The WHIZARD Generator for precision measurements

Jürgen R. Reuter, DESY

WHIZARD: Past and recent timeline

- Original scope: electroweak (multi-fermion) studies at 1.6 TeV TESLA [≈ 1998-2000]
- 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]
- Color flow formalism [≈2005]
- 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 group(s) for CEPC/FCC-ee simulations [≈ 2013-2015]
- 04/2015, ALCW'15 Tokyo: LC generator group endorsed v2.2 for new mass productions
- Ongoing validation for [ee] physics between v1.95 and v2 [until ca. 04/2016]

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

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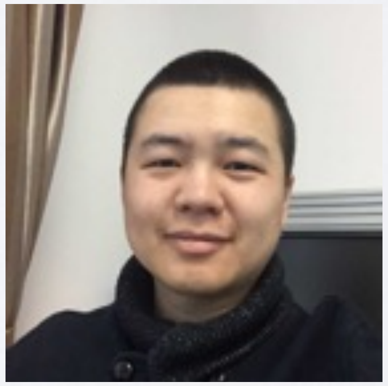
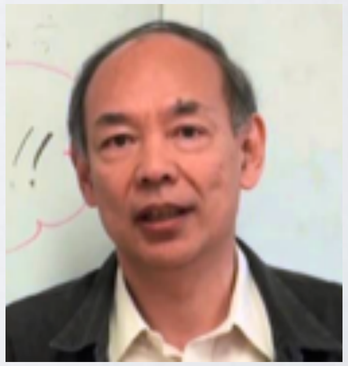
Mikael Berggren

Jean-Jacques Blaising

Moritz Habermehl



Mo Xin



Akiya Miyamoto

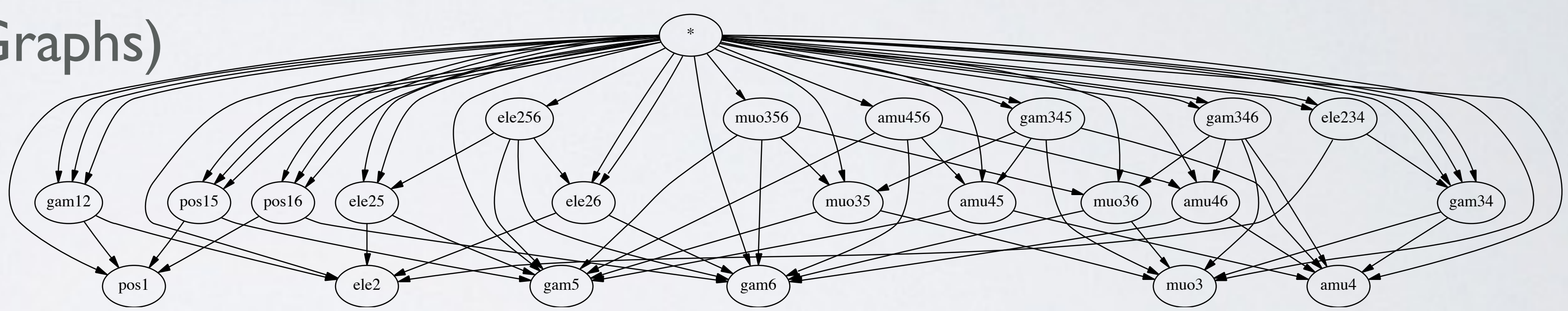
WHIZARD: Introduction

WHIZARD v2.2.8 (22.11.2015)   http://whizard.hepforge.org   <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR, Simon Braß/Bijan Chokoufé/Marco Sekulla/Soyoung Shim/Christian Weiss/Florian Staub/Zhijie Zhao* + *2 Master students*

Publication: EPJ C71 (2011) 1742

- Universal event generator for lepton and hadron colliders
- Modular package:
  - Phase space parameterization (resonances, collinear emission, Coulomb etc.)
  - O'Mega optimized matrix element generator (recursiveness via Directed Acyclical Graphs)



  - VAMP: adaptive multi-channel Monte Carlo integrator
  - CIRCE1/2: generator/simulation tool for lepton collider beam spectra
  - Lepton beam ISR   Kuraev/Fadin, 1986; Skrzypek/Jadach, 1991
  - Color flow formalism   Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011
  - Parton shower   Kilian/JRR/Schmidt/Wiesler, 2011

- 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, [PYTHIA8], StdHep [internal]`

WHIZARD: Manual

WHIZARD Manual @ HepForge

General structure of SINDARIN input

```
model = SM

alias ll = “e-“:”e+”:”mu+”:”mu-“
alias nu = n1:N1:n2:N2:n3:N3
alias jet = u:U:d:D:s:S:g

process tth = e1, E1 => t, tbar, h
process tthfull =
   e1, E1 => ll, nu, ll, nu, b, bbar, jet, jet
process inclusive =
   e1, E1 => (Z, h) + (Z, Z) + (Wp, Wm)
process t_dec = t => E1, nubar, b

sqrts = 500 GeV
beams = e1, E1 => circe1 => ISR

cuts = all M > 10 GeV [jet, jet]

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

n_events = 10000

unstable t (t_dec)

sample_format = lhef, stdhep, hepmc
sample = “mydata”
```

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LCWS ’14, Belgrade, Simulation summary talk:

WHIZARD Task to implement LCIO format

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WHIZARD v2.2.4, 02/2015:

```
sample_format = lcio

simulate (<process>)
```

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process tth = e1, E1 => t, tbar, h
process tthfull =
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process inclusive =
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WHIZARD Task to implement LCIO format

WHIZARD v2.2.4, 02/2015:

```
sample_format = lcio

simulate (<process>)
```

```
==========================================
 - Event  : 1
 - run:  42
 - timestamp 1429387390000000000
 - weight 1
==========================================
 date:      18.04.2015  20:03:10.000000000
 detector : unknown
 event parameters:
 parameter ProcessID [int]: 20,

 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     | endpoint x,    y  ,   z     |    mass |  charge |            spin             | colorflow | [parents] - [daughters]

[00000004]    0|     2212| 0.00e+00, 0.00e+00, 7.00e+03| 7.00e+03| 3 |[s       ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00| 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00|  (0, 0)   | [] - [2,3]
[00000005]    1|     2212| 0.00e+00, 0.00e+00,-7.00e+03| 7.00e+03| 3 |[s       ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00| 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00|  (0, 0)   | [] - [2,3]
[00000006]    2|        1| 7.50e-01,-1.57e+00, 3.22e+01| 3.22e+01| 3 |[s       ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 6.25e-02| 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00|  (501, 0)   | [0,1] - [4,5]
[00000007]    3|       -2|-3.05e+00,-1.90e+01,-5.46e+01| 5.79e+01| 3 |[s       ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 3.38e-01| 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00|  (0, 501)   | [0,1] - [4,5]
[00000009]    4|      -24| 1.52e+00,-2.07e+01,-2.06e+01| 8.59e+01| 3 |[s       ]| 0.00e+00, 0.00e+00, 0.00e+00|-3.00e-01, 5.00e-02, 4.00e-03| 8.08e+01| 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00|  (0, 0)   | [2,3] - [6,7]
[00000008]    5|       22|-3.81e+00, 1.13e-01,-1.83e+00| 4.23e+00| 1 |[s       ]| 0.00e+00, 0.00e+00, 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00| 8.16e-02| 0.00e+00| 6.00e-01, 1.00e+00, 5.00e-01|  (0, 0)   | [2,3] - []
[00000010]    6|        1|-2.44e+00, 2.88e+01, 6.08e+00| 2.96e+01| 1 |[s       ]|-3.00e-01, 5.00e-02, 4.00e-03| 0.00e+00, 0.00e+00, 0.00e+00|-9.95e-02| 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00|  (0, 0)   | [4] - []
[00000011]    7|       -2| 3.96e+00,-4.95e+01,-2.67e+01| 5.64e+01| 1 |[s       ]|-3.00e-01, 5.00e-02, 4.00e-03| 0.00e+00, 0.00e+00, 0.00e+00|-1.74e-01| 0.00e+00| 0.00e+00, 0.00e+00, 0.00e+00|  (0, 0)   | [4] - []

--------------------------------------------------------------------------------
```

BSM Models in WHIZARD

MODEL TYPE	with CKM matrix	trivial CKM
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 coupl.	SM_ac_CKM	SM_ac
SM with anomalous top coupl.	SMtop_CKM	SMtop
SM for e^+e^- top threshold	—	SM_tt_threshold
SM with anom. Higgs coupl.	—	SM_rx / NoH
SM ext. for VV scattering	—	SSC / SSC2/ AltH
SM ext. for unitarity limits	—	SM_ul
SM with Z'	—	Zprime
2HDM	2HDM_CKM	2HDM
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	—	MSSM_Grav
NMSSM	NMSSM_CKM	NMSSM
extended SUSY models	—	PS/E/SSM
Littlest Higgs	—	Littlest
Littlest Higgs with ungauged $U(1)$	—	Littlest_Eta
Littlest Higgs with T parity	—	Littlest_Tpar
Simplest Little Higgs (anomaly-free/univ.)	—	Simplest[_univ]
3-site model	—	Threeshl
UED	—	UED
SM with gravitino and photino	—	GravTest
Augmentable SM template	—	Template

2.2.8: SM_dim6

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QED with e, μ, τ, γ	–	QED
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2HDM	2HDM_CKM	2HDM
MSSM	MSSM_CKM	MSSM
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NMSSM	NMSSM_CKM	NMSSM
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Littlest Higgs	—	Littlest
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3-site model	—	Threeshl
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Augmentable SM template	—	Template

2.2.8: SM_dim6

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

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MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	—	MSSM_Grav
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- Automated models: UFO interface [in connection with new WHIZARD/O'Mega model format]

Decay processes / auto_decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

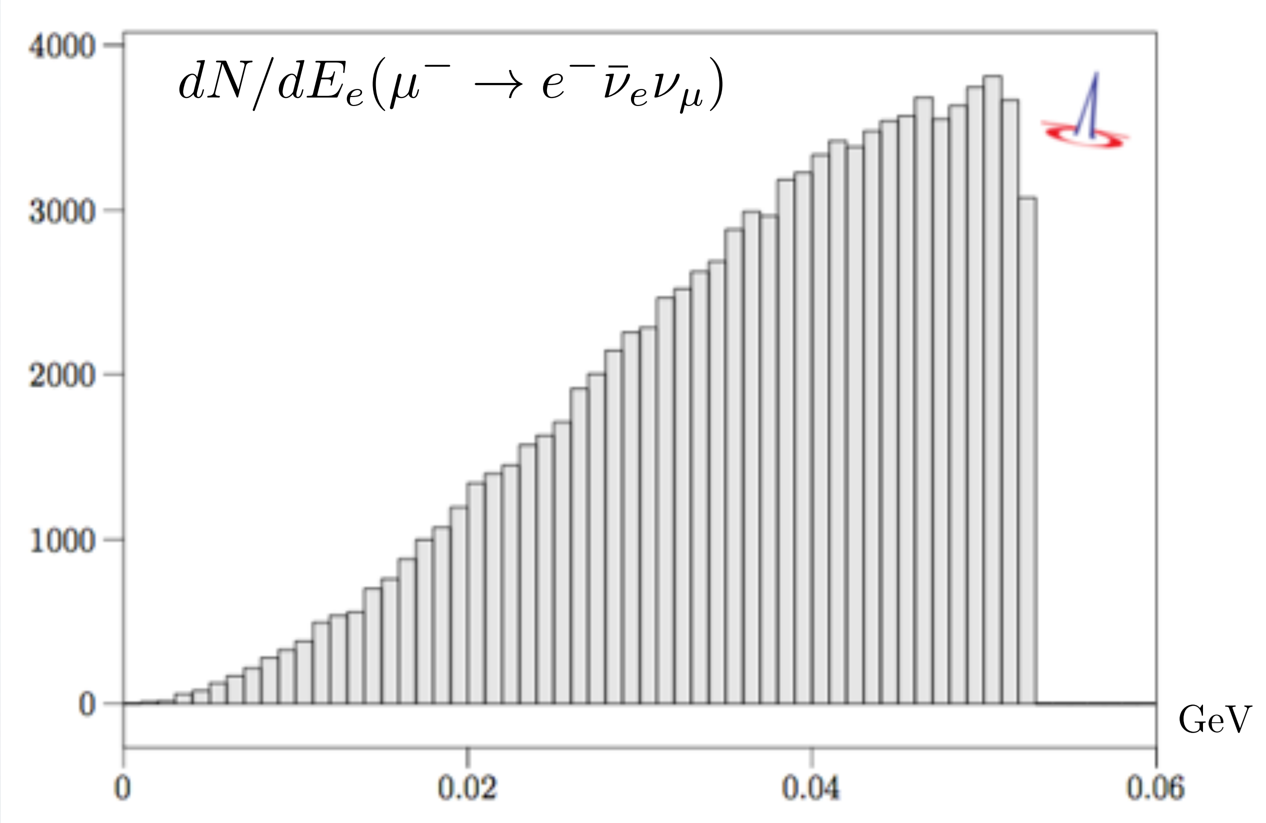
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

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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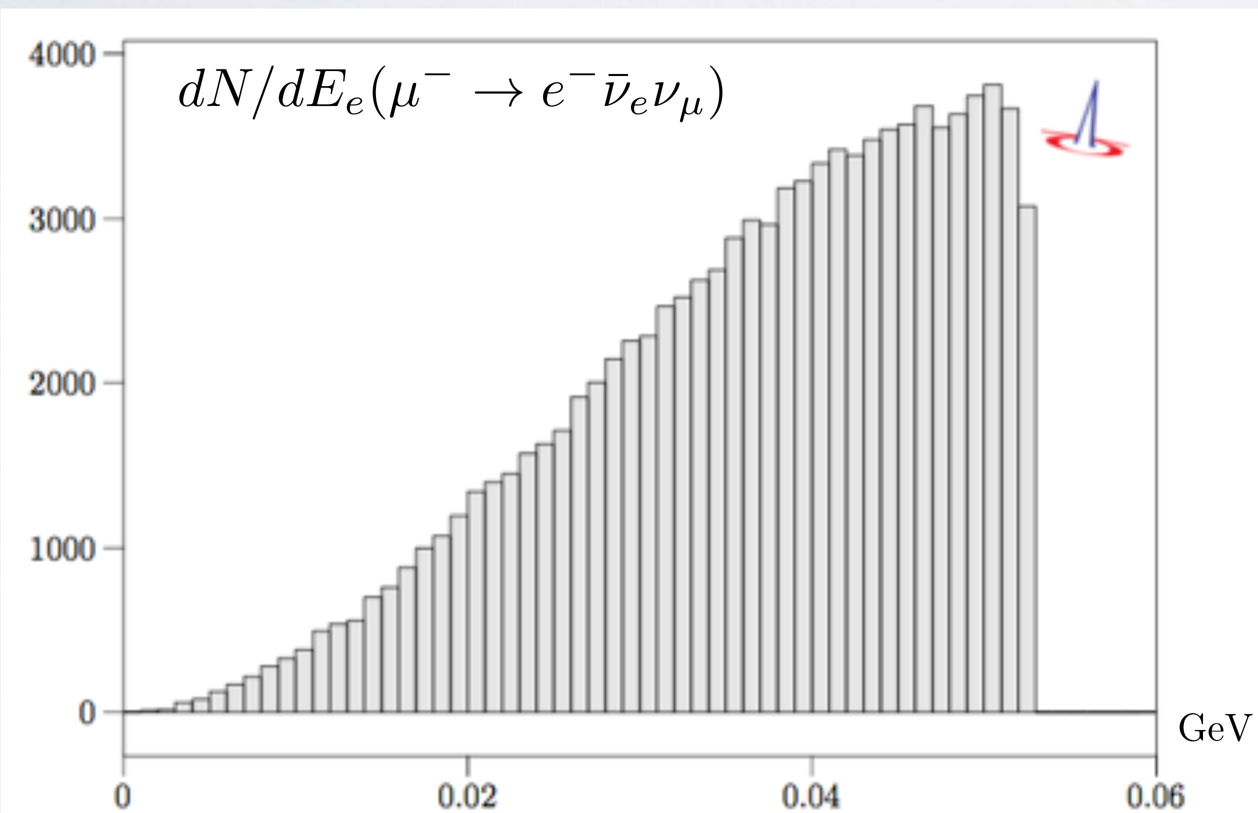


Automatic integration of particle decays

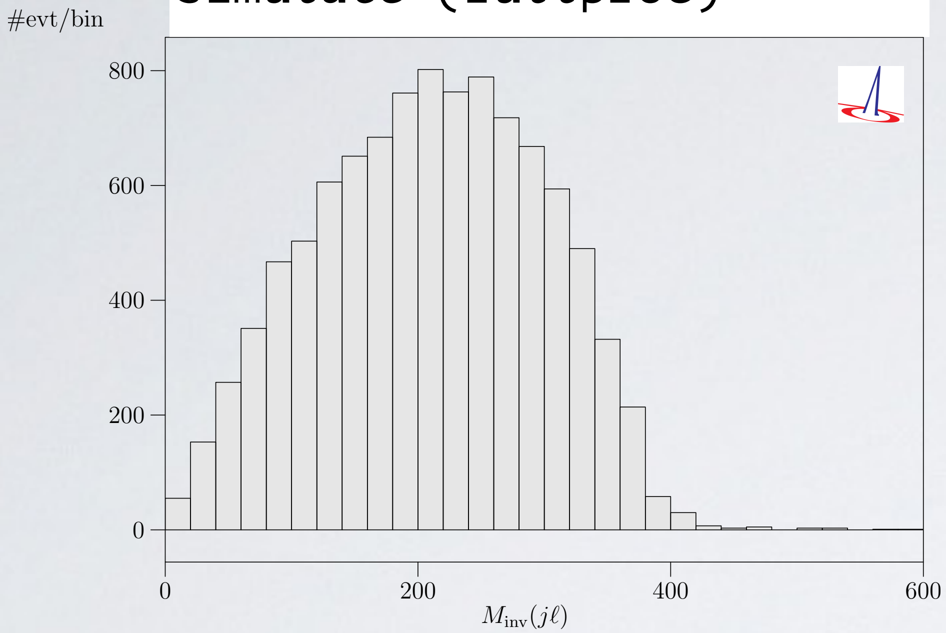
```
auto_decays_multiplicity = 2
?auto_decays_radiative = false

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
```

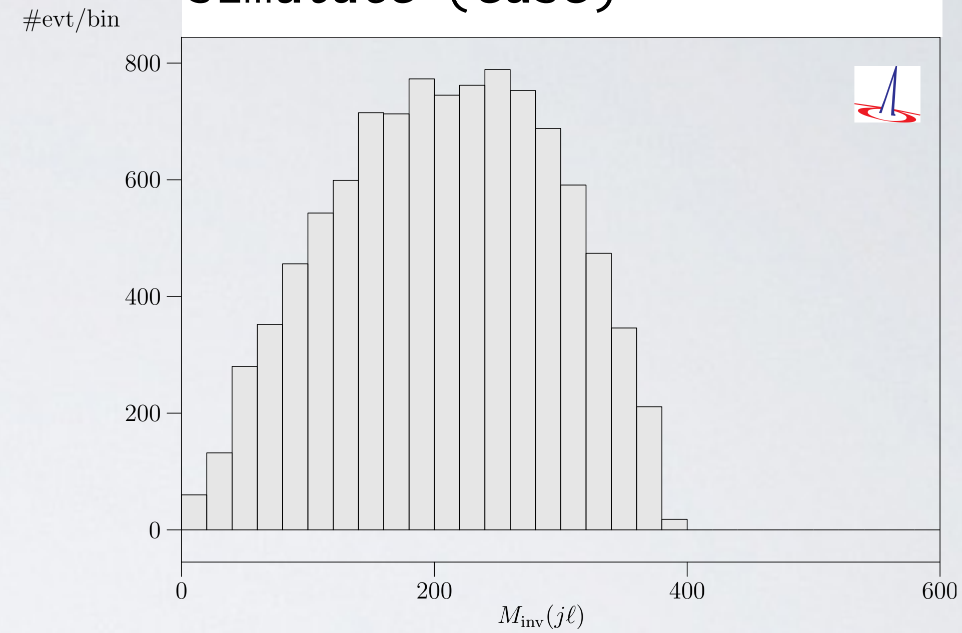
Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay

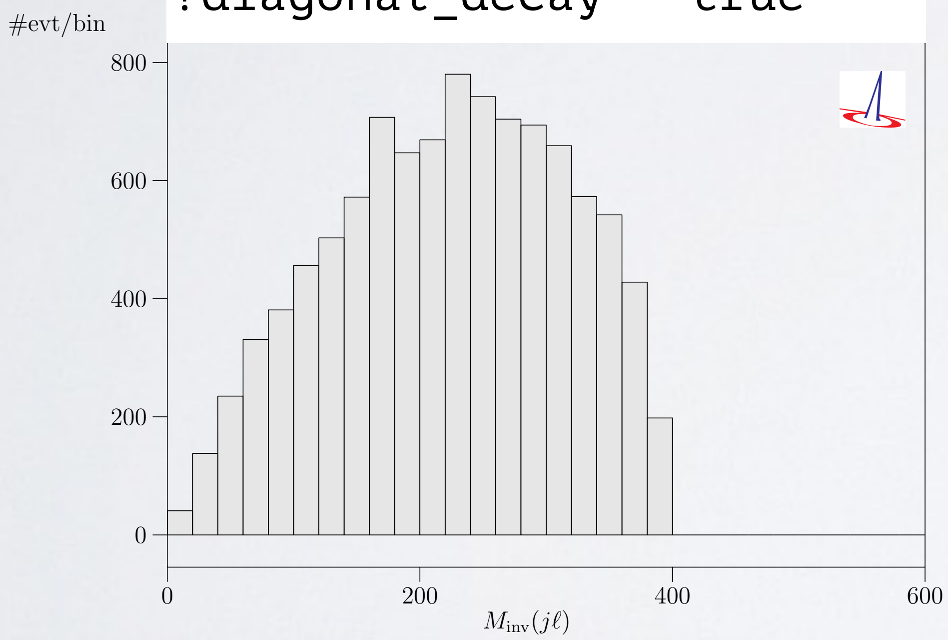
`simulate (fullproc)`



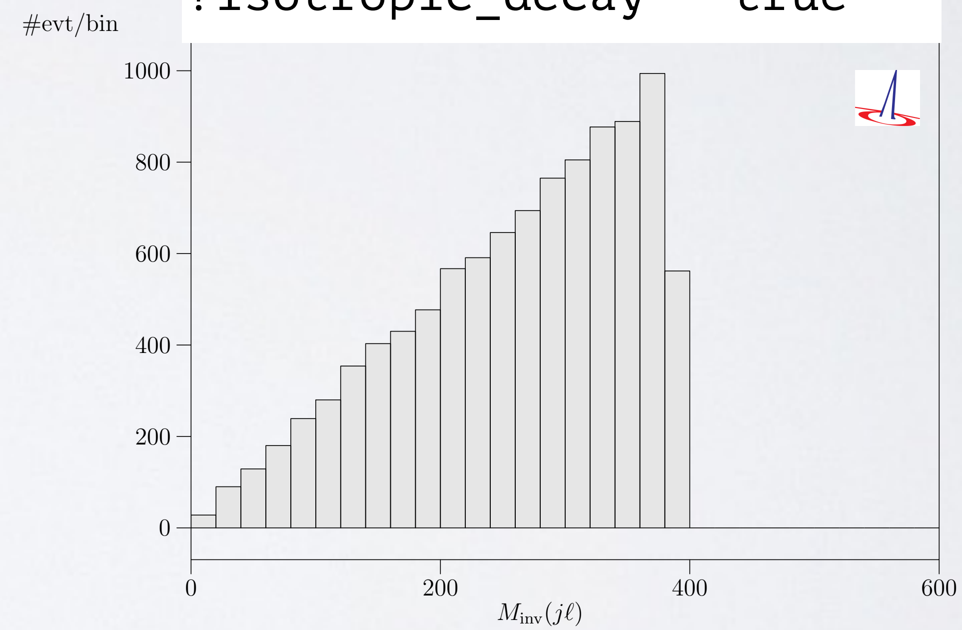
`simulate (casc)`



`?diagonal_decay = true`



`?isotropic_decay = true`



Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay

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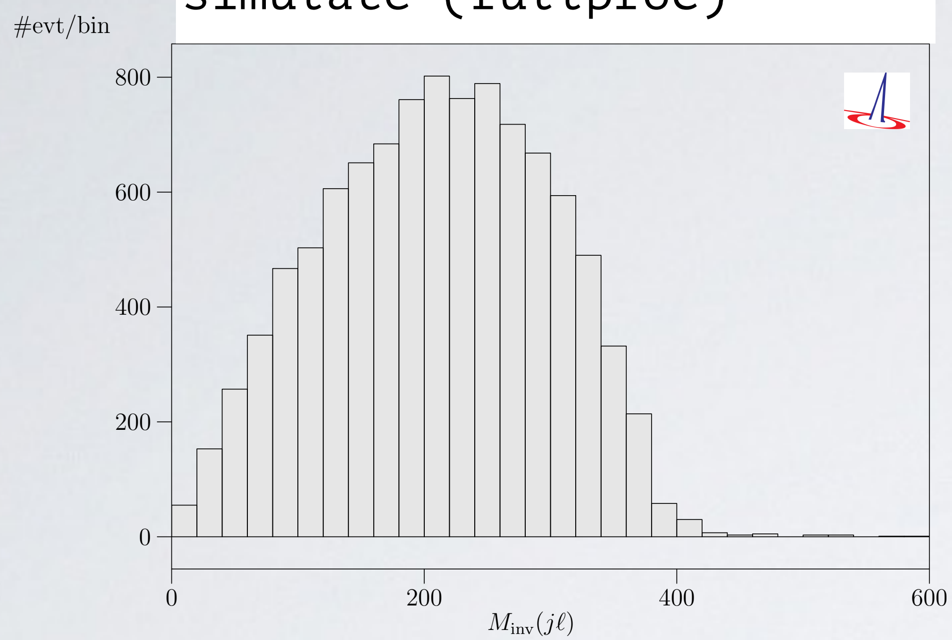

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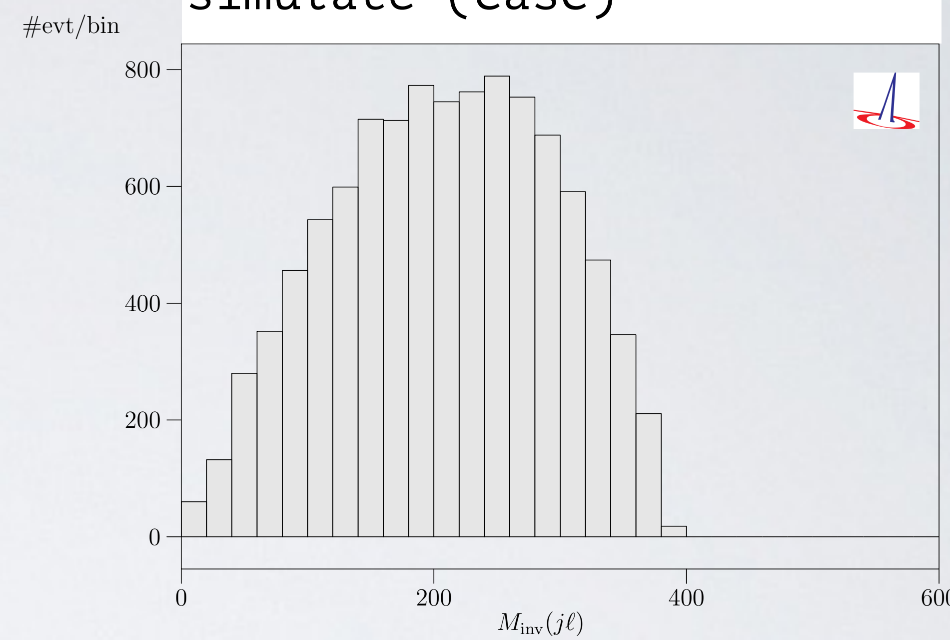

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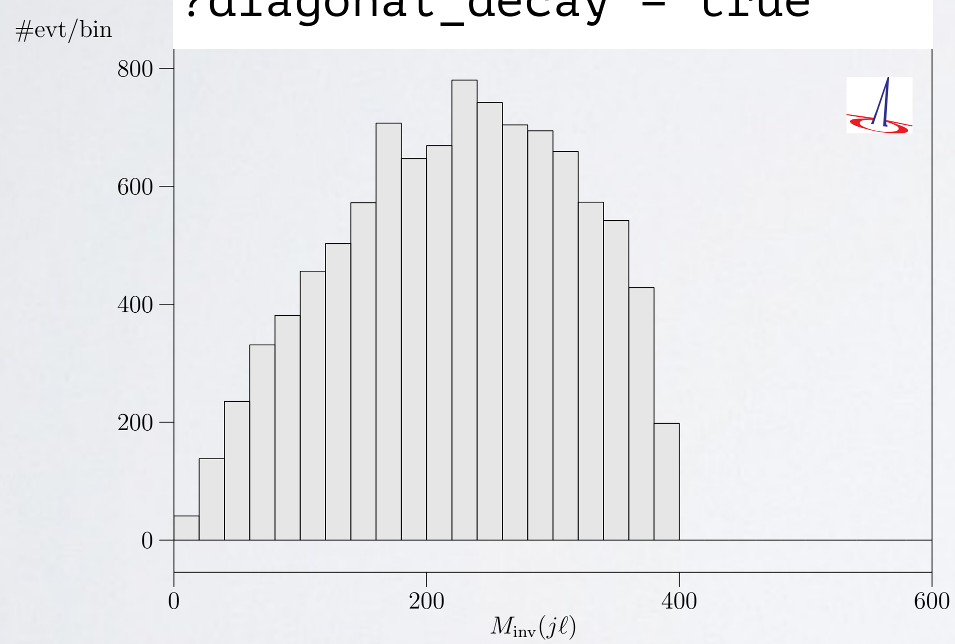

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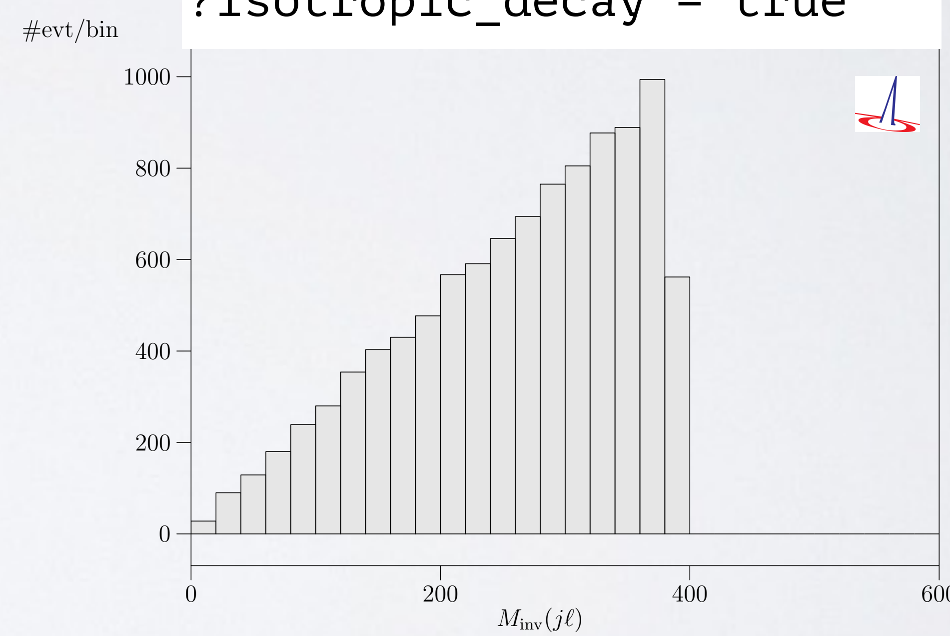
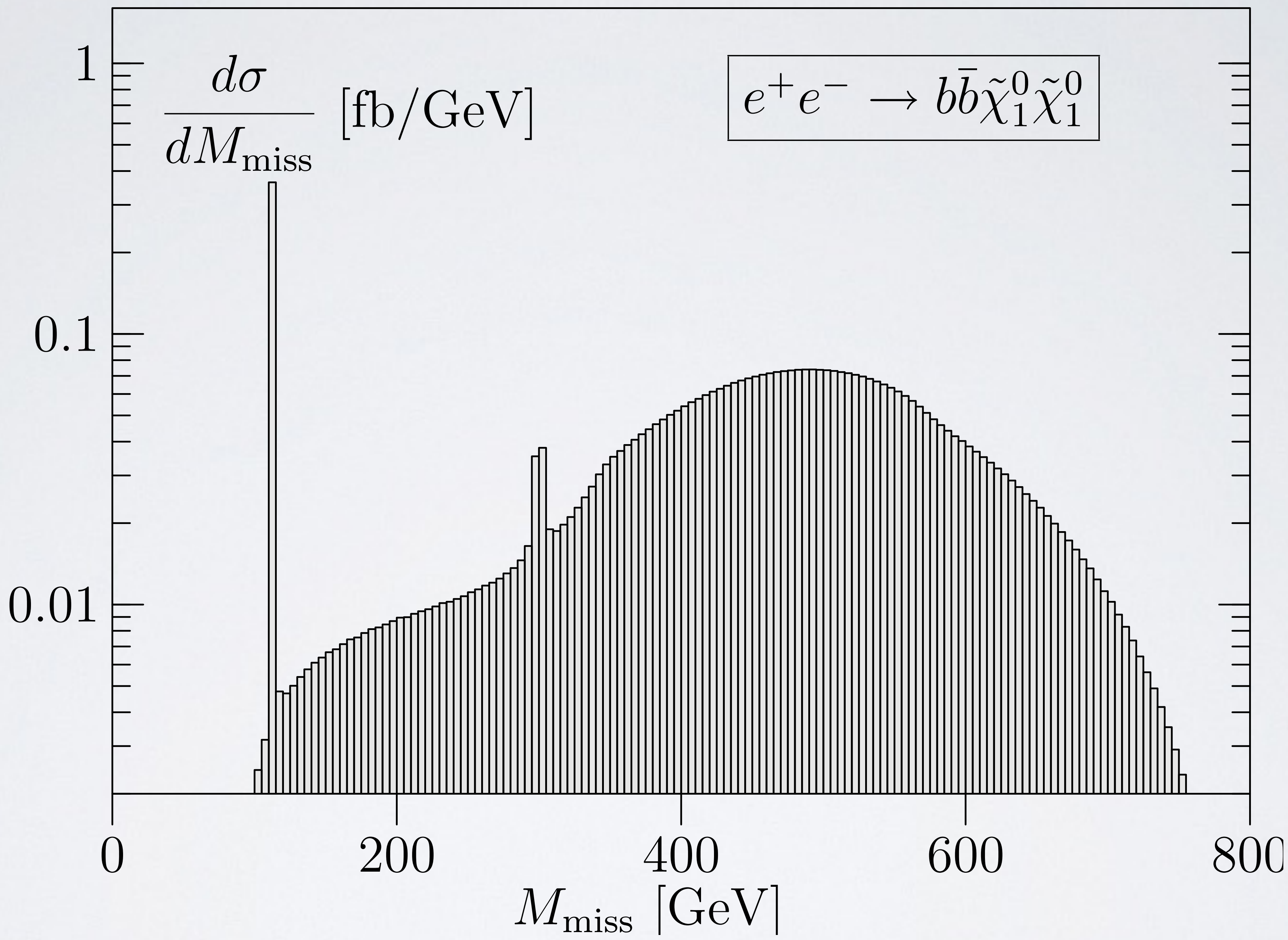


NEW: possibility to select specific helicity in decays!

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

Lepton Collider Beamspectra



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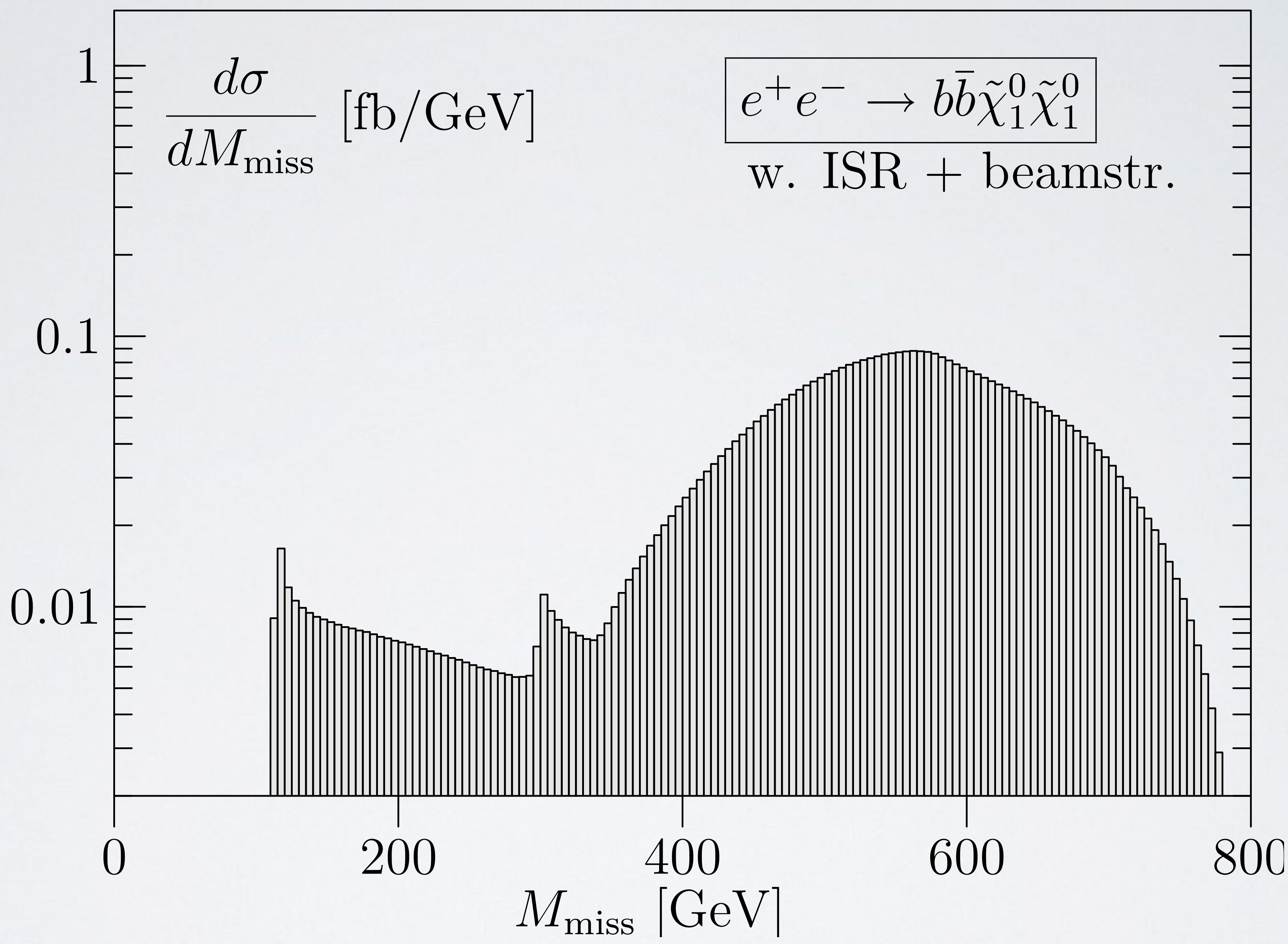
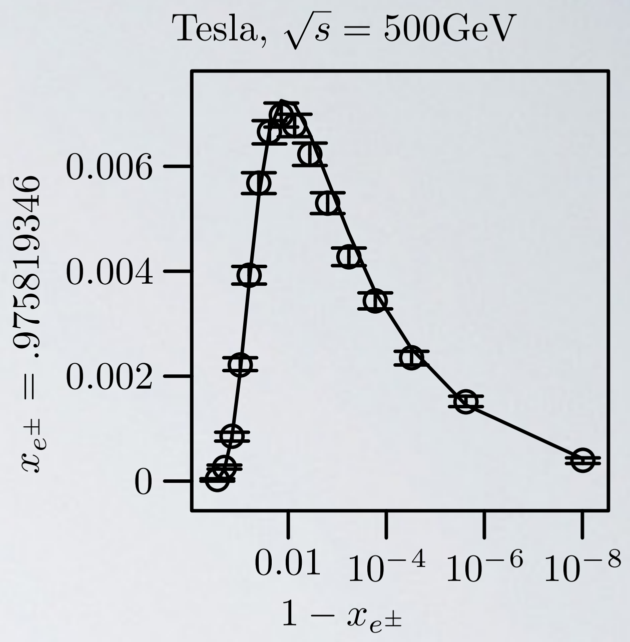


Lepton Collider Beam Simulation

- 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: $D_{B_1 B_2}(x_1, x_2) \neq D_{B_1}(x_1) \cdot D_{B_2}(x_2)$
- No simple power law: $D_{B_1 B_2}(x_1, x_2) \neq x_1^{\alpha_1}(1-x_1)^{\beta_1} x_2^{\alpha_2}(1-x_2)^{\beta_2}$



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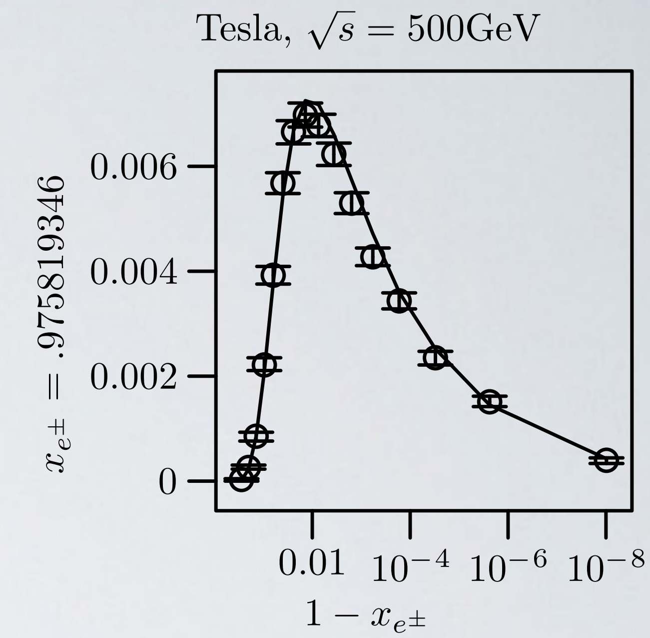
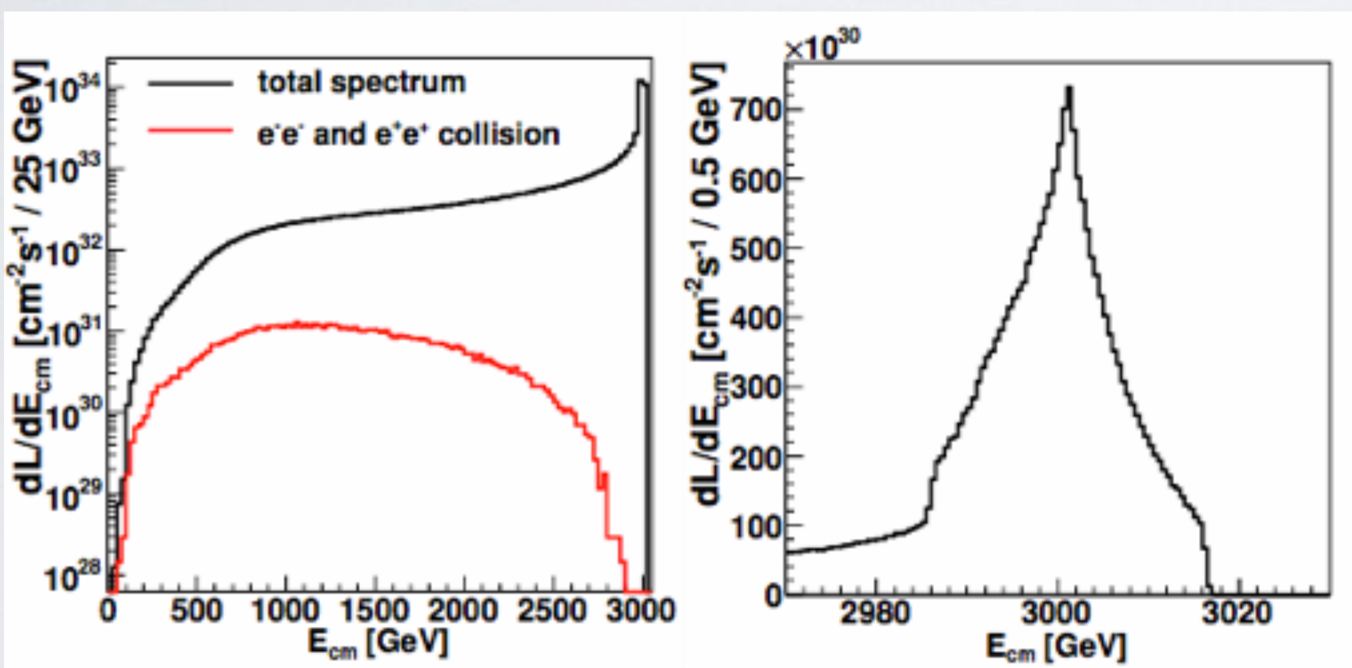


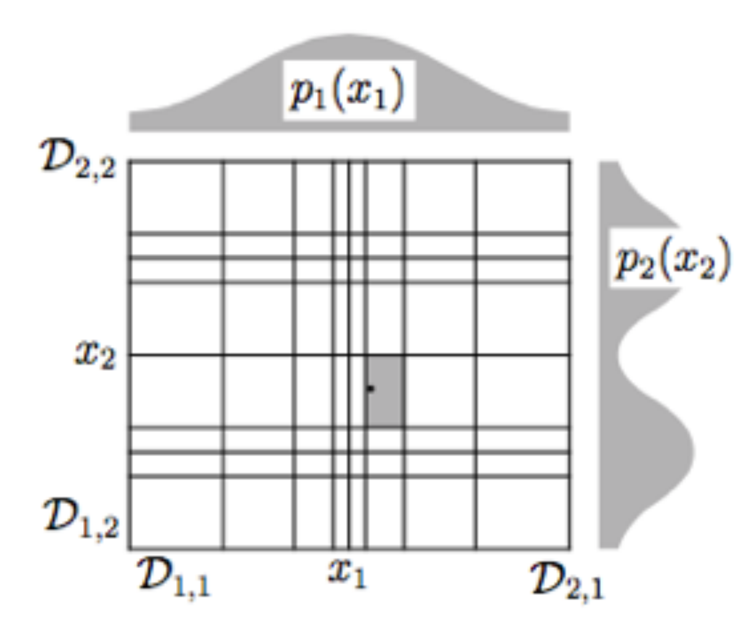


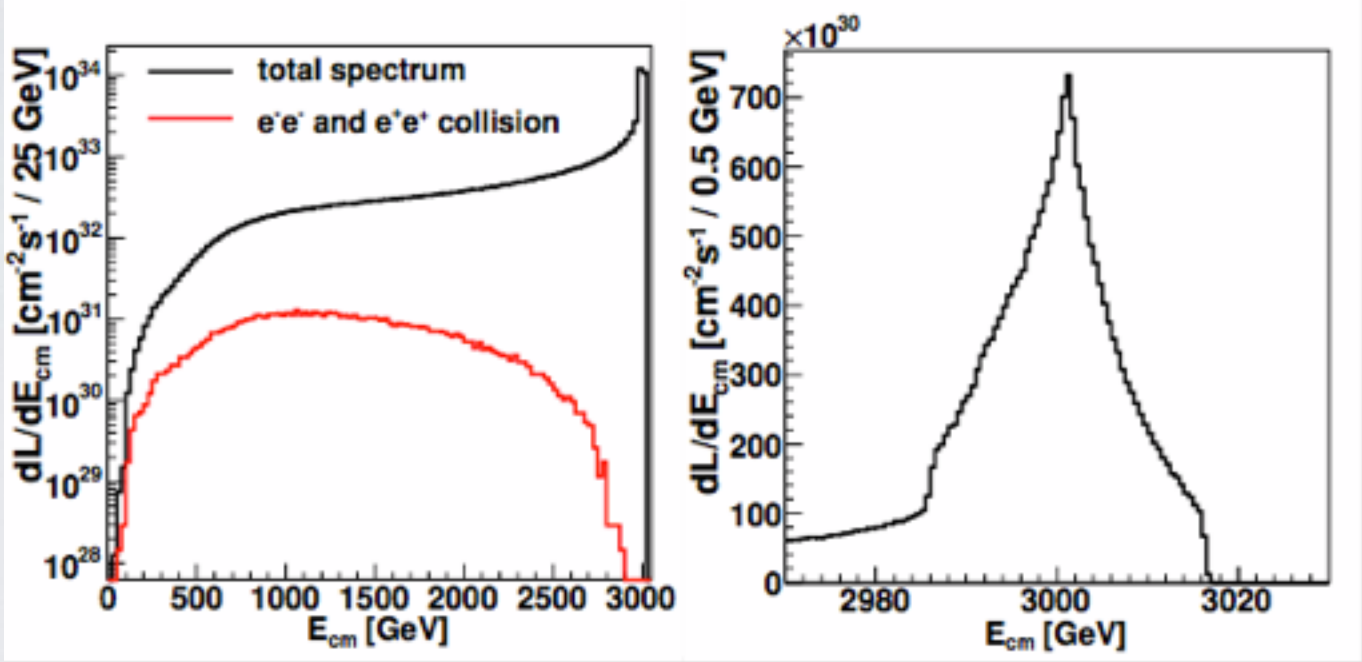
Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)

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: $D_{B_1B_2}(x_1, x_2) \neq x_1^{\alpha_1}(1-x_1)^{\beta_1} x_2^{\alpha_2}(1-x_2)^{\beta_2}$





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]

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:

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3 simulation options

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

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ILC 200/230/250/350/500 GeV
CEPC 240/250 GeV
spectra directly included in CIRCE2

NLO Development in WHIZARD

- Need for precision predictions that match (sub-) percent experimental accuracy
- mainly NLO corrections, but also QED and electroweak (ee)

Binoth Les Houches Interface (BLHA): Workflow

1. Process definition in SINDARIN (contract to One-Loop Program [OLP])
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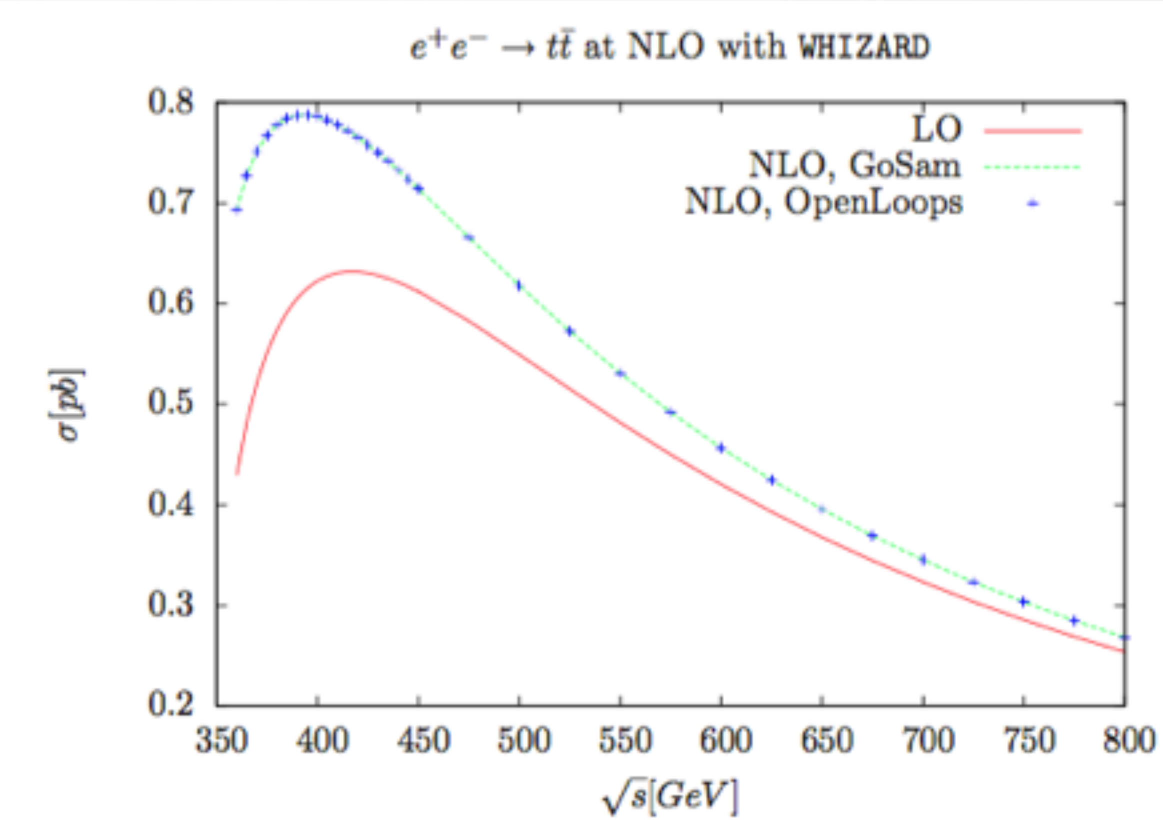

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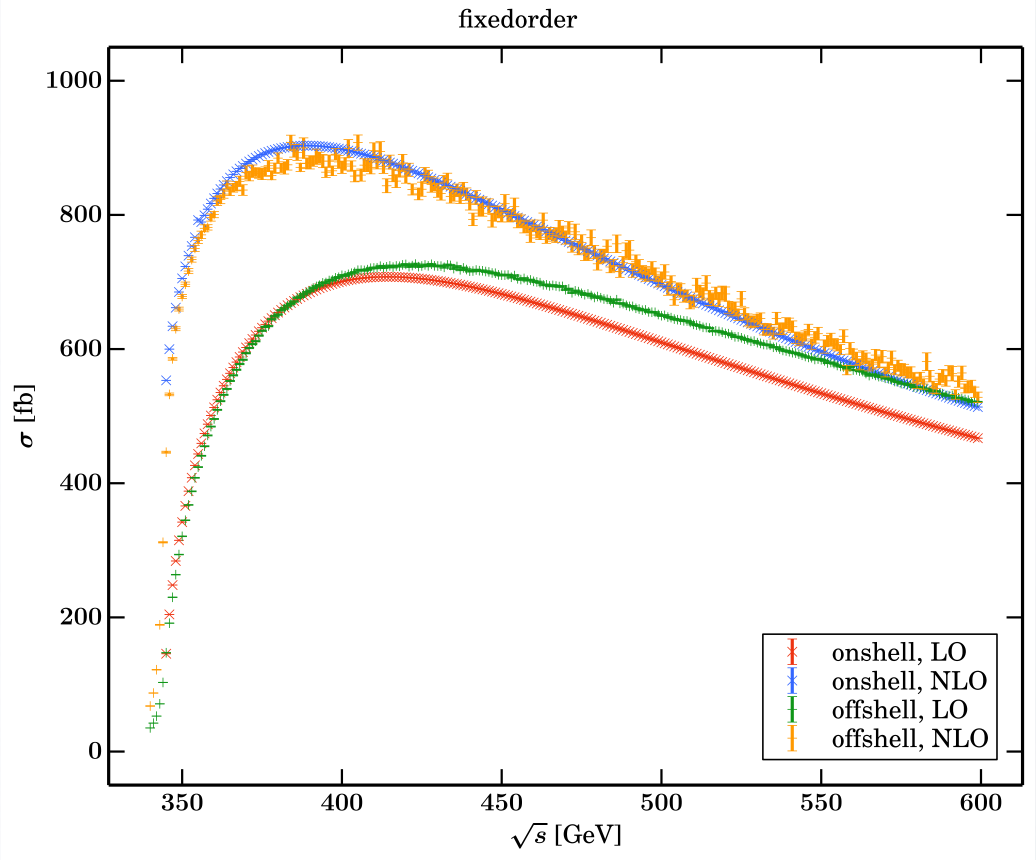

FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

$$d\sigma^{\text{NLO}} = \underbrace{\int_{n+1} \left(d\sigma^R - d\sigma^S\right)}_{\text{finite}} + \underbrace{\int_{n+1} d\sigma^S + \int_n d\sigma^V}_{\text{finite}}$$

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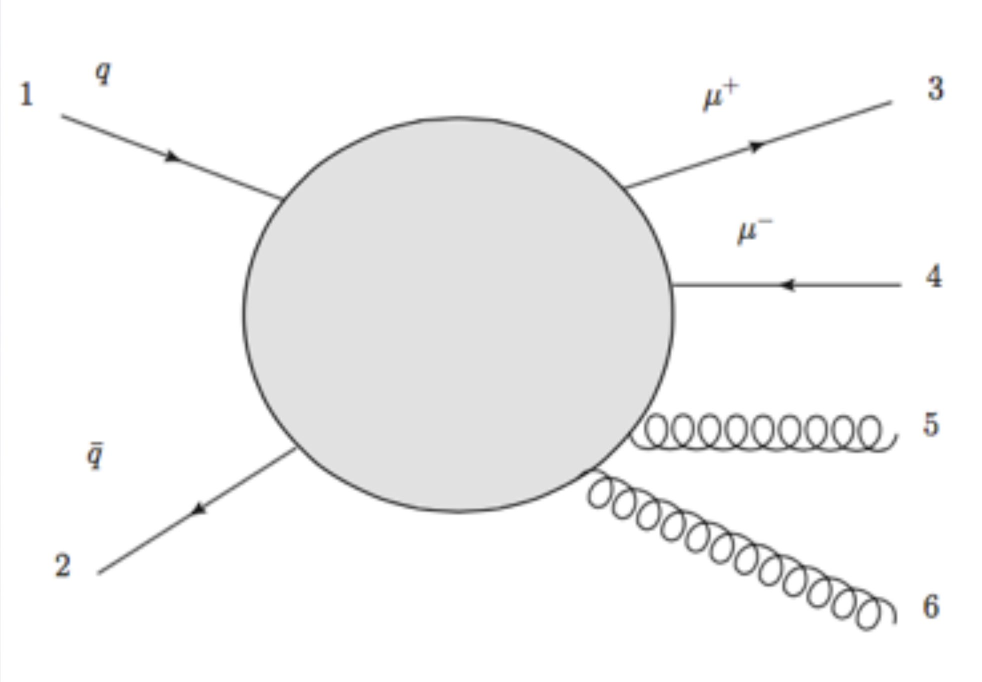

Automated subtraction terms in `WHIZARD`, algorithm:

- ✳ 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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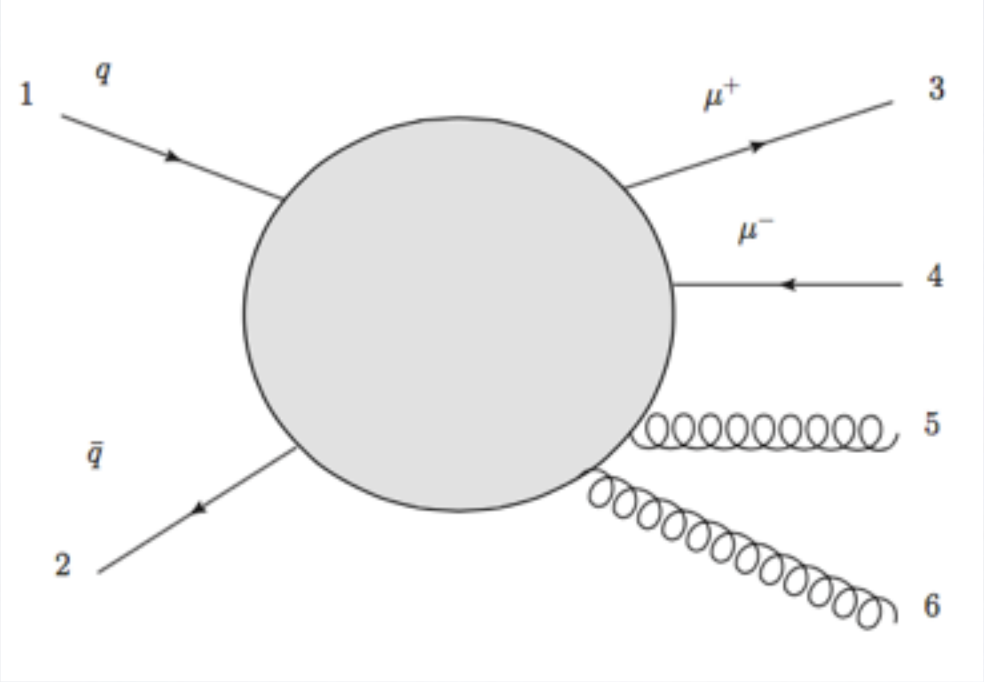

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Soft subtraction involves color-correlated matrix elements:

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

Collinear subtraction involves spin-correlated matrix elements:

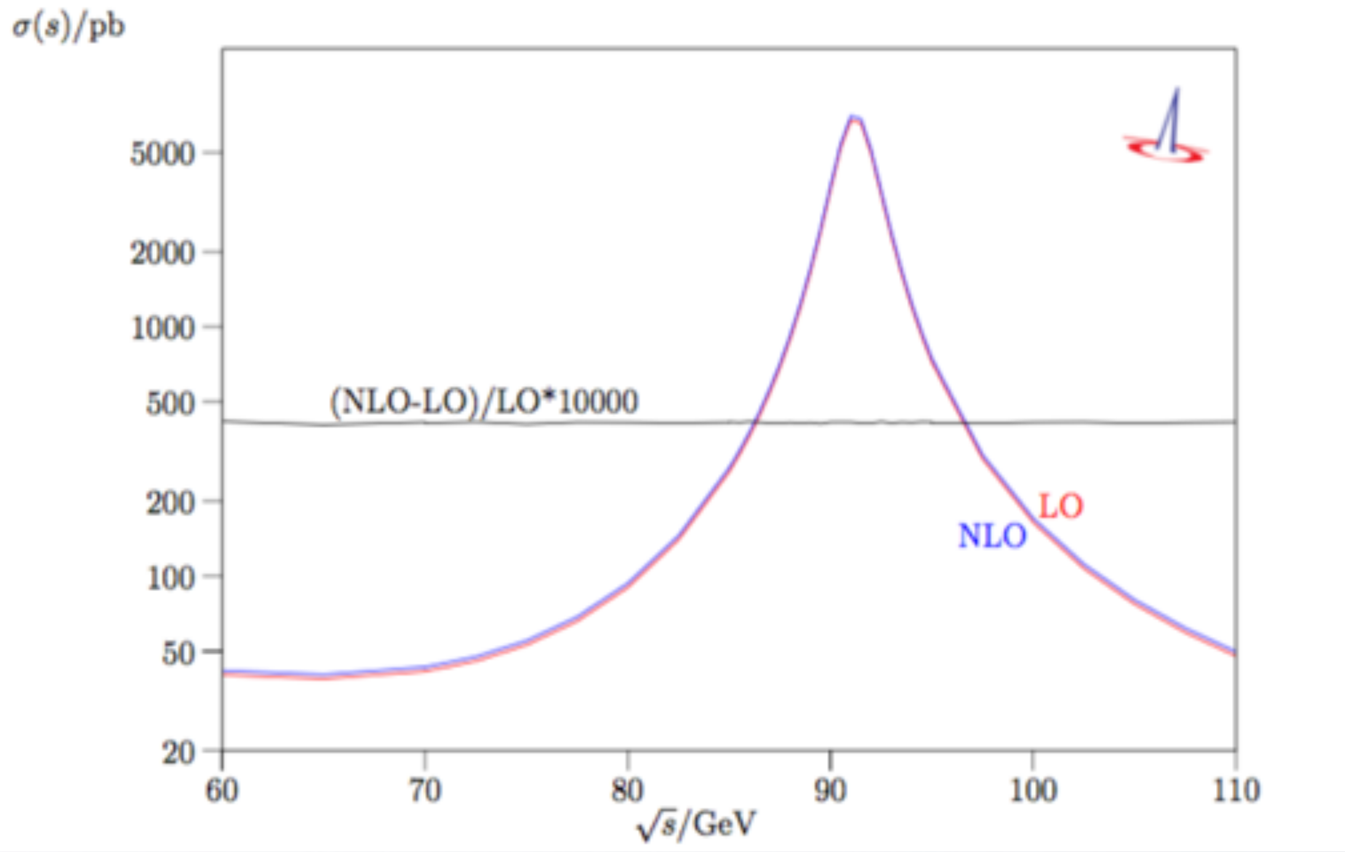
$$\mathcal{B}_{+-} \sim Re \left\{ \frac{\langle k_{\text{em}} k_{\text{rad}} \rangle}{[k_{\text{em}} k_{\text{rad}}]} \sum_{\substack{\text{color}\\\text{spin}}} \mathcal{A}_+^{(n)} \mathcal{A}_-^{(n)*} \right\}$$

Examples and Validation

Simplest benchmark process:

$$e^+e^- \to q\bar{q} \quad \text{with} \quad \left(\sigma^{\rm NLO} - \sigma^{\rm LO}\right)/\sigma^{\rm LO} = \alpha_s/\pi$$

Plot for total cross section for fixed strong coupling constant



List of validated QCD NLO processes

- $e^+e^- \to q\bar{q}$
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- $e^+e^- \to \ell^+\ell^- q\bar{q}$
- $e^+e^- \to \ell^+\nu_\ell q\bar{q}$
- $e^+e^- \to t\bar{t}$
- $e^+e^- \to tW^-b$
- $e^+e^- \to W^+W^-b\bar{b}$
- $e^+e^- \to t\bar{t}H$

- Cross-checks with `MG5_aMC@NLO`
- Phase space integration for virtuals performs great

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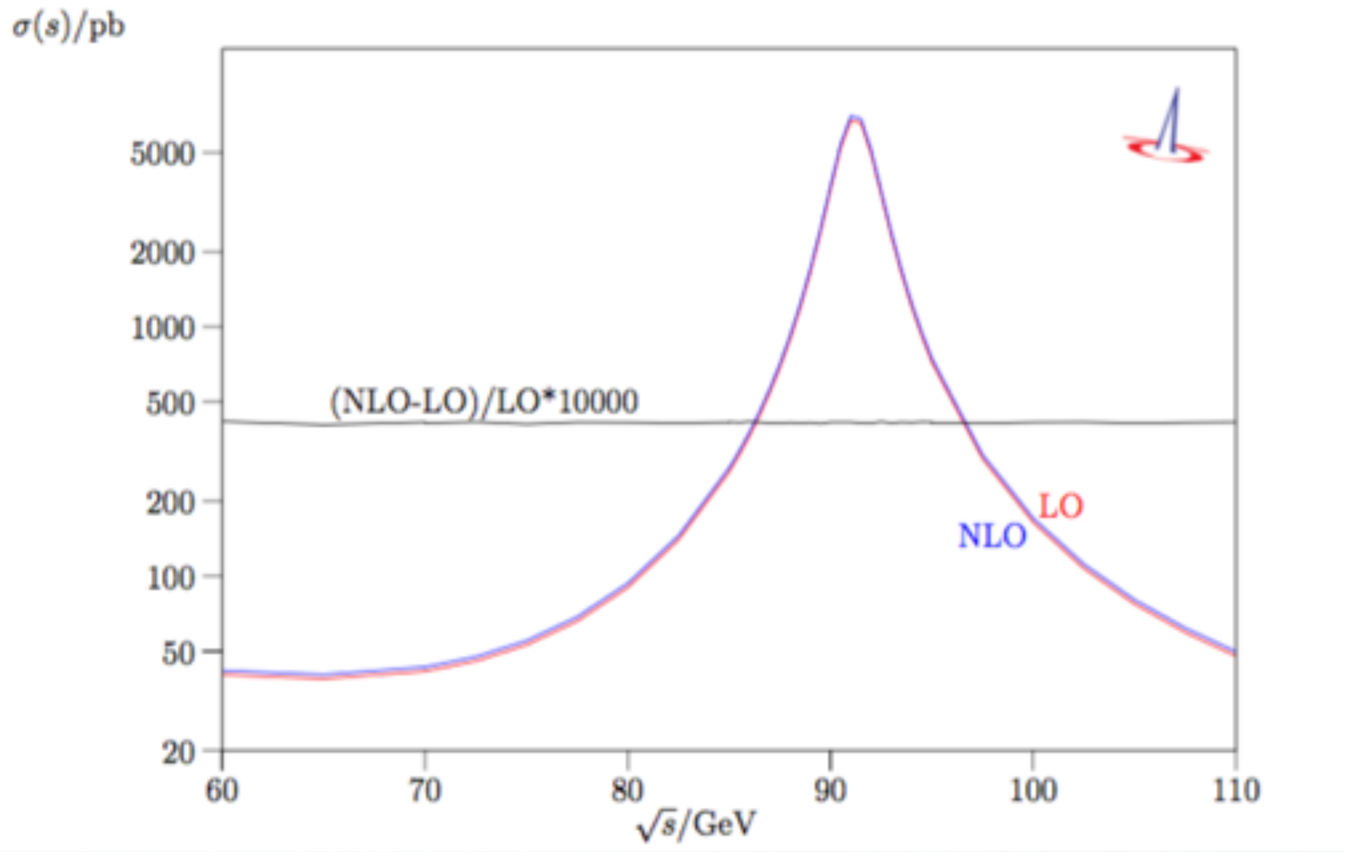

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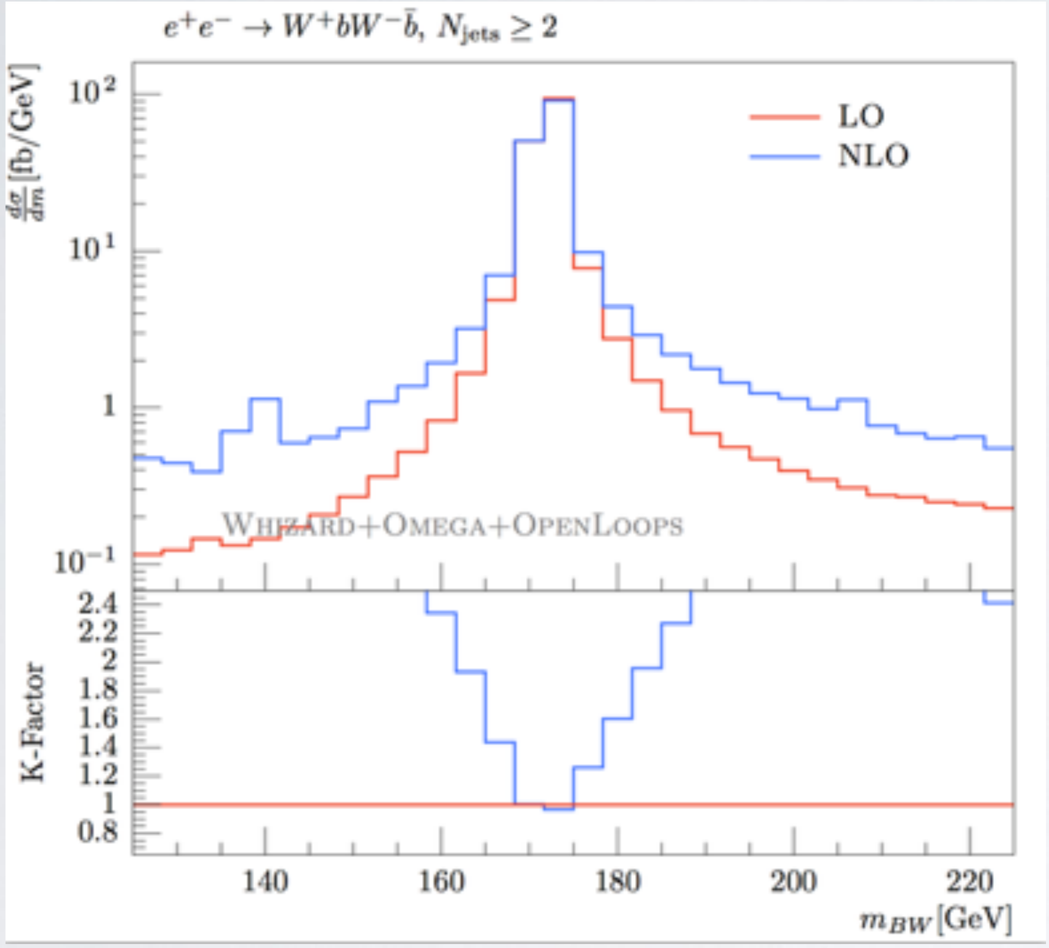
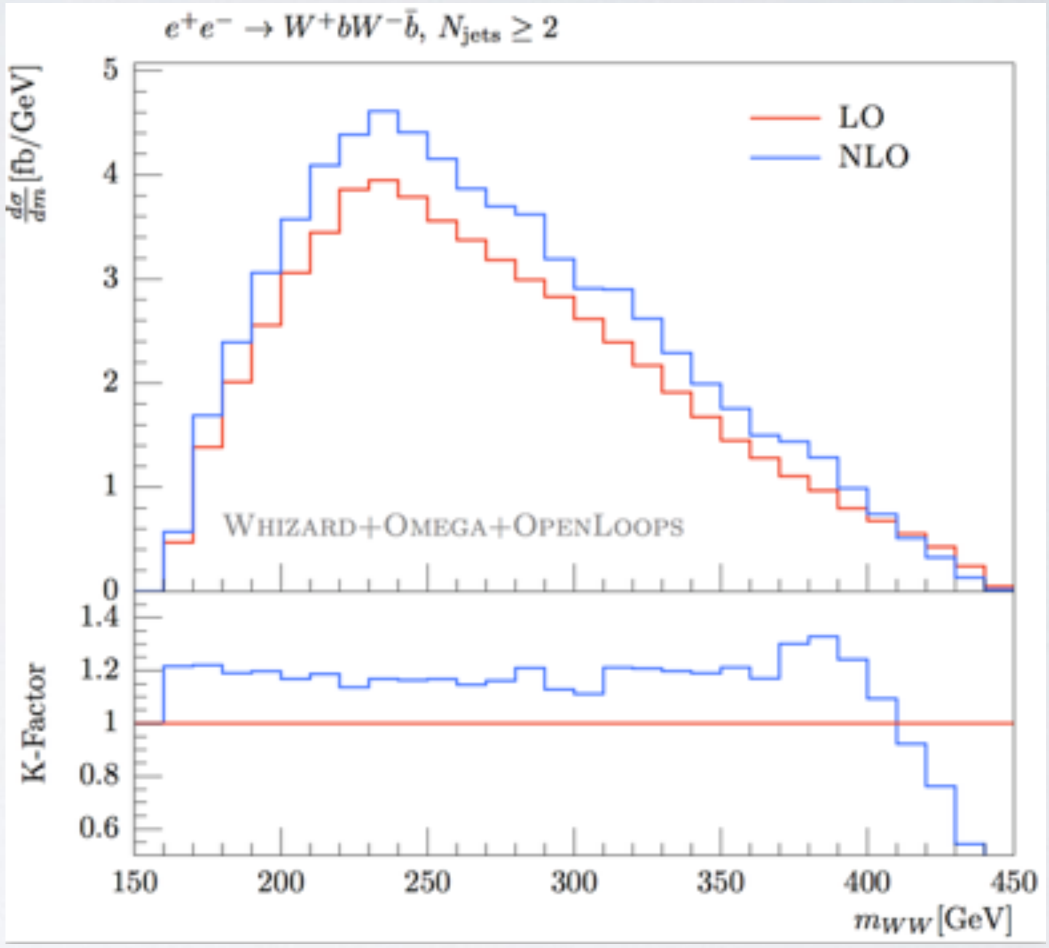
- ✦ QCD NLO infrastructure in pp almost complete
- ✦ First attempts on electroweak corrections, interfacing the `RECOLA` code [Denner et al.]

NLO Fixed-Order Events

- Add weights of real emission events to weight of Born kinematics using the FKS mapping
- Output weighted events in `WHIZARD` (e.g. using `HepMC`), then analysis with `Rivet`
- Example process: $e^+e^- \to W^+W^-b\bar{b}$





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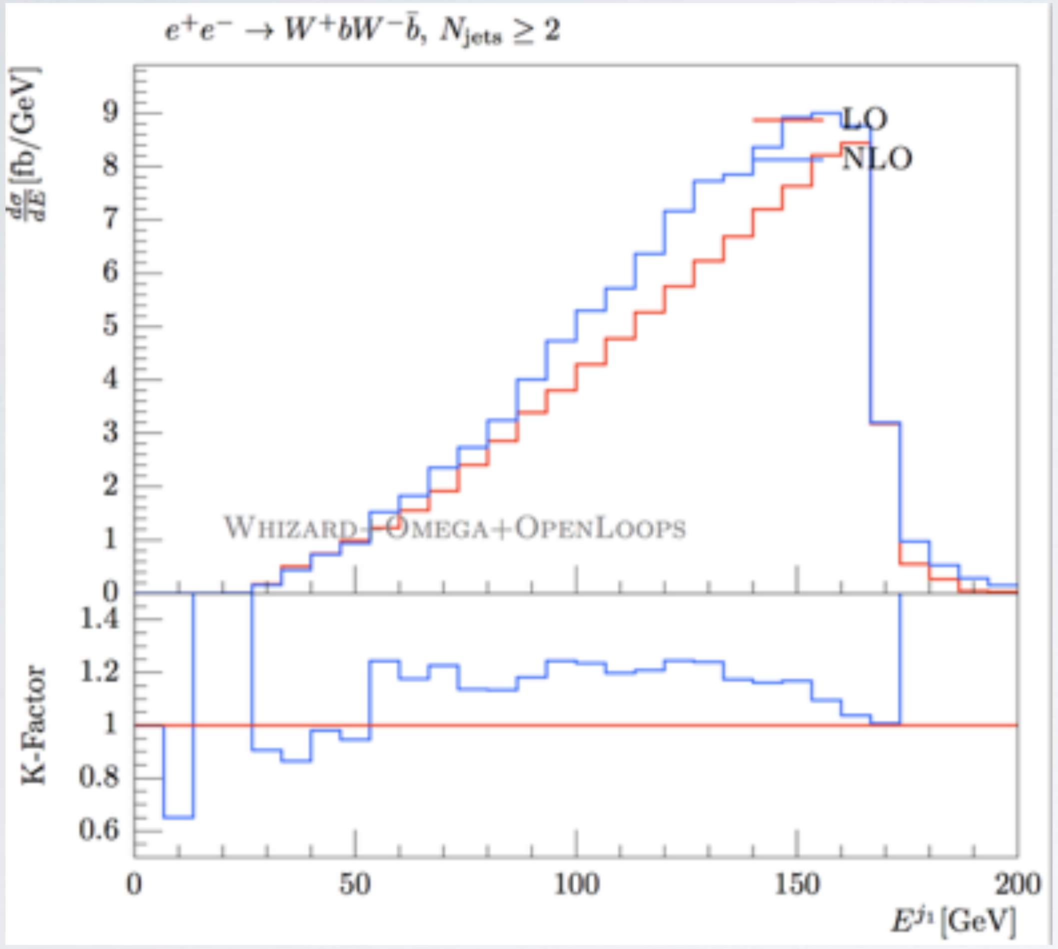

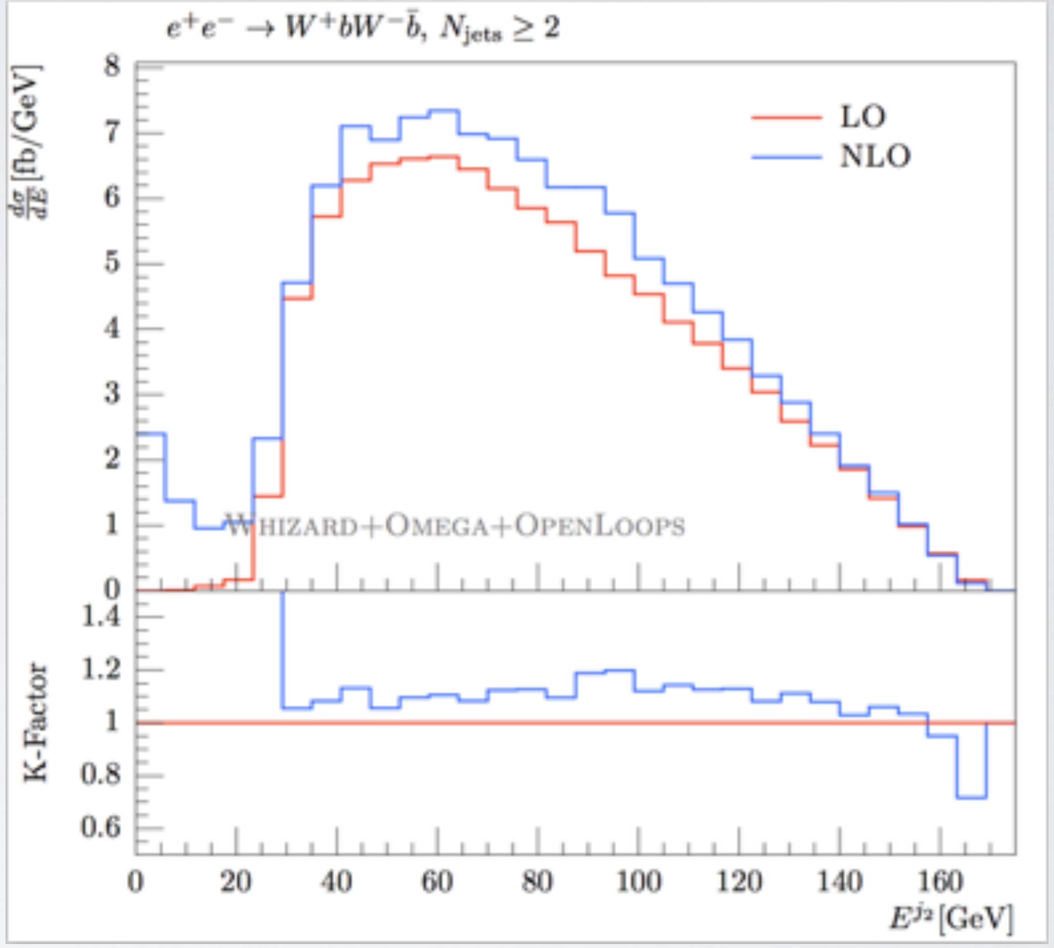

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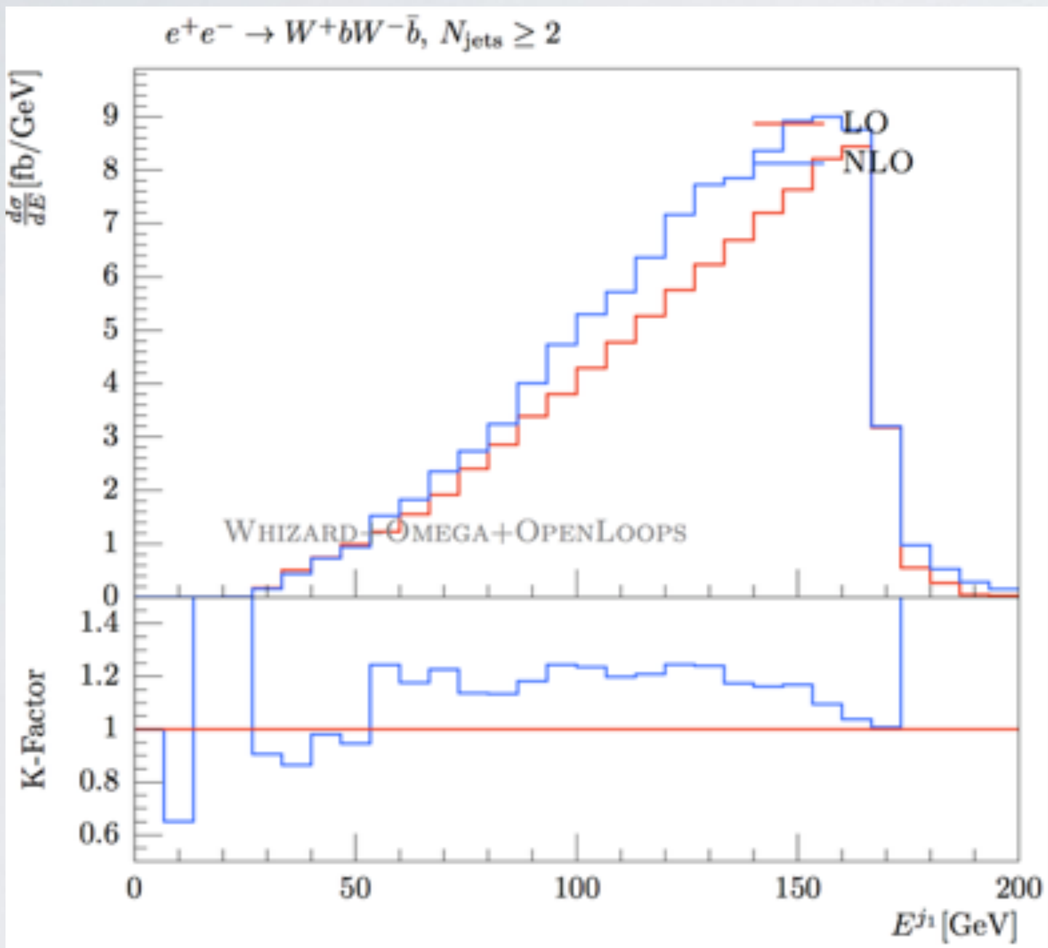
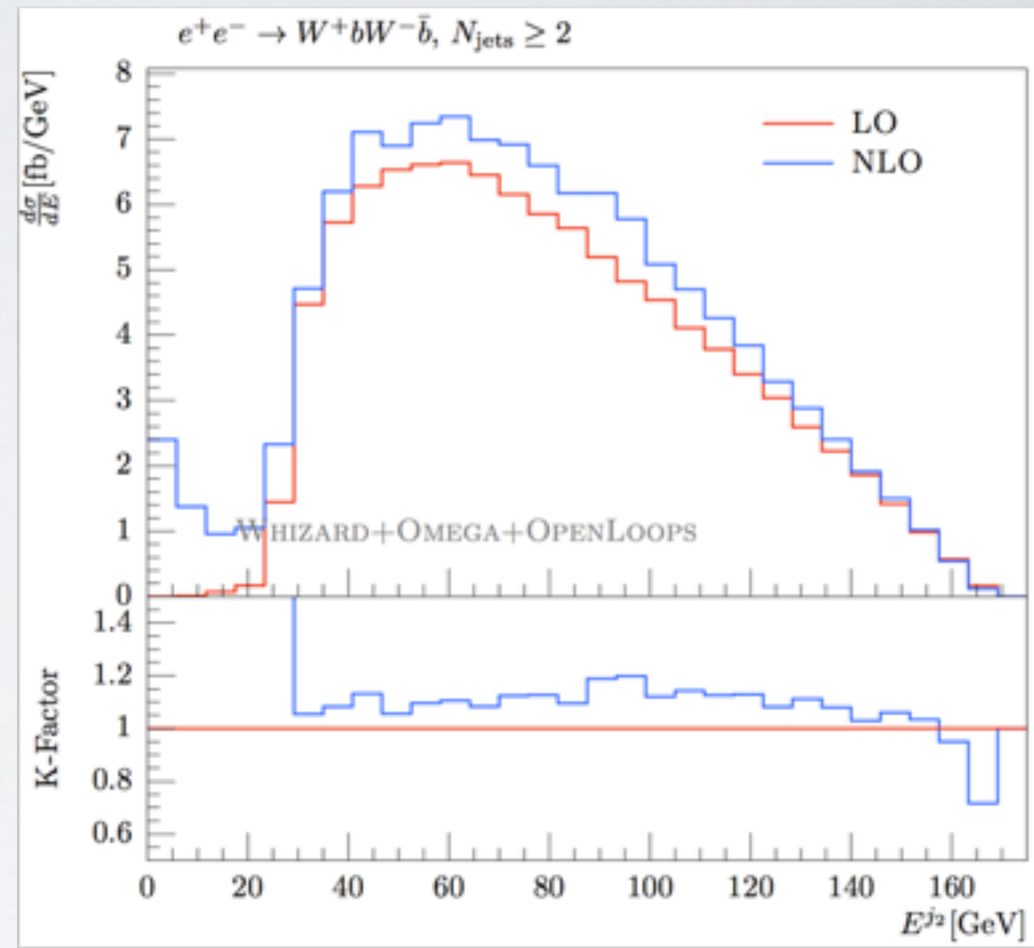
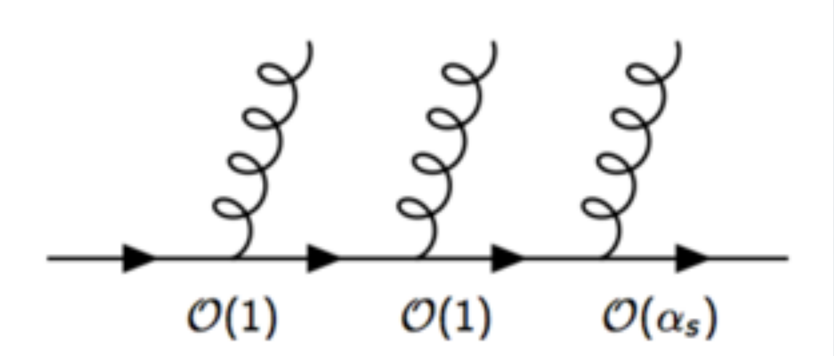




- Completed: polarized NLO results (remember: ILC/CLIC will always run with polarization)
- Combine NLO with complete ISR photon radiation and beamstrahlung
- NLO decays also available (Initial state Jacobian, important for consistent widths)
- Investigate the full 2 → 7 process: e+e- → bbeμνvh [Chokoufé/Kilian/Lindert/JRR/Pozzorini/Weiss]

Automated POWHEG Matching in WHIZARD

- Soft gluon emissions before hard emission generate large logs
- Perturbative α_s : $|\mathcal{M}_{\text{soft}}|^2 \sim \frac{1}{k_T^2} \to \log \frac{k_T^{\max}}{k_T^{\min}}$
- Consistent matching of NLO matrix element with shower
- POWHEG method: hardest emission first [Nason et al.]



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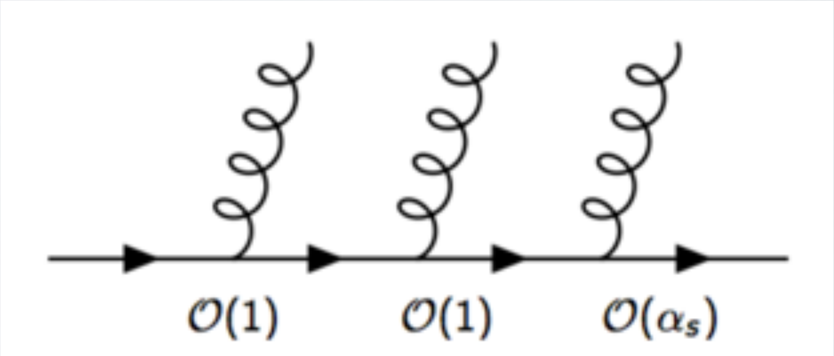

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$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\rm rad} R(\Phi_{n+1})$$

- 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:

$$\Delta_R^{\rm NLO}(k_T) = \exp\left[- \int d\Phi_{\rm rad} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \theta(k_T(\Phi_{n+1}) - k_T) \right]$$

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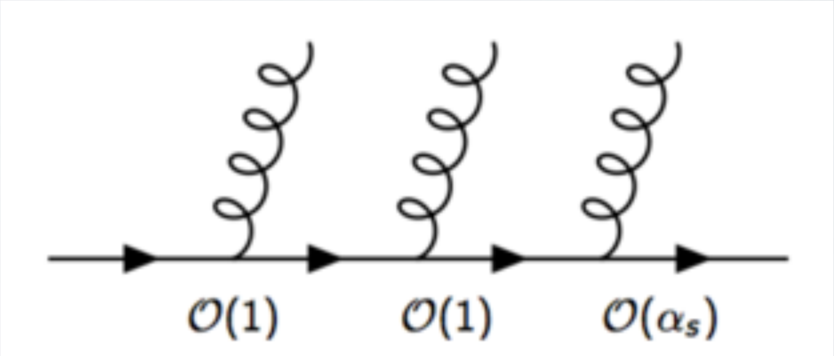

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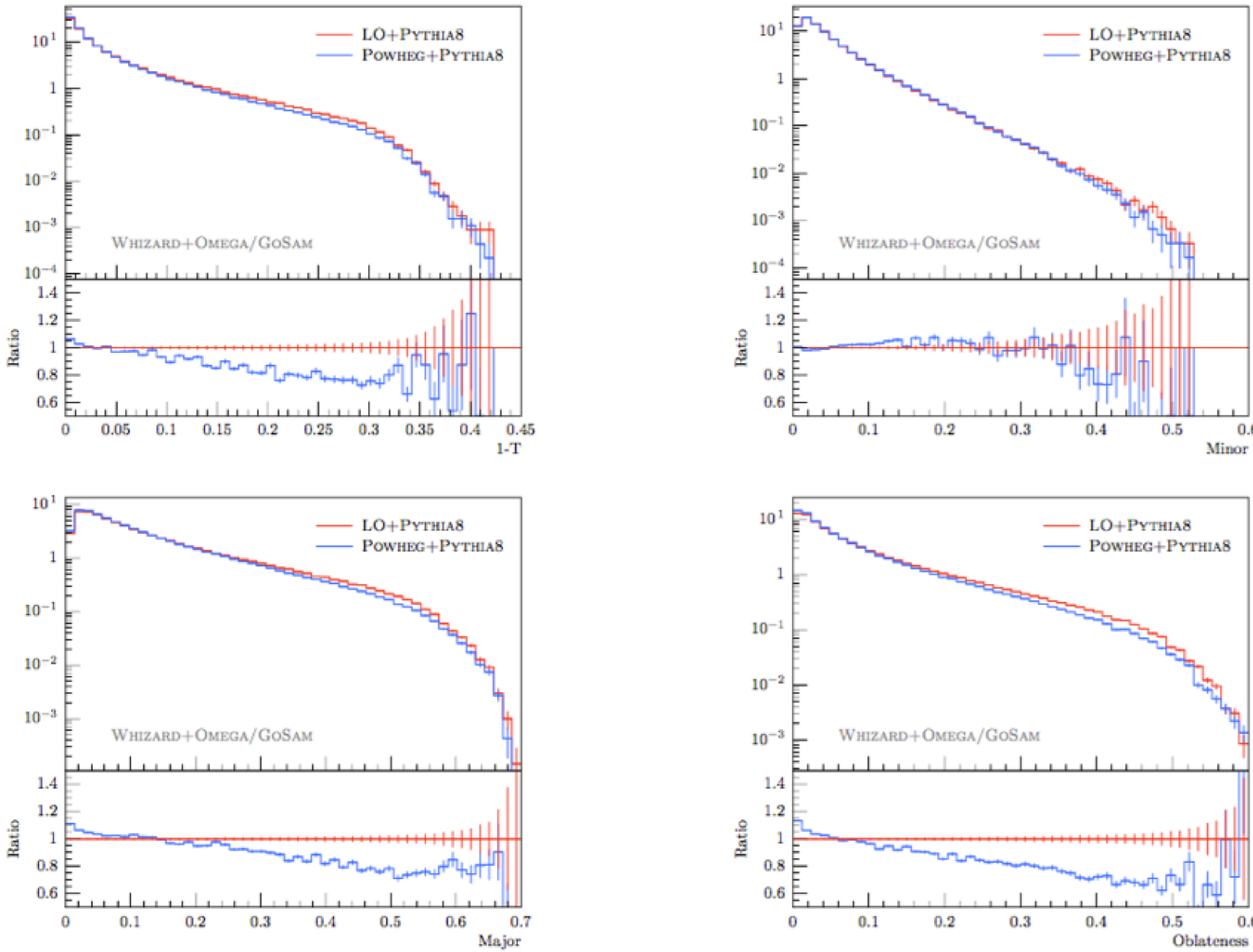
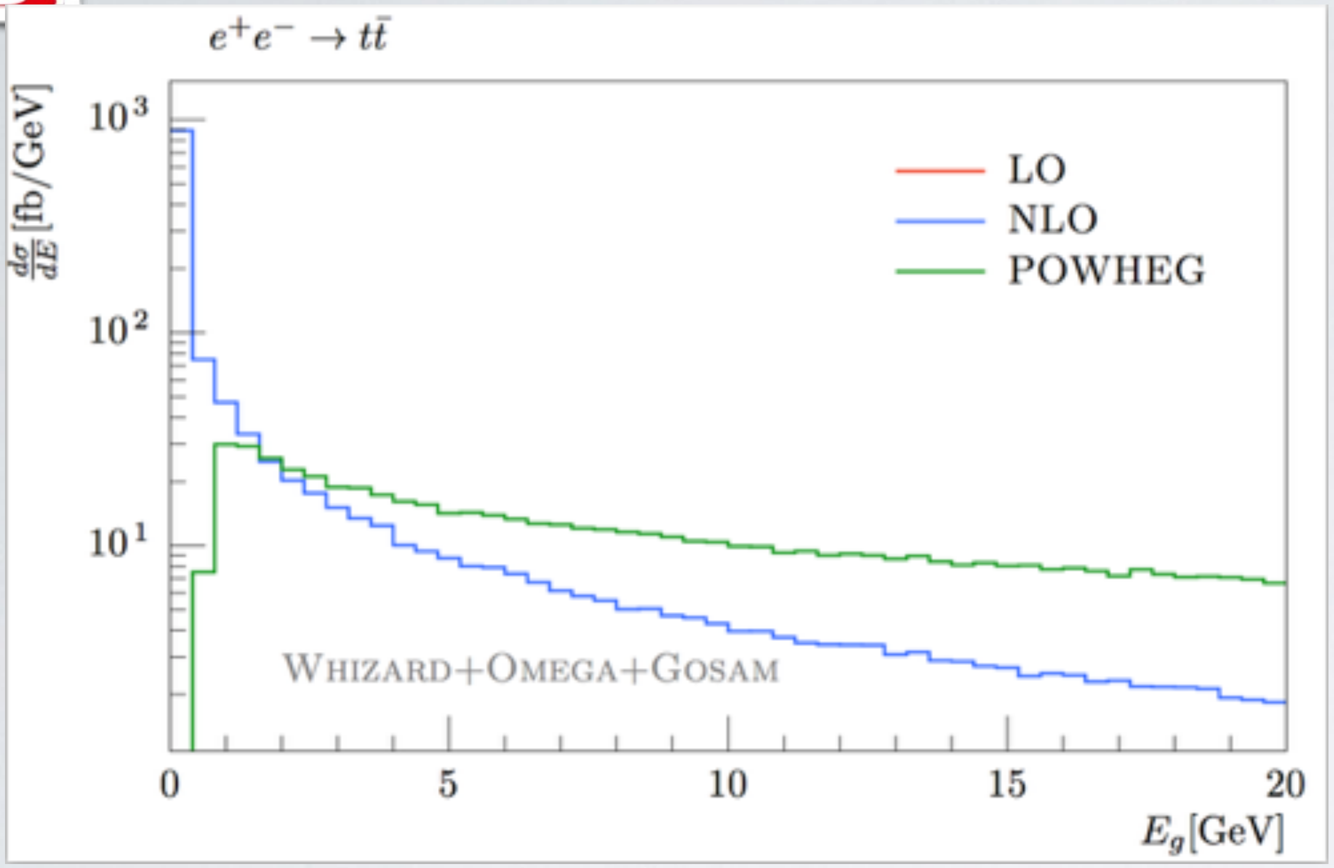
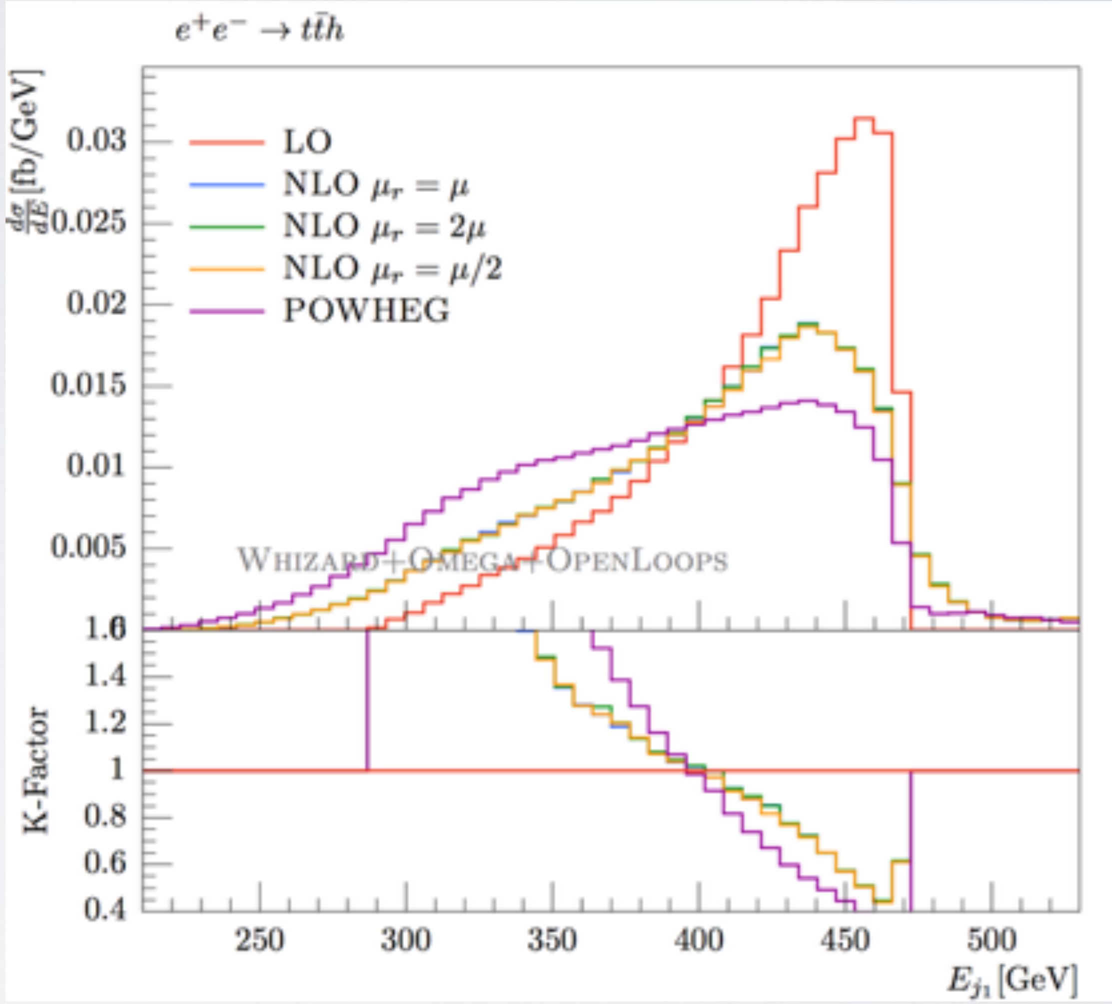
- Hardest emission: $k_T^{\rm max}$; shower with imposing a veto
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator own implementation in `WHIZARD`

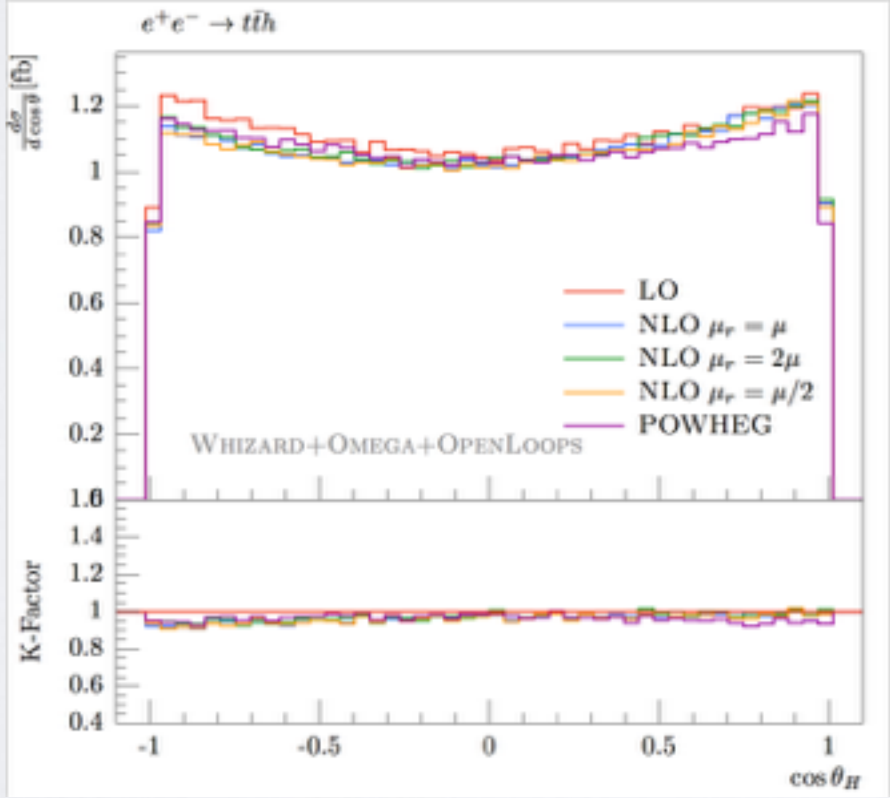
POWHEG Matching, example: e+e- to dijets



Examples: Top pairs and tth production







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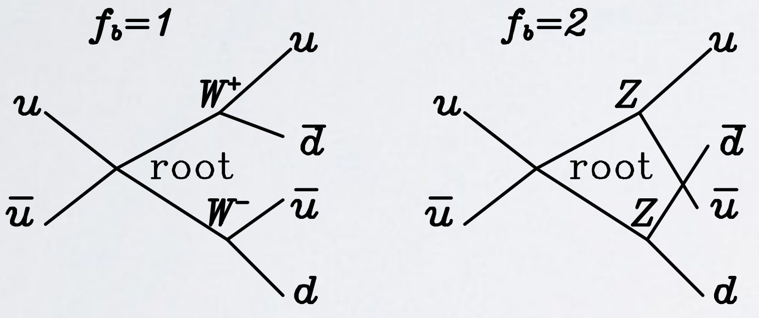

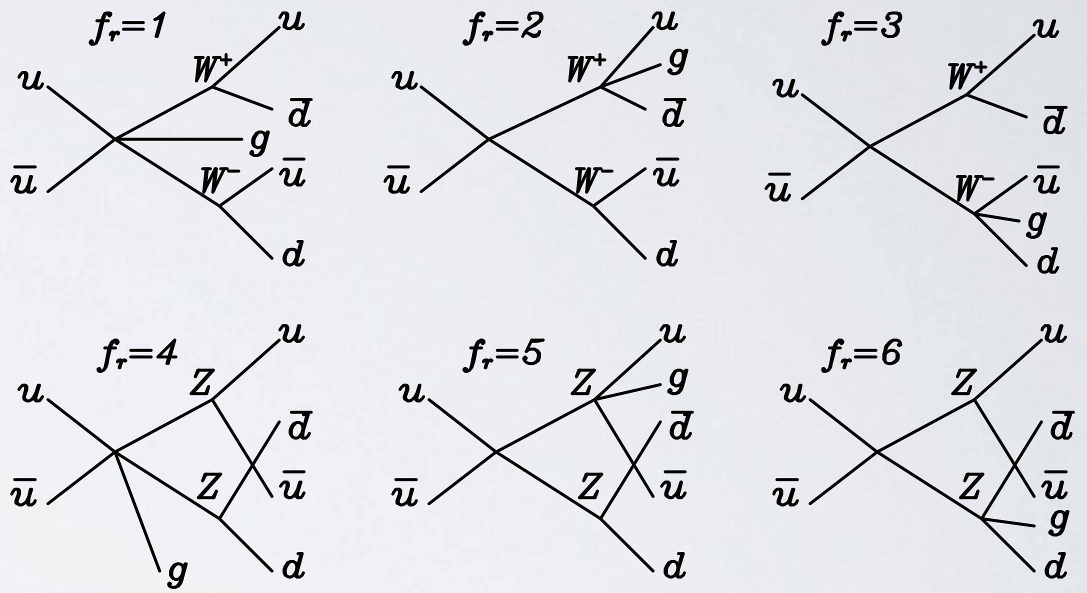

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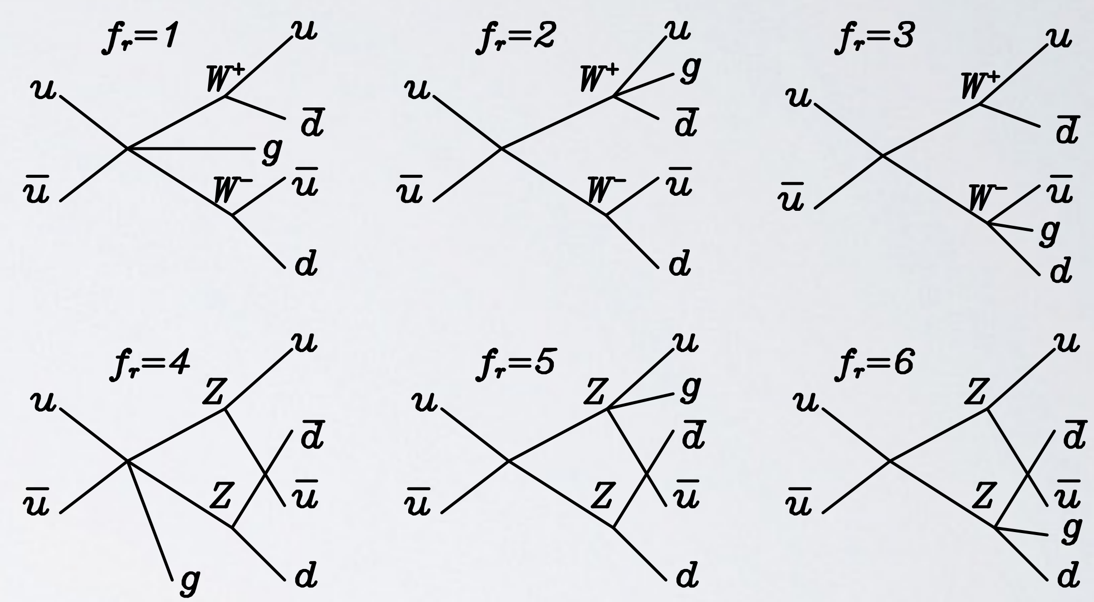
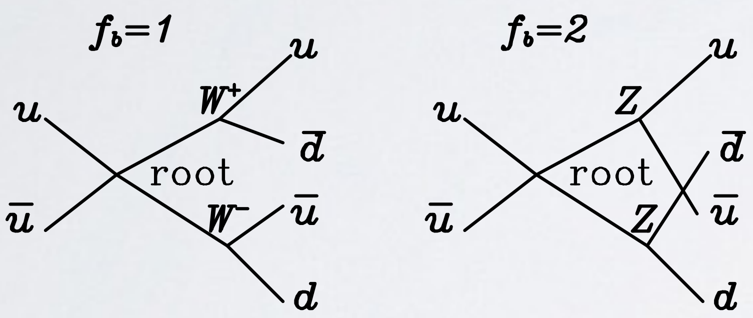




- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (*ZZ, ZH* histories)

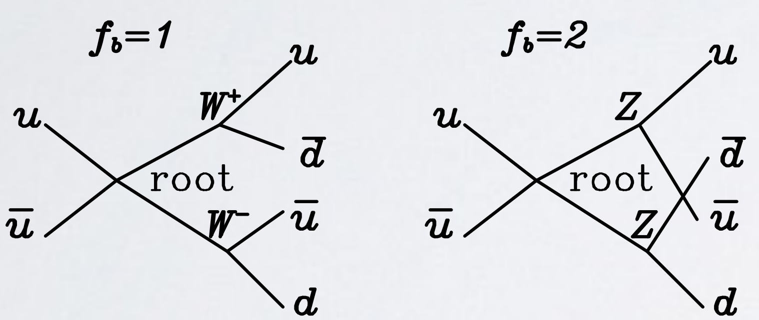
It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	9.6811847E+00	6.42E+00	66.30	72.60*	0.65		
2	11959	2.8539703E+00	2.35E-01	8.25	9.02*	0.69		
3	11936	2.4907574E+00	6.54E-01	26.25	28.68	0.35		
4	11908	2.7695559E+00	9.67E-01	34.91	38.09	0.30		
5	11874	2.4346151E+00	4.82E-01	19.80	21.57*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

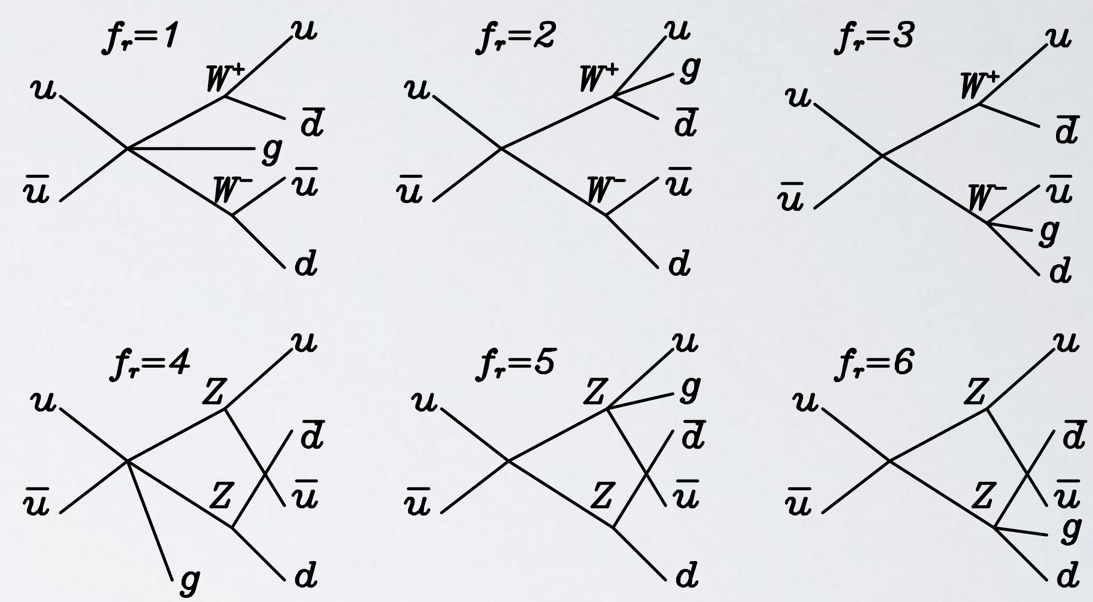
standard FKS

Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances (*Z, W, H, t*)
- In general: resonance masses *not* respected by modified kinematics of subtraction terms
- Collinear (and soft) radiation can lead to mismatch between Born and subtraction terms

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





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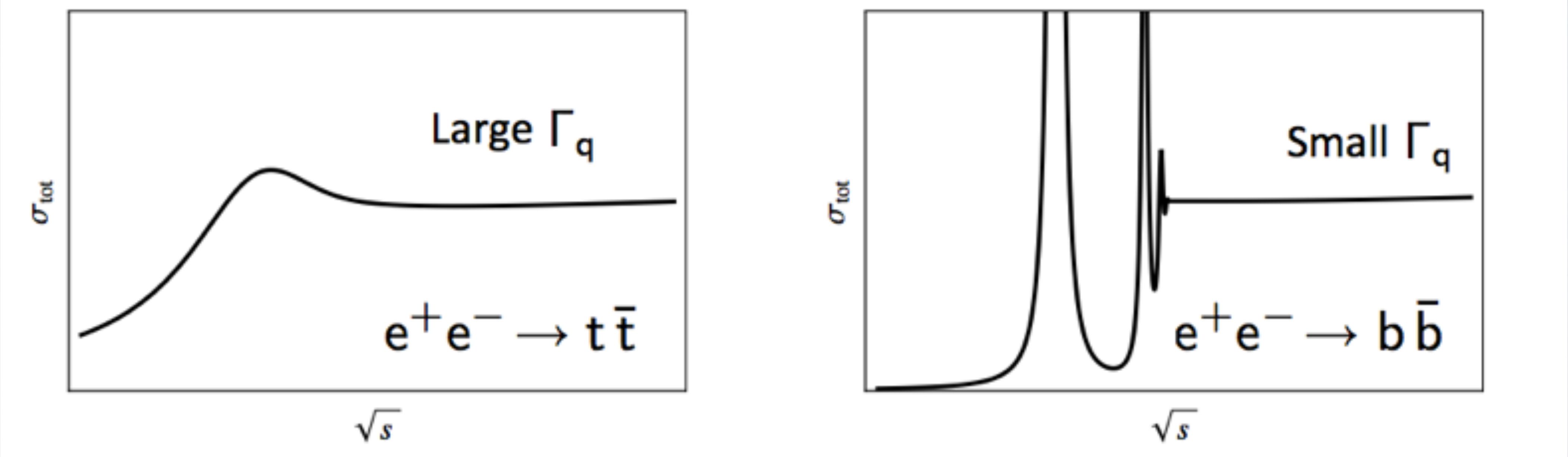
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	5

FKS with resonance mappings

Top Threshold at lepton colliders

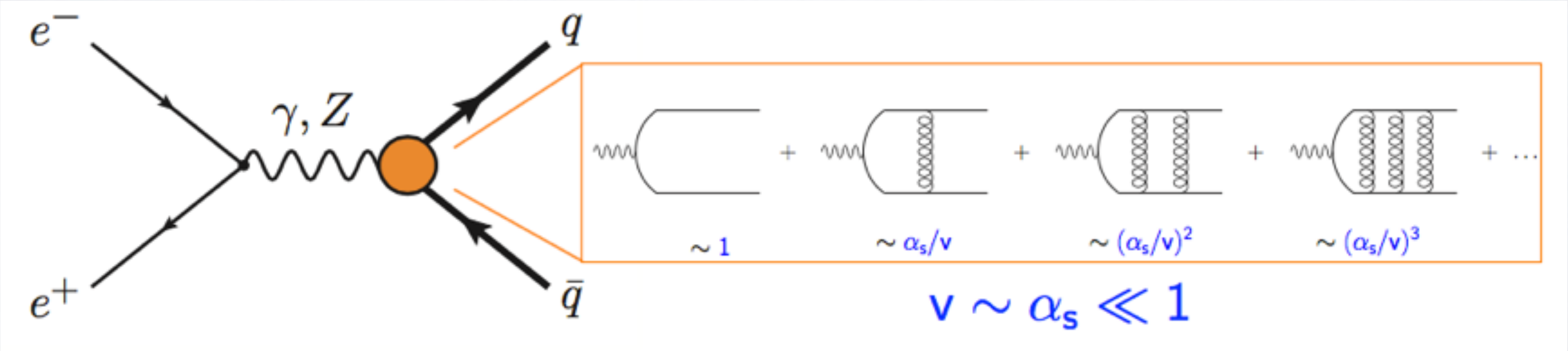
e^+e^- top threshold scan best-known method to measure top quark mass, $\Delta M \sim$ 30-50 MeV

Heavy quark production at lepton colliders, qualitatively:



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

$$v = \sqrt{\frac{\sqrt{s} - 2m_t + i\Gamma_t}{m}}$$



Top Threshold Resummation in (v)NRQCD

- NRQCD is EFT for non-relativistic quark-antiquark systems: separate $M \cdot v$ and $M \cdot v^2$
- Integrate out hard quark and gluon d.o.f.: vNRQCD talk by M. Steinhauser
- Resummation of singular terms close to threshold ($v = 0$) Hoang et al. '99-'01; Beneke et al., '13-'14

Phase space of two massive particles

$$R \equiv \frac{\sigma_{t\bar{t}}}{\sigma_{\mu\mu}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times$$
$$\times \left\{1\,(\mathrm{LL});\ \alpha_s, v\,(\mathrm{NLL});\ \alpha_s^2, \alpha_s v, v^2\,(\mathrm{NNLL})\right\}$$

(p/v)NRQCD EFT w/ RG improvement

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$$R^{\gamma,Z}(s) = \underbrace{F^v(s) R^v(s)}_{\text{s-wave: LL+NLL}} + \underbrace{F^a(s) R^a(s)}_{\text{p-wave}\sim v^2\text{:NNLL}}$$

but contributes at NLL differentially!

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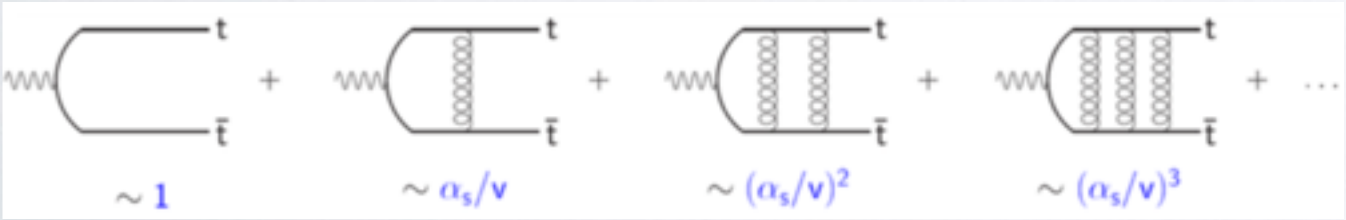
Coulomb potential gluon ladder resummption



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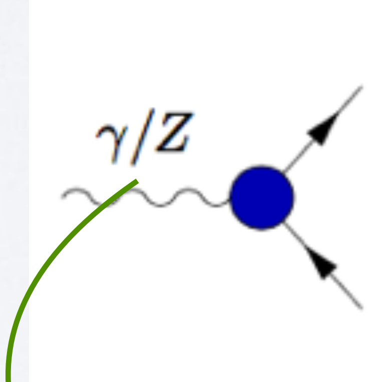
but contributes at NLL differentially!

can be mapped onto effective *ttV* vertex

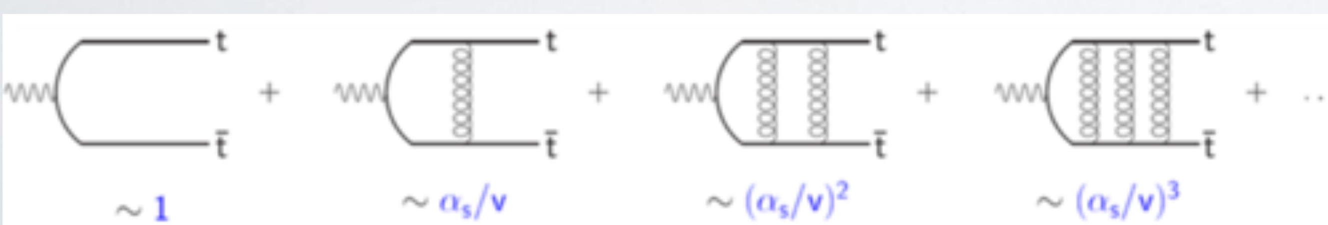


$$\sim \sqrt{R^{v/a}_{\mathrm{(N)LL}}} \sim \frac{\mathcal{G}^{v/a}_{\mathrm{(N)LL}}}{\mathcal{G}^{v/a}\big|_{\alpha_s=0}} \longrightarrow 1$$

$$\mathbb{C} \ni \mathcal{G}^{v/a}_{\mathrm{(N)LL}} = \mathcal{G}^{v/a}_{\mathrm{(N)LL}}(\alpha_s, M_t^{\mathrm{pole}}, \sqrt{s}, |\vec p_t|, \Gamma_t)$$

differential in off-shell *tt* phase space

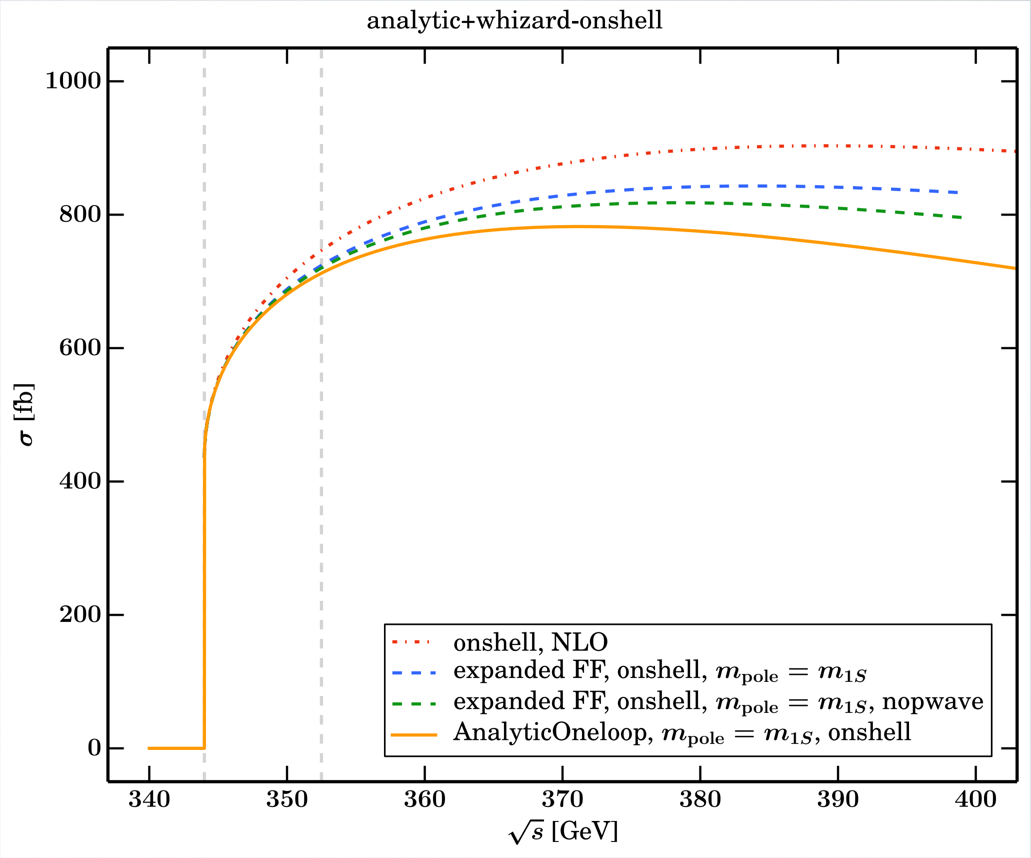
Coulomb potential gluon ladder resummation



Matching to continuum at (LO and) NLO

- Transition region between relativistic and resummation effects
- CLIC benchmark energies:

  0.38 TeV, 1.4 TeV, 3.0 TeV
- Remove double-counting NLO / (N)LL



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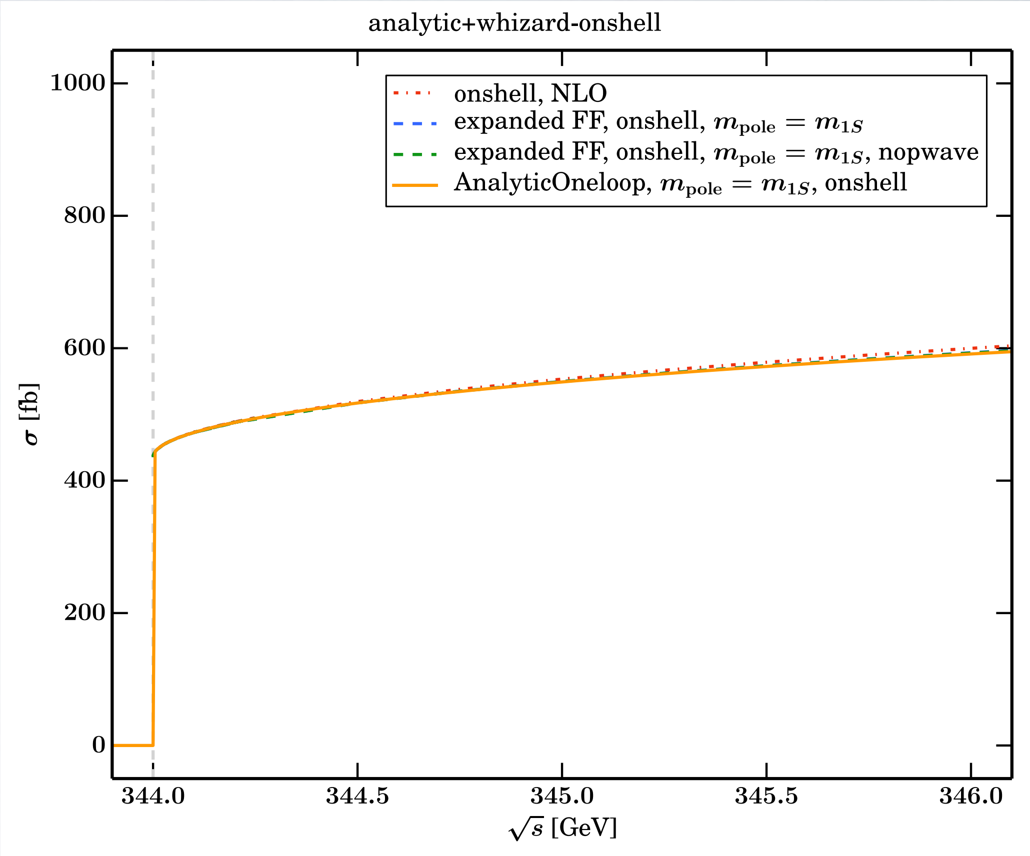

Resummed formfactor, expanded to $\mathcal{O}(\alpha_s)$

$$\nu = \sqrt{\frac{\sqrt{s} - 2m_t + \mathrm{i}\Gamma_t}{m}} \qquad p = |\vec{p}| \qquad p_0 = E_t - m_t$$

$$F^{\text{expanded}}[\alpha_{\mathrm{H}}, \alpha_{\mathrm{S}}] = \alpha_{\mathrm{H}} \left(-\frac{2C_F}{\pi} \right) + \alpha_{\mathrm{S}} \left(\frac{\mathrm{i} C_F m \log \frac{mv+p}{mv-p}}{2p} \right)$$

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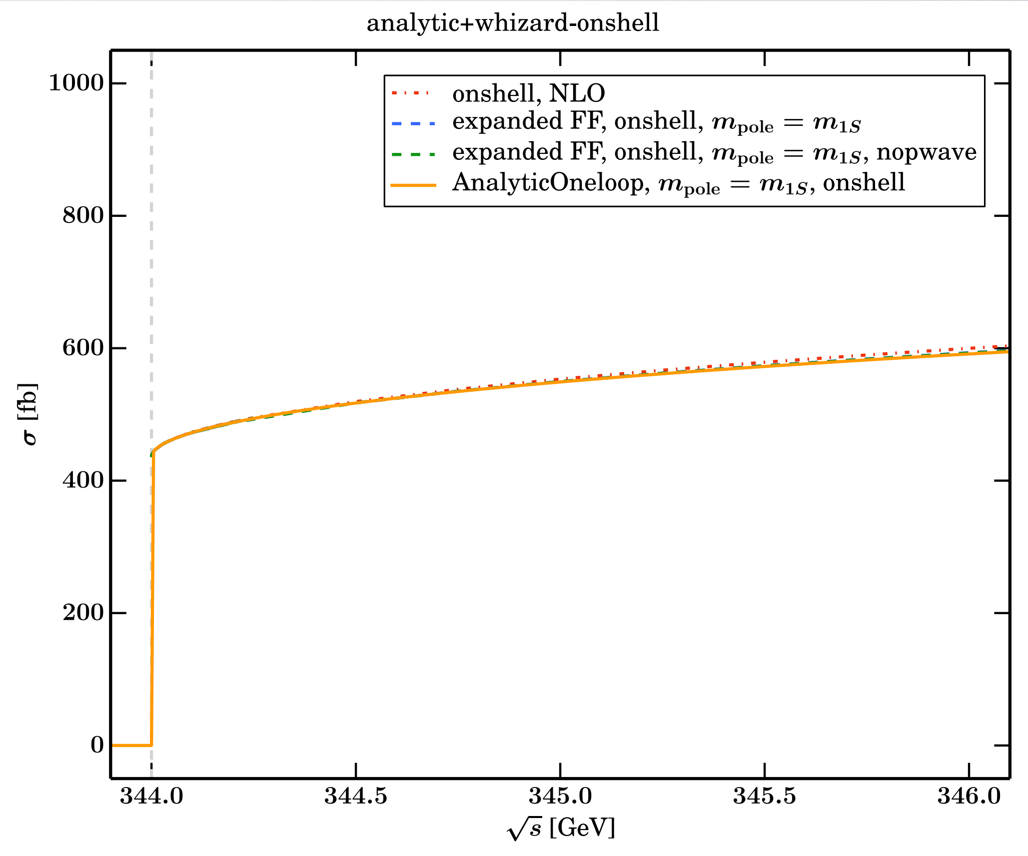

Matching formula

$$\begin{aligned}\sigma_{\text{matched}} = {} & \sigma_{\text{QCD}}\left[\alpha_{\mathrm{H}}\right] - \sigma_{\text{NRQCD}}^{\text{expanded}}\left[\alpha_{\mathrm{H}},\, \alpha_{\mathrm{H}}\right] \\ & + \sigma_{\text{NRQCD}}^{\text{expanded}}\left[\alpha_{\mathrm{H}},\, f_s\,\alpha_{\mathrm{S}} + (1-f_s)\,\alpha_{\mathrm{H}}\right] \\ & + \sigma_{\text{NRQCD}}^{\text{full}}\left[f_s\,\alpha_{\mathrm{H}},\, f_s\,\alpha_{\mathrm{S}},\, f_s\,\alpha_{\mathrm{US}}\right] - \sigma_{\text{NRQCD}}^{\text{expanded}}\left[f_s\,\alpha_{\mathrm{H}},\, f_s\,\alpha_{\mathrm{S}}\right]\end{aligned}$$

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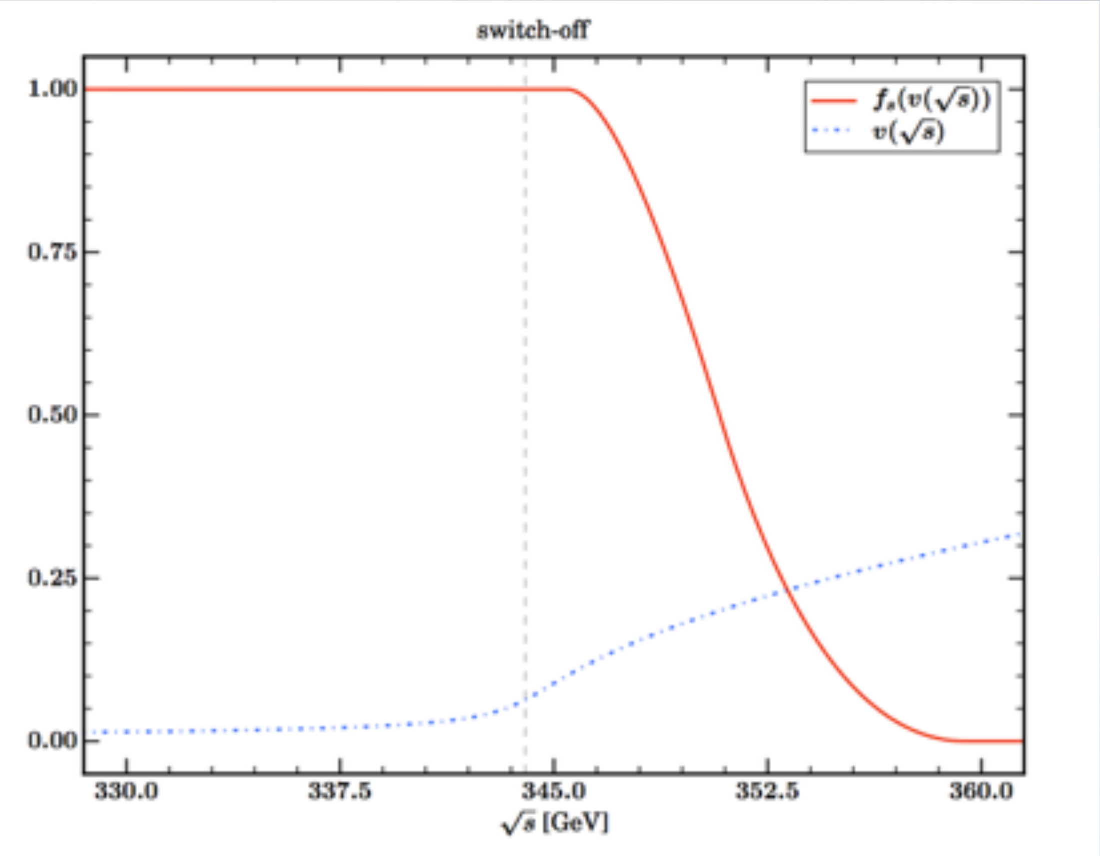

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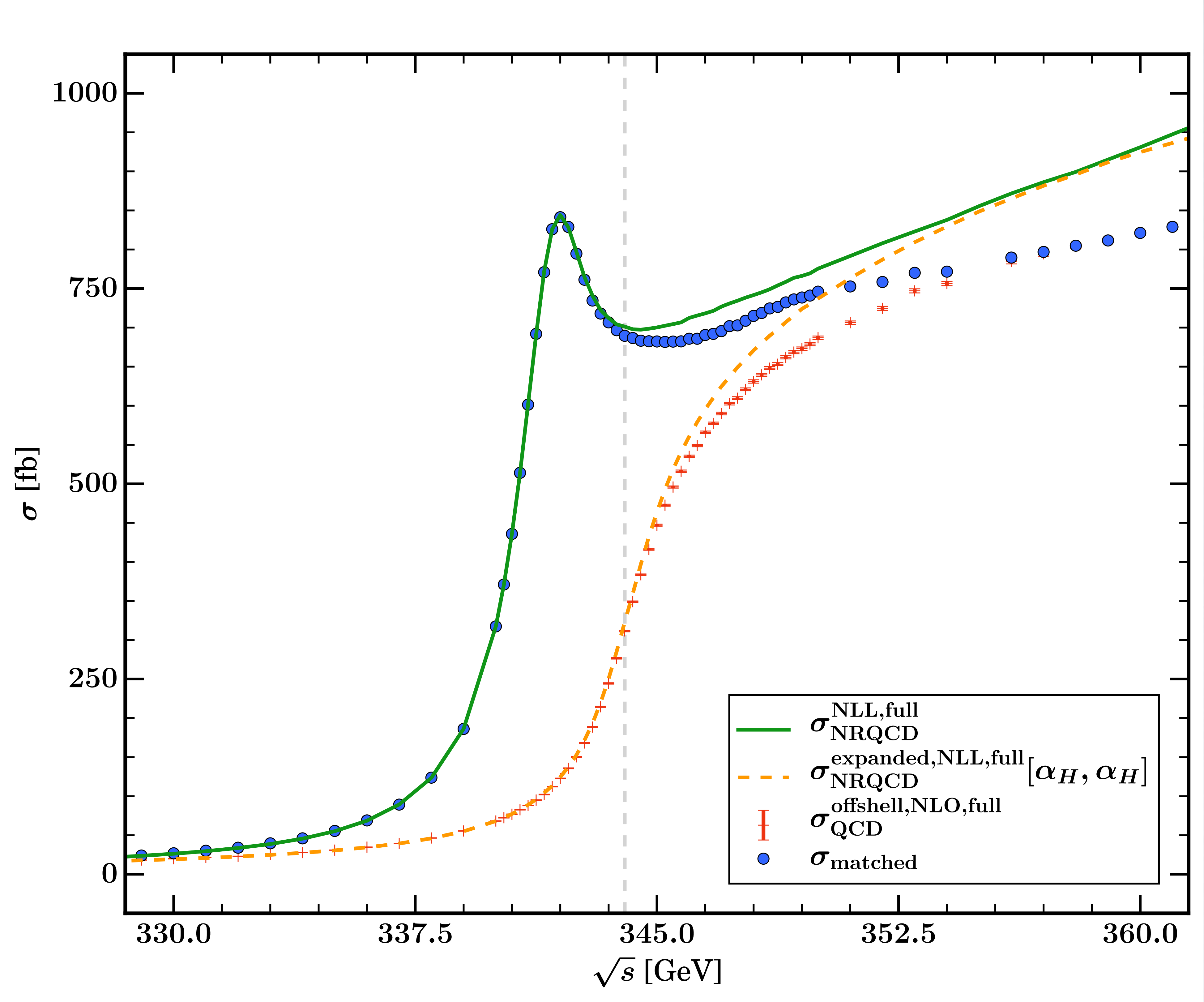
Switch-off function

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

Threshold-continuum matching



Bach/Chokoufé/Hoang/
Kilian/JRR/Stahlhofen/
Teubner/Weiss
work in progress

Conclusions & Outlook

- `WHIZARD 2.2` event generator for collider physics (ee, pp, ep)
- Allows to simulate all possible BSM models
- Allows for all SM backgrounds
- ee physics: beamspectra, LCIO, ee top threshold
- NLO automation: reals and subtraction terms (FKS) [+ virtuals externally] → `WHIZARD 3.0`
- allows to produce NLO fixed-order histograms
- Automated POWHEG matching (other schemes in progress)
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even if it is in an international conference summary talk ⟹ Challenge accepted !


New
WHIZARD
QUANTUM
HIGH PERFORMANCE GREASE
Higher Performance
Superior Protection
Learn More

Projects, Plans, Performance and all that

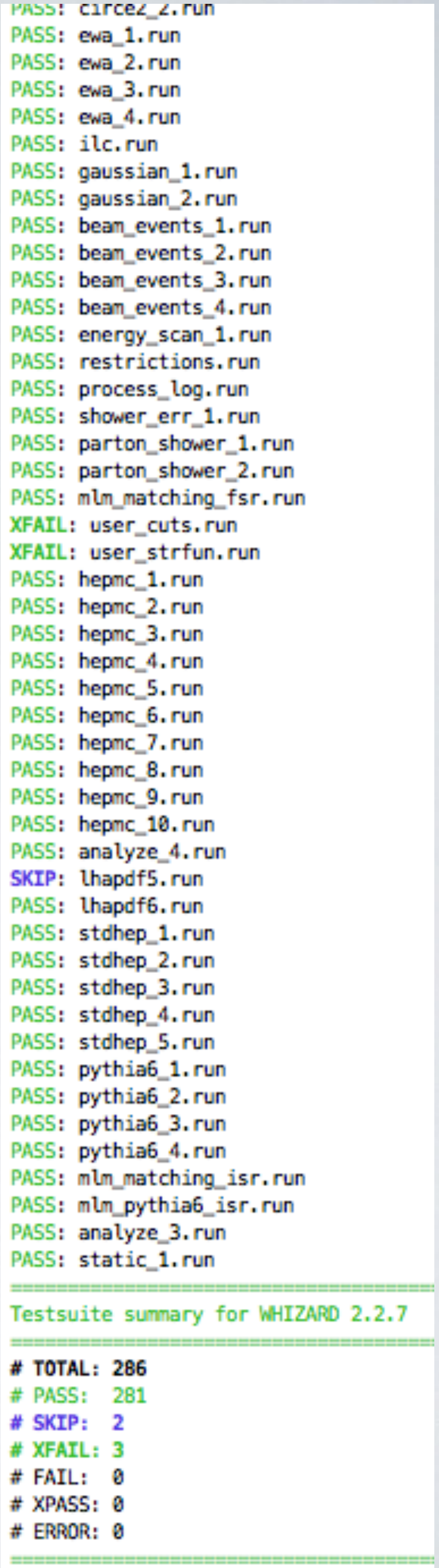
- O'Mega Virtual Machine (OVM): ME via bytecode interpreter than compiled code ✓
- Parton shower: LO merging (MLM ✓) , NLO matching
- QED shower (FSR)
- QED shower (ISR); exclusive part of ISR spectrum
- pT spectrum of ISR radiation
- automated massless/massive QCD NLO corrections: FS ✓ / Initial state in preparation
  → `WHIZARD 3.0`
- QED/electroweak NLO automation: longer time scale
- complete NLL NRQCD top threshold/NLO continuum matching; extension to ttH [✓]
- POWHEG matching implemented ✓ ; maybe also MC@NLO or Nagy-Soper matching
- Monte Carlo over helicities and colors, work on performance (MPI)
- Modified algorithm for multi-leg (tree) matrix elements: includes high-color flow amplitudes, QCD/EW coupling orders, completely general Lorentz structures, UFO format
- Automatic generation of decays (and calculation of decay widths) ✓
- New syntax for nested decay chains

```
process = e1, E1 => (t => (Wp => E2, nu2), b), tbar
```

BACKUP SLIDES

WHIZARD: Installation and Run

- Download: http://www.hepforge.org/archive/whizard/whizard-2.2.8.tar.gz
- Unpack it, intended to be installed in `/usr/local` (or locally)
- Create `build` directory and do `./configure`
- `make`, `[ make check ]`, `make install`
- Working directory: create `SINDARIN` steering file `<input>.sin`
- Working directory: run `whizard <input>.sin`
- Supported event formats: LHA, StdHep, LHEF (i-iii), HepMC, LCIO, div. ASCII
- Interfaces to external packages: `FastJet, GoSam, GuineaPig(++), HepMC, HOPPET, LCIO, LHAPDF(4/5/6), LoopTools, OpenLoops, PYTHIA6, [PYTHIA8], StdHep [internal]`


```
PASS: circe2_2.run
PASS: ewa_1.run
PASS: ewa_2.run
PASS: ewa_3.run
PASS: ewa_4.run
PASS: ilc.run
PASS: gaussian_1.run
PASS: gaussian_2.run
PASS: beam_events_1.run
PASS: beam_events_2.run
PASS: beam_events_3.run
PASS: beam_events_4.run
PASS: energy_scan_1.run
PASS: restrictions.run
PASS: process_log.run
PASS: shower_err_1.run
PASS: parton_shower_1.run
PASS: parton_shower_2.run
PASS: mlm_matching_fsr.run
XFAIL: user_cuts.run
XFAIL: user_strfun.run
PASS: hepmc_1.run
PASS: hepmc_2.run
PASS: hepmc_3.run
PASS: hepmc_4.run
PASS: hepmc_5.run
PASS: hepmc_6.run
PASS: hepmc_7.run
PASS: hepmc_8.run
PASS: hepmc_9.run
PASS: hepmc_10.run
PASS: analyze_4.run
SKIP: lhapdf5.run
PASS: lhapdf6.run
PASS: stdhep_1.run
PASS: stdhep_2.run
PASS: stdhep_3.run
PASS: stdhep_4.run
PASS: stdhep_5.run
PASS: pythia6_1.run
PASS: pythia6_2.run
PASS: pythia6_3.run
PASS: pythia6_4.run
PASS: mlm_matching_isr.run
PASS: mlm_pythia6_isr.run
PASS: analyze_3.run
PASS: static_1.run
============================================
Testsuite summary for WHIZARD 2.2.7
============================================
# TOTAL: 286
# PASS:  281
# SKIP:  2
# XFAIL: 3
# FAIL:  0
# XPASS: 0
# ERROR: 0
============================================
```

Beams, Fields, Colors, Lorentz structures

Lorentz structures:

- Large number of hardcoded terms: pure scalar, pure vector, scalar/vector, fermion/scalar, fermion/vector, fermion/tensor, vector/tensor, gravitino couplings, fermion coupl. SUSY Ward id.
- Growing number of dim. 5/6/7/8 operators: HEFT, aTGCs, aQGCs, anomalous top couplings etc.
- Completely general Lorentz structures: foreseen for major next release (incl. UFO support), v2.3.0

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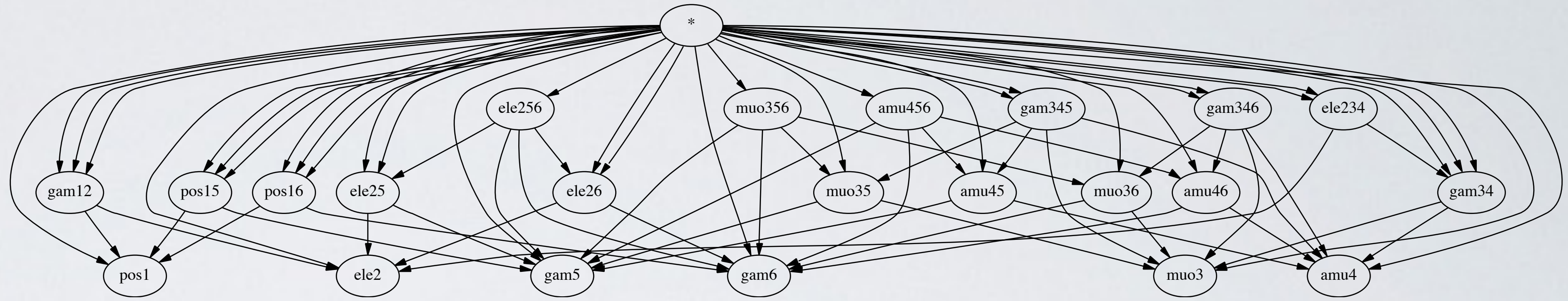
Beams:

- Lepton beam ISR Kuraev/Fadin, 2003; Skrzypek/Jadach, 1991
- Lepton collider beams: `CIRCE1/2`, also photon beams (more later)
- PDFs: interface to `LHAPDF v4/5/6`; internal PDFs: CTEQ6, CT10, MMHT etc.
- QCD parton shower: 2 own implementations [or ext., more later]

The matrix element generator: O’Mega

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



✳ New concept for internal quantum number representation: faster flavor sums, counting of coupling constants (via partial expansion), more speed-up, general Lorentz structures (in prep.)

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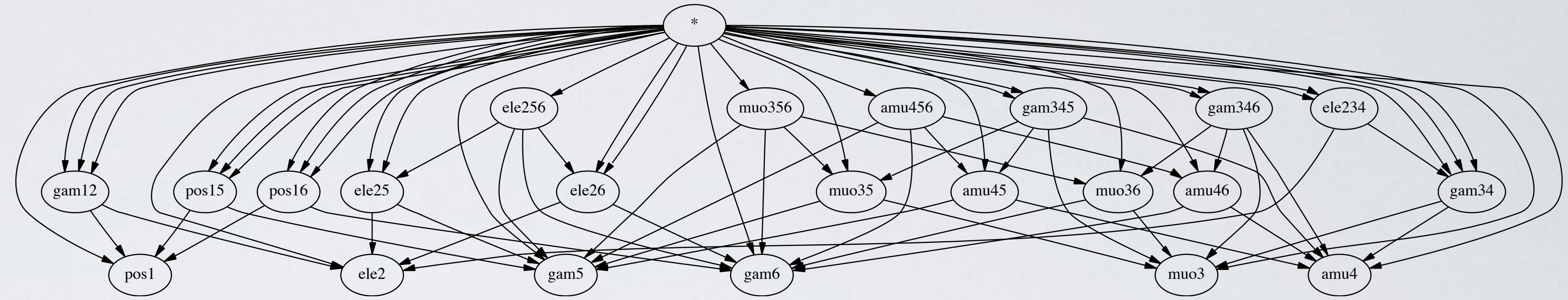

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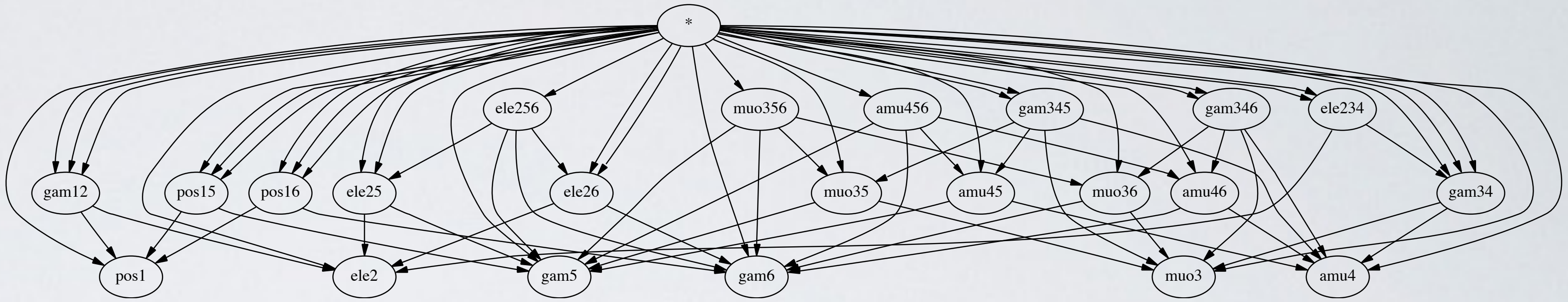
- `O'Mega Virtual Machine (OVM):` matrix elements not as compiled code, but bytecode instructions:

```
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
```

The matrix element generator: O'Mega

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



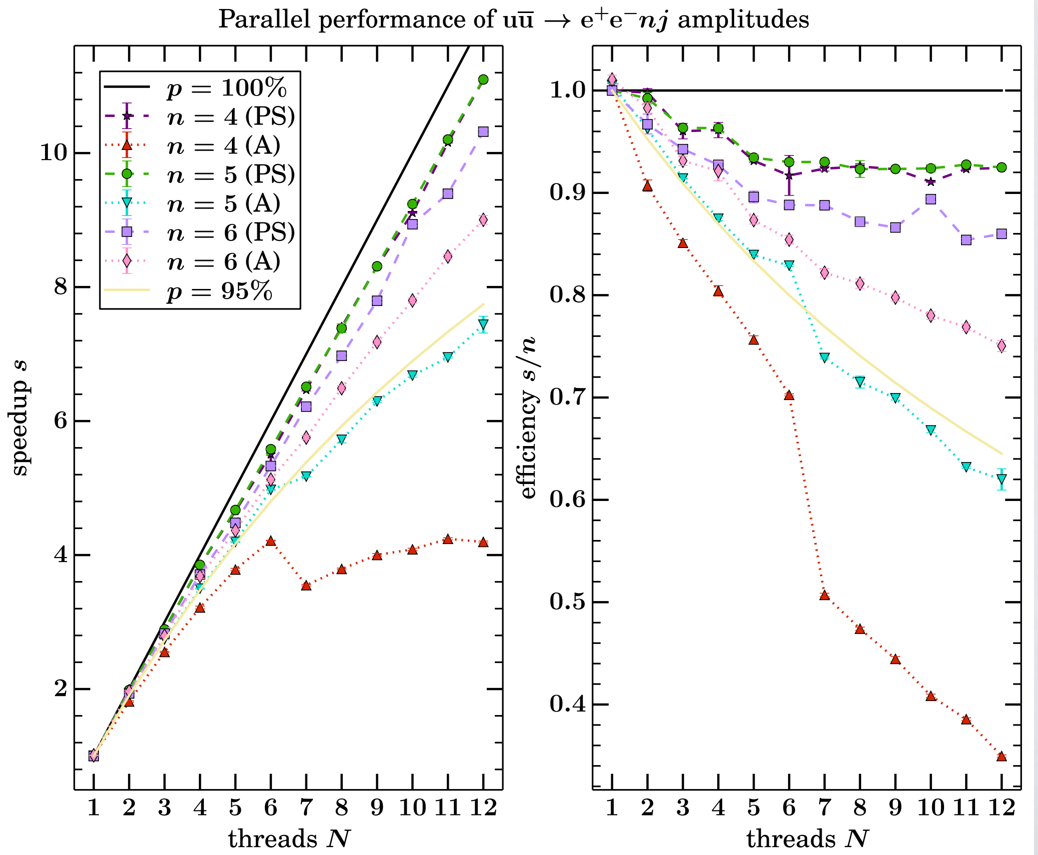
✳ New concept for internal quantum number representation: faster flavor sums, counting of coupling constants (via partial expansion), more speed-up, general Lorentz structures (in prep.)

✳ `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



High-Energy Electroweak Sector

- Vector Boson Scattering: access to New Physics in W, Z selfcoupl. Beyer/JRR/Mönig ...., arXiv:hep-ph/0604048
- 1 TeV, 1/ ab , full 6-fermion states, P(80% e-, 60% e+), binned likelihood
- Contributing channels: WW→WW, WW→ZZ, WZ→WZ, ZZ→ZZ

Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to WW$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu} q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	2.09
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to W^+W^-$	414.
$e^+e^- \to b\bar{b}X$	$e^+e^- \to t\bar{t}$	331.768
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to W^+W^-$	3560.108
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to ZZ$	173.221
$e^+e^- \to e\nu q\bar{q}$	$e^+e^- \to e\nu W$	279.588
$e^+e^- \to e^+e^- q\bar{q}$	$e^+e^- \to e^+e^- Z$	134.935
$e^+e^- \to X$	$e^+e^- \to q\bar{q}$	1637.405

$SU(2)_c$ conserved case, all channels

coupling	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-1.41	1.38
$16\pi^2\alpha_5$	-1.16	1.09

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coupling	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-2.72	2.37
$16\pi^2\alpha_5$	-2.46	2.35
$16\pi^2\alpha_6$	-3.93	5.53
$16\pi^2\alpha_7$	-3.22	3.31
$16\pi^2\alpha_{10}$	-5.55	4.55

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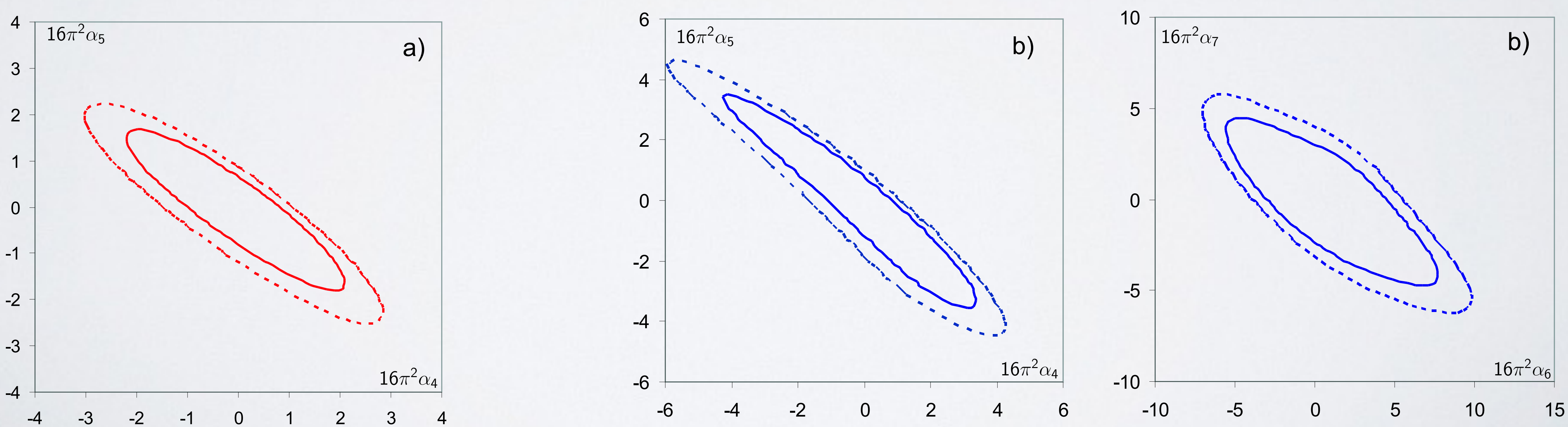
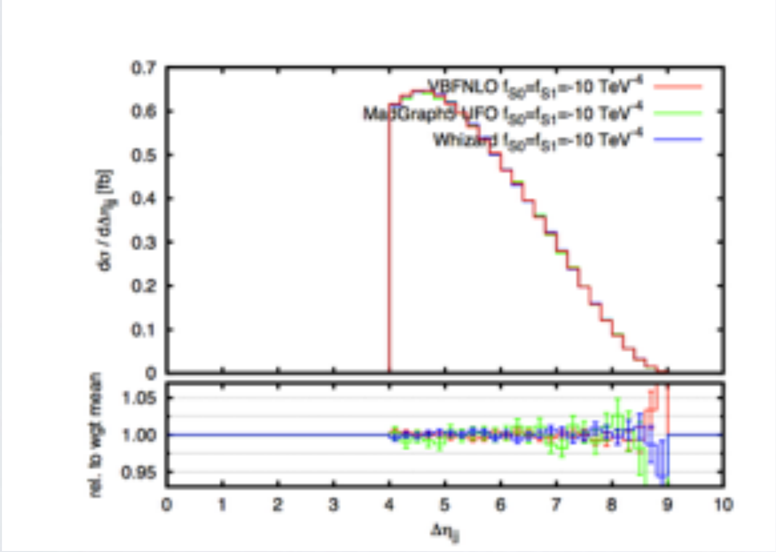
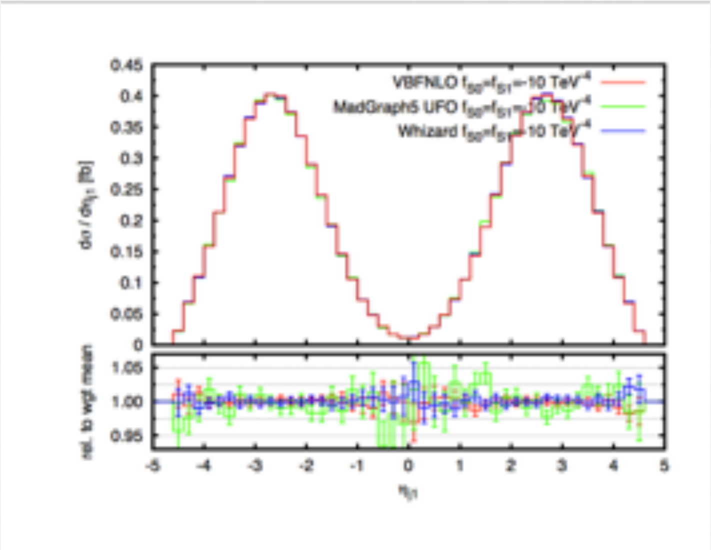


New Physics in Vector Boson Scattering

- Vector Boson Scattering (VBS) major measurement of LHC runs II/III   Gianotti, CERN 01/2014
- Light Higgs suppression makes VBS prime candidate for BSM searches
- Model-independent EFT descriptions (almost) useless: either weakly-coupled resonances in reach or strongly-coupled sectors   Alboteanu/Kilian/JRR, 2008; Kilian/Ohl/JRR/Sekulla, 2014
- Parameterize new physics by dim 6/dim 8 operators, calculate unitarity limits
- K-matrix unitarization implemented in `WHIZARD`   (both for operators and resonances)

For the pure operators: full agreement
between `WHIZARD, Madgraph5, VBFNLO`





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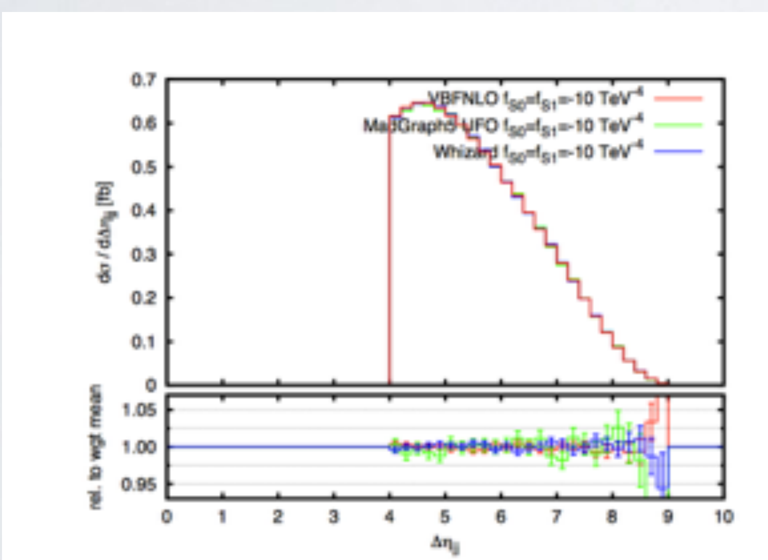
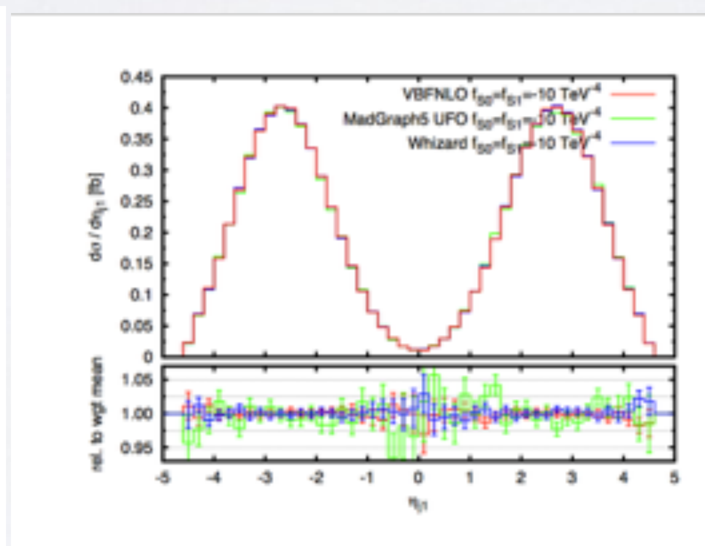
$$\mathcal{L}_{HD} = F_{HD}\ \mathrm{tr}\left[\mathbf{H}^\dagger\mathbf{H} - \frac{v^2}{4}\right]\cdot \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger(\mathbf{D}^\mu\mathbf{H})\right]$$

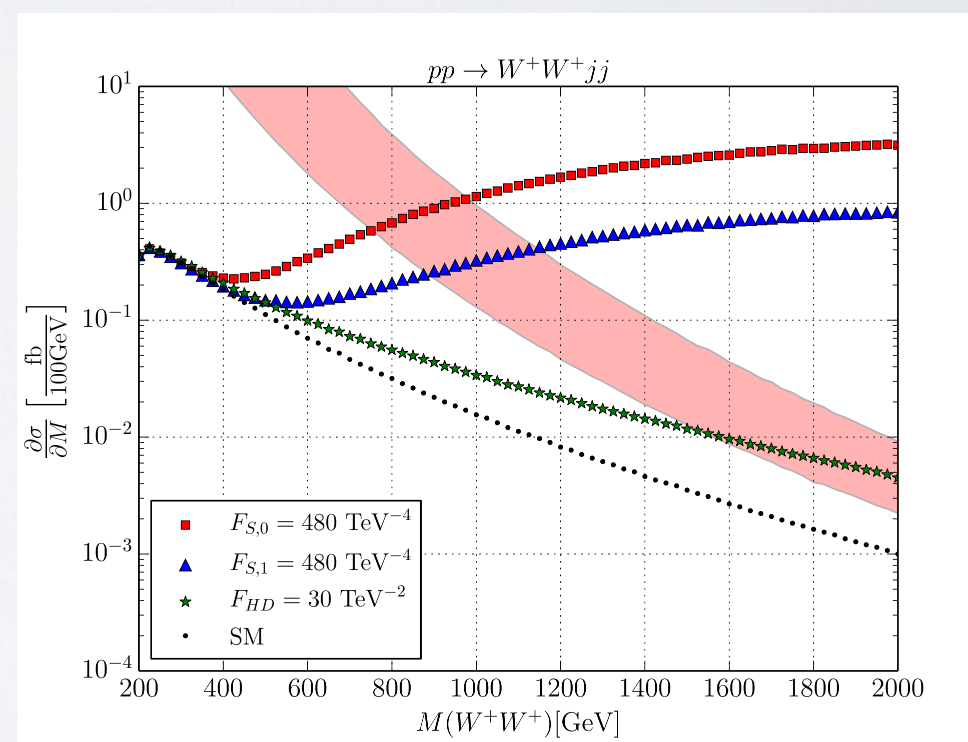
$$\mathcal{L}_{S,0} = F_{S,0}\ \mathrm{tr}\left[(\mathbf{D}_\mu\mathbf{H})^\dagger\mathbf{D}_\nu\mathbf{H}\right]\cdot \mathrm{tr}\left[(\mathbf{D}^\mu\mathbf{H})^\dagger\mathbf{D}^\nu\mathbf{H}\right]$$

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

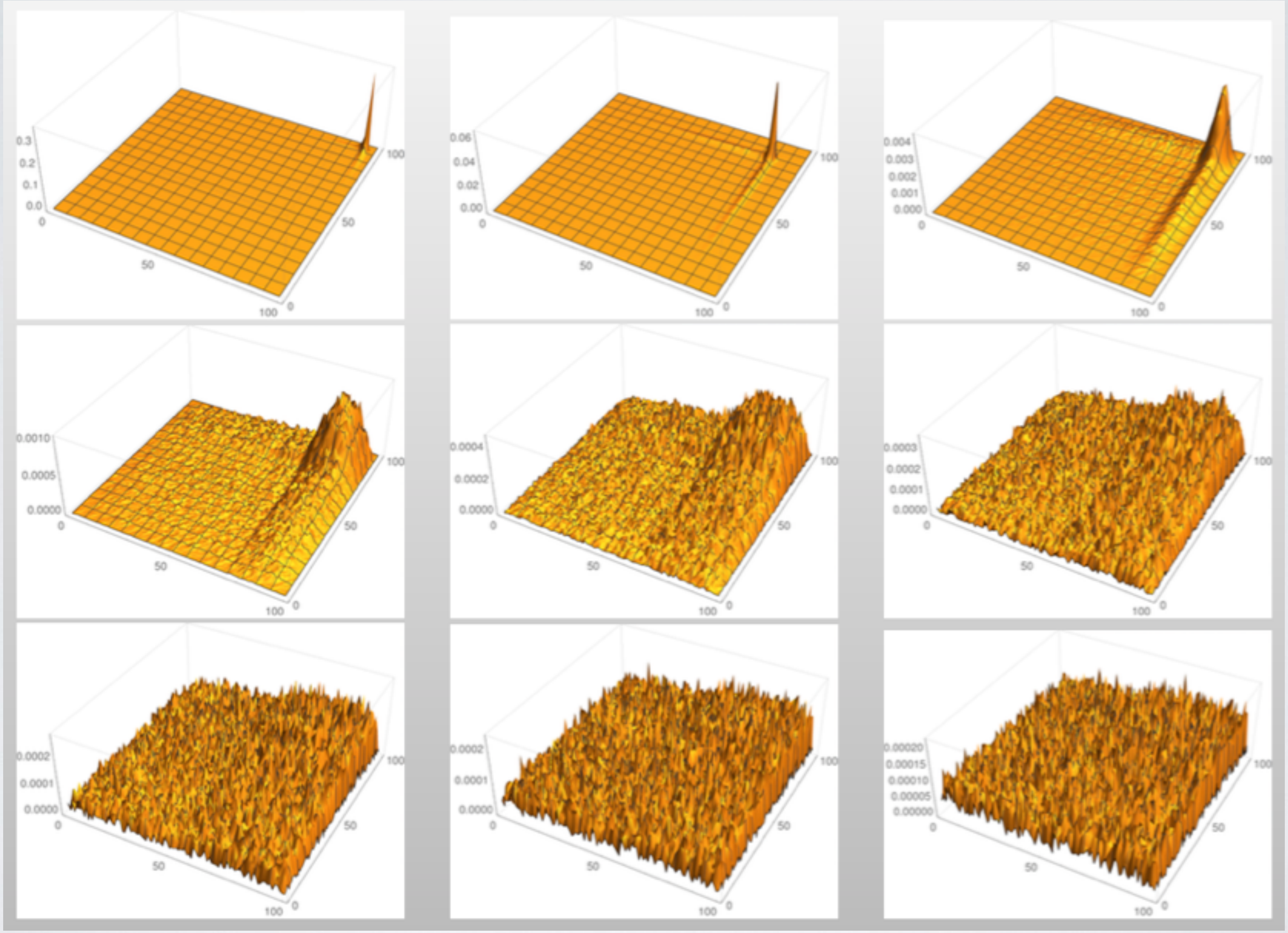
For the pure operators: full agreement between `WHIZARD`, `Madgraph5`, `VBFNLO`







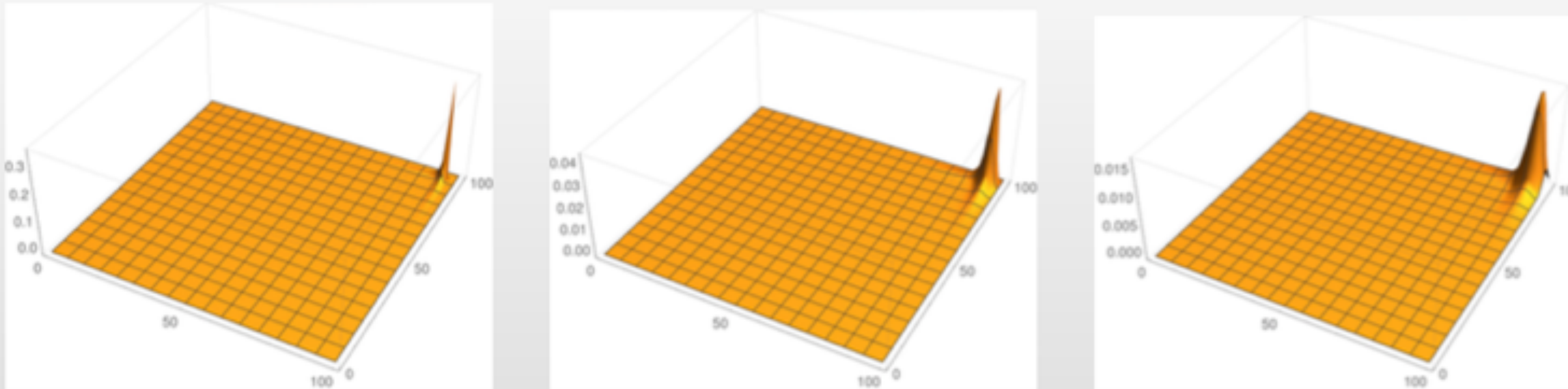
Iterations of Beam Spectrum



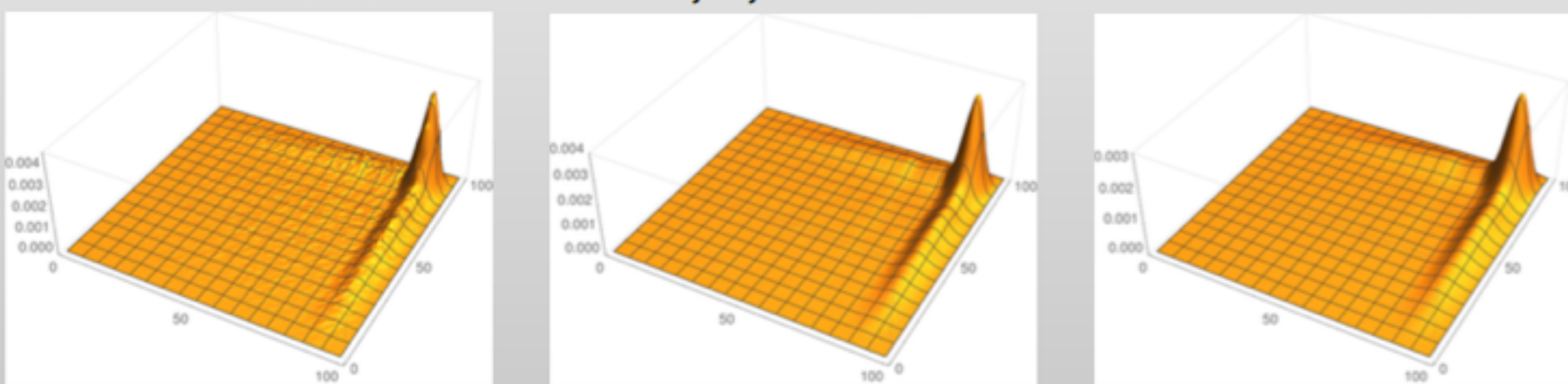
(171,306 GuineaPig events in 10,000 bins)

Iterations of Beam Spectrum

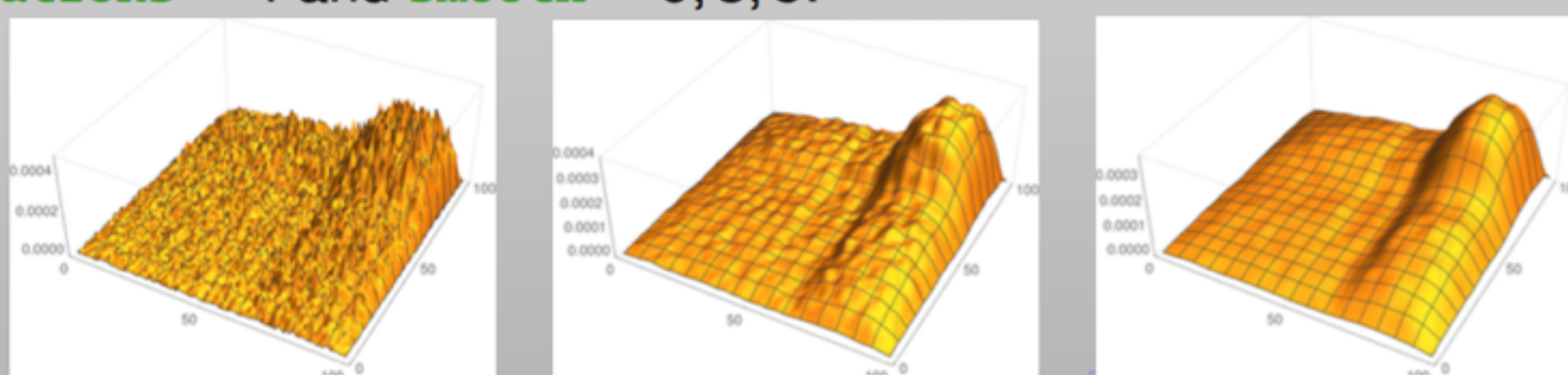
- iterations = 0 and smooth = 0, 3, 5:



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

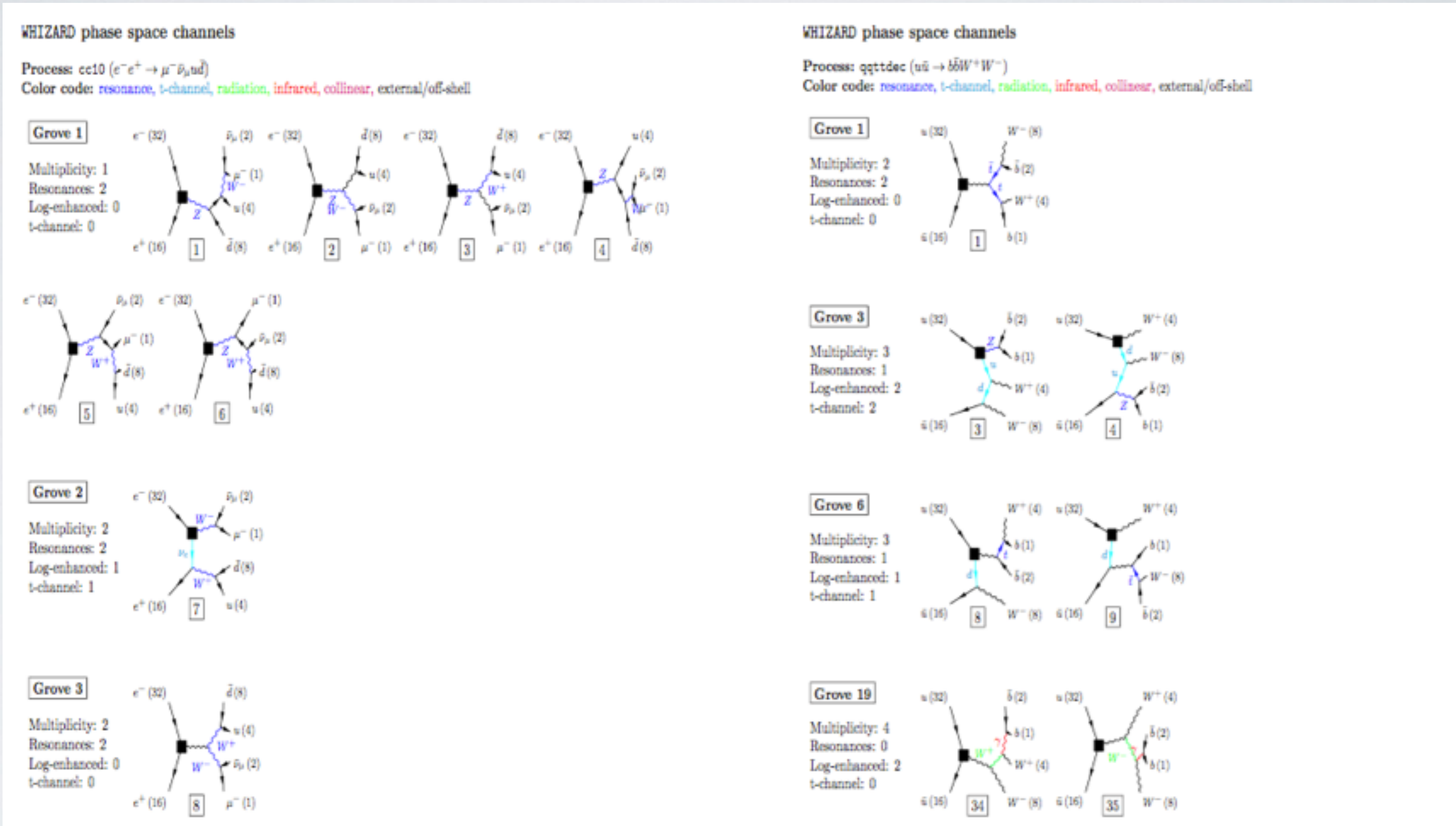


- iterations = 4 and smooth = 0, 3, 5:



Phase Space Setup

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

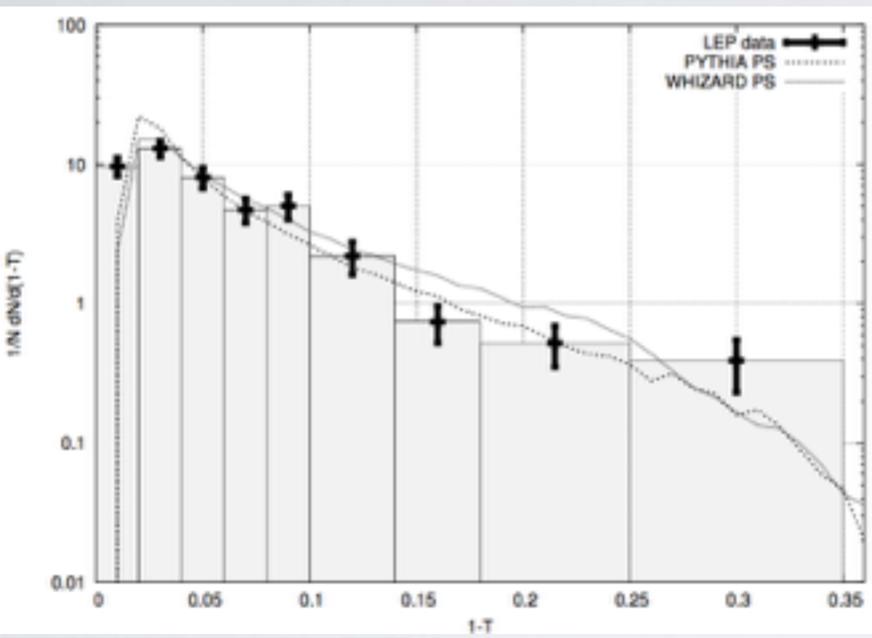


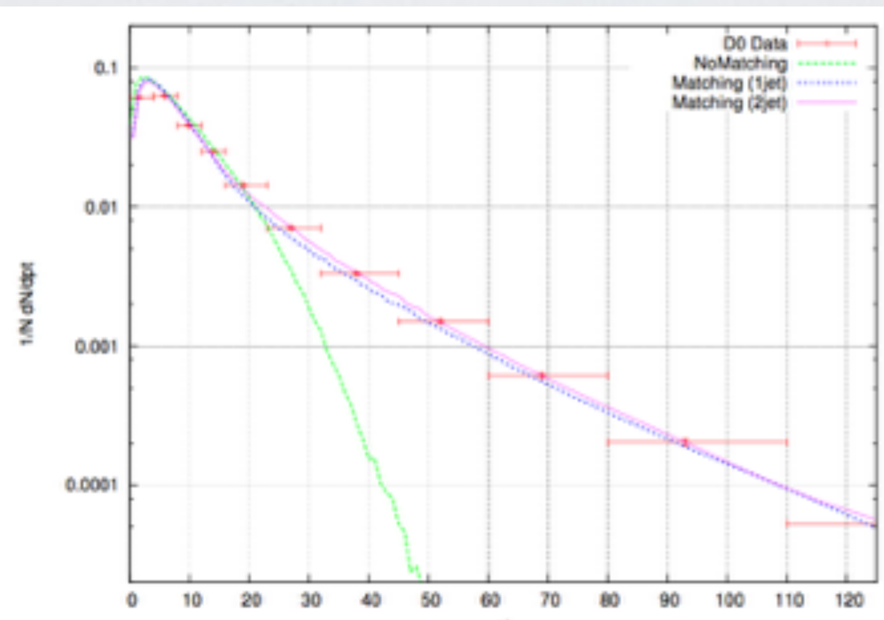
Complicated processes: factorization into production and decay with the `unstable` option

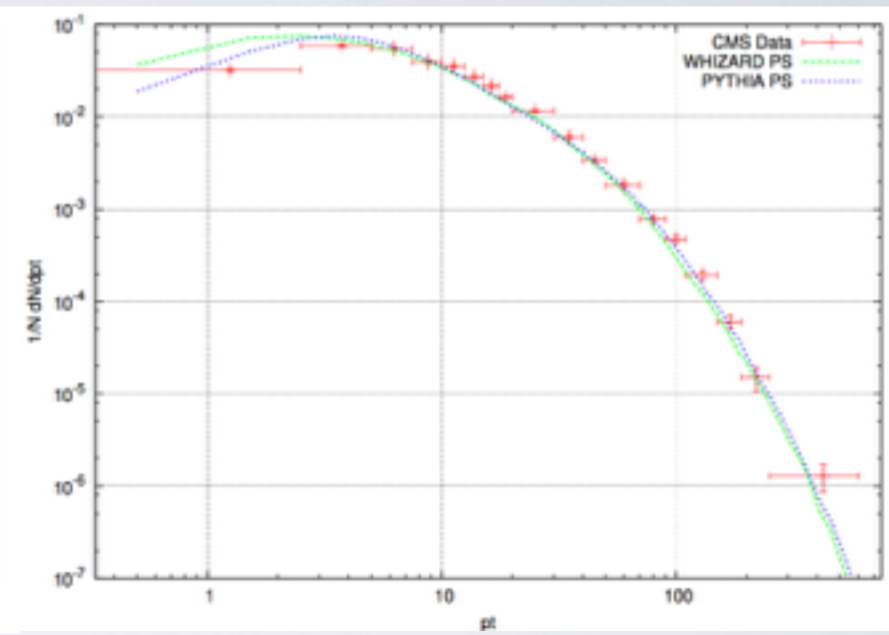
WHIZARD Parton Shower

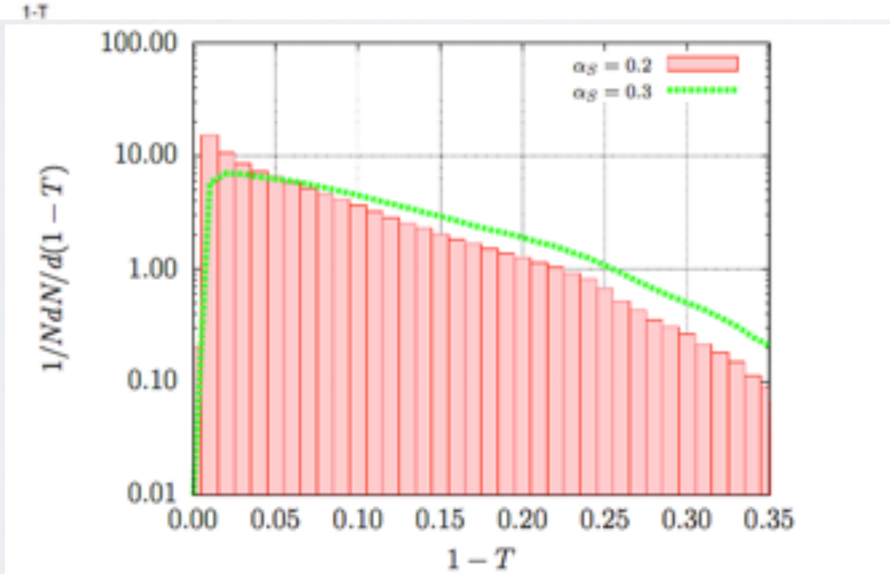
- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

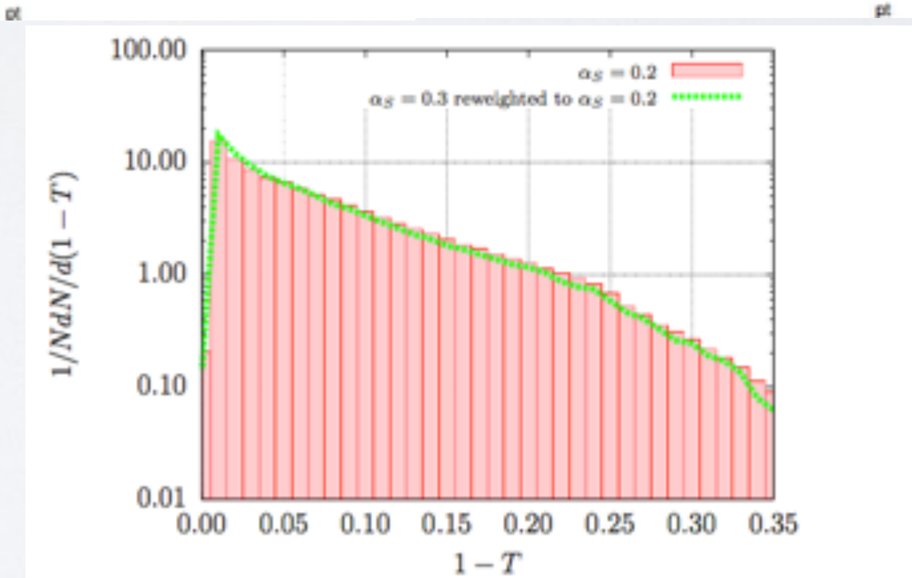
Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)











- 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