

11th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP (BOOST 2019)

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MIT



Book of Abstracts

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1

Heavy Ions

2

Summary

Session / 4

New results from searches with highly boosted top quarks (20' + 10')

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We present new results from searches for beyond-the-standard model physics with highly boosted top quarks in the final state, where the reconstruction and identification of fully-merged hadronic top quark decays is an essential tool. The talk summarizes the use of large-radius jets and substructure techniques in proton-proton collisions at 13 TeV. The searches cover a variety of models, such as heavy resonances decaying to top quarks, pair and single production of vector-like quarks, and the production of third generation squarks.

Session / 5

New results from searches with highly boosted Higgs and vector bosons (20' + 10')

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We present new results from searches for beyond-the-standard model physics with highly boosted Higgs and vector bosons in the final state. The talk summarizes the use of large-radius jets and substructure techniques used for the reconstruction and identification of fully-merged hadronic decays of these particles. New techniques to estimate the standard model backgrounds are discussed. The searches cover a variety of models, such as two-Higgs-doublet models or generic heavy resonances decaying to bosons.

Session / 6

New results from searches with uncommon jet substructure(20' + 10')

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We present new results from searches for beyond-the-standard model physics with highly boosted final states, where the use of jet substructure is essential for the identification of a potential signal.

The searches cover uncommon jet substructure, such as jets containing a hard photon and hadronic activity from N-prong decays, or highly-boosted light resonances decaying to quark anti-quark pairs. Special emphasis is given to the identification of these signal jets and on the methods to derive the standard model backgrounds.

Session / 8

Fitting the strong coupling constant for soft-drop thrust(20'+10')

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Over the years many different types of fits for the strong coupling constant have been performed. However one type of high precision result that currently significantly differs from the world average are results from event shapes at electron positron colliders. One possible source for the difference in these results could be the degeneracy between the fit of the strong coupling constant and non-perturbative parameters. In this talk I will explore the application of modern jet substructure techniques, specifically soft drop, in order to break the impact of the non-perturbative corrections on the fit of the strong coupling constant.

Session / 9

Studies of granularity of a hadronic calorimeter for tens-of-TeV jets at a 100 TeV pp collider (10'+5')

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Co-authors: Sergei Chekanov²; Ashutosh Kotwal³; Nhan Viet Tran⁴; Sourav Sen⁵; James Proudfoot²; Shin-Shan Yu¹

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Jet substructure variables for hadronic jets with transverse momenta in the range from 2.5 TeV to 20 TeV were studied using several designs for the spatial size of calorimeter cells. The studies used the full Geant4 simulation of calorimeter response combined with realistic reconstruction of calorimeter clusters. In most cases, the results indicate that the performance of jet-substructure reconstruction

improves with reducing cell size of a hadronic calorimeter from $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$, which are similar to the cell sizes of the calorimeters of LHC experiments, by a factor of four, to 0.022×0.022 .

Lunch @ MIT and Poster Session / 10

Studies of granularity of a hadronic calorimeter for tens-of-TeV jets at a 100 TeV pp collider

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Jet substructure variables for hadronic jets with transverse momenta in the range from 2.5 TeV to 20 TeV were studied using several designs for the spatial size of calorimeter cells. The studies used the full Geant4 simulation of calorimeter response combined with realistic reconstruction of calorimeter clusters. In most cases, the results indicate that the performance of jet-substructure reconstruction improves with reducing cell size of a hadronic calorimeter from $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$, which are similar to the cell sizes of the calorimeters of LHC experiments, by a factor of four, to 0.022×0.022 .

Session / 11

A Theory of Quark vs. Gluon Discrimination(20'+10')

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We study quark versus gluon discrimination systematically and present explicit calculations for jets on which up through three emissions are resolved. These explicit calculations enable determination of quantities central to machine learning, such as the likelihood, reducibility factors, and area under the ROC curve (AUC), to be calculated within a concrete approximation scheme. We prove many results regarding quark versus gluon discrimination including the reducibility factor for gluon jets with any number of resolved emissions, robust bounds on the AUC, and that the optimal observable for quark versus gluon discrimination is IRC safe.

Session / 12

Uncovering latent jet substructure

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We apply techniques from Bayesian generative statistical modeling to uncover hidden features in jet substructure observables that discriminate between different a priori unknown underlying short distance physical processes in multi-jet events. In particular, we use a mixed membership model known as Latent Dirichlet Allocation to build a data-driven unsupervised top-quark tagger and ttbar event classifier. We compare our proposal to existing traditional and machine learning approaches to top jet tagging. Finally, employing a toy vector-scalar boson model as a benchmark, we demonstrate the potential for discovering New Physics signatures in multi-jet events in a model independent and unsupervised way.

Session / 13

Jet/MET performance in CMS during Run2 (20'+10')

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Jets are the experimental signatures of energetic quarks and gluons produced in high energy processes and they need to be calibrated in order to have the correct energy scale. A detailed understanding of both the energy scale and the transverse momentum resolution of jets at the CMS is of crucial importance for many physics analyses. Furthermore, study of jet substructure properties in boosted topologies are critical for distinguishing jets originating from quarks, gluons, W/ Z/Higgs bosons, top quarks and pileup interactions. Lastly, the precise measurement of the missing transverse momentum (MET) observable is critical for standard model measurements involving W, Z, and the Higgs bosons, and top quarks. MET is also one of the most important kinematic observable used in searches for physics beyond the standard model targeting new weakly interacting neutral particles.

In this talk, we present the measurements of CMS jet energy scale and resolution, MET performance and standard heavy object tagging performance using the data sample collected in proton-proton collisions at a center-of-mass energy of 13 TeV.

Session / 14

Pileup mitigation techniques in CMS (20'+10')

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We present tools developed by CMS for LHC Run II designed for pileup mitigation in the context of jets, MET, lepton isolation, and substructure tagging variables. Pileup mitigation techniques of "Pileup per particle ID" (PUPPI), and pileup jet identification are presented in detail along with the validation in data.

Session / 15

New tagging approaches and validation in data(20'+10')

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Recent advances in neural networks and harsh pileup conditions in the second half on LHC Run 2 with on average 38 PU interactions, have sparked significant developments in techniques for jet tagging. Through the study of jet substructure properties, jets originating from quarks, gluons, W/Z/Higgs bosons, top quarks and pileup interactions are distinguished, surpassing previous performance at lower pileup conditions by using new approaches. This talk will give an overview of the development of machine learning based jet substructure algorithms and their validation using the data collected by the CMS Experiment.

Session / 17

Jet substructure measurements at CMS (20'+10')

Author: CMS Collaboration^{None}

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This talk will present recent advances in measurements of jet mass and jet substructure observables, providing important tests of QCD. The interplay of MC event generator tuning and jet substructure is also discussed.

Session / 18

Mapping the Redistribution of Jet Energy in PbPb Collisions with CMS (20'+10')

Author: CMS Collaboration^{None}

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Measurements of jets produced in collisions of heavy ions, such as dijet asymmetry, boson-jet momentum imbalance, and inclusive jet spectra, have consistently indicated final states of less energy as compared to vacuum reference. This energy loss is interpreted as signature of Quark-Gluon Plasma, the hot and dense medium of deconfined partons produced in the collision of relativistic nuclei. Subsequent studies have shown that the energy lost by jets is redistributed to large angle and in multiplicities of softer particles. In this talk, a thorough accounting of jet energy redistribution through missing momentum techniques, radial scans of jet spectra, and large angle jet shapes as measured with the CMS detector. These results can distinguish between mechanisms of parton-medium interaction as encoded in various Monte Carlo and give insight into the medium response.

Session / 19

Studies of Jet Substructure in PbPb Collisions with CMS(20'+10')

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Hard scattered partons produced in collision of heavy ions are modified when propagating through the hot and dense medium of deconfined quarks and gluons known as the Quark Gluon Plasma. The study of jet substructure is an essential tool in quantifying this modification and in distinguishing between underlying mechanisms of parton-medium interactions. The latest CMS studies of jet substructure observables such as splitting function, groomed mass, boson-tagged fragmentation functions and jet shapes and their corresponding comparisons to theory give insight into the Quark Gluon Plasma, and how parton propagation is modified in QCD matter as opposed to matter.

Session / 20

Searches and techniques for boosted resonances (non-diboson) with the ATLAS detector (20'+10')

Author: ATLAS Collaboration^{None}

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Many new-physics signatures at the LHC produce highly boosted particles, leading to close-by objects in the detector and necessitating jet substructure techniques to disentangle the hadronic decay products. This talk presents the latest ATLAS results for searches for such resonances, including the Higgs boson or top-quark pairs, using 13 TeV data. It will explain the techniques used, including new top-tagging techniques using machine learning and the use of large-radius jets containing electrons.

Session / 21

Jet techniques in supersymmetry searches in the ATLAS experiment(20'+10')

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Many supersymmetric scenarios feature final states with non-standard final state objects. The production of massive sparticles can lead to the production of boosted top quarks or vector bosons, high-pT b-jets. The strongest limits from ATLAS on chargino-neutralino production come from an all-hadronic search for electroweak supersymmetry, one of the first of its kind. At the same time, transitions between nearly mass-degenerate sparticles can challenge the standard reconstruction because of the presence of very soft leptons or jets. The talk will review the application of innovative jet and MET reconstruction techniques to supersymmetry searches in ATLAS.

Session / 24

Measurement of jet fragmentation using the ATLAS detector(20'+10')

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Gluon splitting to b-quark pairs is a unique probe of the properties of gluon fragmentation, as the identified b-tagged jets provide a proxy for the quark daughters of the initial gluon. We present a measurement of key differential distributions related to $g \rightarrow b \bar{b}$ using data collected with the ATLAS detector at $\sqrt{s}=13$ TeV. Track jets are used to probe angular scales below the standard $R=0.4$ jet radius. The observables are unfolded to particle level in order to facilitate direct comparison with predictions from simulations and provide an important constraint to hadronization models. A measurement of the properties of jet fragmentation performed with proton-proton collision data collected with the ATLAS detector at $\sqrt{s}=13$ TeV will also be presented. Charged particle tracks are used to measure charged particle multiplicity, the jet charge, the summed fragmentation function, the momentum transverse to the jet axis, and the radial profile of the jet. Each observable is unfolded to correct for acceptance and detector effects. Exclusive interpretations in terms of quarks and gluons are provided in order to directly compare with state-of-the-art calculations.

Session / 25

Precision measurements using jet substructure techniques at ATLAS(20'+10')

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We present precision measurements of $Z\bar{\chi}$ and Z +jet production utilising jet substructure techniques. They are performed at $\sqrt{s}=13$ TeV using the ATLAS detector. In the first measurement, the Z boson is reconstructed in the $Z\rightarrow b\bar{b}$ decay channel, with both b-quarks contained within a large-radius high-transverse-momentum jet that is subsequently groomed to remove contributions from underlying events and additional proton-proton collisions. The $Z\rightarrow b\bar{b}$ decay is identified using b-tagged track-jets. The measurement is performed twice using two grooming techniques, trimming and soft-drop. The fiducial cross-sections are measured and differential cross-sections for the $b\bar{b}$ invariant mass are presented. In addition, if available, a measurement of kinematic variables in events with a leptonically-decaying Z-boson and a large-radius high-transverse momentum trimmed jet are presented. Differential cross sections are measured in two phase space regions defined by the large R-jet having zero or two b-tagged track-jets.

Session / 26

Measurements with highly boosted top quarks using the ATLAS detector (20'+10')

Corresponding Author: mark.andrew.owen@cern.ch

The high energy of the LHC allows access to large numbers of high transverse momentum top quarks. Measurements of differential cross-sections in top quark pair production at 13 TeV with the ATLAS detector are presented. They are performed using the lepton+jets and all-hadronic final states. Jet substructure techniques are used to identify hadronically decaying top quarks. The measurements are corrected for detector effects to obtain differential cross-sections at particle-level in a fiducial region close to the event selection. These measurements probe our understanding of top quark pair production in the TeV regime. The results, unfolded to particle and parton level, are compared to predictions of Monte Carlo generators implementing NLO matrix elements matched with parton showers and NNLO QCD theory calculations.

Lunch @ MIT and Poster Session / 27

Single and double differential $t\bar{t}$ production cross section measurements in boosted regime

Author: ATLAS Collaboration^{None}

The large energy and luminosity reached by the Large Hadron Collider allow to perform differential measurements also in regions of the phase space where a massive particle, as the top quark, is produced with high transverse momentum.

The analysis presented in this contribution is the differential measurement of $\sigma(t\bar{t})$, obtained considering events collected by the ATLAS experiment in 2015 and 2016 in the single lepton channel, with at least one large-R jet with $p_T > 350$ GeV. The large-R jet mass is requested to be in the range [120,220] GeV and it is directly interpreted as the top quark decaying hadronically. The technique used to reconstruct the large-R (R=1.0) jet is the re-clustering of anti-kT jets with R=0.4. This method allows to forward the calibrations and uncertainties derived on the small-R jets directly on the large-R jet, reducing considerably the uncertainty on the differential measurement in the

boosted region, with respect to previous publications.

The method and dataset employed allowed to perform the first double differential measurement in the

boosted regime. The events selected are corrected for the effects of the detector using an unfolding technique and the results are presented both in a fiducial phase space, defined to follow the detector-level selection, than extrapolated to a larger region of the phase space, limited only by the requirement of a top quark with $p_T > 350$ GeV.

Session / 28

ATLAS Searches for Resonances Decaying to Boson Pairs (20'+10')

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Many extensions to the Standard Model predicts new particles decaying into two bosons (W, Z, photon, or Higgs bosons) making these important signatures in the search for new physics. Searches for such diboson resonances have been performed in final states with different numbers of leptons, photons and jets and b-jets where new jet substructure techniques to disentangle the hadronic decay products in highly boosted configuration are being used. This talk summarizes recent ATLAS searches with LHC Run 2 data collected.

Lunch @ MIT and Poster Session / 29

Calibration of the Boosted $X \rightarrow bb$ Tagger in $g \rightarrow bb$ splitting at the ATLAS Experiment

Author: ATLAS Collaboration^{None}

The physics programme at ATLAS involves a variety of Standard Model and Beyond Standard Model resonances decaying to two b quarks, including the Higgs Boson. In order to overcome the intense QCD backgrounds, probe low mass ranges, or decays of heavy resonances resulting in boosted bb pairs, ATLAS has developed the Boosted $X \rightarrow bb$ tagger. The double b-tagging efficiency scale-factors between MC and data are derived using boosted $g \rightarrow bb$ splitting in multi-jet events. MC simulations are used in our estimates of the fraction of bb events in data. However, simulation of QCD is notoriously imperfect, making it necessary to use a data-driven approach to correct the flavour composition of the MC, such that the double b-tagging efficiencies and scale factors can be derived. This is done by fitting the signed transverse impact parameter distributions of sub-jet tracks in data and rescaling the MC accordingly. This poster describes the current calibration procedure, the challenges the developers were faced with, and the future plans of the group.

Session / 30

Inputs and Procedures of Jet Reconstruction in ATLAS (20+10)

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In order to study hadronic final states, it is of utmost importance to consider the inputs used when building jets, and the definition of the jet reconstruction procedure. These fundamental choices of how to build jets have wide-reaching implications, from pileup stability to the precision of the resulting jet energy scale to the ability to tag and identify hadronic decays encapsulated within the

jets. The inputs to jets and jet reconstruction procedures used by ATLAS will be discussed, as will the subsequent implications of these choices on hadronic physics.

Session / 32

Tagging of hadronically decaying massive particles in ATLAS(20'+10')

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The ability to differentiate between hadronically decaying massive particles and other sources of jets is increasingly important to the LHC physics program. A variety of algorithms which are used in ATLAS to identify large-R jets from such decays are presented, including both cut-based taggers and machine learning discriminants. In order to understand the validity of these identification algorithms, expectations are compared with data in well-understood final states, allowing for the derivation of scale factors accounting for differences between simulation and data.

Session / 33

Tagging of jets initiated by individual b/c-quarks or b-quark pairs in ATLAS (20'+10')

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The production of jets initiated by heavy flavour quarks (b-quarks and c-quarks) is important in many contexts, especially including studies of particles which couple more strongly to massive particles, such as the Higgs boson. The distinct properties of these b-jets and c-jets can be identified by the ATLAS detector and differentiated with respect to jets initiated by light quarks and gluons, where the algorithms used for tagging such heavy flavour jets will be discussed. Additionally, the identification of boosted decays of massive particles to pairs of b-quarks reconstructed within a single large-R jet will be presented, together with methods to evaluate the differences between simulation and data.

Lunch @ MIT and Poster Session / 34

Object-based missing transverse momentum significance at ATLAS

Author: ATLAS Collaboration^{None}

The calculation of missing transverse momentum (ETmiss) has been and will continue to be vital for physics analyses at the ATLAS experiment. Quantifying the momentum imbalance of the event gives physicists the ability to identify non-interacting standard model particles, such as neutrinos, and to search for signatures indicating the presence of physics beyond the Standard Model. In order to determine if the observed ETmiss comes from real non-interacting particle(s) or rather purely detector effects, such as jet mis-measurements, a ETmiss significance was defined. This significance improves the separation of fake sources of ETmiss from real ones. This poster demonstrates the quality of the modelling of the ETmiss significance using the full Run 2 dataset. The analysis is performed using a standard candle with low real missing transverse momentum: Z boson production with decays to two opposite signed leptons. Two different reconstruction schemes for jets, calorime-

ter only and a new particle-flow method, are studied. The agreement between the data and expected Standard Model processes is shown to be very good.

Lunch @ MIT and Poster Session / 35

Forward pile-up jet rejection at ATLAS

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Rejecting jets originating from pile-up vertices in becoming a more important challenge at the LHC as the rates of pile-up increase. In the central region highly efficient rejection can be achieved using track-based variables but in the forward region this is not possible. This poster will cover ways of rejecting forward pile-up jets using the balance between identified central pile-up jets and those in the forward region. Results achieved using central pile-up jets reconstructed using both calorimeter and particle flow information will be compared. Additionally the inefficiency for real, hard-scatter, jets will be shown.

Session / 36

Collinear Drop (10'+5')

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We introduce collinear drop jet substructure observables, which are unaffected by contributions from collinear radiation, and systematically probe soft radiation within jets. These observables can be designed to be either sensitive or insensitive to process-dependent soft radiation originating from outside the jet. Such collinear drop observables can be exploited as variables to distinguish quark, gluon, and color neutral initiated jets, for testing predictions for perturbative soft radiation in Monte Carlo simulations, for assessing methods of determining hadronization corrections, for examining the efficiency of pileup subtraction methods, and for any other application that leaves an imprint on soft radiation. We discuss examples of collinear drop observables that are based both on clustering and on jet shapes. Using the soft-collinear effective theory we derive factorization expressions for collinear drop observables from QCD jets, and carry out a resummation of logarithmically enhanced contributions at next-to-leading-logarithmic order. We also identify an infinite class of collinear drop observables for which the leading double logarithms are absent.

Session: Machine Learning / 37

Jet grooming through reinforcement learning(15'+5')

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We introduce a novel implementation of a reinforcement learning algorithm which is adapted to the problem of jet grooming, a crucial component of jet physics at hadron colliders. We show that the grooming policies trained using a Deep Q-Network model outperform state-of-the-art tools used at the LHC such as Recursive Soft Drop, allowing for improved resolution of the mass of boosted objects. The algorithm learns how to optimally remove soft wide-angle radiation, allowing for a modular jet grooming tool that can be applied in a wide range of contexts.

Lunch @ MIT and Poster Session / 38

Poster: The reaction to medium induced radiation of various jet groomers

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Jet quenching in heavy ion collisions serves as a way to understand the properties of the hot and dense quark-gluon plasma (QGP). Jets interact with the color charges of the QGP leading to a modification of the jet substructure by measuring which we can know the mechanism of jet quenching.

Due to the presence of a QGP, gluon radiation pattern in the parton shower as compared to the vacuum will be modified. To gain insight into this mechanism the internal jet substructure can be studied with the help of the Lund radiation diagram.

Recently a study on the implementation of a reinforcement learning algorithm to optimize jet grooming strategy shows how soft and wide angle radiations are rejected. Meanwhile, it uses Lund diagram as a way to visualize what regions are preferred by the groomer.

In this poster I present how the Lund radiation diagram is modified in jet quenching event generators such as QPYTHIA and JEWEL by using recursive soft drop and reinforcement machine learning techniques.

I study how these novel methods that separate hard and soft QCD processes can be used to extract the QGP transport coefficients. Statistical comparison between final state observables of quenched jet with and without grooming will also be presented.

Session / 39

Precision calculation of the jet shape (20'+10')

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The jet shape is the fraction of the jet transverse momentum within a cone r centered on the jet axis. I will present a calculation of the jet shape at next-to-leading logarithmic accuracy plus next-to-leading order (NLL'), accounting for logarithms of both the jet radius R and the ratio r/R . This is the first phenomenological study that takes the recoil of the jet axis due to soft radiation into account, which is needed to reach this accuracy. This recoil complicates the calculation of collinear

radiation and requires the treatment of rapidity logarithms and non-global logarithms. I will present numerical results, finding good agreement with ATLAS and CMS measurements of the jet shape in an inclusive jet sample, $pp \rightarrow \text{jet} + X$, for different kinematic bins. The effect of the underlying event and hadronization are included using a simple one-parameter model, since they are not part of our perturbative calculation.

Session / 40

Power Corrections for Soft Drop Jet Mass(20'+10')

Author: Iain Stewart¹

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In this talk I provide a field theory based description of hadronization power corrections for soft drop groomed measurements such as the jet mass. It is proven that the leading power corrections are described by 3 universal hadronic parameters, which are independent of the jet kinematics, jet radius, and soft drop grooming parameters z_{cut} and β . These corrections come with 2 non-trivial perturbatively calculable Wilson coefficients which modify the shape of the jet mass spectrum. Unlike other known examples, these hadronization corrections are not simply described by a standard shape function, nor by a shift and normalization correction. These predictions are compared to results from 3 MCs, Pythia, Herwig, and Vincia. The description of these power corrections is important for precision determinations of standard model parameters like the strong coupling and top-mass.

Session: Machine Learning / 41

Interpretable Deep Learning for Two-Prong Jet Classification with Jet Spectra (15'+5')

Authors: Sung Hak Lim¹; Mihoko Nojiri²; Amit Chakraborty³

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Classification of jets with deep learning has gained significant attention in recent times. However, the performance of deep neural networks is often achieved at the cost of interpretability. Here we propose an interpretable network trained on the jet spectrum $S_2(R)$ which is a two-point correlation function of the jet constituents. The spectrum can be derived from a functional Taylor series of an arbitrary jet classifier function of energy flows. An interpretable network can be obtained by truncating the series. The intermediate feature of the network is an infrared and collinear safe C-correlator which allows us to estimate the importance of an $S_2(R)$ deposit at an angular scale R in the classification. The performance of the architecture is comparable to that of a convolutional neural network (CNN) trained on jet images, although the number of inputs and complexity of the architecture is significantly simpler than the CNN classifier. We consider two examples: one is the classification of two-prong jets which differ in color charge of the mother particle, and the other is a comparison between Pythia 8 and Herwig 7 generated jets.

Session: Machine Learning / 42**ParticleNet: Jet Tagging via Particle Clouds (15'+5')****Authors:** Huilin Qu¹; Loukas Gouskos²¹ *Univ. of California Santa Barbara (US)*² *CERN***Corresponding Authors:** huilin.qu@cern.ch, loukas.gouskos@cern.ch

How to represent a jet is at the core of machine learning on jet physics. Inspired by the notion of point cloud, we propose a new approach that considers a jet as an unordered set of its constituent particles, effectively a “particle cloud”. Such particle cloud representation of jets is efficient in incorporating raw information of jets and also explicitly respects the permutation symmetry. Based on the particle cloud representation, we propose ParticleNet, a customized neural network architecture using Dynamic Graph CNN for jet tagging problems. The ParticleNet architecture achieves state-of-the-art performance on two representative jet tagging benchmarks and improves significantly over existing methods.

Session / 43**Phenomenology of groomed event shapes at hadron colliders(10'+5')****Authors:** Jeremy Baron¹; Simone Marzani²; Steffen Schumann³¹ *University at Buffalo*² *Università di Genova and INFN Genova*³ *Georg-August-Universitaet Goettingen***Corresponding Authors:** steffen.schumann@phys.uni-goettingen.de, jfbaron@buffalo.edu, simone.marzani@ge.infn.it

For the past five years, Soft Drop has been a popularly used grooming technique at the LHC, and has shown remarkable efficiency and robustness in reducing non-perturbative effects in jet substructure analyses. Strong coupling constant extractions are known to be contaminated by non-perturbative effects, despite being mostly performed on event shapes from e^+e^- collisions. In this talk, I will discuss the phenomenological application of a more generalized Soft Drop algorithm, called Bottom-Up Soft Drop, to a family of event shapes at hadron colliders. Because commonly used event shapes are global observables, one must find a way to groom these event shapes without jet definitions. Bottom-Up Soft Drop is such an algorithm free from jet definitions, and has been shown to have similar or better efficiency compared to Soft Drop in reducing non-perturbative effects in LHC decay processes. Therefore, it is a natural grooming strategy to use on event shapes, and can potentially lead to state-of-the-art α_s -extractions done at the LHC.

Session / 44**The Machine Learning Landscape of Top Taggers**

Authors: Gregor Kasieczka¹; Tilman Plehn^{None}; Anja Butter^{None}; Kyle Stuart Cranmer²; Dipsikha Debnath³; Malcolm Fairbairn⁴; Wojtek Fedorko⁵; Colin Warren Gay⁶; Loukas Gouskos⁷; Patrick Komiske⁸; Simon Leiss^{None}; Alison Lister⁶; Sebastian Macaluso⁹; Eric Metodiev⁸; Liam Ronald Moore¹⁰; Ben Nachman¹¹; Karl Nordstrom¹²; Jan-nicke Andree Pearkes¹³; Huilin Qu¹⁴; Yannik Alexander Rath¹⁵; Marcel Rieger¹⁵; David Shih¹⁶; Jennifer Thompson¹⁷; Sreedevi Varma^{None}

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Based on the established task of identifying boosted, hadronically decaying top quarks, we compare a wide range of modern machine learning approaches. We find that they are extremely powerful and great fun.

Session / 45

Coherent Showers in Decays of Coloured Resonances(20'+10')

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Monte Carlo event generators remain an indispensable tool in the reconstruction of boosted objects. Typically, in parton shower Monte Carlos, coloured resonances radiate only in production, while any coloured decay products radiate independently of this. This approach fails to take into account interference between the radiation produced in production and decay. Inclusion of these coherence effects not only modifies the radiation pattern, but a different recoil strategy must be employed. Both of these features can potentially modify the shape of distributions used in the reconstruction of such resonances.

In this talk, we present a new implementation of coherent radiation from coloured resonances for VINCIA, an antenna-shower plug-in to the PYTHIA 8 Monte Carlo event generator. We consider top quark pair-production at the LHC as a case study, and present the impact on observables relevant for the measurement of the top quark mass.

Session / 46

Investigating the use of Quantum Computers for Final State Radiation(20'+10')

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Particles produced in high energy collisions that are charged under one of the fundamental forces will radiate proportionally to their charge, such as photon radiation from electrons in quantum electrodynamics. At sufficiently high energies, this radiation pattern is enhanced collinear to the initiating particle, resulting in a complex, many-body quantum system. Classical Markov Chain Monte Carlo simulation approaches work well to capture many of the salient features of the shower of radiation, but cannot capture all quantum effects. We show how quantum algorithms are well-suited for describing the quantum properties of final state radiation. In particular, we develop a polynomial time quantum final state shower that accurately models the effects of intermediate spin states similar to those present in high energy electroweak showers. The algorithm is explicitly demonstrated for a simplified quantum field theory on a quantum computer. See 1904.03196 for details.

Session / 47

The Collinear Limit of the Energy-Energy Correlator: From CFTs to Jet Substructure(20'+10')

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The energy-energy-correlator (EEC) observable measures the energy deposited in two detectors as a function of the angle between the detectors. The collinear limit, where the angle between the two detectors approaches zero, is of particular interest for describing the substructure of jets produced at hadron colliders as well as in e^+e^- annihilation. We derive a factorization formula for the leading power asymptotic behavior in the collinear limit of a generic quantum field theory. The relevant anomalous dimensions are expressed in terms of the timelike data of the theory, in particular the moments of the timelike splitting functions, which are known to high perturbative orders. In QCD and in $\mathcal{N} = 1$ super-Yang-Mills theory, we then perform the resummation to next-to-next-to-leading logarithm, improving previous calculations by two perturbative orders. In conformally invariant $\mathcal{N} = 4$ super-Yang-Mills theory, a particular reciprocity between timelike and spacelike evolution can be used to express our factorization formula as a power law with exponent equal to the spacelike twist-two spin-three anomalous dimensions. This provides a connection between the timelike dynamics of jets and the spectrum of anomalous dimensions of local operators, which is amenable to techniques such as integrability, and we discuss implications of these relations away from the conformal limit.

Session: Machine Learning / 48

Deep-Learning Jets with Uncertainties and More(15'+5')

Authors: Gregor Kasieczka¹; Michel Luchmann²; Tilman Plehn^{None}; Jennifer Thompson³

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Machine learning methods are being increasingly and successfully applied to many different physics problems. However, current machine learning approaches do not model uncertainties well - if at all. In this talk I will discuss how using Bayesian neural networks can give us a handle on uncertainties in machine learning. I will use tagging top quark vs. light quark and gluon jets as an example of how these networks are competitive with other neural network taggers with the advantage of providing an event-by-event uncertainty on the classification. I will then further discuss how this uncertainty changes with experimental systematic effects, using pile-up and jet energy scale as examples.

Session / 49

An approach to constraining the Higgs width at the LHC and HL-LHC (10'+5')

Authors: Philip Coleman Harris¹; Cristina Ana Mantilla Suarez²; Dylan Sheldon Rankin¹

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Despite the discovery of the Higgs boson decay in five separate channels many parameters of the Higgs boson remain unknown. One of these unknown parameters is the Higgs boson total width. Currently, the best known approach to measure the Higgs boson total width at the LHC is indirectly through Higgs interference of off-shell Z boson pair production. In this paper, we present a new approach to constraining the Higgs total width by requiring the Higgs to be resolved as a single high pT jet. We show that this approach is capable of yielding similar sensitivity to the off-shell measurement. Additionally, we outline the theoretical limitations of this and present an attempt at utilizing machine learning to minimize the theoretical assumptions. Finally, we outline the required insights needed to make this approach a truly model independent measurement of the Higgs boson total width.

Session / 50

Jets and parton shower development in heavy-ion collisions(20'+10')

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Jets are now routinely used to probe the quark-gluon plasma (QGP) created in high-energy heavy-ion collisions at the LHC. This talk is meant to report on recent work towards developing a complete picture of how parton cascades and jets form in the QGP in QCD, including both standard parton shower and medium-induced emissions. The talk will first introduce a picture valid in the leading logarithmic accuracy and then discuss its phenomenological implications, focusing mainly on the zg observable.

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Measuring hadrons around leptonic Z bosons in CMS open data using Z drop(10'+5')

Authors: Meng-Hsiu Kuo^{None}; Yu-Wei Kao¹; Yang-Ting Chien²; Kai-Feng Chen¹

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We study the local properties of hadronic event activities using leptonic decaying Z bosons. We use the dimuon events in 8 TeV pp collisions from CMS open data, and we define the “leptonic Z jet” by enclosing particles within an angle R from the Z or by using standard jet clustering algorithms. A new hadronic observable called Z drop is defined which allows us to probe underlying events and pileup contributions. We examine the dependence on the Z transverse momentum, the radius R and the number of pileup events in real data and simulations, and we test the performance of pileup mitigation methods on this observable. The measurement will provide useful information about soft particle distribution uncorrelated with the leptonic Z decay, which allows us to perform precision studies of hadronic decays of Z bosons in future work. We also propose to use Z drop as a new probe of the quark-gluon plasma produced in heavy ion collisions.

Session / 52

The Space of Collider Events (20'+10')

Authors: Eric Metodiev¹; Patrick Komiske¹; Jesse Thaler²

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When are two collider events similar? In this talk, I answer this question by developing a metric between the events based on the earth mover’s distance: the “work” required to rearrange one event into the other. With a metric in hand, I will focus on exploring the metric space of jets. Our metric allows us to visualize the space of jets, extract their dimensionality, perform jet classification, make contact with existing observables, identify the most and least typical jet configurations, and quantify the impact of detector effects in new ways.

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Pileup and Underlying Event Mitigation with Iterative Constituent Subtraction

Authors: Peter Berta¹; Lucia Masetti¹; David Miller²; Martin Spousta³

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Hard-scatter processes in hadronic collisions are often significantly contaminated by background contributions from pileup in proton-proton collisions or underlying event in heavy-ion collisions. This background has a significant impact on jet reconstruction and on the ability to identify the substructures of hadronically decaying boosted objects. We present a new background subtraction method for jet and event observables which is based on the Constituent Subtraction algorithm. The new subtraction method, called Iterative Constituent Subtraction, adopts an iterative approach to the event-wide implementation of Constituent Subtraction. Using particle-level simulation, we provide a comparison of Iterative Constituent Subtraction with several existing methods. Possibilities to use information from charged particles to correct neutral particles are also discussed.

Session / 54

Jet sub-structure studies in full simulation for highly boosted objects at 100 TeV proton-proton collisions of the FCC-hh (10'+5')

Authors: Coralie Neubuser¹; Clement Helsen¹; Ana Maria Henriques Correia¹; Martin Aleksa¹; Jana Faltova²; Anna Zaborowska¹; Valentin Volkl³; David Olivier Jamin⁴; Michele Selvaggi¹

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The physics reach of the Future Circular Collider in hadron mode (FCC-hh) with a centre of mass energy of 100 TeV and unprecedented luminosity has been studied and published in a Conceptual Design Report (CERN-ACC-2018-0058). In order to exploit the full physics potential of such a collider, a conceptual detector design has been developed and tested in fast as well as full-simulations within the common software framework *FCCSW*.

The discovery reach for new heavy resonances, like Z' or graviton decaying into bosons or top quarks, highly depends on the performance of the detector system. Their signals occur with a strong boost in the central region of the detector. The successful reconstruction of e.g. $Z' \rightarrow t\bar{t}$ especially depends on the calorimeter granularity, necessary to distinguish the three body topology of the jets sub-structure from the QCD background.

The reconstruction of boosted, and highly energetic jets sets the calorimeter performance requirements in terms of shower containment, energy resolution and granularity.

We will present the performance of the FCC-hh reference detector in terms of jet energy resolution, discuss the challenges of a 100 TeV proton-proton machine and show first results of jet sub-structure studies, that use multivariate analysis techniques to distinguish boosted W and Z bosons from QCD jets in full *FCCSW* simulations. The results will be compared to results of fast-simulations using the *Delphes* package. Finally, the prospects including particle flow algorithms will be discussed.

Session: Machine Learning / 55

End-to-end particle and event identification at the Large Hadron Collider with CMS Open Data(15'+5')

Authors: Barnabas Poczos¹; Bjorn Burkle²; Emanuele Usai²; John Alison³; Manfred Paulini³; Meenakshi Narain²; Michael Andrews³; Patrick Bryant³; Sergei Gleyzer⁴; Sitong An⁵; Ulrich Heintz²

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We present an innovative end-to-end deep learning approach for jet identification at the LHC. The method combines deep neural networks with low-level detector information, such as calorimeter energy deposits and tracking information, to build a discriminator to identify different particles. Using two physics examples as references: electron and photon discrimination and quark and gluon discrimination, we demonstrate the performance of the end-to-end approach using simulated events with full detector geometry available as CMS Open Data. We also offer insights into the importance of the information extracted from various sub-detectors and describe how end-to-end techniques can be extended to event-level classification using information from the whole detector.

Session / 57

Cutting Multiparticle Correlators Down to Size (10'+5')

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Multiparticle correlators are a broad class of observables that have found significant use at colliders. It is known that there exist mysterious linear relations between specific types of these correlators when their summands satisfy certain properties. In this talk, I will develop graphical methods to understand and classify all such linear relations, showing that they can be derived from a master antisymmetrization identity. Interesting connections to counting the number of independent polynomials in pairwise kinematic variables will be presented along with other potential applications.

Lunch @ MIT and Poster Session / 58

ATLAS Search for Resonance Decaying into Boosted Top Quark Pairs

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Many Beyond Standard Model theories predict an increased number of boosted top quark events making the $t\bar{t}$ system an important stepping stone in the search for new physics. The ATLAS experiment has just finished its second run December 2018 with a total of 140 fb⁻¹ worth of data collected through 2015-2018, with this luminosity, the run 2 data allows an analysis of a greater number of boosted Top quark events with $P_T > 500$ GeV. This analysis focuses on highly boosted $t\bar{t}$ events decaying via an all hadronic channel being compared with predicted values near high

$t\bar{t}$ invariant mass. The prediction values are calculated via Monte Carlo samples for the $t\bar{t}$ decays and a data driven estimate for multijet background. This poster summarizes a simple counting experiment done using a BumpHunter algorithm in a search for a general excess in boosted $t\bar{t}$ events.

Session / 59

Analyzing CMS Open Collider Data through Topic Modeling(10'+5')

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In this talk, I investigate jet substructure at the Large Hadron Collider with the CMS Open Data. I analyze a sample of jets from 2.3/fb of 7 TeV proton-proton collisions detected by the CMS experiment in 2011 with the companion simulated (both pre- and post-detector) datasets, focusing on a high-quality sample of jets with transverse momenta restricted to between 375 and 425 GeV. I further move to a specific analysis of jet classification using the unsupervised algorithm of jet topics to provide a new way of defining the categories of quark and gluon jets through their observable properties.

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Search for a generic heavy Higgs at the LHC

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A generic heavy Higgs has both dim-4 and effective dim-6 interactions with the Standard Model (SM) particles. The former has been the focus of LHC searches in all major Higgs production channels, just as the SM one, but with negative results so far. If the heavy Higgs is connected with Beyond Standard Model (BSM) physics at a few TeV scale, its dim-6 operators will play a very important role - they significantly enhance the Higgs momentum, and reduce the SM background in a special phase space corner to a level such that a heavy Higgs emerges, which is not possible with dim-4 operators only. We focus on the associated VH production channel, where the effect of dim-6 operators is the largest and the SM background is the lowest. Main search regions for this type of signal are identified, and substructure variables of boosted jets are employed to enhance the signal from backgrounds. The parameter space of these operators are scanned over, and expected exclusion regions with 300 fb⁻¹ and 3 ab⁻¹ LHC data are shown, if no BSM is present. The strategy given in this paper will shed light on a heavy Higgs which may be otherwise hiding in the present and future LHC data.

Session / 62

A background estimator for jet studies in p+p and A+A collisions(10'+5')

Author: Alba Soto Ontoso¹

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Jet reconstruction analyses at the high-luminosity phase of the LHC will face a similar challenge as current heavy-ion studies: how to mitigate the impact of the overwhelming and fluctuating energy coming from unrelated soft interactions (pileup/underlying event) on physical observables. In order to address this pressing issue, we propose to improve the momentum reconstruction resolution by exploiting intrinsic correlations among the soft and hard sectors of QCD jets. Our data-driven approach [1] results into a 5-40% improvement on the resolution of the reconstructed jet p_T compared to previous methods in a high-luminosity proton-proton scenario. Its applicability in a heavy-ion context will be also discussed.

[1] Yacine Mehtar-Tani, Alba Soto-Ontoso, Marta Verweij, arXiv:1904.12815

Session: Machine Learning / 63

Reweighting via classification for MC tuning(15'+5')

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Parton shower Monte Carlo programs are a key tool for all aspects of analysis using jet substructure. These programs have many tunable parameters that control aspects of both perturbative and non-perturbative models. Finding the best parameters is non-trivial, and parton showers are typically run both for some optimized parameters as well as variations for uncertainty estimates.

Traditionally, tuned parameters are found using a set of one-dimensional unfolded measurements and optimized using various approximate sampling methods. Simulations with new parameters can be costly and must be run for every new set of parameter values, except for some limited cases where analytic weights can be calculated.

We propose a new data-driven method which uses deep learning with jet constituents to calculate the weights relating any point in the parameter space to another. We show how this method can be trained to relate two discrete points or to interpolate continuously in parameter space. In the continuous case, it can be used to fit for the optimal Monte Carlo parameters by using gradient descent in a classification task between a MC sample with known parameter values and the "data".

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Deep learning with low-level features: A free lunch?

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Recent studies have shown that deep learning techniques applied on low-level features can outperform methods that use only high-level “engineered” features. However, we argue it is worth considering the price of this improved performance. For instance, using physically-motivated inputs such as IRC-safe substructure observables acts as a regularizing prior in the learning procedure. Moreover it can be shown that the sensitivity of a network’s outputs to small perturbations scales directly with the dimensionality of the input data. It is impractical to validate all high-dimensional correlations and the current validation approaches typically only check one-dimensional distributions of high-level features which are not the same data presented to the network. Drawing on ideas from AI safety, we illustrate potential challenges that could arise using jet tagging as our example. In particular, we show that small perturbations to jet constituents can dramatically change classifier performance without significantly affecting high-level observables. Presently, the examples we demonstrate are extreme, but will hopefully start a dialogue about how to assess and ensure robustness of deep learning applications.

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A generative model for jet substructure

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We introduce a generative model to simulate radiation patterns within a jet using the Lund Jet plane. We show that using an appropriate neural network architecture with a probabilistic generation of images, it is possible to construct a model which retrieves the underlying two-dimensional distribution within a few percent. We compare this method with several alternative state-of-the-art generative techniques. Finally, we show how a mapping can be created between different categories of jets, and use this method to retroactively change simulation settings or the underlying process of an existing sample. These results provide a framework for data augmentation of physical measurements, as well as a significant reduction in simulation time through fast inference of the neural network.

Session: Machine Learning / 67

Leveraging symmetries in jet representations with harmonic networks(15’+5’)

Authors: Chase Owen Shimmin¹; Mohammad Abdullah²; Paul Louis Tipton³¹ *Yale University (US)*² *Texas A&M University*³ *Physics Department - Yale University***Corresponding Authors:** paul.louis.tipton@cern.ch, chase.shimmin@cern.ch, mabdullah@tamu.edu

Despite the successful application of deep learning to many problems involving jet substructure, typical approaches involve representing jets either as lists of four-vectors or as 2D images. This is mainly due to the compatibility of these structures with existing architectures, such as recurrent or convolutional networks. However, these networks fail to exhibit equivariance with respect to

obvious symmetries associated to jet physics, such as rotations and boosts. Recent work in the field of representation learning has shown that equivariant (i.e. symmetry-respecting) architectures generally improve learning, allowing networks to perform better with fewer parameters. Using the example of boson tagging, we demonstrate the importance of equivariance, particularly with respect to boosts, for jet observables. We propose representing jets as functions on the 2-sphere, and construct learnable feature-matching kernels using spherical harmonics. We then demonstrate a network whose layers compute generalized convolutional operations over the desired symmetry groups, automatically resulting in equivariant representations throughout the network.

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Experimental Introduction (30'+10')

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Intro

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Theoretical Introduction (30'+10')

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Heavy Ion Theory Intro (25+5)

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Heavy Ion Experimental Intro (25+5)

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Machine Learning (25+5)

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Experimental Summary (45'+10')

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Theory Summary (45'+10')

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Future Collider Intro (25+5)

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Machine Learning Intro (25'+5')

Session: Machine Learning / 78

Uncovering latent jet substructure(15'+5')

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We apply techniques from Bayesian generative statistical modeling to uncover hidden features in jet substructure observables that discriminate between different a priori unknown underlying short distance physical processes in multi-jet events. In particular, we use a mixed membership model known as Latent Dirichlet Allocation to build a data-driven unsupervised top-quark tagger and ttbar event classifier. We compare our proposal to existing traditional and machine learning approaches to top jet tagging. Finally, employing a toy vector-scalar boson model as a benchmark, we demonstrate the potential for discovering New Physics signatures in multi-jet events in a model independent and unsupervised way.

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The Machine Learning Landscape of Top Taggers(15'+5')

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Based on the established task of identifying boosted, hadronically decaying top quarks, we compare a wide range of modern machine learning approaches. We find that they are extremely powerful and great fun.

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Boost Camp Part I

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Boost Camp Part II

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Discussion Panel / 89

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