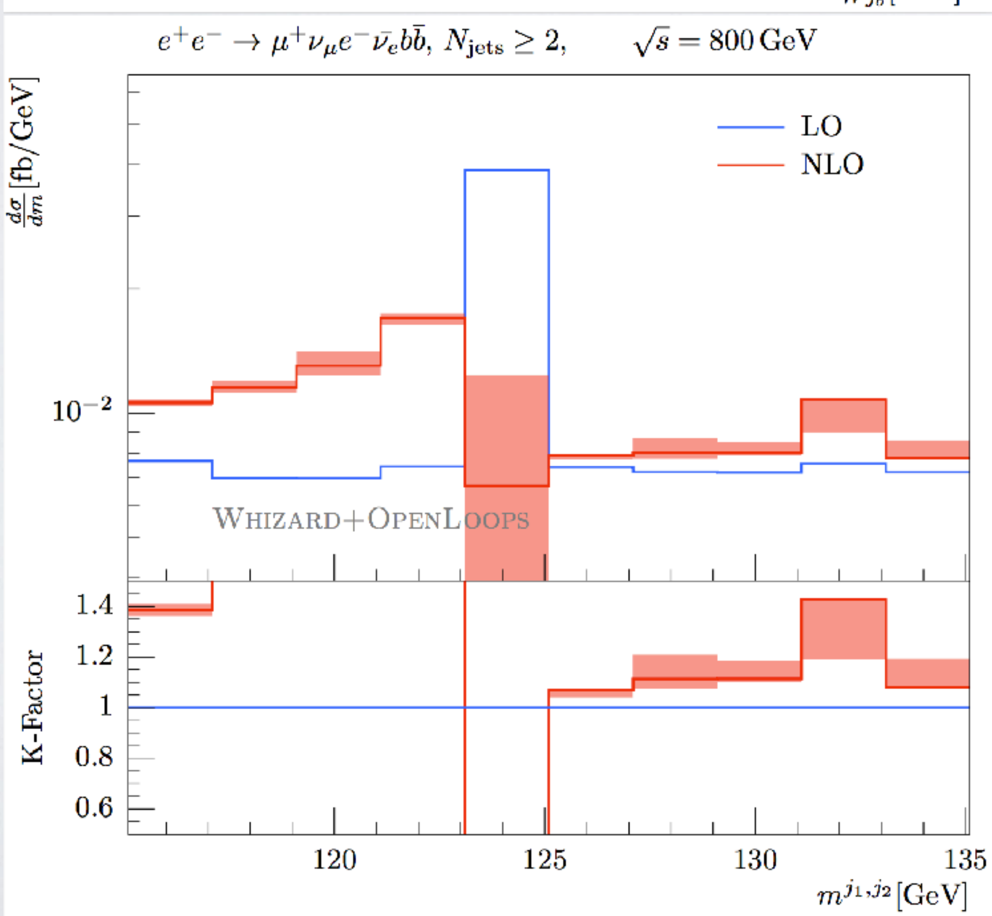


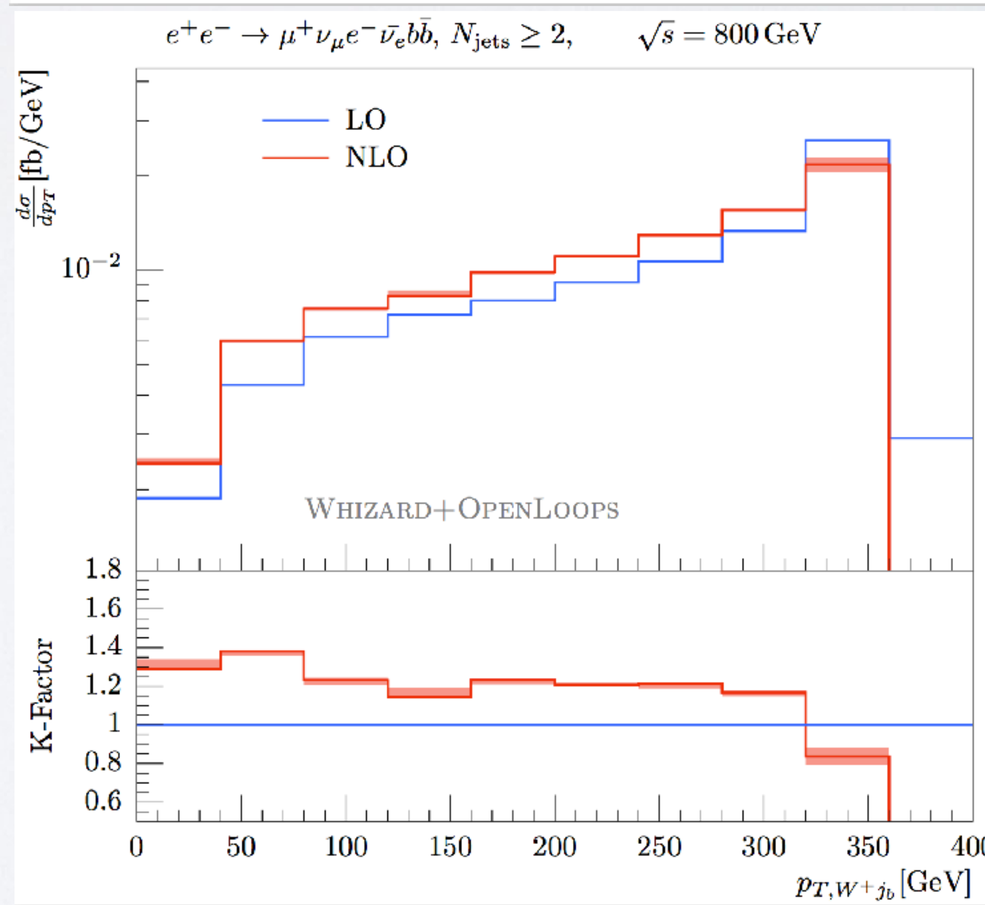
Differential Results for off-shell $e^+e^- \to tt$

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









Top-Forward Backward Asymmetry

$$A_{FB} = \frac{\sigma(\cos\theta_t > 0) - \sigma(\cos\theta_t < 0)}{\sigma(\cos\theta_t > 0) + \sigma(\cos\theta_t < 0)}.$$

Gluon emission symmetric in θ ⇒

NLO QCD corrections small

A_{FB} of the top quark

	$e^+e^- \to$	A_{FB}^{LO}	A_{FB}^{NLO}	A_{FB}^{NLO}/A_{FB}^{LO}
A_{FB}	$t\bar{t}$	-0.535	-0.539	1.013
	$W^+W^-b\bar{b}$	-0.428	-0.426	0.995
	$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$	-0.415	-0.409	0.986
	$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos	-0.402	-0.387	0.964
$\bar{A}_{FB}$	$t\bar{t}$	0.535	0.539	1.013
	$W^+W^-b\bar{b}$	0.428	0.426	0.995
	$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$	0.415	0.409	0.986
	$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos	0.377	0.350	0.928

Resonances: Simplified models

- Resonances might be in direct reach of LHC
- EFT framework EW-restored regime: $SU(2)_L \times SU(2)_R$, $SU(2)_L \times U(1)_Y$ gauged
- Include EFT operators in addition (more resonances, continuum contribution)
- Apply *T*-matrix unitarization beyond resonance ("UV-incomplete" model)

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	isoscalar	isotensor
scalar	σ^0	$\phi_t^{--}, \phi_t^{-}, \phi_t^{0}, \phi_t^{+}, \phi_t^{++}$ $\phi_v^{-}, \phi_v^{0}, \phi_v^{+}$ ϕ_s^{0}
tensor	f^0	$\begin{pmatrix} X_t^{--}, X_t^{-}, X_t^{0}, X_t^{+}, X_t^{++} \\ X_v^{-}, X_v^{0}, X_v^{+} \\ X_s^{0} \end{pmatrix}$
...	...	...

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tensor	f^0	$\begin{pmatrix} X_t^{--}, X_t^-, X_t^0, X_t^+, X_t^{++} \\ X_v^-, X_v^0, X_v^+ \\ X_s^0 \end{pmatrix}$
…	…	…

- $f^{\mu\nu}$: on-shell $f^{\mu\nu}$
- ϕ: $\partial_\mu \partial_\nu f^{\mu\nu}$
- A^μ: $\partial_\nu f^{\mu\nu}$
- σ: $f^\mu{}_\mu$

Gauge fixing: $\sigma = -\phi$

Tensor resonances

- Symmetric tensor $f_{\mu\nu}$
- On-shell: 10 → 5 components
- Tracelessness: $f_\mu{}^\mu = 0$
- Transversality: $\partial_\mu f^{\mu\nu} = 0$

- Fierz-Pauli conditions not valid off-shell
- Fierz-Pauli propagator has bad high-energy behavior
- Stückelberg formalism to make off-shell behavior explicit
- In the MC: compensator fields ⇒ no propagators with momentum factors

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 }

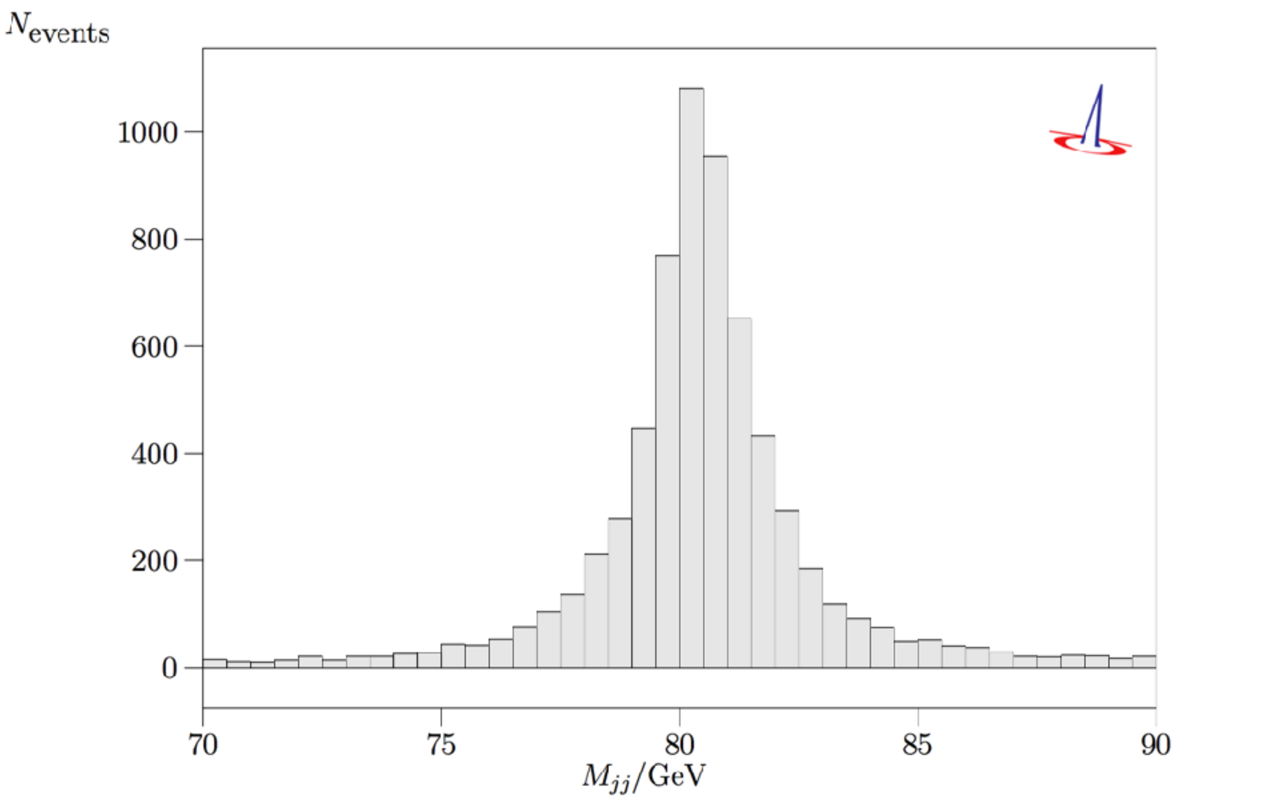
# For better statistics: 100 times LEP
luminosity = 10 / fb

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

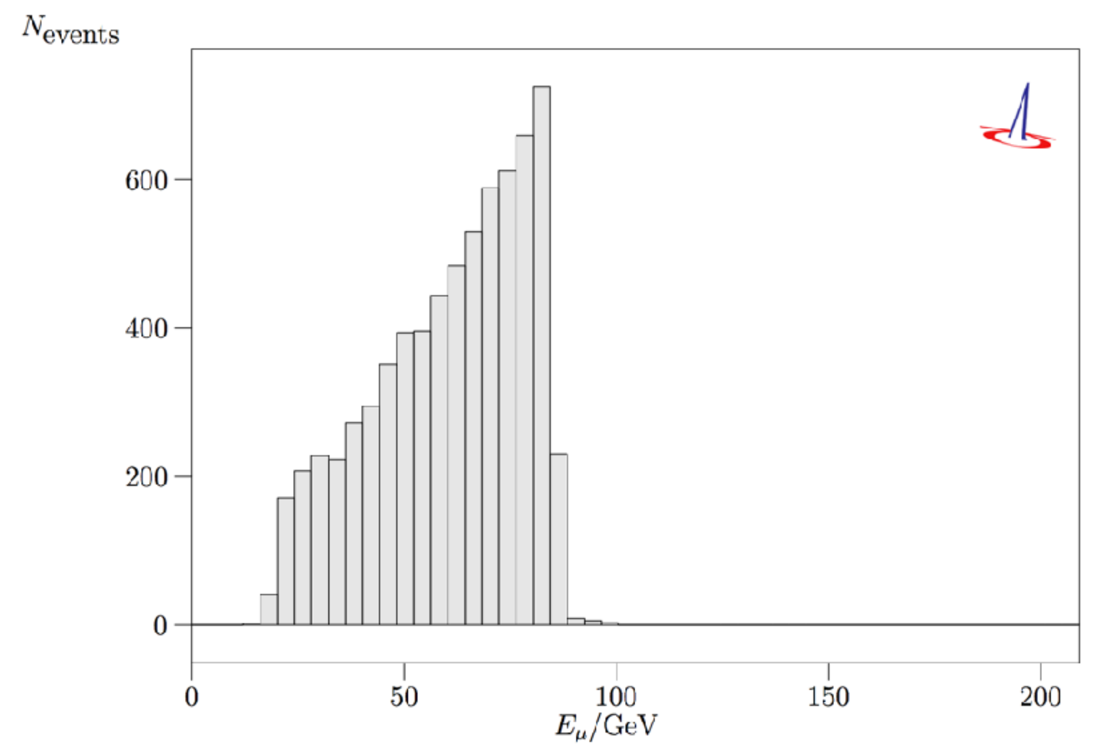
analysis = record m_jets (eval M [u, D]);
           record e_muon (eval E [e2])

simulate (cc10)

compile_analysis ( "out_file" = cc10.dat)
```



Data within bounds:
$\langle\text{Observable}\rangle = 80.466 \pm 0.030$ [$n_{\text{entries}} = 6564$]



Data within bounds:
$\langle\text{Observable}\rangle = 60.52 \pm 0.22$ [$n_{\text{entries}} = 6878$]

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

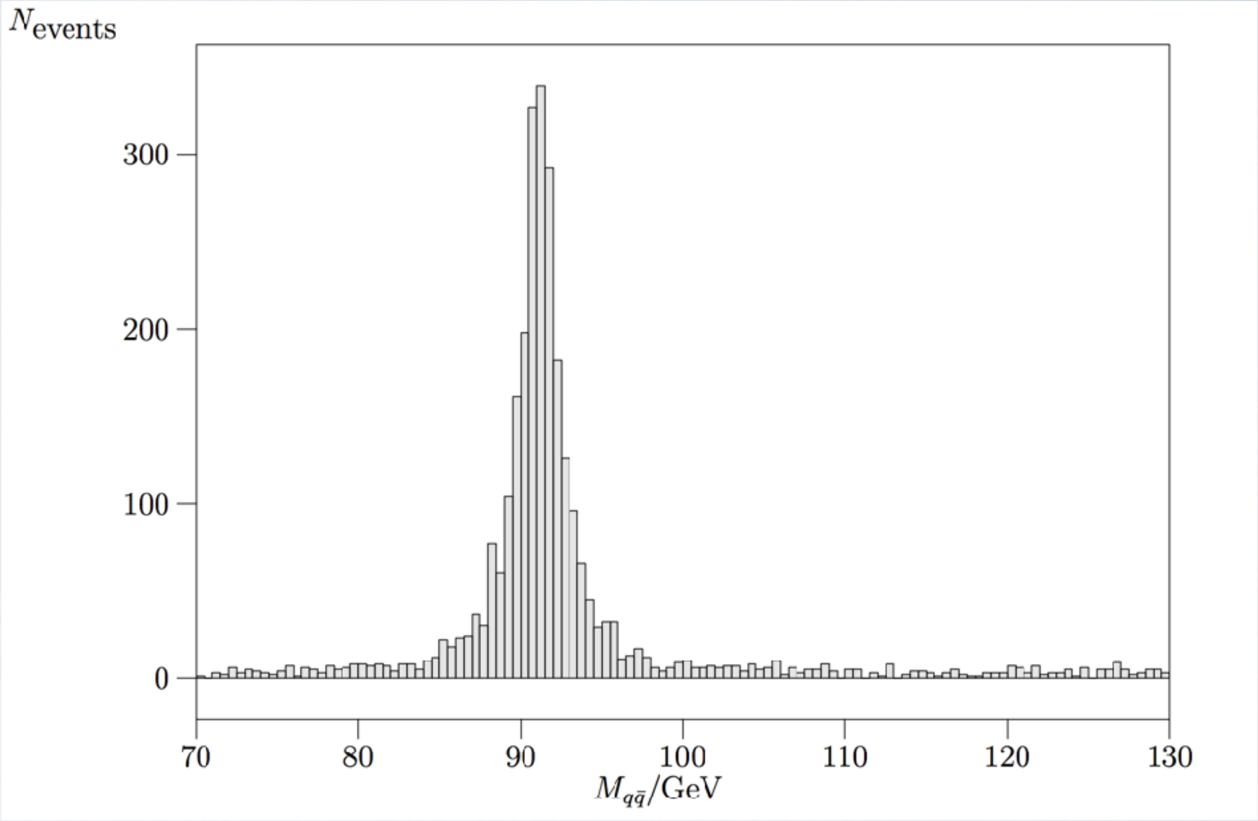
# would-be Higgs mass at LEP
mH = 115 GeV
wH = 3.228 MeV
mb = 2.9 GeV
me = 0  ms = 0  mc = 0

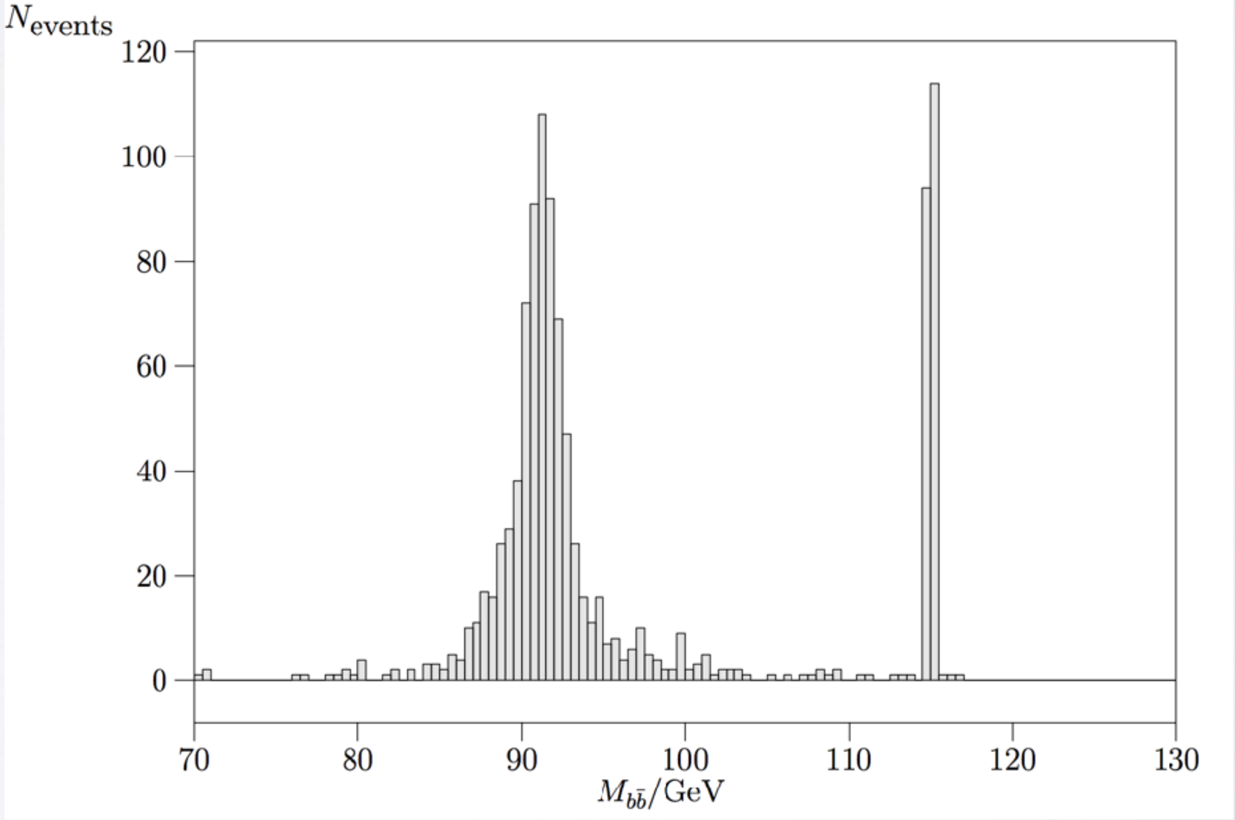
cuts = all M >= 10 GeV [q, Q]
# For better statistics: 100 times LEP
luminosity = 10 / fb

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

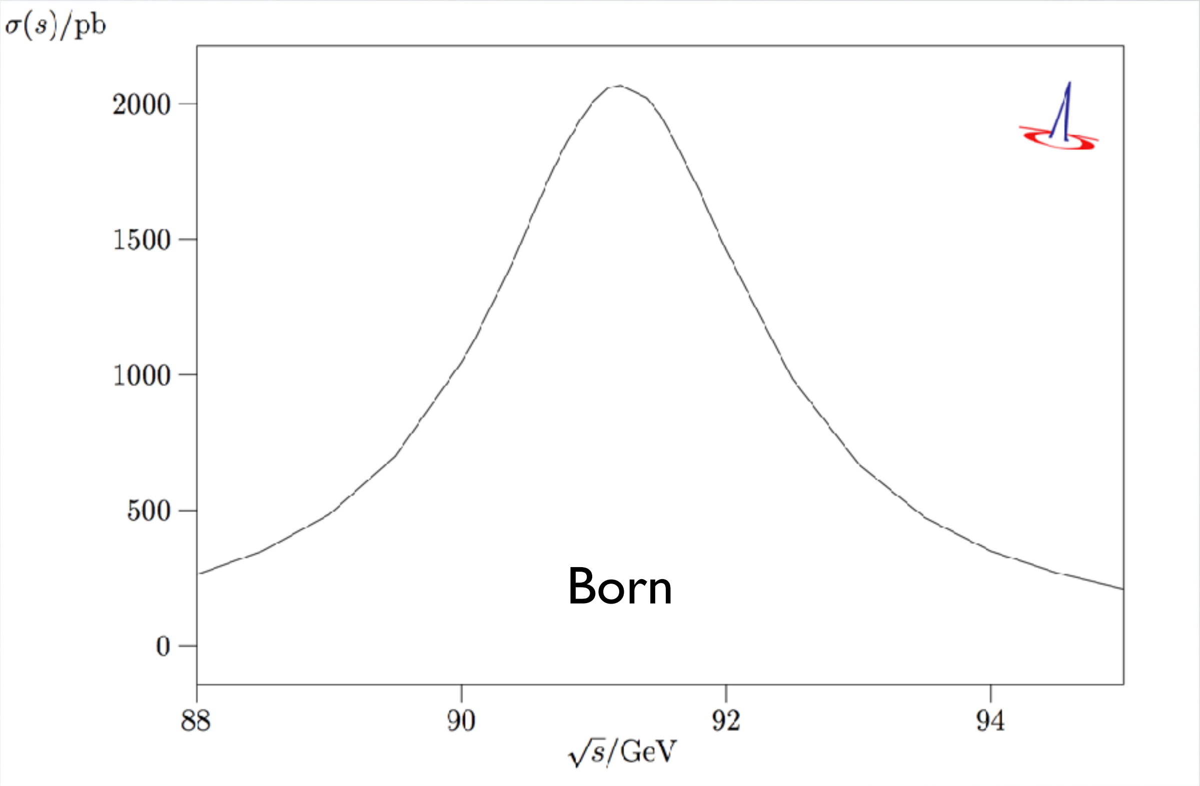
cuts = all E >= 100 MeV [prt]
   and all abs (cos(Theta)) <= 0.99 [prt]
   and all M2 >= (1 GeV)^2 [prt, prt]

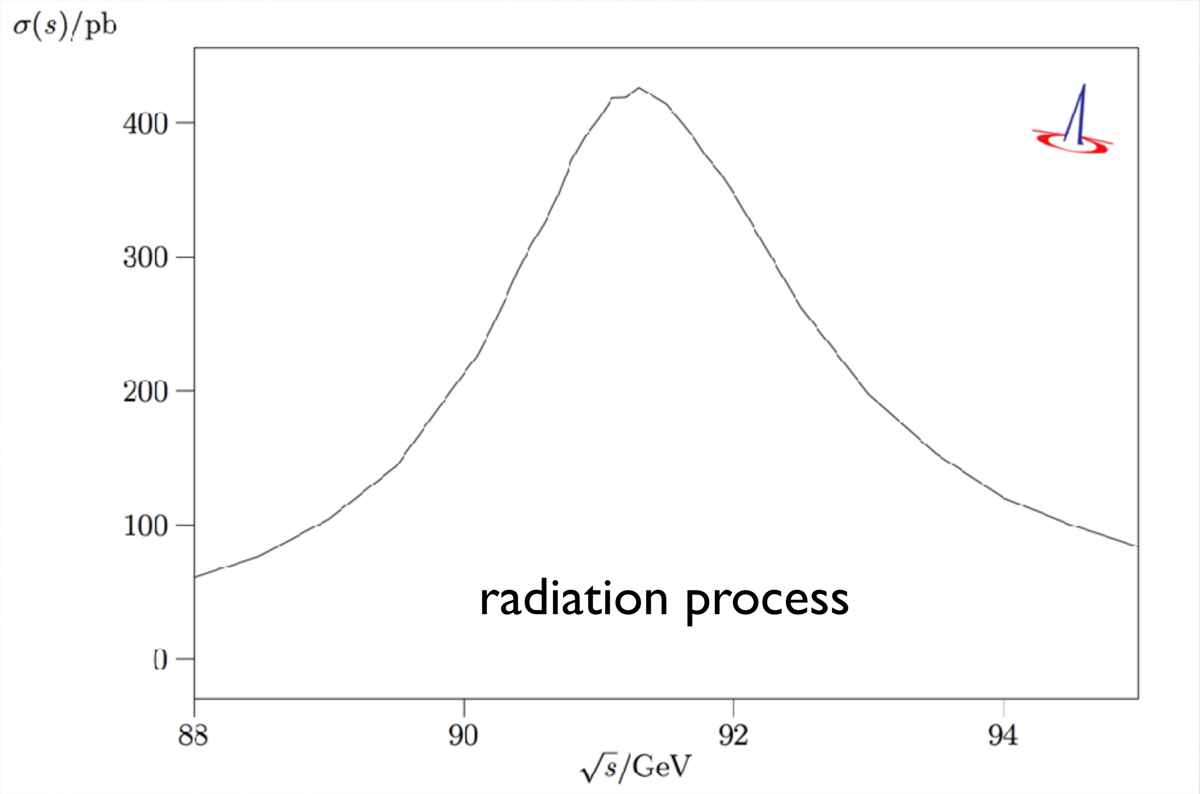
integrate (enj)  { iterations = 5:20000:"gw", 3:10000 }


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 (bornproc) { iterations = 2:1000:"gw", 1:2000 }
   record lineshape_born (sqrts, integral (bornproc) / 1000)
   integrate (rc)  { iterations = 5:3000:"gw", 2:5000 }
   record lineshape_rc (sqrts, integral (rc) / 1000)
}

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





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
```