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# Object Reconstructions in ATLAS

## Highlights on Latest Developments for LHC Run 3

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NIKHEF - Dutch National Institute for Subatomic Physics

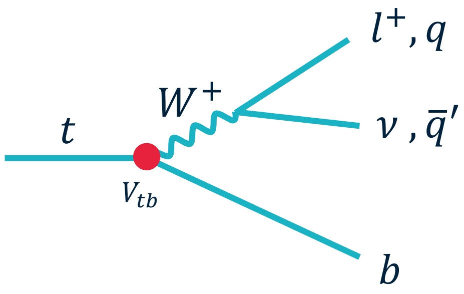
ATLAS EXPERIMENT

NWO

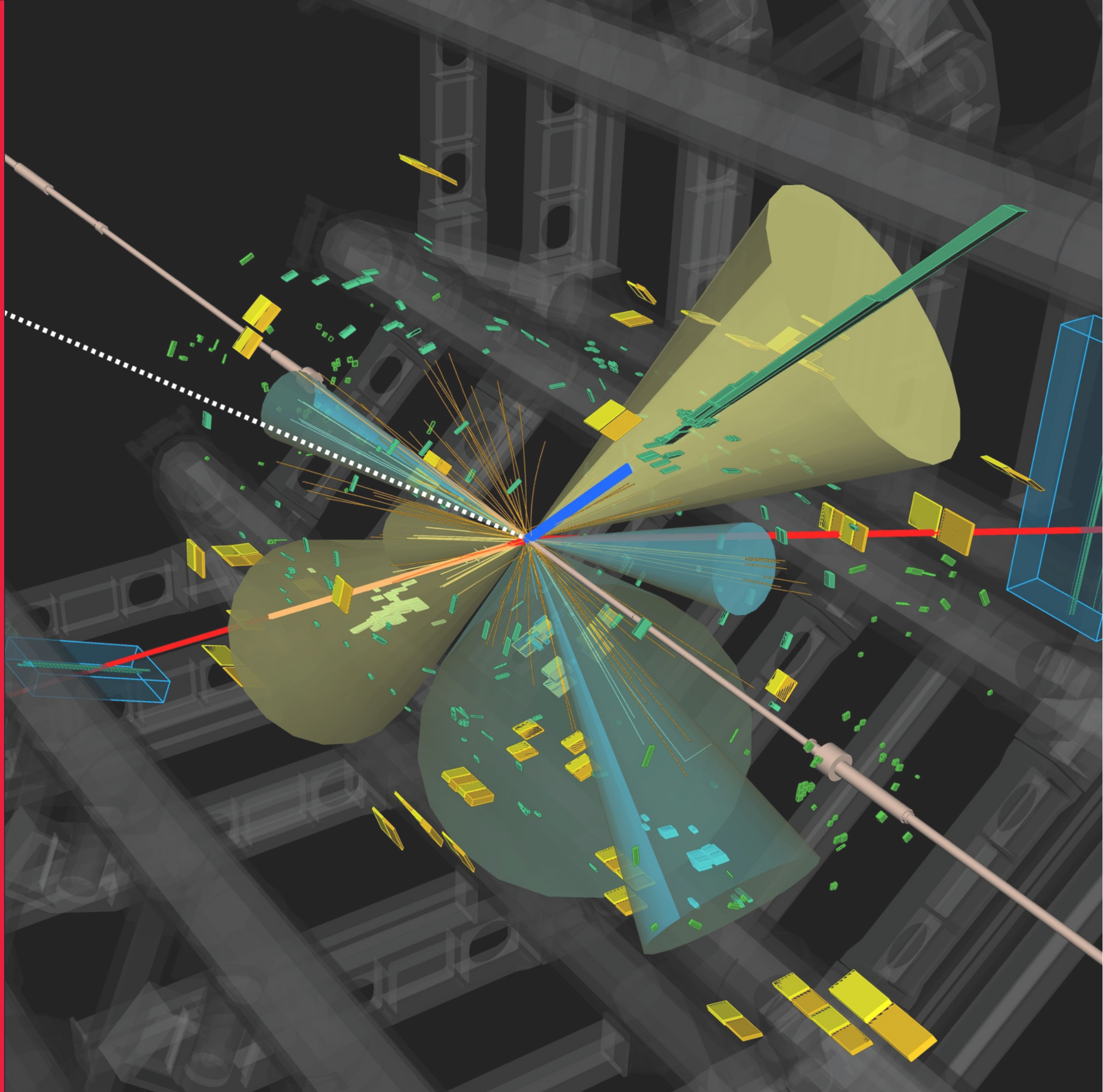
# Introduction

# OBJECT SIGNATURES FOR TOP PHYSICS

- Dominant (99.8%) top-quark decay $t \to W^+b$
  - Topologies dominated by $W$ decay modes



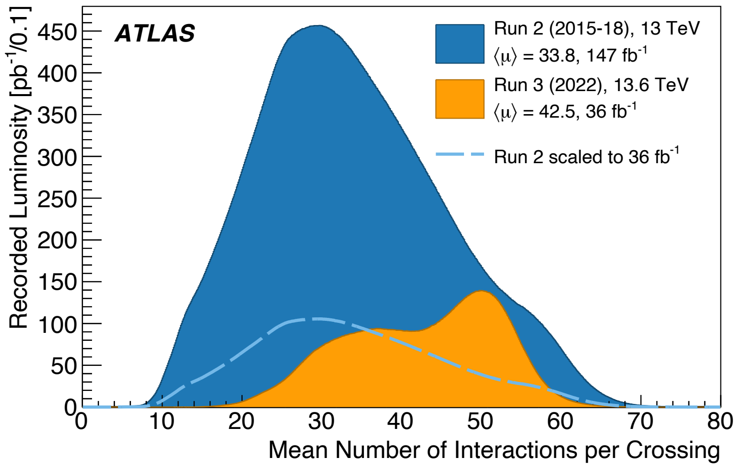

- Nearly all object signatures are important
  - Charged leptons $e^\pm$, $\mu^\pm$ (and $\tau^\pm$)
  - Jets, b-tagged jets and large-R jets
  - Missing energy from neutrinos
  - $\gamma$ in $t\bar{t}\gamma$ / $tq\gamma$ or fakes in multi-lepton channels



Candidate four-top-quark event from data collected by ATLAS in 2016

# RUN 3 UPGRADE

- Significant hardware upgrade during LHC LS2 to enhance trigger capabilities & maintain excellent performance under increased pile-up conditions

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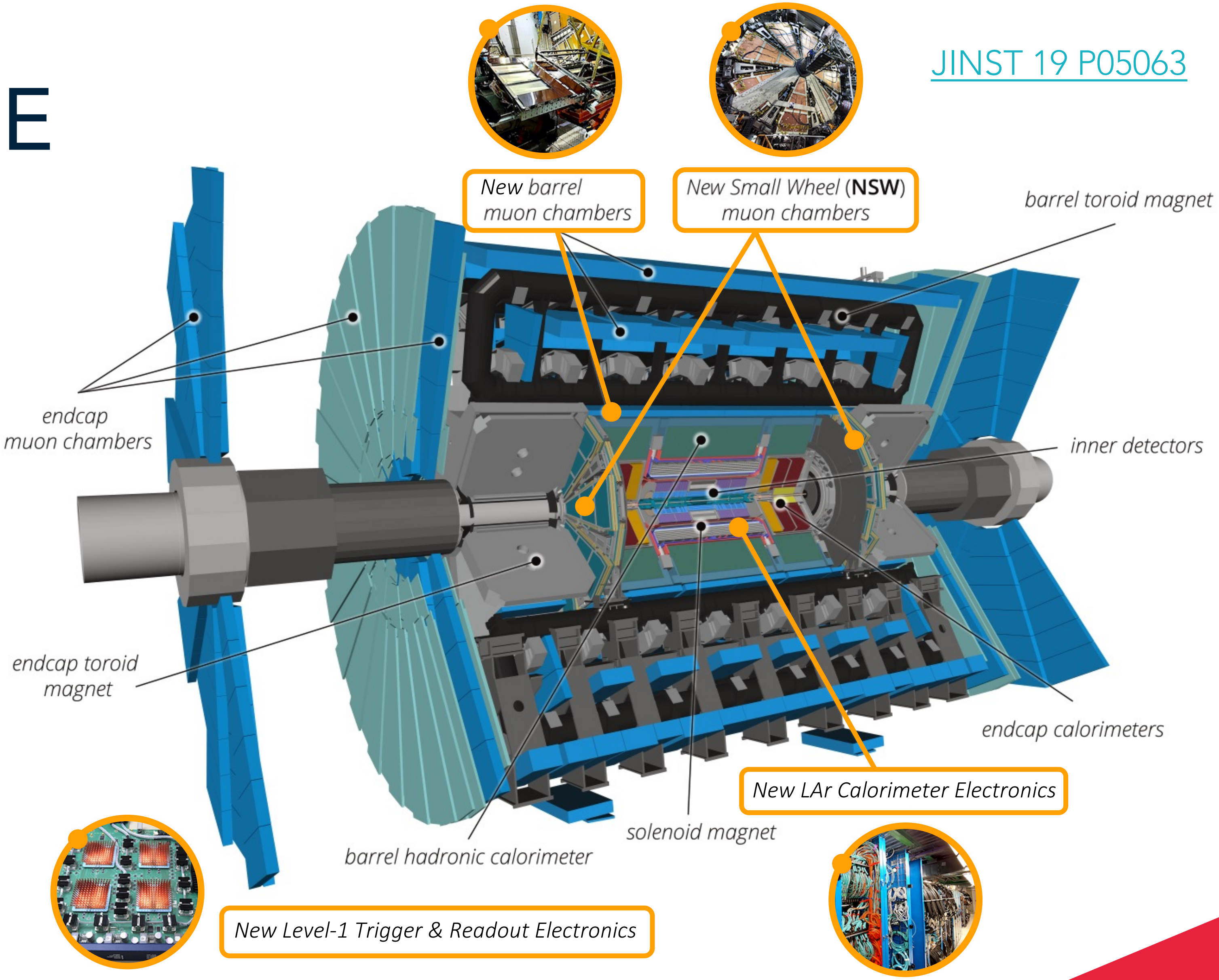

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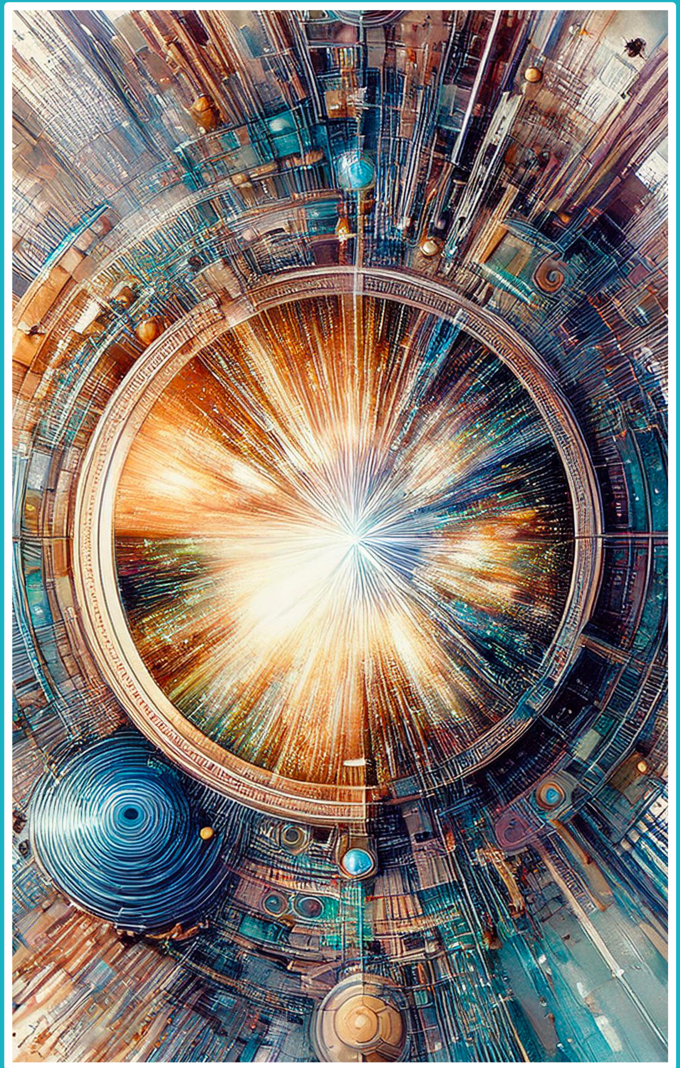
# Inner Tracking & Muon reconstruction

Software & Performance Improvements



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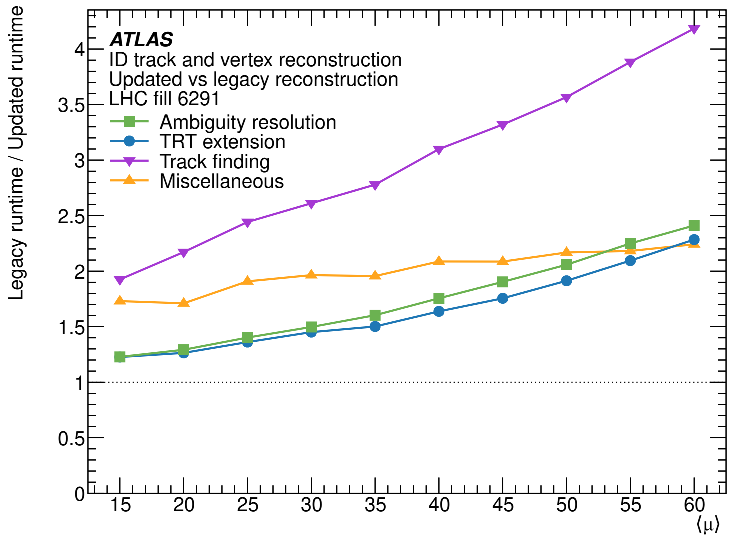
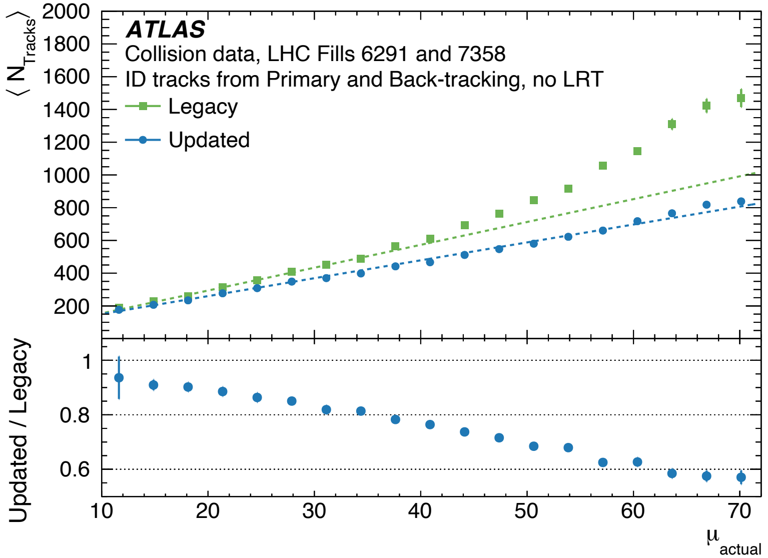
# TRACKING SOFTWARE IMPROVEMENT

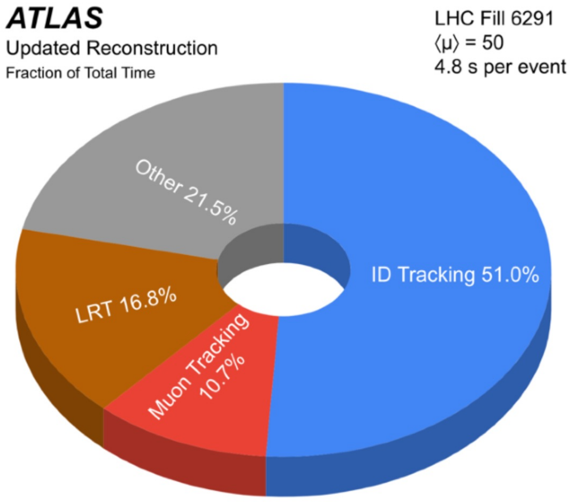
- ATLAS reconstruction software significantly updated
  - Faster decision-making with stricter tolerances and improved algorithms information sharing
  - Early rejection of non-promising tracks and muon candidates
  - Additional large-$d_0$ tracking pass (LRT) for displaced tracks from long-live particle within ID

2-4x faster track reconstruction




Comb. fake tracks reduced by >2x



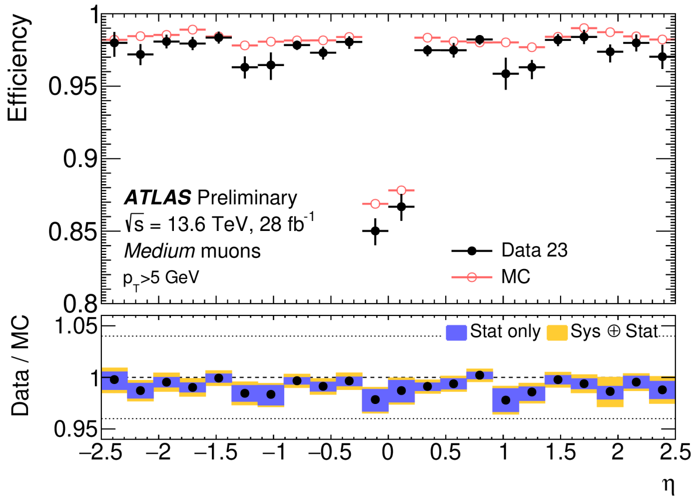



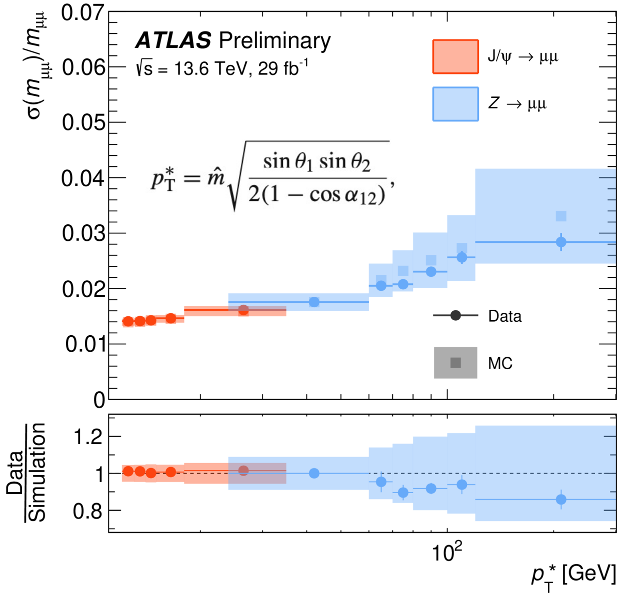
Comput Softw Big Sci 8, 9 (2024) Eur. Phys. J. C 83 (2023) 686 MUON-2023-02

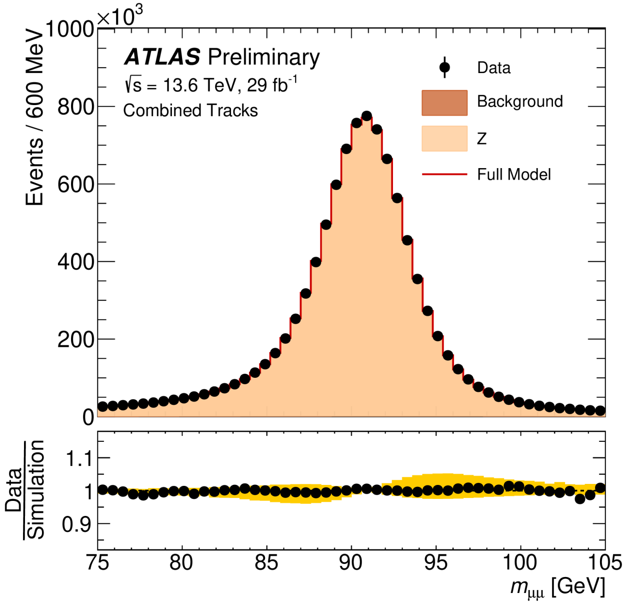
# MUON RECONSTRUCTION & CALIBRATION

- Muons reconstructed separately in ID and MS, where combined tracks (CB) mostly produced
  - Different Isolation WPs determined from prompt resonances ($Z$ or $J/\psi \rightarrow \mu^+\mu^-$), using ID+MS or CB
  - NSW commissioned & included in data tacking with significant eff. improvements measured in 2023
- First calibration on new Run 3 dataset now available
  - Innovative approach correcting charge-dependent momentum bias from detector alignment effects

From $J/\psi \rightarrow \mu^+\mu^-$ events



# Electrons / $\gamma$

Identification, Isolation & Energy Calibration

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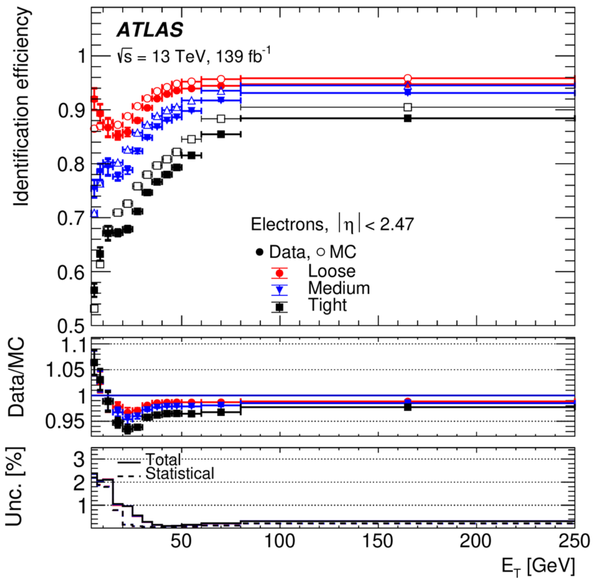
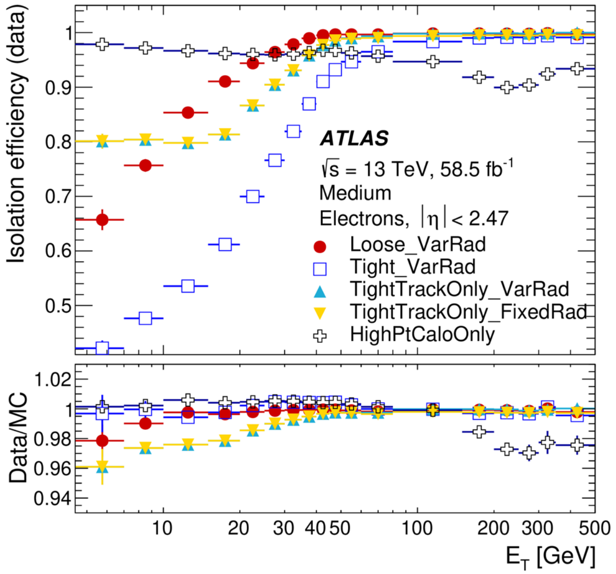
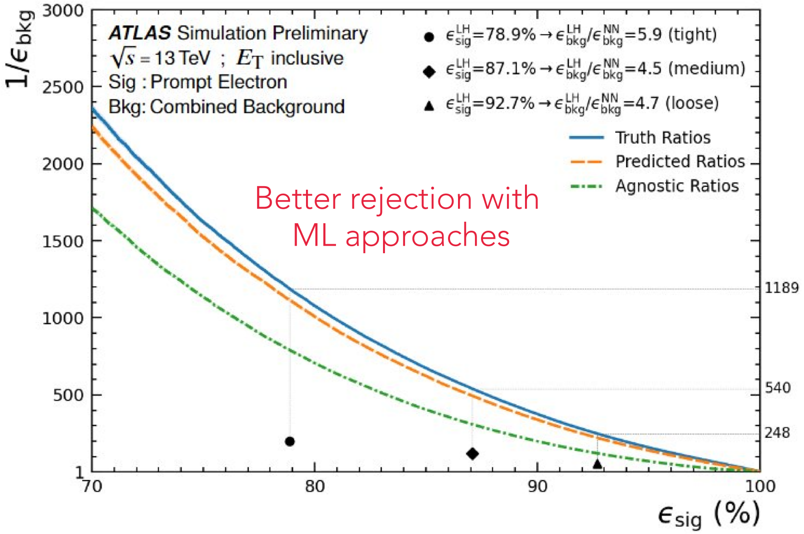
# ELECTRONS / $\gamma$ IDENTIFICATION & ISOLATION

- Identification based on ID and EM Calo. information with high eff. and good bkg rejection
  - Likehood (LH) based approach currently used & exploratory studies on DNN/GNN methods ongoing
- Prescriptions from latest Run 2 precision measurements to benefit to Run 3 analyses
  - Improved approach & more data reduced prompt-electron ($\gamma$) id. Efficiency uncert. by 30-50% (30-40%)
  - Optimizing bkg subtraction, combining measurements & refining pile-up contamination subtraction



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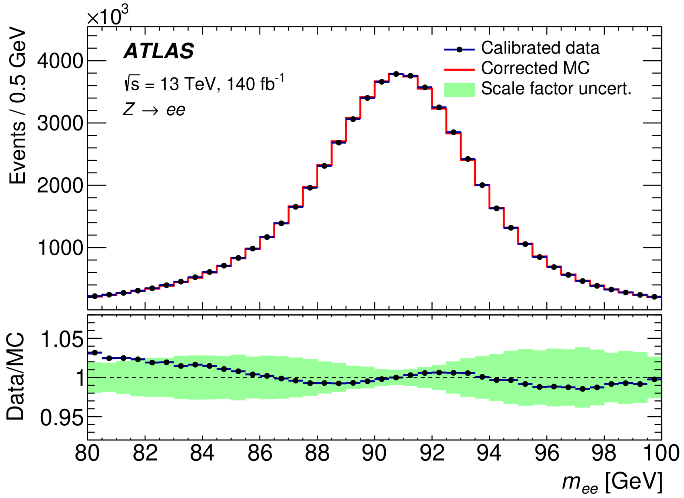
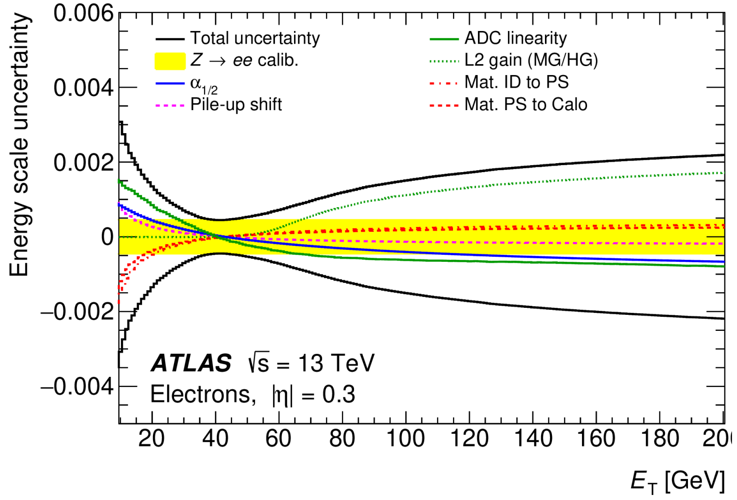
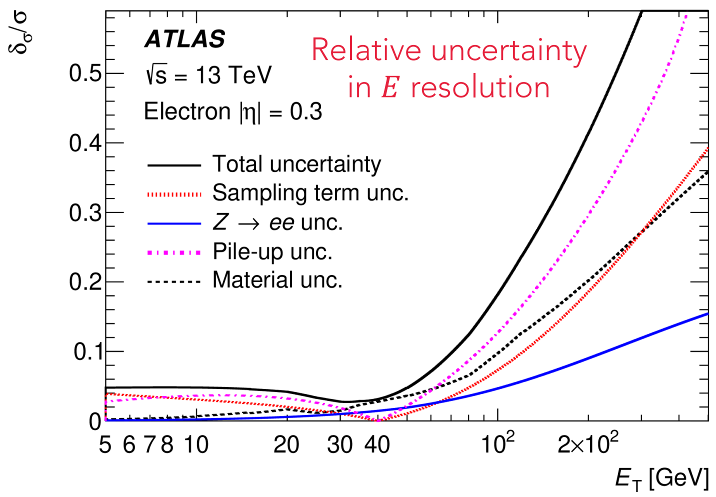
# ELECTRONS / $\gamma$ ENERGY CALIBRATION

- Run 2 legacy precision measurements
  - Re-evaluated uncertainty sources and new methods introduced to reduce their impact
  - Enhanced calo cells / layers calibration, better meas. of lateral energy leakage & energy linearity
  - Overall calibration uncertainty reduced by 2-3x → 0.05% for $e$ at Z peak, 0.2% for $\gamma$ at $E_T$~ 60 GeV
- Run 3 challenge → pile-up uncertainty dominate $E$ res. at $E_T$>100 GeV, will keep increasing

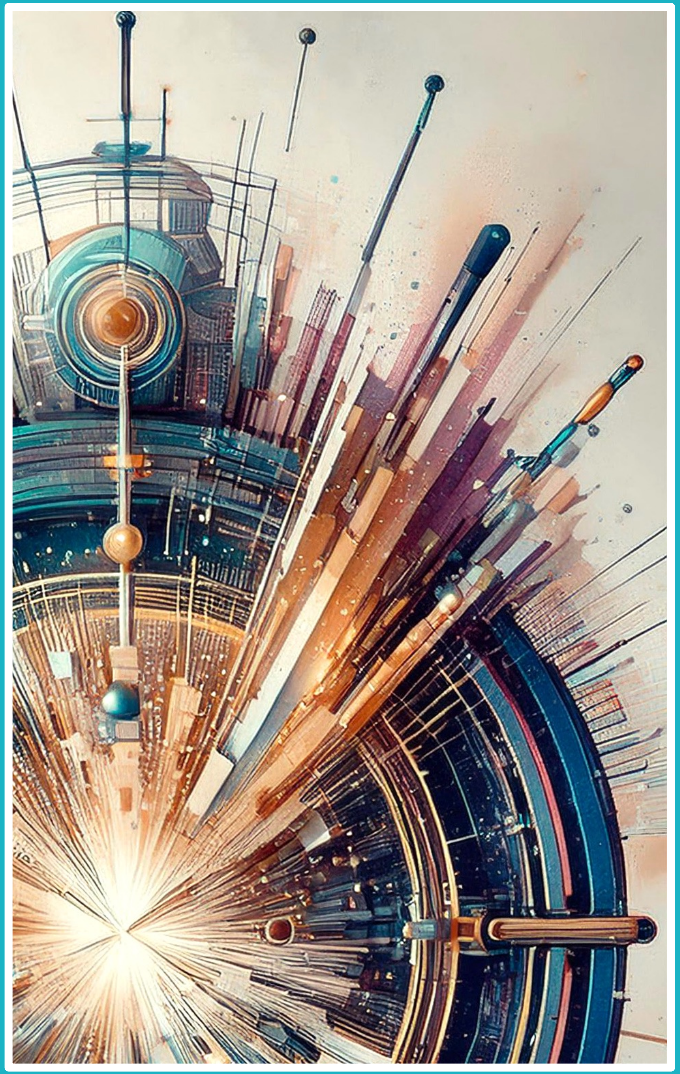


# Hadronic Jets

Reconstruction, Calibration, Flavour-tagging, Large-R jets

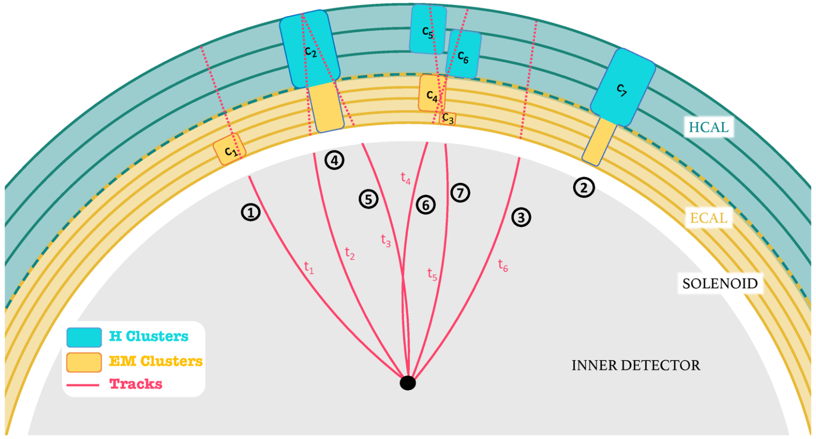


Eur. Phys. J. C 81 (2021) 689 Eur. Phys. J. C 81 (2021) 334 JETM-2023-05

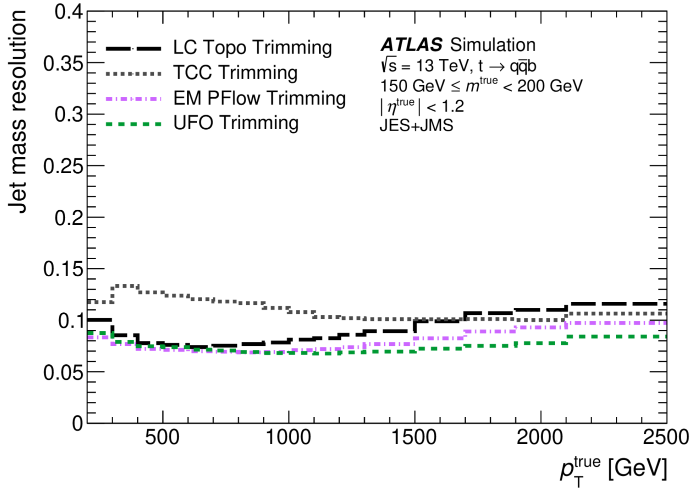
# JET RECONSTRUCTION & CALIBRATION

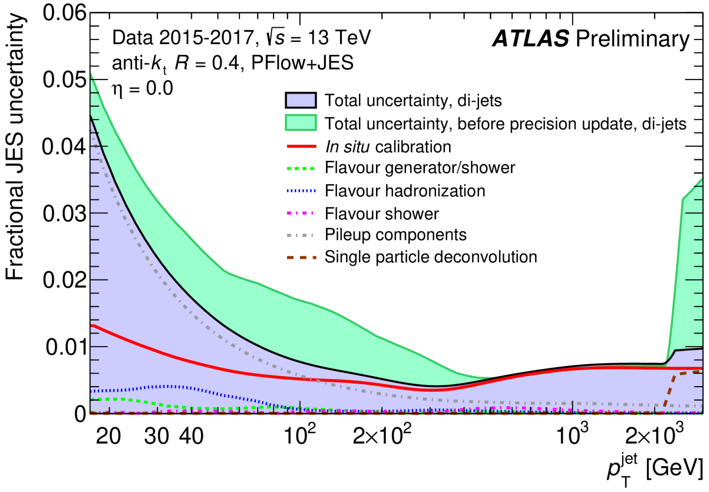
## *IN A NUTSHELL*

- Hadronic jets are clustered using anti-kt algorithm upon
  - **Particle Flow Objects (PFOs)** → Combined track and calorimeter information ☞ Small-R jets (R=0.4)
  - **Unified Flow Objects (UFOs)** → Improved PFOs using track to split up large clusters based on the energy flow and their direction, improving jet mass resolution at high $p_T$ ☞ Large-R jets (R=1.0)
- Jets are calibrated with series of simulation-based corrections & in-situ calibrations
  - Pile-up corrections, jet 4-mom matching to particle-level $E$, reduce flavour dep. / $E$ leakage & residual calib. to data




Examples of track/calo-cluster object creation
ATL-PHYS-PUB-2017-15



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- Hadronic jet
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## First look at new Run 3 dataset

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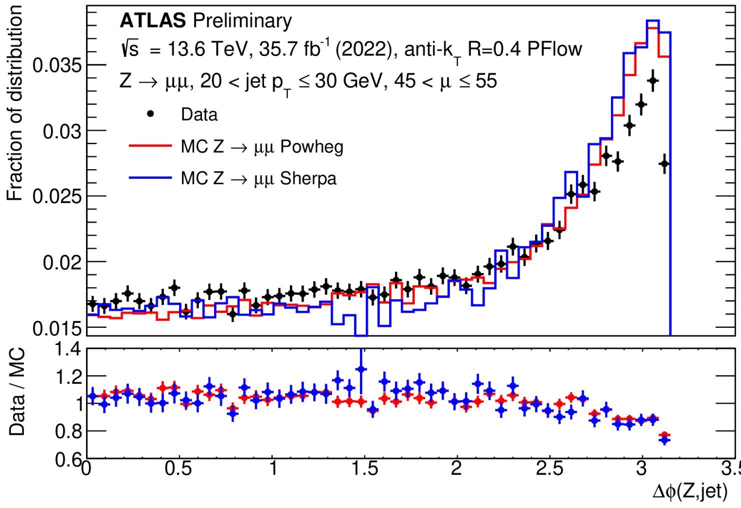
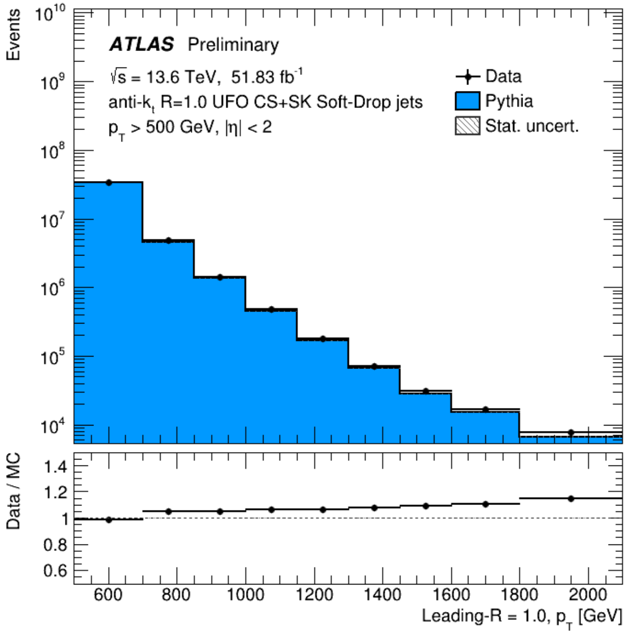
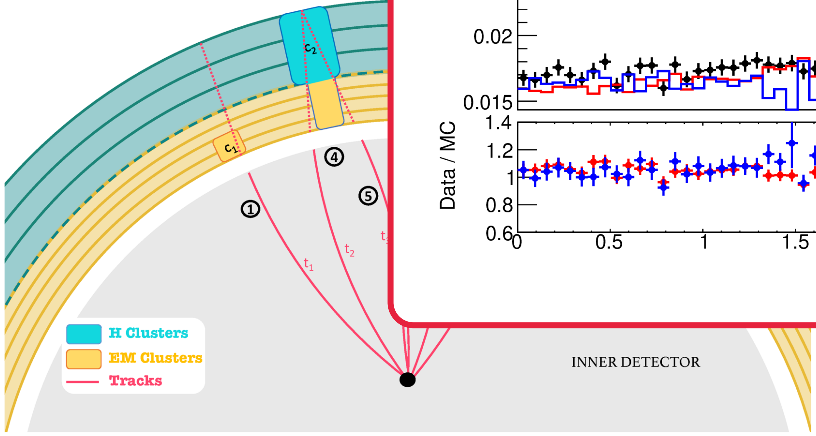
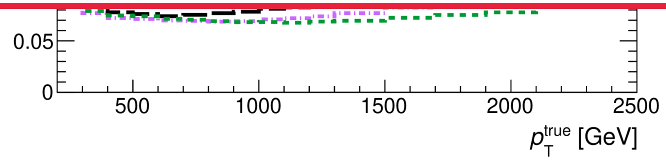


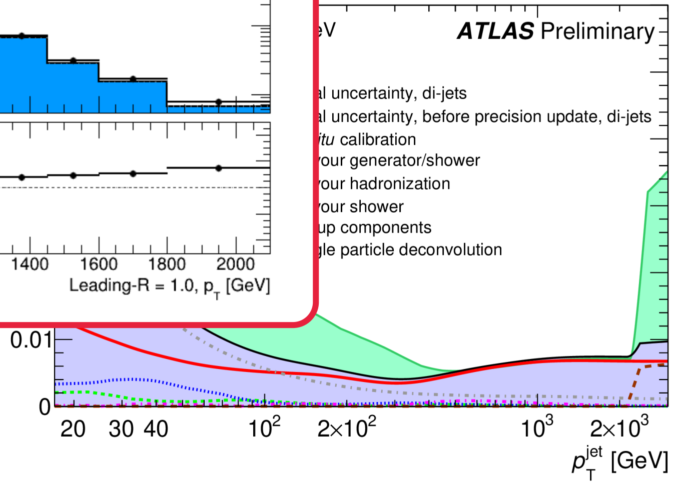




Examples of track/calo-cluster object creation

ATL-PHYS-PUB-2017-15

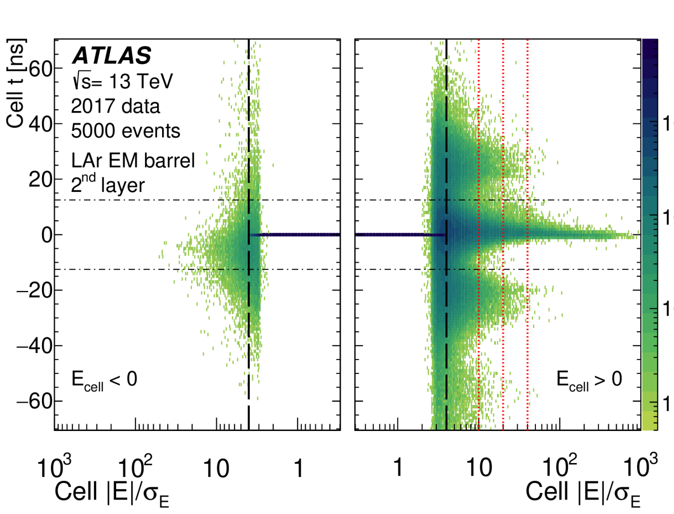


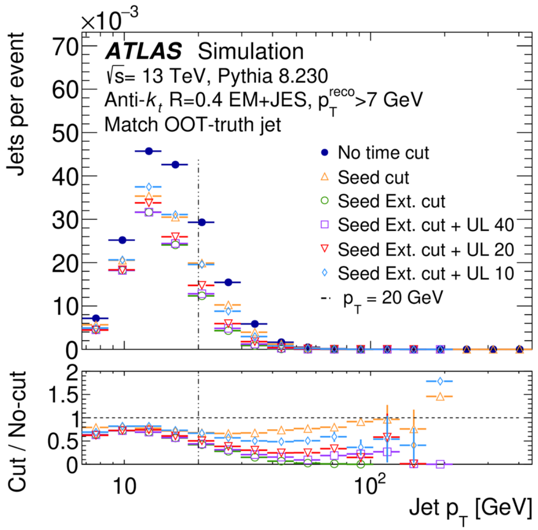



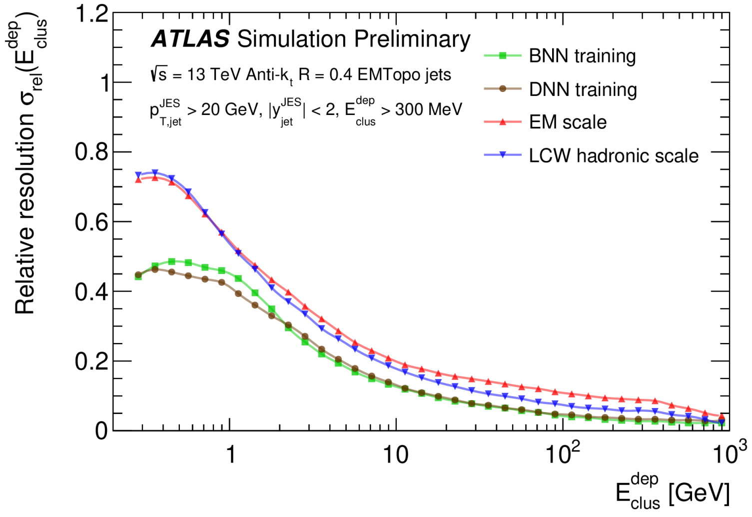
[Eur. Phys. J. C 84 (2024) 455](#) [ATL-PHYS-PUB-2023-019](#)

# IMPROVING CALORIMETER TOPO CLUSTURING

- Topological clustering based on seeding cells of energy significance $|E|/\sigma_E > 4$
- Cell-time selection $|t| < 12.5$ ns now applied to seeding cells
  - Suppress ~60% of out-of-time pile-up jets while retaining in-time signals at $p_T = 20$ GeV
  - Avoid rejecting phase space potentially sensitive to long-lived particles with higher significance
- New calibration based on ML regression techniques competing historical LCW method



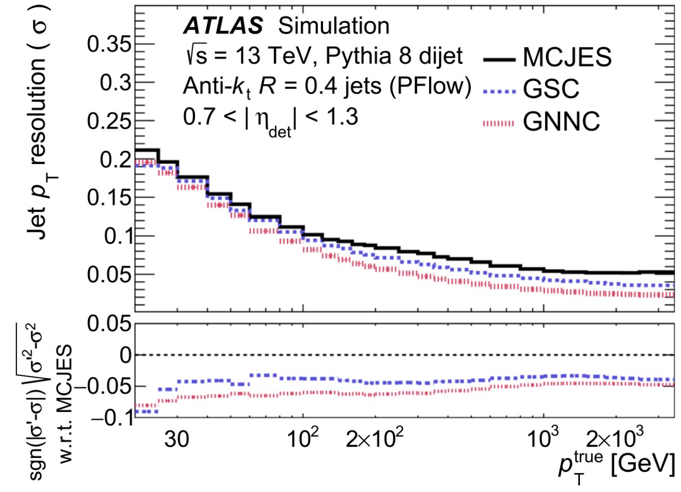

**DNN/BNN**: Deep and Bayesian Neural Network

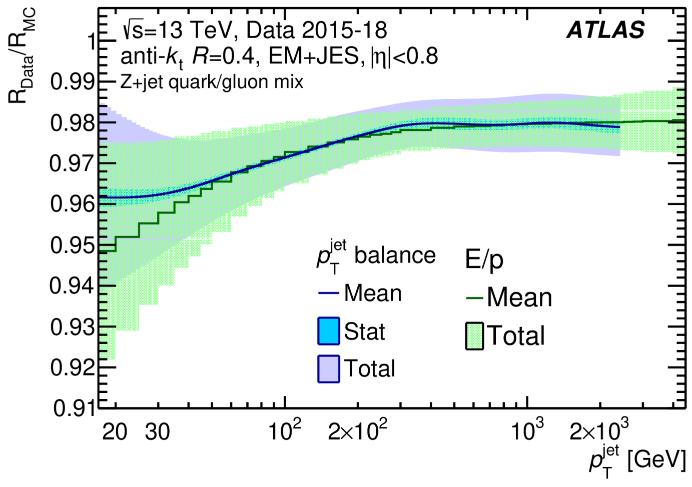
**LCW**: Local hadronic Cell Weighting method

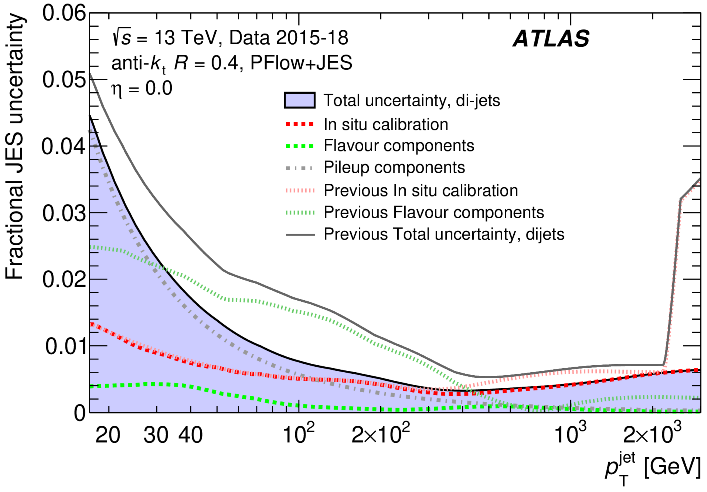
Eur. Phys. J. C 83 (2023) 761 arXiv:2407.15627 ATLAS-PHYS-PUB-2024-015

# PROGRESS IN GLOBAL & IN SITU CALIBRATIONS

- **Global Neural Network Calibration** (GNNC) introduced as an alternative to GSC method
  - DNN learning on correlated jet observables, improving resolution by 15-25% & JES closure at low $p_T$
- **New "E/p" JES in situ calibration from single particle measurements** with $W \to \tau\upsilon$ events
  - Precise measurement by shifting & smearing each jet particle by calorimeter response & uncertainties extended up to $p_T$ = 300 GeV
- **New b-JES calibration based on Transformers** for PFlow and UFO large-R jets
  - Improving $p_T$ resolution by 18-31% for small-R jets & mass/$p_T$ resolutions by 25-35% for large-R jets

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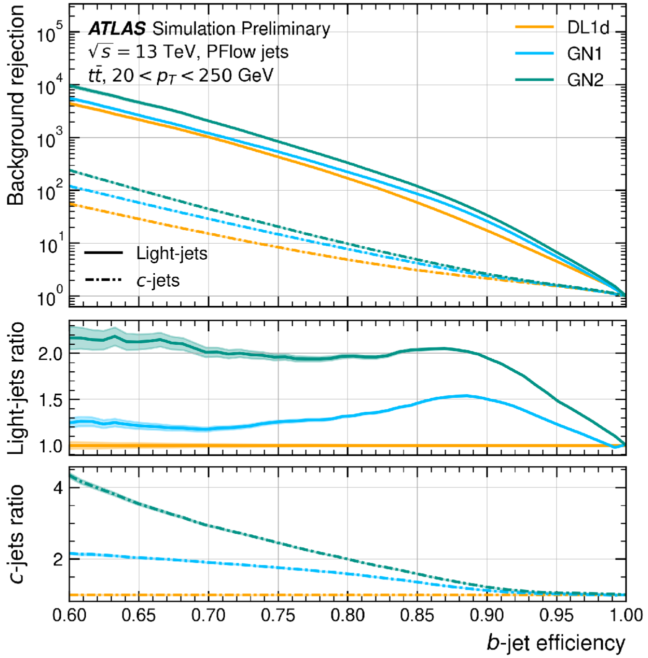
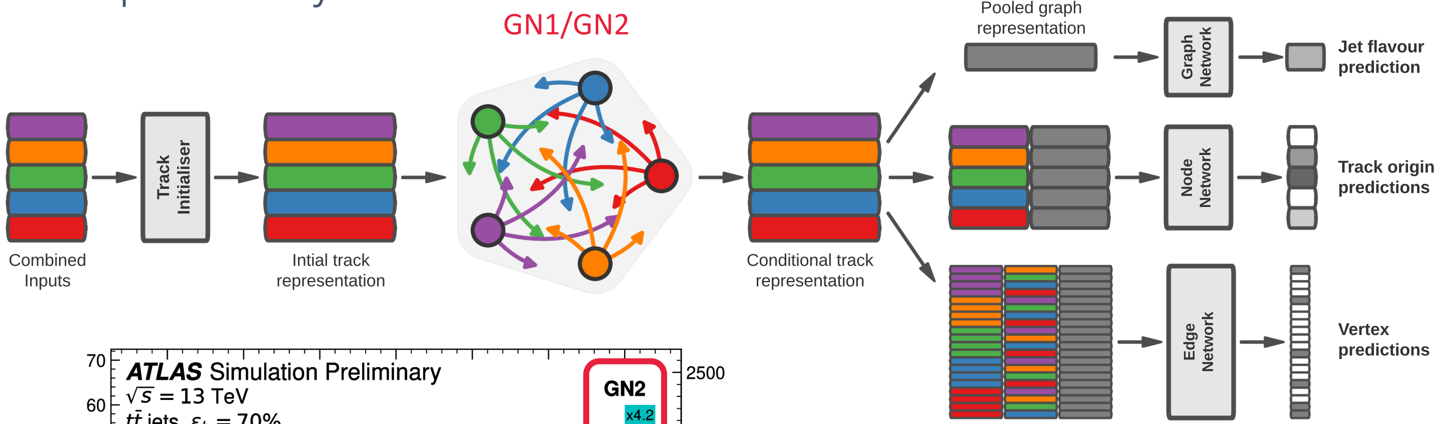
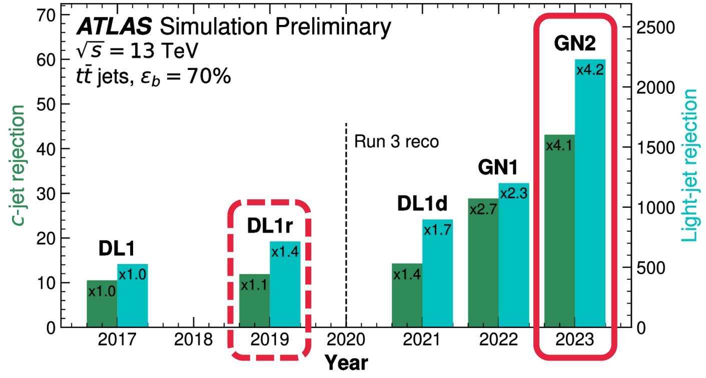
ATL-PHYS-PUB-2022-027

# NEW FLAVOUR-TAGGING PARADIGM FOR RUN 3

- ATLAS experienced profound technological evolutions with novel "GNX" class algorithms
  - Jet flavour, vertexing & track origin task inferred simultaneously using GNN/Transformer networks
  - Improved performance & interpretability



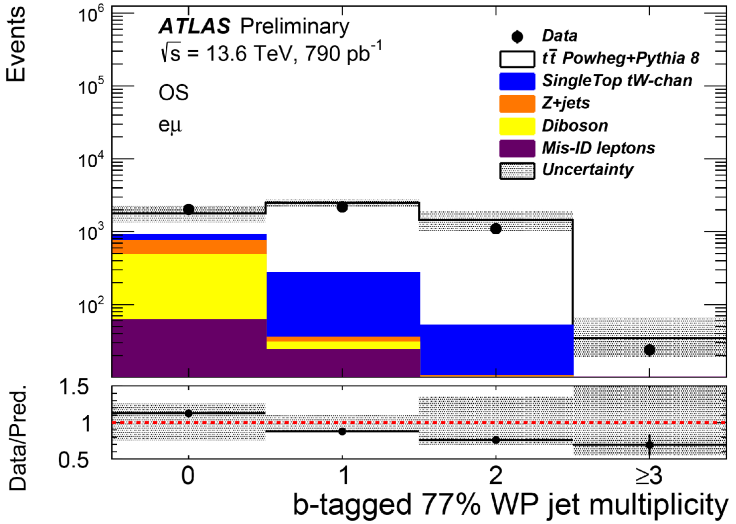

GN2 is an upgraded version of the GN1 tagger, with an improved training procedure, and an optimised Transformer architecture

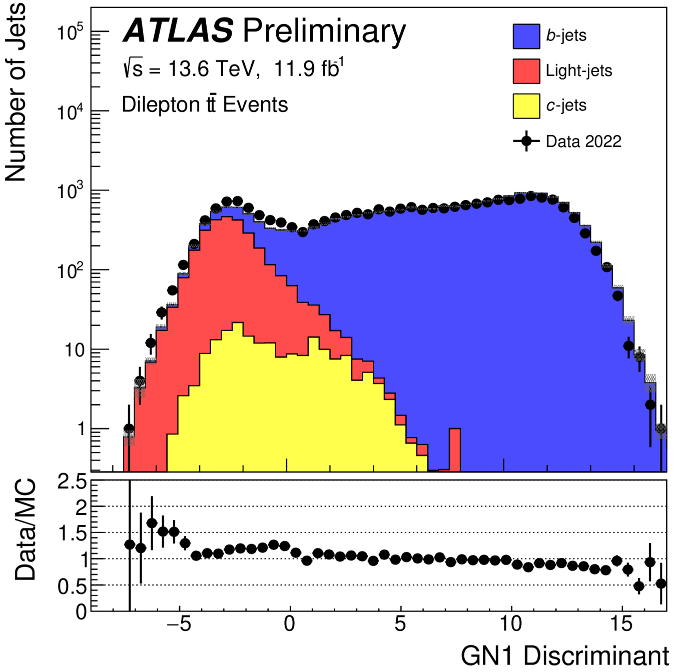
# NEW FLAVOUR-TAGGING PARADIGM FOR RUN 3

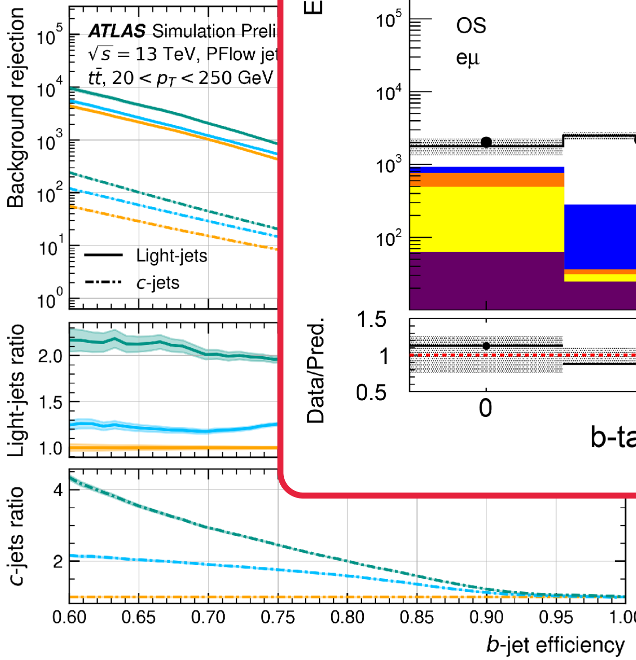
- ATLAS experienced profound technological evolutions with novel "GNX" class algorithms
  - Jet fl… /Transformer networks
  - Impr…

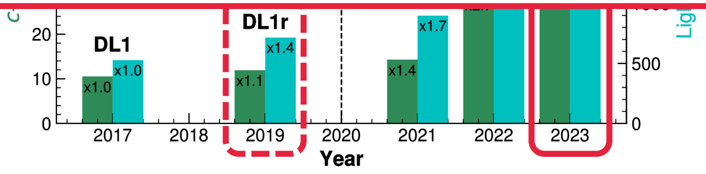
## First look at new Run 3 dataset

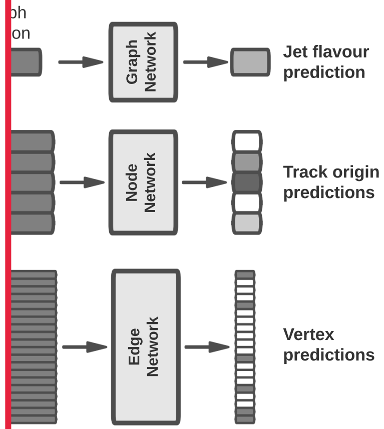
FTAG-2022-003, FTAG-2023-01



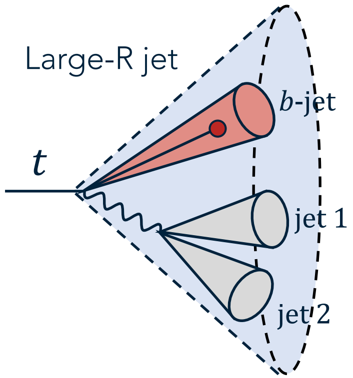



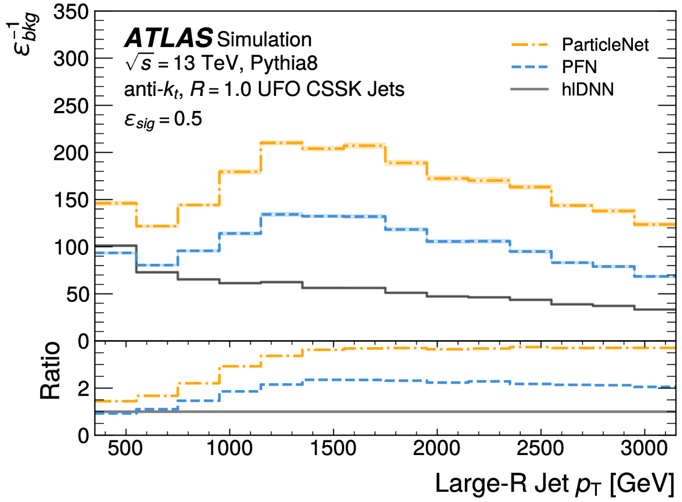

…ded version of the GN1 tagger, with an improved training procedure, and an optimised Transformer architecture

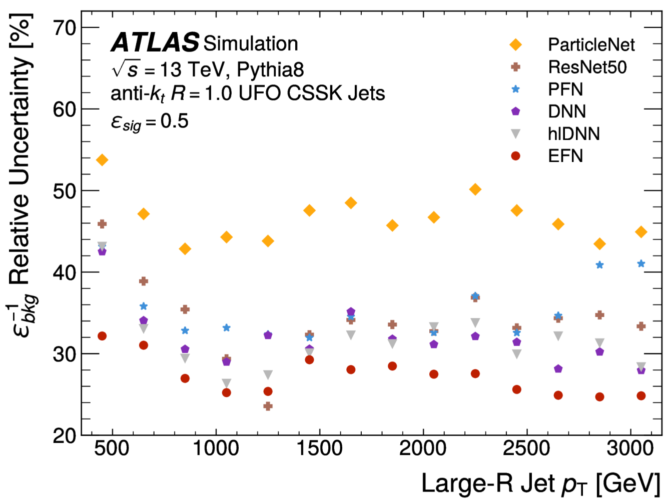
JINST 19 (2024) P08018

# CHALLENGES IN BOOSTED TOP TAGGING

- Identifying top-quark decays in high-$p_T$ regime, essential for SM meas. & BSM searches
- Constituent-based taggers using advanced ML emerged as the most accurate algorithms
  - But significant systematic uncertainties, especially in theoretical modelling, could limit effectiveness
  - Reducing uncertainties without compromising performance is a key research direction at Run 3




**ParticleNet**: GNN algorithm

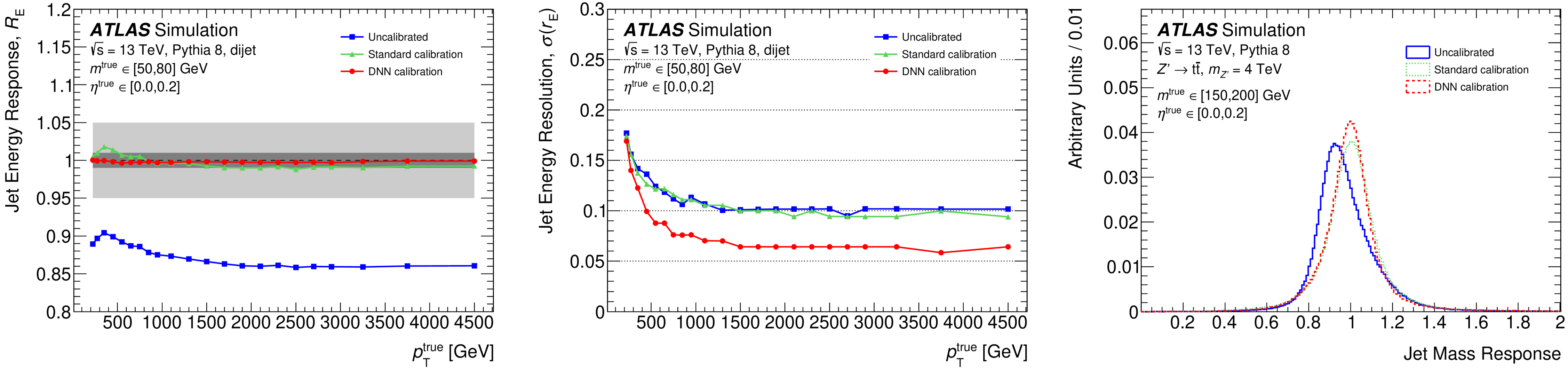
**PFN**: DeepSets-based Particle Flow Network algorithm

**hlDNN**: DNN algorithm learning from high-level jet constituent kinematics

Mach. Learn. Sci. Technol. 5 035051 (2024)

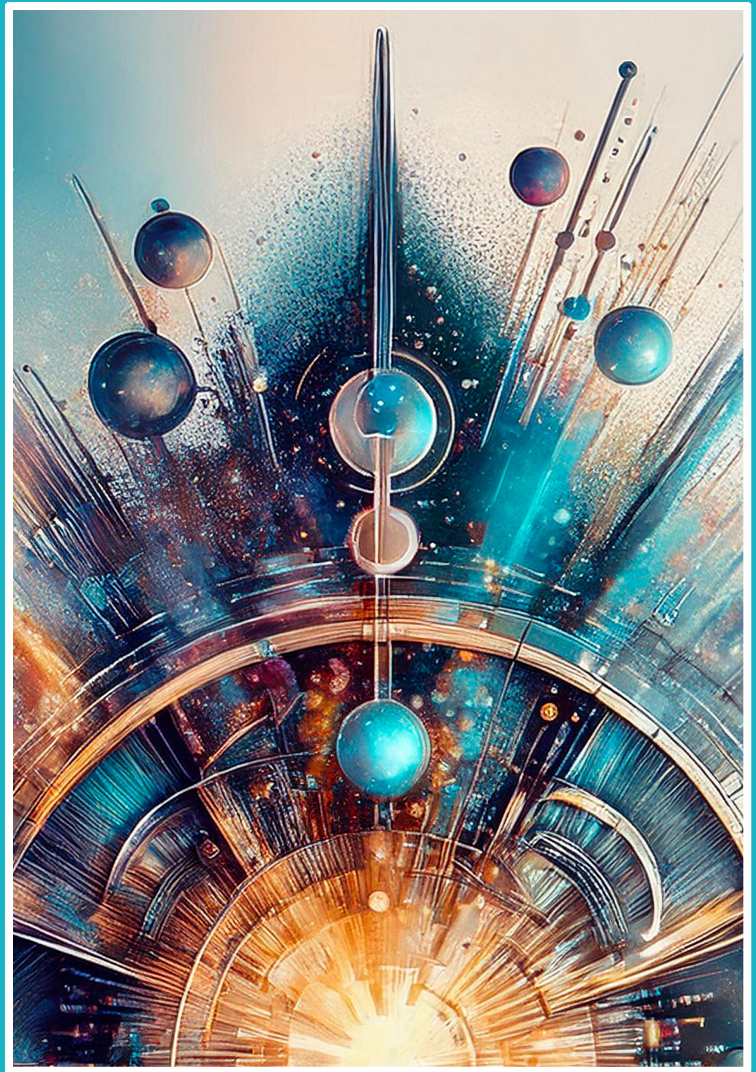
# NOVEL DNN-BASED LARGE-R JETS CALIBRATION

- New joint energy and mass calibration of UFO large-R jets
  - Innovative single-correction-step approach exploiting all shower observables and correlations
  - JER closer to unity & resolution significantly improved compared to standard calibration
  - Jet-mass response for boosted W/Z, H, top also improved



# Miscellaneous

Missing Energy & Tau Leptons

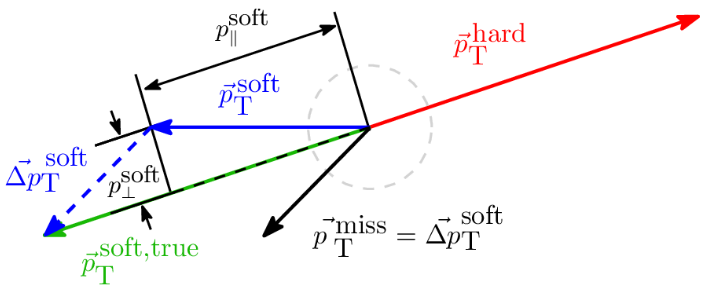


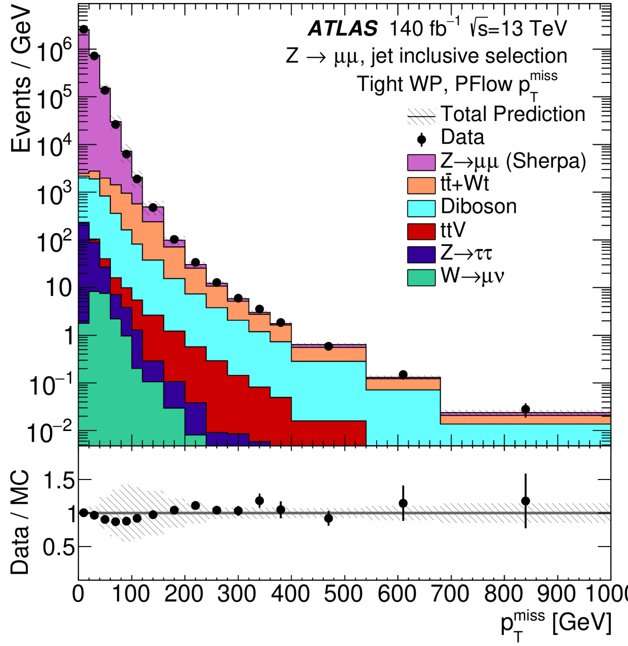
arXiv:2402.05858

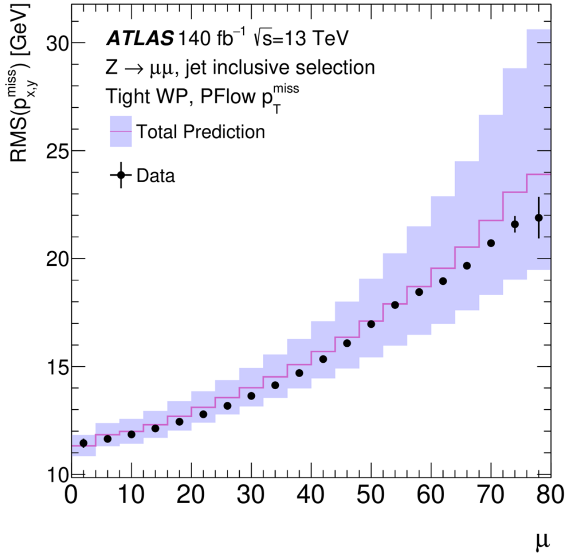
# MISSING TRANSVERSE MOMENTUM RECONSTRUCTION

- Complex reconstruction task well understood & reliable modelling by simulation
  - Double momentum counting avoided with signal ambiguity resolution procedure
  - Managing high pile-up conditions impact, with recent 30% improvement of $p_T^{miss}$ resolution
  - Soft-term scale and resolution uncertainties reduced by 76% and 51%, respectively

$$\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}} = -\left| \underbrace{\sum_{\substack{\text{selected}\\ \text{electrons}}} \boldsymbol{p}_{\mathrm{T}}^{e} + \sum_{\substack{\text{accepted}\\ \text{photons}}} \boldsymbol{p}_{\mathrm{T}}^{\gamma} + \sum_{\substack{\text{accepted}\\ \tau-\text{leptons}}} \boldsymbol{p}_{\mathrm{T}}^{\tau} + \sum_{\substack{\text{selected}\\ \mu}} \boldsymbol{p}_{\mathrm{T}}^{\mu} + \sum_{\substack{\text{accepted}\\ \text{jets}}} \boldsymbol{p}_{\mathrm{T}}^{\text{jet}}}_{\text{hard term}} + \underbrace{\sum_{\substack{\text{unused}\\ \text{tracks}}} \boldsymbol{p}_{\mathrm{T}}^{\text{track}}}_{\text{soft term}} \right|$$



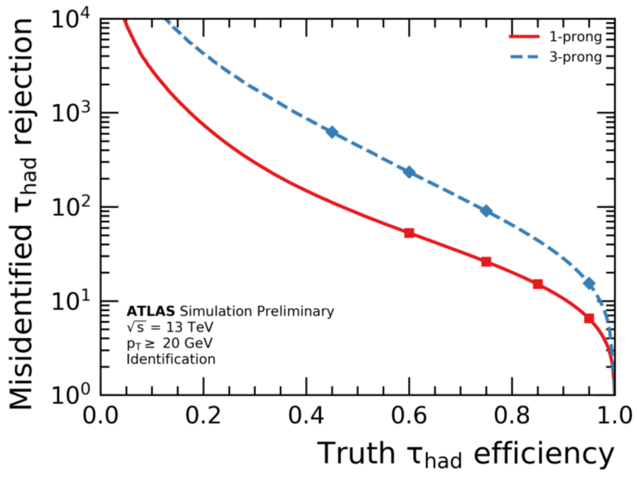



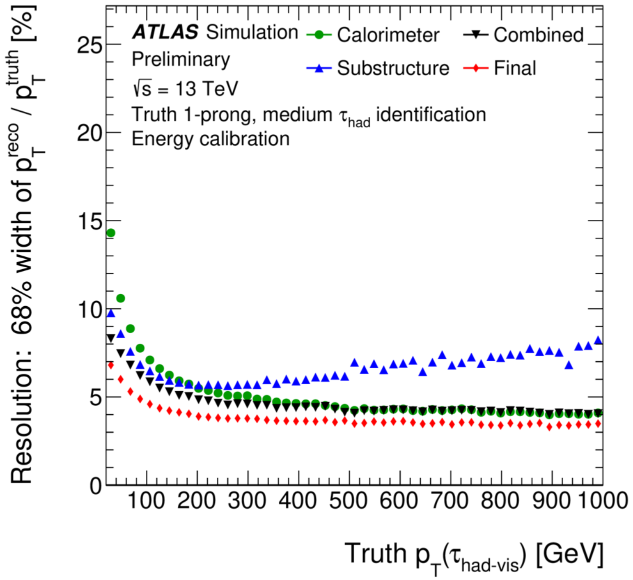



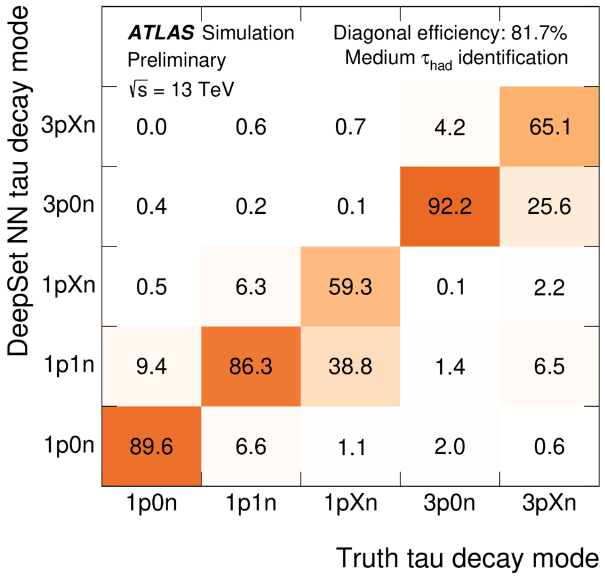
ATLAS-PHYS-PUB-2022-044

# ML FOR $\tau$ RECONSTRUCTION AT RUN 3

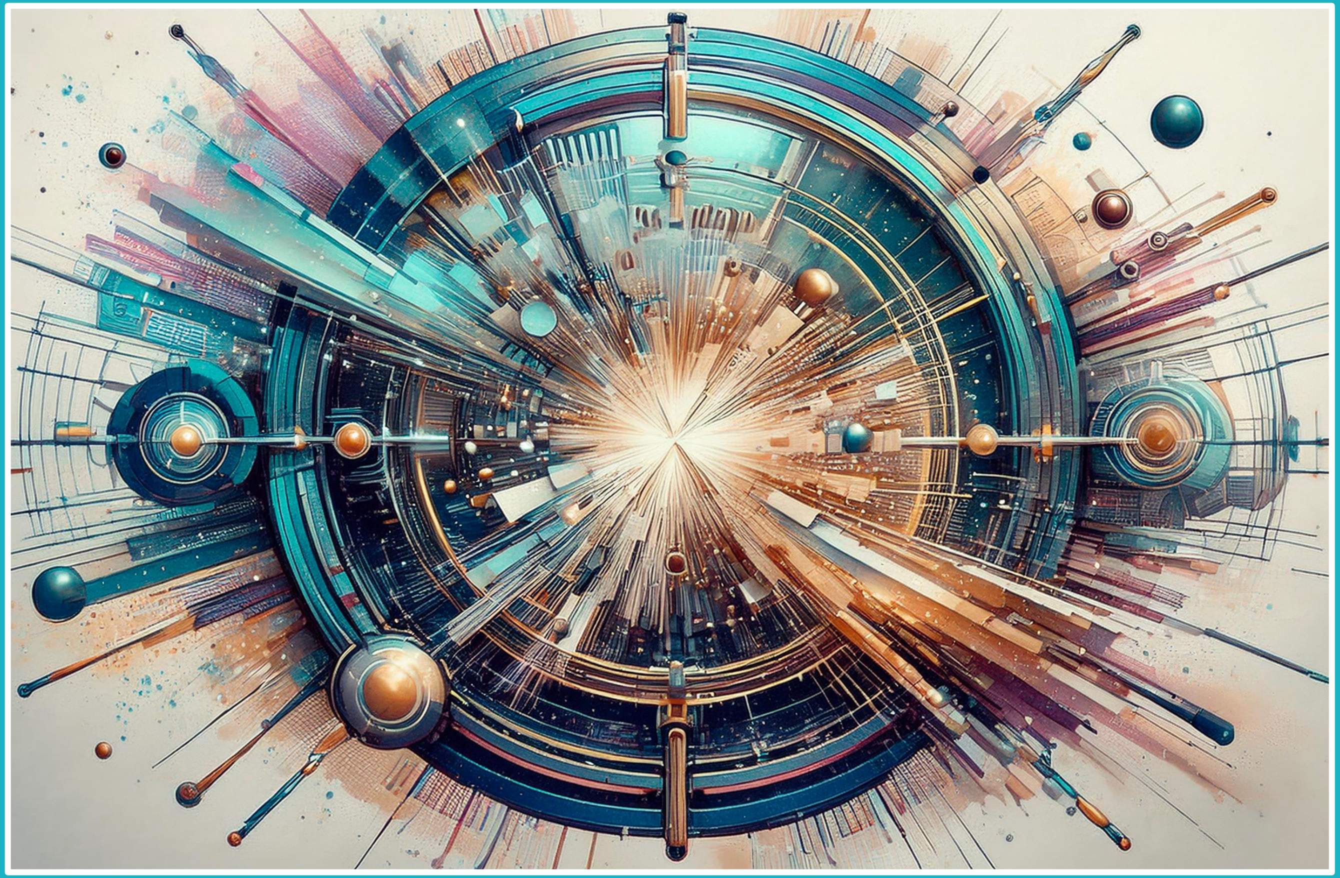
- New ML algorithms series aiming at reconstructing, identifying & calibrating hadronic $\tau$ decays
  - Reconstruction, identification & electron rejection algorithm employ RNN
  - Energy calibration based on BRT combining calorimetric energy & tracking momentum information
  - Decay mode class. algorithms based on DeepSets to differentiate between 5 $\tau$ decay topologies



# Conclusions



# CONCLUSIONS

- Significant advancements across all combined-performance sectors for Run 3
  - Enhanced reconstruction algorithms with advanced ML techniques playing a critical role
  - Legacy Run 2 precision provides a robust and stable framework for efficiency measurements
  - Expected boost in sensitivity for a wide range of top-physics analyses
- Focused efforts on pile-up mitigation in the challenging Run 3 environment
  - Hardware upgrades including new Level-1 trigger system & NSW integration for muons
  - Introduction of innovative techniques to reduce pile-up contamination
- Promising preliminary results from the first Run 3 datasets
  - Ongoing commissioning of Run 2 reconstruction and calibration methods
  - Extensive collaboration-wide contributions to ensure precision measurement readiness

Thank you for your attention