Initial State Radiation Simulation with MadGraph

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ABSTRACT: Initial State Radiation (ISR) effect is implemented in MADGRAPH using photon structure functions. Detailed examinations are performed against other generators including WHIZARD, BabayagaNLO and KKMC, for various physics processes at linear colliders such as 240GeV CEPC and 10.58GeV Belle II. ISR effects on new physics searches are also discussed, taking anomalous gauge boson coupling and dark photon as examples. An ISR plugin \footnote{http://github.com/qliphy/MGISR} is made public for wide usage.

KEYWORDS: ISR, MadGraph, CEPC, Belle II, Dark Photon
1 Introduction

The Initial State Radiation (ISR) is an important issue in high energy processes, especially for lepton colliders, including CEPC [1, 2], ILC [3] and B-factories (for example Belle II [4, 5]). ISR affects both total and differential cross section significantly, for example, reduces the $ZH$ inclusive cross section at CEPC by more than 10% [6]. We have managed for the first time to simulate ISR in MadGraph with lepton ISR structure function [7], that includes all orders of soft and soft-collinear photons as well as up to the third order in hard-collinear photons. Comparisons can be seen in Ref. [6] for $e^+e^- \rightarrow ZH$, from which one can see the good agreement between Whizard [8], and MadGraph with ISR included.

Within MadGraph version 26X, a plugin is now made public to further simplify ISR simulation. The plugin, on top of the user friendly framework of MadGraph, makes relevant studies at linear colliders more accurate, including searching for dark photon [9–11] and probing anomalous triple or quartic gauge couplings [12, 13].

This paper is organized as follows. Section 2 shows the ISR implementation in MadGraph and results at CEPC. Section 3 provides results at Belle II. Section 4 presents the ISR effects on new physics searches. The conclusion is summarized in Section 5.

2 $e^+e^- \rightarrow W^+W^-\gamma$ at CEPC

$W^+W^-\gamma$ production at CEPC and ILC is an interesting process to test the Standard Model and probe anomalous quartic gauge couplings. At 240GeV CEPC with photon transverse momentum $P_{T\gamma} > 10$ GeV, the cross sections from MadGraph read 263.2 and 237.4fb, without or with ISR included, respectively. Fig. 1 gives the normalized differential distributions for $e^+e^- \rightarrow W^+W^-\gamma$ at 240GeV CEPC, from which one can see the good agreement between Whizard and MadGraph with ISR included, on distributions of center-of-mass energy and photon transverse momentum. With ISR included, $P_{T\gamma}$ tends to be softer as expected.
3 $e^+e^- \rightarrow \mu^+\mu^-$ at Belle II

$e^+e^- \rightarrow \mu^+\mu^-$ at Belle II is crucial for background control and luminosity measurement. The cross section from MadGraph with ISR reads 1.14nb (MadGraph without ISR gives about 0.86nb), which agrees well with the precision prediction from Babaya-gaNLO [14] and KKMC [15]. Fig. 2 provides further detailed comparison among Whizard, BabayagaNLO, KKMC and MadGraph. In general, good agreement are found between Whizard and MadGraph, and between KKMC and BabayagaNLO. The discrepancies between the former and later should be related to different treatment of photon structure functions and QED coupling running, etc. Various simulations will be useful for future systematic studies.

4 ISR effects on aQGC and Dark photon searches

As mentioned above, the ISR plugin on top of the user friendly framework of MadGraph, can make new physics simulations at linear colliders more accurate, including searching for dark photon [9–11] and probing anomalous triple or quartic gauge couplings [12, 13]. Fig. 3 shows the dark photon production rate dependence on dark photon mass, for $e^+e^- \rightarrow \gamma A$ at 10.58 GeV Belle II, with cuts $|\cos(\theta_{CM}^\gamma)| < 0.933$ and $E_{CM}^\gamma > 0.5$ GeV, with or without ISR effect included. For light dark photon, the cross section with ISR is larger by 10-20% than the one without ISR included. Fig. 4 shows the comparisons on photon transverse momentum, in SM or aQGC (fM0=2 TeV$^{-4}$), with or without ISR effect included, for the process $e^+e^- \rightarrow W^+W^-\gamma$. One can see the ISR is crucial to be included for aQGC searches, as it changes the tail distributions largely.
Figure 2. Comparisons plots on muon pair invariant mass and muon momentum, among various
 generators, for the process $e^+e^-\rightarrow\mu^+\mu^-$ at Belle II (4 GeV position + 7 GeV electron as beams).
All the curves are normalized to same area.

\begin{equation}
e^+e^-\rightarrow\gamma A@10.58 \text{ GeV Belle II: } |\cos(\theta_{\gamma CM})| < 0.933, E_{\gamma CM} > 0.5 \text{ GeV}
\end{equation}

Figure 3. Cross section dependence on dark photon mass, for $e^+e^-\rightarrow\gamma A$ at 10.58 GeV Belle II,
with cuts $|\cos(\theta_{\gamma CM})| < 0.933$ and $E_{\gamma CM} > 0.5$ GeV, with or without ISR effect included.

5 Summary and Conclusions

ISR effect has been implemented in MadGraph and a easy-to-use plugin is pro-
vided. Detailed examinations are perfomed against other generators including Whizard,
BabayagaNLO and KKMC, for various physics processes at linear colliders such as 240GeV
CEPC and 10.58GeV Belle II. ISR effects on new physics searches are also discussed, taking
Figure 4. Comparisons plots on photon transverse momentum, in SM or aQGC (fM0=2 TeV$^{-4}$), with or without ISR effect included, for the process $e^+e^- \rightarrow W^+W^\gamma$.

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