

## Overview of IR-Improvement in Precision LHC/FCC Physics

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**S. A. Yost,<sup>a,\*</sup> Y. Liu,<sup>b</sup> B. Shakerin<sup>b</sup> and B. F. L. Ward<sup>b</sup>**

<sup>a</sup>*Department of Physics, The Citadel,  
171 Moultrie St., Charleston, South Carolina 29409, USA*

<sup>b</sup>*Department of Physics, Baylor University,  
One Bear Place 97316, Waco, Texas 76798, USA  
E-mail: [Scott.Yost@citadel.edu](mailto:Scott.Yost@citadel.edu), [Yang\\_Liu1@baylor.edu](mailto:Yang_Liu1@baylor.edu),  
[Bahram.Shakerin@gmail.com](mailto:Bahram.Shakerin@gmail.com), [BFL\\_Ward@baylor.edu](mailto:BFL_Ward@baylor.edu)*

We present an overview of the use of IR-improvement of unintegrable singularities in the infrared regime via amplitude-based resummation in  $\text{QED} \times \text{QCD} \subset \text{SU}(2)_L \times \text{U}_1 \times \text{SU}(3)^c$ . We work in the context of precision LHC/FCC physics. While illustrating such IR-improvement in specific examples, we discuss new results and new issues.

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\*Speaker

## 1. Introduction

The LHC and the planned FCC [1] both require precision theory predictions to exploit fully their physics potentials. One of the theoretical tools that is key to precision theory is resummation in the context of quantum field theory.<sup>1</sup> Refs. [3, 5–7] extend the original exact resummation theory of Yennie, Frautschi, and Suura [8] to an amplitude-level exact resummation for the entire QCD⊗EW theory, resulting in IR-improvement of the comparison between data and the respective Standard Model predictions. Here, we give a brief report on the status of this IR-improvement program, beginning with a concise review of exact amplitude-based resummation methods and following with some new results and issues in precision LHC and FCC physics.

## 2. Concise Review of Exact Amplitude-Based Resummation Theory

The application of exact amplitude-based resummation theory to precision LHC/FCC physics begins with the master formula for the process  $q_1 + q_2 \rightarrow q'_1 + q'_2$ , in an obvious notation for the kinematics,

$$d\bar{\sigma}_{\text{res}} = e^{\text{SUM}_{\text{IR}}(\text{QCED})} \sum_{n,m=0}^{\infty} \frac{1}{n!m!} \int \prod_{j_1=1}^n \frac{d^3 k_{j_1}}{k_{j_1}} \frac{d^3 p_2}{p_2^0} \frac{d^3 q_2}{q_2^0} \prod_{j_2=1}^m \frac{d^3 k'_{j_2}}{k'_{j_2}} \int \frac{d^4 y}{(2\pi)^4} e^{iy \cdot (p_1+q_1-p_2-q_2-\sum k_{j_1}-\sum k'_{j_2})+D_{\text{QCED}}} \tilde{\beta}_{n,m}(k_1, \dots, k_n; k'_1, \dots, k'_m), \quad (1)$$

where *new* (YFS-style) *non-Abelian* residuals  $\tilde{\beta}_{n,m}(k_1, \dots, k_n; k'_1, \dots, k'_m)$  have  $n$  hard gluons and  $m$  hard photons. Definitions of the infrared functions  $\text{SUM}_{\text{IR}}(\text{QCED})$  and  $D_{\text{QCED}}$  and of the residuals are given in Ref. [5]. In the framework of shower/ME matching, we have the replacements  $\tilde{\beta}_{n,m} \rightarrow \hat{\beta}_{n,m}$ . These replacements allow us, via the basic formula

$$d\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) d\hat{\sigma}_{\text{res}}(x_1 x_2 s), \quad (2)$$

to proceed with connection to MC@NLO [4] as explained in Ref. [5], to MG5\_aMC@NLO [9] as explained in Refs. [10], or to MG5\_aMC@NLO as explained in Ref. [11], or to KKMChh with a Herwig6.5 [13] or Herwiri1.031 [3] shower as explained in Refs. [6, 7, 12].

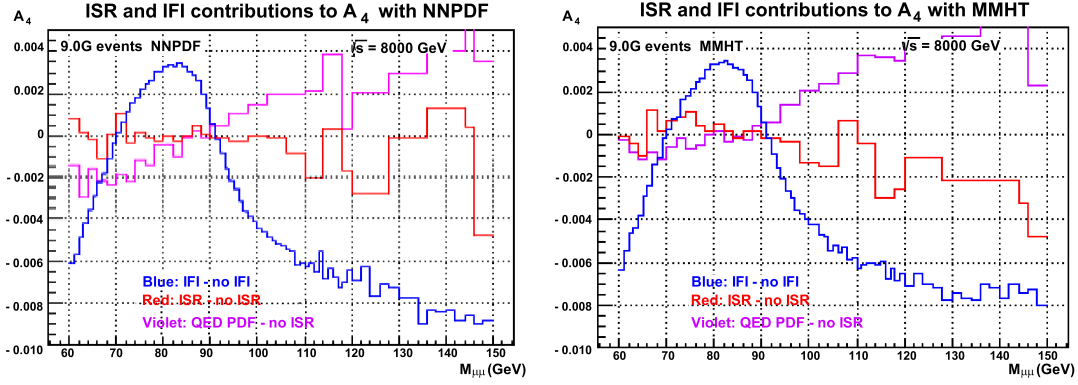
## 3. New Results and New Issues in LHC/FCC Physics

IR-improved results for precision LHC studies, such as those in Refs. [5, 10] where significant improvement is seen the data and the IR-improved theory, show that, for example, in the  $W + \geq 3$  jets and  $W + \geq 1$  jet production at the LHC for the third leading jet  $p_T$ , the improved regime extends out to 100 GeV/ $c$  at 8 TeV cms energies. The robustness of this regime is new.

In the context of the precision studies of the single  $Z$  production at the LHC, KKMChh with Herwig6.5 or Herwiri1.031 carry the CEEX resummed exact  $\mathcal{O}(\alpha^2 L)$  corrections in which the photon transverse degrees of freedom are treated exactly. We see evidence of the importance of these degrees of freedom to precision photonic ISR in Ref. [7].

KKMChh's ISR corrections to forward-backward asymmetry shown in Fig. 1 differ from the effect of simply switching from a standard to QED-corrected PDF set. Issues such as the amount of QED in non-QED PDFs with starting scale  $Q_0 \cong 2$  GeV affect this comparison. The matching of KKMChh's ISR to

<sup>1</sup>See Ref. [2] for more discussion on the various types of resummation in the latter context.



**Figure 1:** ISR and IFI and QED vs normal PDF comparisons for  $A_4$  (calculated as  $\frac{8}{3}A_{FB}$ ) as a function of  $M_{\mu\mu}$  without lepton cuts. The left figure uses NNPDF3.1 NLO [14] and the right figure uses MMHT2014 NLO [15].

a QED-corrected PDF set is addressed by introducing “Negative ISR” (NISR) as explained in Ref. [16, 17], where we find that adding KKMChh’s ISR directly to a non-QED NNPDF3.1 PDF set, closely reproduces the effect of using a QED-corrected NNPDF3.1 set with NISR matching in KKMChh.

The IR-improvement of precision phenomenology also extends to the FCC, to both the FCC-ee [18] and the FCC-hh. For the latter, we note the result in Ref. [12] that, in probing the discovery reach for single Z production in the  $p_{T,Z} > 1$  TeV regime, the IR-improvement does not compromise that reach. The outlook for the IR-improvement of precision physics at the LHC, FCC, and other planned energy frontier colliders, such as CEPC [19], CPPC [20], CLIC [21], and ILC [21], is therefore a rich one.

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## References

- [1] M. Benedikt and F. Zimmermann, *Future Circular Collider Study: Status and Plans*, talk in *2017 FCC Week*, Berlin (2017).
- [2] B.F.L. Ward *et al.*, *IR-improved amplitude-based resummation in quantum field theory: new results and new issues*, *SciPost Phys. Proc.* **7** (2022) 015 [arXiv:2111.01260].
- [3] S. Joseph *et al.*, *New approach to parton shower MC’s for precision QCD theory: HERWIRI1.0(31)*, *Phys. Rev. D* **81** (2010) 076008, [arXiv:1001.1434].
- [4] S. Frixione and B. Webber, *Matching NLO QCD computations and parton shower simulations*, *JHEP* **0206** (2002) 029 [arXiv:hep-ph/0204244]; S. Frixione *et al.*, *NLO QCD corrections in Herwig++ with MCNLO* *JHEP* **1101** (2011) 053, [arXiv:1010.0568].
- [5] S.K. Majhi *et al.*, *Phenomenology of the interplay between IR-improved DGLAP-CS theory and NLO ME matched parton shower MC precision*, *Phys. Lett. B* **719** (2013) 367, [arXiv:1208.4750]; A. Mukhopadhyay and B.F.L. Ward, *Interplay between IR-improved DGLAP-CS theory and the precision of an NLO ME matched parton shower MC in relation to LHCb data*, *Mod. Phys. Lett. A* **31** (2016) 1650063, [arXiv:1412.8717].

- [6] S. Jadach, *et al.*, *KKMChh: Resummed exact  $O(\alpha^2L)$  EW corrections in a hadronic MC event generator*, *Phys. Rev. D* **94** (2016) 074006 [[arXiv:1608.01260](#)]; *ibid.*, *KKMC-hh: Systematic studies of exact  $O(\alpha^2L)$  CEEX EW corrections in a hadronic MC for precision  $Z/\gamma^*$  physics at LHC energies*, *Phys. Rev. D* **99** (2019) 076016 [[arXiv:1707.06502](#)].
- [7] S. A. Yost *et al.*, *ISR and IFI in precision AFB studies with KKMC-hh*, *PoS(RADCOR2019)* **375** (2019) 85 [[arXiv:2002.12477](#)]; S. Jadach *et al.*, *IFI and ISR effects for  $Z/\gamma^*$  Drell-Yan observables using KKMC-hh*, [arXiv:2002.12477](#) (2020).
- [8] D. Yennie, S. Frautschi and H. Suura, *The infrared divergence phenomena and high-energy processes*, *Ann. Phys.* **13** (1961) 379; see also K. T. Mahanthappa, *Multiple production of photons in quantum electrodynamics*, *Phys. Rev.* **126** (1962) 329, for a related analysis.
- [9] A. Alwall *et al.*, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] and references therein.
- [10] B. Shakerin and B.F.L. Ward, *IR-improved DGLAP parton shower effects in  $W$  + jets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV*, *Phys. Rev. D* **100** (2019) 034026 [[arXiv:1809.01492](#)]; *ibid.*, *IR-improved DGLAP parton shower effects for associated production of a  $W$  boson and jets in  $pp$  collisions at  $\sqrt{s} = 8$  and 13 TeV* *Int. J. Mod. Phys. A* **35** (2020) 2050197, [[arXiv:2011.08313](#)].
- [11] Y. Liu *et al.*, BU-HEPP-21-03, to appear.
- [12] B.F.L. Ward *et al.*, *Recent IR-improved results for LHC/FCC physics*, *PoS (RADCOR2017)* (2018) 083 [[arXiv:1801.03303](#)].
- [13] G. Corcella *et al.*, *HERWIG6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)*, *JHEP* **01** (2001) 010 [[arXiv:hep-ph/0011363](#)]; *ibid.*, *HERWIG6.5 release note*, [arXiv:hep-ph/0210213](#) (2002); G. Marchesini *et al.*, *Comput. Phys. Commun.* **67** (1992) 465.
- [14] NNPDF Collaboration, *Parton distributions from high-precision collider data*, *Eur. Phys. J. C* **77(10)** (2017) 663 [[arXiv:1706.00428](#)]; A. V. Manohar, *et al.*, *The photon content of the proton*, *JHEP* **12** (2017) 046 [[arXiv:1708.01256](#)].
- [15] L.A. Harland-Lang *et al.*, *Parton distributions in the LHC era: MMHT 2014 PDFs*, *Eur. Phys. J. C* **75** (2015) 204, [[arXiv:1412.3989](#)]; *ibid.*, *Ad Lucem: QED parton distribution functions in the MMHT framework*, *Eur. Phys. J. C* **79(10)** (2019) 811 [[arXiv:1907.02750](#)].
- [16] S.A. Yost *et al.*, *KKMChh: matching CEEX photonic ISR to a QED-corrected parton shower*, in these *Proceedings*.
- [17] S. Jadach *et al.*, to appear.
- [18] B.F.L. Ward *et al.*, *Overview of theoretical precision of the luminosity at future electron-positron colliders*, in these *Proceedings*.
- [19] H. Cheng *et al.*, *The physics potential of the CEPC. Prepared for the US Snowmass Community Planning Exercise (Snowmass 2021)*, [arXiv:2205.08553](#) (2022).
- [20] M. Ahmad *et al.*, *CEPC-SPPC preliminary conceptual design report. 1. Physics and detector*, IHEP-AC-2015-01.
- [21] P. Burrows, *Current status of the ILC and CLIC projects*, in these *Proceedings*.