ATLAS EXPERIMENT

Enigmass

LPSC GRENOBLE | MODANE

From hadronic jets to dark showers: an exciting search for new physics

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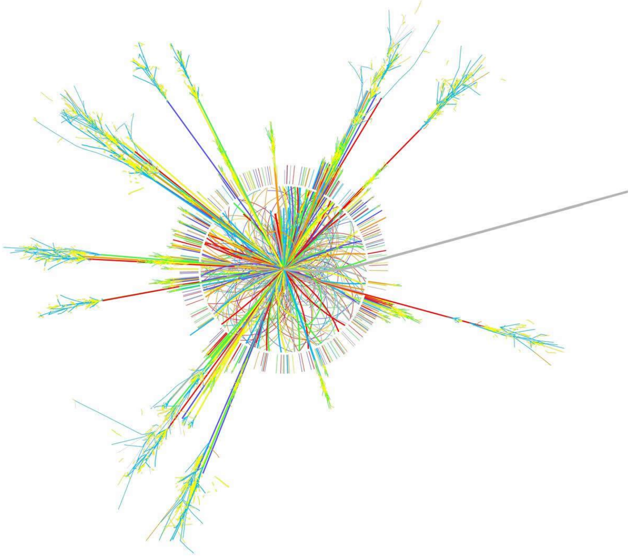
W UNIVERSITY of WASHINGTON

From hadronic jets to dark showers
Outline



Research activities during the last two years:

1. Detector performance: Calibration of hadronic jets using Machine Learning techniques with the ATLAS detector

2. Phenomenology: Dark Quantum Chromodynamics sector and simulation of dark showers

3. Physics analysis: Search for dark matter with a Z′ mediator and emerging jets using ATLAS Run-3 data

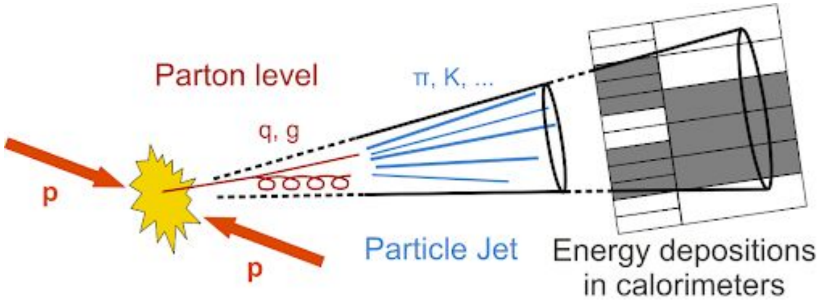
Calibration of hadronic jets
Motivation

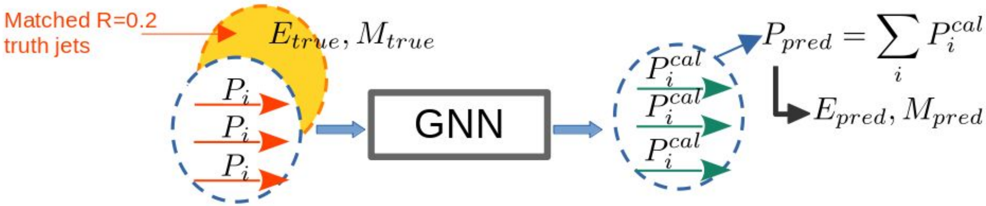
Calibration of jet constituents → Better reconstruction of the energy flow details

- Better substructure reconstruction
- Help mitigating topologies effect
- Longer term may help with event-shape variables

Building very small (R=0.2) jets:

- Small enough: fine angular resolution
- Big enough: contains several constituents





$$\text{Loss} = \lambda_1 (E_{pred} - E_{true})^2 + \lambda_2 (M_{pred} - M_{true})^2$$

Calibration of hadronic jets
Motivation

Group constituents in a graph:

- Nodes == constituents in (η,φ) plane
- Account for spatial relations between constituents
- Could help to correct for energy losses or EM/hadronic nature of showers

Constrain constituents E & angles with R=0.2 jet-level quantities:

- I.e. constrain node-level predictions with graph-level predictions

Correction factors and loss function

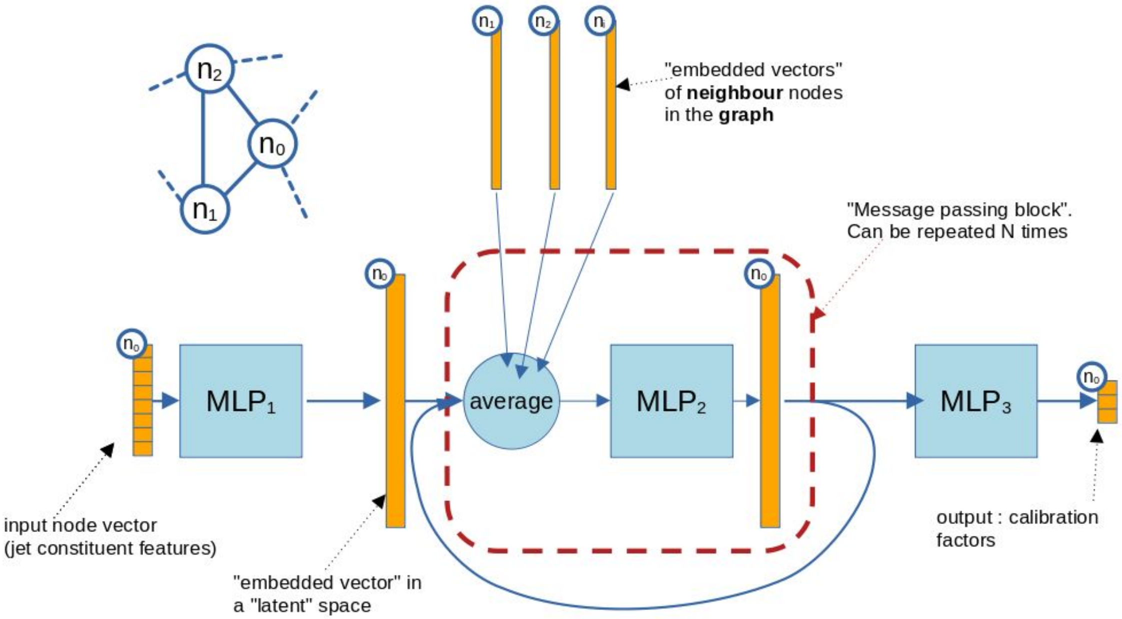
- Predict corrections for constituents' energy and/or y and/or φ
- Constrain this prediction factor and choose a loss in the form of:

$$L = L_{jet}^{energy} + L_{jet}^{y} + L_{jet}^{mass}$$

where L_{jet}^{energy} = Leaky Gaussian Kernel loss because it predicts better mode of distribution than Mean Squared Error: going to constrain jet energy factor

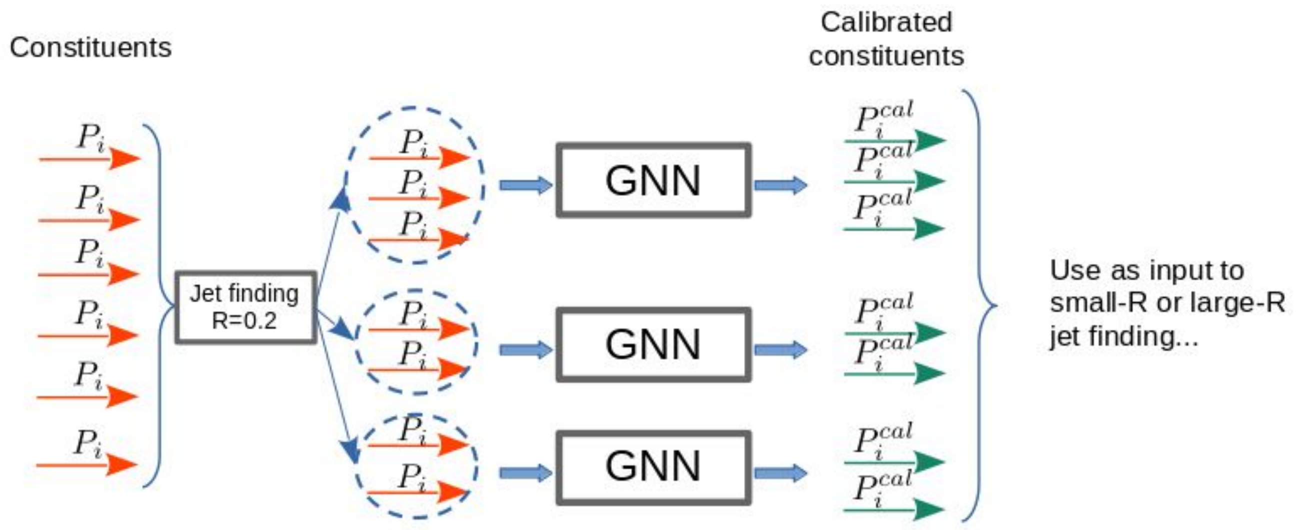
Calibration of hadronic jets
Graph Neural Network

- Using Graph Neural Networks to calibrate jet constituents: performing node-level (constituents) regression from graph-level (jets) constraints



Calibration of hadronic jets
Graph Neural Network

- Once GNN trained apply to list of constituents

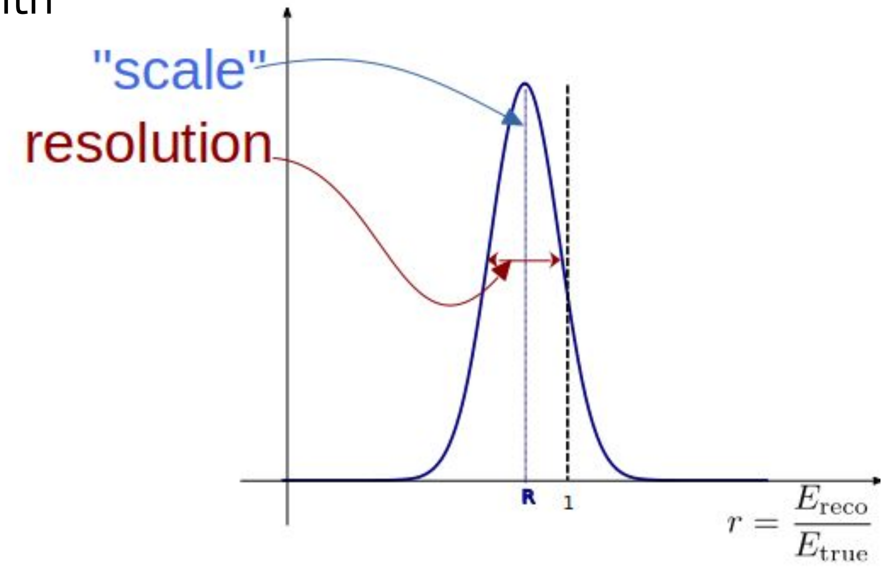


Calibration of hadronic jets
Performance evaluation

Evaluation of the calibration performances with R=1.0 and R=0.4 jets:

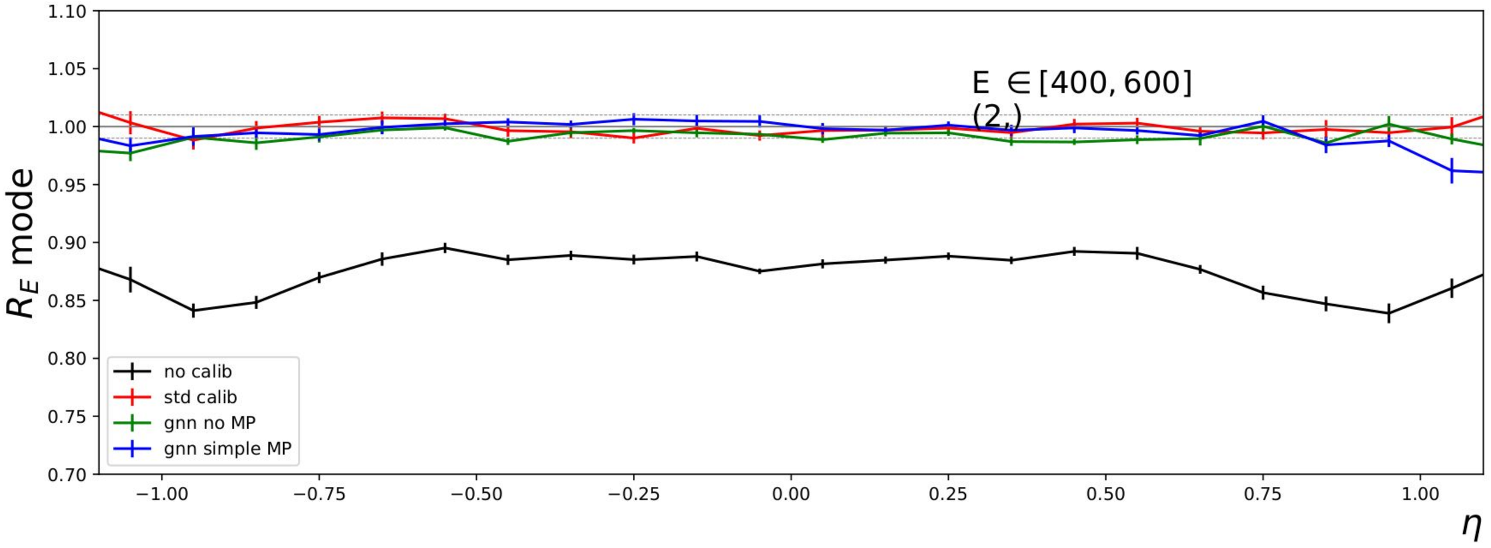
- Check physics jets energy and mass response
- Rebuild jets with GNN calibrated constituents
- Distributions of ratio E_{calib}/E_{true} and M_{calib}/M_{true}
- Consider scale and resolution

⇒ Get this response in many energy and/or mass bins!



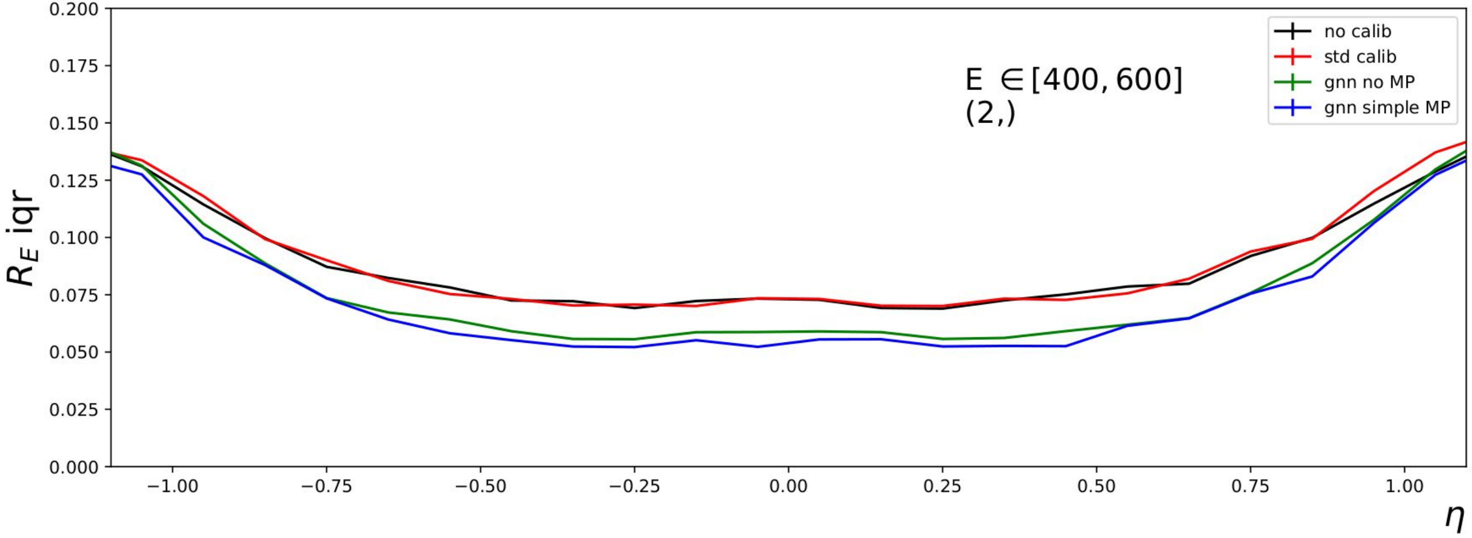
Calibration of hadronic jets
Energy scale and resolution

- Energy scale is well reconstructed - almost as well as standard ATLAS calibration



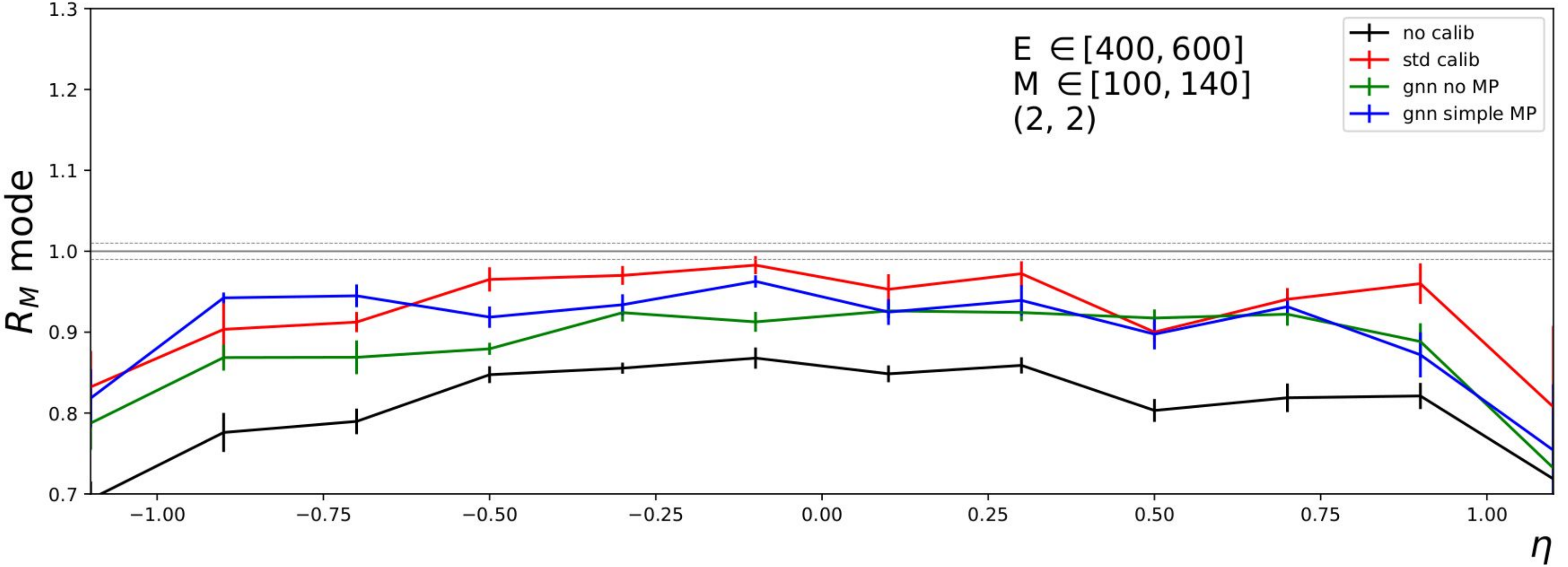
Calibration of hadronic jets
Energy scale and resolution

- Energy scale is well reconstructed - almost as well as standard ATLAS calibration
- Energy resolution is improved



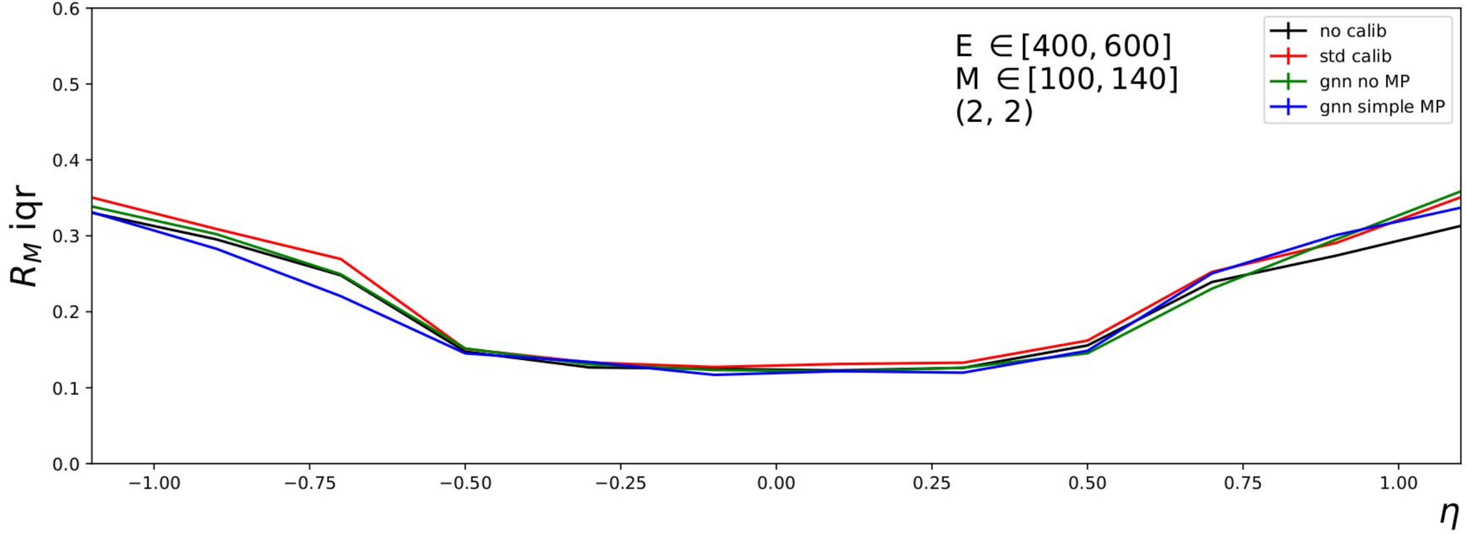
Calibration of hadronic jets
Mass scale and resolution

- Mass scale is improved wrt to no calibration → Not just due to energy scaling, GNN seems to learn more



Calibration of hadronic jets
Mass scale and resolution

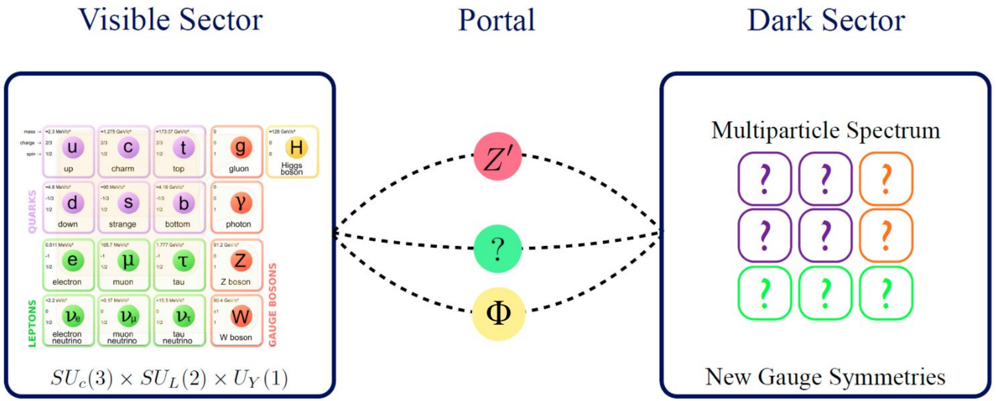
- Mass resolution is improved wrt to standard ATLAS calibration

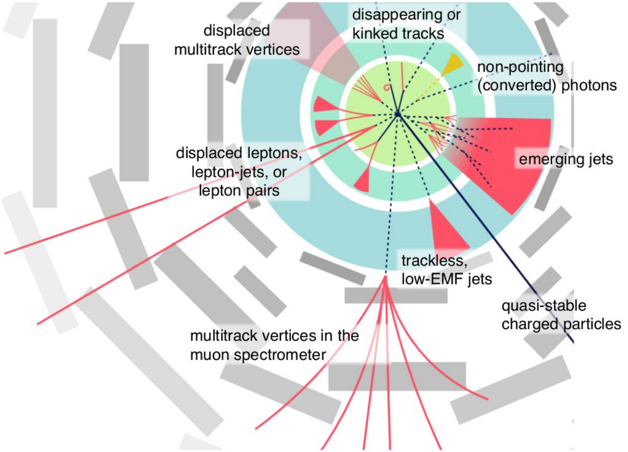


For small-R jets: Promising results also for energy scale and resolution (especially at the central η bins) but with a mass scale not yet fully corrected at 1

Dark Quantum Chromodynamics sector
Motivation

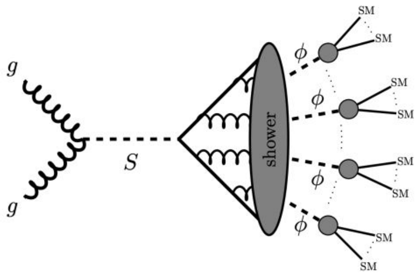
- Dark particles can be produced at hadron colliders via a portal (interactions) between the SM and the dark sector
- Jets from the dark particles can decay to SM particles at the distinct ATLAS sub-detectors
- Depending on the dark jet properties, a rich set of potential final states can be considered: delayed signals, disappearing tracks, displaced tracks/vertices, isolated calorimeter energy deposits, ...





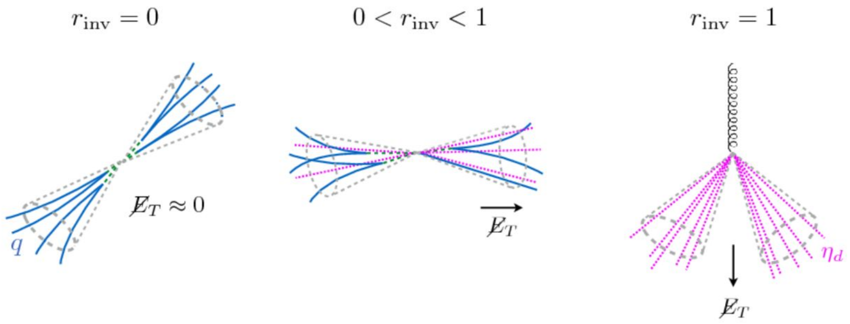
Dark Quantum Chromodynamics sector

Snowmass Project on dark showers



Snowmass project focusing on a systematic survey of a dark QCD sector with a new force from non-Abelian gauge group

- **Theory:** QCD-like scenarios of dark sector and beyond (Soft-Unclustered-Energy Patterns, glueballs, etc)
- **Phenomenology:** Benchmarks from the underlying physical parameters for semi-visible jets and simulation of dark showers
- **Experiment:** Improvement of the search strategies with event-level variables, Graph Neural Networks, Autoencoders, etc



Dark showers
Semi-visible jets

Snowmass 2021 report: theory, phenomenology, and experimental avenues for dark showers.
Eur. Phys. J. C 82, 1132 (2022) (54 authors)

Focusing on the semi-visible jets, possible pathways for consistent theory frameworks were discussed:

- Tentative to build coherent benchmarks

Regime	N_c, N_f	Λ_v [GeV]	**Q**	m_{π_v} [GeV]	m_{ρ_v} [GeV]	Stable dark hadrons	Dark hadron decays
$m_{\pi_v} > m_{\rho_v}/2$	3,4	10	(-1,2,3,-4)	17	31.77	All π_v	$\rho_v^0 \to q\bar{q}$ $\rho_v^\pm \to \pi_v^\pm q\bar{q}$
$m_{\pi_v} < m_{\rho_v}/2$	3,3	5	Various	3	12.55	$0/1/2\pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	10	Various	6	26	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$
	3,3	50	Various	30	125.5	$0/1/2\ \pi_v^0$	$\rho_v^{0/\pm} \to \pi_v^{0/\pm}\pi_v^\mp$ $\pi_v^0 \to c\bar{c}$

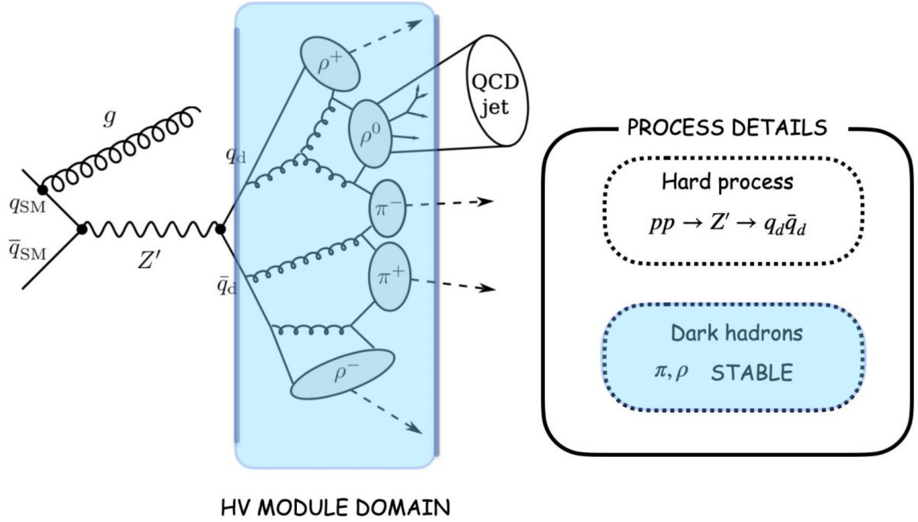
- Lattice computations also considered as by fixing mass ratios with respect to the confinement scale Λ
- Overview of the decays of dark hadronic bound states that are either stable (decaying within the dark sector) or decay to final states including SM particles

Dark showers
Pythia Hidden Valley update

An updated Pythia8 Hidden Valley module is available:

- Full flavour splitting for dark mesons: now possible to access all PDGIDs 4900ij3 (with decays, masses and lifetimes)
- Possibility to add a suppression factor in the production of the highest flavour diagonal meson

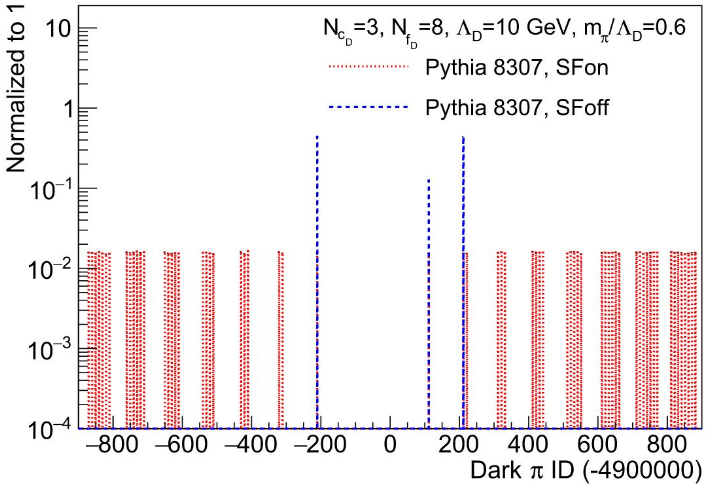
Study performed targeting the flavour splitting parameters validation focusing on the $pp \to Z' \to q_d q_d$ process ($m_{Z'}$ = 1 TeV, Λ_d = 10 GeV)

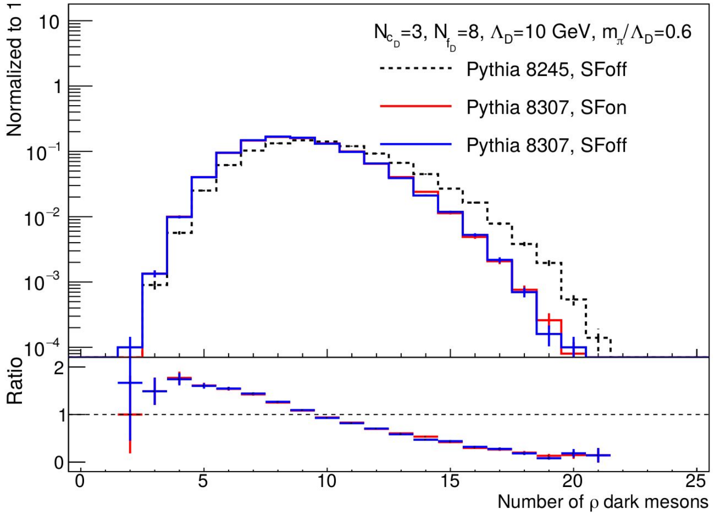


Dark showers
Pythia Hidden Valley update

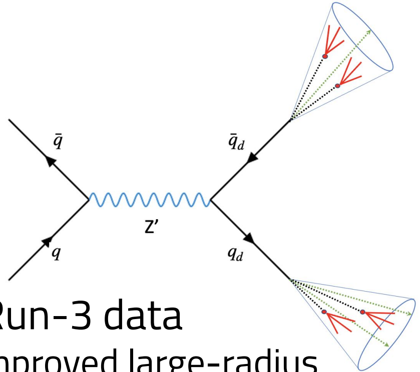
Validation executed considering the $N_c = 3$ with $N_f = 3$ and $N_f = 8$ cases ($N_f < 3\ N_c$):

- With flavour splitting, 9 pseudo-scalars and 9 vectors dark mesons for the $N_f = 3$ scenario while 64 different dark mesons states can be accessed with $N_f = 8$
- For both cases, dark mesons present lower multiplicity and softer pT due to new pT suppression for mini-strings fragmentation with the new module
- In general, similar distributions for the new module with flavour splitting switched on and off and no relevant impact on event kinematic variables

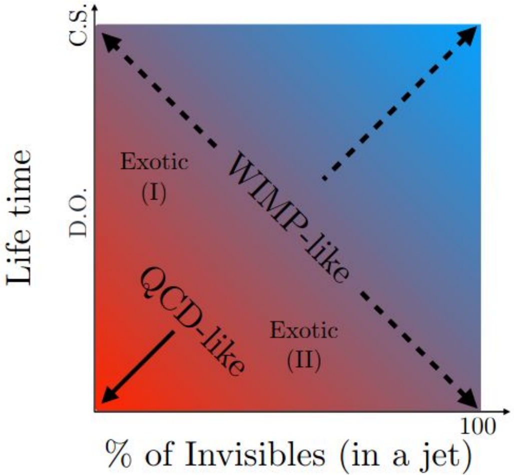




Search for emerging jets
Motivation



- Search for *s*-channel production of dark quarks via Z′ mediator using Run-3 data
  - **Never searched for before at the LHC** with a new dedicated trigger and improved large-radius tracking!
- Dark hadrons can decay in a QCD-like way and dark pions can have a non-null lifetime: high multiplicity of displaced vertices and tracks
- **Selection:** Two large-radius (R=1.0) jets with multiple secondary vertices



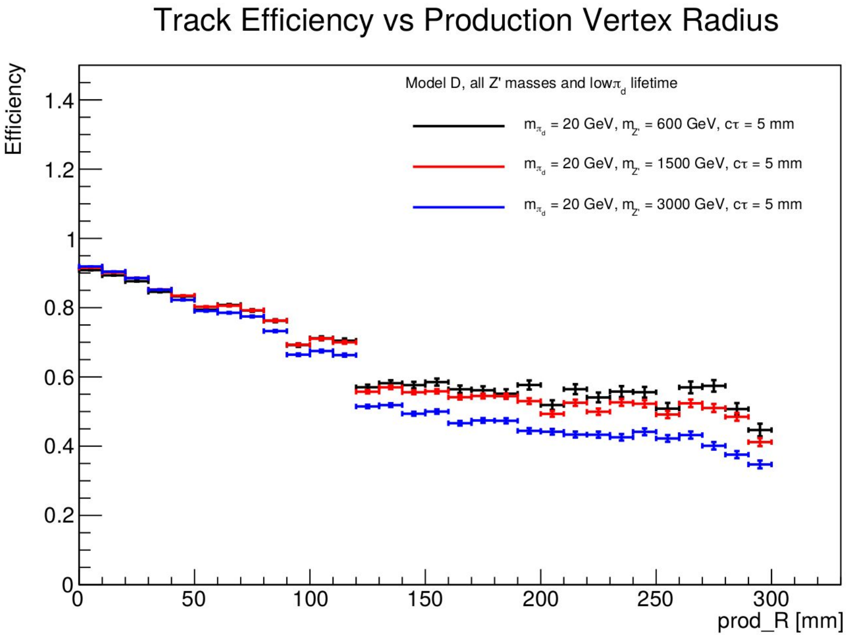
Benchmark models

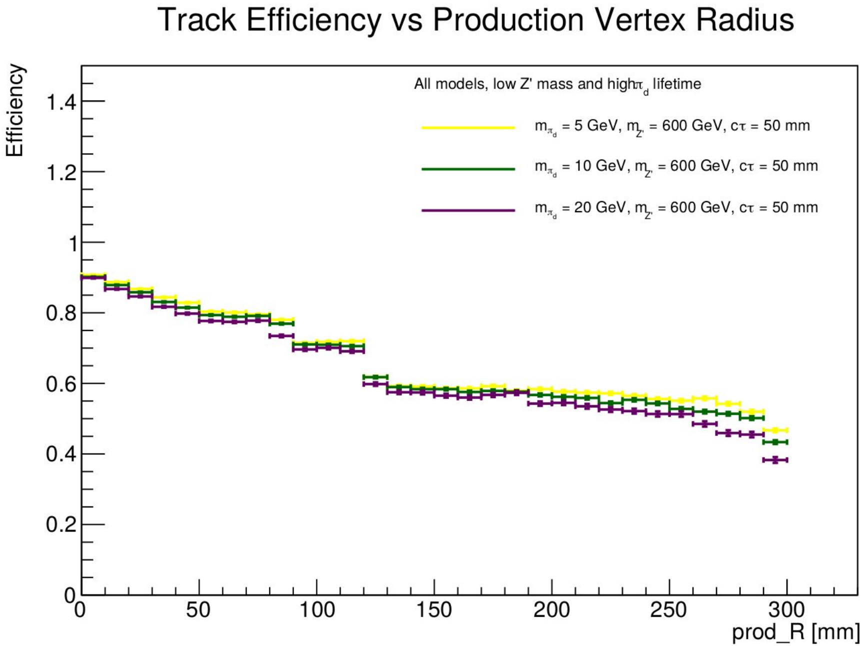
	Model A	Model C	Model D
m_{π_d} (GeV)	5	10	20
$c\tau_{\pi_d}$ (mm)	5-50		
$m_{Z'}$ (GeV)	600-1500-3000		
Decay to SM	Dark pions to quarks		
Decay in dark sector	Dark rhos to dark pions		

Search for emerging jets
Challenges - Tracks + Vertices

Key phenomenological and experimental challenges:

- Selection of experimentally appropriate models for dark QCD signals



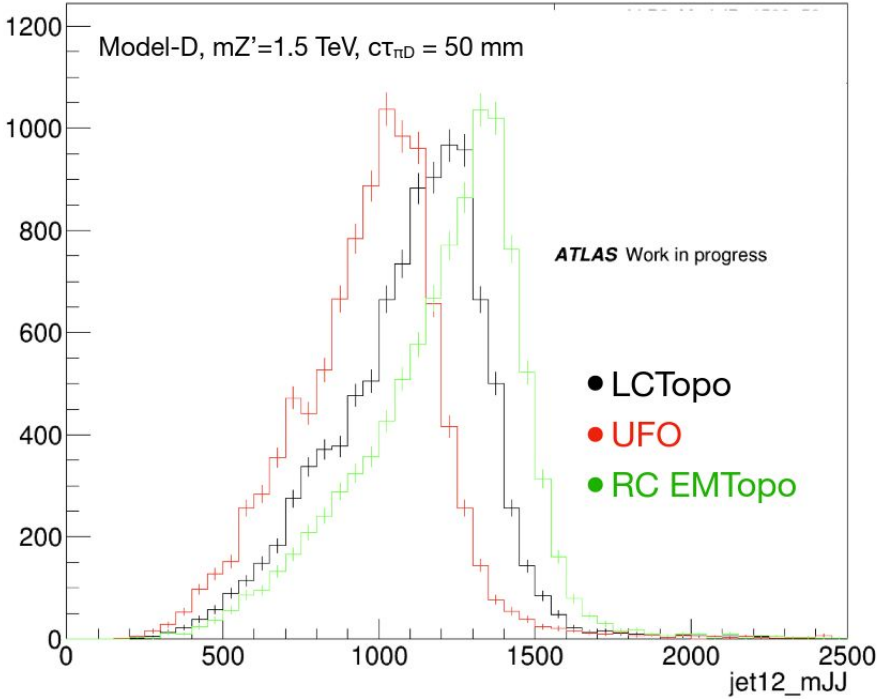


Search for emerging jets
Challenges - Jets

Effective reconstruction and selection of jets, tracks and vertices ⇒ Custom Large-R jet reconstruction reclustering R=0.4 EMTopo jets into R=1.0 jets

- Able to better reproduce Z’ mass (m_{jj}) than LCTopo and UFO jets
- Calibration comes “for free” by using calibrated R=0.4 EMTopo jets

LCTopo = Topoclusters with local cell weight
UFO = Unified Flow Objects
RC EMTopo = Re-clustered EM-scale topocluster jets



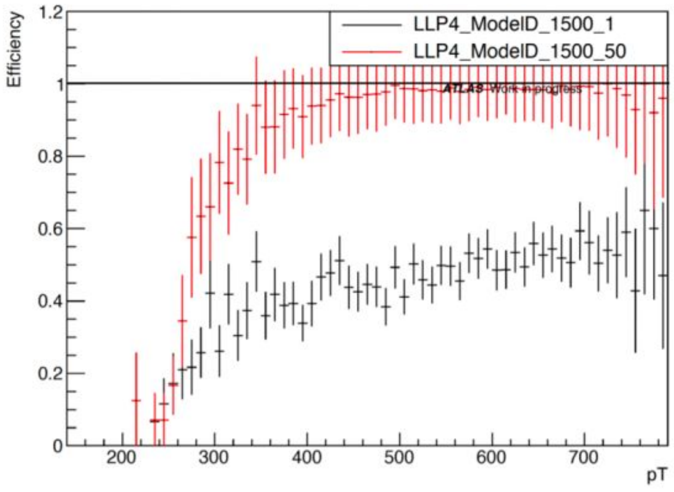
Search for emerging jets
Challenges - Trigger

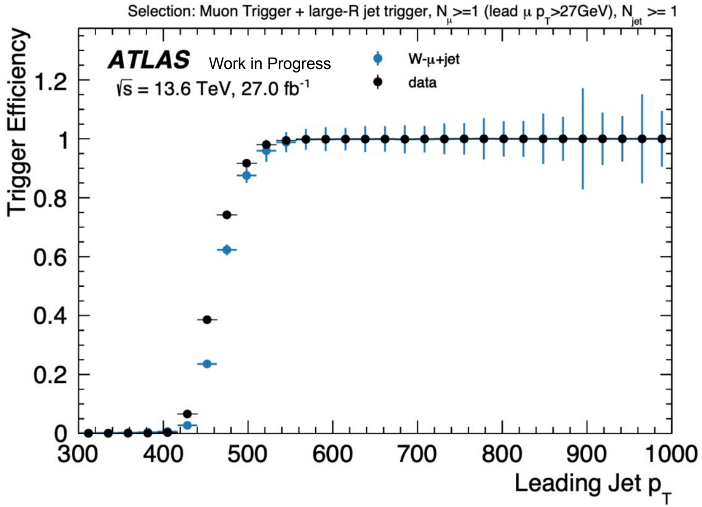
Considering two large-R jet triggers:

1. Dedicated emerging jets trigger developed for Run 3
    - Require jet with pT > 200 GeV , |η| < 1.8 , and “prompt track fraction” PTF < 0.08

$$PTF = \frac{\sum_{\mathrm{trk}\in\mathrm{jet}} p_{\mathrm{T}}^{\mathrm{trk}}(d_0 < 2.5\sigma(d_0))}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

2. Standard Large-R jet trigger: with a high pT threshold for Level 1 (100 GeV) and High-Level Trigger (460 GeV)

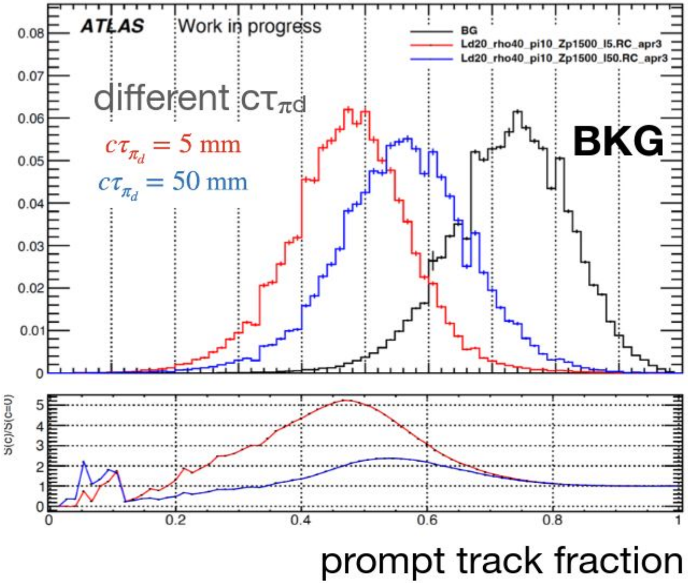


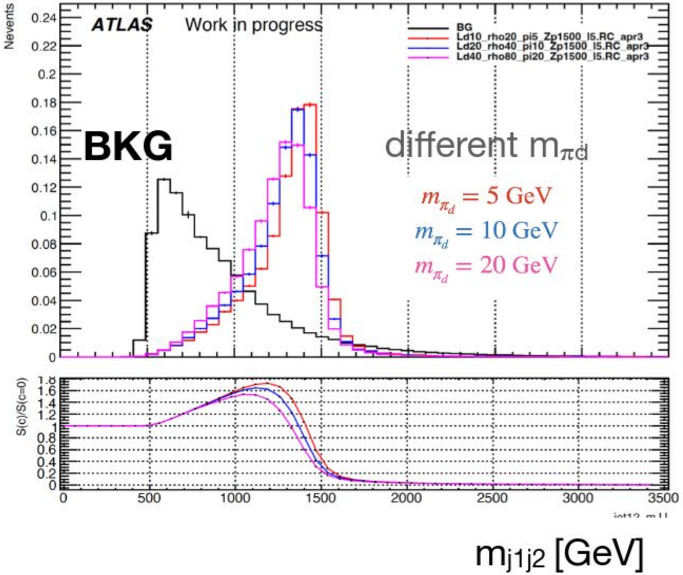


Search for emerging jets

Challenges - Discrimination

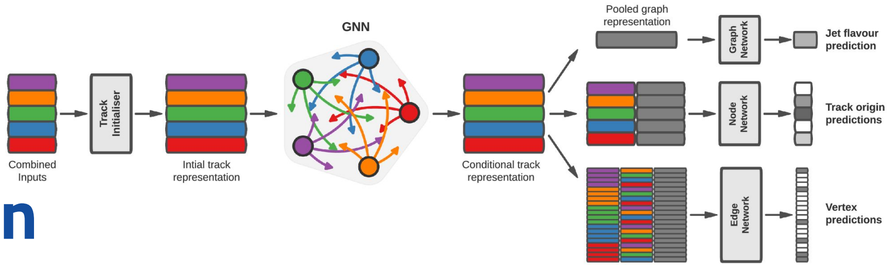
- Discrimination of emerging jets and SM di-jets background ⇒ **Di-jet mass and jet substructure variables, ABCD methods** and a new emerging jets tagger using Graph Neural Networks



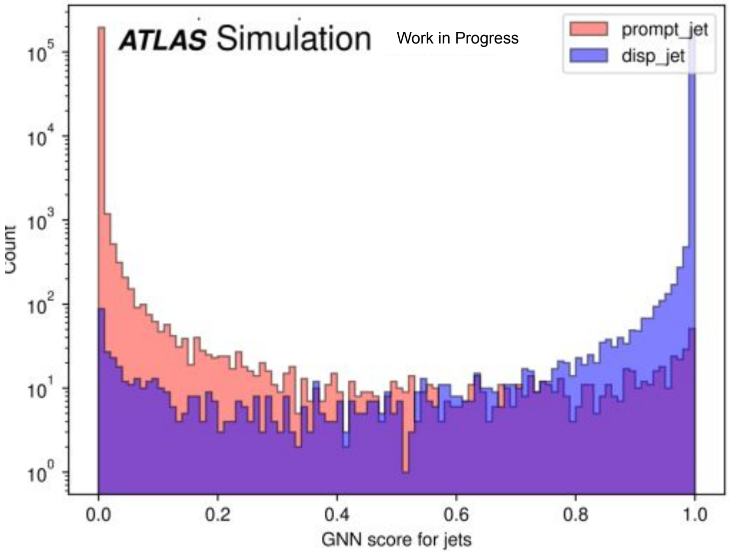


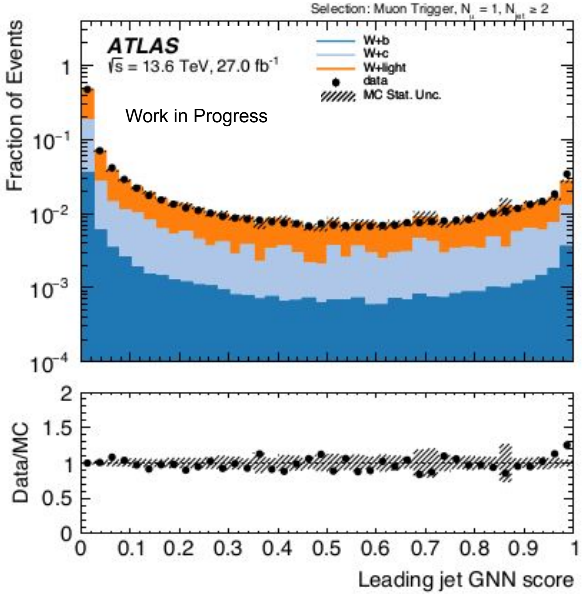
Search for emerging jets

Challenges - Discrimination



- Discrimination of emerging jets and SM di-jets background ⇒ Di-jet mass and jet substructure variables, ABCD methods and a **new emerging jets tagger using Graph Neural Networks**





Conclusions & Next steps

Calibration of hadronic jets using Machine Learning techniques with the ATLAS detector

- Promising results: obtained convergence to reasonable corrections when constraining only energy and rapidity
- GNN seem to learn physical features and physics performance comparable to standard ATLAS calibration
- Limitations in performance are being investigating with more advanced techniques

Dark Quantum Chromodynamics sector and simulation of dark showers

- Overview of existing efforts and of the signature landscape for QCD-like and beyond scenarios
- Improvements to the Pythia Hidden Valley module (motivated by the theory) validated for different viable scenarios with high-level variables

Search for dark matter with a Z' mediator and emerging jets using ATLAS data

- Run-3 early data analysis going strong!
- Finalize trigger strategy and baseline event selection and optimize ABCD plane observables
- Aiming a publication around Moriond 2024

Many thanks!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