Generator Comparisons at Next-to-Leading Order

ECFA Higgs Factories: 2nd Topical Meeting on Generators

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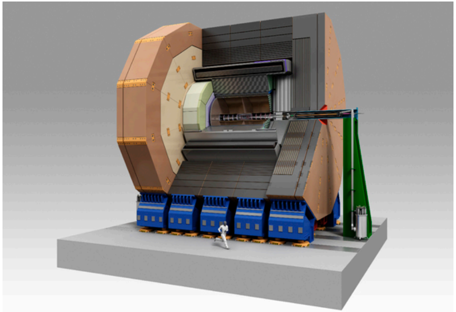
HELMHOLTZ

Overview

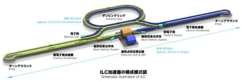
- Introduction
- Test of NLO mode of Whizard:
  - Average Hadron Multiplicities
  - Kinematics distributions
  - Full ILD simulation
- Comparisions of 3 generators at NLO:
  - Whizard
    [W. Kilian *et al.*, 2007]
  - MadGraph5
    [J. Alwall *et al.*, 2014]
  - Sherpa
    [T. Gleisberg *et al.*, 2008]
- Summary



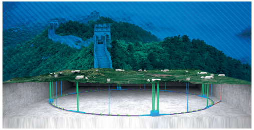
International Large Detector (ILD)

Introduction: Higgs Factories

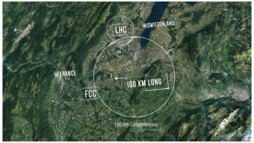
Proposed future colliders:



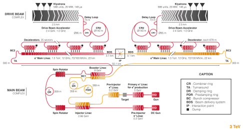
ILC



CEPC



FCC-ee



CLIC

- All of them are e^+e^- colliders.
- They are designed as Higgs factories for high precision physics.
- Features of lepton beams: initial state radiation (ISR), polarization, Beam-strahlung...

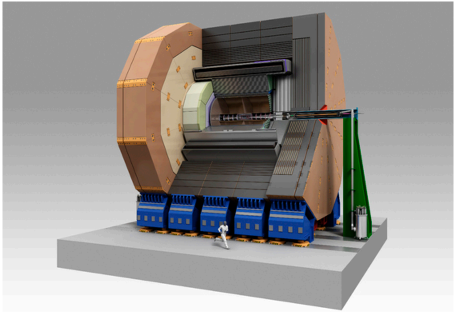
$\rightarrow$ Requirements for Monte-Carlo events generator

Introduction: Detector Concept for Higgs Factories

What is ILD?

- It is designed for e^+e^- collisions between 90 GeV and 1 TeV.
- It is optimized for particle flow algorithm (PFA).
- PFA aims at reconstructing every individual particle created in the event, i.e.:
  - Charged particles
  - Photons
  - Neutral hadrons (has large energy resolution)

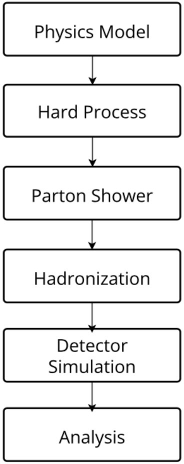
$\rightarrow$ Depends on the tuning of parameters in the MC simulation chain.



International Large Detector (ILD)

Status and Goals

- Present events for analysis of e^+e^- colliders:
  - Leading order matrix elements are calculated by Whizard 1.95.
  - Parton shower and hadronization are performed by Pythia6.
  - OPAL tune for LEP is used.
- Our goals:
  - Upgrade the simulation chain to Whizard3+Pythia8, as well as MadGraph5 and Sherpa.
  - Get agreement with LEP data, especially the neutral hadrons.
  - Include NLO matching because of the requirement of high precision.



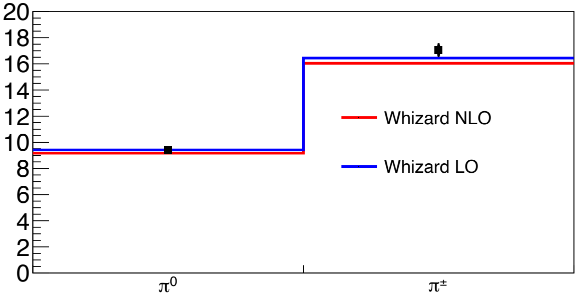
Test of NLO Mode of Whizard

To test the NLO mode, we use the following generator setup (LEP1 condition):

- Process: $e^+e^- \to q\bar{q}$ $(q = u, d, s, c, b)$.
- The center of mass energy is $E_{cm} = 91.19$ GeV.
- Beams are un-polarized.
- Beam-strahlung is not considered.
- ISR is switched off.
- NLO QCD corrections can be calculated by interfacing Whizard with OpenLoops. [F. Bucchioni *et al.*, 2019]
- Whizard supports POWHEG matching. [P. Nason, 2004]
- Finally, events can be showered by Pythia8. [C. Bierlich *et al.*, 2022]

Test of NLO Mode of Whizard: Average Hadron Multiplicities

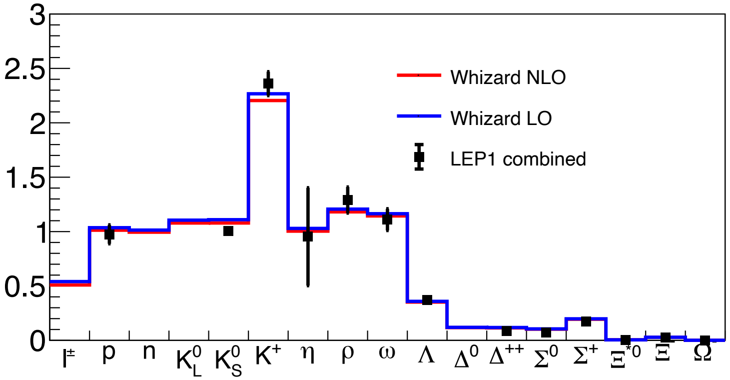
Hadronization rates are crucial for studying particle flow performance. To see the NLO effects, we study the average hadron multiplicities. The dominant hadrons are pions. The average numbers of pions in events are



	n_{π^0}	$n_{\pi^\pm}$
NLO	9.17	16.04
LO	9.41	16.44
LEP1 combined	9.38 ±0.19	17.05 ±0.43

> LEP1 data are taken from [A. Boehrer, 1997] and [R. Barete *et al.*, 1998]

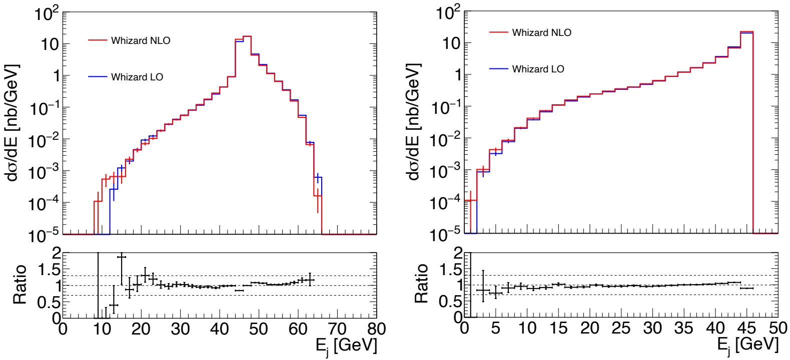
Test of NLO Mode of Whizard: Average Hadron Multiplicities



> The numbers of hadrons at NLO are slightly lower than the LO.

Test of NLO Mode of Whizard: Kinematics Distributions

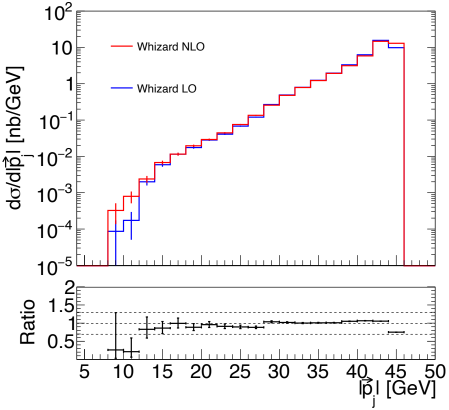
We use FastJet [M. Cacciari *et al.*, 2011] to find jets with the Durham algorithm. [S. Catani *et al.*, 1991] The total number of jets is forced to 2.



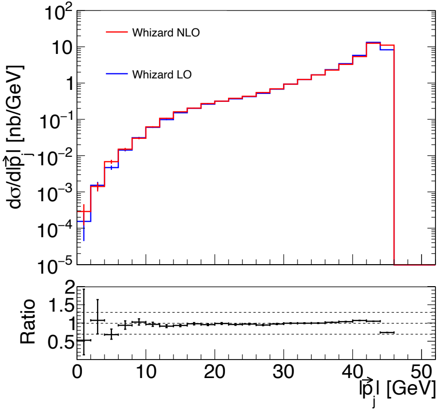
Leading jet

Sub-leading jet

Test of NLO Mode of Whizard: Kinematics Distributions



Leading jet



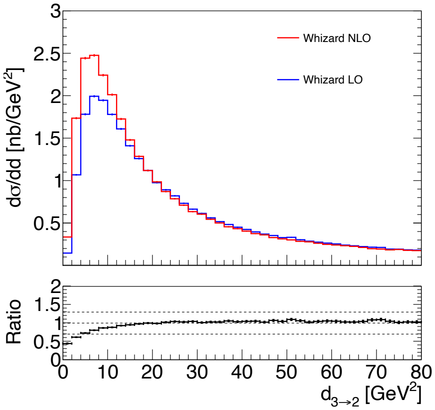
Sub-leading jet

Test of NLO Mode of Whizard: Kinematics Distributions

FastJet define the jets by calculating:

$$d_{ij} = 2\,\text{min}(E_i^2, E_j^2)(1 - \cos\theta_{ij})$$

We can define a d cut $d_{3\to2}$, which is the value associated with merging from 3 to 2 jets.



Test of NLO Mode of Whizard: Full ILD Simulation

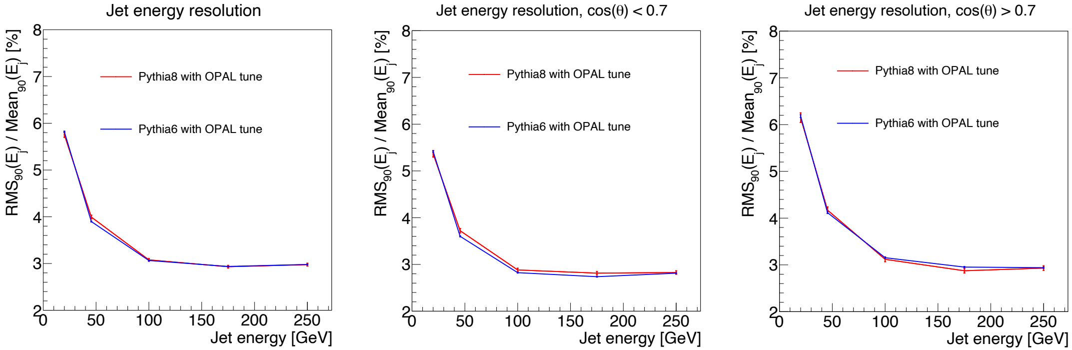
Full Geant4-based MC simulations are crucial to optimize a well performed dectector concept. We take ILD as an example. In this context, an important parameter is the Jet Energy Resolution (JER) of ILD.

To study it, we use the following generator setup:

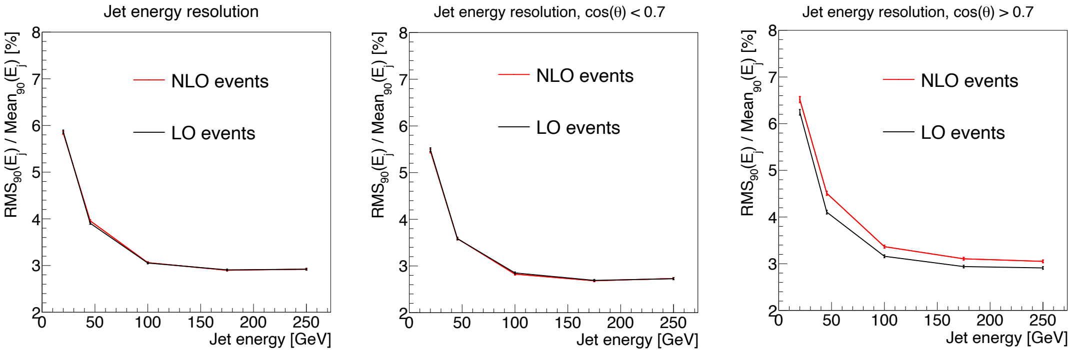
- $e^+e^- \to q\bar{q}\ (q = u, d, s)$
- ISR is switched off.
- $E_{cm} = 40, 91, 200, 350, 500$ GeV.
- Full simulation is performed with ILD-L model.

Test of NLO Mode of Whizard: Full ILD Simulation

- As a first step, we reproduce the results of ILD IDR [arXiv:2003.01116], by using Whizard3+Pythia8 at LO.



Test of NLO Mode of Whizard: Full ILD Simulation



NLO events tend to have fewer events at the forwarded region.

Comparisons of 3 generators at NLO

Generator setup:

- Process: $e^+e^- \to q\bar{q}\ (q = u, d, s, c, b)$.
- $E_{cm} = 91.19$ GeV.
- No ISR.
- No generator level cut.

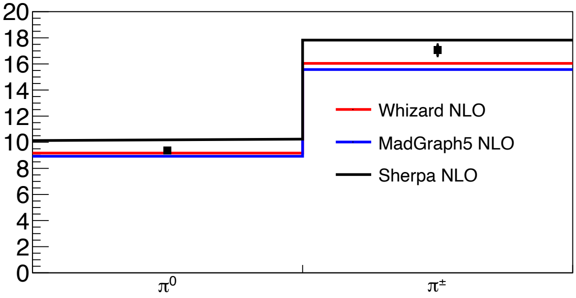
	Loop ME	PS (NLO)	NLO Matching
Whizard	OpenLoops	Pythia8.3	POWHEG
MadGraph5	MadLoop	Pythia8.2	MC@NLO
Sherpa	OpenLoops	Sherpa	MC@NLO

Comparisons of 3 generators at NLO

Cross Sections:

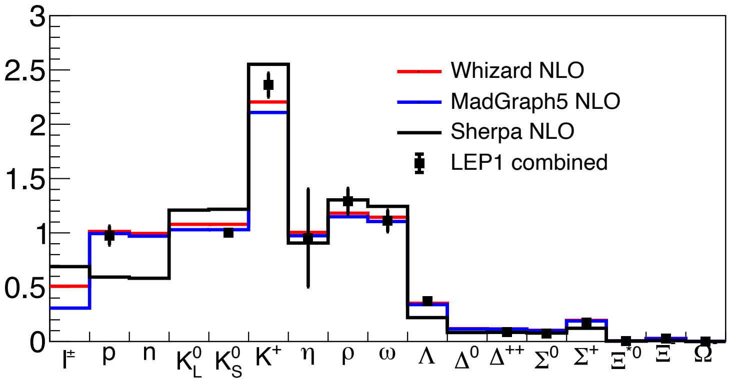
	Whizard	MadGraph5	Sherpa
σ^{uu}_{LO} [nb]	6.907 ± 7.29E-4	6.917 ± 2.20E-3	6.900 ± 3.80E-3
σ^{uu}_{NLO} [nb]	7.175 ± 4.60E-3	7.182 ± 1.37E-2	7.194 ± 2.12E-2
σ^{dd}_{LO} [nb]	8.846 ± 9.58E-4	8.862 ± 3.24E-3	8.837 ± 4.85E-3
σ^{dd}_{NLO} [nb]	9.191 ± 6.06E-3	9.200 ± 1.70E-3	9.207 ± 1.28E-2
σ^{ss}_{LO} [nb]	8.846 ± 9.58E-4	8.862 ± 3.24E-3	8.850 ± 4.74E-3
σ^{ss}_{NLO} [nb]	9.191 ± 6.06E-3	9.183 ± 1.80E-2	9.169 ± 1.36E-2
σ^{cc}_{LO} [nb]	6.907 ± 7.29E-4	6.924 ± 2.63E-3	6.896 ± 3.57E-3
σ^{cc}_{NLO} [nb]	7.175 ± 4.60E-3	7.183 ± 1.36E-2	7.163 ± 1.03E-2
σ^{bb}_{LO} [nb]	8.846 ± 9.58E-4	8.862 ± 3.24E-3	8.830 ± 4.90E-3
σ^{bb}_{NLO} [nb]	9.191 ± 6.06E-3	9.171 ± 1.80E-2	9.179 ± 1.36E-2

Comparisons of 3 generators at NLO



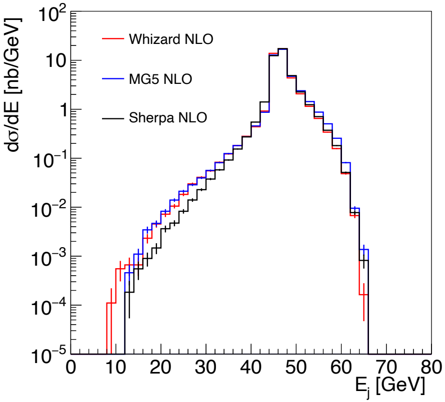
Tunes	n_{π^0}	$n_{\pi^\pm}$
Whizard NLO	9.17	16.04
MadGraph5 NLO	8.93	15.57
Sherpa NLO	10.13	17.82
LEP1 combined	9.38 ± 0.19	17.05 ± 0.43

Comparisons of 3 generators at NLO

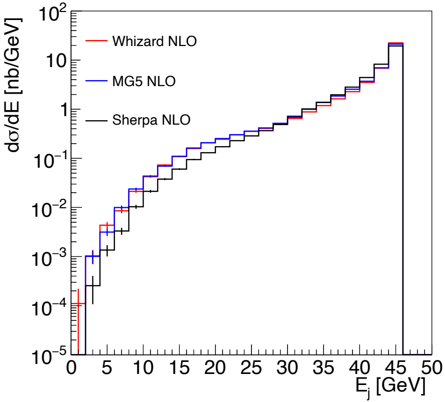


Comparisons of 3 generators at NLO

Durham algorithm is used to find two jets. Jets are sorted by E.



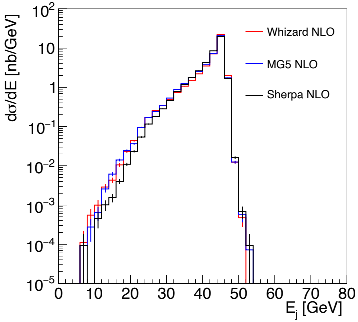
Leading jet



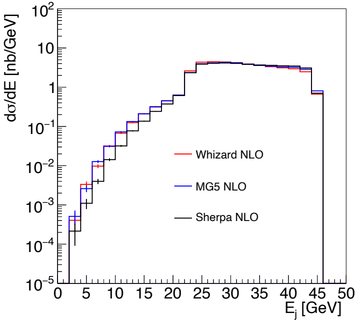
Sub-leading jet

Comparisons of 3 generators at NLO

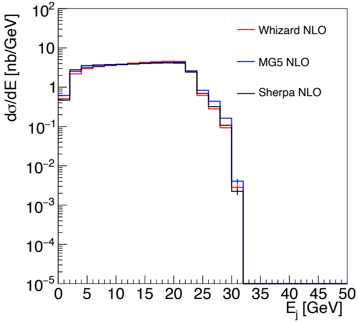
Durham algorithm is used to find three jets. Jets are sorted by E.



1st jet



2nd jet



3rd jet

Summary and Outlook

Summary:

- The MC simulation chain is necessary to upgrade to modern generators with NLO precision.
- We test the NLO mode of 3 generators: Whizard, MadGraph5 and Sherpa.
- The parton shower model plays an important role in the simulation.
- We see how NLO QCD correction changes our results at reconstruction level.

Outlook:

- Full ILD simulation with MG5 and Sherpa events.
- Consider more interesting process like $e^+e^- \rightarrow \mu^+\mu^- b\bar{b}$.
- Tuning parton shower parameters for NLO.

Thank You

Backup slides

Jet Algorithm

- Neutrinos are removed from the particle lists for clustering.
- Leptons are removed if it satisfies the isolation condition:
  - $p_T > 20$ GeV.
  - For each lepton ℓ, we define a isolation variable I:

$$I(\ell) = \frac{\sum_{i\neq\ell}^{\Delta R<R, p_T(i)>p_T^{min}} p_T(i)}{p_T(\ell)},$$

    where the numerator is the sum of p_T above p_T^{min} of all particles within a cone of radius R around the lepton, except ℓ. Here, $p_T^{min} = 0.1$ GeV and $R = 0.1$.
  - If $I(\ell) < 0.1$, the lepton is called isolated.
- Remained particles are added to the list for clustering.

Thrust Distributions