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

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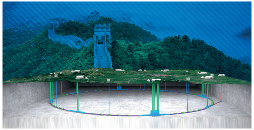
Zhijie Zhao[1,2,3], Mikael Berggren[1], Jenny List[1]
[1]Deutsches Elektronen-Synchrotron DESY
[2]Center for Future High Energy Physics, Institute of High Energy Physics, Chinese Academy of Sciences
[3]University of Chinese Academy of Sciences

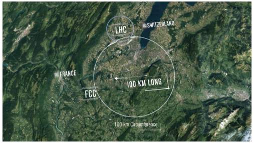
Introduction: Higgs Factories

Proposed future colliders:

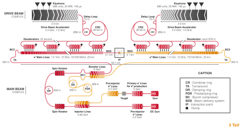
ILC



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...

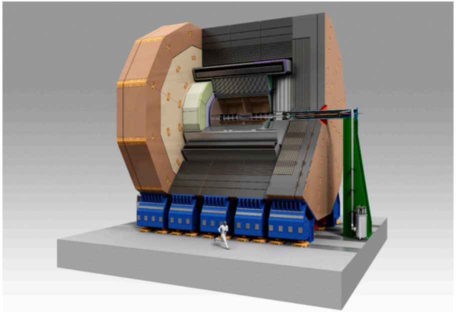
$\rightarrow$ Monte-Carlo events generator Whizard [W. Kilian *et al.*, 2007]

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)

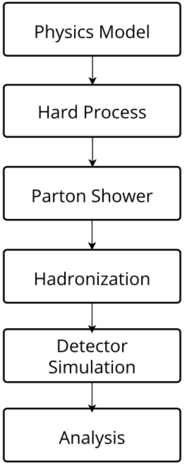
$\rightarrow$ Depends on the tuning of parameters in the MC simulation chain.



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



$e^+e^- \to q\bar{q}$: Test on 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]

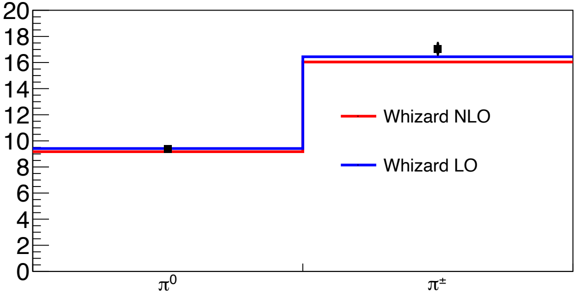
$e^+e^- \to q\bar{q}$: Fixed Order Cross Sections

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

Totally, $\sigma_{NLO}/\sigma_{LO} \approx 103.6\%$

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

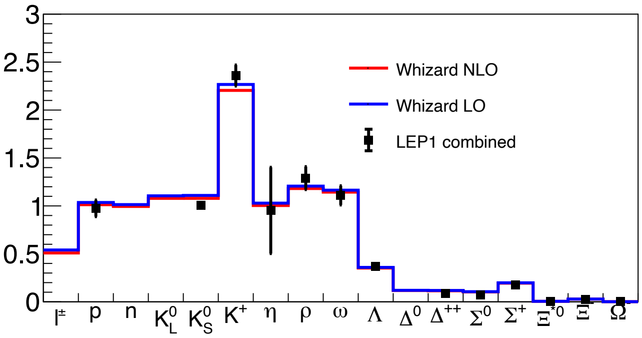
Hadronization rates are crucial for studying particle flow performance. To see the NLO effects, we study the average hadron multiplicities. The dominant hadrons are pions. The average numbers of pions in events are



	n_{π^0}	$n_{\pi^\pm}$
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]

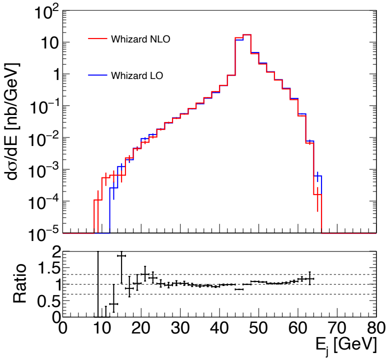
$e^+e^- \to q\bar{q}$: Average Hadron Multiplicities



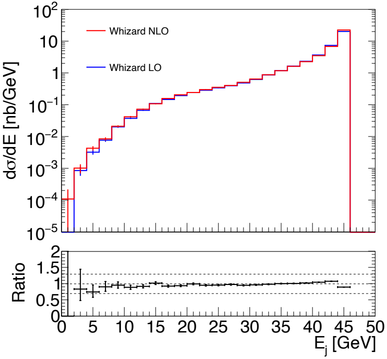
- NLO events have better agreement on proton and K_S^0.
- The numbers of hadrons at NLO are slightly lower than the LO.
- Not surprised! Pythia8 standard tune is based on LO events.

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

We use FastJet [M. Cacciari *et al.*, 2011] to find jets with the Durham algorithm. [S. Catani *et al.*, 1991] We forced the number of jets to 2 and sorted them by energy.

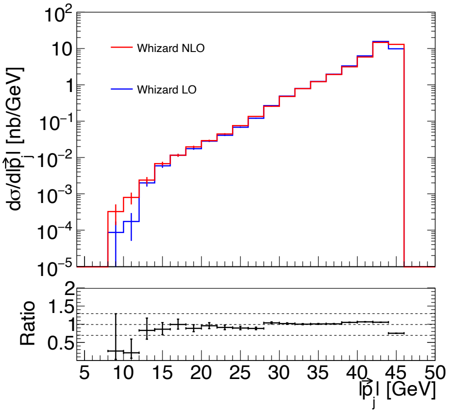


Leading jet

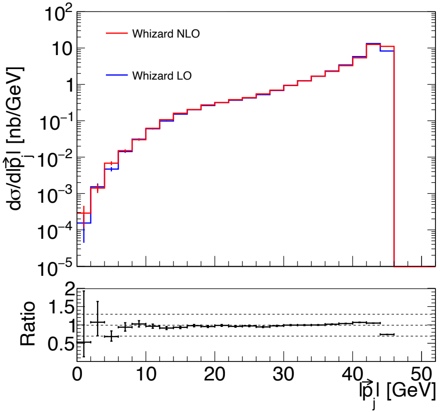


Sub-leading jet

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



Leading jet



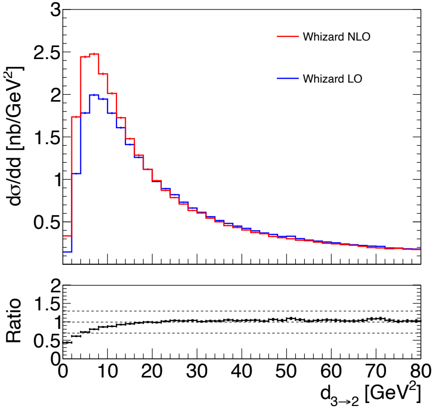
Sub-leading jet

$e^+e^- \to q\bar{q}$: 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 $d_{3\to 2}$, which is the value associated with merging from 3 to 2 jets.



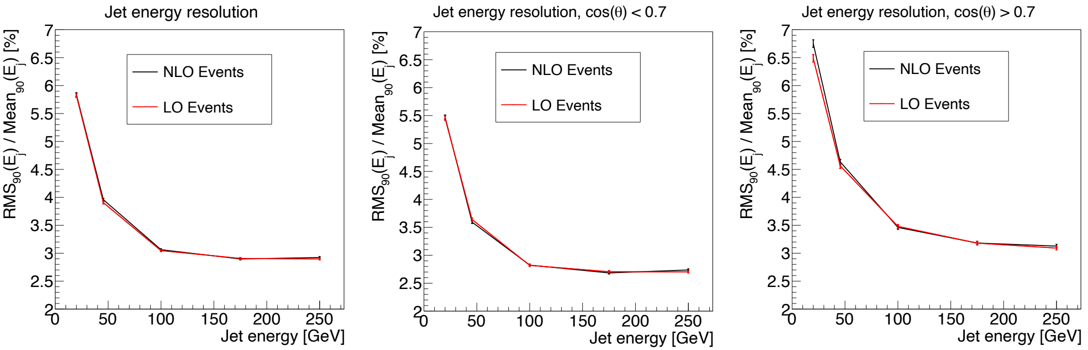
$e^+e^- \to q\bar{q}$: Full ILD Simulation

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.
- Pythia8 standard tune has been used.
- Full simulation is performed with ILD-L model.

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



- Jet energy is defined as total PFO energy divided by 2.
- LO result has good agreement with Pythia6 (see my talk on LCWS2023).

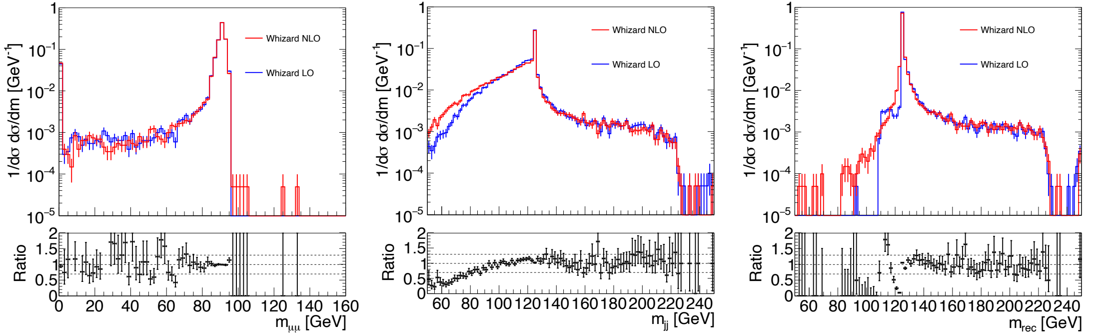
$e^+e^- \to \mu^+\mu^- b\bar{b}$: Fixed Order Cross Sections

- Process: $e^+e^- \to \mu^+\mu^- b\bar{b}$
- The center of mass energy is $E_{cm} = 250$ GeV.
- No ISR, polarization, and Beam-strahlung.
- Cuts: 85 GeV$< M_{\mu\mu} < 95$ GeV and 110 GeV$< M_{bb(g)} < 140$ 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

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

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



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

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

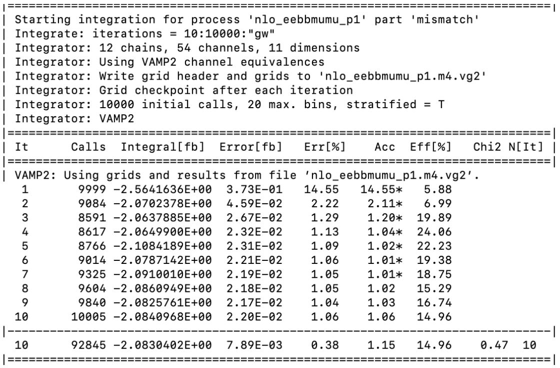
$$p_{bbg}^2 = \bar{p}_{bb}^2 + \Delta_{bbg}^2$$

The mismatch of the Higgs propagator:

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

→ Resonance-aware FKS subtraction

[C. Weiss' Thesis, 2017]



```
|=============================================================================|
| Starting integration for process 'nlo_eebbmumu_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_eebbmumu_p1.m4.vg2'
| Integrator: Grid checkpoint after each iteration
| Integrator: 10000 initial calls, 20 max. bins, stratified = T
| Integrator: VAMP2
|=============================================================================|
| It      Calls  Integral[fb]  Error[fb]   Err[%]    Acc  Eff[%]   Chi2 N[It] |
|=============================================================================|
| VAMP2: Using grids and results from file ’nlo_eebbmumu_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    1.02   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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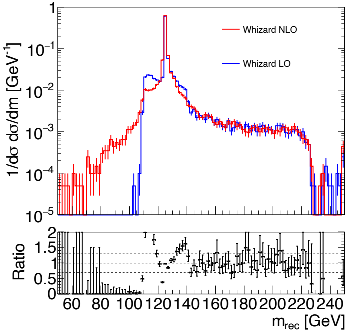
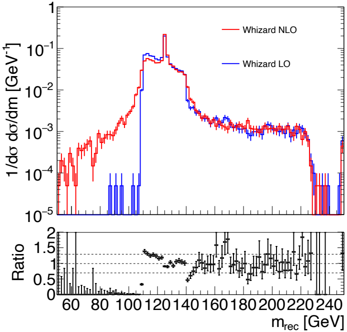
$e^+e^- \to \mu^+\mu^- b\bar{b}$: Effects of Higgs Width

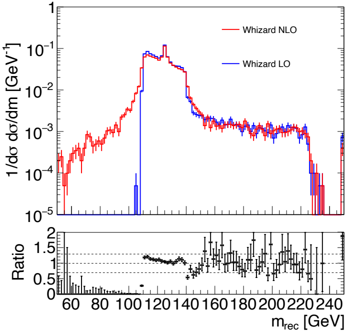
In MC generator, we can input any value of Γ_H



$\Gamma_H = 0.05$ GeV,
$\sigma_{NLO}/\sigma_{LO} \approx 72\%$

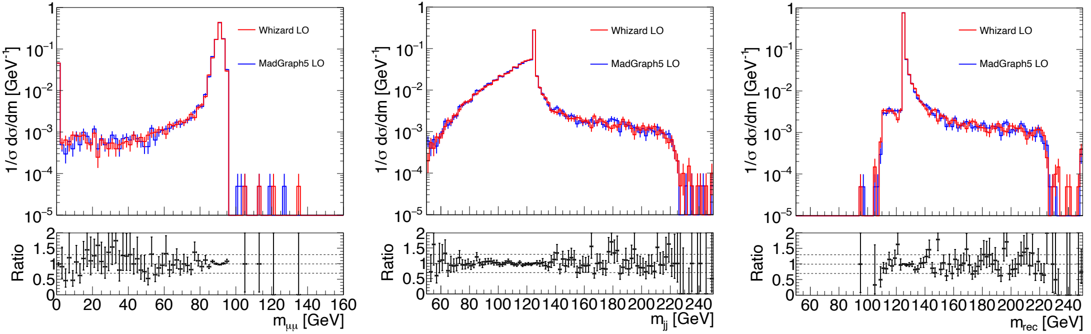


$\Gamma_H = 0.5$ GeV,
$\sigma_{NLO}/\sigma_{LO} \approx 94\%$



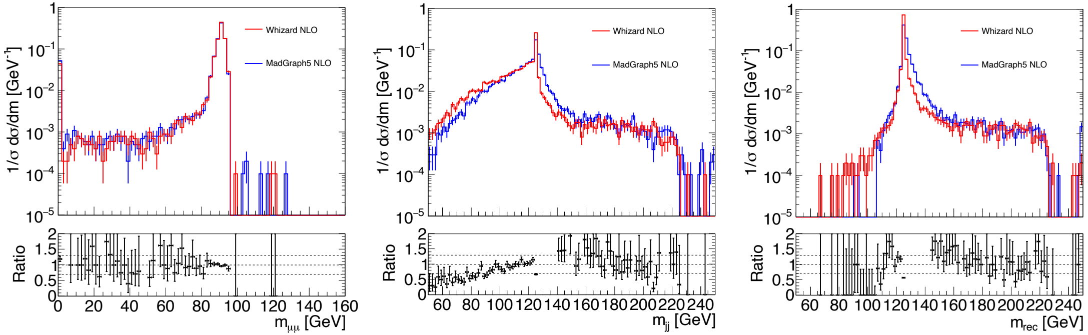
$\Gamma_H = 1$ GeV,
$\sigma_{NLO}/\sigma_{LO} \approx 98\%$

$e^+e^- \to \mu^+\mu^- b\bar{b}$: Comparison with MadGraph5



- Good agreement at LO.

$e^+e^- \to \mu^+\mu^- b\bar{b}$: Comparison with MadGraph5



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

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 for $e^+e^- \to q\bar{q}$.
- The NLO corrections play an important role in $e^+e^- \to \mu^+\mu^-b\bar{b}$.
- Further checks are necessary.

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:

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

    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.