Jet substructure at the LHC

SM@LHC 2021

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On behalf of the CMS, ATLAS and LHCb Collaborations

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Outline

1. Introduction
2. Jet Substructure Tools and Algorithms

   In CMS (CMS-DP-2020-025, CMS-DP-2020-002)

   In ATLAS (JETM-2018-06)
3. Jet Substructure Measurements

   Measurement of charged hadron production in Z-tagged jets in proton-proton collisions at $\sqrt{s} = 8$ TeV (LHCb-2019-012)

   A measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV (Phys. Rev. D 101 (2020) 052007)

   Study of quark and gluon jet substructure in dijet and Z+jet events from pp collisions (CMS-SMP-20-010)
4. Summary

Introduction

Why boosted topologies?

Current LHC conditions bring us challenges and opportunities. For instance, it allows high mass particles to give Lorentz-boost to SM final state particles.

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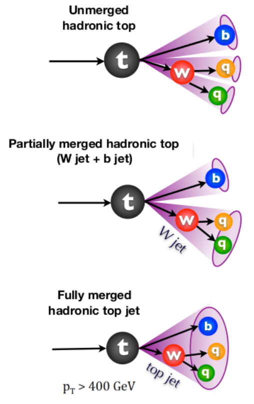
Boosted tops, Ws



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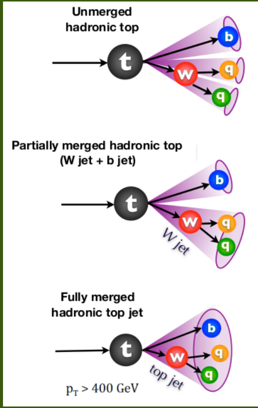
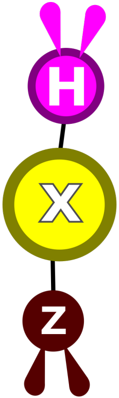
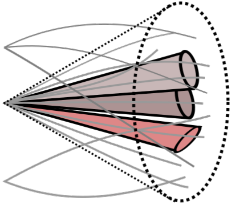


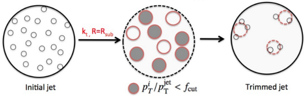
Boosted searches





Large cone size jet

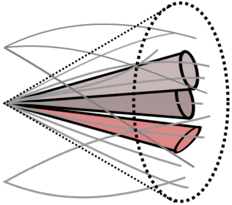
- **"Trimming"** http://arxiv.org/abs/0912.1342 (D. Krohn, J. Thaler, L. Wang)
  - uses k_t algorithm to create subjets of size R_{sub} from the constituents of the large-R jet: any subjets failing $p_T i$ / p_T < f_{cut} are removed



Tuned parameters: f_{cut} and R_{sub}

Clean jet from extra soft radiation, grooming techniques: trimming (ATLAS), softdrop (ATLAS,CMS)

Probing the high-energy regime



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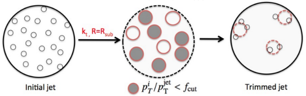

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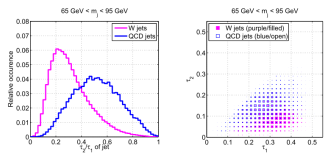

Variables to distinguish QCD jets and high mass particles, substructure variables: τ_{21}(CMS,ATLAS), N_2(CMS), D_2(ATLAS)

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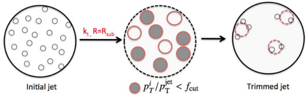

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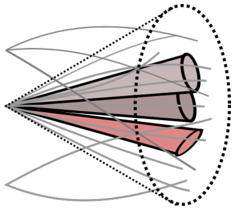

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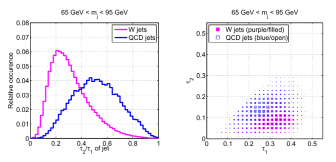

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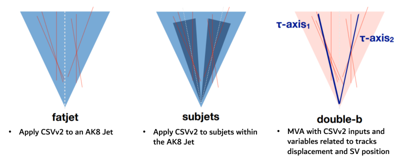
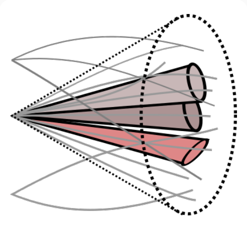
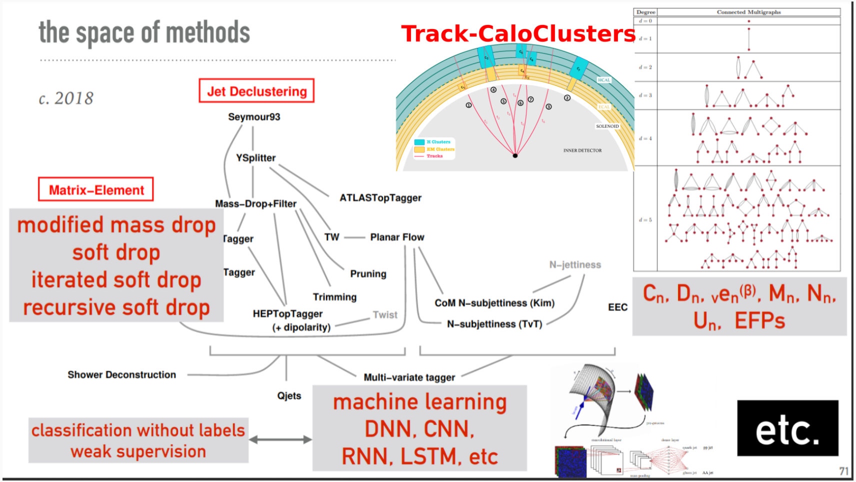


Study the presence of b-hadrons (doubleB taggers)

Probing the high-energy regime





.. and with machine learning techniques or Track-CaloClusters, our taggers are getting more sophisticated.

In this talk ...

... I will concentrate in jet substructure measurements and tools because other colleagues will present the results of searches using boosted topologies.

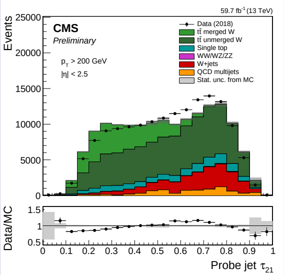
If you are interested in searches, I encourage you to attend the following talks (not a complete list):

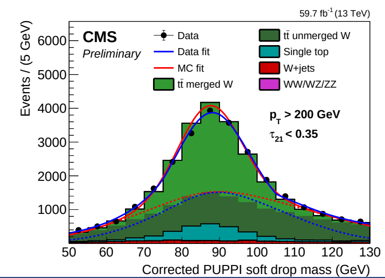
- Jet measurements (including Lund-plane) by Pierre Antoine Delsart.
- State of the art in SM Higgs physics by Kirill Melnikov.
- Triboson Measurements in CMS by Alessandro Da Rold.

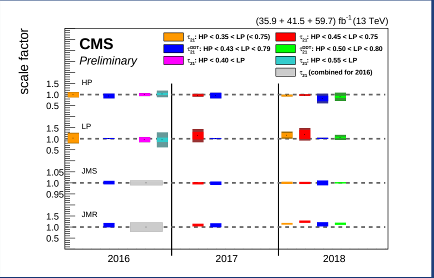
Jet Substructure Tools and Algorithms

Jet Substructure Tools and Algorithms in CMS

W taggers using n-subjetiness (CMS-DP-2020-025)



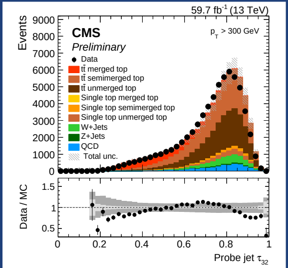


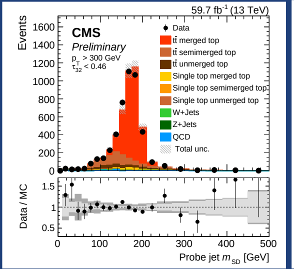


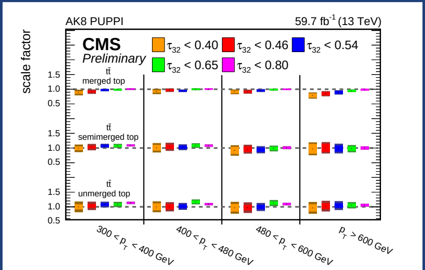
N-subjetiness variables helps us identify boosted objects through its substructure. These variables are widely used in CMS for boosted searches and measurements. Although their modelling in MC is not perfect, we can effectively identify two and three-prong resonances.

Jet Substructure Tools and Algorithms in CMS

top taggers using n-subjetiness (CMS-DP-2020-025)







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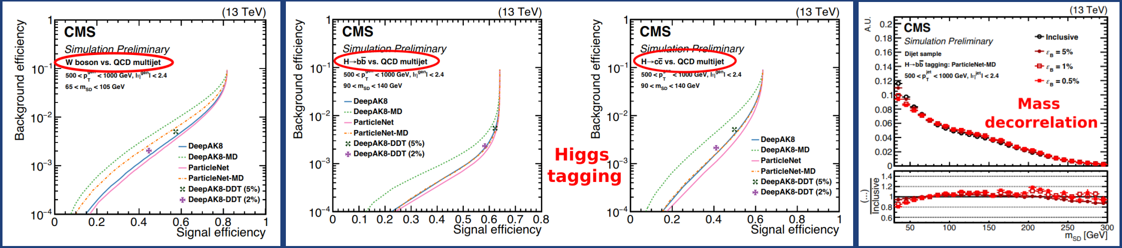
Boosted taggers using Machine Learning (CMS-DP-2020-002)



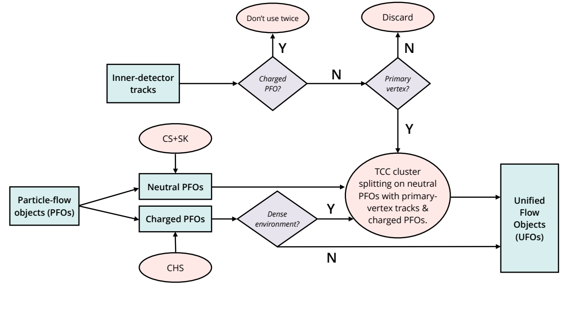
DeepAK8, and its next iteration ParticleNet, are multiclassifier taggers to discriminate for W, top, Higgs (bb/cc), and QCD multijets. More information about the algorithm in backup.

Jet Substructure Tools and Algorithms in ATLAS (JETM-2018-06)

Many combinations of jet types and substructure tools are studied in detail!

	Algorithm	Abbreviation	Settings
Jet input objects	Topological Clusters	Topoclusters	N/A
	Particle-Flow	PFlow	N/A
	Track-CaloClusters	TCCs	N/A
	Unified Flow Objects	UFOs	N/A
Pile-up mitigation algorithms	Constituent Subtraction	CS	$A_g = 0.01$ $\Delta R_{\text{max}} = 0.25$ $\alpha = 0$
	Voronoi Subtraction (*)	VS	N/A
	SoftKiller	SK	$\ell = 0.6$
	Pile-up Per Particle Identification	PUPPI	$R_{\text{min}} = 0.001$ $R_0 = 0.3$ $a = 200$ MeV $b = 14$ MeV
Jet grooming algorithms	Soft-Drop	SD	$z_{\text{cut}} = 0.1$ $\beta = 0, 1, 2(*)$
	Bottom-up Soft-Drop	BUSD	$z_{\text{cut}} = 0.05, 0.1$ $\beta = 0, 1, 2(*)$
	Recursive Soft-Drop	RSD	$z_{\text{cut}} = 0.05, 0.1$ $\beta = 0, 1, 2(*)$ $N = 3, 5(*), \infty$
	Pruning	N/A	$z_{\text{cut}} = 0.015$ $R_{\text{cut}} = 0.25$
	Trimming	N/A	$f_{\text{cut}} = 5\%, 9\%$ $R_{\text{sub}} = 0.1, 0.2$

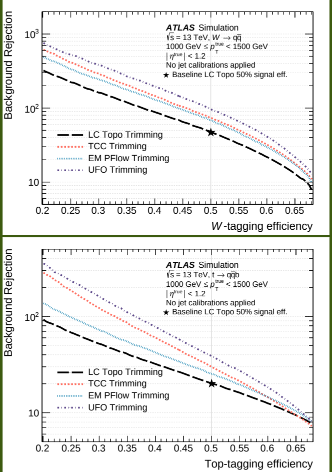
Including a new UFO algorithm!



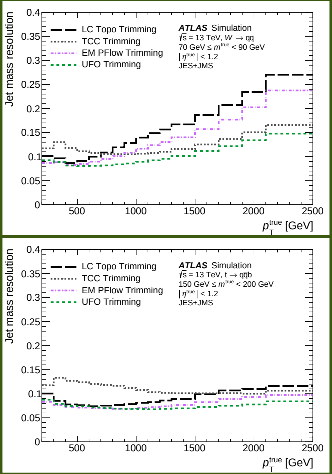
Unified Flow Objects

Jet Substructure Tools and Algorithms in ATLAS (JETM-2018-06)

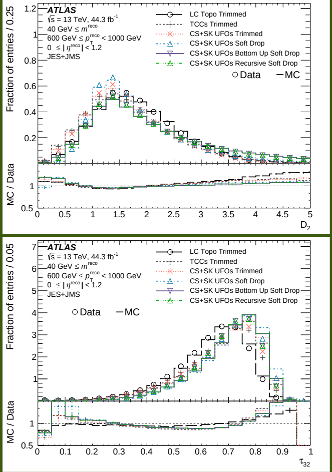
Tagging Efficiency



Jet Mass Resolution



Jet Substructure Variables



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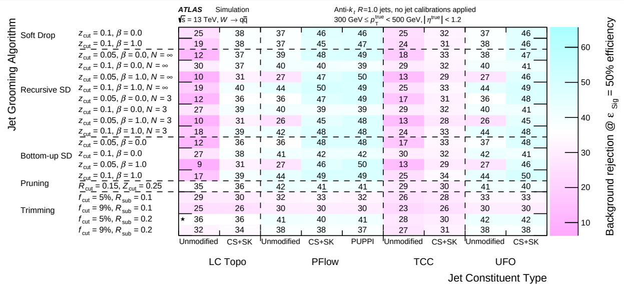
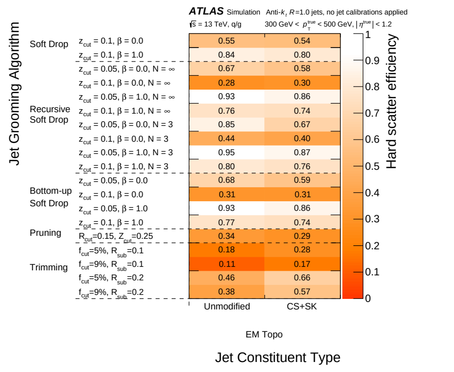


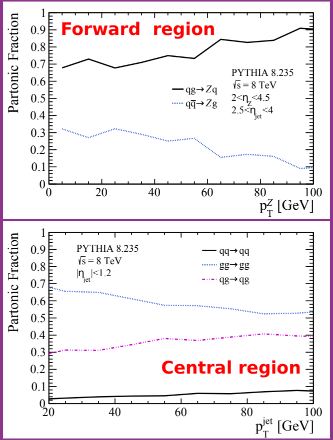


A detailed study to understand the performance of the substructure algorithms, pileup removal tools and tagging efficiencies.

Jet Substructure Measurements

- First measurement of jet hadronization in high eta regions.
- By selecting jets recoiling against a Z boson decaying to charge leptons, $pt > 20$ GeV and $2.5 < |\eta| < 4$, we can ensured a higher light quark jet composition.

Partonic Fraction



Charge hadron production in Z-tagged jets in LHCb (LHCb-2019-012)

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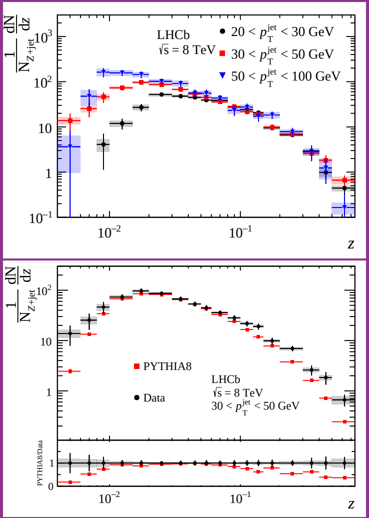
Longitudinal momentum fraction



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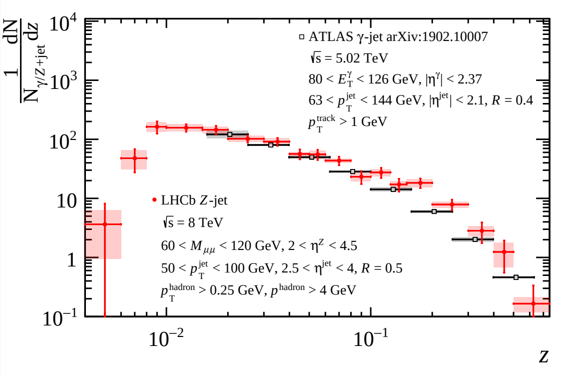
- And compare them with other LHC experiments like ATLAS.

Comparison with ATLAS results



Softdrop jet observables in ATLAS (Phys. Rev. D 101 (2020) 052007)

Soft drop algorithm

Iteratively decluster a jet to remove soft, wide-angle radiation

$$\frac{\min(pt_1, pt_2)}{pt_1 + pt_2} > z_{cut} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$

- Measures three different substructure observables in dijet events using 32.9 fb^{-1} of data at $\sqrt{s} = 13$ TeV.
- Two types of jets are used: calorimenter-based and track-based.
- This allows a direct comparison of how different object definitions affect on the measured observables.

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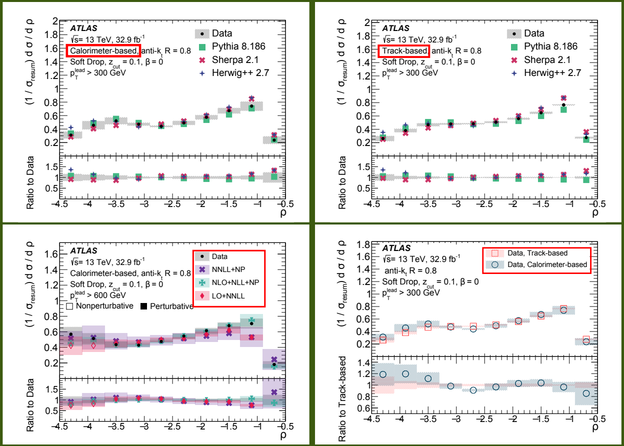
Jet (relative) mass ($\rho = log(m^2/pt^2)$)



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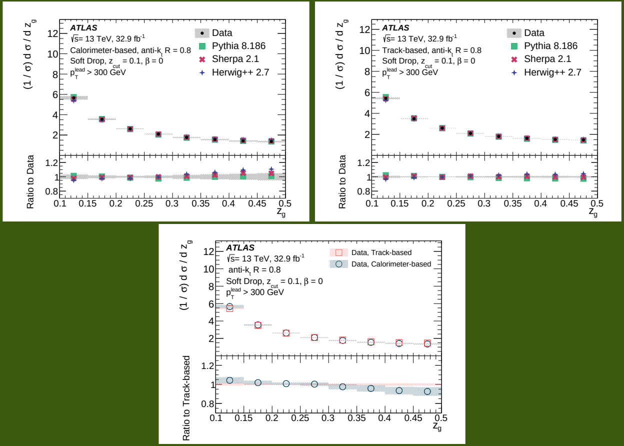
$z_g = \min(pt_1, pt_2)/(pt_1 + pt_2)$



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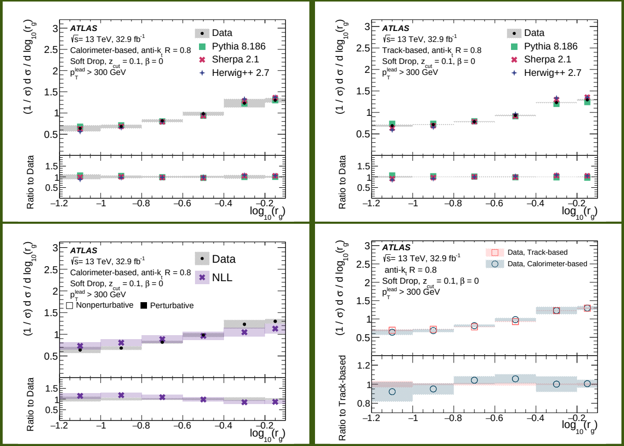
r_g (opening angle between subjets)

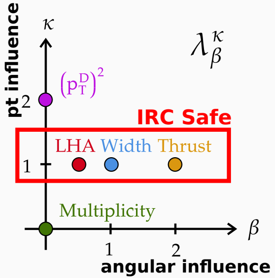


Jet substructure variables in quarks and gluon jets (CMS-SMP-20-010)

Systematic study of observables for the interplay between the soft+hard physics in quark and gluon jets.

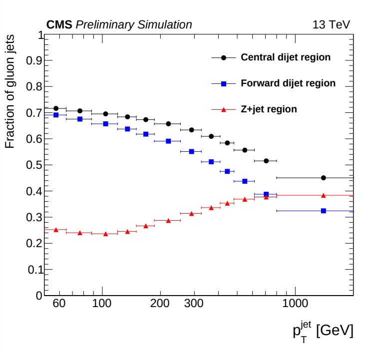
Generalized angularities

$$\lambda_\beta^\kappa = \sum_{i \in jet} z_i^\kappa \left(\frac{\Delta R_i}{R} \right)^\beta$$



Quark and gluon selection

Two main topologies are studied: quark enriched (Z+jets) and gluon enriched (dijets). Additionally, jets are differentiate between the charged+neutral and charged-only constituents, with and without softdrop algorithm.



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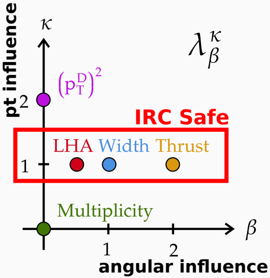
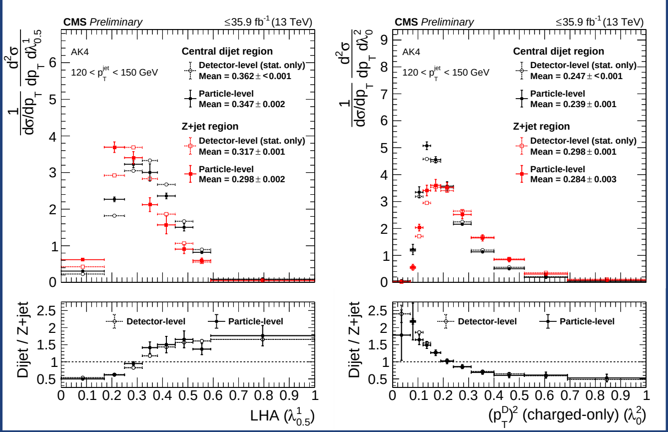


Detector- and particle-level (unfolded) data



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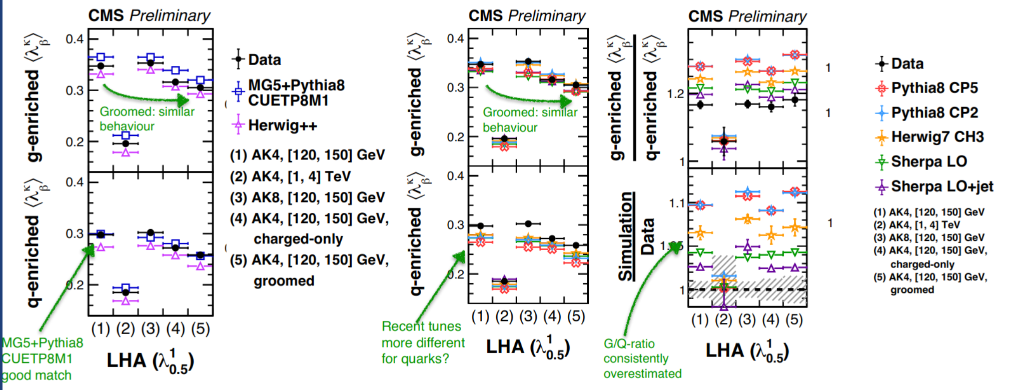
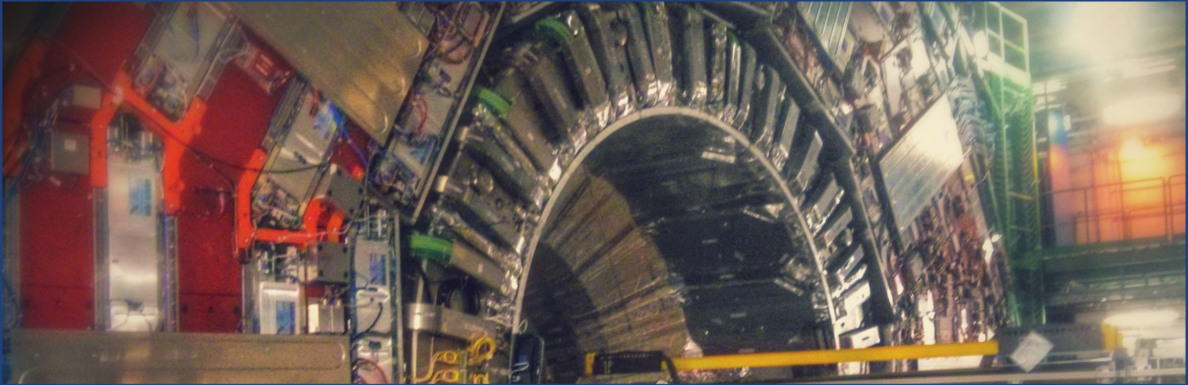


Summary

Summary

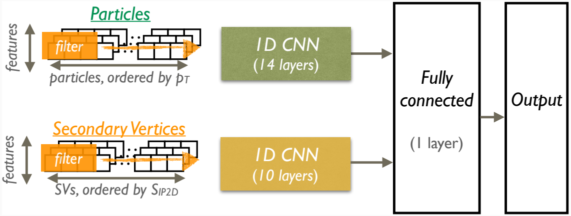
- The current conditions of the LHC help us to study hadronic interactions not accessible before.
- Jet substructure has proven to be an important tool to search and measure the properties of high transverse momentum particles, while effectively remove the overwhelming QCD multijet background.
- However, we passed the times where these novel tools were not fully understood and we are in the times where we are measuring jet substructure features with more precision.
- This was just a (biased) glance of latest results in the field, but more results are yet to come.

Thank you for the attention...



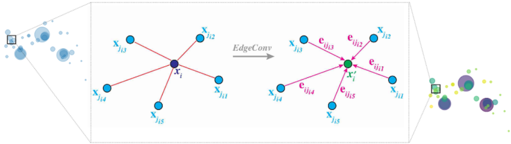
... questions?

DeepAK8/ParticleNet



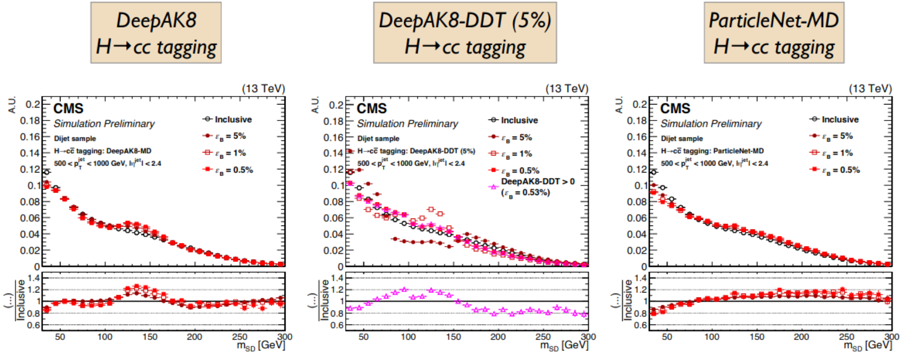
- DeepAK8 is a multiclass classifier for the identification of hadronically decaying particles, with five main categories, W/Z/H/t/other.
- PF candidates and secondary vertex information as inputs.
- It is a one-dimensional CNN based on the ResNet architecture.

- ParticleNet [arXiv: 1902.08570]
  - treating a jet as an unordered set of particles in space
  - using a permutation-invariant graph neural network architecture



Mass Decorrelation

- ML algorithms usually sculpt the jet mass, and therefore additional techniques should be applied to mitigate this effect.



CMS DP-2020/002

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