Recent IR-Improved Results for FCC Physics

B.F.L. Ward

Baylor University, Waco, TX, USA

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in collaboration with S. Jadach, Z. Was, S. Yost

OUTLINE

- Brief Review of Exact Amplitude-Based Resummation Theory
- $\mathcal{KK}$MC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator
- Illustrative Results and Comparisons
- Outlook

Brief Review of Exact Amplitude-Based Resummation Theory

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

where *new* (YFS-style) *non-Abelian* residuals $\tilde{\bar{\beta}}_{n,m}(k_1,\ldots,k_n;k'_1,\ldots,k'_m)$ have n hard gluons and m hard photons.

Here,

$$\begin{aligned} \mathrm{SUM_{IR}(QCED)} &= 2\alpha_s \Re B^{nls}_{QCED} + 2\alpha_s \tilde{B}^{nls}_{QCED} \\ D_{\mathrm{QCED}} &= \int \frac{d^3k}{k^0}\left(e^{-iky} - \theta(K_{max} - k^0)\right)\tilde{S}^{nls}_{QCED} \end{aligned} \quad (2)$$

where K_{max} is “dummy” and

$$\begin{aligned} B^{nls}_{QCED} &\equiv B^{nls}_{QCD} + \frac{\alpha}{\alpha_s} B^{nls}_{QED}, \\ \tilde{B}^{nls}_{QCED} &\equiv \tilde{B}^{nls}_{QCD} + \frac{\alpha}{\alpha_s} \tilde{B}^{nls}_{QED}, \\ \tilde{S}^{nls}_{QCED} &\equiv \tilde{S}^{nls}_{QCD} + \tilde{S}^{nls}_{QED}. \end{aligned} \quad (3)$$

“nls”≡ DGLAP-CS synthesization.

Shower/ME Matching: $\tilde{\bar{\beta}}_{n,m} \rightarrow \hat{\tilde{\bar{\beta}}}_{n,m}$

Connection to MC@NLO

- Basic Formula:

$$d\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) d\hat{\sigma}_{\rm res}(x_1 x_2 s), \qquad (4)$$

- $$d\sigma_{MC@NLO} = \left[B + V + \int (R_{MC} - C) d\Phi_R \right] d\Phi_B [\Delta_{MC}(0) + \int (R_{MC}/B) \Delta_{MC}(k_T) d\Phi_R] + (R - R_{MC}) \Delta_{MC}(k_T) d\Phi_B d\Phi_R \qquad (5)$$

- $$\Delta_{MC}(p_T) = e^{[-\int d\Phi_R \frac{R_{MC}(\Phi_B,\Phi_R)}{B} \theta(k_T(\Phi_B,\Phi_R) - p_T)]},$$

Connection to MC@NLO

- $\Rightarrow$

$$\frac{1}{2}\hat{\tilde{\bar{\beta}}}_{0,0} = \bar{B} + (\bar{B}/\Delta_{MC}(0)) \int (R_{MC}/B)\Delta_{MC}(k_T)d\Phi_R$$
$$\frac{1}{2}\hat{\tilde{\bar{\beta}}}_{1,0} = R - R_{MC} - B\tilde{S}_{QCD} \quad (6)$$

where

$$\bar{B} = B(1 - 2\alpha_s \Re B_{QCD}) + V + \int (R_{MC} - C)d\Phi_R.$$

- Similar formulas hold for POWHEG, SHERPA (BFLW, to appear).

Current Realizations

- Herwig6.5 Environment:
  Herwiri1.031 (LO Shower MC); MC@NLO/Herwiri1.031
  (NLO Shower/ME Matched MC)
- Pythia8 Environment, **CPC 201 (2016) 29**:
  IR-Improved Pythia8 (LO Shower MC);
  MG5_aMC@NLO/IRI-Pythia8
  (NLO Shower/ME Matched MC)
- IRI-FEWZ, in progress for NNLO resummed exact results
- $\mathcal{KK}$MC-ee, FCCee studies with CEEX Exact $\mathcal{O}(\alpha^2 L)$ corrections – SJ&SY in FCC Week 2016, Rome
- $\mathcal{KK}$MC-hh, **PRD 94 (2016) 074006**:
  FCChh studies with CEEX Exact $\mathcal{O}(\alpha^2 L)$ corrections

$\mathcal{KK}$MC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator

- $\mathcal{KK}$MC-hh derives from $\mathcal{KK}$MC 4.22, Phys. Rev. D**88** (2013) 114022, in union with Herwig6.5
- $\mathcal{KK}$MC 4.22 derives from $\mathcal{KK}$MC 4.19, Phys. Rev. D**63** (2001) 113009 – $f\bar{f}$ beams added, $f \neq e$
- $\mathcal{KK}$MC 4.19 continues today to dominate the $e^+e^- \to f\bar{f} + n\gamma$ precision theory predictions, now at BELLE (KEK) and BES (Beijing).

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$\mathcal{KK}$MC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator

- Key Ingredients:
- CEEX and EEX YFS-style Resummation of Large $n\gamma$ Radiative Effects via EW part of (1) for ISR, FSR and IFI.
- EXACT $\mathcal{O}(\alpha)$ Pure Weak Corrections (exchanges with W,Z,Higgs and their (non-abelian) ghosts) from the DIZET6.1 Library of Bardin *et al.*
- EXACT $\mathcal{O}(\alpha^2 L)$ EW Correction Augmented by EXACT $\mathcal{O}(\alpha^2 L^2,\ \alpha^3 L^3)$: This alone would make $\mathcal{KK}$MC UNIQUE in the World for Hadronic Event Generators
  $\Leftrightarrow$ 0.05% for $\Delta\sigma_{\rm th}/\sigma|_{\rm EW}$

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$\mathcal{KK}$MC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator

- Original Notation: HERWIRI PROJECT: High Energy Radiation With InfraRed Improvements
- HERWIRI1.x : IRI - QCD Resummation
- HERWIRI2.x : IRI - EW Resummation
  - HERWIRI2.0: UNION of $\mathcal{KK}$ MC 4.19 and HERWIG6.5 – REQUIRED ADJUSTMENT for SWITCHING BEAMS from e^+e^- to $q\bar{q}$, as HERWIG6.5 DROVE
  - HERWIRI2.1 $\equiv$ $\mathcal{KK}$MC-hh: USES $q\bar{q}$ BEAMS IN $\mathcal{KK}$ MC 4.22 TO DRIVE AND HERWIG6.5 SHOWERS

$\mathcal{KK}$MC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator

- Comments on CEEX vs EEX
- CEEX: Coherent Exclusive EXponentiation
  - IR singulariteis isolated at the level of the spinor amplitudes
  - Quantum interference effects more efficiently handled
  - This is done event-by-event
- EEX: Exclusive EXponentiation (the usual one)
  - IR singularities isolated at the level of the spin-averaged, spin-summed squared amplitudes
  - Quantum interference effects less efficiently handled
  - This is done event-by-event

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$\mathcal{KK}$MC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator

- Theoretical Foundations of $\mathcal{KK}$MC-hh
- From (1) we get for EW effects

$$\sigma = \frac{1}{\text{flux}} \sum_{n=0}^{\infty} \int d\text{LIPS} \rho_A^{(n)}(\{p\},\{k\}),$$

for $A = \text{CEEX},\ \text{EEX}$, with

$$\rho_{\text{CEEX}}^{(n)}(\{p\},\{k\}) = \frac{1}{n!} e^{Y(\Omega;\{p\})} \bar{\Theta}(\Omega) \frac{1}{4} \sum_{\text{helicities } \{\lambda\},\{\mu\}} \left| \mathcal{M} \begin{pmatrix} \{p\}\{k\} \\ \{\lambda\}\{\mu\} \end{pmatrix} \right|^2 .$$

- This is then used in the standard formula

$$\sigma_{\text{DY}} = \int dx_1 dx_2 \sum_i f_i(x_1) f_{\bar{i}}(x_2) \sigma_{\text{DY},i\bar{i}}(Q^2) \delta(Q^2 - x_1 x_2 s),$$

all realized by MC methods.

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$\mathcal{KK}$MC-hh: Resummed Exact $\mathcal{O}(\alpha^2 L)$ EW Corrections in a Hadronic MC Event Generator

- Event Gneneration
- FOAM (an adaptive MC by Jadach) creates an appropriate distribution grid at initialization.
- Four uniform random numbers on $[0, 1]$ are used to pick quark flavor, Q, a light-cone fraction, and the amount of ISR photon radiation.
- The quark distribution is uniform between u, d, c, s and b
- The remaining 3-d volume is mapped into simplicial cells to optimize the MC integration
- $\Rightarrow$ Showering by Herwig6.5 of the hard events created by the $\mathcal{KK}$ MC modules in $\mathcal{KK}$MC-hh yields EXACTLY the terms $\mathcal{O}(\alpha_s^n L^n, \alpha^2 L')$ and that part of the terms $\mathcal{O}(\alpha_s^n L^n \alpha^2 L')$ which factorizes, where $n = 0, 1, 2, \ldots$ and L, L' are the respective QCD and QED big logs
- Exact QCD NLO correction – in progress

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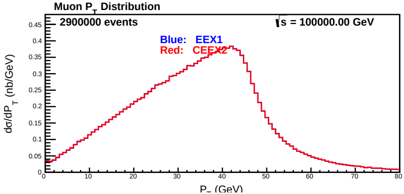
Illustrative Results and Comparisons

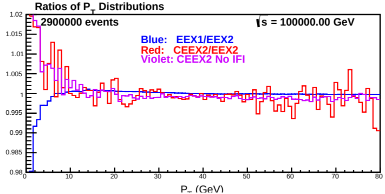
- Sample Monte Carlo Data: 2.9×10^6 events, with MSTW2008 PDFs and cut 50GeV $< M_{q\bar{q}} <$ 200GeV at pp cms of 100 TeV in Tab. 1

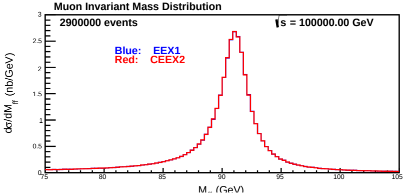
Table : Showered tests with Herwig6.521.

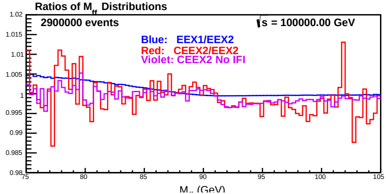
MC	EW-CORR	XSECT
$\mathcal{KK}$MC-hh	EEX1 ISR+FSR+EWK	12.8392 ± 0.0095 nb
$\mathcal{KK}$MC-hh	EEX2 ISR+FSR+EWK	12.8396 ± 0.0095 nb
$\mathcal{KK}$MC-hh	EEX3 ISR+FSR+EWK	12.8394 ± 0.0095 nb
$\mathcal{KK}$MC-hh	CEEX2 ISR+FSR+EWK	12.8377 ± 0.0098 nb

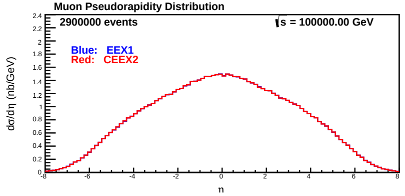
Illustrative Results and Comparisons

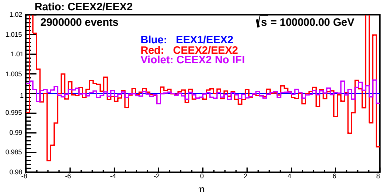












Illustrative Results and Comparisons

Forthcoming updates of $\mathcal{KK}$MC-hh, $\mathcal{KK}$MC-ee for FCC applications:

- τ Simulation:
  - Installation of weights for alternative matrix element for analysis of new physics signatures – ex., see R. Jozefowicz, E. Richter-Was and Z. Was, Phys. Rev. D **94**, no. 9, 093001 (2016), spin weights used as input for algorithm $\Rightarrow$ multi-dimensional observable.
  - Version of TAUOLA with variants of matrix elements and anomalous (e.g. tau neutrinoless) decay channels. Parts of the code into C (rather than to C++) – for another language change before FCC times the code which remains in static form is possibly safer.– M. Chrzaszcz, T. Przedzinski, Z. Was and J. Zaremba, arXiv:1609.04617
- Final state emission of light fermion pairs:
  Added to multiphoton iterative algorithm of PHOTOS. May be used with $\mathcal{KK}$MC-jj on top of its multiphoton algorithm, $j = e,\ h$. Effect is small and consequent degradation of precision due to non-optimal combination of the two effects is substantially below other systematics. – N. Davidson, T. Przedzinski and Z. Was, Comput. Phys. Commun. **199**, 86 (2016)

OUTLOOK

- Precision Theory $\equiv$ Control both

  IR ($z \to 1$)

  and

  Collinear ($p_T \to 0$)

  emission limits

- When Herwiri1.031 is used in the QCD shower step, with $\mathcal{KK}$MC-hh and $\mathcal{KK}$MC-ee we now have control over both for all aspects of the EW$\otimes$QCD corrections.
- Some New Physics may hang in the balance at both FCC and LHC!
- $\mathcal{KK}$MC-hh: Taken together with $\mathcal{KK}$MC-ee, important step in realizing a MC based on nonAbelian QED$\otimes$ QCD resummation and exact $\mathcal{O}(\alpha_s^2, \alpha_s\alpha, \alpha^2 L')$ hard gluon and hard photon residuals for both FCC-hh and FCC-ee precision physics.

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