Performance: Jet/MET and b/c tagging

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On behalf of ALICE, ATLAS and CMS Collaboration

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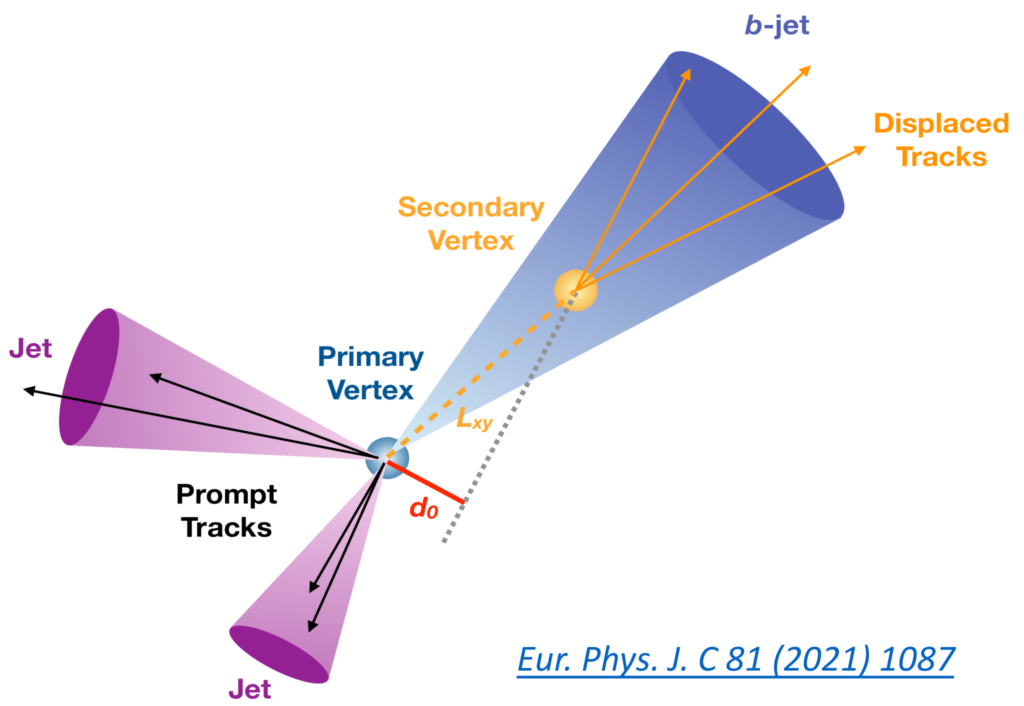
Flavour-tagging performance

- Many measurements at the LHC require efficient identification of heavy-flavour jets, i.e. jets originating from bottom (b) or charm (c) quarks
- Properties of heavy hadron originated from b/c quarks
  - b-quarks have sizeable lifetime
    $c\tau$ ~ 500um → $\beta\gamma c\tau$ ~ 5mm @ 50 GeV
  - The b quark, and then the B-hadrons, have a large mass (~5 GeV)
  - Larger number of charged particles (tracks)
  - A large fraction of the original b-quark momentum is carried by the B-hadron
  - The weak b-decay often produces leptons



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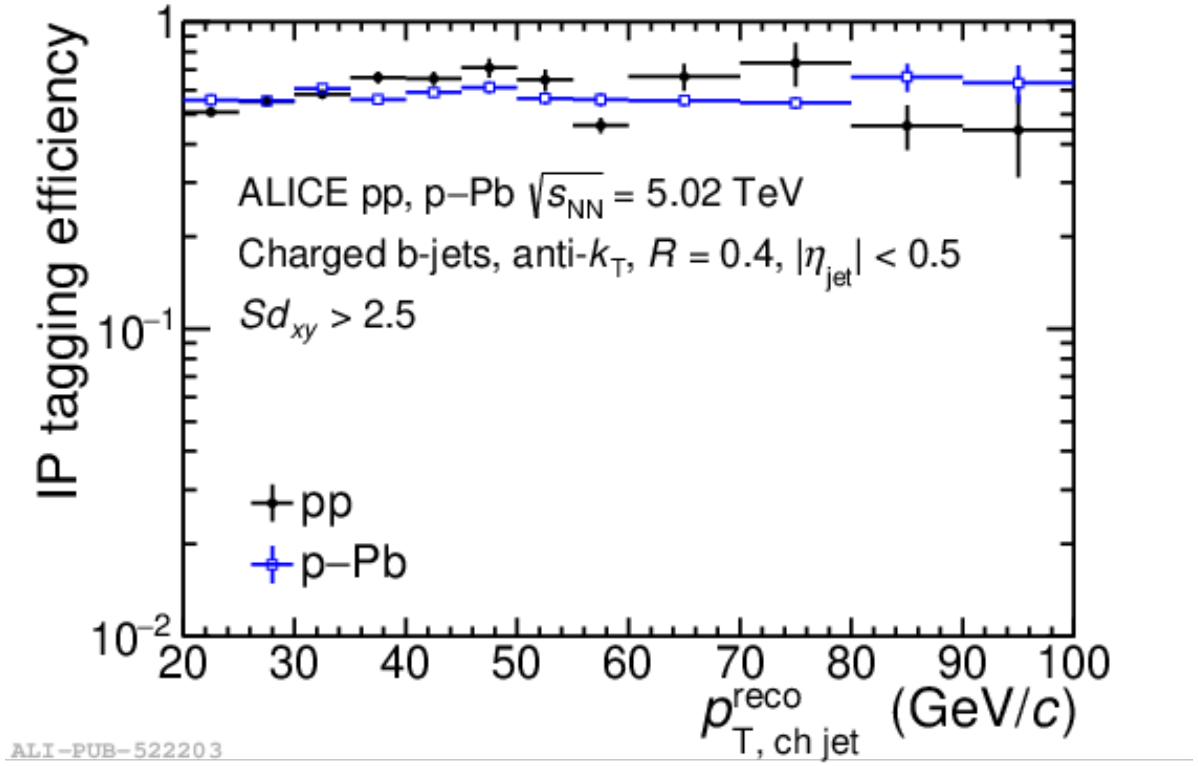
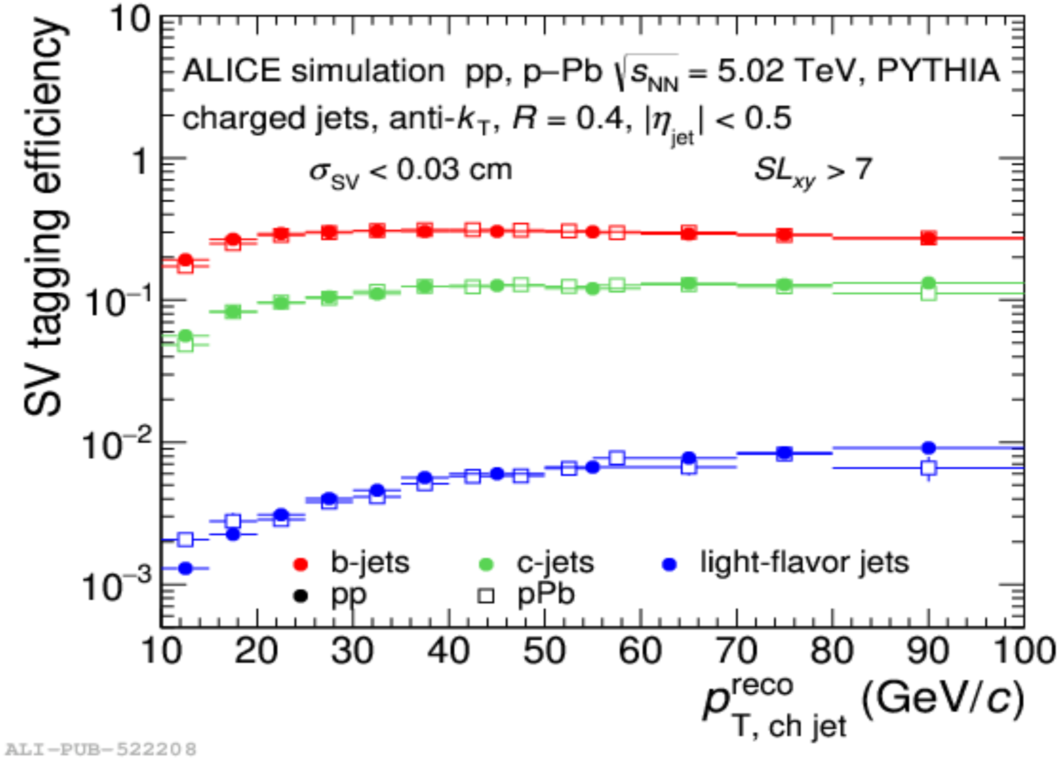
- Flavour tagging relies on a variety of track related observables:
  Impact parameter of tracks, secondary vertices, tracks associated to jets, properties of several charged and neutral jet constituents etc
- Machine Learning techniques are used to combine them into a classifiers

b-jet tagging performance in ALICE

- ALICE supports anti-k_T R=0.4 jets

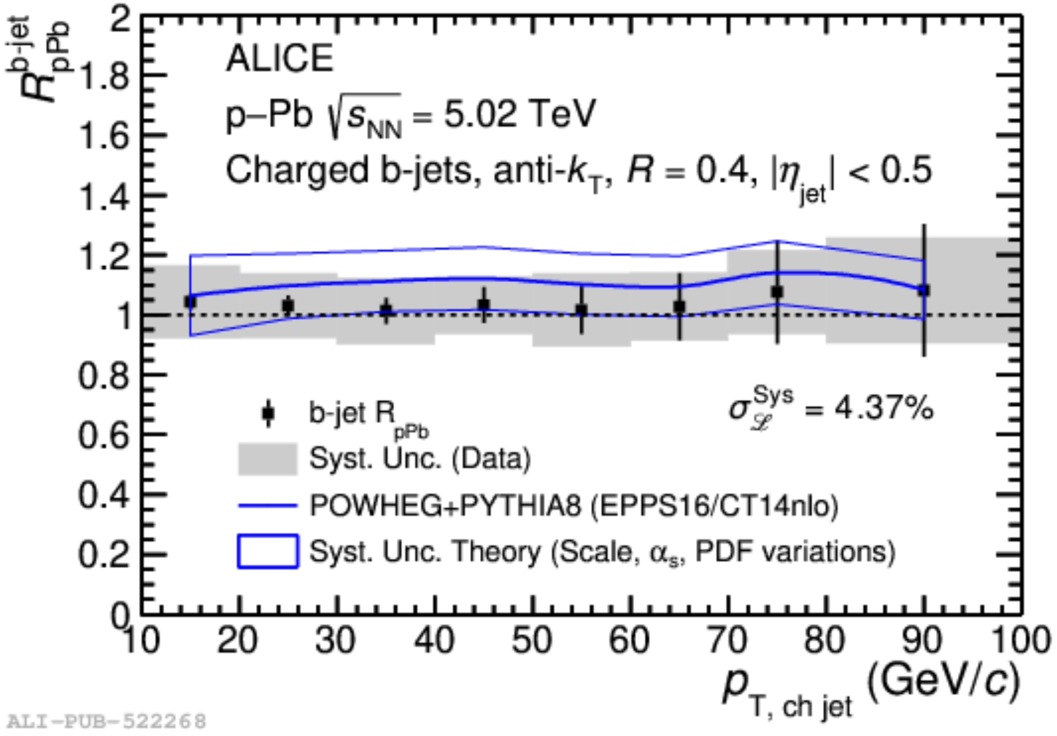


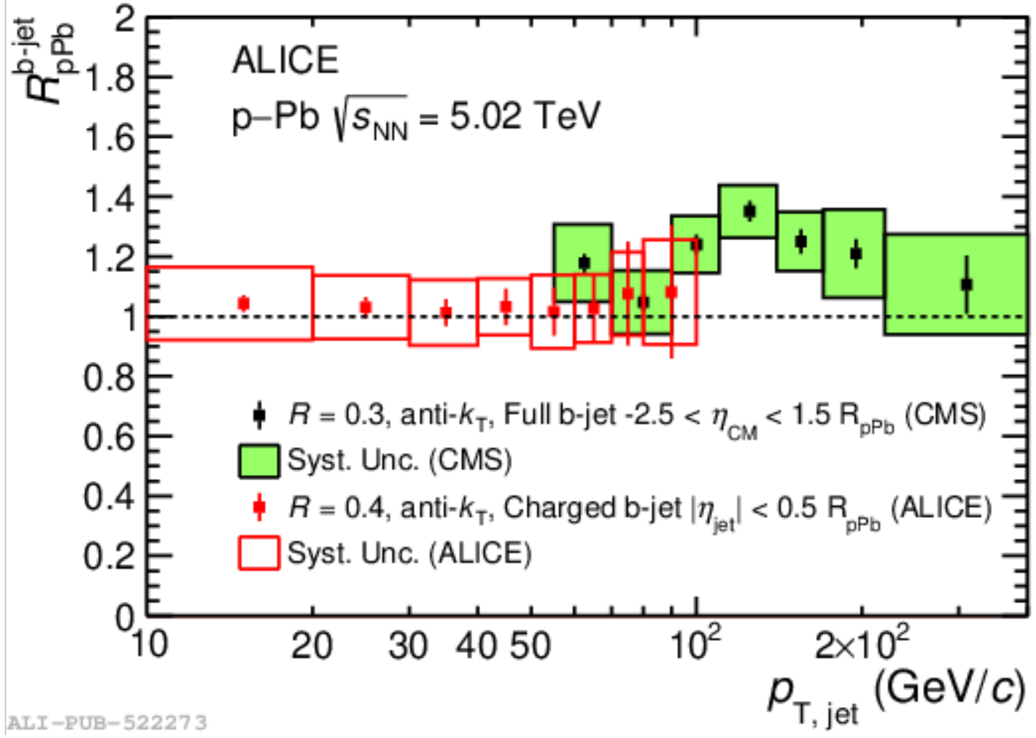


- **Measurement of inclusive charged-particle b-jet production in pp and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV**
  [JHEP 01 (2022) 178]

b-jet tagging performance in ALICE

- The analysis extends the lower p_T limit of b-jet measurements at the LHC.
- The nuclear modification factor is found to be consistent with unity, indicating that the production of b jets in p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV is not affected by cold nuclear matter effects within the current precision.
- The measurements are well reproduced by POWHEG NLO pQCD calculations with PYTHIA fragmentation.



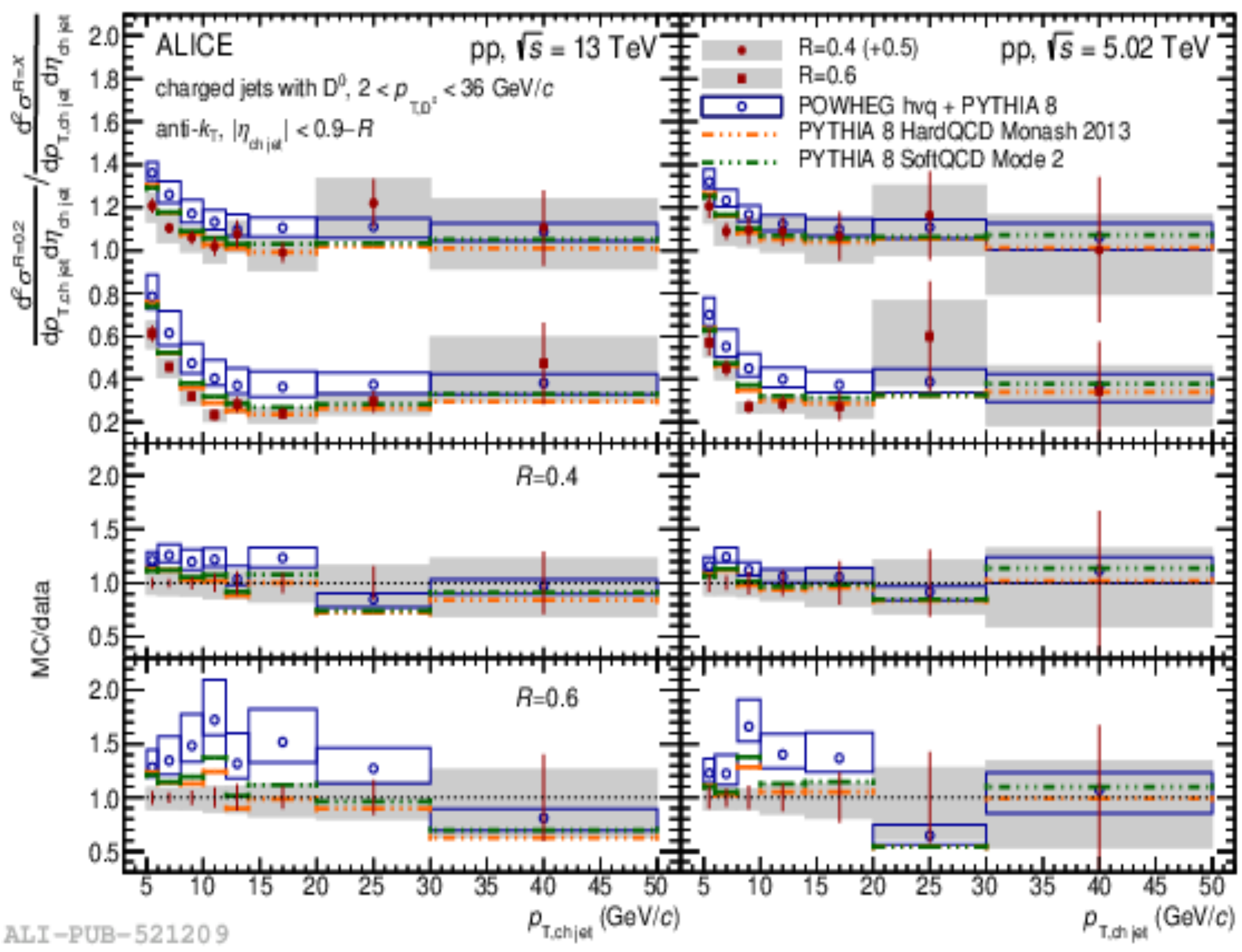


charm tagging in D_0 mesons in ALICE

- A comparison of D_0 jets with different resolution parameters can help in exploring the shower development. It provides insights into the interplay between perturbative and non-perturbative effects.

- The ratios of $p_{T,chjet}$ differential cross sections of D_0 jets reconstructed with resolution parameter R = 0.2 with respect to R = 0.4 and 0.6 for collision energies at √s = 13 TeV (left) and √s = 5.02 TeV (right).

- **Measurement of the production of charm jets tagged with D_0 mesons in pp collisions at √s = 5.02 and 13 TeV** [arXiv:2204.10167 (Submitted to JHEP)](arXiv:2204.10167)

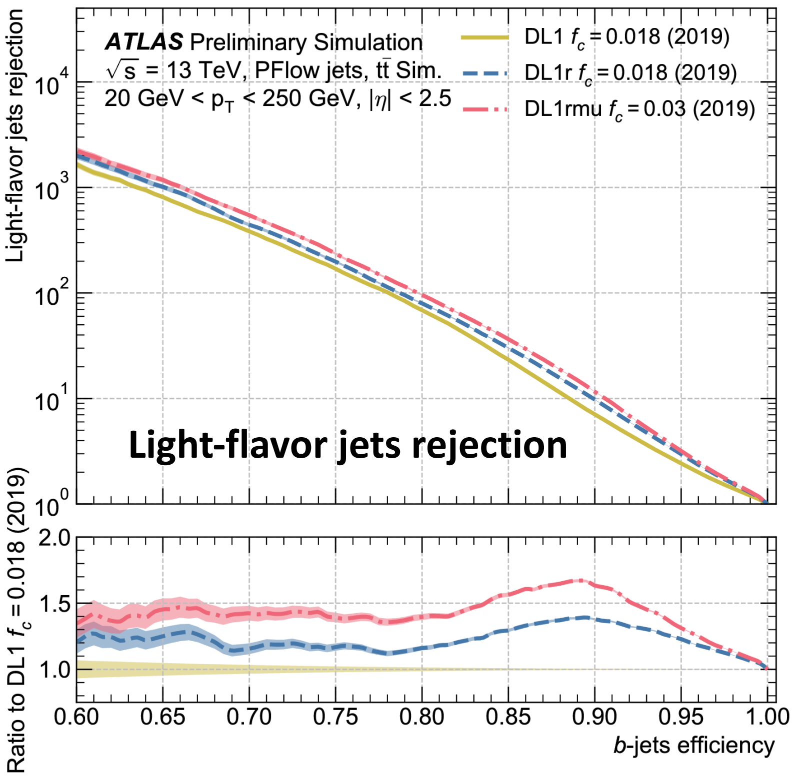


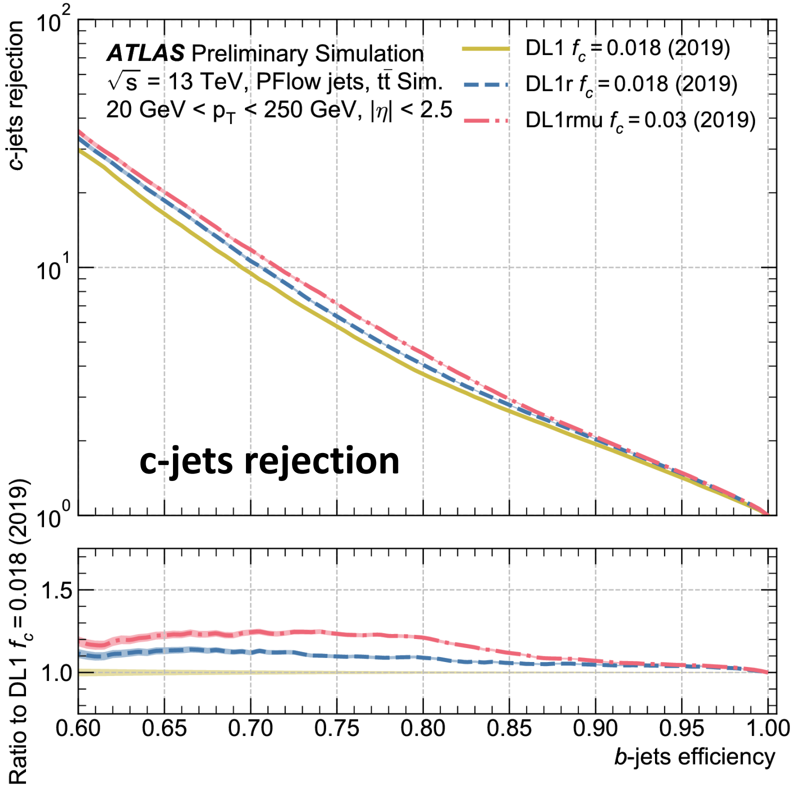
b-jet tagging performance in ATLAS

- A variety of high-level algorithms developed to distinguish b-quark jets (*b*-jets) from jets containing only lighter quarks
- ATLAS supports anti-k_T R=0.4 particle flow (PFlow) jets and anti-k_T Variable-Radius (VR) track jets
- b-tagging algorithms:
  - **DL1**: based on a deep neural network (DNN)
  - **DL1r**: DL1 extension based on a recurrent neural network (RNN) exploiting the correlation between the tracks' impact parameters
  - **DL1rmu**: DL1r plus the soft muon tagger neural network (SMTnn), dedicated to optimizing b-tagging in the case of semi-leptonic B-hadron decays

Significant increase in c-jets and light-flavour jets rejection for DL1r w.r.t DL1

DL1r is the baseline tagger since 2019



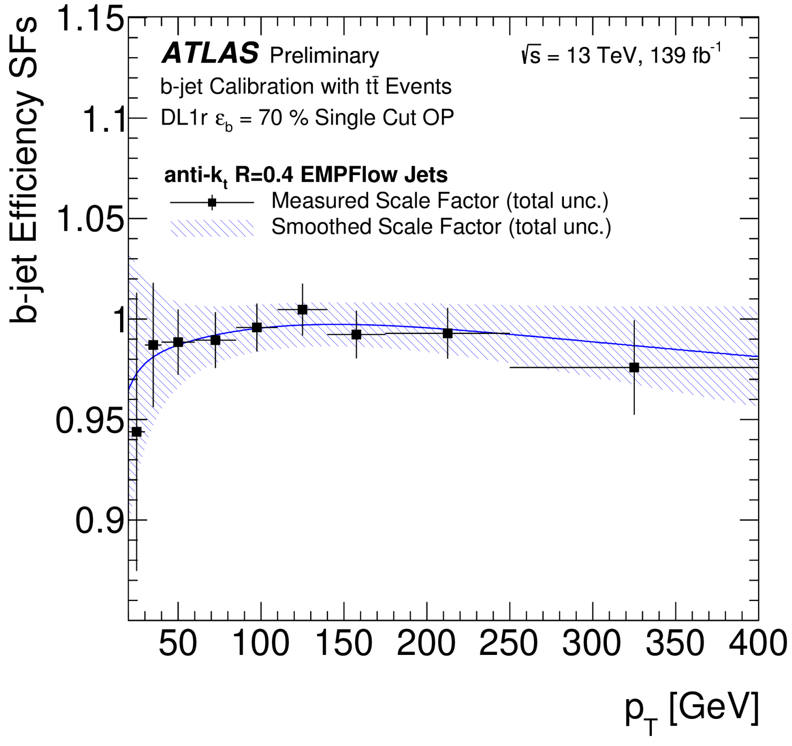


[FTAG-2019-005](#) : anti-k_T R=0.4 Pflow jets
[FTAG-2019-006](#) : anti-k_T VR track jets

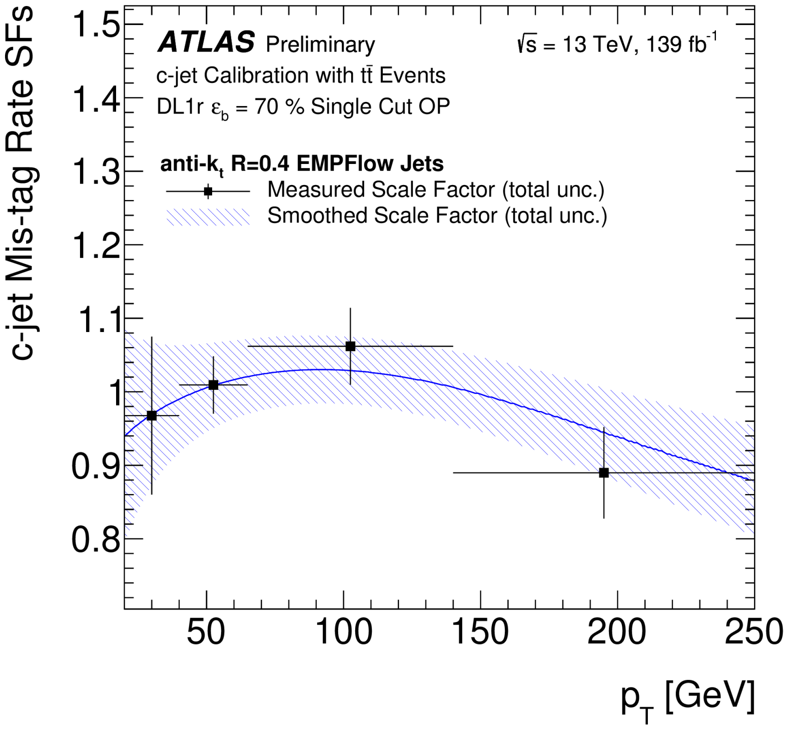
b-jet tagging performance in ATLAS

- The b-tagging performance evaluated with Monte Carlo (MC) simulation is corrected to match the performance in data using dedicated Scale Factors (data-MC SF) FTAG-2021-001
- To properly account for the effects of different MC event generators and parton shower models, these data-MC SF are further corrected using dedicated Monte Carlo to Monte Carlo Scale Factors (MC-MC SF) ATL-PHYS-PUB-2020-009

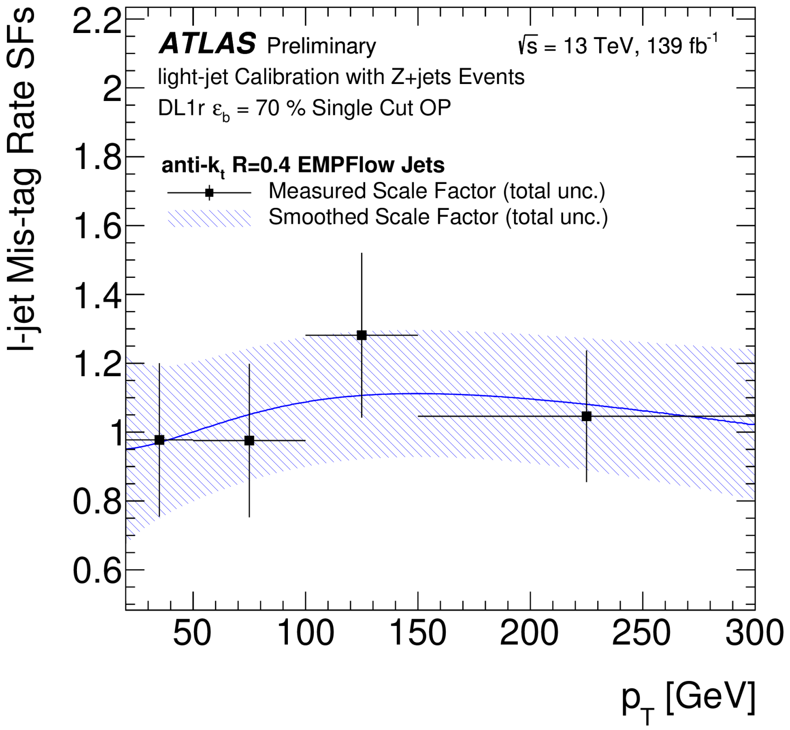
b-jet tagging efficiency SFs



c-jet mistag rate SFs



light-jet mistag rate SFs



b-jet tagging performance in CMS

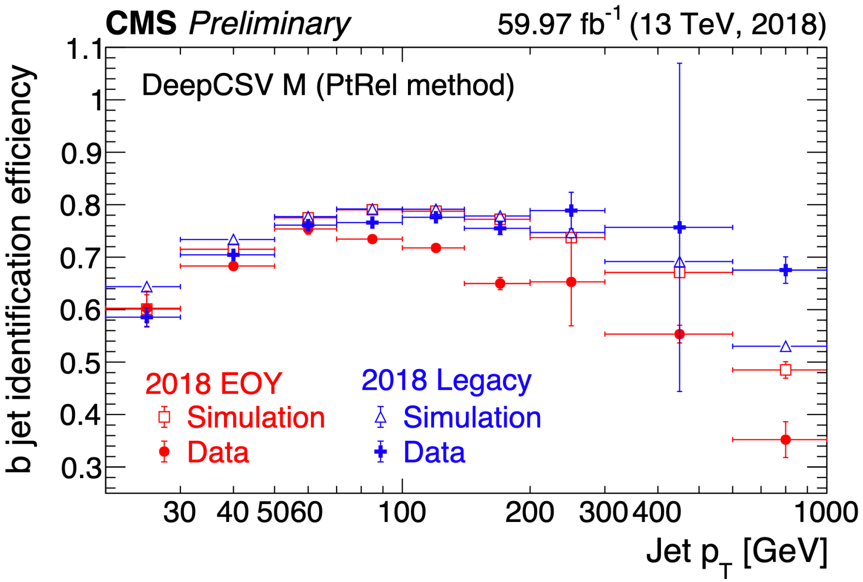
- CMS employs two high level tagging algorithms, both based on DNNs, but with differing input information, network structure and outputs: DeepCSV and DeepJet
- CMS supports anti-k_T R = 0.4, 0.8 and 1.5 particle flow jets referred as AK4, AK8 and AK15 jets respectively.
- **DeepCSV:** A multi-classification deep-neural-network (DNN) algorithm to distinctly identify b-, c- or light (udsg) jets, based on secondary vertex information obtained with the Inclusive Vertex Finder (IVF) algorithm and track-based lifetime information.
- **DeepJet:** A multi-classification deep-neural-network (DNN) algorithm with a more complex architecture compared to DeepCSV, replacing the track-based lifetime information used in DeepCSV with more general (low-level) properties of several charged and neutral particle-flow jet constituents, supplemented also with properties of secondary vertices (using the IVF algorithm) associated with a jet.

CMS-DP-2021-004

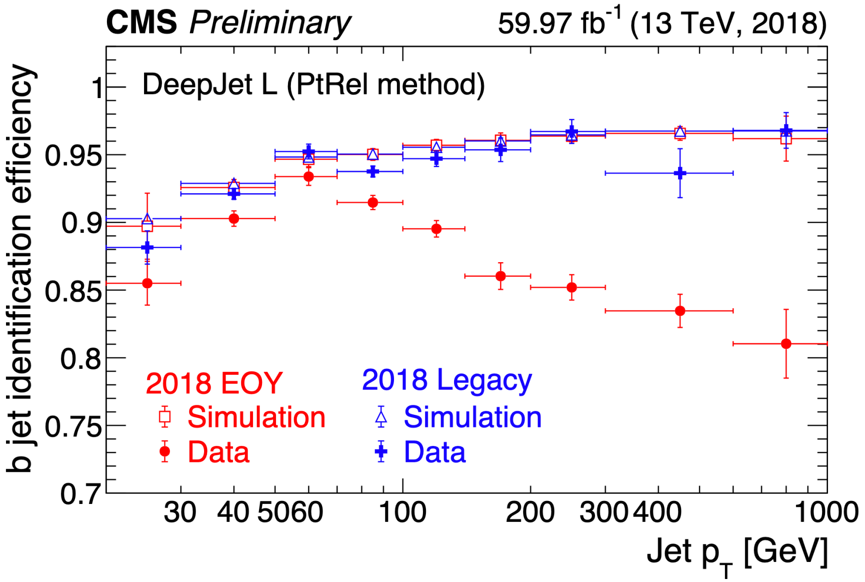
Improved b-jet tagging efficiency and reduced b-jet SFs on reprocessed data

Reprocessing expected to improve the tracking performance and jet reconstruction

DeepCSV



DeepJet



c-jet tagging performance in CMS

- c-jet tagging algorithm is composed of two discriminators, one to discriminate c from b jets (CvsB) and another to discriminate c from light-flavour and gluon jets (CvsL).

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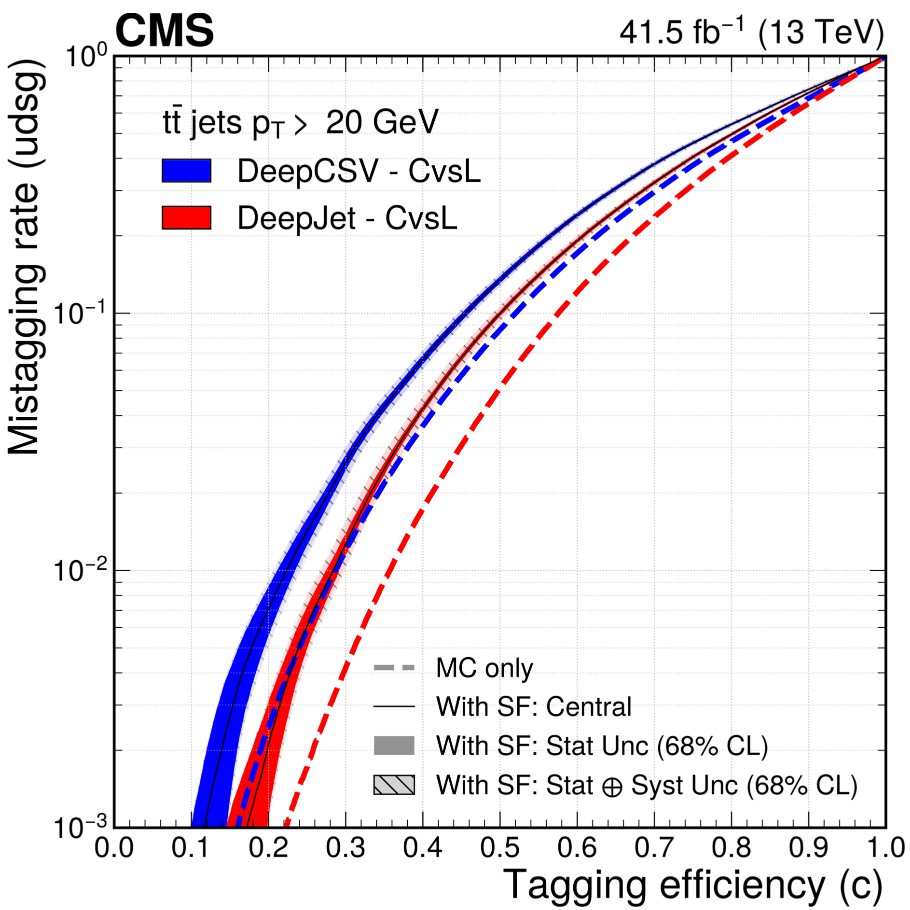
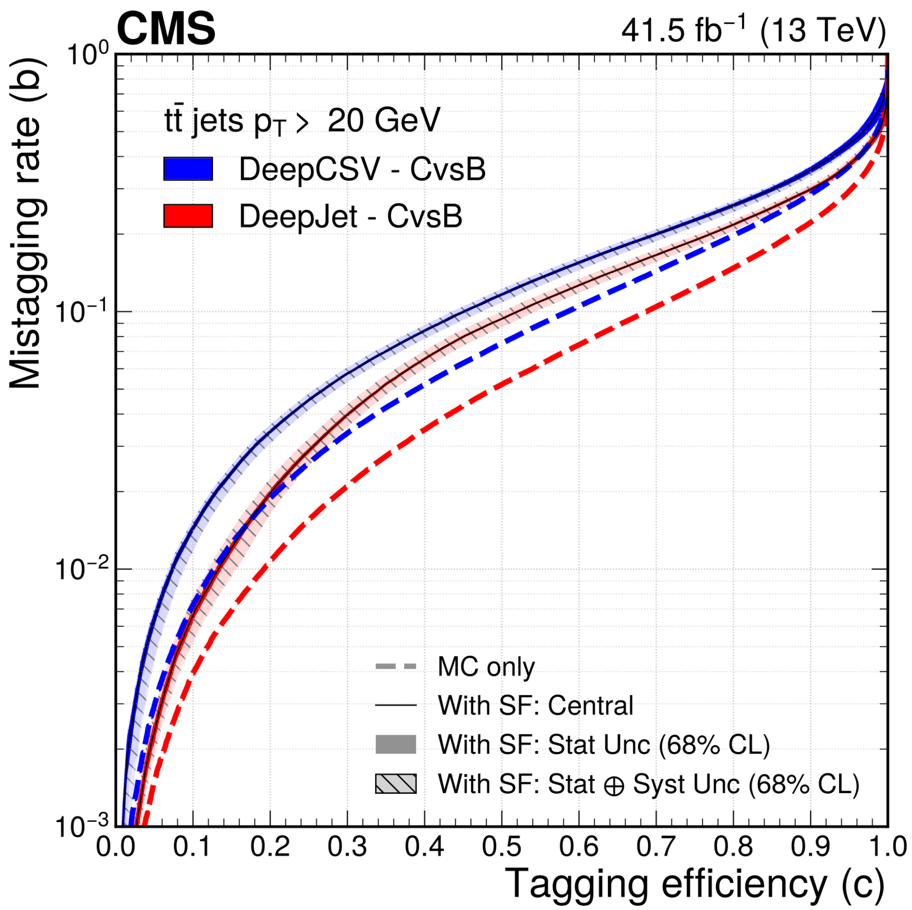
DeepJet outperforms DeepCSV in all areas of the discriminant space.

Measured correction factors are applied on simulated data sets.

Good agreement is seen between the adjusted simulation and collision data.

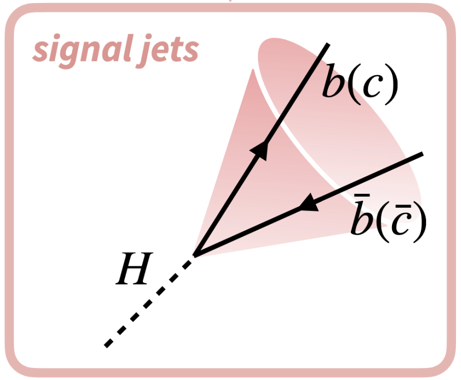




b-jet tagging performance in CMS: AK8 jets

CMS-DP-2022-005

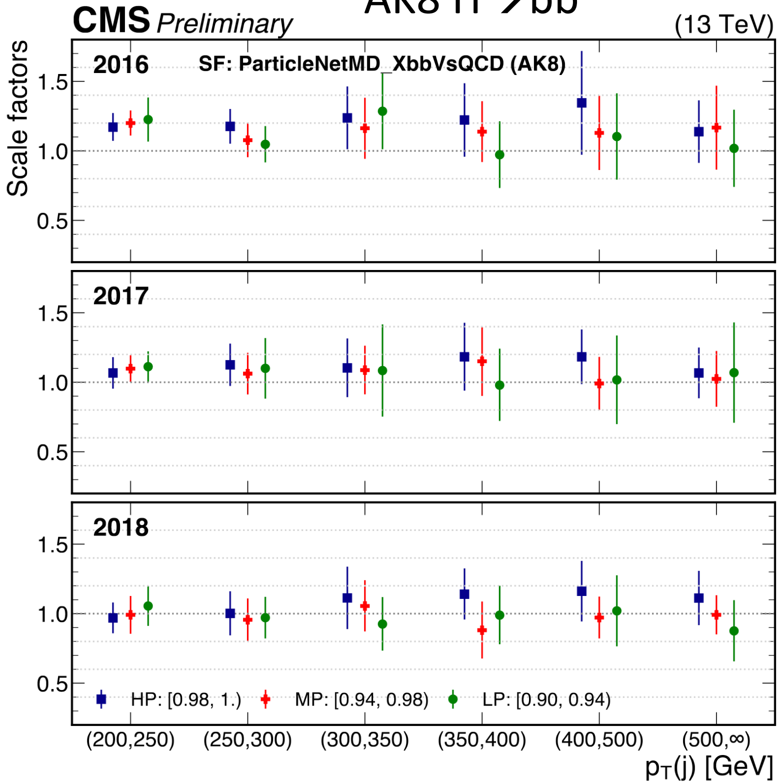
- **ParticleNet-MD tagger**: A graph neural network with mass-decorrelation (MD) based particle identification algorithm for identifying hadronic decays of highly Lorentz-boosted top quarks and W, Z, and Higgs bosons and classifying various decay modes. The network is trained using particle-flow candidates and secondary vertices associated with the AK8/AK15 jet.



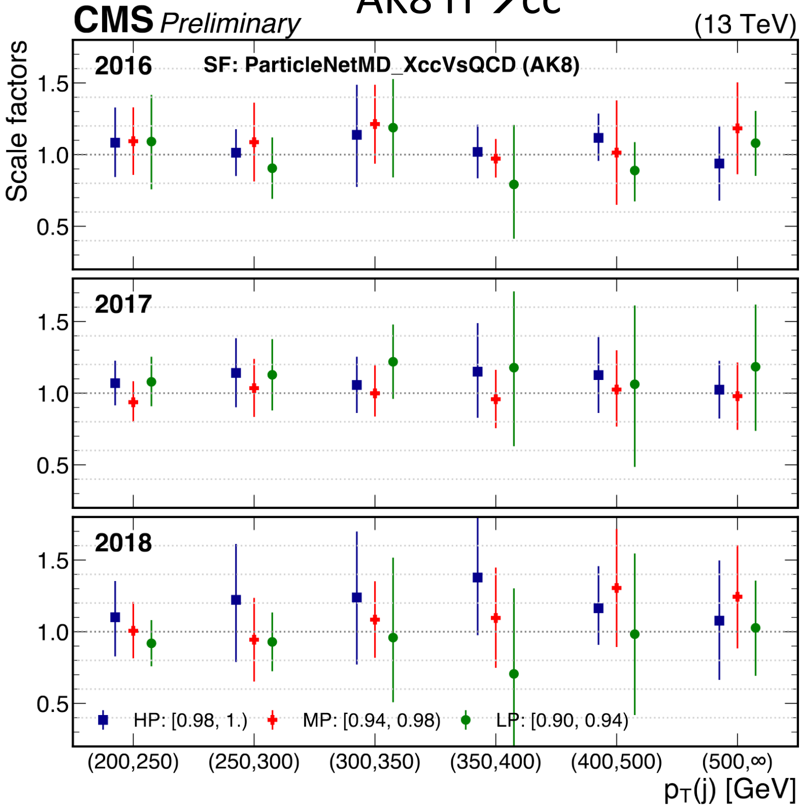
Summary of the scale factors in the context of ParticleNet-MD AK8 X→bb discriminant calibration for H→bb jets (left) and AK8 H→cc jets (right).

The results are derived in the three data taking years of Run 2

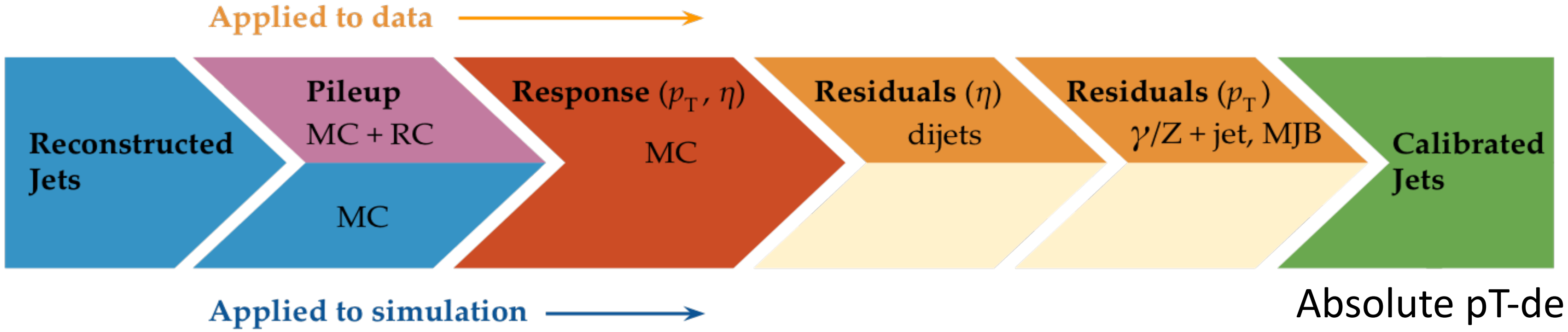
AK8 H→bb



AK8 H→cc

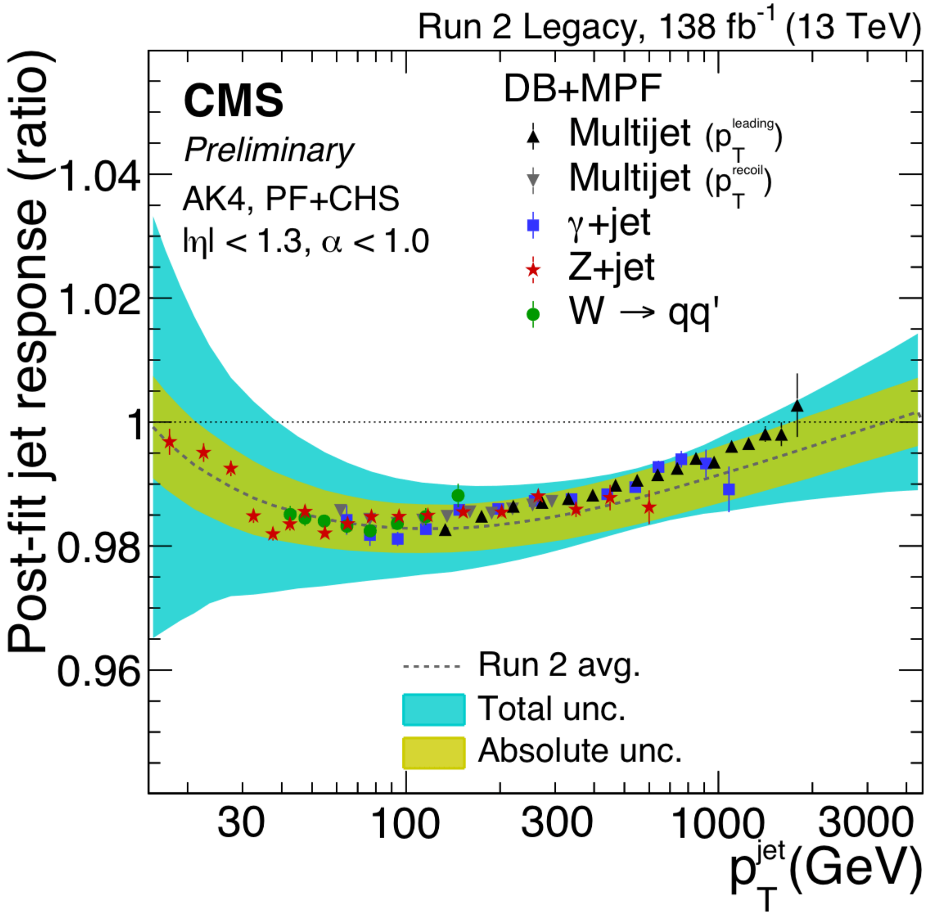


Jet energy scale and resolution measured at 13 TeV



CMS-DP-2021-033

Absolute pT-dependent Residual Correction

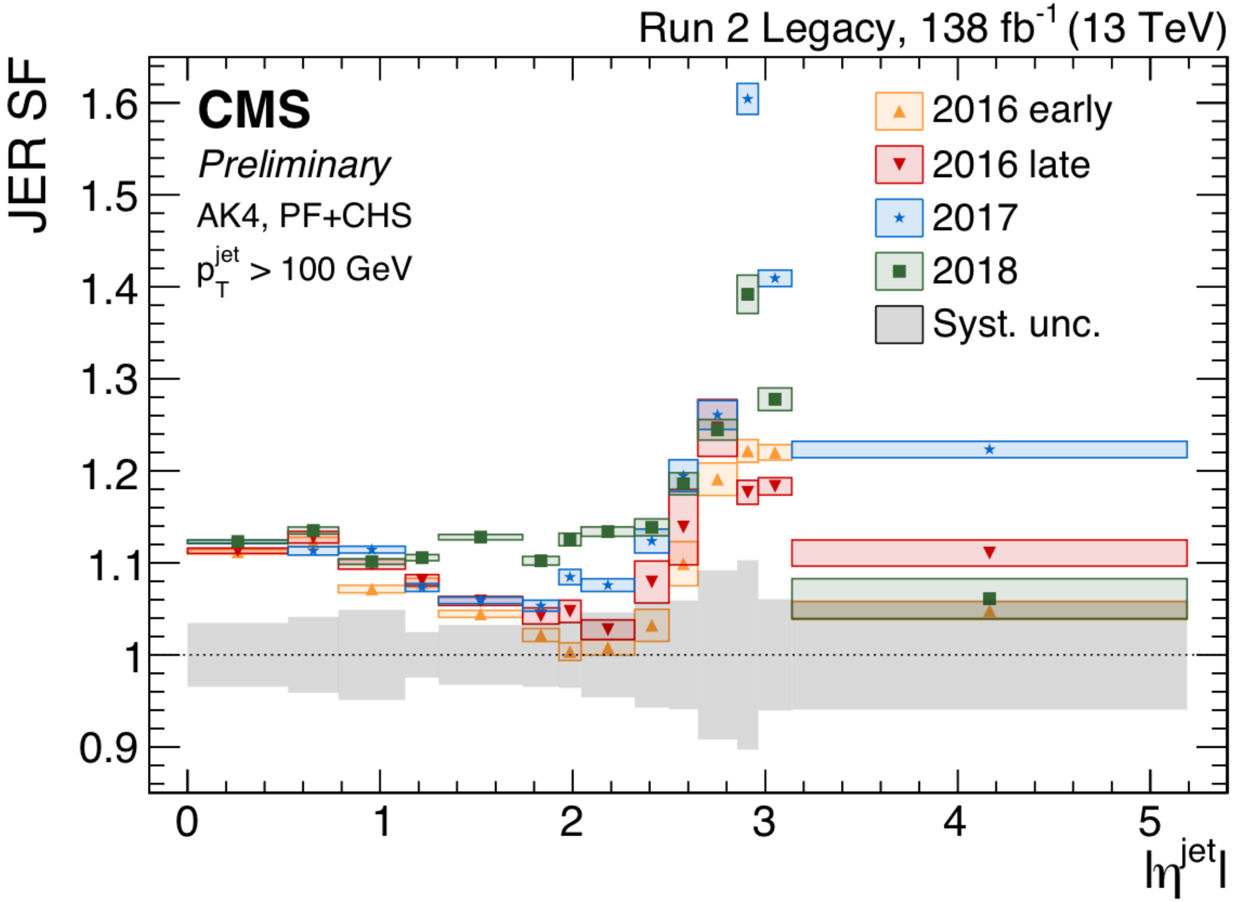


- The jet energies are corrected up to the level of jets clustered from stable (cτ >1 cm) and visible (non-neutrino) final state particles, referred to as particle jets.
- The jet energy scale (JES) is calibrated sequentially with:
  - pileup offset subtraction
  - detector response correction from simulation
  - residual corrections for differences between data and detector simulation
  - optional corrections for jet flavour composition

Jet energy scale and resolution measured at 13 TeV

Jet Energy Resolution (JER)

CMS-DP-2021-033



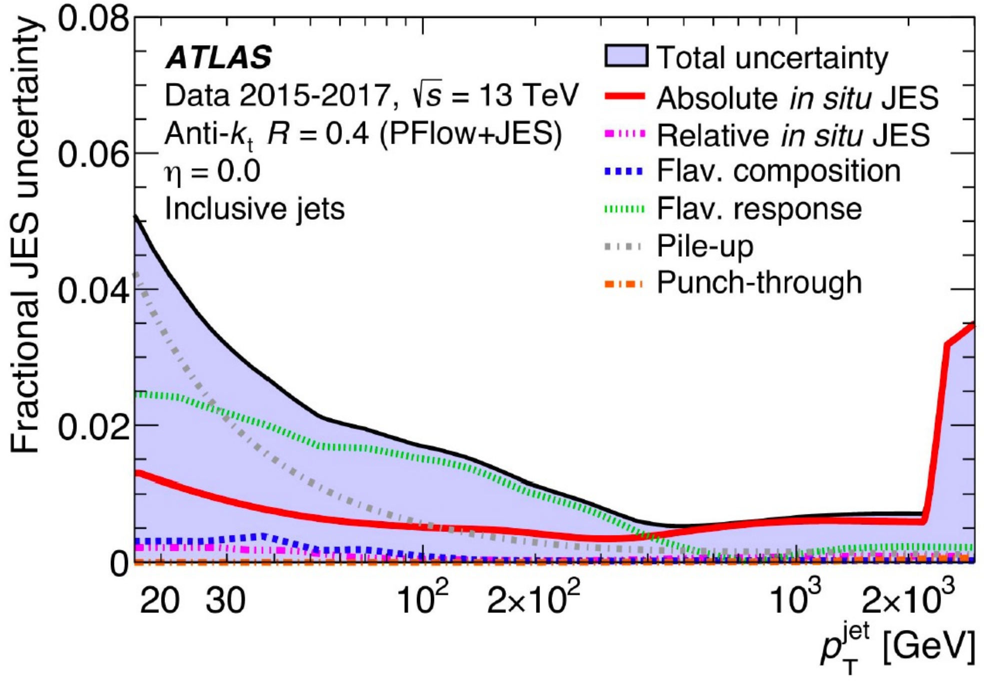
- The JER is measured in dijet and Z/γ+jet events in data and simulation using JES-corrected jets
- Data/MC scale factors (SFs) are extracted
- JER SFs ~ 1.1 to 1.2, except in |η| ∈ [2.5, 3] due to the EC-HF transition region
- SFs are not pT dependent, except in|η|∈[2.5,3]

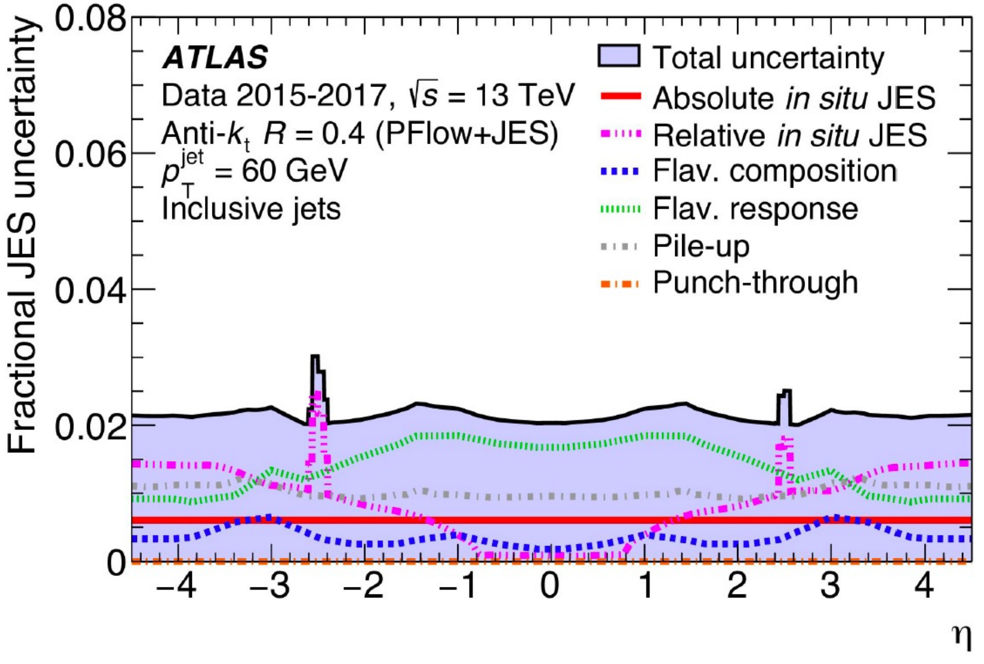
Jet energy scale and resolution measured at 13 TeV

Uncertainties dominated by pile-up (low p_T), flavour (intermediate p_T) and in situ JES (high p_T)

Note:

- Spikes in $|\eta| \sim 2.4$–2.6 are due to the non-closure uncertainties on the relative in situ JES (mismodelling within detector transitions)
- The Absolute in situ JES includes the single-particle uncertainty which dominates at high p_T





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Jet energy scale and resolution measured at 13 TeV

Fractional Jet Resolution for JES-corrected jets

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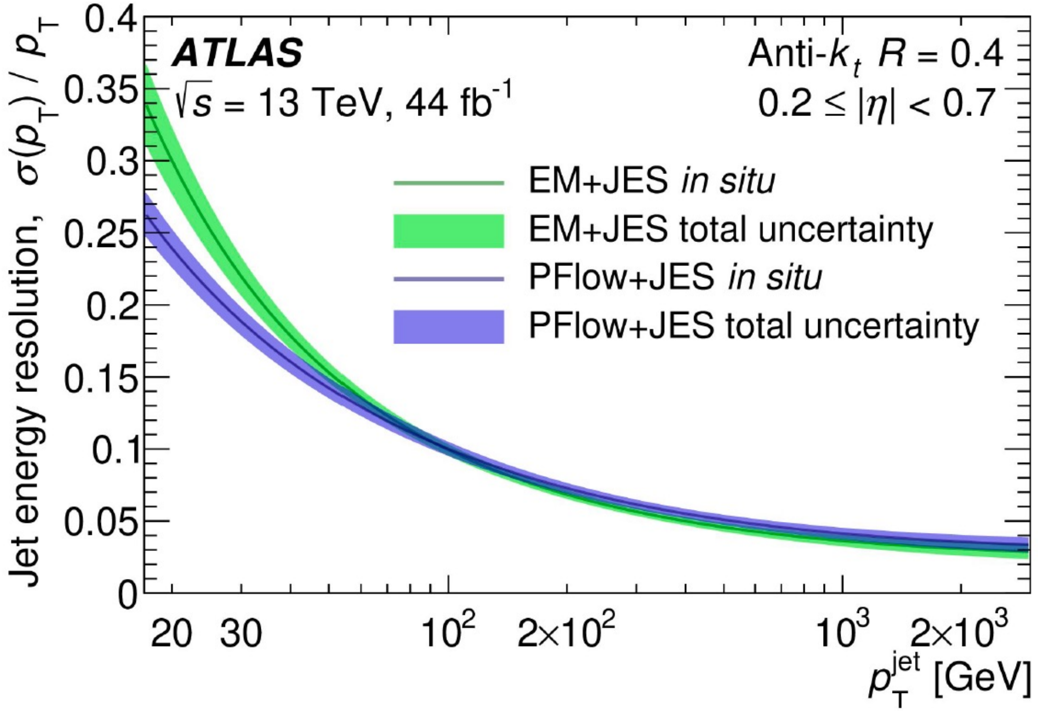

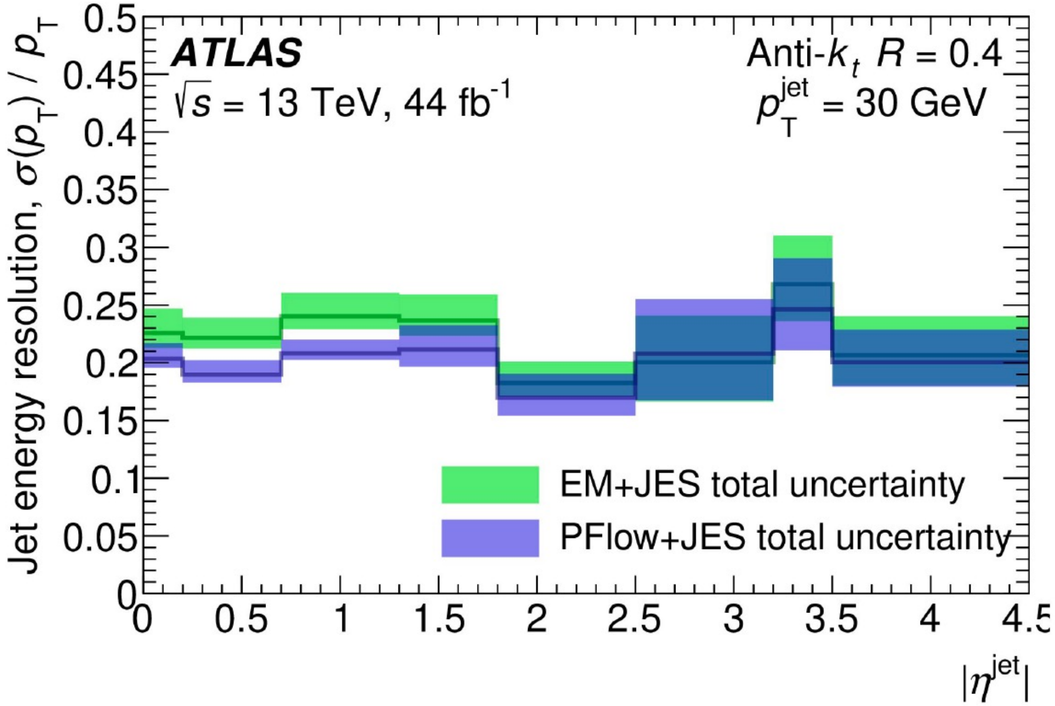

Particle-flow (PFlow) jets have better resolution at low p_T and $|\eta|< 2.5$ w.r.t. calorimeter-only based (EM) jets, since the former use tracking information (tracker has better resolution at low p_T)

MET performance in ATLAS

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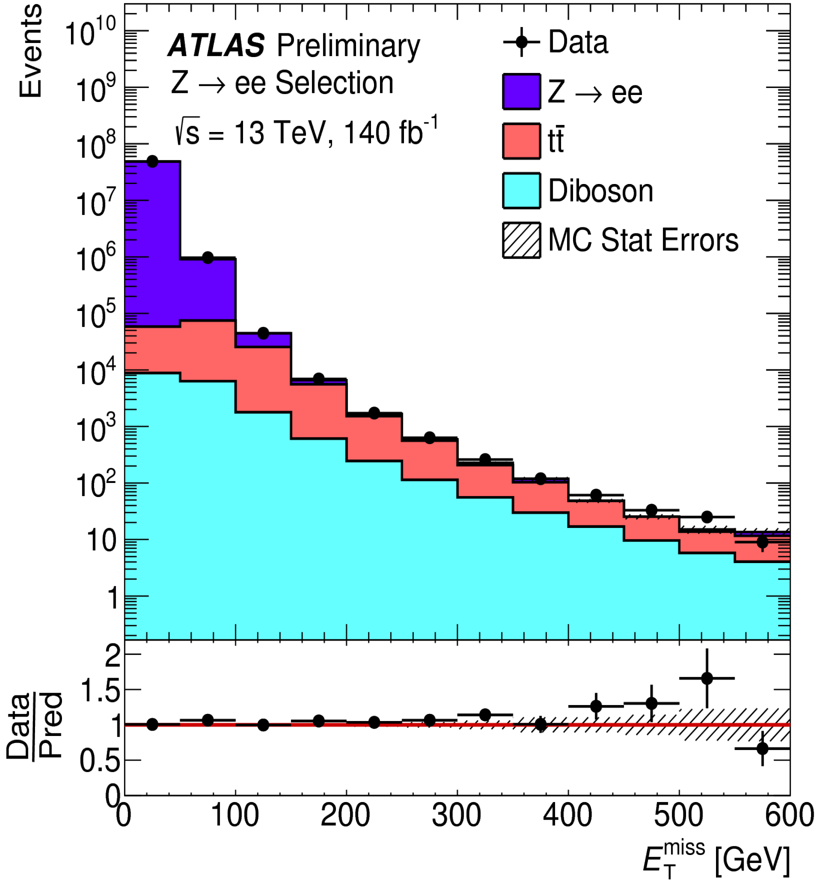
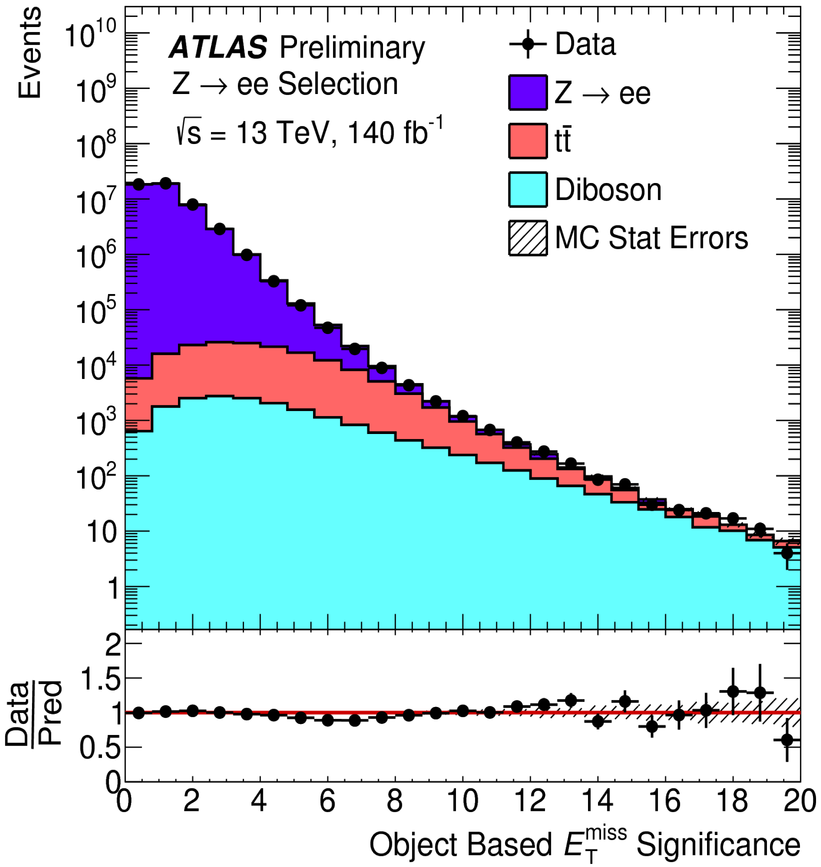
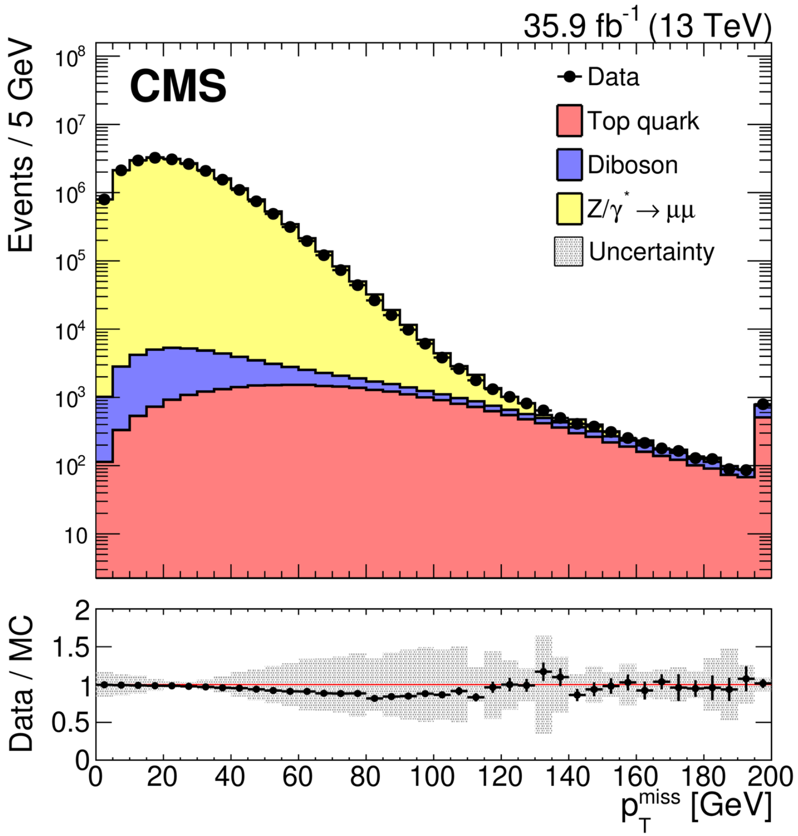


- The total missing transverse momentum (E_T^{miss}) is calculated from reconstructed electrons, muons and jets as well as tracks which are not associated to any of these objects.
- These un-associated tracks constitute charged soft particles and are known as the Track-based Soft Term (TST).
- Jets have transverse momentum (p_T) greater than 30 GeV and $|\eta| > 2.5$. Central jets ($|\eta| < 2.5$) coming from the hard scatter vertex are selected using the Jet Vertex Tagger (JVT)



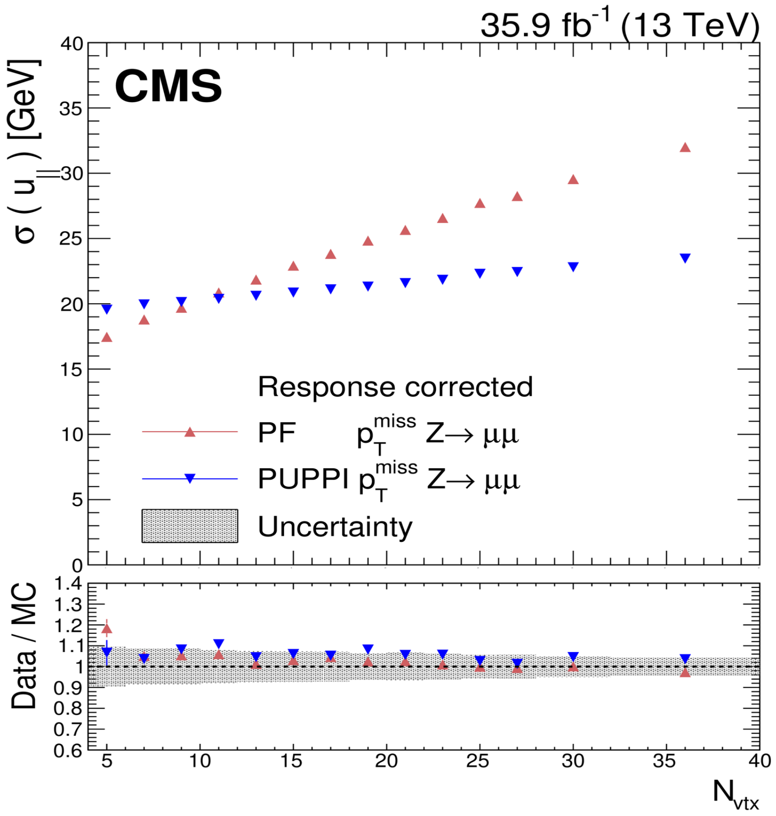
Good agreement between data and MC on E_T^{miss} spectrum and E_T^{miss} significance

MET performance in CMS



- The effects of multiple p-p interactions on the missing transverse momentum (defined as the negative vector pT sum of all the PF candidates) are mitigated thanks to the Pileup Per Particle Identification (PUPPI) method:
  - Better resolution starting from Nvtx>12
  - More stable performance vs pileup

- PUPPI: The momenta of neutral particles are rescaled according to the probability that they originate from the Primary Vertex



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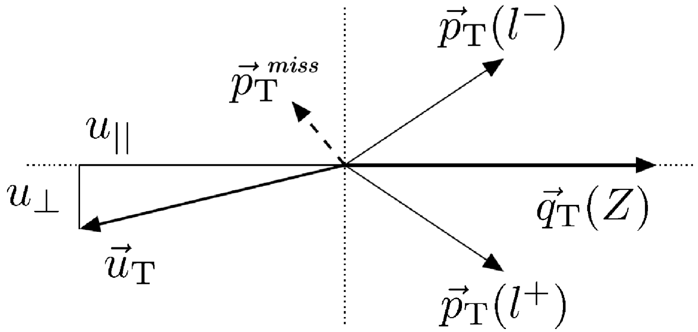

The vector $\vec{u}_T$ denotes the vectorial sum of all particles reconstructed in the event except for the two leptons from the Z decay.

Summary & Conclusions

- Inclusive charged-particle b-jet production in pp and p-Pb collisions and charm jets tagged with D_0 mesons in pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV at ALICE are shown
- The state of the flavour tagging, jet and MET performance at 13 TeV from ATLAS and CMS has been shown
- Performance is systematically being improved by both experiments
- Use of PFlow jets in ATLAS, benefiting from better track resolution at low pT
- Better resolution and more stable MET performance vs pileup when using PUPPI in CMS
- Improved light-flavour jet and c-jet rejection from ATLAS with DL1r tagger
- Improved CMS c-tagging performance with DeepJet w.r.t. DeepCSV (reduced mis-tagging rate)