

Impact of NLO QCD on Key Physics Processes at Future Higgs Factories

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Zhijie Zhao^{1,2,3}, Mikael Berggren¹, Jenny List¹

¹Deutsches Elektronen-Synchrotron DESY

²Center for Future High Energy Physics, Institute of High Energy Physics, Chinese Academy of Sciences

³University of Chinese Academy of Sciences



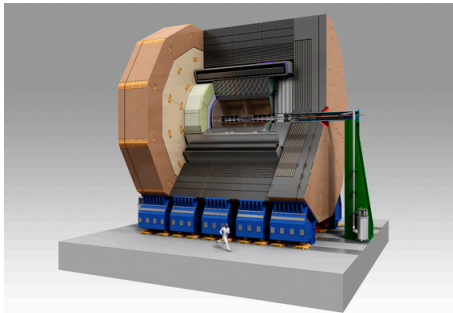
中国科学院高能物理研究所
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HELMHOLTZ

Overview

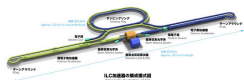
- > Introduction
- > Test on NLO mode of Whizard:
 - $e^+e^- \rightarrow q\bar{q}$
 - $e^+e^- \rightarrow \mu^+\mu^-b\bar{b}$
- > Summary



International Large Detector (ILD)

Introduction: Higgs Factories

Proposed future colliders:



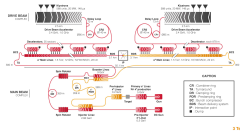
ILC



CEPC



FCC-ee



CLIC

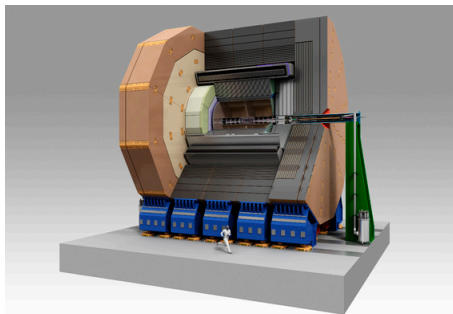
- > All of them are e^+e^- colliders.
 - > They are designed as Higgs factories for high precision physics.
 - > Features of lepton beams: initial state radiation (ISR), polarization, Beam-strahlung...
- Monte-Carlo events generator **Whizard** [W. Kilian *et al.*, 2007]

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)

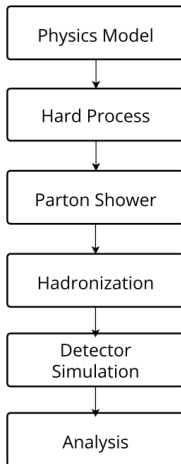
→ Depends on the **tuning** of parameters in the MC simulation chain.



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**.
 - Get agreement with LEP data, especially the neutral hadrons.
 - Include NLO matching because of the requirement of high precision.



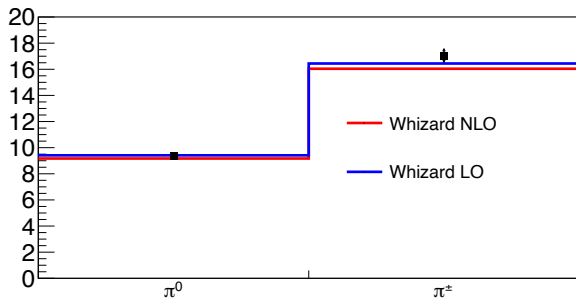
Test of NLO Mode of Whizard: $e^+e^- \rightarrow q\bar{q}$

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

- > Process: $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c, b$).
- > 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]

$e^+e^- \rightarrow q\bar{q}$: Average Hadron Multiplicities

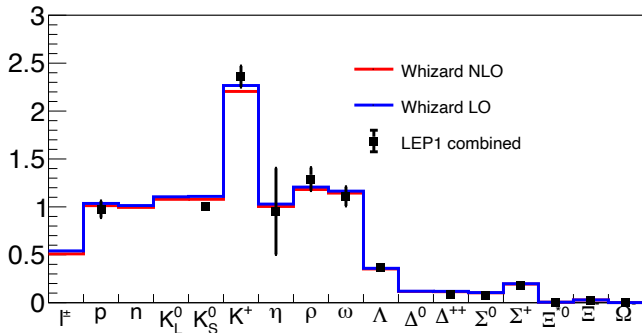
Hadronization rates are crucial for studying particle flow performance. To see the NLO effects, we study the average hadron multiplicities. The dominant hadrons are pions. The average numbers of pions in events are



	n_{π^0}	n_{π^\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. Boehrler, 1997] and [R. Barete *et al.*, 1998]

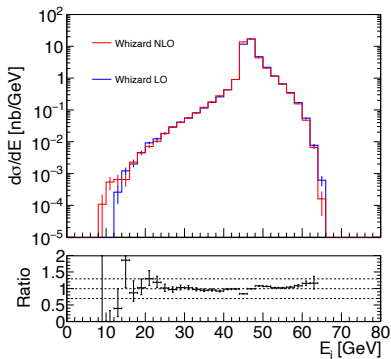
$e^+e^- \rightarrow q\bar{q}$: Average Hadron Multiplicities



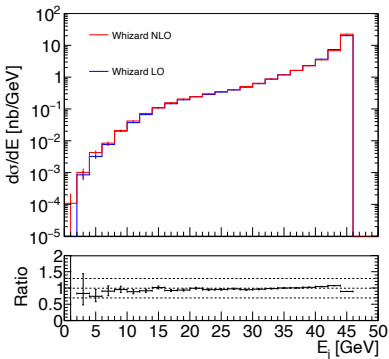
- > NLO events have better agreement on proton and K_S^0 .
- > The numbers of hadrons at NLO are slightly lower than the LO.
- > Not surprised! Pythia8 standard tune is based on LO events.

$e^+e^- \rightarrow q\bar{q}$: 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.

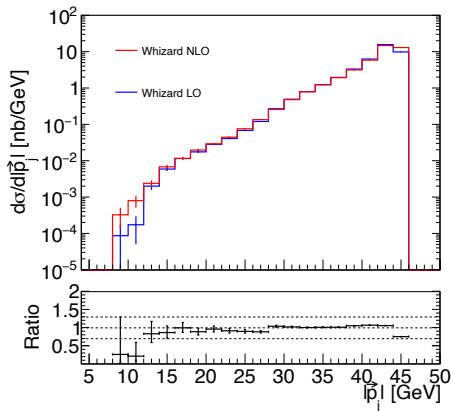


Leading jet

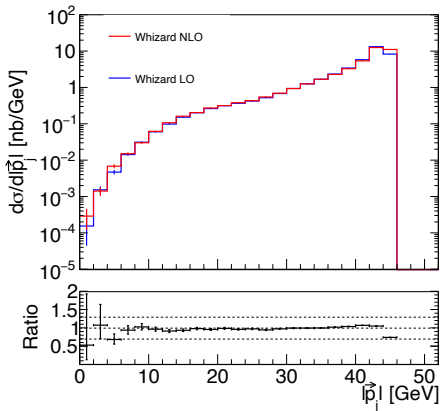


Sub-leading jet

$e^+e^- \rightarrow q\bar{q}$: Kinematics Distributions



Leading jet



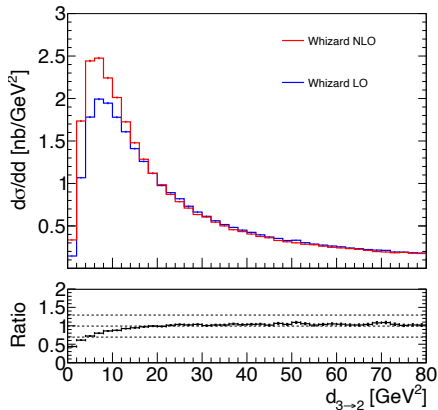
Sub-leading jet

$e^+e^- \rightarrow q\bar{q}$: Kinematics Distributions

FastJet define the jets by calculating:

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

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



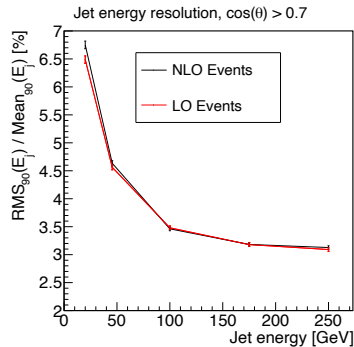
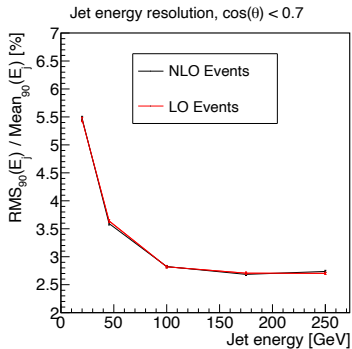
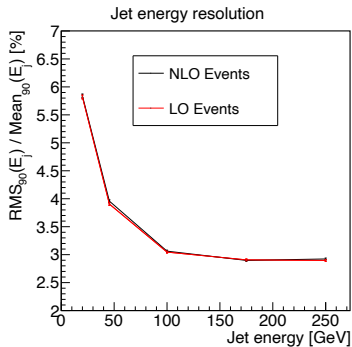
$e^+e^- \rightarrow q\bar{q}$: Full ILD Simulation

Full Geant4-based MC simulations are crucial to optimize a well performed detector 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:

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

$e^+e^- \rightarrow q\bar{q}$: Full ILD Simulation



> Jet energy is defined as total PFO energy divided by 2.

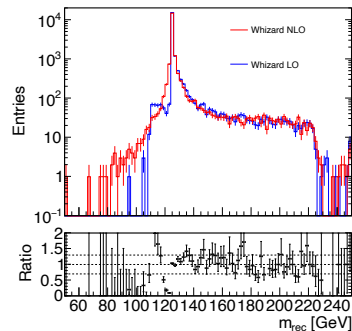
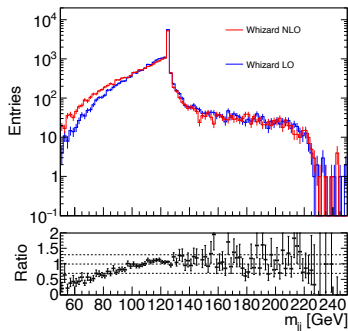
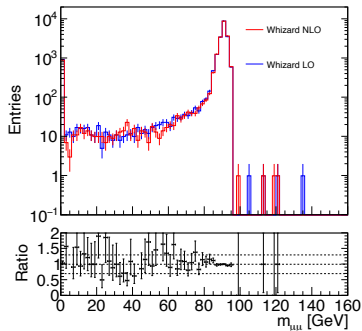
$e^+e^- \rightarrow \mu^+\mu^-b\bar{b}$: Fixed order cross sections

- > Process: $e^+e^- \rightarrow \mu^+\mu^-b\bar{b}$
- > The center of mass energy is $E_{cm} = 250$ GeV.
- > Cuts: $85 \text{ GeV} < M_{\mu\mu} < 95 \text{ GeV}$ and $110 \text{ GeV} < M_{bb(g)} < 140 \text{ GeV}$.
- > Scale: $\frac{1}{2} \sum \sqrt{p_T^2 + m^2}$.

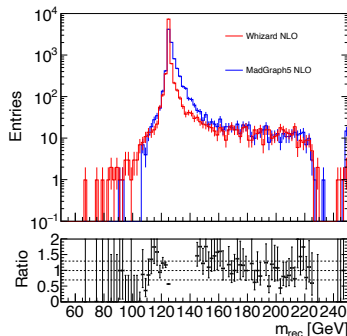
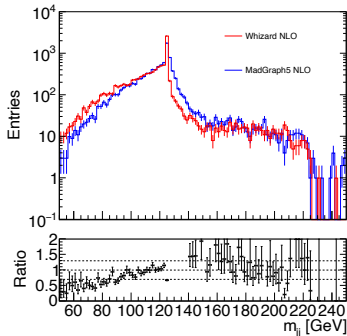
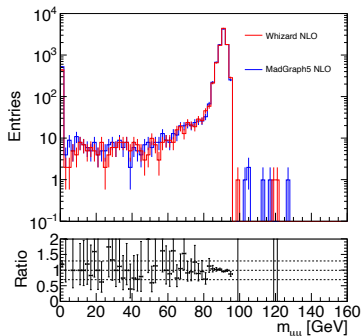
	Whizard	MadGraph5
σ_{LO} [fb]	6.068 ± 0.032	6.089 ± 0.014
σ_{NLO} [fb]	3.895 ± 0.027	3.878 ± 0.022

$$\sigma_{NLO}/\sigma_{LO} \sim 63\%$$

$e^+e^- \rightarrow \mu^+\mu^-b\bar{b}$: Hadron Level Distributions



$e^+e^- \rightarrow \mu^+\mu^-b\bar{b}$: Hadron Level Distributions



- > Whizard+Pythia8.3 vs MadGraph5+Pythia8.2
- > POWHEG vs MC@NLO

$e^+e^- \rightarrow \mu^+\mu^-b\bar{b}$: Soft Mismatch

The emission of gluon moves the invariant mass of Higgs from its Born value:

$$p_{bbg}^2 = \bar{p}_{bb}^2 + \Delta_{bbg}^2$$

The mismatch of the Higgs propagator:

$$\frac{D_H^{\text{Born}}}{D_H^{\text{Real}}} = \frac{[(\bar{p}_{bb}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2]^{-1}}{[(p_{bbg}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2]^{-1}}$$
$$\approx 1 + \frac{\Delta_{bbg}^4}{m_H^2 \Gamma_H^2}$$

→ Resonance-aware FKS subtraction

[C. Weiss' Thesis, 2017]

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Starting integration for process 'nlo_eebbmu_p1' part 'mismatch'
Integrate: iterations = 10:10000:"gw"
Integrator: 12 chains, 54 channels, 11 dimensions
Integrator: Using VAMP2 channel equivalences
Integrator: Write grid header and grids to 'nlo_eebbmu_p1.m4.vg2'
Integrator: Grid checkpoint after each iteration
Integrator: 10000 initial calls, 20 max. bins, stratified = T
Integrator: VAMP2
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It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
VAMP2: Using grids and results from file 'nlo_eebbmu_p1.m4.vg2'.								
1	9999	-2.5641636E+00	3.73E-01	14.55	14.55*	5.88		
2	9084	-2.0702378E+00	4.59E-02	2.22	2.11*	6.99		
3	8591	-2.0637885E+00	2.67E-02	1.29	1.20*	19.89		
4	8617	-2.0649900E+00	2.32E-02	1.13	1.04*	24.06		
5	8766	-2.1084189E+00	2.31E-02	1.09	1.02*	22.23		
6	9014	-2.0787142E+00	2.21E-02	1.06	1.01*	19.38		
7	9325	-2.0910010E+00	2.19E-02	1.05	1.01*	18.75		
8	9604	-2.0860949E+00	2.18E-02	1.05	1.01	15.29		
9	9840	-2.0825761E+00	2.17E-02	1.04	1.03	16.74		
10	10005	-2.0840968E+00	2.20E-02	1.06	1.06	14.96		
10	92845	-2.0830402E+00	7.89E-03	0.38	1.15	14.96	0.47	10

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Summary

Summary:

- > The MC simulation chain is necessary to upgrade to modern generators with NLO precision.
- > We test the NLO mode of Whizard.
- > We get good agreement between LO and NLO events at reconstruction level.
- > The NLO corrections play an important role in $e^+e^- \rightarrow \mu^+\mu^-b\bar{b}$.
- > Further checks are necessary.

Thank You

Backup slides