The Event Generator WHIZARD for LC Top Physics

Jürgen R. Reuter, DESY

Outline of the talk

1) Introduction into `WHIZARD`

2) Fixed-order NLO automation & POWHEG matching in `WHIZARD`

3) Top threshold in (N)LL (p)NRQCD matched to fixed order (N)LO in `WHIZARD`

1) Introduction to WHIZARD

WHIZARD: Some (technical) facts

WHIZARD v2.2.6 (02.05.2015) http://whizard.hepforge.org

<whizard@desy.de>

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

Bijan Chokoufé/Marco Sekulla/Christian Weiss/Florian Staub + *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

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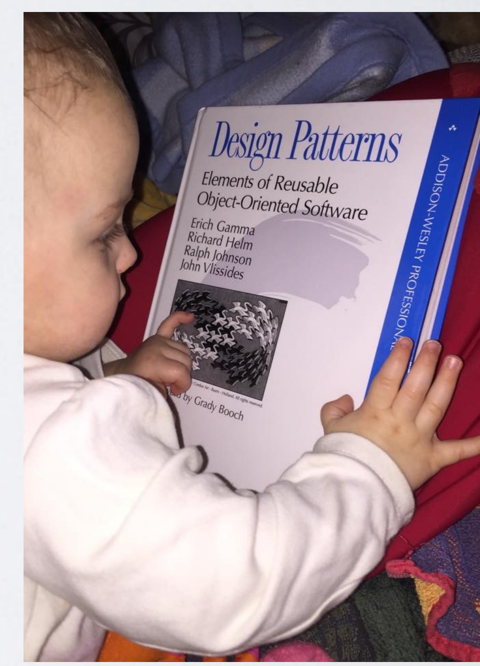

support junior developers

WHIZARD: Introduction

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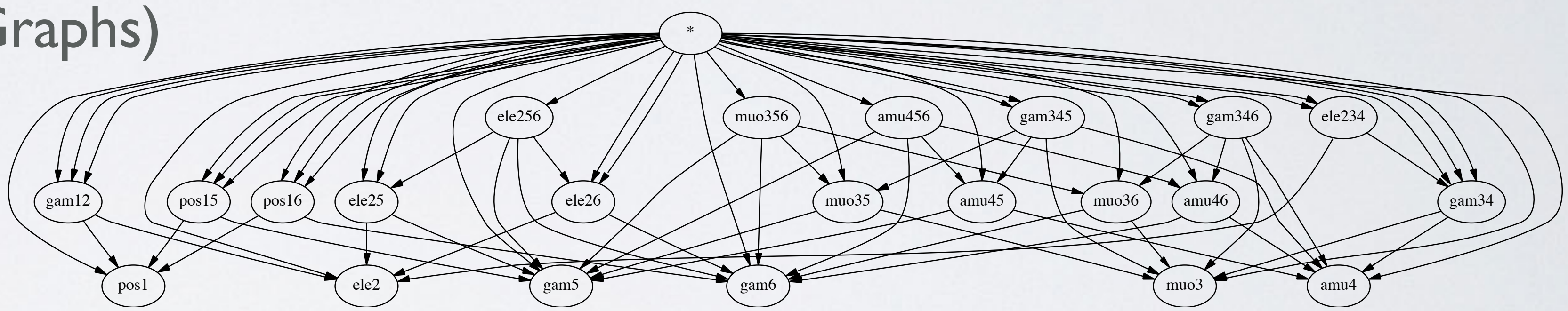
EPJ C71 (2011) 1742

- 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)

Ω



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

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 study group(s) for CEPC simulations [≈ 2013-2015]
- 04/2015, ALCW'15 Tokyo: ILC generator group endorsed v2.2 for new mass productions
- Ongoing validation for LC [ee] physics between v1.95 and v2 [until ca. 08/2015]

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

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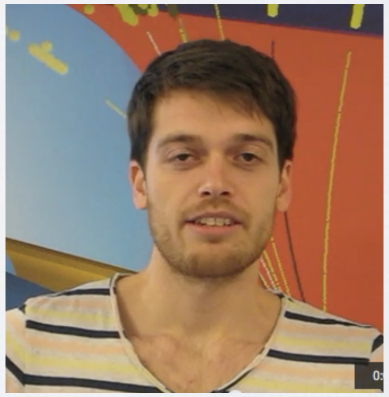
Mikael Berggren

Jean-Jacques Blaising



Moritz Habermehl

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)
```

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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sample_format = lcio

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] - []

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

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

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

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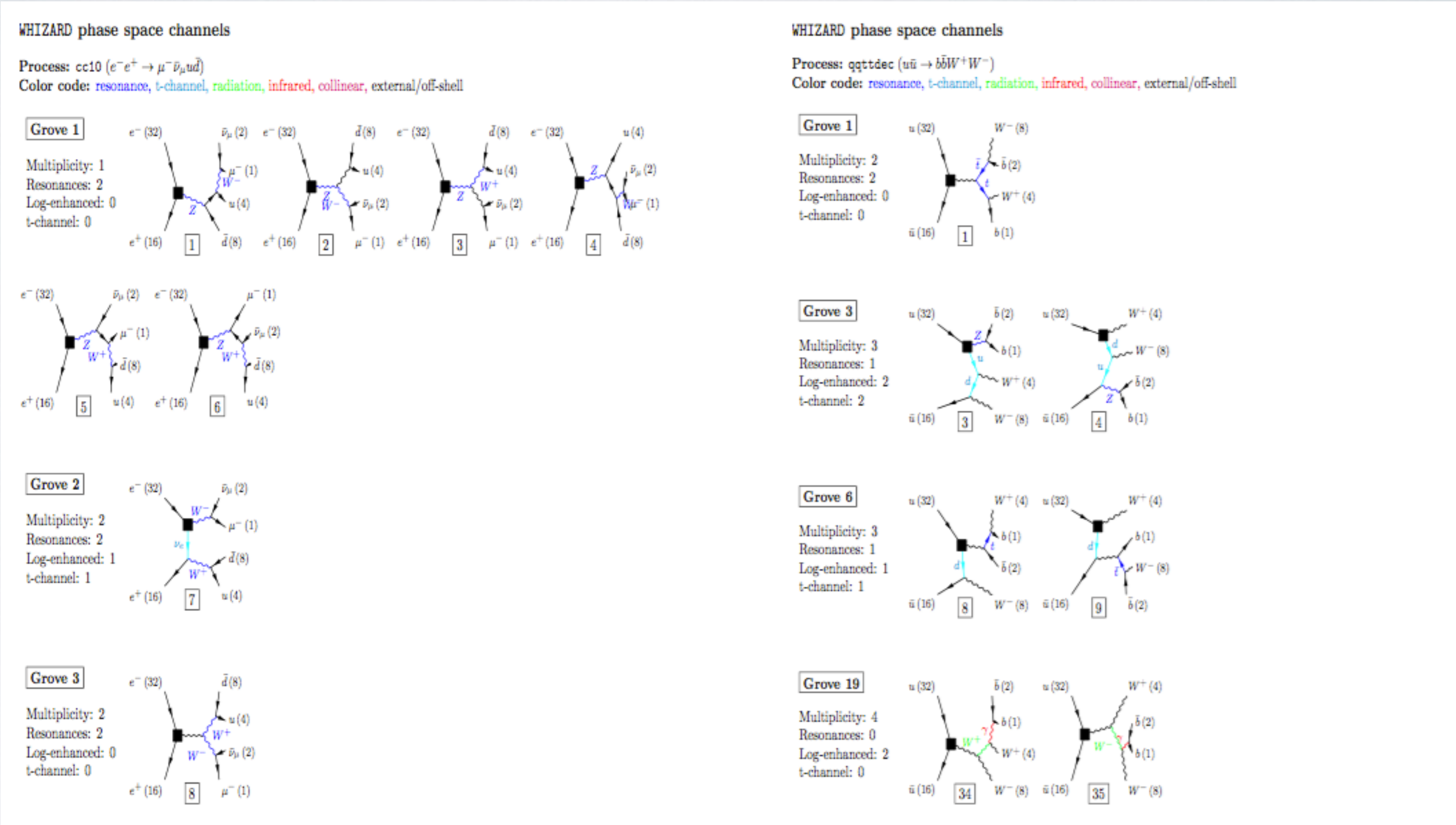
- Automated models: interface to `FeynRules` Christensen/Duhr; Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251
- Automated models: UFO interface [in connection with new `WHIZARD/O'Mega` model format]

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

Decay processes / auto_decays

`WHIZARD` cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

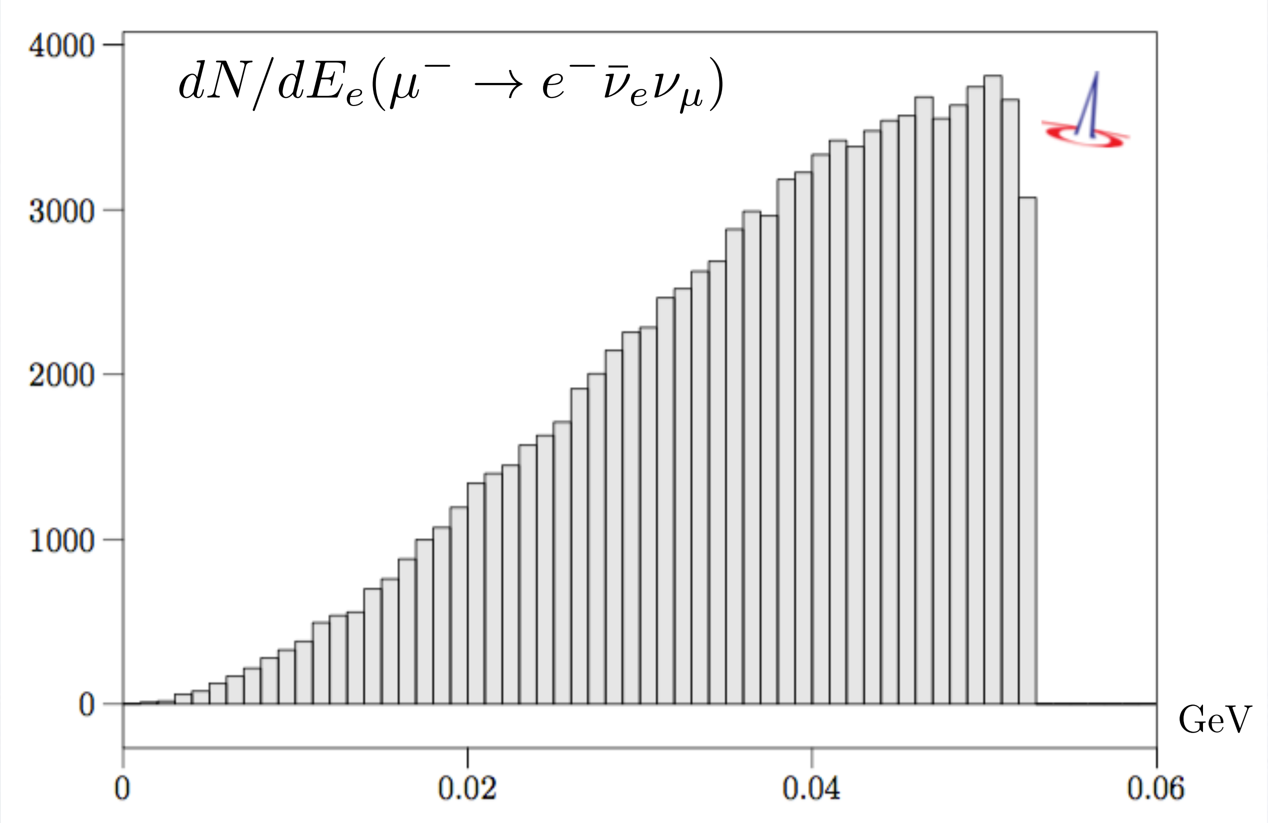
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

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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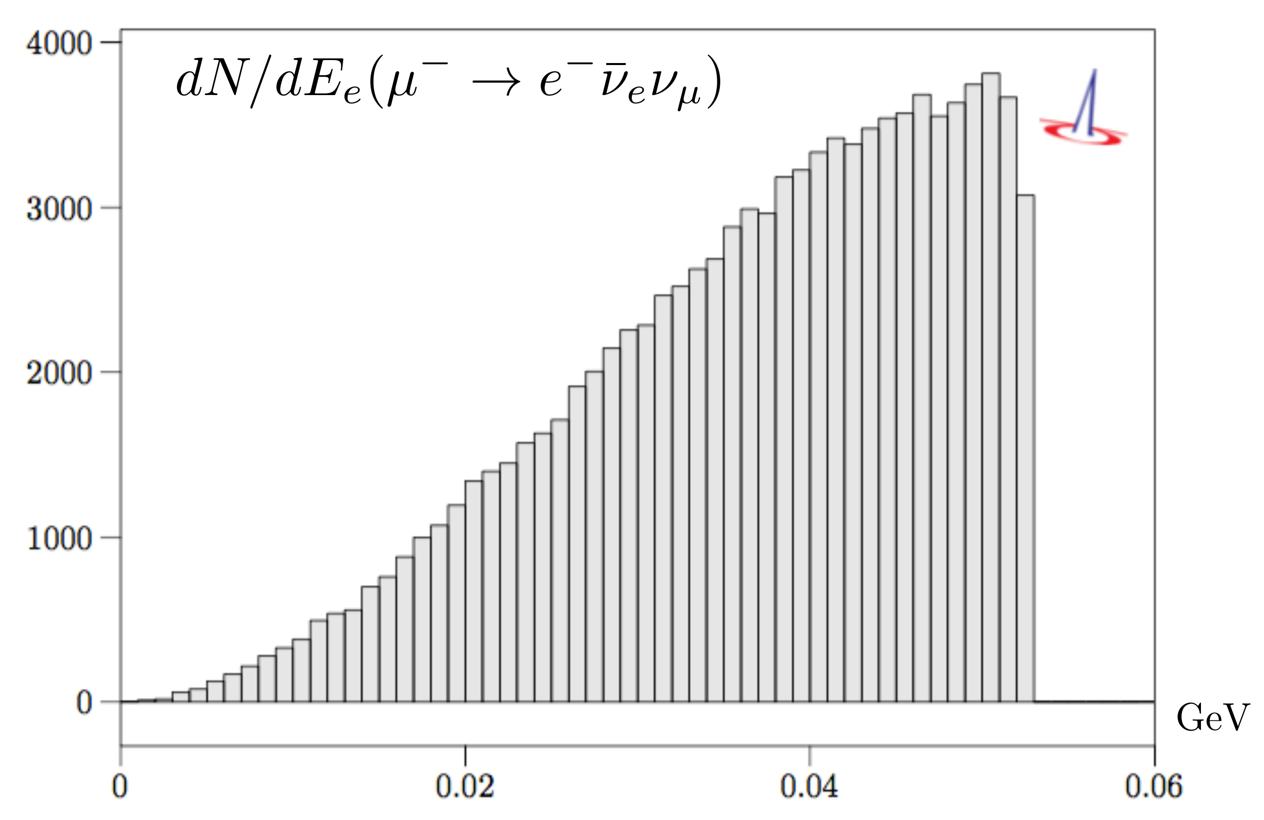


Automatic integration of particle decays

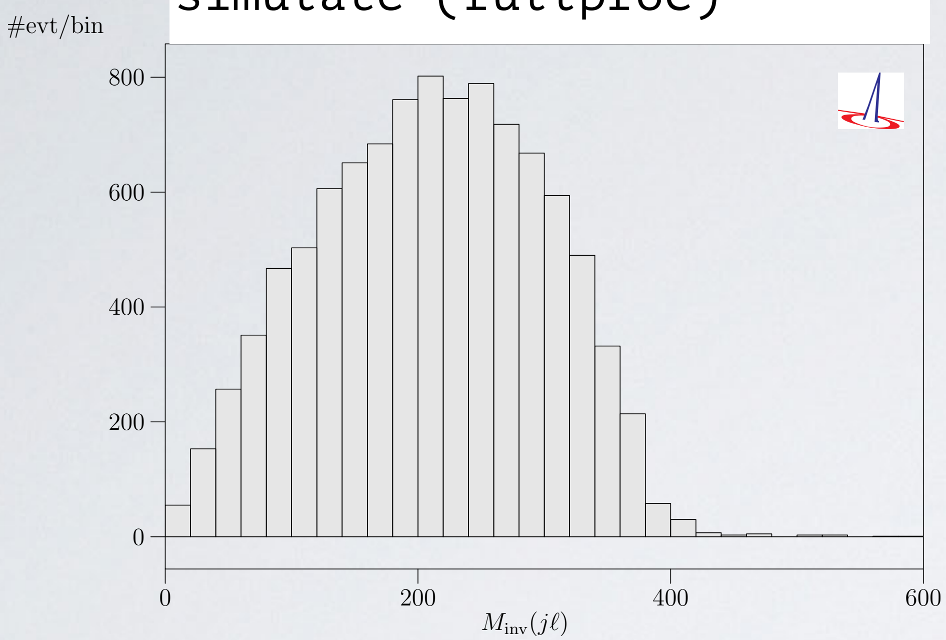
```
auto_decays_multiplicity = 2
?auto_decays_radiative = false

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
```

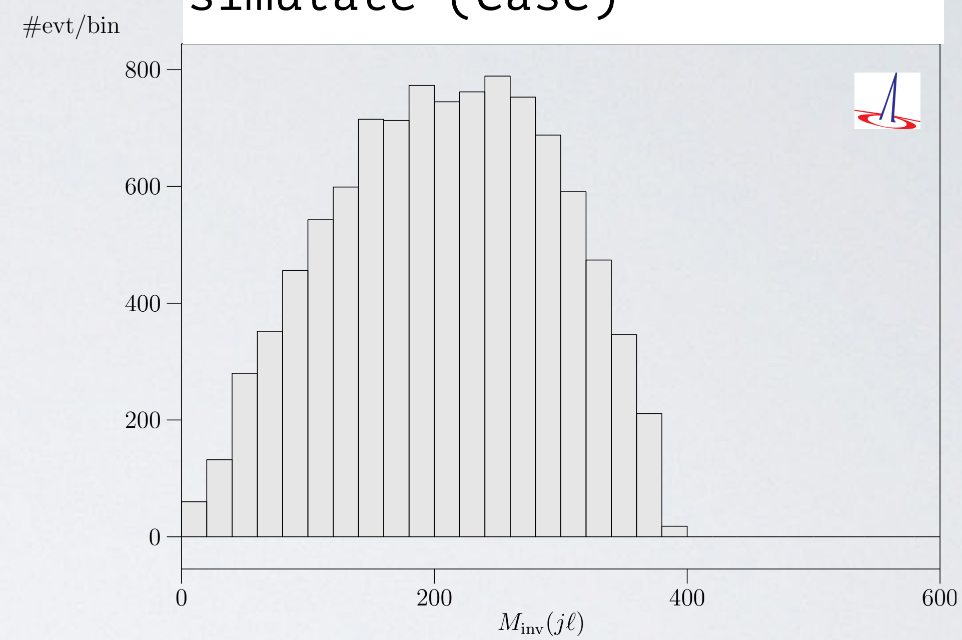
Spin Correlation and Polarization in Cascades

Cascade decay, factorize production and decay

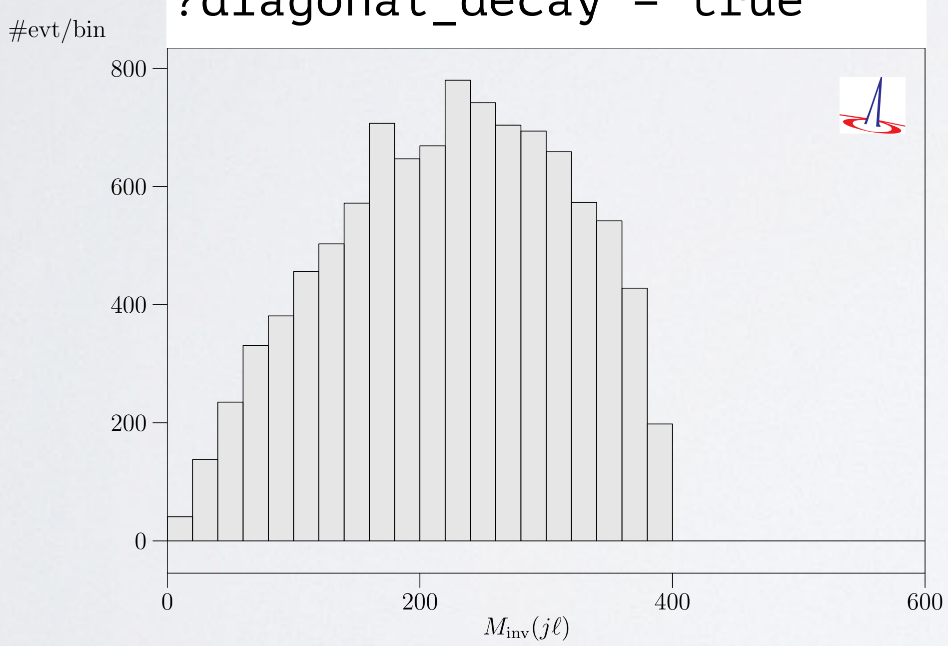
`simulate (fullproc)`



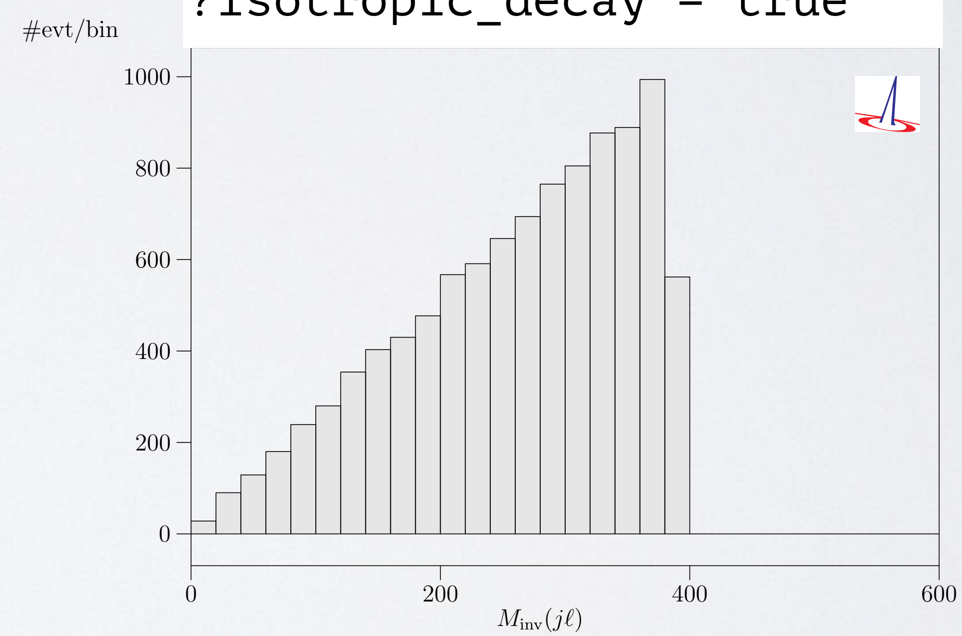
`simulate (casc)`



`?diagonal_decay = true`



`?isotropic_decay = true`



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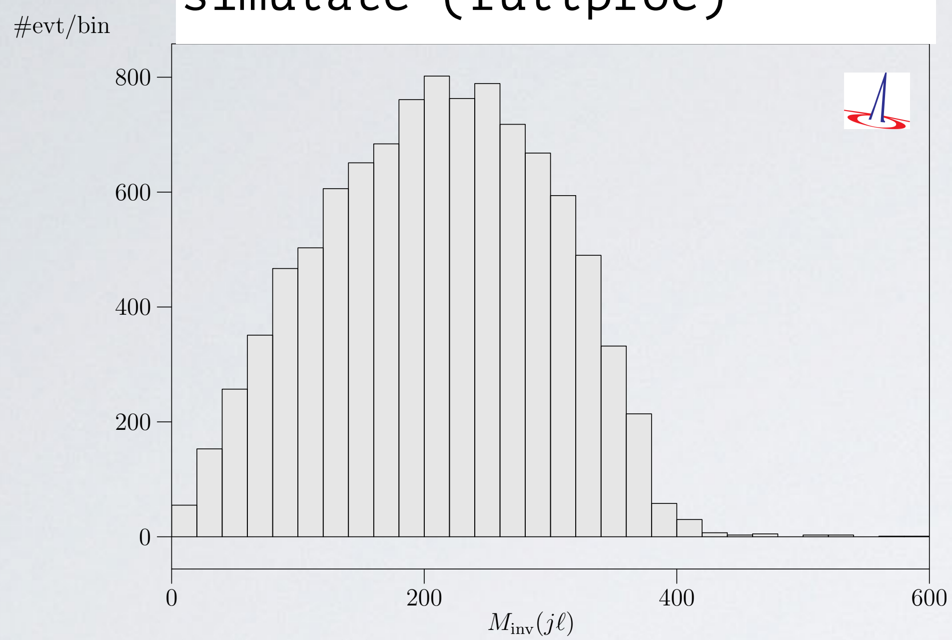

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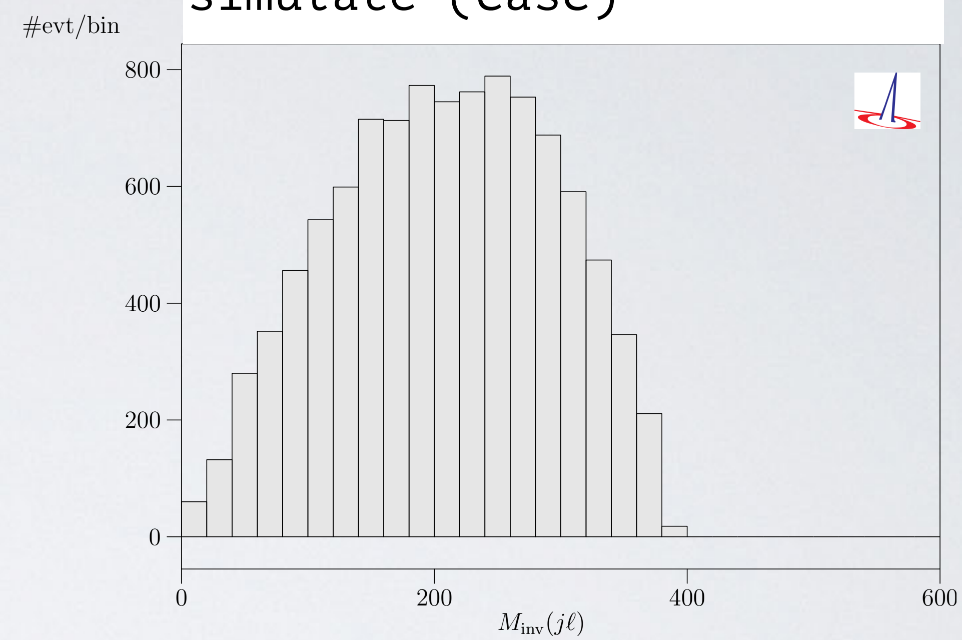

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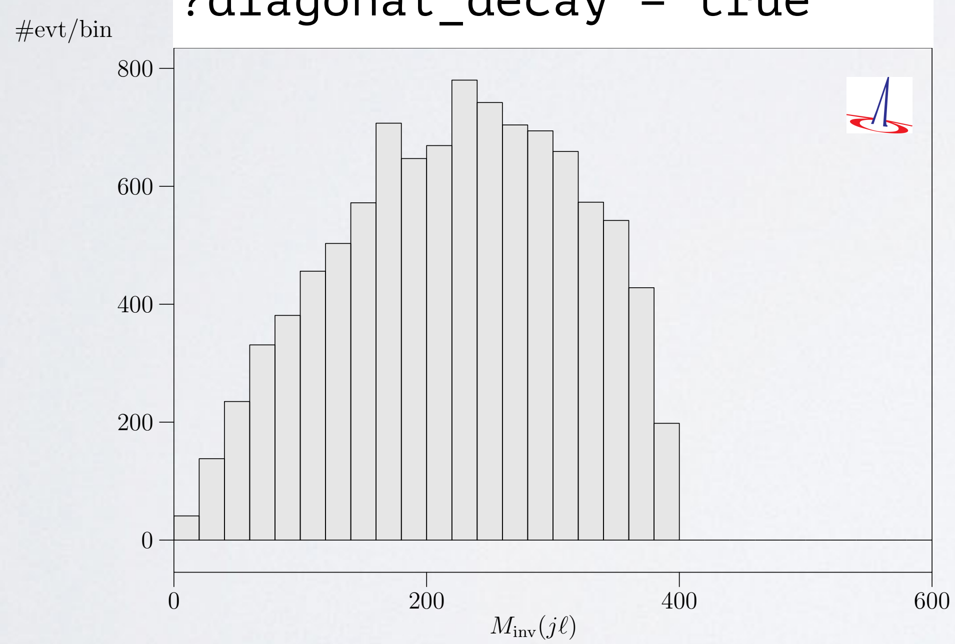

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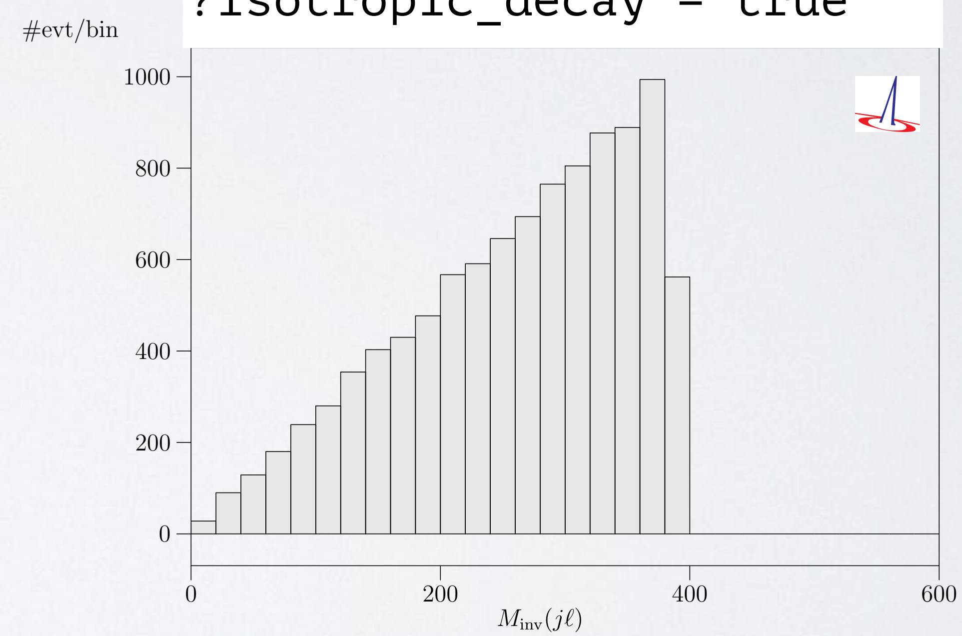
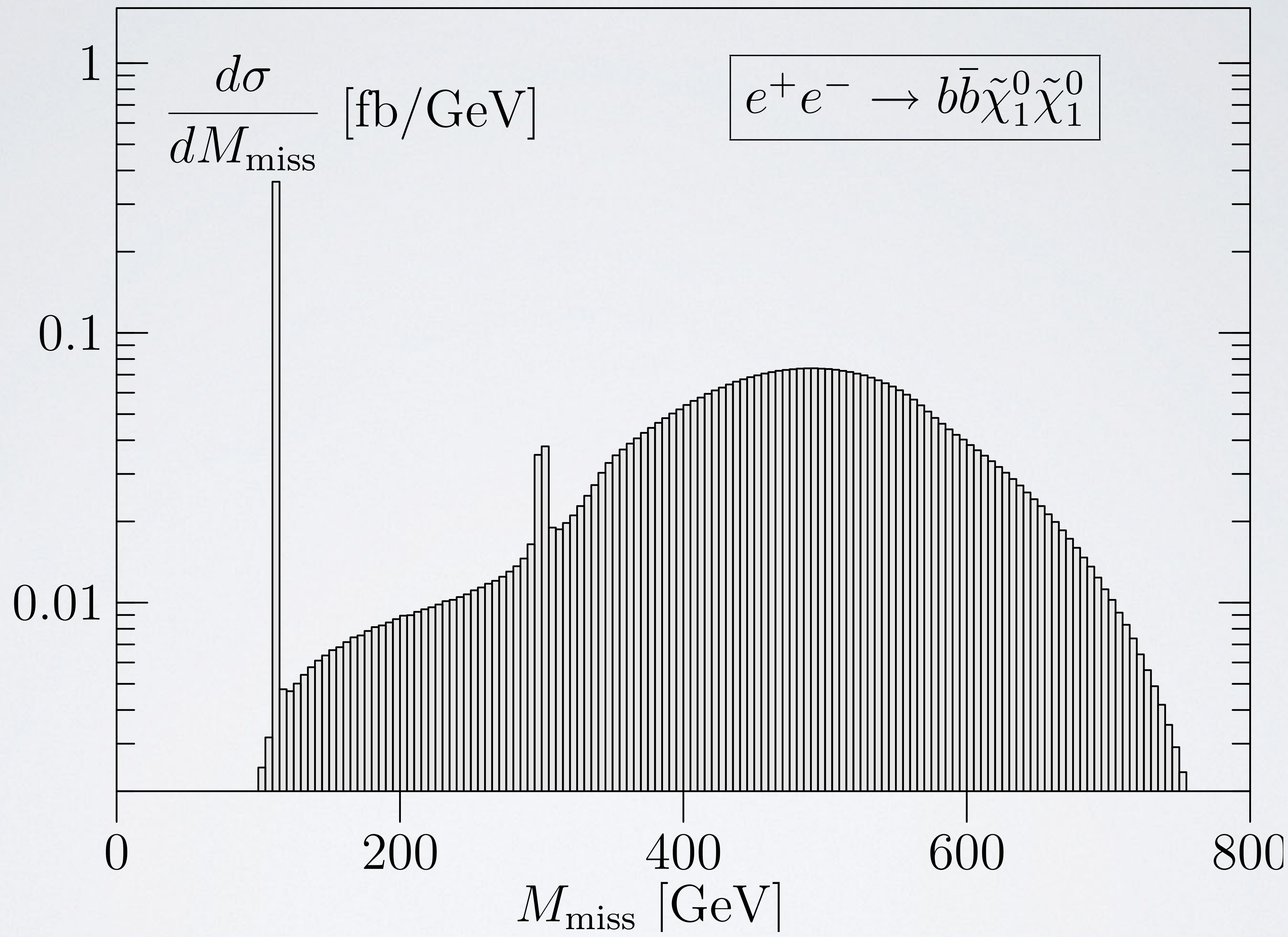


NEW: possibility to select specific helicity in decays!

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

Why care about beamstrahlung / ISR ?



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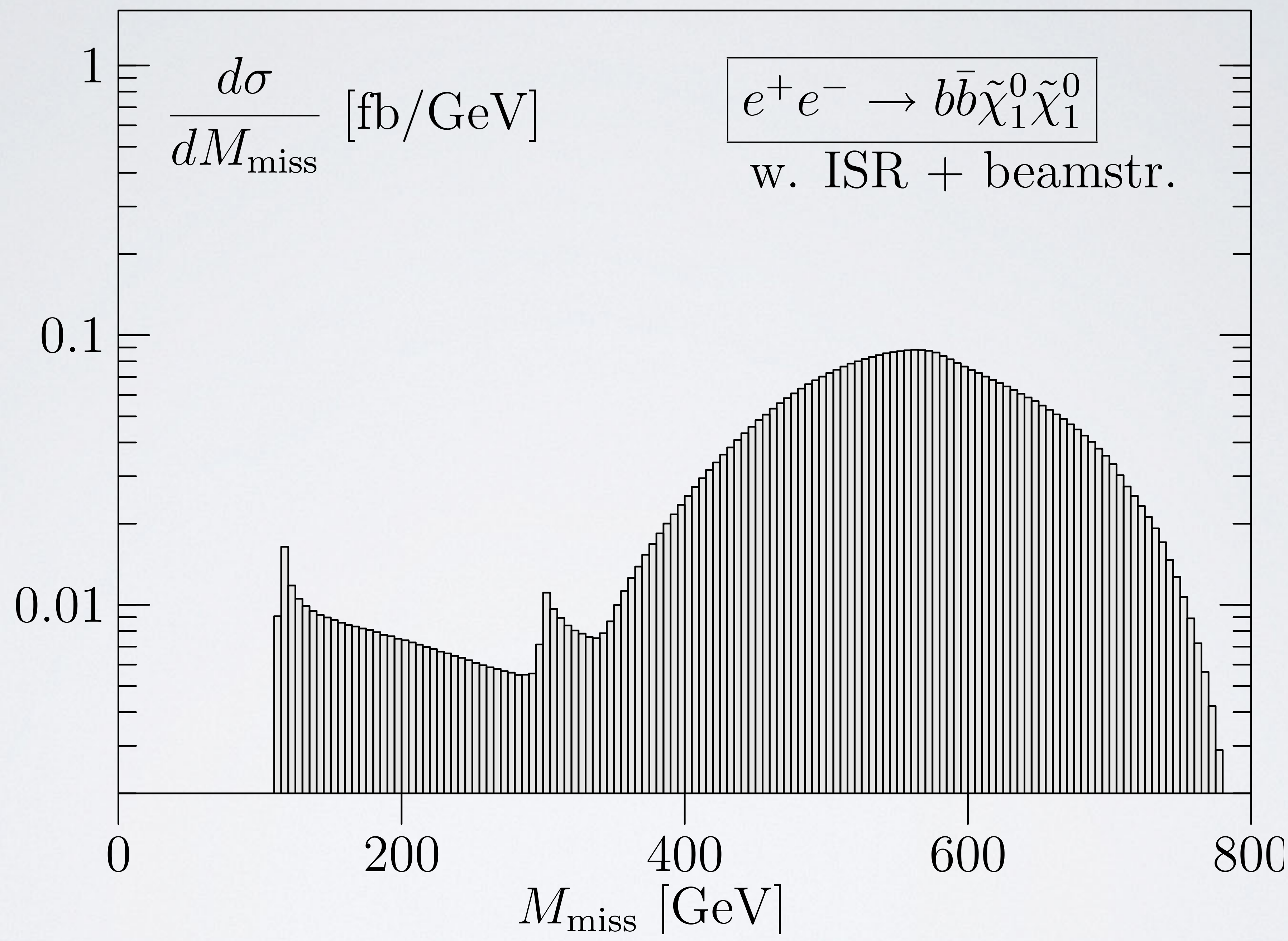
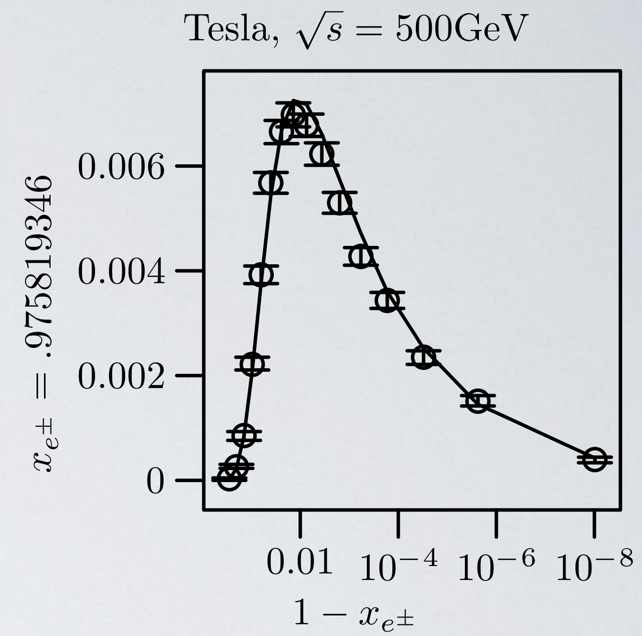


Lepton Collider Beam Simulation

- 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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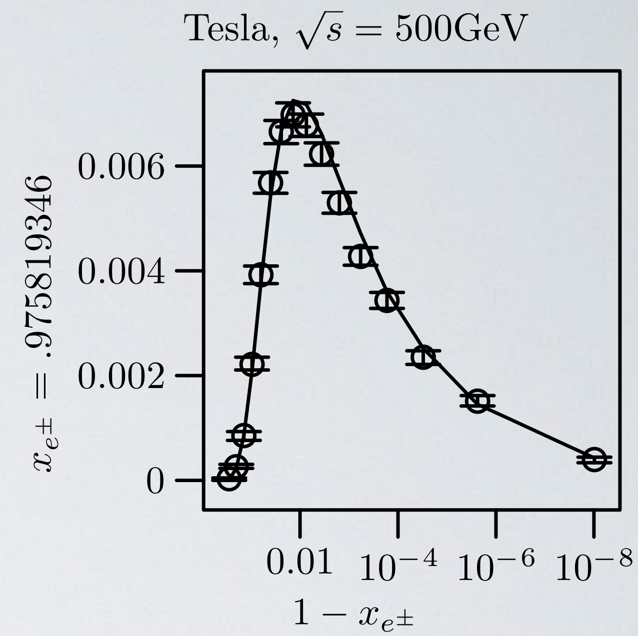

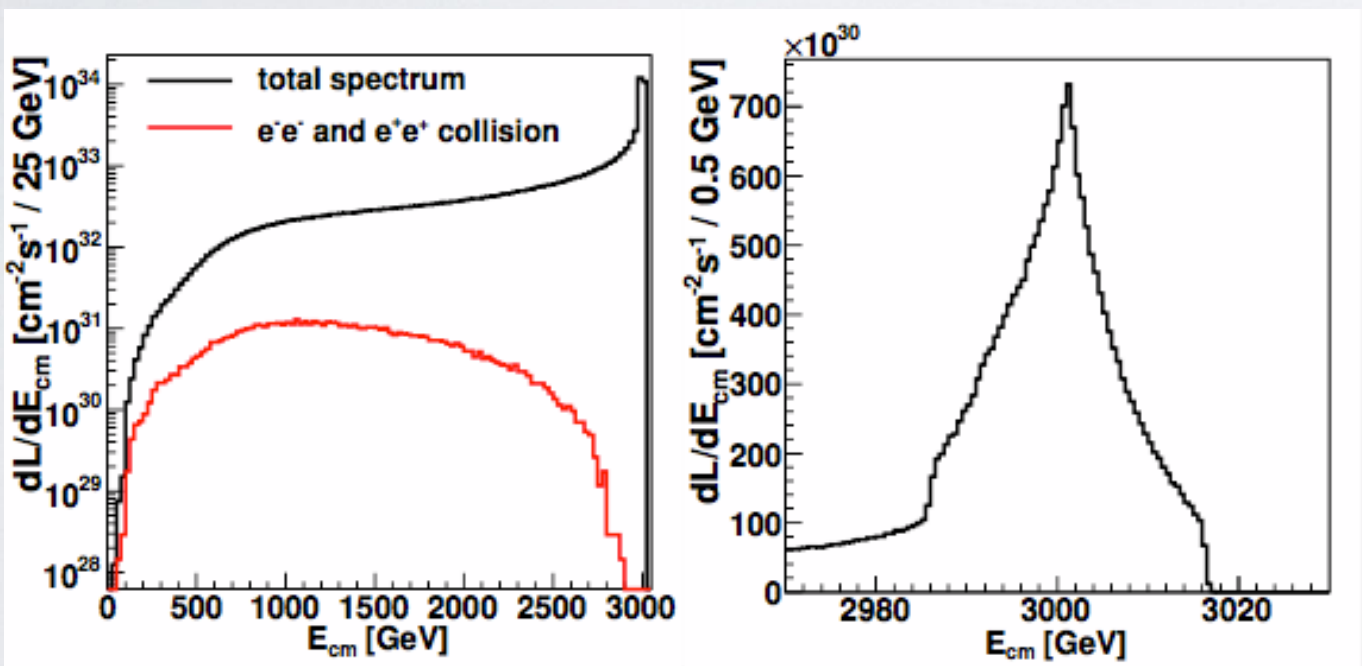

Dalena/Esbjerg/Schulte [LCWS 2011]

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: $D_{B_1B_2}(x_1, x_2) \neq D_{B_1}(x_1) \cdot D_{B_2}(x_2)$
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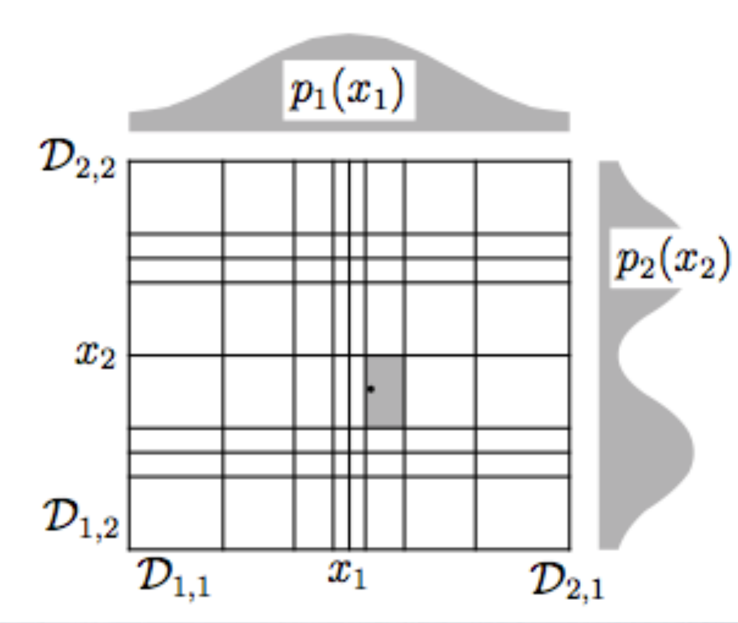

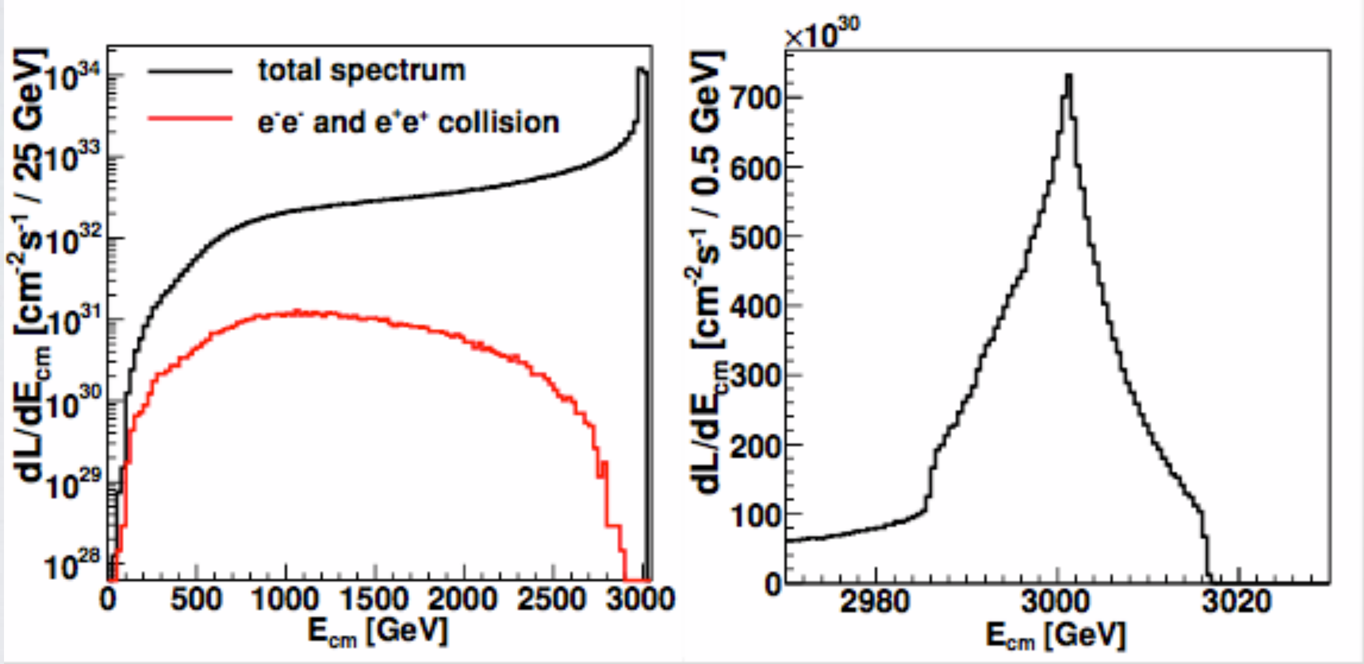

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Tails @ CLIC much more complicated (wakefields)

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

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

Workflow GuineaPig/CIRCE2/WHIZARD

1. Run Guinea-Pig++ with

```
do_lumi=7;num_lumi=100000000;num_lumi_eg=100000000;num_lumi_gg=100000000;
```

to produce lumi.[eg][eg].out with (E_1, E_2) pairs.

[Large event numbers, as Guinea-Pig++ will produce only a small fraction!]

2. Run circe2_tool.opt with steering file

```
{ file="ilc500/beams.circe"                         # to be loaded by WHIZARD
  { design="ILC" roots=500 bins=100 scale=250 # E in [0,1]
    { pid/1=electron pid/2=positron pol=0       # unpolarized e-/e+
      events="ilc500/lumi.ee.out" columns=2     # <= Guinea-Pig
      lumi = 1564.763360                        # <= Guinea-Pig
      iterations = 10                           # adapting bins
      smooth = 5 [0,1) [0,1)                    # Gaussian filter 5 bins
      smooth = 5 [1] [0,1) smooth = 5 [0,1) [1] } } }
```

to produce correlated beam description

3. Run WHIZARD with SINDARIN input:

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

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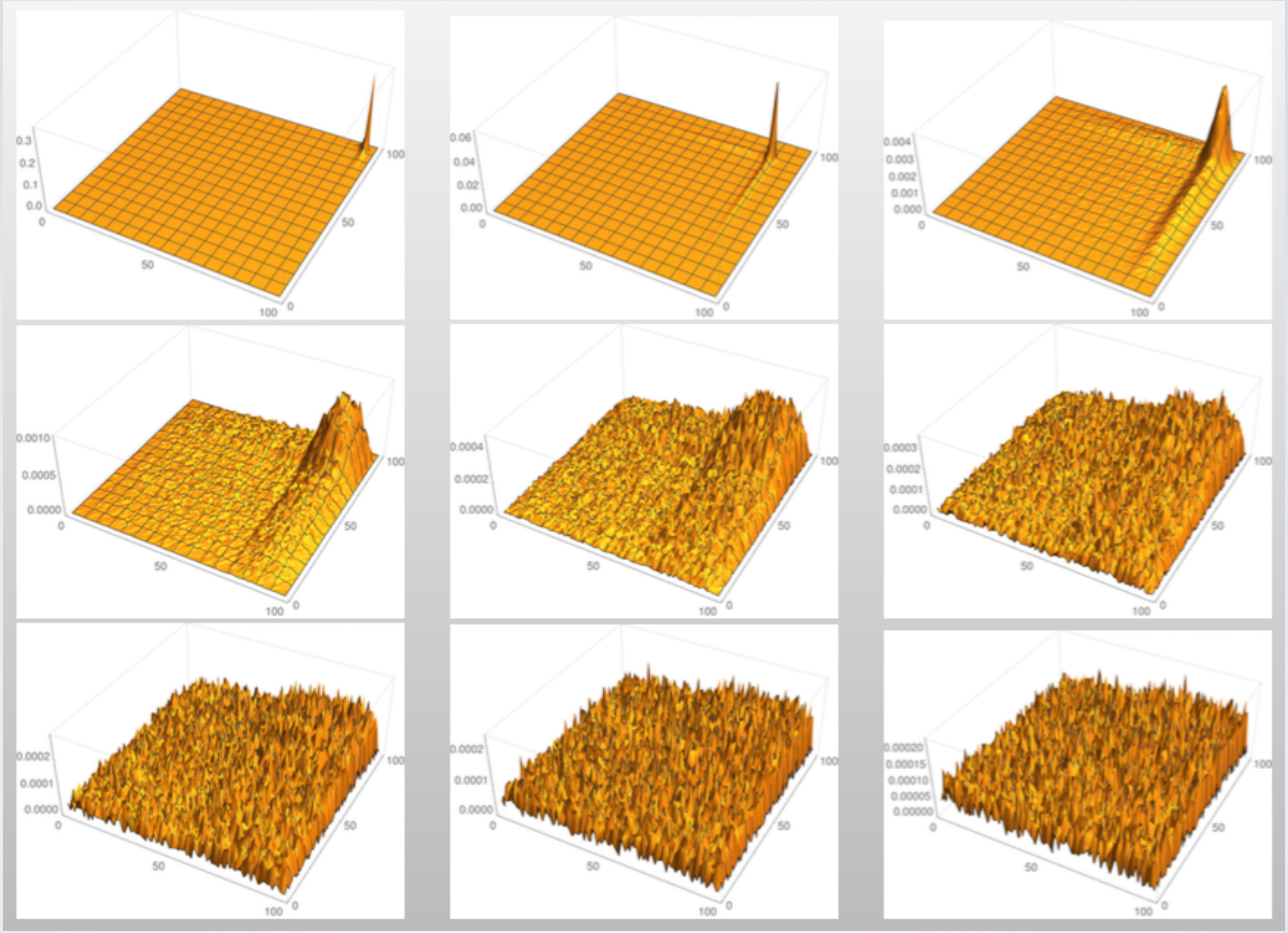
```

3 simulation options

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

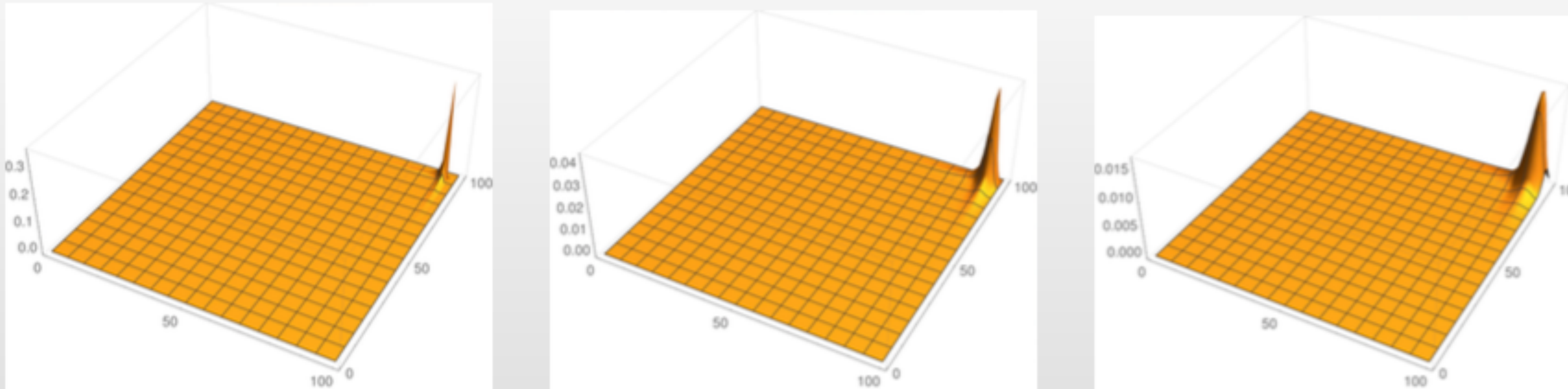
Iterations of Beam Spectrum



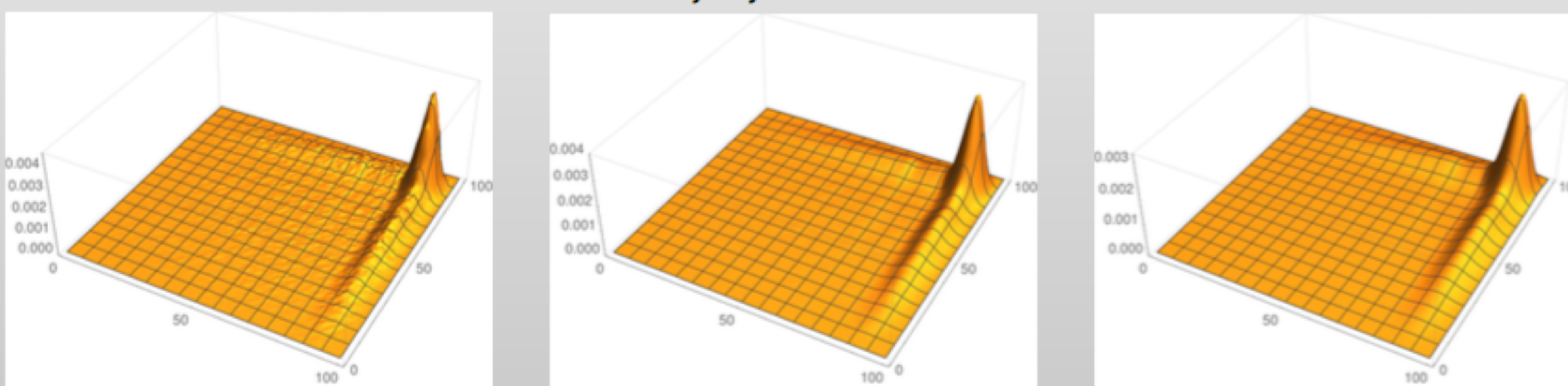
(171,306 GuineaPig events in 10,000 bins)

Iterations of Beam Spectrum

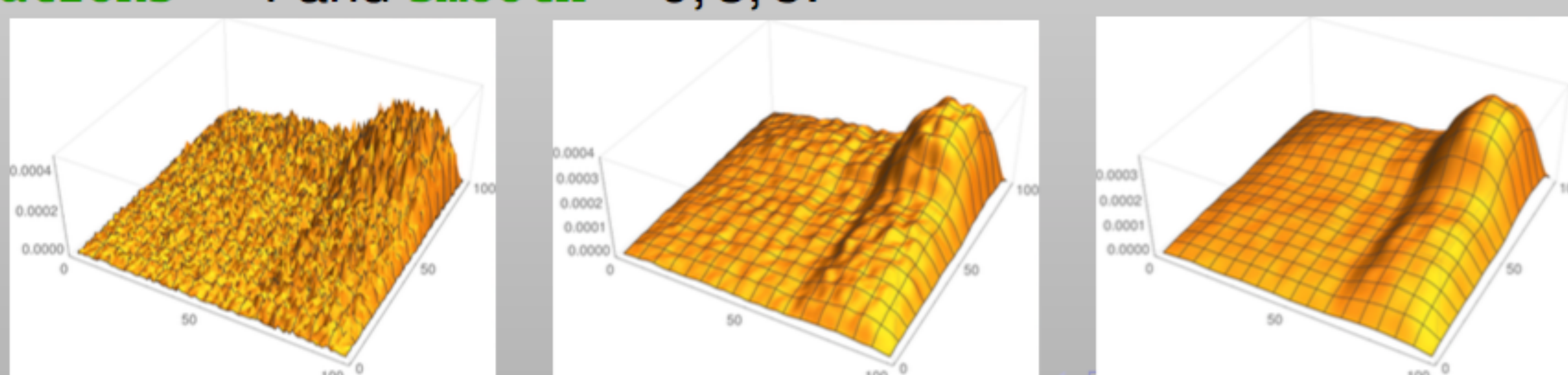
- `iterations` = 0 and `smooth` = 0, 3, 5:



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



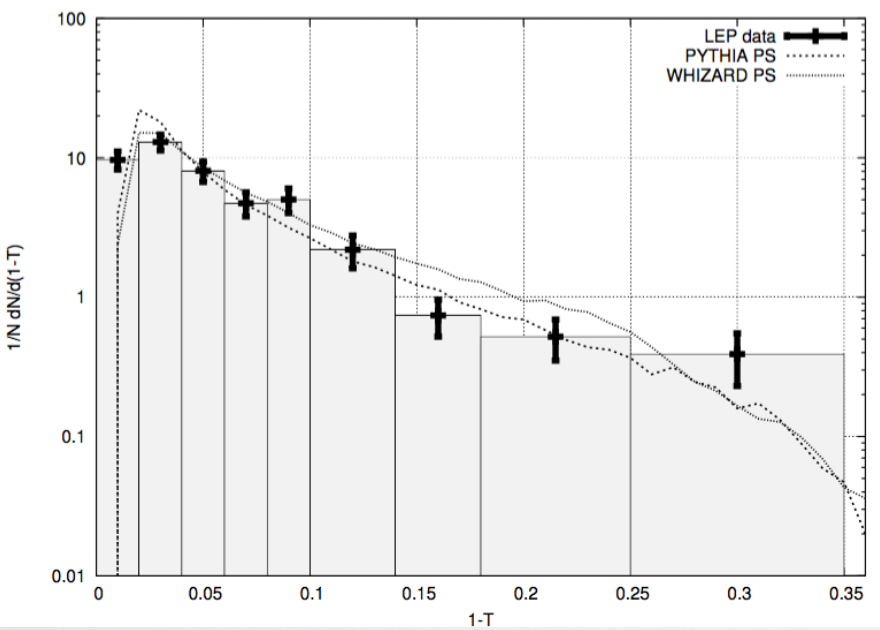
- `iterations` = 4 and `smooth` = 0, 3, 5:

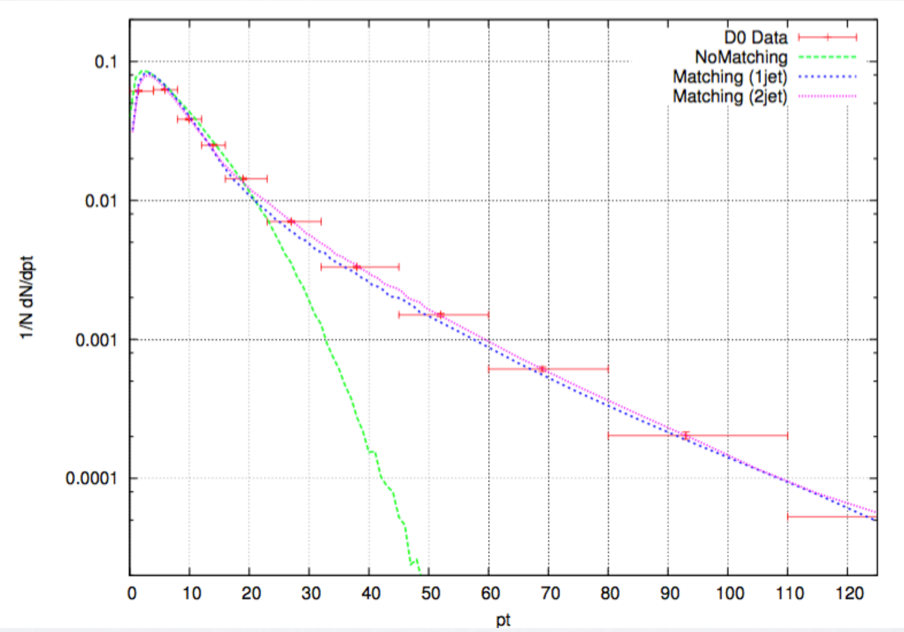


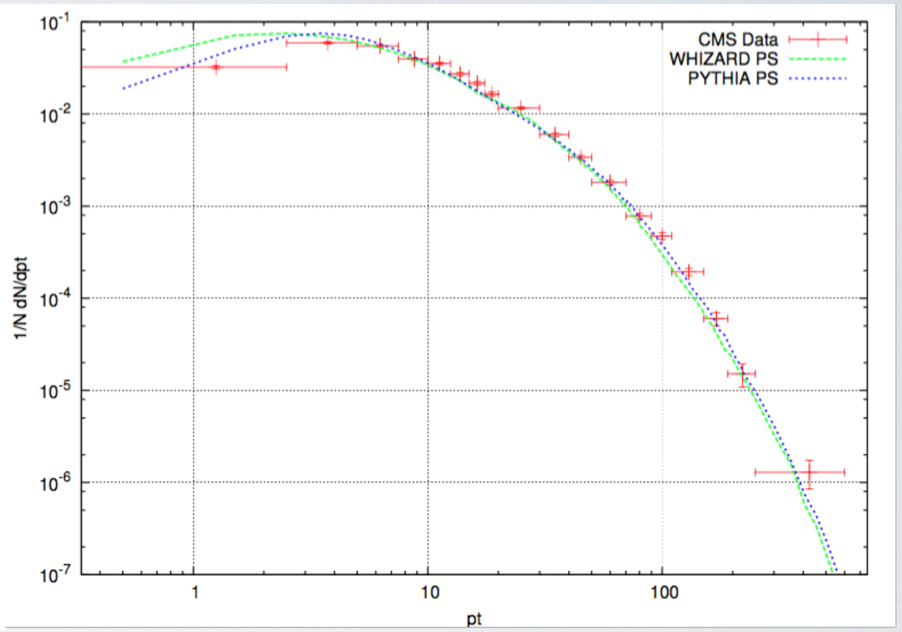
WHIZARD Parton Shower

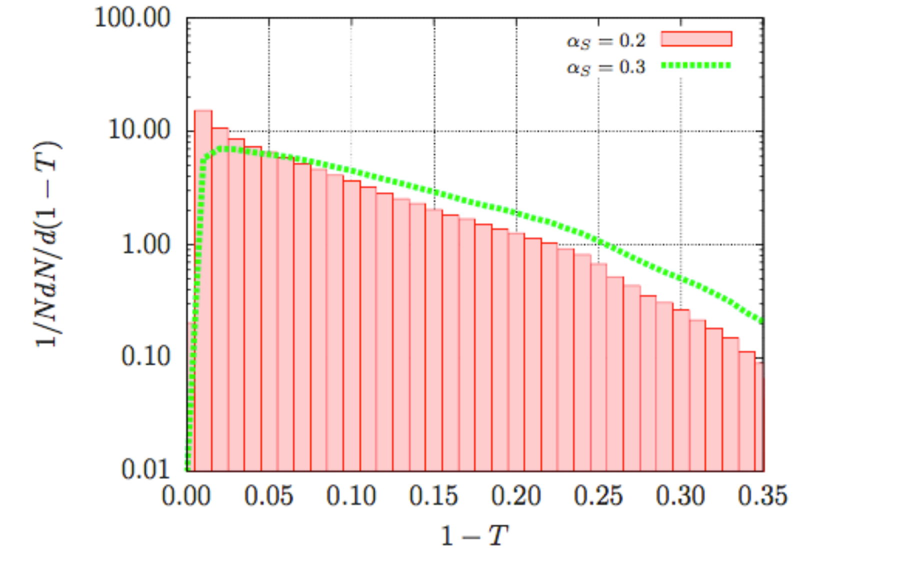
- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

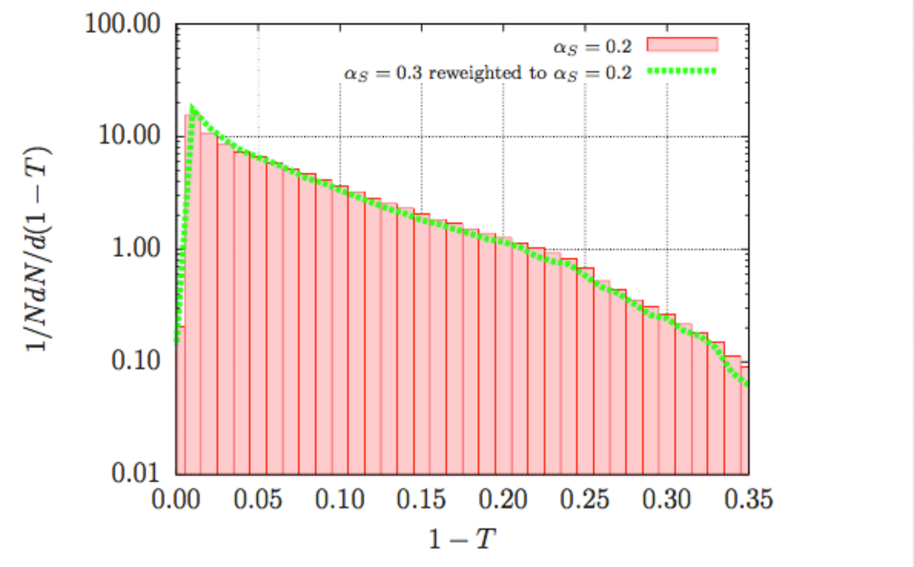
Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)











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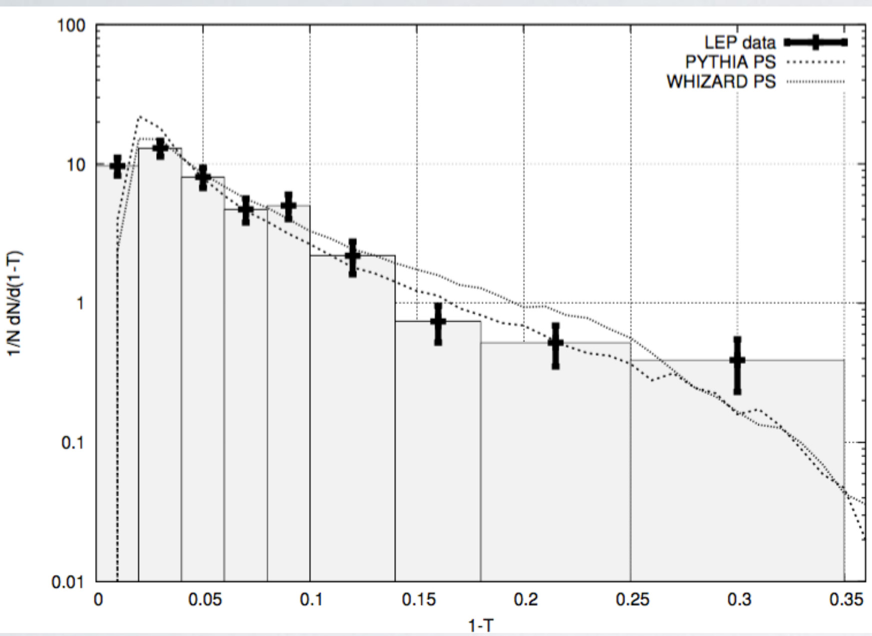

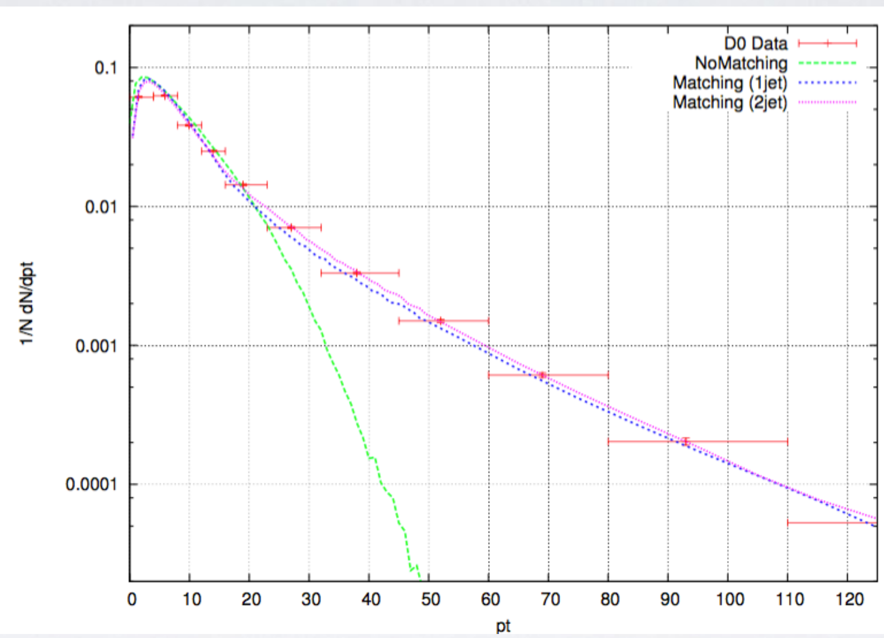

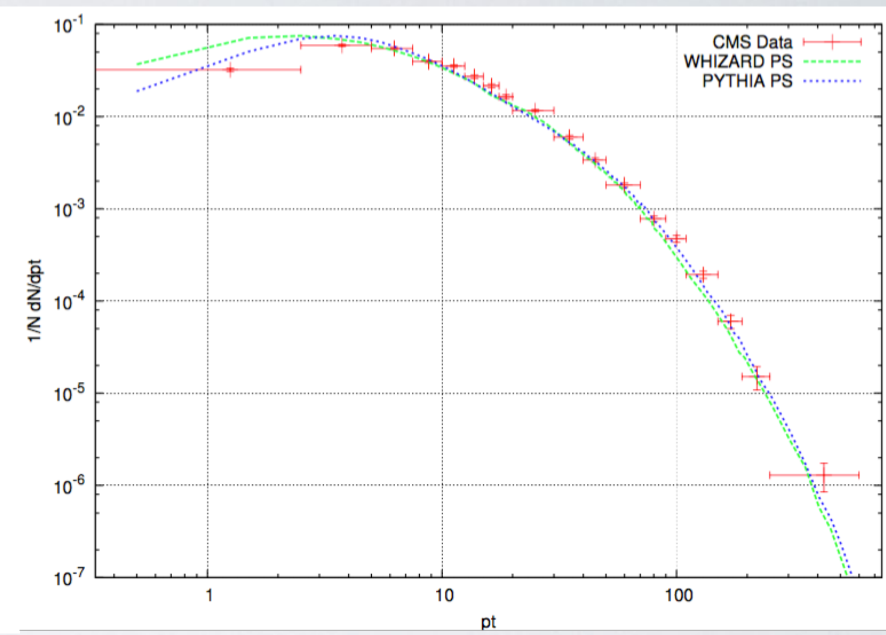

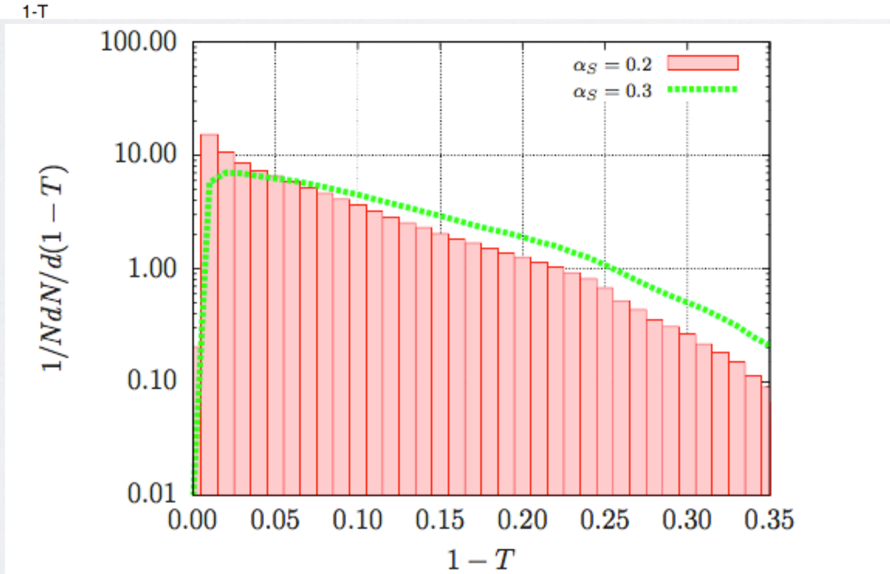

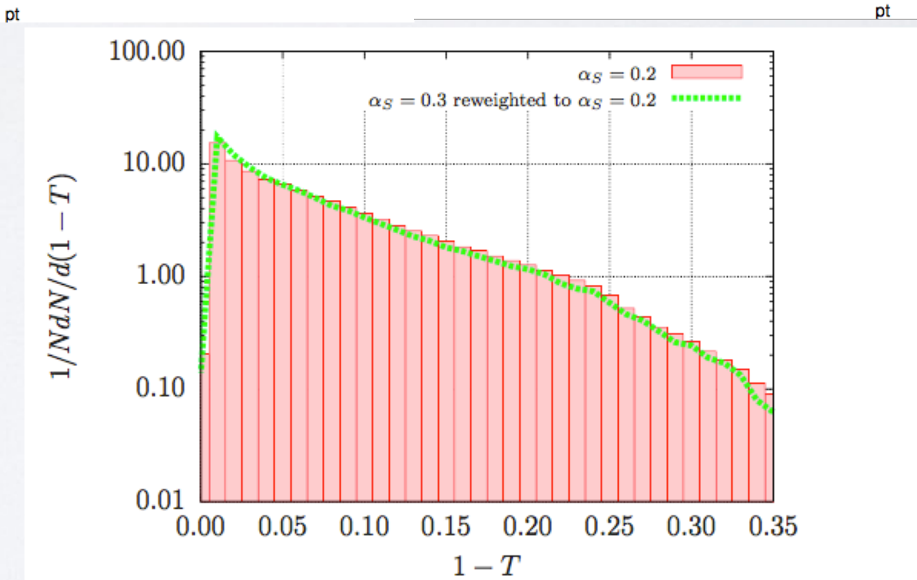

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2) Fixed-order NLO automation & POWHEG matching in WHIZARD

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

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(first focus on QCD corrections)

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QCD corrections (massless and massive emitters)

```
alpha_power = 2
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process eett = e1,E1 => t, tbar
     { nlo_calculation = “full” }
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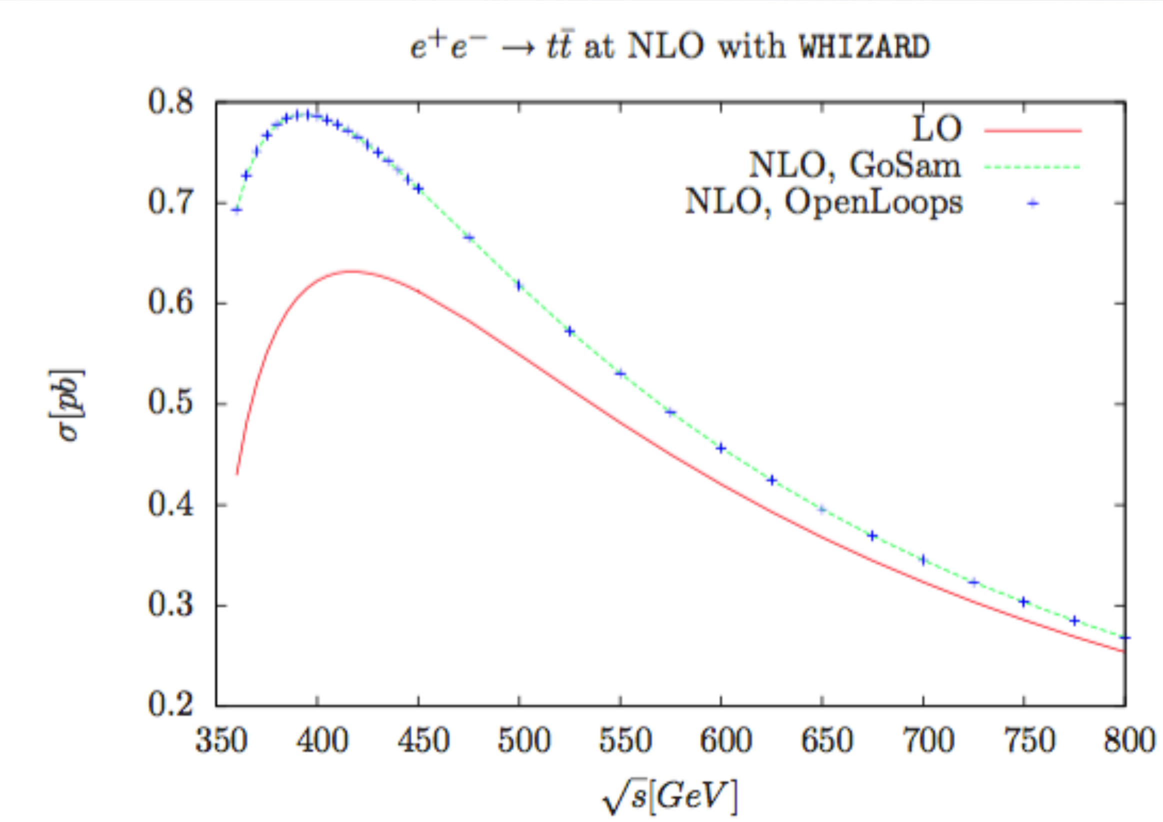

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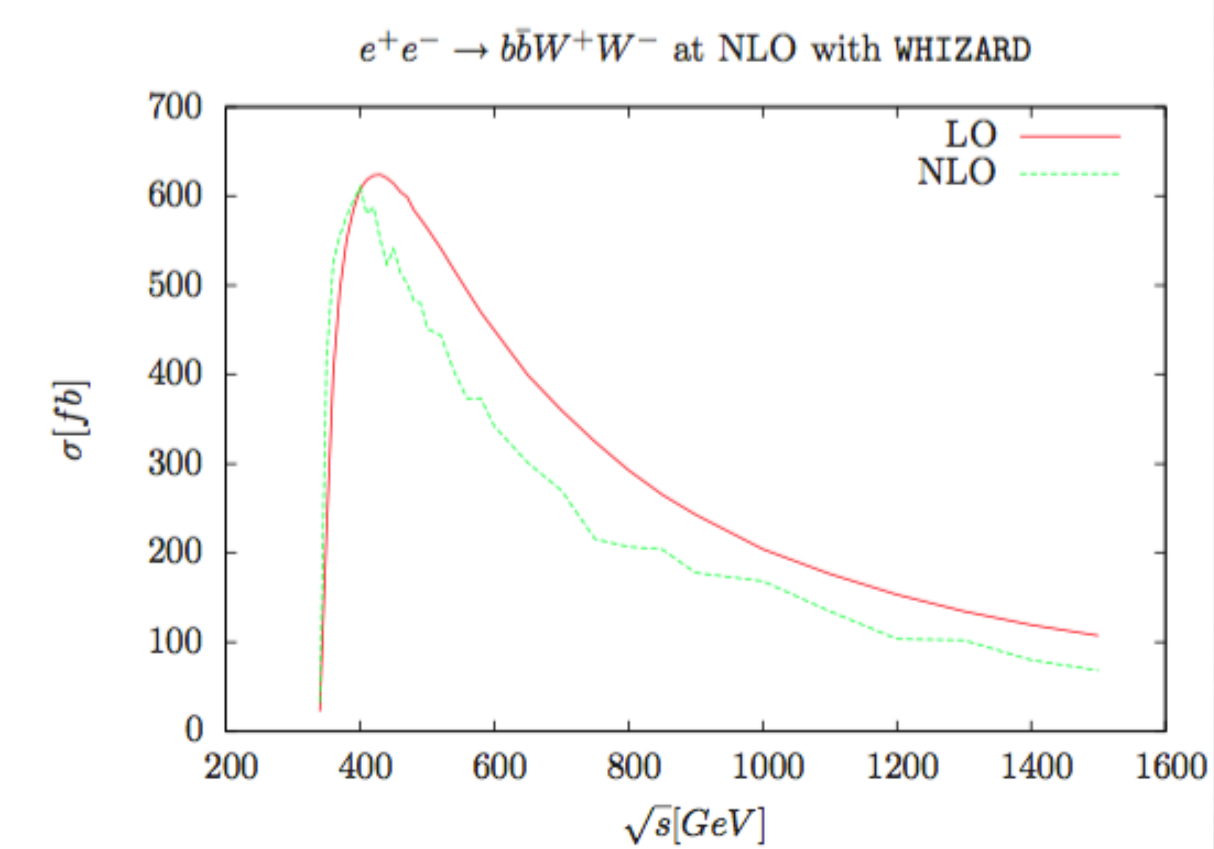

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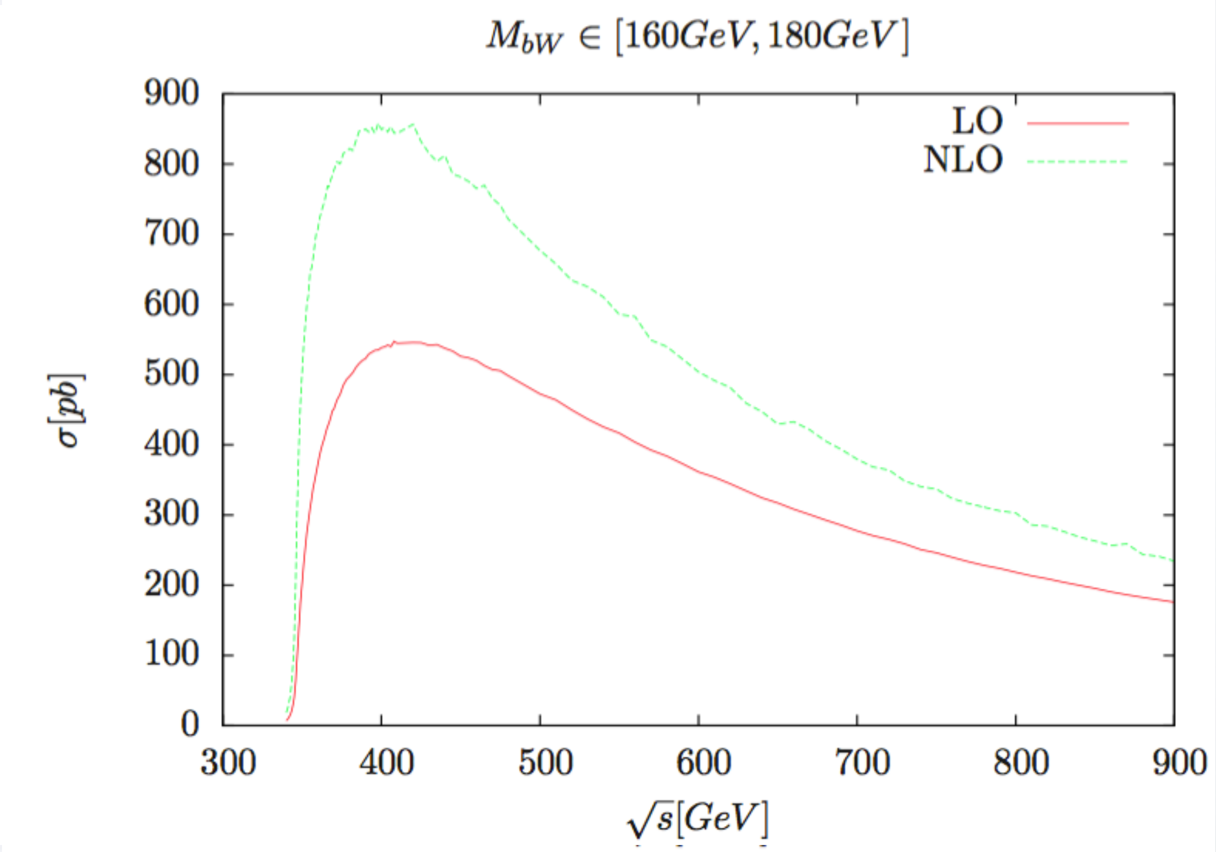

FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

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

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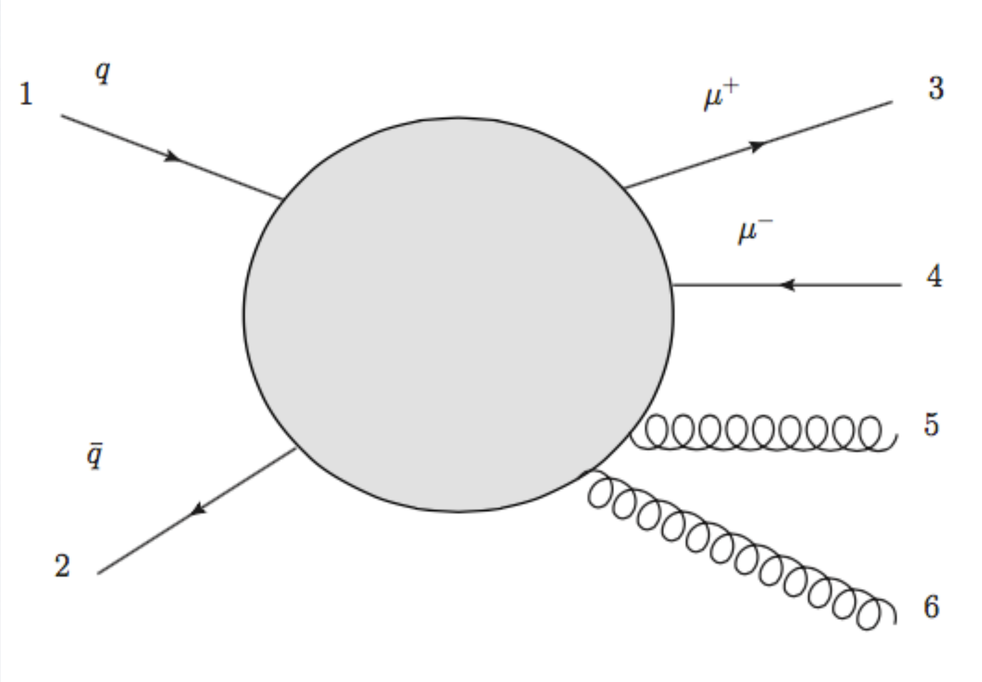

Automated subtraction terms in `WHIZARD`, algorithm:

- ✳ Find all singular pairs

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

- ✳ Partition phase space according to singular regions

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

- ✳ Generate subtraction terms for singular regions

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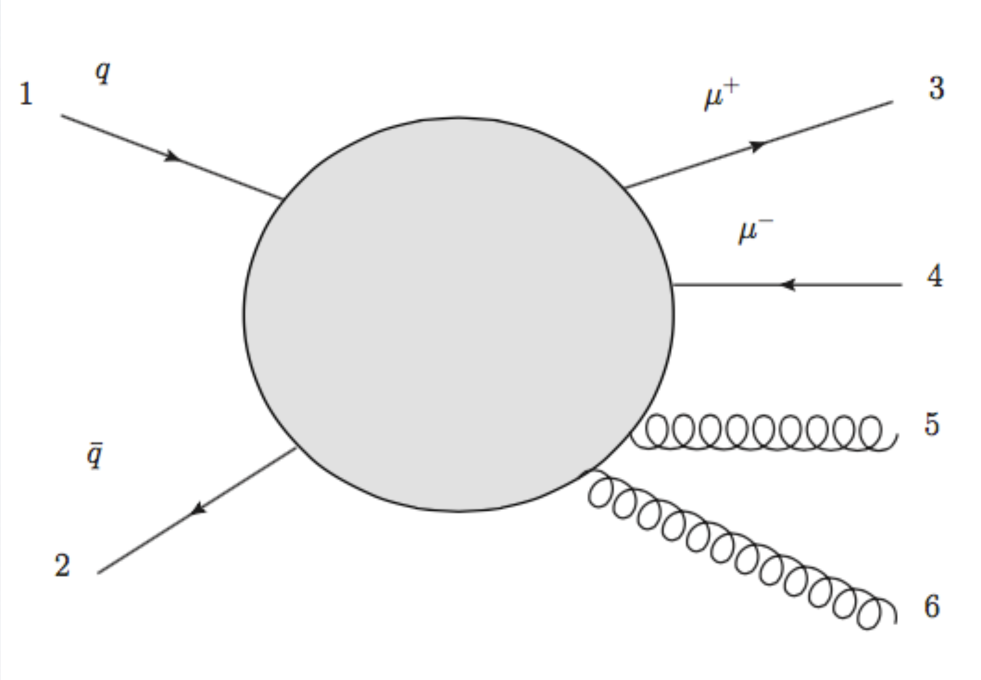

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* Generate subtraction terms for singular regions

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:

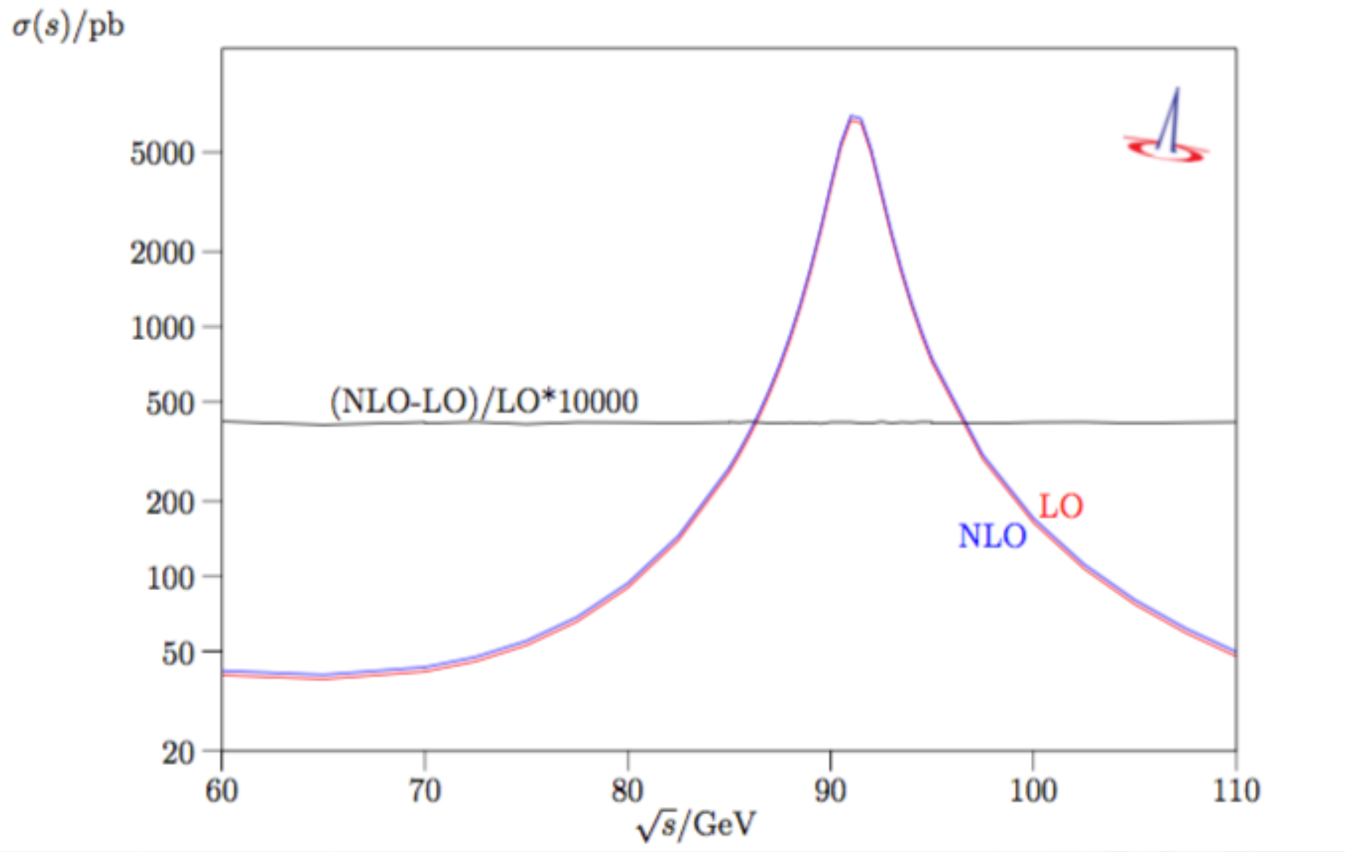
$$\mathcal{B}_{+-} \sim Re \left\{ \frac{\langle k_{\text{em}} k_{\text{rad}} \rangle}{[k_{\text{em}} k_{\text{rad}}]} \sum_{\substack{\text{color}\\\text{spin}}} \mathcal{A}_+^{(n)} \mathcal{A}_-^{(n)*} \right\}$$

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

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

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

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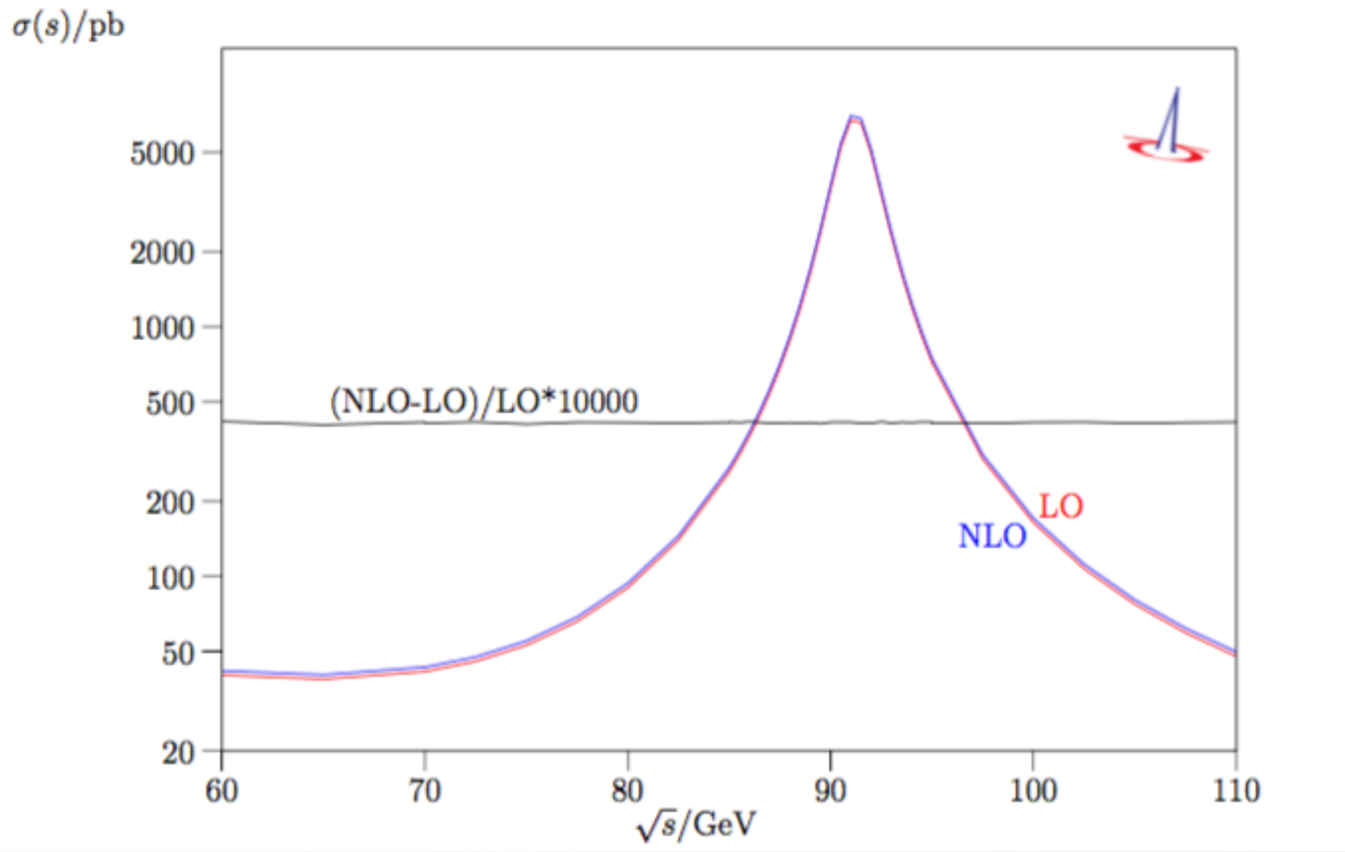

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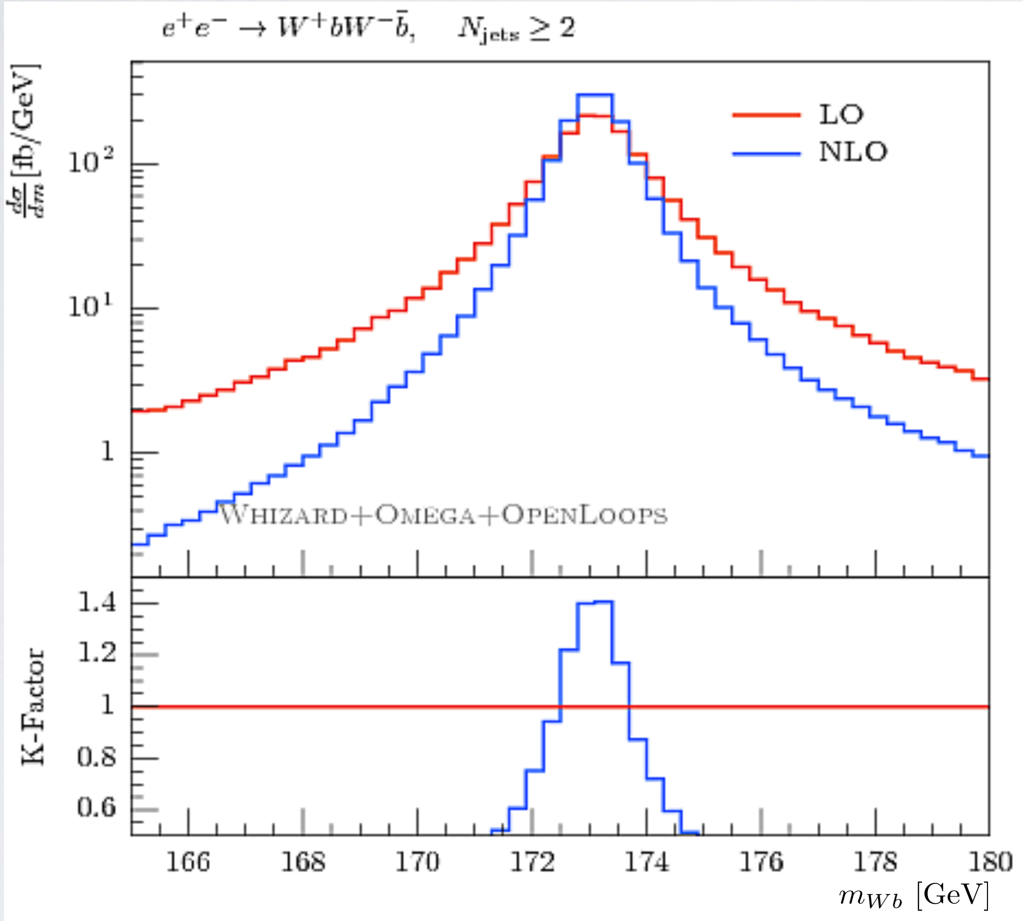
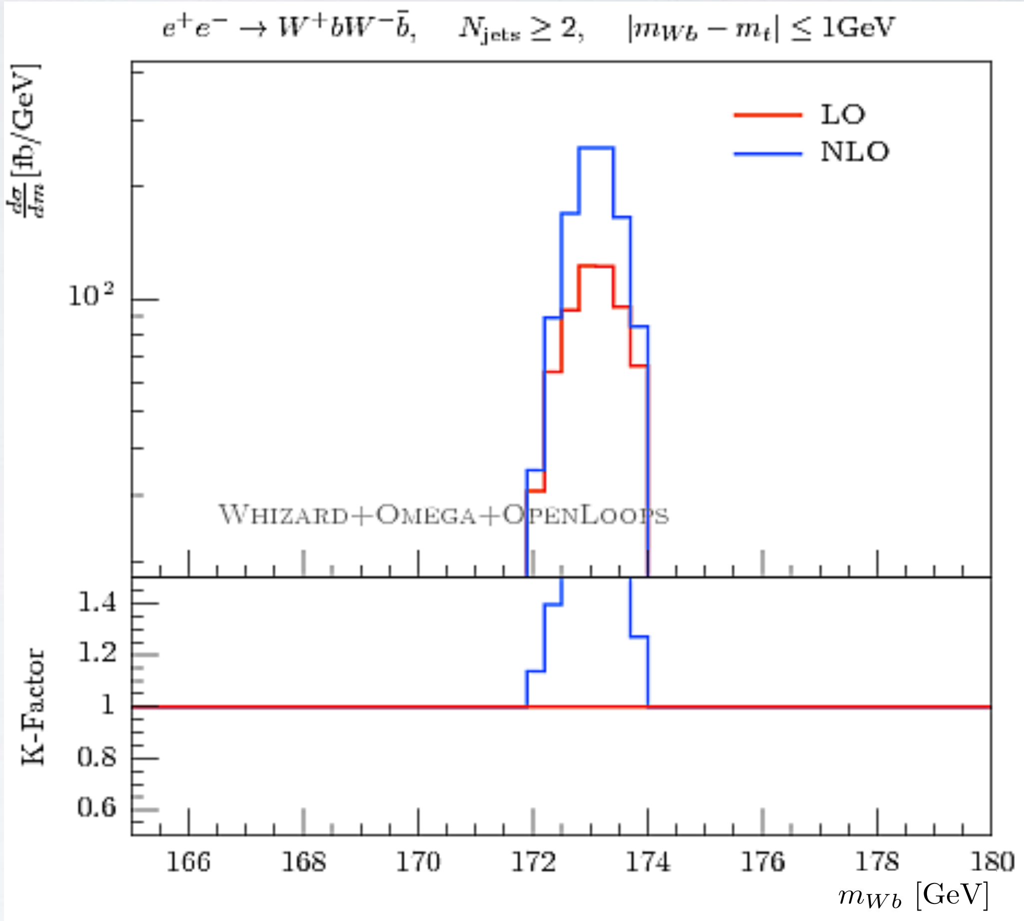
- ✦ QCD NLO infrastructure in pp almost complete
- ✦ First attempts on electroweak corrections, interfacing the `RECOLA` code [Denner et al.]

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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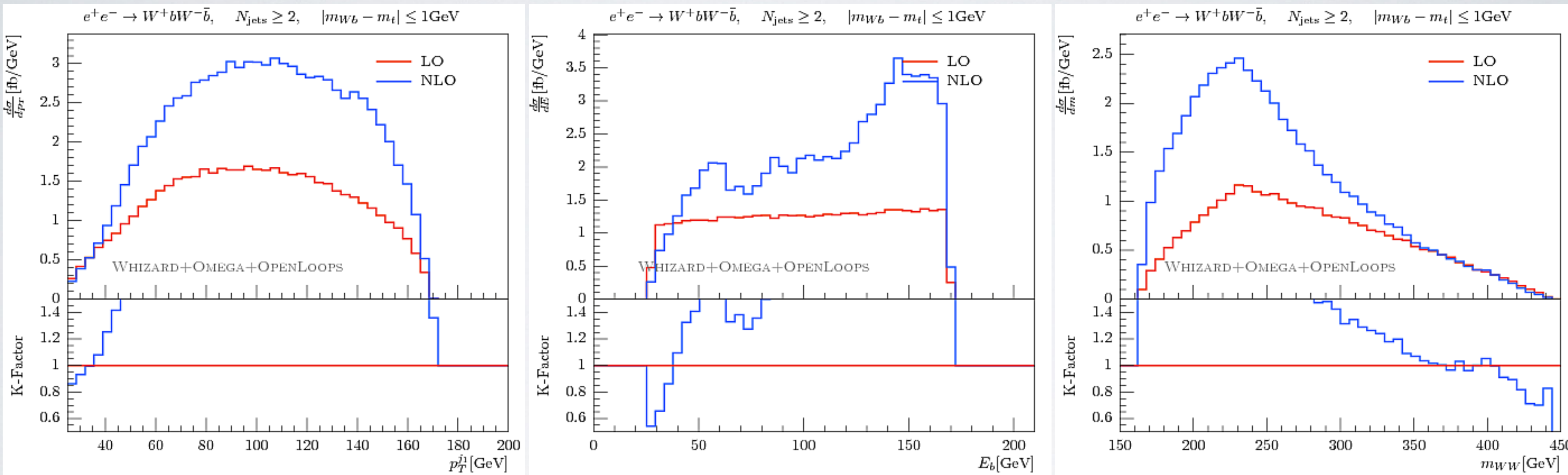

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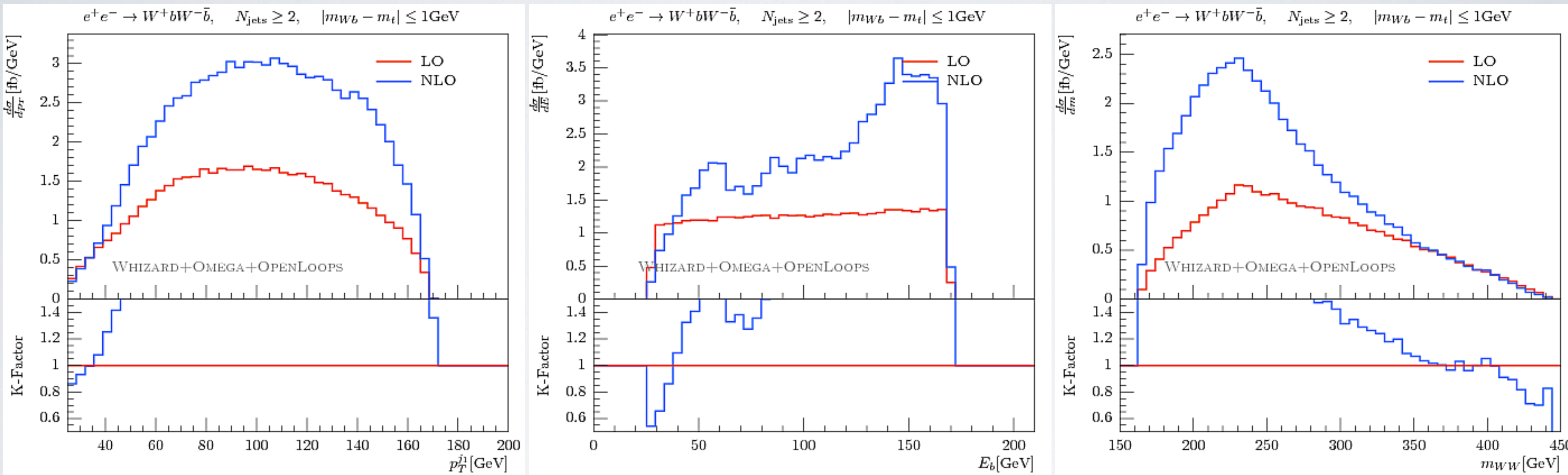
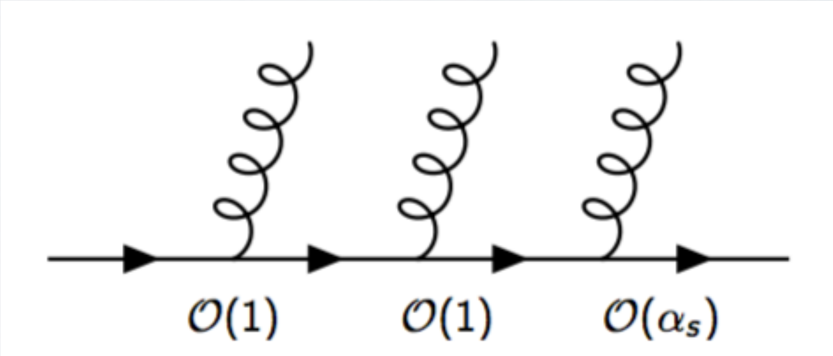


- Next steps: produce polarized results (remember: ILC will always run with polarization)
- Produce also plots including complete ISR photon radiation and beamstrahlung
- Investigate the full 2 → 6 process: e+e- → bbeμνν [Chokoufé/Kilian/Lindert/JRR/Pozzorini/Weiss]

Automated POWHEG Matching in WHIZARD

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



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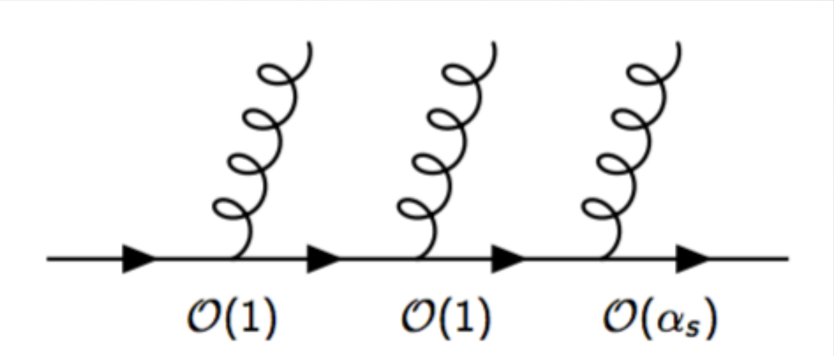


- Complete NLO events

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

- POWHEG generate events according to the formula:

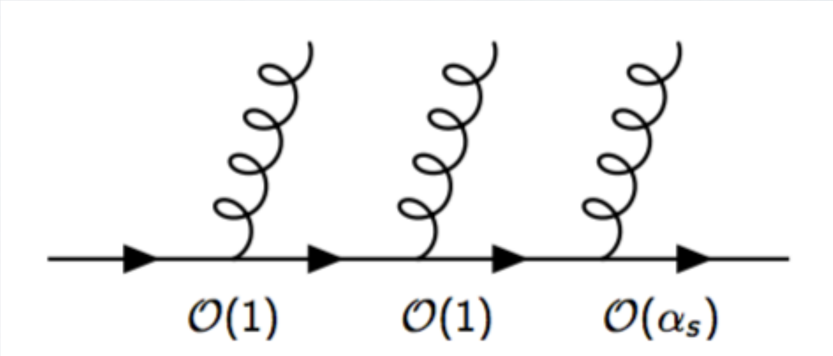
$$d\sigma = \overline{B}(\Phi_n) \left[\Delta_R^{\text{NLO}}(k_T^{\min}) + \Delta_R^{\text{NLO}}(k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\text{rad}} \right]$$

- Uses the modified Sudakov form factor:

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

Automated POWHEG Matching in WHIZARD

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



- Complete NLO events

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

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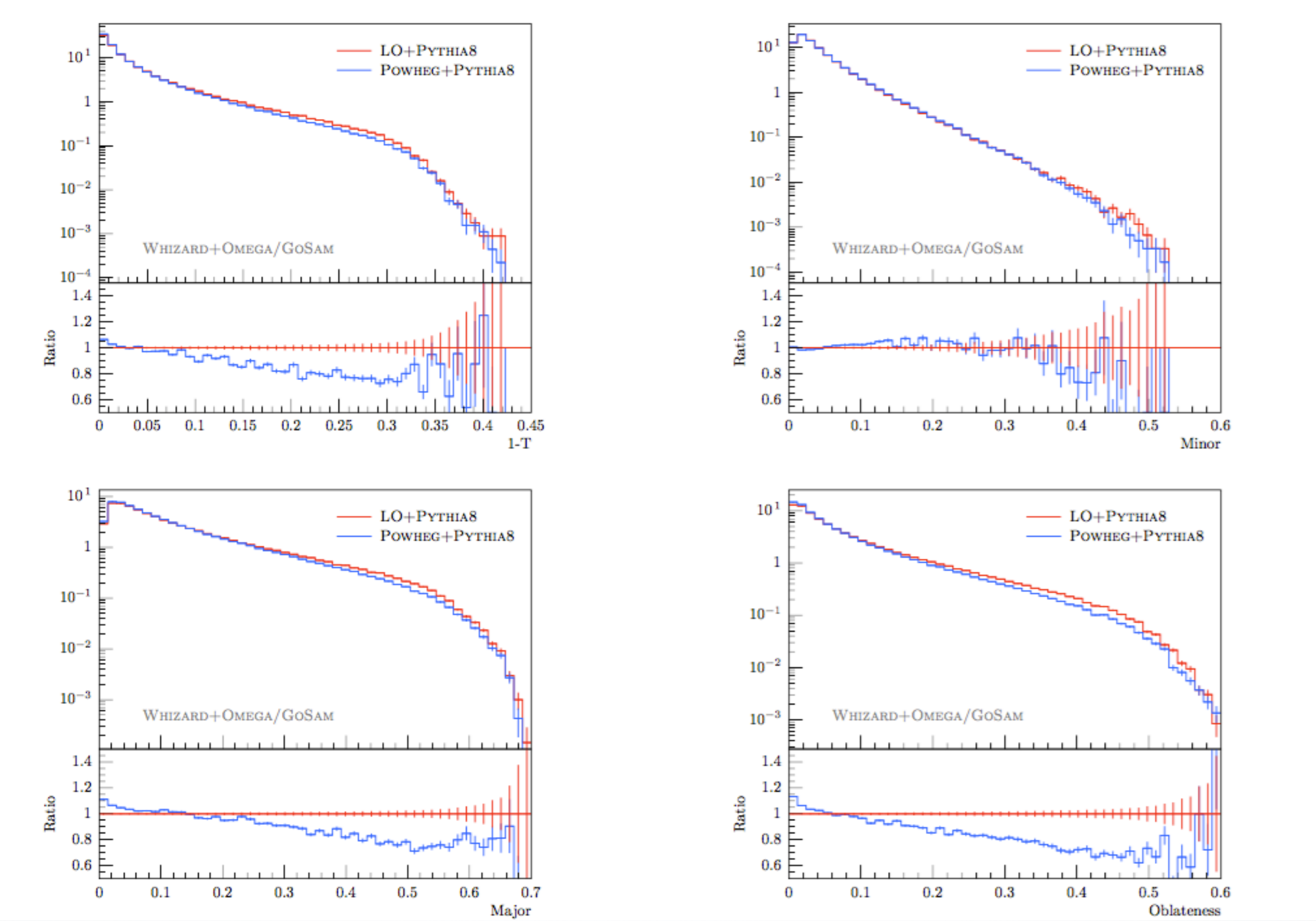
- Hardest emission: $k_T^{\max}$; shower with imposing a veto
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator own implementation in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

POWHEG Matching, example: e+e- to dijets

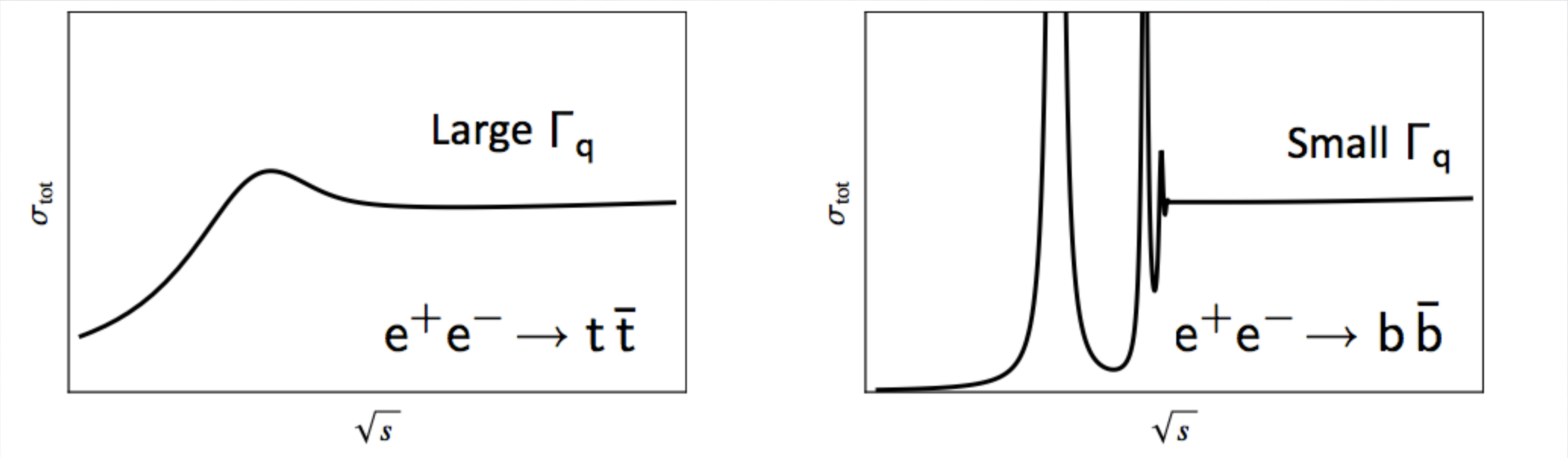


3) Top threshold in (N)LL (p)NRQCD matched to (N)LO QCD in WHIZARD

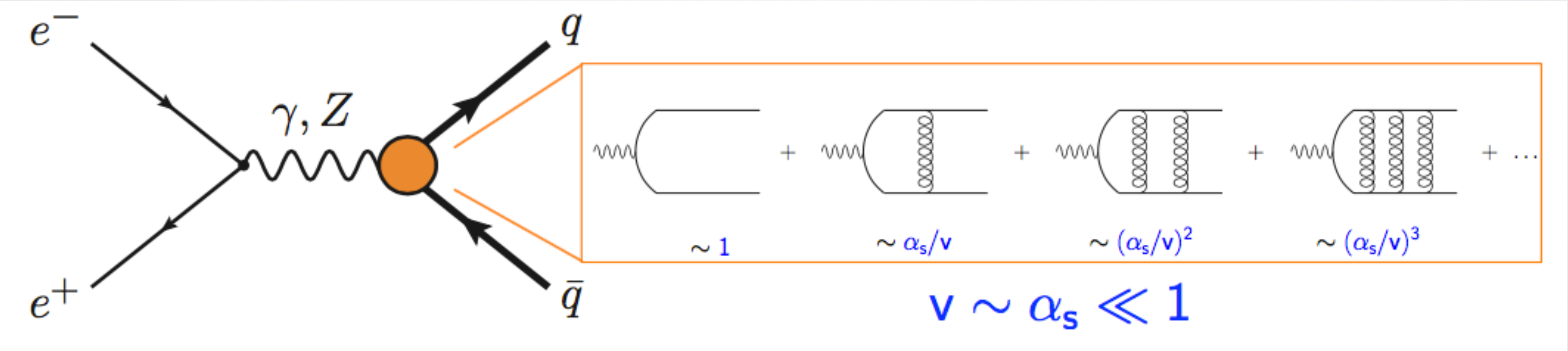
Top Threshold at lepton colliders

ILC 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 $v \sim \alpha_s \ll 1$



Top Threshold Resummation in (p)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. (for more details: Talk M. Beneke)
- 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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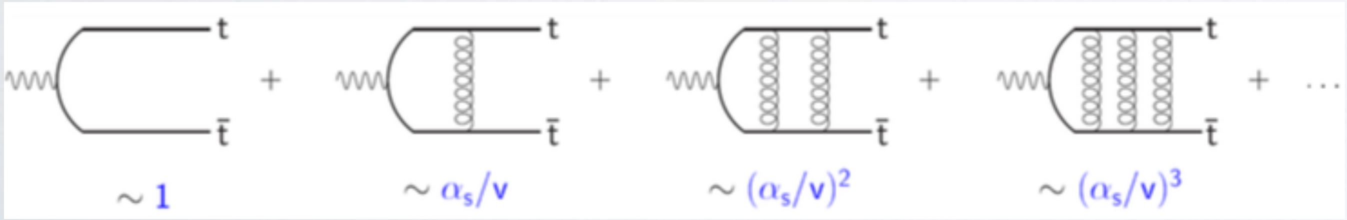
Coulomb potential gluon ladder resummation



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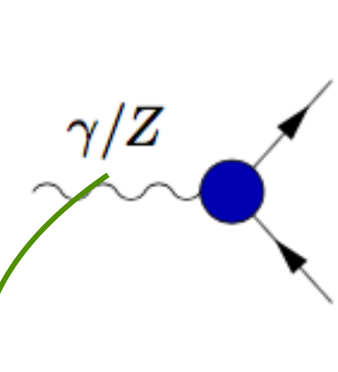
can be mapped onto effective *ttV* vertex



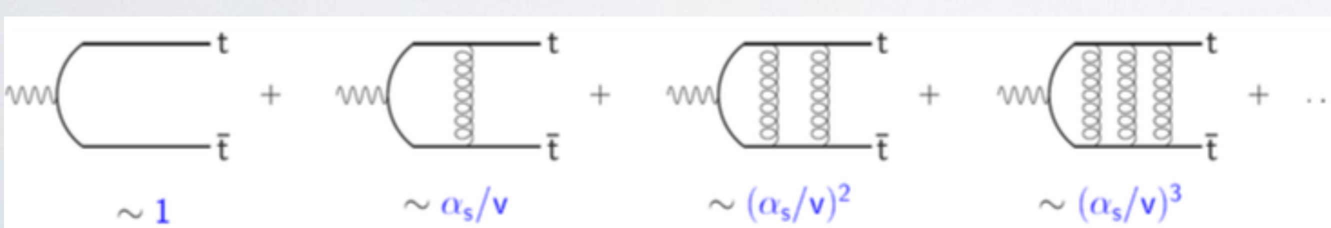
$$\sim \sqrt{R^{v/a}_{\mathrm{(N)LL}}} \sim \frac{\mathcal{G}^{v/a}_{\mathrm{(N)LL}}}{\mathcal{G}^{v/a}\big|_{\alpha_s=0}} \longrightarrow 1$$

far away from threshold

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

differential in off-shell *tt* phase space

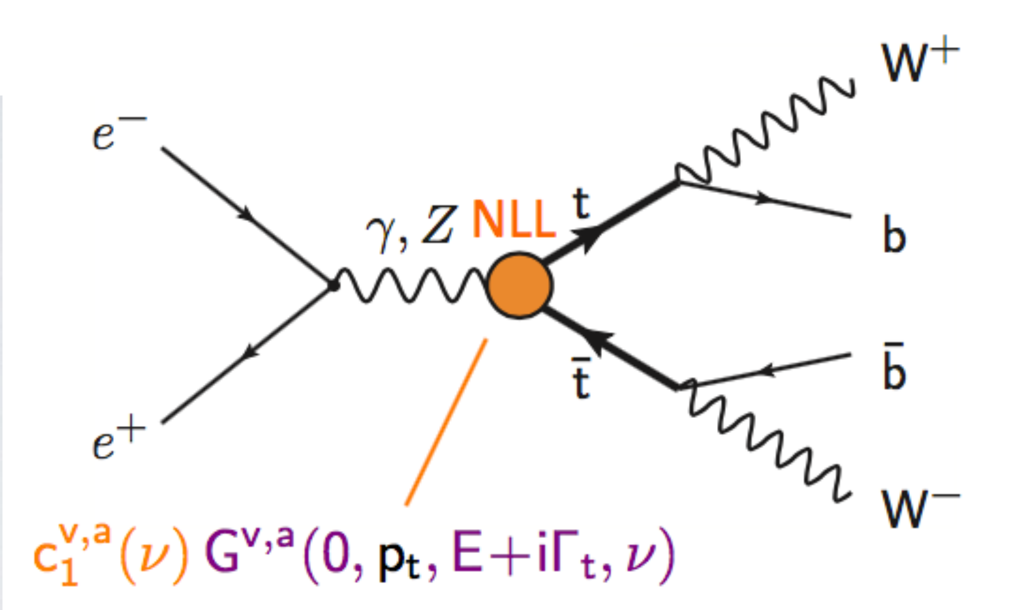
Coulomb potential gluon ladder resummation



Top Threshold in WHIZARD

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

- 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:

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

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

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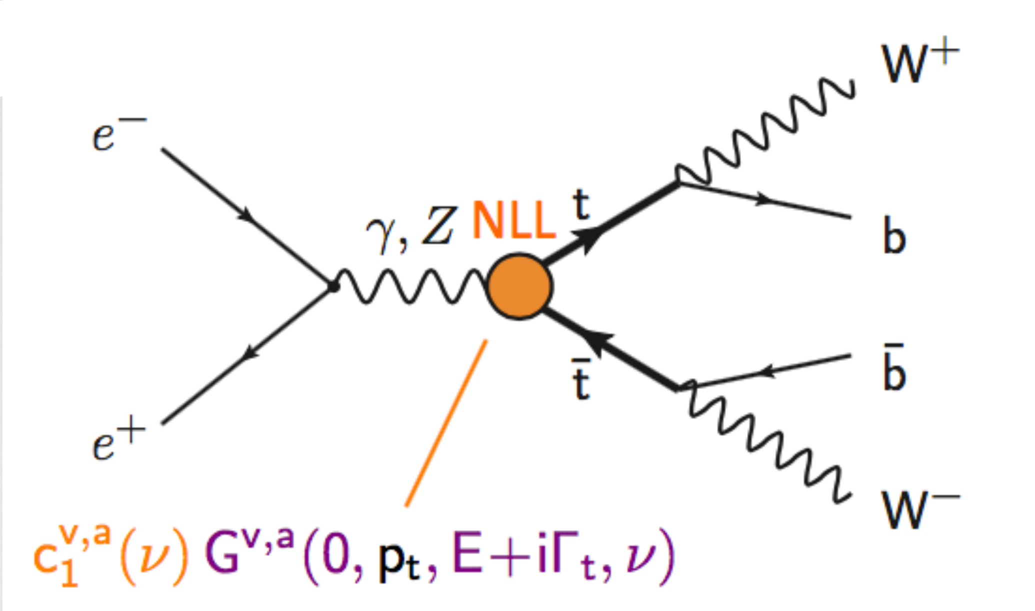

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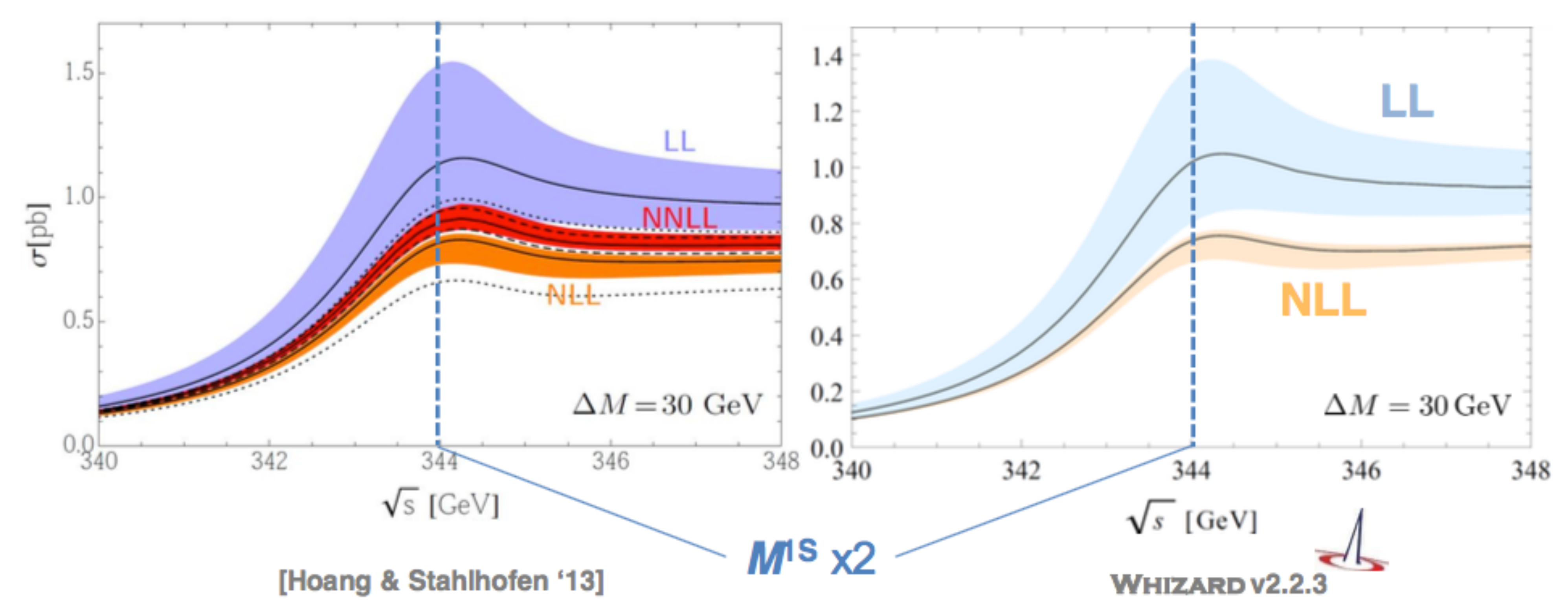

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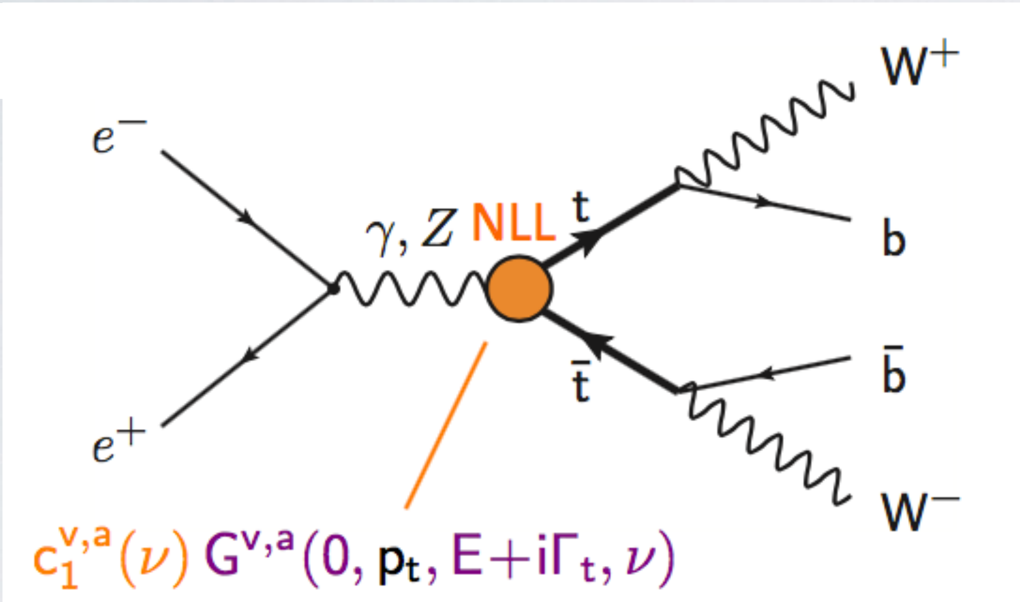

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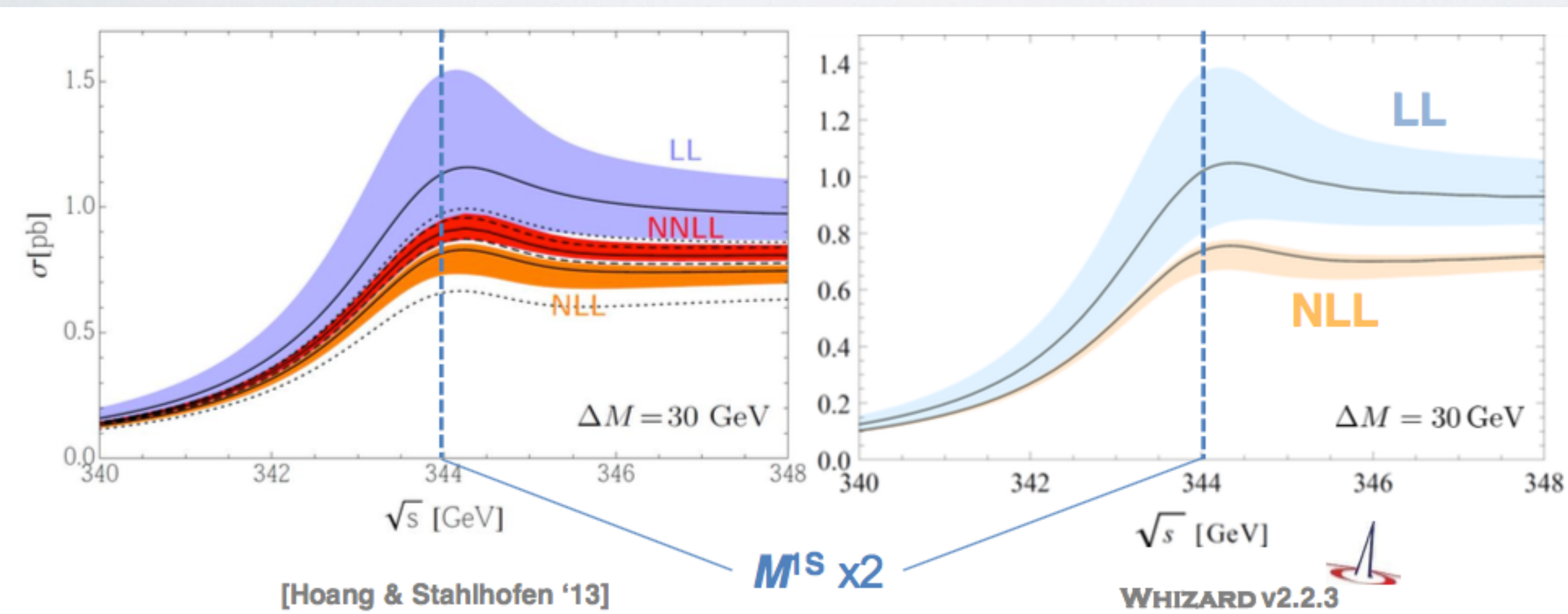
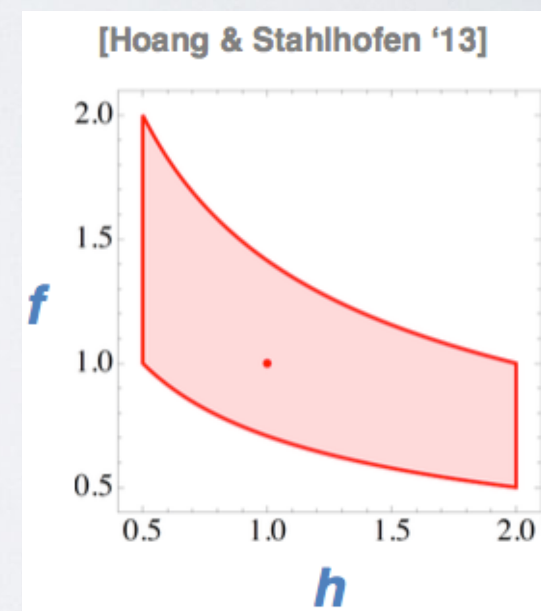
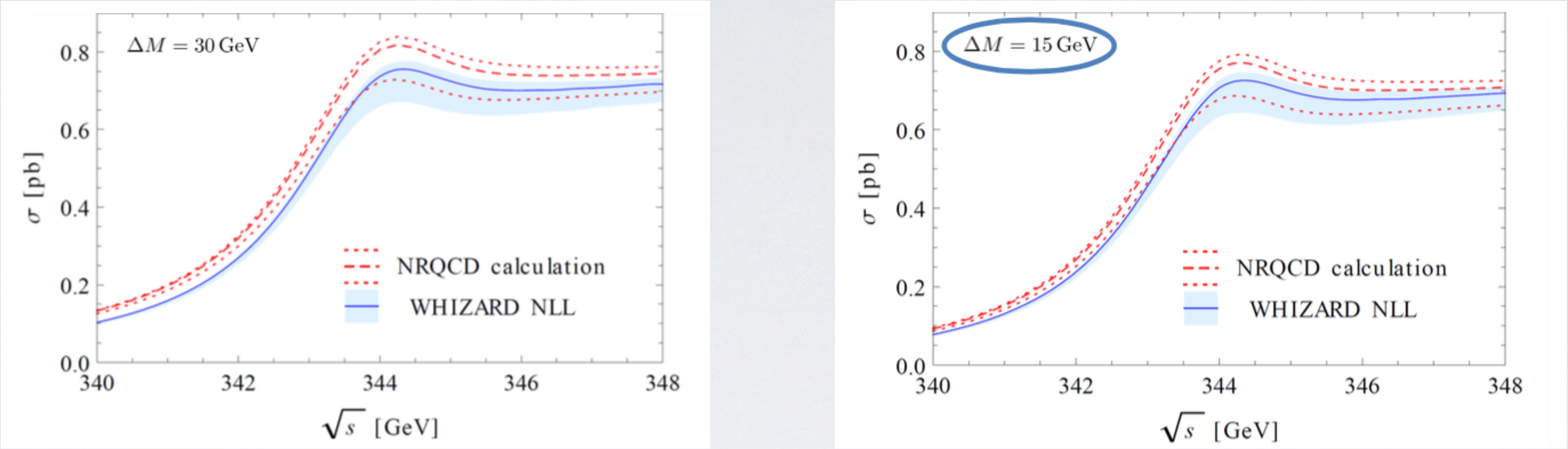
Theory uncertainties from scale variations:
hard and soft scale

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





Sanity checks: correct limit for $\alpha_s \longrightarrow 0$, stable against variation of cutoff ΔM [15-30 GeV]



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  - Important effects: beamstrahlung; ISR; LO electroweak terms
  - More exclusive observables accessible

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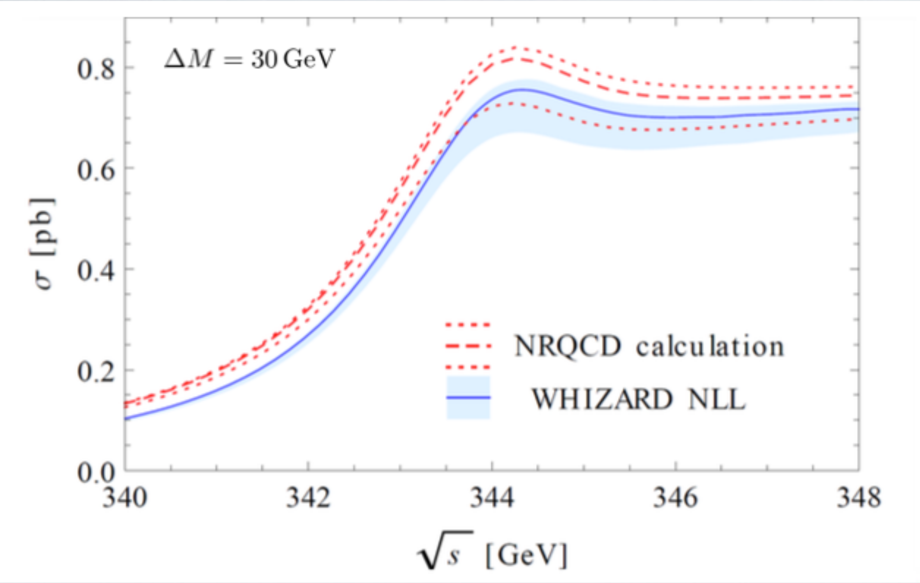

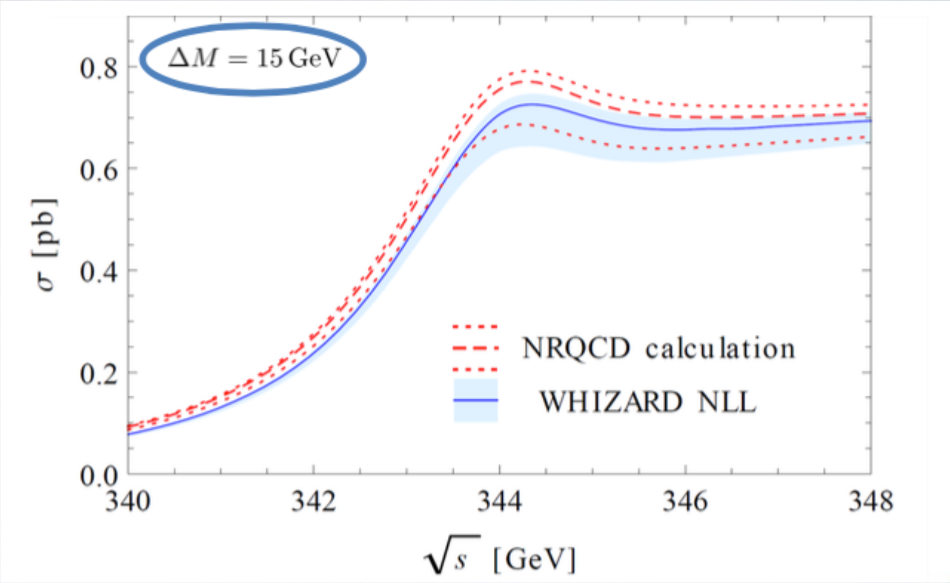

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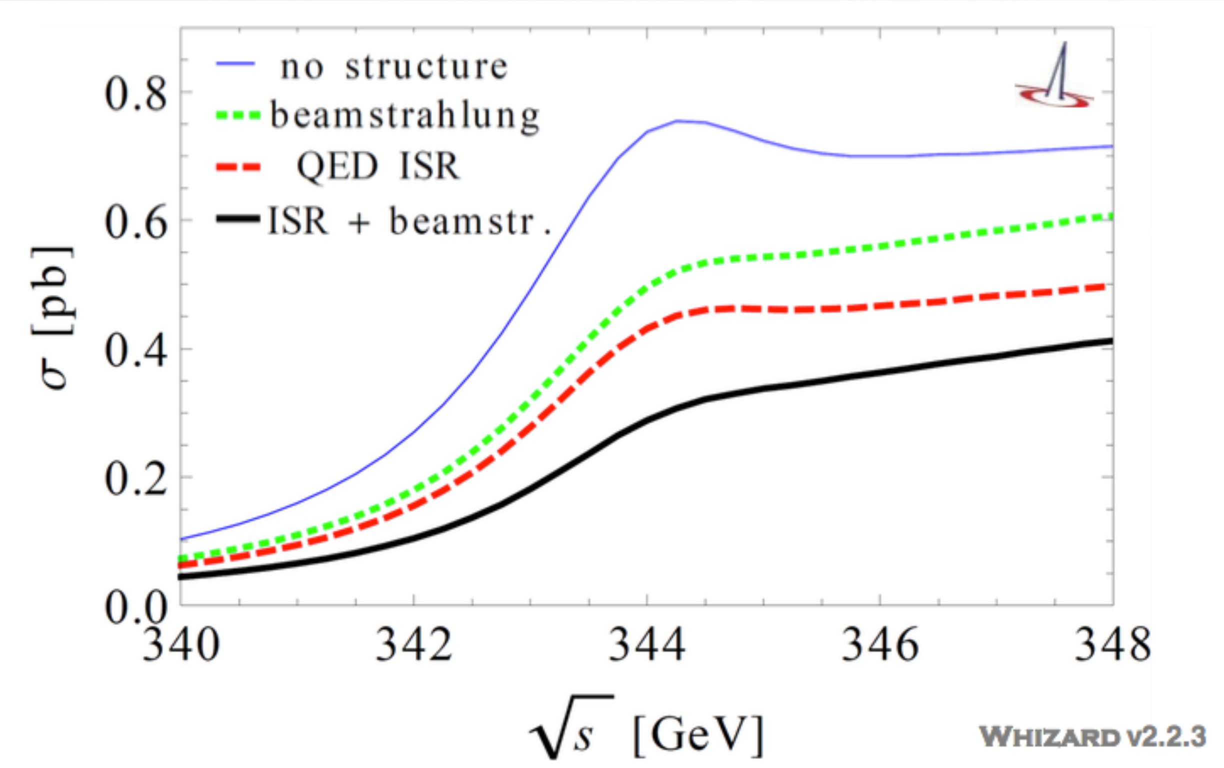

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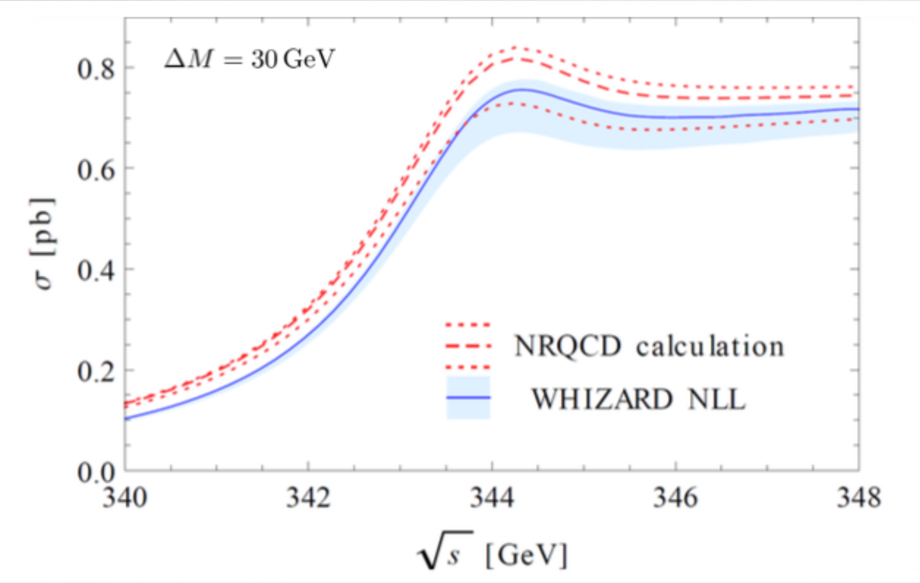

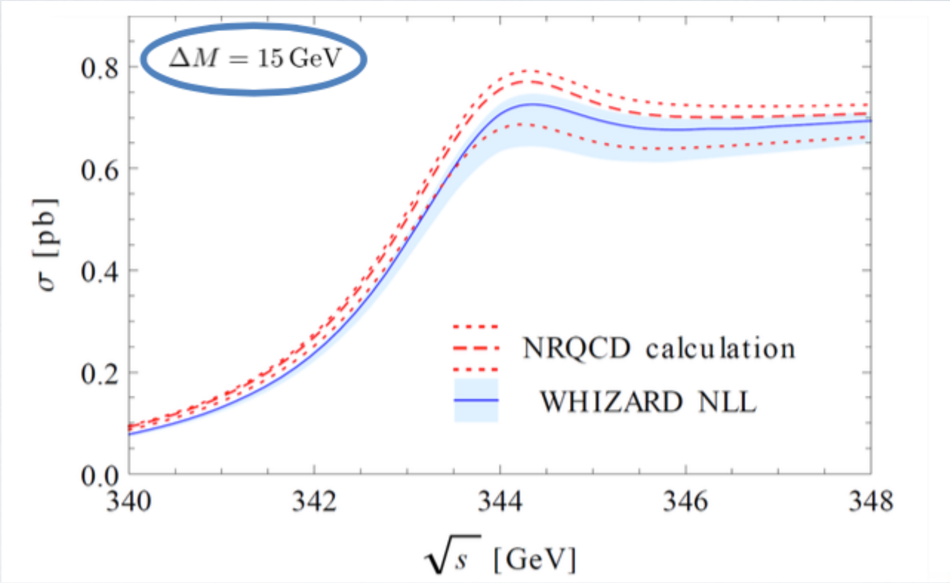

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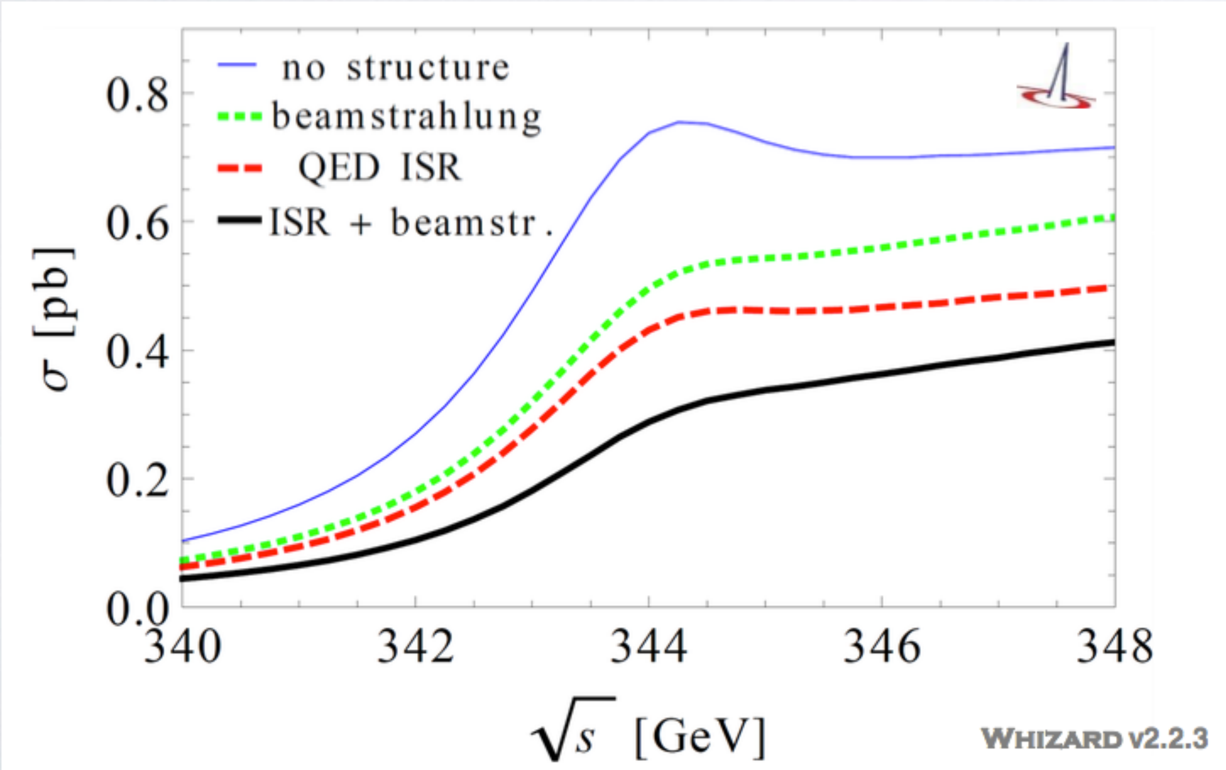
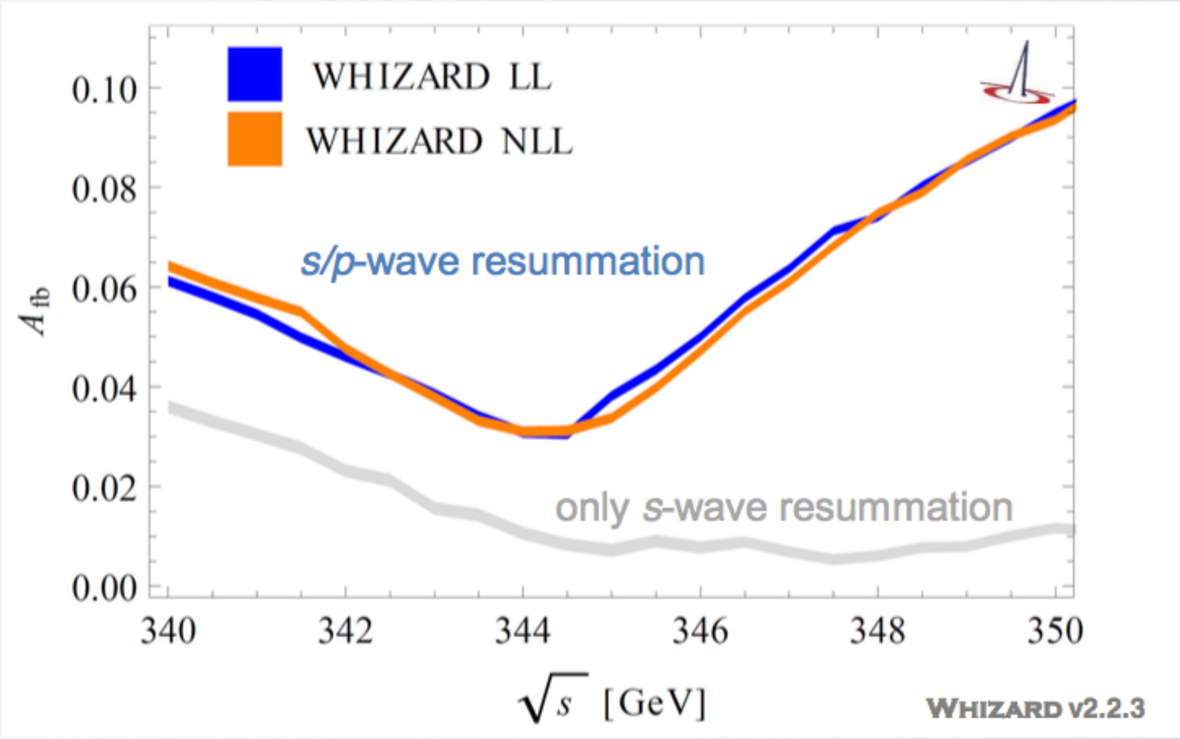
Forward-backward asymmetry (norm. ⇒ good shape stability)

$$A_{fb} := \frac{\sigma(p_z^t > 0) - \sigma(p_z^t) < 0)}{\sigma(p_z^t > 0) + \sigma(p_z^t < 0)}$$





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 [Talk L. Linssen]

Comparison of different approximations

- Leading order approximation
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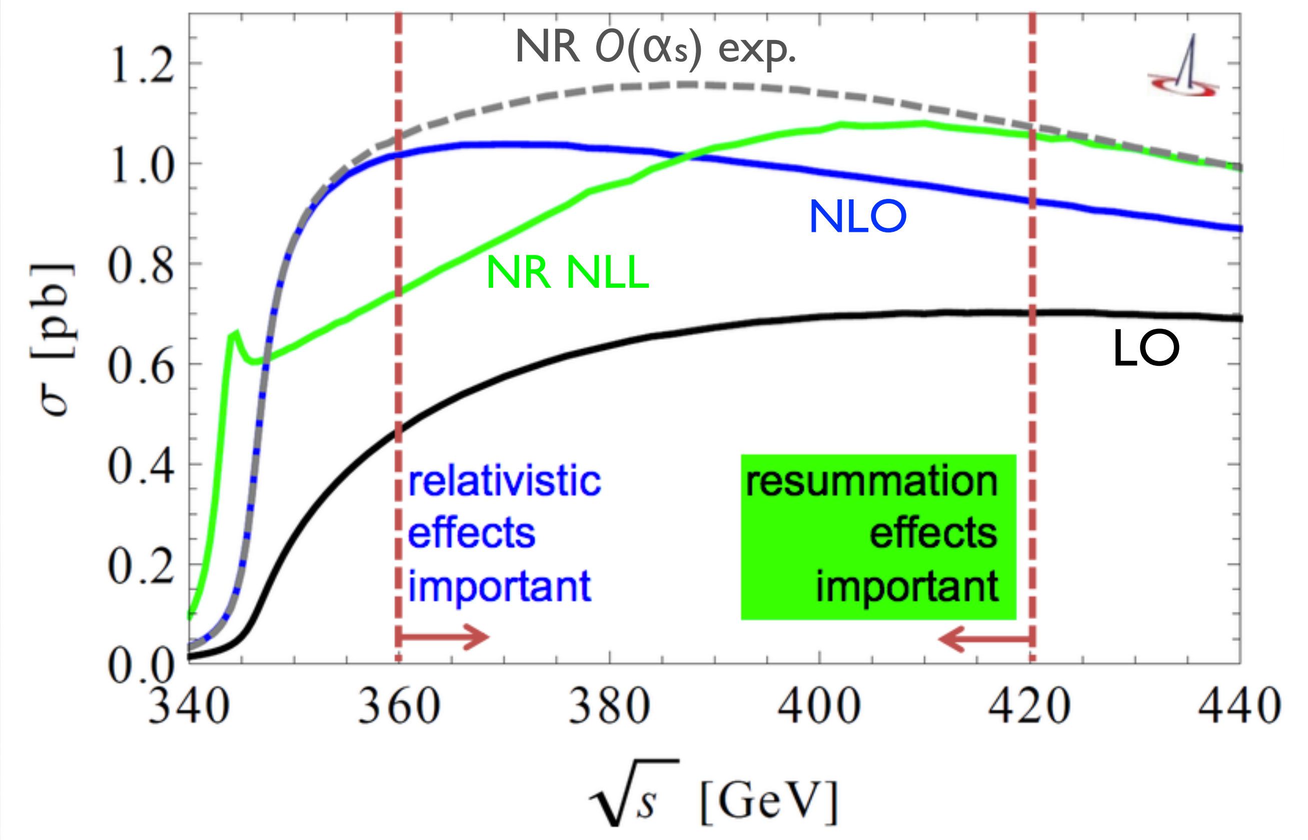

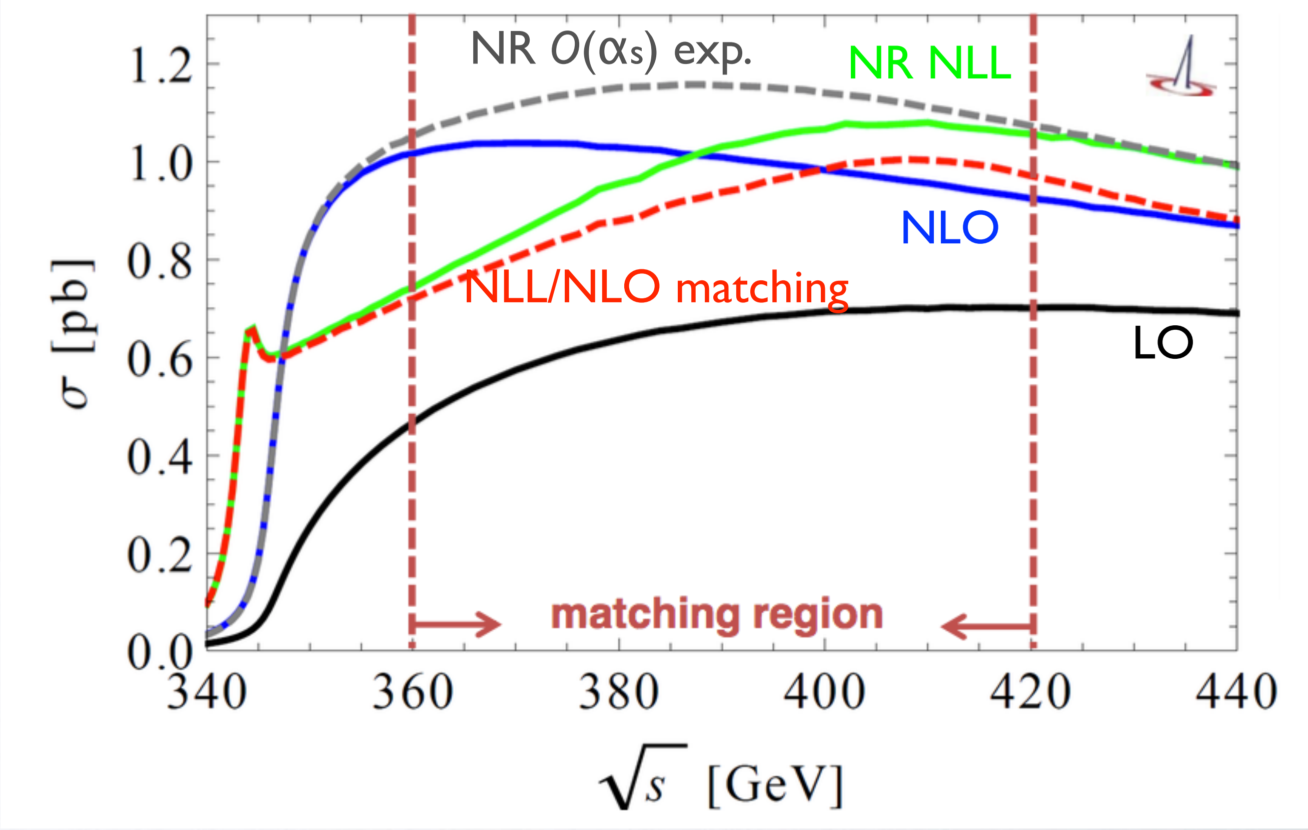

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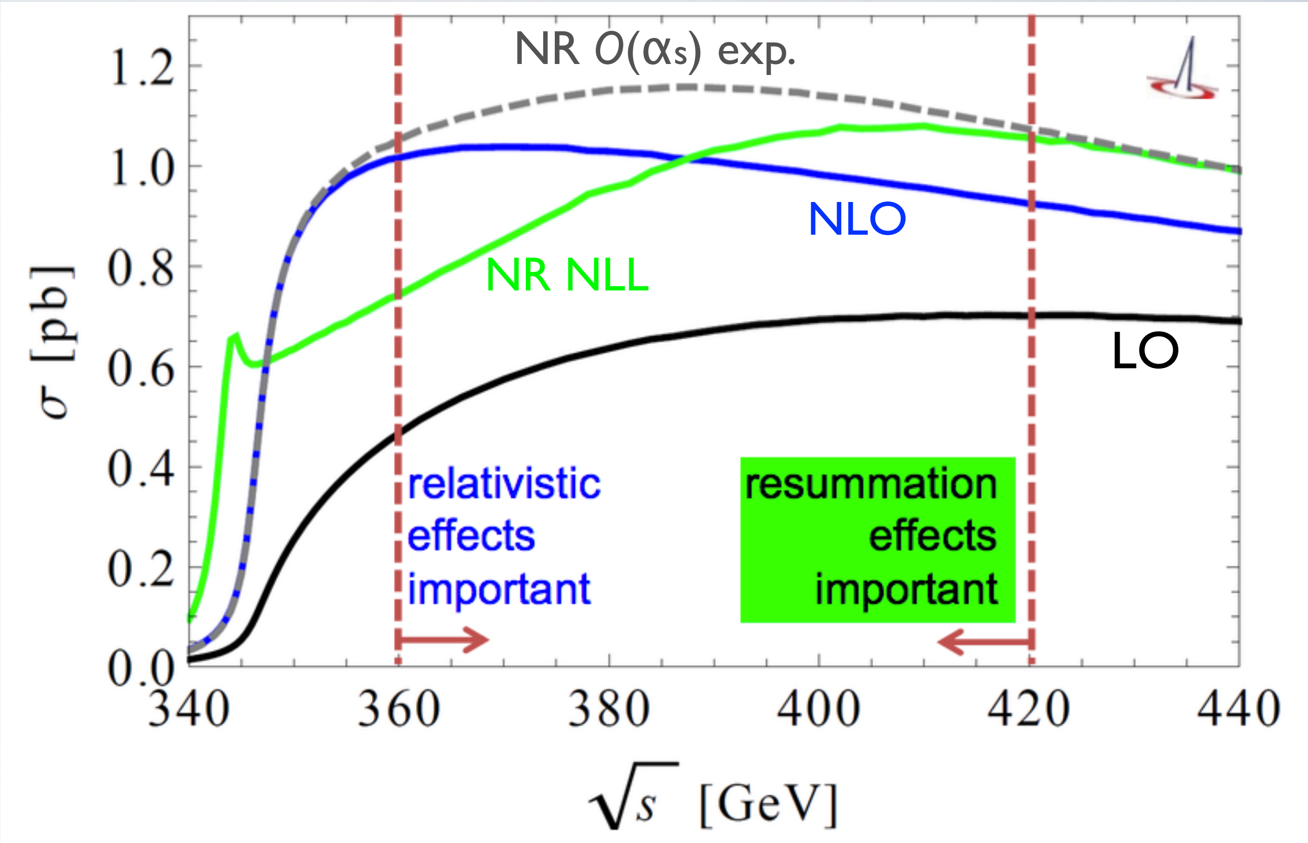

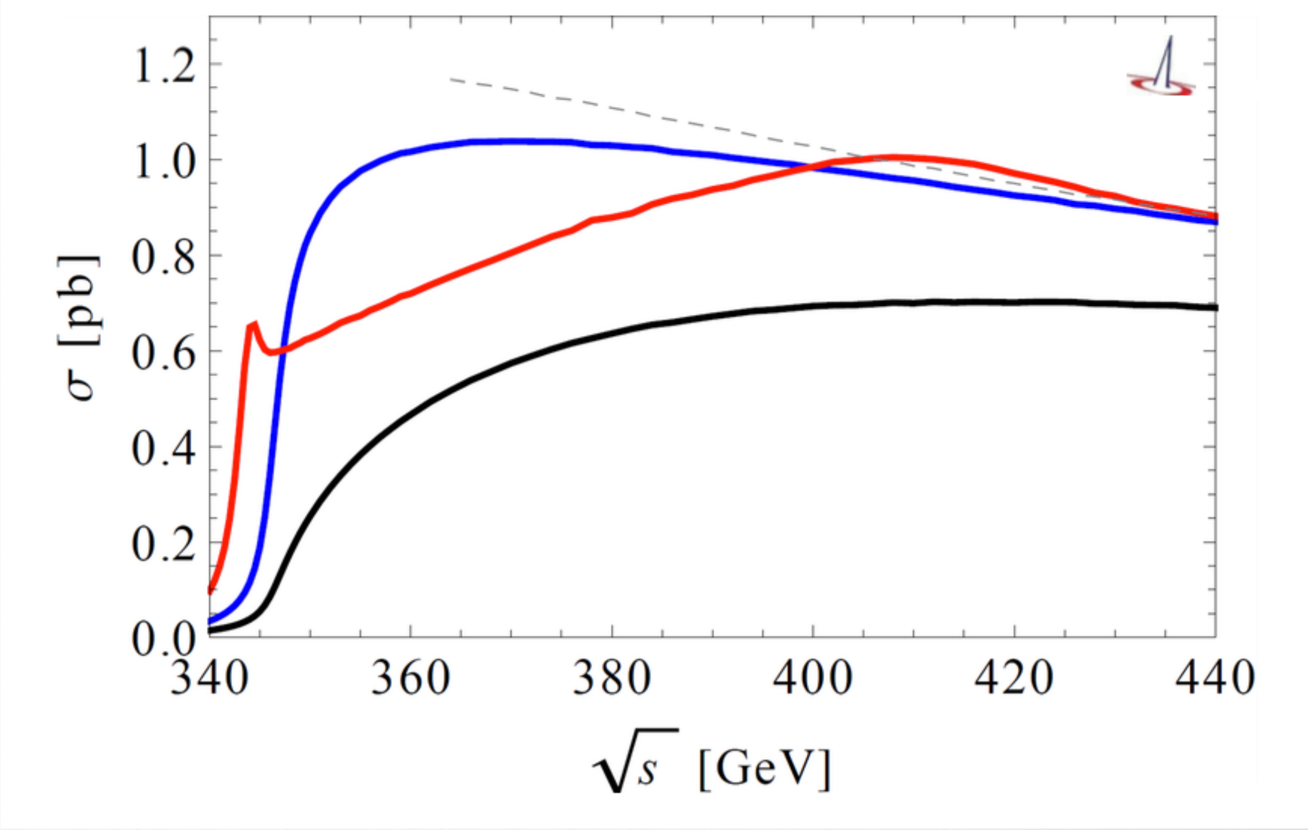

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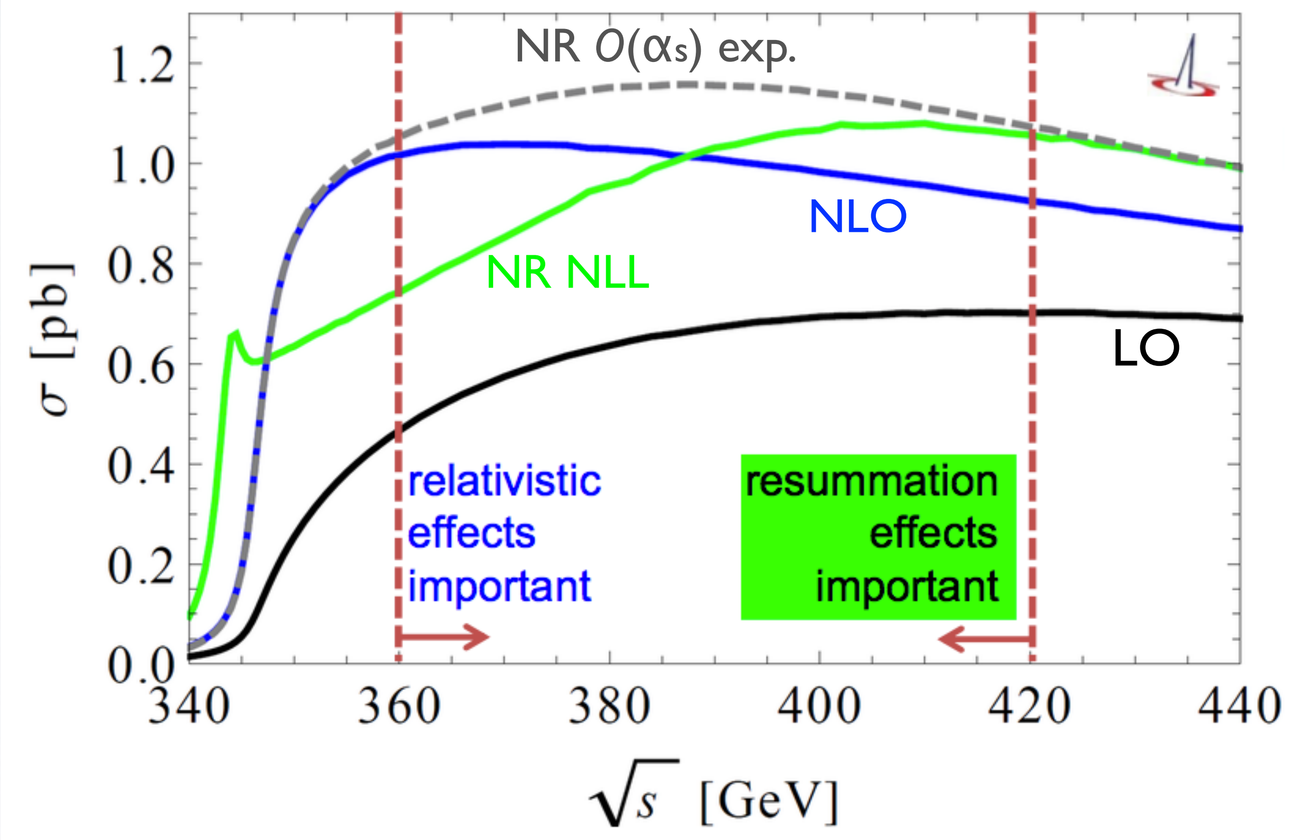
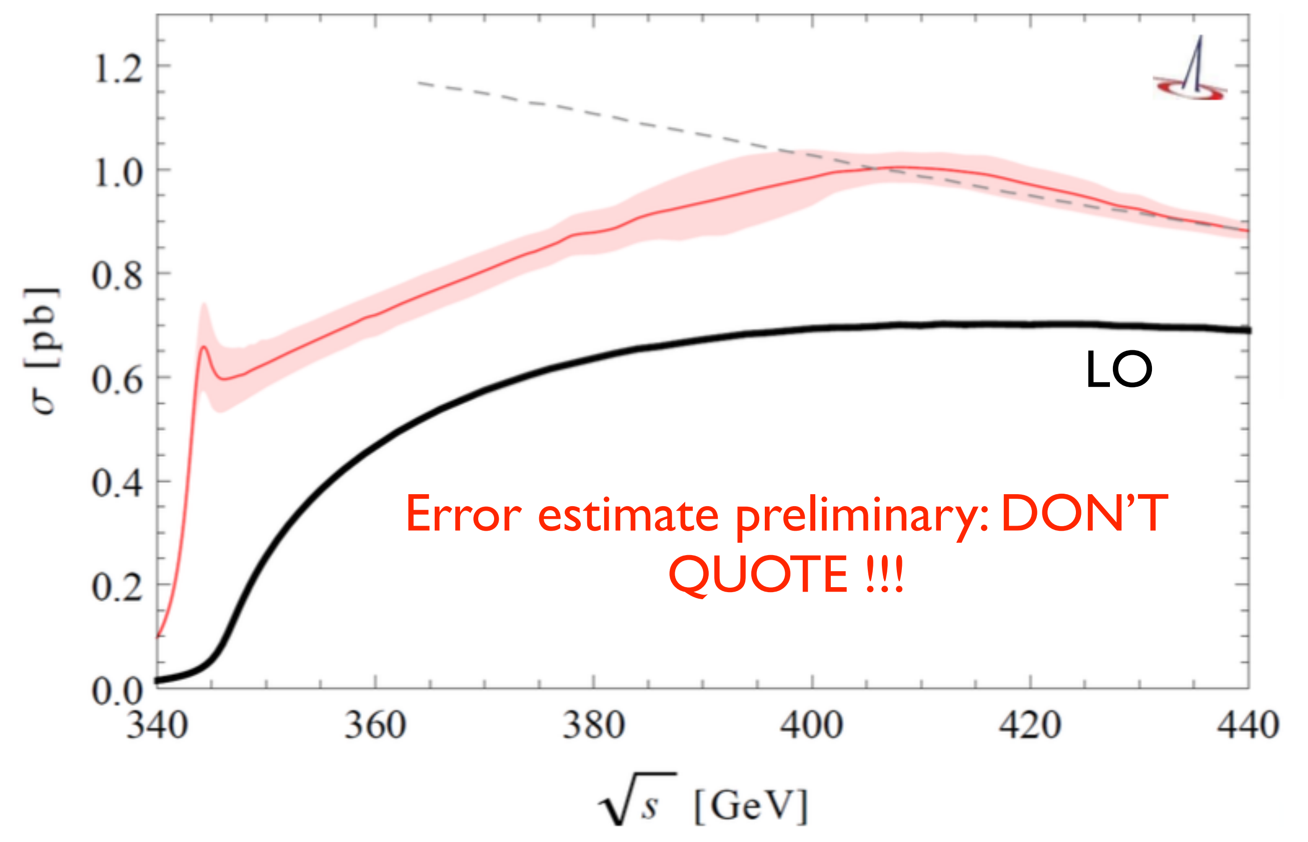
Total uncertainty: matching and *h-f* variation band





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, 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
```

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, LC top threshold
- NLO automation: reals and subtraction terms (FKS) [+ virtuals externally] → `WHIZARD 3.0`
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even if it is in a conference summary talk $\Longrightarrow$ Challenge accepted !

Pictorial summary: loops, legs, and subtractions

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BACKUP SLIDES:

WHIZARD: Installation and Run

- Download: http://www.hepforge.org/archive/whizard/whizard-2.2.6.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`

```
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.
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Color structures:

- Color flow formalism Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011
- Fundamental, antifundamental and adjoint representations
- Inofficial version for color sextets and diquark couplings
- General color structures coming tied to general Lorentz structures

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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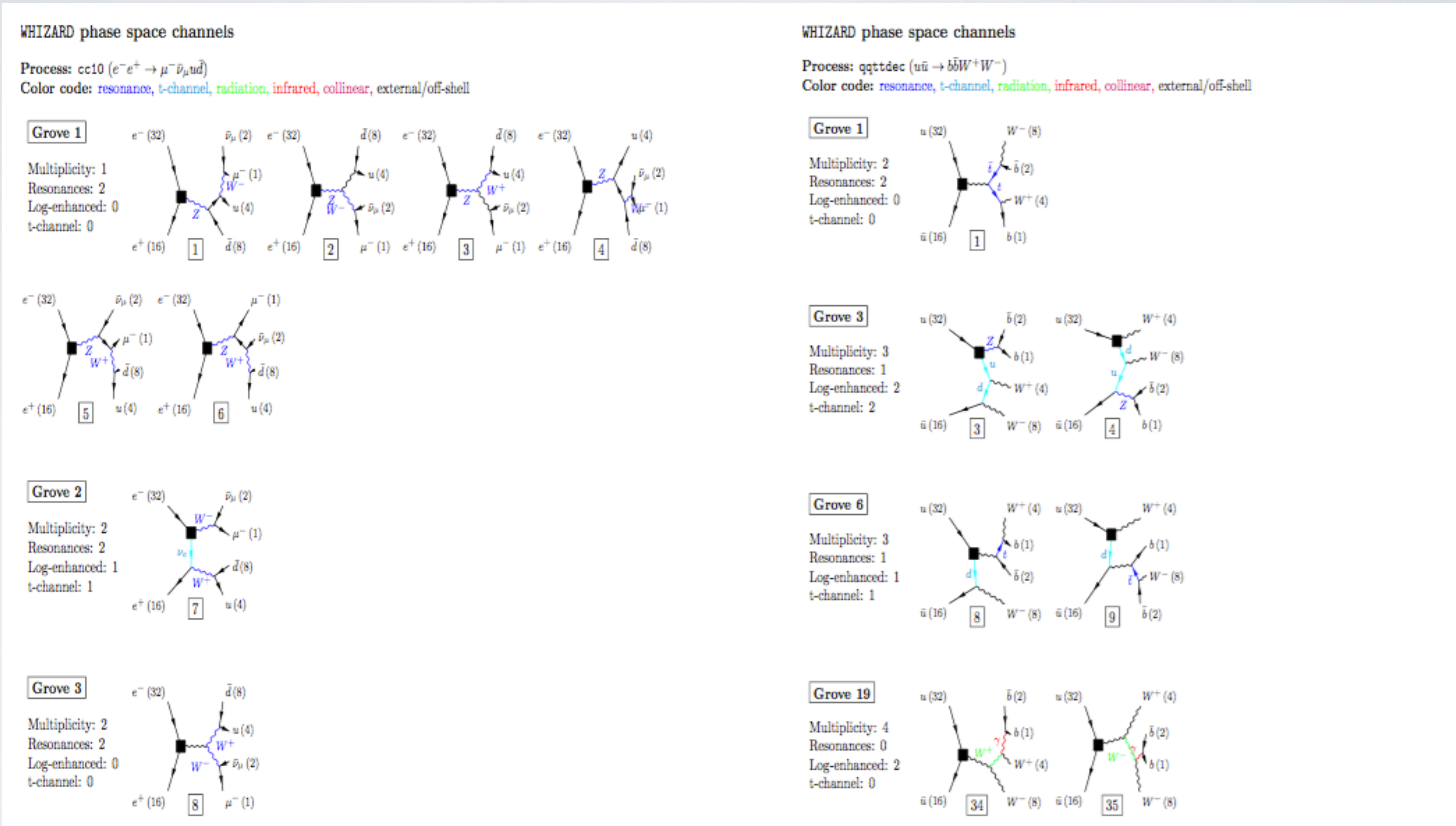
Beams:

- 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]

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