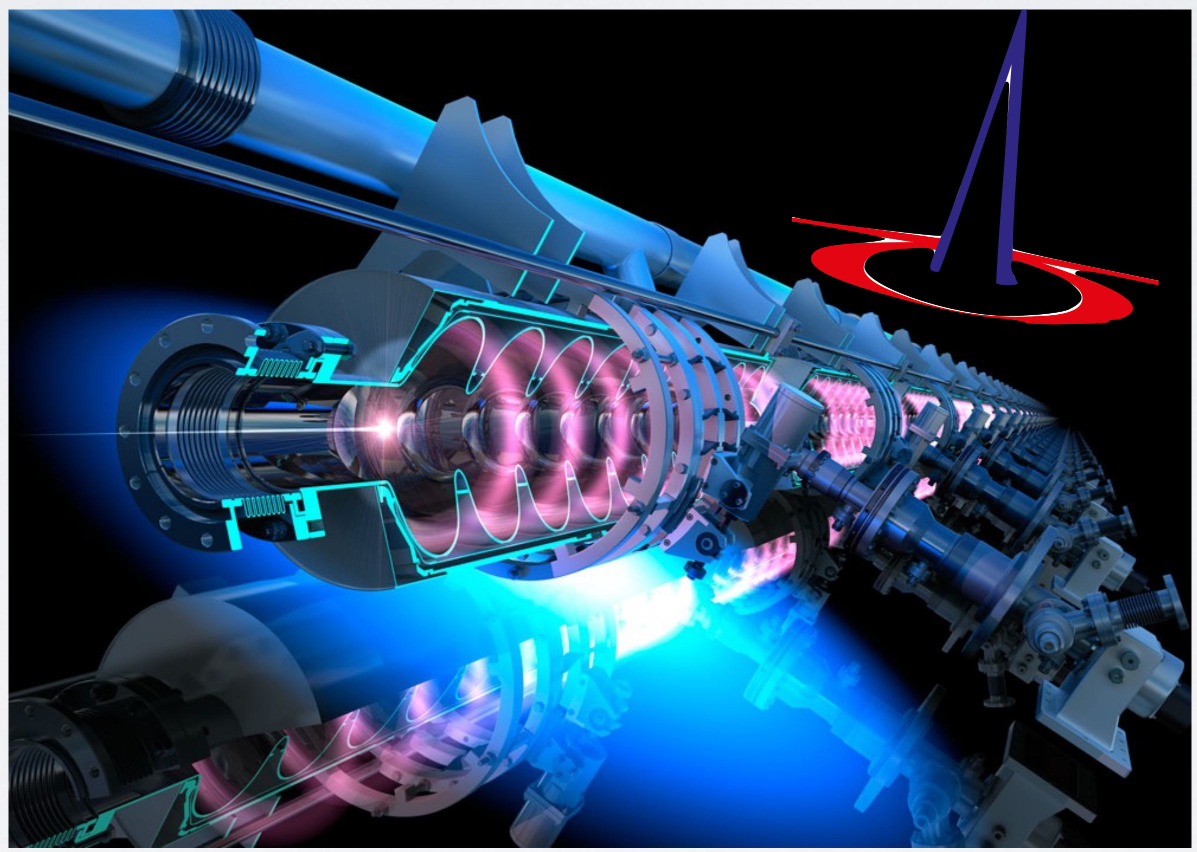
Status Report on the Event Generator WHIZARD



Jürgen R. Reuter, DESY

The WHIZARD Event Generator

- Universal event generator for lepton and hadron colliders
- Modular package:
  - Phase space parameterization (resonances, collinear emission, Coulomb etc.)
  - O'Mega optimized matrix element generator (tree level, NLO external)
  - VAMP: adaptive multi-channel Monte Carlo integrator
  - CIRCE1/2: generator/simulation tool for lepton collider beam spectra
  - Modules for beam structure, parton shower, matching/merging, event formats, analysis, cascade decays, polarized initial/final states, [NLO subtractions] etc.
  - Interfaces to external packages for Feynman rules, hadronization, tau decays, event formats, analysis, jet clustering etc.
  - SINDARIN: free-format steering language for all inputs (!)

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  - SINDARIN: free-format steering language for all inputs (!)

v1.0	Project start ca. 1999 (parts early 90's): TESLA studies → W, Z, Higgs (+ resp. decays)
v1.20	02/2002: optimized matrix elements (O'Mega)
v1.25	06/2003: first ever multi-leg implementation of the MSSM
v1.50	02/2006: QCD color flow formalism
v1.95/97	02/2010: NMSSM, UED, parton shower (alpha), development stop v1
v2.0.0	04/2010: OO overhaul (38 months), modern v2 version, faster matrix elements
v2.1.0	06/2012: FSR/ISR shower, SINDARIN, unit tests etc., cascade processes
v2.2.0	04/2014: 2nd OO overhaul (18 months)
v2.2.5	02/2015: production version, LCIO, NLO alpha, POWHEG alpha, top threshold

WHIZARD: Some (technical) facts

WHIZARD v2.2.5 (27.02.2015) http://whizard.hepforge.org

<whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR*
Bijan Chokoufé/Marco Sekulla/Christian Weiss + *2 Master + 2 PhD (soon)*
(some losses: C. Speckner [software engineering], F. Bach [ESA Space Defense], S. Schmidt [Philosophy])

Publication: EPJ C71 (2011) 1742 (and others for O'Mega, Interfaces, color flow formalism)

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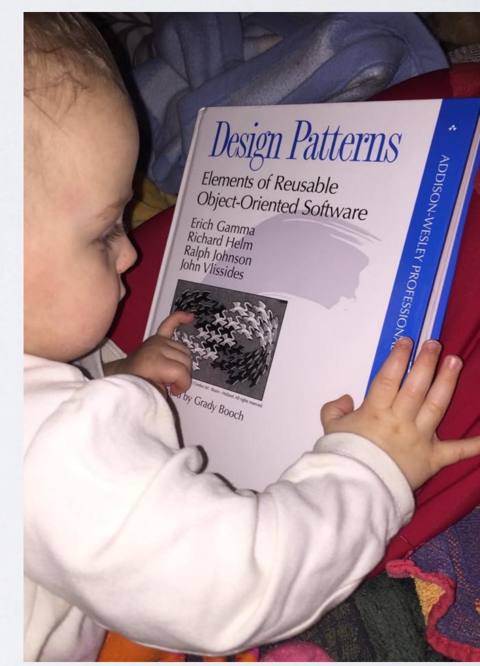
2nd WHIZARD Workshop Würzburg, 03/2015



support junior developers

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- Large self test suite, unit tests [module tests], regression testing
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- NEW: ticketing system (`JIRA` @ DESY) for user support issues (questions, bug reports)

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WHIZARD Manual @ Hepforge

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Talk concentrates on NEW features and current developments/ (near) future plans

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:

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simulate (<process>)
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```
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

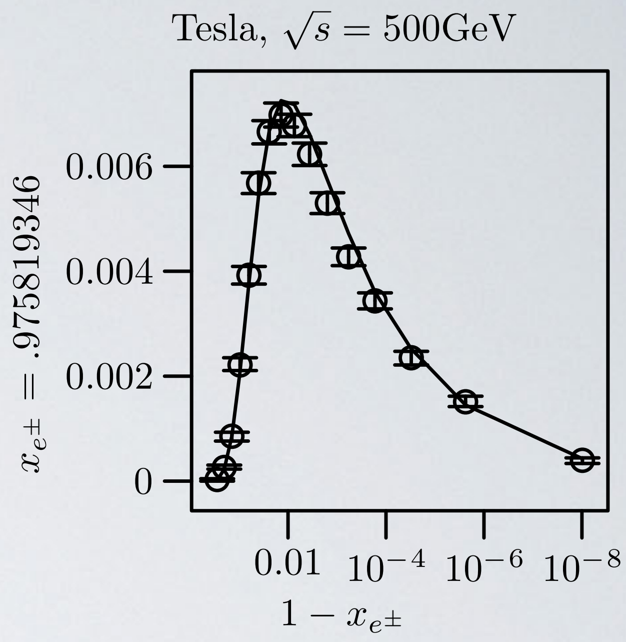
[   id   ]index|      PDG |    px,       py,        pz     | energy  |gen|[simstat ]| vertex x,      y   ,   z     | endpoint x,    y  ,   z     |    mass |  charge |            spin             | colorflow | [parents] - [daughters]

[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] - []

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

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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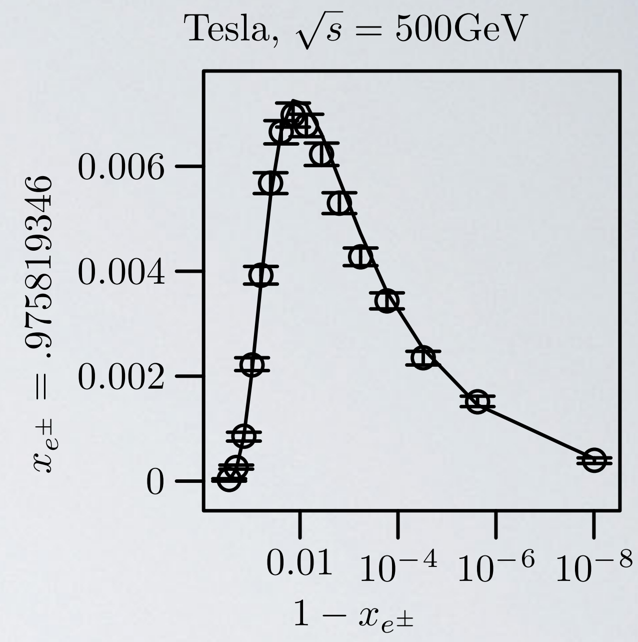

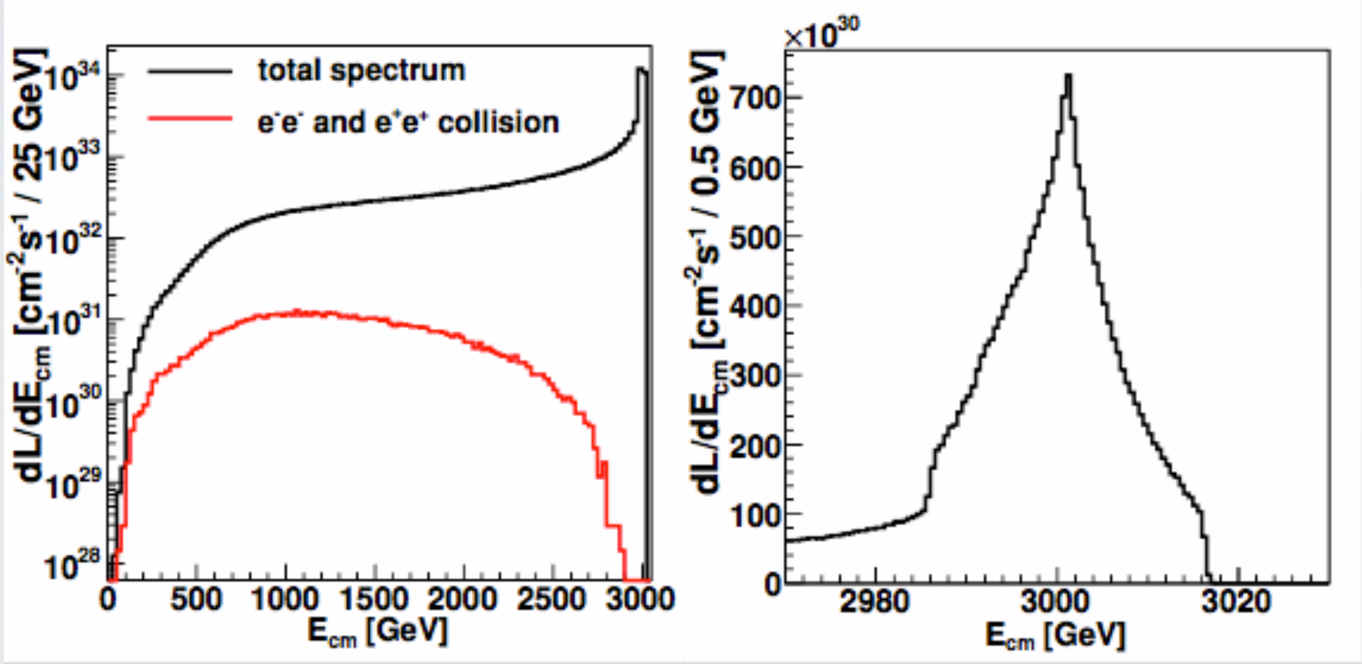

Dalena/Esbjerg/Schulte [LCWS 2011]

Tails @ CLIC much more complicated (wakefields)

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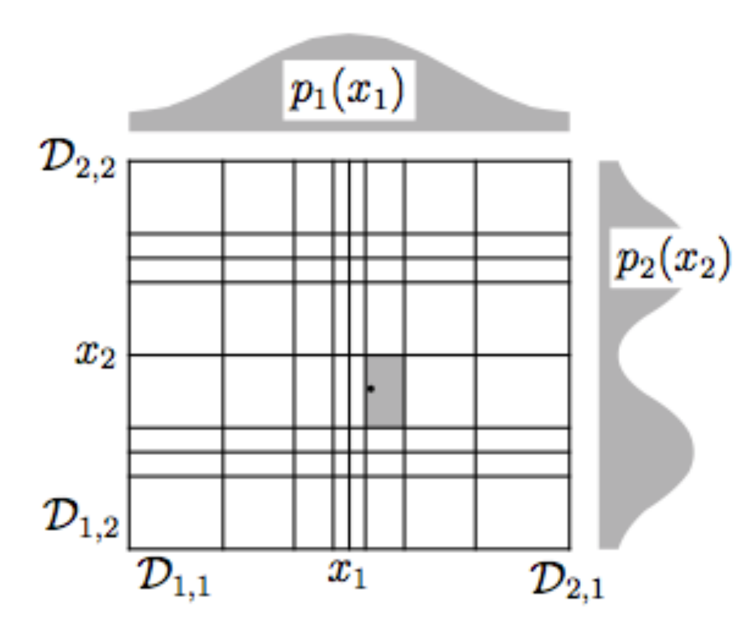

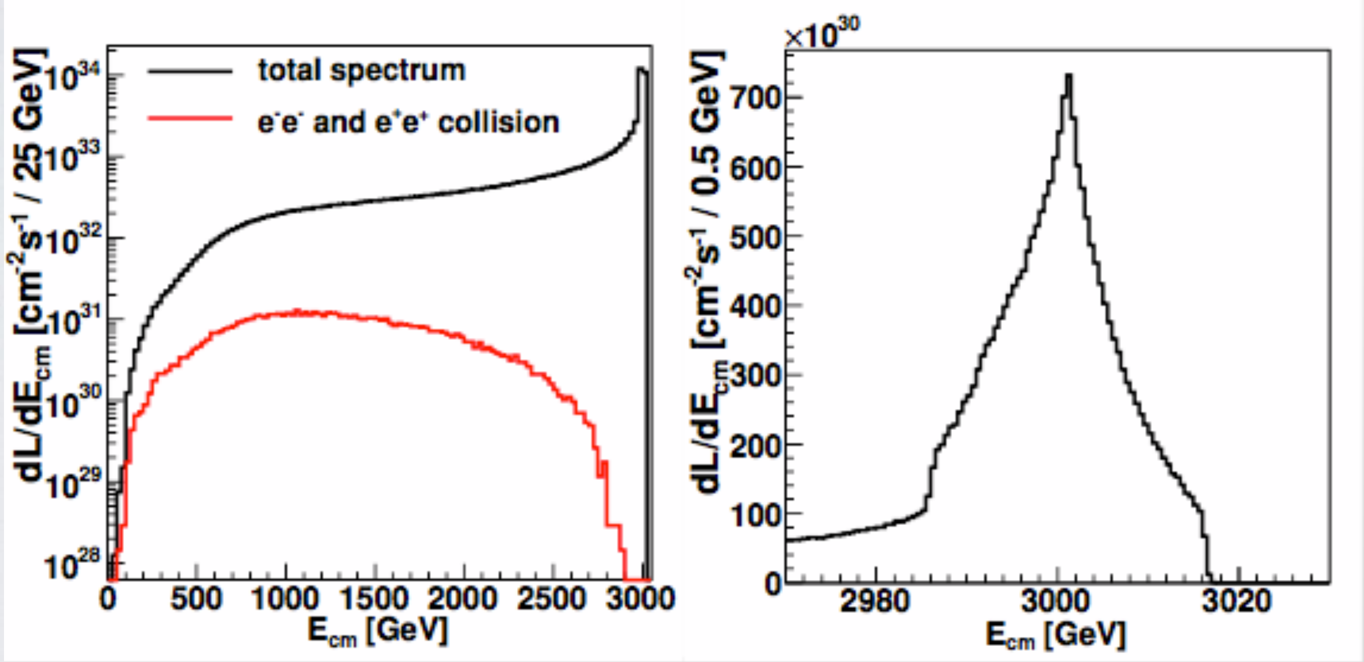

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`CIRCE2` algorithm (`WHIZARD 2.2.5`, 02/15)

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

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

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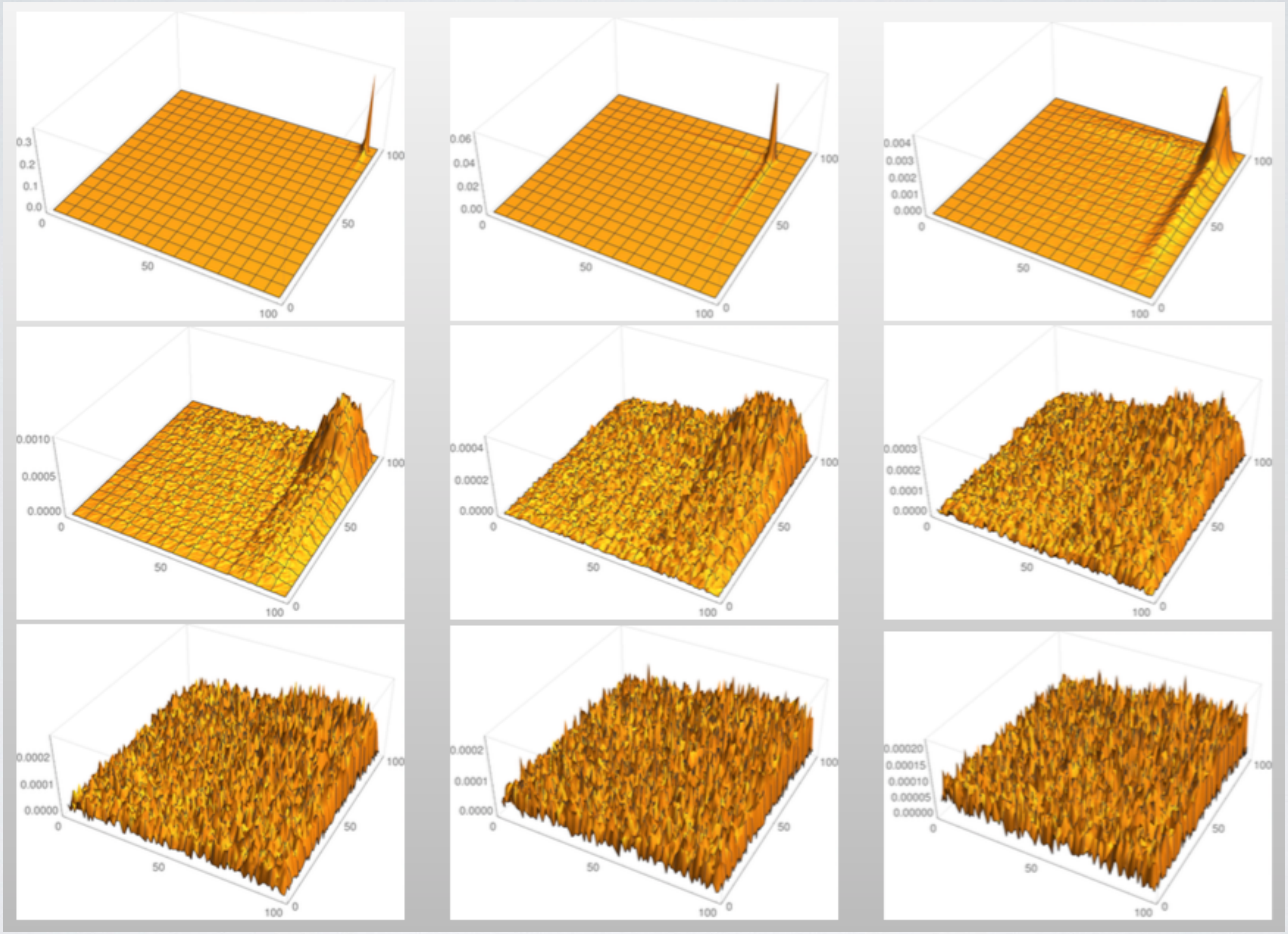
   ```

   polarized spectra on demand

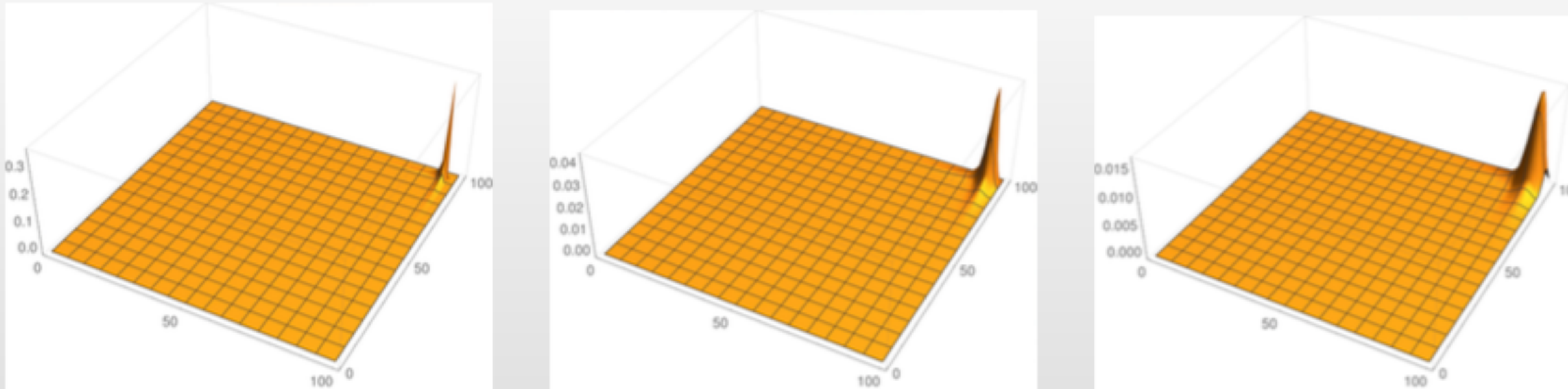
Iterations of Beam Spectrum



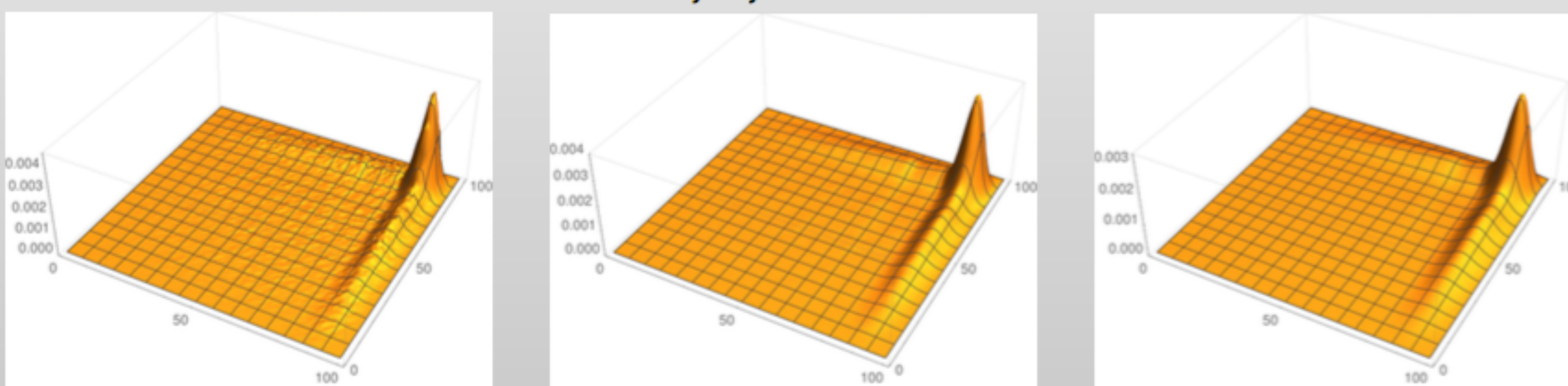
(171,306 GuineaPig events in 10,000 bins)

Iterations of Beam Spectrum

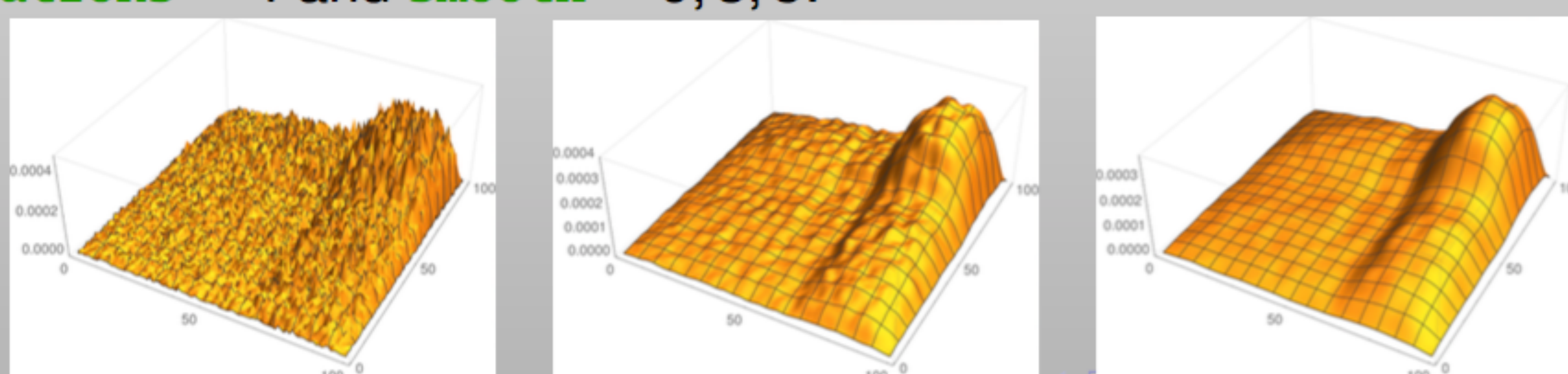
- iterations = 0 and smooth = 0, 3, 5:



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



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



NLO Development in WHIZARD

- Need for precision predictions that match (sub-) percent experimental accuracy
- Scary challenge for the theory community [ok, we have some time still …]
- Mostly electroweak corrections, but also QCD and pure QED

Binoth Les Houches Interface (BLHA): Workflow

1. Process definition in SINDARIN (contract to One-Loop Program [OLP])
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(first focus on QCD corrections)

- ★ GoSam [G. Cullen et al.]
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WHIZARD v2.2.5 contains alpha version

QCD corrections (massless and massive emitters)

```
alpha_power = 2
alphas_power = 0

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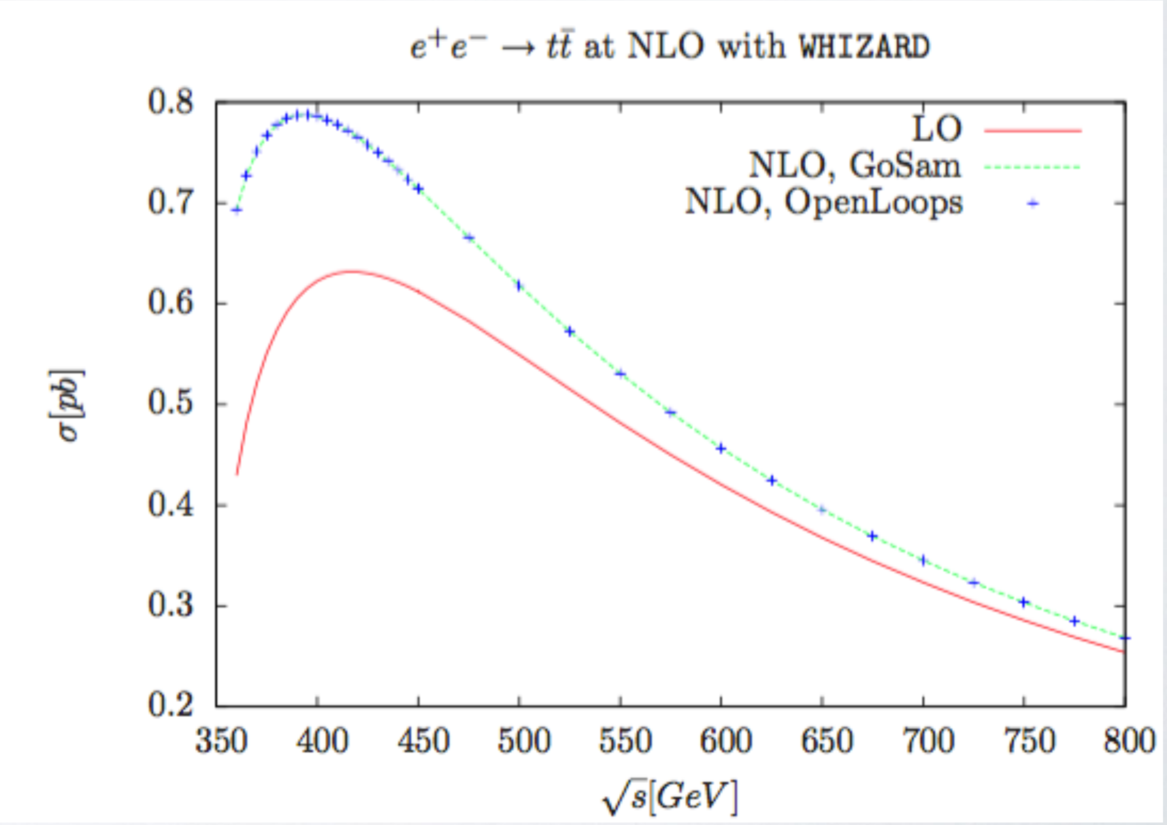

FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

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

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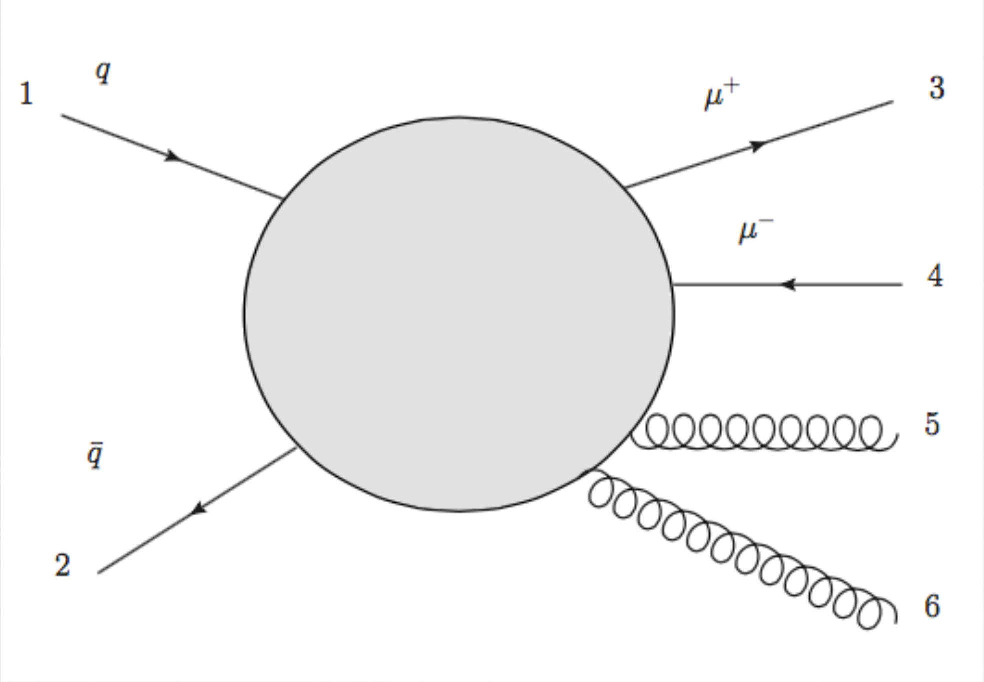
Subtraction formalism to make real and virtual contributions separately finite

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



Automated Subtraction 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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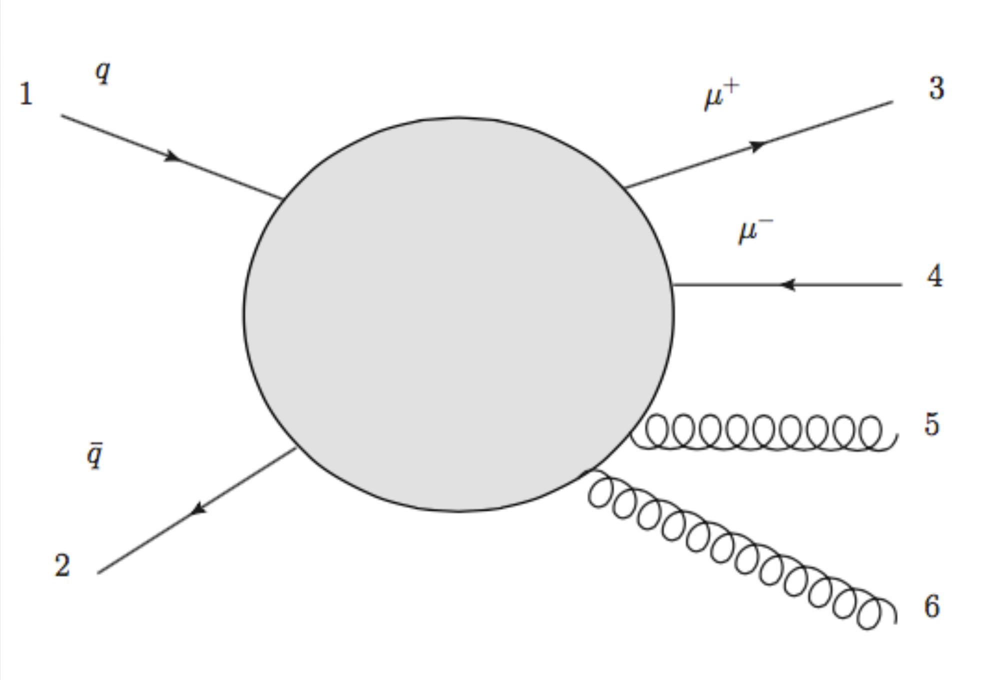

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Soft subtraction involves color-correlated matrix elements:

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

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

- $e^+e^- \to q\bar{q}$
- $e^+e^- \to q\bar{q}g$
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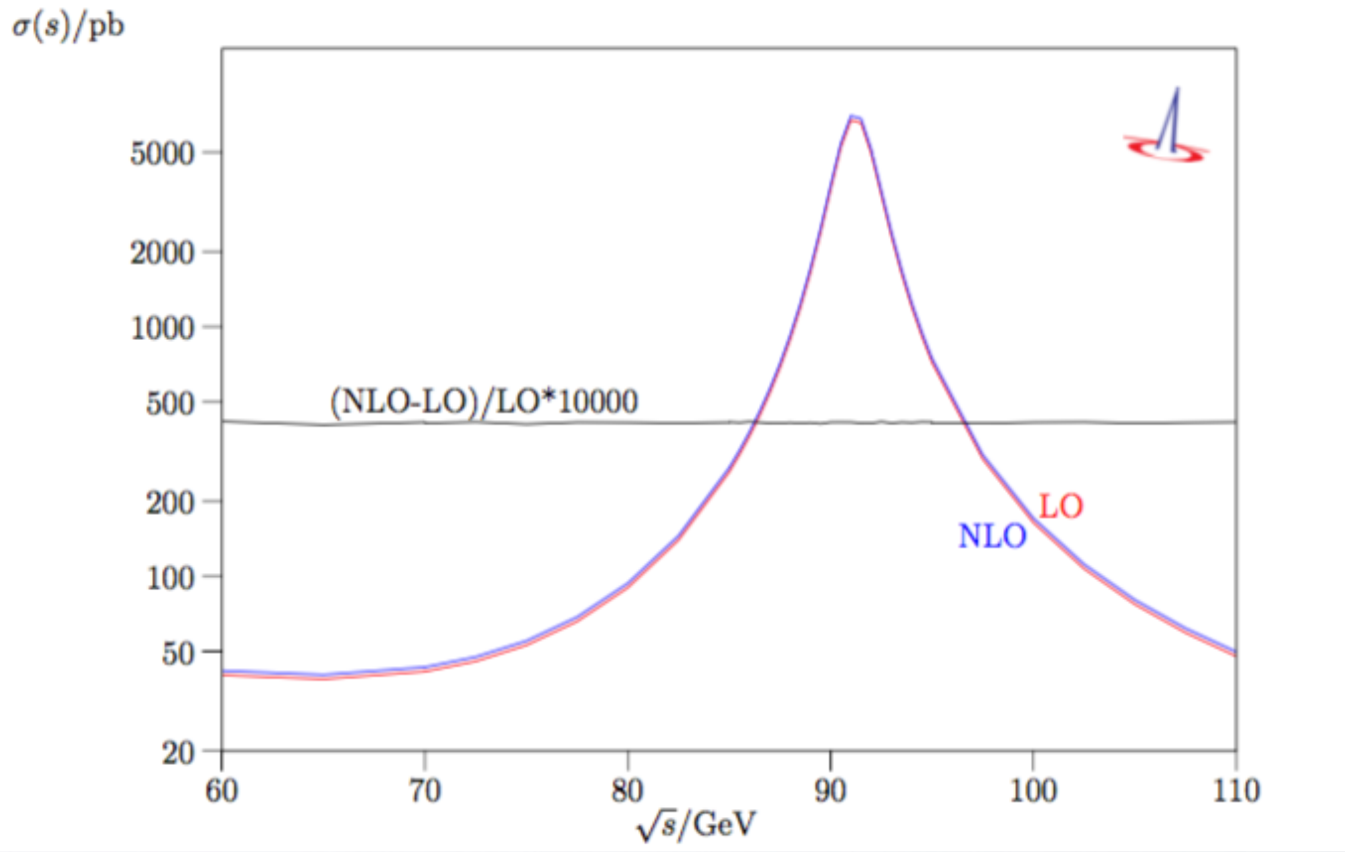

Caveat: no fixed-order NLO event generation due to missing counter-event infrastructure

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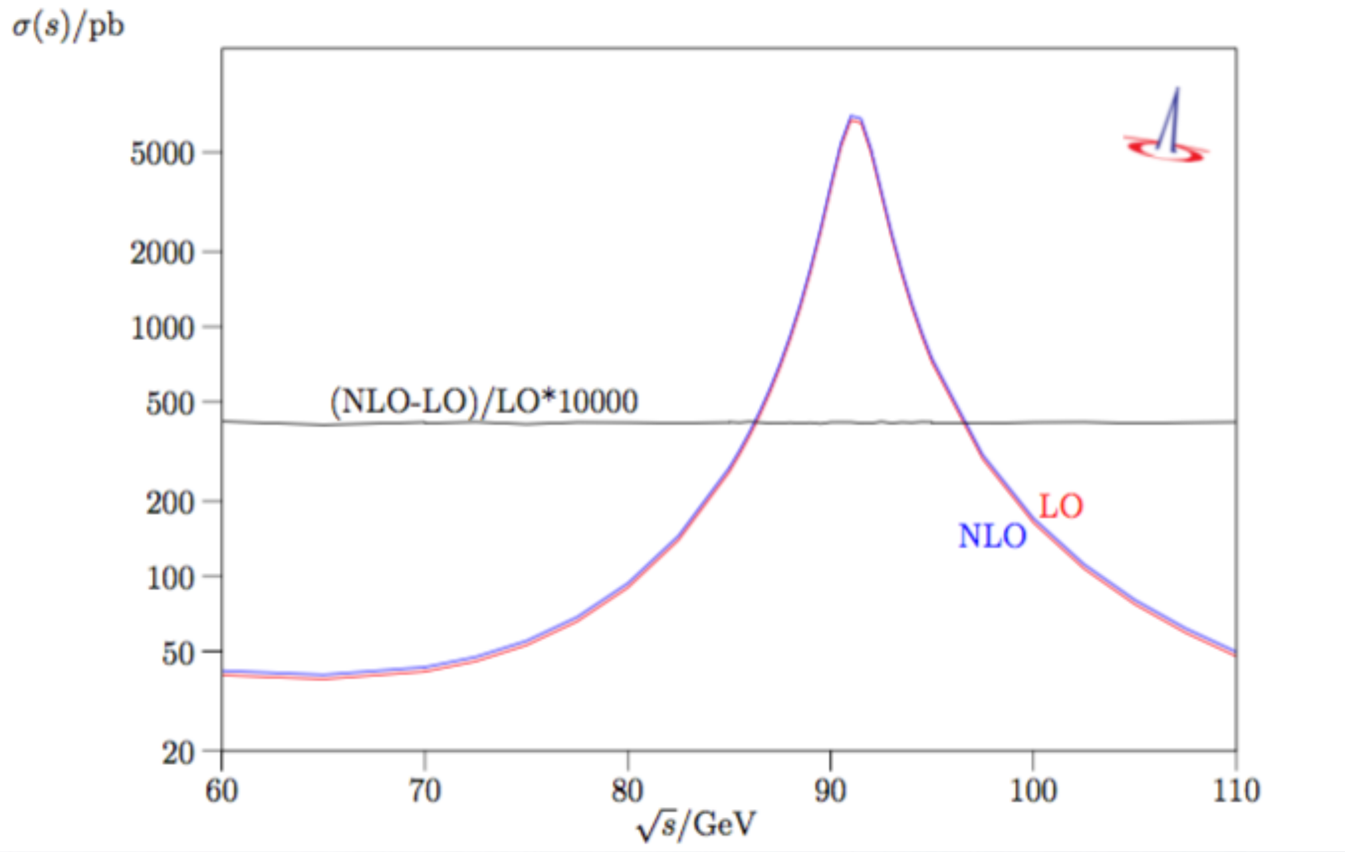

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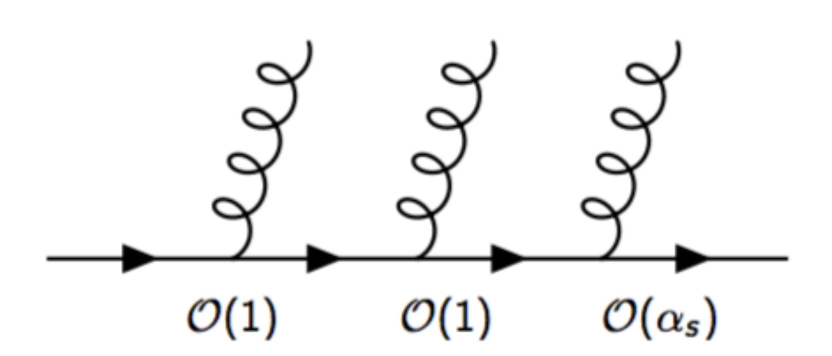
✦ First working infrastructure for QCD NLO in pp

✦ First attempts on electroweak corrections, interfacing the `RECOLA` code [Denner et al.]

POWHEG Matching in WHIZARD

- Soft gluon emission before hard emission generate large logs
- Perturbative α_s : $|\mathcal{M}_{\rm soft}|^2 \sim \frac{1}{k_T^2} \to \log \frac{k_T^{\rm max}}{k_T^{\rm min}}$
- Matrix element + parton shower has to take this into account
- POWHEG method: hardest emission first [Nason et al.]



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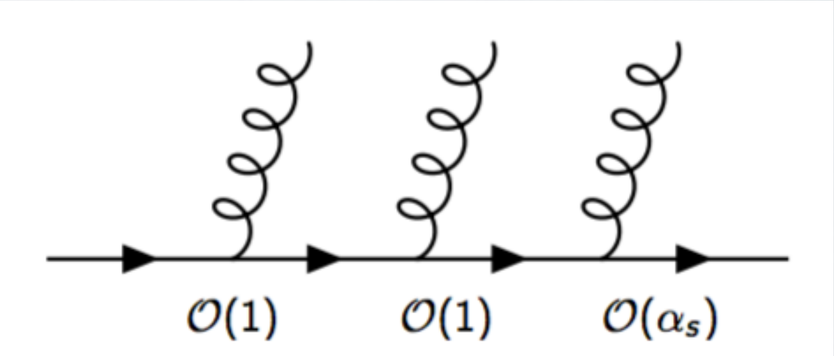

- Complete NLO events

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

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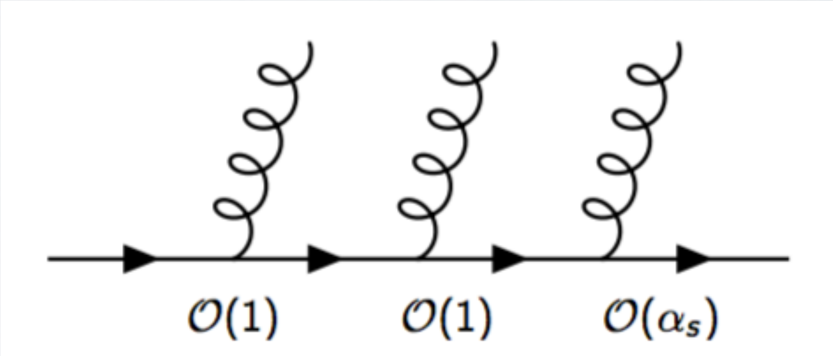

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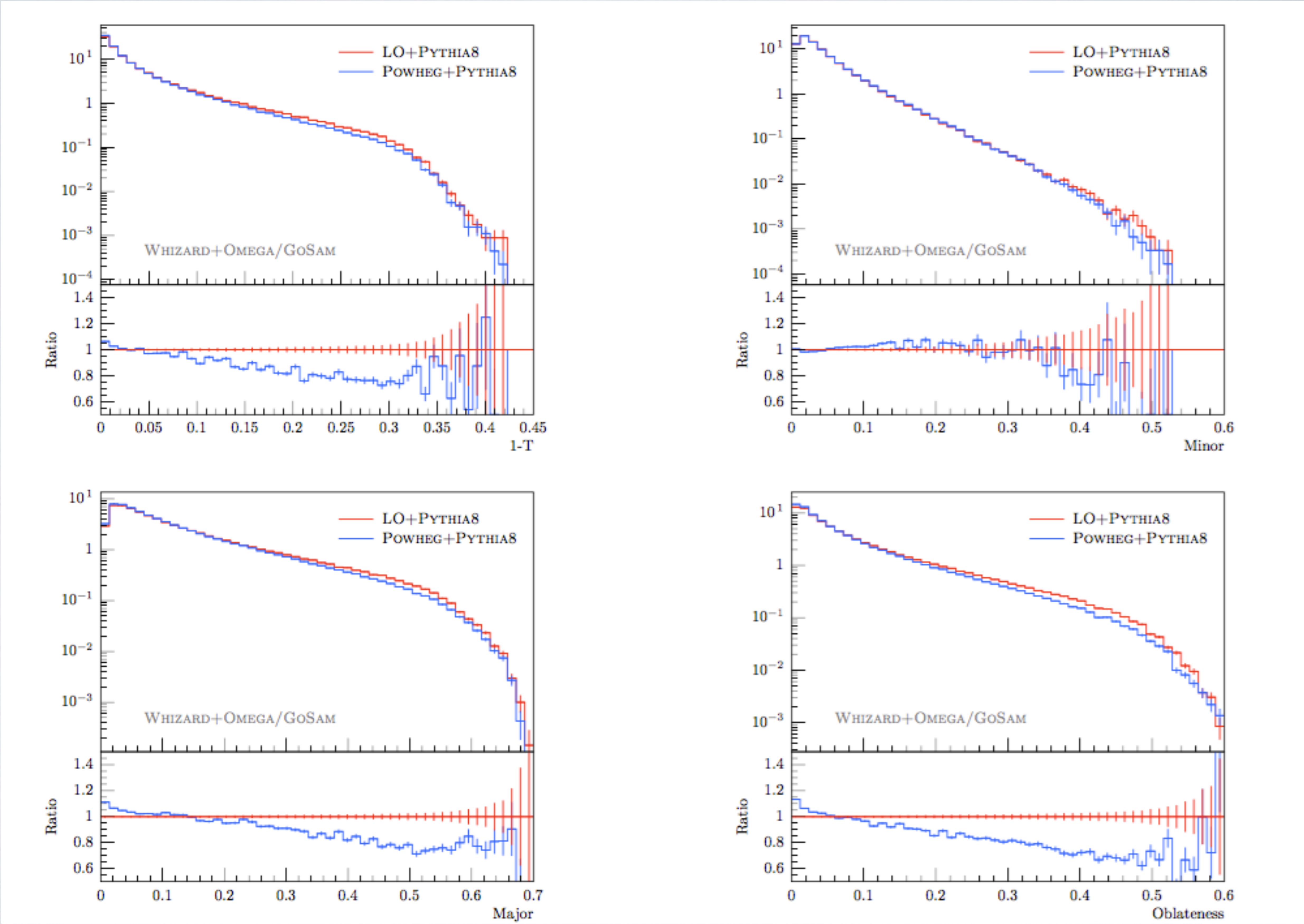
- Hardest emission: $k_T^{\max}$; shower with imposing a veto:
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator now implemented in `WHIZARD`

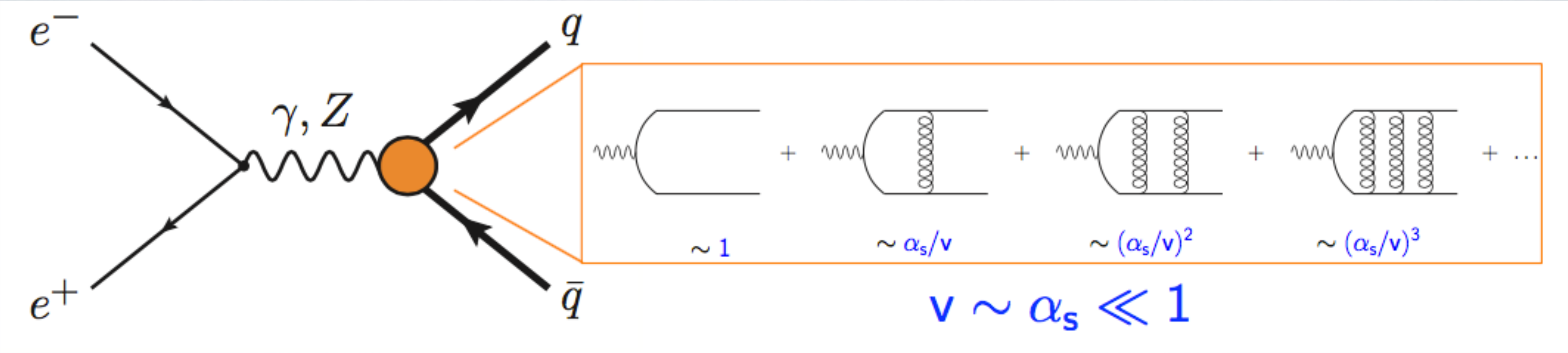
POWHEG Matching in e+e- to dijets



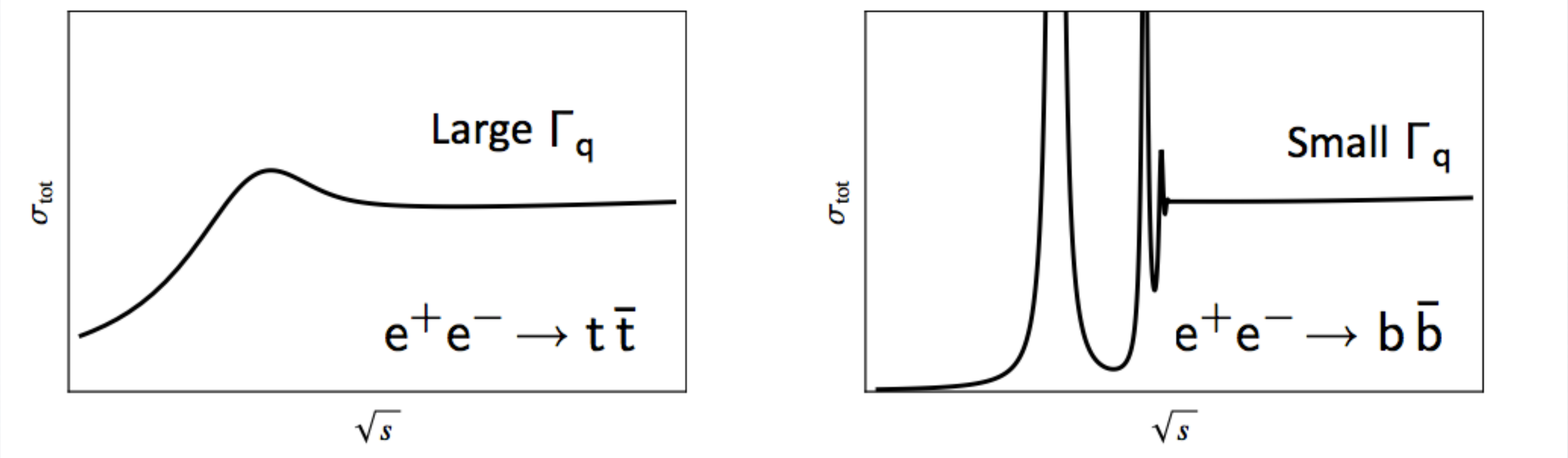
Top Threshold at lepton colliders

ILC top threshold scan best-known method to measure top quark mass, $\Delta M \sim 100$ MeV

Heavy quark production at lepton colliders



Threshold region (quantitatively)



Top Threshold in WHIZARD

with F. Bach/A. Hoang/M. Stahlhofen

- Implement resummed threshold effects as effective tab vertex [form factor] in `WHIZARD`
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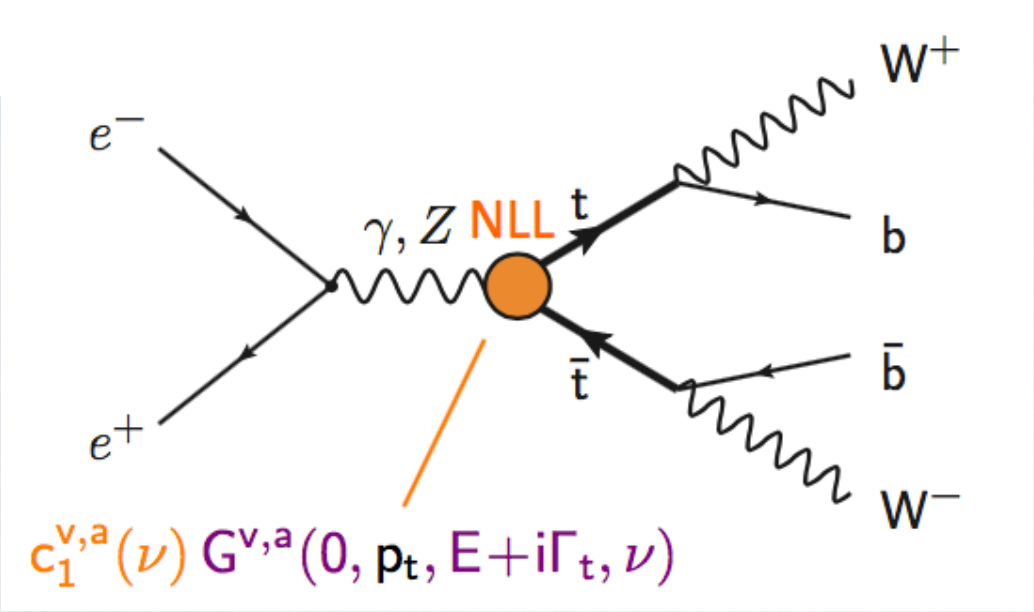

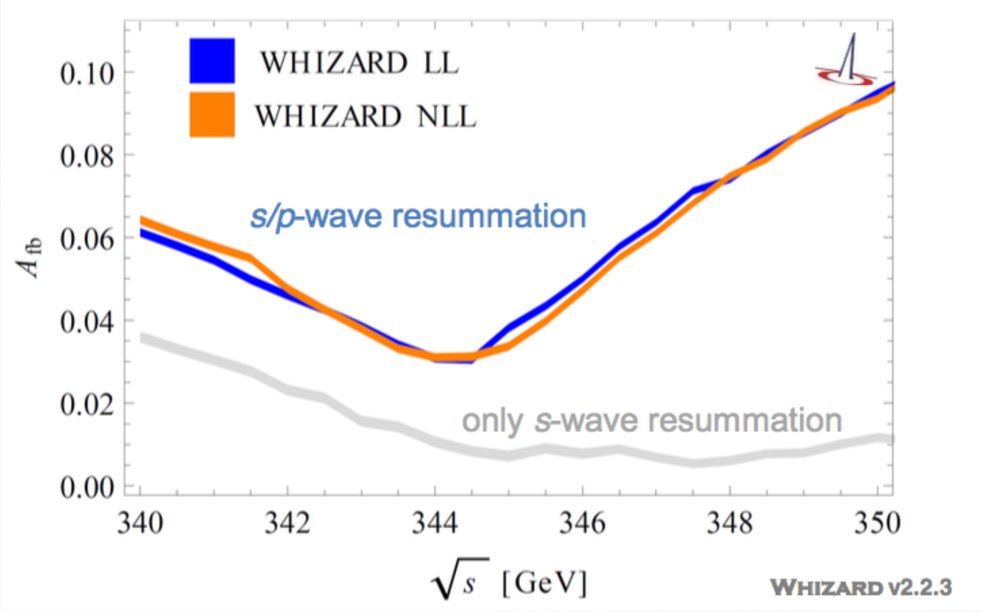

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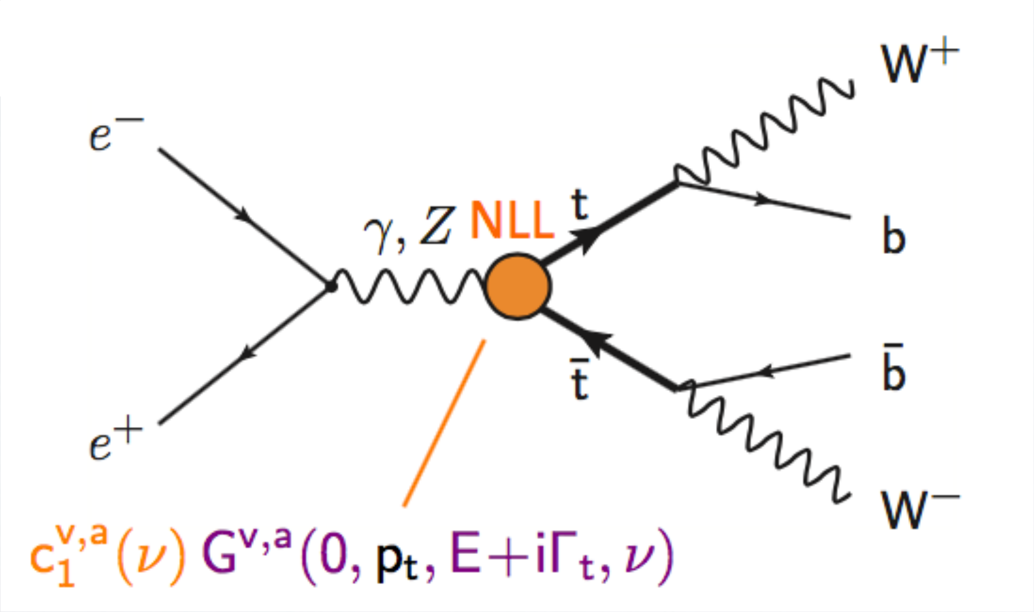

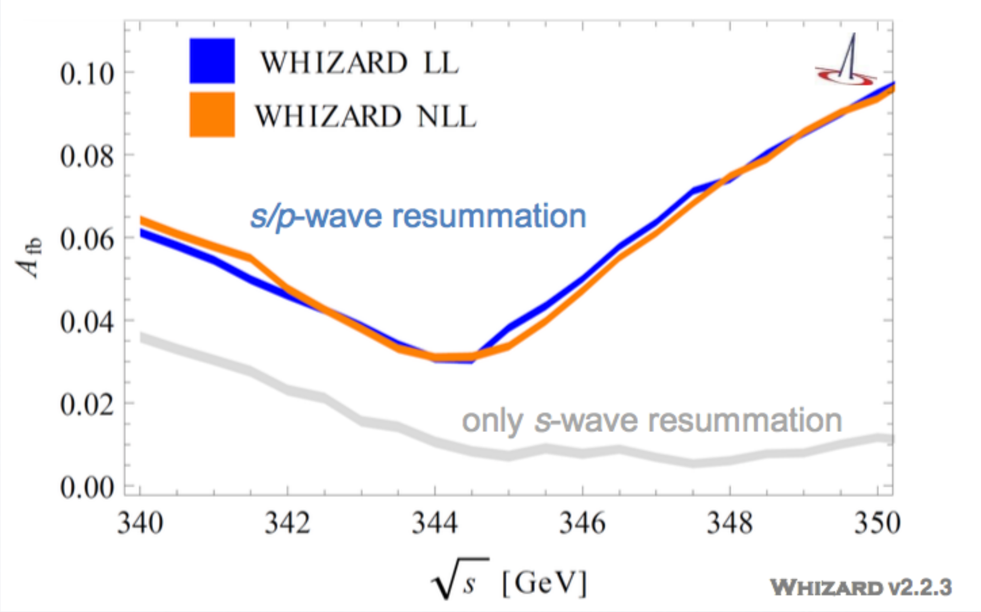

$$R^{\gamma,Z}(s) = \underbrace{F^v(s)R^v(s)}_{\text{s-wave: LL+NLL}} + \underbrace{F^a(s)R^a(s)}_{\text{p-wave}\sim v^2\text{:NNLL}}$$

BUT: differentially p-wave at NLL !

- Default parameters:

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

Threshold/Continuum Matching: WIP

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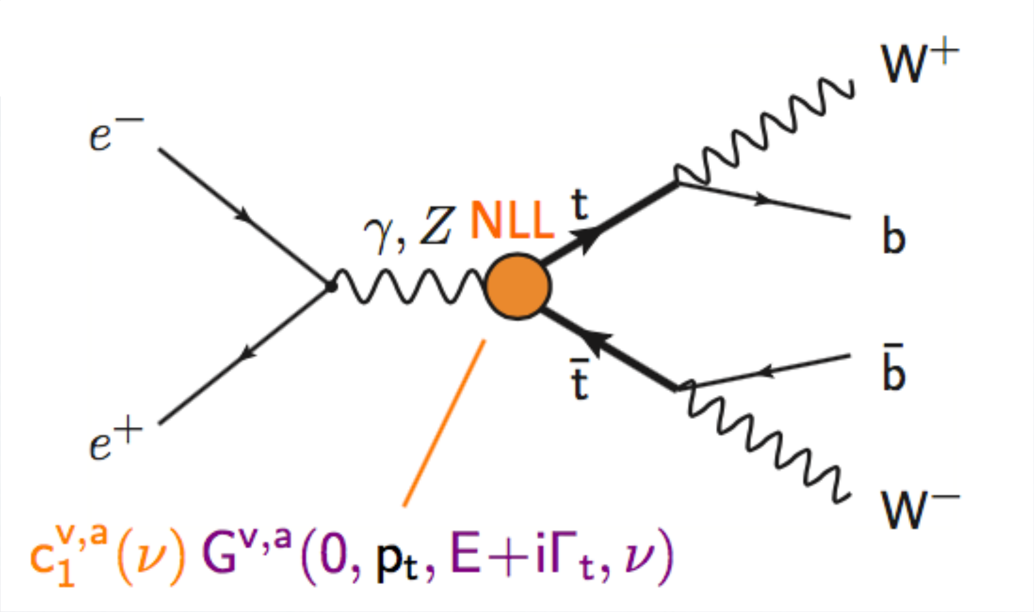

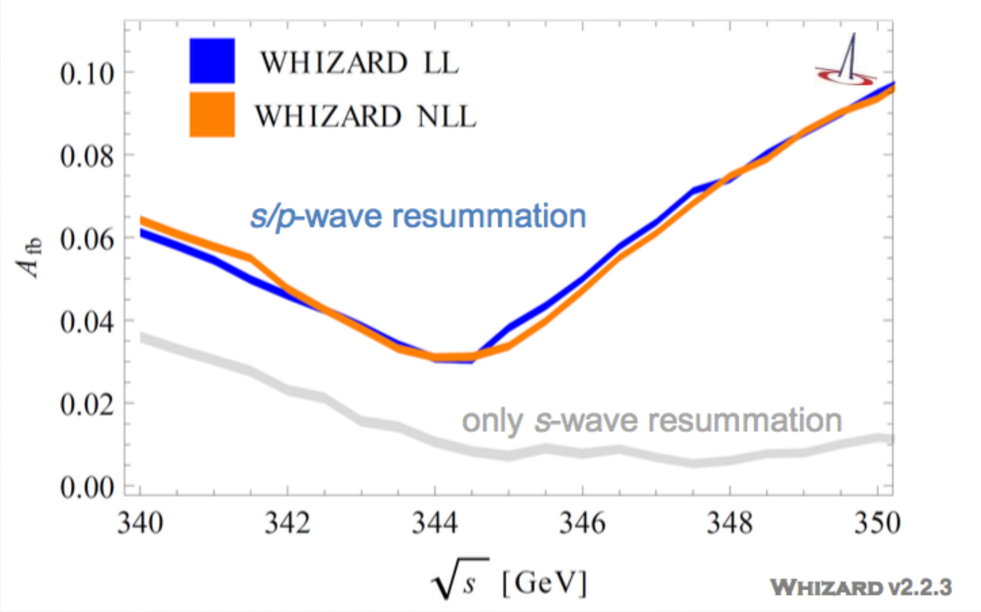

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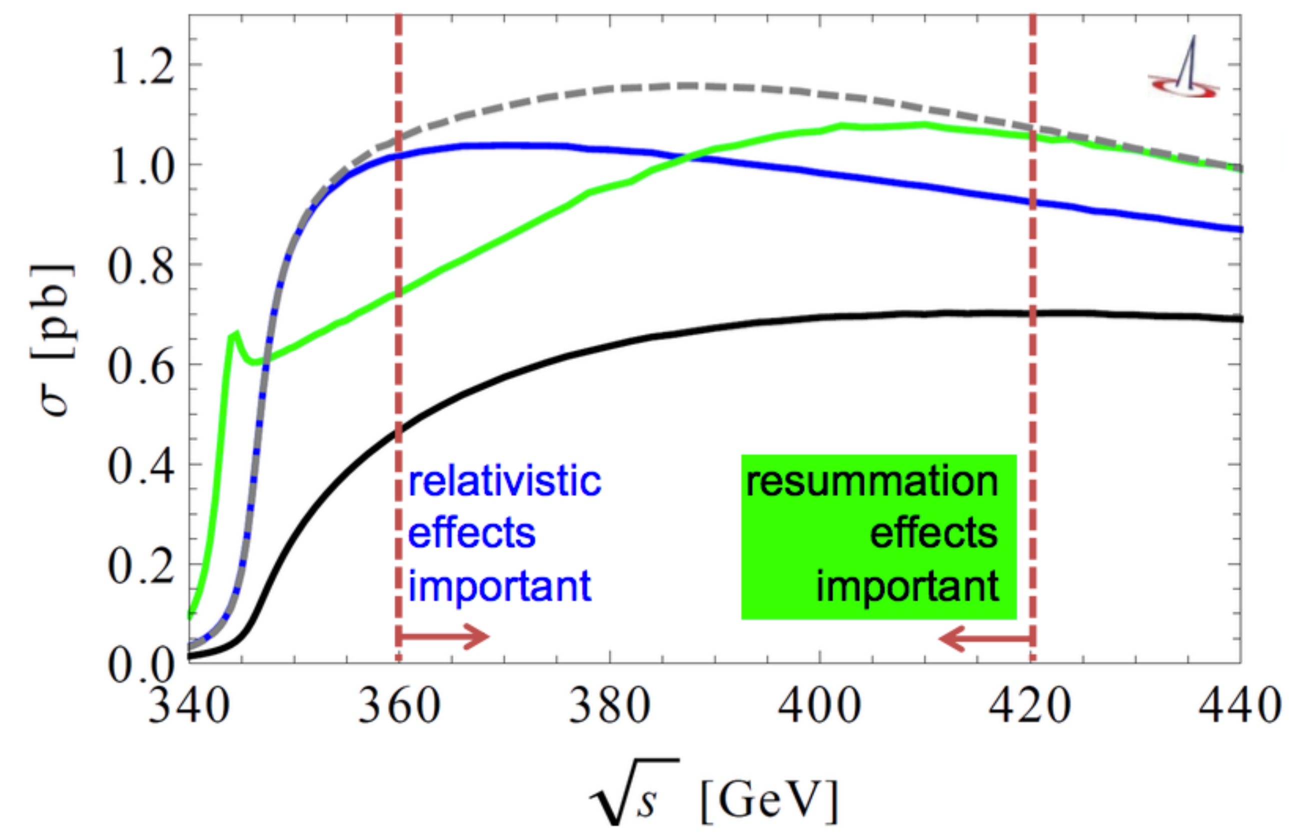

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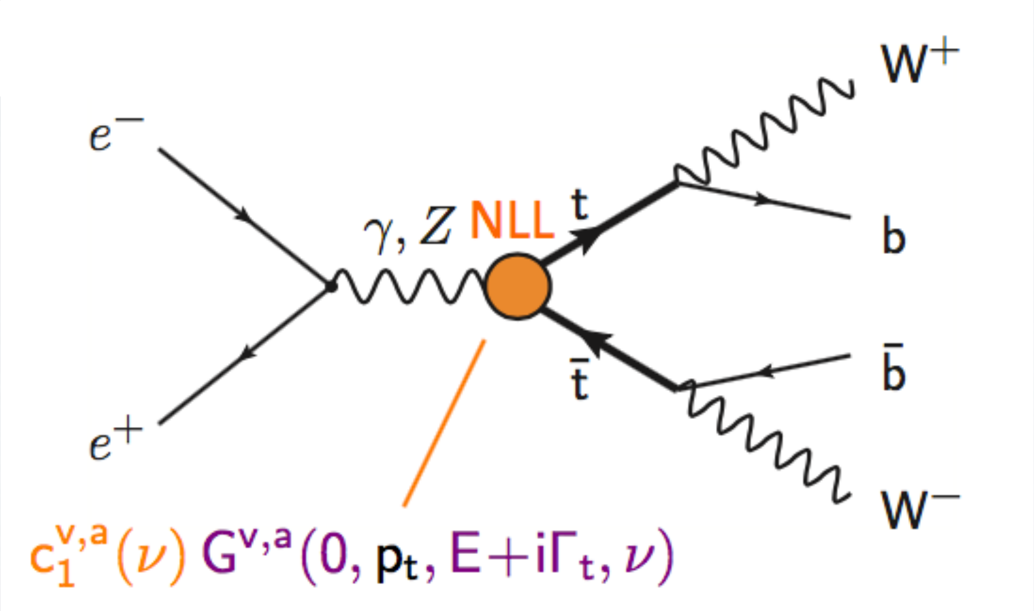

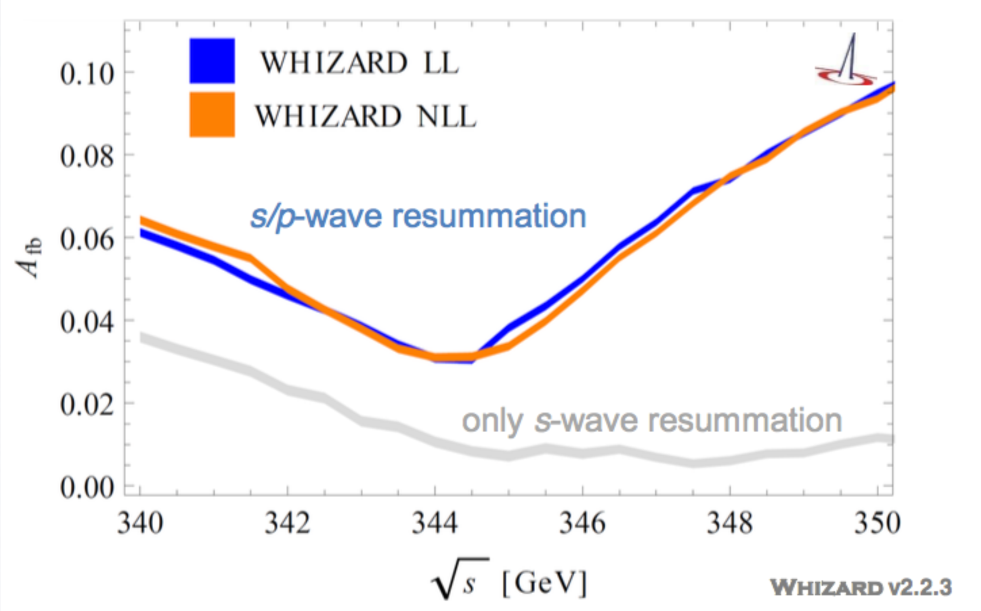

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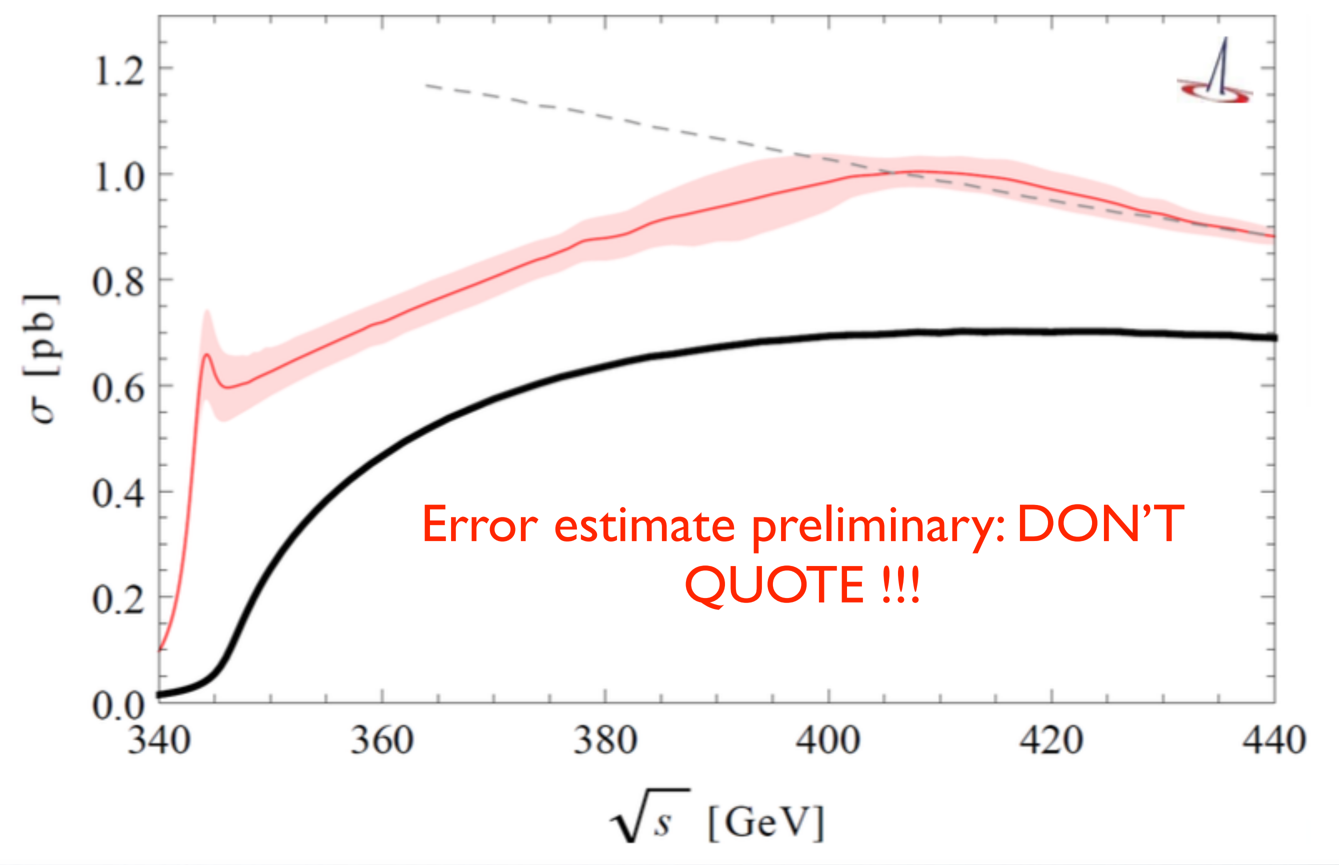
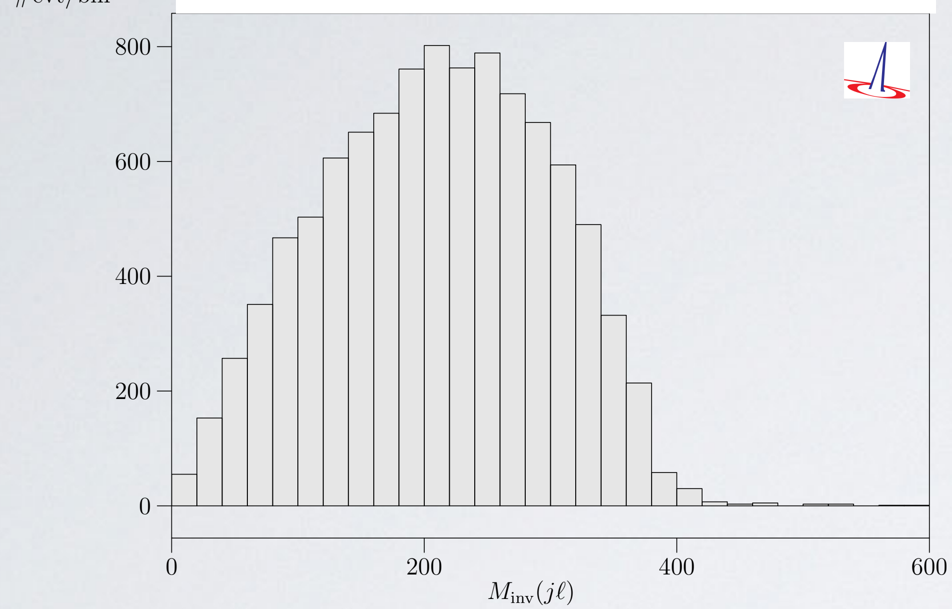


Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay

`simulate (fullproc)`



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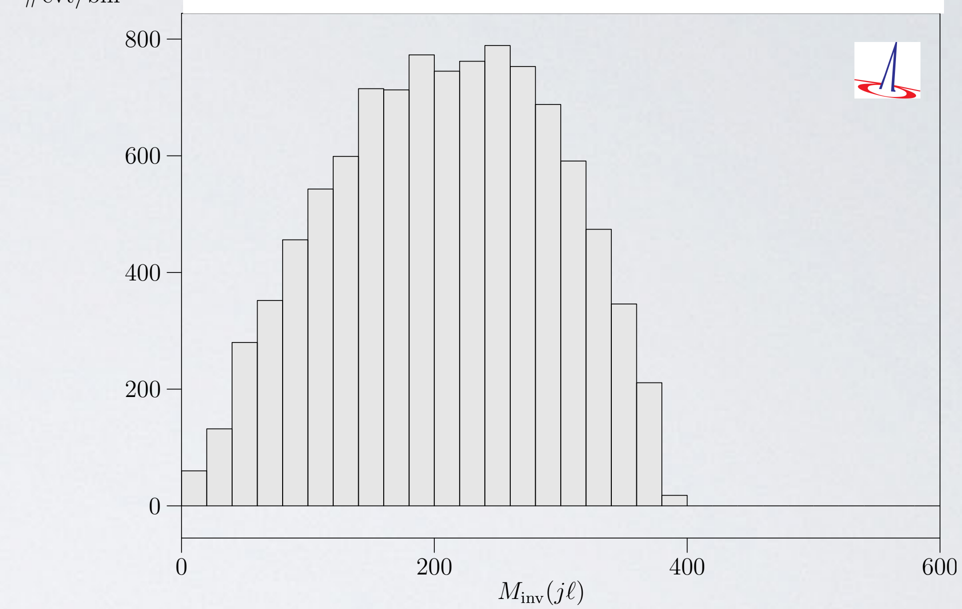
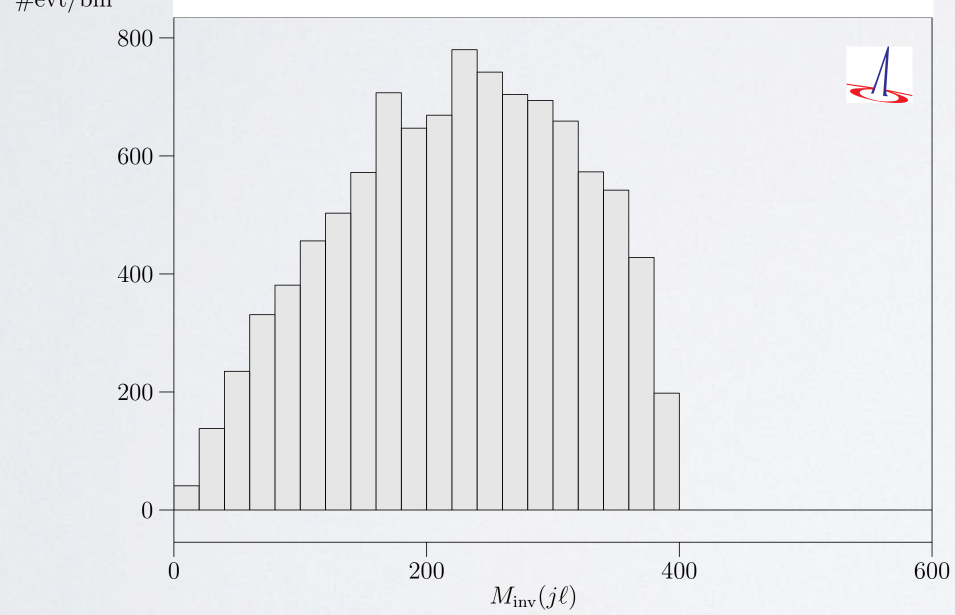


`?diagonal_decay = true`



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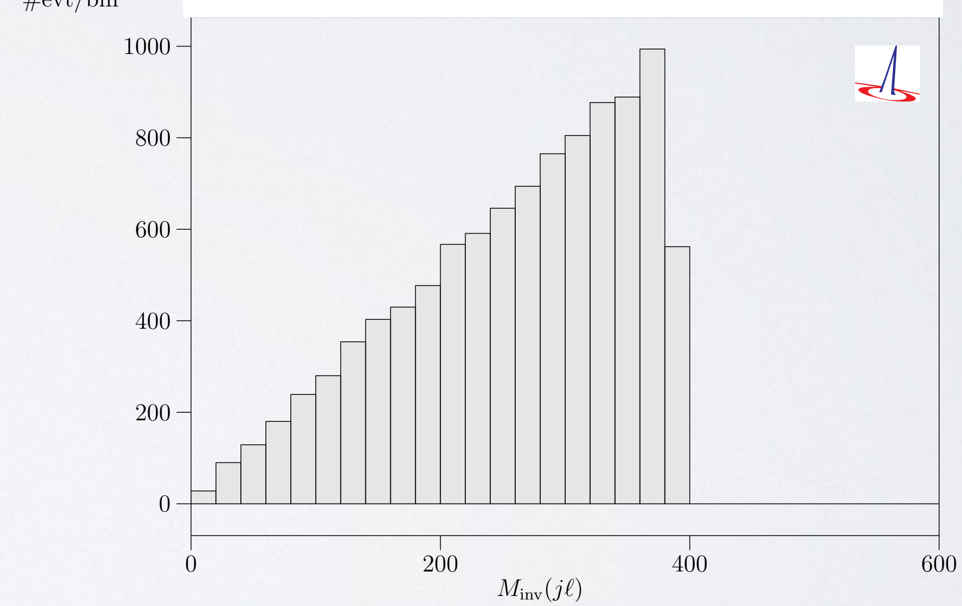

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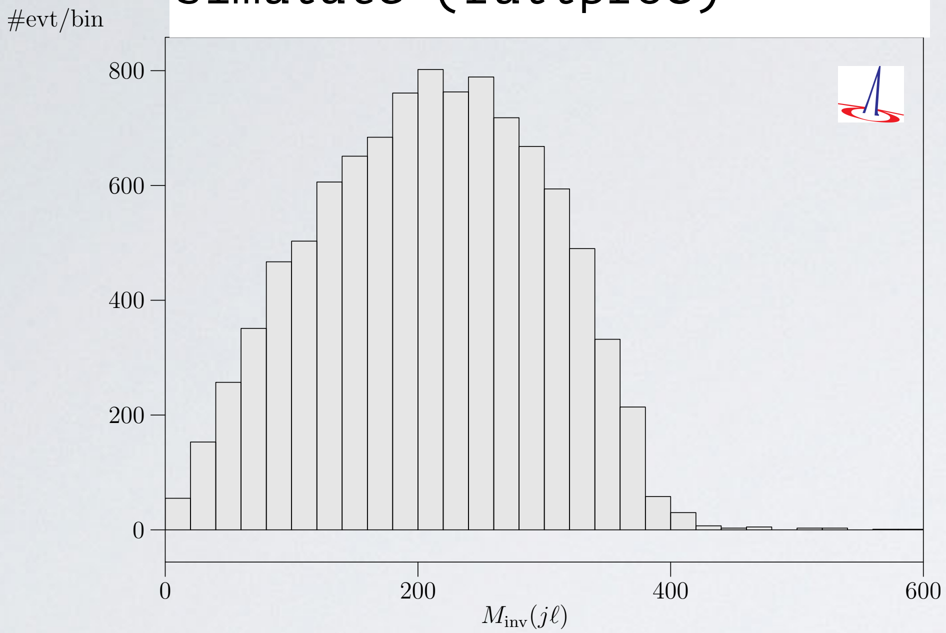

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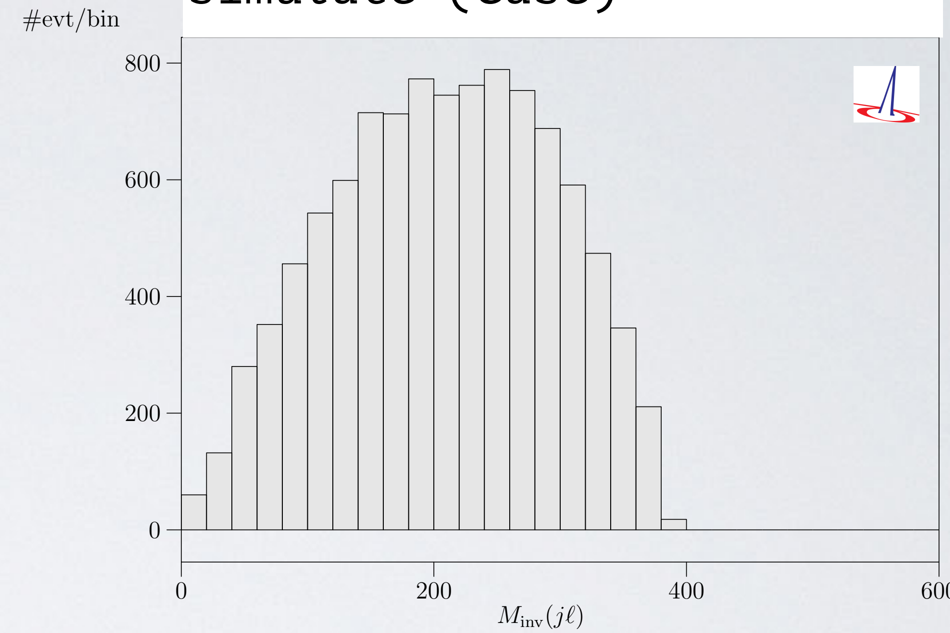

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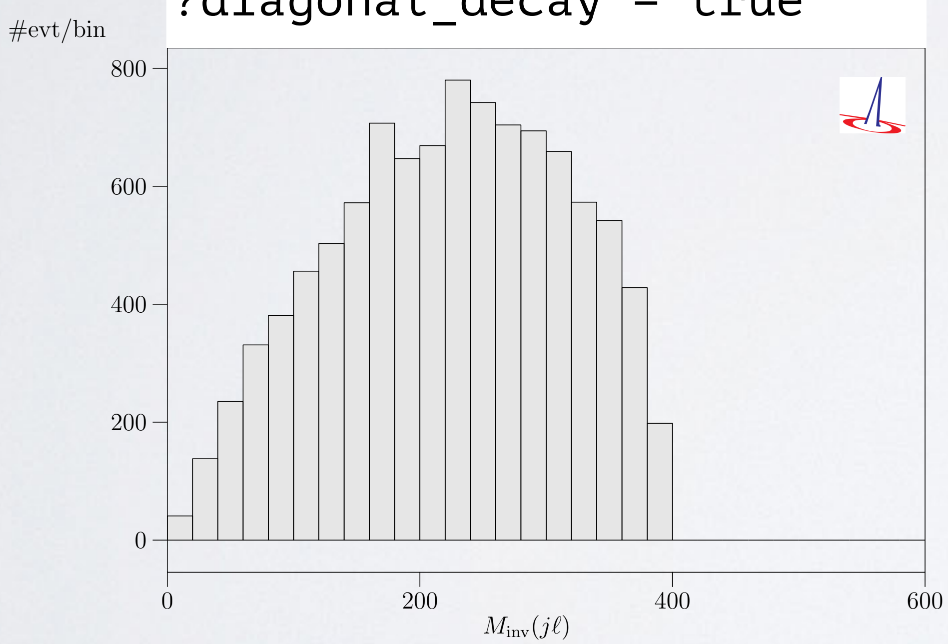

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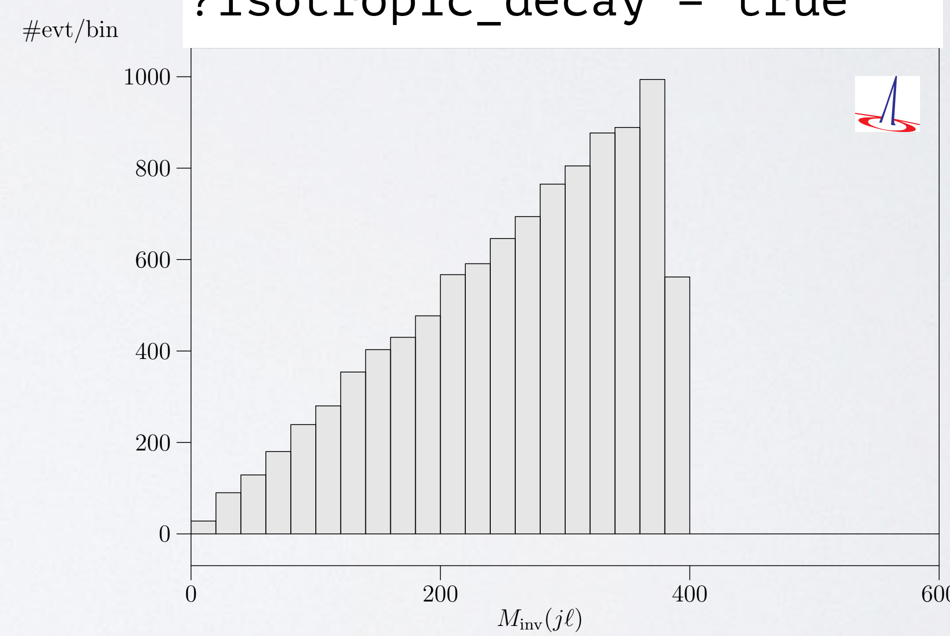

NEW: possibility to select specific helicity in decays!

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

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
- Modified algorithm for multi-leg (tree) matrix elements: includes high-color flow amplitudes, QCD/EW coupling orders, general Lorentz structures
- Automatic generation of decays (and calculation of decay widths)
- New syntax for nested decay chains

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

Conclusions & Outlook

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- [`WHIZARD 2.2` excellent tool for LHC Physics]
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- Beamspectra, LCIO, LC top threshold
- Main focus in physics: NLO automation $\rightarrow$ `WHIZARD 3.0`
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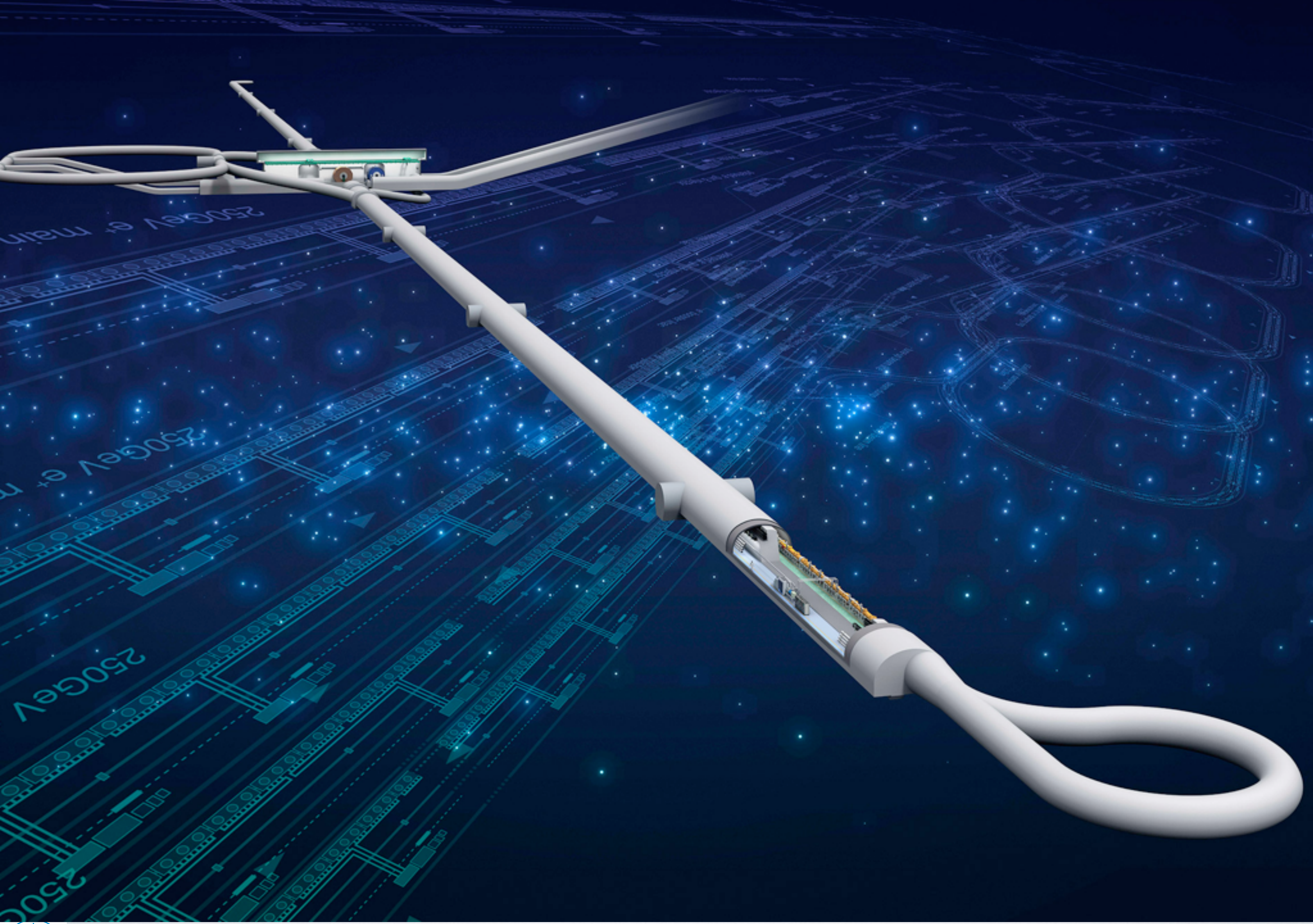
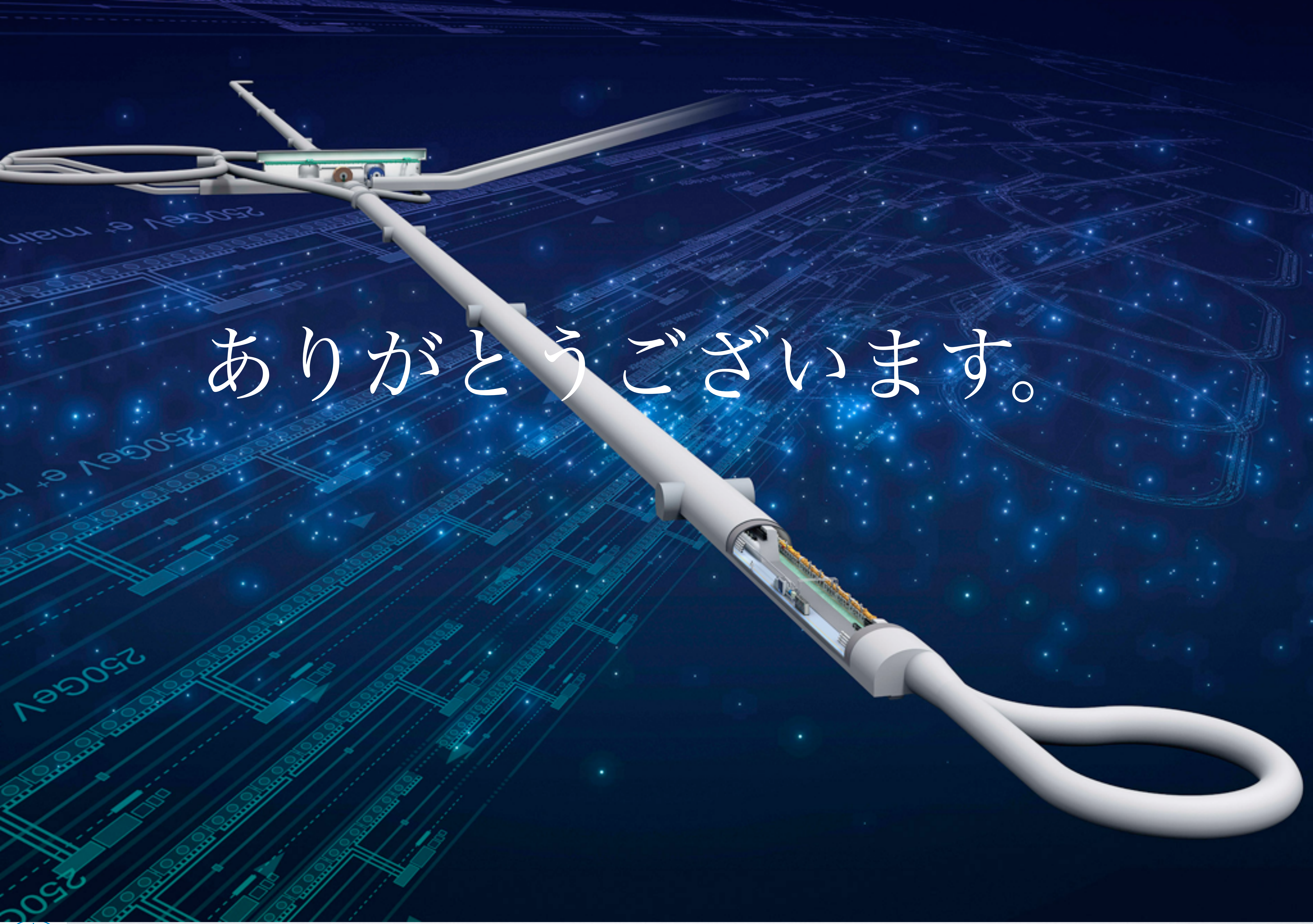
(Personal) Memory to LCWS 2013: 金閣寺




ありがとうございます。