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Inclusive Jets in CMS Experiment

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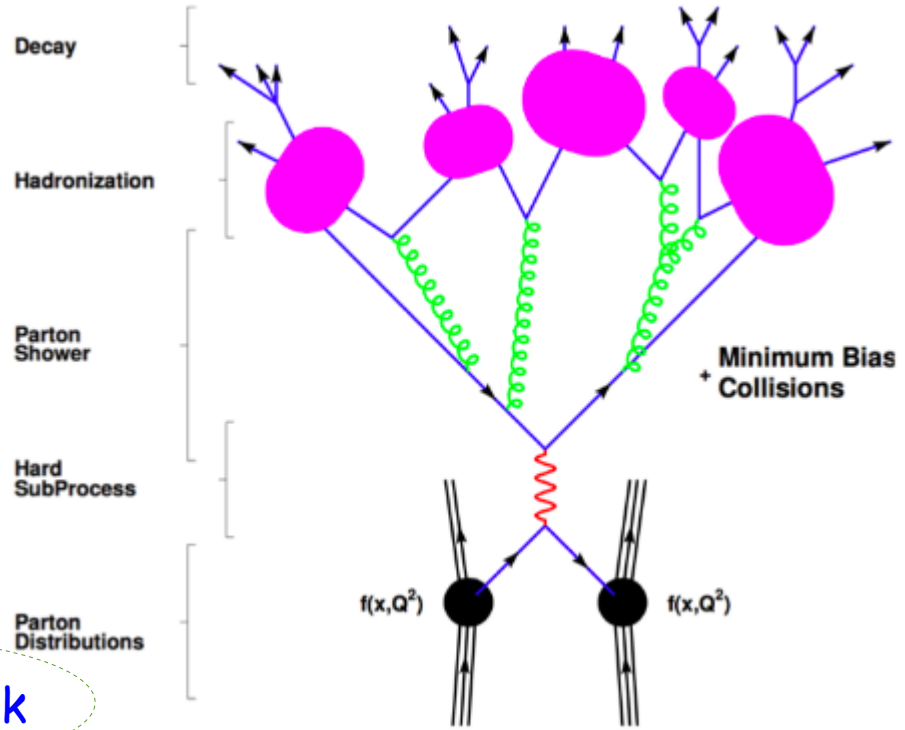
Inclusive Jets : Why?

- Jets : collimated particle clusters
  <= surrogates of quarks & gluons produced in hard interaction
- Inclusive jets : p p -> jets + X
  <= flooded by QCD

Access to the highest energy scale available

- Useful for
  better determination of PDF
  measurement of strong coupling constant
  improved understanding of
  p-QCD & resummation
  tuning the general purpose
  event generators
  . ...

Focus of this talk

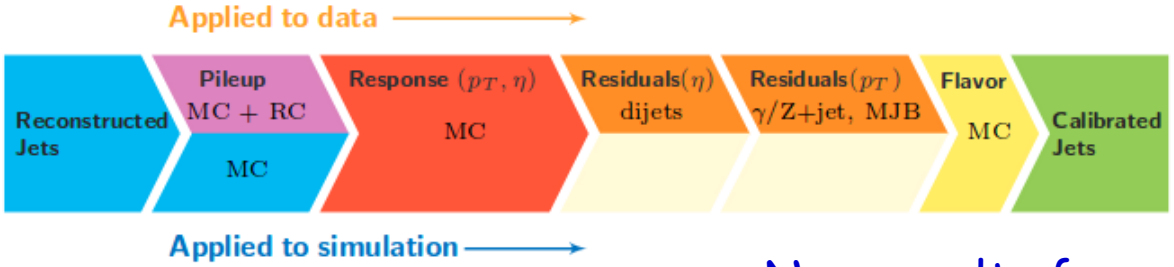


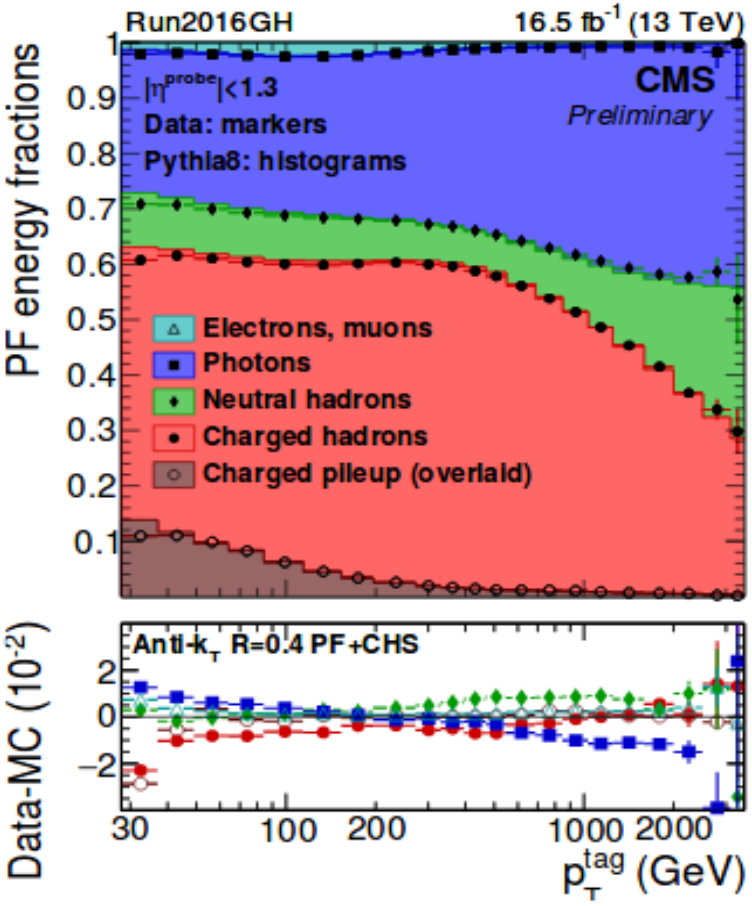
Also common background for BSM searches in hadronic final state

- Information from all sub-detectors are combined to reconstruct and identify particles (Particle Flow) → PF candidates CMS-PRF-14-001
- Jets, in CMS, are reconstructed with PF candidates using anti-kT algoirthm

Understanding Jets and Jet Algorithms

- Factorized approach to match energy of detector level jets to particle level jets (on avergae)



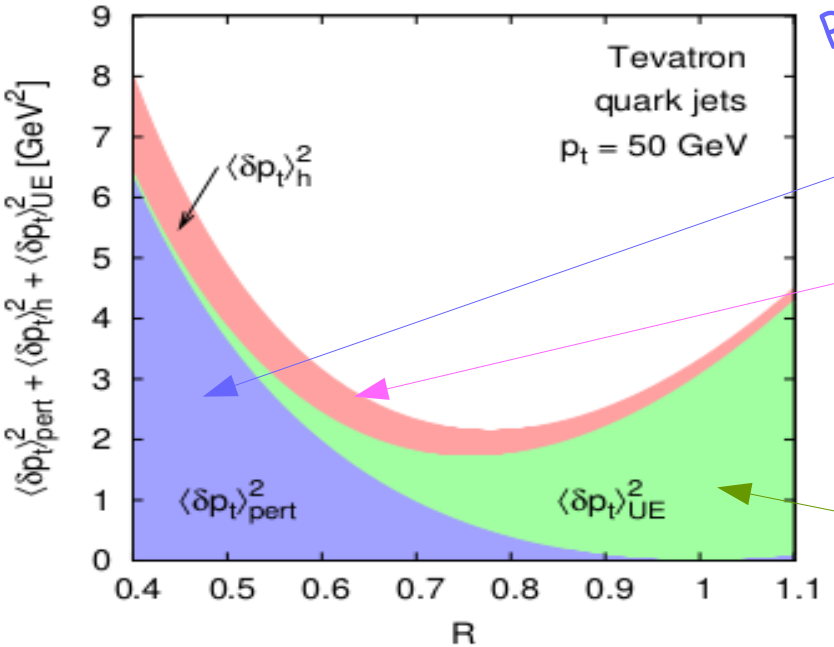


New results from CMS
CMS-PAS-SMP-19-003

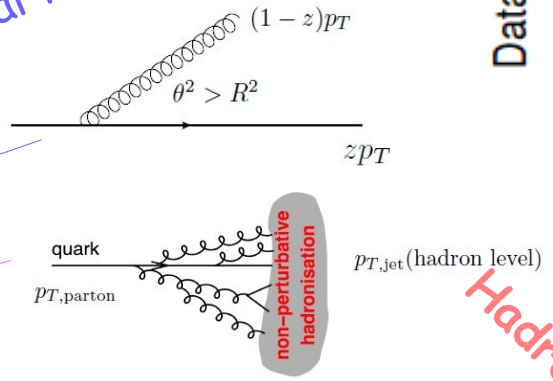
Choice of jet size :

Interplay between loosing radiation
vs adding contamination from underlying event

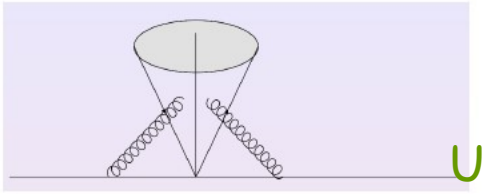
hep-ph : 0712.3014



Parton branching



Hadronization



Underlying event

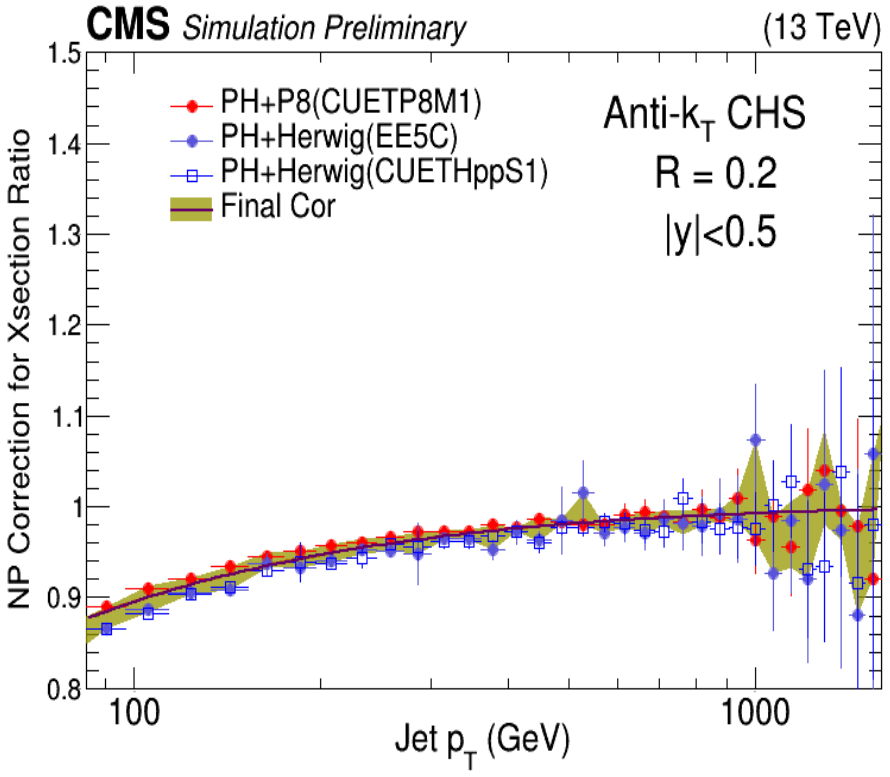
CMS-DP-2018-028

Excellent tracking performance even in ~ TeV scale

Nonperturbative Correction for Fixed Order Prediction

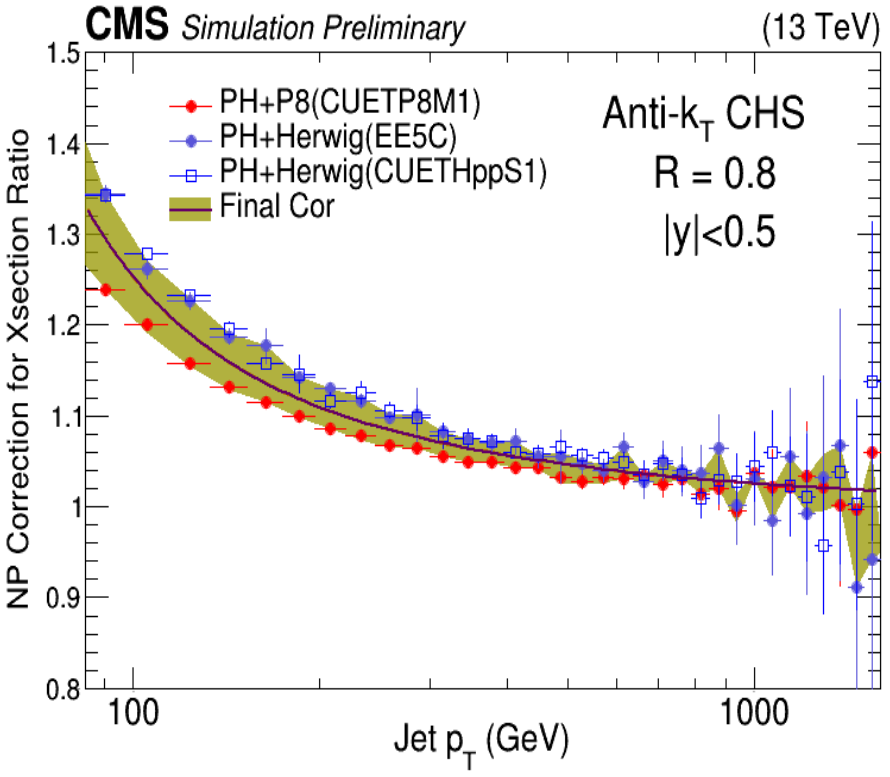
- Fixed order calculation provides differntial cross section for parton level jets but jets in data are made from hadrons => needs additional correction
- Based on MC prediction from hadronization models & MPI tunes in parton shower
- Hadronization correction is larger more small jet sizes & MPI correction has significant size for large jet radii

CMS-PAS-SMP-19-003



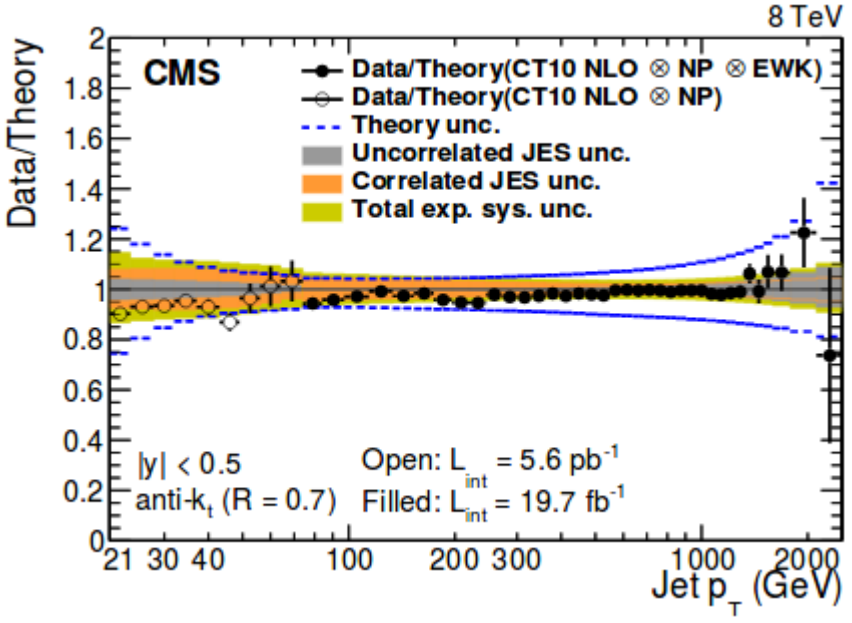
Ratio is w.r.t. AK4 jets

Common Powheg generator with Pythia8 and Herwig++ PS



- Correction = average from Powheg+Pythia8 & Powheg+Herwig++
  Uncertainty = (difference of Powheg+Pythia8 & Powheg+Herwig++)/2

Cross Section of Inclusive Jets at √s =8 and 2.76 TeV



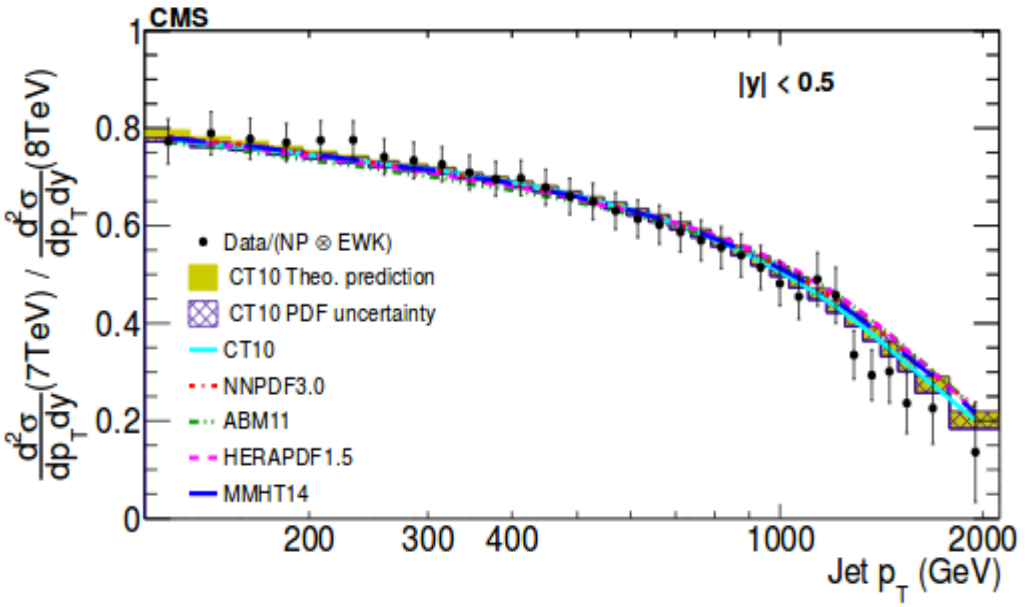
Inclusive jet cross section is well described by NLO calculations with NP and EWK corrections

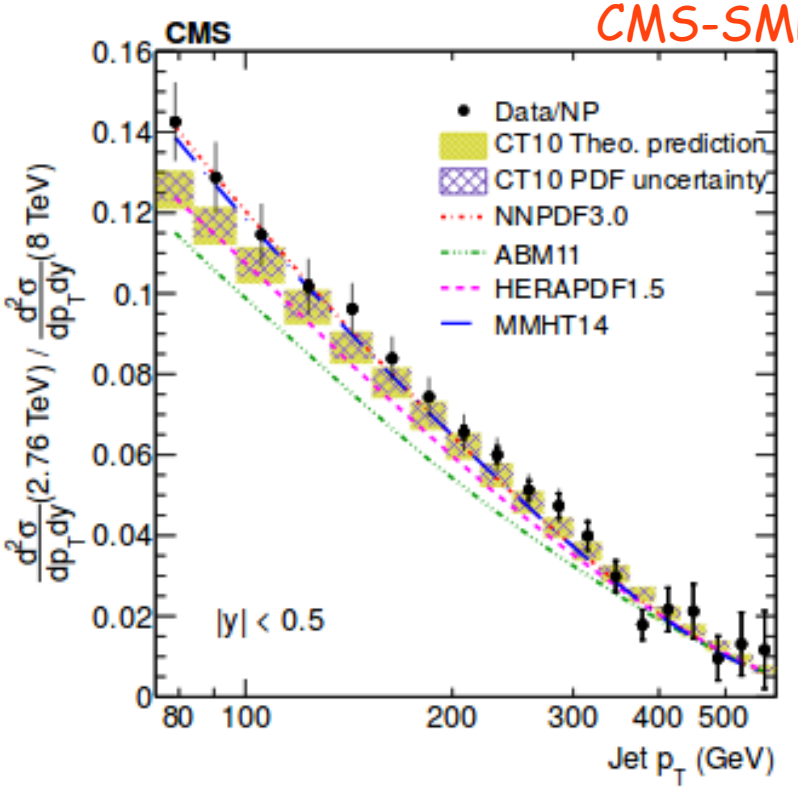
Low p_T data -> 5.6 pb^{-1} (<PU> = 4)

High p_T data -> 19.7 pb^{-1} (<PU> = 21)

Ratio of inclusive jet cross sections between two different √s is sensitive to PDF

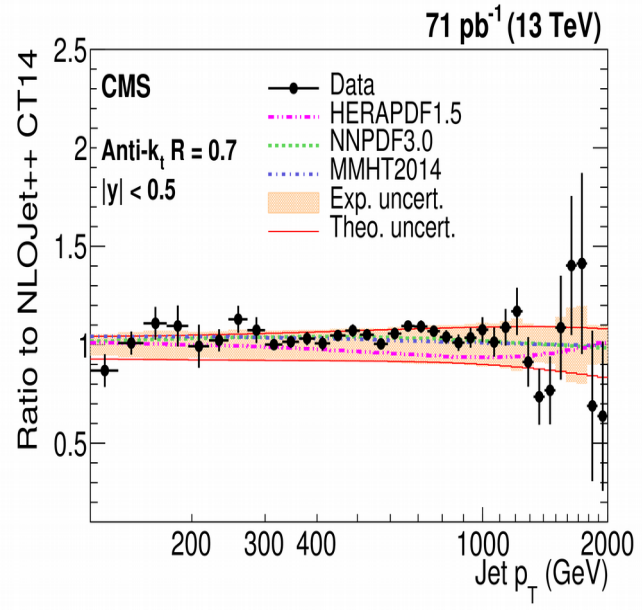
CMS-SMP-14-001

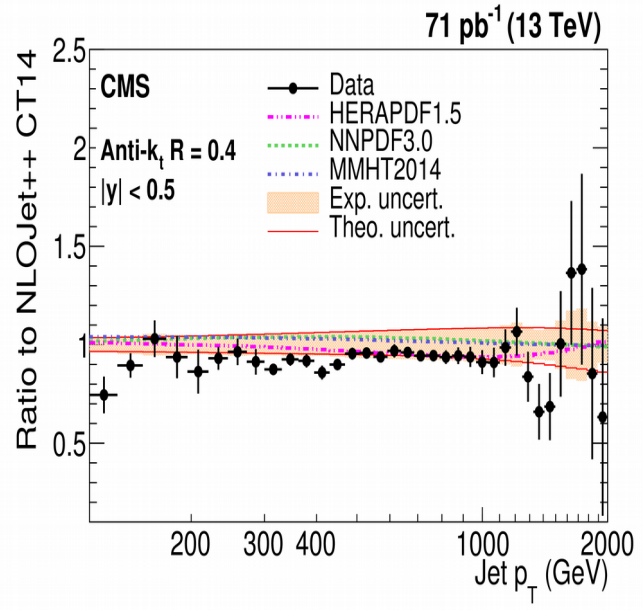




- Fixed order prediction is compatible to data within systematics for cross section ratio

Cross Section of Inclusive Jets at √s =13 TeV

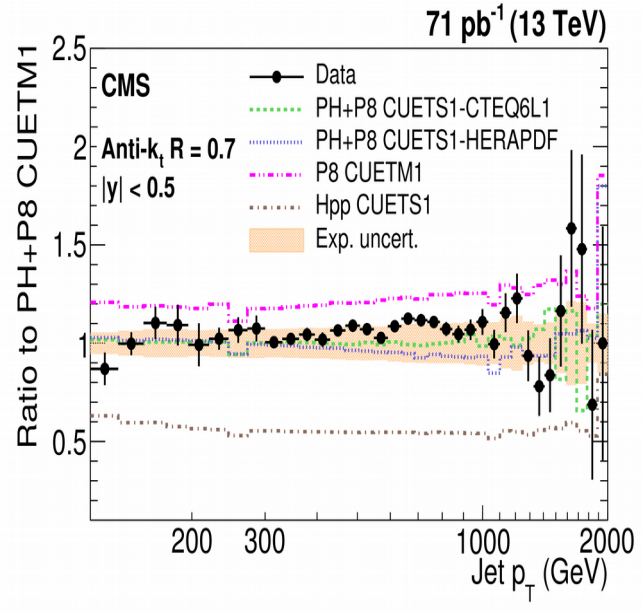


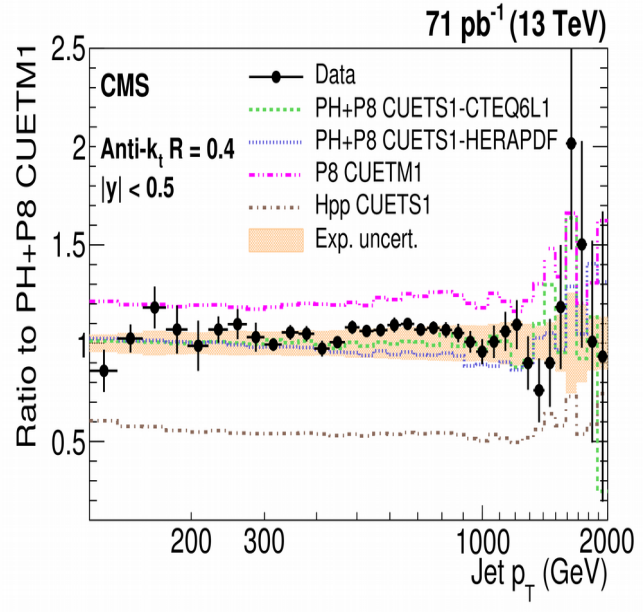


Inclusive jet data is sensitive to PDF

MMHT, NNPDF give similar Prediction to CT14NLO

CMS-SMP-15-007





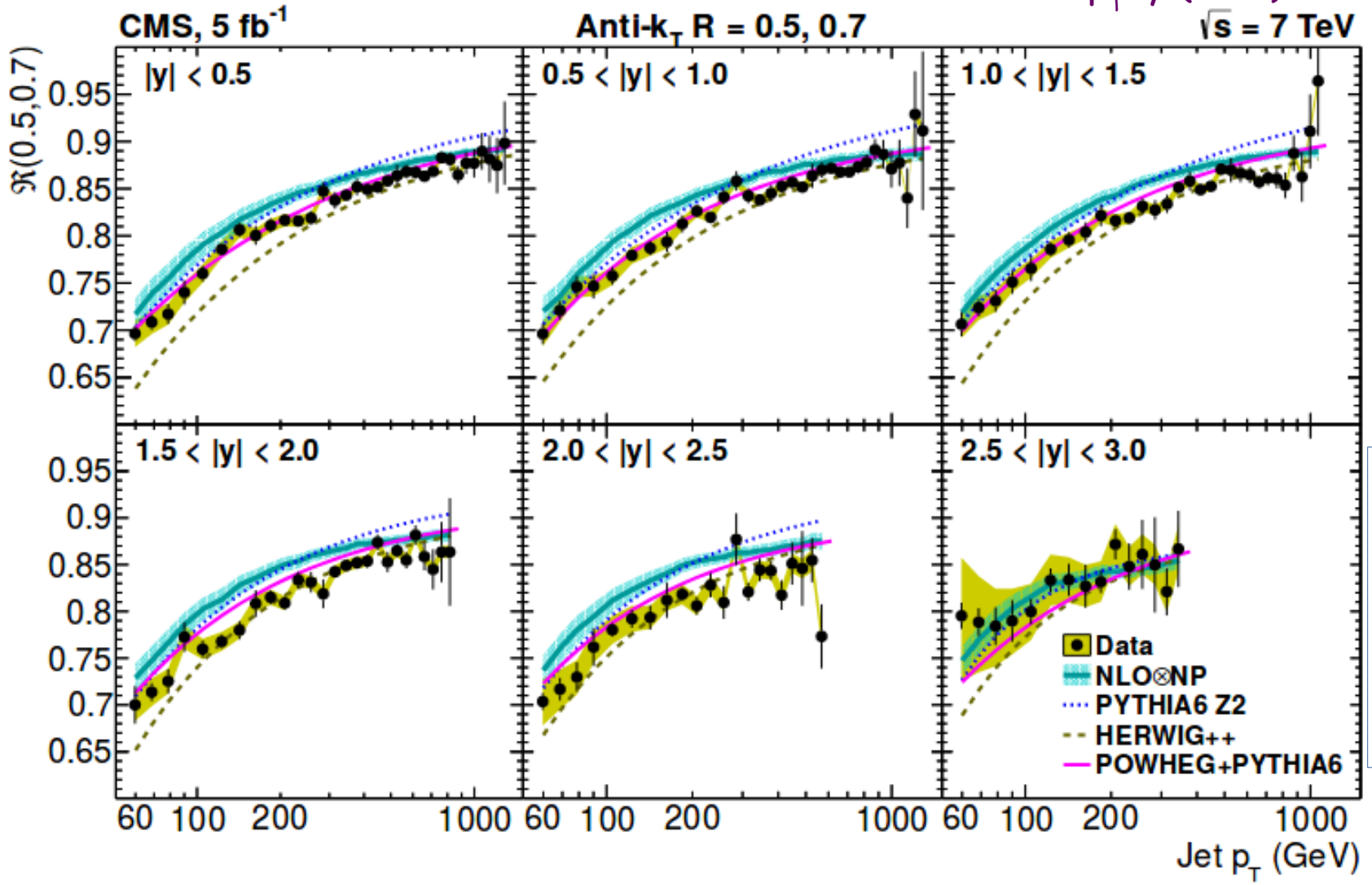
Two LO predictions are in opposite directions w.r.t. data

Powheg+Pythia8 is between Pythia8 & Herwig++, describes data quite well

- For AK4 jets, NLO+PS provides better description compared to fixed order calculation

Comparison of Ratio of Cross Sections at √s = 7 TeV

$d^2\sigma/dp_T dy\ (AK5)/d^2\sigma/dp_T dy\ (AK7)$



Power of ratio

CMS-SMP-13-002

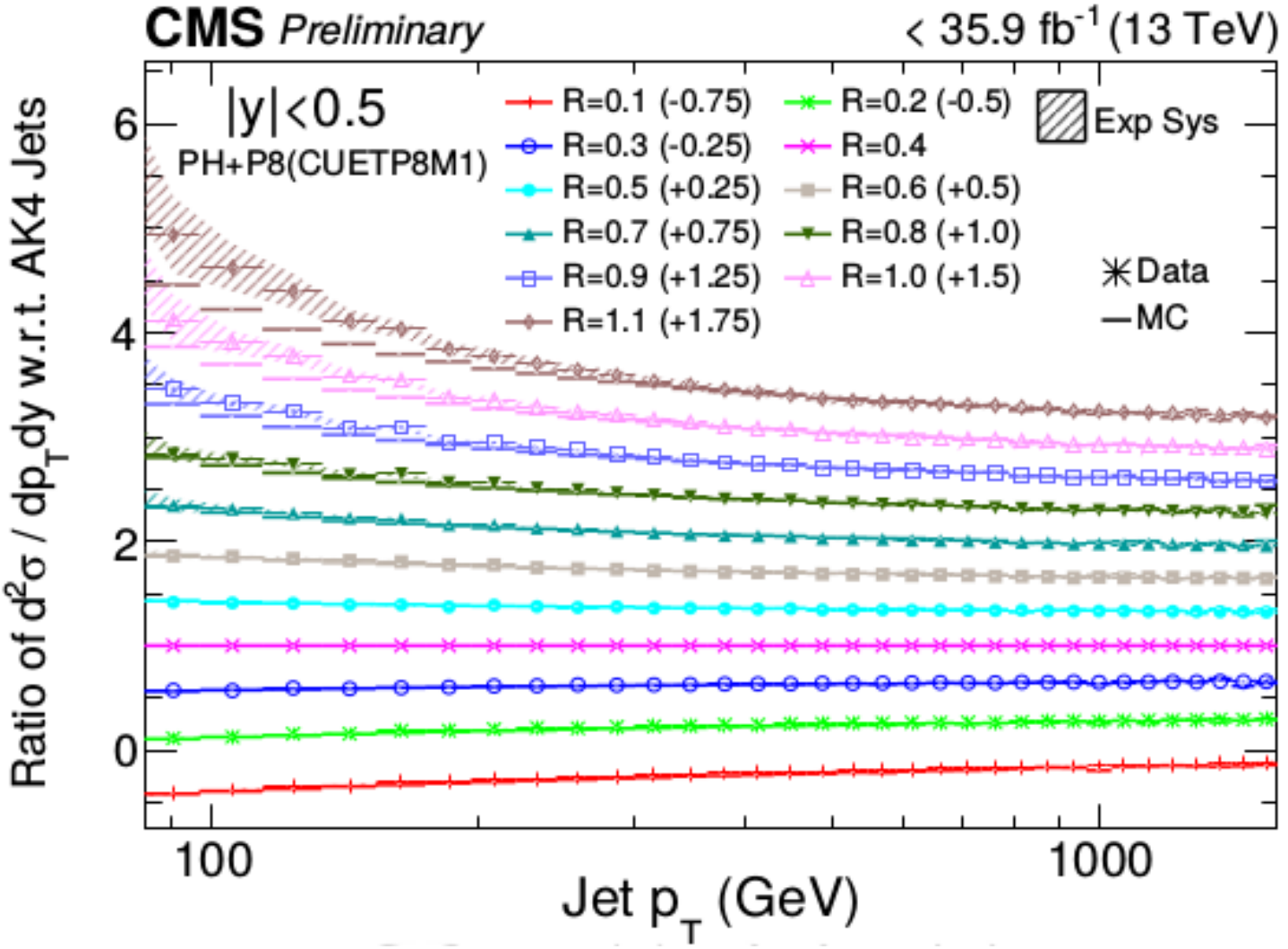
Cancellation of systematics => more precise comparison of data to theory predictions

- Good description of ratio in data by fixed order NLO prediction with nonperturbative correction
- Better modelling of data by using NLO generator followed by parton shower ; Shows the importance of final state radiation to describe the ratio

Comparison of Ratio of Cross Sections at √s = 13 TeV

$d^2\sigma/\ dp_T dy\ (AKx)\ /d^2\sigma\ /\ dp_T dy\ (AK4)$

x = 1,2,....



Data is compared to Powheg+Pythia8 prediction for a large set of jet sizes

CMS-PAS-SMP-19-003

For large jet radii, PU component of JER uncertainty increases at low pT other than uncertainties from calibration

- NLO + PS prediction describes data well till moderate values of jet radii and also at high jet pT
- Deviation occurs in low pT region for large jet sizes

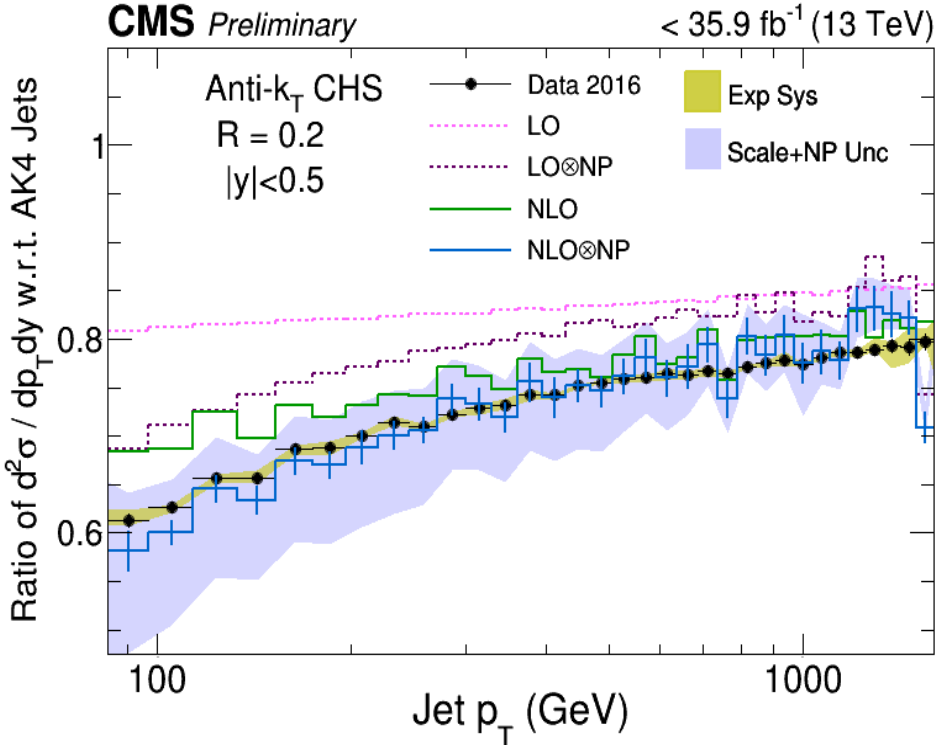
Comparison of Ratio of Cross Sections

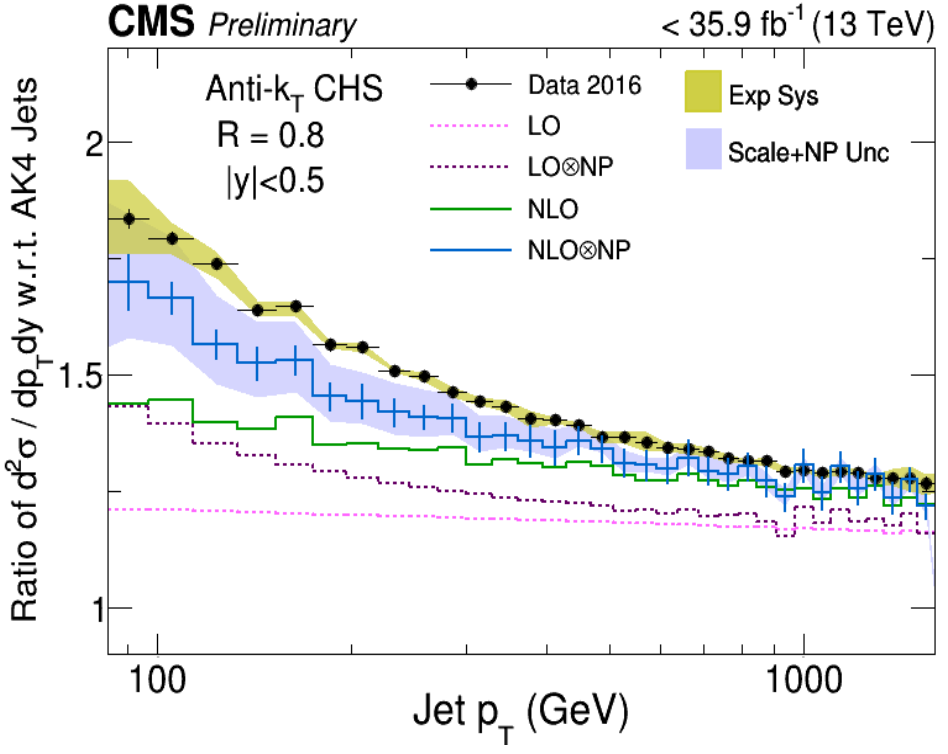
- $(\sigma^{AKn} - \sigma^{AK4})$: 3-jet cross section computed with terms up to α_s^4

hep-ph :0110315, 1101.2665

- Ratio = $(\sigma^{AKn} - \sigma^{AK4})/\sigma^{AK4} + 1$
- Calculated using NLOJet++ (in FastNLO framework)

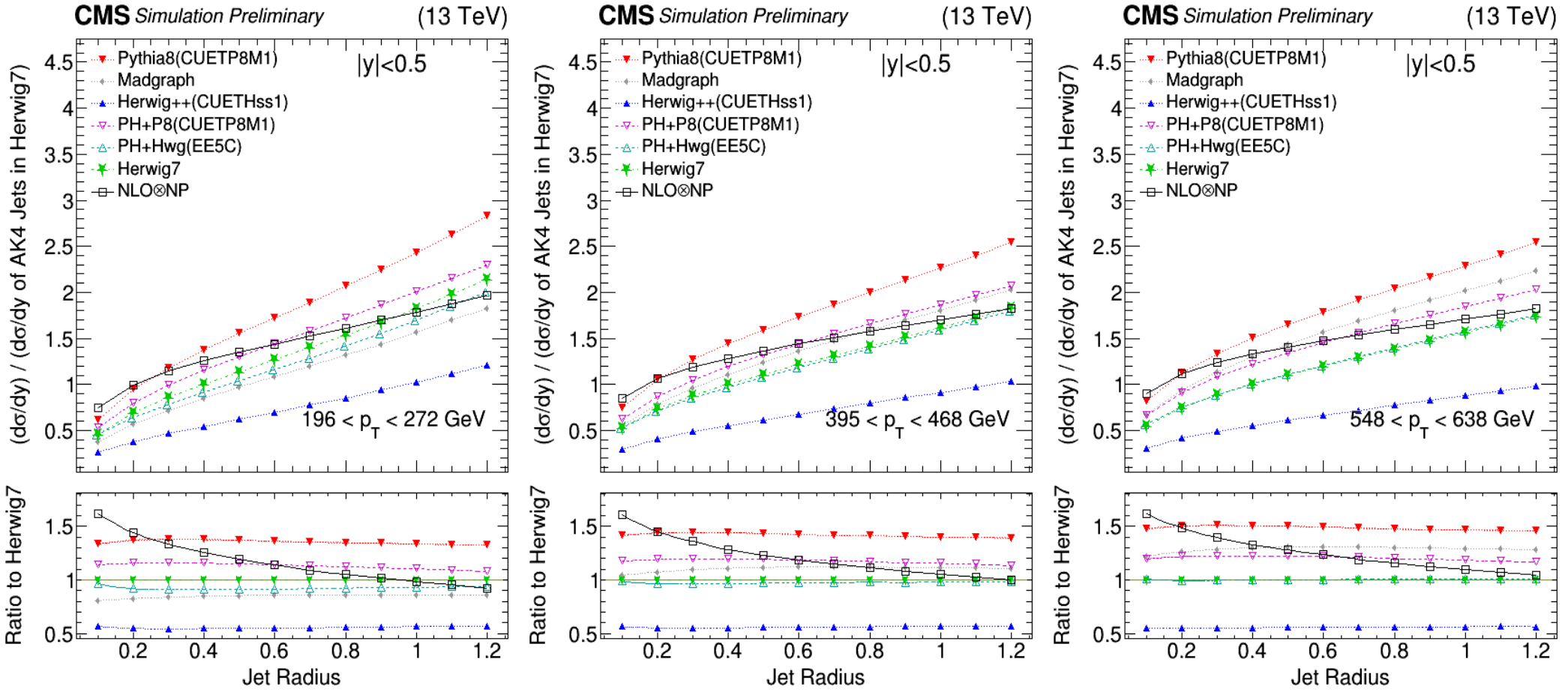
CMS-PAS-SMP-19-003





- Good description of data by NLO prediction at high pT
- NP correction is essential to describe data
- LO->NLO: Prediction comes significantly closer to data

Comparison of Ratio of Cross Sections vs R



CMS-PAS-SMP-19-003

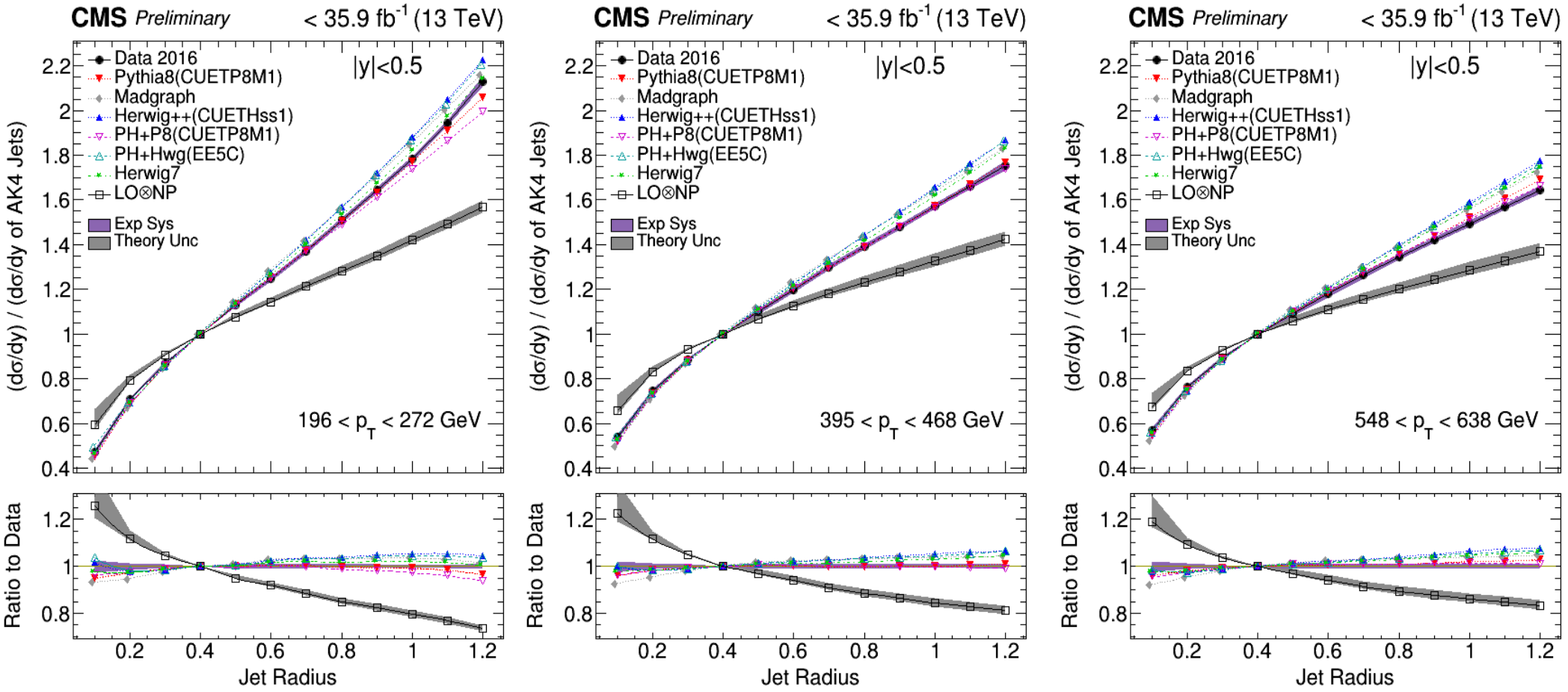
Inclusive jet cross sections are determined in pT and y bins for all the jet sizes

Ratio is taken with respect to the AK4 jet cross section in Herwig7 in the same pT and y bin

Fixed order prediction shows a different trend of the ratio versus R as compared to MC predictions

(fixed order prediction at NLO)

Comparison of Ratio of Cross Sections vs R



CMS-PAS-SMP-19-003

Inclusive jet cross sections are determined in pT and y bins for all the jet sizes

Ratio is taken with respect to AK4 inclusive jet cross section in the same pT and y bin

Fixed leading order prediction shows a different trend of the ratio versus R

MC predictions are quite stable with R as compared to data

(ratio of two fixed order NLO predictions is at LO <= change compared to last slide)

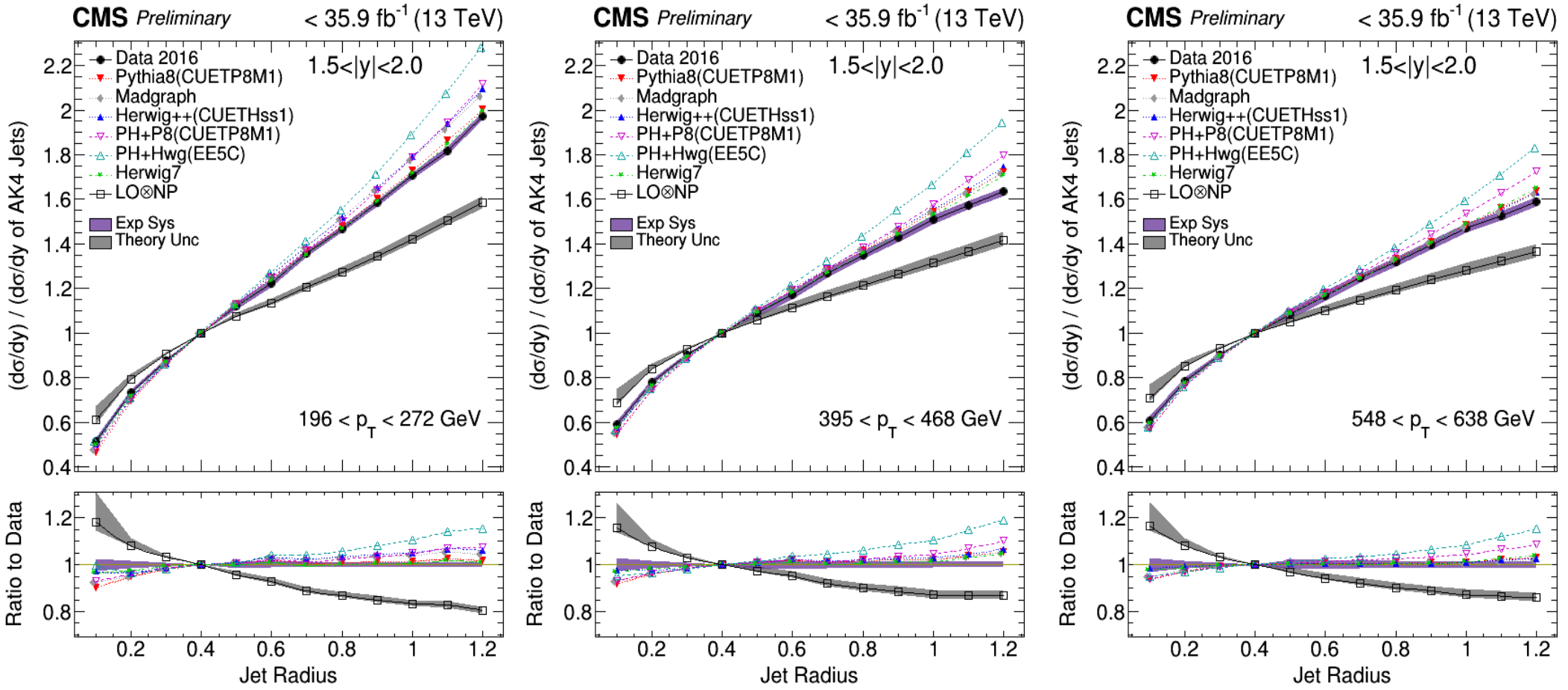
But please don't judge predictions on an absolute scale !!

Summary & Outlook

- Wealth of inclusive jet data at 13 TeV is being analyzed by CMS (both absolute cross sections and ratios)
- Measurements are useful to constrain PDF, sources of theory uncertainties, to understand p-QCD dynamics at different jet sizes,...
- Ratio of cross section of different jet sizes emphasizes the need of resummation by parton shower to describe trend as a function of jet size
- Measurement also shows the importance of nonperturbative correction for fixed order prediction and urges the quest for higher order calculation

More Material ..

Comparison of Ratio of Cross Sections vs R



SMP-19-003

Inclusive jet cross sections are determined in pT and y bins for all the jet sizes

Ratio is taken with respect to AK4 inclusive jet cross section in the same pT and y bin

Fixed order prediction shows a different trend of the ratio versus R

MC predictions are quite stable with R as compared to data

Similar trend in different y bins

But please don't judge predictions on an absolute scale !!

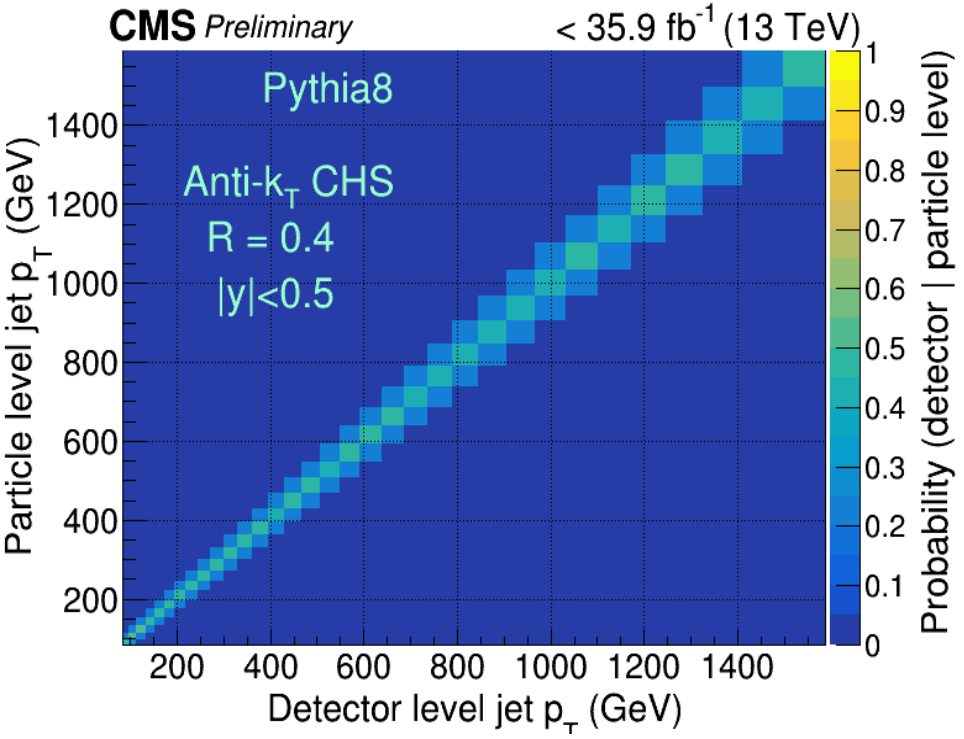
Unfolding : Journey of Jets from Detector to Particle

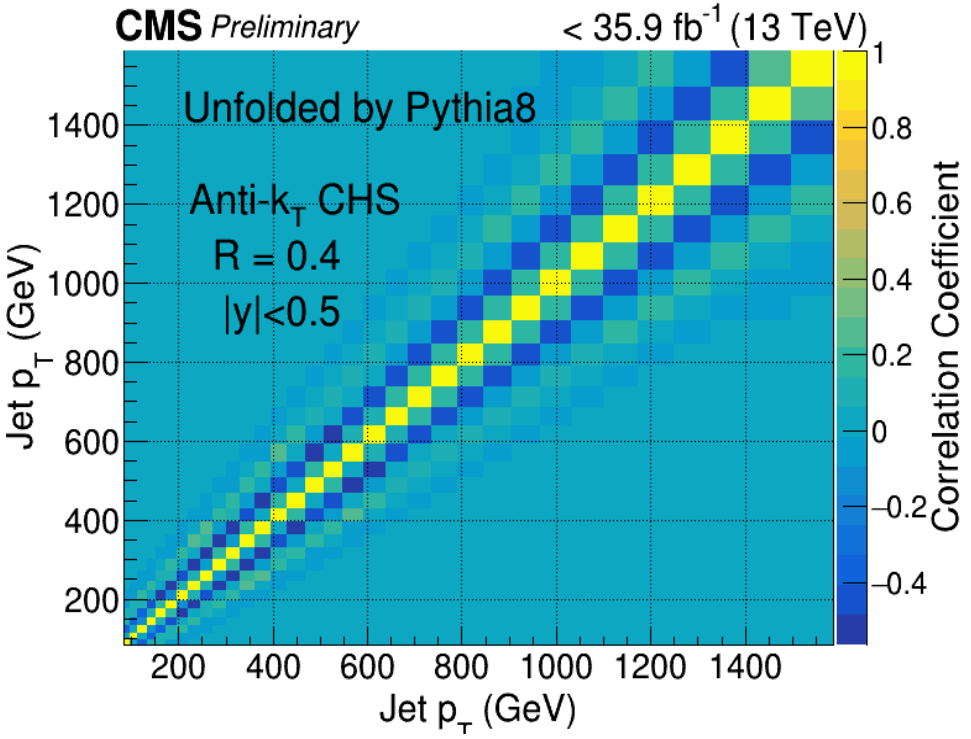
Unfolding removes detector effects (inefficiency & resolution)

Technique used : D'Agostini as central choice

cross checked with SVD, Bin-by-bin, χ^2 minimization with Tikhonov regularization

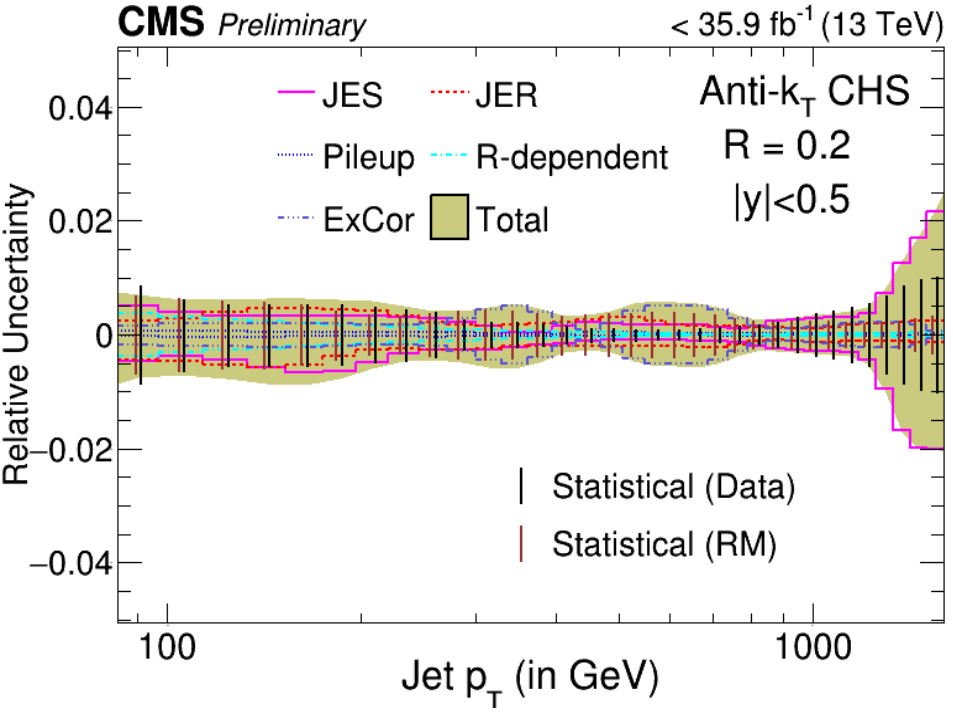
SMP-19-003

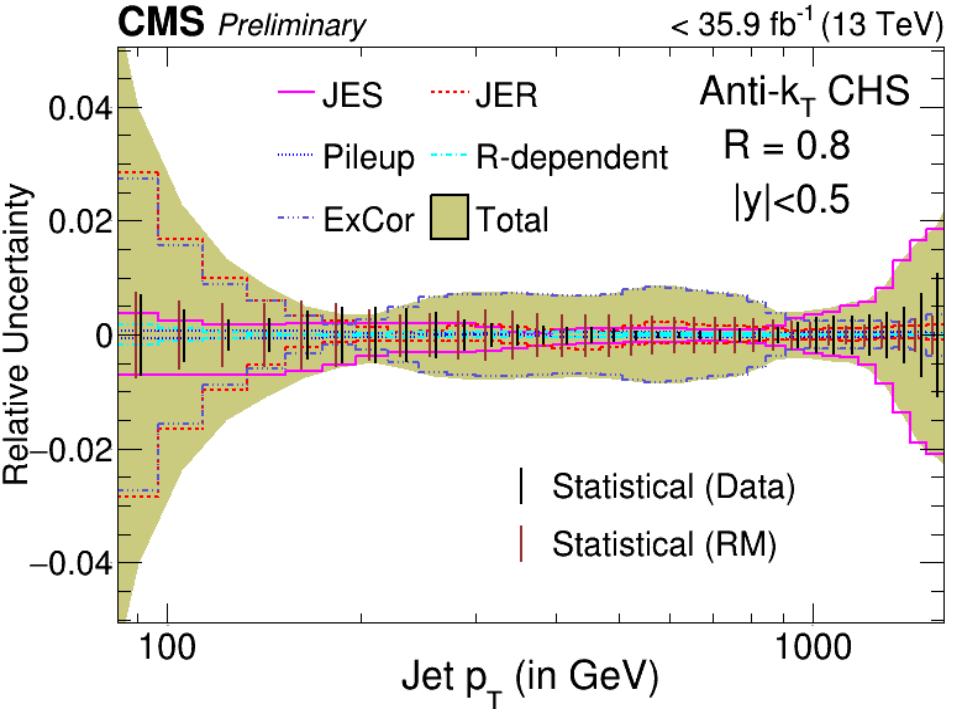




- MC is corrected to match jet energy scale & resolution in data
- Response matrix made using the closest detector level-particle level jet pairs within $\Delta R < 0.5 *$ (jet size)
- Response matrix and correlation matrix are mostly diagonal

Experimental Systematic Uncertainty for Cross Section Ratio





* Statistical unc, derived using delete-10% Jackknife method, is comparable to experimental systematics
  At low pT, triggers are prescaled
  => stat unc is larger
  In medium pT, RM statistics dominates stat unc

* Jet energy scale mostly cancels in ratio, statistical component of JES dominates at high pT

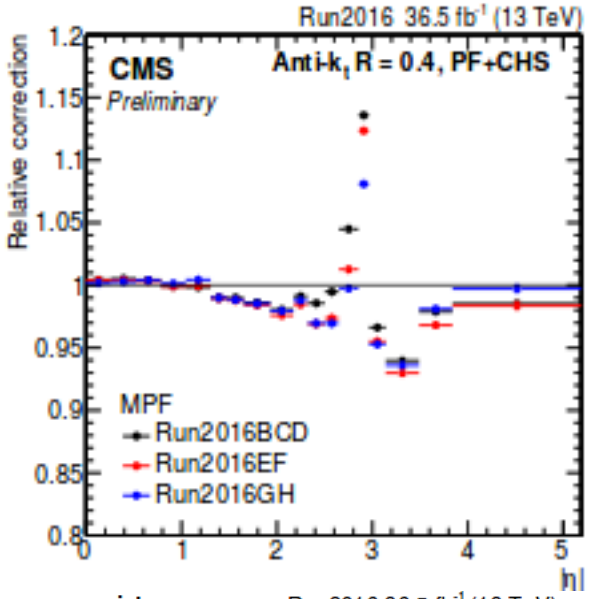
* Extra correction, R-dependent corrections arise from MC based correction on jets not directly calibrated in experiment

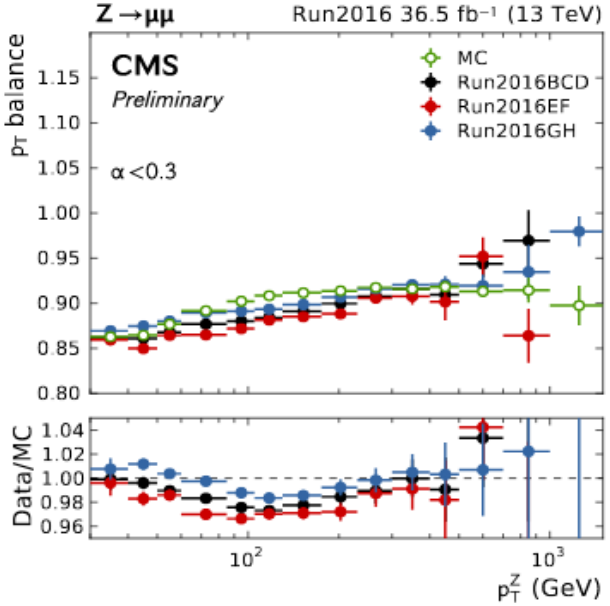
* PU component of JER unc causes larger unc for large jet sizes

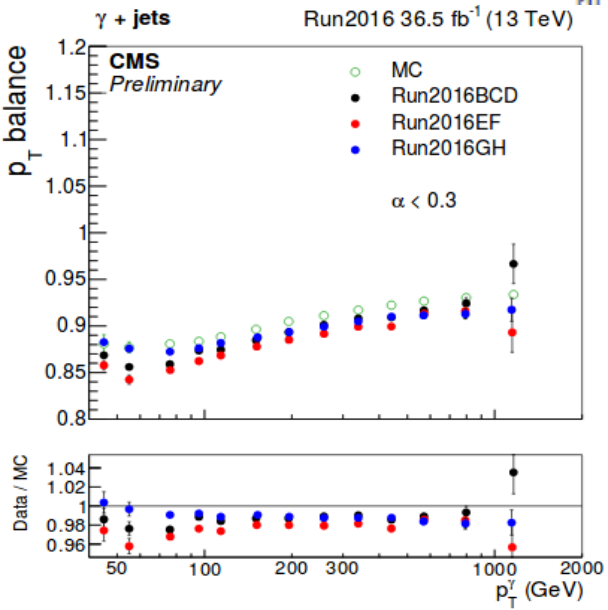
* Radius dependence comes through unc from extra correction, JER

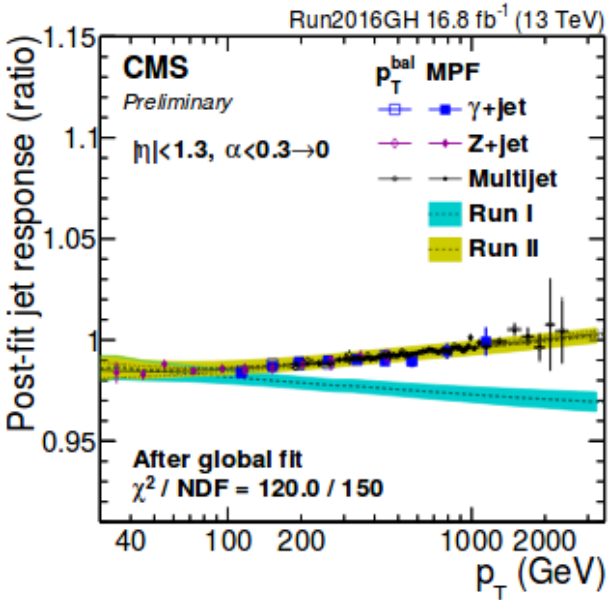
Jet Energy Calibration & Resolution

- Response correction as a function of η by balancing dijet / minimisig MET (MPF)
- Absolute scale correction using photon+jet, Z+jet balance
- Additional correction for data using combination of photon+jet, Z+jet, multijet



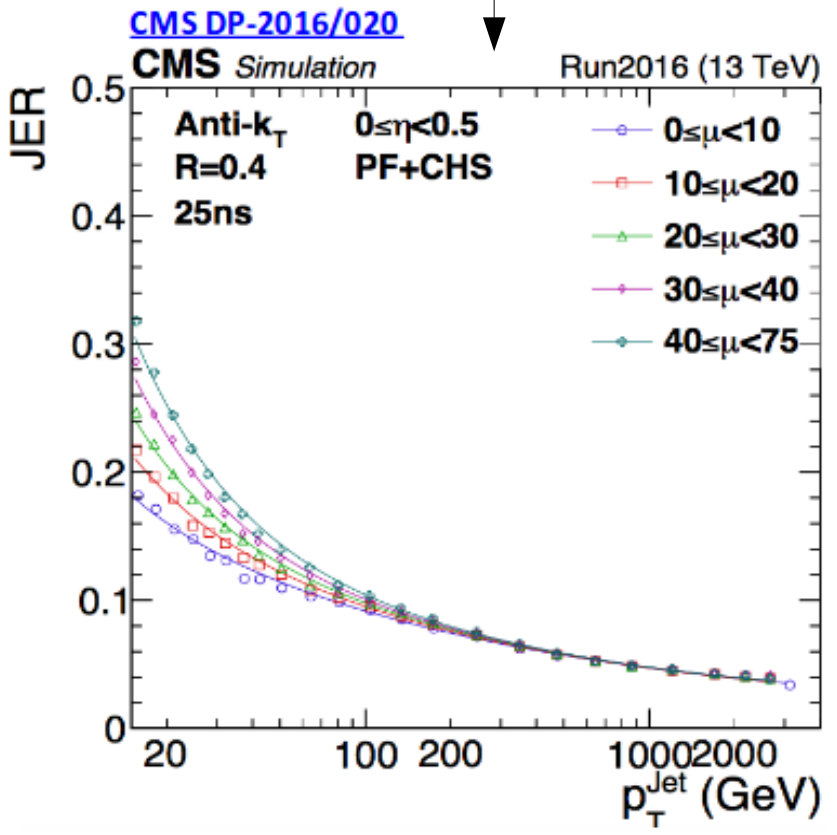






CMS DP-2018/028

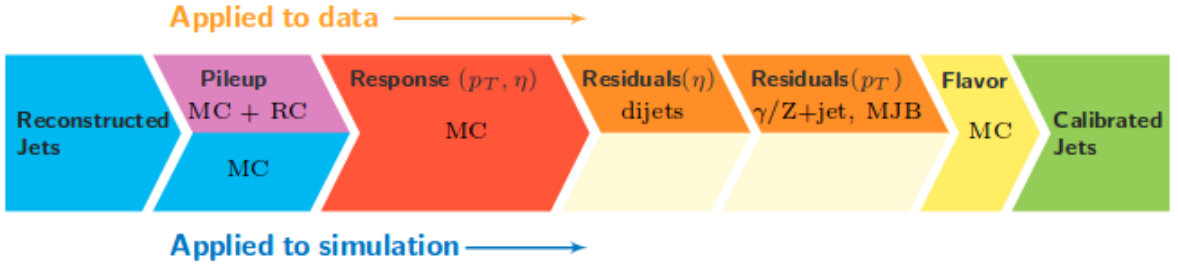
Effect of Pile up below pt <100 GeV



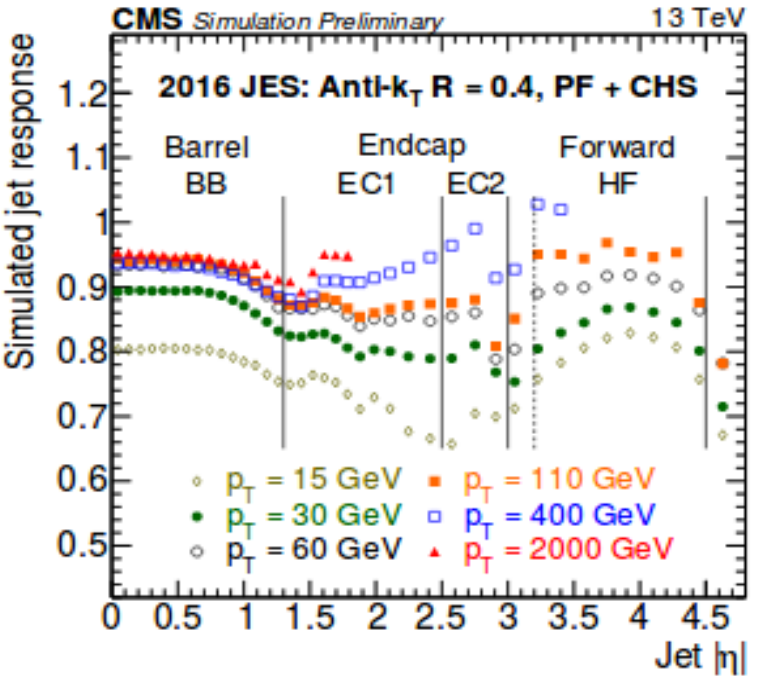
Jet Energy Calibration

- Cross-section measurement depends crucially on energy calibration and resolution → (steep spectra mis-measurement leads to bin migration)
- Factorised approach to match energy scale (mean of $(pT_{Det} - pT_{Gen})/pT_{Gen}$) of detector level jets to particle level jets (on avergae)

L1 L2 & L3 L2L3 Residual



CMS DP-2018/028



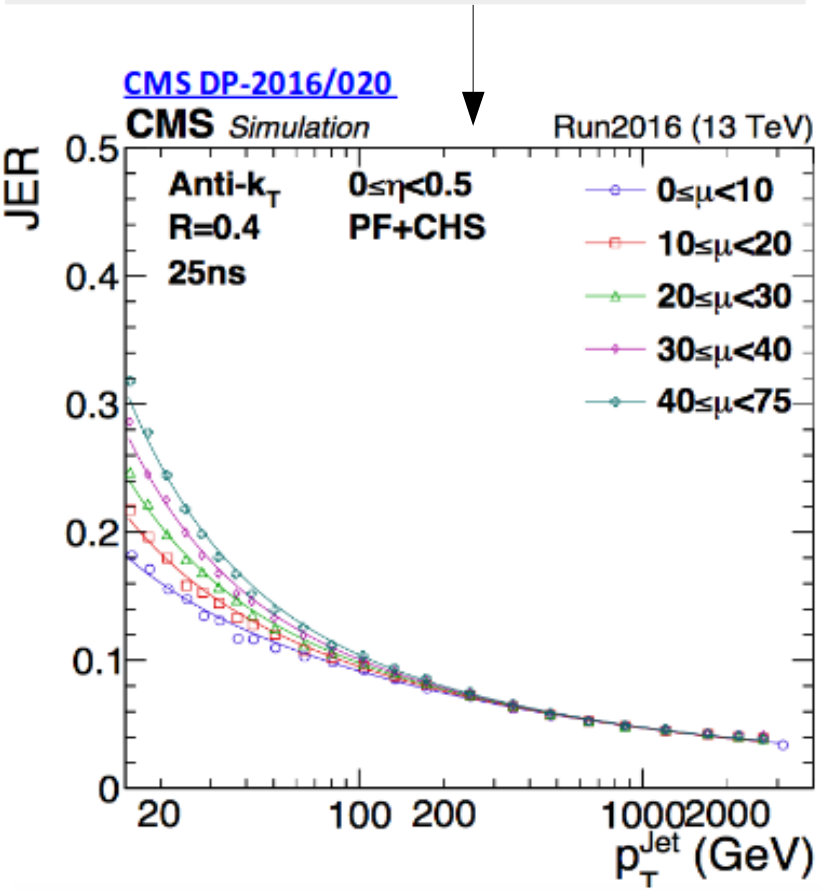
- L1 : Pile-up subtraction by removing tracks coming from secondary vertices and neutrals by area-subtraction using pile-up simulation (and random cone method)
- L2 & L3: Correction as a function of jet pseudorapidity and p_T based on simulation
- L2L3 : Additional correction for data based on MET minimisation in γ/Z + jet, dijet events

Jet Energy Resolution

- Cross-section measurement depends crucially on energy calibration and resolution → (steep spectra mis-measurement leads to bin migration)
- Resolution = spread in $(pT_{Det} - pT_{Gen})/pT_{Gen}$
- Effect of energy resolution appears through unfolding => leads to systematic uncertainty
- Jet energy resolution (JER) in MC is obtained (after applying JEC) by matching detector level jets to particle level jets,
- Data/MC scale factor is derived using photon+jet balance, di-jet asymmetry
- Uncertainty in JER comes from ISR+FSR, pile-up contamination, OOC showering, difference in flavour response ...

CMS DP-2018/028

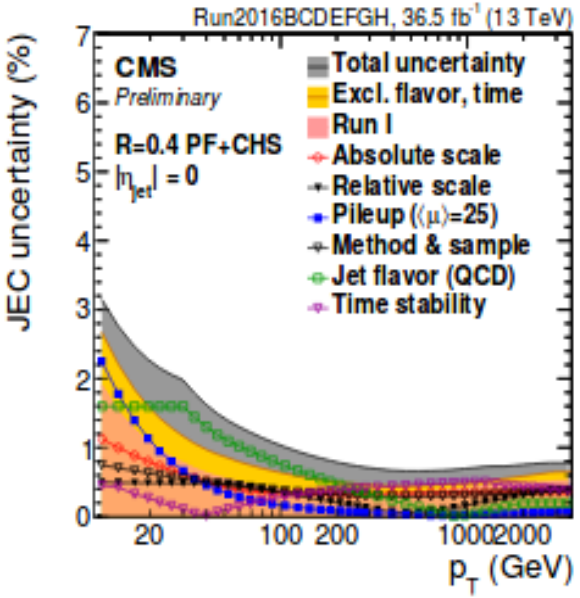
Effect of Pile up below pt <100 GeV

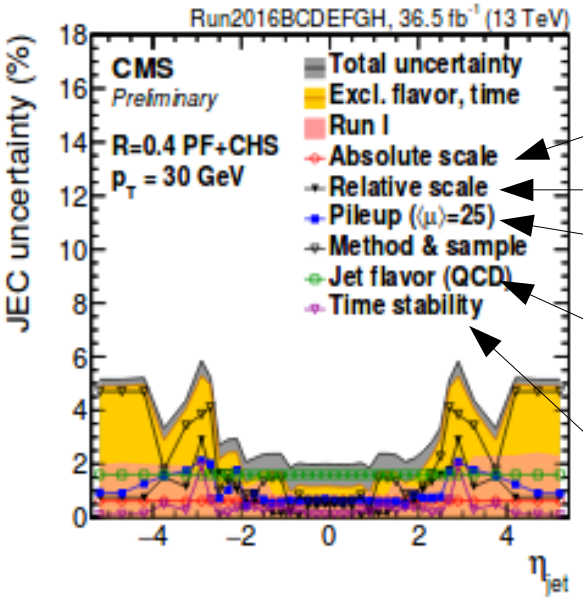


Uncertainty Jet Energy Calibration

- Normally below 1-2% in the phase space used for differential cross-section measurement

CMS DP-2018/028





Uncertainty Components:

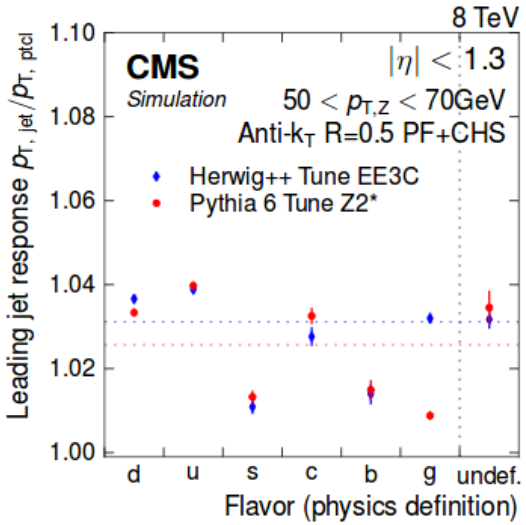
Combined γ, Z-> ee, Z-> mumu reference scale & ISR-FSR

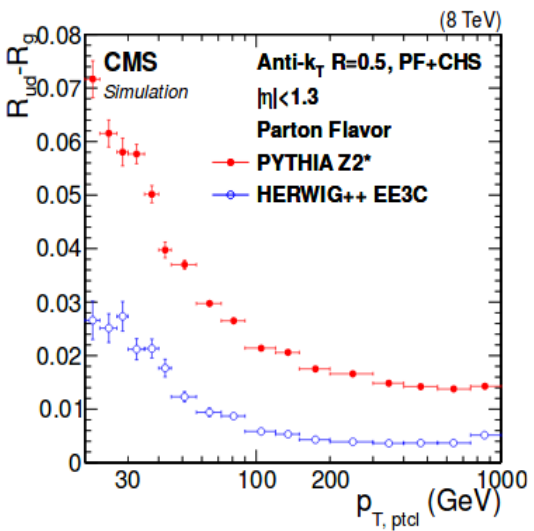
JER SF & ISR-FSR

Bias from residual offset

PYTHIA8 / HERWIG++ difference for parton response after data-based JEC

CMS JME-2013-004





Closure of lumi weigted correction per era

Response difference between uds, b, c, gluon is crucial (gluon radiation pattern is less tuned in parton shower)