Snowmass2021 - Letter of Interest

CMB-Like Observable Scheme for Collider Searches

Thematic Areas:

■ (TF07) Collider phenomenology
■ (CompF3) Machine Learning
■ (EF01) EW Physics: Higgs Boson properties and couplings
■ (EF04) EW Precision Physics and constraining new physics

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Abstract: In a previous study[1] we introduced a CMB-like observable scheme to address information deformation and loss caused by jet clustering. In this scheme the event-level kinematics is encoded as Fox-Wolfram (FW) moments at leading order and multi-spectra of spherical harmonics at higher orders. Then the said problem can be solved by synergizing these observables into jet-level analysis order by order. This method is relatively "transparent" in terms of the underlying kinematics, compared to a brute-force analysis at full event level (e.g., using image-recognition techniques of deep neural network). The study in[1] demonstrated that incorporating FW moments indeed reduces the performance gap between the jet-level and full event-level classifiers in a general context, but can not eliminate it completely. This implies that the observables in this scheme not applied yet (such as FW moments at different orders, bispectrum, trispectrum, etc.) may play a significant role in this regard. Thus, we plan to pursue a comprehensive exploration on the role played by each of these observables. We expect that the remaining sensitivity gap shown in[1] will be eventually explained by these observables. Most importantly, this study will provide a general guidance on the application of this observable scheme to future data analysis at colliders.

Lots of efforts have been made to explore precision electroweak and Higgs physics at future lepton colliders[2–16]. Since most of these measurements rely on final states with W, Z and Higgs bosons, the hadronic modes containing (anti-)quarks or/and gluons are dominant and even overwhelmingly dominant over the purely leptonic ones. Because of this, the baseline sensitivities in the CEPC/FCC-ee/ILC/CLIC documents[17–23] for many benchmark precision measurements are based on such hadronic modes, with jet-level analysis being generally applied.

Yet, the precision based on the jet-level analysis is limited for several reasons. First of all, due to the imperfectness of jet clustering algorithms, some visible particles could be clustered into a wrong jet. This becomes especially significant if the jet ancestral partons are collimated, where their hadronizations might badly overlap with each other in space. This effect will deform the jet kinematics from its truth, and may negatively impact the reconstruction of the intermediate particles or events with jets[24]. Secondly, the jet clustering in essence is an operation of dimensionality reduction in the feature space of the visible particles. This operation aims reconstructing four momentum of the partons. But, it removes the dimensions reflecting jet substructure and superstructure, generically resulting in a loss of information.

A significant improvement to many precision measurements would be expected if the information deformation and loss in jet clustering can be well-addressed. As pointed out in[1], the most effective approach is to pursue the analysis in a brute-force way, using the event-level data as input. With this method, the problem of information deformation at jet level becomes irrelevant, while the kinematic information at event level could be exploited to the greatest extent for data analysis. Naively this method are confronted with a challenge, $i.e.$, how to efficiently synergize large amount of event-level information into the data analysis, given the complexity of its structure.

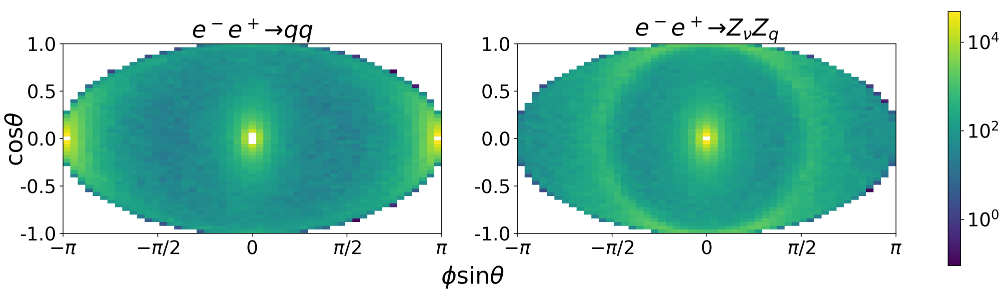

Figure 1: Cumulative Mollweide projections of 10000 events: $e^-e^+ \to qq$ (left) and $e^-e^+ \to ZZ \to \nu\nu qq$ (right), with the brightness of each cell scaling with the total energy (GeV) of the particle hits received. See[1] for more details.

To properly handle the event-level input, we introduce the CMB-like observable scheme, especially at e^-e^+ colliders. It is first invented based on the analogy between collider measurements and cosmological observations. In an event at collider, information from the interaction point is imprinted in the detector sphere as a Mollweide projection (examples of such Mollweide projection are plotted in Figure 1). Analogously, in the all-sky CMB map, the message on the early Universe is encoded in the celestial sphere. Quite generally, we can build up a dictionary between the Mollweide projection of each e^-e^+ collision event and the all-sky CMB map, as is summarized in Table 1. In this scheme the famous Fox-Wolfram (FW) moments[25] play important roles as the counterpart of CMB power spectrum. The FW moments on observables

Mollweide projection at e^-e^+ colliders	All-sky CMB map
Projection sphere	Celestial sphere
Equatorial plane	Galactic plane
Energy (p_T, timing, charge, d_0, etc.) projection	Temperature (polarization) map
Event-level kinematics	Anisotropy
Fox-Wolfram moments	Power spectrum (TT, TB, BB, etc.)
Multi-spectra	Bispectrum, trispectrum, etc.
... ...	... ...

Table 1: Dictionary between the Mollweide projection at e^-e^+ colliders and the all-sky CMB map.

A and B are defined as

$$H_{AB;l} = \sum_{m=-l}^{l} H_{AB;l,m} = \frac{4\pi}{2l+1} \sum_{i,j} \frac{A_i B_j}{s} \sum_{m=-l}^{l} (Y_l^m(\Omega_i)^* Y_l^m(\Omega_j)) = \sum_{i,j} \frac{A_i B_j}{s} P_l(\cos\Omega_{ij}) \ . \quad (1)$$

Here $Y_l^m(\Omega_i)$ is spherical harmonics of degree l and order m, $P_l(\cos\Omega_{ij})$ is Legendre polynomials, and Ω_{ij} is the geometric angle between particle i and j. Naturally, the event-level kinematics is manifested as the anisotropy of the projection. The relevant information thus can be encoded as the FW moments at leading order and multi-spectra at higher orders, an analogue to the CMB power spectrum and its bispectrum, trispectrum, etc. And the spherical projection of collider observables including energy and momentum, timing, tracker parameters such as charge, impact parameter d_0, etc., can be mapped to the all-sky map of the CMB temperature and polarization.

We expect that with the CMB-like observable scheme the kinematic information lost at jet level can be systematically reconstructed. In the previous work[1] we tested only to what extent the FW moments of energy, as part of the leading-order CMB-like observables, can compensate for that. We have observed that the incorporation of these FW moments can greatly reduce the performance gap between the jet-level and event-level classifiers in a general context, but cannot eliminate completely. This implies that the observables such as FW moments at different orders or multi-spectra that are not applied in the previous analysis may play a significant role. Thus, we plan to comprehensively explore each of these observables and fill the existing performance gap with them. This will allow us to test the (approximate) completeness of this CMB-like observable scheme and dissect the underlying physics of the event-level kinematics. We hope that with this study, a general guidance on the application of this observable scheme to future data analysis at colliders will be clear.

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