CEEX EW Corrections for $f \bar{f} \rightarrow f' \bar{f}'$ at LHC, Muon Colliders and FCC-ee as Realized in KK MC 4.22

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Abstract
With an eye toward the precision physics of the LHC, FCC-ee and possible high energy muon colliders, we present the extension of the CEEX (coherent exclusive exponentiation) realization of the YFS approach to resummation in our KK MC to include the processes $f \bar{f} \rightarrow f' \bar{f}'$, $f = \mu, \tau, q, \nu \ell$, $f' = e, \mu, \tau, q, \nu \ell$, $q = u, d, s, c, b, t$, $\ell = e, \mu, \tau$ with $f \neq f'$. After giving a brief summary of the CEEX theory with reference to the older EEX (exclusive exponentiation) theory, we illustrate theoretical results relevant to the LHC, FCC-ee, and possible muon collider physics programs.

Keywords: Coherent Exclusive Exponentiation EW Corrections Collider Physics

1. Introduction
In the context of the precision era for QCD in LHC physics (QCD precision tags $\leq 1\%$), higher order EW corrections are a necessity, as we have explained in Ref. [1]. Similarly, the muon collider physics program involves precision studies of the properties of the recently discovered [2, 3] BEH boson [4] and treatment of the effects of higher order EW corrections will be essential, as we illustrate in Ref. [1]. Building on our successful YFS/CEEX exponentiation [5, 6, 7, 8] realization in $\chi MC4.13$ [9] in precision LEP, B-Factor and Tau-Charm factory physics, we have extended it to $\chi MC4.22$ [10] wherein the incoming beams choice, previously restricted to $e^+$, $e^-$, now allows $f \bar{f}$, $f = e, \mu, \tau, q, \nu \ell$, $q = u, d, s, b, t$, $\ell = e, \mu, \tau$. We note that previous versions of $\chi MC$ even though not adapted for the LHC were already found useful in estimations of theoretical systematic errors of other calculations [10, 11]. We also note the approaches of Refs. [12, 13, 14, 15, 16] to EW corrections to heavy gauge boson production at the LHC. In LEP studies [17] per mille level accuracy required higher order corrections beyond the exact $O(\alpha)$ EW corrections. Our studies in ref. [11], briefly exhibited below, show that this is still the case so that the approaches in Ref. [12, 14, 16, 15] must be extended to higher orders for precision LHC studies. Observe that the QED parton shower approach used in Ref. [13] for these higher order corrections is intrinsically a $0-\mathbf{p}_T$ formalism and that ad hoc procedures, with varying degrees of success, are used to re-introduce non-zero $\mathbf{p}_T$ for the higher order effects whereas our CEEX exponentiation with exact $O(\alpha^2 L)$ corrections gives the higher effects systematically the non-$\mathbf{p}_T$ profile that is exactly correct in the soft limit to all orders in $\alpha$. Here, we give a short summary in the next Section of the main features of YFS/CEEX exponentiation [7, 8] in the SM EW theory. In Sect. [8] we discuss the changes required to extend the incoming beam choices in the $\chi MC$ to the more inclusive list of the SM fermions, present examples of theoretical results relevant for the LHC, FCC-ee [18] and possible muon collider [19] precision physics programs, and present our summary remarks.
2. Review of Standard Model calculations for $e^+e^-$ annihilation with CEEX YFS exponentiation

We note that CEEX replaces the older EEX [6] – both are derived from the YFS theory [5]. Like what is also now featured in the MC’s Herwig++ [20] and Sherpa [21] for particle decays, EEX, Exclusive EXponentiation, is very close to the original Yennie-Frautschi-Suura formulation. CEEX, Coherent EXclusive exponentiation, is actually an extension of the YFS theory. The coherence of CEEX is friendly to quantum coherence among the Feynman diagrams: we have the complete $|\Sigma_{\text{diag.}} M_{ij}|^2$ rather than the often incomplete $\Sigma_{i,j} M_{ij}^*$. The proper treatment of narrow resonances, $\gamma\oplus Z$ exchanges, $t\oplus s$ channels, ISR$\oplus$FSR, angular ordering, etc. are all readily obtained as a consequence. Examples of the EXX formulation are KORALZ/YFS2, BHLUMI, BHWISE, YFSWW, KoralW and YFSZZ in our MC event generator approach; the only example of the CEEX formulation is $\mathcal{X}^{\mathcal{X}}$MC.

For the process $e^- (p_1, \lambda_1) + e^- (p_2, \lambda_2) \rightarrow f(q_1, \lambda'_1) + f(q_2, \lambda'_2) + \gamma(k_1, \sigma_1) + \ldots + \gamma(k_n, \sigma_n)$, we illustrate CEEX schematically for the full scale and YFSZZ in our MC event generator approach; the new version of $\mathcal{X}^{\mathcal{X}}$MC is version 4.22. We have made considerable cross-checks [11] both during and after the extension, as we now illustrate.

In the most important cross-check, we exhibit in Tab. 1 here that, for the $e^+e^- \rightarrow \mu^+\mu^-$ process, $\mathcal{X}^{\mathcal{X}}$MC 4.22 reproduces the results in the corresponding $\sqrt{s} = 189$GeV studies done in Ref. [11] for the dependence of the CEEX calculated cross section and $A_{FB}$ on the energy cut-off on $\nu = 1 - s'/s$ where $s' = M_{\mu\mu}^2$ is the invariant mass of the $\mu\mu$-system. This and its companion results given in ref. [11] show that our introduction of the new beams has not spoiled the precision of the $\mathcal{X}^{\mathcal{X}}$MC for the incoming $e^+e^-$ state.

Proceeding pedagogically, especially given the interest in muon collider precision physics [19], we consider next the process $\mu^+\mu^- \rightarrow e^+e^-$ as our first new beam scenario, again at $\sqrt{s} = 189$GeV to have as a reference the usual incoming $e^+e^-$ annihilation scenario. In this new $\mu^+\mu^-$ scenario, while the EW...
charges are all the same, the ISR probability to radiate factor $\gamma = \frac{1}{2} \left( \ln(s/m^2) - 1 \right) \approx 0.114$ becomes $\gamma = \frac{1}{2} \left( \ln(s/m^2) - 1 \right) \approx 0.6649$. This means that we expect the EW effects where the photonic corrections dominate to show reduction in size for ISR dominated regimes, the same size for the IFI dominated regimes. This is borne-out by the results in Tab. 6 and the companion results in ref. [11], which together provide a precision tag of 0.2% at an energy cut of 0.6. Precision results for EW effects would be available for the muon collider physics as it will be discussed elsewhere [25].

Turning next to the case of incoming quark anti-quark beams and proceeding as indicated above, for the process $u\bar{u} \rightarrow \mu^+\mu^-$ we obtain the results in Tab. 5 and the companion results given in ref. [11], from which we get the precision tag 0.8% for the energy cut 0.6. This satisfies the requirements of precision LHC studies.

The third step in our extension is the introduction of PDF’s for the quark beams. This is currently done in a hard-wired way using the beamsschaltung module in the $\chi^\prime$MC. A more algorithmic formulation of this part of the extension is in progress [25]. In Appendix A of ref. [11], sample output (three events in the LUND MC format) is given from a run of $\chi^\prime$MC version 4.22 for $pp \rightarrow u\bar{u} \rightarrow \Gamma^+\Gamma^- + n\gamma$ where simple parton distribution functions (PDF’s) of $u$ and $\bar{u}$ quarks in the proton are replacing beamsschaltung distributions (see function BornVzfoamC in the source code). The proton remnants are now represented by two photons in the event record with the exactly transverse mo-

Table 2: Study of total cross section $\sigma(v_{max})$ and charge asymmetry $A_{qq}(v_{max})$, $u\bar{u} \rightarrow \mu^+\mu^-$, at $\sqrt{s} = 189$GeV. See Table 1 for definition of the energy cut $v_{max}$, scattering angle and M.E. type.

| $v_{max}$ | $\Delta\sigma_{qq}(0.1)$ | $\Delta\sigma_{qq}(0.2)$ | $\Delta\sigma_{qq}(0.3)$ | $\Delta\sigma_{qq}(0.4)$ | $\Delta\sigma_{qq}(0.5)$ | $\Delta\sigma_{qq}(0.6)$ | $\Delta\sigma_{qq}(0.7)$ | $\Delta\sigma_{qq}(0.8)$ | $\Delta\sigma_{qq}(0.9)$ |
|----------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 0.01     | 1.2714 ± 0.0000  | 1.2718 ± 0.0009  | 1.2718 ± 0.0009  | 1.2718 ± 0.0009  | 1.2718 ± 0.0009  | 1.2718 ± 0.0009  | 1.2718 ± 0.0009  | 1.2718 ± 0.0009  | 1.2718 ± 0.0009  |
| 0.99     | 0.4285 ± 0.0000  | 0.4283 ± 0.0004  | 0.4274 ± 0.0004  | 0.4238 ± 0.0004  | 0.4238 ± 0.0004  | 0.4238 ± 0.0004  | 0.4238 ± 0.0004  | 0.4238 ± 0.0004  | 0.4238 ± 0.0004  |

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$R = \frac{\sigma_{\text{CEEX2}}}{\sigma_{\text{CEEX1}}}$ for CEEX2 (red), $R$ for CEEX1 (blue), $i\nu\nu\gamma\mu\gamma_1$.

Figure 1: QED correction estimate in $\sigma(\nu\gamma)/\sigma(\mu\bar{\nu})$: QED corrections seem to cancel dramatically in this ratio and drop to $\sim 0.03\%$. This preliminary result is undergoing further tests.

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