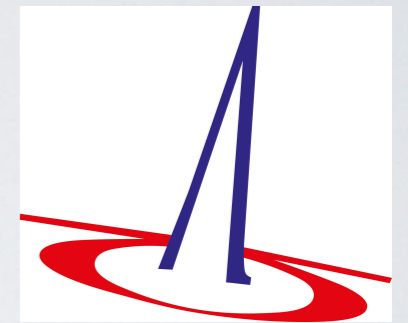
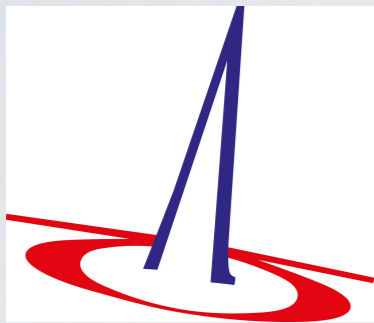
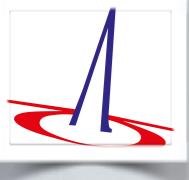


# The Event Generator WHIZARD for LC Top Physics



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](mailto:whizard@desy.de)>

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

*Bijan Chokouf /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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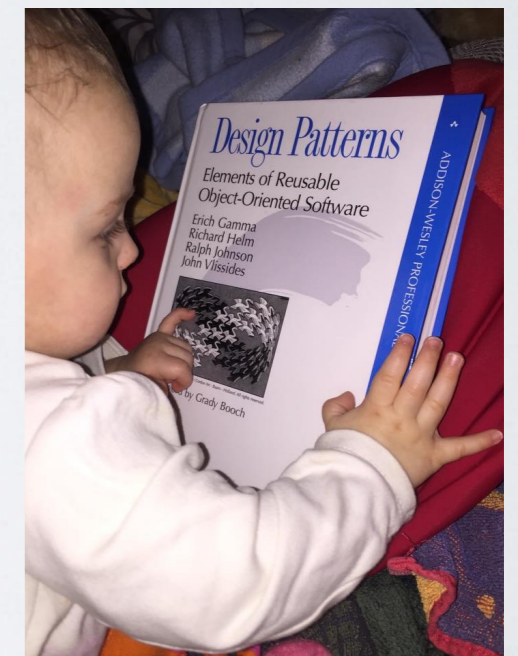
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2nd WHIZARD Workshop W rzburg, 03/2015



support junior developers





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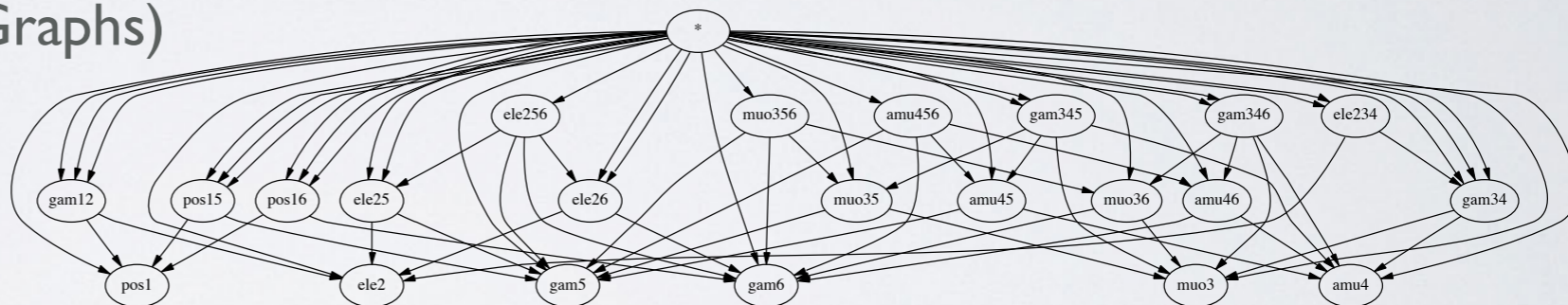
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EPJ C71 (2011) 1742

- 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)



- **VAMP**: adaptive multi-channel Monte Carlo integrator
- **CIRCEI/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, LCI0, 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 [ $\approx$  1998-2000]
- Used for many TESLA studies and most ILC CDR and TDR, CLIC CDR and detector Lol studies (versions v1.24, v1.50, v1.95) [ $\approx$  2002-2013]
- Color flow formalism [ $\approx$ 2005]
- Major refactoring phase I: **LHC physics**  $\rightarrow$  **v2.0.0** [ $\approx$  2007-2010]
- Validation inside ATLAS and CMS [ $\approx$ 2011-2014]
- 2nd refactoring phase II: **NLO automation / maintainability**  $\rightarrow$  **v2.2.0** [ $\approx$  2012-2014]
- Strong interest of CEPC study group(s) for CEPC simulations [ $\approx$  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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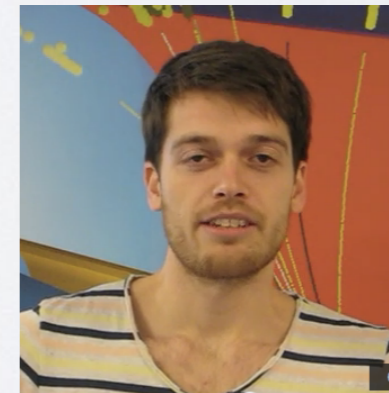
[beam spectra, photon background, event formats, shower/hadronization]



Mikael Berggren



Jean-Jacques Blaising



Moritz Habermehl





# General structure of SINDARIN input

LCWS '14, Belgrade, Simulation summary talk:

**WHIZARD Task to implement LCIO format**

```
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

sqrt_s = 13000 GeV
beams = p, p => lhpdf

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

n_events = 10000

sample_format = lhef, stdhep, hepvc
sample = "susydata"

simulate (susyprod)
```



# 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

sqrt_s = 13000 GeV
beams = p, p => lhpdf

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**

**WHIZARD v2.2.4, 02/2015:**

```
sample_format = lcio
simulate (<process>)
```



# General structure of SINDARIN input

LCWS '14, Belgrade, Simulation summary talk:

**WHIZARD Task to implement LCIO format**

**WHIZARD v2.2.4, 02/2015:**

```
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
```

```
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, 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, 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 $e, \mu, \tau, \gamma$                 | —                | QED                    |
| QCD with $d, u, s, c, b, t, g$                  | —                | QCD                    |
| <b>Standard Model</b>                           | <b>SM_CKM</b>    | <b>SM</b>              |
| <b>SM with anomalous gauge coupl.</b>           | <b>SM_ac_CKM</b> | <b>SM_ac</b>           |
| <b>SM with anomalous top coupl.</b>             | <b>SMtop_CKM</b> | <b>SMtop</b>           |
| <b>SM for <math>e^+e^-</math> top threshold</b> | —                | <b>SM_tt_threshold</b> |
| 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                                    | —                | Threesh1               |
| 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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| <b>SM for <math>e^+e^-</math> top threshold</b> | —                | <b>SM_tt_threshold</b> |
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| SM ext. for VV scattering                       | —                | SSC / SSC2/ Alth       |
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| SM with $Z'$                                    | —                | Zprime                 |
| 2HDM  | 2HDM_CKM         | 2HDM                   |
| MSSM  | MSSM_CKM         | MSSM                   |
| MSSM with gravitinos                            | —                | MSSM_Grav              |
| NMSSM   | NMSSM_CKM        | NMSSM                  |
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| 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]        |
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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/0' Mega model format]





# Phase Space Setup

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

**WHIZARD phase space channels**

Process:  $cc10 (e^- e^+ \rightarrow \mu^- \bar{\nu}_\mu u \bar{d})$

Color code: resonance, t-channel, radiation, infrared, collinear, external/off-shell

**Grove 1**

Multiplicity: 1  
Resonances: 2  
Log-enhanced: 0  
t-channel: 0

**Grove 2**

Multiplicity: 2  
Resonances: 2  
Log-enhanced: 1  
t-channel: 1

**Grove 3**

Multiplicity: 2  
Resonances: 2  
Log-enhanced: 0  
t-channel: 0

**WHIZARD phase space channels**

Process:  $q\bar{q}t\bar{d}cc (u\bar{u} \rightarrow b\bar{b}W^+W^-)$

Color code: resonance, t-channel, radiation, infrared, collinear, external/off-shell

**Grove 1**

Multiplicity: 2  
Resonances: 2  
Log-enhanced: 0  
t-channel: 0

**Grove 3**

Multiplicity: 3  
Resonances: 1  
Log-enhanced: 2  
t-channel: 2

**Grove 6**

Multiplicity: 3  
Resonances: 1  
Log-enhanced: 1  
t-channel: 1

**Grove 19**

Multiplicity: 4  
Resonances: 0  
Log-enhanced: 2  
t-channel: 0

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:

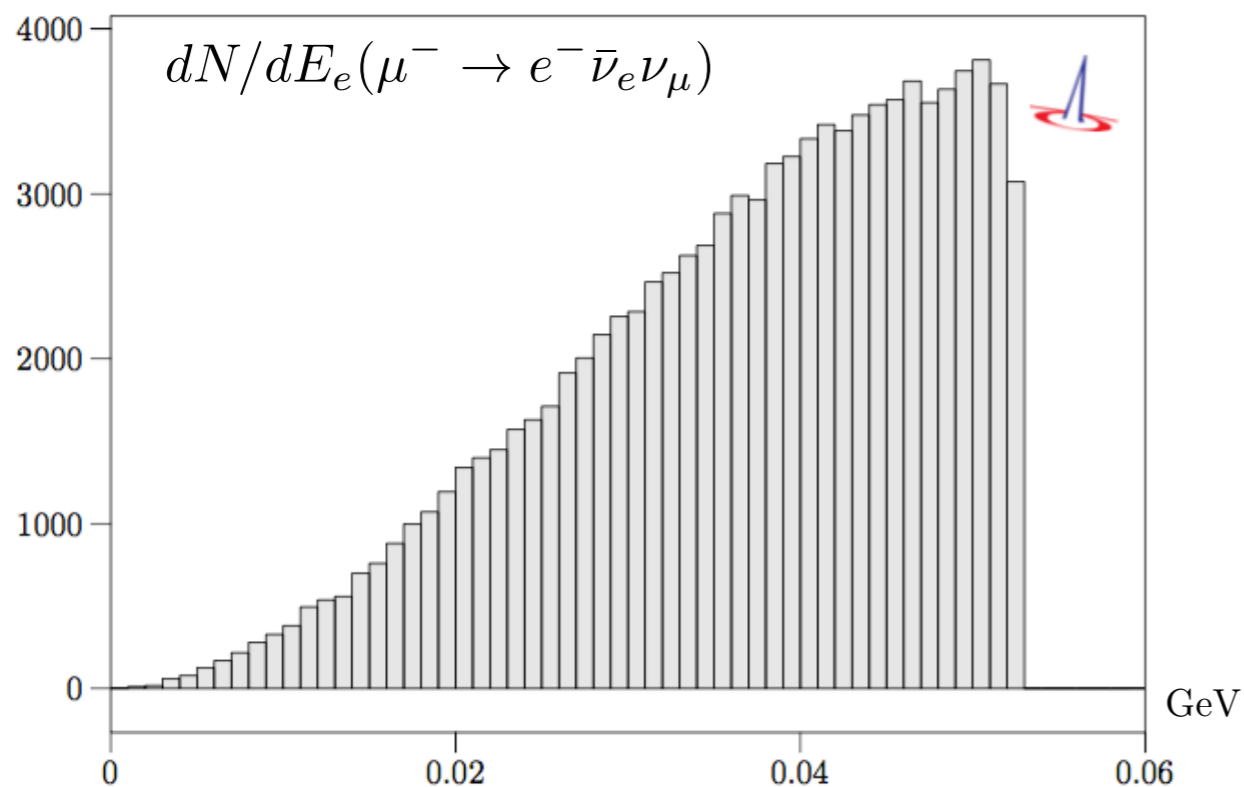
```
model = SM
process mudec = e2 => e1, N1, n2
integrate (mudec)

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" }
```





# Decay processes / auto\_decays

WHIZARD cannot only do scattering processes, but also decays

Example Energy distribution electron in muon decay:

```

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process mudec = e2 => e1, N1, n2
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```

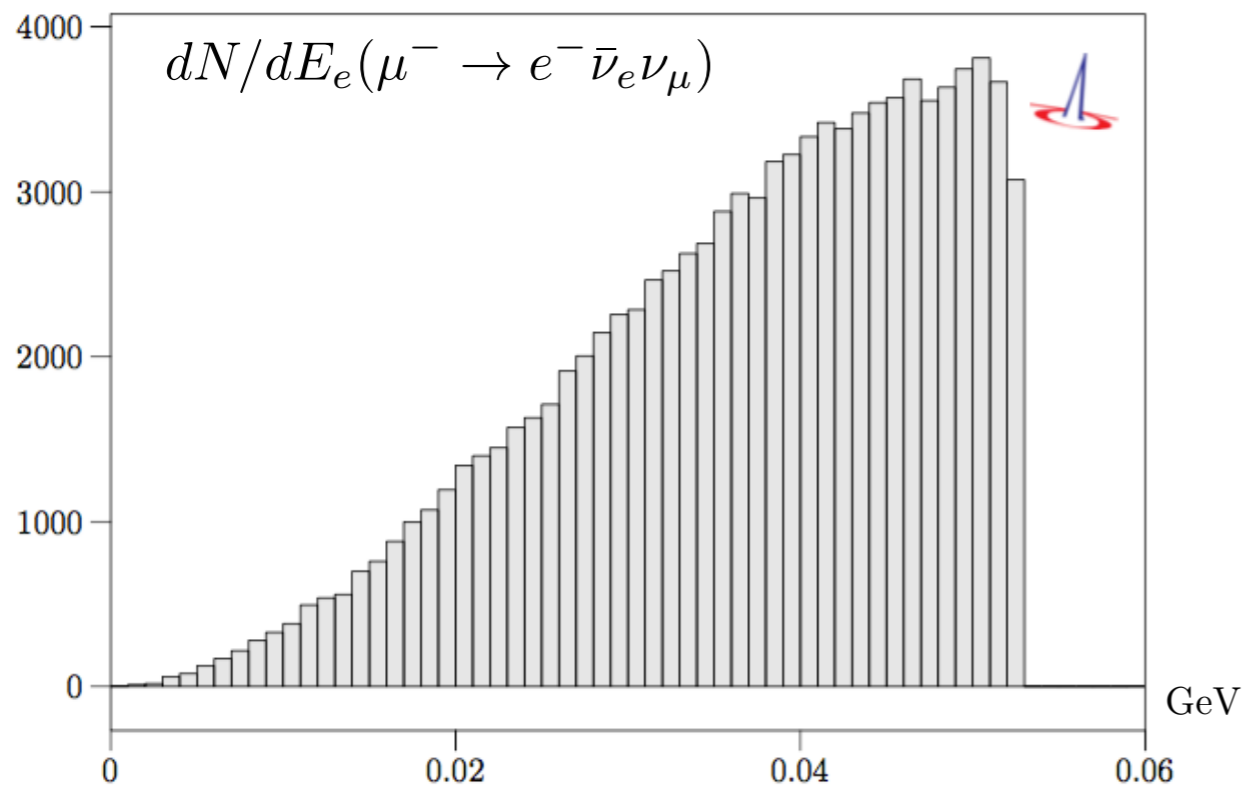
## Automatic integration of particle decays

```

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

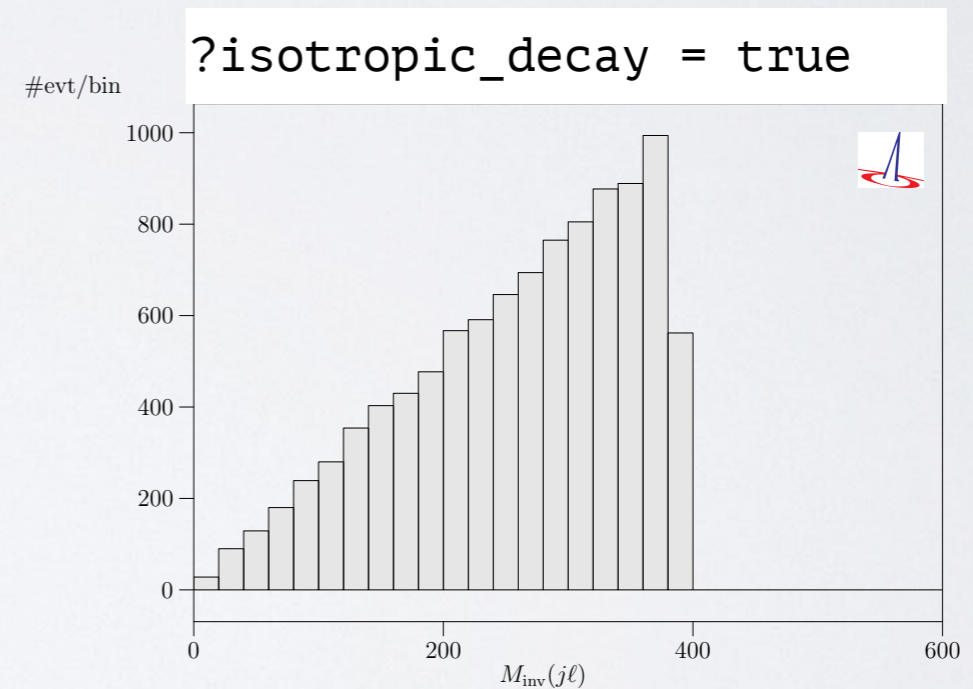
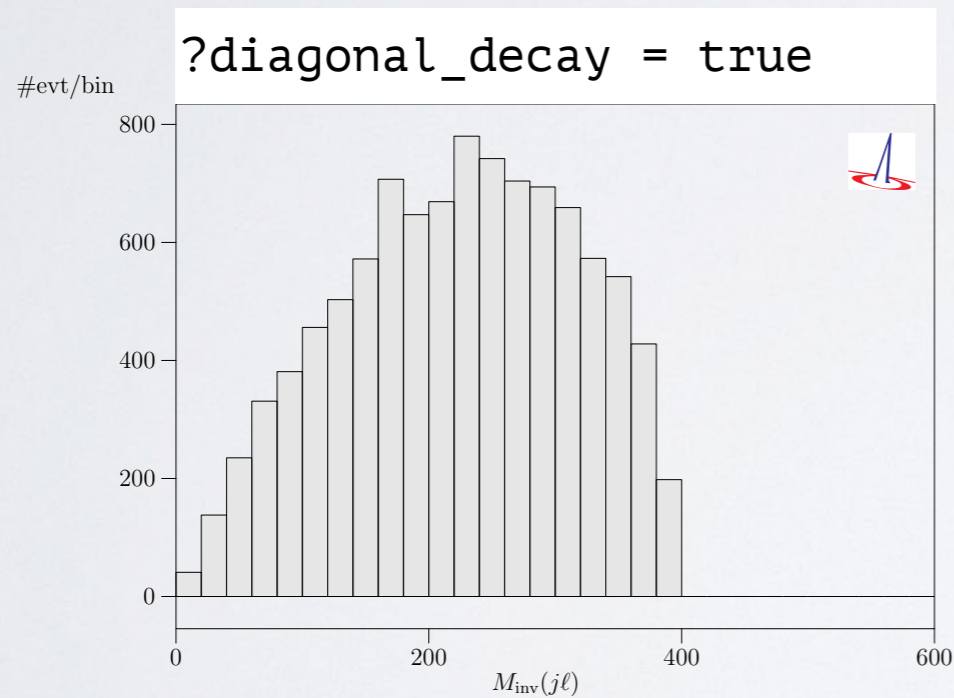
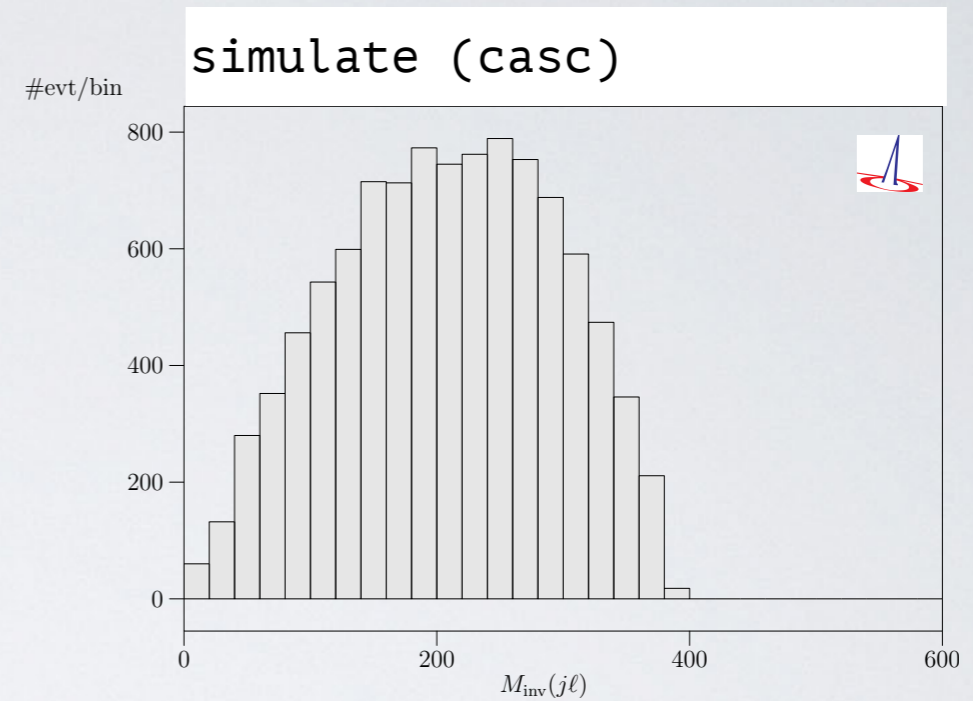
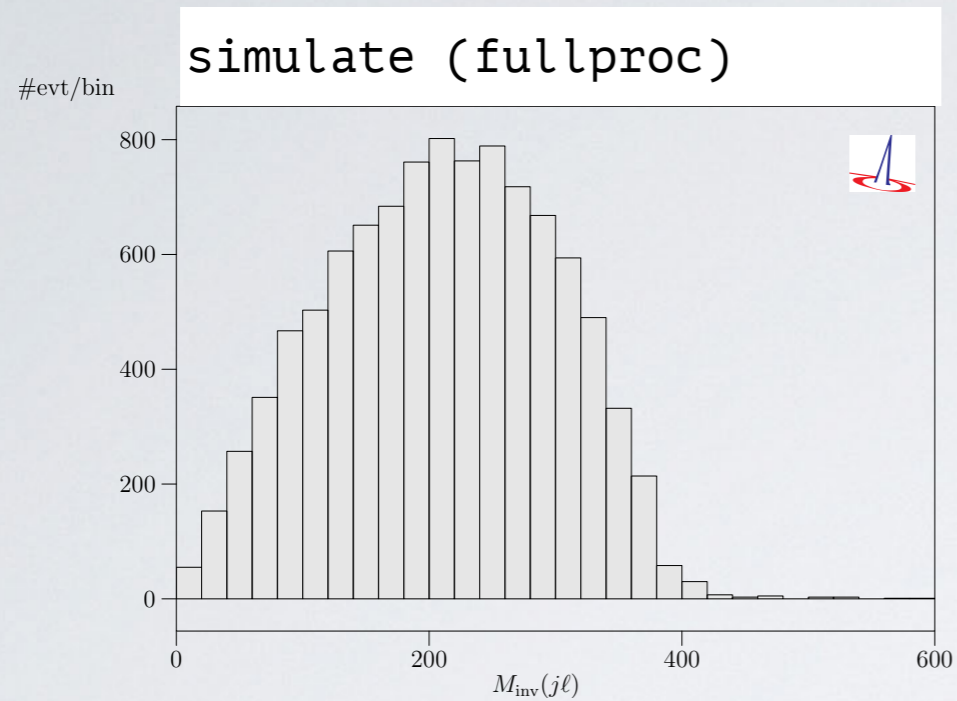
```





# Spin Correlation and Polarization in Cascades

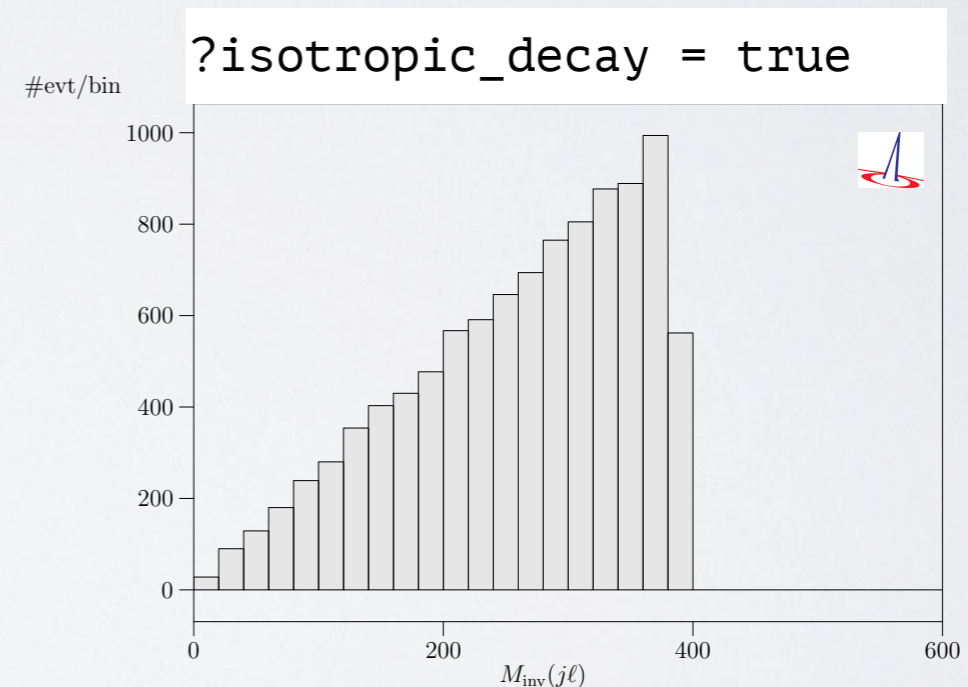
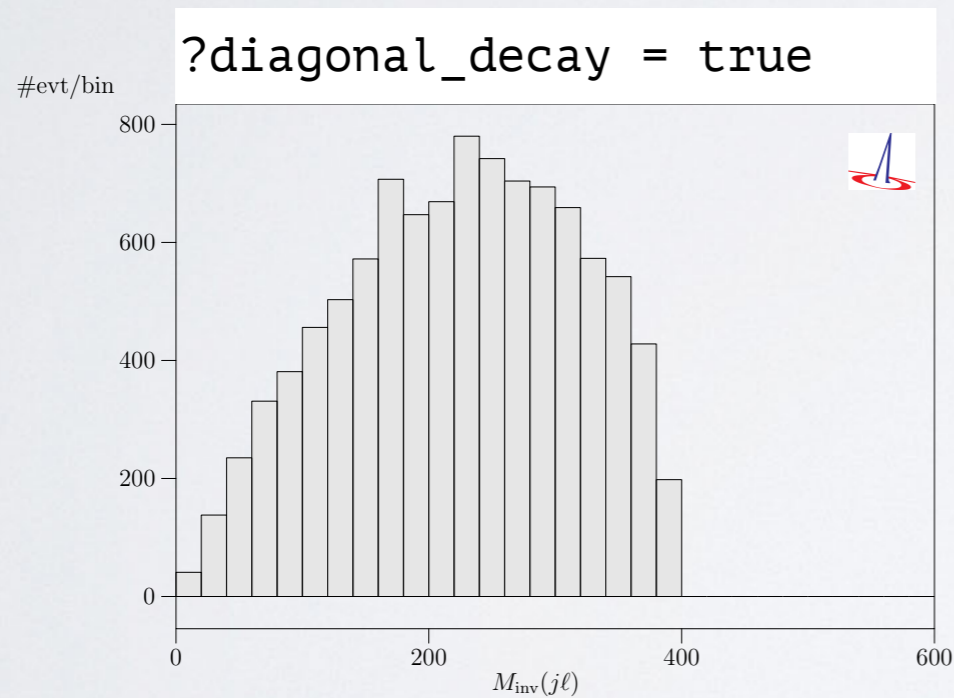
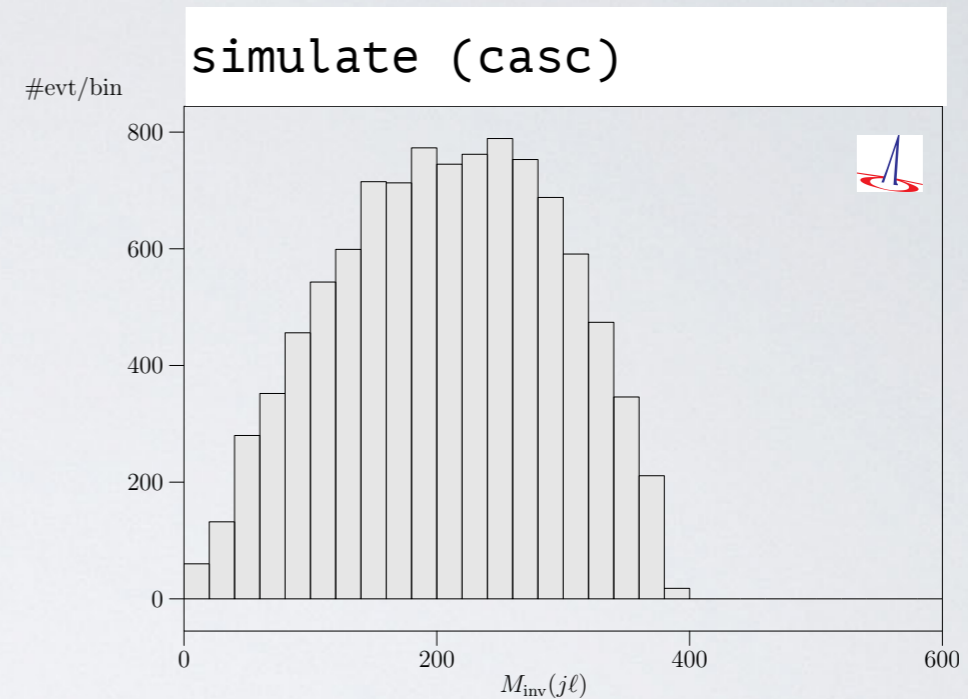
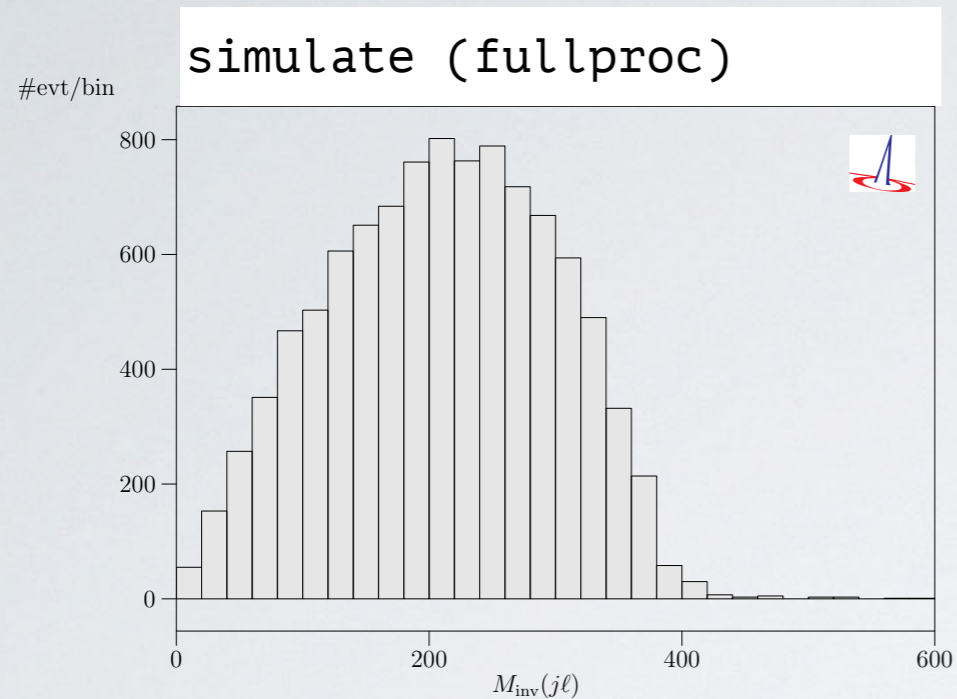
Cascade decay, factorize production and decay





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Cascade decay, factorize production and decay



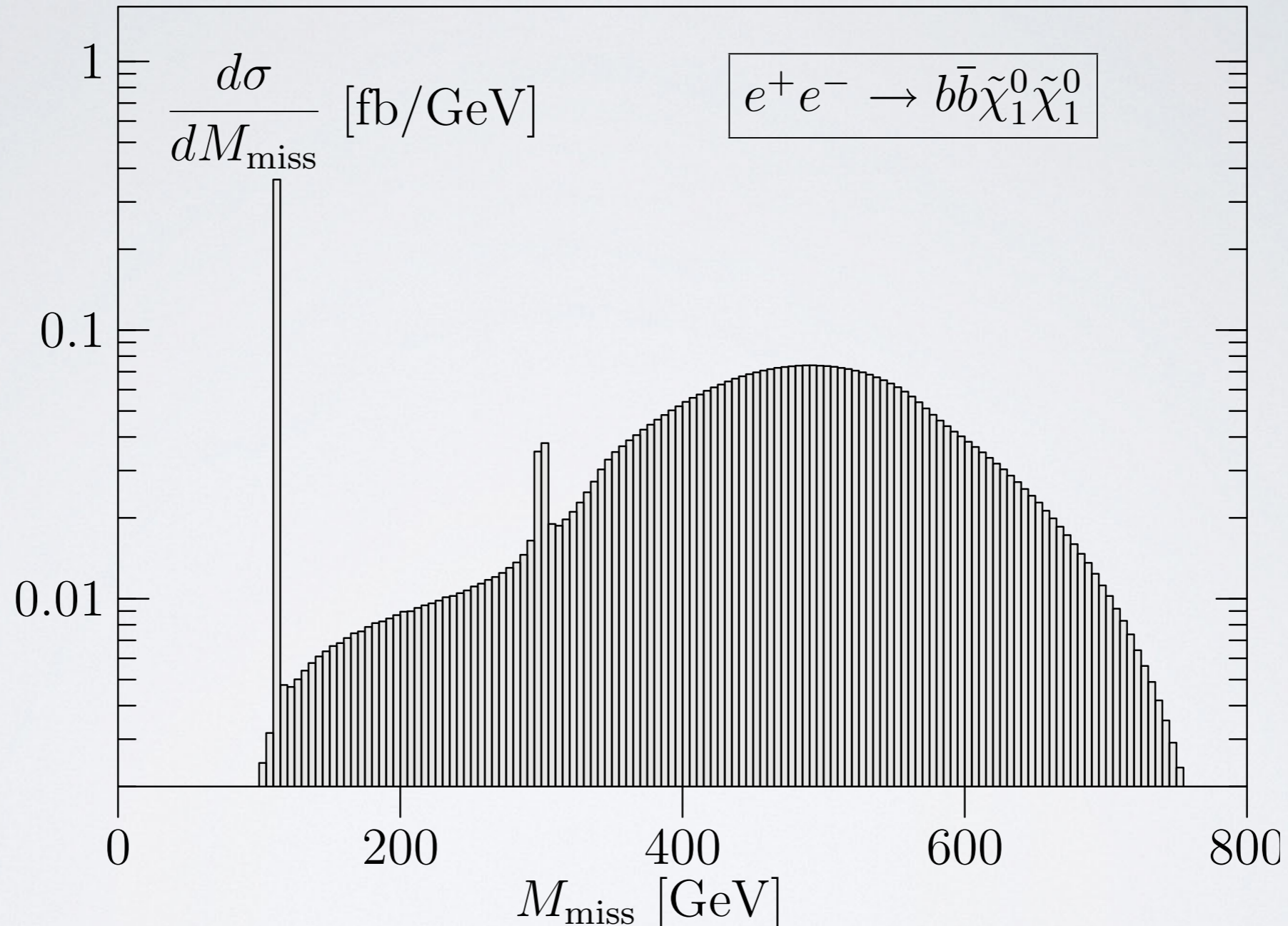
**NEW: possibility to select specific helicity in decays!**

unstable "W+" { decay\_helicity = 0 }



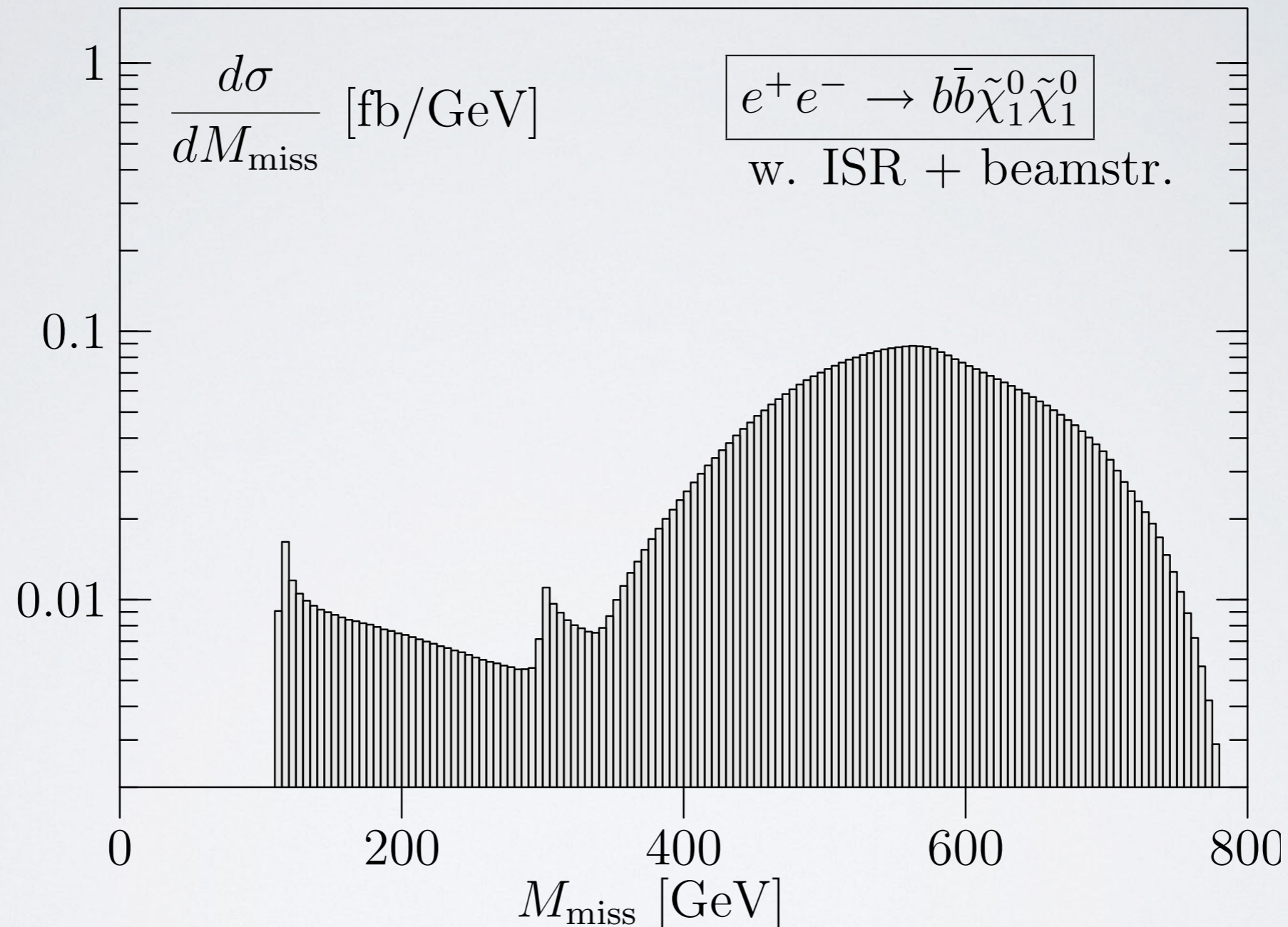


# Why care about beamstrahlung / ISR ?





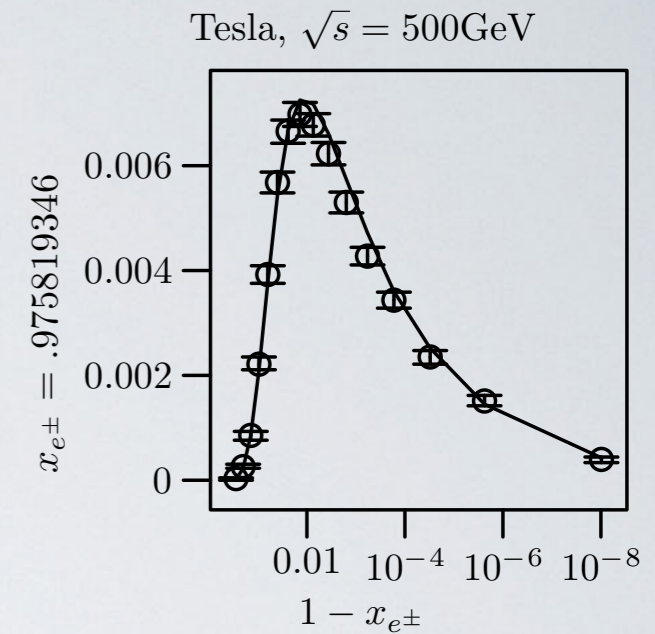
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# Lepton Collider Beam Simulation

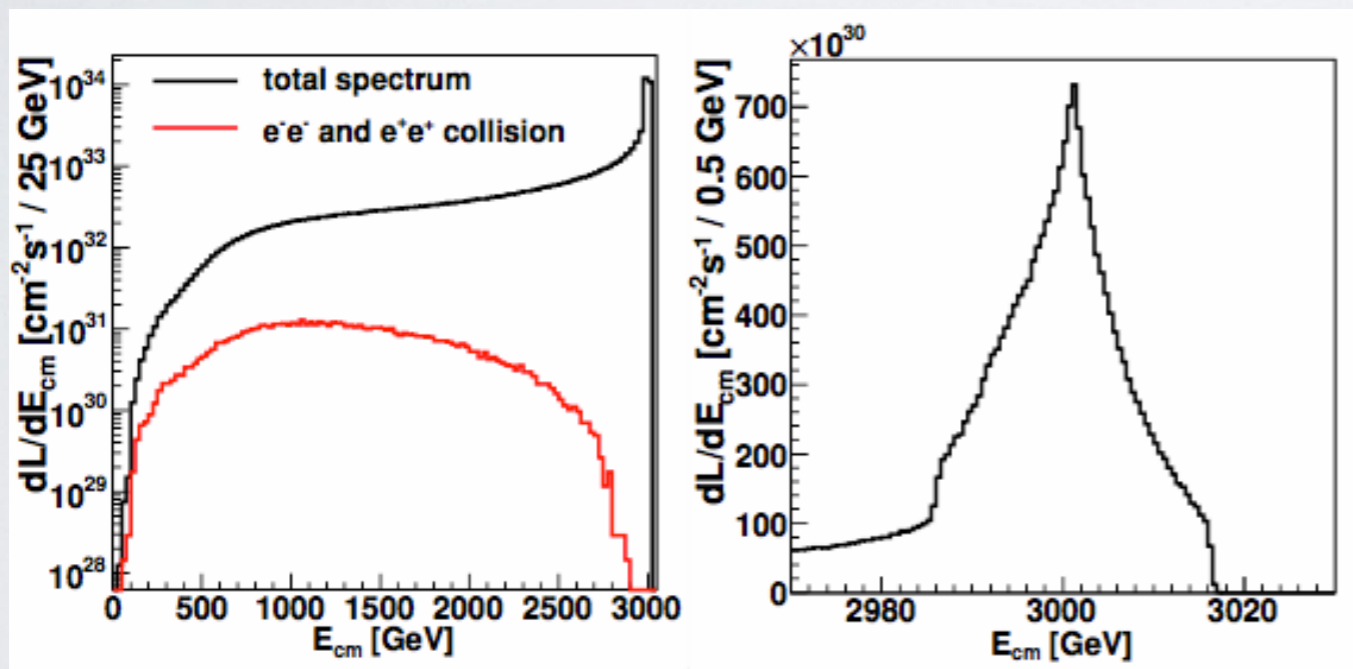
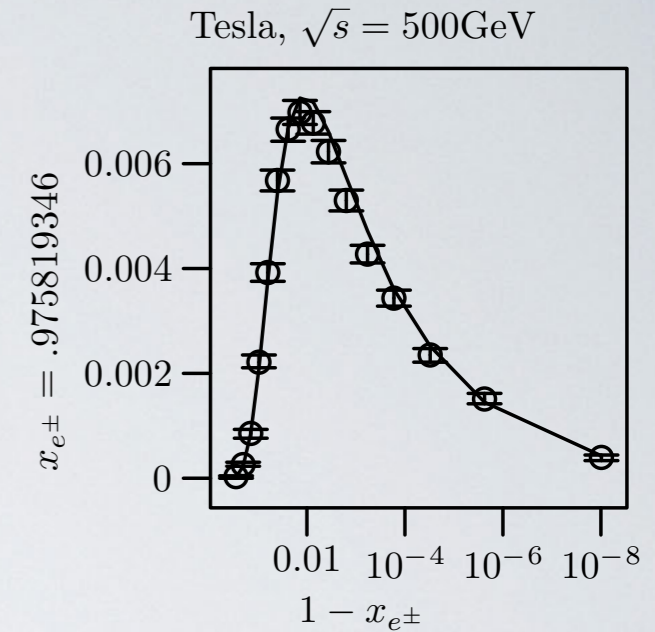
- Another demand: adapt GuineaPig beam spectra for WHIZARD v2
- For WHIZARD v1.95 simulations done by Lumilinker [\[T. Barklow\]](#)
- TESLA/SLC spectra were rather simple
- Fits with 6 or 7 parameters possible [CIRCE1]
- **Beams not factorizable:**  $D_{B_1 B_2}(x_1, x_2) \neq D_{B_1}(x_1) \cdot D_{B_2}(x_2)$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

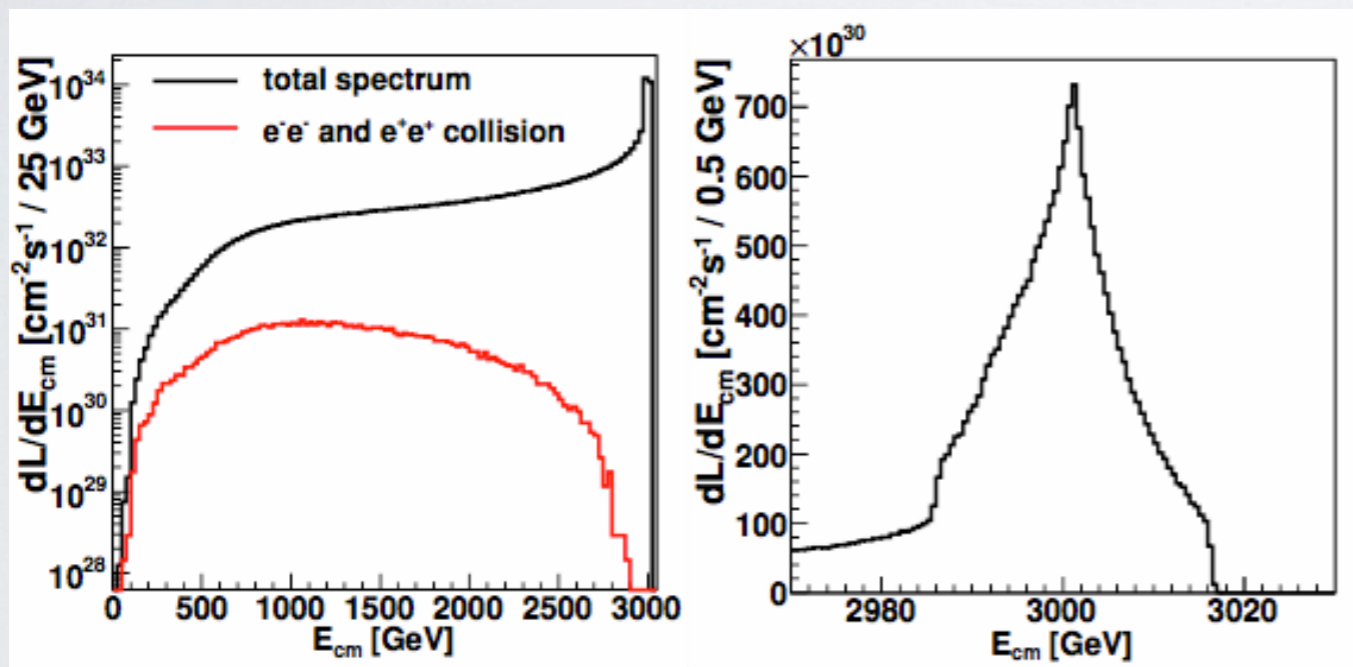
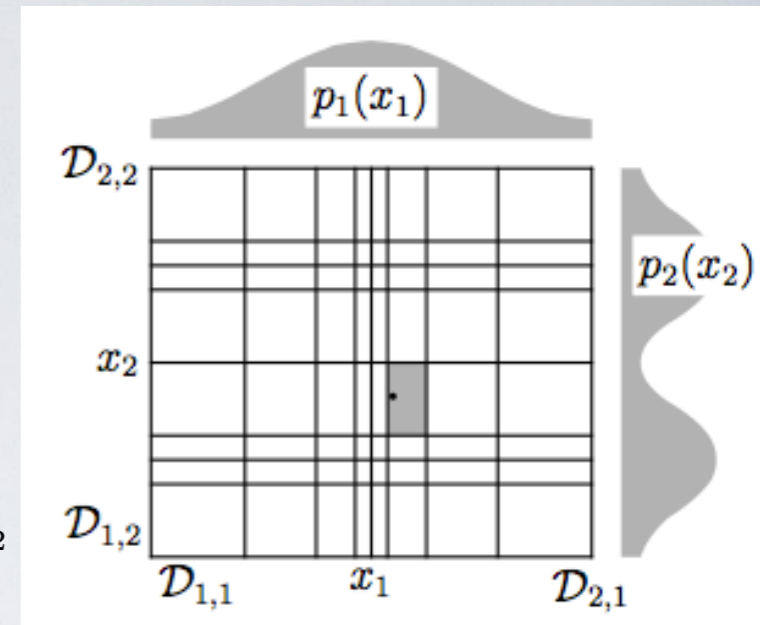






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Tails @ CLIC much more complicated (wakefields)

## 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
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$circe2_design = "ILC"
?circe_polarized = false
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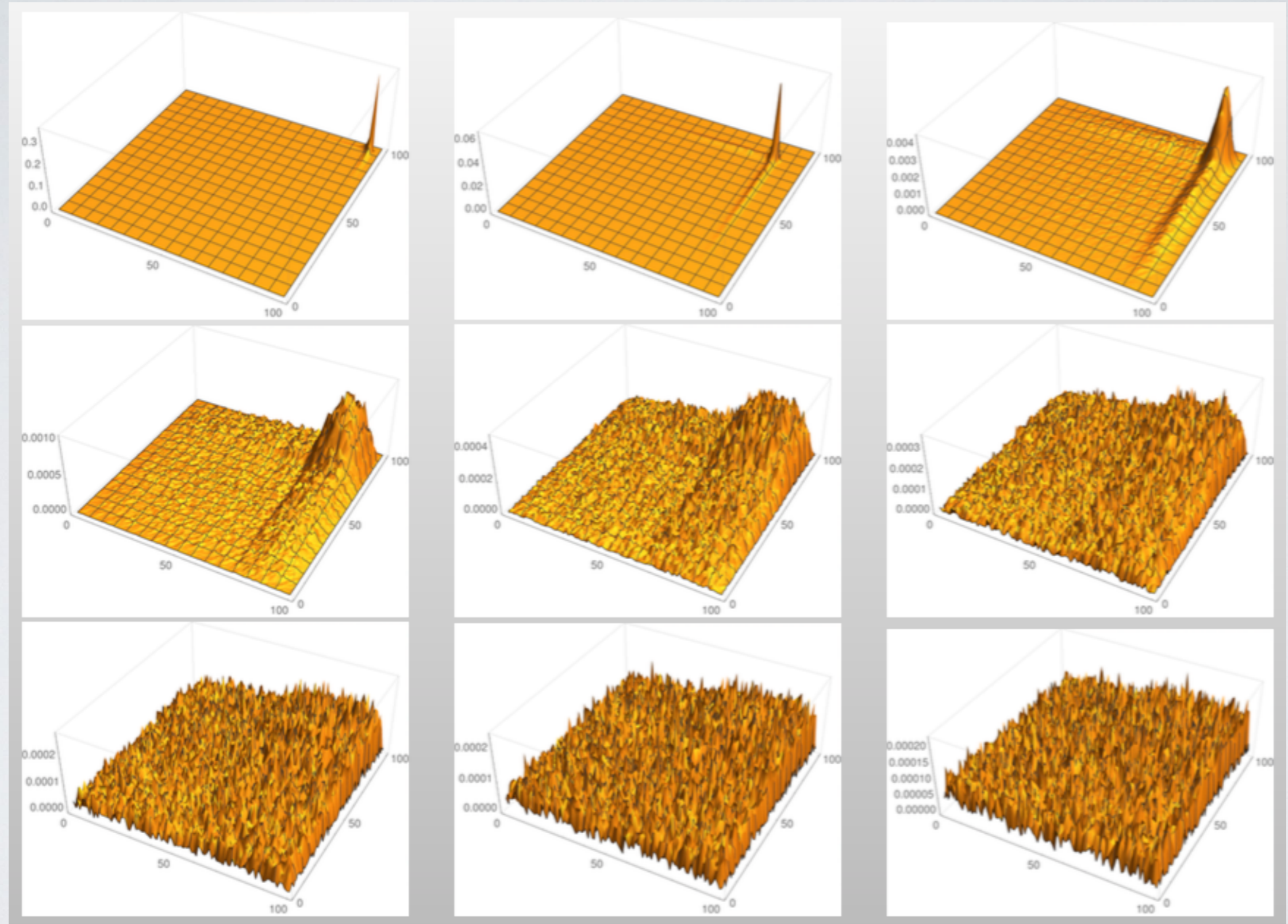
3 simulation options

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

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



# Iterations of Beam Spectrum



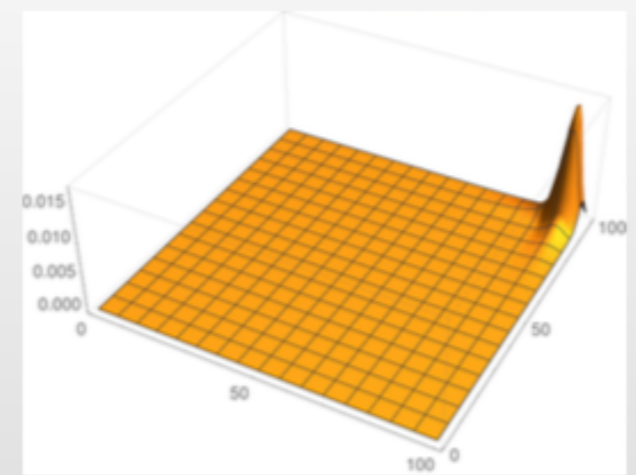
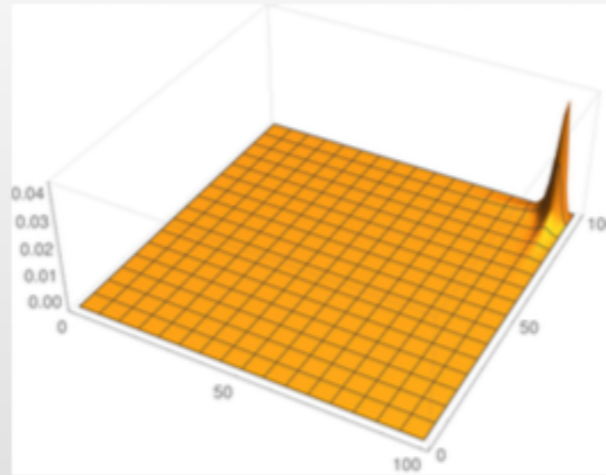
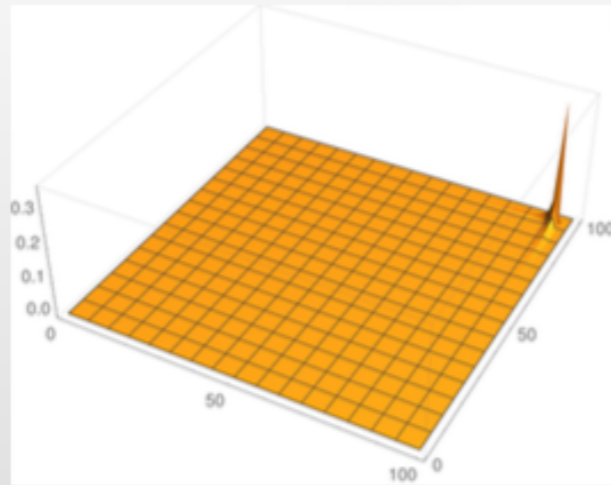
(171,306 GuineaPig events in 10,000 bins)



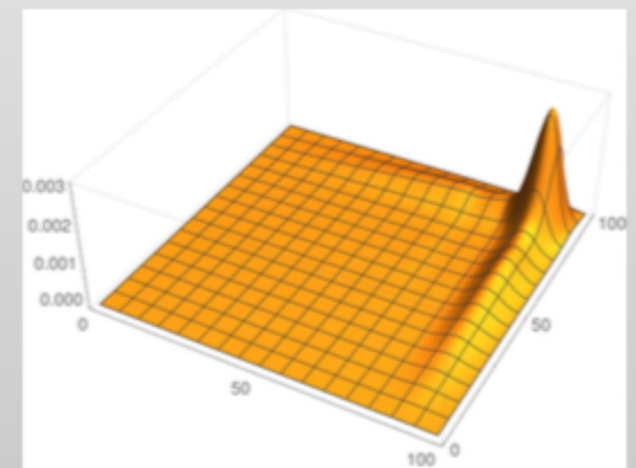
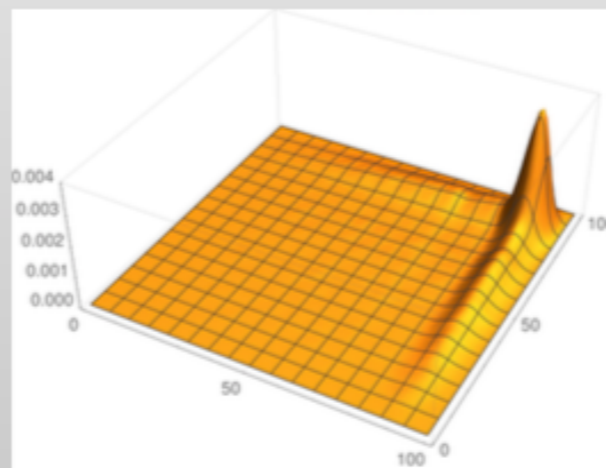
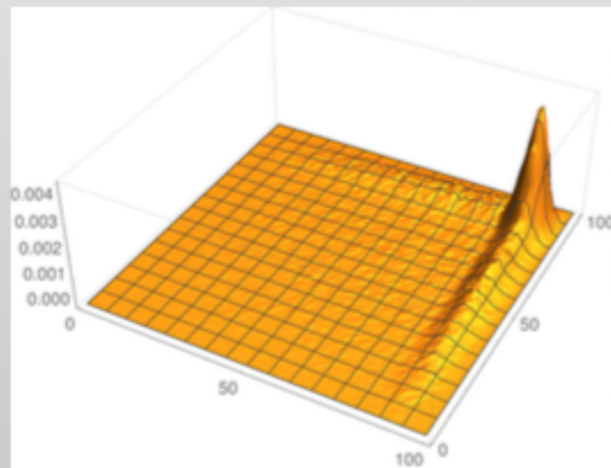


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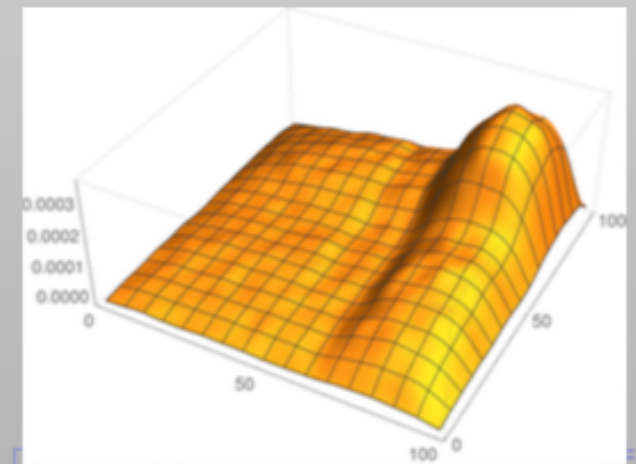
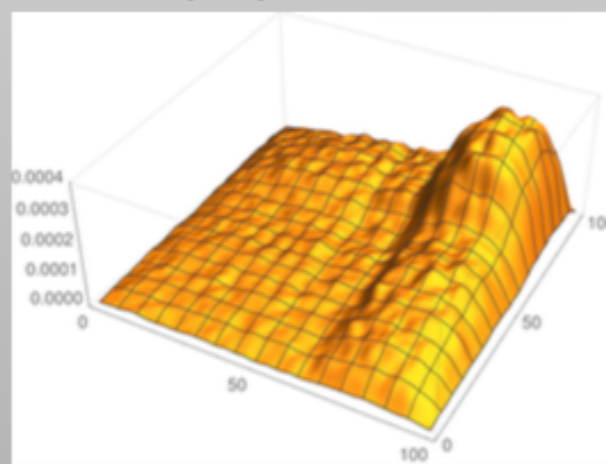
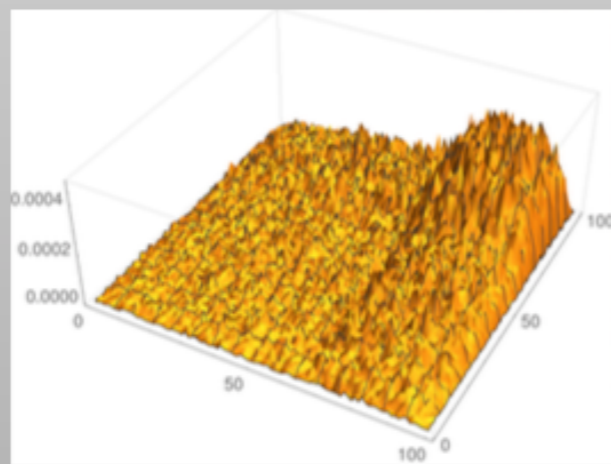
- ▶ **iterations = 0** and **smooth = 0, 3, 5:**



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



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

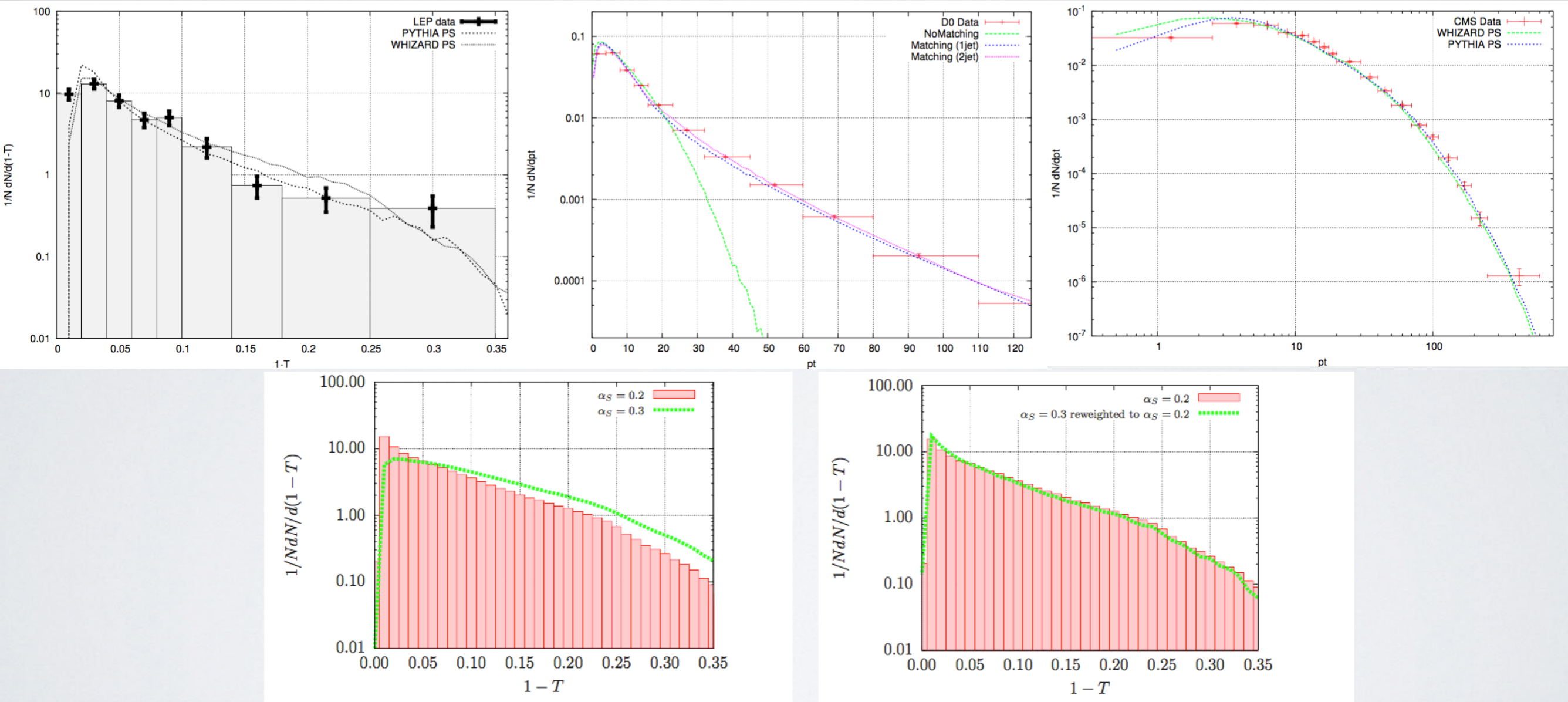




# WHIZARD Parton Shower

- ▶ Two independent implementations: kT-ordered QCD and Analytic QCD shower
- ▶ Analytic shower: no shower veto  $\Rightarrow$  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)

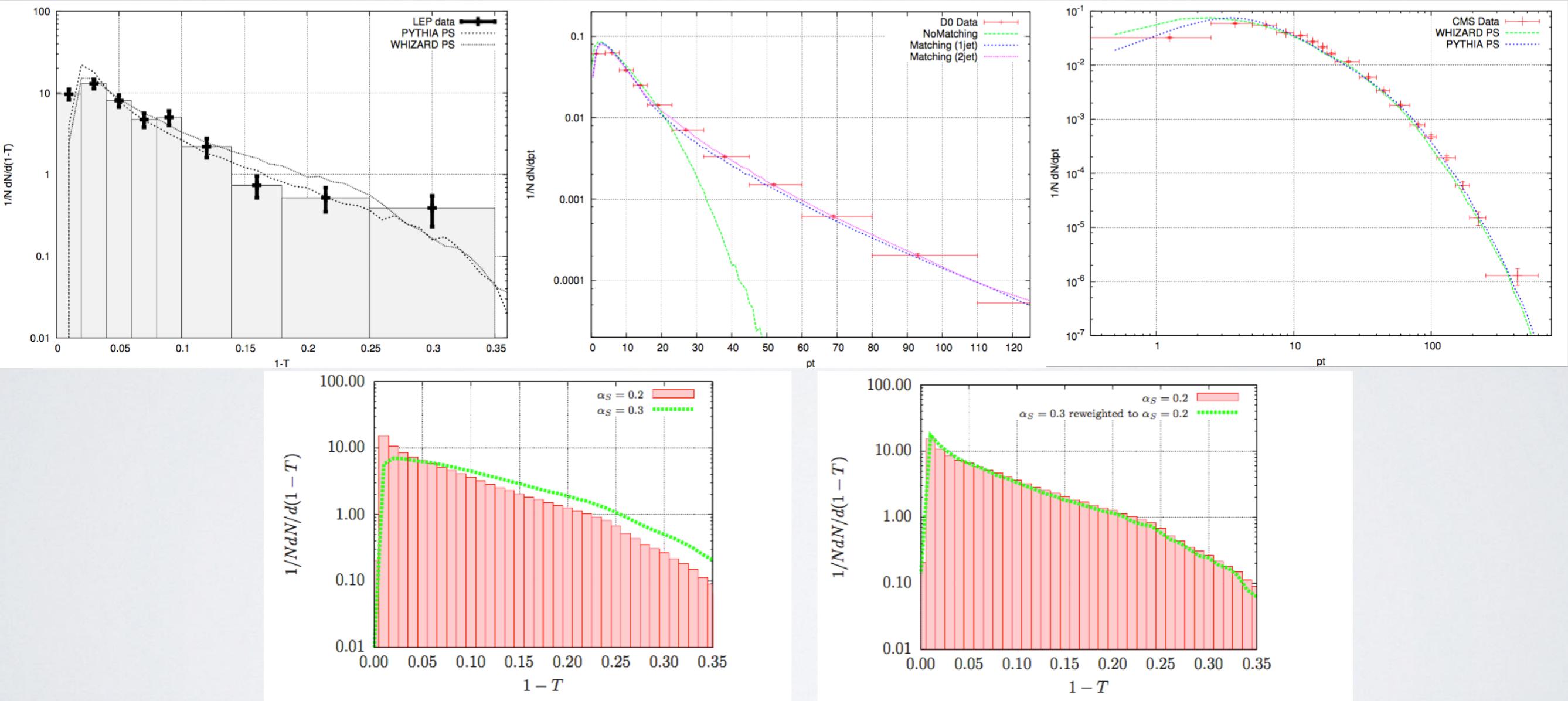




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## 2) Fixed-order NLO automation & POWHEG matching in WHIZARD





# 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

1. Process definition in SINDARIN (contract to One-Loop Program [OLP])
2. OLP generates code (Born/virtual interference), WHIZARD reads contract
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Working NLO interfaces to:

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QCD corrections (massless and massive emitters)

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alpha_power = 2
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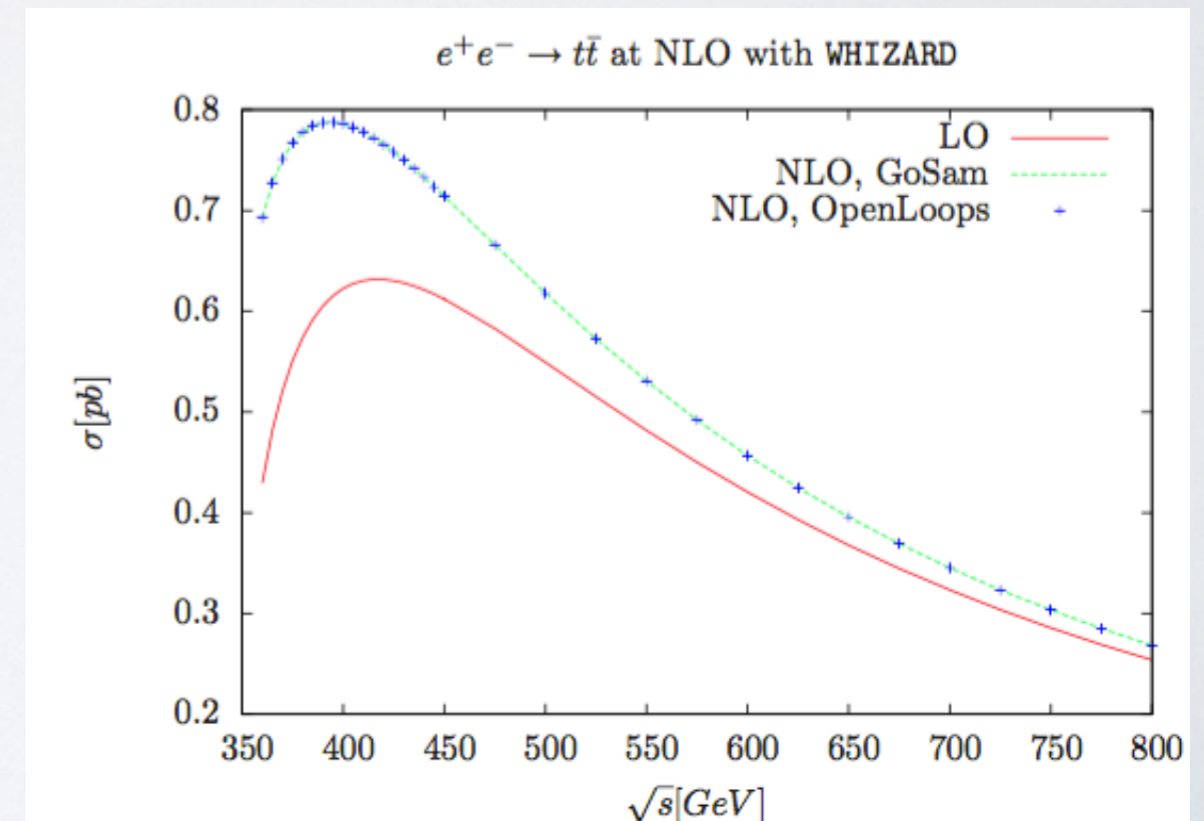
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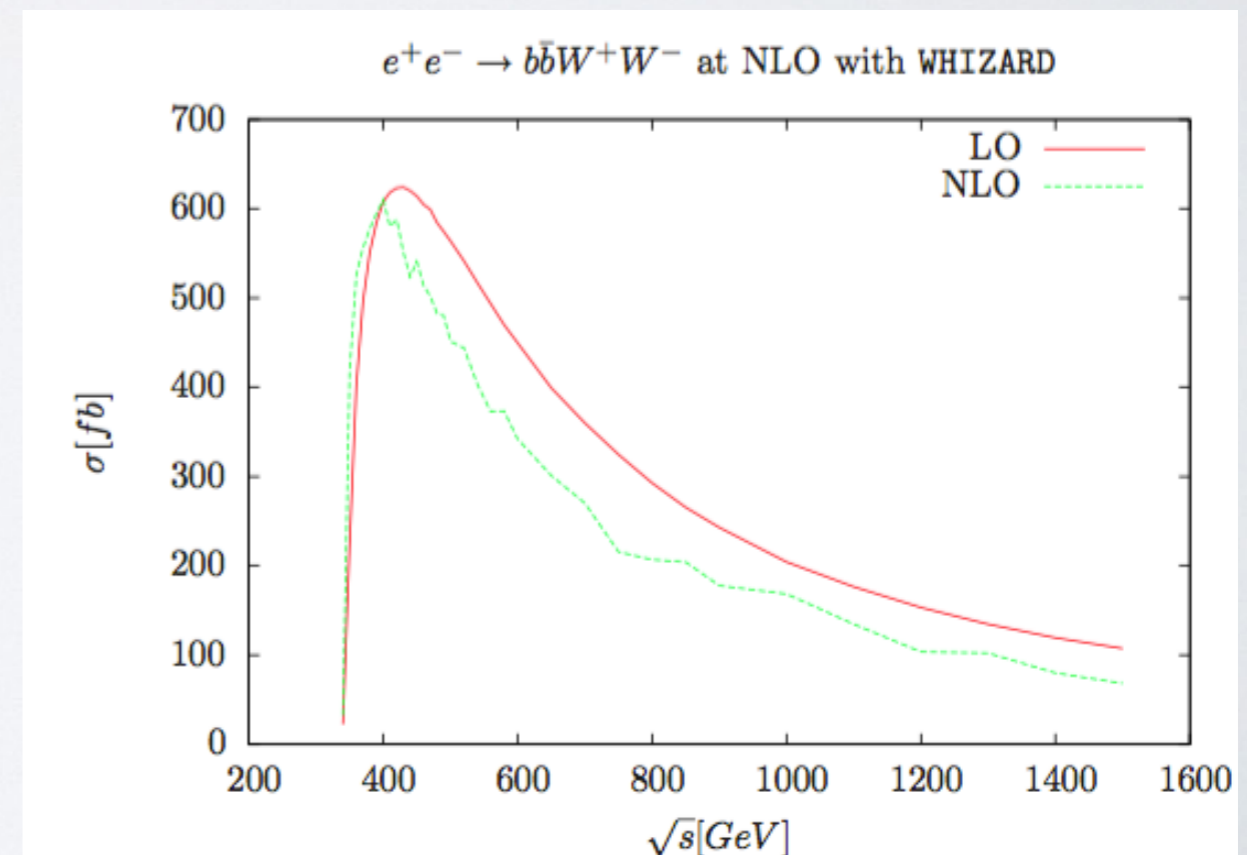
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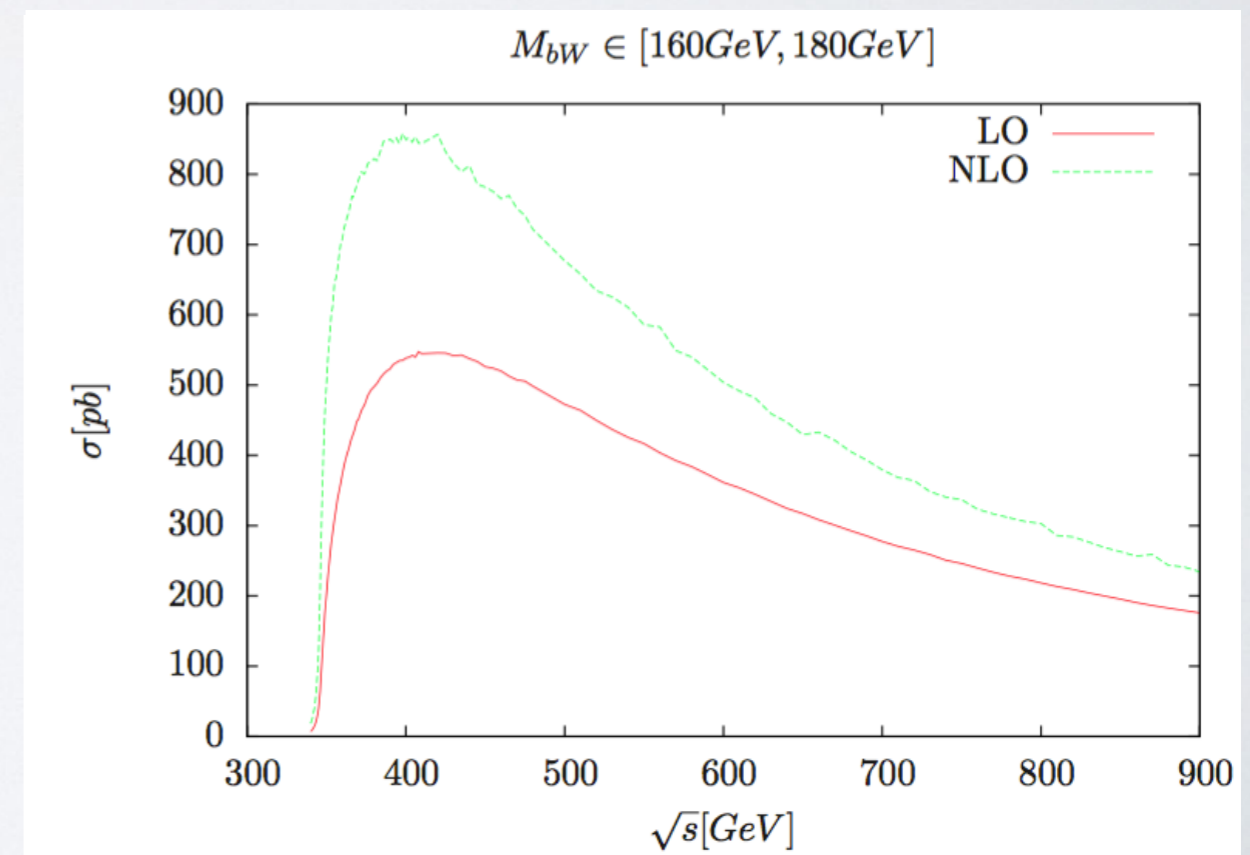
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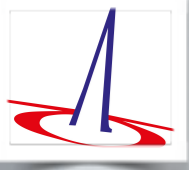
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# FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

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

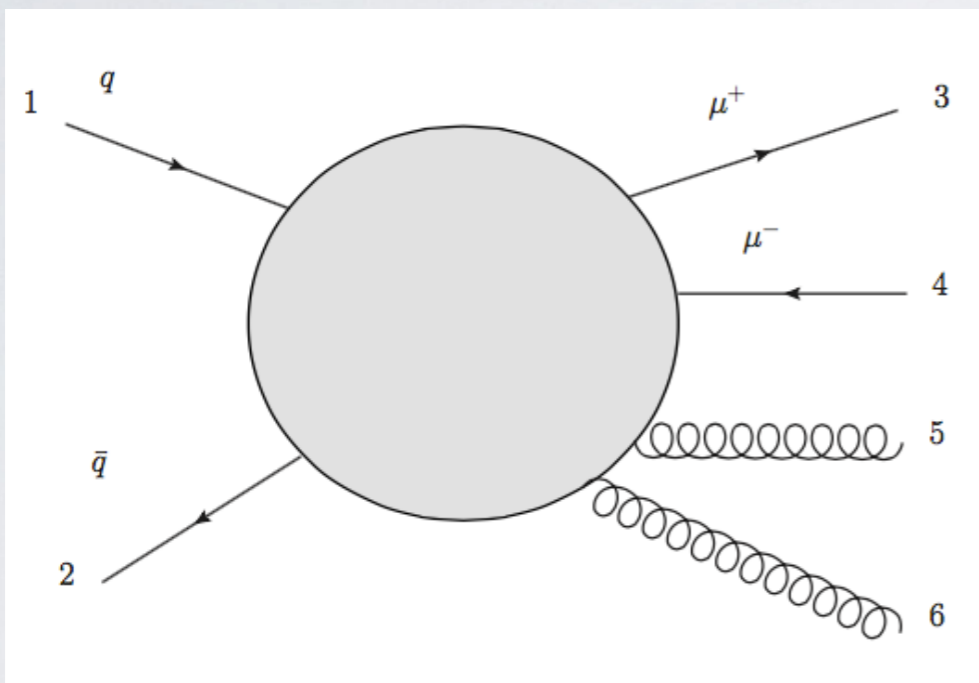


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Automated subtraction terms in WHIZARD, algorithm:



- \* 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



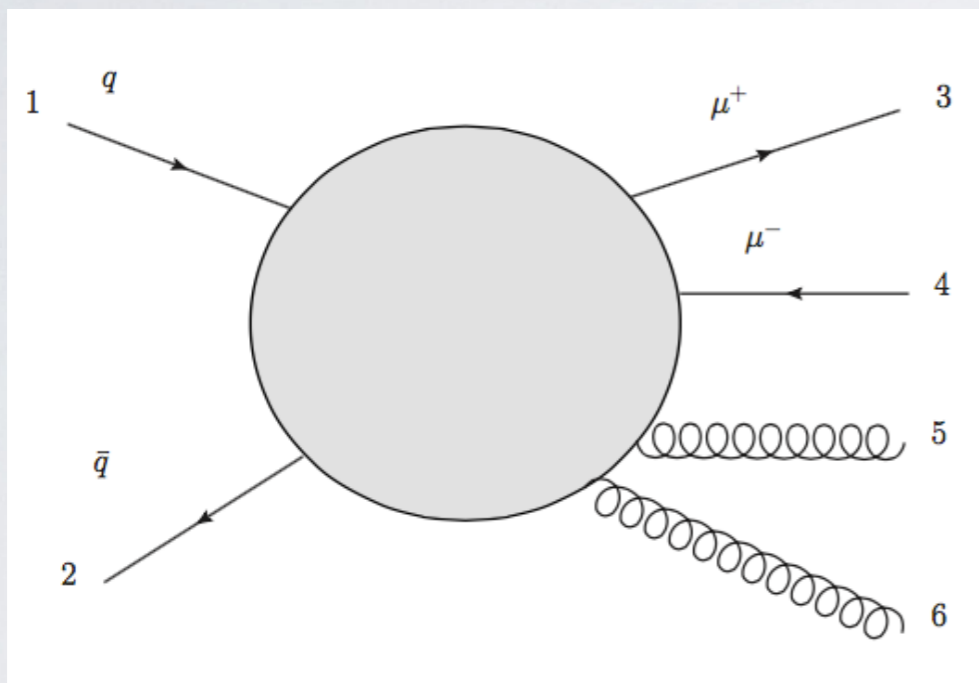


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- \* Generate subtraction terms for singular regions

Soft subtraction involves color-correlated matrix elements:

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

Collinear subtraction involves spin-correlated matrix elements:

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



# Examples and Validation

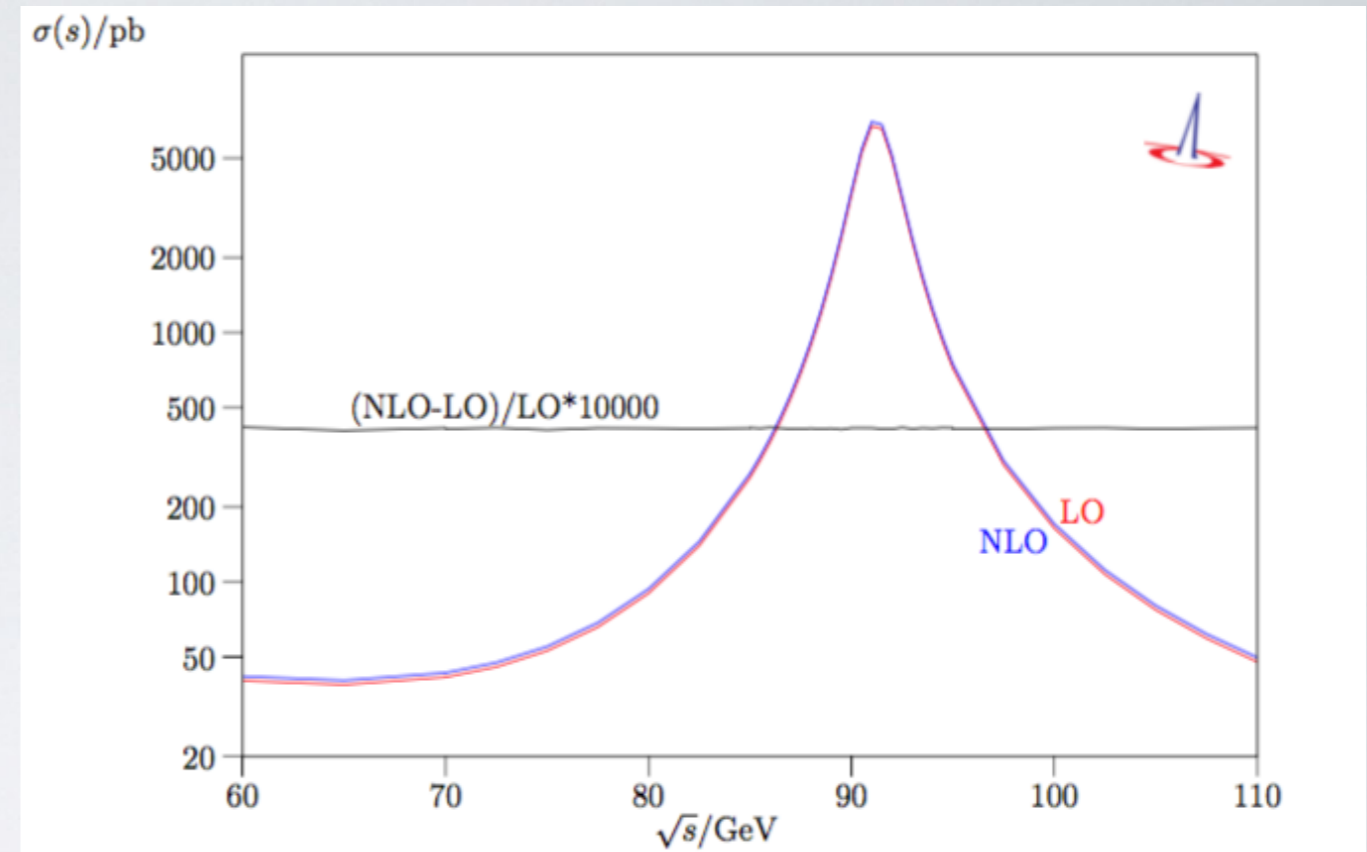
## Simplest benchmark process:

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

Plot for total cross section for fixed strong coupling constant

## List of validated QCD NLO processes

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



- Cross-checks with MG5\_aMC@NLO
- Phase space integration for virtuals performs great



# Examples and Validation

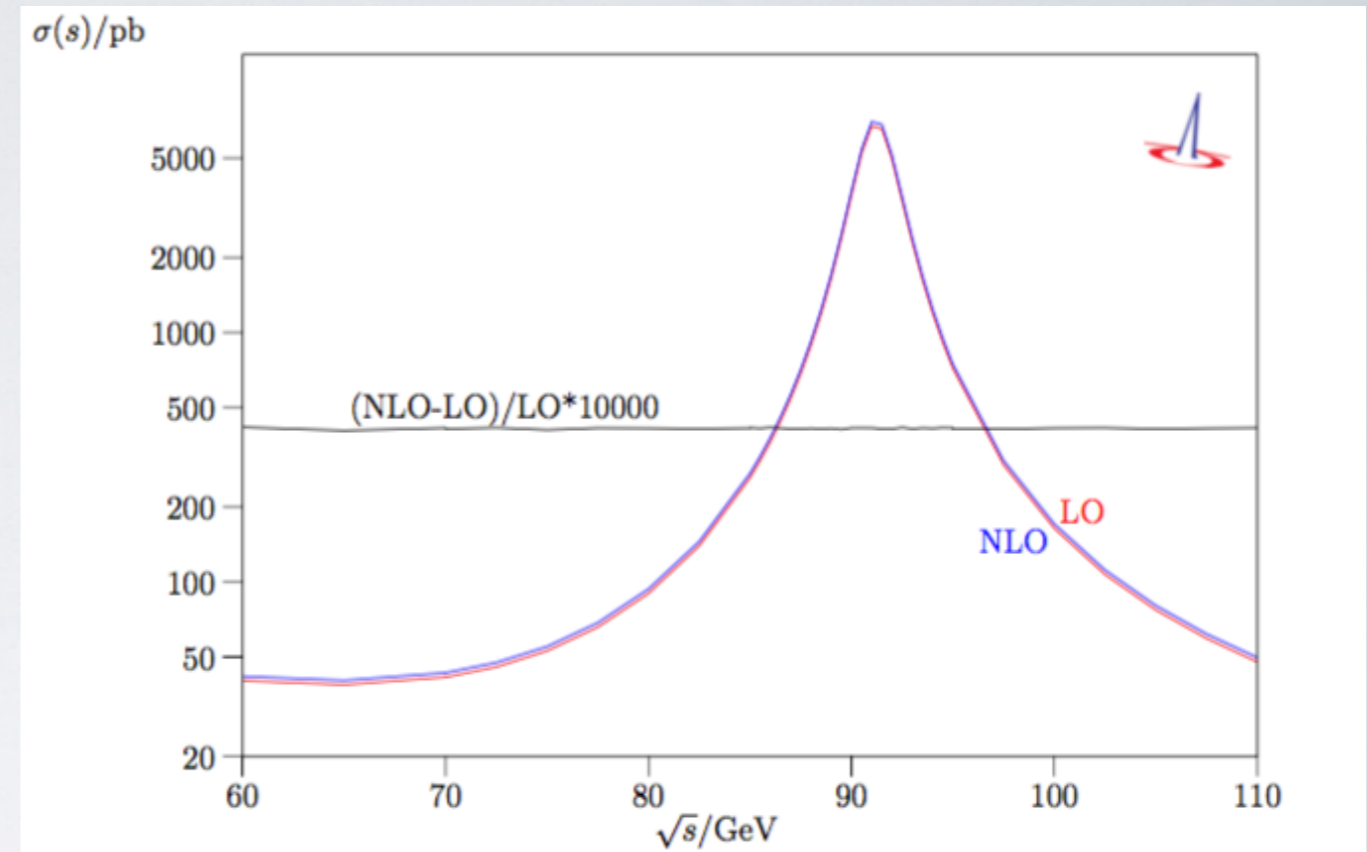
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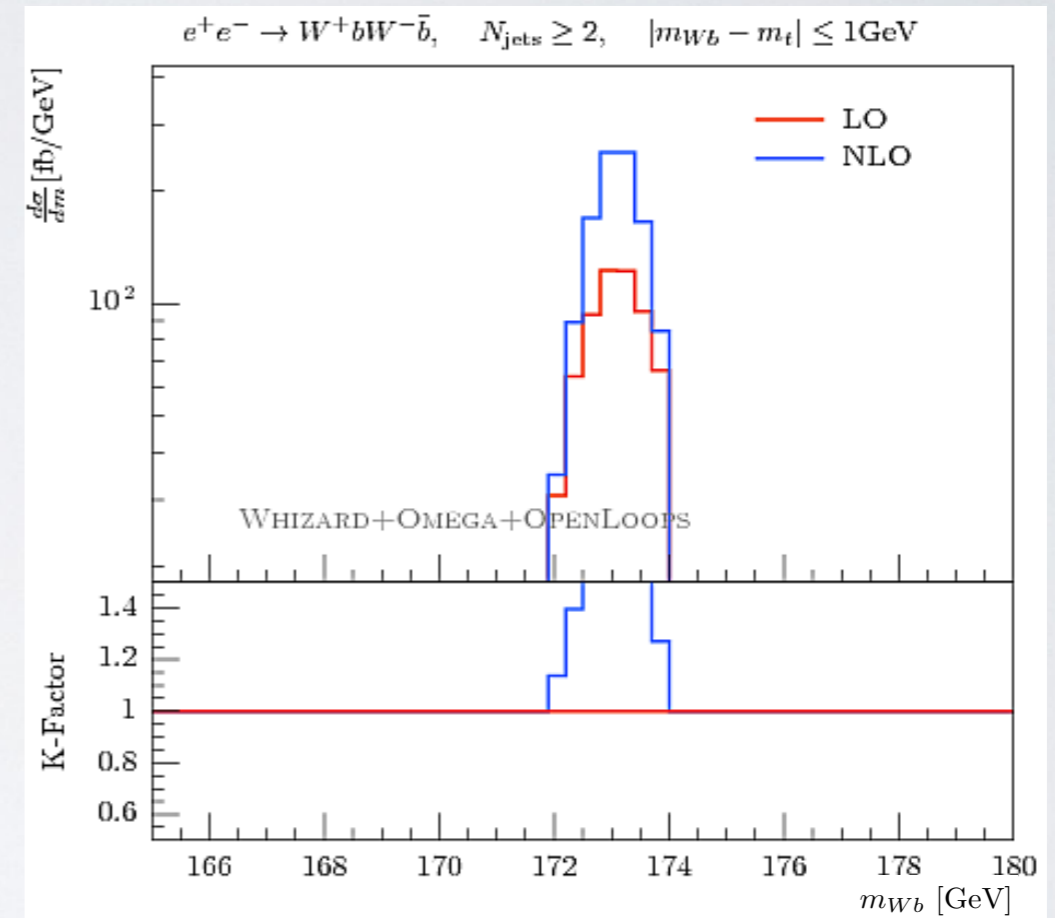
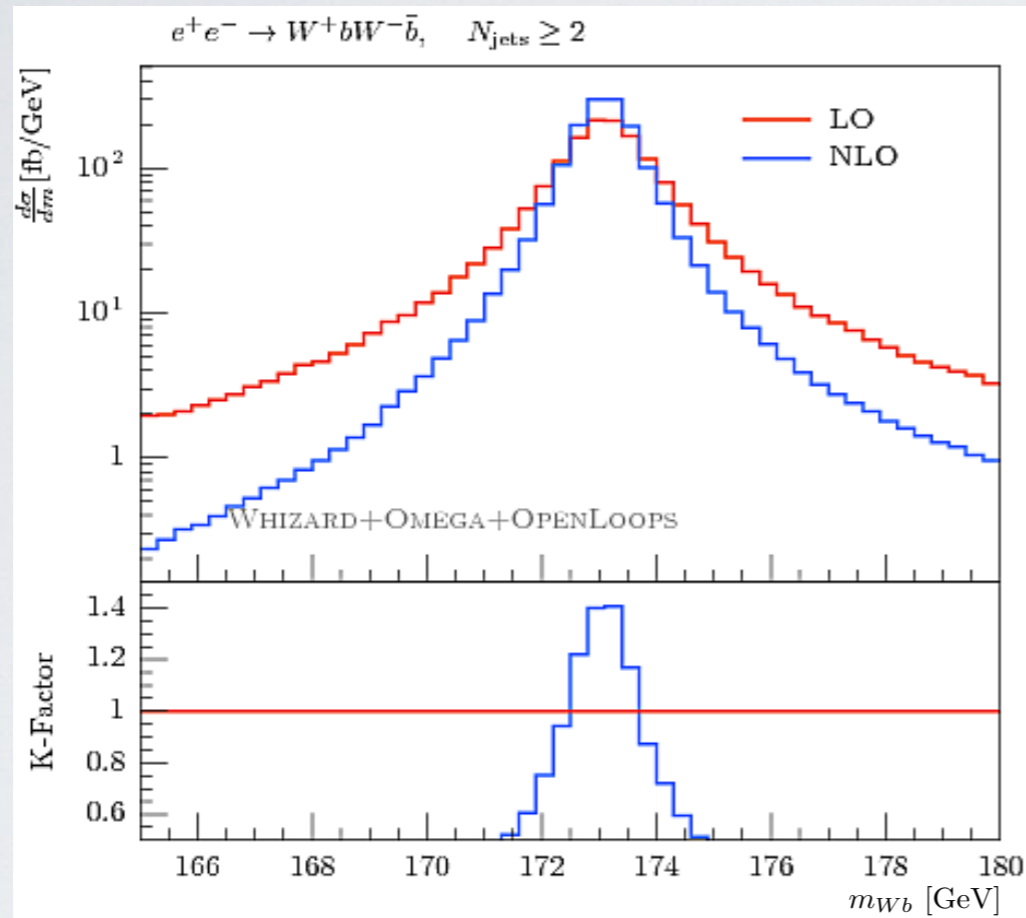
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- ◆ QCD NLO infrastructure in pp almost complete
- ◆ First attempts on electroweak corrections, interfacing the RECOLA code [Denner et al.]



# NLO Fixed-Order Events

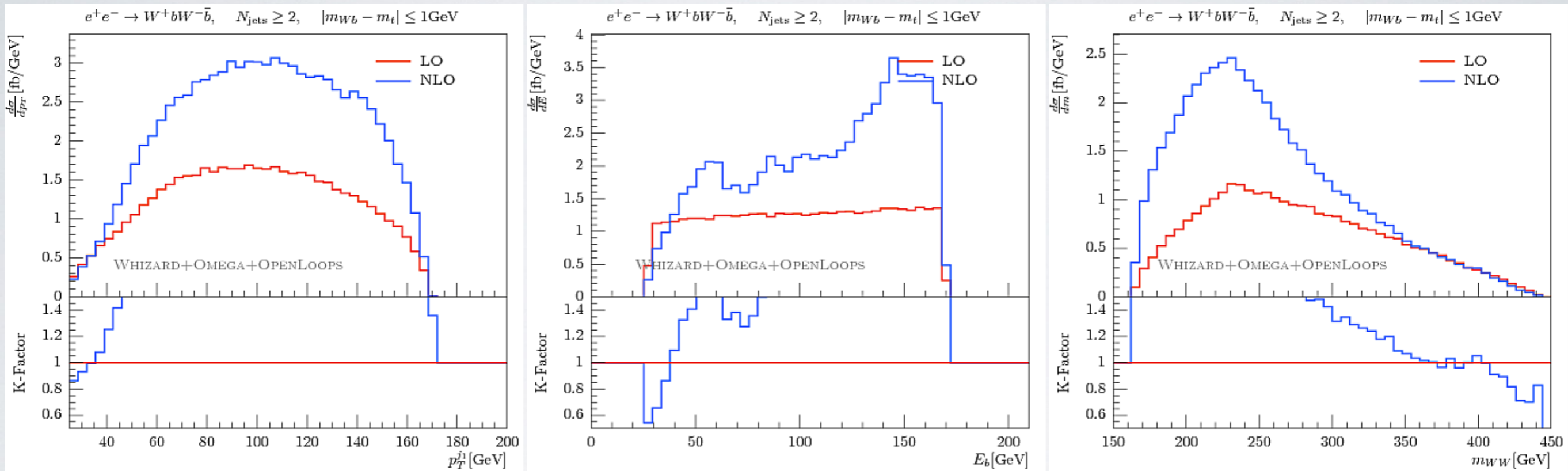
- Add weights of real emission events to weight of Born kinematics using the FKS mapping
- Output weighted events in WHIZARD (e.g. using HepMC), then analysis with Rivet
- Example process:  $e^+e^- \rightarrow W^+W^-b\bar{b}$





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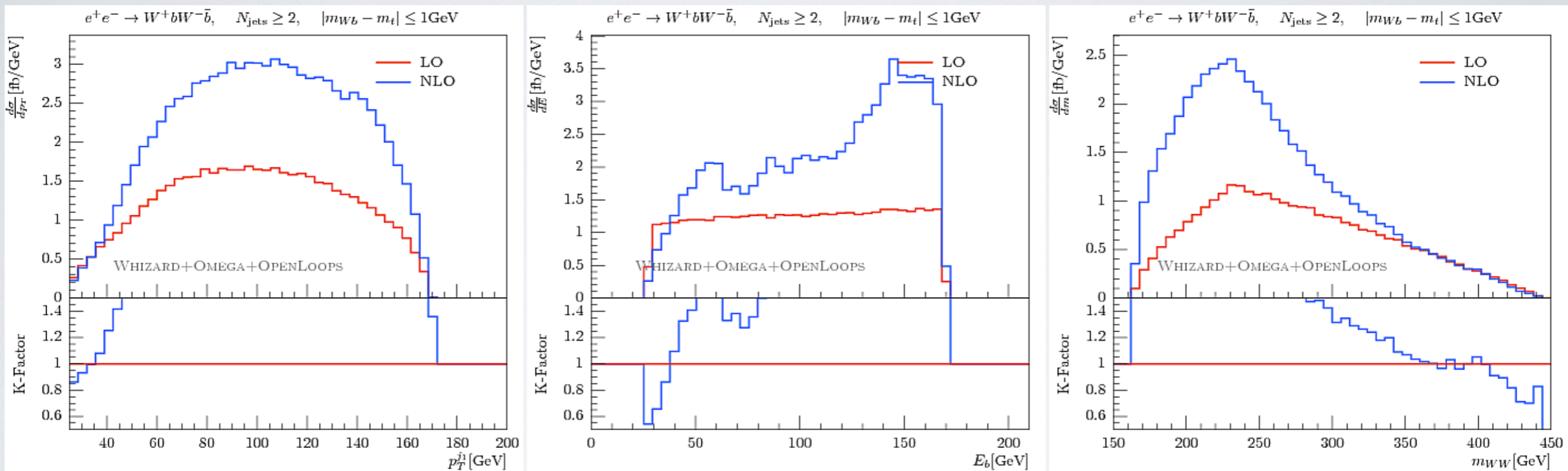
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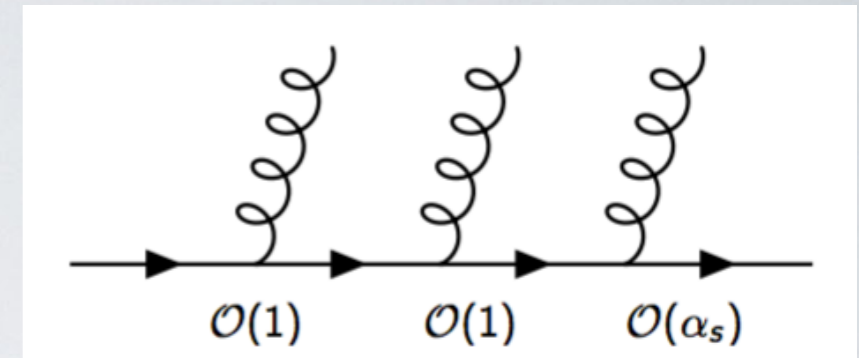
- Next steps: produce polarized results (remember: ILC will always run with polarization)
- Produce also plots including complete ISR photon radiation and beamstrahlung
- Investigate the full  $2 \rightarrow 6$  process:  $e^+e^- \rightarrow bbe\mu\nu\nu$  [Chokouf /Kilian/Lindert/JRR/Pozzorini/Weiss]

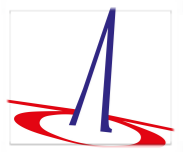




# Automated POWHEG Matching in WHIZARD

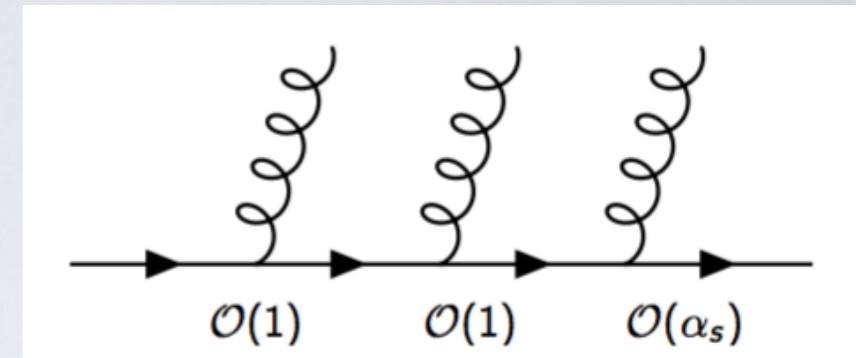
- **Soft gluon emissions before hard emission generate large logs**
- Perturbative  $\alpha_s$ :  $|\mathcal{M}_{\text{soft}}|^2 \sim \frac{1}{k_T^2} \rightarrow \log \frac{k_T^{\text{max}}}{k_T^{\text{min}}}$
- Consistent matching of NLO matrix element with shower
- **POWHEG method**: hardest emission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





# Automated POWHEG Matching in WHIZARD

- **Soft gluon emissions before hard emission generate large logs**
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- **Complete NLO events**

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

- POWHEG generate events according to the formula:

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

- **Uses the modified Sudakov form factor:**

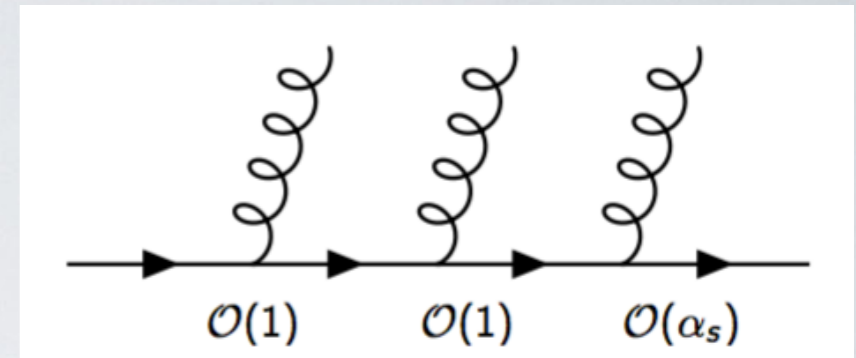
$$\Delta_R^{\text{NLO}}(k_T) = \exp \left[ - \int d\Phi_{\text{rad}} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \theta(k_T(\Phi_{n+1}) - k_T) \right]$$





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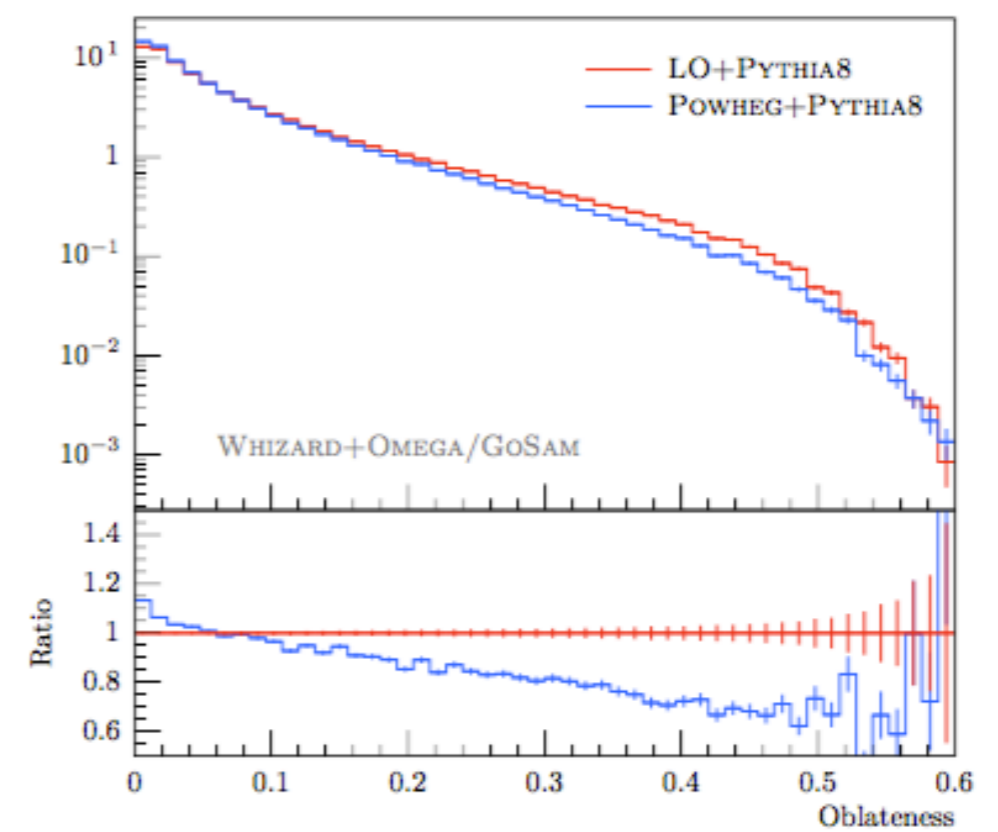
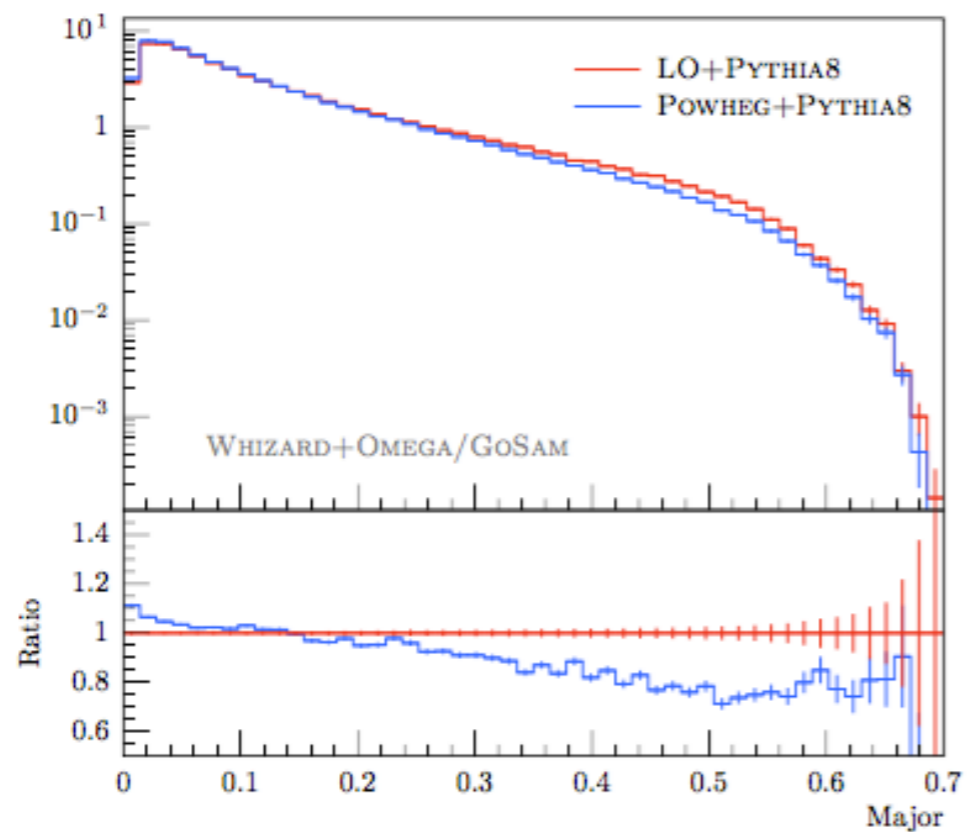
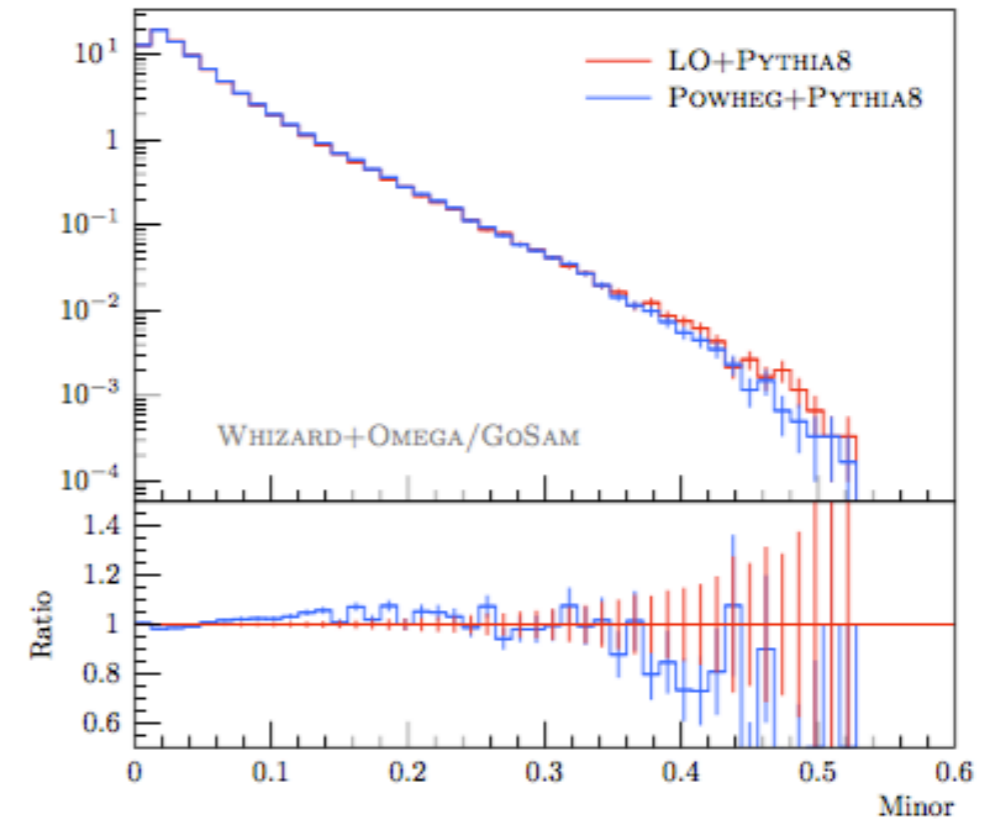
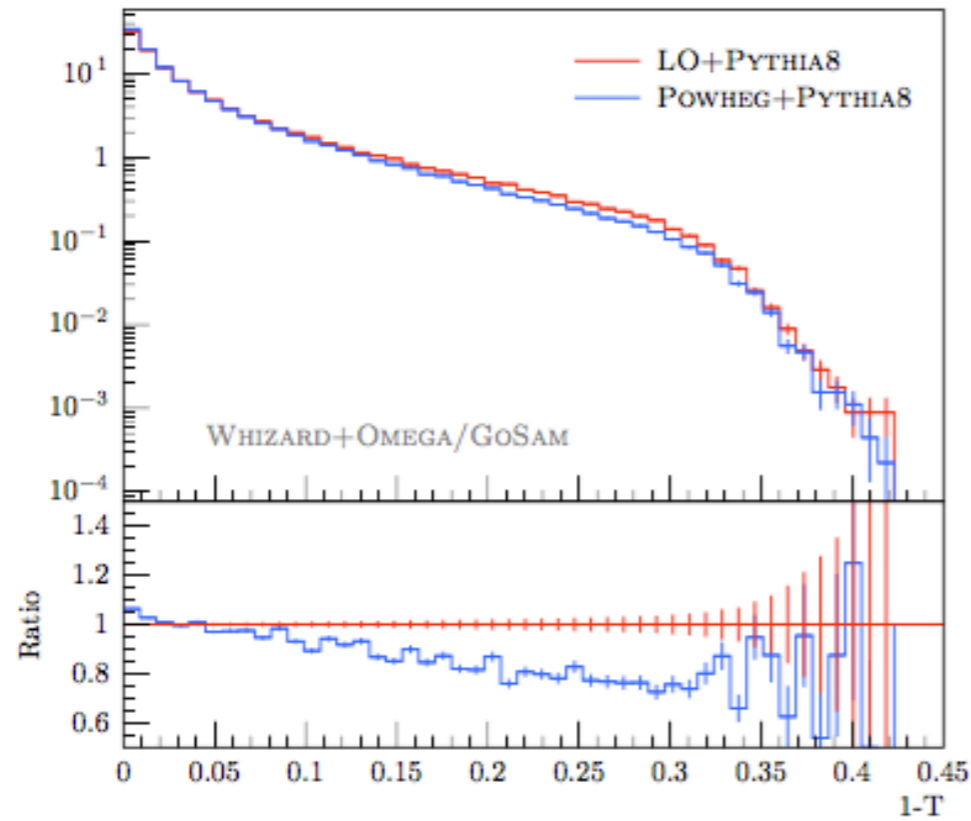
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- Hardest emission:  $k_T^{\text{max}}$  ; shower with **imposing a veto**
- $\bar{B} < 0$  if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that  $\bar{B} > 0$  for all events
- **POWHEG: Positive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



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





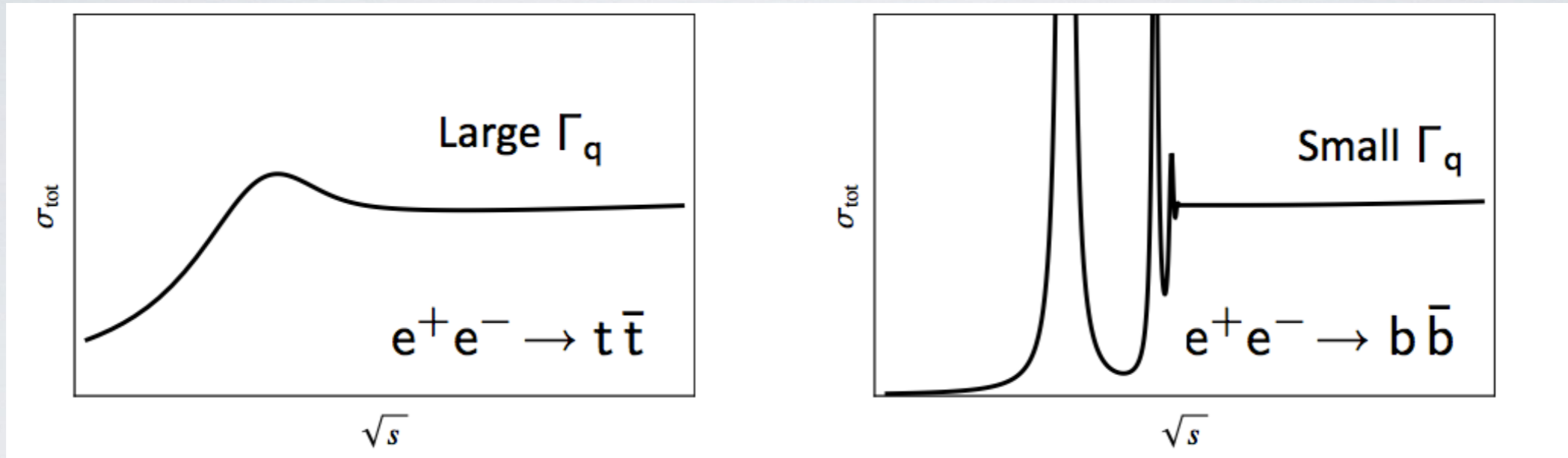
# 3) Top threshold in (N)LL (p)NRQCD matched to (N)LO QCD in WHIZARD



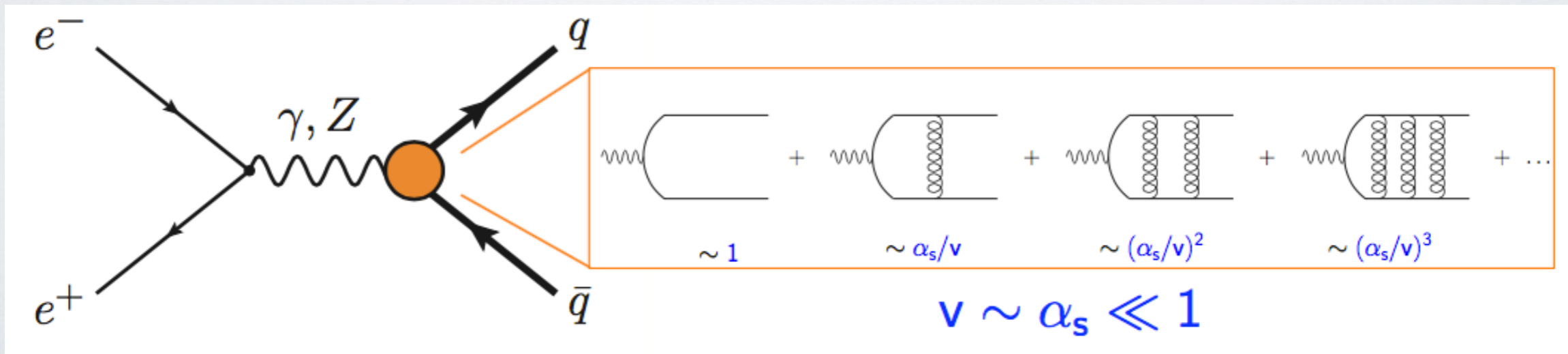
# Top Threshold at lepton colliders

ILC top threshold scan best-known method to measure top quark mass,  $\Delta M \sim 30\text{-}50 \text{ MeV}$

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

$$R \equiv \frac{\sigma_{t\bar{t}}}{\sigma_{\mu\mu}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times$$

$$\times \{1 (\mathbf{LL}); \alpha_s, v (\mathbf{NLL}); \alpha_s^2, \alpha_s v, v^2 (\mathbf{NNLL})\}$$

(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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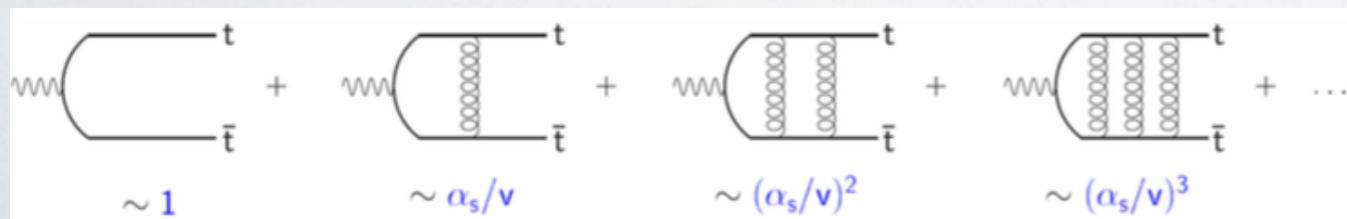
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Coulomb potential gluon ladder resummation





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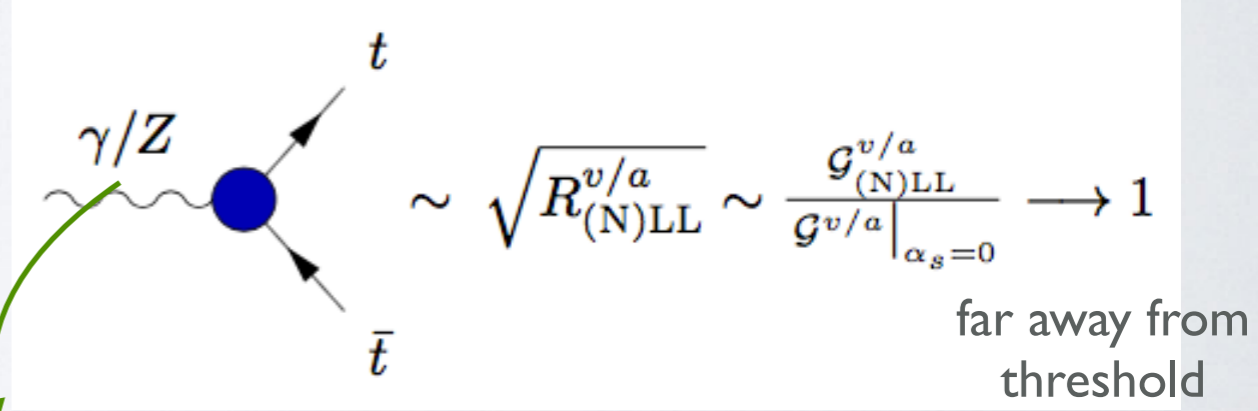
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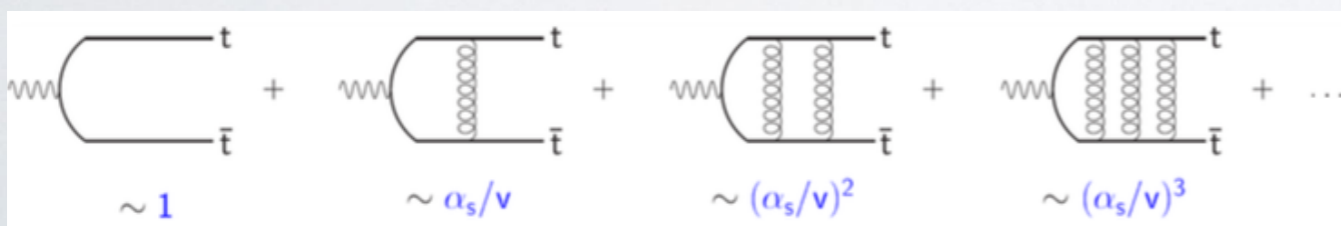
(p/v)NRQCD EFT w/ RG improvement

can be mapped onto effective  $t\bar{t}V$  vertex

but contributes at NLL differentially!



Coulomb potential gluon ladder resummation



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

differential in off-shell  $t\bar{t}$  phase space



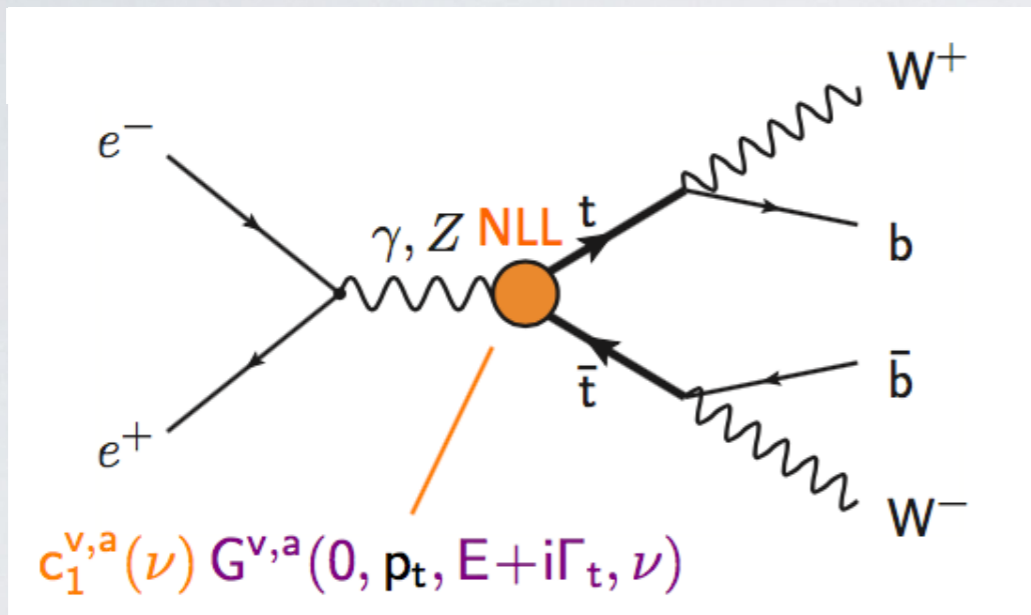




# Top Threshold in WHIZARD

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:

$$M^{1S} = 172 \text{ GeV}, \quad \Gamma_t = 1.54 \text{ GeV},$$

$$\alpha_s(M_Z) = 0.118$$

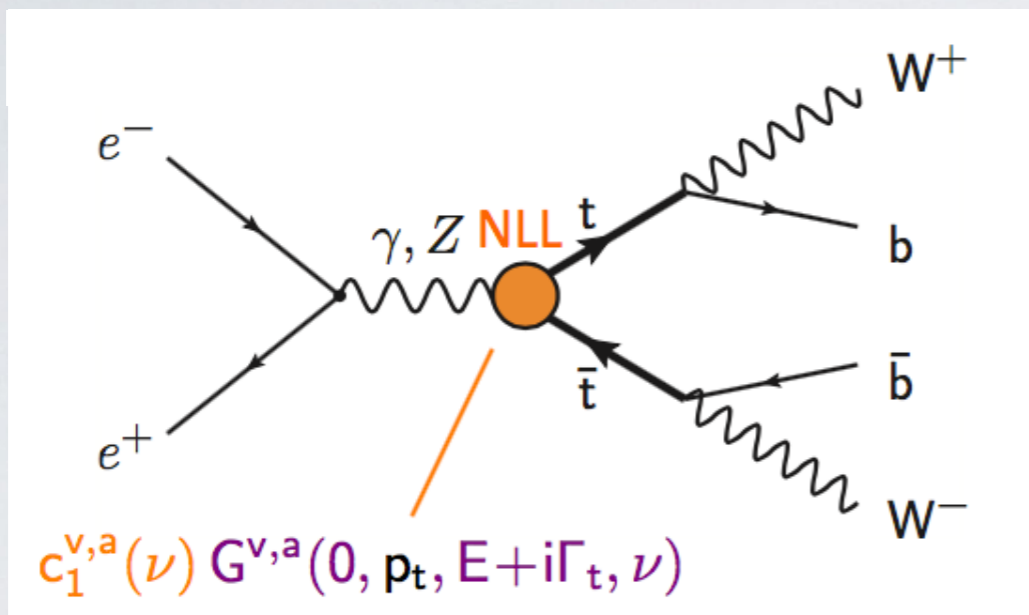
$$M^{1S} = M_t^{pole} \left( 1 - \Delta_{(Coul.)}^{LL/NLL} \right)$$



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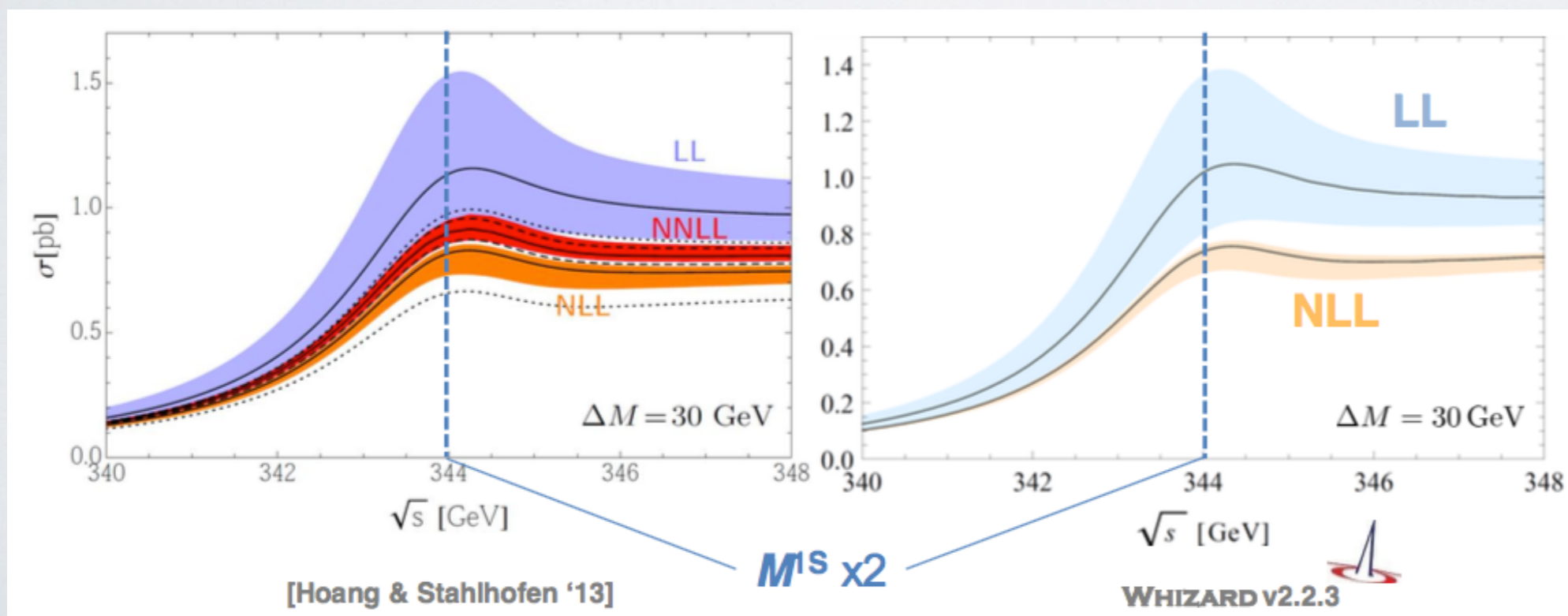


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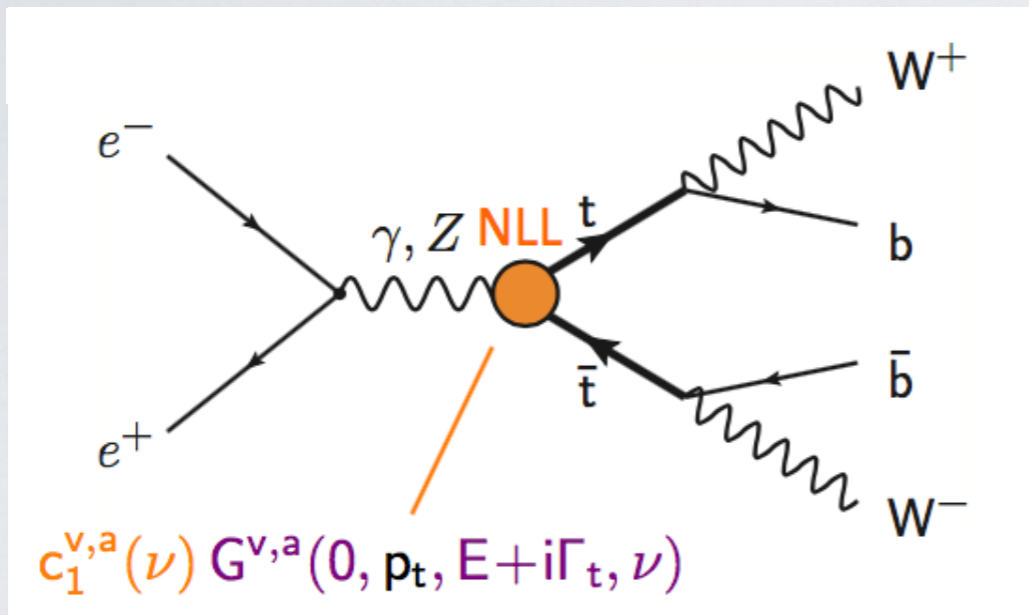




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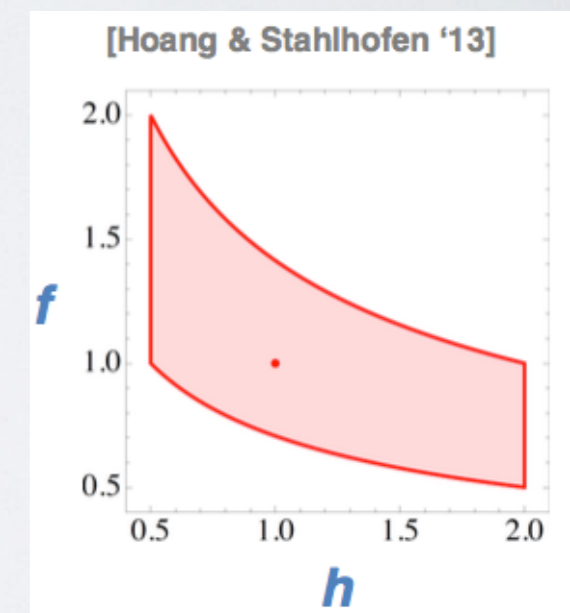
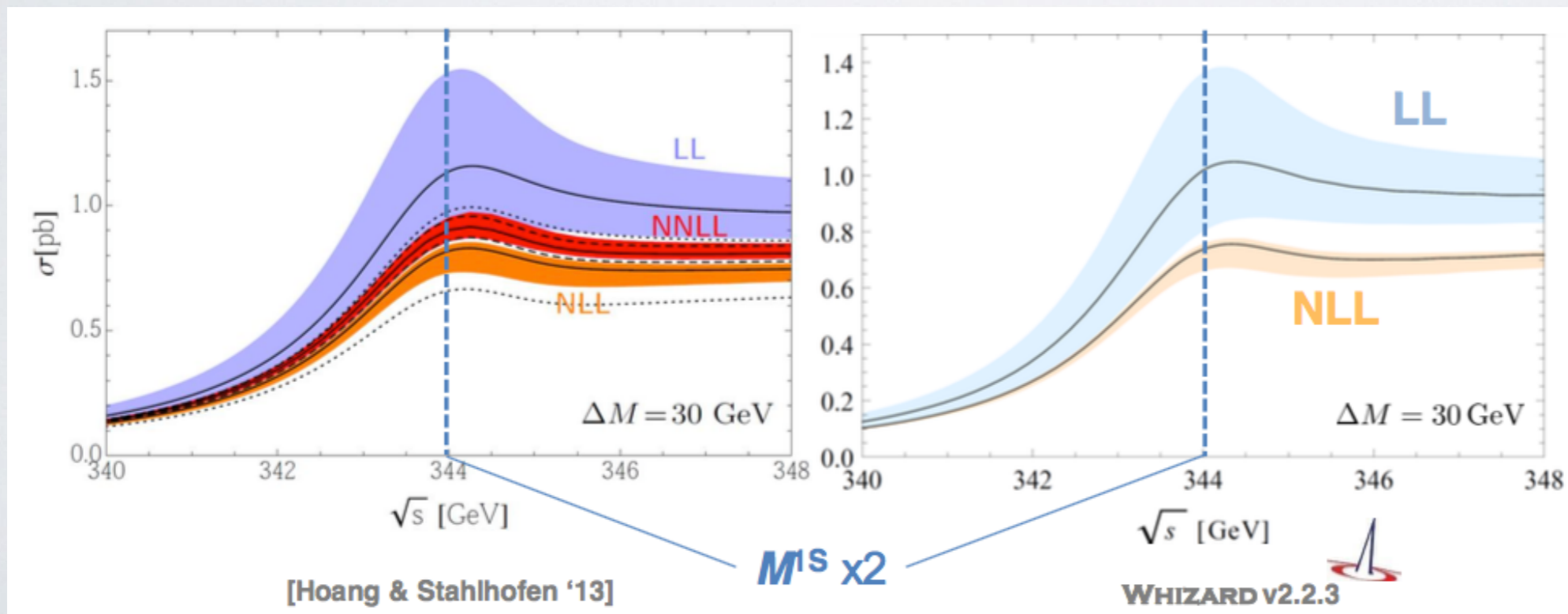
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Theory uncertainties from scale variations:  
hard and soft scale

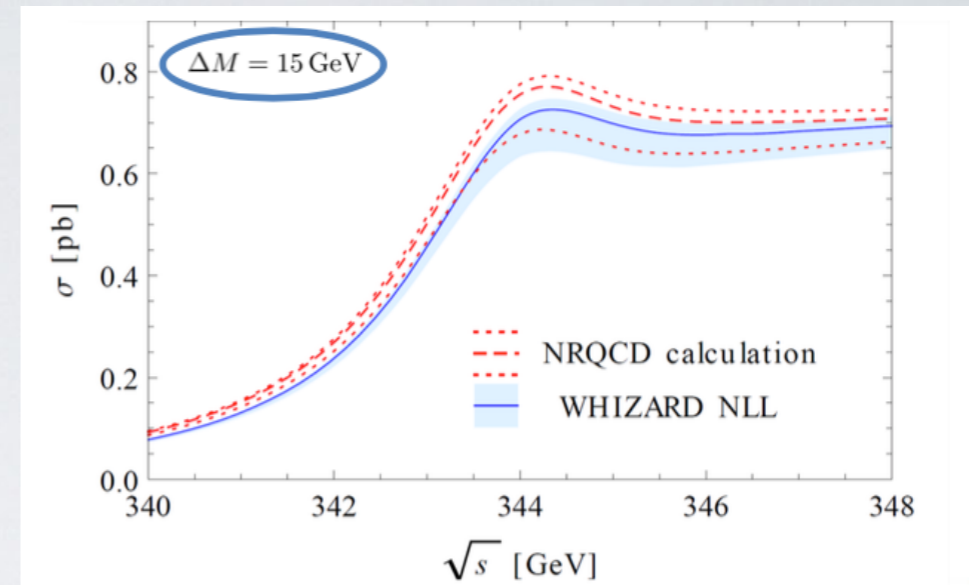
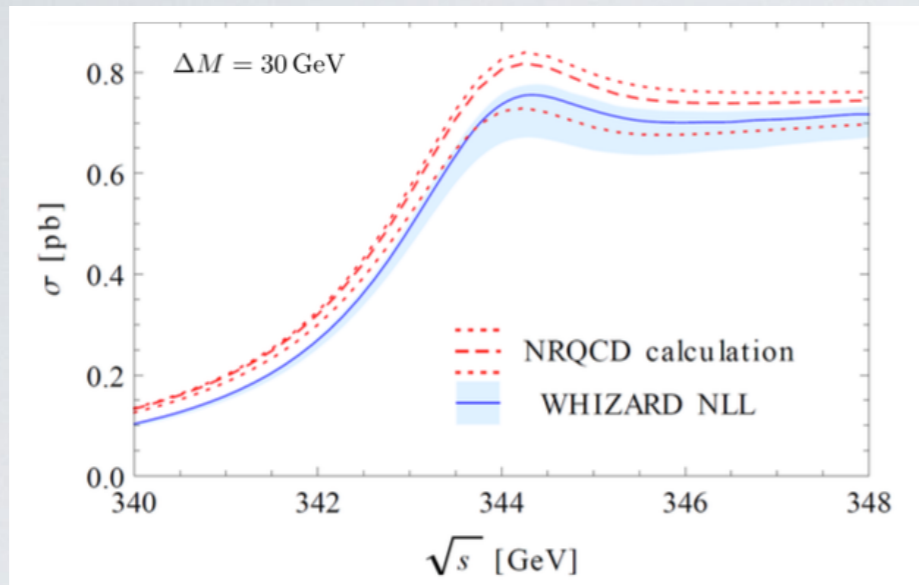
$$\mu_h = h \cdot m_t$$

$$\mu_s = f \cdot m_t v$$





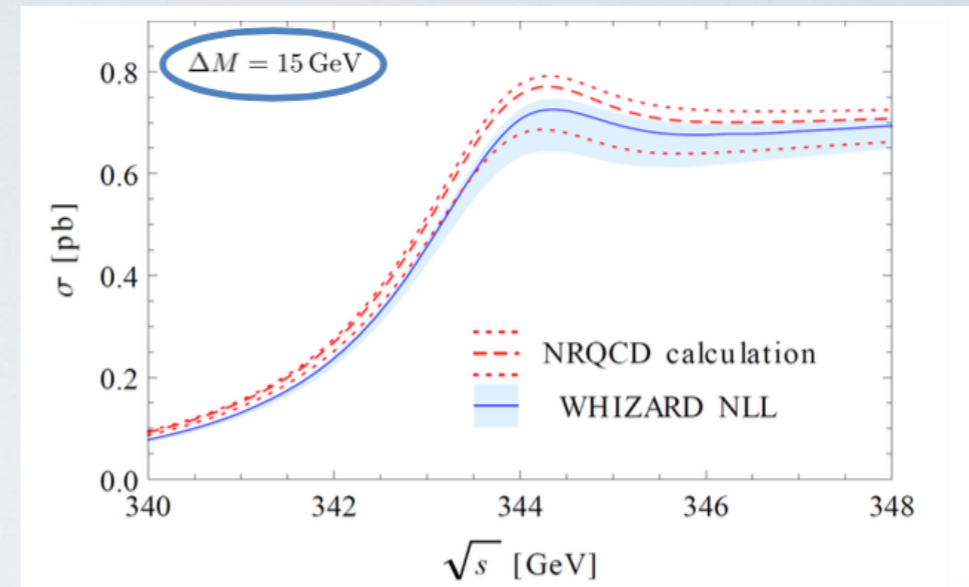
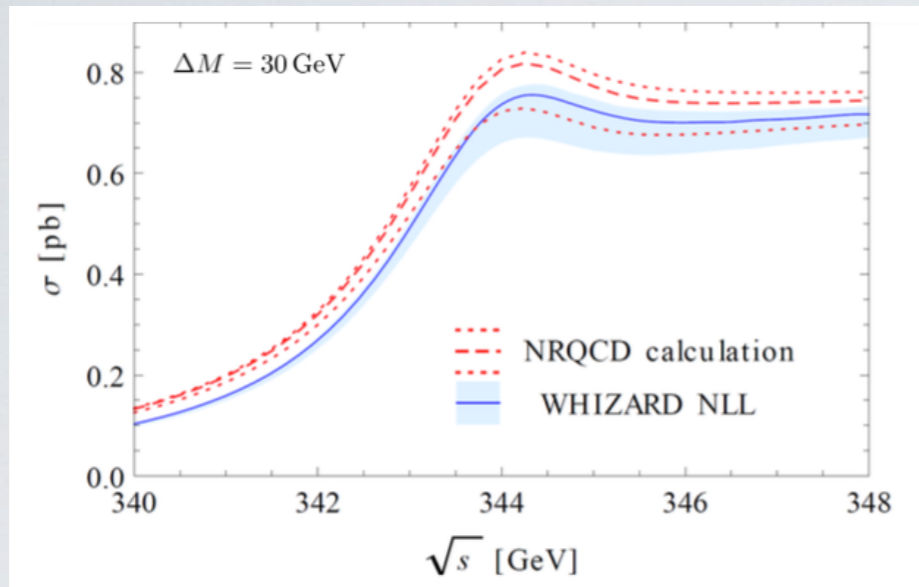
Sanity checks: correct limit for  $\alpha_s \rightarrow 0$ , stable against variation of cutoff  $\Delta M$  [15-30 GeV]



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



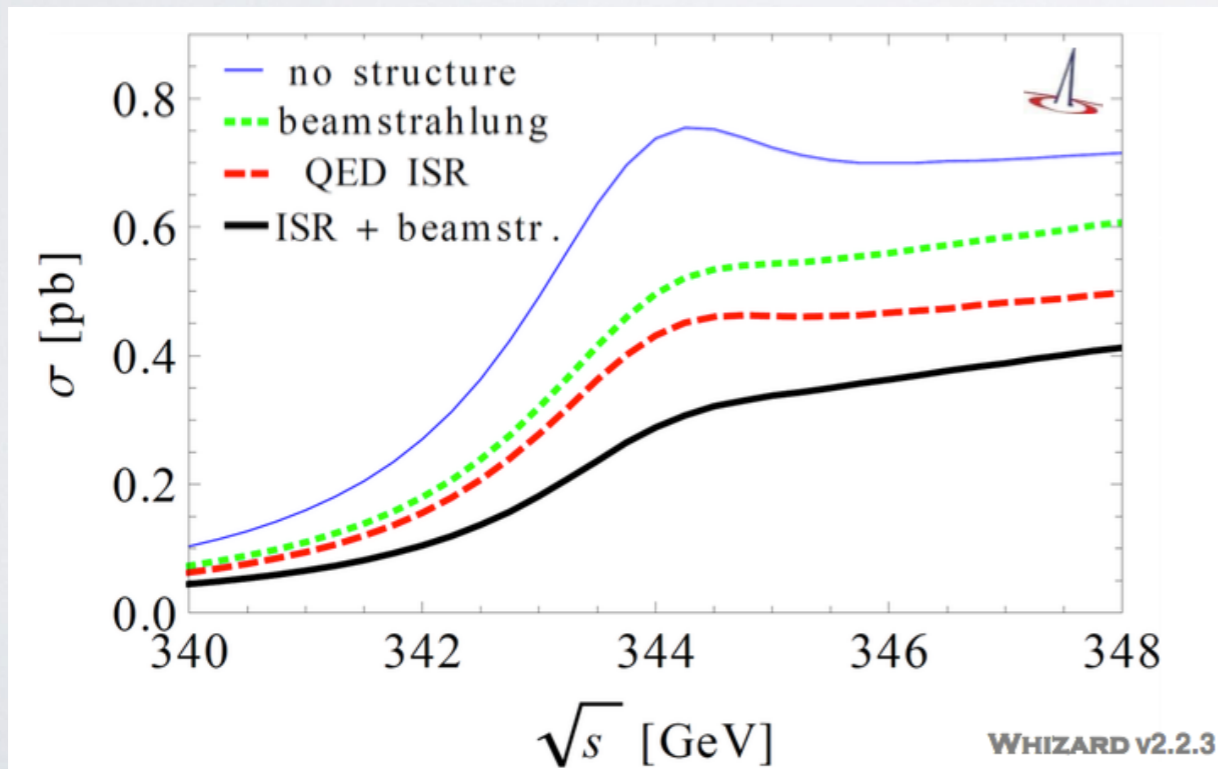
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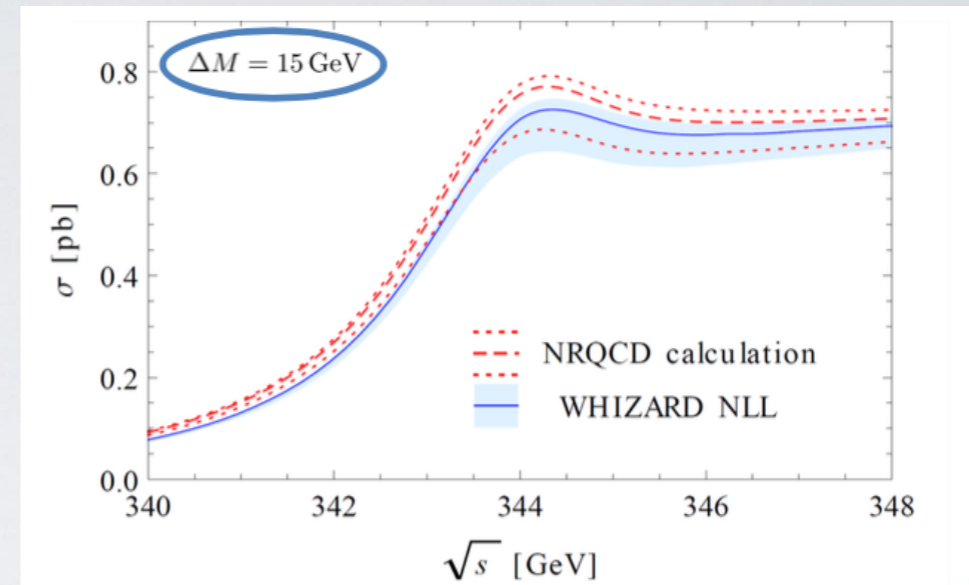
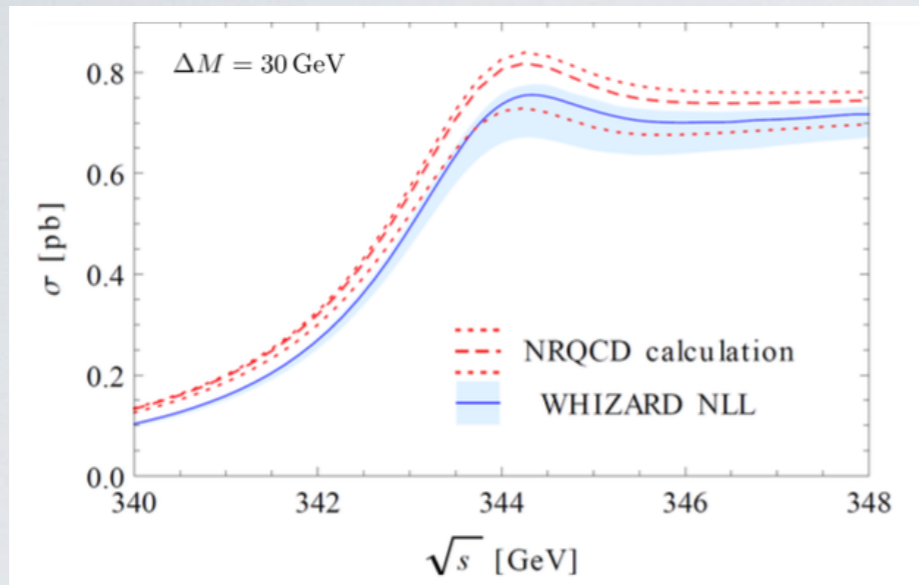
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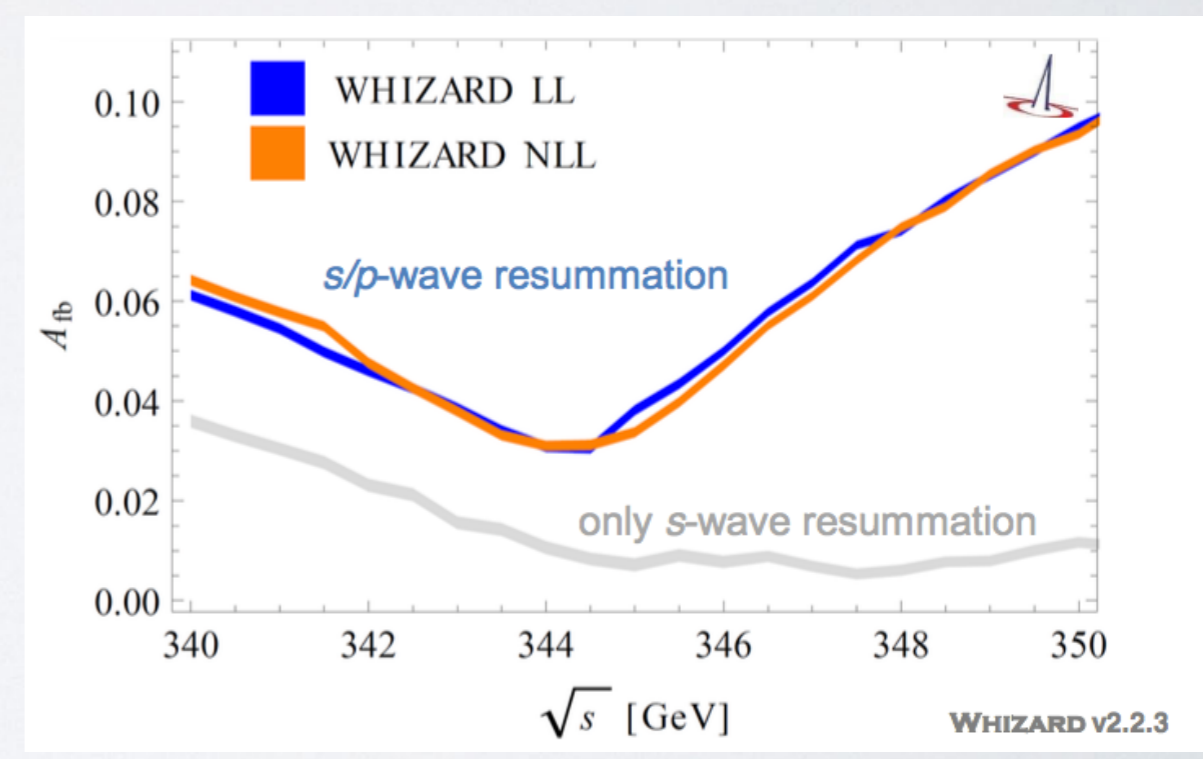
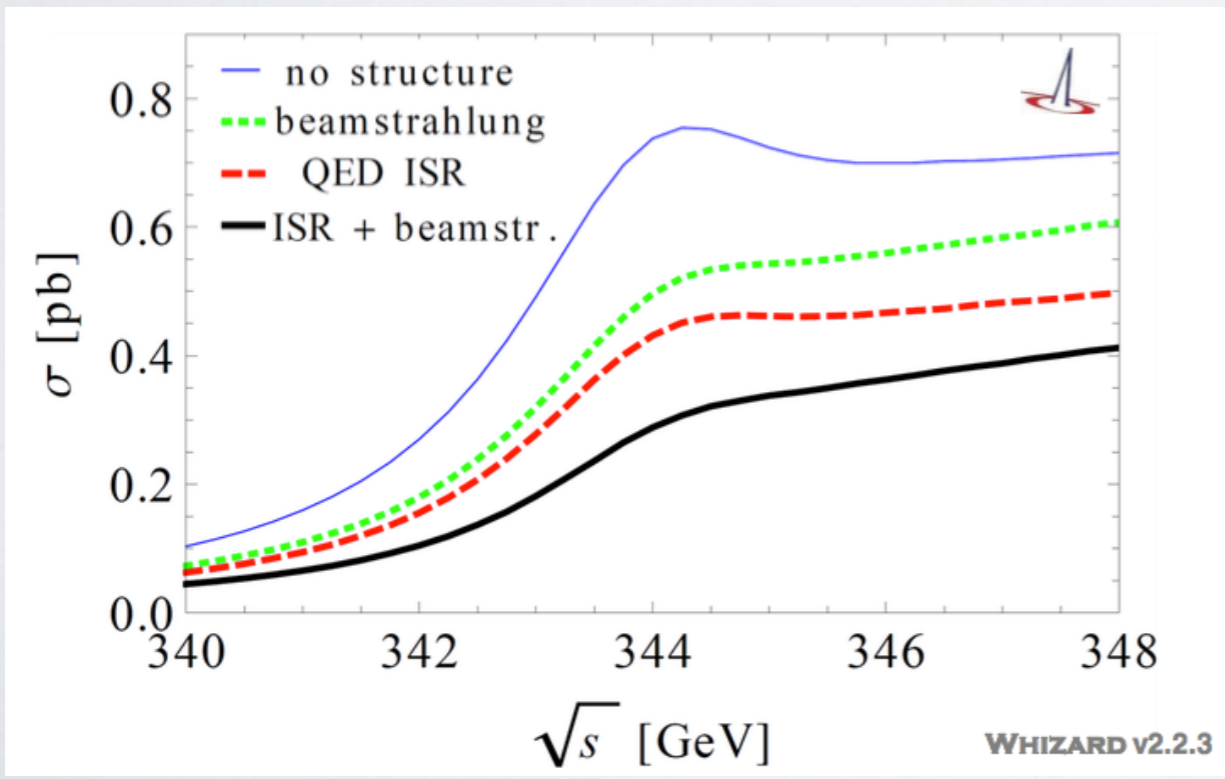
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Forward-backward asymmetry (norm.  $\Rightarrow$  good shape stability)

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



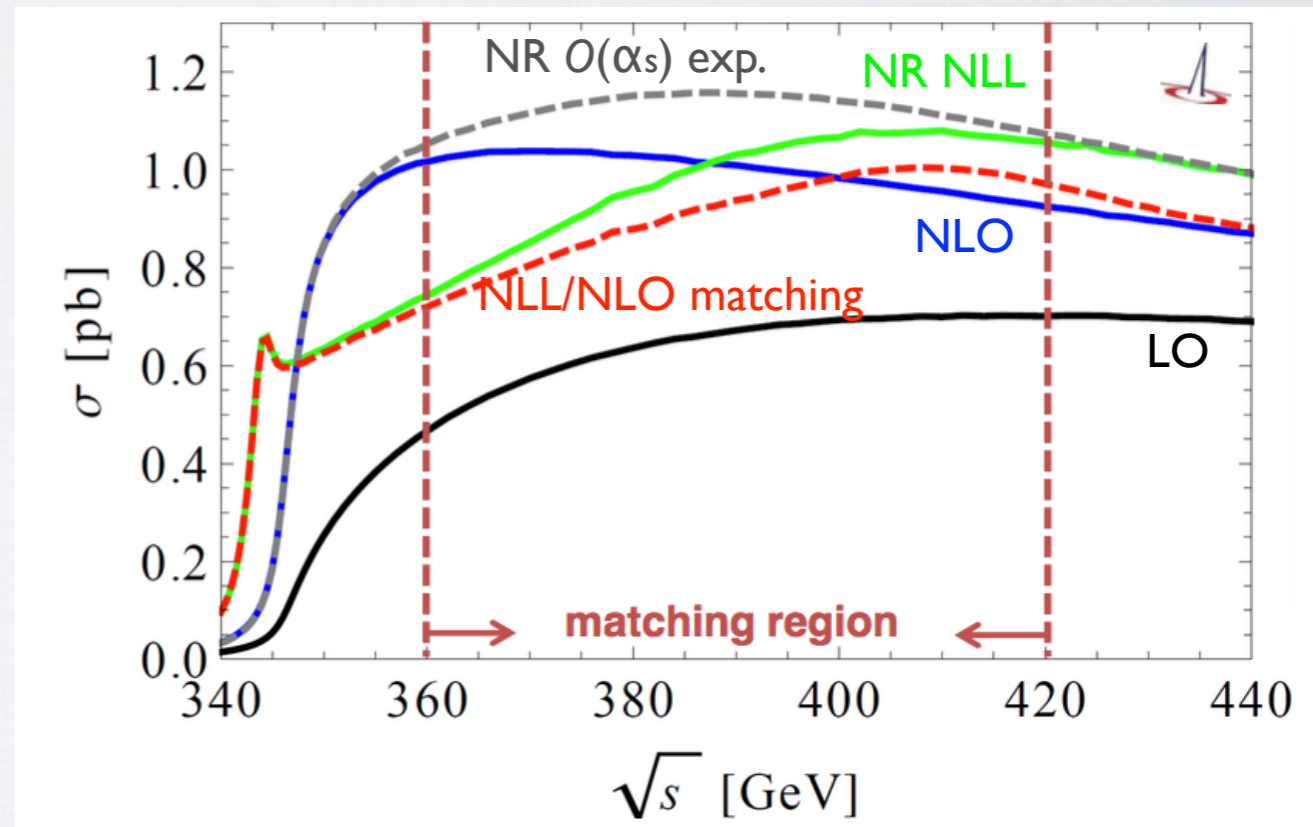
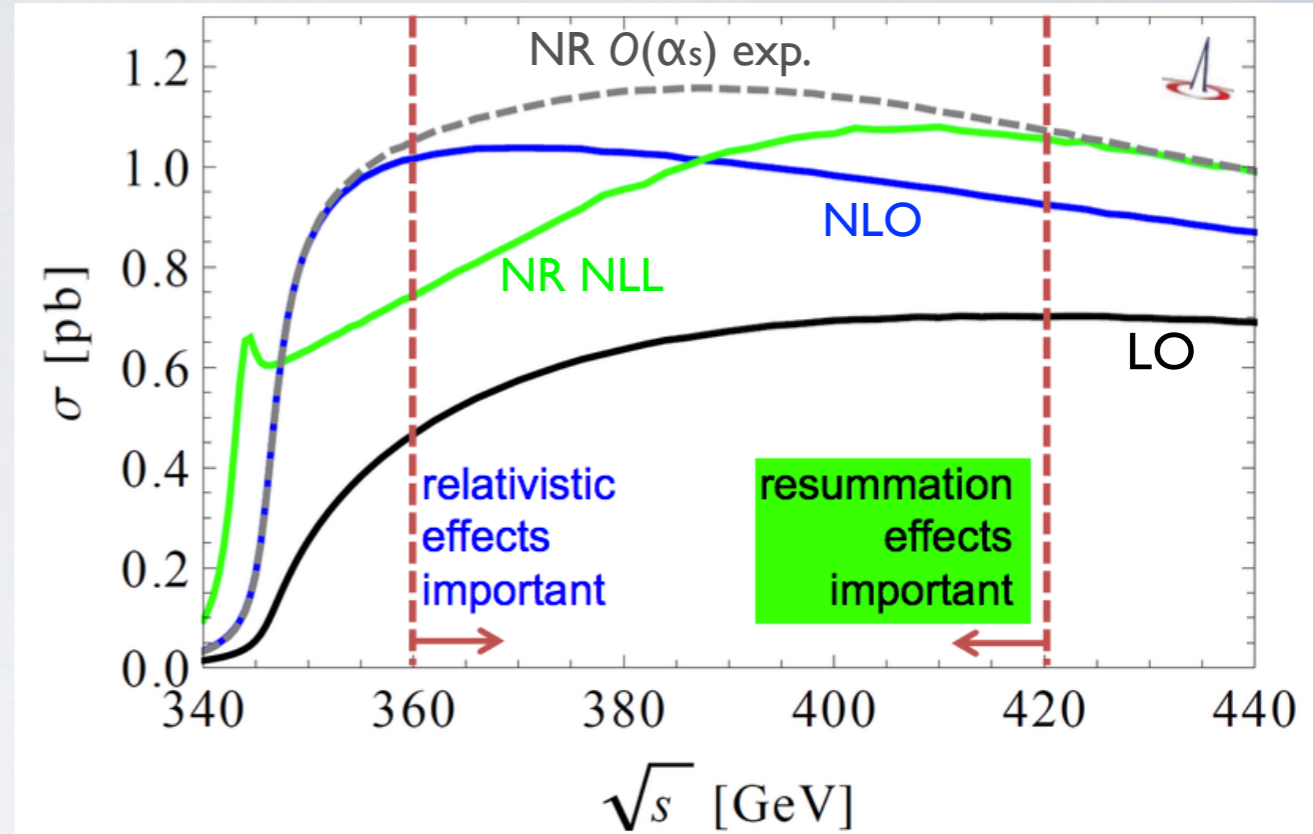


# Matching to continuum at LO and NLO

- 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
- **non-relativistic NLL approx. using TOPPIK**
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- nonrelativistic  $O(\alpha_s)$  expansion
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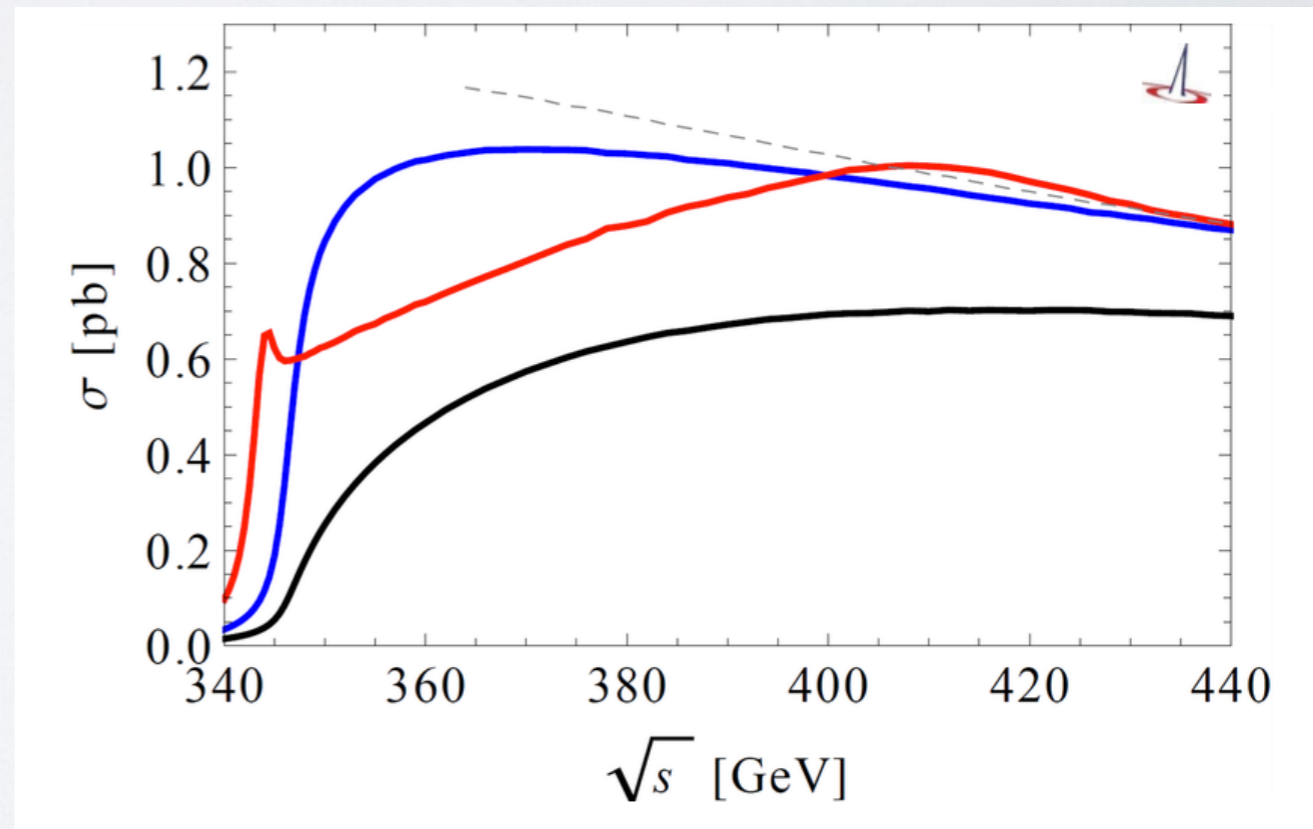
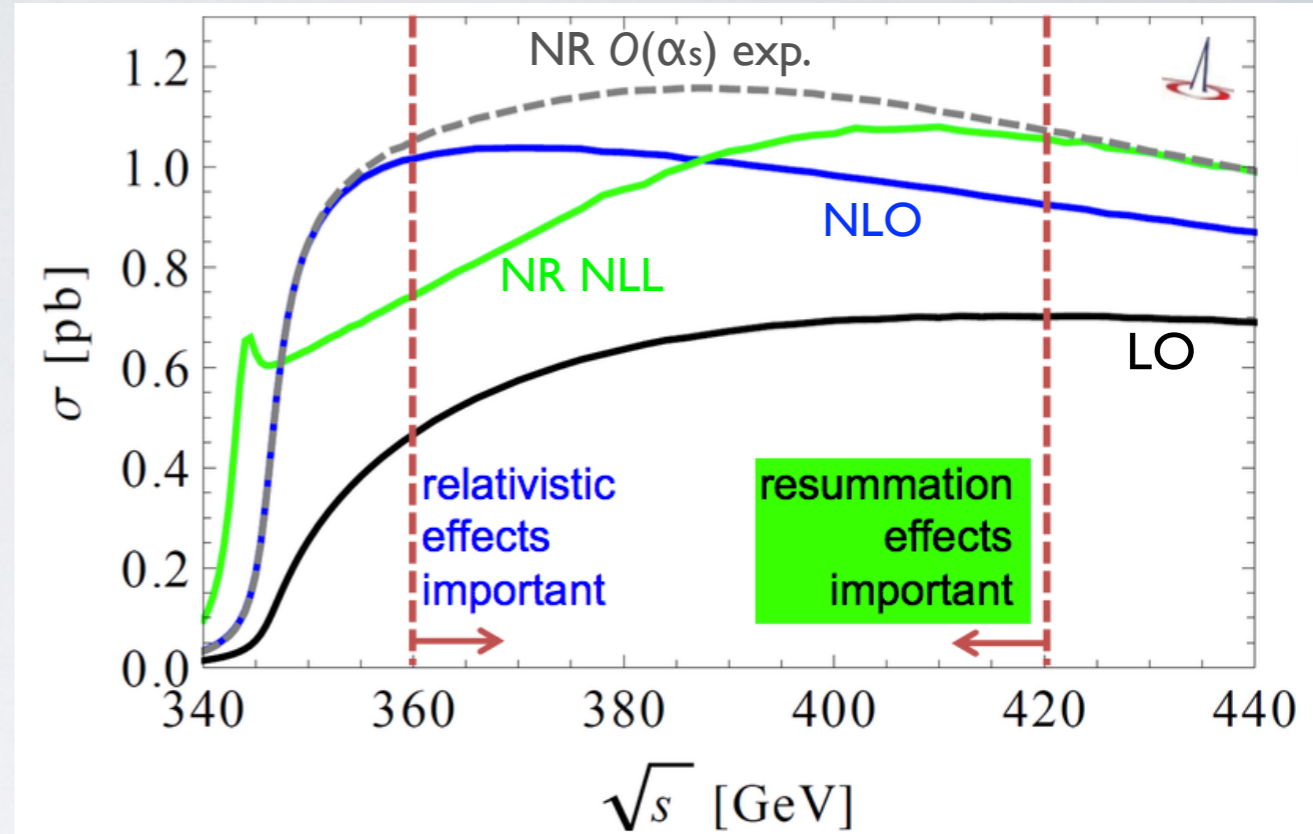


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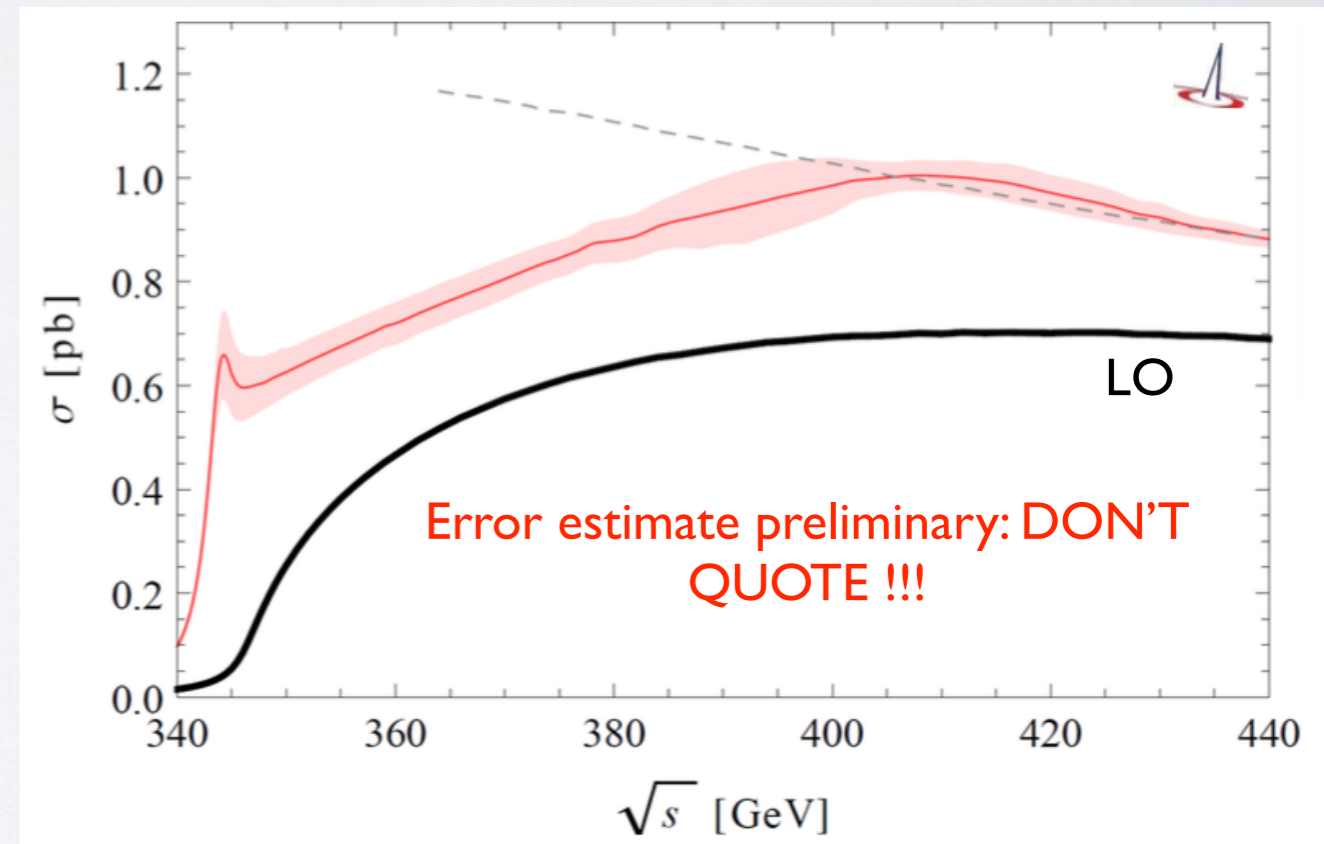
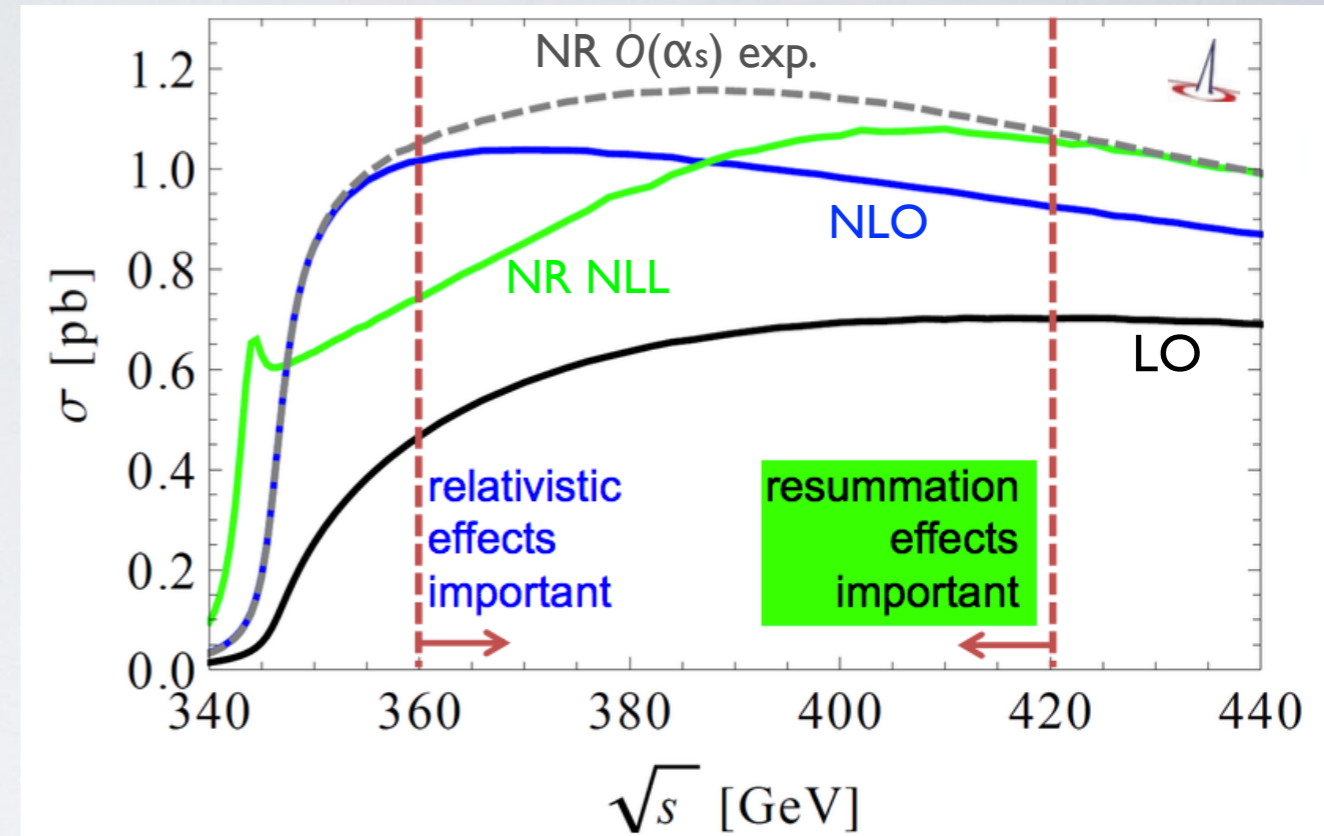
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**Total uncertainty: matching and  $h$ - $f$  variation band**





# 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
- allows to produce NLO fixed-order histograms
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- Ongoing projects: Lorentz structure, showers, merging
- Tell us what is missing, insufficient, annoying, desirable





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even if it is in a conference summary talk  $\implies$  Challenge accepted !



# Pictorial summary: loops, legs, and subtractions





# Pictorial summary: loops, legs, and subtractions





# 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: mln_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: lhpdf5.run
PASS: lhpdf6.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: mln_matching_isr.run
PASS: mln_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.
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# Beams, Fields, Colors, Lorentz structures

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- Color structures:**
- ▶ **Color flow formalism** [Stelzer/Willenbrock, 2003](#); [Kilian/Ohl/JRR/Speckner, 2011](#)
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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  $\implies$  resonant, t-channel, radiation, infrared, collinear, off-shell

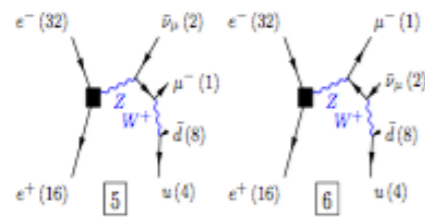
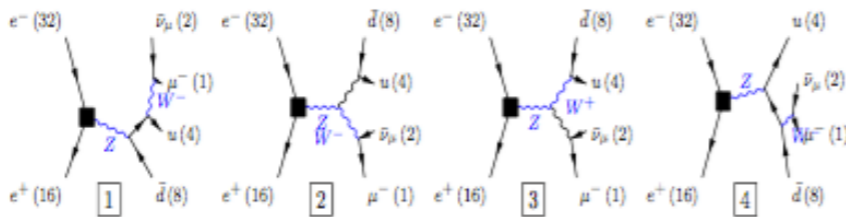
## WHIZARD phase space channels

Process:  $cc10 (e^- e^+ \rightarrow \mu^- \bar{\nu}_\mu u \bar{d})$

Color code: resonance, t-channel, radiation, infrared, collinear, external/off-shell

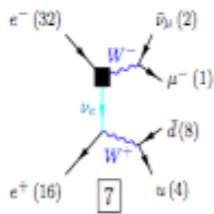
### Grove 1

Multiplicity: 1  
Resonances: 2  
Log-enhanced: 0  
t-channel: 0



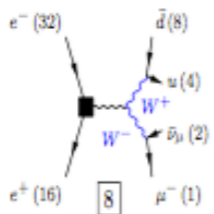
### Grove 2

Multiplicity: 2  
Resonances: 2  
Log-enhanced: 1  
t-channel: 1



### Grove 3

Multiplicity: 2  
Resonances: 2  
Log-enhanced: 0  
t-channel: 0



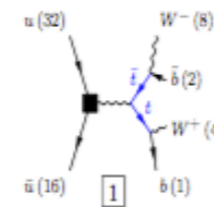
## WHIZARD phase space channels

Process:  $qqttdec (u\bar{u} \rightarrow b\bar{b}W^+W^-)$

Color code: resonance, t-channel, radiation, infrared, collinear, external/off-shell

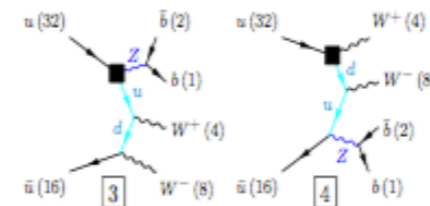
### Grove 1

Multiplicity: 2  
Resonances: 2  
Log-enhanced: 0  
t-channel: 0



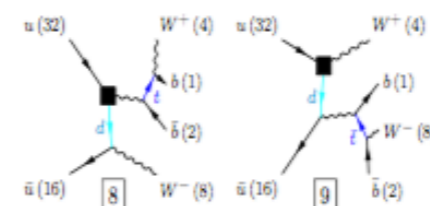
### Grove 3

Multiplicity: 3  
Resonances: 1  
Log-enhanced: 2  
t-channel: 2



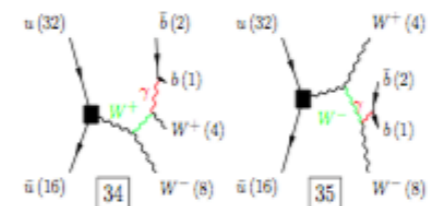
### Grove 6

Multiplicity: 3  
Resonances: 1  
Log-enhanced: 1  
t-channel: 1



### Grove 19

Multiplicity: 4  
Resonances: 0  
Log-enhanced: 2  
t-channel: 0



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

