12th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP (BOOST 2020 webinars)

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Online

Book of Abstracts

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Learning Physics at Future e^-e^+ Colliders with Machine

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Information deformation and loss in jet clustering are one of the major limitations for precisely measuring hadronic events at future e^-e^+ colliders. Because of their dominance in data, the measurements of such events are crucial for advancing the precision frontier of Higgs and electroweak physics in the next decades. We show that this difficulty can be well-addressed by synergizing the event-level information into the data analysis, with the techniques of deep neutral network. In relation to this, we introduce a CMB-like observable scheme, where the event-level kinematics is encoded as Fox-Wolfram (FW) moments at leading order and multi-spectra at higher orders. Then we develop a series of jet-level (w/ and w/o the FW moments) and event-level classifiers, and analyze their sensitivity performance comparatively with two-jet and four-jet events. As an application, we analyze measuring Higgs decay width at e^-e^+ colliders with the data of 5ab^{-1}@240GeV. The precision obtained is significantly better than the baseline ones presented in documents. We expect this strategy to be applied to many other hadronic-event measurements at future e^-e^+ colliders, and to open a new angle for evaluating their physics capability.

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Dynamical grooming: from QCD jets to boosted W/top tagging

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We would like to introduce a new set of jet substructure observables and an associated grooming technique, called dynamical grooming, rooted on identifying the hardest splitting in an angular ordered shower and discarding prior splittings that occur at larger angles. In our first paper (https://arxiv.org/abs/1911.00375) we use p+p collisions to benchmark the method with pQCD calculations through the computation of the Sudakov form factor at modified leading-log accuracy in the context of vetoed showers. We find the analytic properties of the dynamically tagged splitting, such as its momentum sharing fraction, are in qualitative agreement with Monte Carlo simulations. In addition, the method yields a remarkable resilience against non-perturbative effects. The feasibility of boosted W/top tagging is explored in our second paper (https://arxiv.org/abs/2005.0758) where we introduce an extension of the dynamical grooming technique to multi-prong decays. For W jets, the out-of-the-box version of dynamical grooming, free of ad-hoc parameters, results into a comparable performance to SoftDrop. Regarding the top tagger efficiency, 3-prong dynamical grooming, in spite of its simplicity, presents better performance than SoftDrop and similar results to Recursive SoftDrop. In both cases, dynamical grooming turns out to be quite robust against background fluctuations, namely pileup.

Session 6 / **21**

Quantum information and entanglement with top quarks at the LHC

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Entanglement is a key subject in quantum information theory. Due to its genuine relativistic and fundamental nature, high-energy colliders are attractive systems for the experimental study of quantum information theory. We propose the detection of entanglement between the spins of top-antitop quark pairs at the LHC, representing the first proposal of entanglement detection in a pair of quarks, and also the entanglement observation at the highest energy scale so far. We show that entanglement can be observed by direct measurement of the angular separation between the leptons arising from the decay of the top-antitop pair. The detection can be achieved with more than 5 statistical deviations, using the current data recorded at the LHC. In addition, we develop a simple protocol to implement the quantum tomography of the top-antitop pair, providing a new experimental tool to test theoretical predictions for the quantum state of the top-antitop pair. Our work explicitly implements canonical experimental techniques of the quantum information field, paving the way to use high-energy colliders to study quantum information theory.

Session 6 / **22**

Multi-Differential and Unbinned Measurements of Hadronic Event Shapes in e+e- Collisions at sqrt(s)=91 GeV from ALEPH Open Data

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First results are presented on the use of a new machine-learning based unfolding technique, OmniFold, applied to archival hadronic e+e- collisions using 730 pbˆ-1 of data collected at 91 GeV with the ALEPH detector at LEP. With the archived data and unfolding procedure, multiple classic hadronic event-shape variables are measured in a fully unbinned and multi-differential manner. Of particular interest, the differential distribution of log one minus thrust is presented and is expected to be helpful for extracting alpha_s via a fit to precision QCD calculations. The analysis is accompanied by a public release of the archived data set and the unfolding results, so that users may make their own versions of plots, either with different binning or with different combinations of observables in a multi-differential distribution.

Session 6 / **23**

Calculation for Non-global Logarithms with Neural Networks

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High-precision all-order calculations can only be performed for a narrow class of observables, which are sensitive to radiation over the entire final state phase-space. When phase-space boundaries are introduced, the resummation is affected by so-called non-global logarithms, which have an intricate all-order structure. In this talk, we present a first-principle calculation for the non-global logarithms, and some improvements for higher-order calculation and resummation are proposed with artificial neural networks, which can dramatically speed up needed theory calculations.

Session 6 / **24**

Groomed jet mass as a direct probe of collinear parton dynamics

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We study the link between parton dynamics in the collinear limit and the logarithmically enhanced terms of the groomed jet mass distribution, for jets groomed with the modified mass-drop tagger (mMDT). While the leading logarithmic structure is linked to collinear evolution with leading-order splitting kernels, here we derive the NLL structure directly from triple-collinear splitting functions. The calculation we present is a fixed-order calculation in the triple-collinear limit, independent of resummation ingredients and methods. It therefore constitutes a powerful cross-check of the NLL results derived using the SCET formalism and provides much of the insight needed for resummation within the traditional QCD approach.

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Neural Network-based Top Tagger with Two-Point Energy Correlations and Geometry of Soft Emissions

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Deep neural networks trained on jet images have been successful in classifying different kinds of jets. In this paper, we identify the crucial physics features that could reproduce the classification performance of the convolutional neural network in the top jet vs. QCD jet classification. We design a neural network that considers two types of substructural features: two-point energy correlations, and the IRC unsafe counting variables of a morphological analysis of jet images. The new set of IRC unsafe variables can be described by Minkowski functionals from integral geometry. To integrate these features into a single framework, we reintroduce two-point energy correlations in terms of a graph neural network and provide the other features to the network afterward. The network shows a comparable classification performance to the convolutional neural network. Since both networks are using IRC unsafe features at some level, the results based on simulations are often dependent on the event generator choice. We compare the classification results of Pythia 8 and Herwig 7, and a simple reweighting on the distribution of IRC unsafe features reduces the difference between the results from the two simulations.

Session 6 / **26**

Explainable AI for ML jet taggers using expert variables and layerwise relevance propagation

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A method is presented to extract salient information from a deep neural network classifier of jet substructure tagging techniques, using expert variables that augment the inputs, using layerwise relevance propagation. The results show that these eXpert AUGmented (XAUG) variables can be used to easily interpret the behavior of the classifier, and in some cases can capture the behavior of the classifier completely. This can be used both to understand the behavior of complicated classifiers, and also to utilize them to guide development of expert variables that can encapsulate the physics the classifier is learning.

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Measurements of Event Shapes and Jet Substructure with the ATLAS Detector

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Measurements of Event Shapes and Jet Substructure with the ATLAS Detector

In order to achieve the highest levels of precision at the Large Hadron Collider, a detailed understanding of the strong interaction is required. Three recent measurements made by the ATLAS Collaboration in $\sqrt{s} = 13$ TeV pp collisions are reported, which are sensitive to different aspects of perturbative and non-perturbative quantum chromodynamics. These results include a measurement

of hadronic event shapes in multijet final states with large momentum transfer, a measurement of jet substructure quantities with jets groomed using the Soft Drop algorithm, and a measurement of the Lund jet plane using charged particle tracks inside of jets. These measurements are corrected for acceptance and detector effects, and are compared to state-of-the-art parton shower Monte Carlo models and analytical calculations. The measured data have been made publicly available for use in future studies.

References:

Measurement of hadronic event shapes in multijet final states at sqrt(s)=13 TeV with the ATLAS detector (Prelim.)
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2020-011/

Measurement of soft-drop jet observables in pp collisions with the ATLAS detector at sqrt(s)=13 TeV
https://arxiv.org/abs/1912.09837
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-33/

Measurement of the Lund jet plane using charged particles in 13 TeV proton-proton collisions with the ATLAS detector
https://arxiv.org/abs/2004.03540
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-57/

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Lorentz Group Networks: Lorentz equivariant neural networks forparticle physics

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We present the implementation and performance of a new neural network architecture based on the structure of the Lorentz symmetry group for applications in particle physics. This architecture is inherently and fully equivariant with respect to transformations under the Lorentz group and is able to learn the kinematics and properties of complex systems of particles. In a companion article [[1]], we describe the representation theory, mathematical design, and neural network structure of this architecture in detail. In this article, we summarize these aspects and focus on assessments of the performance of the neural network in the context of high energy collider particle physics. Specifically, we choose the benchmark task of classifying and discriminating jets formed from the hadronic decays of Lorentz-boosted top quarks from the background of light quarks and gluon jets. We show that we are able to achieve comparable performance compared to other state-of-the-art deep learning approaches for this particular classification task while also maintaining significantly broader generality regarding the structural origin of the physical processes involved. We discuss applications of this novel network architecture for a variety of classification and regression (measurement) tasks for high energy particle interactions.

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Higgs tagging and deep learning for the Higgs self-coupling at the HL-LHC

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We study the di-Higgs to 4b final state and systematically compare Higgs tagging strategies to probe the Higgs self-coupling at the HL-LHC. We compare small-radius jets and boosted reconstruction of large-radius jets with two-prong substructure for double b-tagging. We perform dedicated optimisation for BSM self-coupling values using deep neural networks and apply recent advances in machine learning interpretability to understand what physical information is learned. Based on arXiv:2004.04240

Session 6 / **30**

Disentangling Boosted Higgs Boson Production Modes with Machine Learning

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Higgs Bosons produced via gluon-gluon fusion (ggF) with large transverse momentum (p_T) are sensitive probes of physics Beyond the Standard Model. However, high p_T Higgs Boson production is contaminated by a diversity of production modes other than ggF: vector boson fusion, production of a Higgs boson in association with a vector boson and with a top-quark pair. Combining jet substructure and event information with modern machine learning, we demonstrate the ability to focus on particular production modes. These tools hold great discovery potential for boosted Higgs bosons produced via ggF and may also provide additional information about the Higgs Boson sector of the Standard Model in extreme phase space regions for other production modes as well.

Session 6 / **31**

Hadronic W boson and top quark tagging at ATLAS

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The reconstruction and identification of boosted hadronic final states is a key part for beyond the Standard Model (BSM) physics searches and precision measurements of Standard Model processes at ATLAS. Identification algorithms designed to identify boosted hadronically decaying W bosons and top quarks, known as taggers, have been updated and optimized from previous efforts to include the data collected between 2015 and 2017, corresponding to 80 inverse femtobarns of integrated luminosity. The data are used to derive scale factors to correct the relative difference in the tagging efficiency between data and MC simulation for these taggers. This poster describes the latest tagger developments and derivation procedure of the signal efficiency scale factors using lepton+jets events with a ttbar topology for a cut-based tagger using hadronic jet properties optimized to identify jets containing the full decay of a W boson and two Deep Neural Network top taggers that use jet substructure moments as inputs; one optimized to identify jets containing all the energy from a hadronically decaying top quark, and the other optimized to identify jets containing part of the hadronic top quark decay regardless of containment.

Session 6 / 32

ML approach to VBF event topology classification: Recurrent Neural Network based on jets information

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A new approach for the identification of VBF topology is presented. A Recurrent Neural Network (RNN) approach based on the 4-momentum of the small-R jets in the event has been developed in the context of the search of high mass resonances decaying into diboson semi-leptonic final states (X —> VV —> vv/lv/ll + qq). The class of RNN networks shows high performances and opportunity to deal with variable length input set as the 4-momentum of jets in an event. The analysis is performing the classification of VBF vs ggF/DY events based on the score of the RNN before the full analysis flow. This method shows higher classification performances and an higher signal
efficiency respect to usual approaches based on the tagging of the VBF-like jets. The simple 4-momentum (low-level variables) of the small-R jets in the event are used instead of other variables built starting from them (high-level variables). Furthermore, this approach based on jets information of the event is independent by the lepton channel of the diboson decay and it has been used for different spin hypothesis.

Session 6 / 33

Towards Machine Learning Analytics for Jet Substructure

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The past few years have seen a rapid development of machine-learning algorithms. While surely augmenting performance, these complex tools are often treated as black-boxes and may impair our understanding of the physical processes under study. Moving a first step into the direction of applying expert-knowledge in particle physics, we test whether the optimal decision function is achieved by standard training. In particular, we consider the binary classification problem of discriminating quark-initiated jets from gluon-initiated ones. We construct a new version of the widely used N-subjettiness variable, which features a simpler theoretical behaviour than the original one, while maintaining, if not exceeding, the discrimination power. We input these new observables to the simplest possible neural network, the one made by a single neuron (perceptron) and we analytically study the network behaviour at leading logarithmic accuracy. We are able to determine under which circumstances the perceptron achieves optimal performance. We also compare our analytic findings to an actual implementation of a perceptron and to a more realistic neural network and find very good agreement.

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calculating the primary Lund-plane density

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In BOOST 2018, we proposed the Lund jet plane as a powerful substructure tool. Measurements of the primary Lund plane density were presented at BOOST 2019 by the ATLAS collaboration. For BOOST 2020, we are reporting on a calculation of the Lund-plane density in QCD. This work provides a single-log accurate calculation, including in particular non-global/clustering effects. Our resummed prediction is matched to exact NLO results. We extract non-perturbative corrections from general-purpose Monte-Carlo generators and compare our results to the ATLAS measurement.

Session 6 / **35**

Pareto optimization for decorrelated taggers

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Jet taggers that are decorrelated from certain observables, such as mass, are of increasing interest for experimental measurements.
Several methods have been proposed to design taggers that balance discrimination power against correlation.
As a fundamentally multi-objective optimization problem, there is an infinite set of Pareto-efficient solutions, known as the Pareto frontier.
We demonstrate that while most existing methods can generally converge to some solution near this frontier, there is often limited control over the exact trade-off point achieved, even when the surrogate objective includes a tunable hyperparameter.
We also demonstrate some qualitative features of this Pareto frontier using a toy model with an analytic likelihood, allowing us to probe the exact points at which optimal discrimination and decorrelation occur.
Lastly, we discuss the use of these qualitative features as a map for locating optimal working points for real-world taggers, for which no tractable likelihood is available.

Session 6 / **36**

Anomaly Awareness for new physics searches

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In this talk we will present a new algorithm to search for new physics called Anomaly Awareness. By making our algorithm 'aware' of the presence of a range of different anomalies, we improve its capability to detect anomalous events even when it hasn't been exposed to them in the past. As

an example, we apply this method to boosted jets and use it to uncover new resonances or EFT effects.

Session 6 / **37**

Measurement of suppression of large-radius jets and its dependence on substructure in Pb+Pb with ATLAS

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Measurements of the jet substructure in Pb+Pb collisions provide information about the mechanism of jet quenching in the hot and dense QCD medium created in these collisions, over a wide range of energy scales. This poster presents the ATLAS measurement of the suppression of yields of large-radius jets and its dependence on the jet substructure, characterized by the presence of sub-jets and their angular correlations. This measurement is performed using the large Pb+Pb data sample at the center-of-mass energy of 5.02 TeV recorded in 2018 and compared to the result from 2017 pp collisions at the same collision energy. This study of the suppression of inclusive yields of large-R jets brings new information about the evolution of the parton shower in the medium and tests the sensitivity of the jet quenching to the color coherence effects.

Session 6 / **38**

Machine Learning for Pion Identification and Energy Calibration with the ATLAS Detector

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Separating charged and neutral pions as well as calibrating the pion energy response is a core component of reconstruction in the ATLAS calorimeter. This poster presents an investigation of deep learning techniques for these tasks, representing the signal in the ATLAS calorimeter layers as pixelated images. Machine learning approaches outperform the classification applied in the baseline local hadronic calibration and are able to improve the energy resolution for a wide range in particle momenta, especially for low energy pions. This work demonstrates the potential of machine-learning-based low-level hadronic calibrations to significantly improve the quality of particle reconstruction in the ATLAS calorimeter.

Session 6 / **39**

High Fidelity Simulation of High GranularityCalorimeters with High Speed

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The Monte Carlo simulation of calorimeter showers is a vital part of particle physics. However, individually modeling the paths and interactions of each particle in a shower is a very time consuming process. This computation time requirement becomes even more problematic as we move to higher luminosities. Therefore we aim to speed up shower simulations through the use of Generative Machine Learning methods. Specifically we apply a new architecture, the so called Bounded Information Bottleneck AutoEncoder. We are able to show that this architecture, in combination with a novel Neural Network based Post Processing step, is capable of modeling calorimeter showers with a higher precision than other generative setups, while providing a significant speed up over the state of the art simulation tool GEANT4.

Session 1 / **40**

Welcome

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Session 6 / **41**

Search for Boosted Higgs decaying into bottom quark pairs in CMS

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I will present the search for boosted Higgs boson with transverse momentum greater than 450 GeV decaying into bottom quark pairs using LHC full run 2 dataset collected by the CMS experiment.
In this search, we employed the latest jet substructure variables and b-tagging techniques based on a deep neural network to reduce the overwhelming QCD backgrounds.
An excess of events above background is observed with a local significance of 2.5 standard deviation, while the expectation is 0.7.
The measured Higgs production cross sections is also presented as a function of transverse momentum of the Higgs boson and compared with the latest gluon-gluon fusion prediction with finite top-mass corrections.

Session 6 / **42**

A Robust Measure of Event Isotropy at Colliders

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We introduce a new event shape observable – event isotropy – that quantifies how close the radiation pattern of a collider event is to a uniform distribution. This observable is based on a normalized

version of the energy mover's distance, which is the minimum "work" needed to rearrange one radiation pattern into another of equal energy. We investigate the utility of event isotropy both at electron-positron colliders, where events are compared to a perfectly spherical radiation pattern, as well as at proton-proton colliders, where the natural comparison is to either cylindrical or ring-like patterns. Compared to traditional event shape observables like sphericity and thrust, event isotropy exhibits a larger dynamic range for high-multiplicity events. This enables event isotropy to not only distinguish between dijet and multijet processes but also separate uniform N-body phase space configurations for different values of N. As a key application of this new observable, we study its performance to characterize strongly-coupled new physics scenarios with isotropic collider signatures.

Session 6 / **43**

Measurement of boosted top quark pair production

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A measurement of the production cross section for high transverse momentum top quark pairs is reported. The data set was collected during 2016 with the CMS detector at the LHC from pp collisions at 13 TeV, and corresponds to an integrated luminosity of 35.9 fb-1. The measurement uses events where either both top quark candidates decay hadronically and are reconstructed as large-radius jets with pt>400 GeV, or where one top quark decays hadronically and is identified as a single large-radius jet with pt>400 GeV and the other top quark decays leptonically to a b jet, an electron or a muon, and a neutrino. The cross section is extracted differentially as a function of kinematic variables of the top quark or the top quark pair system. The results are presented at the particle level, within a region of phase space close to that of the experimental acceptance, and at the parton level, and are compared to various theoretical models. The measured differential cross sections are significantly lower in both decay channels in the phase space of interest, compared to the theory predictions, while the normalized differential cross sections are consistent between data and theory.