

Jet and missing p_T reconstruction: Run 2 and perspective for Run 3

Andrea Malara
on behalf of the CMS Collaboration

29th July 2020

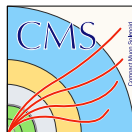


Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG



Bundesministerium
für Bildung
und Forschung

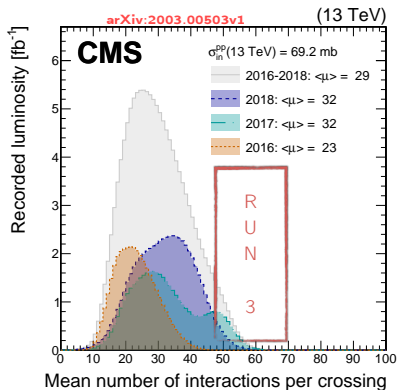
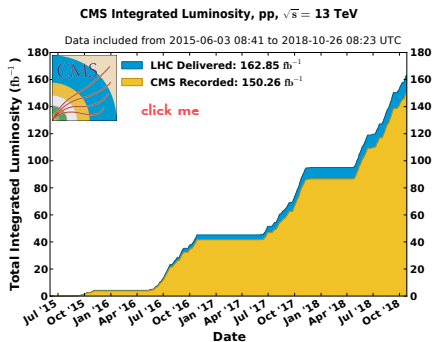


CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

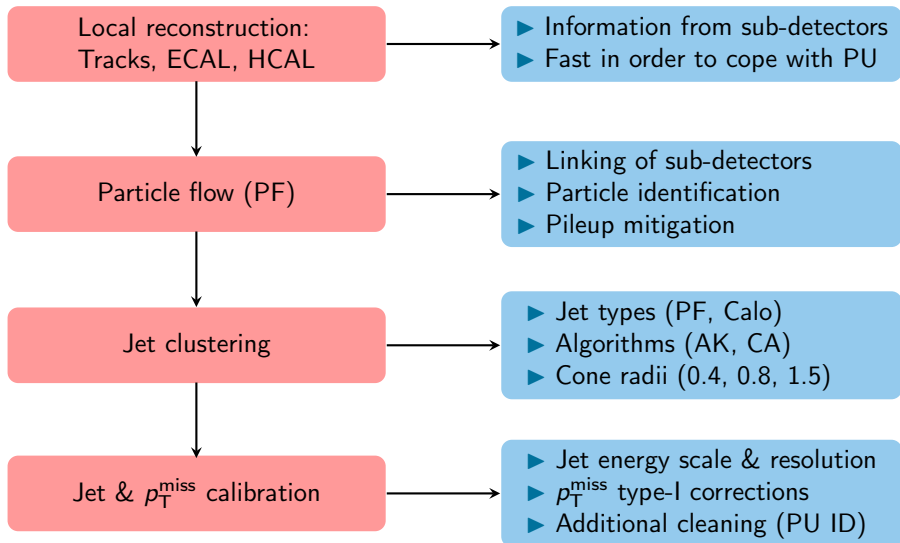


Overview

- ▶ **Run 2:** About 150 fb^{-1} at 13 TeV with average pileup of ~ 30 interactions
- ▶ **Challenge:** Achieve the best performance for jets and p_T^{miss}
- ▶ **Run 3:** Around the corner, presenting a number of challenges (Ageing detector, pileup, ...)



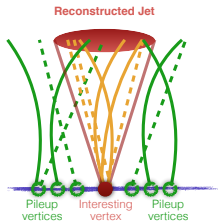
Building Jets & p_T^{miss}



Pileup Mitigation Techniques

Pileup

- ▶ Multiple interactions during a bunch crossing
- ▶ Additional particles deteriorate measurements
- ▶ Major challenge in LHC physics
- ▶ Several approaches to cope with up to 200 interactions



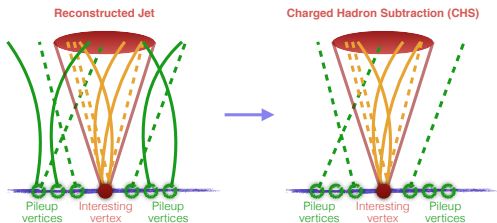
Pileup Mitigation Techniques

Pileup

- ▶ Multiple interactions during a bunch crossing
- ▶ Additional particles deteriorate measurements
- ▶ Major challenge in LHC physics
- ▶ Several approaches to cope with up to 200 interactions

Charged Hadron Subtraction (CHS)

- ▶ Tracker information to remove charged particles associated to PU
- ▶ Applicable for $|\eta| < 2.4$



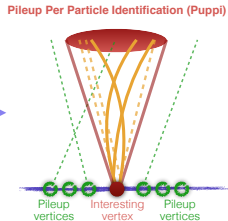
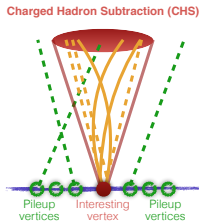
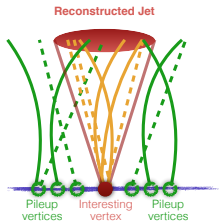
Pileup Mitigation Techniques

Pileup

- ▶ Multiple interactions during a bunch crossing
- ▶ Additional particles deteriorate measurements
- ▶ Major challenge in LHC physics
- ▶ Several approaches to cope with up to 200 interactions

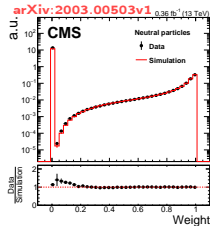
Charged Hadron Subtraction (CHS)

- ▶ Tracker information to remove charged particles associated to PU
- ▶ Applicable for $|\eta| < 2.4$



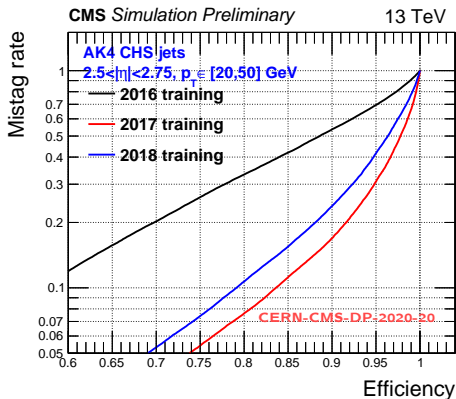
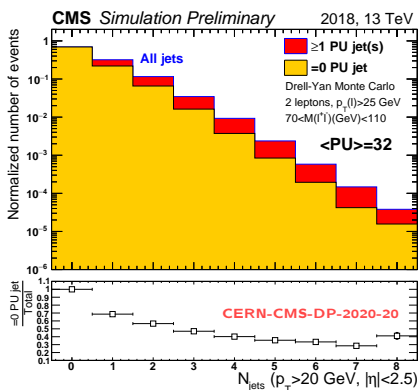
Pileup Per Particle Identification (Puppi)

- ▶ Per-particle weight
- ▶ Scale 4-momentum before clustering
- ▶ Charged particles similar to CHS



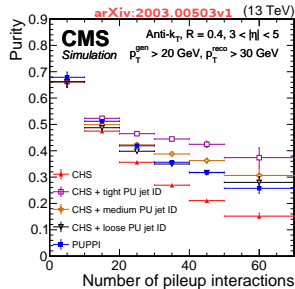
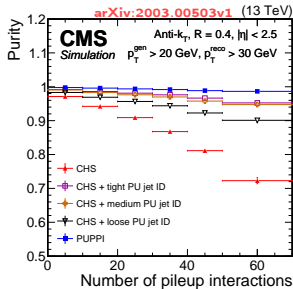
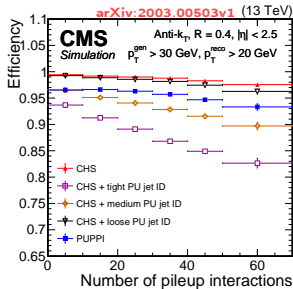
Pileup Mitigation Techniques – PU jet ID

- ▶ BDT-based discriminator to identify low- p_T jets coming from PU
- ▶ High rejection power and low mistag rate at 95% efficiency
- ▶ Large improvement from Phase-1 upgrade of pixel detector after 2017: extended coverage from $|\eta| < 2.5$ to 2.7



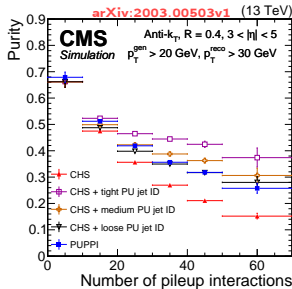
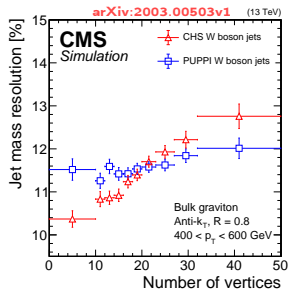
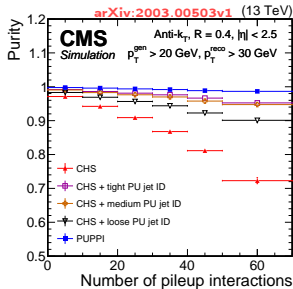
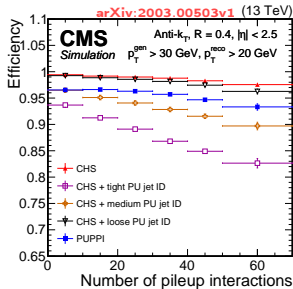
Pileup Mitigation Techniques – CHS vs. PUPPI

- ▶ **Puppi**: Good balance between purity and efficiency for $|\eta| < 2.5$
- ▶ **CHS**: Improves purity at cost of efficiency in combination with PU jet ID



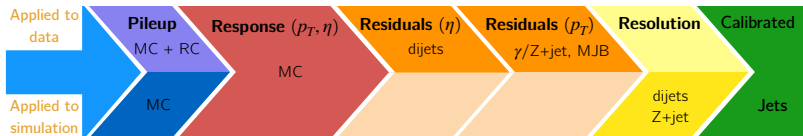
Pileup Mitigation Techniques – CHS vs. PUPPI

- ▶ **Puppi**: Good balance between purity and efficiency for $|\eta| < 2.5$
- ▶ **CHS**: Improves purity at cost of efficiency in combination with PU jet ID
- ▶ **Puppi**: Jet variables stable against PU (e.g. mass resolution)
 - ▶ For more details see Dennis' talk "New jet tagging techniques at CMS"





Jet Calibration



Strategy:
Factorized
approach

Jet Calibration

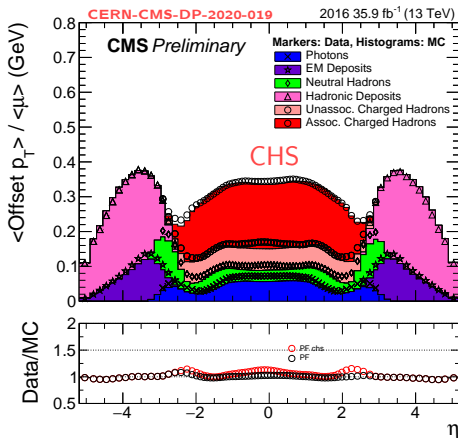


Strategy:
Factorized
approach

MC truth correction:

PU subtraction

- ▶ Average difference (offset) in p_T between matched jets
- ▶ Simulation-based corrections (multijet sample w/ and w/o PU) applied to data and simulation
- ▶ Residual corrections derived with Random Cone algorithm applied to data
- ▶ Monitored for each type of PF candidates





Jet Calibration



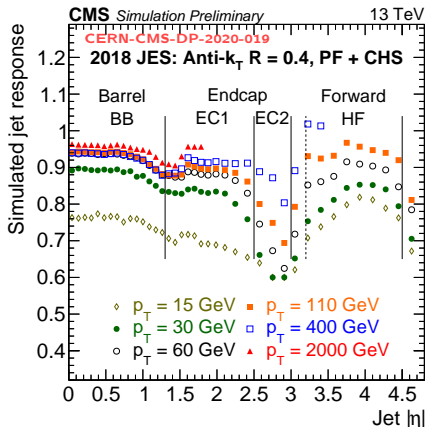
Strategy:
Factorized
approach

MC truth correction:

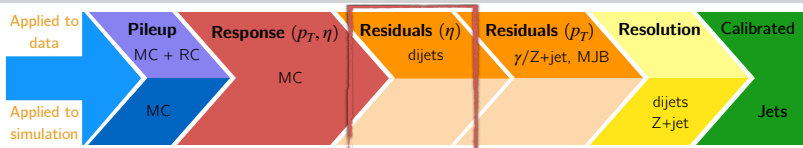
PU subtraction

Jet response calibration

- Core of the JEC
- Measured in simulation and applied to data as well
- Accounts for detector effects
- Change in performance at high $|\eta|$ and low p_T due to detector acceptance



Jet Calibration



Strategy:
Factorized
approach

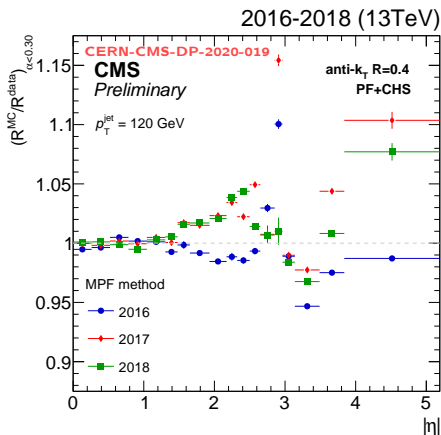
MC truth correction:

PU subtraction

Jet response calibration

Residual corrections

- ▶ Small residual correction of jet response applied to data
- ▶ Address different response in each sub-detector (η dep.)
- ▶ Sizeable corrections in detector transition regions



Jet Calibration



Strategy:
Factorized
approach

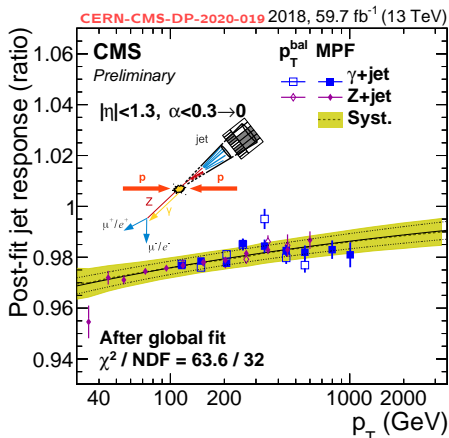
MC truth correction:

PU subtraction

Jet response calibration

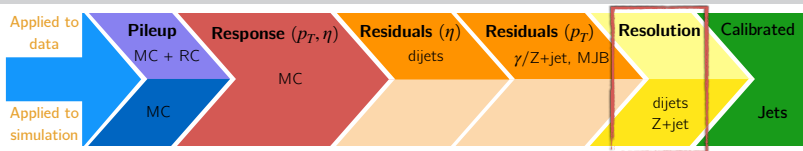
Residual corrections

- ▶ Additional p_T dep. corrections accounting for abs. scale in barrel
- ▶ Determined relative to precisely measured reference objects (μ, e, γ)
- ▶ Combined in a global fit (reference object scales as nuisance parameters)





Jet Calibration



Strategy:
Factorized
approach

MC truth correction:

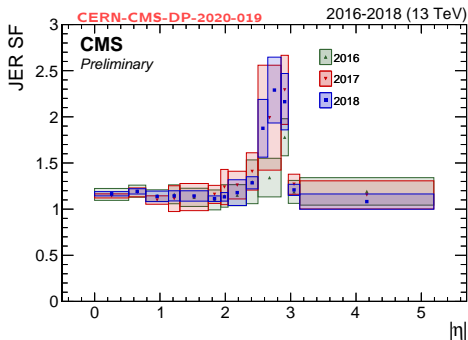
PU subtraction

Jet response calibration

Residual corrections

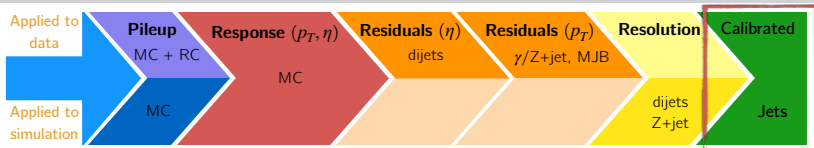
Jet energy resolution smearing

- ▶ Scale factors (SFs) applied to simulation to match jet resolution in data
- ▶ p_T and η dependent SFs aim for coverage of full phase space





Jet Calibration



Strategy:
Factorized
approach

MC truth correction:

PU subtraction

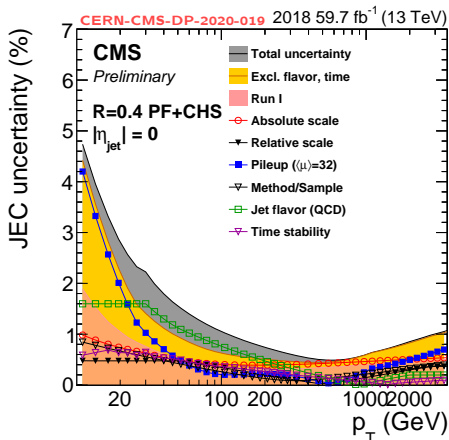
Jet response calibration

Residual corrections

Jet energy resolution smearing

Jet Energy Scale Uncertainty

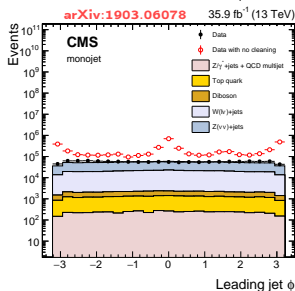
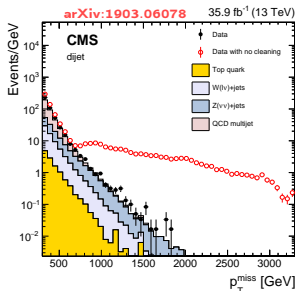
- ▶ Uncertainty $\sim 1\%$ for jets with $p_T \geq 100$ GeV
- ▶ Large contribution from PU corrections





p_T^{miss} – Noise Rejection

- ▶ p_T^{miss} from invisible particles (ν , new physics)
- ▶ Estimated from momentum conservation in the transverse plane
- ▶ Mis-calibrated objects (mostly jets) lead to inaccurate estimation of p_T^{miss}
- ▶ Anomalous high- p_T^{miss} events can arise from detector effects, beam halo, ...
- ▶ Algorithms to suppress spurious events in data
- ▶ Rejection $\geq 85 - 90\%$, mistag $< 0.1\%$

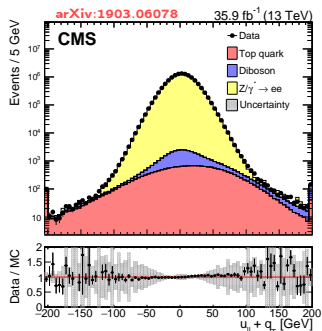
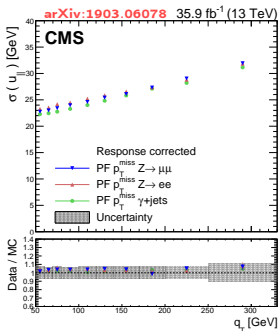
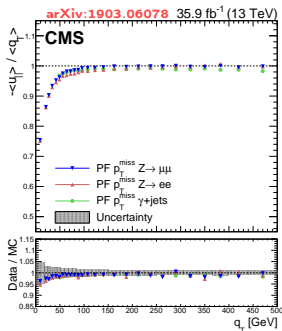
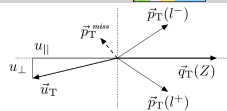


Full Run 2 studies: CERN-CMS-DP-2020-018



p_T^{miss} - Performance

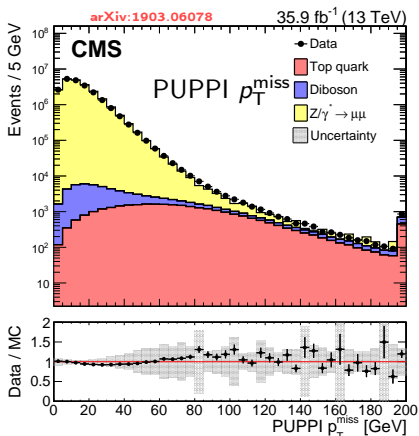
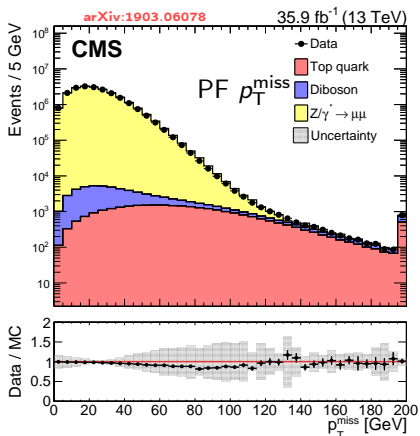
- ▶ Measured in 3 channels w.r.t. well-calibrated Z/γ
- ▶ No genuine p_T^{miss} expected
- ▶ Lower response due to uncalibrated components (low- p_T jets)
- ▶ Resolution dominated by hadronic recoil
- ▶ Good data/simulation agreement within 2%





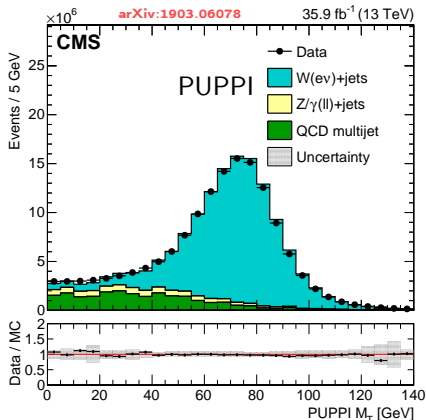
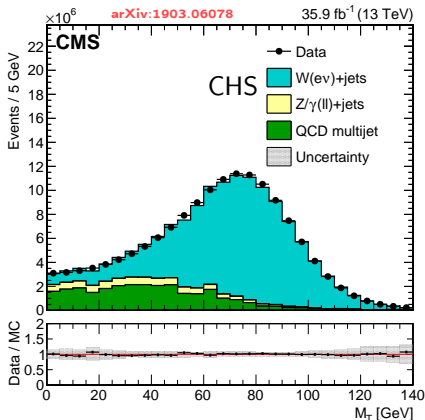
p_T^{miss} - CHS vs. PUPPI

- ▶ Puppi reduces fake p_T^{miss}
- ▶ Any wrong weight assignment could lead to fake p_T^{miss} - larger tails



p_T^{miss} – CHS vs. PUPPI

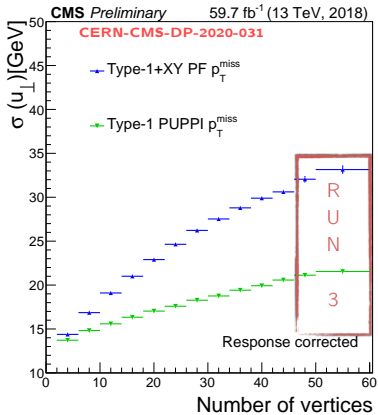
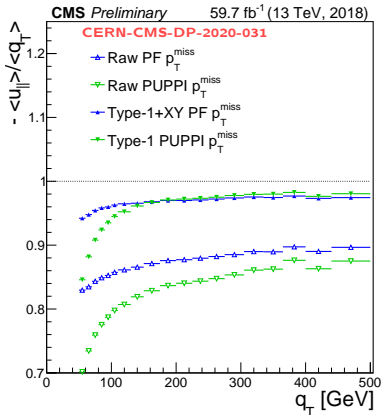
- ▶ Puppi reduces fake p_T^{miss}
- ▶ Any wrong weight assignment could lead to fake p_T^{miss} – larger tails
- ▶ Impressive resolution improvements for W+jets events





p_T^{miss} - CHS vs. PUPPI

- ▶ Puppi reduces fake p_T^{miss}
- ▶ Any wrong weight assignment could lead to fake p_T^{miss} - larger tails
- ▶ Impressive resolution improvements for W+jets events
- ▶ Down-weighting neutral component of PV \rightarrow slower p_T^{miss} turn-on
- ▶ Puppi performance stable against pileup

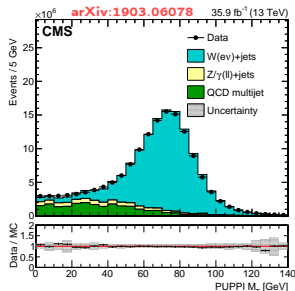
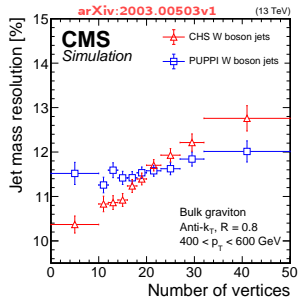


Outlook



- ▶ Run 2 experience fully exploited for accurate jet/ p_T^{miss} performance
- ▶ Several high-performance methods presented
- ▶ Ready to cope with high PU expected for Run 3 (Puppi very promising)
- ▶ But it's not the end of the story
 - ▶ Run 2 legacy corrections to improve performances (planned $<1\%$ JEC unc.)
 - ▶ Increasing the granularity of the corrections to tackle detector ageing
 - ▶ ML-based approaches will help

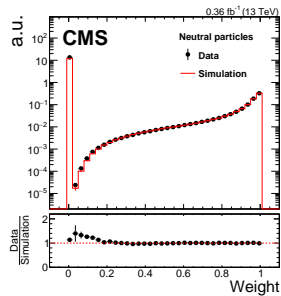
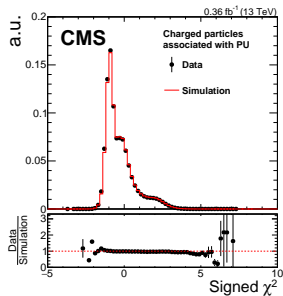
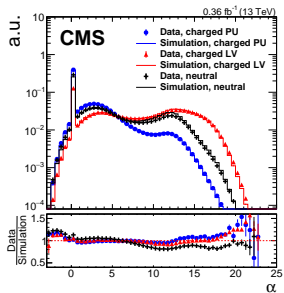
More exciting results are yet to come



—Additional Material—

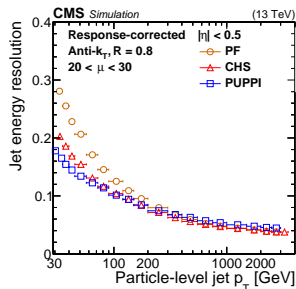
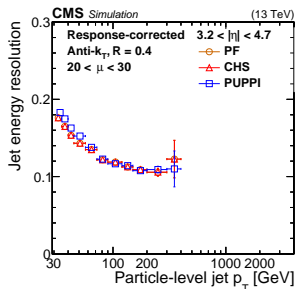
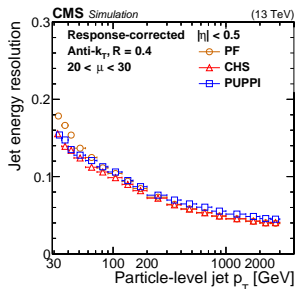
Puppi – Weights

arXiv:2003.00503v1



Puppi – Jet Resolution vs p_T

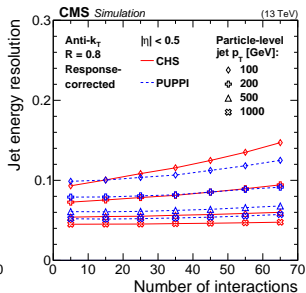
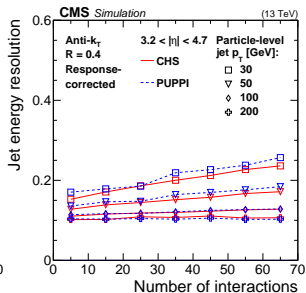
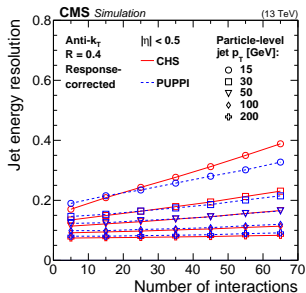
arXiv:2003.00503v1



Significant gain with PUPPI particularly at low- p_T jets
 Updated PUPPI tune in place to improve jet resolution at high- p_T

Puppi – Jet Resolution vs PU

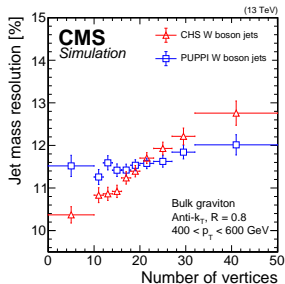
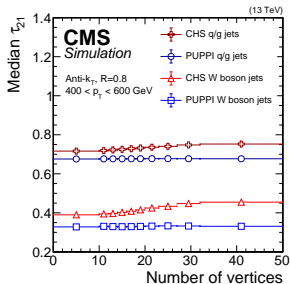
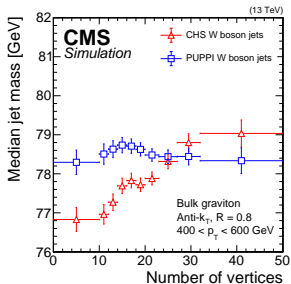
arXiv:2003.00503v1



Significant gain with PUPPI particularly at low- p_T jets
 Updated PUPPI tune in place to improve jet resolution at high- p_T

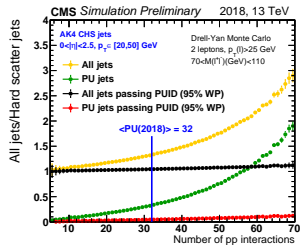
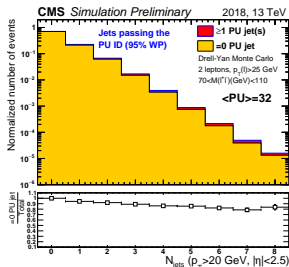
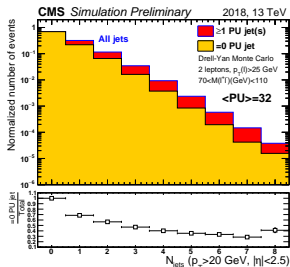
Puppi – Jet Variables

arXiv:2003.00503v1



PU jet ID

CERN-CMS-DP-2020-20

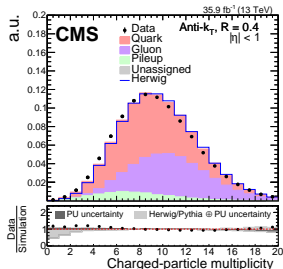
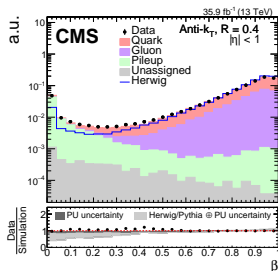


PU jet ID – Input Variables

arXiv:2003.00503v1

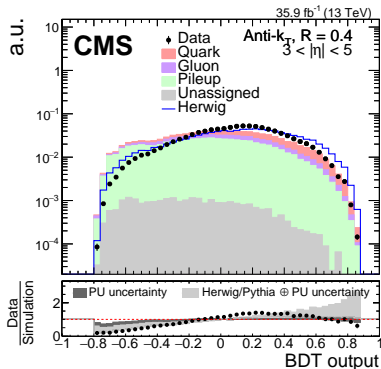
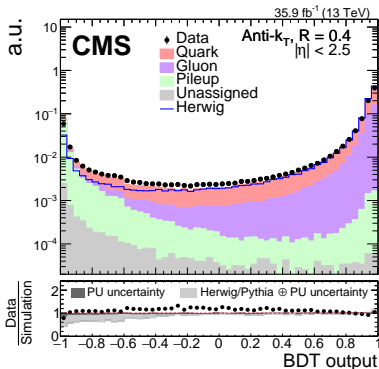


Input variable	Definition
β	Fraction of p_T of charged particles associated with the LV, defined as $\sum_{i \in LV} p_{T,i} / \sum_i p_{T,i}$ where i iterates over all charged PF particles in the jet
N_{vertices}	Number of vertices in the event
$\langle \Delta R^2 \rangle$	Square distance from the jet axis scaled by p_T^2 average of jet constituents: $\sum_i \Delta R^2 p_{T,i}^2 / \sum_i p_{T,i}^2$
$f_{\text{ring}, X}$, $X = 1, 2, 3, \text{ and } 4$	Fraction of p_T of the constituents ($\sum p_{T,i} / p_T^{\text{jet}}$) in the region $R_i < \Delta R < R_{i+1}$ around the jet axis, where $R_i = 0, 0.1, 0.2, \text{ and } 0.3$ for $X = 1, 2, 3, \text{ and } 4$
$p_T^{\text{lead}} / p_T^{\text{jet}}$	p_T fraction carried by the leading PF candidate
$p_T^{\text{1.ch.}} / p_T^{\text{jet}}$	p_T fraction carried by the leading charged PF candidate
$ \vec{m} $	Pull magnitude, defined as $ (\sum_i p_T^i r_i \vec{r}_i) / p_T^{\text{jet}} $ where \vec{r}_i is the direction of the particle i from the direction of the jet
N_{total}	Number of PF candidates
N_{charged}	Number of charged PF candidates
σ_1	Major axis of the jet ellipsoid in the η - ϕ space
σ_2	Minor axis of the jet ellipsoid in the η - ϕ space
p_T^D	Jet fragmentation distribution, defined as $\sqrt{\sum_i p_{T,i}^2} / \sum_i p_{T,i}$



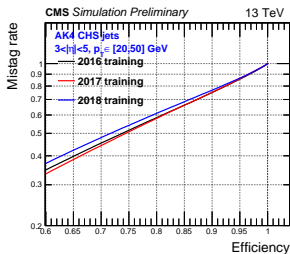
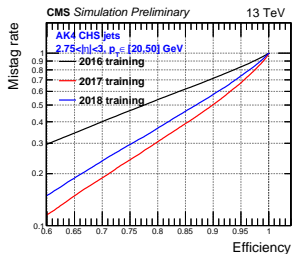
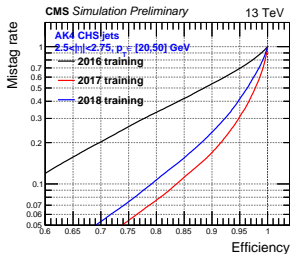
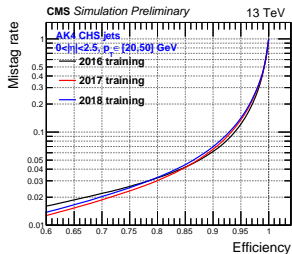
PU jet ID – BDT Output

arXiv:2003.00503v1



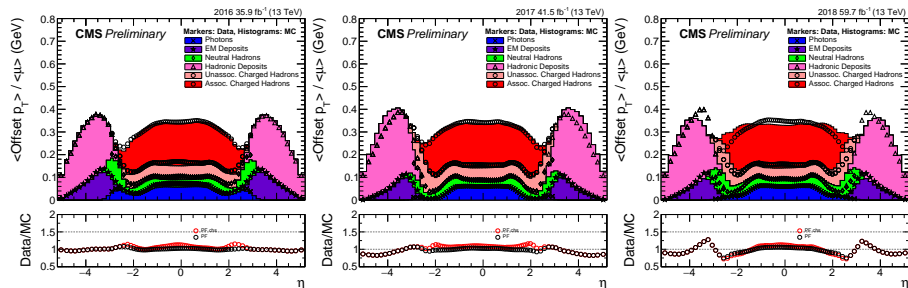
PU jet ID – ROC

CERN-CMS-DP-2020-20



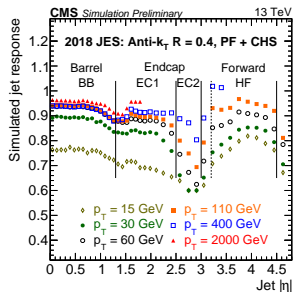
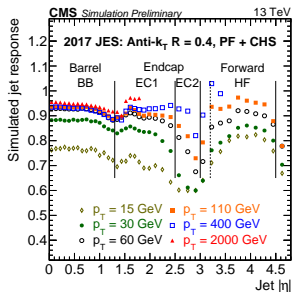
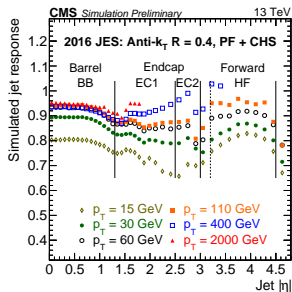
PU Offset

CERN-CMS-DP-2020-019



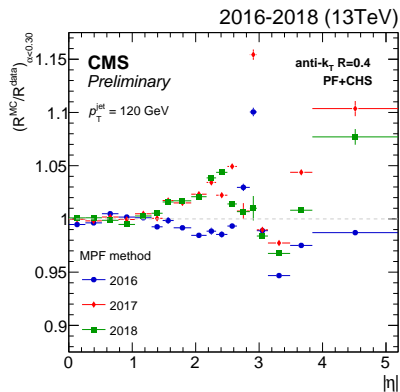
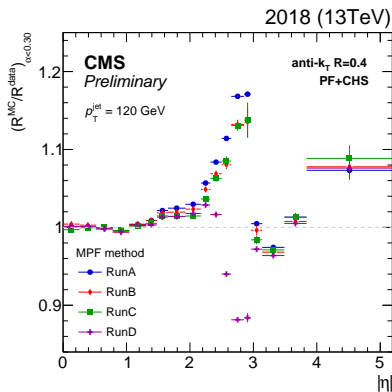
Jet Response

CERN-CMS-DP-2020-019



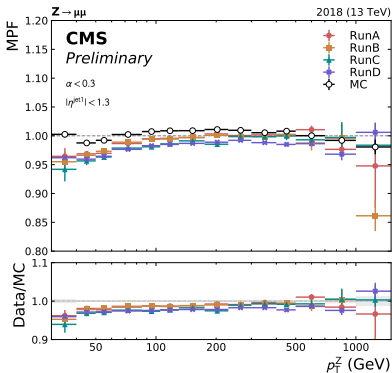
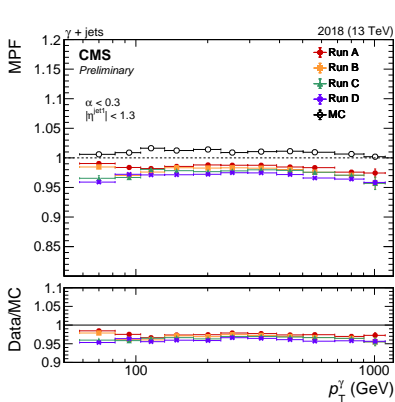
Residuals – η

CERN-CMS-DP-2020-019



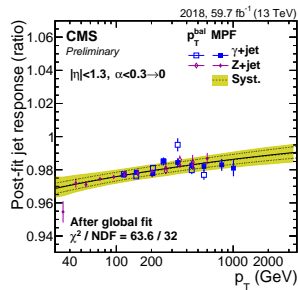
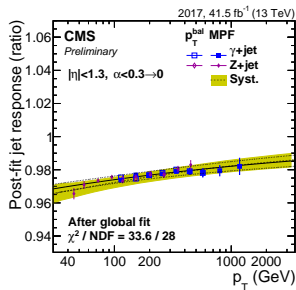
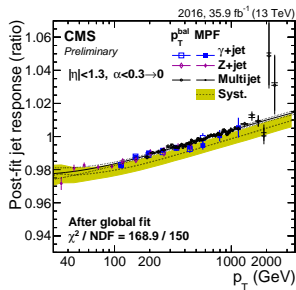
Residuals – p_T

CERN-CMS-DP-2020-019



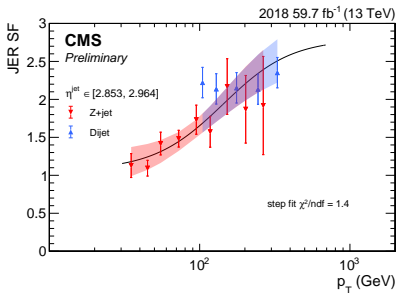
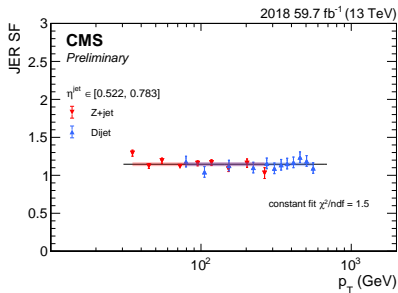
Residuals – Global fit

CERN-CMS-DP-2020-019



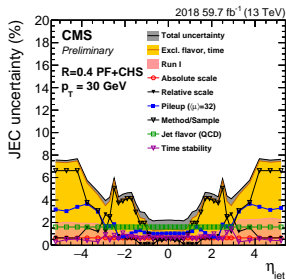
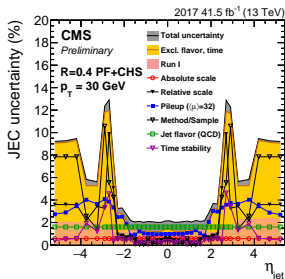
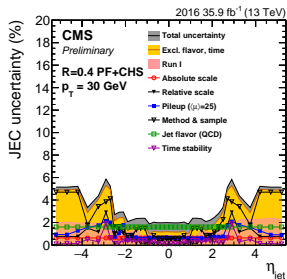
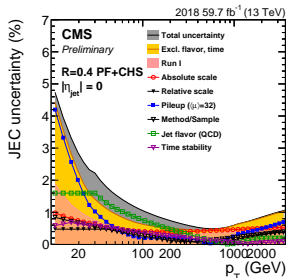
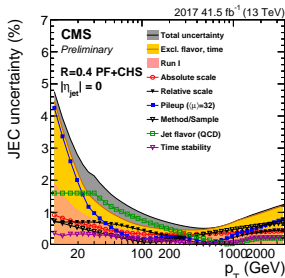
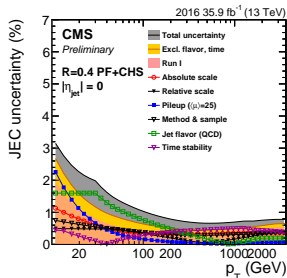
JER SF

CERN-CMS-DP-2020-019



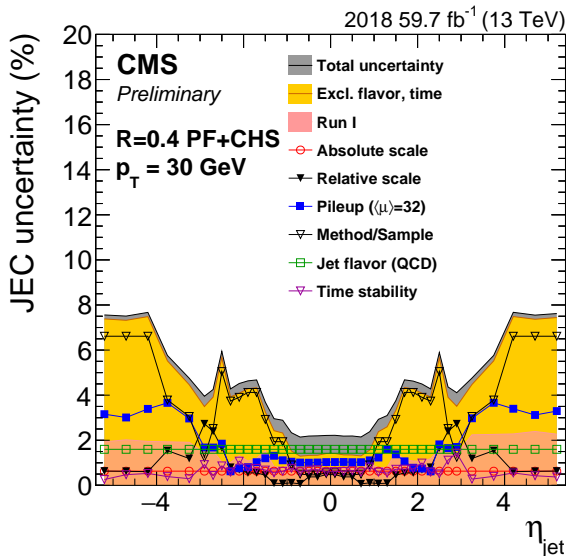
JEC Uncertainty

CERN-CMS-DP-2020-019



JEC Uncertainty

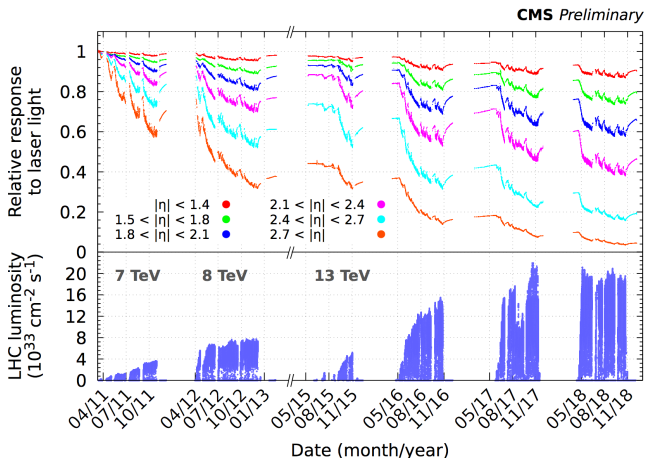
CERN-CMS-DP-2020-019



► Issues impacting uncertainty:

- PU
- Detector ageing (ECAL transparency loss)
- Malfunctions (TKR damage)

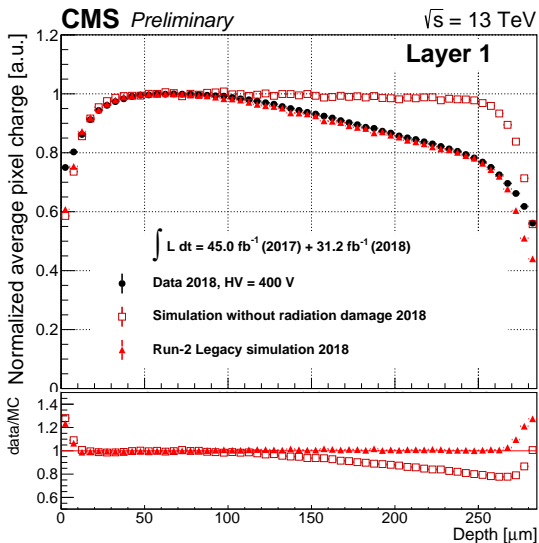
Run 2 ($\sim 2 - 8\%$)Run 1 ($\sim 1 - 2\%$)



Evolution of crystal transparency in different regions of the detector during LHC Run 1 and Run 2

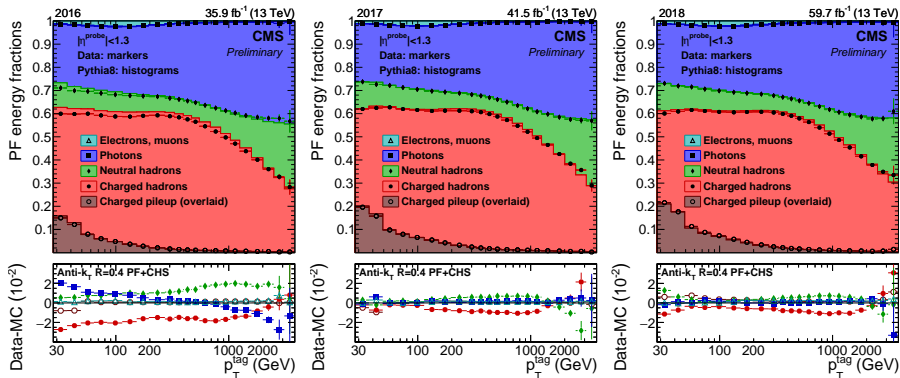
PIX/TRK radiation damage

CERN-CMS-DP-2020-026



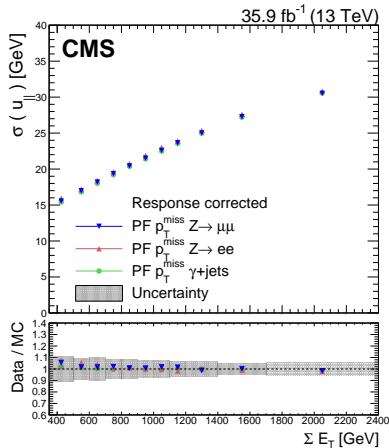
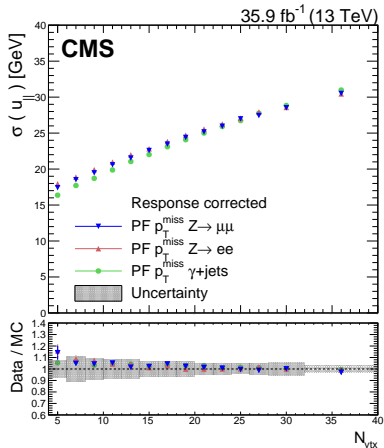
PF composition

CERN-CMS-DP-2020-019



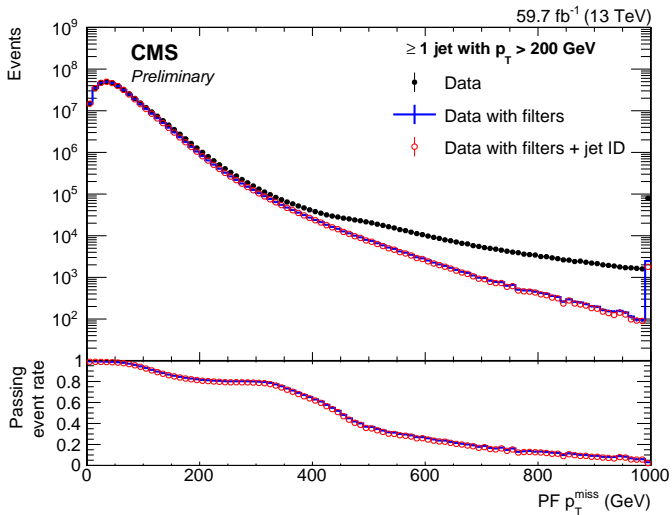
MET Resolution

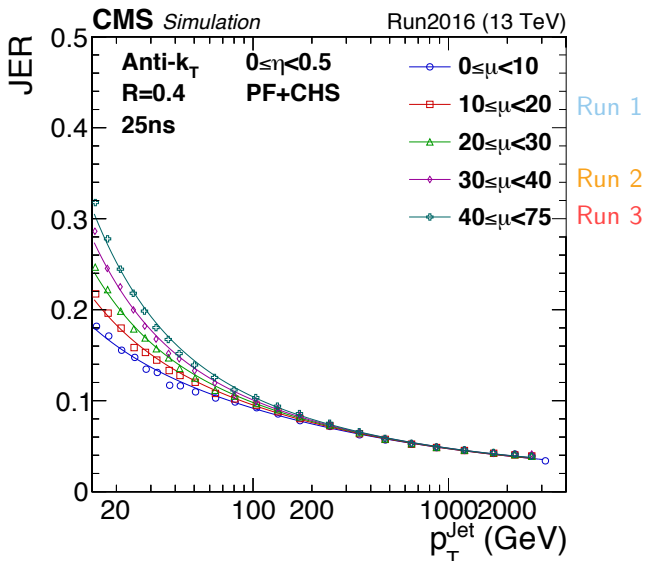
arXiv:1903.06078



MET Performance 2018

CERN-CMS-DP-2020-031





ML for Hbb regression – Resolution

CMS-PAS-HIG-18-027

