Differential Cross Section for Inclusive Jets and Event Properties in CMS Experiment
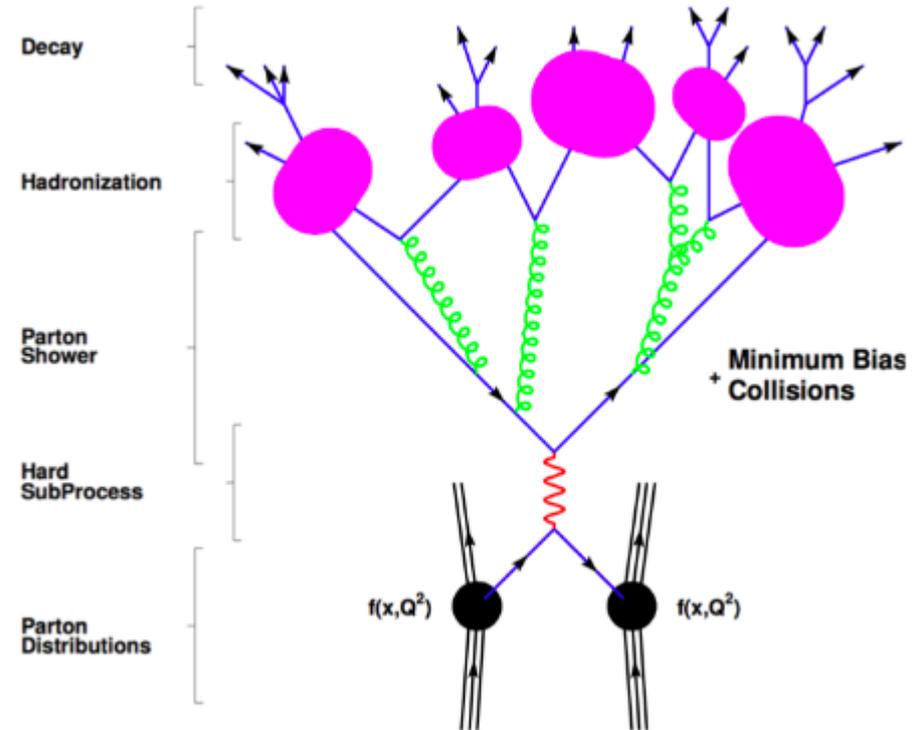
Suman Chatterjee
Tata Institute of Fundamental Research
Mumbai, India

International Workshop on Forward and Jet Physics
BoseInstitute, Kolkata
11th Feb, 2019

Inclusive Jets : Why?
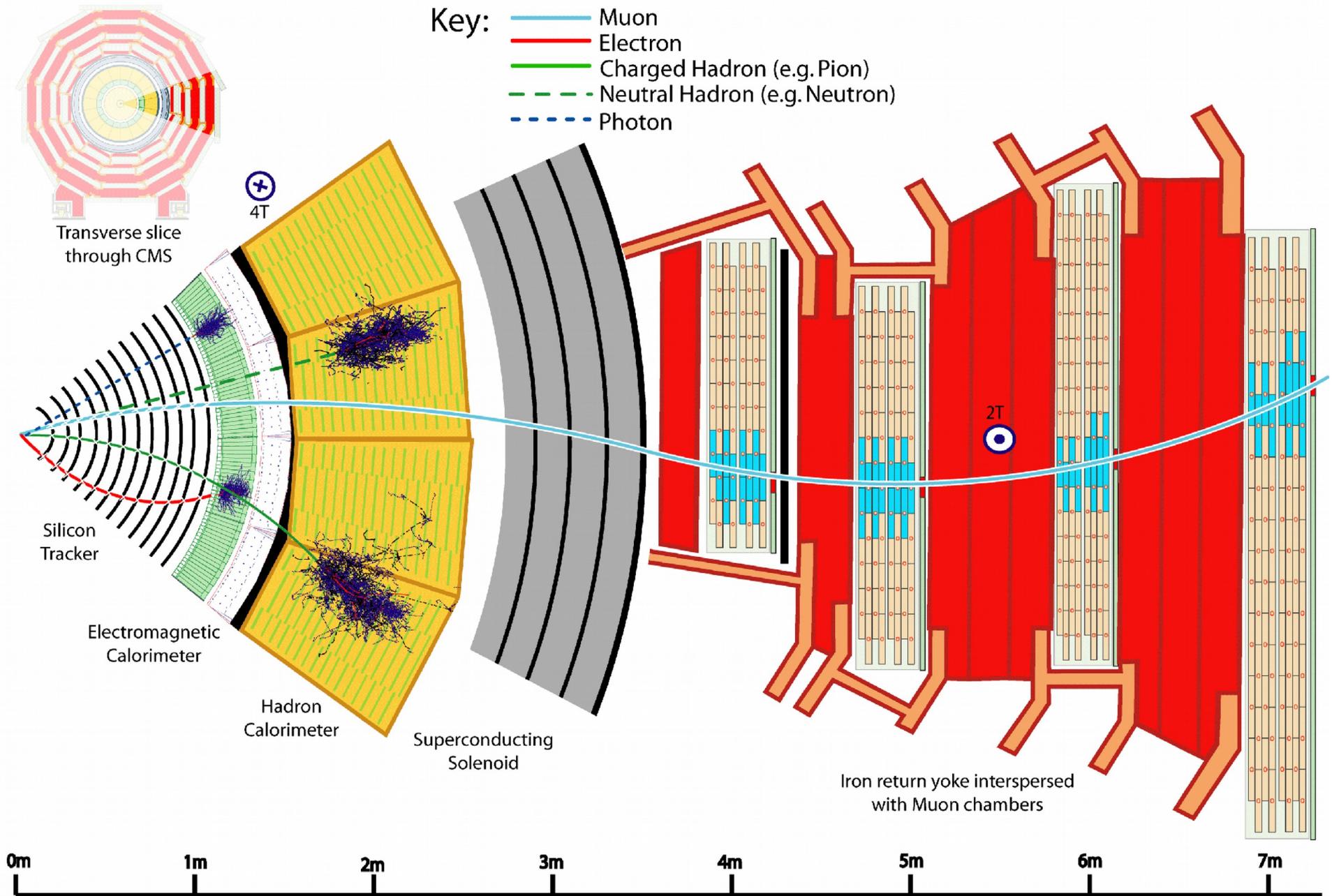
- Jets : collimated particle clusters in detector surrogates of quarks & gluons produced in hard interaction

- Inclusive Jets : p p -> jets + X flooded by QCD

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

Decay

Hadronization

Parton Shower

Hard SubProcess

Minimum Bias + Collisions

Parton Distributions

$f(x,Q^2)$ $f(x,Q^2)$

Common bkg for BSM search with hadronic final states

Skeleton of Compact Muon Soleniod

Key:
— Muon
— Electron
— Charged Hadron (e.g. Pion)
– – – Neutral Hadron (e.g. Neutron)
········· Photon

Transverse slice through CMS

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid
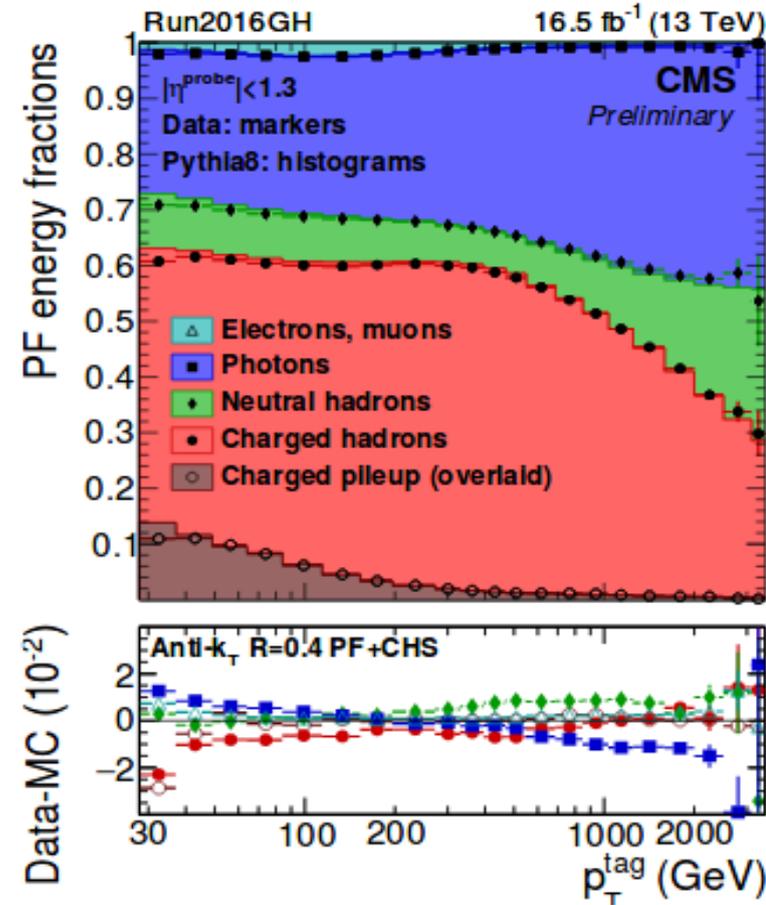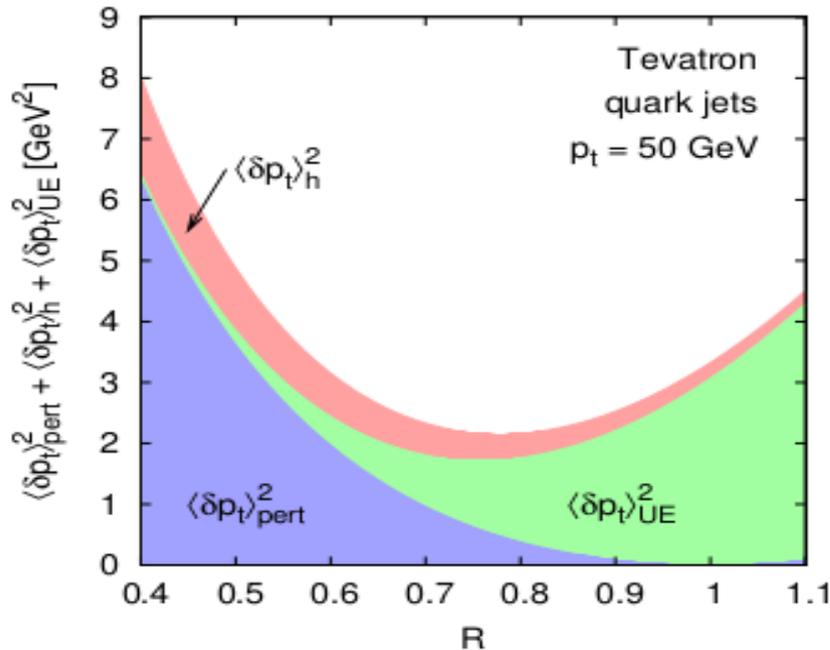
Iron return yoke interspersed with Muon chambers

0m   1m   2m   3m   4m   5m   6m   7m

Unserstanding Jets

- Information from all sub-detectors are combined to reconstruct and identify particles (Particle Flow) ⟶ PF candidates

- Jets, in CMS, are reconstructed using PF candidates using anti-kT algoirthm
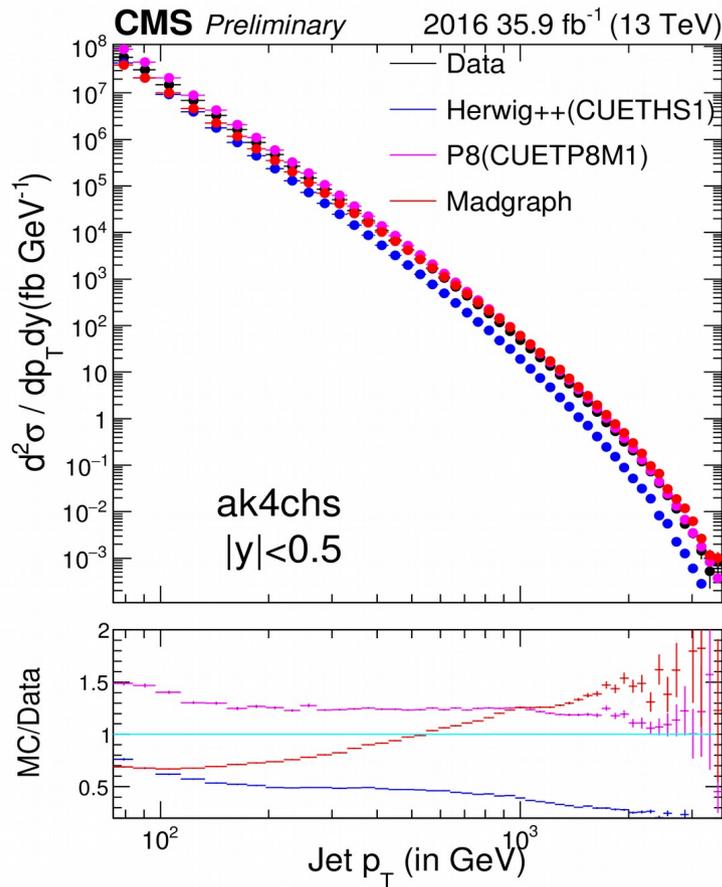
Choice of jet size :
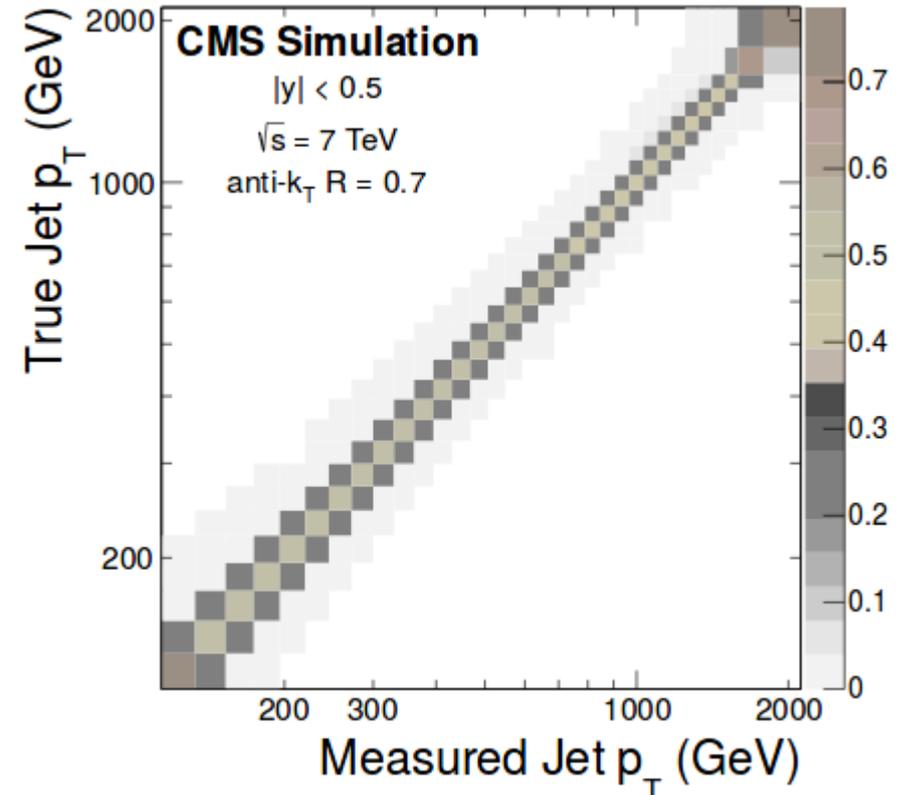Interplay between loosing radiation vs adding pile-up

Excellent tracking performance even in ~ TeV scale

Higher P_T => Larger shower depth
=> Larger EM fraction

4

Detector Level Spectra & Unfolding
(Journey of Jets from Detector to Particle)

Unfolding removes detector effects
(inefficiency & resolution)!

CMS QCD-11-004

What we measure in data
(MC with full detector simulation)

CMS private

Correlation between
detector & particle level spectra!

Difference between unfolded and detector level spectra : 5-20%

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
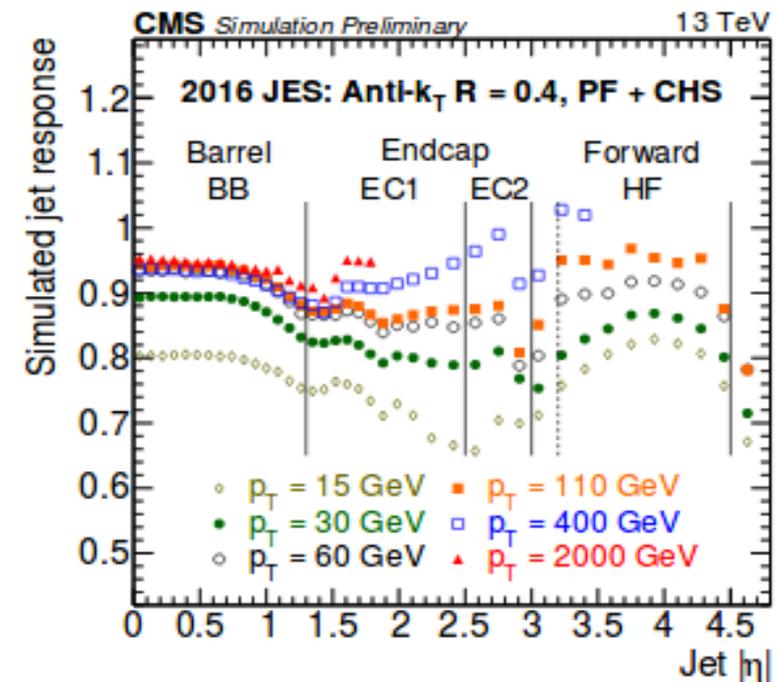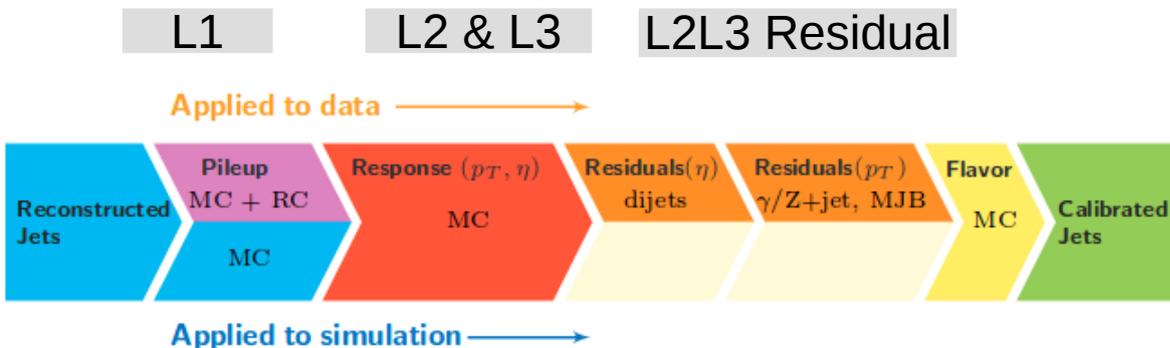
- L1 : Pile-up subtraction by removing tracks coming from secondary vertices and neutrals by subtraction using pile-up simulation cone method)

- 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
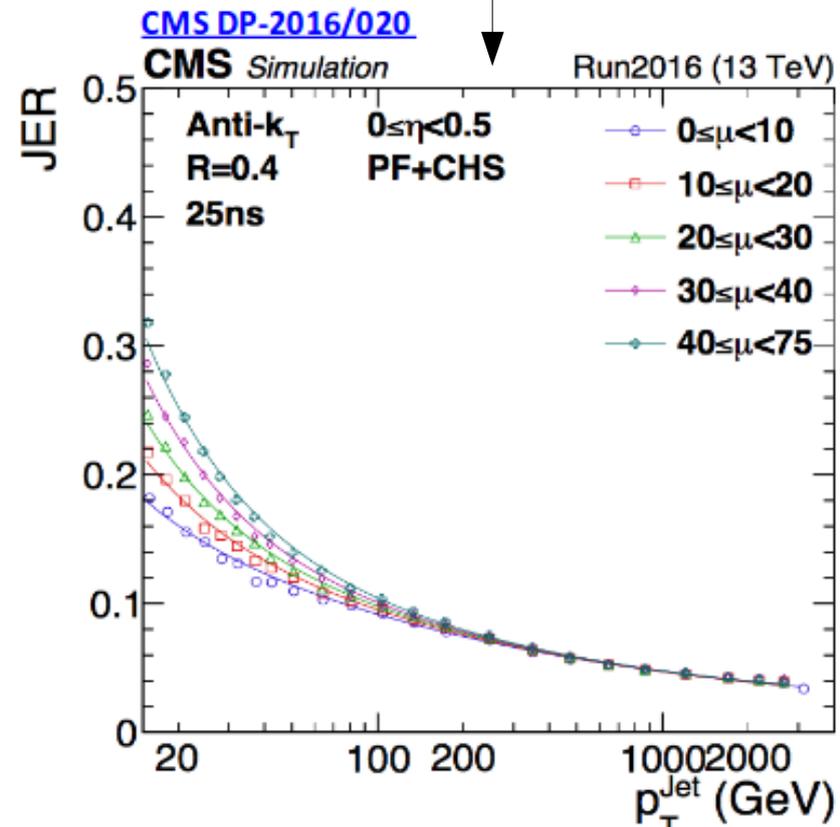
# Systematics in Cross-Section Measurement

Experimental Sources	Theoretical Sources
Jet Energy Scale (JES) (8-65 % for AK4& AK7)	Scale choice (AK7 : 1-12% AK4 : 1-10%)
Jet Energy Resolution (JER) (1-2%)	PDF (AK7 : 1-8% AK4 : 2-10%)
Pile-up (~0.1%)	Non-perturbative cor (AK7 : 1%, AK4 : 2%)
Uncertainty in Luminosity (4.8%)	Uncertainty in α_S (~1%)
Unfolding (~1%)	Values quoted for 13 TeV Measurement (50 ns data)

These numbers are for inclusive jet Cross-section measurement
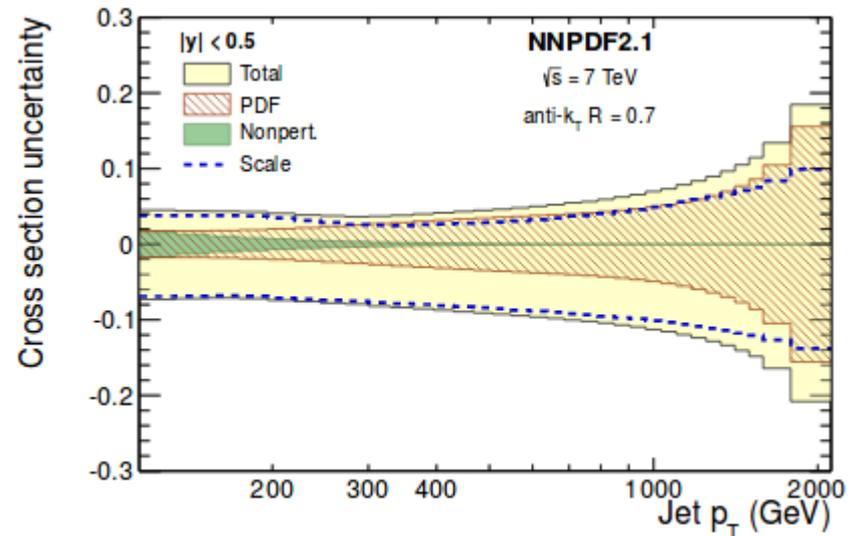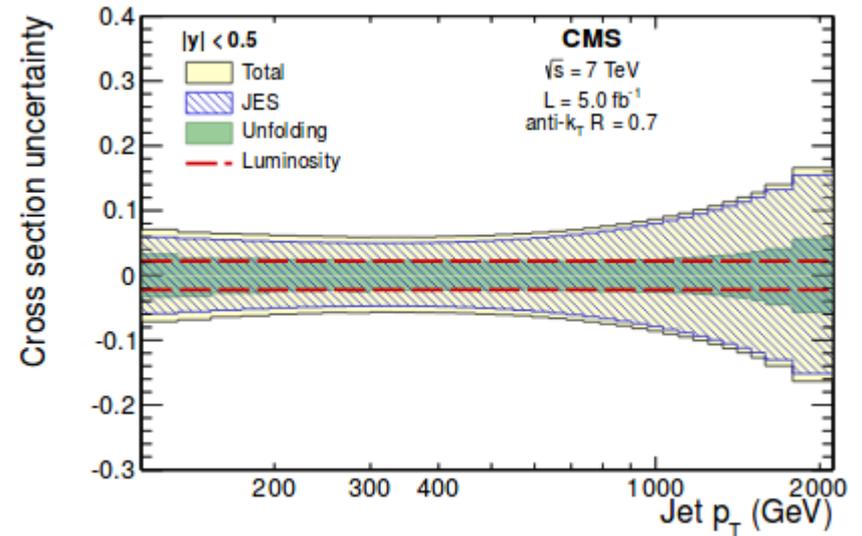
- JES dominates exp uncertainty
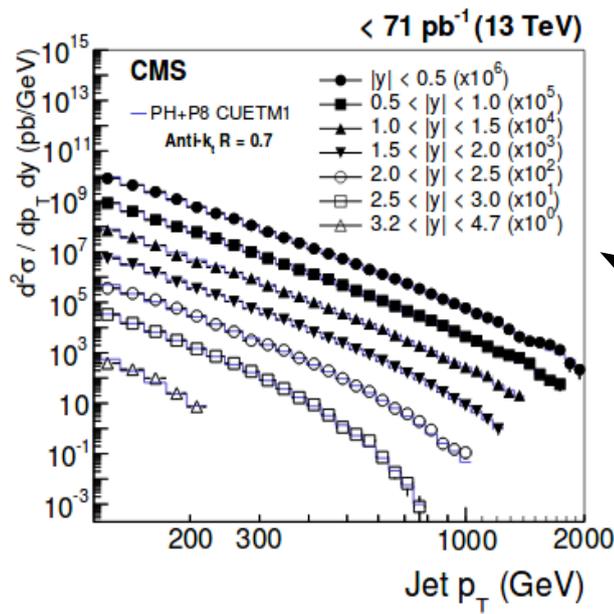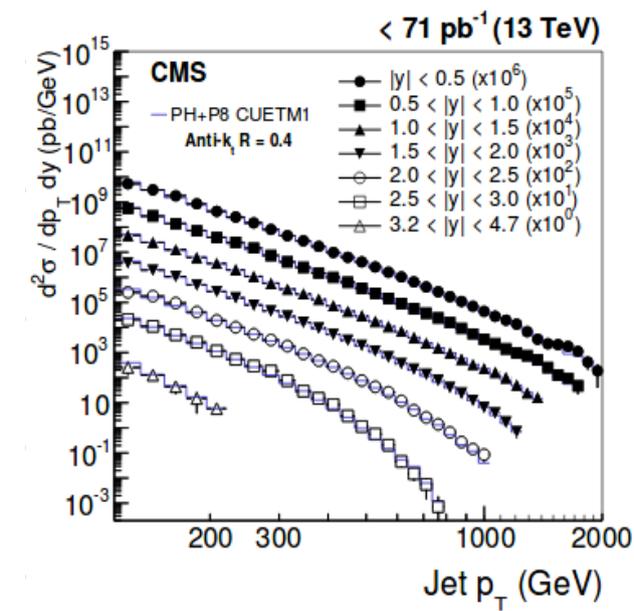
- Scale and PDF control theory systematics

Inclusive Jet Cross-Section at 13 TeV
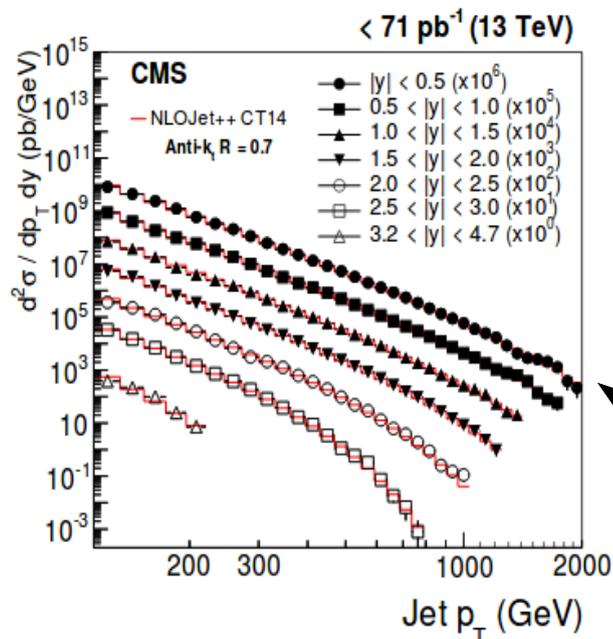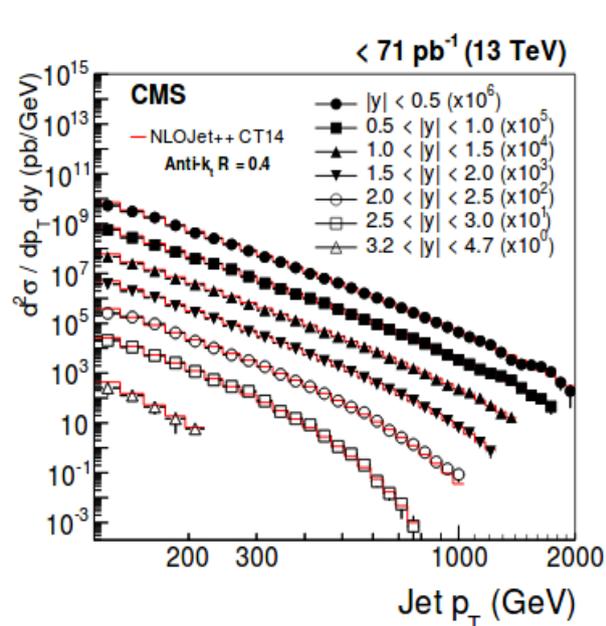
Two different jet sizes
to understand parton evolution
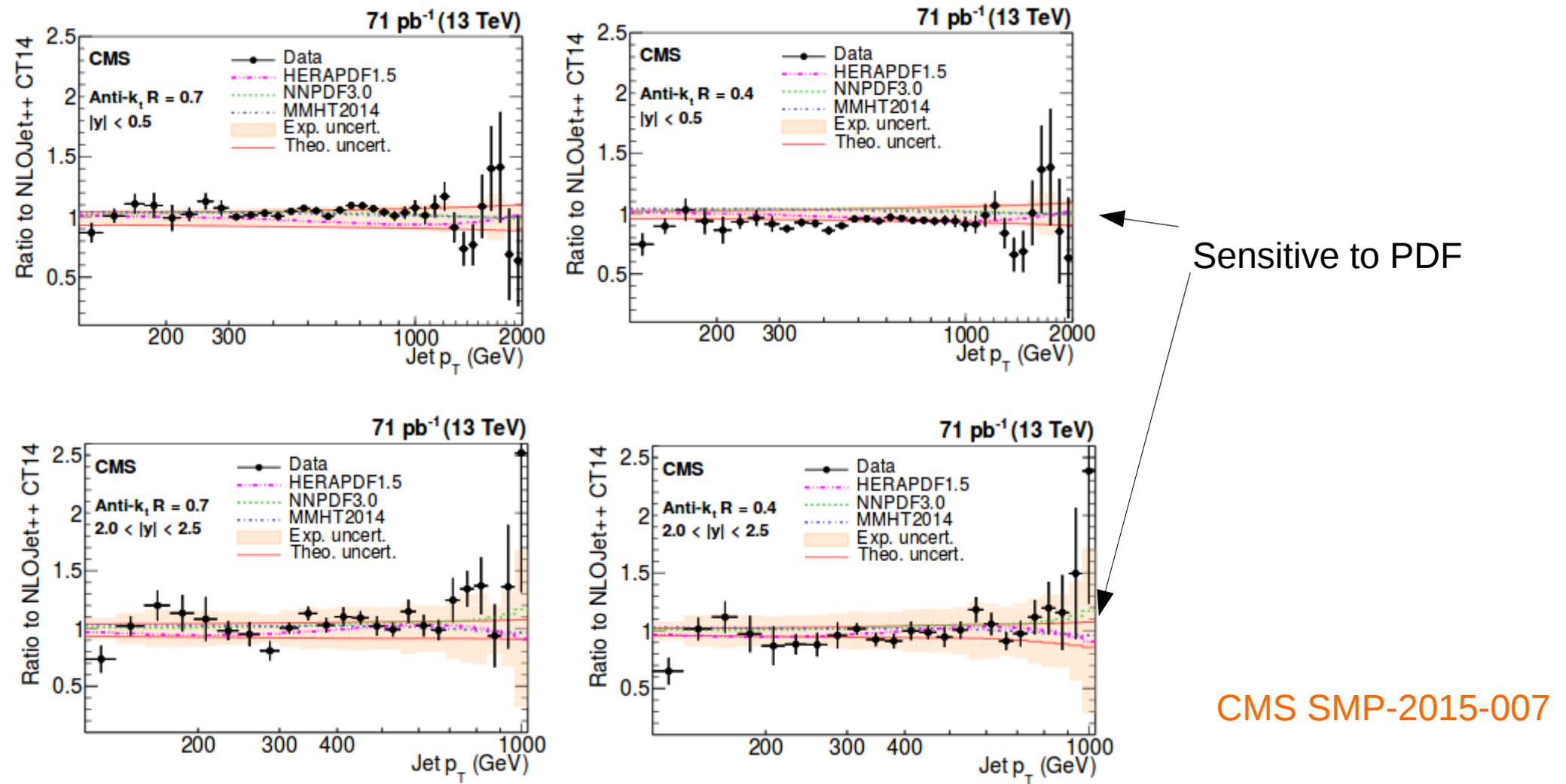
Fixed order (NLO) prediction
* NP * EW correction

Correction for
parton to hadron level change

Good agreement between
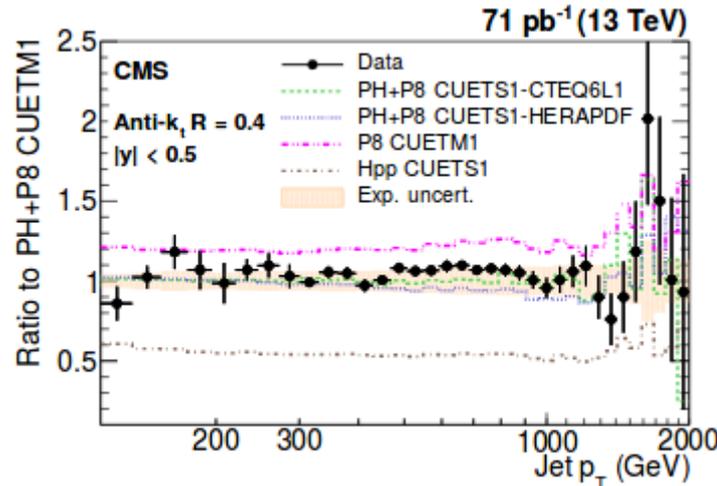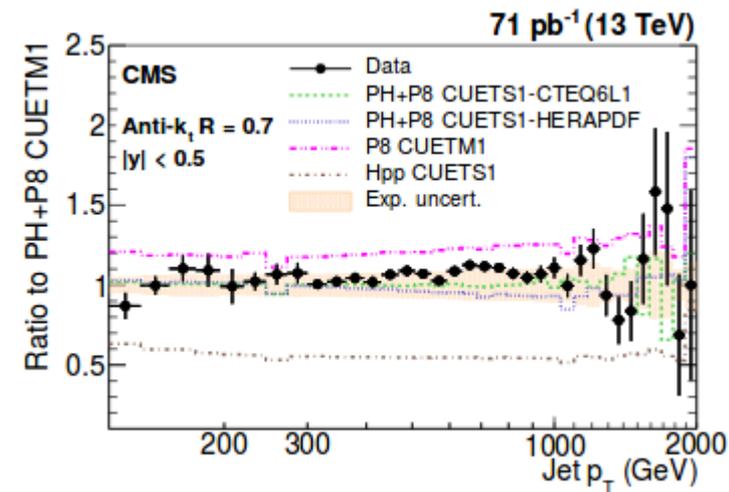Data and NLO prediction
over 8 orders of magnitude

NLO + PS (parton shower)

9

Comparison to Fixed Order Prediction at 13 TeV


Sensitive to PDF

CMS SMP-2015-007

- Overall good agreement with NLO prediction for AK7 jets (with larger fluctuation in data in forward region

- Cross-section is little overestimated for AK4 jets
  (resummation of radiated soft gluons is absent in NLO prediction :
  more important for jets of small sizes)

Comparison to Parton Shower MC at 13 TeV

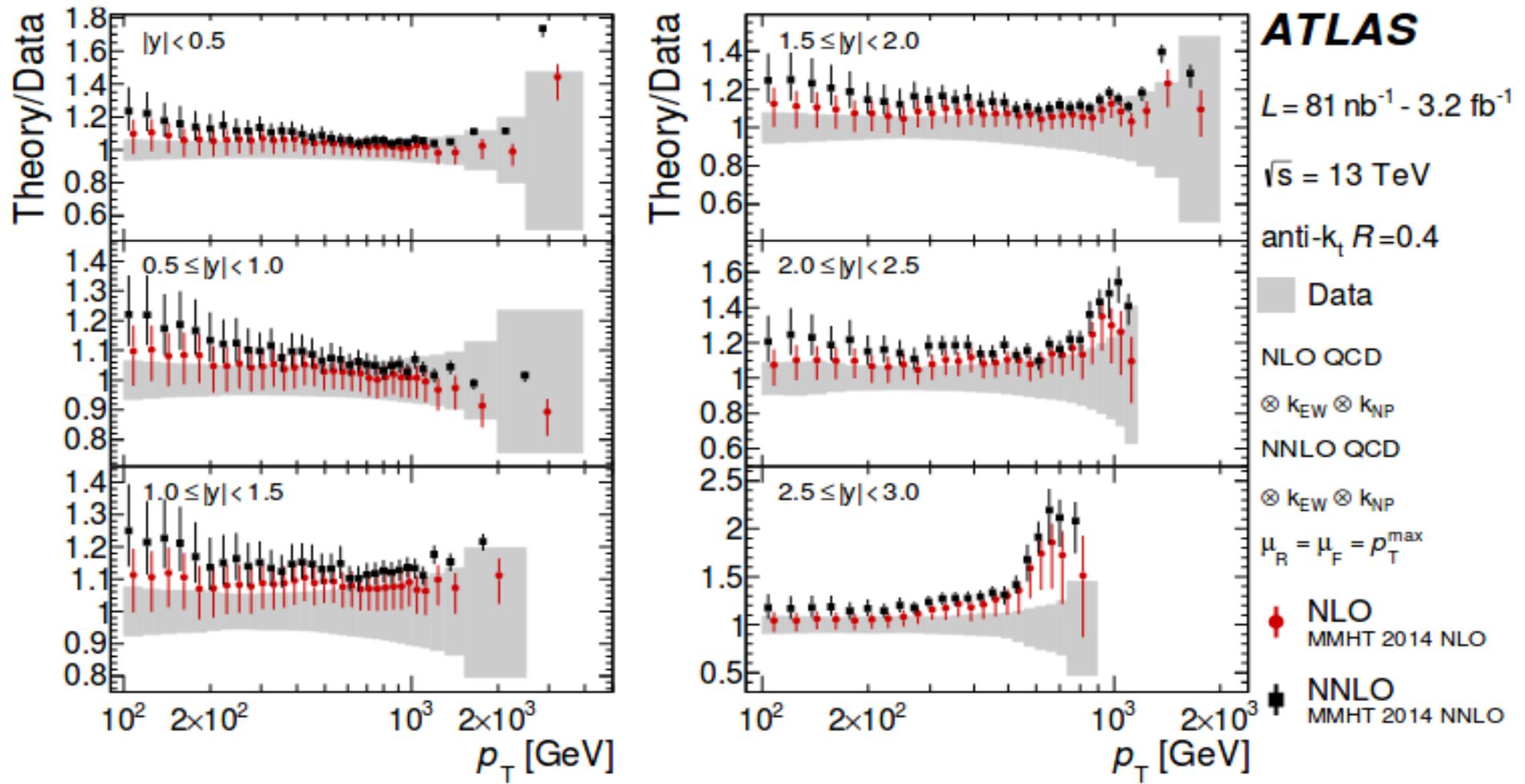Two LO predictions are in opposite directions w.r.t. data

NLO is between PYTHIA8 & HERWIG++, describes data quite well
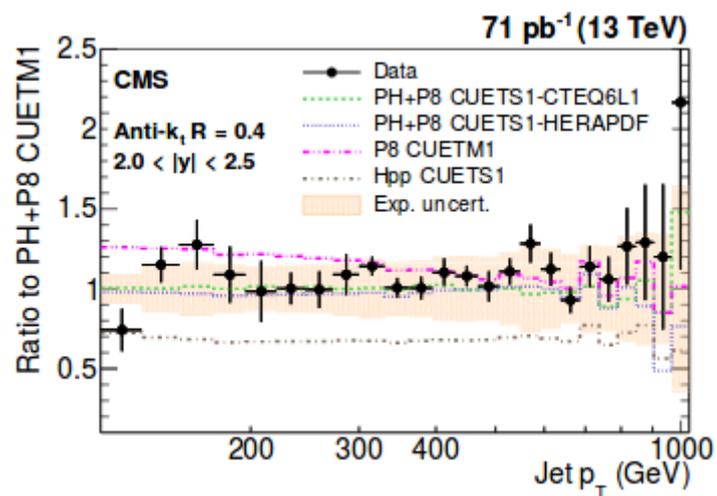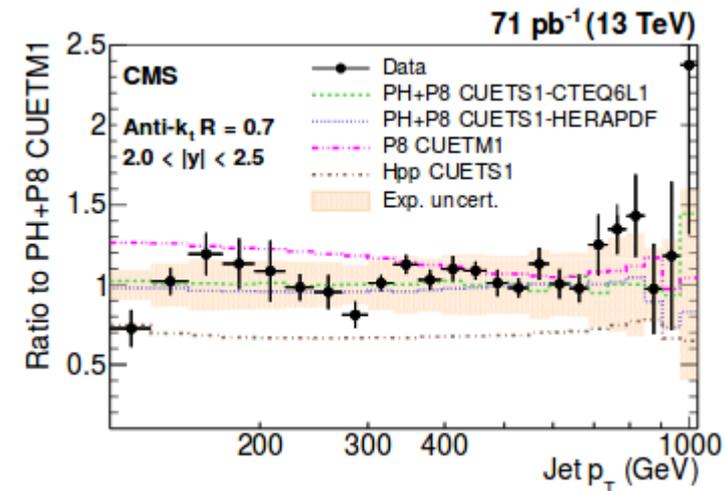
CMS SMP-2015-007

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

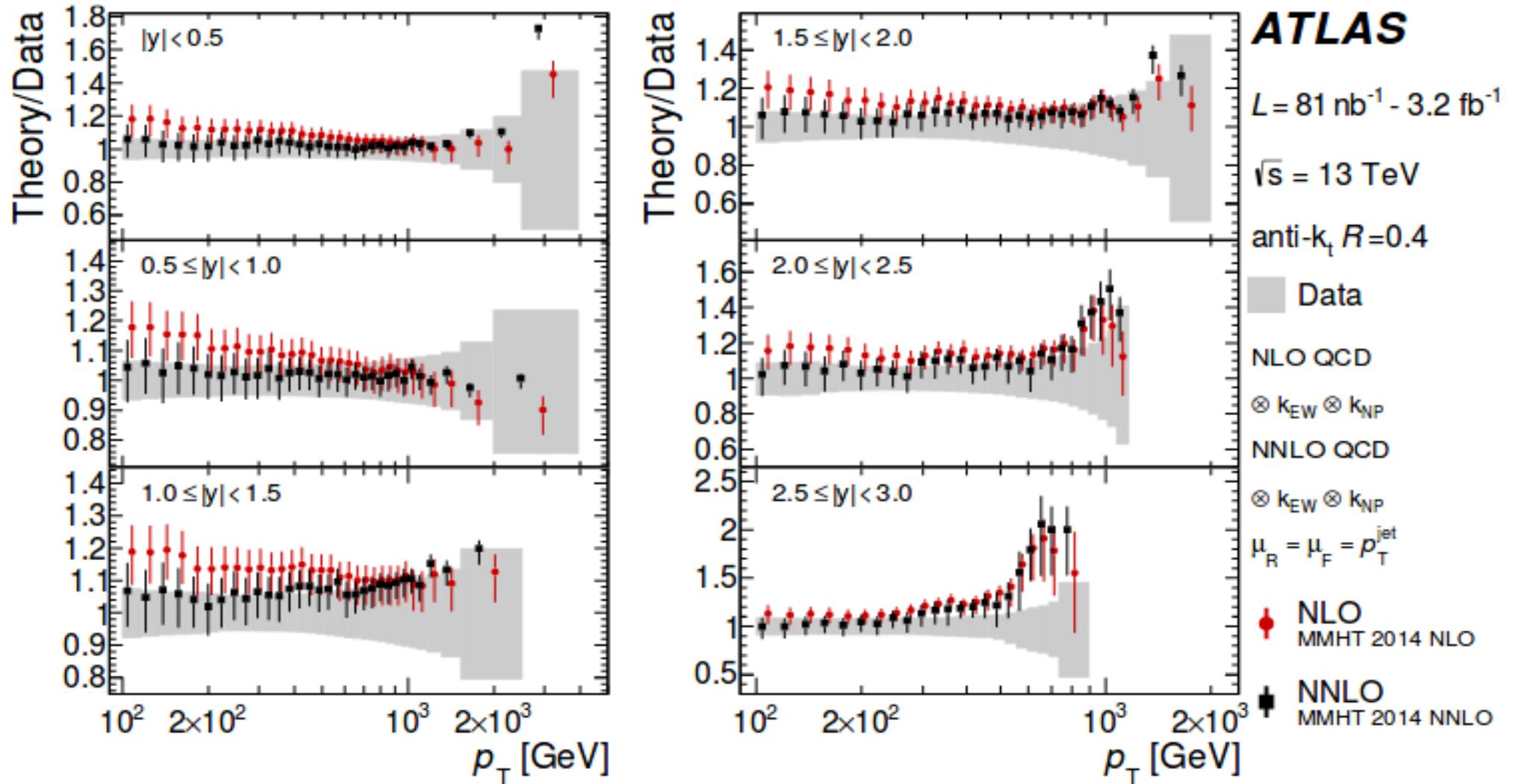- For AK7 jets, prediction is quite similar to the one from fixed order NLO calculation

11

Scale Choice for Higher Order Calculation

- With pT(max) scale, NLO prediction describes data better

Scale Choice for Higher Order Calculation

ATLAS

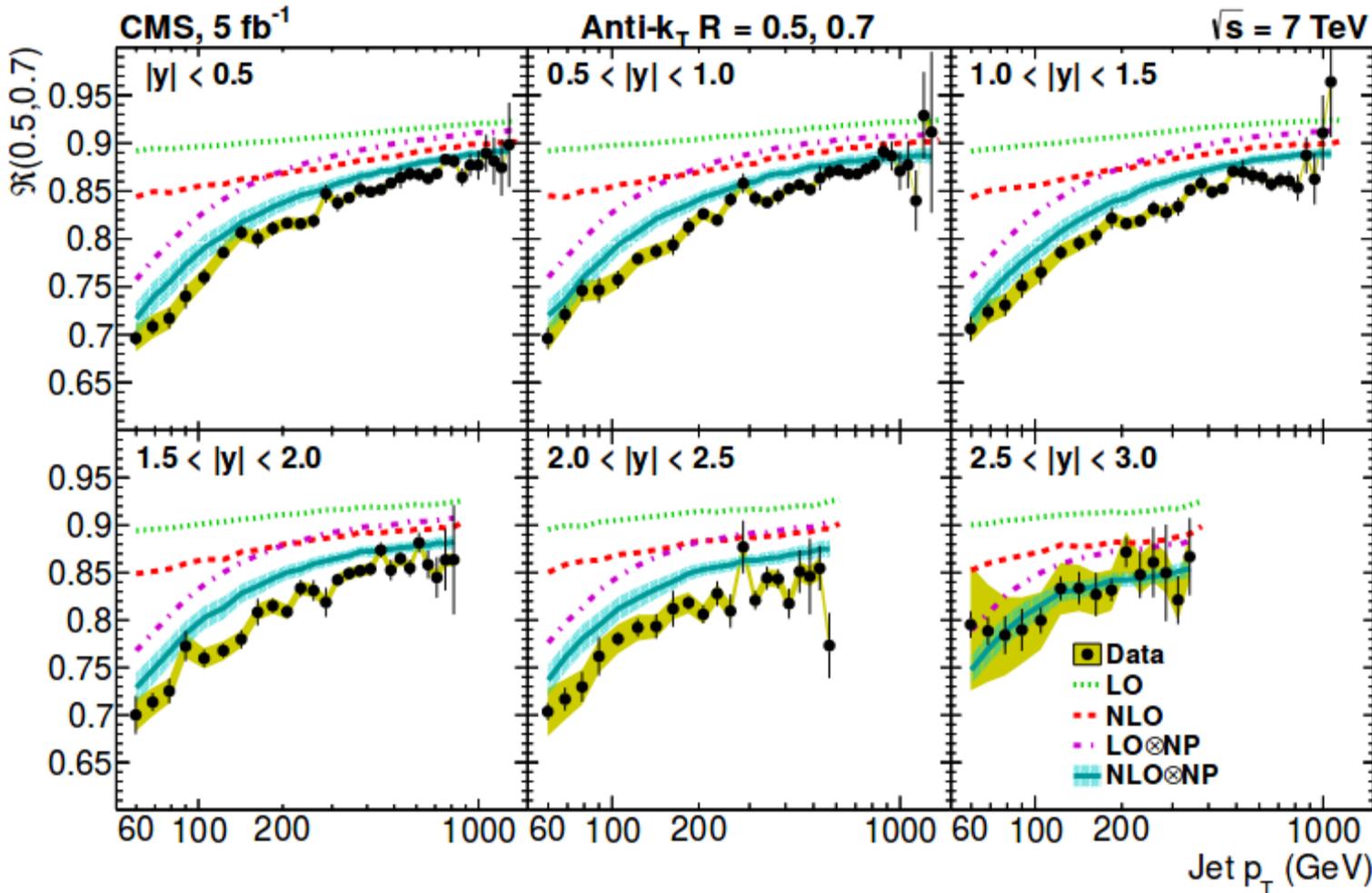$L = 81\ nb^{-1} - 3.2\ fb^{-1}$

$\sqrt{s} = 13$ TeV

anti-k_t $R = 0.4$

Data

NLO QCD
$\otimes\ k_{EW} \otimes k_{NP}$

NNLO QCD
$\otimes\ k_{EW} \otimes k_{NP}$

$\mu_R = \mu_F = p_T^{jet}$

NLO
MMHT 2014 NLO

NNLO
MMHT 2014 NNLO

- With pT(avg) scale, NNLO prediction describes data better

13

Cross-Section Ratio of Two Jet Sizes
at √s = 7 TeV   : Power of Ratio

Many of the systematics (JES, luminosity for exp side PDF, α_s for theory side) mostly cancel in ratio!

Data lies below
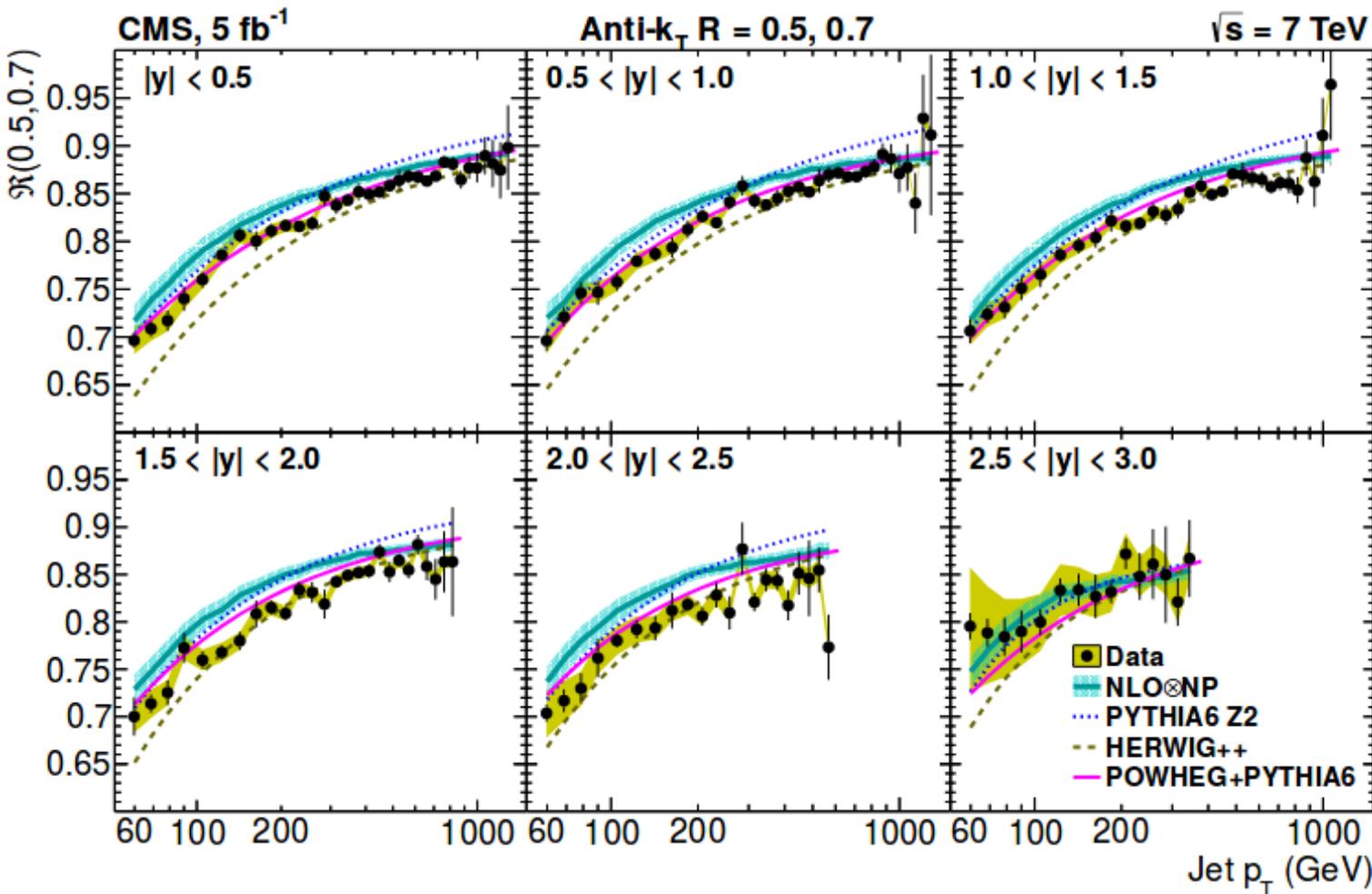the prediction
almost everywhere

CMS SMP-2013-002

- Non-perturbative correction is evident to be essential to complement fixed order prediction

- NNLO prediction (effectively NLO for ratio) improves the agreement with data

14

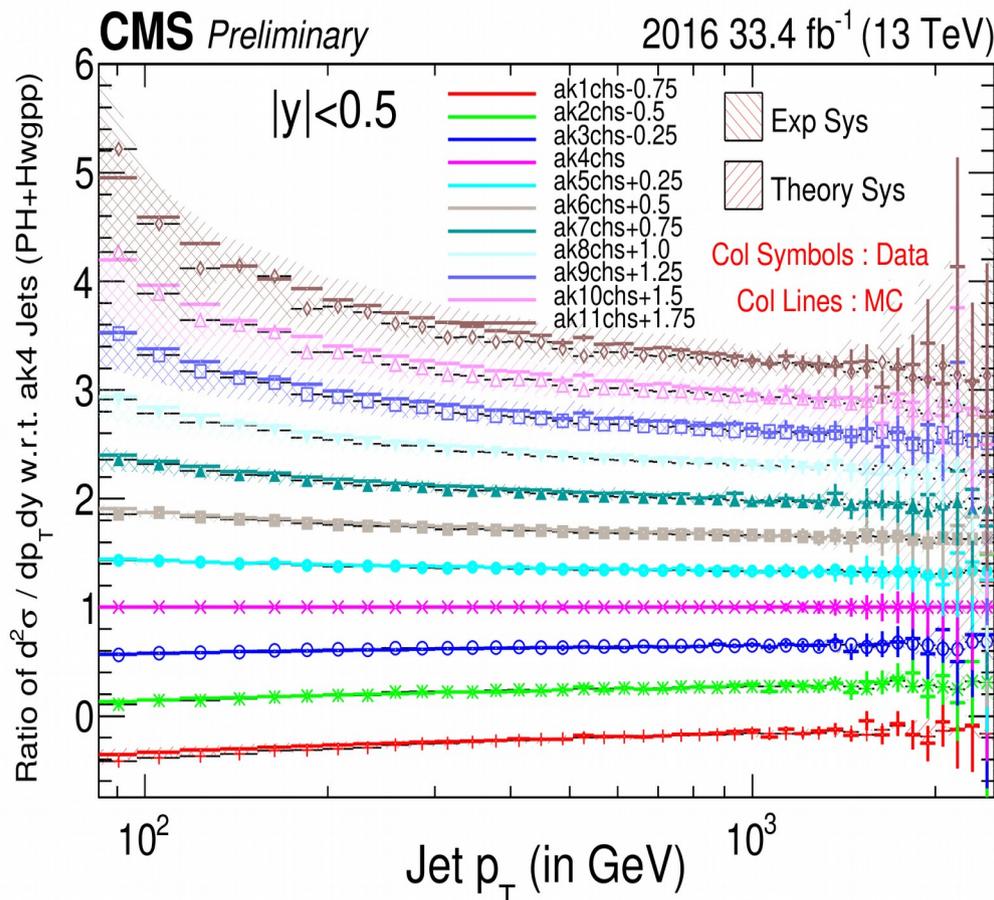# Cross-Section Ratio of Two Jet Sizes at √s = 7 TeV : Power of Ratio

CMS SMP-2013-002

- Better modelling of data by using parton shower, best with NLO generator followed by parton shower

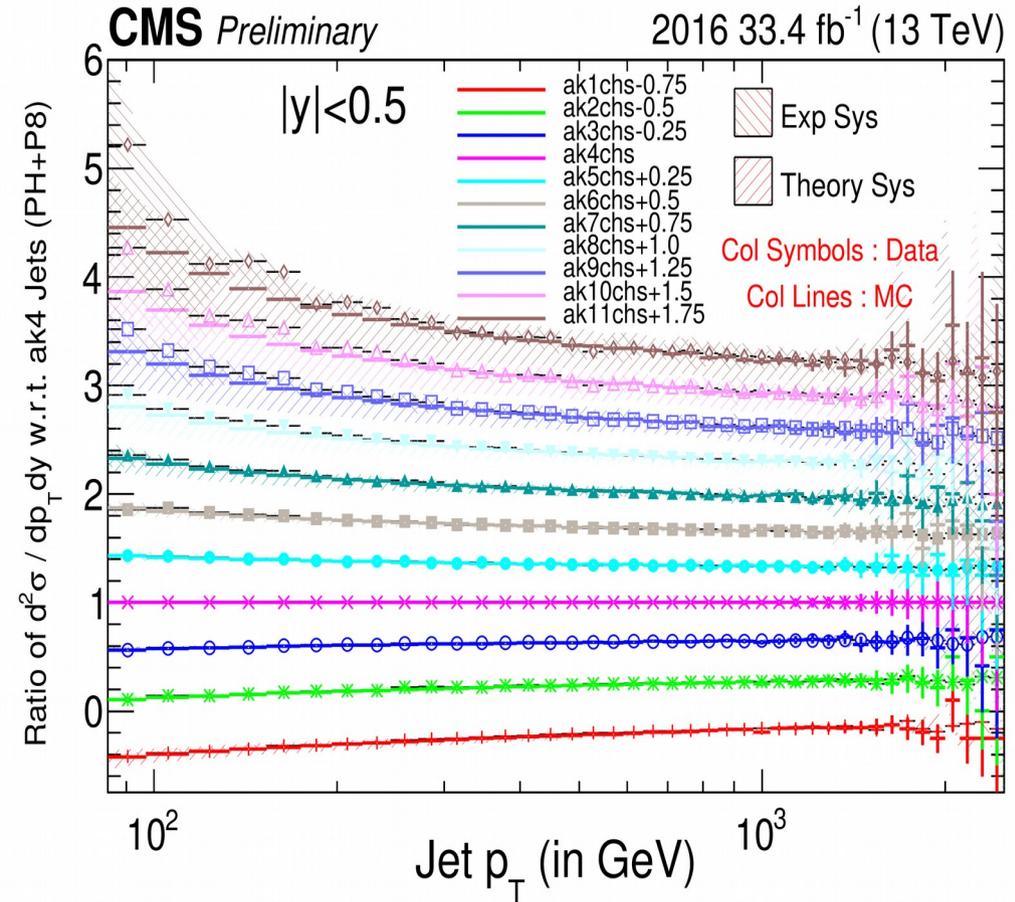- Shows the importance of final state radiation to describe the ratio

15

Cross-Section Ratio of Different Jet Sizes at √s = 13 TeV   : Power of Ratio
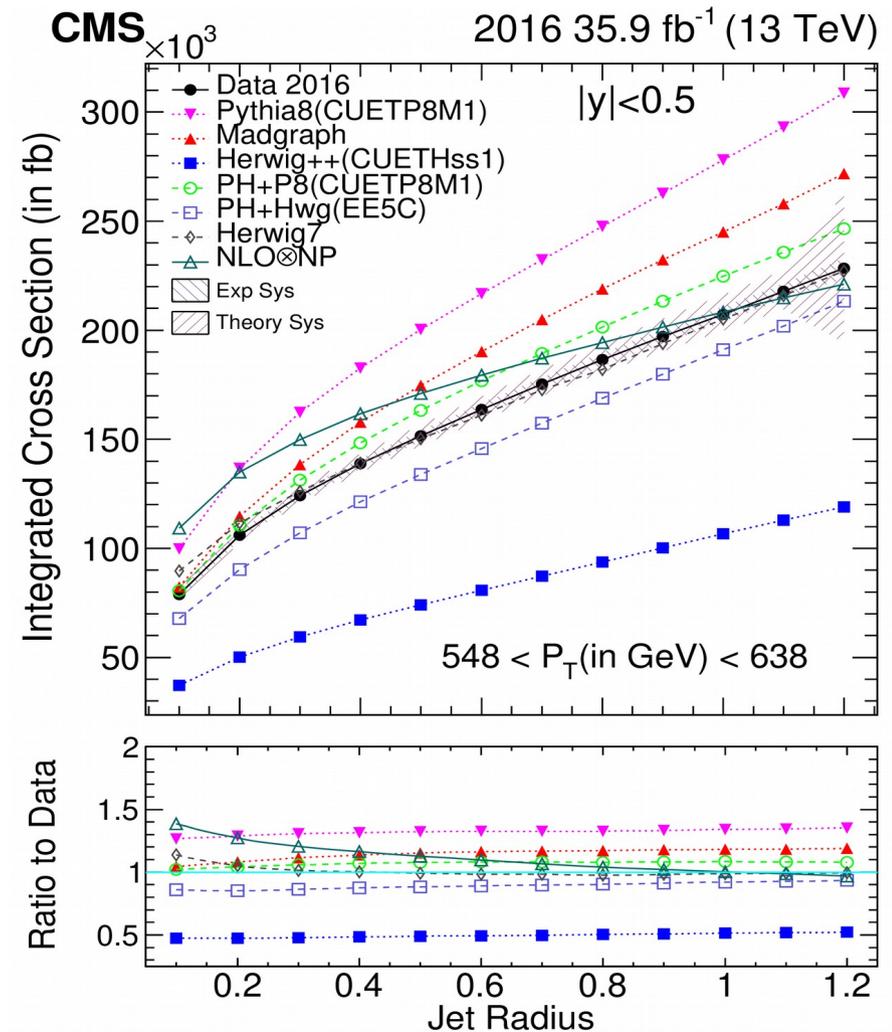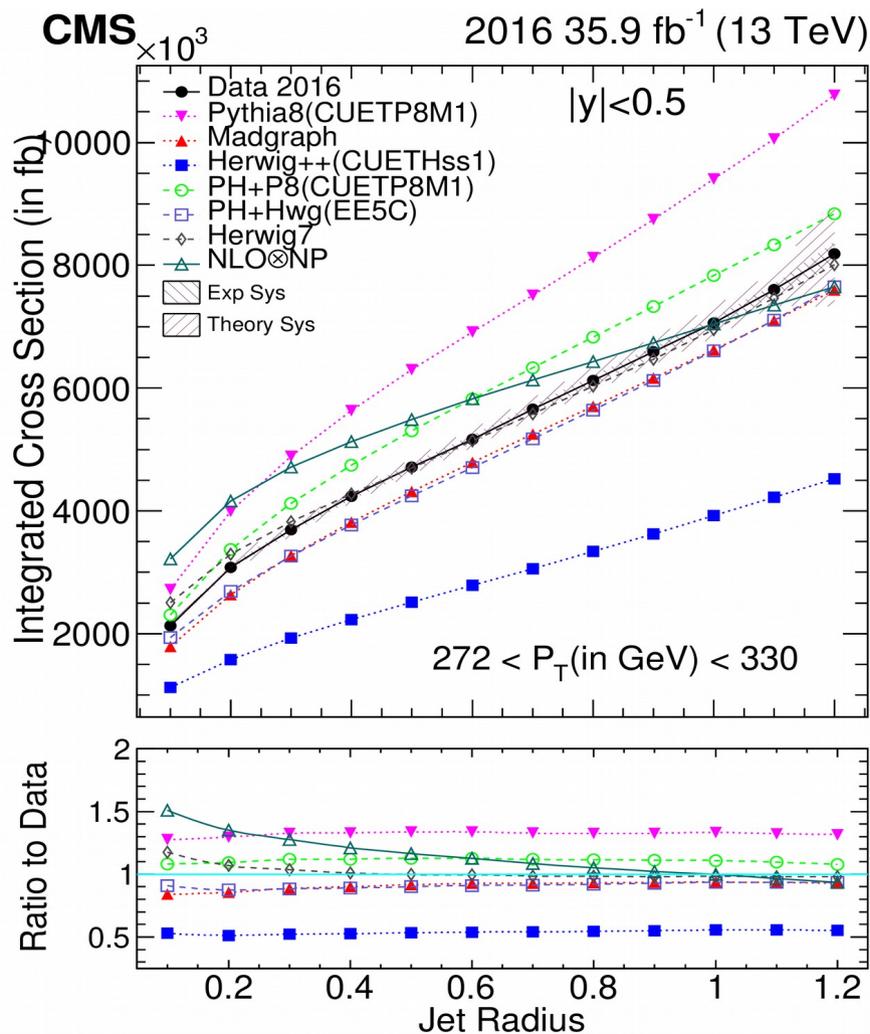

Data & Powheg+Herwig++

Data & Powheg+Pythia8

- Ratio is taken w.r.t. AK4 jets

- Powheg augmented with Pythia8 describes ratio for smaller jets better & Powheg+Herwig++ is optimum for large radius jets

Integrated Cross-Section of Different Jet Sizes at √s = 13 TeV

Fixed order prediction (NLOJet++) is unable to describe the trend as a function of jet size :
Need of resummation and higher order correction at low R

NLO Powheg with Pythia8 / Herwigg++ PS are much closer to data than P8/Hwg alone : still on the opppsoite sides

MC generators supplemented by parton shower can describe the cross-section variation with jet size : parton shower helps!

CMS private

Impact of Inclusive Jets on PDF

- Dominated by $gg \to gg$ at low p_T , $qg \to qg$ at medium p_T & $qq \to qq$ at high p_T => quark & gluon PDFs are sensitive
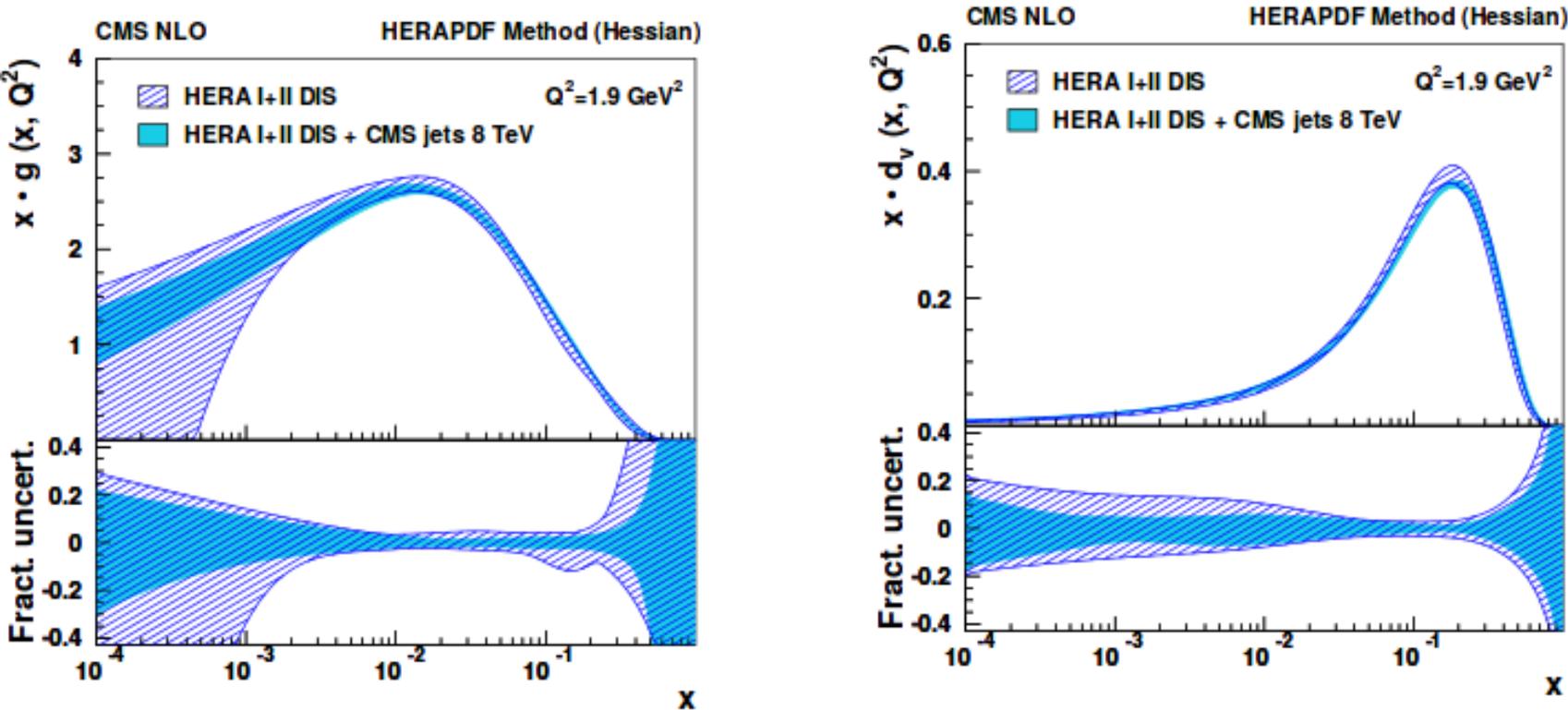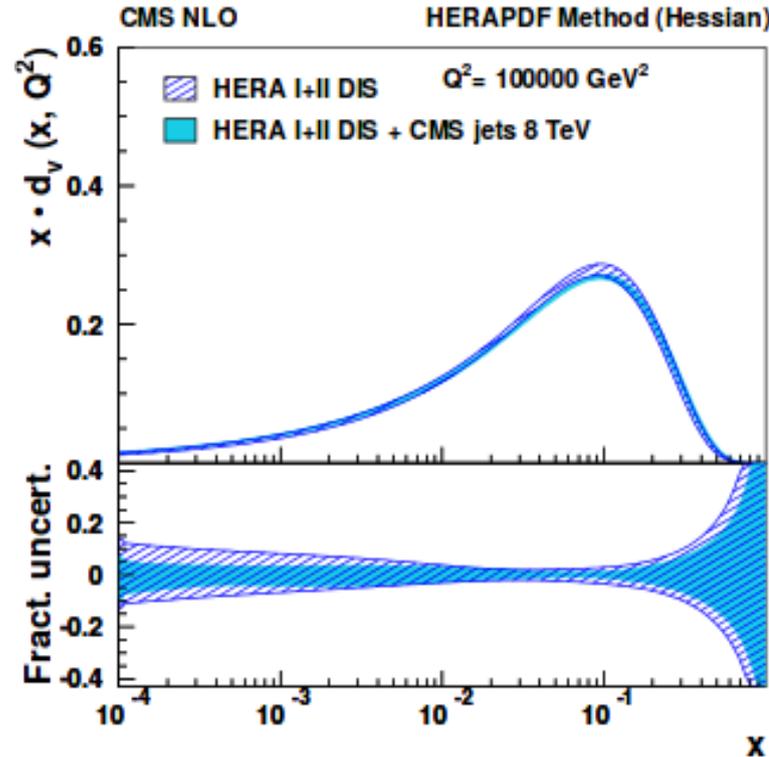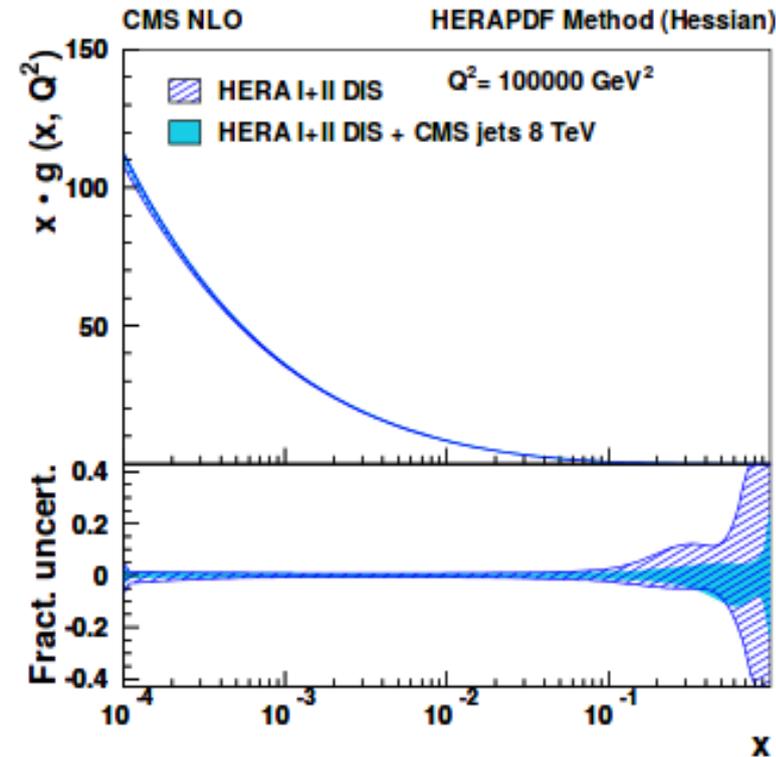
Using HERAFitter 1.1.1

- Significant reduction in uncertainty band for gluon both at low and high x

- Improvement in valence d quark PDF in low x region

Impact of Inclusive Jets on PDF

- Dominated by $gg \rightarrow gg$ at low p_T, $qg \rightarrow qg$ at medium p_T & $qq \rightarrow qq$ at high p_T => quark & gluon PDFs are sensitive

High Q^2

- Description of gluon improves at large x

  …. Useful for BSM search ;)

arXiv:1609.05331

Determination of Strong Coupling Constant using Inclusive Jets

$$\frac{d\sigma}{dp_T} = \alpha_S^2(\mu_R)\hat{X}^{(0)}(\mu_F, p_T)[1 + \alpha_S(\mu_R)K1(\mu_R, \mu_F, p_T)]$$

NLO prediction

$$\chi^2(\alpha_S(M_Z)) = \left(D - T(\alpha_S(M_Z))\right)^T C^{-1}\left(D - T(\alpha_S(M_Z))\right)$$

$$C = C^{\text{stat}} + C^{\text{unfolding}} + \sum C^{\text{JES}} + C^{\text{uncor}} + C^{\text{lumi}} + C^{\text{PDF}} + C^{\text{NP}}$$
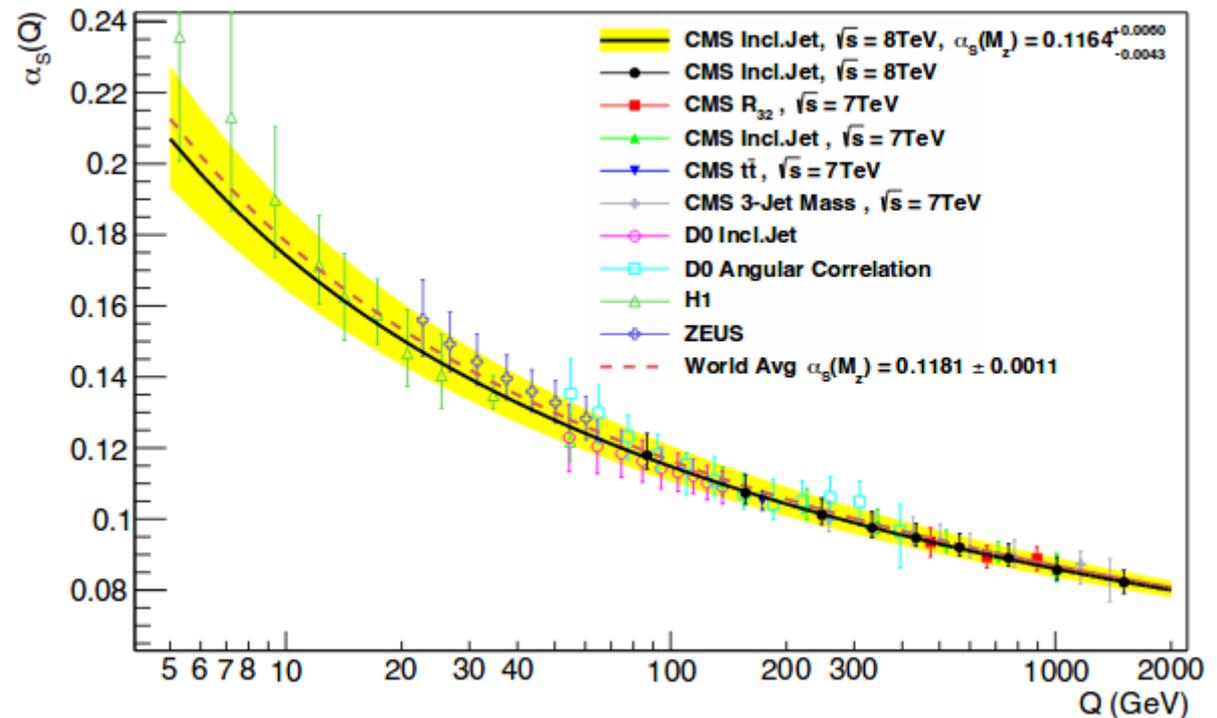
- χ^2 has been computed between NLO prediction (with CT10 PDF) and measured data in both exclusive and inclusive p_T & y bins with different choices of $a_s(M_Z)$ (in steps of 0.001 with range 0.112-0.127)

- a_s is determined in 9 bins in p_T range 74-2500 GeV (uncertainty from $\Delta\chi^2 = 1$)

  Q : x-section reweighted bin centre ($a_s(M_Z)$ evolved to Q scale using 2 loop 5F RG)

arXiv:1609.05331
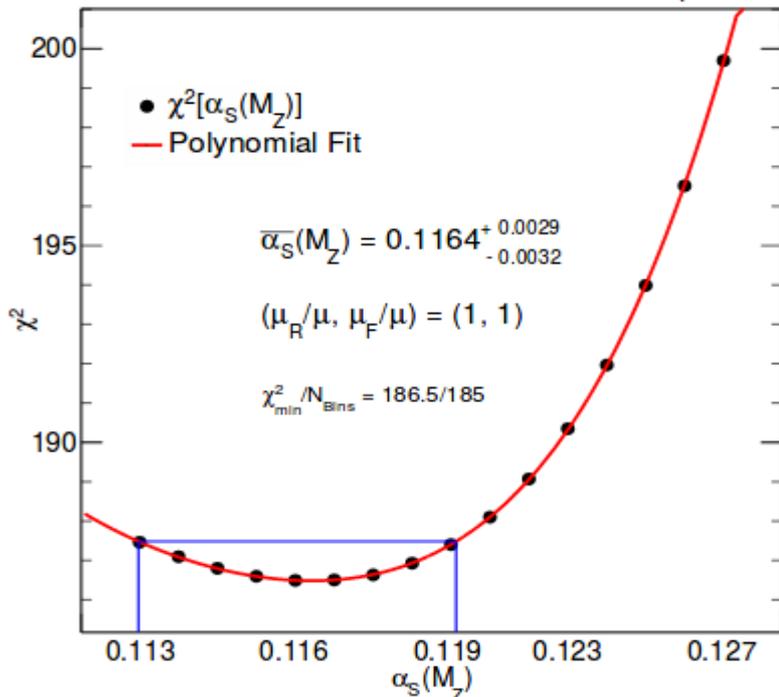
Jet Mass at 13 TeV : Massive Story

- Jet mass is the most commonly used observable to discriminate jets containing heavy objects from QCD & in BSM searches
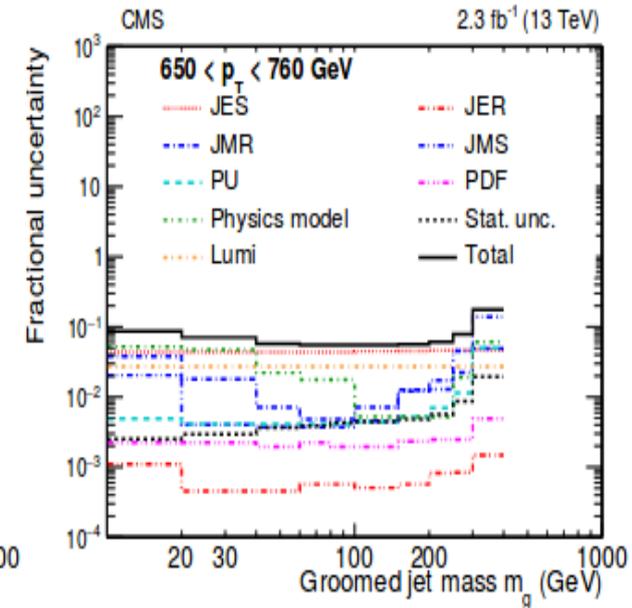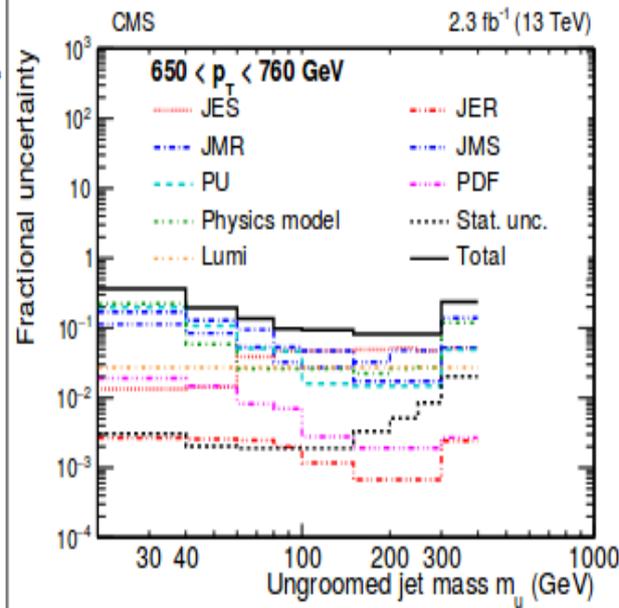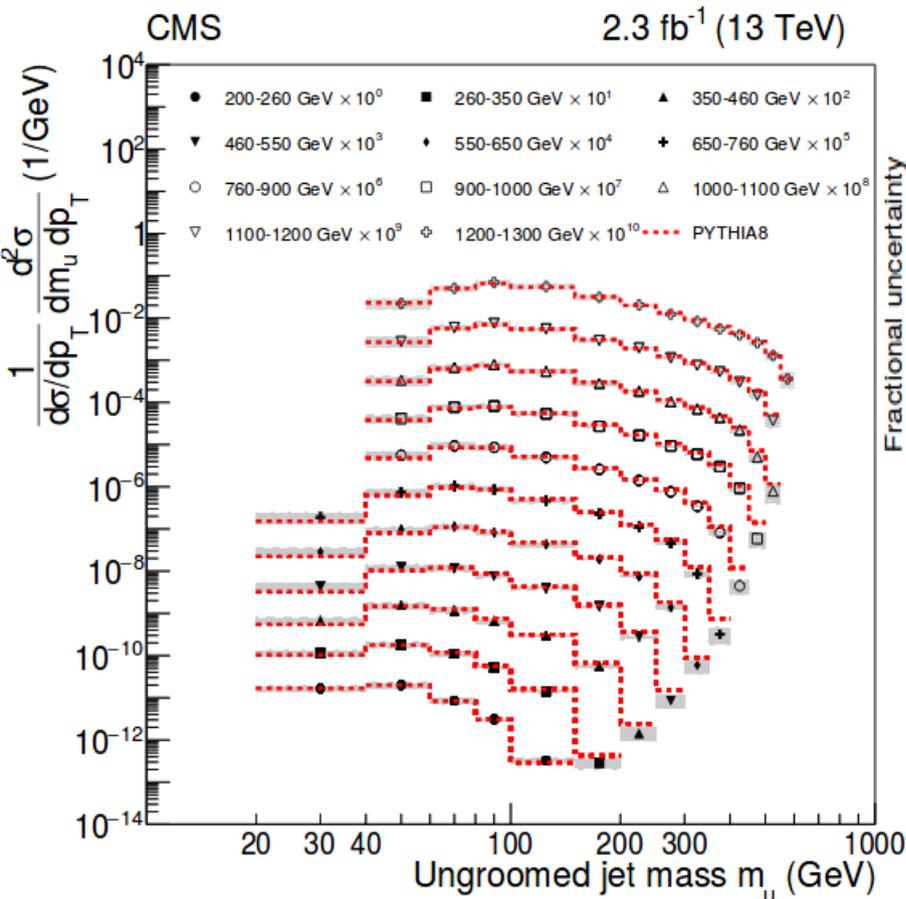
  CMS SMP-2016-010

- In QCD, jet mass arises from radiation :
  Sensitive to dynamics of QCD evolution starting from a parton

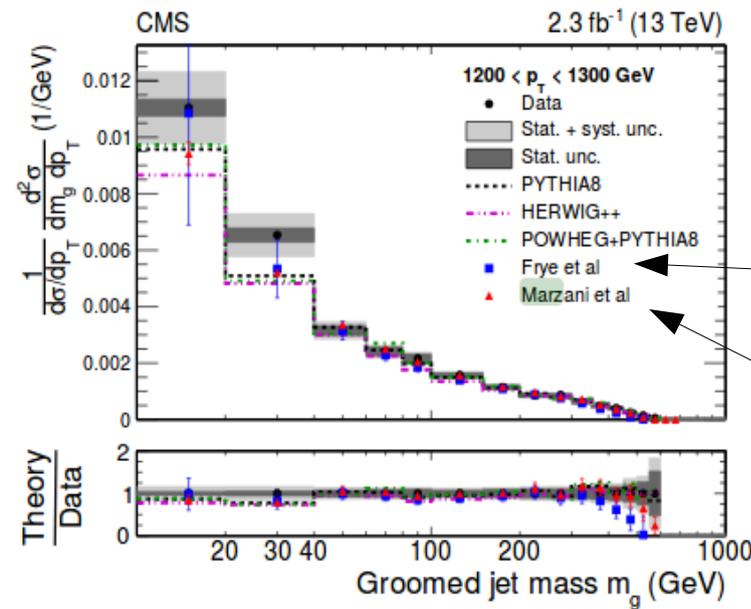- Radiation from partons exited from jet cone adds NGL : hard to compute =>
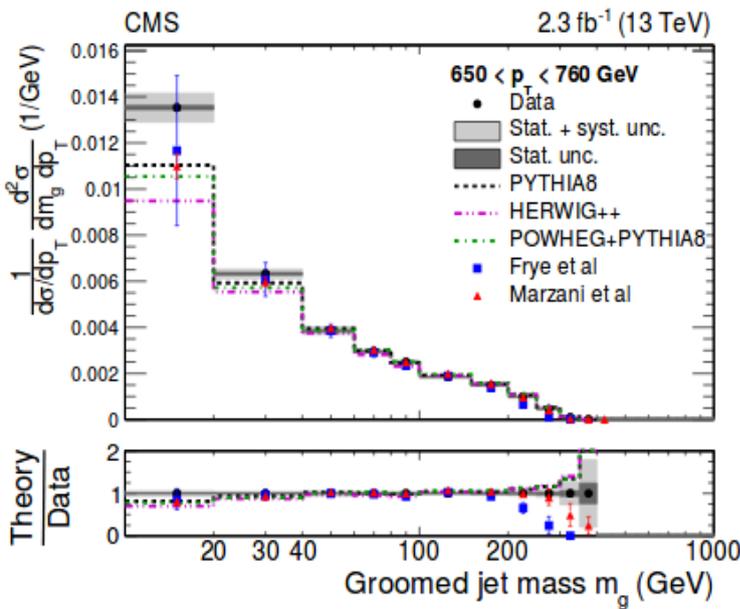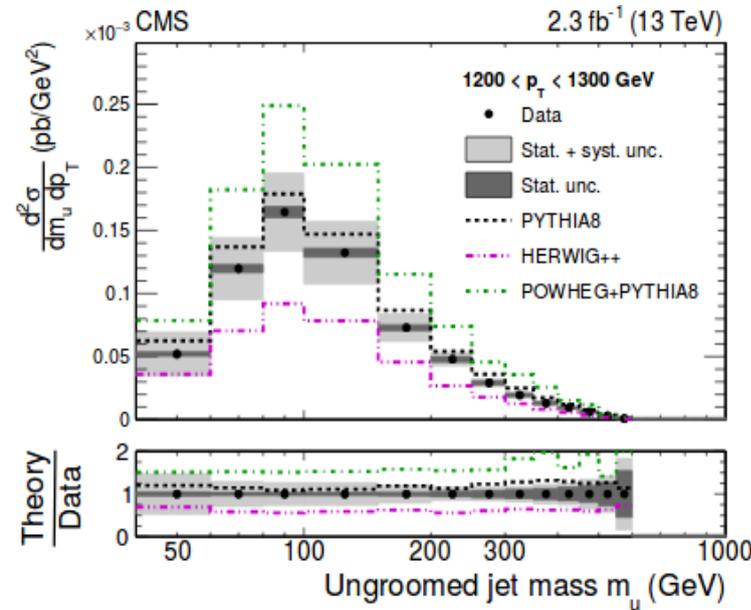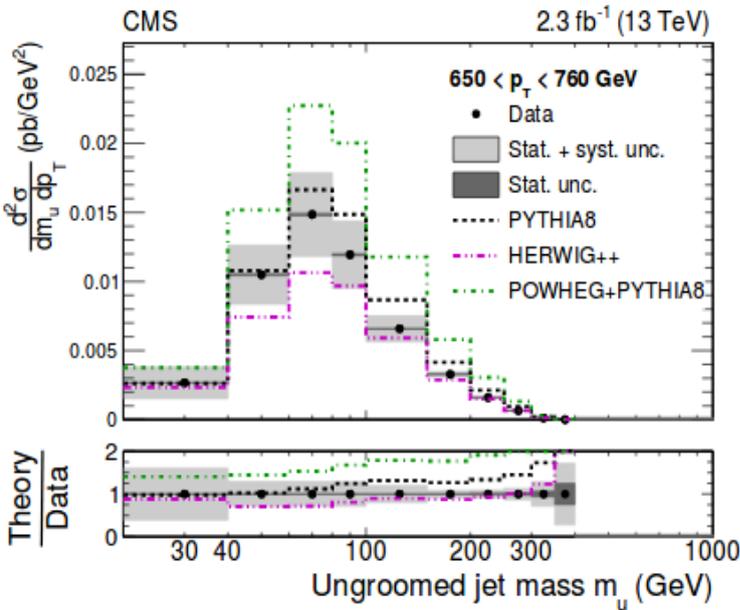 Use Soft Drop grooming to get rid of NGL

  Event Selection:
  At least 2 AK8 jets, $p_T > 200$ GeV, $|y| < 2.4$ &

  $$(p_{T_1} - p_{T_2})/(p_{T_1} + p_{T_2}) < 0.3 \quad \Delta(\phi_1 - \phi_2) > \pi/2$$

With grooming, PU sensitivity is reduced
Also modelling uncertainty is reduced
as Soft Drop removes soft gluons (hard to model)

Jet Mass at 13 TeV : Massive Story

Powheg + PYTHIA8 is unable to describe jet mass dist in data (for absolute x-section)

PYTHIA8 seems to be the best to predict distribution both for ungroomed & groomed jet mass

Analytic calculation can describe jet mass dist in data (for normalised x-section)

LO + NNLL (using SCET)

NLO + NLL

- Sudakov peak disappears in soft drop mass distribution

Event Shapes

- Measures geometrical properties of hadronic energy flow in an event (IRC safe)

- Sensitive to hard scattering & soft radtiation, hadronisation, MPI

- Used to tune MC generators and parton shower (LEP data)

- Also used on jet to tag boosted objects

- For this talk -

- Thrust :

  Choose axis (n_T) maximizing the numerator $\longrightarrow$
  $$T_\perp \equiv \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}}.$$
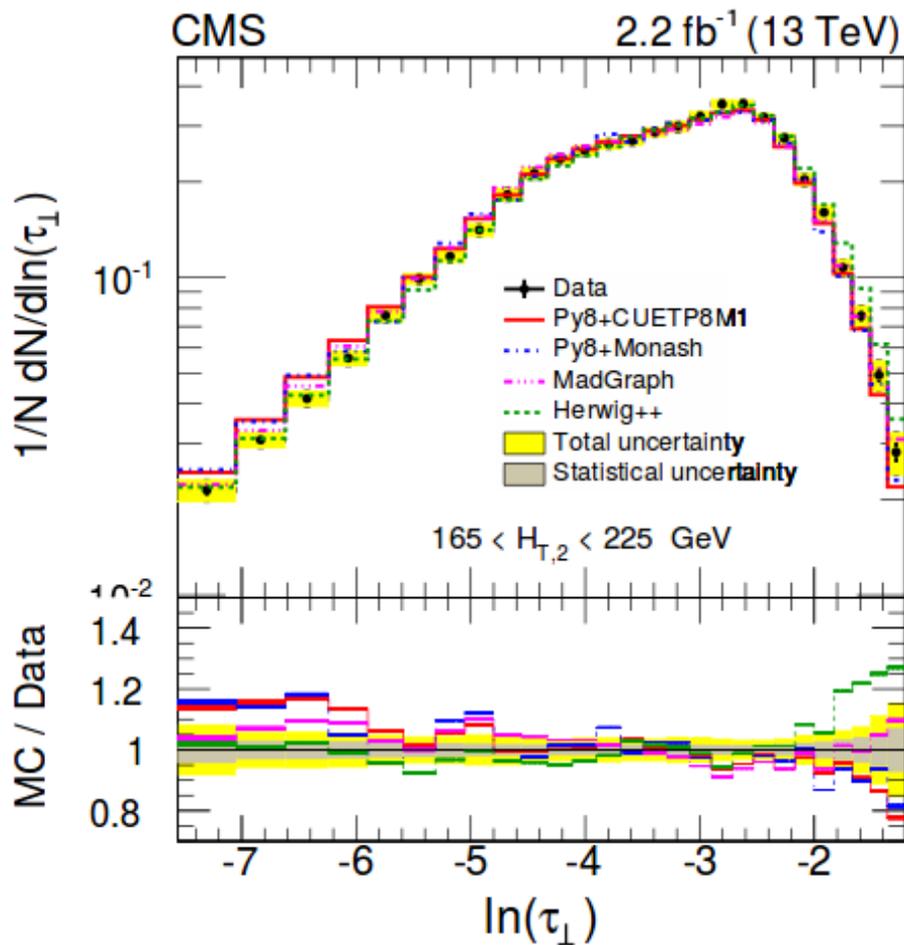 $$\tau_\perp \equiv 1 - T_\perp$$

- Broadening :
  Thrust axis (n_T) divides the event into upper (U) and lower (L) regions (denoted commonly by X)

  $$\eta_X \equiv \frac{\sum_{i \in X} p_{T,i} \eta_i}{\sum_{i \in X} p_{T,i}}, \phi_X \equiv \frac{\sum_{i \in X} p_{T,i} \phi_i}{\sum_{i \in X} p_{T,i}}$$

$$B_X \equiv \frac{1}{2 P_T} \sum_{i \in X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$$
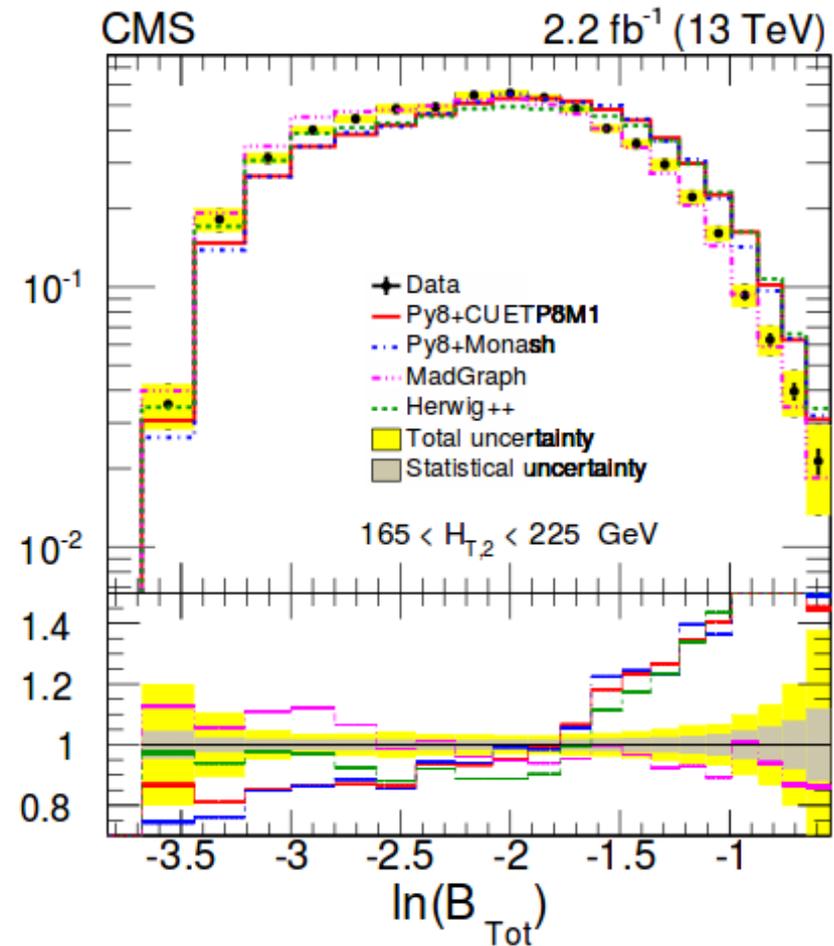
$$B_{\text{Tot}} \equiv B_U + B_L$$

23

Event Shapes : Data-MC Comparison

Sensitive to energy flow
in transverse plane

Use transverse and longitudinal
components equally

Different tunes of pythi8
agree well   =>
less sensitive to MPI tuning

CMS-SMP-17-003

Pythia8 moderately describes
Energy flow in transverse plane
But fails for out of plane flow
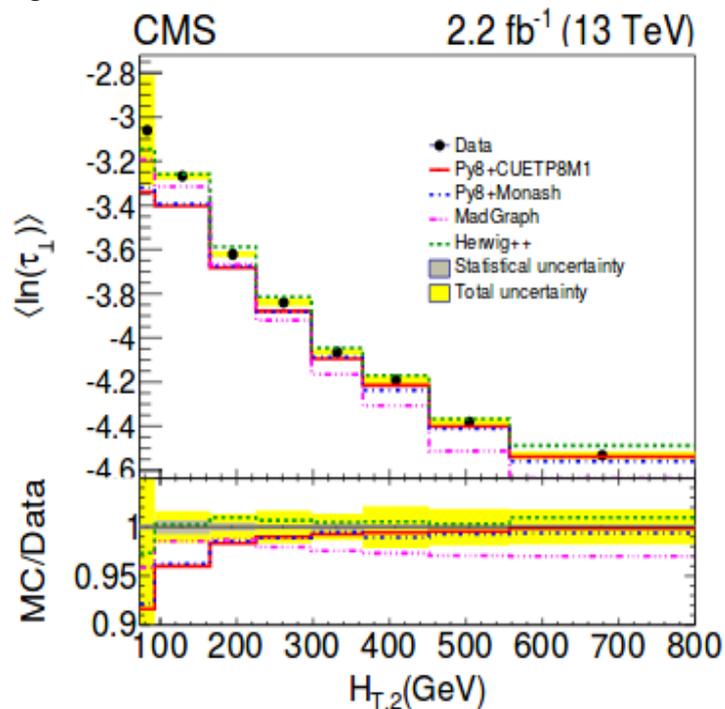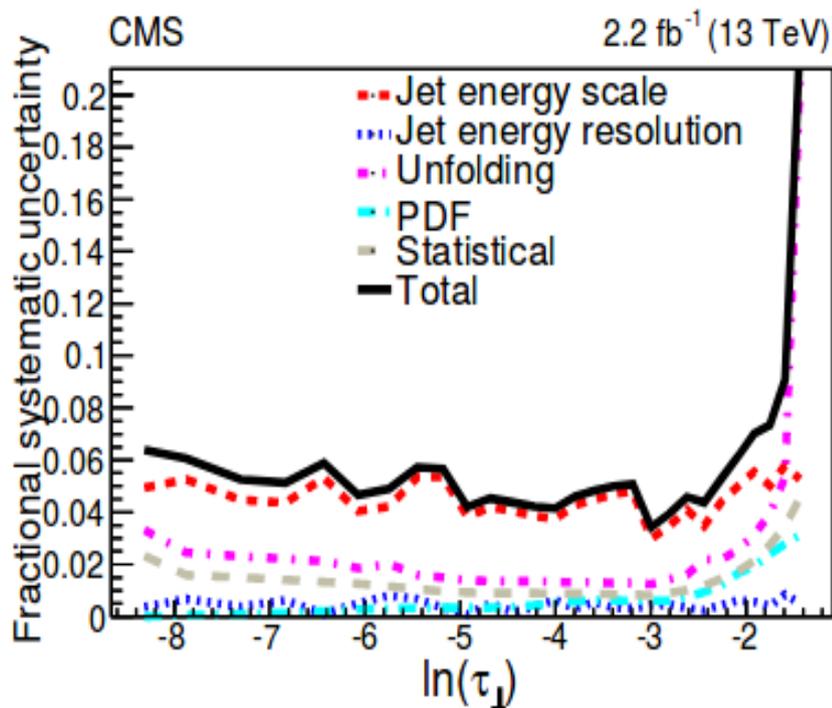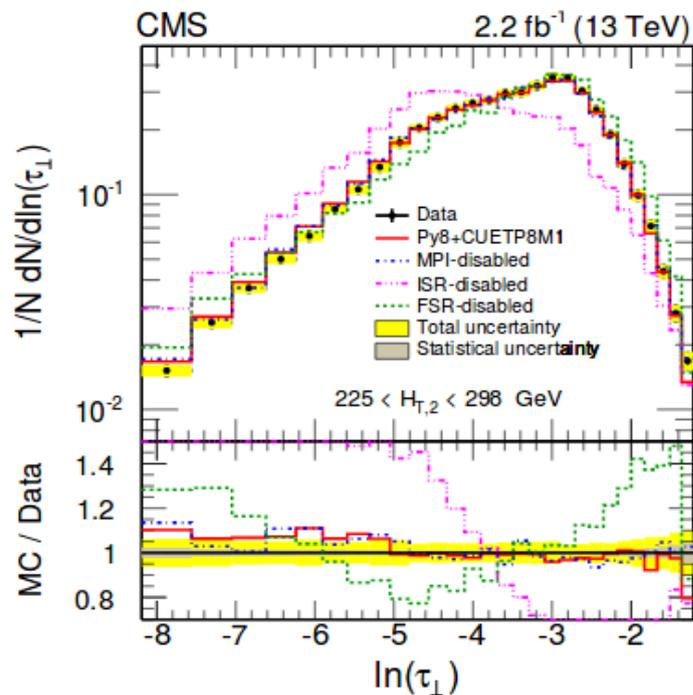
Herwig++ & Madgraph describes
the full event structure better

24

Event Shapes : Systematics

ISR has significant effect to predict even-shape

FSR moderately affects the prediction
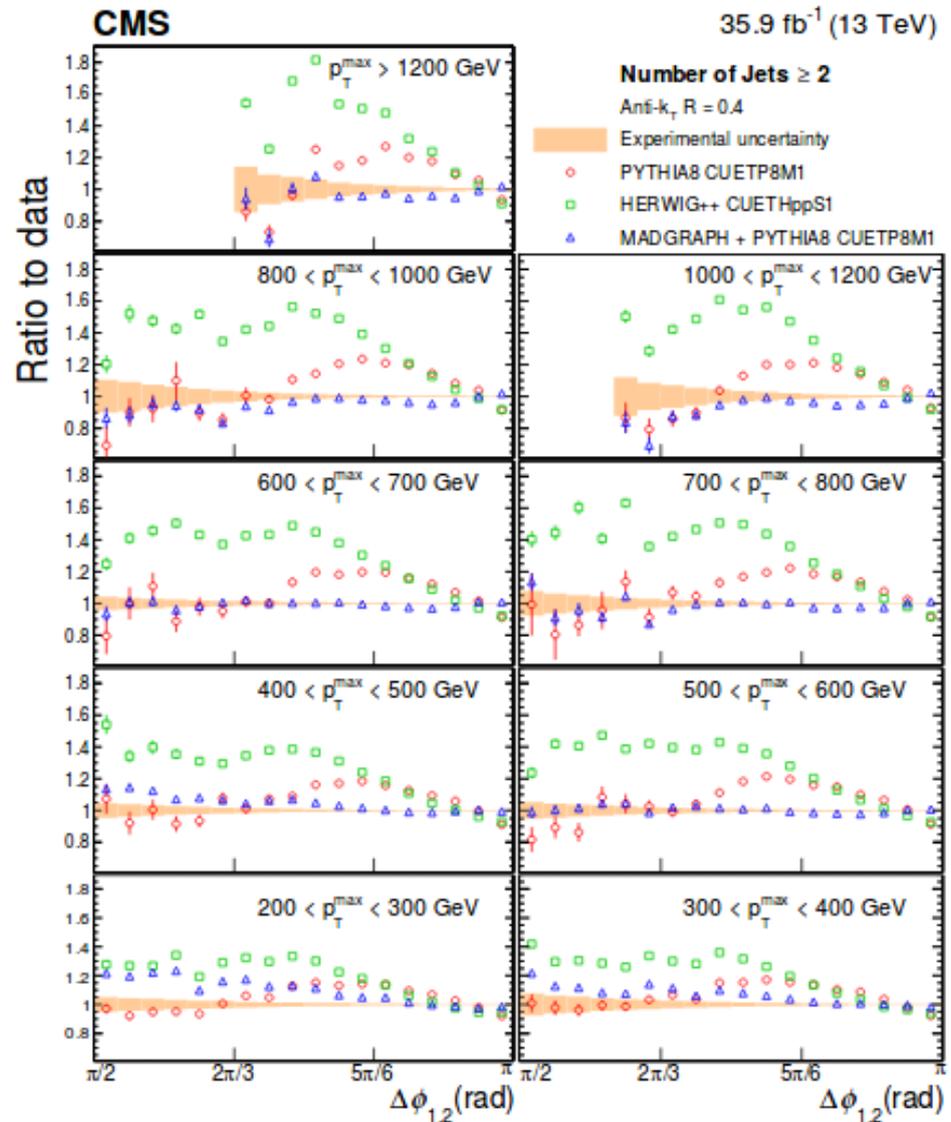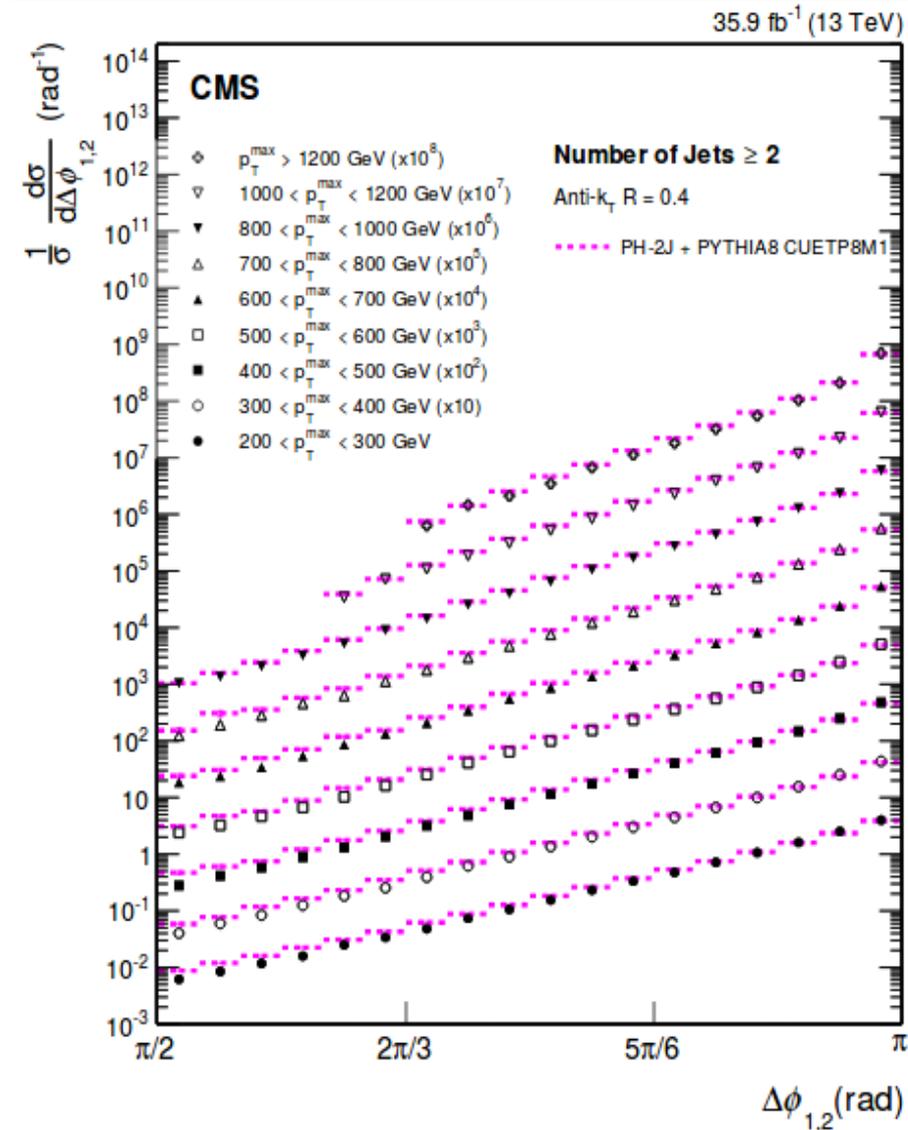
Sensitivity is very small for MPI

Very small theory uncertainty,
jet energy calibration dominates the systematics

In highly energetic phase space, α_s is smaller, less radiation
=> event tends to dijet topology

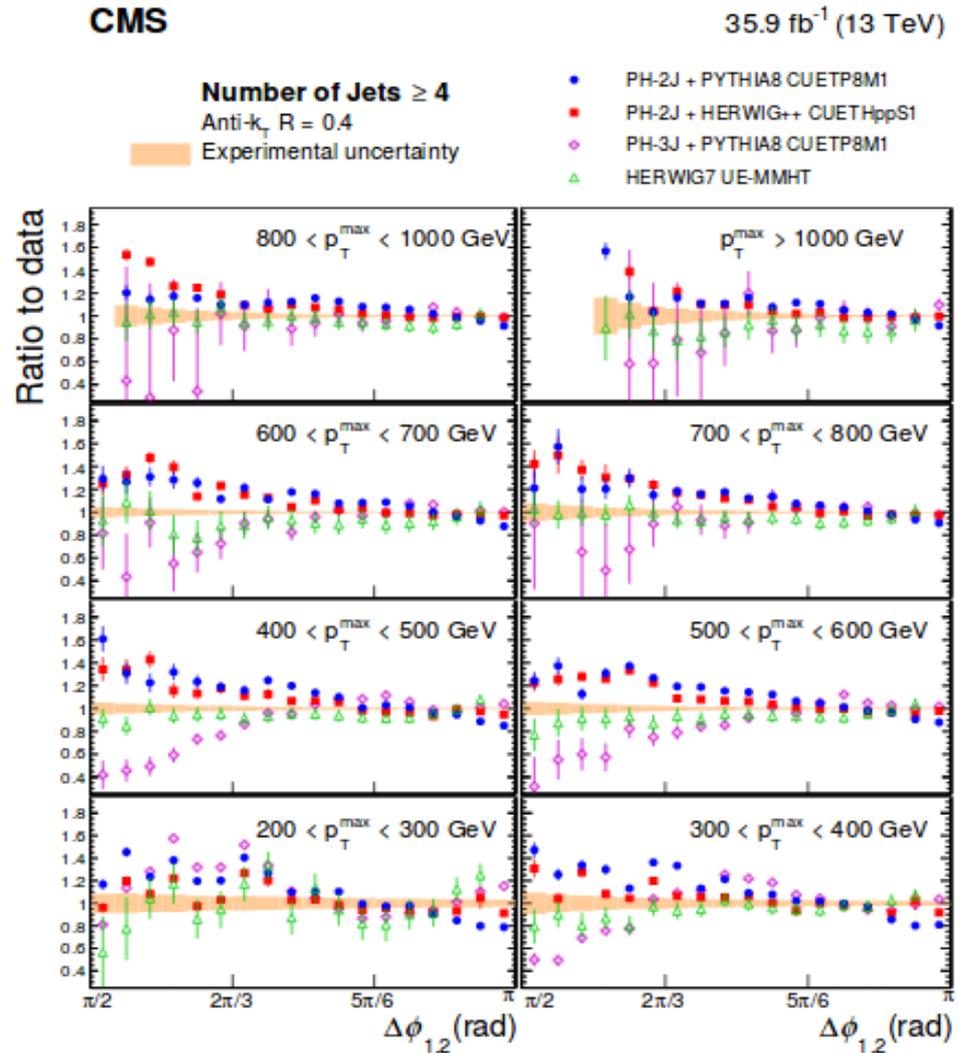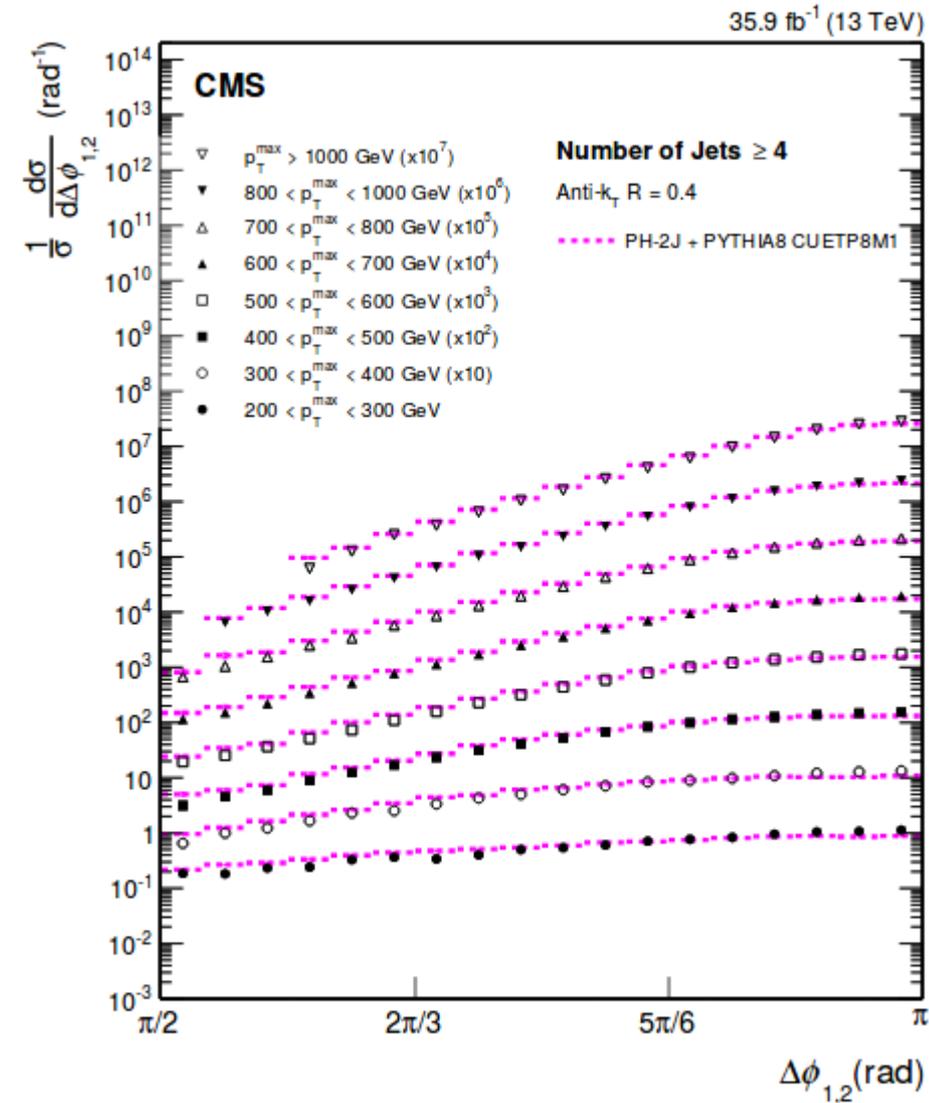CMS-SMP-17-003

Dijet Azimuthal Correlation

- Sensitive to radiation from hard leg & correlation between jets

- Choice of MC generator is crucial to describe the data

- Jet size also plays a threshold on lower side of Δφ

Dijet Azimuthal Correlation

- Sensitive to radiation from hard leg & correlation between jets

- Even NLO generator is unable to describe data in parts of phase space

- Herwig7 (NLO generator + PS from Herwig++) performs best

Conclusion

- CMS has a wealth of results on inclusive jets   (many more to come)

- Inclusive jets have been established as a powerful tool to understand QCD, measure α_S, constrain PDFs, …

- Better calibration helps to make measurements more precise

- Experimental uncertainty is similar or less than theoretical uncertainty

- Fixed order NLO prediction (with NP & EW correction) describes large jets almost all over the phase space

- NLO+PS are found to make better prediction for small R jets, angular correlation and also for the cross-section ratio of two jet sizes

- Motivates higher order calculation with resummation to be the state-of-the-art

THANK YOU!

More Material ..

Impact of Inclusive Jets on PDF

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + E_g x^2) - A'_g x^{B'_g} (1-x)^{C'_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + D_{u_v} x + E_{u_v} x^2),$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} (1 + D_{d_v} x),$$

$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}} (1-x)^{C_{\overline{U}}} (1 + D_{\overline{U}} x),$$

$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}} (1-x)^{C_{\overline{D}}} (1 + D_{\overline{D}} x + E_{\overline{D}} x^2).$$

-

arXiv:1609.05331

$$\alpha_S(M_Z) = 0.1185^{+0.0019}_{-0.0021} (\text{exp})^{+0.0002}_{-0.0015} (\text{model})^{+0.0000}_{-0.0004} (\text{param})^{+0.0022}_{-0.0018} (\text{scale})$$

-

- For PDF Experimental uncertainty using Hessian method
  Modelling uncertainty from b-mass, c-mass, Q_{min}
  Parameterisation uncertainty from additional terms in function

Jet Energy Calibration : Prep for Measurement

- Cross-section measurement depends crucially on energy calibration (steep spectra ➜ mis-measurement leads to bin migration)

- Factorised approach to match energy scale of detector level jets to particle level L1 (L2 & L3 e L2L3 Residual
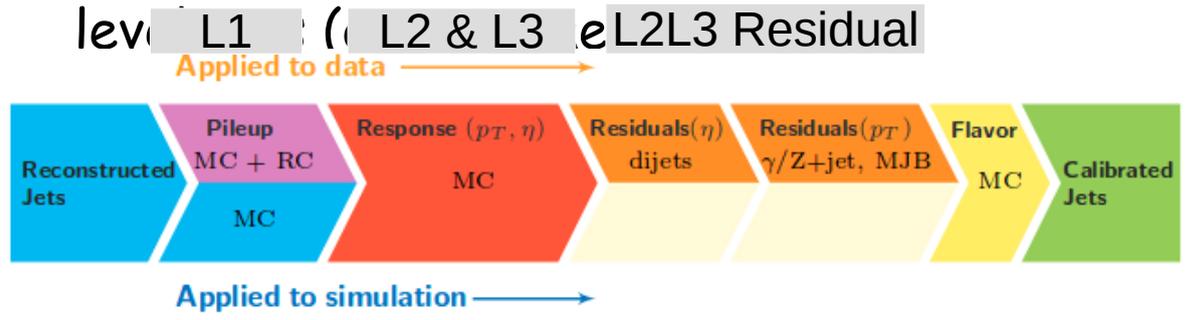
CMS DP-2018/028

-

- Pile-up subtraction by removing tracks coming fr neutrals by hybrid area-subtraction using pile-up method

- Correction as a function of jet pseudorapidity an based on simulation

Stable response
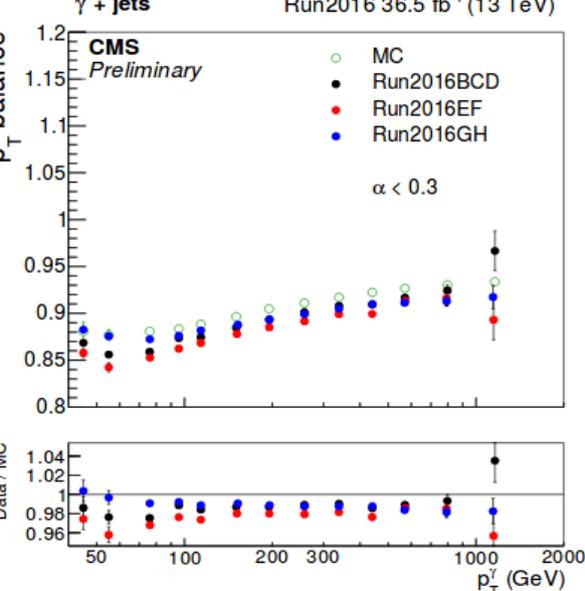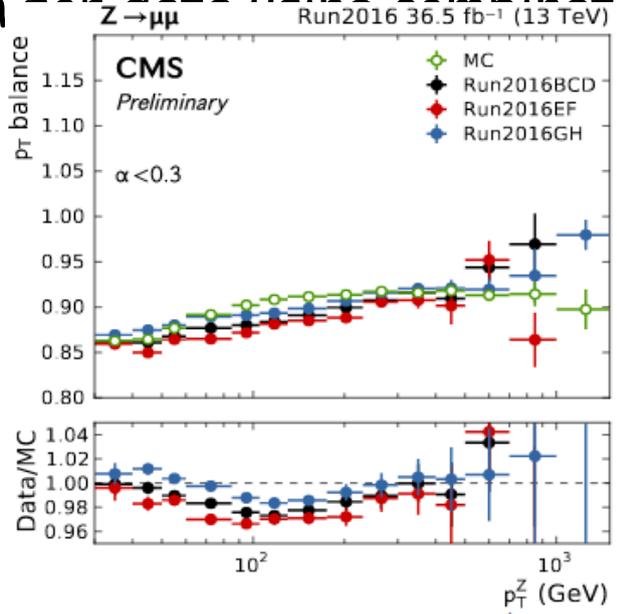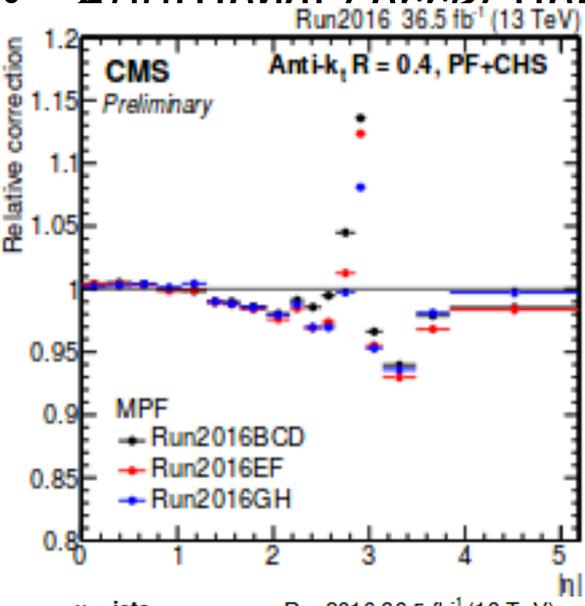In barrel,
Requires pt dependent
Correction in EC & HF
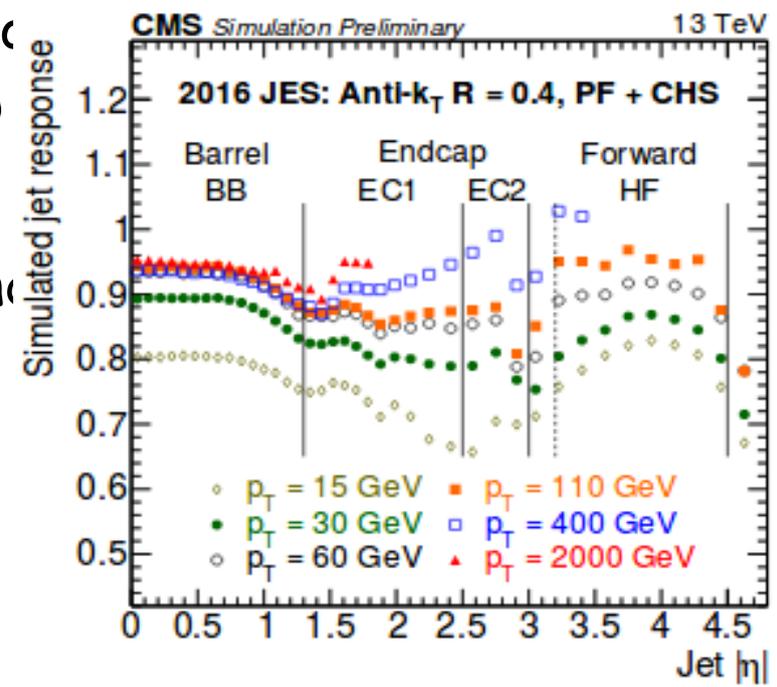
Jet Energy Calibration & Resolution

- 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

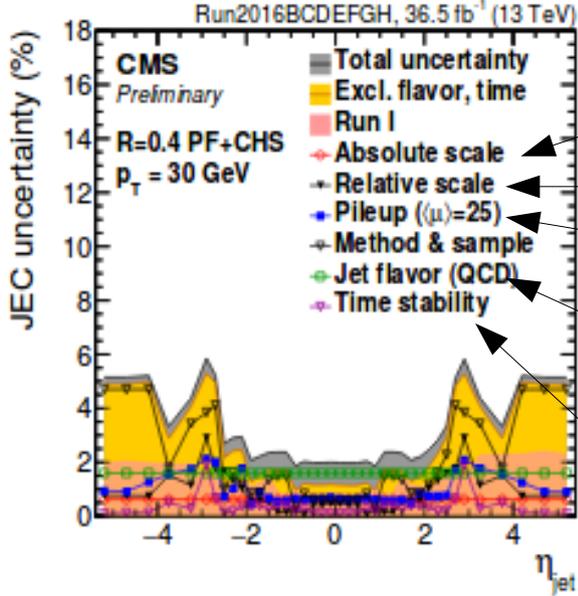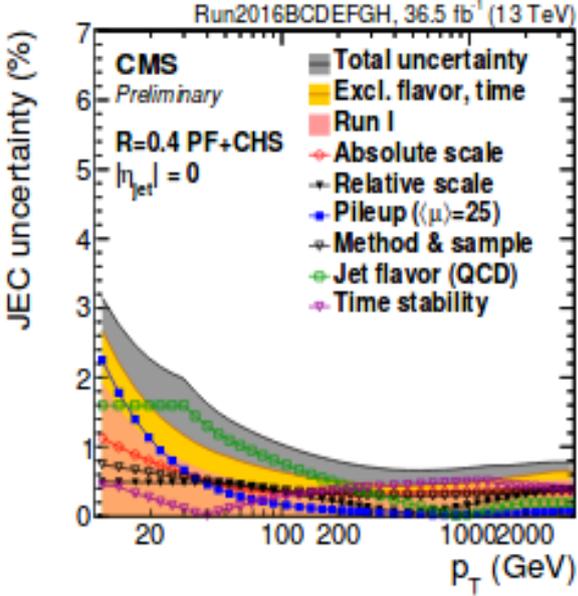Effect of Pile up below pt <100 GeV
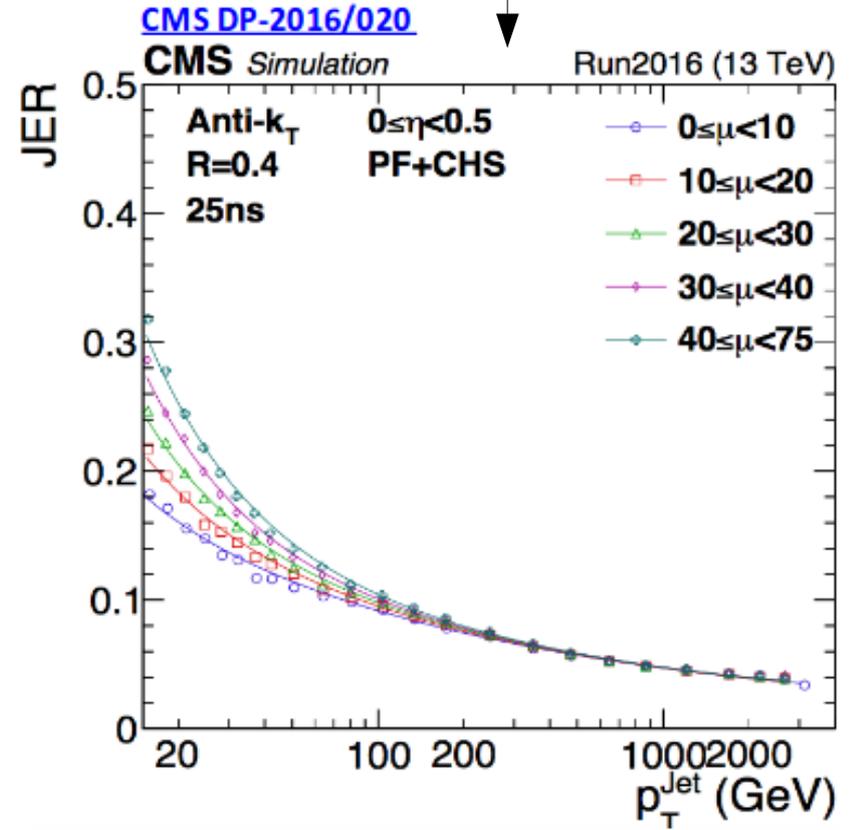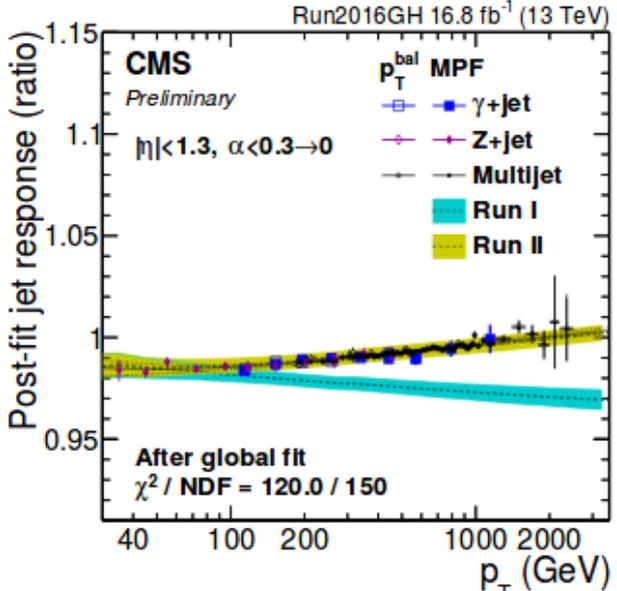
Uncertainty Jet Energy Calibration

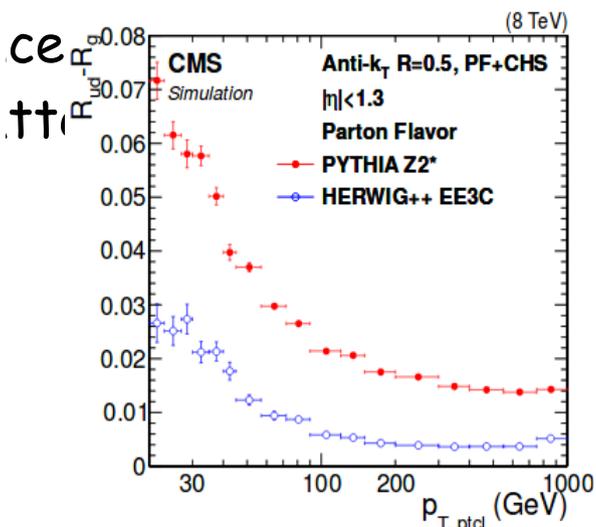- Normally below 1-2% in the phase space used for differential cross-section measurement

CMS DP-2018/028
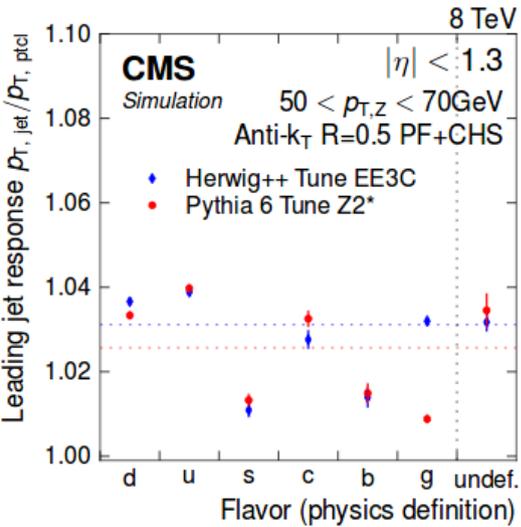
Uncertainty Components:

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

Closure of lumi weigted correction
per era

-

ce ... tt ... on is crucial

rton shower)

CMS JME-2013-004

33