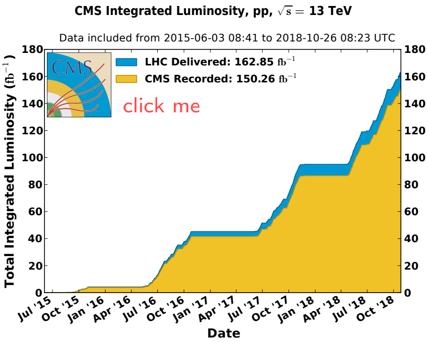
Jet and missing p_T *reconstruction: Run 2 and perspective for Run 3*

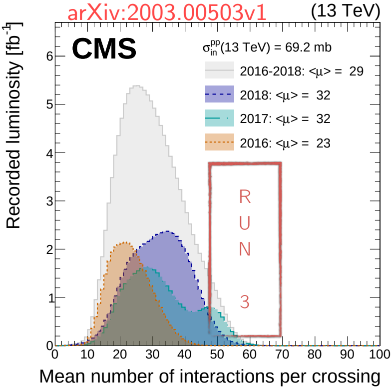
Andrea Malara
on behalf of the CMS Collaboration

29th July 2020

Overview

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





Building Jets & $p_{\mathrm{T}}^{\mathrm{miss}}$

Local reconstruction: Tracks, ECAL, HCAL

- Information from sub-detectors
- Fast to cope with PU

Particle flow (PF)

- Linking of sub-detector
- Particle identification
- Pileup mitigation

Jet & $p_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction

- Clustering
- Jet types (PF, Calo)
- Algorithms (AK, CA)
- Cone radius (0.4, 0.8, 1.5)

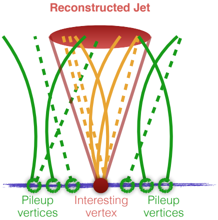
Jet & $p_{\mathrm{T}}^{\mathrm{miss}}$ calibration

- Jet energy scale & resolution
- $p_{\mathrm{T}}^{\mathrm{miss}}$ type-I corrections
- Additional cleaning (PU ID)

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 70 interactions



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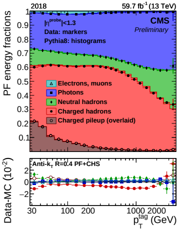
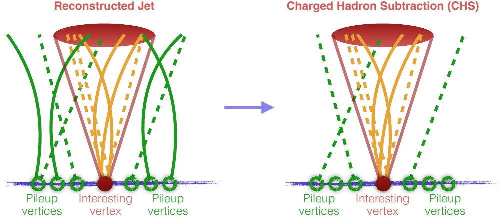
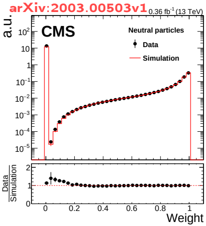


Charged Hadron Subtraction (CHS)

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



Pileup Mitigation Techniques



Pileup

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Charged Hadron Subtraction (CHS)

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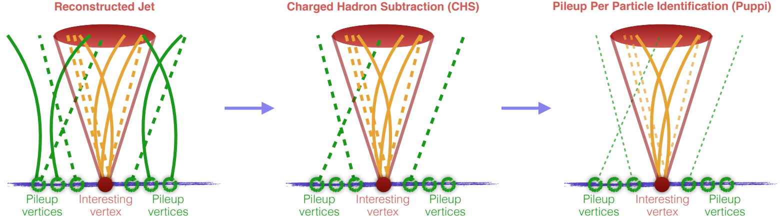
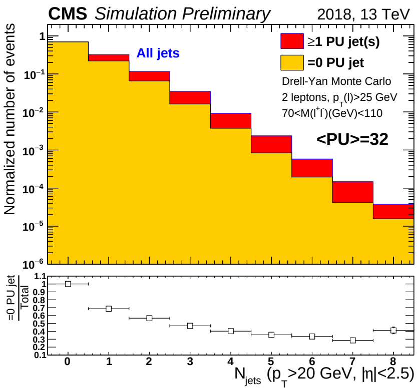
Pileup Per Particle Identification (Puppi)

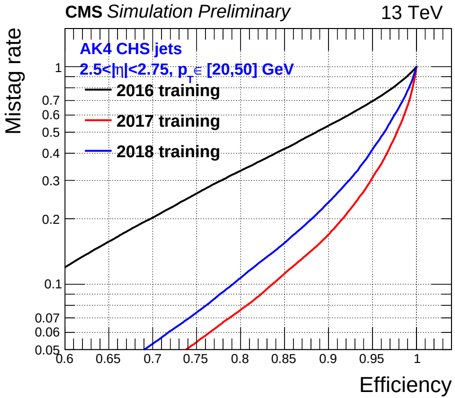
- Per-particle weight
- Scale 4-momentum before clustering
- Charged particles same as in CHS



Pileup Mitigation Techniques – PU jet ID

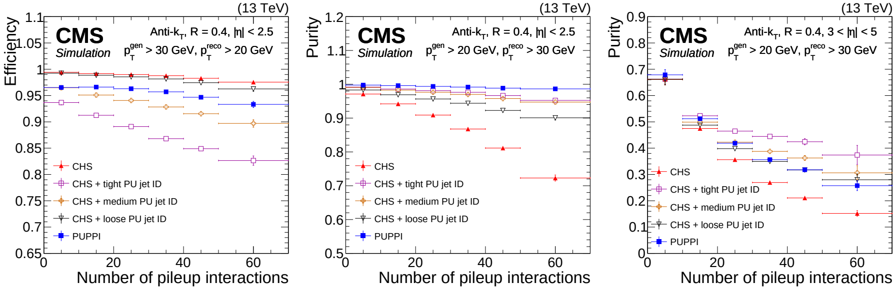
- BDT-based discriminator to identify low-p_T jets coming from PU
- High rejection power and low mistag rate at 95% efficiency
- Large improvement from Phase-1 upgrade of pixel detector after 2017: extended coverage from $|\eta|$ <2.5 to 2.7





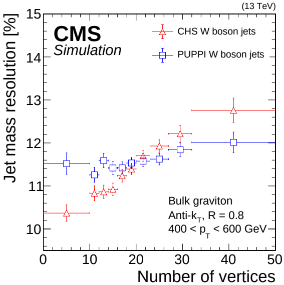
Pileup Mitigation Techniques – CHS vs. PUPPI

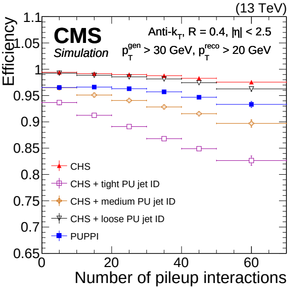
- Puppi: Good balance between purity and efficiency for $|\eta| < 2.5$
- CHS: Improves purity at cost of efficiency in combination with PU jet ID

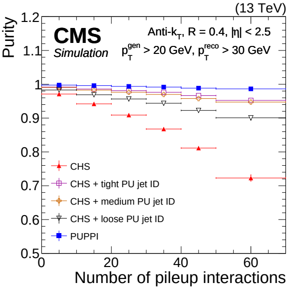


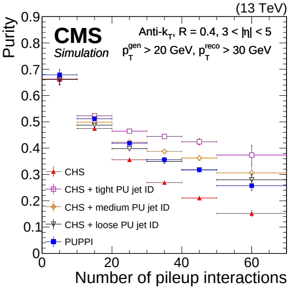
Pileup Mitigation Techniques – CHS vs. PUPPI

- 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)

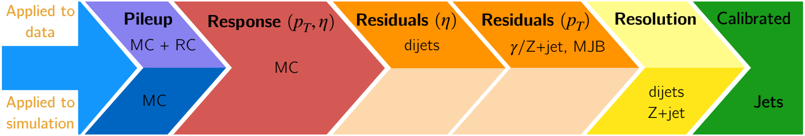






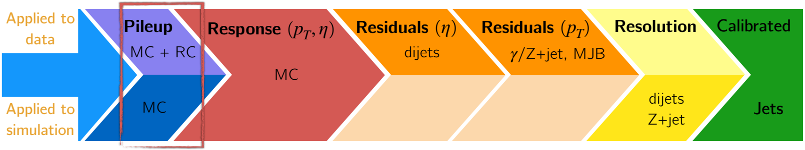


Jet Calibration



Strategy:
Factorized approach

Jet Calibration

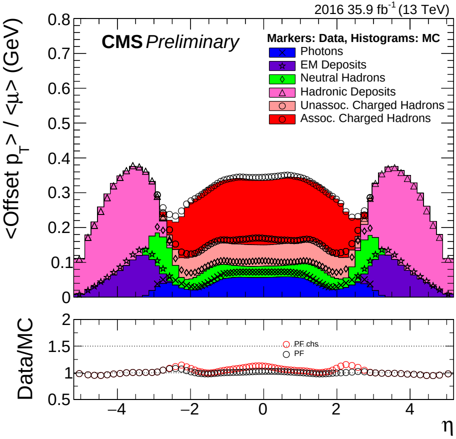


Strategy: Factorized approach

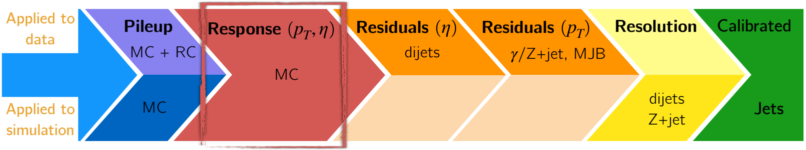
MC truth correction:

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



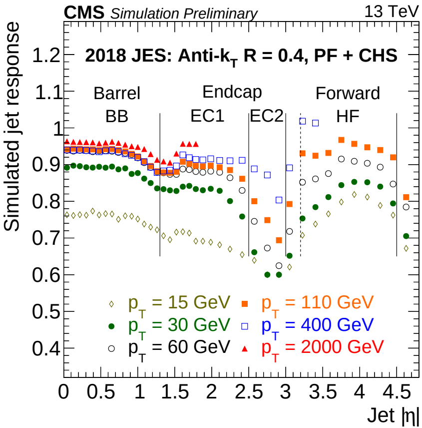
Strategy: Factorized approach

MC truth correction:

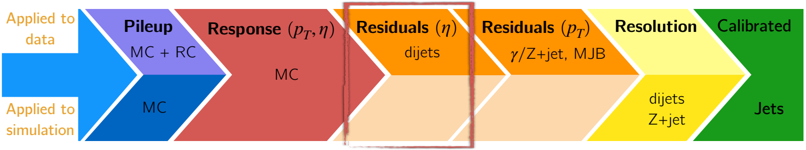
PU subtraction

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

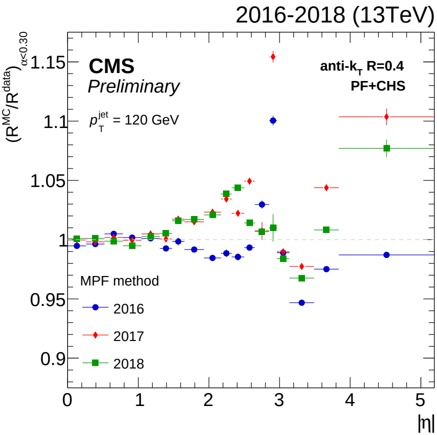
MC truth correction:

PU subtraction

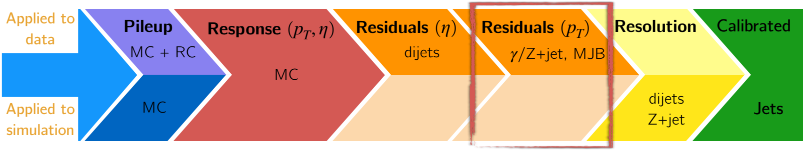
Jet response calibration

Residual corrections

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



Jet Calibration



Strategy:
Factorized approach

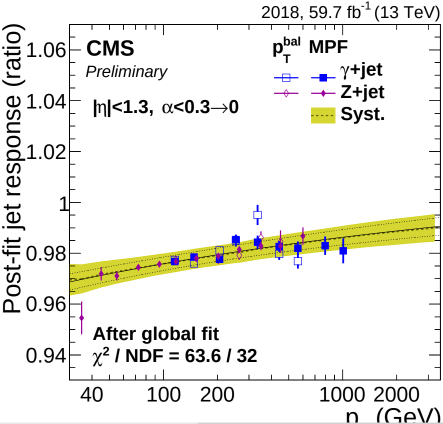
MC truth correction:

PU subtraction

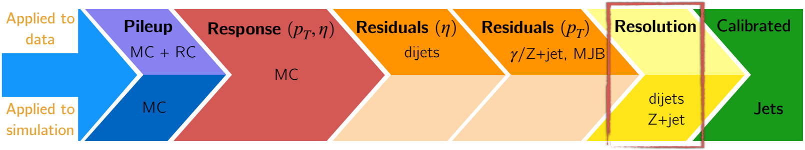
Jet response calibration

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 objects scales as nuisance parameters)



Jet Calibration



Strategy: Factorized approach

MC truth correction:

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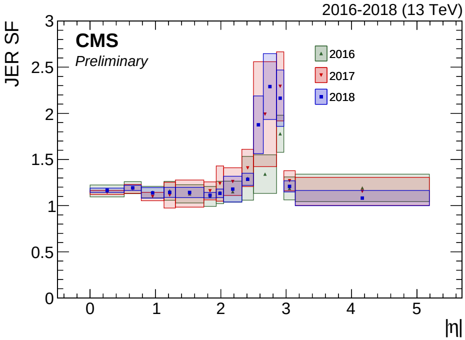
Jet response calibration

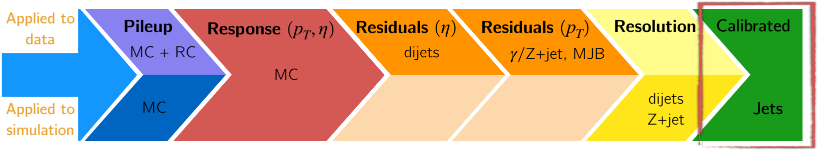
Residual corrections

Jet energy resolution smearing

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



Jet Calibration



Strategy: Factorized approach

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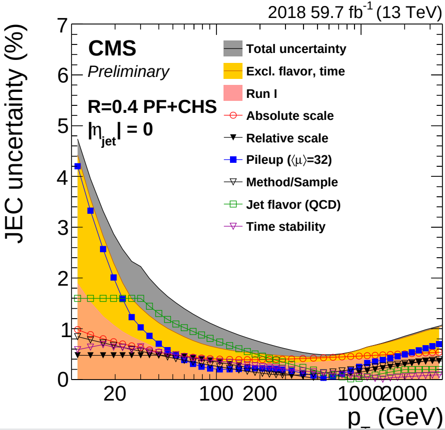
Jet energy resolution smearing

Jet Energy Scale Uncertainty

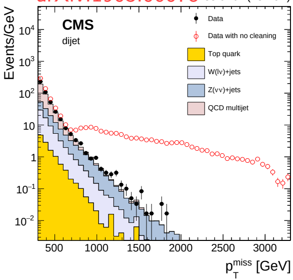
- Well-calibrated jets with uncertainty $\sim 1\%$ for $p_T \geq 100$ GeV
- Larger contribution from PU corrections



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 large 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 $< 0.1\%$

arXiv:1903.06078



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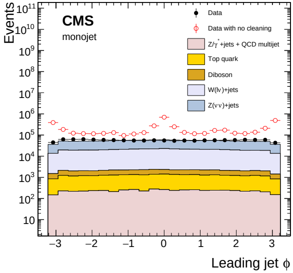
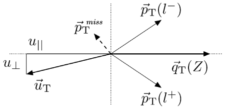
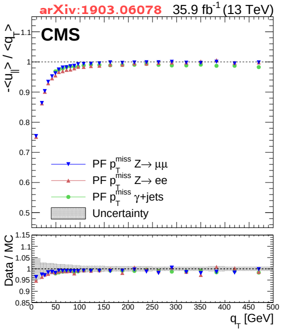


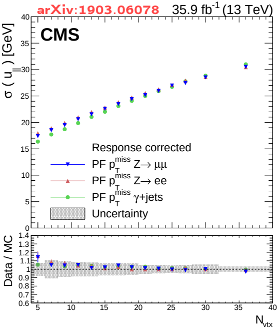
Full Run 2 studies: CERN-CMS-DP-2020-018

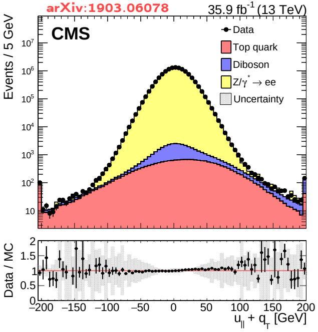
p_T^{miss} – Performance



- 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%

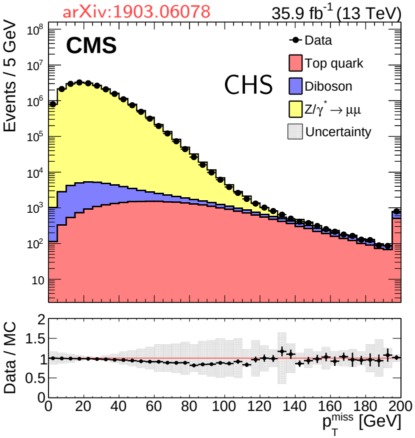


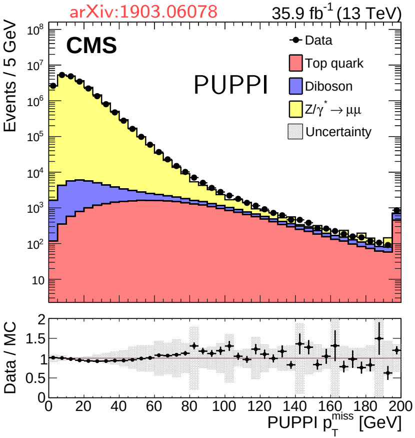




p_T^{miss}– CHS vs. PUPPI

- Puppi improves p_T^{miss} resolution
- Any wrong weight assignment could lead to fake p_T^{miss}– larger tails





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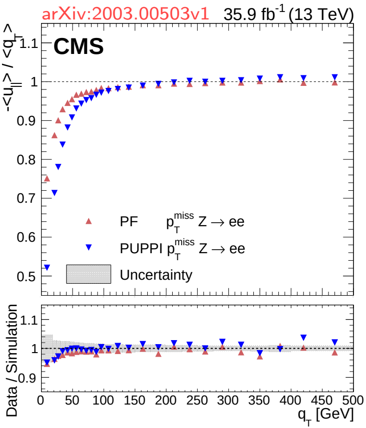
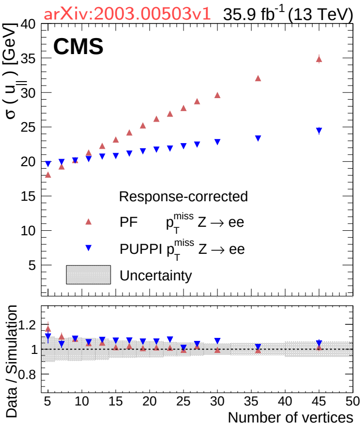
- Down-weighting neutral component of PV $\rightarrow$ slower p_T^{miss} turn-on
- Puppi performance stable against pileup





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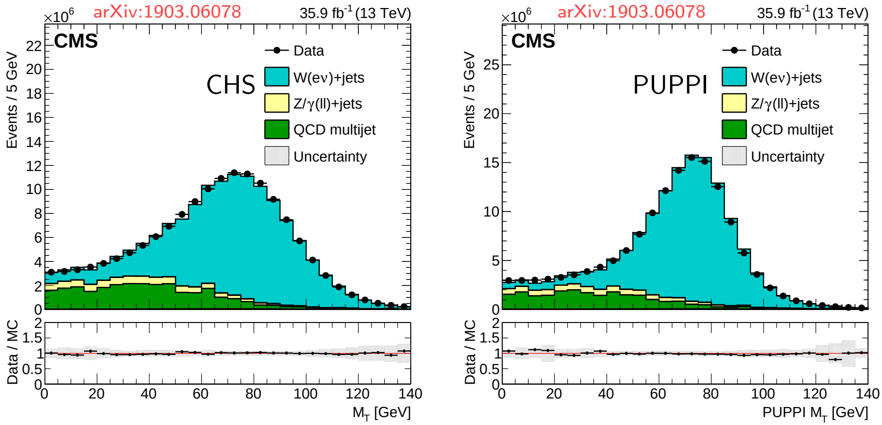
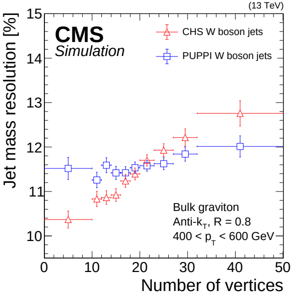
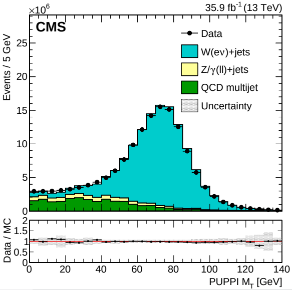
- Puppi performance stable against pileup
- Impressive resolution improvements for W+jets events



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 Run3 (Puppi is very promising)
- But it's not the end of the story
    - Increasing the dimensionality of the corrections to tackle ageing detector
    - ML-based approaches will help

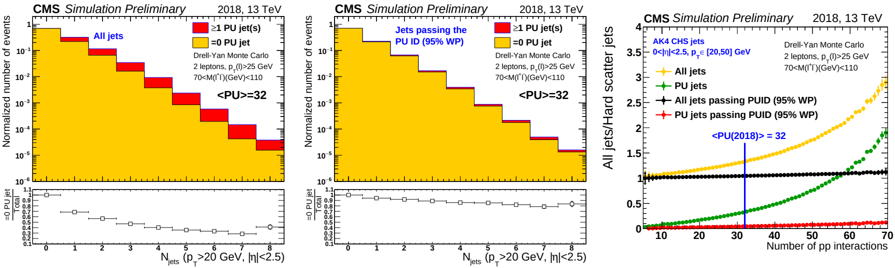




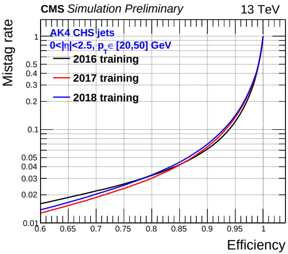
More exciting results are yet to come

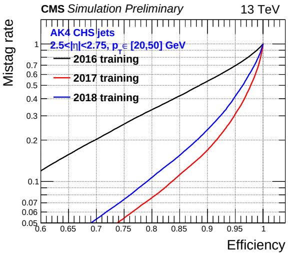
—Additional Material—

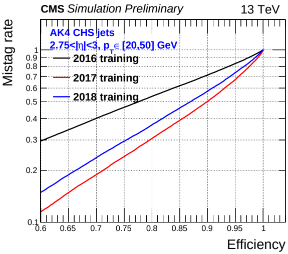
PU jet ID

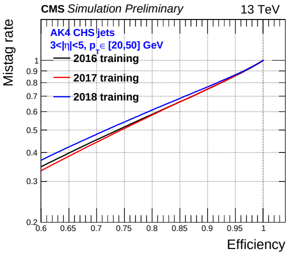

CMS Simulation Preliminary
2018, 13 TeV
All jets
≥1 PU jet(s)
=0 PU jet
Drell-Yan Monte Carlo
2 leptons, $p_T(l)$>25 GeV
70<$M(l^+l^-)$(GeV)<110
<PU>=32
Normalized number of events
=0 PU jet / Total
N_{jets} (p_T>20 GeV, |η|<2.5)
Jets passing the PU ID (95% WP)
AK4 CHS jets
0<|η|<2.5, p_T∈ [20,50] GeV
All jets
PU jets
All jets passing PUID (95% WP)
PU jets passing PUID (95% WP)
<PU(2018)> = 32
All jets/Hard scatter jets
Number of pp interactions

PU jet ID – ROC

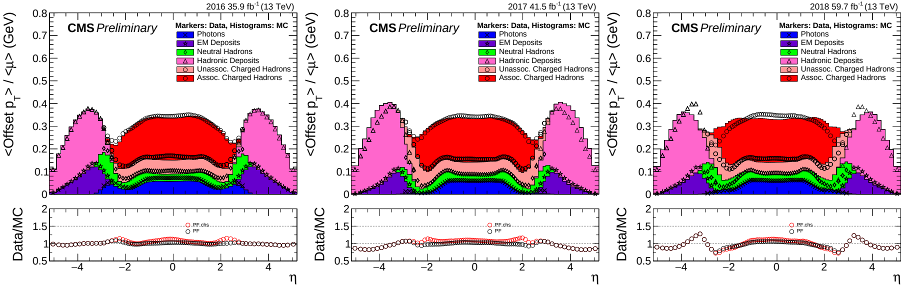

CMS Simulation Preliminary
13 TeV
AK4 CHS jets
0<|η|<2.5, p_T ∈ [20,50] GeV
2016 training
2017 training
2018 training
Mistag rate
Efficiency


CMS Simulation Preliminary
13 TeV
AK4 CHS jets
2.5<|η|<2.75, p_T ∈ [20,50] GeV
2016 training
2017 training
2018 training
Mistag rate
Efficiency

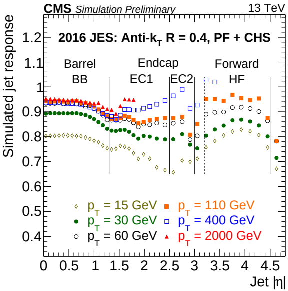

CMS Simulation Preliminary
13 TeV
AK4 CHS jets
2.75<|η|<3, p_T ∈ [20,50] GeV
2016 training
2017 training
2018 training
Mistag rate
Efficiency

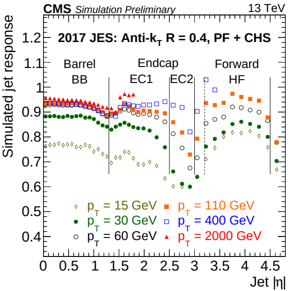

CMS Simulation Preliminary
13 TeV
AK4 CHS jets
3<|η|<5, p_T ∈ [20,50] GeV
2016 training
2017 training
2018 training
Mistag rate
Efficiency

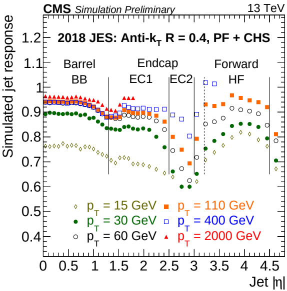
PU Offset


2016 35.9 fb-1 (13 TeV)
2017 41.5 fb-1 (13 TeV)
2018 59.7 fb-1 (13 TeV)
CMS Preliminary
Markers: Data, Histograms: MC
Photons
EM Deposits
Neutral Hadrons
Hadronic Deposits
Unassoc. Charged Hadrons
Assoc. Charged Hadrons
<Offset pT> / <μ> (GeV)
Data/MC
PF chs
PF
η

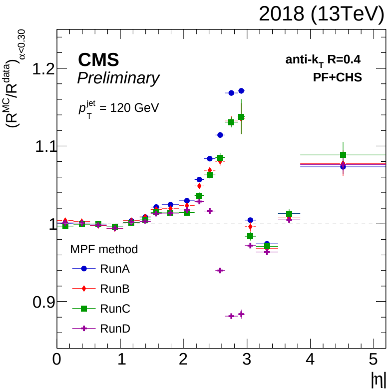
Jet Response

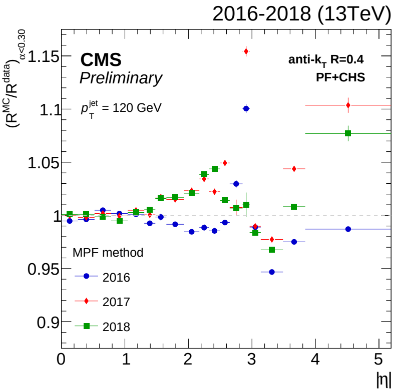




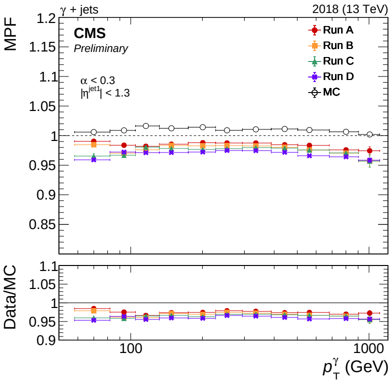


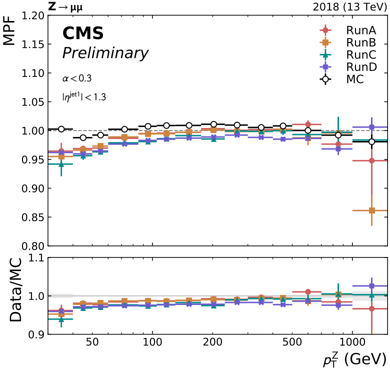
Residuals – η



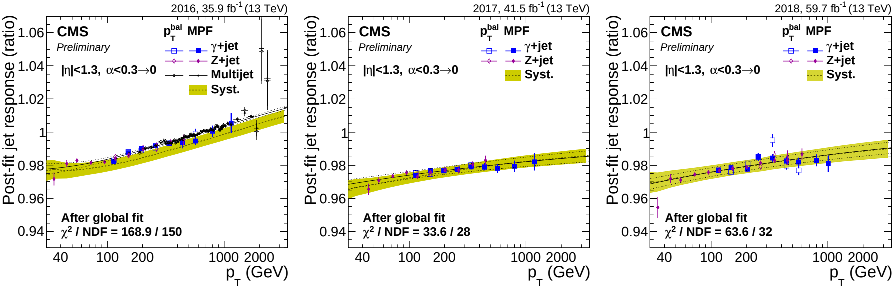


Residuals – p_T

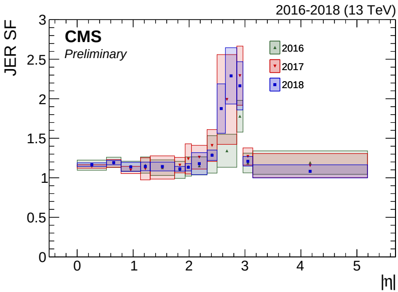


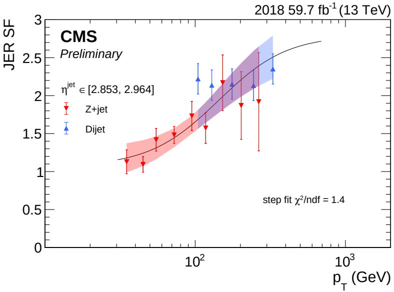


Residuals – Global fit

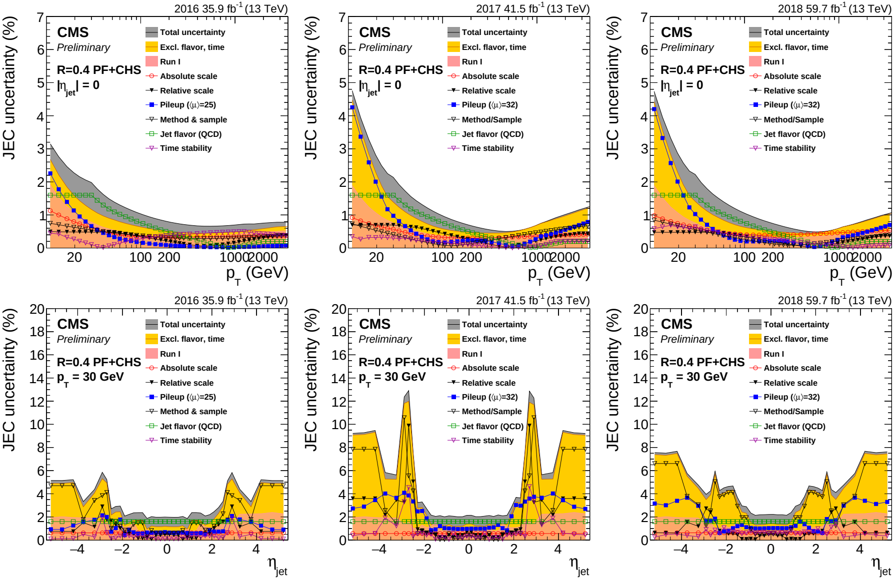


JER SF

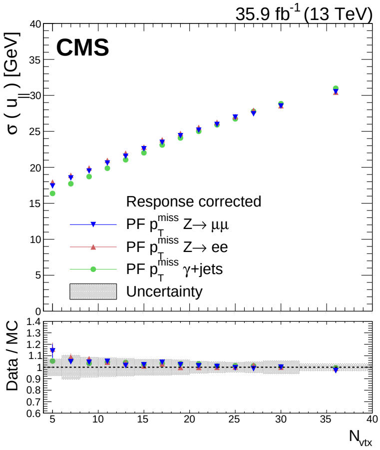

2016-2018 (13 TeV)
CMS
Preliminary
2016
2017
2018
JER SF
|η|

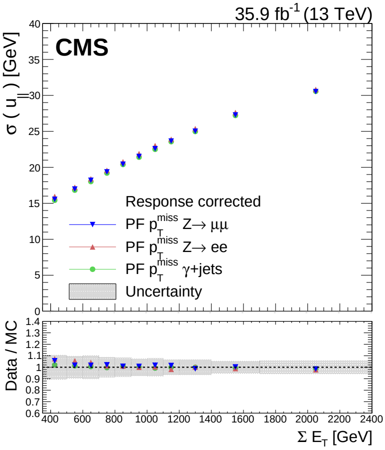

2018 59.7 fb^{-1} (13 TeV)
CMS
Preliminary
$\eta^{jet} \in [2.853, 2.964]$
Z+jet
Dijet
step fit χ^2/ndf = 1.4
JER SF
p_T (GeV)

JEC Uncertainty

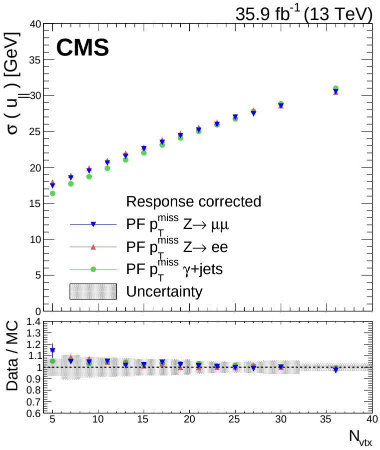


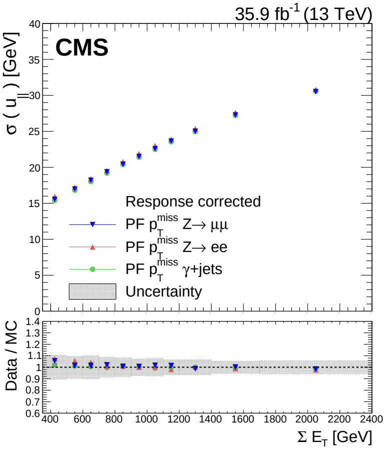
MET Scale


35.9 fb-1 (13 TeV)
CMS
σ (u∥) [GeV]
Response corrected
PF pTmiss Z→ μμ
PF pTmiss Z→ ee
PF pTmiss γ+jets
Uncertainty
Data / MC
Nvtx

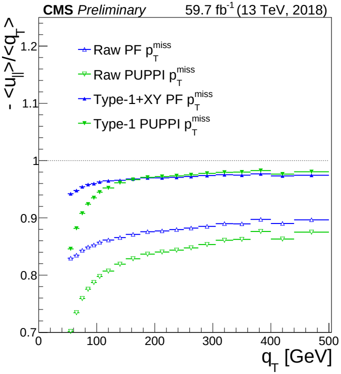

35.9 fb-1 (13 TeV)
CMS
σ (u∥) [GeV]
Response corrected
PF pTmiss Z→ μμ
PF pTmiss Z→ ee
PF pTmiss γ+jets
Uncertainty
Data / MC
Σ ET [GeV]

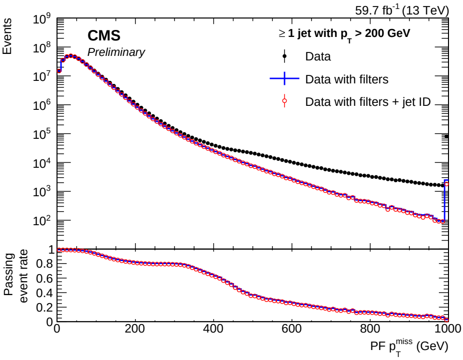
MET Scale


35.9 fb^{-1} (13 TeV)
CMS
σ ($u_{\parallel}$) [GeV]
Response corrected
PF p_T^{miss} $Z\rightarrow \mu\mu$
PF p_T^{miss} $Z\rightarrow ee$
PF p_T^{miss} γ+jets
Uncertainty
Data / MC
N_{vtx}

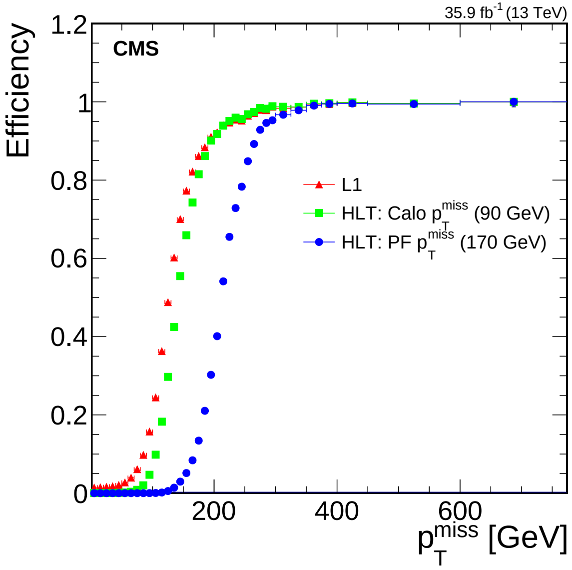

35.9 fb^{-1} (13 TeV)
CMS
σ ($u_{\parallel}$) [GeV]
Response corrected
PF p_T^{miss} $Z\rightarrow \mu\mu$
PF p_T^{miss} $Z\rightarrow ee$
PF p_T^{miss} γ+jets
Uncertainty
Data / MC
ΣE_T [GeV]

MET Performance 2018





MET trigger


35.9 fb^{-1} (13 TeV)
CMS
Efficiency
1.2
1
0.8
0.6
0.4
0.2
0
200
400
600
p_T^{miss} [GeV]
L1
HLT: Calo p_T^{miss} (90 GeV)
HLT: PF p_T^{miss} (170 GeV)